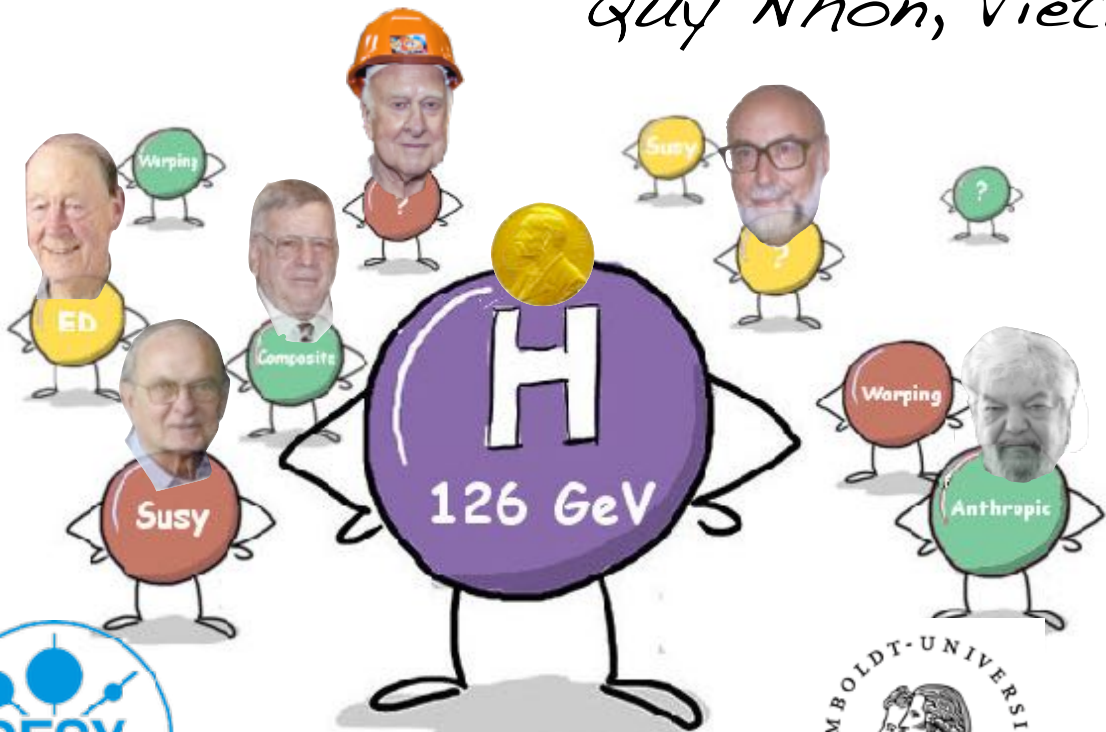
Higgs and BSM Physics

AEPSHEP 2018

Quy Nhon, Vietnam



Lecture 4/4

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Outline

Lecture #1

- From Fermi theory to the Standard Model
- Chirality, fermion masses, spontaneous symmetry breaking
- Custodial symmetry
- Gauge boson masses, unitarity and the Higgs boson

Lecture #2

- Higgs phenomenology (decay and production at colliders)
- Higgs quantum potential (vacuum (meta)stability, naturalness)
- Hierarchy problem

Lecture #3

- Supersymmetry
- Composite Higgs
- Extra dimensions

Lecture #4

- Connections particle physics-cosmology
- Quantum gravity: landscape vs swampland
- BSM searches beyond colliders: AMO, EDMs, nñ, GW, PBH

Cosmological relaxation

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- $m_H(t)$: $m_H^2(t=-\infty) = \Lambda^2_{\rm cutoff} \to m_H^2(\rm now) = -(125\,\rm GeV)^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But "Why/How/When does it stop evolving?"
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

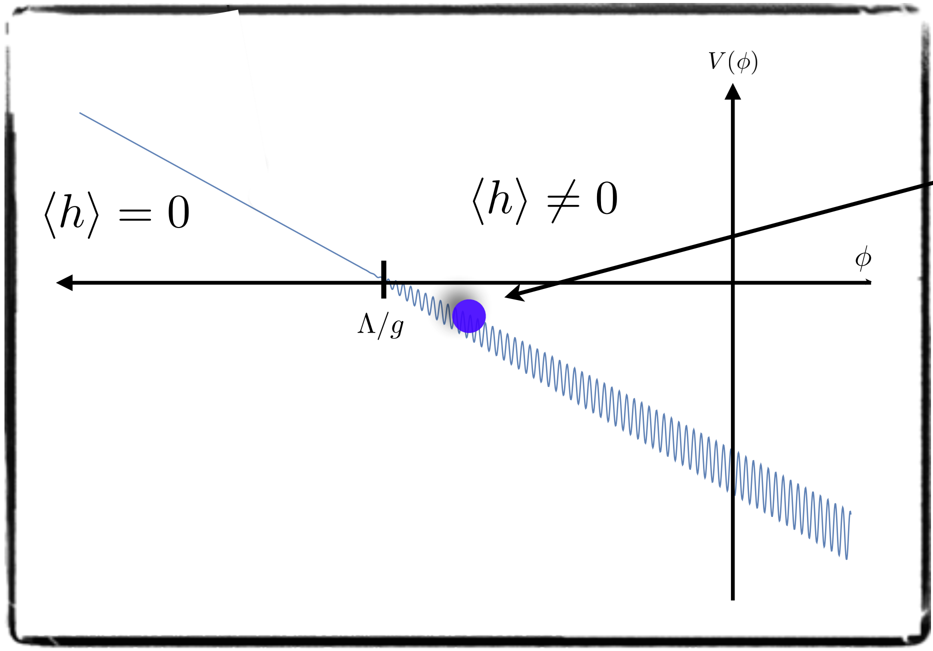
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

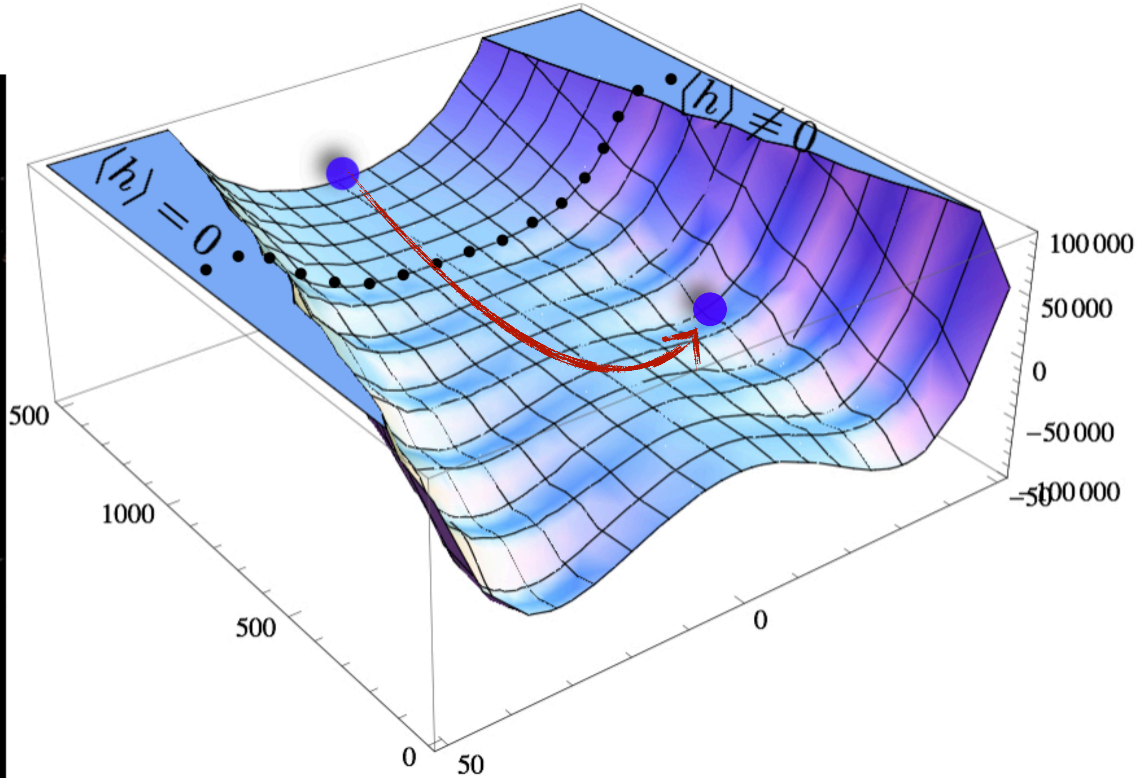
$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$



If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15



Hierarchy problem solved by light weakly coupled new physics and not by TeV scale physics

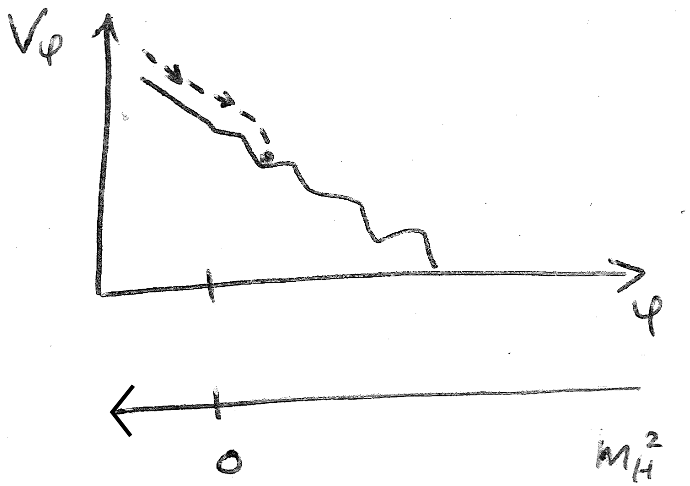
Two classes of relaxion models (so far)

- H-dependent potential barrier

Graham, Kaplan, Rajendran '15

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

potential barriers in the relaxion potential appear soon after EWSB occurs and the relaxion gets trapped in one minimum



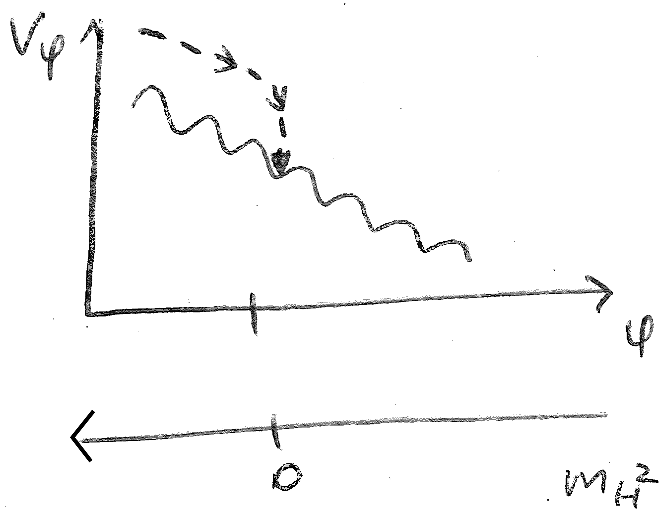
- H-dependent friction

Hook, Marques-Tavares '16

You '17

Fonseca, Morgante, Servant '18

the potential barriers in the relaxion potential always exist but there is no friction to stop the relaxion in one the minimum until the Higgs vev approaches a critical value



drawings borrowed from A. Matsedonskyi, DESY workshop seminar '17

Consistency Conditions

note: v<<Λ provided that g<<1. It doesn't explain why the coupling is small (that question can be postponed to higher energies, requires more model-building engineering, relaxion=PGB?) but it ensures that the solution is stable under quantum correction.

- **Higgs vev stops cosmological rolling**

$$\Lambda^3_{\rm QCD}\frac{v}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$$

- **Slow rolling:** $H_I > \frac{\Lambda^2}{M_P}$

ensures that the energy density stored in ϕ does not affect inflation

- **Classical rolling:** $H_I^3 < g\Lambda^3$

classical displacement over one Hubble time > quantum fluctuation

$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2} > H_I$$

$$\frac{\Lambda^6}{M_P^3} < g\Lambda^3 = \Lambda^3_{\rm QCD}\frac{v}{f} \quad \text{i.e.} \quad \Lambda < 10^7\,\text{GeV}\left(\frac{10^9\,\text{GeV}}{f}\right)^{1/6}$$

Pbs.

1. θ_{QCD}~ 1 ≫10^{-10}. Can be solved but Λ < 30 TeV
2. large field excursion: $\Delta\phi \sim \Lambda/g \sim f\Lambda^3/(v\Lambda_{QCD}^3) \gg 1$, $N_e \sim \frac{f^2\Lambda^8}{v^2\Lambda^6_{QCD}M_P^2} \gg 1$

Quantum stability of relaxing Lagrangians...

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \Lambda_B^4\cos(\phi/f) + \ldots$$

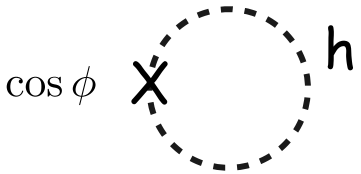
$$\Lambda_B^4 = \Lambda_{B(0)}^4 + \Lambda_{B(1)}^3 h + \Lambda_{B(2)}^2 h^2 + \ldots$$

necessary condition for the Higgs vev to stop the relaxion: $\Lambda_B^4 < v^4$

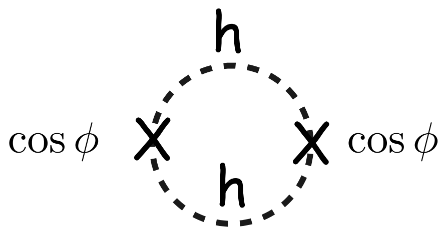
- **n=1:** need another source of EWSB
  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor

    ⊩ new physics @ TeV, coincidence problem? ⫣

- **n=2:** no extra source of EWSB needed
  - quantum stability? h-loops generate extra interactions that will stop ϕ before the Higgs vev develops unless Λ_B<v (new physics below TeV again)



$\Lambda_{B(2)}^2\Lambda^2\cos(\phi/f)$



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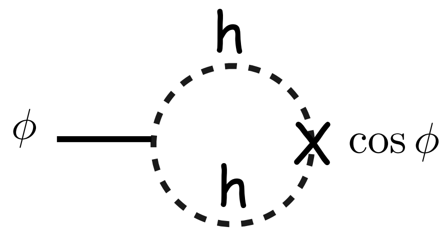

$g\Lambda\Lambda_{B(2)}^2\phi\cos(\phi/f)$

Cosmological Higgs-Axion Interplay (CHAIN)

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

introduce a second field to scan the potential barrier

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) - \Lambda^2\left(\alpha-\frac{g\phi}{\Lambda}\right)|H|^2 + \frac{1}{2}\lambda|H|^4 + A(\phi,\sigma,H)\cos\left(\phi/f\right)$$

$$\epsilon = \left(\frac{\Lambda_B}{\Lambda}\right)^4 \qquad A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

quantum generated new terms from the $|H|^2\cos(\phi/f)$ term

the new interaction that saves our day

original relaxion-type term

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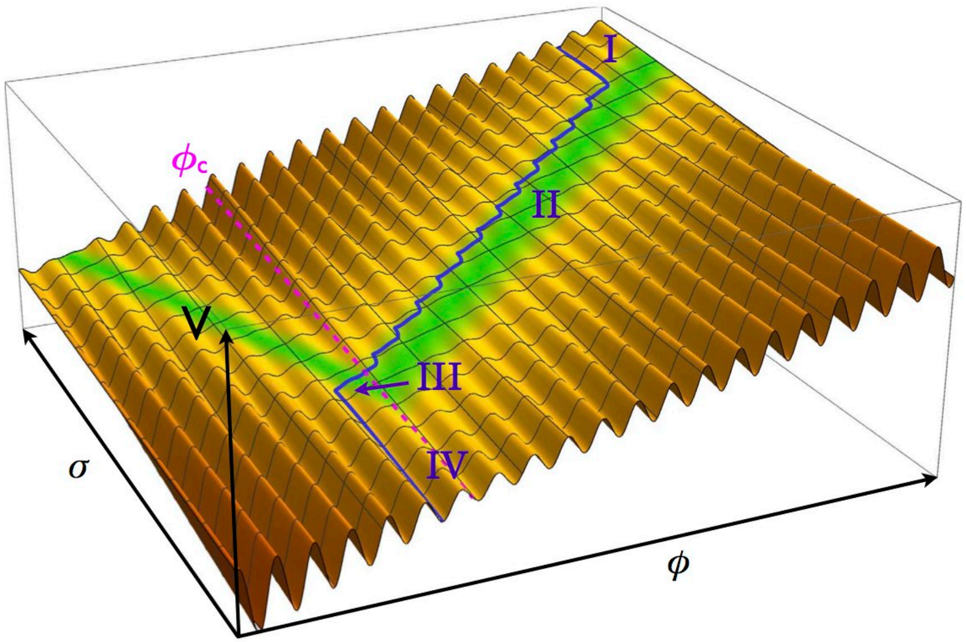
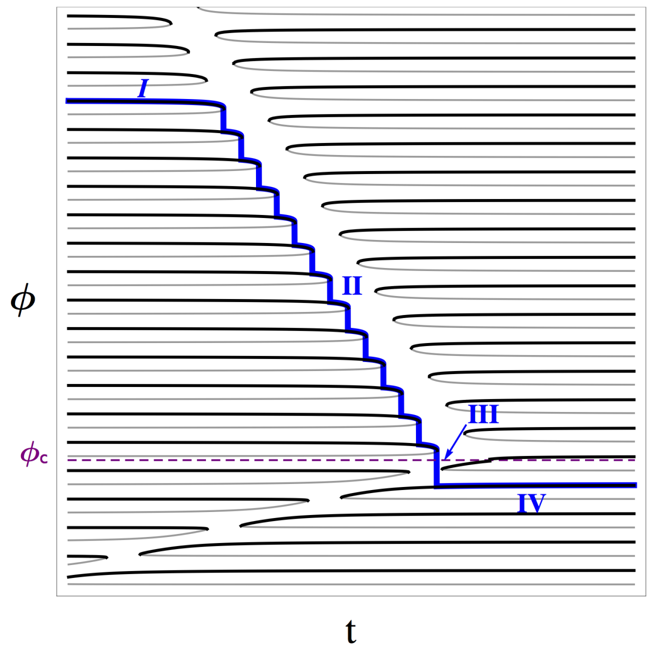




Same problem, same solution?

EW SCALE AS COSMOLOGICAL ERRATIC

courtesy to JR Espinosa

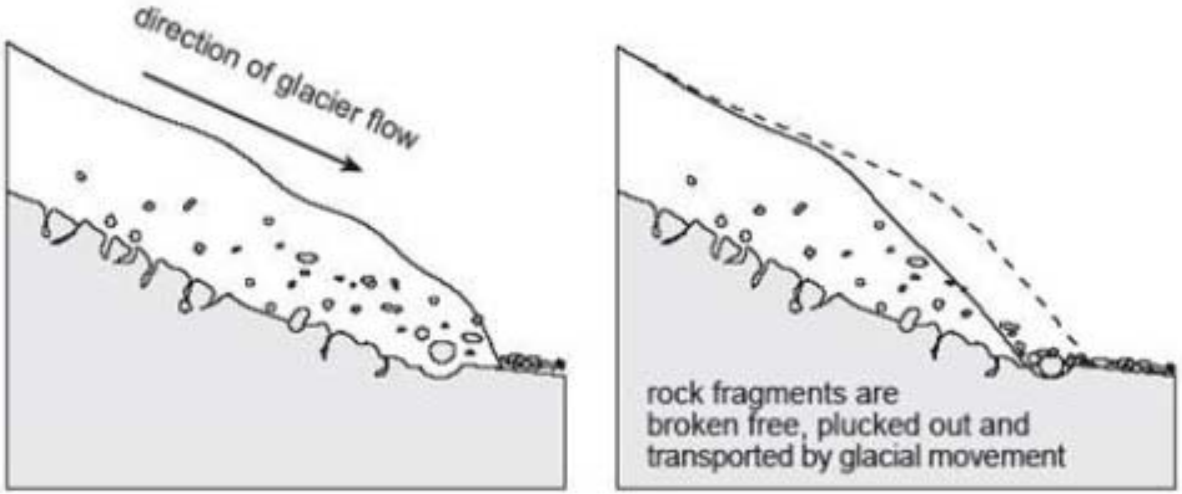
okotoks glacial erratic,
Alberta, Canada

Unnatural large rocks differing in composition from the typical surrounding ones

Same problem, same solution?

EW SCALE AS COSMOLOGICAL ERRATIC

courtesy to JR Espinosa



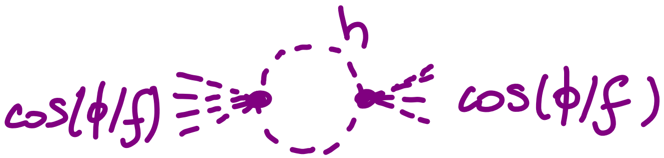
Standard geological history:
they were transported by ancient glaciers over hundreds of kilometers

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

Ex.



$\epsilon^2\Lambda^4\cos^2(\phi/f)$

should be subleading compared to $\epsilon\Lambda^2 h^2\cos(\phi/f)$

Requires $\epsilon \lesssim v^2/\Lambda^2$

courtesy to JR Espinosa

large potential barrier allowed: $\Lambda_B^4 < v^2\Lambda^2$

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

  ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

- Higgs vev stops cosmological rolling $\frac{\epsilon\Lambda^2 v^2}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$

- Slow rolling: $H_I > \frac{\Lambda^2}{M_P}$ ensures that the energy density stored in σ and ϕ does not affect inflation

- Classical rolling: $H_I^3 < g_\sigma\Lambda^3$

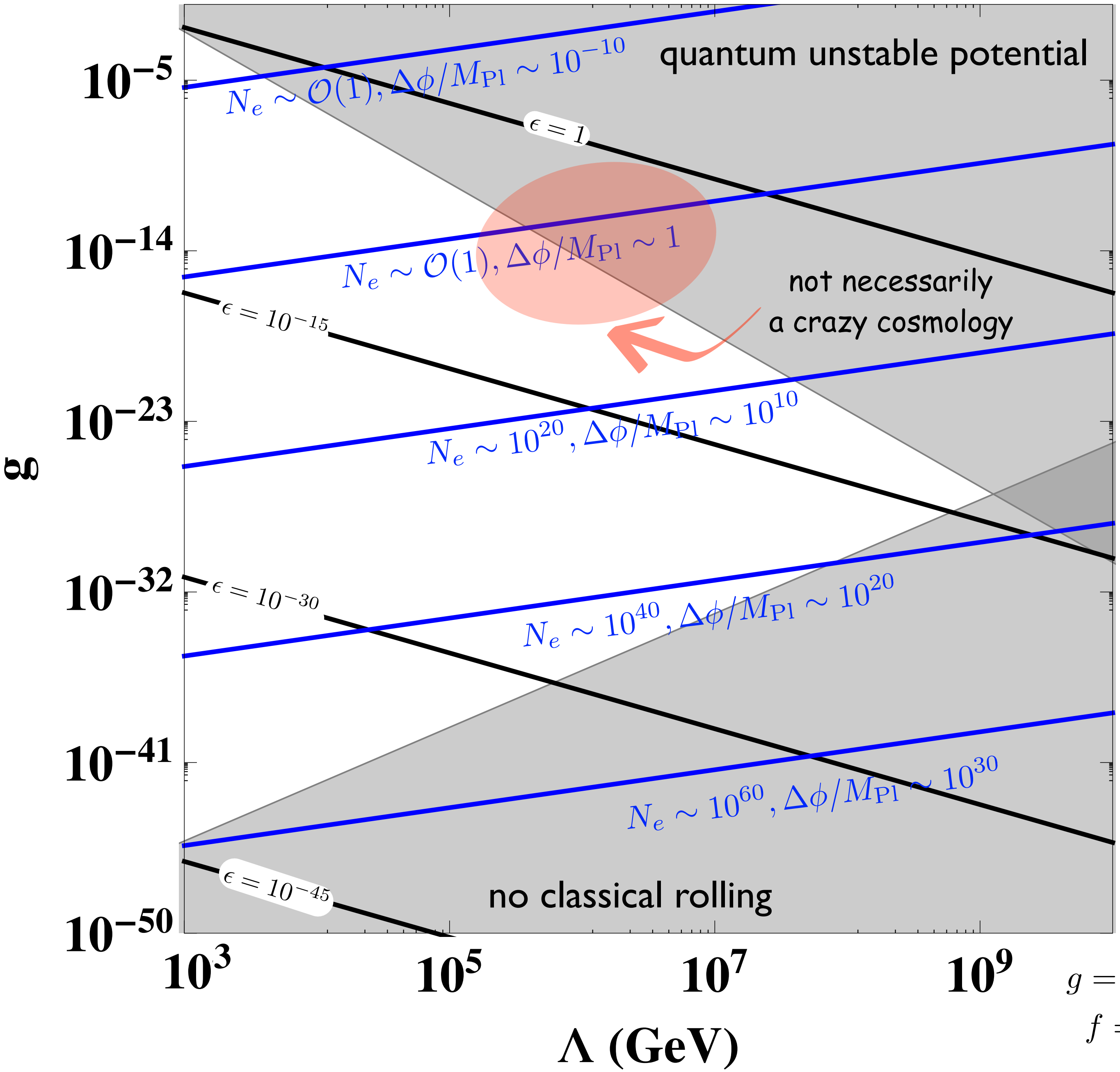
- ϕ tracks σ in the barrier-free valley before EWSB: $c_\phi g^2 > c_\sigma g_\sigma^2$

- ϕ exits the barrier-free valley after EWSB: $(c_\phi - \frac{1}{2\lambda})g^2 < c_\sigma g_\sigma^2$

- large field excursions: $\Delta\phi, \Delta\sigma > \Lambda/g$ to ensure that the Higgs mass scans from Λ to the weak scale

$$\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3} \quad \Rightarrow \quad \Lambda \lesssim \left(v^4 M_{\rm Pl}^3\right)^{1/7} \simeq 2\times 10^9\,{\rm GeV}$$

Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Best solution to little hierarchy pb?

Long epoch of **inflation** to allow the field to explore large range values and reach the critical point without fine-tuning

$$\Delta\sigma \sim N_e \left(\frac{g_\sigma \Lambda^3}{H_I^2}\right) > \Lambda/g_\sigma$$

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

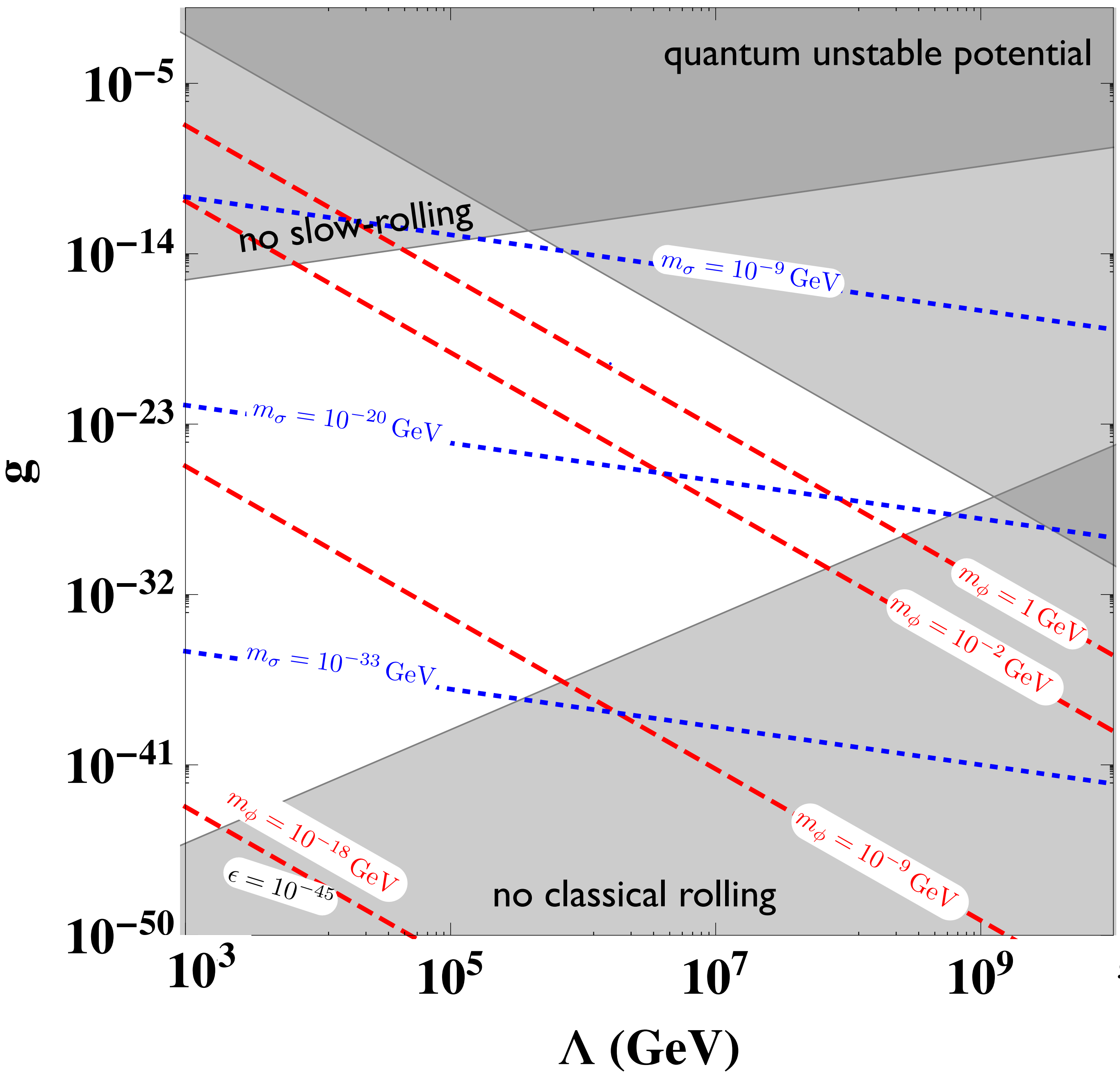
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim \left(\frac{g\,\Lambda^5}{f\,v^2}\right)^{1/2} \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim g_\sigma \Lambda \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

Phenomenological signatures



$g = 10 g_\sigma$

$f = \Lambda$

Phenomenological signatures

A QFT rationale for light and weakly coupled degrees of freedom

Espinosa et al '15

Flacke et al '16

Choi and Im '16

~interesting cosmology signatures~

◎ BBN constraints
◎ decaying DM signs in γ-rays background
◎ ALPs
◎ superradiance

~interesting signatures @ SHiP~

◎ production of light scalars by B and K decays

~interesting atomic physics~

◎ change of atom sizes

G. Perez et al 'in progress

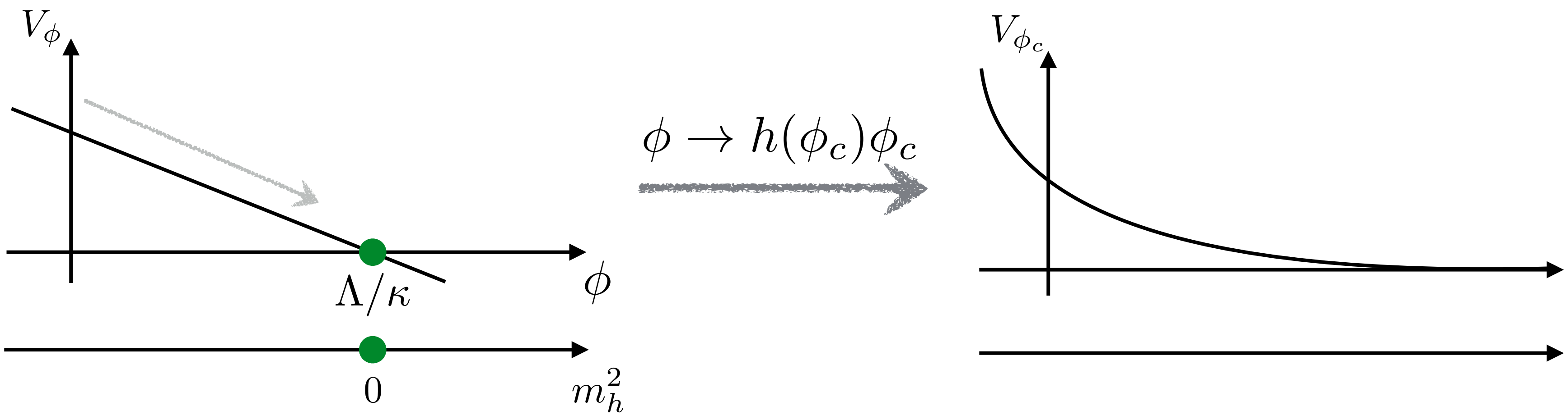
Relaxing without multiple vacua: pole attractors

Matsedonskyi, Montull '17

- The Higgs mass is scanned by the relaxion field ϕ

$$V_h \supset (-\Lambda^2 + \kappa\Lambda\phi)\, h^2 \qquad\qquad (V_\phi = -\kappa\Lambda^3\phi)$$

- The relaxion has a non canonical kinetic term $\frac{1}{h^{2n}}(\partial_\mu\phi)^2$
- When $\phi \to \Lambda/\kappa$ then $h \to 0$ and the kinetic term grows.

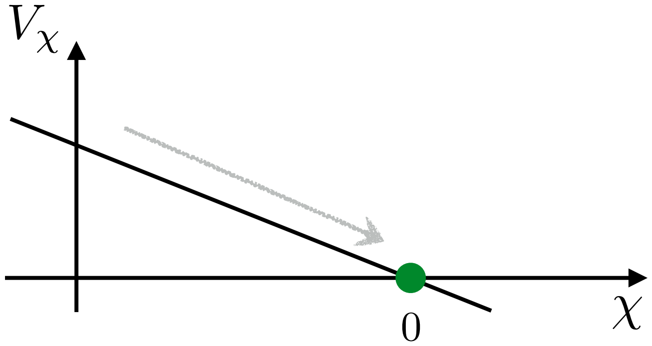


- The slope of the relaxion potential and coupling to the Higgs decrease and the scanning effectively stops.

- derivative Higgs-relaxion couplings becomes non-perturbative
- UV completions unknown

Pole attractors: minimal realistic model

Matsedonskyi, Montull '17

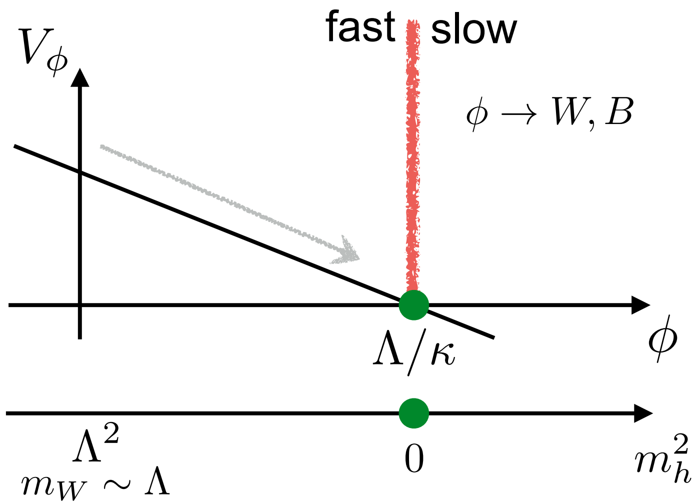


1) kinetic terms controlled by a new field χ

$$\frac{1}{\chi^2}\left\{(\partial\chi)^2 + (\partial\phi)^2\right\}$$

motivated by SUSY-based inflation models

2) χ provides a limited time for a scan until it gets to zero and blocks all the evolution



3) ϕ moves quickly before reaching h~0, and after it's slowed down by particle friction provided

$$\dot{\phi} \gtrsim m_W\, f$$

* f controls particle friction

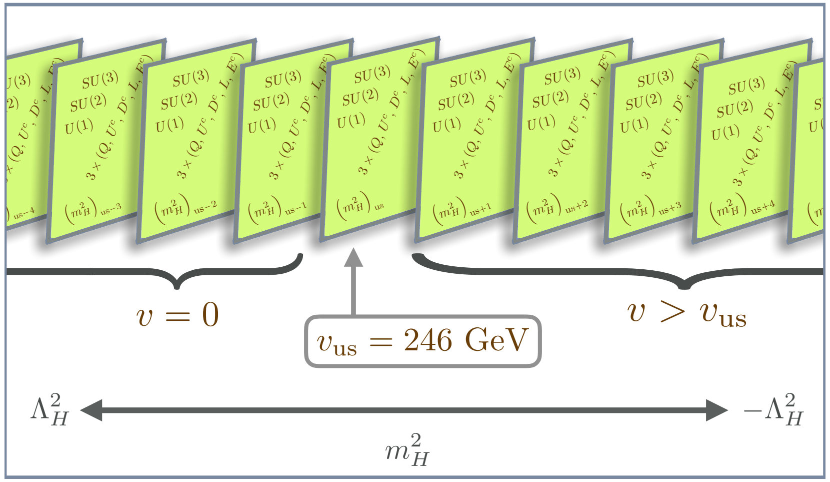
4) remaining part of the limited time relaxion is very slow, almost no scan is possible

NNaturalness

or another way to select our vacuum

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

NNaturalness



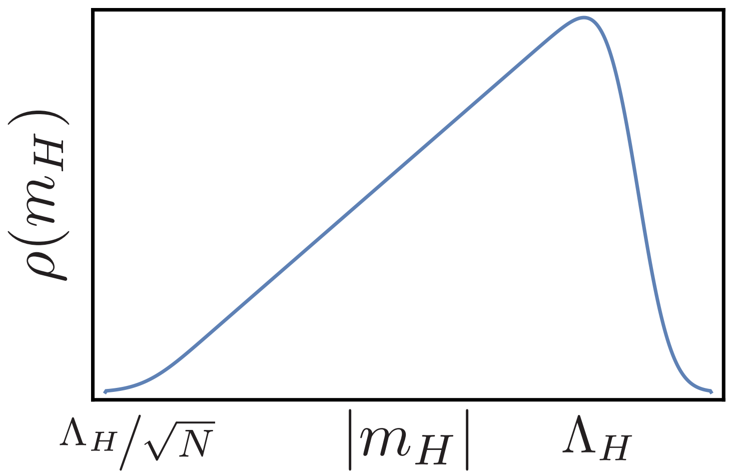
N copies of the SM

High Higgs cutoff Λ_H, high gravity cutoff Λ_G

Two effects:

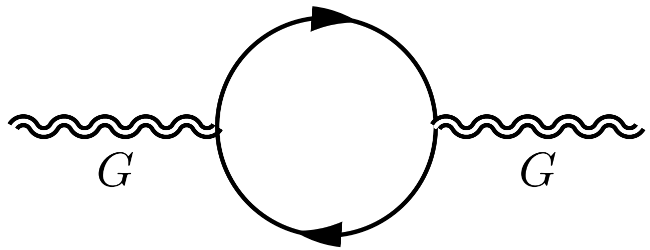
(N. Craig @ Paris'18)

1. Random UV contributions → flat distribution of m_H^2 between $\pm\Lambda_H^2$



At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$

2. Large number of species renormalizes Planck scale (e.g. graviton wavefunction renorm.)



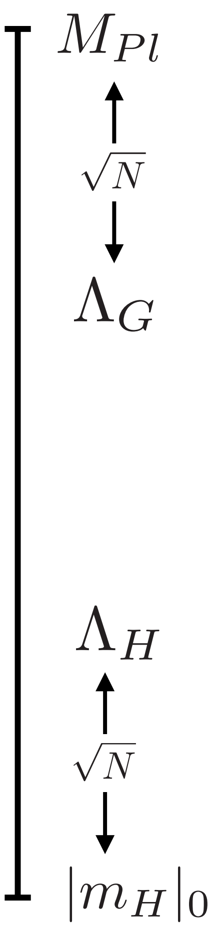
Gravitational strong coupling scale Λ_G below M_{Pl}

$$M_{Pl}^2 \sim N\Lambda_G^2$$

NNaturalness

(N. Craig @ Paris'18)

Scale separation from large N:



For example:
One copy w/ weak-scale Higgs for

N=10^16: $\Lambda_H = 10^{10}$ GeV
$\Lambda_G = 10^{10}$ GeV
(That's it.)

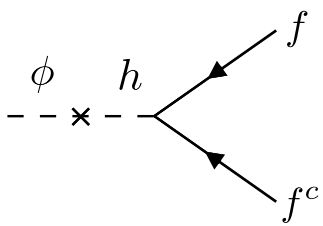
N=10^4: $\Lambda_H = 10^{4}$ GeV
$\Lambda_G = 10^{16}$ GeV
(SUSY or compositeness at Λ_H)

Now…why does the copy with the smallest m_H dominate?
Cosmology.

Reheaton ϕ starts universe via $\phi\, |H_i|^2$ couplings

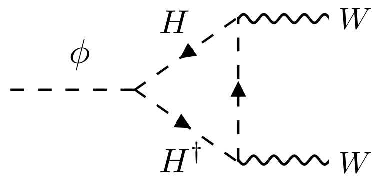
Decays (provided $m_\phi < |m_{H_i}|$)

$m^2_{H,i} < 0$



$\Gamma \propto \frac{1}{m^2_{H,i}}$

$m^2_{H,i} \geq 0$



$\Gamma \propto \frac{1}{m^4_{H,i}}$

Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2 < 0$

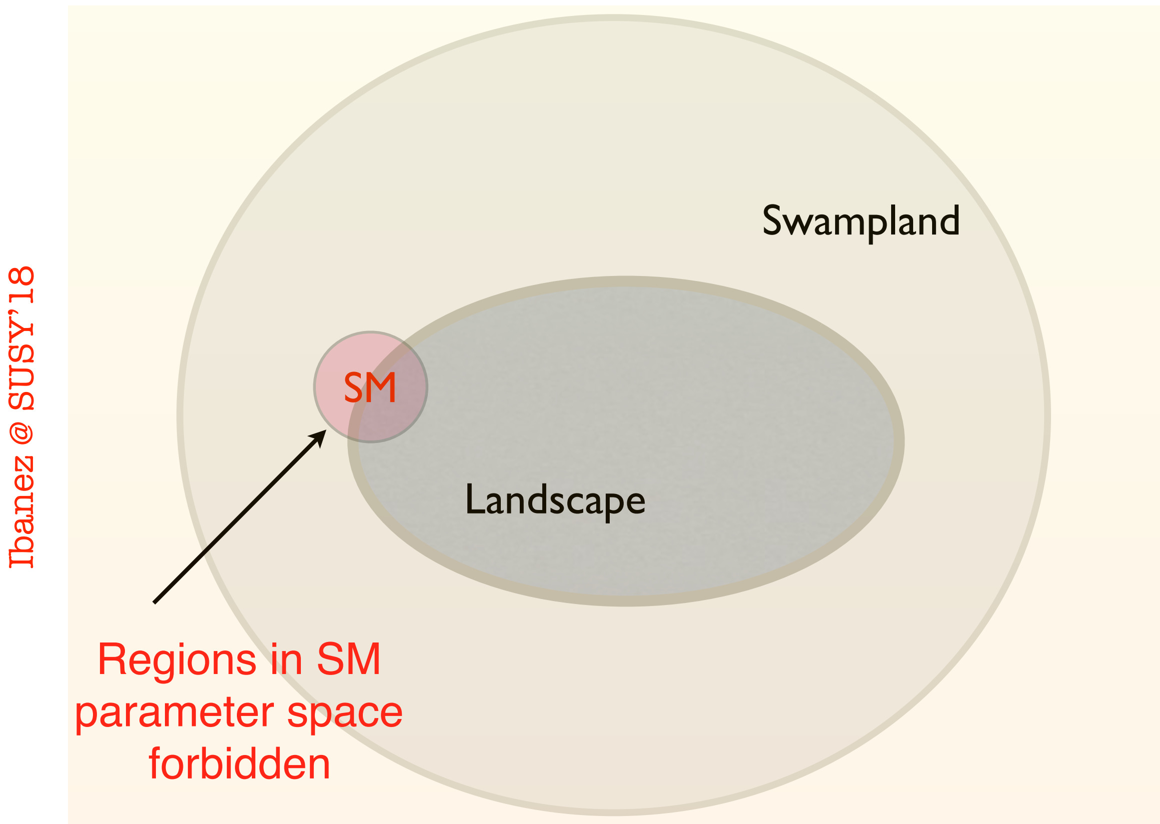
Swampland: UV/IR mixing

Particle Physics & Quantum Gravity

Can the SM be embedded in a theory of quantum gravity at the Planck scale?
Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**



This conjecture has potentially far-reaching implications for phenomenology

Landscape/Swampland Conjectures

0) No exact global symmetry

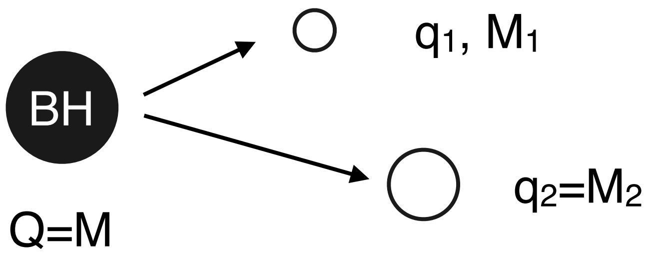
For a review, see Banks, Seiberg '10

1) Gravity is the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa '06

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that: $M/M_P < g \cdot q$

Why? otherwise extremal charged BH cannot decay!



BH can decay iff $M_1+M_2<M$, i.e. $M_1<M-M_2=Q-q_2=q_1$

Landscape/Swampland Conjectures

2) non-susy AdS vacua (Vmin<0) are unstable

Ooguri, Vafa '16

Consider the SM (with cc) compactified on a circle of radius R

Ibanez, Martin-Lozano, Valenzuela '17

$$V(R) \simeq \frac{2\pi r^3 \Lambda_4}{R^2} - 4\left(\frac{r^3}{720\pi R^6}\right) + \sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R)$$

From 4D c.c. (first term); $\gamma, g_{\mu\nu}$ (second term); ν_i (sum)

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi R m n)}{(2\pi R m n)^2}$$

Ibanez @ SUSY'18

Heavier particles have exponentially small contribution

Majorana neutrinos leads to an AdS vacuum ⇒ in swampland

Dirac neutrinos avoid AdS vacuum iif $m_\nu^4 < \Lambda_4$

$\langle H \rangle < 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$ ⇒ Large quantum corrections end up in swampland (for fixed Λ_4 and Y_ν)

SM with 3 families but without Higgs also develops AdS vacuum ⇒ in swampland

Swampland Conjectures

3) $M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel > c\, V(\phi_i)$ with c is O(1) for any field configuration

Obied, Ooguri, Spodyneiko, Vafa '18

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden
- Quintessence: Agrawal, Obied, Steinhart, Rafa '18

$$V(\phi) = \Lambda^4 e^{-\kappa\phi/M_P}$$

$$0.6 > \kappa > c$$

Planck data (0.6 > κ) — swampland conjecture (κ > c)

- Quintessence + Higgs: Denef, Hebecker, Wrase '18

$$V(H,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \lambda(|H|^2 - v^2)^2 + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{cases} \dfrac{\kappa\Lambda^4}{\Lambda^4 + \lambda v^4 + V_0} & @(H=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(H=v,\phi=0) \end{cases}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{EW}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(100\,\text{GeV})^4} \sim 10^{-56}$$

- Quintessence + axion: Murayama, Yamazaki, Yanagida '18

$$V(\theta,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \Lambda_{QCD}^4(1-\cos(\theta/f)) + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{cases} \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(\theta=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + \Lambda_{QCD}^4 + V_0} & @(\theta=\pi f,\phi=0) \end{cases}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{QCD}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(200\,\text{MeV})^4} \sim 10^{-44}$$

Swampland Conjectures

It is not that SM as we know it rules out string theory
But non-trivial interactions among seemingly decoupled sectors must exist
UV forces interactions among IR dof
like anomaly condition forces WZ interactions below the top quark

The Standard Model: Matter

~~The particles seen in a detector~~

Absolutely stable particles	Collider stable particles	Sort of stable particles	Displaced vertex particles
γ (m=0) (G (m=0)) (ν (m~0)) e^- (m=511keV) p (m=938MeV)	n (m=940MeV, ct=10^{14}mm) μ (m=940MeV, ct=10^6mm) K_L (m=500MeV, ct=10^4mm) $\pi^\pm$ (m=140MeV, ct=10^4mm) $K^\pm$ (m=500MeV, ct=10^3mm)	Ξ, Λ, Σ, Ω (m=1-2GeV, ct=10-100mm) K_S (m=500MeV, ct=30mm)	B, D $\Xi_{c,b}$, $\Lambda_{c,b}$ (m=2-5GeV, ct=0.1-0.5mm)

You don’t “see” most of the SM particles!
You have to infer their existence

Test: have you ever seen dinosaurs? You “reconstruct” them from their decay products

Physics probed at Colliders

Colliders are best places to search for

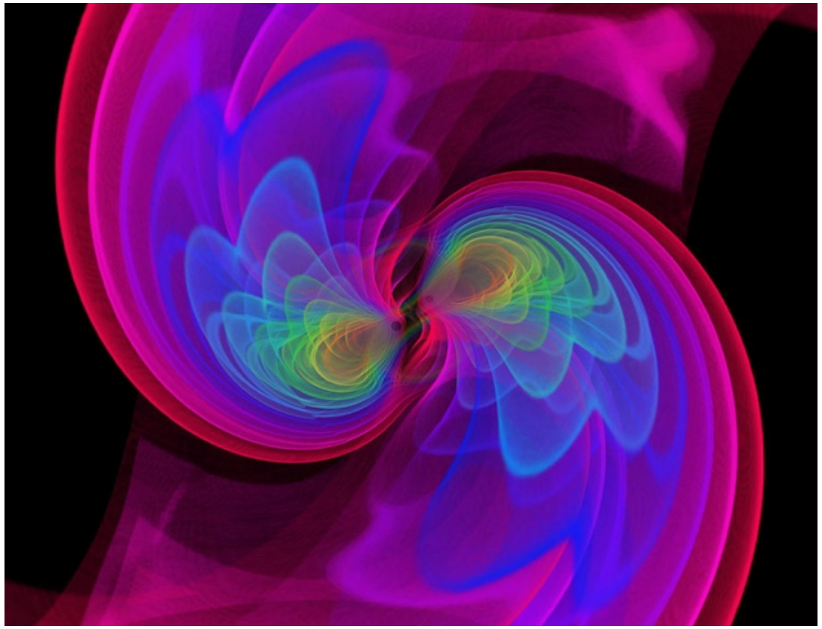
Heavy objects
With short lifetime
That are rarely produced
That have a direct coupling to quarks/gluons or electrons

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions
There are compelling arguments that BSM can be seen at colliders
But we can also find mind-bogging BSM signatures beyond colliders

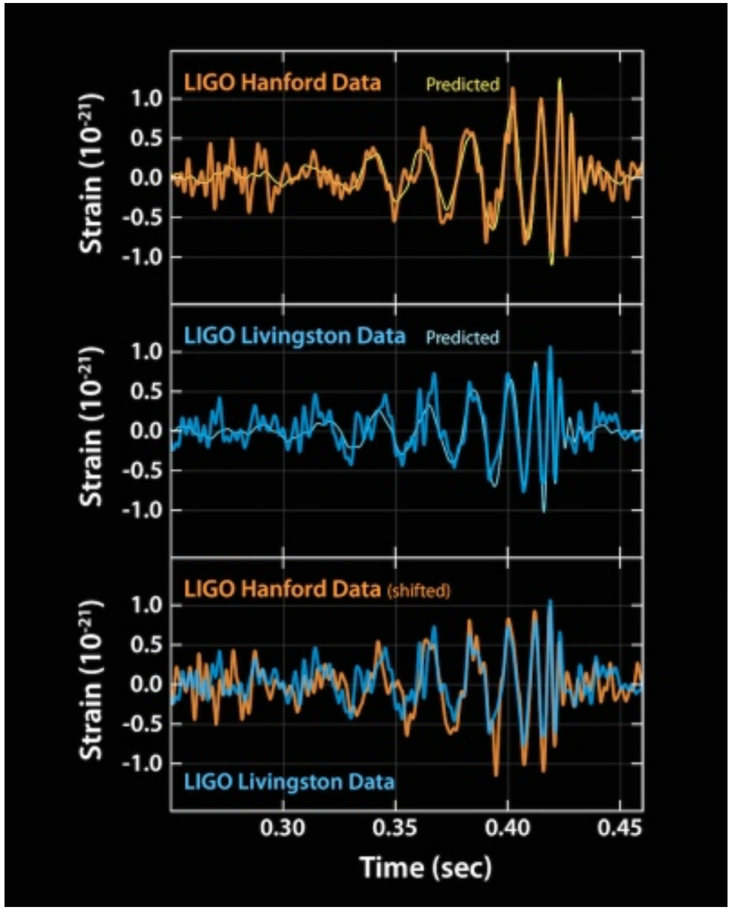
Gravitational waves

The pictures that shook the Earth

GW150914



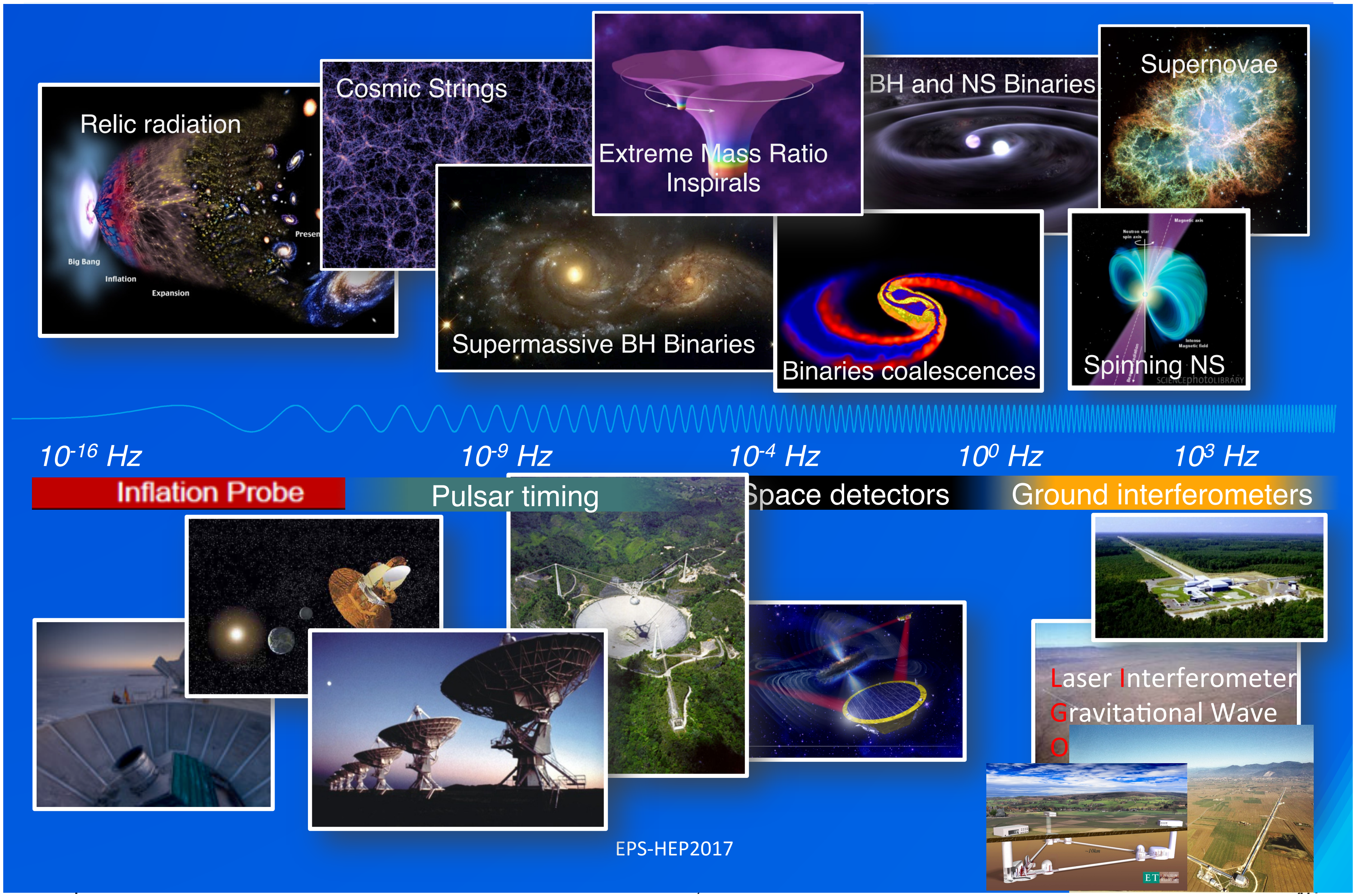
1.3 billion years later on earth



what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

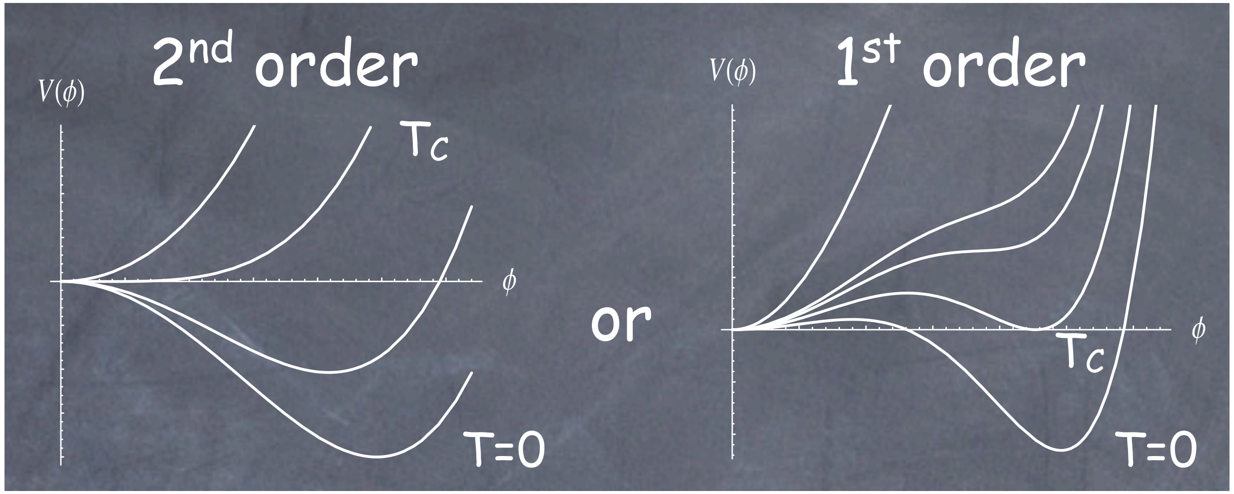
GW and astrophysics/cosmology



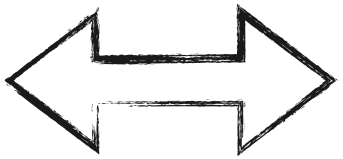
Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)



finite T
Higgs potential

Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

⇓ ⇓

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\, T = 100 \text{ GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}}\frac{T^2}{M_{Pl}} \sim 10^{-15} \text{ GeV}$$

redshifted ⇓ freq.

~ today ~

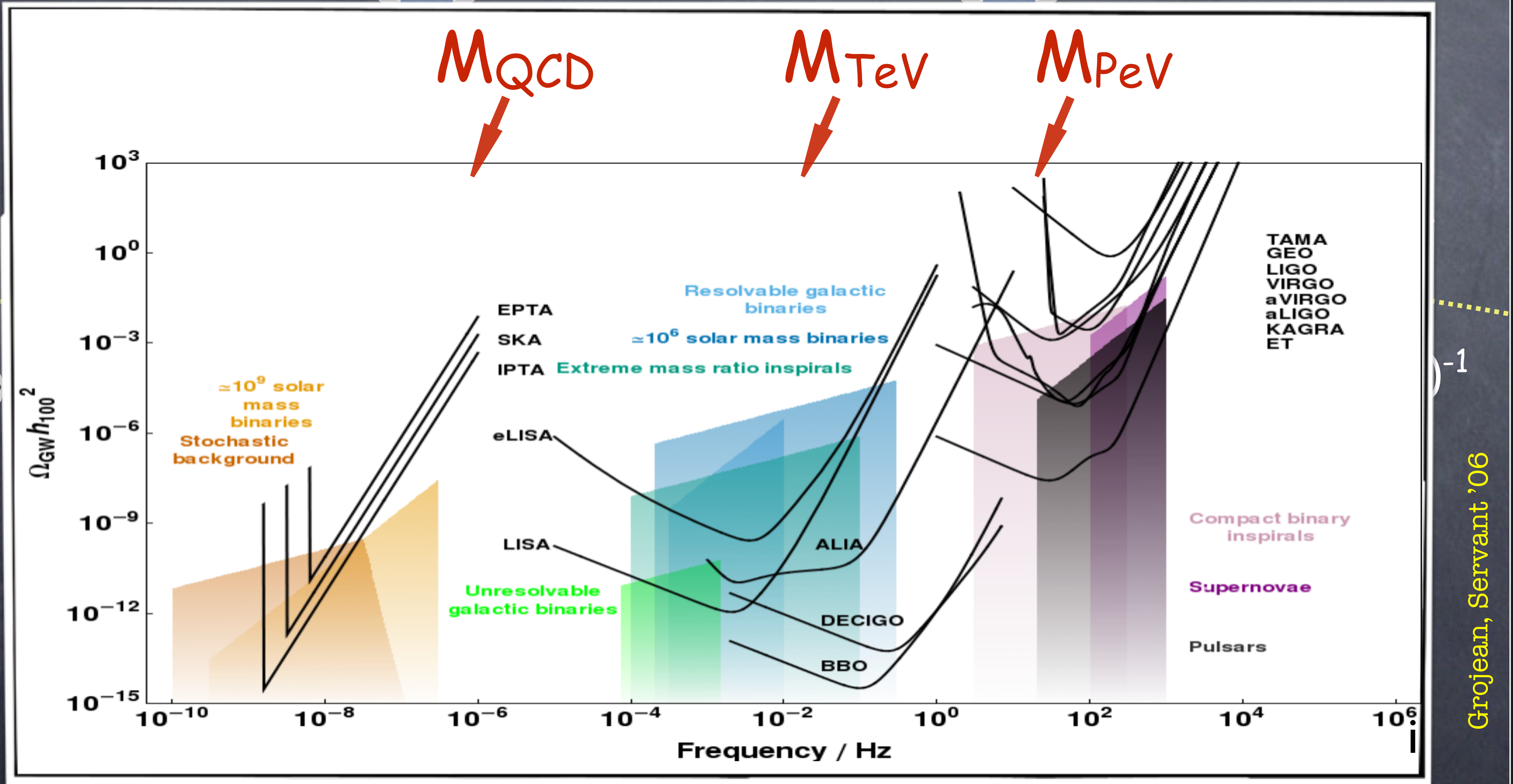
$$f \sim \# \frac{2\cdot 10^{-4} \text{ eV}}{100 \text{ GeV}} 10^{-15} \text{ GeV} \sim \# 10^{-5} \text{ Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

GW and the ElectroWeak Phase Transition

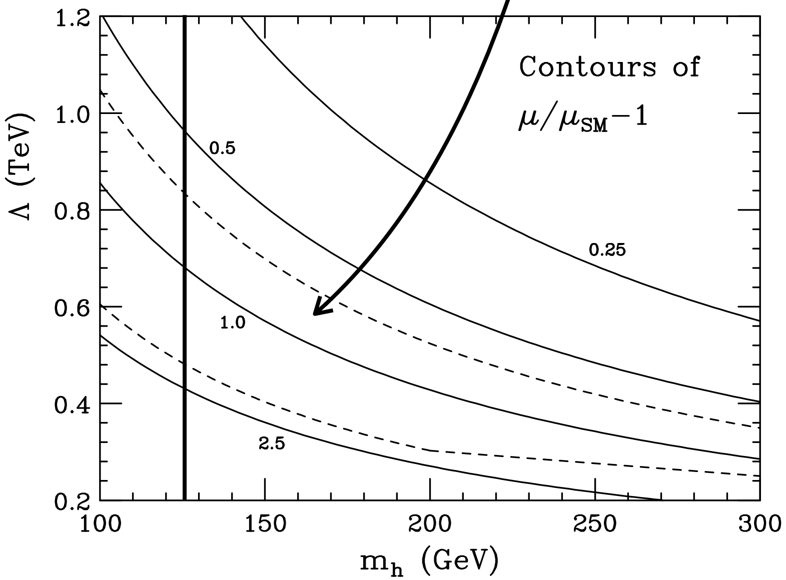
GW interact very weakly and are not absorbed



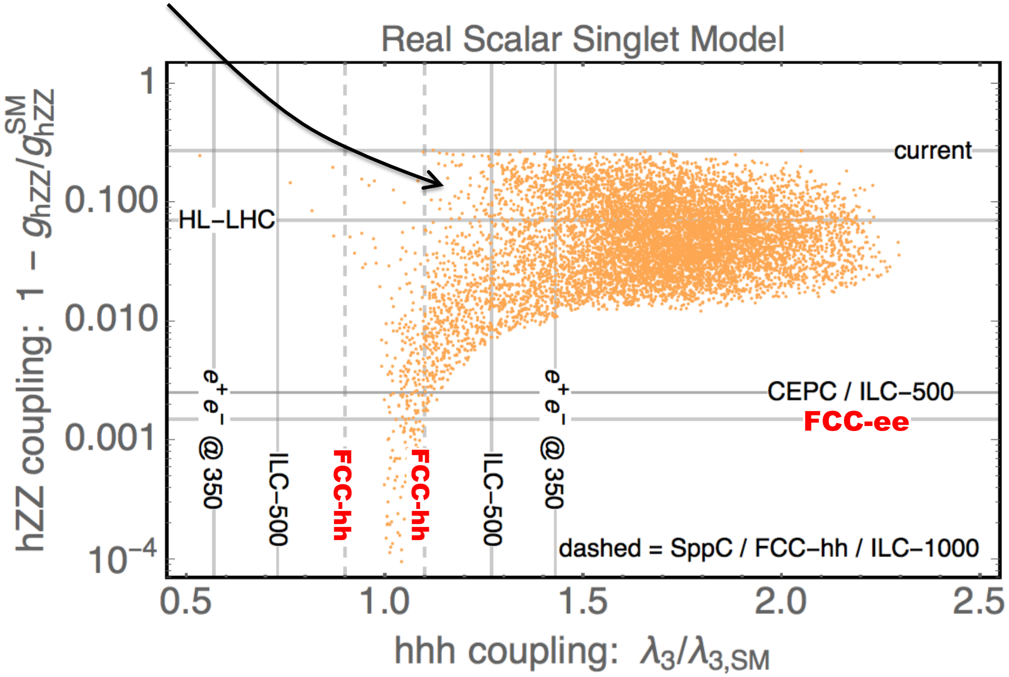
The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Complementary GW - Colliders

EWPT is 1st order and gives rise to GW stochastic background



Grojean, Servant, Wells '04

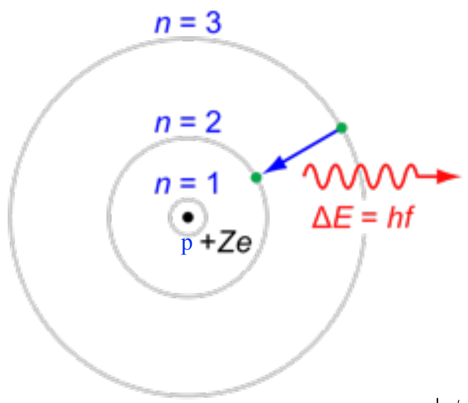


Huang, Long, Wang '16

"Large" deviations of the Higgs (self-)couplings expected to obtain a 1st order phase transition

BSM and Atomic Physics

Atomic Clocks as a BSM probe



Physics beyond QED contributes to the frequency of the radiation

$$\frac{1}{\lambda} = R\,Z^2 \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

$|\psi(0)|^2/n^3$ is the wave-function-density at the origin.

$$V_{\text{weak}}(r) = -\frac{8 G_{\text{F}} m_{Z^0}^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} \frac{e^{-r m_{Z^0}}}{r} \quad \Rightarrow \quad \delta E_{nlm}^{\text{weak}} = -\frac{8 G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi m_Z^2} |\psi(0)|^2 \frac{\delta_{l,0}}{n^3}$$

fifth force ⇒ ?

Exp sensitivity in atomic clock measurements $O(10^{-18})$

(ms over one billon years)

Not all transitions can be used (yet) for BSM

frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity $O(10^{-6:-9})$

can be used to detect new (long range) forces

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A-A')$$

mass shift — field shift — BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed but they are the same for different isotopes

The King Plot

W. H. King, *J. Opt. Soc. Am.* 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta\langle r^2\rangle_{AA'}/\mu_{AA'}$ and substitute back into transition 2:

$$F_{21} \equiv F_2/F_1 \quad K_{21} \equiv K_2 - F_{21}K_1 \quad H_{21} \equiv H_2 - F_{21}H_1$$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

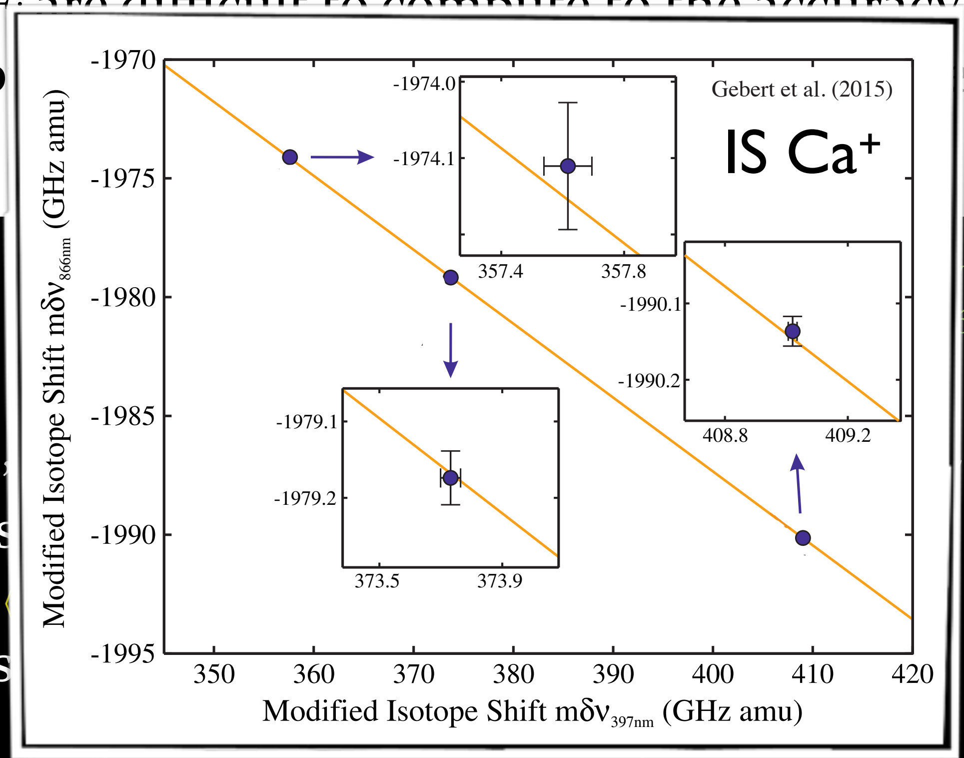
$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A-A')$$

mass shift — field shift — BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed

b ... es

The ... . H. King, ... 538 (1963)



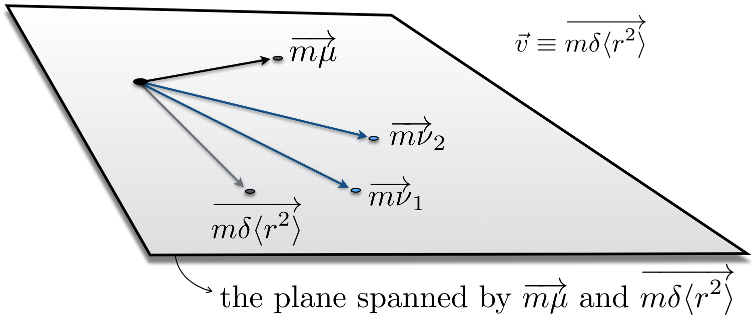
- First, ... AA'
- Meas ... 1 to set δ ... trans ...

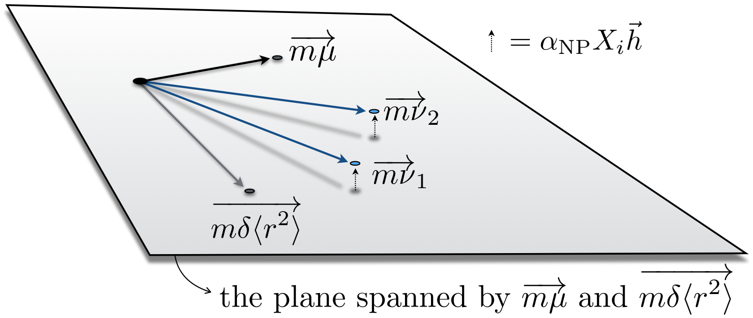
$\equiv F_2/F_1$
$\equiv K_2 - F_{21}K_1$
$\equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

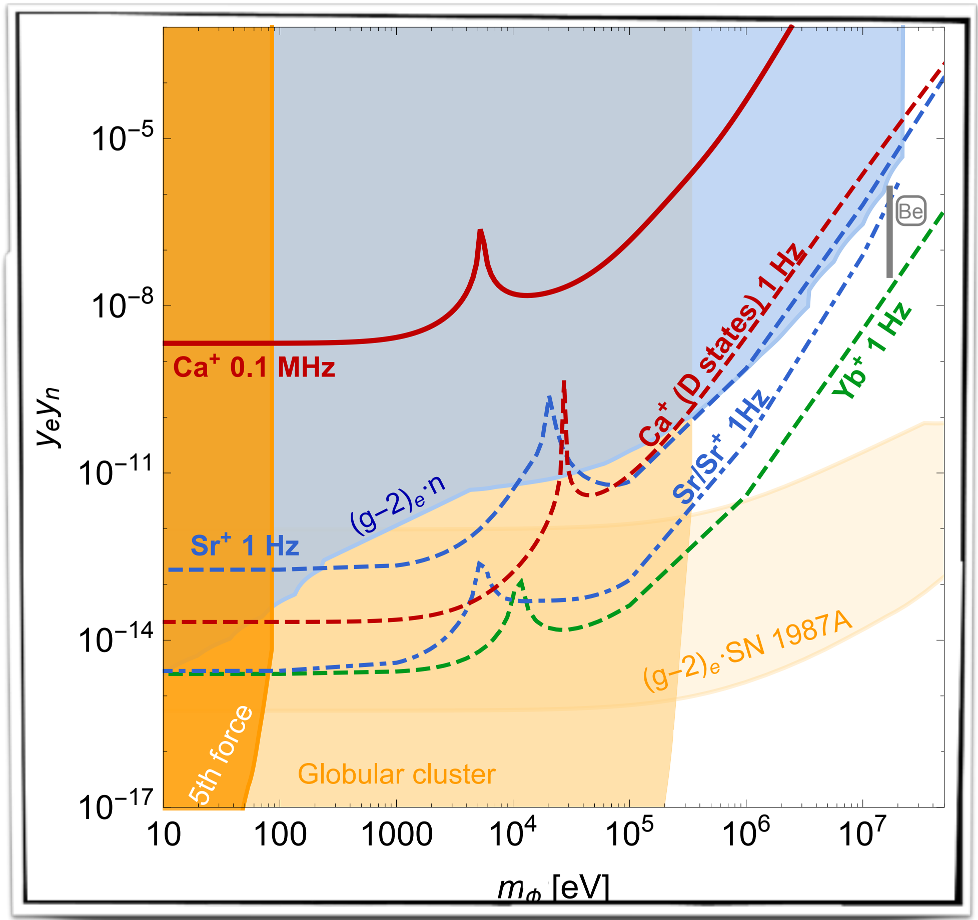
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP





As long as
King linearity deviation
is not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



arXiv:1704.05068v1 [hep-ph]

EDM

Electric Dipole Moment

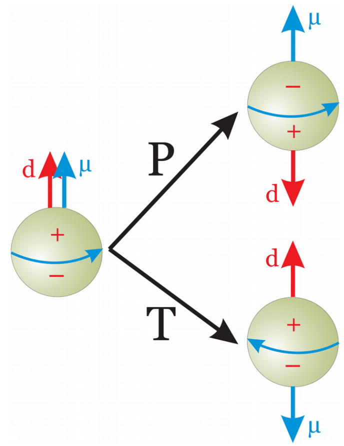
(M. Riembau, PhD defense '18)

$$\mathcal{L}_{dipole} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

Non-relativistic limit

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$

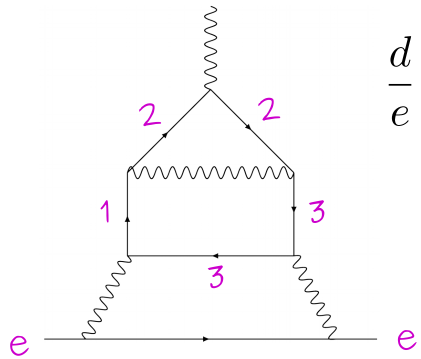
Nonvanishing EDM breaks CP



Nonvanishing d breaks CP

SM predictions

3-loop since needs to involve 3 family to break CP



$$\frac{d}{e} \sim \left(\frac{g^2}{16\pi^2}\right)^3 \frac{m_e J}{m_W^{14}}\mathcal{N}$$

Jarsklog invariant $\sim 10^{-4}\, m_t^4 m_b^4 m_c^2 m_s^2$

Integral factor $\sim 10^{10}$

$$\rightarrow d_e/e \sim 10^{-40}\ cm$$

SM contribution is ridiculously small
EDM is clear signal of New Physics

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

$$d_e \sim \delta_{\rm CPV}\left(\frac{\lambda}{16\pi^2}\right)^k \frac{m_e}{M^2}$$

Then dimensional analysis tells us that the experiment probes masses **Preliminary: experimental result not yet known**

0-loop	1-loop	2-loop
800 TeV	40 TeV	2 TeV

(M. Reece, SUSY '18)

EDM - experimental status

Science 343, p. 269-272 (2014)

$$|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{at } \; 90\% \text{ CL}$$

$$|d_e| \lesssim 0.5 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{(ACME II)}$$

$$|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm} \qquad \text{(ACME III)}$$

$$|d_e| \lesssim 10^{-30}\, e\ cm$$ arXiv:1704.07928

$$|d_e| \lesssim 5 \cdot 10^{-30}\, e\ cm$$ arXiv:1804.10012

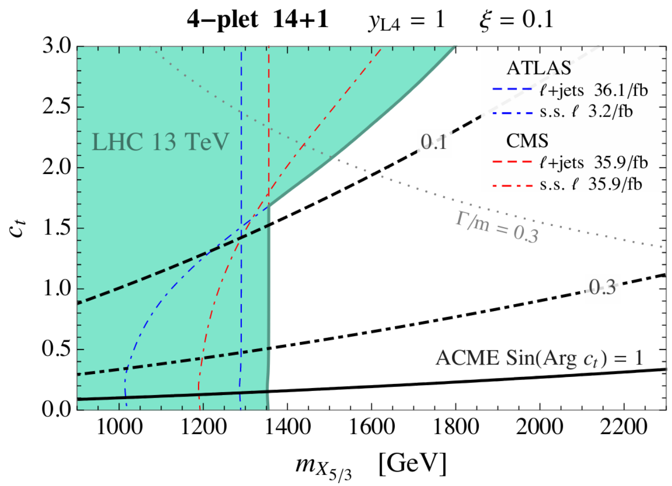
$$|d_e| \lesssim 10^{-35}\, e\ cm$$ arXiv:1710.08785

EDM as a BSM probe

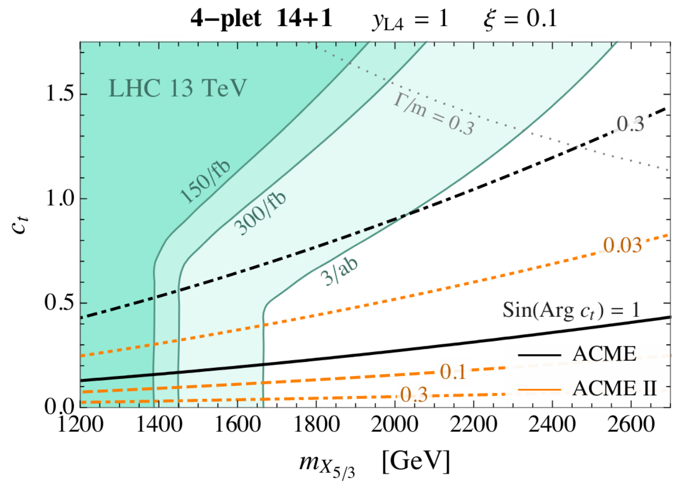
Panico, Riembau, Vantalon '17

e.g., EDM can help testing the presence of top partners in composite Higgs models

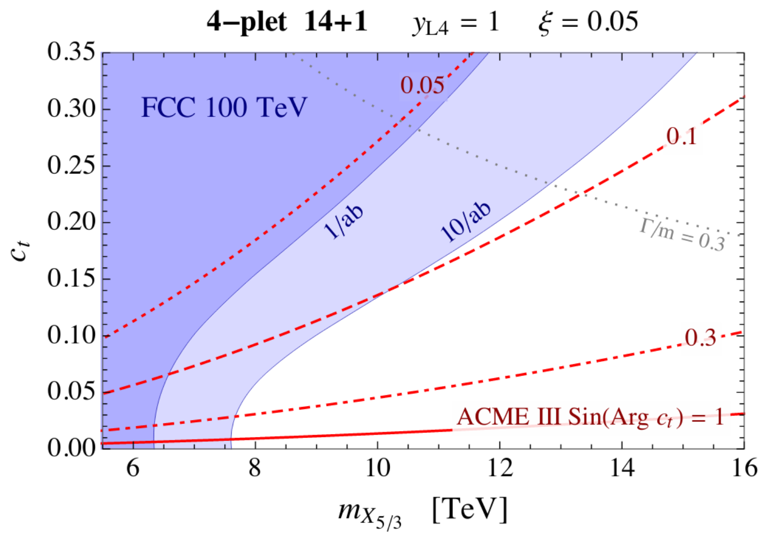
LHC



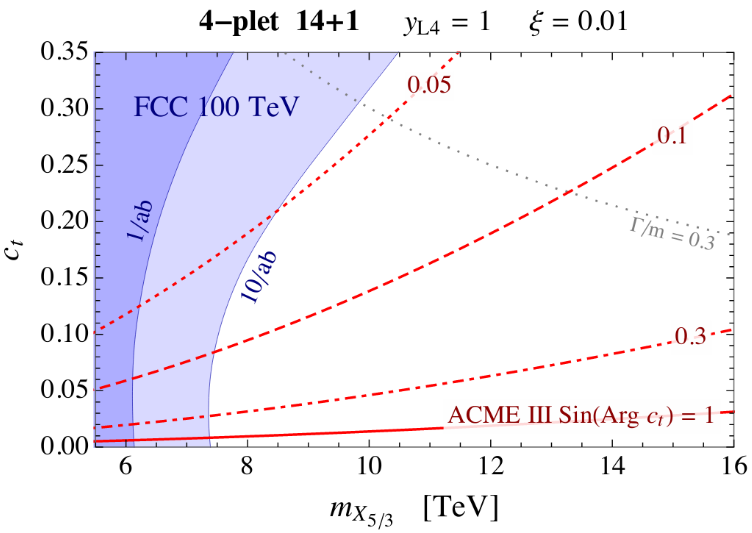
HL-LHC



FCC-hh



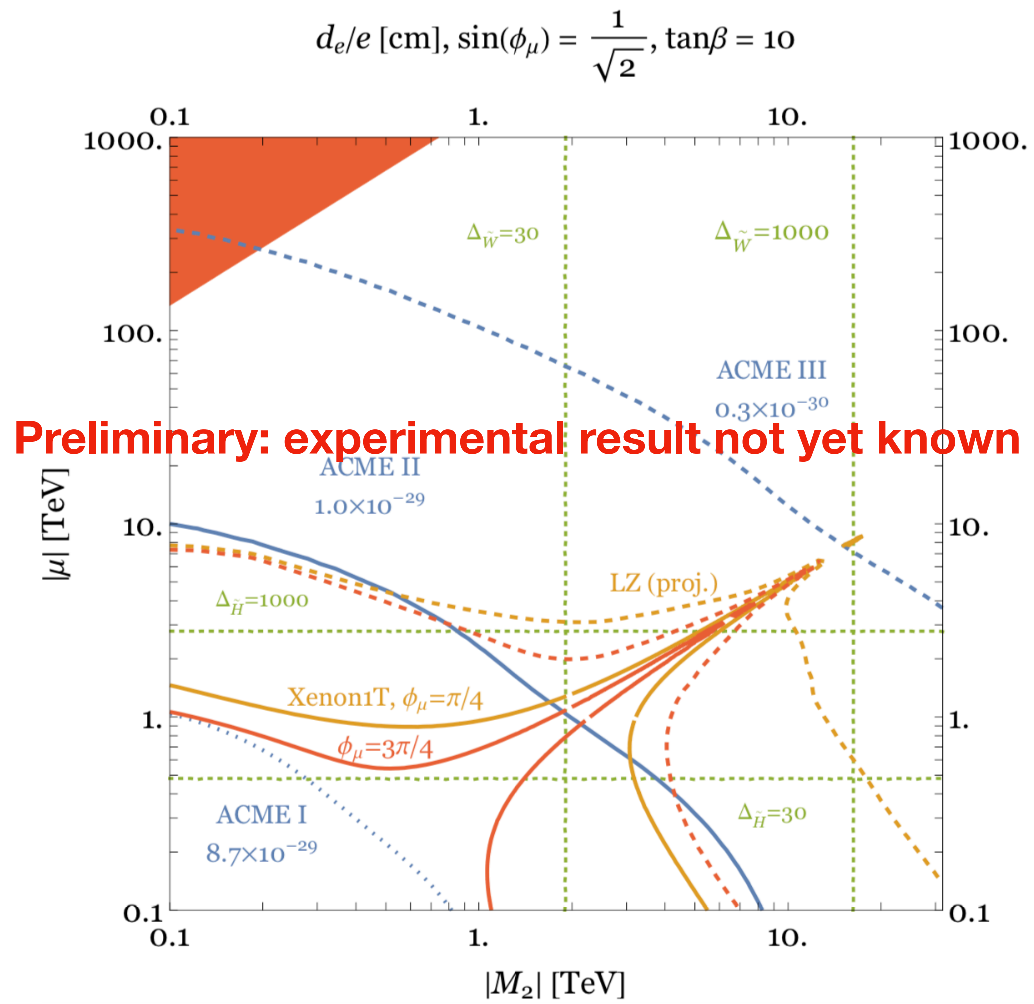
FCC-hh



EDM as a BSM probe

(M. Reece, SUSY '18)

Powerful split SUSY constraints (forecast) from ACME 2!



Heavy Baryogenesis Models

& Neutron-antineutron oscillations

Baryon number violation(s)

Why are we expecting B violation(s)?

1) Neutral meson oscillations, neutral lepton oscillations (very likely), why not neutral baryon oscillations?

2) Global symmetry are not consistent with quantum gravity

3) Need to generate matter-antimatter imbalance

Selection rule

conservation of angular momentum ⇒ spin of nucleon should be transferred to another fermion

1) $\Delta B = \Delta L$ (nucleon → antilepton)
2) $\Delta B = -\Delta L$ (nucleon → lepton)
3) $\Delta L = \pm 2$ ($0\nu\beta\beta$)
4) $\Delta B = \pm 2$ ($n\bar{n}$ oscillations, dinucleon decays)

Proton stability doesn't exclude baryogenesis!

If h3 coupling is SM-like, unlikely that baryogenesis occurs at weak scale
Large scale baryogenesis requires B-L violation
otherwise any B asymmetry created above EWSB scale is wiped out by active EW sphalerons

Constraints on Baryon # violation

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
τ_{79}	$pn \to$ invisible	$> 2.1 \times 10^{-5}$	90%
τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

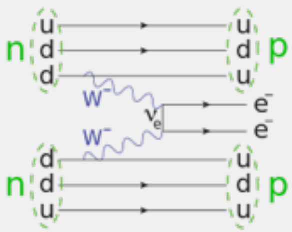
*For flavour universal models, nn gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might be win

Pattern of B violation in SM(EFT)

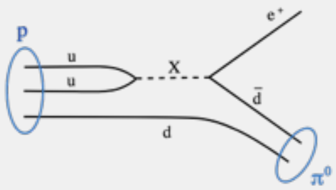
$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed (ΔB, ΔL)	(0, 0)	**(0, 2)**	(0, 0), **(1, 1)**	(0, 2), (1, -1)	(0, 0), (1, 1)	**(2, 0)**, (1, -1), (0, 2), (1, 3)

A. Kobach '16

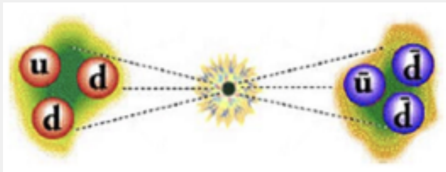
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation

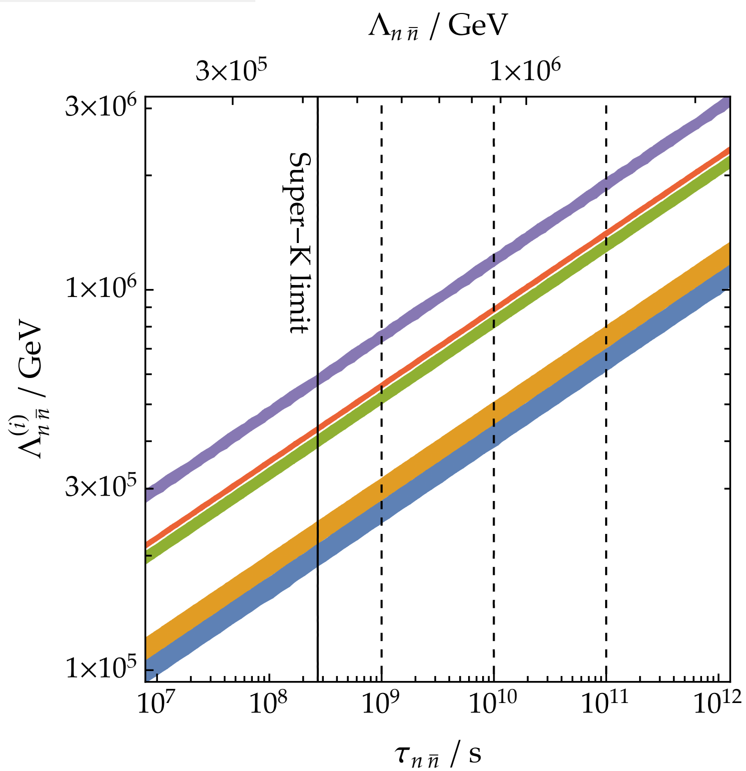


Slide stolen to Z. Zhang @ Pascos'18

12 operators (of the type 'uudddd')

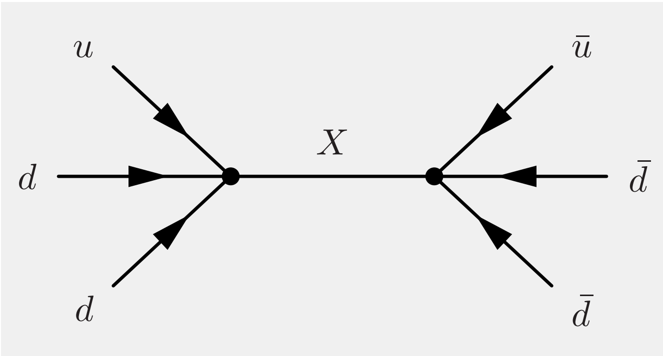
$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right|$$

SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV



n$\bar{\text{n}}$ oscillations and baryogenesis

Grojean, Shakya, Wells, Zhang '18



Mediator X

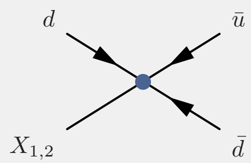
Single mediator X decays cannot generate a baryon asymmetry at leading order in the B violating coupling (Nanopoulos-Weinberg theorem '1979)

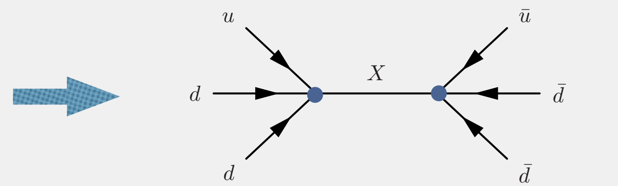
Two mediators X_1, X_2 ($M_{X1}<M_{X2}$)

$$
\begin{aligned}
\mathcal{L} \supset\ & \eta_{X_1}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_1) \\
& + \eta_{X_2}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_2) \\
& + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}
\end{aligned}
$$

$$|\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,, \ |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,, \ |\eta_c| \equiv \Lambda_c^{-2}\,.$$

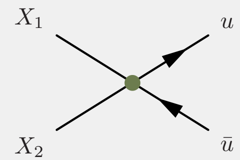
- 2 *B-violating* operators





$$c_1 = \frac{1}{\left(\Lambda_{n\bar{n}}^{(1)}\right)^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}$$

- 1 *B-conserving* operator

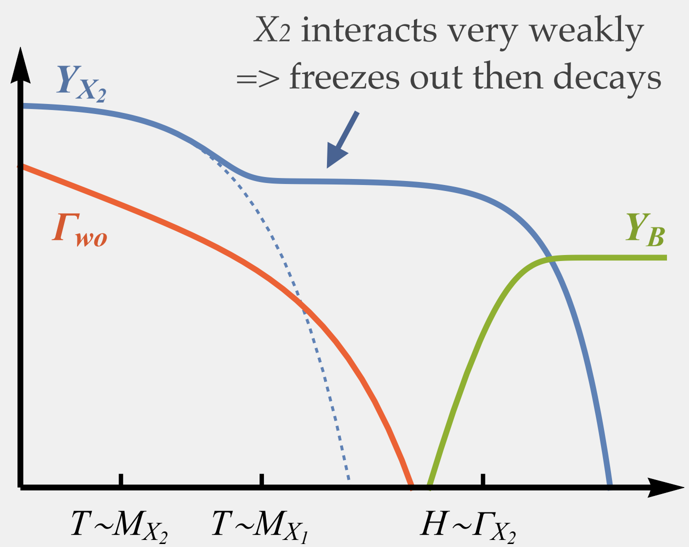


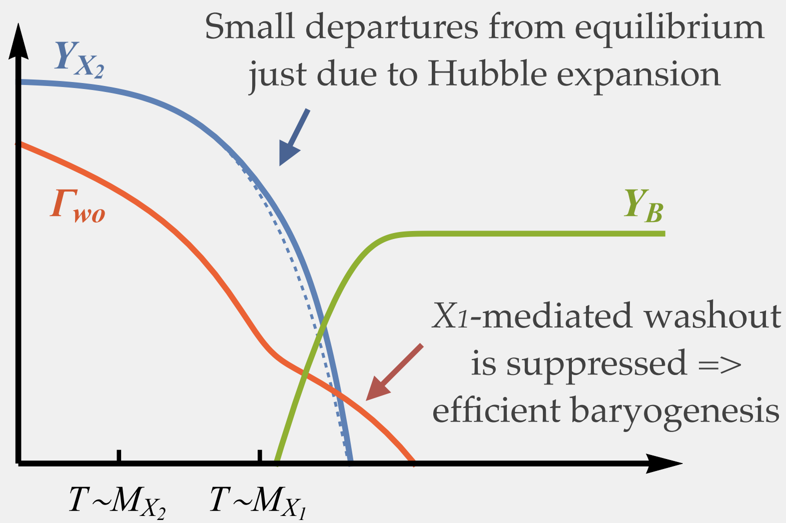
Two mediators with both B and $\not B$ couplings are enough to evade Nanopoulos-Weinberg

Baryogenesis

Grojean, Shakya, Wells, Zhang ‘18

Late decay scenario	Early decay scenario
$\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$	$\Lambda_{X_1} \gg \Lambda_{X_2} \gtrsim \Lambda_c$





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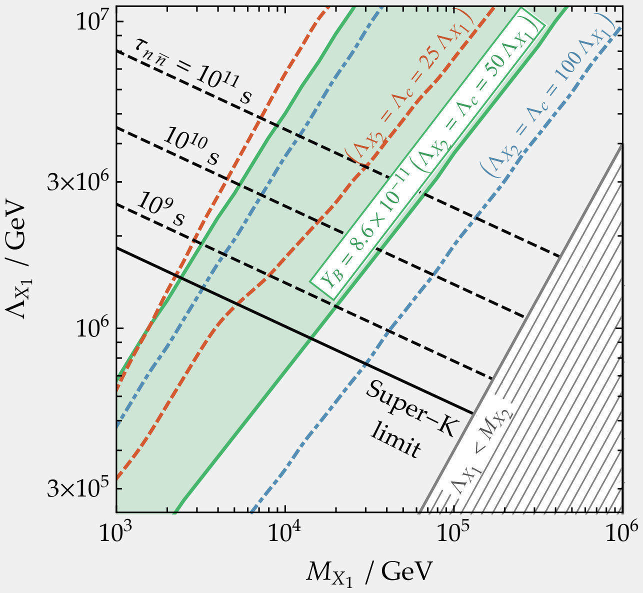
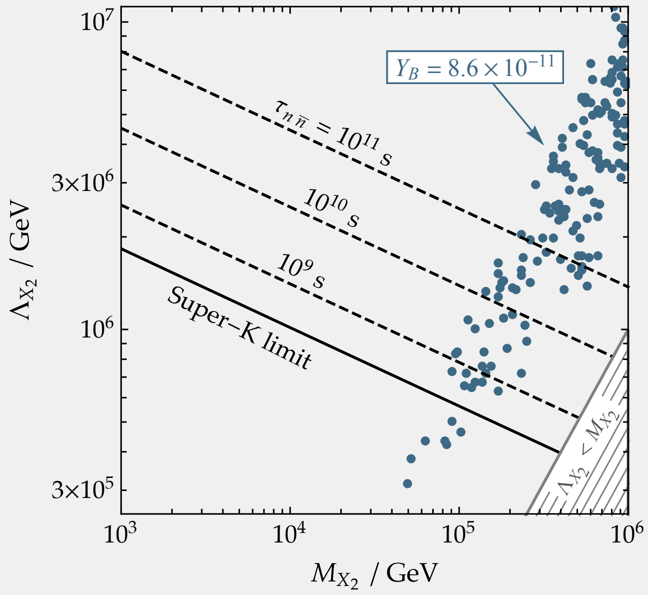




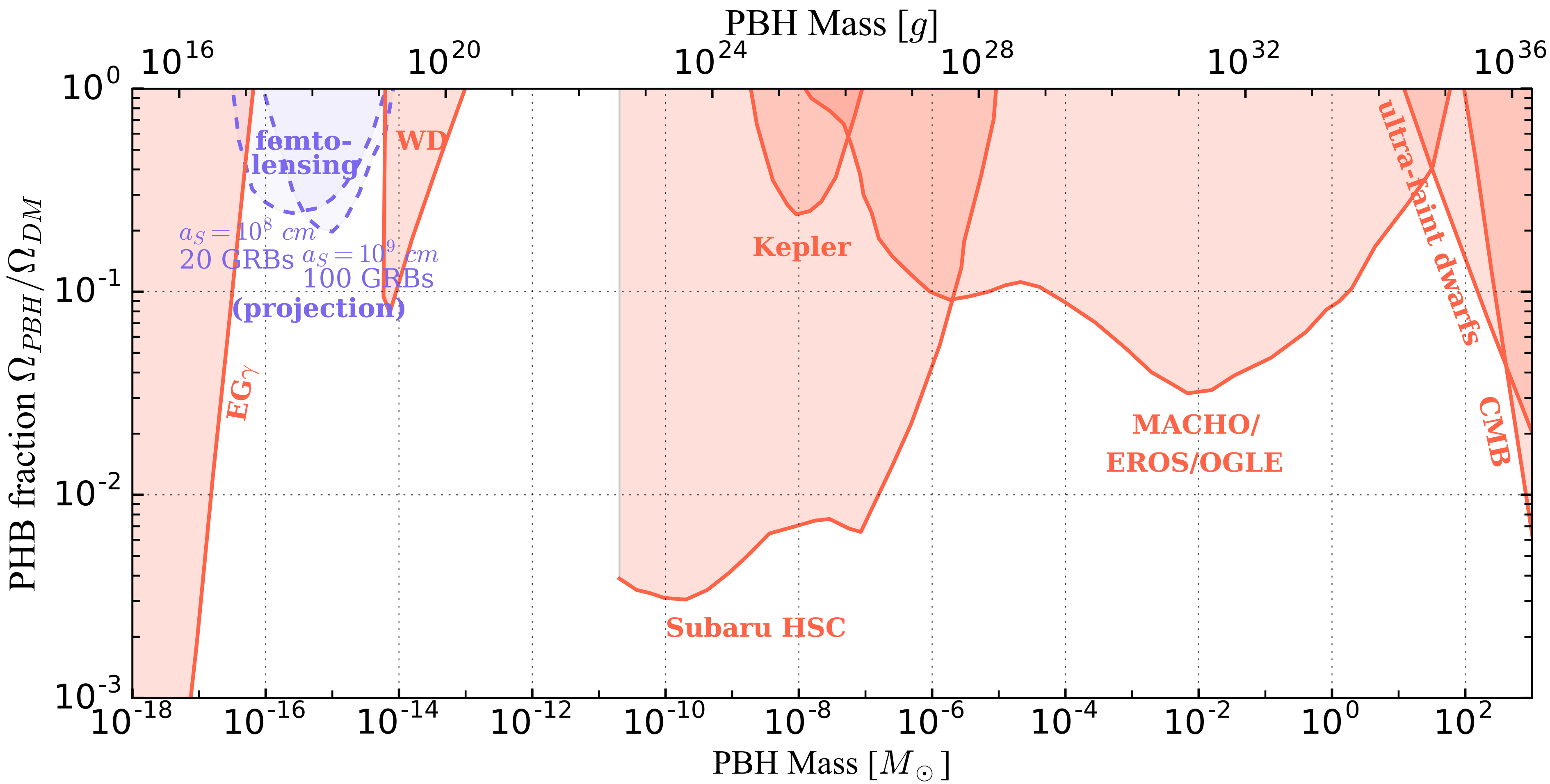
Explicit realisation of late decay scenario:
RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

$n\bar{n}$ oscillations can probe direct baryogenesis scenarios @ $10^{5\text{-}6}$ GeV

Searching for a black moon

PBHs as DM

$$t_{\text{evaporation}} > 10^{64} \left(\frac{M_{BH}}{M_\odot}\right)^3 \text{ year} \quad \Rightarrow \quad M_{PBH} > 10^{-17} M_\odot$$



Katz+ 1807.11495

PBH abundance

Production of PBH is still subject to research and debates (gravitational collapse of large over-densities during inflation? Topological defects?...)

JR Espinosa @ Benasque 2018

$$\rho_{DM} \sim 0.3\,\mathrm{GeV/cm^3} \sim 10^{-15} M_\odot / V_{\text{Solar system}}$$

If

$$M_{\rm PBH}\ \ 10^{-16} M_\odot, \ \text{ i.e., } \ R_{\rm Sch}\ \ 10^{-13}\,\mathrm{cm}$$

We expect a few in the Solar system

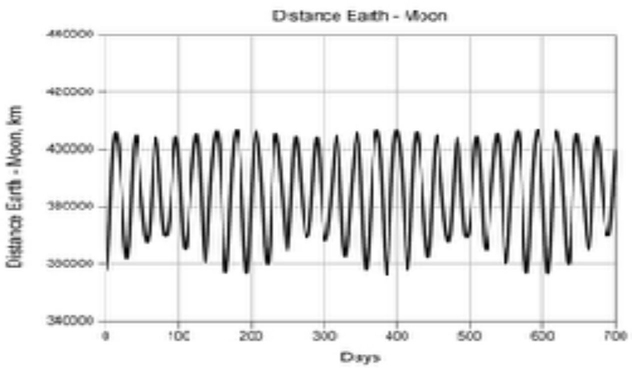
How can we detect such PBHs living in the Solar system?

A PBH orbiting around Earth

Grojean, Ruderman et al, in progress

Is there a black moon around Earth and interacting only gravitationally?

A black moon between the Earth and the Moon will induce a variation of the distance Earth-Moon, which is measured with an accuracy of 1mm (10^{-11} relative accuracy)



$$\Delta d_{\oplus - \circ} = \frac{d_{\oplus - \mathrm{PBH}} M_{\mathrm{PBH}}}{M_\oplus}$$

numerically

$$1\,\mathrm{mm} = \frac{1000\,\mathrm{km} \times 10^{-16} M_\odot}{M_\oplus}$$

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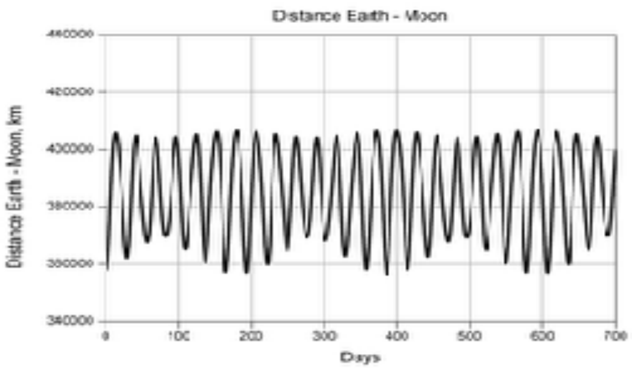

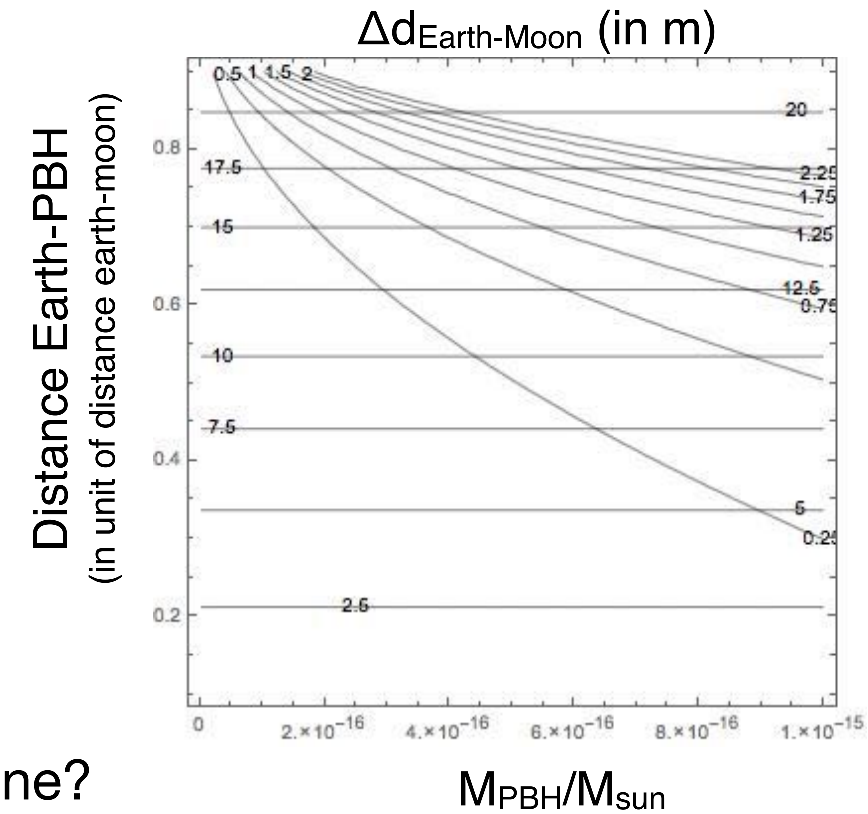

Can also use GPS measurements…
Looking for a black moon with your cell-phone?

Conclusion(s)

Executive summary on status of BSM

BAD NEWS

Experimentalists haven't found (yet)
what theorists told them they will find

GOOD NEWS

There are rich opportunities
for mind-boggling signatures
@ colliders and beyond

Sailing to India with the right tool...

Once upon a time...

Columbus had a great proposal: “reaching India by sailing towards the West”

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250’000 stadia
- other measurements later found smaller values ☞Toscanelli’s map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70’000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost

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His proposal was scientifically rejected twice (by Portuguese's & Salamanca U.)
by the decision was overruled by Isabel ... and America became great (already)

Moral(s)

"if your proposal is rejected, submit it again"

"you need the right technology to beat your competitors"

"theorists don't need to be right!
but progress needs theoretical models to motivate exploration"

Knowledge is power

B. Clinton, Davos 2011

ippog.web.cern.ch/resources/2011/bill-clinton-davos-2011

Homework:
imagine what the current US president could say about science and HEP

Thank you for your attention.
Good luck for your studies!

if you have question/want to know more

do not hesitate to send me an email

christophe.grojean@desy.de