Pheno of Ultimate Colliders

Imagination is unlimited

Hyung Do Kim (Seoul National University)

2025 July 29

Galileo Galilei Institute, Florence, Italy

Globatron

Enrico Fermi

proposed circling the earth as the ultimate collider in 1954

3 TeV (fixed target) to 5 PeV

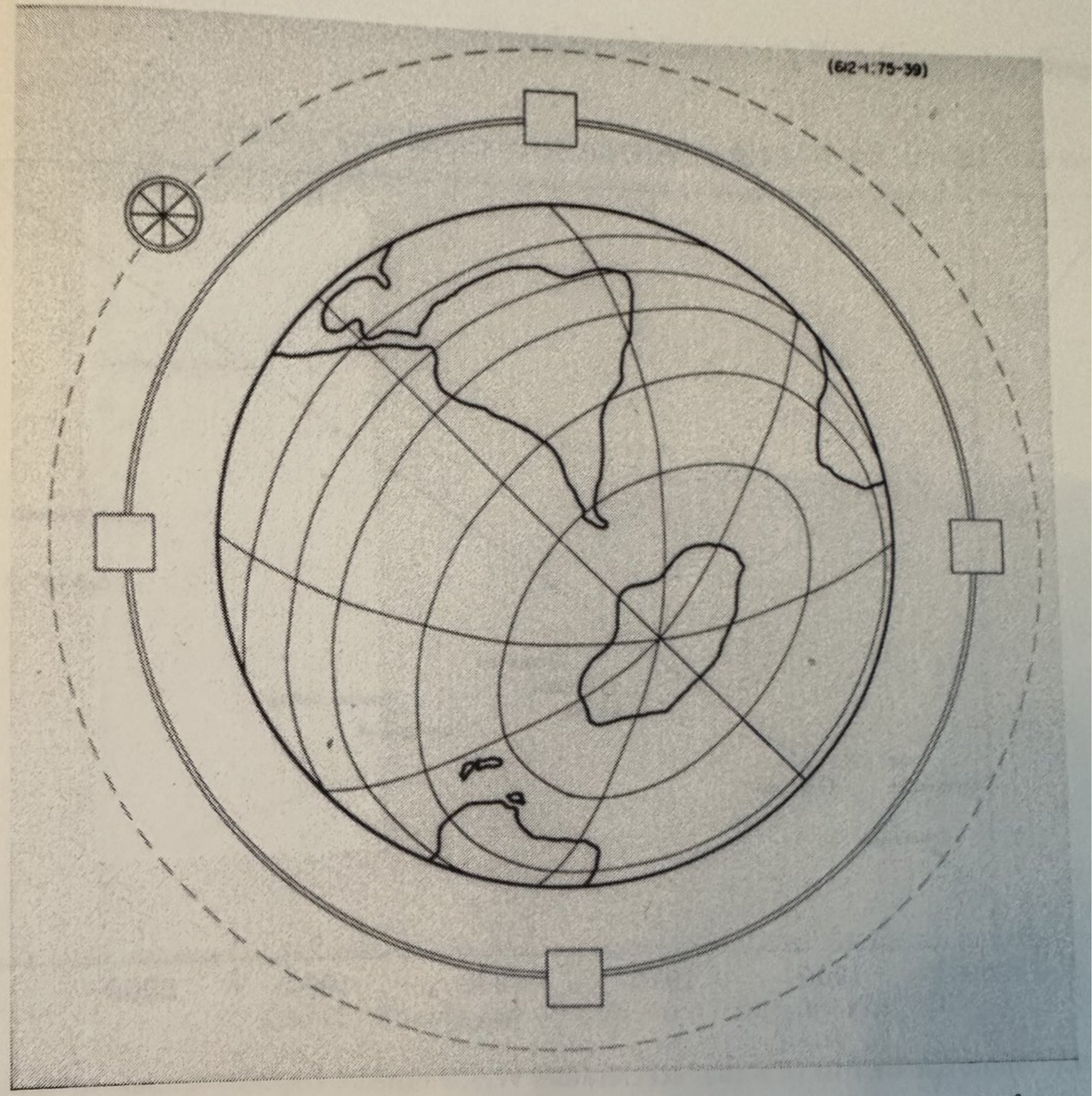
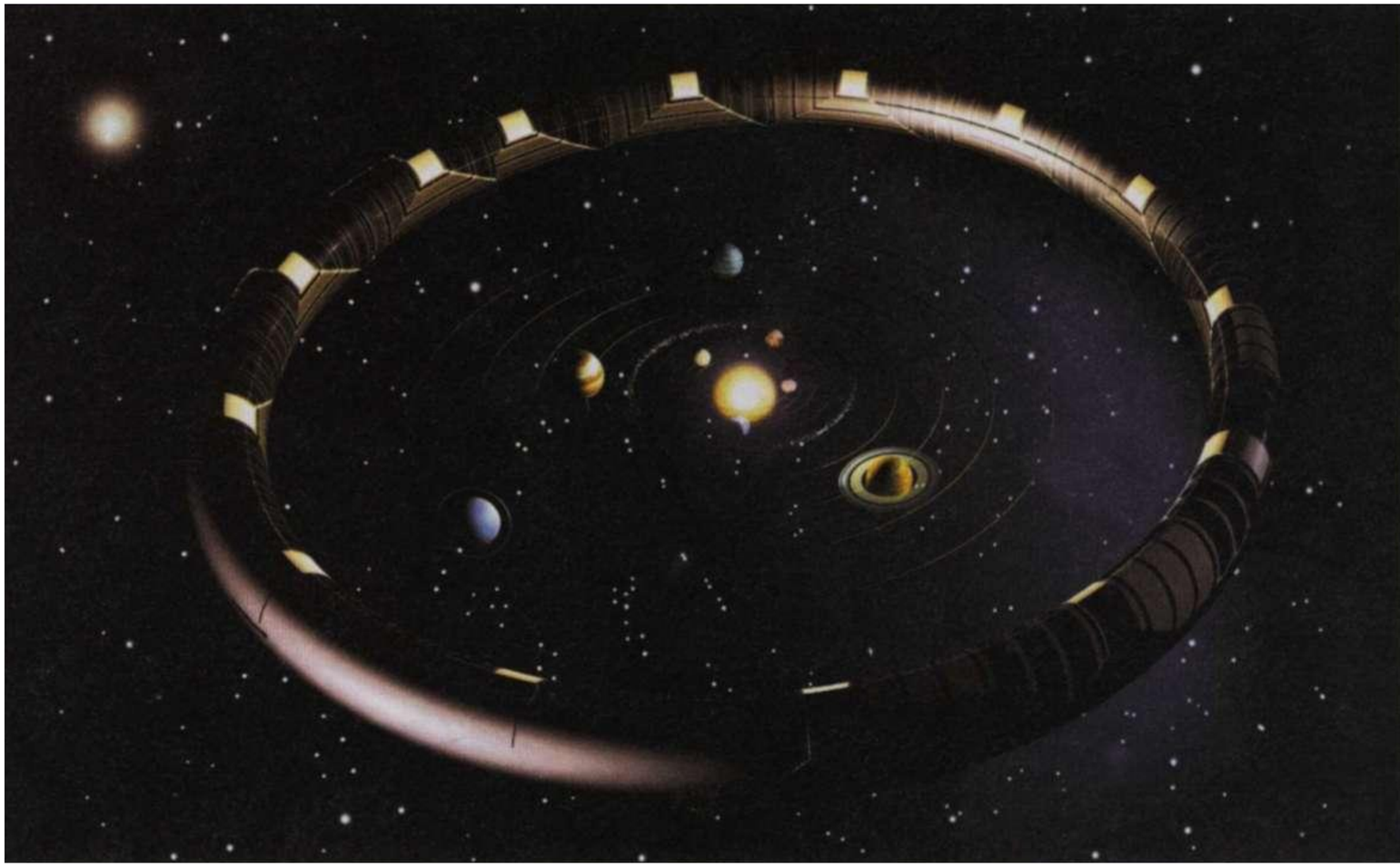


Figure 9.4 Fermi's slide 2, the "Globatron." (Reproduced with permission of Special Collections, University of Chicago Libraries.)

Solartron



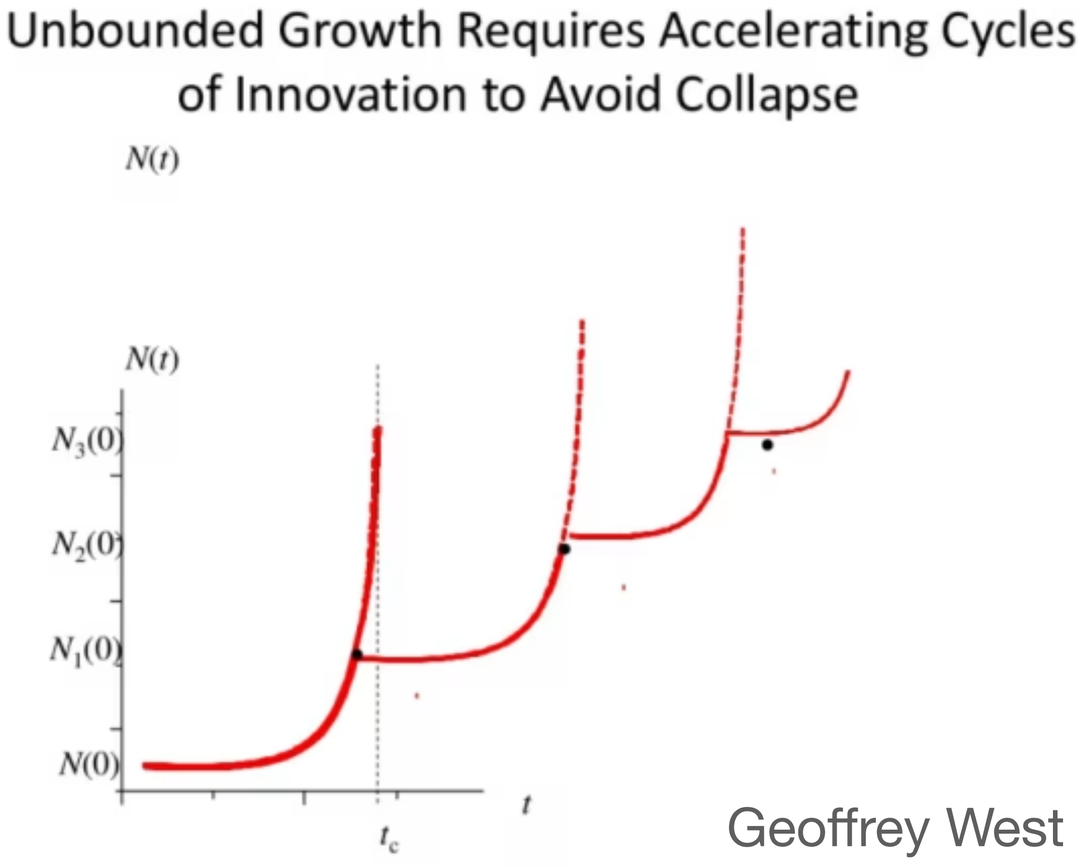
Steven Hawking

Universe in a nutshell

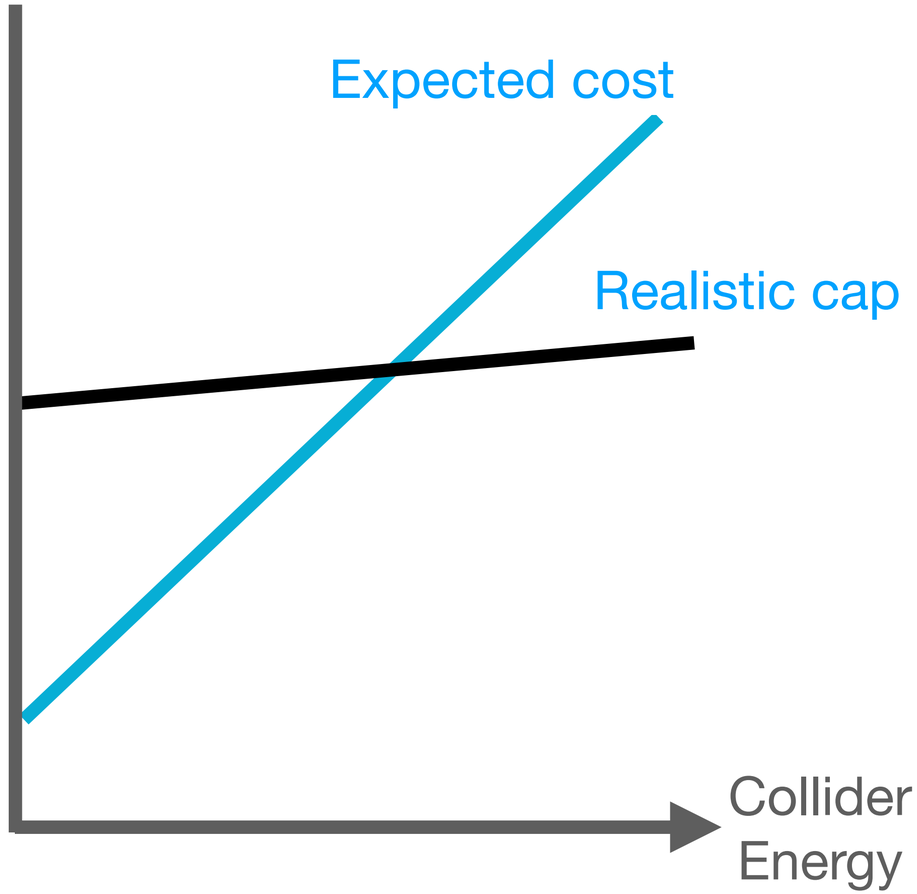
GUT scale energy
needs solar system
(syncrotron radiation is huge)

Scale

Geoffrey West



Geoffrey West



Where is new physics?

Where is new physics?

50 years of BSM

- Higgs (and nothing else)
- Nightmare scenario
- Is there anything wrong in our understanding?

Beyond the Standard Model

Why?

Why not?

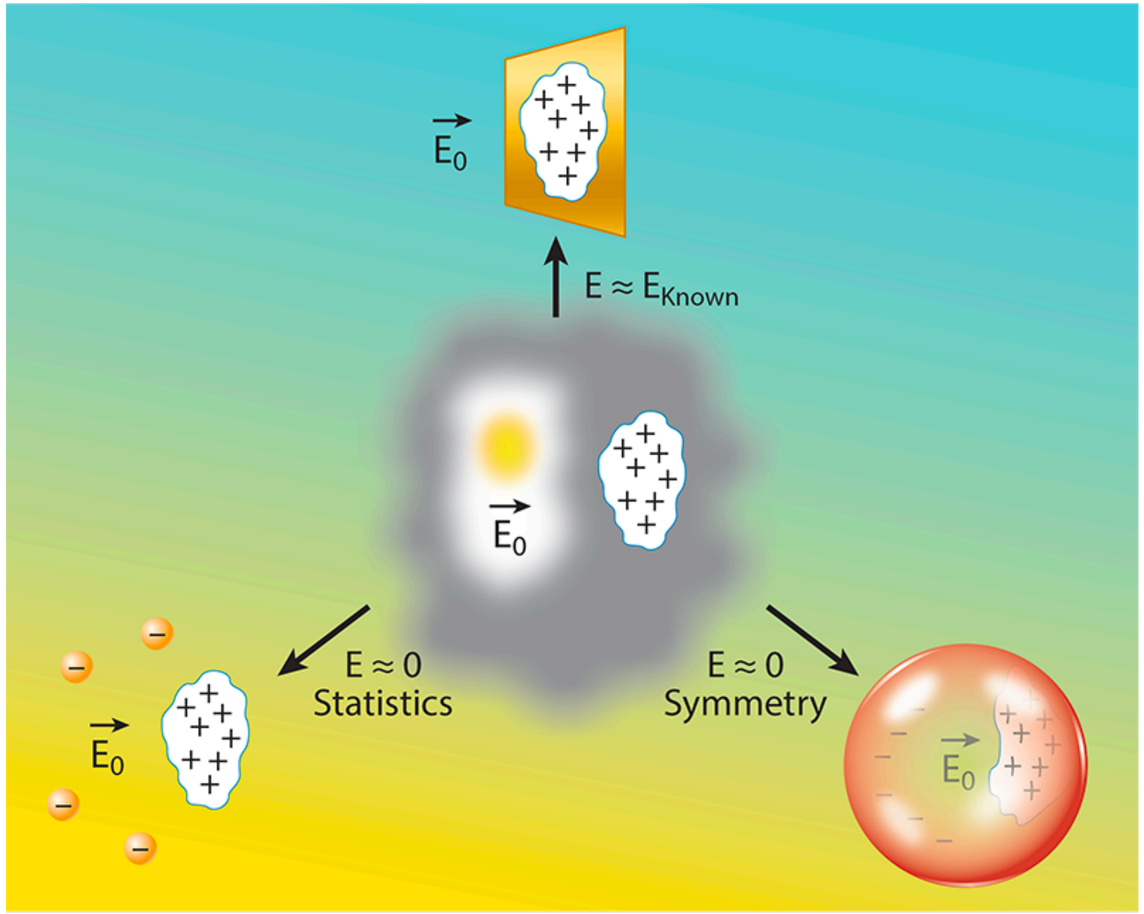
motivated?

unmotivated?

Unmotivated BSM : lamp post principle

Motivated BSM

Francesco Riva



multiverse/statistics

symmetry/naturalness

Possible candidates of motivated BSM

Hierarchy problem before and after Higgs discovery

Symmetry (naturalness)

-Supersymmetry

-Running top Yukawa coupling (composite)

Cosmological solution

-Relaxion

-Nnaturalness (multiverse in our universe)

Selection mechanism

-Weak scale as a trigger

(-Coleman-Weinberg Higgs)

Phenomenology of motivated BSM

Hierarchy problem before and after Higgs discovery

Symmetry (naturalness)

-Top partner

-Strong interaction at the compositeness scale

-Color neutral new particle at or above the weak scale

Cosmological solution

-ALP

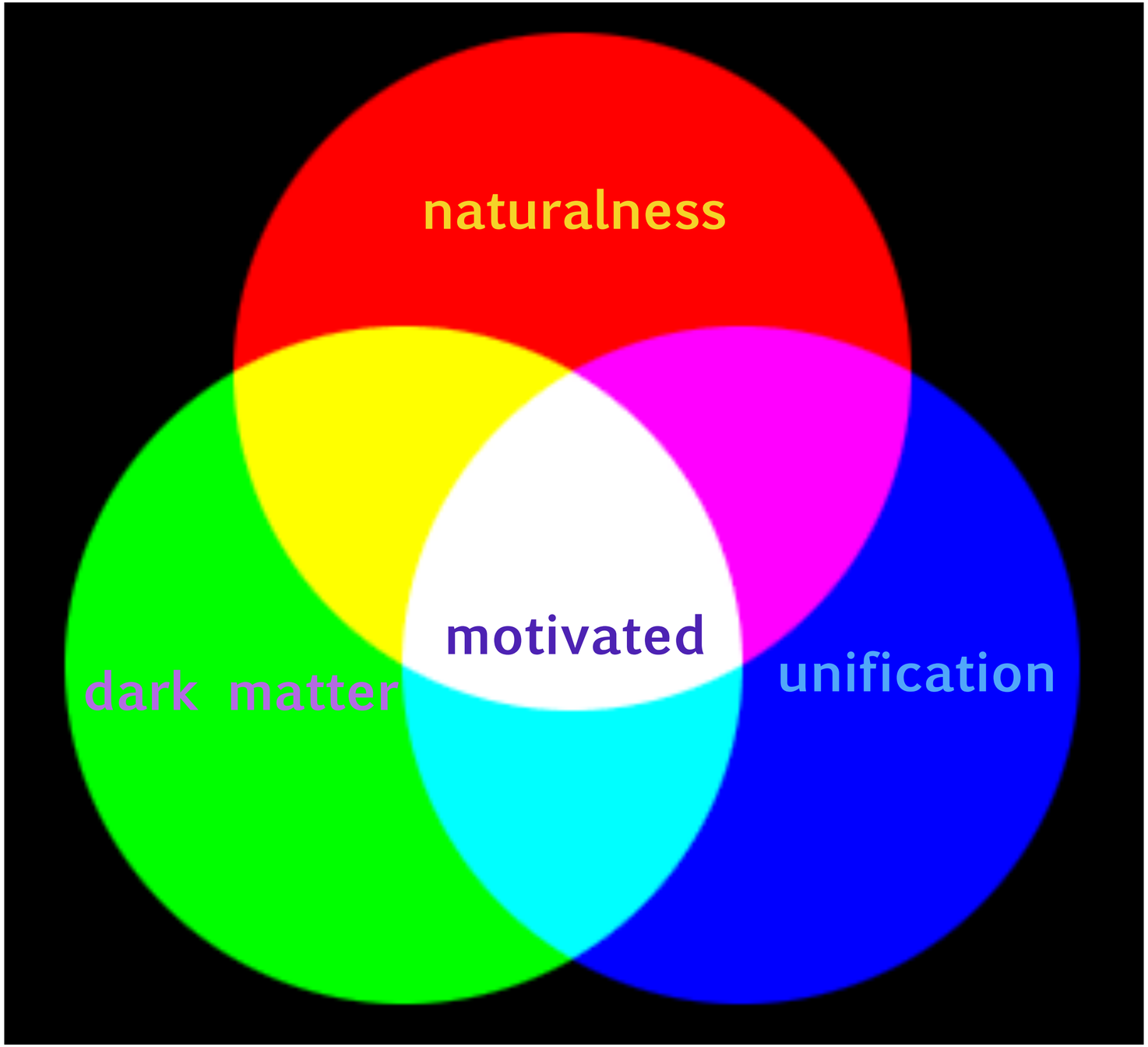
-$\Delta N_{\rm eff} \sim \mathcal{O}(1)$, feebly interacting reheaton, structure formation

Selection mechanism

-Extremely light scalar, other Higgs bosons

(-new scalar particles at and above the weak scale)

before Higgs discovery


naturalness
motivated
dark matter
unification

unification of gauge couplings

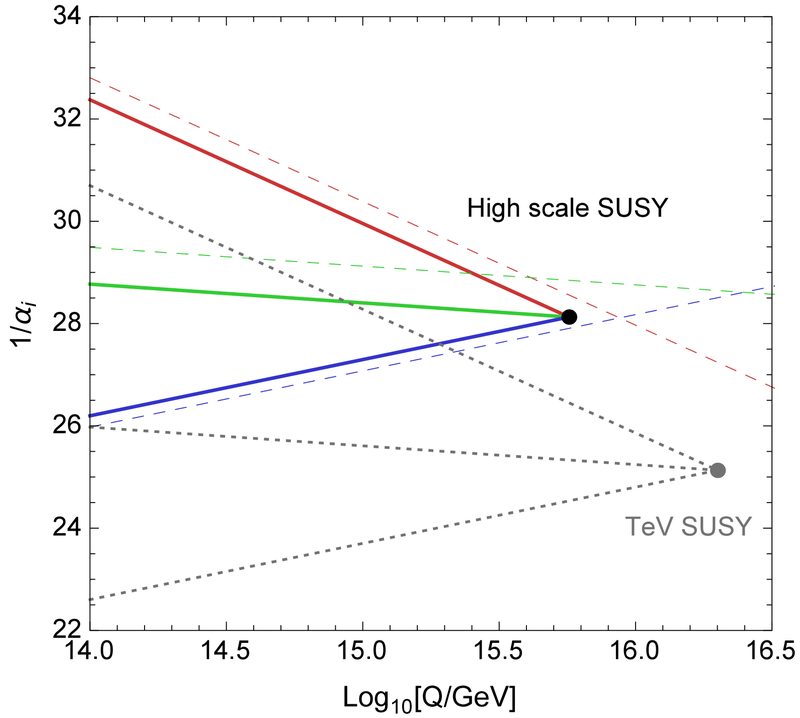
charge quantization is one of the puzzle in the SM

$$Q_d = \frac{1}{3} Q_e \qquad\qquad 2Q_u + Q_d + Q_e = 0$$

anomaly cancellation could have worked differently

furthermore,
accidental observations

0. two lines meet at one point (or ||)
1. three lines meet at one point
2. below Planck scale & avoid proton decay



Dimopoulos, Giudice (1995)

Cohen, Kaplan, Nelson (1996)

bino, wino,
1&2nd squarks & sleptons,
stau, tau sneutrino

> 2 TeV

Natural Supersymmetry

fine tuning ~ 10%

Asano, HD Kim, Kitano, Shimizu JHEP(2010)

MSSM : mh ~ 115 GeV

…

gluino

< 1.1 TeV

< 200*$\sqrt{\tan\beta}$ GeV

H, A, H+

stop'

< 550 GeV

m_t

sbottom

m_t

300 GeV

stop

< 200 GeV

chargino/neutralino

< 300 GeV

< 120 GeV

Higgs (h)

goldstino

> eV

After Higgs discovery

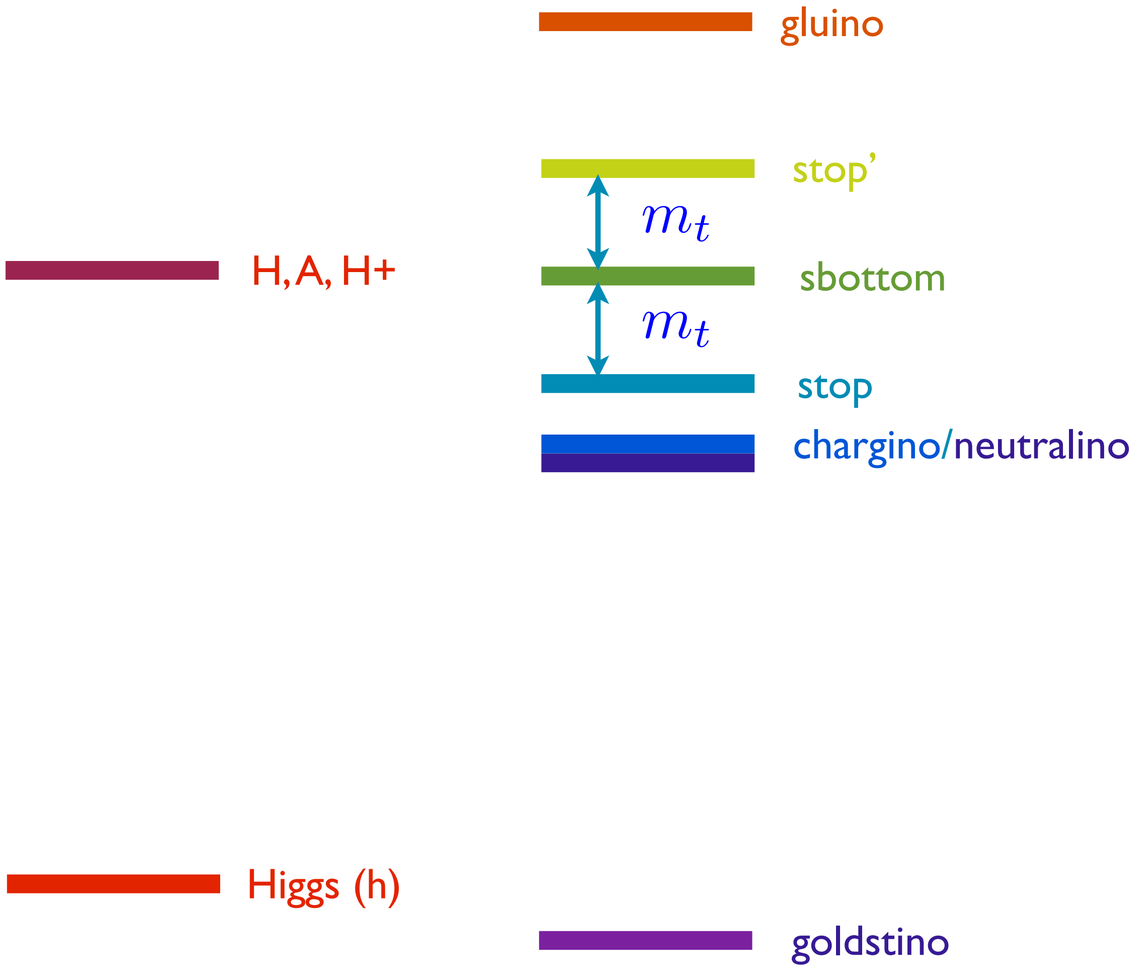
Least Unnatural Supersymmetry

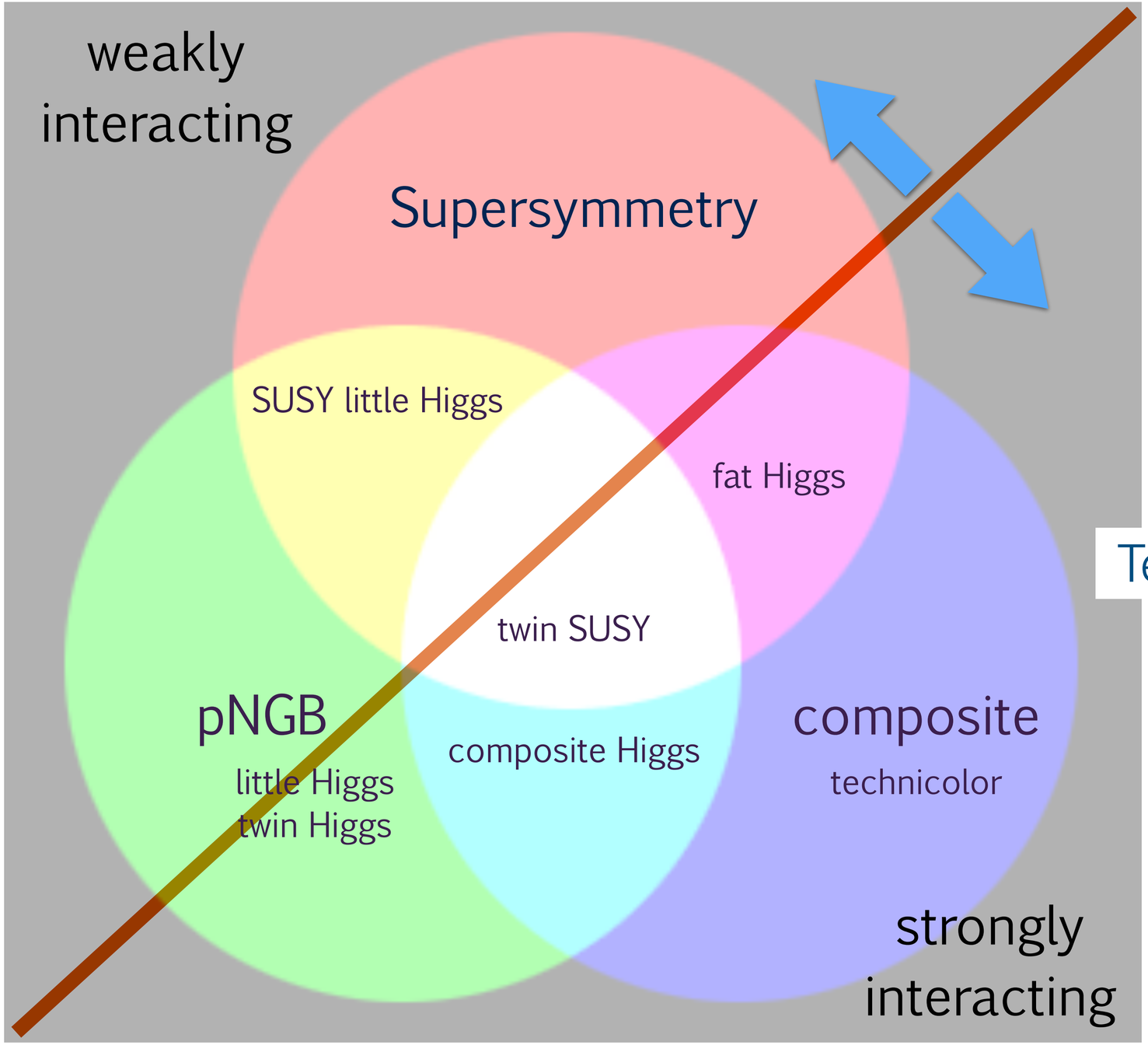
fine tuning ~ 1%

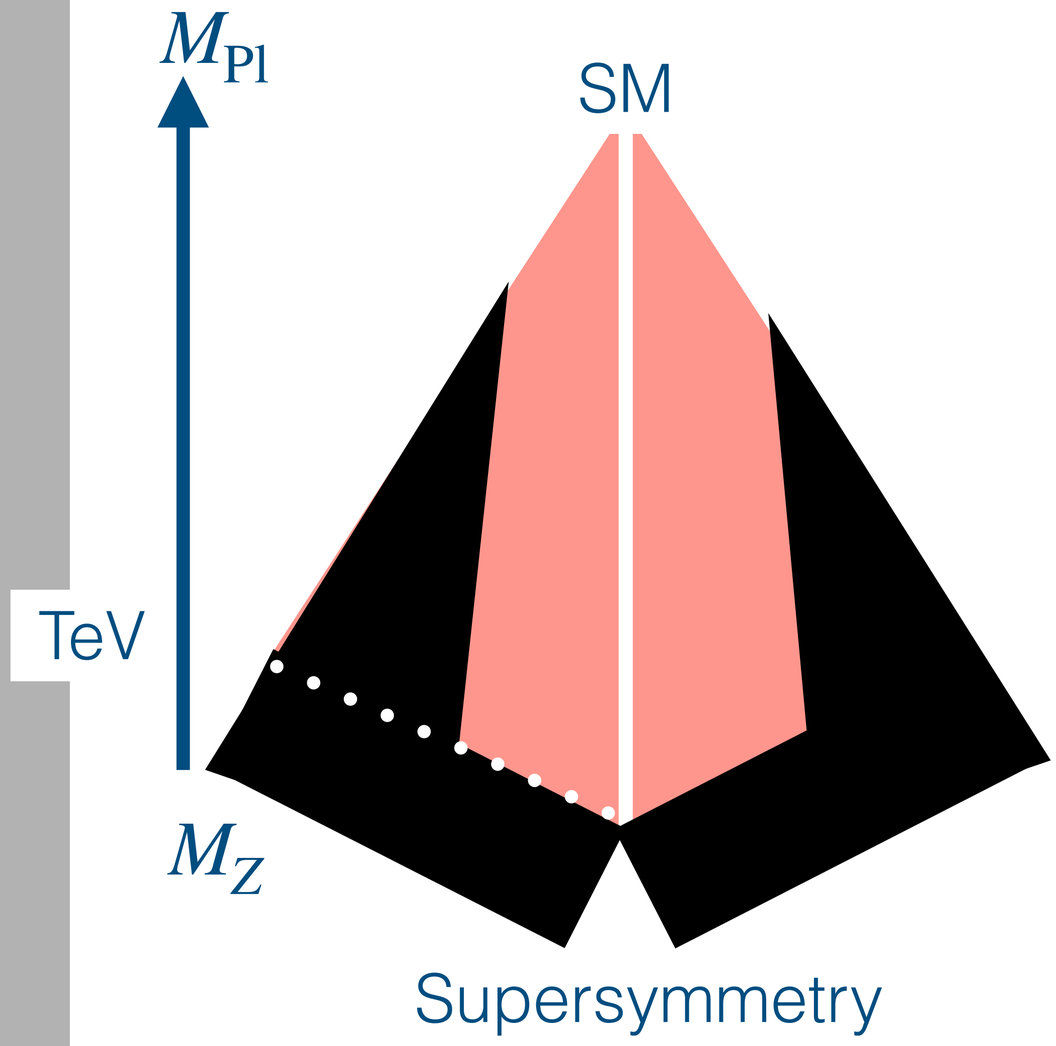
MSSM : mh ~ 125 GeV

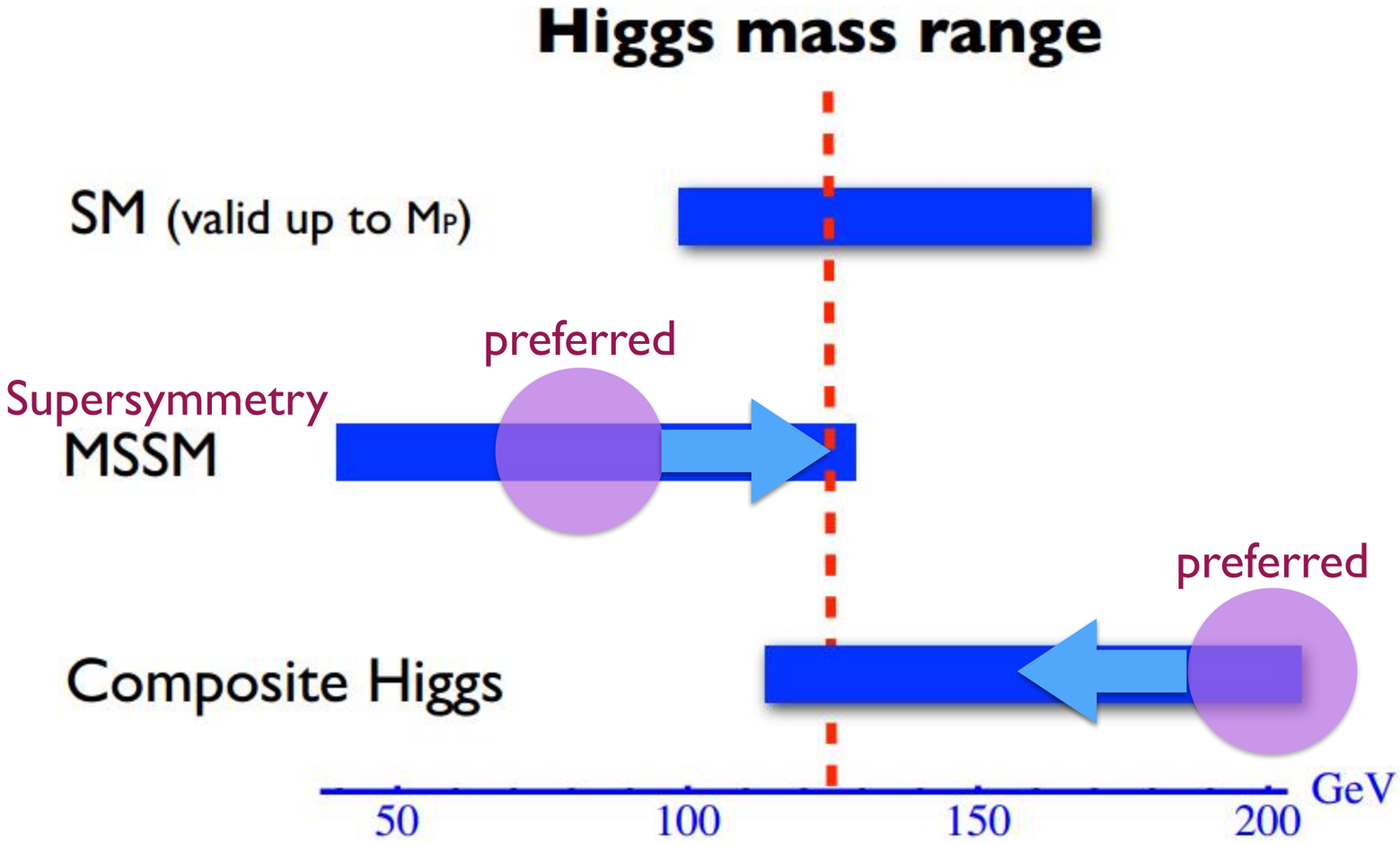
from Higgs mass

TeV




weakly
interacting
Supersymmetry
SUSY little Higgs
fat Higgs
twin SUSY
pNGB
little Higgs
twin Higgs
composite Higgs
composite
technicolor
strongly
interacting


$M_{\rm Pl}$
SM
TeV
M_Z
Supersymmetry


Higgs mass range
SM (valid up to MP)
preferred
Supersymmetry
MSSM
preferred
Composite Higgs
50
100
150
200
GeV

By A Pomarol

My psychological reaction

Coleman-Weinberg Higgs :

alternative benchmark for Ginzburg-Landau potential

Chway Dermisek Jung HDK, PRL (2014)

$$V(\phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

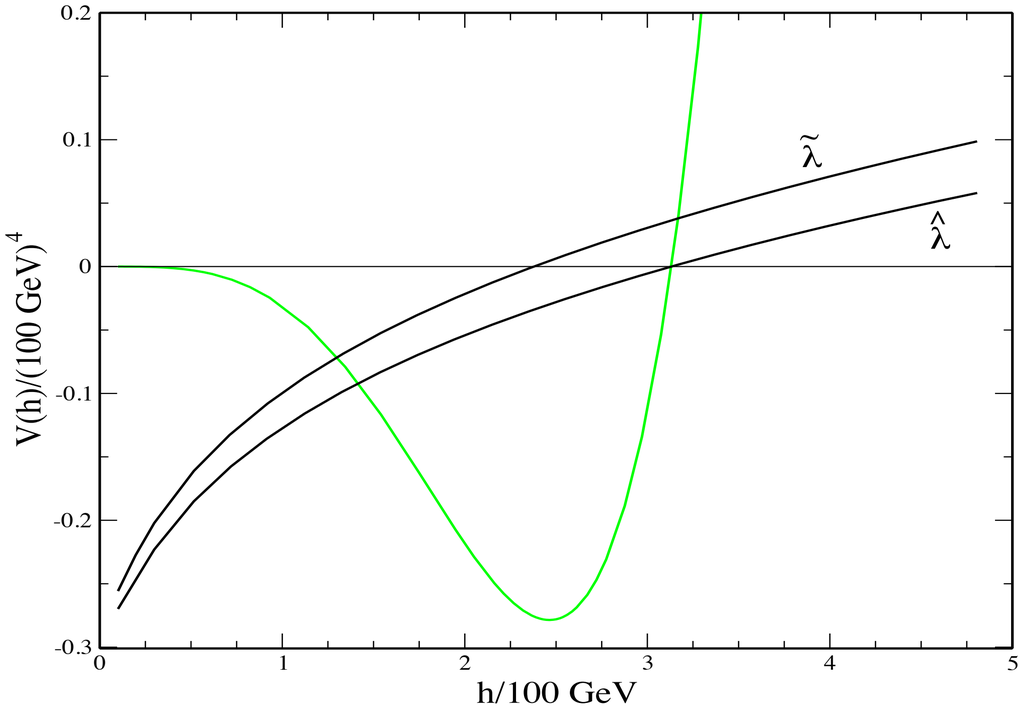
$$m^2 = 0$$

Spontaneous symmetry breaking can occur
by radiative corrections.

If the quartic changes
sign at low energy,
nontrivial minimum
is developed

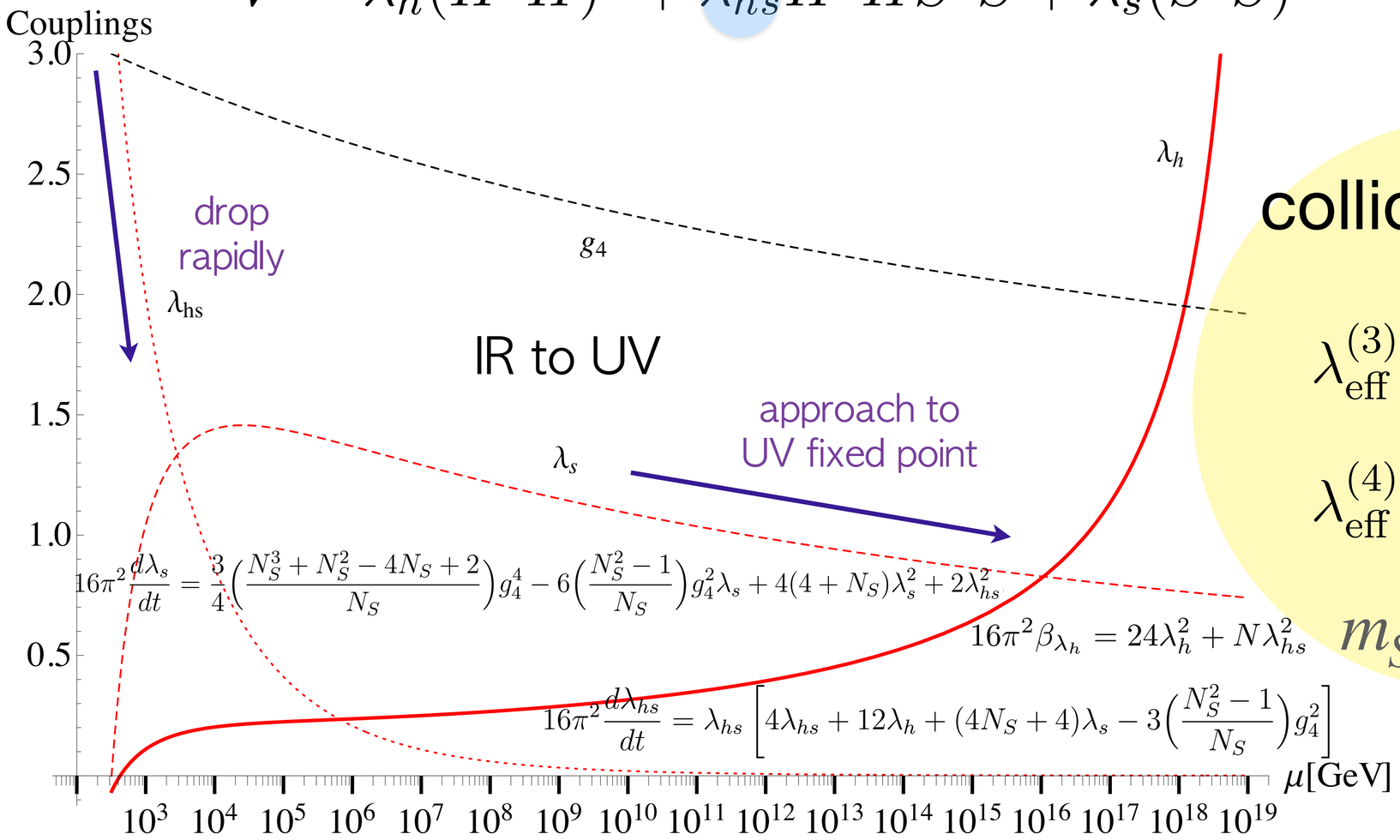
Strong 1st order
electroweak phase
transition is possible

Espinosa and Quiros, PRD (2007)



If there is a sizable mixed quartic coupling with the extra scalar S which is charged under hidden SU(N), the theory can be kept perturbative up to the Planck scale

$$V = \lambda_h (H^\dagger H)^2 + \lambda_{hs} H^\dagger H S^\dagger S + \lambda_s (S^\dagger S)^2$$



collider pheno

$$\lambda_{\rm eff}^{(3)} = \frac{5}{3}\lambda_{\rm eff}^{(2)},$$

$$\lambda_{\rm eff}^{(4)} = \frac{11}{3}\lambda_{\rm eff}^{(2)}.$$

$m_S \sim$ TeV

FIG. 2. (rigid, dashed, dotted) : $\lambda_{(h,s,hs)}$

Chway Dermisek Jung HDK, PRL (2014)

Running top Yukawa coupling

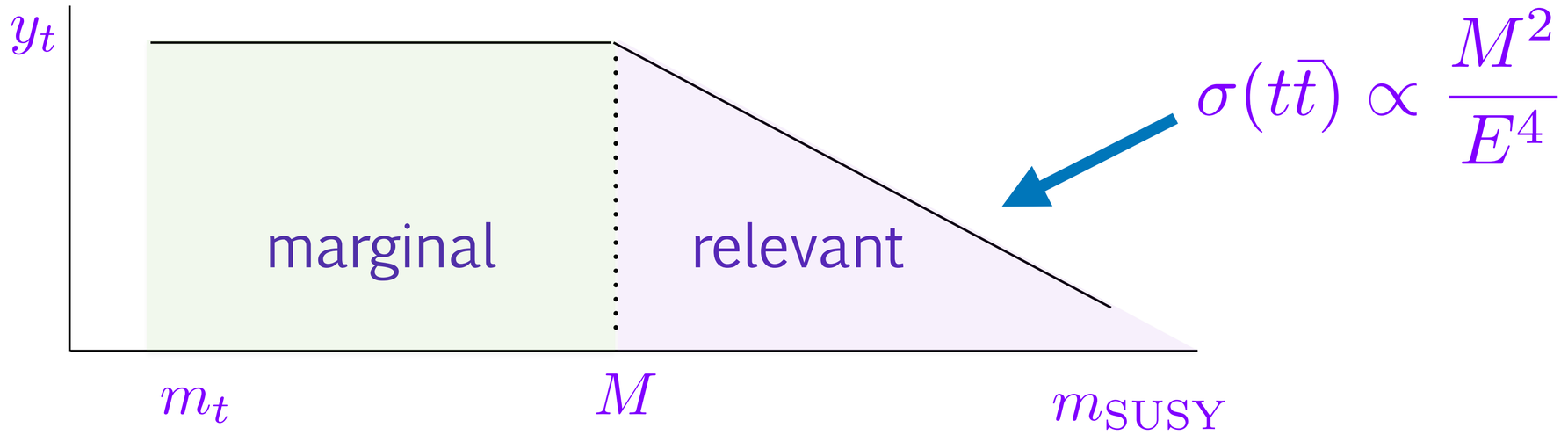
Running top Yukawa coupling

HDK 1706.00766

The fine tuning can be determined by M rather than SUSY breaking

< 1% tuning can be extended to a few %

Composite Supersymmetry : not fully explored yet

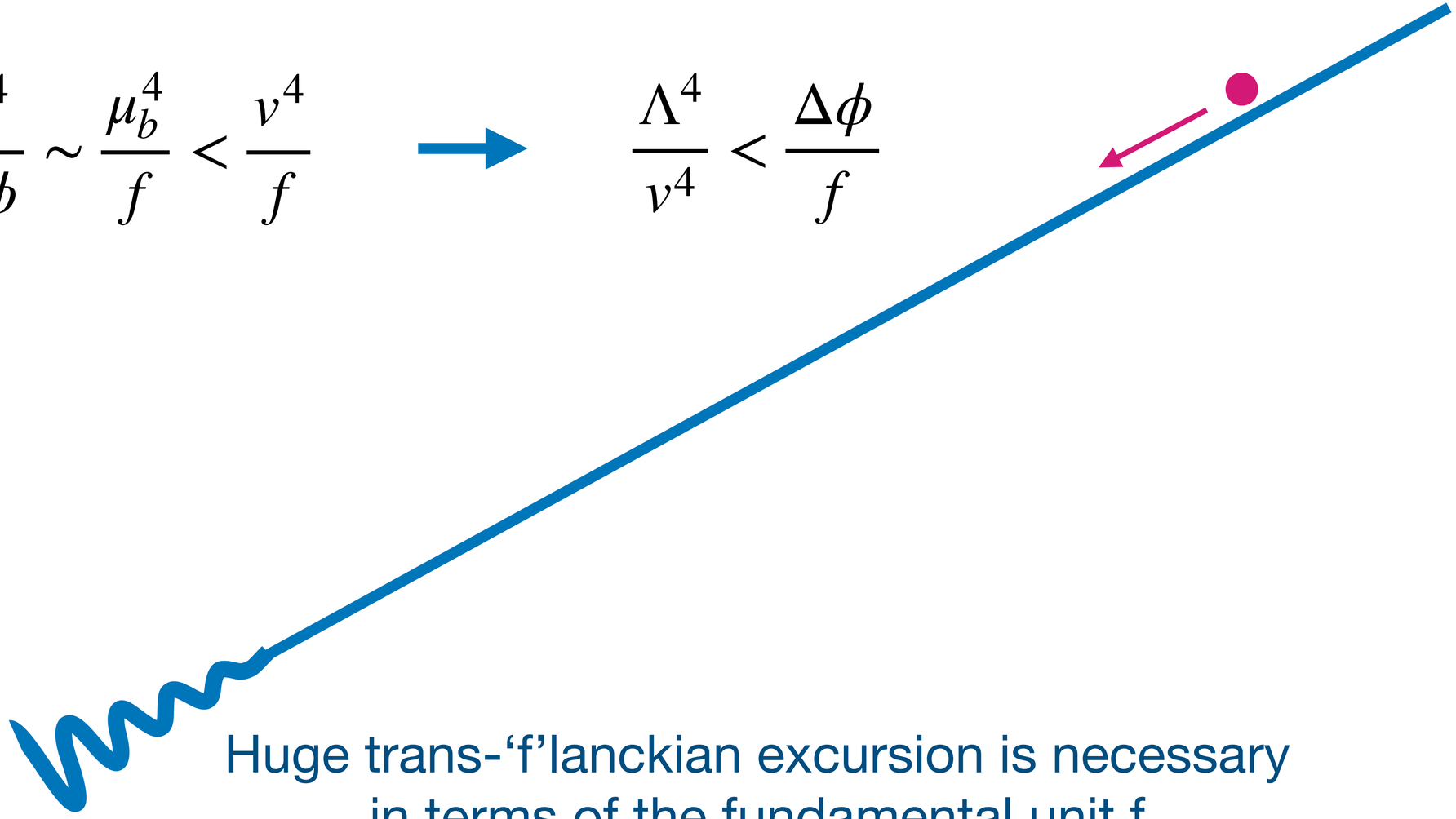


Cosmological solutions

Relaxion

Graham Kaplan Rajendran 2015

$$\frac{\Lambda^4}{\Delta\phi} \sim \frac{\mu_b^4}{f} < \frac{v^4}{f} \quad \rightarrow \quad \frac{\Lambda^4}{v^4} < \frac{\Delta\phi}{f}$$

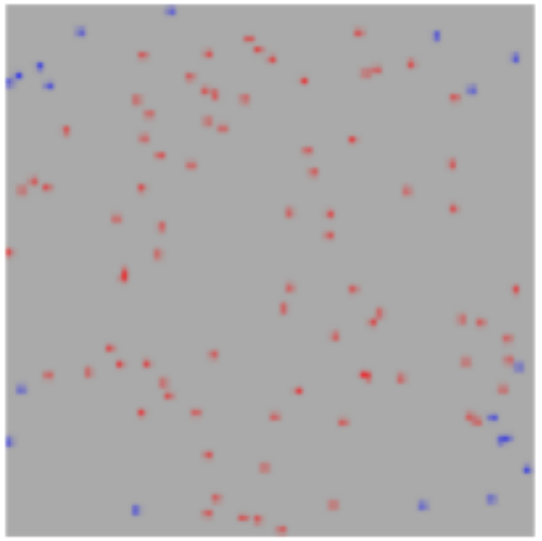


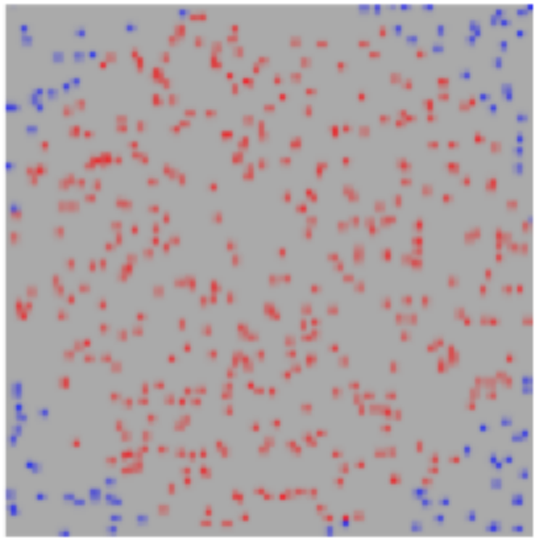
Huge trans-‘f’lanckian excursion is necessary
in terms of the fundamental unit f

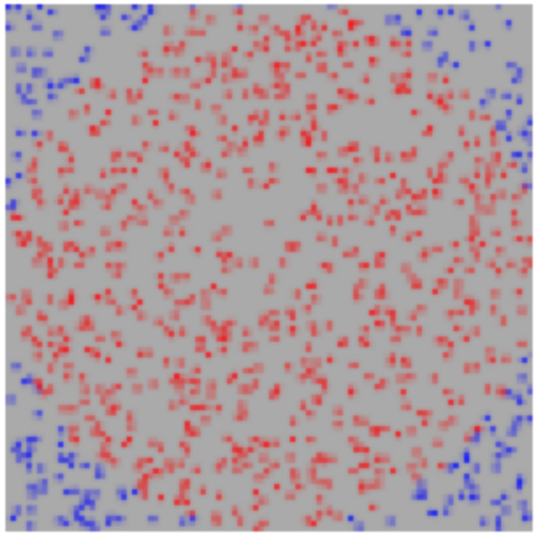
N-naturalness

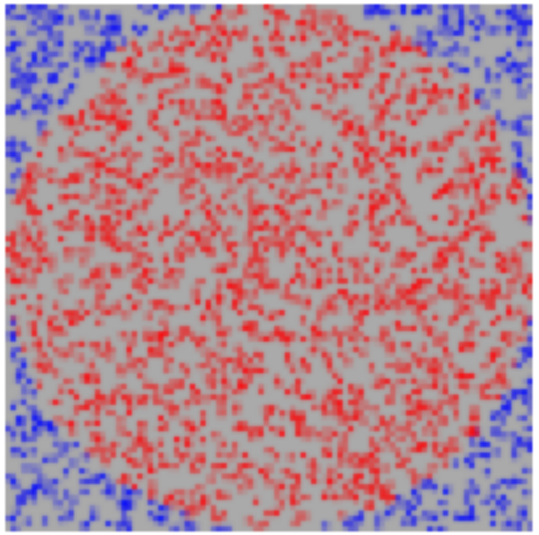
Nnaturalness

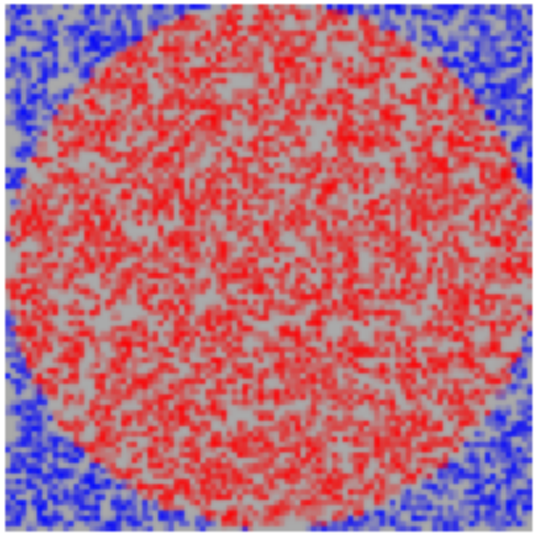
Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)











Dvali Redi PRD(2009)

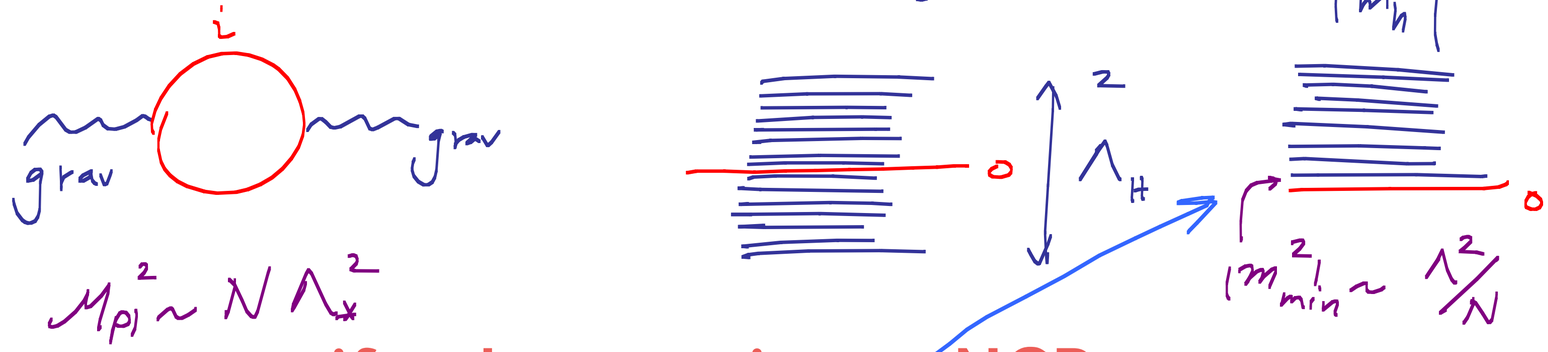
Arkani-Hamed Cohen D'agnolo
Hook HDK Pinner, PRL (2016)

$N = 10^{32}$

$\Lambda_* = 100$ GeV

$\sqrt{}$ copies of (MS) SM

enormous reduction of dof



if reheaton is a pNGB

Cosmology Dominantly Reheats Bottom of Spectrum

scenario I

$N = 10^{16}$

$\Lambda_* = \Lambda_H = 10^{10}$ GeV

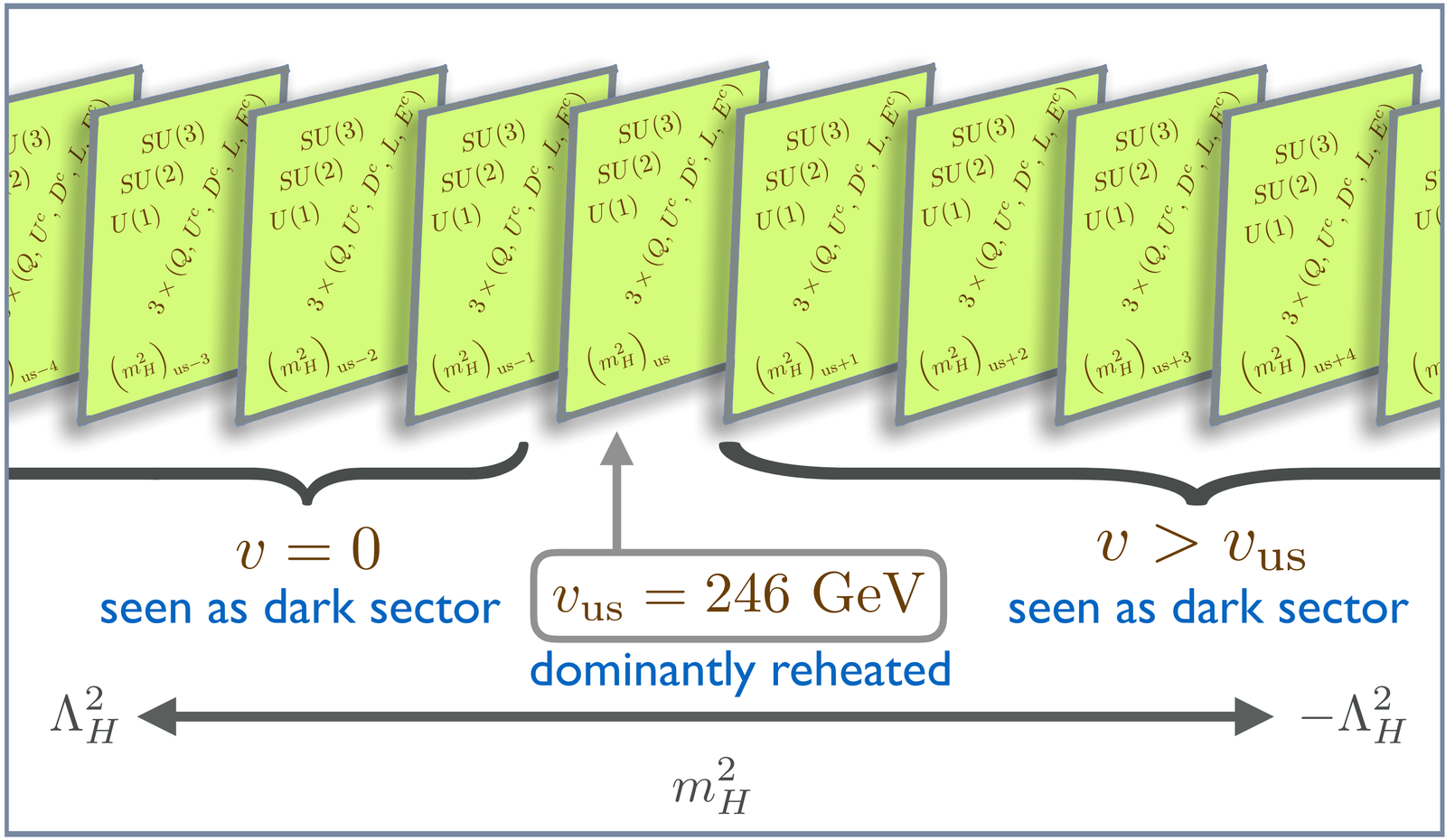
scenario II

$N = 10^4$

$\Lambda_* = 10^{16}$ GeV

$\Lambda_H = 10$ TeV

by N Arkani-Hamed



$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right), \qquad -\frac{N}{2} \le i \le \frac{N}{2}$$

Arkani-Hamed Cohen D'agnolo
Hook HDK Pinner, PRL (2016)

Arkani-Hamed Cohen D'agnolo
Hook HDK Pinner, PRL (2016)

scalar reheat

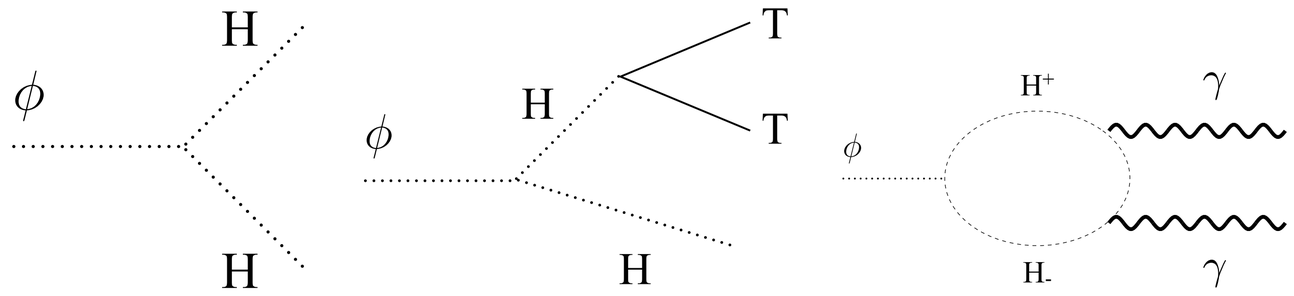
$A\phi H^\dagger H$

fermion reheat

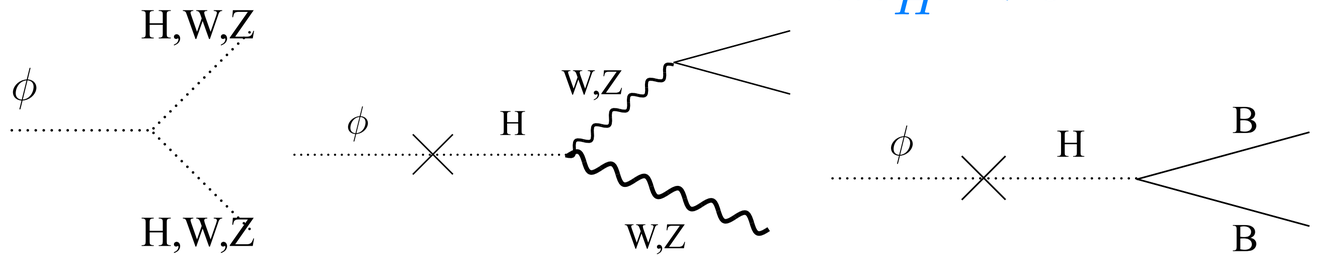
$\lambda S L H$

population of the sectors

$m_H^2 > 0$



$m_H^2 < 0$



collider pheno

$m_\phi \sim 100$ GeV

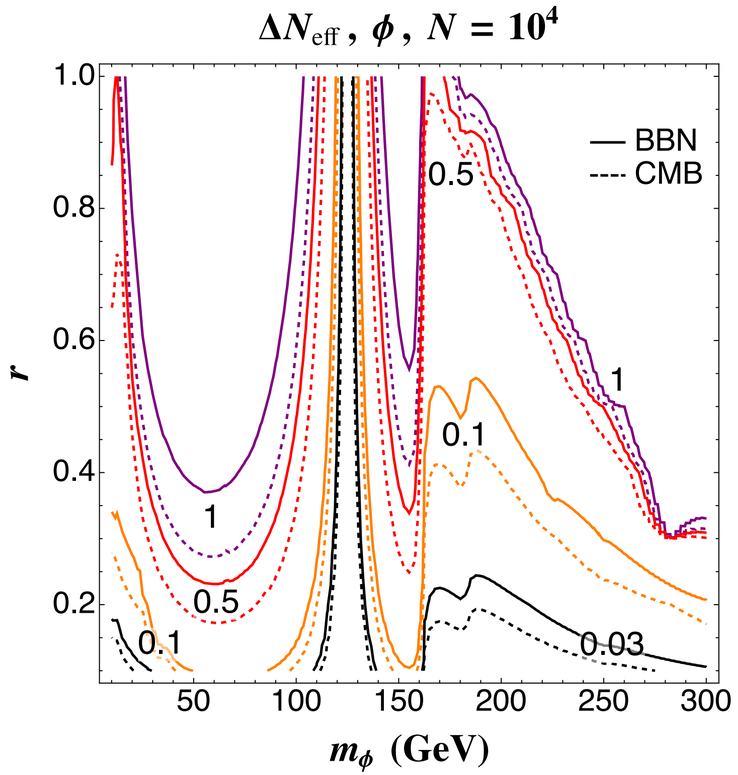
$A \ll$ MeV

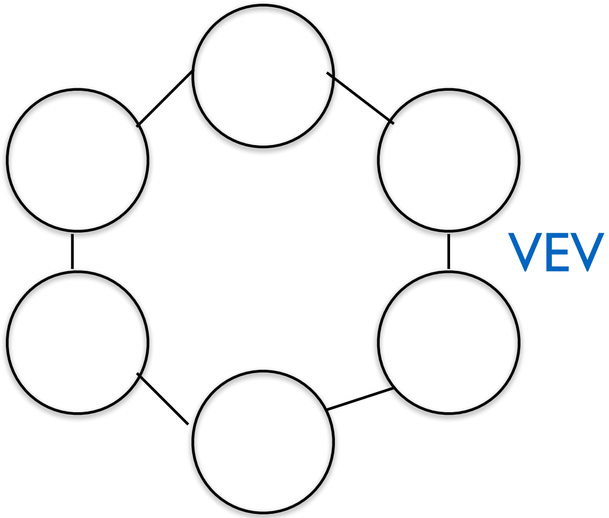
$\theta_{h\phi} < 10^{-6}$

$$\mathcal{L}_\phi^{\langle H\rangle\neq 0} \supset \mathcal{C}_1^\phi \, a \, y_q \frac{v}{m_h^2} \phi \, q \, q^c \, ;$$

$$\mathcal{L}_\phi^{\langle H\rangle= 0} \supset \mathcal{C}_3^\phi \, a \, \frac{g^2}{16\,\pi^2} \frac{1}{m_H^2} \, \phi \, W_{\mu\nu} W^{\mu\nu} \, ,$$

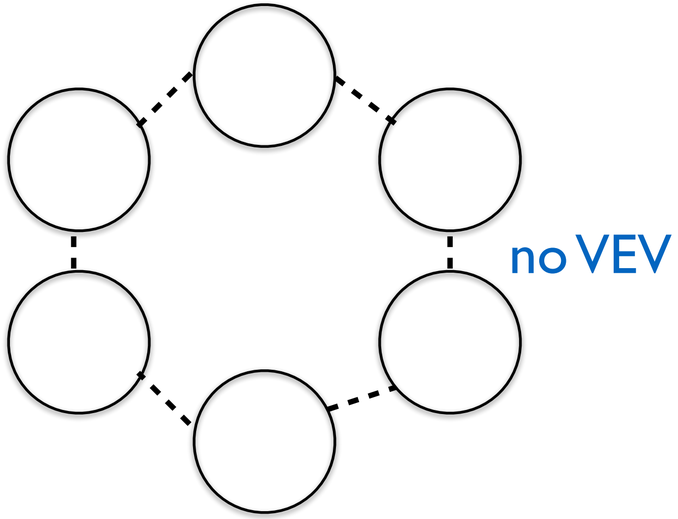
different phase of deconstruction





phase A : extra dimension

phase B : Nnaturalness



Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

dark radiation $4.4 + 3 = 7.4$

photon neutrino

Br(i=2)~ 0.1

generic prediction $\Delta N_{\rm eff} \sim \mathcal{O}(1)$

Weak scale as a trigger

Weak scale as a trigger

Arkani-Hamed, D'agnolo, HDK (2021)

Weak scale

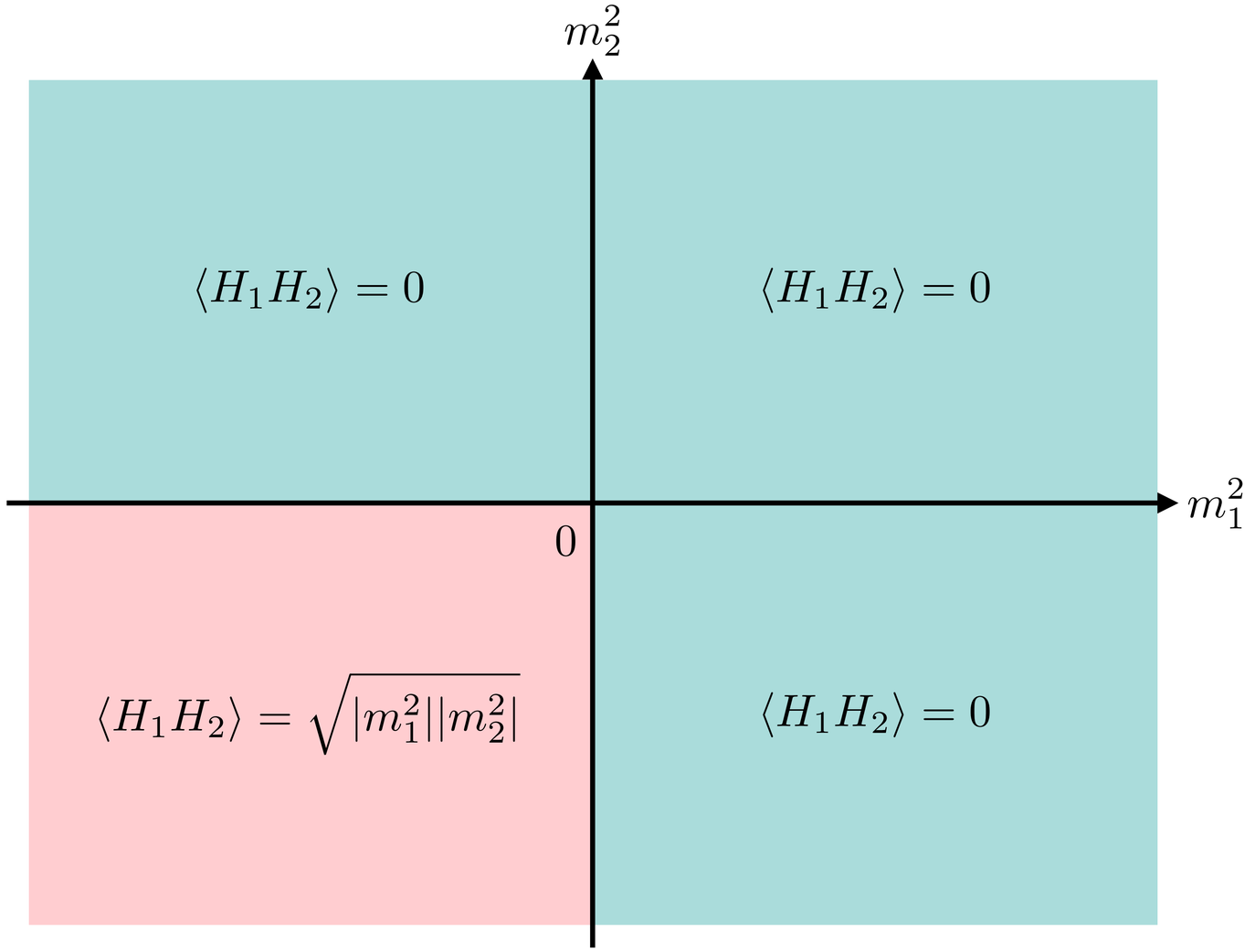
Cosmological constant

Higgs VEV can trigger the scanning of the cosmological constant

$\mathcal{O}_H = H_1 H_2$ 2HDM

Values of μ^2 in the landscape (classical)

(quartic couplings are taken to be order one)



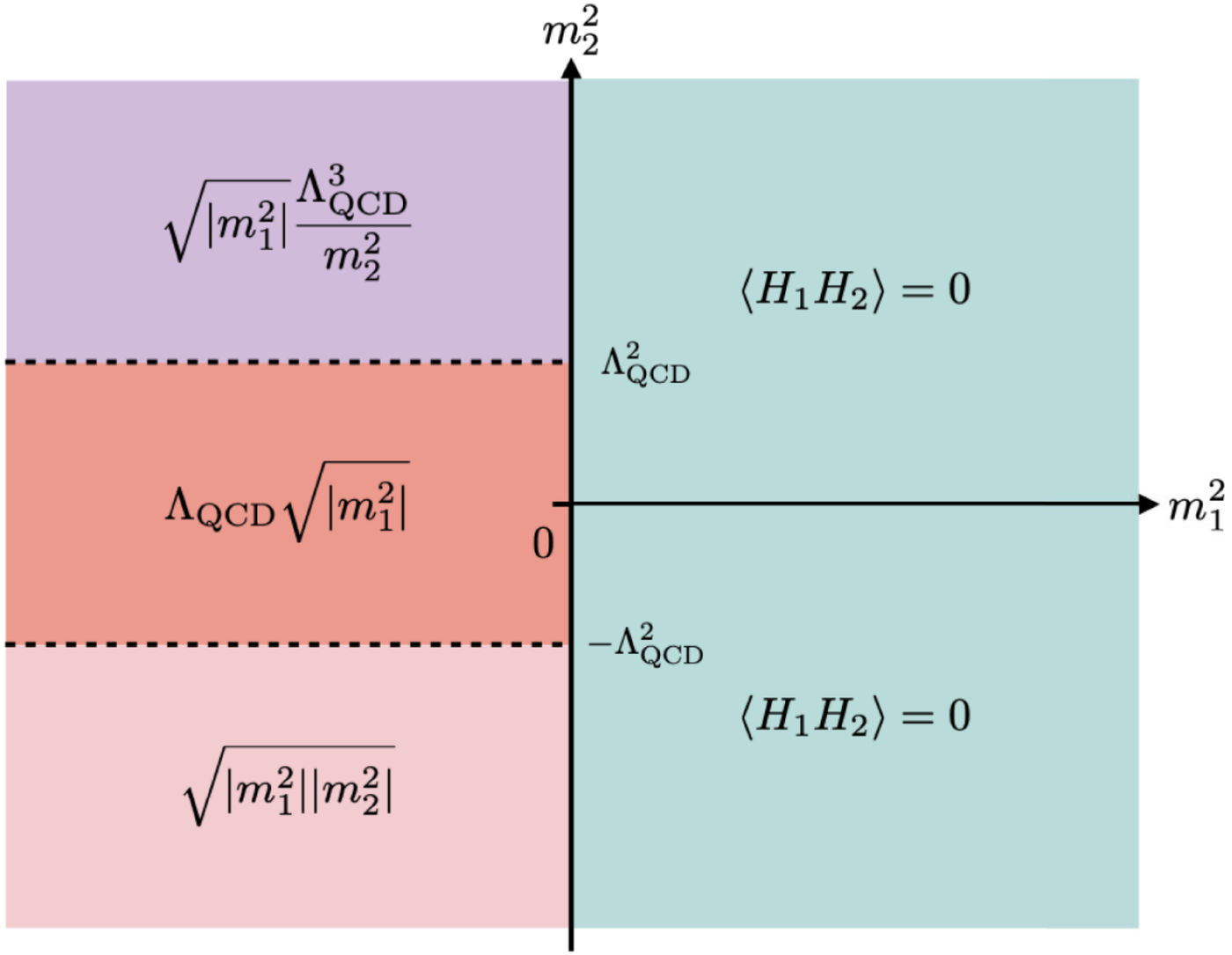
Values of μ^2 in the landscape (quantum)

$V = \Lambda_{\rm QCD}^3 h_2^0 + m_{H_2}^2 (h_2^0)^2 + \lambda (h_2^0)^4$ (quartic couplings are taken to be order one)

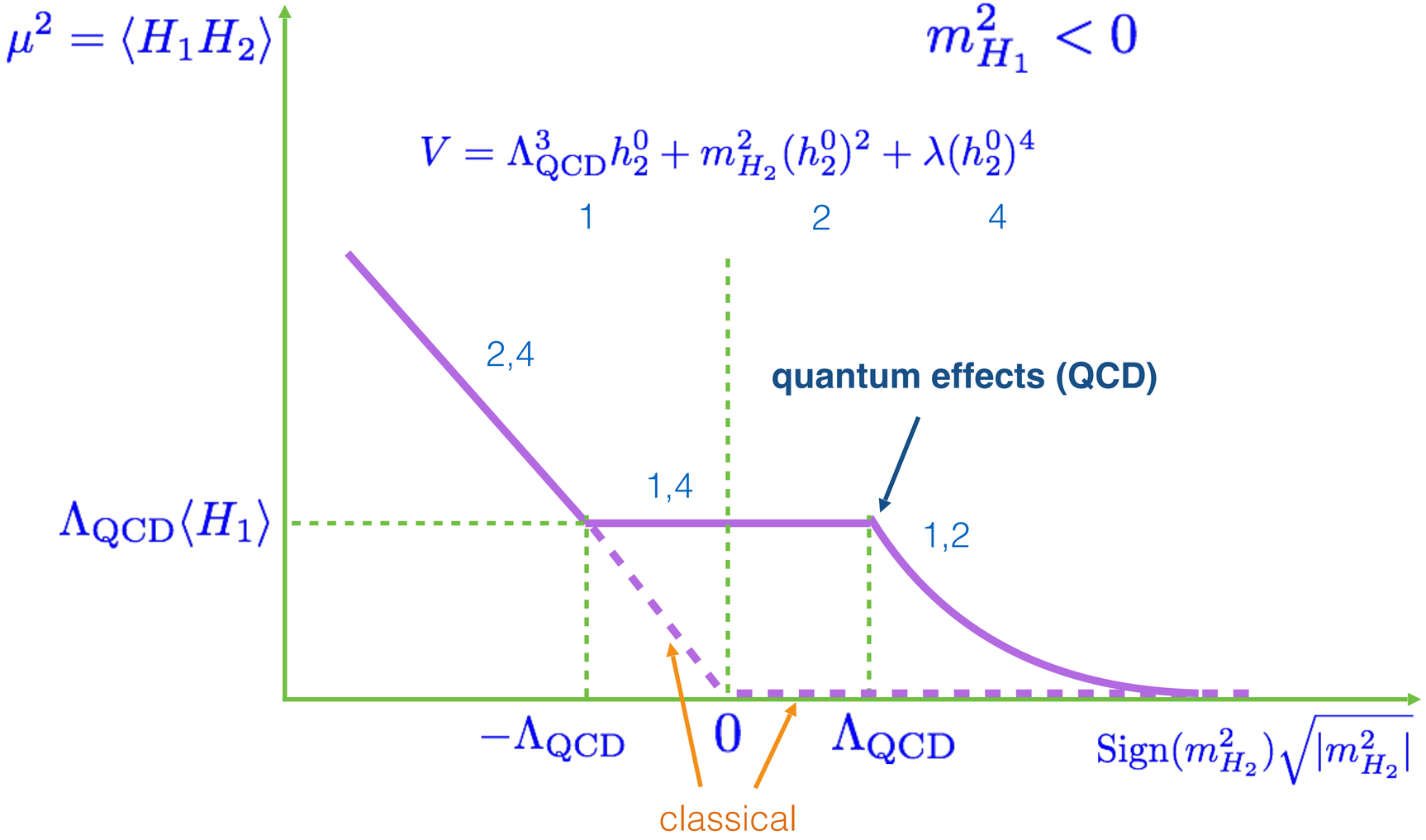
$h_2^0 \sim \dfrac{\Lambda_{\rm QCD}^3}{m_{H_2}^2}$

$m_{H_2} \sim \Lambda_{\rm QCD}$

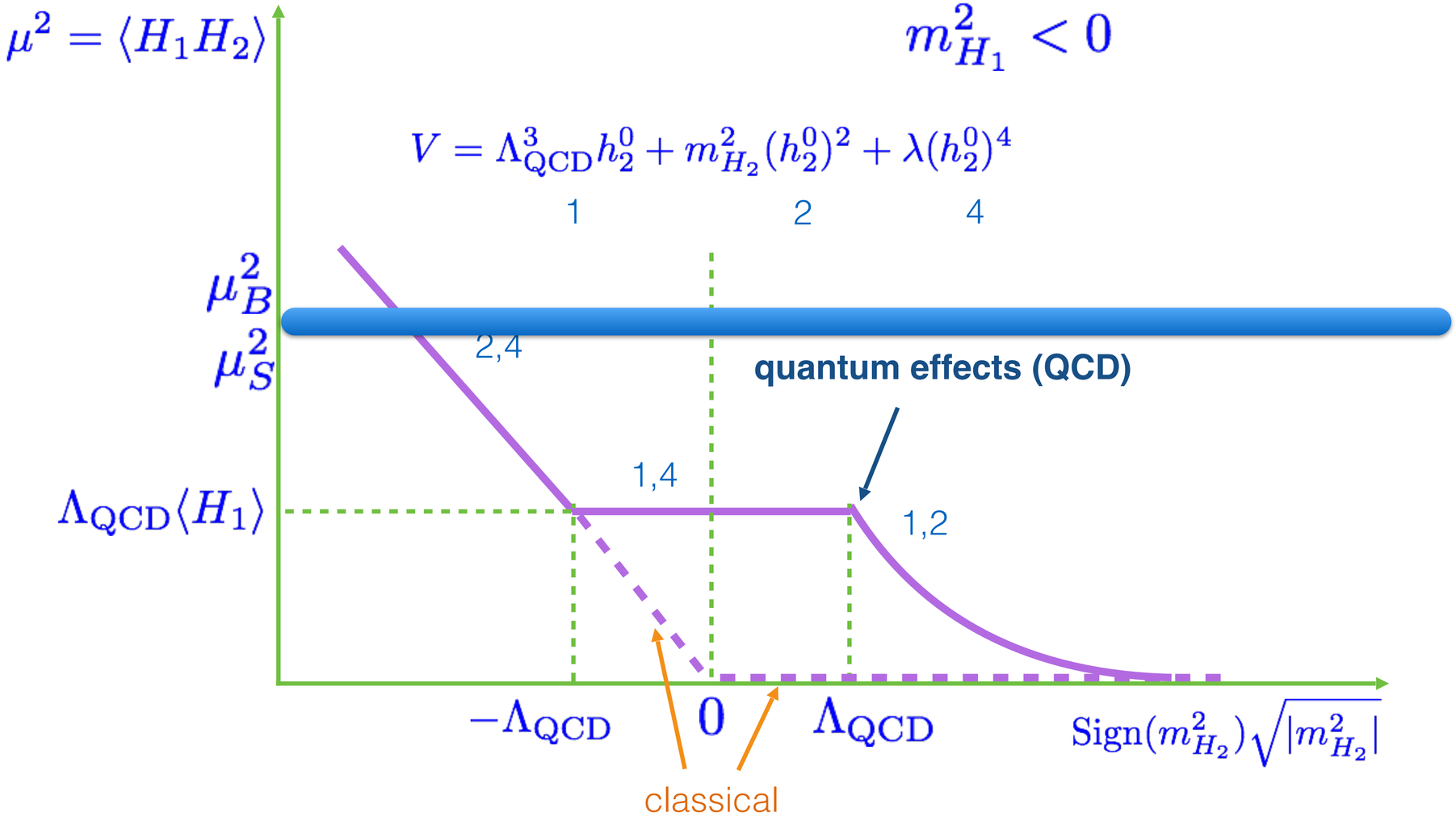
$h_2^0 \sim \dfrac{\Lambda_{\rm QCD}}{\lambda^{1/3}}$



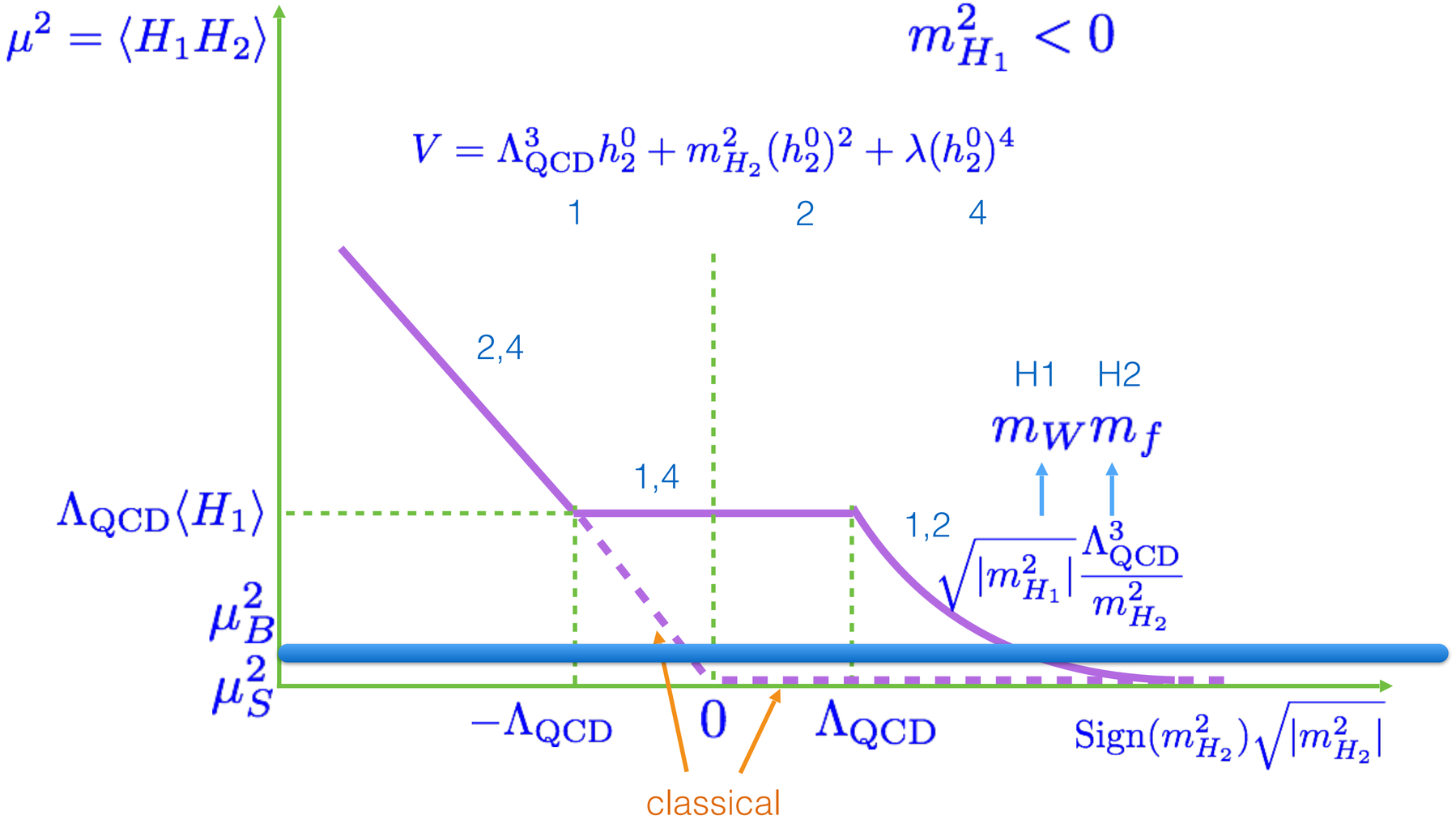
Triggering parameter



Universe including ours



Strange universe with $\Lambda \sim (\frac{v}{\Lambda_H})^4 \Lambda_{\rm us}$ for the atom formation



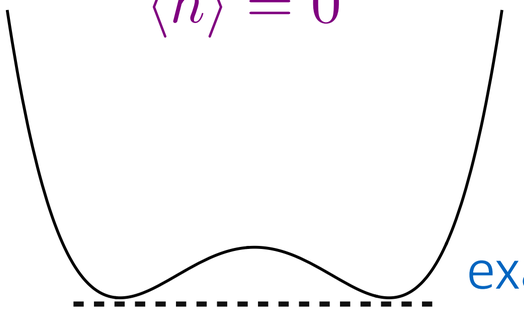
HE Landscape

+

LE Landscape degeneracy

$\mu = 0$

$\langle h \rangle = 0$

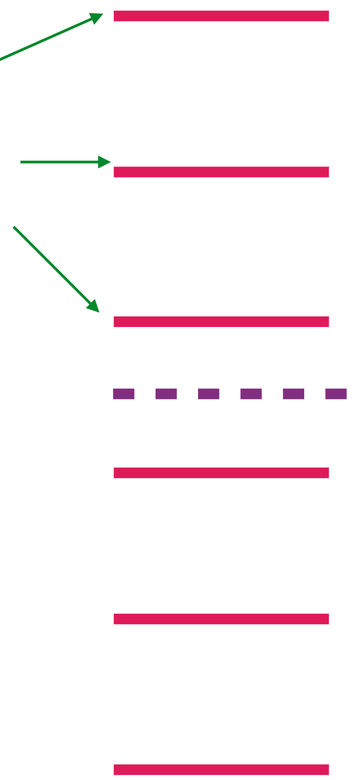


exact degeneracy

$\langle h \rangle = 0$

2^{n_ϕ}

degeneracy



Possible cc

in the landscape

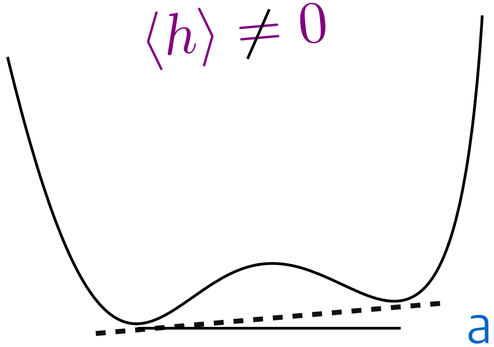
HE Landscape

+

LE Landscape degeneracy lifted

$\mu \leq \mu_S$

$\langle h \rangle \neq 0$



approximate degeneracy

$\langle h \rangle < \mu_S$

2^{n_ϕ} degeneracy

HE Landscape

+

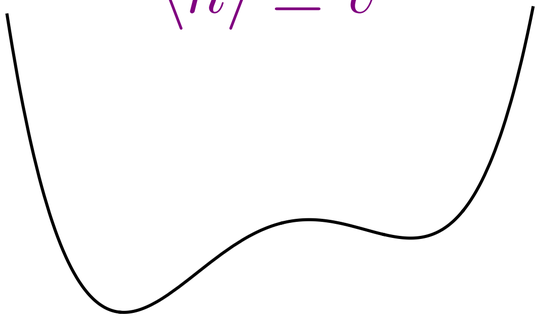
LE Landscape degeneracy lifted

fill up the gap of the HE landscape

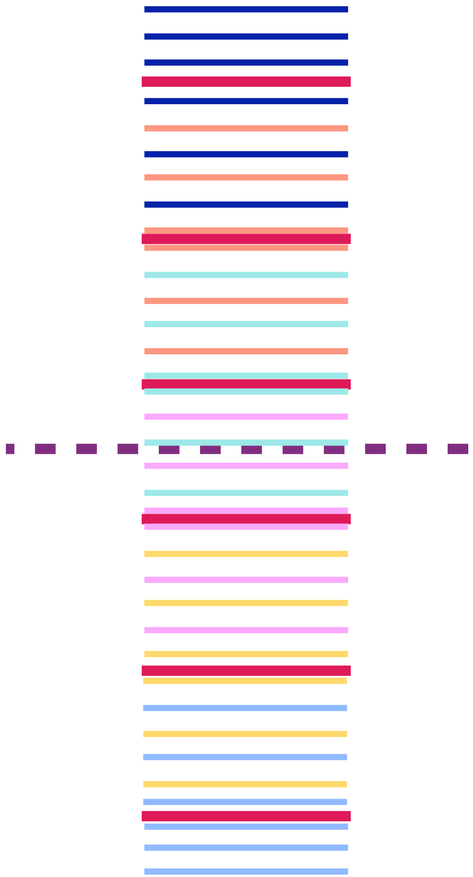
no distinction between HE and LE landscape

$$\mu_S \leq \mu \leq \mu_B$$

$$\langle h \rangle \simeq v$$



$$\mu_S \lesssim \langle h \rangle \lesssim \mu_B$$



HE Landscape

+

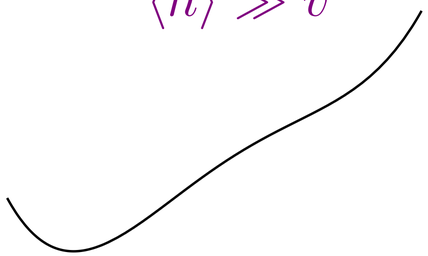
LE Landscape degeneracy lifted

$\langle h \rangle \gg \mu_B$

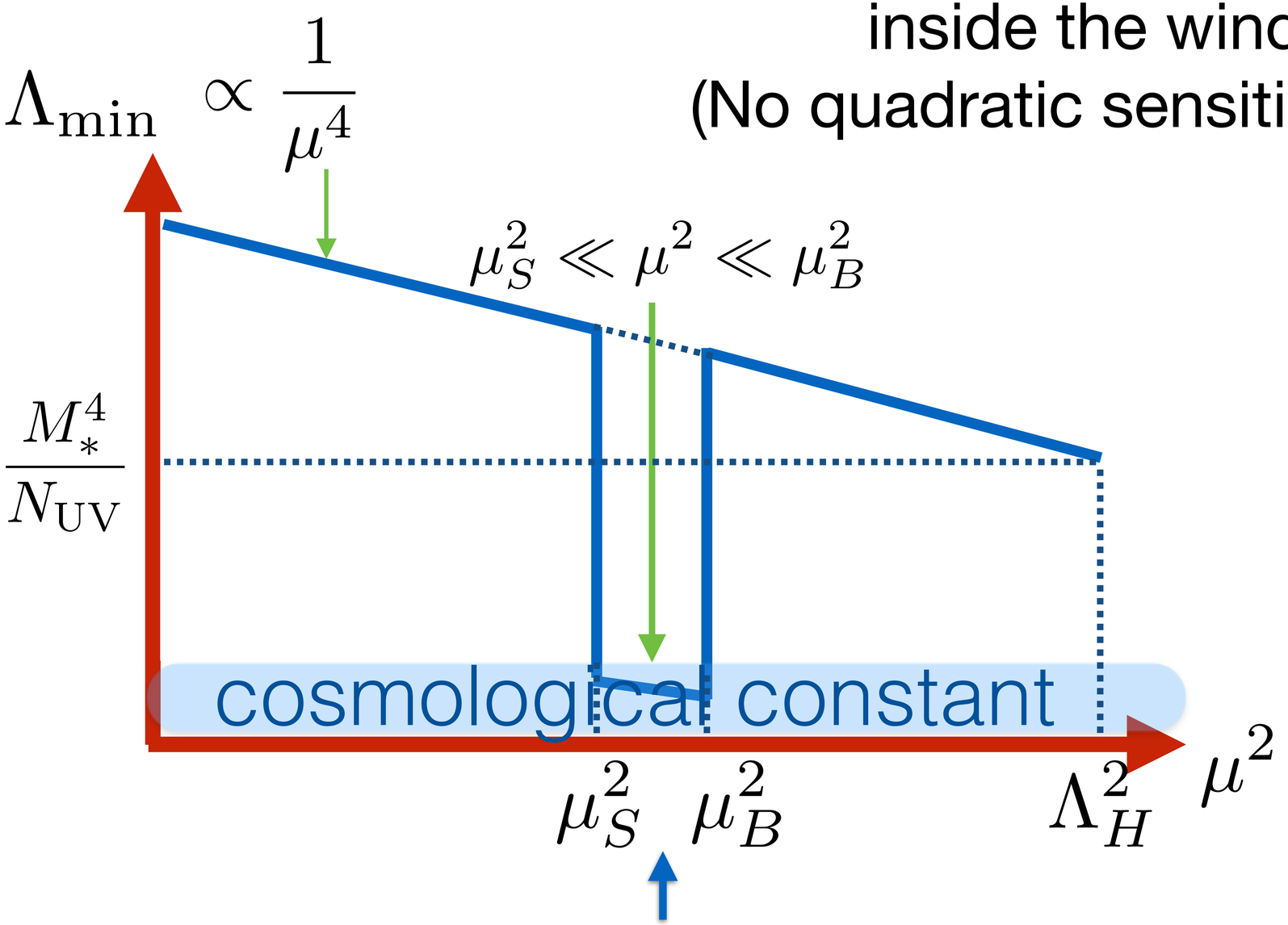
$\mu \geq \mu_B$

no degeneracy

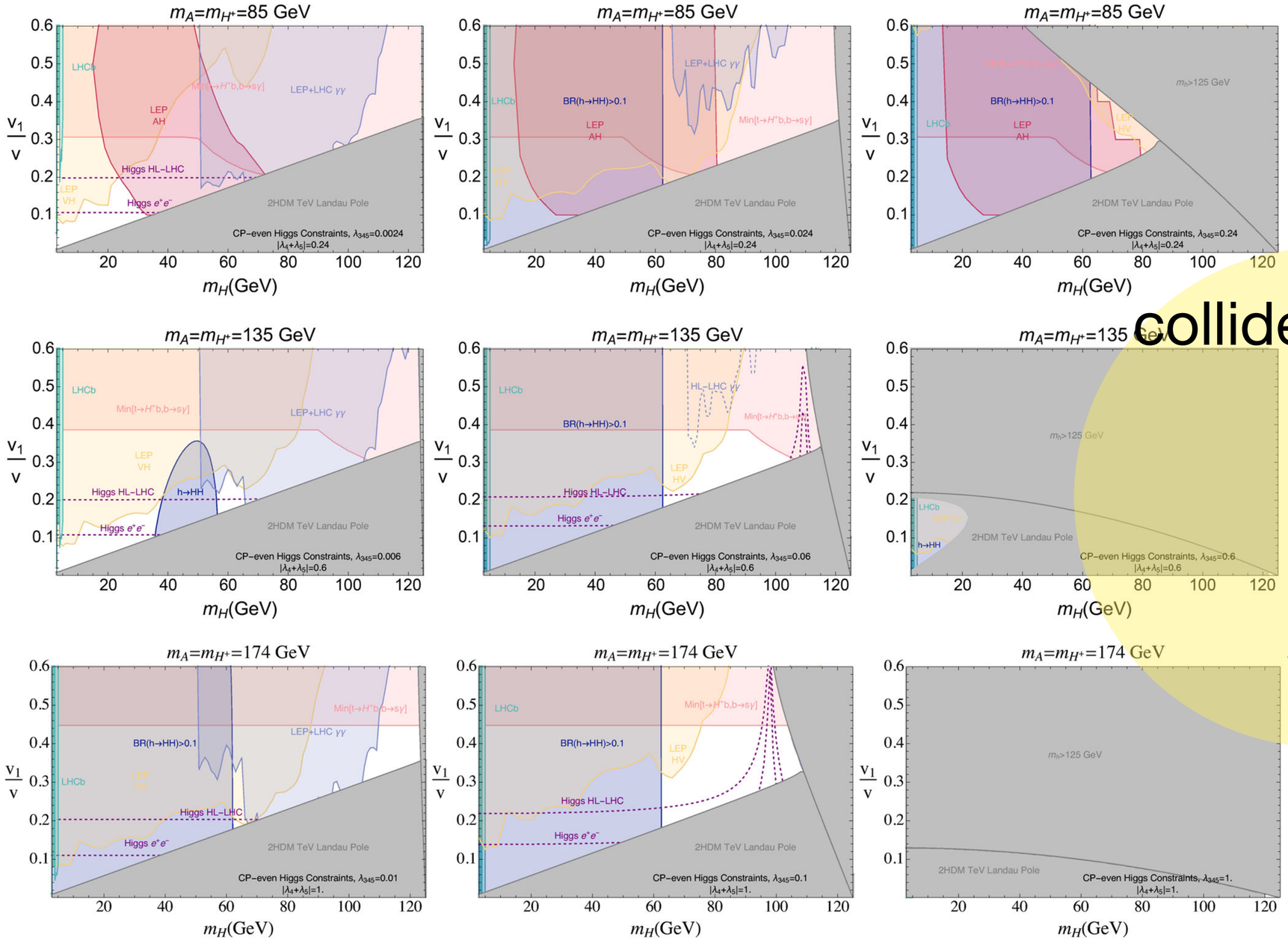
$\langle h \rangle \gg v$



Weak scale have a flat distribution
inside the windows
(No quadratic sensitivity on UV)



Higgs mass



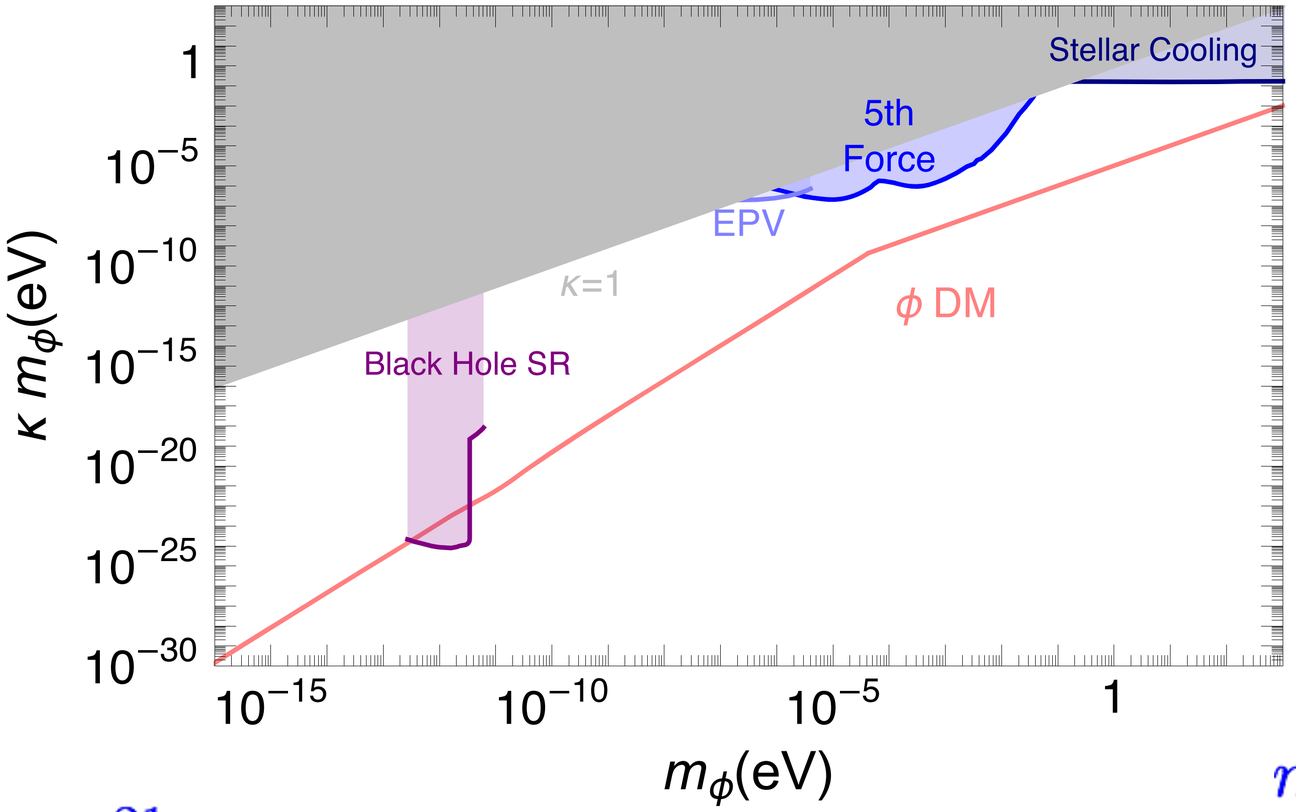
collider pheno

$$\frac{v_1}{v} \sim 0.2$$

$$m_H \sim M_Z$$

$$m_{H^+} \sim m_t$$

Light Scalar Dark Matter
(Wave Dark Matter)



collider pheno

$10^{-21}\ \mathrm{eV} < m_\phi < 1\ \mathrm{keV}$

$10^{-30}\ \mathrm{eV} < \kappa m_\phi < 10^{-5}\ \mathrm{eV}$

$\kappa m_\phi \phi H_u H_d$

$m_\phi \geq 10^{-21}\mathrm{eV}$

Astrophysical constraints on fuzzy dark matter

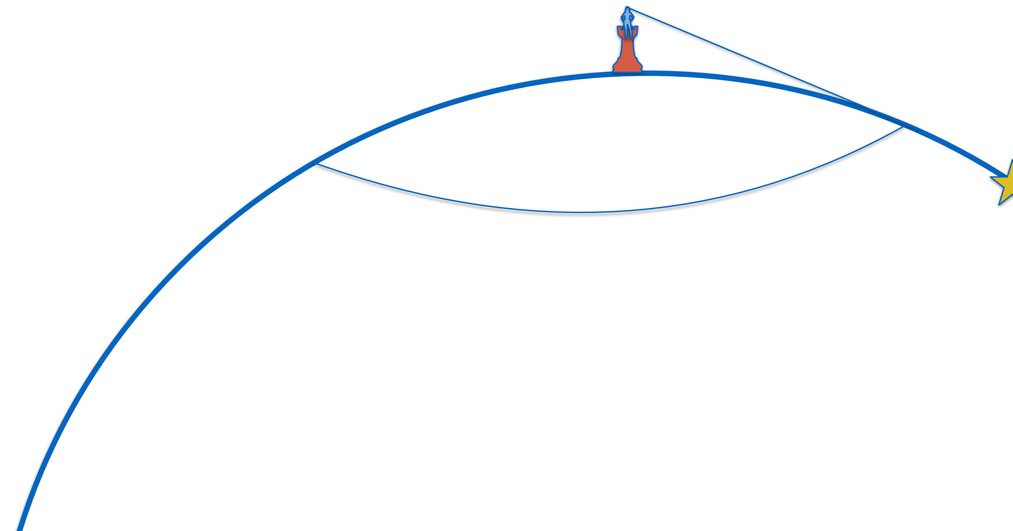
$m_\phi \leq 1\mathrm{keV}$

$M_* \leq 10\mathrm{TeV}$

Where is new physics?

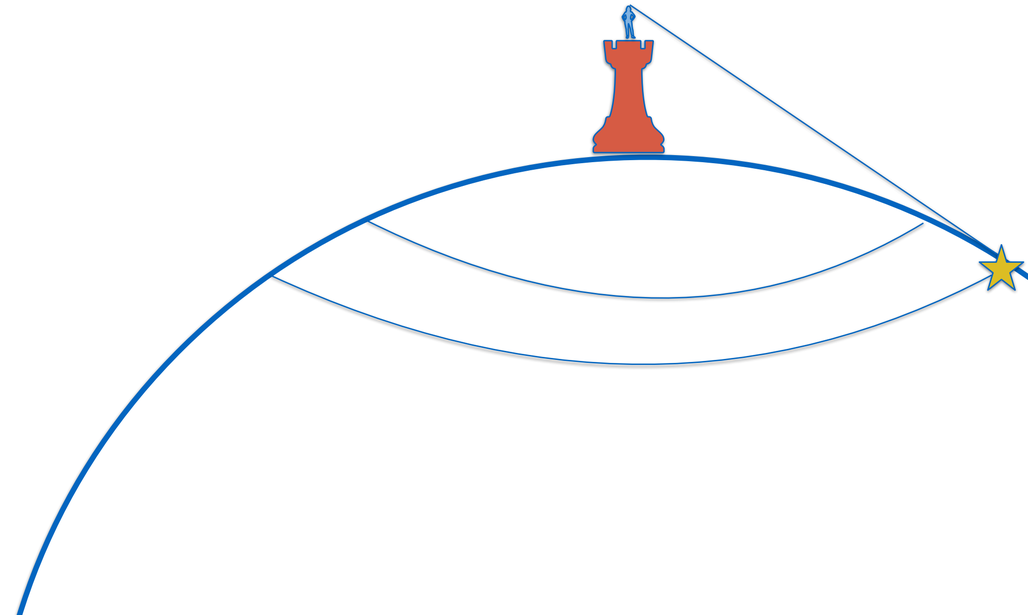
My belief on new physics

- Weak scale supersymmetry at multi-TeV (suggested by Higgs mass)
- It is beyond the horizon we can see now and we need a taller tower to extend the horizon

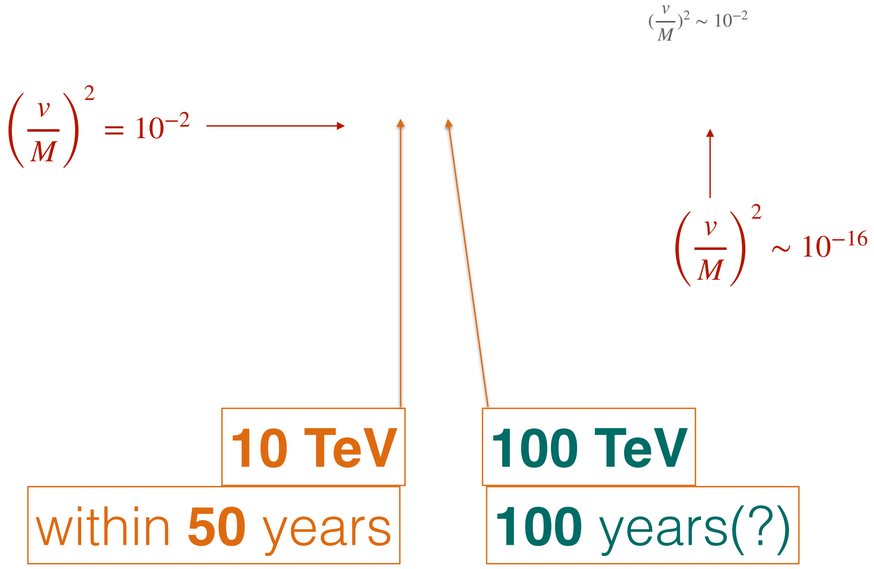


My belief on new physics

- Weak scale supersymmetry at multi-TeV (suggested by Higgs mass)
- Tall tower? bending light? mirror?



Giudice Strumia (2011)



too long compared to physicist lifetime

How small is small?

Charge quantization for $|Q_{\rm atom}| \leq 10^{-20}e$ $\longrightarrow$ $Q_{\rm atom} = 0$,
GUT, monopole, …

$m_\gamma < 10^{-18}$ eV from MHD of solar wind $\longrightarrow$ $m_\gamma = 0$

Kepler's model

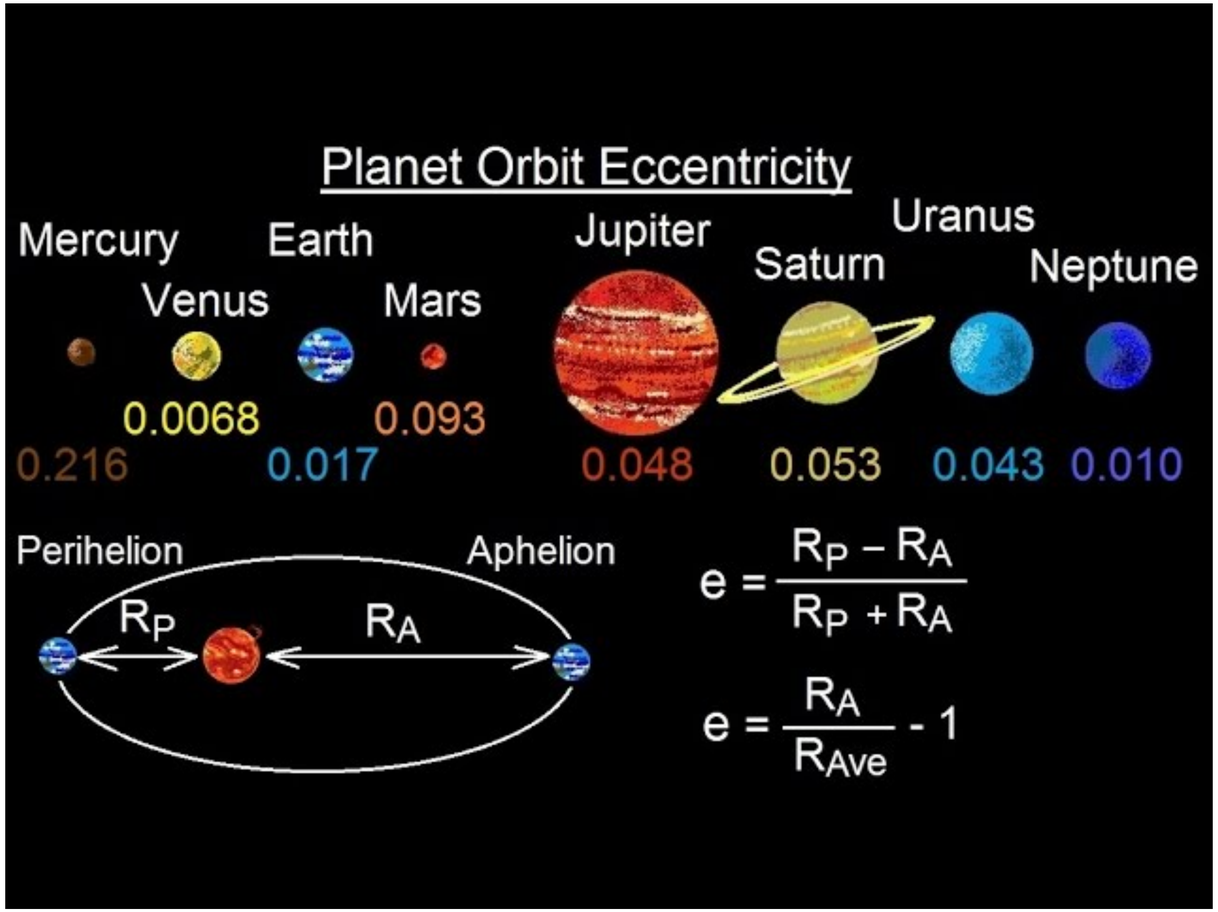
Solar Orbit Eccentricity

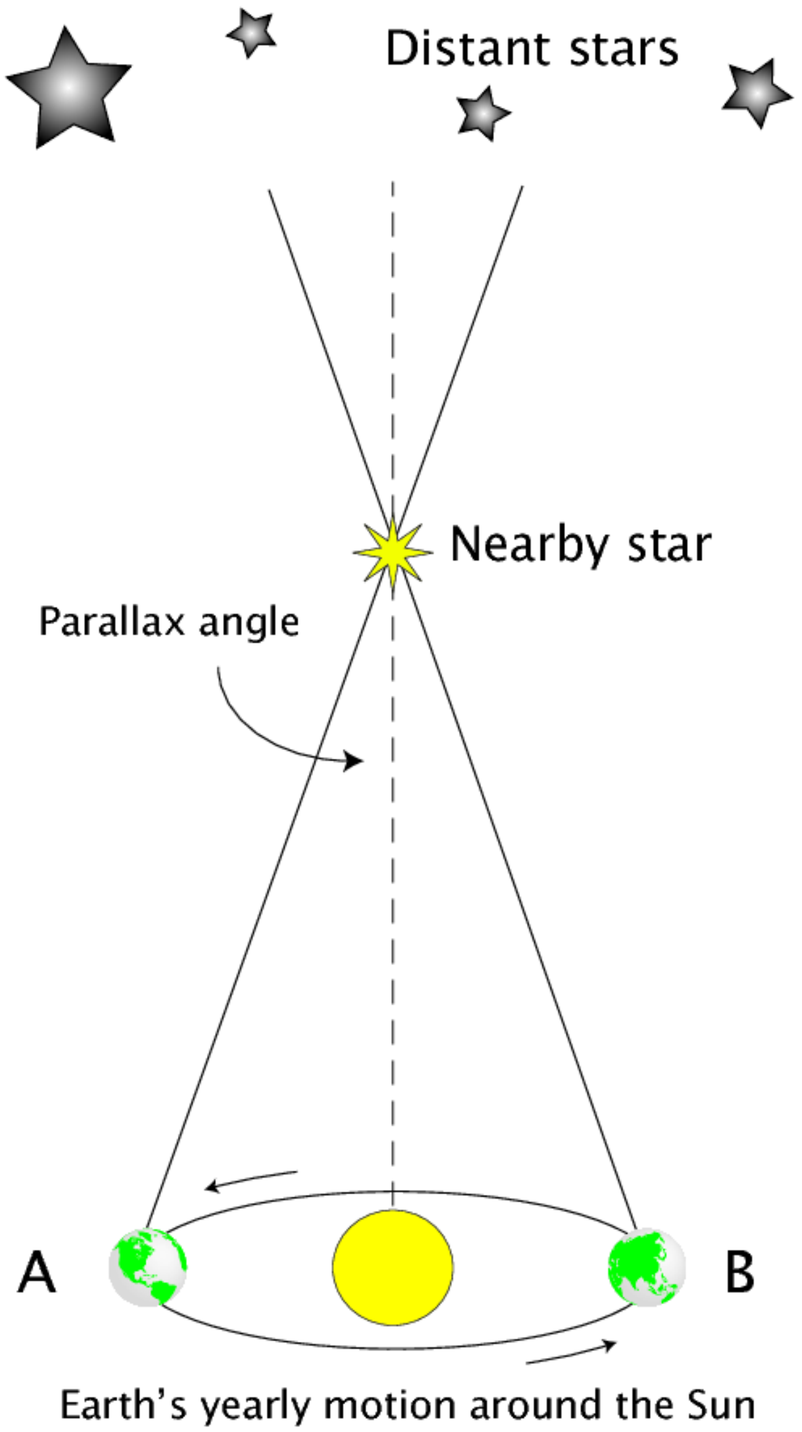
Kepler's law

$$\epsilon = 0$$

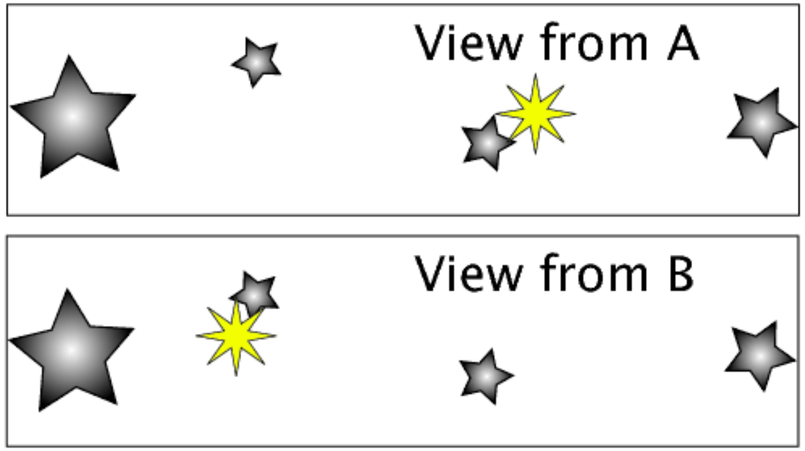
$$\frac{1}{10} \sim \frac{1}{100} \ll 1$$

$$\epsilon \neq 0$$





Proxima Centauri
4.22 lyr
270,000 AU



Is there a certain criterion to believe it is zero?

Geocentrism	Kepler model	-1997	1/1000 without DM
$\frac{\text{D to the first nearest star}}{\text{D to the second nearest star}}$	eccentricity	cosmological constant	density perturbation
$\frac{1}{10^5}$	$\frac{1}{10}$	$\frac{1}{10^{120}}$	$\frac{1}{10^5}$

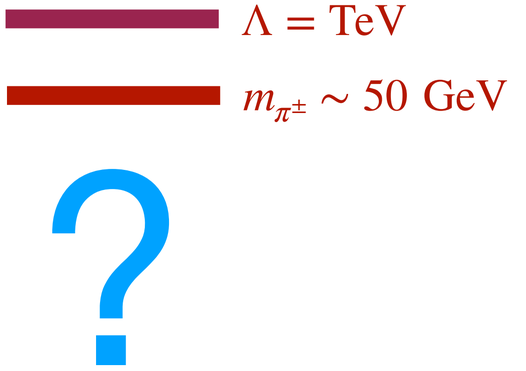
All small numbers are related to the observer.
(Anthropic principle)

Where is new physics?

Absence of new physics below TeV might be due to anthropic principle.

Toy World

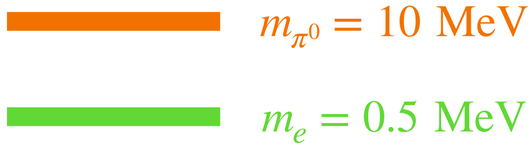
e+e- and pion at MeV
QCD at TeV



Suppose we build colliders at the pion mass

$$e^+e^- \to \pi^0 \to \gamma\gamma$$

$$m_{\pi^\pm}^2 - m_{\pi_0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$$



What can we know from physics at the pion mass?

Lesson from X750

Diphoton excess from Dec. 2015

ECFA Linear Collider Workshop, June 2016, Santander, Spain

People started to discuss photon collider at 750 GeV

Copious production of pions?

Be humble!

Don’t give up!

Axion…

Monopole…

Thank you