

# Higgs Parity, Strong CP, and Dark Matter

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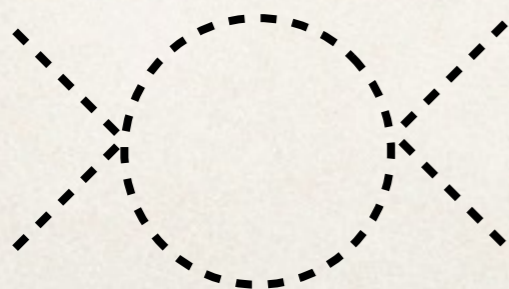
*arXiv:1902.07726*

# The Higgs Quartic

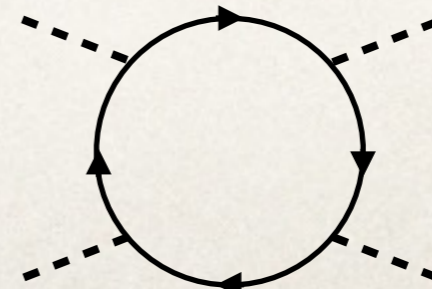
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$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$

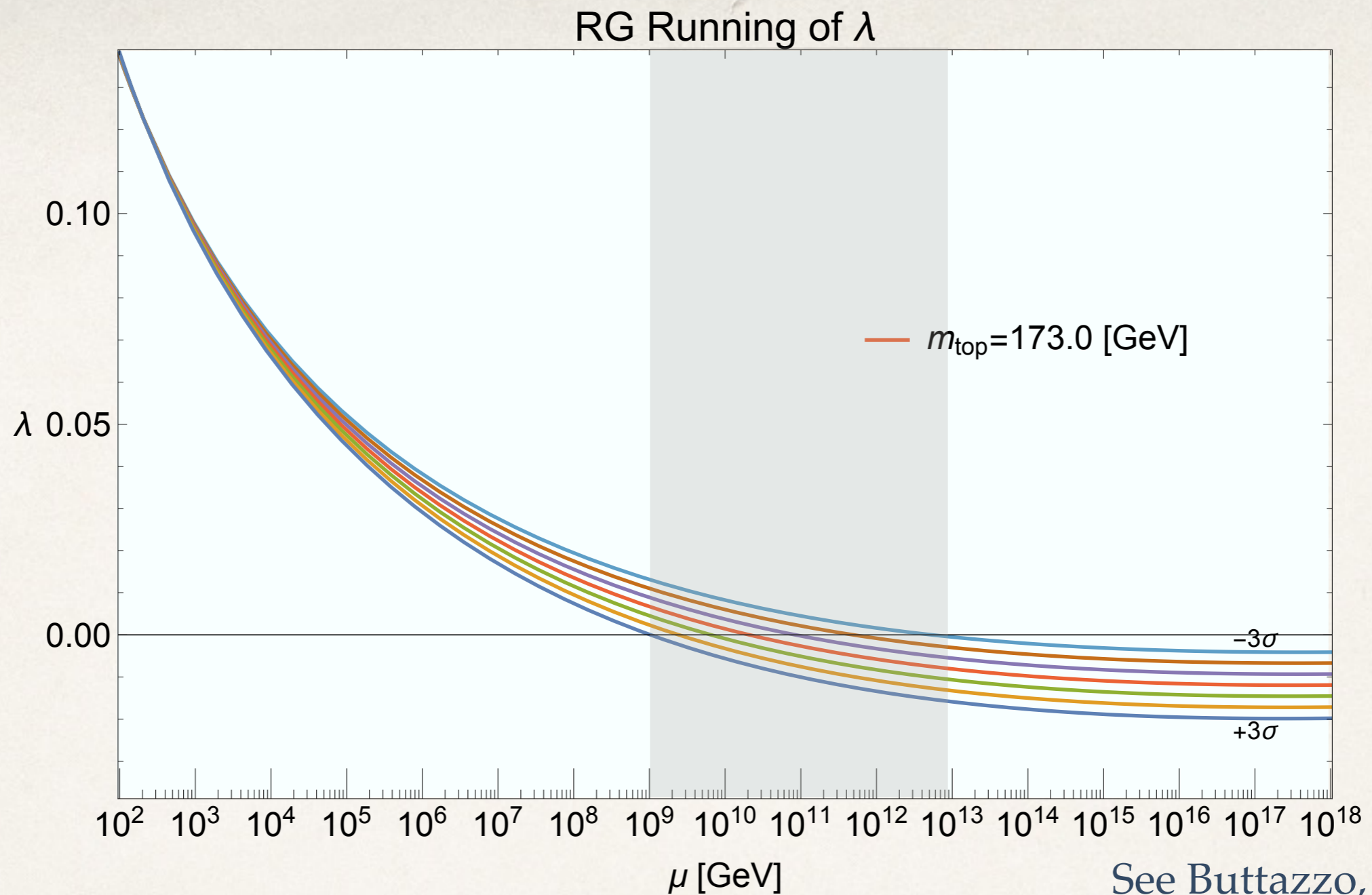
- 1967:  $\langle H \rangle = v$  Weinberg
- 2012:  $m, \lambda$  ATLAS, CMS
- Measured value  $\lambda$  of appears special



$\lambda$  ↑



$\lambda$  ↓



- Why is  $\lambda \sim .01$  above  $10^9$  GeV?
- Why  $\lambda$  crosses 0 between  $10^9 - 10^{13}$  ?
- Vanishing of  $\lambda$  hint of new physics?

# Vanishing of Higgs Quartic by a $Z_2$

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- Consider a  $Z_2$   $SU(2) \leftrightarrow SU(2)'$   
 $H \leftrightarrow H'$   
 $(2, 1) \quad (1, 2)$

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↑  
(174 GeV)<sup>2</sup>

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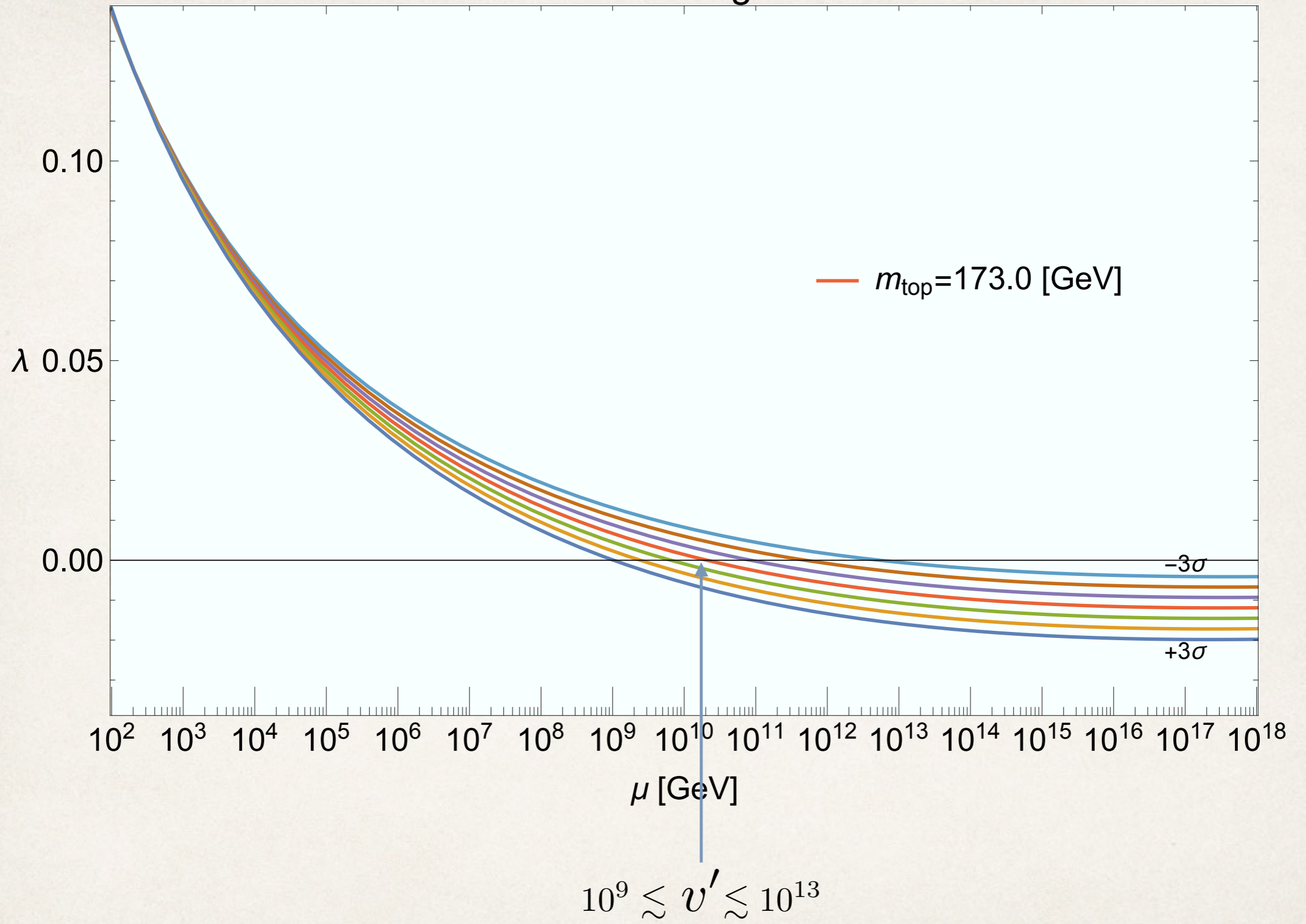
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$\underbrace{\hspace{10em}}_{-m_{\text{SM}}^2} \qquad \underbrace{\hspace{10em}}_{\lambda_{\text{SM}}}$

$$(174 \text{ GeV})^2$$

- Requiring  $v \ll v' \longrightarrow \lambda' \ll 1 \longrightarrow \lambda_{\text{SM}} \approx 0$

# RG Running of $\lambda$



# Fine-Tuning

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- Fine tuning required, but same as SM

$$\left(\frac{v^2}{m^2}\right) \times \left(\frac{m^2}{\Lambda^2}\right) = \frac{v^2}{\Lambda^2}$$

Tuning of  $\lambda'$

Tuning of  $v'$

# The Mirror Electroweak Sector

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- (1) Extend  $Z_2$  to mirror electroweak sector
- (2) Identify  $Z_2$  with spacetime parity

$$SU(2) \times U(1) \leftrightarrow SU(2)' \times U(1)'$$

$$\vec{x} \leftrightarrow -\vec{x}$$

$$q, \bar{u}, \bar{d}, l, \bar{e} \leftrightarrow (q', \bar{u}', \bar{d}', l', \bar{e}')^\dagger$$

$$H \leftrightarrow H'$$

- Implications?

# Solves Strong CP Problem

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- $SU(3) \times (SU(2) \times U(1)) \times (SU(2)' \times U(1)')$  solves strong CP

Babu, Chang, Senjanovic (1991)

- Parity is a symmetry

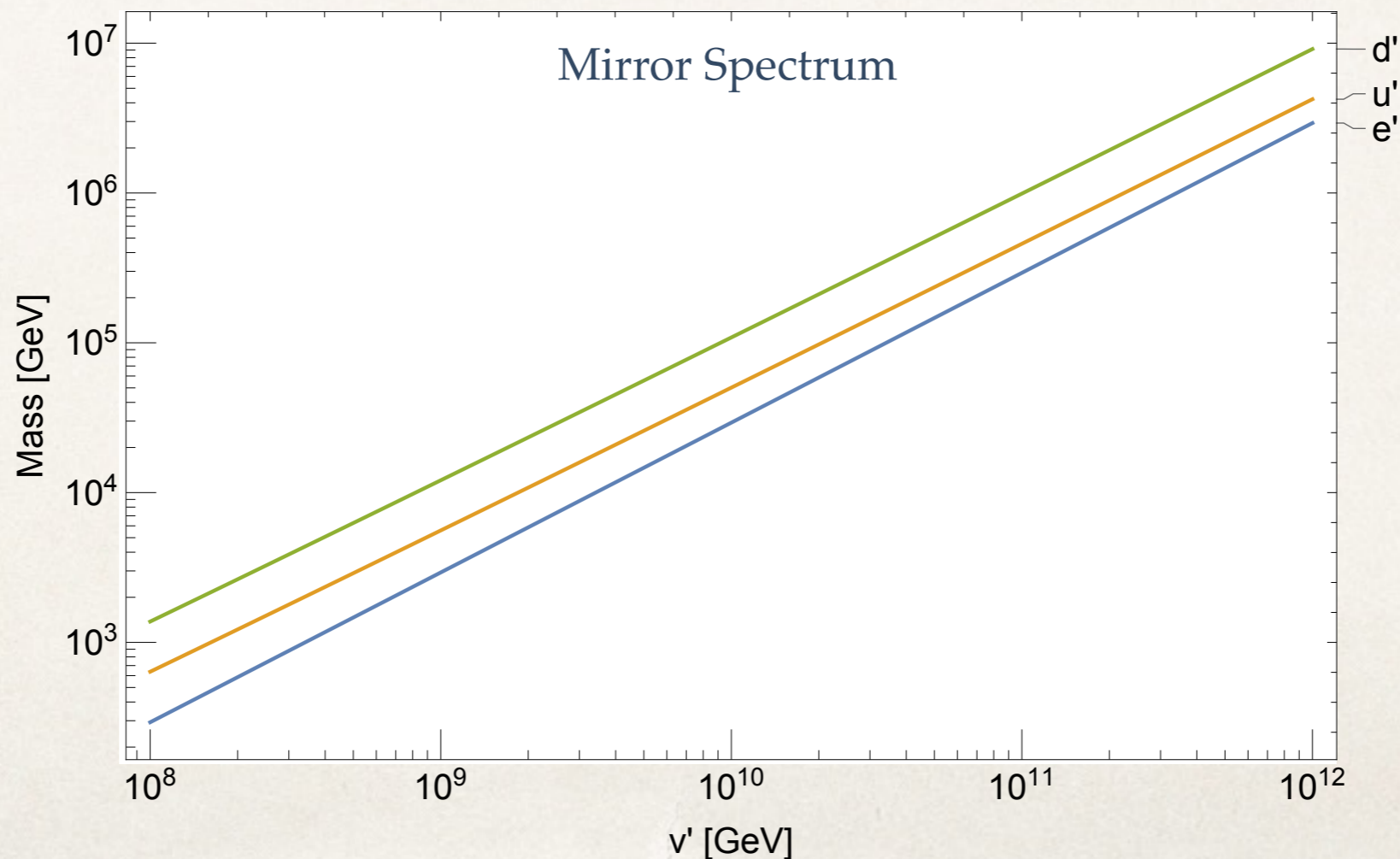
- $\frac{\theta}{32\pi^2} G\tilde{G}$  forbidden

- No CP violation in Yukawa sectors

$$\arg \det \begin{pmatrix} y_{u,d} v & 0 \\ 0 & y_{u,d}^* v' \end{pmatrix} = 0$$

# Mirror Dark Matter

- Natural DM candidate lightest  $U(1)'_{EM}$  particle,  $e'$
- DM mass  $m_{e'} = y_{e'} v' = m_e \frac{v'}{v}$  (1-10<sup>4</sup> TeV)



# Signals: Neutron EDM

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- Higher dimensional operators generate  $\theta$

- $$\mathcal{L}_6 = \frac{C}{M_{Pl}^2} (|H|^2 - |H'|^2) G\tilde{G}$$

↓

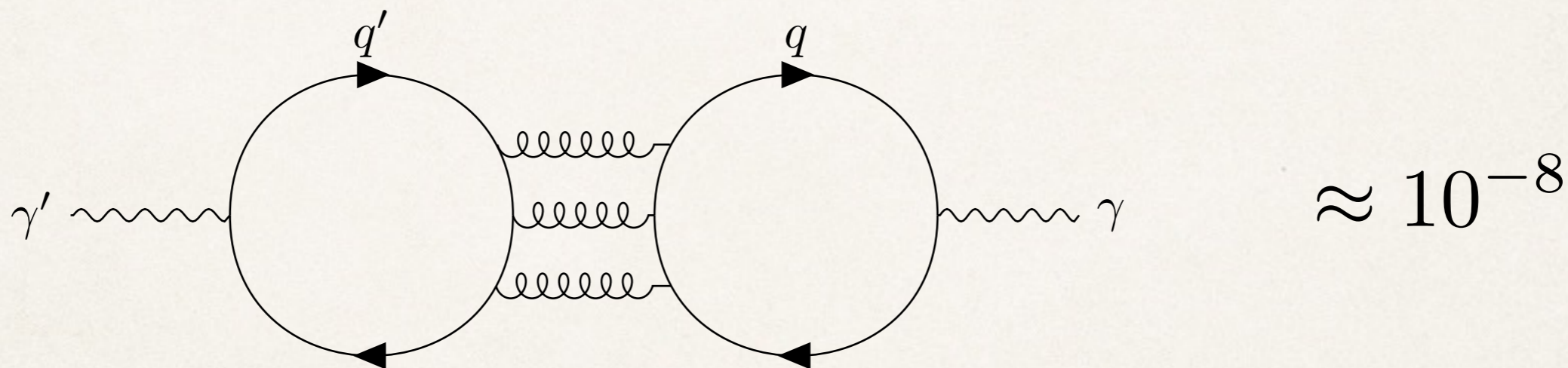
$$\theta = 32\pi^2 C \left( \frac{v'}{M_{Pl}} \right)^2 = 5 \times 10^{-11} C \left( \frac{v'}{10^{12} \text{ GeV}} \right)^2$$

- Current neutron EDM limit  $\theta < 10^{-10}$  Baker, et al (2006)

# Signals: Kinetic Mixing

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- $\mathcal{L} \supset -\frac{\epsilon_B}{2} B^{\mu\nu} B'_{\mu\nu}$  allowed
- Generated by

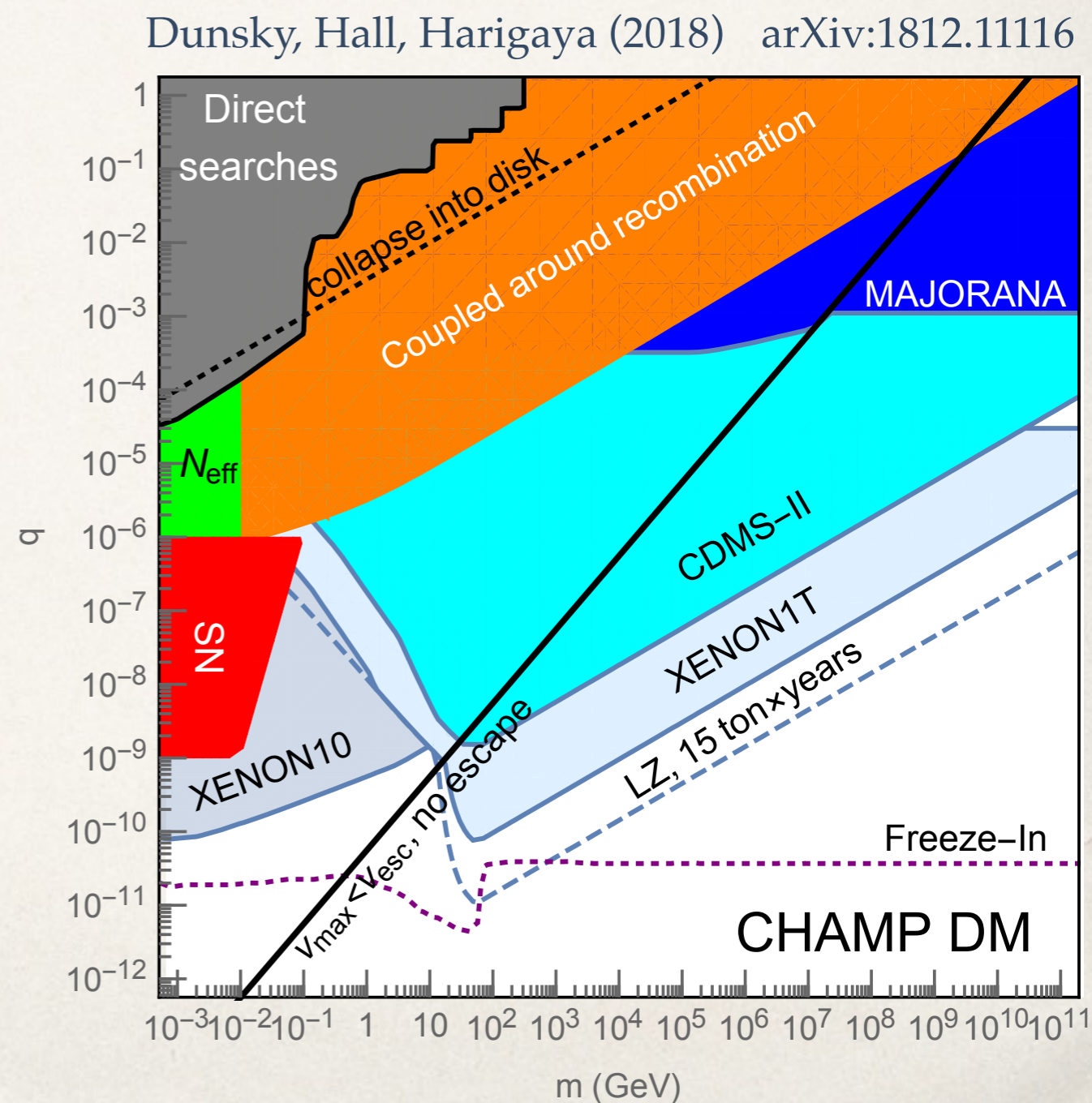
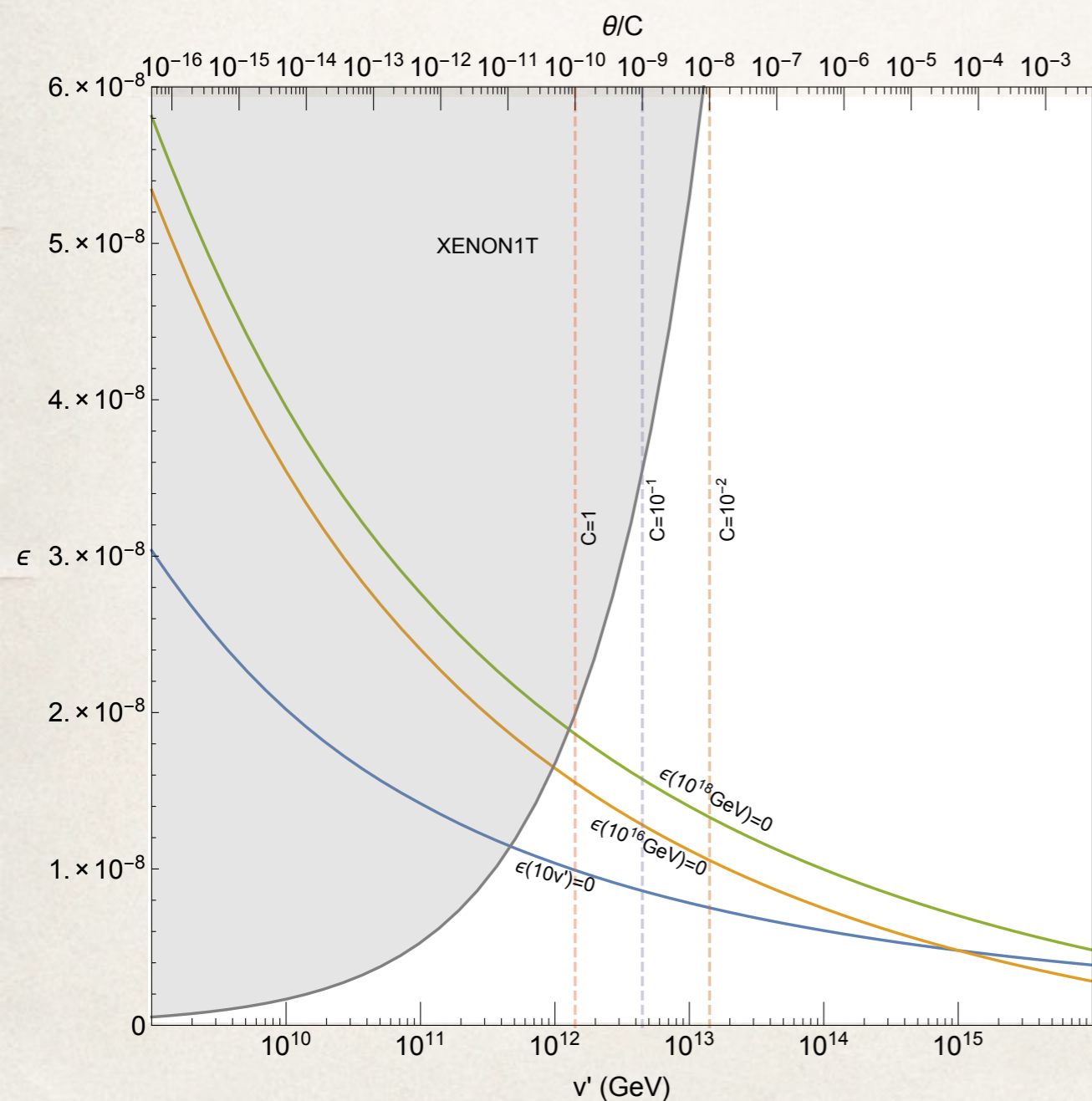


(Calculable from 4-loop QCD beta function)

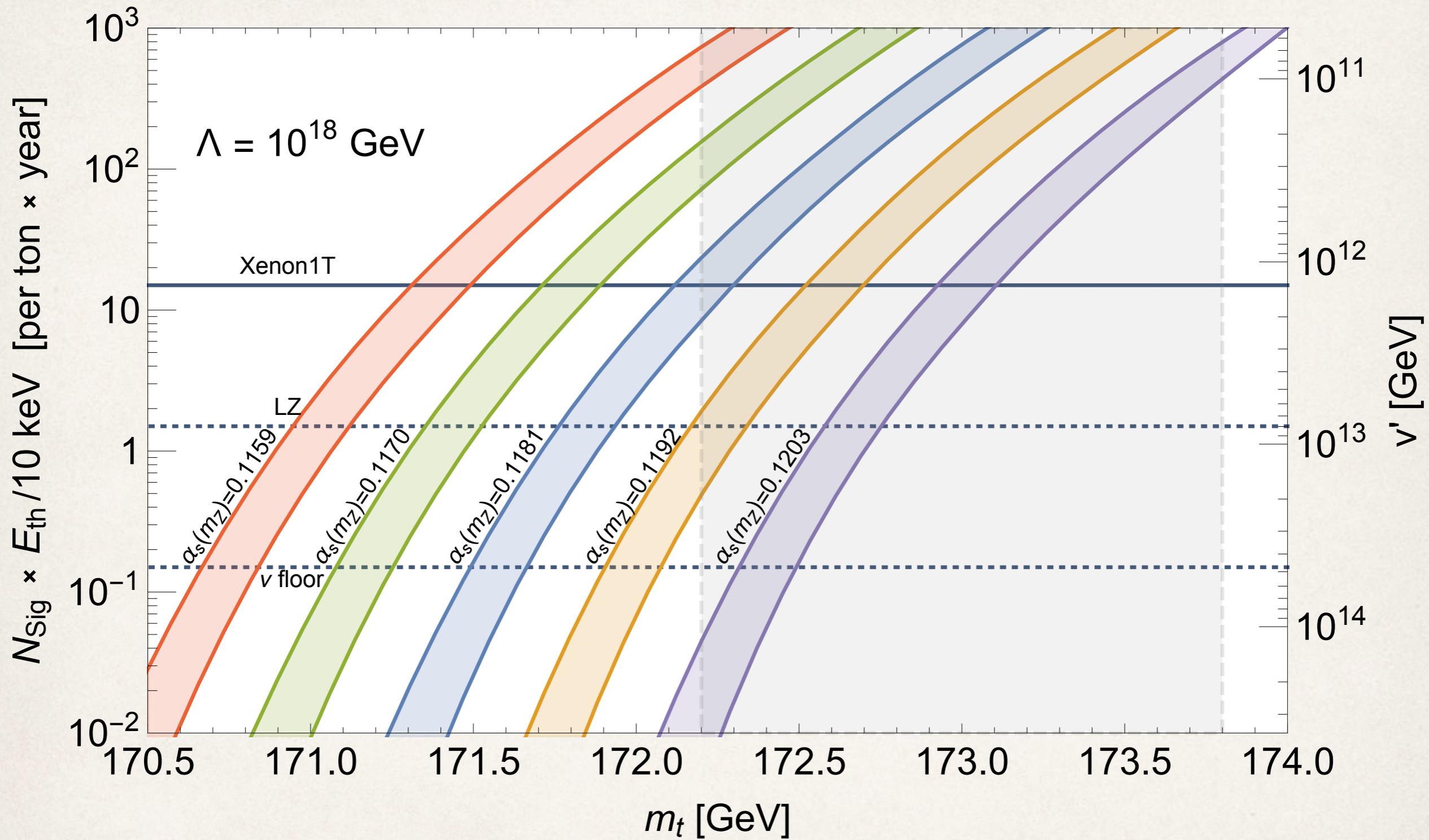
van Ritbergen, Vermaseren, Larin (1997)



# Signals: Kinetic Mixing



# e' DM Direct Detection Rate



# Summary

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- Observed Higgs mass imply next symmetry breaking scale of nature?
- Motivated by Strong CP  $\longrightarrow$  Higgs Parity, no QCD'
- Motivated by DM  $\longrightarrow$  mirror electroweak
- Same number of parameters as SM below  $v'$
- Future measurements of  $\{m_t, m_h, \alpha_s(M_Z)\}$  will hone in on  $v'$
- Entire parameter space will be probed by future detectors

# Cosmology

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- Freeze-Out and Freeze-In of  $e'$  DM does not work
- Too much  $u'$  produced  $\rightarrow$  fractional charged hadrons
- Non-thermal production, kinematic suppression of  $u'$