Higgs Parity, Strong CP, and Dark Matter

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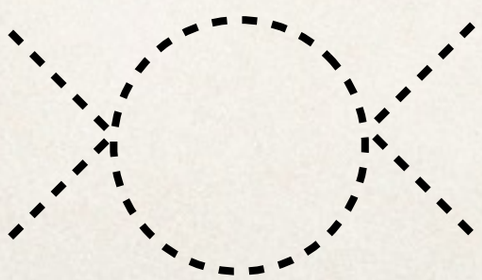
arXiv:1902.07726

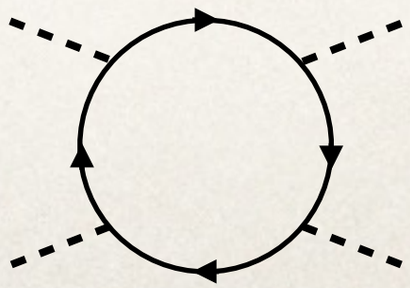
The Higgs Quartic

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

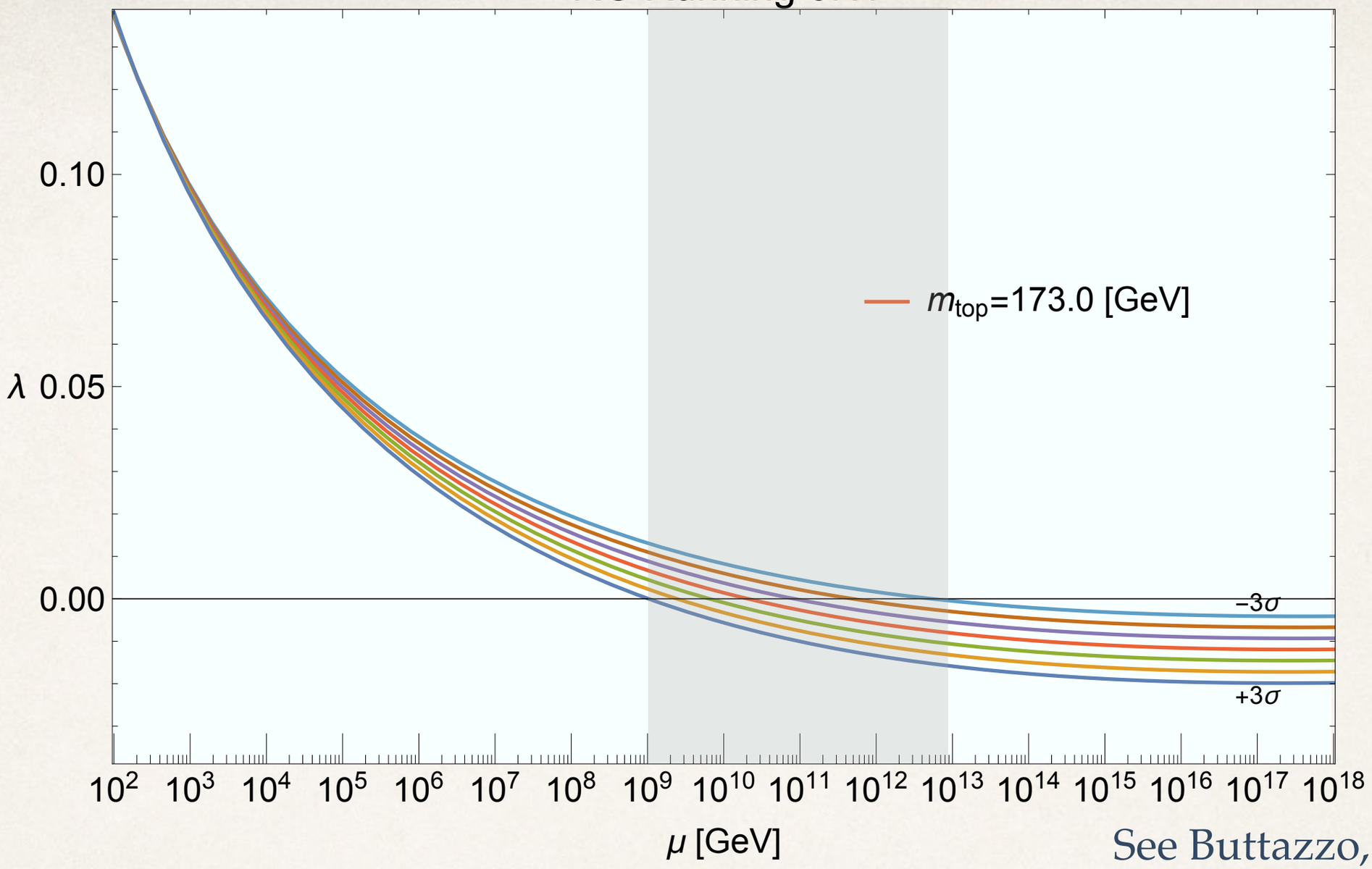
- 1967: $\langle H \rangle = v$ Weinberg
- 2012: m, λ ATLAS, CMS
- Measured value λ of appears special



λ



λ



See Buttazzo, et al (2013)

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

Vanishing of Higgs Quartic by a Z_2

- Consider a Z_2 $\qquad SU(2) \leftrightarrow SU(2)'$

$$\underset{(2,1)}{H} \leftrightarrow \underset{(1,2)}{H'}$$

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

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$$(174\,\mathrm{GeV})^2$$

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Integrate out H' $\qquad \langle H' \rangle^2 \equiv v'^2 = \dfrac{m^2}{\lambda} \gg v^2$ ($(174\,\mathrm{GeV})^2$)

$$V_{\mathrm{LE}}(H) = \lambda' v'^2 |H|^2 - \lambda' \left(1 + \frac{\lambda'}{2\lambda}\right) |H|^4$$

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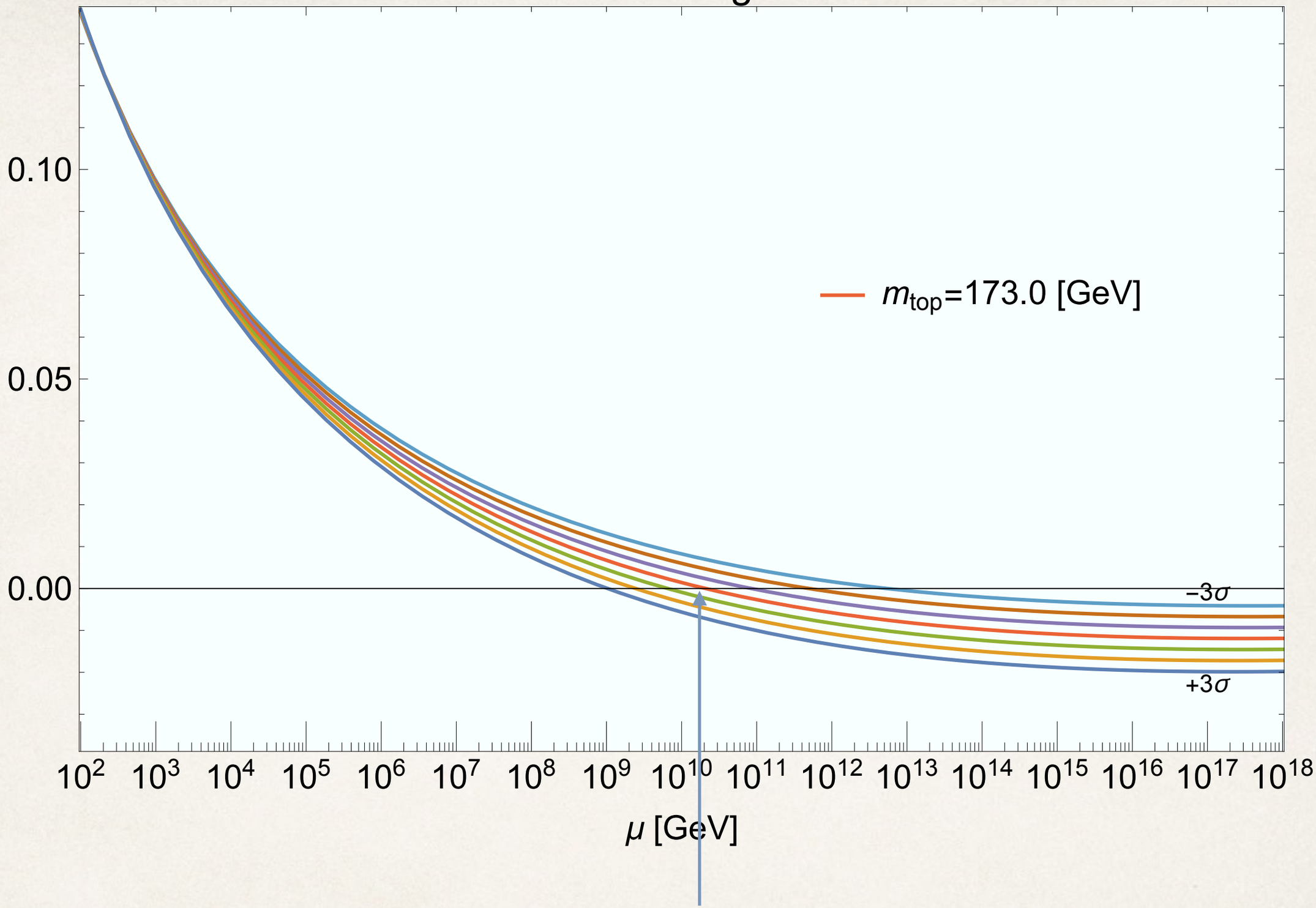
$-m^2_{\text{SM}}$ $\qquad$ λ_{SM}

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

RG Running of λ



$$10^9 \lesssim v' \lesssim 10^{13}$$

Fine-Tuning

- Fine tuning required, but same as SM

$$\frac{v^2}{m^2} \times \frac{m^2}{\Lambda^2} = \frac{v^2}{\Lambda^2}$$

Tuning of λ' Tuning of v'

The Mirror Electroweak Sector

- (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

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

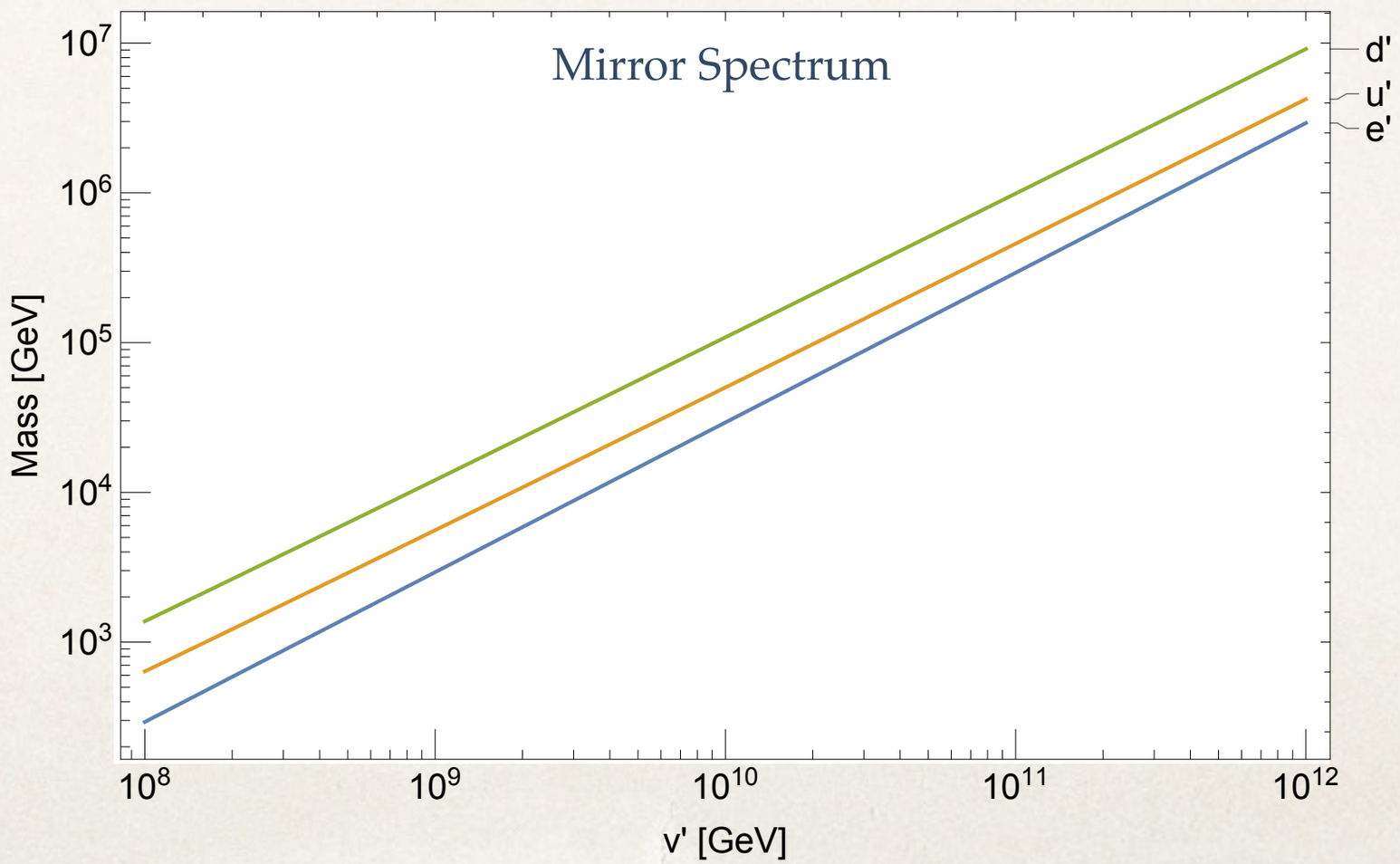
Babu, Chang, Senjanovic (1991)

- Parity *is* a symmetry
  - $\dfrac{\theta}{32\pi^2} G\tilde{G}$ forbidden
- No contribution from 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 $U(1)'_{\rm EM}$ particle, e'
- DM mass $m_{e'} = y_{e'} v' = m_e \dfrac{v'}{v}$ (1-10^4 TeV)



Signals: Neutron EDM

- Higher dimensional operators generate θ

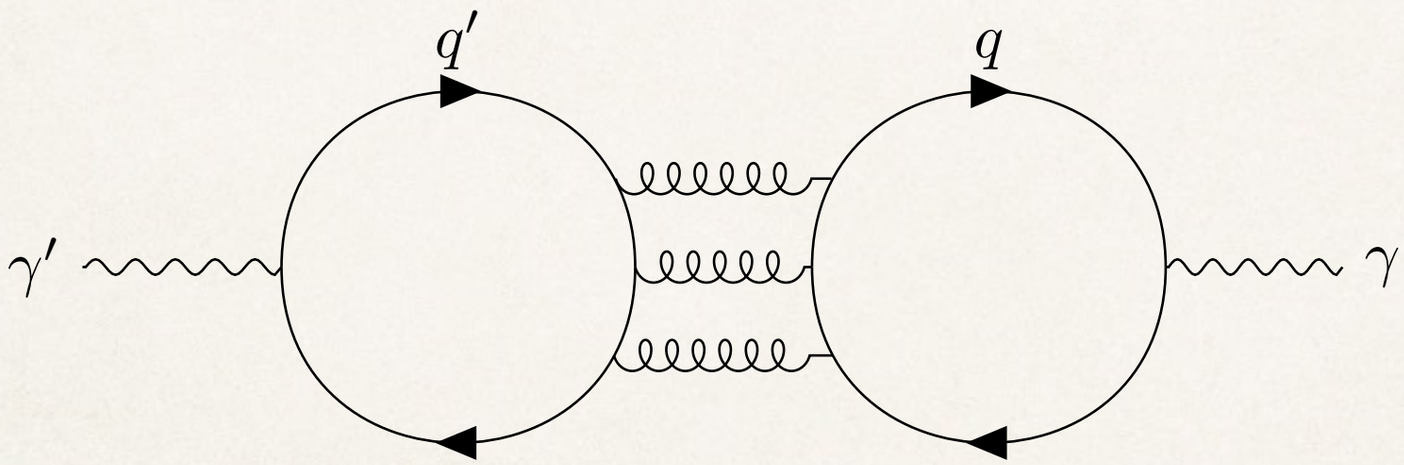
- $$\mathcal{L}_6 = \frac{C}{M_{Pl}^2}\left(|H|^2 - |H'|^2\right) G\tilde{G}$$

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

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

Signals: Kinetic Mixing

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



$\approx 10^{-8}$

(Calculable from 4-loop QCD beta function)

van Ritbergen, Vermaseren, Larin (1997)

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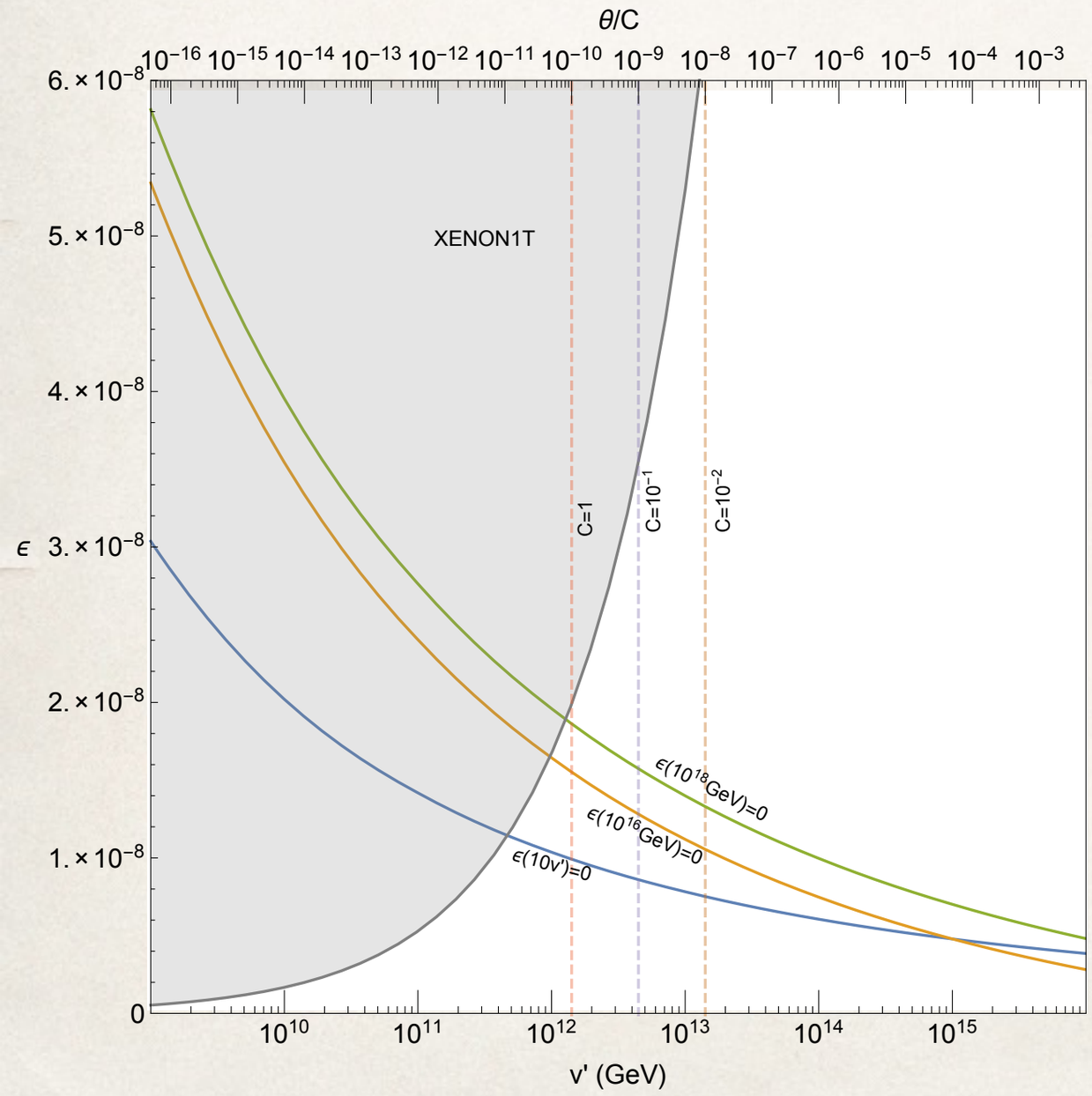
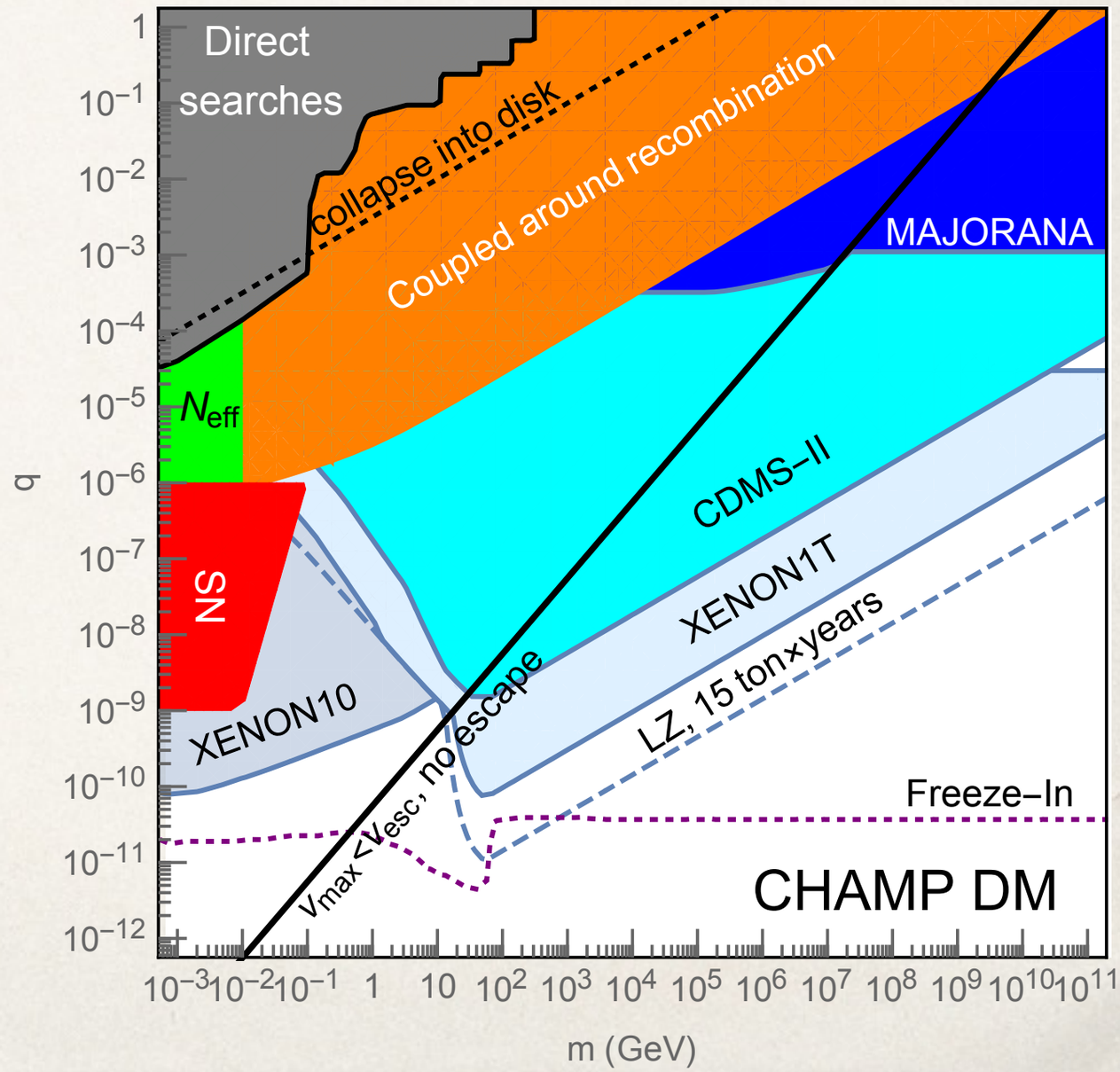
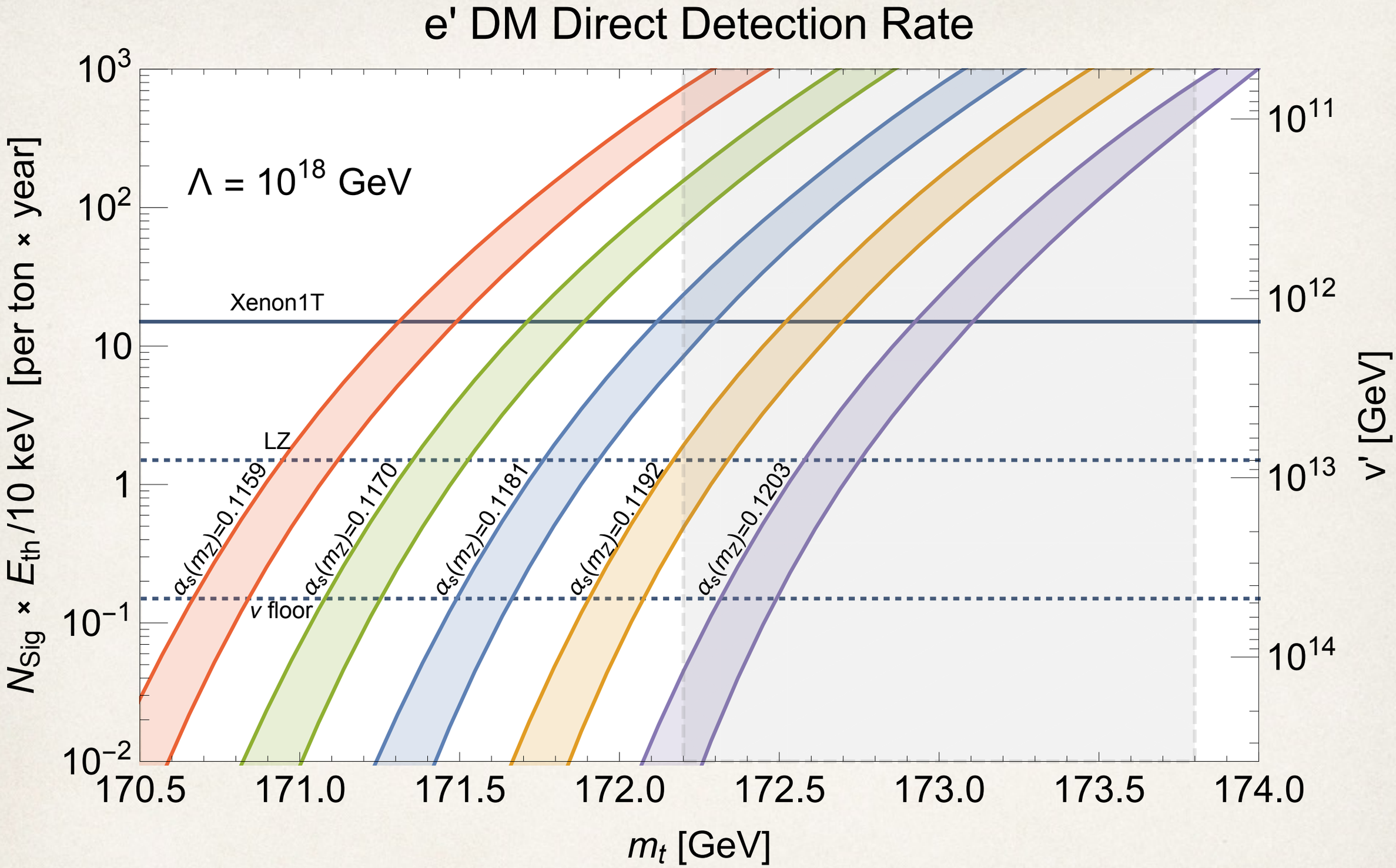


Dunsky, Hall, Harigaya (2018) arXiv:1812.11116




e' DM Direct Detection Rate
Λ = 10^18 GeV
Xenon1T
LZ
ν floor
α_s(m_Z)=0.1159
α_s(m_Z)=0.1170
α_s(m_Z)=0.1181
α_s(m_Z)=0.1192
α_s(m_Z)=0.1203
N_Sig × E_th /10 keV [per ton × year]
m_t [GeV]
v' [GeV]
10^3
10^2
10
1
10^-1
10^-2
10^11
10^12
10^13
10^14
170.5
171.0
171.5
172.0
172.5
173.0
173.5
174.0

Summary

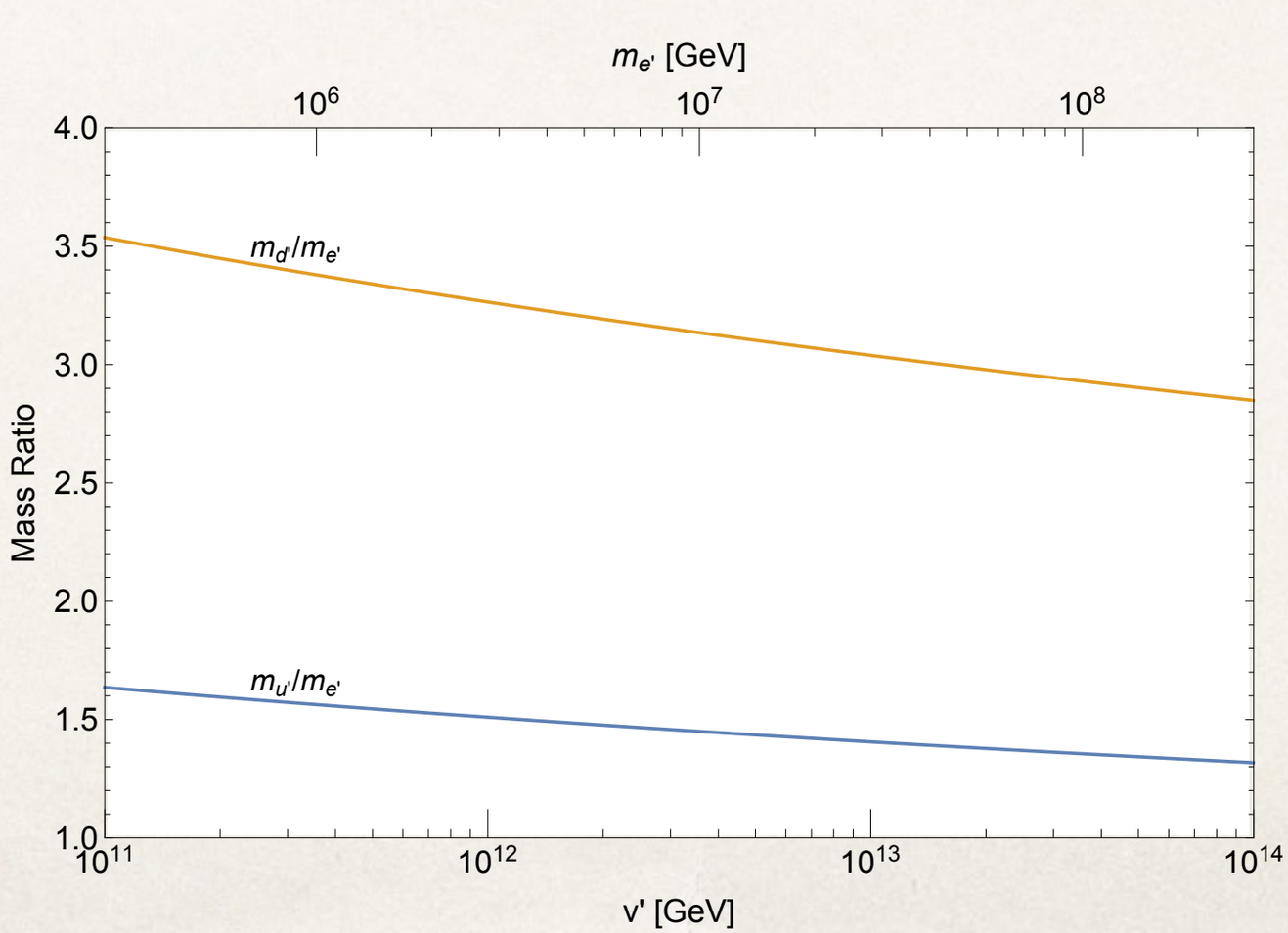
- Observed Higgs mass imply next symmetry breaking scale of nature?

- 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

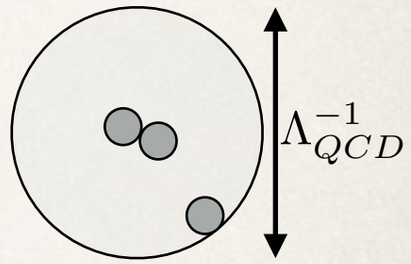
- Freeze-Out and Freeze-In of e' DM problematic:
- Thermally produce e' ⟶ also produce dangerous u'

(also stable)



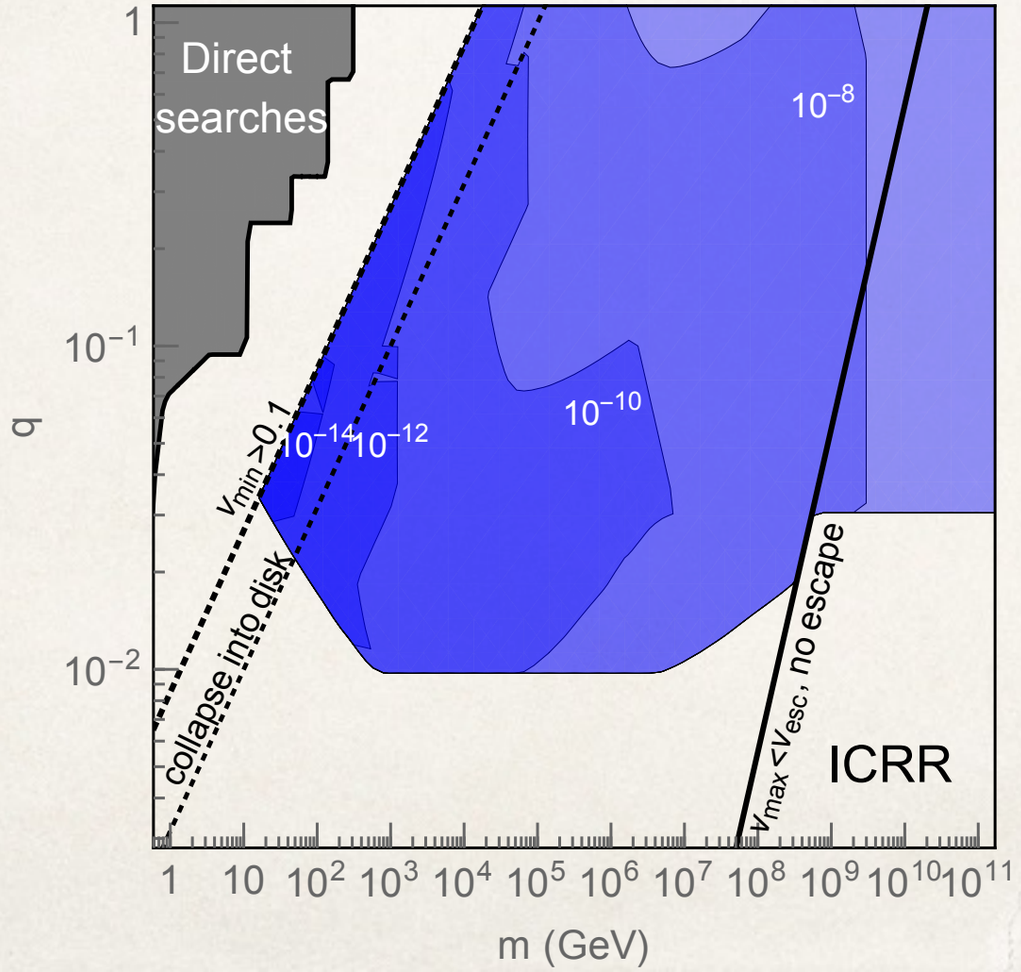
Fractionally Charged Hadrons

- Below, $T = \Lambda_{QCD}$ quarks hadronize



$u' u' q$

- Mixed hadrons fractionally charged



$$\frac{\Omega_{u'}}{\Omega_{\rm DM}} \lesssim 10^{-8}$$

Dunsky, Hall, Harigaya (2018)
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Non-Thermal Production of e' DM

- Non-thermal production of e' required, via decays

- Ingredients for an abundance hierarchy:

1. $T_{RH} \lesssim \dfrac{m_{u'}}{40}$ → Prevent u' thermal production (Boltzmann suppression)

2. $\mathrm{B}_{u'} \lesssim 10^{-8}\mathrm{B}_{e'}$ → Prevent u' non-thermal production (kinematic suppression)

3. $\mathrm{B}_{e'} \simeq \dfrac{\mathrm{eV}}{T_{RH}} \dfrac{m_\phi}{m_{e'}}$ → Get correct DM abundance

- Possible via inflaton decays, ν' beta decays, etc.