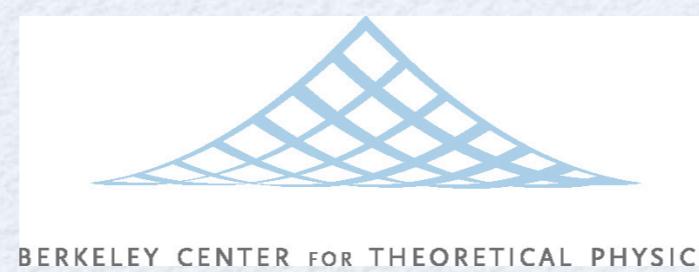


Gravity, Cosmology and Physics
Beyond the Standard Model
UPMC, Paris *June 11, 2018*

Higgs Mass, Strong CP and Unification

Lawrence Hall
University of California, Berkeley



Outline

- (I) 125 GeV Higgs and a new Z_2 Symmetry
- (II) A Parity Solution of Strong CP
- (III) A New Unification Scheme

Outline

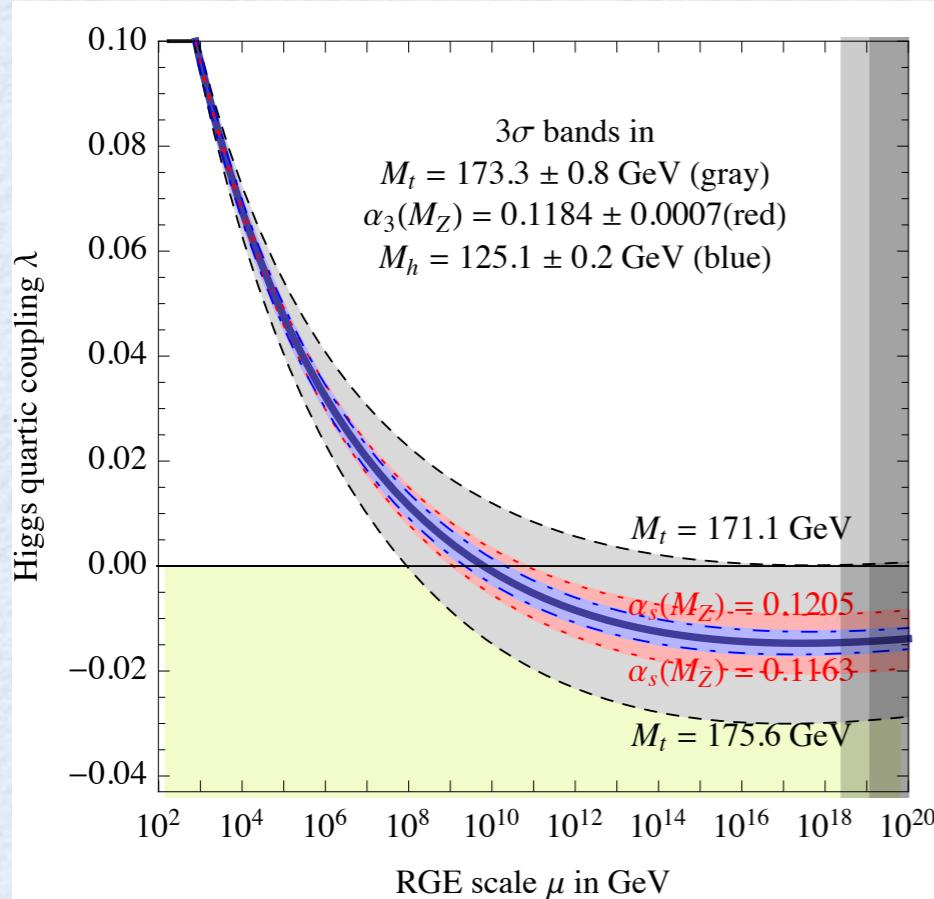
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- (II) A Parity Solution of Strong CP
- (III) A New Unification Scheme

LJH and Keisuke Harigaya 1803.08119

(I)

125 GeV Higgs
and
a new Z_2 Symmetry

A Small Higgs Quartic Coupling in UV

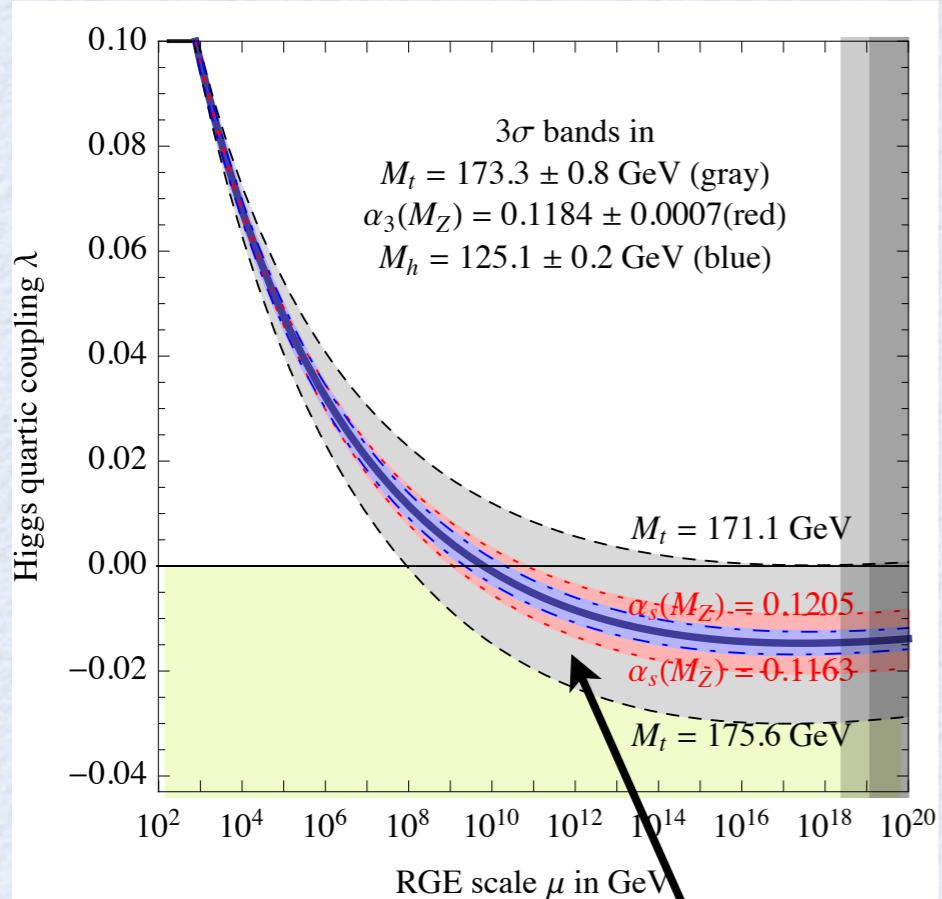


$$\mu_c \sim (3 \times 10^8 - 3 \times 10^{12}) \text{ GeV}$$
 at 2 σ

Perhaps the key discovery of LHC

Buttazzo, Degrassi,
Giardino, Giudice,
Sala, Salvio, Strumia
1307.3536

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Why is
high-scale quartic
 $\mathcal{O}(10^{-2})$?

- Supersymmetry?
- Anthropicics of vacuum stability?
- ...

An Exact Z_2 Symmetry

Introduce H' with

$$H \xleftrightarrow{Z_2} H'$$

Spontaneously break Z_2

$$\langle H' \rangle = v' \gg v$$

H' must be $SU(2)$ singlet

$$\begin{aligned} SU(2) &\xleftrightarrow{Z_2} SU(2)' \\ H(2, 1) &\xleftrightarrow{Z_2} H'(1, 2) \end{aligned}$$

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- Total Mirror Sector
- Electroweak Mirror Sector
- $SU(2)' = SU(2)_R$
- ...



$$V(H, H') = -m^2(H^\dagger H + H'^\dagger H') + \frac{\lambda}{2}(H^\dagger H + H'^\dagger H')^2 + \lambda' H^\dagger H H'^\dagger H'$$

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- Assume $m^2 \gg v^2$, $\lambda \sim \mathcal{O}(1)$
- Then $\langle H' \rangle = v'$ with $v'^2 = m^2/\lambda$
- Fine tune for light SM Higgs $\lambda' \rightarrow 0$
- H is PGB of SU(4) at scale v' $\begin{pmatrix} H \\ H' \end{pmatrix}$

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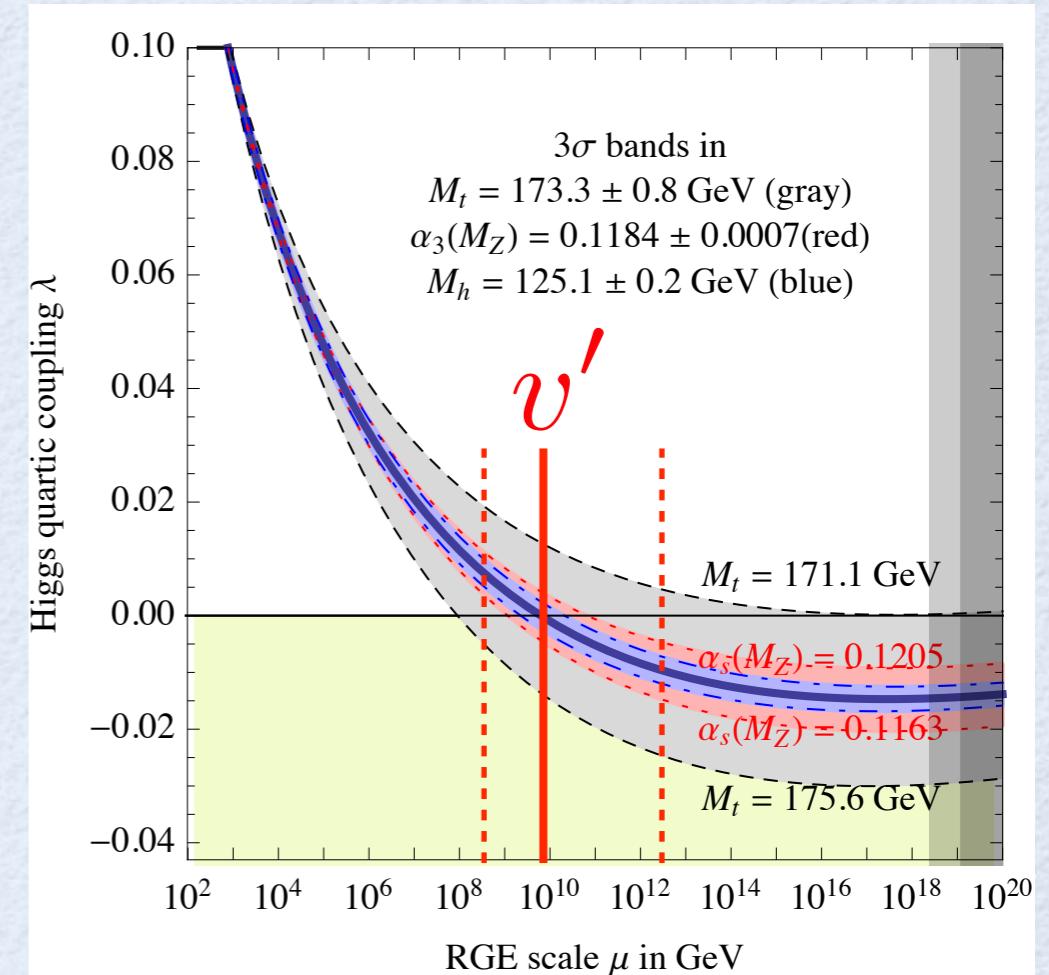
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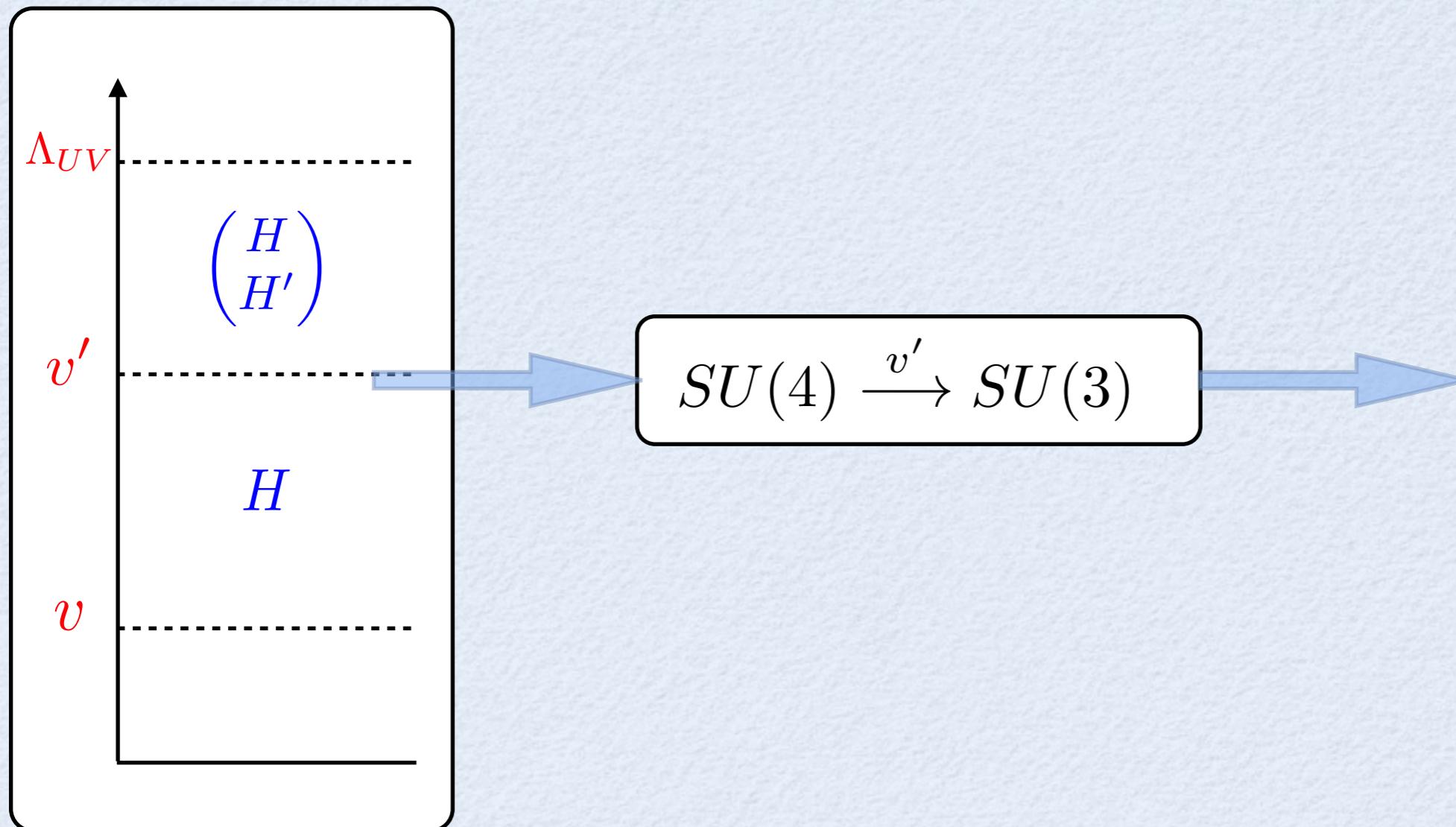
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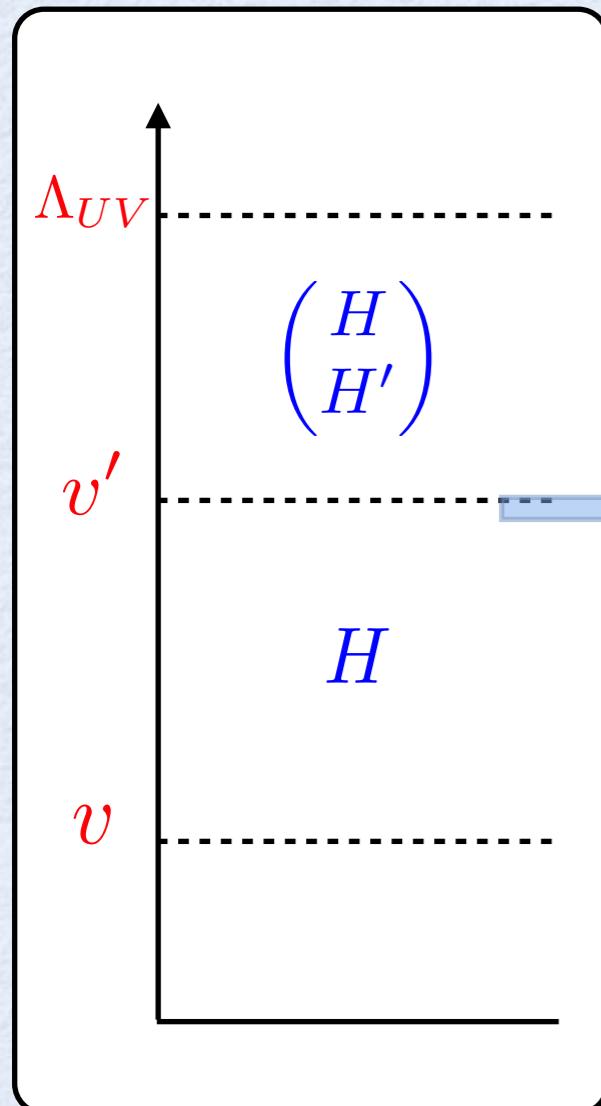


$$v' \sim \mathcal{O}(\mu_c)$$

Summary of Setup



Summary of Setup



$$SU(4) \xrightarrow{v'} SU(3)$$

7 Goldstones

- 3 are W'
- 4 are H

Fine Tuning

$$\frac{v'^2}{\Lambda_{UV}^2} = \frac{v^2}{v'^2} = \frac{v^2}{\Lambda_{UV}^2}$$

as in Standard Model

Anthropic Weak Scale?

- Complex stable nuclei?
- Escape He universe at BBN?

SM' and LR Versions

How do quarks and leptons transform under $SU(2) \times SU(2)' \text{ and } Z_2$?

Assume $q(2, 1), \ell(2, 1)$

SM'

Doublets

$$q(2, 1), \ell(2, 1) \xrightarrow{Z_2} q'(1, 2), \ell'(1, 2)$$

Singlets

$$\bar{u}, \bar{d}, \bar{e} \longleftrightarrow \bar{u}', \bar{d}', \bar{e}'$$

SM' and LR Versions

How do quarks and leptons transform under $SU(2) \times SU(2)' \text{ and } Z_2$?

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LR Doublets $q(2, 1), \ell(2, 1) \longleftrightarrow q'(1, 2), \ell'(1, 2)$

$SU(2)' = SU(2)_R$ $\bar{u}, \bar{d}, \bar{e}, \bar{\nu}$

(II)

A Parity Solution
Of
Strong CP Problem

$Z_2 \rightarrow P$ and Strong CP

Extend Z_2 to include
spacetime parity

$$\begin{array}{ccc} SU(2) & \xleftrightarrow{P} & SU(2)' \\ H(2,1) & \xleftrightarrow{P} & H'(1,2) \end{array} \quad \begin{array}{ccc} \bar{x} & \xleftrightarrow{P} & -\bar{x} \\ \psi & \xleftrightarrow{P} & \psi'^{\dagger} \end{array}$$

Theories with SM'

SM fermions and Yukawa couplings all replicated

$$q, \bar{u}, \dots \xleftrightarrow{P} q'^{\dagger}, \bar{u}'^{\dagger}, \dots$$

$$q y \bar{u} H \xleftrightarrow{P} q' y^* \bar{u}' H'$$

$$\mathcal{L}_u = (u' \ u) \begin{pmatrix} y^* v' & 0 \\ 0 & yv \end{pmatrix} \begin{pmatrix} \bar{u}' \\ \bar{u} \end{pmatrix}$$

v, v' real

$$\det M_q \text{ real if } \textcolor{red}{SU(3)} \xleftrightarrow{P} \textcolor{red}{SU(3)}$$

$Z_2 \rightarrow P$ and Strong CP

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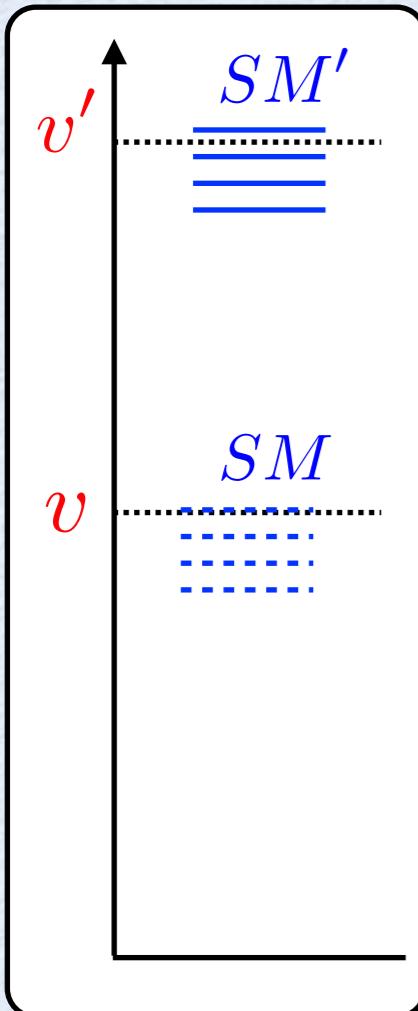
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Strong CP problem solved
via key ingredients

$$\begin{array}{c} \textcolor{red}{Z_2 \rightarrow P} \\ \textcolor{red}{SU(3) \xleftrightarrow{P} SU(3)} \end{array}$$

Theories with SM'

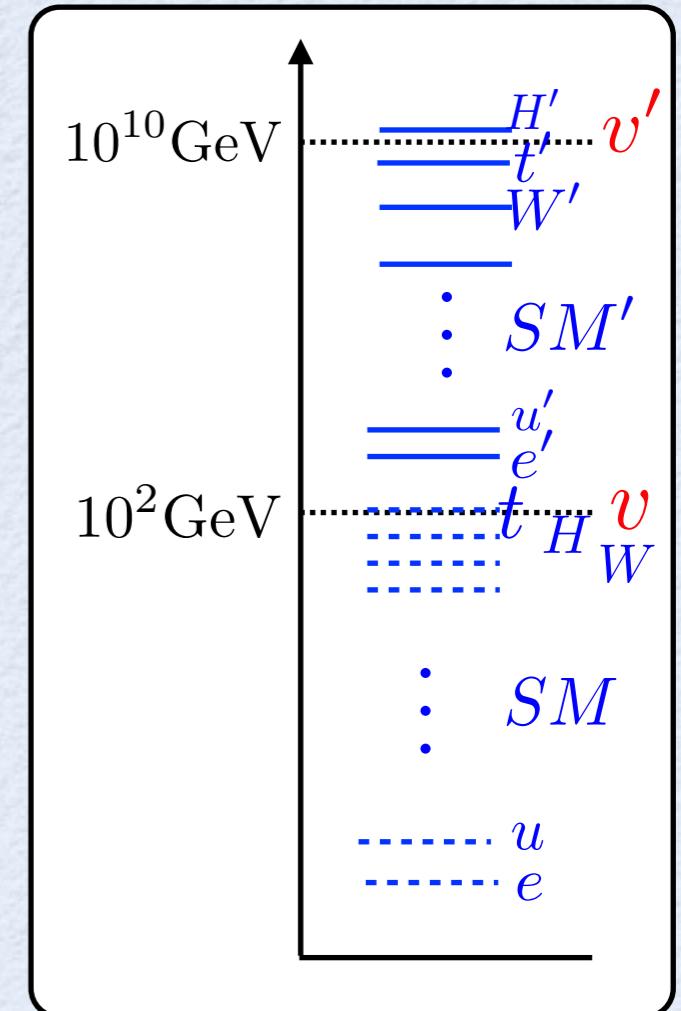


Two minimal gauge groups

$$G = 3 - 2 - 2' - \begin{Bmatrix} 1 & 1' \\ & 1 \end{Bmatrix}$$

Key feature of each choice

- 1-1' $e' u'$ dark matter
- 1 No dark matter



Theories with Left-Right Symmetry

$$SU(2)' = SU(2)_R$$

$$SU(2)_L \xleftrightarrow{P} SU(2)_R$$

Not necessary to introduce
singlet fermions $\bar{u}, \bar{d}, \bar{e}$

$$q, \ell \xleftrightarrow{P} q'^\dagger, \ell'^\dagger$$

$$q_L, \ell_L \xleftrightarrow{P} q_R, \ell_R$$

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Flavor from d>4

$$\mathcal{L}_5 = \frac{1}{M} (q_i \tilde{y}_{ij} q'_j) H H'$$

$$P \Rightarrow \tilde{y}^\dagger = \tilde{y}$$

Eigenvalues real
 $\delta_{CKM} \sim \mathcal{O}(1)$

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Two Types of Theories

SM'

$$q, \bar{u}, \dots \xleftrightarrow{P} q'^\dagger, \bar{u}'^\dagger, \dots$$

$$G = 3 - 2 - 2' - 1$$

$$G = 3 - 2 - 2' - 1 - 1'$$

$$G = \dots$$

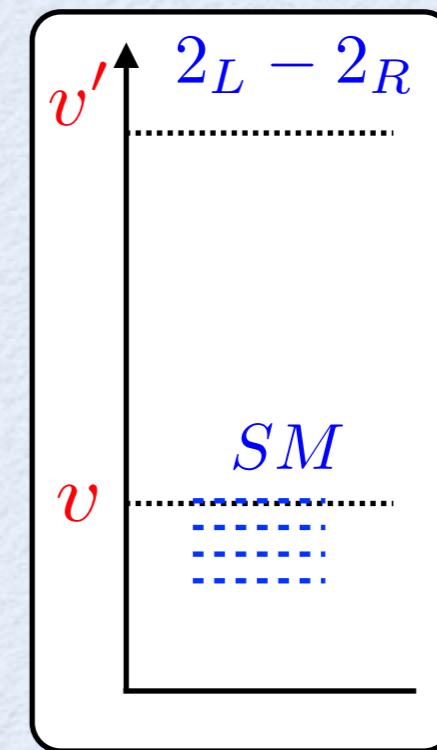
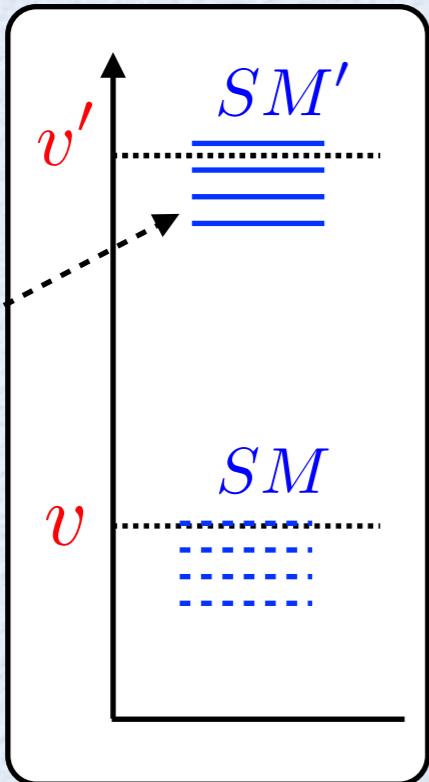
LR

$$q, \ell \xleftrightarrow{P} q'^\dagger, \ell'^\dagger$$

$$G = 3 - 2_L - 2_R - 1_{B-L}$$

$$G = 4 - 2_L - 2_R$$

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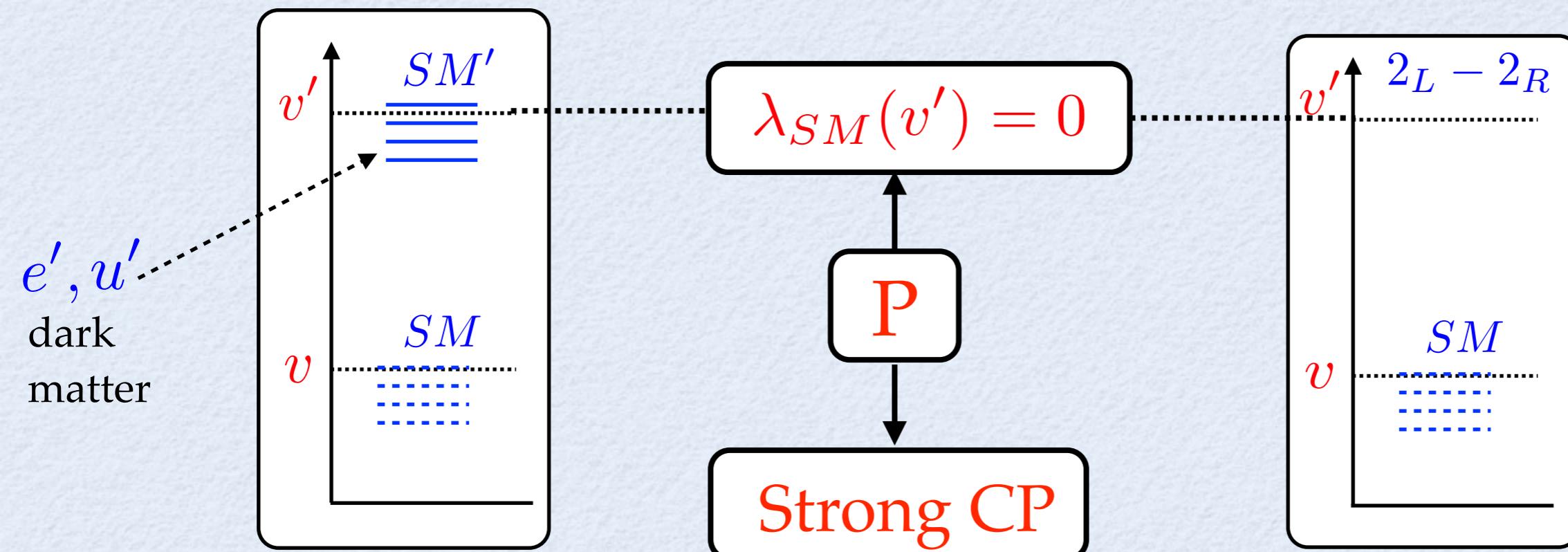
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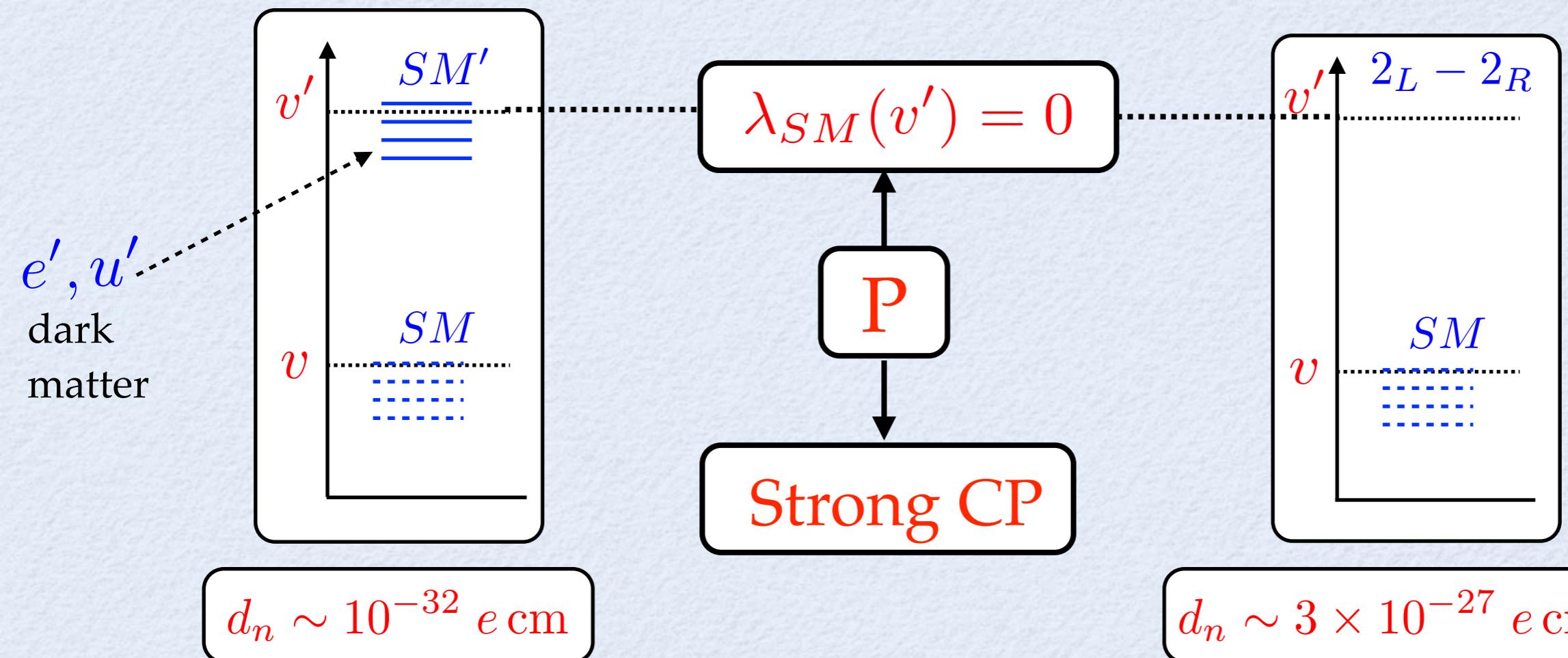
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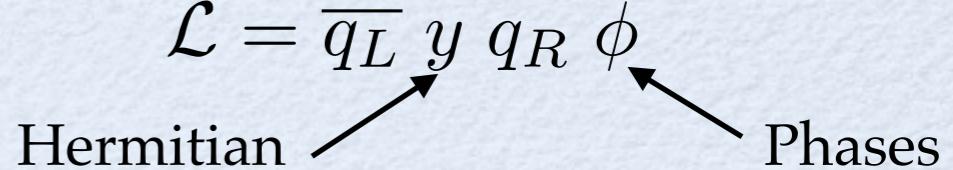
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Long History of LR for Strong CP

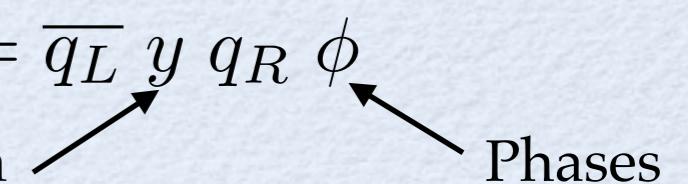
- 1978 Beg, Tsao and Mohapatra, Senjanovic
P can lead to Hermitian quark mass matrices
- 1970s and 1980s
LR models developed with standard Higgs sector $\phi(2, 2), \Delta(3, 1), \Delta(1, 3)$
- 1991 Barr, Chang and Senjanovic
Standard LR theory does not solve strong CP
$$\mathcal{L} = \overline{q_L} y q_R \phi$$

Hermitian 
- 1990 Babu and Mohapatra. *Phys. Rev D41, 1286*
First LR theory to solve strong CP
Introduced $H(2,1) + H'(1,2)$ Higgs sector based on a softly broken Z_2

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Hermitian  Phases

For decades the axion has ruled as the best solution for strong CP

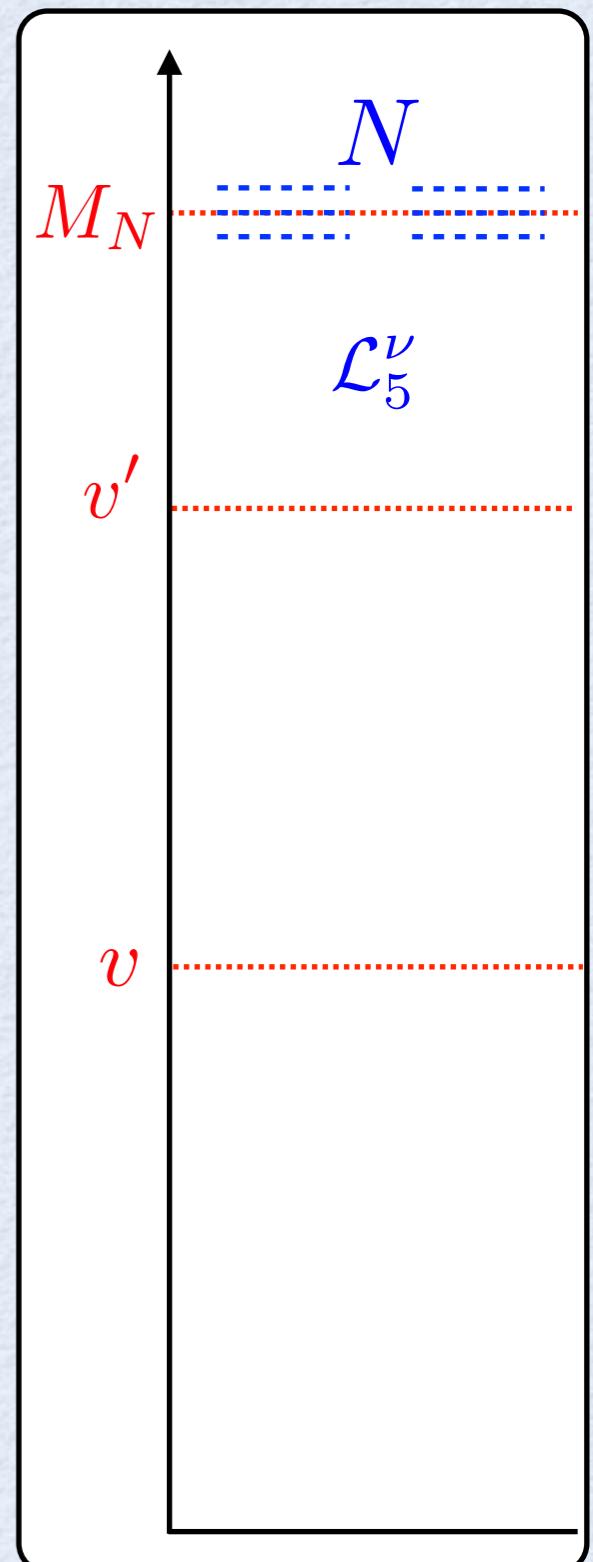
Parity provides a strong competitor

Neutrino Masses (SM' and LR)

- In all such Z_2 theories (ℓH) and $(\ell' H')$ are gauge singlets
- Hence, the most general seesaw leads to d=5 operators

$$\mathcal{L}_5^\nu = \left(\ell' \frac{\eta}{2M_M} \ell' \right) H' H' + \left(\ell \frac{\eta}{2M_M} \ell \right) H H + \left(\ell' \frac{\xi}{M_D} \ell \right) H' H$$

- Mass scales: M_M, M_D
- 3 X 3 flavor matrices: η, ξ



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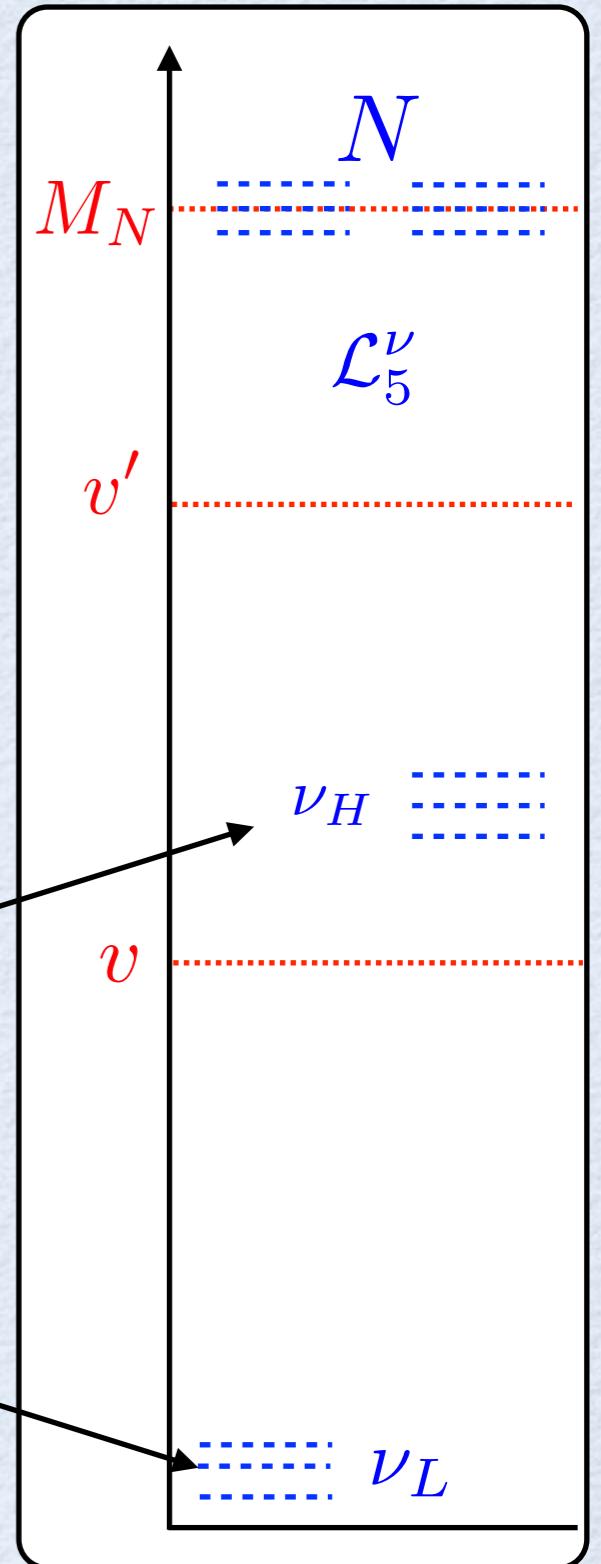
- For one generation

$$\mathcal{L}_\nu = \frac{1}{2} (\nu' \quad \nu) \begin{pmatrix} \frac{v'^2}{M_M} & \frac{vv'}{M_D} \\ \frac{vv'}{M_D} & \frac{v^2}{M_M} \end{pmatrix} \begin{pmatrix} \nu' \\ \nu \end{pmatrix}$$

giving

$$m_{\nu_H} = \frac{v'^2}{M_M}$$

$$m_{\nu_L} = \frac{v^2}{M_M} \left(1 - \frac{M_M^2}{M_D^2} \right)$$



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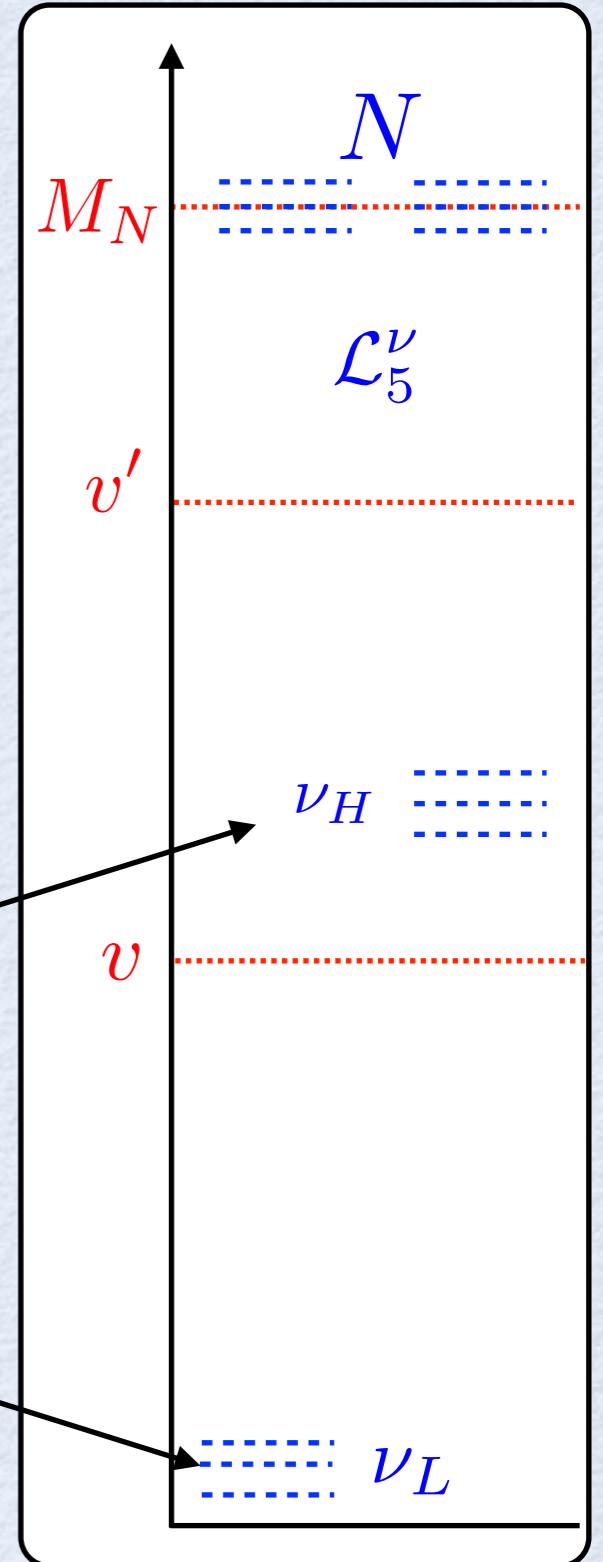
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Z_2 partner neutrinos typically around 100 TeV



(III)

Structure and Unification
of
LR Theories

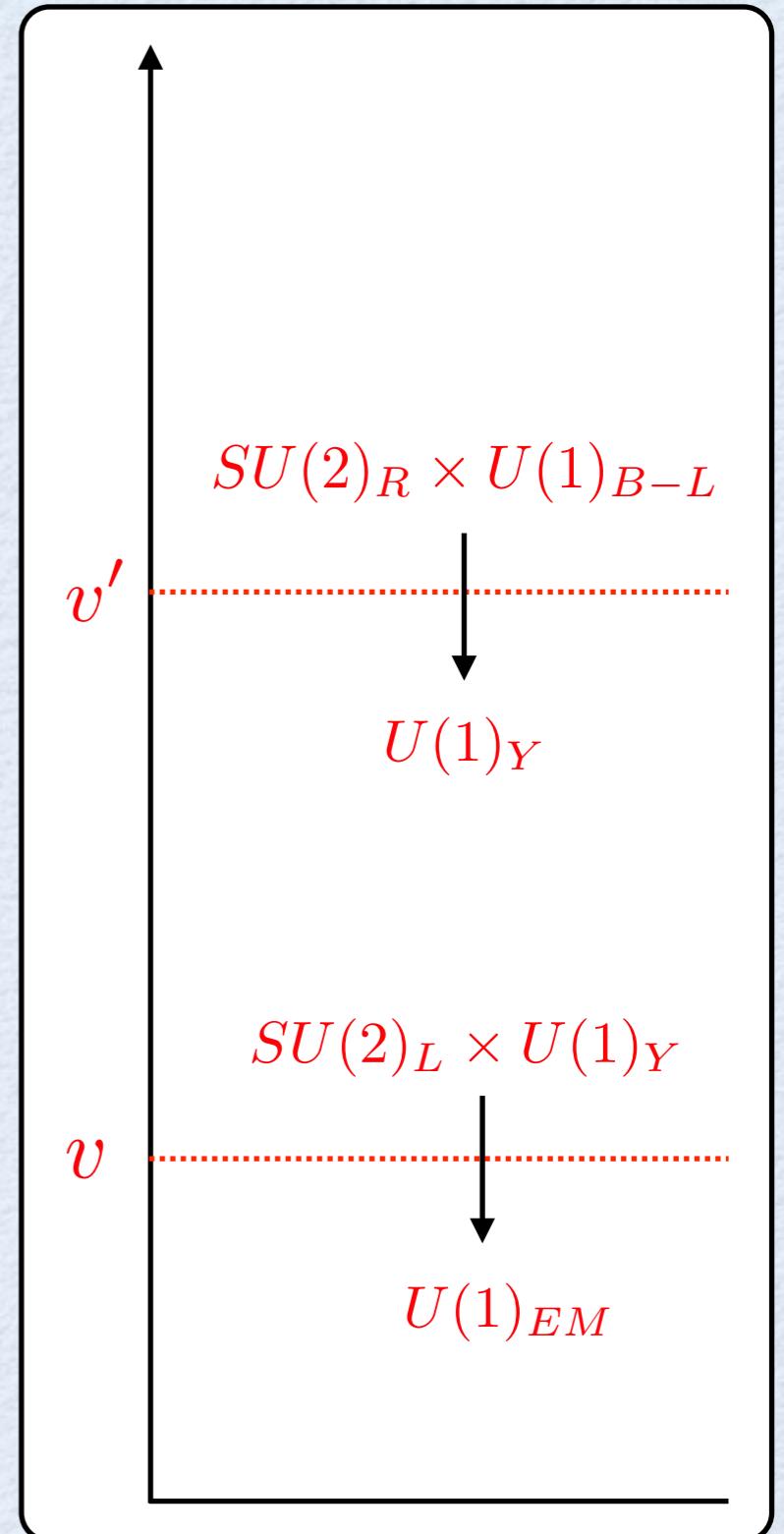
The Scalar Potential

$$\begin{aligned} SU(2) &\xleftrightarrow{P} SU(2)' \\ H(2,1) &\xleftrightarrow{P} H'(1,2) \end{aligned}$$

$$V(H, H') = -m^2(H^\dagger H + H'^\dagger H') + \frac{\lambda}{2}(H^\dagger H + H'^\dagger H')^2 + \lambda' H^\dagger H H'^\dagger H'$$

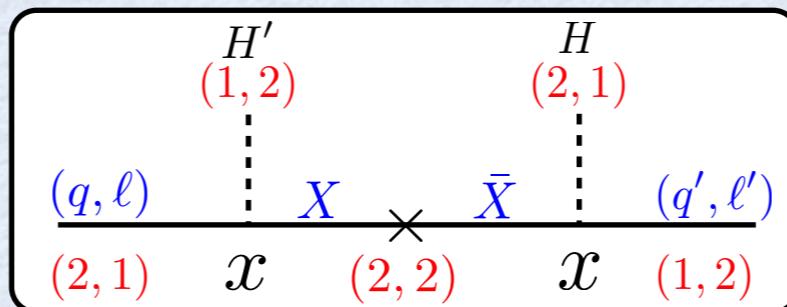
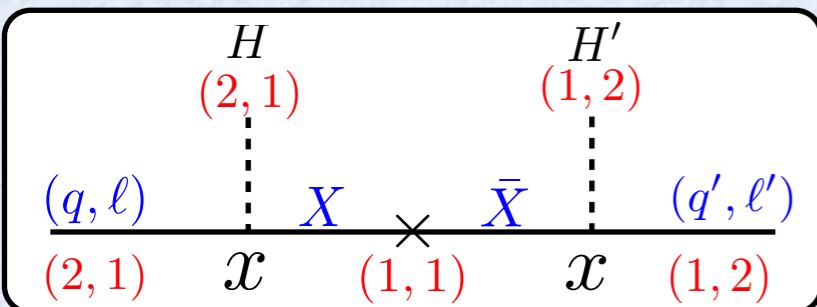
- P is exact
- For $v \ll v'$ must fine tune $\lambda' \rightarrow 0$

- Two copies of $SU(2) \times U(1) \rightarrow U(1)$
- Remarkably simple — no phases



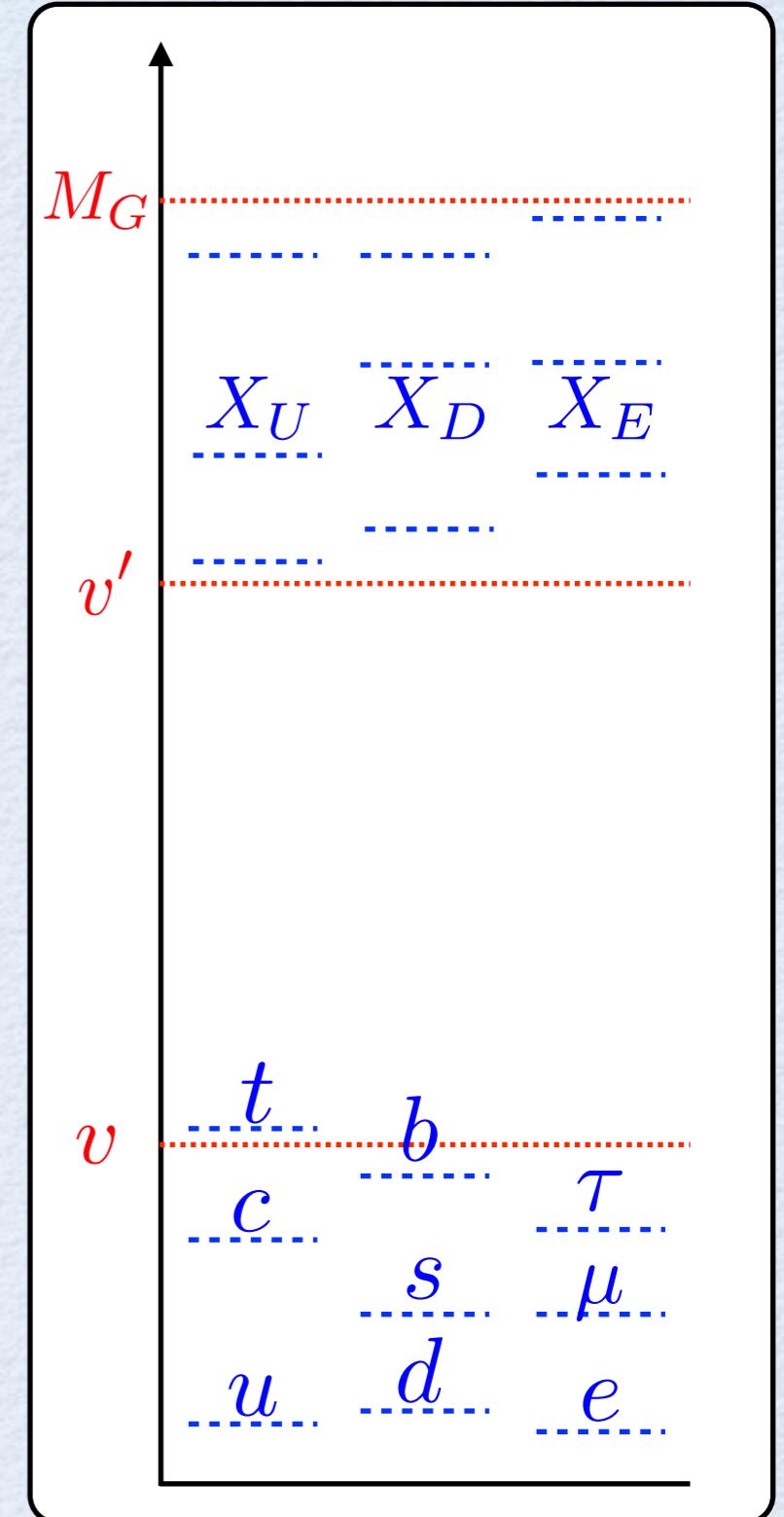
Quark and Charged Lepton Masses

- Arise from Froggatt-Nielsen mechanism
- eg. from leading diagrams with $\mathcal{O}(1)$ couplings



$$y_f = x_f \frac{v'}{M_{X_f}} x'_f \quad f = U, D, E$$

- X between v' and M_G
- Highly constrained in SO(10)



An Estimation of $\bar{\theta}$

- Below M_X we have

$$\mathcal{L} = \frac{1}{M_X} qq' HH' + \frac{1}{M_X^2} \mathcal{O}_6 + \frac{1}{M_X^3} \mathcal{O}_7 + \dots$$

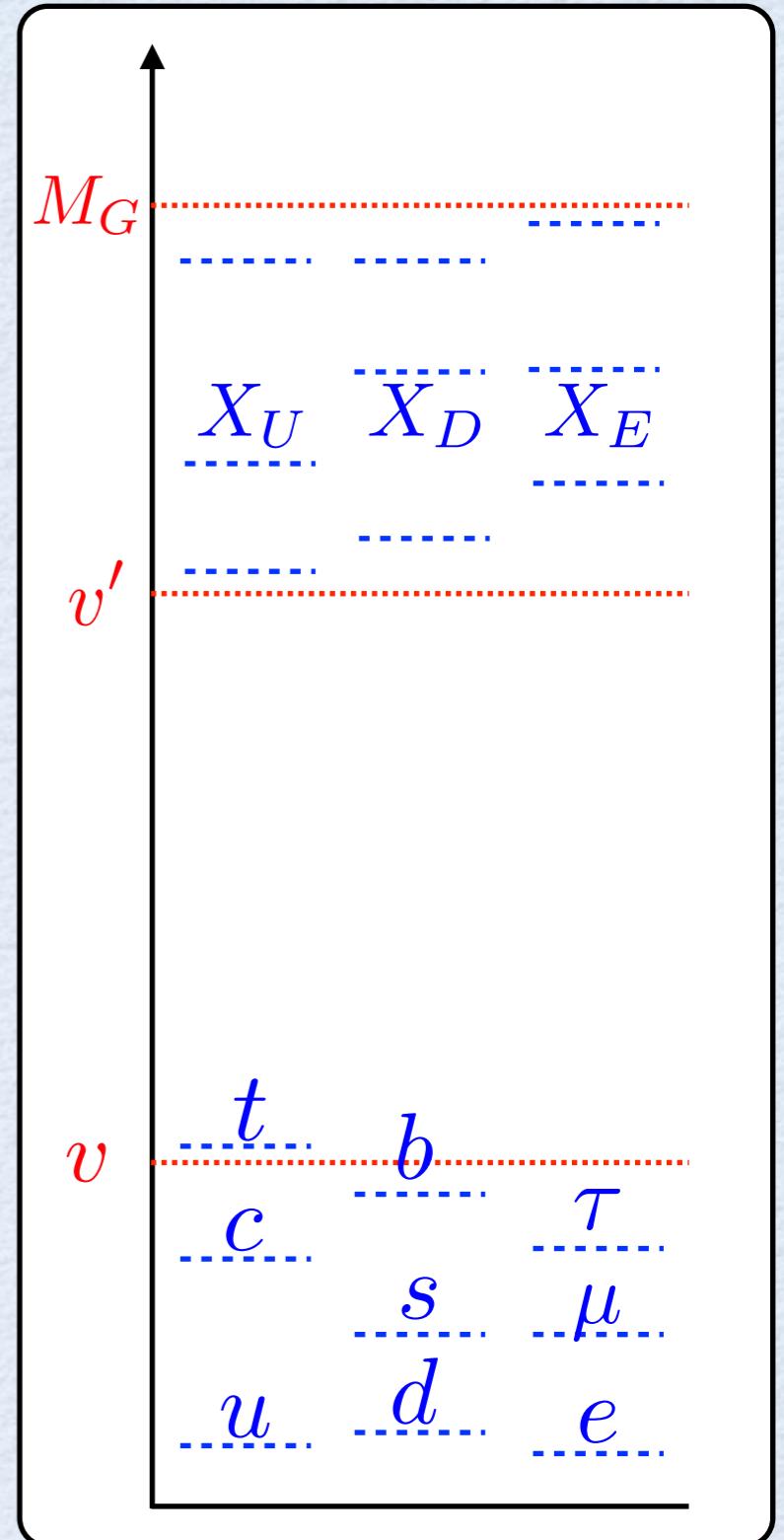
Leading term
for quark masses

Leading contribution to $\bar{\theta}$
occurs at two loops

- Quark mass hierarchies
from M_X hierarchies

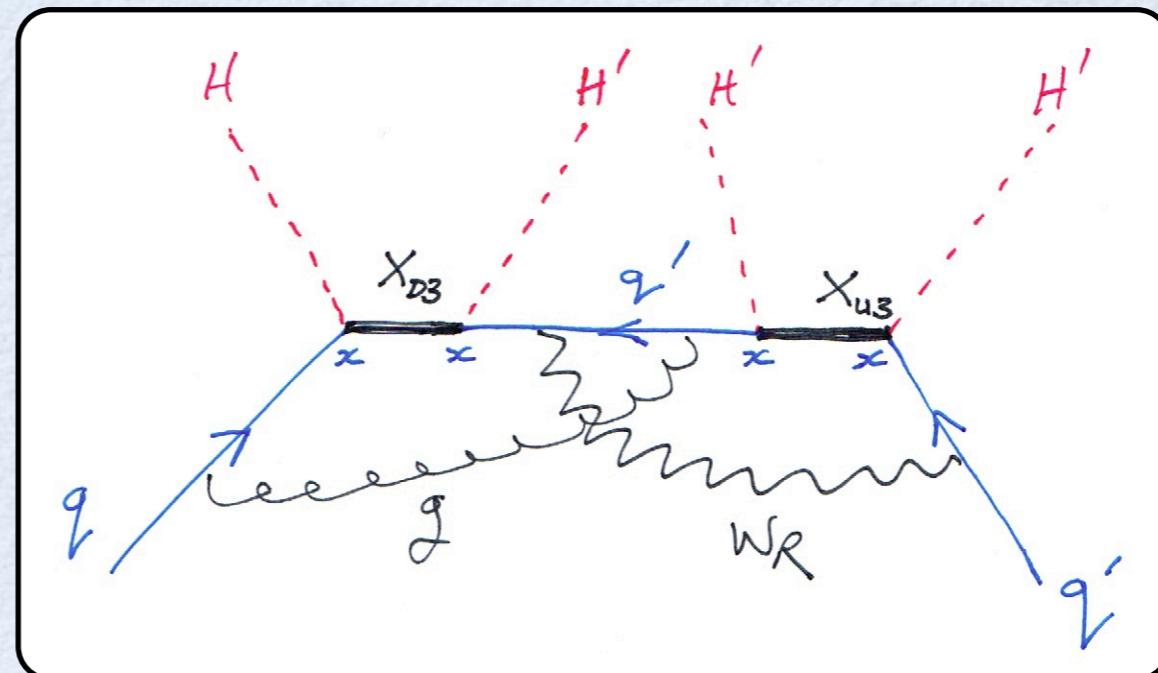


$\bar{\theta}$ mainly
from X_{U3}, X_{D3}



An Estimation of $\bar{\theta}$

- Threshold correction at M_X



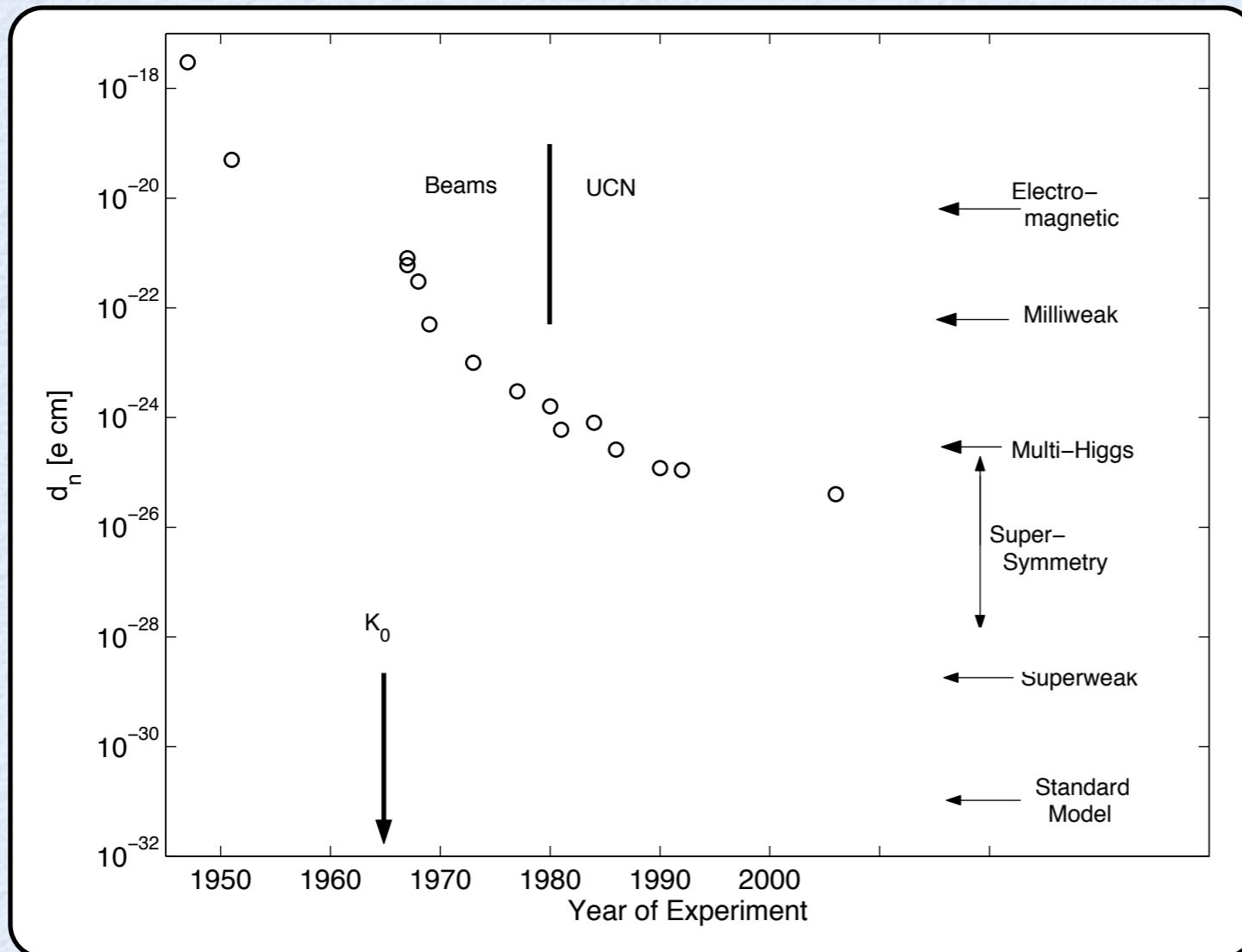
- Phase arises when $k \sim M_{D3}$
- Careful analysis of flavor gives
- For order unity phases

$$\delta y_D \sim \frac{g_3^2 g_2^2}{(16\pi^2)^2} \frac{x^4 v'^3}{M_{D3}^3}$$

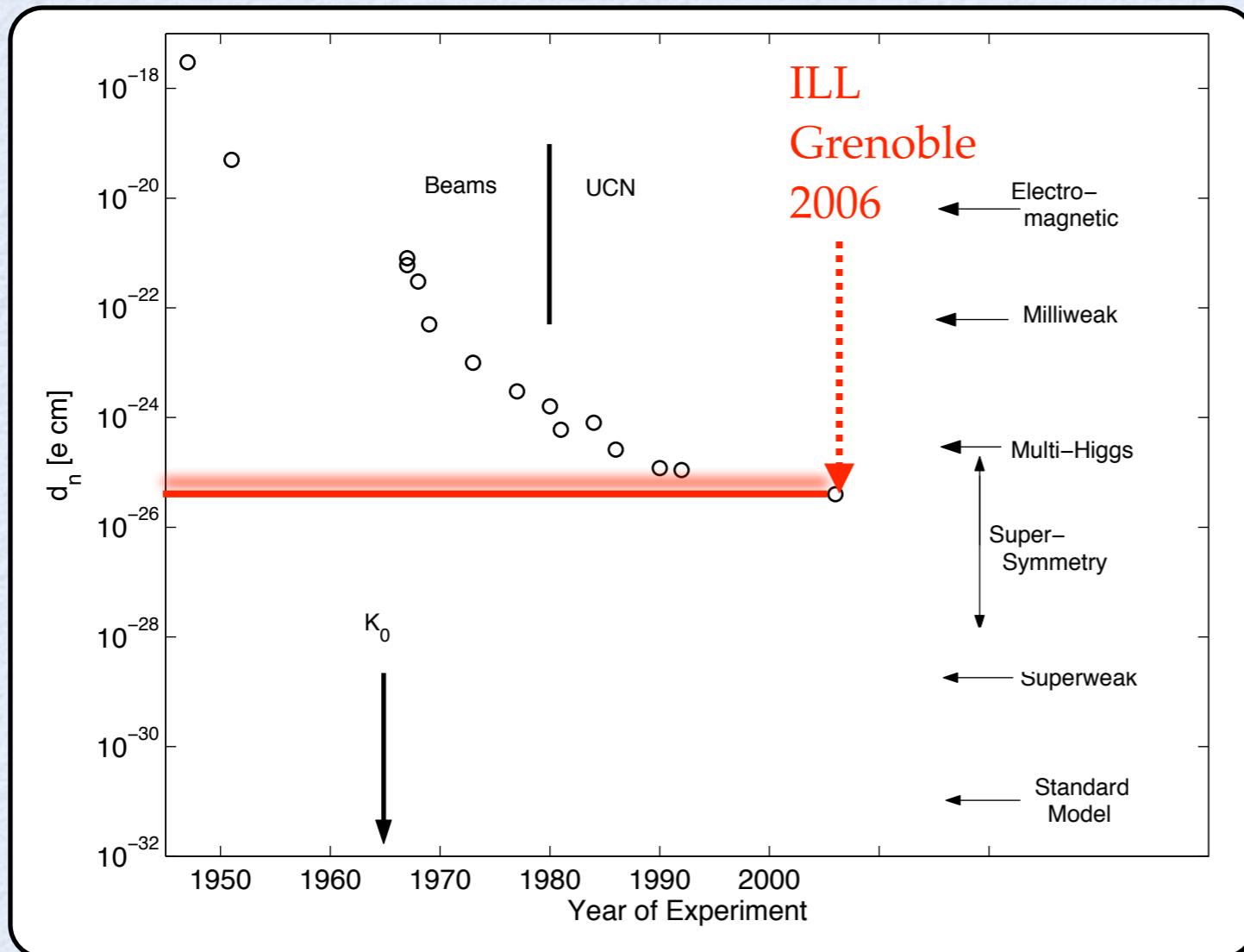
$$\bar{\theta} \sim \frac{g_3^2 g_2^2}{(16\pi^2)^2} \theta_{23}^U \theta_{23}^D \frac{y_b^3}{y_s^2} \xrightarrow{\theta_{23}^U \sim \theta_{23}^D} 10^{-11}$$

$$(V_{cb} = |\theta_{23}^U - \theta_{23}^D|)$$

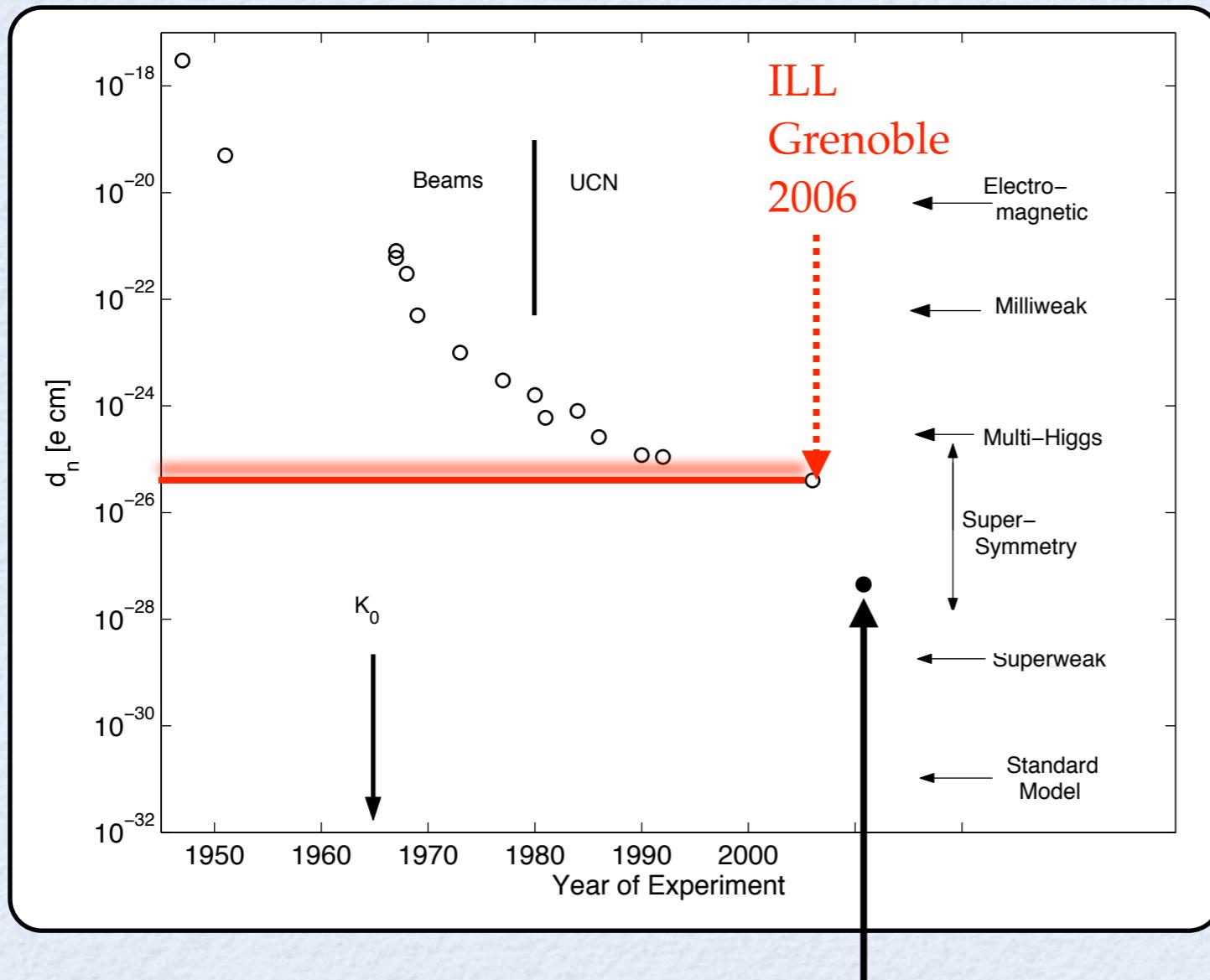
Neutron edm Experiments



Neutron edm Experiments

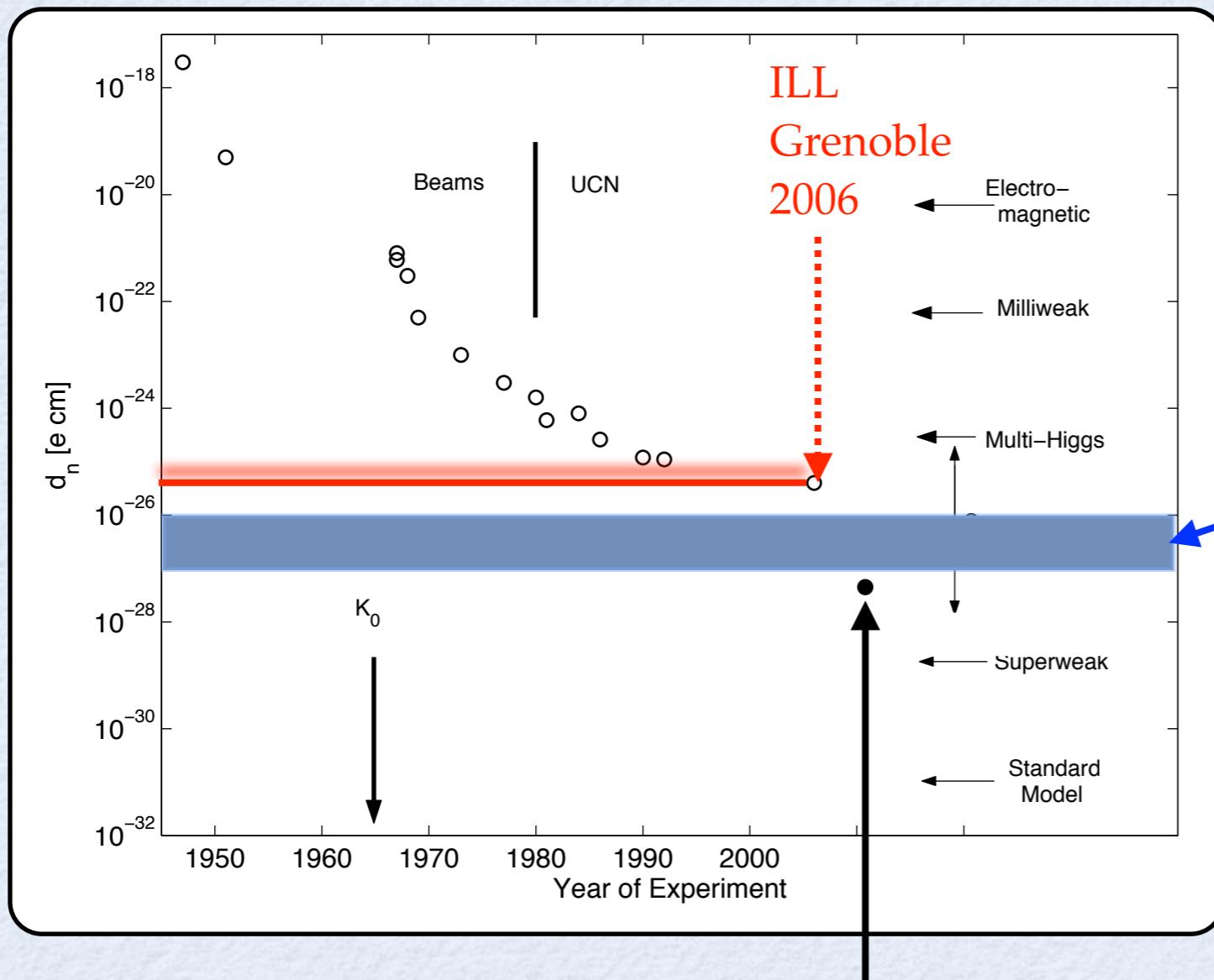


Neutron edm Experiments



- PSI, Switzerland
- SNS, Oak Ridge

Neutron edm Experiments

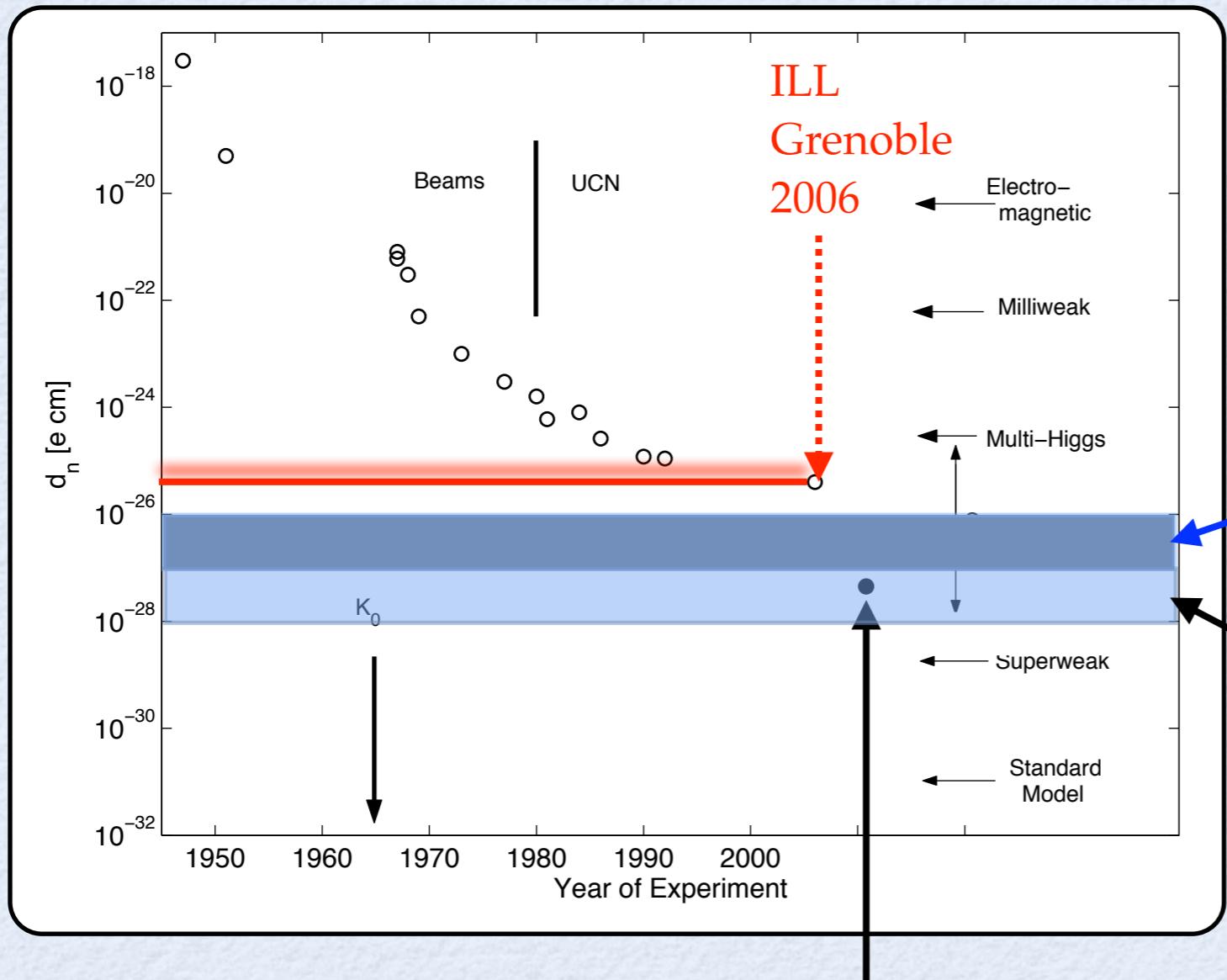


Central prediction

$$\theta_{23}^{U,D} \sim V_{cb}$$

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- SNS, Oak Ridge

Neutron edm Experiments



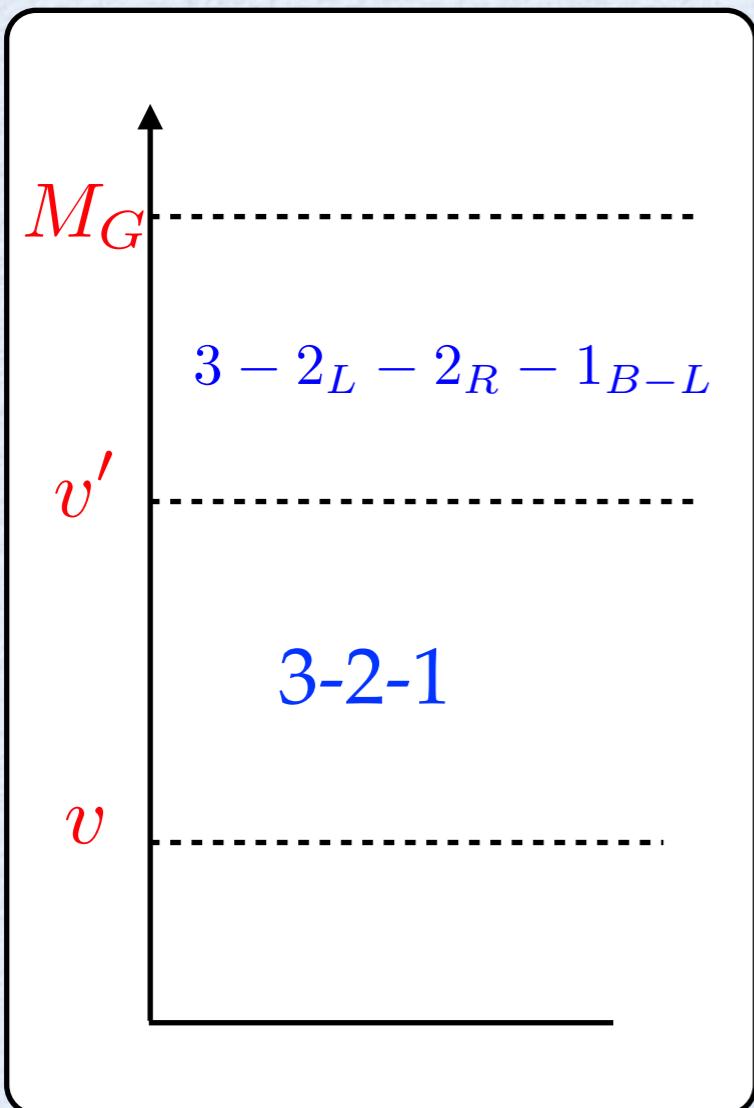
Central prediction

$$\theta_{23}^{U,D} \sim V_{cb}$$

$$\min(\theta_{23}^{U,D}) \sim V_{cb}/10$$

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- SNS, Oak Ridge

Gauge Coupling Unification: $3 - 2_L - 2_R - 1_{B-L}$

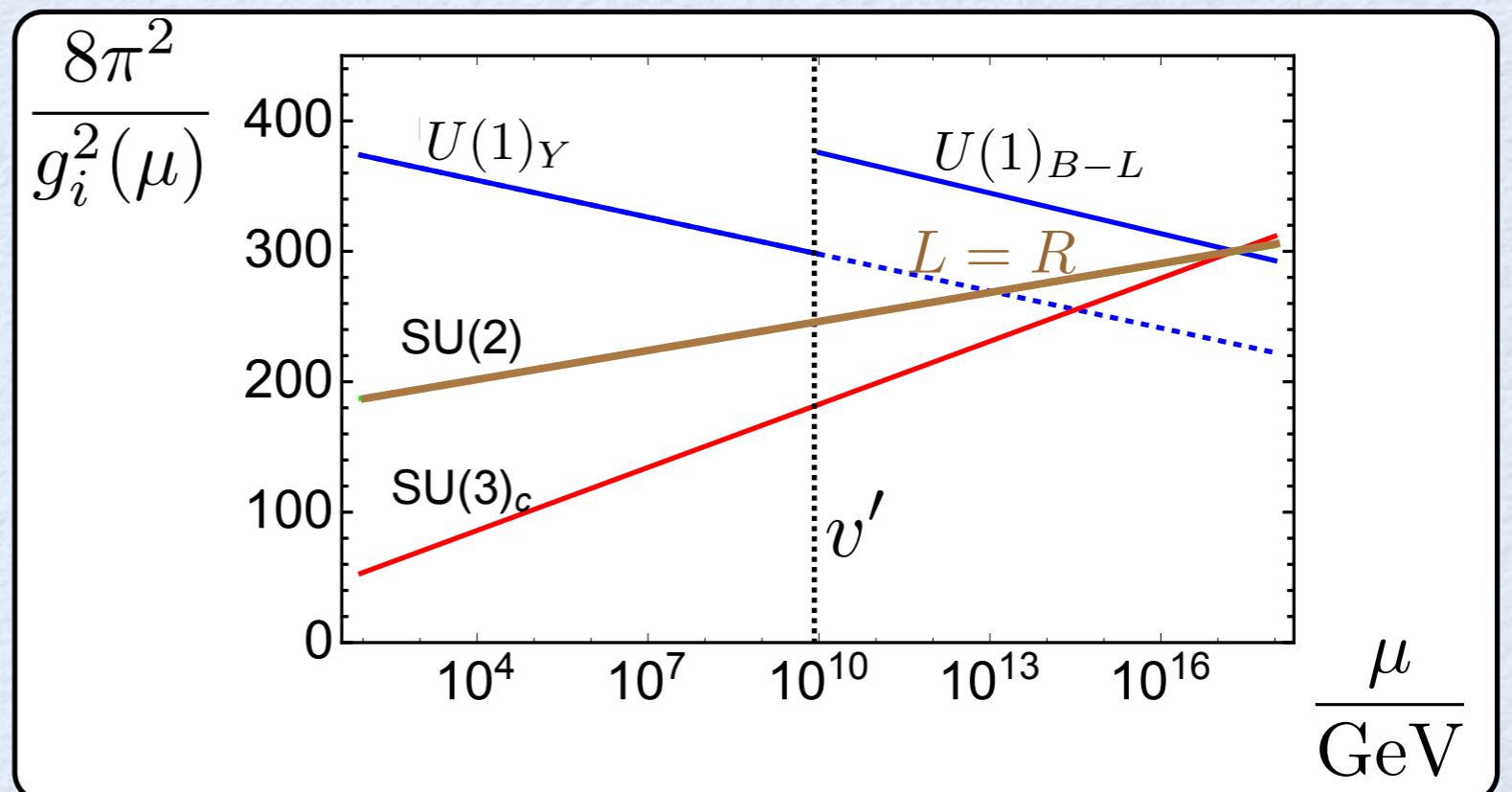


Is there a value of v' that gives precision gauge coupling unification?

Gauge Coupling Unification: $3 - 2_L - 2_R - 1_{B-L}$

- Assume X fill out complete unified multiplets, small enough to preserve perturbative couplings
- No threshold corrections

$$\frac{d}{\ln \mu} \left(\frac{8\pi^2}{g_i^2(\mu)} \right) = b_i$$



$v' \sim 10^{10}$ GeV solves unification problems of Standard Model

Gauge Coupling Unification: Threshold Corrections

Near unification scale define

$$\frac{8\pi^2}{\bar{g}(\mu)^2} \equiv \frac{8\pi^2}{3} \left(\frac{1}{g_{B-L}^2(\mu)} + \frac{1}{g_2^2(\mu)} + \frac{1}{g_3^2(\mu)} \right)$$
$$\Delta^2(\mu) = \frac{1}{3} \sum_i \left(\frac{8\pi^2}{\bar{g}(\mu)^2} - \frac{8\pi^2}{g_i(\mu)^2} \right)^2,$$

For each v'

$$\Delta_{\min} = \min_{\mu} \Delta(\mu)$$

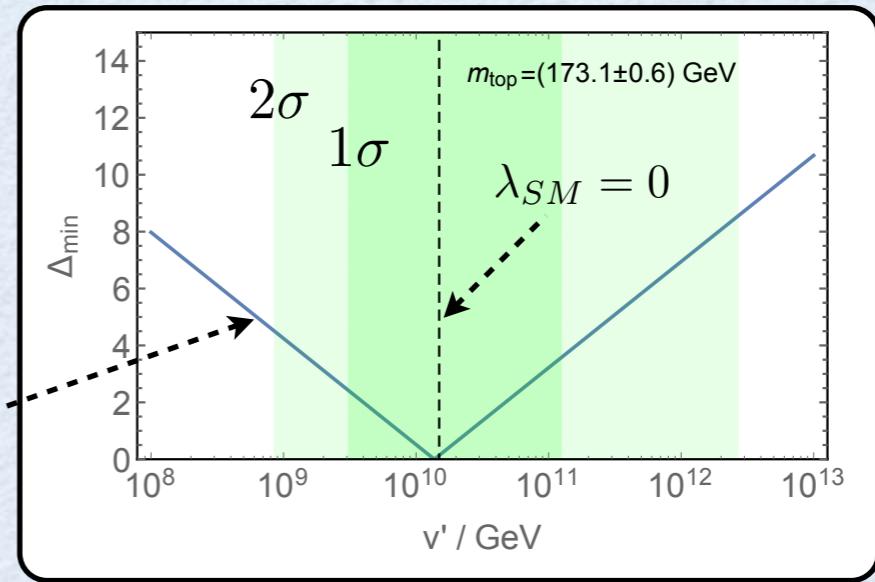
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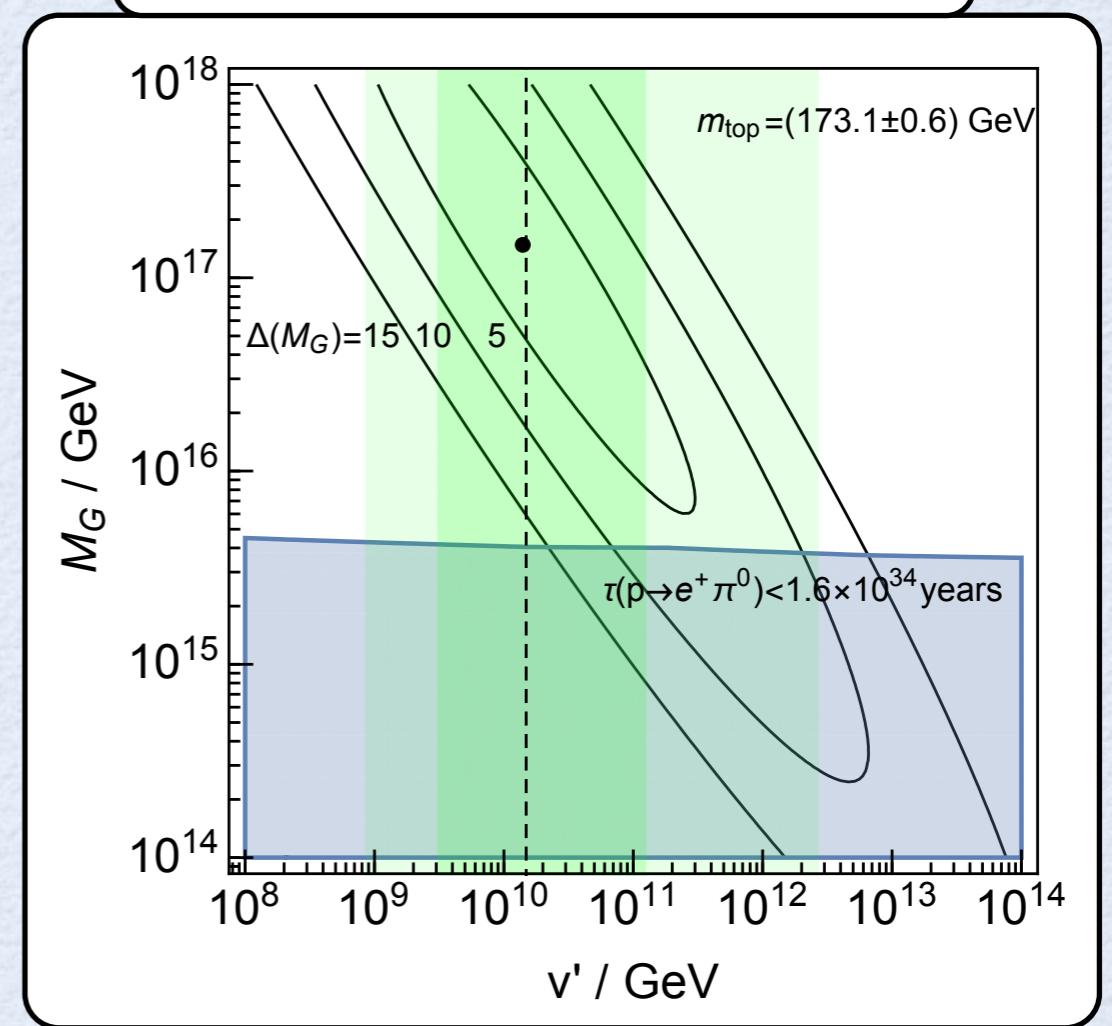
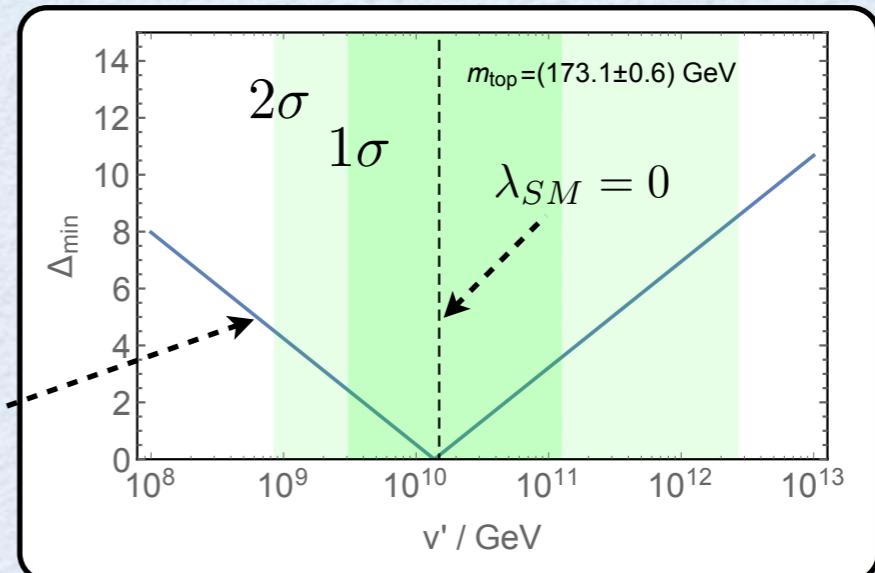
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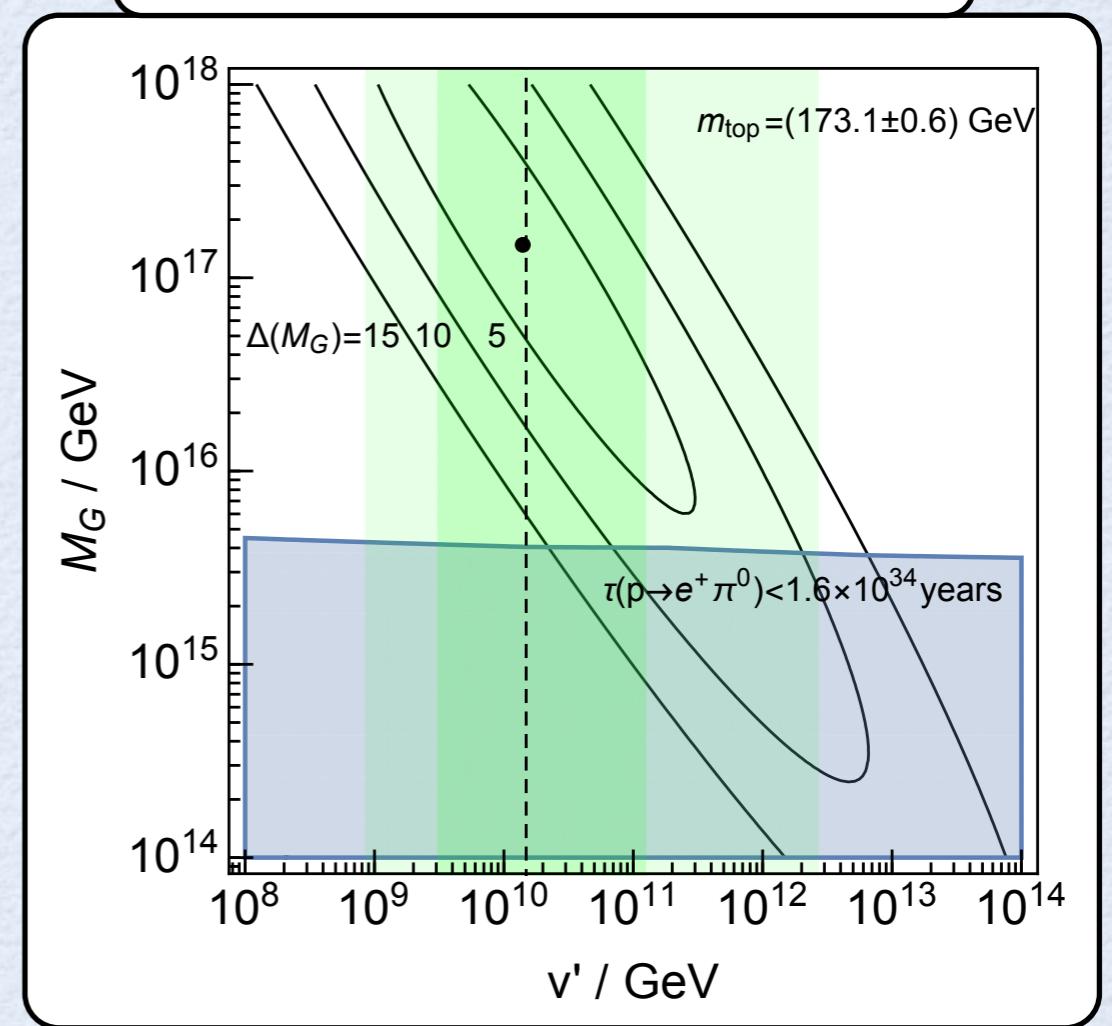
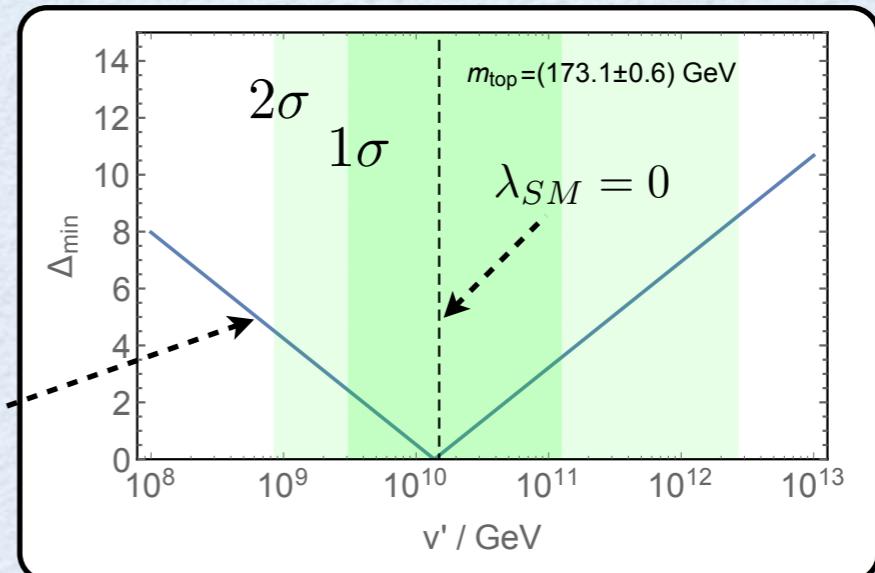
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A remarkable correlation between

- the Higgs/top quark masses
- Gauge coupling unification

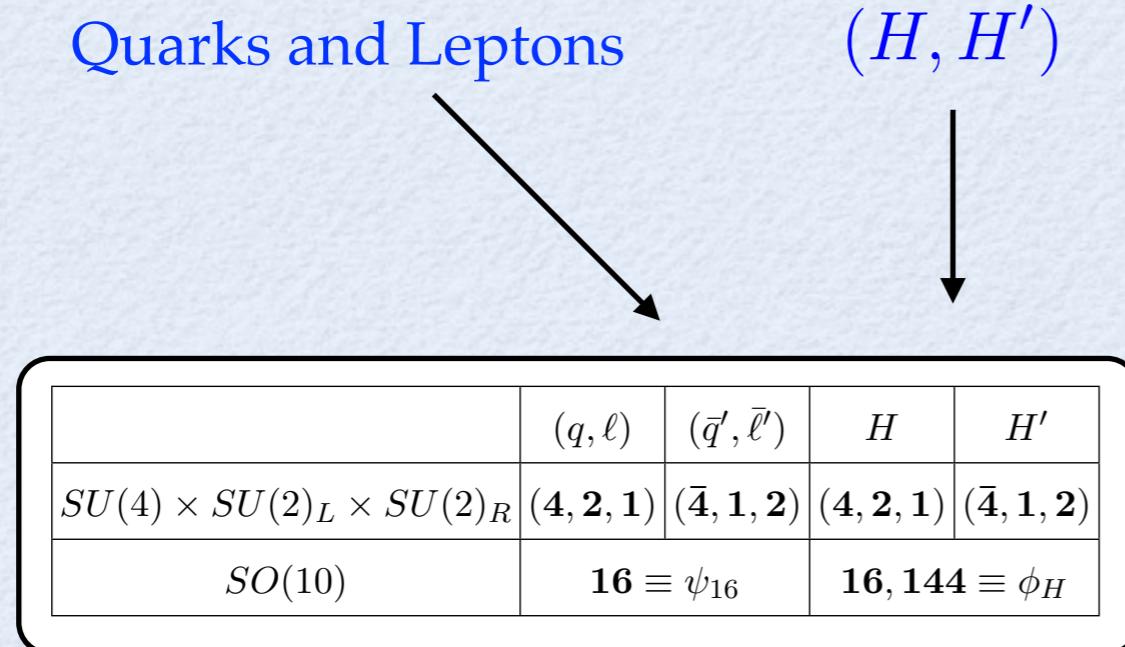
Proton decay

- Non-susy problem solved
- Discovery possible



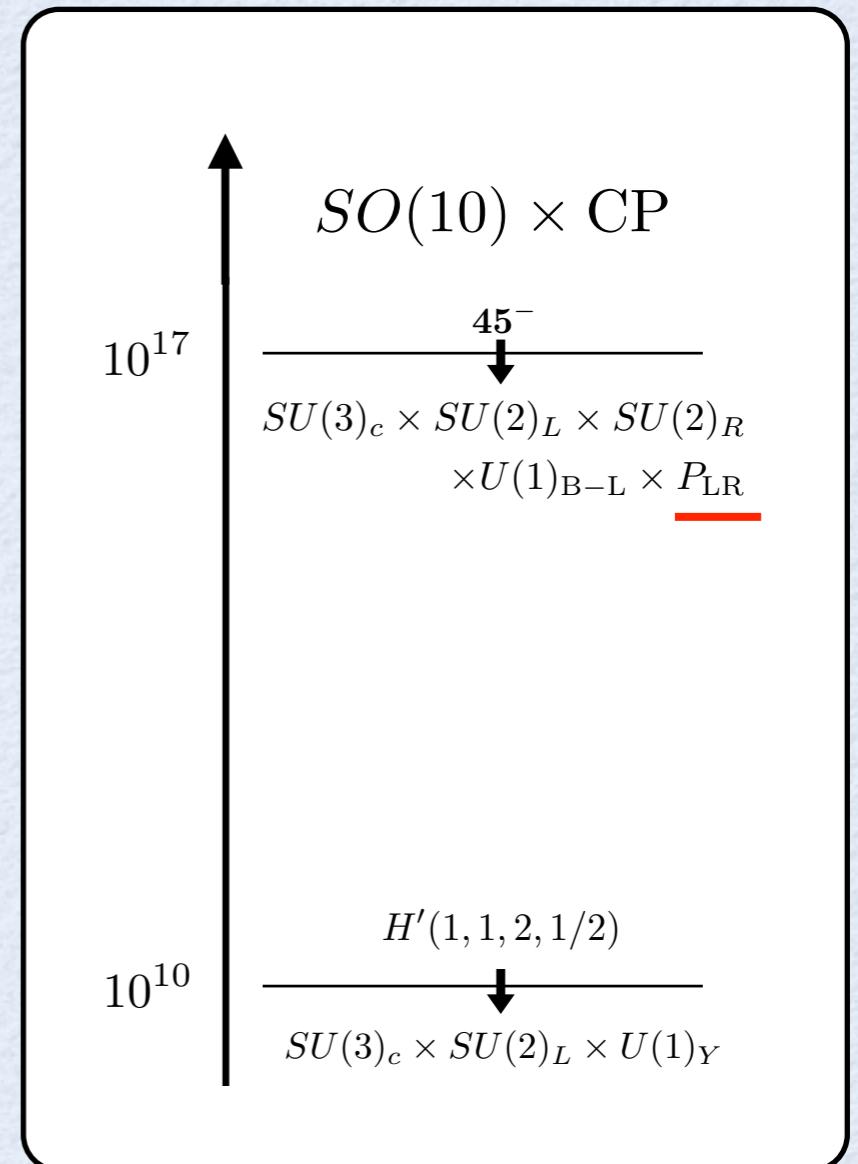
Embedding in SO(10)

Key point: $SO(10) \times CP \supset C_{LR} \times CP \rightarrow P_{LR}$



$16_{1,2,3}$

16_H

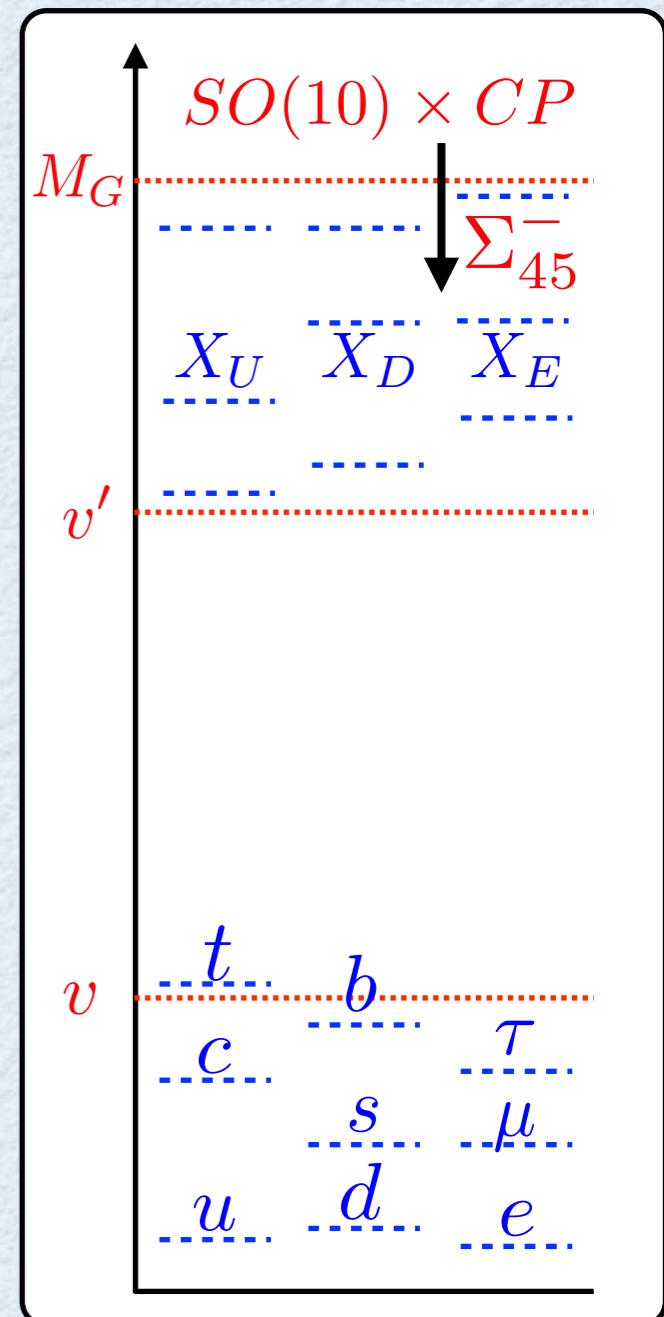


Flavor in SO(10)

Froggatt-Nielsen
for U,D E

unified with

Seesaw
for neutrinos



Flavor in SO(10)

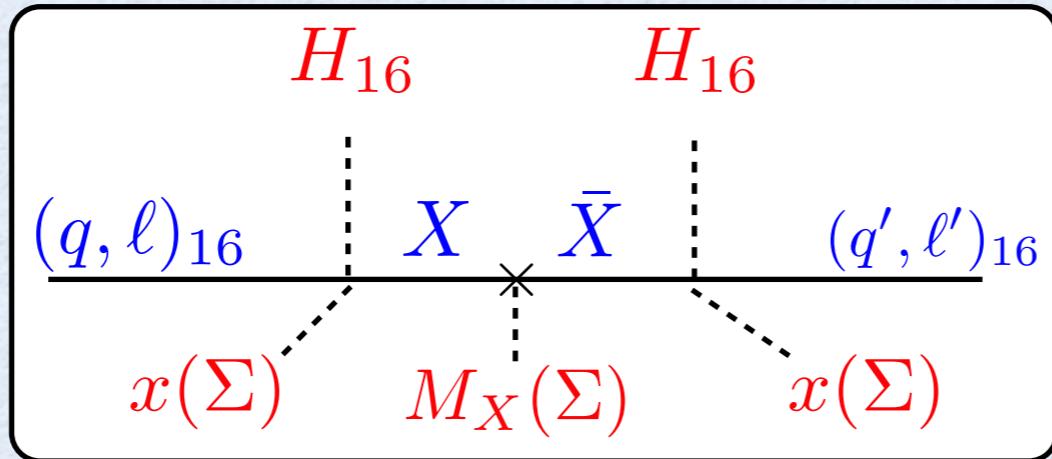
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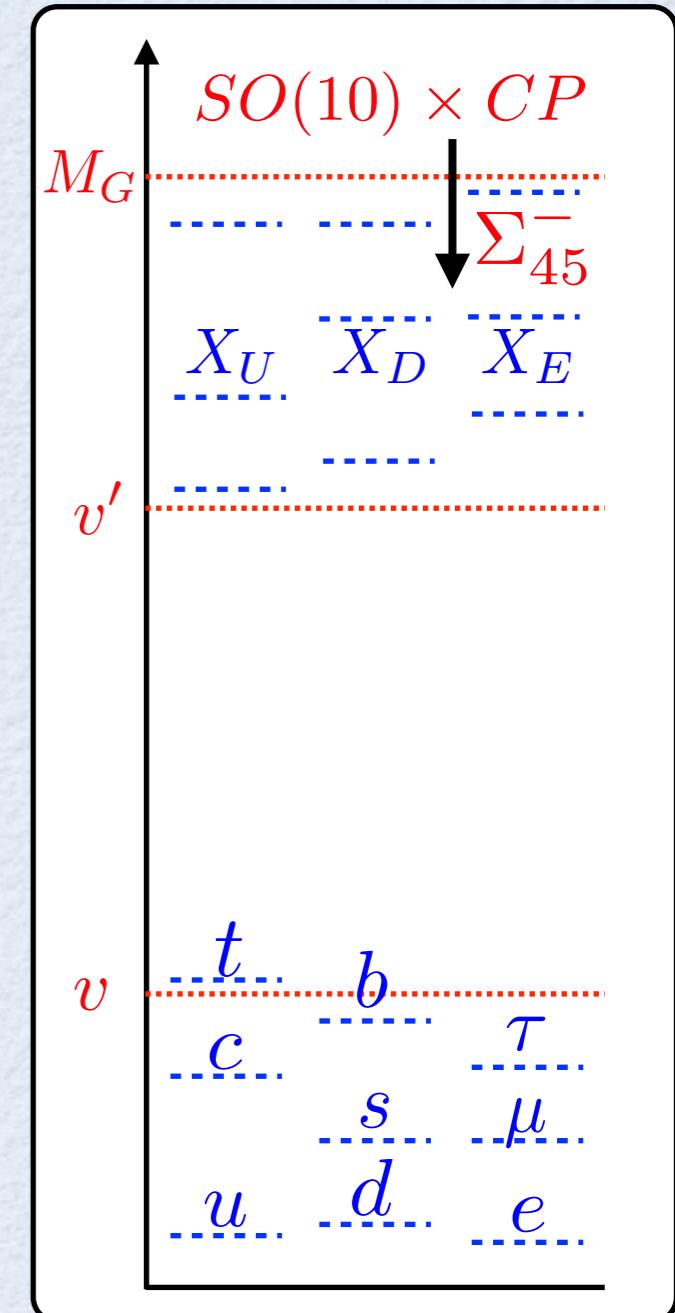
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$$y_f = x_f \frac{v'}{M_{X_f}} x'_f \quad f = U, D, E, \nu$$

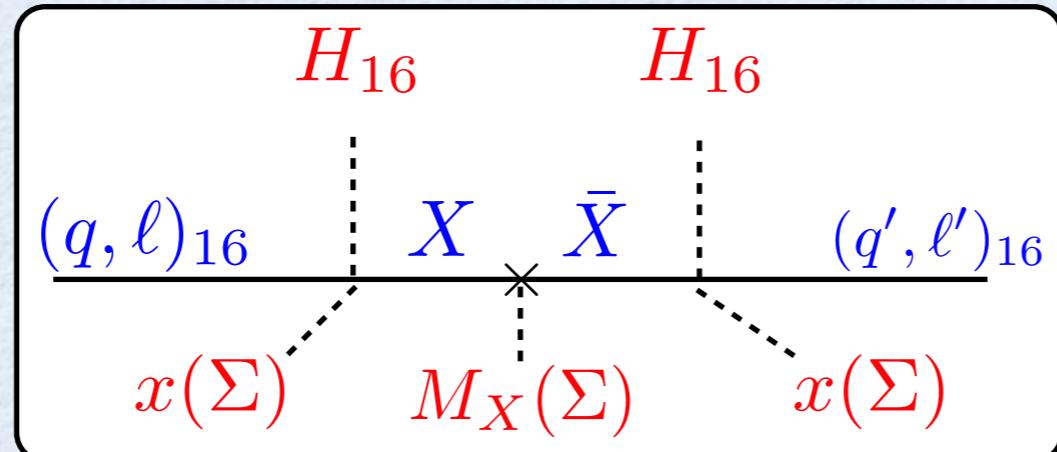


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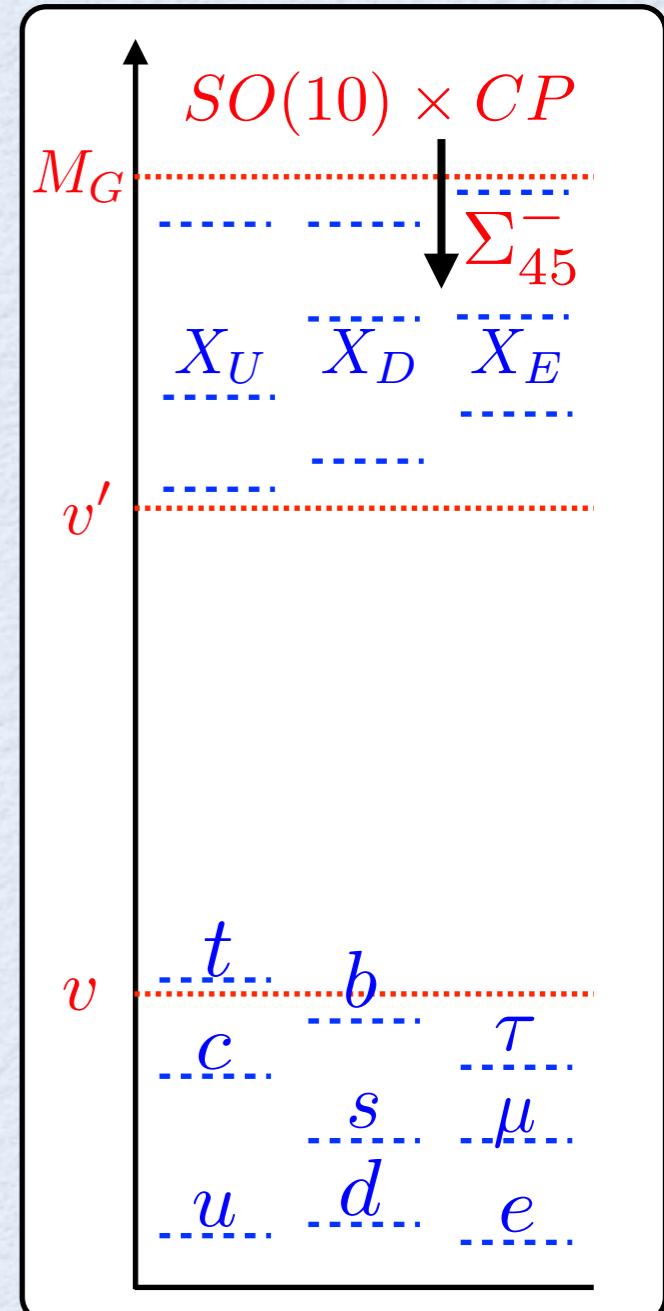
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$$y_f = x_f \frac{v'}{M_{X_f}} x'_f \quad f = U, D, E, \nu$$



Example

$$X_{10} \text{ for } D, E \quad \mathcal{L}_{D,E} = (\psi_{16} x_{10} X_{10}) H_{16} + X_{10} (M + i\lambda \Sigma_{45}^-) X_{10}$$

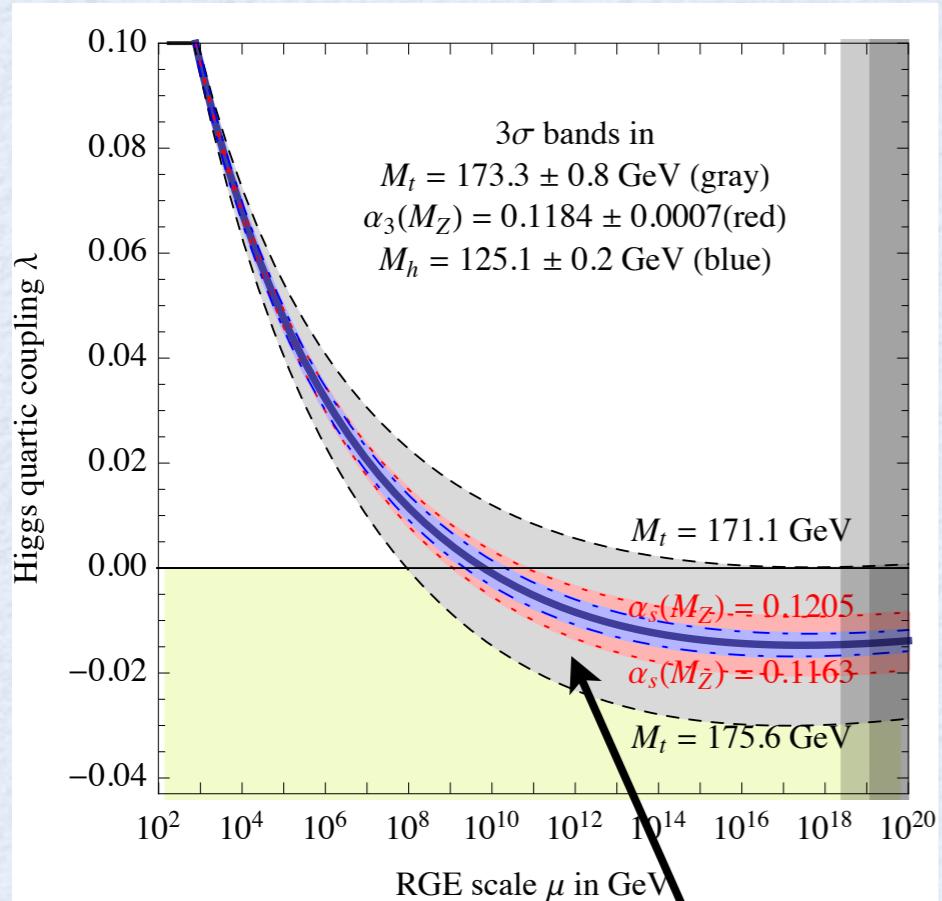
- CP : M_{ij}, λ_{ij} real
- Σ_{45} : $y_D \neq y_E, \delta_{CKM} \neq 0$

$$X_{45/54} \text{ for } U, \nu \quad \mathcal{L}_{U,\nu} = (\psi_{16} x X) H_{16} \mathcal{O}_{10} + (X M X) \mathcal{O}_{10}$$

- $y_U \neq 0$
- $m_{\nu_H} \sim v'^2/M \quad m_{\nu_L} \sim v^2/M$
- Avoid hierarchical neutrinos via \mathcal{O}_{10}

Conclusions

A Small Higgs Quartic Coupling in UV



Perhaps the key discovery of LHC

$$\lambda_{SM}(\mu_c) = 0$$

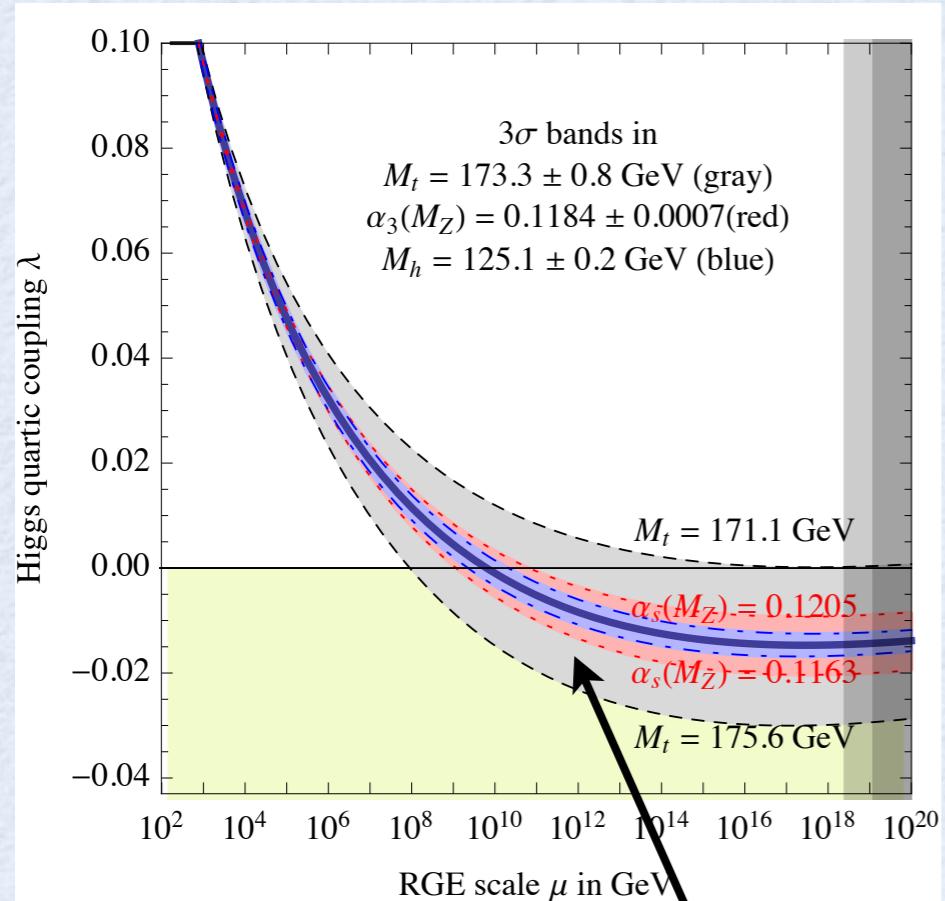
$$\mu_c \sim (3 \times 10^8 - 3 \times 10^{12}) \text{ GeV} \text{ at } 2\sigma$$

Buttazzo, Degrassi,
Giardino, Giudice,
Sala, Salvio, Strumia

1307.3536

Why is
high-scale quartic
 $\mathcal{O}(10^{-2})$?

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Higgs sector has

$$SU(2) \xleftrightarrow{Z_2} SU(2)'$$

$$H(2,1) \xleftrightarrow{Z_2} H'(1,2)$$

spontaneously broken at

$$\langle H' \rangle = \mu_c$$

Buttazzo, Degrassi,
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Why is
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2. Z_2 Suggests a Particular Solution to Strong CP

Strong CP problem
solved via
key ingredients

$$\begin{aligned} Z_2 &\rightarrow P \\ SU(3) &\xleftrightarrow{P} SU(3) \end{aligned}$$

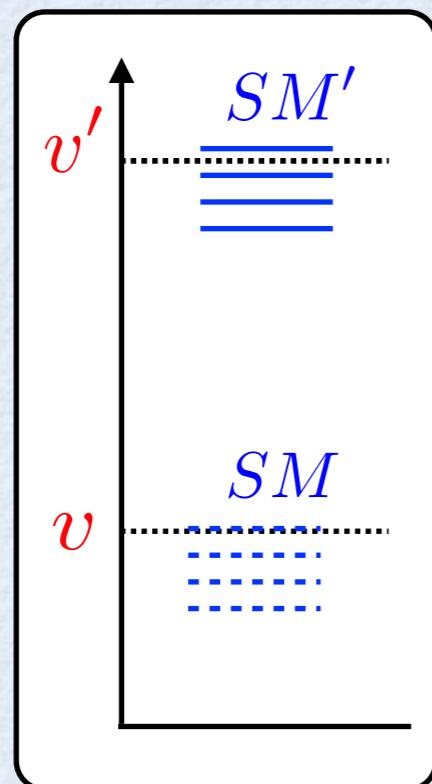
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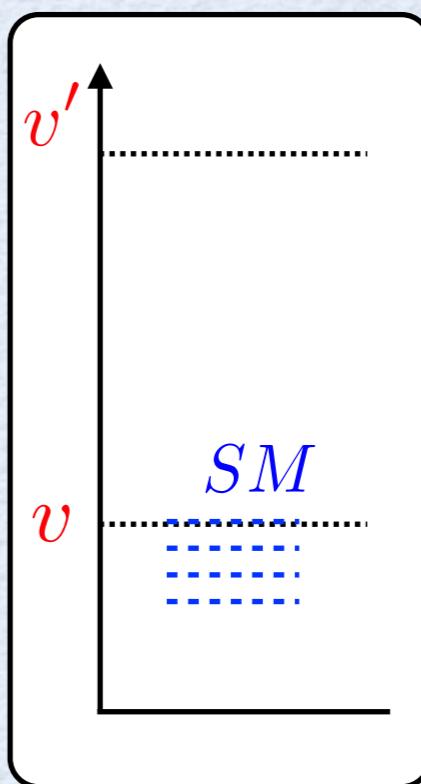
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SM'

$$\begin{pmatrix} y^* v' & 0 \\ 0 & yv \end{pmatrix}$$



LR



$$y^\dagger = y$$

$$d_n \sim 10^{-32} \text{ e cm}$$

$$d_n \sim 3 \times 10^{-27} \text{ e cm}$$

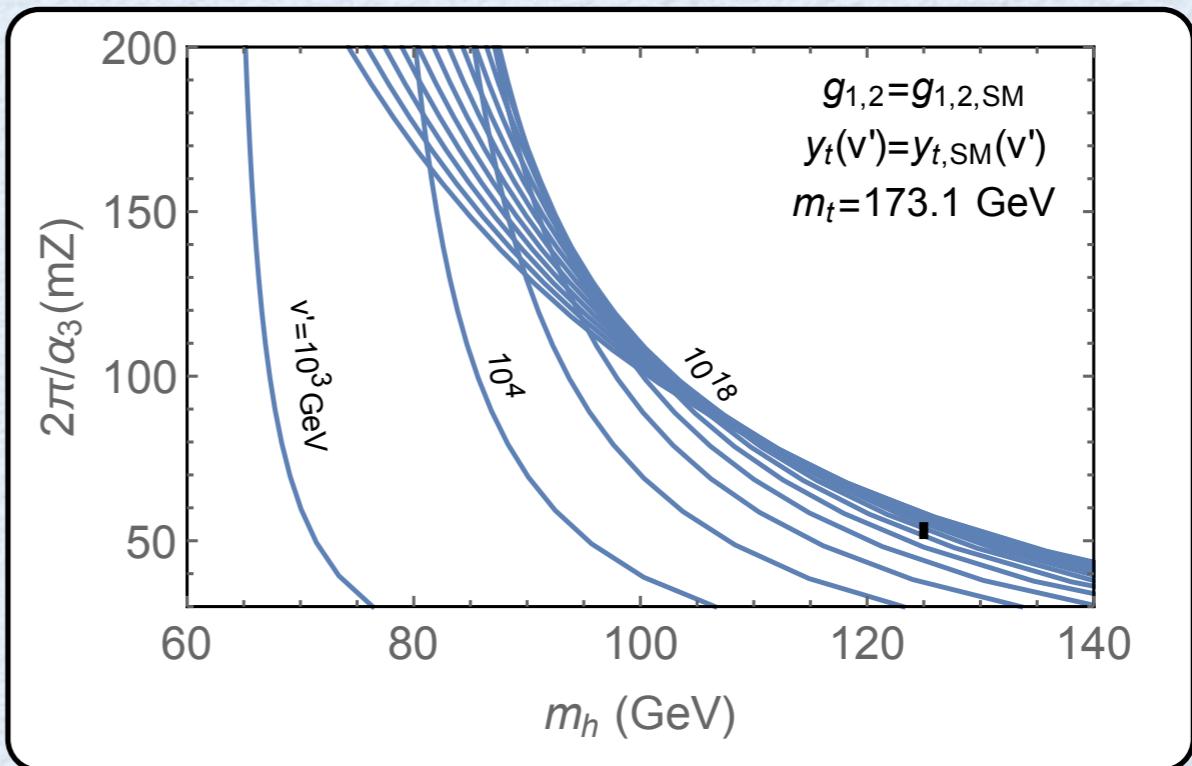
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For any fixed v'

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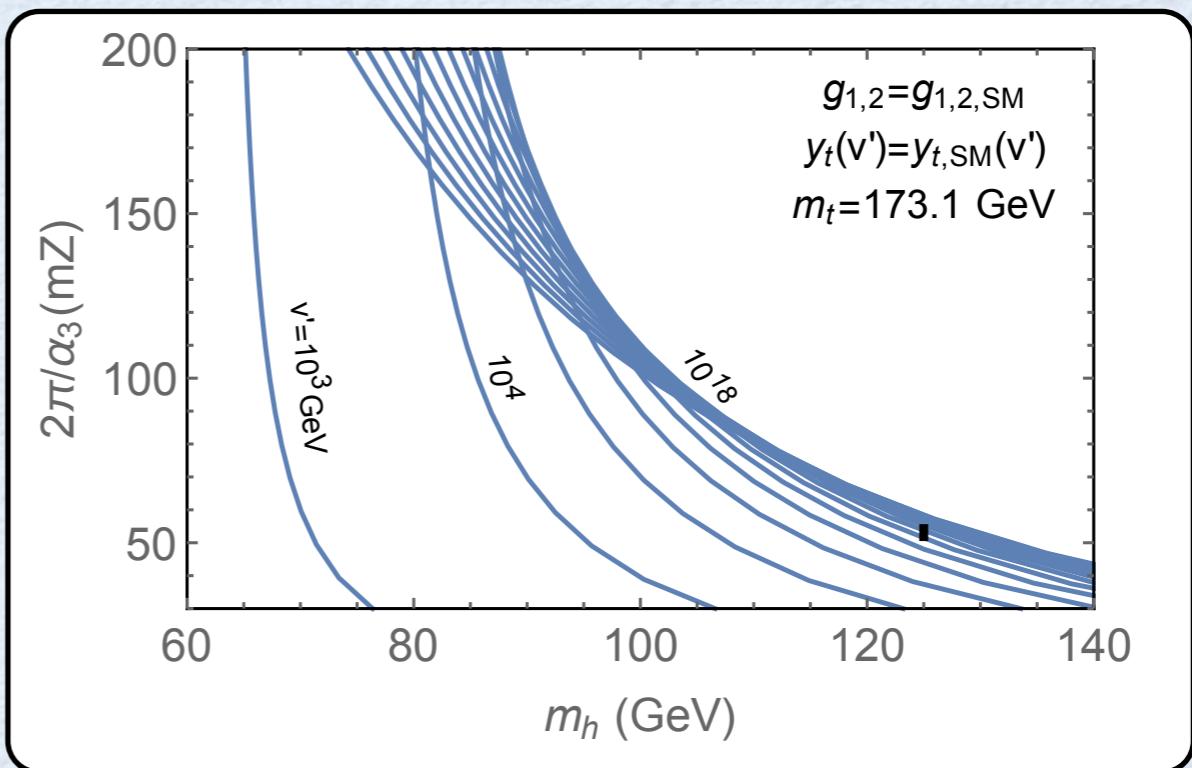
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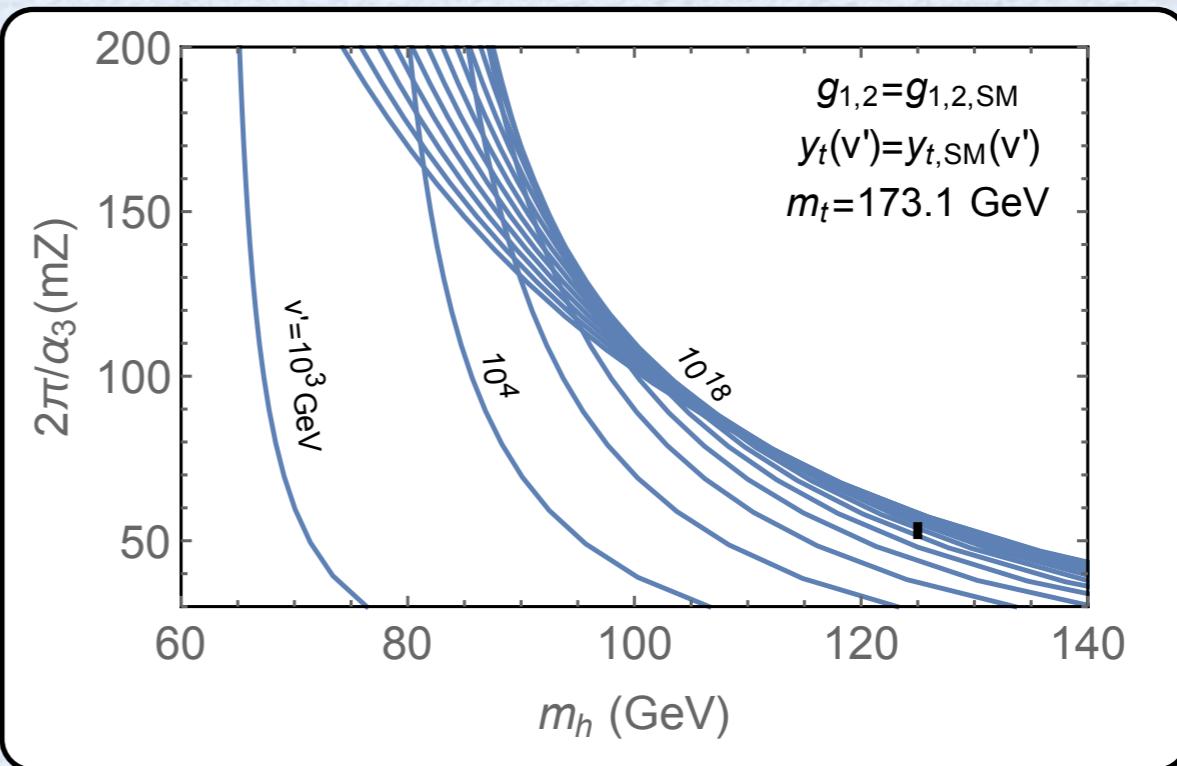
Higgs Partner GUTs

4 parameters: $\alpha_G, y_{tG}, M_G, v'$

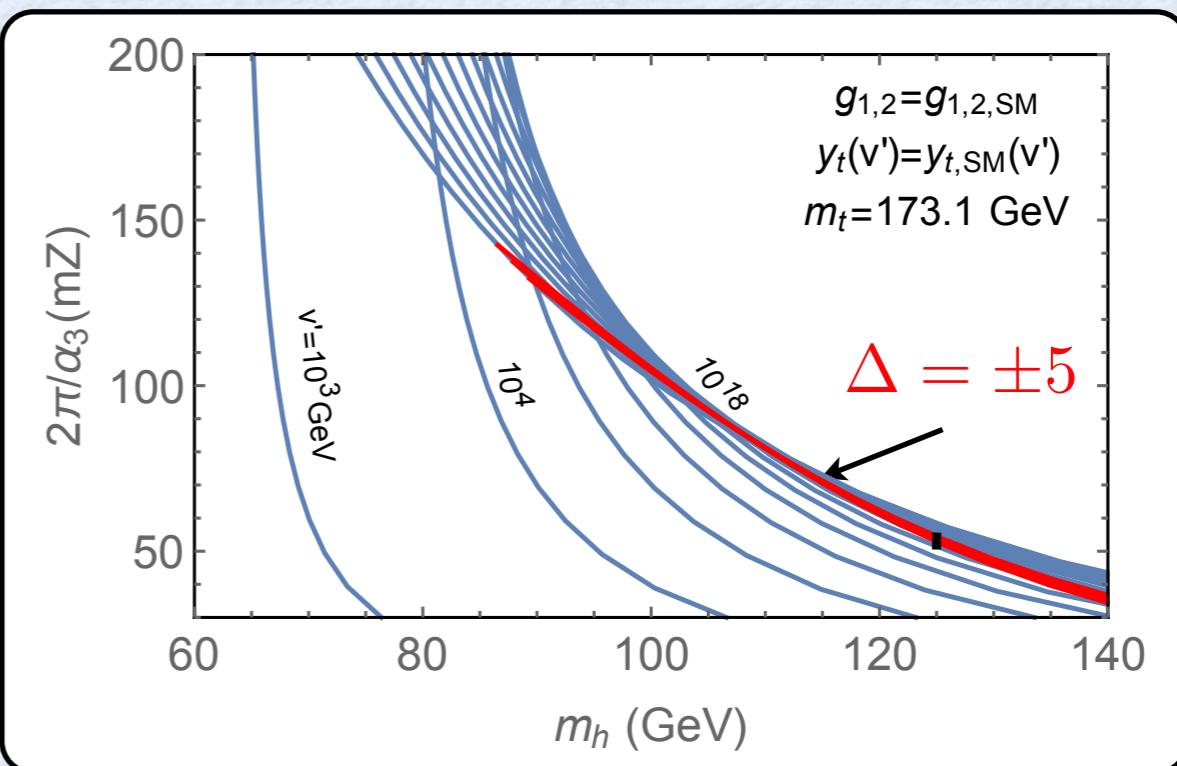
5 observables: $\alpha_1, \alpha_2, \alpha_3, m_t, m_h$

1 prediction

Input α_1, α_2, m_t



Fixed
 $y_t(v')$



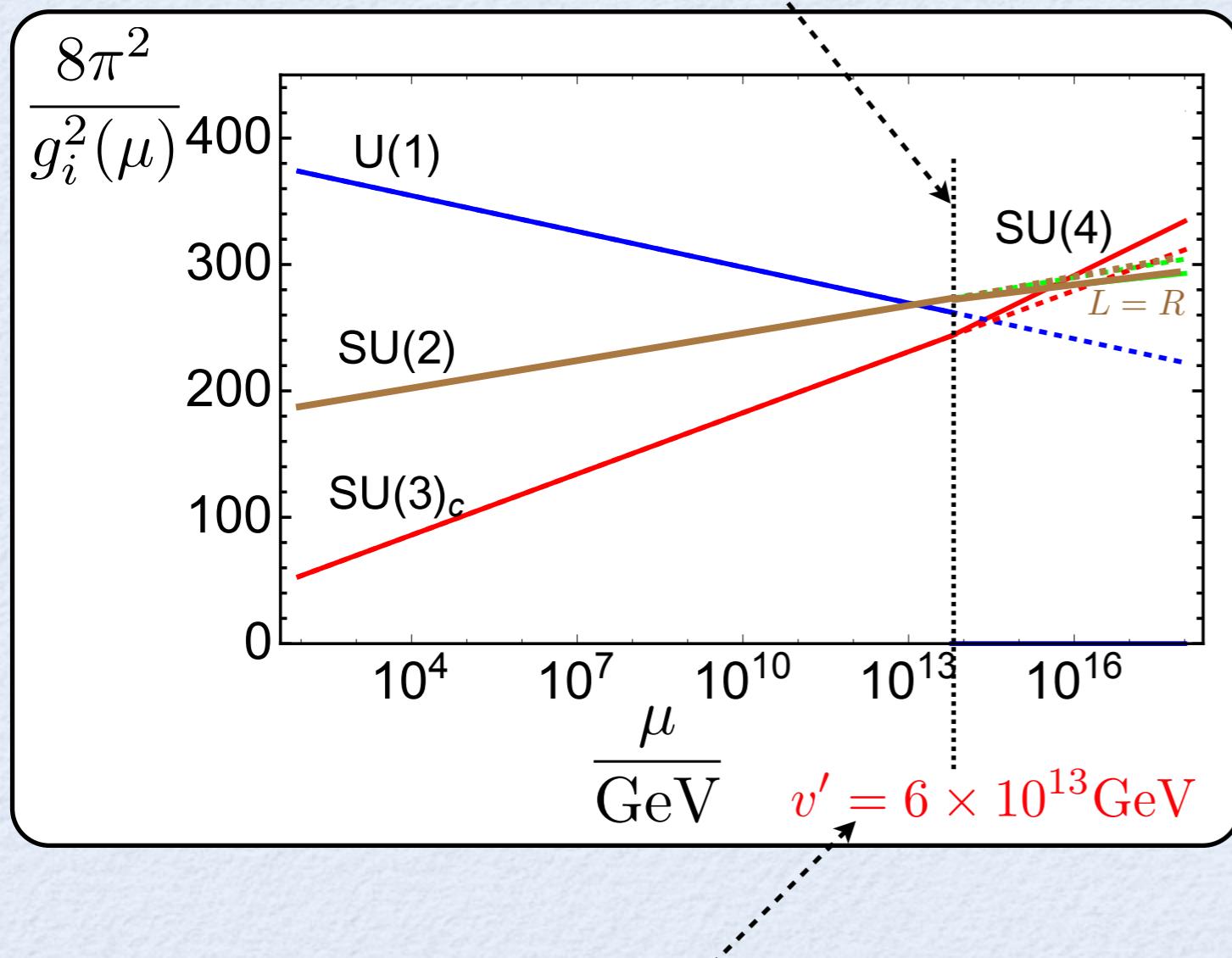
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Extra

Gauge Coupling Unification: $4 - 2_L - 2_R$

Assume zero threshold corrections

$$H(4, 2, 1) + H'(\bar{4}, 1, 2)$$

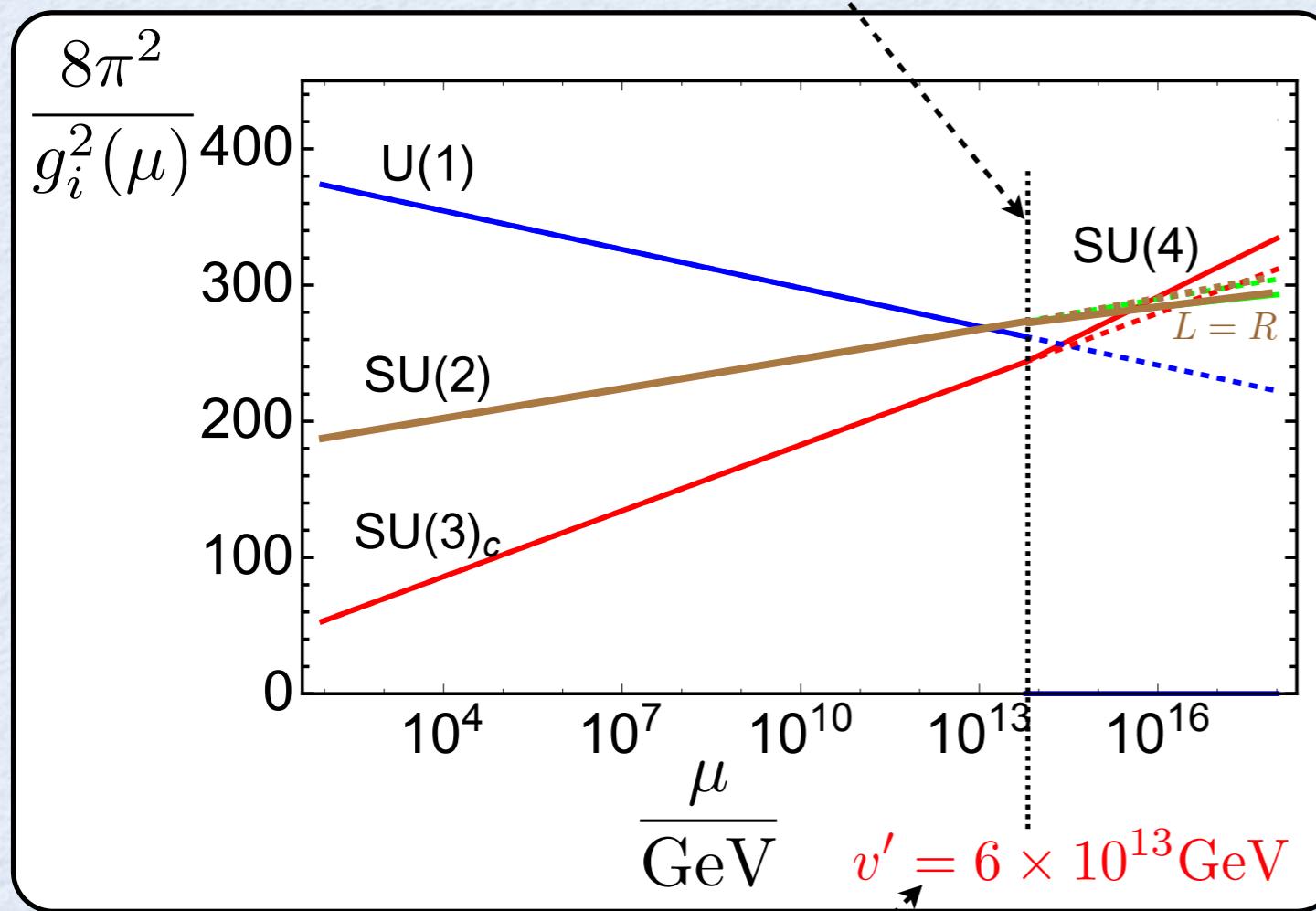


Predict low top mass

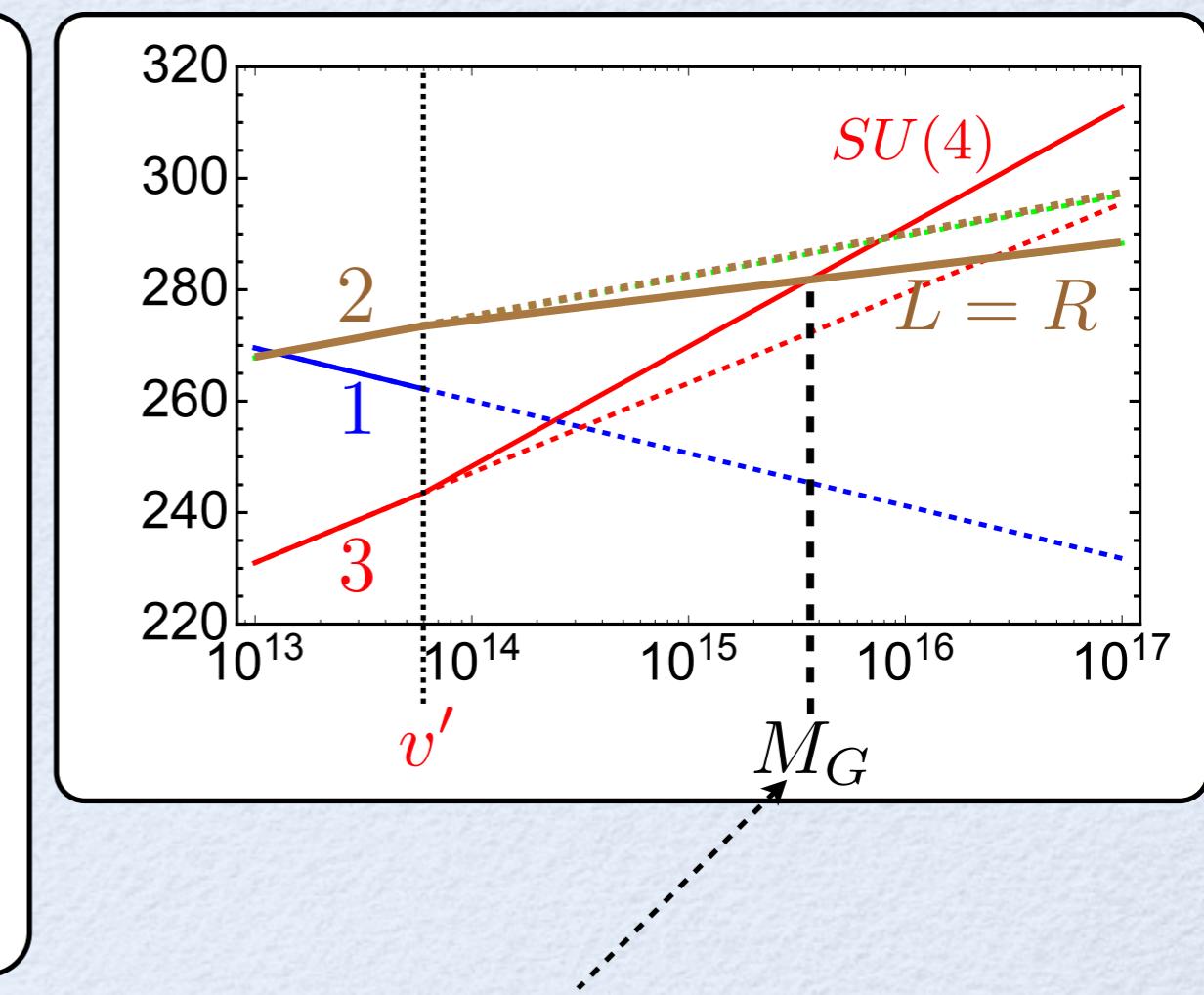
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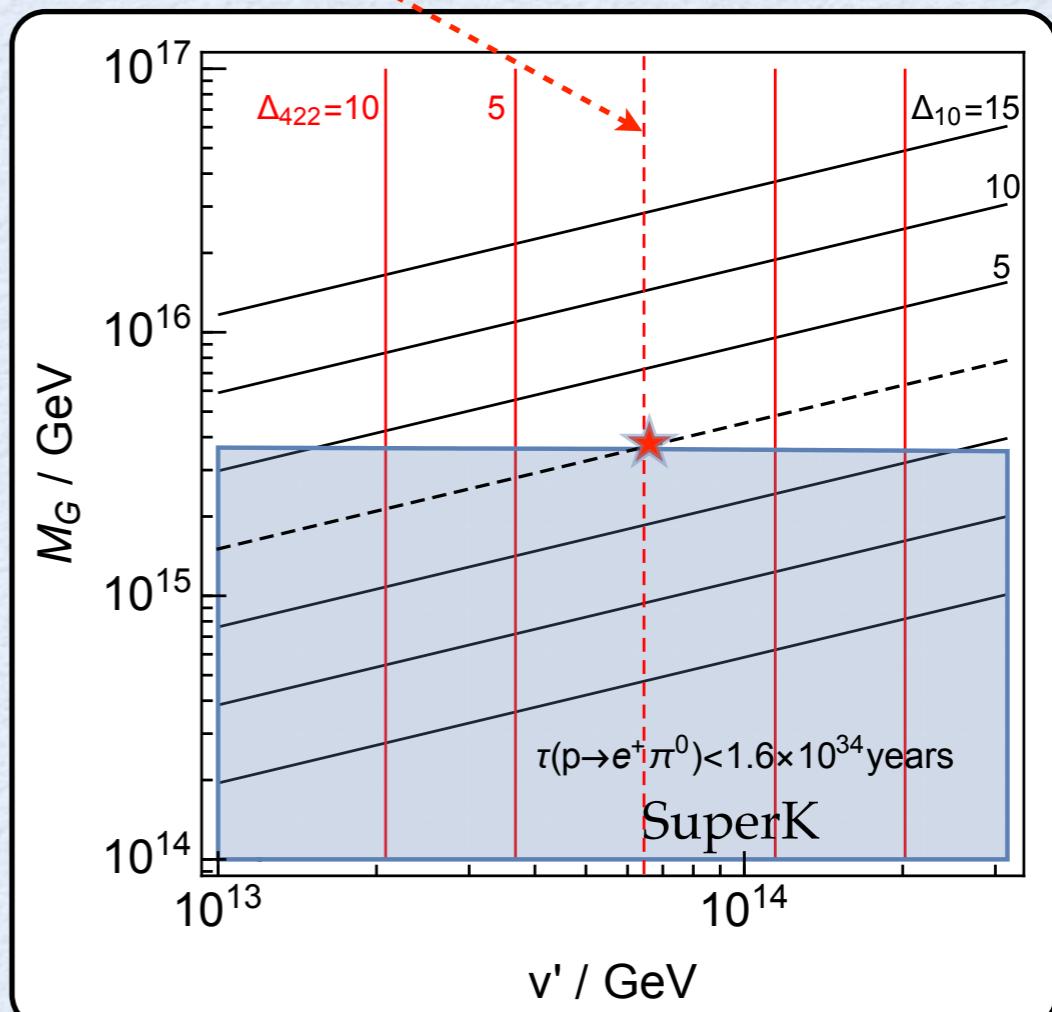
Precision unification with
 M_G centered on 4×10^{15} GeV

Gauge Coupling Unification: Threshold Corrections

$$\Delta_{422}(v') \equiv \left| \frac{3}{5} \frac{8\pi^2}{g_2^2(v')} + \frac{2}{5} \frac{8\pi^2}{g_3^2(v')} - \frac{8\pi^2}{g_1^2(v')} \right|$$

$$\Delta_{10}(M_G) \equiv \left| \frac{8\pi^2}{g_4^2(M_G)} - \frac{8\pi^2}{g_2^2(M_G)} \right|$$

$422 \xrightarrow{v'} 321$
via scalars in $(4, 2, 1) + (\bar{4}, 1, 2)$



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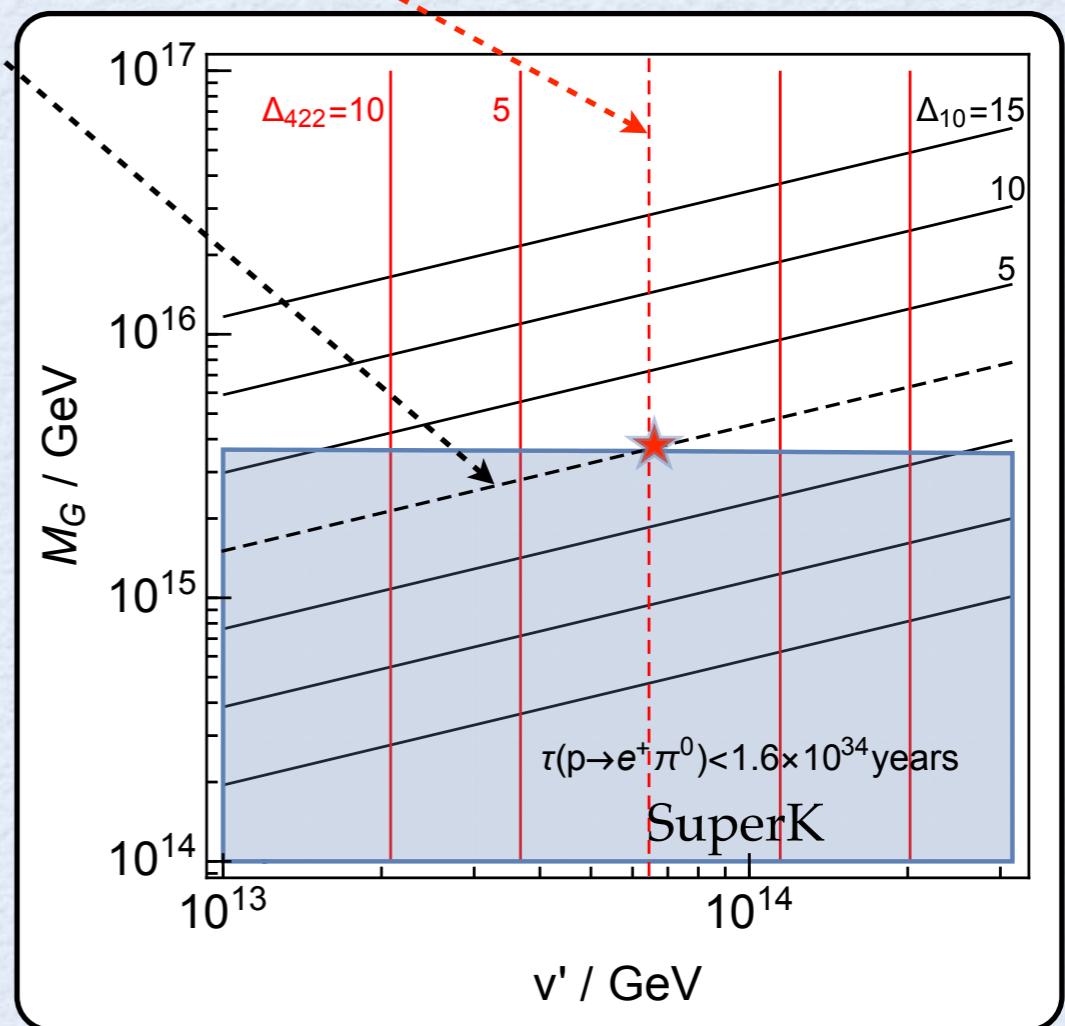
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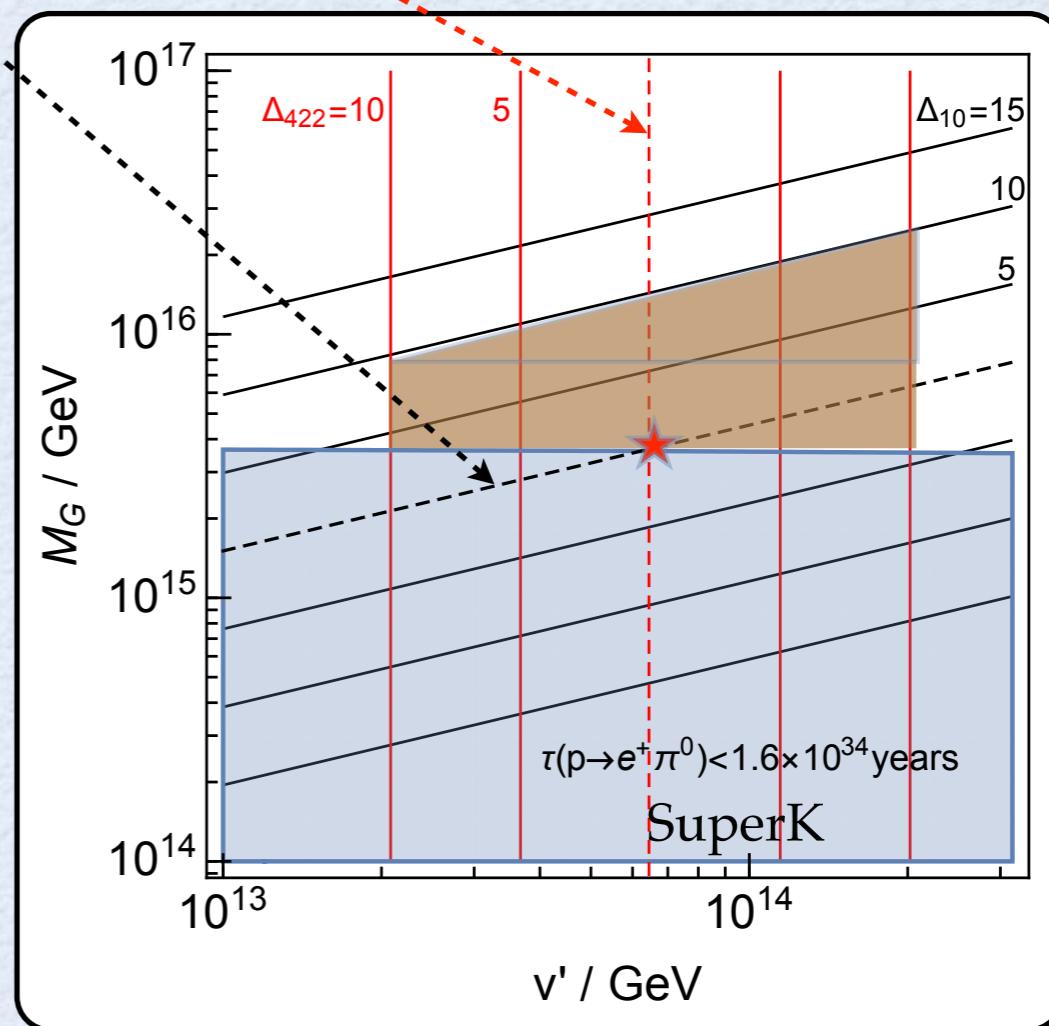
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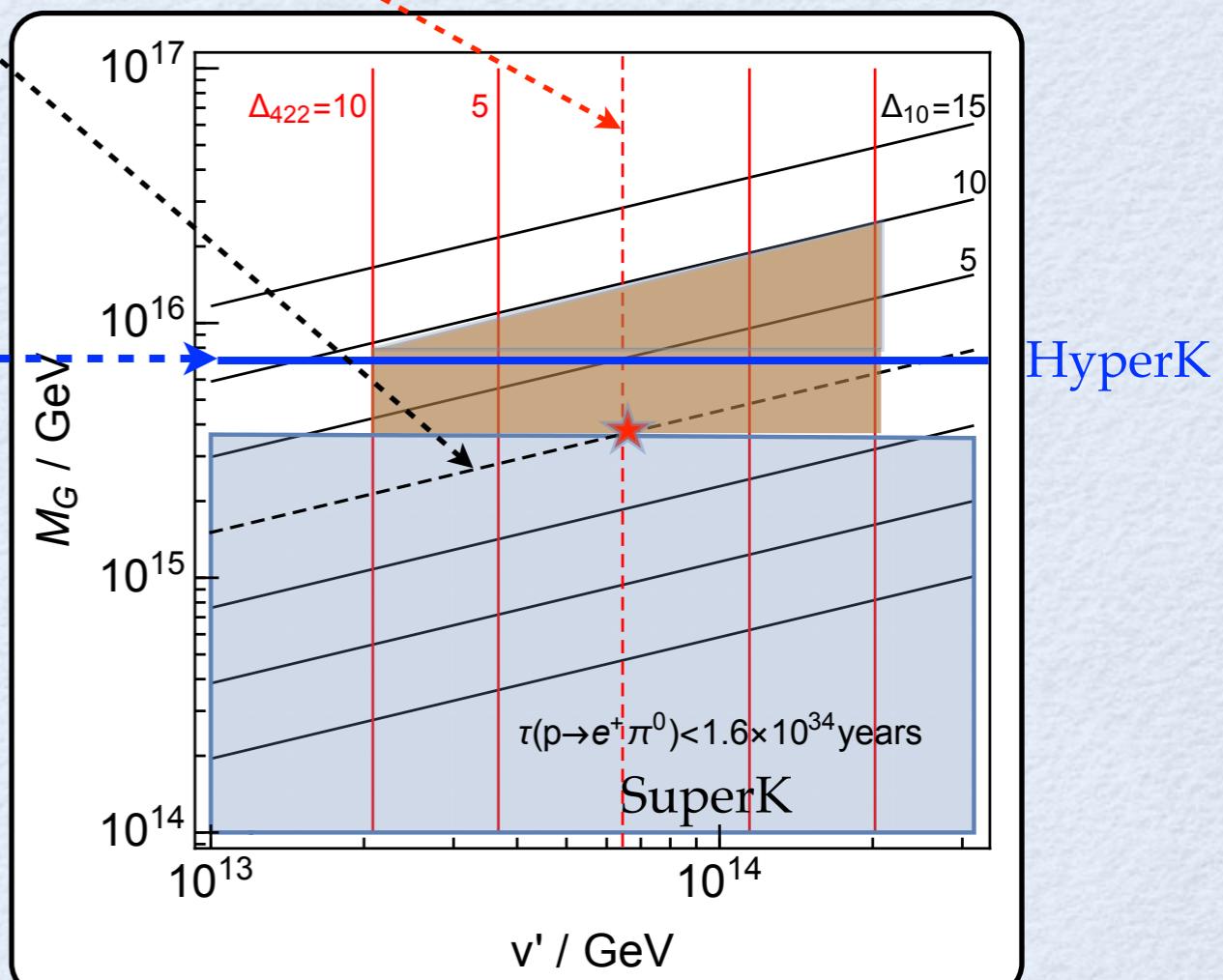
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Proton decay
Very good prospects

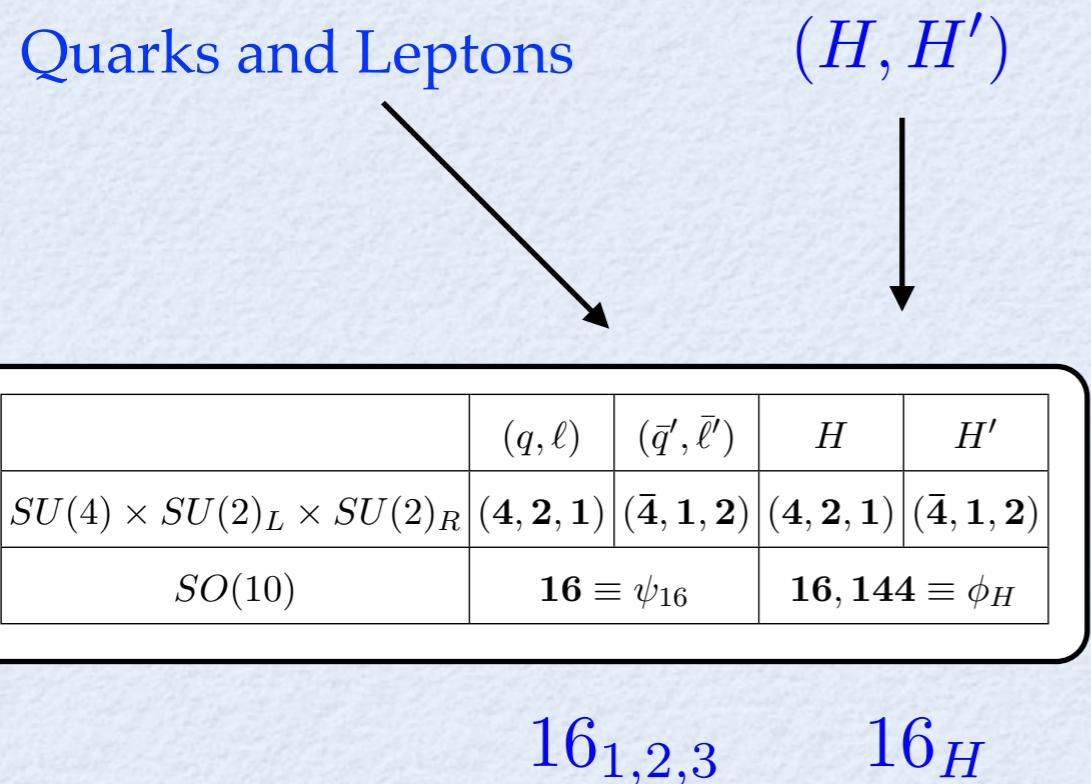
Higgs mass/gauge coupling
Predict m_t will go down by $(2 - 3)\sigma$

$422 \xrightarrow{v'} 321$
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Embedding in $SO(10)$

Key point: $SO(10) \times CP \supset C_{LR} \times CP \rightarrow P_{LR}$



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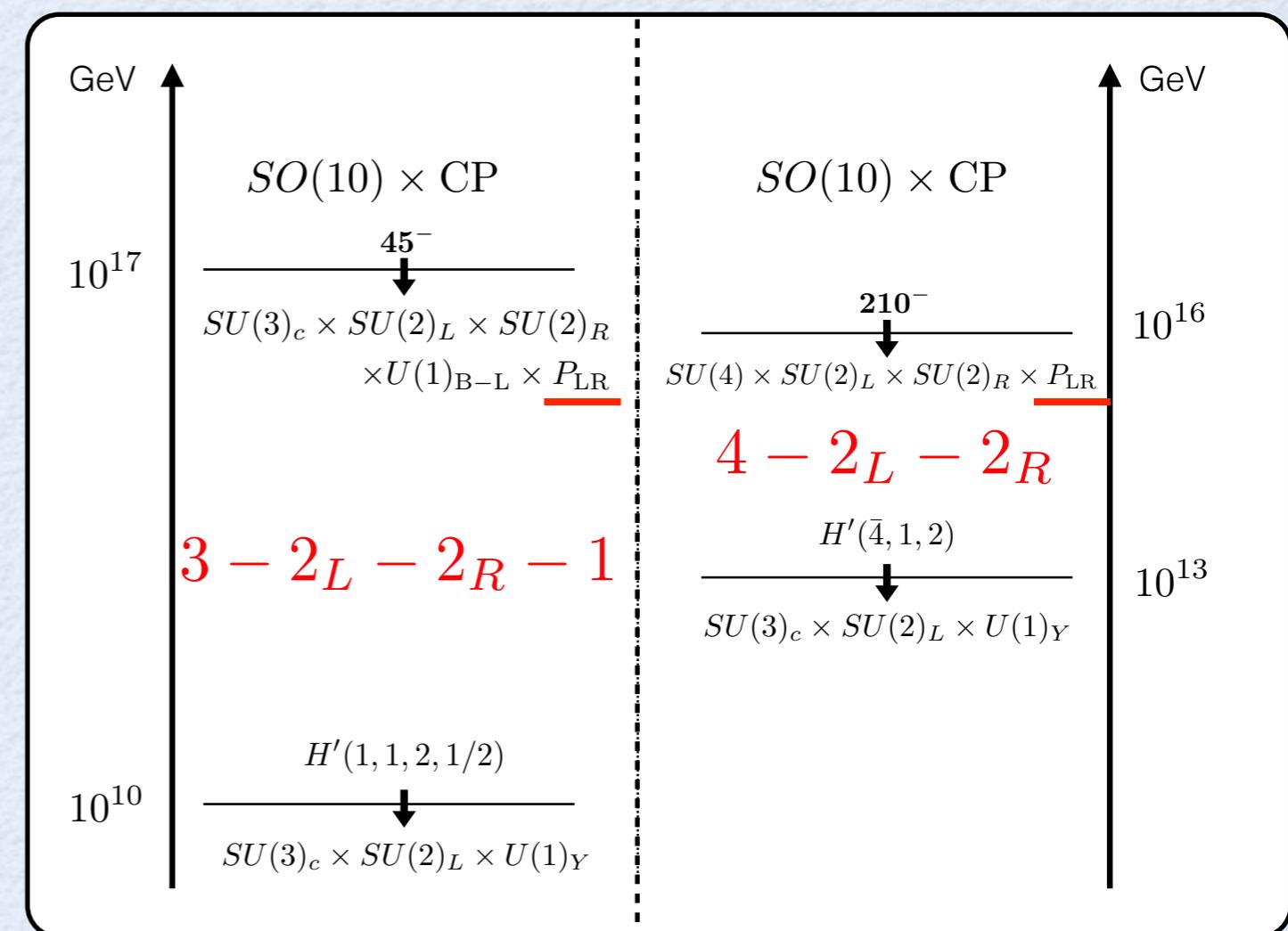
Quarks and Leptons

	(q, ℓ)	$(\bar{q}', \bar{\ell}')$	H	H'
$SU(4) \times SU(2)_L \times SU(2)_R$	$(\mathbf{4}, \mathbf{2}, \mathbf{1})$	$(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$	$(\mathbf{4}, \mathbf{2}, \mathbf{1})$	$(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$
$SO(10)$	$\mathbf{16} \equiv \psi_{16}$		$\mathbf{16}, \mathbf{144} \equiv \phi_H$	

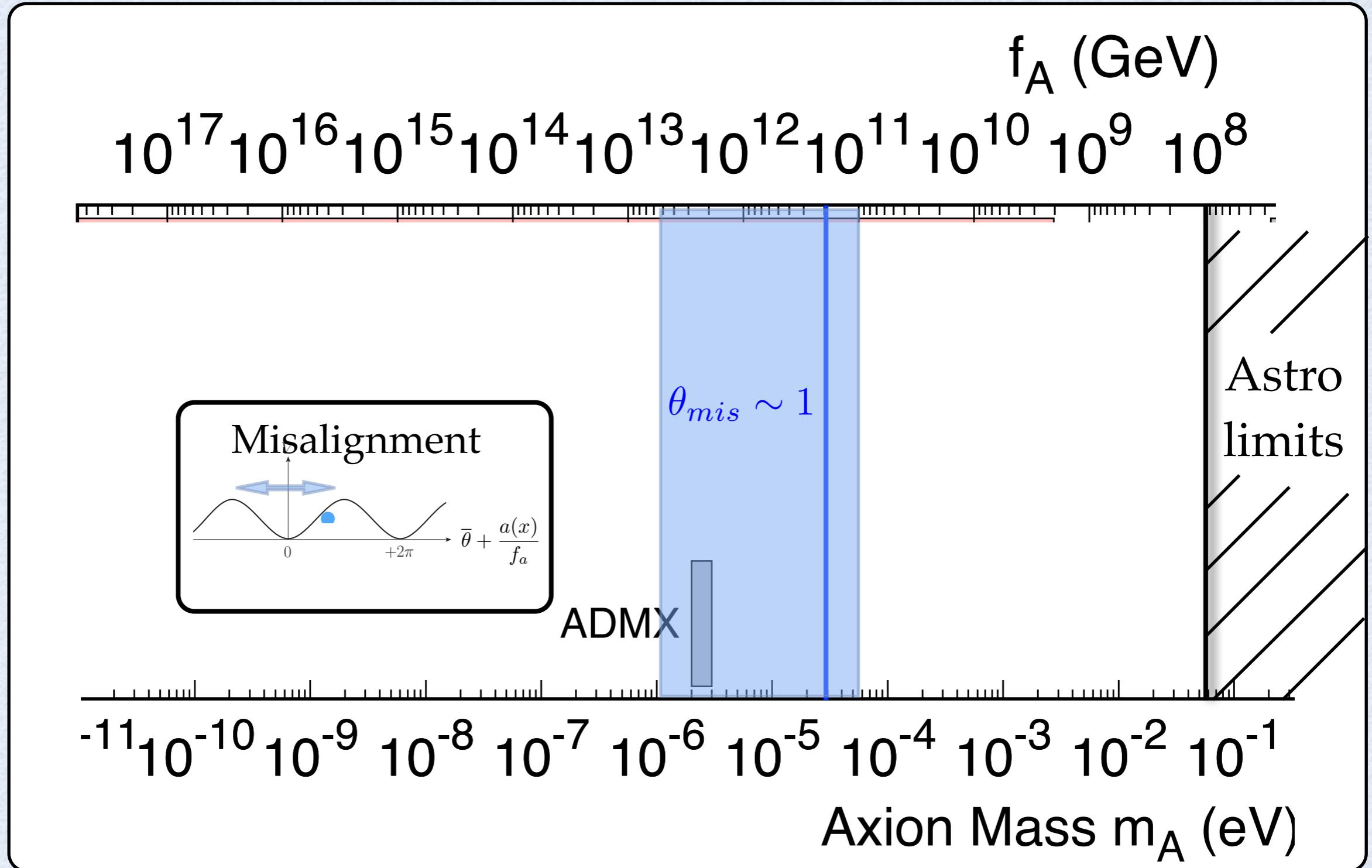
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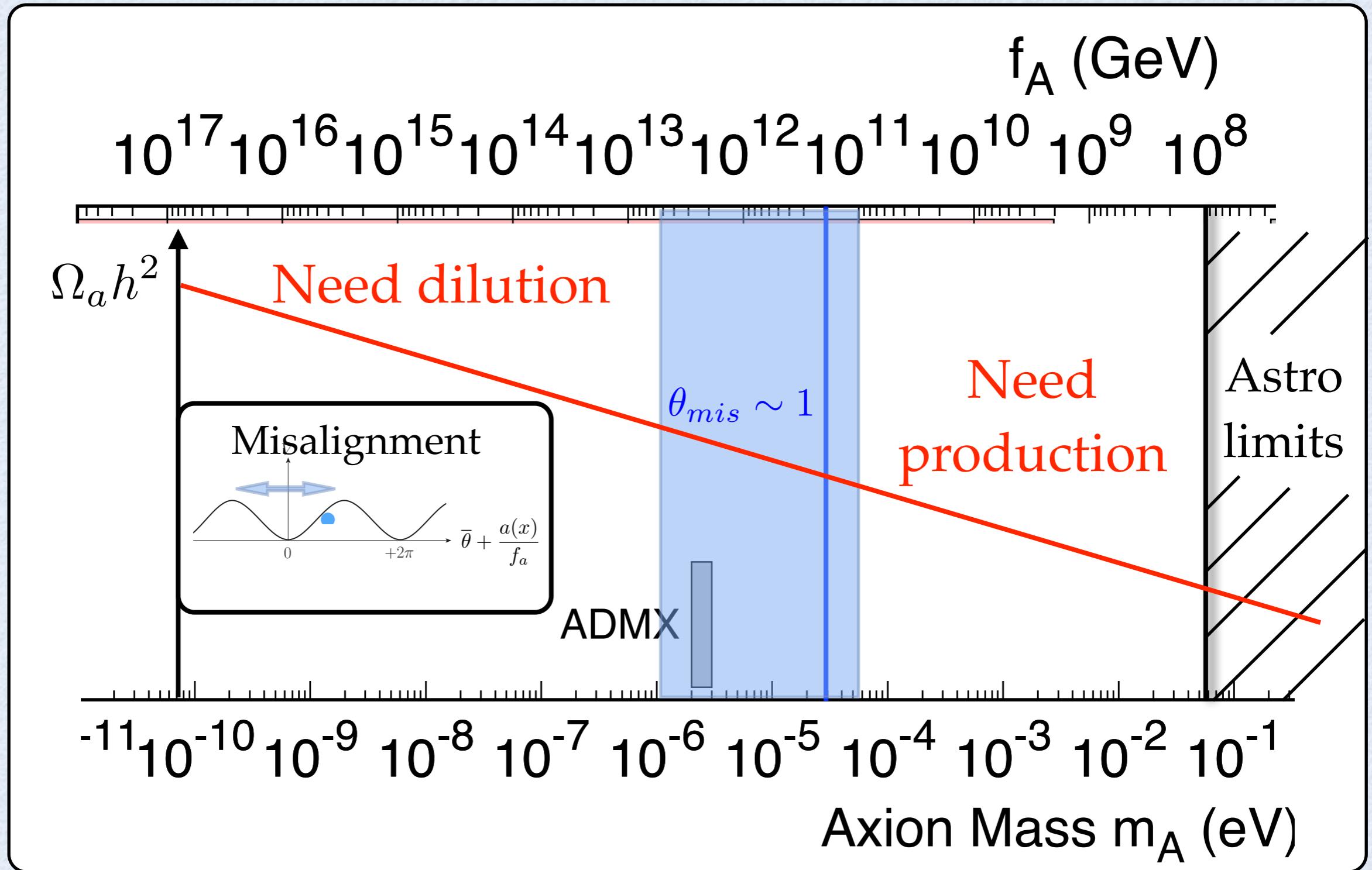
(H, H')



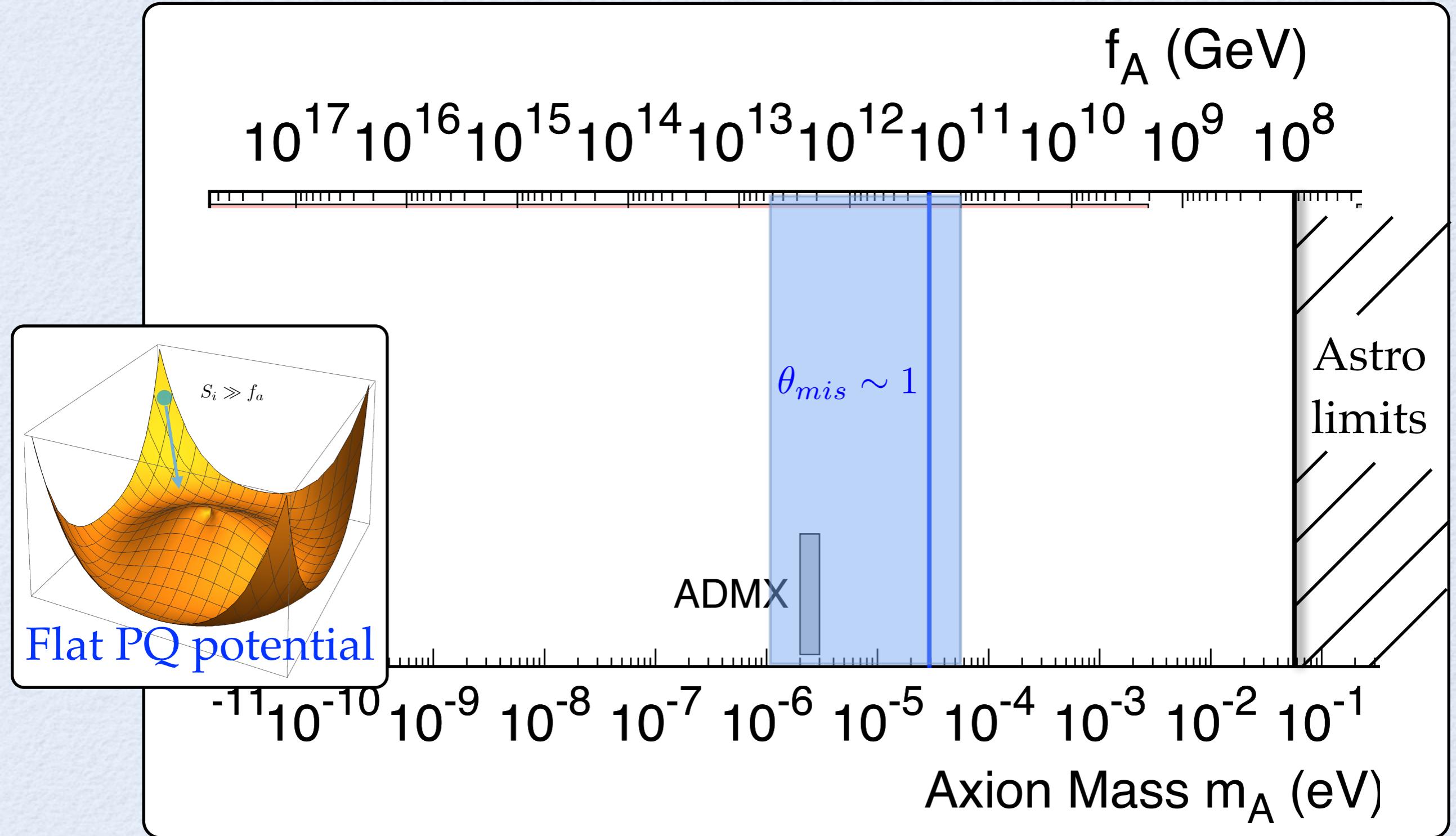
Standard Axion Dark Matter



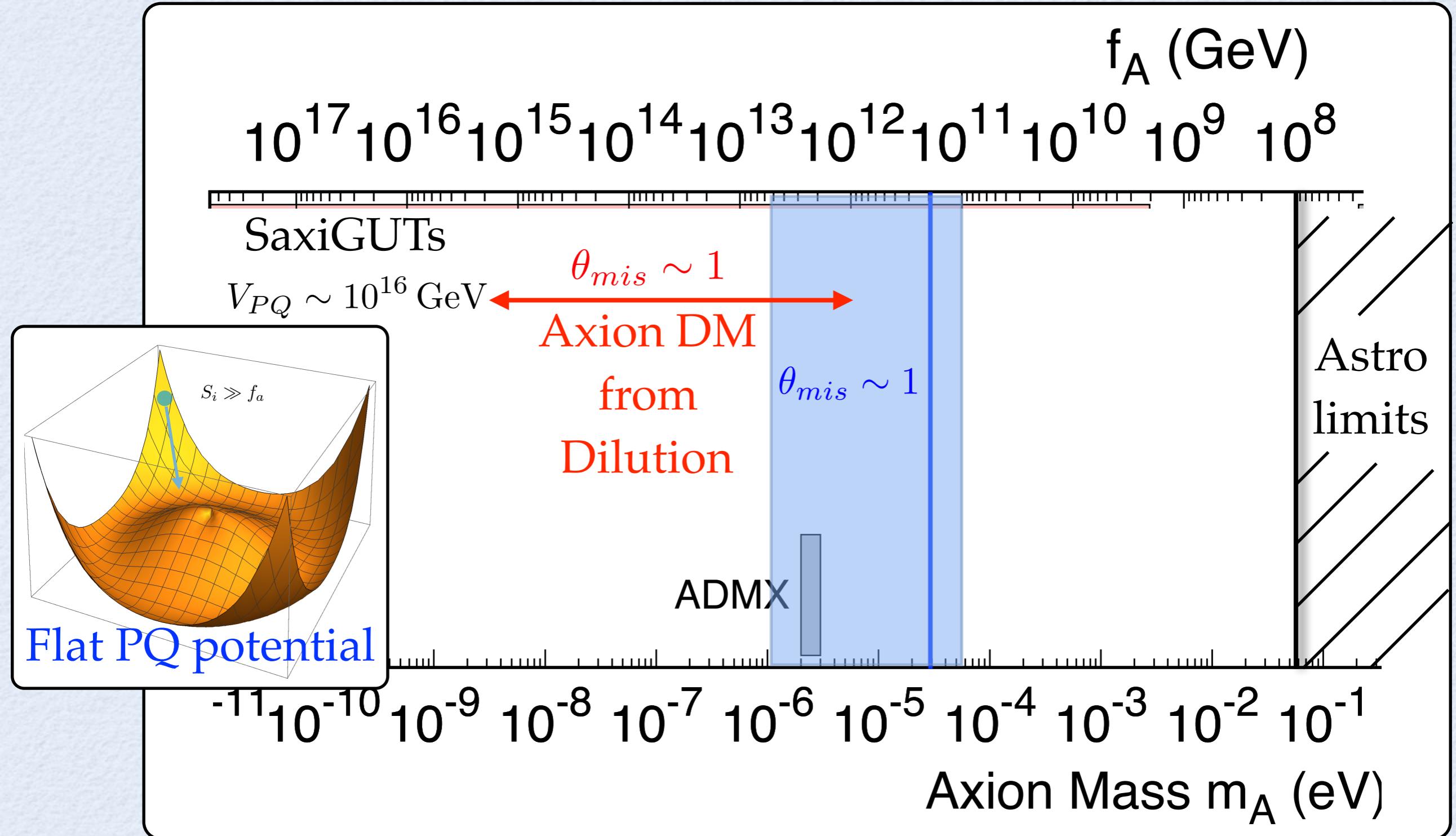
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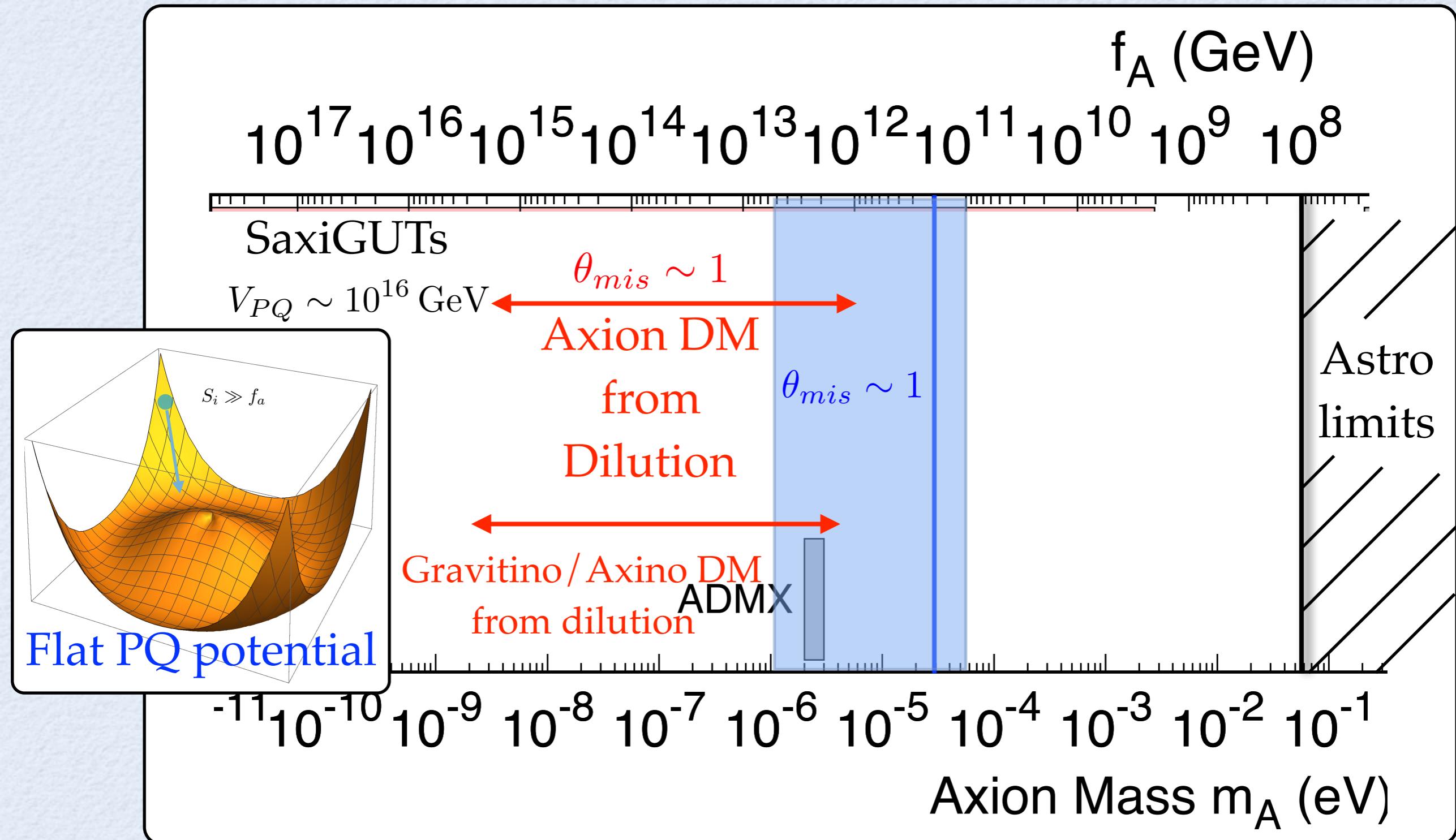
The PQ Condensate!



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