東京大学
THE UNIVERSITY OF TOKYO

UTIAS
東京大学国際高等研究所
THE UNIVERSITY OF TOKYO
INSTITUTES FOR ADVANCED STUDY

KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Cosmology Dark Matter

AESHEP Sep 20, 2018

Kavli IPMU, University of Tokyo
UC Berkeley, Lawrence Berkeley Laboratory
Hitoshi Murayama

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

How did the Universe begin?

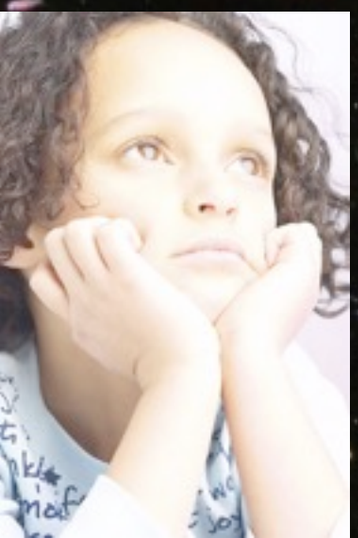
What is its fate?

What is it made of?

What are its fundamental laws?

Why do we exist?

interdisciplinary institute of
astronomy, physics and mathematics
10-year program by Japanese
government since 2007



UTIAS
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KAVLI IPMU

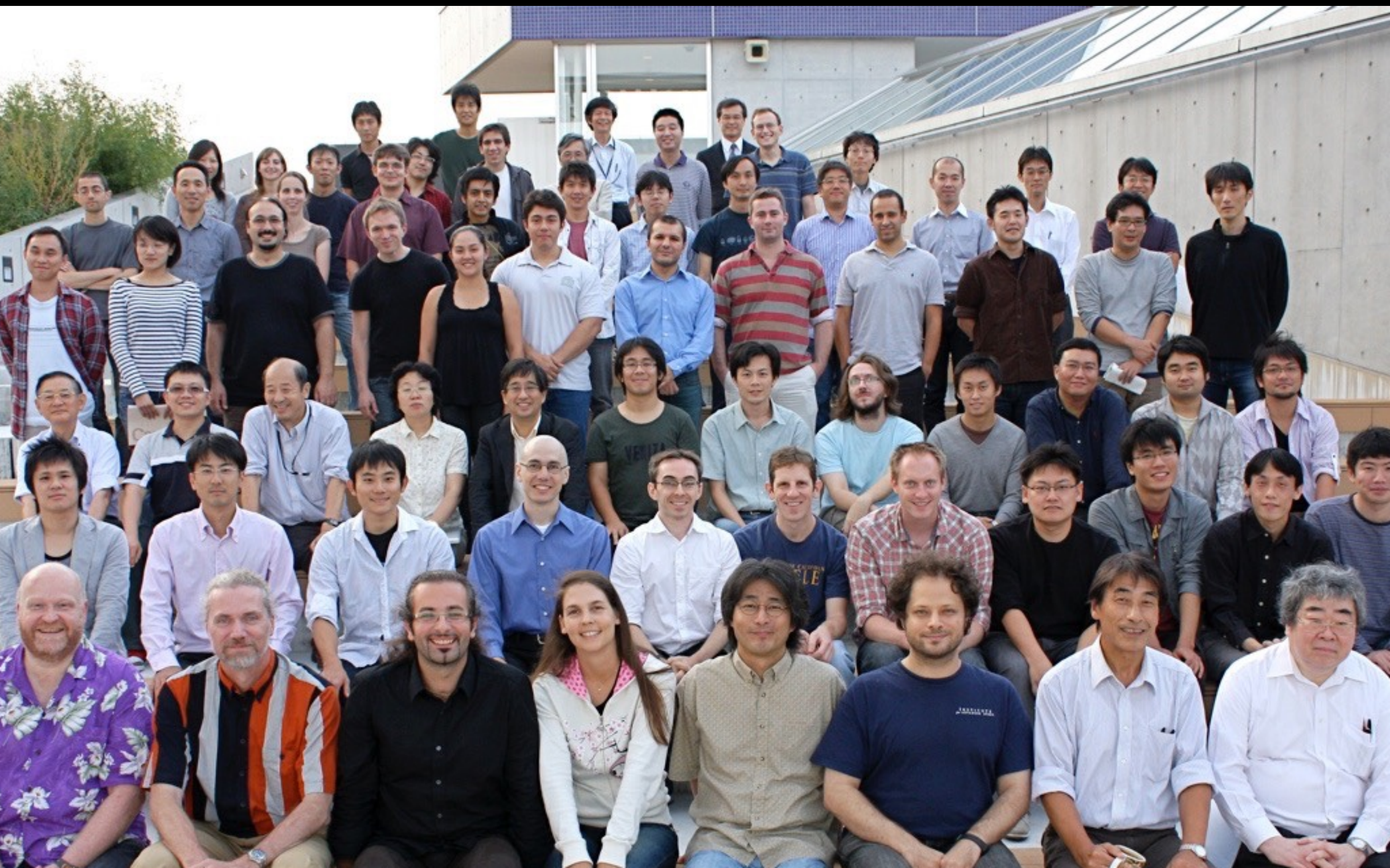
Oct 2007

Oct 2008

KAVLI IPMU

学国際高等研究所
UNIVERSITY OF TOKYO
TES FOR ADVANCED STUDY

Oct 2010



Oct 2016

Non Japanese ~50%

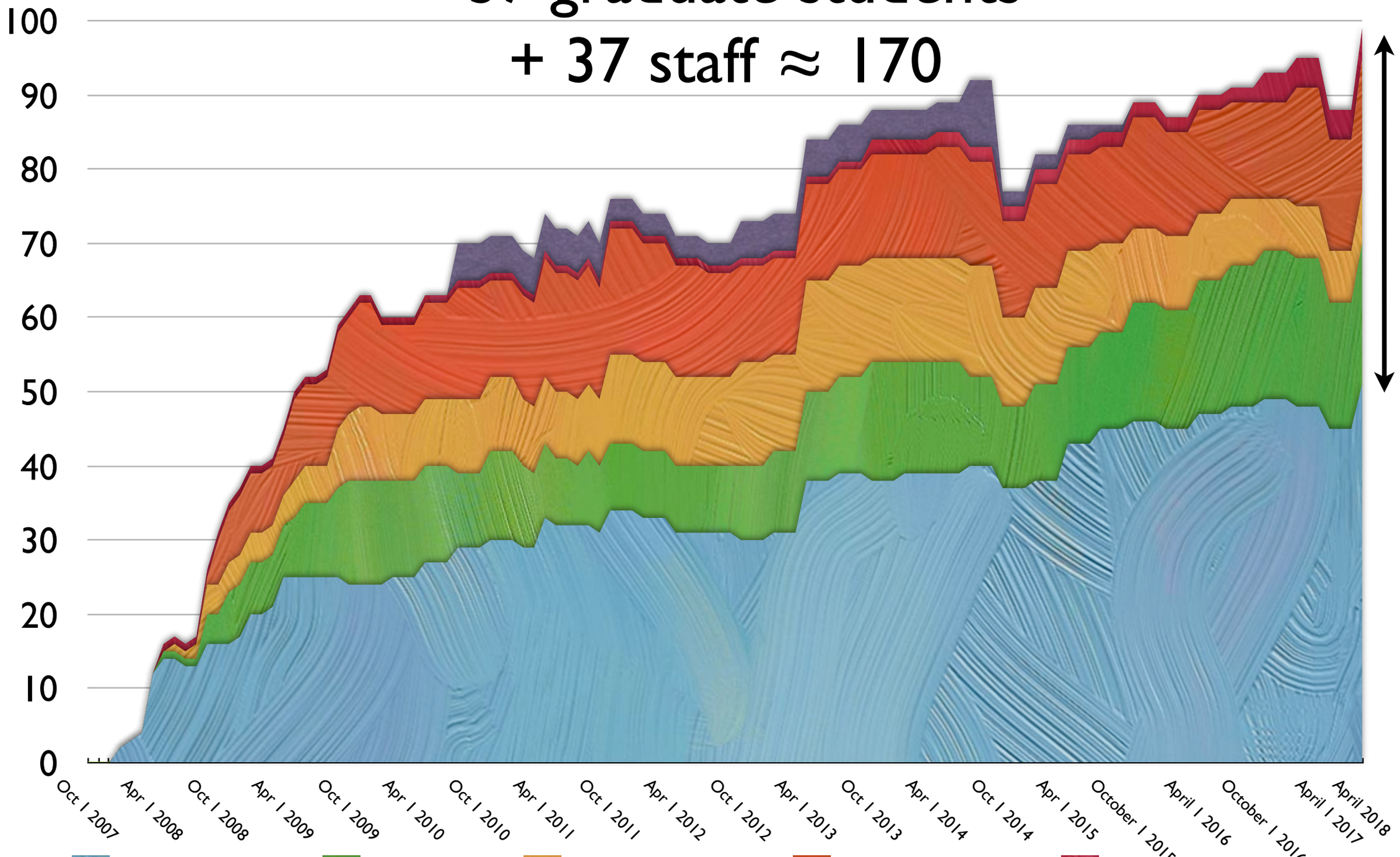
Oct 2017

Full-time Scientists paid by IPMU

+37 graduate students

+ 37 staff ≈ 170

04/01/2018



*Argentina,Canada, Chile

brand-new building 2010

“European town square”

obelisk

“L’Universo é scritto in lingua matematica”


日本の頭脳
iPMU
Institute for the Physics and Mathematics of the Universe
2007年設立
東京大学国際高等研究所数物連携宇宙研究機構
Institute for the Physics and Mathematics of the Universe

Asahi TV

KAVLI

IPMU

INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

THE KAVLI FOUNDATION

officially Kavli IPMU on April 1, 2012

First research institute in Japan named after a donor, breaking new grounds

Cosmology
Dark Matter

AESHEP Oct 25, 2012

Kavli IPMU, University of Tokyo
UC Berkeley, Lawrence Berkeley Laboratory
Hitoshi Murayama

The whole Universe was smaller than an atom

13.7Gyr

Big Bang

dark ages

particle soup

star

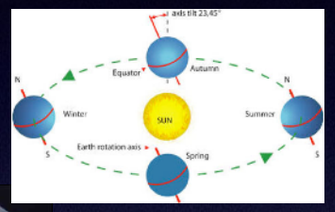
Earth

scales

10^{27}m

10^{23}m

10^{20}m

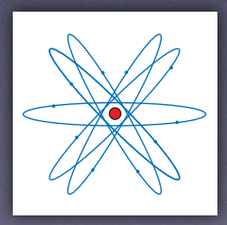


10^{11}m

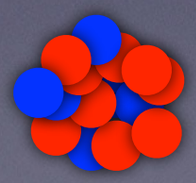
10^{7}m

10^{3}m

0.1m



10^{-10}m

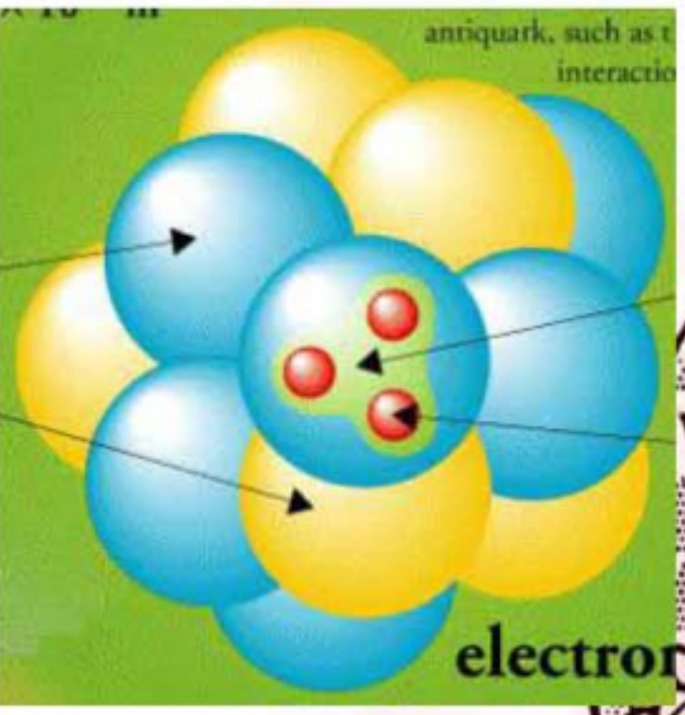


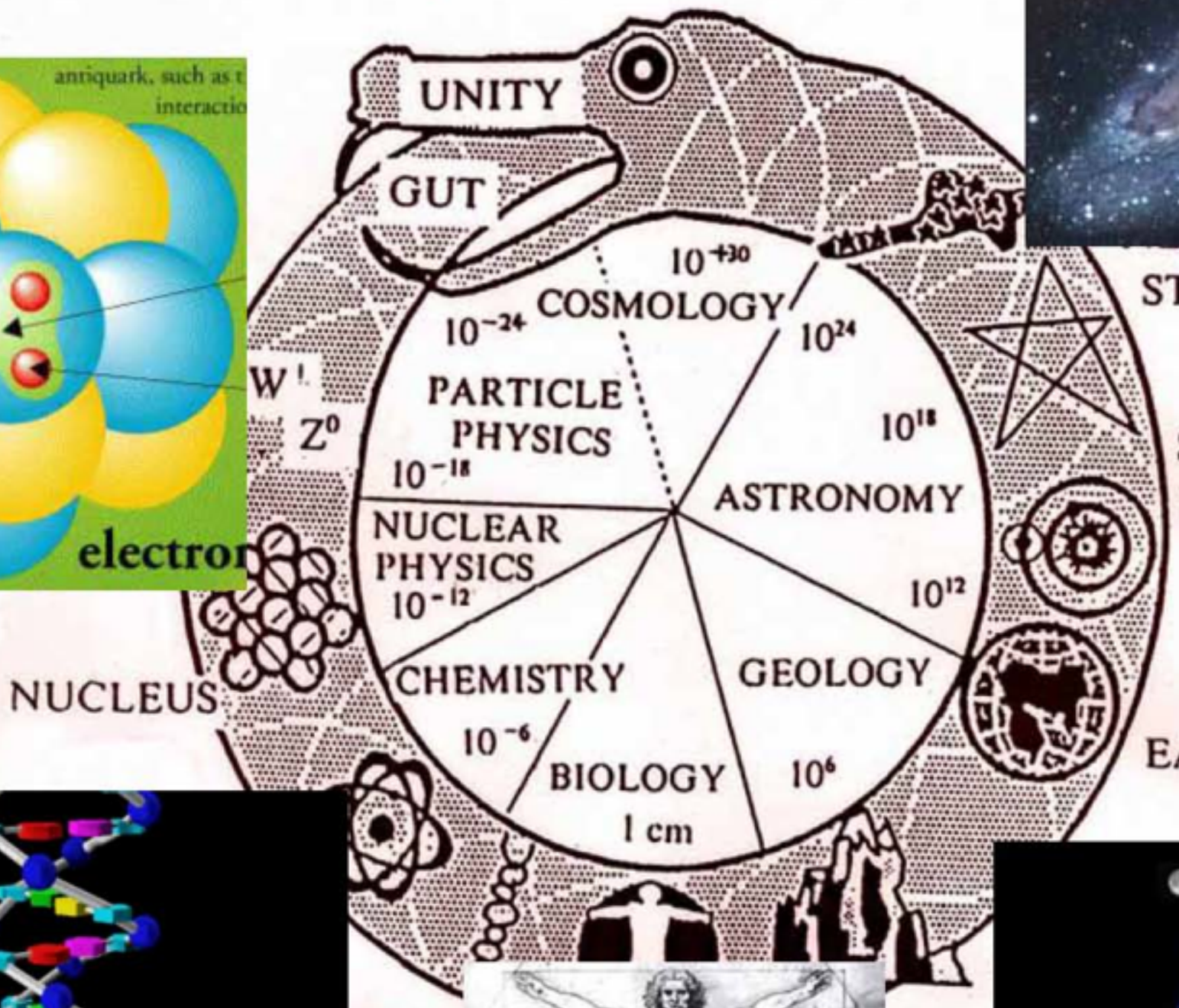
10^{-15}m

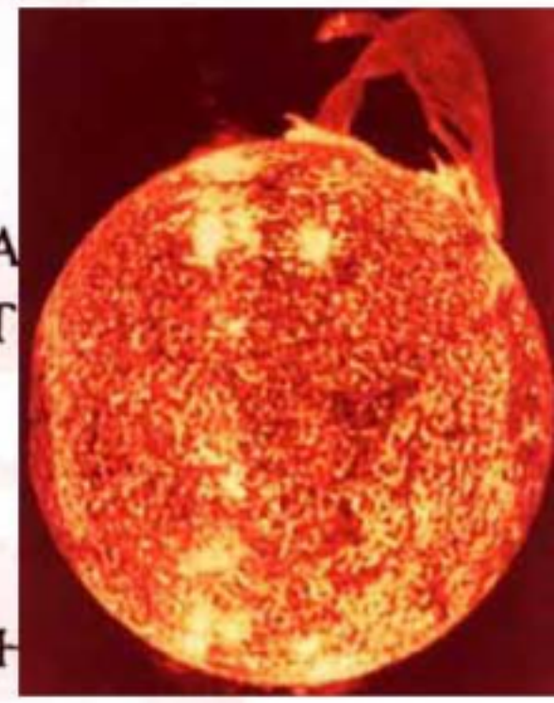
10^{-19}m

- distance scales in nature

Snake of Sizes



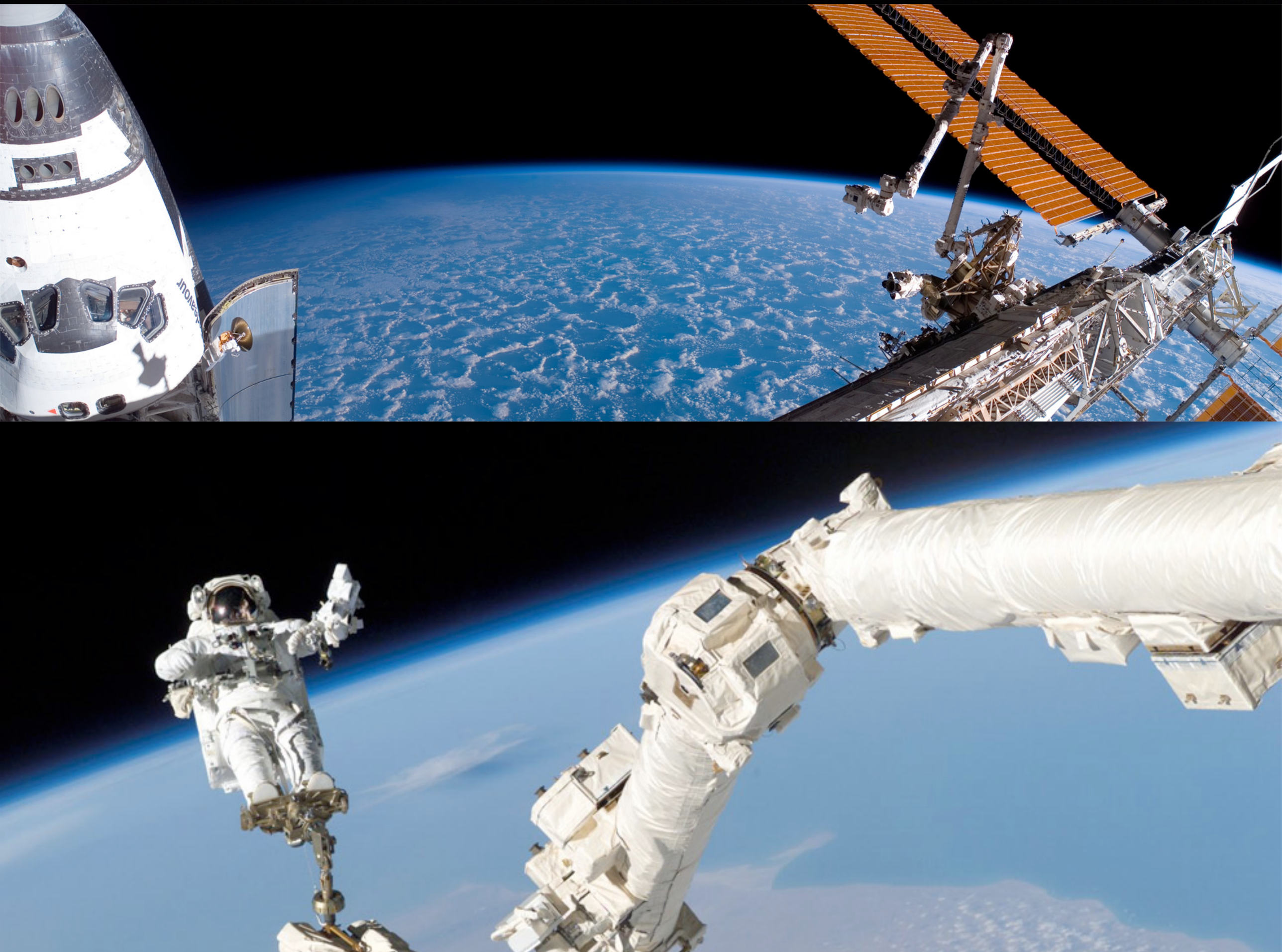




Time Machine

Time Machine

Solar System



Apr 7 2012

375 km above ground

skin of peach

Sep 30, 2008
Kaguya

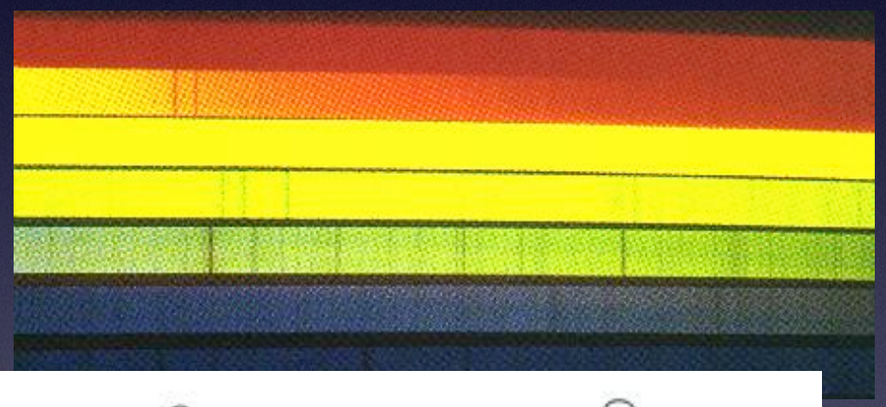
380,000km
=1.3 light seconds

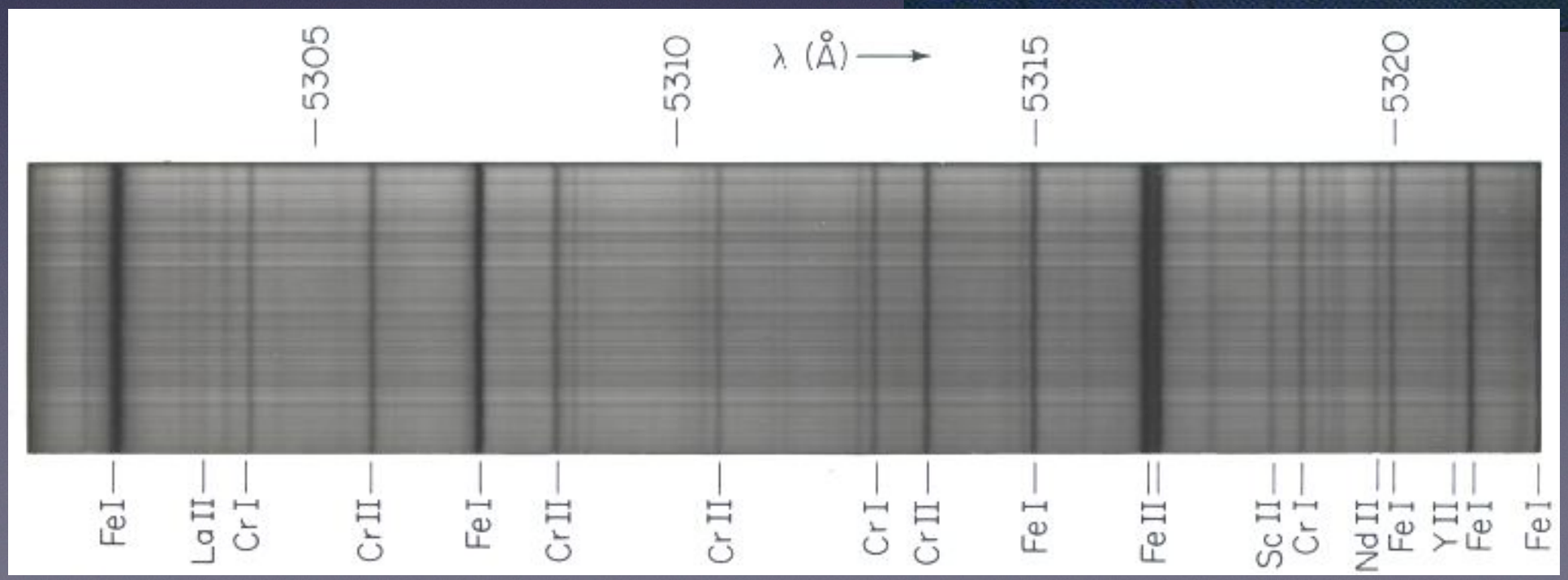
380,000km
=1.3 light seconds

1.5×10^8km
=8.3 light minutes

Made of atoms

- everything around us is made of atoms
- stars are made of atoms, too
- spectroscopy





PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

GROUP

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 **H** HYDROGEN																	2 4.0026 **He** HELIUM
2	3 6.941 **Li** LITHIUM	4 9.0122 **Be** BERYLLIUM											5 10.811 **B** BORON	6 12.011 **C** CARBON	7 14.007 **N** NITROGEN	8 15.999 **O** OXYGEN	9 18.998 **F** FLUORINE	10 20.180 **Ne** NEON
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5	37 85.468 **Rb** RUBIDIUM	38 87.62 **Sr** STRONTIUM	39 88.906 **Y** YTTRIUM	40 91.224 **Zr** ZIRCONIUM	41 92.906 **Nb** NIOBIUM	42 95.94 **Mo** MOLYBDENUM	43 (98) **Tc** TECHNETIUM	44 101.07 **Ru** RUTHENIUM	45 102.91 **Rh** RHODIUM	46 106.42 **Pd** PALLADIUM	47 107.87 **Ag** SILVER	48 112.41 **Cd** CADMIUM	49 114.82 **In** INDIUM	50 118.71 **Sn** TIN	51 121.76 **Sb** ANTIMONY	52 127.60 **Te** TELLURIUM	53 126.90 **I** IODINE	54 131.29 **Xe** XENON
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RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME

Metal
Semimetal
Nonmetal
1 Alkali metal
2 Alkaline earth metal
Transition metals
Lanthanide
Actinide
16 Chalcogens element
17 Halogens element
18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Ga - liquid
Fe - solid
Tc - synthetic

metals

LANTHANIDE

57 138.91 **La** LANTHANUM	58 140.12 **Ce** CERIUM	59 140.91 **Pr** PRASEODYMIUM	60 144.24 **Nd** NEODYMIUM	61 (145) **Pm** PROMETHIUM	62 150.36 **Sm** SAMARIUM	63 151.96 **Eu** EUROPIUM	64 157.25 **Gd** GADOLINIUM	65 158.93 **Tb** TERBIUM	66 162.50 **Dy** DYSPROSIUM	67 164.93 **Ho** HOLMIUM	68 167.26 **Er** ERBIUM	69 168.93 **Tm** THULIUM	70 173.04 **Yb** YTTERBIUM	71 174.97 **Lu** LUTETIUM

ACTINIDE

89 (227) **Ac** ACTINIUM	90 232.04 **Th** THORIUM	91 231.04 **Pa** PROTACTINIUM	92 238.03 **U** URANIUM	93 (237) **Np** NEPTUNIUM	94 (244) **Pu** PLUTONIUM	95 (243) **Am** AMERICIUM	96 (247) **Cm** CURIUM	97 (247) **Bk** BERKELIUM	98 (251) **Cf** CALIFORNIUM	99 (252) **Es** EINSTEINIUM	100 (257) **Fm** FERMIUM	101 (258) **Md** MENDELEVIUM	102 (259) **No** NOBELIUM	103 (262) **Lr** LAWRENCIUM

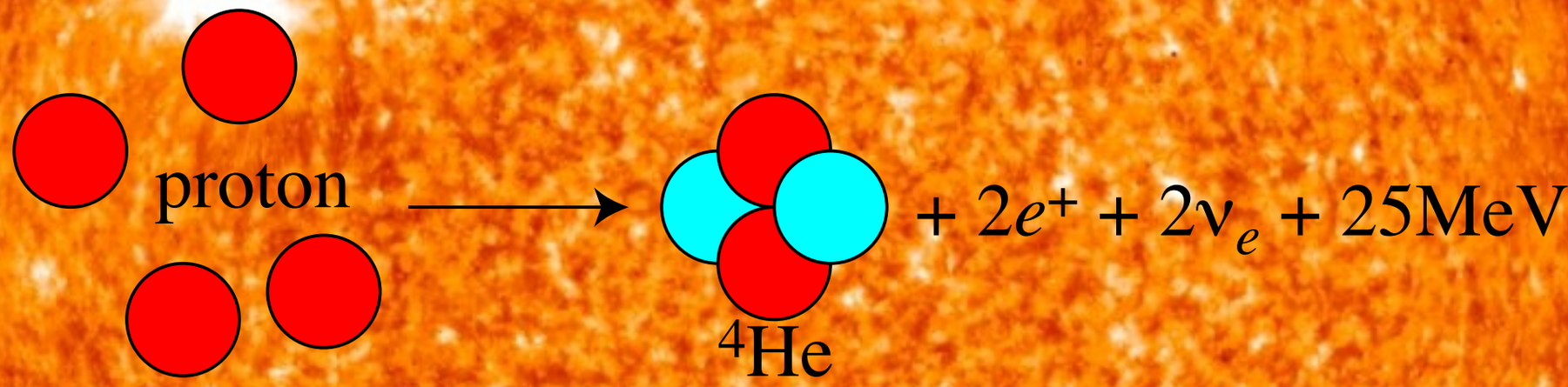
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

1.5×10^8km
=8.3 light minutes



$E=mc^2$

5 Mt lighter every second

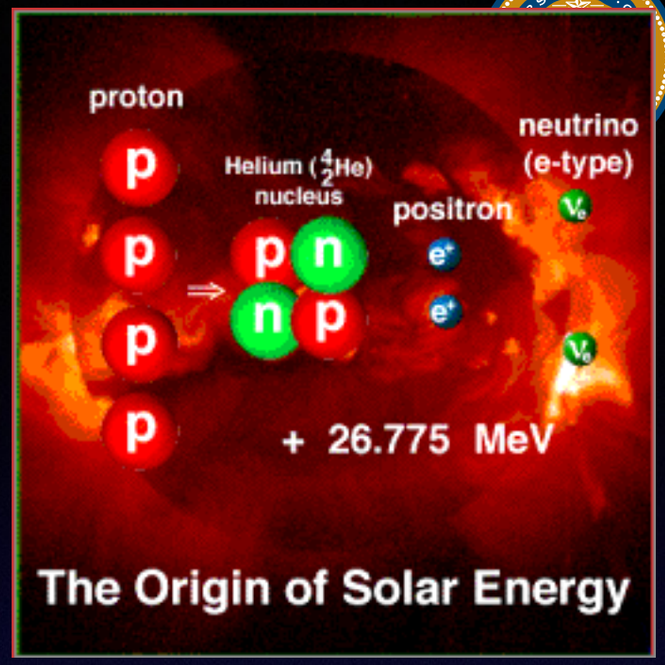
turning mass to energy

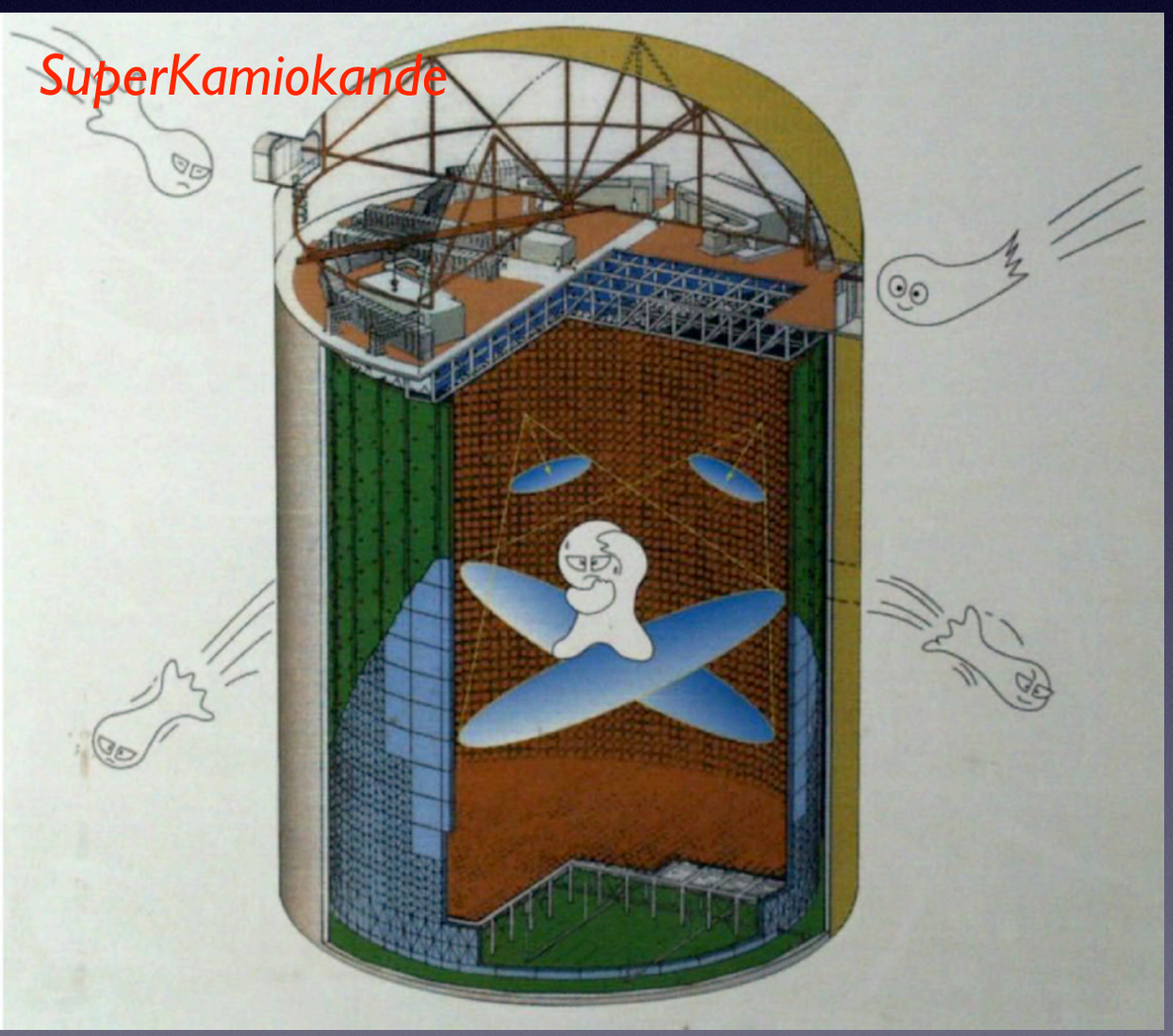
burning hydrogen

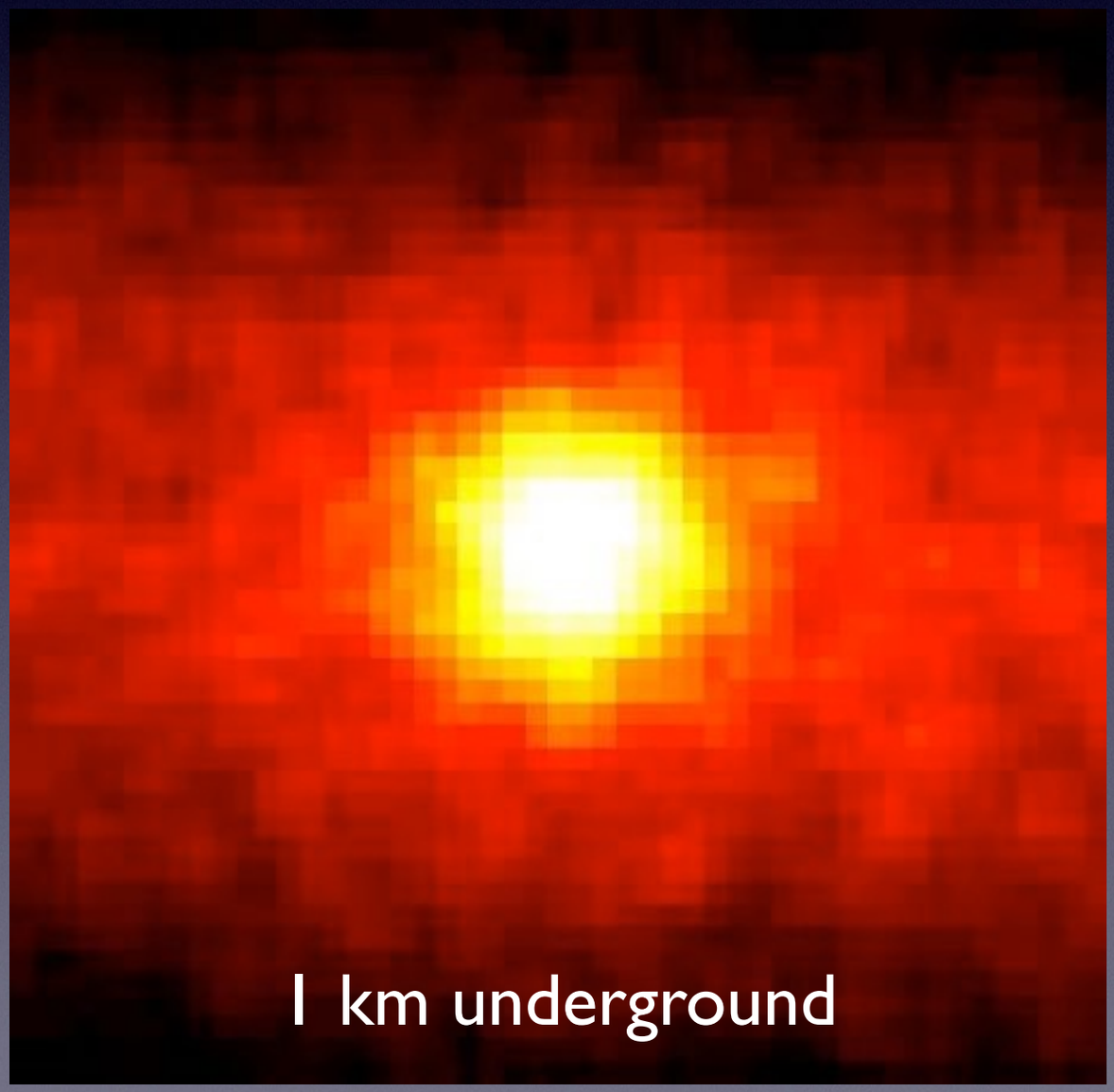
proof

nuclear fusion also produces neutrinos

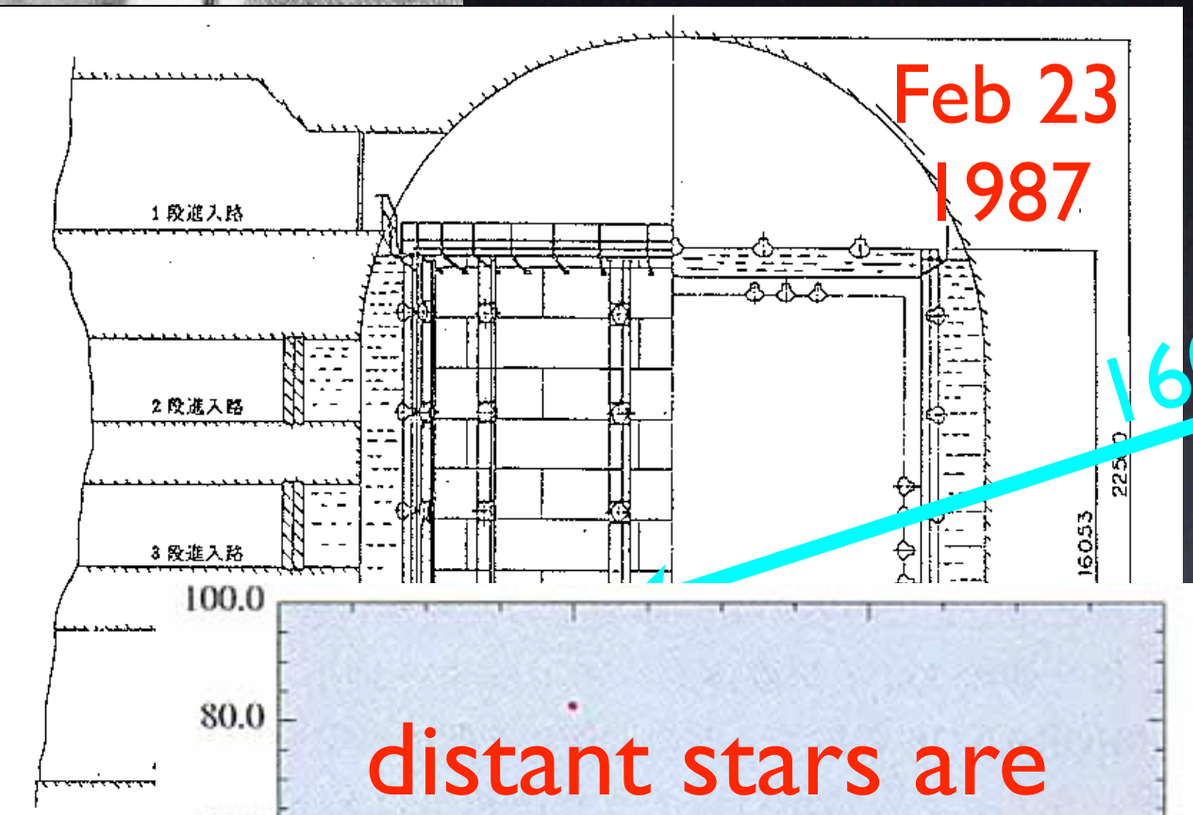
tens of trillions of neutrinos going through our body every second





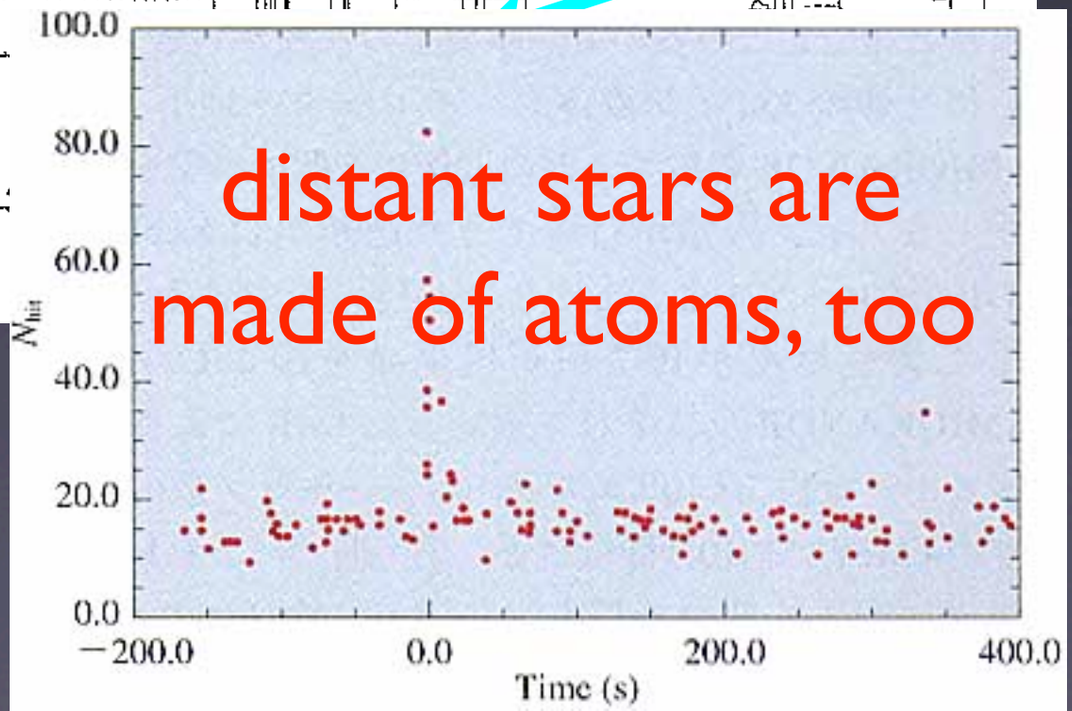


luck

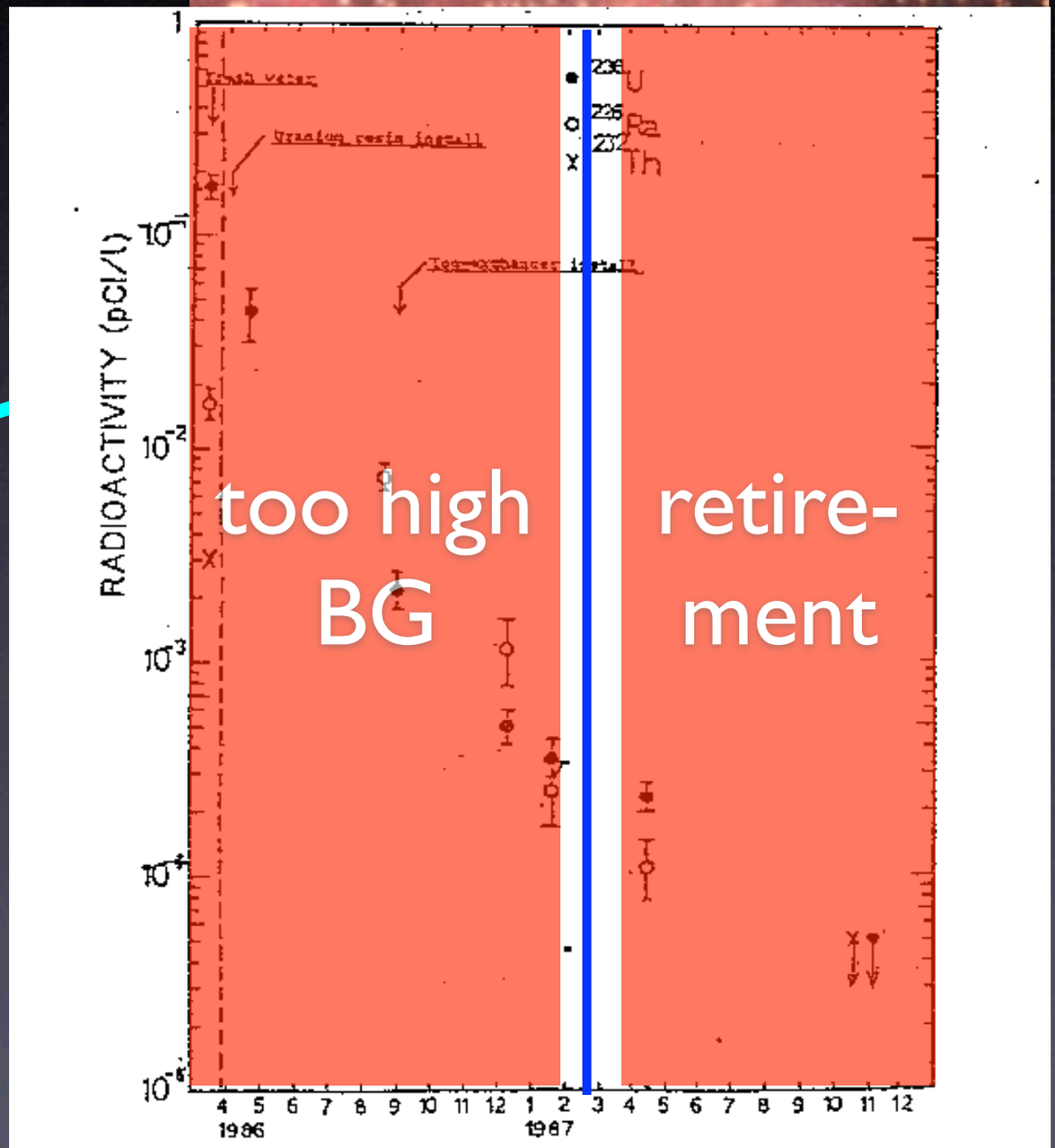


Feb 23
1987

160,000



distant stars are
made of atoms, too



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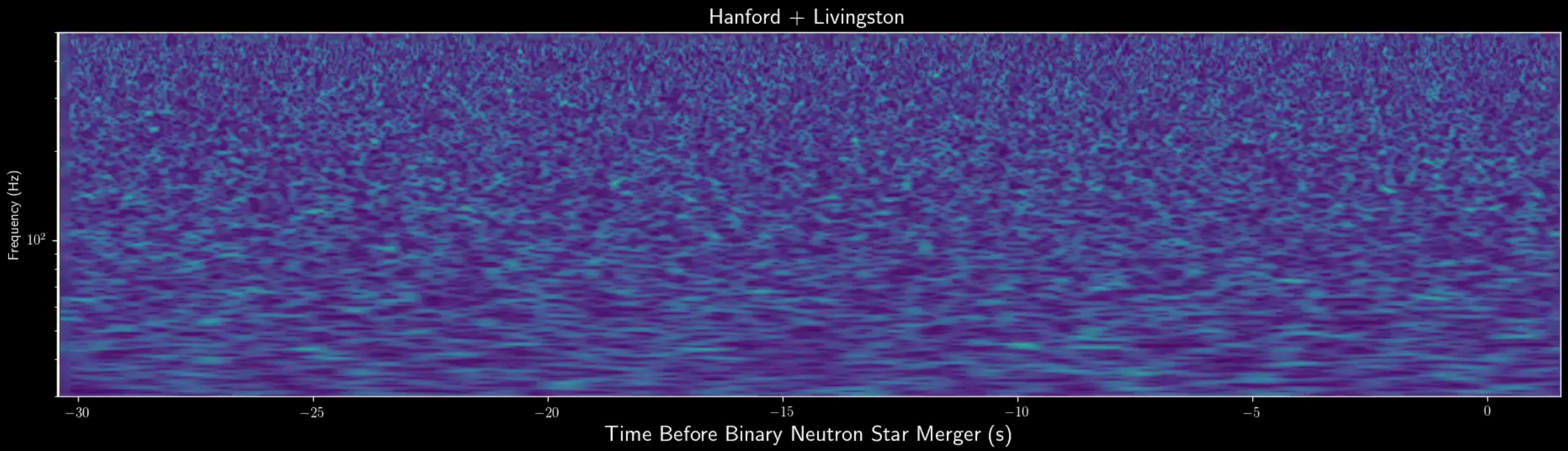
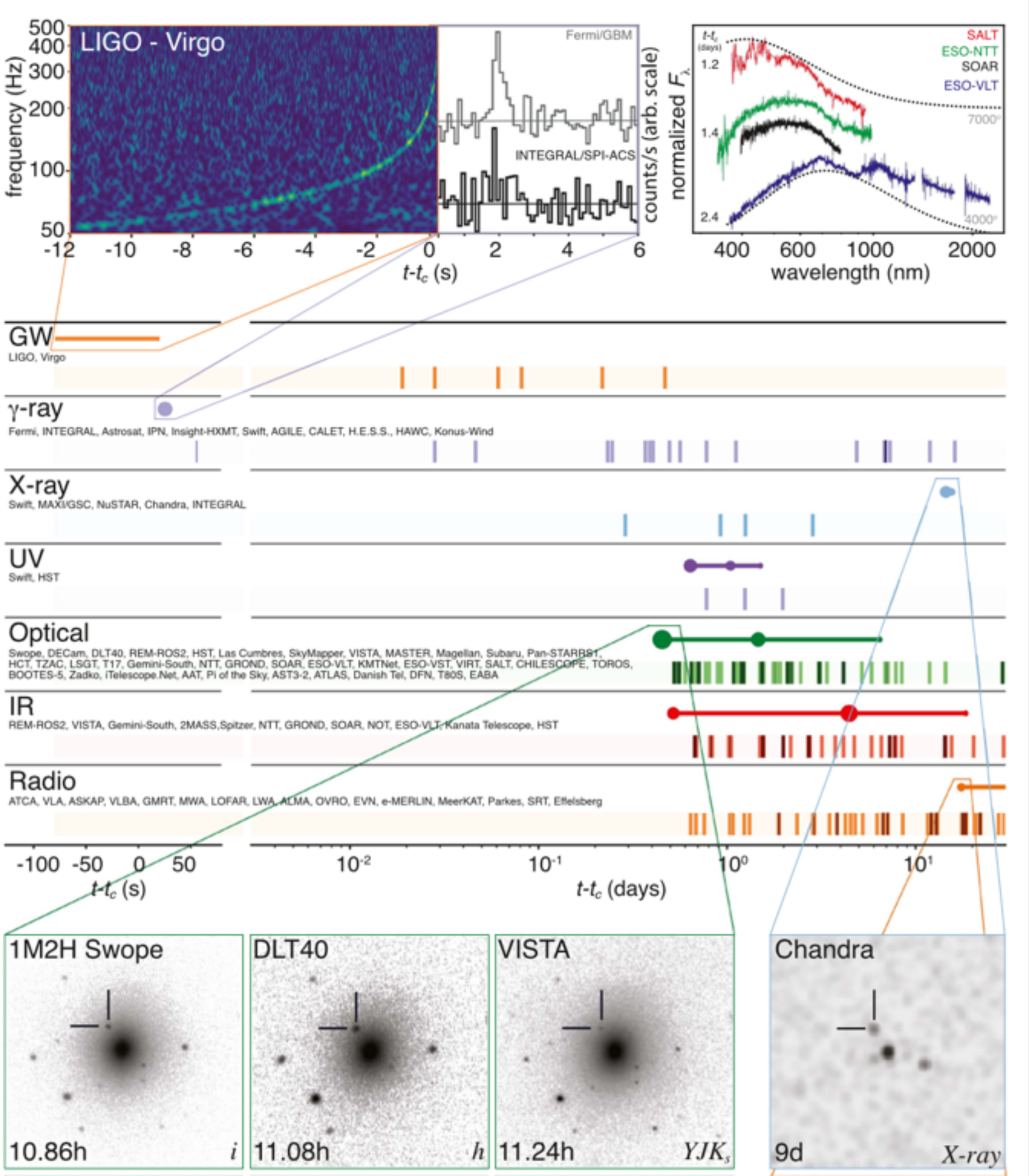
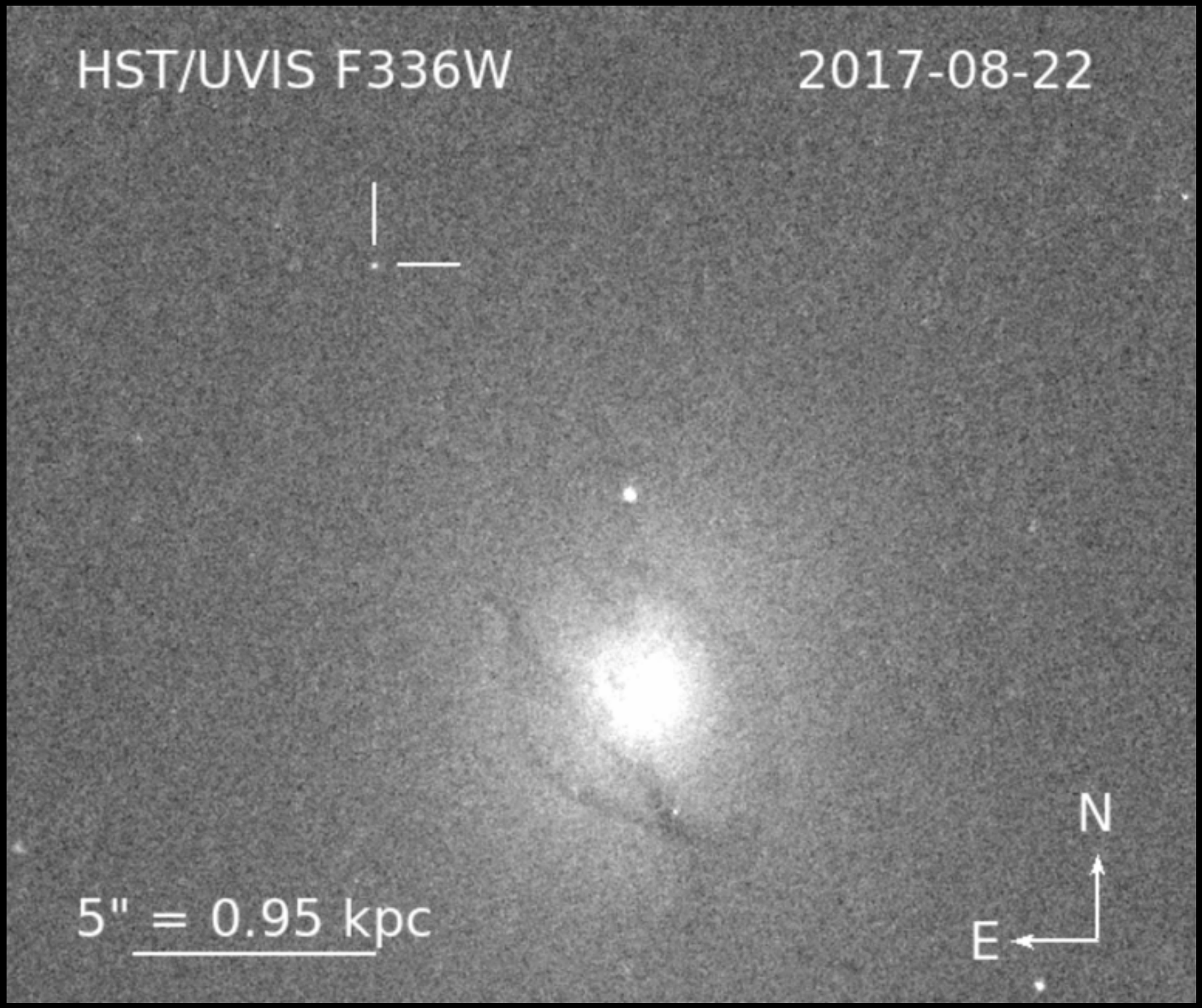
Editor: Aditya Vardhan (adivar@nettlinx.com)

merger of neutron stars


Hanford + Livingston
Frequency (Hz)
10^2
−30
−25
−20
−15
−10
−5
0
Time Before Binary Neutron Star Merger (s)

"Multi-messenger Observations of a Binary Neutron Star Merger "
Abbott et al. 2017, ApJL, 848, 12





Kasliwal et al. 2017 (Science)

37km from the Nippon Sea

Ikenoyama Mt.

1000m Underground

Mozumi area

3km

KAGRA project

XMASS

Kamland

SG

Super Kamiokande

CLIO

358m Altitude

KAGRA

Image

Atotsu

Entrance

to Toyama

to Takayama

to Tateyama

Takahara river

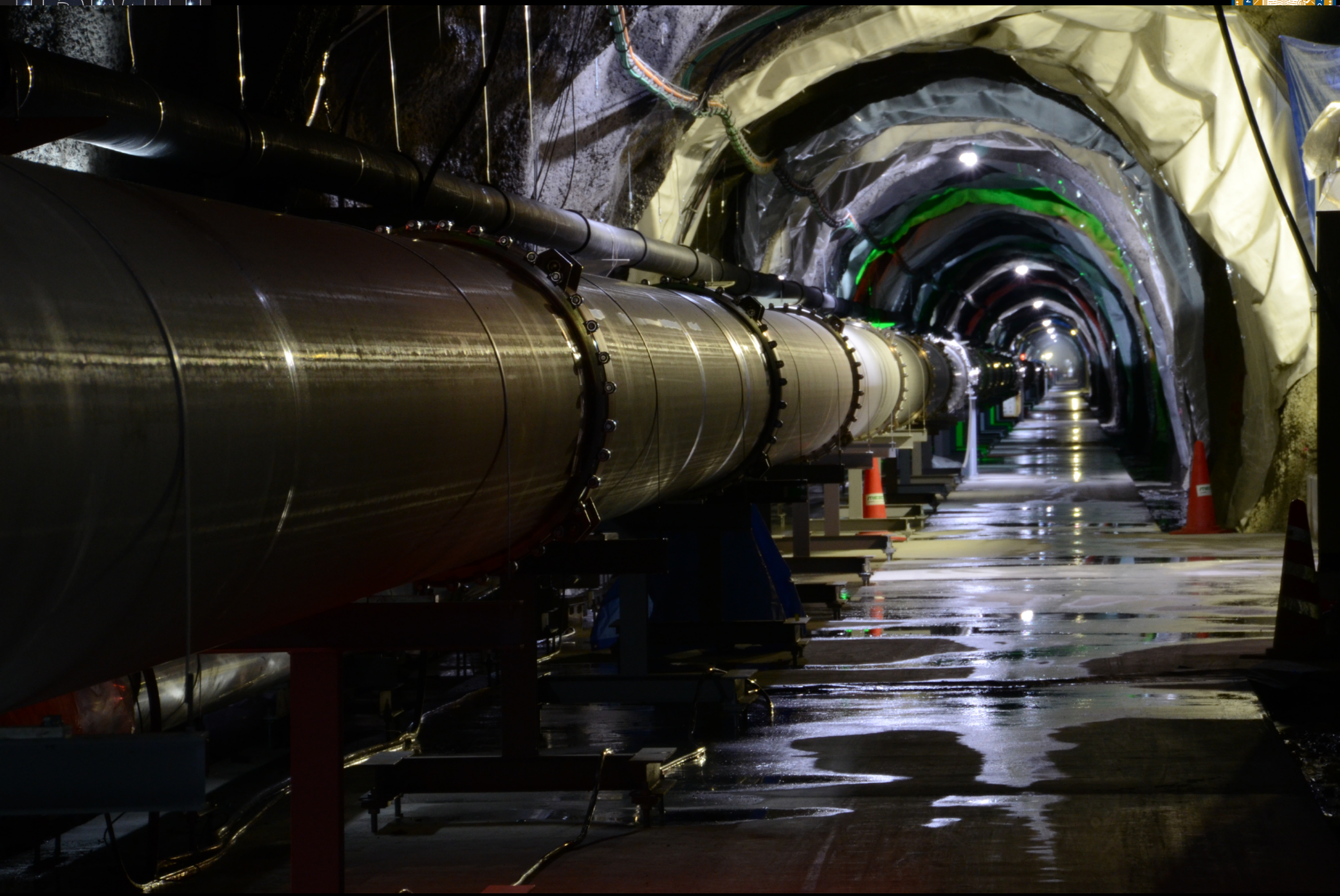
Atotsu river

41

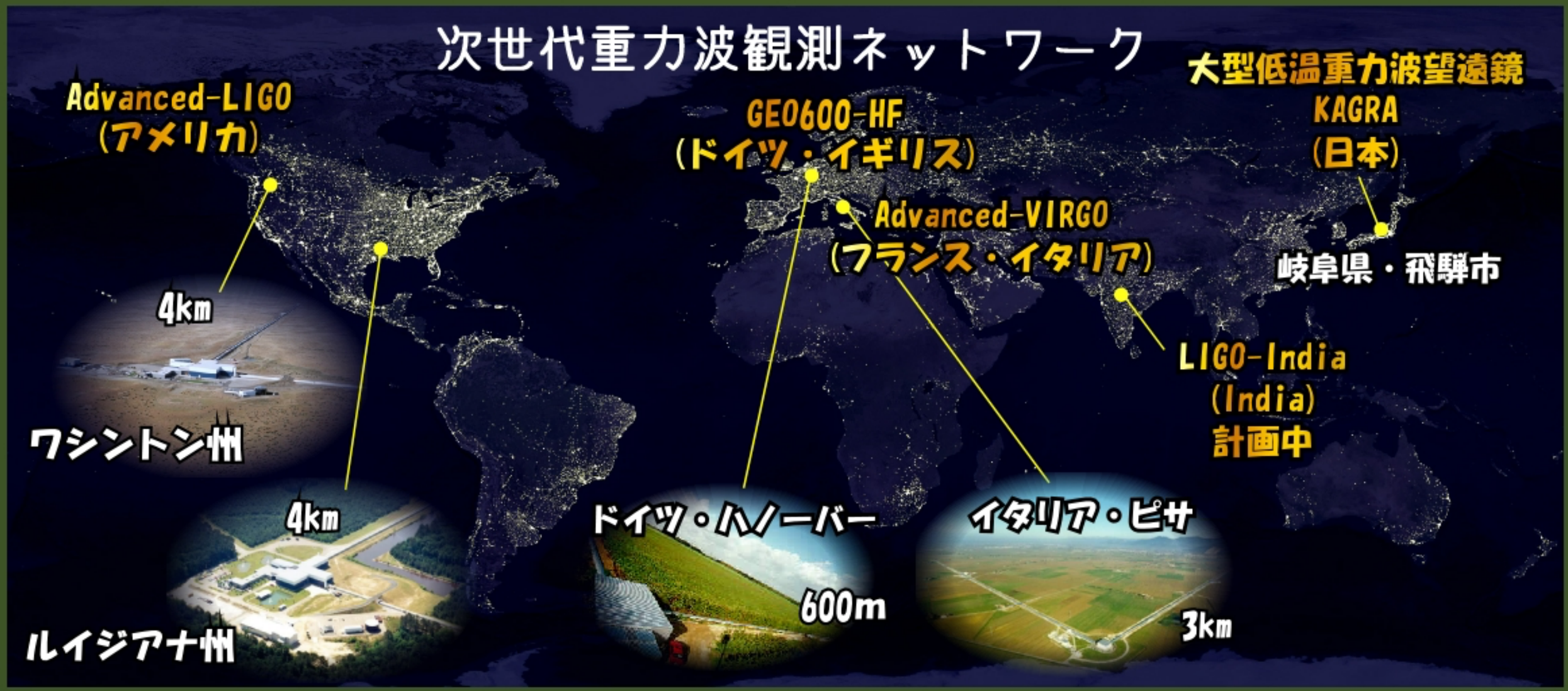
一(ichi)
分(bu)
厘(rin)
毛(mou)
糸(shi)
忽(kotsu)
微(bi)
繊(sen)
沙(sya)
塵(zin)
埃(ai)
渺(byou)
漠(baku)
模糊(moko)
逡巡(syunjun)
須臾(syuyu)
瞬息(syunsoku)
弾指(danshi)
刹那(setuna)
六徳(rittoku)

1京
1000兆
100兆
10兆
1兆
1000億
100億
10億
1億
1000万
100万
10万
1万
1000
100
10
1
1/10
1/100
1/1000
1/1万
1/10万
1/100万
1/1000万
1/1億
1/10億
1/100億
1/1000億
1/1兆
1/10兆
1/100兆
1/1000兆
1/1京
1/10京
1/100京
1/1000京

3

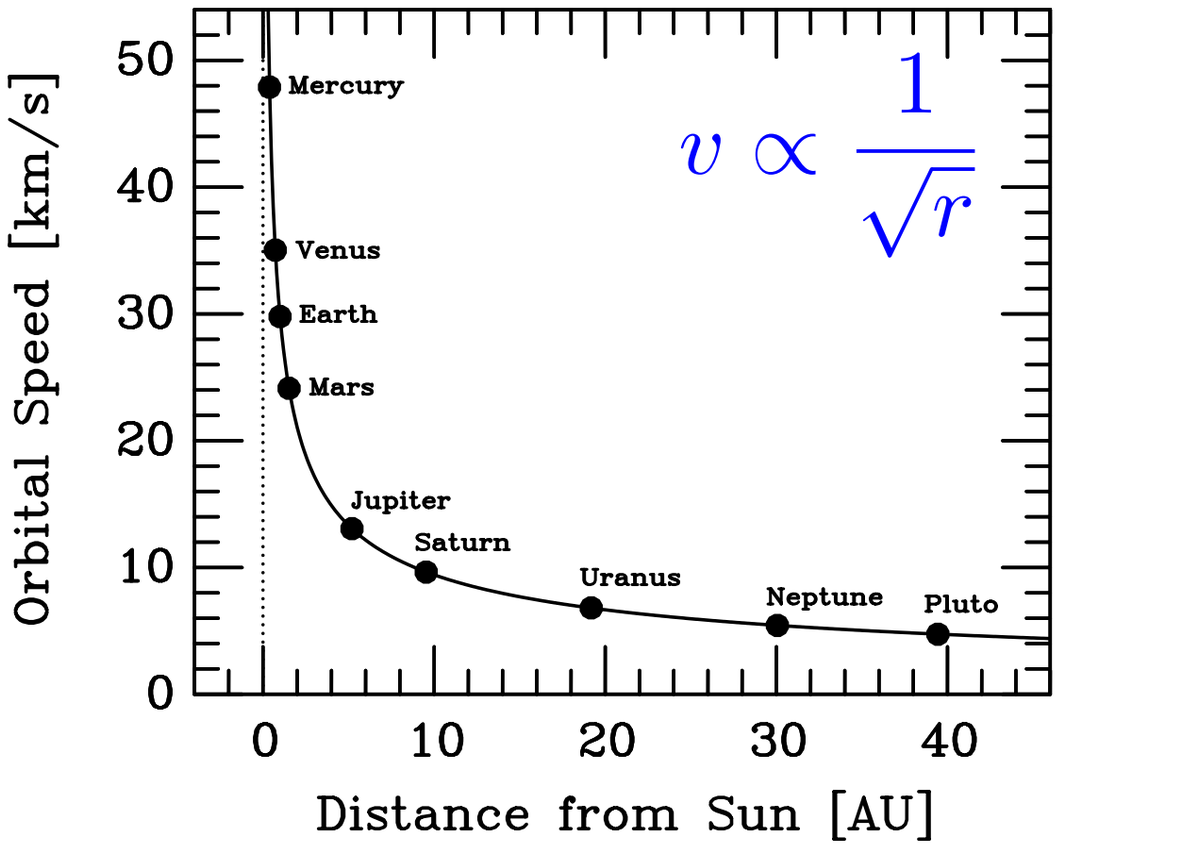


http://www.nao.ac.jp/news/topics/2015/20151116-kagra.html


次世代重力波観測ネットワーク
Advanced-LIGO
(アメリカ)
4km
ワシントン州
4km
ルイジアナ州
GEO600-HF
(ドイツ・イギリス)
ドイツ・ハノーバー
600m
Advanced-VIRGO
(フランス・イタリア)
イタリア・ピサ
3km
大型低温重力波望遠鏡
KAGRA
(日本)
岐阜県・飛騨市
LIGO-India
(India)
計画中

Neptune
4 light hours

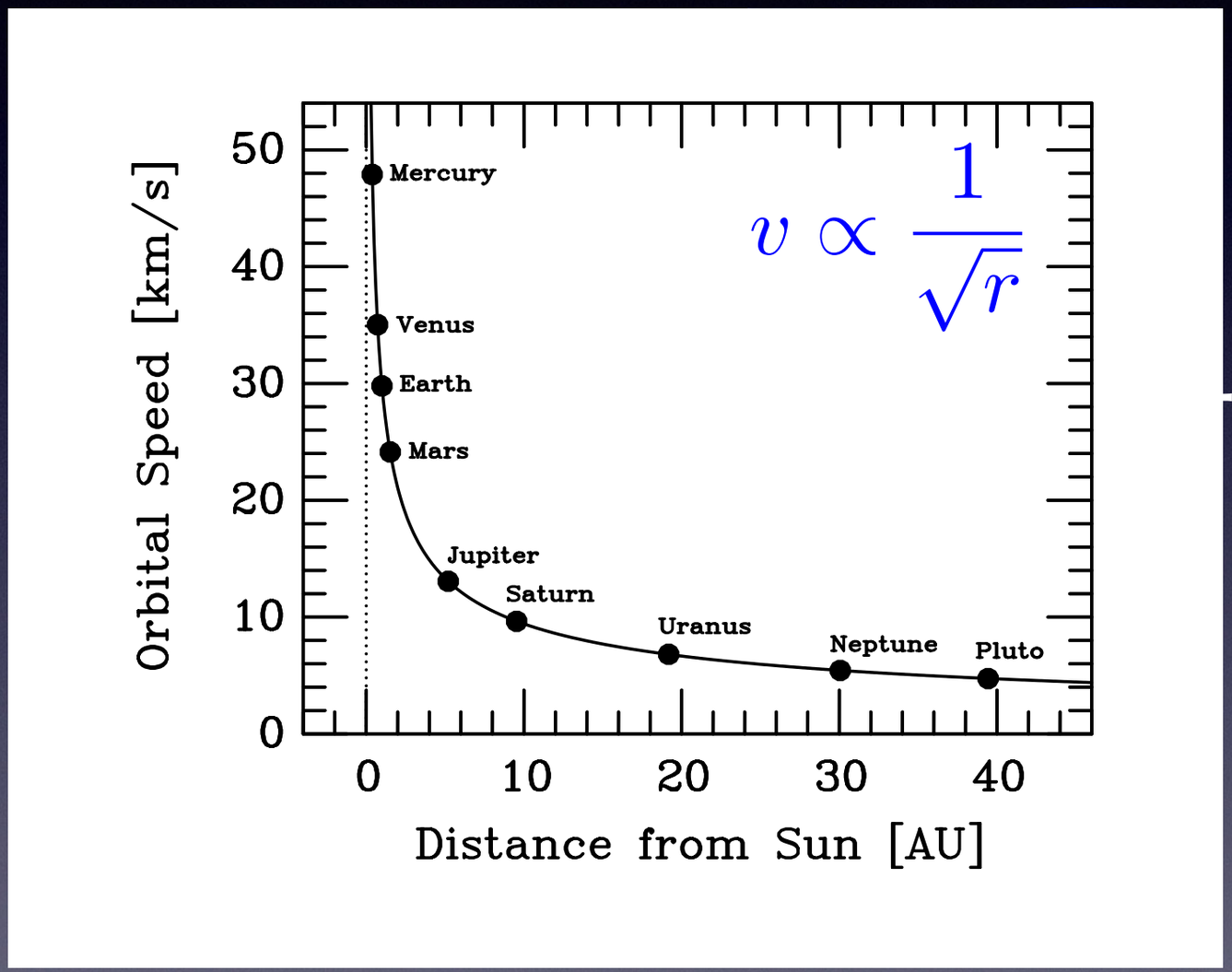
Solar S



Itokawa
20 light minutes

Earth resolves around the Sun with 30km/sec

High School physics



$$v \propto \frac{1}{\sqrt{r}}$$

$$F = \frac{GM_\odot m}{r^2}$$

$$ma = m\frac{v^2}{r}$$

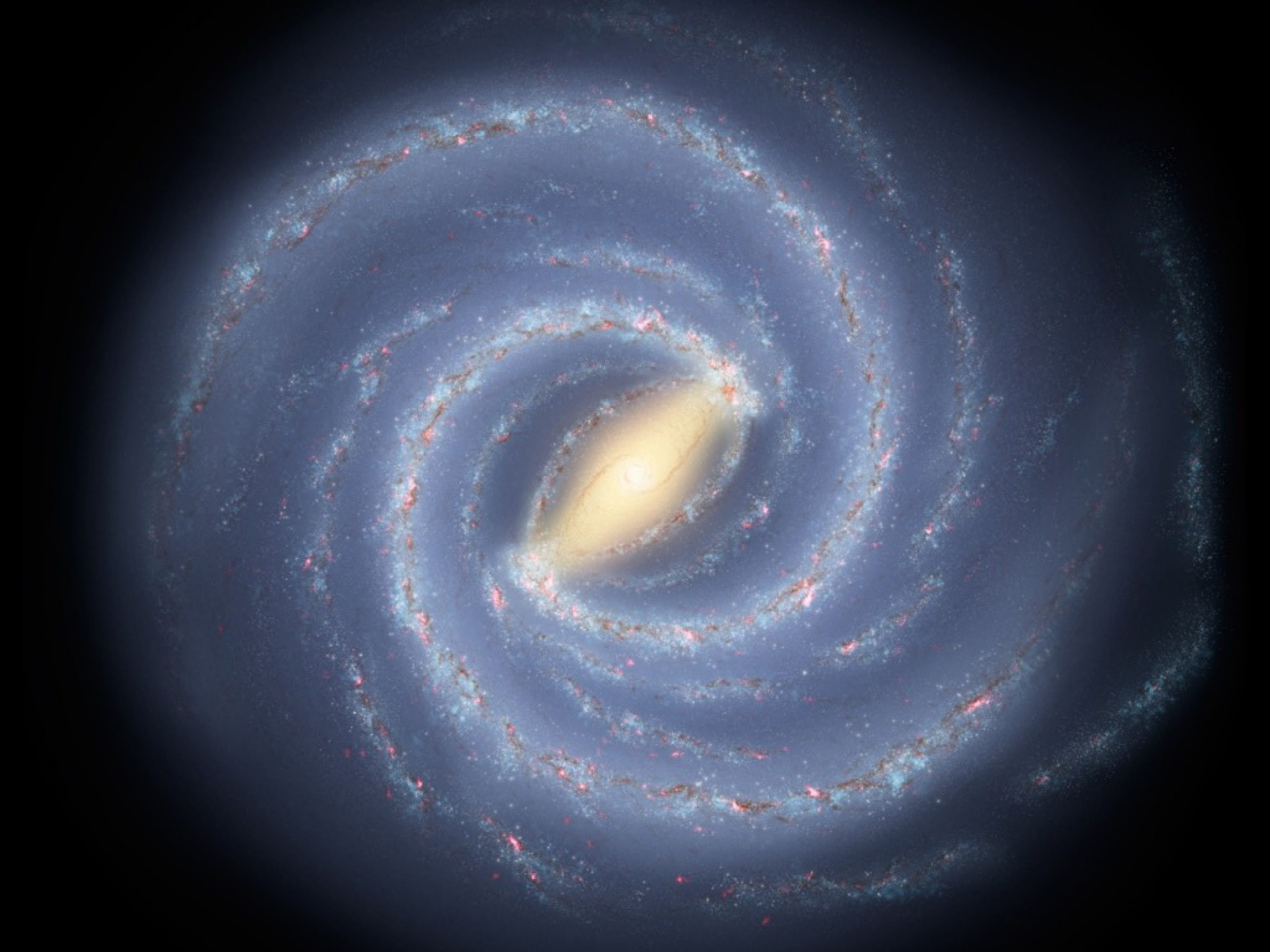
$$\frac{GM_\odot m}{r^2} = m\frac{v^2}{r}$$

$$v = \sqrt{\frac{GM_\odot}{r}} \propto \frac{1}{\sqrt{r}}$$

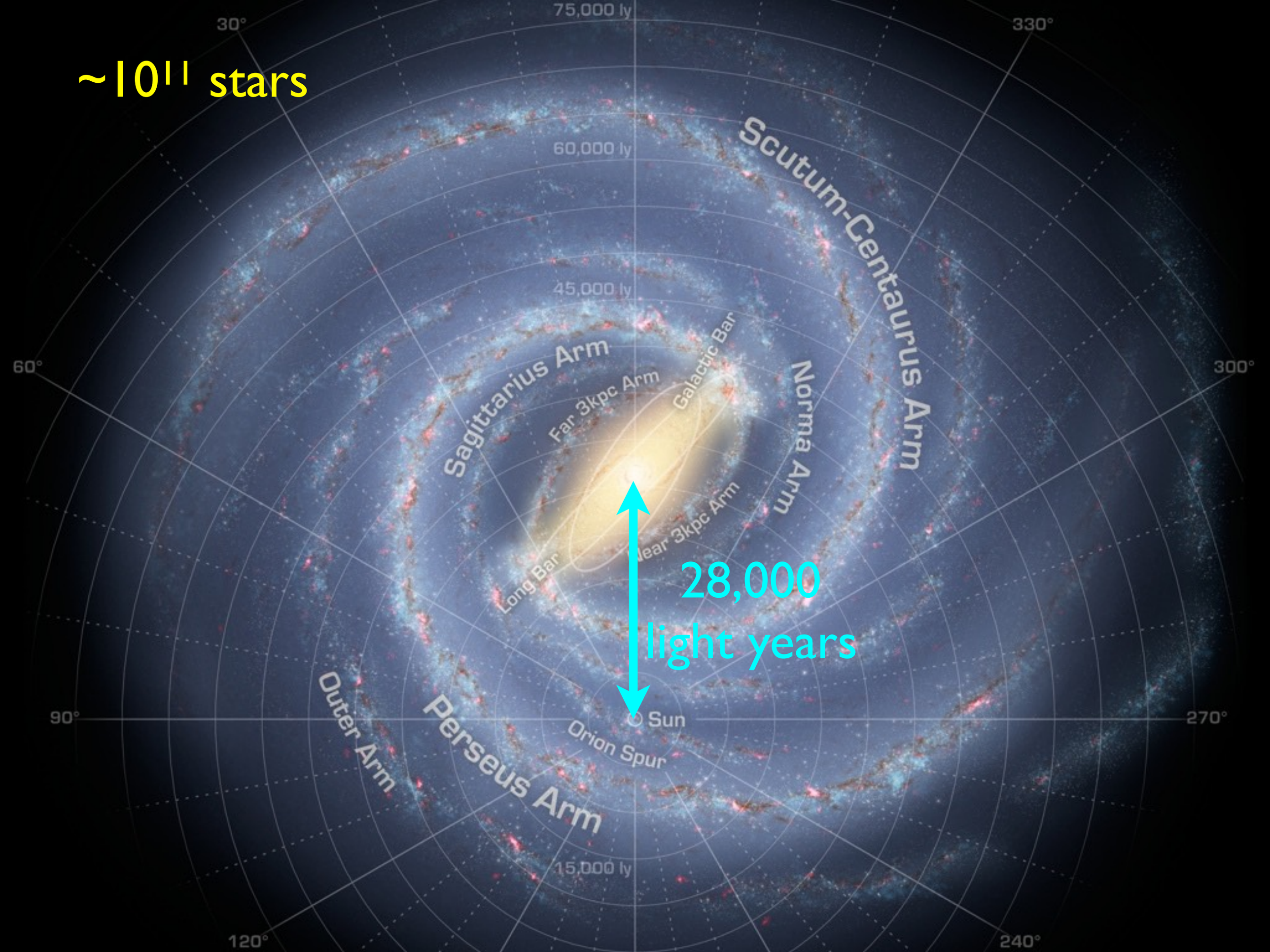
closest star

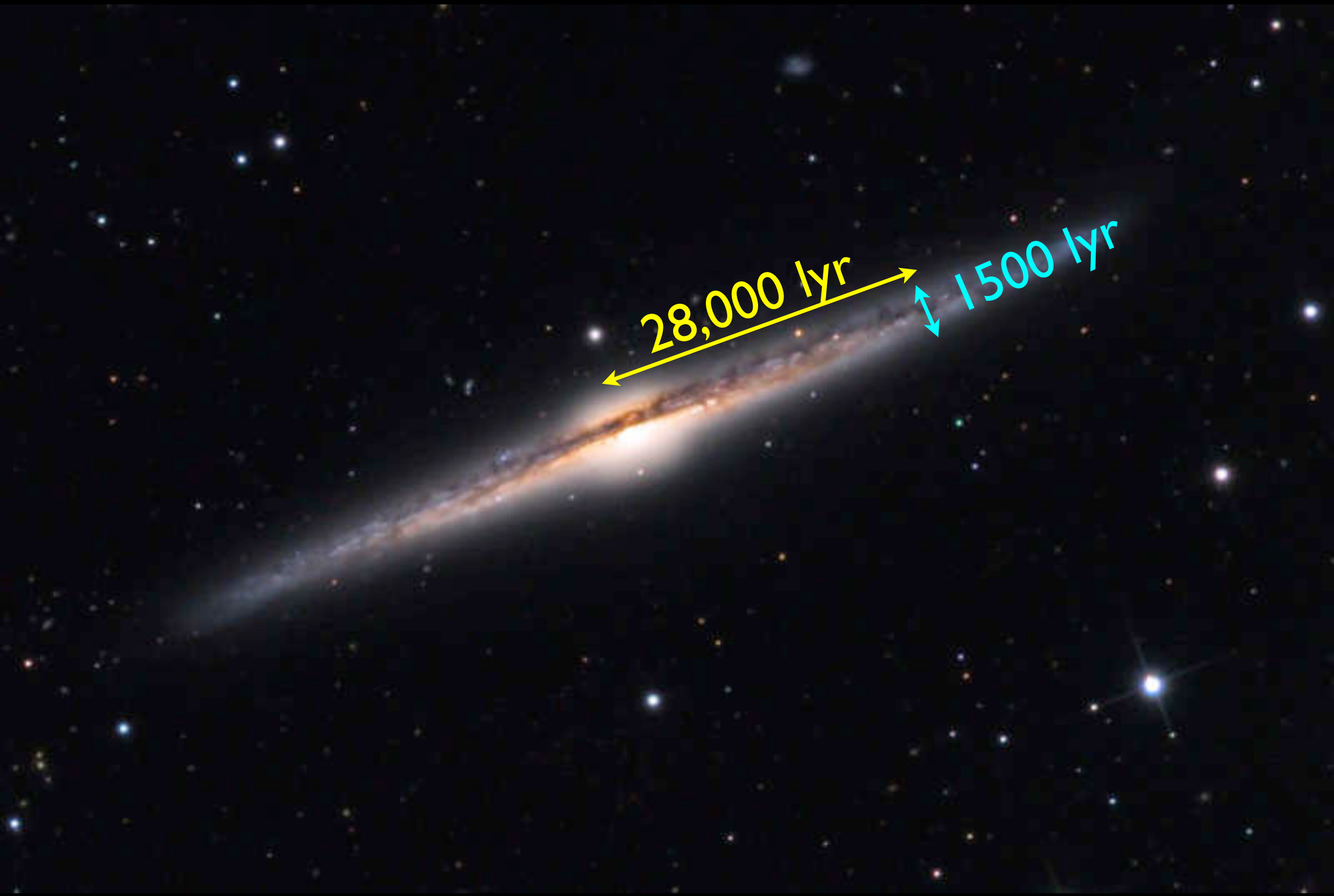
Proxima Centauri
4.2 light years

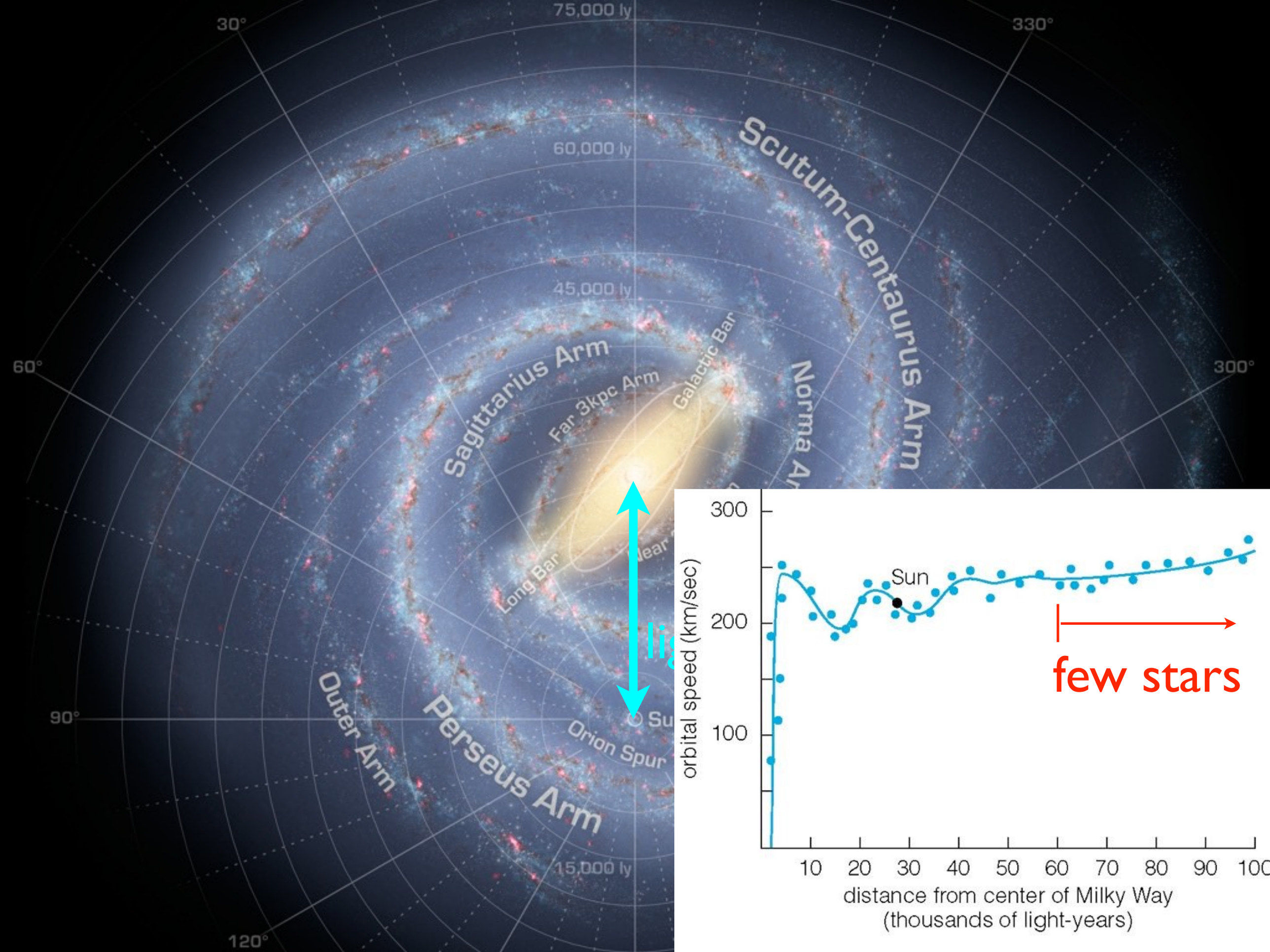
Milky Way and Galaxies

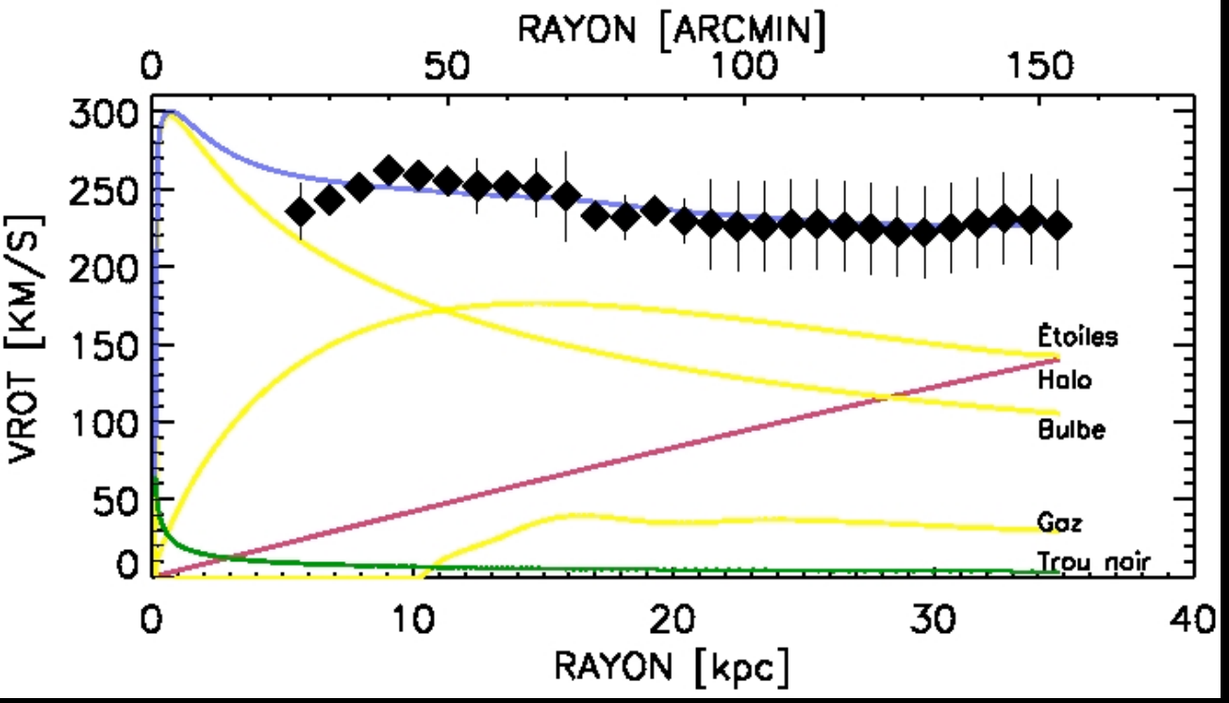


~10^{11} stars


75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
28,000
light years
Sun
Orion Spur
Outer Arm
Perseus Arm
15,000 ly


28,000 lyr
1500 lyr


75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
120°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
15,000 ly
Sun
300
200
100
orbital speed (km/sec)
Sun
few stars
10
20
30
40
50
60
70
80
90
100
distance from center of Milky Way
(thousands of light-years)



will collide with us
in 4.5 billion years

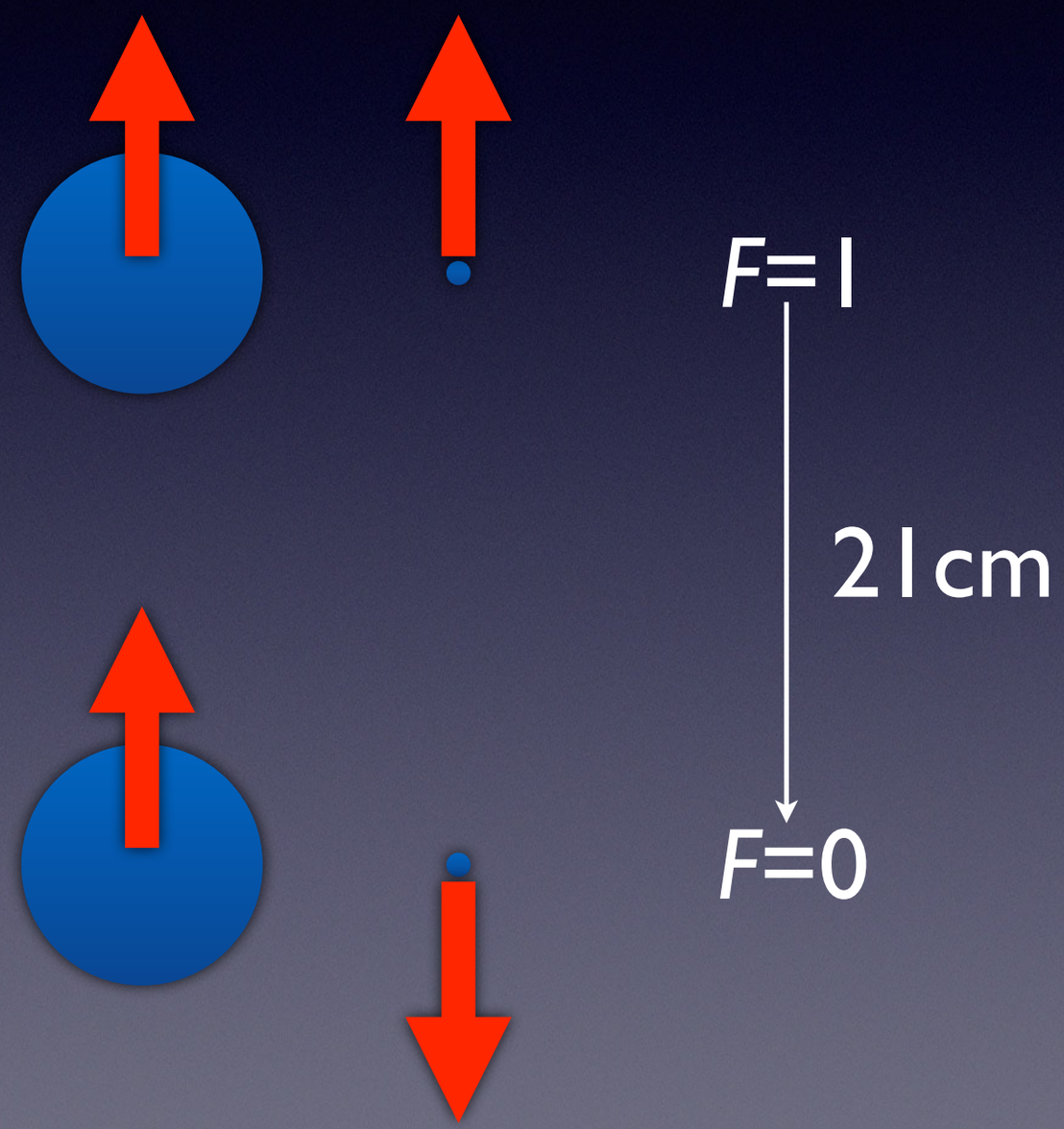
Andromeda M33 = 2.5M lyr

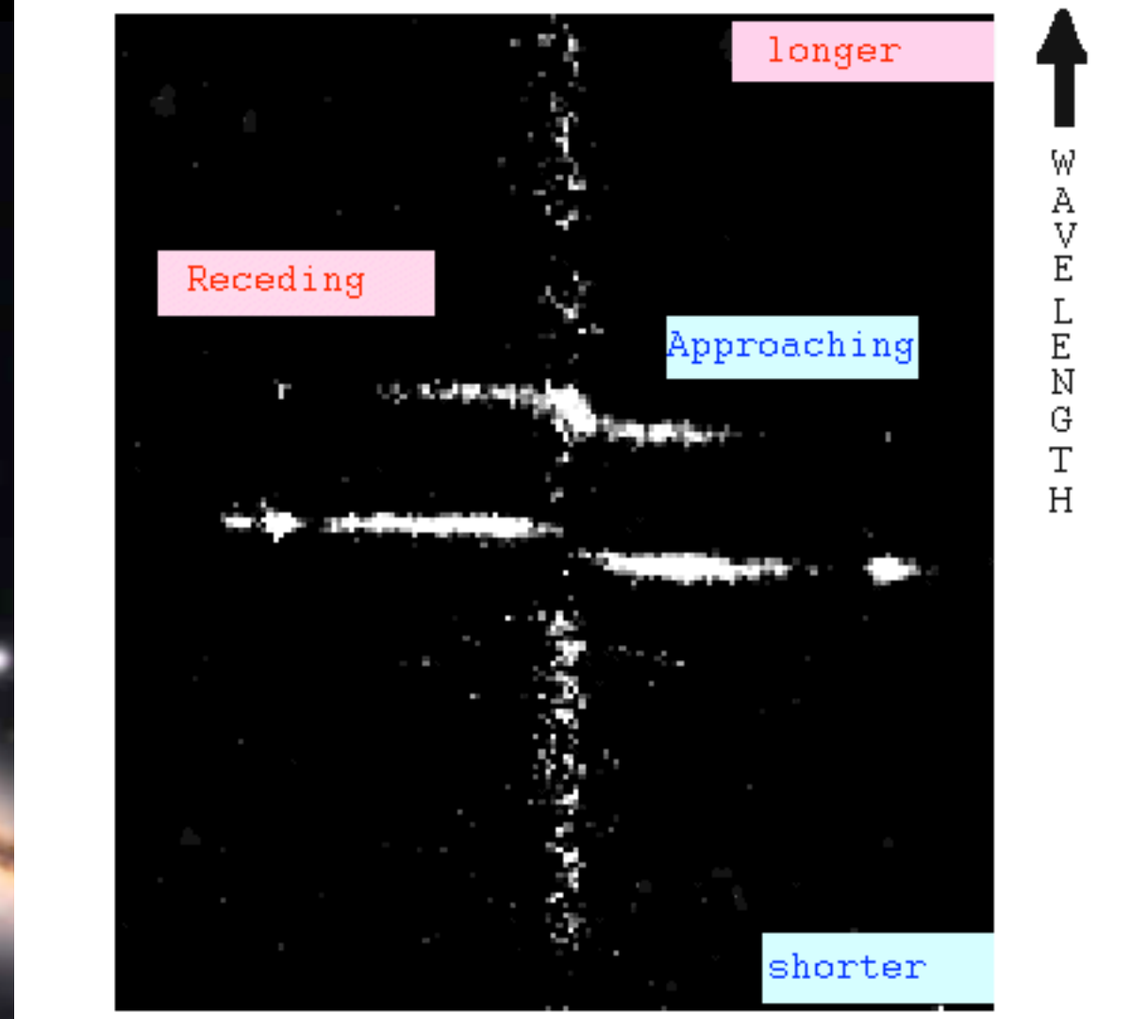
How do we measure the rotation curve?

- Special relativity

$$f' = \sqrt{\frac{c \mp v}{c \pm v}}\, f \approx \left(1 \mp \frac{c}{v}\right) f$$

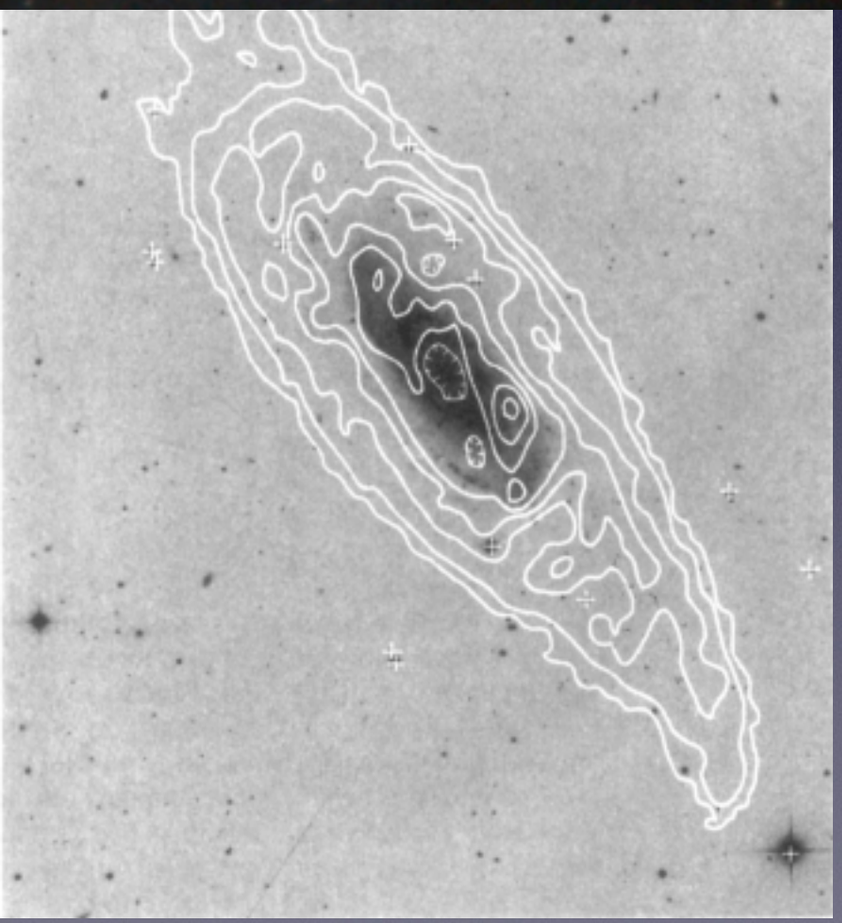
- hyperfine splitting in neutral hydrogen
- 21cm line can be excited by the cosmic microwave background
- kT_0=0.23 meV
- $h\,c$/21cm = 0.94 μeV

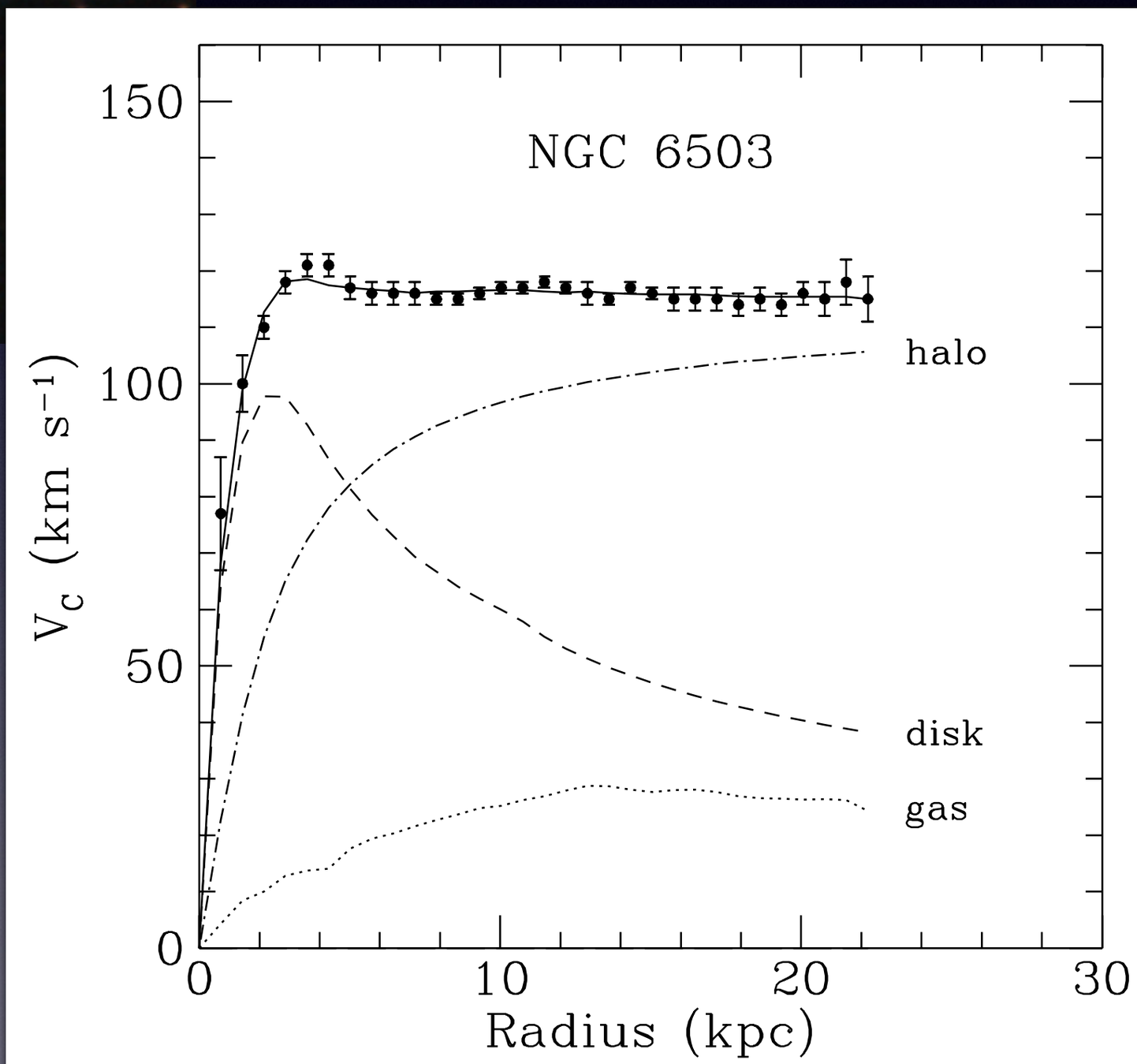



Galaxy rotation curve
longer
Receding
Approaching
shorter
WAVELENGTH
Distance along galaxy major axis

Vera Rubin

1960s




NGC 6503
150
100
50
0
0
10
20
30
V_c (km s^{-1})
Radius (kpc)
halo
disk
gas

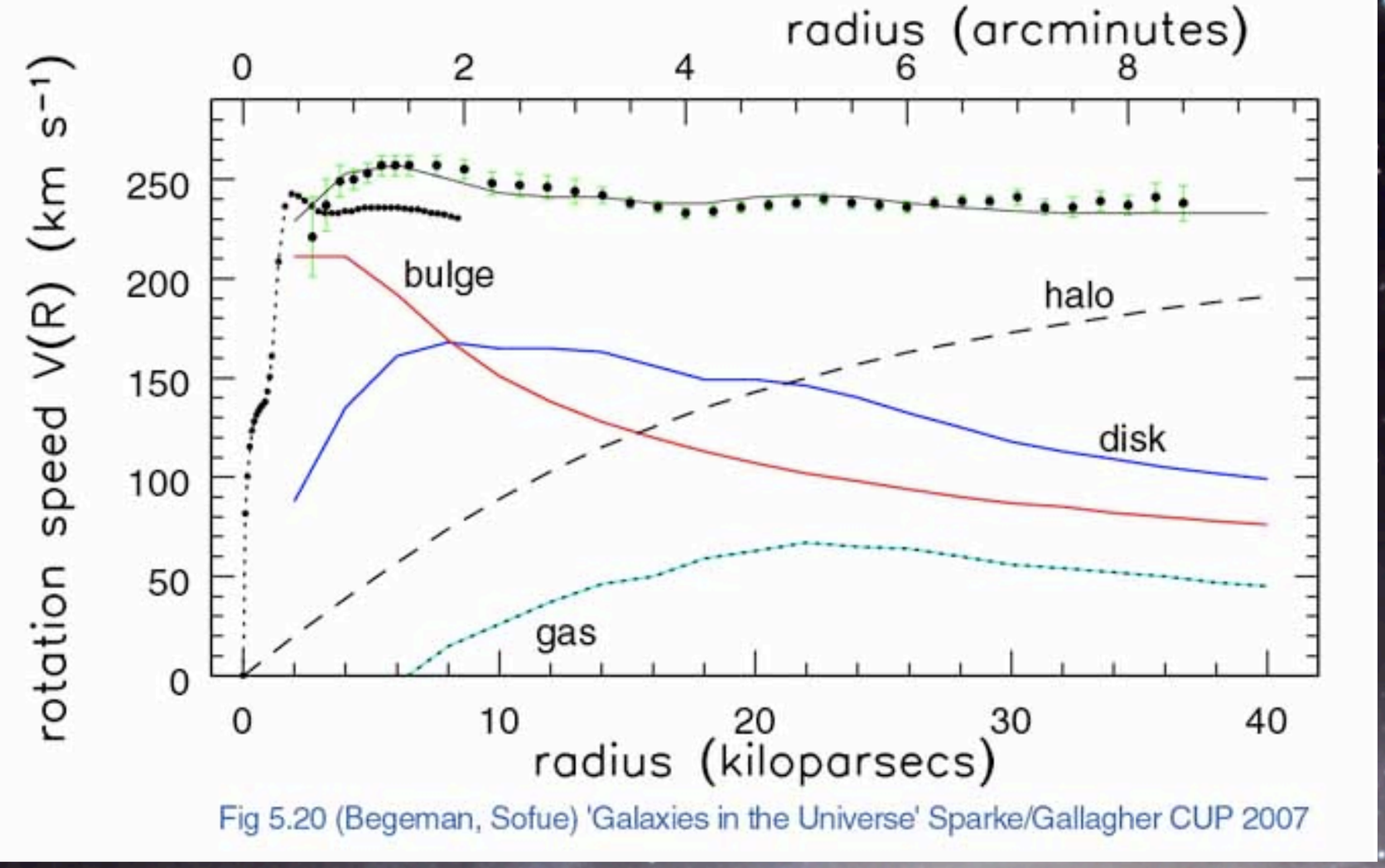
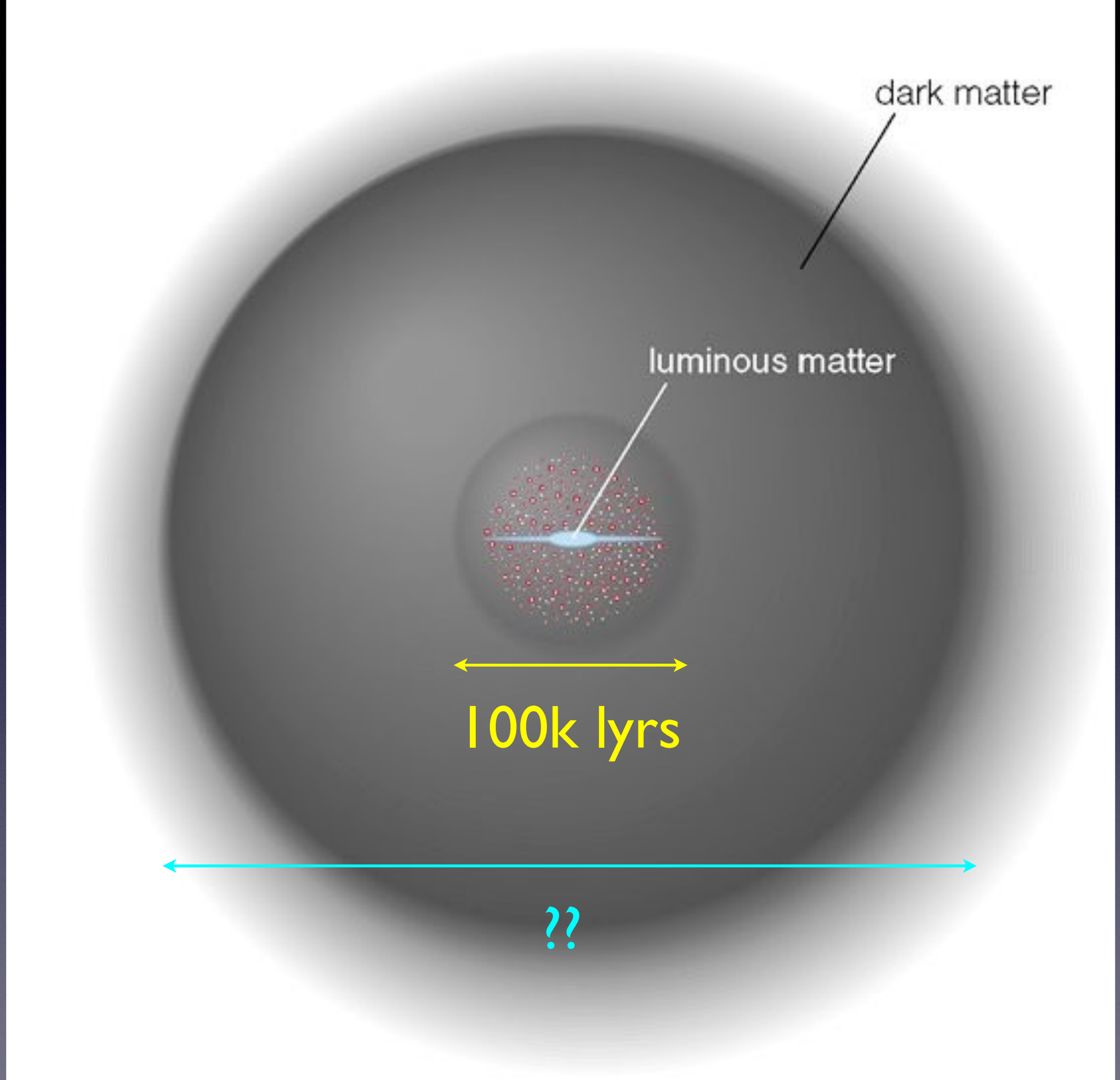


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007


dark matter
luminous matter
100k lyrs
??

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connects galaxies

stacking 85k quasars near 20M galaxies

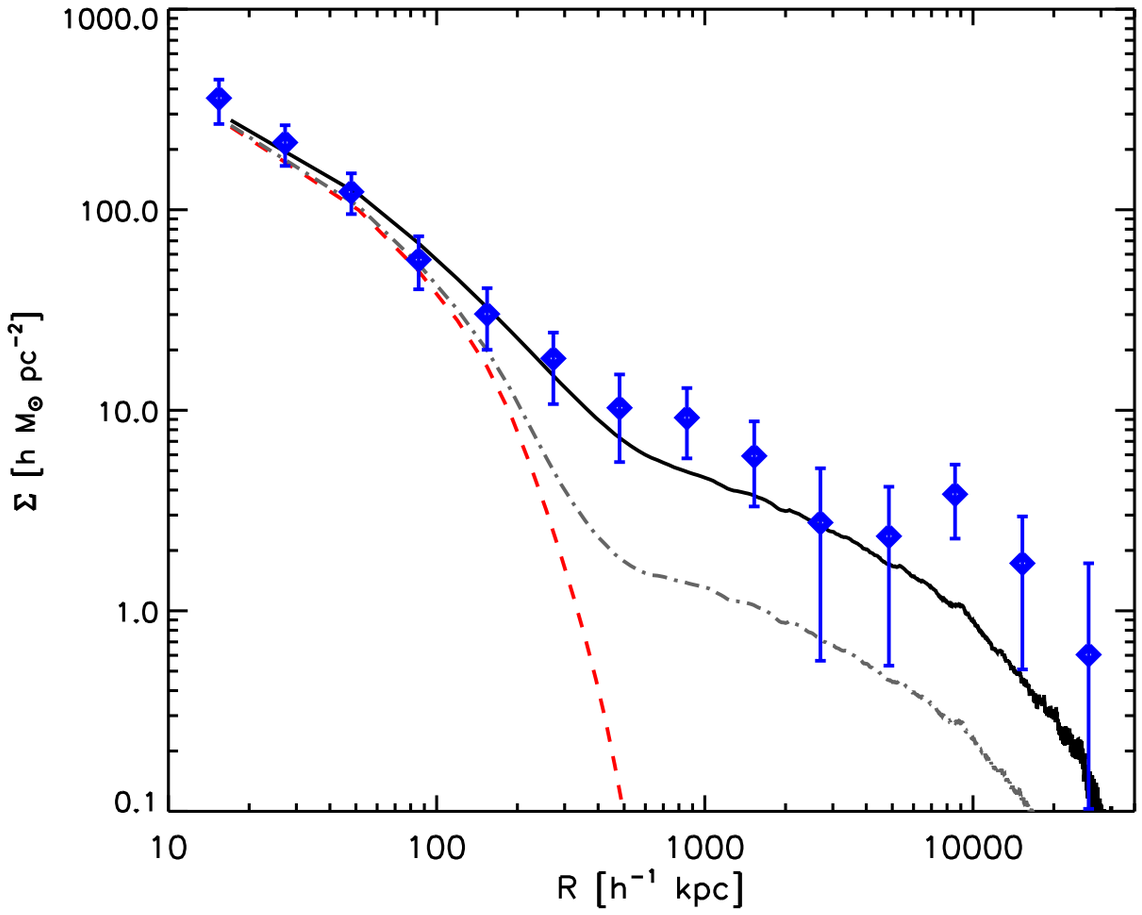

Fig. 2.— The mean surface mass density profile as a function of the distance from the centre of galaxies. The thick solid curve is the mean of all haloes above the mass threshold. The dash-dotted curve represents the contribution from particles bound to haloes, i.e., particles that reside within the virial radius of all haloes. The data with error bars are the observational estimate by MSFR as in the previous figure.

Ménard et al 2009

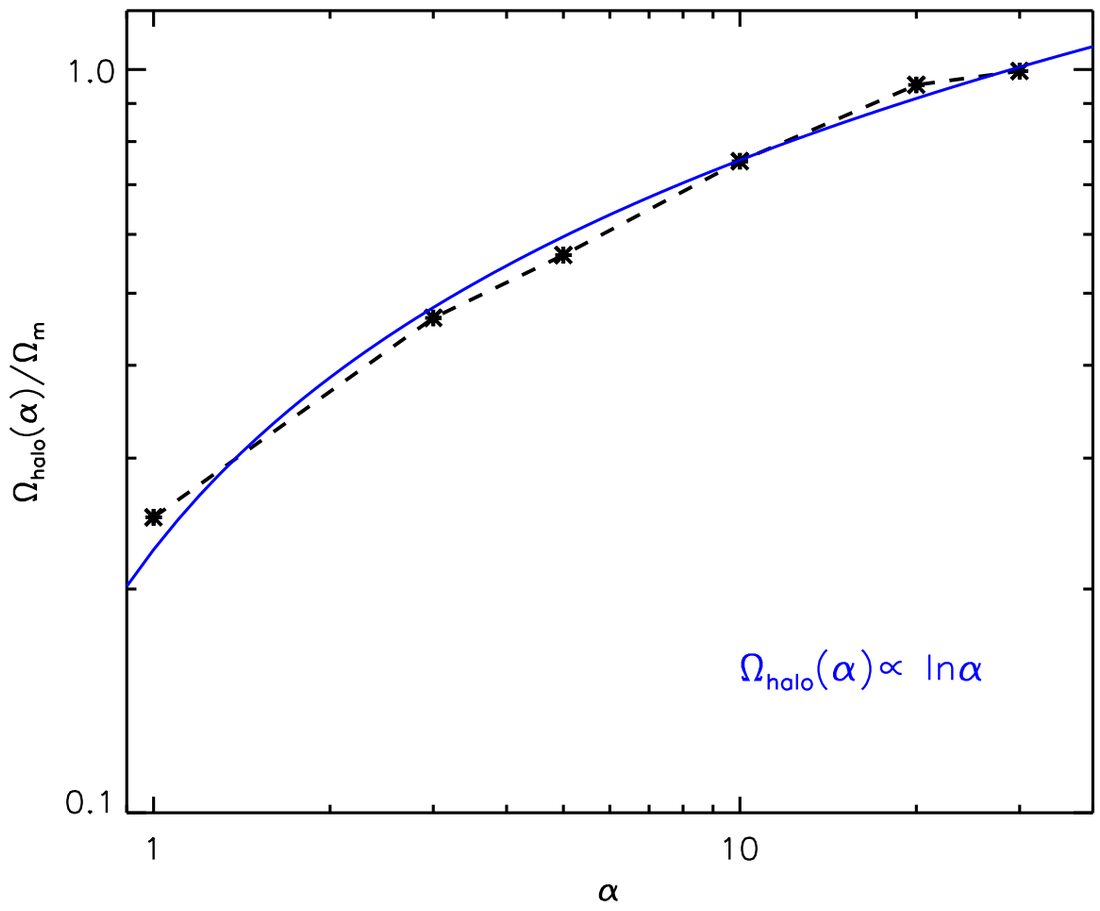

Fig. 4.— Fraction of mass contained in the sphere centred on individual haloes with radius $\alpha R_{\rm vir}$, where $R_{\rm vir}$ is the pseudovirial radius and α is the multiplier represented in the abscissa. The solid curve is $0.23\ln+0.23$ given in the text.

Masaki Fukugita Yoshida 2011

galaxies
rejuvenated
after mergers

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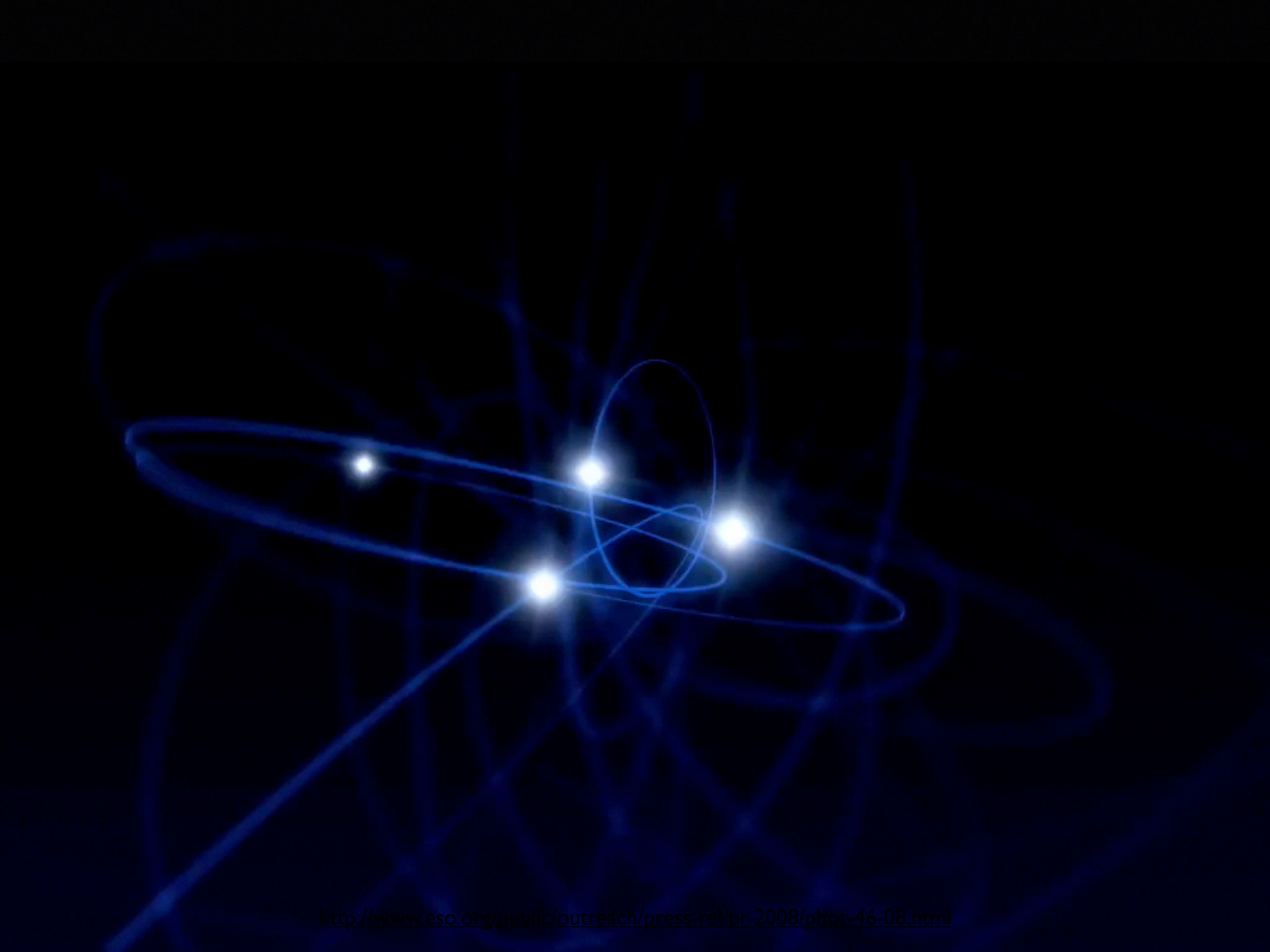
THE UNIVERSITY OF TOKYO

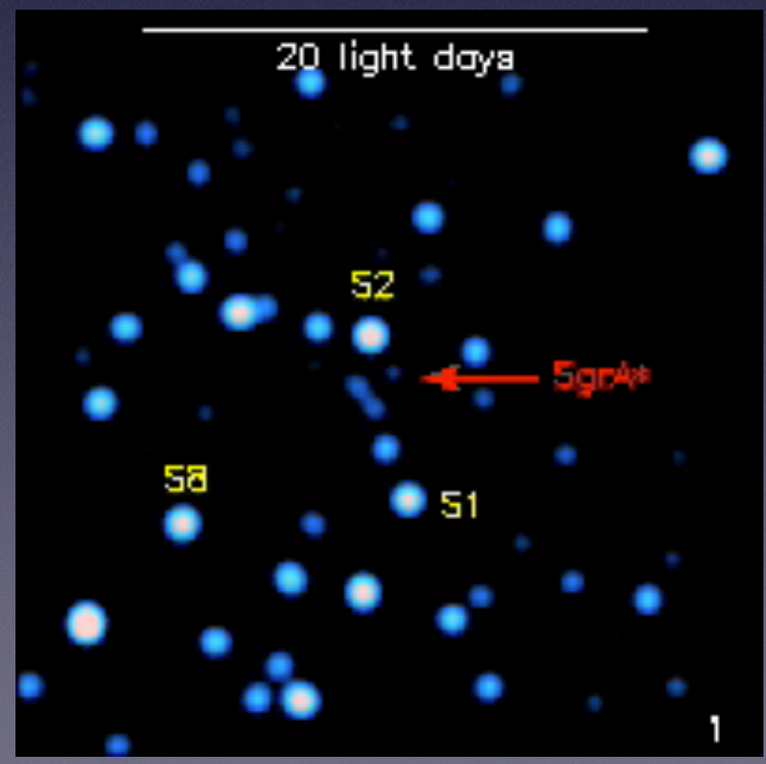
Center of Milky Way



http://www.eso.org/public/outreach/press-rel/pr-2008/phot-46-08.html

Supermassive Black Hole

- supermassive blackhole of mass ~4M M_{sun} at the center of Milky Way
- swallows gas around it
- “death cry” for about 30 min
- but can’t be dark matter, far less than 100billion stars



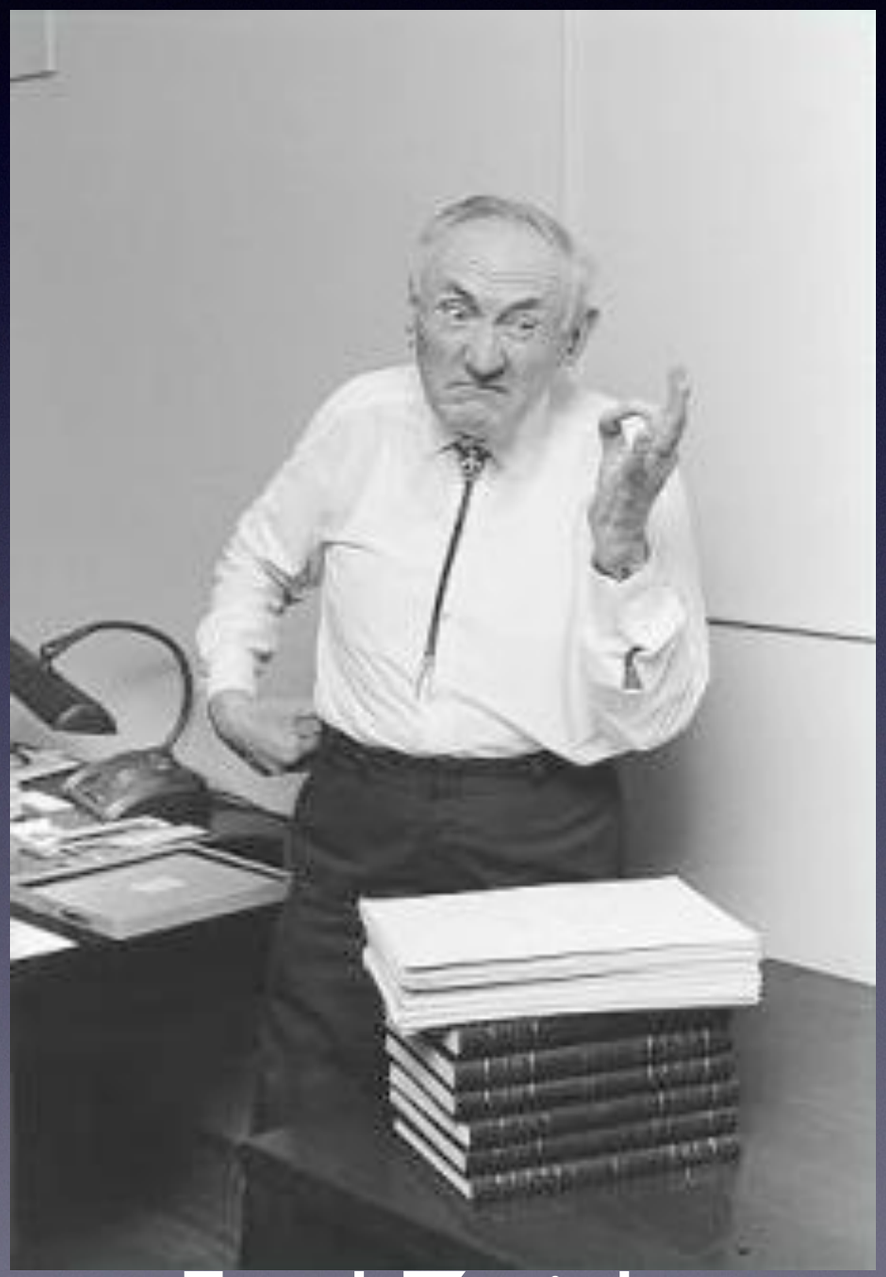
http://www.eso.org/public/outreach/press-rel/pr-2008/phot-46-08.html

Cluster of Galaxies

Coma cluster

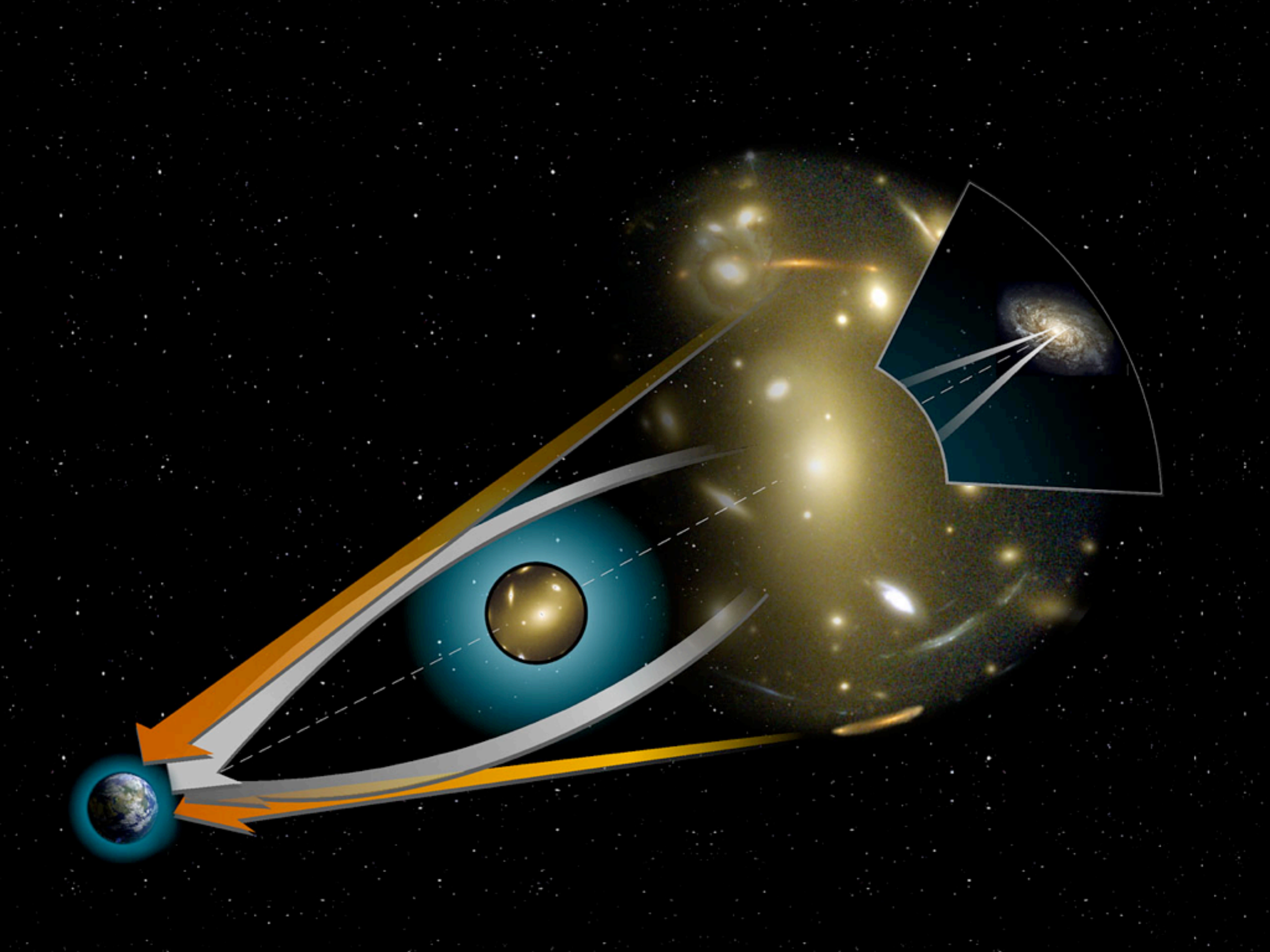
motion of galaxies

- galaxies are moving in the mutual gravitational potential
- assume virialized motion $\langle v^2 \rangle = G_N M/r$
- but they are too fast, too
- first proposal of "dark matter"

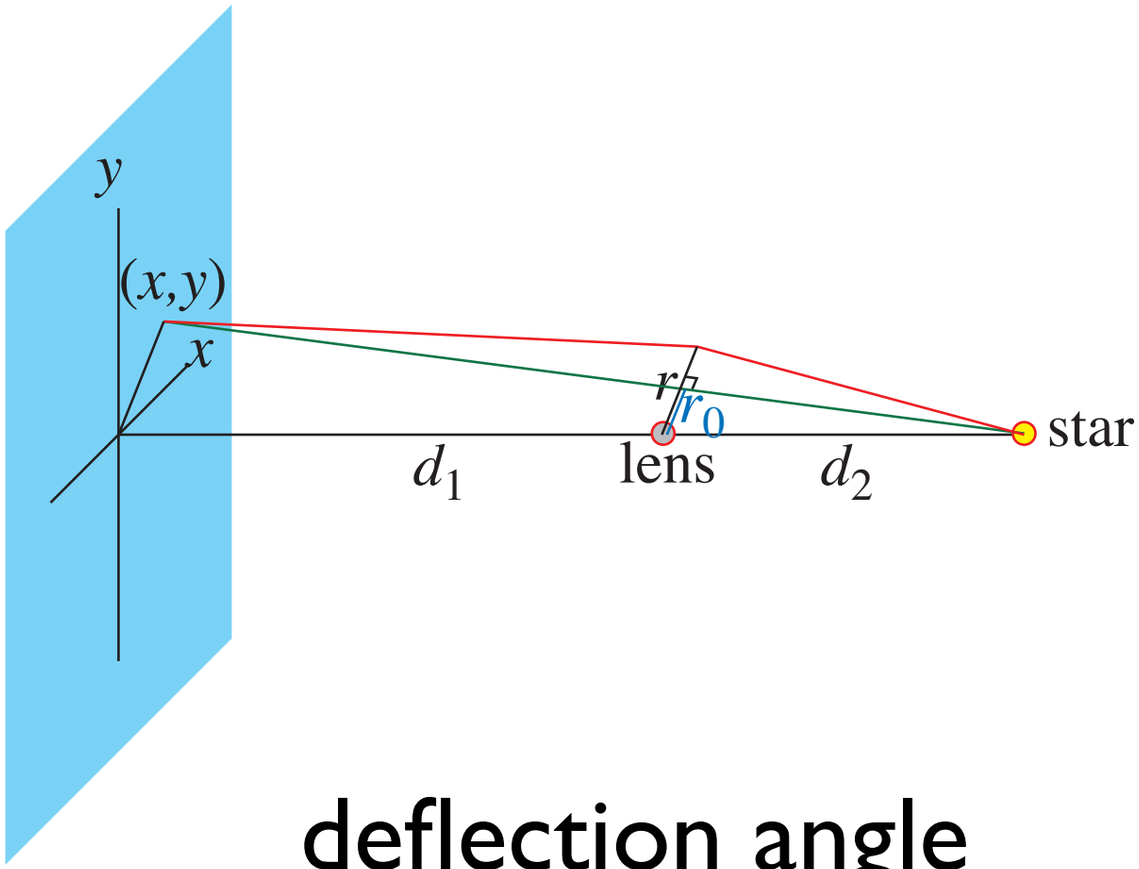


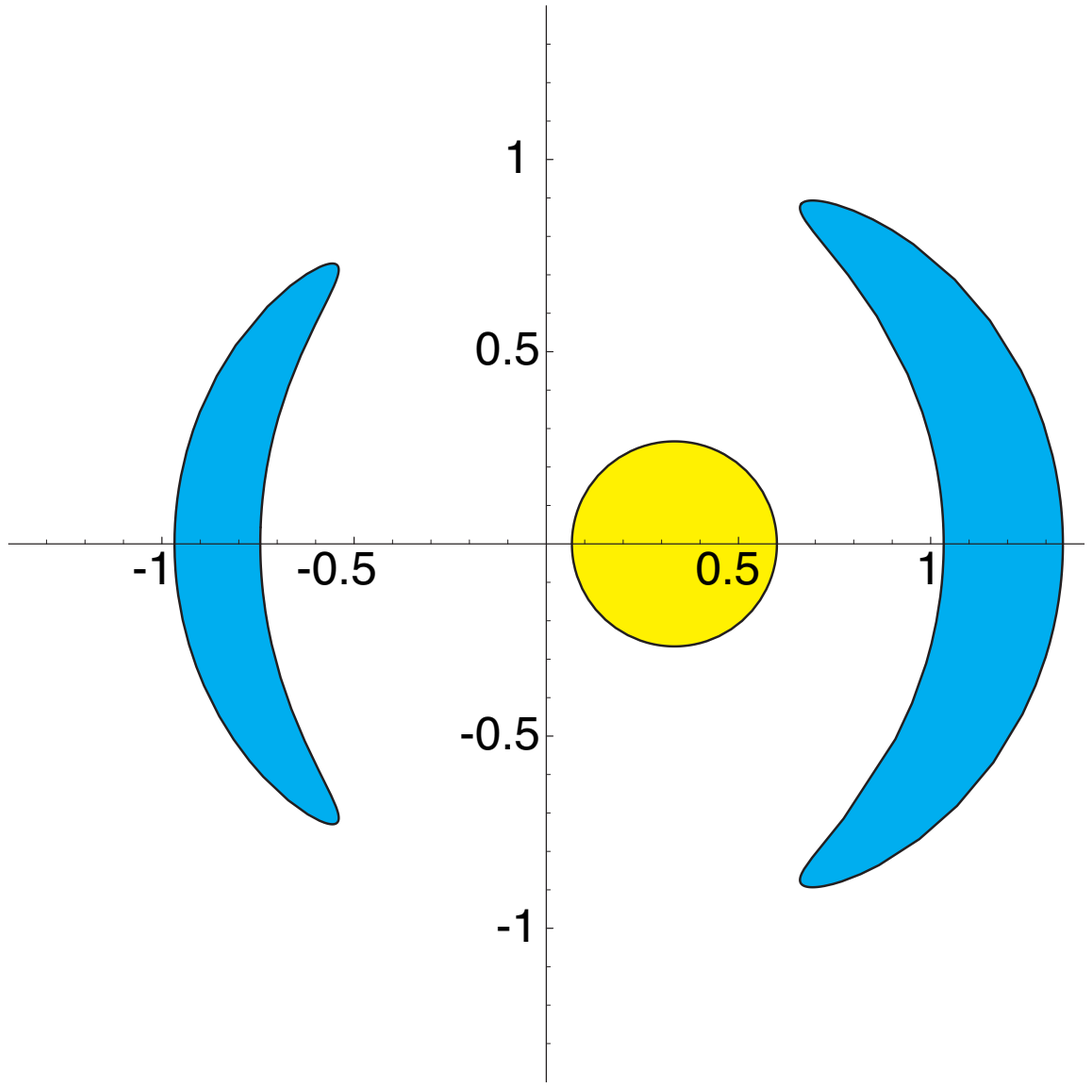
Fred Zwicky

gravitational lensing



gravitational lensing





deflection angle

$$\theta = 2\frac{r_S}{r} = 4\frac{G_N M}{c^2 r}$$

gravitational lensing

$$ds^2 = \left(1 - \frac{r_S}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - r_S/r} - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

$$g^{\mu\nu} \partial_\mu S \partial_\nu S = mc^2 = 0$$

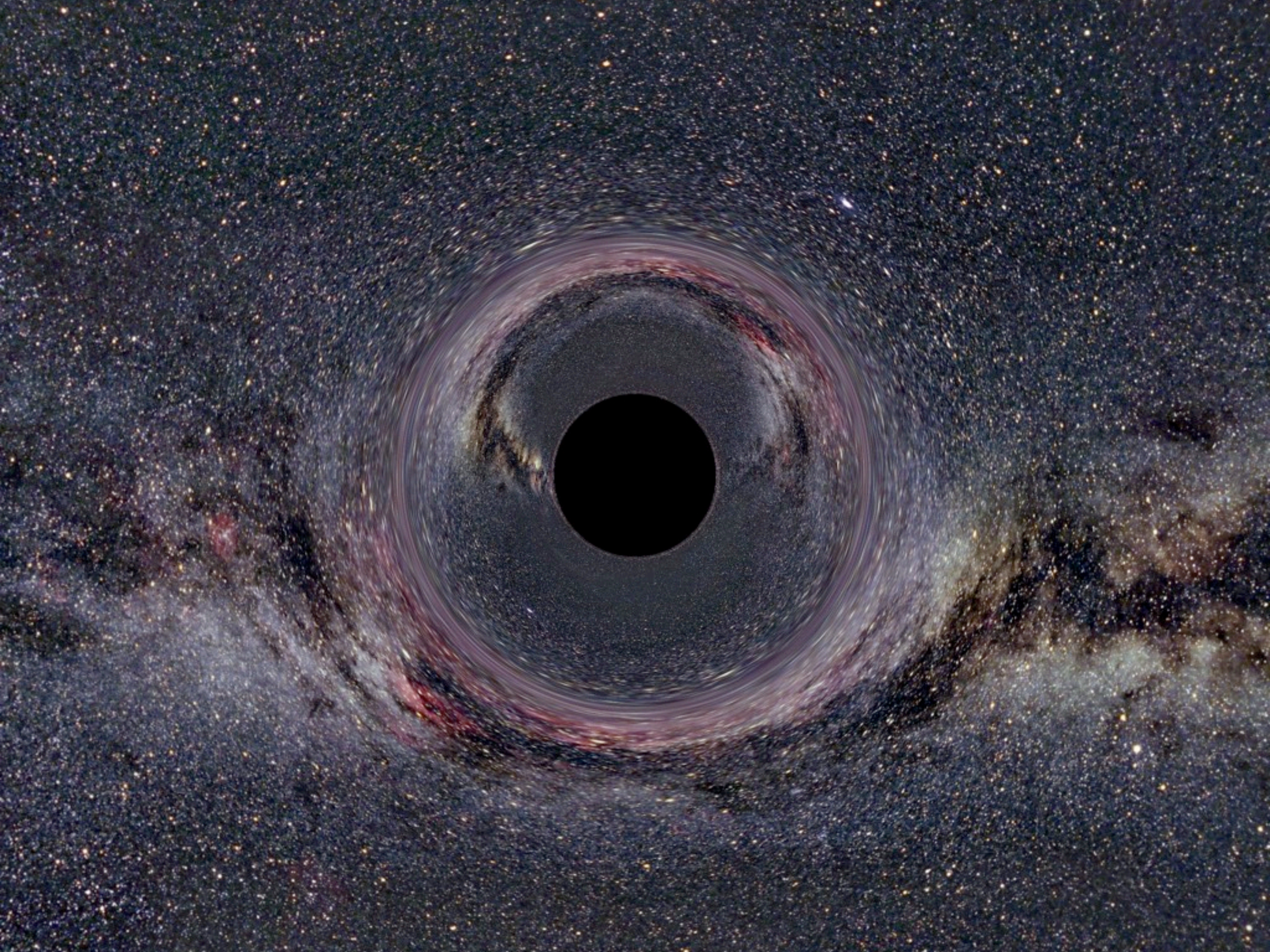
$$S(t, r, \theta) = Et - L\theta + W(E, r, L)$$

$$(\partial_r W)^2 = \left(1 - \frac{r_S}{r}\right)^{-2} \frac{E^2}{c^2} - \left(1 - \frac{r_S}{r}\right)^{-1} \frac{L^2}{r^2}$$

The closest approach r_c is where $\partial_r W = 0$

$$E^2 = c^2 \left(1 - \frac{r_S}{r_c}\right) \frac{L^2}{r_c^2}$$

$$\pi + \Delta\theta = \partial_L W = 2 \int_{r_c}^{\infty} \frac{dr}{r \sqrt{\left(1 - \frac{r_S}{r_c}\right) \frac{r^2}{r_c^2} - \left(1 - \frac{r_S}{r}\right)}} = \pi + \frac{2 r_S}{r_c} + O(r_S^2)$$



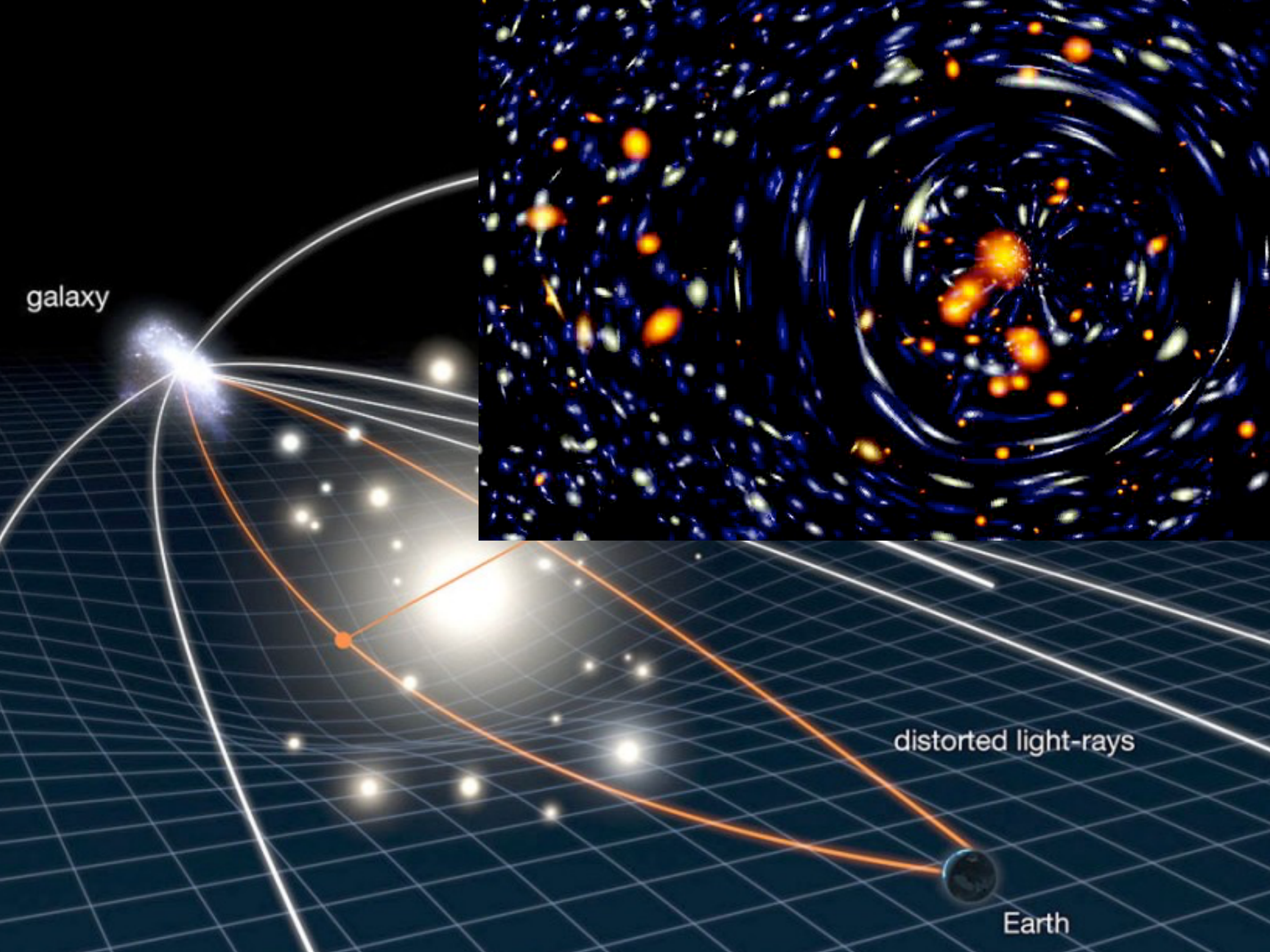
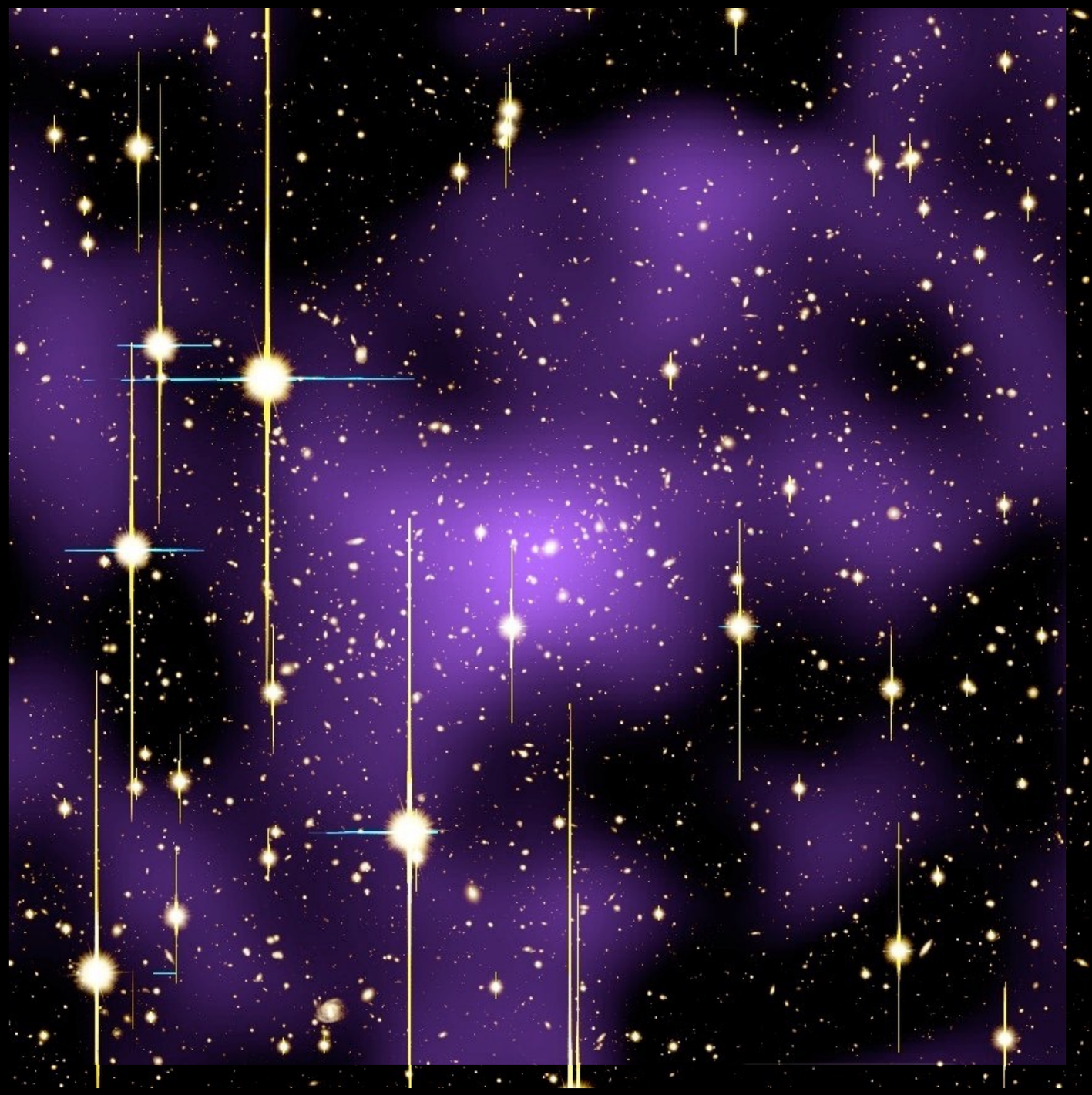

galaxy
distorted light-rays
Earth

image invisible dark matter



more than 80% of matter in the Universe is not atoms

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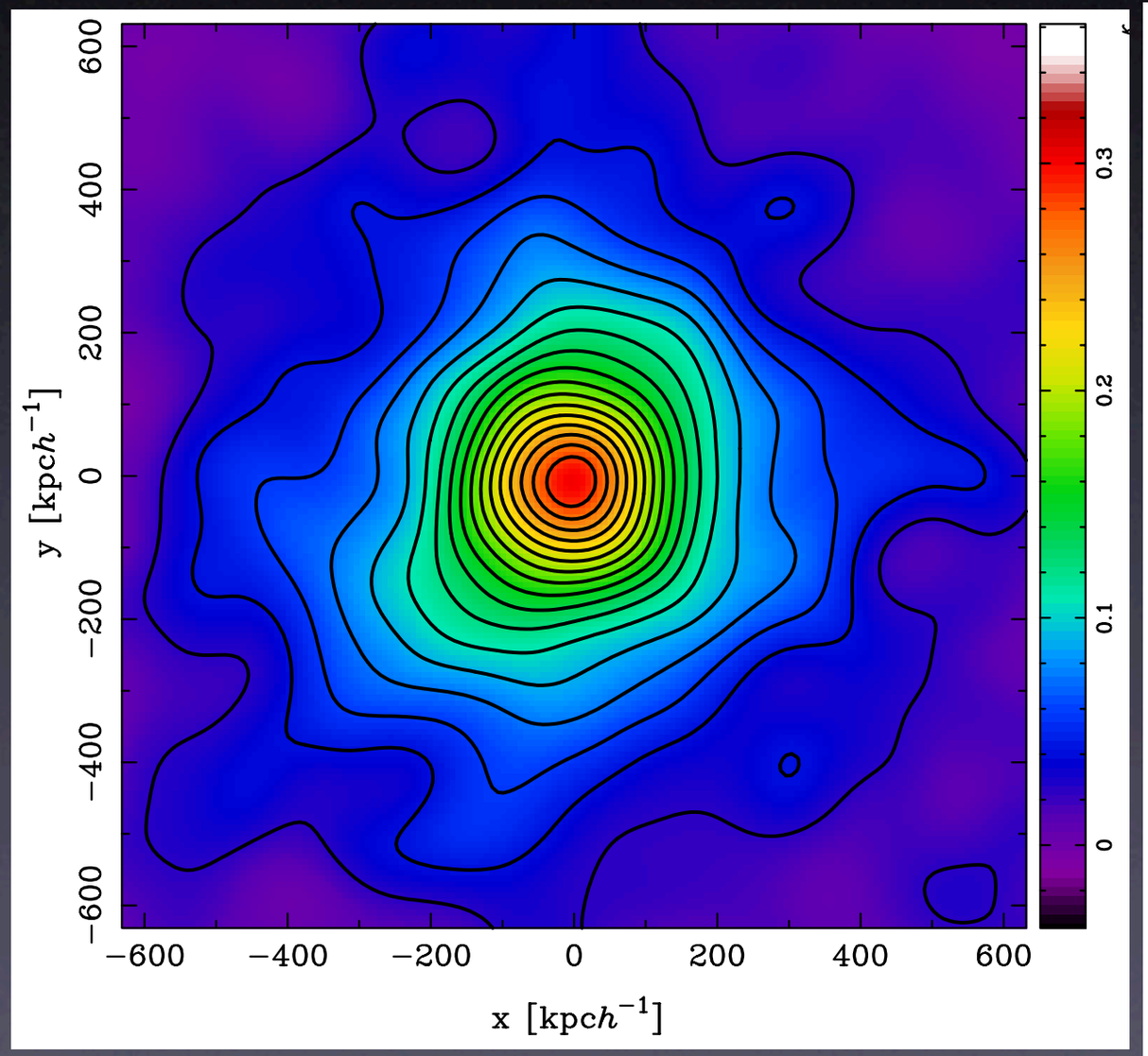
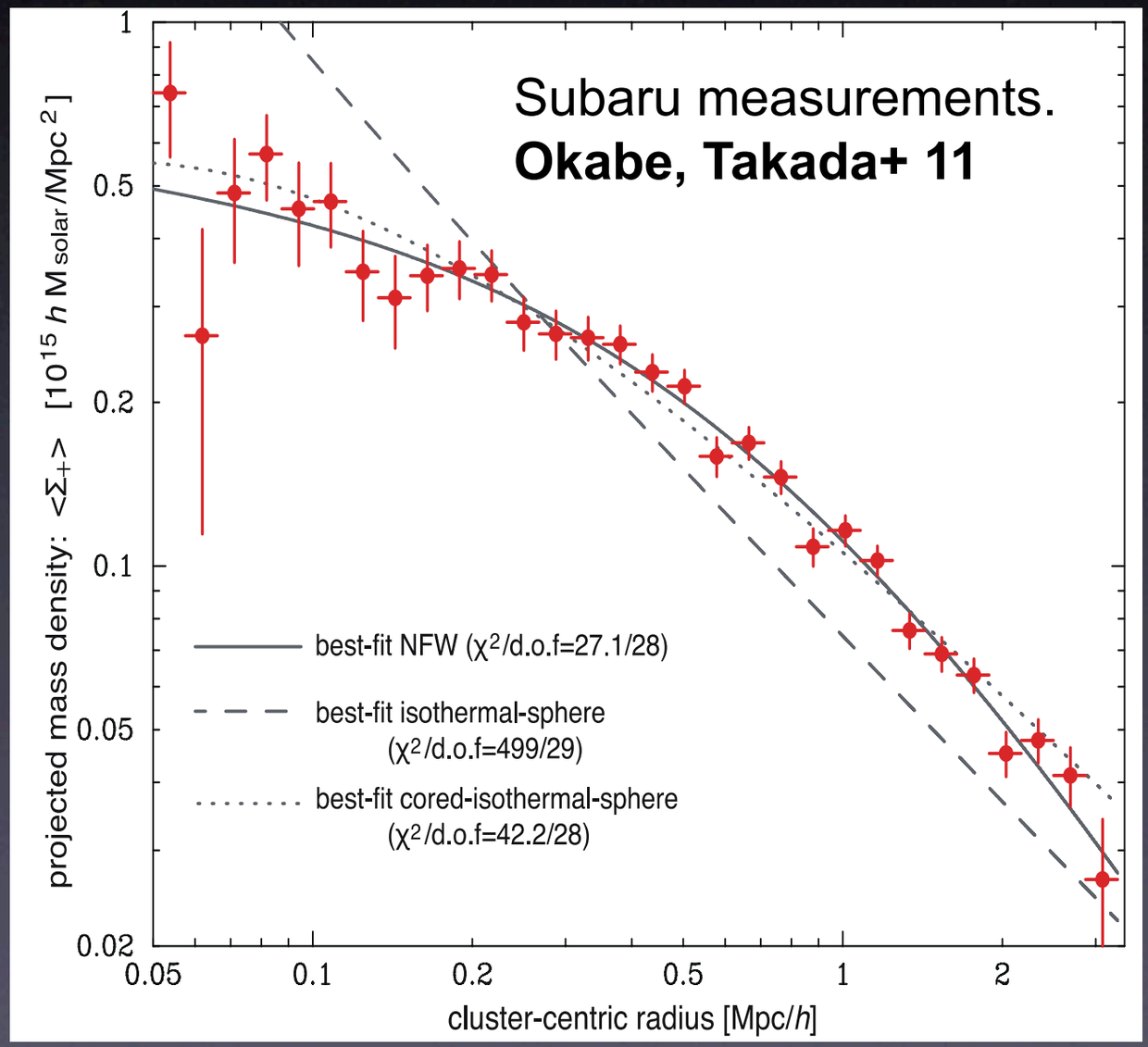
as expected by theory

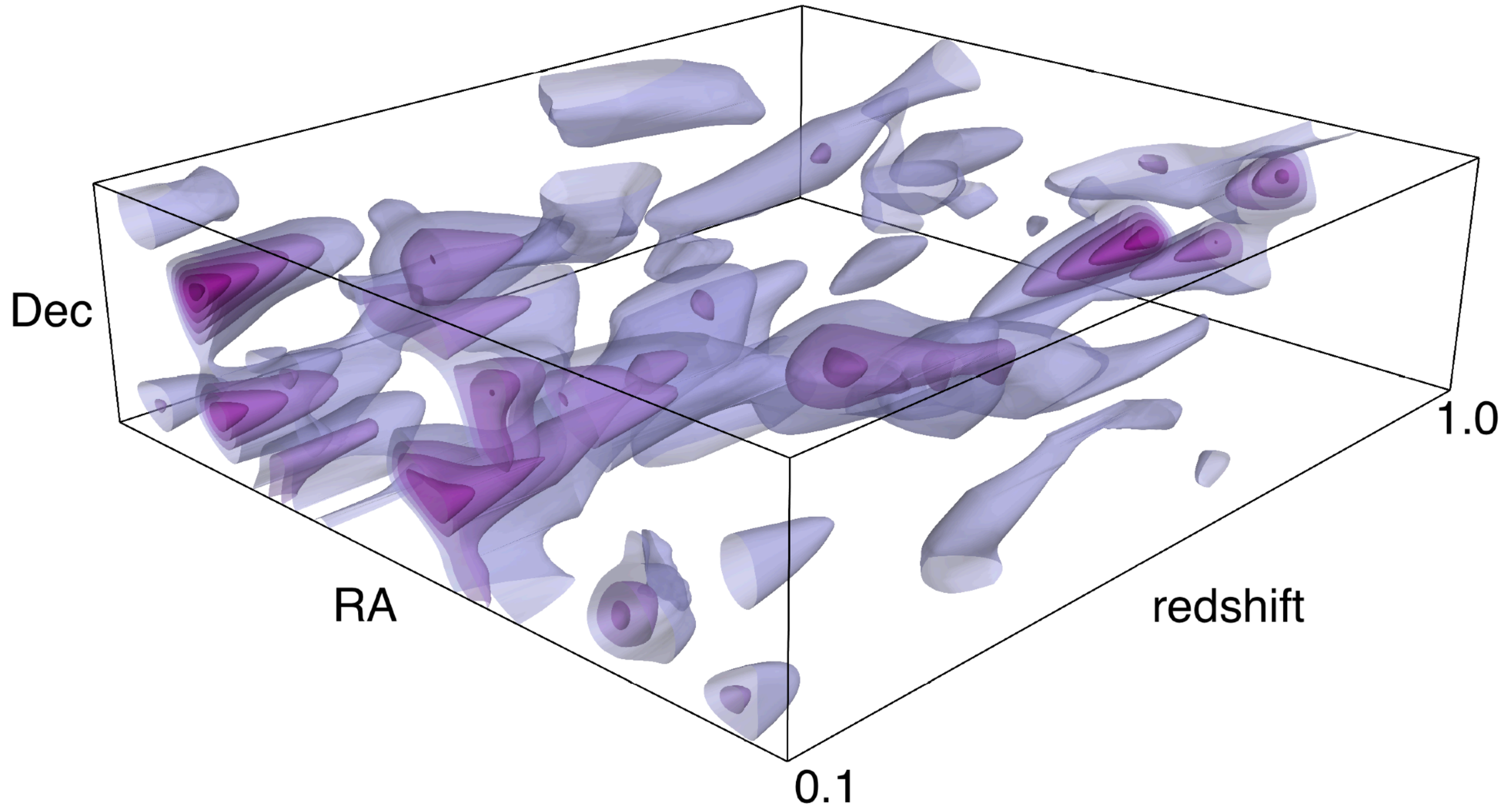


45 clusters stacked

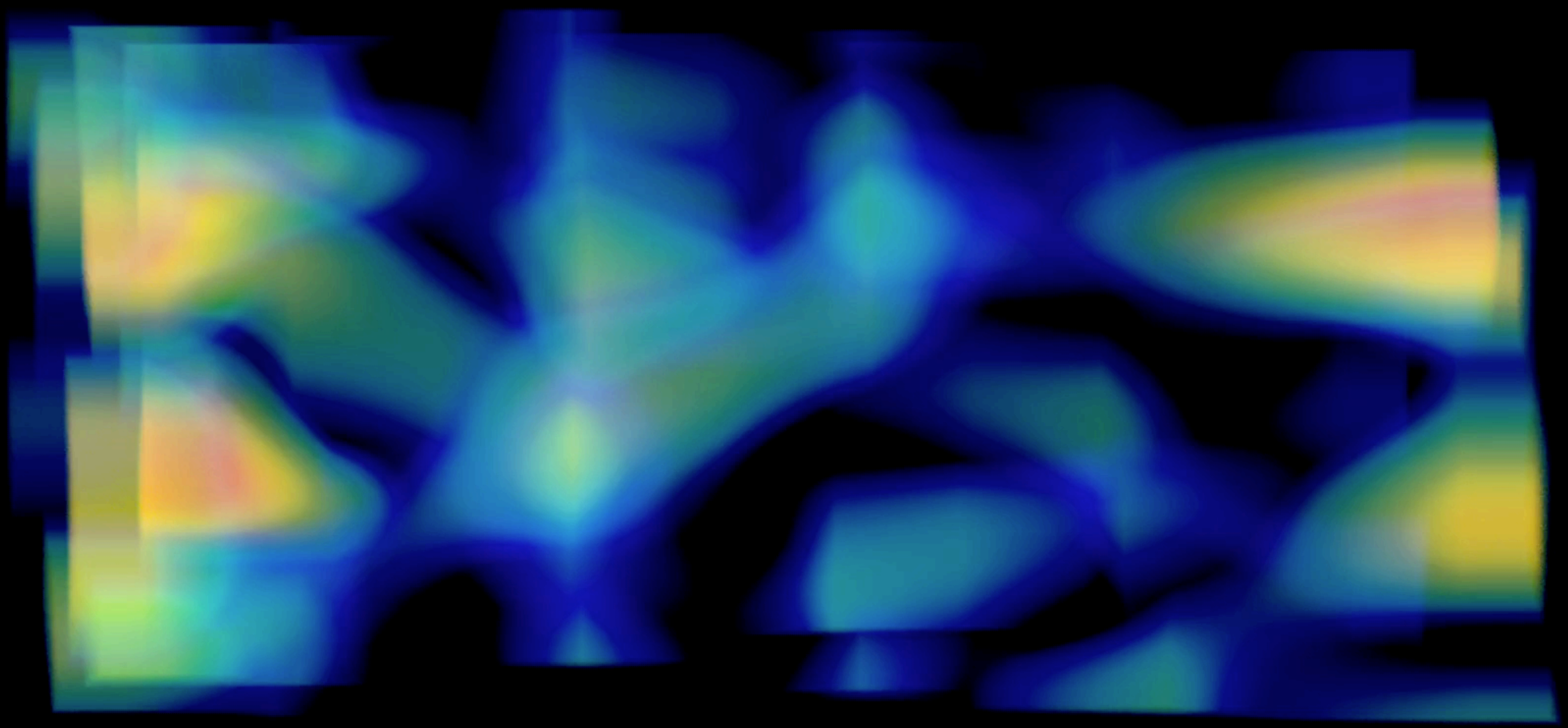


consistent with NFW profile

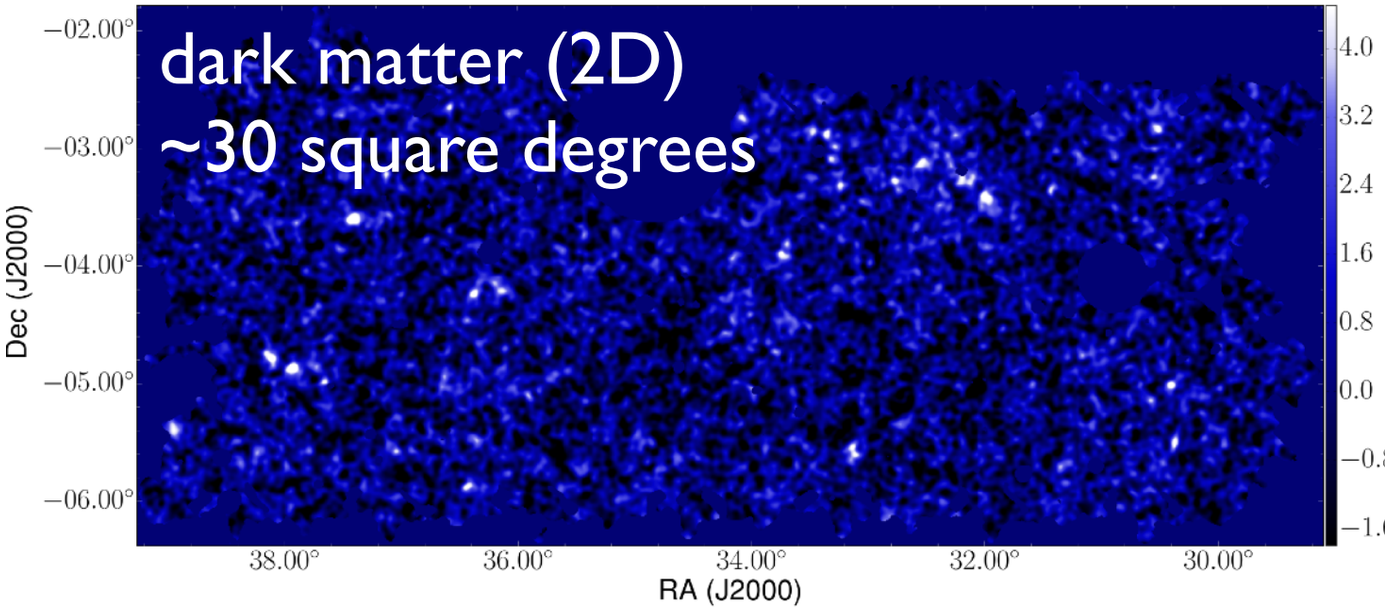
world's largest 3D map of dark matter

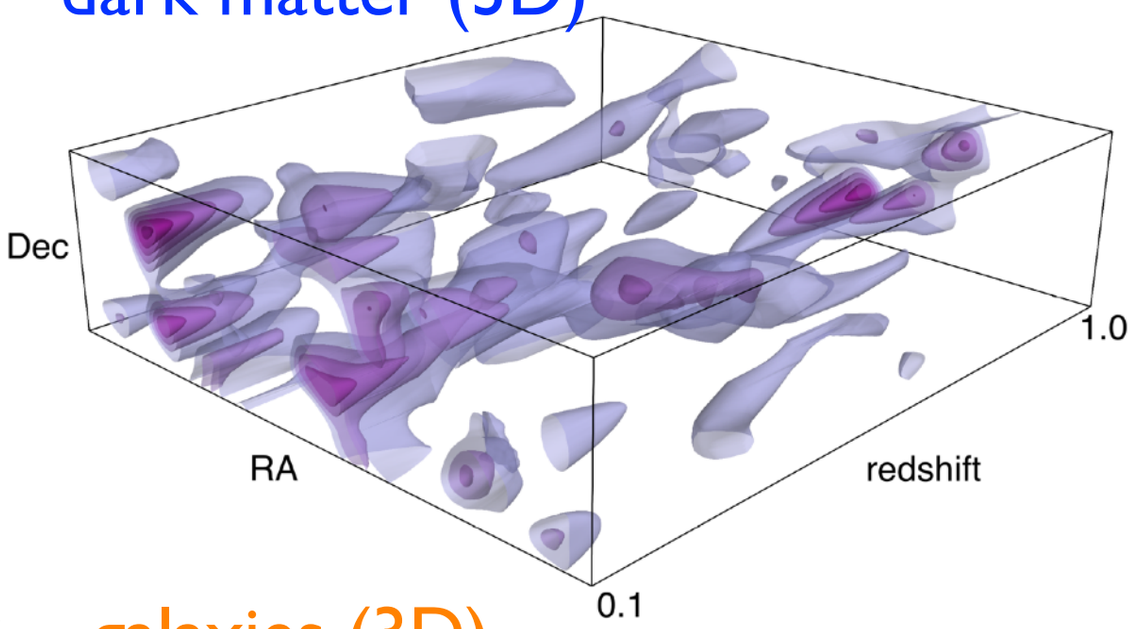


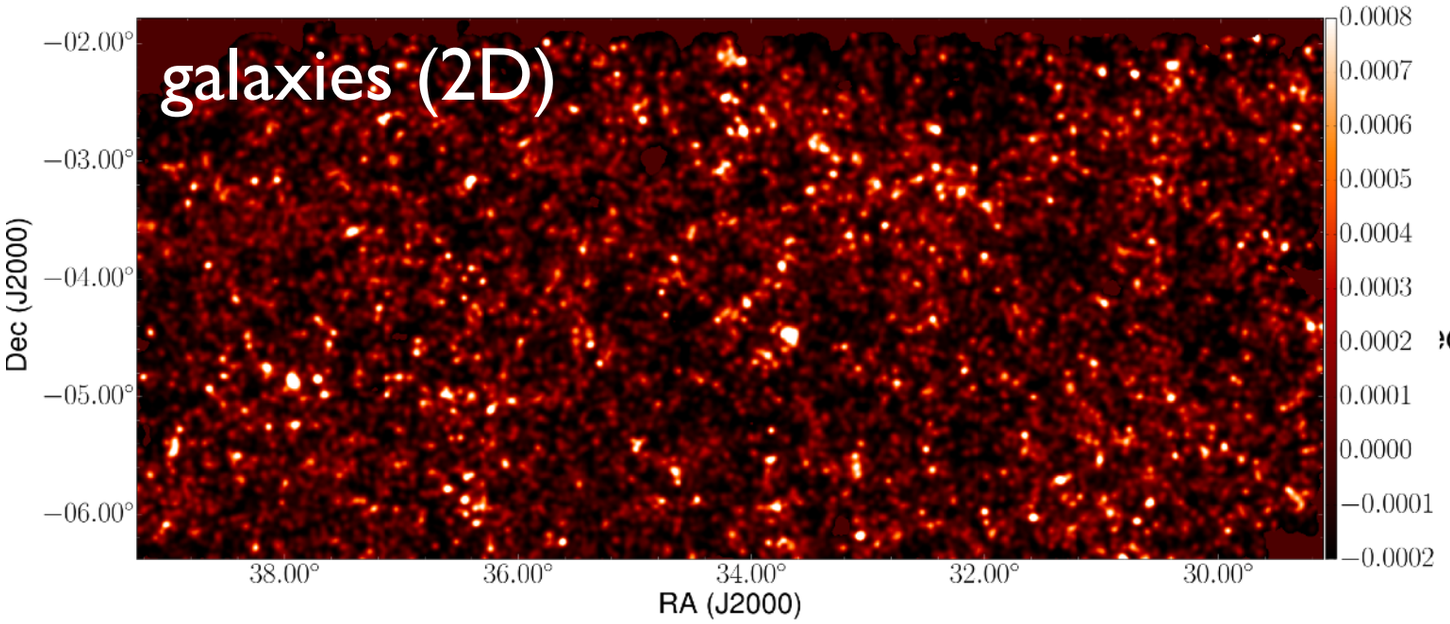
world’s largest 3D map of dark matter

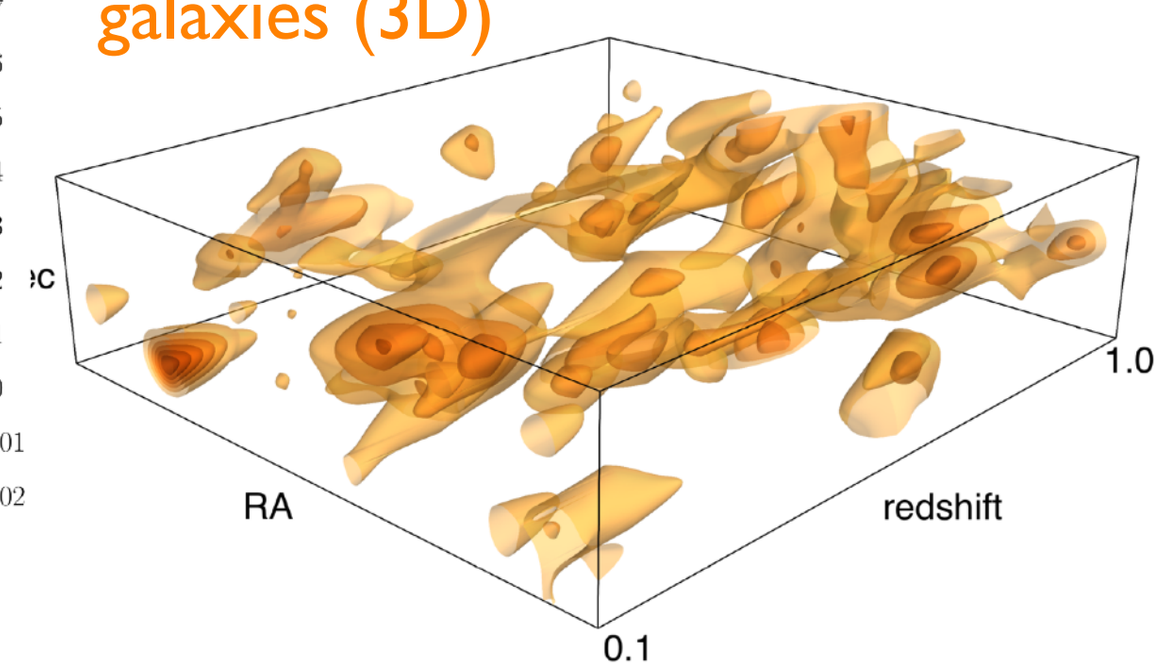


dark matter is our Mom

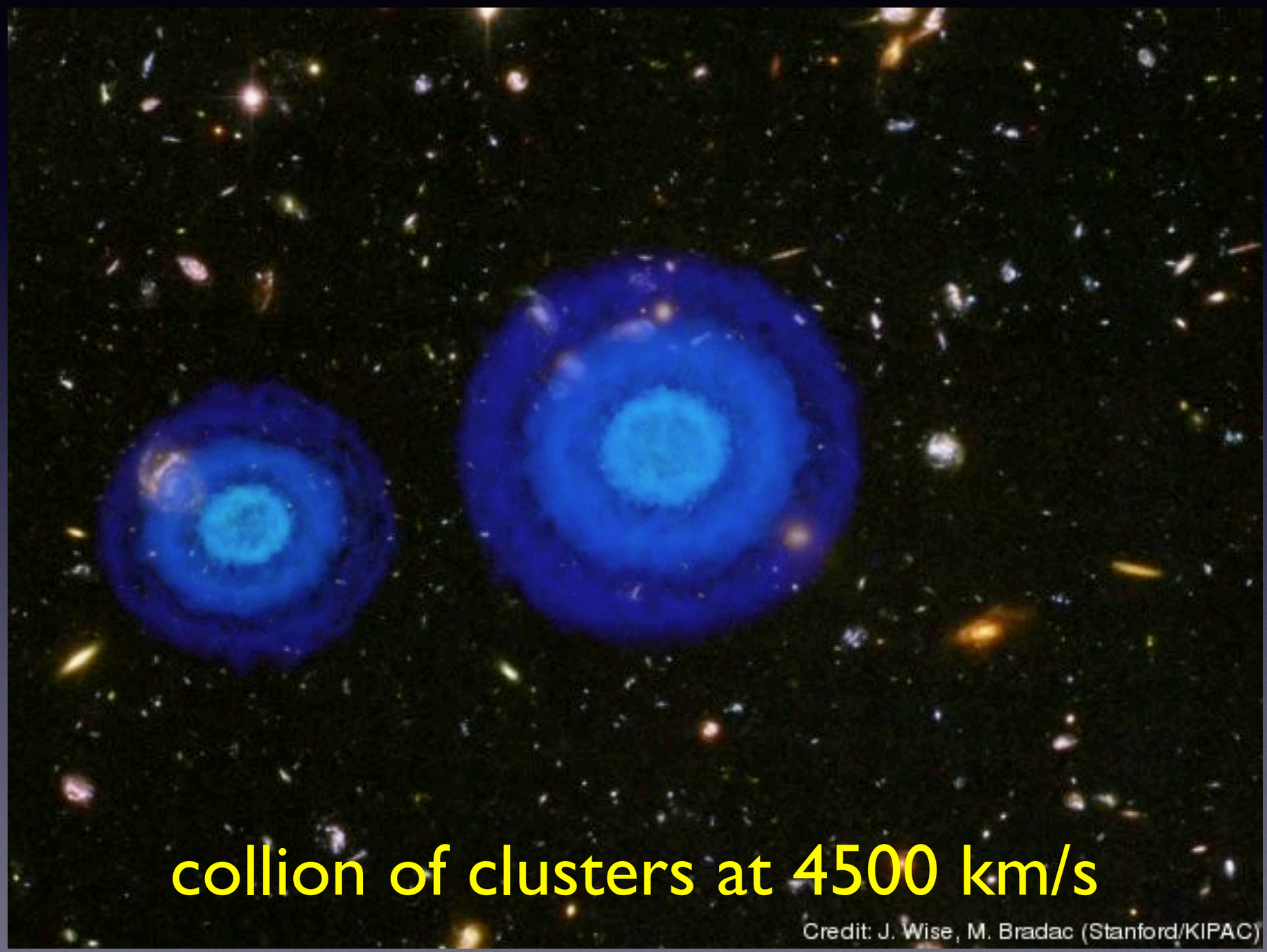






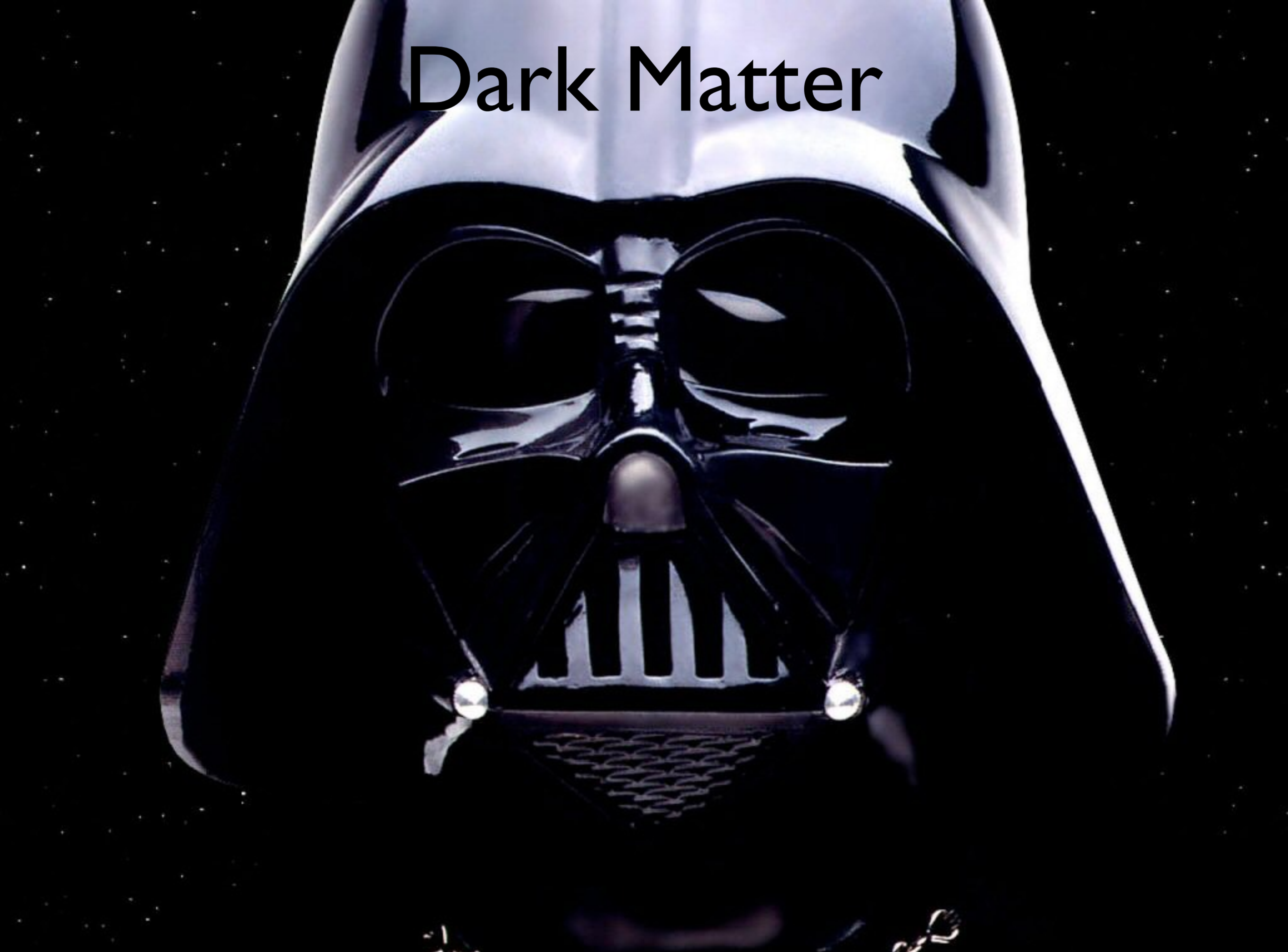


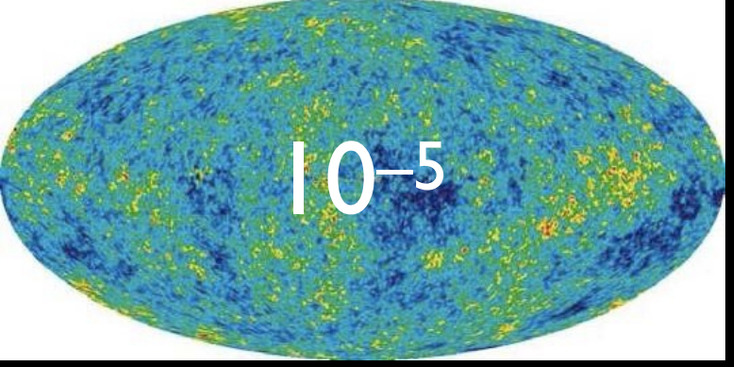
lucky we are not here



4 billion lyr away

Dark Matter

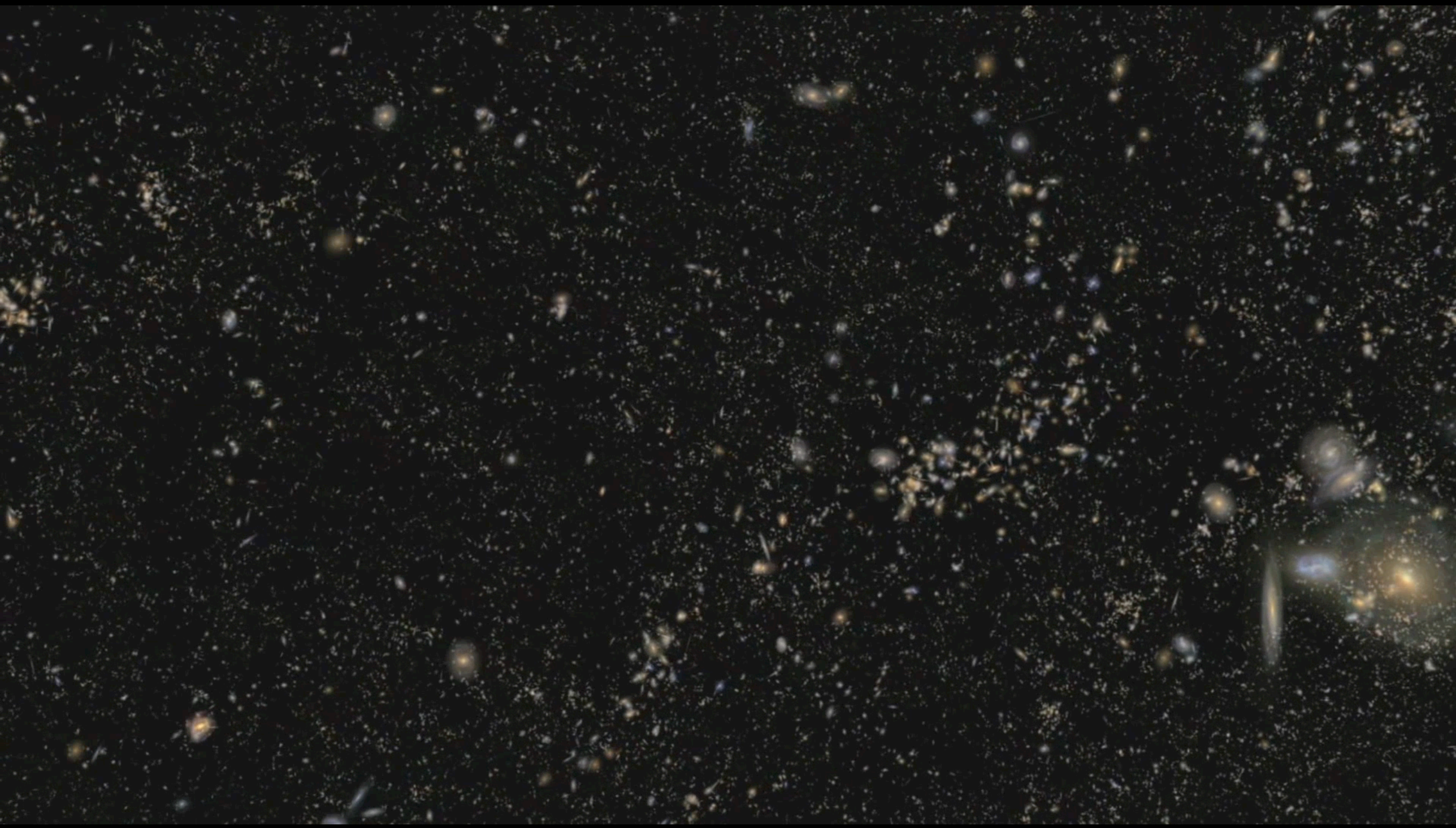




Dark Matter is our Mom

without dark matter

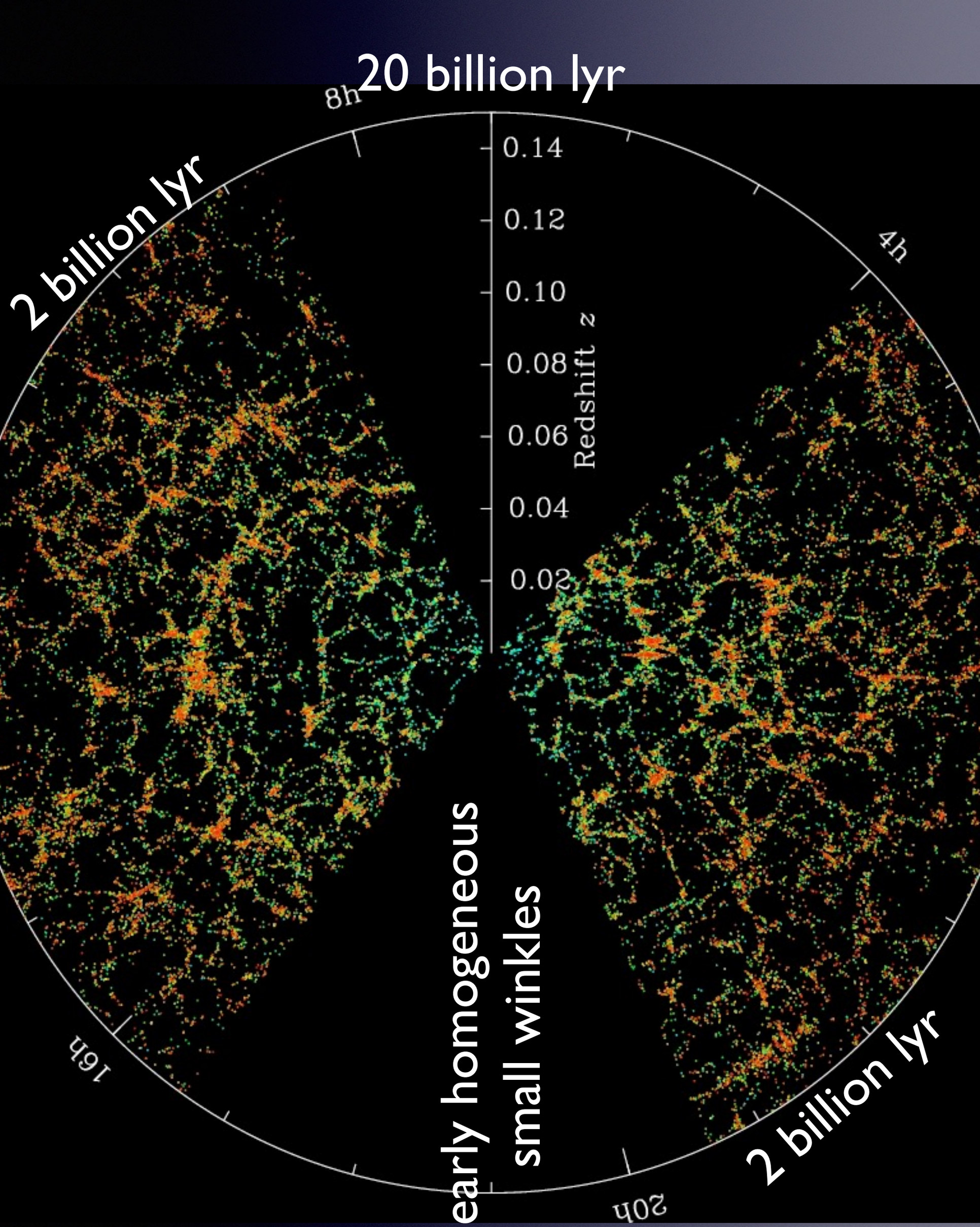
with dark matter



fly-through based on SDSS-III data

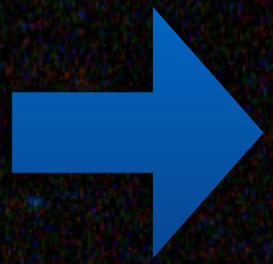
20 billion lyr

2 billion lyr



nearly homogeneous
small winkles

2 billion lyr



galaxy 13.2 billion lyr away

Galaxy Cluster MACS J1149+2223

High-Redshift Galaxy MACS1149-JD

A Distant Gravitationally-Lensed Galaxy at Redshift = 9.6

NASA / ESA / STScI/ J. Hora (Harvard-Smitsonian CfA)

Hubble Space Telescope • ACS • WFC3

ssc2012-12a

dark ages
13.6 billion lyr away

Friedmann Universe

Expanding space

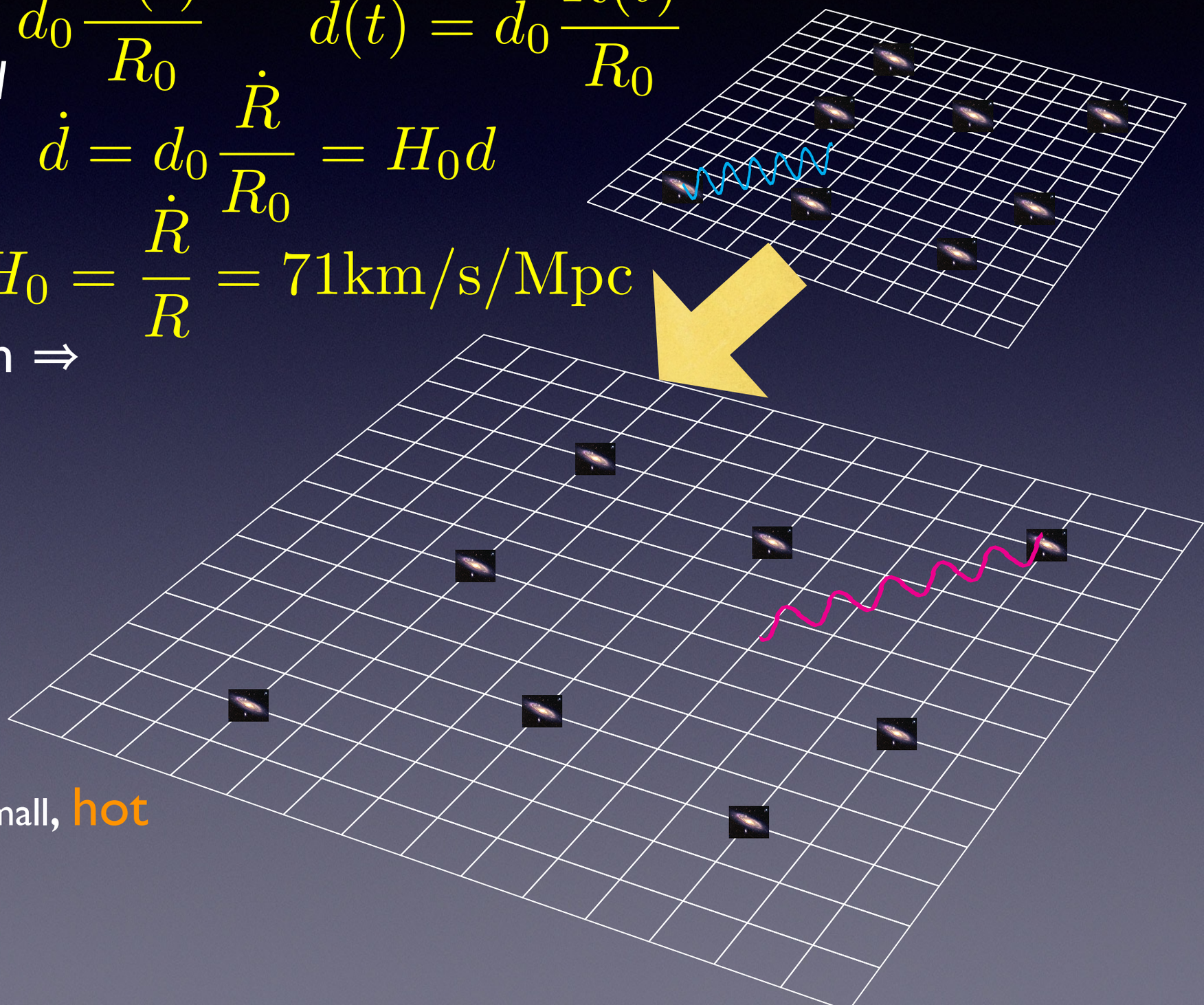
$$d = d_0 \frac{R(t)}{R_0} \qquad \dot{d}(t) = d_0 \frac{\dot{R}(t)}{R_0}$$

$$\dot{d} = d_0 \frac{\dot{R}}{R_0} = H_0 d$$

$$H_0 = \frac{\dot{R}}{R} = 71 \mathrm{km/s/Mpc}$$

- Hubble law: $v=H_0 d$
- $\lambda=\lambda_0(1+z)$
- z: redshift = R_0/R
- adiabatic expansion ⇒

  $T \propto R^{-1}$
- $T=T_0(1+z)$
- bigger and colder



- Universe started small, hot

Big Bang!

very distant galaxy

distant galaxy

nearby galaxy

star

laboratory reference

λ_0

λ'

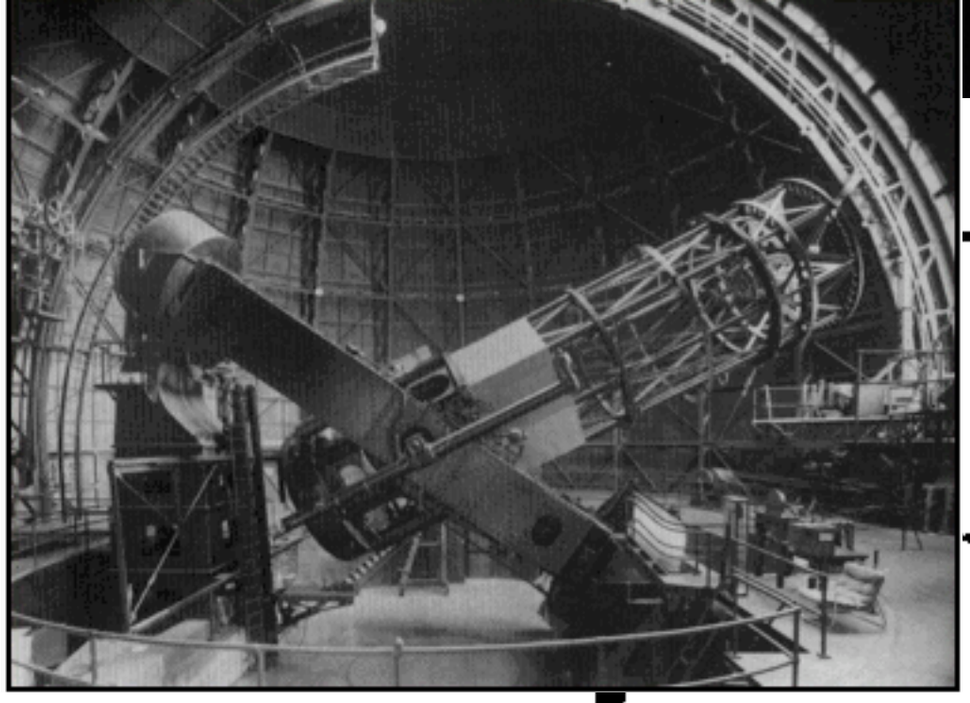
400

500

600

700

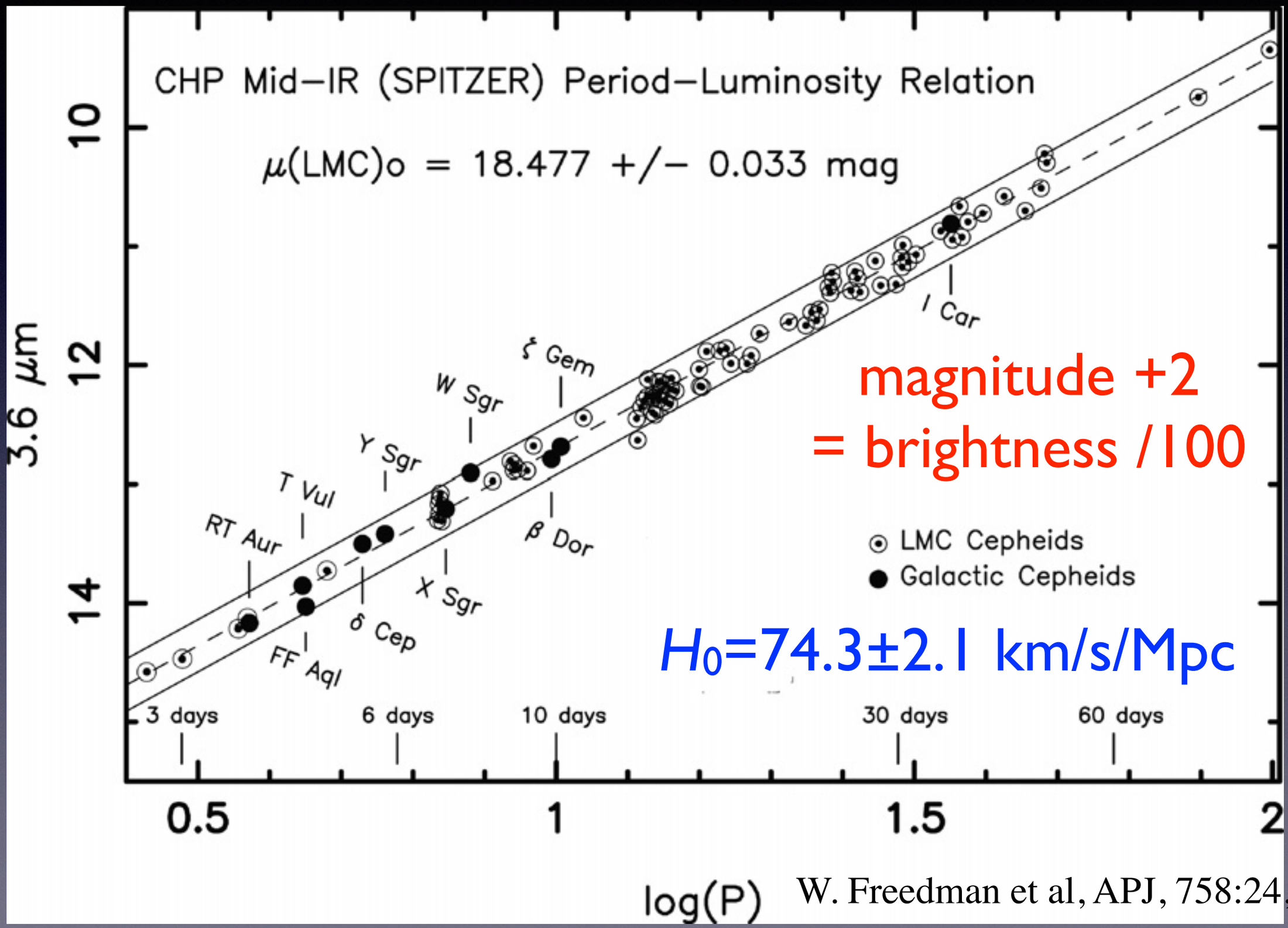
Wavelength (λ)



7 times larger
than the current value!

FIGURE 1

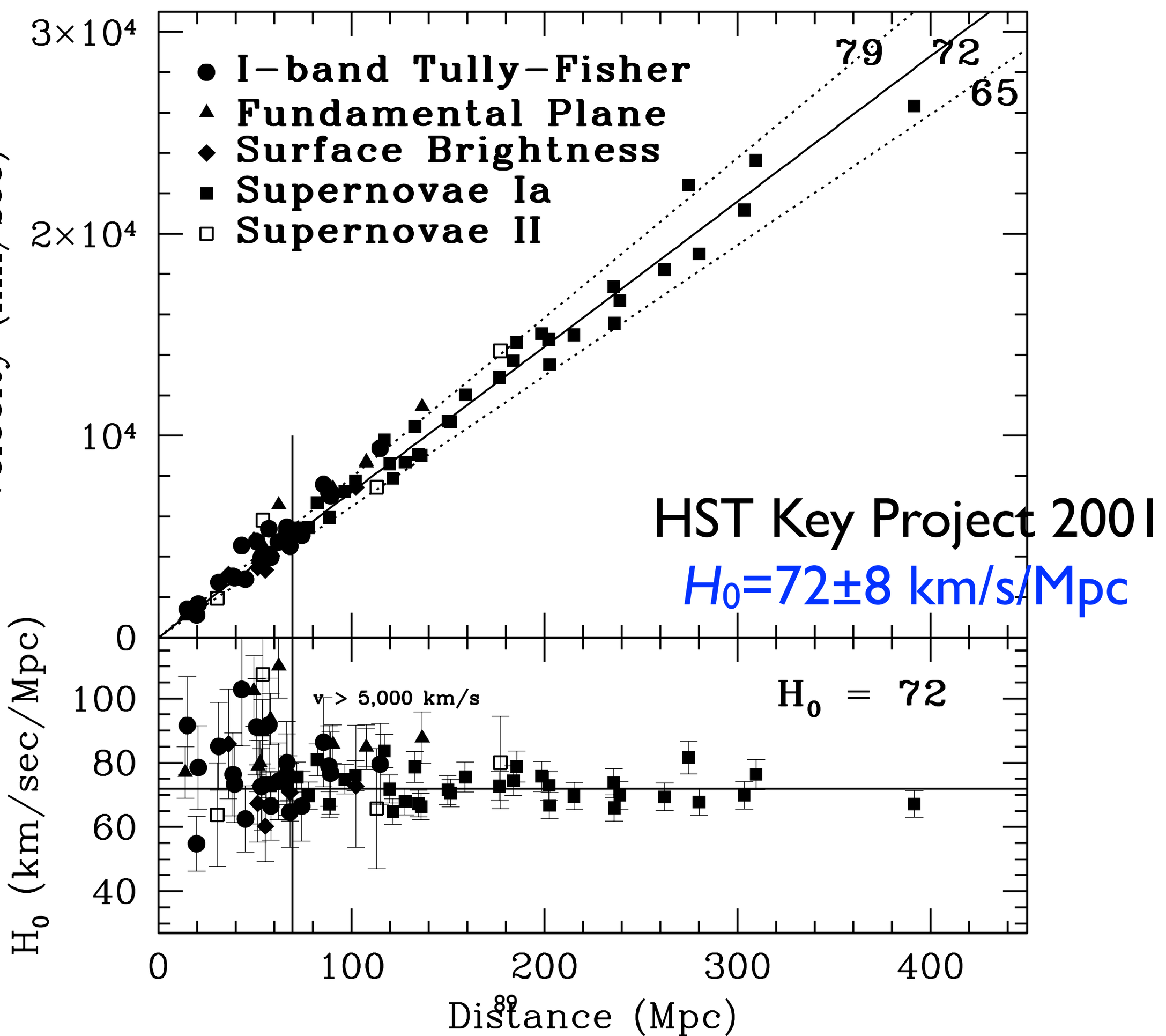
Cepheids calibration



magnitude +2
= brightness /100

H_0=74.3±2.1 km/s/Mpc

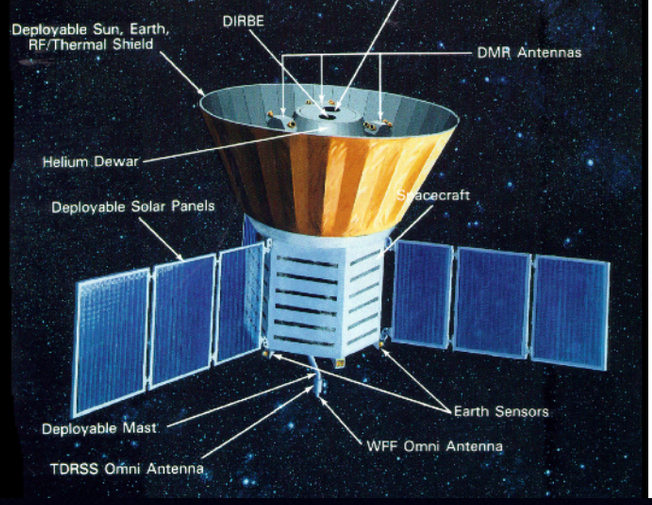
W. Freedman et al, APJ, 758:24, 2012

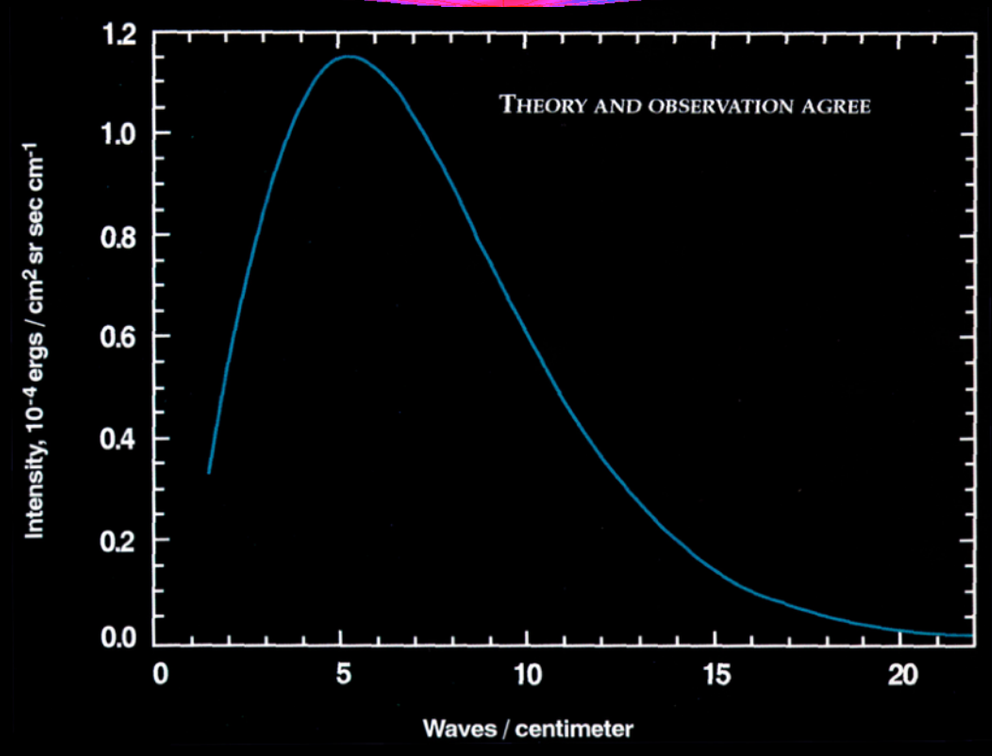


HST Key Project 2001

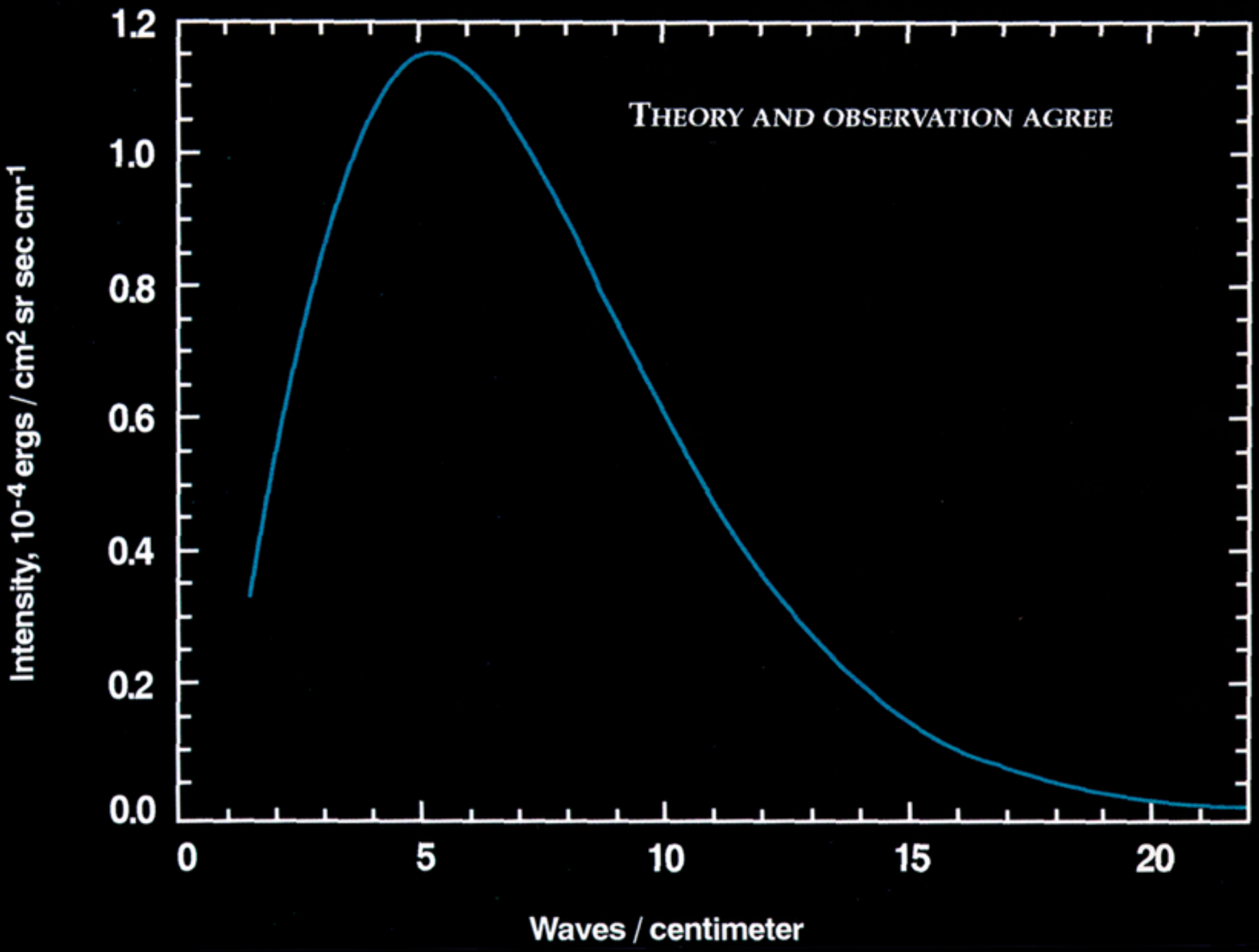
H_0=72±8 km/s/Mpc

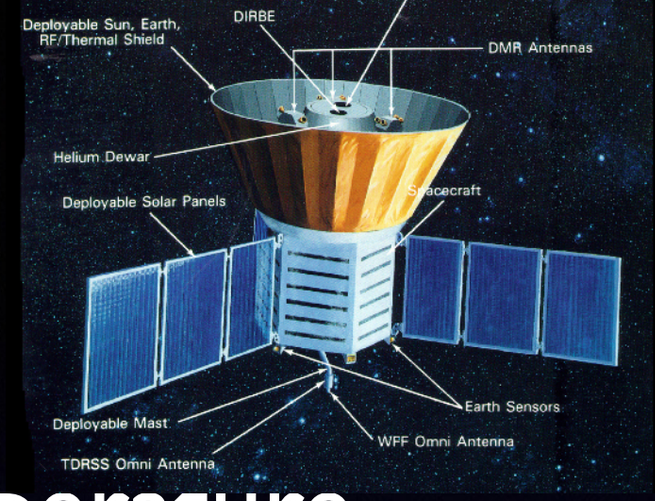
13.7 G lyr away
= 13.7 Gyr ago

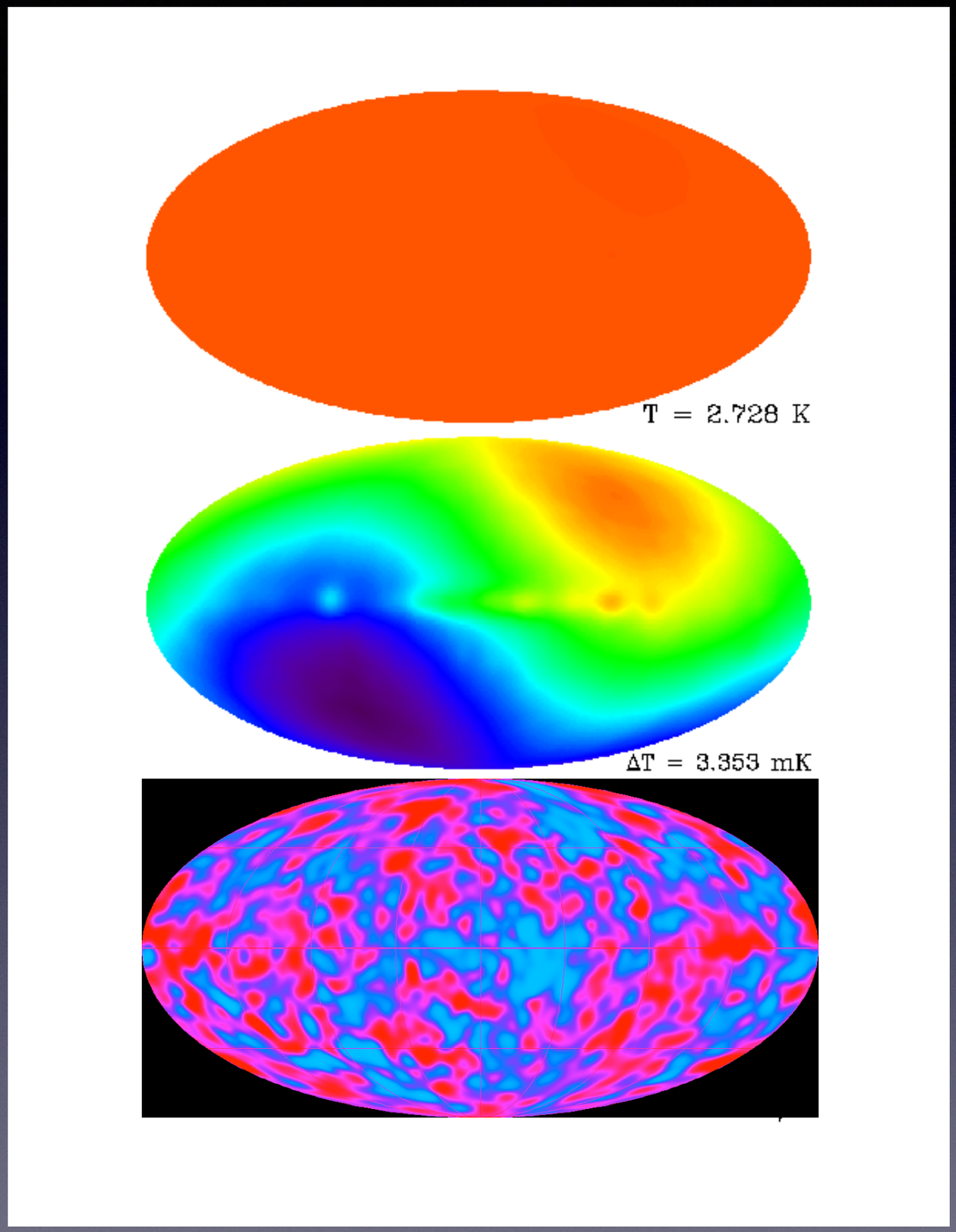




Cosmic Microwave Background Spectrum from COBE





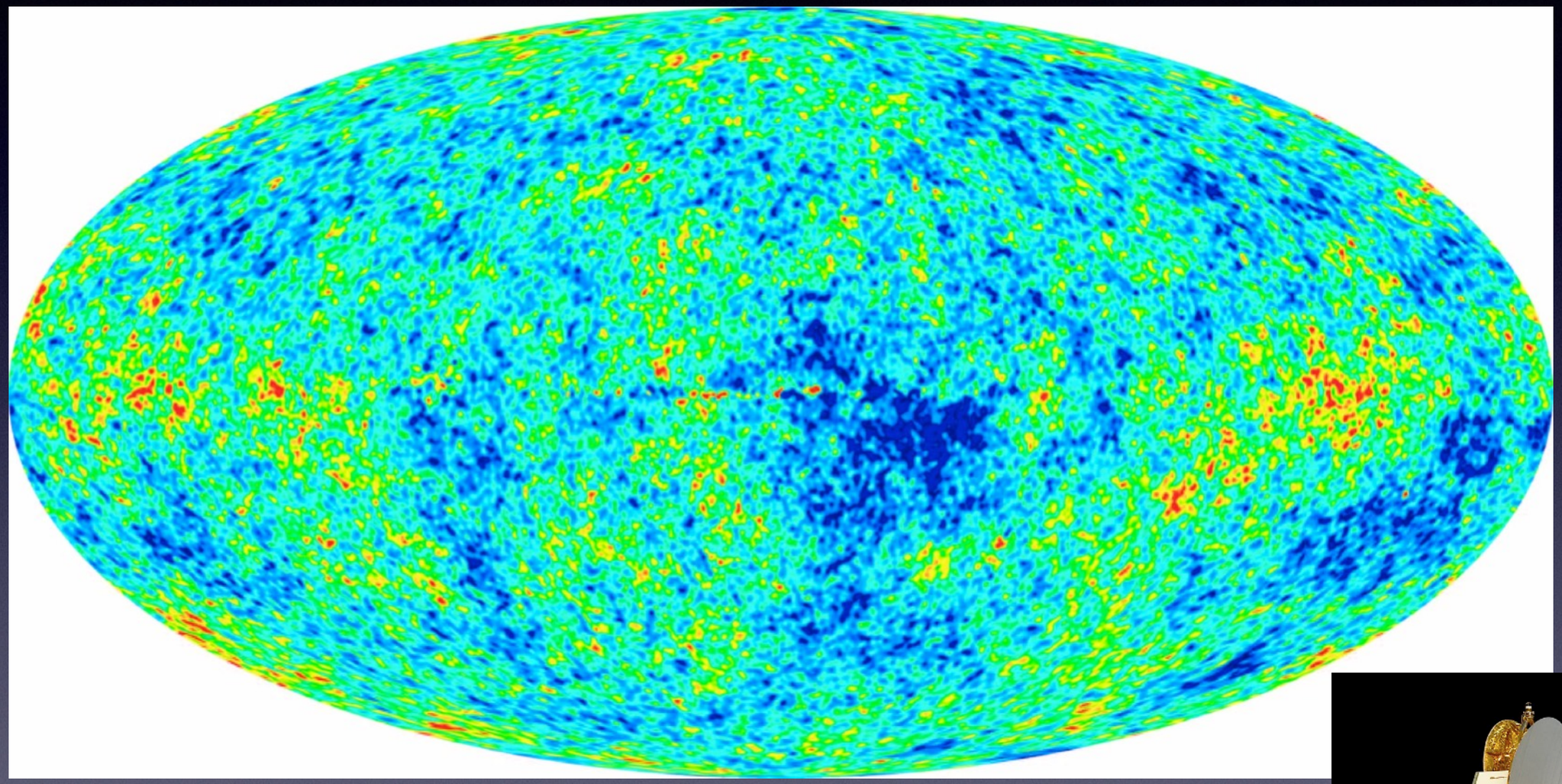


CMB temperature

CMB dipole
we are moving at
~1% of *c* relative to CMB

CMB anisotropy
at ~10^{-5}
1mm ripple on 100m sea

wall @ 13.7Glyr away



You can never see beyond this wall
using light

WMAP
Wilkinson Microwave
Anisotropy Probe

protons

electrons

quasars

Cosmic Microwave Background Radiation

recombination

galaxies

soup of particles

Big Bang

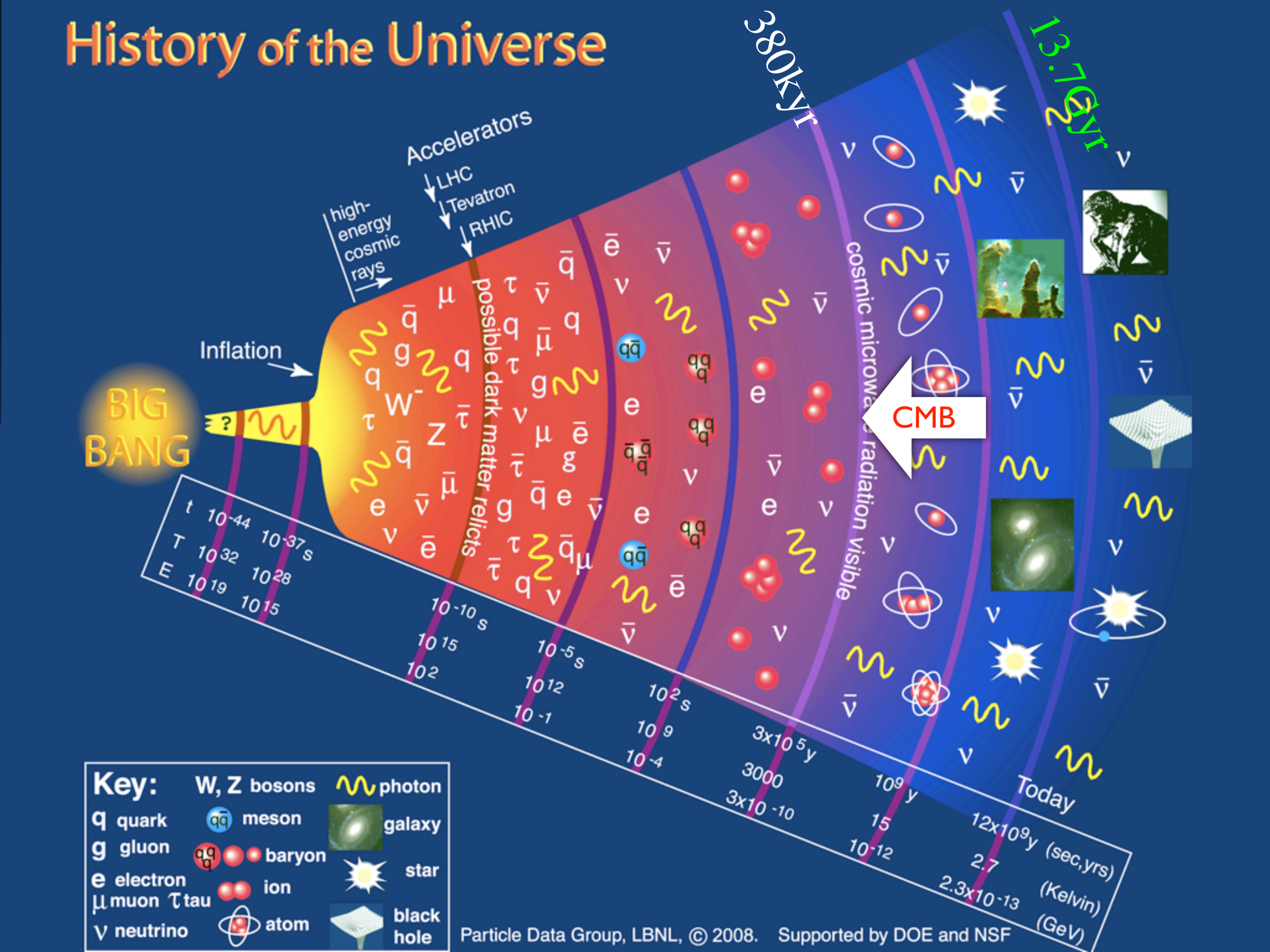
380,000 yrs

10 Gyrs

13.7 Gyrs

time

History of the Universe



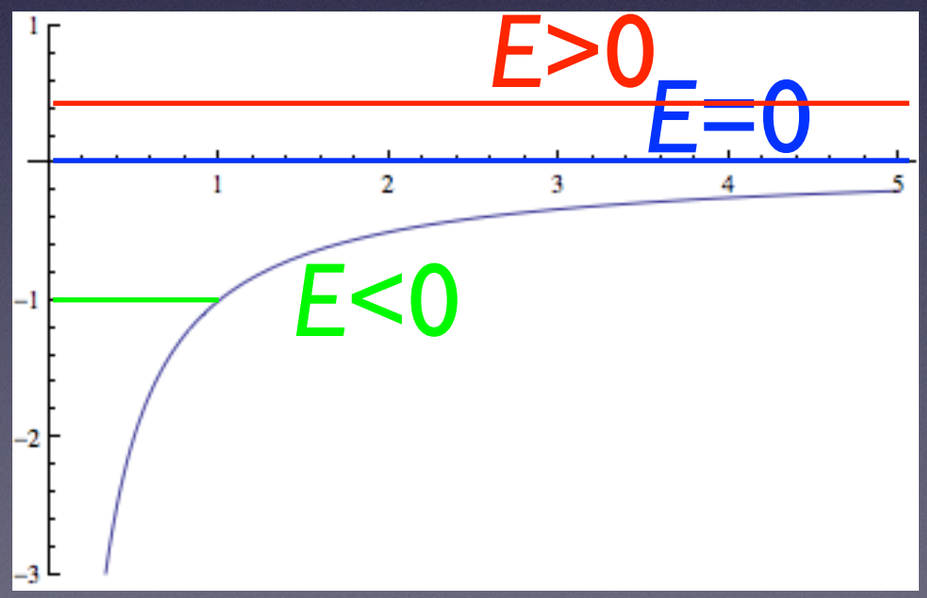
Friedmann Equation

$$E = \frac{m}{2}\dot{R}^2 - G_N\left(\frac{4\pi}{3}\rho R^3\right)\frac{m}{R}$$

- "non-relativistic derivation"
- assume spherical distribution of mass density ρ

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G_N\rho - \frac{k}{R^2}$$

- *same as full relativistic equation with a curvature term k=–1, 0, 1*



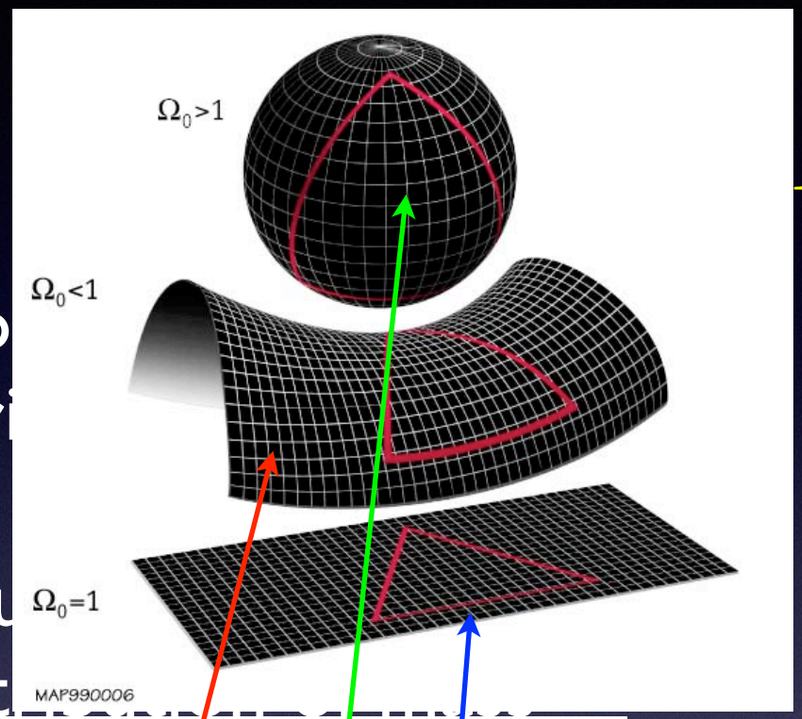
$$\frac{4\pi}{3}\rho R^3 = M$$

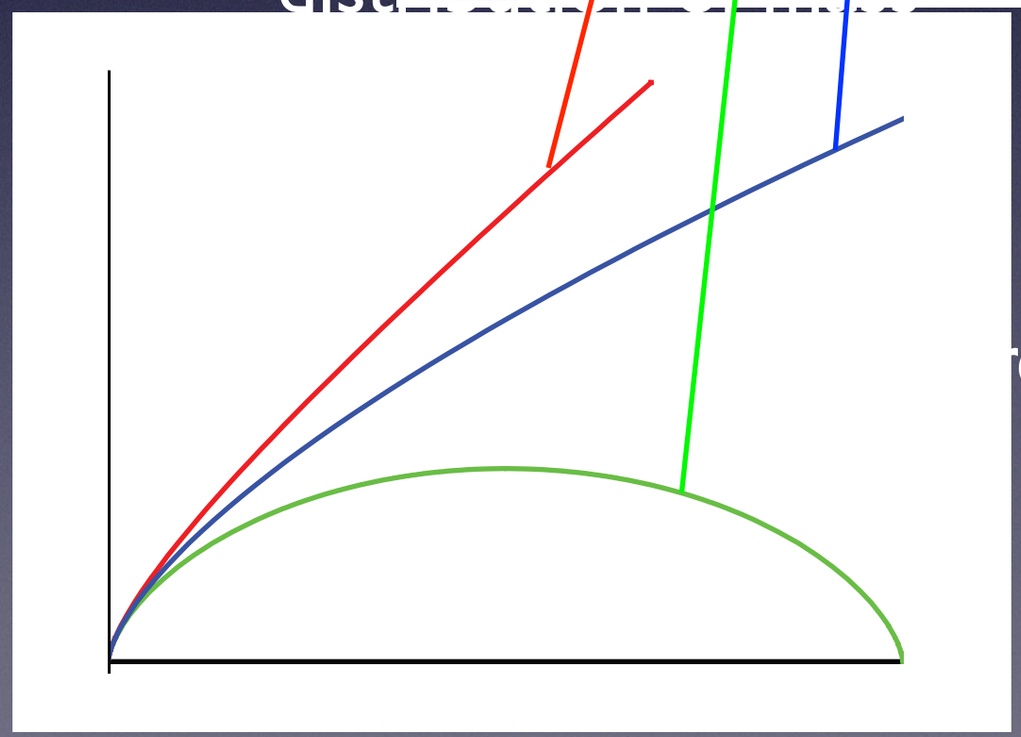
Friedmann Equation

- "no
deri
- assu
dist

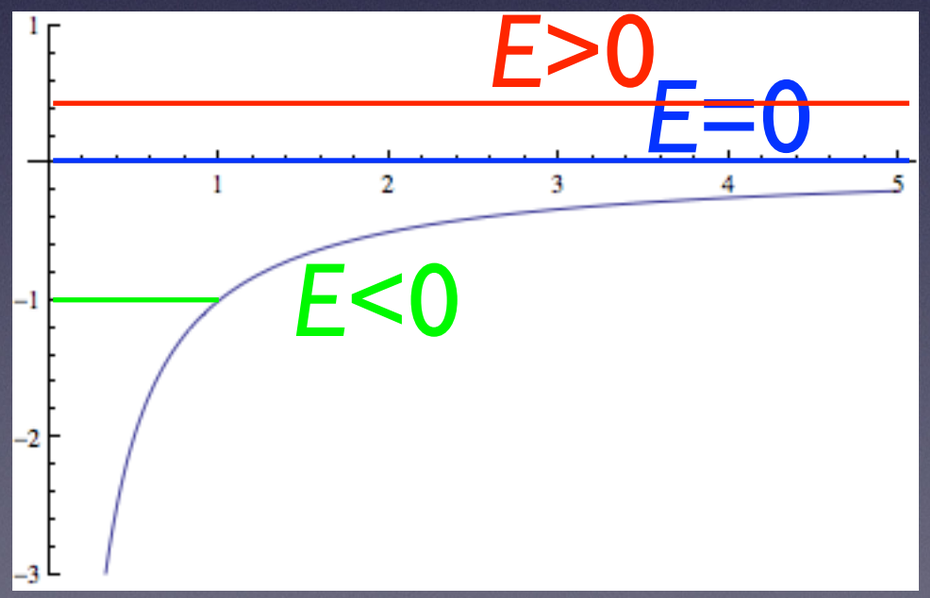
$$E = \frac{m}{2}\dot{R}^2 - G_N\left(\frac{4\pi}{3}\rho R^3\right)\frac{m}{R}$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G_N\rho - \frac{k}{R^2}$$





re



$$\frac{4\pi}{3}\rho R^3 = M$$

Current Universe

- knowing the l.h.s. tells us the current energy density
- l.h.s. = H_0^2 from Hubble law $v=H_0\, d$
- r.h.s. defines the *critical density* ρ_c

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{R^2}$$

$$H_0 = \frac{\dot{R}}{R} = 71 \mathrm{km/s/Mpc}$$

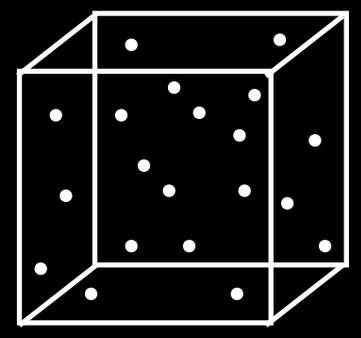
$$\rho_c = \frac{3}{8\pi} G_N^{-1} H_0^2 = 5.3 \times 10^{-6} \mathrm{GeV cm}^{-3}$$

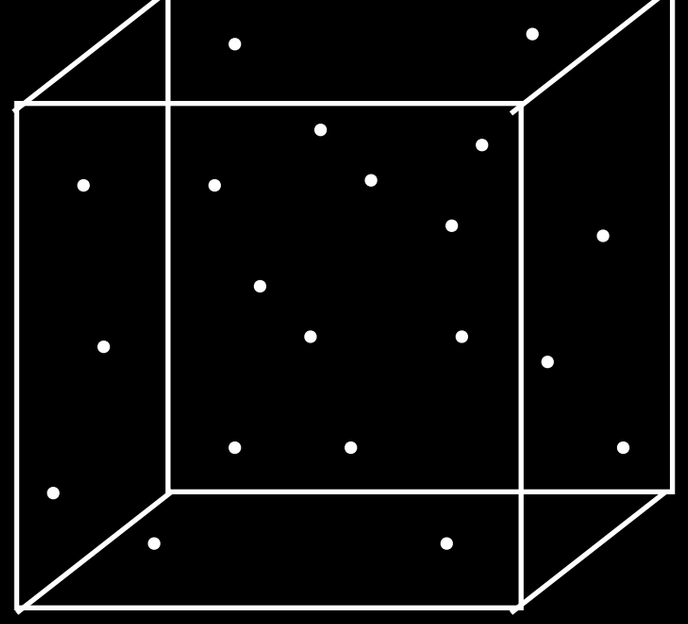
- define energy fraction $\Omega_i=\rho_i/\rho_c$
- $\Sigma_i\, \Omega_i=1$

$$1 = \Omega_{\mathrm{rad}} + \Omega_{\mathrm{matter}} + \Omega_k + \Omega_\Lambda$$

$$\rho(z) = \rho_c(\Omega_{\mathrm{rad}}(1+z)^4 + \Omega_{\mathrm{matter}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

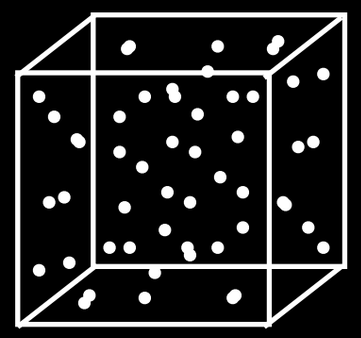
matter

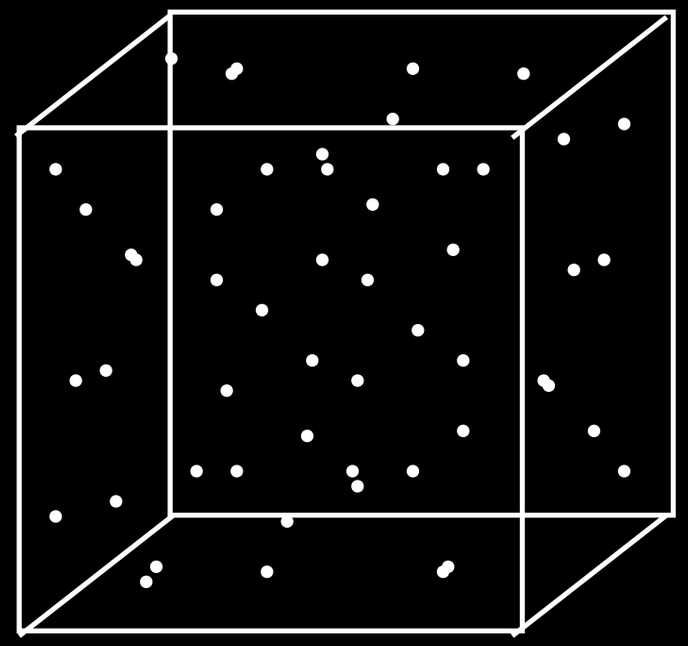




$\rho \propto R^{-3}$

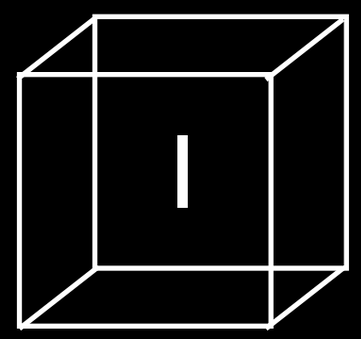
radiation

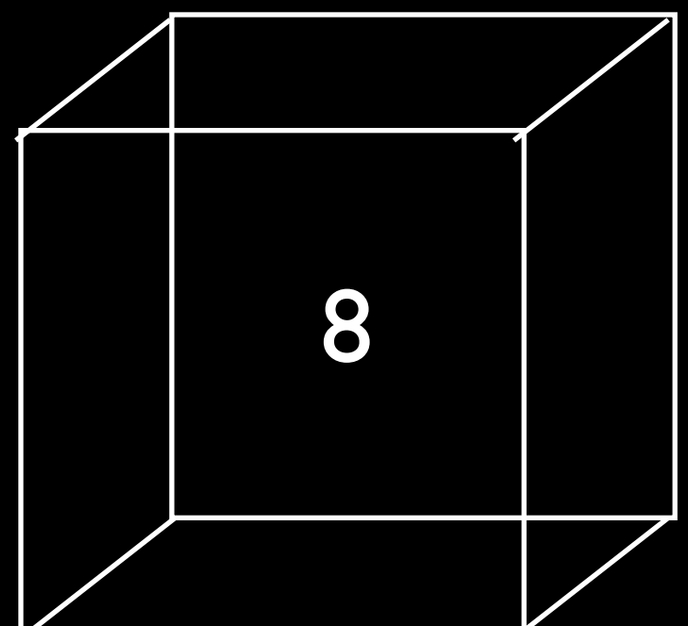




each one
$E \propto R^{-1}$
$\rho \propto R^{-4}$

vacuum
energy
68%





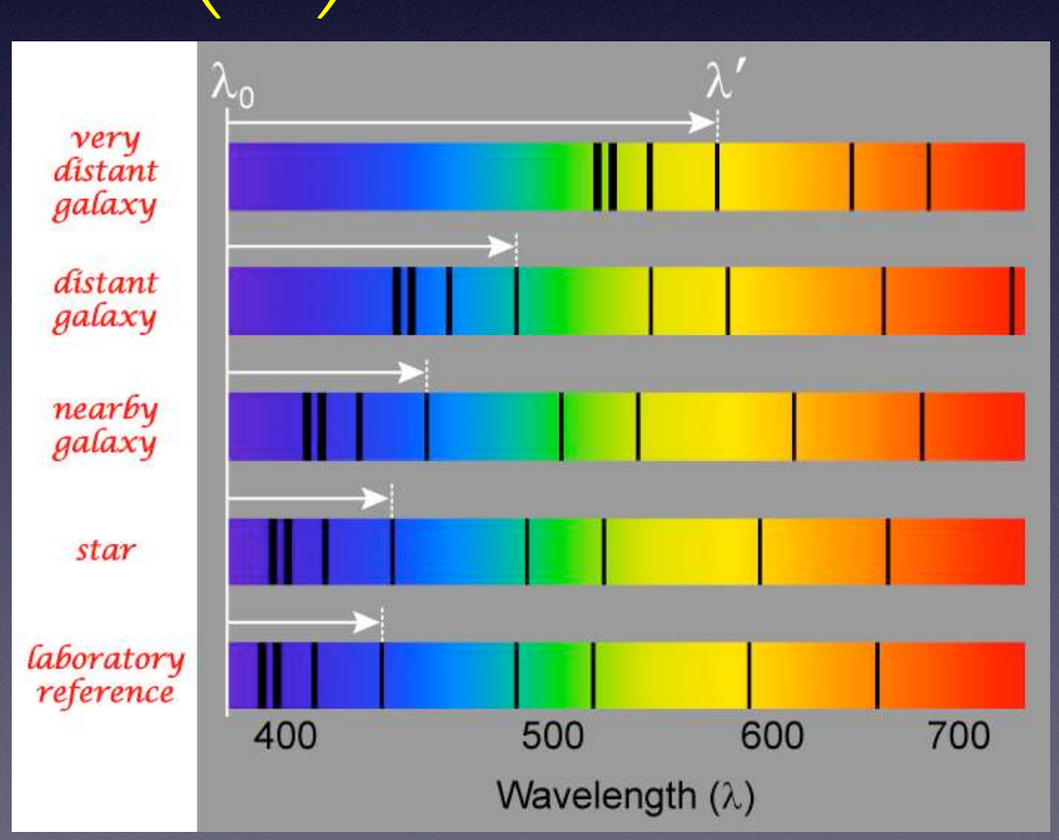
$\rho \propto R^{0}$

Expanding Universe

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{R^2}$$

- $\lambda = \lambda_0(1+z)$
- z: redshift
- $1+z = R_0/R = a(t)^{-1}$
- adiabatic expansion ⇒

  $T \propto R^{-1}$
- $T = T_0(1+z)$



$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

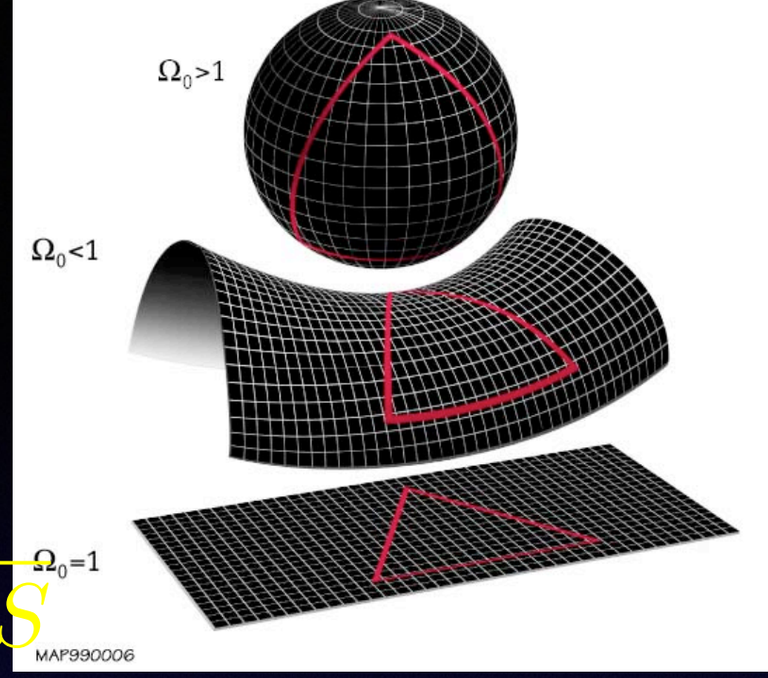
distance

- luminosity distance $d_L = \sqrt{L/4\pi S}$
- comoving distance $d_C(z) = c\int_t^{t_0} \frac{dt'}{a(t')}$
- light travel distance $c(t_0 - t)$
- angular diameter distance $d_A = x/\theta$

$$\frac{\dot{a}}{a} = H \qquad dt = \frac{1}{H}\frac{da}{a} = \frac{1}{H}\frac{dz}{1+z}$$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

distance



- luminosity distance $d_L = \sqrt{L/4\pi S}$
- comoving distance $d_C(z) = c\int_0^z \frac{dz'}{H(z)}$
- light travel distance $d_T(z) = c\int_0^z \frac{dz'}{(1+z')H(z)}$
- angular diameter distance $d_A = x/\theta$
- transverse comoving distance $d_M(z) = \frac{c}{H_0}\frac{1}{\sqrt{\Omega_k}}\sinh\frac{\sqrt{\Omega_k}H_0 d_C(z)}{c}$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

distance

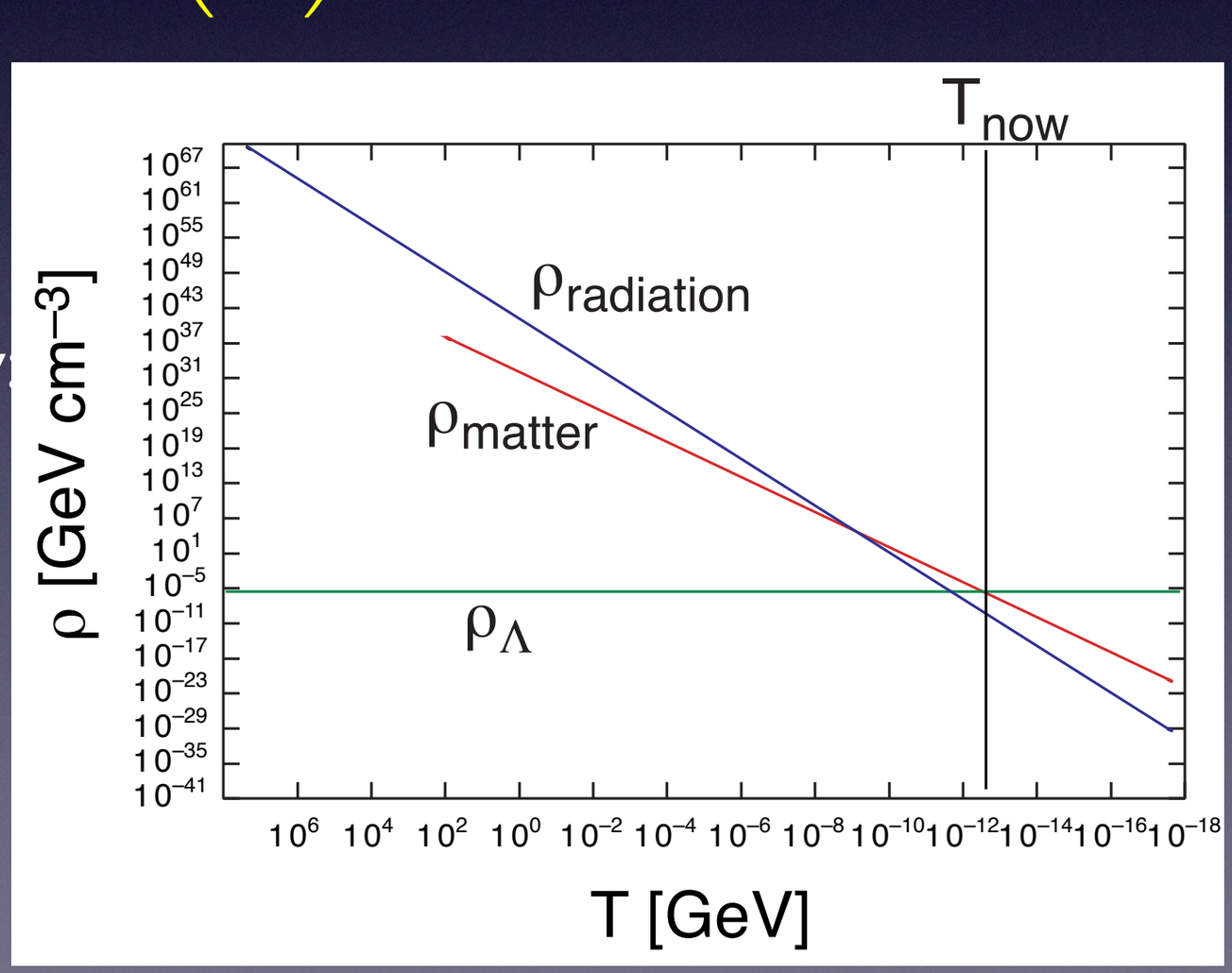
- luminosity distance $d_L(z) = (1+z) d_M(z)$
- comoving distance $d_C(z) = c \int_0^z \frac{dz'}{H(z)}$
- light travel distance $d_T(z) = c \int_0^z \frac{dz'}{(1+z')H(z)}$
- angular diameter distance $d_A(z) = \frac{d_M(z)}{(1+z)}$
- transverse comoving distance $d_M(z) = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_k}} \sinh \frac{\sqrt{\Omega_k} H_0 d_C(z)}{c}$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

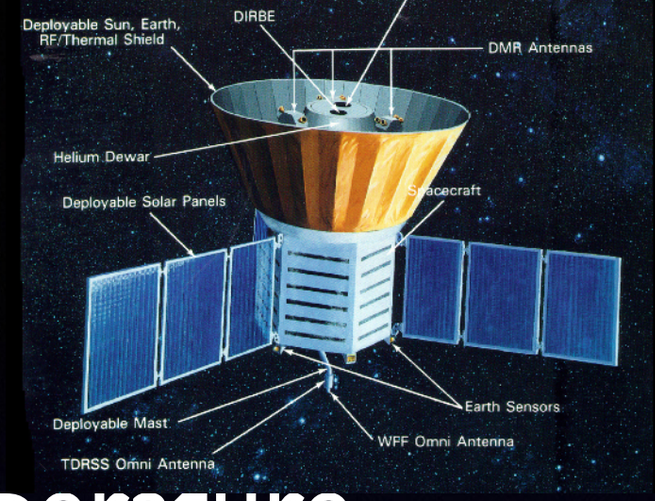
Early Universe

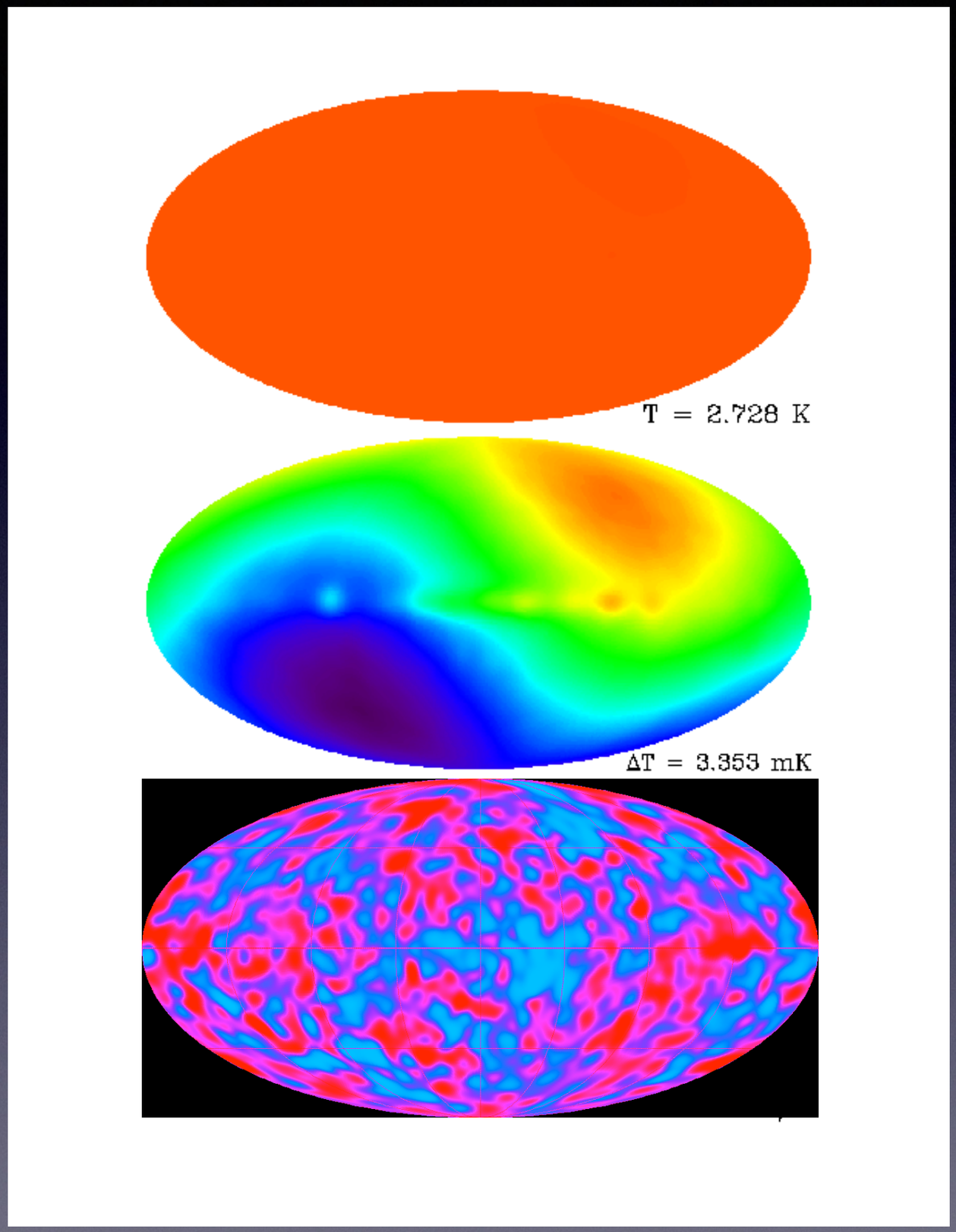
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{R^2}$$

- temperature: $T \propto (1+z)$
- matter: $\rho \propto (1+z)^3$
- radiation (massless particles): $\rho \propto (1+z)^4$
  matter-radiation equality: $z \approx 3300$
- recombination: $z \approx 1300$



Large-Scale Structure





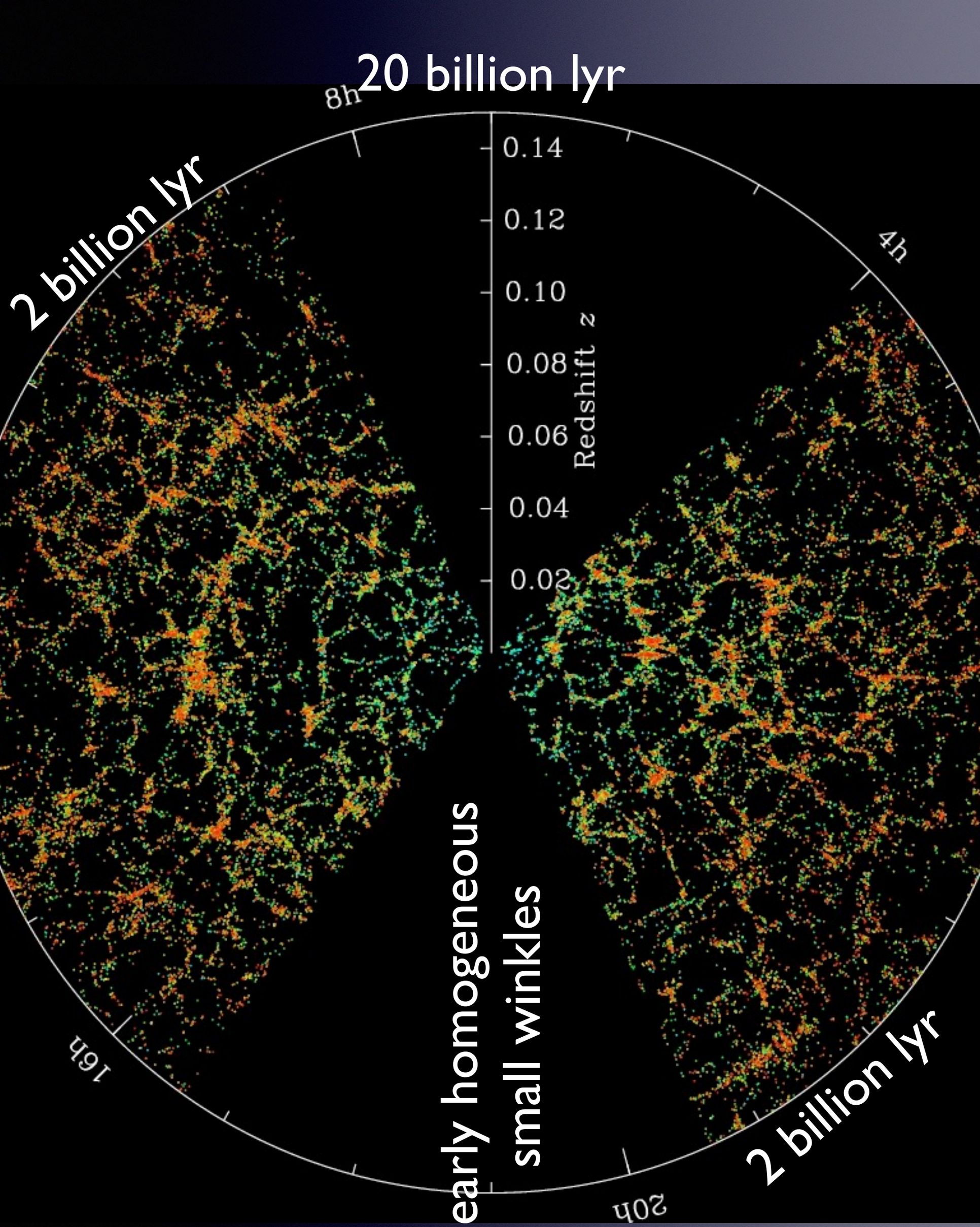
CMB temperature

CMB dipole
we are moving at
~1% of *c* relative to CMB

CMB anisotropy
at ~10^{-5}
1mm ripple on 100m sea

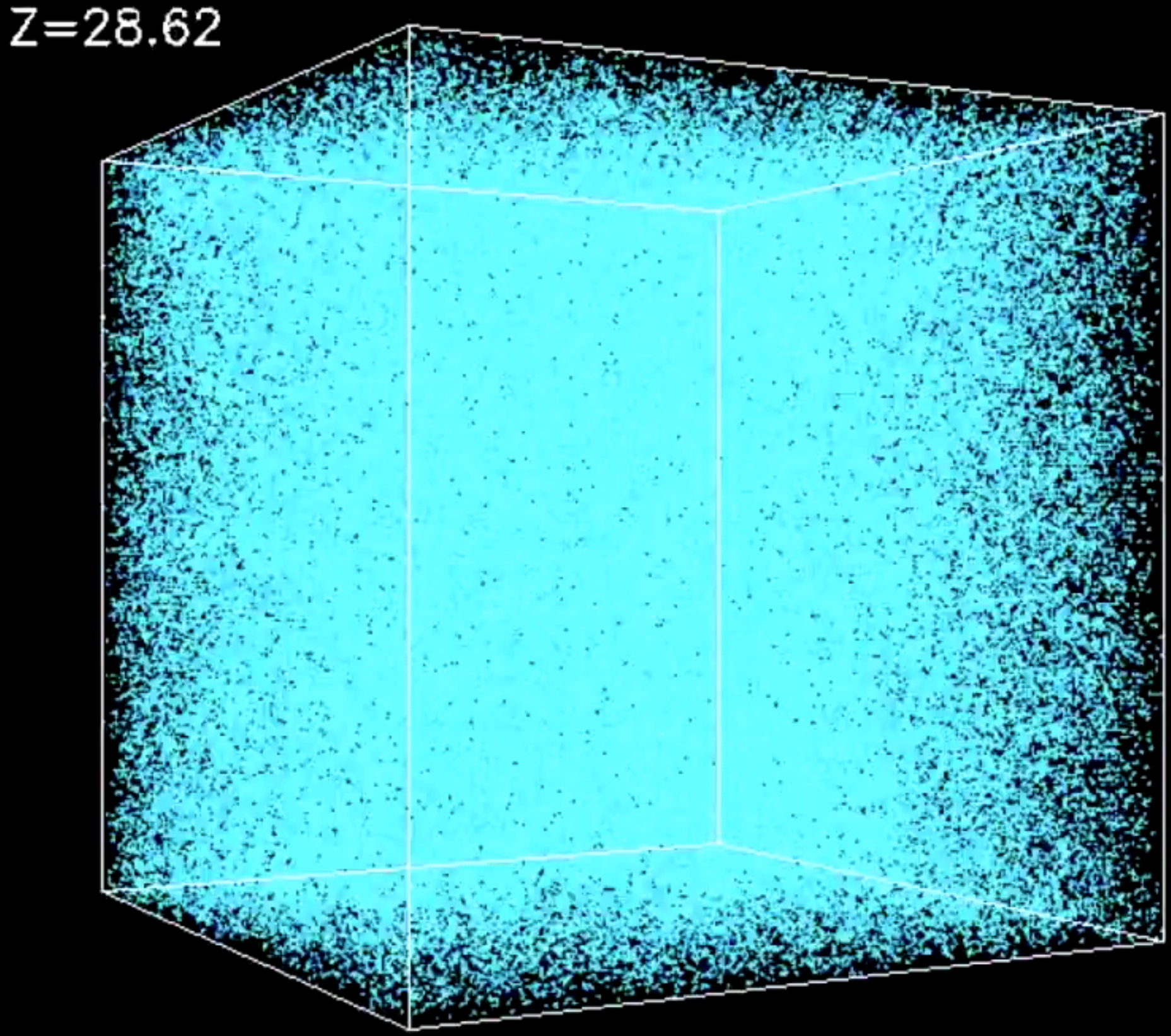
20 billion lyr

2 billion lyr



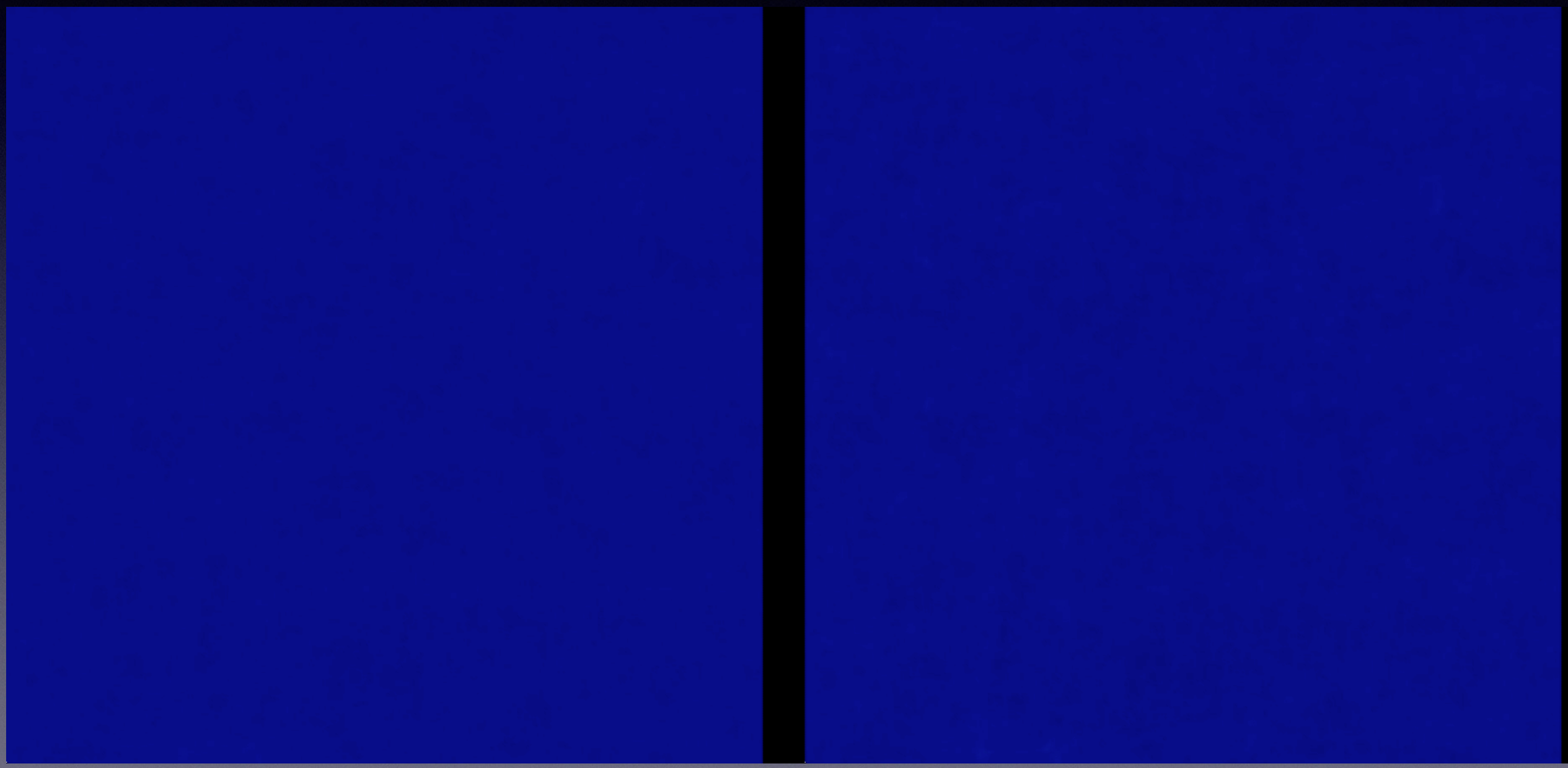
nearly homogeneous
small winkles

2 billion lyr


Z=28.62

KAVLI IPMU

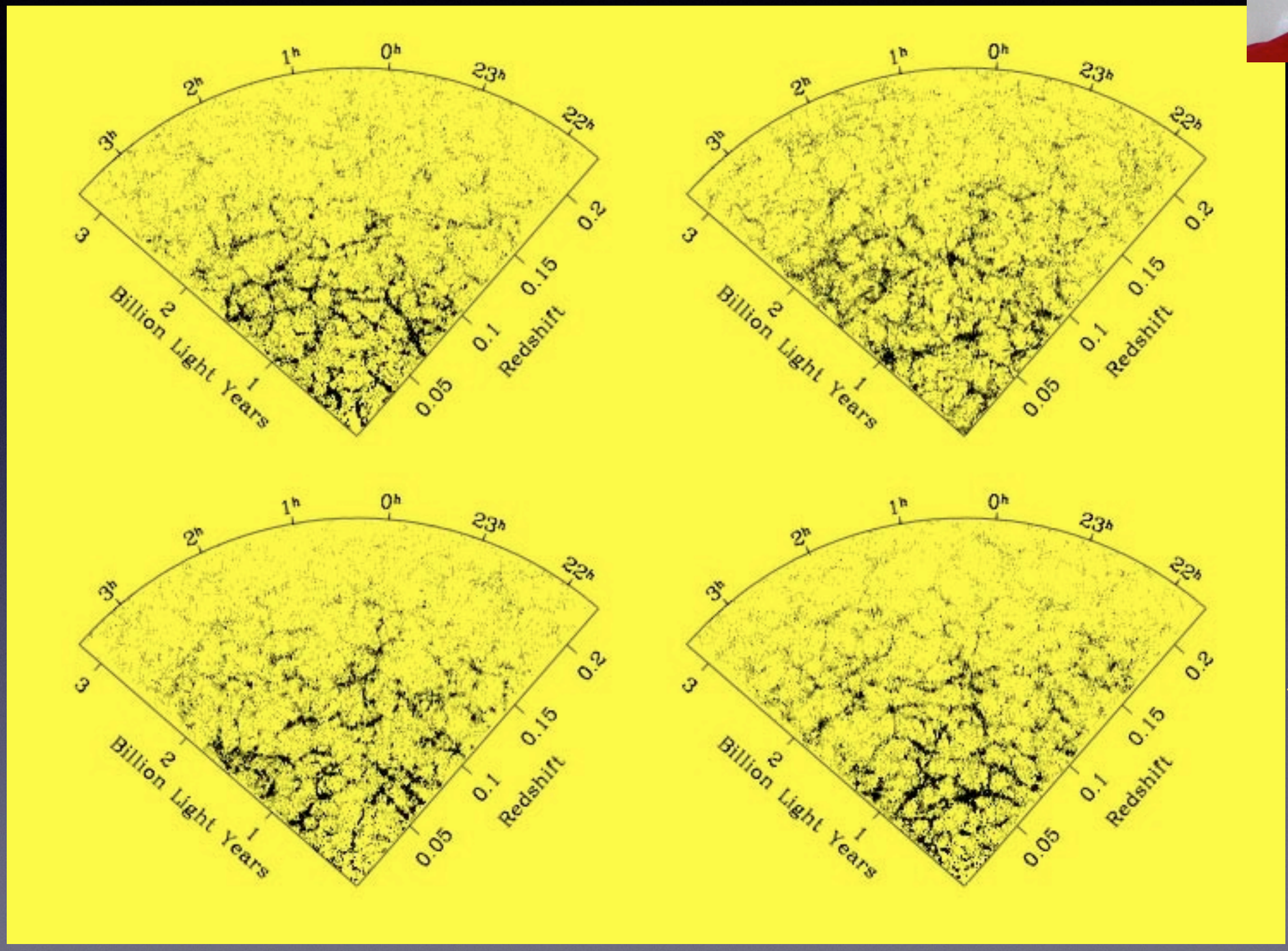
Dark Matter is our birth mother



no dark matter

with dark matter

one is real

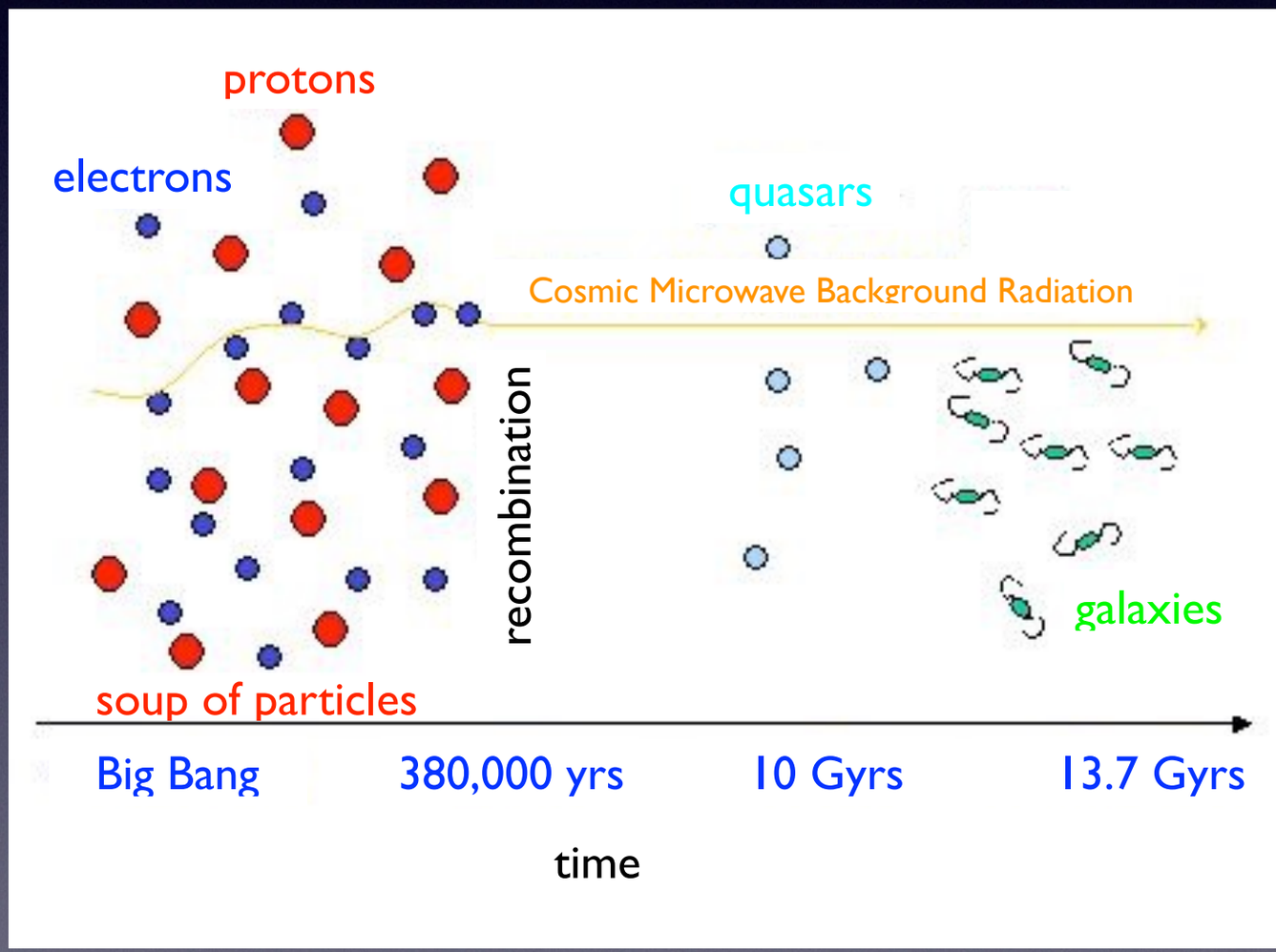

0h
1h
2h
3h
23h
22h
3
2
1
Billion Light Years
0.2
0.15
0.1
0.05
Redshift

reenacting Big Ban with Cal Band

power spectrum

CMB

- before recombination, there was a fluid of protons, electrons, photons, dark matter (and neutrinos)
- photon pressure ⇒ "sound waves"



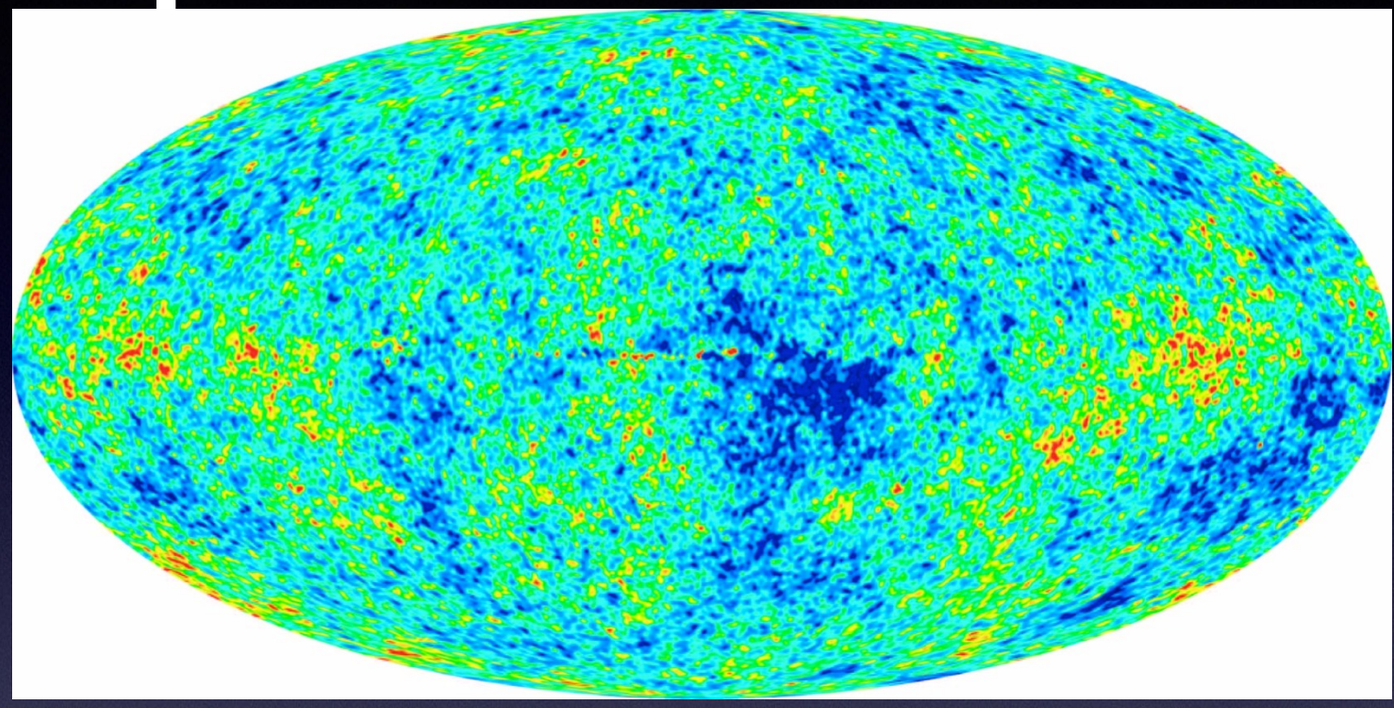
WMAP
Wilkerson Microwave
Anisotropy Probe

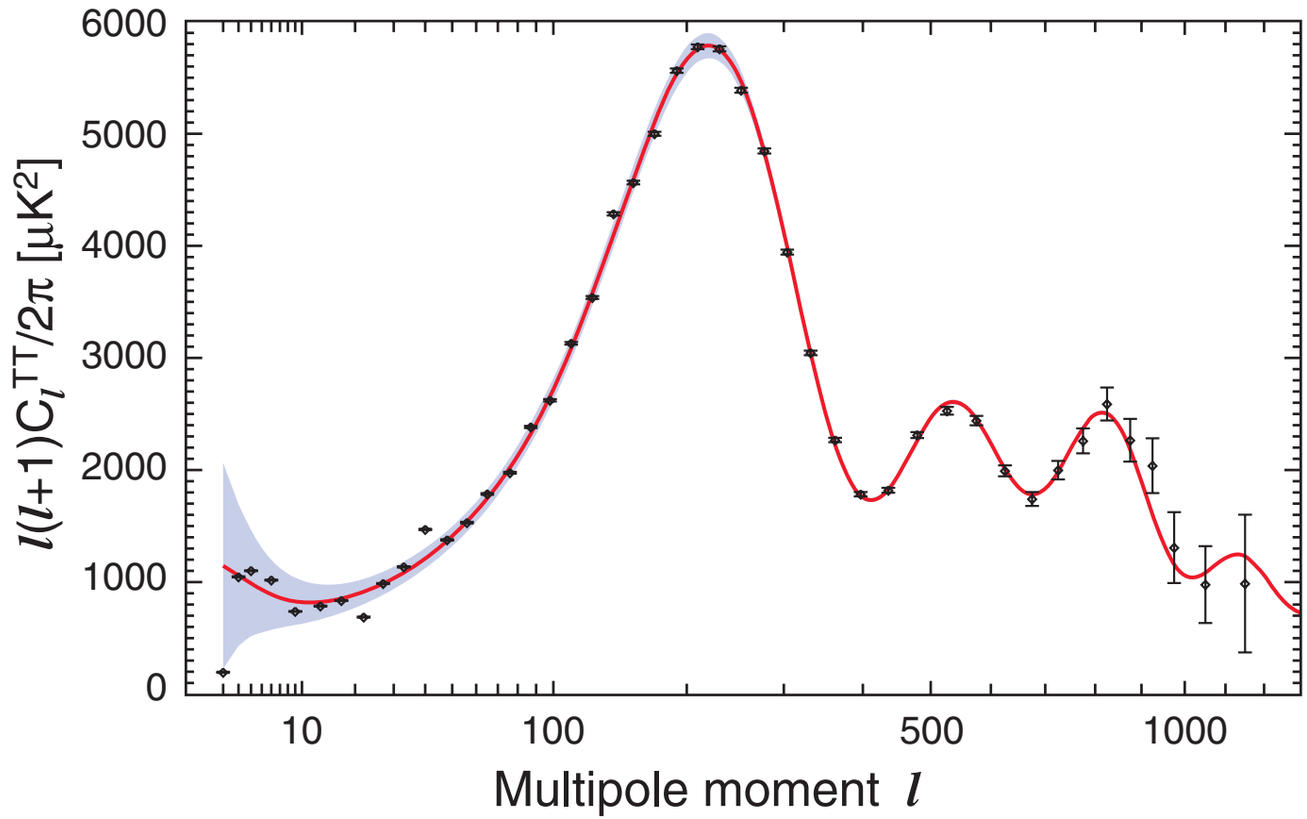
assumption

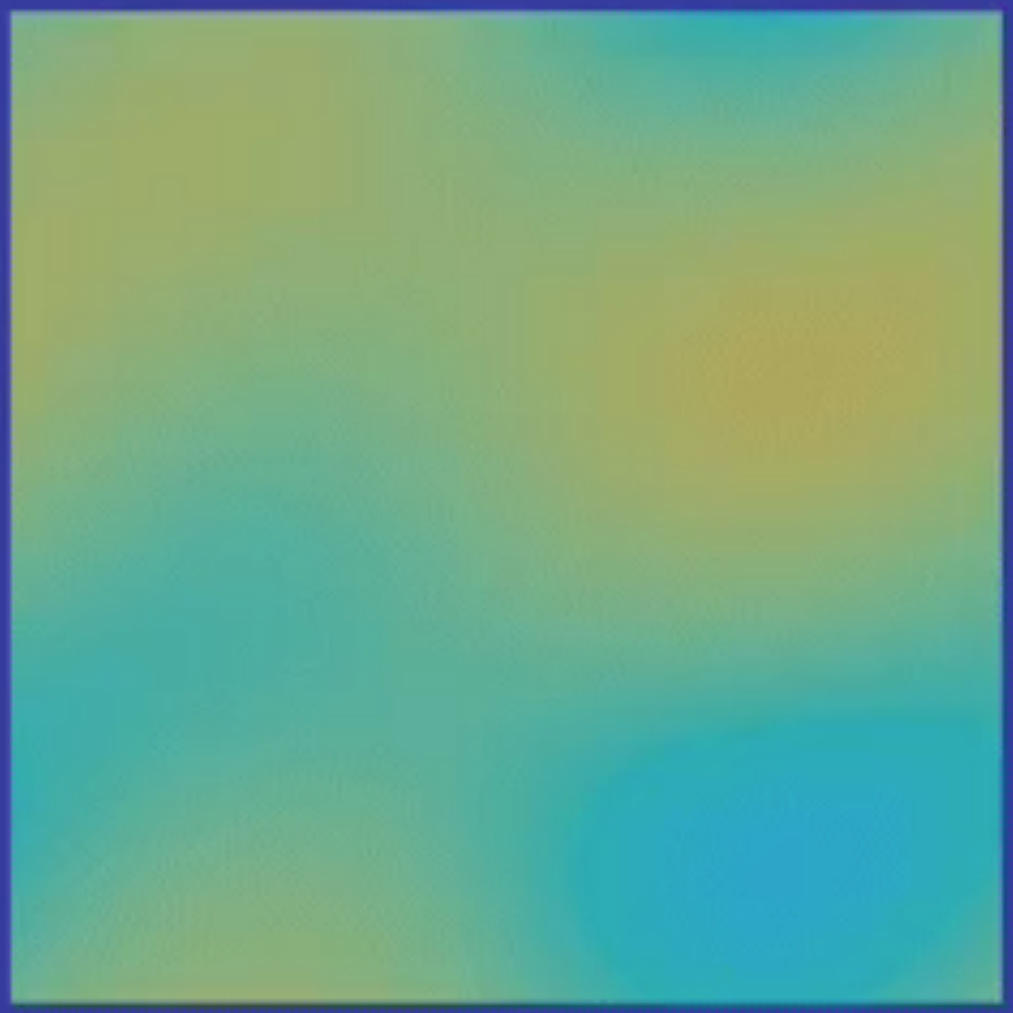
- a random density fluctuations ~O(10^{-5}) more-or-less scale invariant $P(k) \propto k^{ns-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between $0<z<1300$

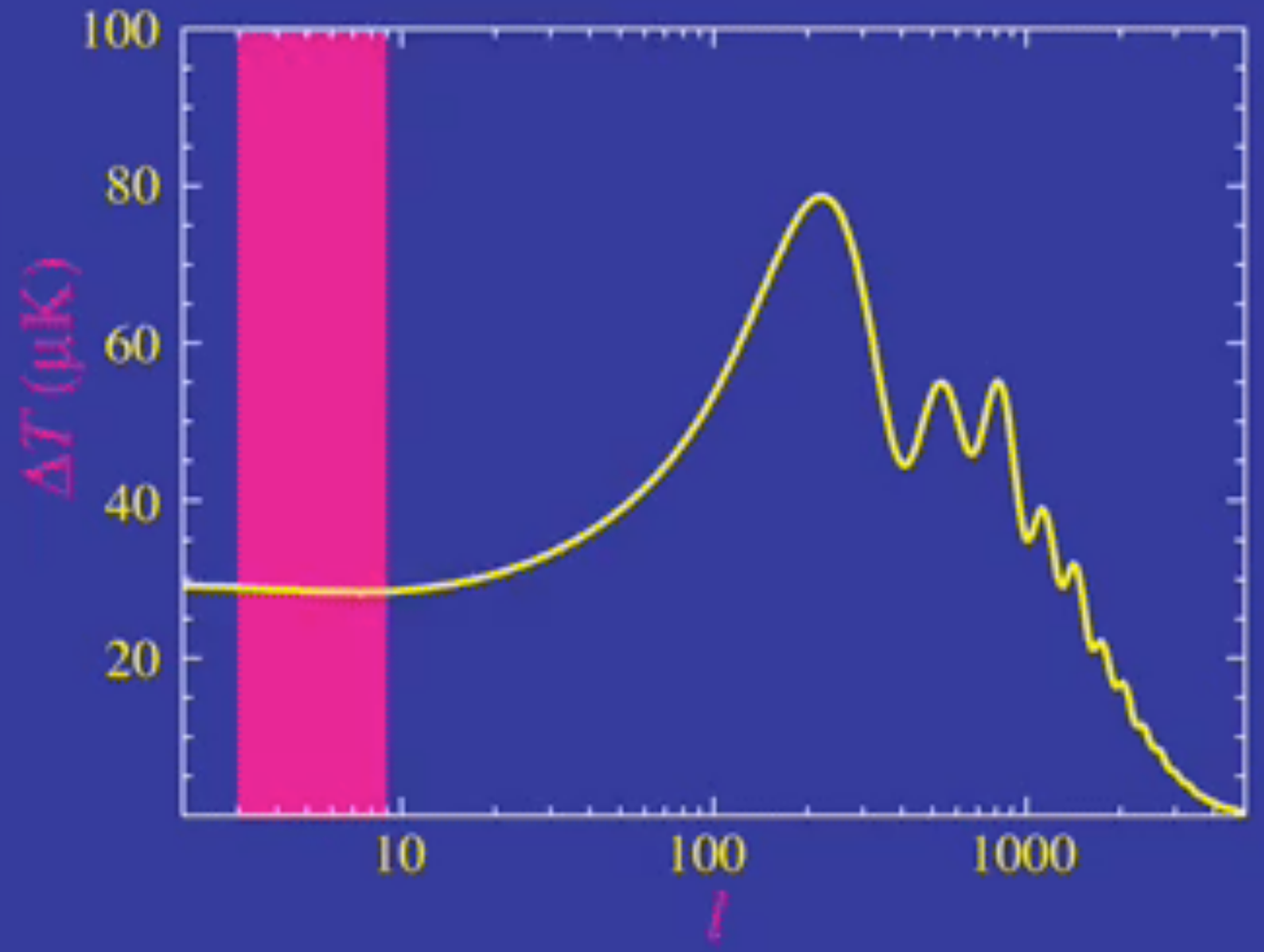
$$\delta T/T = a_{lm}\ Y_l^m$$

$$(2l+1)c_{lm} = \Sigma_m\ a_{lm}{}^* a_{lm}$$

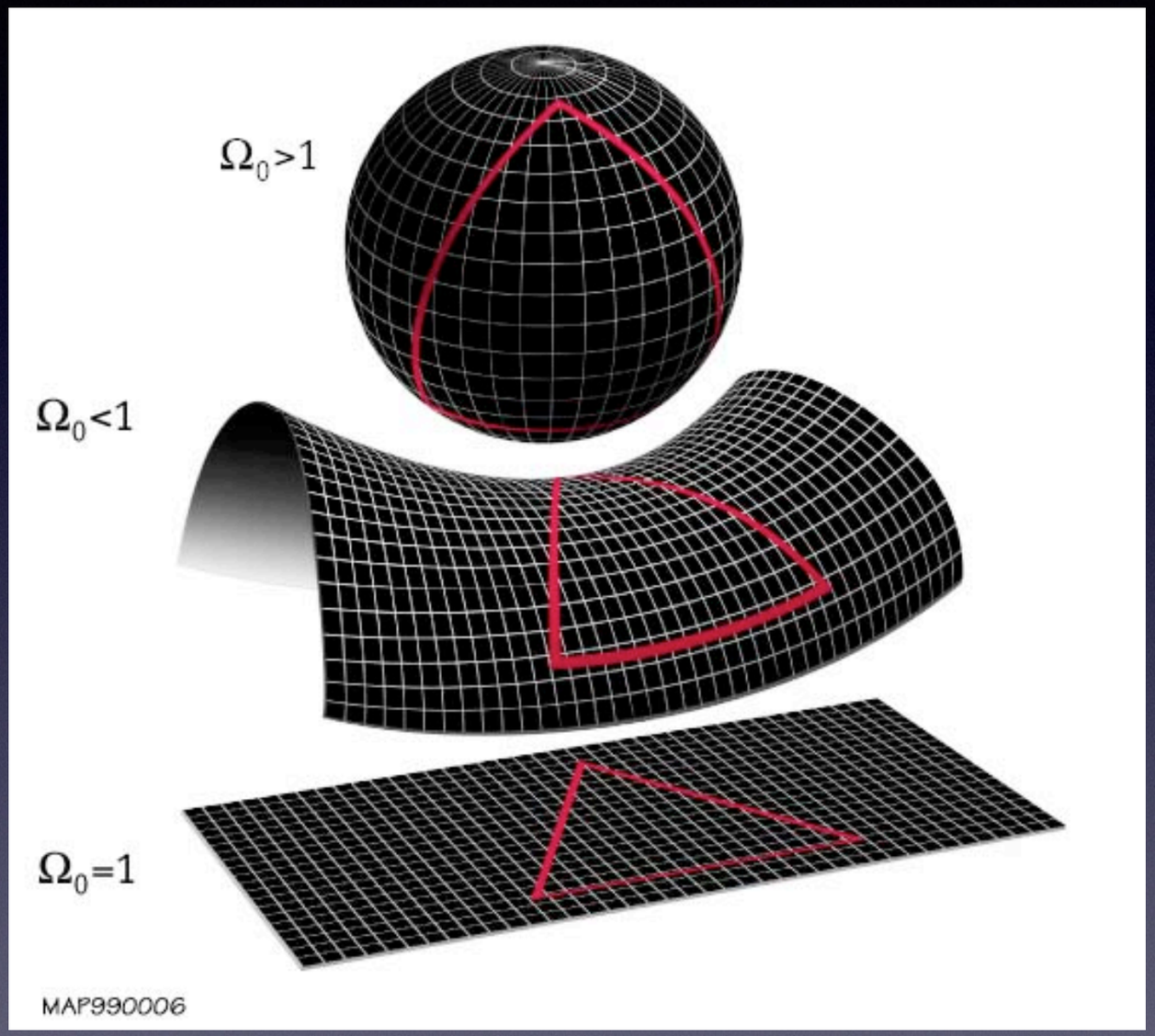


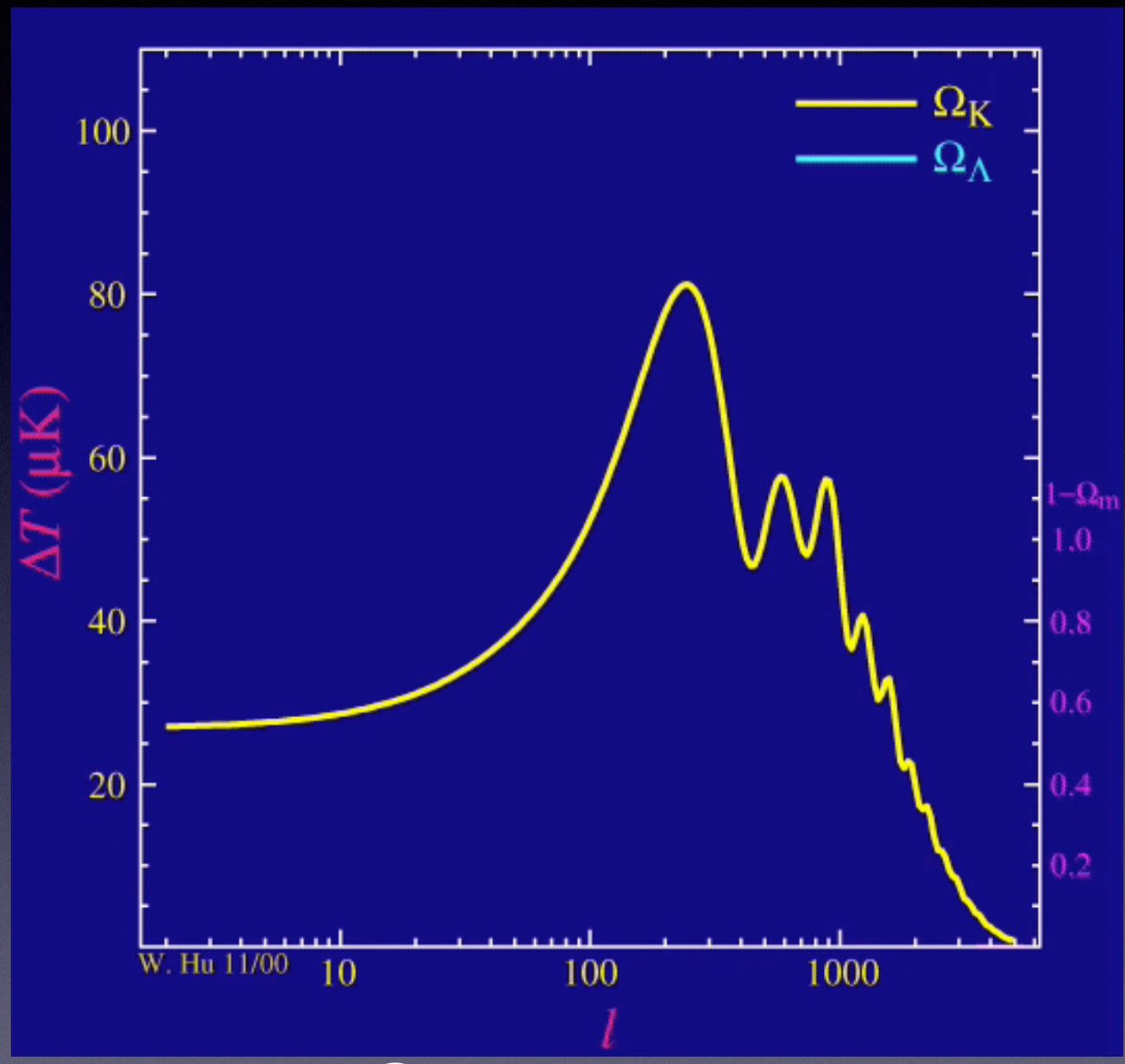




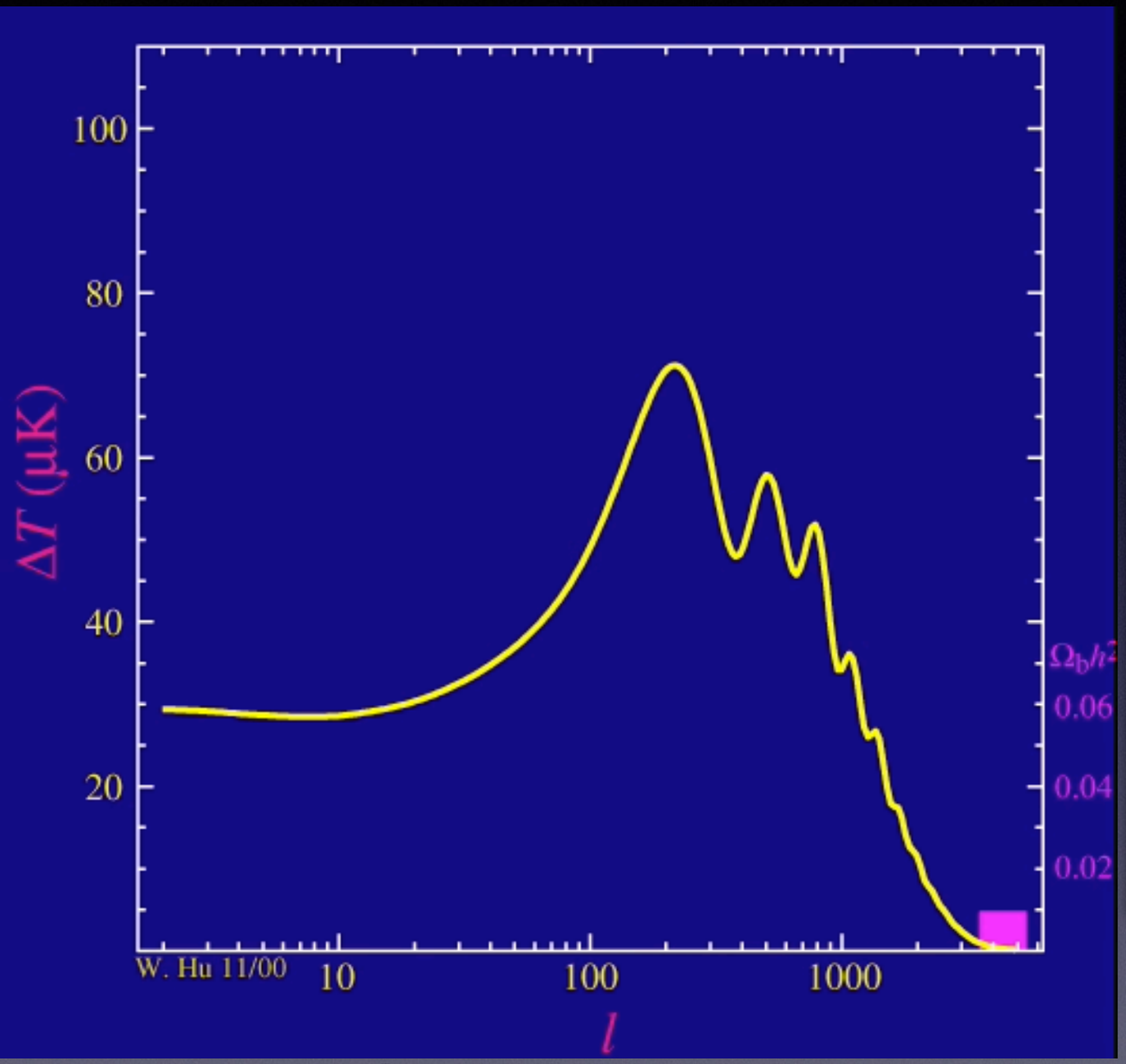


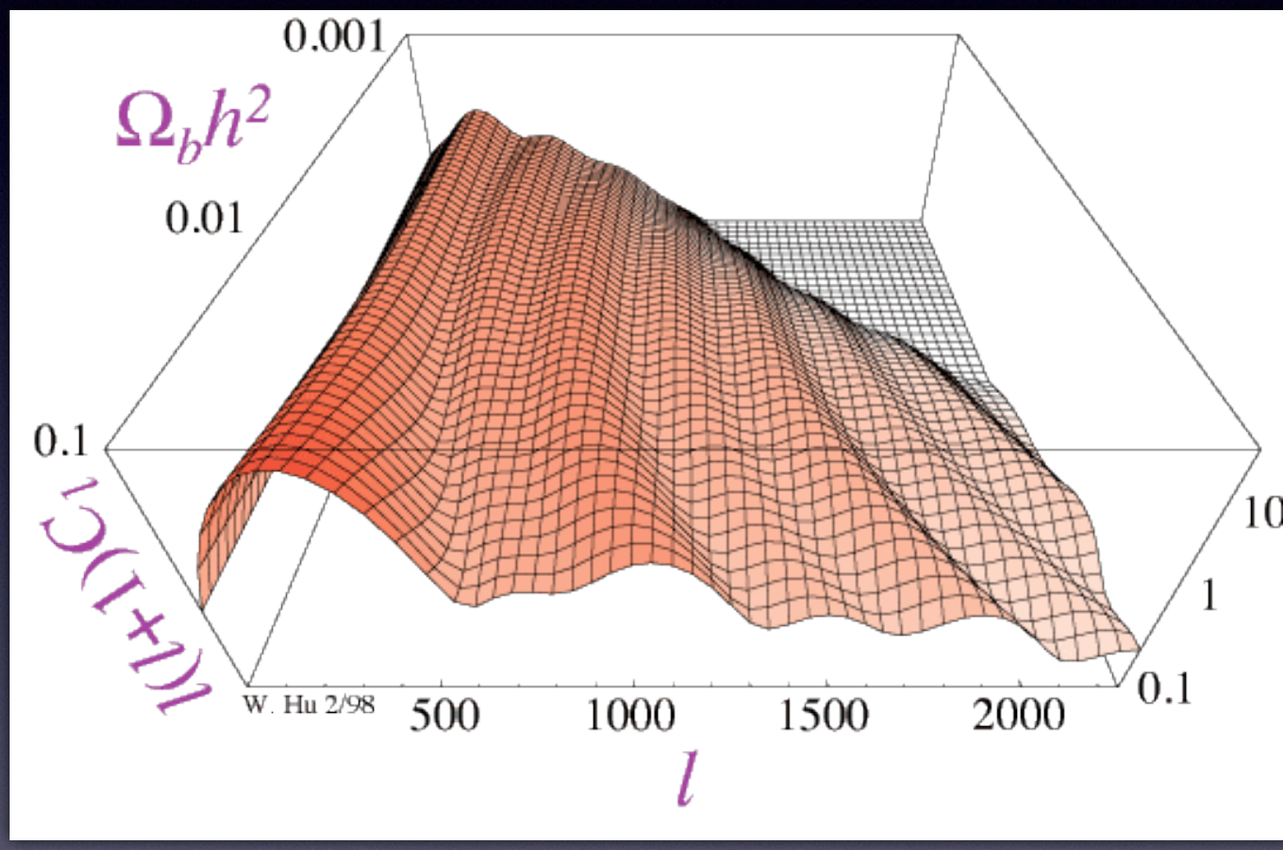
Wayne Hu





Ω_k changes
the apparent angular size
of the peak positions



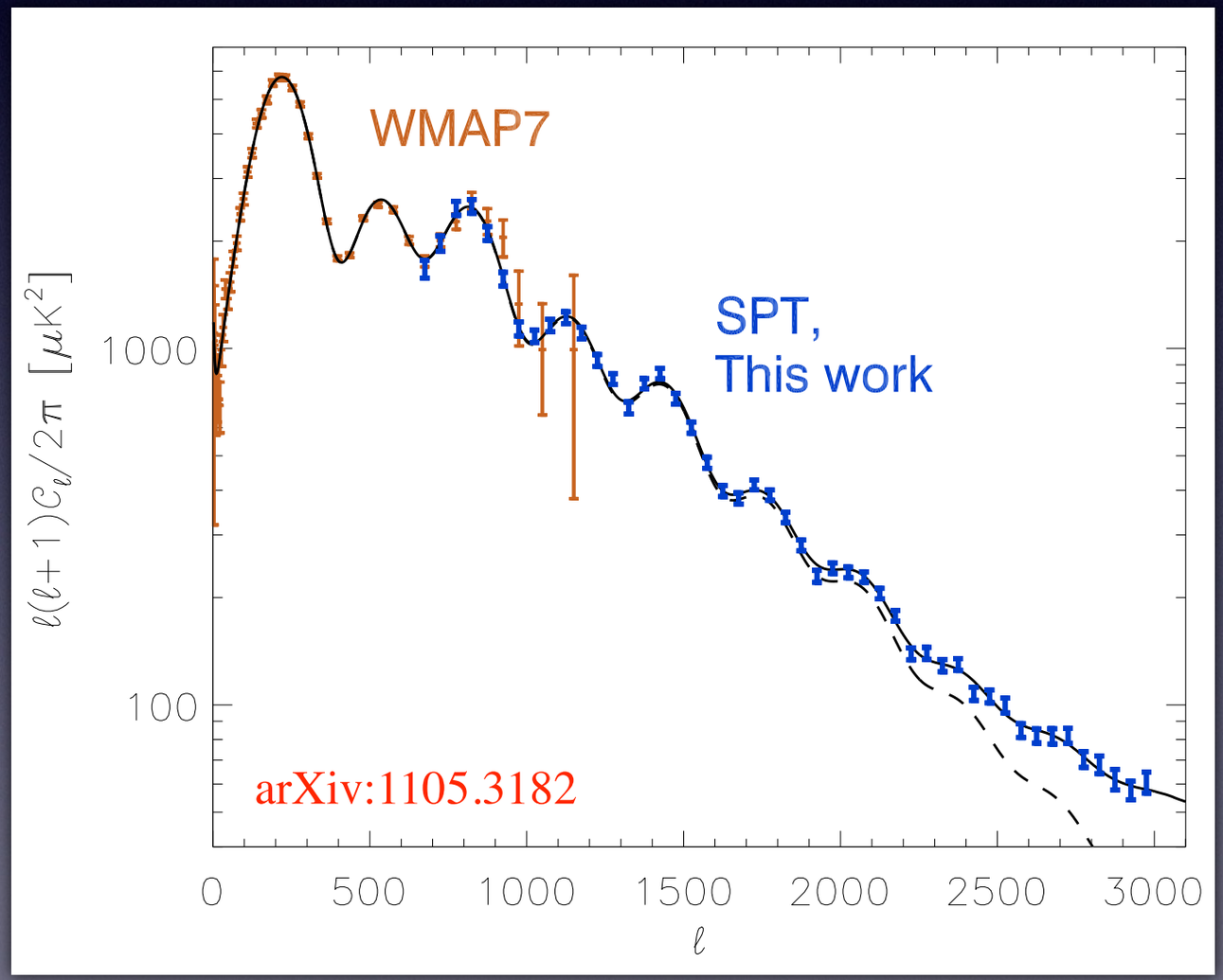


Ω_b changes
the relative size of
even and odd peaks

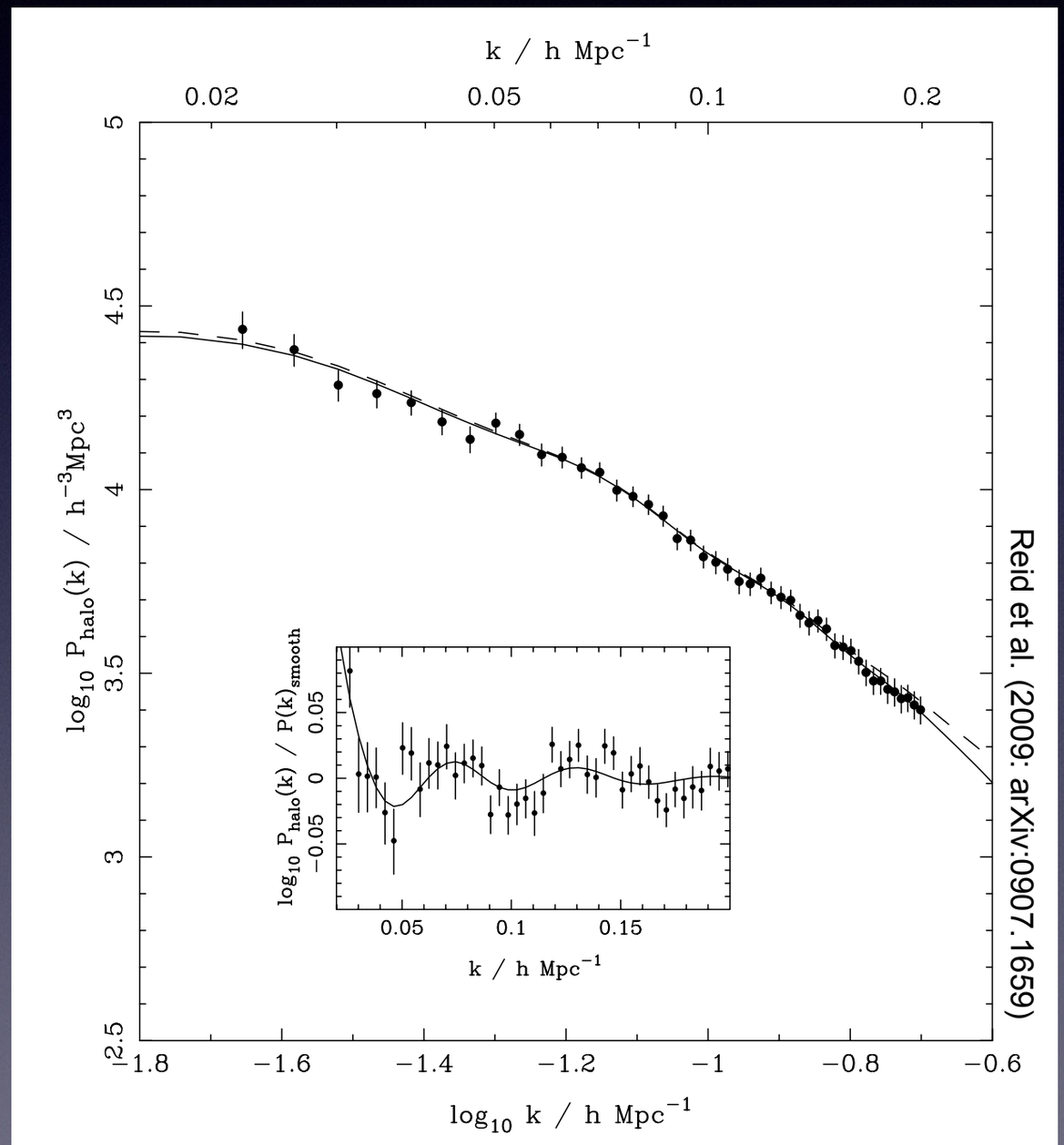
standard cosmology

ΛCDM

works like SM @ LEP



CMB power spectrum



galaxy power spectrum

standard cosmology ΛCDM

- flat universe Ω_k=0
- perturbation $P(k) \propto k^{ns-1}$ with single exponent n_s for both scalar and tensor modes
- three massless neutrinos

	Planck TT+lowP+lensing	*Planck* TT+lowP+lensing+ext
$\Omega_b h^2$	0.02226 ± 0.00023	0.02227 ± 0.00020
$\Omega_c h^2$	0.1186 ± 0.0020	0.1184 ± 0.0012
$100\,\theta_{MC}$	1.0410 ± 0.0005	1.0411 ± 0.0004
n_s	0.968 ± 0.006	0.968 ± 0.004
τ	0.066 ± 0.016	0.067 ± 0.013
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.062 ± 0.029	3.064 ± 0.024
h	0.678 ± 0.009	0.679 ± 0.006
σ_8	0.815 ± 0.009	0.815 ± 0.009
Ω_m	0.308 ± 0.012	0.306 ± 0.007
Ω_Λ	0.692 ± 0.012	0.694 ± 0.007

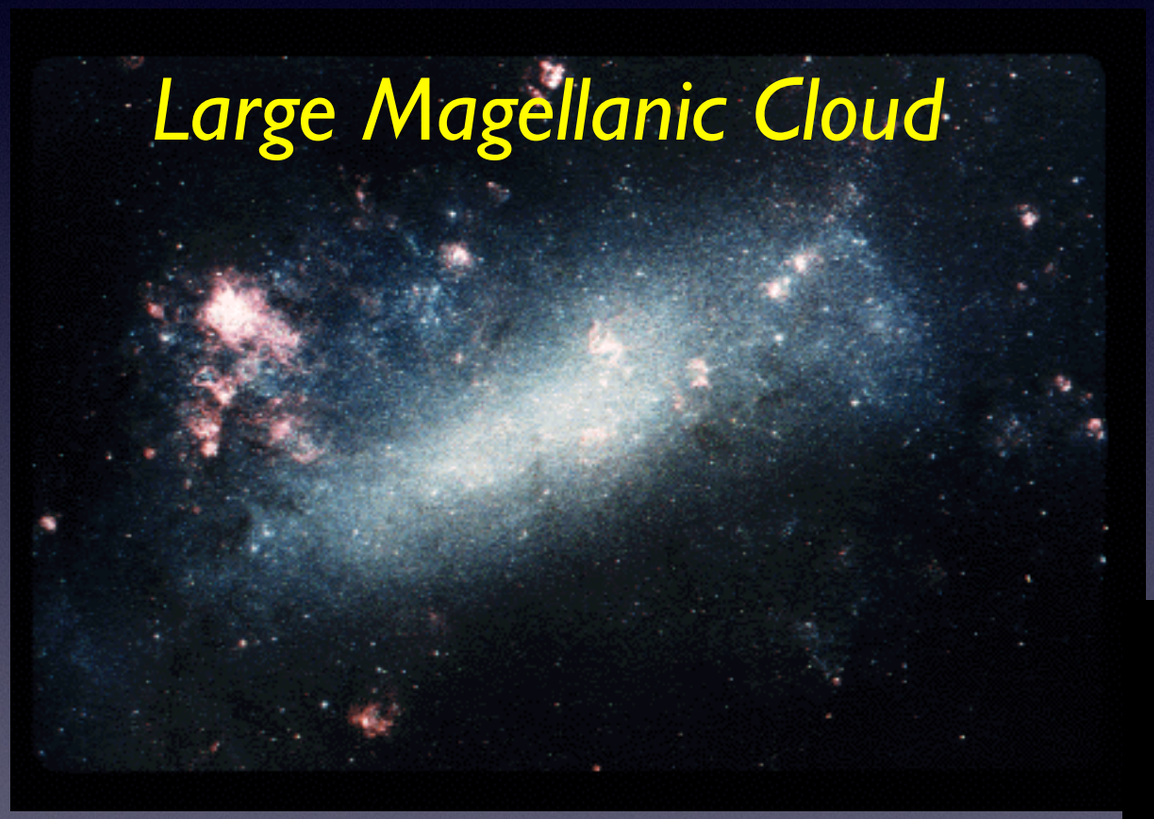
Known Facts about Dark Matter

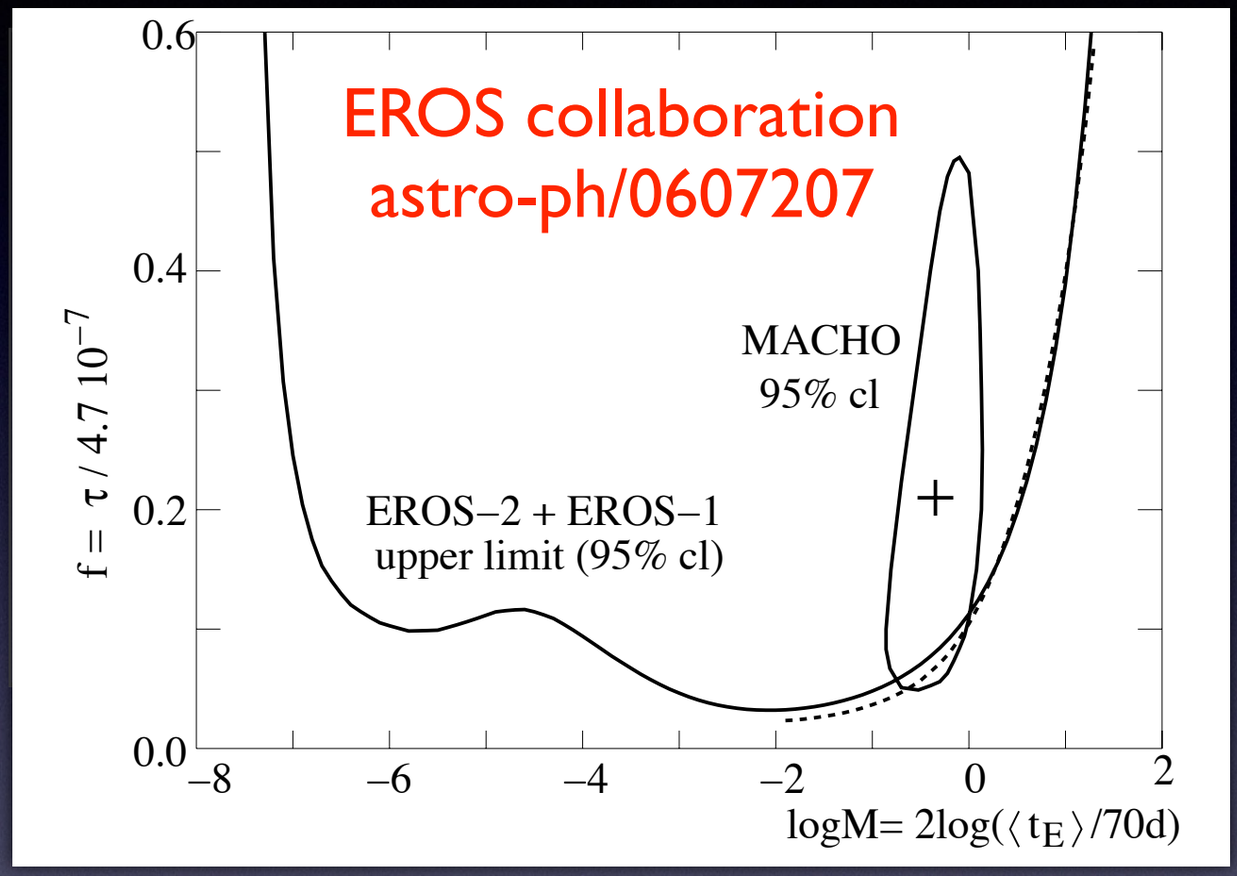
Cold and Neutral

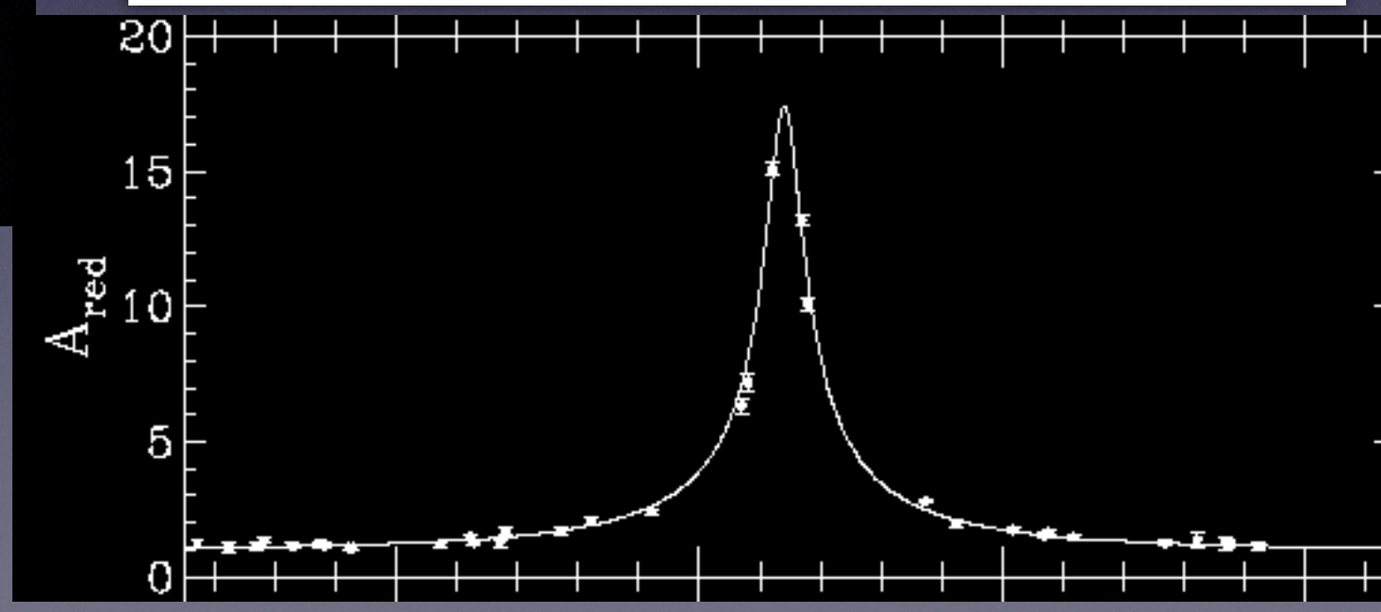
- By the time of matter-radiation equality and until now, dark matter must be non-relativistic and clump together by gravitational attraction
- must be electrically neutral

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)







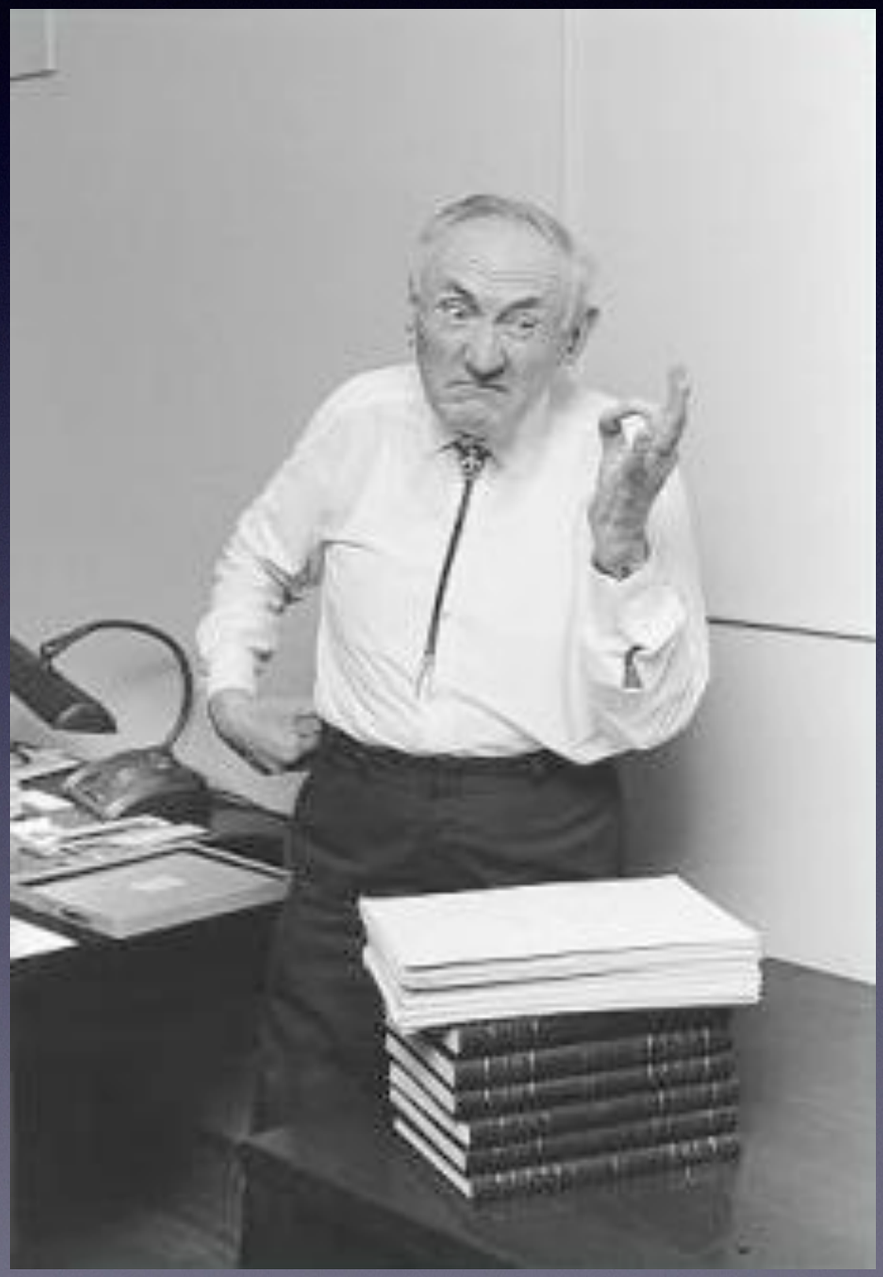
Not enough of them!

Mass Limits "Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m > 10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

Mass Limits

- 10^{-31} GeV to 10^{50} GeV
- we narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



Self-Couplin

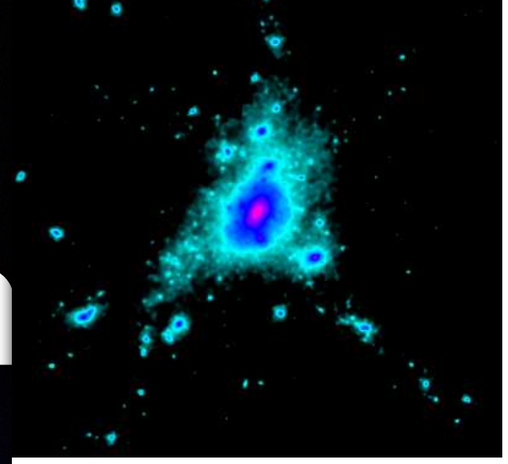
- if self-coupling too big, will "smooth out" cuspy profile at the galactic center
- some people want it

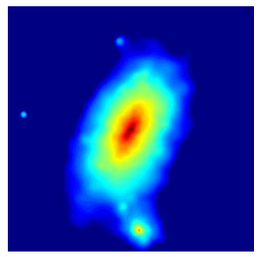
  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

  $\sigma < 1.7 \times 10^{-25}$ cm^2 (m/GeV)

  (Yoshida, Springel, White, astro-ph/0006134)
- bullet cluster:

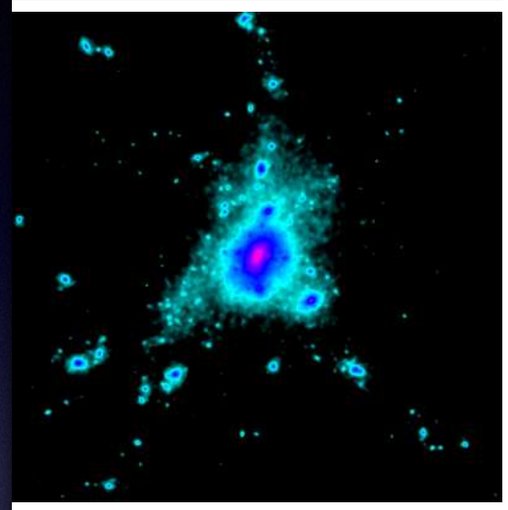
  $\sigma < 1.7 \times 10^{-24}$ cm^2 (m/GeV)
  (Markevitch et al, astro-ph/0309303)

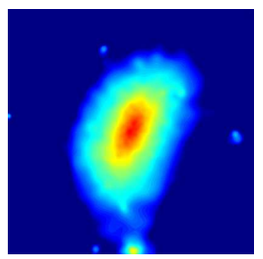




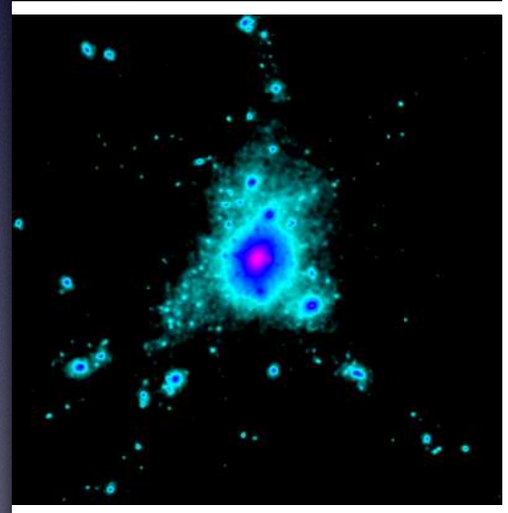
S1

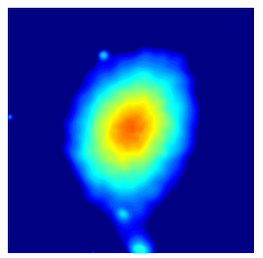
$1 : 0.82 : 0.65$



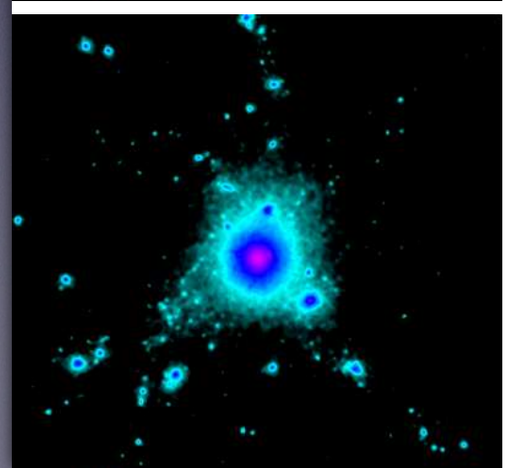


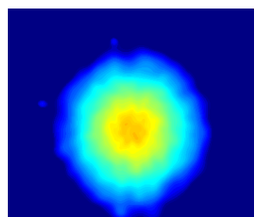
S1Wa
$\sigma^\star = 0.1\,\mathrm{cm}^2\mathrm{g}^{-1}$
$r_\mathrm{c} = 40\,h^{-1}\mathrm{kpc}$
$1 : 0.88 : 0.66$





S1Wb
$\sigma^\star = 1.0\,\mathrm{cm}^2\mathrm{g}^{-1}$
$r_\mathrm{c} = 100\,h^{-1}\mathrm{kpc}$
$1 : 0.91 : 0.72$





S1Wc
$\sigma^\star = 10.0\,\mathrm{cm}^2\mathrm{g}^{-1}$
$r_\mathrm{c} = 160\,h^{-1}\mathrm{kpc}$
$1 : 0.98 : 0.89$

Lifetime

- At least of the order of age of the universe 14Gyr
- Beyond that, it depends on decay modes, branching fractions, all model-dependent

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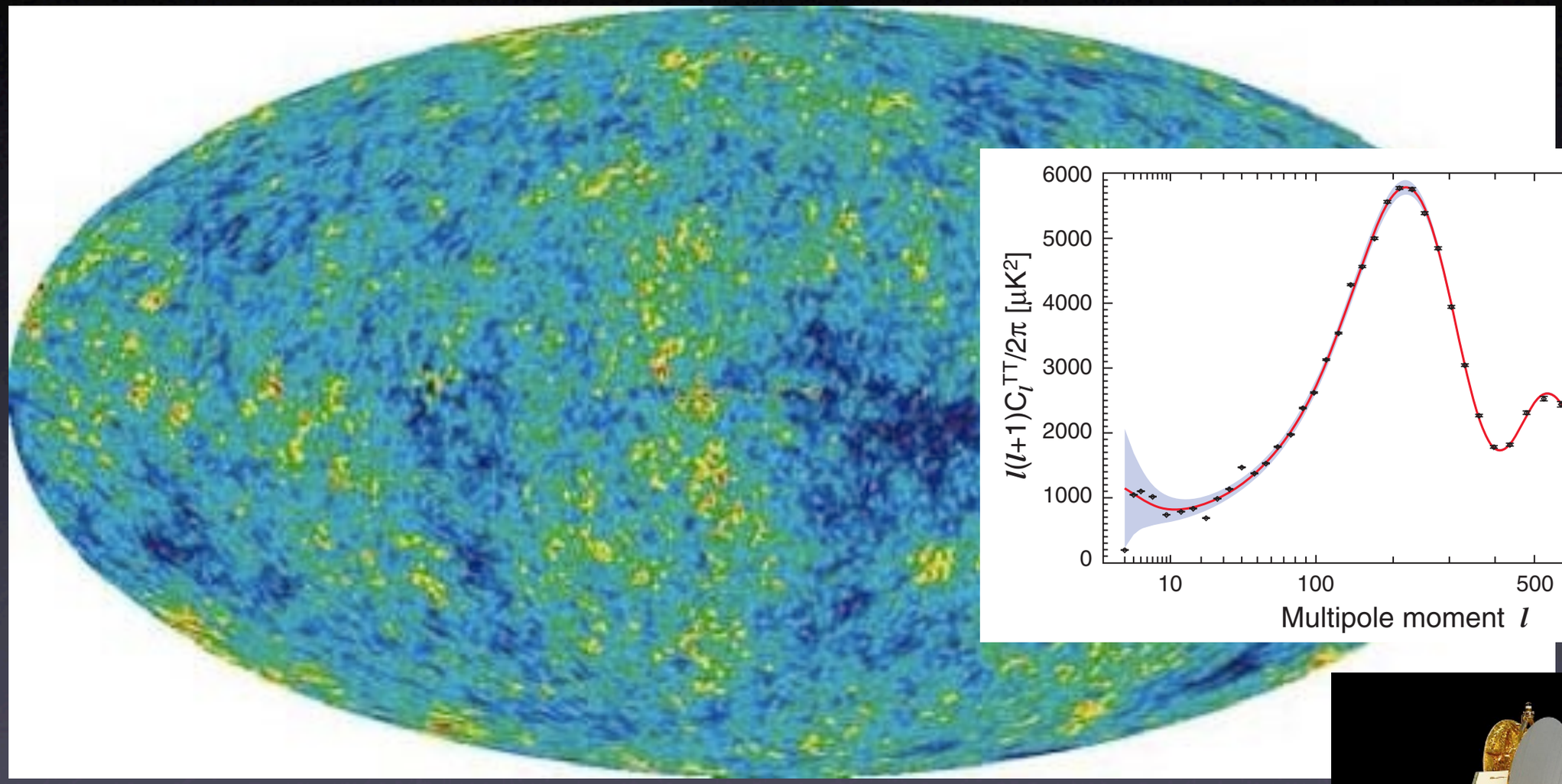
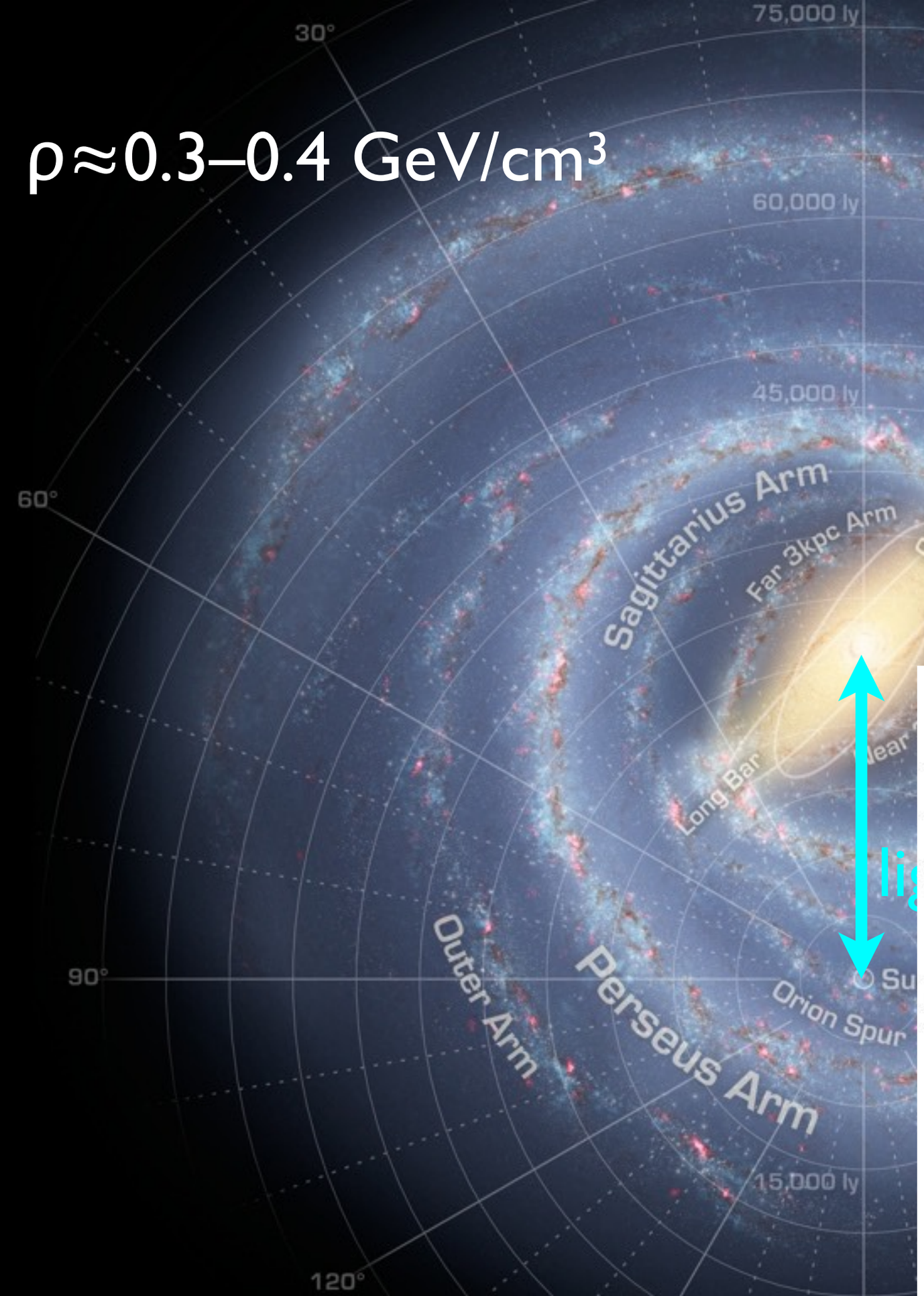
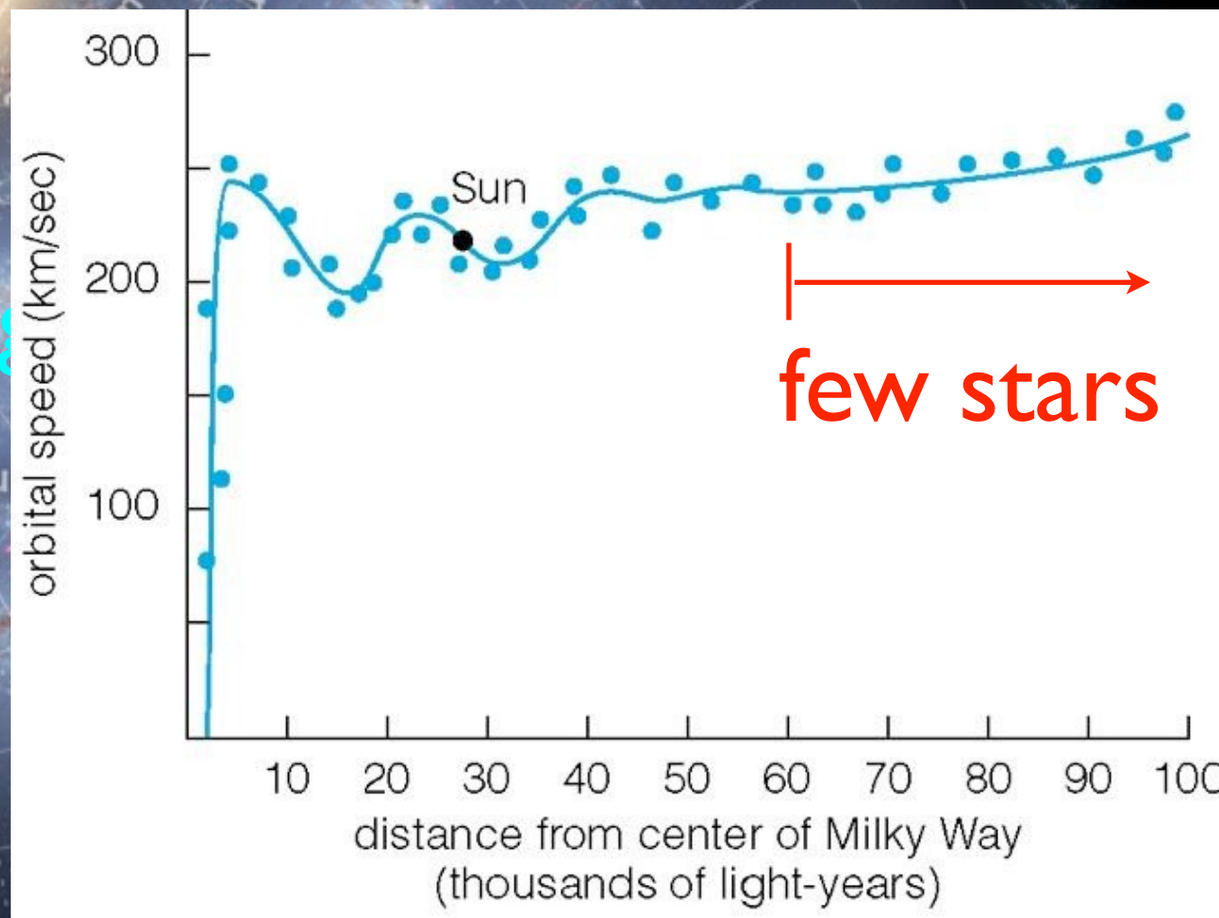
Cosmological scales



$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

$\rho \approx 0.3–0.4$ GeV/cm^3





WIMP paradigm

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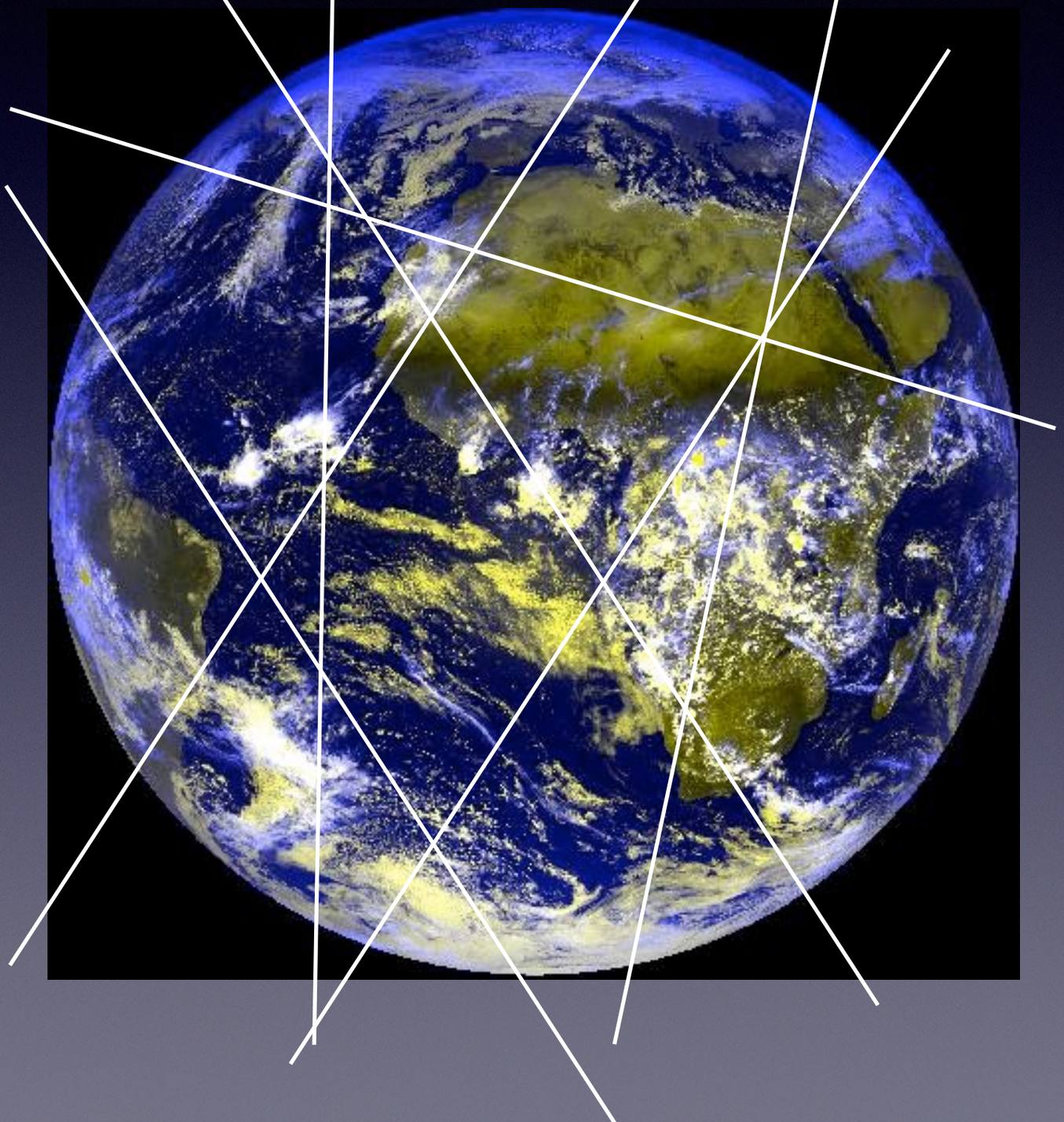
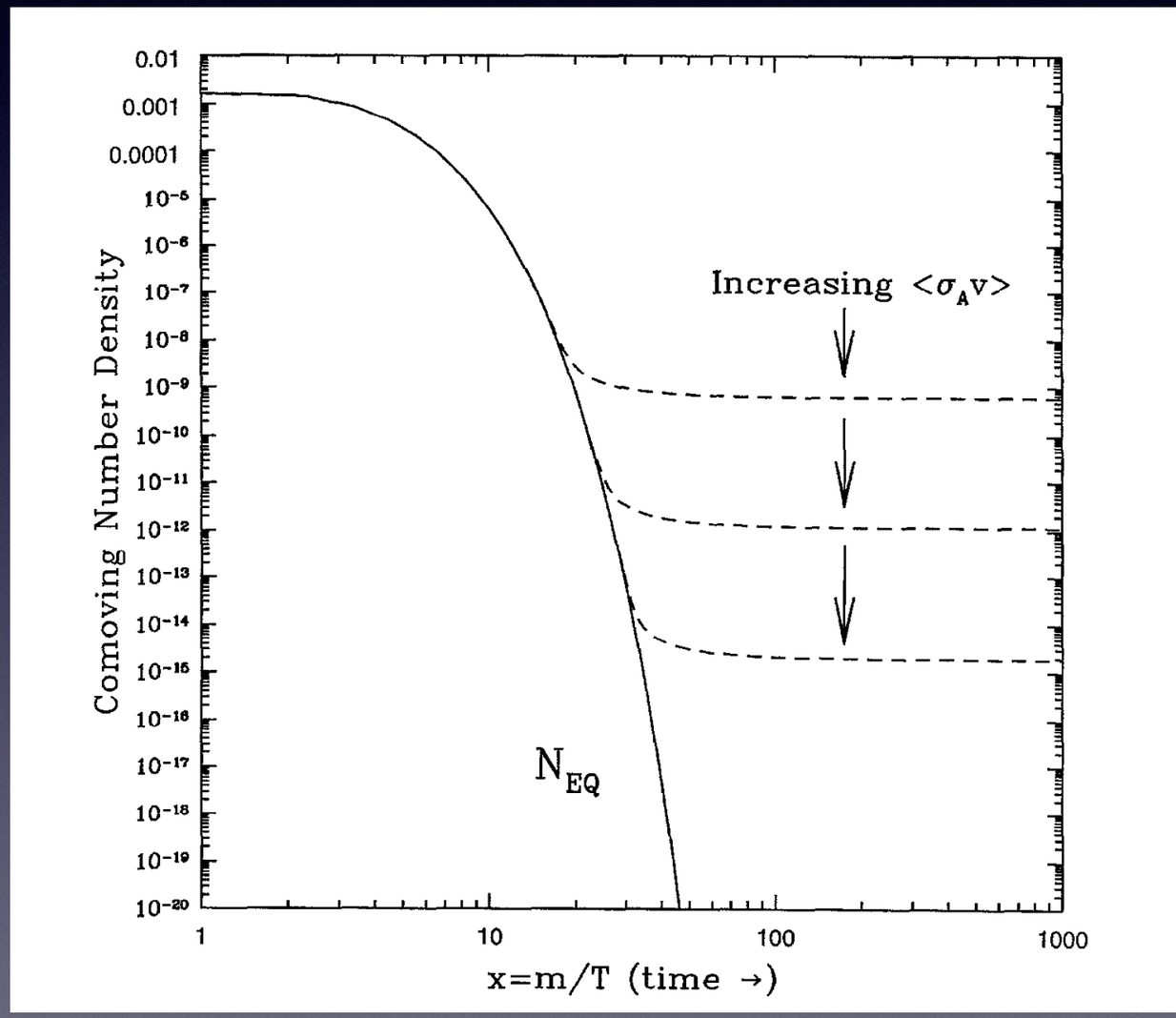
MACHOs to WIMP



- *The dominant paradigm: WIMP (Weakly Interacting Massive Particle)*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

thermal relic

- thermal equilibrium when $T>m_\chi$
- Once $T<m_\chi$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield $Y=n/s$ constant under expansion
- stronger annihilation ⇒ less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} {\rm GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

$$\sim 10^{-9} {\rm GeV}^{-2}$$

- simple estimate of the annihilation cross section

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

- weak-scale mass!!!

$$m_\chi \approx 300 \ {\rm GeV}$$

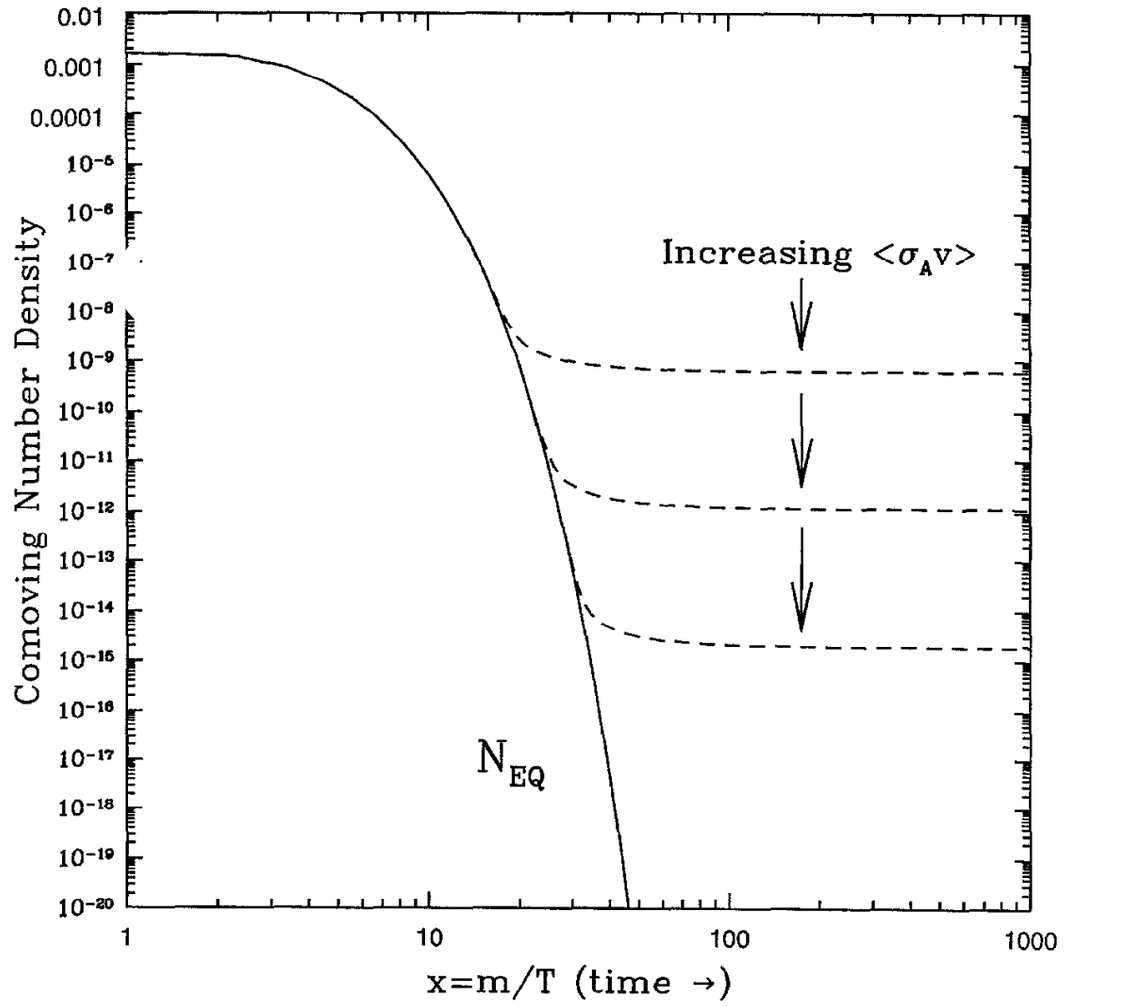
WIMP miracle

therma

- Solve the Boltzmann eq

$$\frac{dn_1}{dt} + 3Hn_1 = -\int \prod_{i=1}^{4} \frac{d^3p_i}{(2\pi)^3 2E_i} |\mathcal{M}(1$$

$$[f_1 f_2(1 \pm f_3)(1 \pm f_4) -$$



- assume Maxwell distribution, $1=2=\chi$, $E_1=E_2=m_\chi$

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\rm ann} v \rangle (n^2 - n_{eq}^2)$$

- Note momentum dependence may be important close to thresholds, resonances
- reproduce the estimate with

$$x_f \approx 24 + \ln \frac{m_\chi}{100{\rm GeV}} + \ln \frac{\langle \sigma_{\rm ann} v \rangle}{10^{-9}{\rm GeV}^{-2}} - \frac{1}{2} \ln \frac{g_*}{100}$$

WIMP

- A stable particle at the weak scale with "EM-strength" coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem!
- Many candidates of this type: SUSY, little Higgs with *T*-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators

Minimal Model

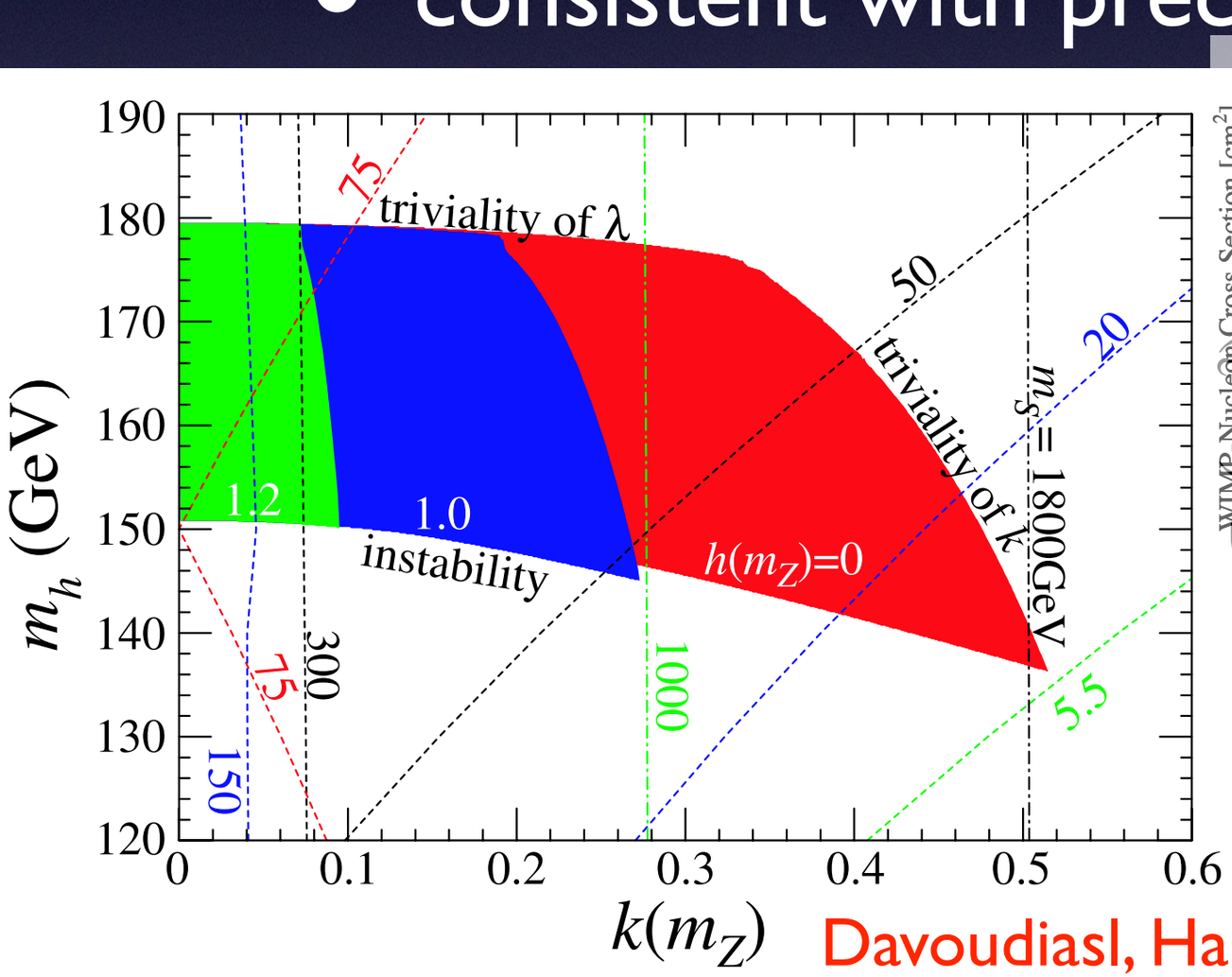
- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field S: dof=1
- assign odd Z_2 parity to S, everything else even
- Most general renormalizable coupling

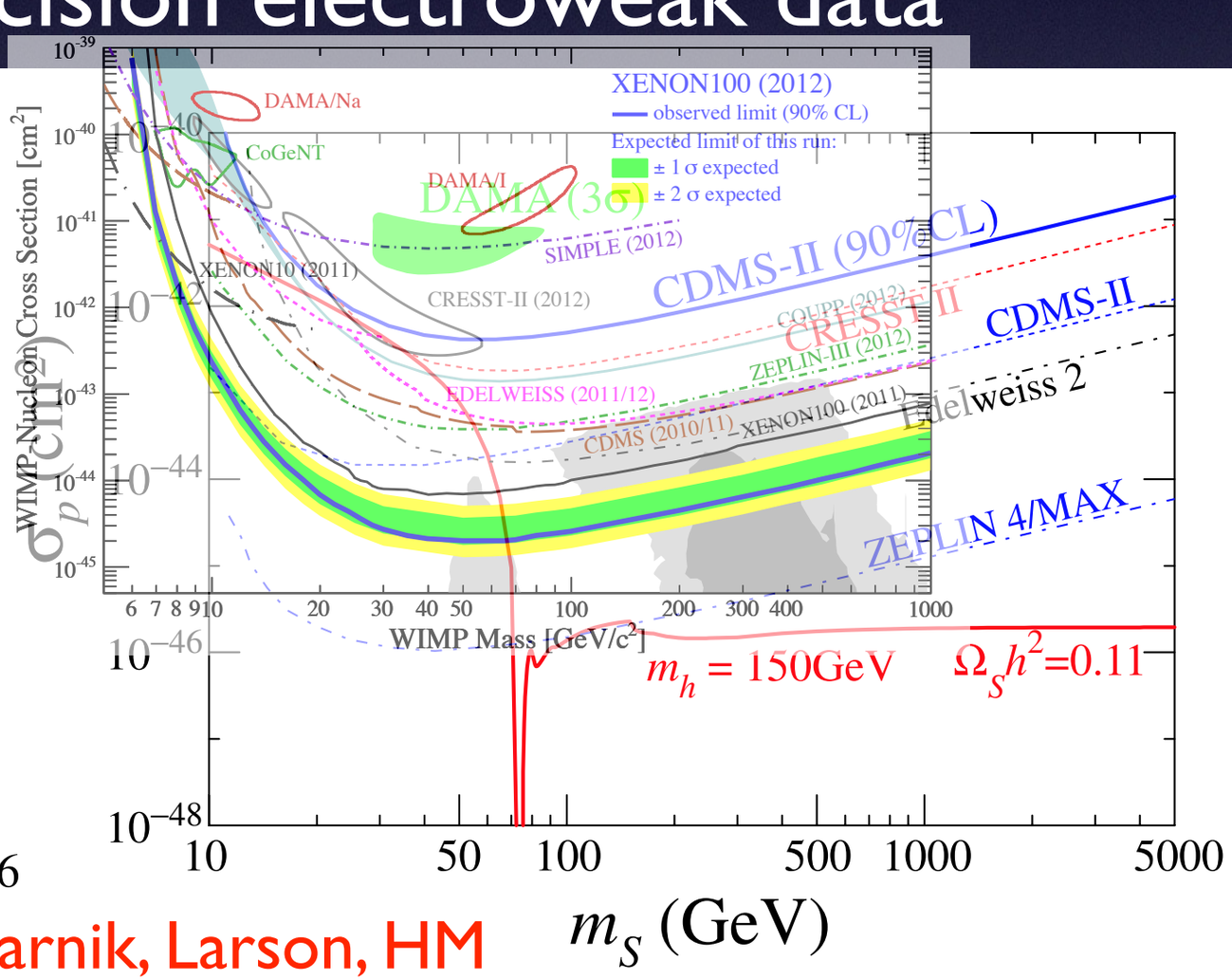
$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!}S^4.$$

Davoudiasl, Harnik, Larson, HM

Consistency check

- correct Dark Matter abundance 5.5–1800 GeV
- evades direct detection limits >60 GeV
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data



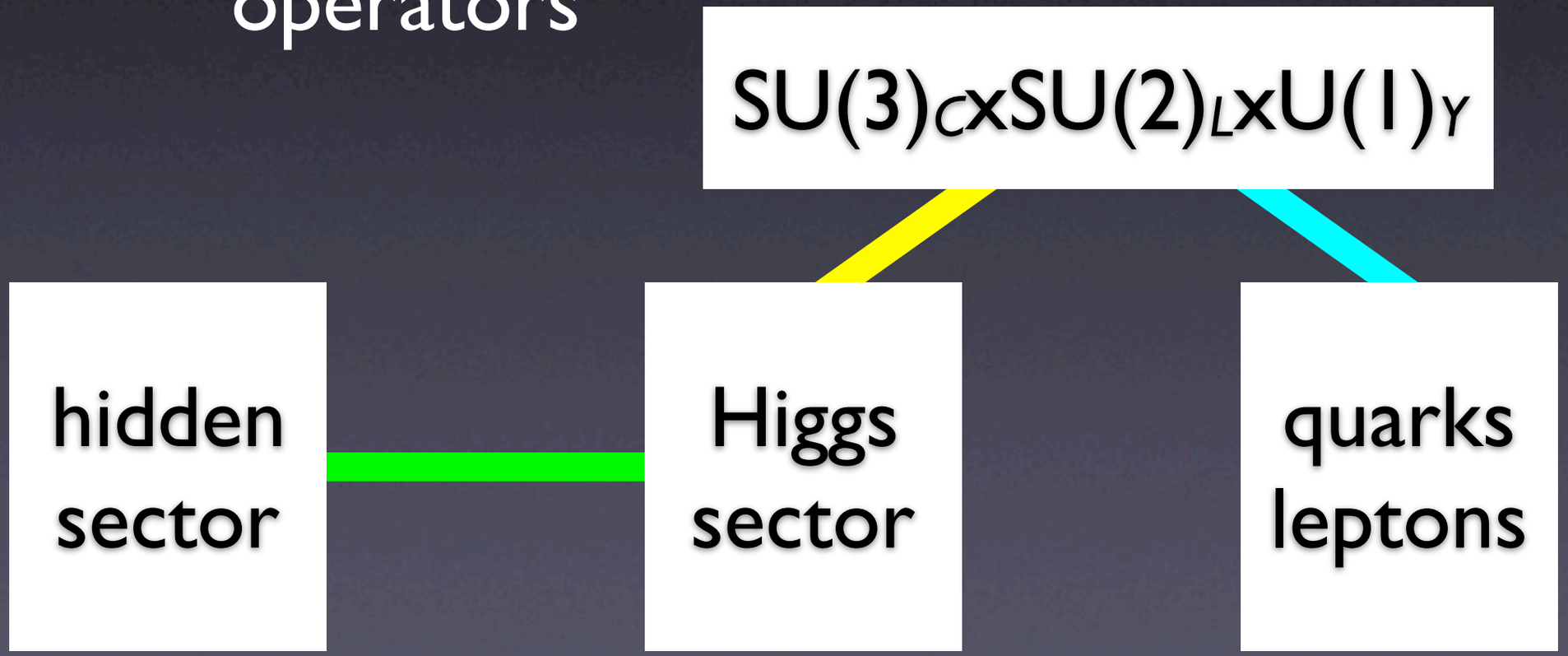


Davoudiasl, Harnik, Larson, HM

Higgs as a portal

$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!}S^4.$$

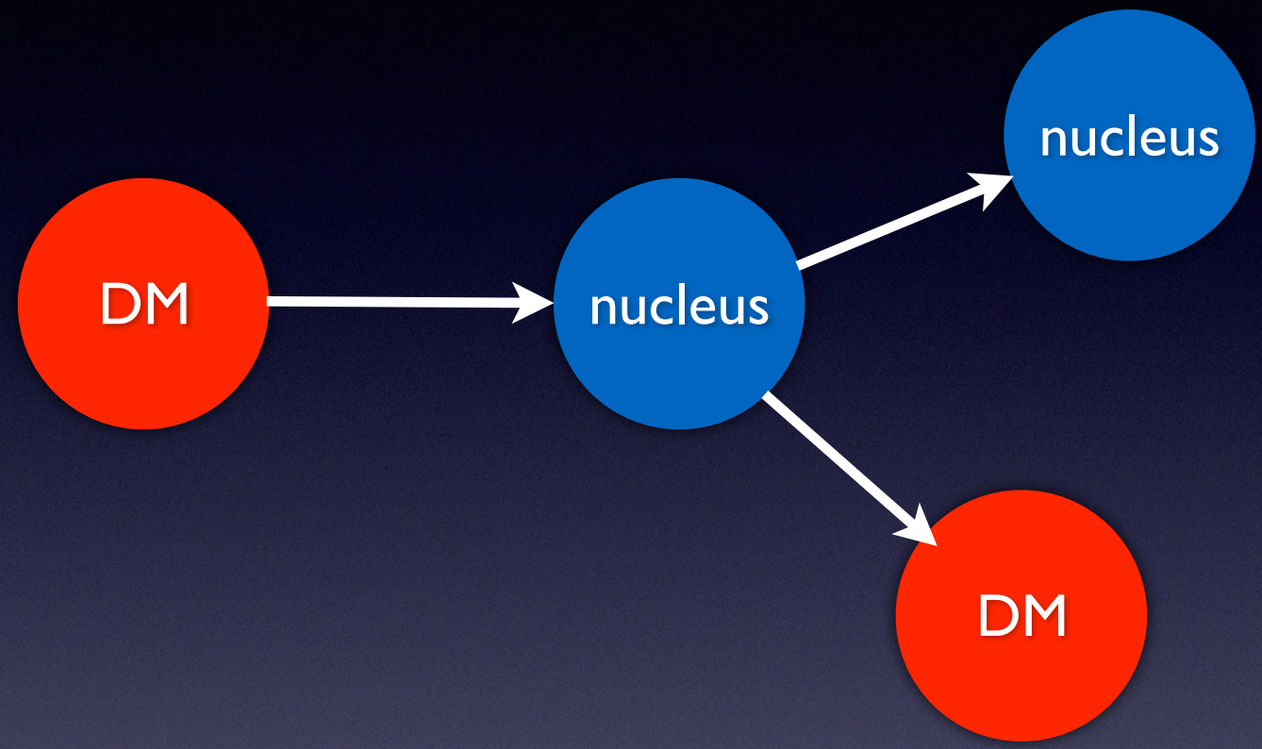
- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors" via lowest-dim operators



$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

basic idea

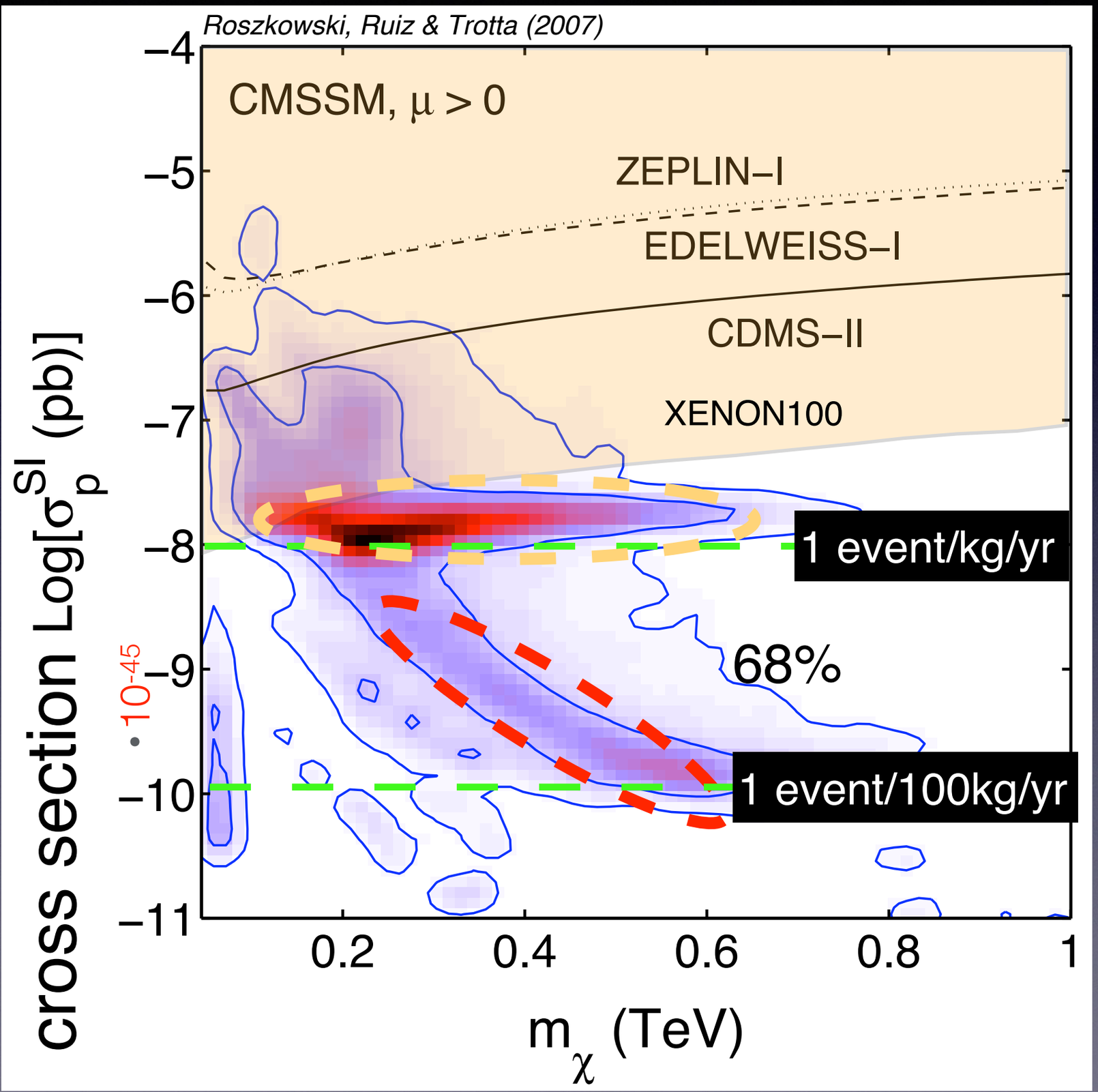
- maximum energy transfer to nucleus when $m_X \sim M_A$
- energy of the nucleus leads to a combination of
  - ionization
  - phonon
  - scintillation



$$E_f = \frac{1}{2} m_\chi \frac{m_\chi M_A}{(m_\chi + M_A)^2} 2(1 - \cos\hat{\theta})$$

Sensitivity and SUSY Parameter

Masaki Yamashita



CMSSM in 2007
hep-ph 0705.2012v1
Roszkowski et al.

near future

Super CDMS, XENON100, LUX, XMASS, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

Future experiments

SuperCDMS1t, XENON1t, LZ, Darwin ArDM ,XMASS 20T, ...

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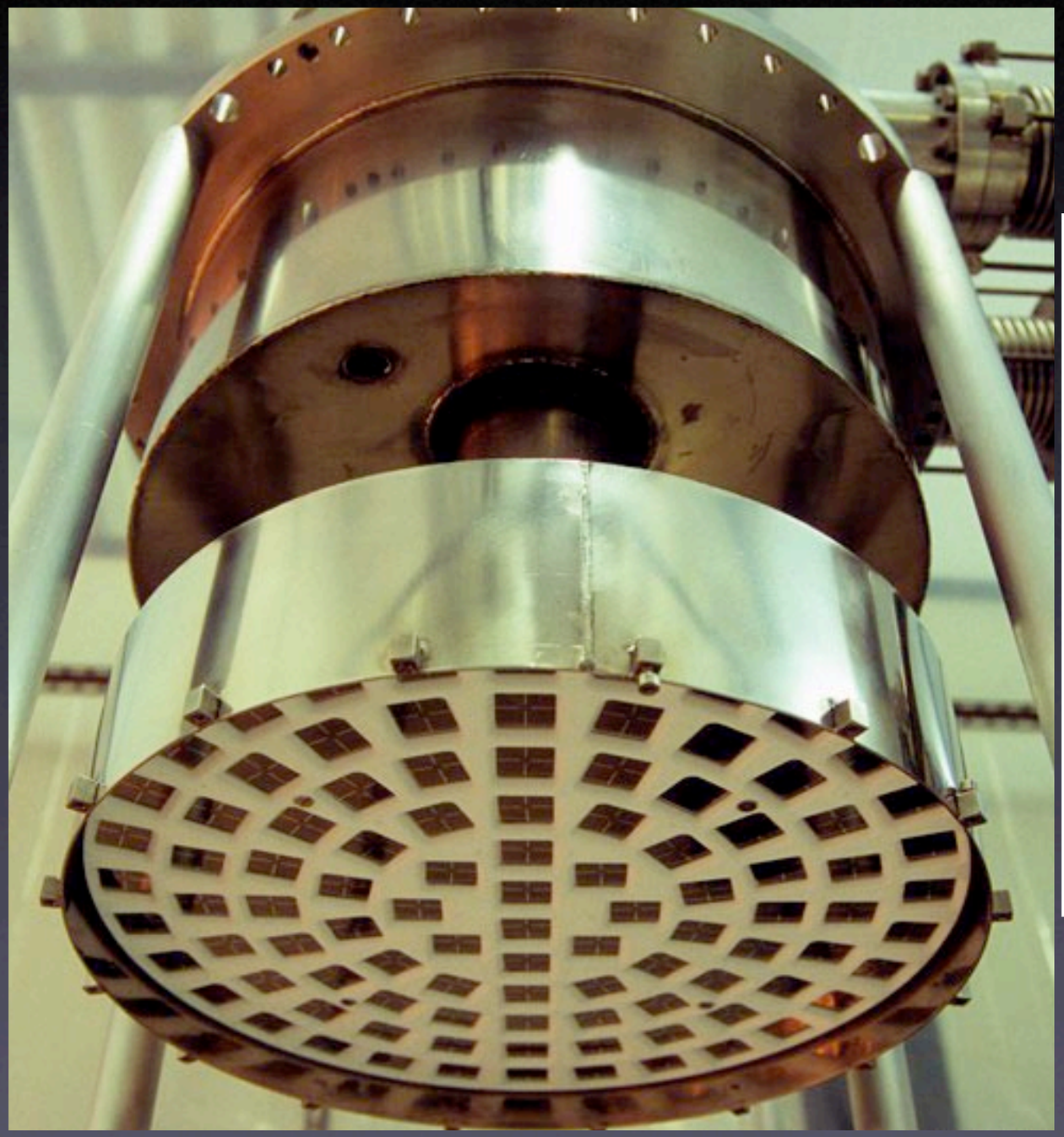
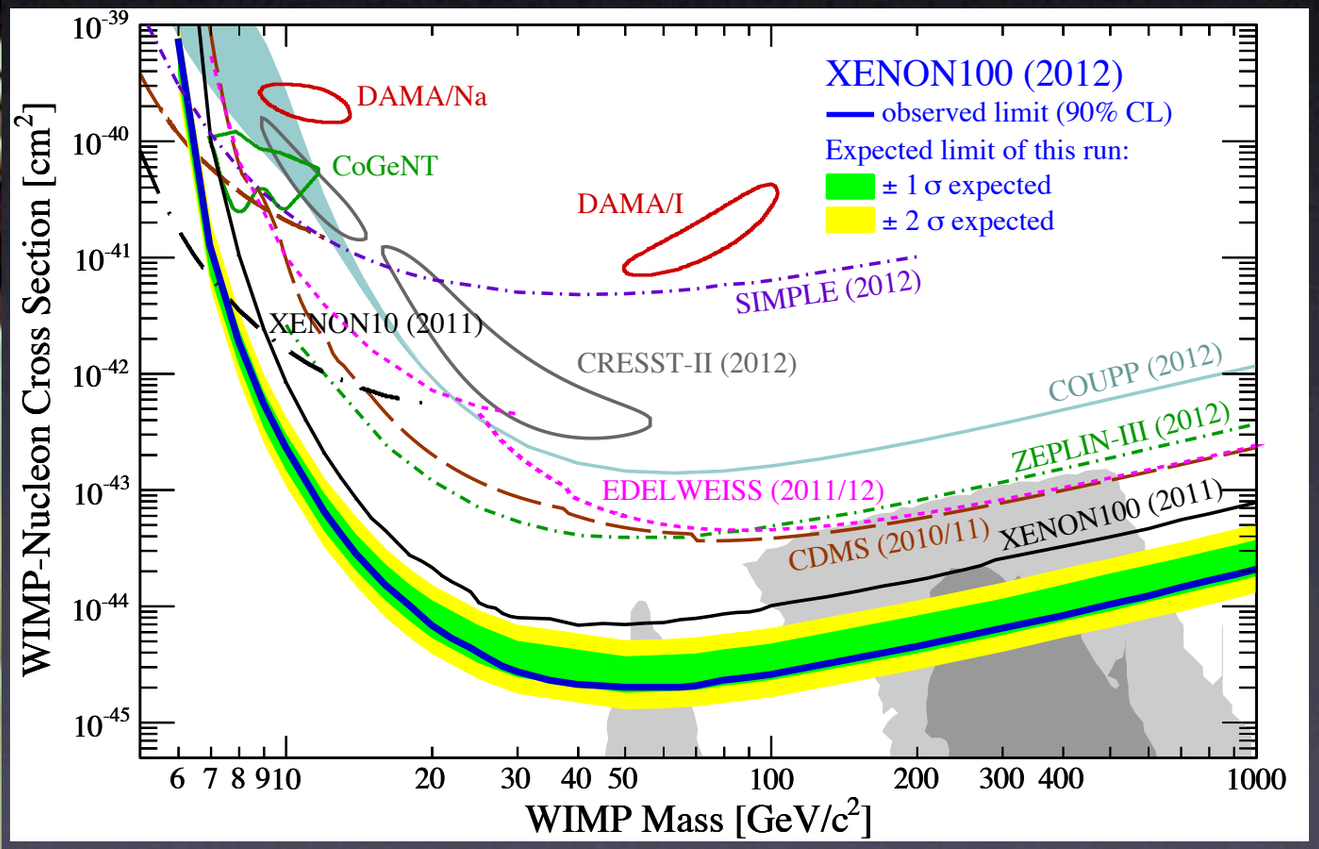
direct search

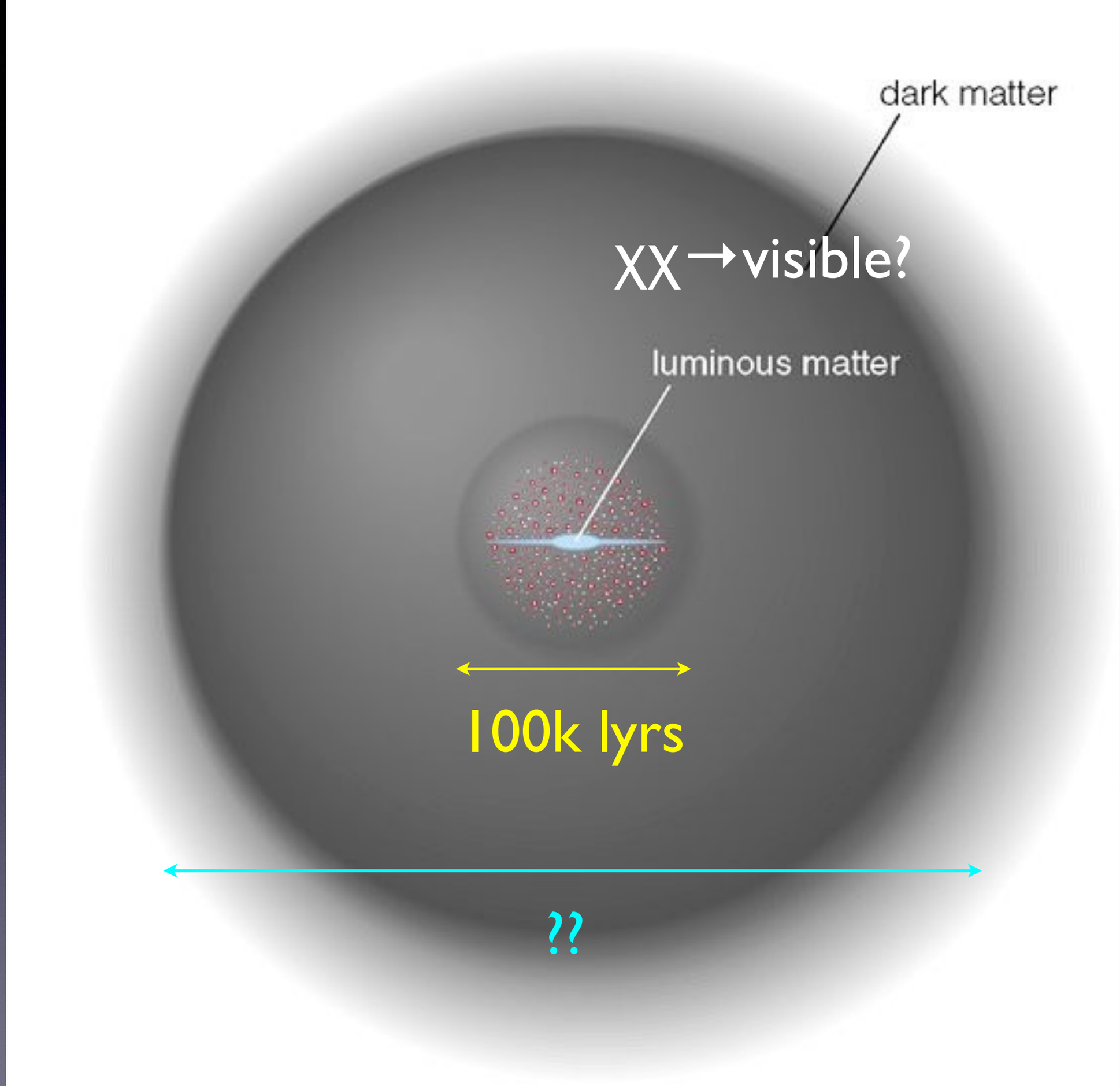


XENON 100

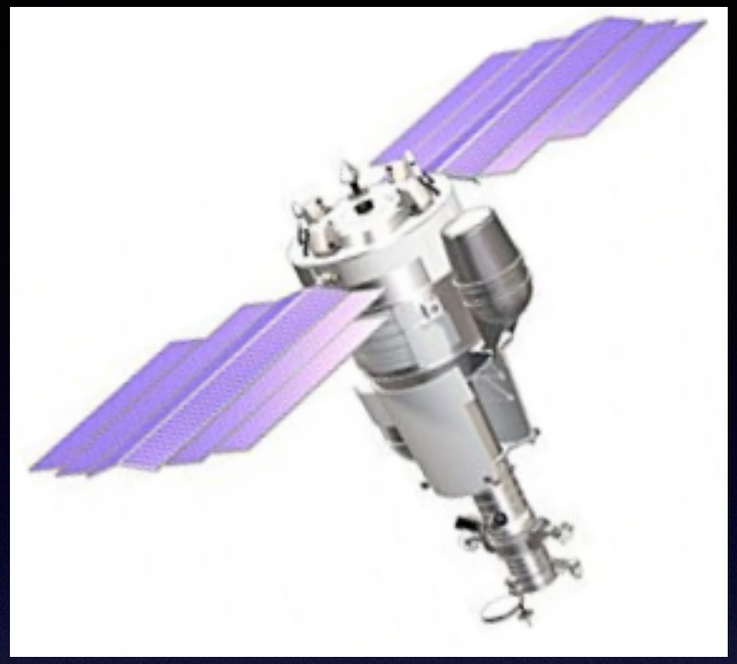


cf. σ~10^{-36} cm^2
for a heavy neutrino

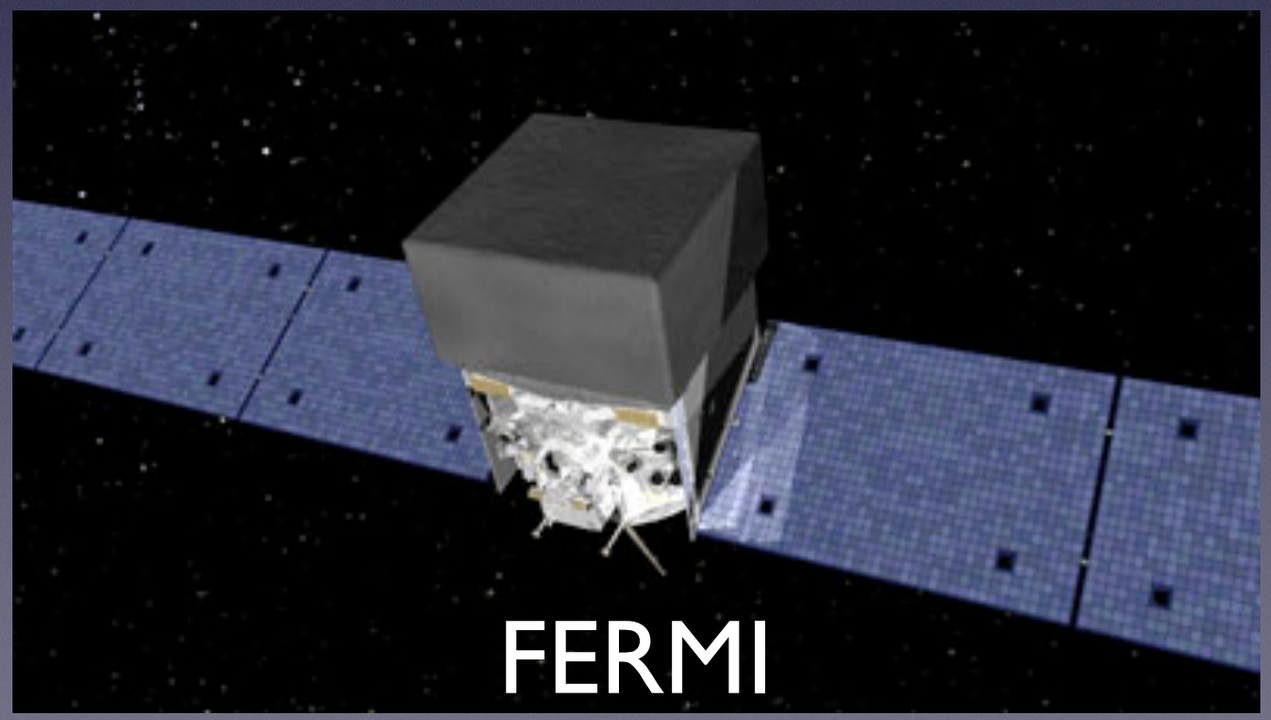
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4

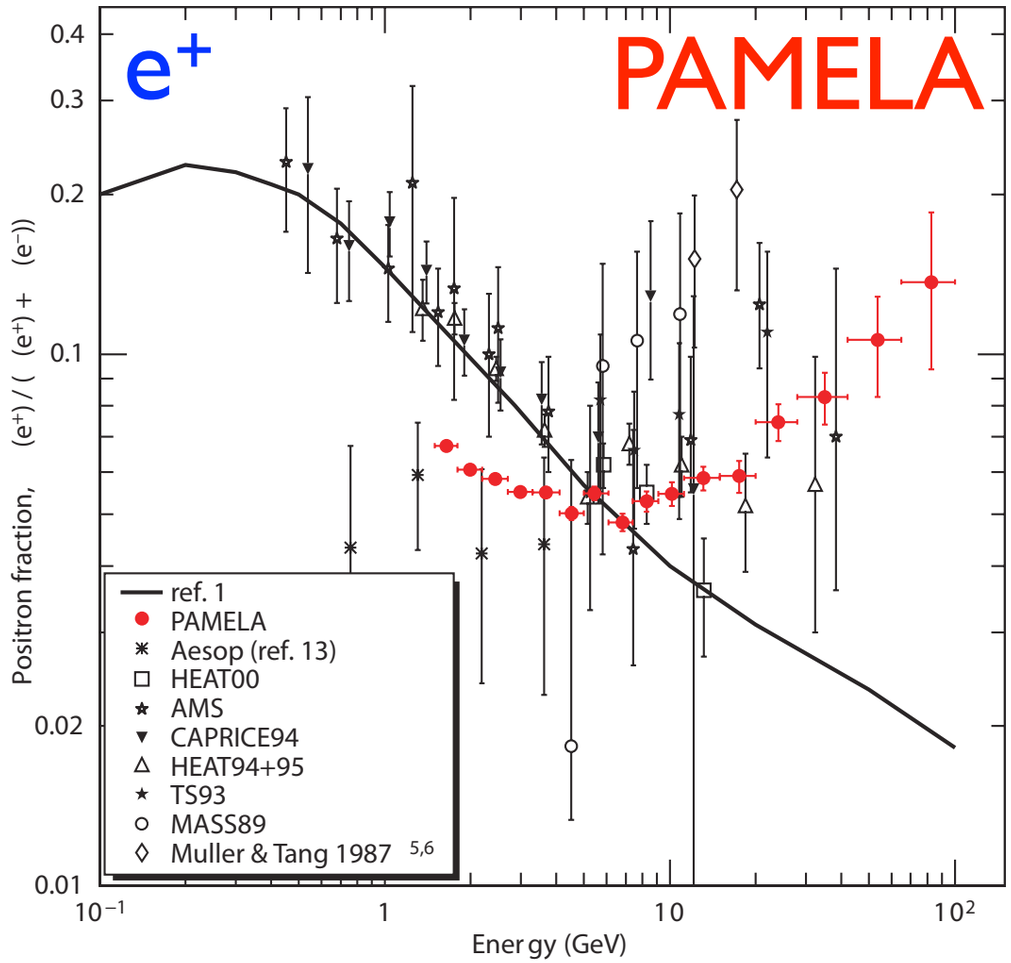

dark matter
XX→visible?
luminous matter
100k lyrs
??

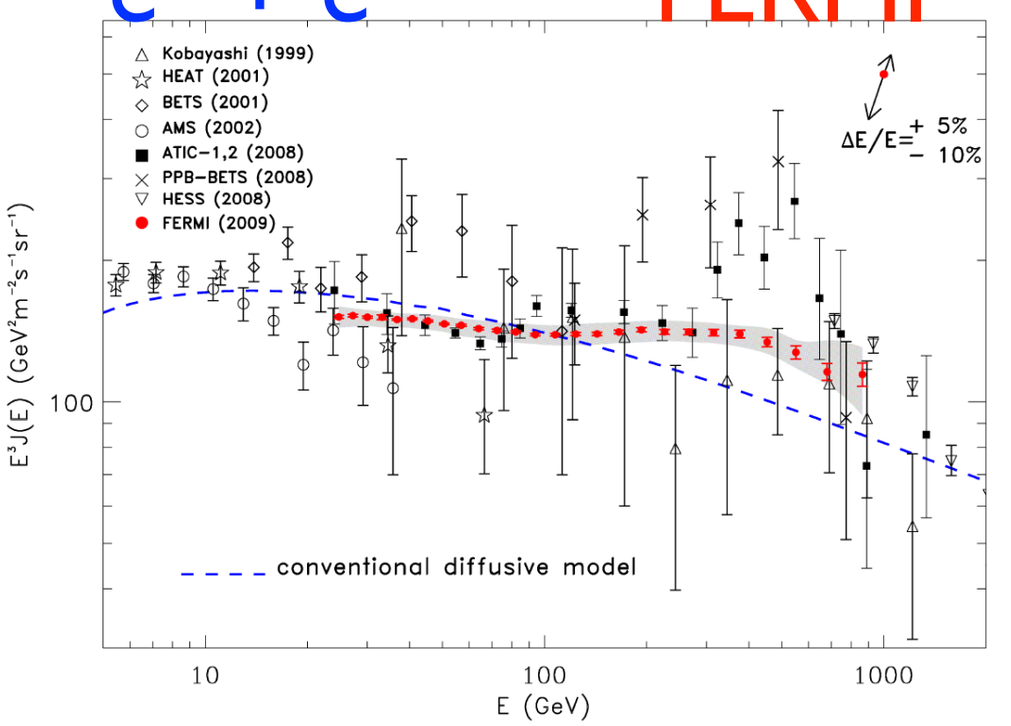
PAMELA



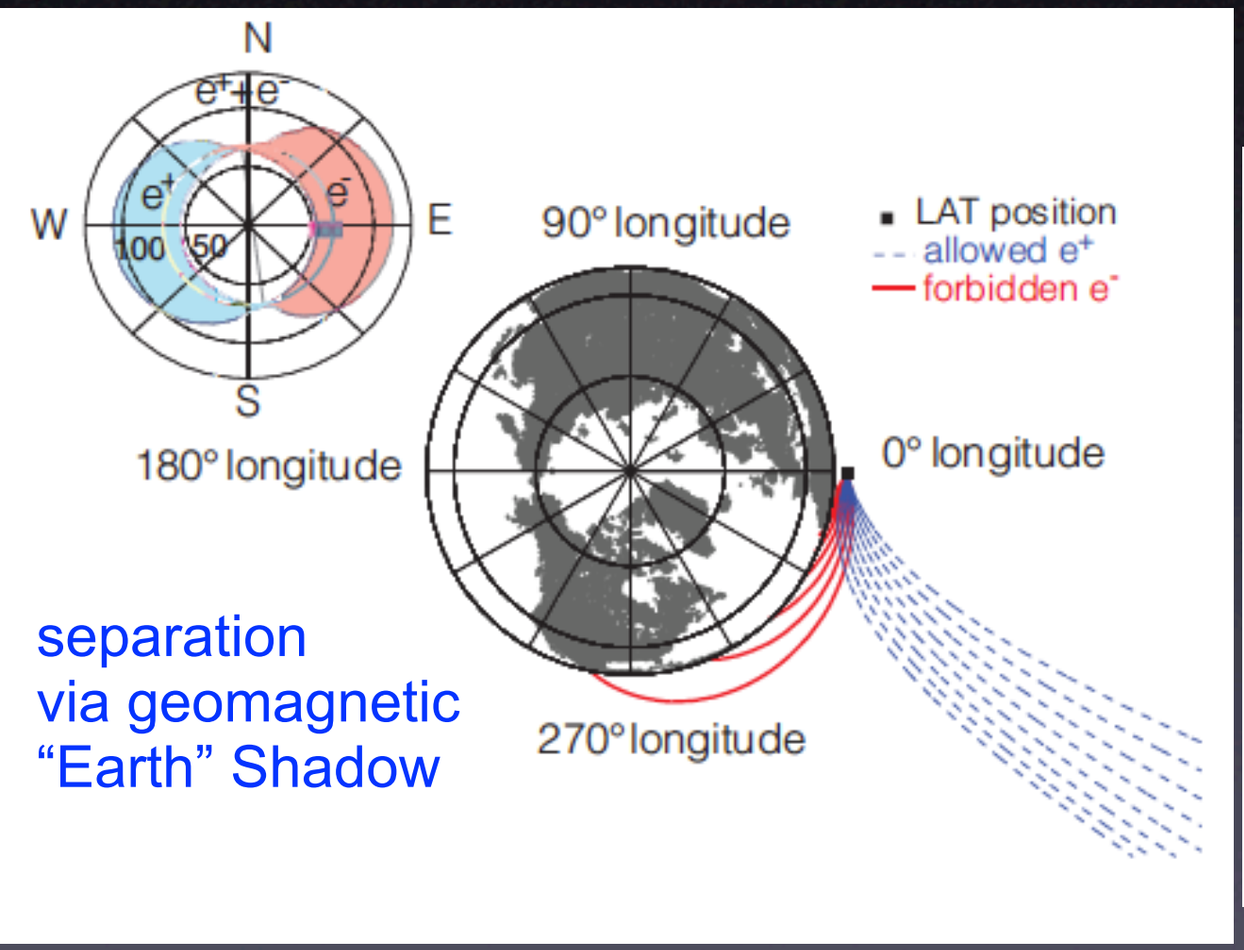
dark matter annihilation or decay in the galactic halo?



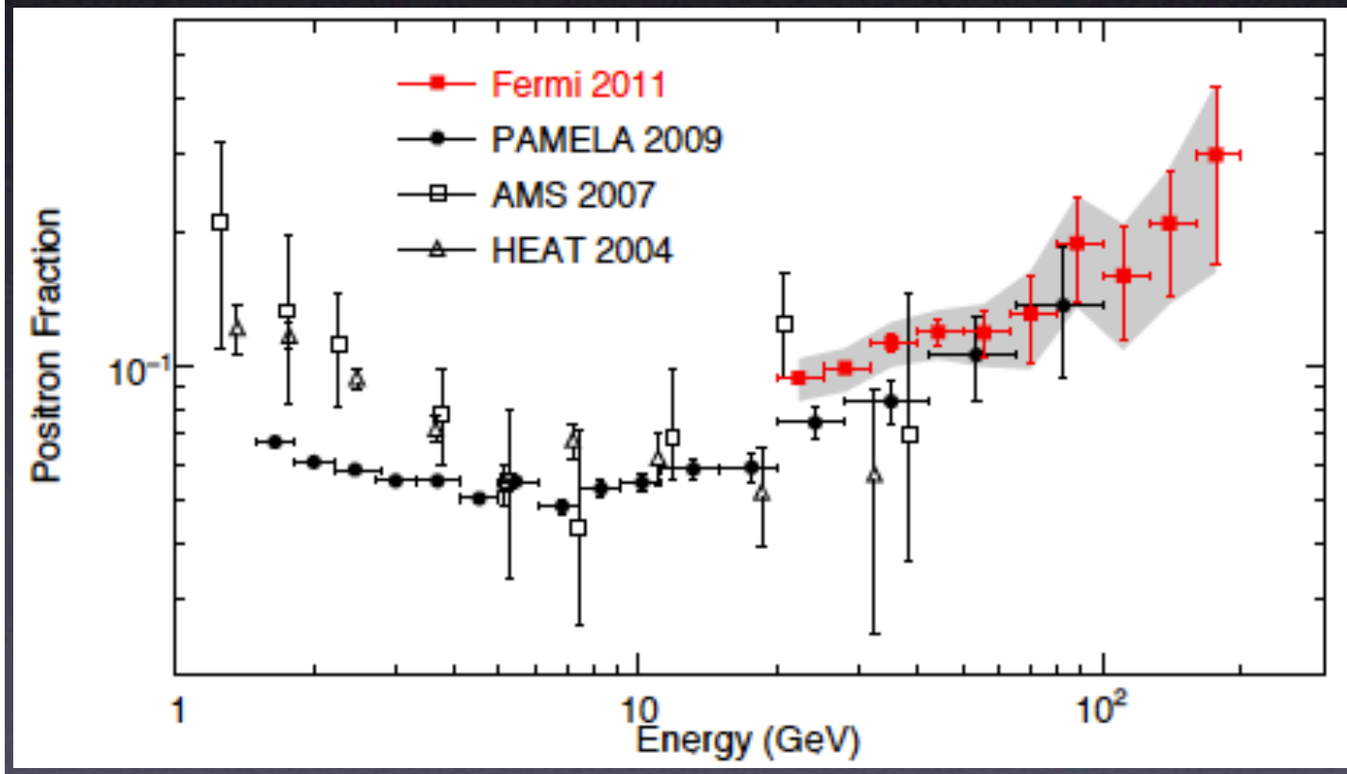


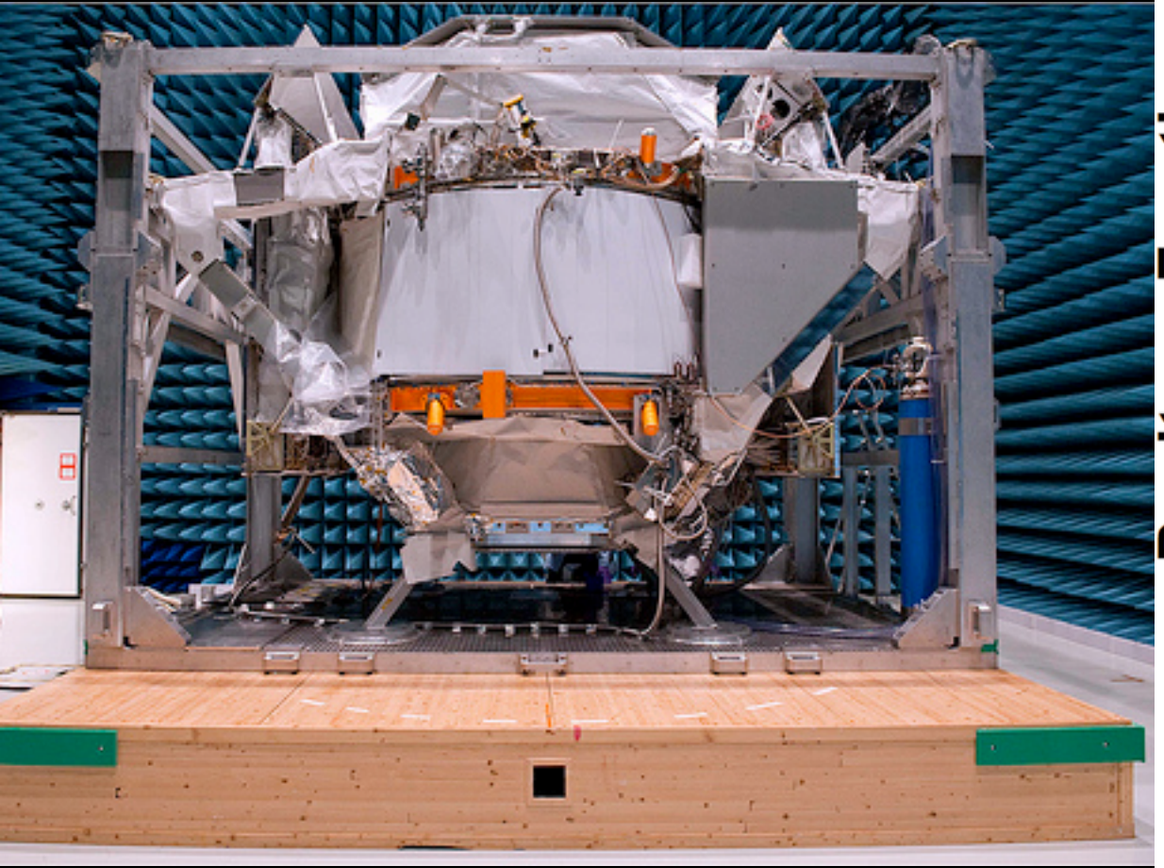


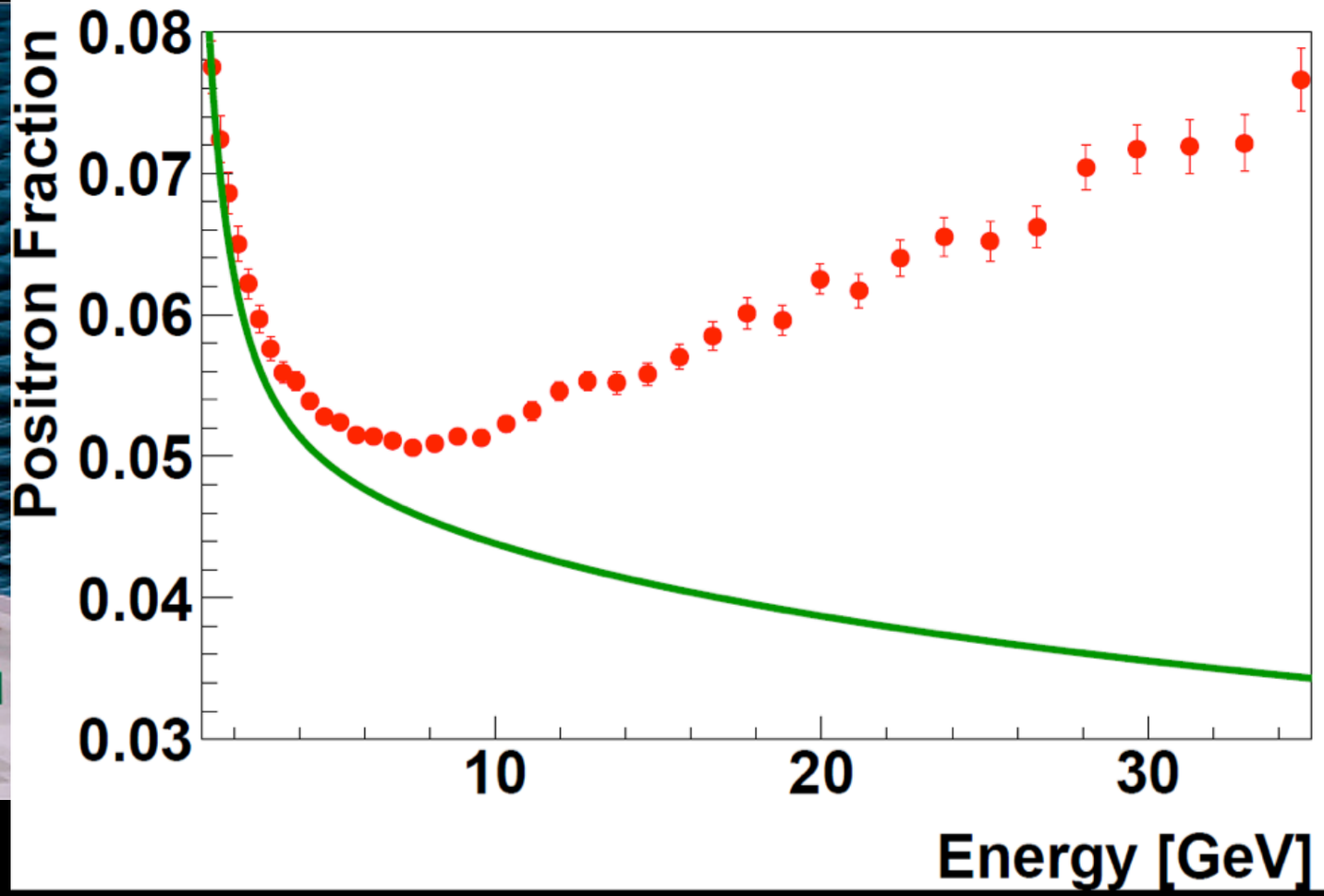
rise in e^+ fraction confirmed by Fermi



separation
via geomagnetic
“Earth” Shadow

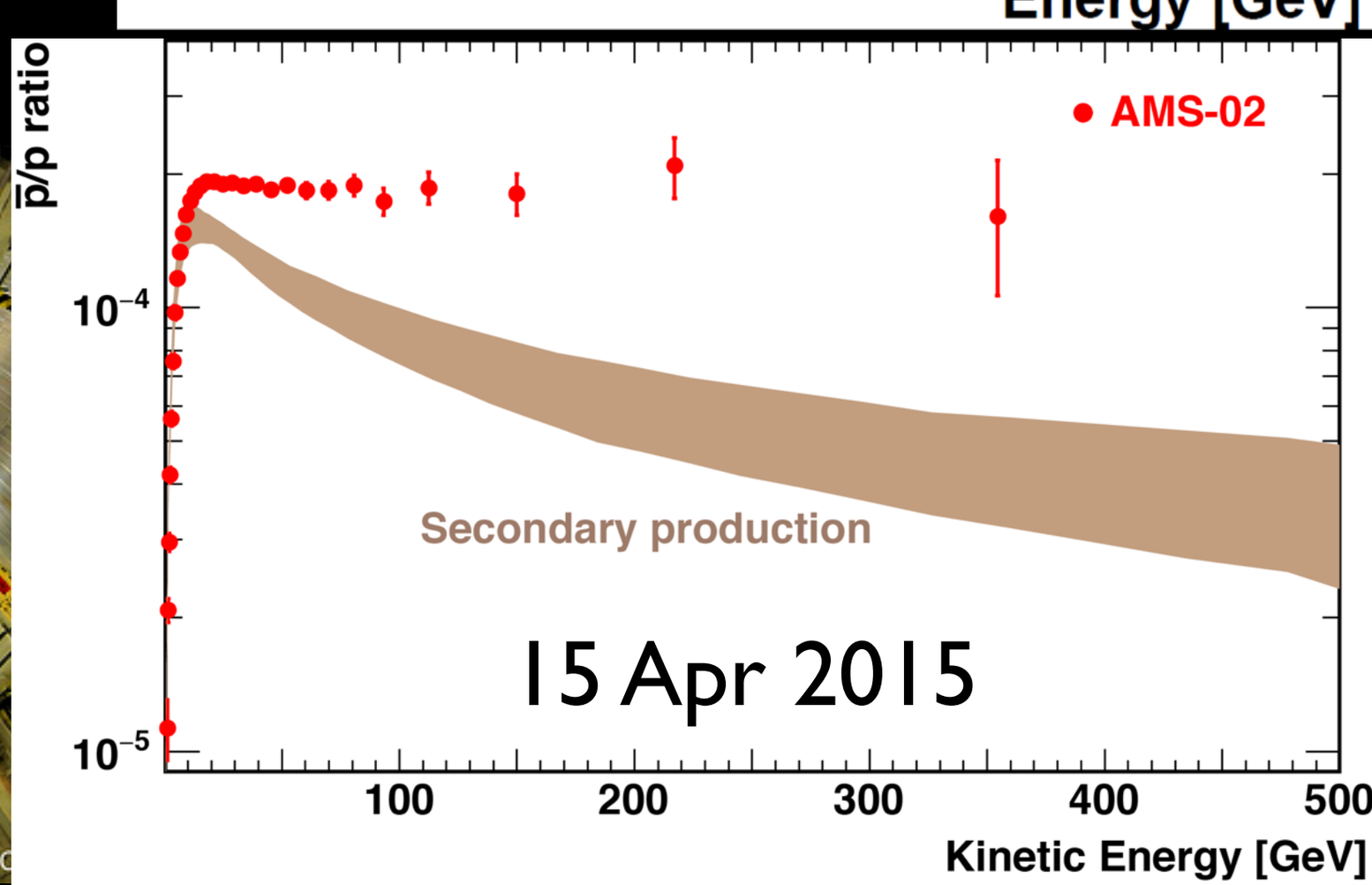





Positron Fraction
0.08
0.07
0.06
0.05
0.04
0.03
10
20
30
Energy [GeV]

AMS


AMS
AMS
© Michele Famiglietti / AMS C


p̄/p ratio
AMS-02
Secondary production
15 Apr 2015
10⁻⁴
10⁻⁵
100
200
300
400
500
Kinetic Energy [GeV]

IPMU

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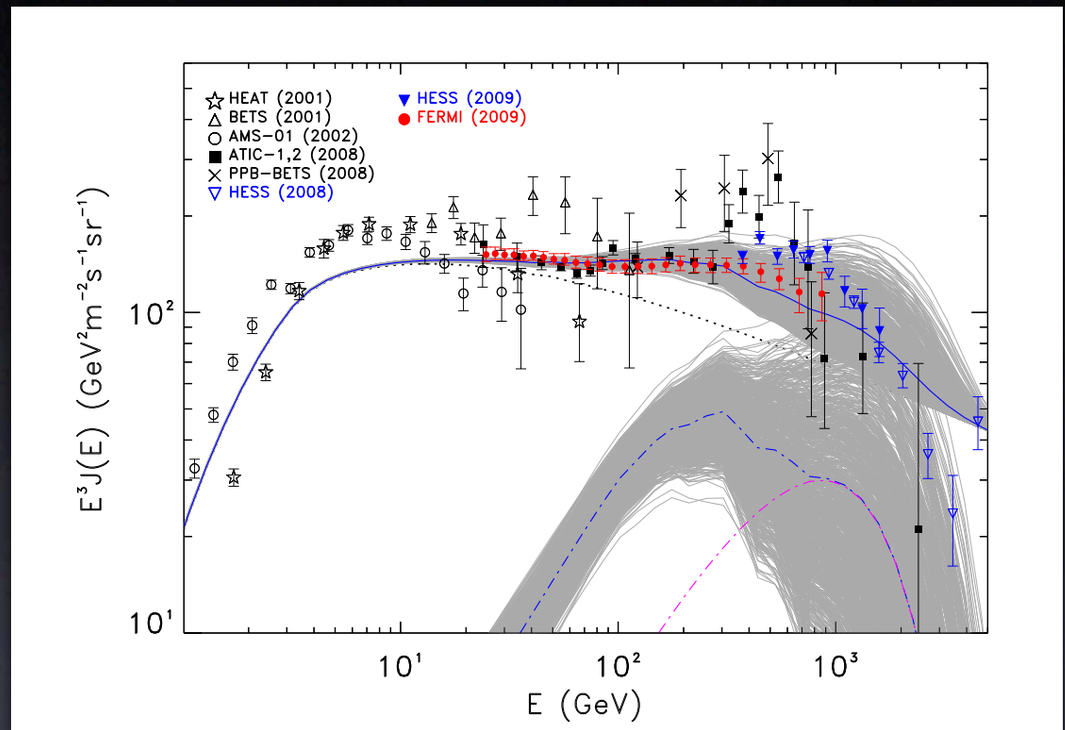
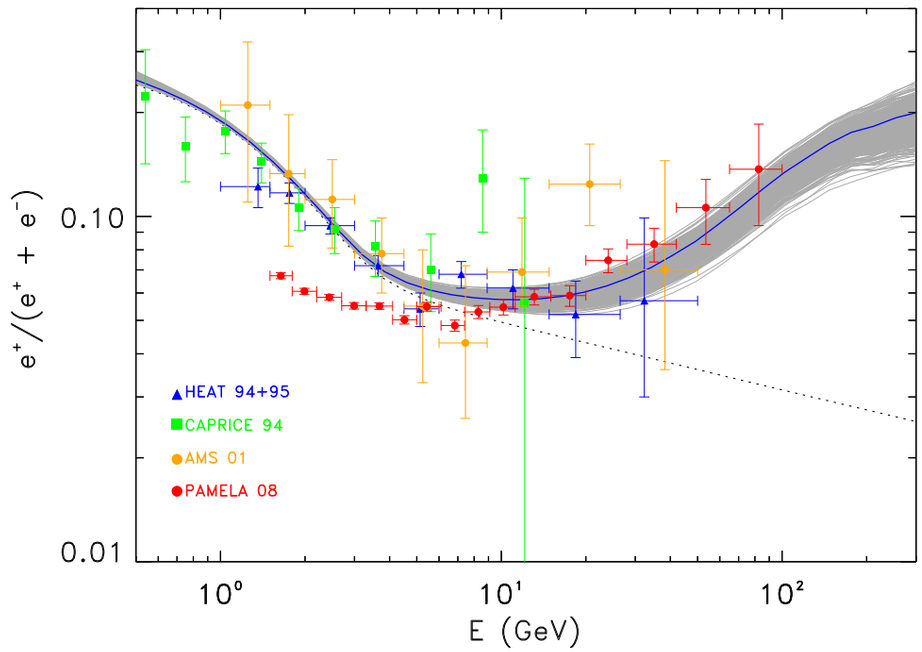
pulsars?





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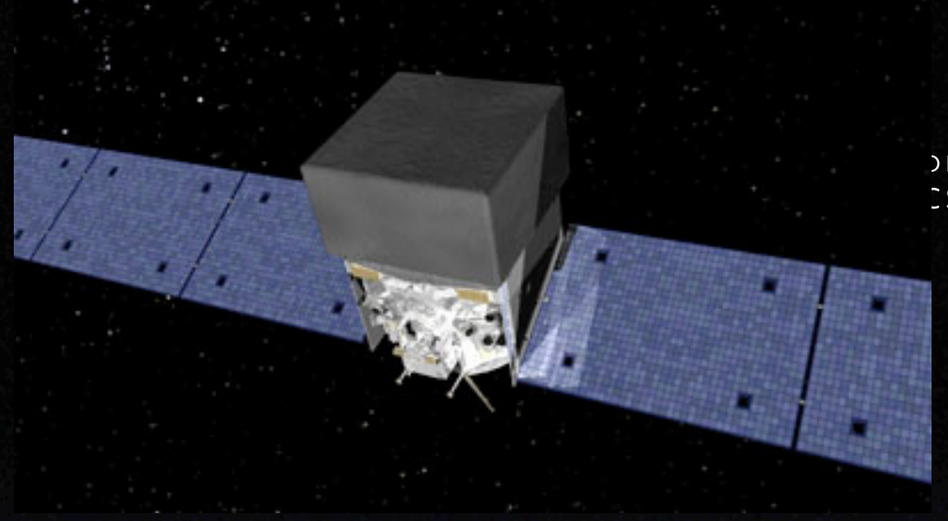
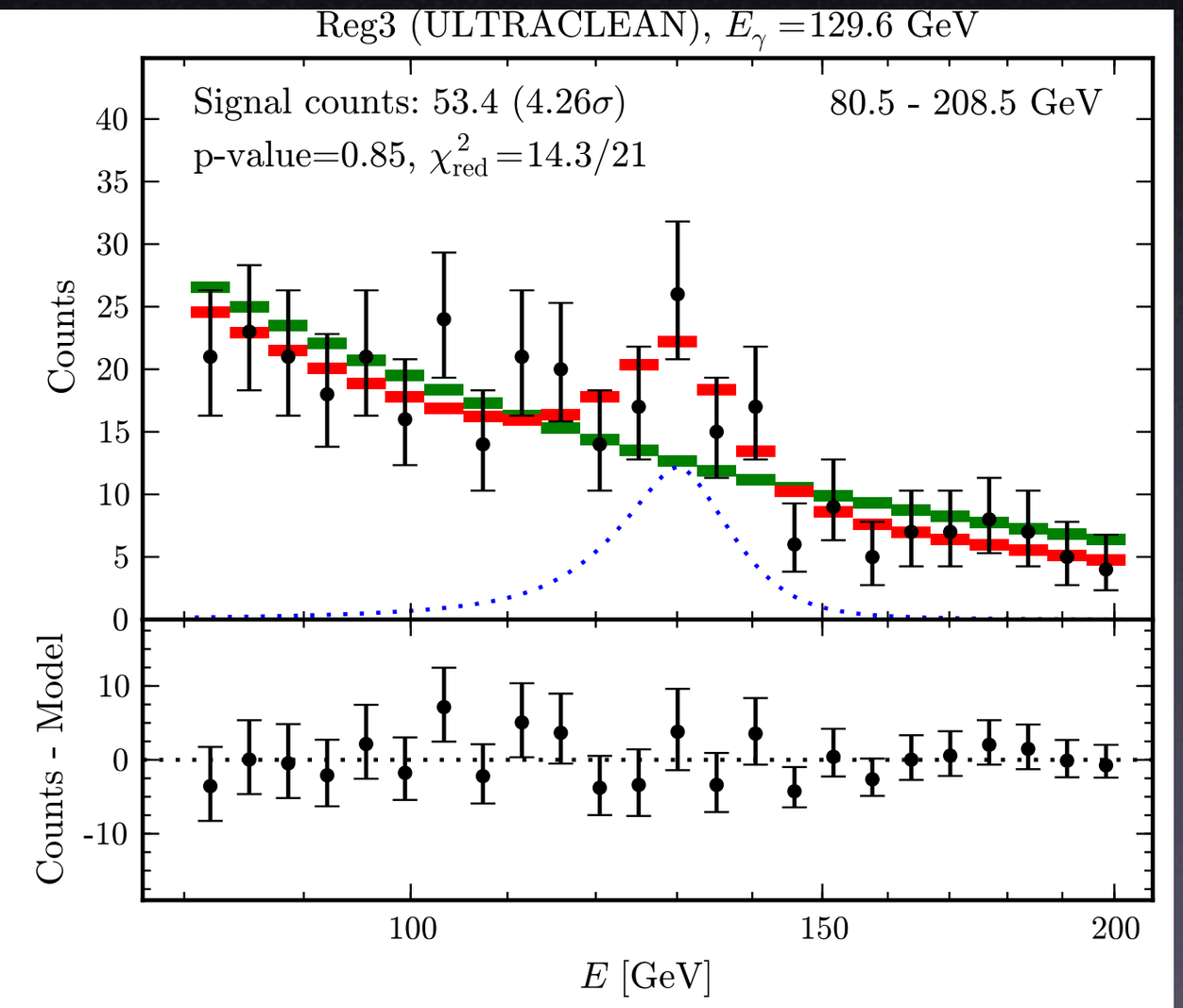
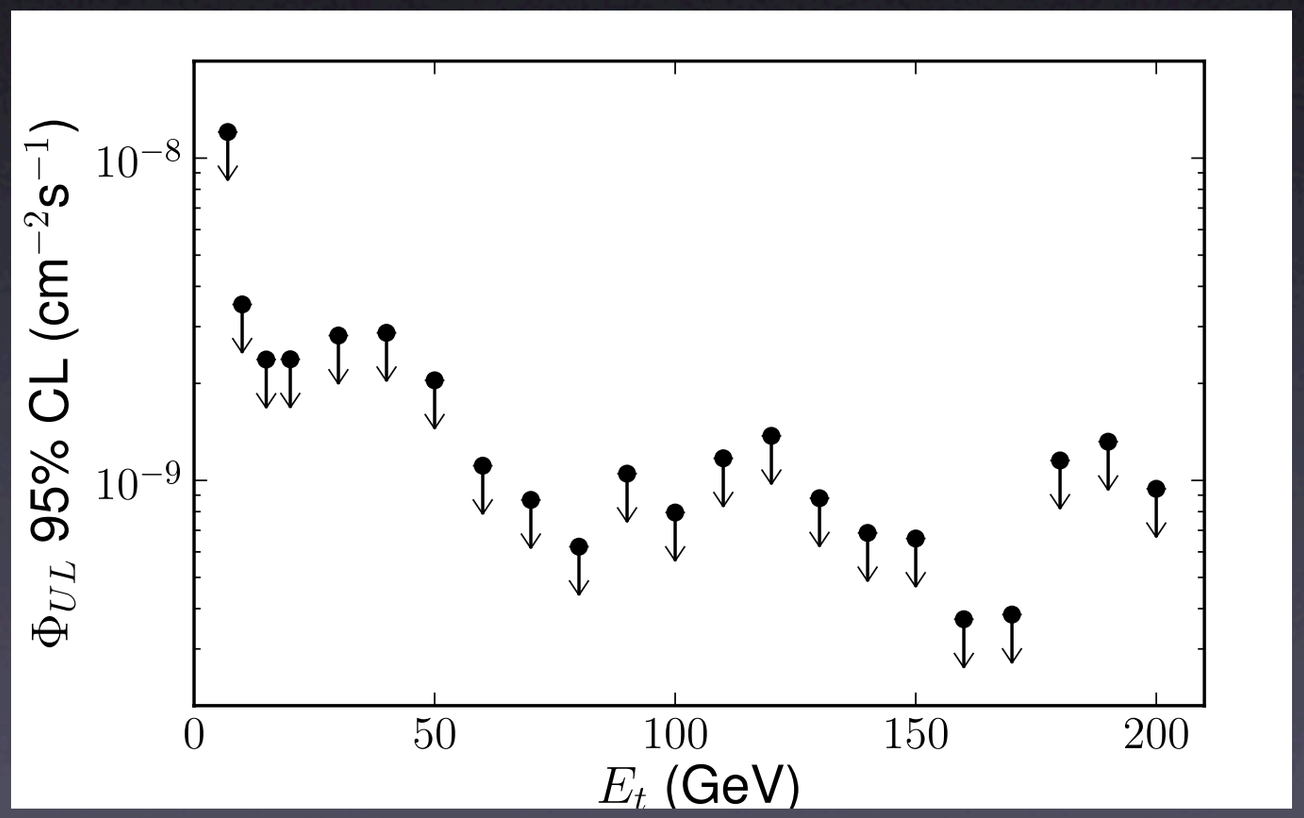
bump?





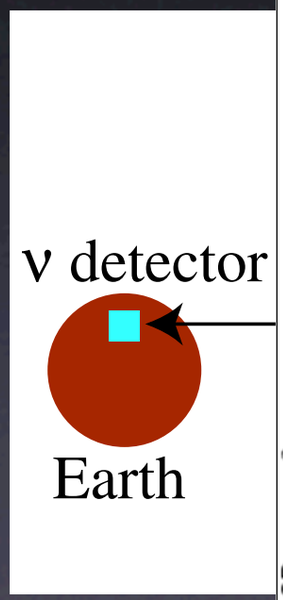
Christoph Weniger

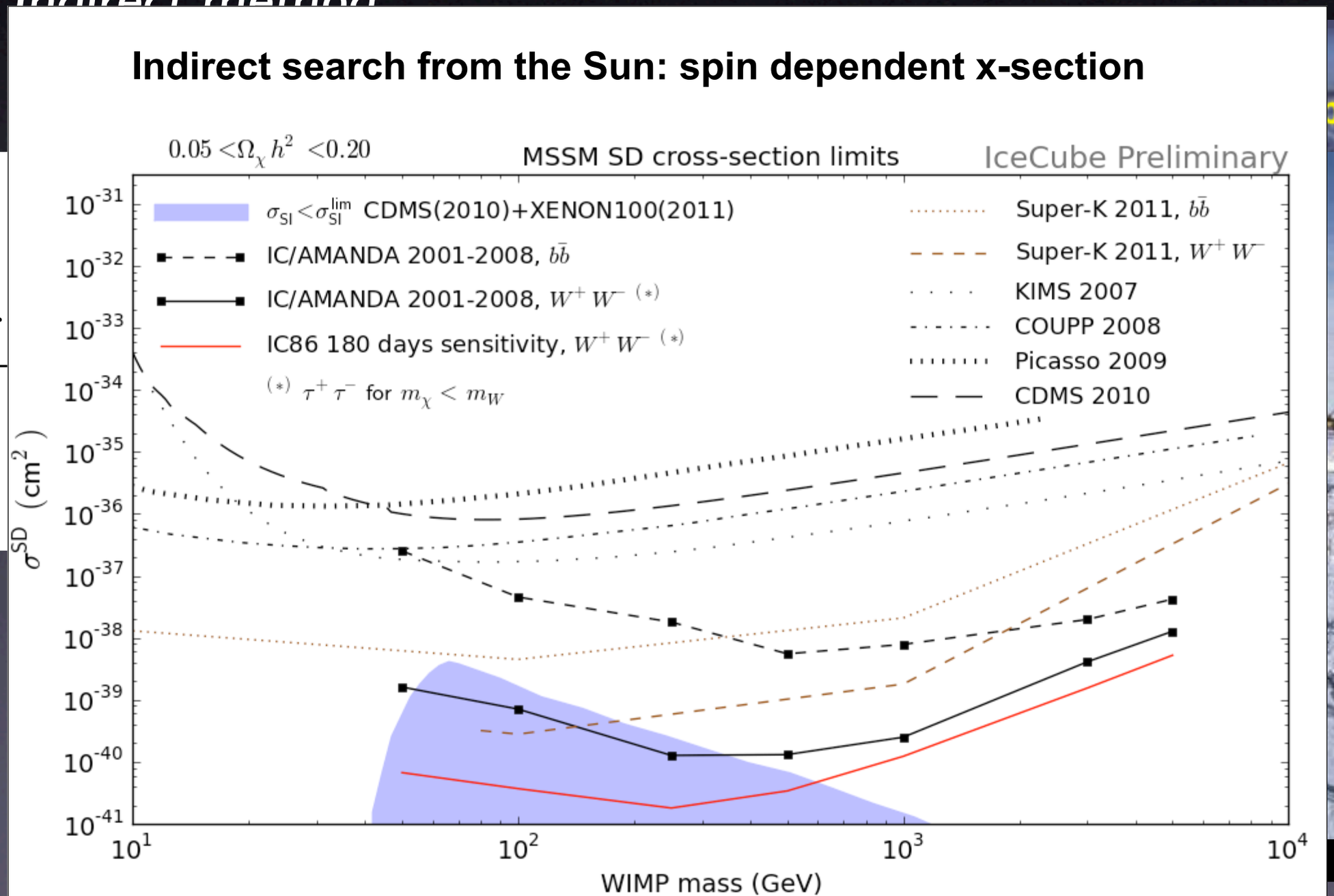


Fermi-LAT collab

Finding Dark Matter

Indirect method

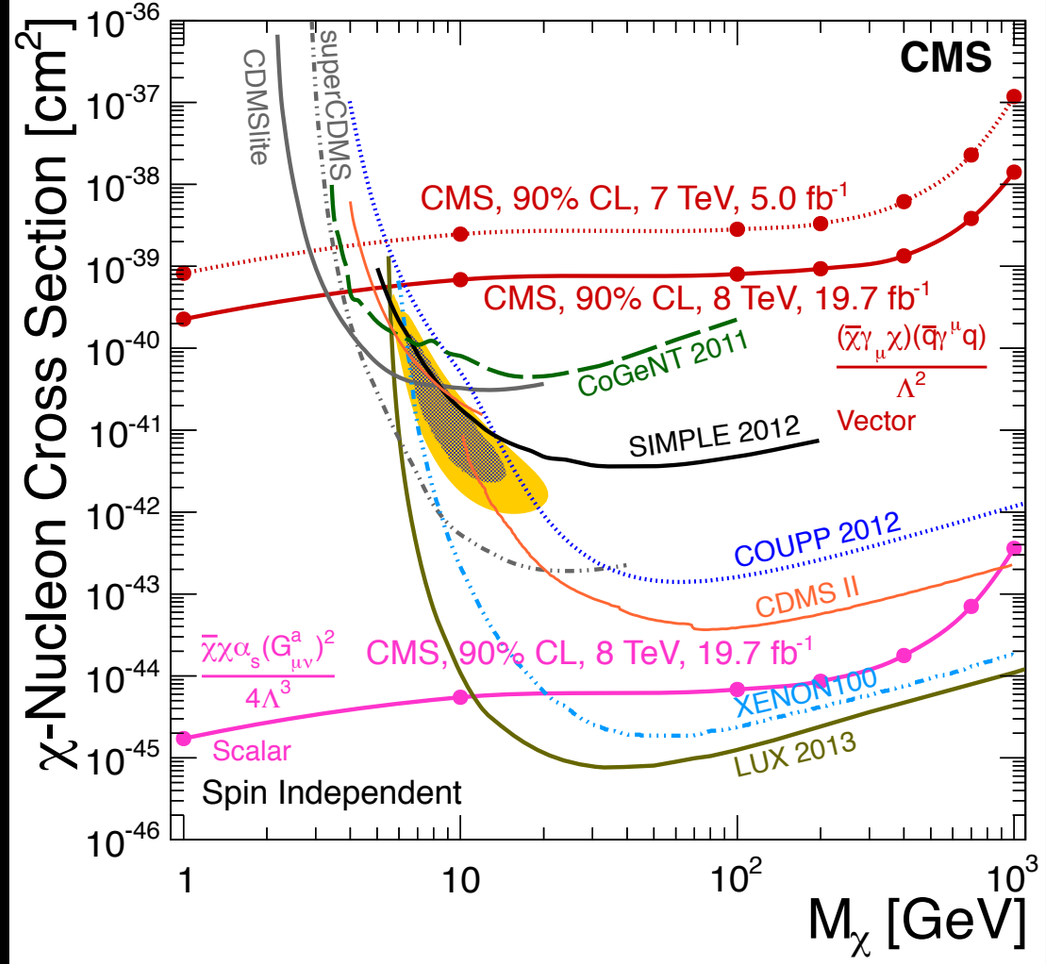


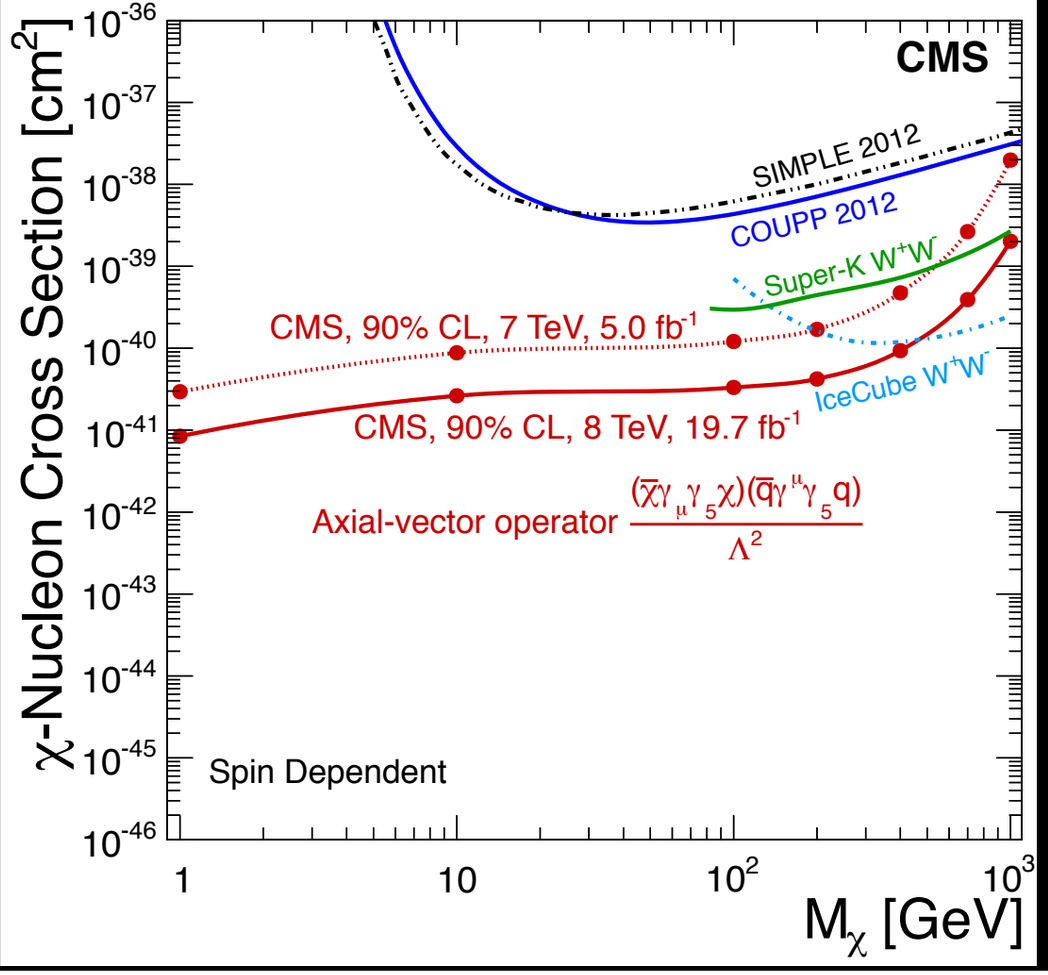


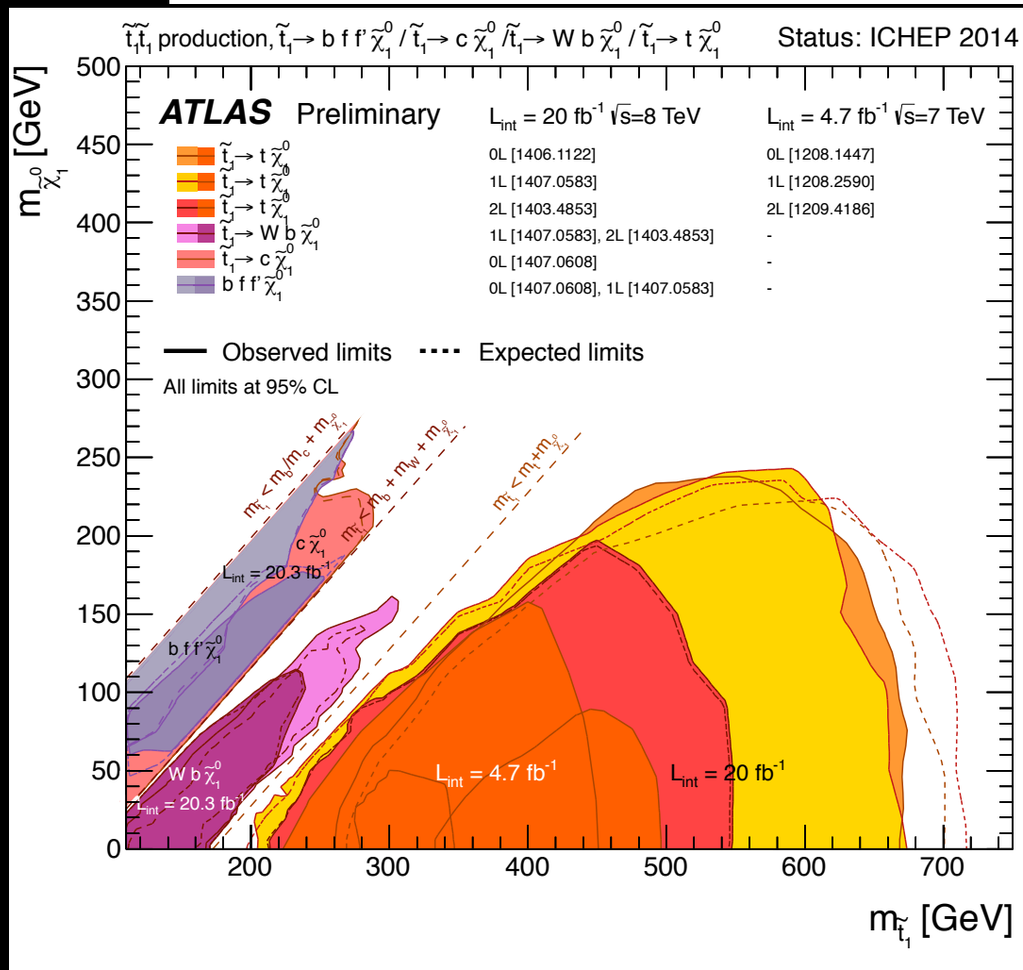
Hadron Collider (LHC)

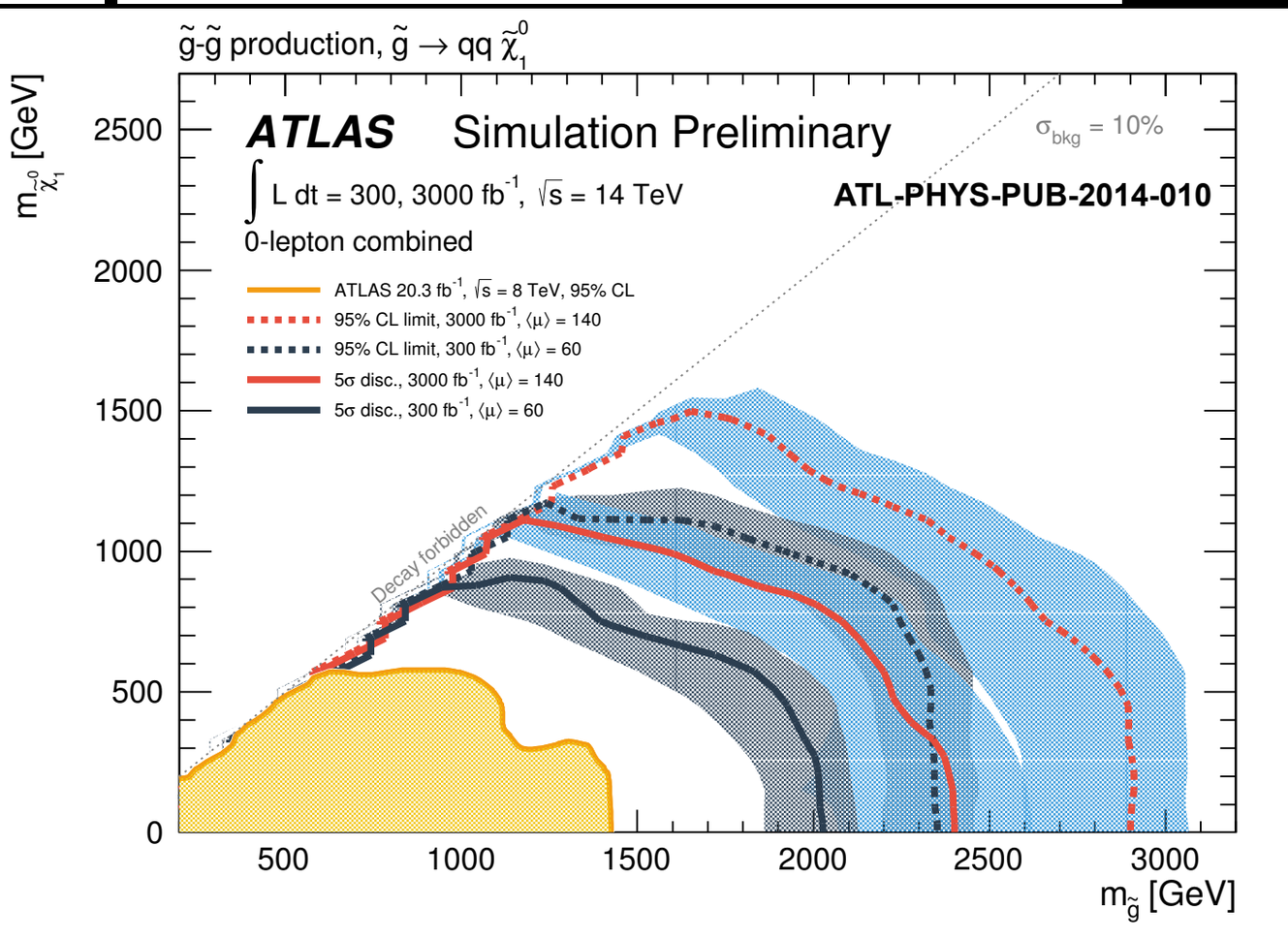
Recreating Big Bang

running!


CMS
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb-1
CMS, 90% CL, 8 TeV, 19.7 fb-1
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
LUX 2013
Scalar
Vector
Spin Independent
χ-Nucleon Cross Section [cm2]
Mχ [GeV]


CMS
SIMPLE 2012
COUPP 2012
Super-K W+W-
IceCube W+W-
CMS, 90% CL, 7 TeV, 5.0 fb-1
CMS, 90% CL, 8 TeV, 19.7 fb-1
Axial-vector operator
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV]


ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
Status: ICHEP 2014
Lint = 20.3 fb-1
Lint = 4.7 fb-1
Lint = 20 fb-1
mt̃1 [GeV]
mχ̃01 [GeV]


ATLAS Simulation Preliminary
ATL-PHYS-PUB-2014-010
0-lepton combined
Decay forbidden
mg̃ [GeV]
mχ̃01 [GeV]

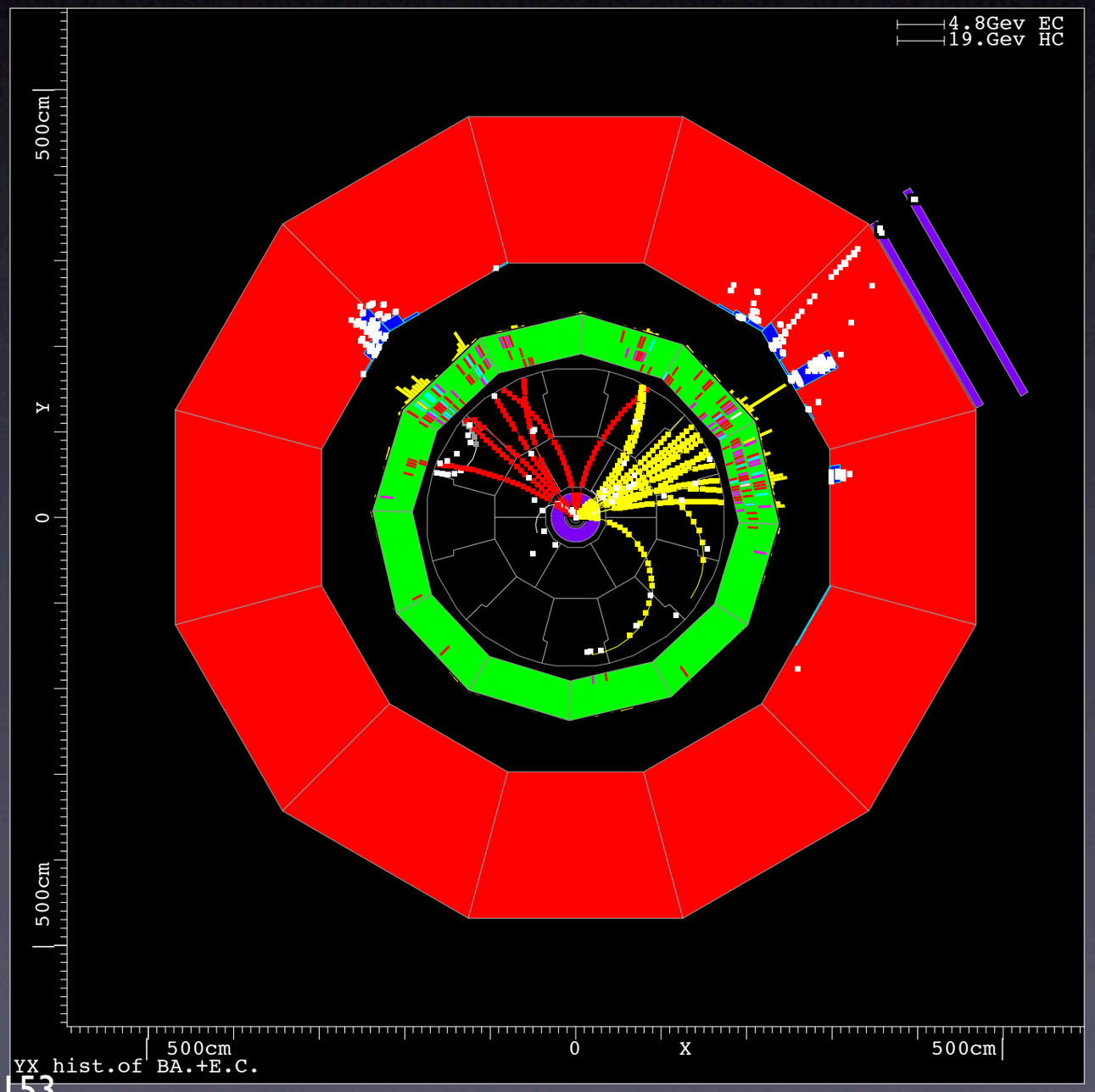
Producing Dark Matter in the laboratory

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector

⇒Dark Matter!?

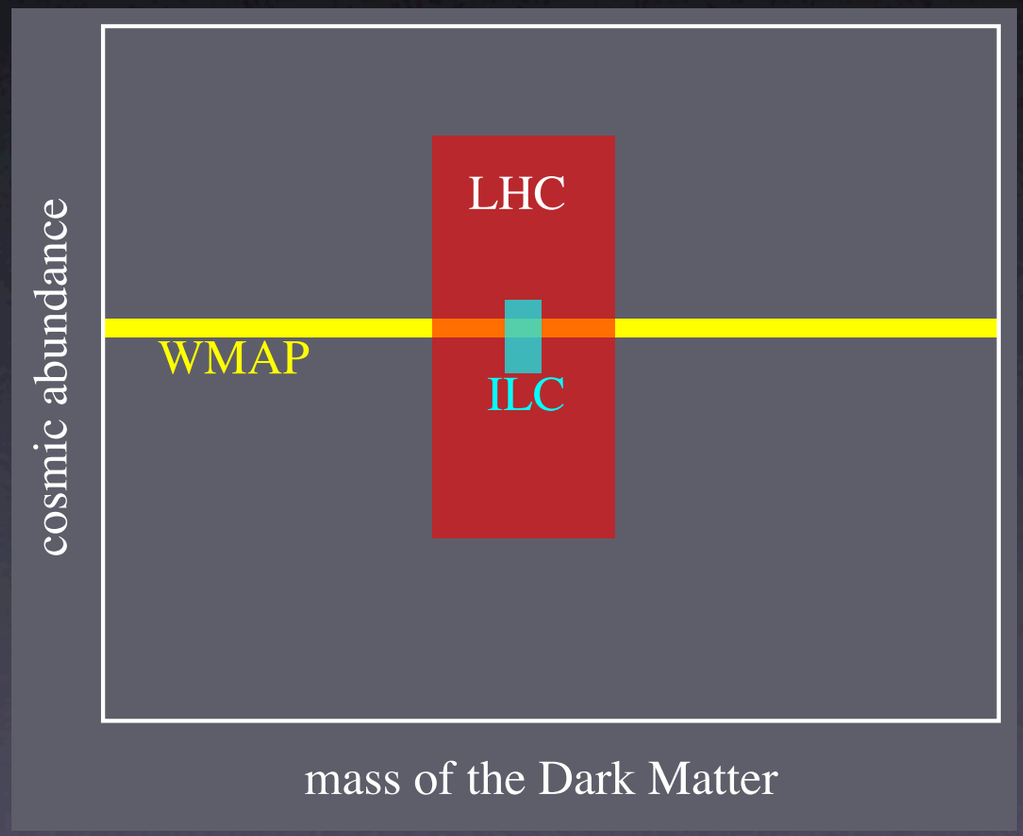


How do we know what Dark Matter *is*?

- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:

$\Rightarrow$ Will know *what Dark Matter is*

$\Rightarrow$ Will understand universe back to $t \sim 10^{-10}$ sec



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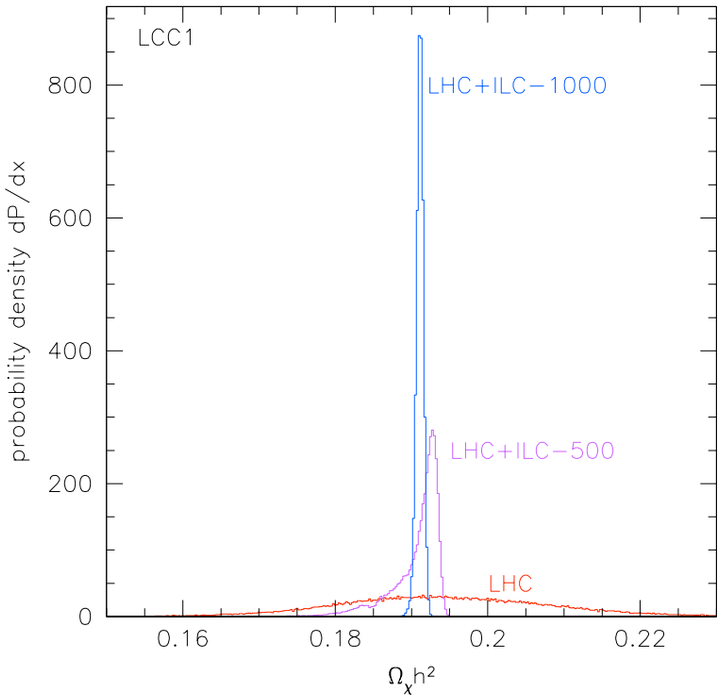
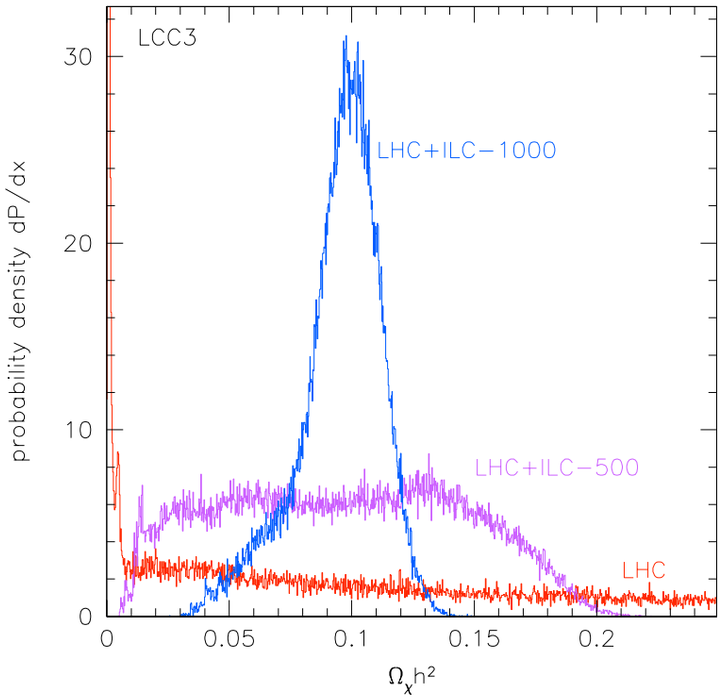
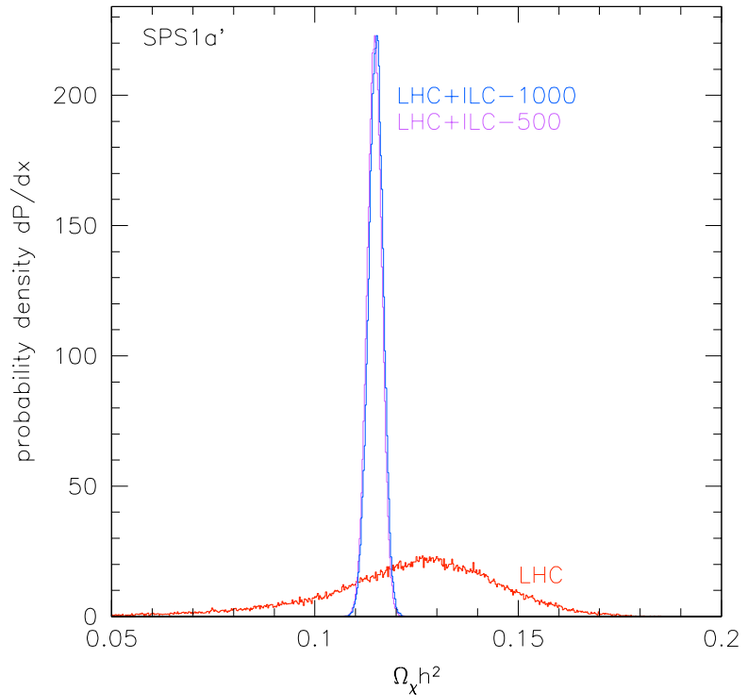
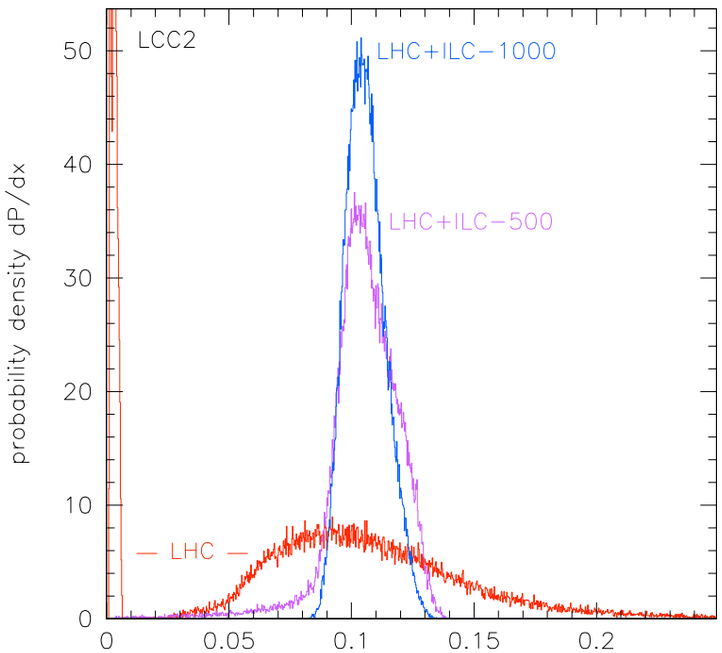
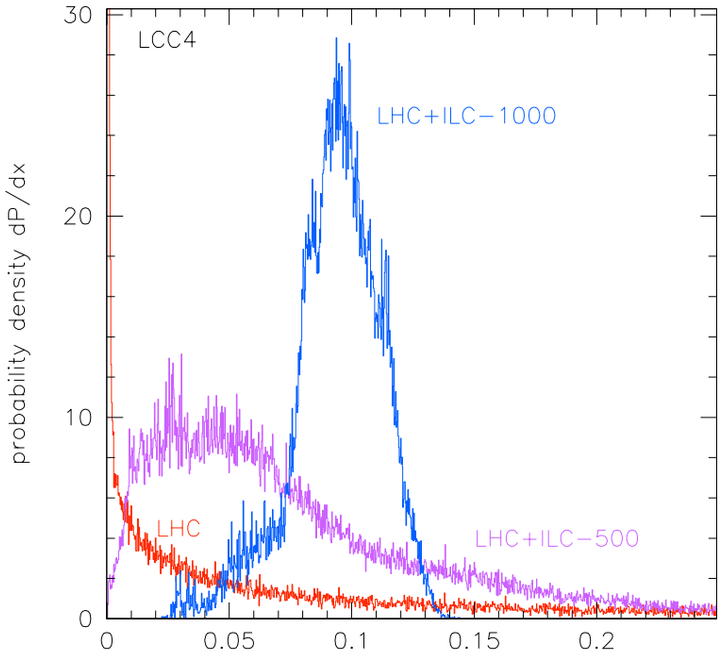
Omega from colliders







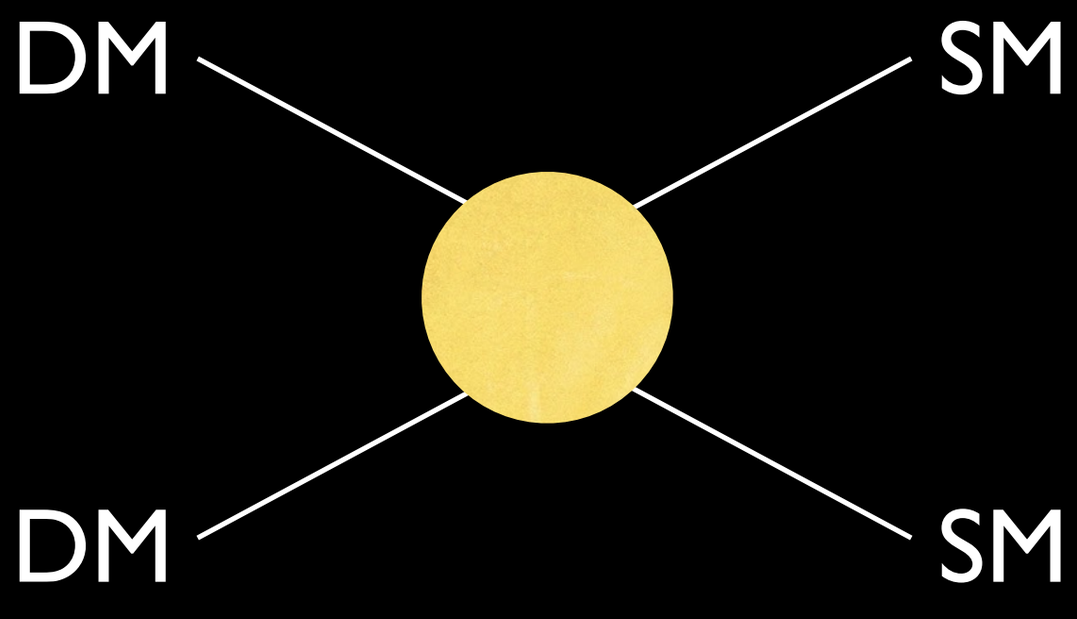




SUSY case study
Baltz, Battaglia, Peskin,
Wizansky hep-ph/0602187

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,\frac{\rm GeV}{m_{\rm DM}}$$

Miracles

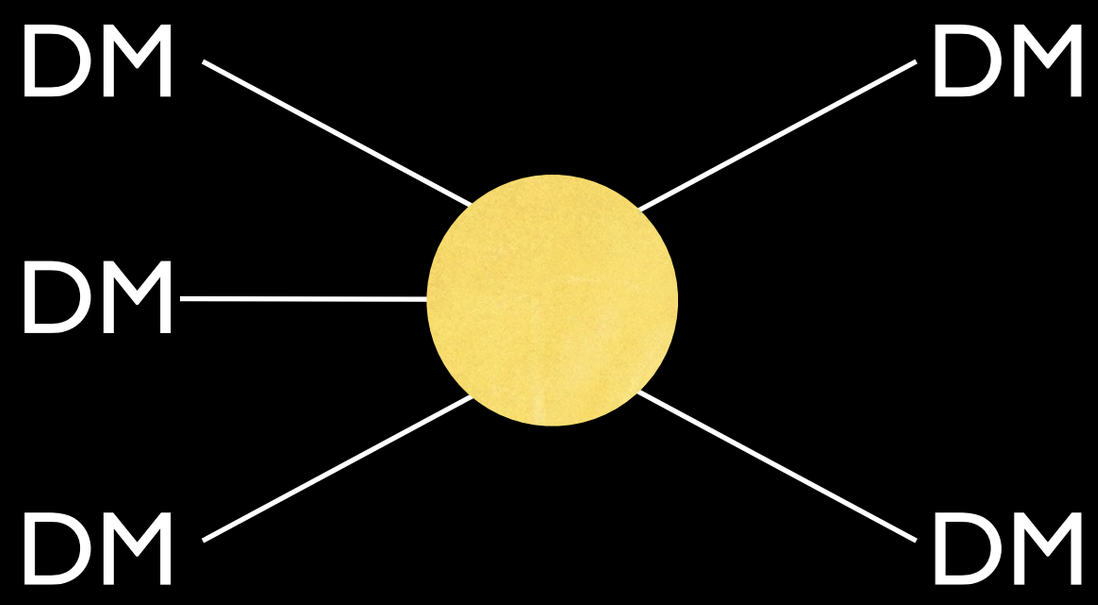


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300\ \text{GeV}$$

WIMP miracle!



$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

$$m \approx 300\text{MeV}$$

SIMP miracle!

3→2 LEE WEINBERG FREEZE-OUT

Back of the envelope calculation

$$\Gamma_{\rm ann} \simeq H|_{\rm freezeout}$$

$$\Gamma_{\rm ann} \simeq n_{\rm dm}^2 \langle \sigma v^2 \rangle_{3\to 2}$$

$$m_{\rm dm} n_{\rm dm} \sim m_p n_b$$

$$\langle \sigma v^2 \rangle_{3\to 2} \simeq \frac{\alpha^3}{m_{\rm dm}^5}$$

$$n_b \sim \eta_b s$$

$$\eta_b \simeq T_{\rm eq}/m_p \qquad s \simeq T^3$$

$$\Gamma_{\rm ann} \simeq \frac{T_{\rm eq}^2 \alpha^3}{x_F^4 \times m_{\rm dm}}$$

$$H \simeq \frac{T^2}{M_{\rm pl}}$$

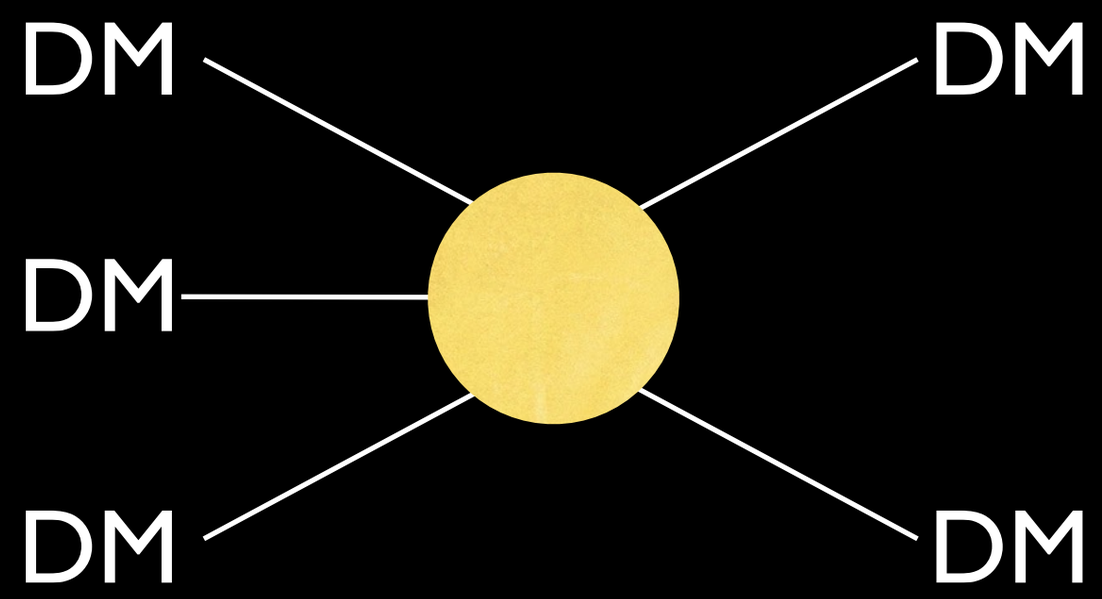
$$H \simeq \frac{m_{\rm dm}^2}{M_{\rm pl} x_F^2}$$

Eric Kuflik

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,{\rm GeV}\,\frac{}{m_{\rm DM}}$$

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle³
- DM = pions
- e.g. SU(4)/Sp(4) = S^5



+HM
arXiv:1411.3727

$$\mathcal{L}_{\rm chiral} = \frac{1}{16 f_\pi^2}{\rm Tr}\partial^\mu U^\dagger \partial_\mu U$$

$$\mathcal{L}_{\rm WZW} = \frac{8N_c}{15\pi^2 f_\pi^5}\epsilon_{abcde}\epsilon^{\mu\nu\rho\sigma}\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e + O(\pi^7)$$

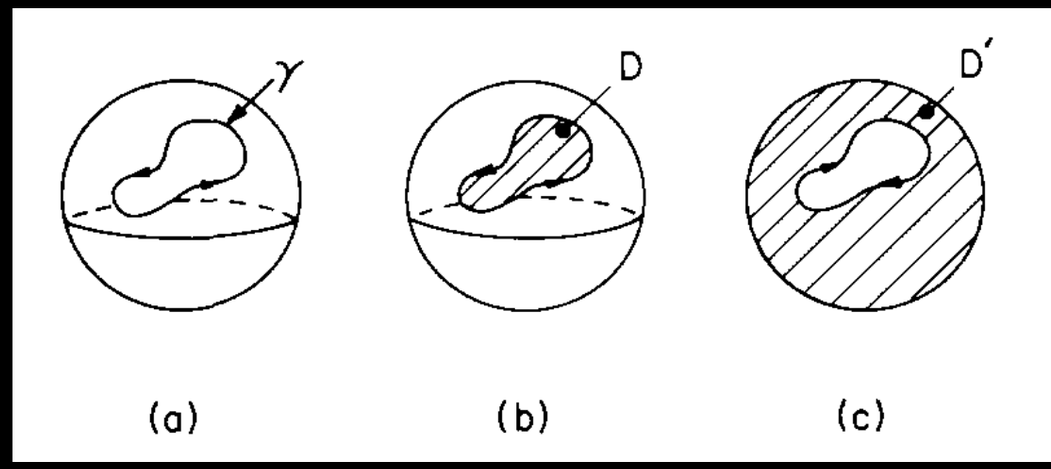
$$\pi_5(G/H) \neq 0$$

SIMPlest Miracle

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=S^5
- $\pi_5(S^5)=\mathbb{Z} \Rightarrow$ Wess-Zumino term
- $\mathcal{L}_{WZ}=\varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

Wess-Zumino term

- SU(N_c) gauge theory
  - $\pi_5(SU(N_f))=\mathbb{Z}$ ($N_f \geq 3$)
- Sp(N_c) gauge theory
  - $\pi_5(SU(2N_f)/Sp(N_f))=\mathbb{Z}$ ($N_f \geq 2$)
- SO(N_c) gauge theory
  - $\pi_5(SU(N_f)/SO(N_f))=\mathbb{Z}$ ($N_f \geq 3$)



Witten

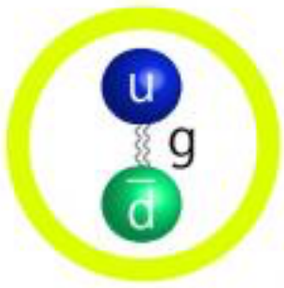
LAGRANGIANS

Quark theory

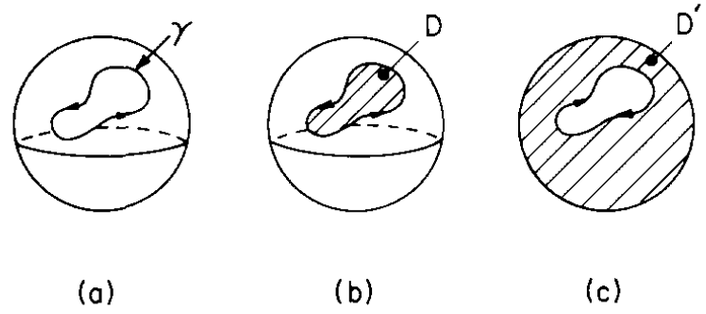
$$\mathcal{L}_{\rm quark} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \bar{q}_i i \not{D} q_i \; -\frac{1}{2} m_Q \; J^{ij} q_i q_j + h.c.$$

Sigma theory

$$\mathcal{L}_{\rm Sigma} = \frac{f_\pi^2}{16}{\rm Tr}\partial_\mu \Sigma \; \partial^\mu \Sigma^\dagger - \frac{1}{2} m_Q \mu^3 {\rm Tr} J\Sigma + h.c. - \frac{iN_c}{240\pi^2}\int {\rm Tr}(\Sigma^\dagger d\Sigma)^5$$

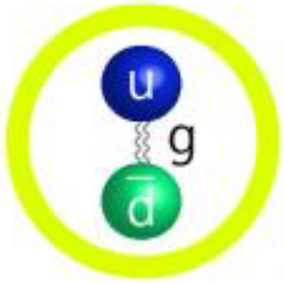


Pion theory

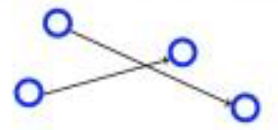


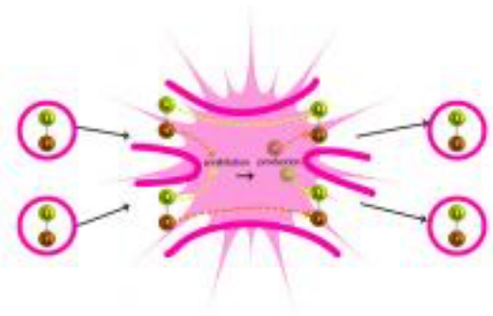
$$\mathcal{L}_{\rm pion} = \frac{1}{4}{\rm Tr}\partial_\mu \pi \partial^\mu \pi - \frac{m_\pi^2}{4}{\rm Tr}\pi^2 + \frac{m_\pi^2}{12 f_\pi^2}{\rm Tr}\pi^4 - \frac{1}{6 f_\pi^2}{\rm Tr}\left(\pi^2 \partial^\mu \pi \partial_\mu \pi - \pi \partial^\mu \pi \pi \partial_\mu \pi\right)$$

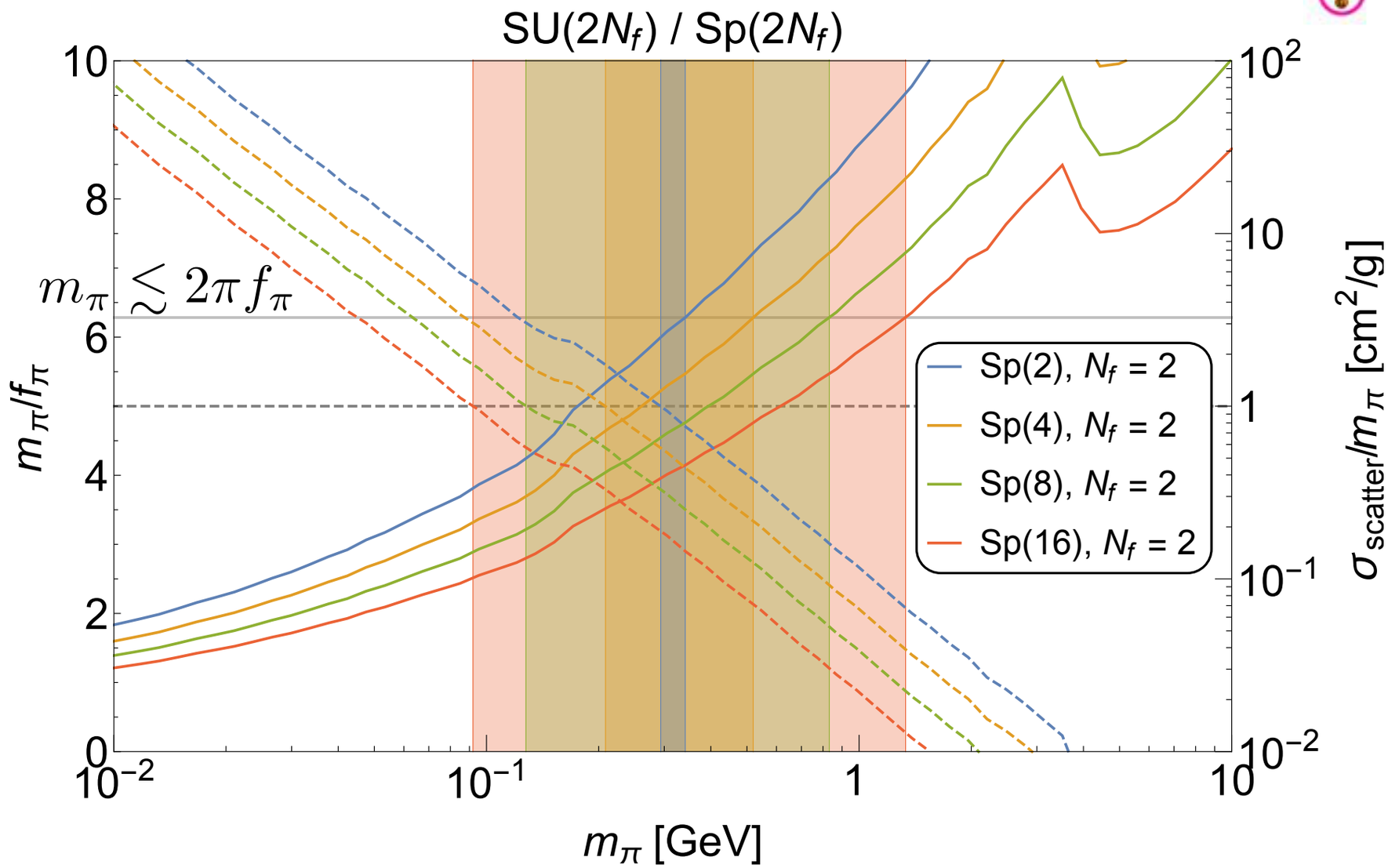
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$



The Results





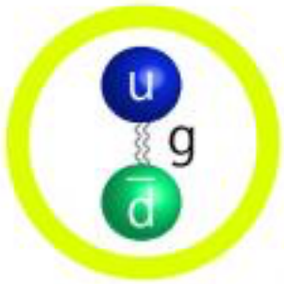


Solid curves: solution to Boltzmann eq.

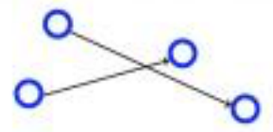
Dashed curves: along that solution

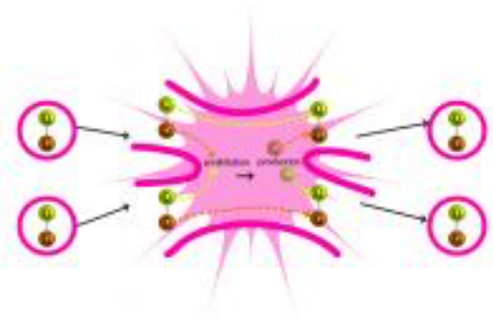
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

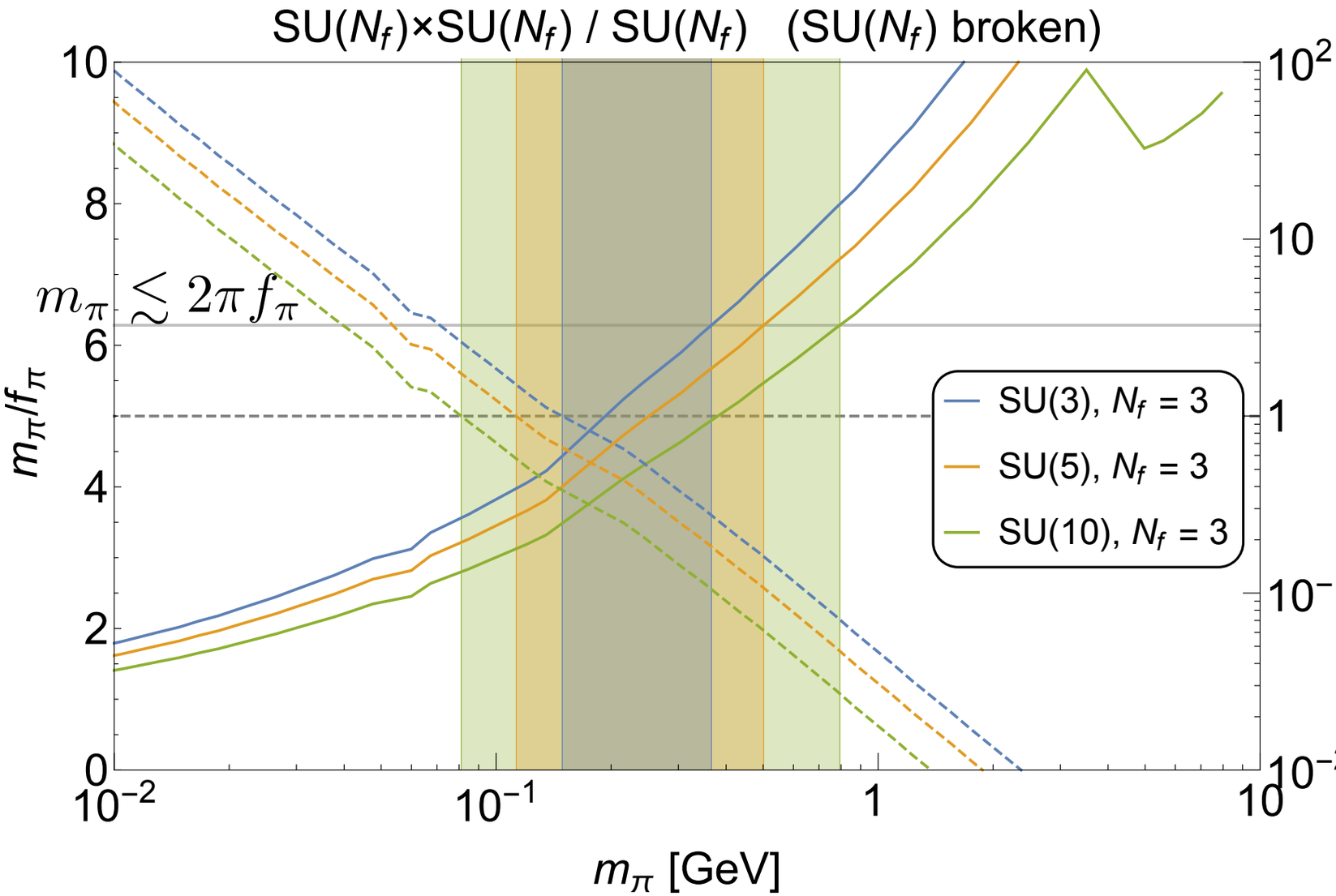
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$



The Results







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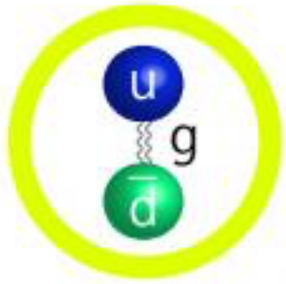
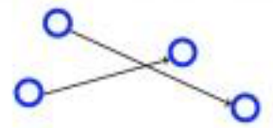
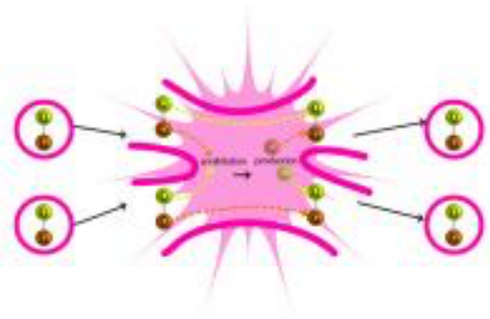
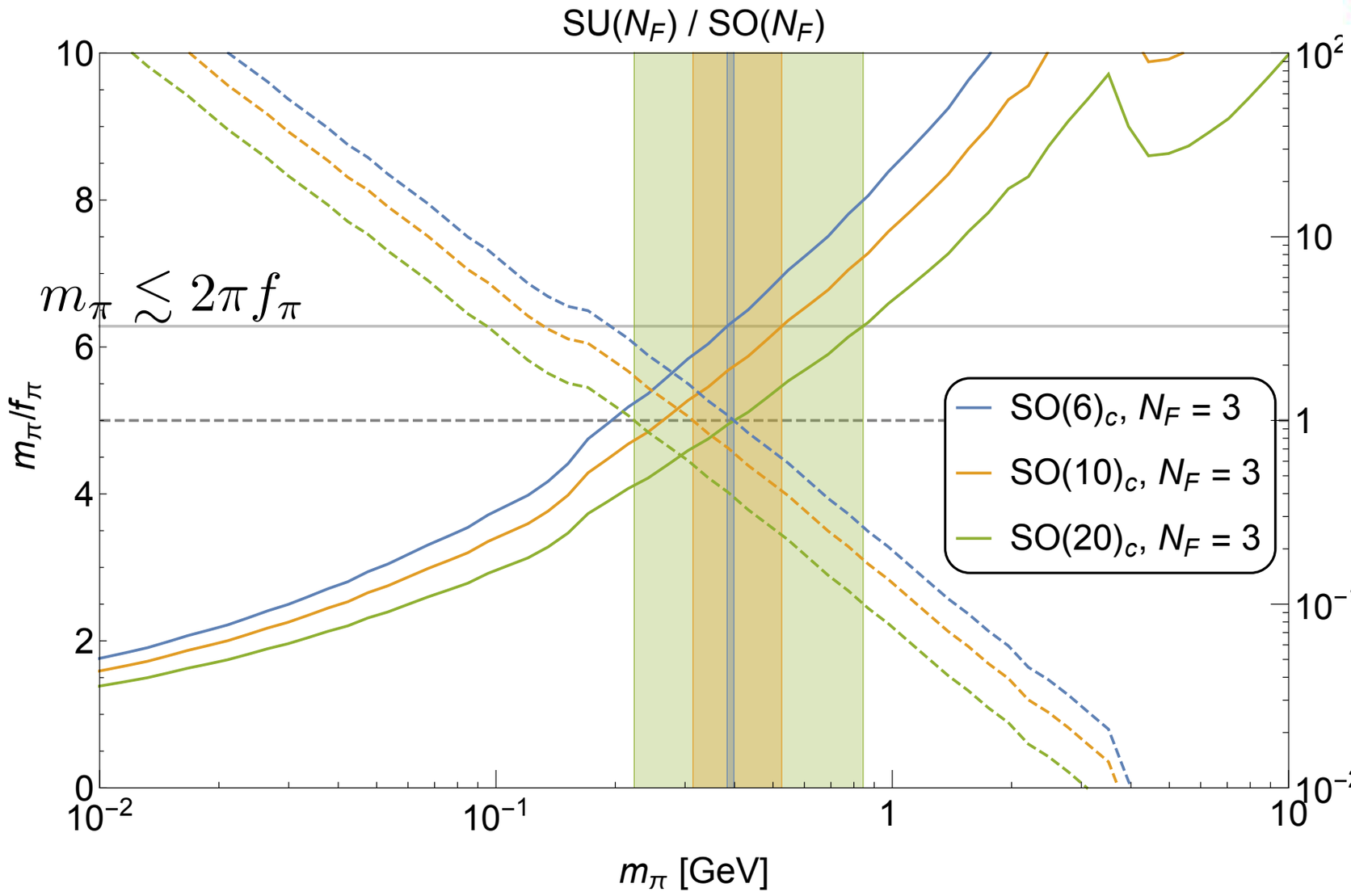


The Results







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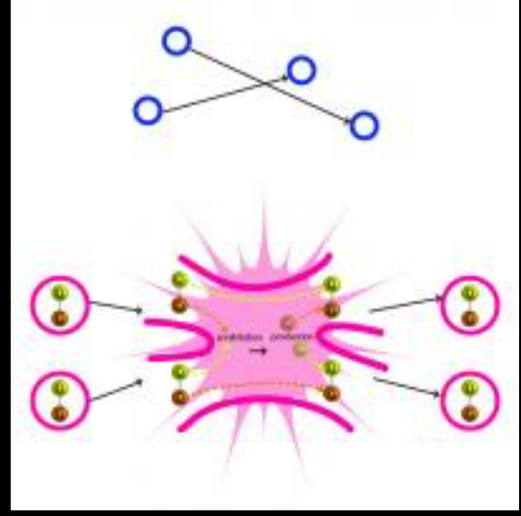
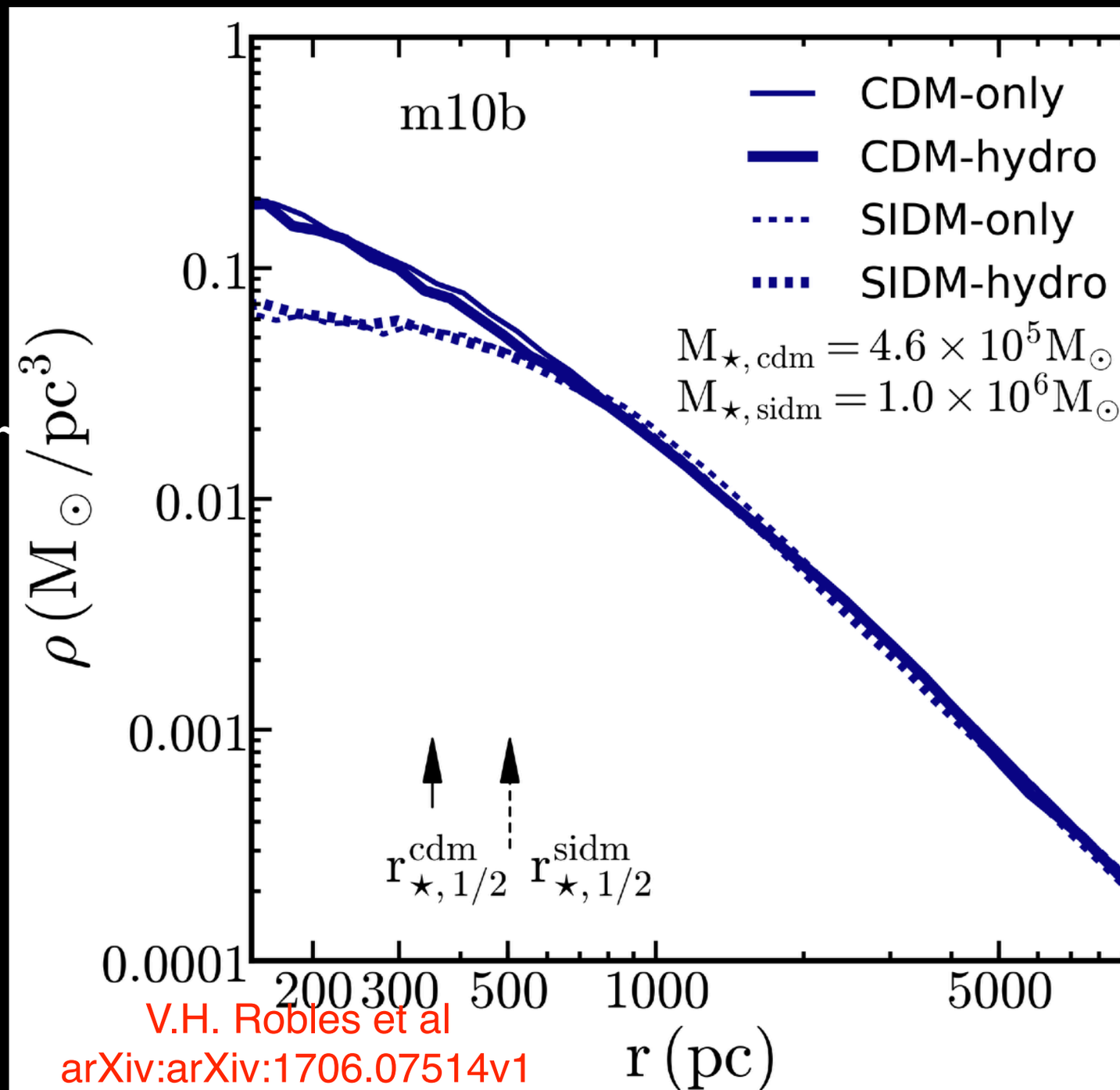
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

self interaction



- $\sigma/m \sim cm^2/g$
  $\sim 10^{-24} cm^2$ / 300MeV
- flattens the cusps in NFW profile
- suppresses substructur
- actually desirable for dwarf galaxies?

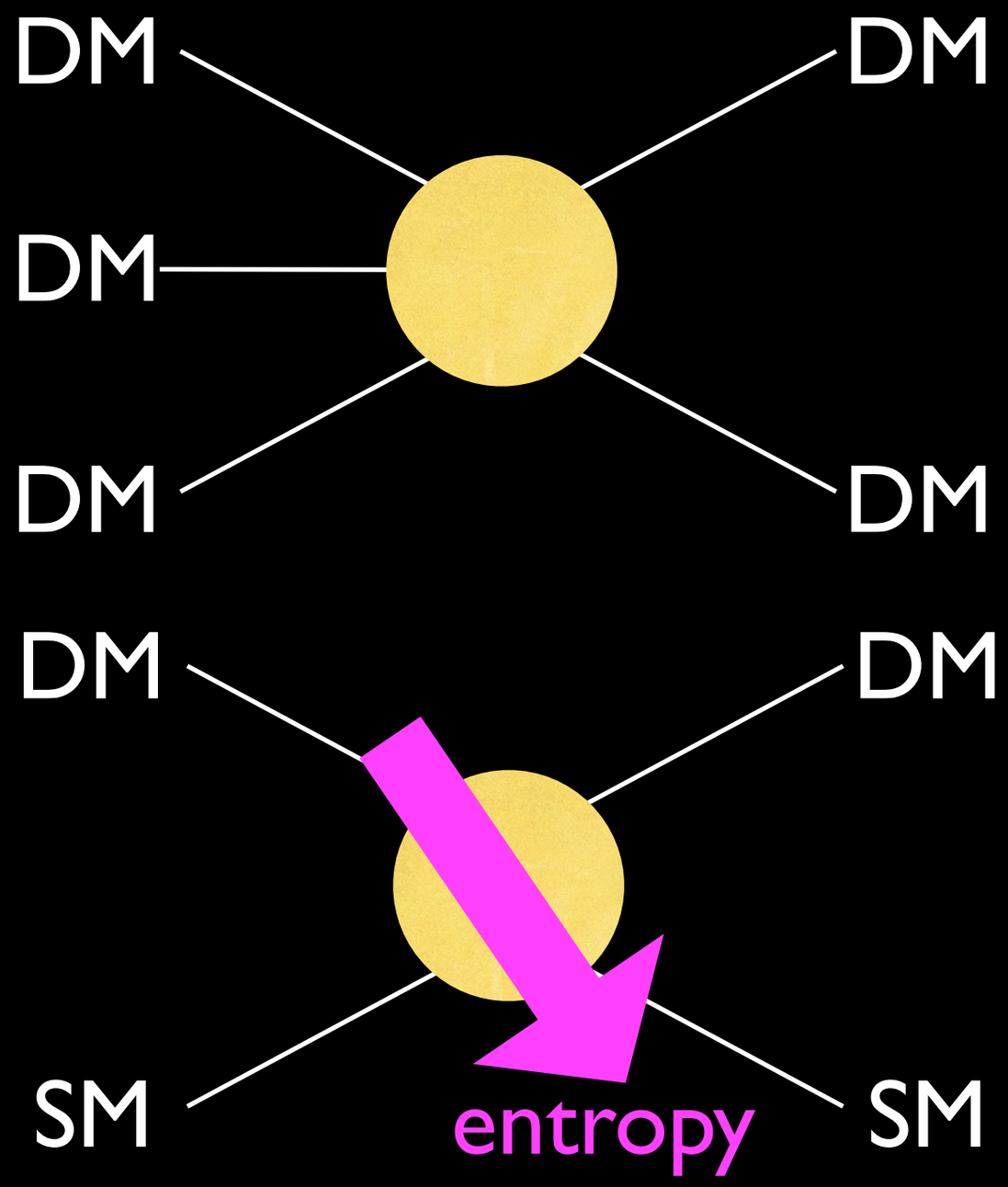
SIDM
Spergel & Steinhardt (2000)
now complete theory



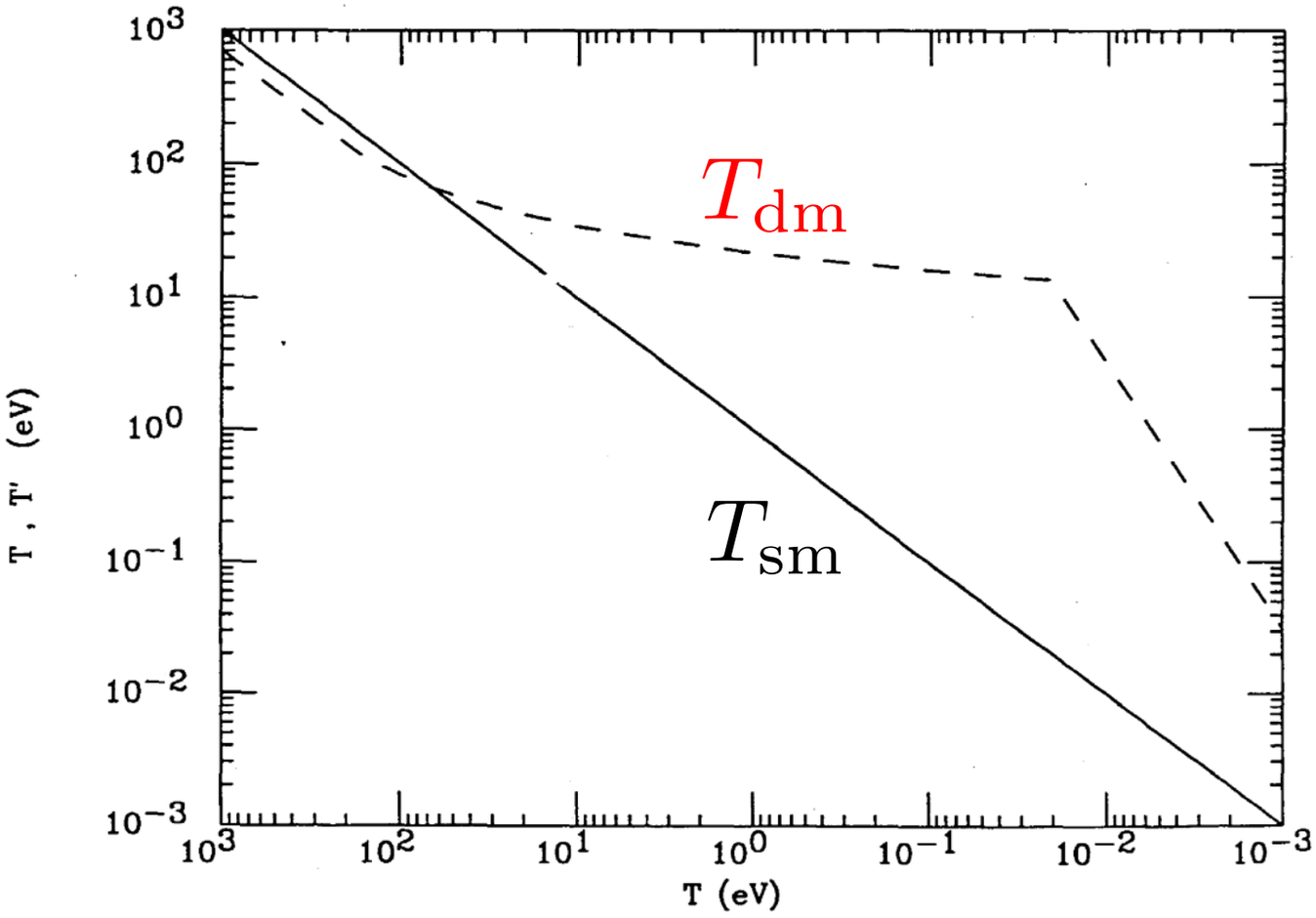
V.H. Robles et al
arXiv:arXiv:1706.07514v1

communication

- 3 to 2 annihilation
- excess entropy *must* be transferred to $e^{\pm}$, γ
- need communication at some level
- leads to experimental signal



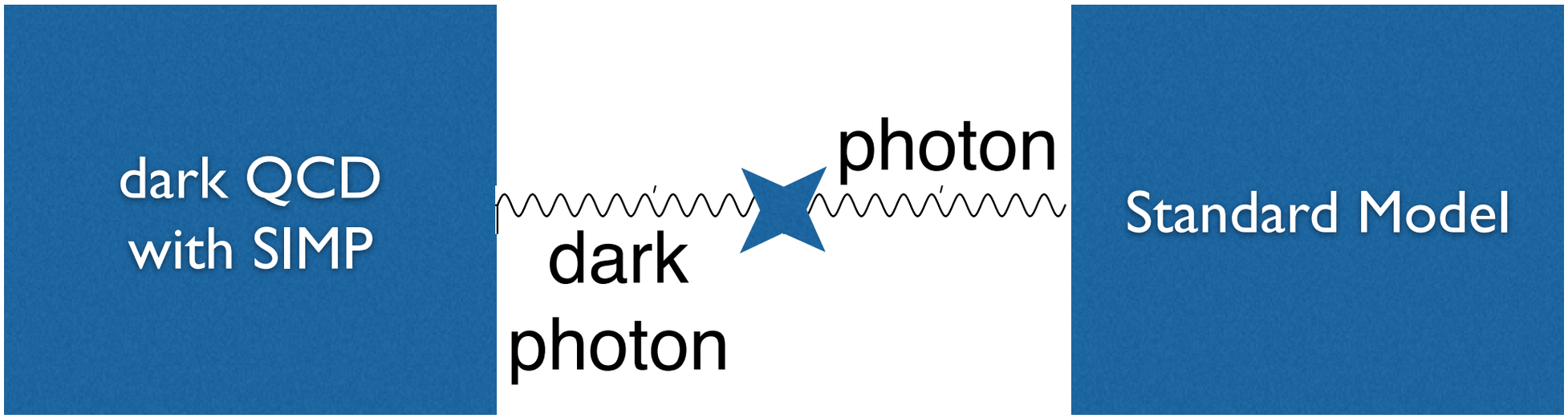
if totally decoupled



Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

- 3→2 annihilations without heat exchange is excluded by structure formation, [de Laix, Scherrer and Schaefer, Astrophys. J. 452, 495 (1995)]

vector portal



$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

Kinetically mixed U(1)

- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- gauge U(1)=SO(2) $\subset$ SO(2) ×SO(3) $\subset$ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation

$$SU(4)/Sp(4) = S^5$$

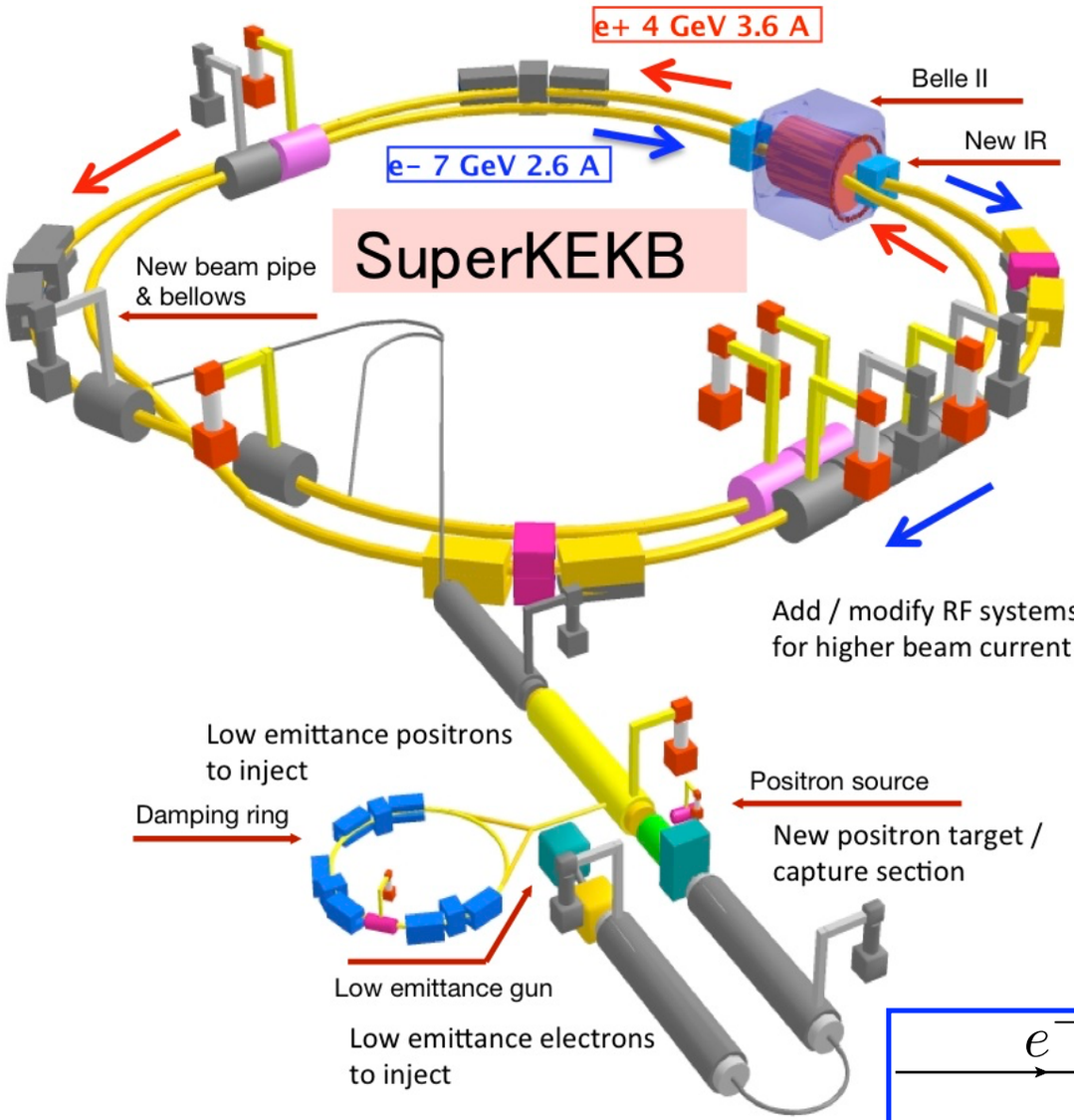
$$(q^+, q^+, q^-, q^-)$$

$$(\pi^{++}, \pi^{--}, \pi^0_x, \pi^0_y, \pi^0_z)$$

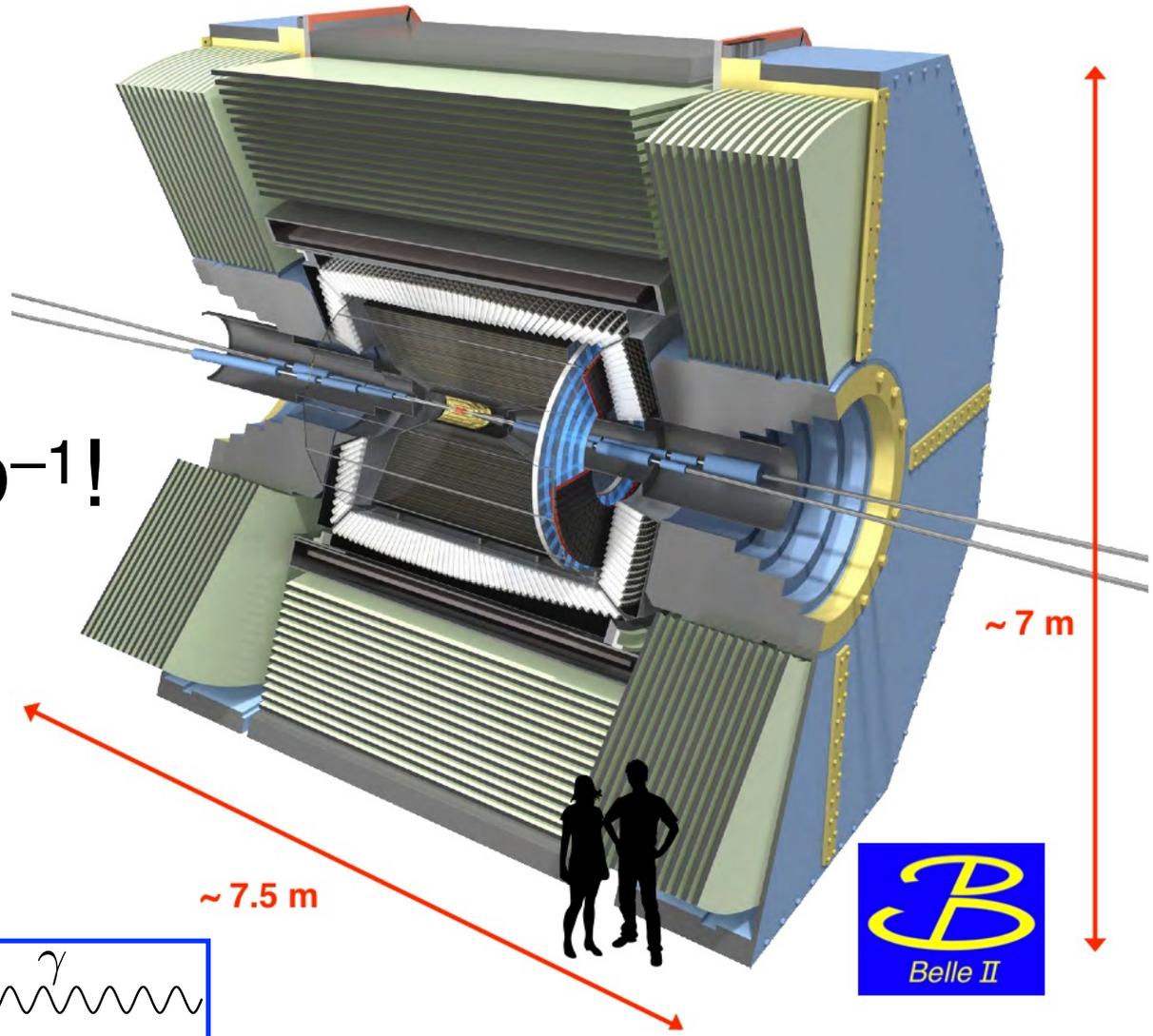
$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

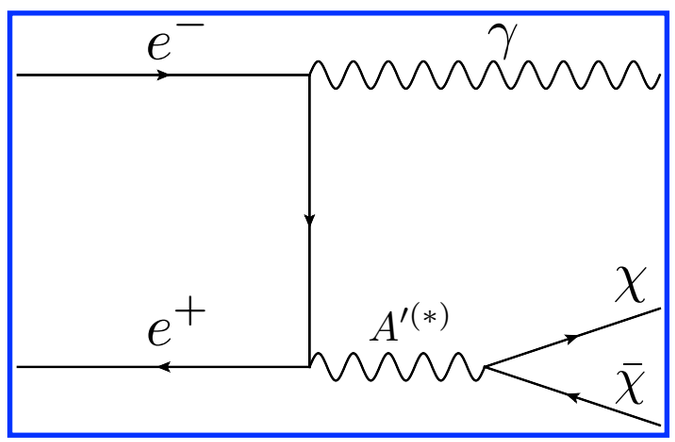
DELPHI
monojet
$h \to ZV$
CMS7, DY
contact
LHC8, DY
$\pi\pi \to \mathrm{SM}$
EWPO
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
10^{1}
10^{2}
10^{3}

Super KEK B & Belle II



50 ab^{-1}!





$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$

Belle II projection

$\sqrt{s} = 10$ GeV, 50 ab^{-1}

$\sigma_{E_\gamma}/E_\gamma = 1\%$

$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$

γ_d

Dark sector

Binned

$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$

$\nu\nu\gamma$

Events/100 MeV

10^5

10^4

10^3

10^2

2.0 2.5 3.0 3.5 4.0 4.5 5.0

E_γ [GeV]

BES III projection

$\sqrt{s} = 4$ GeV, 100 fb^{-1}

$\sigma_{E_\gamma}/E_\gamma = 2\%$

$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$

Dark sector

Binned

$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$

$\nu\nu\gamma$

Events/40 MeV

E_γ [GeV]

Belle II projection

$\sqrt{s} = 10$ GeV, 50 ab^{-1}

$\sigma_{E_\gamma}/E_\gamma = 1\%$

$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$

$\psi_d(2S)$

J/ψ_d

ϕ_d

Mirror QCD

Binned

$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$

$\nu\nu\gamma$

Events/50 MeV

E_γ [GeV]

10^5

10^4

10^3

10^2

10

1

4.0

4.2

4.4

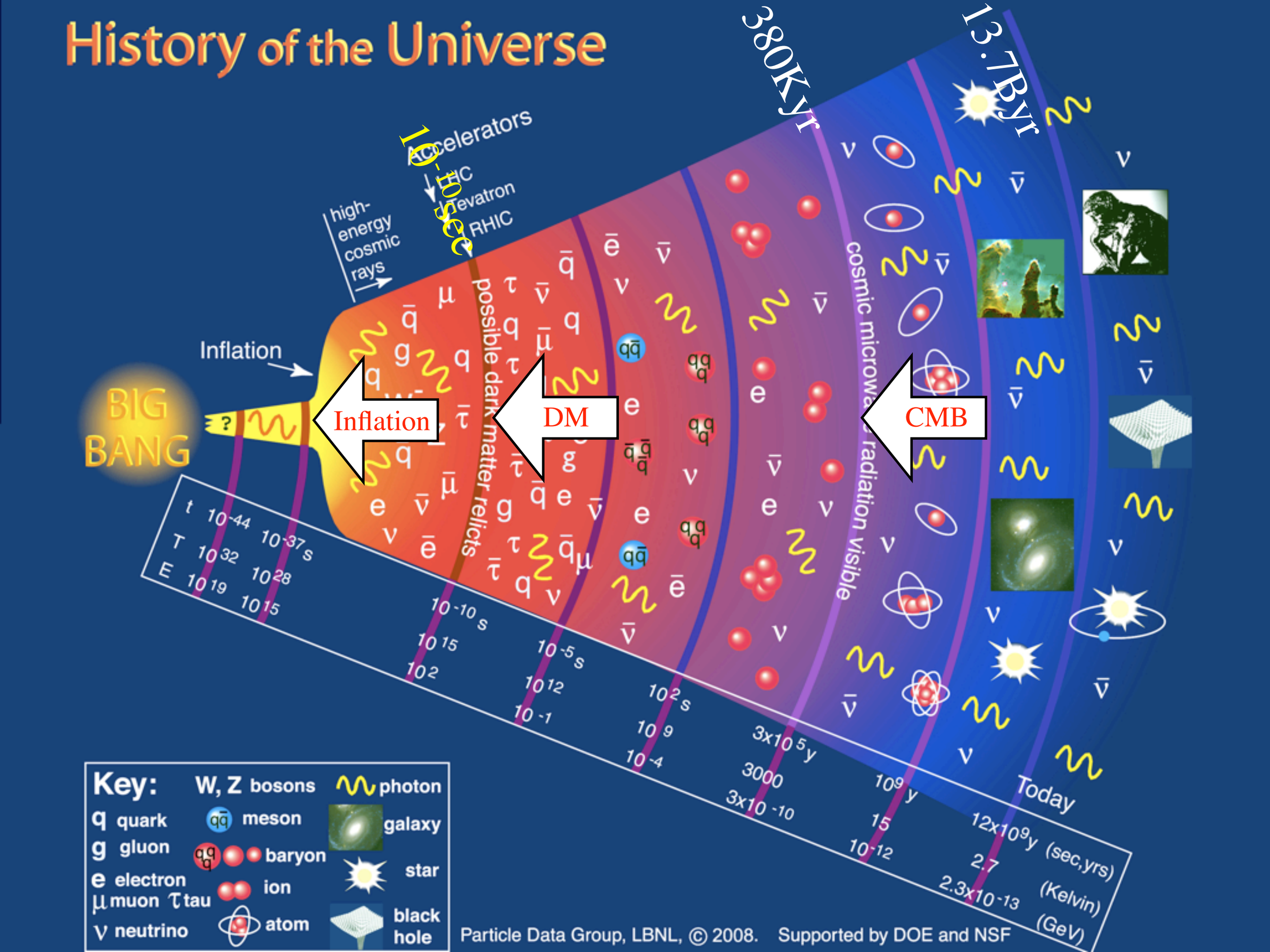
4.6

4.8

5.0

ILC (contact)
(LHC14)
(LHC14)
(100TeV)
DY@pp
EWPO (ILC)
APEX
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
monophoton
(ILC)
Belle−II (vis)
Belle−II (inv)
SHiP
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
10^{1}
10^{2}
10^{3}

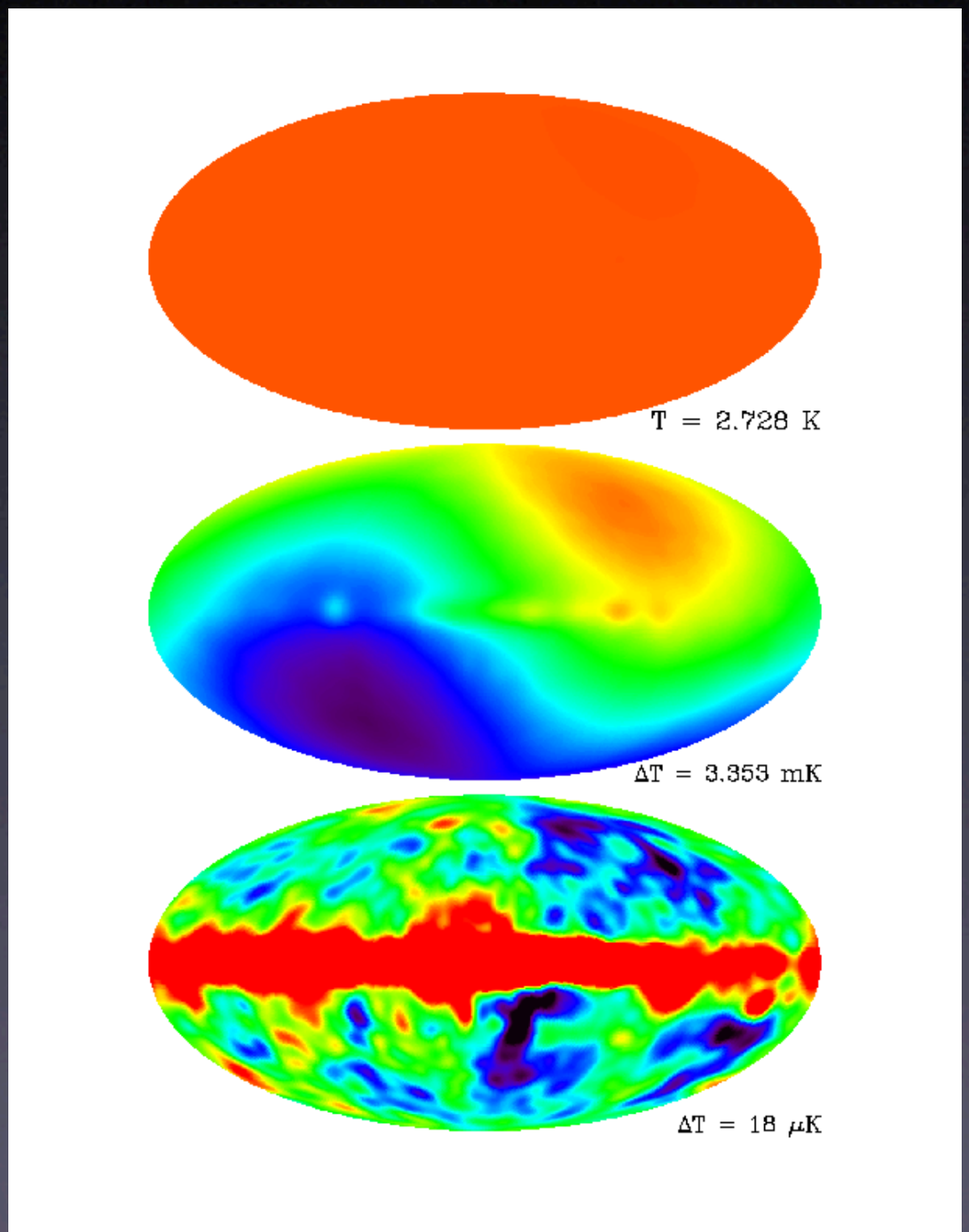
History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Inflation

Why do they all look the same?



- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication

History of the Universe

BIG BANG

Inflation

?

high-energy cosmic rays

Accelerators
LHC
Tevatron
RHIC

10-10 sec

1min

400Kyr

13.7Byr

possible dark matter relicts

cosmic microwave radiation visible

Today

t 10-44 10-37 s
T 1032 1028
E 1019 1015

10-10 s
1015
102

10-5 s
1012
10-1

102 s
109
10-4

3x105 y
3000
3x10-10

109 y
15
10-12

12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)

Key:

q quark
g gluon
e electron
μ muon τ tau
ν neutrino

W, Z bosons
qq̄ meson
qqq baryon
ion
atom

photon
galaxy
star
black hole

 Supported by DOE and NSF

inflaton

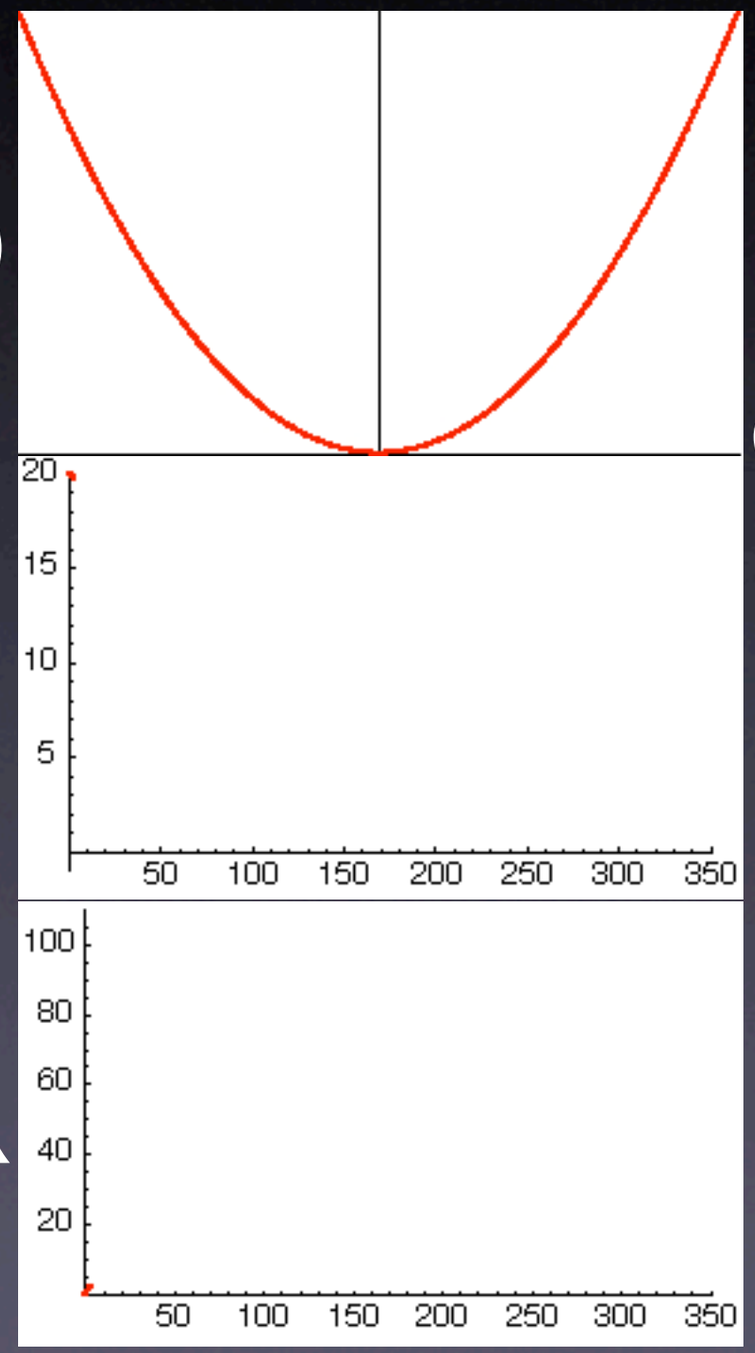
- scalar field with rather flat potential (compared to the Planck scale), $\lambda \approx 10^{-11}$
- the equation of motion has a "friction term"

$$\ddot{\phi} + 3H\dot{\phi} = V'(\phi)$$

- slow-roll solution with more or less constant H

$$|\ddot{\phi}| \ll |\dot{\phi}| = V'(\phi) \quad H^2 = \frac{8\pi}{3}\frac{V}{M_{Pl}^2}$$

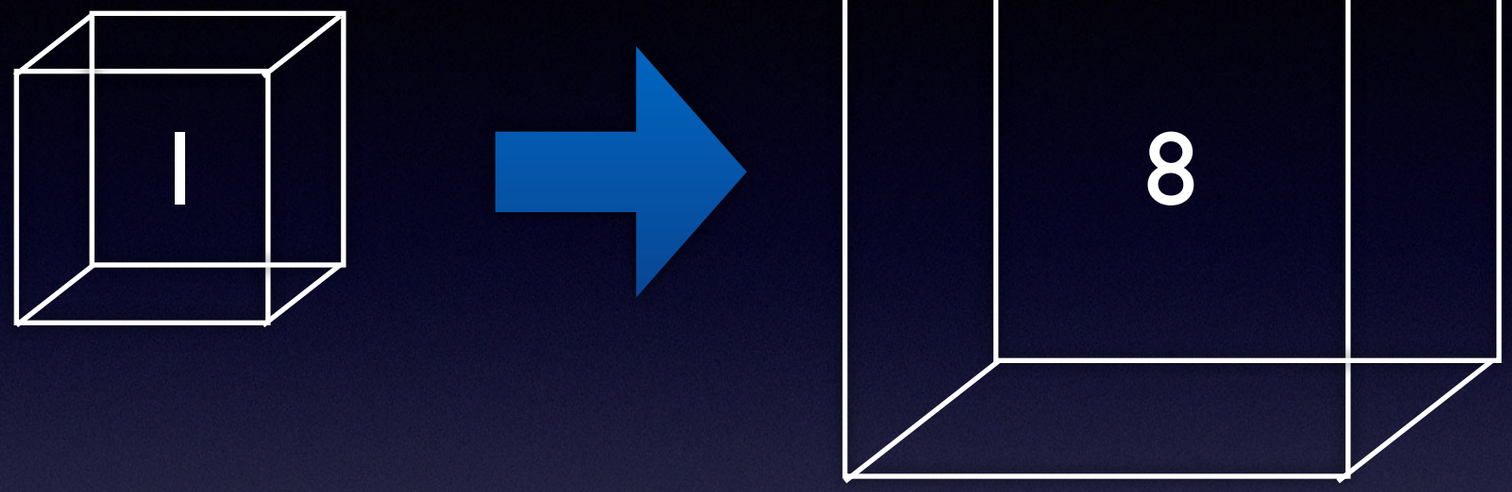
- Universe expands exponentially $R(t) \propto e^{Ht}$
- need e-*folding* $N=Ht > 60$ to solve the problem



HM, Suzuki, Yanagida, Yokoyama

Ultimate Free Lunch!

vacuum energy 74%



$\rho \propto R^0$

total energy keeps growing like volume $R(t)^3 \propto e^{3Ht}$

near sighted

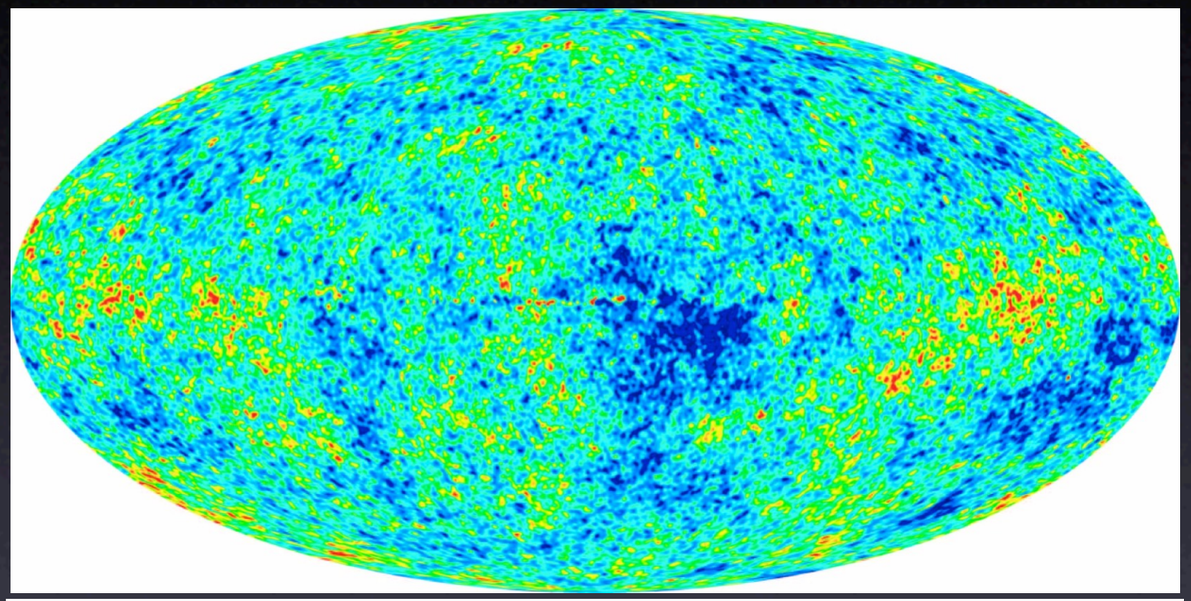
- What you are seeing one moment is *gone* by inflation the next moment
  - feel very near-sighted
  - "horizon" $\approx H_I^{-1}$
  - uncertainty principle: quatum fluctuation $\delta\varphi \approx H_I / 2\pi$

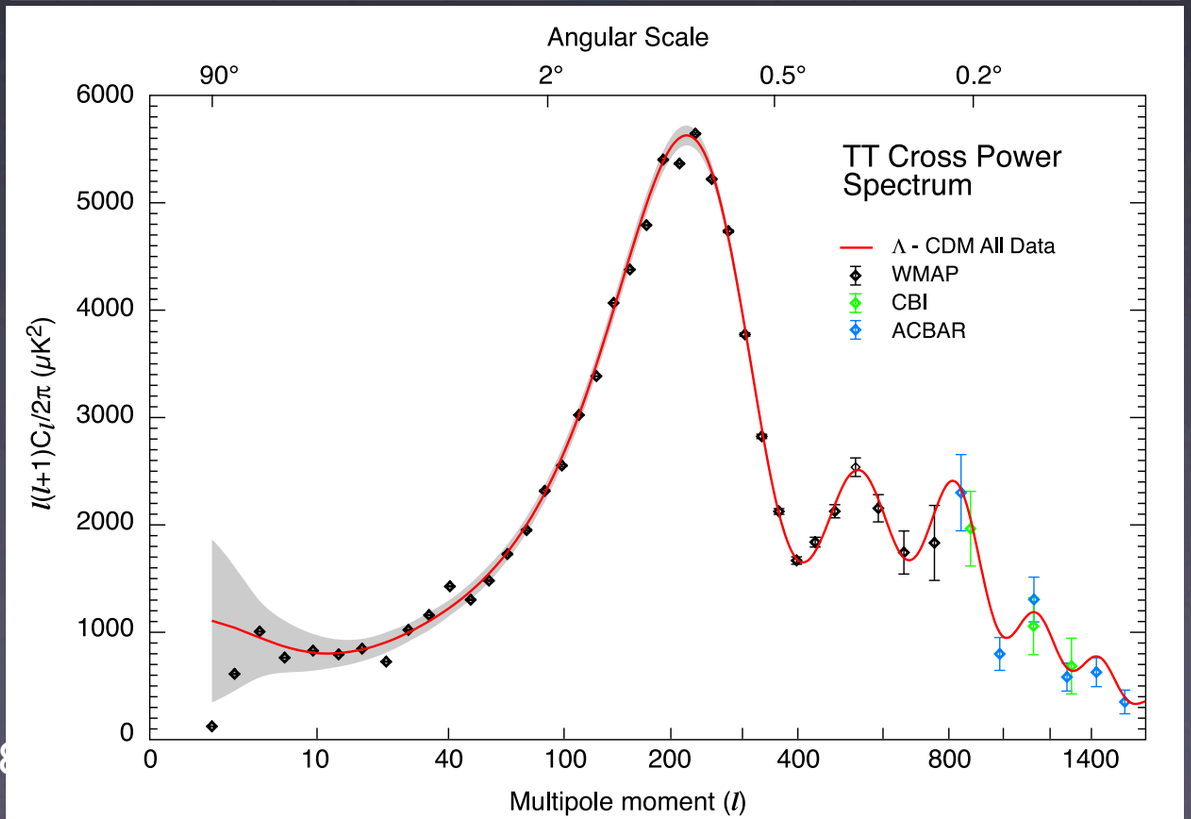
$$\zeta = \frac{\delta\rho}{\rho + p} = \frac{V'\delta\varphi}{\dot{\phi}^2} = \frac{V'}{\dot{\phi}^2}\frac{H}{2\pi}$$

  - nearly scale-invariant density fluctuation

Seeds for structure

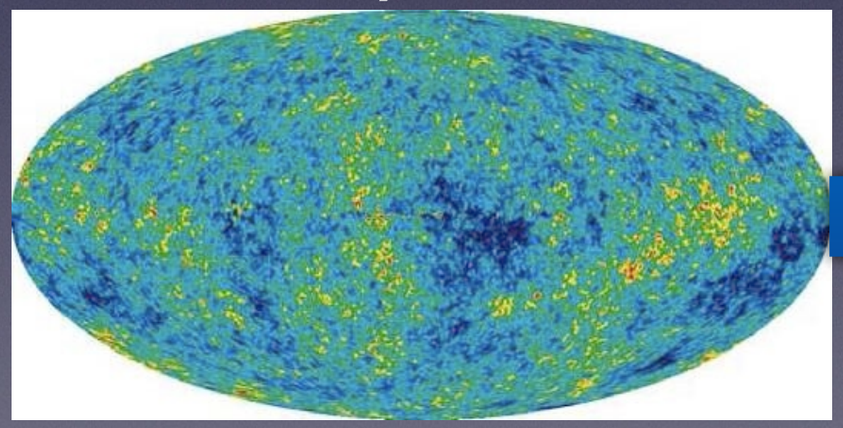
- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Observed structure originates from quantum fluctuation of inflaton
- Large-Scale Structure, CMB E-mode polarization consistent with this picture

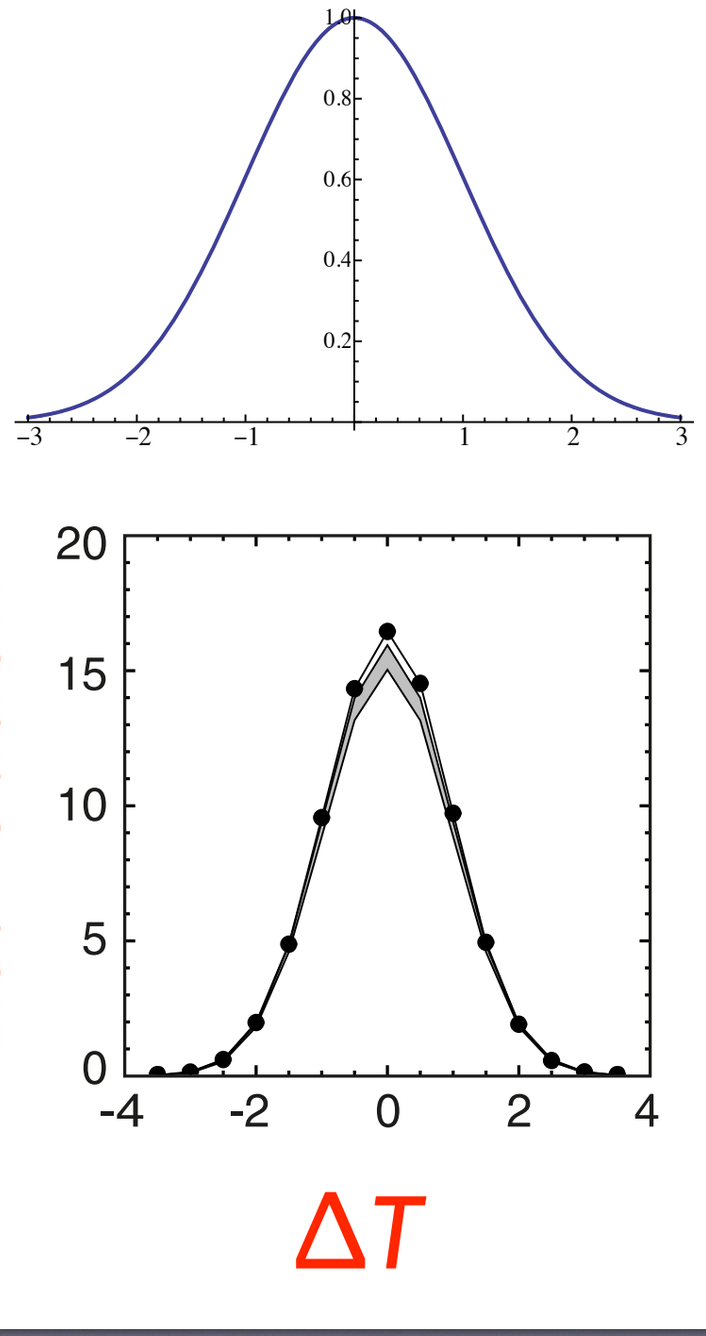




Getting stronger

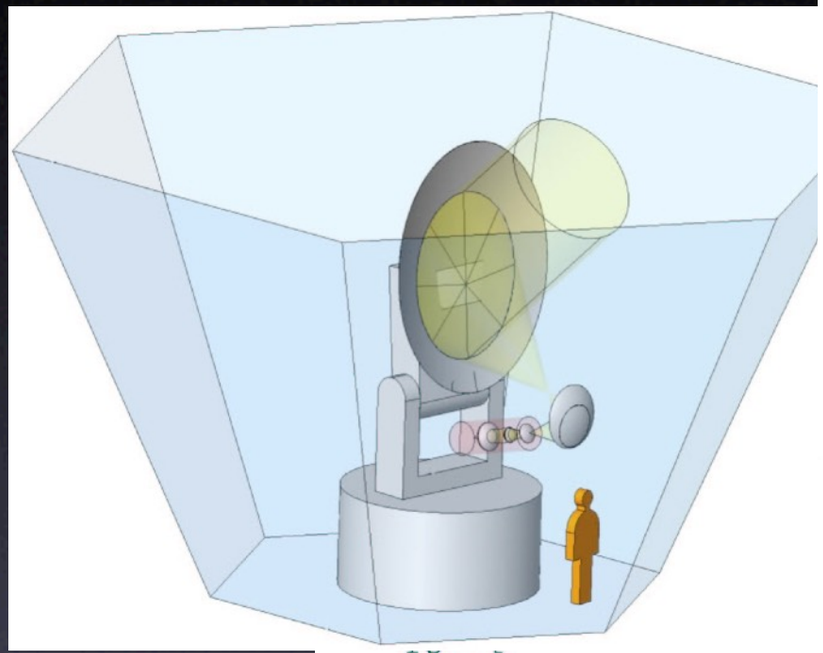
- If simple quantum fluctuation, it must be distributed as Gaussian
- Indeed!
- further tests of non-Gaussianity at Planck

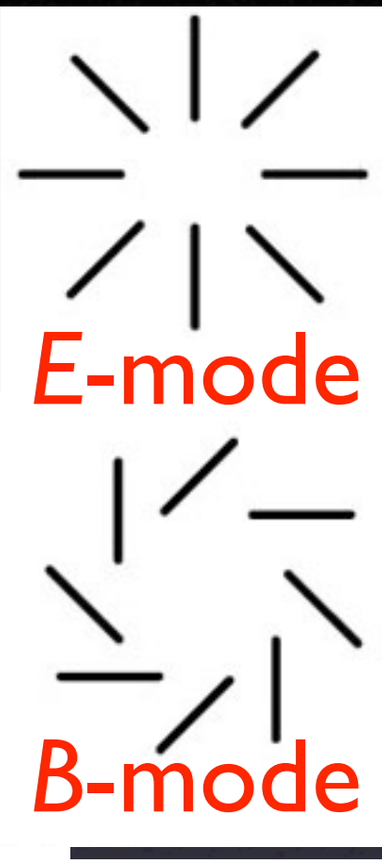


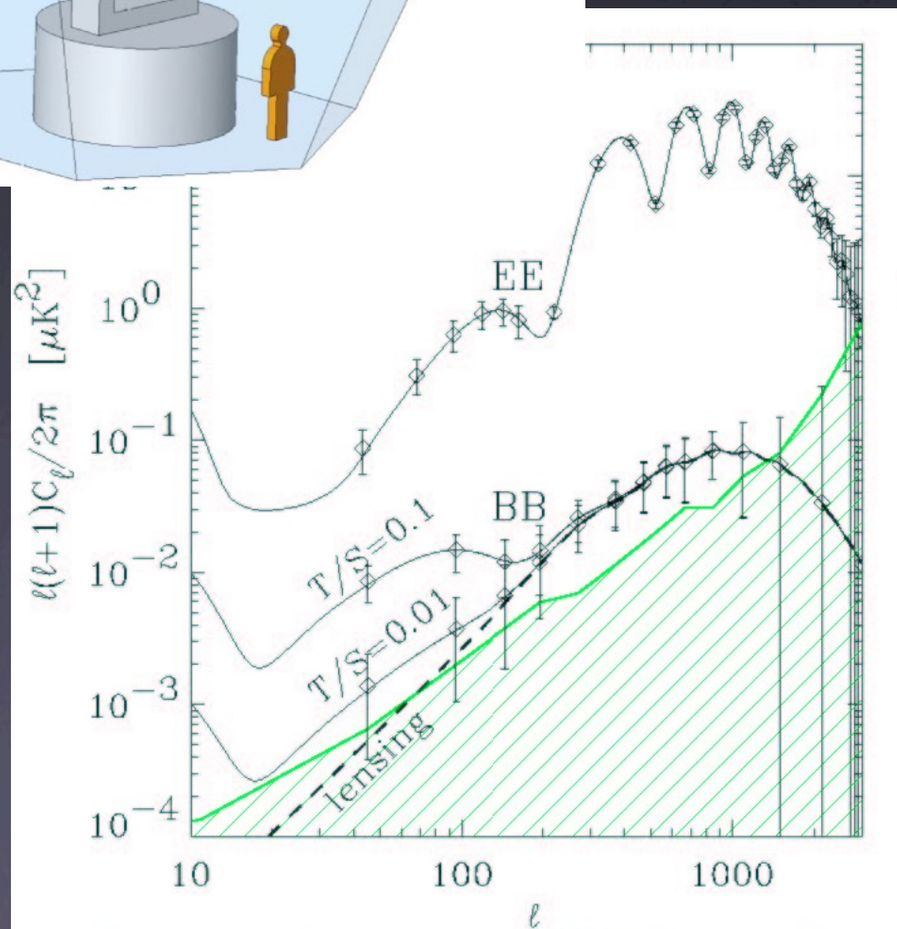


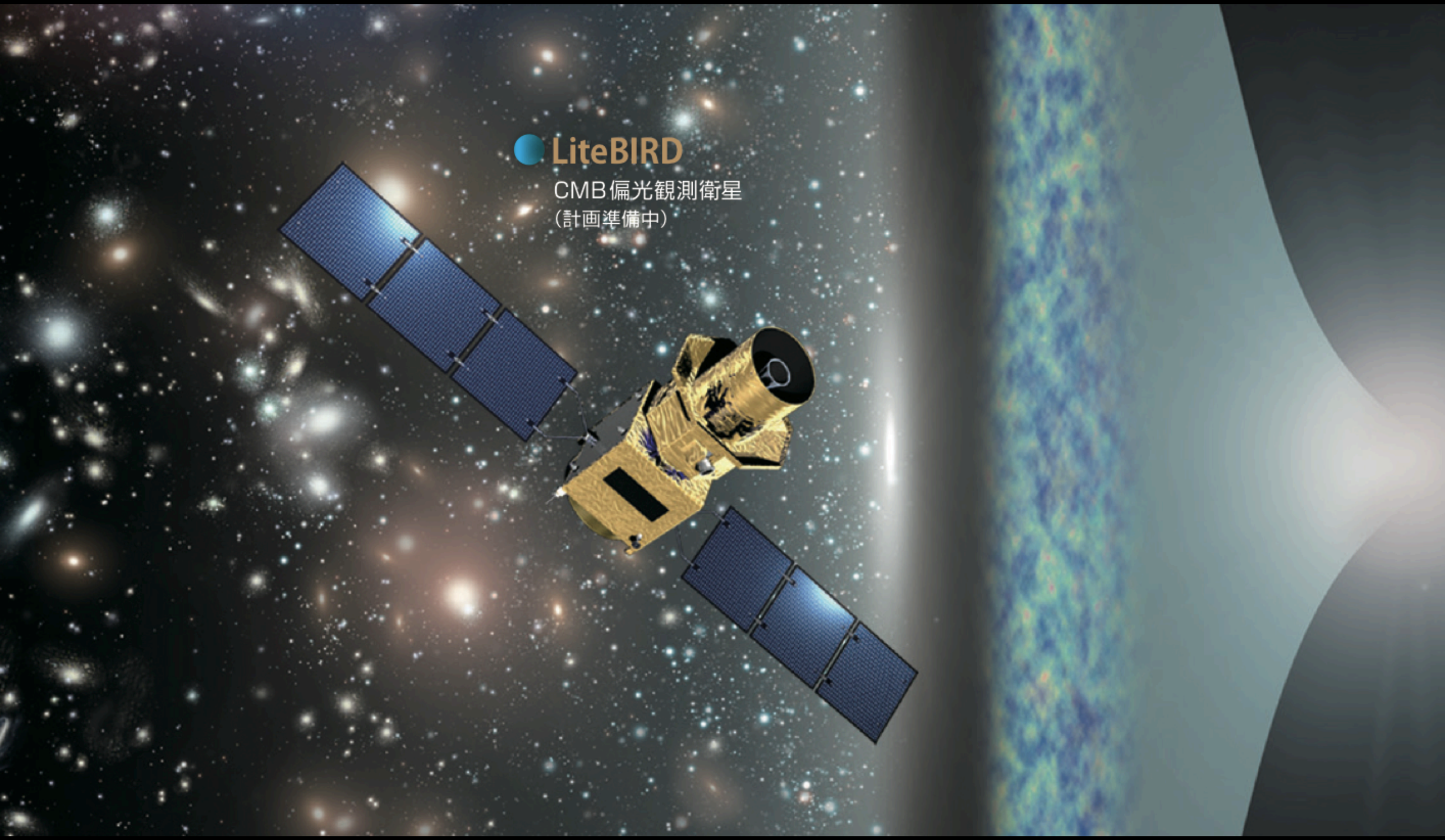
How do we know it really happened?

- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale
  ⇒ e.g., Simons Observatory, CMB S-4, LiteBIRD satellite








LiteBIRD
CMB偏光観測衛星
(計画準備中)

DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BKP
SPTpol
POLARBEAR

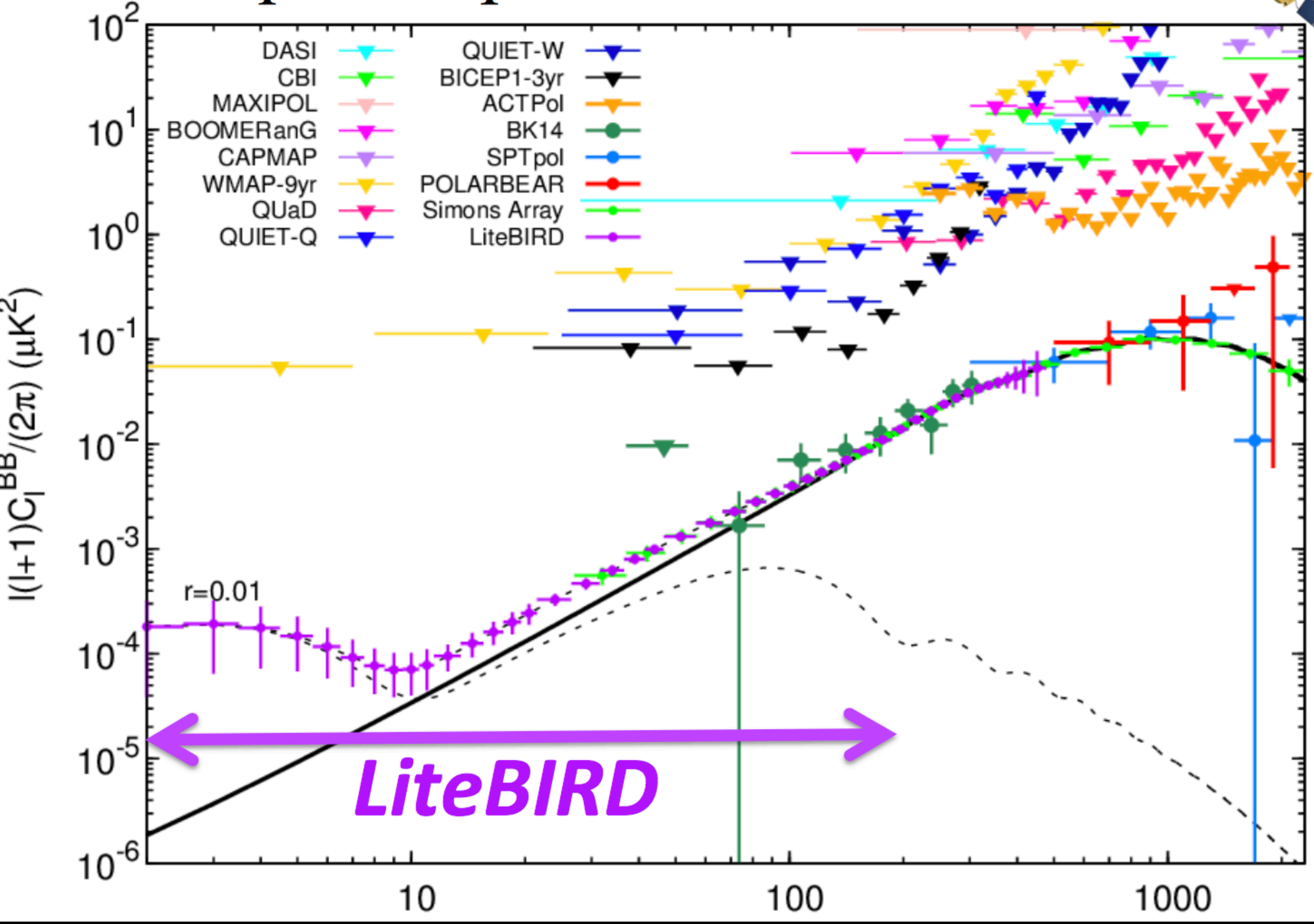
Lensing B-mode

Primordial B-mode
(r=0.01)

$l(l+1)C_l^{BB}/(2\pi)$ (μK^2)

Multipole Moment, ell

Figure courtesy of Dr. Chinone



downselect by JAXA 2018, expected launch 2025

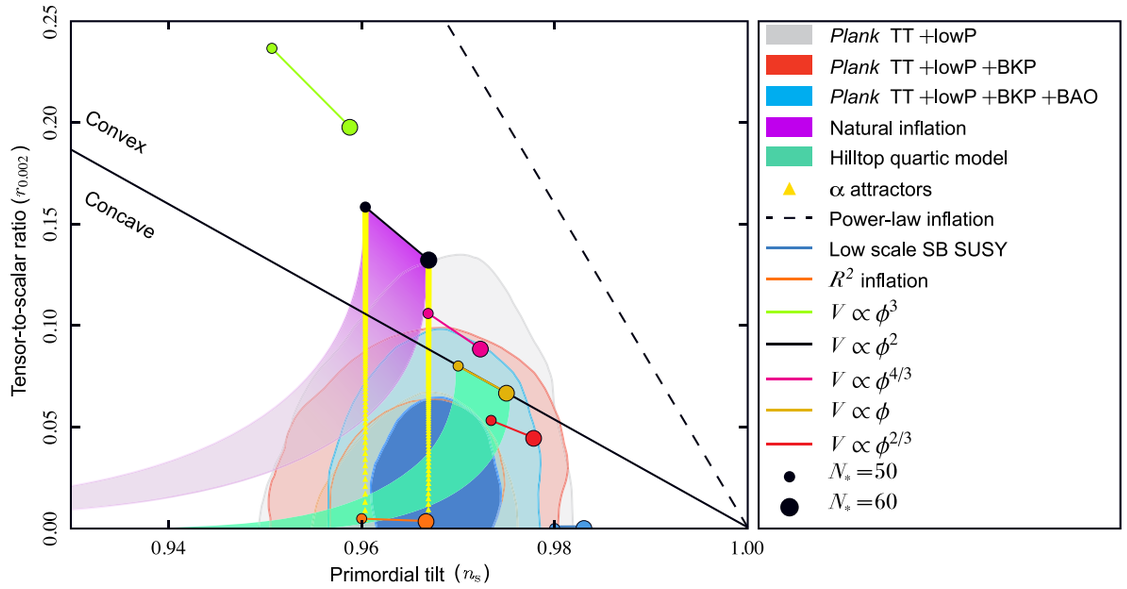
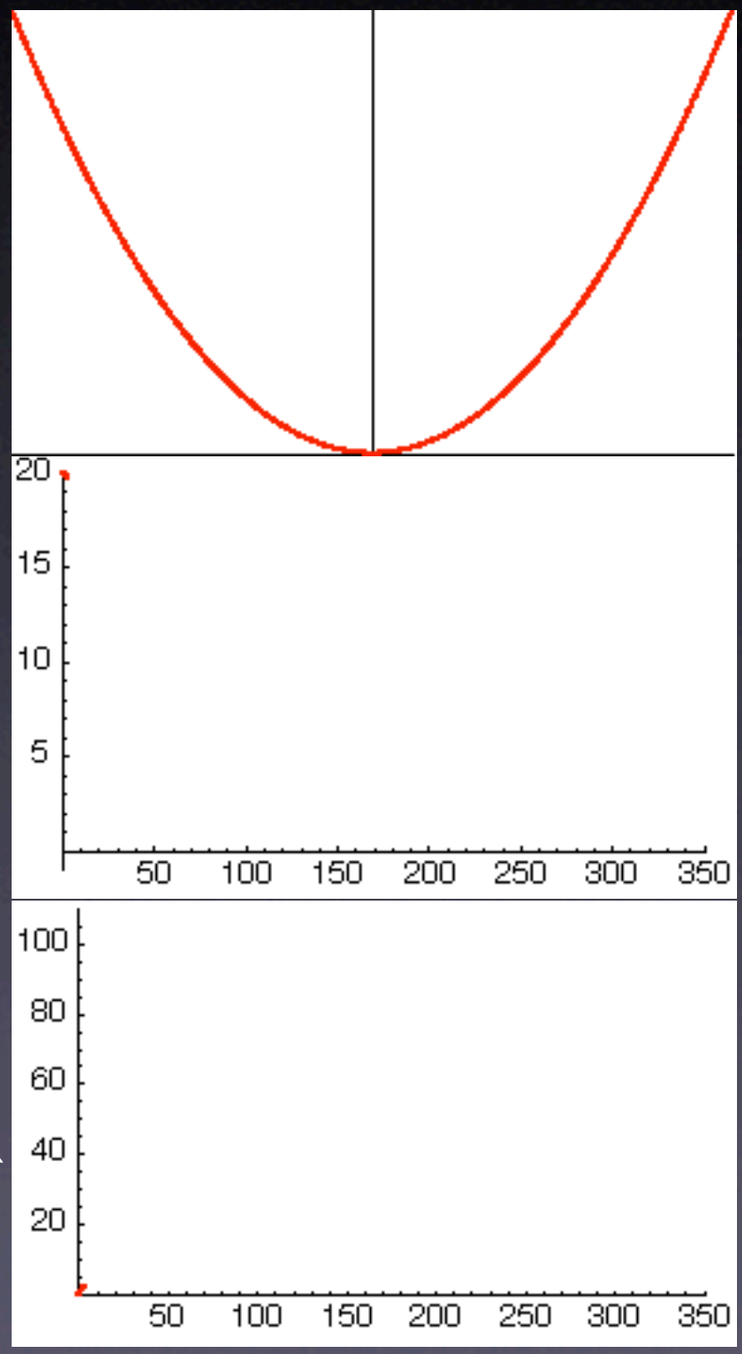


Figure 22.1: The marginalized joint 68 and 95% CL regions for the tilt in the scalar perturbation spectrum, n_s, and the relative magnitude of the tensor perturbations, r, obtained from the Planck 2015 data and their combinations with BICEP2/Keck Array and/or BAO data, confronted with the predictions of some of the inflationary models discussed in this review. This figure is taken from [44].

m together

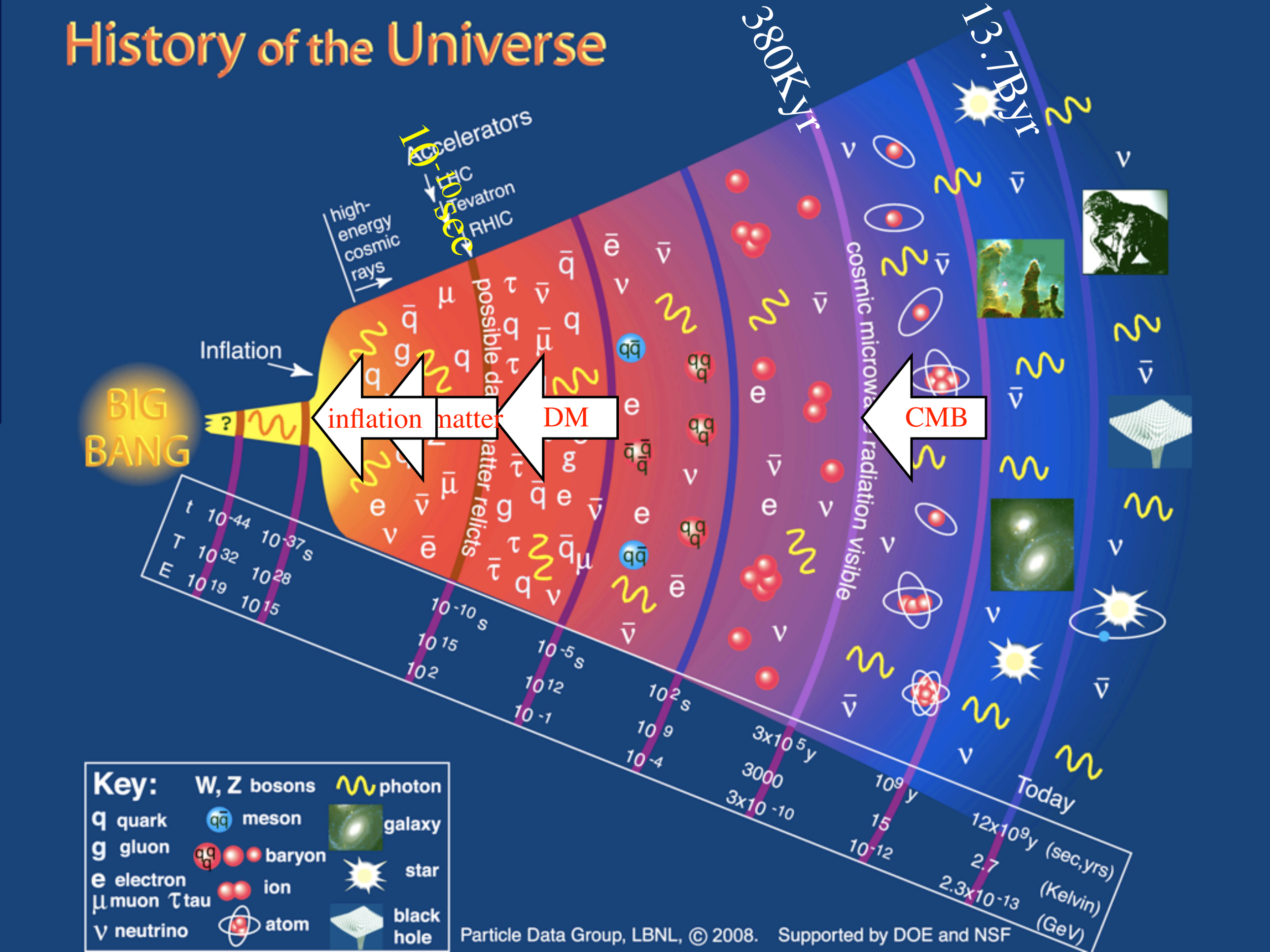
V(φ)



- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

HM, Suzuki, Yanagida, Yokoyama

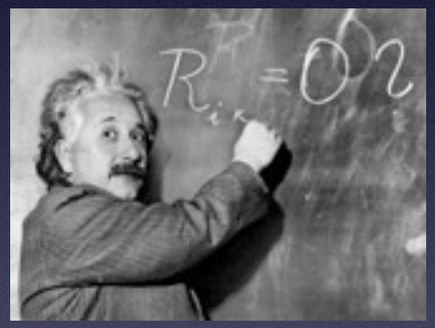
History of the Universe

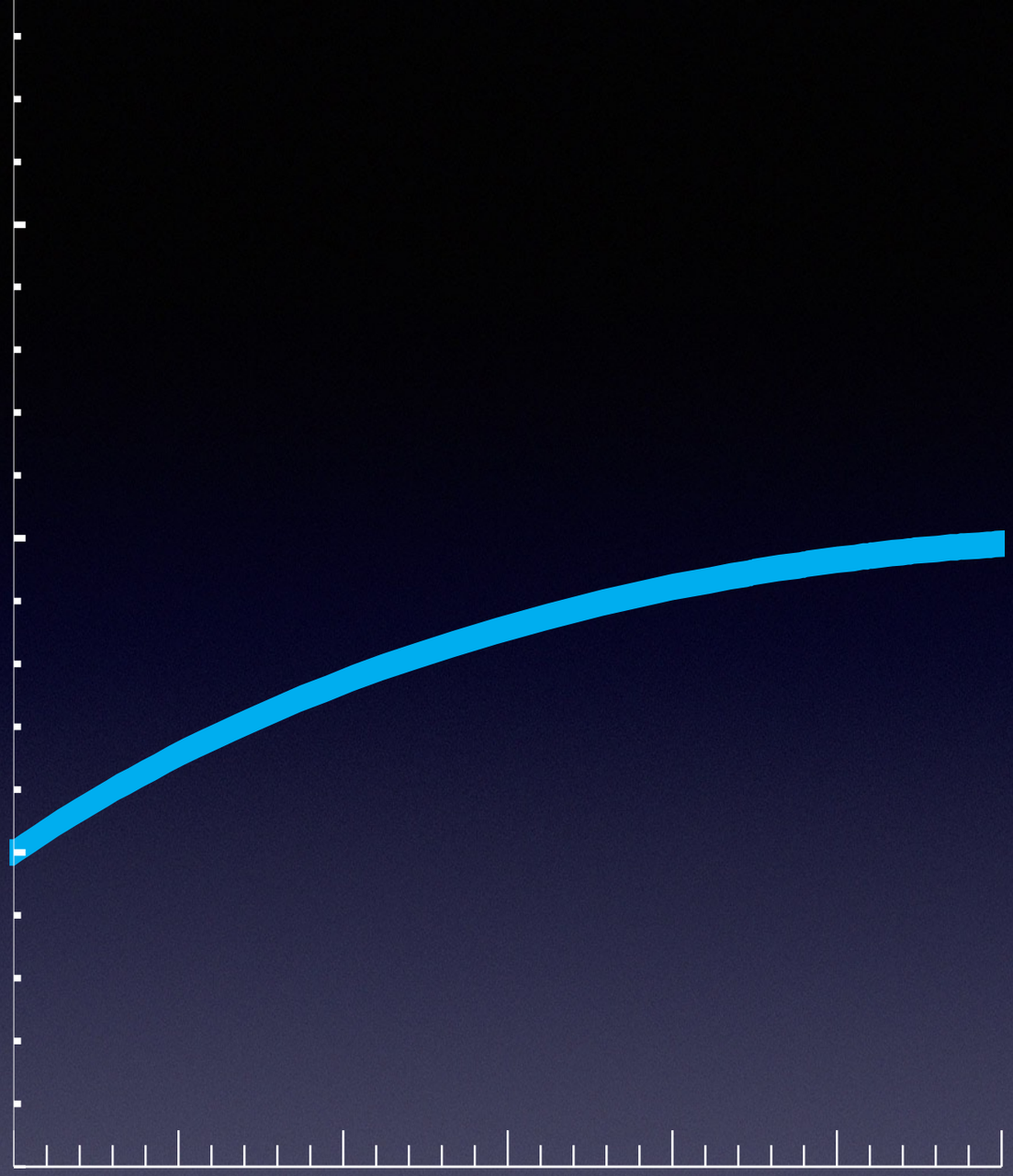


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

fate of the Univese

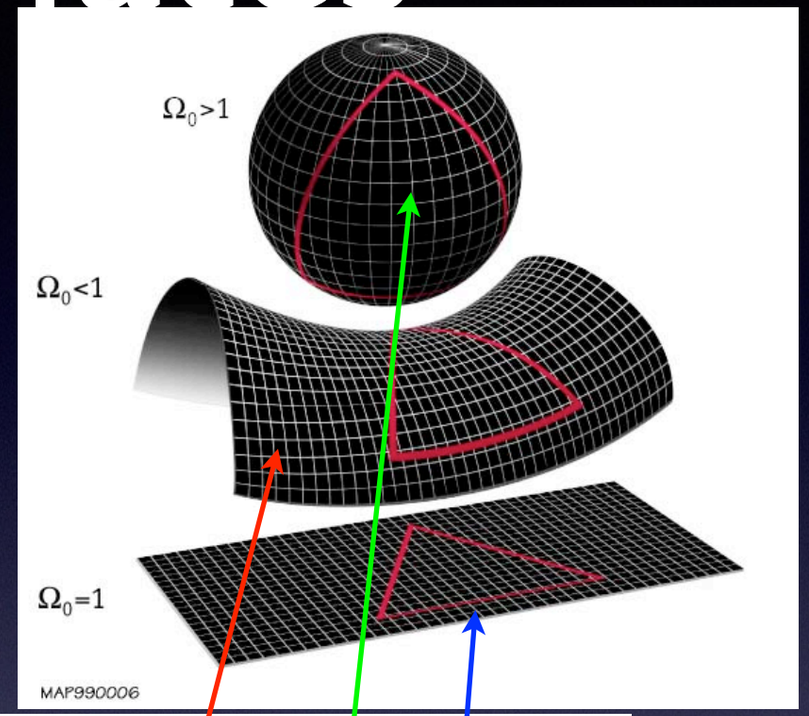
expansion

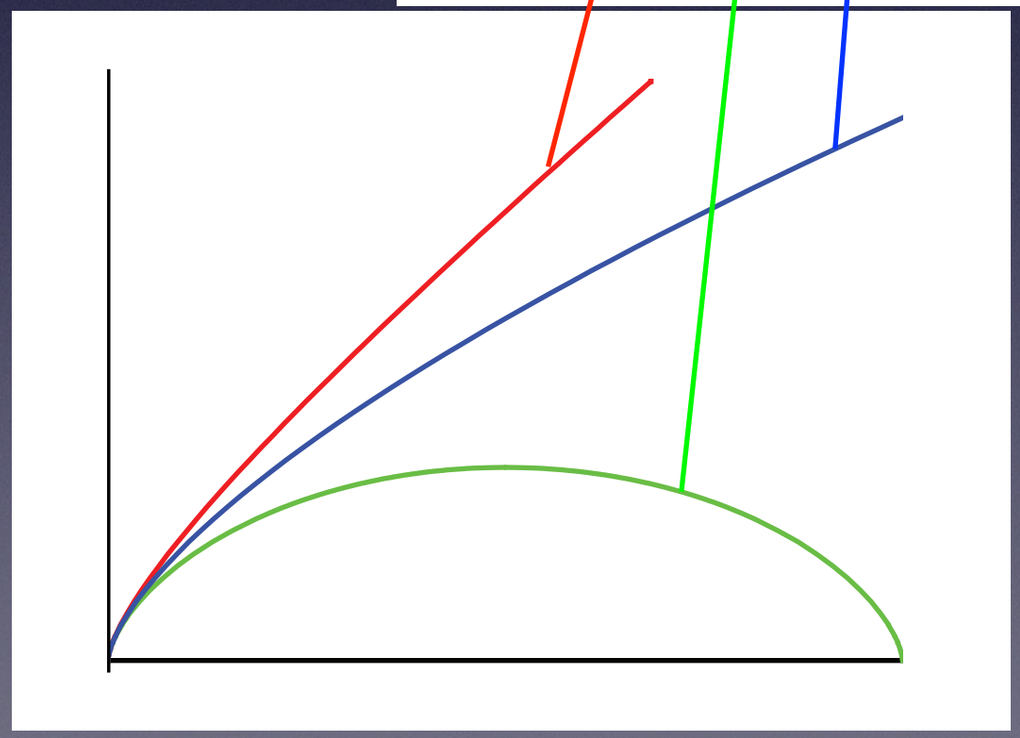




three possible fates

- if large amount of matter, expansion stops and heads back to a Big Crunch
- if small amount of matter, expansion will go on forever
- study the expansion history and predict the future!





future observers

- as the Universe gets better, more and more galaxies come into sight

- observation becomes more fun!

Dark Energy

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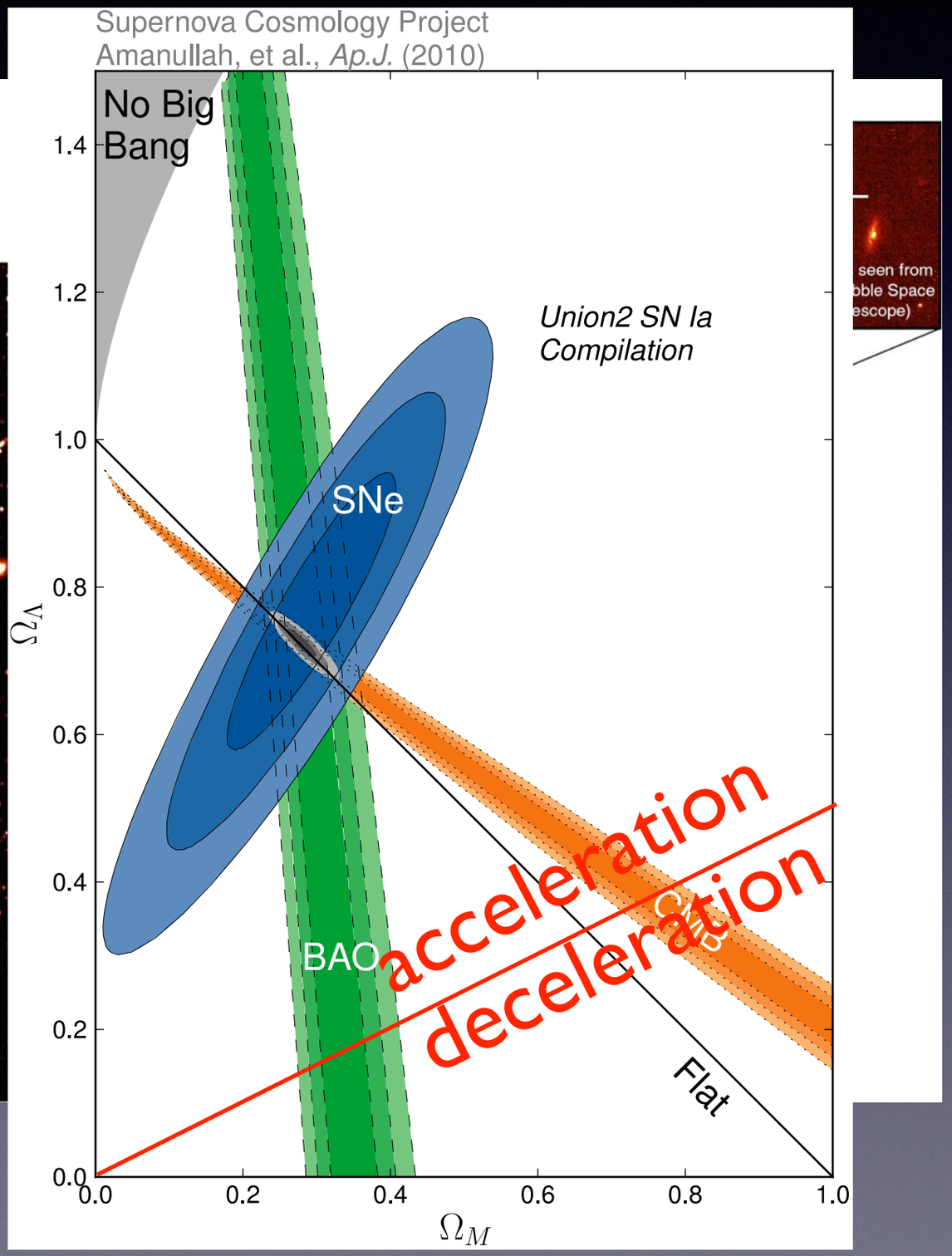
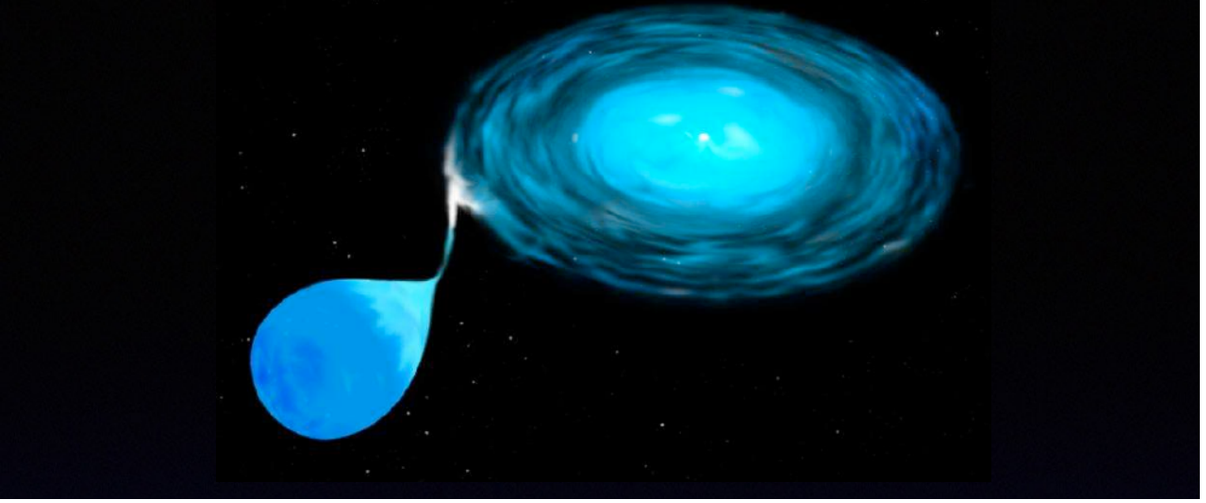
BERKELEY CENTER FOR THEORETICAL PHYSICS

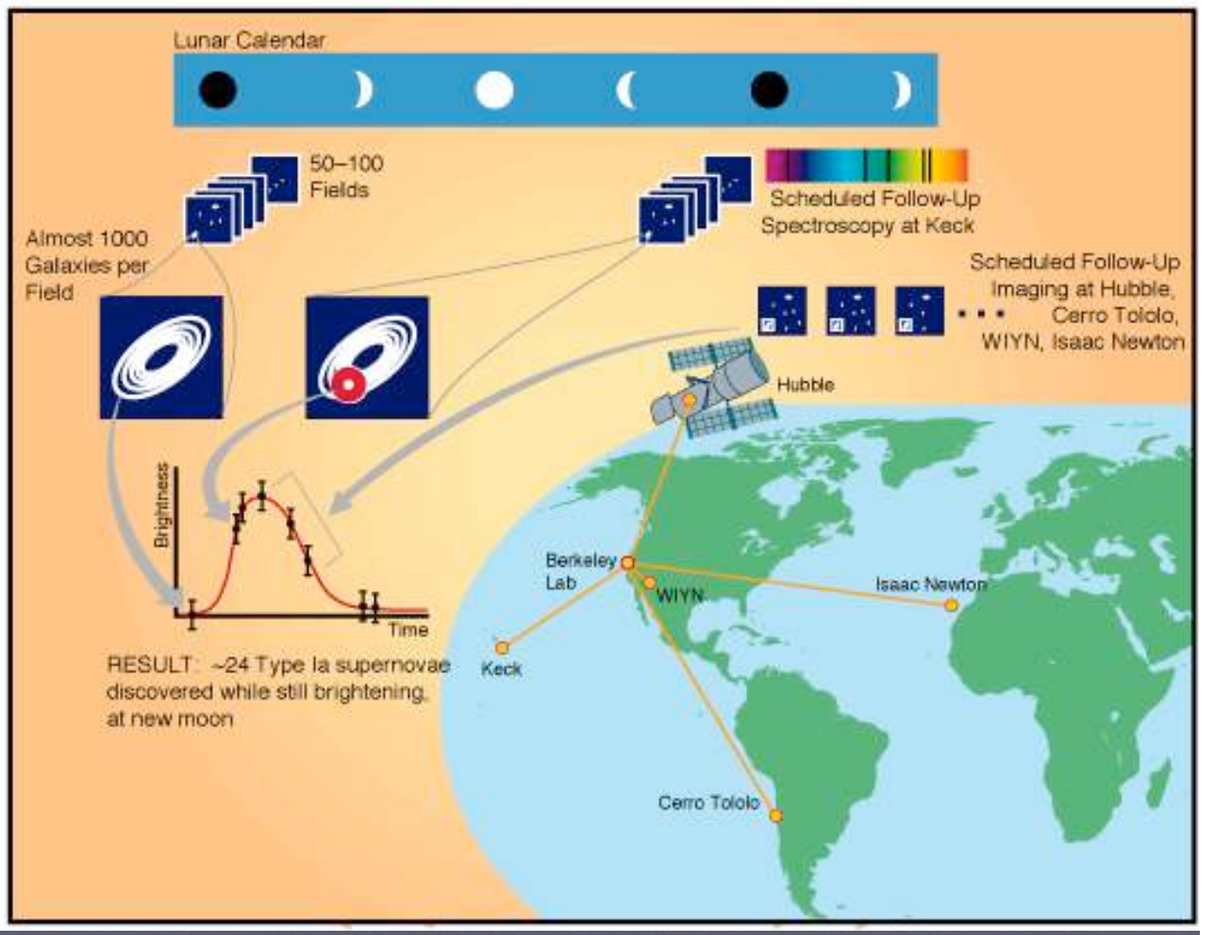
Type-Ia supernovae

- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away
  ⇒ How far back in time
- *How red it looks*
  ⇒ How much expansion
- Expansion of the Universe is getting faster!

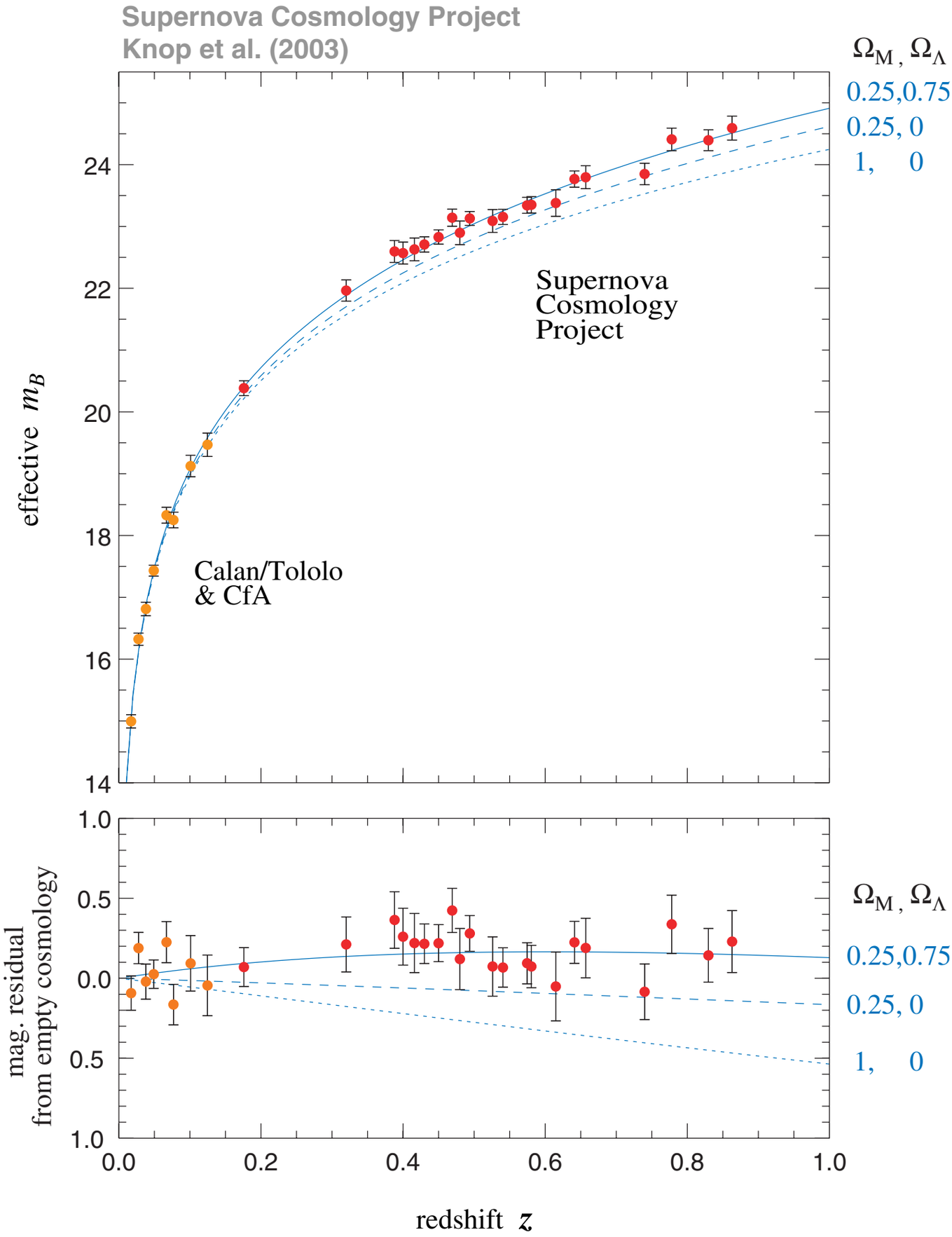




Strategy

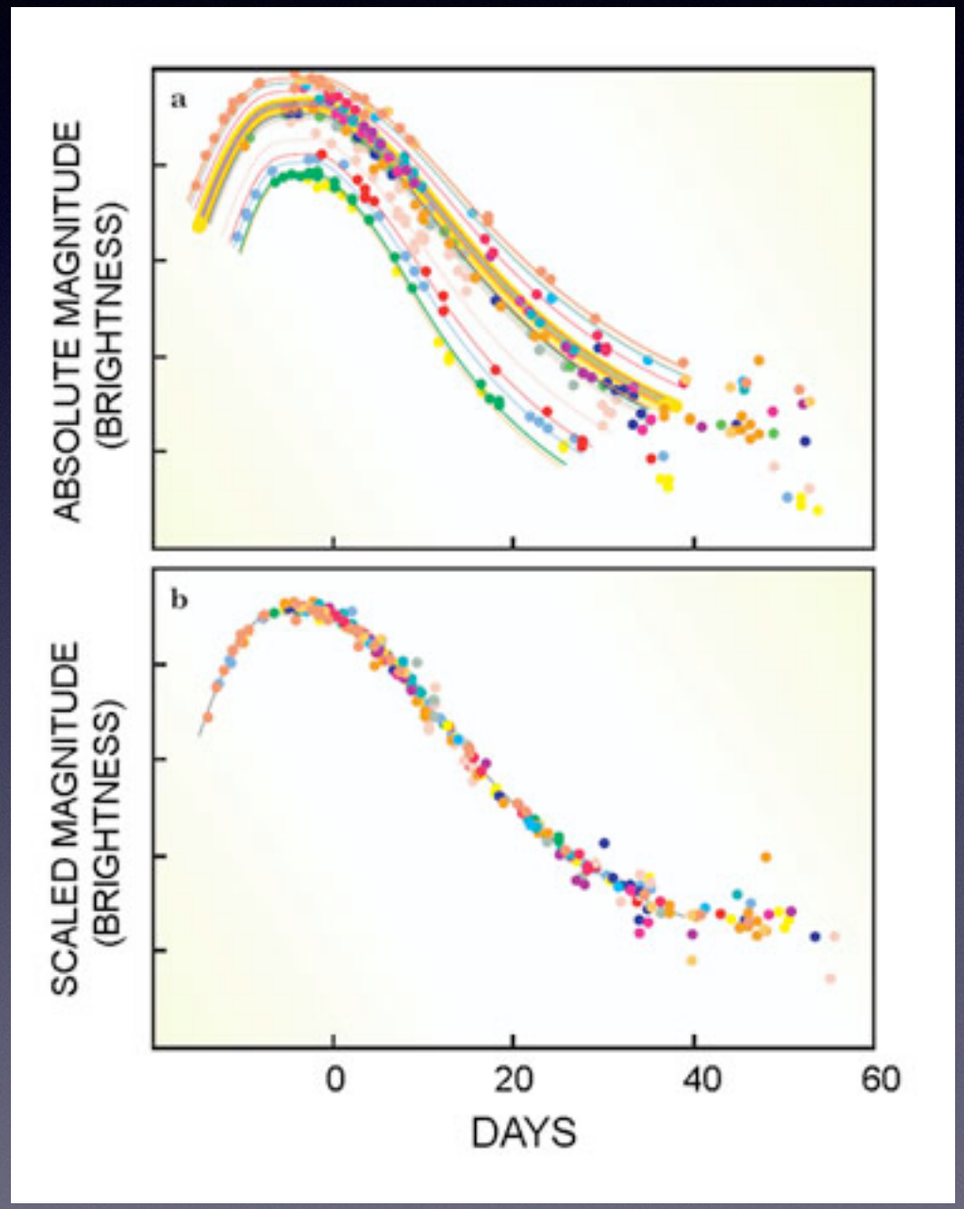


supernovae
on demand



stretch factor

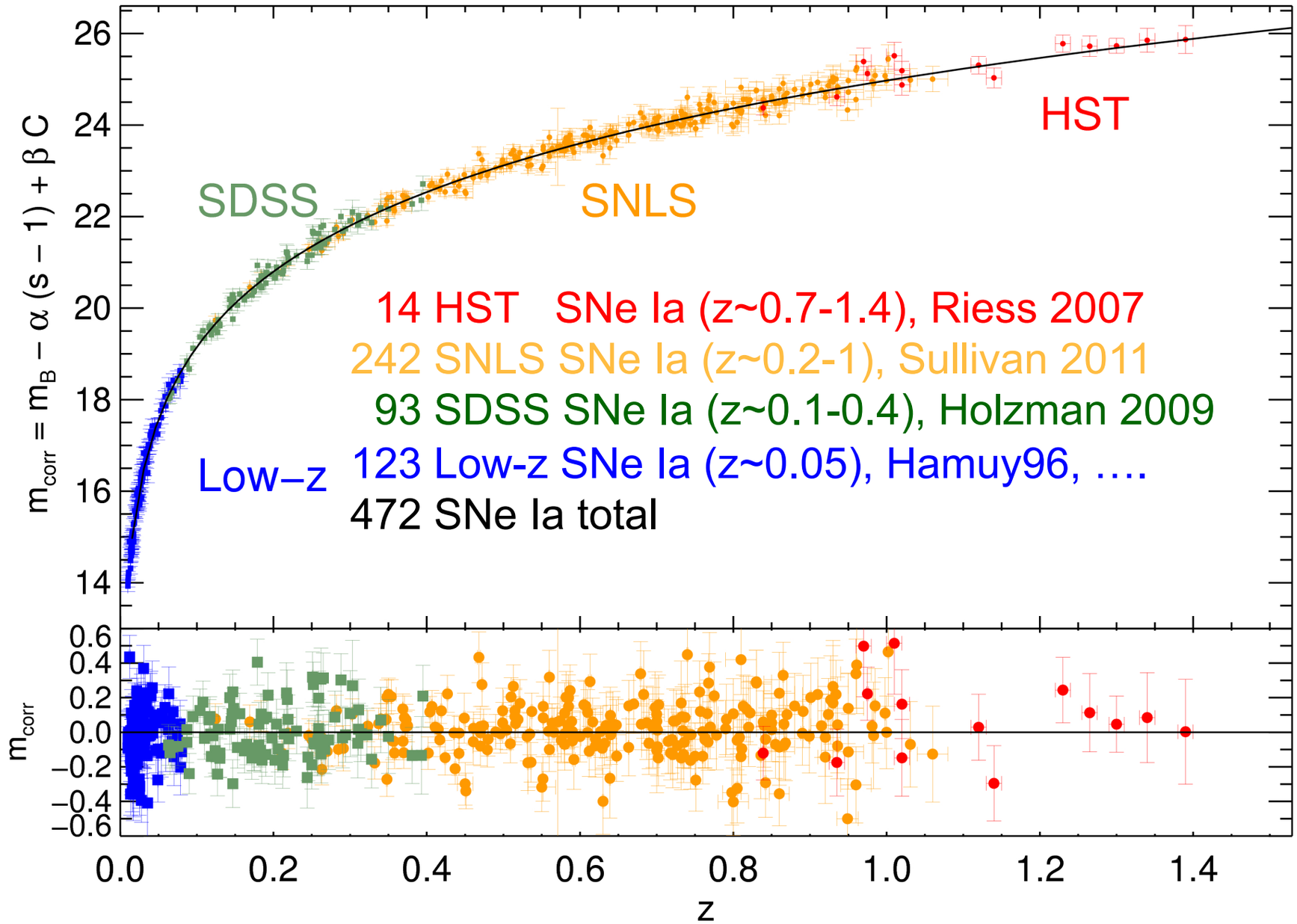
- it is not quite standard
- correlation between duration time and the absolute brightness
- can be “fixed” by a “stretch factor”
- other smaller concerns with environment (metallicity), dust extinction, etc



SNLS-3 years Combined Hubble diagram

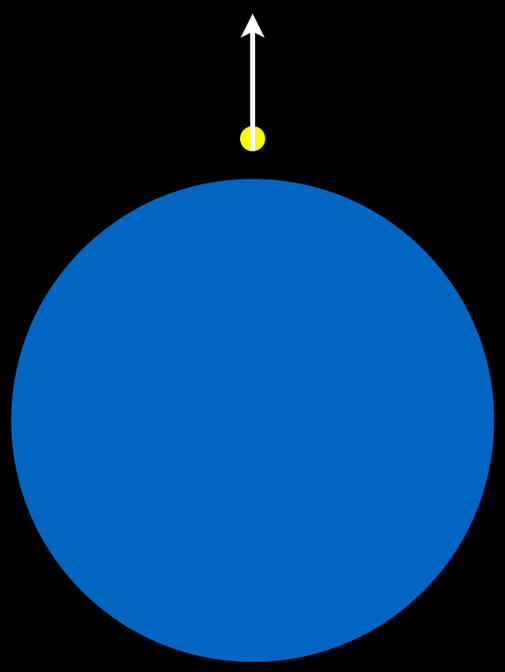
Pierre Antilogus
Marc Betoule

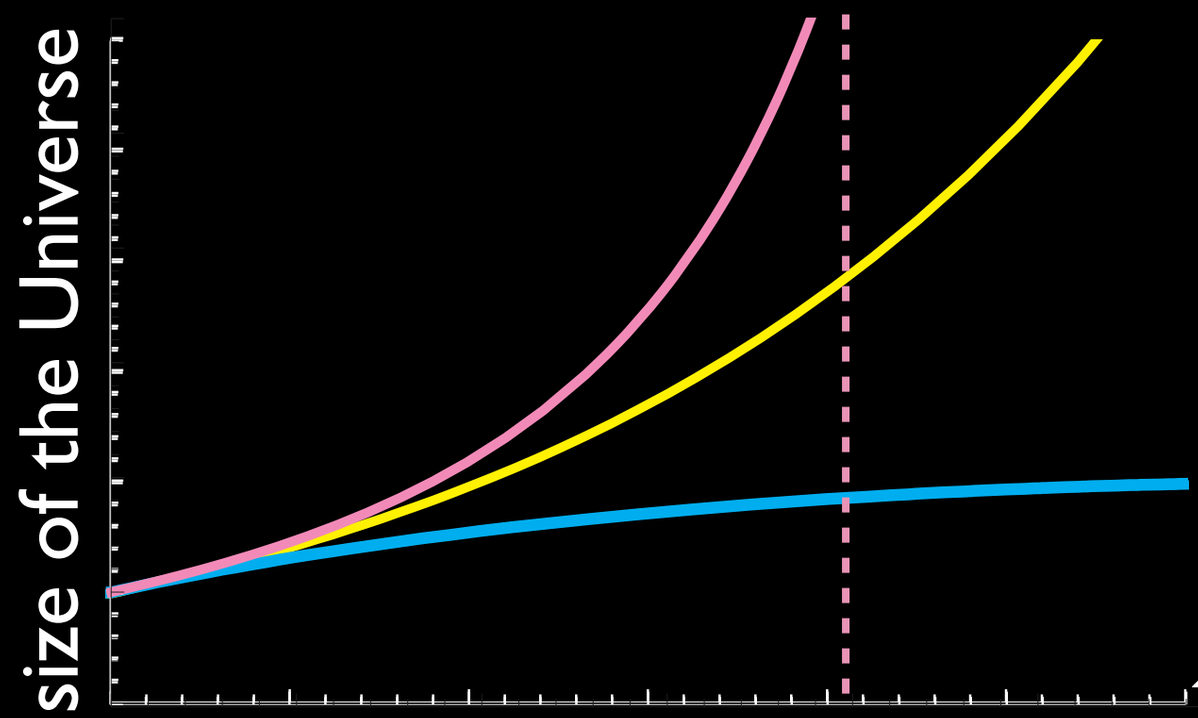
Stat ~ x 10 since the 1998 discovery papers



Guy et al, 2010 – Conley et al 2010, Sullivan et al, 2011

expansion

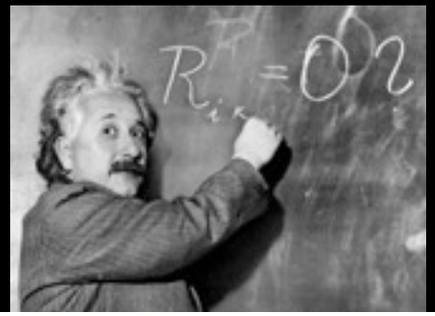


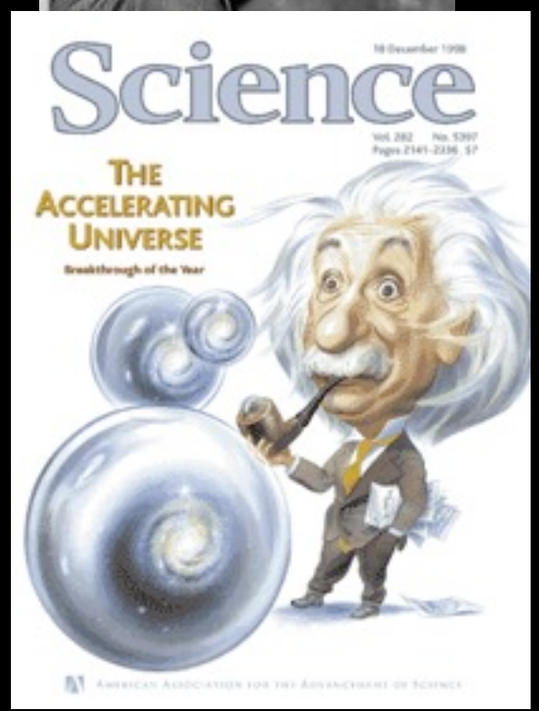


speeding up!

~~should slow down~~

- expansion started to speed up recently (~7Byr)





- energy is increasing!
- infinite source of energy?? dark energy
- Was Einstein wrong?
- new paradigm of the Universe, fundamental laws
- If the rate of energy increase very quick, eventually the expansion becomes infinitely fast
  ⇒ Will the Universe end??
- Need to measure the rate of energy increase!

Acceleration

- *w*: equation of state parameter
  - radiation: *w*=1/3
  - matter: *w*=0
  - vacuum energy: *w*=–1
  - acceleration: *w*<–1/3

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho$$

$$\rho = wp$$

$$dU = d(\rho R^3) = -pdV = -w\rho dR^3$$

$$\rho \propto R^{-3(1+w)}$$

$$\ddot{R} \propto -(1-3w)$$

Does the Universe end?

- If $w<-1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- Universe ends with an infinite speed and empty!
- or it may be "Inflation Strikes Back", $w>-1$
- We need to know the equation of state

アナログ

ZERO 衝撃の終末 ビッグリップ

NHK Science Zero 2010.9.4

Embarrassment

- A naïve estimate of the cosmological constant in Quantum Field Theory:

$$\rho_\Lambda \sim M_{Pl}^4 = G_N^{-2} \sim 10^{120} \textit{ times observation}$$

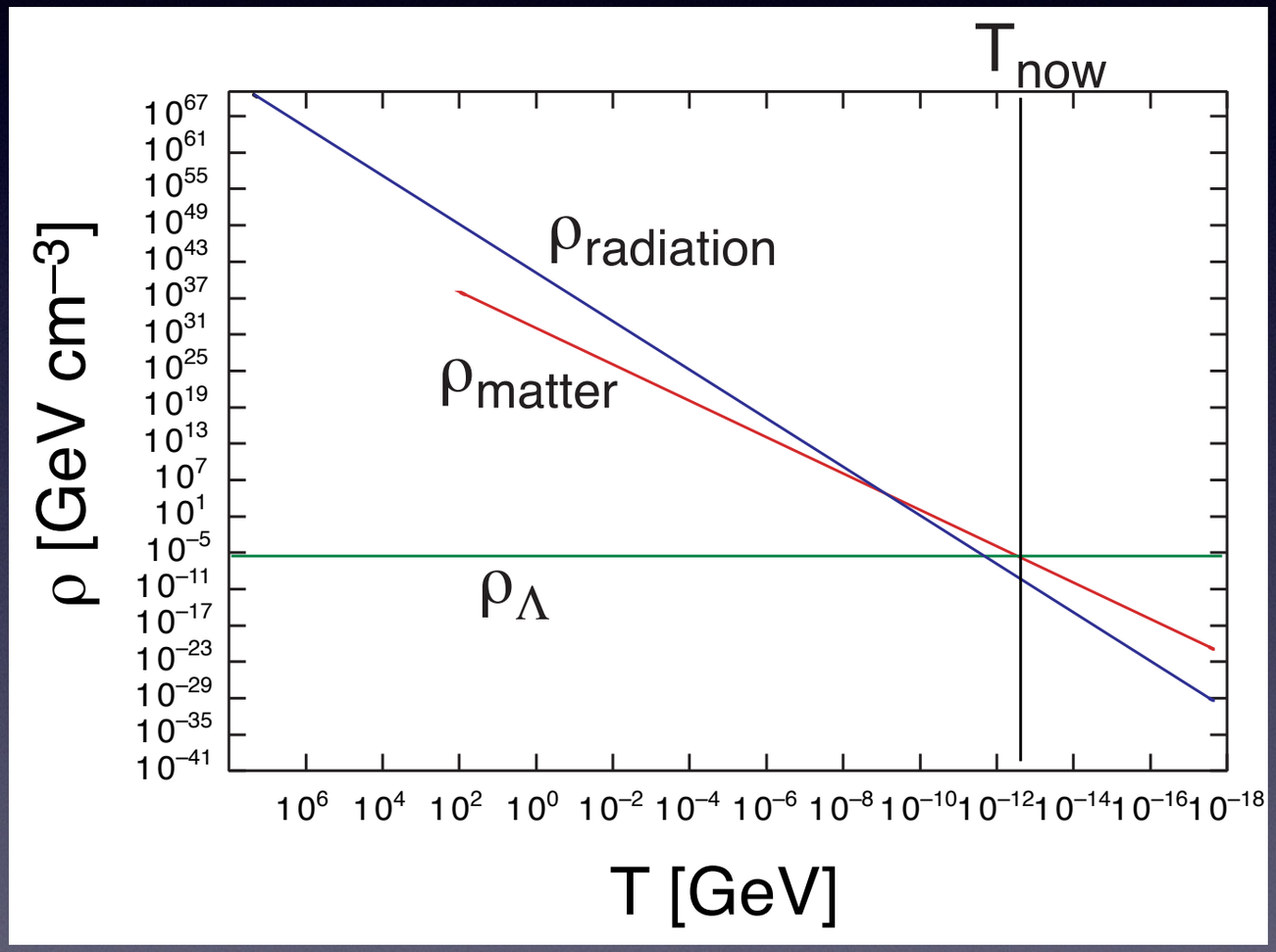
The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Multiverse

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- *Actually a triple coincidence problem including the radiation*
- If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural

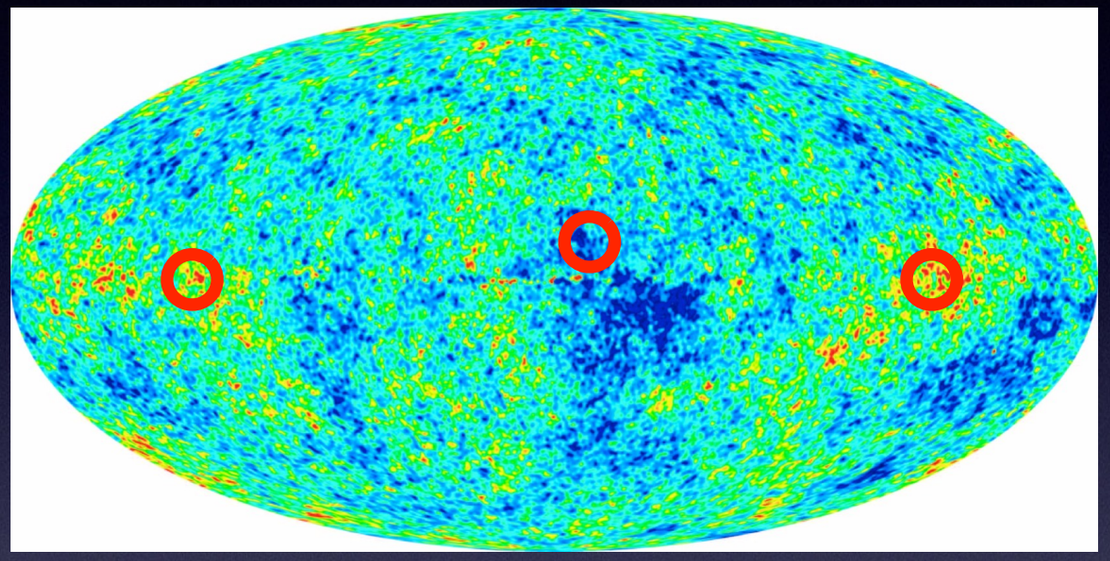


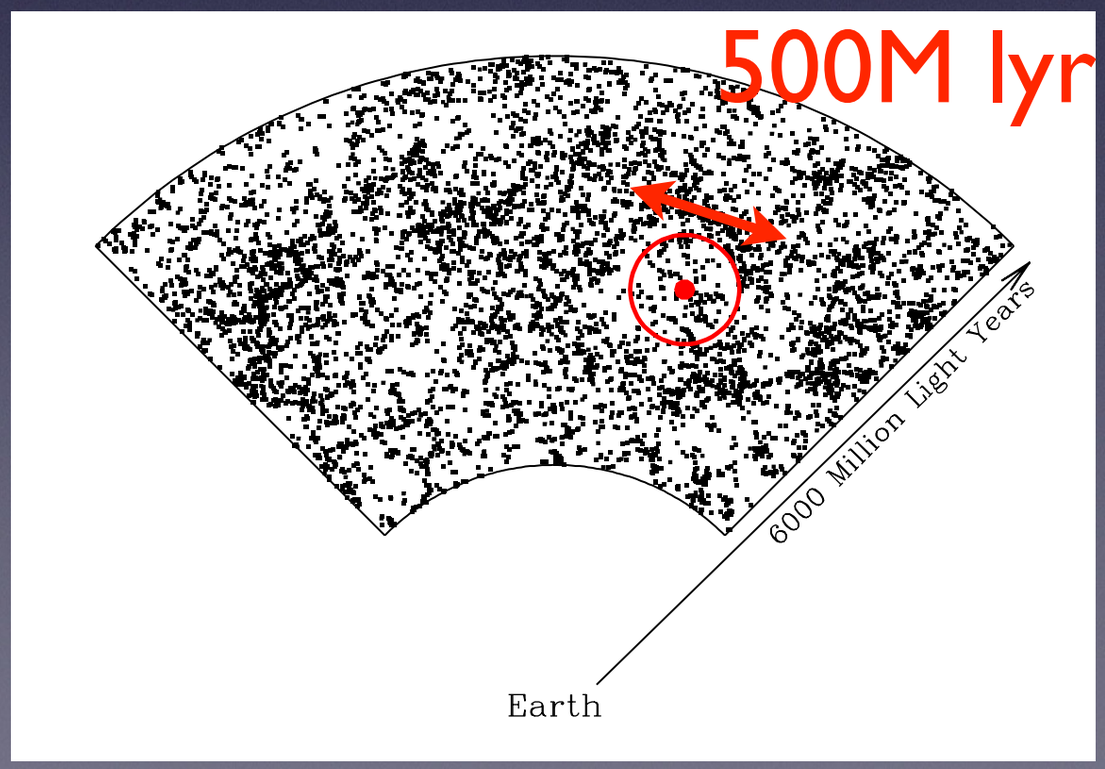
Arkani-Hamed, Hall, Kolda, HM

We can study cosmology only now.
Need funding ASAP.

Standard Ruler

- characteristic scales for acoustic peaks
- acoustic peak shows up in galaxy distributions, too, at ~500M lyr
- use this scale as a "standard ruler" to measure distances accurately
- Will the Universe end?



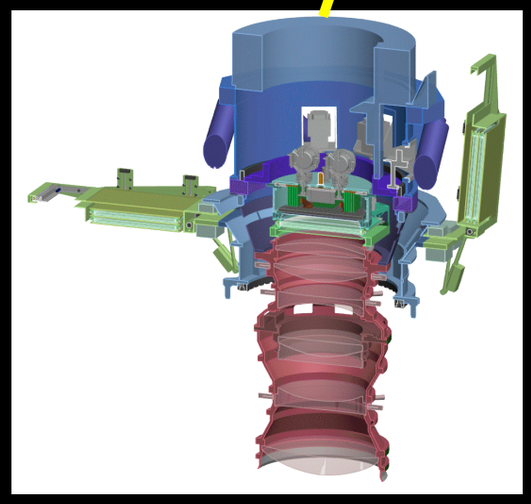


SuMIRe Prime Focus Spectrograph

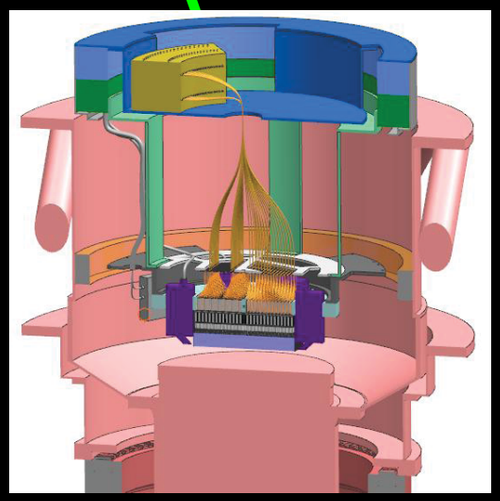
Subaru Measurement of Images and Redshifts

- one of the largest telescopes: 8.2m
- big field of view ~1.5°
- Imaging with Hyper Suprime-Cam (HSC)
  - 900M pixels
  - ~300M galaxy images
  - 2014–2019, 300 nights
- spectroscopy with PrimeFocusSpectrograph (PFS)
  - 2400 optical fibers
  - >1M redshifts
  - 2021–2026 360 nights?

Subaru



HSC



PFS

First Light later this year!

KAVLI IPMU

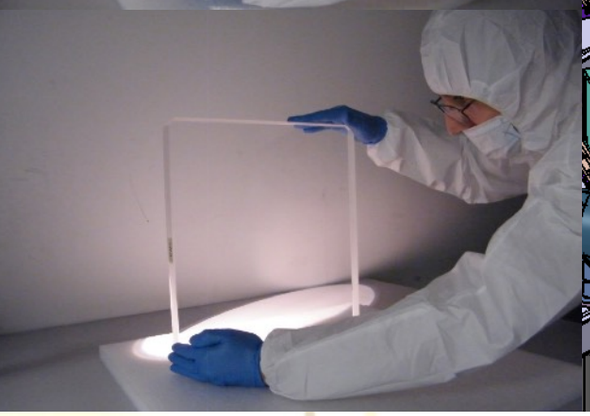
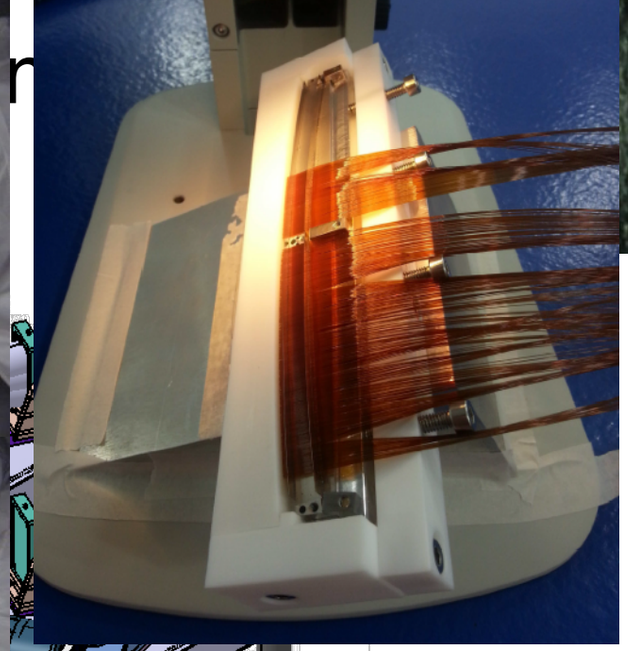
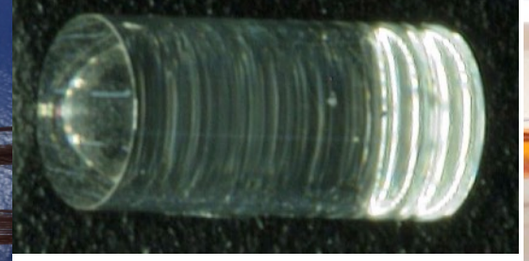
World's Best Digital Camera: 3tons!

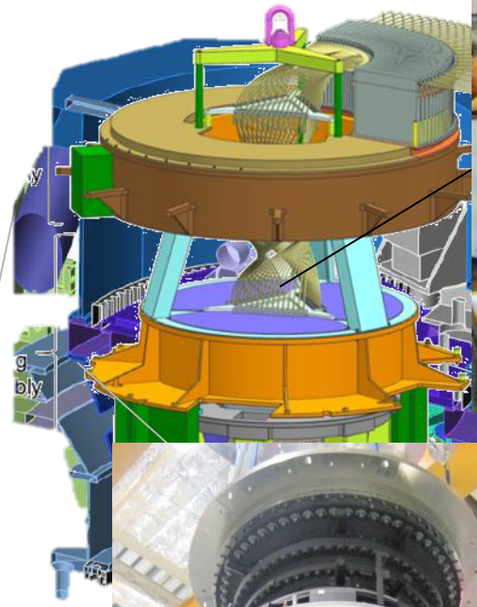
Top Unit

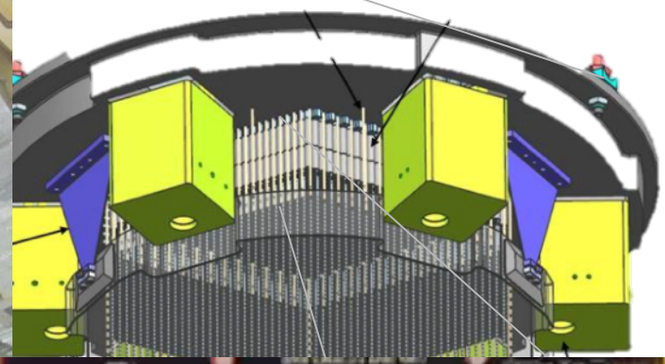
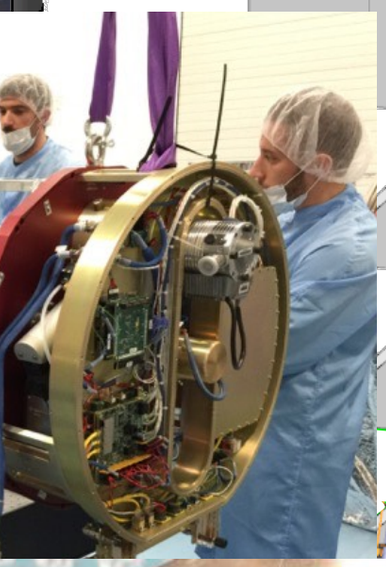
<10μ

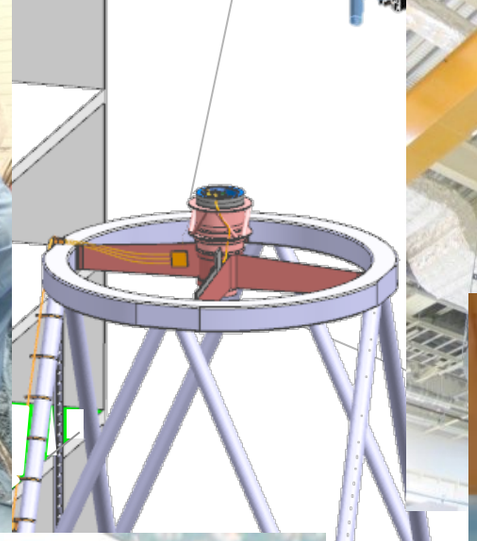
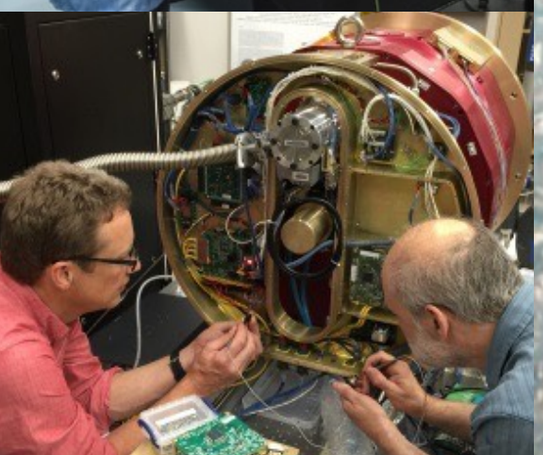
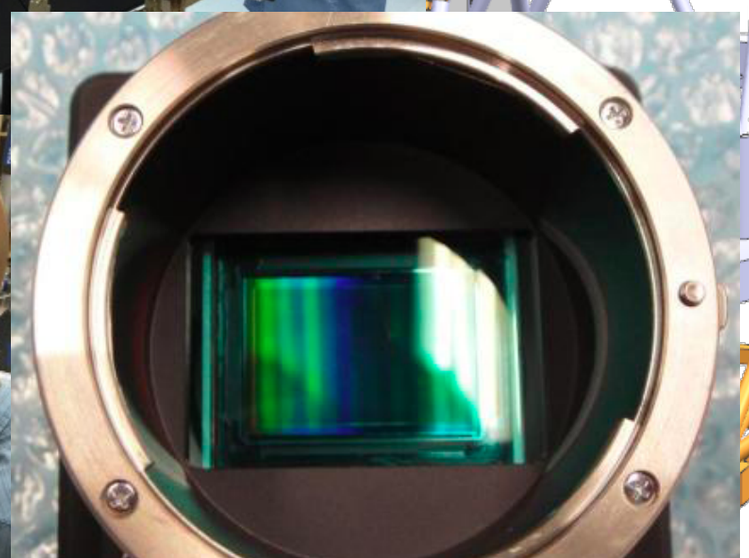
Wide Field Corrector

<0.3”

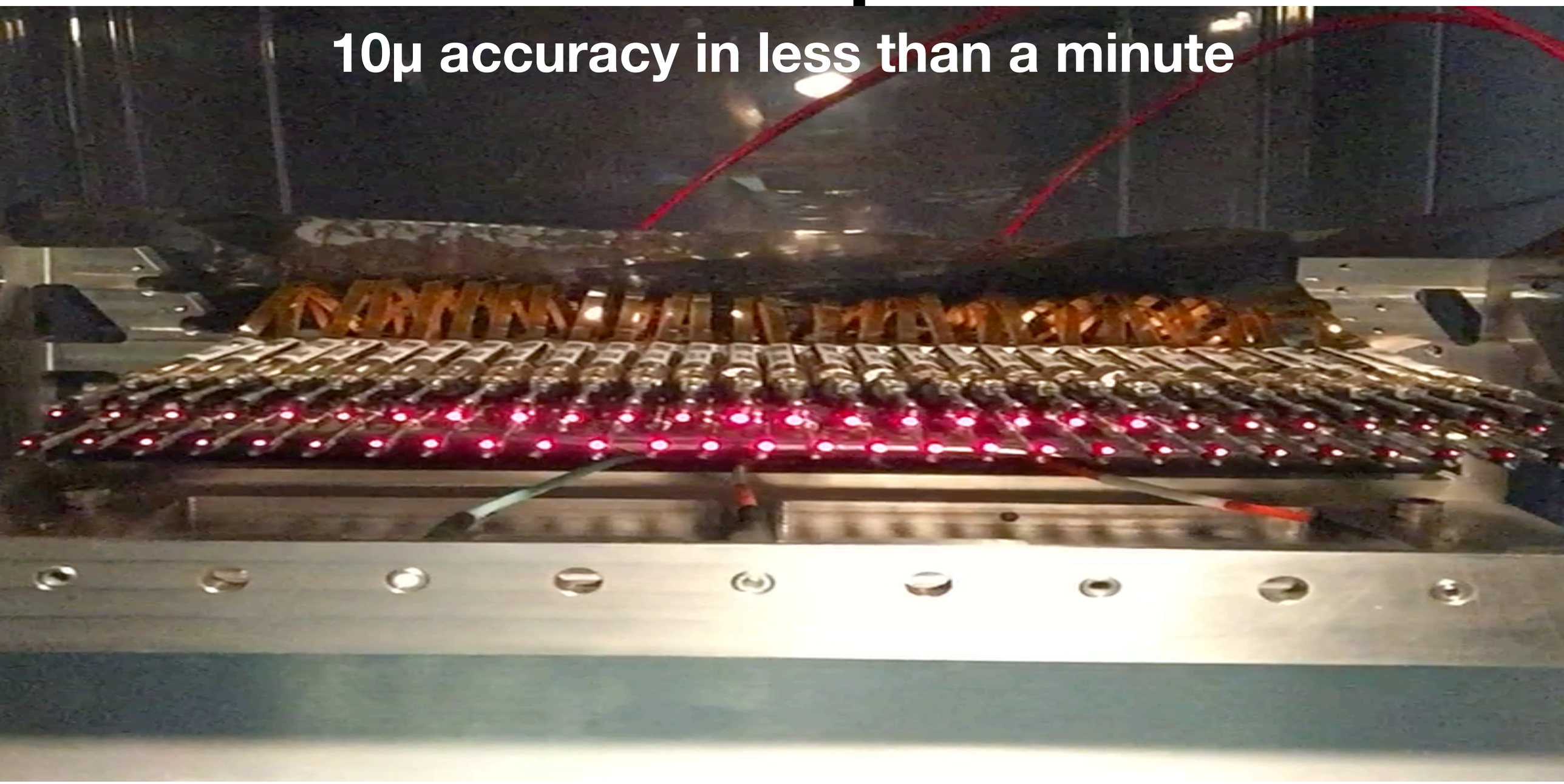







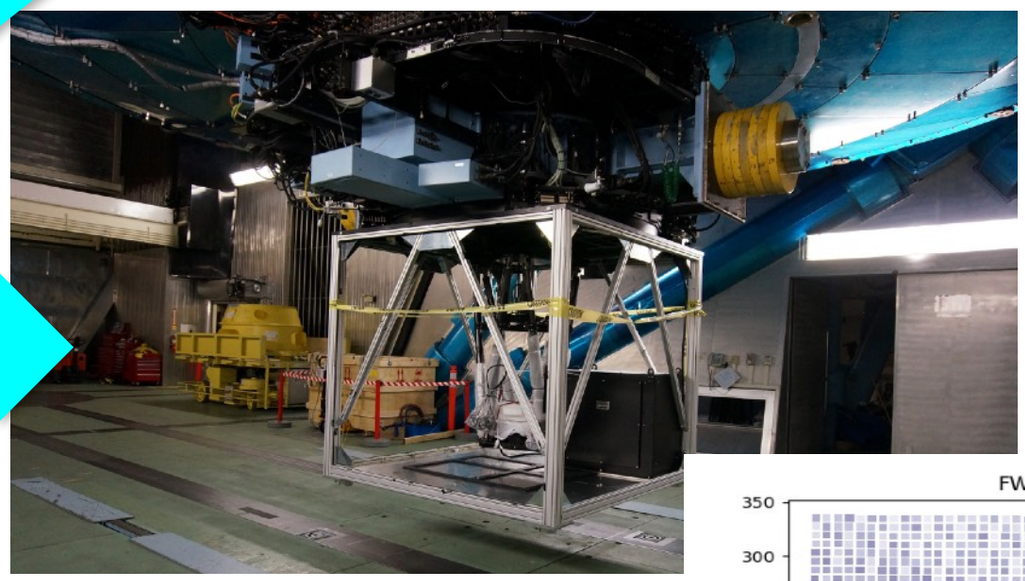

2550 Fiber Positioners "Cobra" all produced

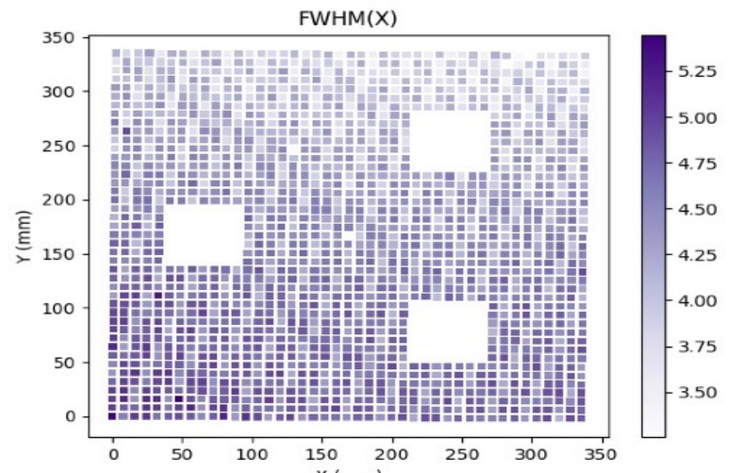


co-developed with Caltech, NASA/JPL

Metrology Camera System (MCS)

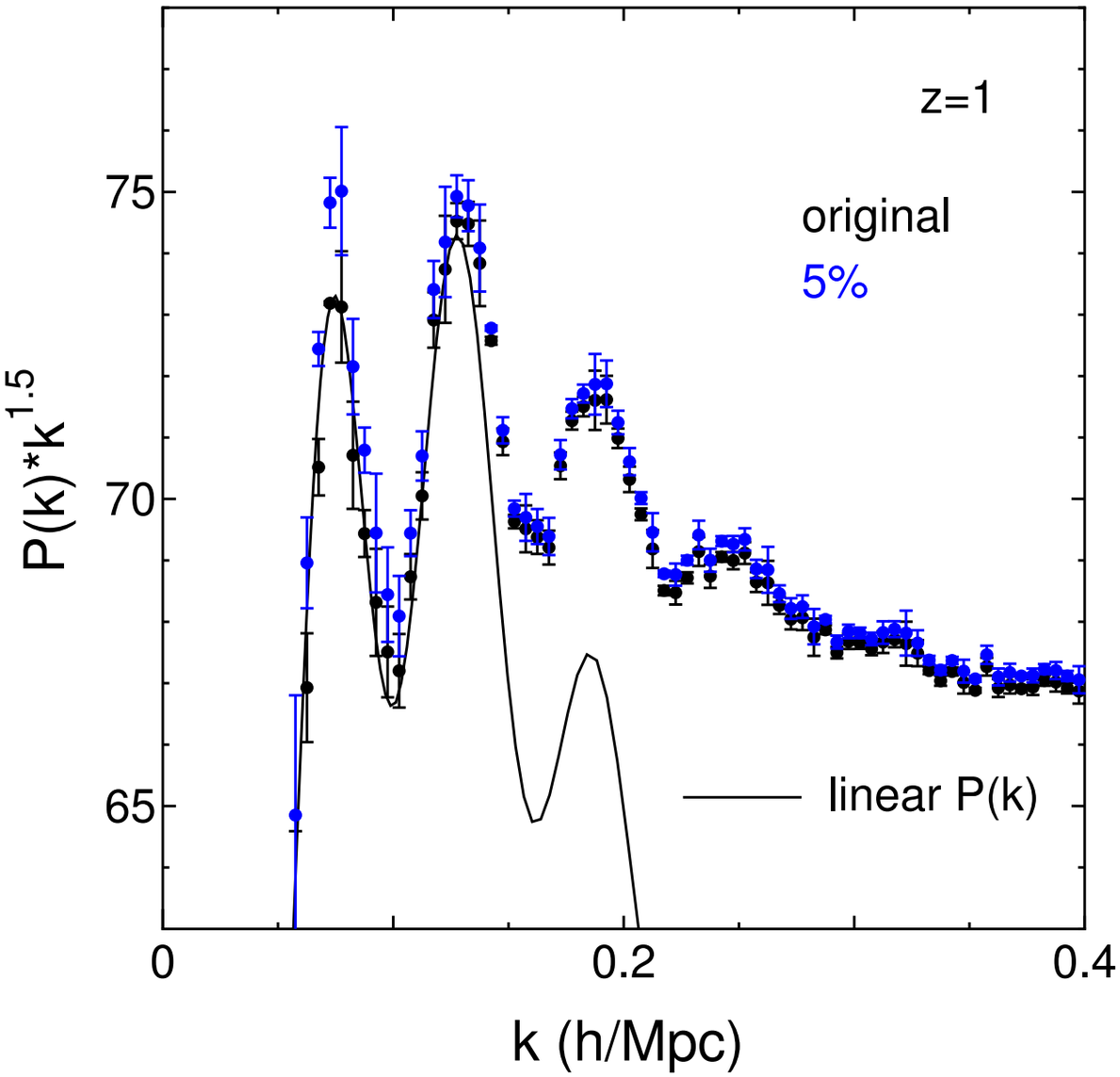
Wang [ASIAA]

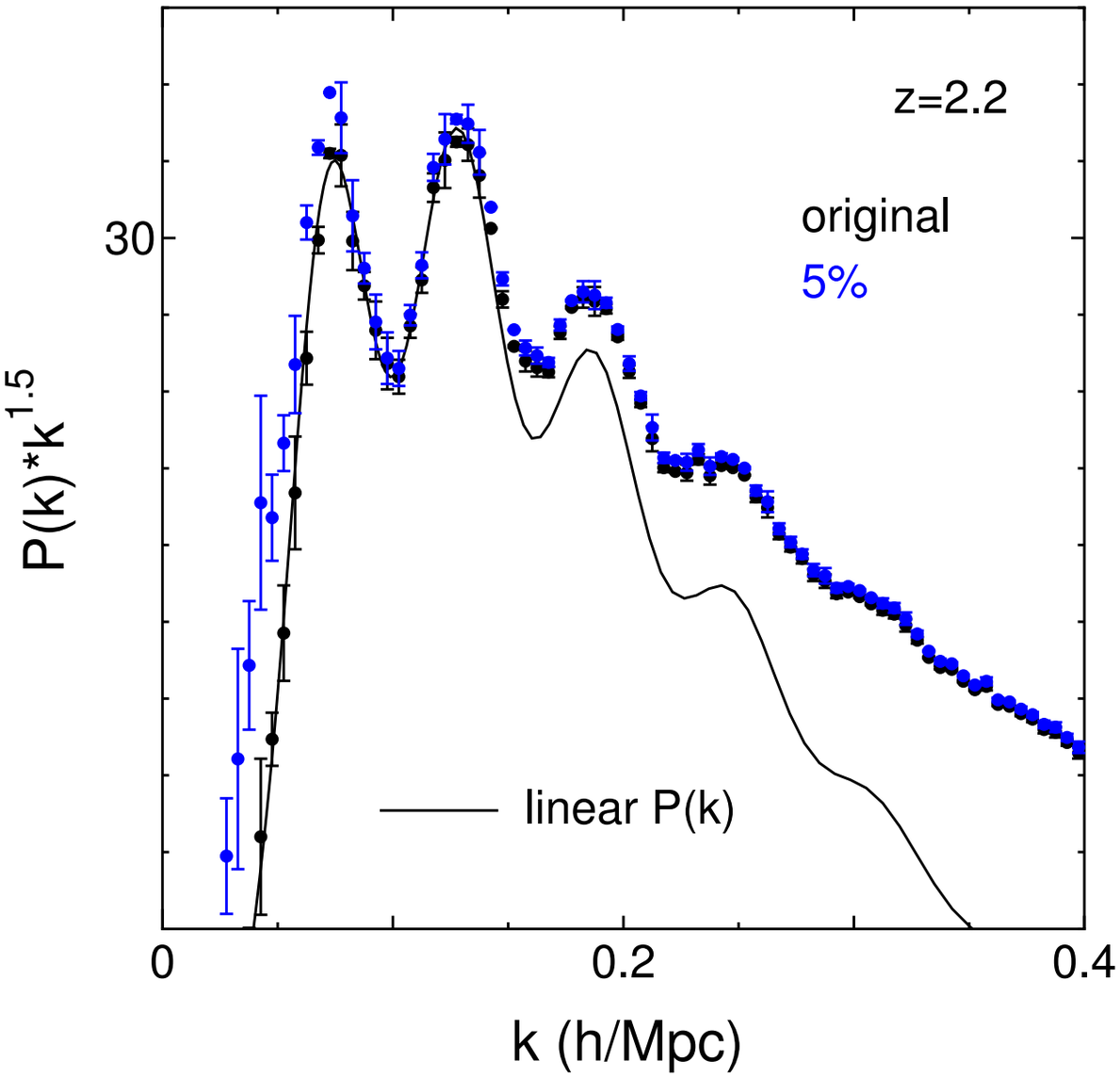




June 8 2018: one the telescope!

Baryon Acoustic Oscillation

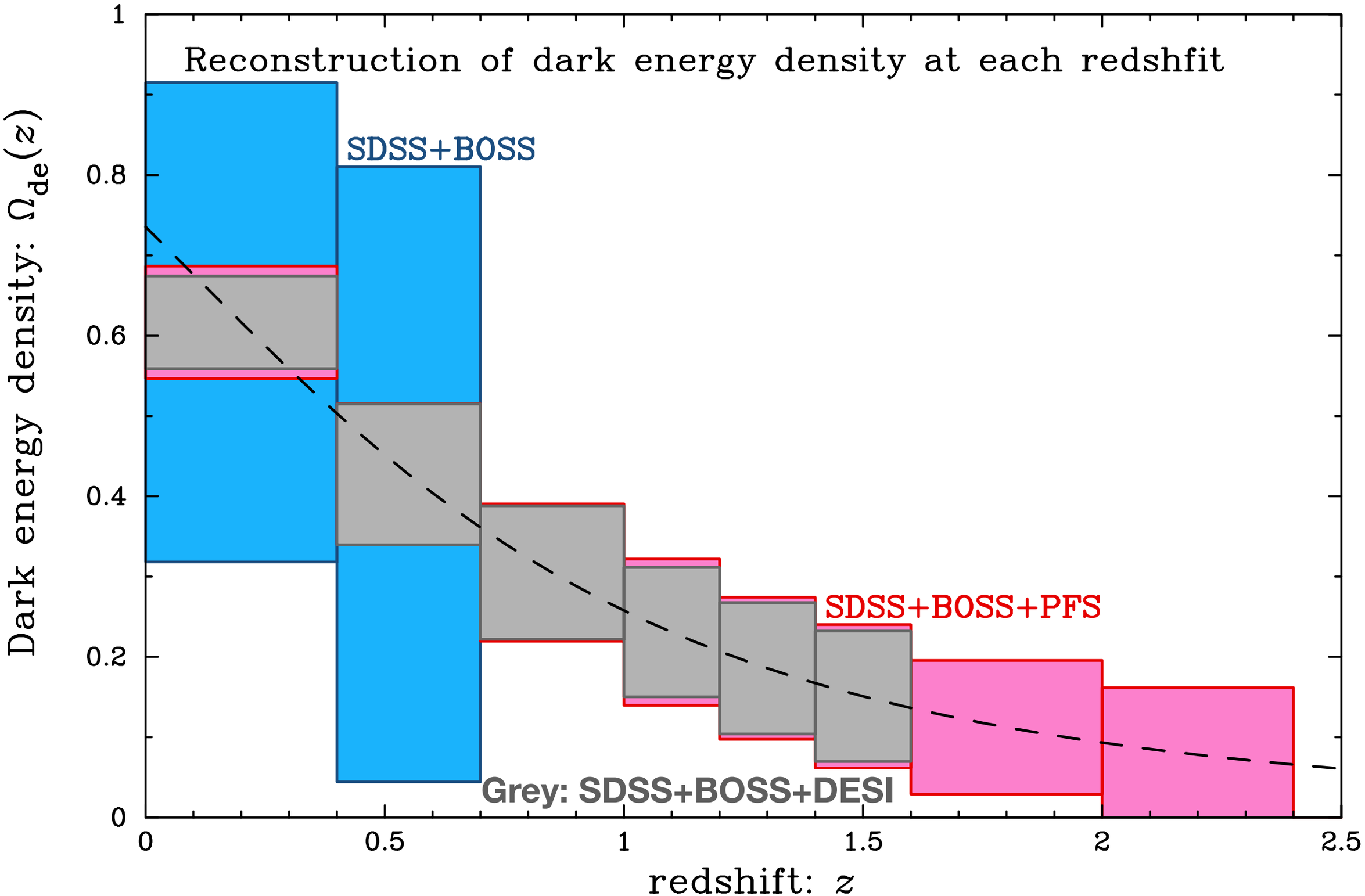




ELGs [OII], ~15 min exposure

Ruling out ΛCDM by mapping out time evolution of

Dark Energy Density



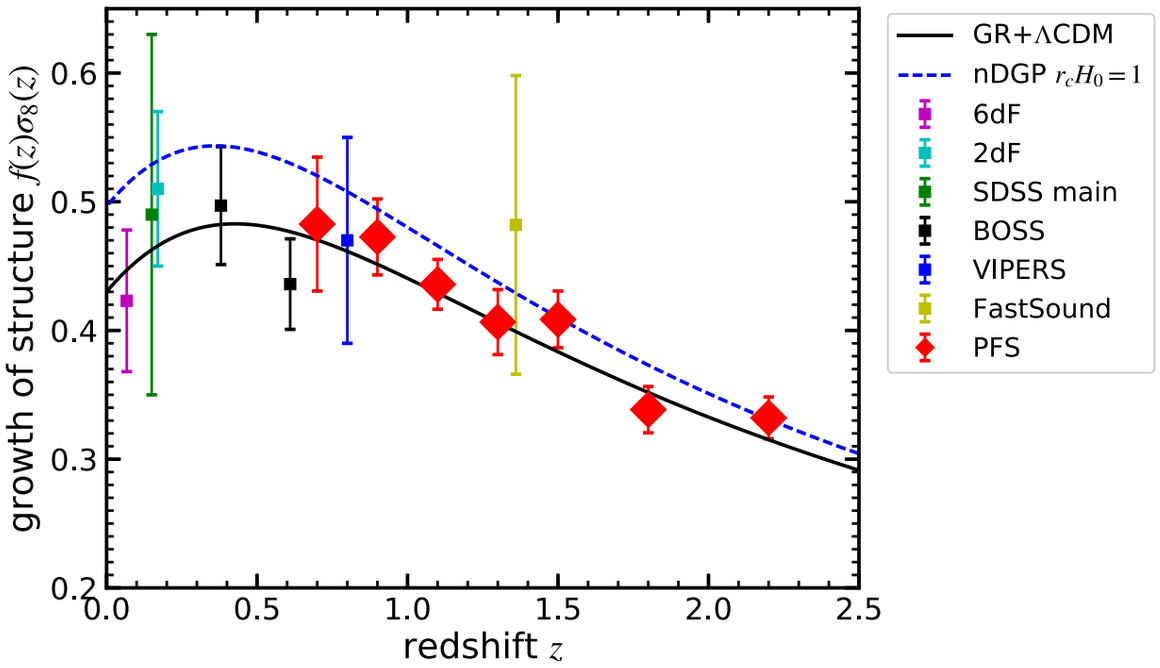


Figure 11. Expected 1σ constraints on $f\sigma_8$ from one realisation of the PFS data combined with the Planck data, as well as the current constraints. The blue line shows the example prediction of a model of modified gravity called "nDGP+DE".

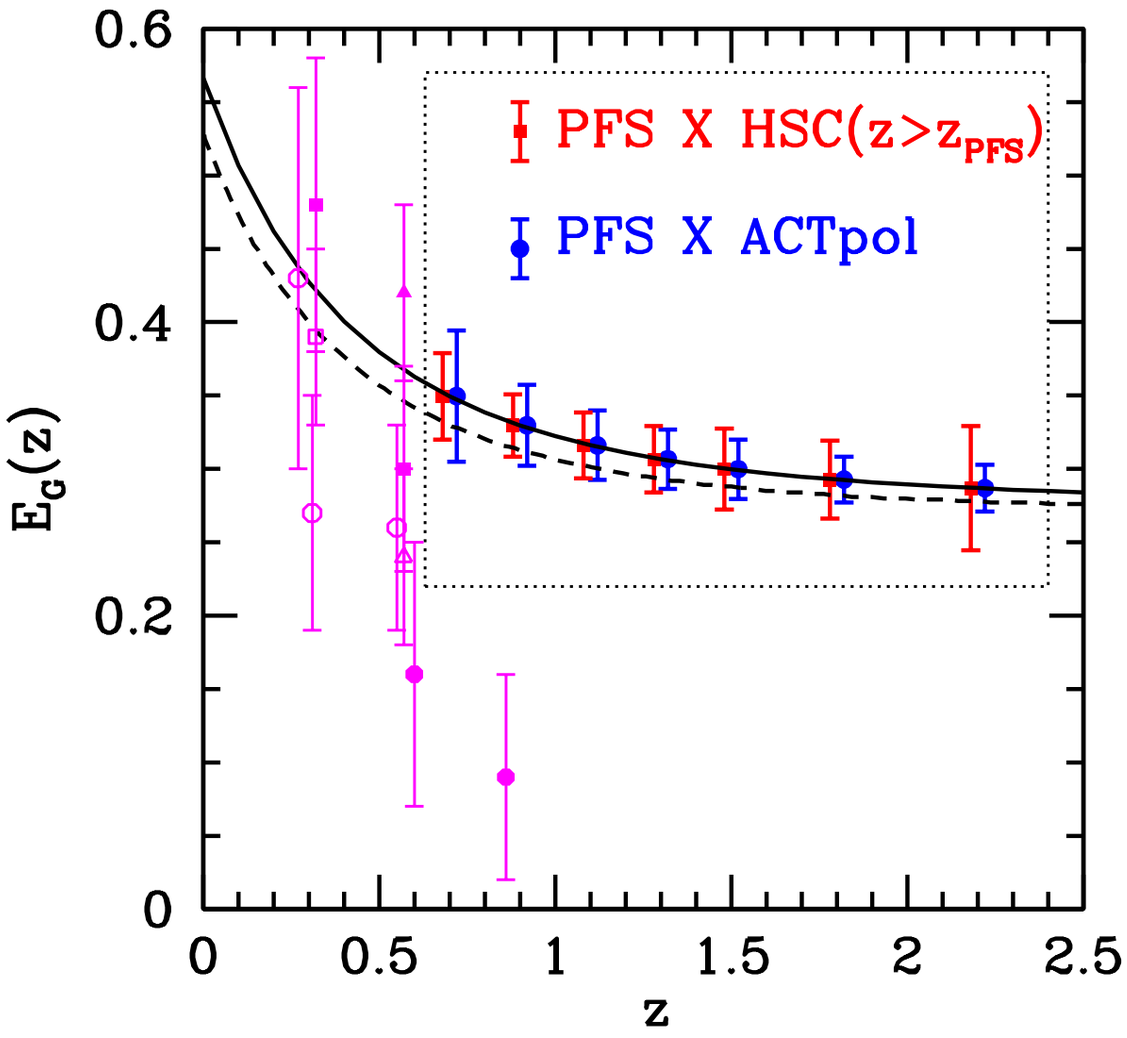
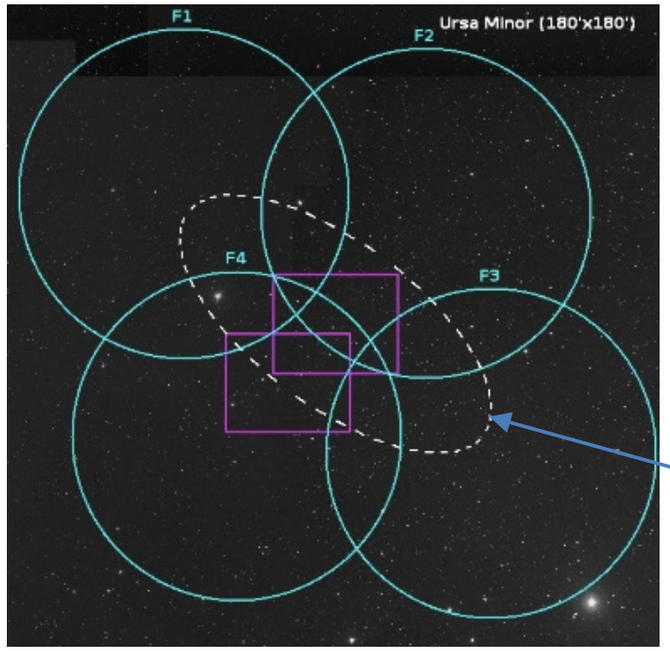


Figure 13. Expected 1-σ error bars of E_G for the PFS in combination with lensing data from HSC and ACT.The dashed line is the prediction of a "nDGP+DE" model described in Sec. 4.4. The E_G measurement can exclude this model at more than 2σ. Existing E_G measurements (magenta points with error bars) are also included for comparison.

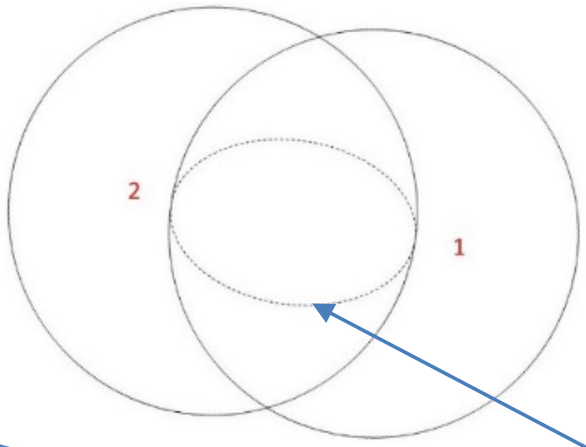
Is CDM correct?

precision study of nearby dwarf galaxies using PFS
established survey plan based on the HSC data

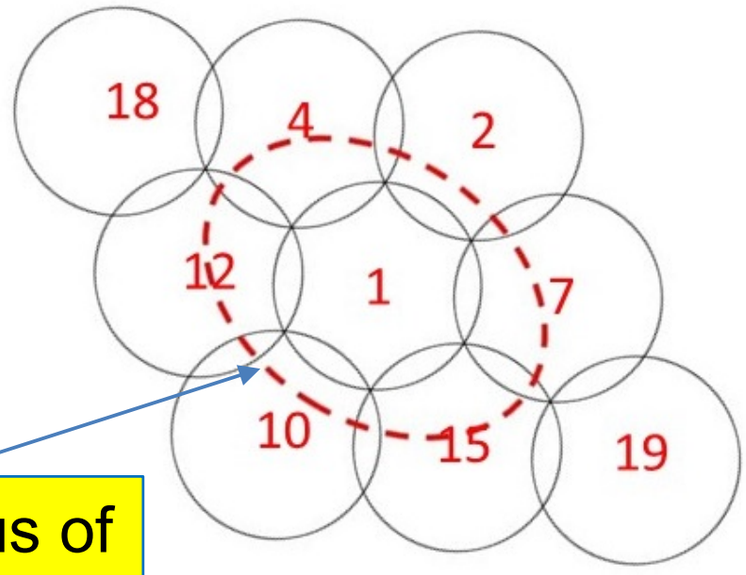
Ursa Minor



Draco



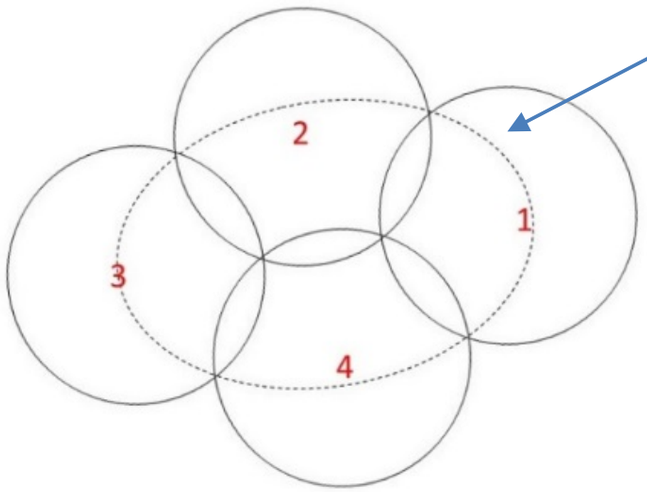
Sextans



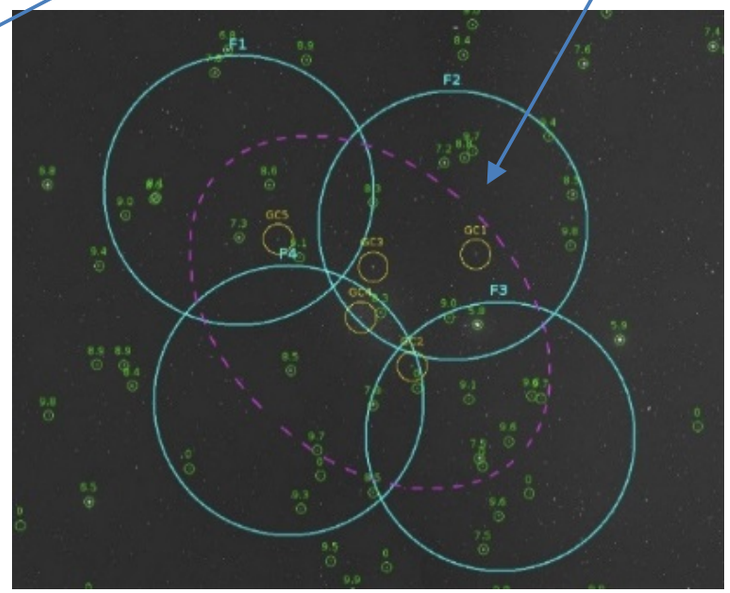
+Bootes I

tidal radius of stellar comp.

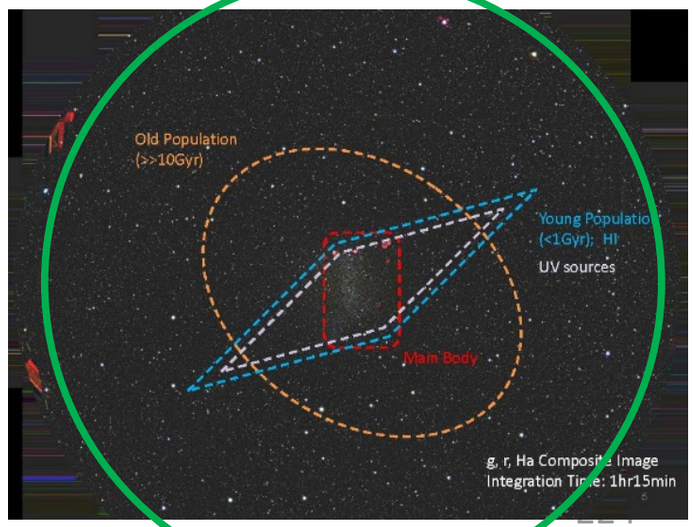
Sculptor



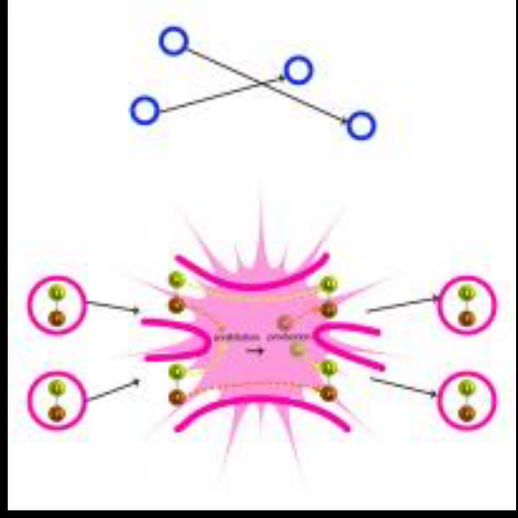
Fornax



NGC6822

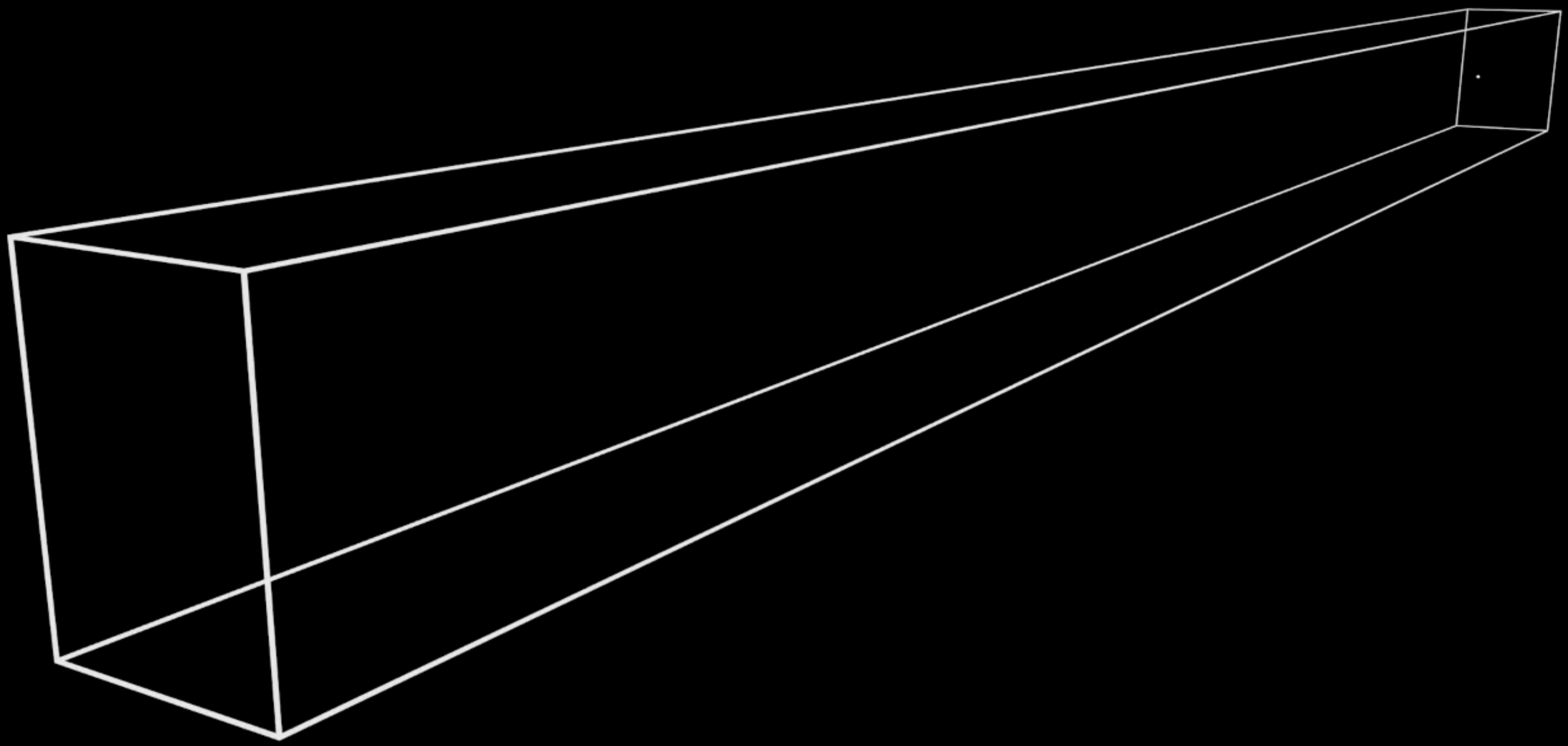


size matters



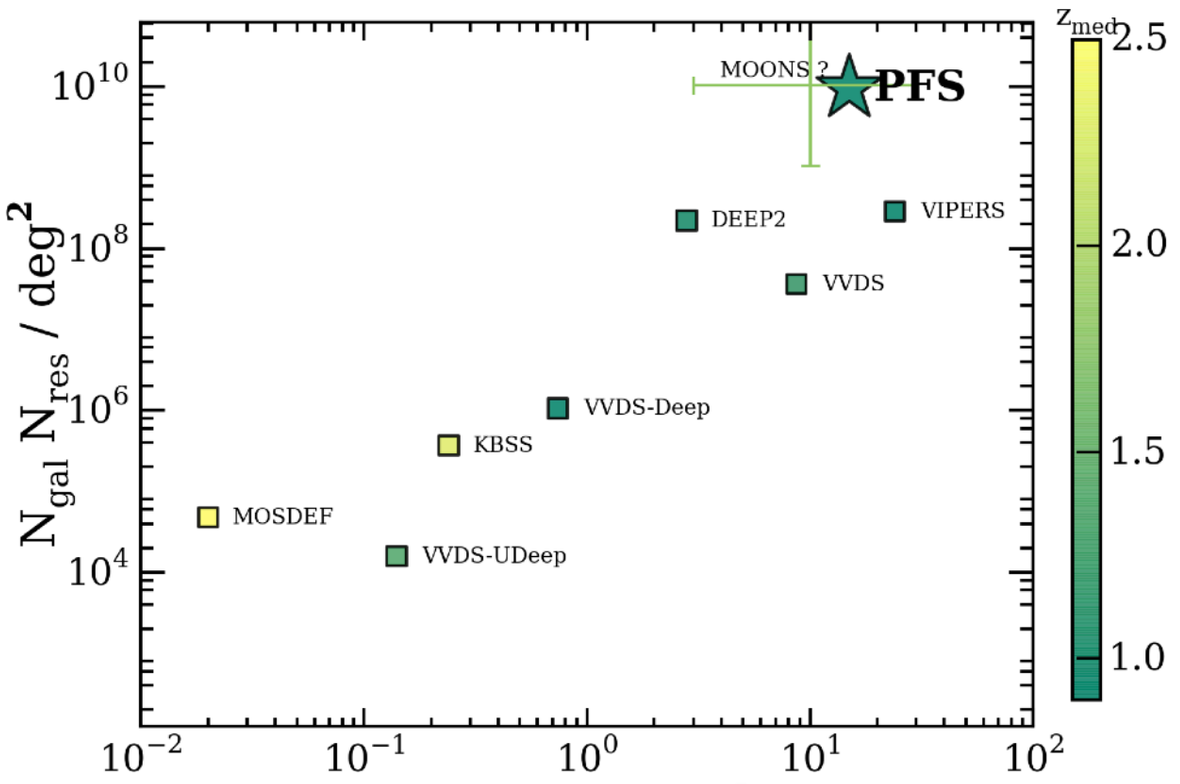
- Perhaps dark matter is a *composite*?
- *dark pions* in *dark QCD*
- SIMP: Strongly Interacting Massive Particles
- Then it has *a finite size*
- flattens the spikes in dark matter profile
- actually desirable for dwarf galaxies?

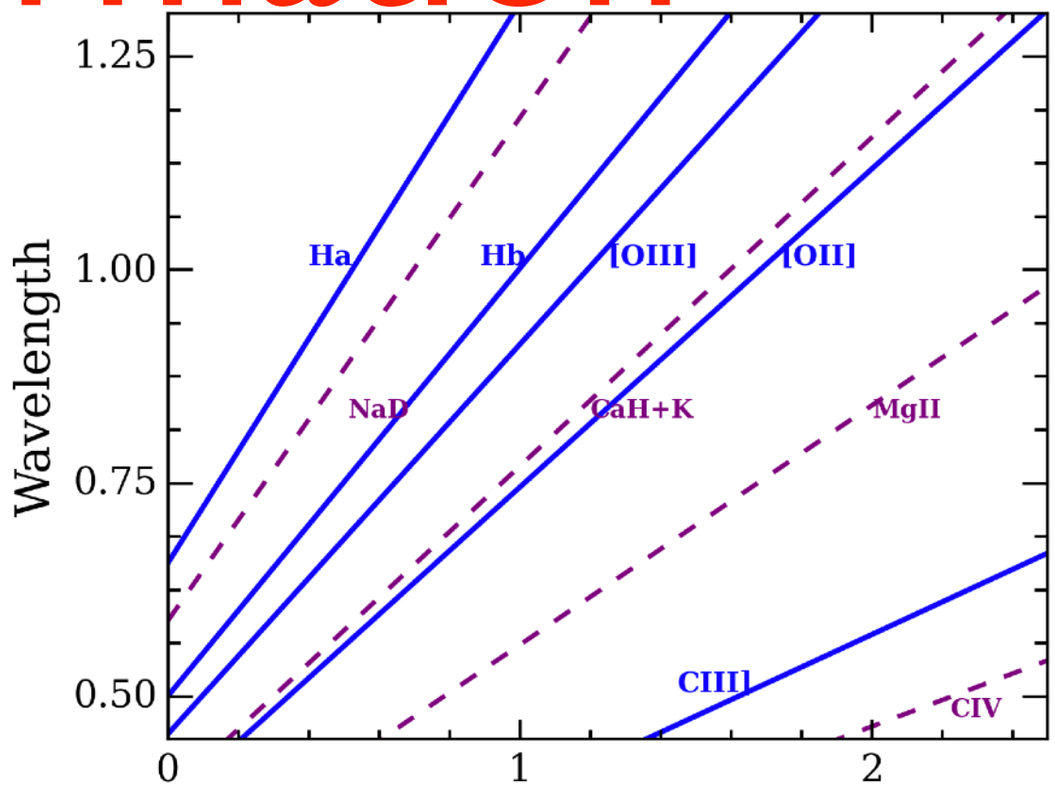
IGM tomography

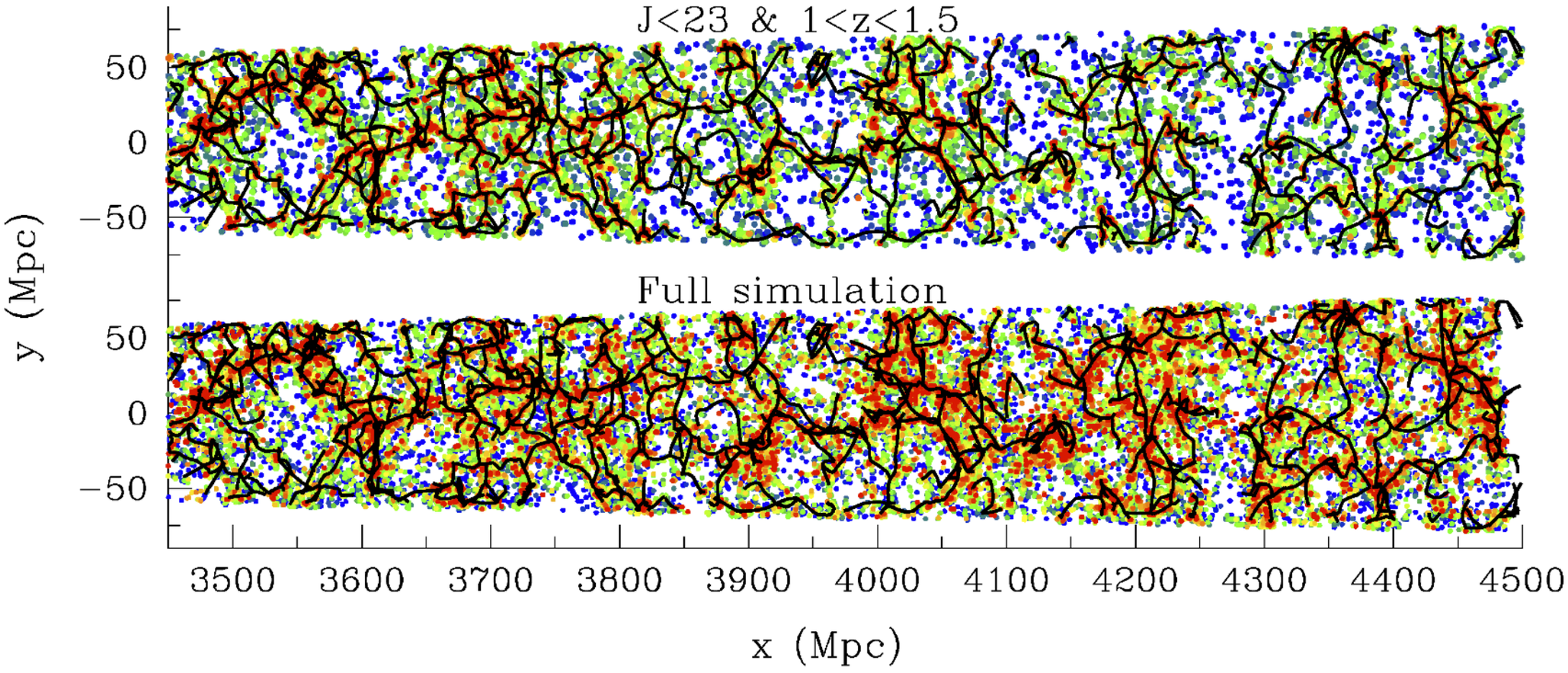


PFS ~ Keckx100

structure formation

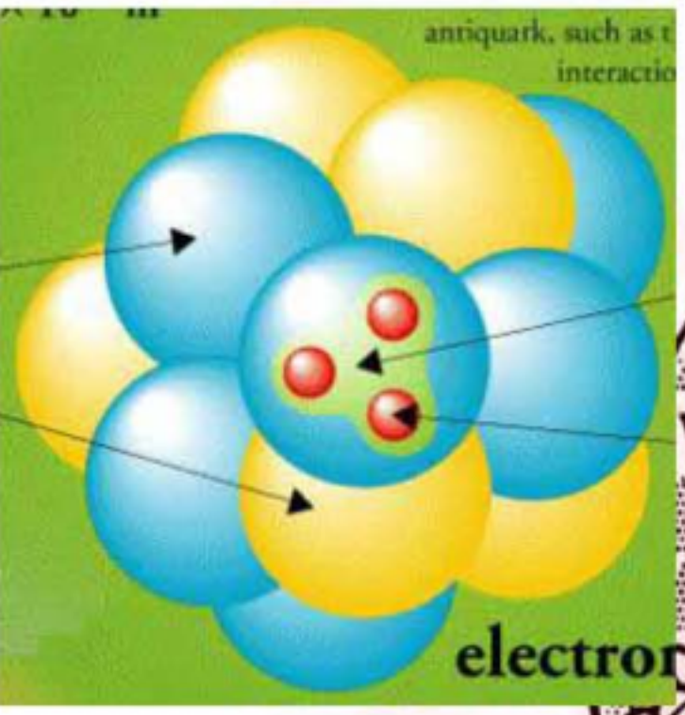


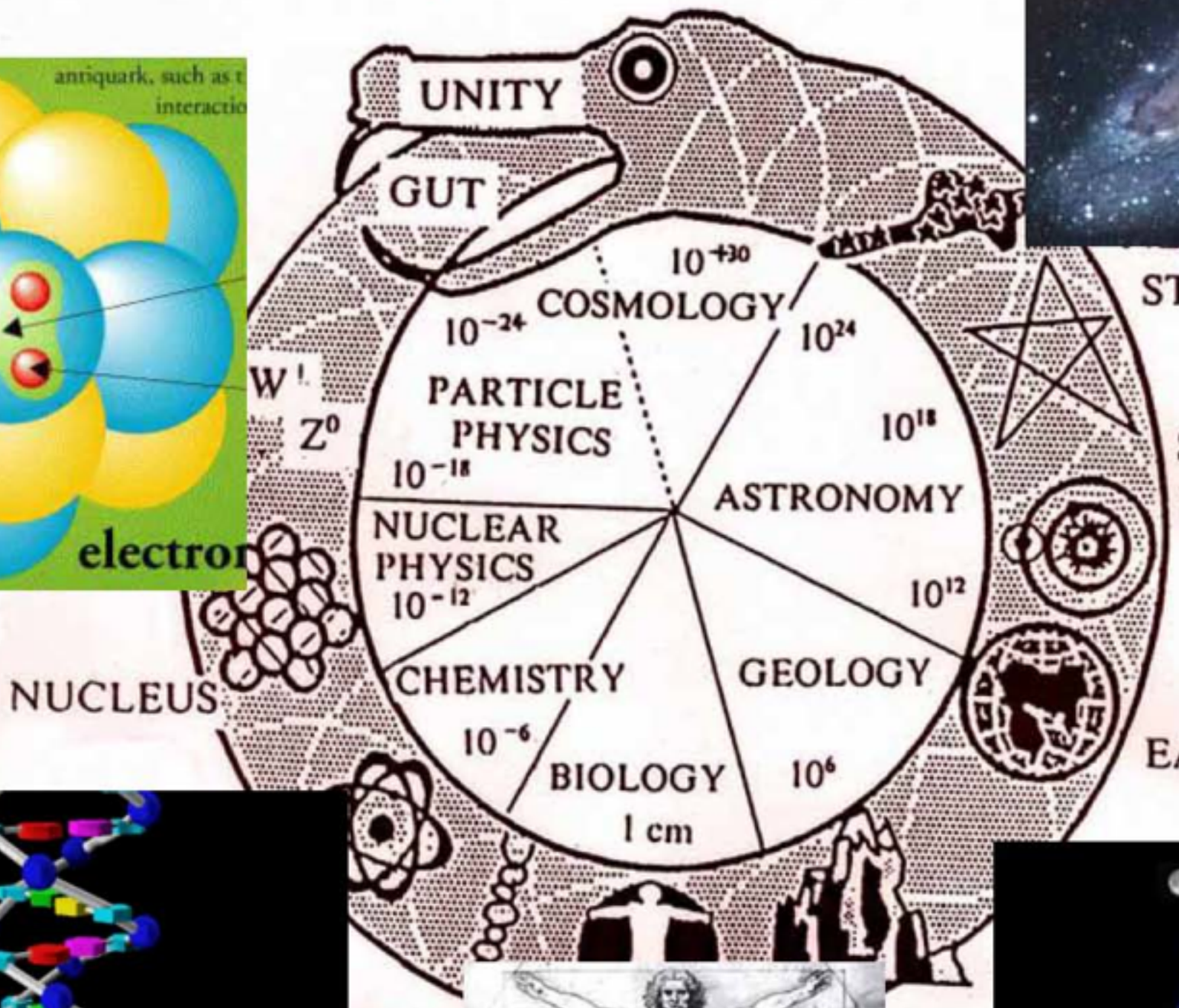


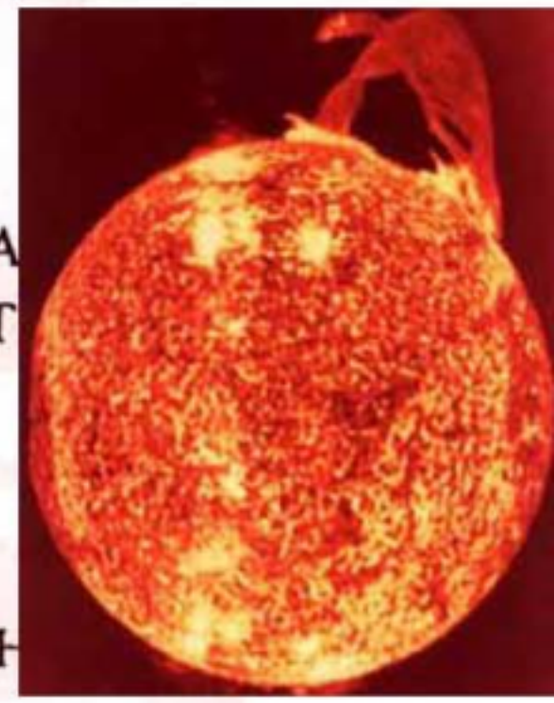


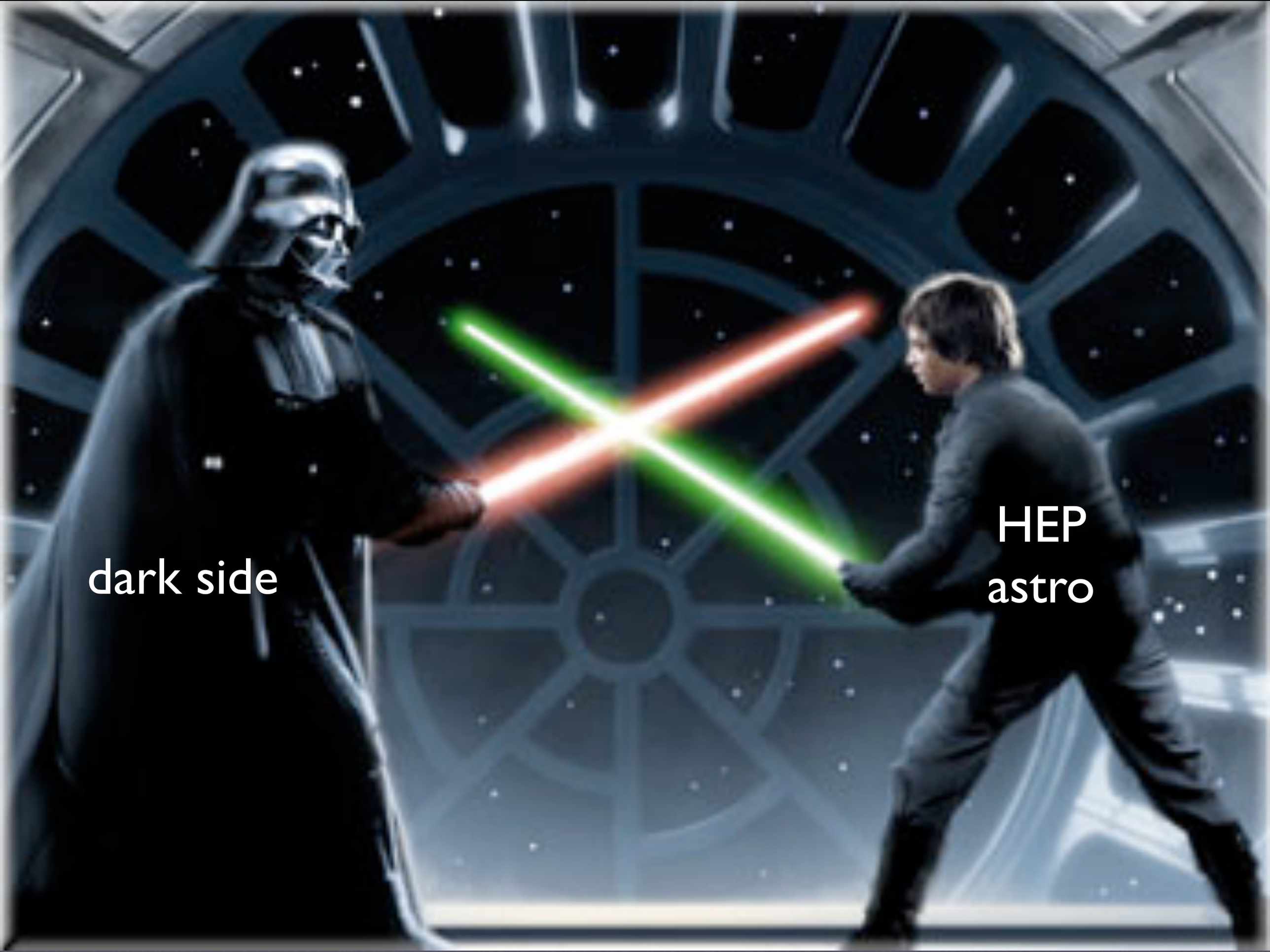
http://sumire.ipmu.jp/pfs/intro.html

Snake of Sizes








dark side
HEP
astro