Searching for new paradigms in particle physics

Towards the origin of the electroweak scale

ICTP-SAIFR, Sao Paulo

Alex Pomarol,
IFAE &UAB (Barcelona)

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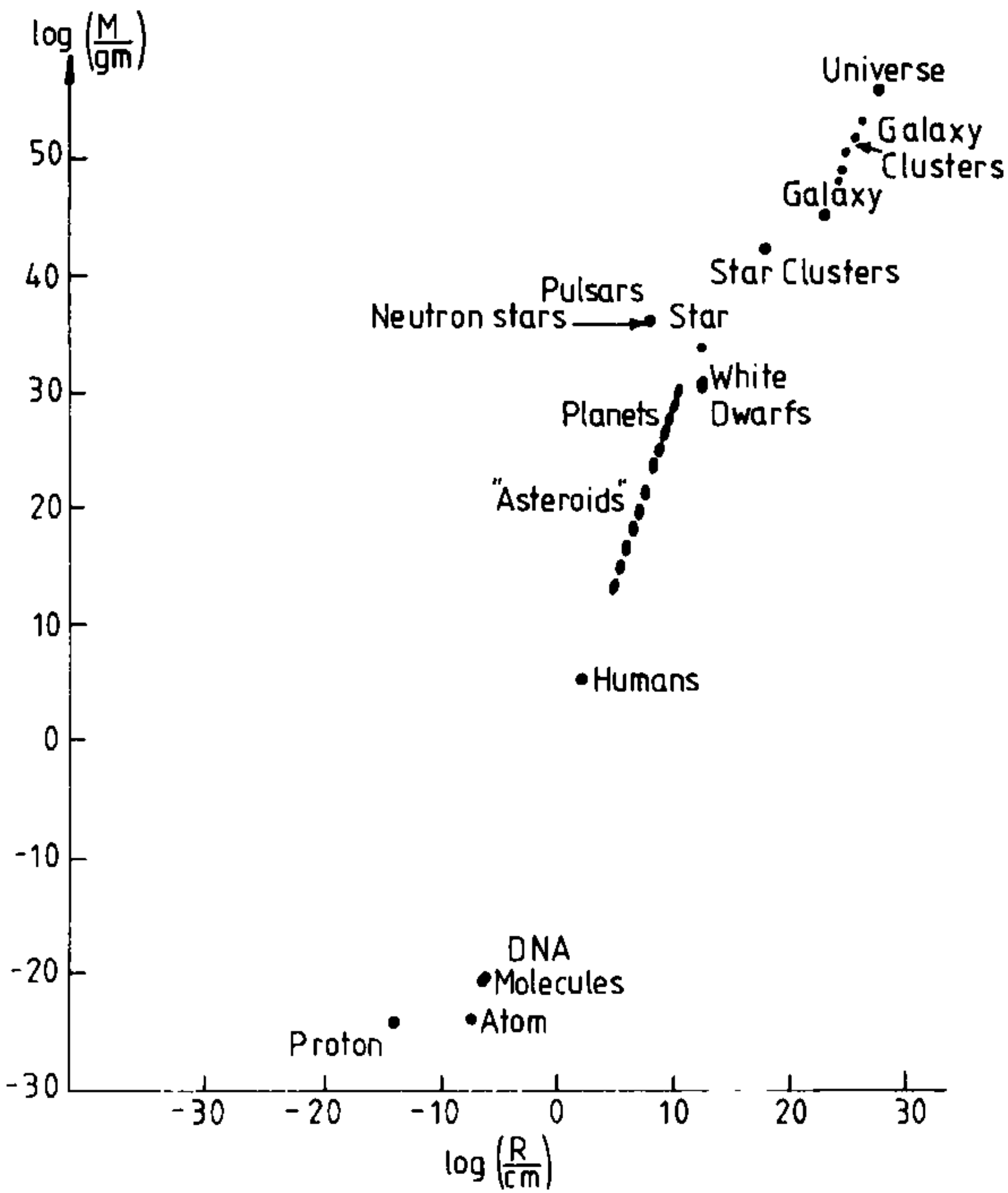
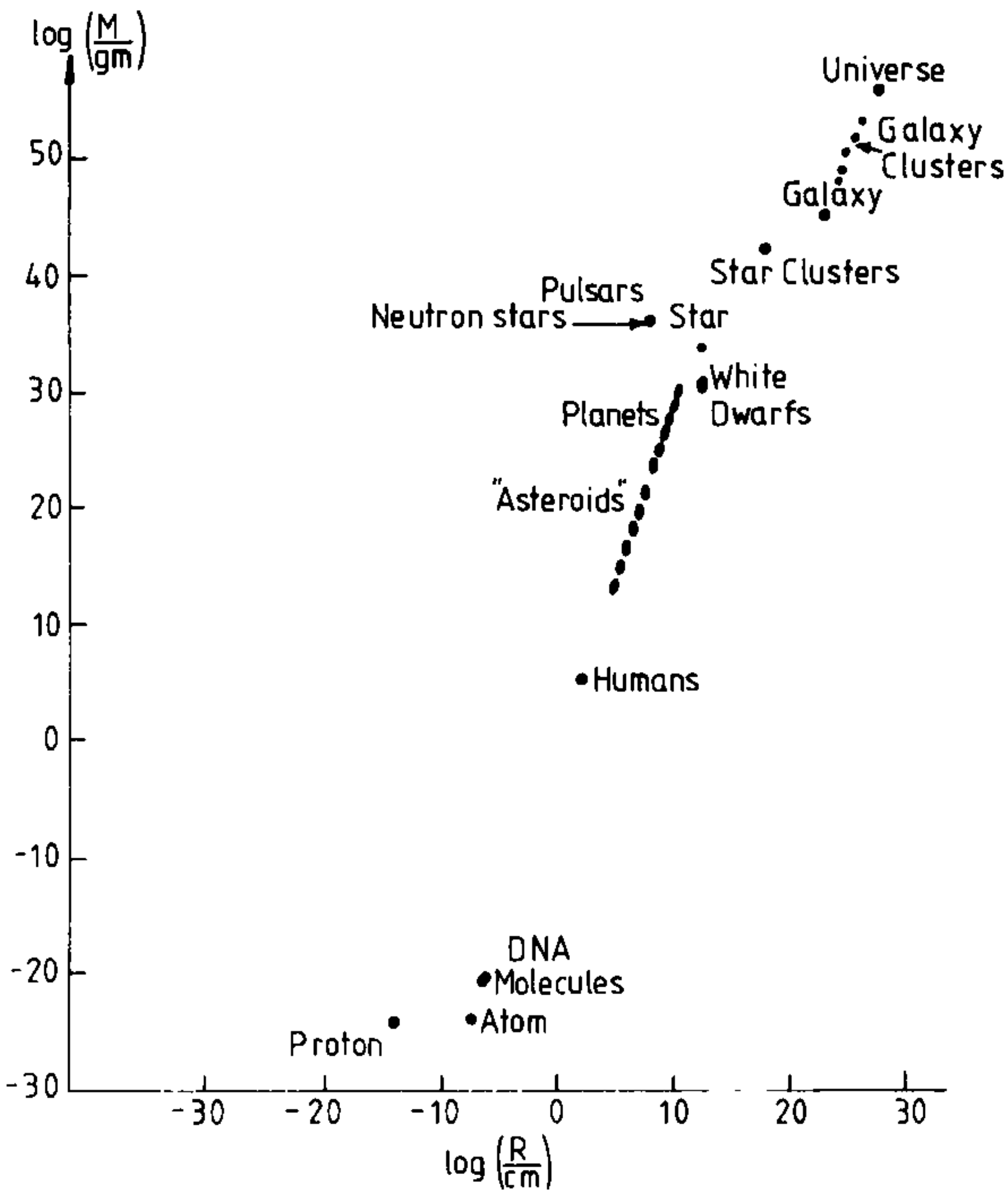
Understanding scales: The driving force of physics



Understanding scales: The driving force of physics



$$\mathbf{M_{star}} \sim \left(\frac{\mathbf{M_P}}{\mathbf{m_N}}\right)^{\mathbf{3}} \mathbf{m_N}$$

$$\mathbf{R_{planet}} \sim \frac{\mathbf{m_N}}{\mathbf{M_P}} \frac{\mathbf{1}}{\sqrt{\alpha}\,\mathbf{m_e}}$$

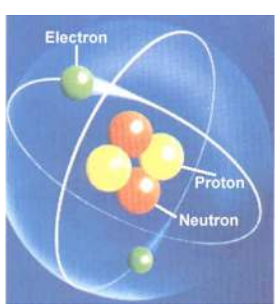
$$\mathbf{T_{room}} \sim \mathbf{10^{-3}}\alpha^{\mathbf{2}}\mathbf{m_e}$$

$$\mathbf{r_{atom}} \sim \frac{\mathbf{1}}{\alpha \mathbf{m_e}}$$

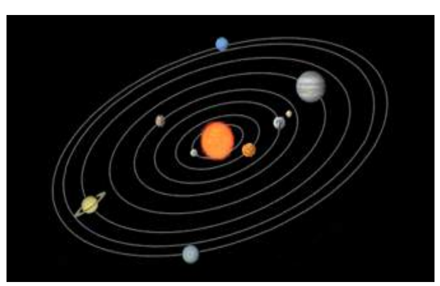
$$\mathbf{r_{proton}} \sim \frac{\mathbf{1}}{\mathbf{m_N}}$$

Based on few underlying fundamental interactions

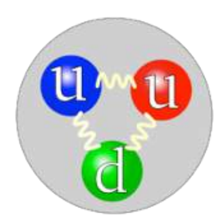
EM interaction & Gravity	Strong interaction	Weak interaction
"Coulomb phase"	**"Confining phase"**	**"Higgs phase"**
$\mathbf{V(r) \sim \frac{1}{r}}$	$\mathbf{V(r) \sim r}$	$\mathbf{V(r) \sim e^{-r}}$



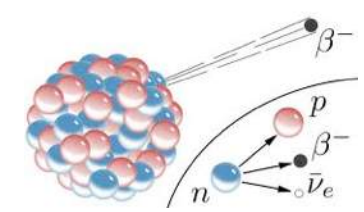
responsible for atoms

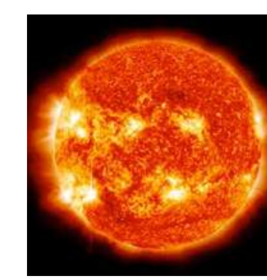


solar system



responsible for nuclei





$pp \rightarrow D + e^+ + \nu_e$

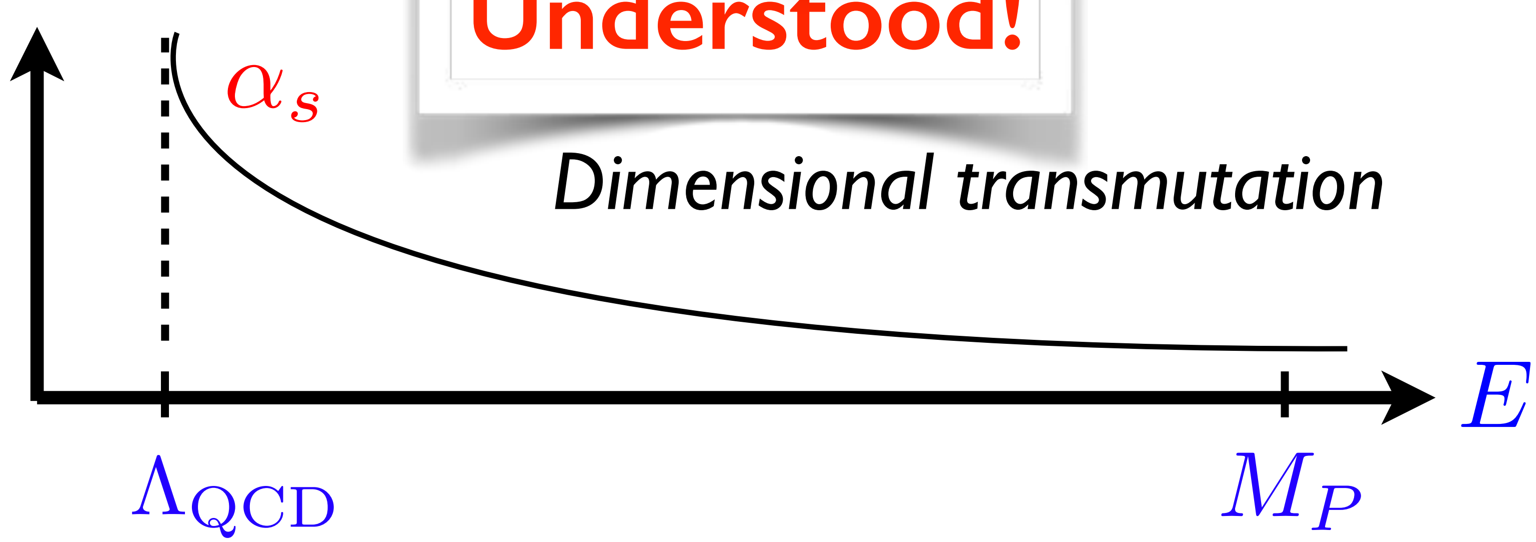
responsible for sun's ignition

Underlying mass scales in the universe

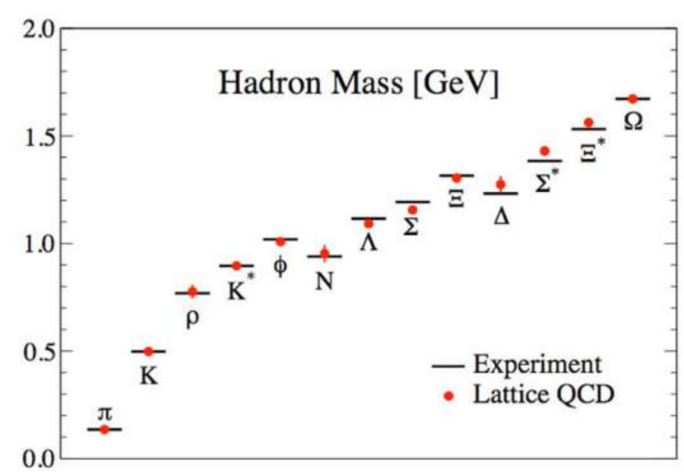
Underlying mass scales in the universe

Understood!

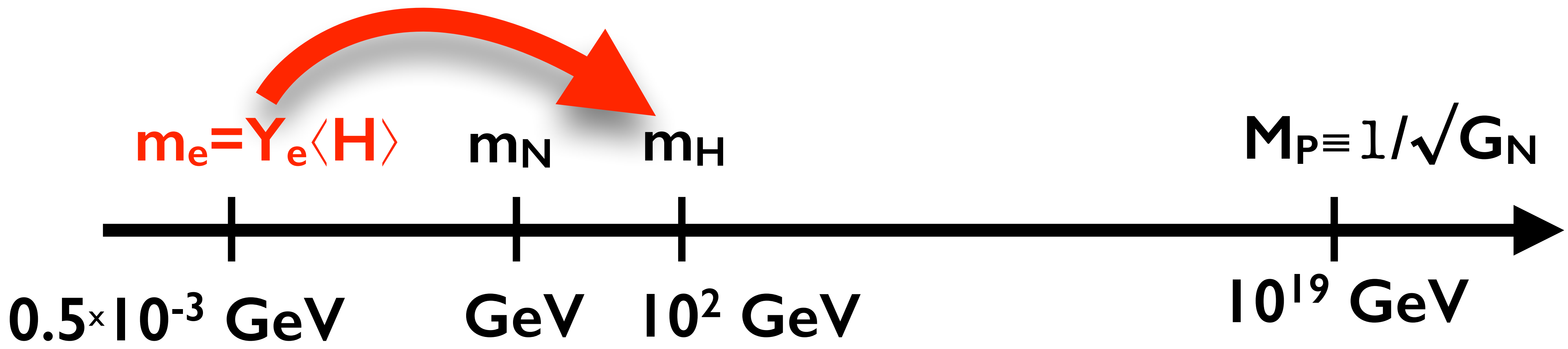
Dimensional transmutation



Explains why $\Lambda_{QCD} \ll M_P$
and the origin
of most hadron masses



Underlying mass scales in the universe

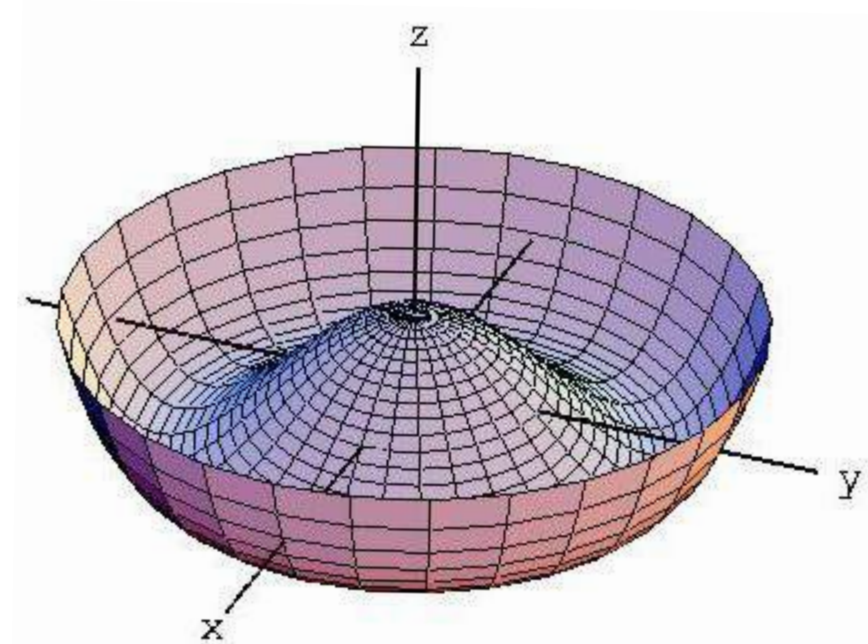


Standard Model

masses from the Higgs VEV:

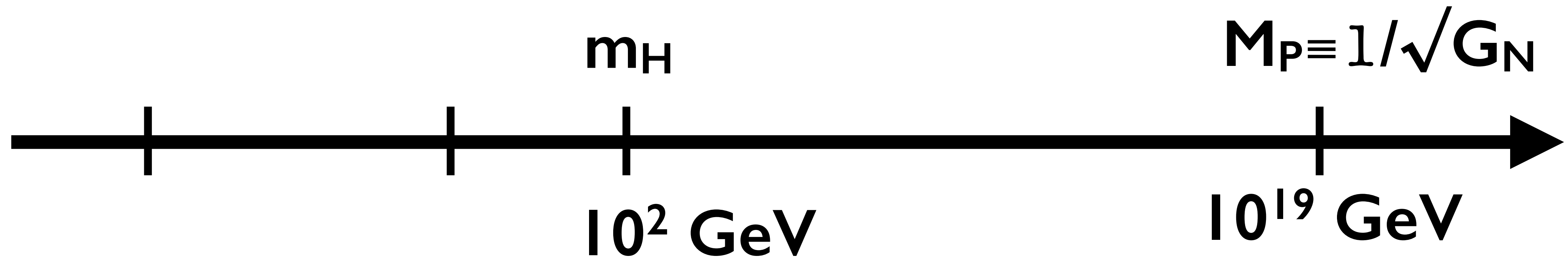
$\langle H \rangle \sim m_H / \sqrt{\lambda}$

Reinforced by
the 2012 Higgs discovery

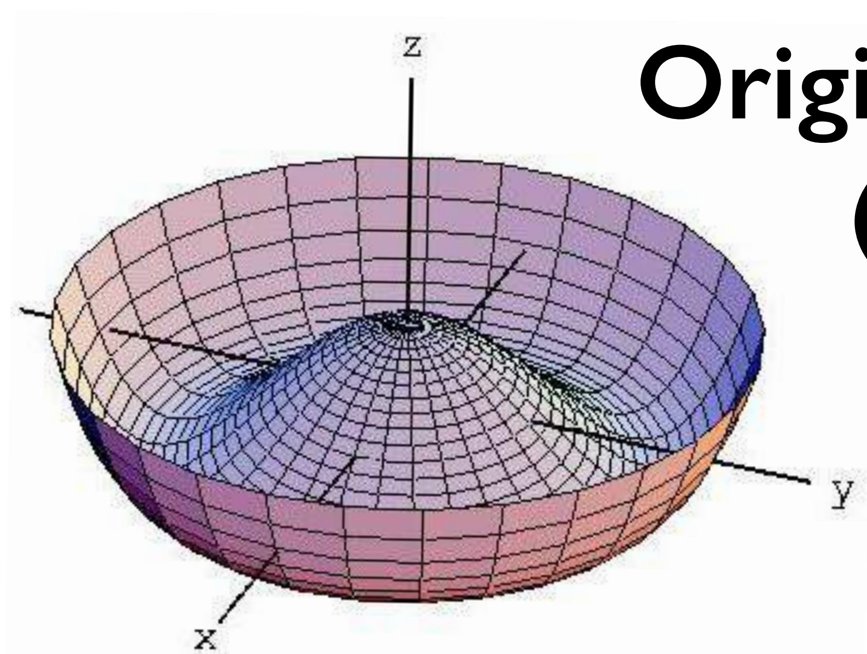


$$V(H) = -m_H^2 |H|^2 + \lambda |H|^4$$

Underlying mass scales in the universe



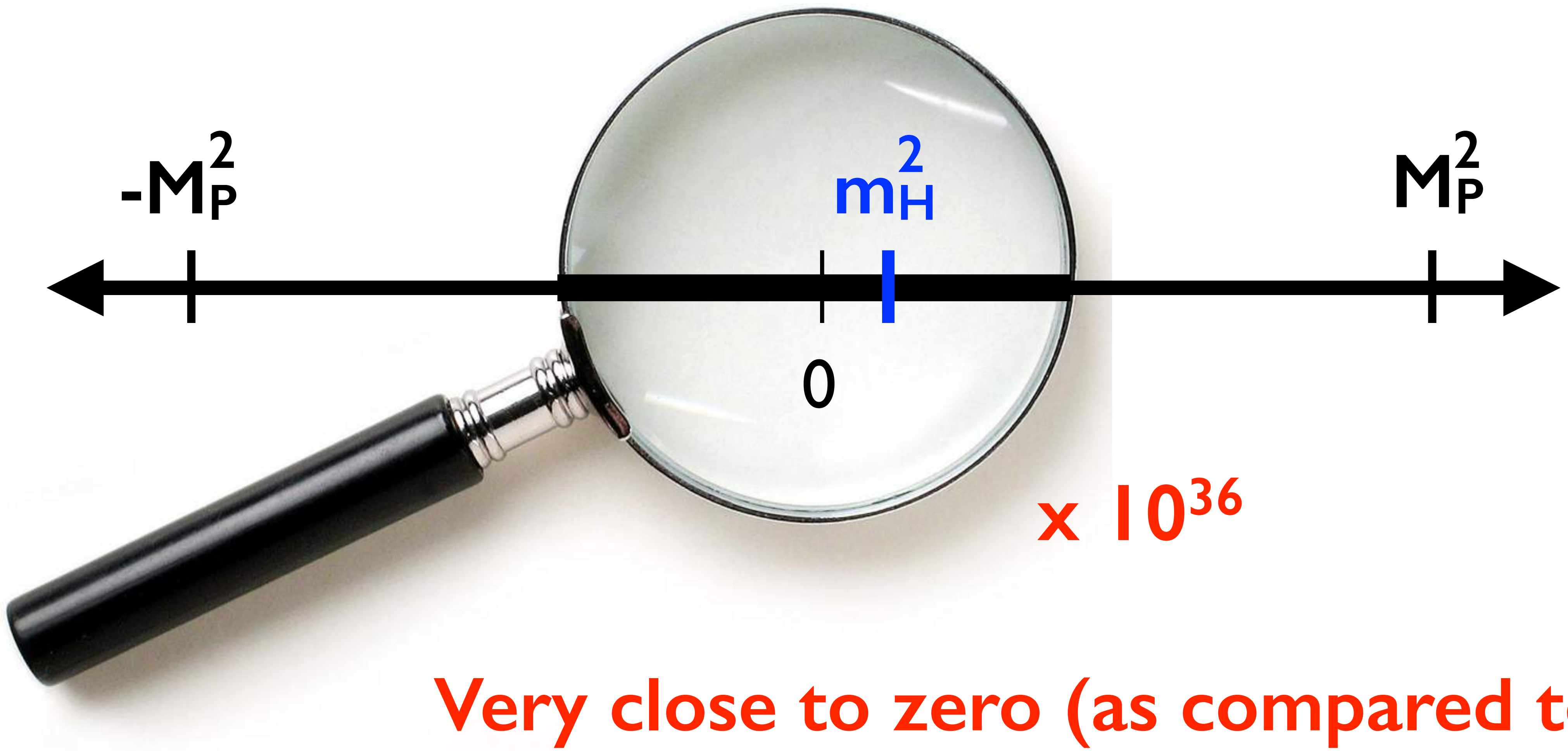
Remaining mystery!



Origin of the Higgs potential
(electroweak scale)

$$\mathbf{V(H) = -m_H^2|H|^2 + \lambda|H|^4}$$

Hierarchy problem

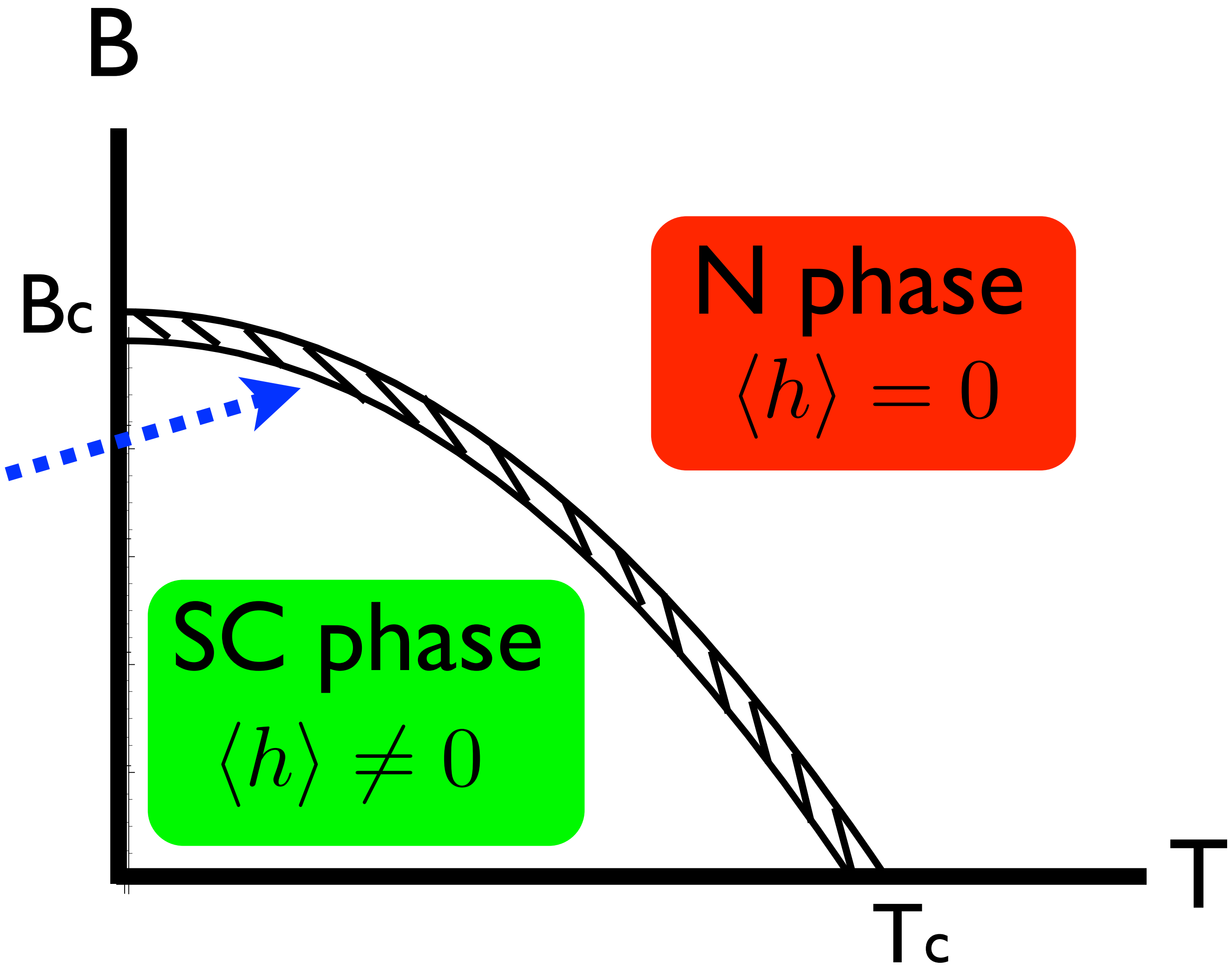


Very close to zero (as compared to M_P)

Analogy with Superconductivity

$$\langle h \rangle = \langle e^- e^- \rangle$$

We must (in the lab)
fine-tune B & T
to be close
to the critical line

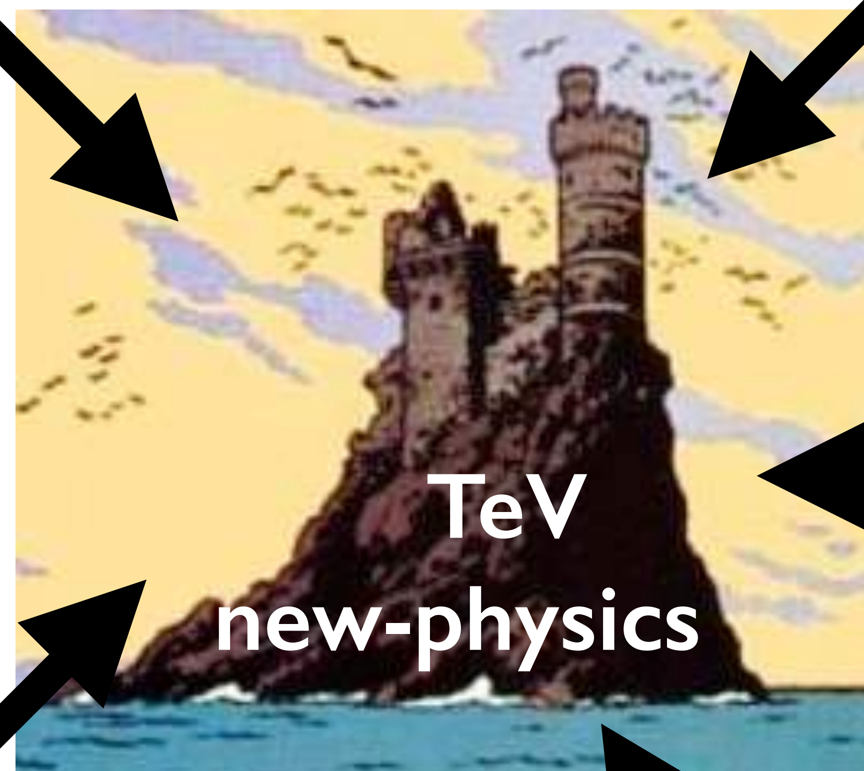


But who is tuning $m_H \ll M_P$?

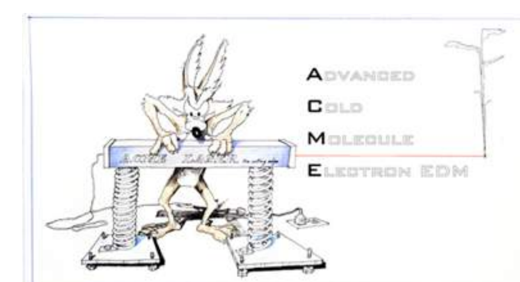
Most of our <u>effort in experimental particles physics</u> has been to *attack* the TeV territory from different fronts

Looking for deviations in SM couplings

Looking for new flavor-transitions



Looking for Electric Dipole Moments



Looking for new particles

Looking for for WIMPs (Dark Matter)

Theoretical proposals for the origin of the Electroweak Scale ($m_H \ll M_P$)

Idealized models have a useful role to play,

as ways to clarify your thinking

Paul Krugman

& status of their *health* (experimental) *checkups*

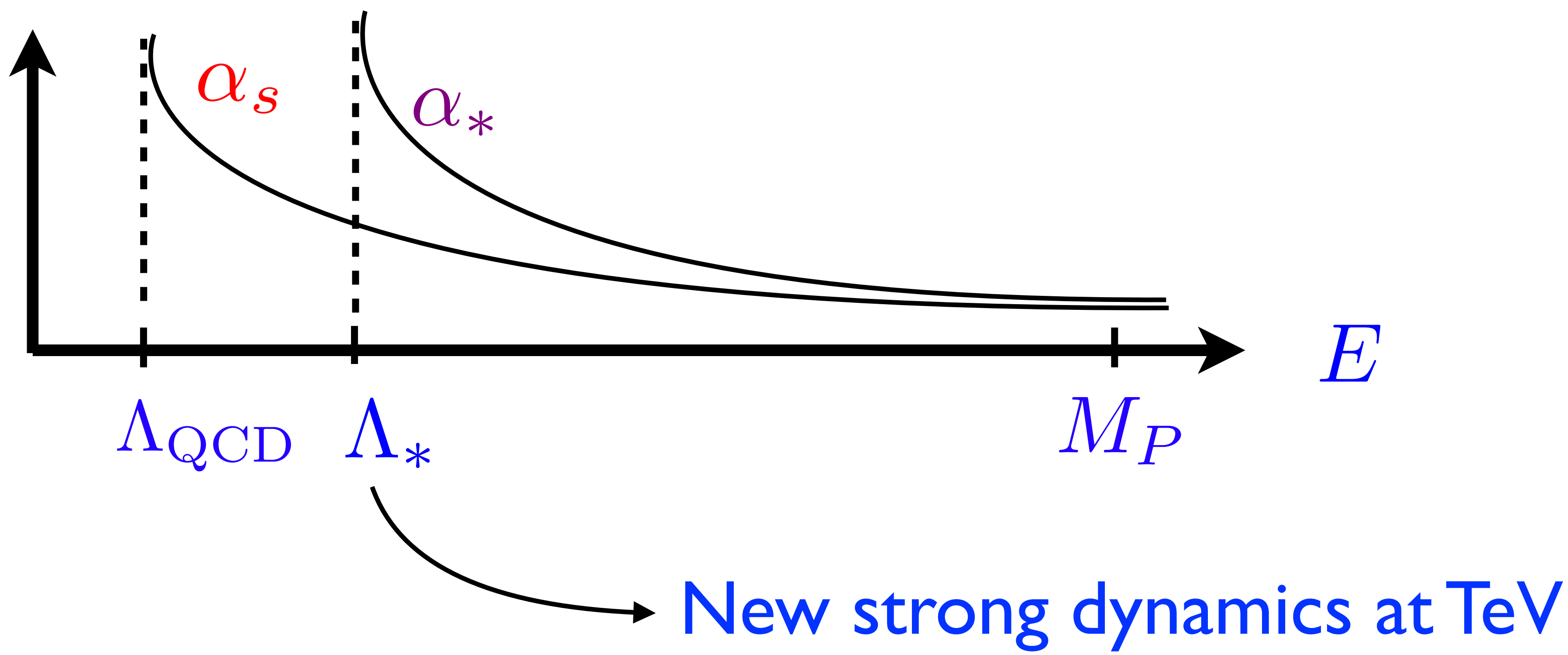
I

QCD approach: Compositeness

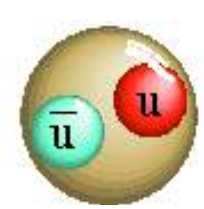
Follow the path of QCD:

Lets try the same for the EW scale

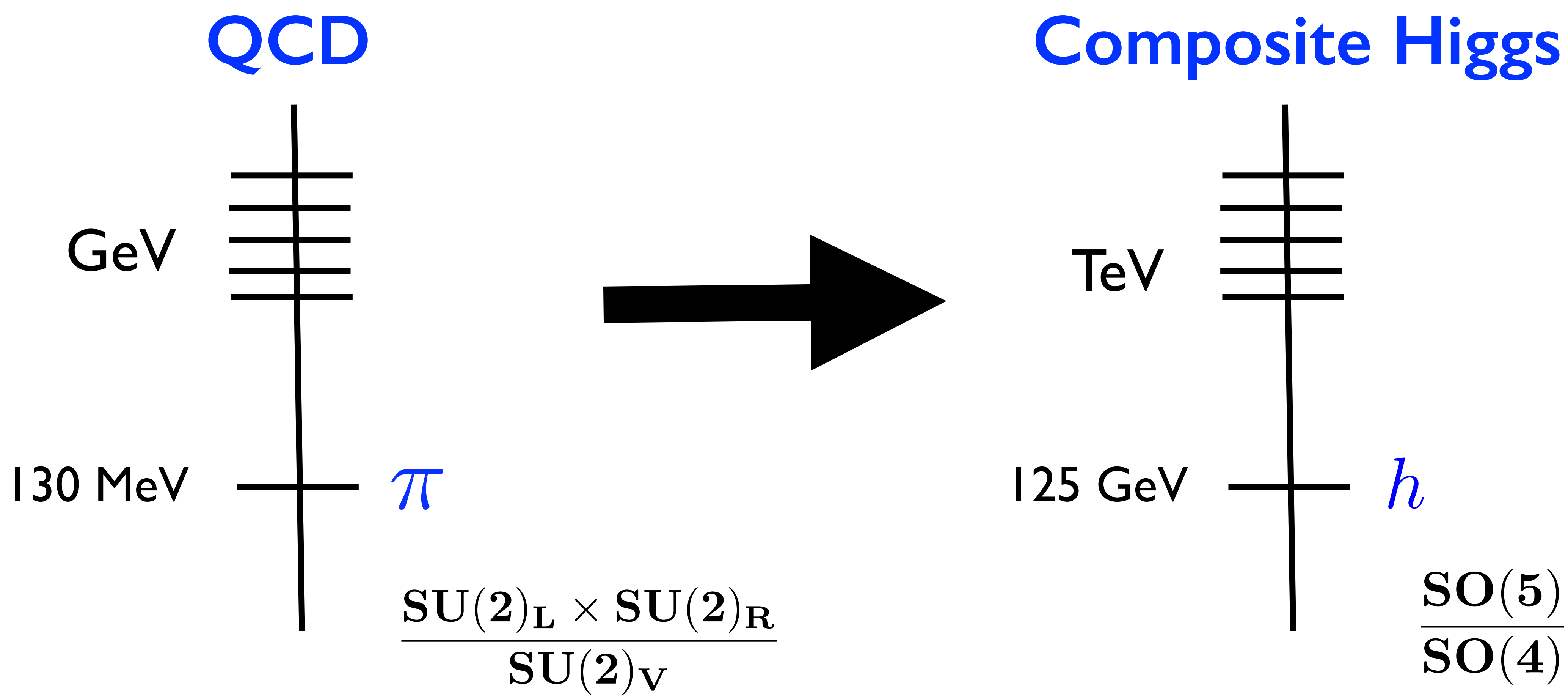
➠ Assume that there is a **New Strong sector** at around the TeV-scale:



It could explain why $m_H \lesssim \Lambda_* \sim \mathrm{TeV} \ll M_P$

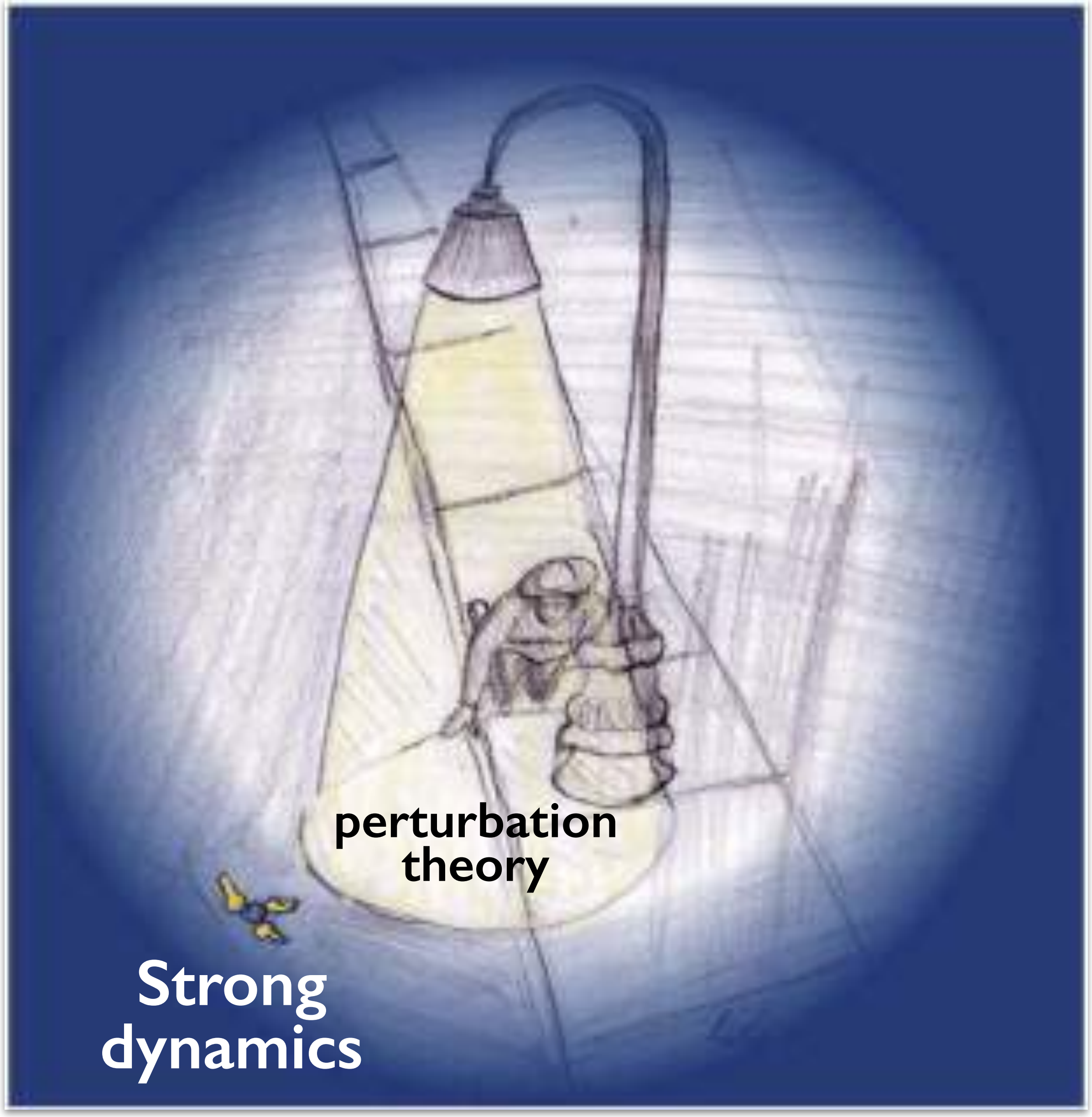
Composite Higgs: **H =** 

The **Higgs, the lightest** of the new strong resonances,
as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)



Dealing with strong dynamics….

Beyond the lamp-post:



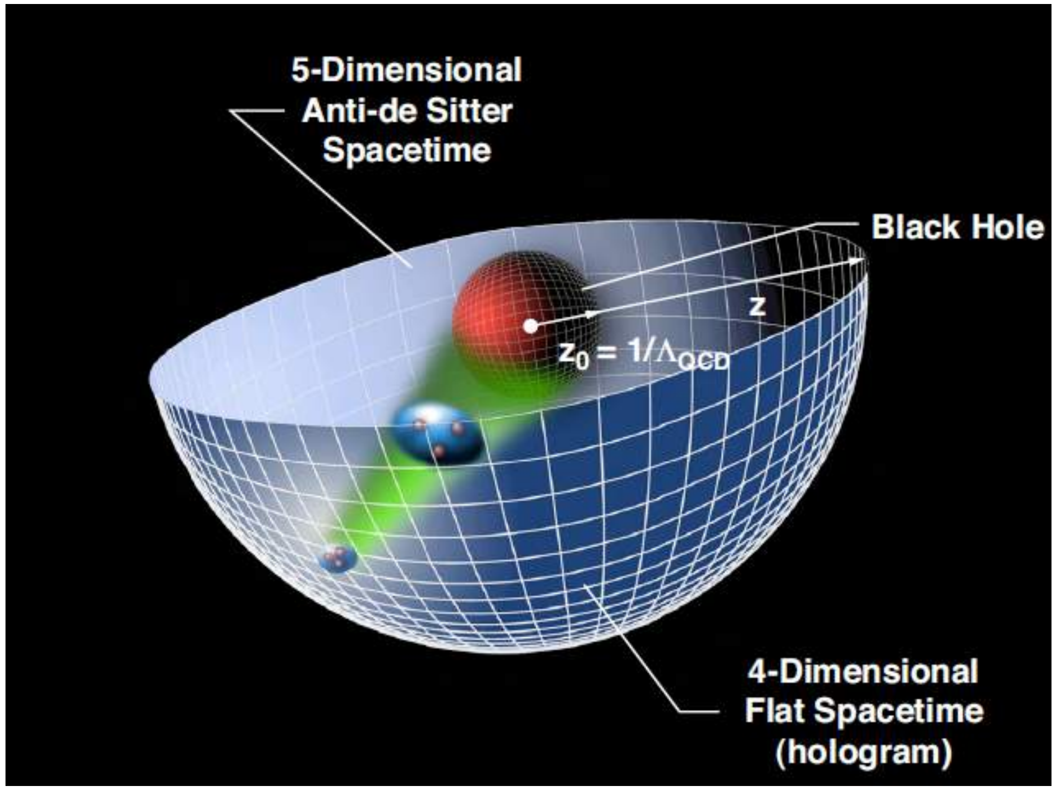
The AdS/CFT correspondence

Maldacena 97

Strongly coupled 4D theories in certain limits ⟷ duality ⟷ Weakly coupled gravity theories in higher-dimensions

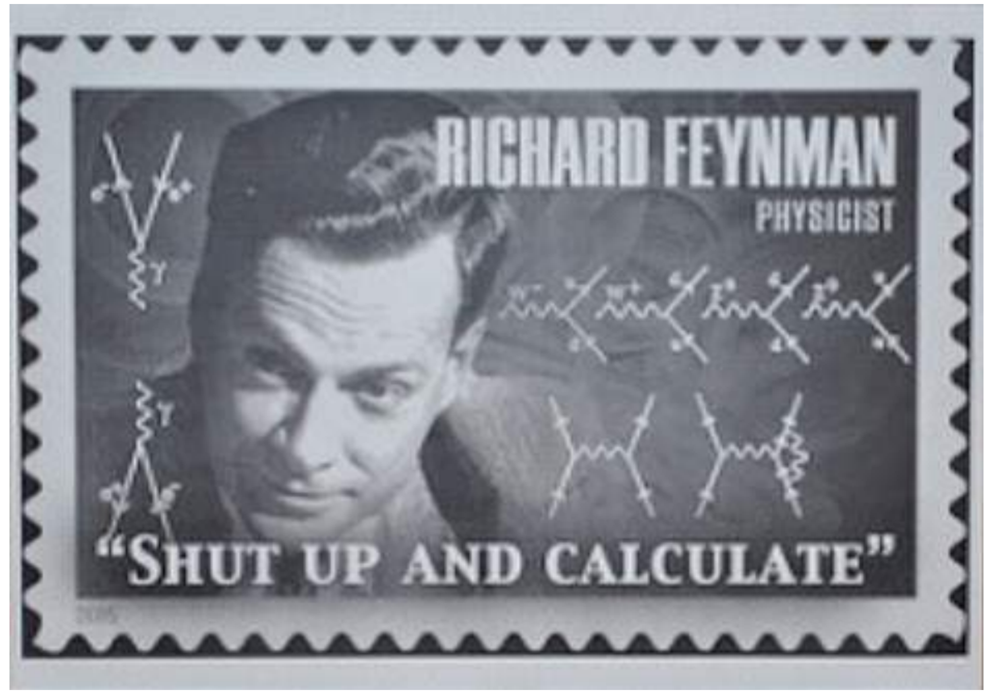
☛ Holographic models:

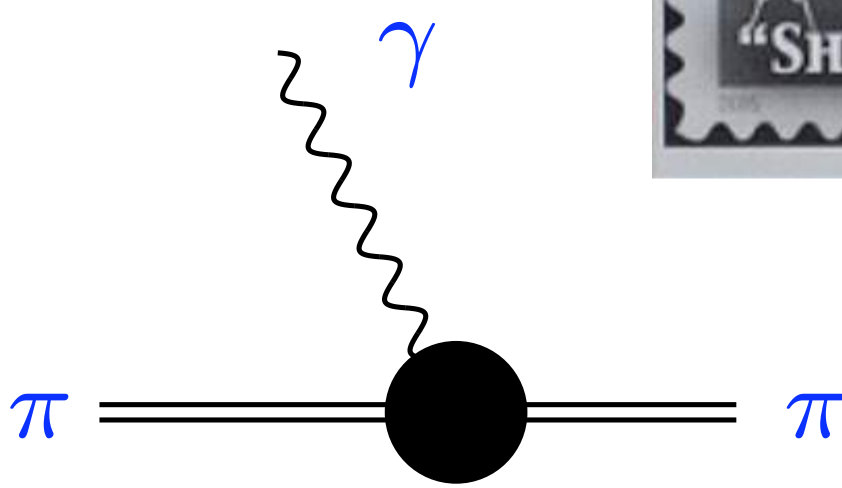
5D models with the properties of a composite Higgs



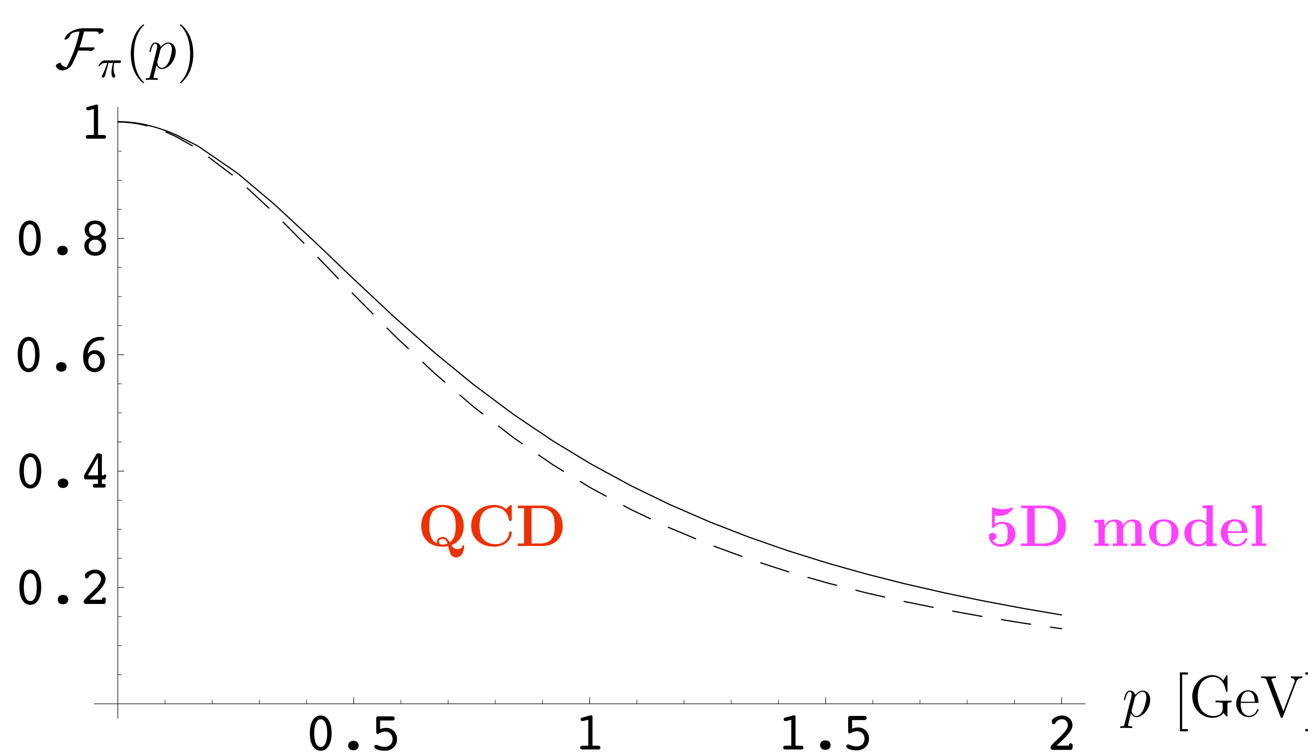
Picture from G.F. de Teramond

Why extra-dimensional models are models of compositeness?





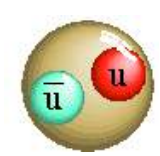
summing over
Kaluza-Klein



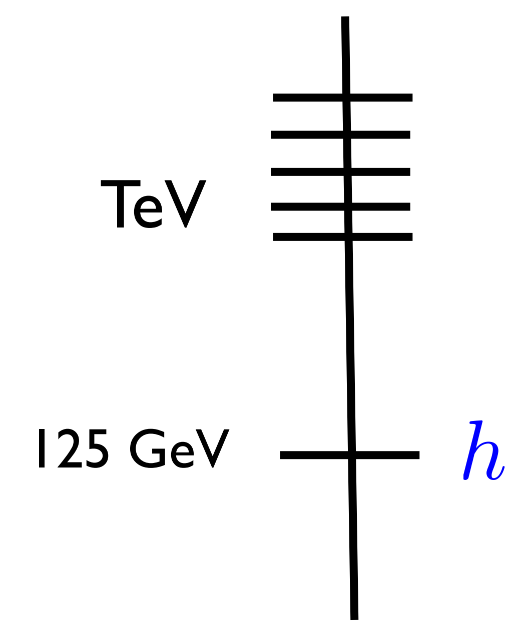
Physical implications of TeV strong-dynamics

New **flavor-violating & CP-violating** transitions

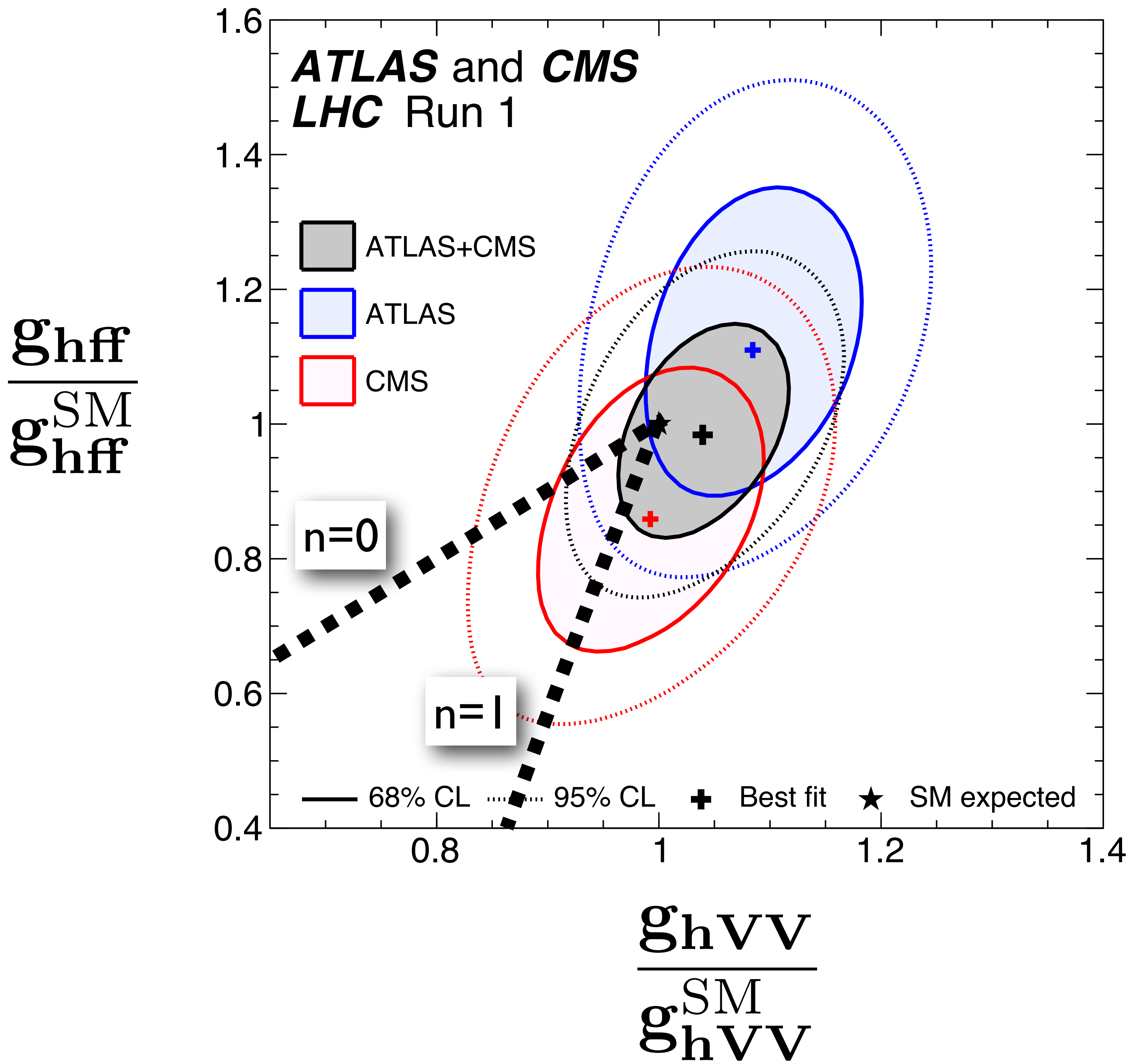
Signs of **compositeness** in the Higgs (and top)



New **resonances**

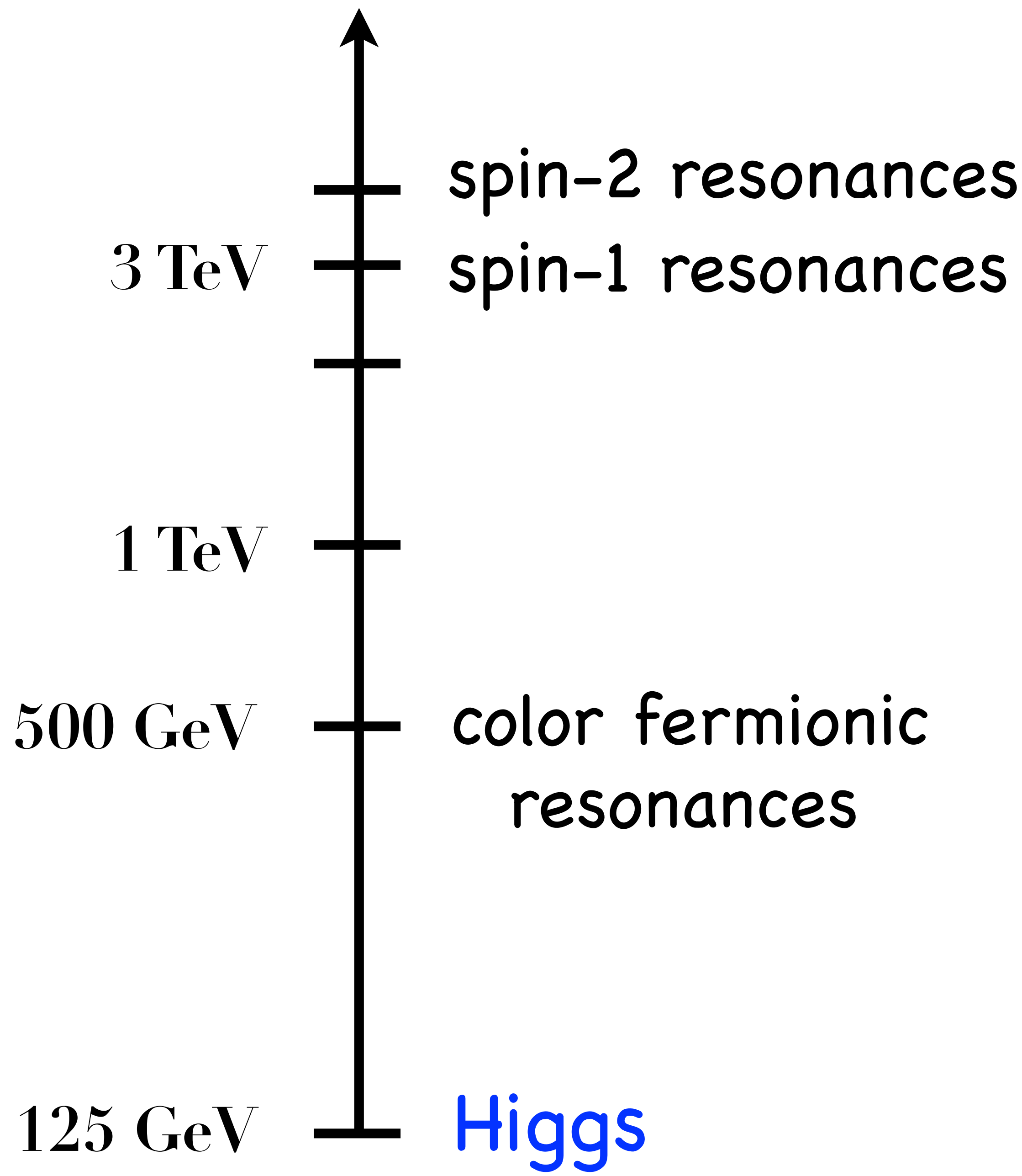


Signs of compositeness of the Higgs

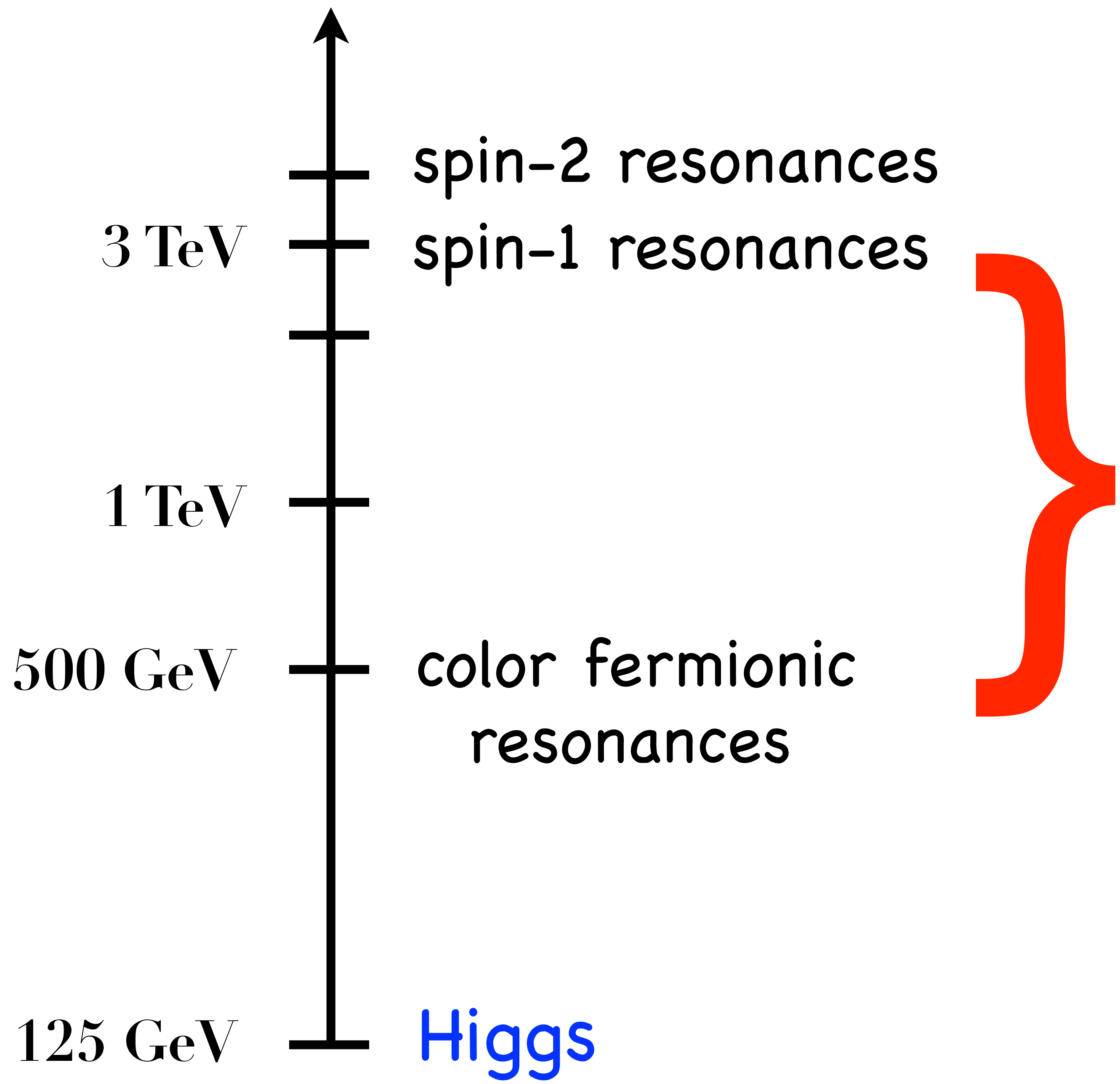


Entering the interesting region: bounds getting below 10%!

Expected spectrum in Composite Higgs Scenarios



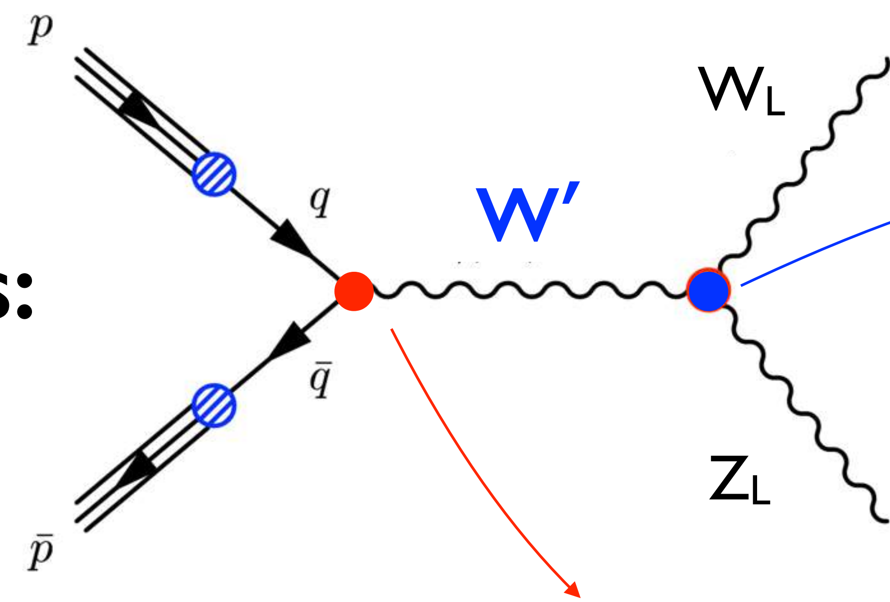
Expected spectrum in Composite Higgs Scenarios



Best way to unravel new dynamics:

Discovering new resonances !

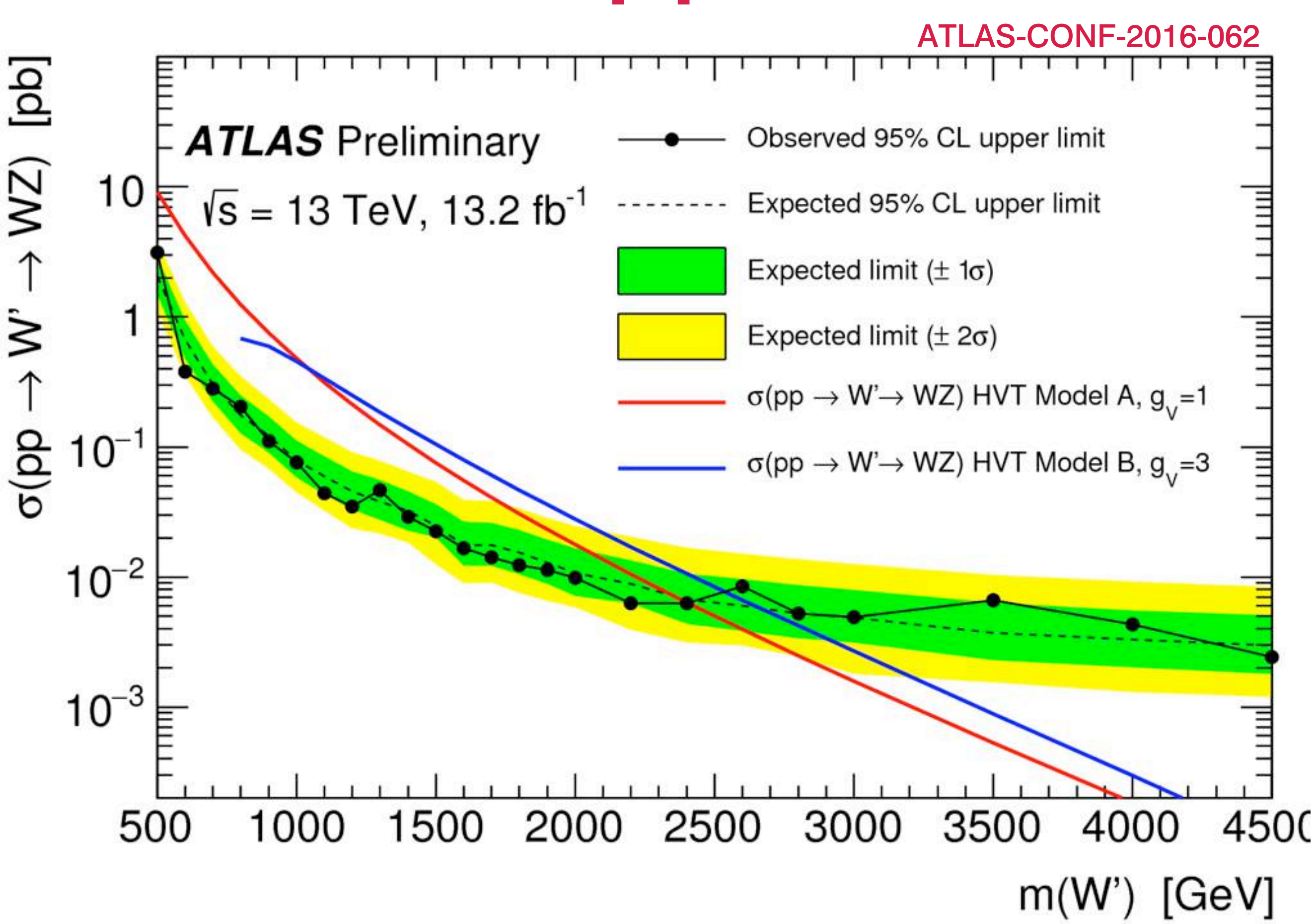
Spin-1 resonance searches:



enhanced by large couplings from the composite sector

through mixing with the SM W:
suppressed by large couplings from the composite sector

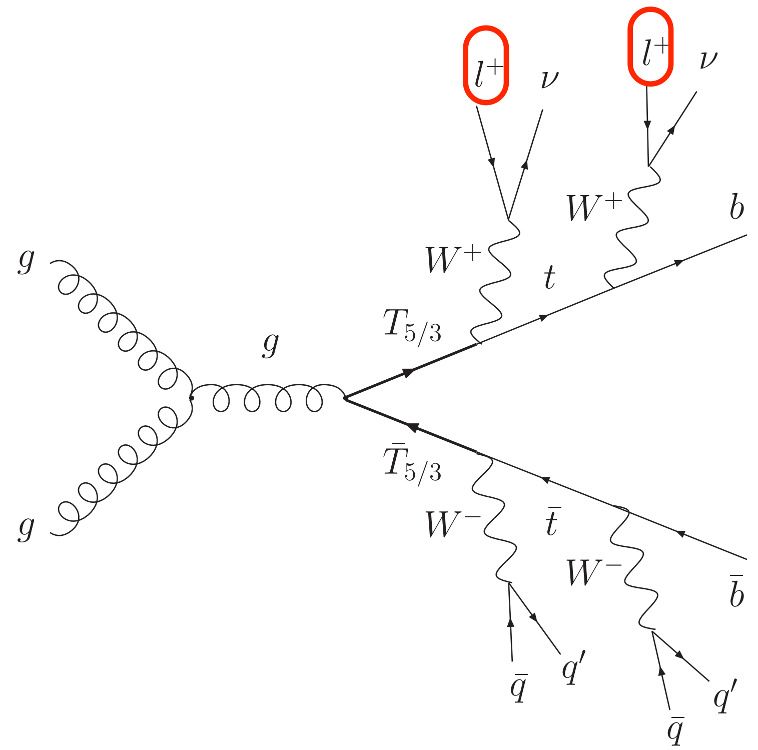
VV → ℓνqq

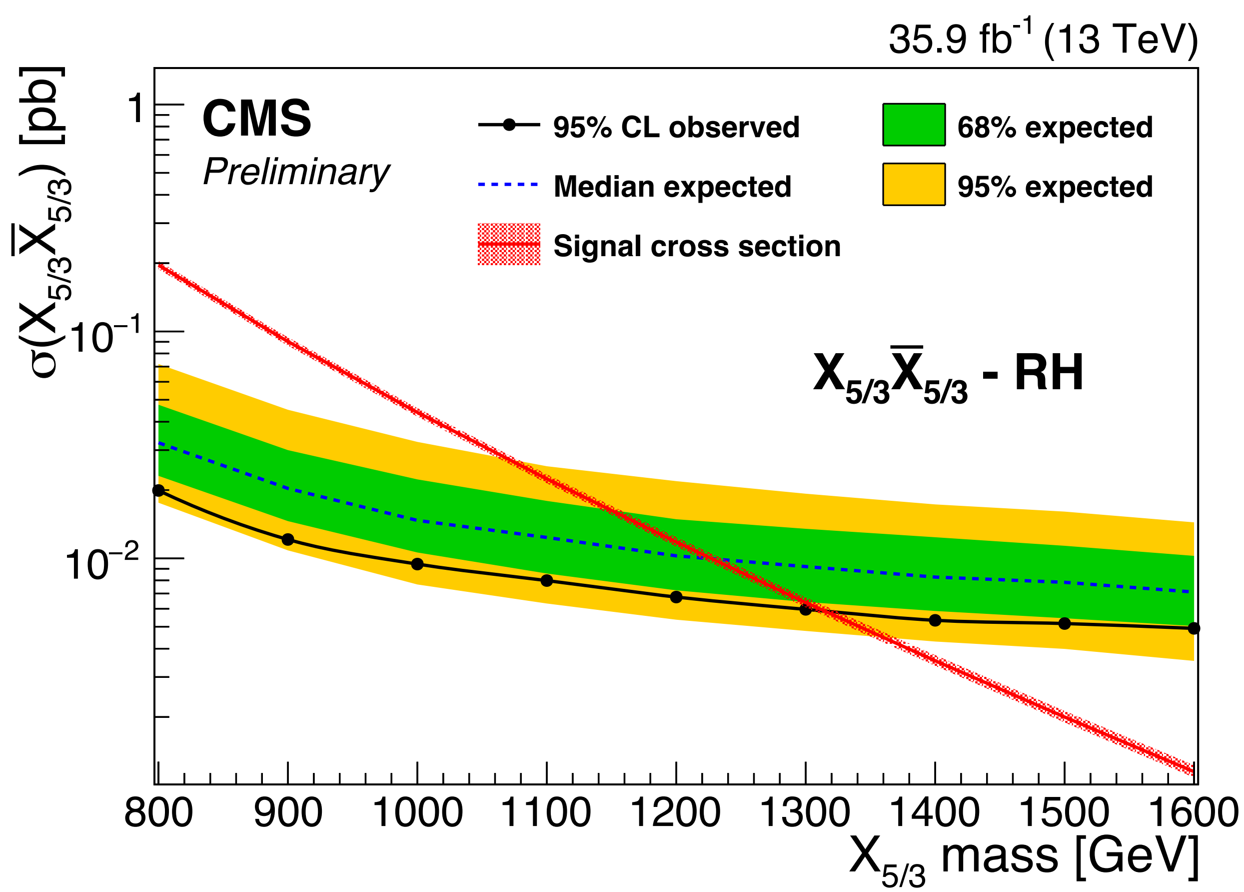


$$\mathbf{m(W') \gtrsim 2.5\ TeV}$$

scratching
the interesting regions!

Colored fermion resonances at LHC 13 TeV

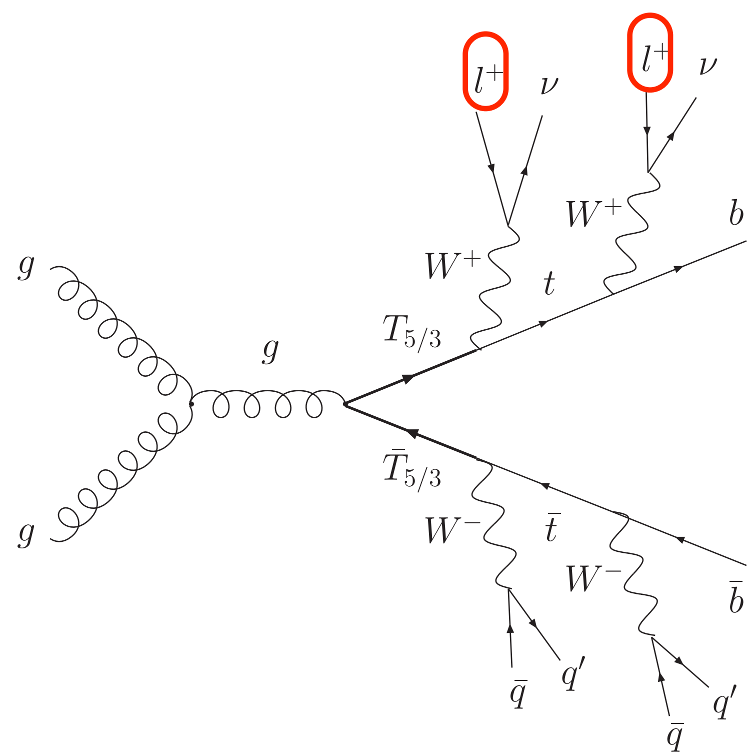


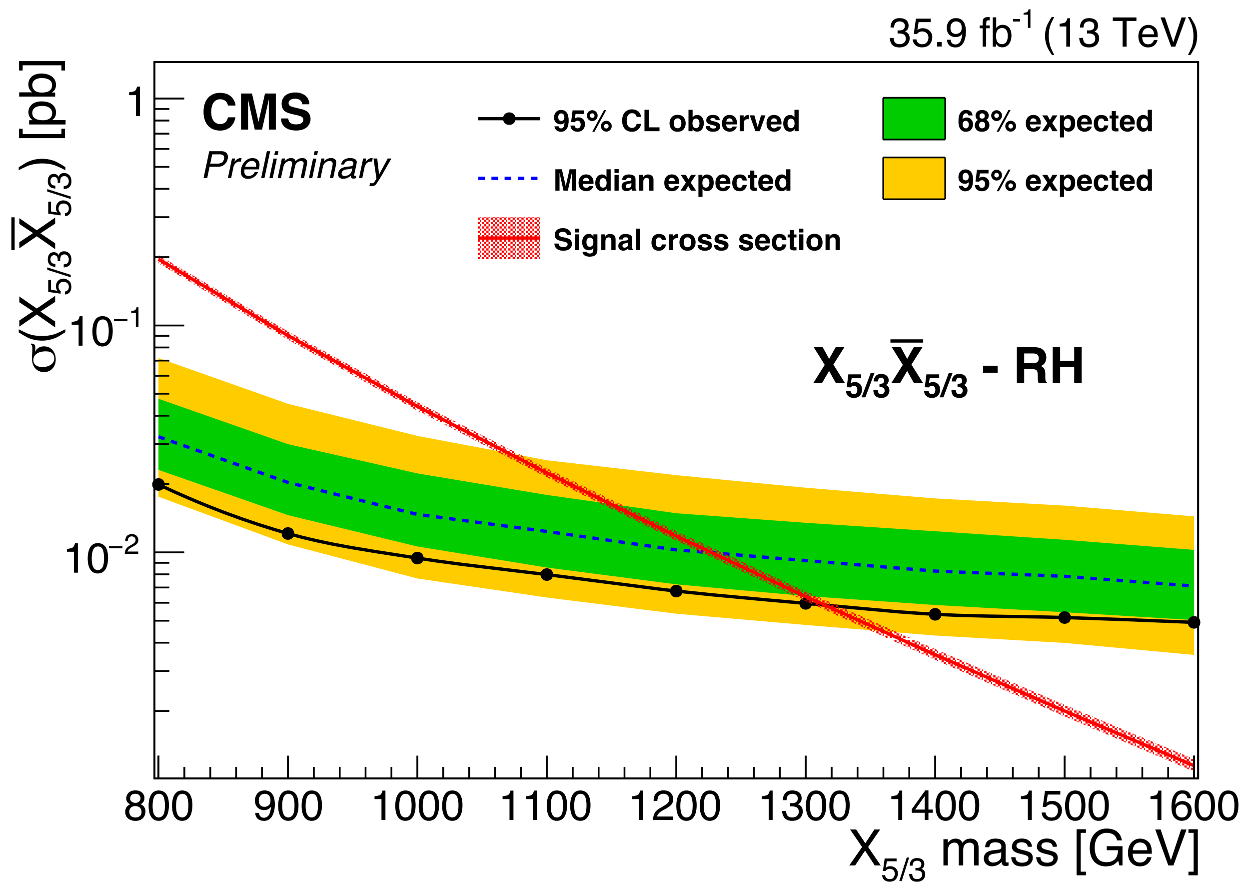


First important constraint from LHC:

$$\mathbf{M(X_{5/3}) \gtrsim 1.3\ TeV}$$

Colored fermion resonances at LHC 13 TeV





First important constraint from LHC:

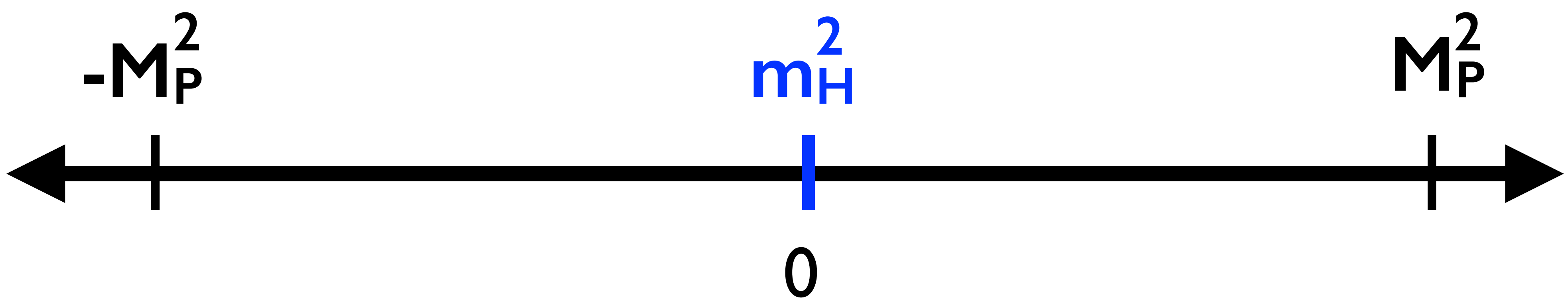
$$\mathbf{M(X_{5/3}) \gtrsim 1.3\ TeV}$$

The situation starts being worrisome..

but not yet desperate

II

Symmetry approach: $m_H \to 0$ a special point?



Why special? More symmetry?

Not in the SM but possible if extended

Supersymmetry: boson $\leftrightarrow$ fermion

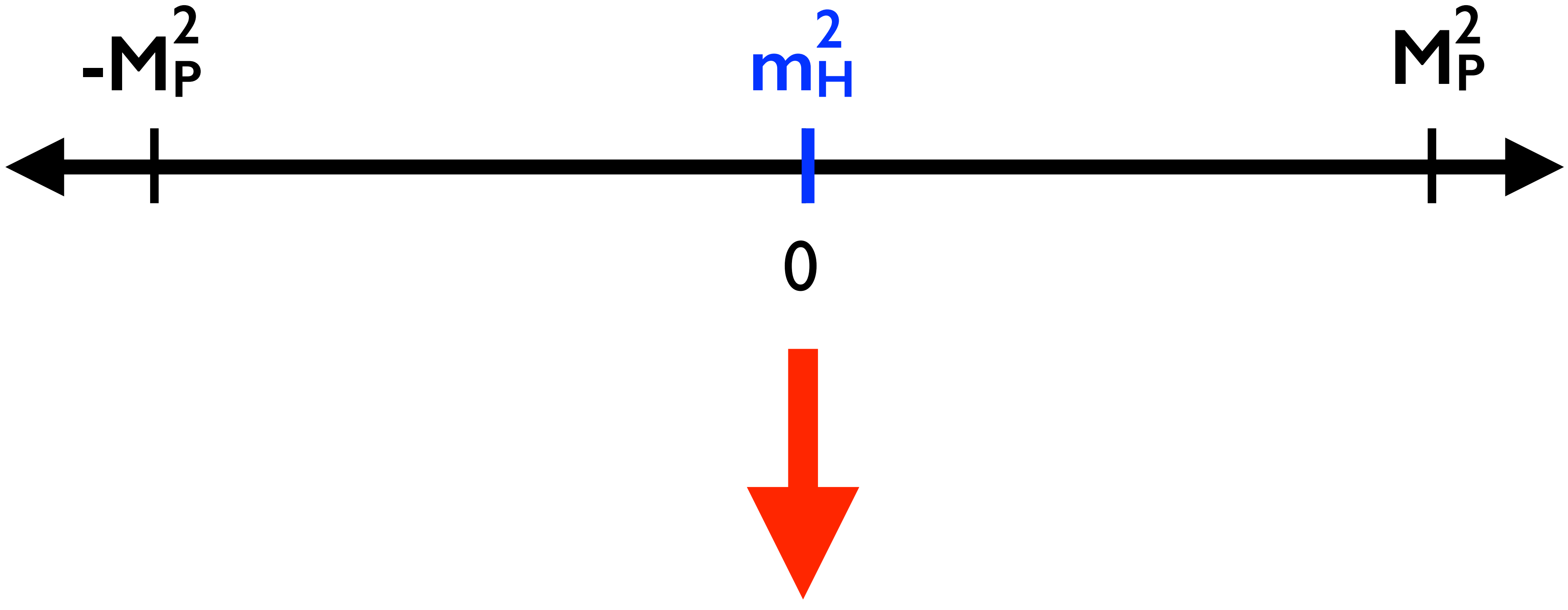
$m_{boson} \leftrightarrow m_{fermion}$

$m_{fermion}$ = 0 of a fermion can be guaranteed:

	Massless	Massive
Fermion (charged)	2 *dof* Ψ_L	4 *dof* Ψ_L, Ψ_R

$\Downarrow$

Supersymmetry guarantees m_{boson}=0



Supersymmetric point!

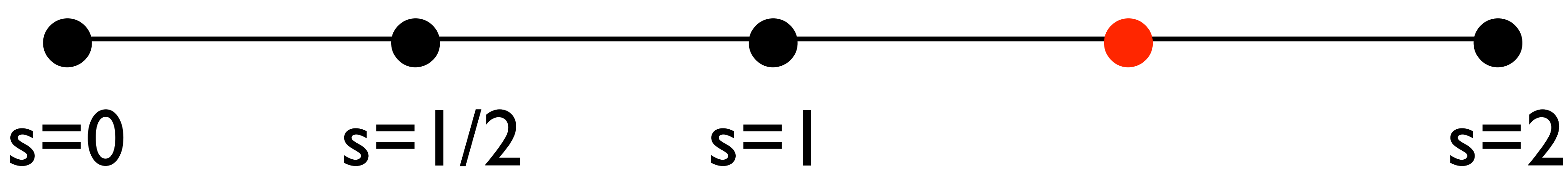
Lesson from the present SM of particles

Symmetries must be *accidental*

or needed for consistency of the model

SM+Gravity:

Consistent theory of s=0, s=1/2, s=1 and s=2 particles



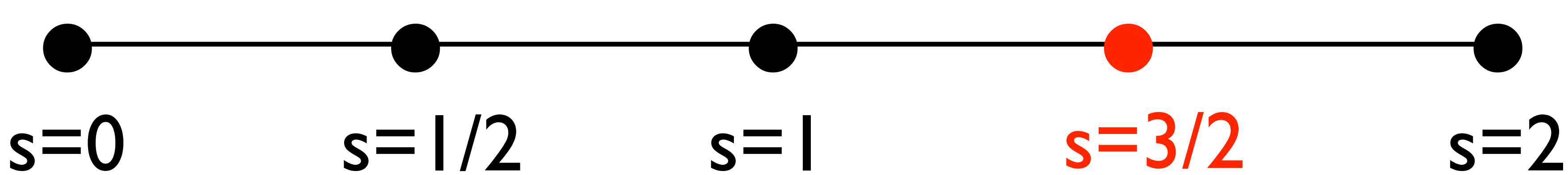
Lesson from the present SM of particles

Symmetries must be *accidental*

or needed for consistency of the model

SM+Gravity → **Add spin=3/2 particle**

Consistent theory of s=0, s=1/2, s=1 and s=2 particles



Gravitino!

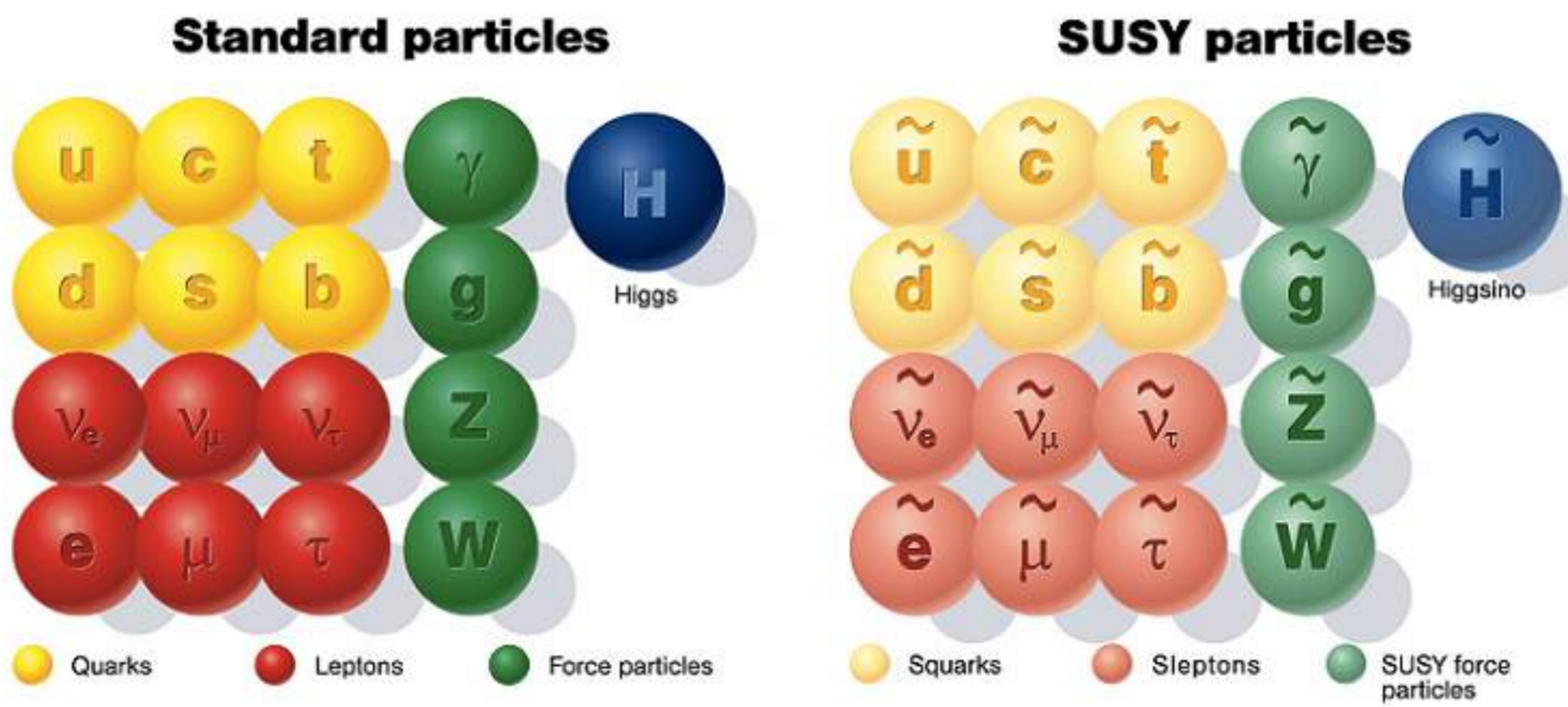
Consistent theory of spin-3/2 must have supersymmetry!

Imposing supersymmetry to the **SM** ➡ **MSSM**

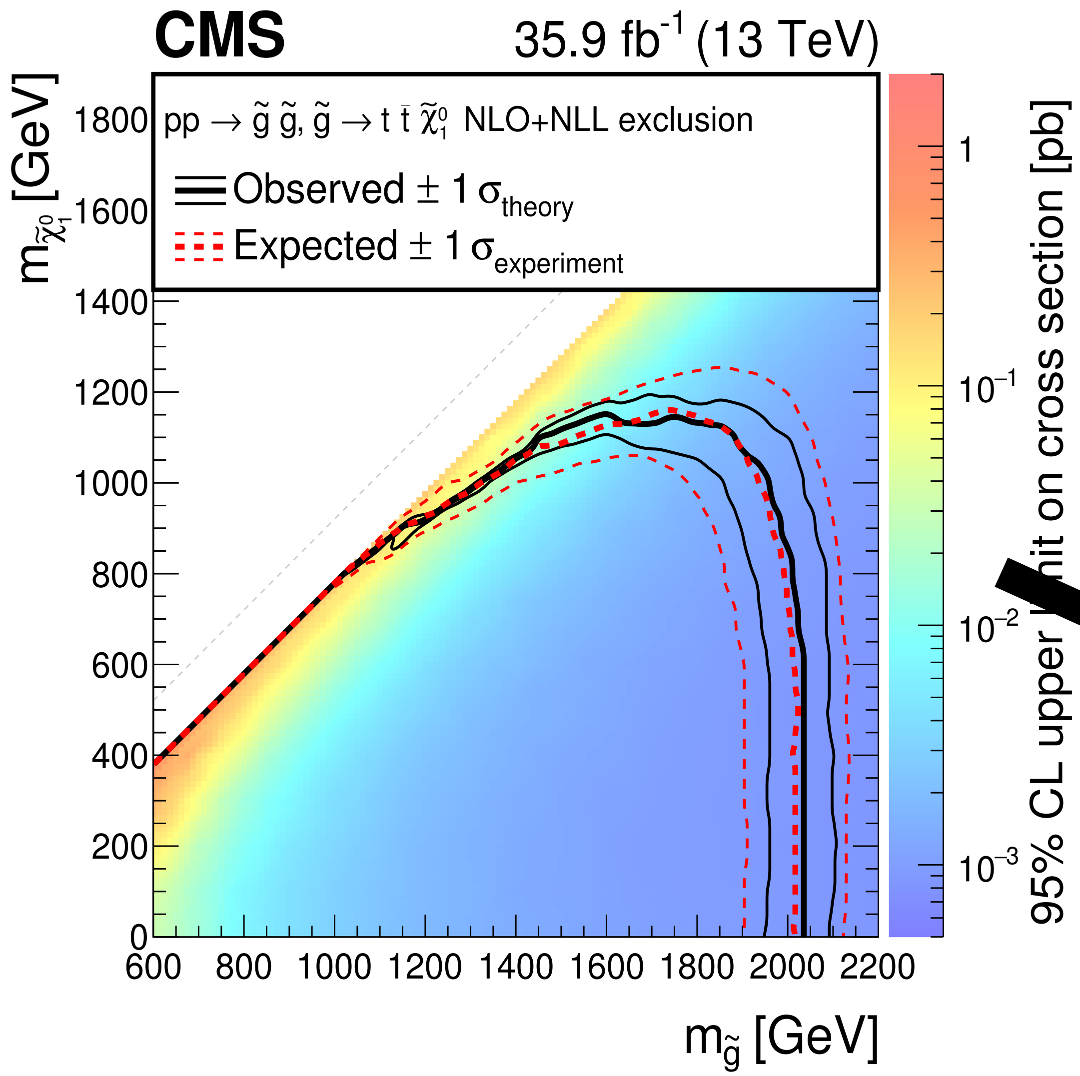
The spectrum is doubled:

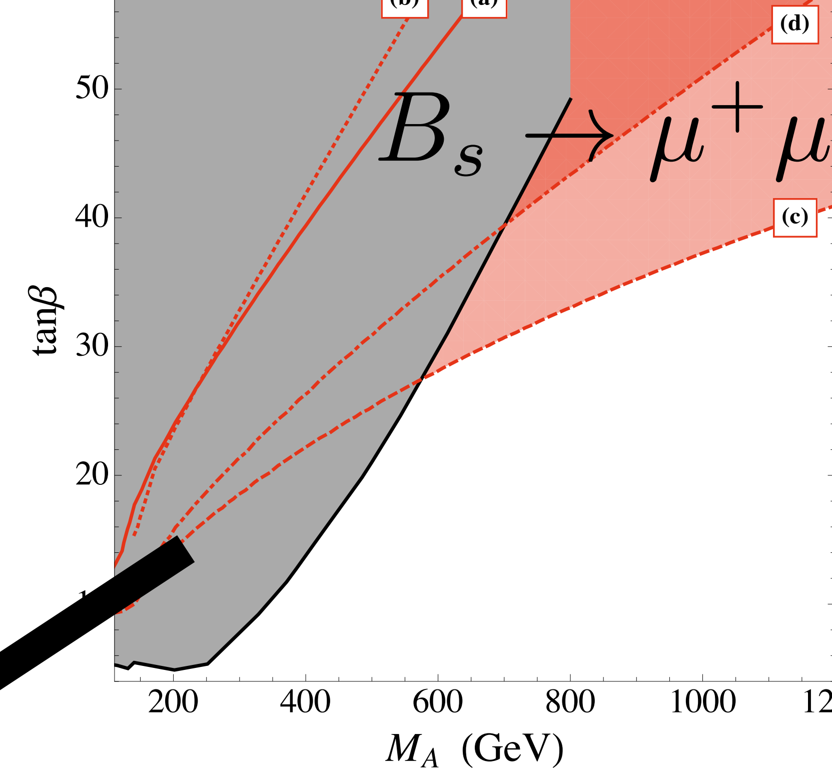
SM fermion ➡ New scalar

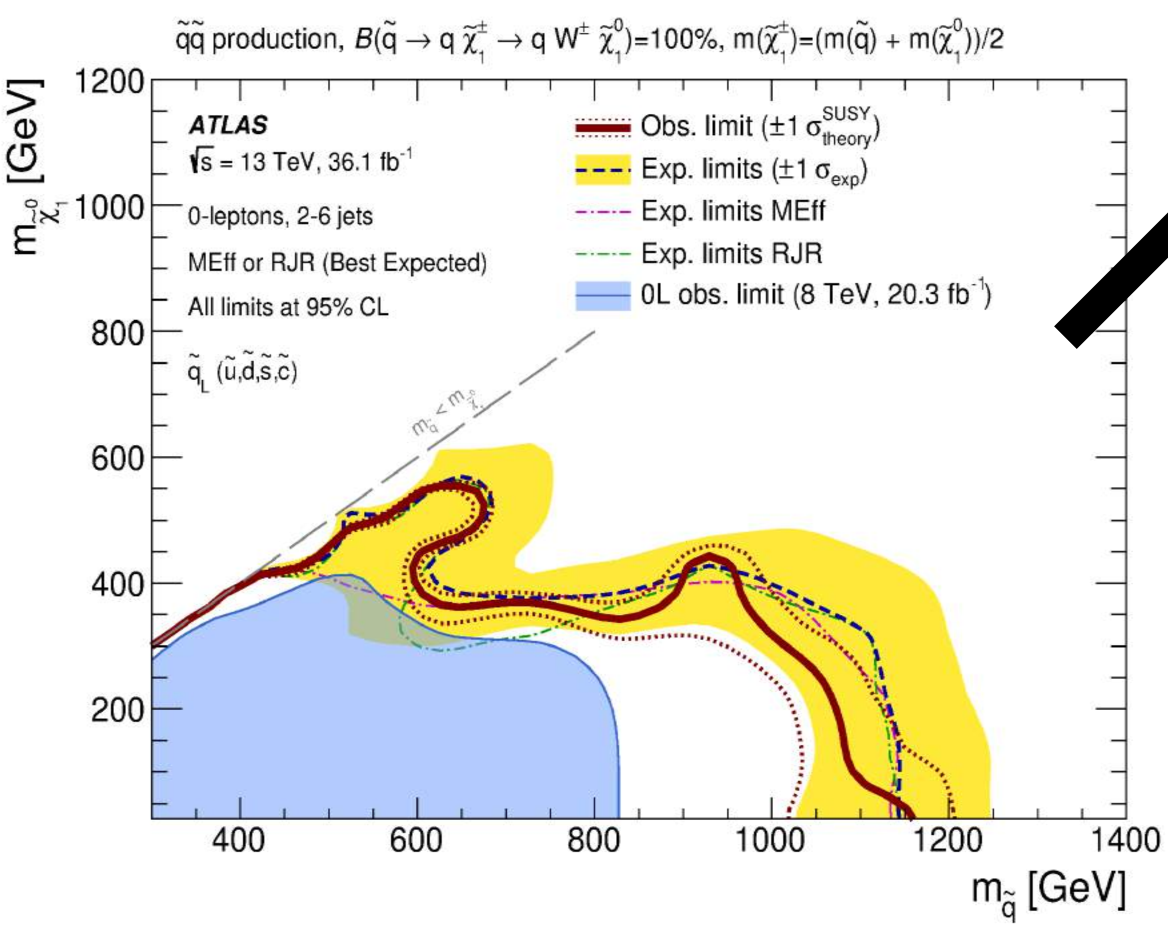
SM boson ➡ New majorana fermion

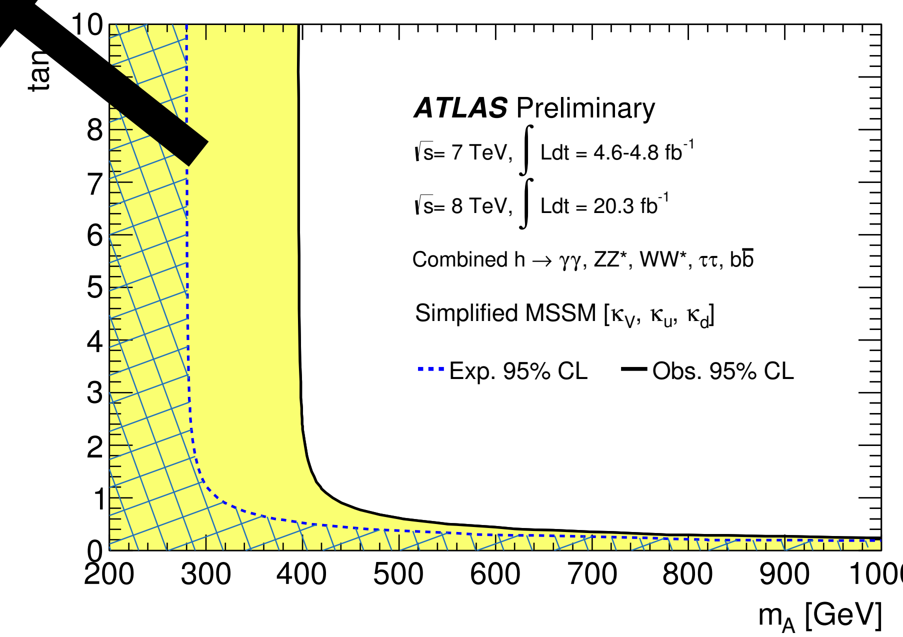


we must break supersymmetry to give them mass









Higgs coupling measurements

New-Physics at the TeV

Pros

Hierarchy problem

Cons

No new particles seen,
no new flavor-violations seen,
no deviations on Higgs couplings seen,
no deviations on Z/W couplings seen,
no WIMP detected,
no EDMs seen,

New-Physics at the TeV

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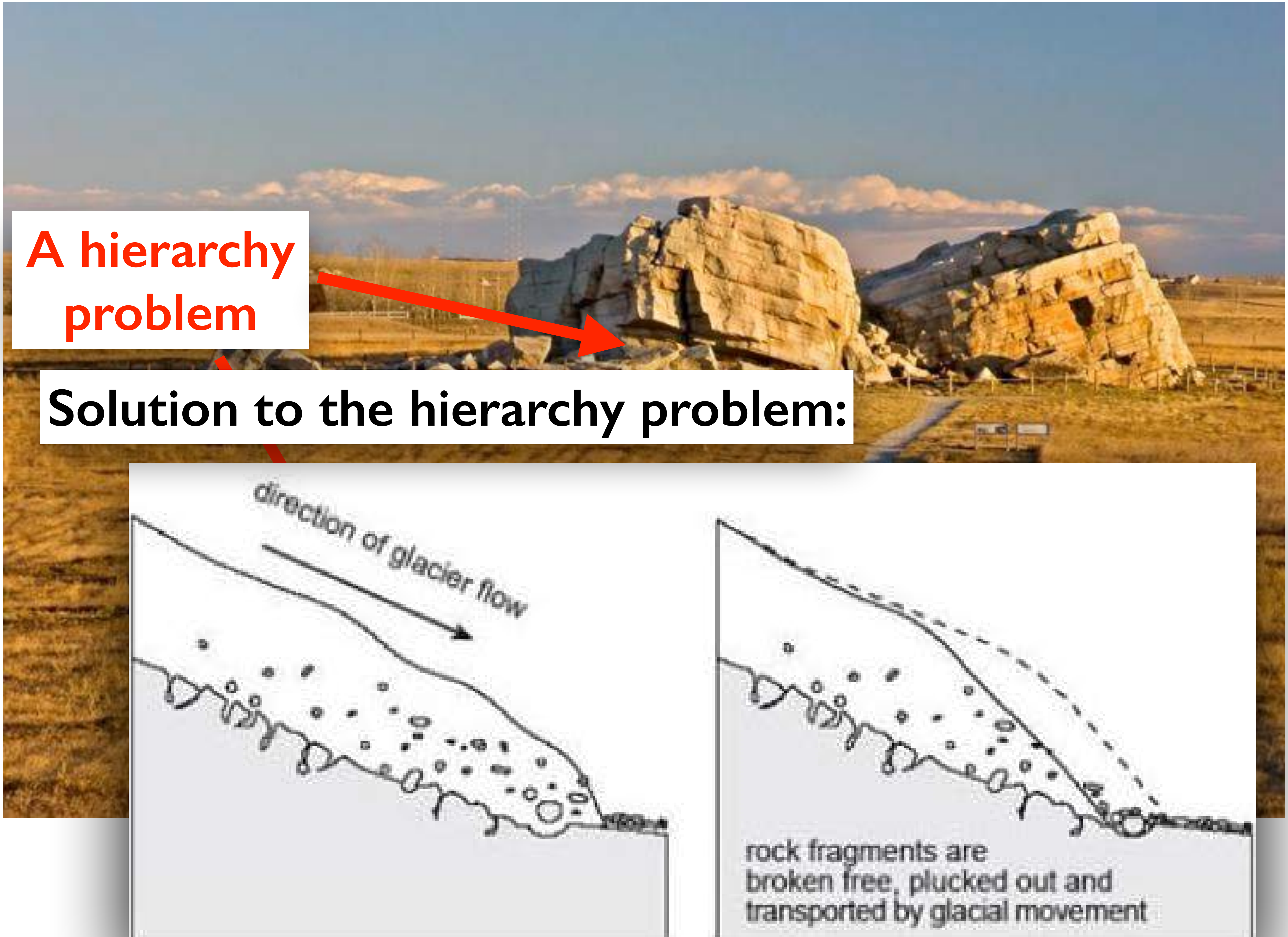
III

Putting Time into the game

explaining fine-tunings by *accidents* in history

Canadian Prairies in Alberta

Canadian Prairies in Alberta



A hierarchy problem

Solution to the hierarchy problem:

"Relaxation" mechanism

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

Higgs-mass parameter $\longrightarrow$ Field-dependent Higgs mass

$$m_H^2 |H|^2 \qquad\qquad m_H^2(\phi)|H|^2$$

$\boldsymbol{\phi}$ could evolve
to a value where

$$m_H^2(\phi) \ll M_P^2$$

Axion-like ϕ & Higgs h potential:

"technically natural"

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

P.W. Graham, D.E. Kaplan, S.Rajendran
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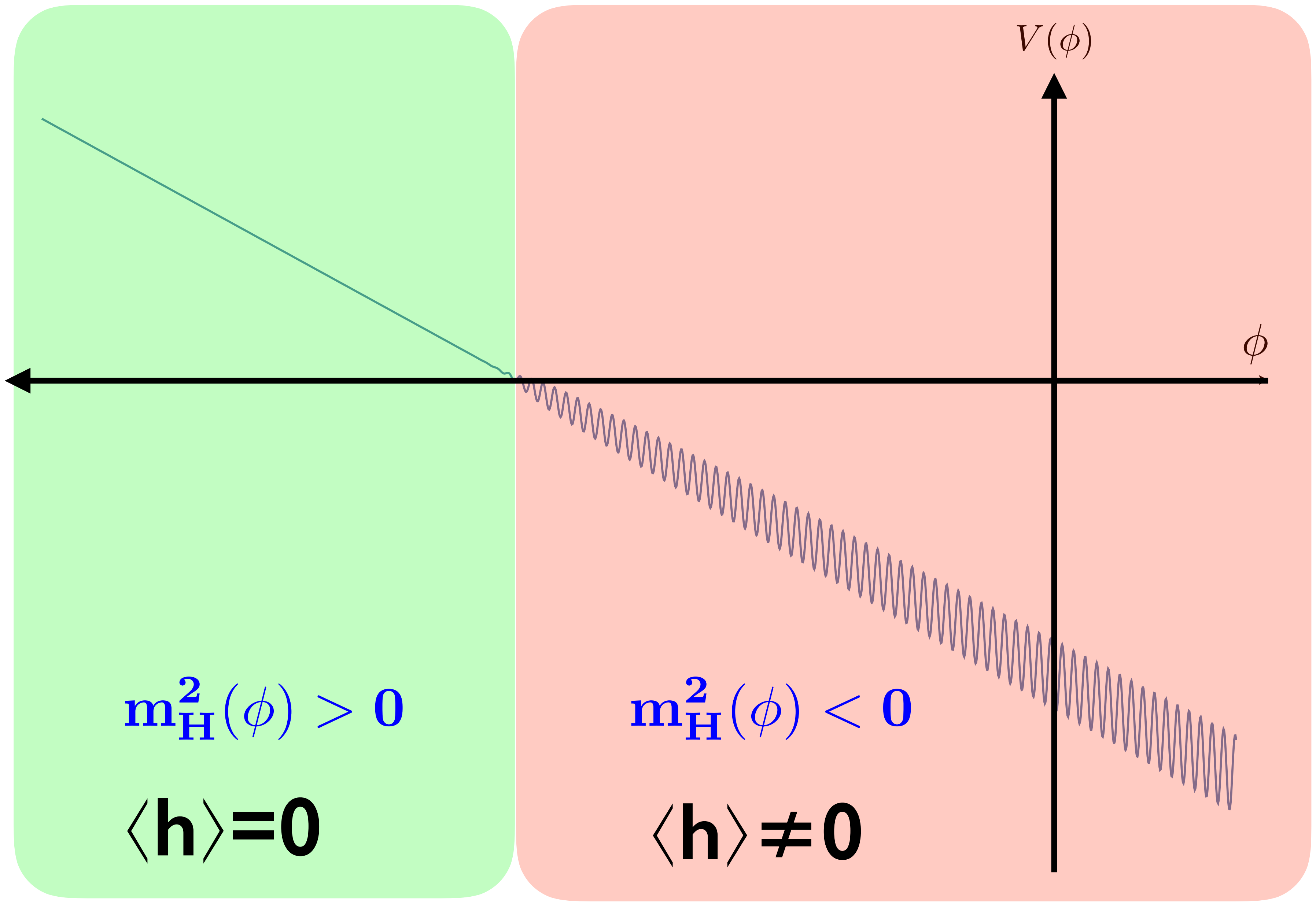

Cosmological evolution can lead to a small EW scale

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

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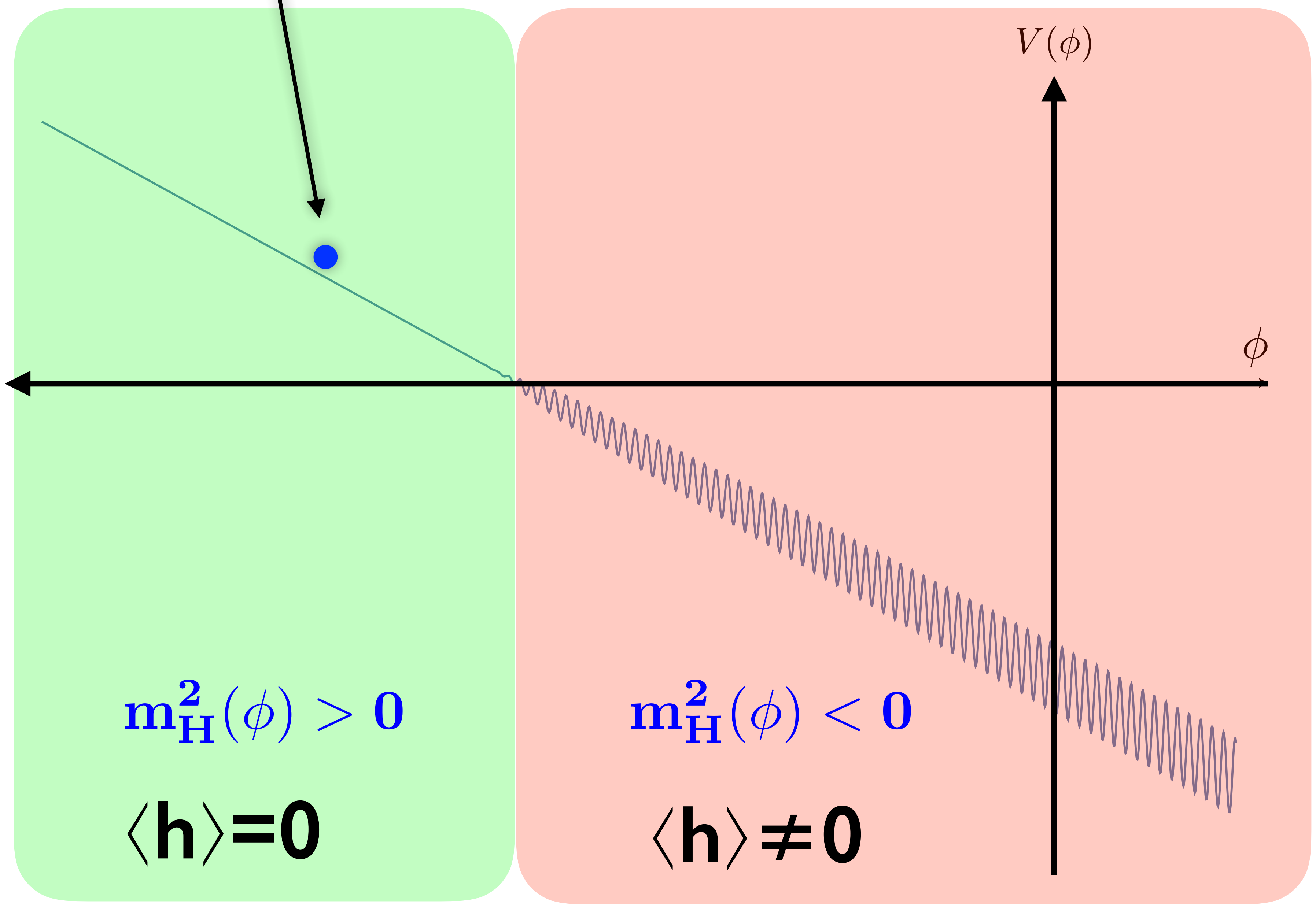

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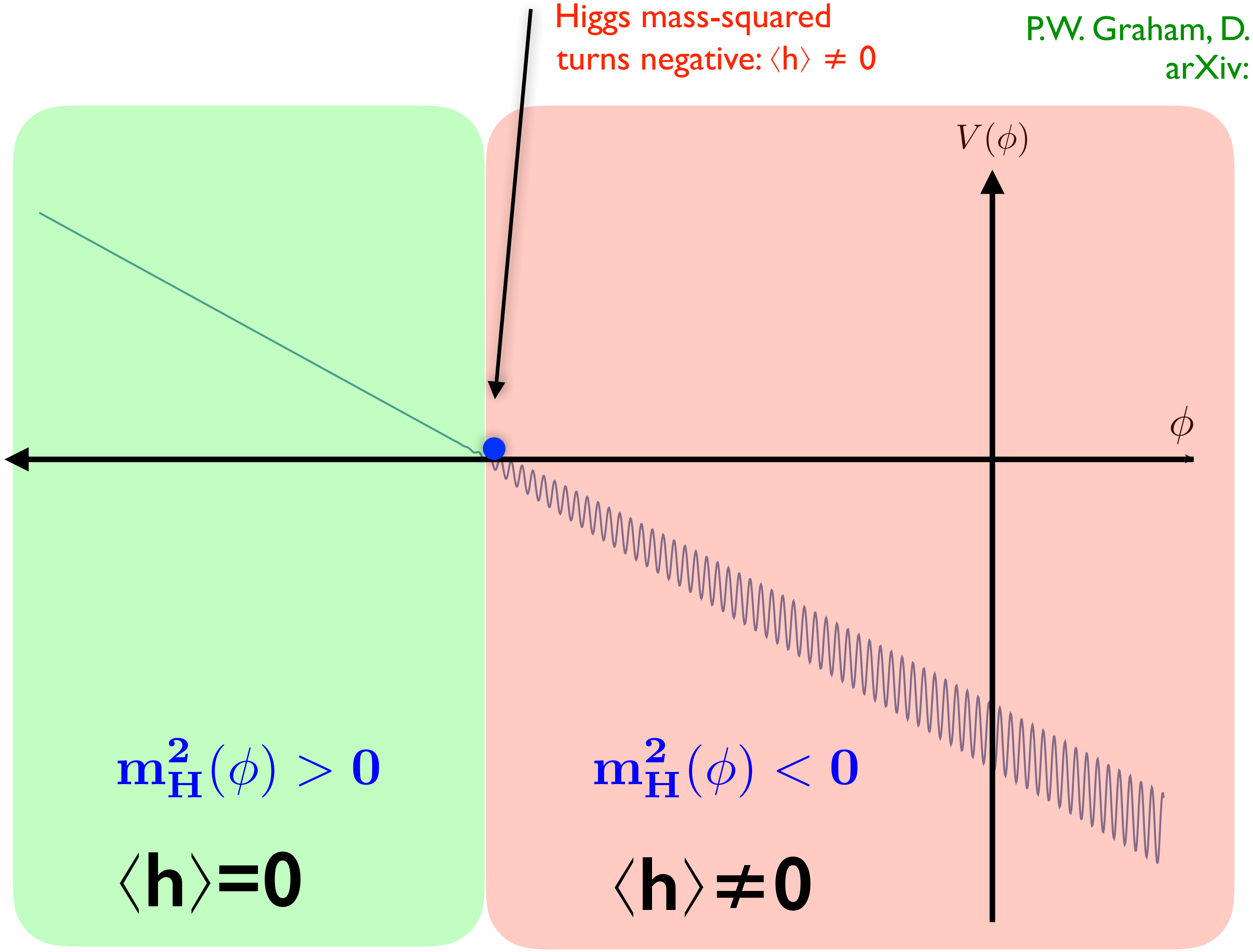

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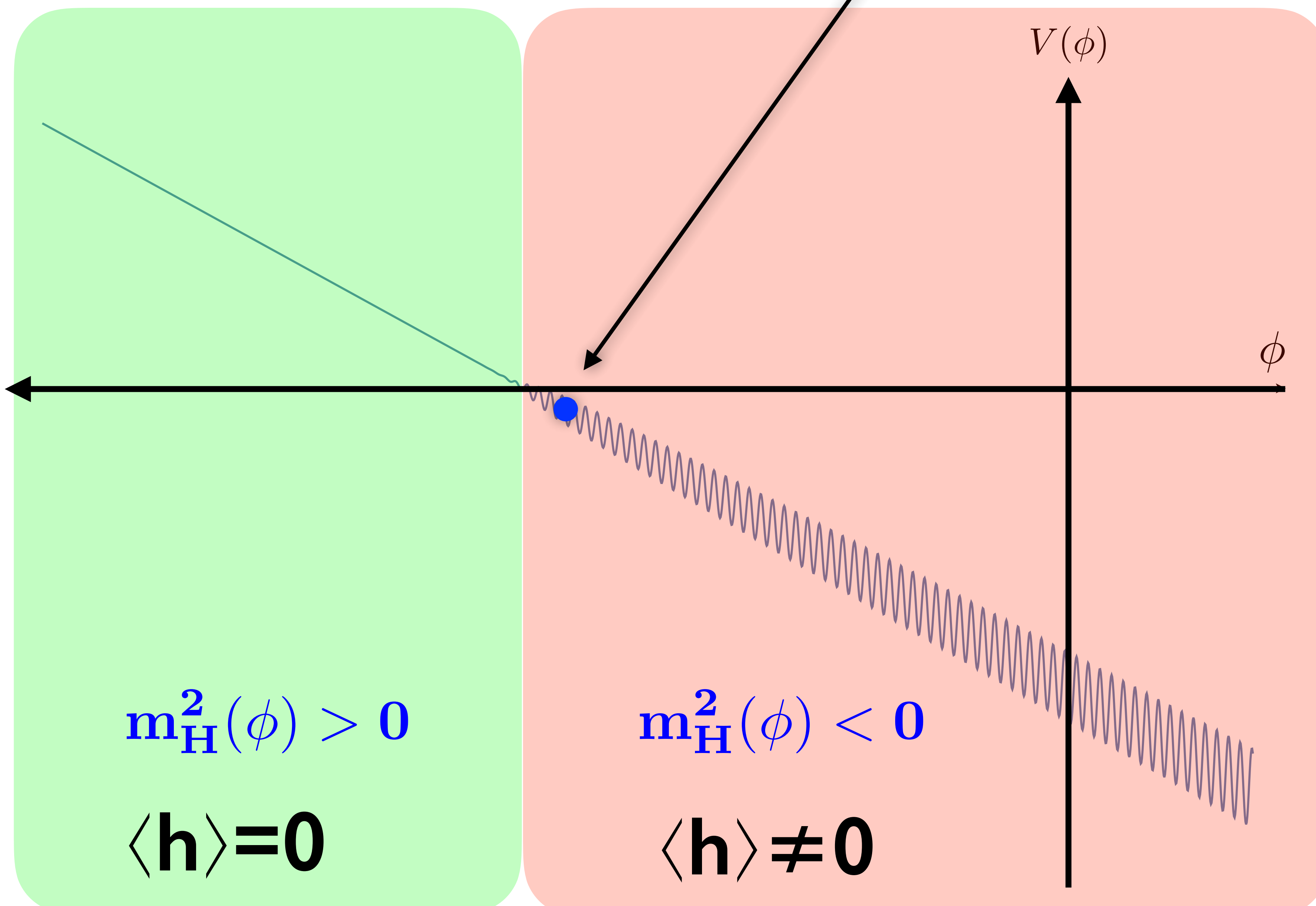
becomes
more & more
important

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551



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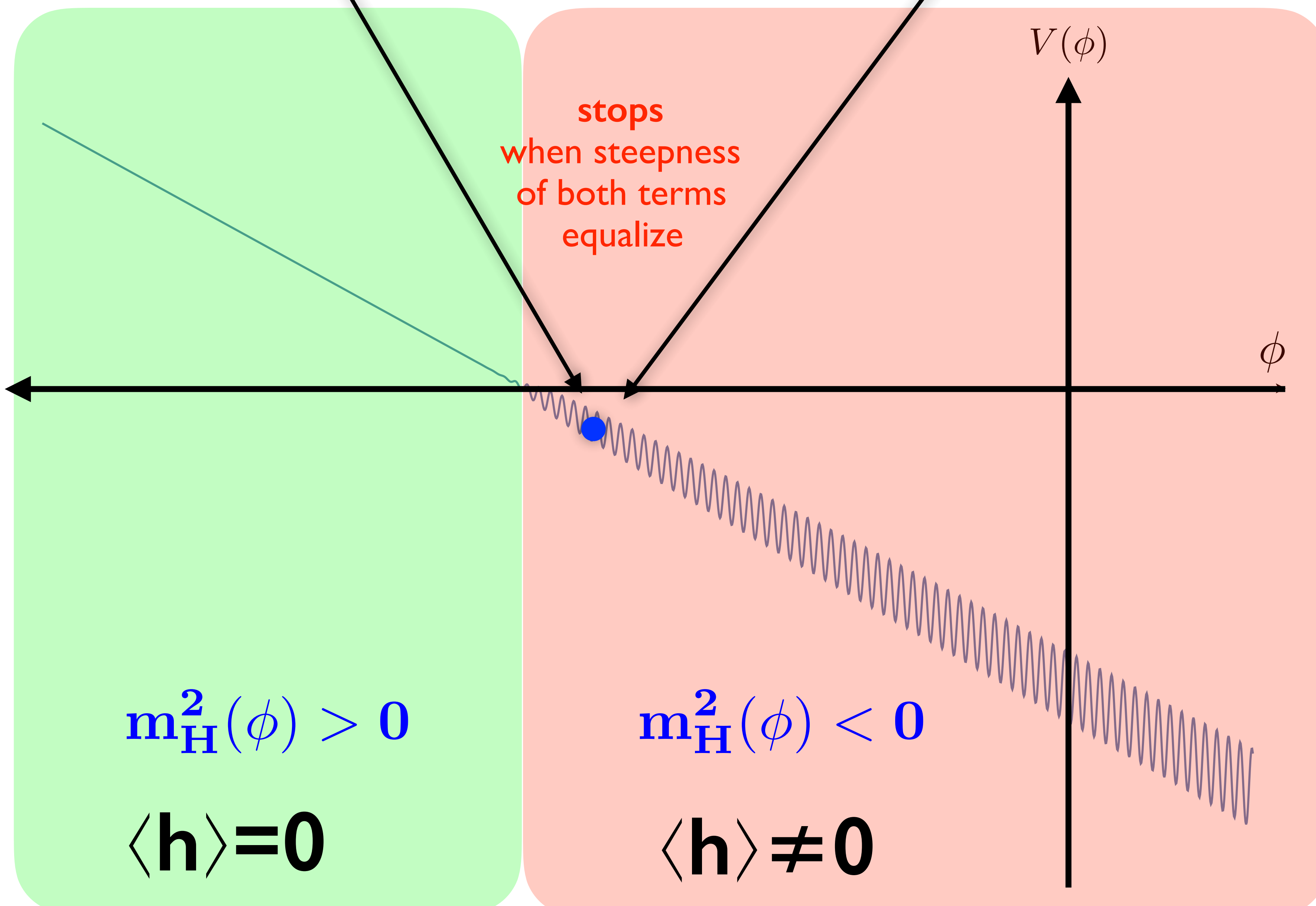

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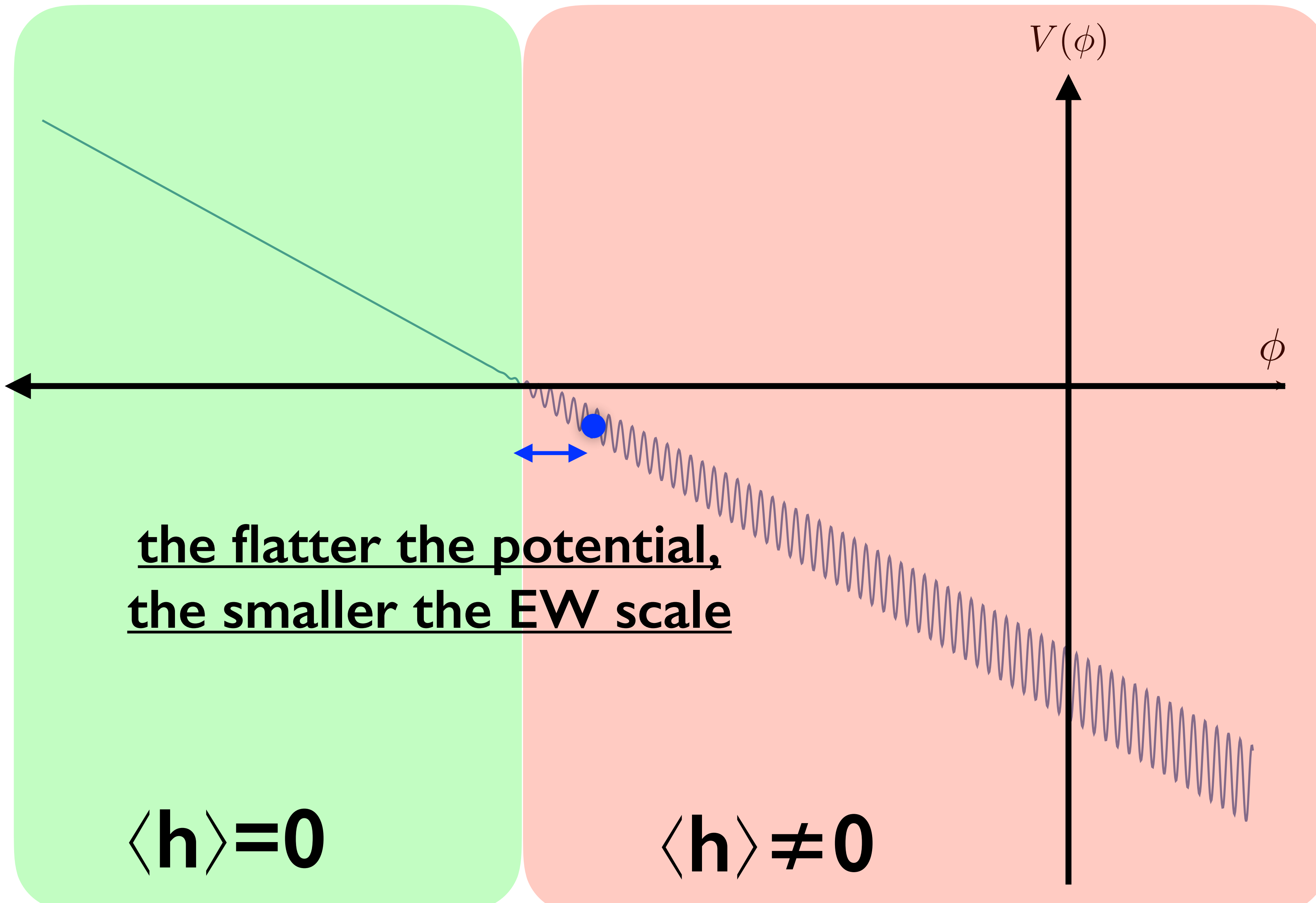
arXiv:1504.07551



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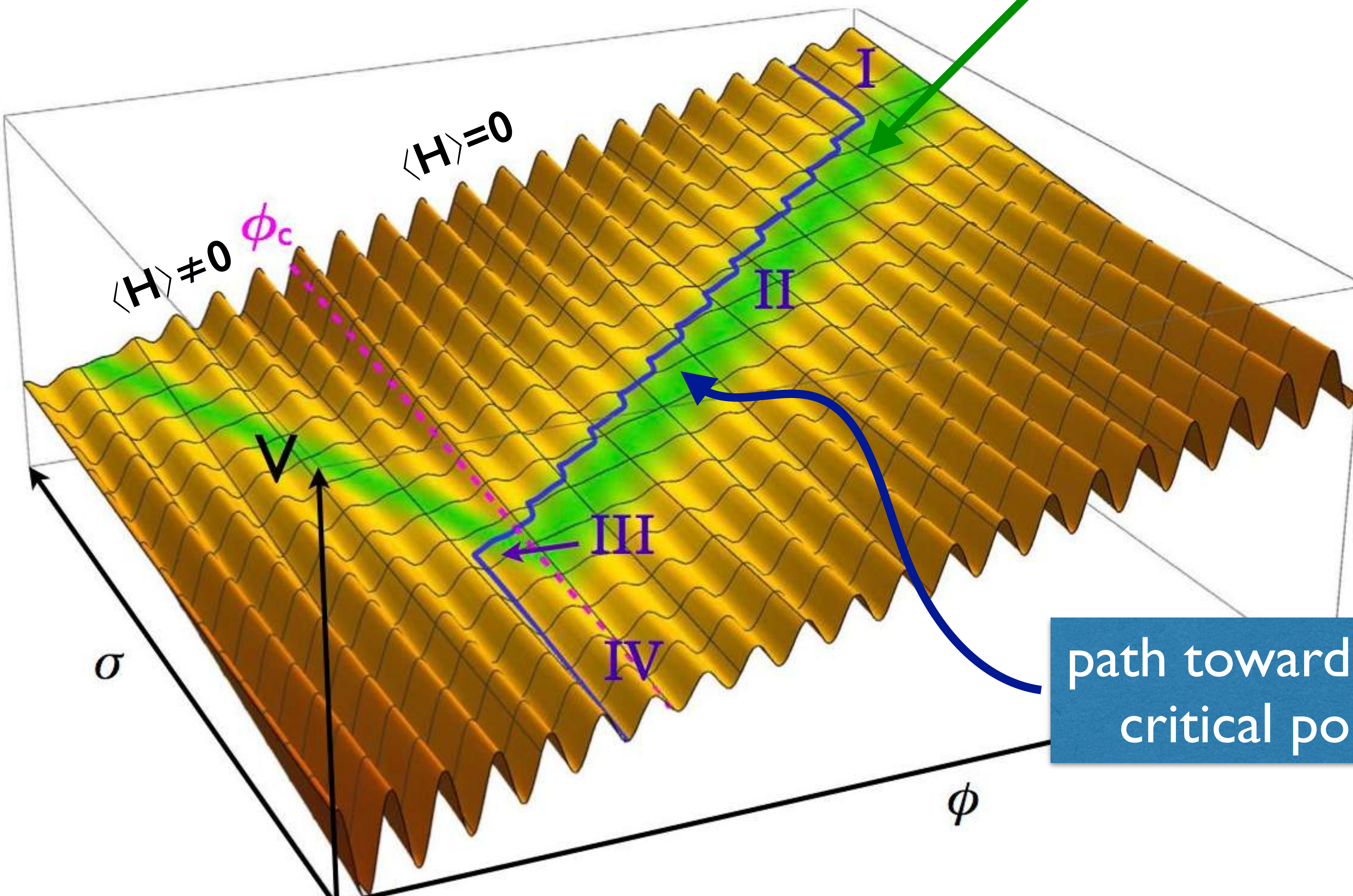
ALPine Cosmology:

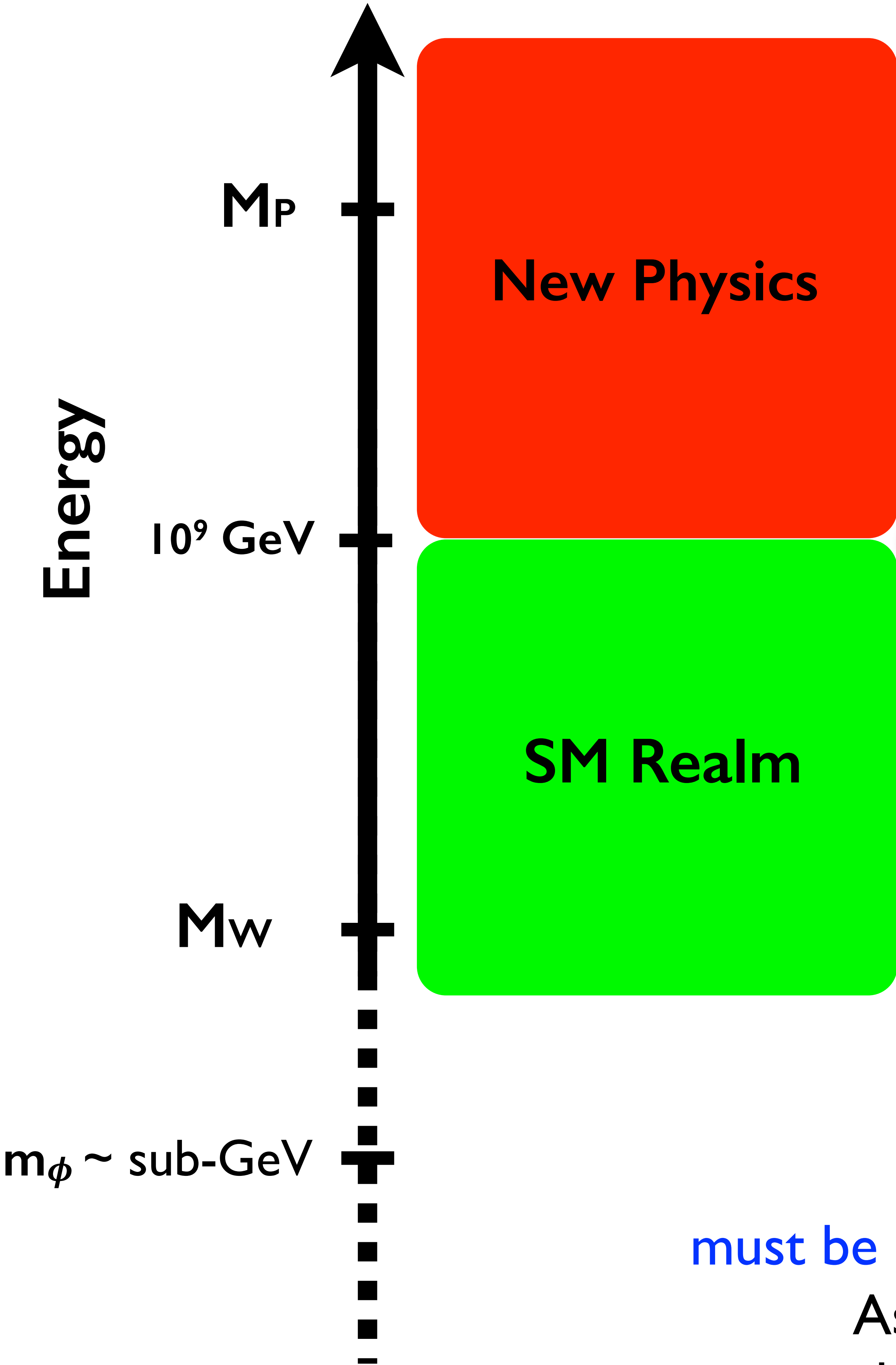
Phys.Rev.Lett. 115 (2015) 25, 251803

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

area where A≈0



path towards the critical point



New physics scale can be pushed up naturally to at least 10^9 GeV

see for example, J.R.Espinosa,C.Grojean,G.Panico,A.P., O.Pujolàs,G.Servant 15

Main prediction:

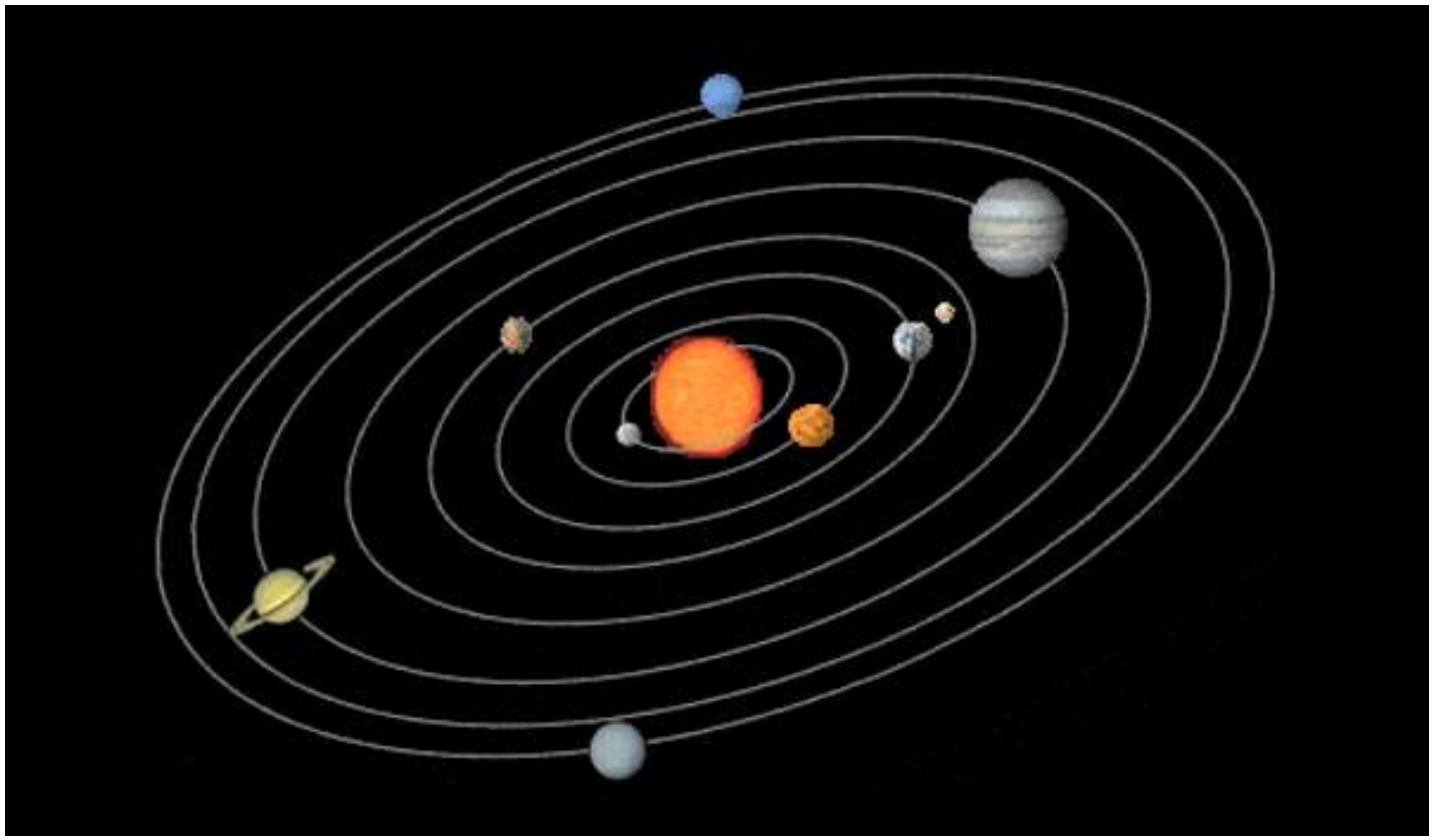
ϕ's: very light & extremely weakly-coupled states (*axion-like*)

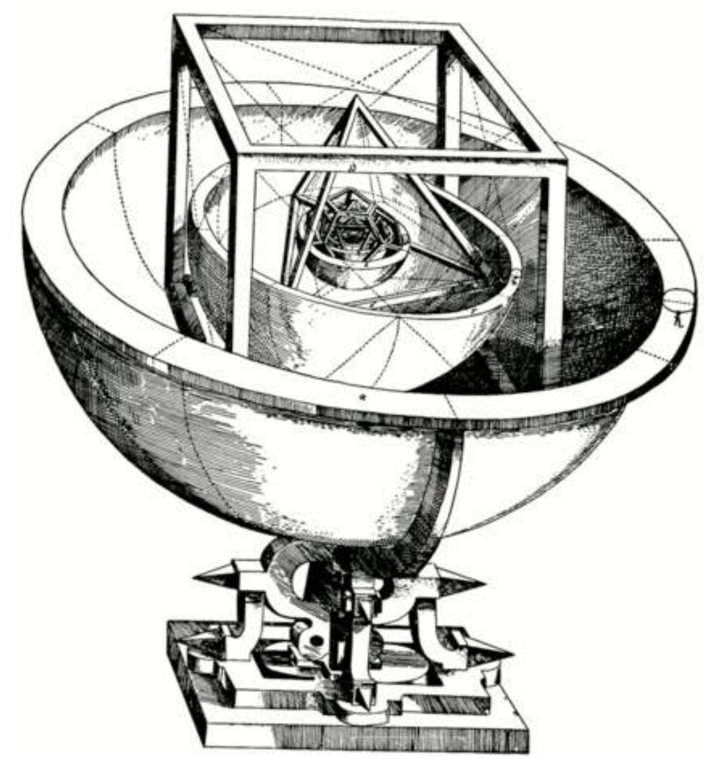
must be searched in different type of experiments:

Astro (γ-rays, pulsar timing, …), CMB,
table-top (fifth-force searches, EPV), …

Alternative approach: *Lesson from history*

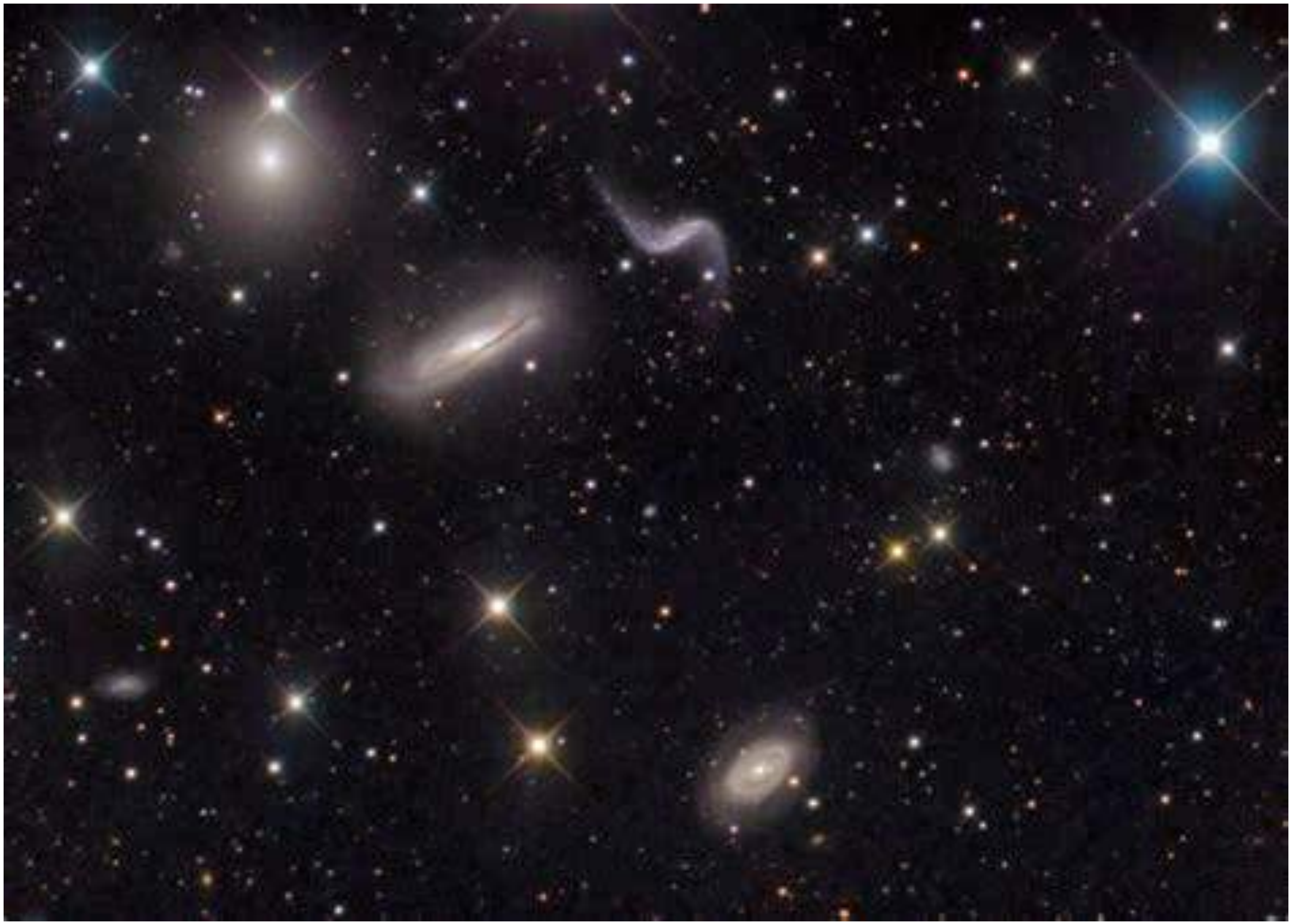
Orbit's planet: Fundamental scales?



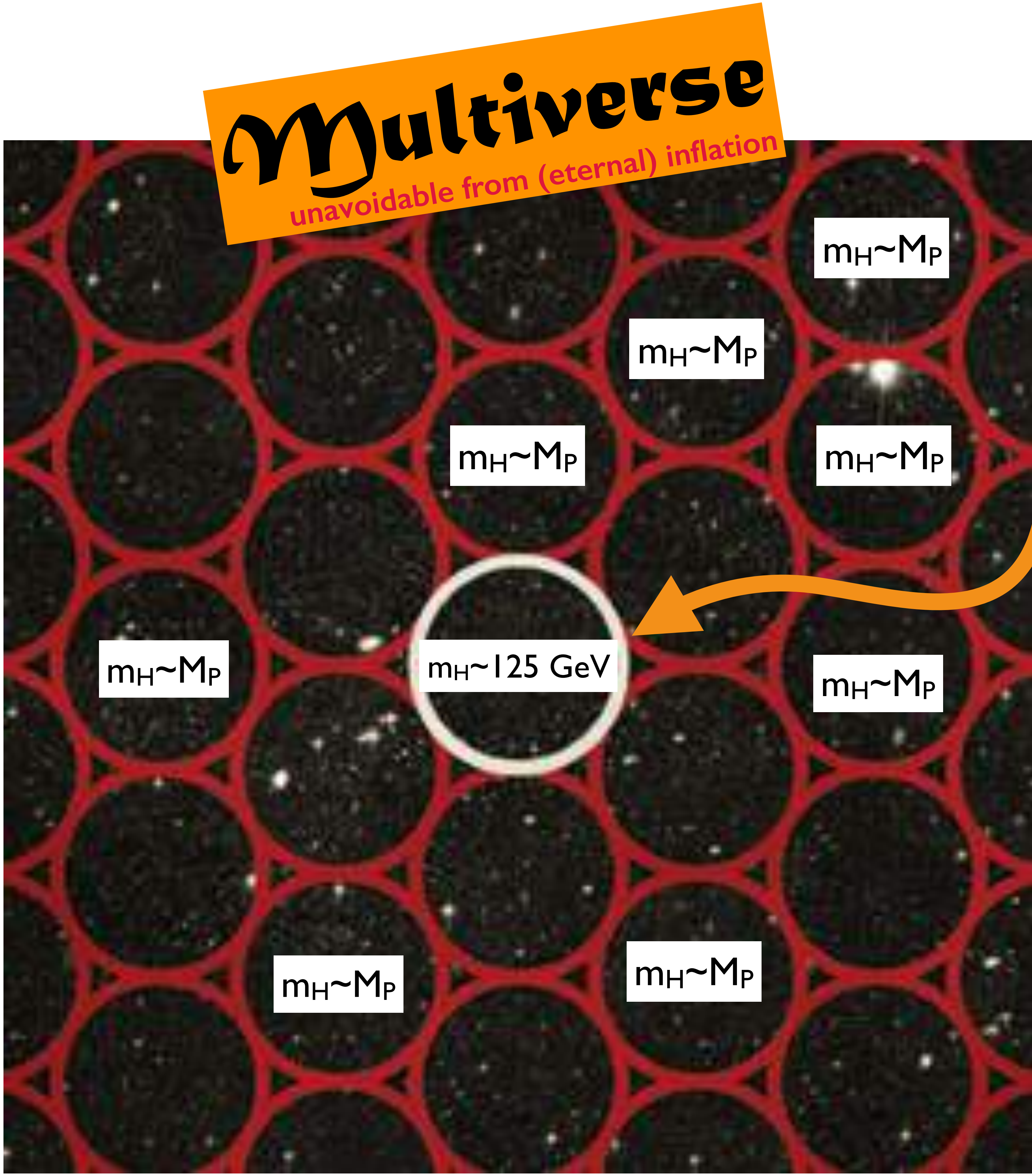


Kepler's Mysterium Cosmographicum

But many solar systems discovered



Orbit's planet don't seem to be fundamental entities



Our **Universe** is very delicate:
Change the SM parameters and could be uninhabitable

"Natural", since only we can "live" in a Universe with these "fine-tuned" parameters

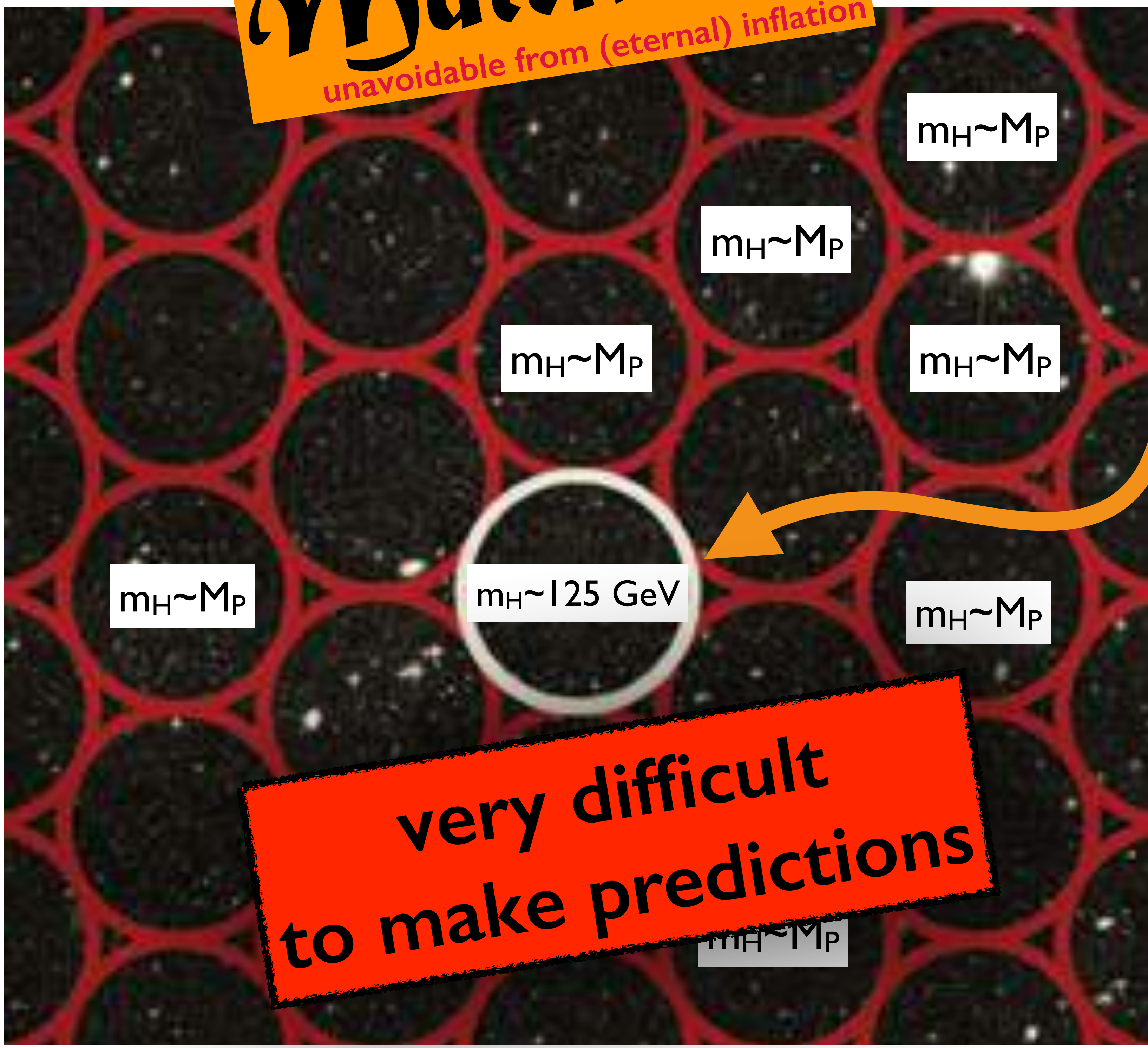
↓

No new physics at the TeV!

(new physics in another universes)

Multiverse

unavoidable from (eternal) inflation



At present, the only scenario that could "explain" the present smallness of the cosmological constant!

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IV

“Quantum” constraints

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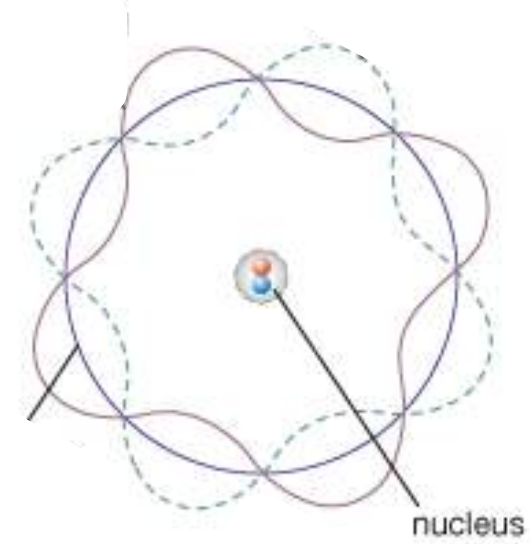
Quantum mechanics
restrict the atomic orbits:



Can some “quantum” condition restrict m_H to be small?

Weak Gravity Conjecture:

For a consistent theory of quantum gravity, there must be a state of charge **q** and mass **m** satisfying

Arkani-Hamed, Molt, Nicolis, Vafa 06

$$\mathrm{q} > \frac{\mathrm{m}}{\mathrm{M_P}}$$

bound on mass scale

See Cheung, Remmen 14, for proposals along these lines

Conclusions

- One the most important remaining questions in particle physics:

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Let’s enjoy a different problem of scales: