MSSM$^{4G^{\mathrm{QUE}}}$

Reviving Bino Dark Matter with Vector-like 4th Generation Particles

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Based on 1510.06089 with Jonathan Feng
and 1606.xxxx ± 0001.0000 with Jonathan Feng, Sho Iwamoto and Benjamin Lillard

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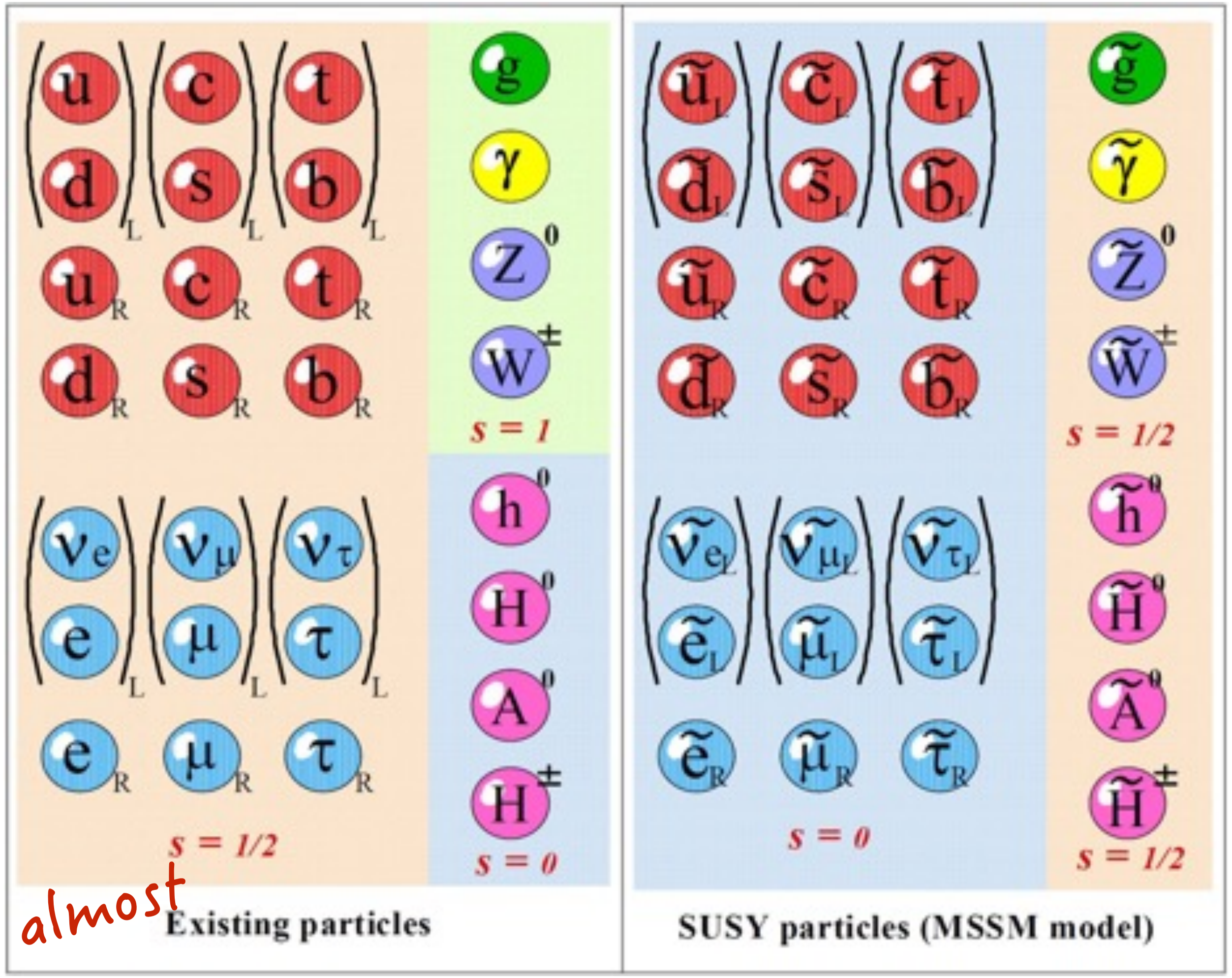
May 10, 2016

Minimal Supersymmetric Standard Model

Perks:

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



almost Existing particles

SUSY particles (MSSM model)

Credit: KEK

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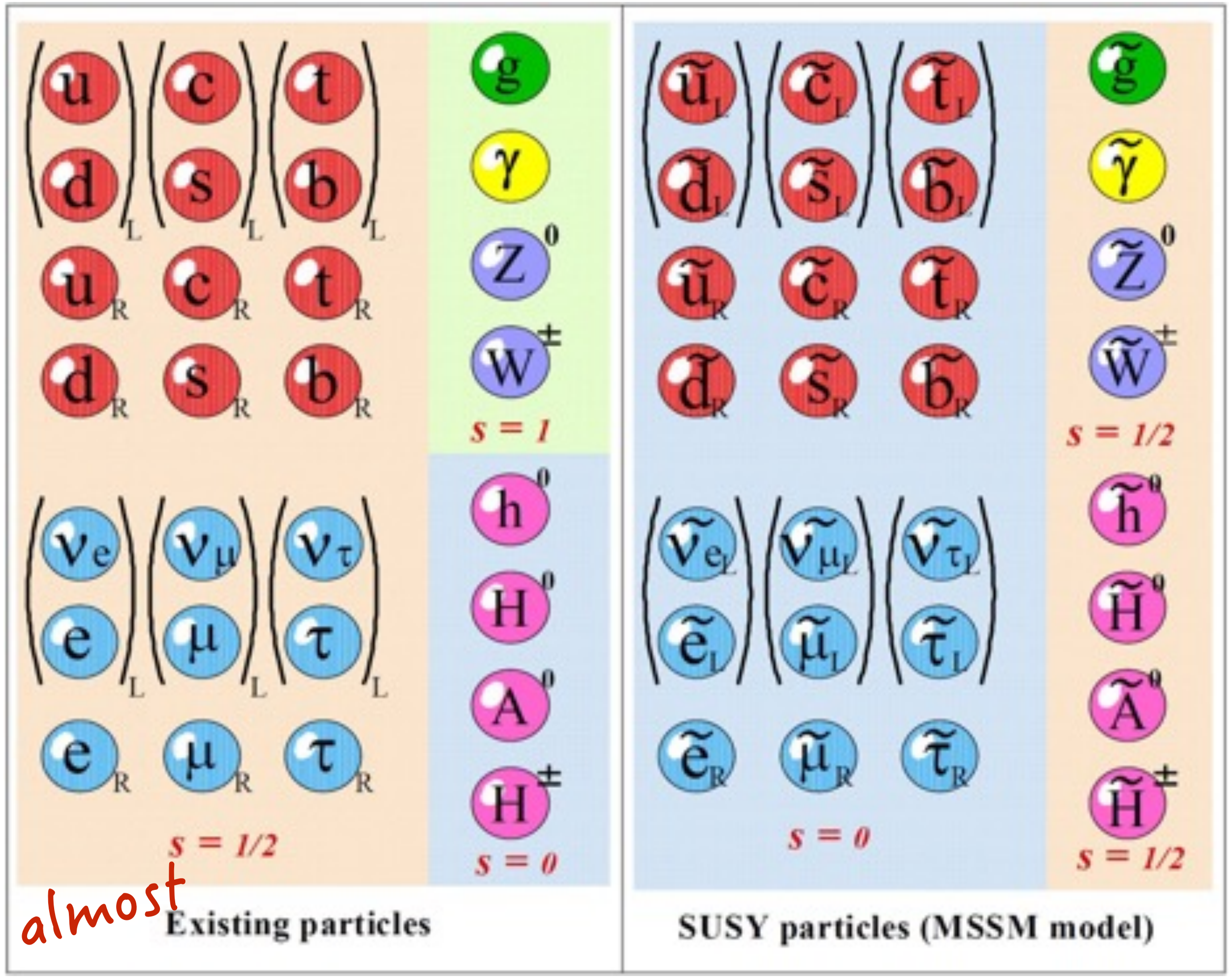

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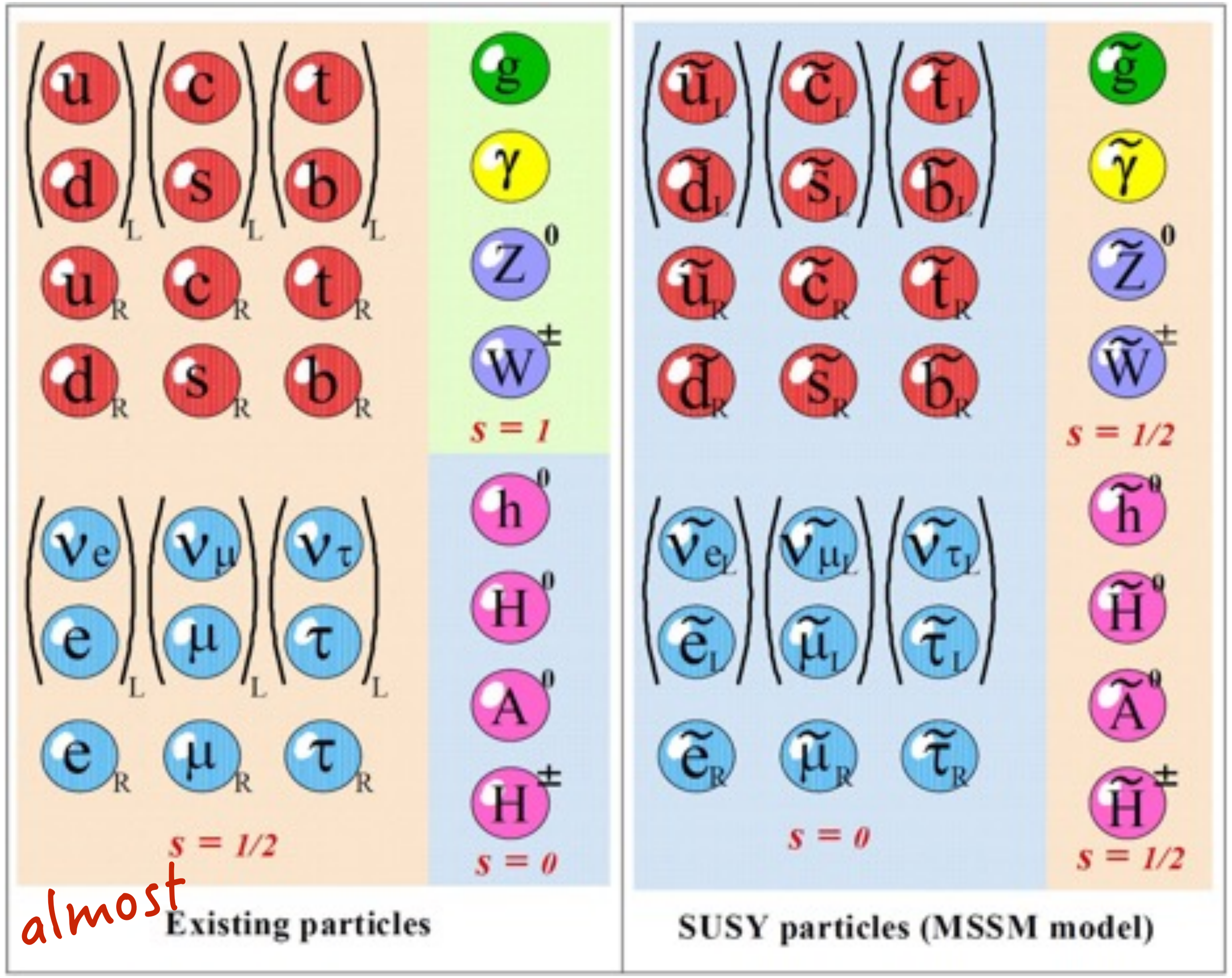

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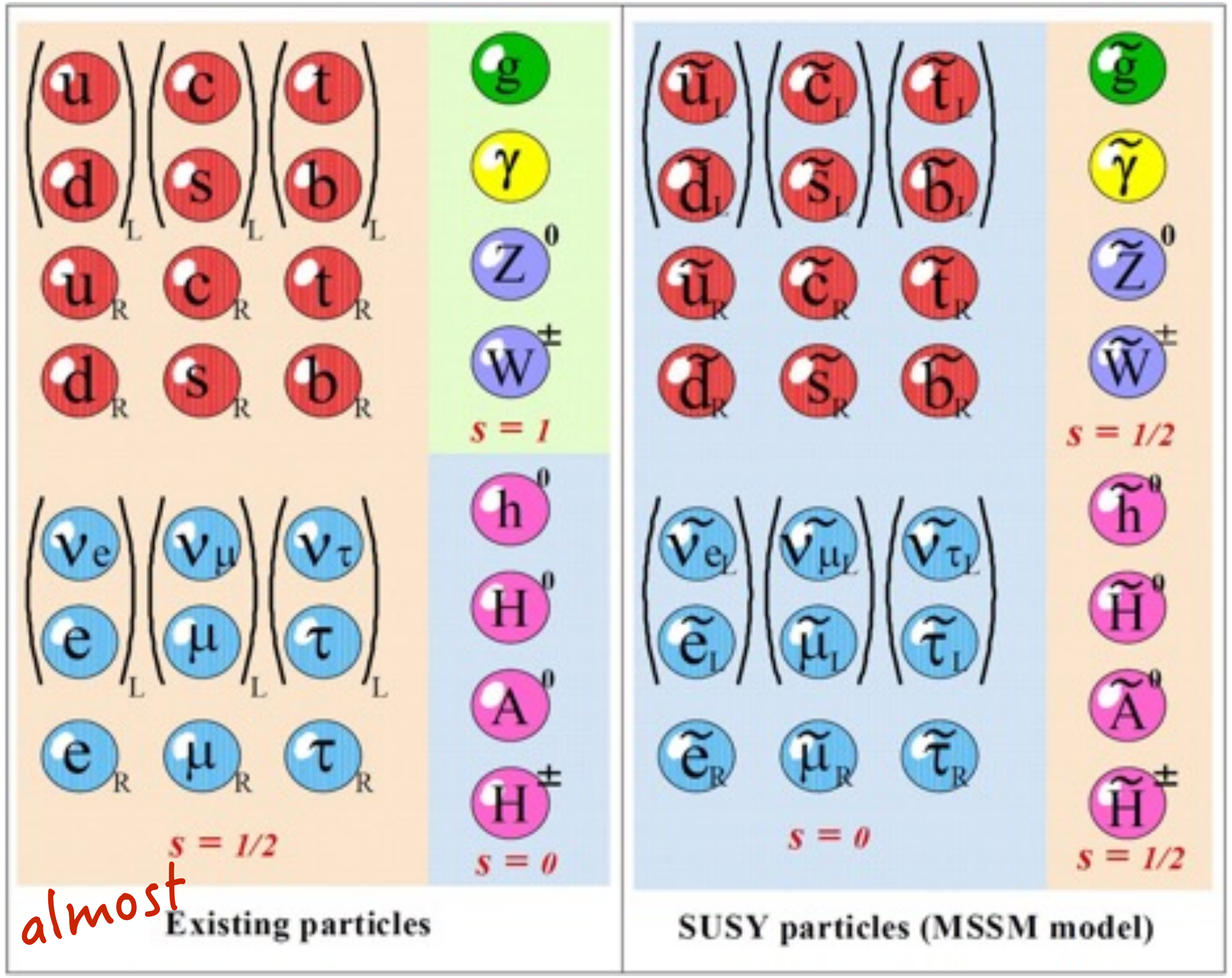

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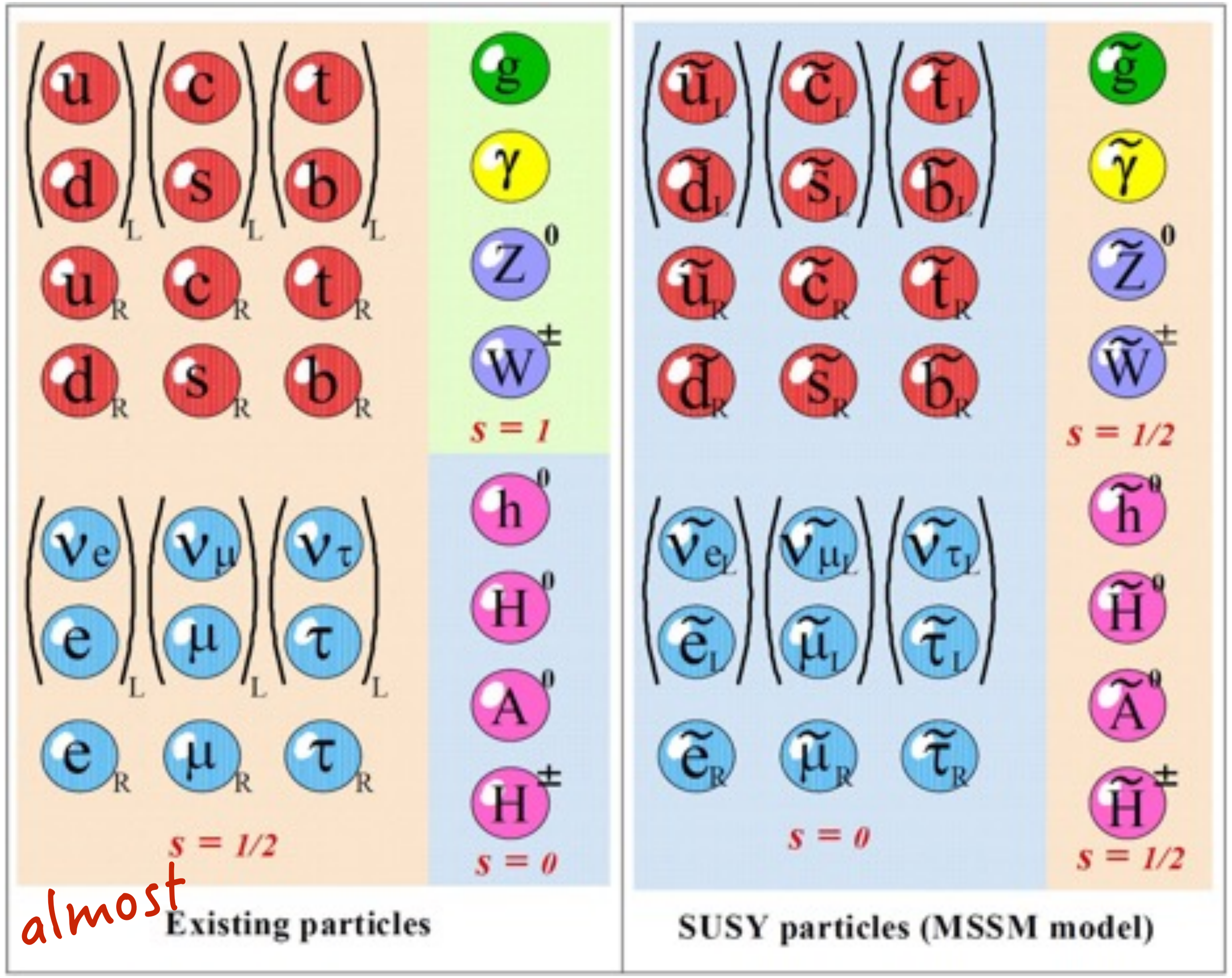

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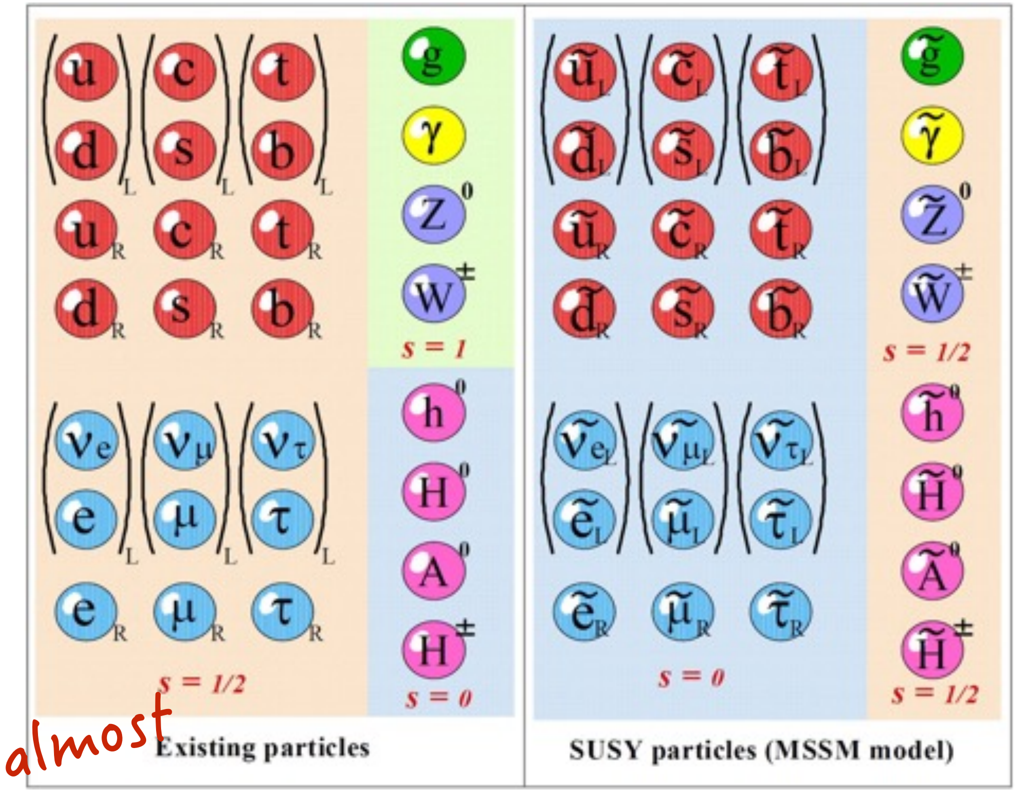
Problems:

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

- Binos need to be lighter than 300 GeV
- Such masses are disfavored

Minimal Supersymmetric Standard Model

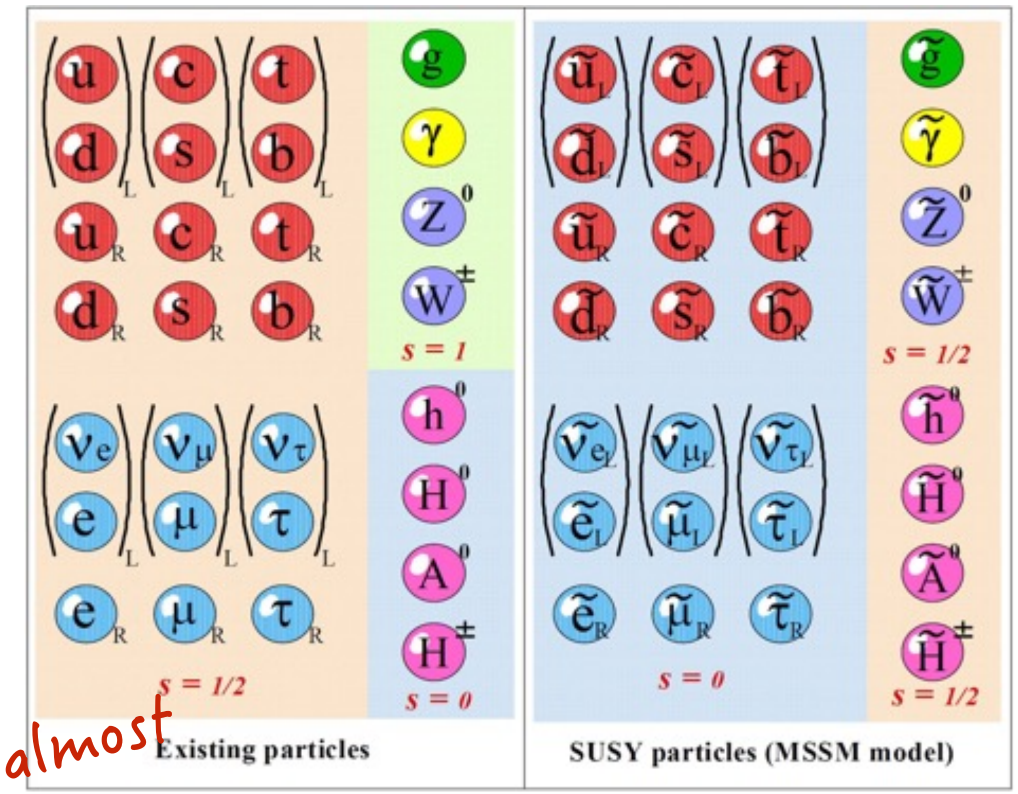


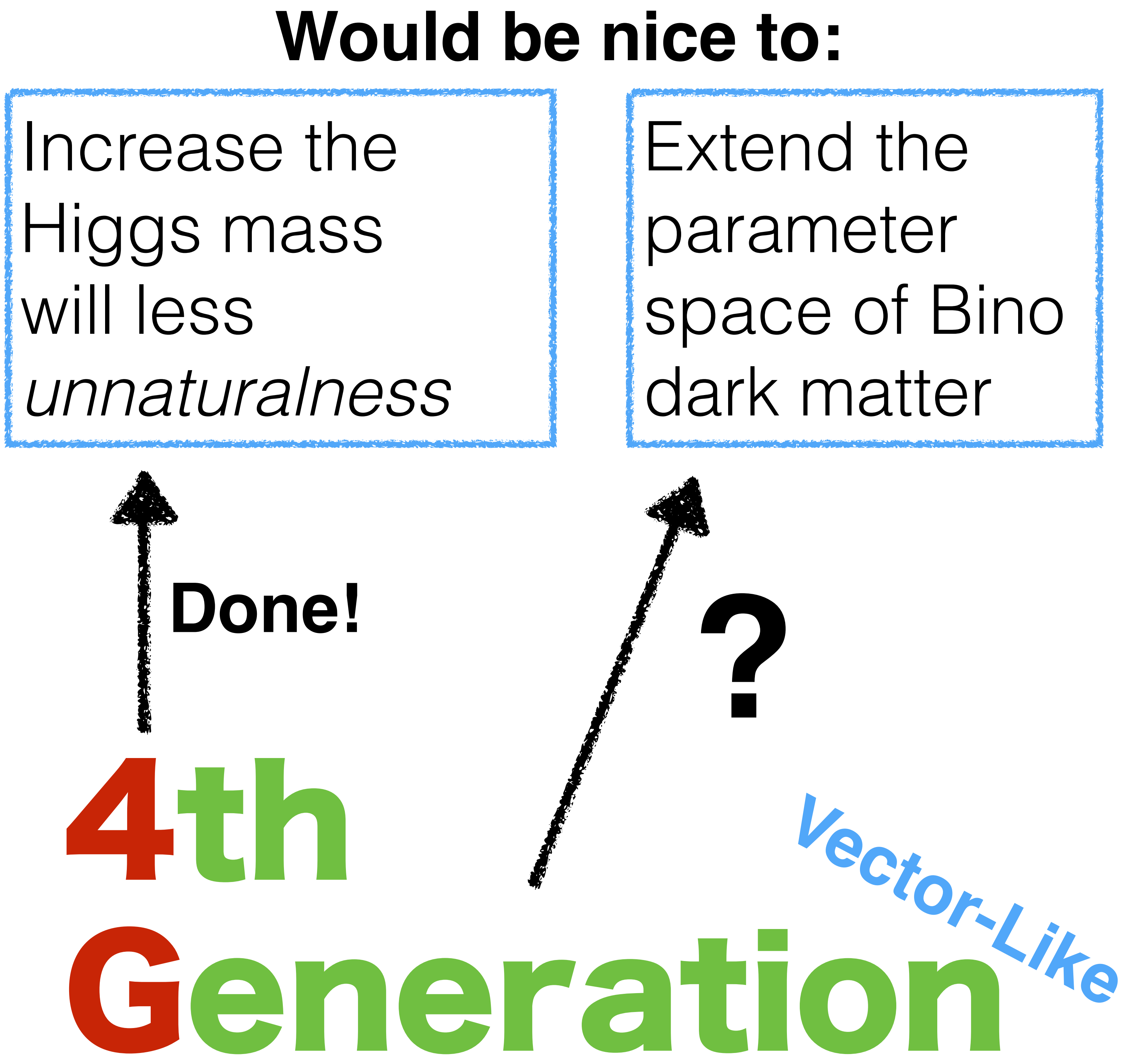
Would be nice to:

Increase the Higgs mass without too much fine tuning

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

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- To preserve gauge coupling unification, new fields must be added in full **SU(5)** multiplets: **1, 5, or 10**

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S. Martin arXiv: 0910.2732

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- Perturbativity up to the unification scale restricts us to either a **single 10** or up to **three 5**'s (and **any 1**'s)

S. Martin arXiv: 0910.2732

- Increasing the Higgs mass is difficult using **5**'s

and we are left with…

The QUE Model

Dirac fermions: T_4, B_4, t_4, τ_4

Complex scalars: $\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

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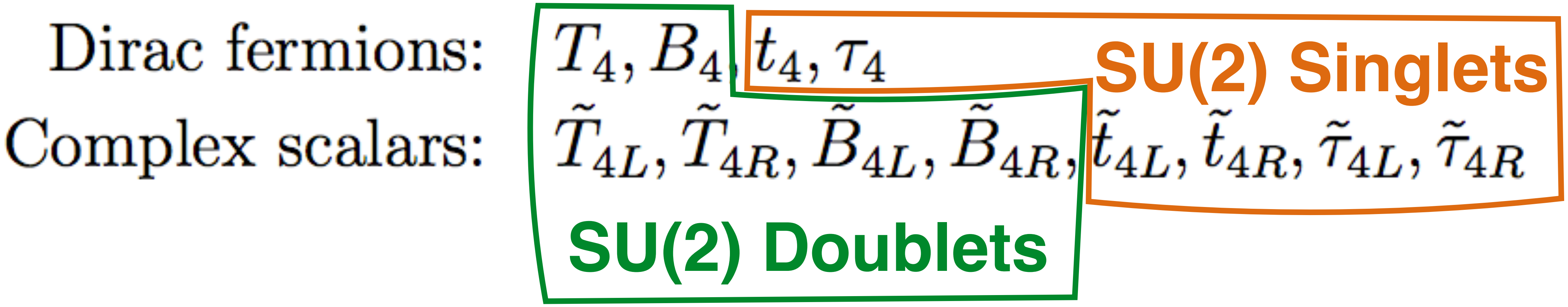

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SU(2) Singlets

SU(2) Doublets

actually we also have

The QDEE Model **Not an SU(5) multiplet**

Dirac fermions: $T_4, B_4, b_4, \tau_4, \tau_5$

Complex scalars: $\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{b}_{4L}, \tilde{b}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}, \tilde{\tau}_{5L}, \tilde{\tau}_{5R}$

SU(2) Singlets

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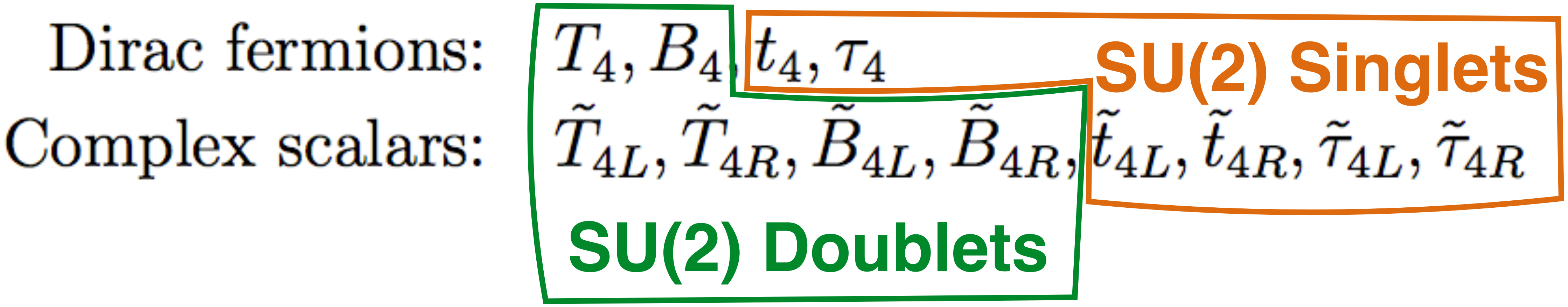
and we are left with…

The QUE Model



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SU(2) Singlets

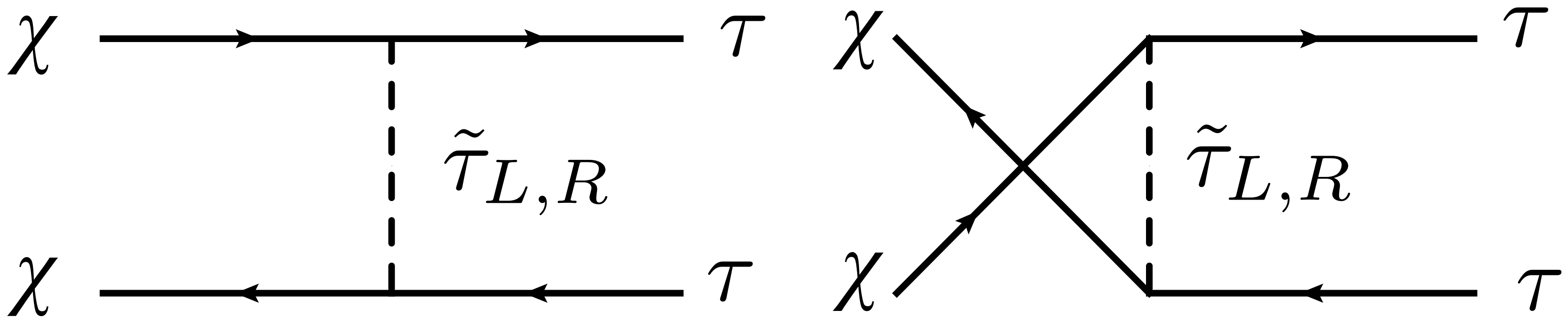
SU(2) Doublets

Minimize number of physical masses

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

Relic Density

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



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

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

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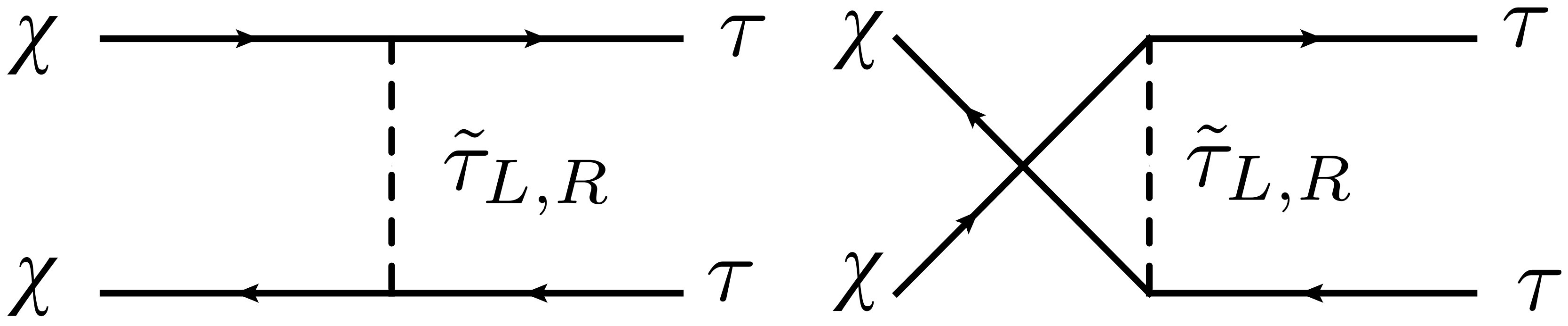

Maximal = 2 for right-handed leptons

$$
\begin{aligned}
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} \Big[17 m_f^8 - 2 m_f^6 \left(17 m_{\tilde{f}}^2 + 20 m_{\tilde{B}}^2\right) \\
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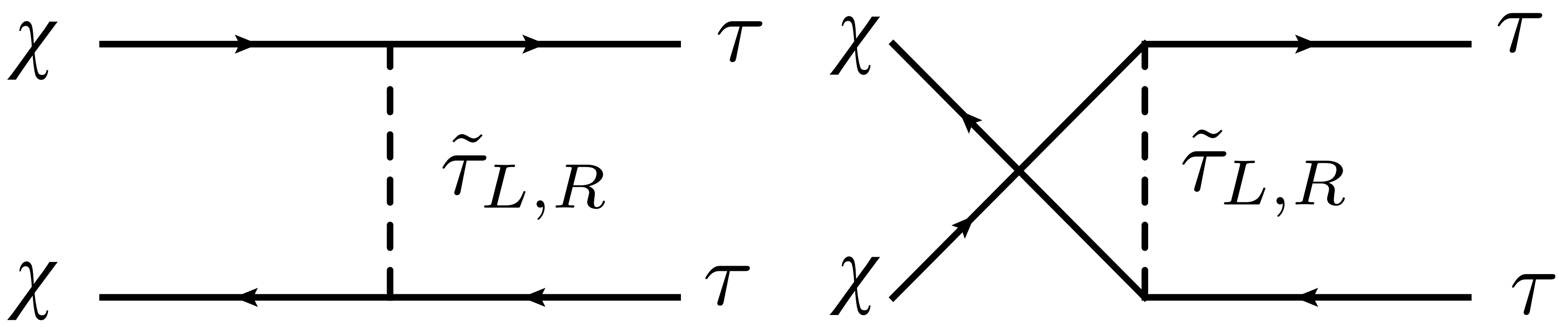

Maximal = 2 for right-handed leptons

Small in SM

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

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

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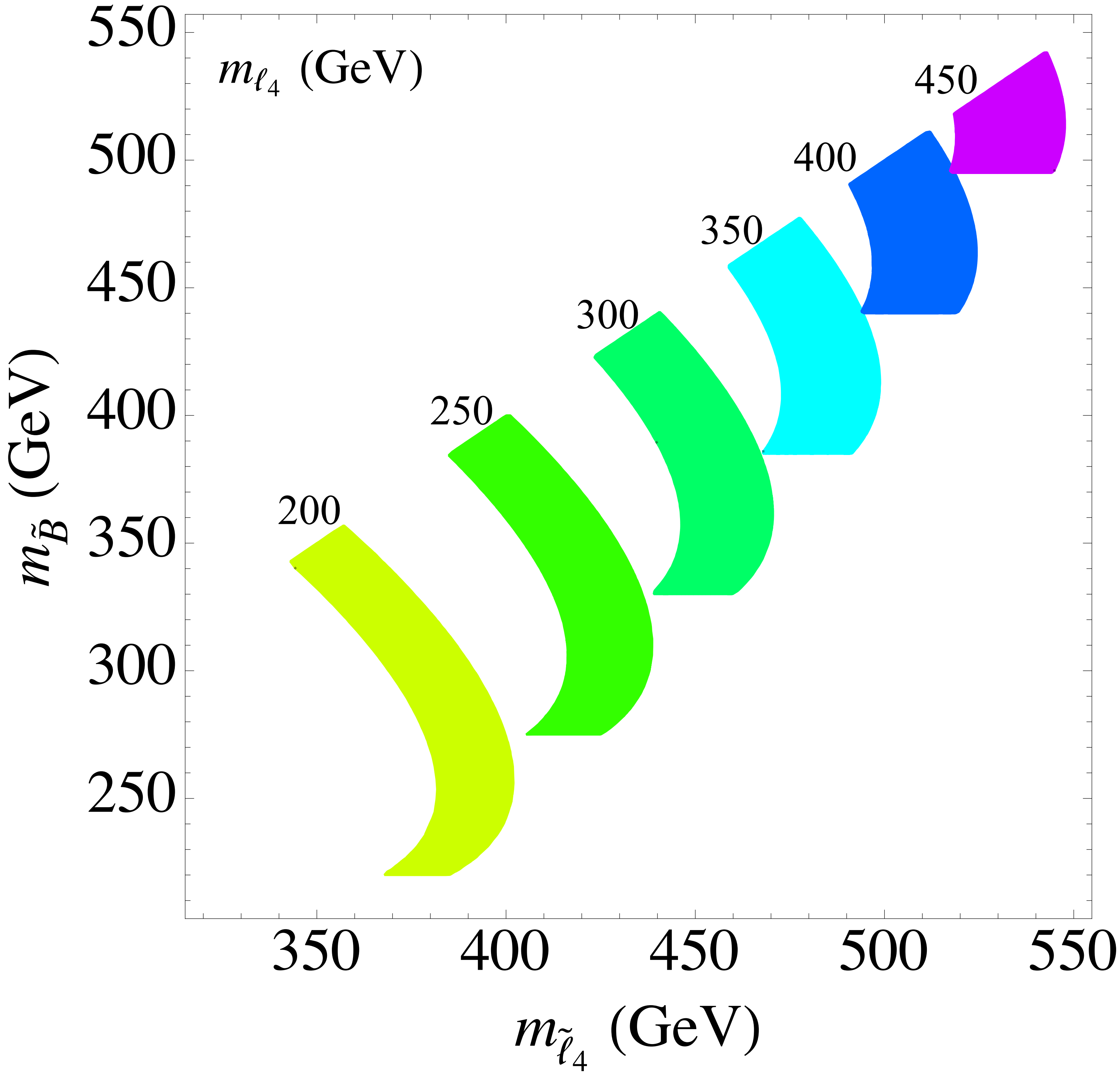
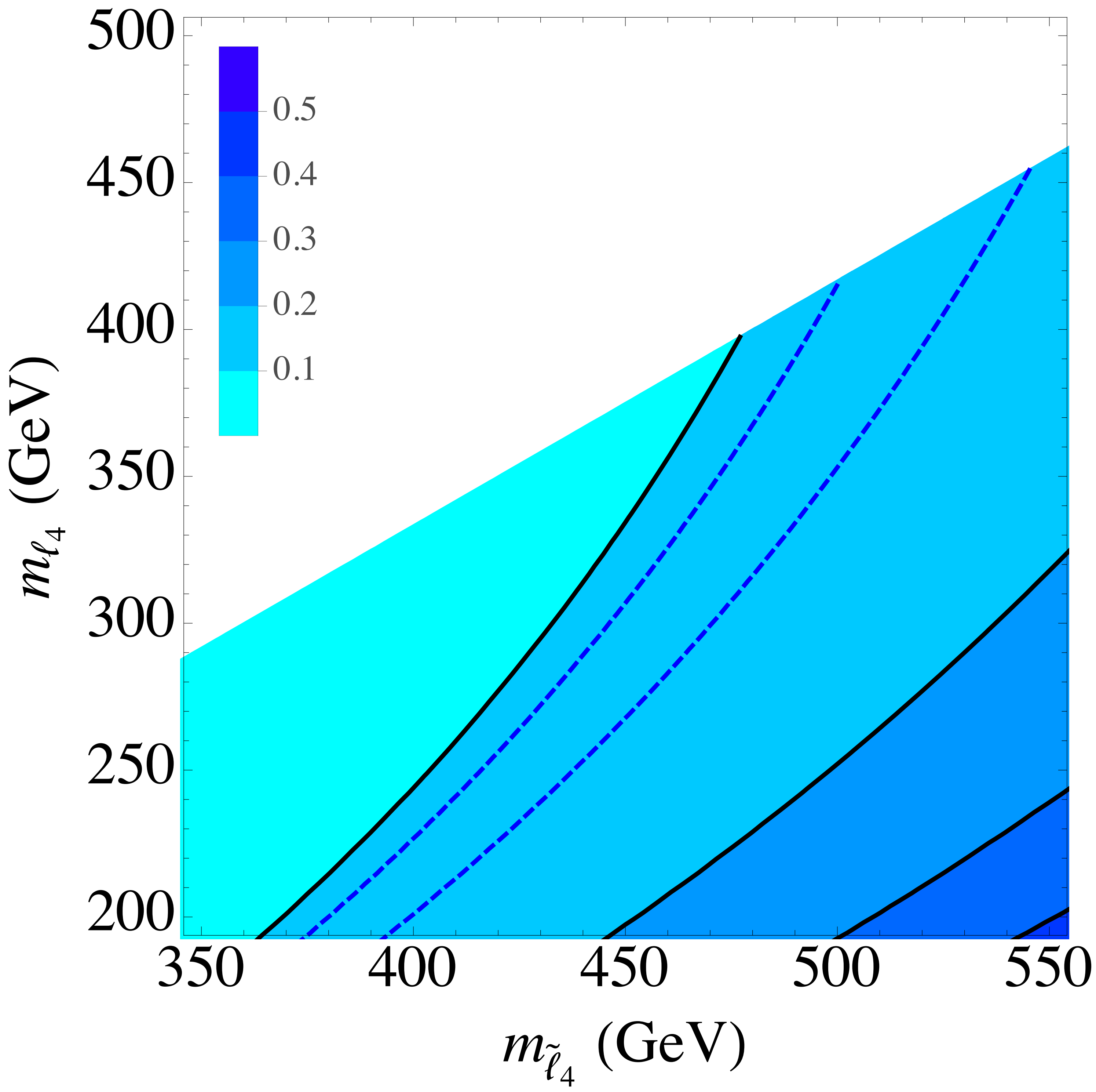


Relic Density Bands
QUE Model

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

Relic Density

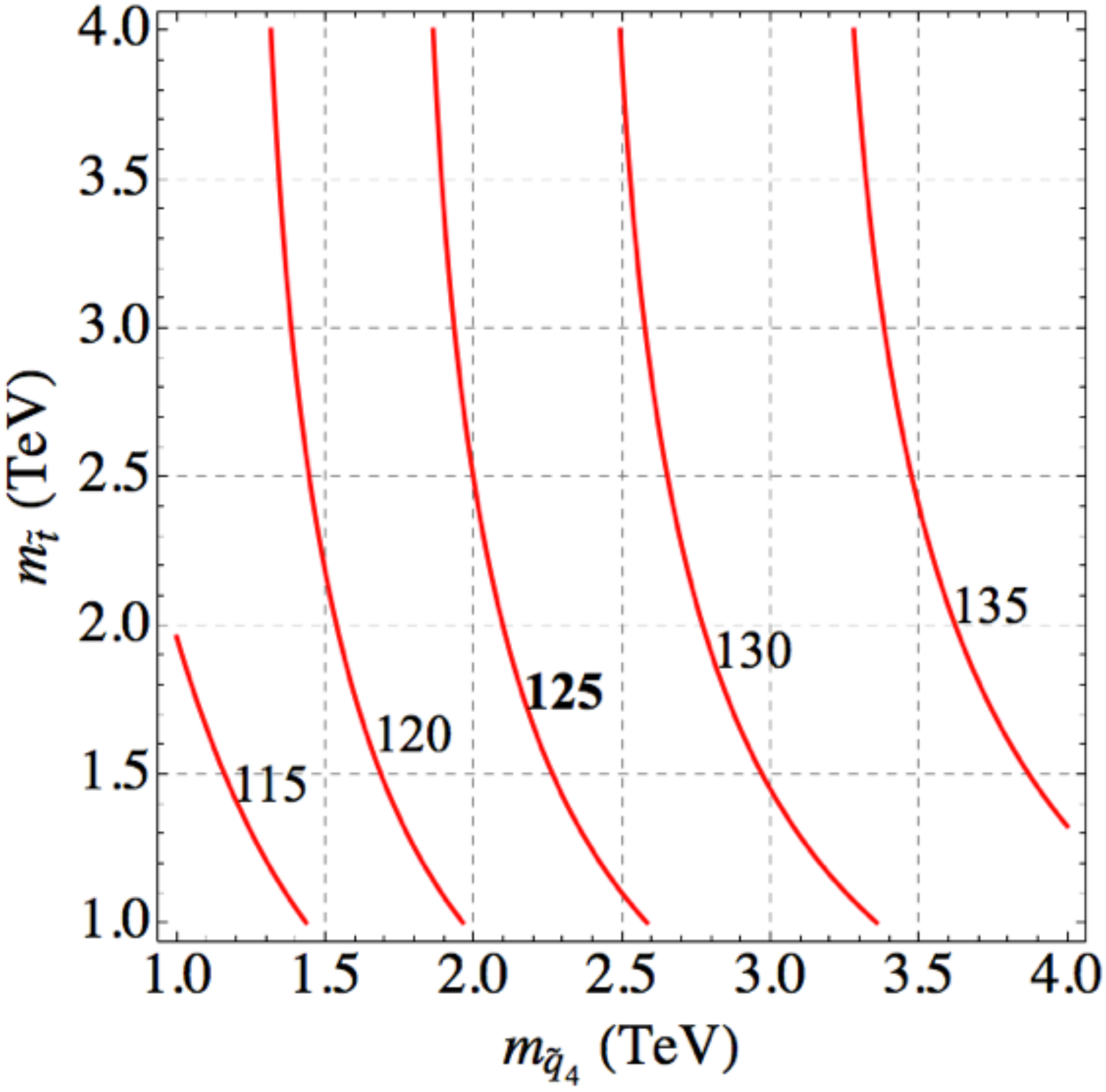


Relic Density Contours

QUE Model

$$m_{\tilde{B}} = 1.2 m_{\ell_4}$$

Higgs Mass



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

Chosen to:

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

How do we test this?

Collider Searches

Assuming tau mixings only

- **L**ong **L**ived **C**harged **P**article Searches:
  - Applicable for small mixings $\epsilon \lesssim 10^{-8}$
  - We use limits from:
    - ATLAS; 8 TeV, 19.8 fb^{-1}
    - CMS; 7 TeV, 5 fb^{-1}; 8 TeV, 18.8 fb^{-1}

$$m_{\ell_4} > 574 \qquad \& \qquad m_{\tilde{\ell}_4} > 410\ \mathrm{GeV}$$

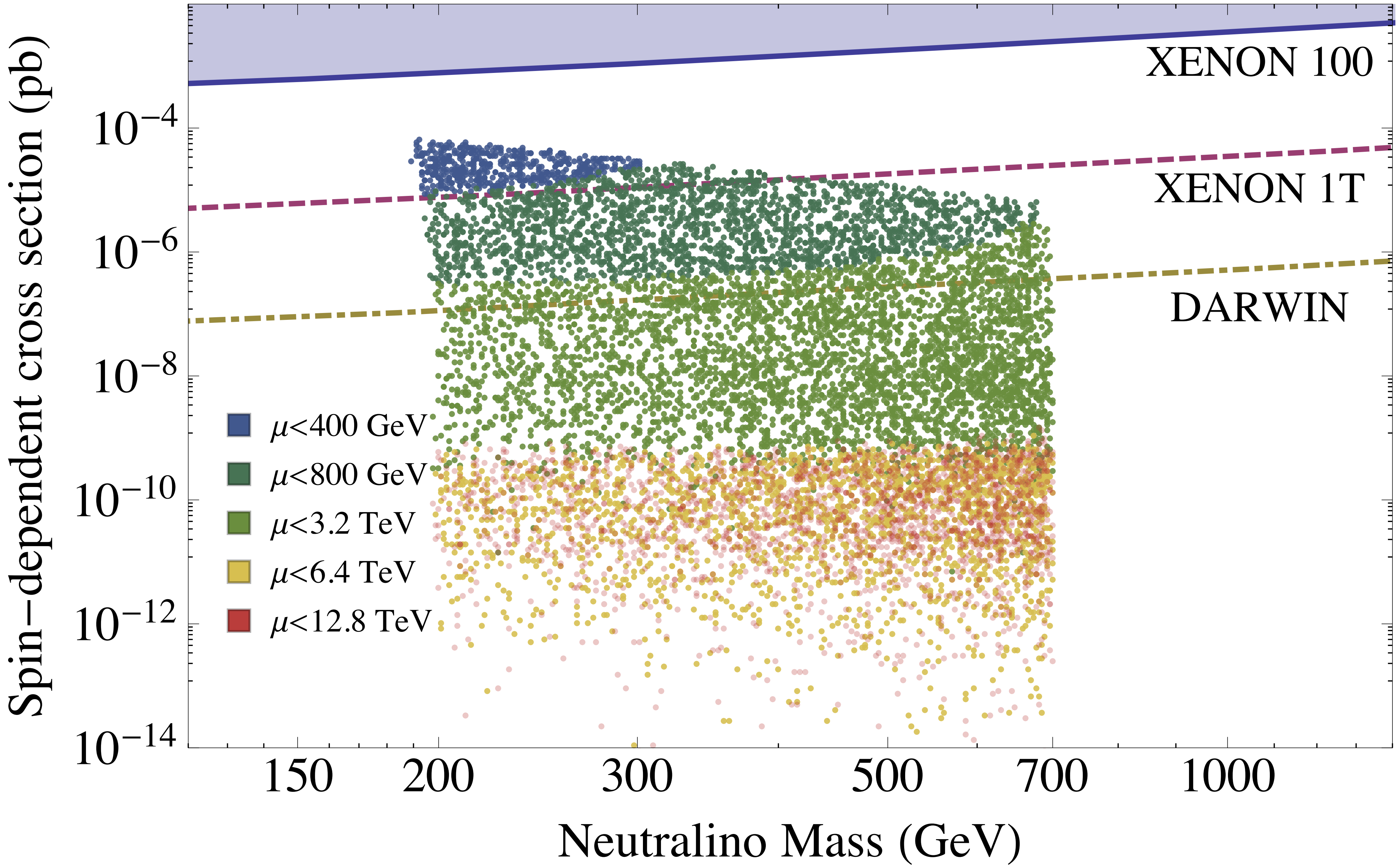
- Vector-Like Lepton Searches:
  - We adapt the analysis of N. Kumar and S. Martin 1510.03456
  - 13 TeV, 3000 fb^{-1}

$$m_{\ell_4} > 234\ \mathrm{GeV}$$

Direct Detection

Spin-Dependent

microOMEGAs



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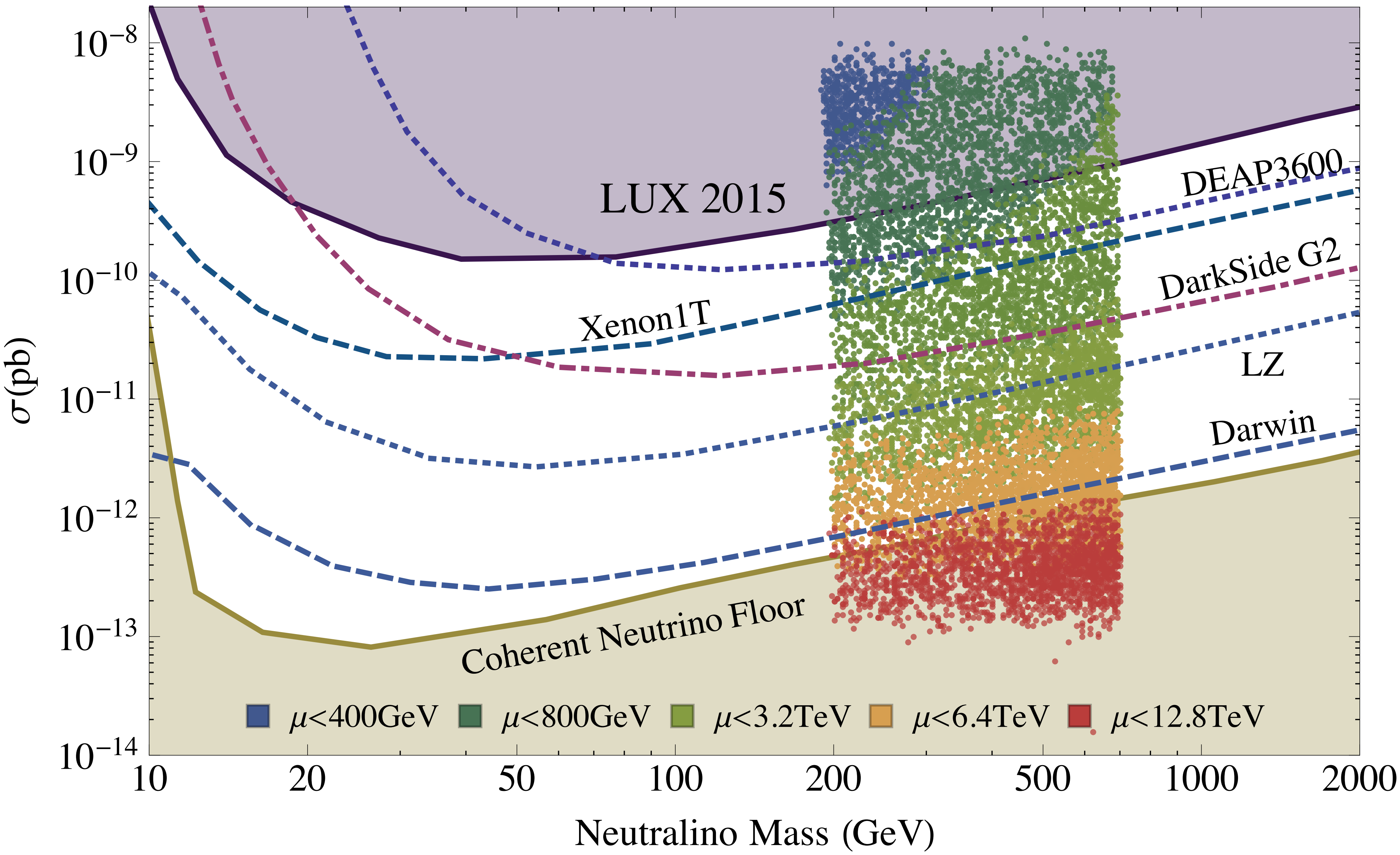
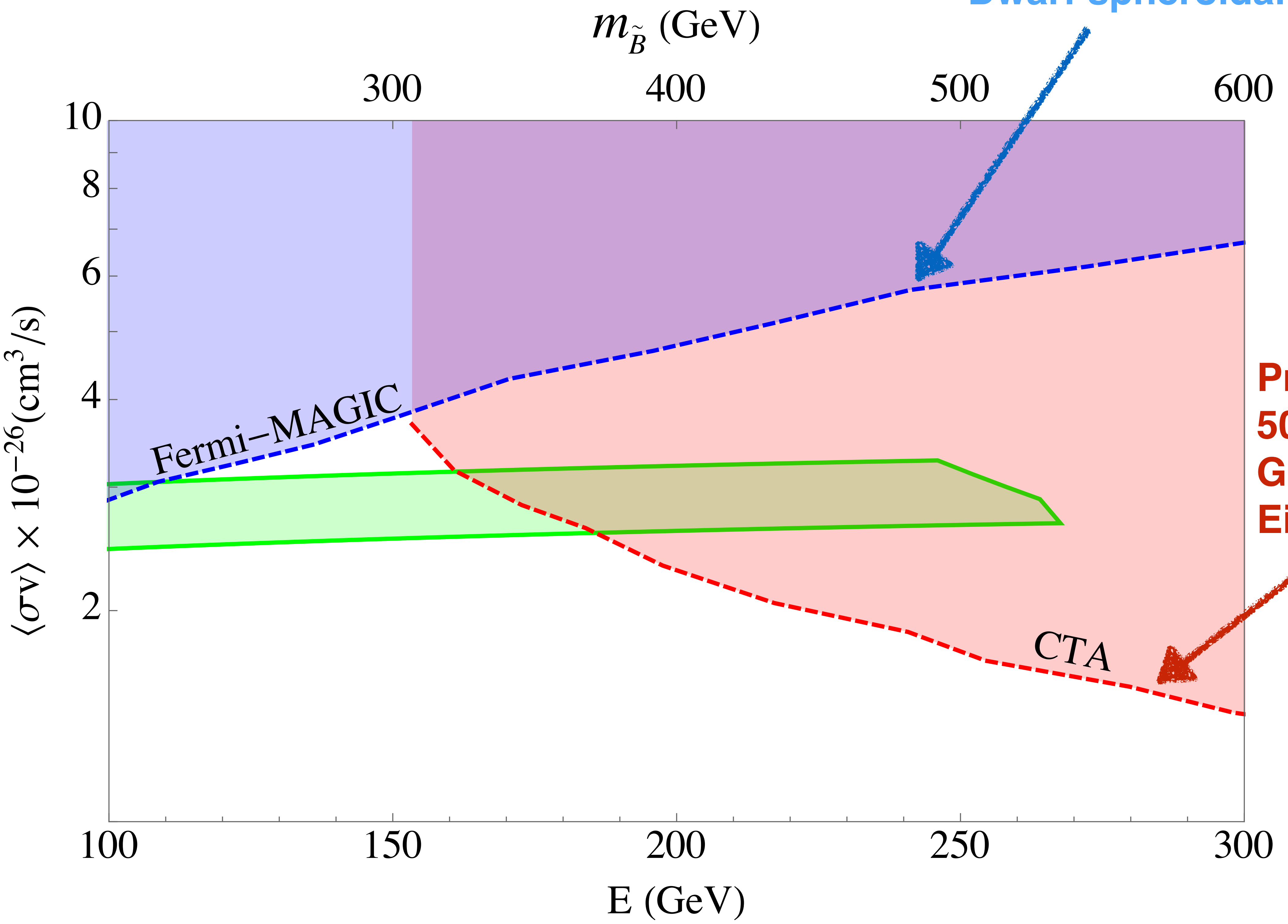


Indirect Detection

W+Z+h Channels



Current bounds
Dwarf spheroidal satellites

Prospect
500 Hours
Galactic Center
Einasto

Indirect Detection

Tau Channel

Assuming tau mixings only

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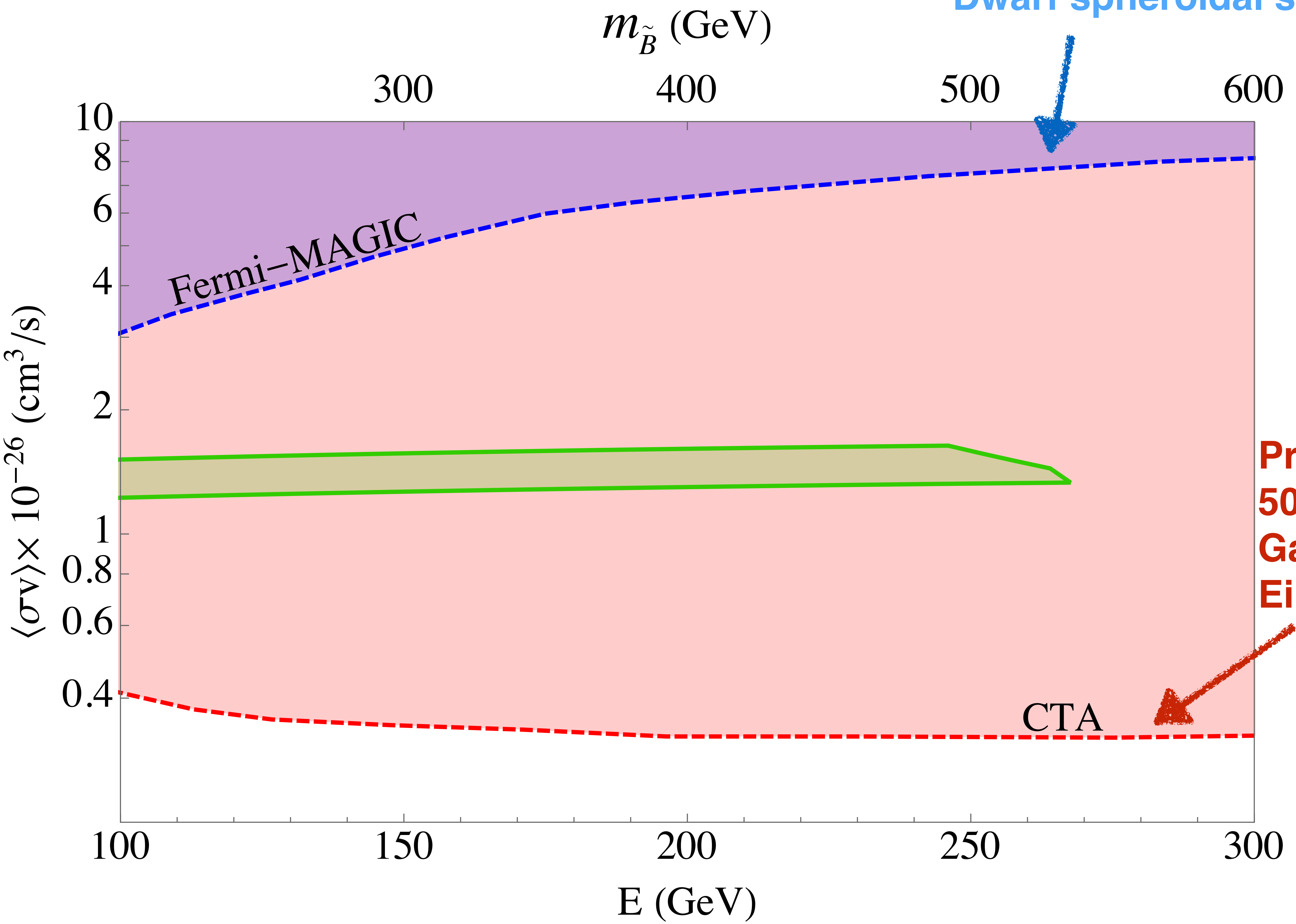

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Conclusion

- 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 bark matter
    - Preserve gauge coupling unification
- The number of such allowed models is heavily reduced by the requirement of gauge coupling unification
- The whole parameter space will (hopefully) be explored by future experiments

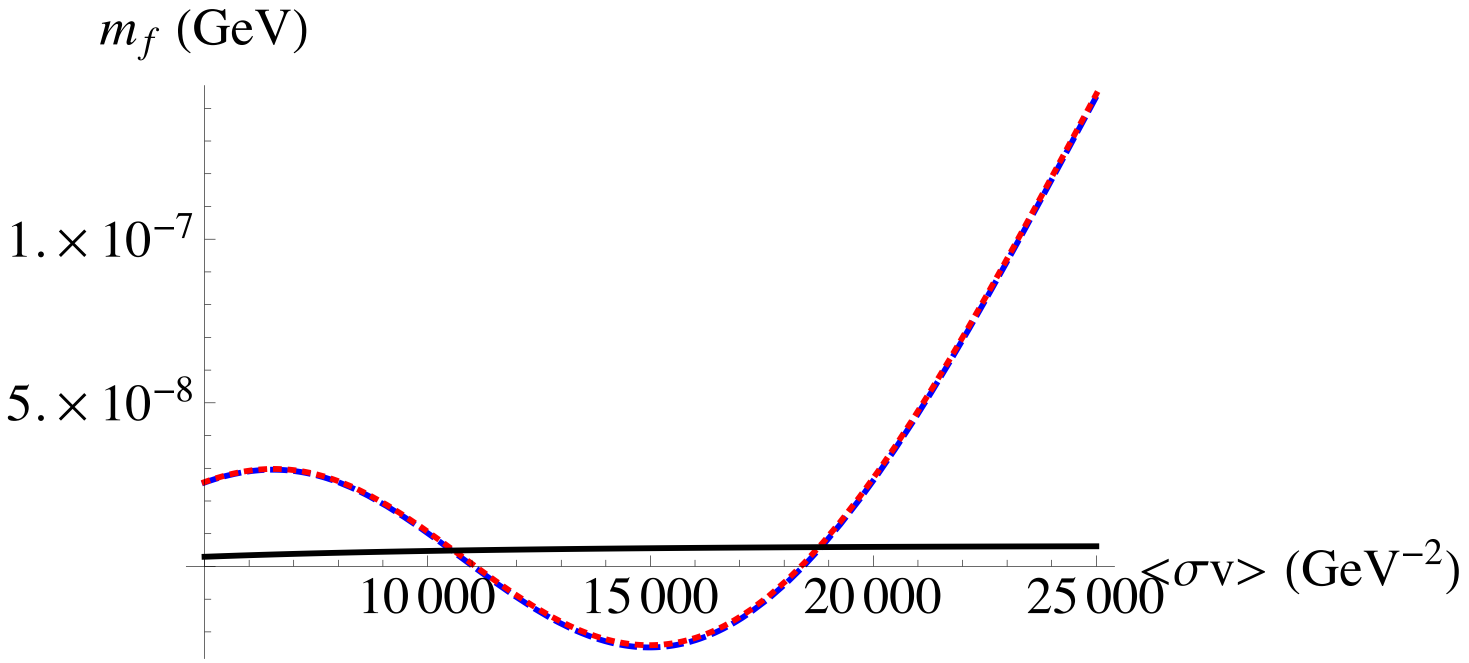
Thanks!

BACK UP

A Detour

The p-wave velocity expansion can give **inaccurate**, and even **negative** results when the Bino and Fermion are very **mass degenerate**

Take a closer look
at the velocity expansion:

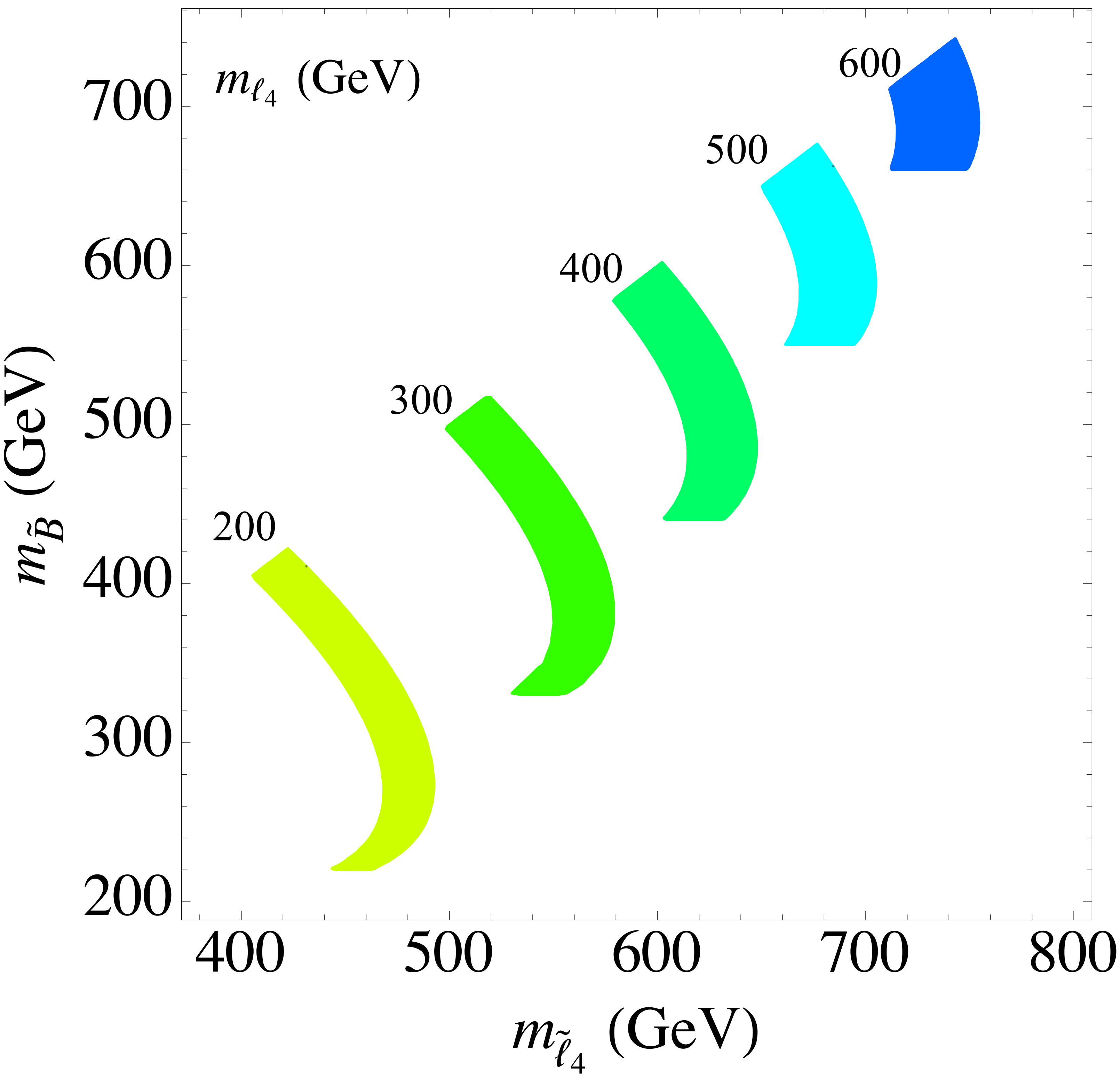


$$\frac{d\sigma}{d\Omega} \propto \sqrt{m_\chi^2 - m_f^2 + p_\chi^2} = \sqrt{m_\chi^2 - m_f^2}\sqrt{1 + \frac{p_\chi^2}{m_\chi^2 - m_f^2}} \longrightarrow$$

$$m_f < 0.85 m_{\tilde{B}}$$

for less than
10% error

Relic Density



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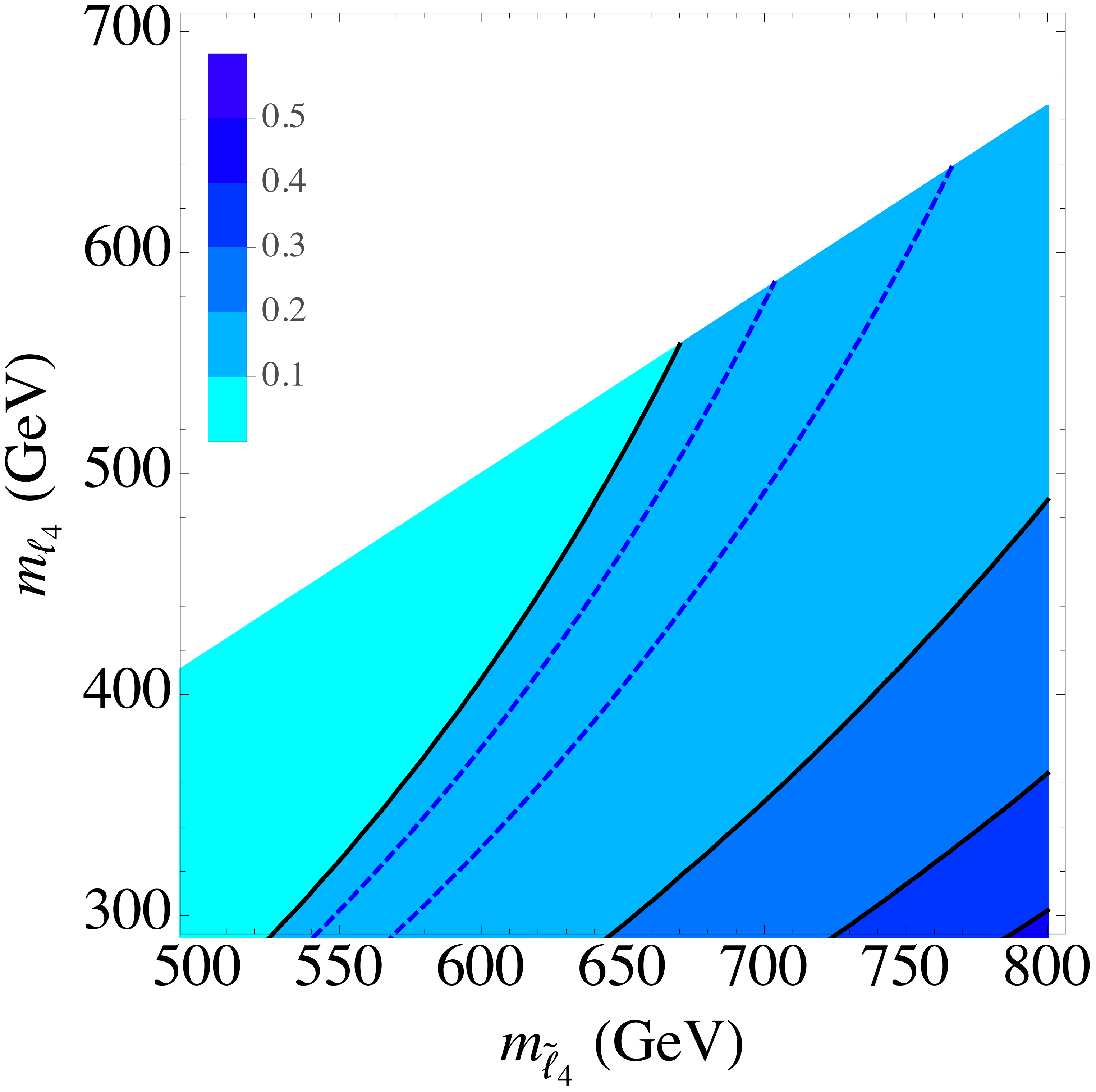

Relic Density Contours

QDEE Model

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Higgs Mass

2-loop mass in the MSSM without mixing

$$m_h^2 = M_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2}t\right) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)t^2\right]$$

Can only go up to 115 GeV

$$\begin{aligned} t &= \ln \frac{M_{\tilde{t}}^2}{M_t^2} \\ m_t &= \frac{M_t}{1 + \frac{4}{3\pi}\alpha_3(M_t)} \\ \alpha_3 &= \frac{\alpha_3(M_Z)}{1 + \frac{b_3}{4\pi}\alpha_3(M_Z)\ln(M_t^2/M_Z^2)} \\ b_3 &= 11 - 2N_f/3 = 7\,, \end{aligned}$$

1-loop correction from 4th generation quarks-squarks

$$\Delta m_h^2 = \frac{v^2}{4\pi^2}(k \sin\beta)^4 f(x)$$

$$\begin{aligned} f(x) &= \ln x - \frac{1}{6}\left(5 - \frac{1}{x}\right)\left(1 - \frac{1}{x}\right) \\ x &= \frac{m_{\tilde{q}_4}}{m_{q_4}}\,. \end{aligned}$$

Depends only on the hierarchy, not the absolute masses