Physics of the weak scale trigger

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Editors' Suggestion   Featured in Physics

Weak scale as a trigger

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Does the value of the Higgs mass parameter affect the expectation value of local operators in the Standard Model? For essentially all local operators the answer to this question is "no", and this is one of the avatars of the hierarchy problem: Nothing is "triggered" when the Higgs mass parameter crosses zero. In this article, we explore settings in which Higgs mass parameters *can* act as a "trigger" for some local operators $\mathcal{O}_T$. In the Standard Model, this happens for $\mathcal{O}_T = \mathrm{Tr}(G\tilde{G})$. We also introduce a "type-0" two Higgs doublet model, with a Z_4 symmetry, for which $\mathcal{O}_T = H_1 H_2$ is triggered by the Higgs masses, demanding the existence of new Higgs states necessarily comparable to or lighter than the weak scale, with no wiggle room to decouple them whatsoever. Surprisingly, this model is not yet entirely excluded by collider searches, and will be incisively probed by the high-luminosity run of the LHC, as well as future Higgs factories. We also discuss a possibility for using this trigger to explain the origin of the weak scale, invoking a landscape of extremely light, weakly interacting scalars ϕ_i, with a coupling to $\mathcal{O}_T$ needed to make it possible to find vacua with small enough cosmological constant. The weak scale trigger links the tuning of the Higgs mass to that of the cosmological constant, while coherent oscillations of the ϕ_i can constitute dark matter.

Domain wall physics
phi physics
(super radiance)
quadratic vs logarithmic

Type0 2HDM

“Weak scale as a trigger”

PRD (2021)

Editor’s suggestion

Featured in Physics

Physics — VIEWPOINT

A Third Way to Explain Fine Tuning

A theoretical proposal offers a new way to relate the Higgs boson mass and the cosmological constant to each other and explain why these quantities appear to be implausibly tuned to values much smaller than expected.

By Francesco Riva

What do the Higgs mass and Earth’s orbit ellipticity have in common? Both have values that are orders of magnitude smaller than theoretical estimates would suggest. These quantities appear to result from an extremely fine-tuned cancellation of two much larger quantities—a fact that many physicists find implausible (Fig. **1**). These and other “fine tunings,” however, might only be apparent, and their explanation may hold the key for paradigmatic changes in our understanding of nature. Particle physics features two of the most intriguing fine-tuning puzzles: the Higgs boson mass and the cosmological constant.

Figure 1: Certain physical parameters appear implausibly “fine tuned” to produce the Universe as we know it. Arkani-Hamed and co-workers have proposed a new approach for explaining the fine tuning of two such parameters—the Higgs mass and the cosmological constant.
Credit: Gevorg/stock.adobe.com

For a long time, the lore had it that these particle-physics tunings may be related to new symmetries, such as the elusive supersymmetry, or to statistical arguments—our fine-tuned Universe is just one of many possible multiverses. In recent years, however, new possible explanations have emerged [**1**–**5**], culminating in a new proposal by Nima Arkani-Hamed of the Institute for Advanced Study, New Jersey, Raffaele Tito D’Agnolo of the University of Paris-Saclay, and Hyung Do Kim of Seoul National University [**6**]. The trio identified a new class of mechanisms for producing fine tunings, in which only specific values of the Higgs mass can “trigger” the formation of multiverses. The appeal of their model is that it makes testable predictions—the existence of new, potentially observable Higgs particles.

To understand fine tuning, consider a measurable quantity that could be theoretically computed were it not for the fact that the necessary information is partially unavailable. Take, for example, the electric field near a charged conducting surface of which we can observe only a small region (Fig. **2**). The field can be computed from the known charges in this region but may be affected by other, unknown charges. The observed value will be the sum of a known and unknown contribution. An observed value close to that derived from the known contribution would indicate that the unknown contribution isn’t significant, and the difference may have a trivial explanation, such as some unaccounted-for difference in the conductor’s geometry.

But if the observed value is much smaller than that expected from the known contribution, it means that the known and unknown parts almost exactly cancel out. Often, this fine tuning reveals something new about the system. For instance, the

Universe is just one of many possible multiverses. In recent years, however, new possible explanations have emerged [**1**–**5**], culminating in a new proposal by Nima Arkani-Hamed of the Institute for Advanced Study, New Jersey, Raffaele Tito D'Agnolo of the University of Paris-Saclay, and Hyung Do Kim of Seoul National University [**6**]. The trio identified a new class of mechanisms for producing fine tunings, in which only specific values of the Higgs mass can "trigger" the formation of multiverses. The appeal of their model is that it makes testable predictions—the existence of new, potentially observable Higgs particles.

UV landscape $\Lambda_{\rm UV} = \frac{M_*^4}{\mathcal{N}_{\rm UV}} \sim v^4$

IR landscape $\Lambda_{\rm IR} = \frac{\Lambda_{\rm UV}}{\mathcal{N}_{\rm IR}} \sim \frac{v^8}{M_*^4}$

$$\mathcal{N}_{\rm IR} = 2^{n_\phi}$$

$$m_\phi \lesssim \frac{v^2}{M_*} \longrightarrow m_\phi^2 M_*^2 \sim v^4$$

Type 0 2HDM

Light scalar dark matter from EWPT

Question #1

What varies as we change the Higgs mass parameter in the SM?

Answer to Q#1

All the spectrum of the Standard Model including W and Z bosons,
quarks and leptons and the Higgs boson itself.

Question #2

Is there any gauge invariant local operator which has a value sensitive to the Higgs mass parameter?

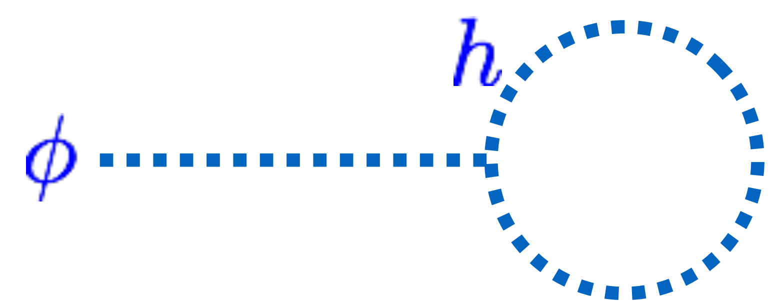
Answer to Q#2

$$\mathcal{O}_h = h^\dagger h$$

However, $\mathcal{O}_h$ is **not calculable** in the SM

Probing by $\xi \phi h^\dagger h$

1 loop tadpole is generated



$$\frac{1}{16\pi^2}\xi\phi\Lambda_H^2$$

Λ_H: cutoff of the Higgs loop

$\langle h^\dagger h \rangle$ is independent of m_h^2

depends on Λ_H^2 unless the cutoff is at the weak scale

Hierarchy Problem

making m_h^2 to be calculable

Closely related question

Is $\langle h^\dagger h \rangle$ calculable?

Two calculable examples

Supersymmetry

$$\langle h^\dagger h \rangle \sim m_{\rm SUSY}^2$$

Composite Higgs

$$\langle h^\dagger h \rangle \sim f_\pi^2$$

$$\mathcal{O}_G = \mathrm{tr} G\tilde{G}$$

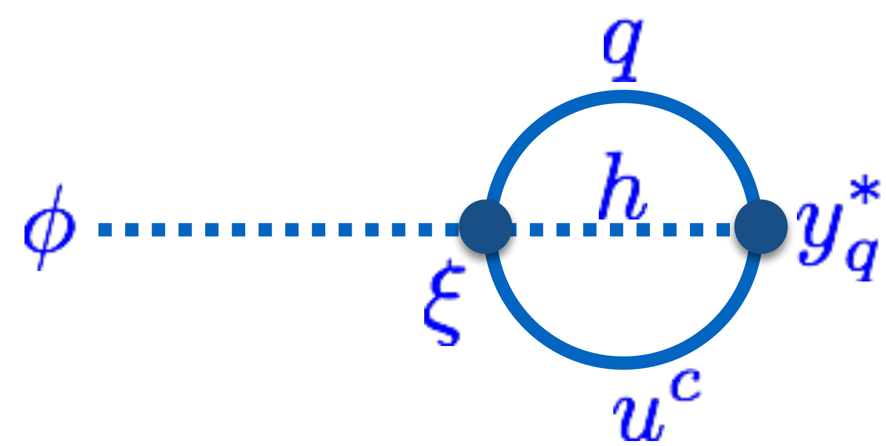
SM

Possible operators?

$$\mathcal{O}_q = q h u^c$$

ϕ : dimensionless $\longrightarrow (\frac{\phi}{M_*})$

$$y_q \mathcal{O}_q + \xi \phi \mathcal{O}_q + \mathrm{h.c.} \longrightarrow \frac{\xi y_q^*}{(16\pi^2)^2} \phi \Lambda^4$$



Massless up quark provides the operator $\mathcal{O}_u = q h u^c$

one of the solutions to the strong CP problem but is not viable any longer

$$\boxed{\mathcal{O}_G = \mathrm{tr} G\tilde{G}}$$

$$\mathcal{O}_G = \partial_\mu K^\mu$$

$$\langle G\tilde{G}\rangle \sim \theta \boxed{(m_u + m_d)\Lambda^3_{\mathrm{QCD}}}$$

depends on the weak scale and is insensitive to UV

size is too small $\longrightarrow$ $\Lambda_* \sim (100\ \mathrm{keV})^4$ strong CP

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

2HDM

Weak scale as a trigger

Type 0 2HDM → $B\mu$ is forbidden

We need a symmetry under which the operator is charged
Otherwise, the operator is UV sensitive (e.g., Yukawa term)

$$\phi \to -\phi$$
$$H_1 H_2 \to -H_1 H_2$$

↓

Z_4 symmetry

$$H_1 \to +ie^{i\alpha} H_1, \qquad H_2 \to +ie^{-i\alpha} H_2,$$

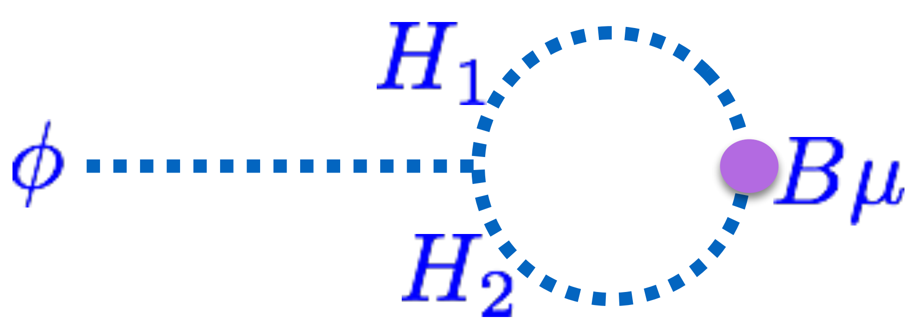
alpha in U(1)_Y

$$(H_1 H_2) \to -(H_1 H_2),$$
$$(qu^c) \to -ie^{i\alpha}(qu^c), \qquad (qd^c) \to +ie^{-i\alpha}(qd^c),$$
$$(le^c) \to +ie^{-i\alpha}(le^c).$$

$$V_Y = Y_u q H_2 u^c + Y_d q H_2^\dagger d^c + Y_e l H_2^\dagger e^c.$$

$$V_{H_1 H_2} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 H_2|^2 + \left(\frac{\lambda_5}{2}(H_1 H_2)^2 + \text{H.c.}\right),$$

Peccei-Quinn symmetry is explicitly broken



$$\frac{1}{16\pi^2}\xi \phi B\mu^* \log \frac{\Lambda_H^2}{|m_{H_{1,2}}^2|}$$

$B\mu$ generates tadpole and should be forbidden

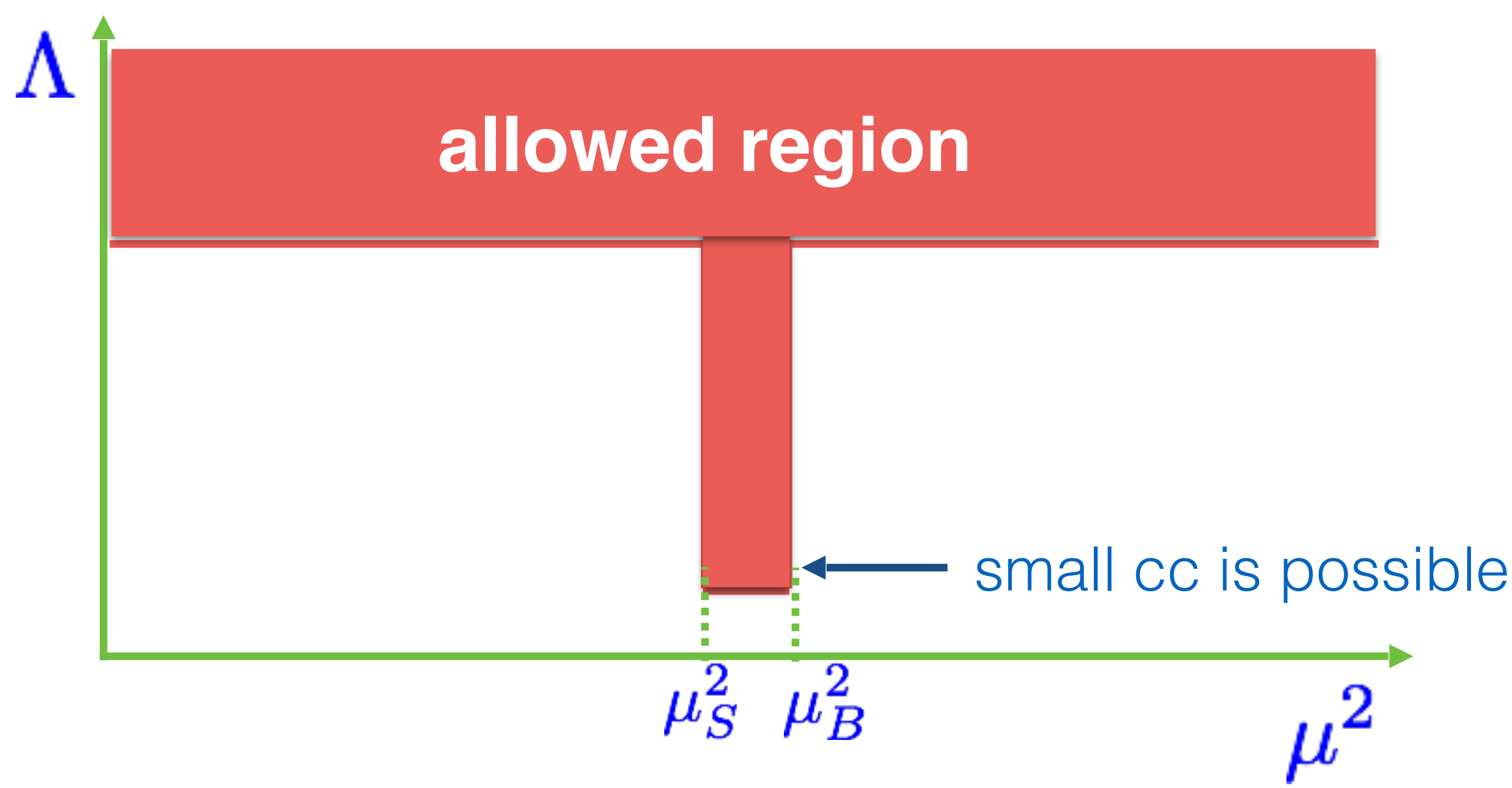
or should be small enough not to spoil the mechanism

Weak scale as a trigger

$$\mu^2 \equiv \langle \mathcal{O}_H \rangle \equiv \langle H_1 H_2 \rangle$$

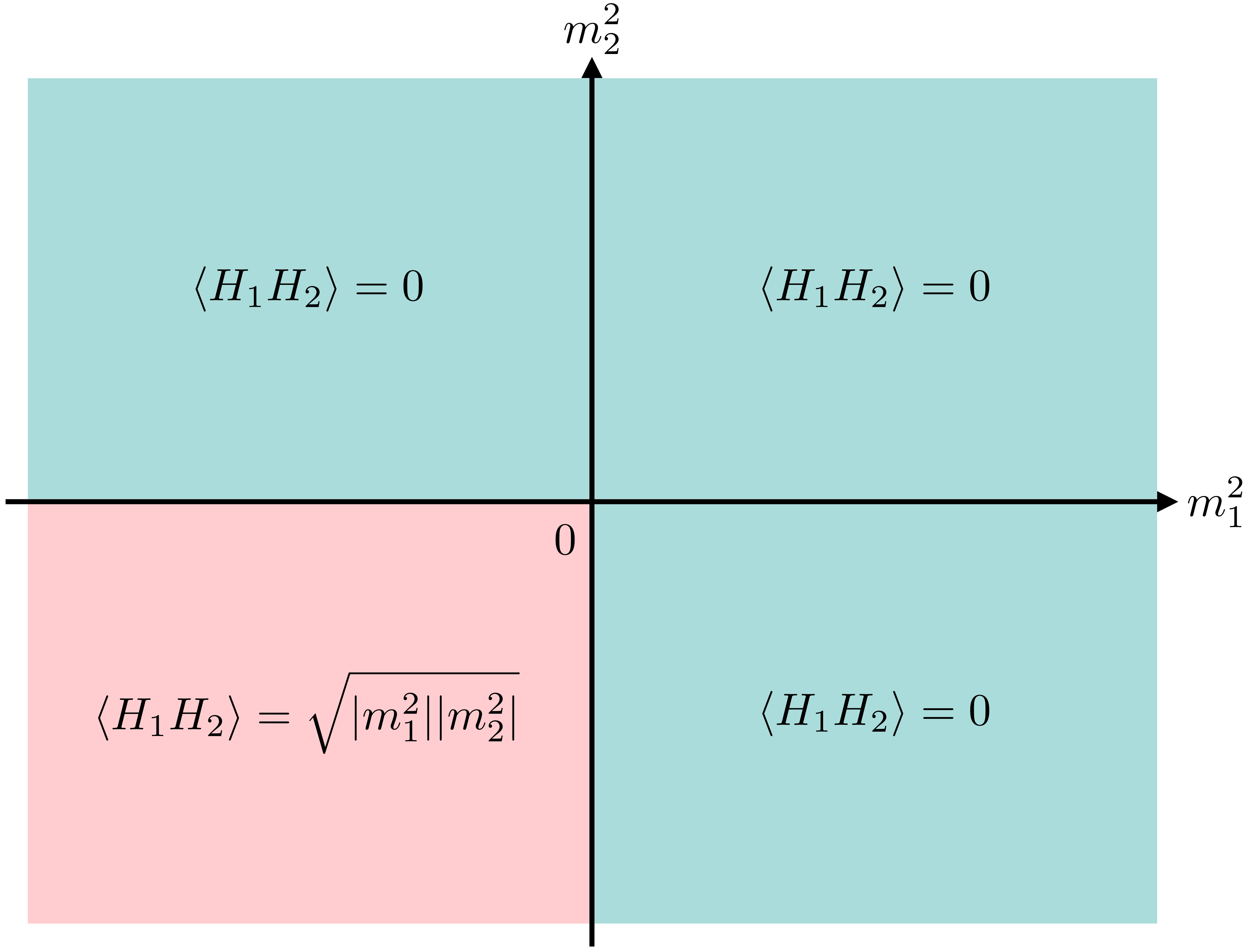
as a function of m_h^2 (m1 and/or m2)

Λ can be small only if $\mu_S^2 \leq \mu^2 \leq \mu_B^2$



Values of μ^2 in the landscape (classical)

(quartic couplings are taken to be order one)



Values of μ^2 in the landscape (quantum)

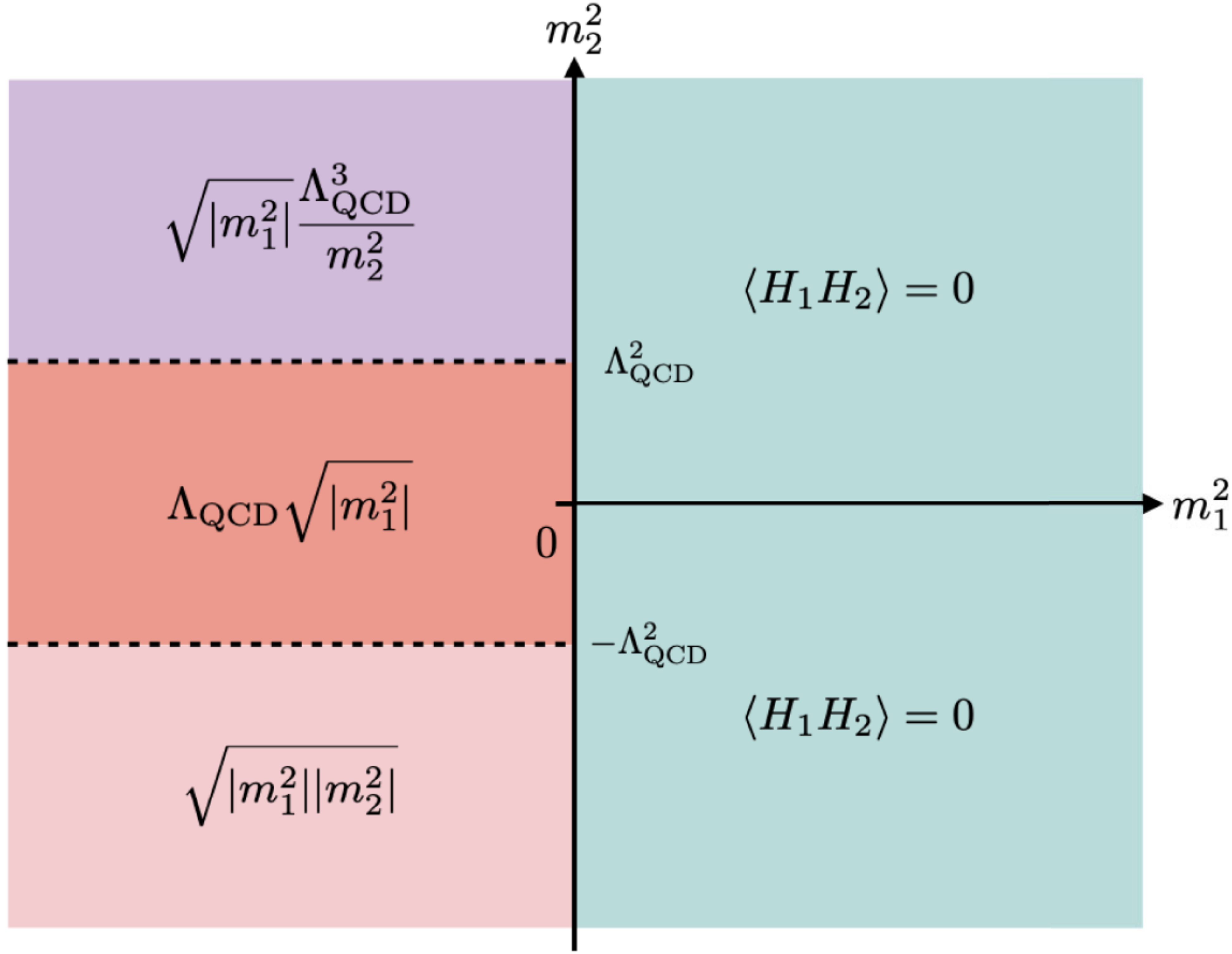
$$V = \Lambda_{\rm QCD}^3 h_2^0 + m_{H_2}^2 (h_2^0)^2 + \lambda (h_2^0)^4$$

(quartic couplings are taken to be order one)

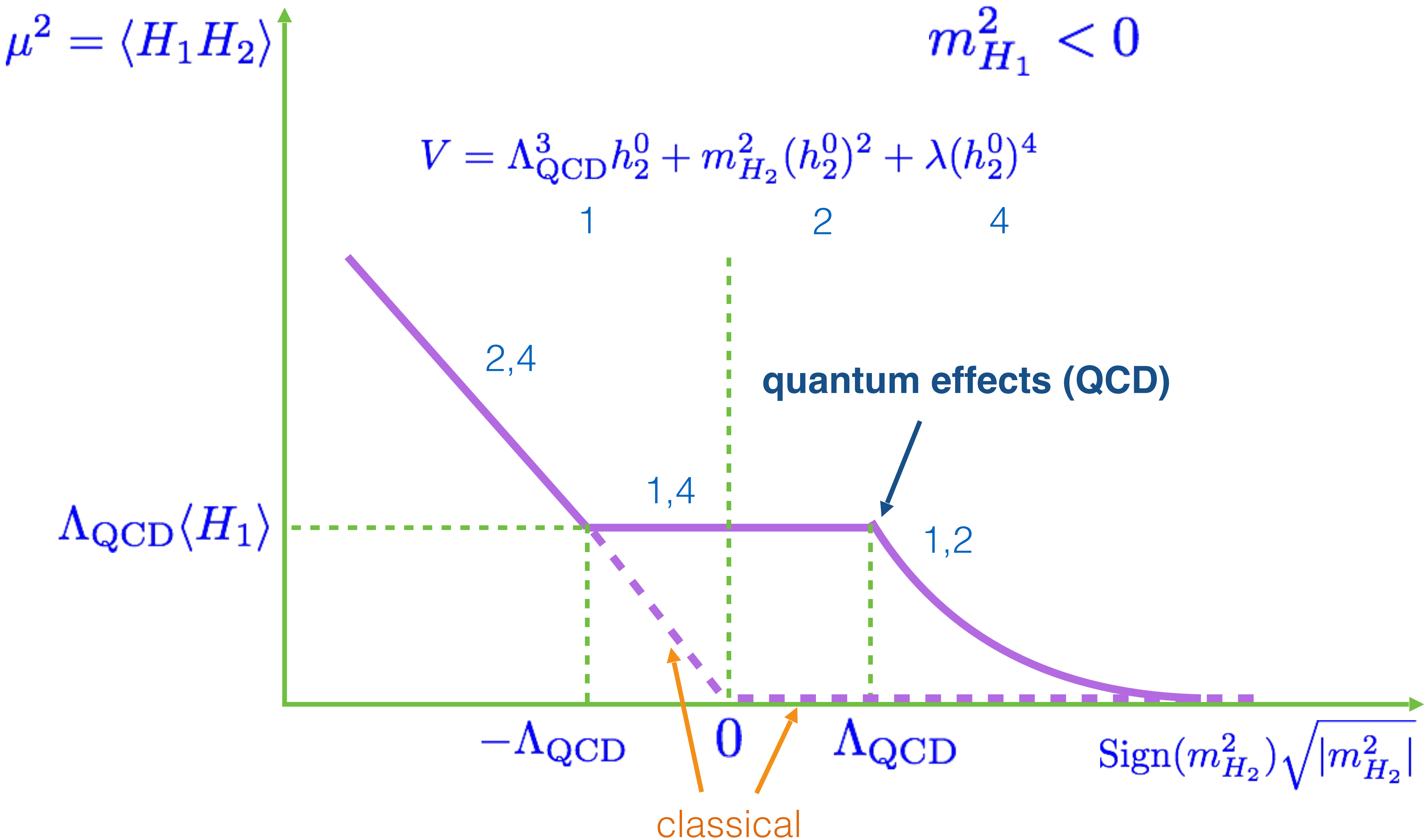
$$h_2^0 \sim \frac{\Lambda_{\rm QCD}^3}{m_{H_2}^2}$$

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

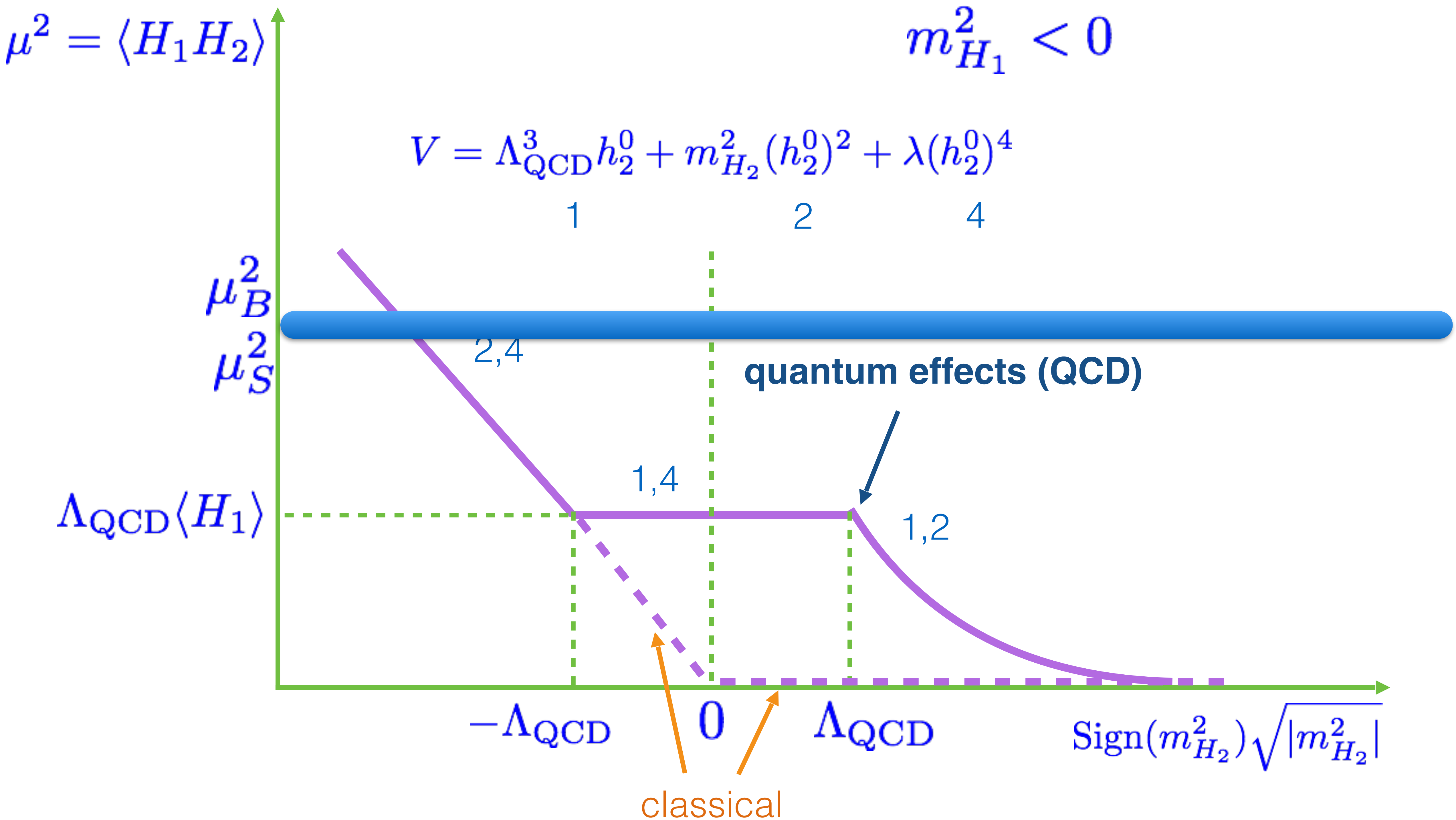
$$h_2^0 \sim \frac{\Lambda_{\rm QCD}}{\lambda^{1/3}}$$



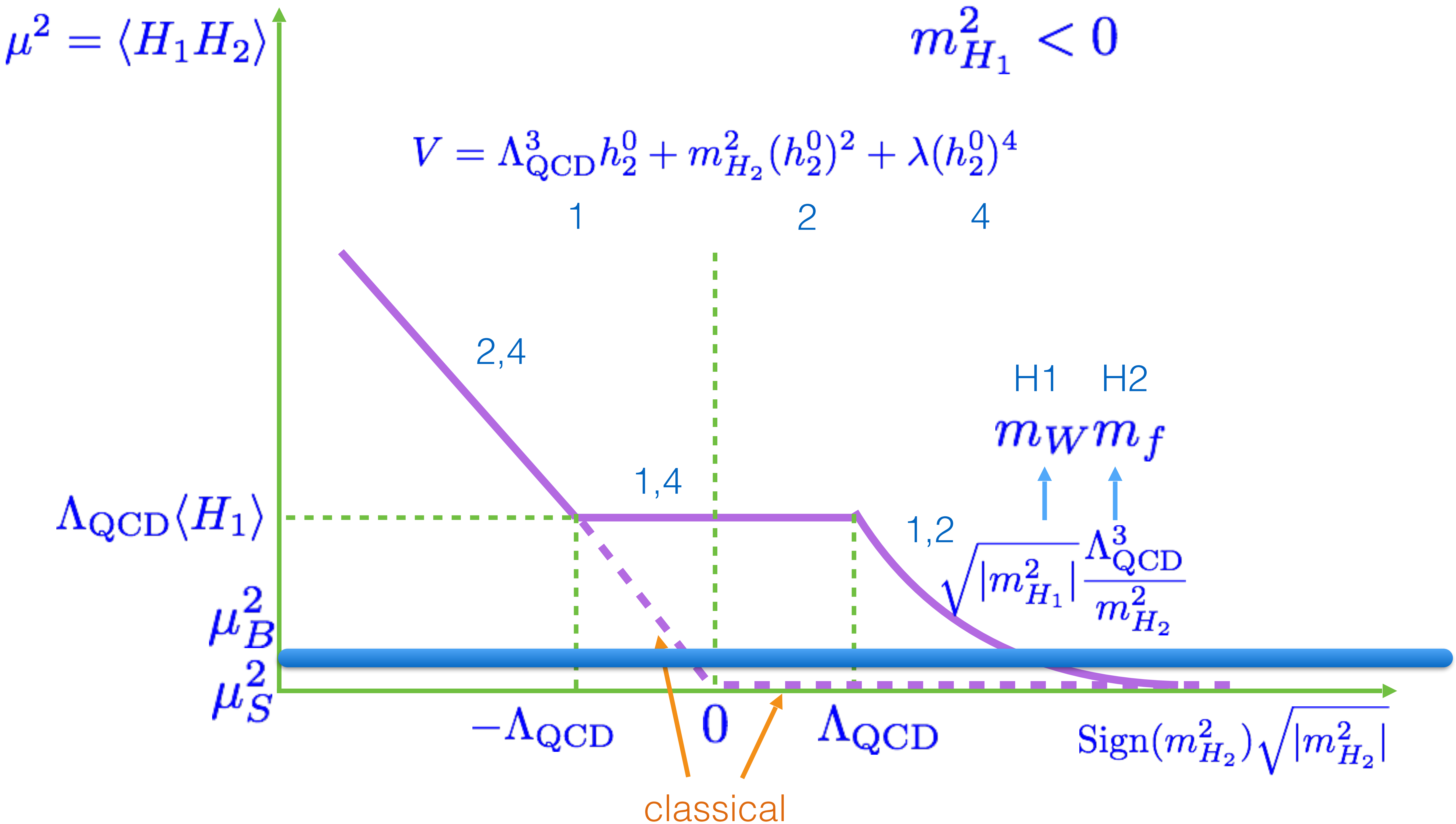
Triggering parameter



Universe including ours



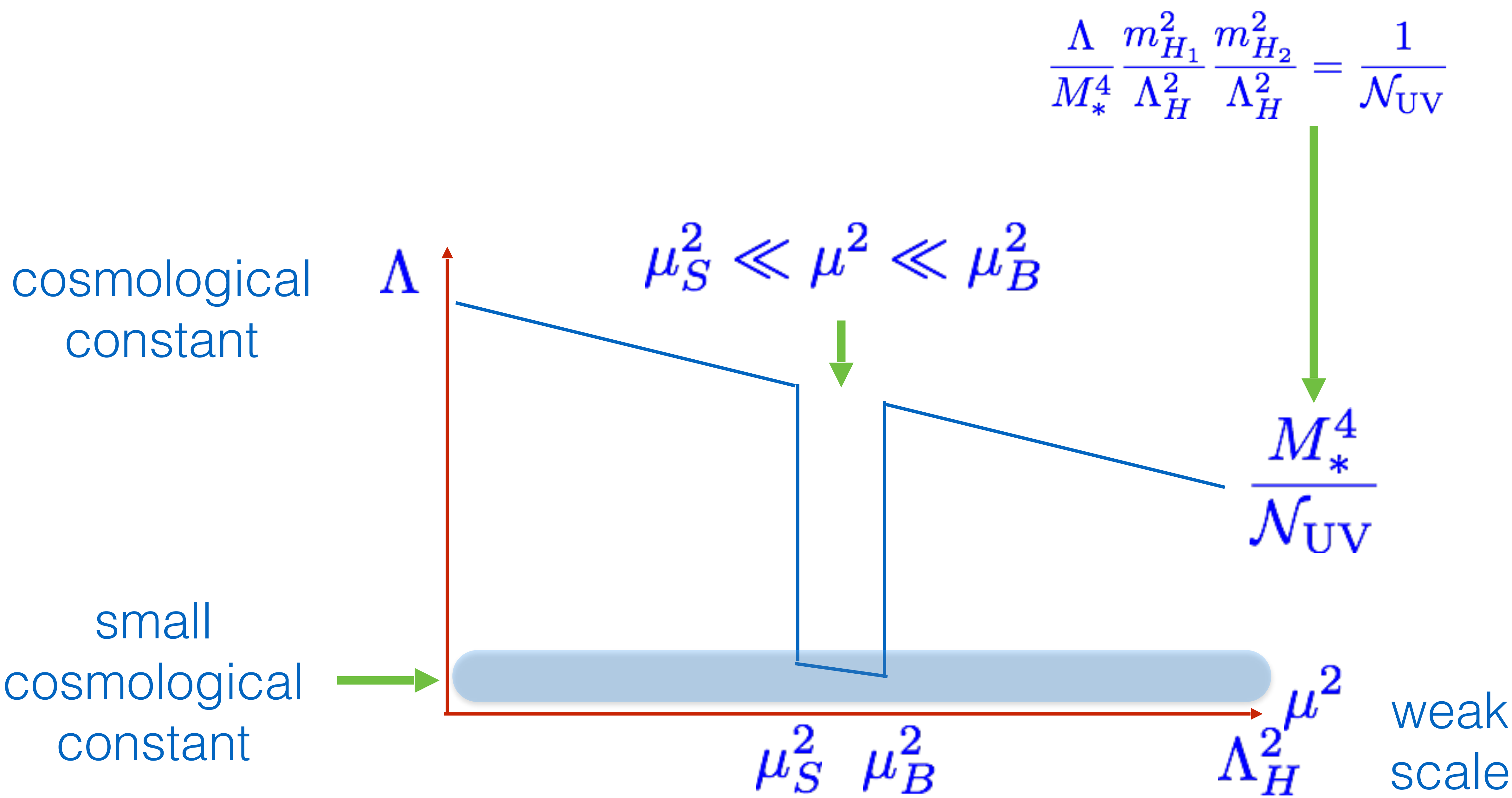
Strange universe with $\Lambda \sim (\frac{v}{\Lambda_H})^4 \Lambda_{\rm us}$ for the atom formation



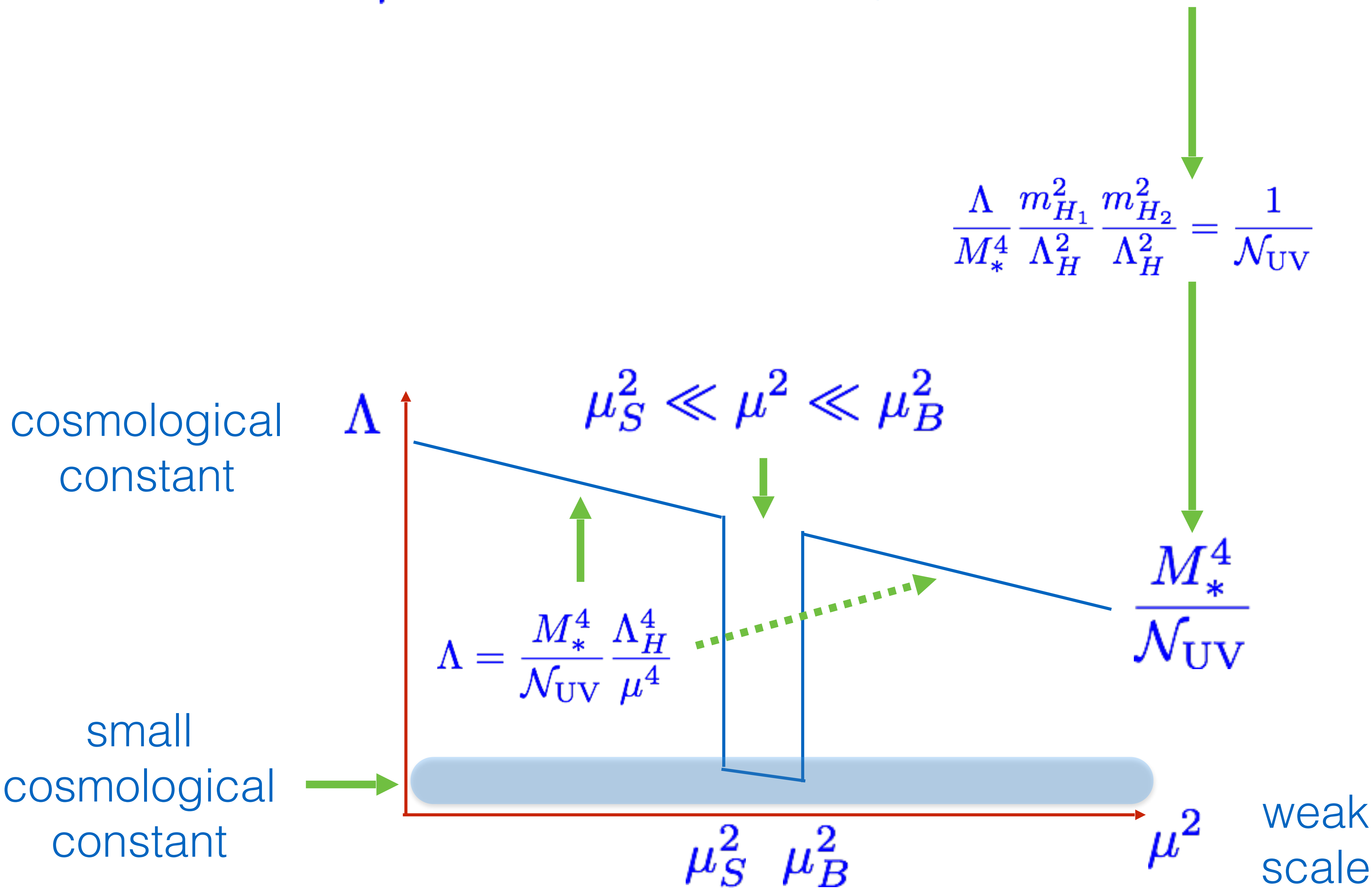
Weak scale as a trigger

$$\mu^2 \equiv \langle \mathcal{O} \rangle$$

as a function of m_h^2



small μ^2 is achieved by tuning in the landscape



(friendly : only **dimensionful parameters** scan)

Arkani-Hamed Dimopoulos Kachru hep-th/0501082

Pictures of the (friendly) landscapes

Two big problems in theoretical physics

A. Cosmological constant problem

B. Gauge hierarchy problem

$$\Lambda \sim 10^{-120} M_{\rm Pl}^4$$

$$v^2 \sim 10^{-30} M_{\rm Pl}^2$$

We need at least 10^{150} vacua to explain two small parameters

$$\mathcal{N}_{\text{UV}} \ll 10^{150}$$

$$v^2 \sim 10^{-30}$$

$$\Lambda_{\text{cc}} \sim 10^{-120}$$

not possible in the HE landscape

Low energy landscape

A set of light scalar fields with degenerate vacua

$\phi\mathcal{O}$ can break the degeneracy

Extra scanning of the cc is triggered by the weak scale

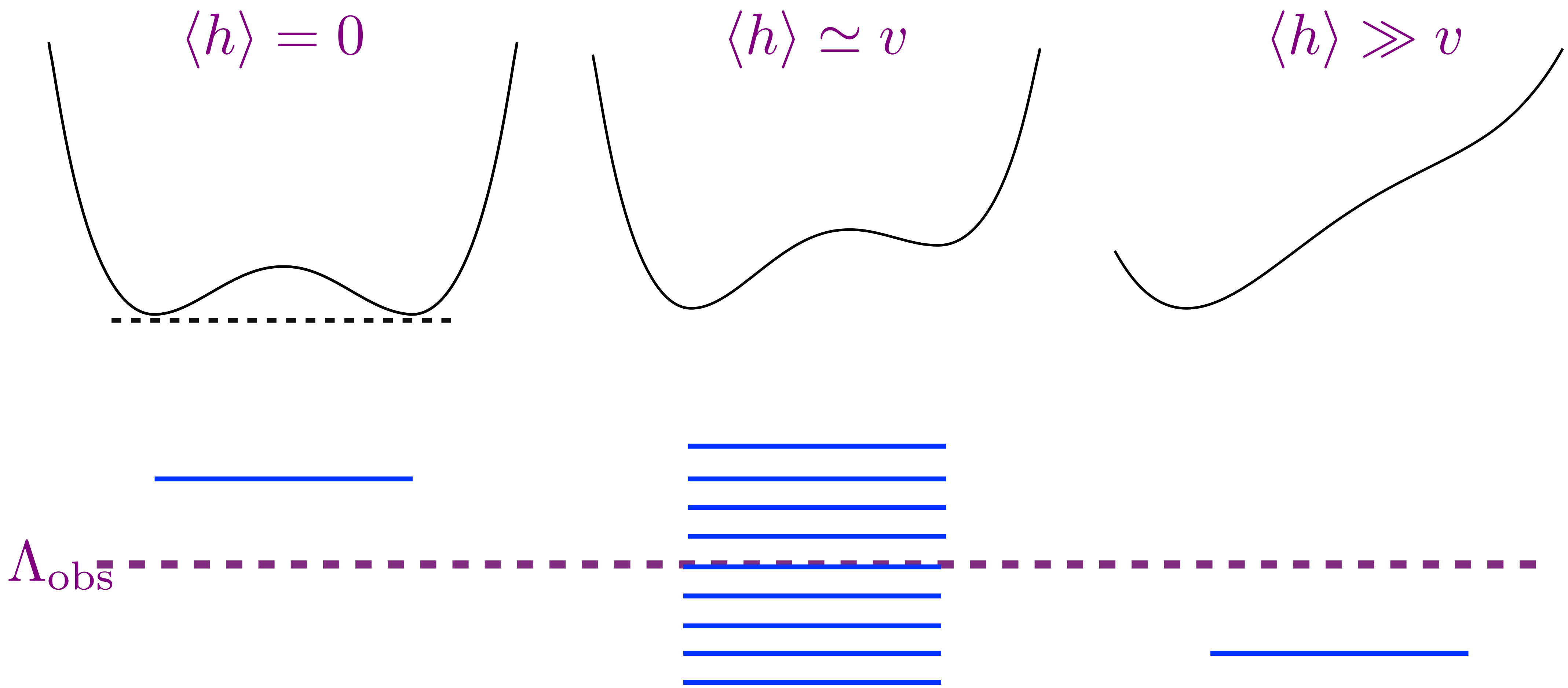
$$\mu^2 = \langle \mathcal{O} \rangle$$

$\mu > \mu_B$ → the other vacuum disappears

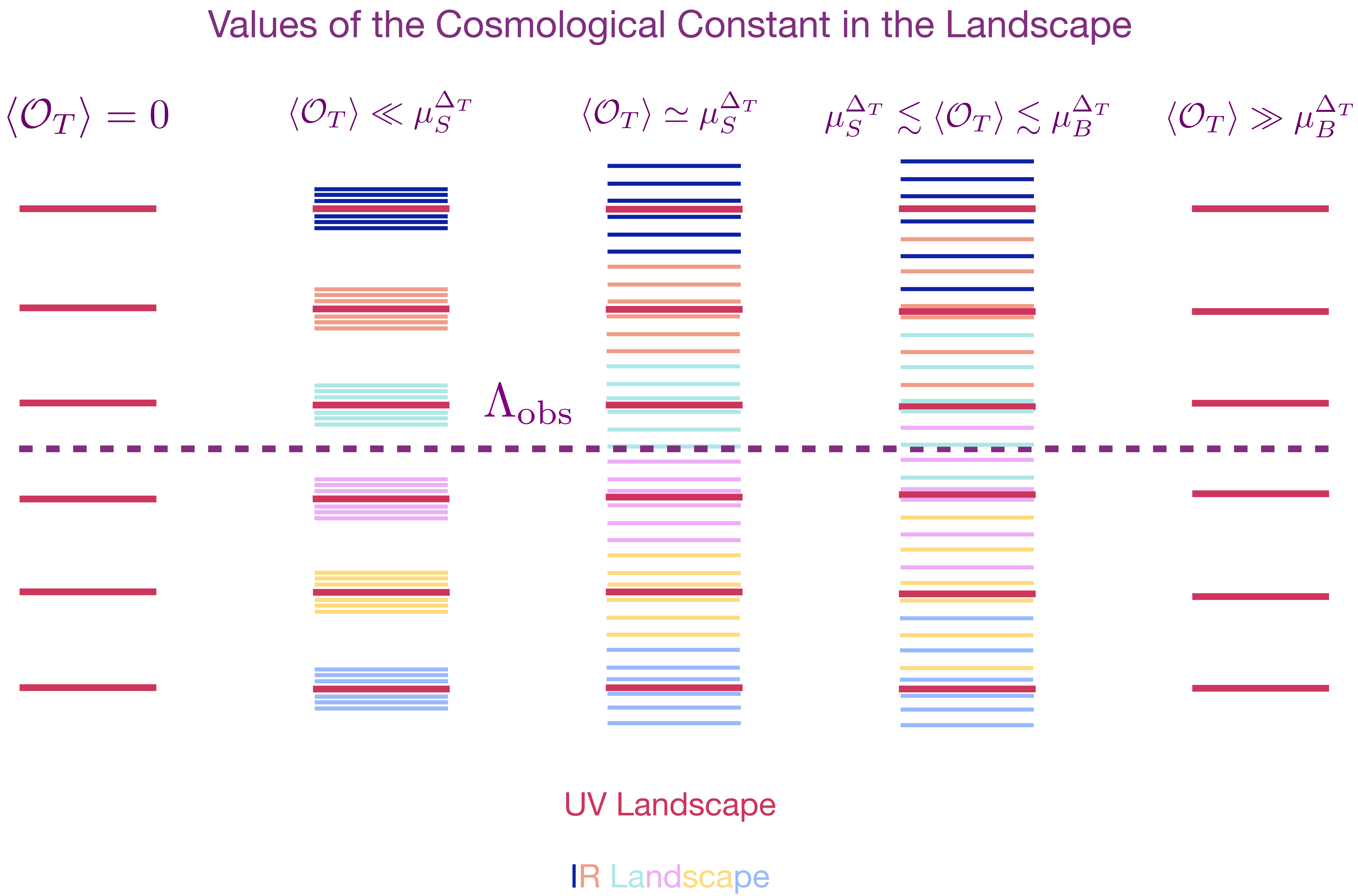
$\mu < \mu_S$ → hyperfine splitting of the scanning and it doesn't help to reduce the cc

Low Energy Landscape

$$m_\phi \sim v^2/M_* \quad \langle \phi \rangle \sim M_*$$



$$V_\phi = \sum_{i=1}^{n_\phi} \frac{\epsilon_i^2}{4}\left(\phi_i^2 - M_{*,i}^2\right)^2 + \left(\sum_{i=1}^{n_\phi} \frac{\kappa_i \epsilon_i M_{*,i}^{3-\Delta_T}}{\sqrt{n_\phi}} \phi_i \mathcal{O}_T + \text{h.c.}\right)$$



Values of the Cosmological Constant in the Landscape
$\langle \mathcal{O}_T \rangle = 0$
$\langle \mathcal{O}_T \rangle \ll \mu_S^{\Delta_T}$
$\langle \mathcal{O}_T \rangle \simeq \mu_S^{\Delta_T}$
$\mu_S^{\Delta_T} \lesssim \langle \mathcal{O}_T \rangle \lesssim \mu_B^{\Delta_T}$
$\langle \mathcal{O}_T \rangle \gg \mu_B^{\Delta_T}$
$\Lambda_{\rm obs}$
UV Landscape
IR Landscape

$$\mathcal{O}_H = \kappa\epsilon M_* \phi H_1 H_2$$

$$V_{\rm loop} \sim \kappa^2\epsilon^2 M_*^2 \phi_i \phi_j$$

$$\langle \mathcal{O}_H \rangle = \kappa\epsilon M_*^2 \mu^2$$

$$\epsilon^2 M_*^4 \sim \kappa\epsilon M_*^2 \mu_B^2$$

splitting by the trigger

$$\kappa^2\epsilon^2 M_*^4 \ll \Lambda_* = \frac{M_*^4}{\mathcal{N}_{\rm UV}}$$

to prevent IR scan from V_loop

$$\Lambda(\mu^2) = \frac{\Lambda_H^4}{|m_{H_1}^2 m_{H_2}^2|}\Lambda_* = \frac{\Lambda_H^4}{\mu^4}\Lambda_*$$

CC from UV scan

splitting should be larger than the CC from UV scan

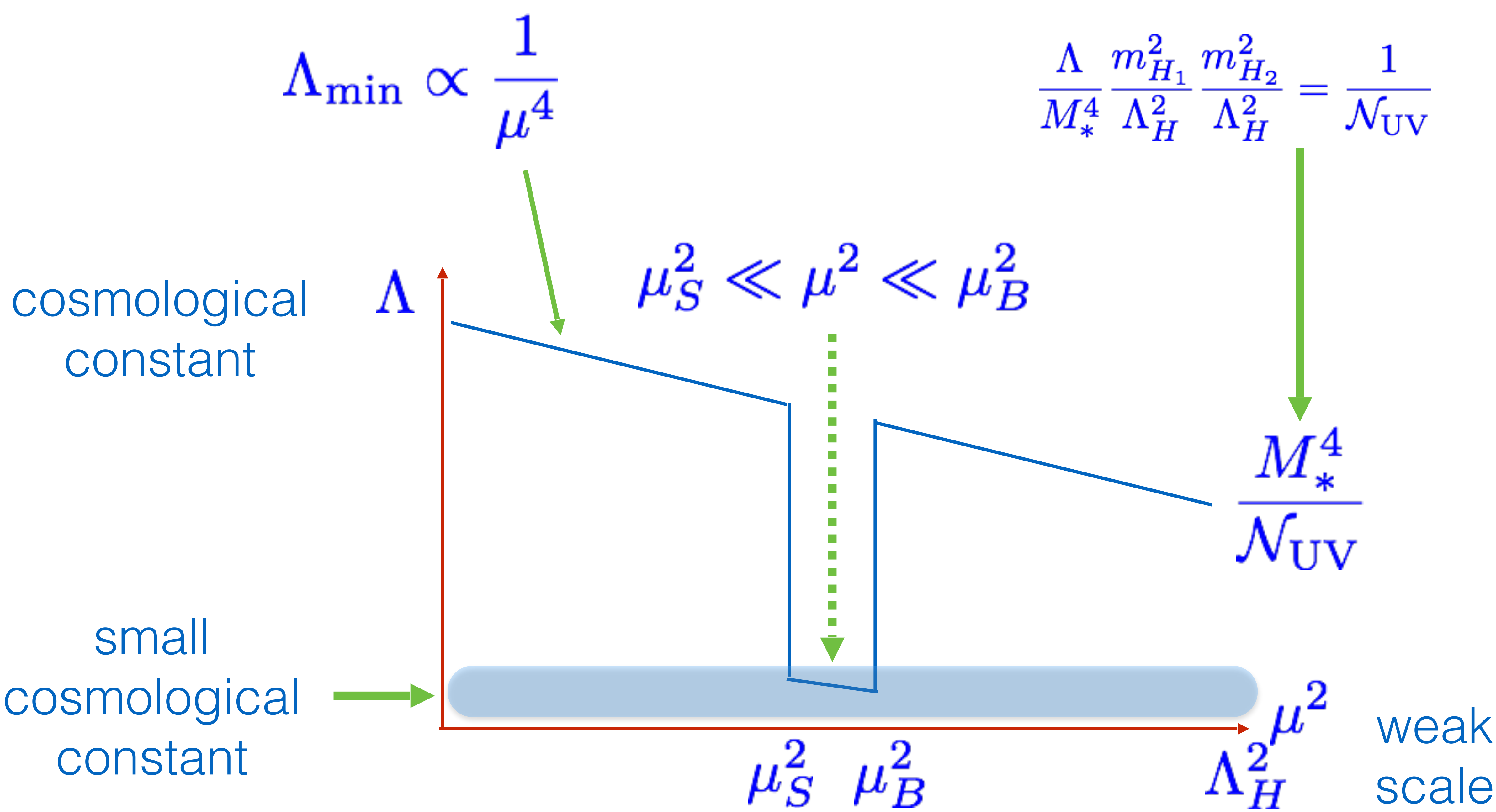
$$\boxed{\frac{\Lambda_H^8 M_*^4}{v^{12}} \ll \mathcal{N}_{\rm UV} \ll 10^{120}\frac{\Lambda_H^2}{v^2}} \longrightarrow \Lambda_H \ll 10^{12}\ \mathrm{GeV}$$

$$\kappa \ll \frac{\mu_H^2}{\Lambda_H^2} \sim \frac{v^2}{\Lambda_H^2} \longrightarrow \langle \mathcal{O}_H \rangle \sim \kappa v^4 \ll v^4$$

Weak scale as a trigger

$$\mu^2 \equiv \langle \mathcal{O} \rangle$$

as a function of m_h^2



Quadratic vs Logarithmic distribution

Quadratically more likely for large mass in general

$$m_h^2 \sim M_{\mathrm{UV}}^2 \qquad\qquad m_h^2 \sim v^2$$

fine tuning: $\dfrac{M_{\mathrm{UV}}^2}{v^2} \gg 1$

$$\mu^2 = v_1 v_2$$

$v_1 \sim v_2 \sim v$ and $v_1 \ll v_2$ are equally probable

fine tuning: $|\log \dfrac{\Lambda_H}{\Lambda_{\mathrm{QCD}}}| \sim 1$

A possibility of entirely different universe

$$m^2_{H_1} < 0 \qquad m^2_{H_2} > 0$$

weak scale $\mu^2 = \Lambda_H \dfrac{\Lambda^3_{\rm QCD}}{m^2_{H_2}}$

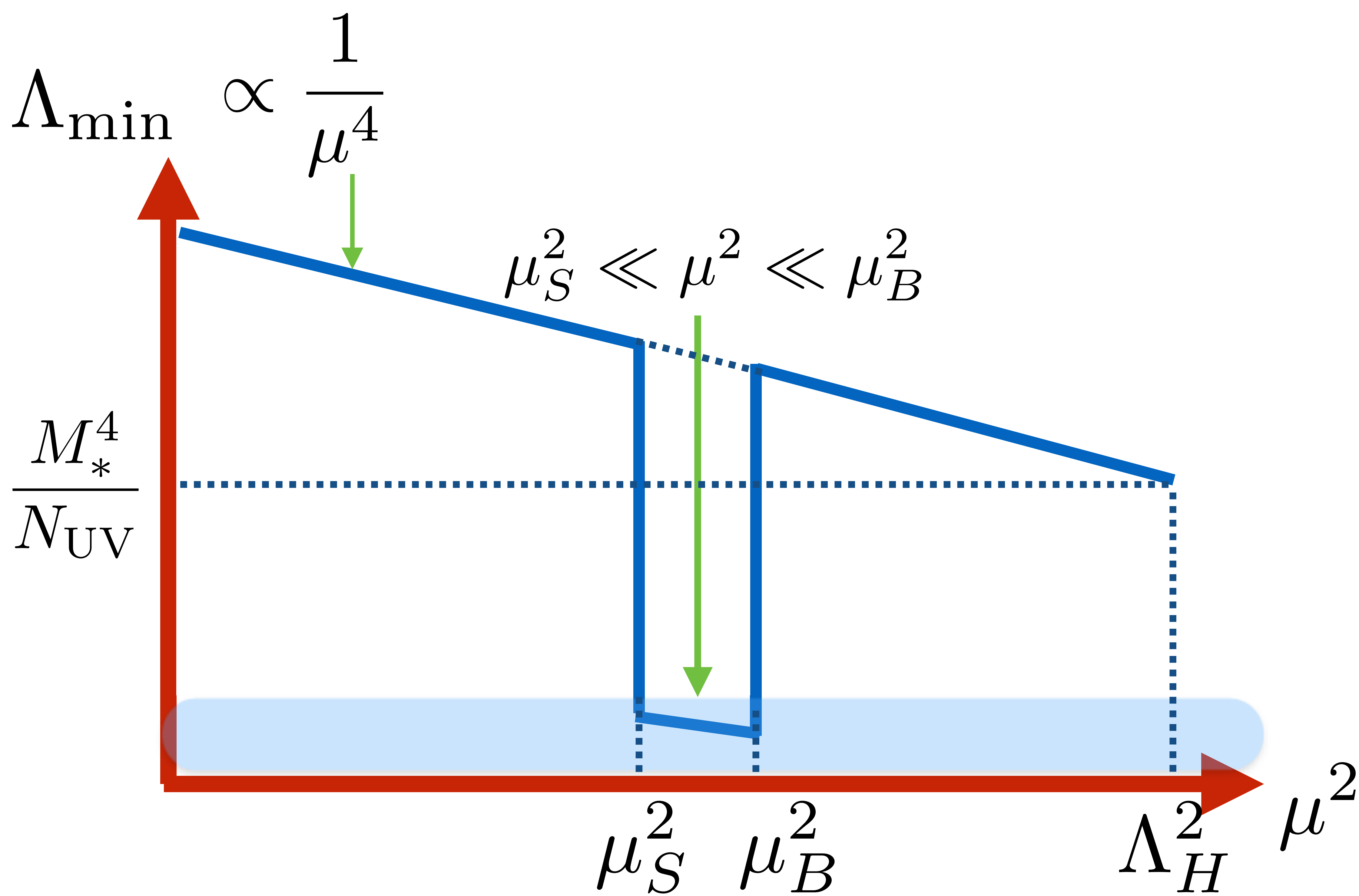
cc $\Lambda(\mu^2) = \dfrac{\Lambda^2_H}{m^2_{H_2}} \dfrac{M^4_*}{\mathcal{N}_{\rm UV}} = \dfrac{\Lambda_H \mu^2}{\Lambda^3_{\rm QCD}} \dfrac{M^4_*}{\mathcal{N}_{\rm UV}}$

$$\kappa^2 \mu^2_B \mu^2 > \Lambda(\mu^2)$$

condition for IR scan $\longrightarrow$ $\mathcal{N}_{\rm UV} > \dfrac{1}{\kappa^2} \dfrac{\Lambda_H M^4_*}{\Lambda^3_{\rm QCD} \mu^2_B}$

Fermion mass $\dfrac{\Lambda^3_{\rm QCD}}{m^2_{H_2}} = \dfrac{\mu^2}{\Lambda_H} \leq \dfrac{v^2}{\Lambda_H}$ smaller at least by $\dfrac{v}{\Lambda_H}$

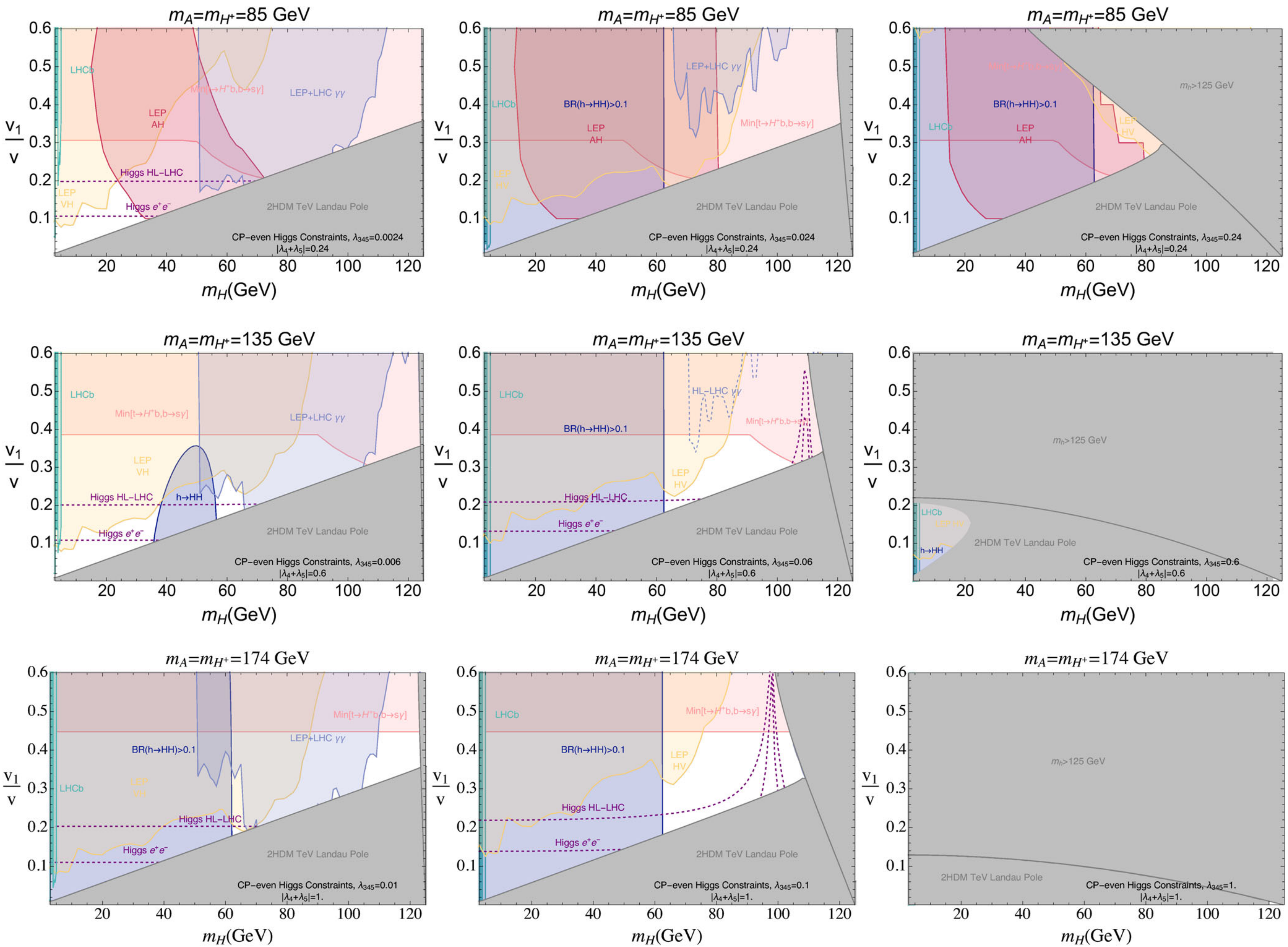
The cc should be smaller by $(\dfrac{v}{\Lambda_H})^4$ for atoms to form



$\Lambda_{\min} \propto \frac{1}{\mu^4}$
$\mu_S^2 \ll \mu^2 \ll \mu_B^2$
$\frac{M_*^4}{N_{\rm UV}}$
μ_S^2
μ_B^2
Λ_H^2
μ^2

The weak scale as a trigger

I. Type 0 2HDM



mA=mH+=85 GeV
LHCb
LEP AH
Min[t→H+b,b→sγ]
LEP+LHC γγ
Higgs HL-LHC
LEP VH
Higgs e+e−
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.0024
|λ4+λ5|=0.24
mA=mH+=85 GeV
LHCb
BR(h→HH)>0.1
LEP AH
LEP+LHC γγ
Min[t→H+b,b→sγ]
LEP HV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.024
|λ4+λ5|=0.24
mA=mH+=85 GeV
mh>125 GeV
BR(h→HH)>0.1
LHCb
LEP AH
LEP HV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.24
|λ4+λ5|=0.24
mA=mH+=135 GeV
LHCb
Min[t→H+b,b→sγ]
LEP+LHC γγ
LEP VH
Higgs HL-LHC
h→HH
Higgs e+e−
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.006
|λ4+λ5|=0.6
mA=mH+=135 GeV
LHCb
HL-LHC γγ
BR(h→HH)>0.1
LEP HV
Higgs HL-LHC
Higgs e+e−
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.06
|λ4+λ5|=0.6
mA=mH+=135 GeV
mh>125 GeV
LHCb
h→HH
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.6
|λ4+λ5|=0.6
mA=mH+=174 GeV
Min[t→H+b,b→sγ]
LEP+LHC γγ
BR(h→HH)>0.1
LHCb
Higgs HL-LHC
Higgs e+e−
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.01
|λ4+λ5|=1.
mA=mH+=174 GeV
LHCb
Min[t→H+b,b→sγ]
BR(h→HH)>0.1
LEP HV
Higgs HL-LHC
Higgs e+e−
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.1
|λ4+λ5|=1.
mA=mH+=174 GeV
mh>125 GeV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=1.
|λ4+λ5|=1.
v1/v
mH(GeV)

Domain wall from Z2 symmetry of H1

$$\kappa \epsilon M_* \langle \phi \rangle H_1 H_2$$

$$B\mu_{\rm eff} = \kappa \epsilon M_* \langle \phi \rangle \sim \kappa v^2$$

spontaneous breaking of Z2 from phi misalignment

Domain wall energy density starts to dominate at

$$T \sim \left(\frac{v}{M_{\rm Pl}}\right)^{1/2} v \sim {\rm keV}$$

$$\frac{B\mu_{\rm eff} v^2}{v^3} \sim H$$ biased potential annihilates domain walls

No domain wall problem for $B\mu_{\rm eff} \geq \dfrac{v^4}{M_{\rm Pl}^2}$

Scalar dark matter from the electroweak phase transition

Misalignment of the light scalar provides a dark matter

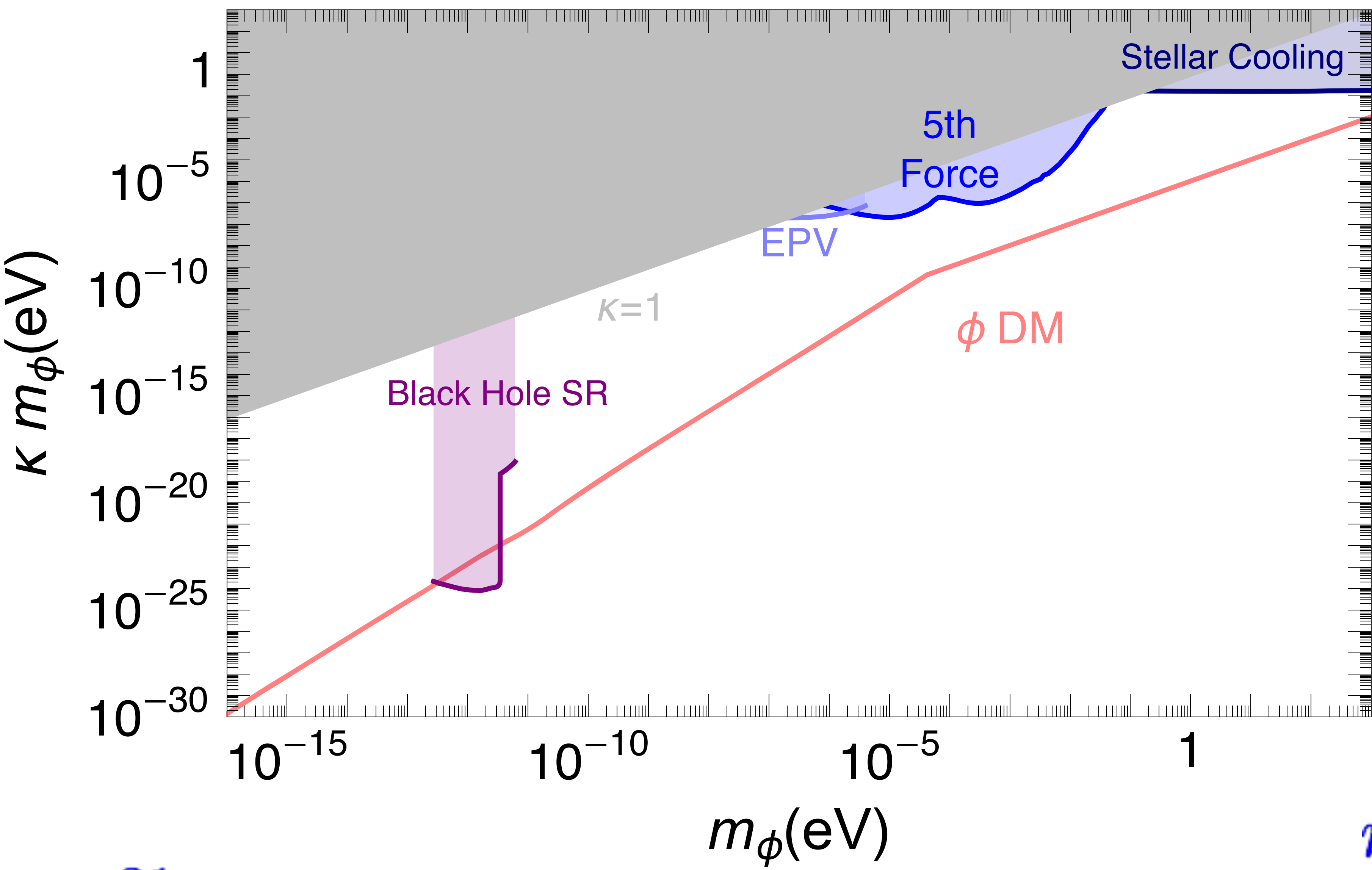
$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + c\langle\phi\rangle_T\langle H_1 H_2\rangle_T = 0$$

The last term provides a kick to the light scalar at EWPT

$$\Delta\phi \sim \mathcal{O}(M_*)$$

The relic density is determined from EWPT

Light Scalar Dark Matter



$$m_\phi \le 1\text{keV}$$

$$M_* \le 10\text{TeV}$$

$$m_\phi \ge 10^{-21}\text{eV}$$

Astrophysical constraints on fuzzy dark matter

Summary

The smallness of the cc and the observed weak scale might have a tight connection in the landscape

In the friendly landscape in which only the dimensionful parameters scan, the big landscape the cc scan might be sparse

Electroweak symmetry breaking might break the degeneracy of light scalar vacua and can further scan the cc down to small one

For the mechanism to work, **(type 0) 2HDM** is predicted and we would expect to discover additional Higgs bosons at the LHC

Lots of **light scalars** can provide an excellent candidate of **dark matter** from their coherent oscillations (misalignment is made at the electroweak phase transition)

Thank you!

Trigger: Good or Bad

Tadpole for Triggeron is problematic
when Triggeron is not charged under the symmetry

is absent or suppressed if Triggeron is charged under the symmetry which is unbroken or approximately preserved

(Discrete PQ symmetry for 2HDM with tiny Bmu is the case)

Therefore it is natural to ask if we can use
B and/or L violating operators as a trigger

B and/or L is an accidental symmetry in the Standard Model which is explicitly broken by higher dim. operators

Trigger: Good or Bad

Mixed bilinears for Triggerons are generated at one loop and scan the cc independently of the weak scale

If the trigger has a coupling with a positive mass dimension, the induced bilinears can be logarithmically divergent

The dimension of the triggering operator should be 2
Again 2HDM H1H2 was the example

There is no operator which is a gauge singlet and can carry nontrivial charge under the discrete symmetry in the SM

Baryon number violation

Baryon (lepton) number is an accidentally preserved

B and L are accidental symmetries of the Standard Model

$$\partial_\mu J^\mu_B = \frac{1}{32\pi^2}(g_2^2 W^a \tilde{W}^a + g_1^2 B\tilde{B})$$

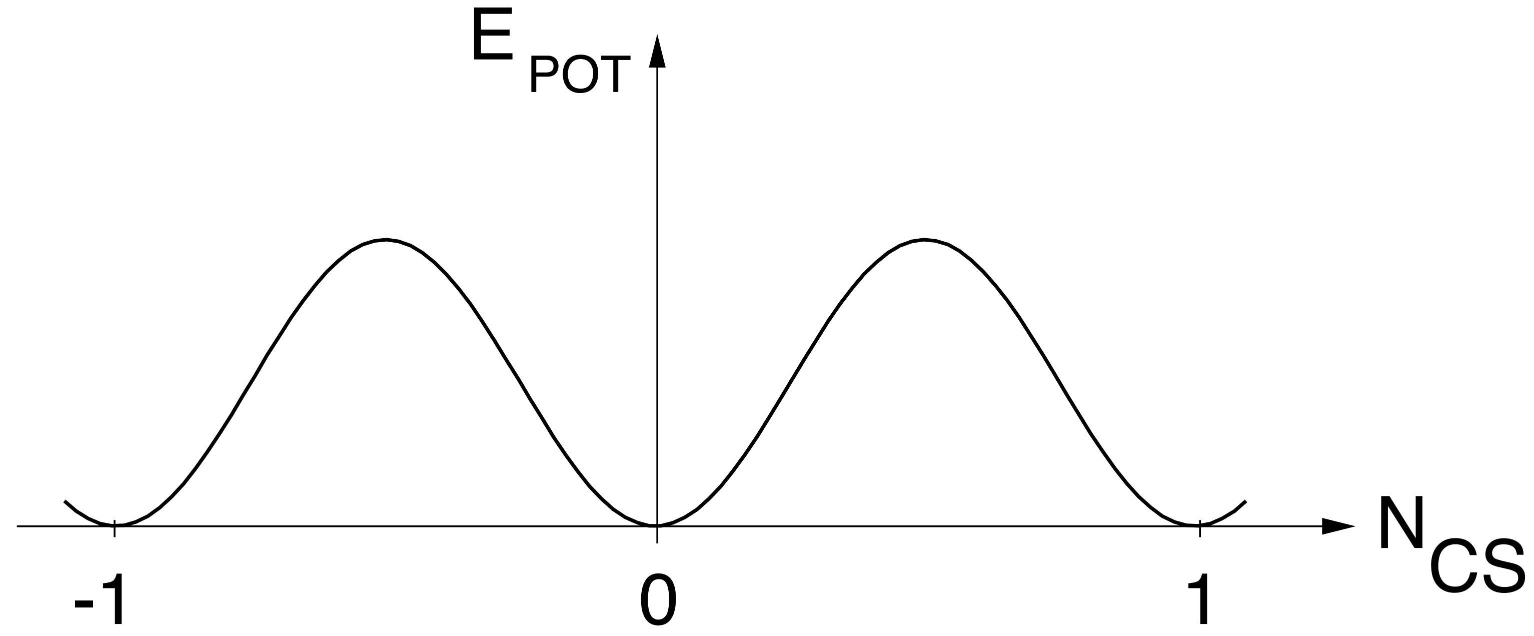
and the same for Lepton number

B-L is anomalous free

B+L is anomalous

B+L violation and SU(2) instantons

$$N_{\rm CS} = \frac{g^2}{32\pi^2}\int d^4x W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$



For the change of the Chern-Simons number,

$$\Delta(B-L) = 0$$

$$\Delta(B+L) = 2N_g\Delta N_{\rm CS}$$

Baryon and lepton number violating operators

B+L violating operators (dim 6)

$$QQQL \qquad u^c u^c d^c e^c$$

$$QLu^{c\dagger}d^{c\dagger} \qquad QQu^{c\dagger}e^{c\dagger}$$

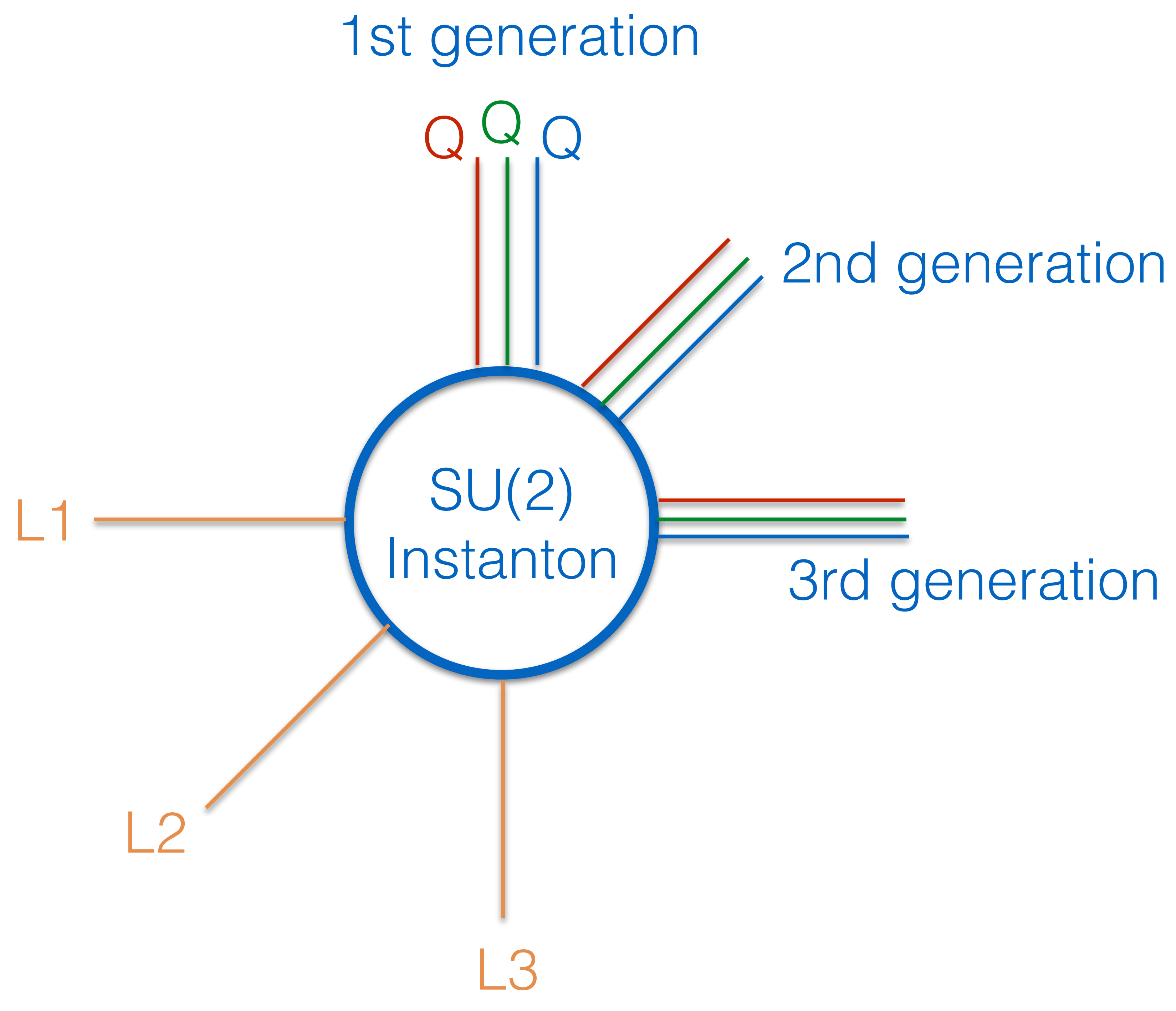
SU(2) instantons emit the zero modes of SU(2) doublets

$QQQL$ is the operator which only contains the doublets

$$\xi \phi W \tilde{W}$$

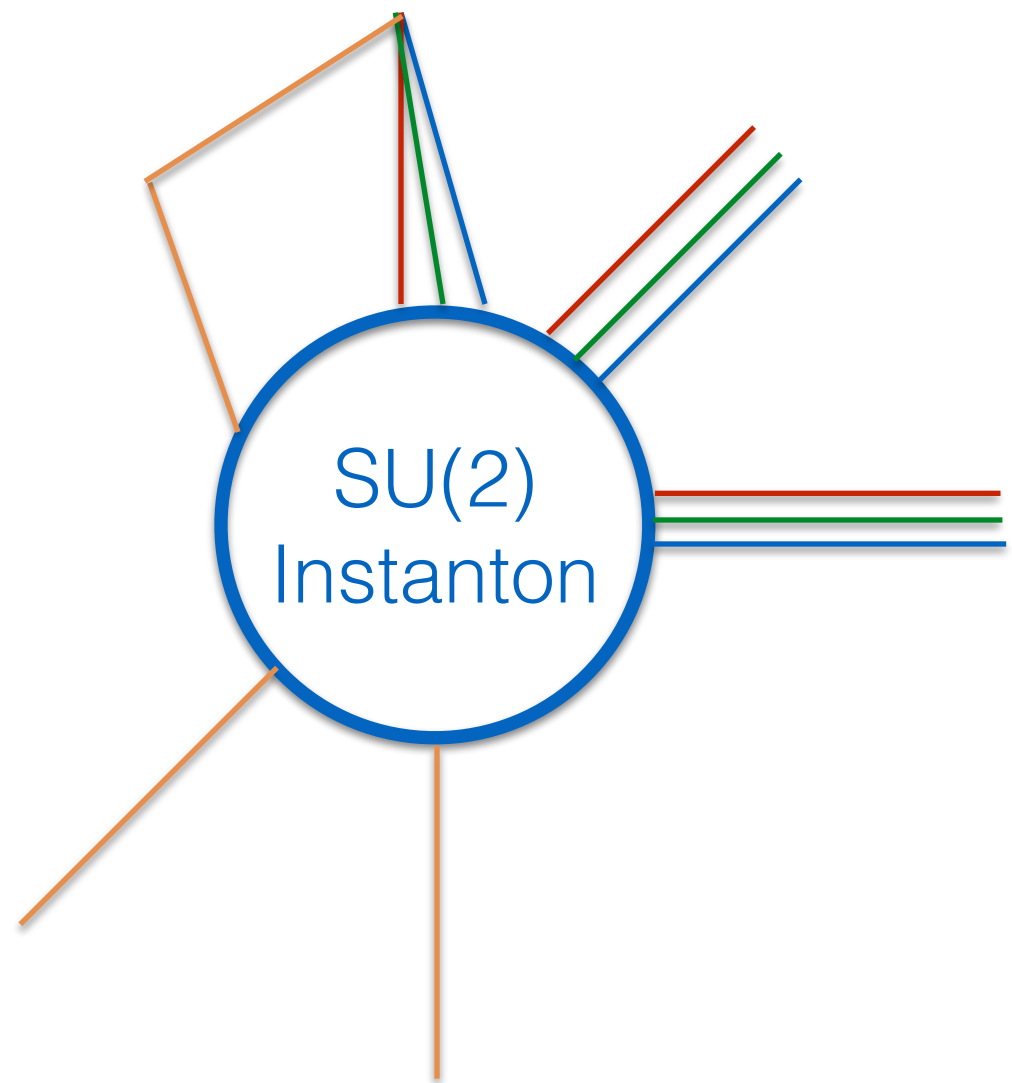
with B and/or L violating operators

SU(2) instanton has 9Q and 3L zero modes

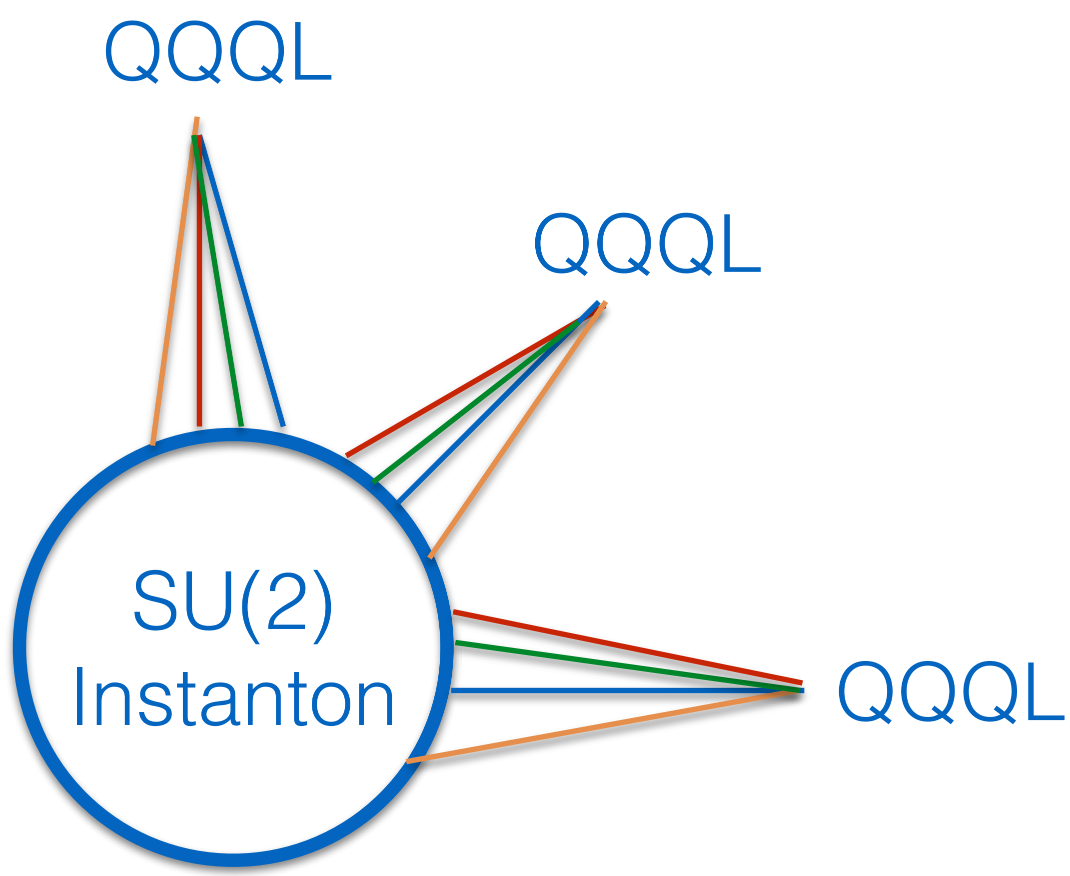


SU(2) instanton has 9Q and 3L zero modes

QQQL can close the loop for the zero modes



SU(2) instanton has 9Q and 3L zero modes



The generated potential does not have
the weak scale dependence

The structure of color SU(3), weak SU(2) and generation index

$$\epsilon_{abc}\epsilon^{IJ}Q^a_{Ii}Q^b_{Jj}\epsilon^{KL}Q^c_{Kk}L_{Ll}$$

Lorentz spinor index is omitted

SU(3) color : a,b,c = 1,2,3

SU(2) weak : I,J & K,L = 1,2

generation index : i,j,k,l=1,2,3

Fermions should be antisymmetric under the exchange

i and j should be different for the operator to exist

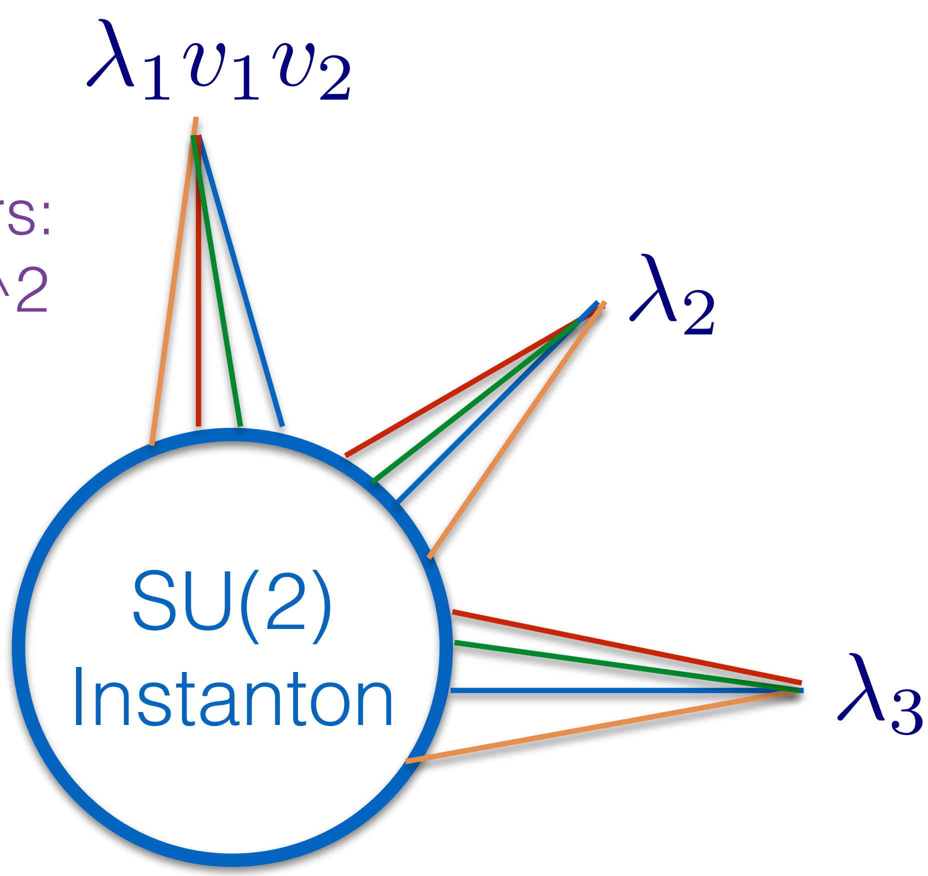
SU(2) instanton has 9Q and 3L zero modes

higher dim. (8 and 6) operators:
suppressed by M*^4 and M*^2

$$\lambda_1 Q_1 Q_2 Q_1 L_1 H_1 H_2$$

$$\lambda_2 Q_2 Q_3 Q_2 L_2$$

$$\lambda_3 Q_3 Q_1 Q_3 L_3$$



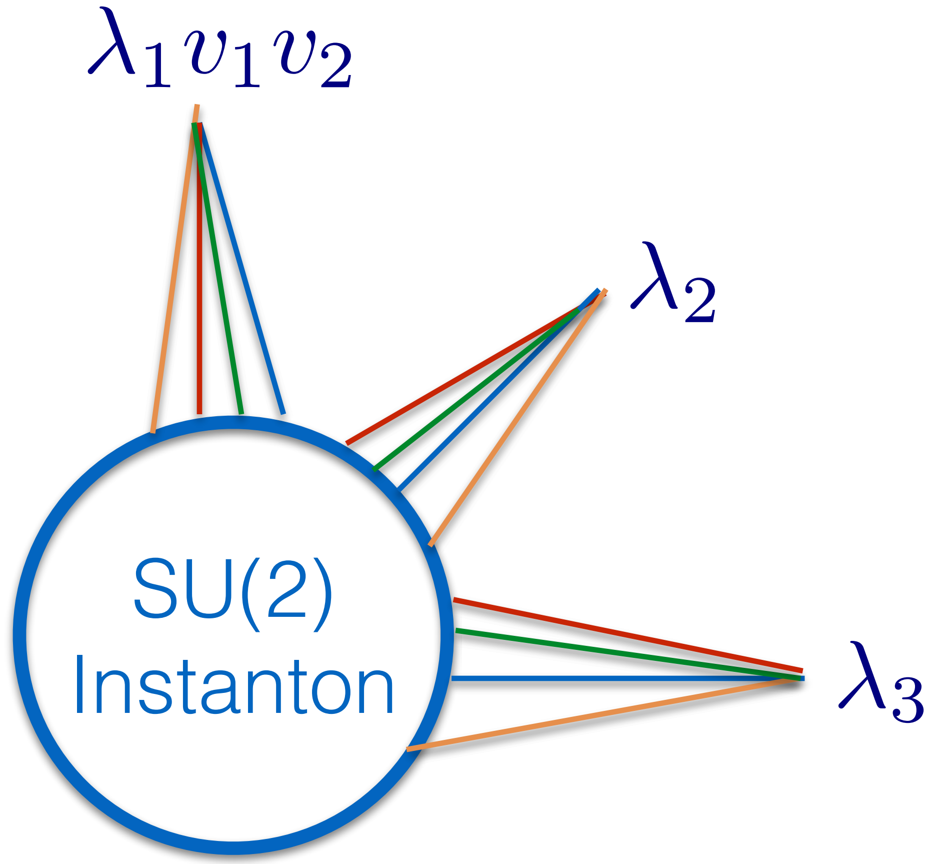
Q2 and H1H2 are odd under Z2 symmetry

Small instanton contribution to Triggeron

$\lambda_1 Q_1 Q_2 Q_1 L_1 H_1 H_2$

$\lambda_2 Q_2 Q_3 Q_2 L_2$

$\lambda_3 Q_3 Q_1 Q_3 L_3$



$$V \sim \int_{\rho_{\mathrm{small}}}^{\rho_{\mathrm{large}}} \frac{d\rho'}{\rho'^5} e^{-S_{\mathrm{eff}}(\frac{1}{\rho'})} F \cos(\xi\phi + \delta)$$

can be dominated by small instantons
if SU(2) couplingis strong in the UV

Small instanton contribution to Triggeron

$$V \sim \int_{\rho_{\rm small}}^{\rho_{\rm large}} \frac{d\rho^{'}}{\rho^{'5}} e^{-S_{\rm eff}\left(\frac{1}{\rho^{'}}\right)} F \cos(\xi\phi + \delta)$$

can be dominated by small instantons
if SU(2) coupling is strong in the UV

$$V \sim \lambda_1 \lambda_2 \lambda_3 F^{'} e^{-\frac{2\pi}{\alpha_2(M_*)}} M_*^2 H_1 H_2 \, \delta \frac{\xi}{M_*} \phi$$

F’ contains the loop suppresion factor

$V = \kappa \epsilon M_* \phi H_1 H_2$ is generated

Galactic Principle

$\frac{\delta\rho}{\rho}$ starts to grow linearly (a) after matter radiation equality

The cc should be smaller than the energy density at the moment of order one density perturbation

$$\Lambda \leq \rho_{\rm eq}(\frac{\delta\rho}{\rho})^3$$

$$\Lambda \leq (1~\mathrm{eV})^4(10^{-4})^3 = (10^{-3}~\mathrm{eV})^4$$

Galactic Principle

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$$\Lambda \leq \rho_{\rm eq}\left(\frac{\delta\rho}{\rho}\right)^3$$

$$\sigma v n = H \longrightarrow \frac{\alpha^2}{m_{\rm DM}^2} T^3 = \frac{T^2}{M_{\rm Pl}}$$

$$\rho_{\rm eq} = \left(\frac{m_{\rm DM}^2}{\alpha^2 M_{\rm Pl}}\right)^4 \longleftarrow T_{\rm eq} = \frac{\alpha^2 M_{\rm Pl}}{m_{\rm DM}^2}$$

$$\Lambda^{1/4} \leq \frac{\delta^{3/4}}{\alpha^2}\frac{m_{\rm DM}^2}{M_{\rm Pl}}$$

Galactic Principle

$$\Lambda^{1/4} \leq \frac{\delta^{3/4}}{\alpha^2} \frac{m_{\mathrm{DM}}^2}{M_{\mathrm{Pl}}}$$

DM mass is at around the weak scale,
the observed cc can be explained

However, heavier DM mass allows large cc

Special argument for m_DM ~ v0 is needed

Galaxy rather than DM halo needs an atom

Is EW symmetry broken by H or QCD?

Galactic Principle

$$\Lambda^{1/4} \leq \frac{\delta^{3/4}}{\alpha^2} \frac{m_{\rm DM}^2}{M_{\rm Pl}}$$

Is EW symmetry broken by H or QCD?

If mh^2 > 0, EW symmetry is broken by QCD

Sphaleron process is active and converts
all the baryons to the leptons:
no (or suppressed) B asymmetry

Electron mass is extremely light:
suppressed by (QCD/mh)^3 10^{-9}

$$\Lambda^{1/4} \leq T_{\rm rec} = \alpha^2 m_e = 10^{-10}\ {\rm eV}$$

Atomic Principle

$$m_n = 7\frac{v}{v_0}\ \mathrm{MeV}$$

$$m_p = 4\frac{v}{v_0}\ \mathrm{MeV}$$

$$m_e = 0.5\frac{v}{v_0}\ \mathrm{MeV}$$

electromagnetic correction

$$m_n - m_p = (3\frac{v}{v_0} - 1.7)\ \mathrm{MeV}$$

$$\Lambda_{\mathrm{QCD}} \propto v^{\zeta}$$

$$0.25 \leq \zeta \leq 0.3$$

$$-2 \leq \log\frac{v}{v_0} \leq 4$$

Atomic Principle

$$m_n - m_p = (3\frac{v}{v_0} - 1.7)\ \mathrm{MeV}$$

$$B_d = [2.2 - a(\frac{v - v_0}{v_0})]\ \mathrm{MeV}$$

$$\frac{v}{v_0} \leq 1.4(1.2)$$ for Deuterium bound state

$$m_{3/2} - m_{1/2} = 300(\frac{v}{v_0})^{0.3}$$

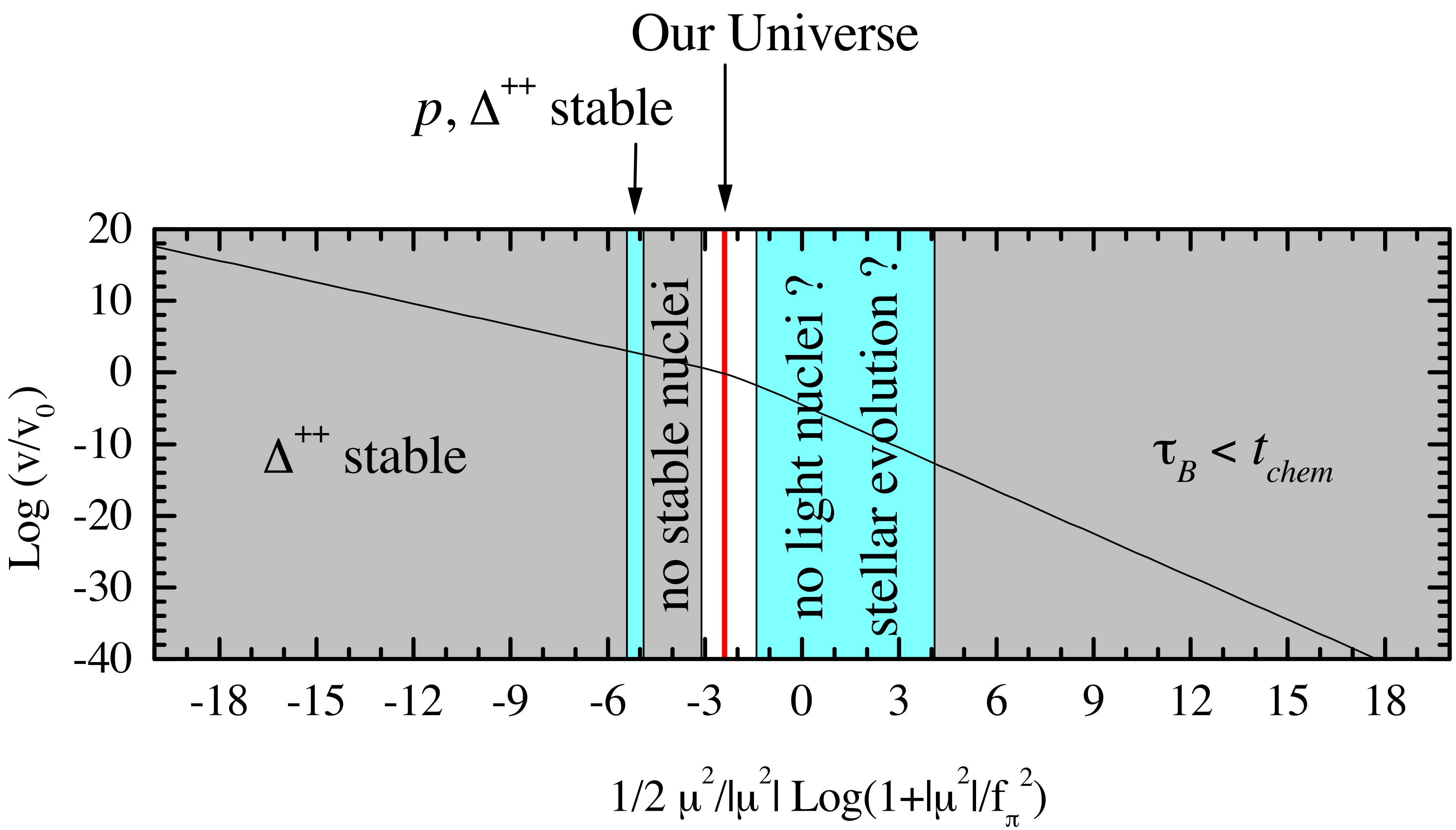
$$\frac{v}{v_0} \geq 10^3$$

Delta++(uuu) is stable

Inert atom

(no chemical/nuclear reaction)

Atomic Principle



Large v (~5v_0) : Nuclei involving n are unstable (only H)

Small v (~0.2v_0) : p decays to n (no atom)

Backup

Basics of Type 0 2HDM

CP odd Higgs A : PQ Goldstone boson

$$m_A^2 = -\lambda_5 v^2 \longleftarrow \lambda_5 < 0$$

CP even neutral Higgs h and H : $m_H \leq m_h$

$$\left(\begin{array}{cc} \lambda_1 v_1^2 & \lambda_{345} v_1 v_2 \\ \lambda_{345} v_1 v_2 & \lambda_2 v_2^2 \end{array} \right)$$

$$\downarrow \; v_1 \ll v_2$$

$$m_h^2 = \lambda_2 v_2^2$$ SM-like

$$m_H^2 = (\lambda_1 - \frac{\lambda_{345}^2}{\lambda_2}) v_1^2$$ H lighter than h

charged Higgs $$m_{H\pm}^2 = -\frac{\lambda_4 + \lambda_5}{2} v^2$$

Basics of Type 0 2HDM

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

$$g_{H\psi\psi} \simeq -g^{\rm SM}_{h\psi\psi} \frac{\lambda_{345}}{\lambda_2} \frac{v_1}{v}$$

Fermion couplings of H
have double suppression

Fermio-phobic H

$$\lambda_{345} = 0$$

$$g_{H\psi\psi} = 0$$

Basics of Type 0 2HDM

$$g_{H^+t^cb} \simeq g^{\rm SM}_{htt}\frac{v_1}{v}$$

$$g_{H^-tb^c} \simeq g^{\rm SM}_{hbb}\frac{v_1}{v}$$

$$g_{A\psi\psi} \simeq \pm g^{\rm SM}_{h\psi\psi}\frac{v_1}{v}$$

$$g_{HVV} \simeq g^{\rm SM}_{hVV}\lambda_2|1-\frac{\lambda_{345}}{\lambda_2}|\frac{v_1}{v}$$

Gauge phobic H

$$\lambda_{345} = \lambda_2$$

$$\Downarrow$$

$$g_{HVV} = 0$$

Basics of Type 0 2HDM

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

$$g_{HVV} \simeq g_{hVV}^{\mathrm{SM}} \frac{|\lambda_2 - \lambda_{345}|}{\lambda_2} \frac{v_1}{v}$$

$$\lambda_{hHH} \simeq \lambda_{345} v$$

$$\lambda_{hAA} \simeq (\lambda_{345} - 2\lambda_5) v$$

$$g_{AVV} = 0$$

$$g_{ZAH} \simeq -\frac{g}{2\cos\theta_W}(p_A + p_H)$$ independent of λ_i

Basics of Type 0 2HDM

CP even Higgs H is predicted to be lighter than h

$$\Lambda_{\rm QCD}^2 \leq m_H^2 \leq m_h^2$$

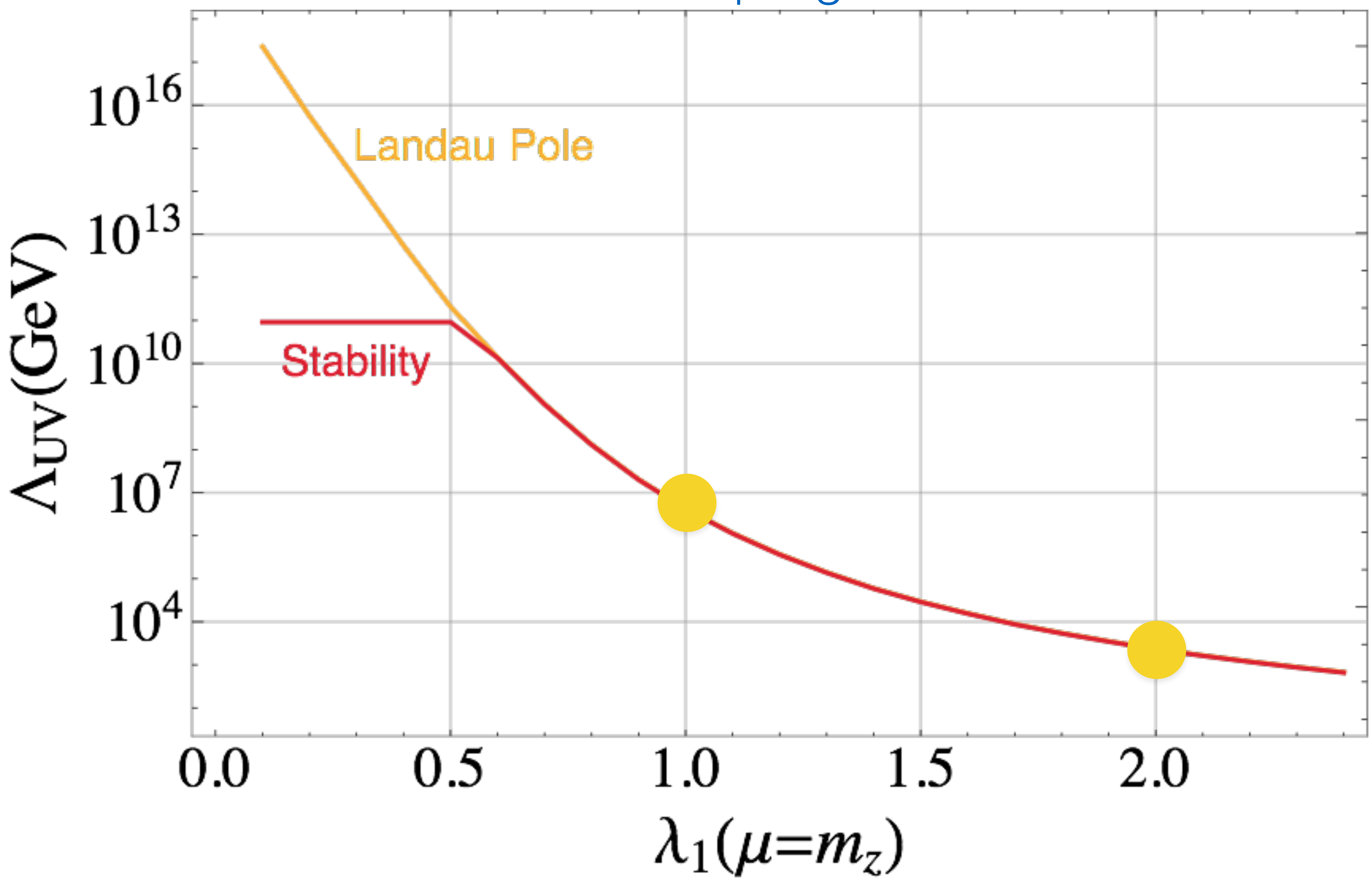
Charged Higgs and CP odd Higgs are lighter than 200 GeV

$$m_{H_\pm}, m_A \leq 250\ \mathrm{GeV} \longleftarrow \Lambda_{UV} = 500\ \mathrm{GeV}$$

$$175\ \mathrm{GeV} \longleftarrow \Lambda_{UV} = 10^7\ \mathrm{GeV}$$

UV cutoff from Landau pole

The scale of Landau pole depending on the couplings



Scalar dark matter from the electroweak phase transition

Misalignment of the light scalar provides a dark matter

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + c\langle\phi\rangle_T\langle H_1 H_2\rangle_T = 0$$

Misalignment of the light scalar provides a dark matter

1. There is a misalignment of the light scalar after inflation
2. When $H \sim m_\phi$, the scalar starts the oscillation
3. **Electroweak phase transition** also gives a **misalignment**

Scalar dark matter from the electroweak phase transition

Misalignment of the light scalar provides a dark matter

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + c\langle\phi\rangle_T\langle H_1 H_2\rangle_T = 0$$

The last term provides a kick to the light scalar at EWPT

$$\Delta\phi \sim \mathcal{O}(M_*)$$

The relic density is determined from EWPT

A kick to the light scalar at EWPT

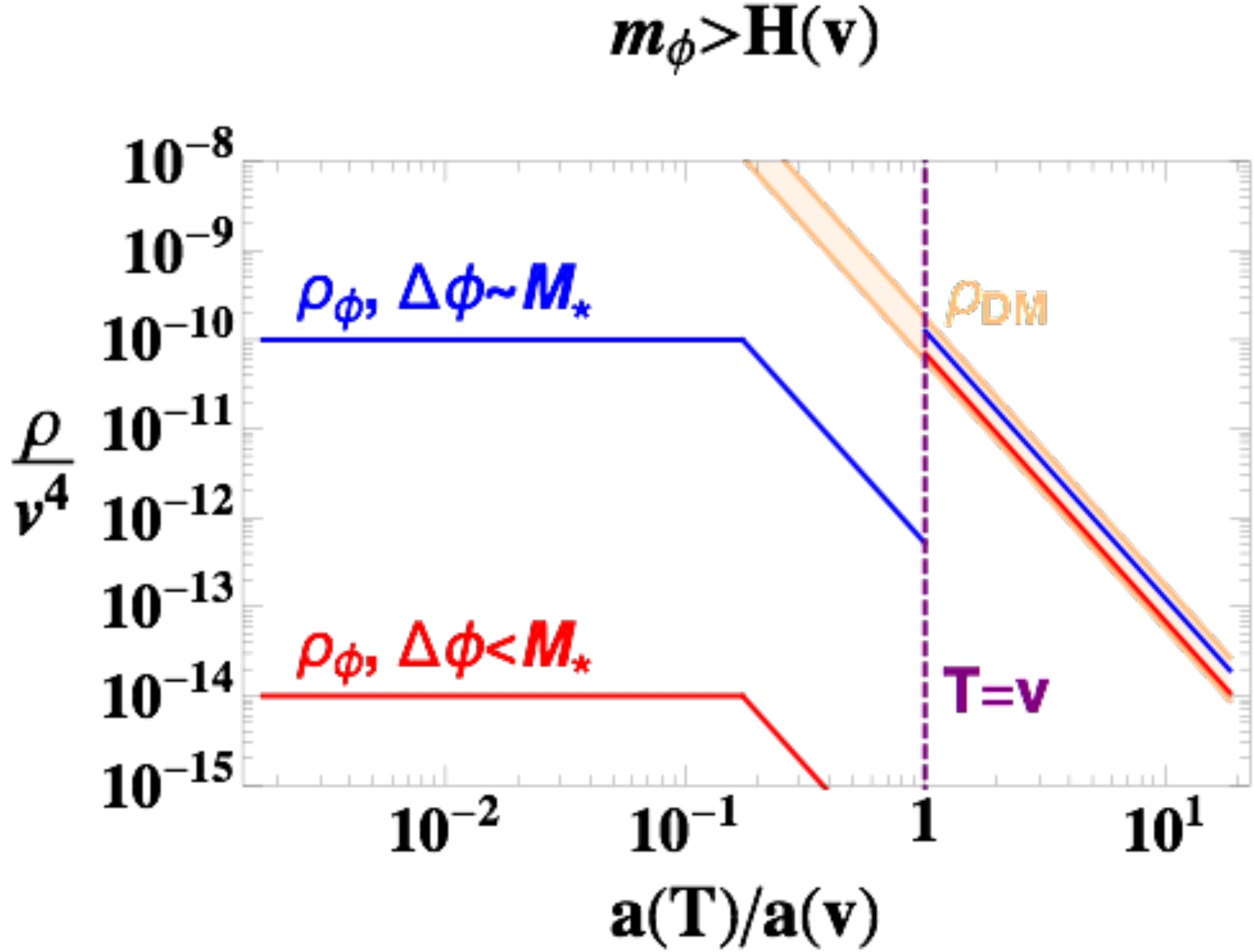
$$\kappa^2 \mu_B^4 \frac{\Delta\phi}{M_*} \sim \kappa^2 \mu^2 \mu_B^2$$

$$\frac{\Delta\phi}{M_*} \sim \frac{\mu^2}{\mu_B^2}$$

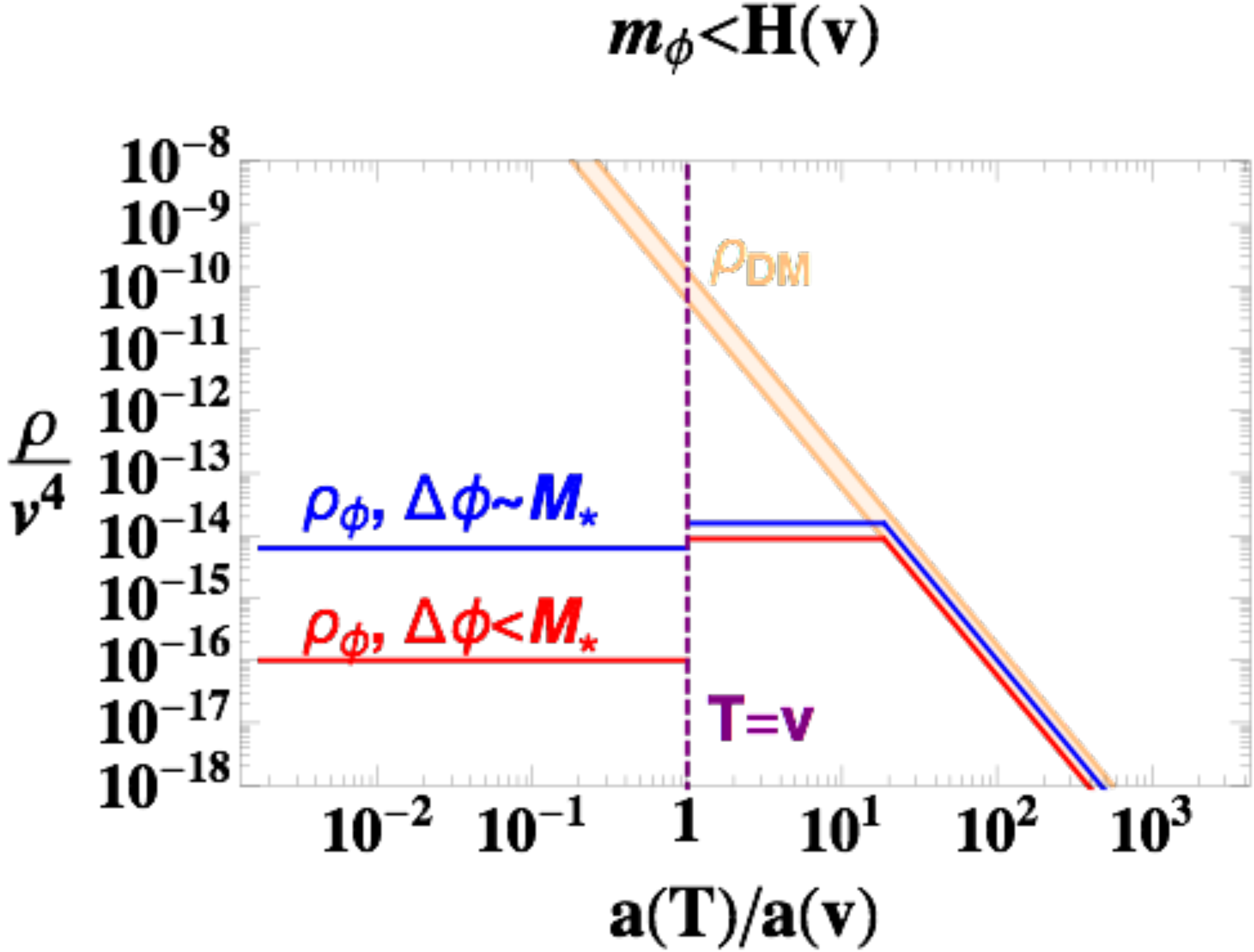
When we are close to the upper bound on mu,

$$\mu \sim \mu_B \qquad \Delta\phi \sim M_*$$

$$\kappa^2 \mu_B^4 \sim \kappa^2 v^4$$



m_ϕ>H(v)
ρ_ϕ, $\Delta\phi$~M_*
ρ_ϕ, $\Delta\phi$<M_*
ρ_{DM}
T=v
$\frac{\rho}{v^4}$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-2}
10^{-1}
1
10^{1}
a(T)/a(v)



m_ϕ<H(v)
$\frac{\rho}{v^4}$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
ρ_{DM}
ρ_ϕ, $\Delta\phi \sim M_*$
ρ_ϕ, $\Delta\phi < M_*$
T=v
10^{-2}
10^{-1}
1
10^{1}
10^{2}
10^{3}
a(T)/a(v)

Sketch for the relic abundance of light scalar dark matter

At the EWPT, the amount of the misaligned energy denstiy : $\kappa^2 v^4$

current dark matter density : $\frac{v^8}{M_{\rm Pl}^4}$

EWPT to matter radiation equality : $\frac{T_{\rm eq}}{T_W} \sim \frac{v^2/M_{\rm Pl}}{v} = \frac{v}{M_{\rm Pl}}$

scalar oscillation : $1/a^3$

radiation : $1/a^4$

Sketch for the relic abundance of light scalar dark matter

$$m_\phi > H(v) \longrightarrow 10^{-5}\ \text{eV}$$

$$\kappa \sim \sqrt{\frac{v}{M_{\text{Pl}}}} \sim 10^{-8}$$

$$m_\phi < H(v)$$

$$T_{\text{eq}} \sim \frac{v^2}{M_{\text{Pl}}}$$

$$T_{\text{osc}} \sim \sqrt{m_\phi M_{\text{Pl}}}$$

$$\kappa^2 v^4 \left(\frac{T_{\text{eq}}}{T_{\text{osc}}}\right)^3 \sim \frac{v^8}{M_{\text{Pl}}^4}$$

$$\kappa \sim \left(\frac{M_*}{M_{\text{Pl}}}\right)^{1/4} \sqrt{\frac{v}{M_{\text{Pl}}}} \lesssim 10^{-8}$$