The Weak Scale as a Trigger

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CAU BSM workshop

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

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

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

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

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

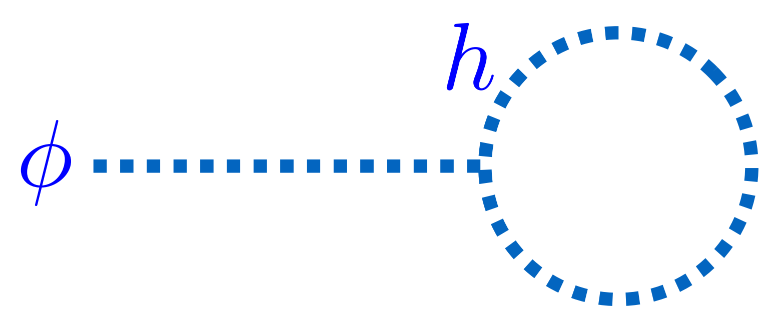
Is there any gauge invariant local operator which has a value sensitive to the Higgs mass parameter?

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

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

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

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

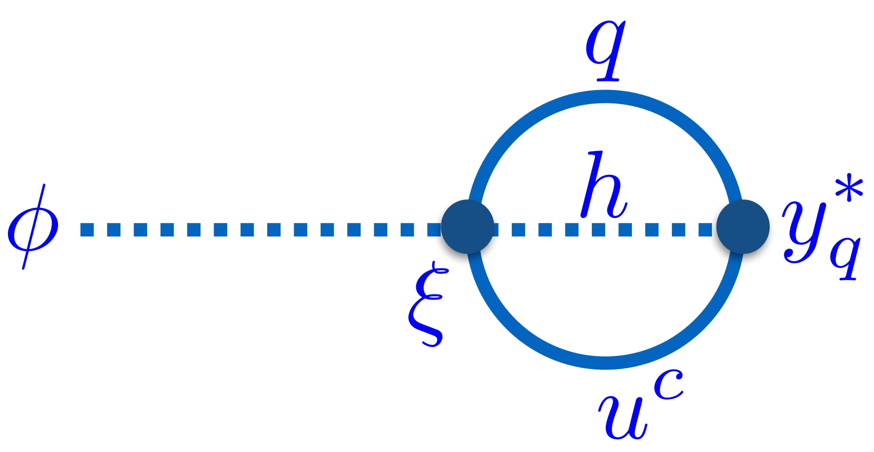
SM

Possible operators?

$$\mathcal{O}_q = qhu^c$$

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

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



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

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

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

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

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

depends on the weak scale and is insensitive to UV

size is too small ⟶ $\Lambda_* \sim (100 \text{ keV})^4$ 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

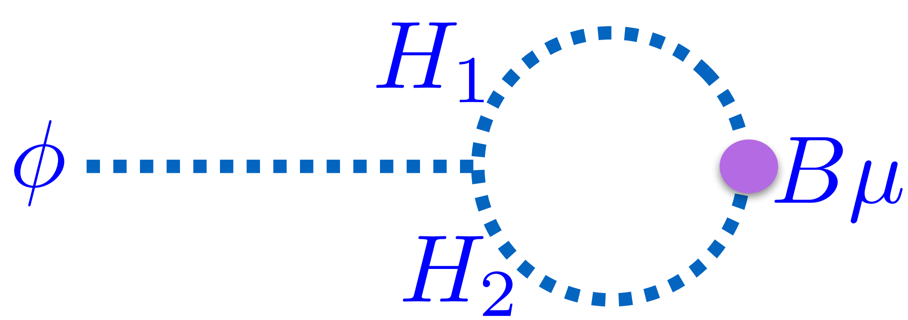
	PQ Q	$\mathbb{Z}_2$
$H_1 H_2$	$+1$	$-$
$B\mu$	-1	$-$
λ_6	-1	$-$
λ_7	-1	$-$
λ_5	-2	$+$

forbidden by Z2 → $B\mu$, λ_6, λ_7

$$H_1 \to +iH_1, H_2 \to +iH_2,$$
$$(H_1 H_2) \to -(H_1 H_2),$$
$$(qu^c) \to +i(qu^c),$$
$$(qd^c) \to -i(qd^c),$$
$$(le^c) \to -i(le^c).$$

$$-\mathcal{L} \supset m_{H_2}^2 |H_2|^2 + m_{H_1}^2 |H_1|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4$$
$$+ \lambda_3 |H_2|^2 |H_1|^2 + \lambda_4 |H_1 H_2|^2 + (\frac{\lambda_5}{2}(H_1 H_2)^2 + \text{h.c.})$$

Peccei-Quinn symmetry is explicitly broken



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

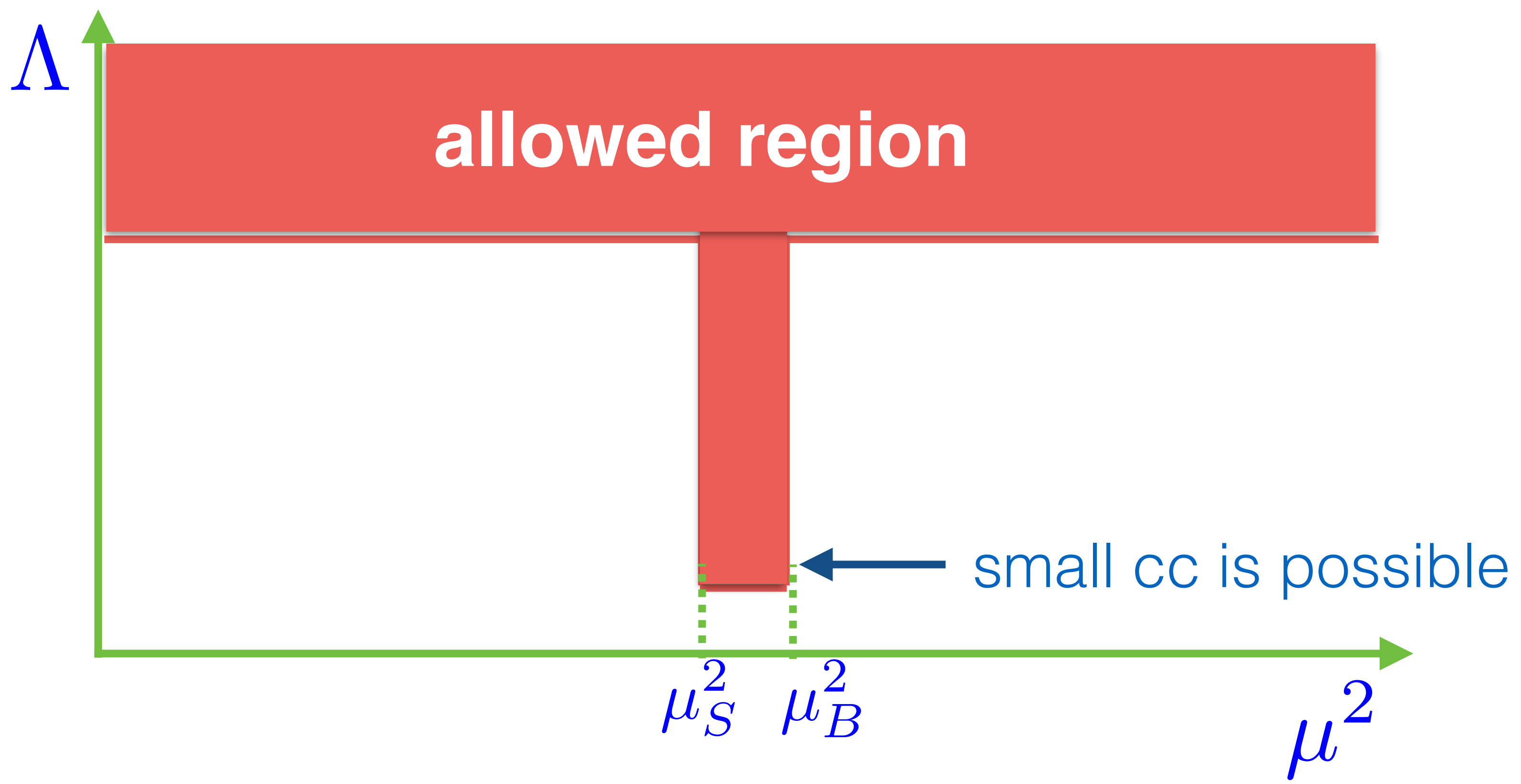
$B\mu$ generates tadpole and should be forbidden

Weak scale as a trigger

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

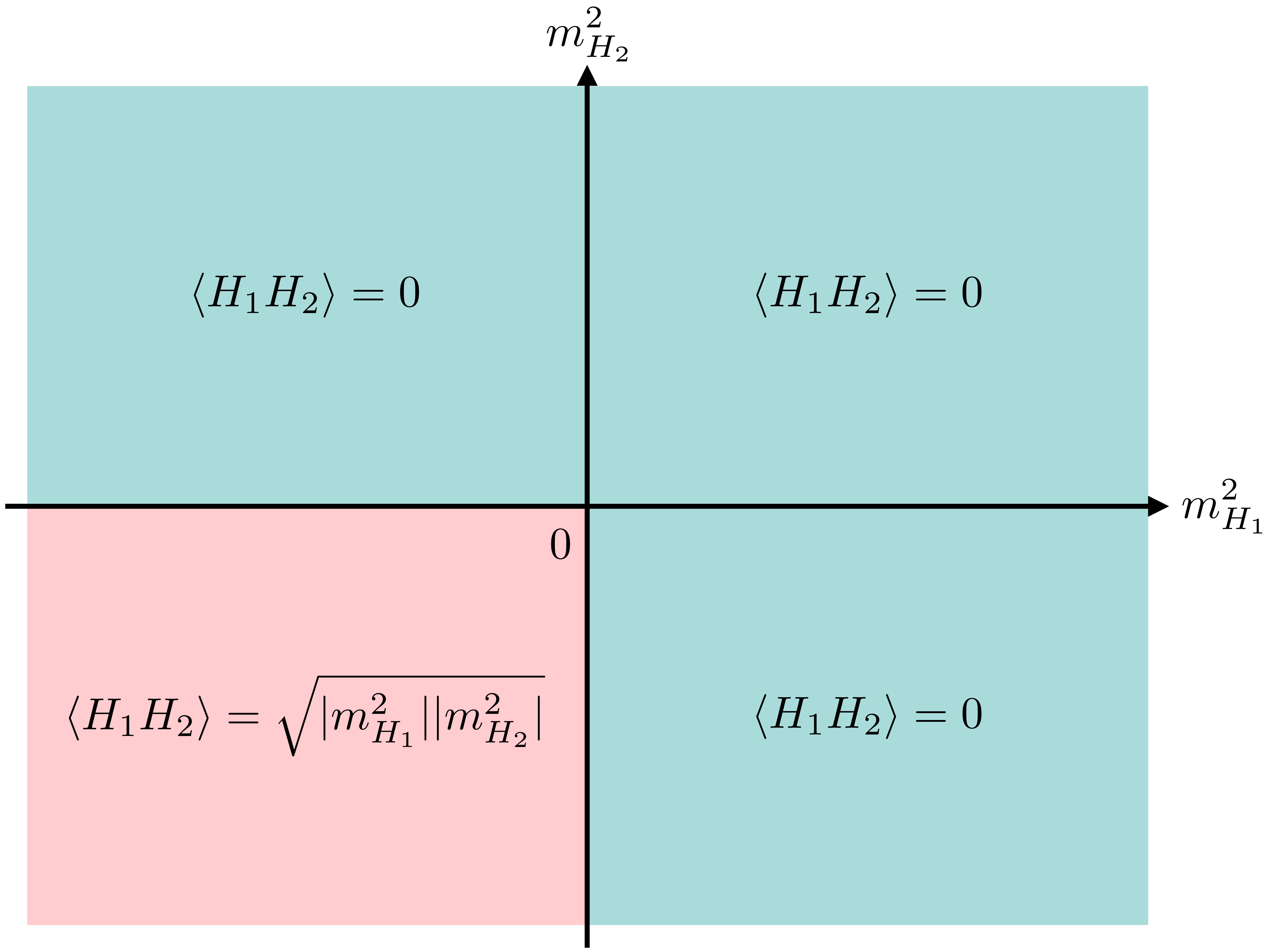
as a function of m_h^2

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)

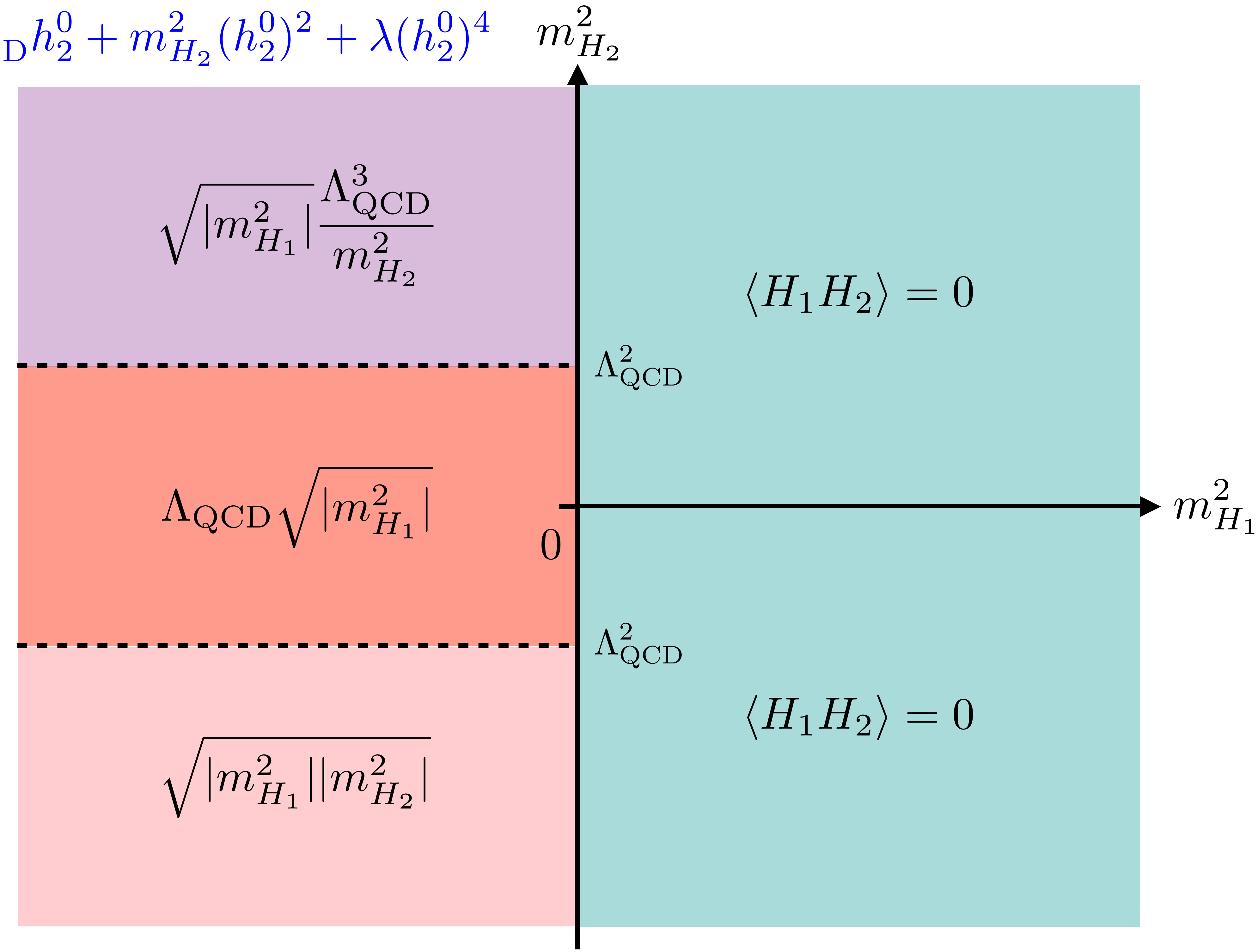
(quartic couplings are taken to be order one)

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

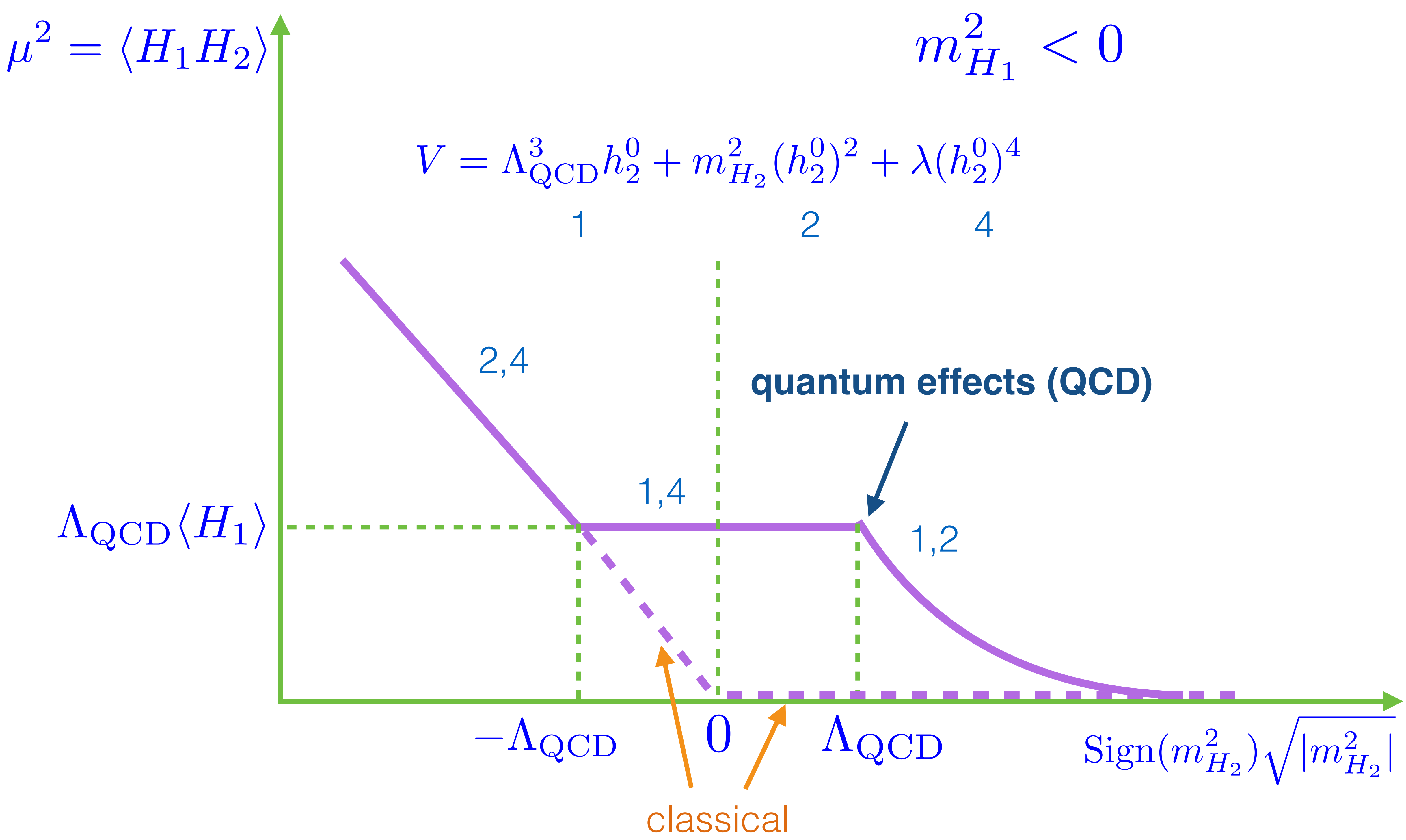
$$h_2^0 \sim \frac{\Lambda_{\rm QCD}^3}{m_{H_2}^2}$$

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

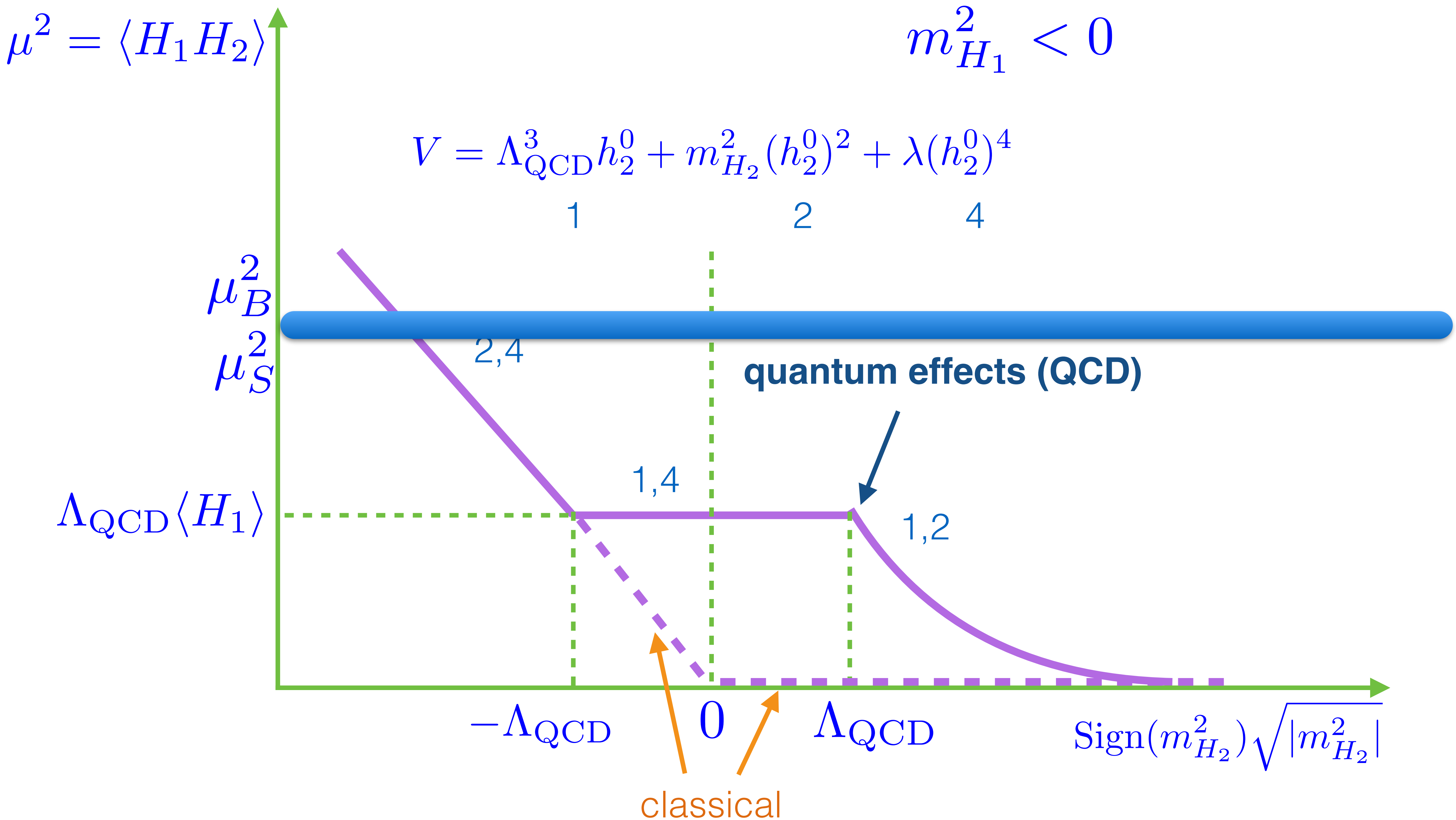
$$h_2^0 \sim \frac{\Lambda_{\rm QCD}}{\lambda^{1/3}}$$



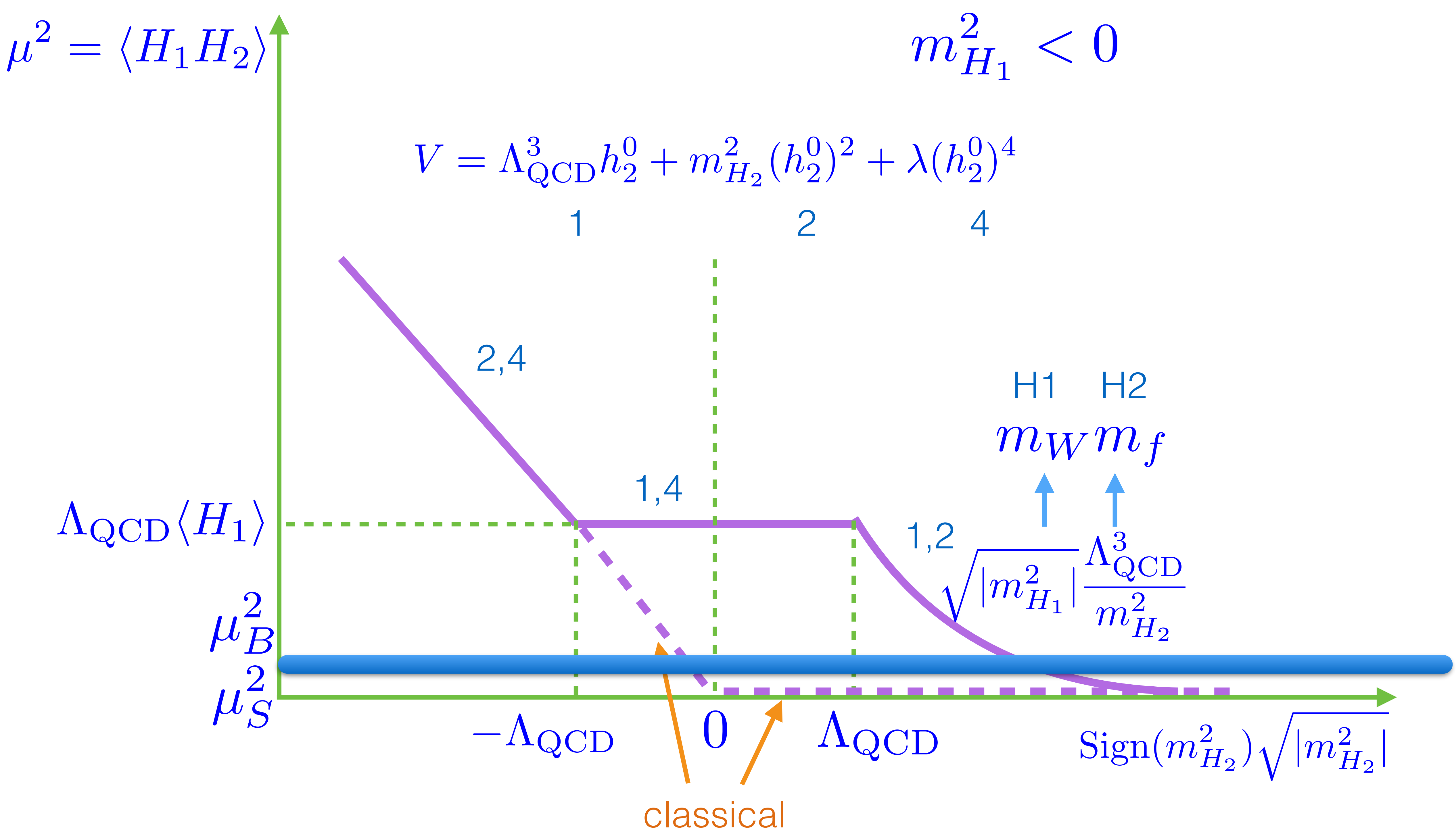
Triggering parameter



Universe including ours



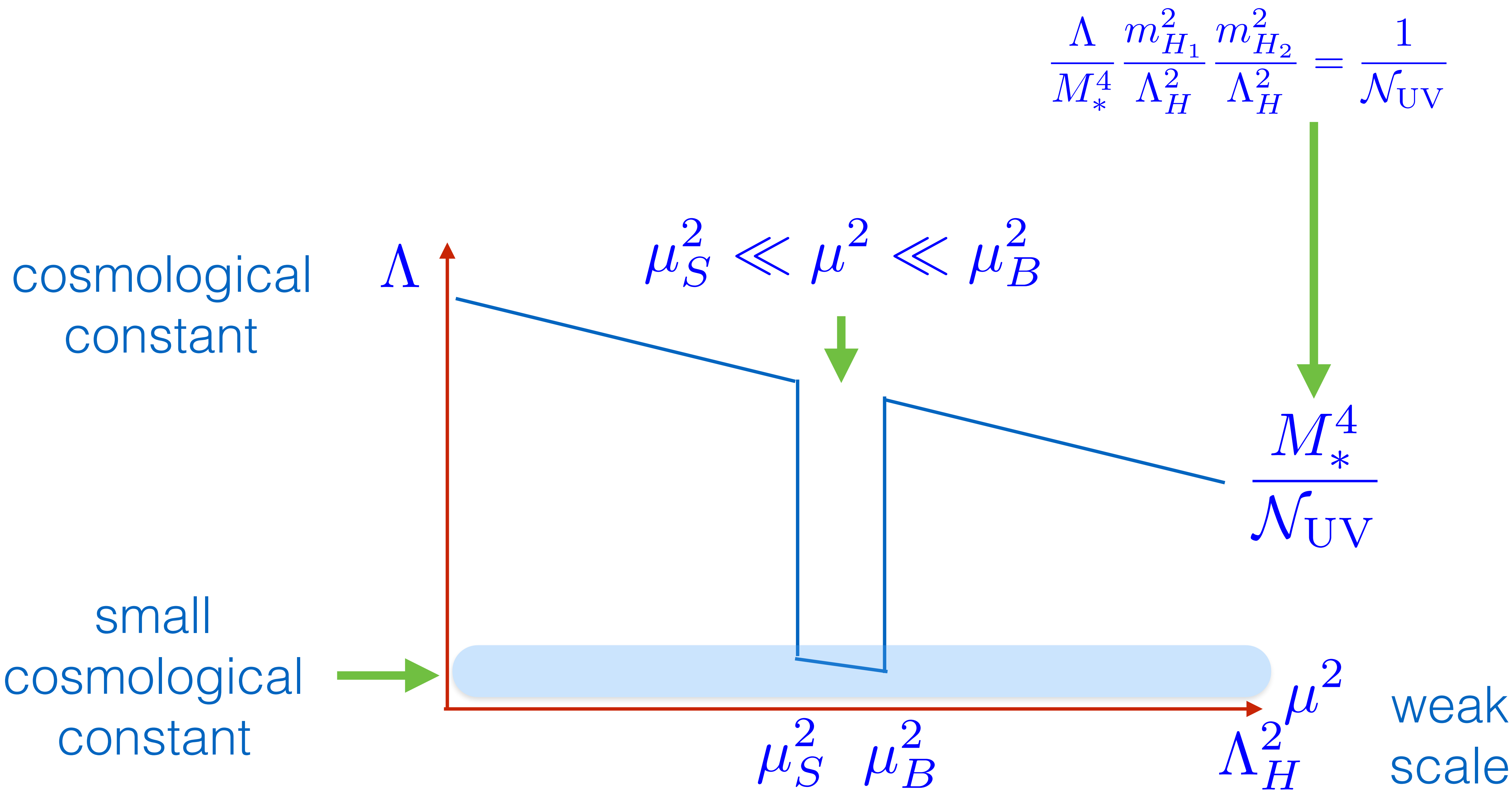
Strange universe with $\Lambda \sim (\frac{v}{\Lambda_H})^4 \Lambda_{\rm us}$ for the atom formation



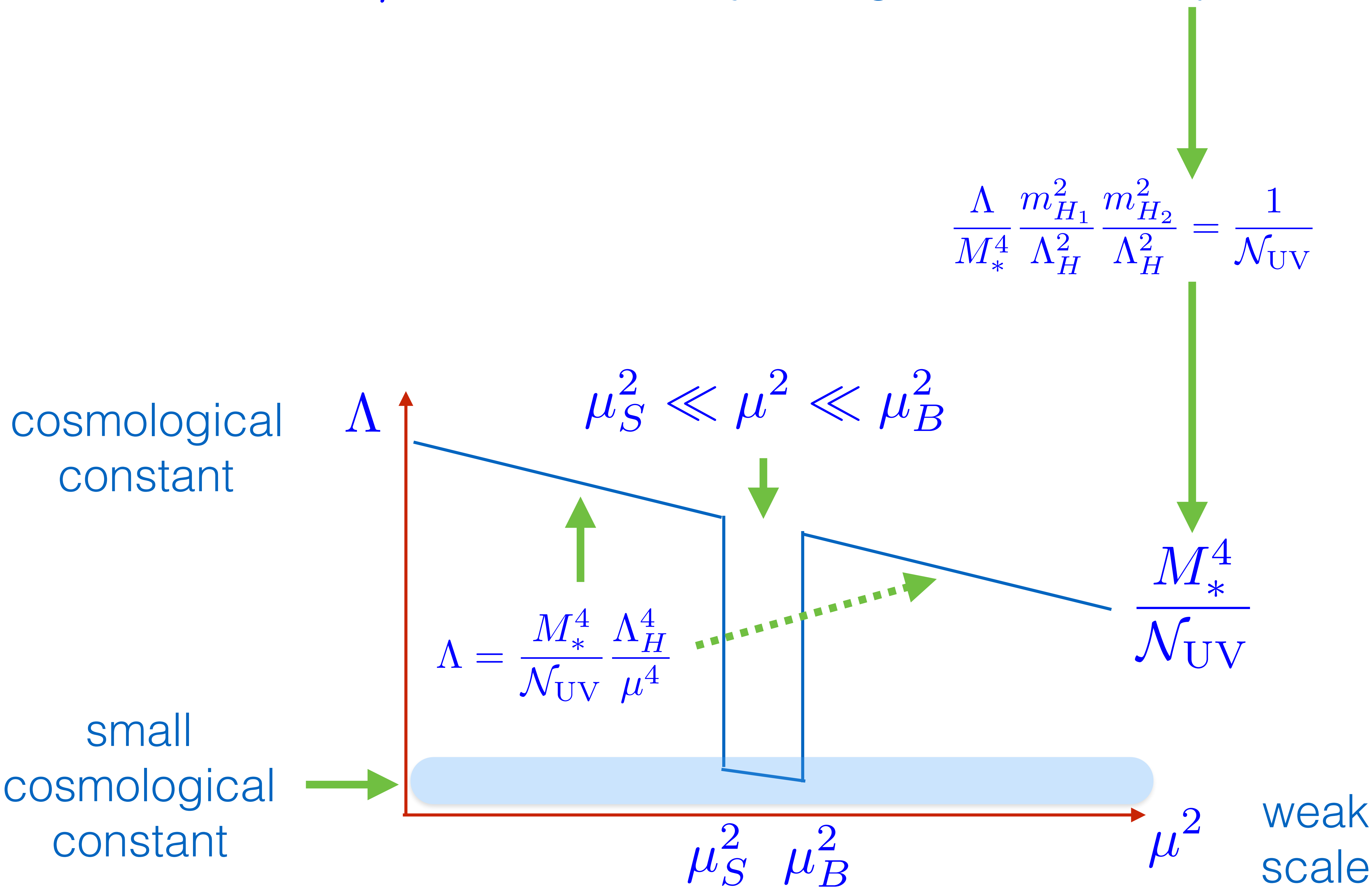
Weak scale as a trigger

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

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

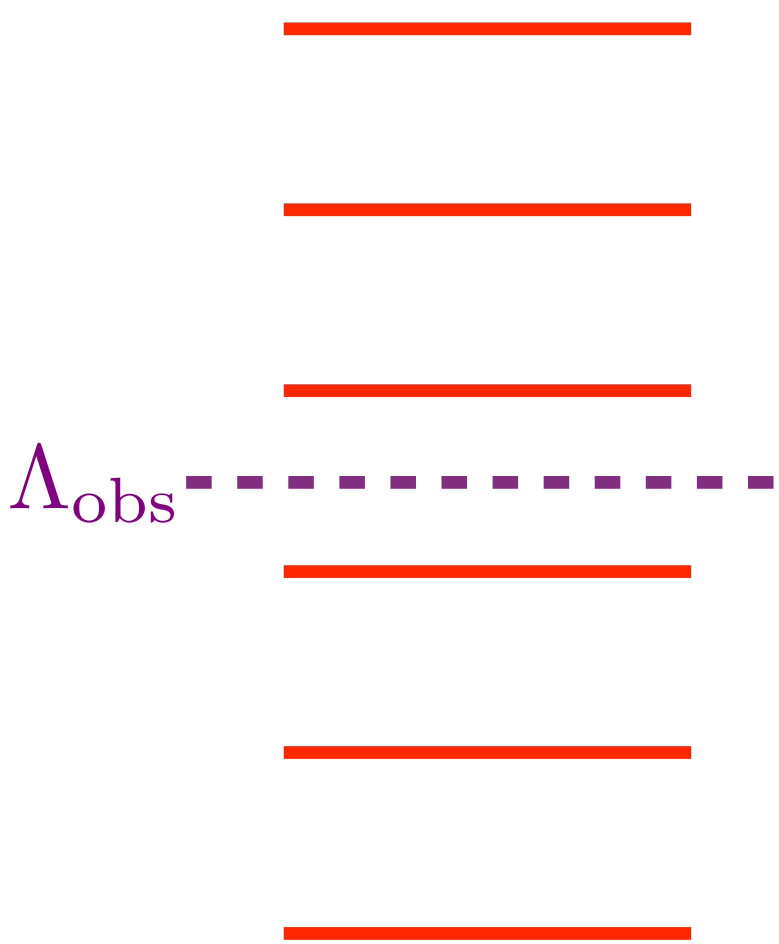
$$\Lambda \sim 10^{-120} M_{\rm Pl}^4$$

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

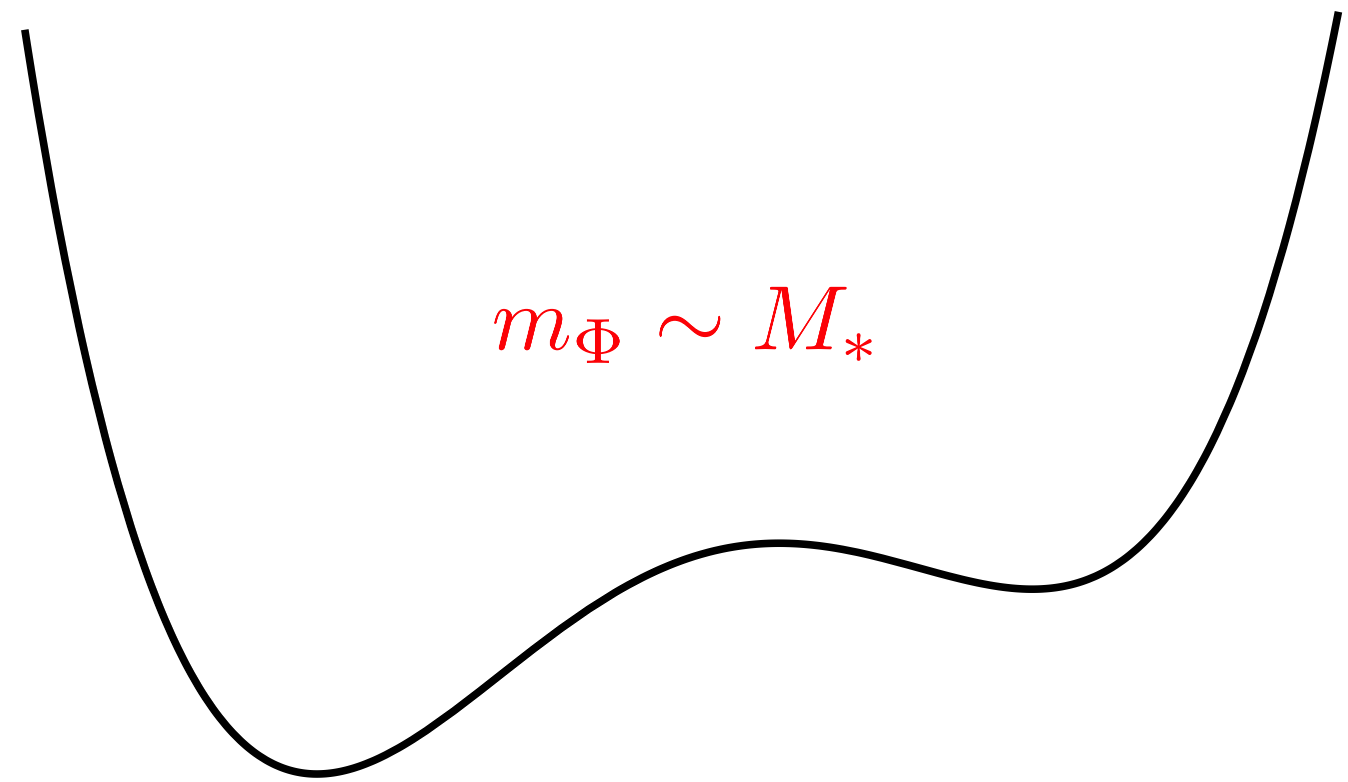
We need at least 10^{150} vacua to explain two small parameters

High Energy Landscape

Values of the CC in the Landscape



V_Φ



$$V_\Phi = \sum_{i=1}^{N_1} \left[\frac{M_i^2}{2} \Phi_i^2 + A_i \Phi_i^3 + \frac{\lambda_i}{4} \Phi_i^4 + \underline{M_{H,i}^2 \frac{\Phi_i}{M_*} |H|^2} + \ldots \right] .$$

m_H^2 scans

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

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

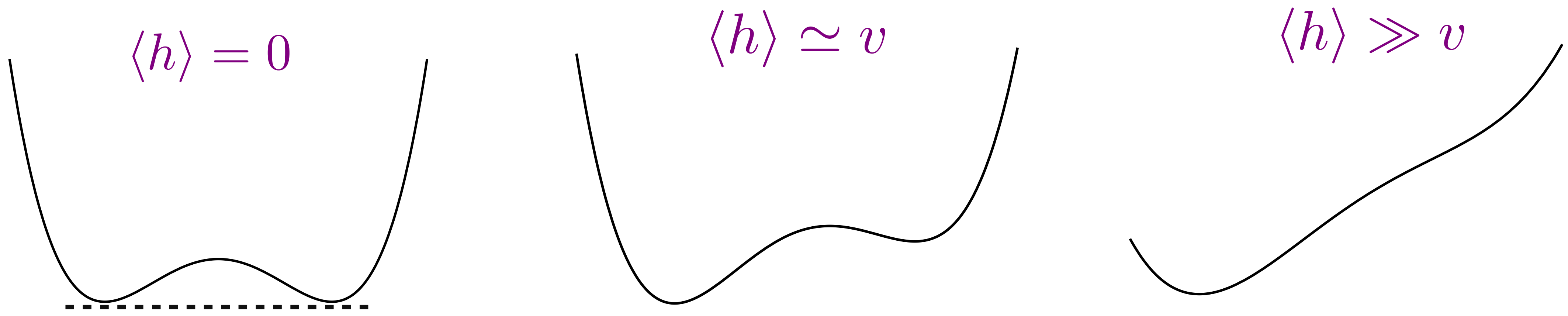
$$\Lambda_{\mathrm{cc}} \sim 10^{-120}$$

not possible in the HE landscape

Low Energy Landscape

$$V^{(I)} = \sum_i \epsilon^2(\phi_i^2 - M_*^2)^2 + \epsilon\kappa M_* \phi_i H_1 H_2 + V_H^{(I)},$$

$$V_H^{(I)} = (m_1^2)^{(I)}|H_1|^2 + (m_2^2)^{(I)}|H_2|^2 + \text{quartics} + q\lambda_u u^c H_1^* + q\lambda_d d^c H_1 + l\lambda_e e^c H_1 + \Lambda^{(I)}$$



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

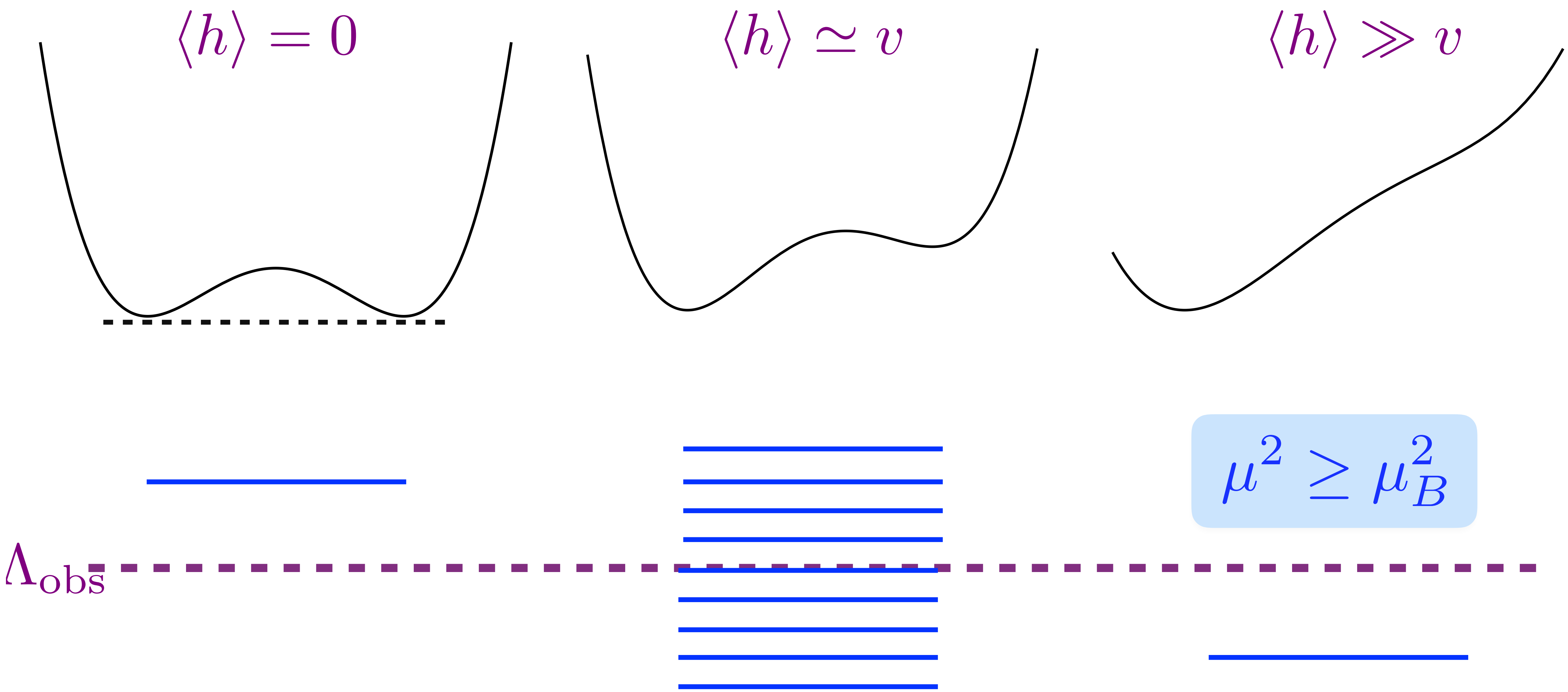
$$\mu^2 = \langle \mathcal{O} \rangle$$

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

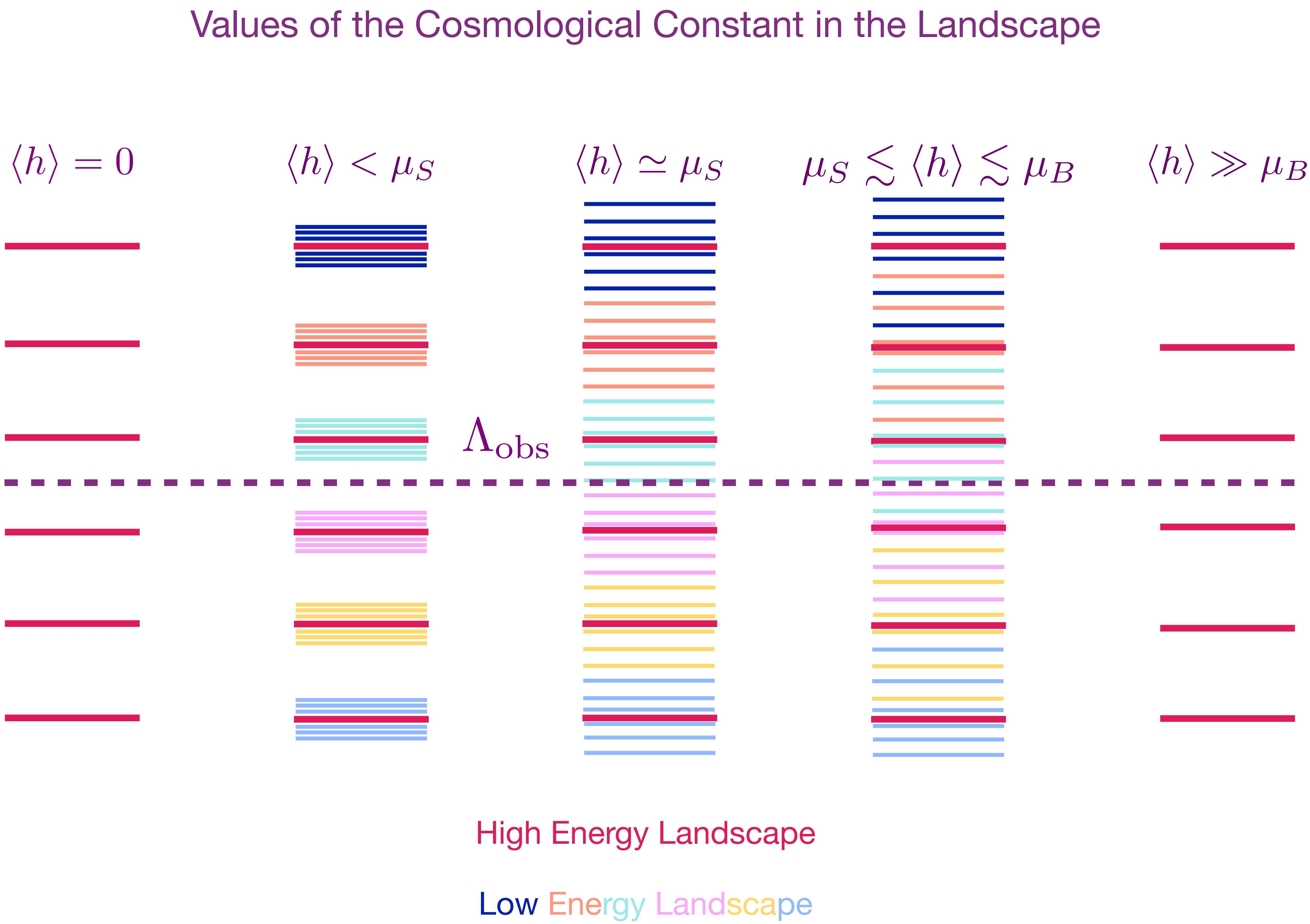
$\mu < \mu_S$ → hyperfine splitting of the scanning and it doesn't help to reduce the cc

Low Energy Landscape

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



$$V_\phi = \sum_{i=1}^{N_2} \frac{\epsilon_i^2}{4}\left(\phi_i^2 - M_{*,i}^2\right)^2 + \left(\sum_{i=1}^{N_2} \frac{\kappa_i \epsilon_i M_{*,i}^{3-\Delta_T}}{\sqrt{N_2}} \phi_i \mathcal{O}_T + \text{h.c.}\right)$$



Values of the Cosmological Constant in the Landscape
$\langle h \rangle = 0$
$\langle h \rangle < \mu_S$
$\langle h \rangle \simeq \mu_S$
$\mu_S \lesssim \langle h \rangle \lesssim \mu_B$
$\langle h \rangle \gg \mu_B$
Λ_{obs}
High Energy Landscape
Low Energy Landscape

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

$$\downarrow$$

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

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

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

splitting by the trigger

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

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

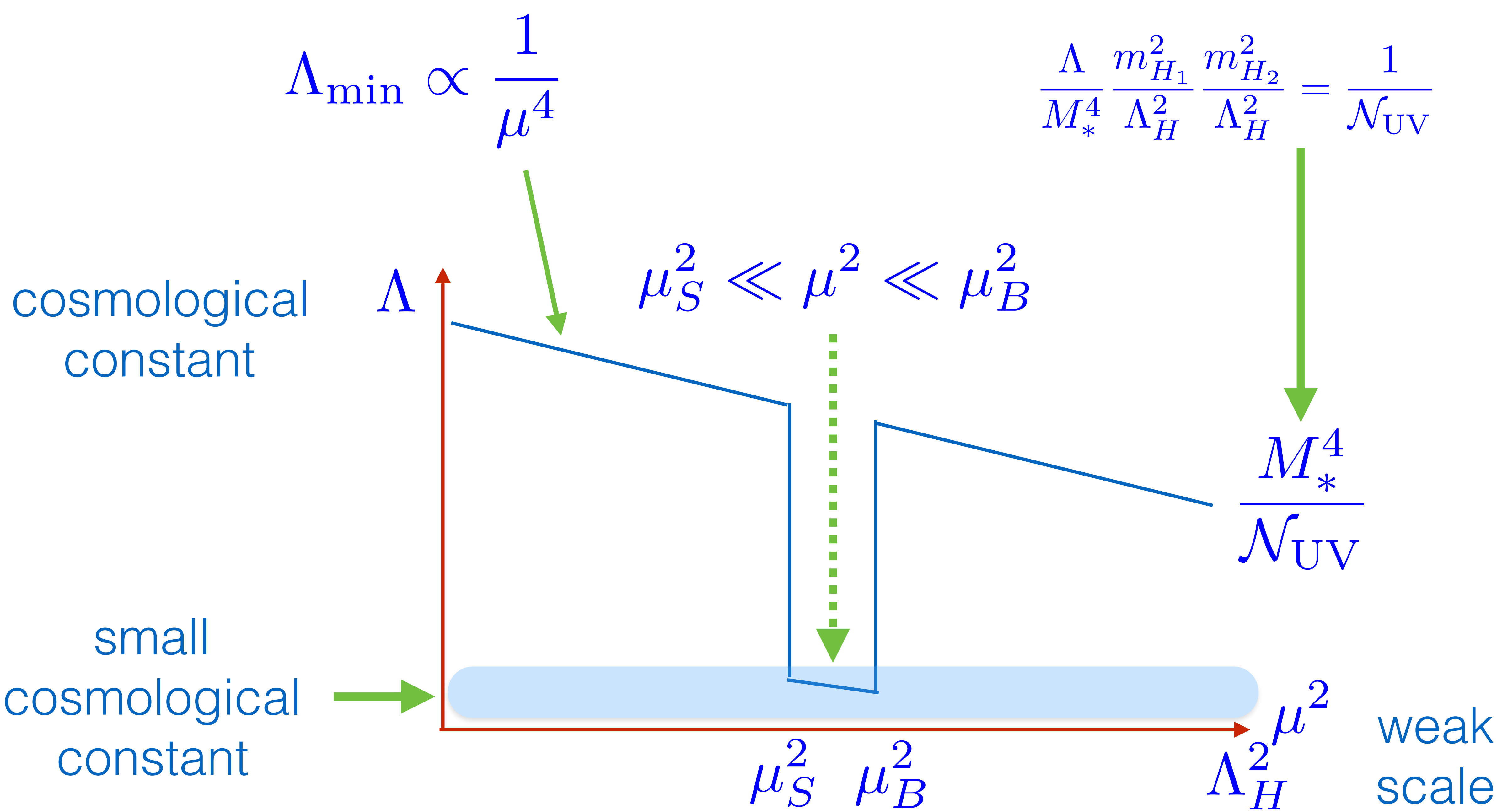
$$\frac{\Lambda_H^8 M_*^4}{v^{12}} \ll \mathcal{N}_{\text{UV}} \ll 10^{120}\frac{\Lambda_H^2}{v^2} \longrightarrow \Lambda_H \ll 10^{12}\ \text{GeV}$$

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

Weak scale as a trigger

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

as a function of m_h^2



A possibility of entirely different universe

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

weak scale $\mu^2 = \Lambda_H \dfrac{\Lambda_{\rm QCD}^3}{m_{H_2}^2}$

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

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

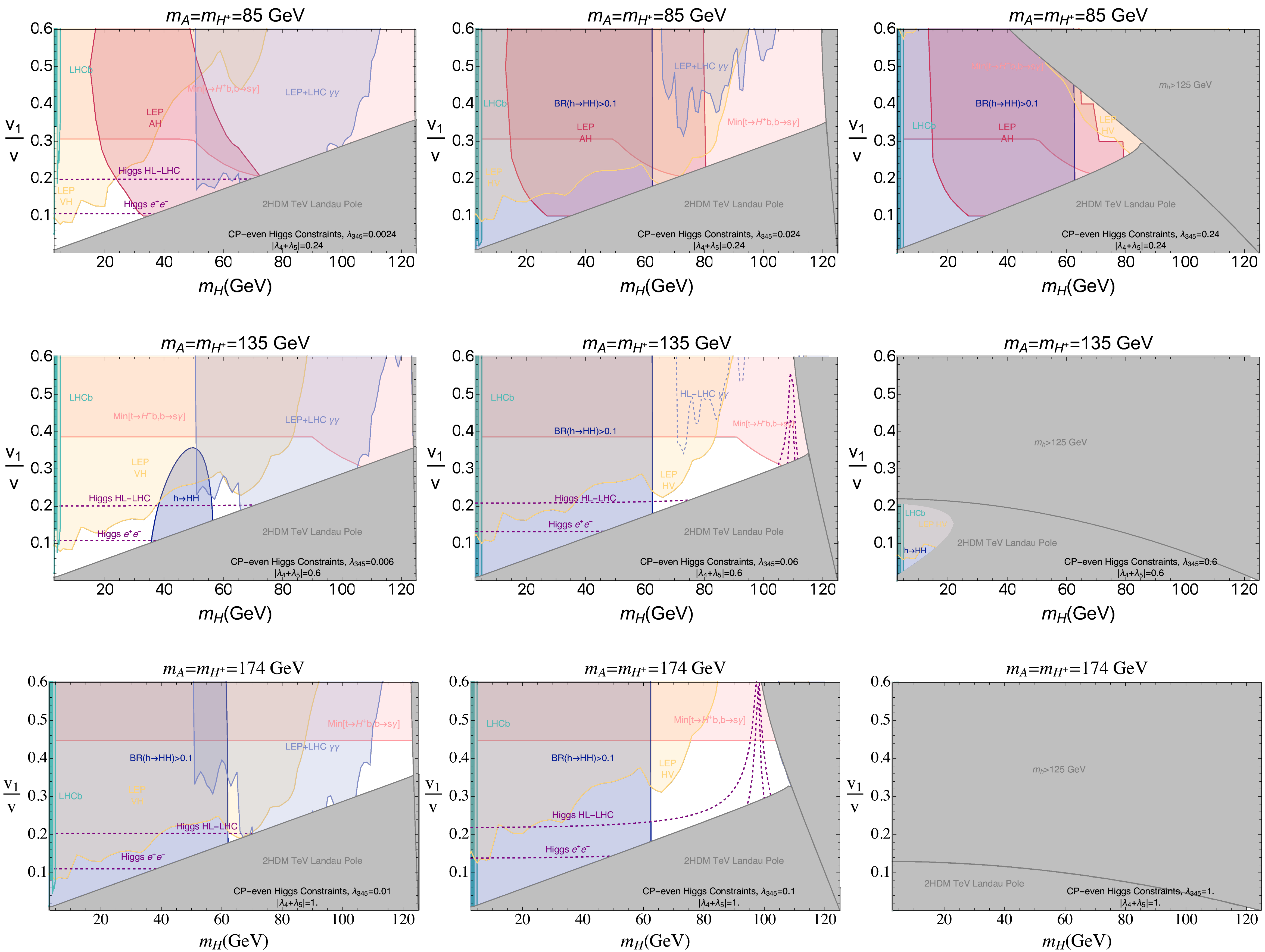
condition for IR scan ⟶ $\mathcal{N}_{\rm UV} > \dfrac{1}{\kappa^2}\dfrac{\Lambda_H M_*^4}{\Lambda_{\rm QCD}^3 \mu_B^2}$

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

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

The weak scale as a trigger

I. Type 0 2HDM



m_A=m_{H^+}=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, λ_{345}=0.0024
$|\lambda_4+\lambda_5|$=0.24
m_A=m_{H^+}=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, λ_{345}=0.024
$|\lambda_4+\lambda_5|$=0.24
m_A=m_{H^+}=85 GeV
m_h>125 GeV
LHCb
BR(h→HH)>0.1
LEP AH
LEP HV
2HDM TeV Landau Pole
CP–even Higgs Constraints, λ_{345}=0.24
$|\lambda_4+\lambda_5|$=0.24
m_A=m_{H^+}=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, λ_{345}=0.006
$|\lambda_4+\lambda_5|$=0.6
m_A=m_{H^+}=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, λ_{345}=0.06
$|\lambda_4+\lambda_5|$=0.6
m_A=m_{H^+}=135 GeV
m_h>125 GeV
LHCb
h→HH
2HDM TeV Landau Pole
CP–even Higgs Constraints, λ_{345}=0.6
$|\lambda_4+\lambda_5|$=0.6
m_A=m_{H^+}=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, λ_{345}=0.01
$|\lambda_4+\lambda_5|$=1.
m_A=m_{H^+}=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, λ_{345}=0.1
$|\lambda_4+\lambda_5|$=1.
m_A=m_{H^+}=174 GeV
m_h>125 GeV
2HDM TeV Landau Pole
CP–even Higgs Constraints, λ_{345}=1.
$|\lambda_4+\lambda_5|$=1.
$\frac{v_1}{v}$
m_H(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 $B\mu_{\rm eff} \geq \frac{v^4}{M_{\rm Pl}^2}$

Scalar dark matter from the electroweak phase transition

Misalignment of the light scalar provides a dark matter

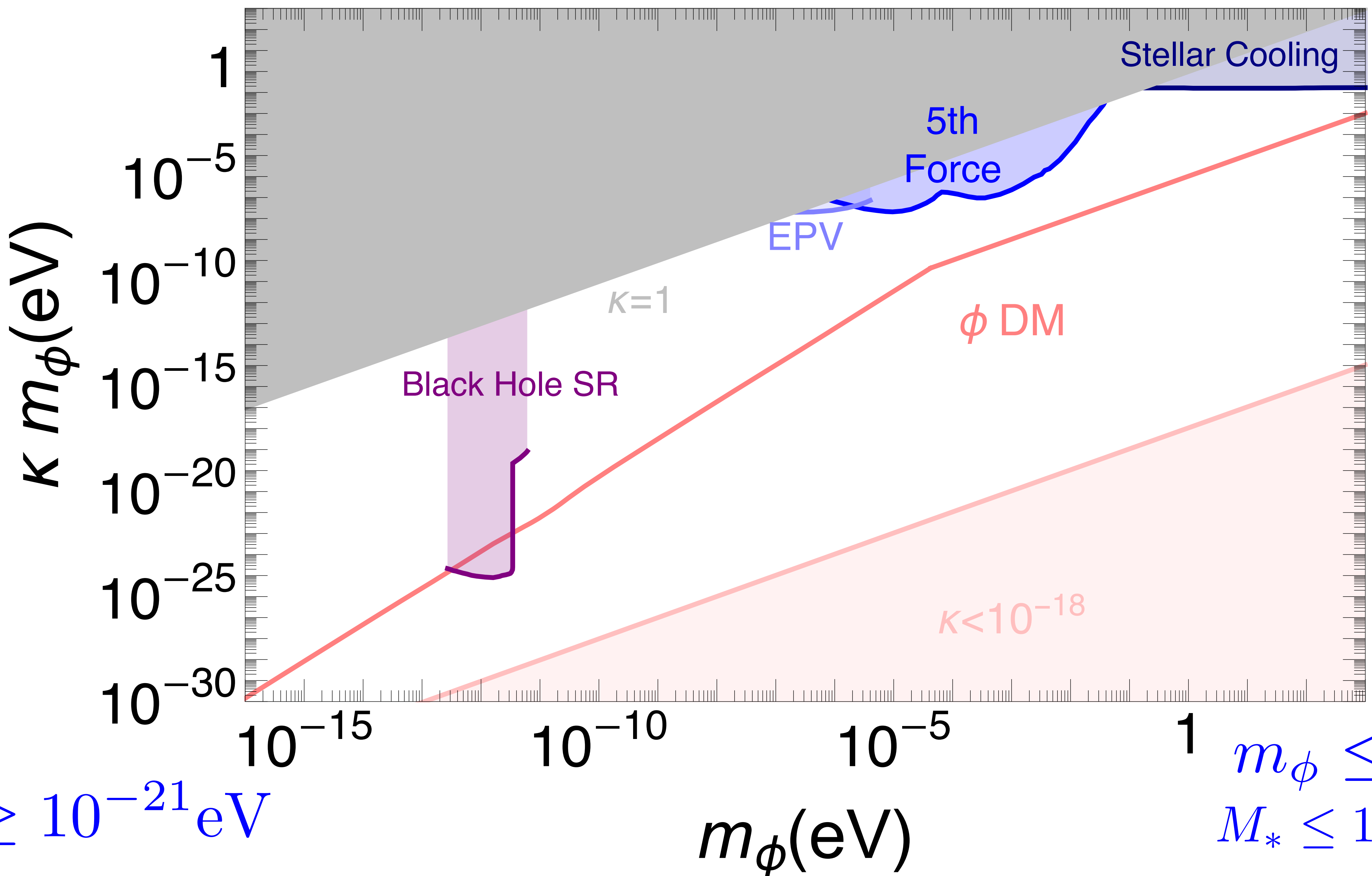
$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + c\langle\phi\rangle_T \langle H_1 H_2\rangle_T = 0$$

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



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

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

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

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)

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 : $m_H \leq m_h$

$$\begin{pmatrix} \lambda_1 v_1^2 & \lambda_{345} v_1 v_2 \\ \lambda_{345} v_1 v_2 & \lambda_2 v_2^2 \end{pmatrix}$$

$$\downarrow v_1 \ll v_2$$

$$m_h^2 = \lambda_2 v_2^2$$ 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

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

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

Fermion couplings of H have double suppression

Fermio-phobic H

$$\lambda_{345} = 0$$

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

Basics of Type 0 2HDM

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

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

$$g_{A\psi\psi} \simeq \pm g_{h\psi\psi}^{\text{SM}} \frac{v_1}{v}$$

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

Gauge phobic H

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

↓

$$g_{HVV} = 0$$

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

$$\frac{g_{hVV} - g_{hVV}^{\rm SM}}{g_{hVV}^{\rm SM}} \simeq -\frac{v_1^2}{2v^2}\left(1 - \frac{\lambda_{345}v^2}{m_h^2 - m_H^2}\right)^2$$

$$\frac{g_{h\psi\psi} - g_{h\psi\psi}^{\rm SM}}{g_{h\psi\psi}^{\rm SM}} \simeq -\frac{v_1^2}{2v^2}\left(1 - \frac{\lambda_{345}^2 v^4}{\left(m_h^2 - m_H^2\right)^2}\right)$$

The deviation can be made to be small by choosing the ratio to be 1

$$\lambda_{345}v^2 = m_h^2 - m_H^2$$

Basics of Type 0 2HDM

CP even Higgs H is predicted to be lighter than h

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

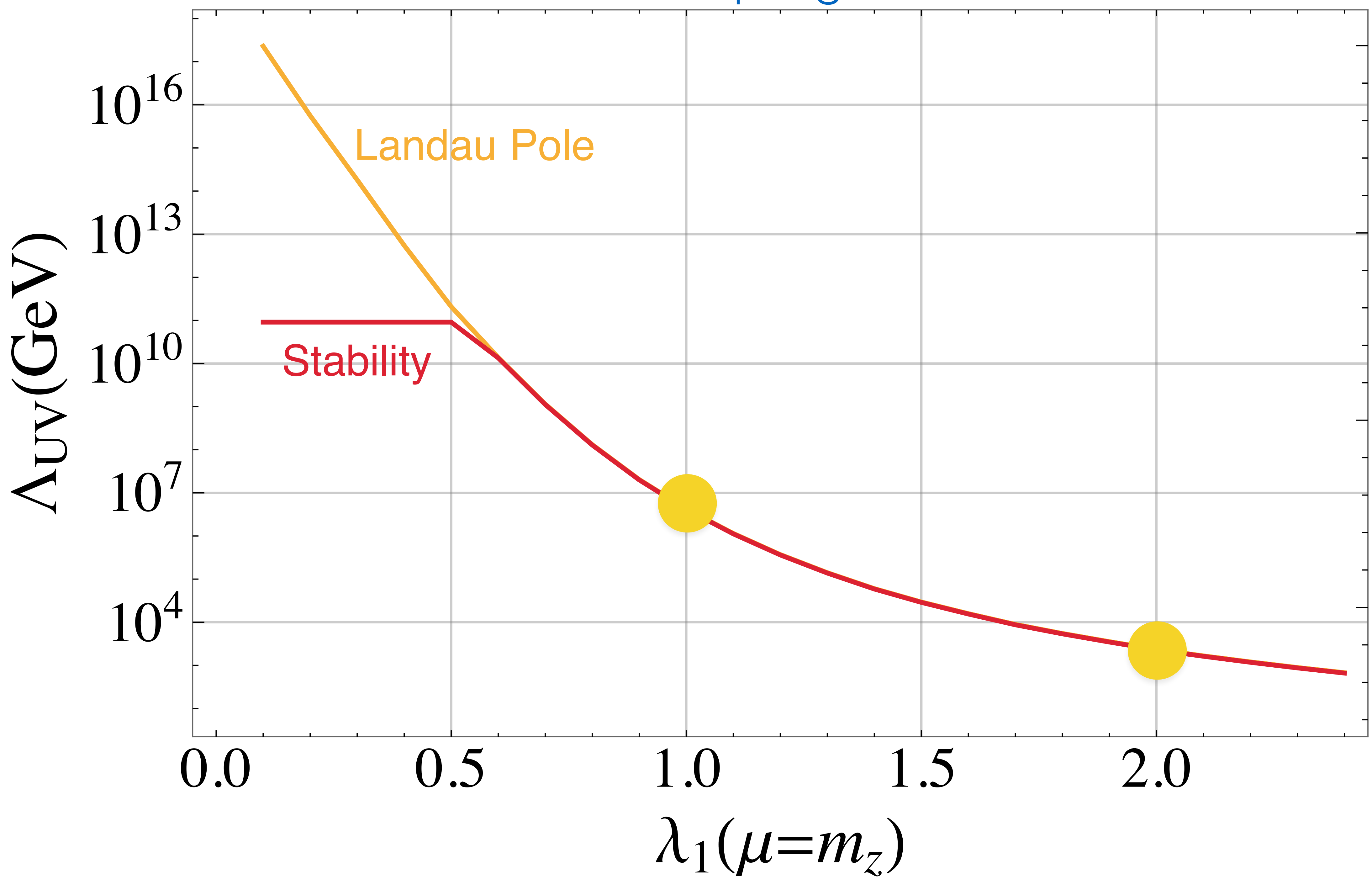
Charged Higgs and CP odd Higgs are lighter than 200 GeV

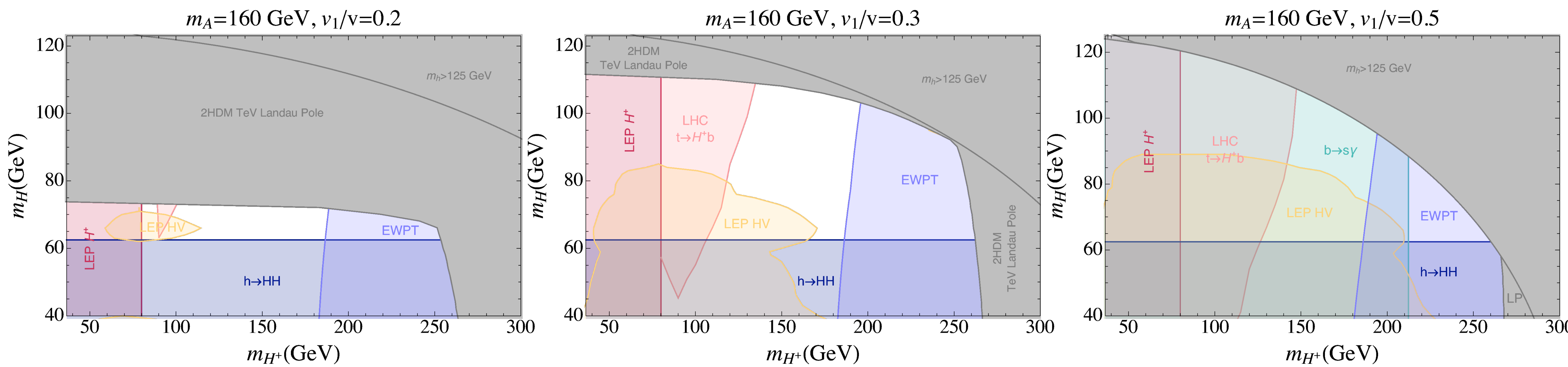
$$m_{H_\pm}, m_A \leq 250~\mathrm{GeV} \quad \longleftarrow \quad \Lambda_{UV} = 500~\mathrm{GeV}$$

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

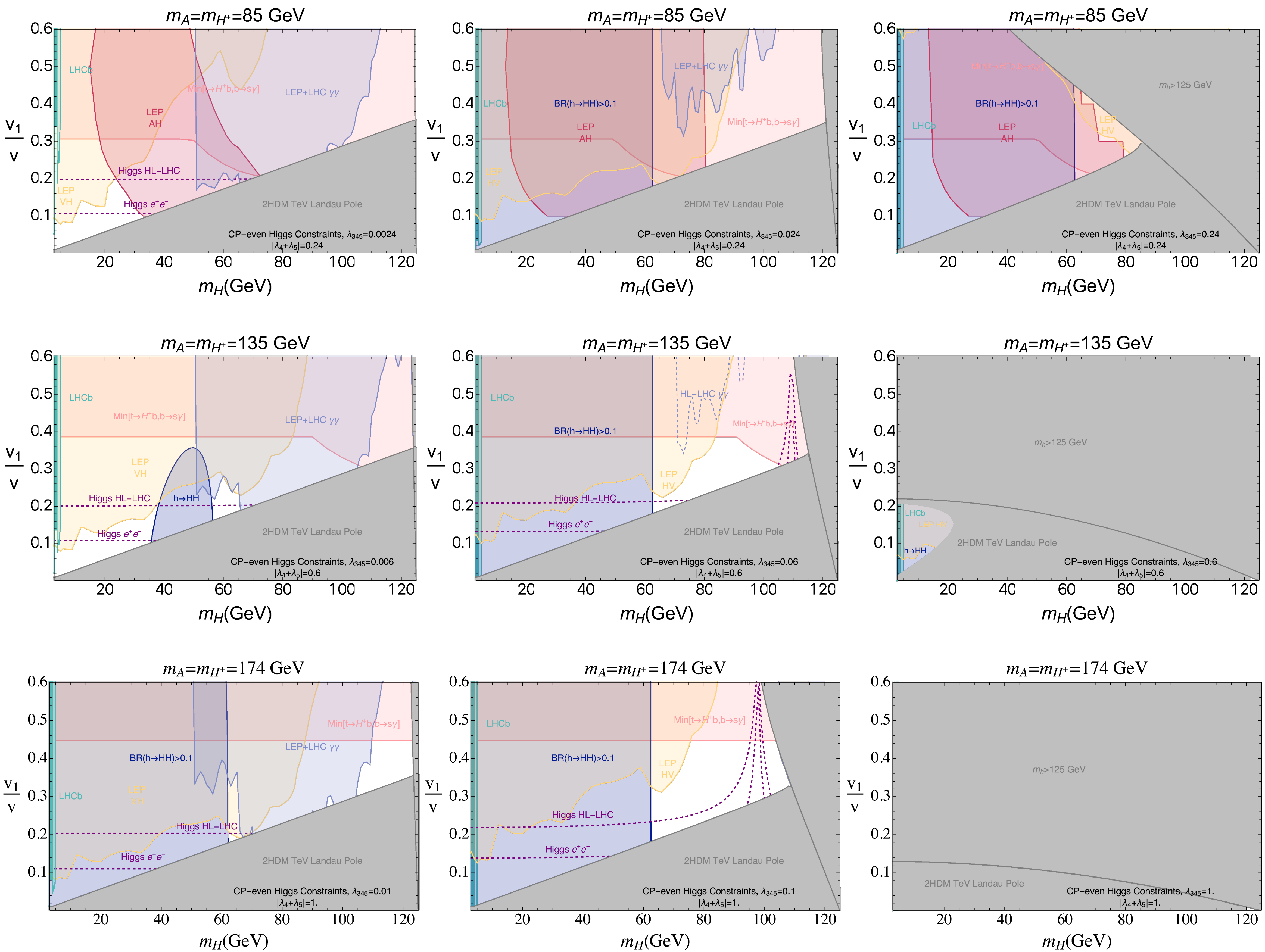
UV cutoff from Landau pole

The scale of Landau pole depending on the couplings





m_A=160 GeV, v_1/v=0.2
m_h>125 GeV
2HDM TeV Landau Pole
LEP HV
LEP H^+
EWPT
h→HH
m_H(GeV)
m_{H^+}(GeV)
m_A=160 GeV, v_1/v=0.3
2HDM
TeV Landau Pole
m_h>125 GeV
LEP H^+
LHC
t→H^+b
EWPT
LEP HV
h→HH
2HDM
TeV Landau Pole
m_H(GeV)
m_{H^+}(GeV)
m_A=160 GeV, v_1/v=0.5
m_h>125 GeV
LEP H^+
LHC
t→H^+b
b→sγ
LEP HV
EWPT
h→HH
LP
m_H(GeV)
m_{H^+}(GeV)



$m_A=m_{H^\pm}$=85 GeV
LHCb
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LEP+LHC γγ
Higgs HL-LHC
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CP-even Higgs Constraints, λ_{345}=0.0024
$|\lambda_4+\lambda_5|$=0.24
$m_A=m_{H^\pm}$=85 GeV
LEP+LHC γγ
LHCb
BR(h→HH)>0.1
Min[t→H^+b,b→sγ]
LEP AH
LEP HV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=0.024
$|\lambda_4+\lambda_5|$=0.24
$m_A=m_{H^\pm}$=85 GeV
m_h>125 GeV
BR(h→HH)>0.1
LHCb
LEP AH
LEP HV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=0.24
$|\lambda_4+\lambda_5|$=0.24
$m_A=m_{H^\pm}$=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, λ_{345}=0.006
$|\lambda_4+\lambda_5|$=0.6
$m_A=m_{H^\pm}$=135 GeV
LHCb
HL-LHC γγ
BR(h→HH)>0.1
Min[t→H^+b,b→sγ]
LEP HV
Higgs HL-LHC
Higgs e^+e^-
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=0.06
$|\lambda_4+\lambda_5|$=0.6
$m_A=m_{H^\pm}$=135 GeV
m_h>125 GeV
LHCb
h→HH
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=0.6
$|\lambda_4+\lambda_5|$=0.6
$m_A=m_{H^\pm}$=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, λ_{345}=0.01
$|\lambda_4+\lambda_5|$=1.
$m_A=m_{H^\pm}$=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, λ_{345}=0.1
$|\lambda_4+\lambda_5|$=1.
$m_A=m_{H^\pm}$=174 GeV
m_h>125 GeV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ_{345}=1.
$|\lambda_4+\lambda_5|$=1.
$\frac{v_1}{v}$
m_H(GeV)

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

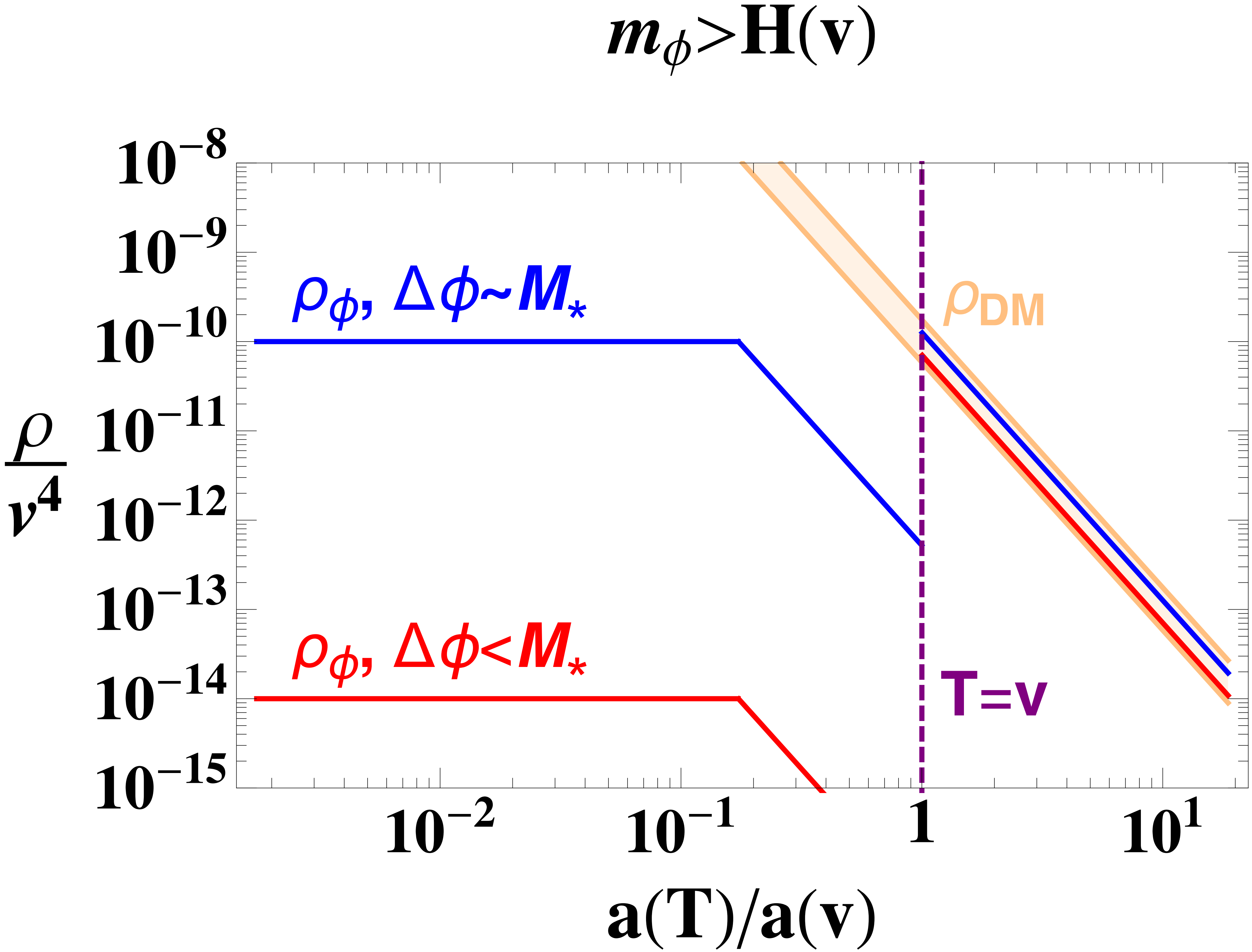
$$\kappa^2 \mu_B^4 \frac{\Delta\phi}{M_*} \sim \kappa^2 \mu^2 \mu_B^2$$

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

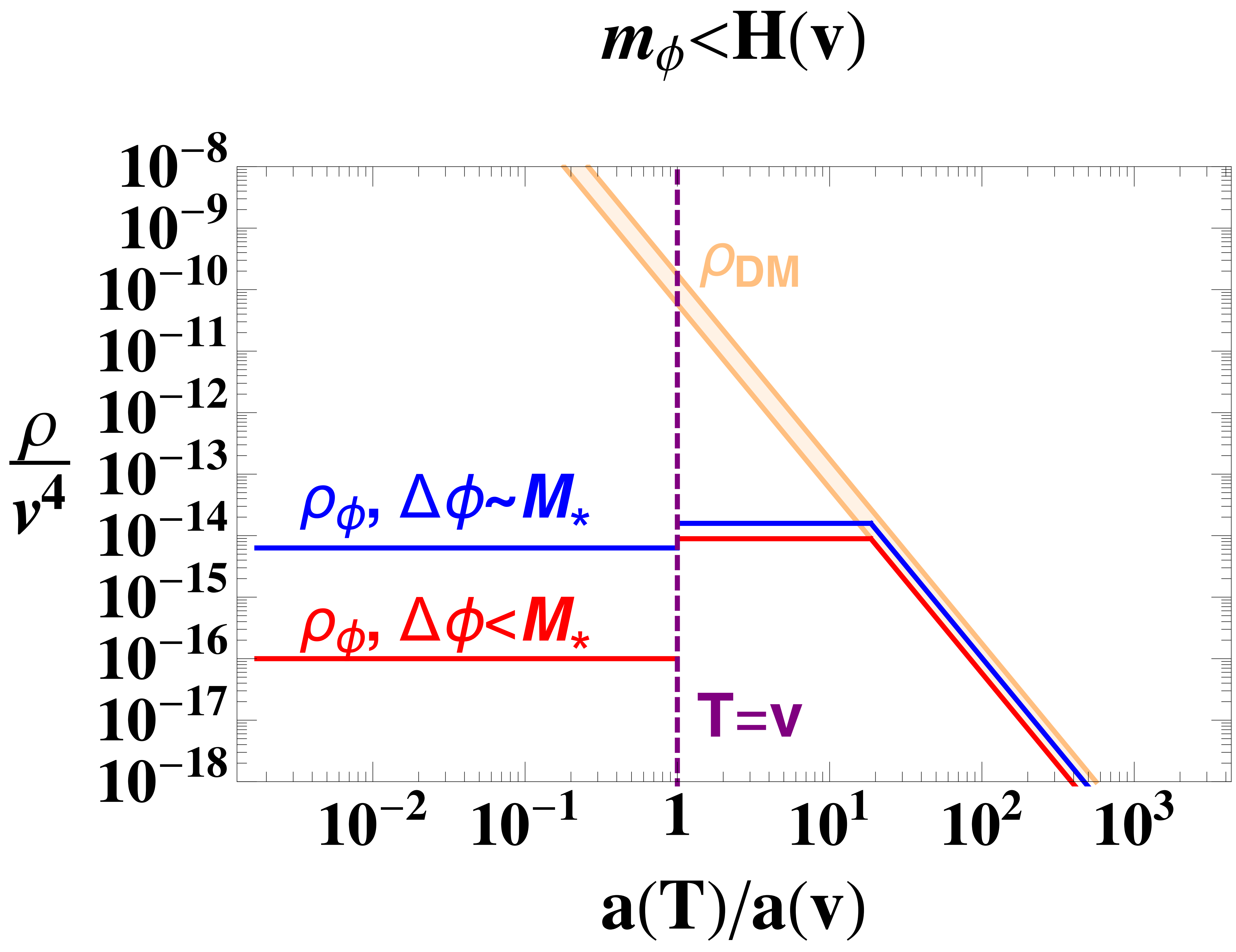
When we are close to the upper bound on mu,

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

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



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

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

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

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

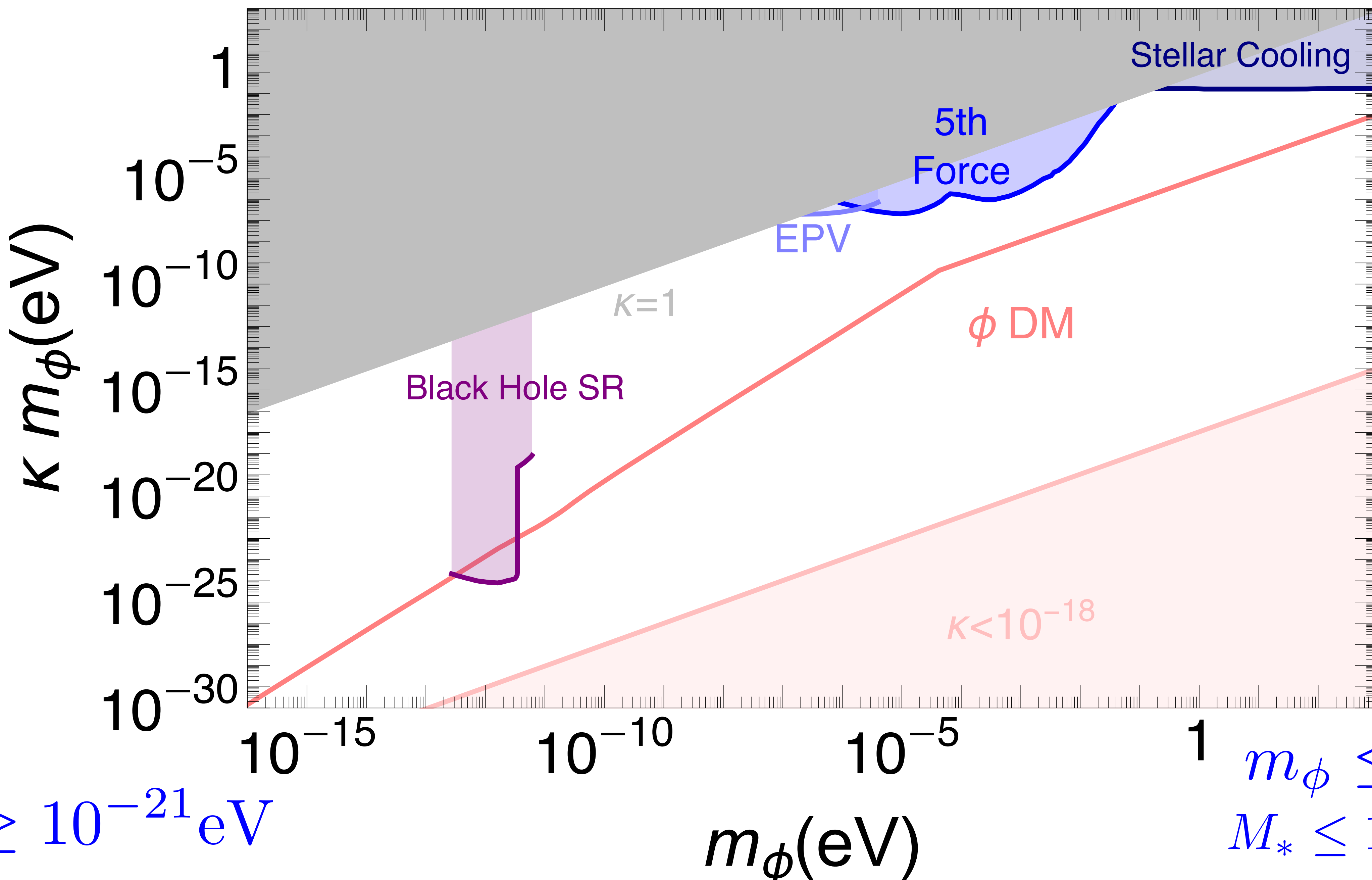
$$T_{\mathrm{eq}} \sim \frac{v^2}{M_{\mathrm{Pl}}}$$

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

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

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

Light Scalar Dark Matter



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

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

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

Astrophysical constraints on fuzzy dark matter