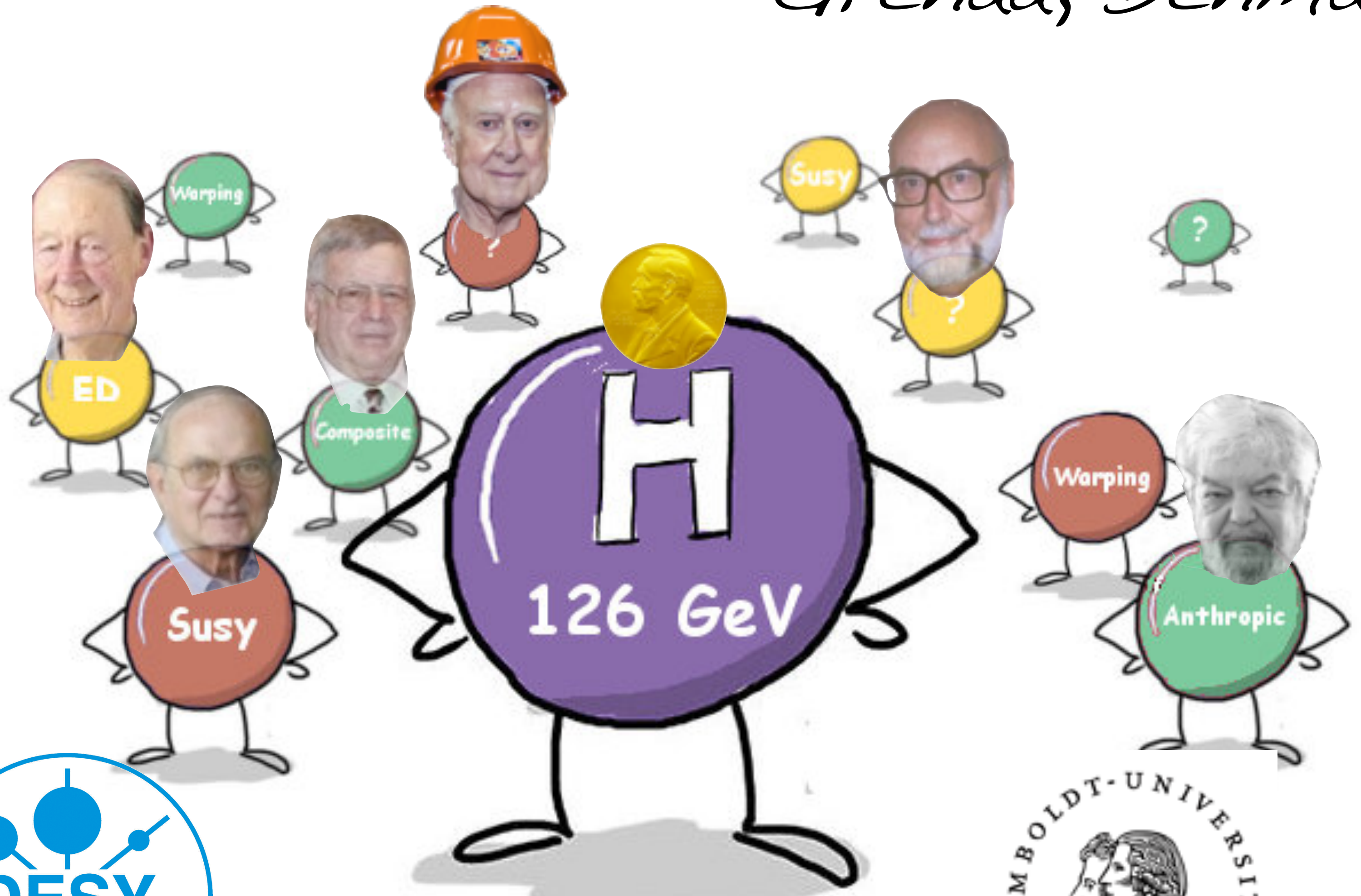
Higgs and Beyond

ESHEP 2023

Grenaa, Denmark

Lecture 4/4



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Outline

Lecture #1

- Symmetries, Fields, Lagrangians
- From Fermi theory to the Standard Model
- Chirality and mass problem

Lecture #2

- Spontaneous symmetry breaking, aka Higgs mechanism
- Particles masses, unitarity and the Higgs boson
- 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

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\mathrm{BSM}}^2}$

current (and future) LHC sensitivity
O(10-20)% ⇔ $\Lambda_{\mathrm{BSM}} > 500(g_*/g_{SM})$ GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavour number violation as in $h \to \mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

What is the scale of New Physics?

High Scale Wishes

small EDMs, FCNC: $\frac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\frac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\frac{UUDE}{M_{\rm NP}^2}$

Low Scale Wishes

small EDMs: $\text{argdetY} \leq 10^{-10}$

↳ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\text{eV}\right)^4$

↳ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\text{GeV})^2$

↳ light susy?

Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy ◁

Neutral naturalness ◁
(twin Higgs, folded susy)

Relaxion ◁

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^{6}mm) K_L (m=500MeV, ct=10^{4}mm) $\pi^\pm$ (m=140MeV, ct=10^{4}mm) $K^\pm$ (m=500MeV, ct=10^{3}mm)	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.

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.

Cosmological relaxation

Is the Higgs doing anything for the Universe?

- **Astrophysics**: it gives mass to the W and allows the stars to burn

- **Nucleosynthesis**: it gives masses to the up and down quarks and in a subtle (fine-tuned?) way prevents the proton to decay into neutron

- **Baryogenesis**: source of CP-violation and out-of-equilibrium phase?

- **Inflation**: slow-rolling scalar energy density to drive the (early) inflationary expansion of the Universe?

The first 2 points only rely on the Higgs vev (static)

The last 2 points need the Higgs field (dynamic)
(and also additional new physics beyond the Standard Model)

Is Cosmology doing anything for the Higgs?

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

- $m_H(t)$: $m_H^2(t=-\infty) = \Lambda^2_{\text{cutoff}} \to m_H^2(\text{now}) = -(125\,\text{GeV})^2$
- Higgs mass-squared promoted to a field, the “relaxion"
- 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 reaches 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

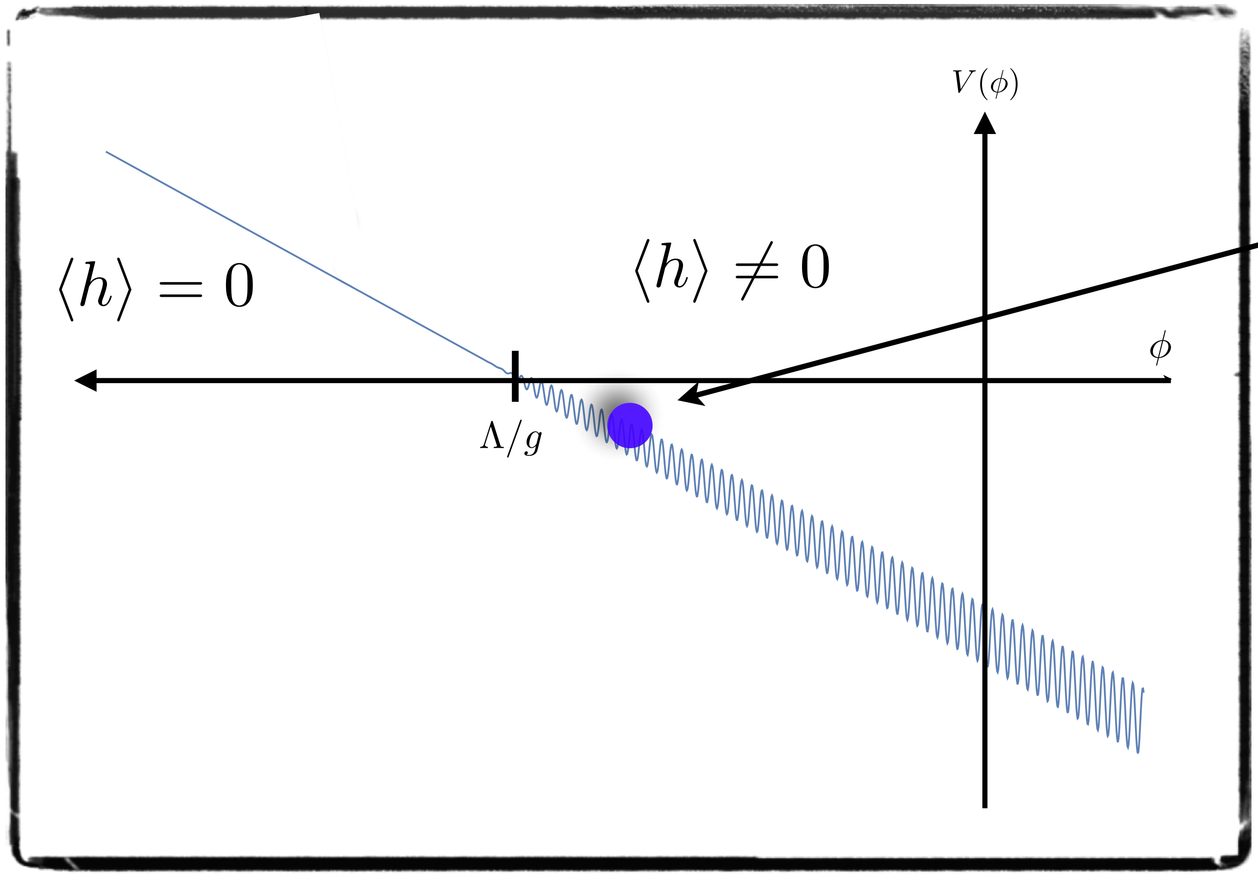
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

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

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

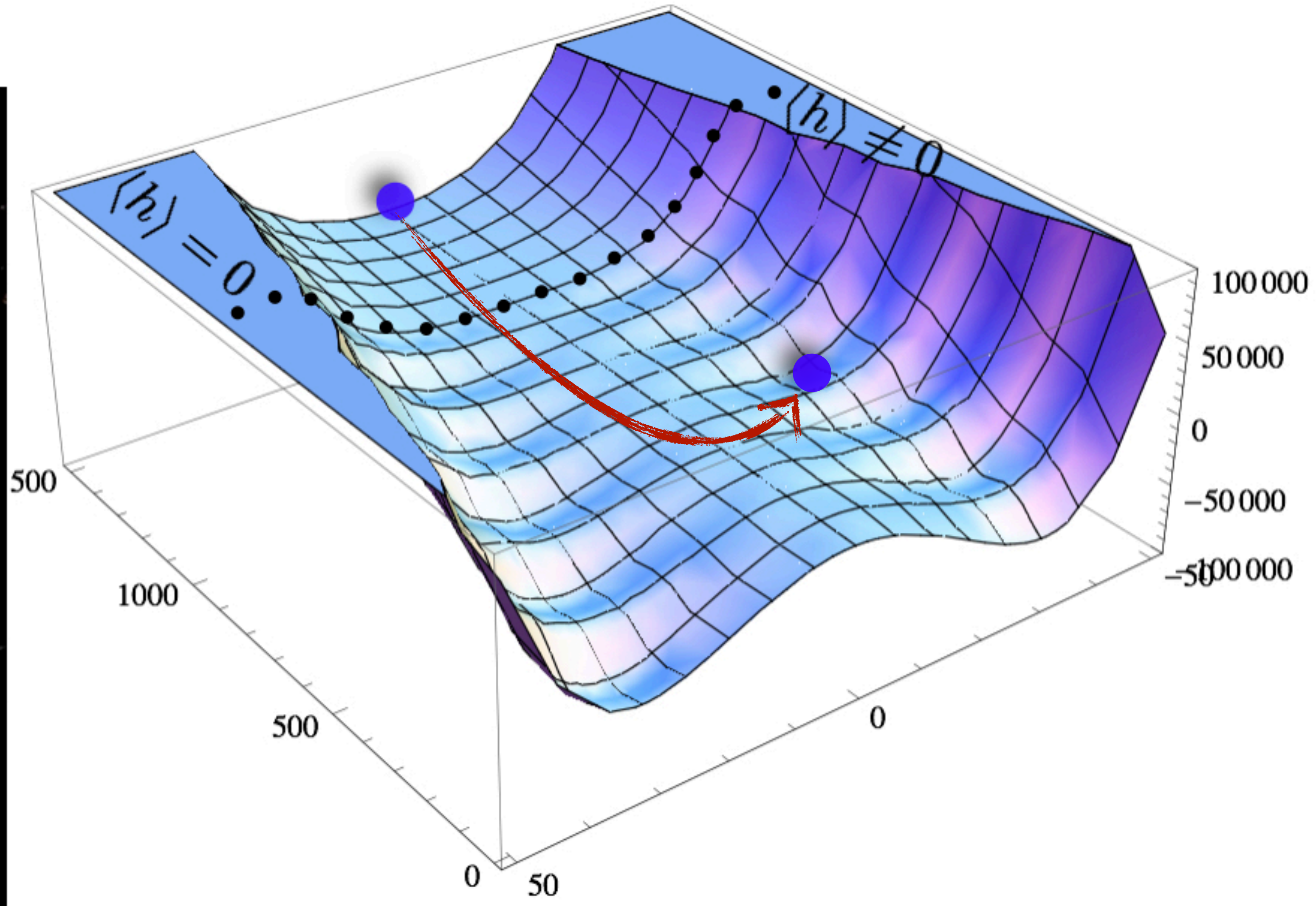
$$\Lambda_{\rm QCD}^3\, h \cos\frac{\phi}{f}$$



If ϕ continues rolling, the Higgs vev increases, the potential barrier gets larger 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

Consistency Conditions

- **Higgs vev stops cosmological rolling**

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

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.

- **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

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

$>$

quantum fluctuation

$$H_I$$

altogether

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

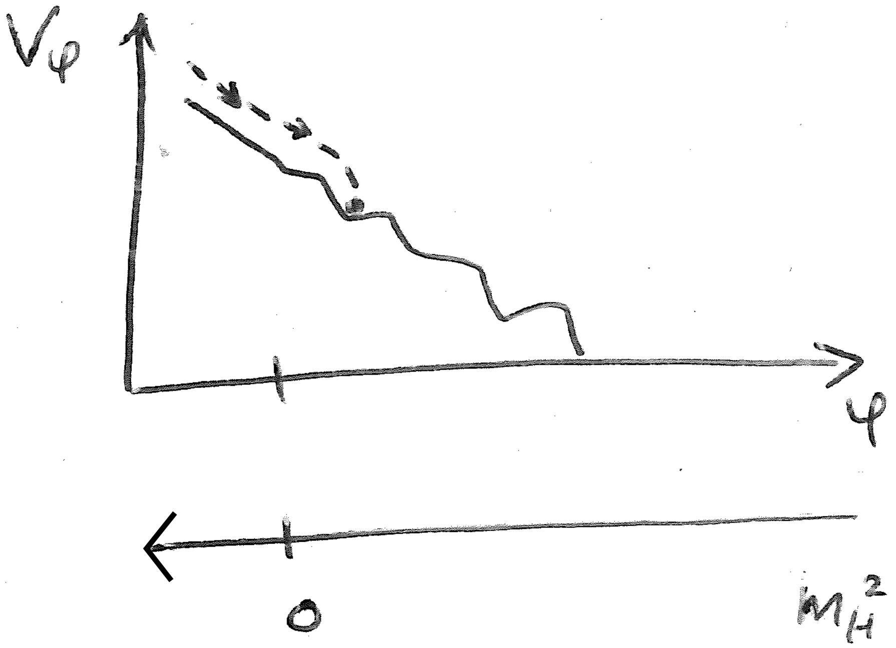
Two classes of relaxion models

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.



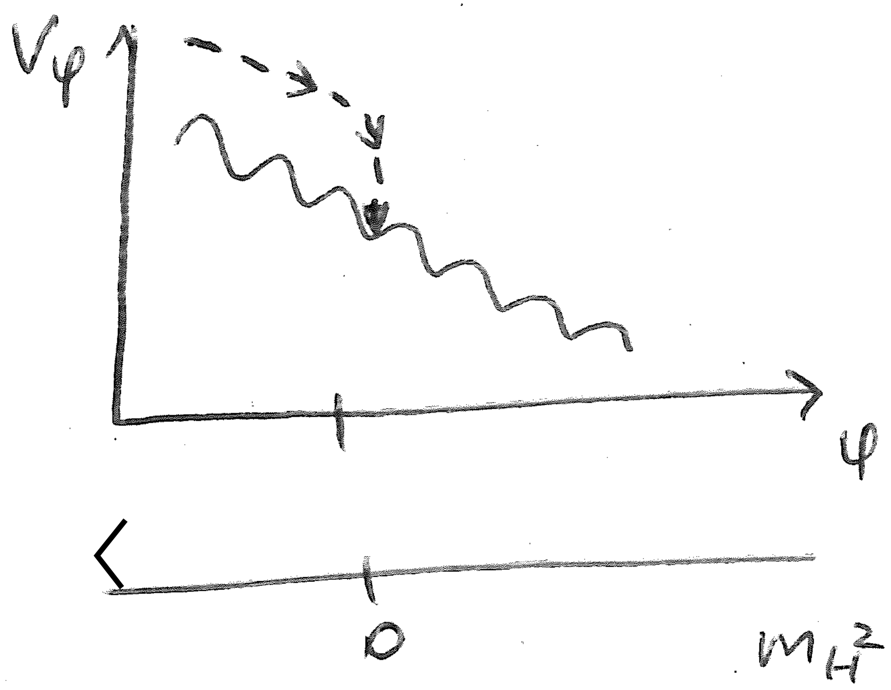
H-dependent friction

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 until the Higgs vev approaches a critical value where **particle production** takes place and stops the evolution.
But beware of relaxion fragmentation due to fluctuation growth.



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

Phenomenological Signatures

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

only BSM physics below Λ~10^9GeV is in the form of

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

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

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
◎ relaxion halo around earth/sun which induce $\delta m_e/m_e$ and $\delta\alpha/\alpha$

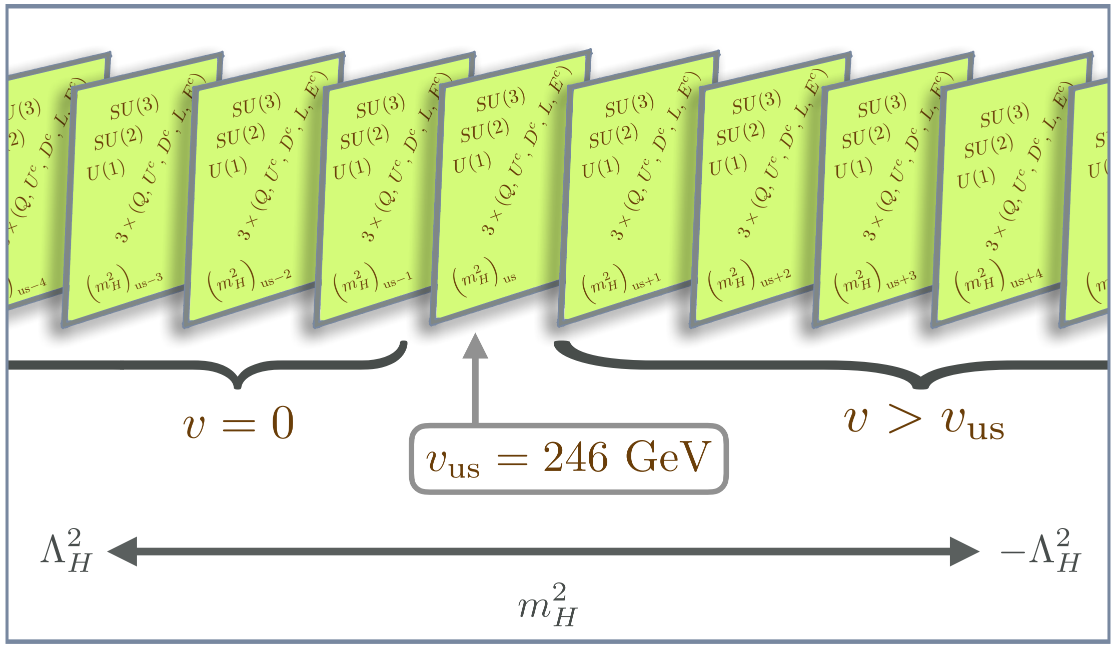
Banerjee et al ‘19

NNaturalness

or another way to dynamically select our vacuum

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

NNaturalness



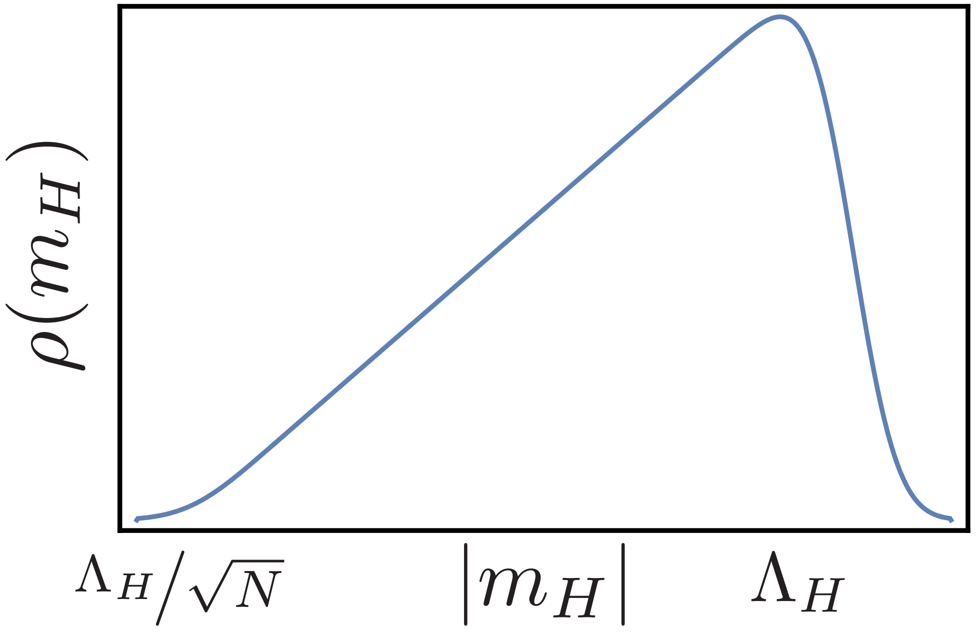
N copies of the SM

High Higgs cutoff Λ_H, high gravity cutoff Λ_G

Two effects:

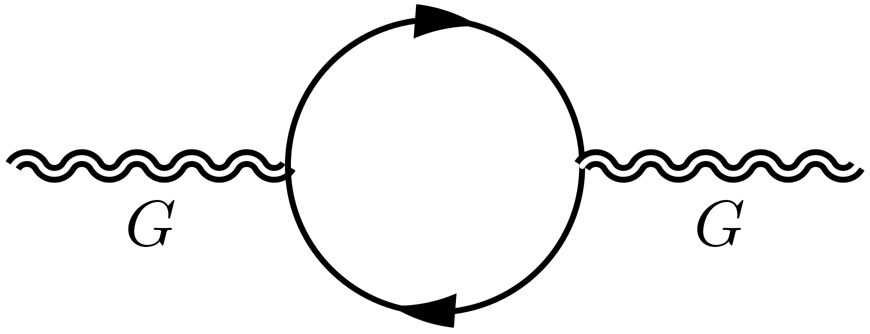
(N. Craig @ Paris'18)

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.)



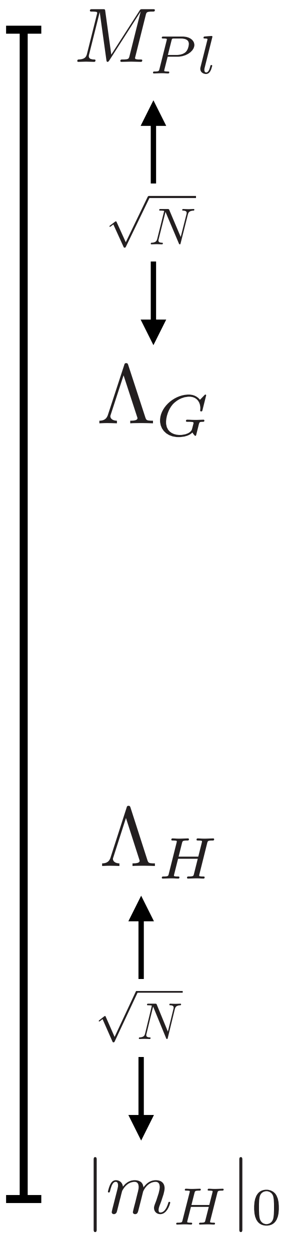
Gravitational strong coupling scale Λ_G below M_{Pl}

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

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.)

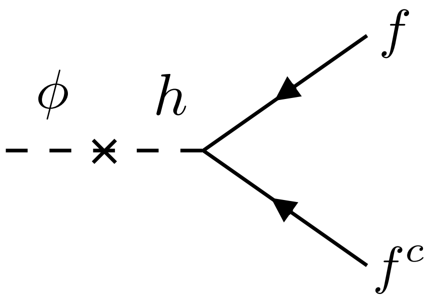
$N=10^{4}$:
$\Lambda_H=10^{4}$ GeV
$\Lambda_G=10^{16}$ GeV
(SUSY or compositeness at Λ_H)

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

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

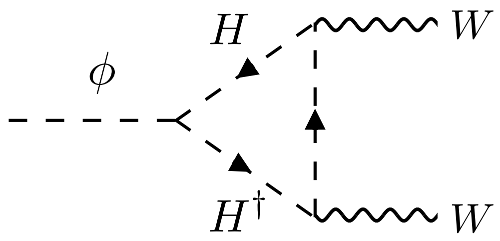
Decays (provided $m_\phi < |m_{H_i}|$)

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



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

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



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

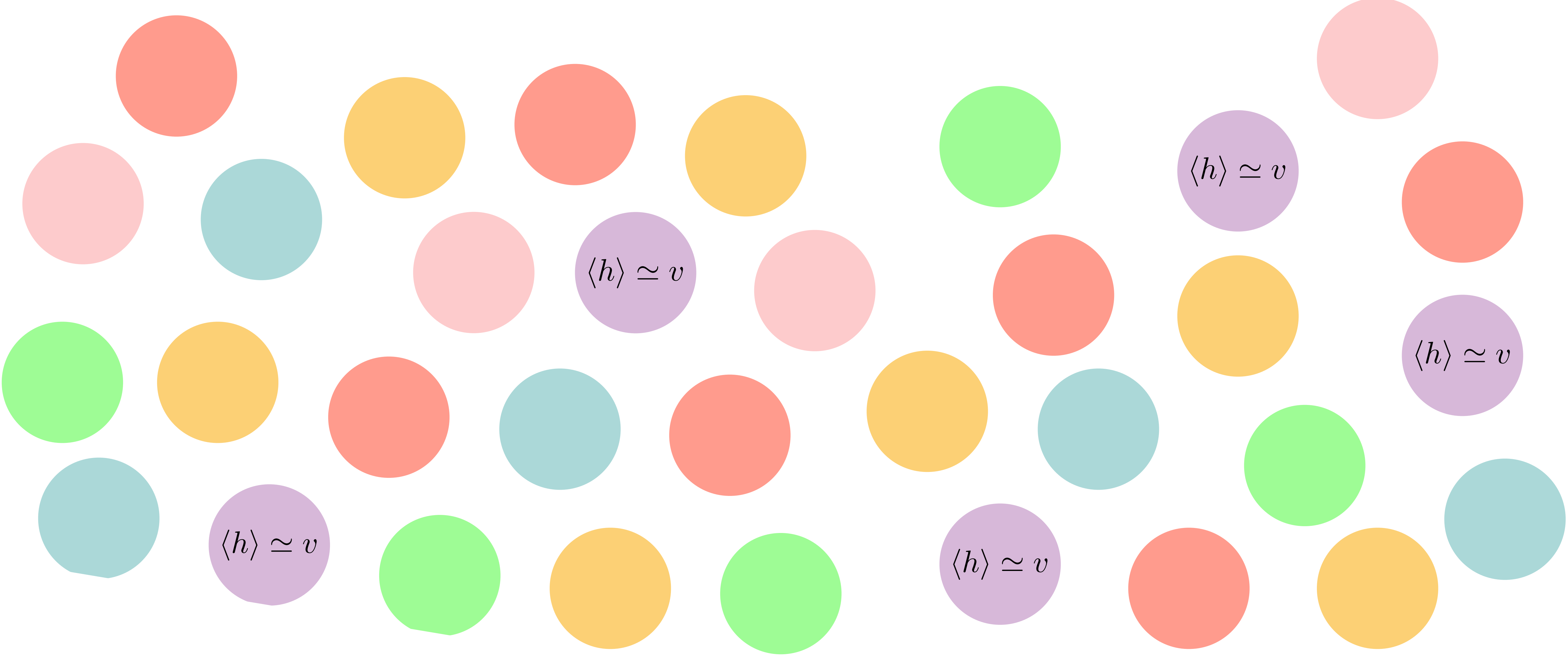
Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2<0$

The Universe reheats/populates the patch with EWSB and light Higgs, the other patches are left empty.

Sliding Naturalness

Landscape of Higgs Masses populated by inflation

$$-M_*^2 \leq m_H^2 \leq M_*^2$$



Sliding Naturalness

After reheating and a time

$$t_c \sim 1/H(\Lambda_{\rm QCD}) \sim 10^{-5}\ s$$

All patches where the Higgs vev

$$\langle H^0 \rangle \equiv h$$

Is outside of a certain range

$$h_{\rm min} \lesssim h \leq h_{\rm crit}$$

crunch

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

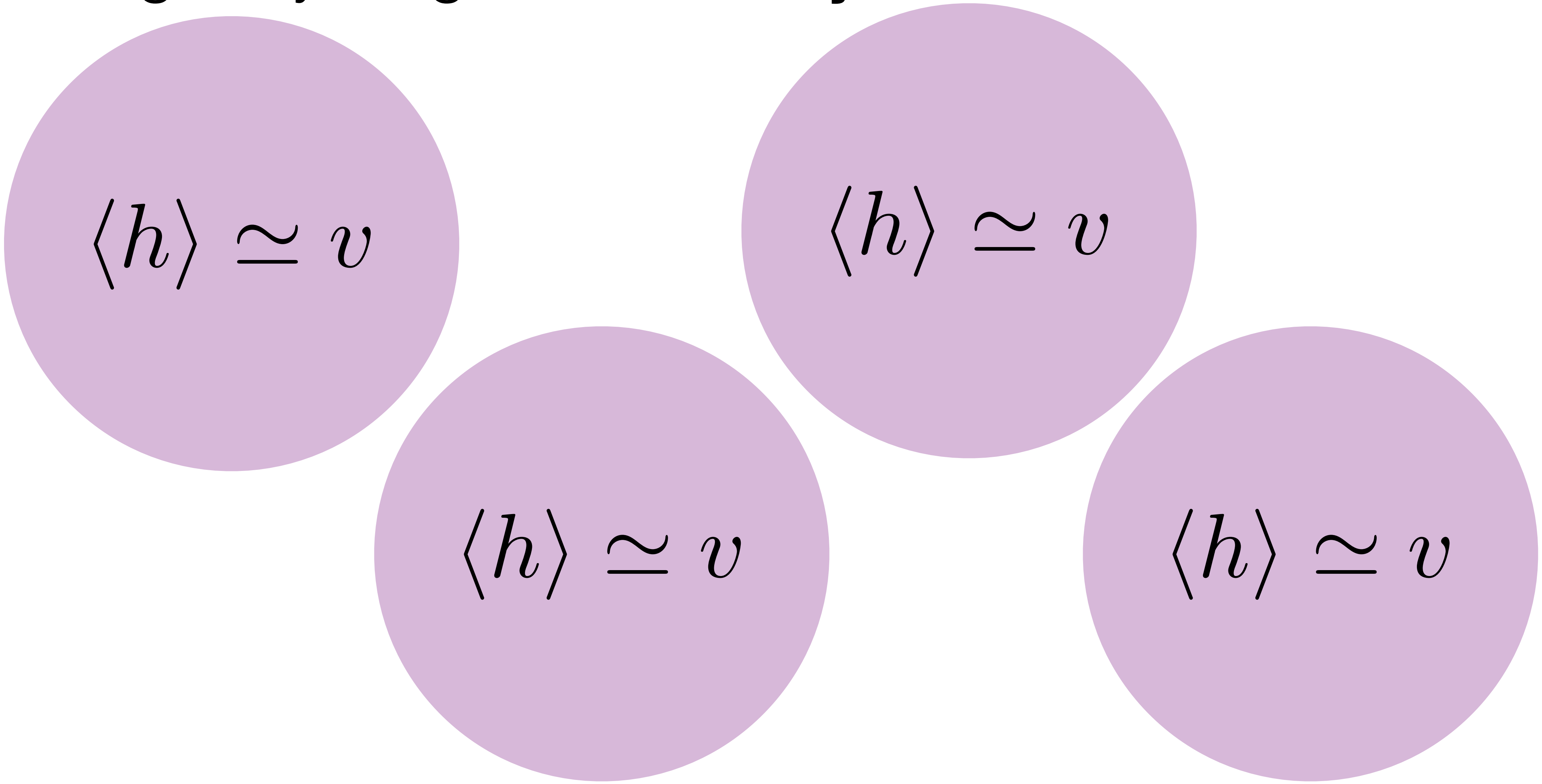
$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

Sliding Naturalness

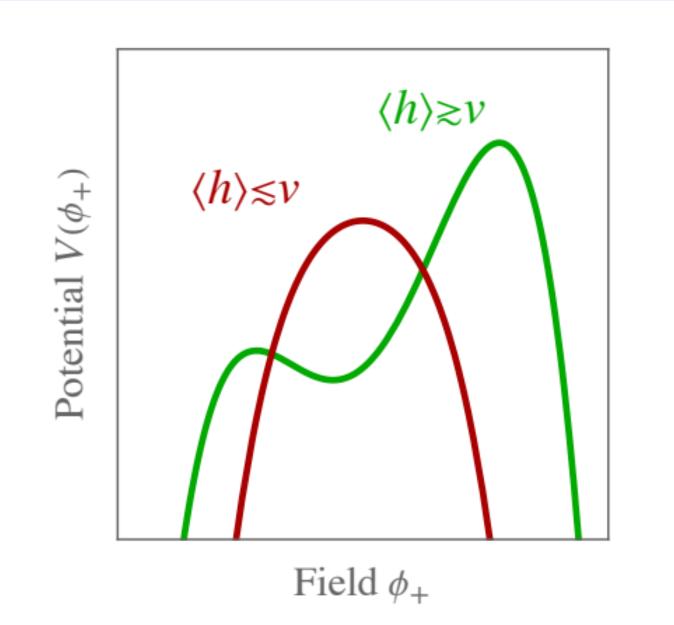
Only universes with the observed value of the weak scale can live cosmologically long times. **Today the multiverse looks like**:

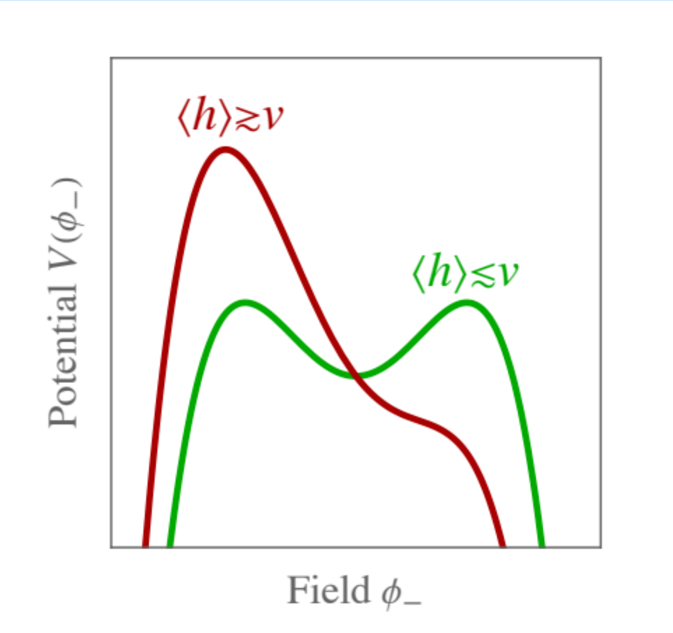


Sliding Naturalness

$$V_+ = -\frac{m_+^2}{2}\phi_+^2 - \frac{m_+^2}{M_+^2}\phi_+^4$$

$$V_- = +\frac{m_-^2}{2}\phi_-^2 - \frac{m_-^2}{M_-^2}\phi_-^4$$





$$V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$

$$\longrightarrow -m_\pi^2 f_\pi^2 \cos(\ldots)$$

$$\sim \frac{\Lambda(\langle h\rangle)^4}{2}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)^2$$

This scenario can be realised by two new scalars apparently decoupled from each other with suitable interactions with the Higgs field.

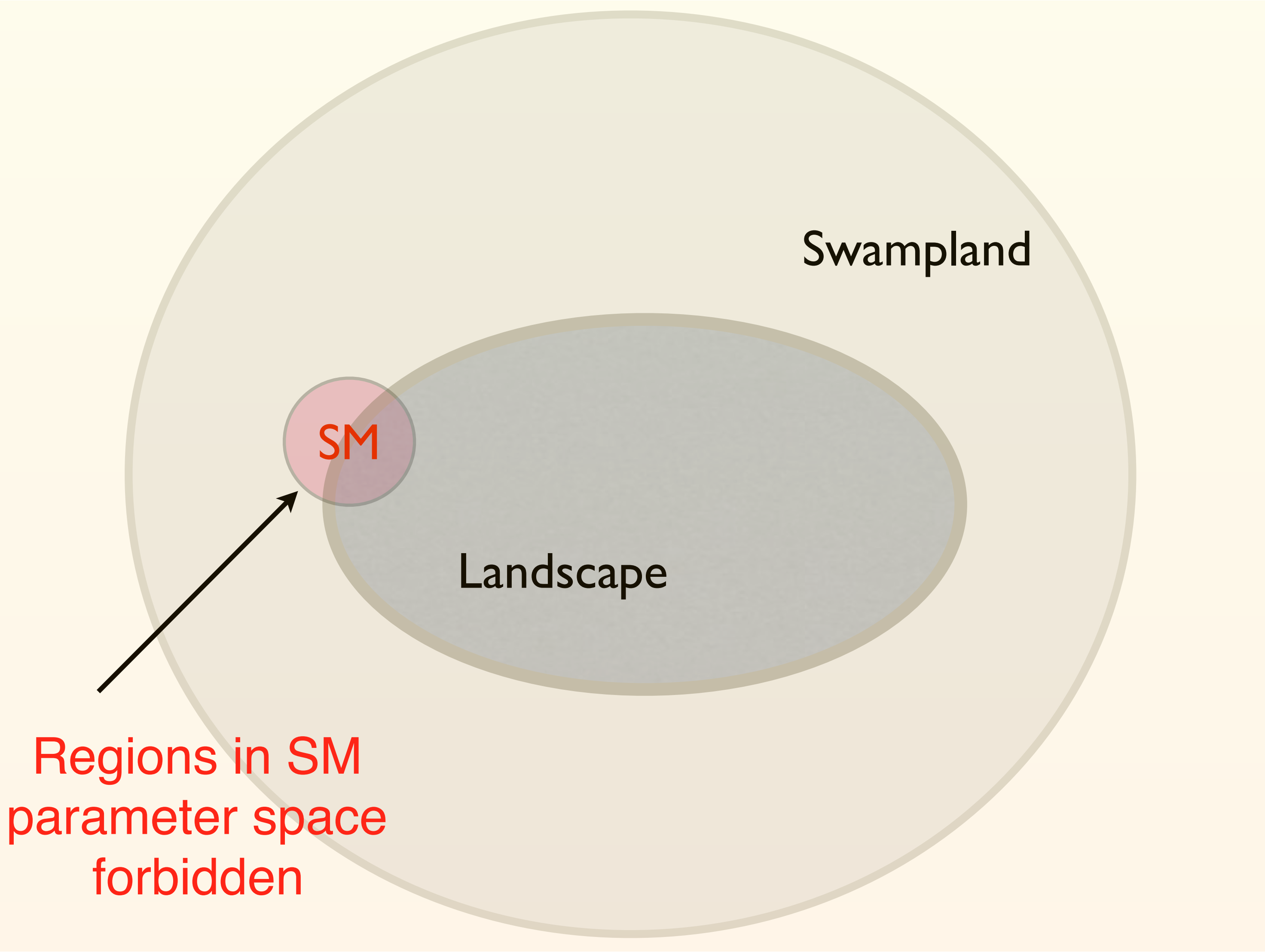
Swampland: UV/IR mixing

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**



Regions in SM parameter space forbidden

Ibanez @ SUSY'18

This conjecture has potentially far-reaching implications for phenomenology

Landscape/Swampland Conjectures

0) No exact global symmetry

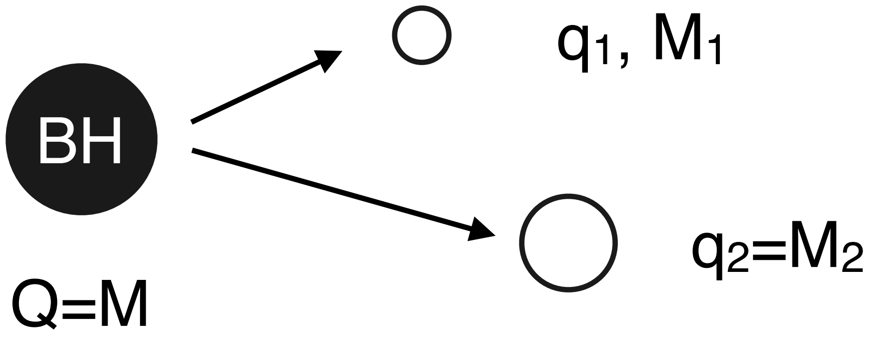
For a review, see Banks, Seiberg '10

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. $M_1<M-M_2=Q-q_2=q_1$

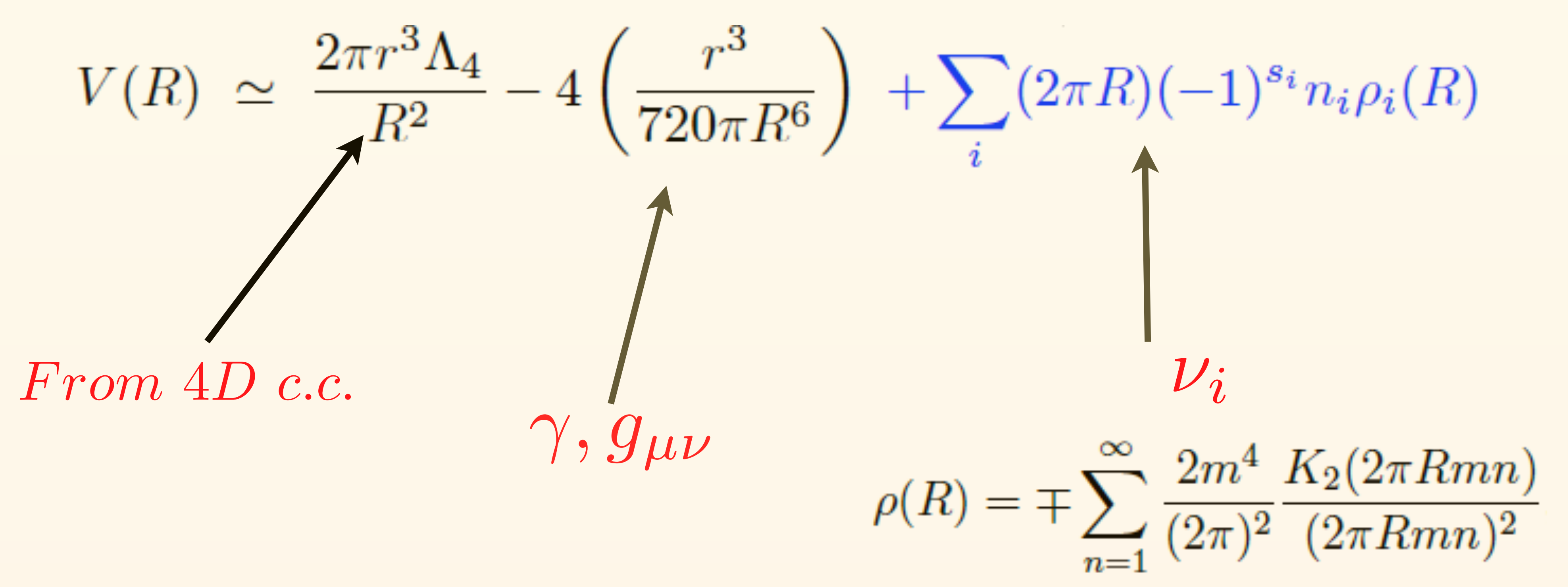
Landscape/Swampland Conjectures

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



$$V(R) \simeq \underbrace{\frac{2\pi r^3 \Lambda_4}{R^2}}_{From\ 4D\ c.c.} - 4\underbrace{\left(\frac{r^3}{720\pi R^6}\right)}_{\gamma,\, g_{\mu\nu}} + \underbrace{\sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R)}_{\nu_i}$$

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

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

swampland conjecture

- Quintessence + Higgs:

Denef, Hebecker, Wrase ‘18

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

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

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

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

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

at least one of them is as small as

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

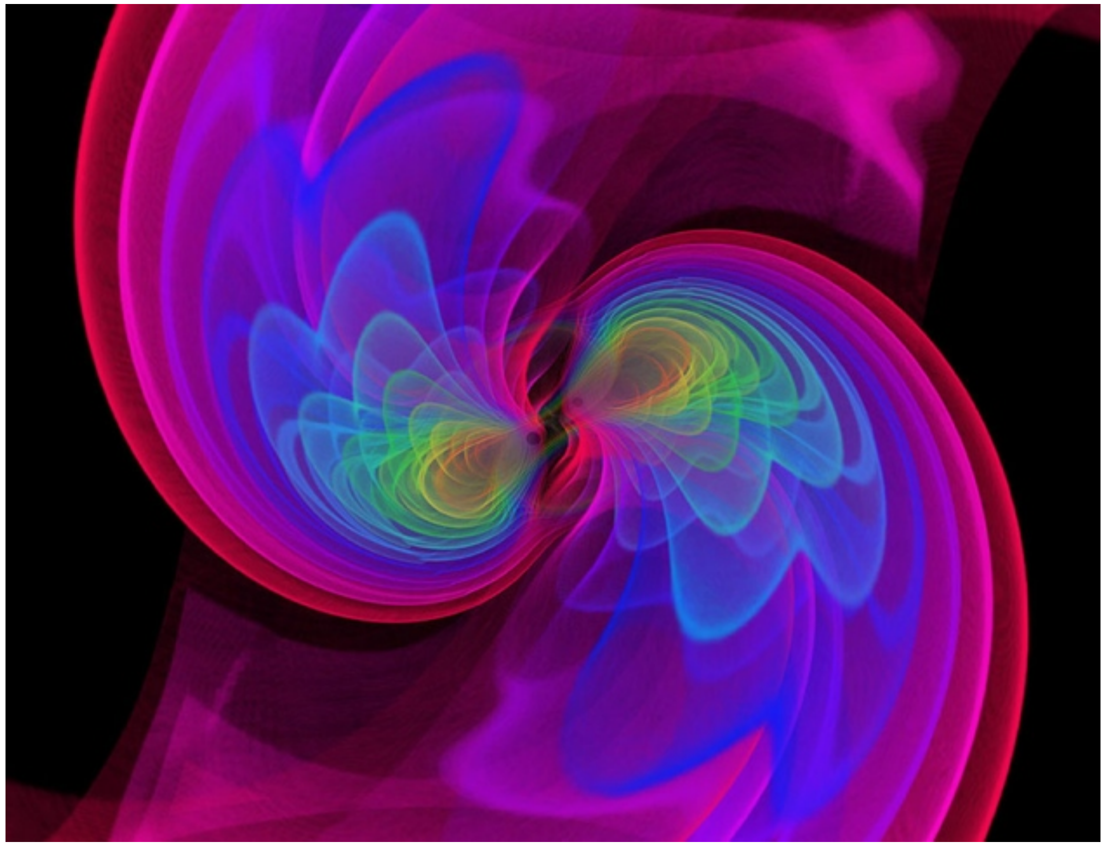
Swampland Conjectures

It is not that String Theory rules out the SM as we know it.
But non-trivial interactions among seemingly decoupled sectors must exist:
UV enforces interactions among IR degrees of freedom,
like anomaly conditions enforce constraints on IR physics.

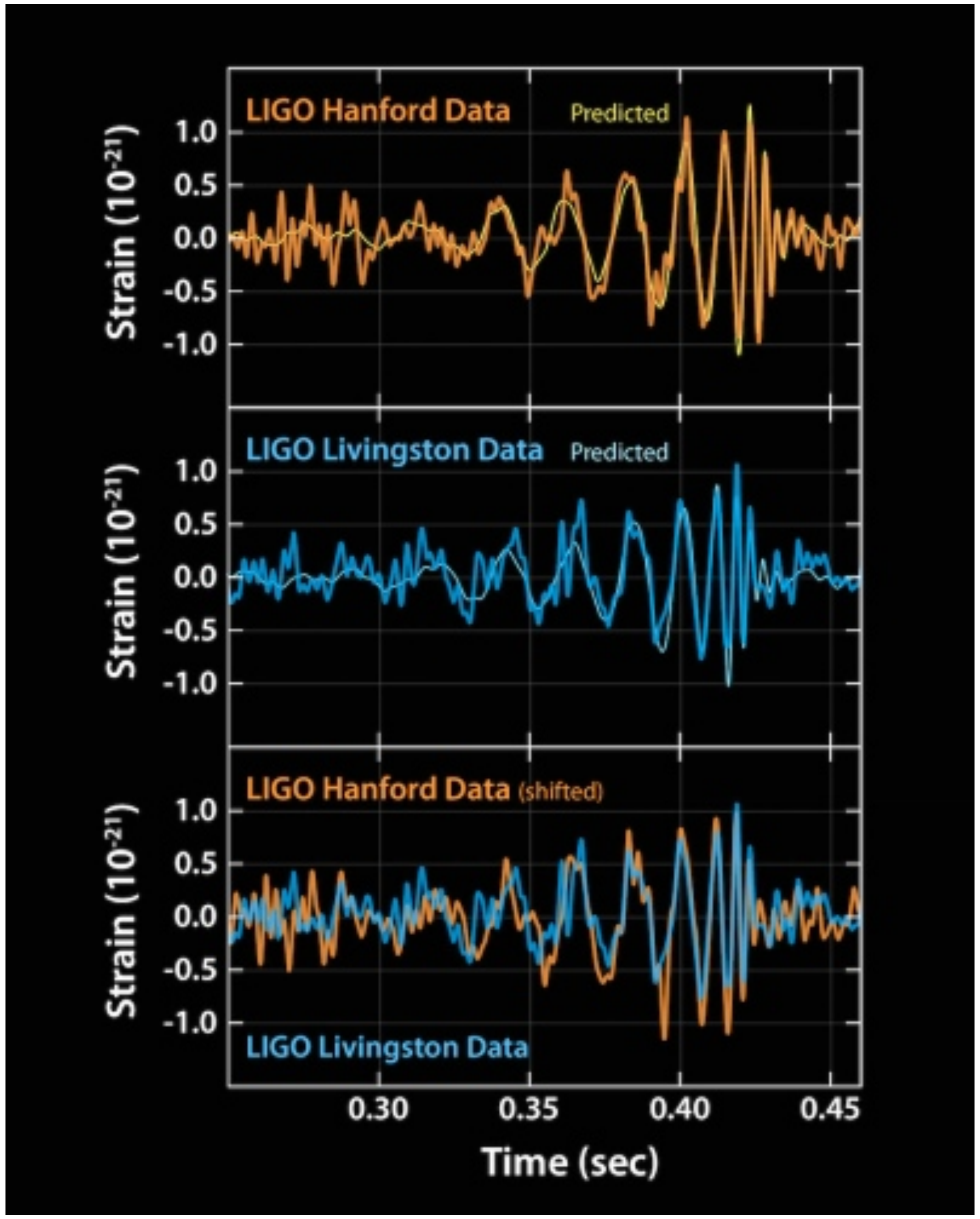
Gravitational waves

The pictures that shook the Earth

GW150914



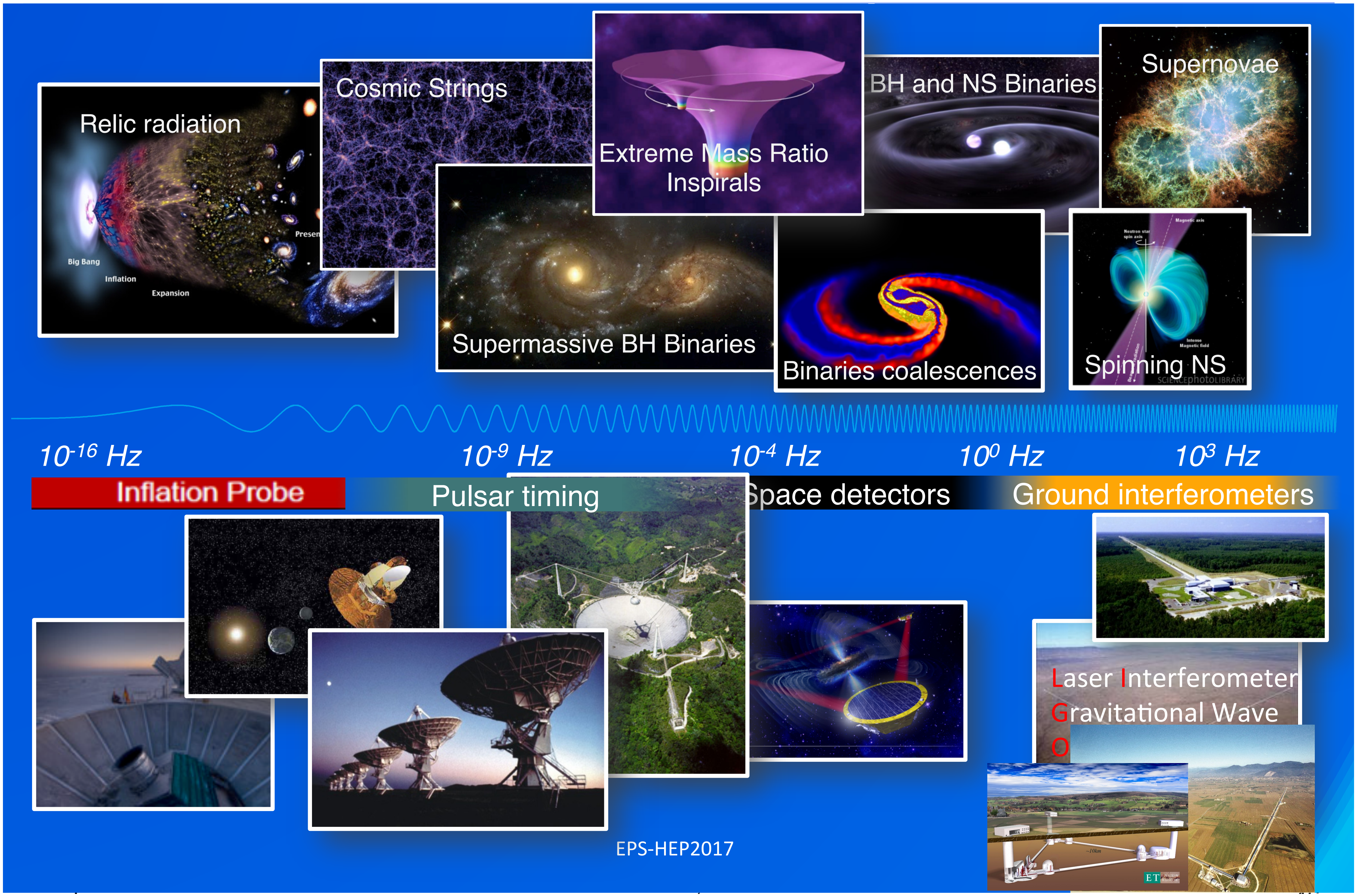
1.3 billion
years
later
on earth



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

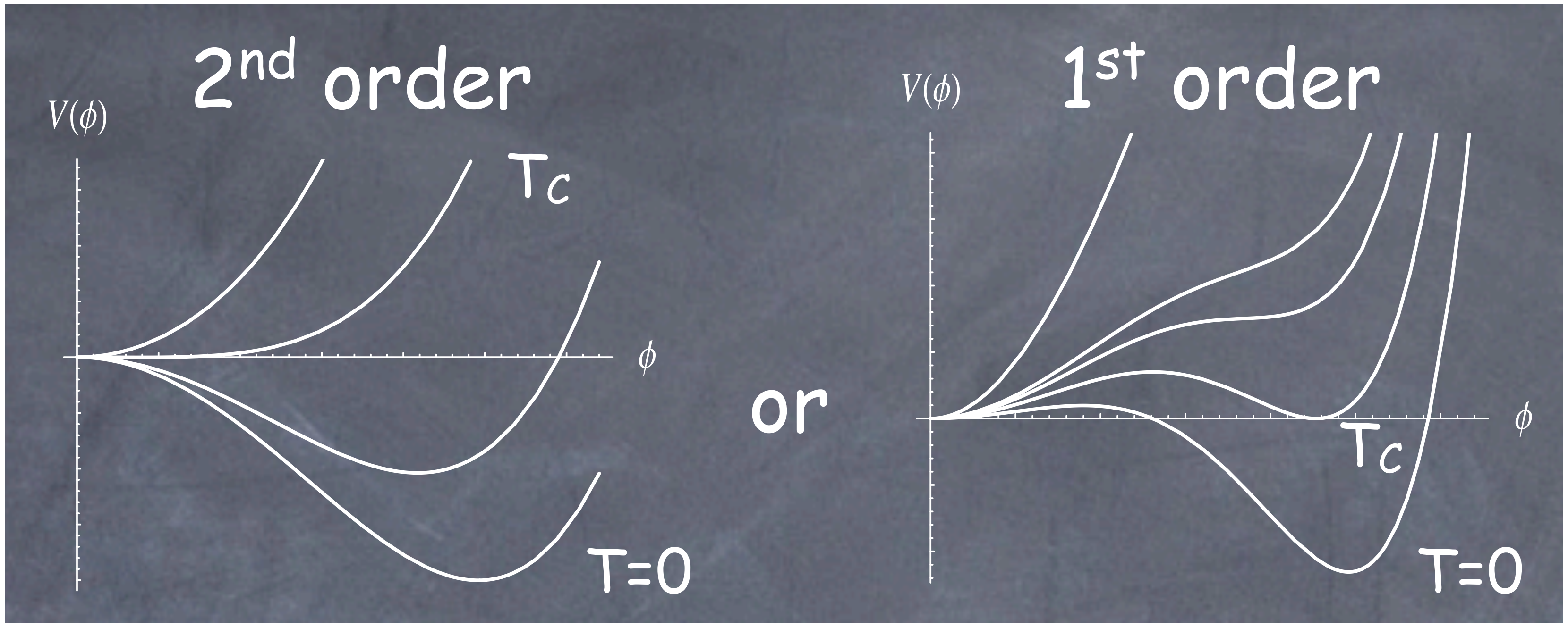


EPS-HEP2017

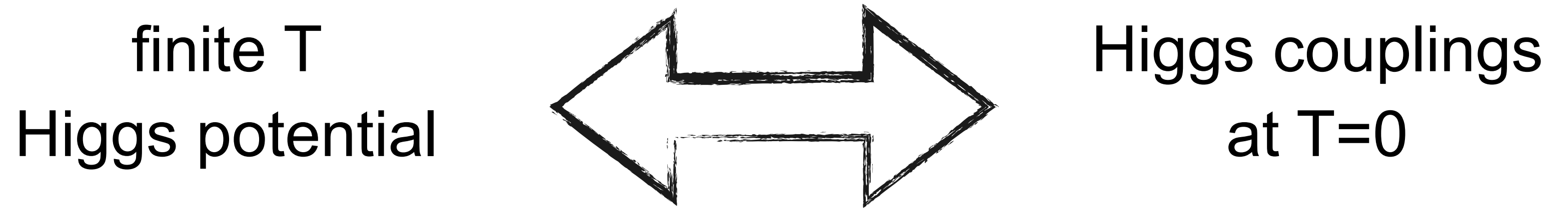
Dynamics of EW phase transition

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)$^{-1}$

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

redshifted freq.

~ today ~

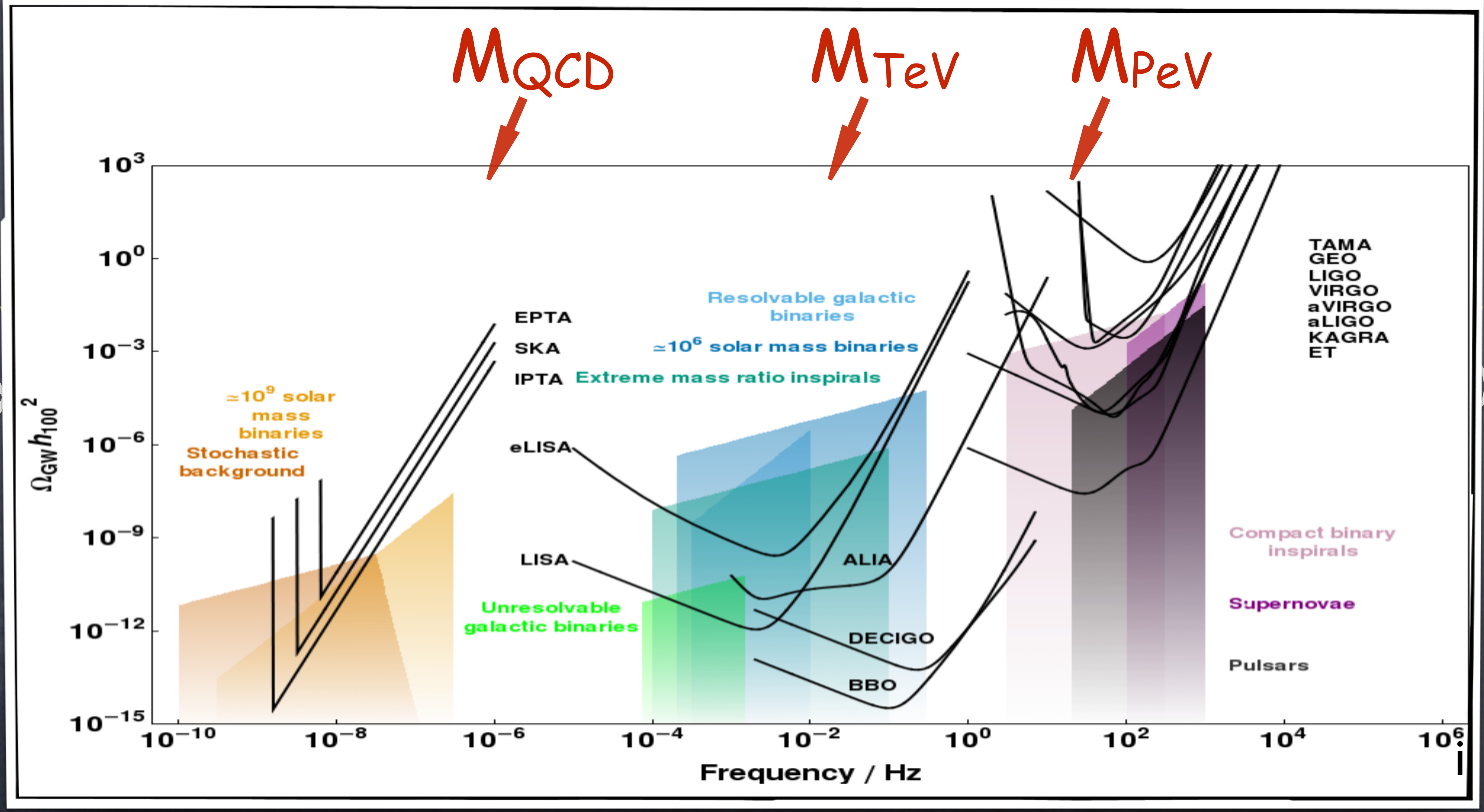
$$f \sim \# \frac{2\cdot 10^{-4}\ \mathrm{eV}}{100\ \mathrm{GeV}}\, 10^{-15}\ \mathrm{GeV} \sim \# 10^{-5}\ \mathrm{Hz}$$

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

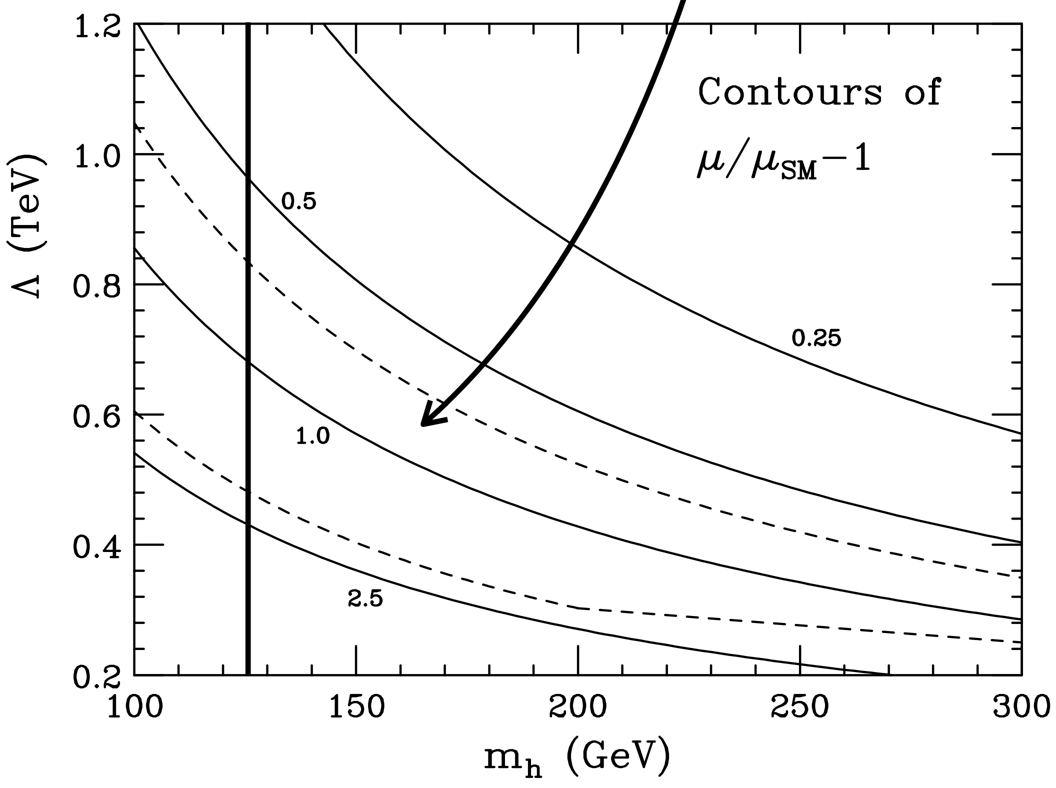


Grojean, Servant '06

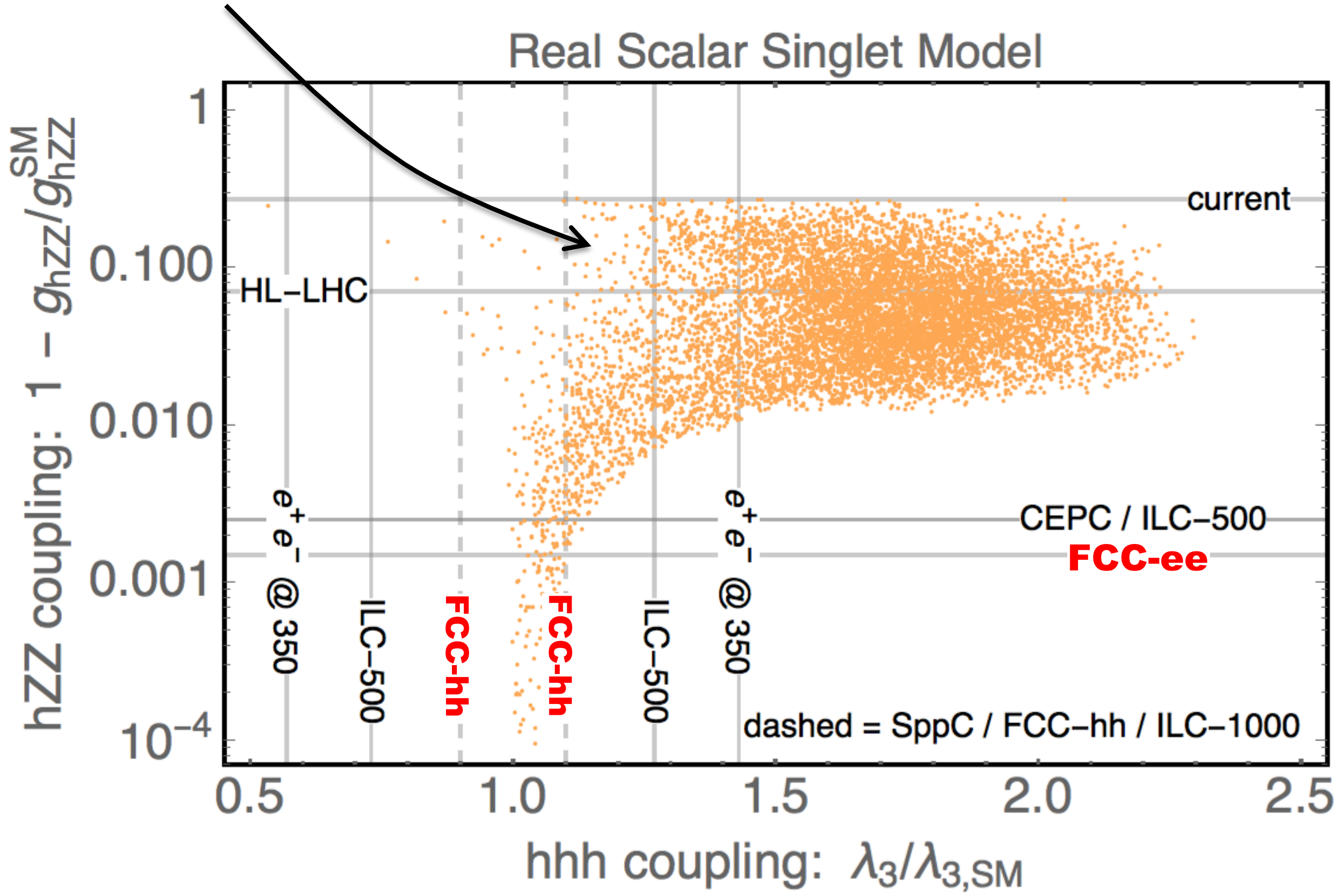
The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Complementary GW - Colliders

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



Grojean, Servant, Wells '04

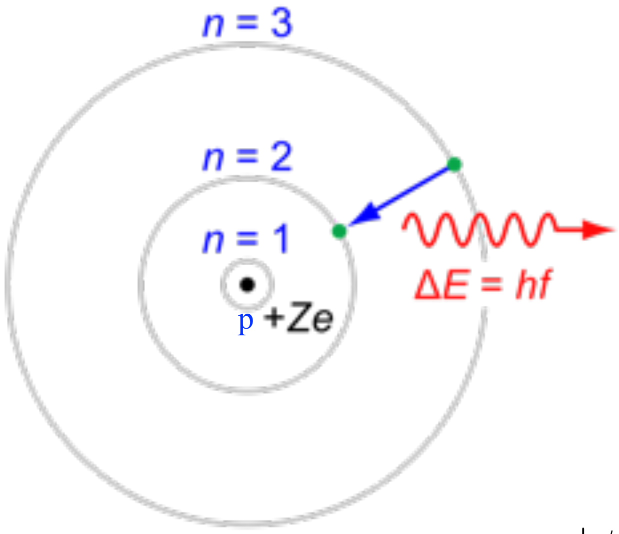


Huang, Long, Wang '16

"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.

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

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

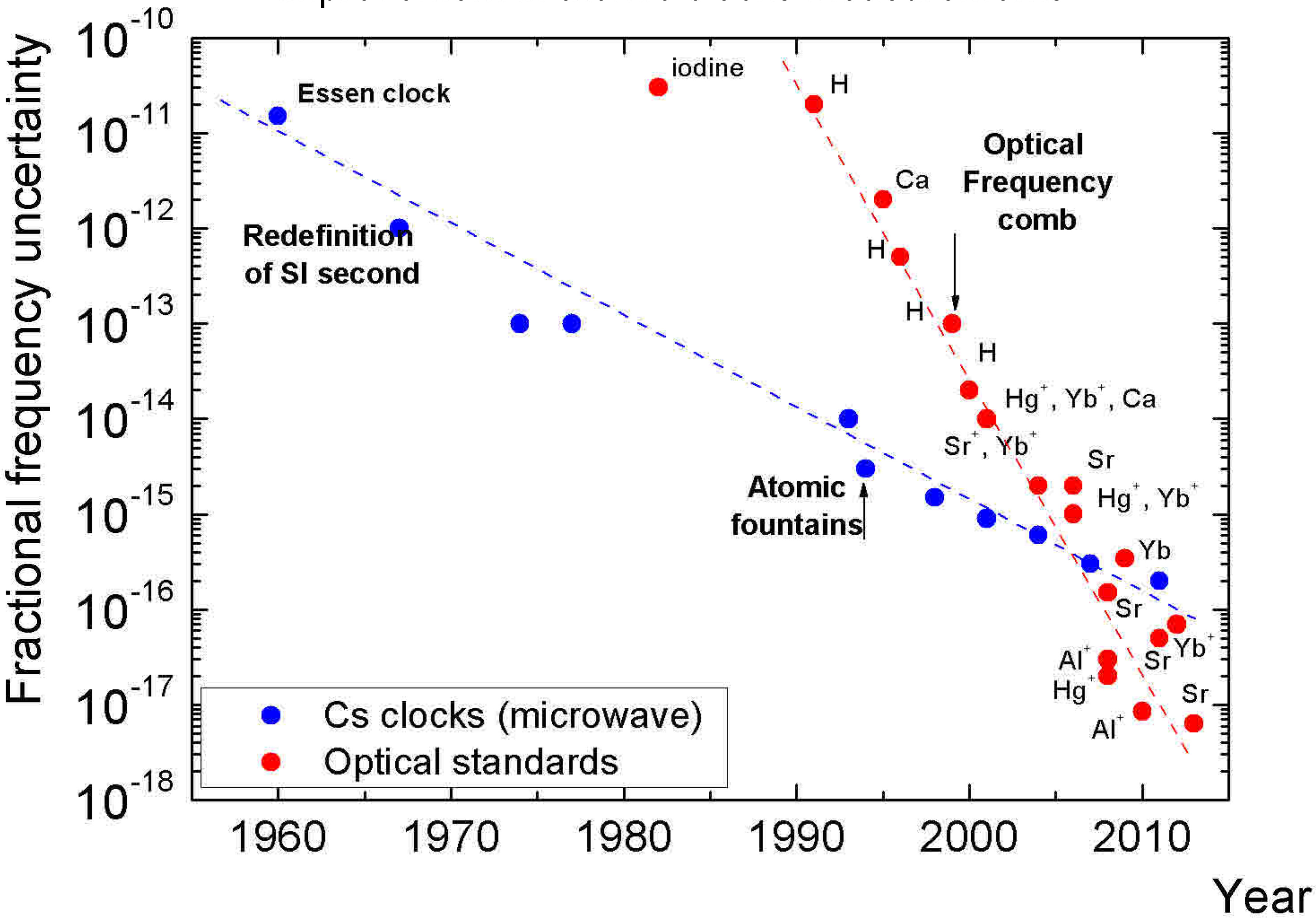
frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity $O(10^{-6:-9})$

can be used to detect new (long range) forces

Atomic Clocks as a BSM probe

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$

improvement in atomic clocks measurements



Isolating the signal: isotope shifts

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

$$\delta\nu^{i}_{AA'} = \underbrace{K_i\,\mu_{AA'}}_{\text{mass shift}} + \underbrace{F_i\delta\langle r^2\rangle_{AA'}}_{\text{field shift}} + \underbrace{H_i(A-A')}_{\text{BSM or NLO SM/QED}}$$

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:

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

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

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

Isolating the signal: isotope shifts

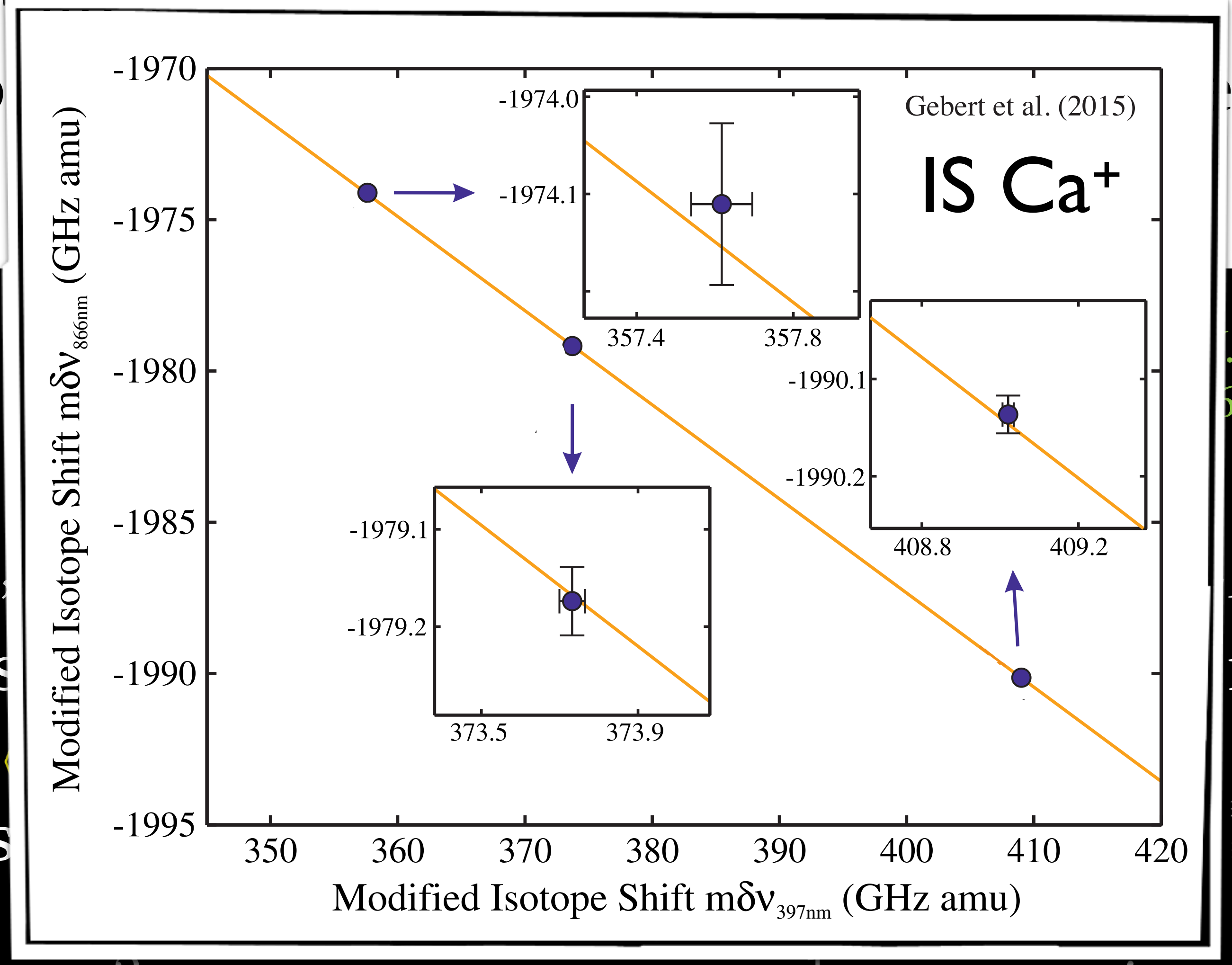
$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

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

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)

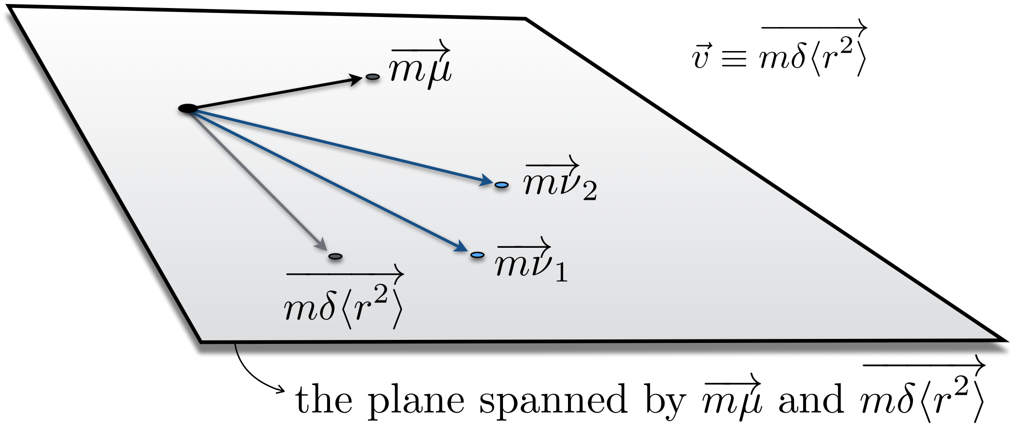
- First, … AA'
- Meas … 1 to set δ … trans …

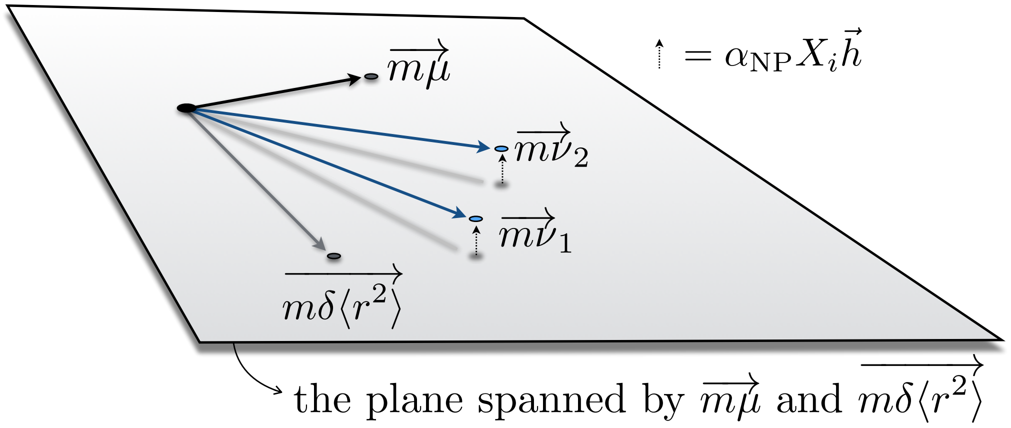
$\equiv F_2/F_1$
$\equiv K_2 - F_{21}K_1$
$\equiv H_2 - F_{21}H_1$

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

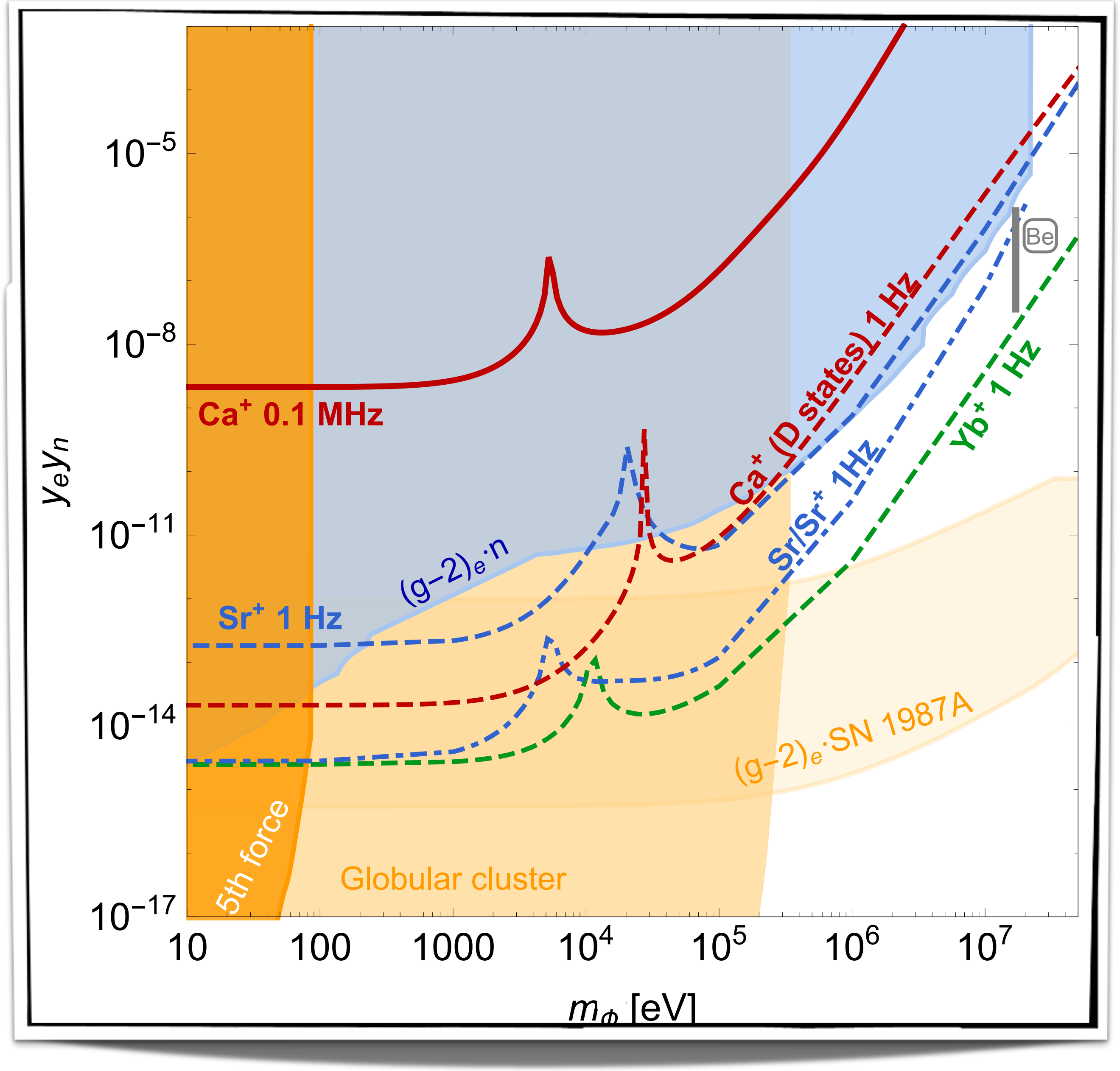
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP





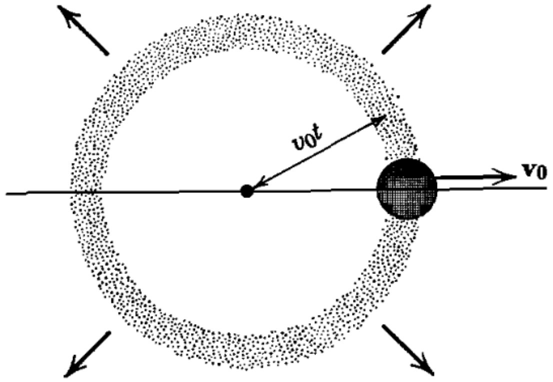
As long as
King linearity deviation
is not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



arXiv:1704.05068v1 [hep-ph]

Quantum sensing (metrology) for HEP

D. Blas, EPS'23



- Allow measuring events with tiny depositions of energy **(even with practically no-momentum transfer)**
- **Coherent/fragile** effects may allow to **enhance** detection possibilities
- **Low thresholds** ideally for "substantial" fluxes with **tiny cross-sections**.
- May represent a **fundamental frontier** to be understood in any measurement
- There is a revolution in the **frontier of** cutting-edge quantum metrology

Quantum sensing (metrology) for HEP

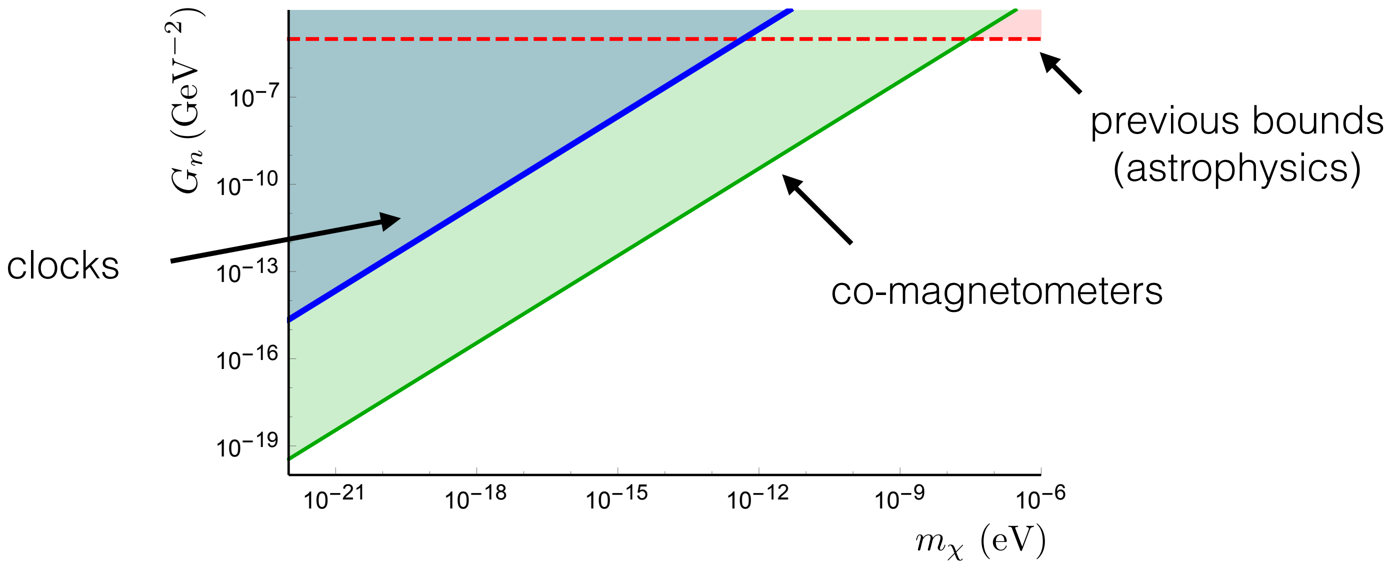
D. Blas, EPS'23

i) DM and cosmic neutrinos w/ atomic clocks and co-magnetometers

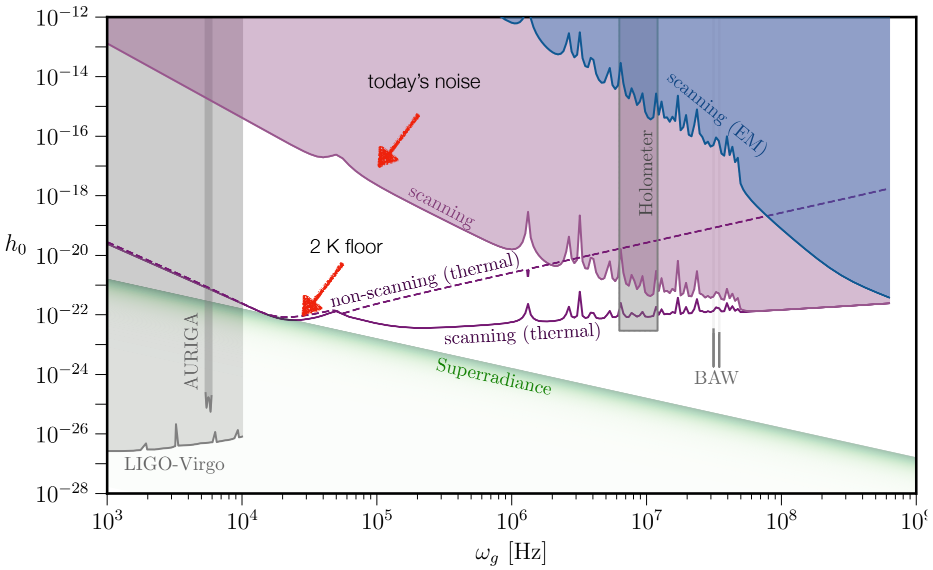
ii) Large atomic interferometers

iii) GWs in (superconducting radio-frequency) cavities

light DM



high frequency GW



EDM

Electric Dipole Moment

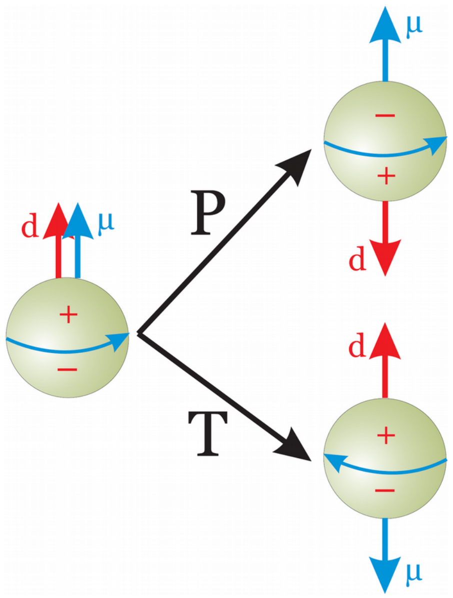
(M. Riembau, PhD defense '18)

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

Non-relativistic limit

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

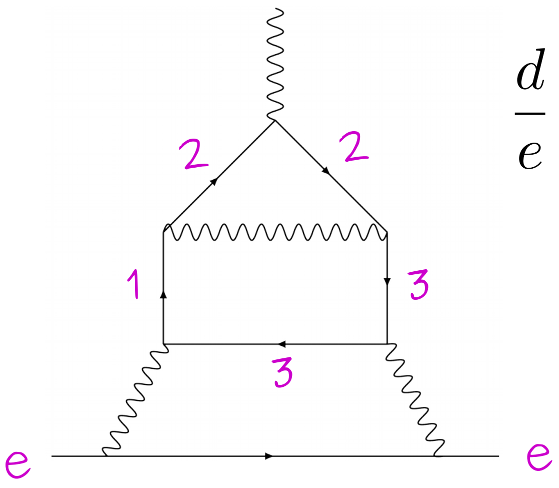
Nonvanishing EDM breaks CP



Nonvanishing d breaks CP

SM predictions

3-loop since one needs
to involve 3 families of quarks
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)

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

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

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

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

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

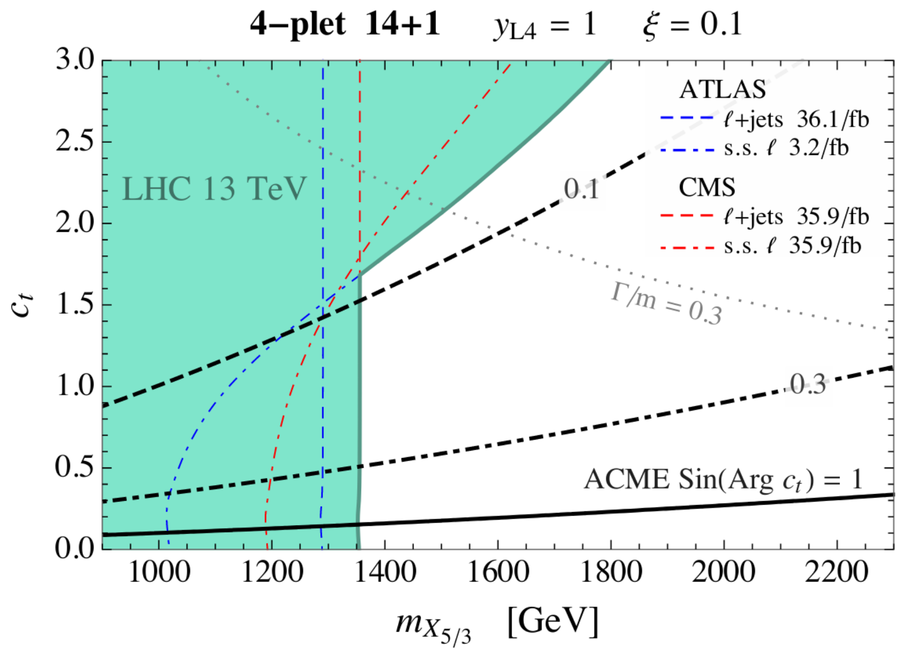
$|d_e| \lesssim 10^{-35}\; e\; cm$ arXiv:1710.08785

EDM as a BSM probe

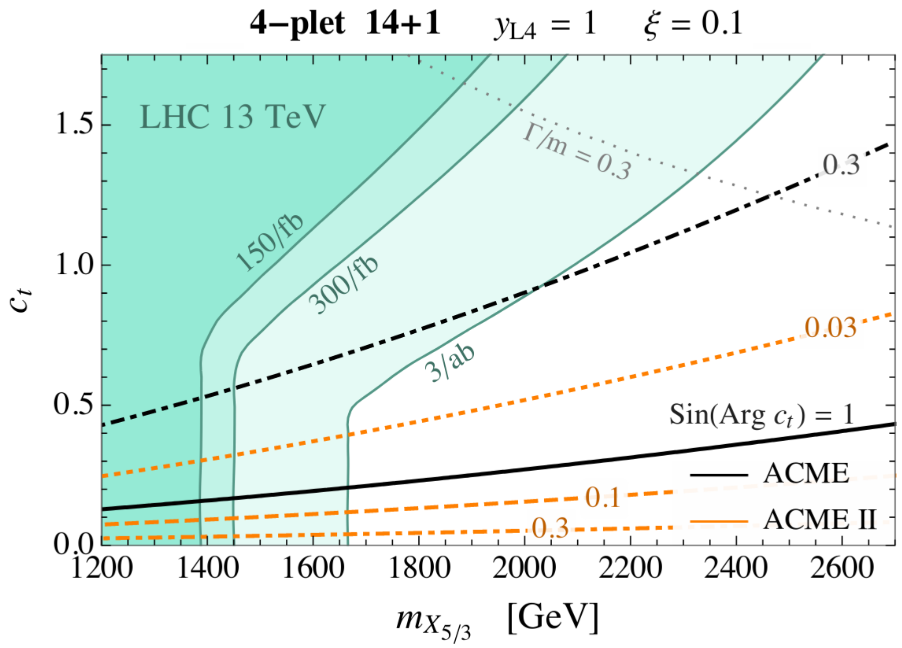
Panico, Riembau, Vantalon ‘17

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

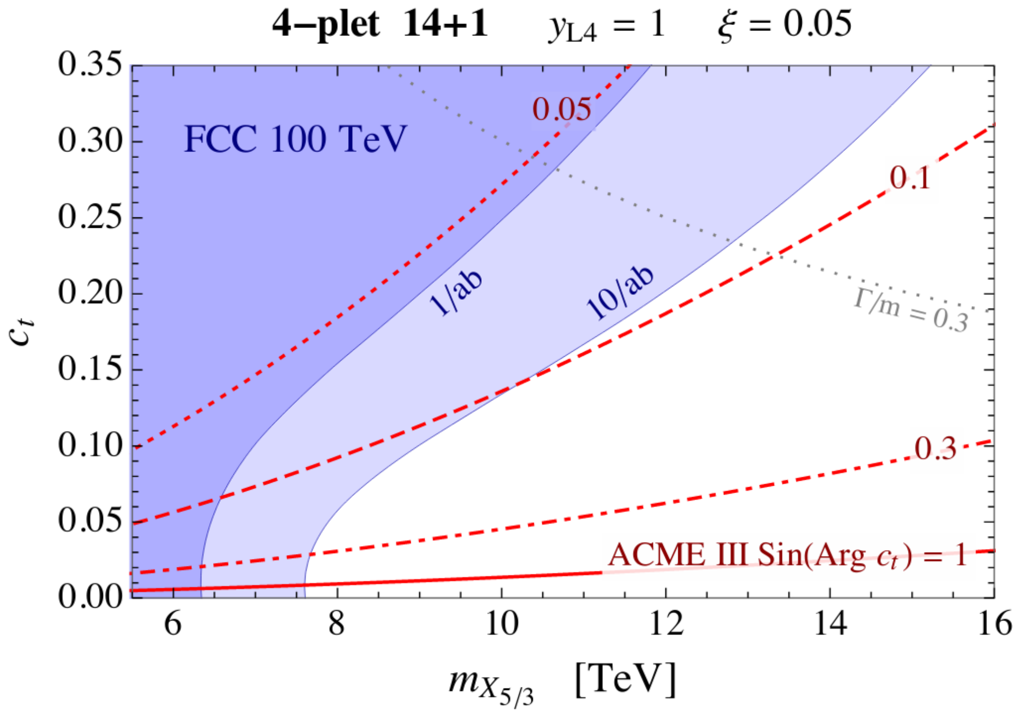
LHC



HL-LHC



FCC-hh



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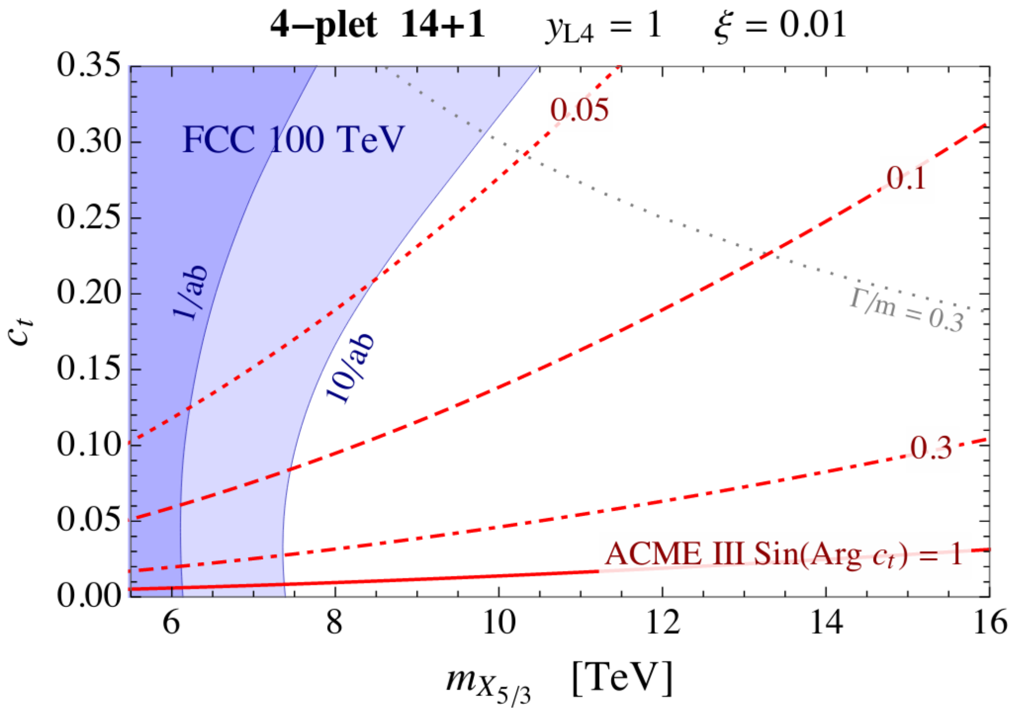


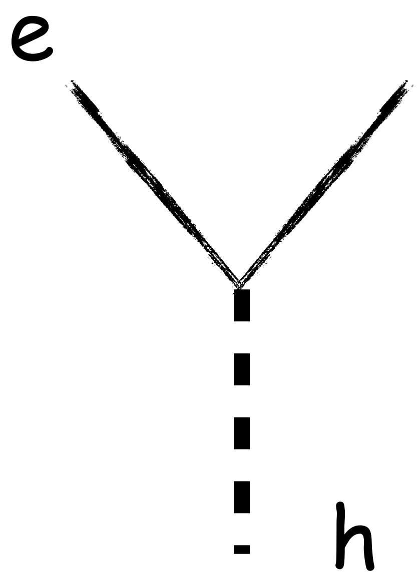
Conclusion(s)

Higgs boson at the LHC

producing a Higgs boson is a rare phenomenon
since its interactions with particles are proportional to masses
and ordinary matter is made of light elementary particles

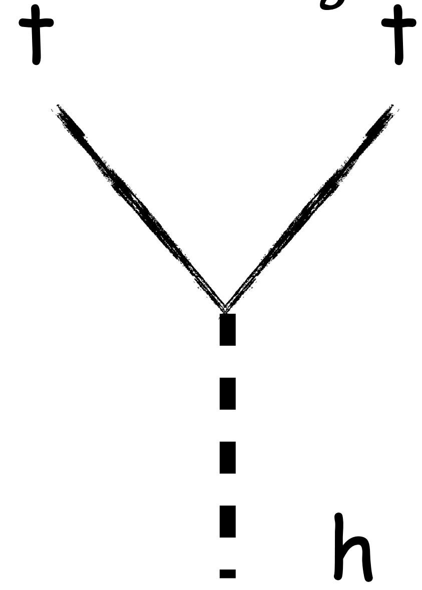
NB: the proton is not an elementary particle,
its mass doesn't measure its interaction with the Higgs substance

From electrons



probability ~ 10^{-11}

From top quarks



probability ~ 1

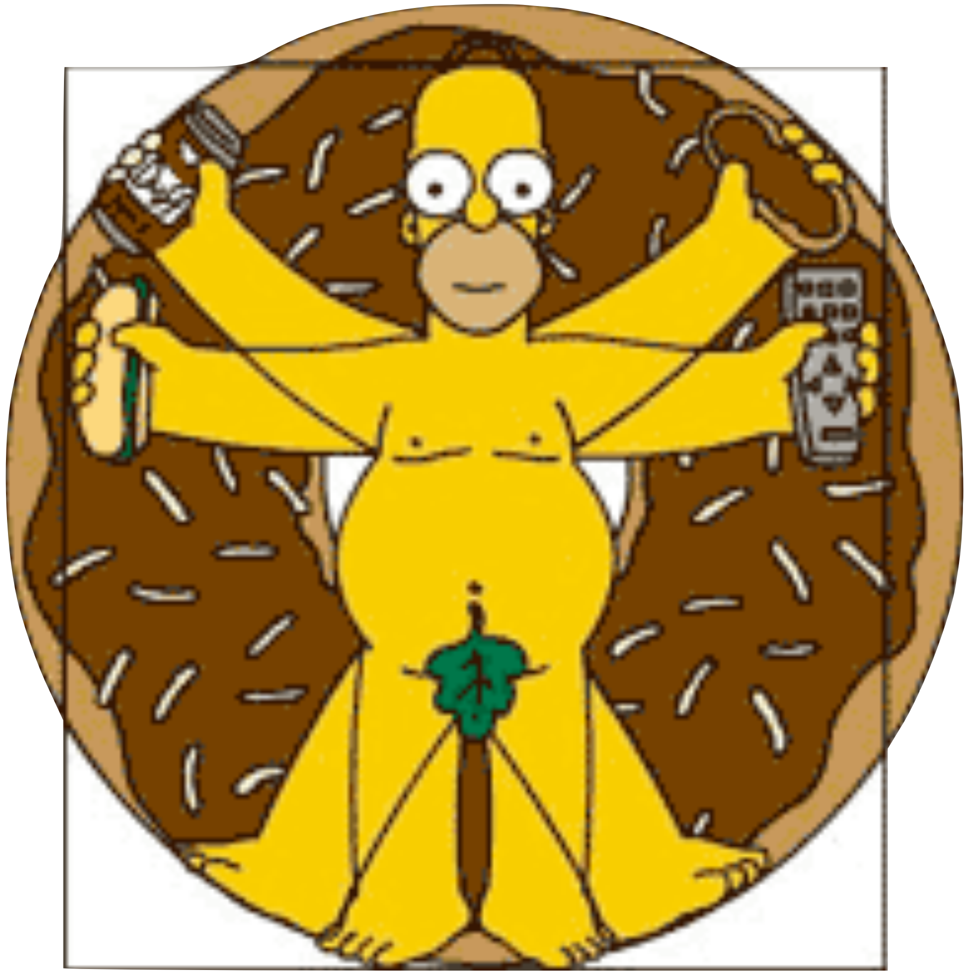
but no top quark at our disposal

Higgs boson at the LHC

Difficult task

Homer Simpson's principle of life:

If something's hard to do, is it worth doing?



The Higgs Boson is Special

LHC will make remarkable progress
but it won't be enough
A new collider will be needed!

The knowledge of the values of the **Higgs couplings** is essential to understand the deep structure of matter/Universe

m_W, m_Z ↔ Higgs couplings ✓

↑

lifetime of stars

(why $t_{Sun} \sim t_{life\ evolution}$?)

m_e, m_u, m_d ↔ Higgs couplings ?

size of atoms ↗ nuclei stability ↖

EWSB @ $t \sim 10^{-10}$s ↔ Higgs self-coupling ?

matter/anti-matter ↔ CPV in Higgs sector ?

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...

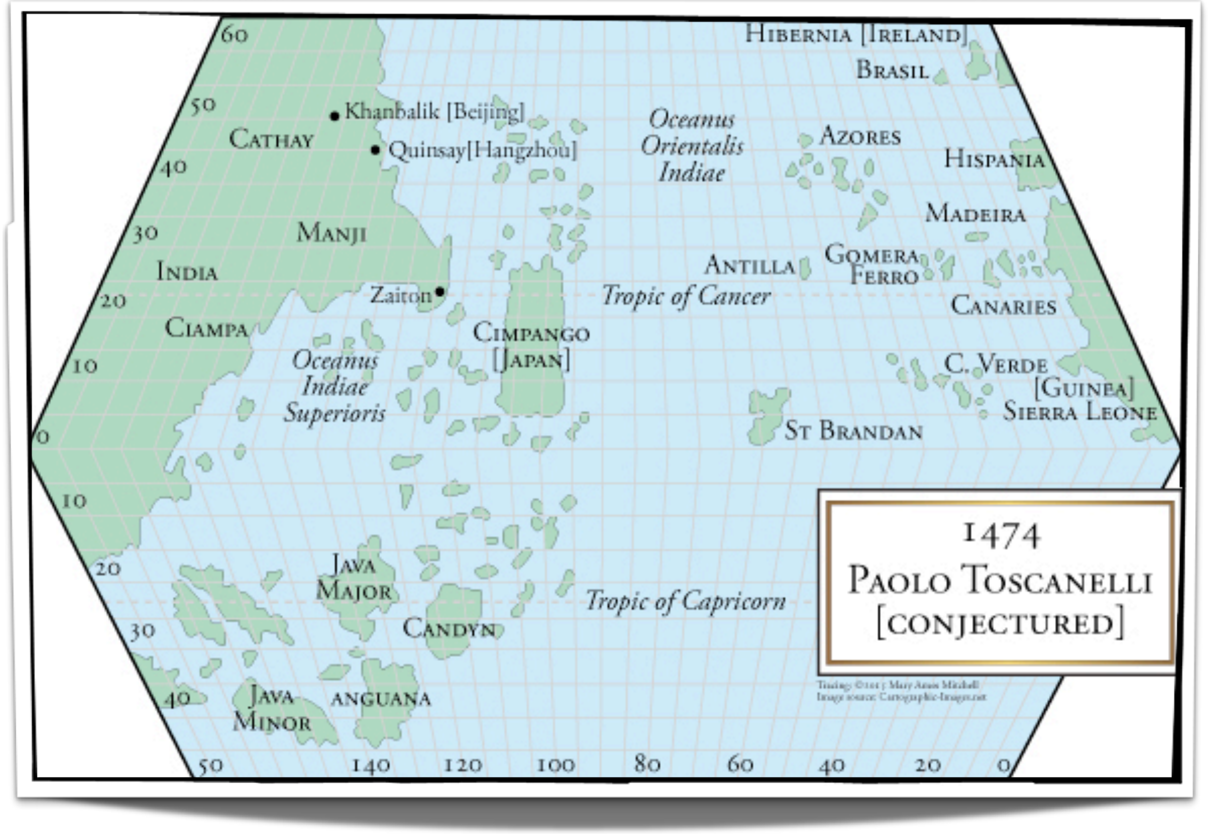
Columbus had a great proposal: “reaching India by sailing towards the West”

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



1474
Paolo Toscanelli
[conjectured]

Image source: Cartographic-Images.net

Sailing to India with the right tool...

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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 (*2nd part of the outreach competition*):
imagine what the former 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

Bonus Slides
on topics requested by some students

Evolution of coupling constants

Classical physics: the forces depend on distances

Quantum physics : the charges depend on distances

QED

virtual particles screen

the electric charge: α ↘ when d ↗

QCD

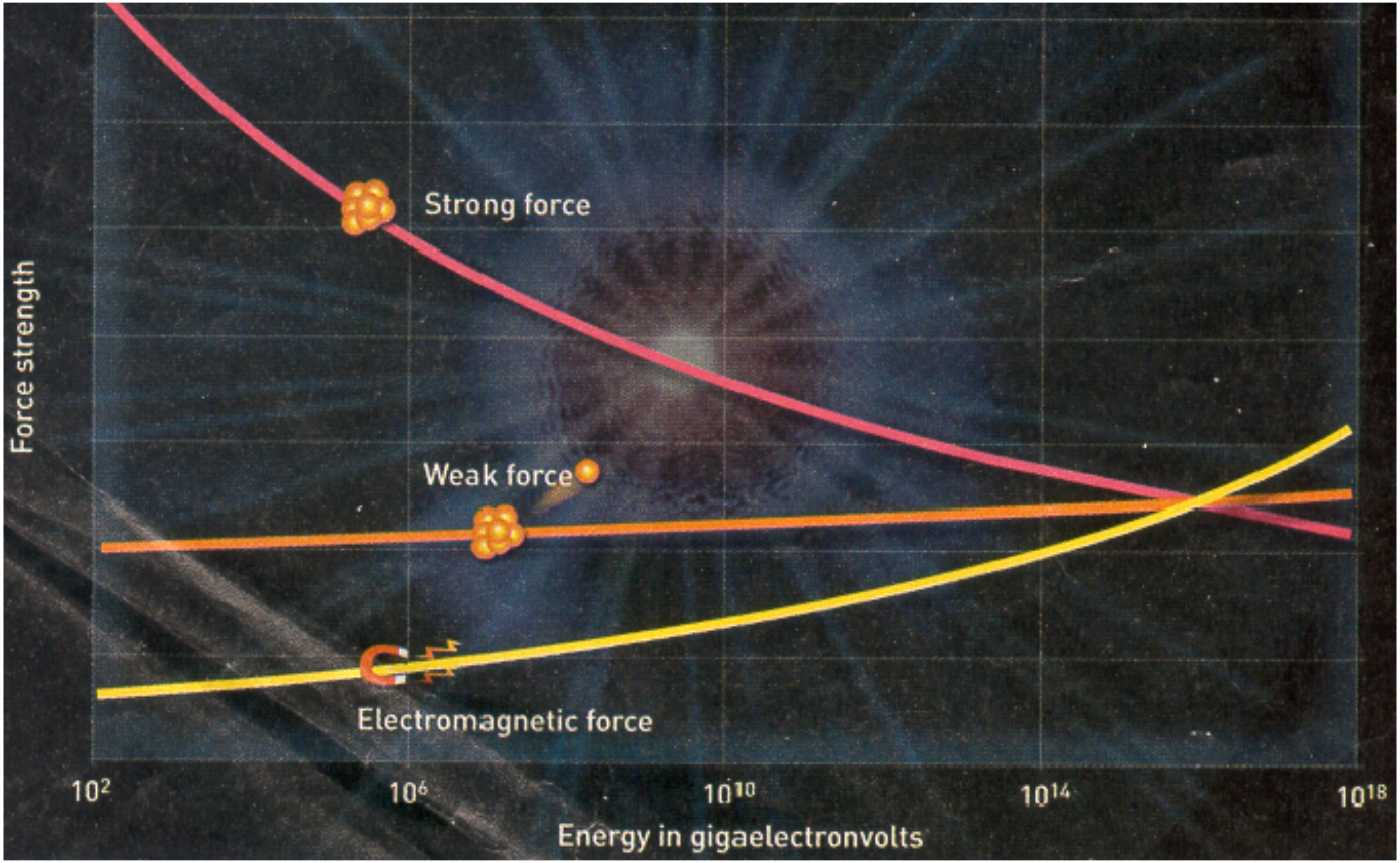
virtual particles (quarks and *gluons*) screen

the strong charge: α_s ↗ when d ↗

‘asymptotic freedom’

$$\frac{\partial \alpha_s}{\partial \log E} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi}\left(-\frac{11N_c}{6}+\frac{N_f}{3}\right)$$

Grand Unified Theories



A single form of matter
A single fundamental interaction

SU(5) GUT: Gauge Group Structure

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$: SM Matter Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad u_R^c = (\bar{3},1)_{-2/3}, \quad d_R^c = (\bar{3},1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad e_R^c = (1,1)_1$$

How can you ever remember all these numbers?

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$ ⊂ SU(5)

SU(5)
Adjoint rep.

$$\left(\begin{array}{c|c} SU(2) & \\ \hline & SU(3) \end{array}\right)$$

$$\mathrm{Tr}(T^a T^b) = \frac{1}{2}\delta^{ab}$$

additional U(1) factor that commutes with SU(3)xSU(2)

$$T^{12} = \sqrt{\frac{3}{5}} \left(\begin{array}{cc|ccc} 1/2 & & & & \\ & 1/2 & & & \\ \hline & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{array}\right)$$

$$\boxed{\begin{array}{c} \bar{5} = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}} \\ \bar{5} = L + d_R^c \end{array}}$$

$$\boxed{\begin{array}{c} 10 = (5 \times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}} \\ 10 = u_R^c + Q_L + e_R^c \end{array}}$$

$$T^{12} = \sqrt{\frac{3}{5}} Y \qquad g_5 \sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

$$g_5 T^{12} = g' Y$$

$\sin^2\theta_W = \frac{3}{8}$ @ M$_{GUT}$

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How can you ever remember all these

SU(3)$_c$xSU(2)

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

that

SU

U(2)

Adjoi

$\mathrm{Tr}(T^a T^b$

$$\begin{pmatrix} & \vline & \\ \hline & \vline & -1/3 & & \\ & \vline & & -1/3 & \\ & \vline & & & -1/3 \end{pmatrix}$$

$$\boxed{\begin{gathered} \bar{5} = (\bar{1},2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}} \\ \bar{5} = L + d_R^c \end{gathered}}$$

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$$g_5 T^{12} = g' Y$$

$$\sin^2\theta_W = \frac{3}{8}$$ @ M$_{GUT}$

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$ ← experimental inputs

b_3, b_2, b_1 ← predicted by the matter content

3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation on low energy parameters

$$\epsilon_{ijk} \frac{b_j - b_k}{\alpha_i(M_Z)} = 0 \quad ⇨ \quad \boxed{\sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)}}$$

$$\alpha_{em}(M_Z) \approx \frac{1}{128} \qquad \alpha_s(M_Z) \approx 0.1184 \pm 0.0007$$

⇩

$\sin^2\theta_W \approx 0.207$ not bad… (observed value: 0.23)
Even better in MSSM

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

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3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation on low energy parameters

$$M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 7 \times 10^{14} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 41.5$$

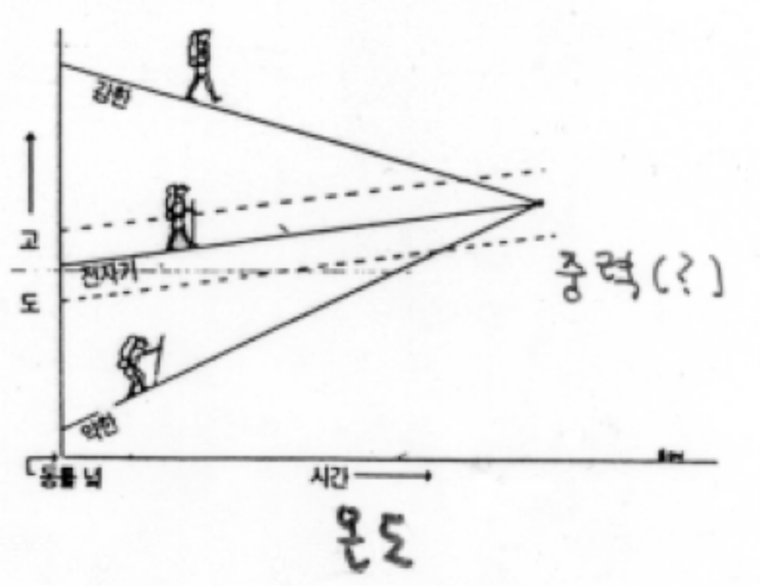
self-consistent computation:

- $M_{GUT} < M_{Pl}$ safe to neglect quantum gravity effects
- $\alpha_{GUT} << 1$ perturbative computation

SU(5) GUT: SM β fcts

g, g' and g$_s$ are different but it is a low energy artifact!

$$\boxed{\beta = \frac{dg}{d\log\mu} = -\frac{1}{16\pi^2} b g^3 + \dots}$$



$$\boxed{\frac{1}{g^2(Q)} = \frac{1}{g^2(Q_0)} + \frac{b}{16\pi^2}\ln\frac{Q^2}{Q_0^2}}$$

$$b = \frac{11}{3}T_2(\texttt{spin-1}) - \frac{2}{3}T_2(\texttt{chiral spin-1/2}) - \frac{1}{3}T_2(\texttt{complex spin-0})$$

$$\mathrm{Tr}\left(T^a(R)T^b(R)\right) = T_2(R)\delta^{ab} \qquad T_2(\texttt{fund}) = \frac{1}{2} \qquad T_2(\texttt{adj}) = N$$

$$\boxed{b_{SU(3)}} = \overset{g}{\frac{11}{3}\times 3} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{u_R^c}{\frac{1}{2}\times 1\times 3} + \overset{d_R^c}{\frac{1}{2}\times 1\times 3}\right) = \boxed{7}$$

$$\boxed{b_{SU(2)}} = \overset{W^\pm, Z}{\frac{11}{3}\times 2} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H}{\frac{1}{3}\times\frac{1}{2}} = \boxed{\frac{19}{6}}$$

$$b_Y = -\frac{2}{3}\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{u_R^c}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{d_R^c}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{e_R^c}{(1)^2\times 3}\right) - \overset{H}{\frac{1}{3}\left(\frac{1}{2}\right)^2\times 2} = -\frac{41}{6} \Rightarrow \boxed{b_{T^{12}} = -\frac{41}{10}}$$

exercise

SU(5) GUT: SM vs MSSM β fcts

chiral superfield

complex spin-0
Weyl spin-1/2
in same representation of gauge group

vector superfield

Weyl spin-1/2
real spin-1
in same representation of gauge group

$$b = \frac{11}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{chiral}) - \frac{1}{3}T_2(\texttt{chiral}) = 3\,T_2(\texttt{vector}) - T_2(\texttt{chiral})$$

MSSM Chiral Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6},\quad U = (\bar{3},1)_{-2/3},\quad D = (\bar{3},1)_{1/3},\quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2},\quad E = (1,1)_1,\ H_u = (1,2)_{1/2},\quad H_d = (1,2)_{-1/2}$$

$$b_{SU(3)} = \overset{g}{3\times 3} - \left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{U}{\frac{1}{2}\times 1\times 3} + \overset{D}{\frac{1}{2}\times 1\times 3}\right) = \boxed{3}$$

$$b_{SU(2)} = \overset{W^\pm, Z}{3\times 2} - \left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H_u}{\frac{1}{2}} - \overset{H_d}{\frac{1}{2}} = \boxed{-1}$$

$$b_Y = -\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{U}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{D}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{E}{(1)^2\times 3}\right) - \overset{H_u}{\left(\frac{1}{2}\right)^2\times 2} - \overset{H_d}{\left(\frac{1}{2}\right)^2\times 2} = -11 \;\Rightarrow\; \boxed{b_{T^{12}} = -\frac{33}{5}}$$

SU(5) GUT: MSSM GUT

$$b_3 = 3, \quad b_2 = -1, \quad b_1 = -33/5$$

low-energy consistency relation for unification

$$\sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1}\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.23$$

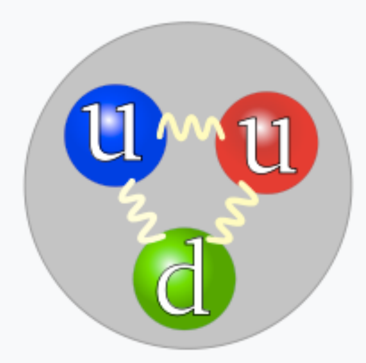
squarks and sleptons form complete SU(5) reps ➛ they don't improve unification!
gauginos and higgsinos are improving the unification of gauge couplings

GUT scale predictions

$$M_{GUT} = M_Z \exp\left(2\pi\frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 2\times 10^{16}\ \text{GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 24.3$$

Proton Decay

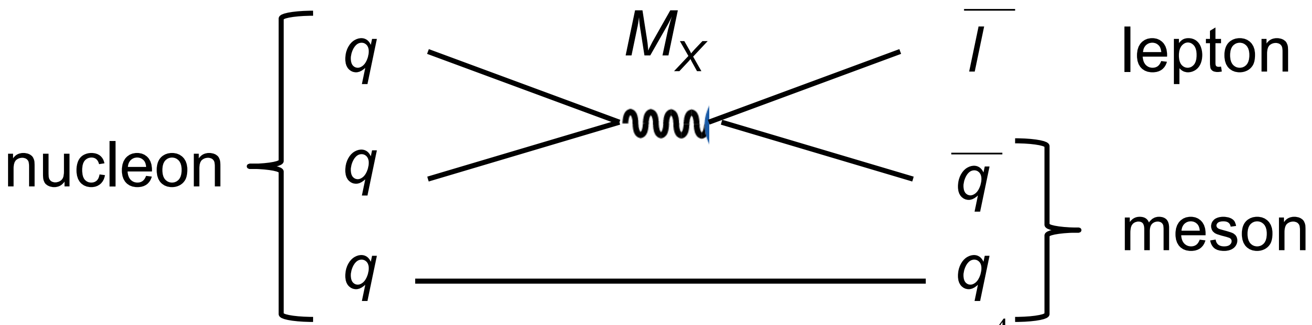


why is the proton stable?

electric charge conservation?

baryon number conservation?

938.2720813(58) MeV



in GUT, “matter” is unstable

decay of proton mediated by new SU(5)/SO(10) gauge bosons

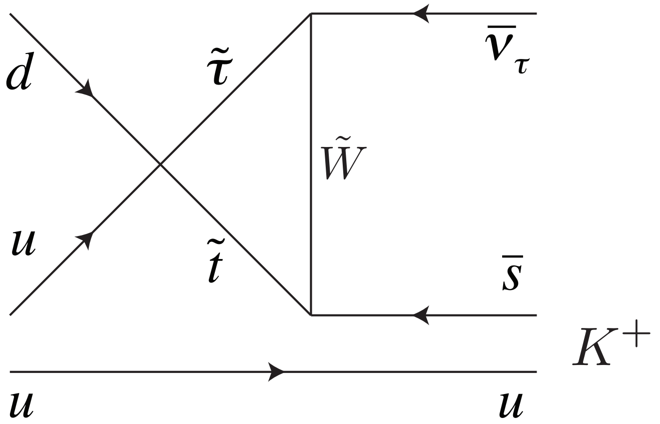
$$\text{GUT:}\quad \tau_p(p\to e^+\pi^0)=\left(\frac{M_X}{10^{15}\ \text{GeV}}\right)^4 10^{31-32}\ \text{yr}$$

$$\text{Exp:}\quad \tau_p(p\to e^+\pi^0)>8.2\times10^{33}\ \text{yr}$$

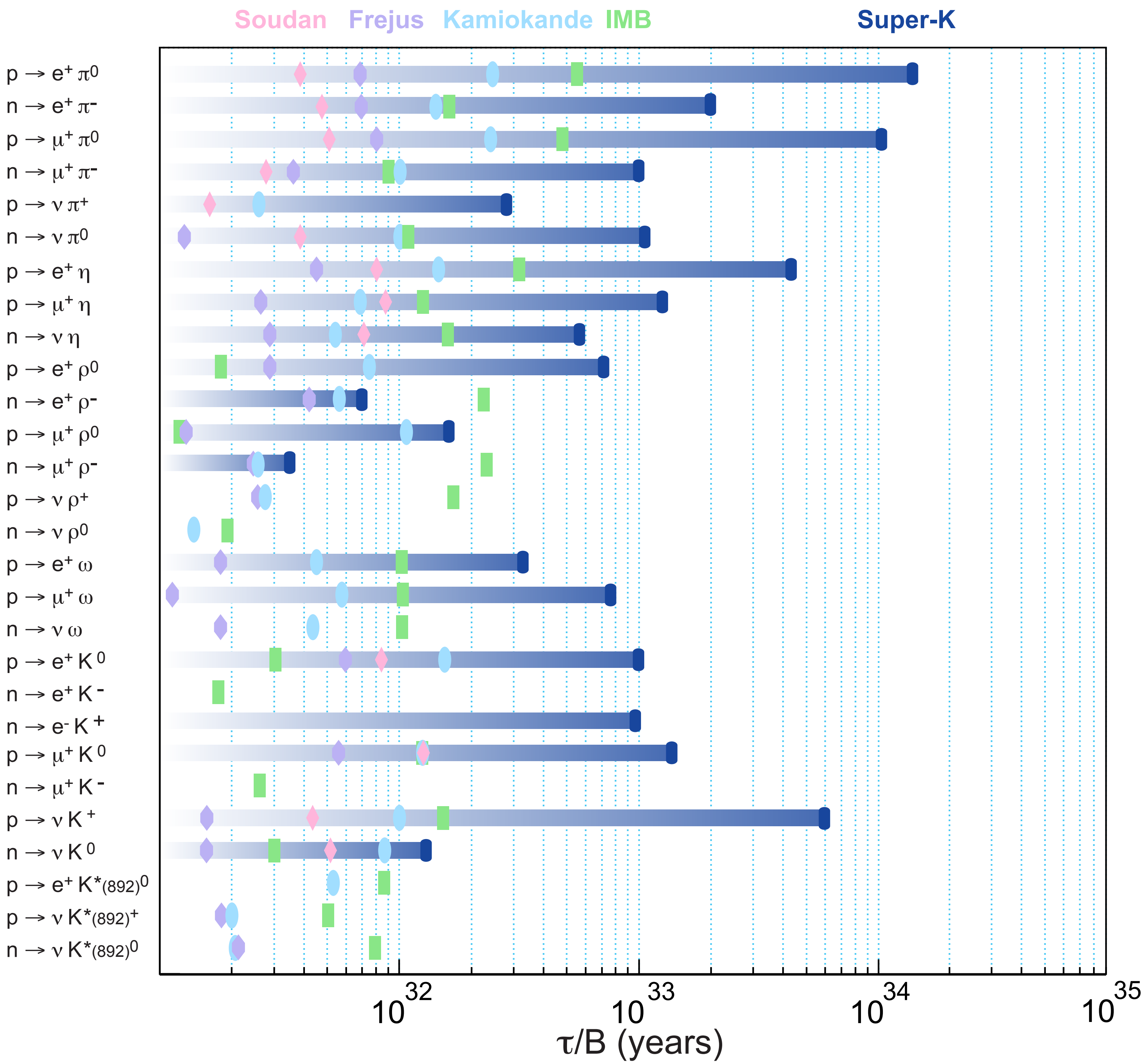
(G. Giudice SSLP'15)

other decay mode:

$$p^+\to K^+\overline{\nu}$$



Proton Decay

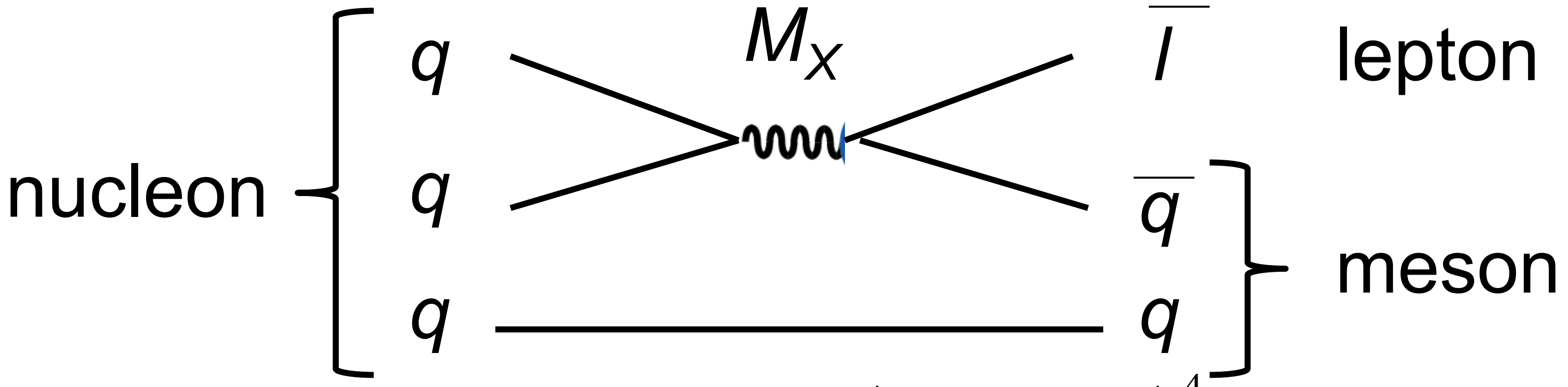


Babu et al '13

Proton Decay

(G. Giudice SSLP'15)

in GUT, matter is unstable
decay of proton mediated by new SU(5)/SO(10) gauge bosons

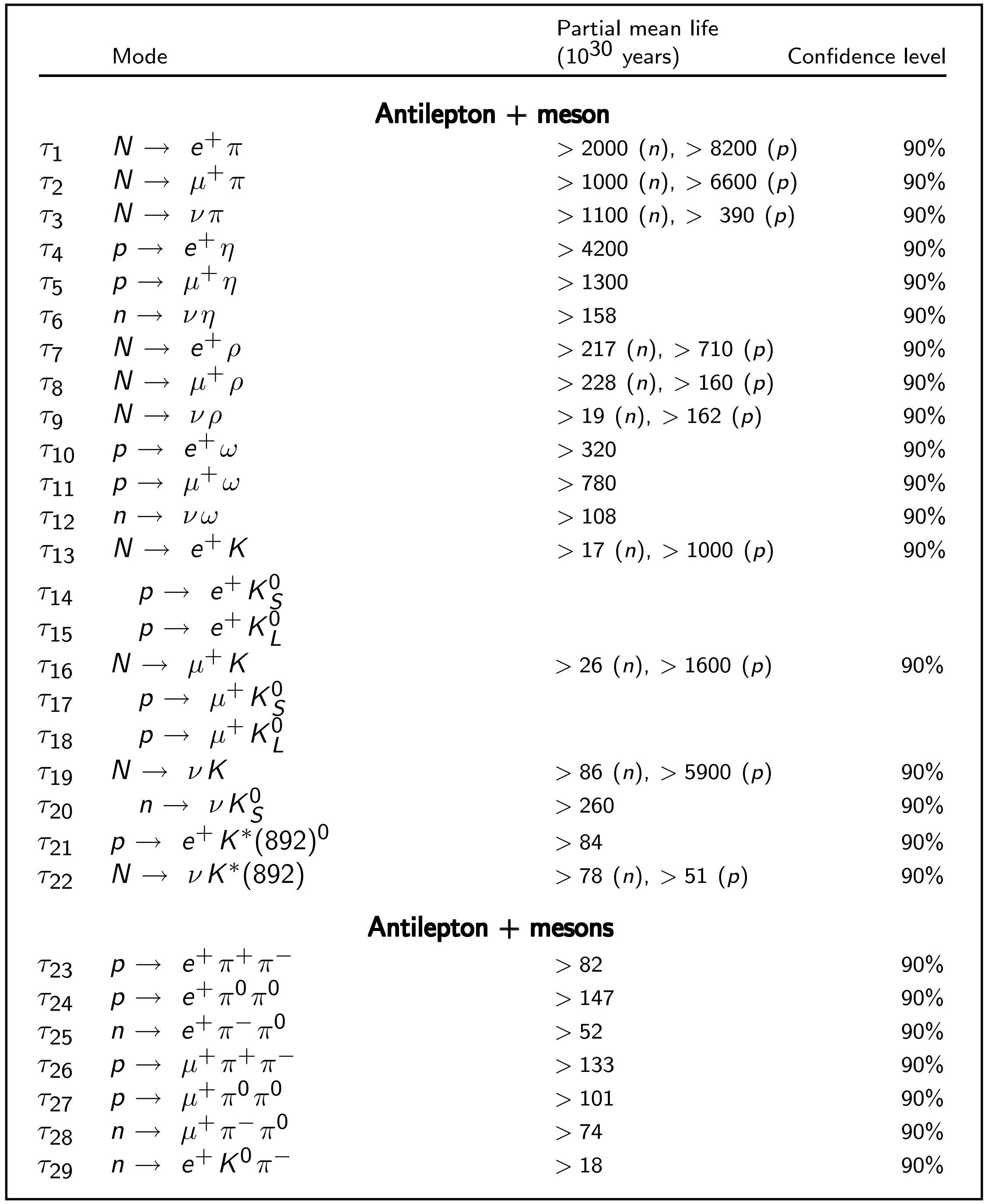


$$\text{GUT:}\quad \tau_p(p \to e^+\pi^0) = \left(\frac{M_X}{10^{15}\ \text{GeV}}\right)^4 10^{31-32}\ \text{yr}$$

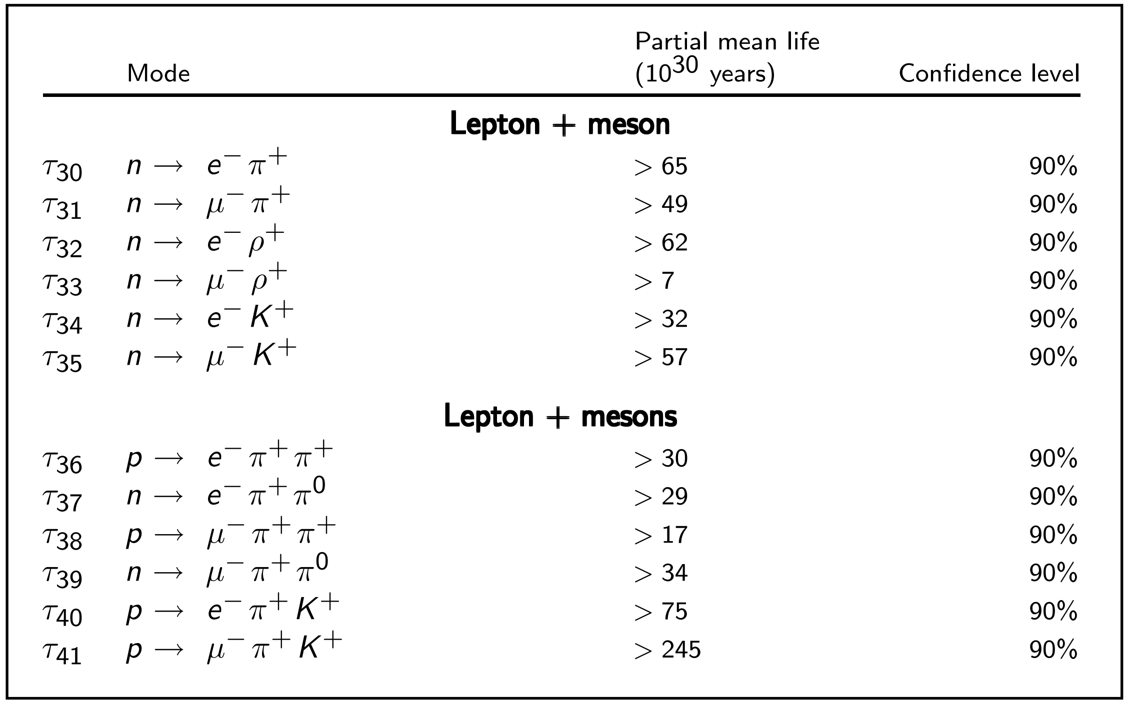
$$\text{Exp:}\quad \tau_p(p \to e^+\pi^0) > 8.2\times 10^{33}\ \text{yr}$$

(Age of the Universe: 10^{10} years)

Proton Decay



	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%



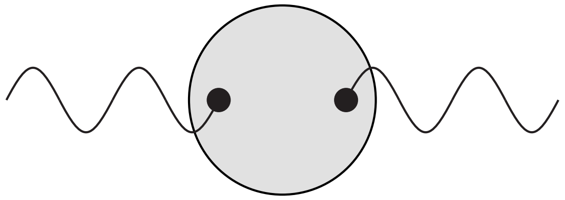
	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^- \pi^+$	> 65	90%
τ_{31}	$n \to \mu^- \pi^+$	> 49	90%
τ_{32}	$n \to e^- \rho^+$	> 62	90%
τ_{33}	$n \to \mu^- \rho^+$	> 7	90%
τ_{34}	$n \to e^- K^+$	> 32	90%
τ_{35}	$n \to \mu^- K^+$	> 57	90%
	Lepton + mesons		
τ_{36}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

ΔB=ΔL=1 decay bounds

SU(5) GUT: Composite Higgs β fcts

Agashe, Contino, Sundrum '05
Frigerio, Serra, Varagnolo '11



strong sector
SU(5) invariant

interactions between
strong & elementary sectors
SU(5) breaking

$$\frac{d\alpha_i}{d\ln Q} \in -\frac{b_{\rm comp}}{2\pi}\alpha_i^2 + \frac{B_{ij}}{2\pi}\frac{\alpha_j^3}{4\pi} + \frac{C_{if}}{2\pi}\frac{\lambda_f^2}{16\pi^2}$$

doesn't contribute to the *differential* running
cannot be computed
(non-perturbative)
but negative and bounded from below

affect the unification of the gauge couplings

Higgs = light composite state → may contribute to the differential running only below composite scale

t_R = light composite fermion → doesn't contribute to the running either

subtract H, t_R and t_R^c from the β fcts

SU(5) GUT: Composite Higgs β fcts

Agashe, Contino, Sundrum ’05

Higgs = light composite state ➙ may contribute to the differential running only below composite scale

t_R = light composite fermion ➙ doesn’t contribute to the running either

$\}$ subtract H, t_R and t_R^c from the β fcts

$$b_{SU(3)} = b^{SM}_{SU(3)} + \frac{2}{3}\left(\frac{1}{2}+\frac{1}{2}\right) = \boxed{\frac{23}{3}}$$

$$b_{SU(2)} = b^{SM}_{SU(2)} + \frac{1}{3}\times\frac{1}{2} = \boxed{\frac{10}{3}}$$

$$b_Y = b_Y^{SM} + \frac{2}{3}\left(\left(-\frac{2}{3}\right)^2\times 3+\left(-\frac{2}{3}\right)^2\times 3\right)+\frac{1}{3}\left(\frac{1}{2}\right)^2\times 2 = -\frac{44}{9} \quad \Rightarrow \quad \boxed{b_{T^{12}} = -\frac{44}{15}}$$

low-energy consistency relation for unification

$$\sin^2\theta_W = \frac{3(b_3-b_2)}{8b_3-3b_2-5b_1}+\frac{5(b_2-b_1)}{8b_3-3b_2-5b_1}\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.228$$

improving the unification of gauge couplings by removing chiral matter!

SU(5) GUT: SM vs MSSM vs MCHM