Unravelling the Particle World and the Cosmos at Berkeley

Sep. 28th, 2024

Higgs and Z_2 symmetry

Keisuke Harigaya (U Chicago)

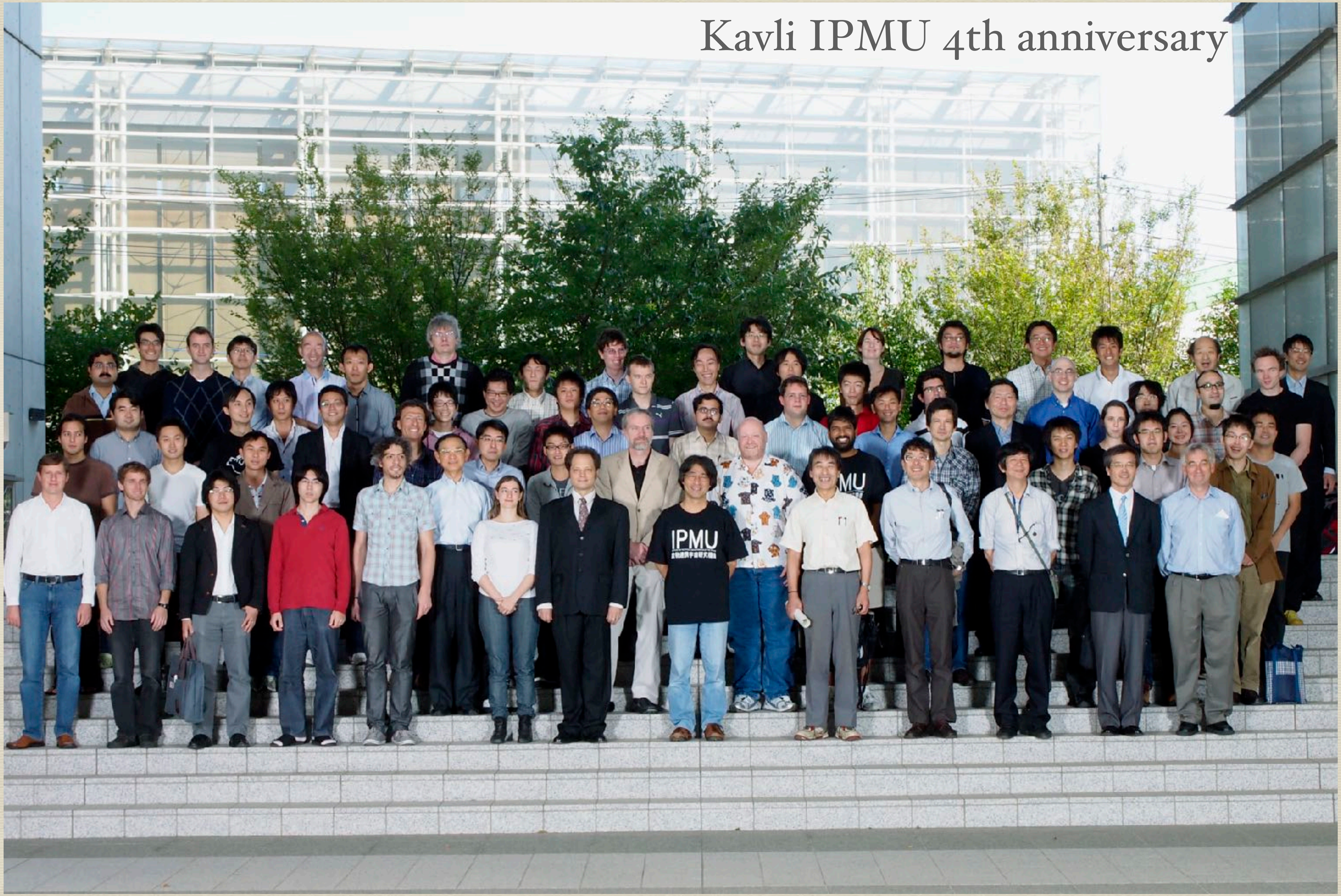
Hitoshi, particle, and cosmos

"Mystery of missing antimatter"

https://www.ipmu.jp/ja/story/7534

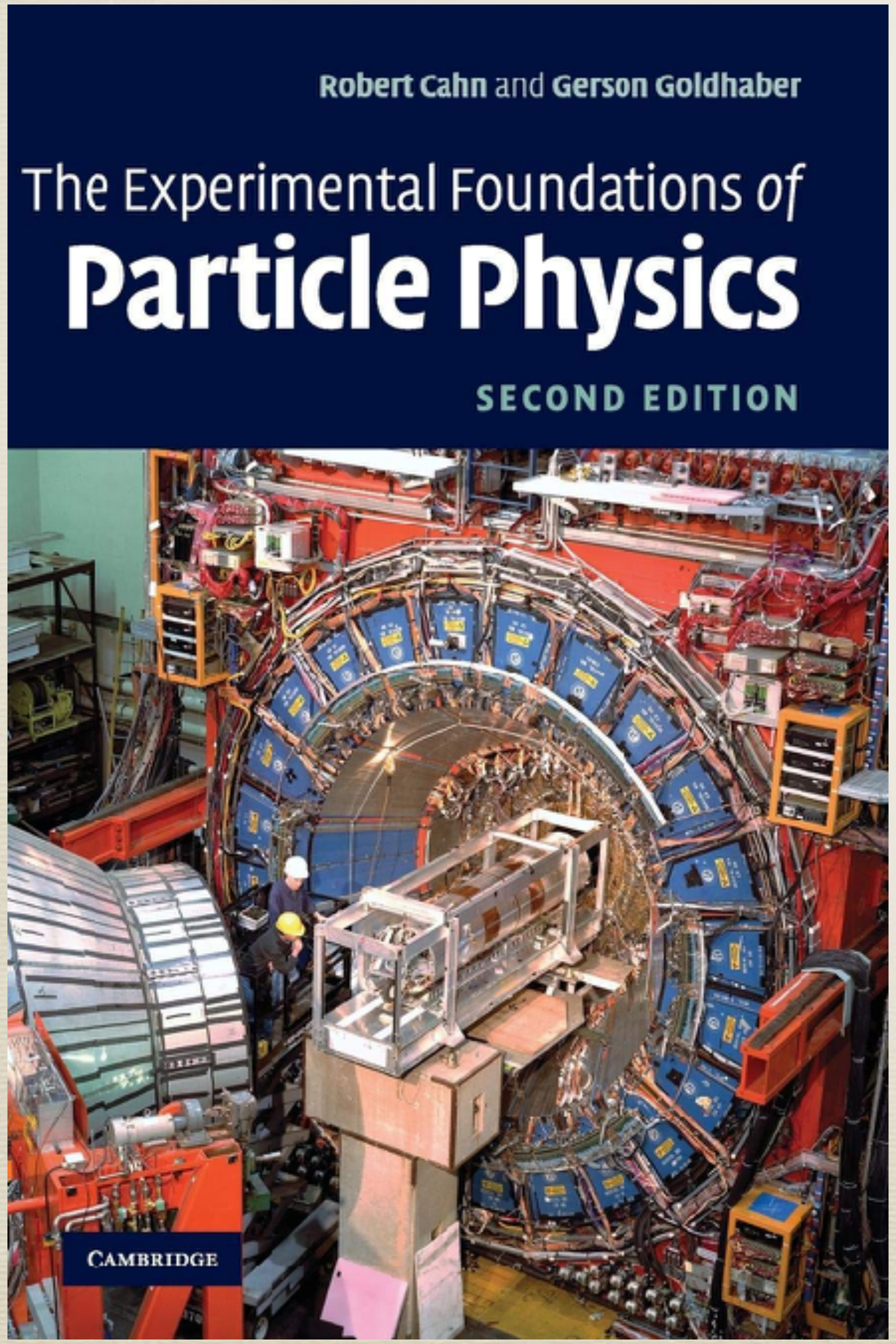
Oct. 25th, 2008
at the University of Tokyo

Kavli IPMU 4th anniversary



Reading club

Hitoshi organized a weekly reading club for first-year Ph.D students



We learned the use of symmetry,
the Standard Model (except for Higgs),
etc.

Berkeley and Kavli IPMU

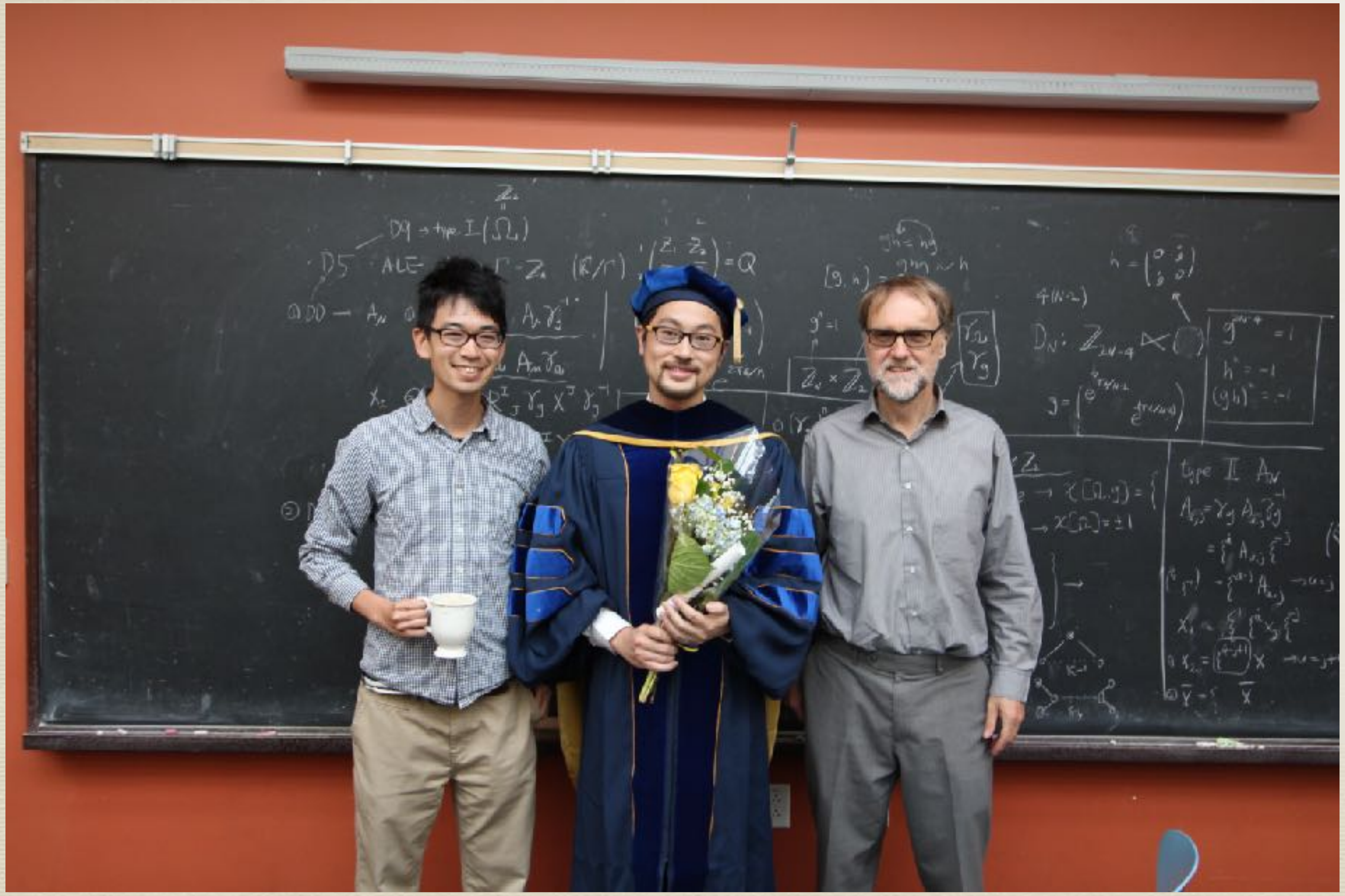
2013? at Kyoto

2016 Berkeley-IPMU week

Berkeley and Kavli IPMU

2018 Berkeley-IPMU week

Working with Lawrence



2017

Development in QCD axion cosmology with Lawrence, Raymond Co, Aaron Pierce, ...

Raymond Co's talk

Outline

* Z_2 symmetry of Higgs and its spontaneous breaking, how it is correlated with Standard Model parameters
* Parity, SO(10), and dark matter

Z_2 symmetry of Higgs

Z_2 symmetry

Standard Model Higgs H
$SU(2)_L$ doublet

$\longleftrightarrow$

Its Z_2 partner H'
$SU(2)'_L$ doublet

* If Z_2 introduces the mirror copy of the SM, dark matter candidates

Mirror baryons, electrons, atoms, ...

$SU(3)_c \times SU(2)_L \times U(1)_Y \times (SU(3)_c \times SU(2)_L \times U(1)_Y)'$ Goldberg and Hall (1986)

* If Z_2 involves space-time parity, the strong CP problem can be solved

Babu and Mohapatra (1989), Barr, Chang and Senjanovic (1991),
Hall and KH (2018,2019)

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$

$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(2)'_L \times U(1)'_Y$

$\cancel{\theta G \tilde{G}}$

Z_2 needs to be broken

* For mirror Z_2, there would be too much extra radiation in the universe. Also, mirror atom dark matter would be too strongly self-interesting

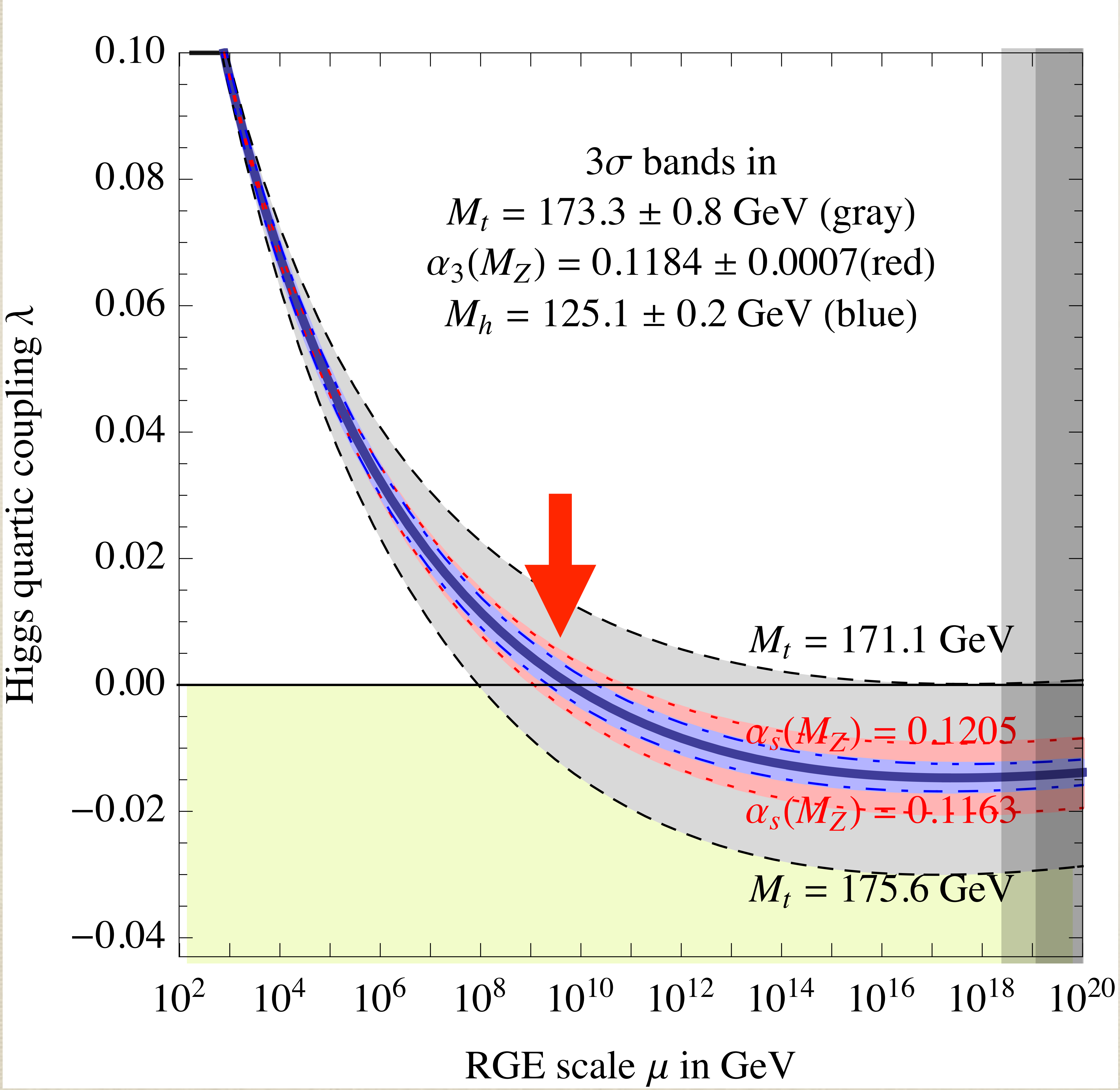
$$\sigma_{\text{atom}} \sim \frac{1}{m_{e'}^2 \alpha^2}$$

* For space-time parity, there would too light particles that has O(1) coupling to SM particles

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \qquad m_{W_R} = m_{W_L}$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(2)'_L \times U(1)'_Y \quad m_{q'} = m_q$$

Z_2 and vanishing SM Higgs quartic



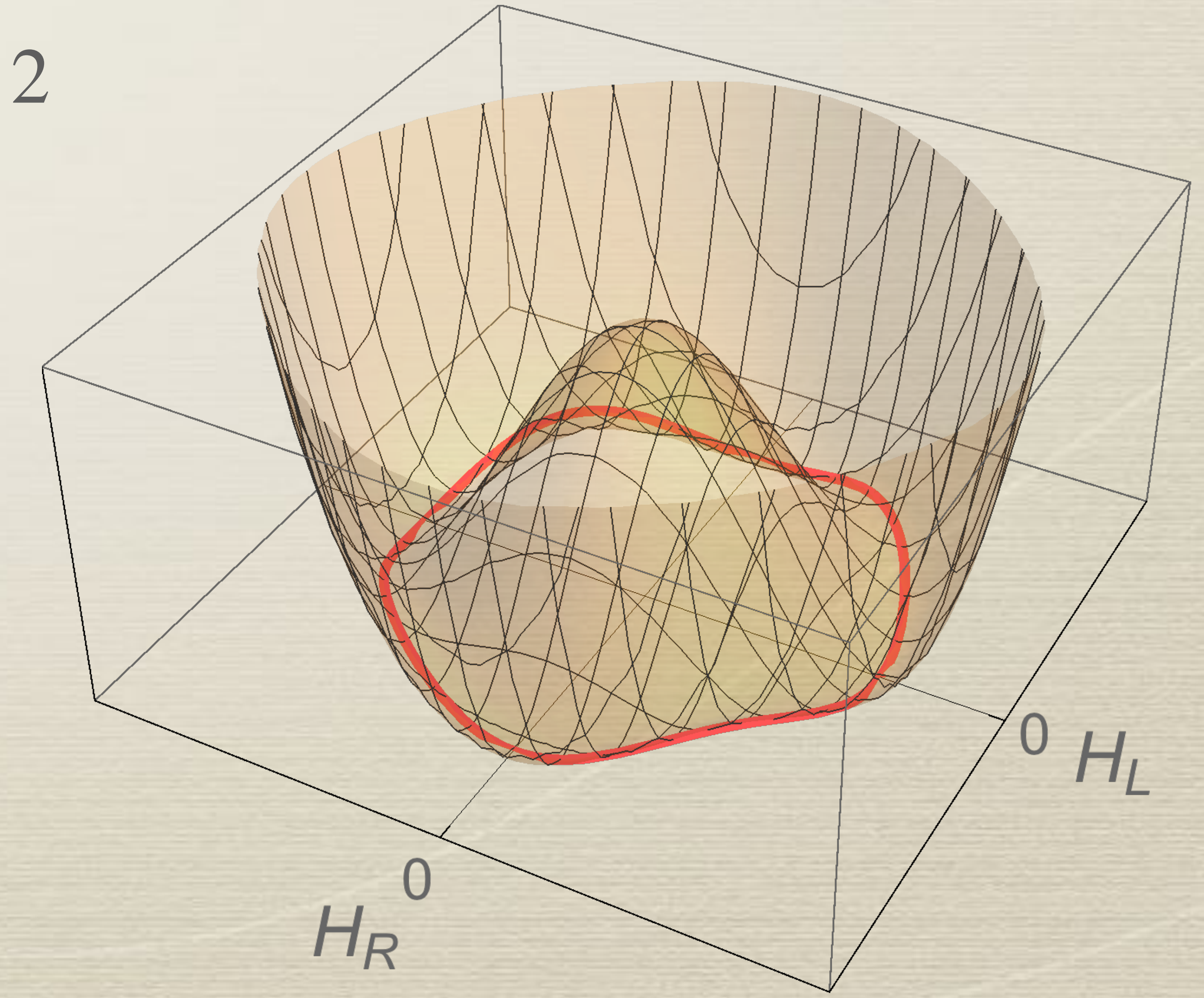
Buttazzo et.al (2013)

In 2017, we found a relation between the vanishing quartic coupling and Z2 symmetry

Higgs potential

$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\,|H|^2\,|H'|^2$$

$$= \lambda \left(|H|^2 + |H'|^2 - v'^2\right)^2 + y\,|H|^2 |H'|^2$$

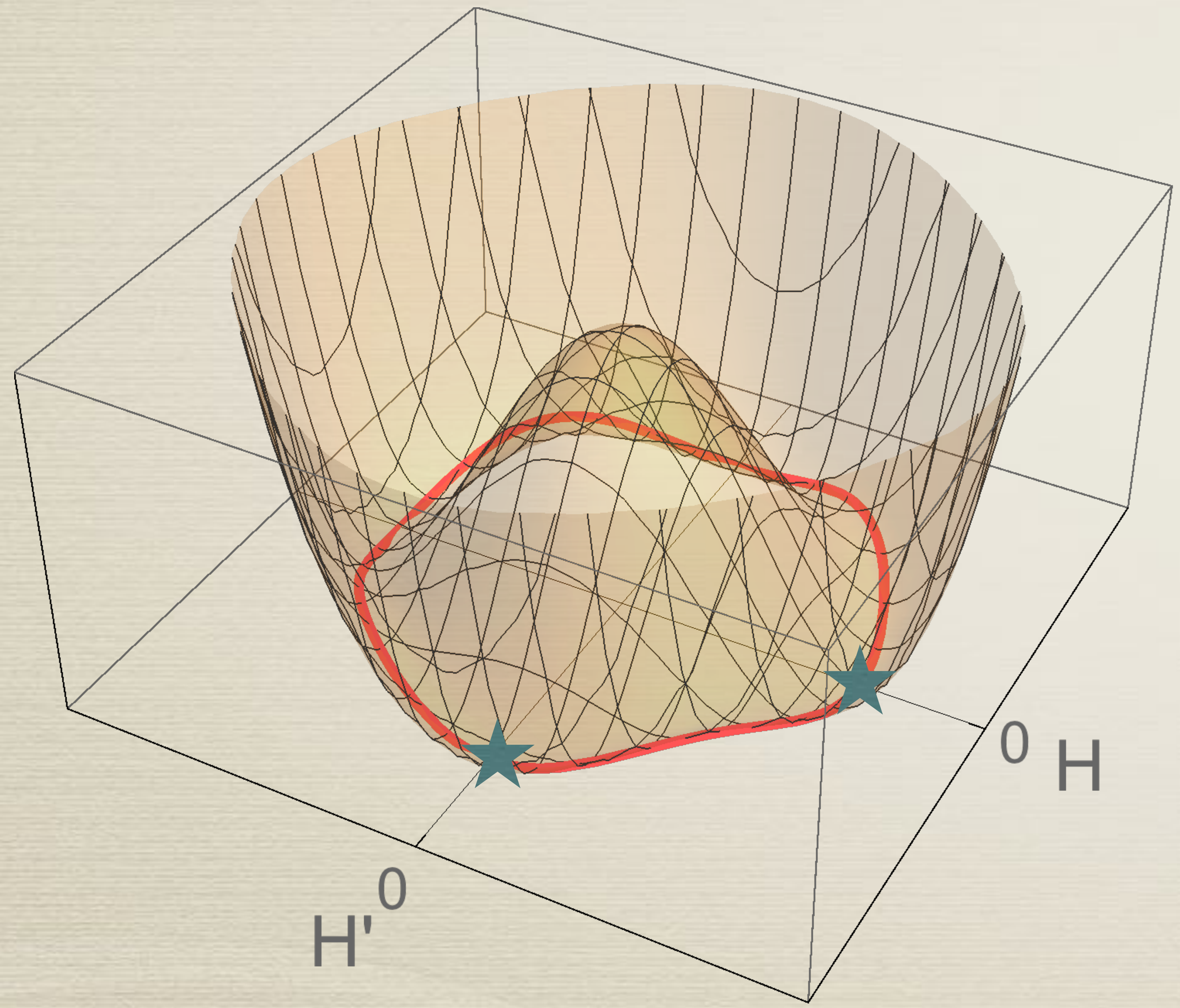


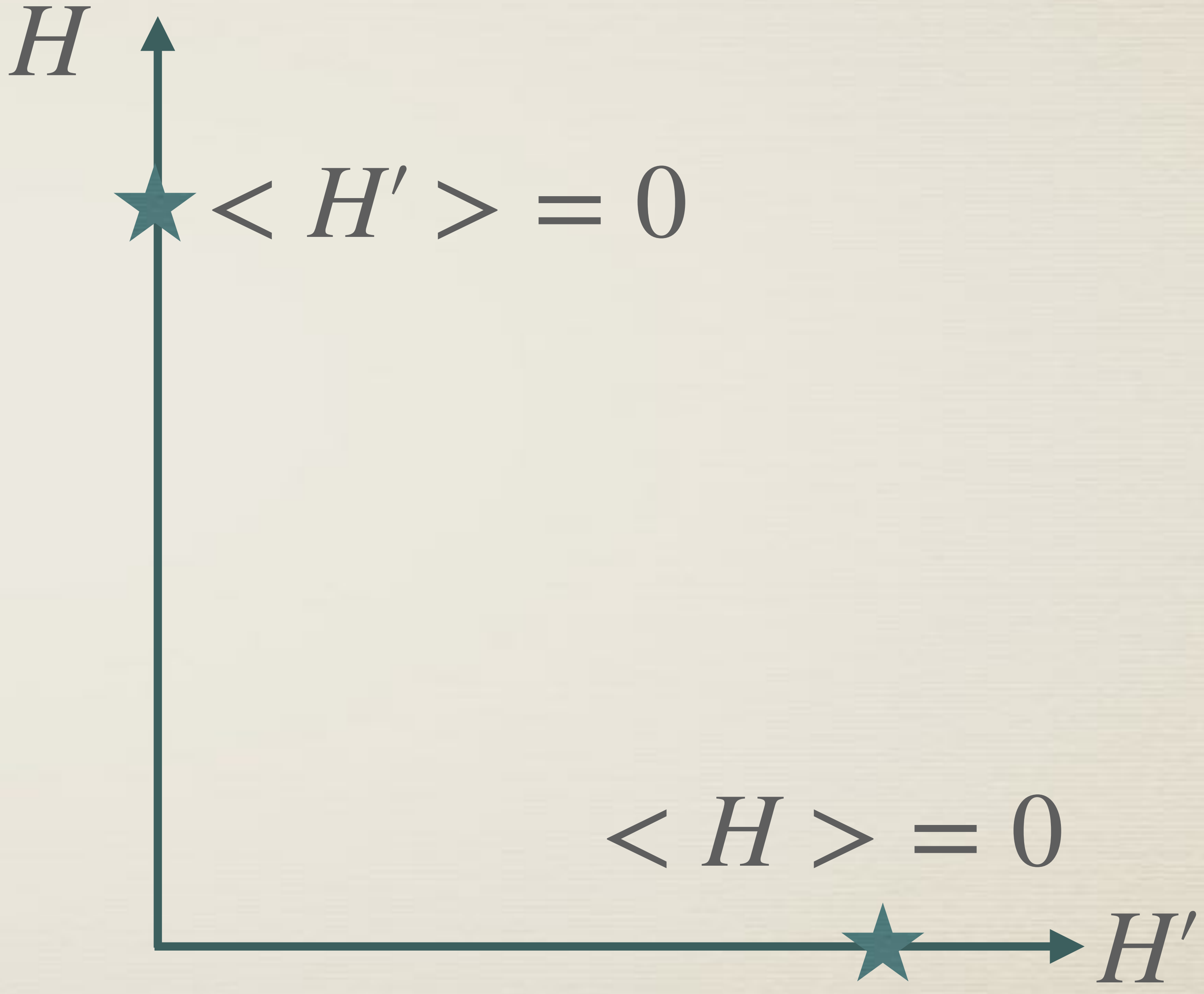
Can we find the minimum with

$$\langle H \rangle \ll \langle H' \rangle \quad ?$$

$y > 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

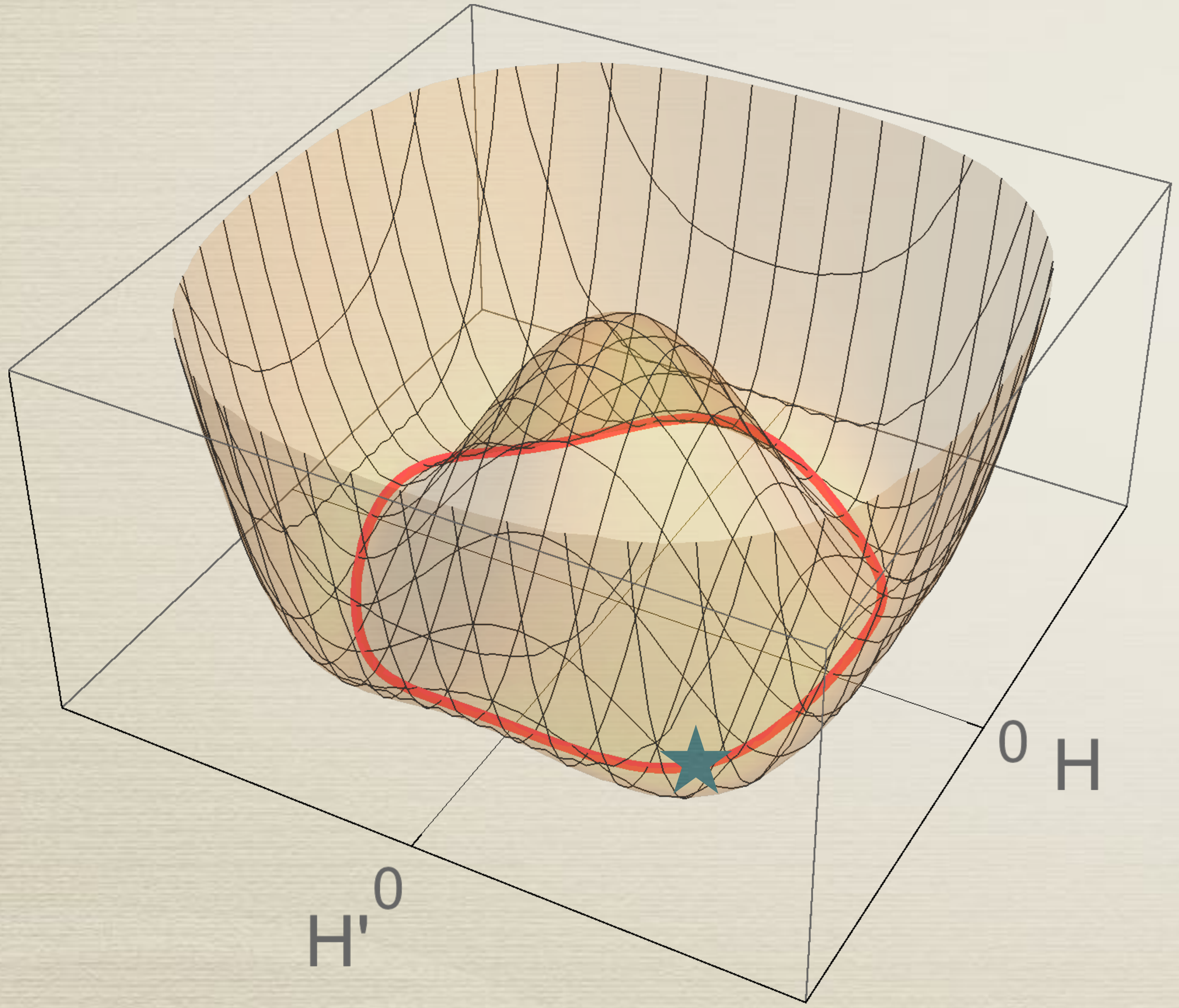


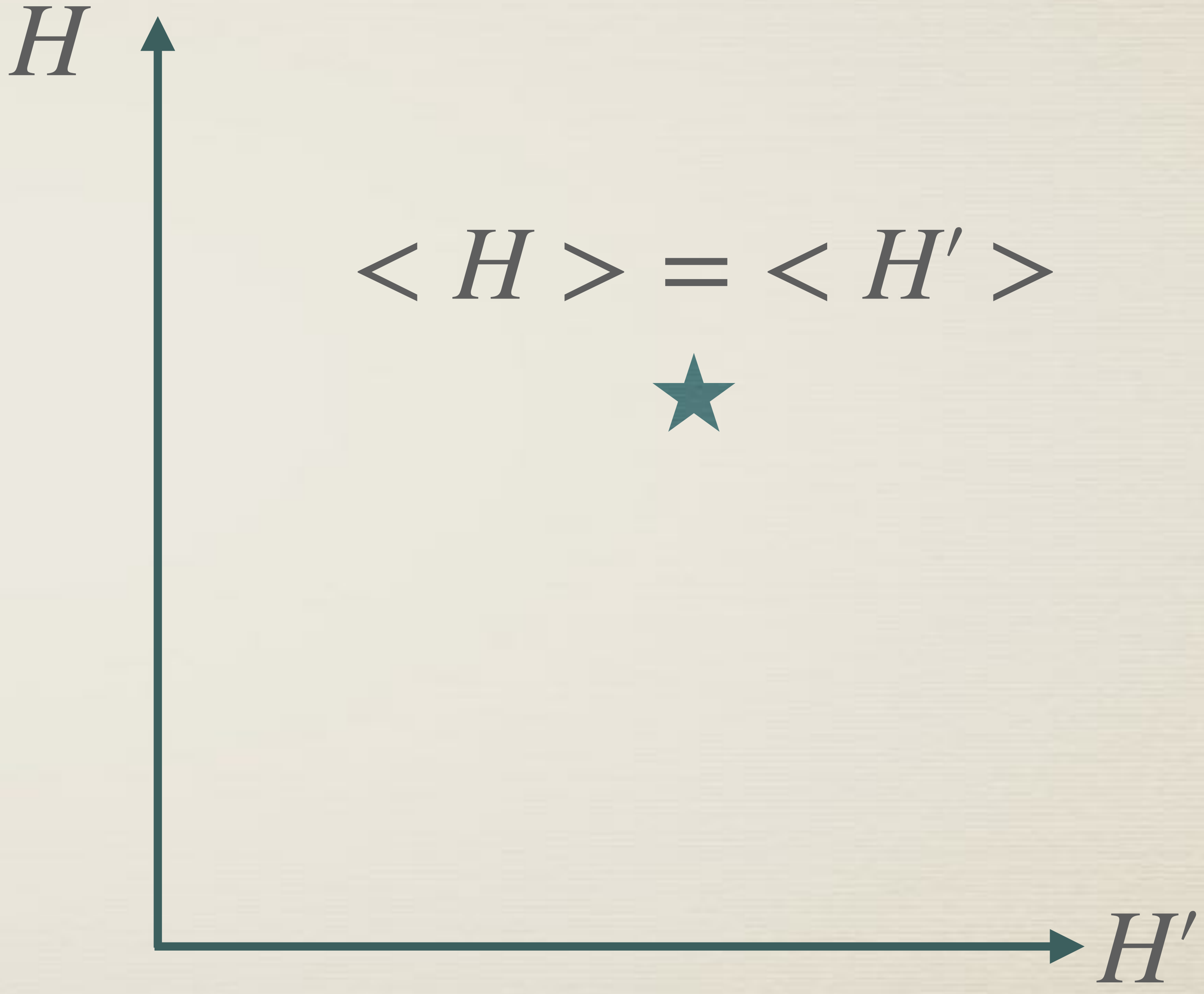


$$0 \neq \langle H \rangle \ll \langle H' \rangle$$

$$y < 0$$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

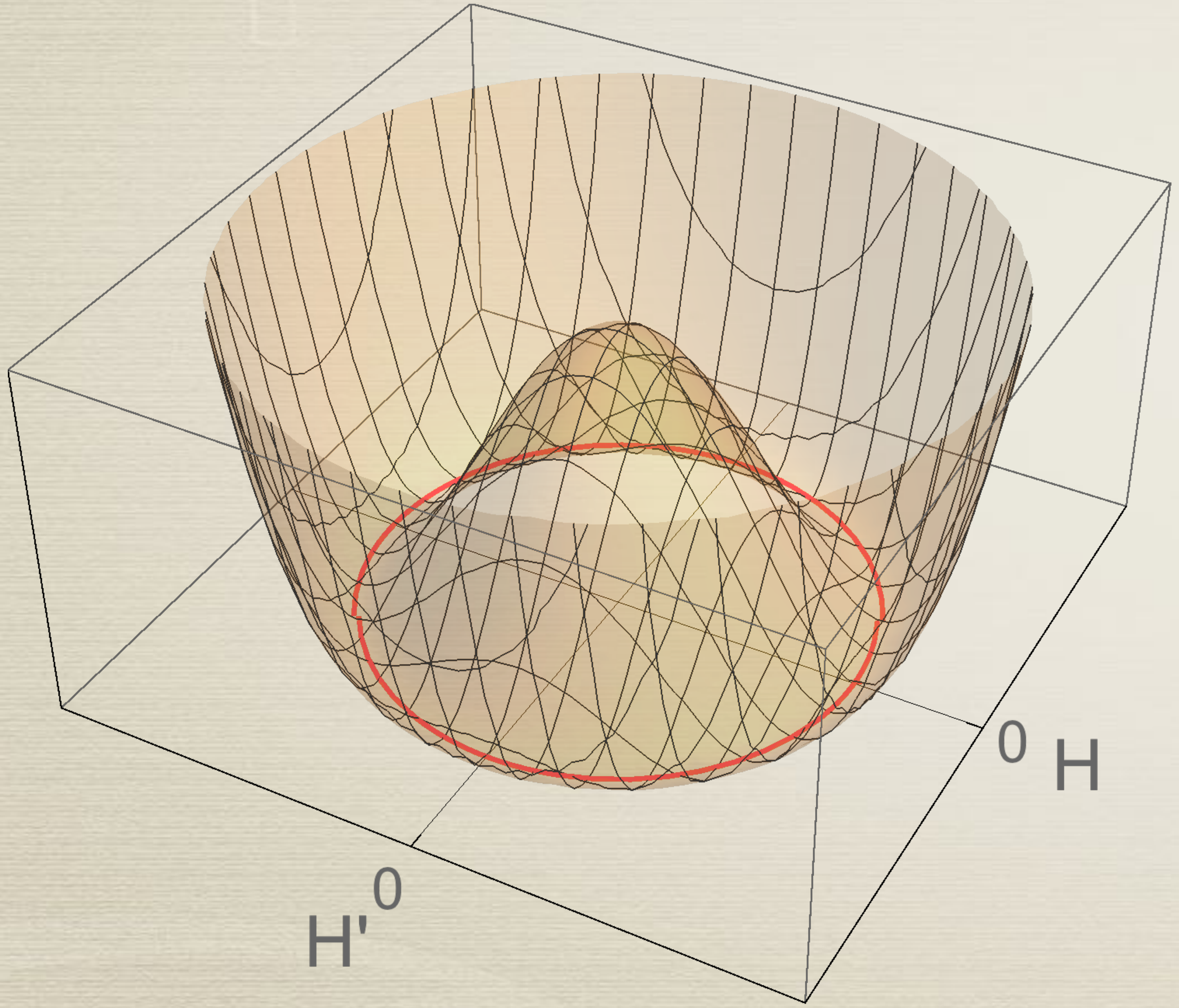


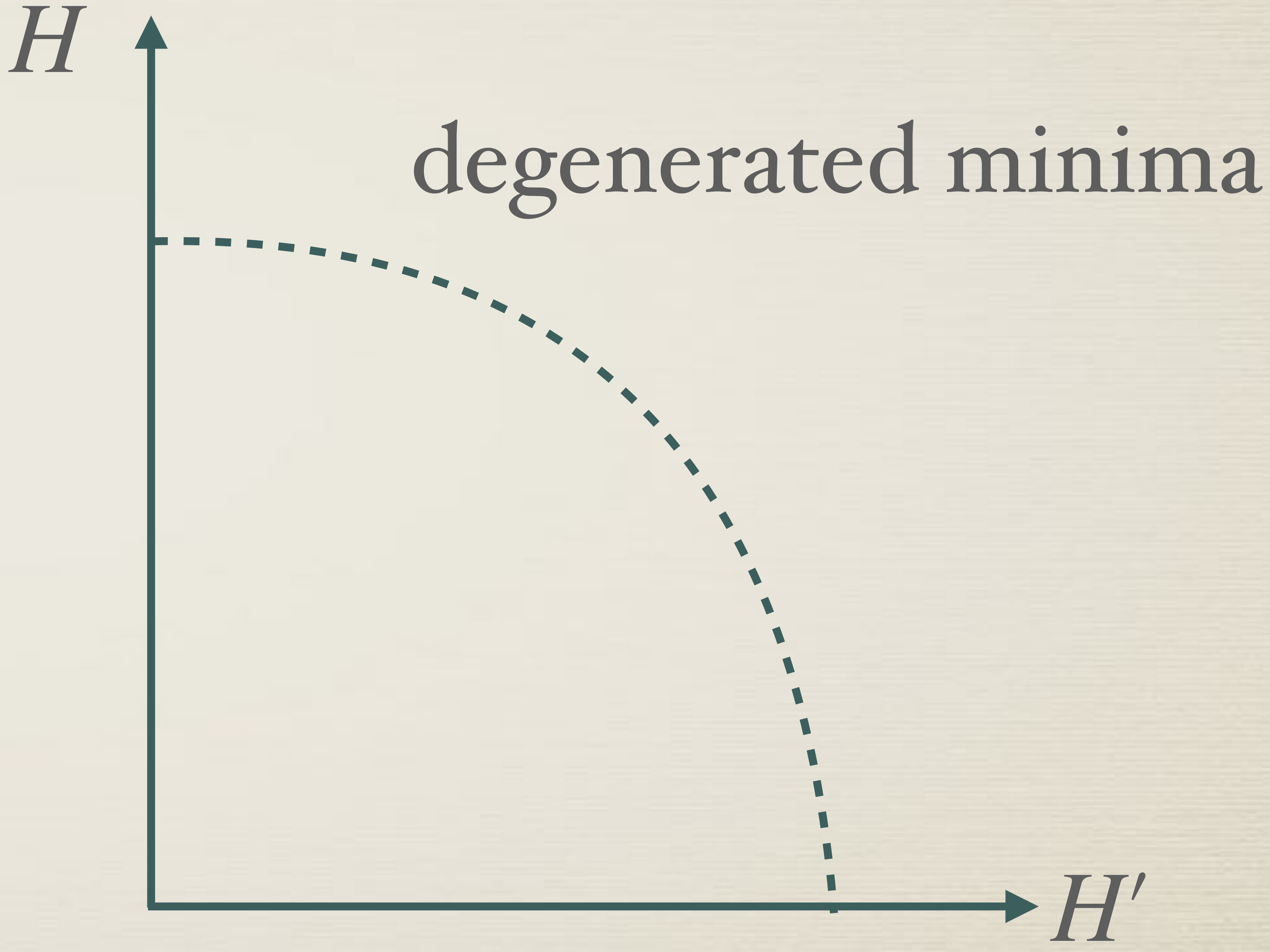


$$\langle H \rangle \ll \langle H' \rangle$$

$$y \simeq 0$$

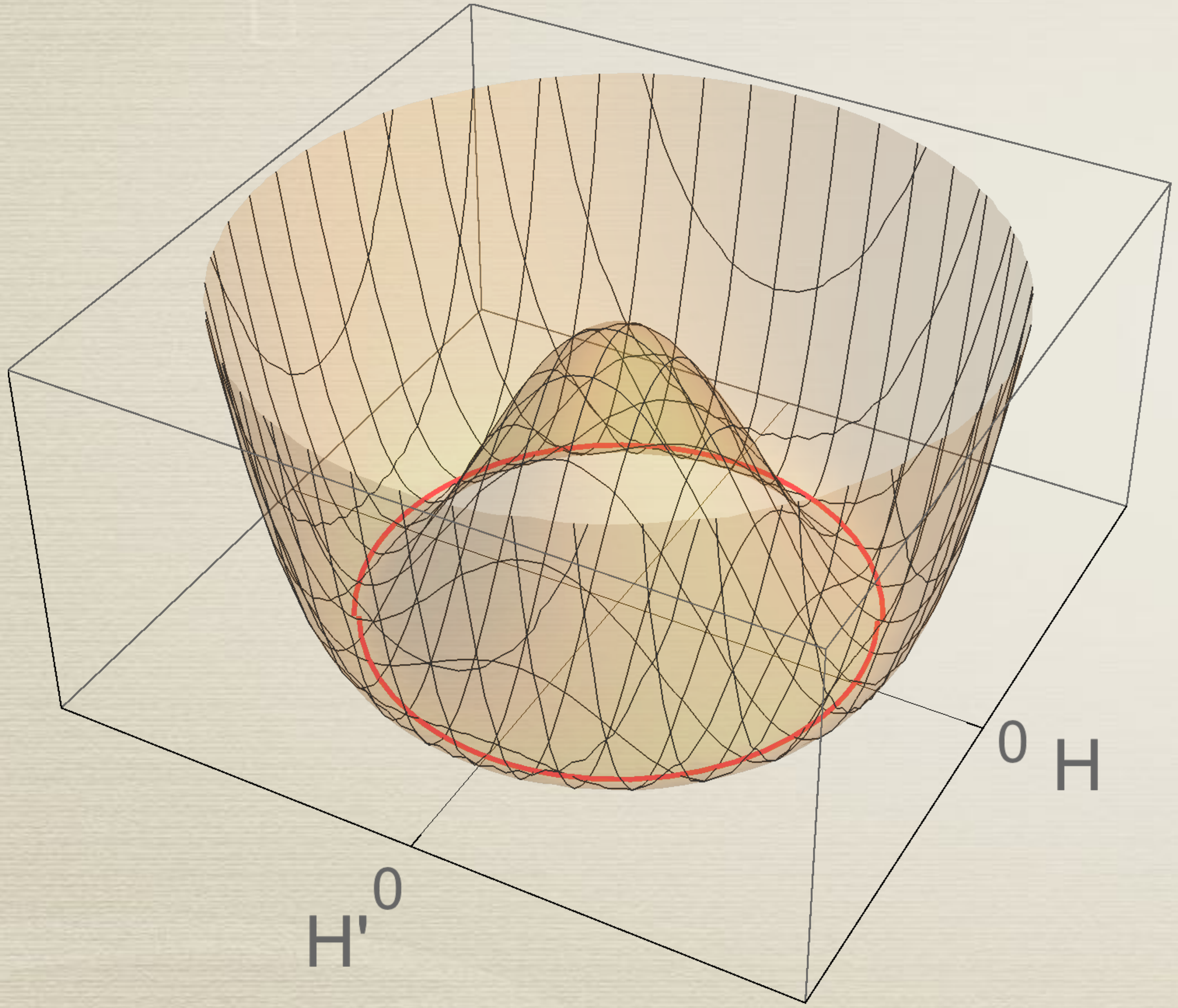
$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$

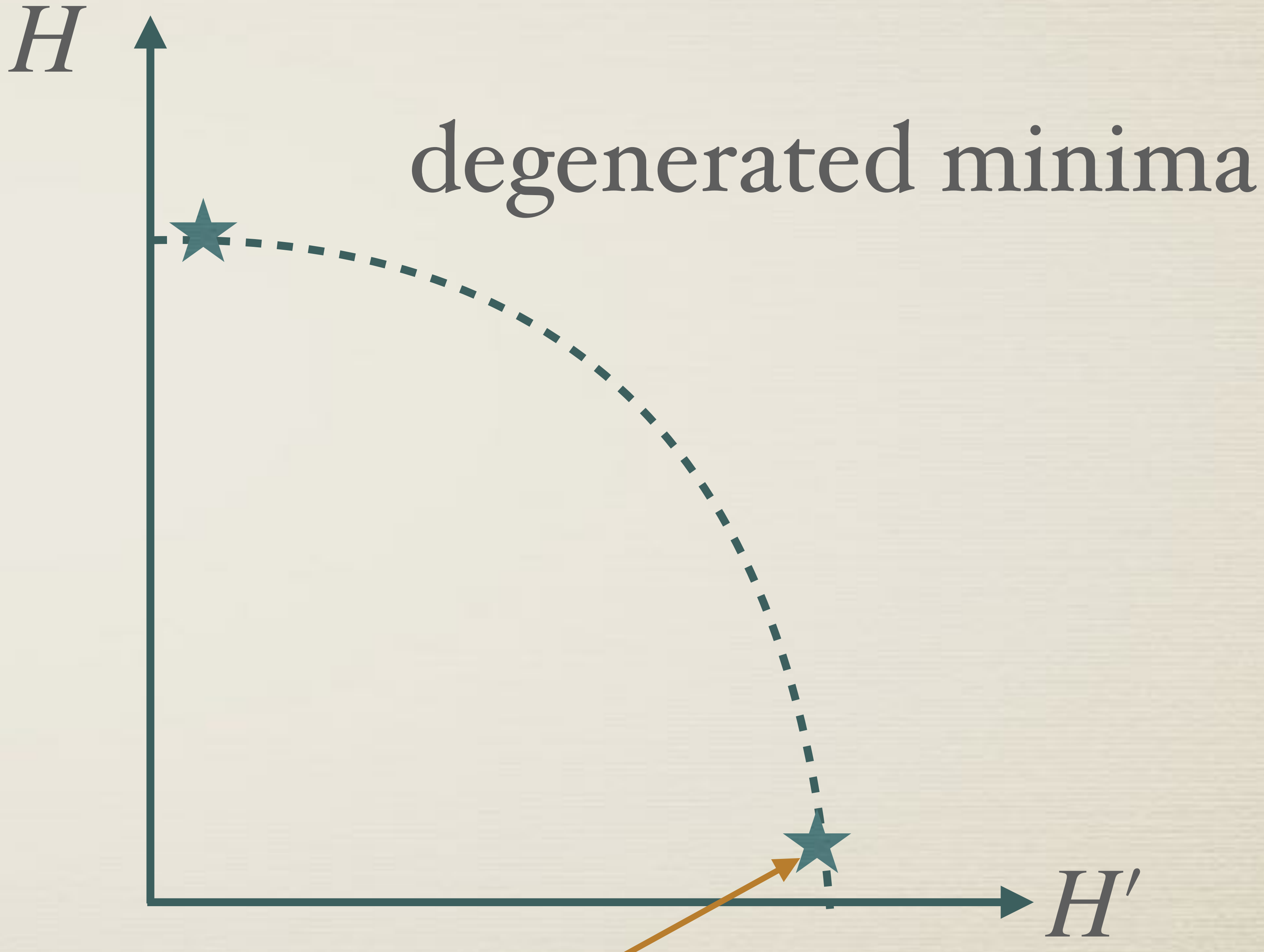




$y \simeq 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$





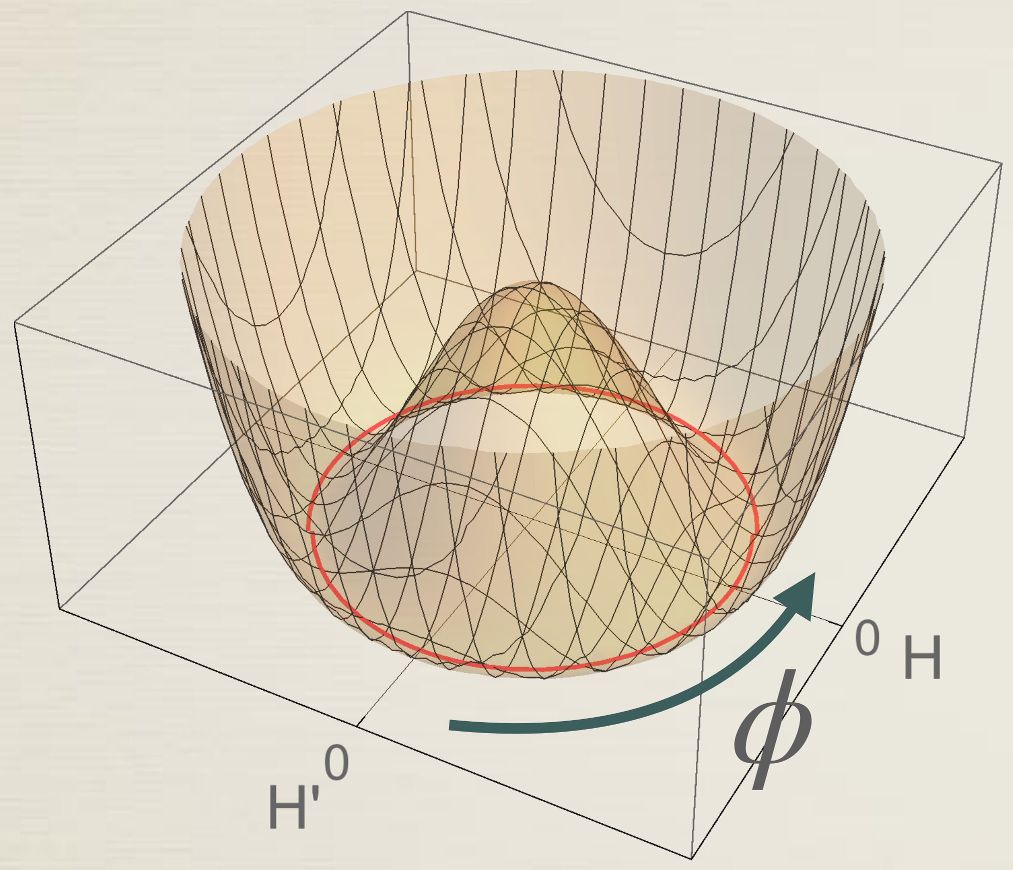
$$\langle H \rangle \ll \langle H' \rangle$$

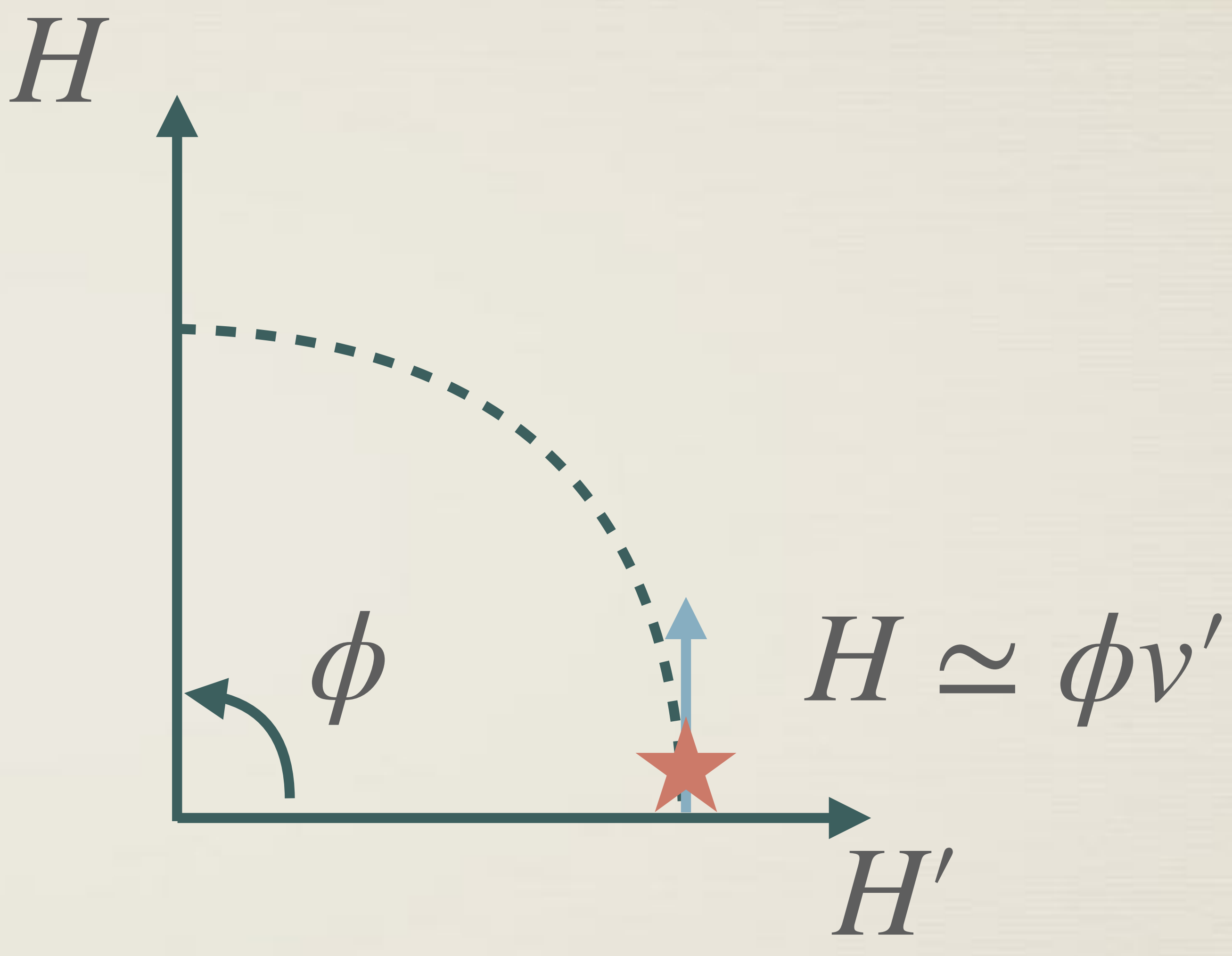
This point can become a minimum by quantum corrections

Prediction on the quartic coupling

$V \simeq \lambda(|H|^2 + |H'|^2 - v'^2)^2$ + small corrections

Hall, KH (2018)





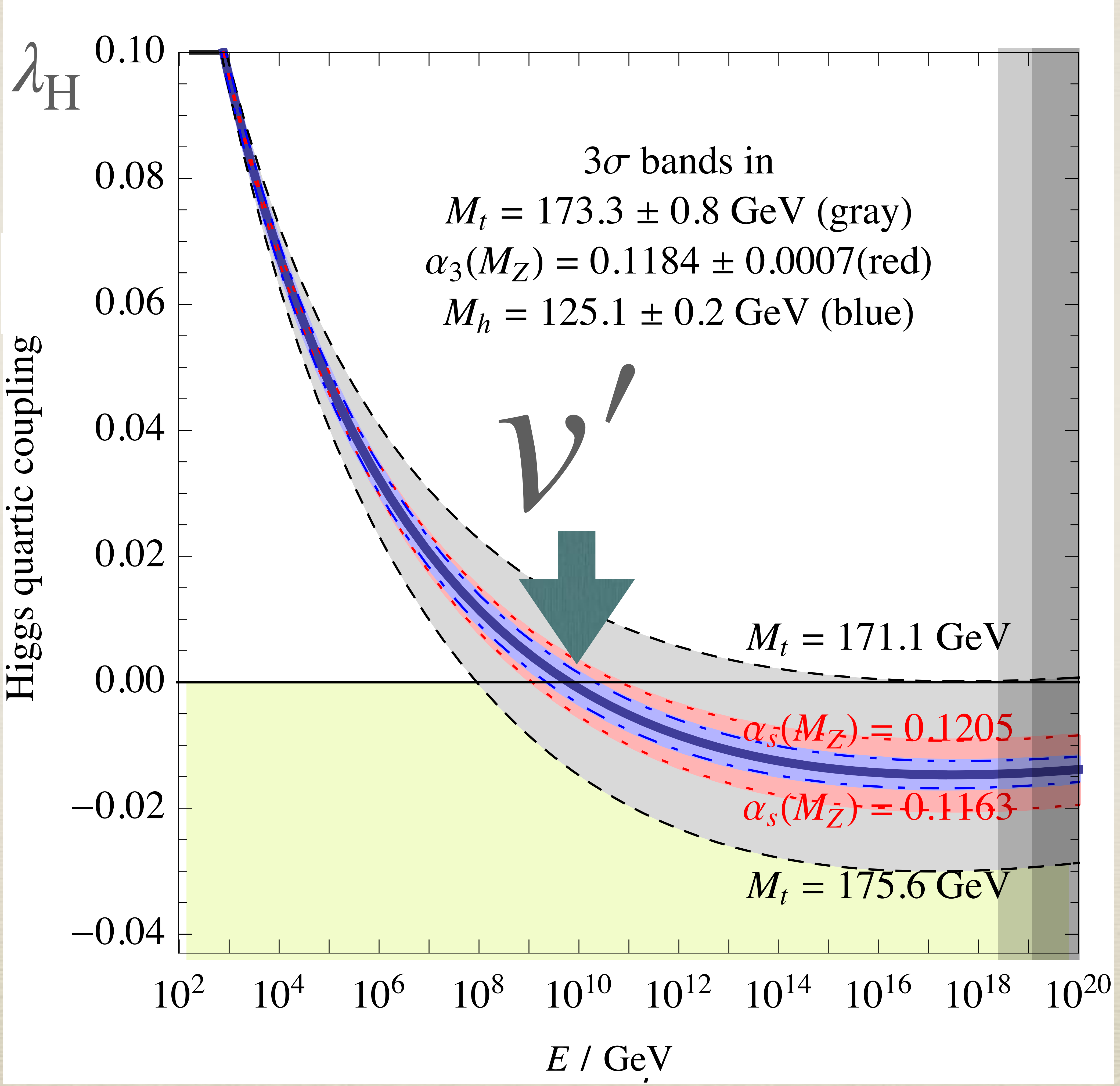
symmetry rotating the vector (H, H')

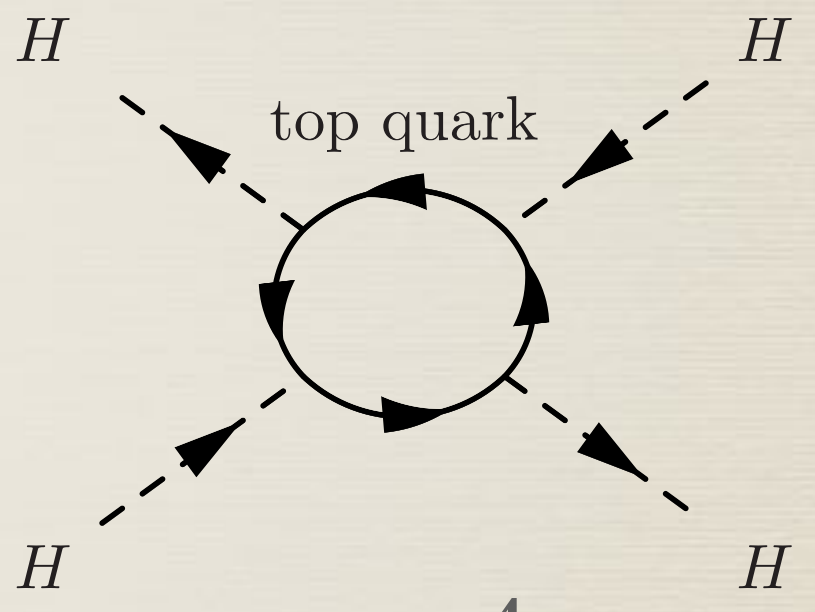
Standard Model Higgs is a (pseudo) Nambu-Goldstone boson associated with symmetry breaking by $\langle H' \rangle = v'$

$$\boxed{\lambda_{\mathrm{SM}}(v') \simeq 0}$$

(up to calculable threshold correction)

Vanishing quartic coupling





$\propto m_{\rm top}^4$

Buttazzo et.al (2013)

Fine-tuning

$$V = \lambda\left(|H|^2 + |H'|^2 - v'^2\right)^2 + y|H|^2|H'|^2$$

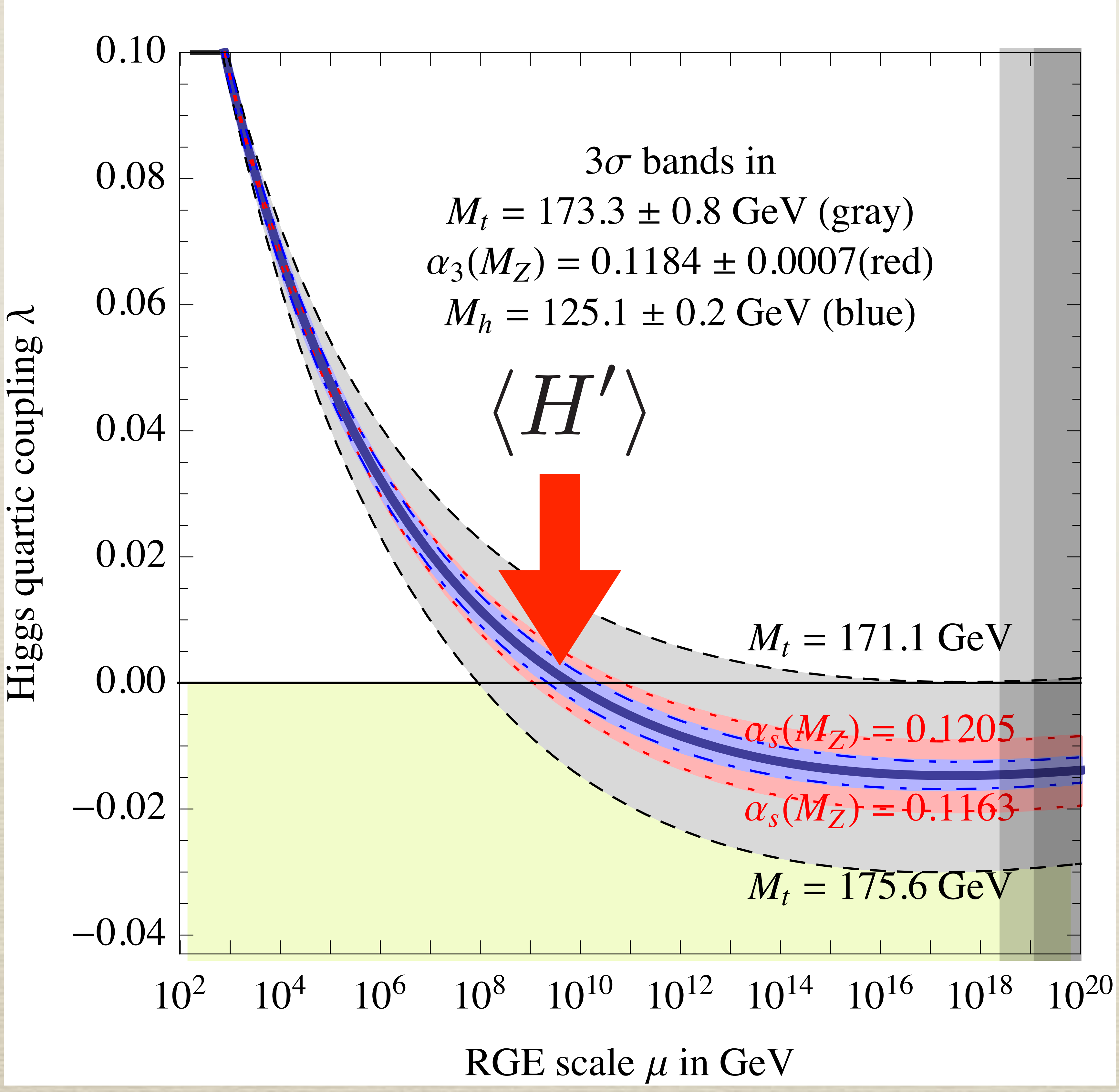
$$\frac{v'^2}{\Lambda_{\mathrm{cut}}^2} \times \frac{v^2}{v'^2} = \frac{v^2}{\Lambda_{\mathrm{cut}}^2}$$

Despite the intermediate scale v',

same as that of standard model

Generic Z_2

The scheme is applicable to generic models with the SM Higgs H and its Z2 partner H'



Higgs Parity

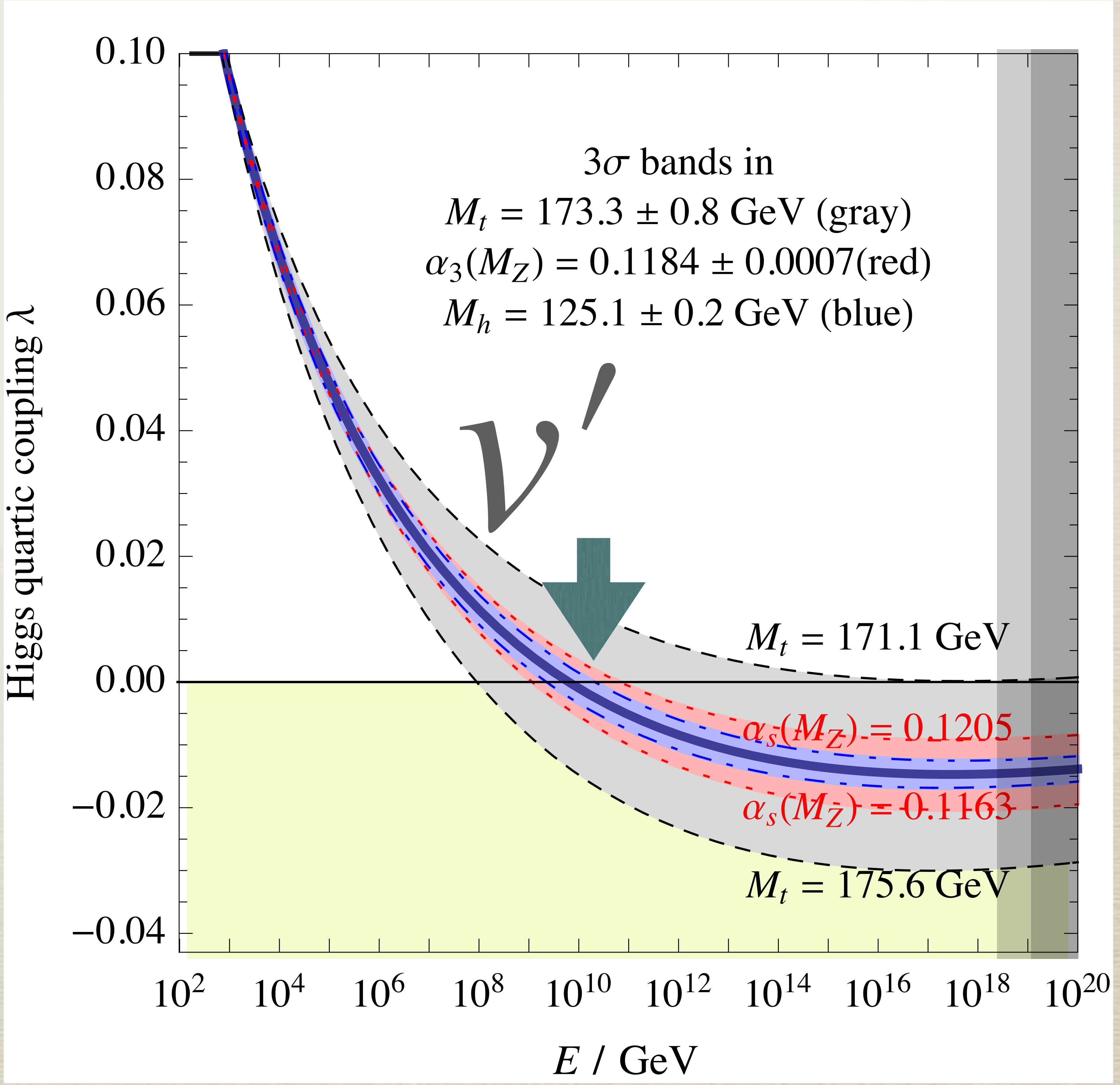
Mirror Z2, Left-Right symmetry with or without space-time parity, ...

Precise measurement and Z_2

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019, 2020, 2022)
Carrasco-Martinez, Dunsky, Hall and KH (2023)

top quark mass
Higgs mass
strong coupling constant

Z2 symmetry
breaking scale



Precise measurement and new physics

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top quark mass
Higgs mass
strong coupling constant

Dark matter and its detection,
gauge coupling unification
and proton decay, baryogenesis, …

Z2 symmetry
breaking scale

Precise measurement and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019, 2020, 2022)
Carrasco-Martinez, Dunsky, Hall and KH (2023)

2023 at Flatiron Institute

Dark matter and its detection,
gauge coupling unification
and proton decay, baryogenesis, ...

Z2 symmetries

* Mirror Z2

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times (SU(3)_c \times SU(2)_L \times U(1)_Y)'$$

e' dark matter, dark radiation, GWs from mirror QCD PT

* Left-Right symmetry

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$

SO(10) unification, leptogenesis, right-handed neutrino DM

* Left-Right Parity

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$

above + solving strong CP problem

* Mirror Parity

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(2)'_L \times U(1)'_Y$$

e' dark matter, solving strong CP problem

Z2 symmetries

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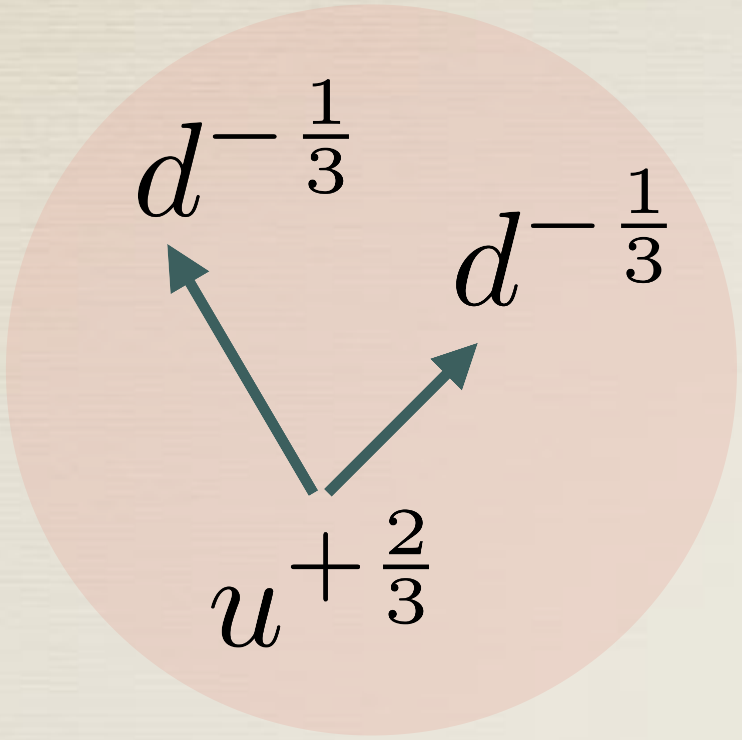
e' dark matter, solving strong CP problem

Outline

* Z_2 symmetry of Higgs and its spontaneous breaking
* Parity, SO(10), and dark matter

The strong CP problem



Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

$$d_n/e < 2.9 \times 10^{-26} \text{ cm}$$ Baker et.al (2006)

Suggests CP symmetry

$$d_n \vec{E} \cdot \vec{S} \overset{\text{CP}}{\Longrightarrow} -d_n \vec{E} \cdot \vec{S}$$ $$d_n = 0$$

CP is not preserved in SM

$$\mathscr{L} = y^u_{ij} H^\dagger q_i \bar{u}_j + y^d_{ij} H q_i \bar{d}_j + \frac{\theta_{\rm QCD}}{32\pi^2} G\tilde{G}$$

CP violation

observed $\theta_{\rm CKM} = O(1)$ ➡ $y^{u,d}$ must have O(1) complex phases

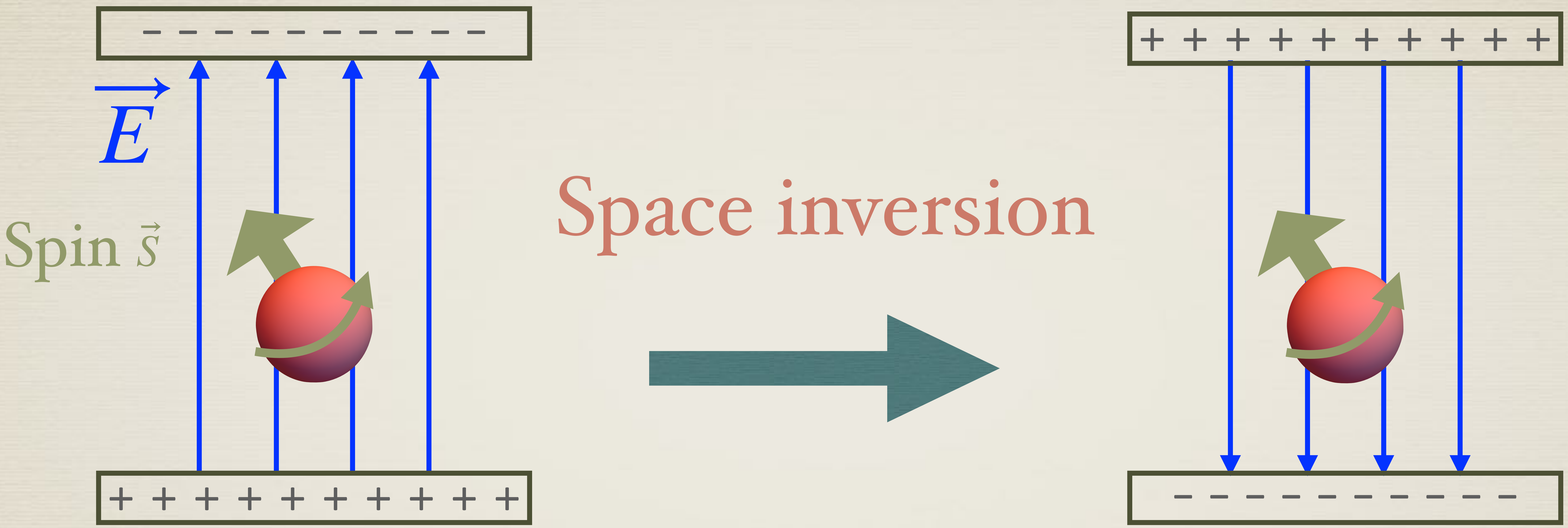
➡ CP is violated

$d_n/e \simeq 5 \times 10^{-16} \bar{\theta}$ cm Crewther, Vecchia and Witten (1979)

$$\bar{\theta} = \arg\det(m^u m^d) + \theta_{\rm QCD} < 10^{-10}$$

The strong CP problem

Parity solution



$$\cancel{H = d_n \vec{E} \cdot \vec{S}}$$

Parity symmetry can forbid the neutron electric dipole moment

Left-Right Parity

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{\mathrm{LR}}$$

Parity

$q = (u, d)$	$\longleftrightarrow$	$\bar{q} = (\bar{u}, \bar{d})$
$(3, 2_L, 1, 1/6)$		$(\bar{3}, 1, 2_R, -1/6)$
$\ell = (\nu, e)$		$\bar{\ell} = (\bar{N}, \bar{e})$
H_L		H_R
$(1, 2_L, 1, -1/2)$		$(1, 1, 2_R, 1/2)$

$$q(t, x) \leftrightarrow i\sigma_2 \bar{q}^*(t, -x)$$

Left-Right Parity

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{\mathrm{LR}}$$

Parity

$q = (u, d)$

$(3, 2_L, 1, 1/6)$

$\bar{q} = (\bar{u}, \bar{d})$

$(\bar{3}, 1, 2_R, -1/6)$

$\bar{\ell} = (\bar{N}, \bar{e})$

H_R

$(1, 1, 2_R, 1/2)$

Mystery of missing antimatter (2008)

Carrasco-Martinez, Dunsky, Hall and KH (2023)

Left-Right Parity

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{\rm LR}$$

Parity

$q = (u, d)$	$\longleftrightarrow$	$\bar{q} = (\bar{u}, \bar{d})$
$(3, 2_L, 1, 1/6)$		$(\bar{3}, 1, 2_R, -1/6)$
$\ell = (\nu, e)$		$\bar{\ell} = (\bar{N}, \bar{e})$
H_L		H_R
$(1, 2_L, 1, -1/2)$		$(1, 1, 2_R, 1/2)$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{\rm LR} \xrightarrow{H_R} SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{H_L} SU(3)_c \times U(1)_{\rm EM}$$

Left-Right in SO(10)

SO(10) contains left-right symmetry without space-time inversion

$$\psi_{16} = (\ell, \bar{\ell}, q, \bar{q})$$

$$H_{16} = (H_L, H_R, H^c_L, H^c_R)$$

$$C_{\mathrm{LR}} : \; q \leftrightarrow \bar{q}, \; \ell \leftrightarrow \bar{\ell}$$

$$SO(10) \xrightarrow[H_{45}]{} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{\mathrm{X}}$$

C_{LR} is spontaneously broken

Left-Right Parity in SO(10)

Add CP: $\psi_{16}(t, x) \to i\sigma_2 \psi^*_{16}(t, -x)$

$C_{\mathrm{LR}}: \; q \leftrightarrow \bar{q}, \; \ell \leftrightarrow \bar{\ell}$

(CP and C_{LR}) $= P_{\mathrm{LR}}: \; q(t, x) \leftrightarrow i\sigma_2 \bar{q}^*(t, -x), \ell(t, x) \leftrightarrow i\sigma_2 \bar{\ell}^*(t, -x)$

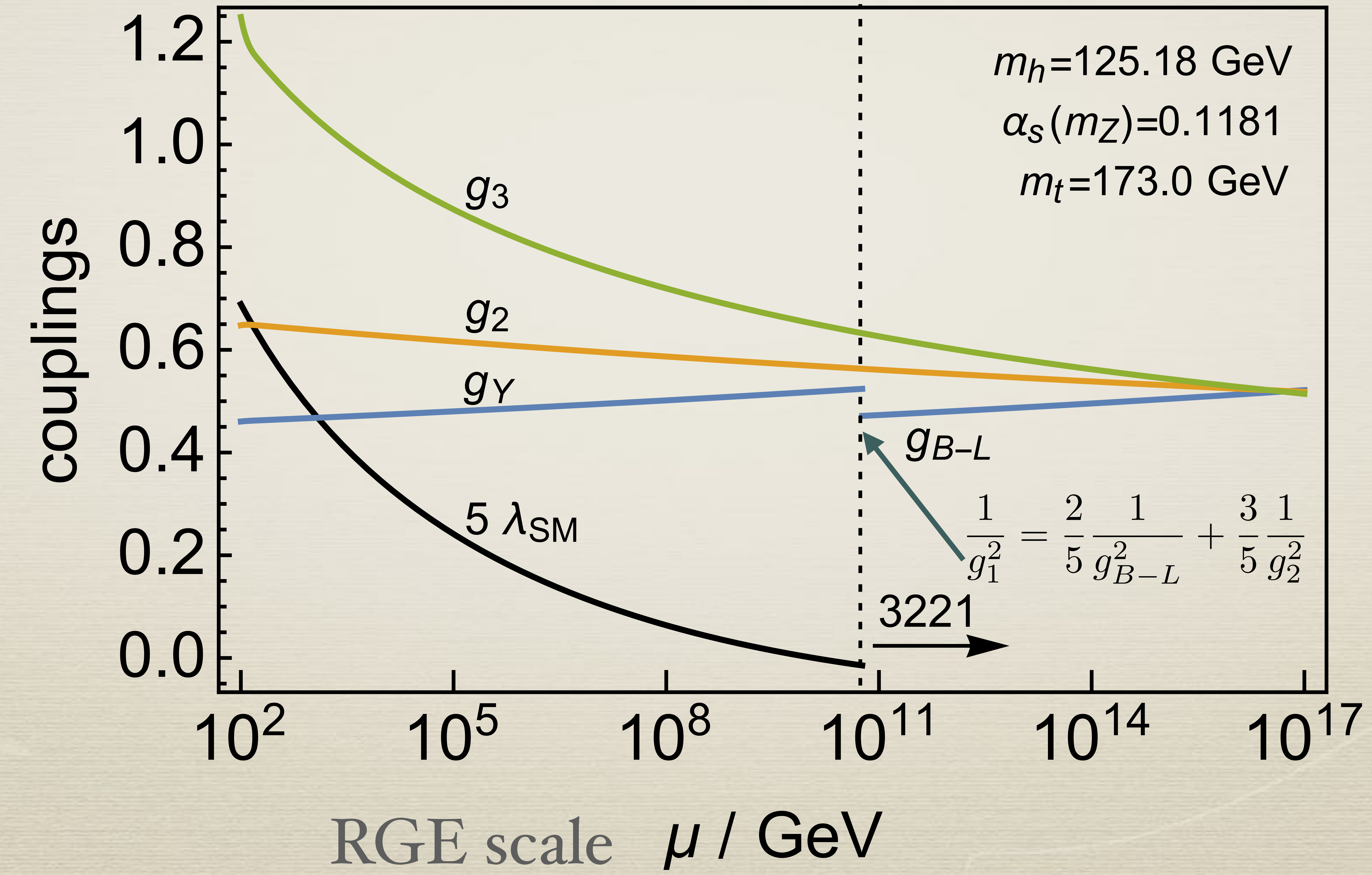
$$SO(10) \times CP \xrightarrow[H_{45}]{} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{\mathrm{X}} \times P_{\mathrm{LR}}$$

assuming H_{45} is CP odd

Coupling unification

Hall, KH (2018, 2019)

energy-dependent couplings

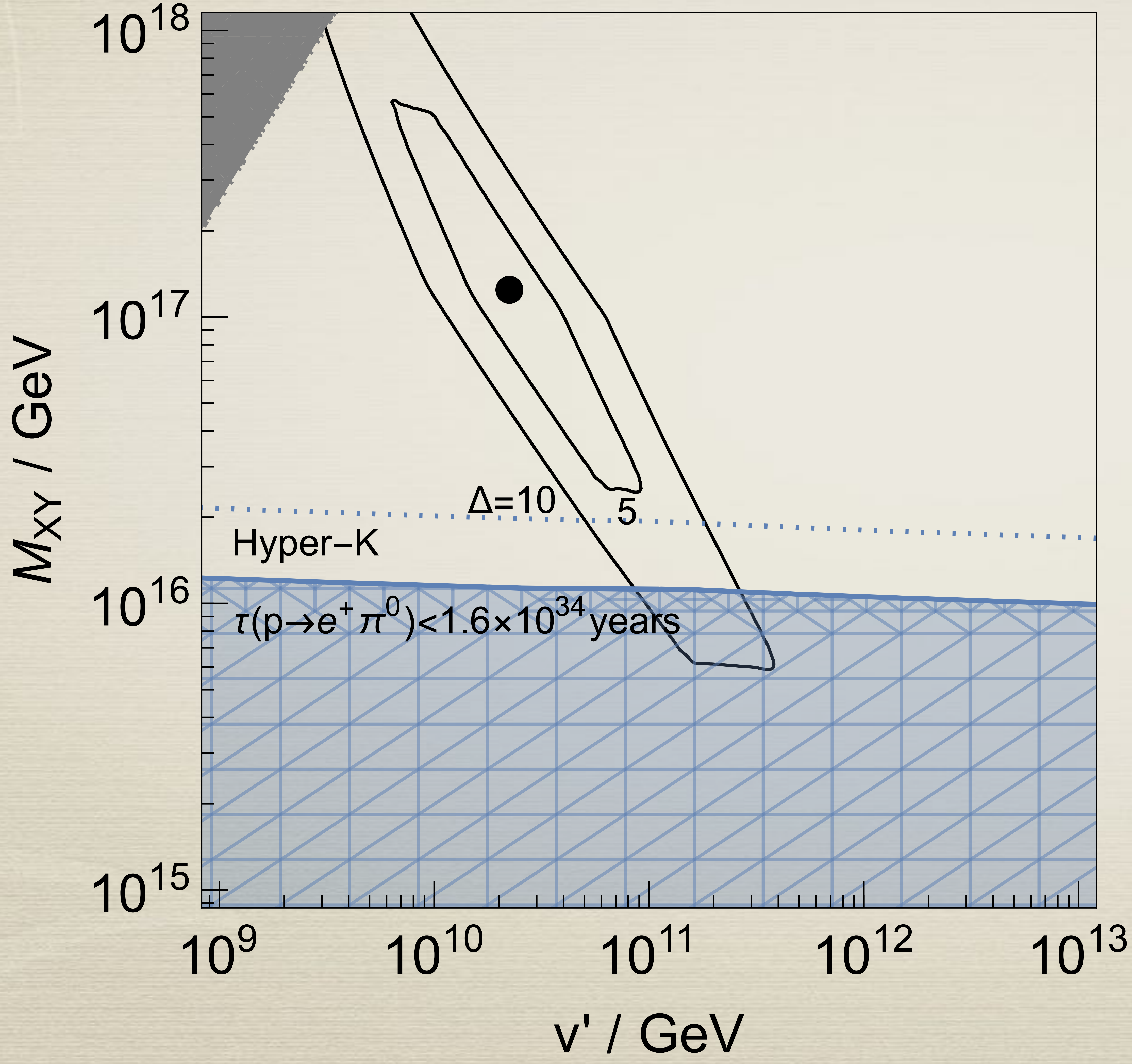


RGE scale

Quantify unification

Hall, KH (2019)

mass of new gauge boson mediating proton decay



There can be quantum corrections from heavy particles around the GUT scale

$$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$$

typically

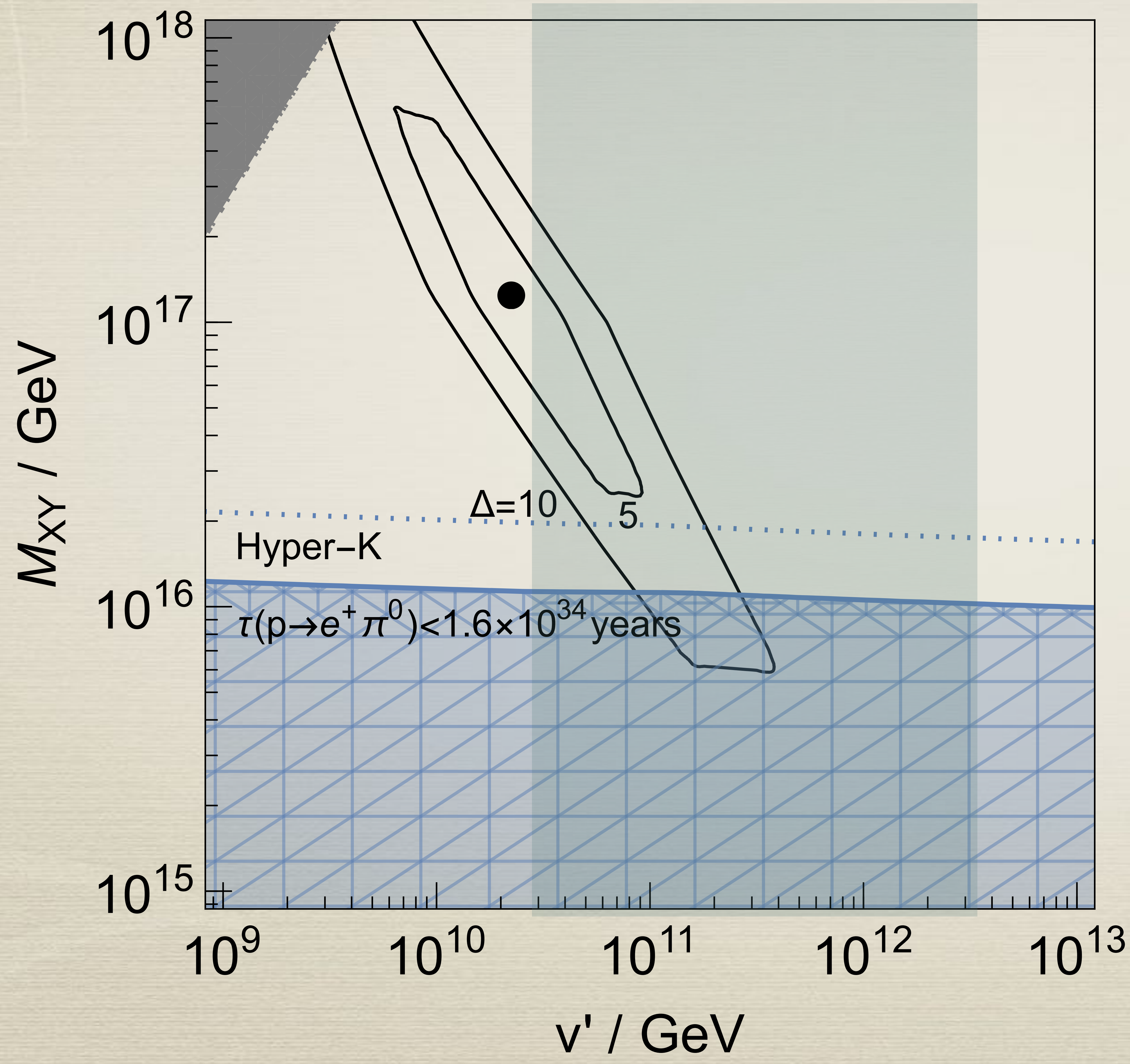
$$\Delta = \text{few} - 10$$

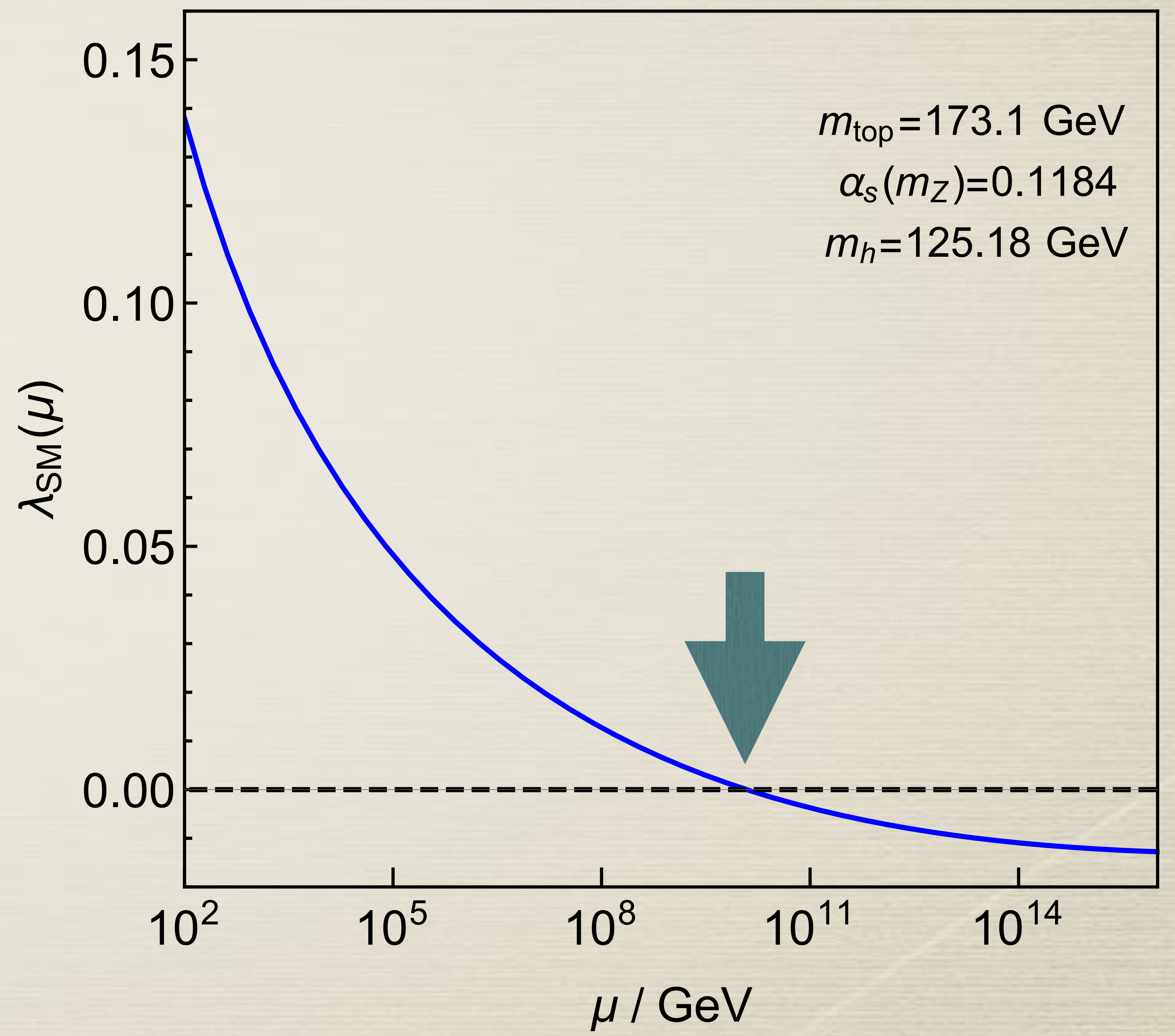
(smaller than SUSY GUT)

Quantify unification

Hall, KH (2019)

mass of new gauge boson mediating proton decay





Dark Matter?

* One of the right-handed neutrinos?

  Difficult because of the up-neutrino unification

* Dark sector?
* Free massive scalar?
* A new particle with non-trivial electroweak charge?

DM in 10

Let us add a fermion χ in 10 of $SO(10)$

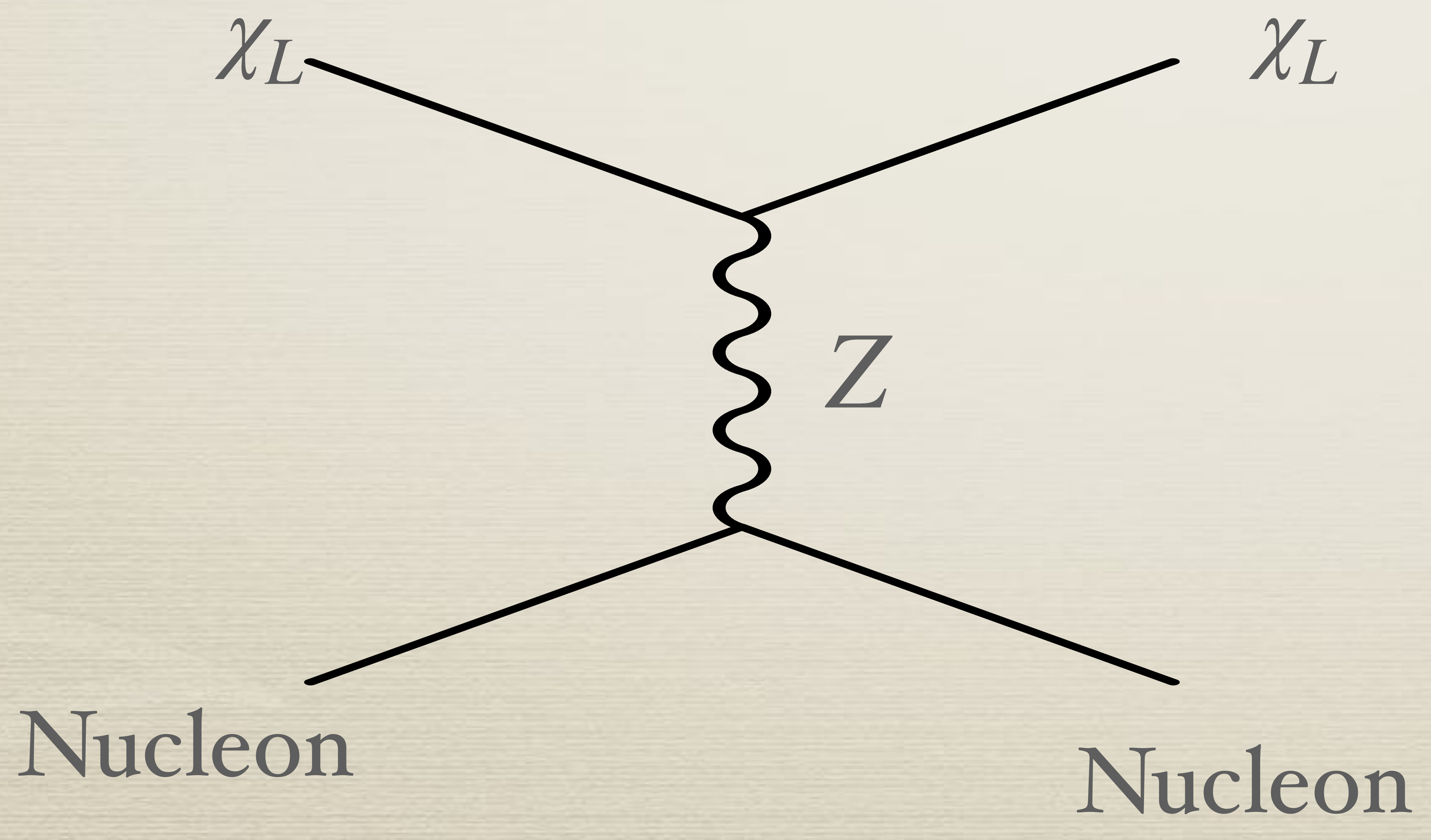
	χ_D	$\chi_{\bar{D}}$	χ_L	$\chi_{\bar{L}}$
$SU(3)$	3	$\bar{3}$		
$SU(2)$			2	2
$U(1)$	$-1/3$	$1/3$	$-1/2$	$1/2$

Higgsino-like DM

Higgsino-like DM

Freeze-out mechanism : $m_L \simeq 1$ TeV

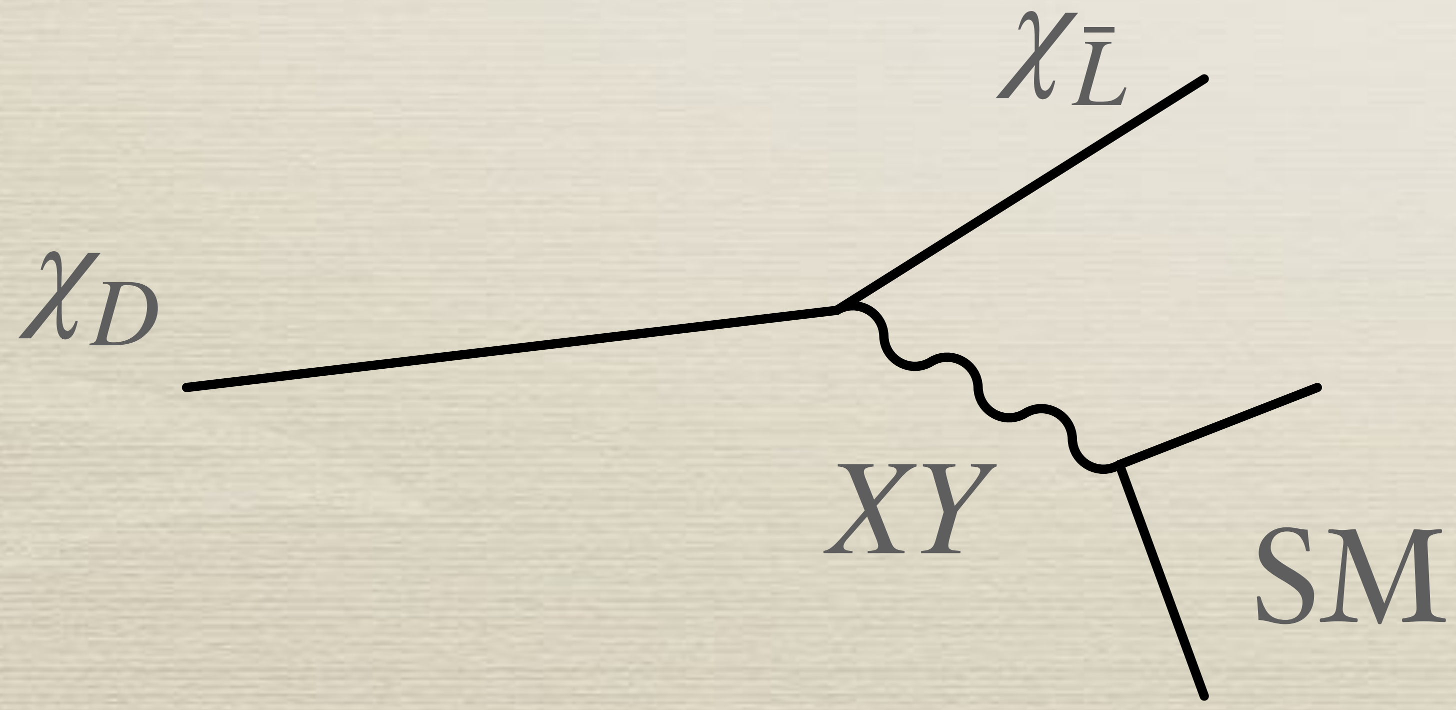
It should not remain a Dirac fermion
in order to avoid direct detection bound



Add a mixing with a singlet
that has a Majorana mass

Colored partner

	χ_D	$\chi_{\bar{D}}$	χ_L	$\chi_{\bar{L}}$
$SU(3)$	3	$\bar{3}$		
$SU(2)$			2	2
$U(1)$	$-1/3$	$1/3$	$-1/2$	$1/2$



The lifetime is longer than the age of the universe if $m_D \sim$ TeV

Exotic stable relic

χ_D annihilation freezes-out around $T \sim 0.1 m_D$

They re-annihilate around the QCD PT

$$\chi_D \bar{u} + \chi_{\bar{D}} u \to SM$$

$$\chi_D \chi_D u + \chi_D \bar{u} \to \chi_D \chi_D \chi_D + SM$$

Majority of them end up in $\chi_D \chi_D \chi_D$, as $\chi_D \bar{u}$ etc has large radius

$$\Omega_{\chi_D \chi_D \chi_D} h^2 \sim 0.1 \left(\frac{m_D}{10 \text{ TeV}} \right)^2$$

De Luca et.al (2018)

Charged particles with such large abundance is excluded by heavy isotope searches

Splitting by missing VEV

$$\langle H_{45}\rangle = -iv_{45} \times \begin{pmatrix} \sigma_2 & 0 & 0 & \\ 0 & \sigma_2 & 0 & 0_{4\times 6} \\ 0 & 0 & \sigma_2 & \\ & 0_{6\times 4} & & 0_{4\times 4} \end{pmatrix}$$

$SU(2)_R$ symmetry

$$\chi^{1-6} : \chi_{D,\bar{D}},\ \chi^{7-10} : \chi_{L,\bar{L}}$$

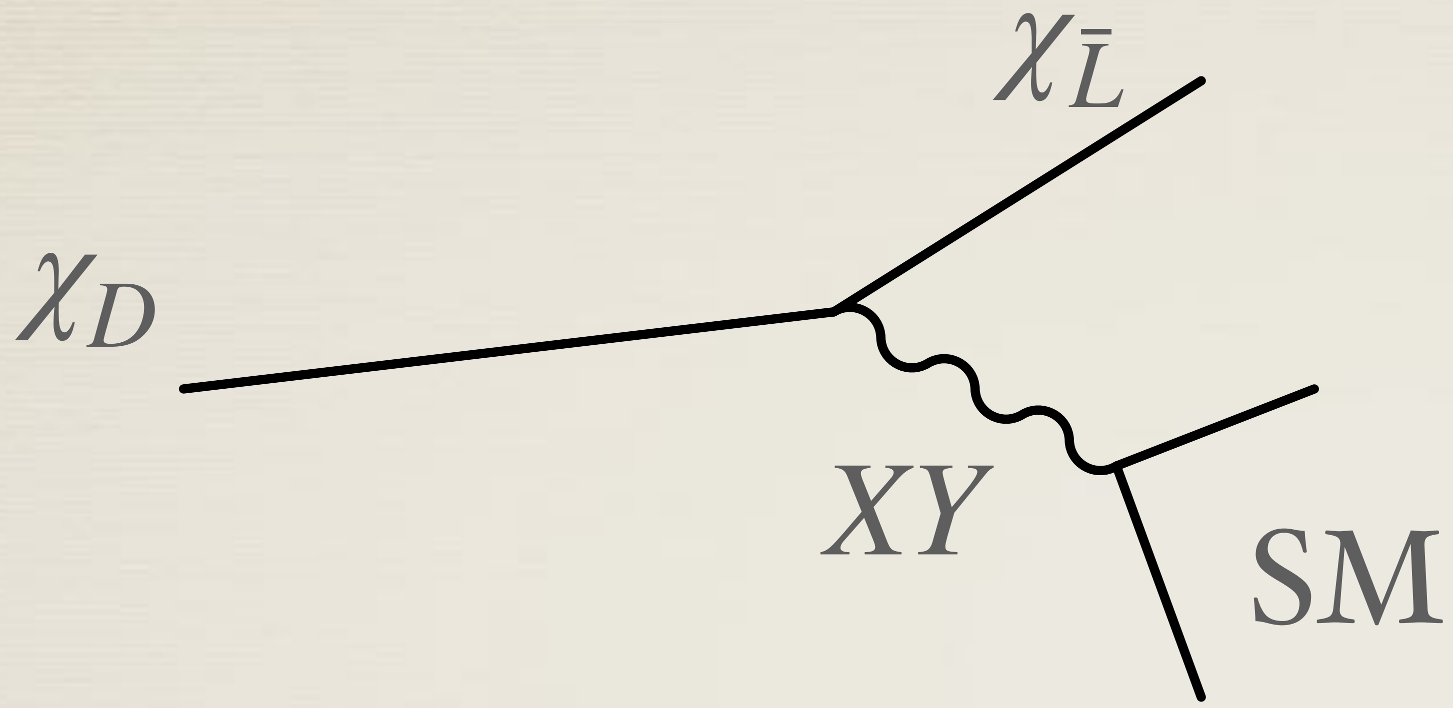
See Dimopoulos and Wilczek (1981)
for models with SUSY protection

By giving mass to χ by H_{45} maybe large mass splitting can be achieved

Baldwin and KH (2024)

(Models with small enough quantum corrections need one more 10-plet)

Lower bound on the mass

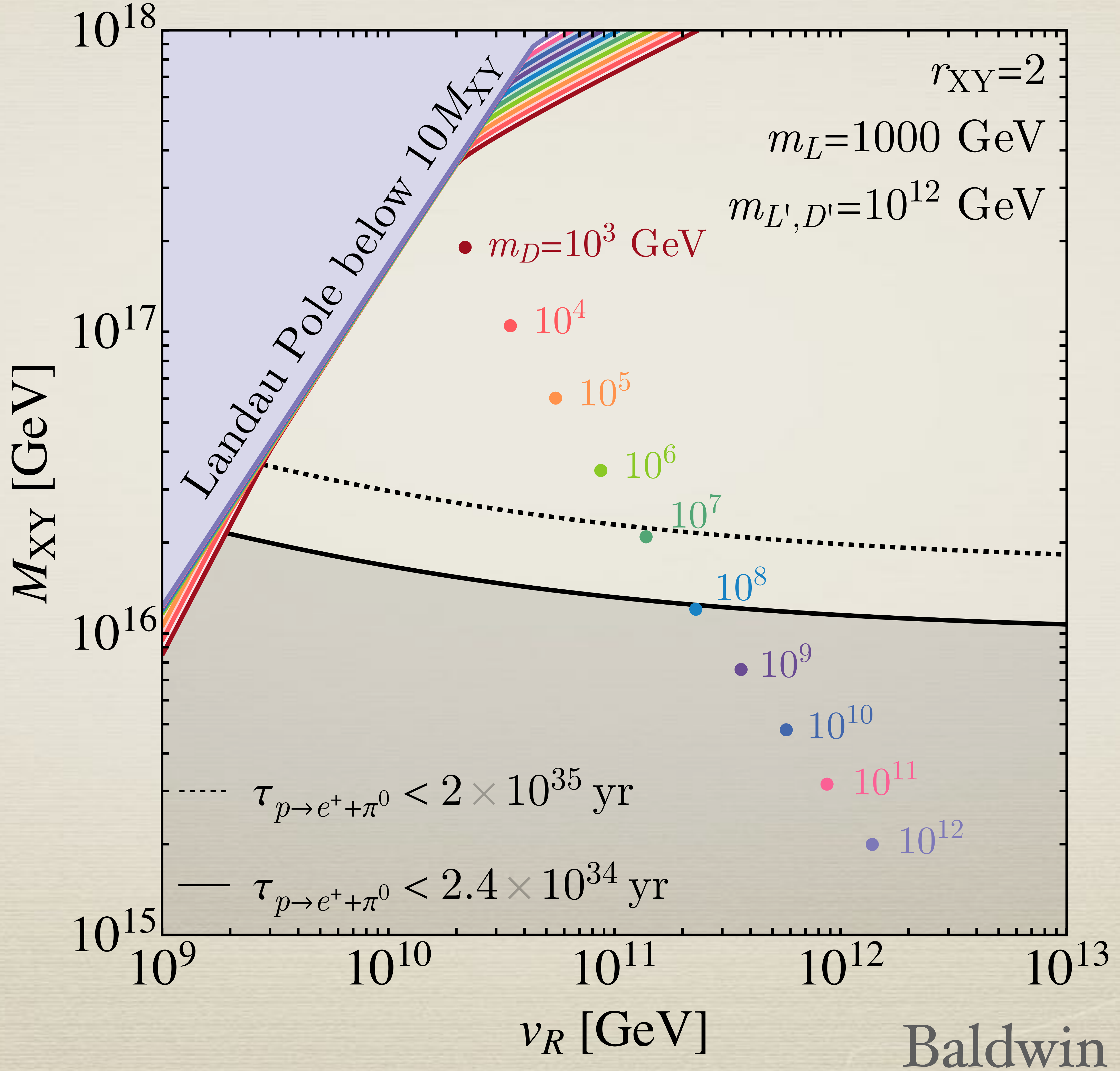


DM overproduction

$$\frac{\rho_{\rm DM}}{s} \simeq 0.4\ {\rm eV} \left(\frac{m_L}{100\ {\rm GeV}}\right)^3 \frac{0.05\ {\rm GeV}}{T_{\rm dec}}$$

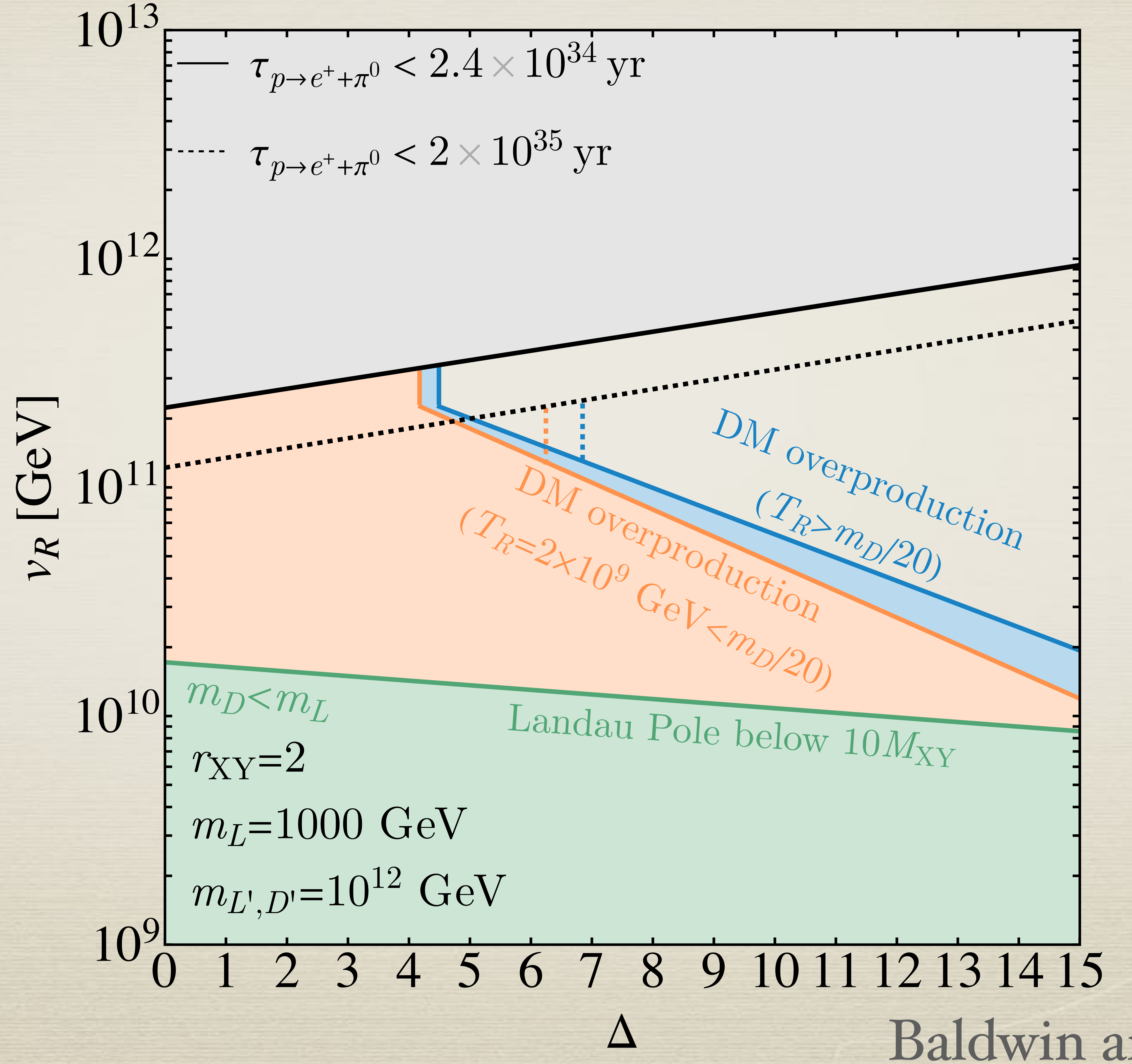
$$m_D > 3 \times 10^9\ {\rm GeV} \times \left(\frac{m_{XY}}{10^{16}{\rm GeV}}\right)^{4/5} \left(\frac{m_L}{100{\rm GeV}}\right)^{6/5}$$

Gauge coupling unification



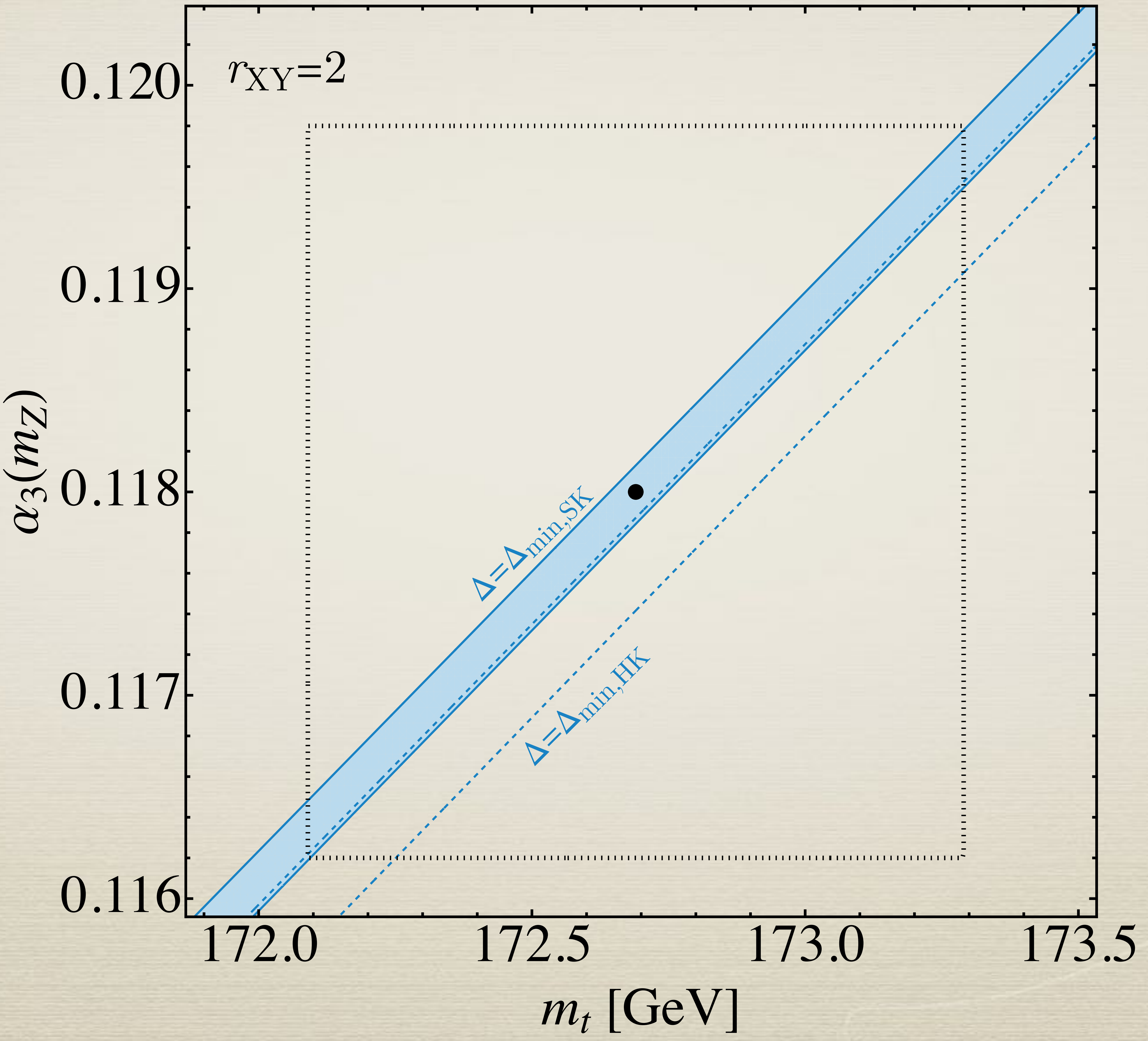
Baldwin and KH (2024)

Constraints



Baldwin and KH (2024)

SM parameters



Summary

* Z_2 symmetry of Higgs is phenomenologically interesting
* The breaking scale of a class of Z_2 symmetry, Higgs Parity, is correlated with the SM parameters
* Combined with space-time parity, the strong CP problem can be solved
* Implications to SO(10) unification, dark matter detections, etc.

Back up

Fermion masses

$$xH_{16}\psi_{16}X + \frac{1}{2}m_X X^2$$

X : 10 for down and electron, 45 or 54 for up and neutrino

CKM phase

$$xH_{16}\psi_{16}X + \frac{1}{2}m_X X^2$$

CP requires that x and m_X are real

$$i\frac{H_{45}}{M}H_{16}\psi_{16}X + \frac{1}{2}i\lambda H_{45}X^2$$

Setup

$\chi^a \chi^b H_{45}^{ab}$ identically vanishes

$$\chi^a \chi^b H_{45}^{ac} H_{45}^{bc} \xrightarrow[\text{quantum correction}]{} \chi^a \chi^a H_{45}^{bc} H_{45}^{bc}$$

So let us introduce two fermions : χ_1 and χ_2

Setup

$$\lambda\chi_1^a\chi_2^b H_{45}^{ab} + \frac{1}{2}M_2\chi_2^a\chi_2^a$$

For example, for $\lambda v_{45} < M_2$,

χ_2	M_2
χ_{D_1}	$\lambda^2 v_{45}^2/M_2$
χ_{L_1}	0

Corrections

$$\lambda \chi_1^a \chi_2^b H_{45}^{ab} + \frac{1}{2} M_2 \chi_2^a \chi_2^a$$

The first term preserve Z_4 under which $\chi_{1,2}(1)$, $H_{45}(2)$

Ignoring the second terms,
corrections always involve odd number of H_{45}

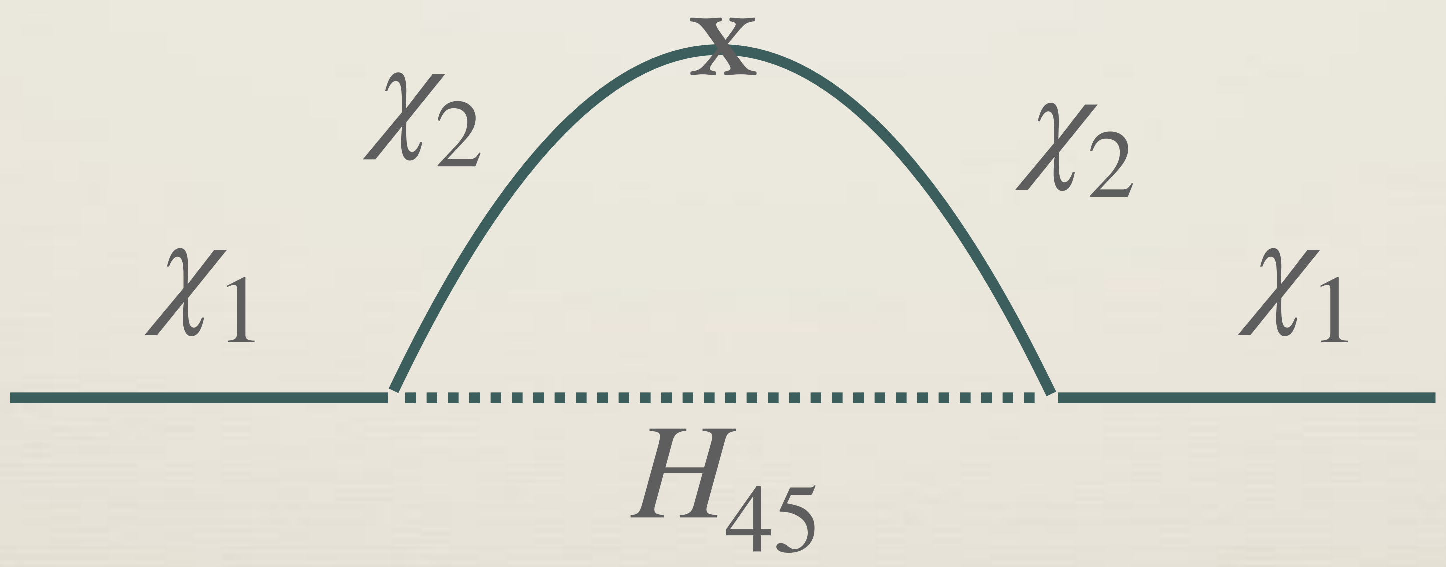
Two of the indices of H_{45}s must be contracted with χ

Correction to χ_L mass vanishes

Corrections

$$\lambda \chi_1^a \chi_2^b H_{45}^{ab} + \frac{1}{2} M_2 \chi_2^a \chi_2^a$$

Using the second term,



$$\delta m \sim \frac{1}{16\pi^2} \lambda^2 m_2 = 100 \text{ GeV} \left(\frac{\lambda}{10^{-4}} \right)^2 \frac{M_2}{10^{12} \text{ GeV}}$$

Corrections

$$\langle H_{45} \rangle = -iv_{45} \times \begin{pmatrix} \sigma_2 & 0 & 0 & \\ 0 & \sigma_2 & 0 & 0_{4\times 6} \\ 0 & 0 & \sigma_2 & \\ & 0_{6\times 4} & & 0_{4\times 4} \end{pmatrix}$$

$SU(2)_R$ symmetry

The vev should be non-zero after $SU(2)_R$ symmetry breaking

Indeed, $H_{45}H_{45}H_{16}H_{16}^*$ gives

$$\frac{\delta v}{v_{45}} \sim \frac{v_R^2}{v_{45}^2}$$