QUE & QDEE

MSSM^{4G}

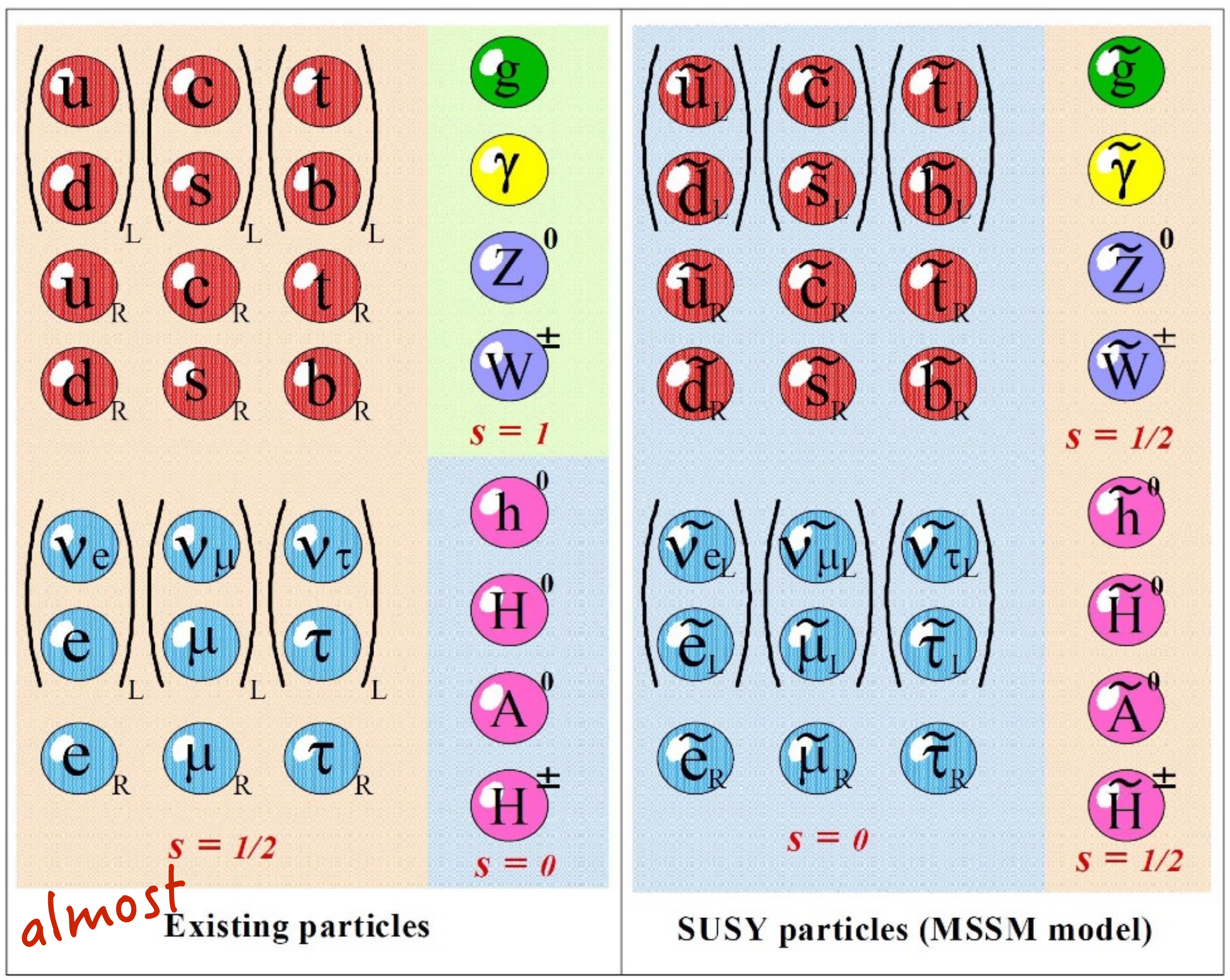
Reviving and Testing Bino Dark Matter with Vector-like Particles

Mohammad “Mo” Abdullah

Based on arXiv:1510.06089 with Jonathan Feng (Phys.Rev. D93 (2016) no.1, 015006) and arXiv:1608.00283 with Jonathan Feng, Sho Iwamoto and Benjamin Lillard (Phys.Rev. D94 (2016) no.9, 095018)

Mitchell Workshop
Texas A&M University
May 19, 2017

Minimal **S**upersymmetric **S**tandard **M**odel

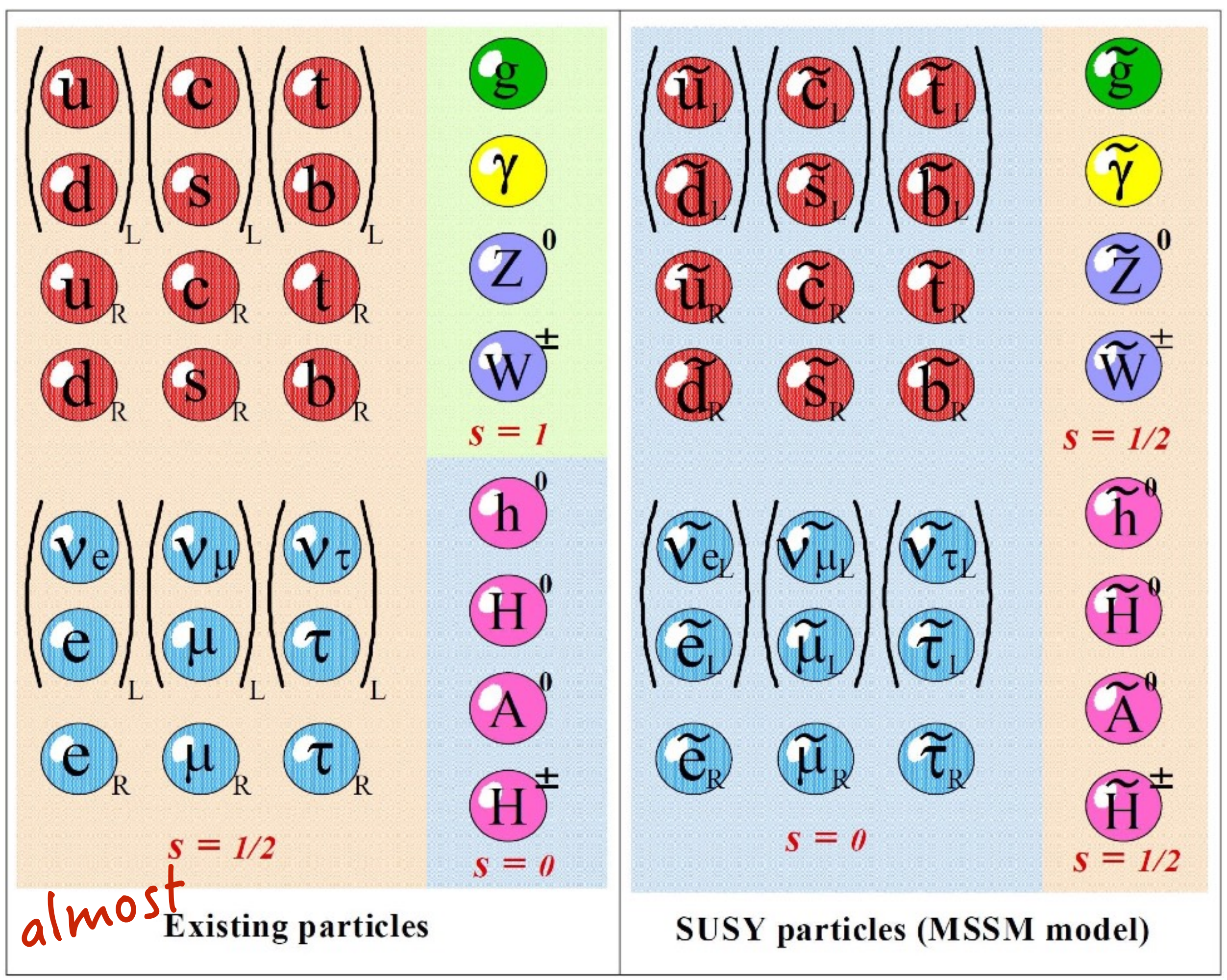


Credit: KEK

Perks:

- Solves the hierarchy problem
- Improves gauge coupling unification
- Provides a natural dark matter candidate

Minimal Supersymmetric Standard Model



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Problems:

- The Higgs mass is too large
- Dark matter candidates are rather constrained

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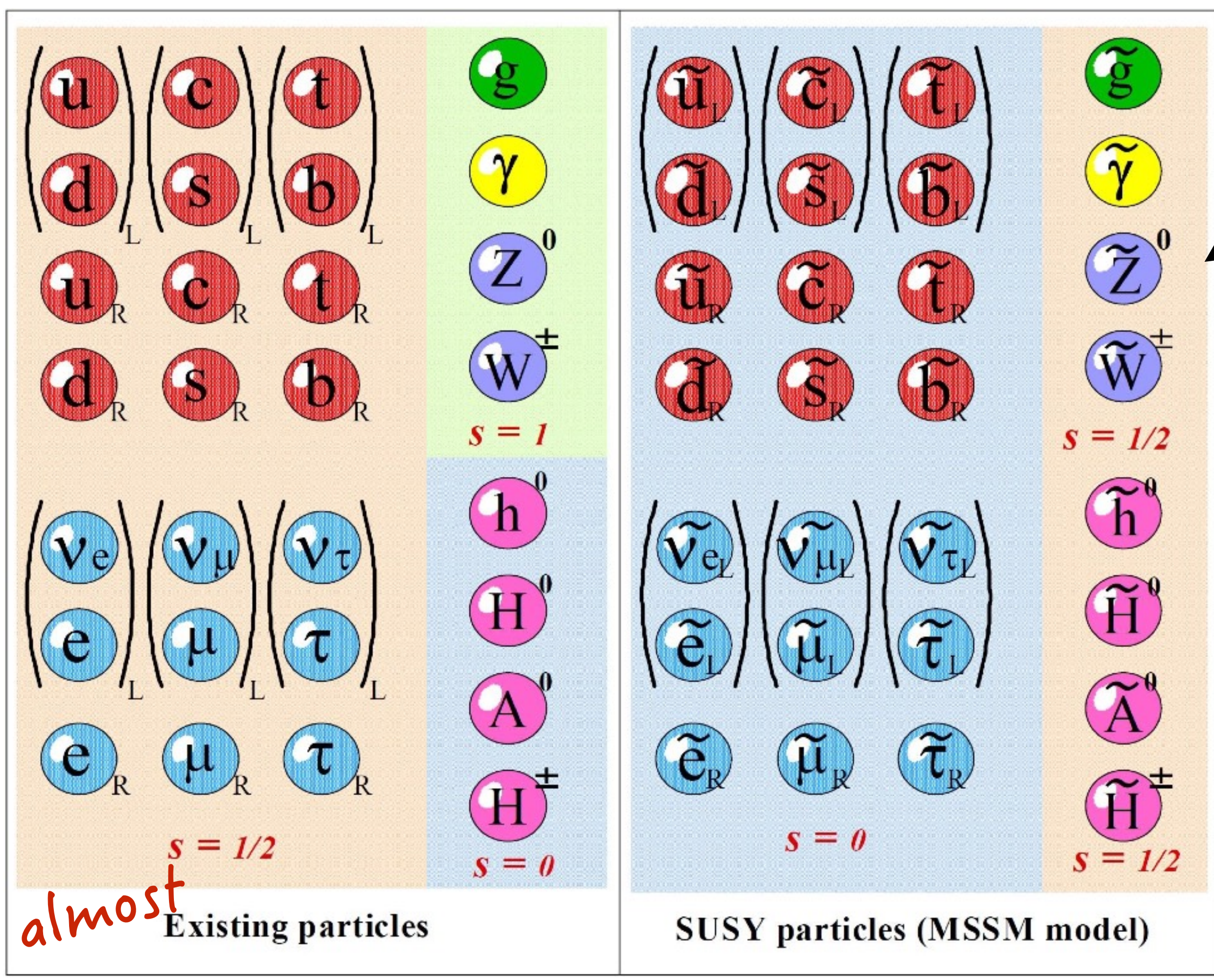

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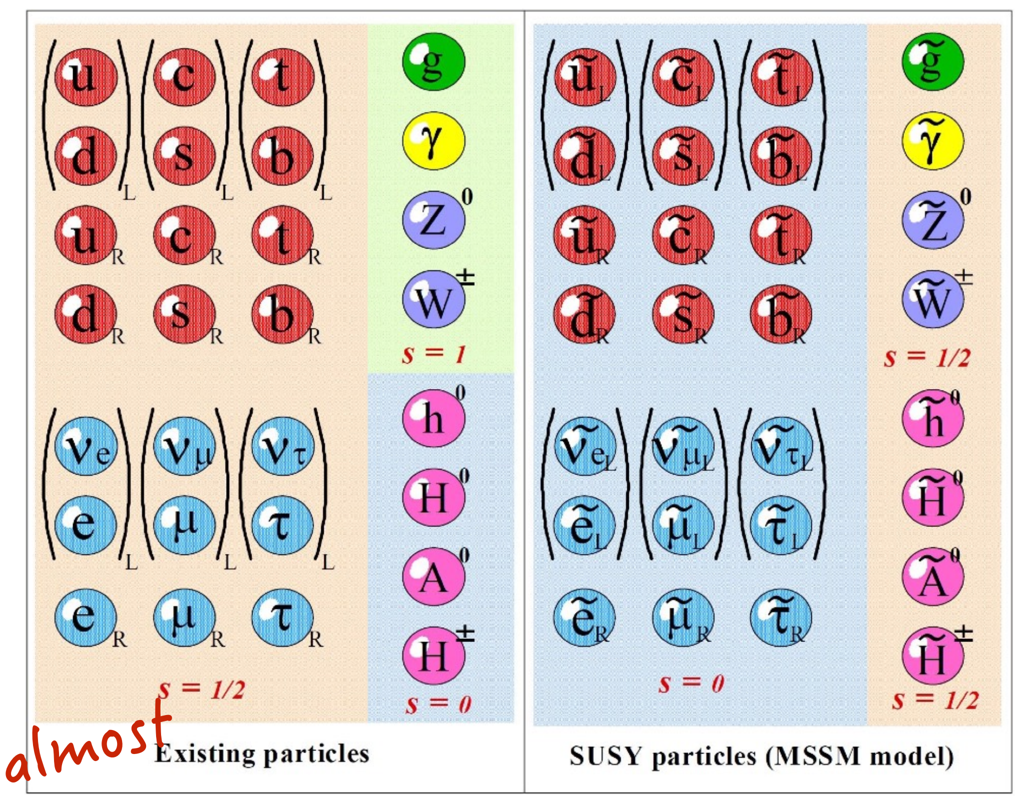
Specifically, the Bino

- **Annihilates very weakly**
- **Will overpopulate the universe if heavier than 300 GeV**

Minimal
Supersymmetric
Standard
Model

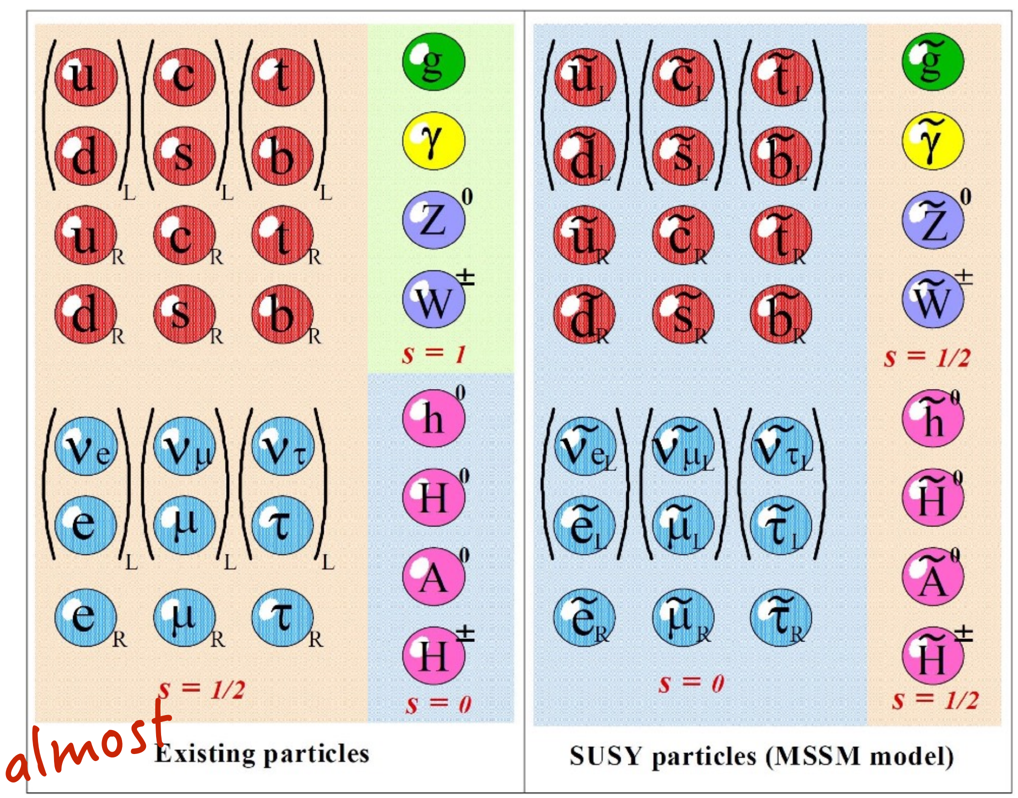


Would be nice to:

Increase the Higgs mass will less *unnaturalness*

Extend the parameter space of Bino dark matter

Minimal Supersymmetric Standard Model



Would be nice to:

Increase the Higgs mass will less *unnaturalness*

Extend the parameter space of Bino dark matter

Done!

?

4th Generation

Vector-Like

Filtering Models

S. Martin, arXiv: 0910.2732

Filtering Models

- To preserve gauge coupling unification, new fields must be added in full (flipped) **SU(5)** multiplets

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- The Higgs mass corrections are too small for **5**'s

# of generations ↖   # of colors ↑   Yukawa coupling ↗

$$N_g \times N_c \times k^4$$

10	1 x 3	x 1.050^4	~ 3.6	
5	3 x 1	x 0.765^4	~1.0	← Too small!

S. Martin, arXiv: 0910.2732

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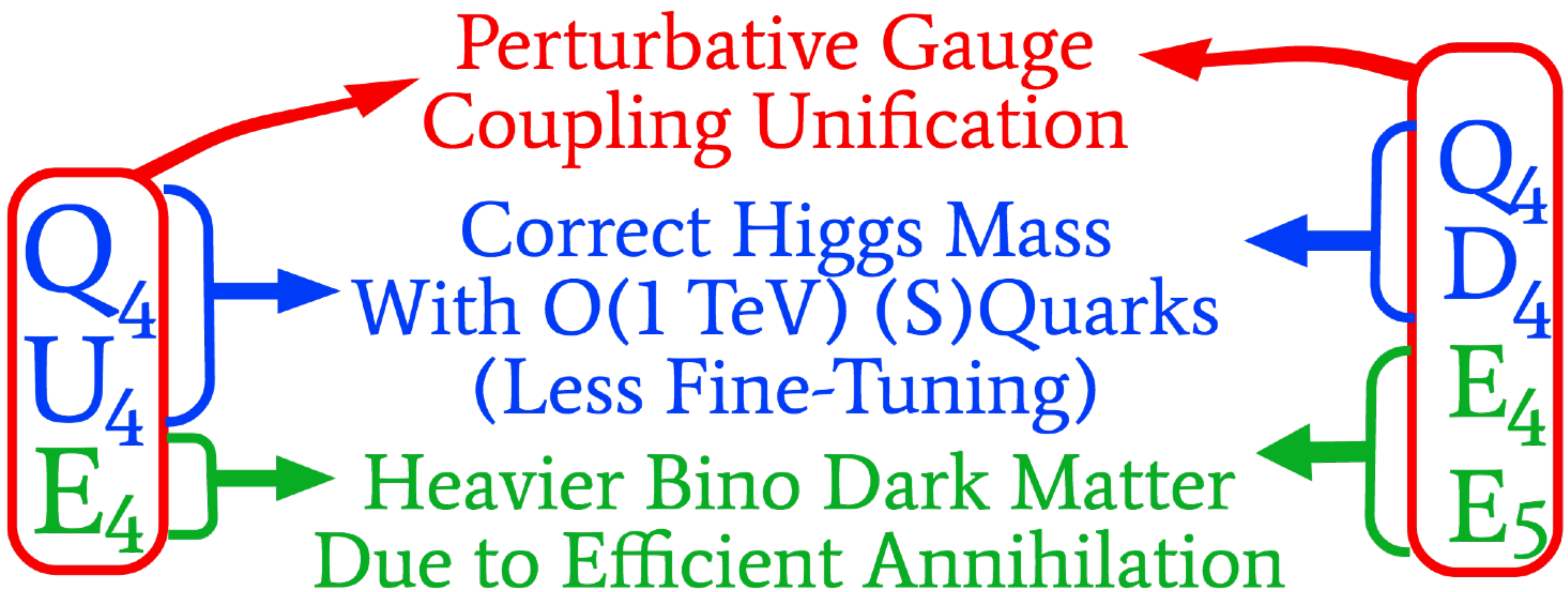
10	1	x 3	x 1.050^4	~ 3.6
5	3	x 1	x 0.765^4	~ 1.0 ⟵ Too small!

- Our only options is to add a **10** of SU(5) or flipped SU(5)

S. Martin, arXiv: 0910.2732

and we are left with…



Q: Quark isodoublet
U: Up-type quark isosinglet
D: Down-type quark isosinglet
E: Charged lepton isosinglet

Simplifying Assumptions

Zero mixing

$$A_k - \mu \; cot\beta = 0$$

$$A_h - \mu \; tan\beta = 0$$

$$\mu H_u H_d$$

$$tan\beta = \frac{v_u}{v_d}$$

Minimize number of physical masses

$$\begin{aligned}
m_{\tilde{q}_4} &\equiv m_{\tilde{T}_{4L}} = m_{\tilde{T}_{4R}} = m_{\tilde{B}_{4L}} = m_{\tilde{B}_{4R}} = m_{\tilde{t}_{4L}} = m_{\tilde{t}_{4R}} \\
m_{\tilde{\ell}_4} &\equiv m_{\tilde{\tau}_{4L}} = m_{\tilde{\tau}_{4R}} \\
m_{q_4} &\equiv m_{T_4} = m_{B_4} = m_{t_4} \\
m_{\ell_4} &\equiv m_{\tau_4} \; .
\end{aligned}$$

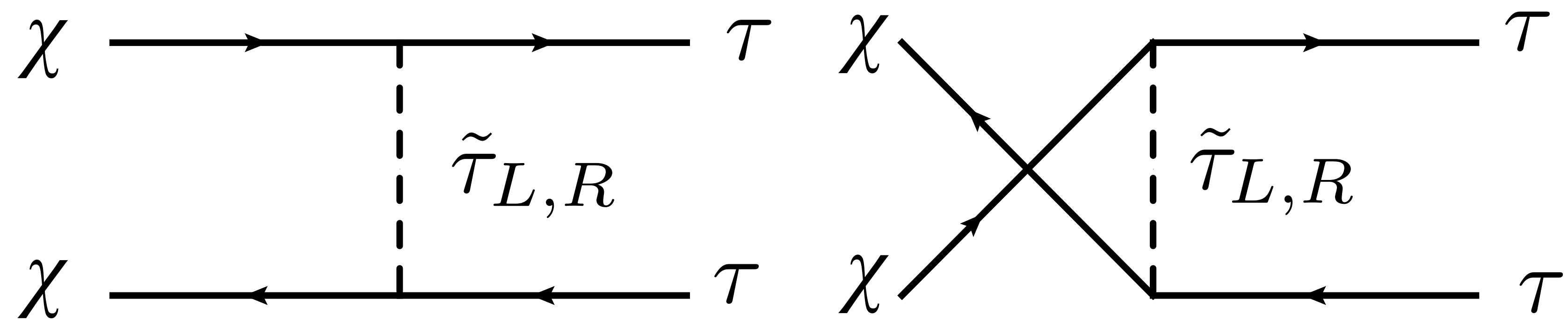
$$m_{\tilde{q}_4}, m_{\tilde{\ell}_4}, m_{q_4} > m_{\tilde{B}} > m_{\ell_4}$$

Bino is the LSP

Bino can annihilate

Relic Density

$$\langle \sigma v \rangle = a + b\, x_F^{-1}$$



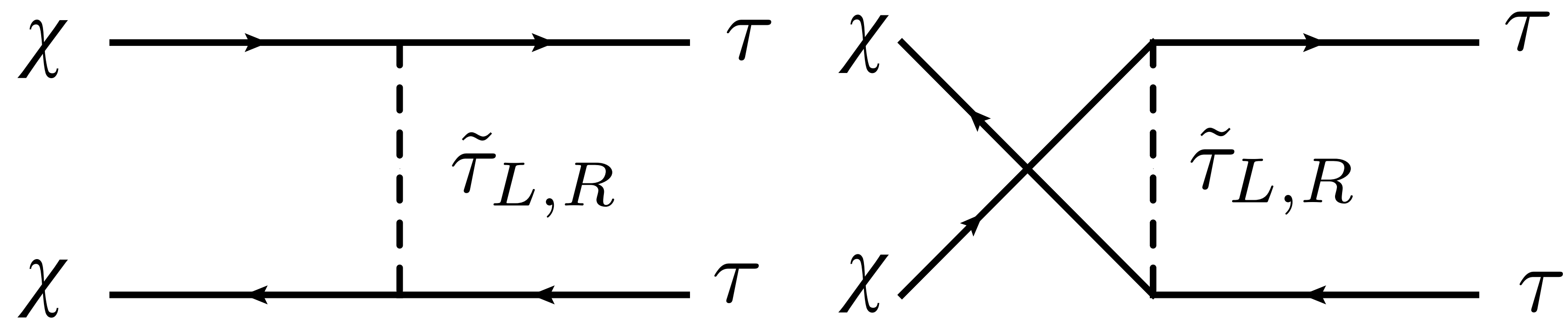
$$a = \frac{g_Y^4 Y_V^4}{32\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

$$b = \frac{g_Y^4 Y_V^4}{128\pi} \frac{1}{m_{\tilde{B}}} \frac{1}{\sqrt{m_{\tilde{B}}^2 - m_f^2}\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^4} \left[17 m_f^8 - 2 m_f^6 \left(17 m_{\tilde{f}}^2 + 20 m_{\tilde{B}}^2\right) \right.$$
$$+ m_f^4 \left(86 m_{\tilde{B}}^2 m_{\tilde{f}}^2 + 17 m_{\tilde{f}}^4 + 37 m_{\tilde{B}}^4\right)$$
$$\left. - 2 m_f^2 \left(26 m_{\tilde{B}}^4 m_{\tilde{f}}^2 + 11 m_{\tilde{B}}^2 m_{\tilde{f}}^4 + 11 m_{\tilde{B}}^6\right) + 8 m_{\tilde{B}}^4 \left(m_{\tilde{f}}^4 + m_{\tilde{B}}^4\right)\right] .$$

Relic Density

$$\langle \sigma v \rangle = a + b\, x_F^{-1}$$

Maximal = 2 for right-handed leptons



$$a = \frac{g_Y^4 Y_V^4}{32\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

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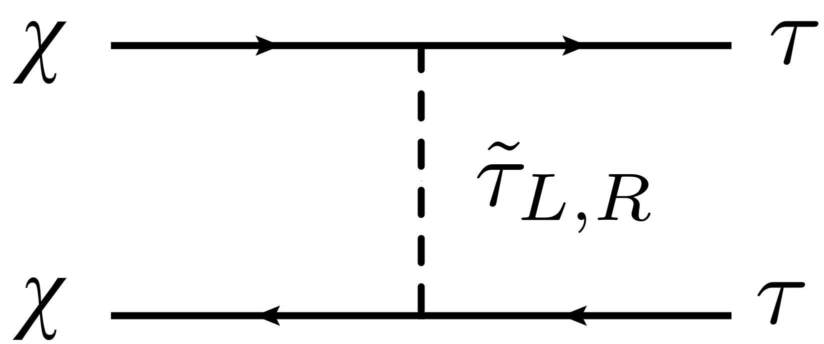

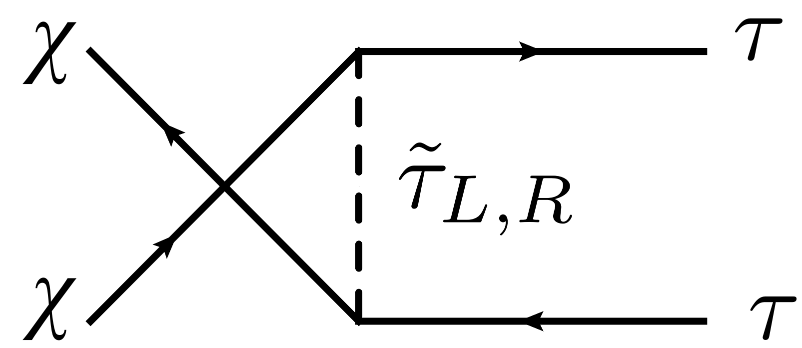

Maximal = 2 for right-handed leptons

Small in SM

$$a = \frac{g_Y^4 Y_V^4}{32\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

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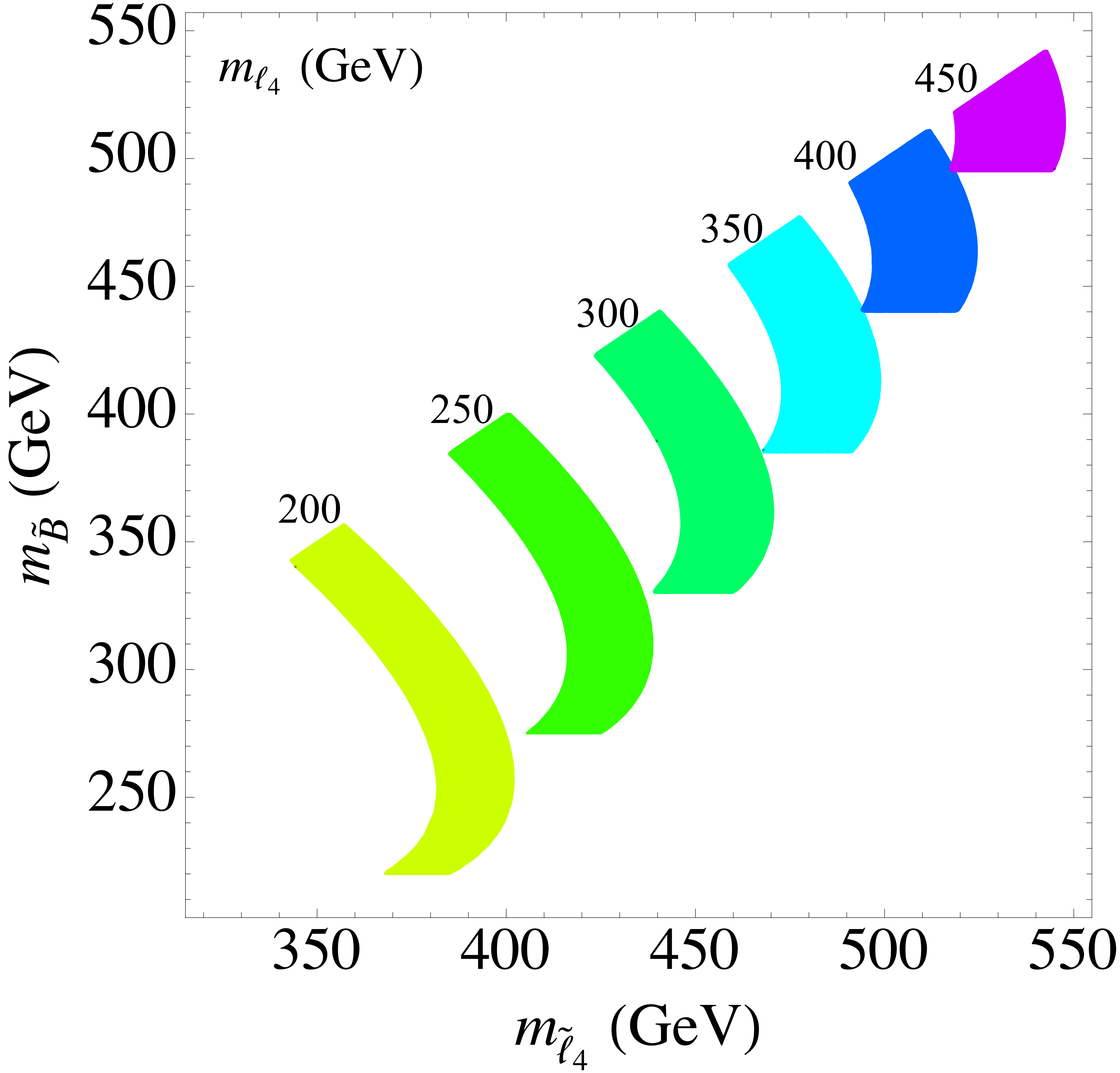
Relic Density

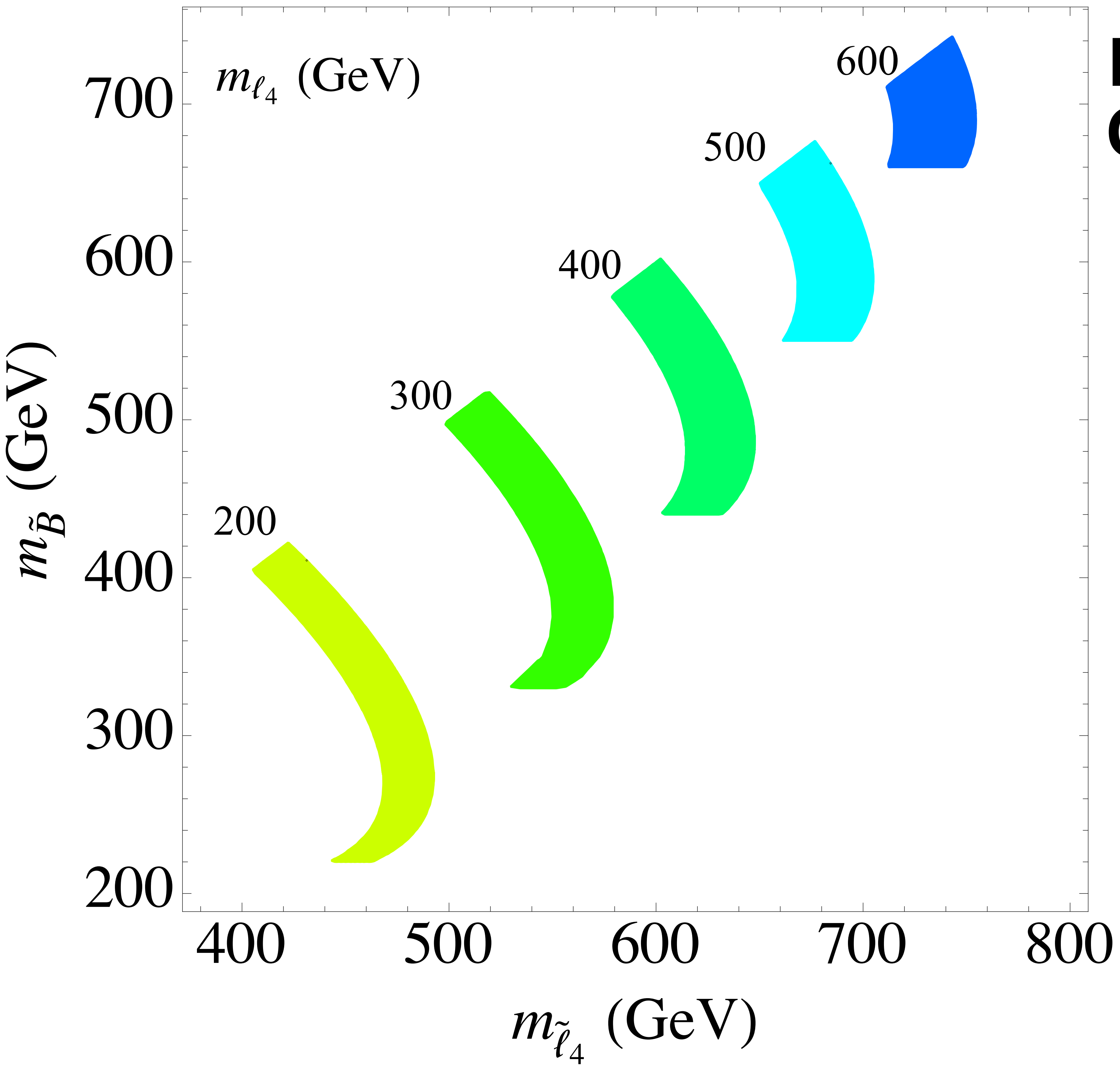


Relic Density Bands
QUE Model

$$\Omega_{\tilde{B}} = 0.12 \pm 0.012$$

MA & J. L. Feng [1510.06089]

Relic Density

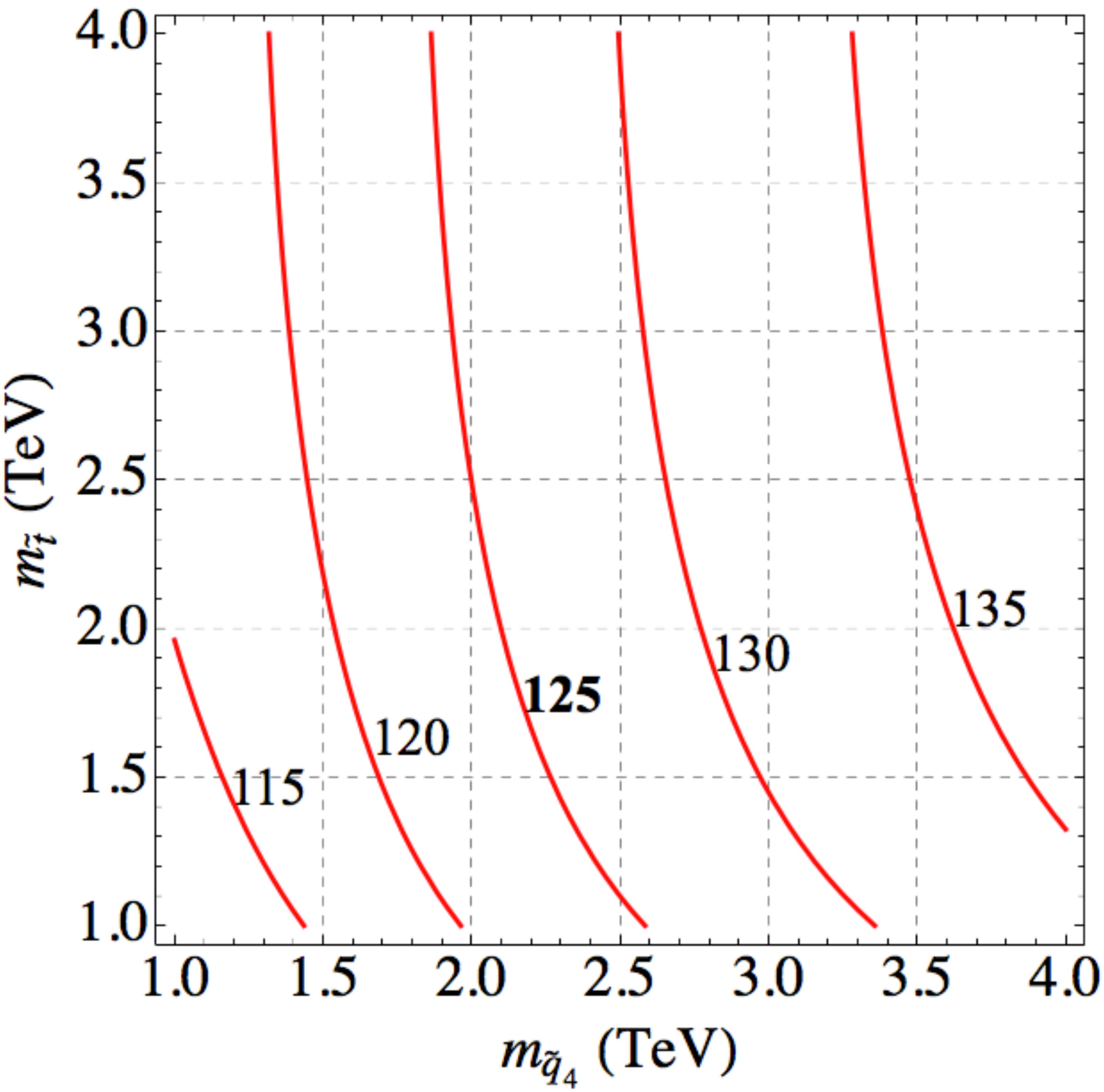


Relic Density Bands
QDEE Model

$$\Omega h^2 = 0.12 \pm 0.012$$

MA & J. L. Feng [1510.06089]

Higgs Mass



$$m_{t_4} = 1 \text{ TeV}$$

Chosen to:

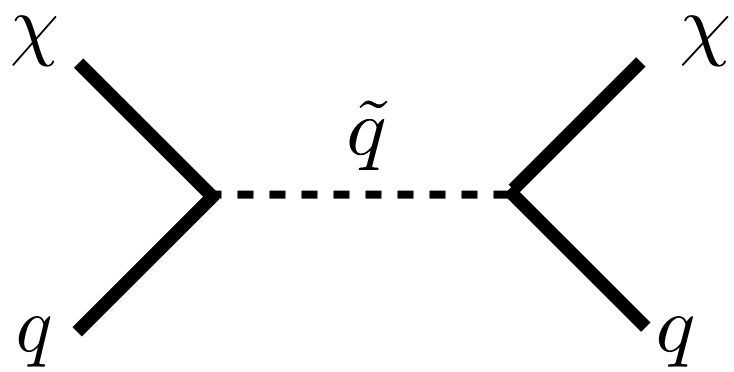
1. Avoid direct t' searches (> 790 GeV)
2. Satisfy EW and Higgs bounds

MA & J. L. Feng [1510.06089]

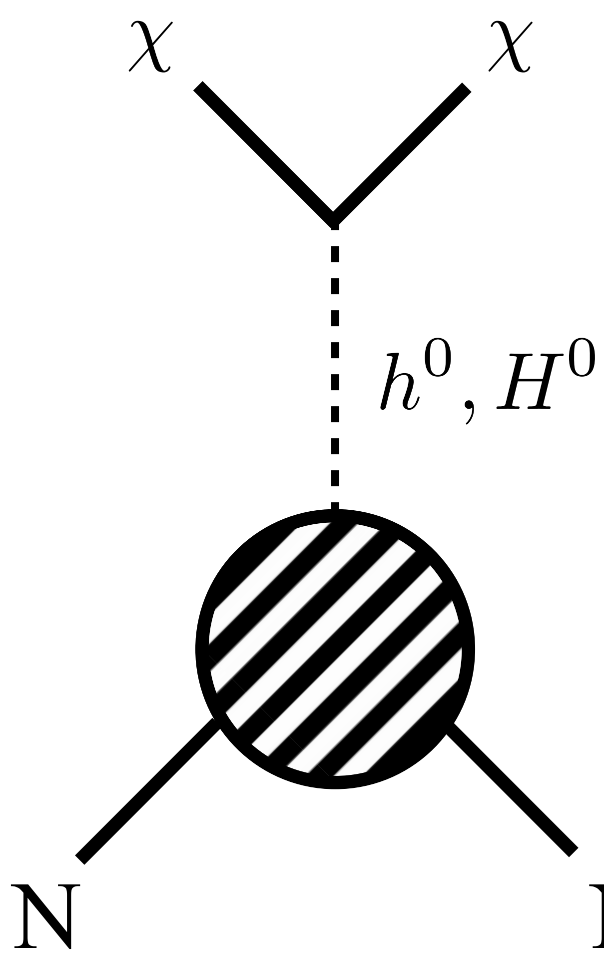
How do we test this?

Direct Detection

Effective Neutralino-Nucleon Coupling



Suppressed by squark masses

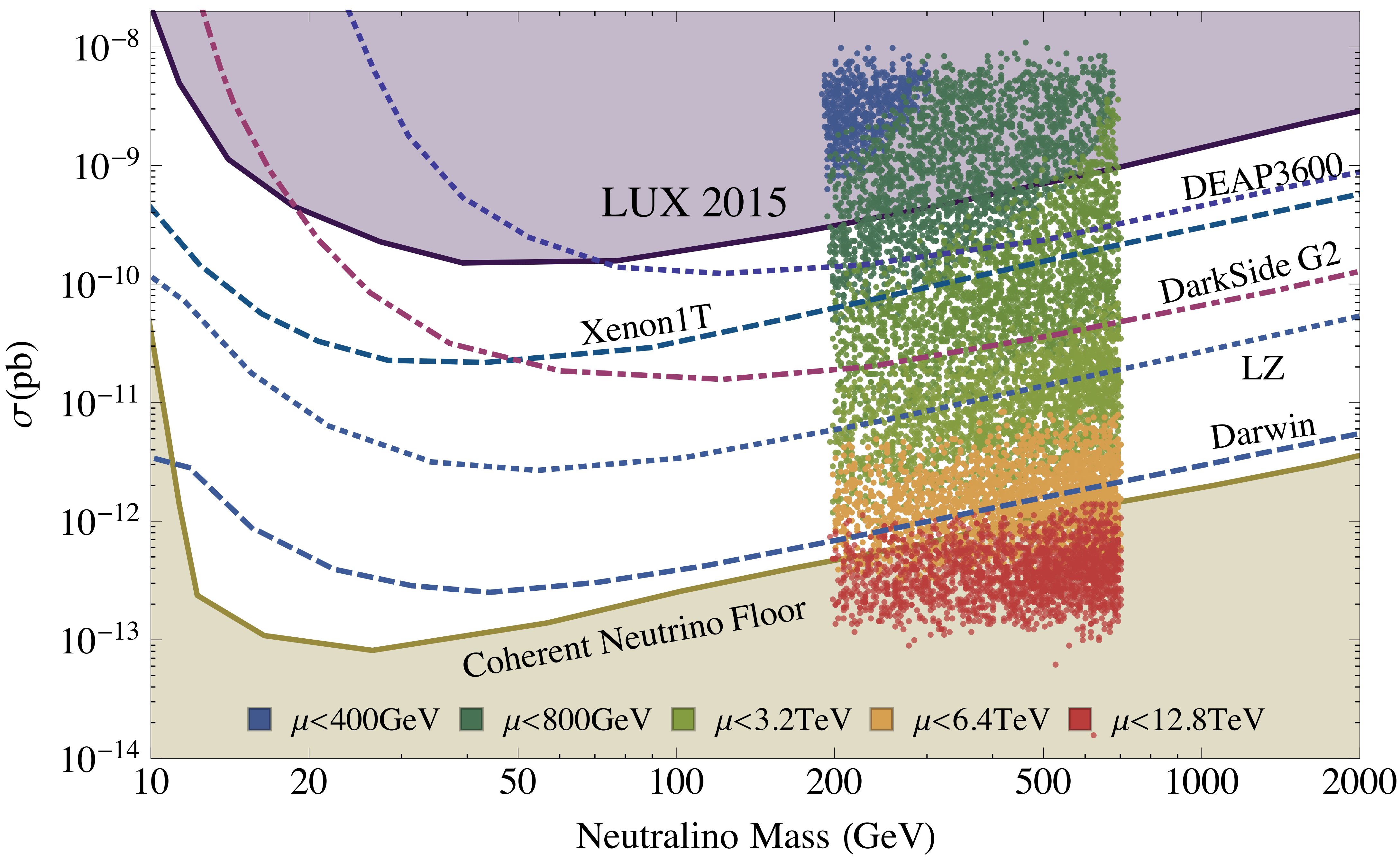


Suppressed by Yukawas and Higgsino fraction

Direct Detection

Spin-Independent

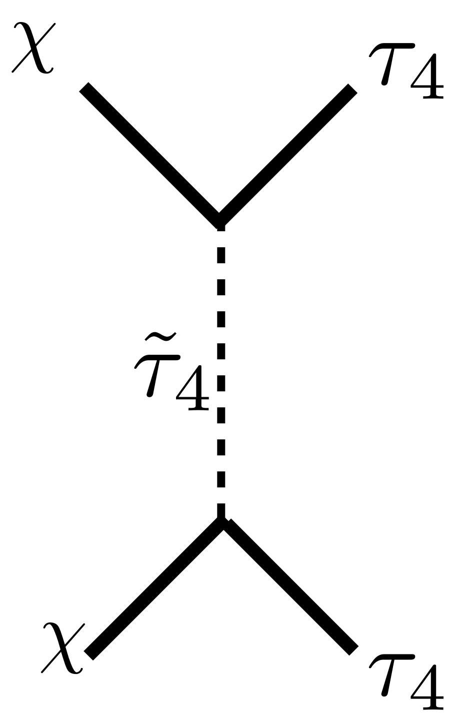
microOMEGAs



MA, J. L. Feng, S. Iwamoto, & B. Lillard [1608.00283]

Indirect Detection

Vector-like lepton decays



$$\tau_4 \to W\nu,\ Z\ell,\ h\ell$$

- → Pions → Photons
- → Positrons
- → Neutrinos

$$\langle \sigma v \rangle = \frac{g_Y^4 Y_L^2 Y_R^2}{32\pi} \frac{m_f^2}{m_{\tilde{B}}} \frac{\sqrt{m_{\tilde{B}}^2 - m_f^2}}{\left(m_{\tilde{B}}^2 + m_{\tilde{f}}^2 - m_f^2\right)^2}$$

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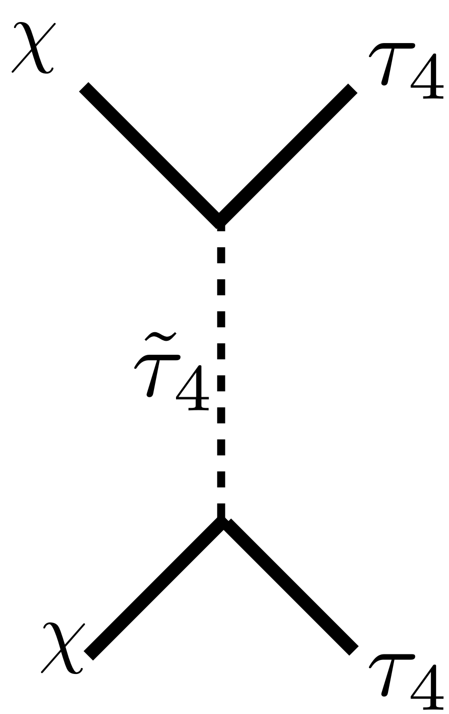

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→ Pions → Photons

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$$\Gamma(\tau_{4,5} \to W\nu_\ell) = \frac{\epsilon^2}{32\pi} m_{\tau_{4,5}} r_W (1 - r_W)^2 (2 + 1/r_W)\ ,$$

$$\Gamma(\tau_{4,5} \to Z\ell) = \frac{\epsilon^2}{64\pi} m_{\tau_{4,5}} r_Z (1 - r_Z)^2 (2 + 1/r_Z)\ ,$$

$$\Gamma(\tau_{4,5} \to h\ell) = \frac{\epsilon^2}{64\pi} m_{\tau_{4,5}} (1 - r_h)^2\ ,$$

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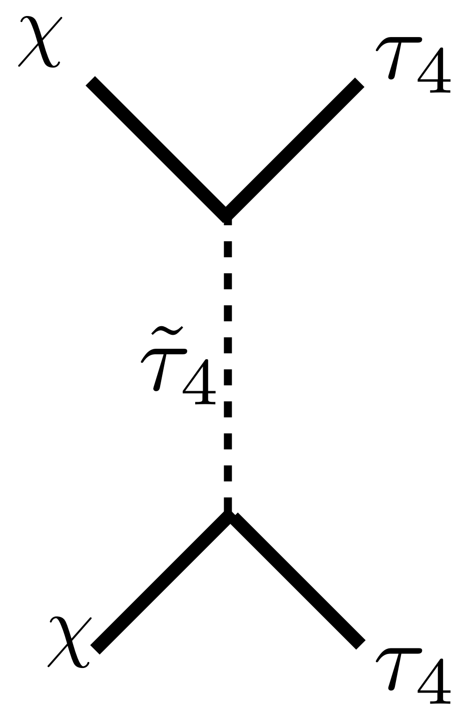
$$r_X = m_X^2 / m_{\tau_{4,5}}^2$$

$$X = W, Z, h;\ \ell = e,\ \mu,\ \tau$$

Indirect Detection

Vector-like lepton decays



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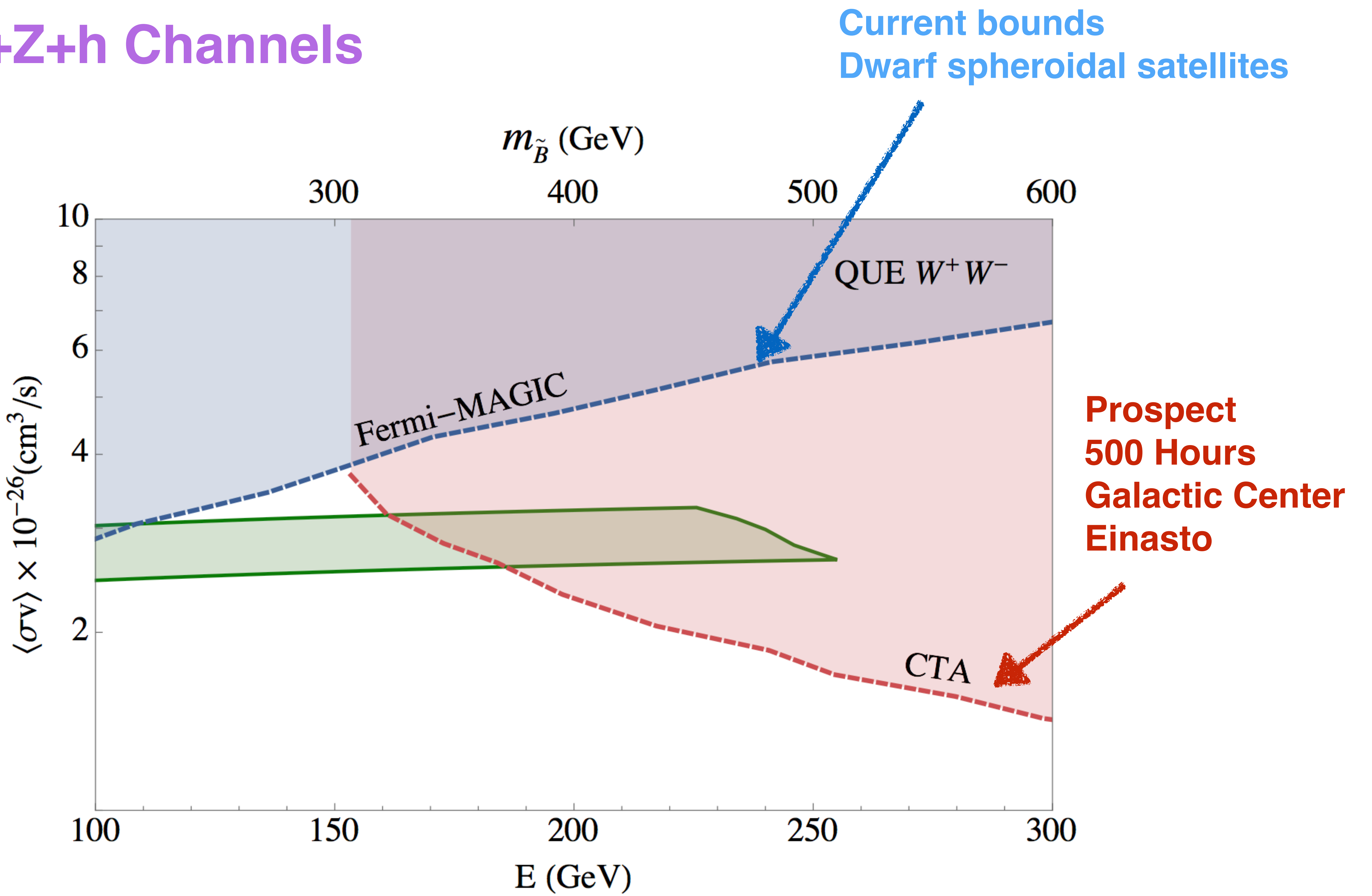
$m_{\tau_{4,5}} \gg m_W, m_Z, m_h \Rightarrow$ BR(Wν):BR(Zl):BR(hl) = 2:1:1

Indirect Detection

W+Z+h Channels



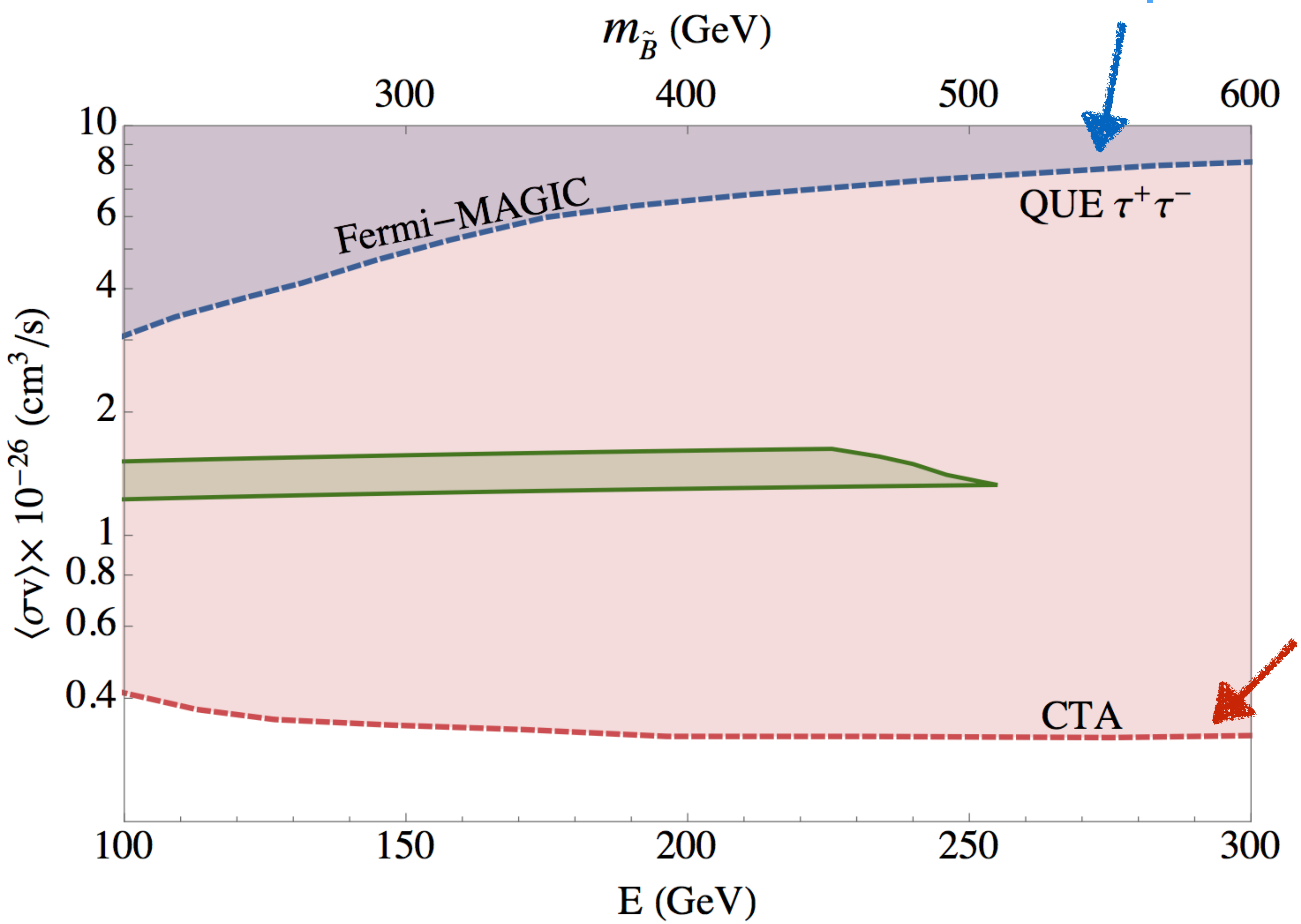
MA, J. L. Feng, S. Iwamoto, & B. Lillard [1608.00283]

Indirect Detection

Tau Channel

Assuming tau mixings only

Current bounds
Dwarf spheroidal satellites



Prospect
500 Hours
Galactic Center
Einasto

MA, J. L. Feng, S. Iwamoto, & B. Lillard [1608.00283]

Collider Searches

Strategy A: Long Lived Charged Particles

CMS and ATLAS searches place stringent limits from Run 1 data (7-8 TeV, 20 fb^{-1})

QUE	$m_{\ell_4} > 574\ GeV$	$m_{\tilde{\ell}_4} > 410\ \mathrm{GeV}$
QDEE	$m_{\ell_4} > 650\ \mathrm{GeV}$	$m_{\tilde{\ell}_4} > 470\ \mathrm{GeV}$

CMS [1305.0419]
CMS [CMS-PAS-EXPO-15-010]
ATLAS [1411.6795]

J. L. Feng, S. Iwamoto, Y. Shadmi, & S. Tarem [1505.02996]

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CMS [1305.0419]
CMS [CMS-PAS-EXPO-15-010]
ATLAS [1411.6795]

For intermediate decay lengths

- **Current limits are weaker**
- **Run 3 (14 TeV, 300 fb^{-1}) is expected to explore sleptons up to 800 GeV**

J. L. Feng, S. Iwamoto, Y. Shadmi, & S. Tarem [1505.02996]

Collider Searches

Strategy B: VL Searches

Electron and muon mixing:

QUE model		$300\,\text{fb}^{-1}$	$1000\,\text{fb}^{-1}$	$3000\,\text{fb}^{-1}$
95% CL exclusion	e-mixed	240^{+60} GeV	310^{+50}_{-60} GeV	350^{+40}_{-40} GeV
	μ-mixed	270^{+50} GeV	330^{+40}_{-60} GeV	370^{+40}_{-40} GeV
3σ discovery	e-mixed	0^{+250} GeV	250^{+60}_{-40} GeV	300^{+50}_{-50} GeV
	μ-mixed	0^{+280} GeV	260^{+70}_{-60} GeV	320^{+50}_{-40} GeV
5σ discovery	e-mixed	—	0^{+210} GeV	220^{+20}_{-20} GeV
	μ-mixed	—	0^{+210} GeV	240^{+20}_{-20} GeV

QDEE model		$300\,\text{fb}^{-1}$	$1000\,\text{fb}^{-1}$	$3000\,\text{fb}^{-1}$
95% CL exclusion	e-mixed	350^{+40}_{-50} GeV	390^{+40}_{-40} GeV	430^{+40}_{-40} GeV
	μ-mixed	360^{+40}_{-40} GeV	400^{+40}_{-40} GeV	440^{+40}_{-40} GeV
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5σ discovery	e-mixed	0^{+200} GeV	260^{+40}_{-50} GeV	310^{+20}_{-30} GeV
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@ 14 TeV

Complementary to indirect detection searches

Collider Searches

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@ 14 TeV

Complementary to indirect detection searches

Tau mixing:
Assuming 3000 fb^{-1} @ 13 TeV

QUE $m_{\tau_4} > 234$ GeV

QDEE $m_{\tau_4} > 264$ GeV

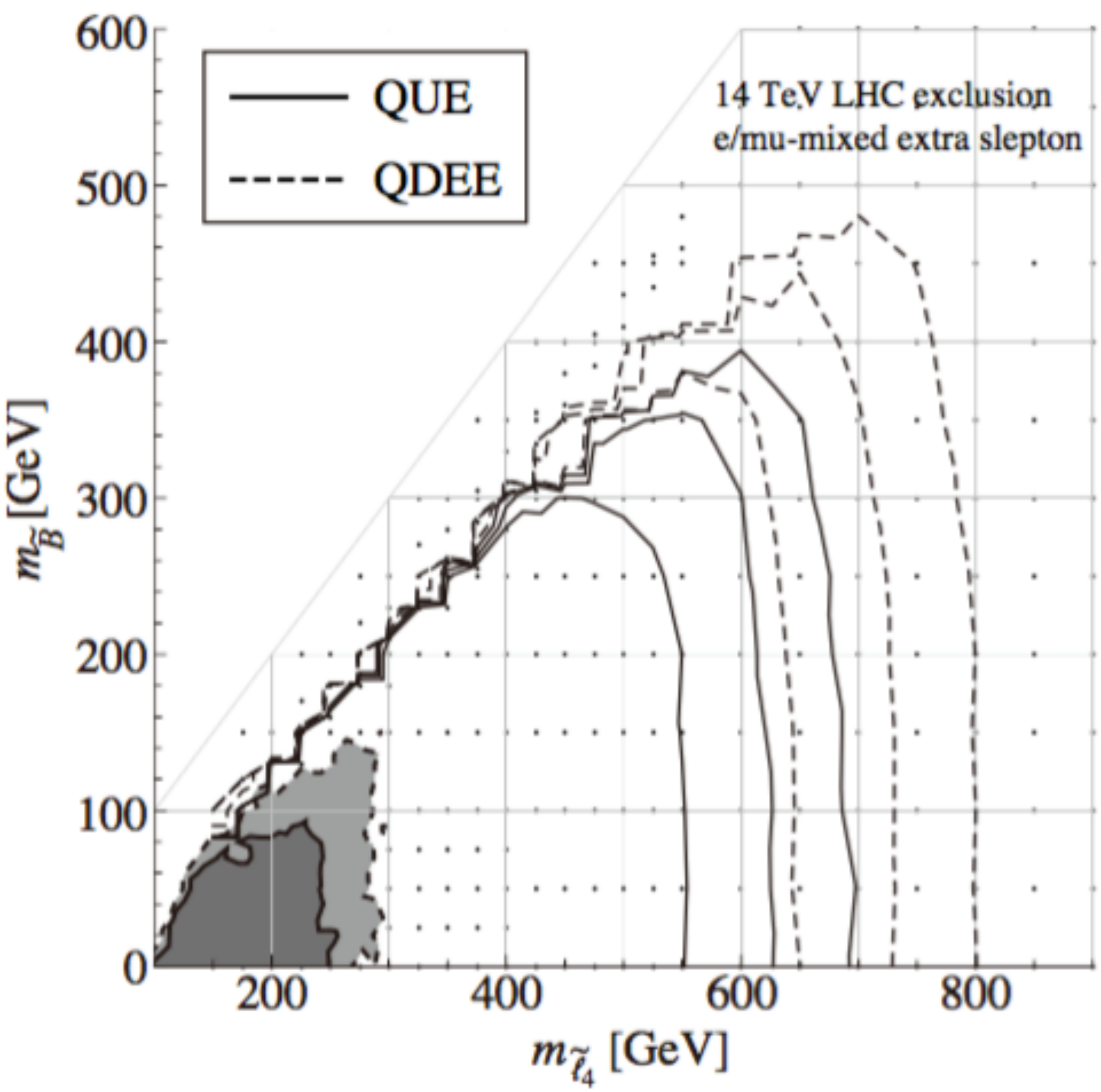
N. Kumar & S. P. Martin [1510.03456]

Collider Searches

Strategy C: Slepton Searches

Only e and mu mixing cases

$$pp \to \tilde{\tau}^+_{aM}\tilde{\tau}^-_{aM} \to (l^+B)(l^-B)$$



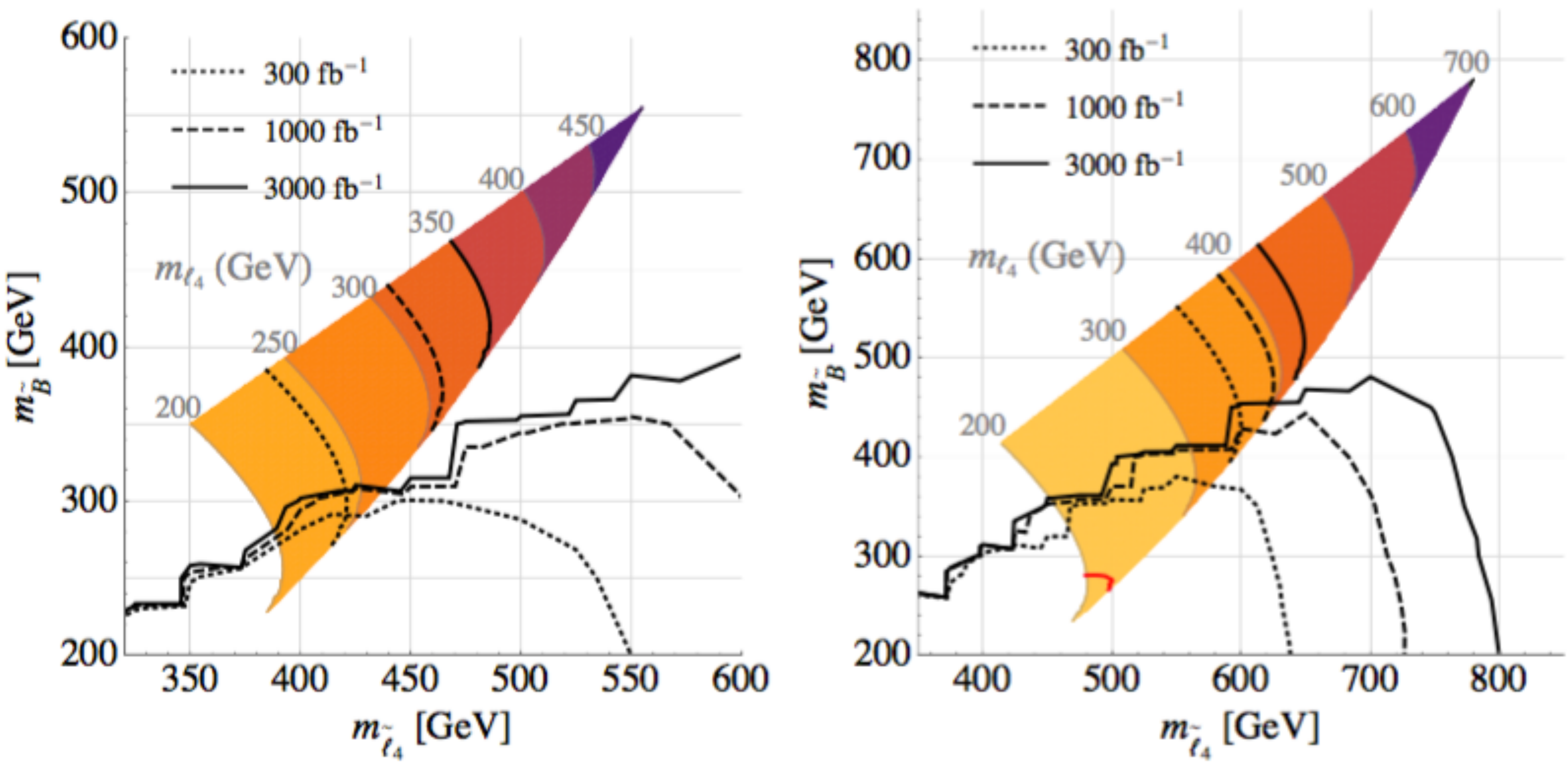
From left to right

- Current limits
- 14 TeV with
    - 300 fb^{-1}
    - 1000 fb^{-1}
    - 3000 fb^{-1}

ATLAS [1403.5294]
J. Eckel, M. J. Ramsey-Musolf, W. Shepherd, & S. Su [1408.2841]

Collider Searches
Summary

e-mixing (mu-mixing results similar)



Conclusion

- By supplementing the MSSM with 4th generation vector-like copies of Standard Model fermions we can:
  - Achieve the correct Higgs mass with less fine-tuning
  - Extend the mass range of allowed Bino dark matter
  - Preserve perturbative gauge coupling unification
- The number of such allowed models is heavily reduced by the requirement of gauge coupling unification
- The parameter space is projected to be comprehensively probed by a combination of LHC searches, direct detection and indirect detection.

Thanks!