Higgs/SUSY Workshop
UC Davis
April 2013

TeV-Scale Superpartners without Naturalness

Lawrence Hall
University of California, Berkeley

BERKELEY CENTER FOR THEORETICAL PHYSICS

Outline

(I) Status of Susy after 20 fb^{-1}

What if
Naturalness Argument
is wrong?

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Freeze-Out of
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Is This Robust?

TeV scale
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(III)

An unnatural theory
for
125 GeV Higgs
+ Dark Matter
“Best Guess?”

A Third of a Century of Weak Scale Susy

1980 — Natural Weak Scale

Plausible

1990 — LEP1: Gauge Coupling Unification

Leading

2000 — LEP2: $m_h > 114\,\mathrm{GeV}$

Leading but puzzling

2010

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2012 + $m_h \sim 125\,\mathrm{GeV}$ but still puzzling

Is SUSY Natural with 125 GeV Higgs?

Natural

$\tilde{m} \sim v$

Unnatural ("Split")

$\tilde{m} \gg v$

Is SUSY Natural with 125 GeV Higgs?

Natural

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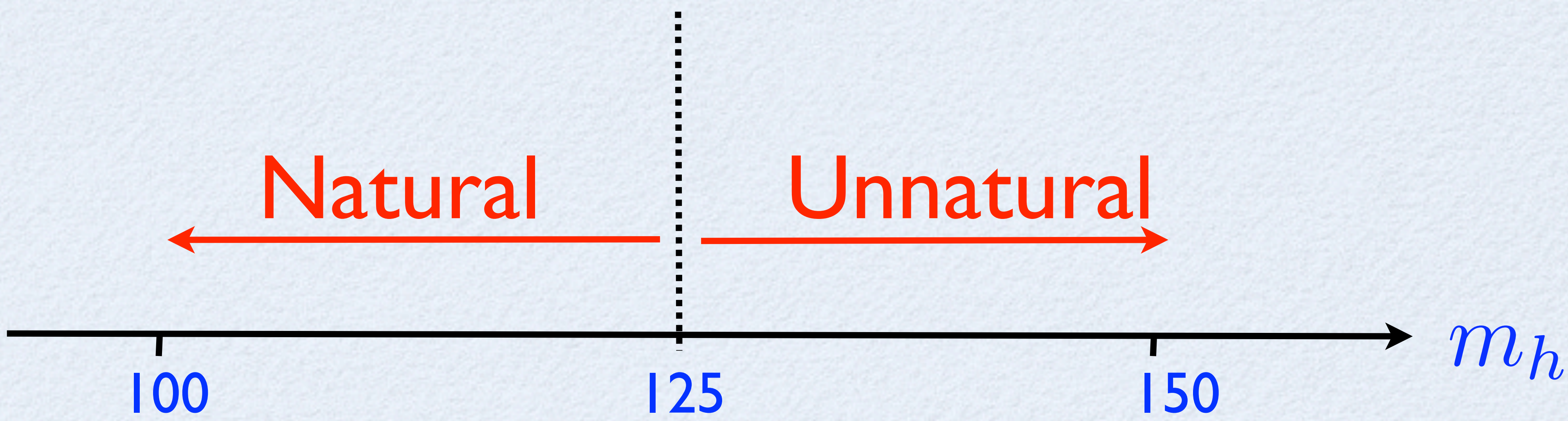
$\tilde{m} \gg v$



We simply don't know!

Fine-Tuning in the MSSM: 2012

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

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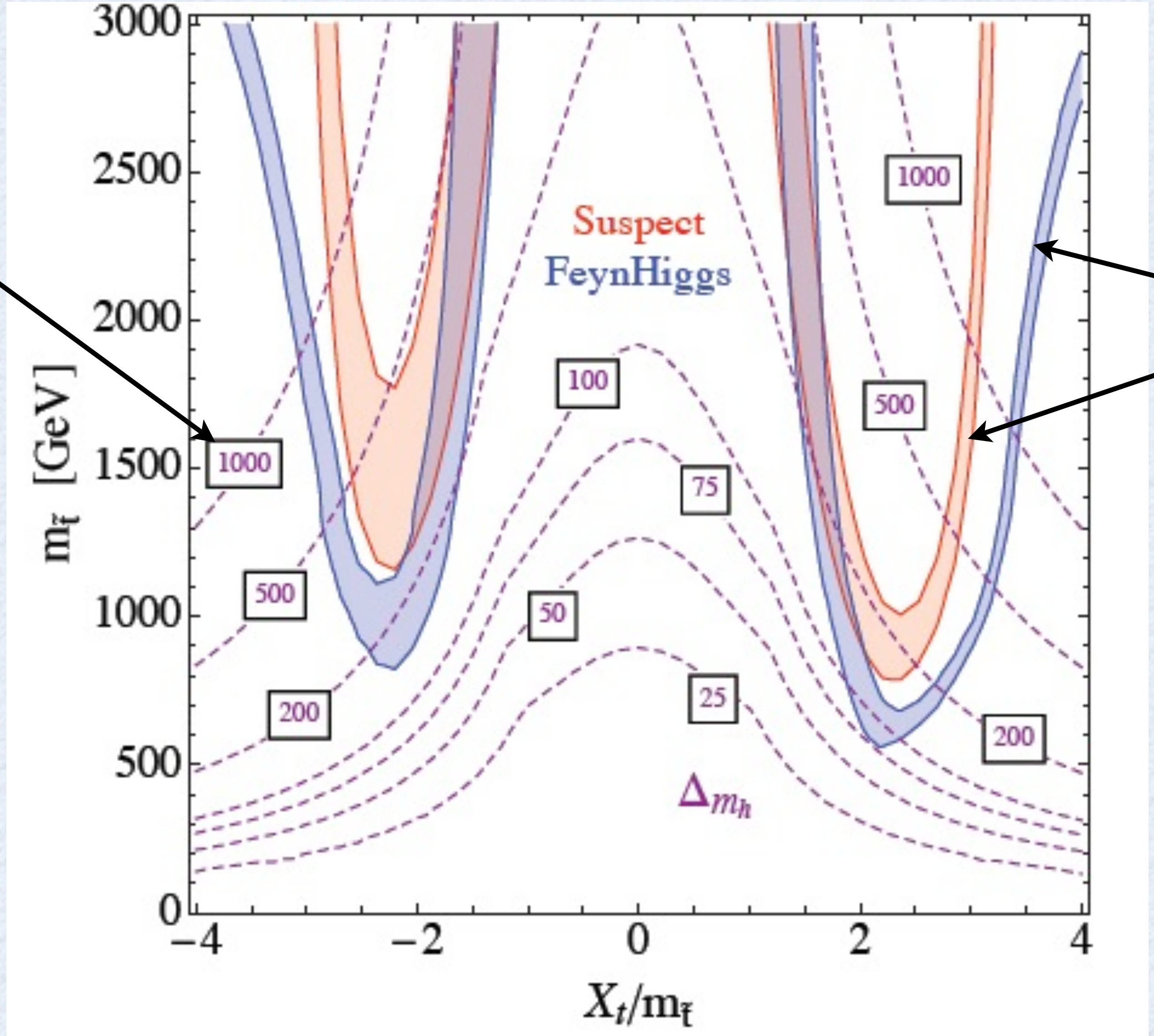
$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

$$\Delta = \frac{\partial \ln m_h}{\partial \ln p}$$



$m_h = 124 - 126$ GeV

Minimize Δ

$\tan\beta > 10$

$m_{Q_3} = m_{U_3} = m_{\tilde{t}}$

messenger scale of 10 TeV

David Pinner, Josh Ruderman, LJH 1112.2703

$\Delta > 100$ The MSSM is fine-tuned

The Future of Susy Searches

1980 Natural Weak Scale

... ...

+ $m_h \sim 125\,\mathrm{GeV}$ but still puzzling

2012

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- No superpartner signals at LHC

The Future of Susy Searches

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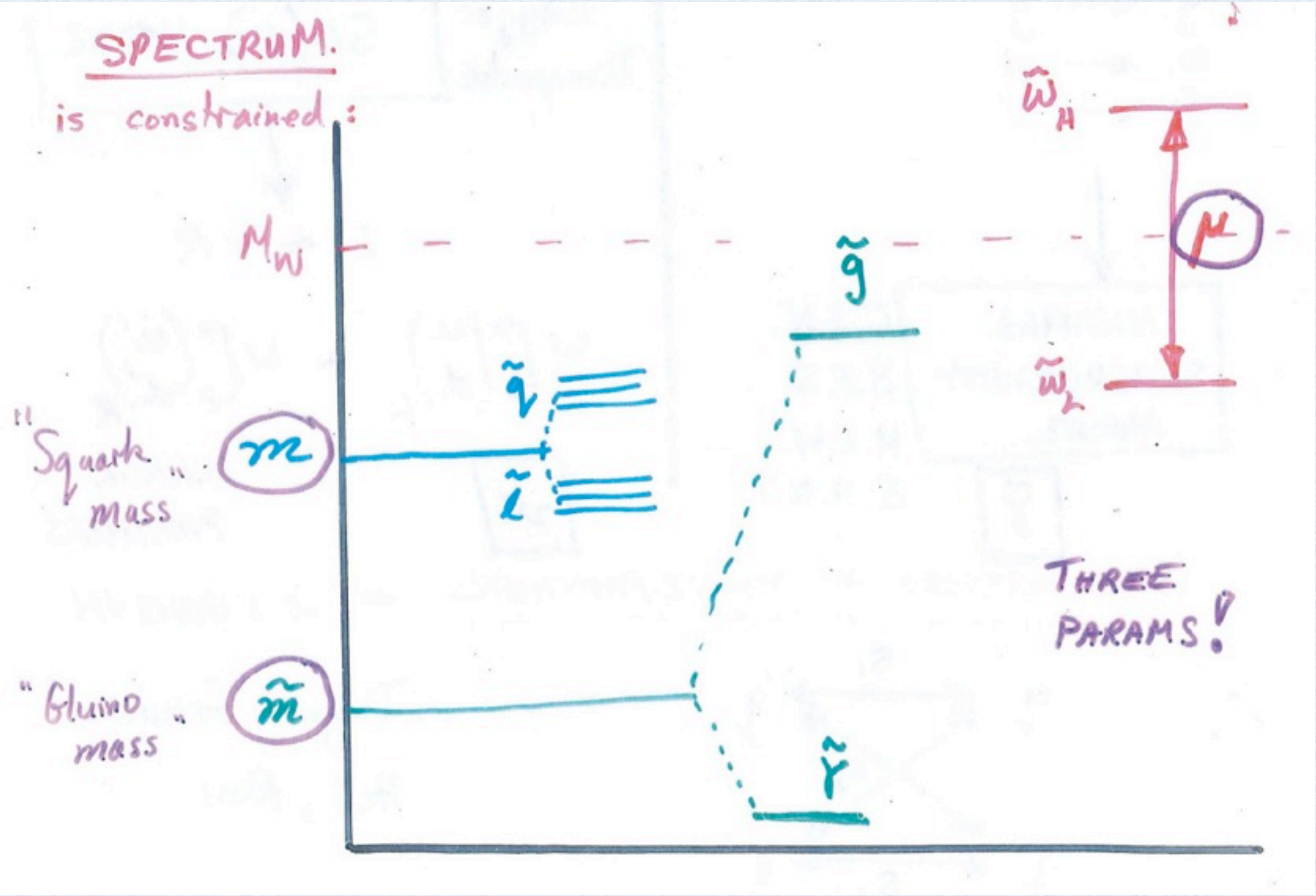
2012 - No WIMP signals at Xenon100

\- No superpartner signals at LHC

2013 .... - 3 WIMP events at CDMS

Leave no stone unturned
at LHC for Natural Susy

SUSY Spectrum, 1984



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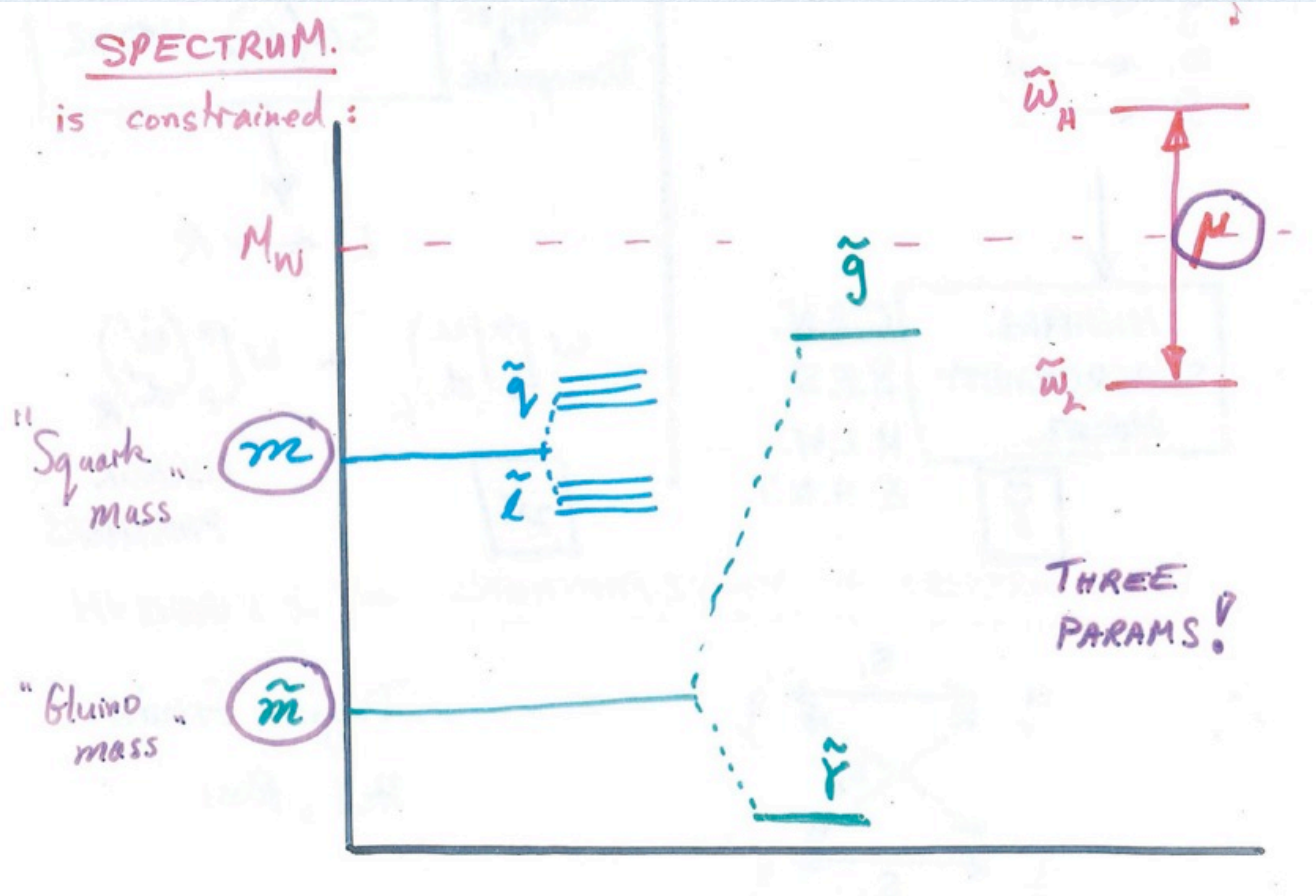
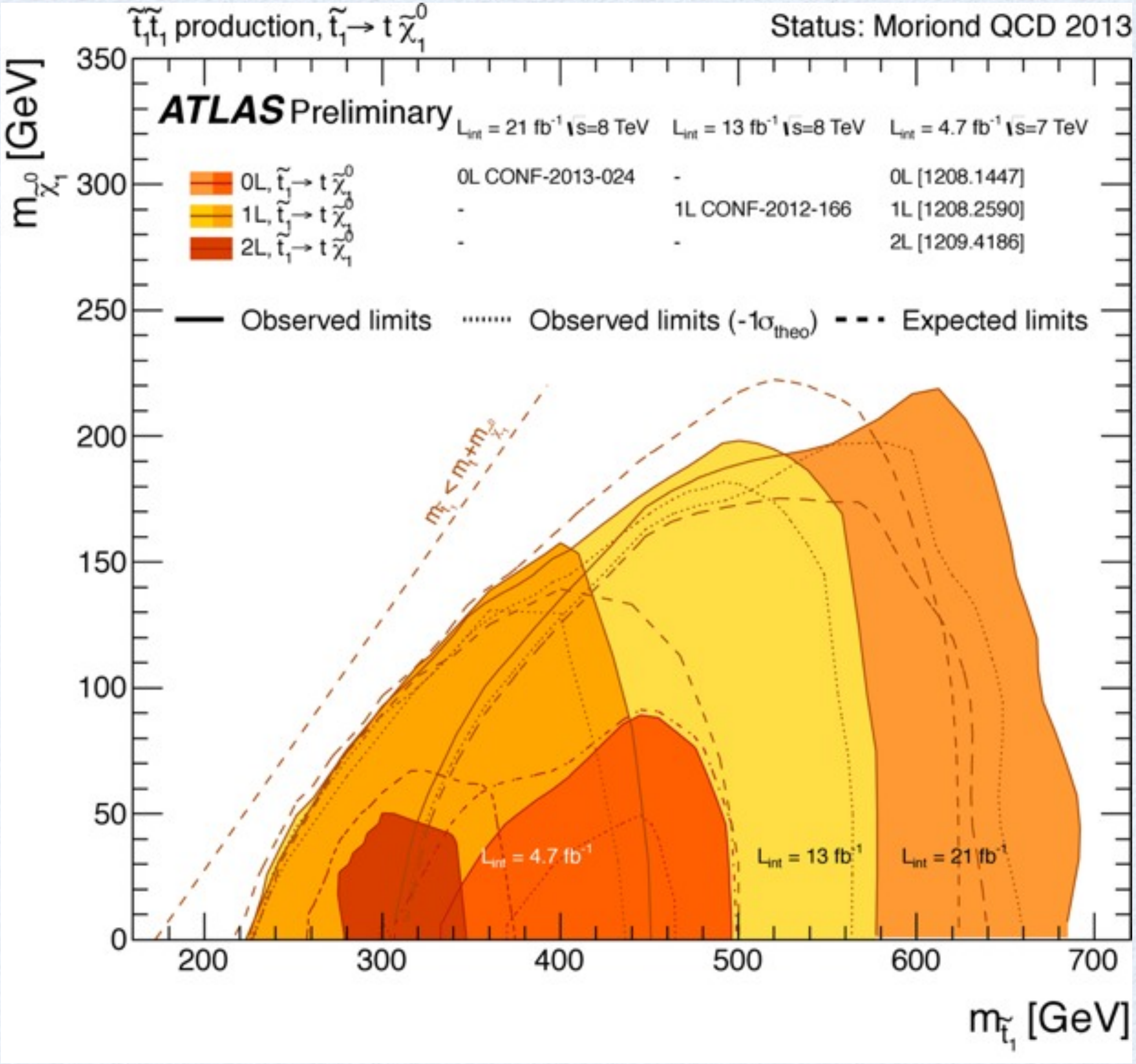


Over 3 decades of susy: seismic shifts!

Stop Search with $21 fb^{-1}$



Simplified Model
-- care!

What if Naturalness is Wrong?

Must rethink SUSY

→ Back to Basics

Motivations for TeV Scale Susy

	Theory Assumptions	Experimental Component	TeV Scale?
1. Naturalness	?		❉❉❉

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2. Gauge Coupling Unification	❈	❈❈	❈

Motivations for TeV Scale Susy

	Theory Assumptions	Experimental Component	TeV Scale?
1. Naturalness	?		❉❉❉
2. Gauge Coupling Unification	❉	❉❉	❉
3. Dark Matter (Freeze-Out)	❉❉	❉❉❉	❉❉

(II) How Robust is Argument for TeV Scale from Dark Matter?

Dark Matter from Freeze-Out

The assumptions:

1. The LSP is cosmologically stable
2. $T_R \geq \tilde{m}$
3. No Dilution

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The result:

$$\Omega h^2 \propto \frac{1}{\langle \sigma_A v \rangle} \qquad \langle \sigma_A v \rangle = \frac{4\pi\alpha_{\text{eff}}^2}{m_{LSP}^2}$$

$$m_{LSP} \sim \alpha_{\text{eff}} \sqrt{T_{\text{eq}} M_{\text{P}}} \approx \left(\frac{\alpha_{\text{eff}}}{0.01}\right) 1\,\text{TeV}$$

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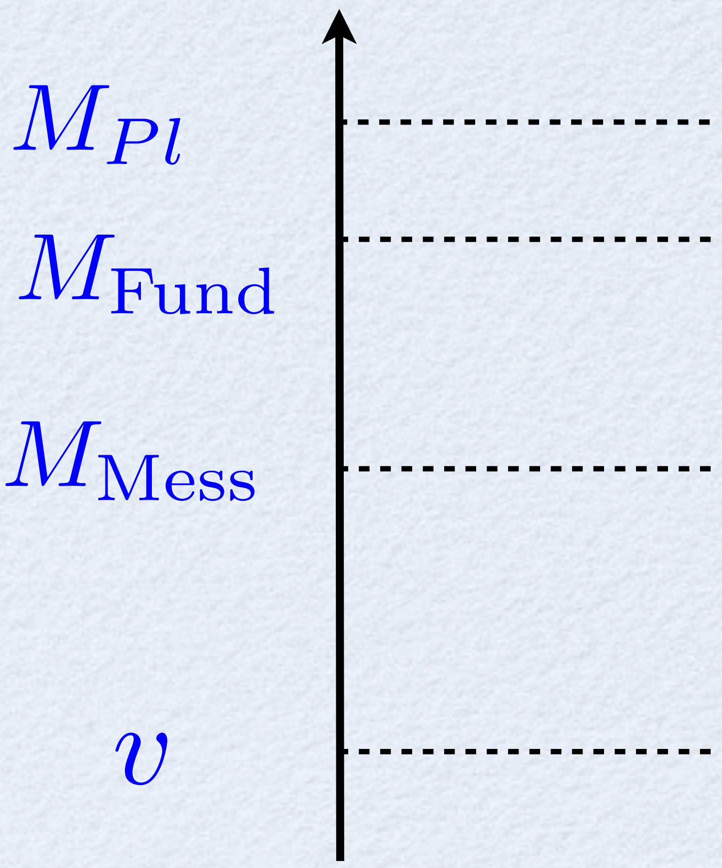
BUT HIDDEN ASSUMPTION

4. LSP reached thermal equilibrium

ALL Susy theories contain a Gravitino

Key mass scales

$$M_{Pl} \geq M_{\rm Fund} \geq M_{\rm Mess}$$



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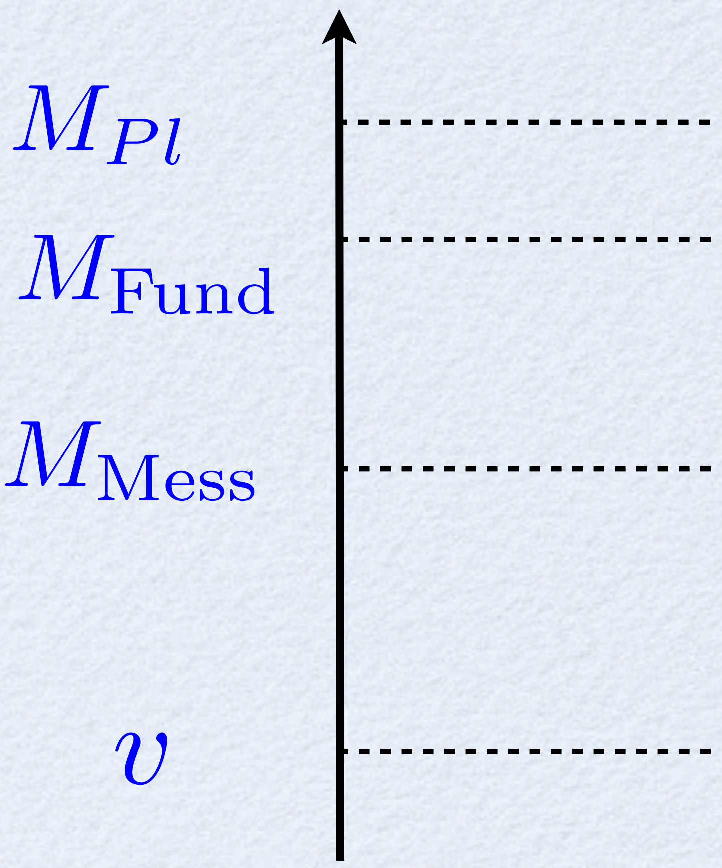

$$M_{Pl} \geq M_{\rm Fund} \geq M_{\rm Mess}$$

Generic result: $$\frac{m_{3/2}}{\tilde{m}} \sim \frac{M_{\rm Mess}}{M_{Pl}}$$

$\tilde{G}$ is a very likely LSP candidate

Can be avoided in special cases

The Hidden Assumption is Big

4. LSP reached thermal equilibrium

Gravitino LSP is quite typical

If gravitinos are the CDM they are too weakly interacting to reach thermal equilibrium and did not Freeze-Out.

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The argument for TeV superpartners from DM has a huge loop-hole!

Cosmological Gravitino Production

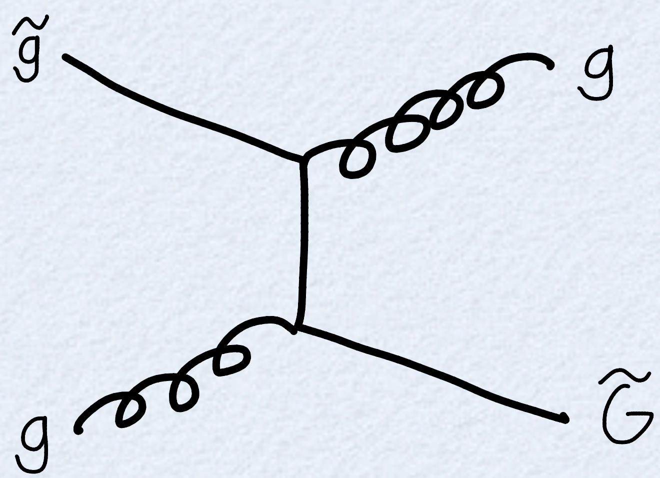
Several processes contribute

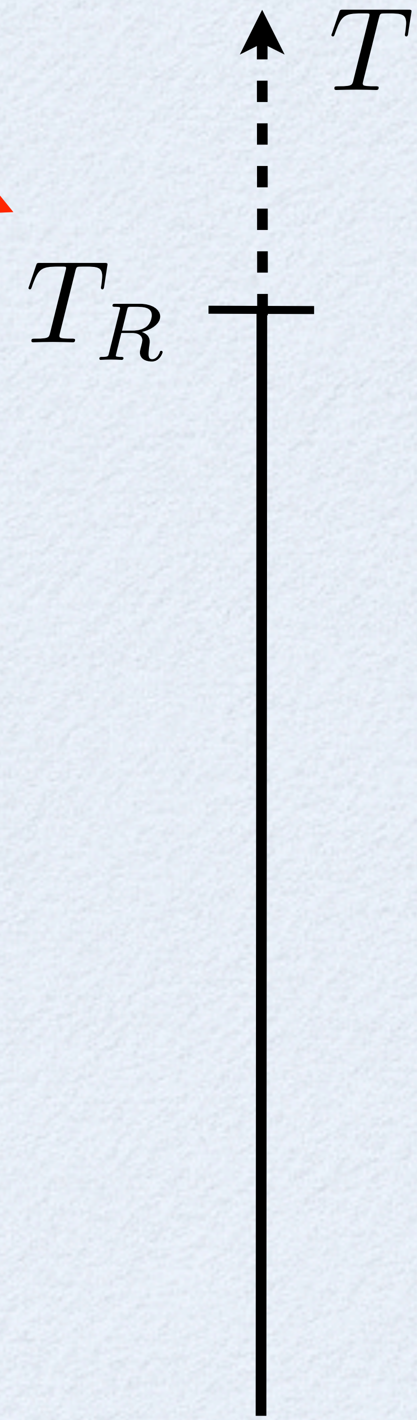
Claim that Gravitino DM also points to TeV scale superpartners

LJH, Josh Ruderman, Tomer Volansky
arXiv: 1302.2620

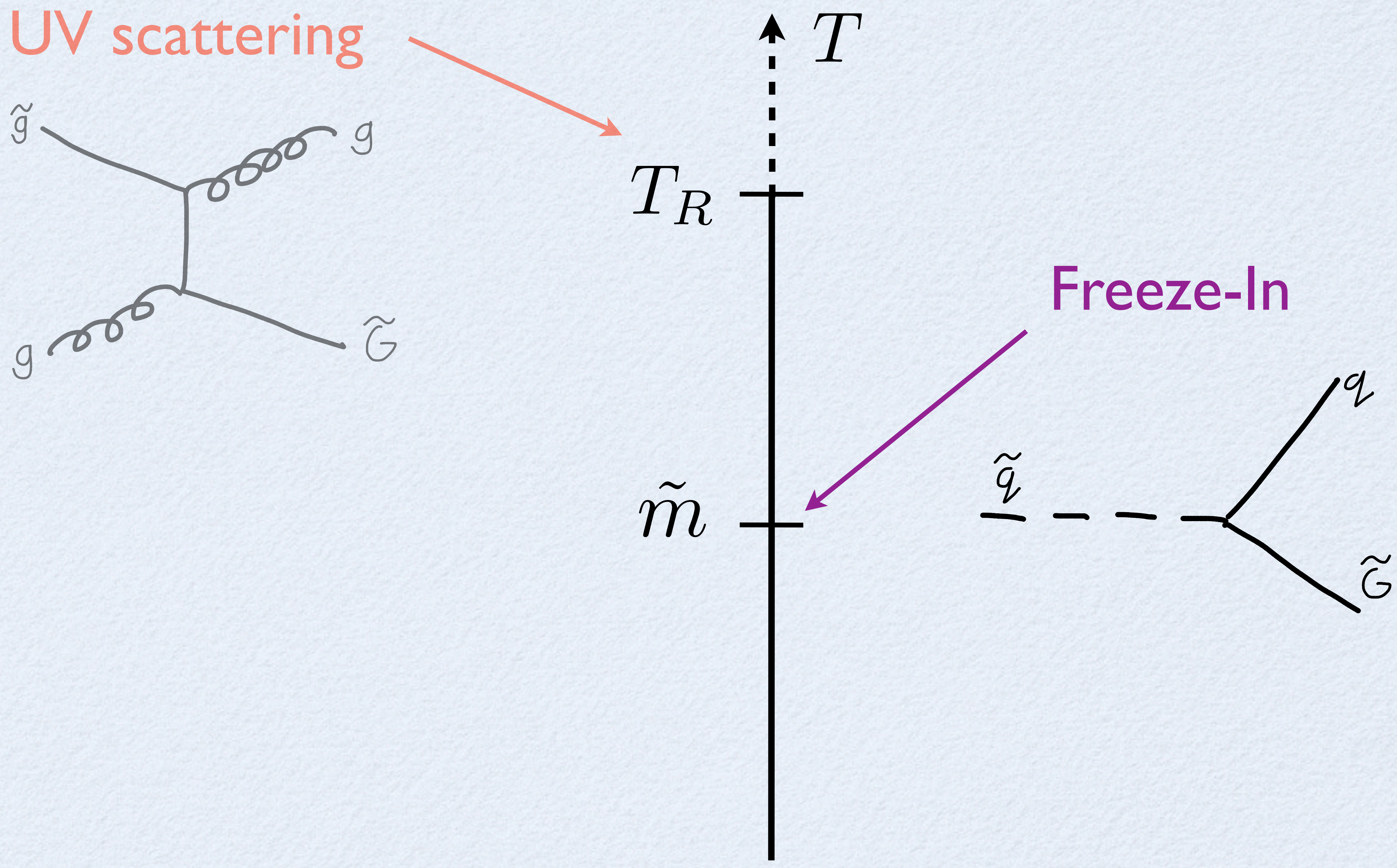
UV Scattering

UV scattering

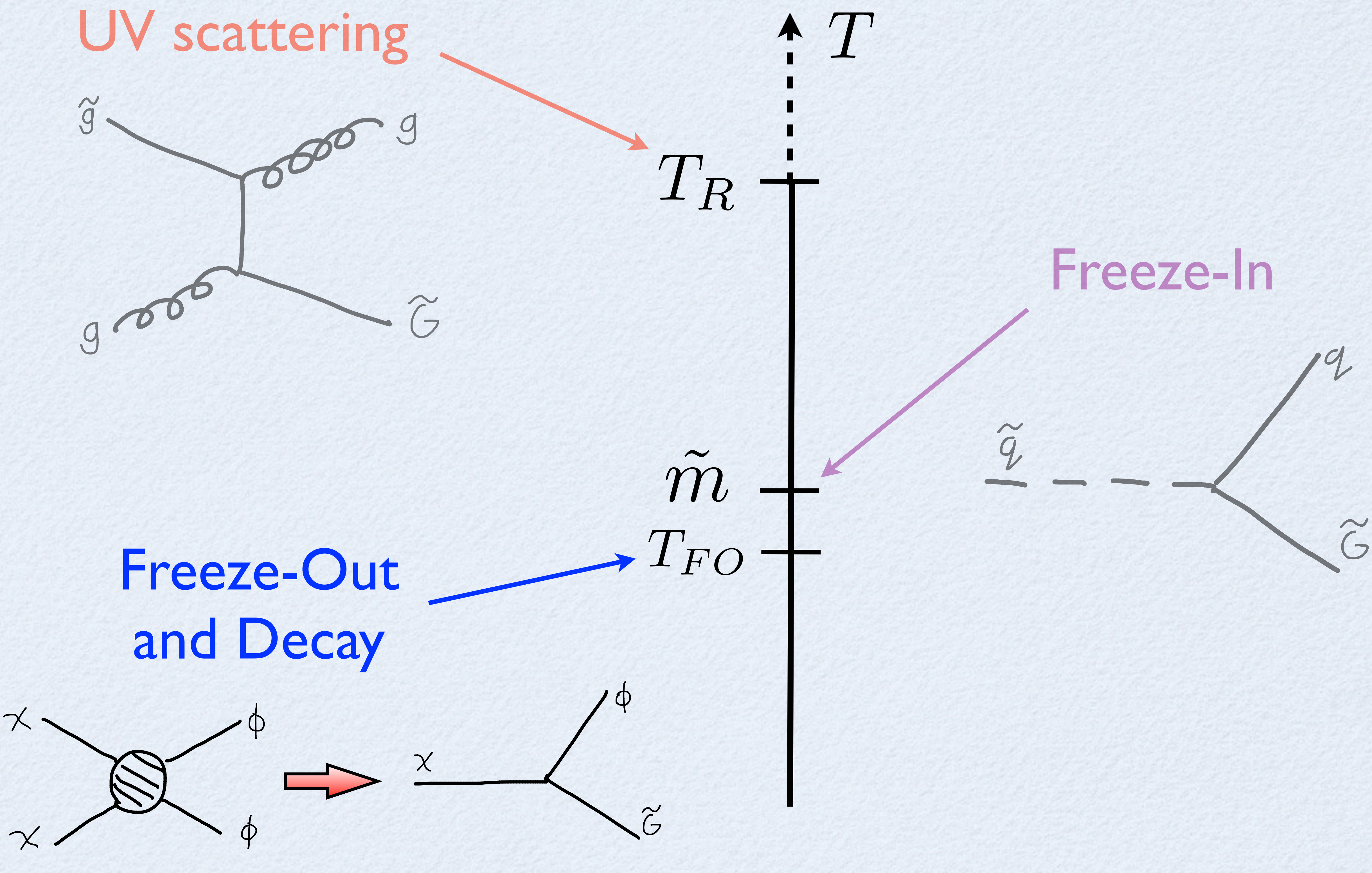




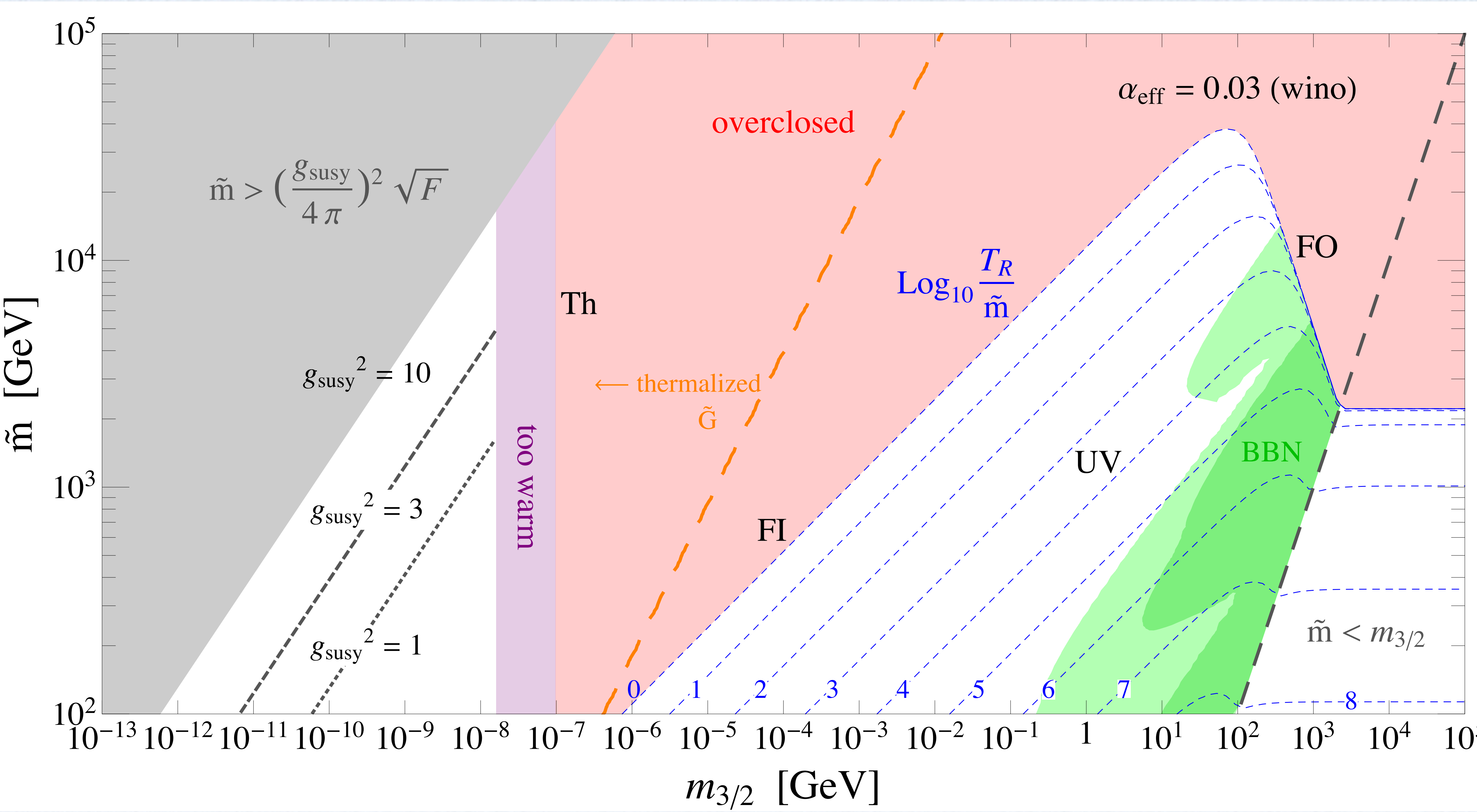
Freeze-In


UV scattering
$\tilde{g}$
g
g
$\tilde{G}$
T
T_R
Freeze-In
$\tilde{m}$
$\tilde{q}$
q
$\tilde{G}$

Freeze-Out and Decay



Superpartner Mass Bound



LJH, Josh Ruderman, Tomer Volansky arXiv: 1302.2620

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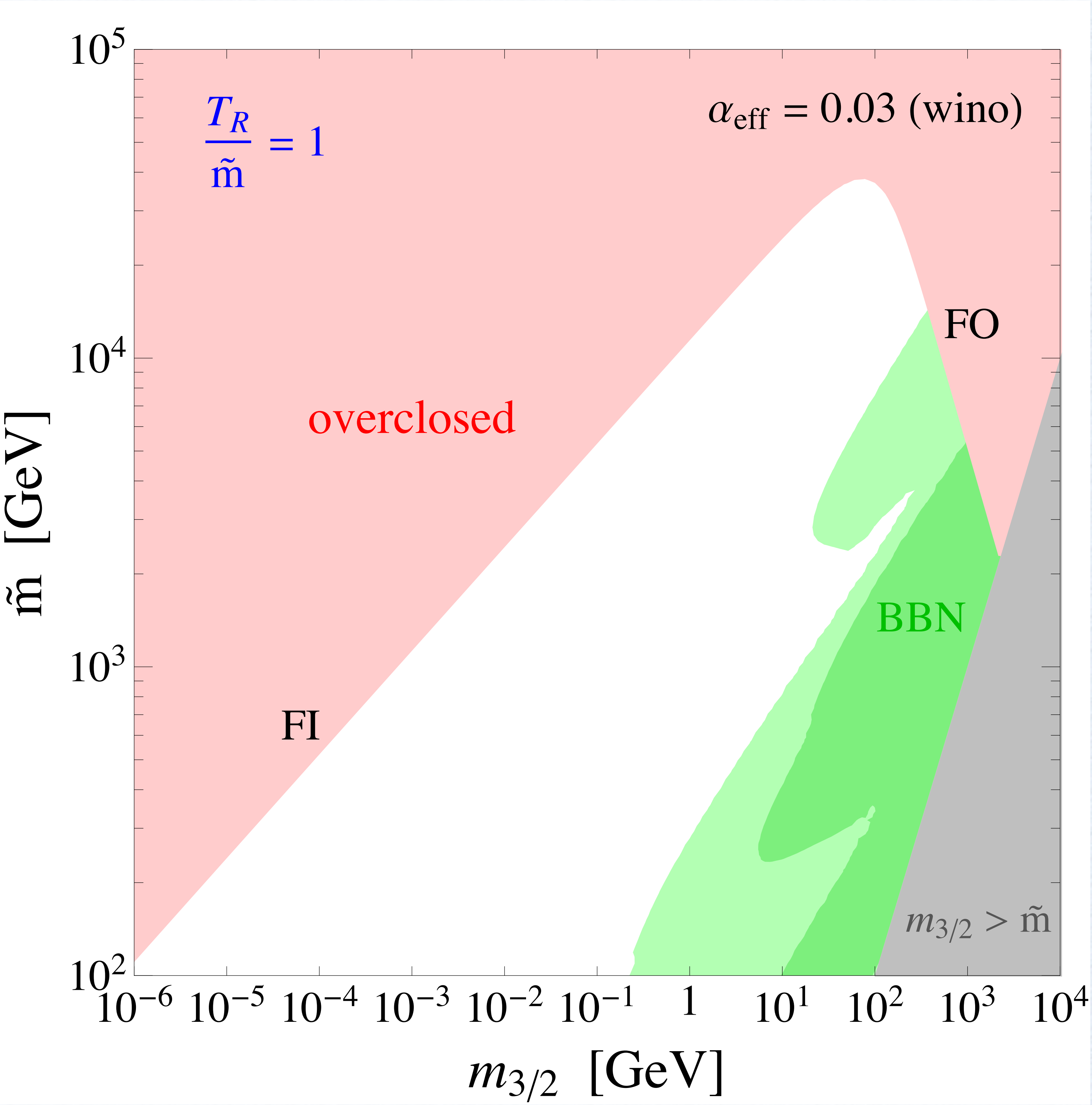
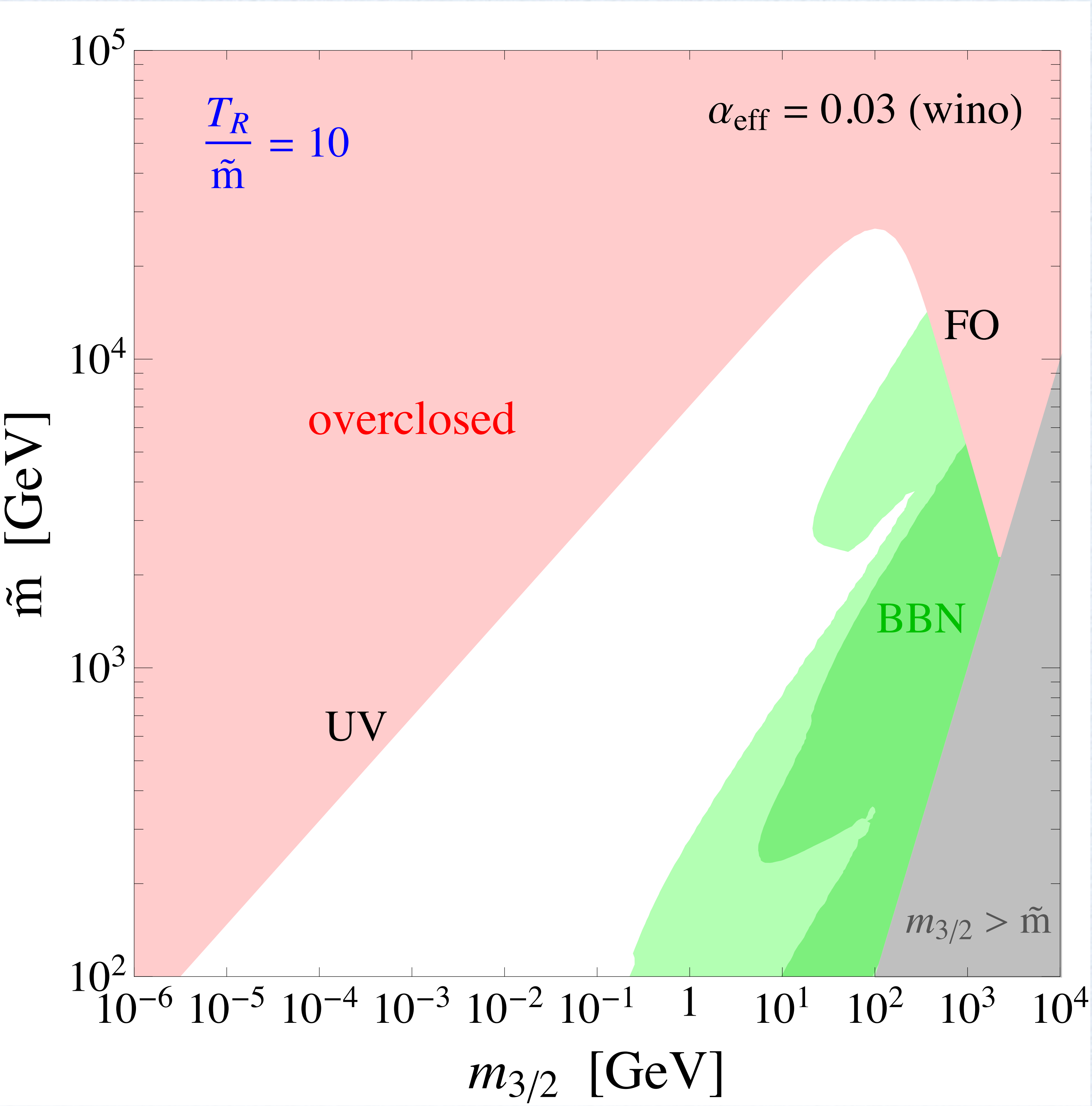


$$\frac{T_R}{\tilde{m}} = 1$$

$$\tilde{m} \lesssim 38 \text{ TeV}$$

LJH, Josh Ruderman, Tomer Volansky
arXiv: 1302.2620

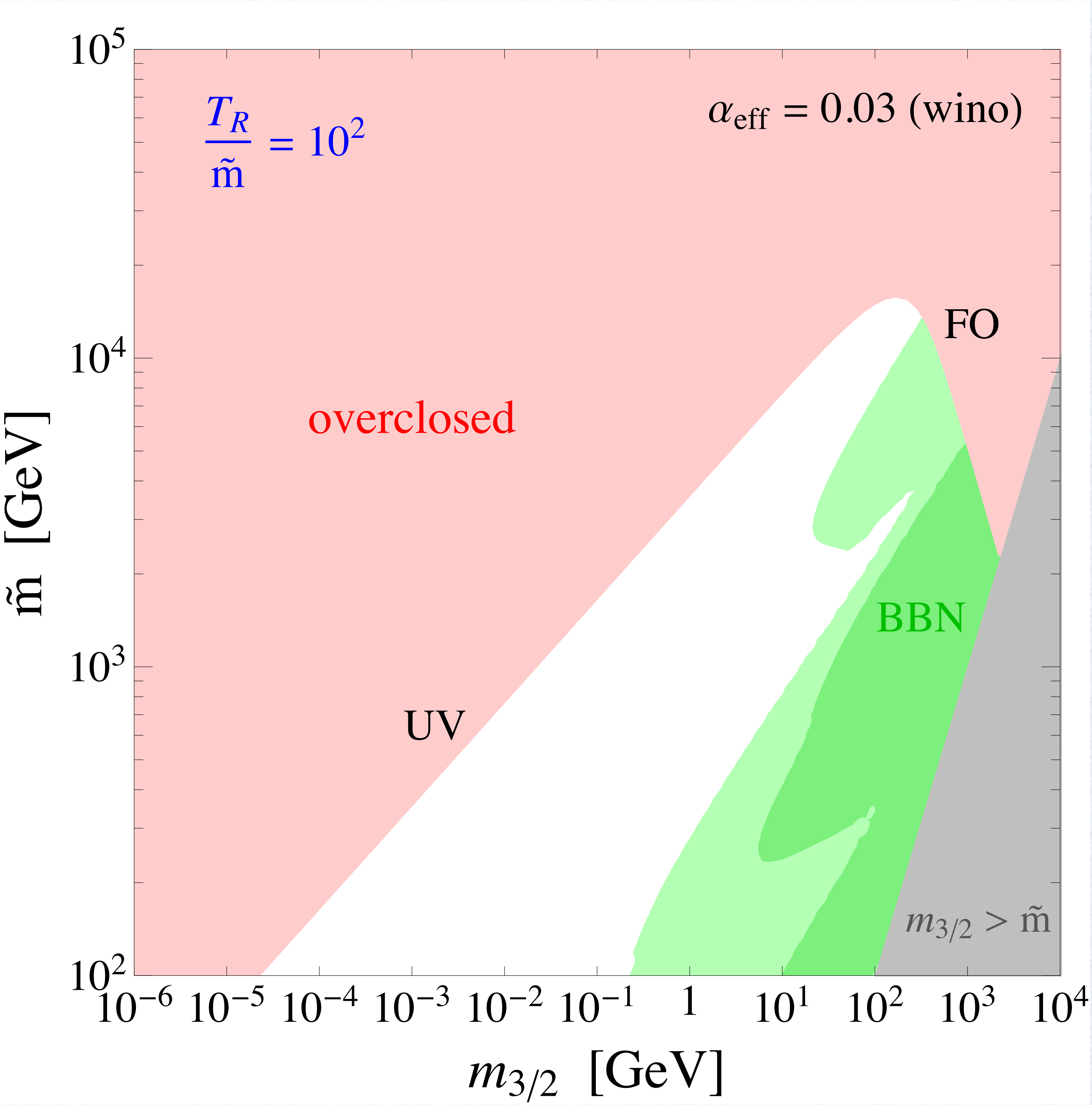
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10$$

$$\tilde{m} \lesssim 27 \text{ TeV}$$

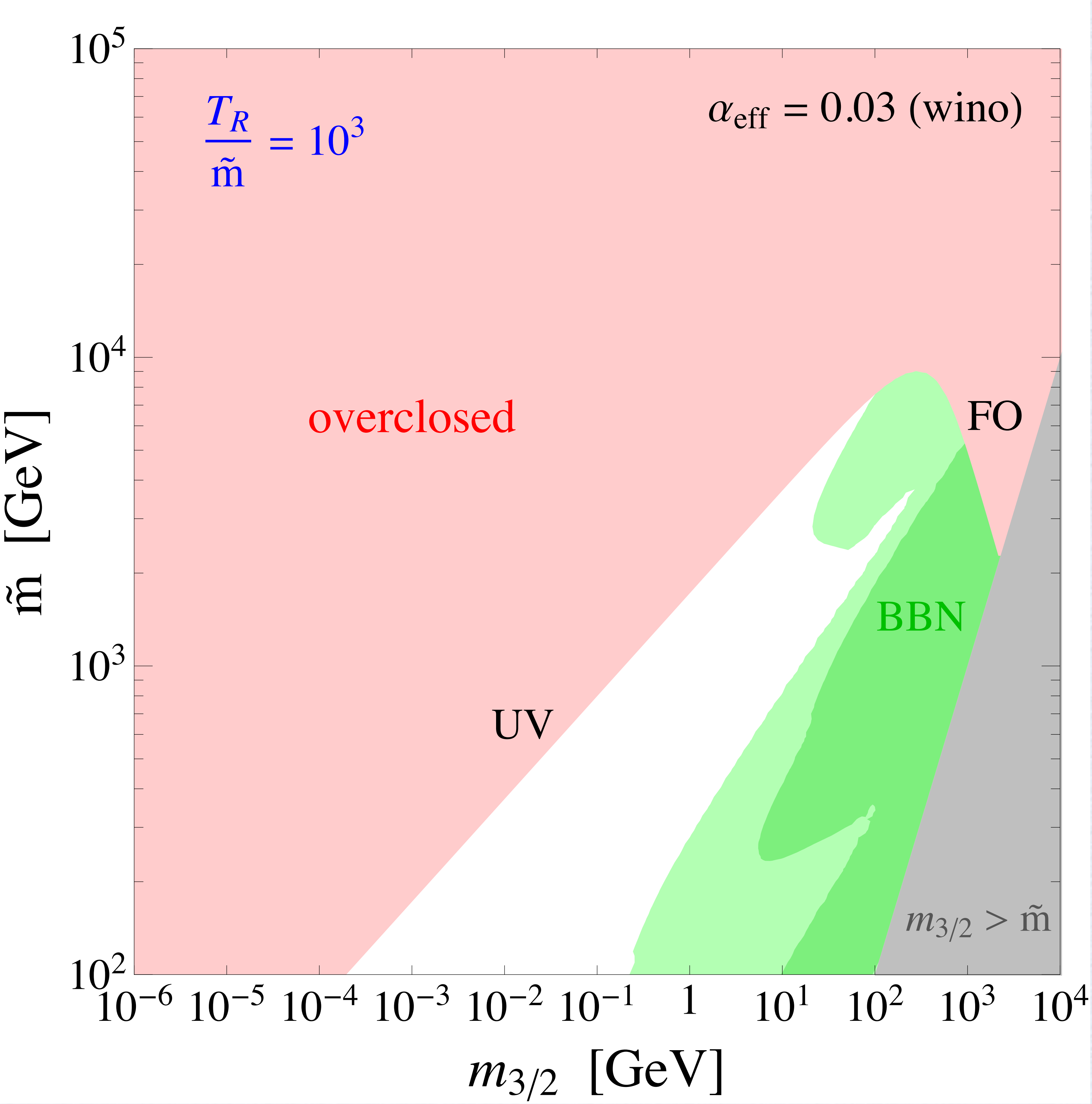
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10^2$$

$$\tilde{m} \lesssim 16 \text{ TeV}$$

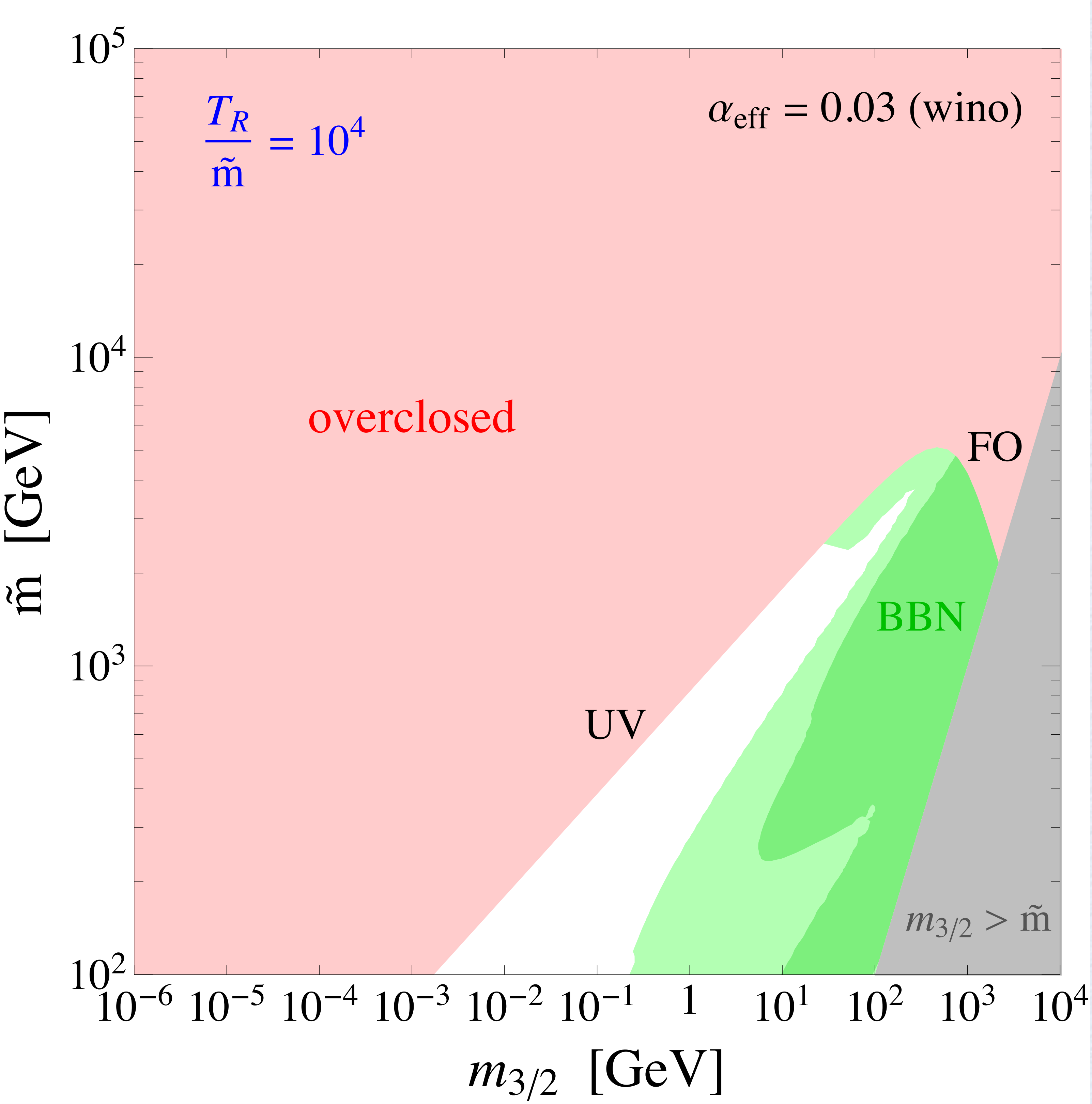
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10^3$$

$$\tilde{m} \lesssim 9 \text{ TeV}$$

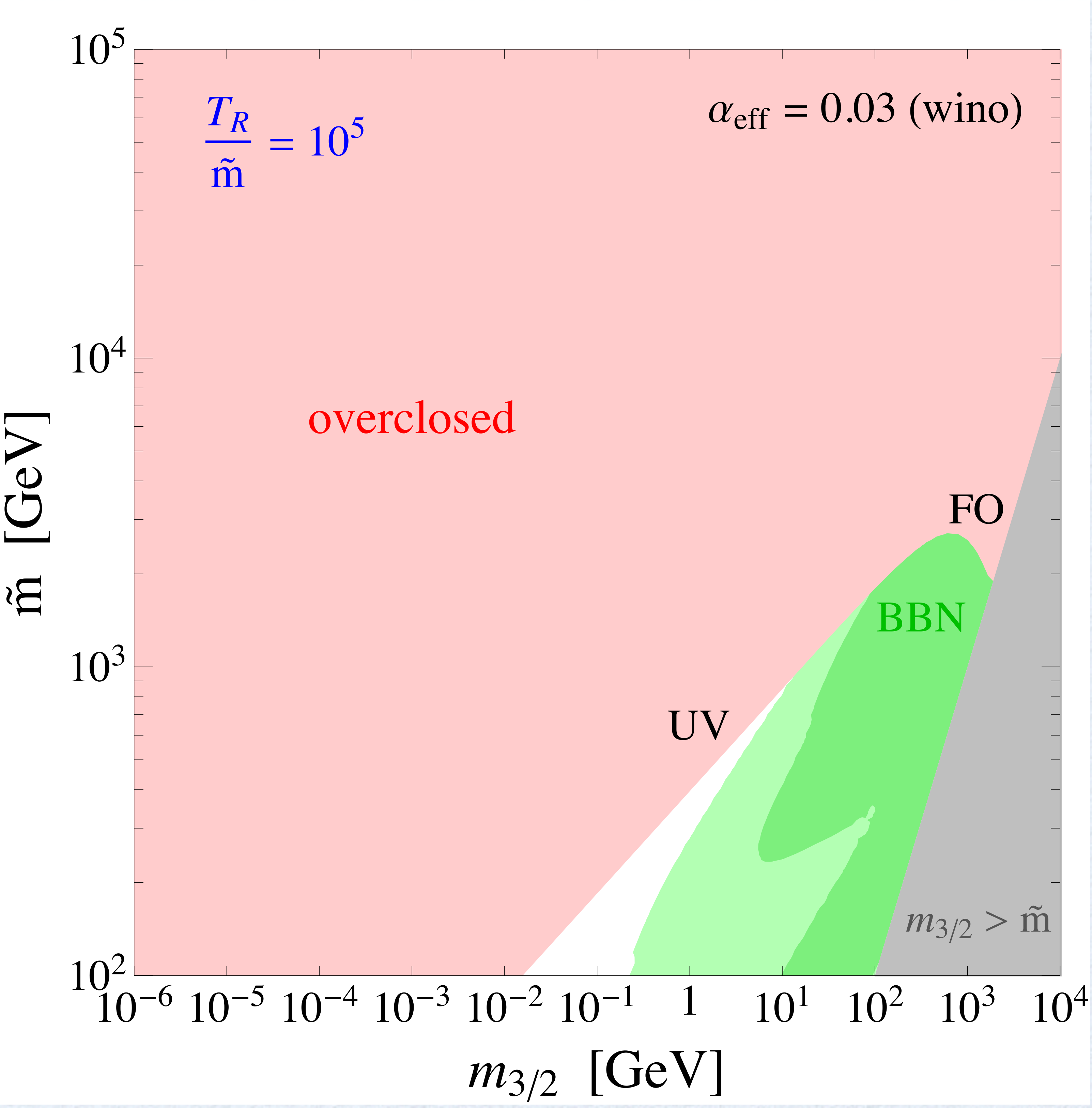
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10^4$$

$$\tilde{m} \lesssim 5 \text{ TeV}$$

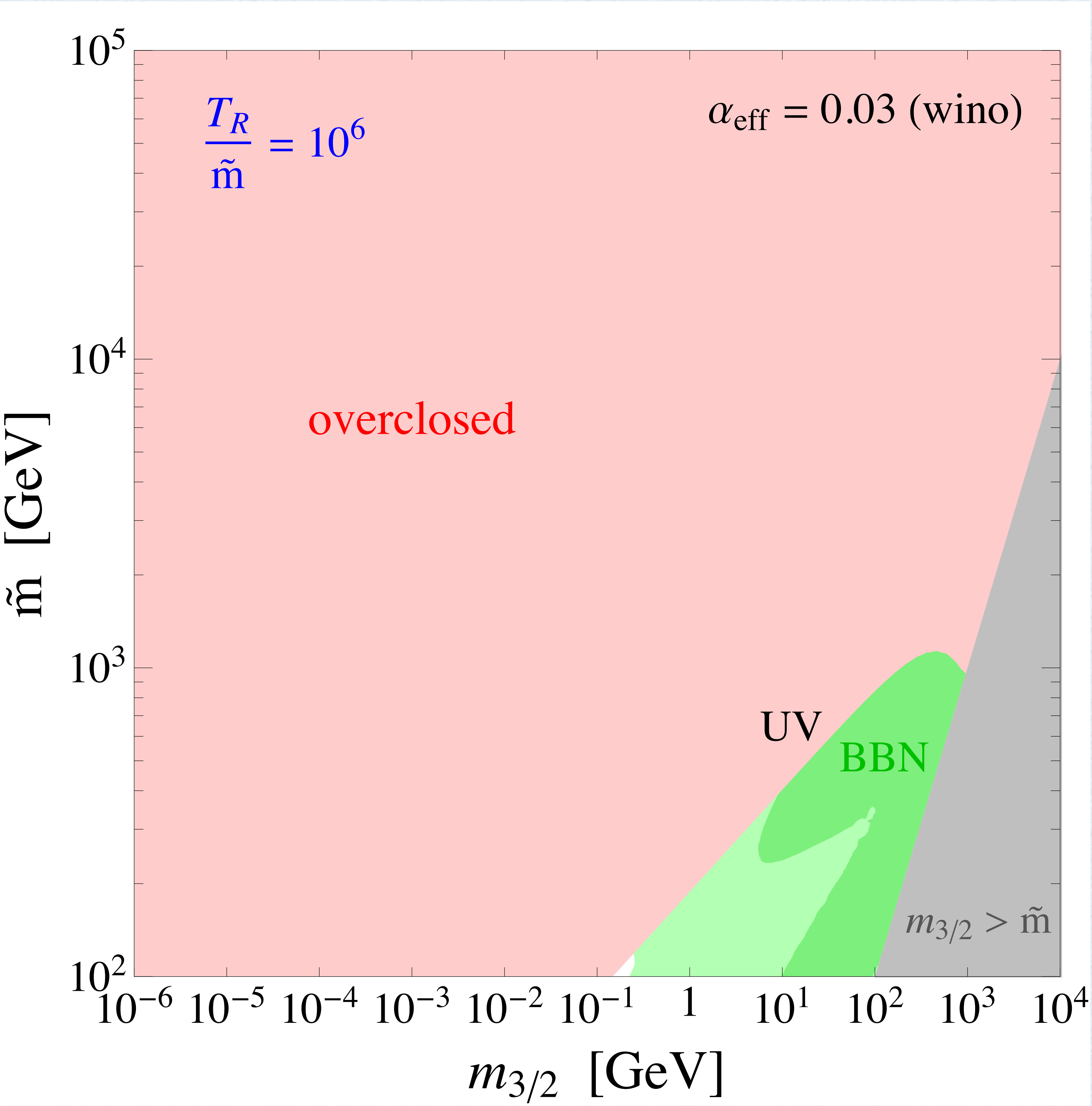
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10^5$$

$$\tilde{m} \lesssim 2.7 \text{ TeV}$$

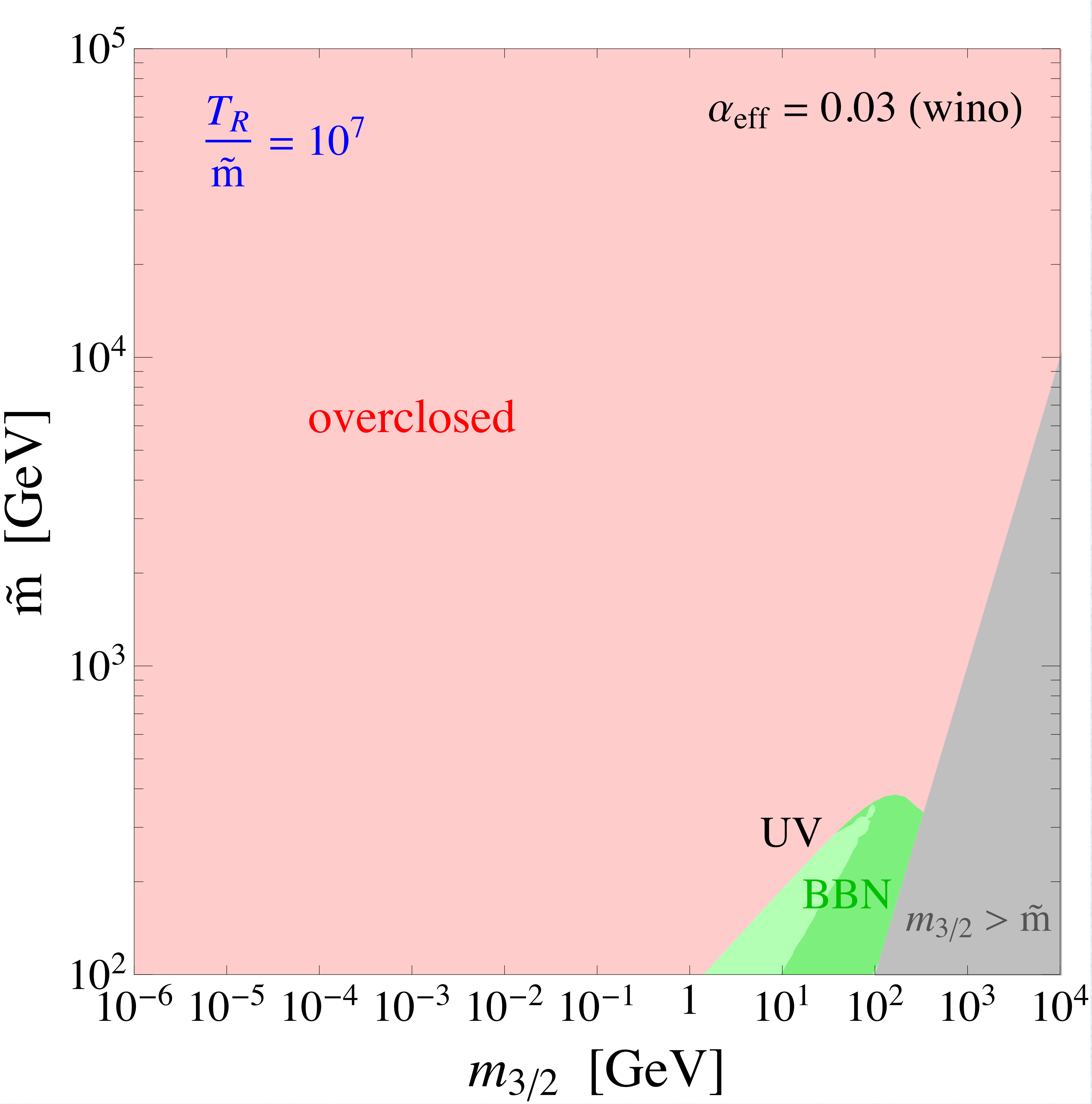
Superpartner Mass Bound



$$\frac{T_R}{\tilde{m}} = 10^6$$

$$\tilde{m} \lesssim 1.1 \text{ TeV}$$

Superpartner Mass Bound



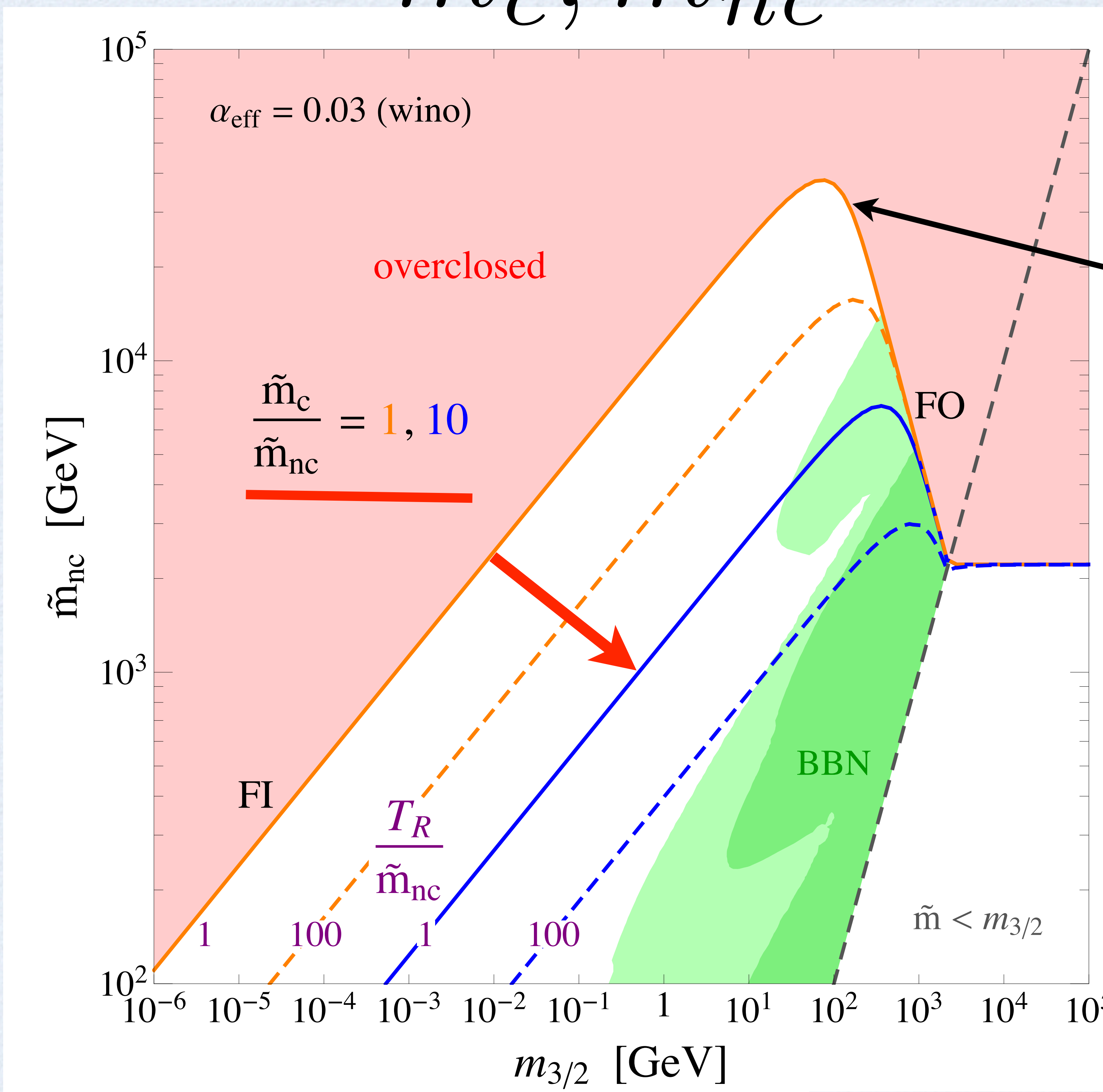
$$\frac{T_R}{\tilde{m}} = 10^7$$

$$\tilde{m} \lesssim 400 \text{ GeV}$$

Non-Degenerate Susy Spectrum

$$\tilde{m}_c, \tilde{m}_{nc}$$

$\tilde{m}_{nc}$



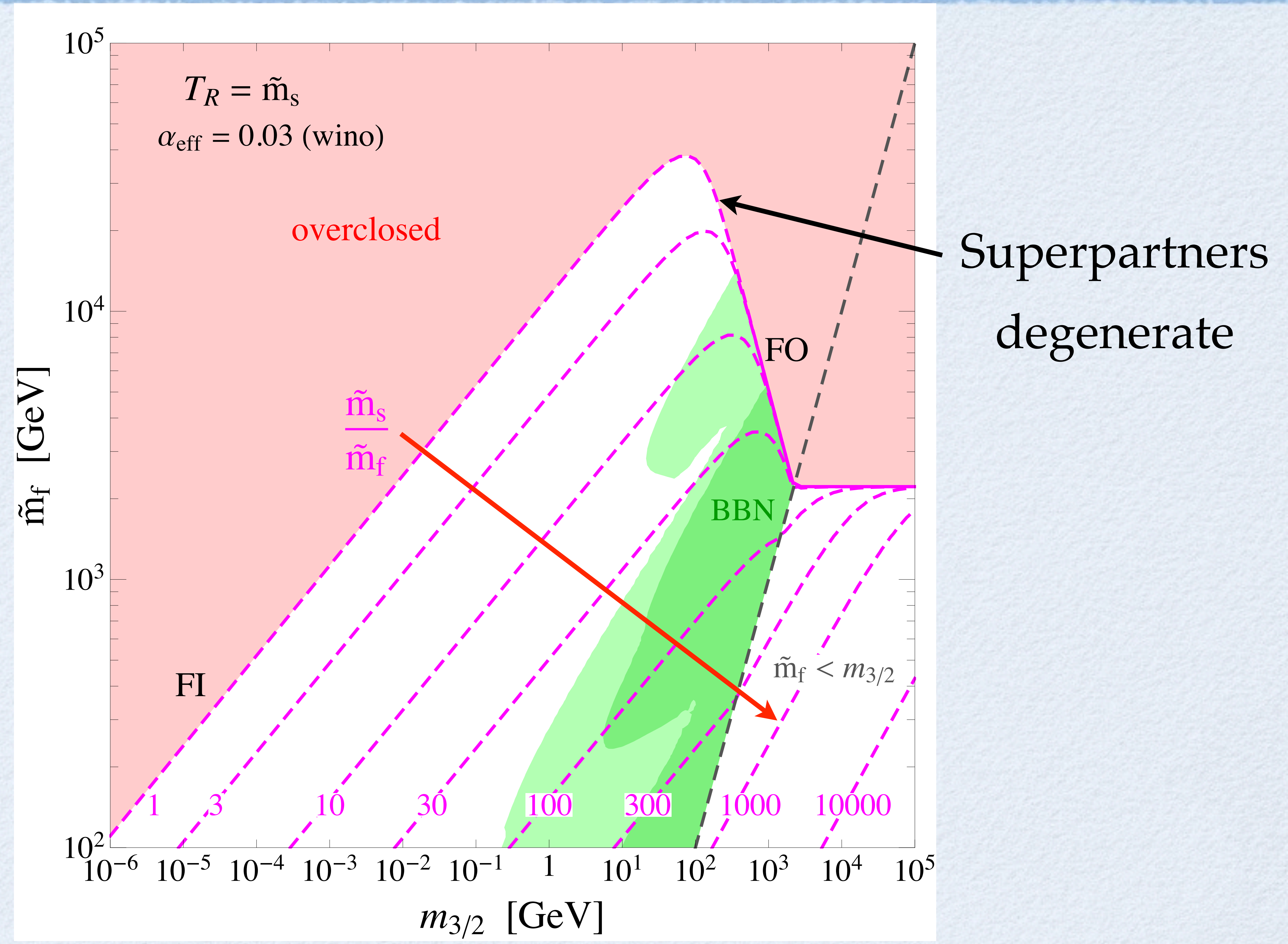
Superpartners degenerate

LJH, Josh Ruderman, Tomer Volansky arXiv: 1302.2620

Split Susy: $\tilde{m}_s, \tilde{m}_f$

$$\frac{T_R}{\tilde{m}_s} = 1$$

$\tilde{m}_f$



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TeV Scale from SUSY Dark Matter

1. The LSP is cosmologically stable
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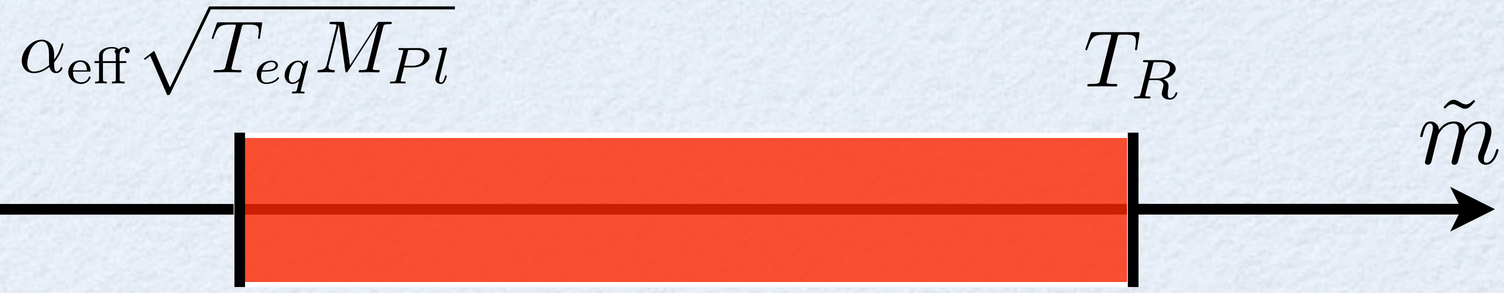
$m_{3/2} > \tilde{m}$



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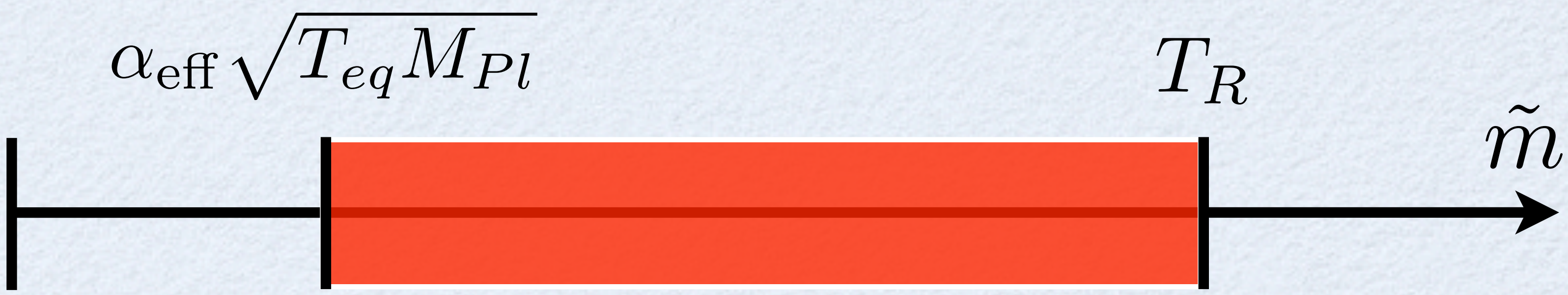
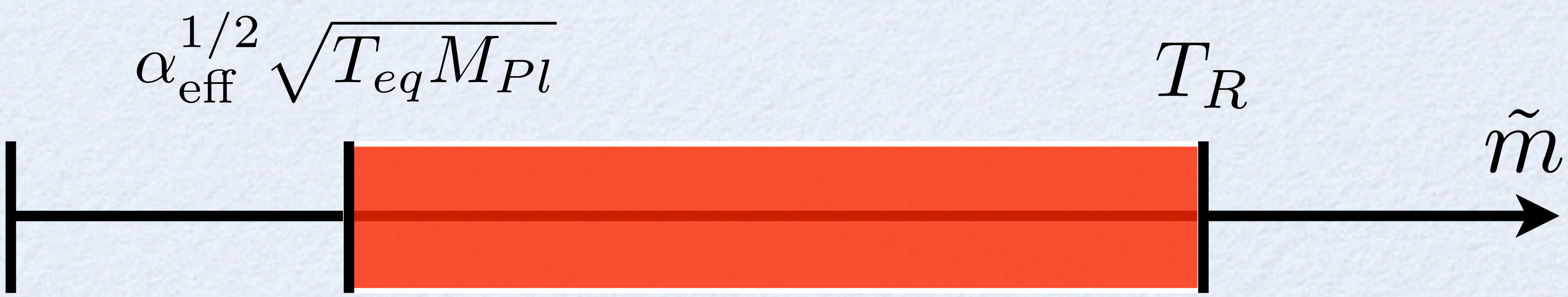


$m_{3/2} < \tilde{m}$



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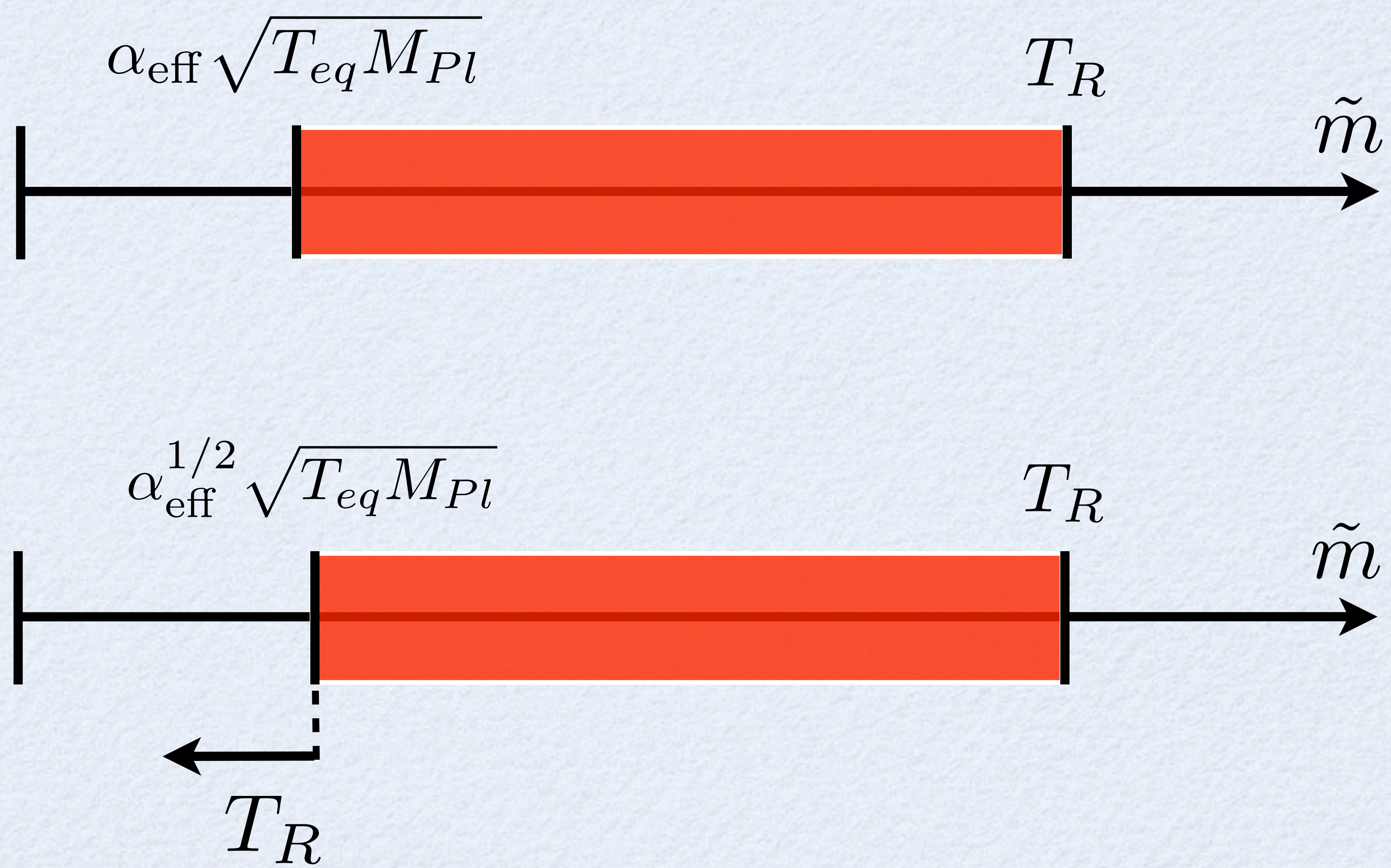

(III) A SUSY Theory for:

125 GeV Higgs

Dark Matter

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125 GeV Higgs
Dark Matter

Current Best Guess?

Spread Supersymmetry

Seek a scheme where:

- 125 GeV Higgs is “effortless”
- LHC susy constraints “effortless”
- Dark Matter is the LSP

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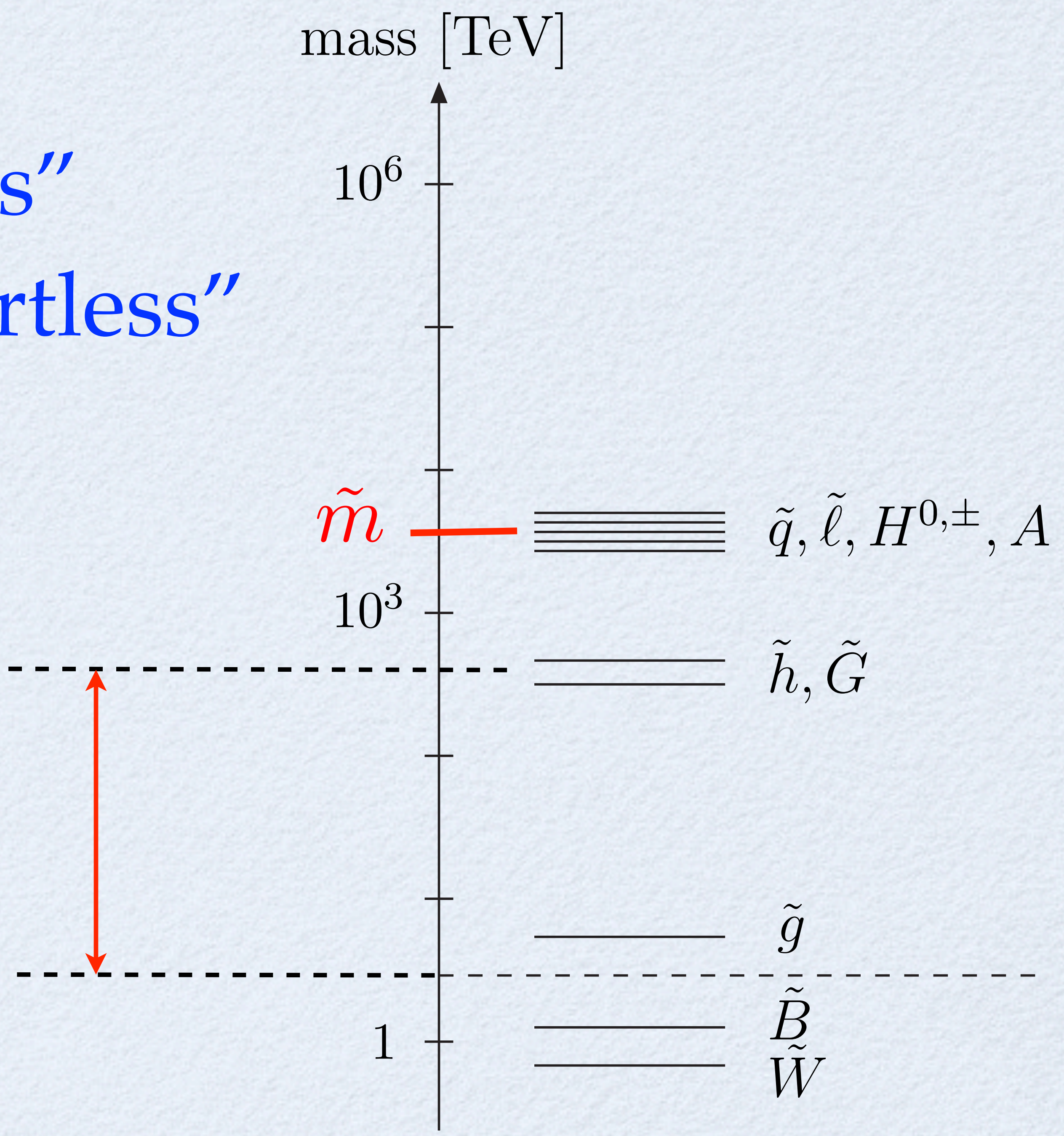
LHC susy constraints "effortless"

Dark Matter is the LSP

A 1-loop mass hierarchy from Anomaly Mediation

Giudice, Luty, Murayama, Rattazzi hep-ph/9810442



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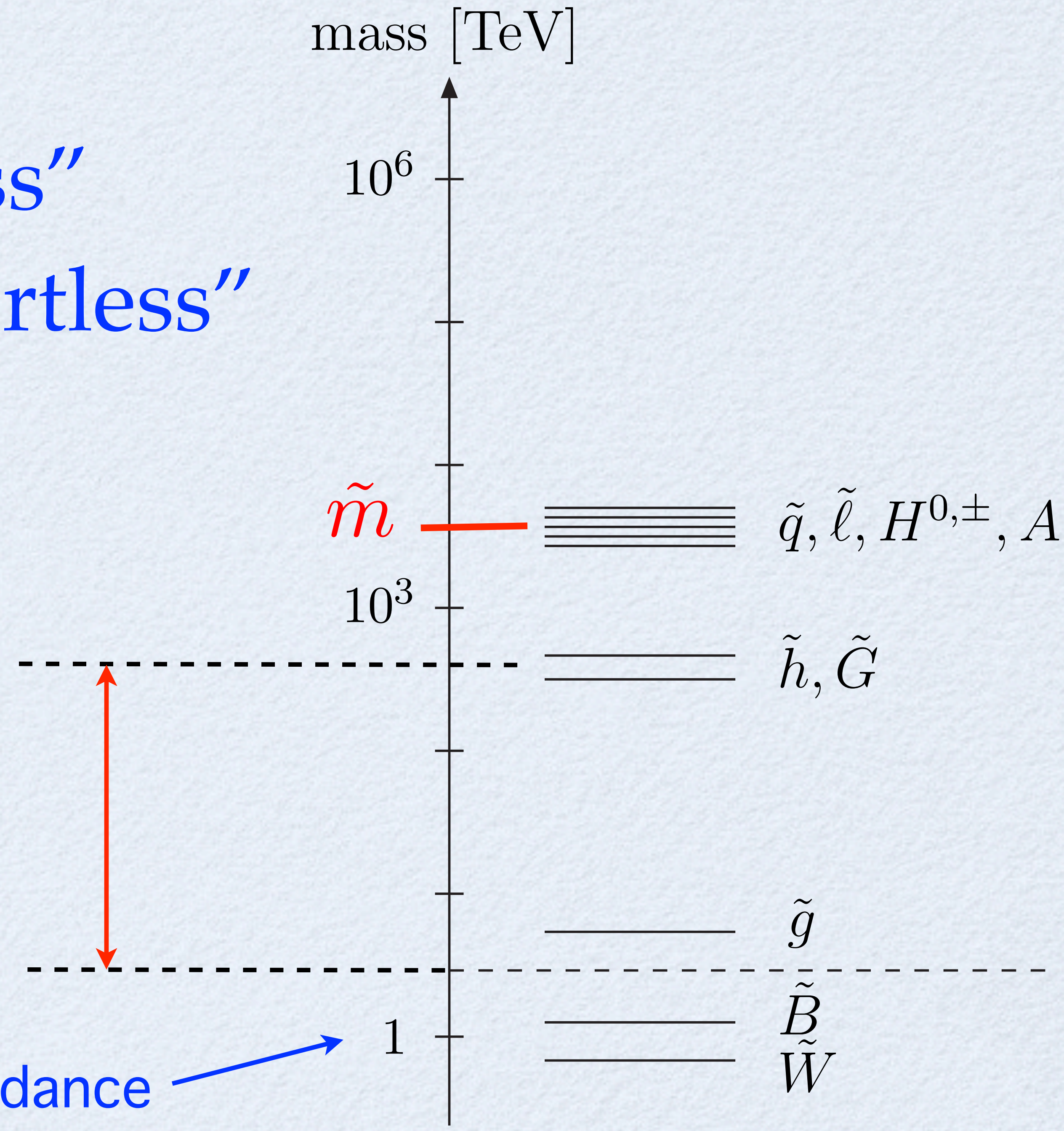

Mass scale normalized by dark matter abundance

Early studies:

Wells hep-ph/0411041
Arkani-Hamed, Delgado, Giudice ph/0601041

The LHC-Induced Revival

Spread

Hall, Nomura arXiv:1111.4519

Pure Gravity Mediation

Ibe, Yanagida arXiv:1112.2462

Mini-Split

Arvanitaki, Craig, Dimopoulos, Villadoro arXiv:1210.0555

Simply Unnatural

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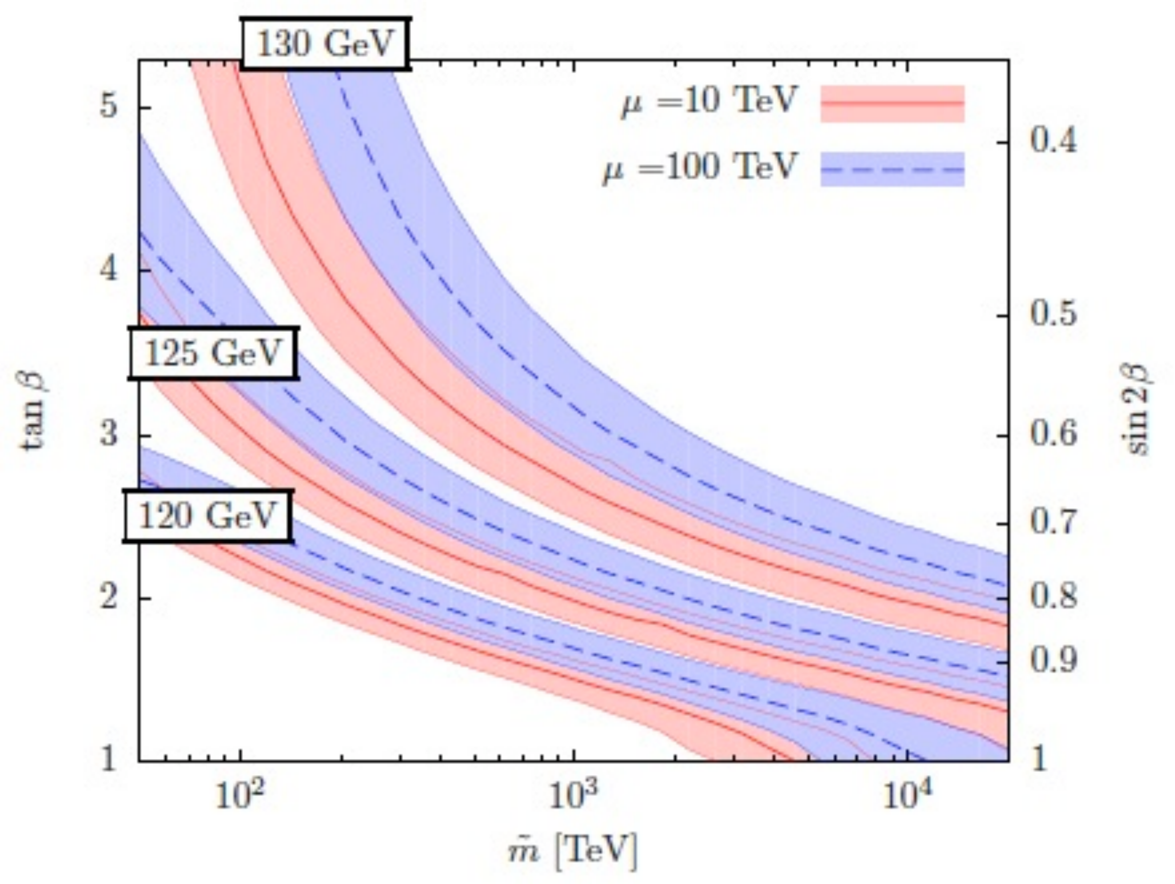
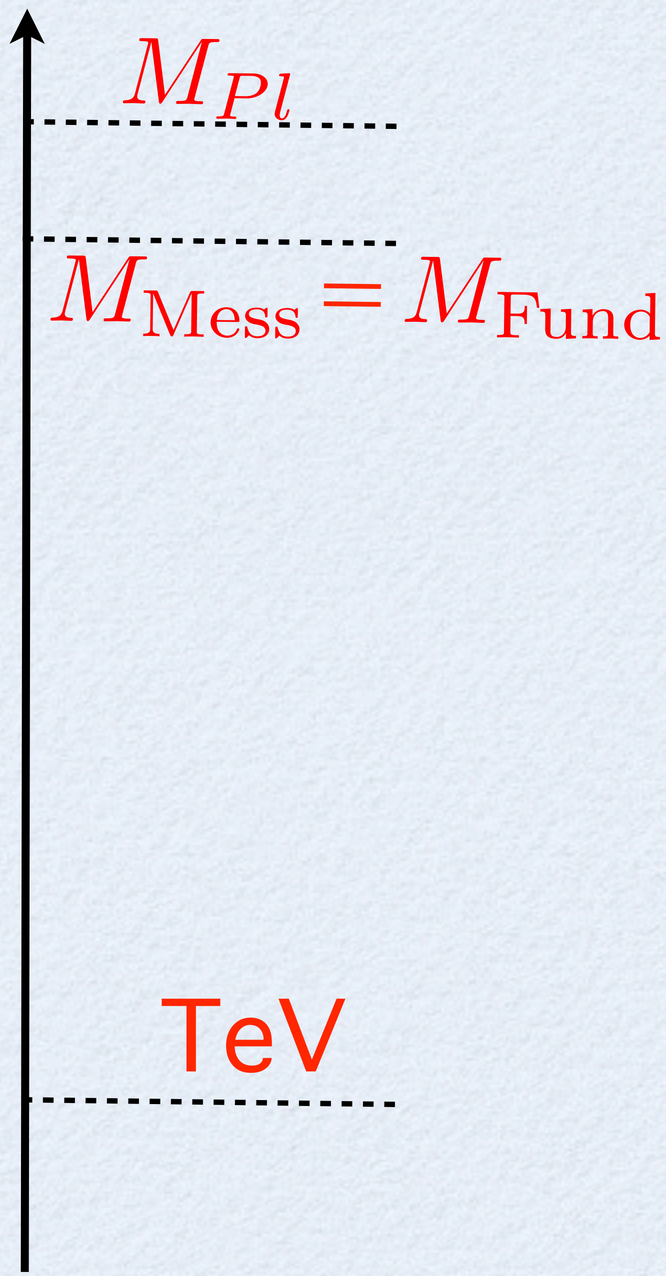


Hall, Nomura, Shirai arXiv:1210.2395

Mass Scales

Key mass scales



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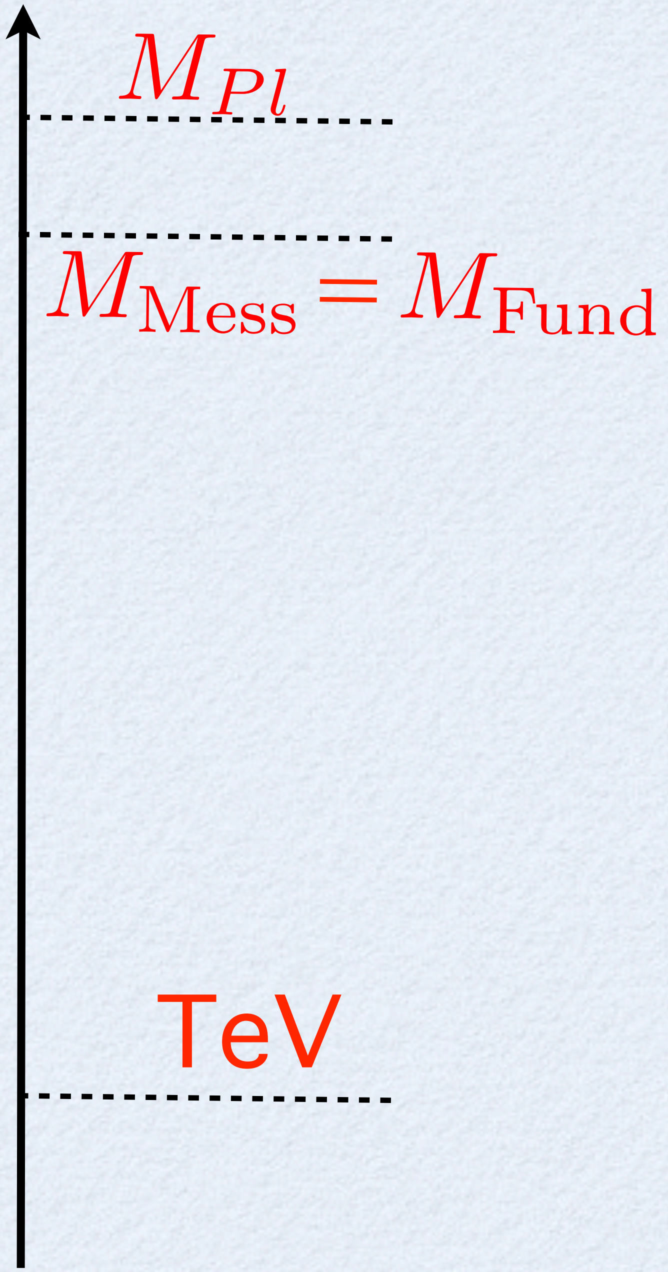
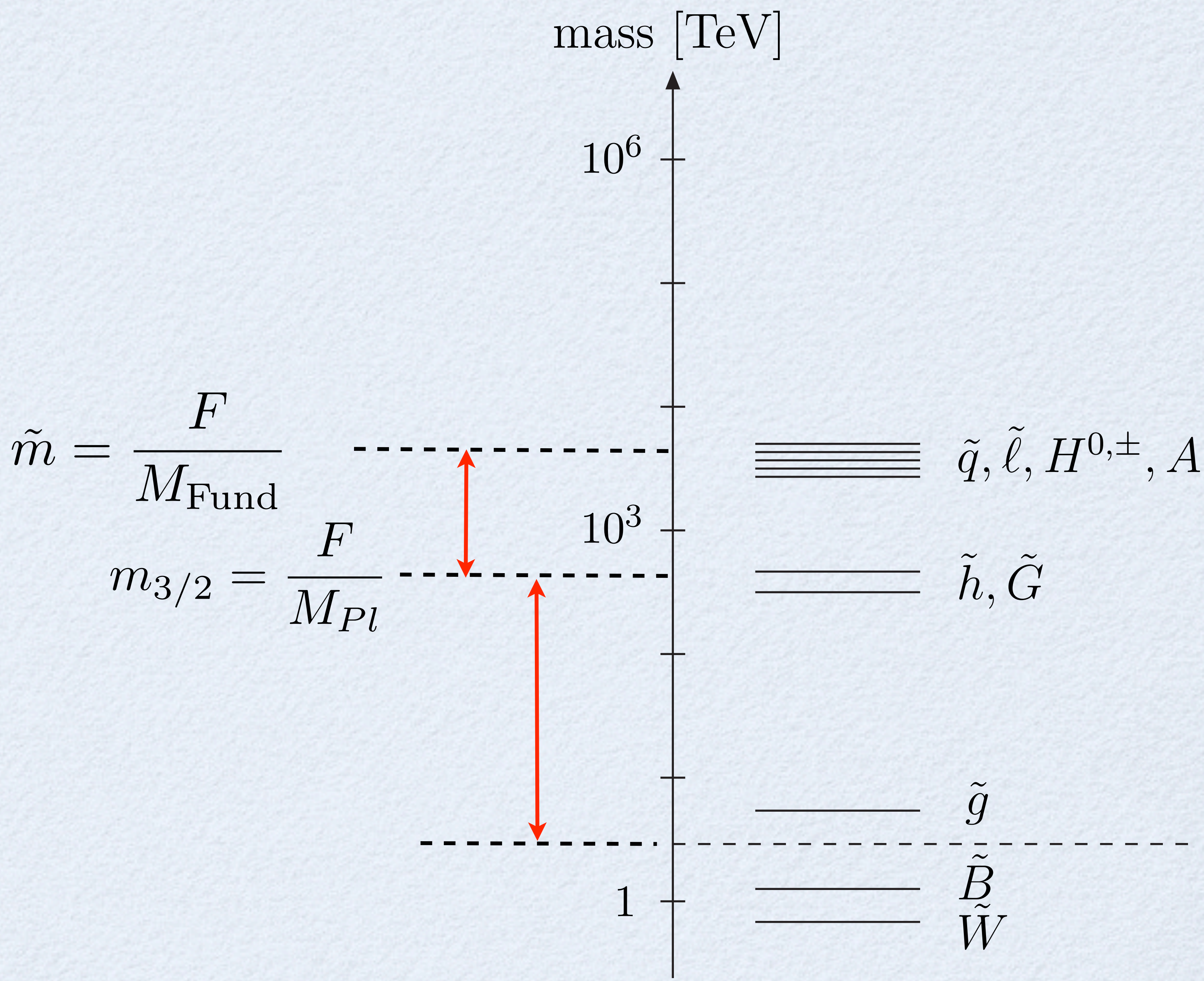


A Spread Susy spectrum



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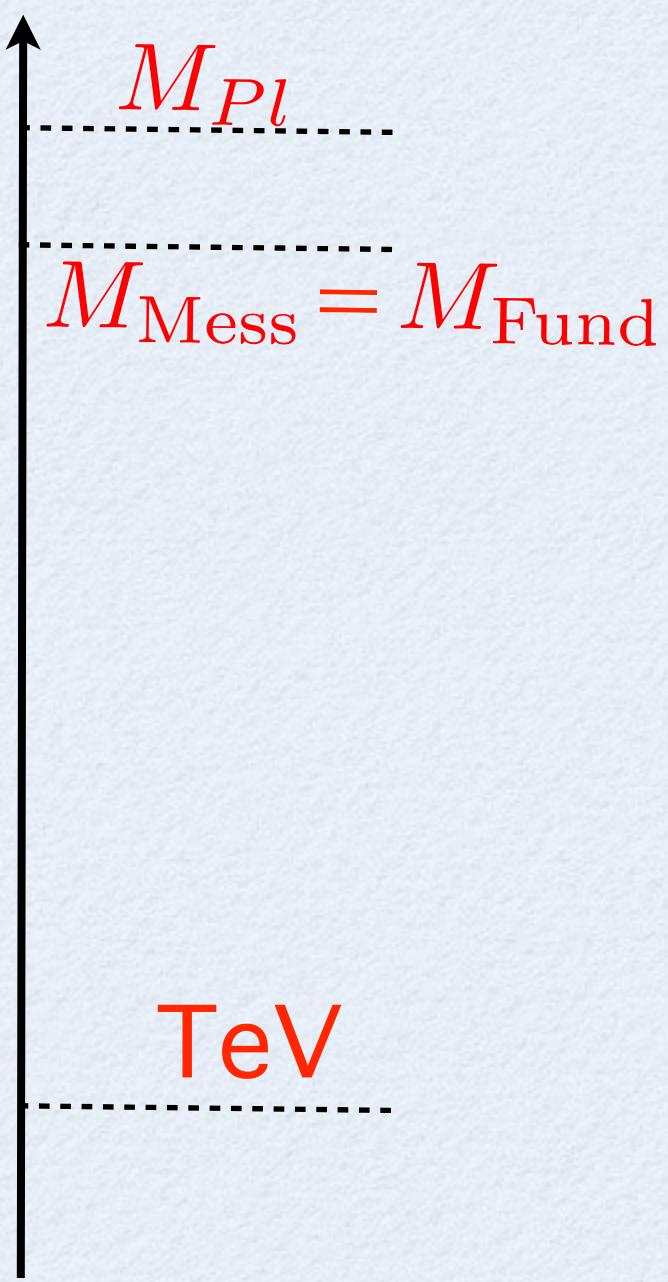

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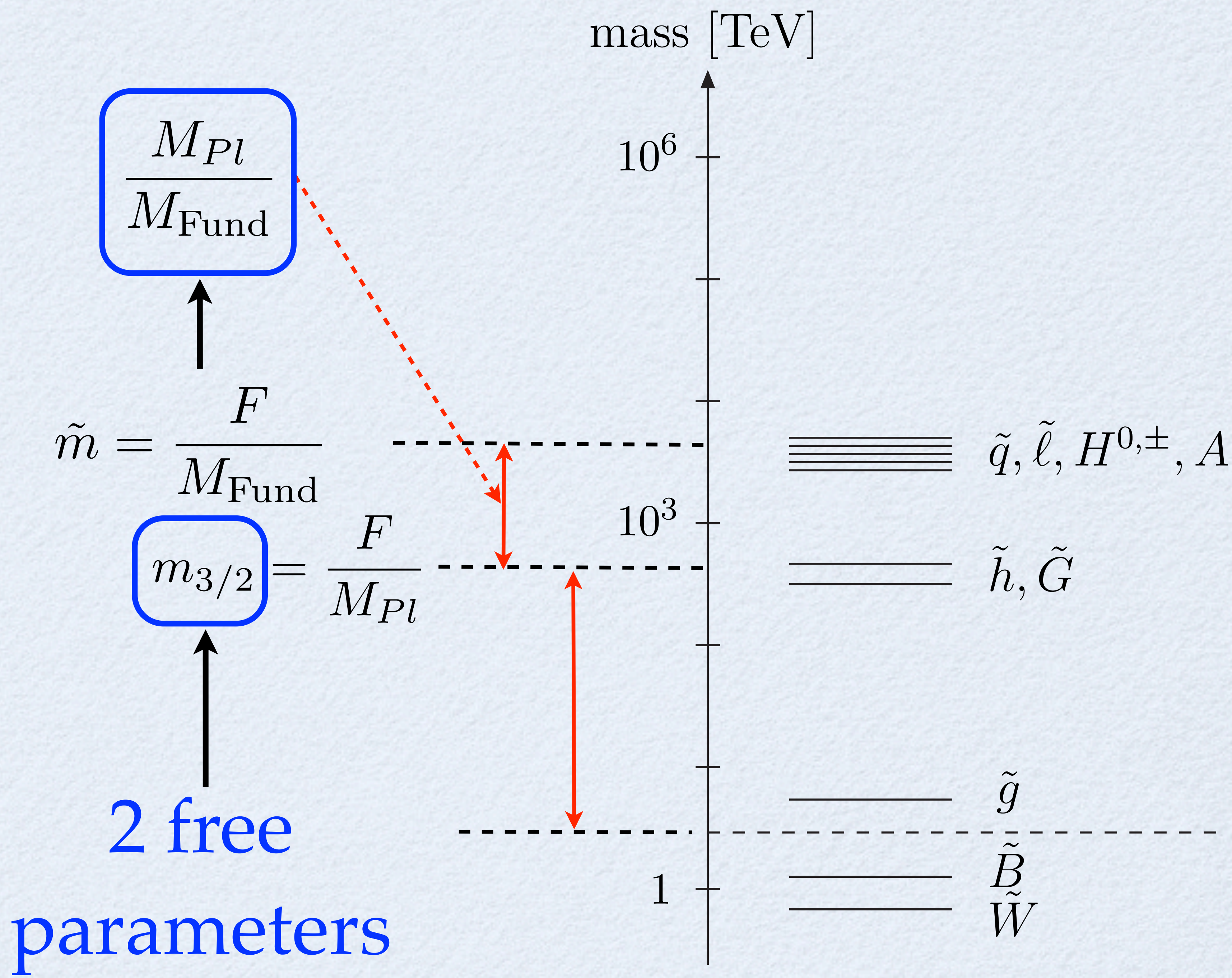

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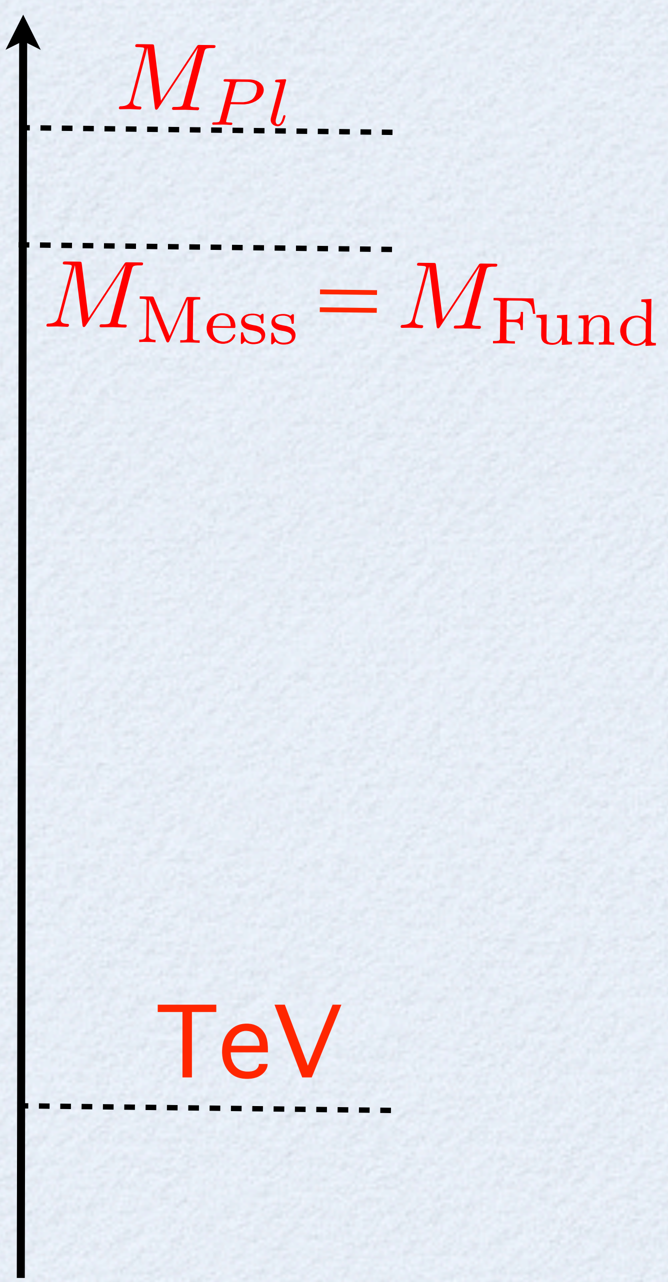

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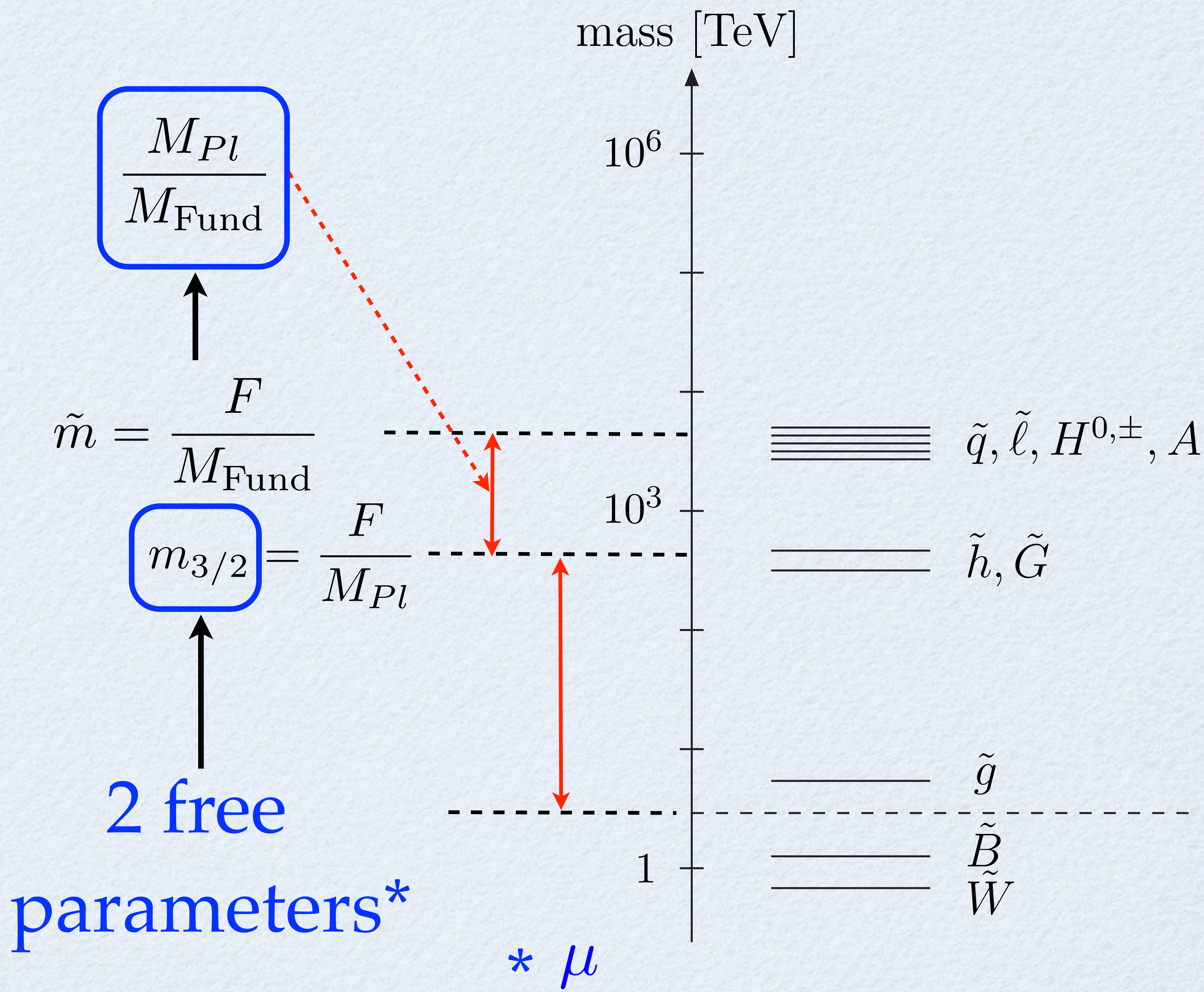
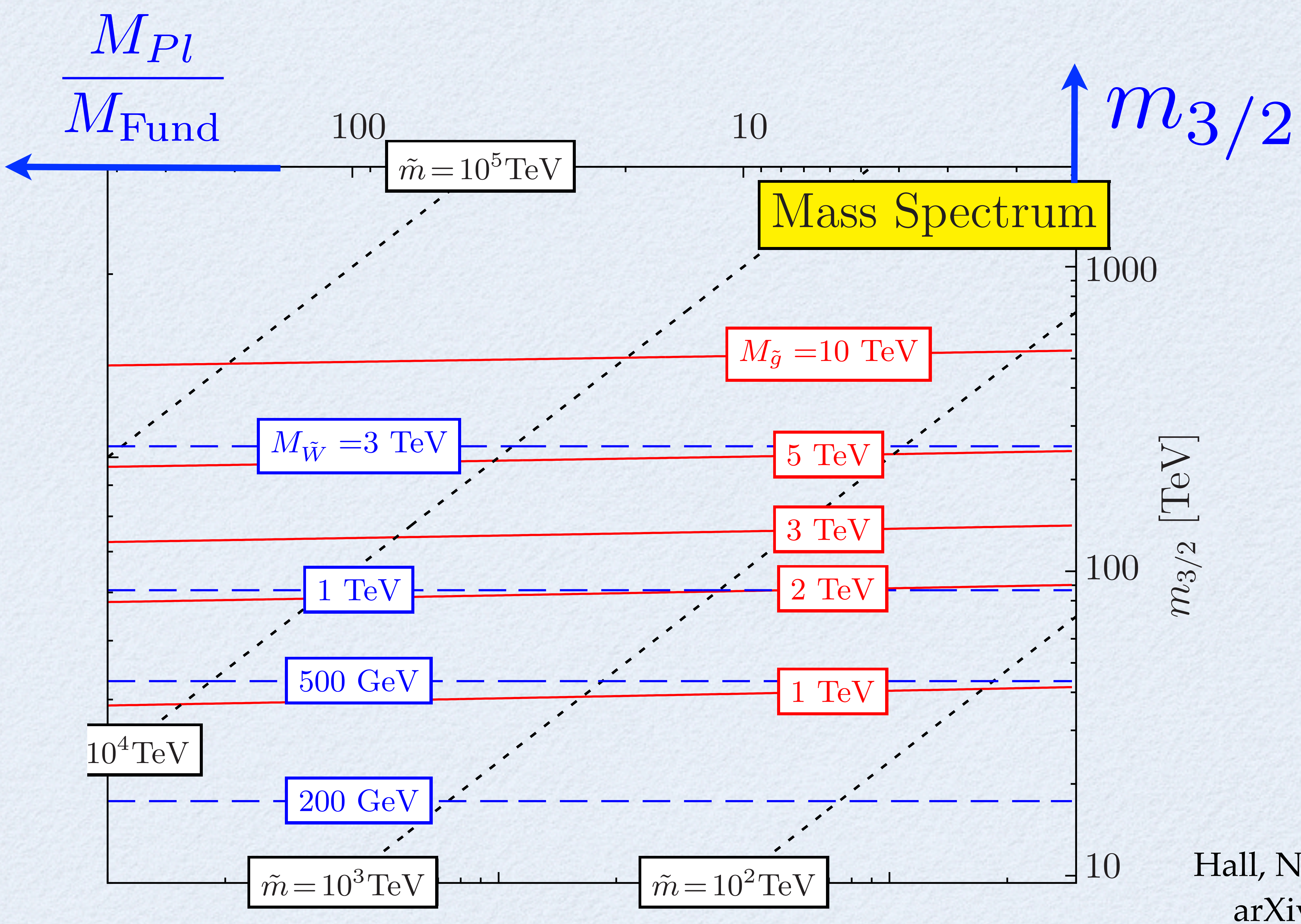
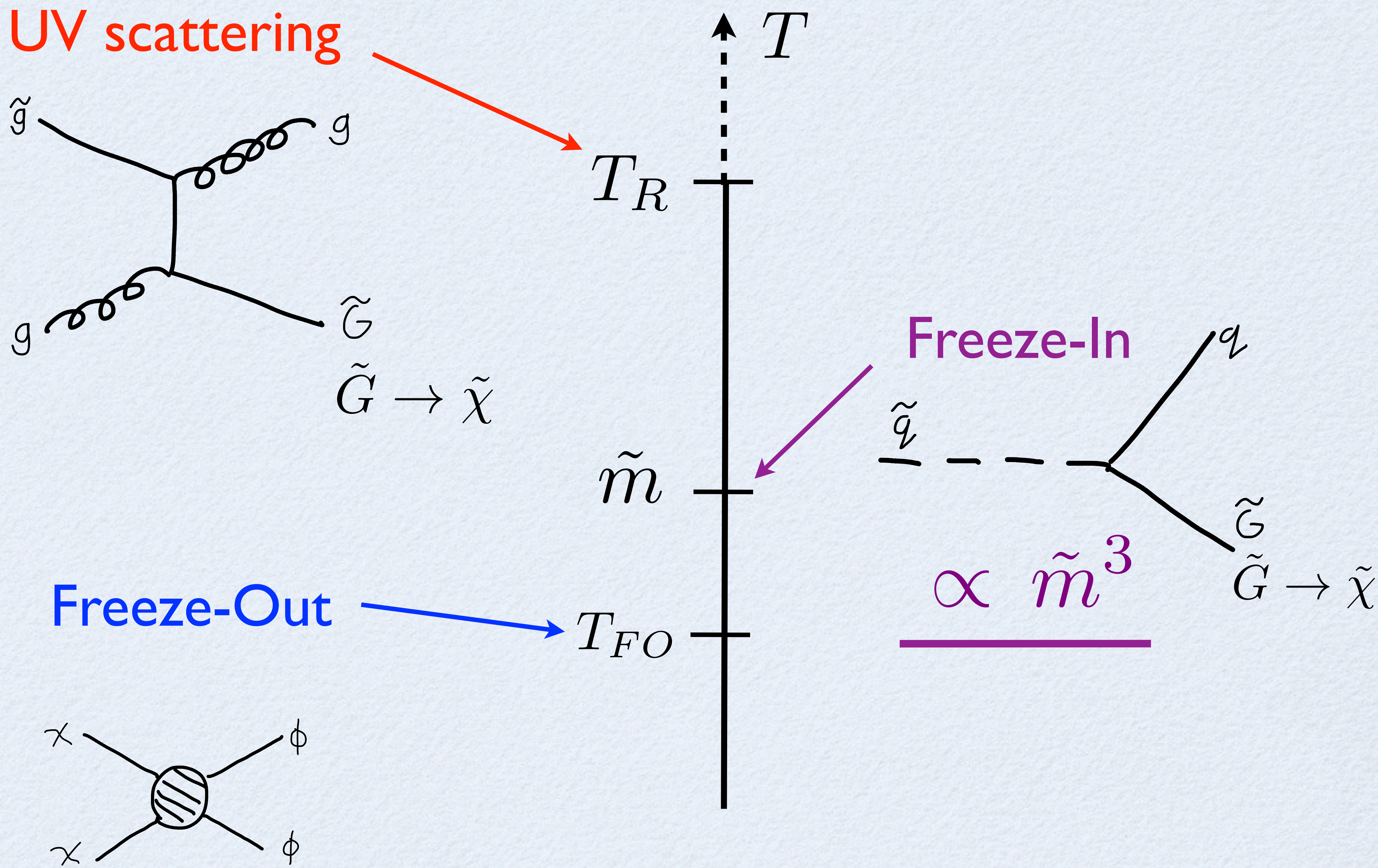


Susy Spectrum

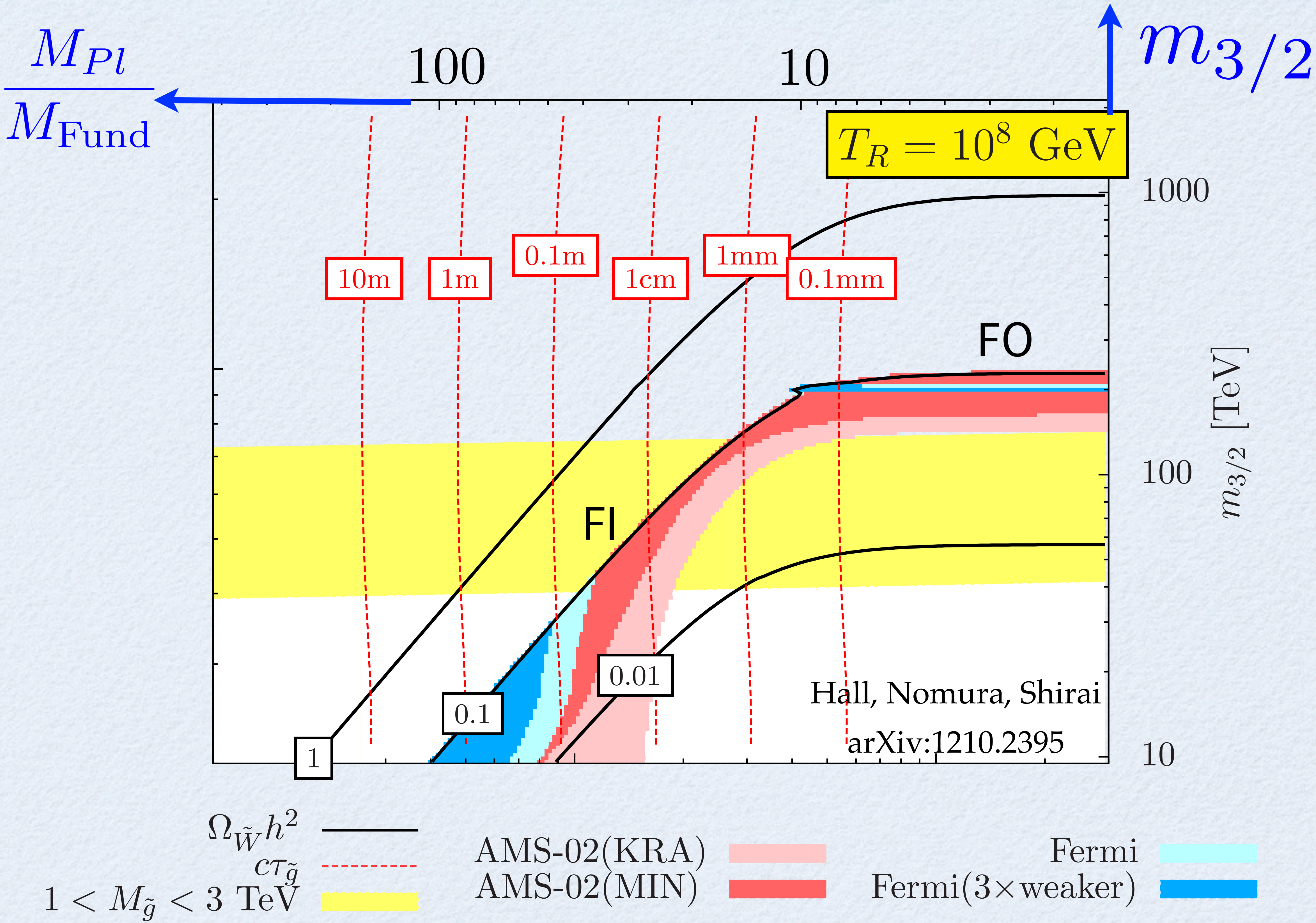


Hall, Nomura, Shirai
arXiv:1210.2395

3 Dark Matter Production Mechanisms



Dark Matter Abundance



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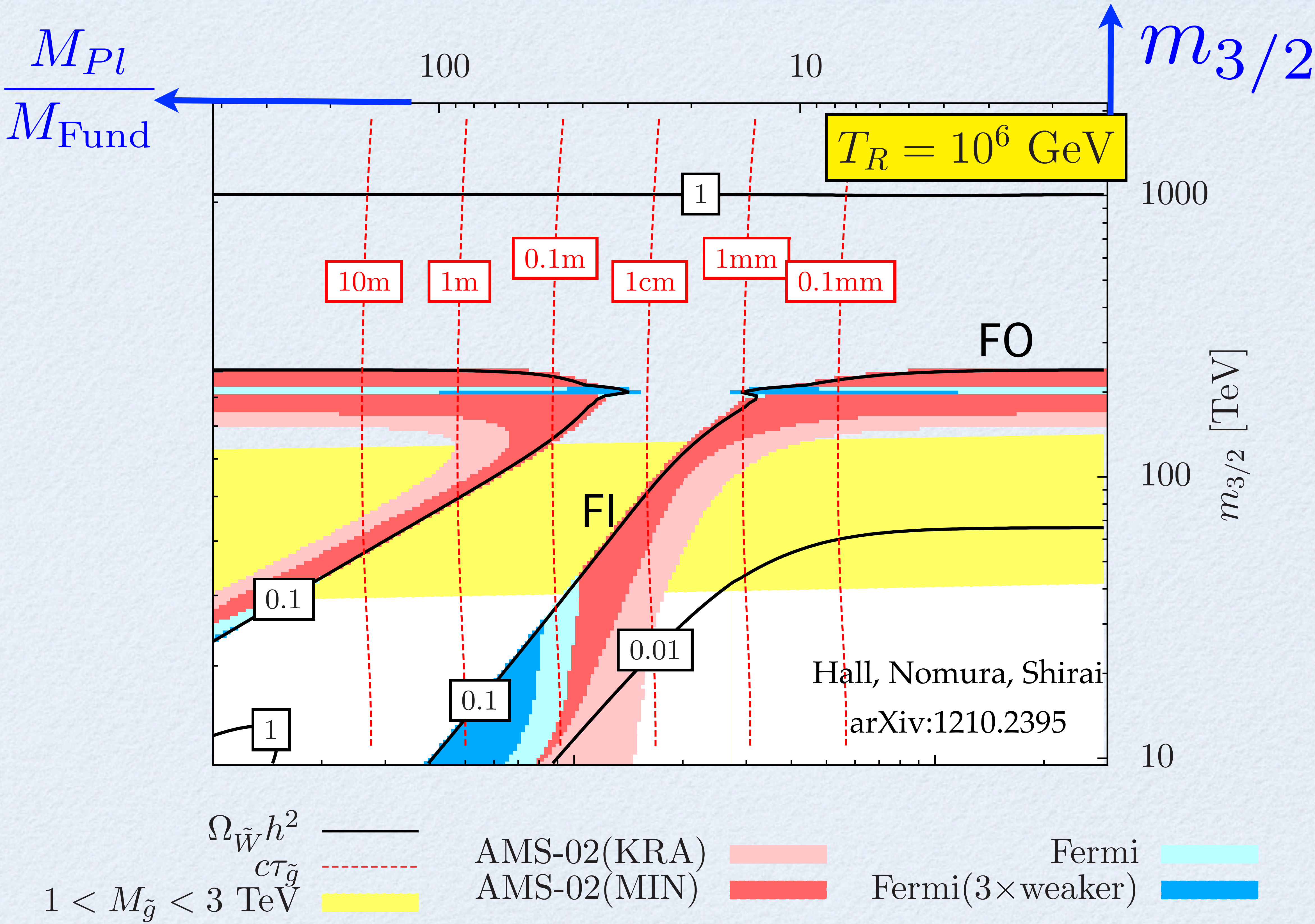
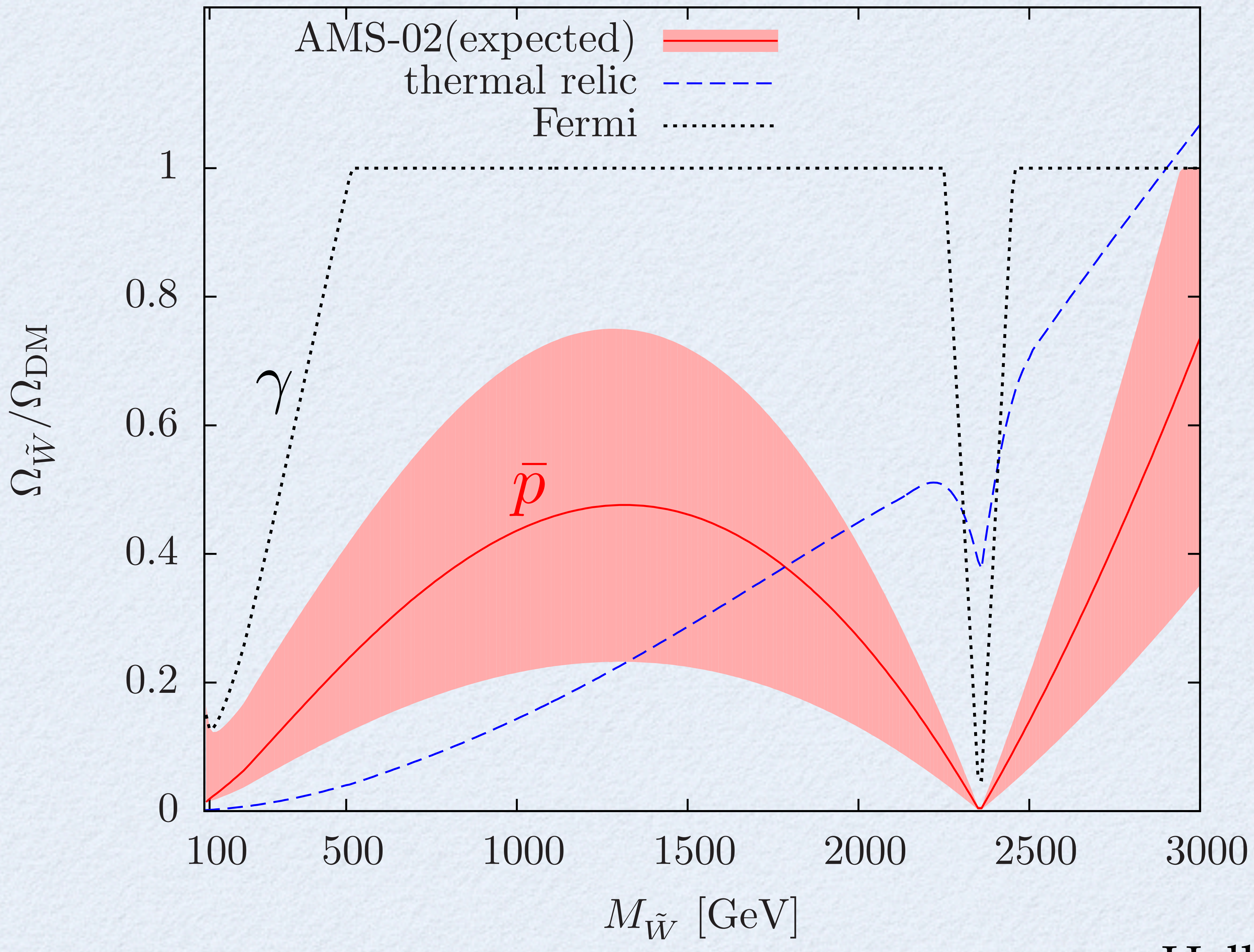


Indirect Detection of Wino DM



Hall, Nomura, Shirai
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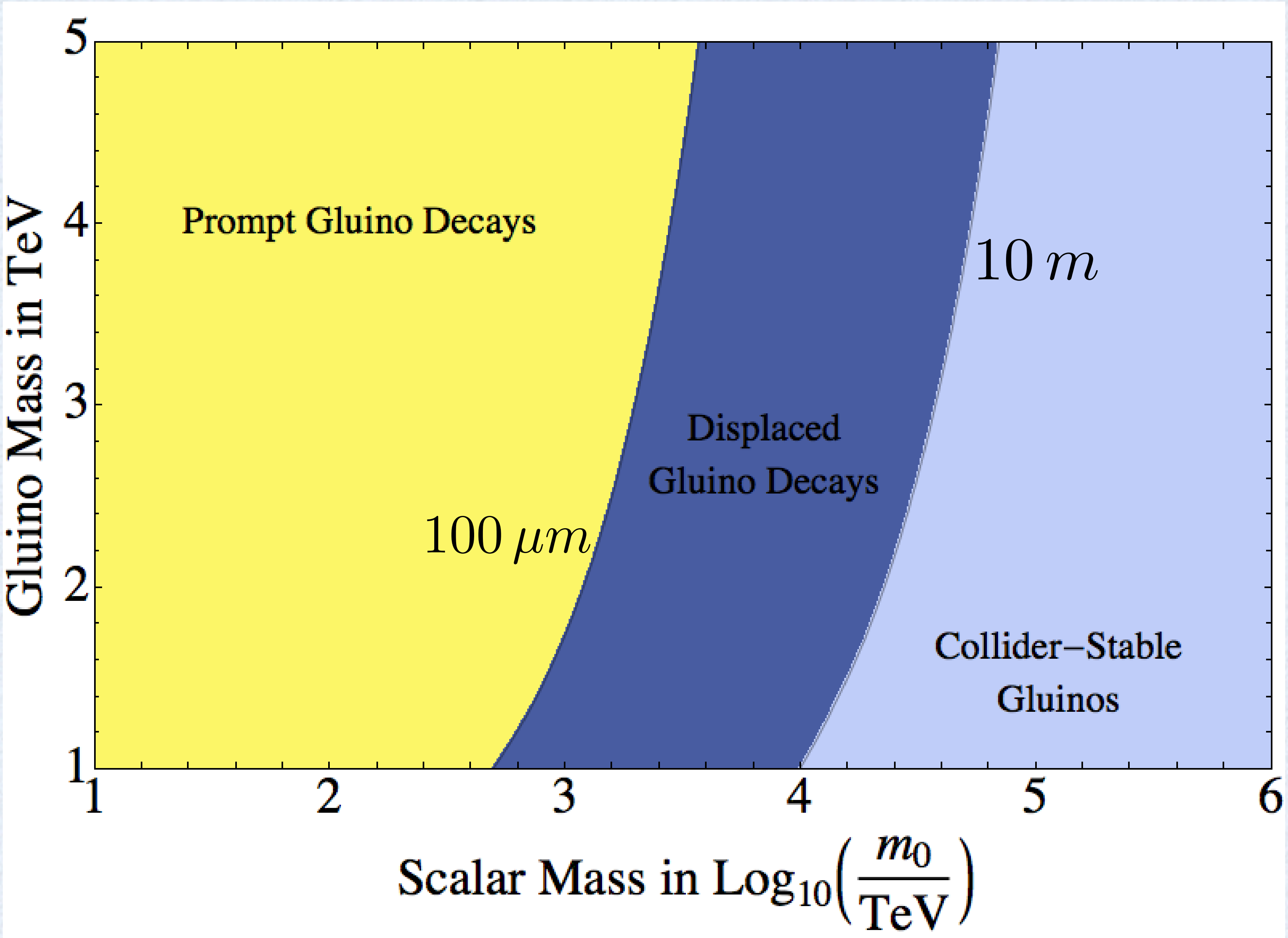
Gluino Pheno



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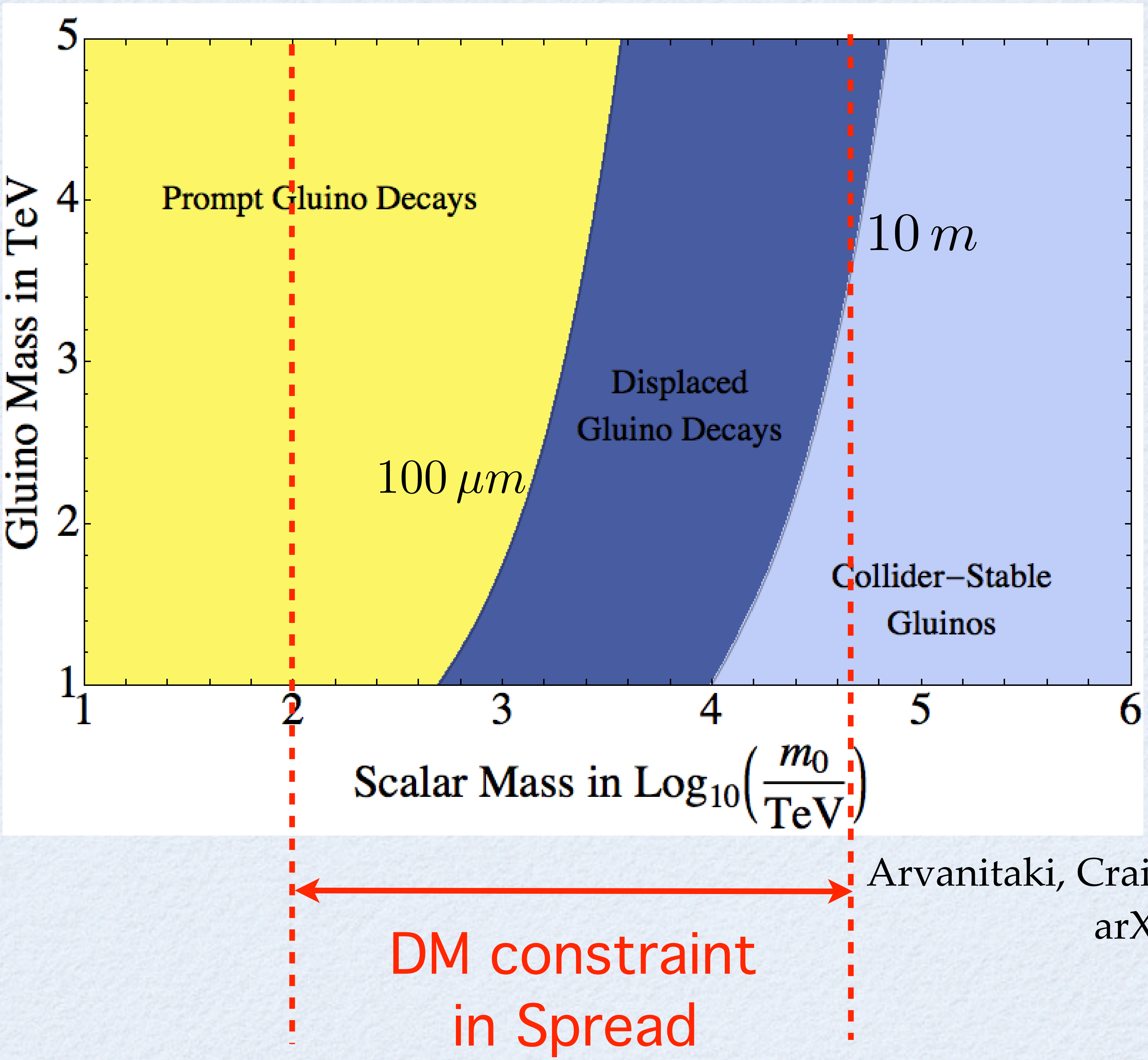


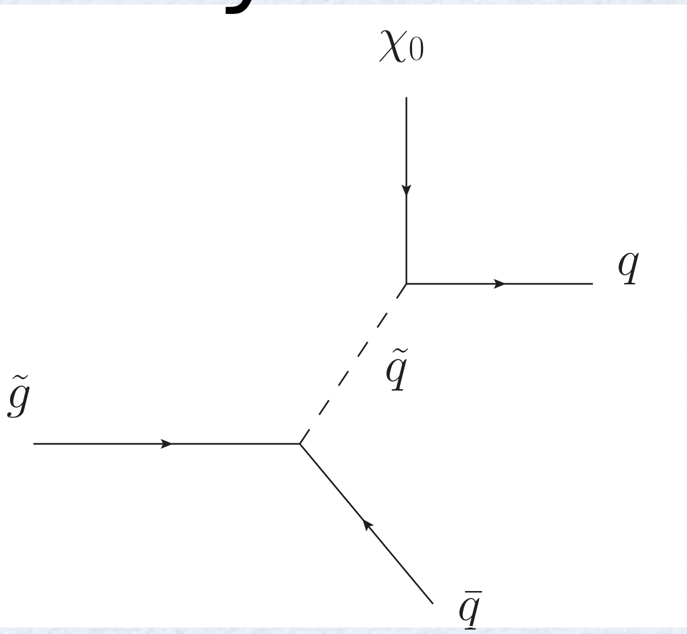
DM constraint
in Spread

Arvanitaki, Craig, Dimopoulos, Villadoro
arXiv:1210.0555

Decay Cascades

Gluino Decays

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski arXiv:1210.0555



$$\tilde{g} \to \bar{t}t\tilde{W}^0$$

$$\tilde{g} \to \bar{b}b\tilde{W}^0$$

only UV 3 params (comb. $\tilde{q}, \tilde{u}, \tilde{d}$ masses)

$$\tilde{g} \to \bar{t}b\tilde{W}^+$$

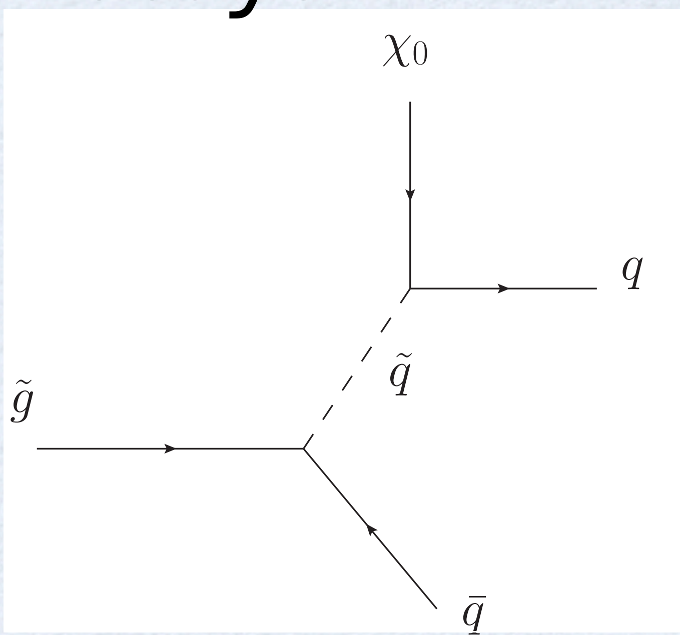
$$\tilde{g} \to \bar{t}t\tilde{B}^0$$

$$\tilde{g} \to \bar{b}b\tilde{B}^0$$

Decay Cascades

Gluino Decays

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski arXiv:1210.0555



$$\tilde{g} \to \bar{t}t\tilde{W}^0$$

$$\tilde{g} \to \bar{b}b\tilde{W}^0$$

only UV 3 params (comb. $\tilde{q}, \tilde{u}, \tilde{d}$ masses)

$$\tilde{g} \to \bar{t}b\tilde{W}^+$$

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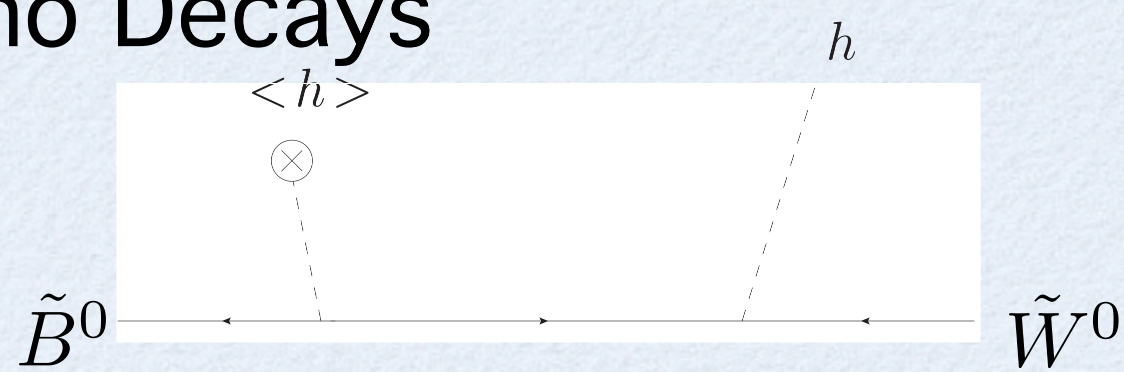
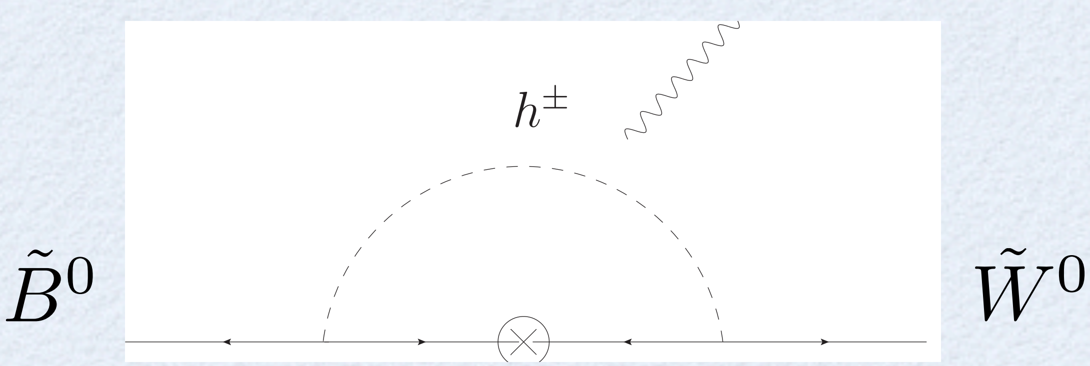
Bino Decays





$$\tilde{B}^0 \to \tilde{W}^0 h$$

$$\tilde{B}^0 \to \tilde{W}^- W^+$$

only μ

$$\tilde{B}^0 \to \tilde{W}^0 Z$$

$$\tilde{B}^0 \to \tilde{W}^0 \gamma$$

$$\sin^2\theta_W / \cos^2\theta_W \sim 1/3.$$

Decay Cascades

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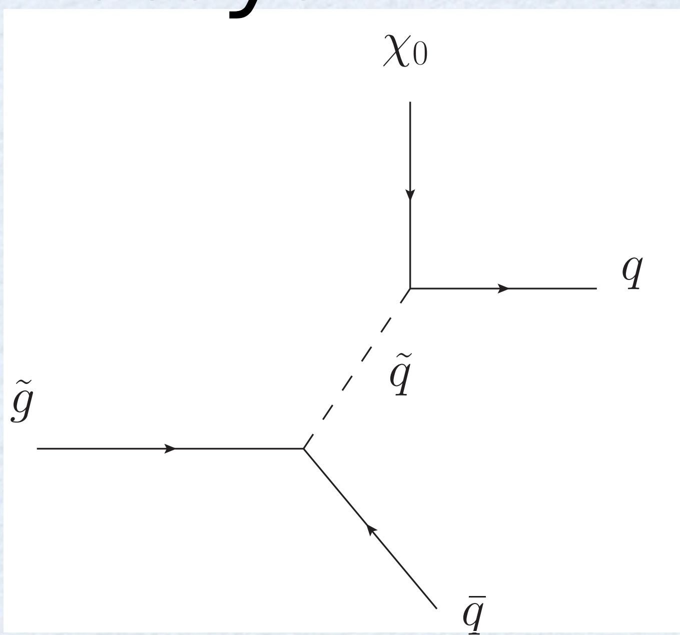


$\tilde{g} \to \bar{t}t\tilde{W}^0$

$\tilde{g} \to \bar{b}b\tilde{W}^0$

only UV 3 params (comb. $\tilde{q}, \tilde{u}, \tilde{d}$ masses)

$\tilde{g} \to \bar{t}b\tilde{W}^+$

$\tilde{g} \to \bar{t}t\tilde{B}^0$

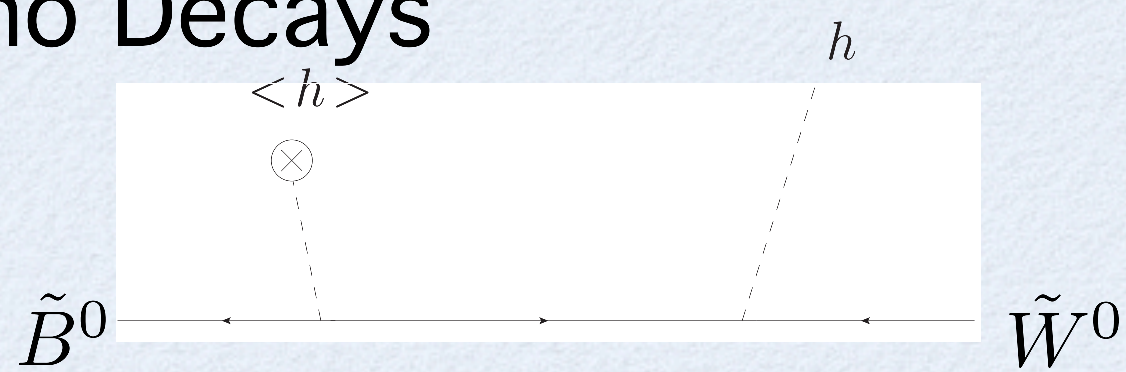
$\tilde{g} \to \bar{b}b\tilde{B}^0$

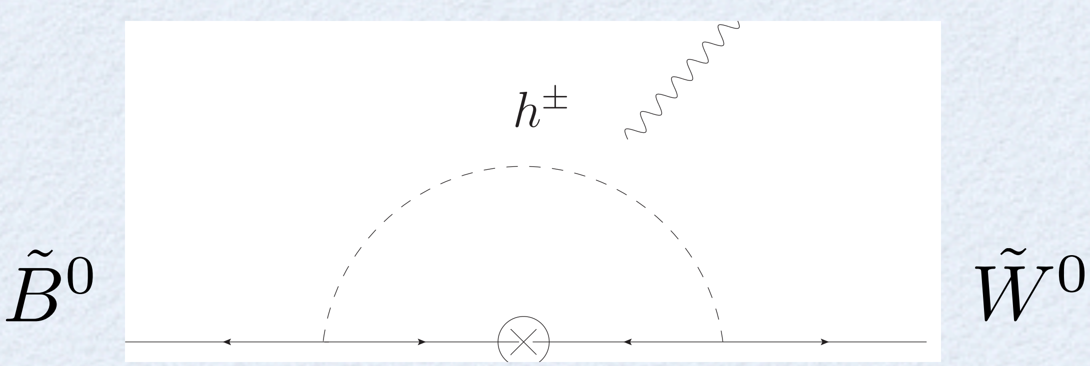
Wino Decays

$\tilde{W}^\pm \to \tilde{W}^0\pi^\pm$

$\approx 10\,\mathrm{cm}$

Bino Decays





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$h \to \gamma\gamma$

If μ reduced

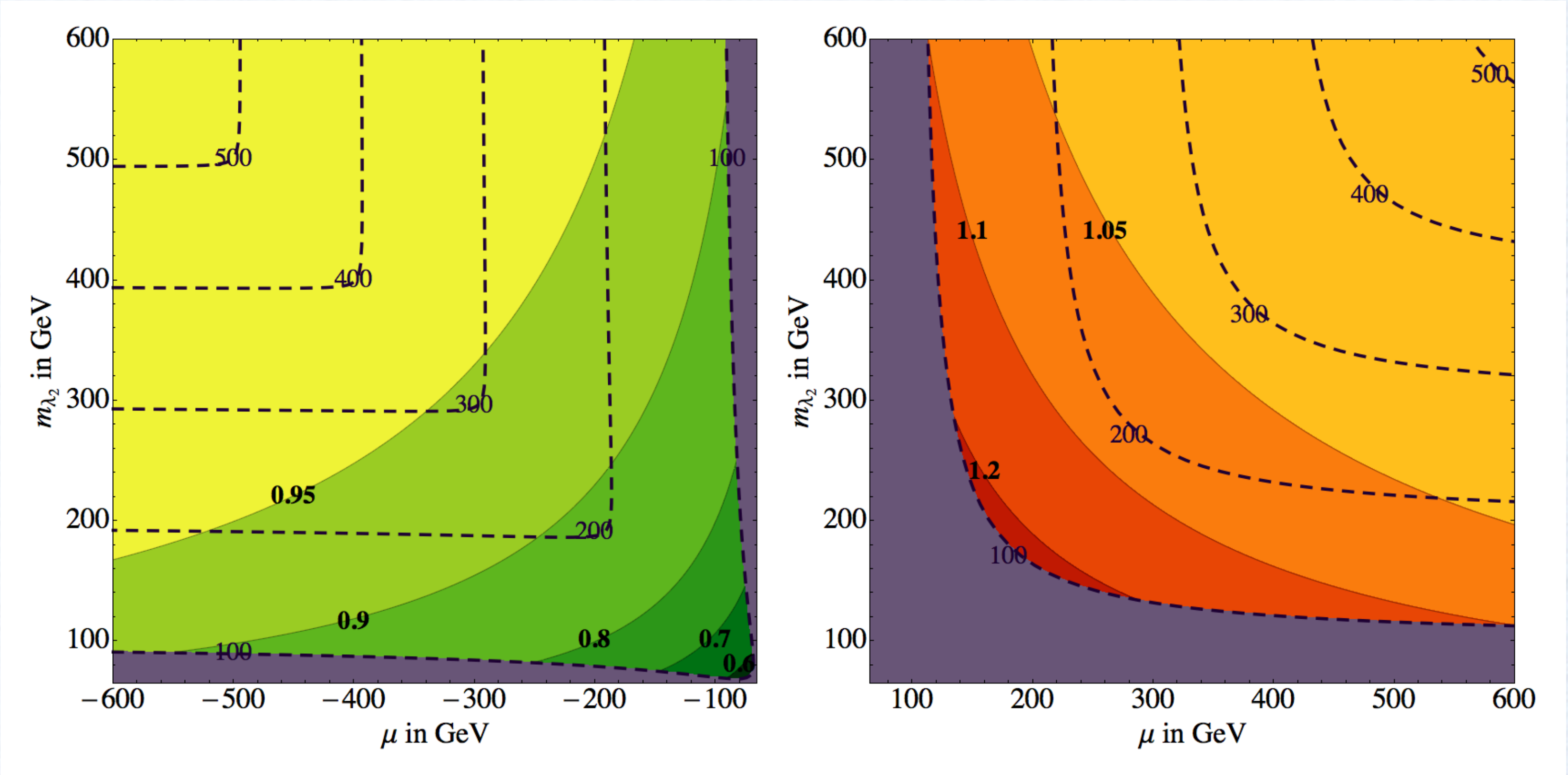

Figure 12: Contours of $\Gamma_{h\to\gamma\gamma}/\Gamma^{SM}_{h\to\gamma\gamma}$ in the higgsino-wino mass plane for $\mu m_{\lambda_2} < 0$ (left) and $\mu m_{\lambda_2} > 0$ (right) with $\tan\beta = 1$. The dashed contours denote the lightest chargino mass in GeV. The purple-shaded region indicates the LEP2 exclusion of charginos lighter than ~ 100 GeV.

Arvanitaki, Craig, Dimopoulos, Villadoro
arXiv:1210.0555

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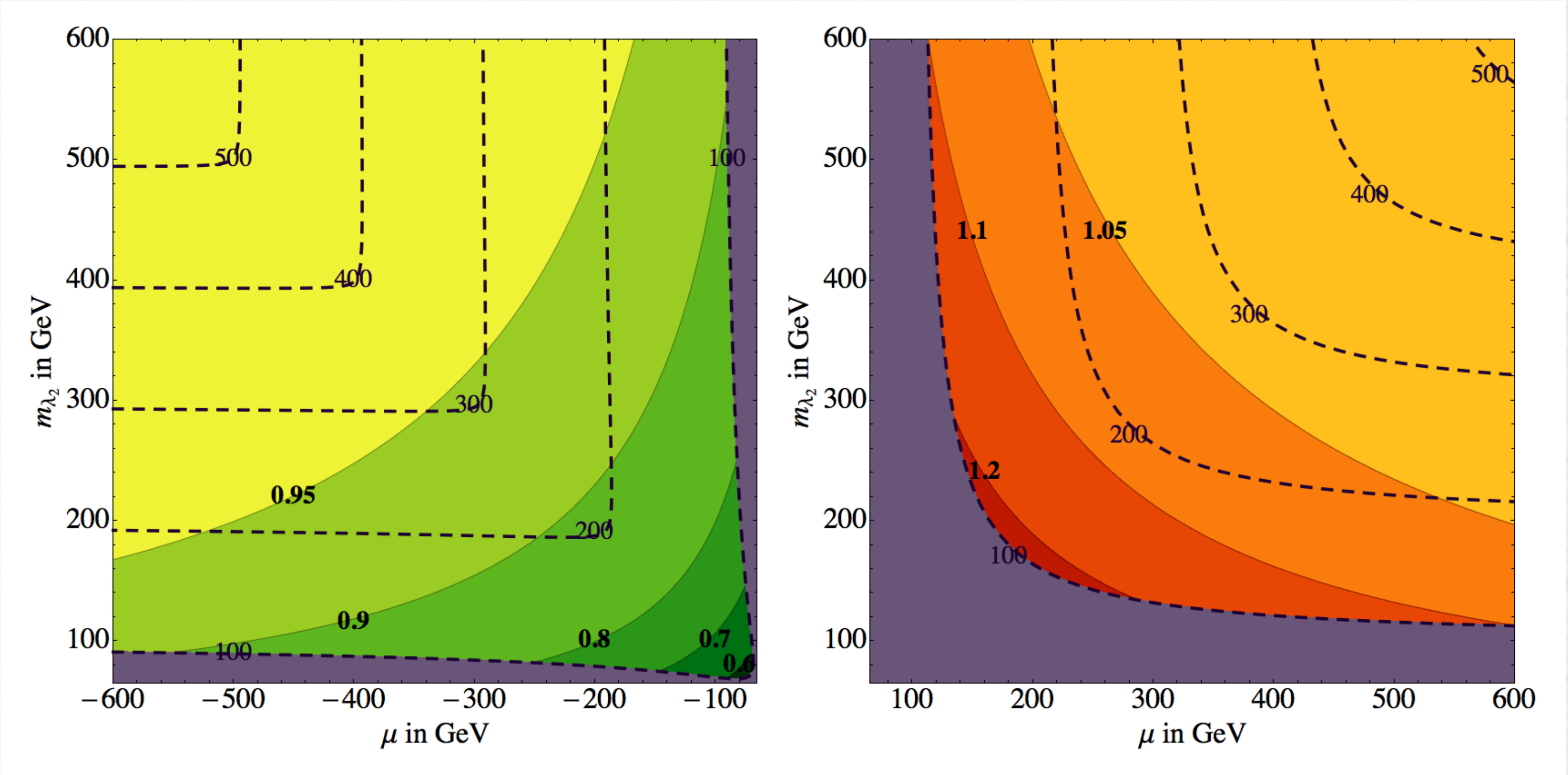

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Arvanitaki, Craig, Dimopoulos, Villadoro arXiv:1210.0555

Large $\mu_{\gamma\gamma}$ would exclude Spread SUSY and many other unnatural theories

Arkani-Hamed, Blum D'Agnolo, Fan arXiv:1207.4482

Flavor and CP

$\tilde{m} \sim 10^3\,\mathrm{TeV}$

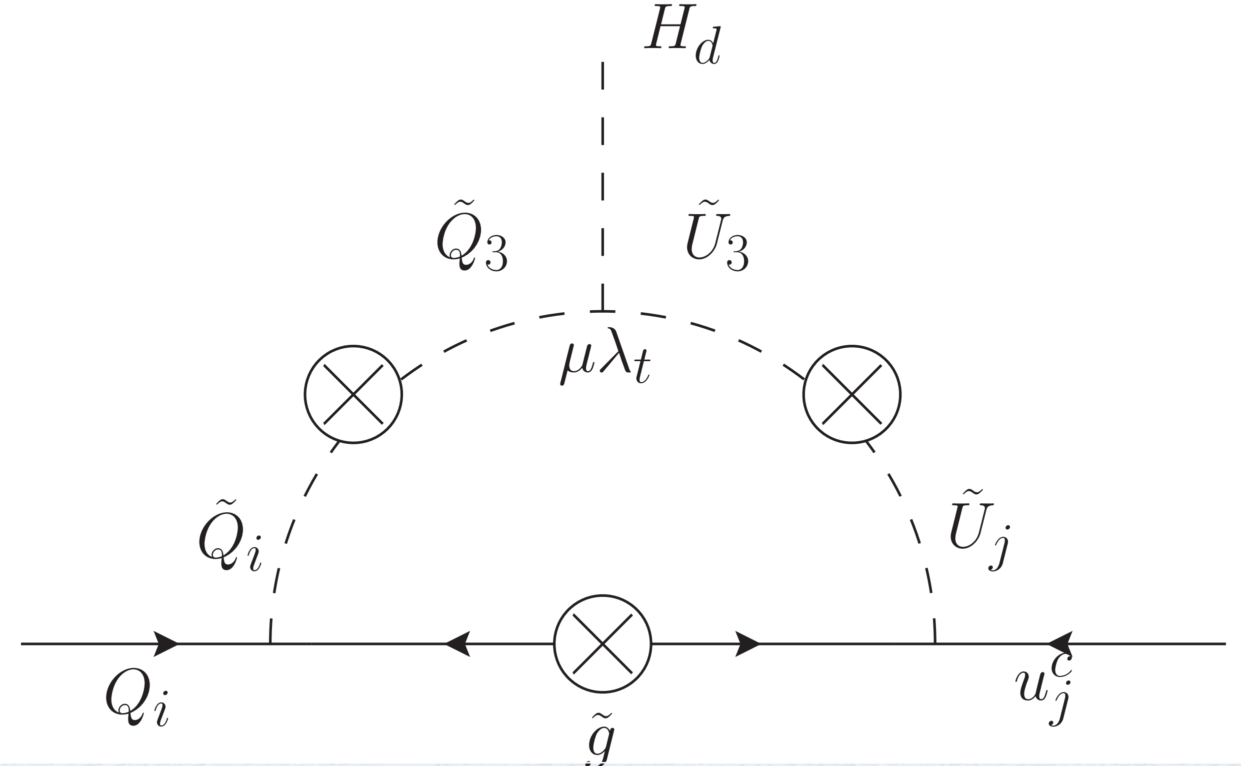
Solves susy flavor/CP problem

Flavor and CP

$\tilde{m} \sim 10^3$ TeV

Solves susy flavor/CP problem

Changes the game of radiative quark and lepton masses



$$\delta\lambda_u^{ij} \sim \frac{\alpha_s}{4\pi}\frac{m_{Qi3}^2}{m_{sc}^2}\frac{m_{Uj3}^2}{m_{sc}^2}\frac{\lambda_t}{\tan\beta}\frac{\mu m_{\tilde{g}}}{m_{sc}^2}$$

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski arXiv:1210.0555

Nuclear EDMs

McKeen, Pospelov, Ritz
arXiv:1303.1172

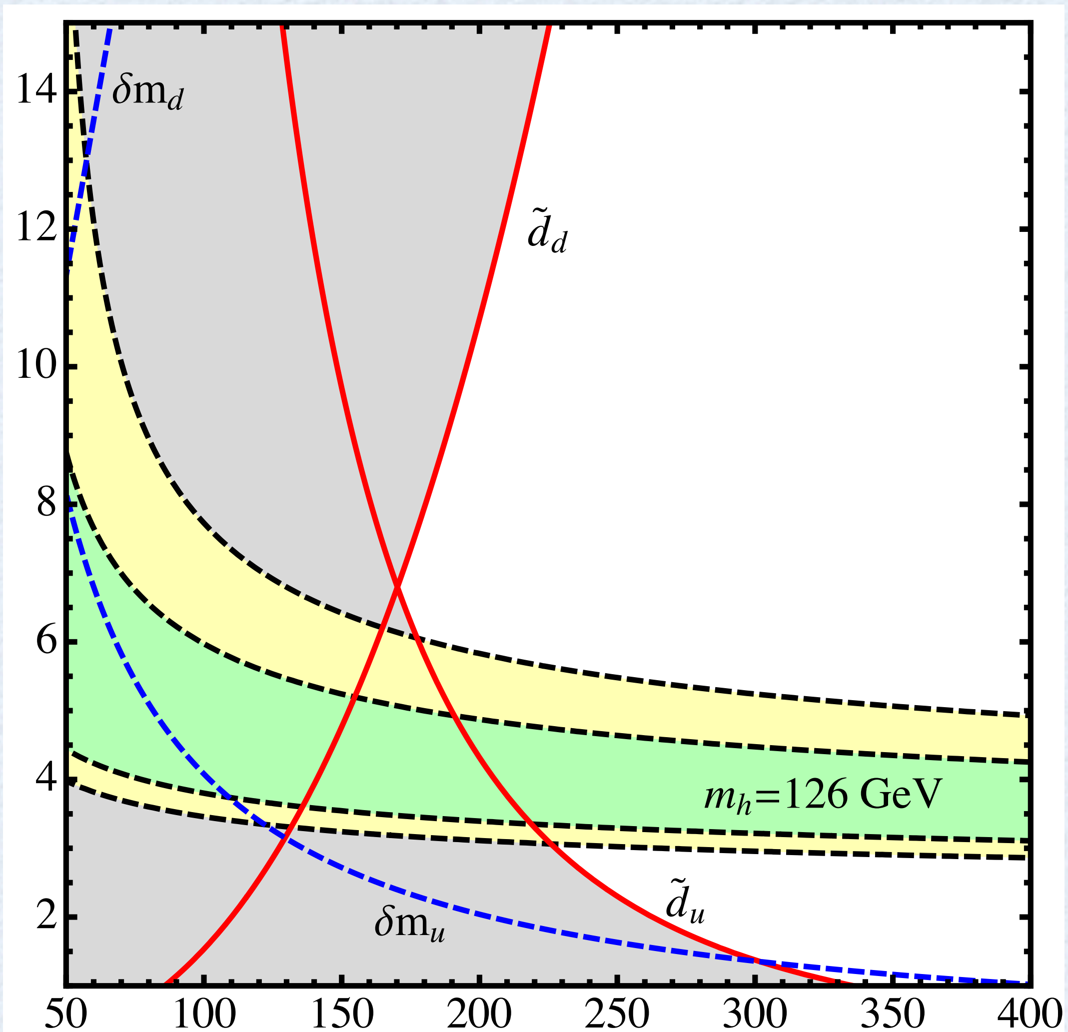


FIG. 2. Contours of $\delta m_u = 1\,\text{MeV}$ and $\delta m_d = 2\,\text{MeV}$ (blue, dashed) and $\tilde{d}_q = 6 \times 10^{-27}$ cm for $q = u, d$ (red, solid) are shown, with $\theta^2_{q13} = 1/3$, $M_3 = 1$ TeV, and $\sin\phi_{\tilde{q}\mu} = 1/\sqrt{2}$. If the limit $|\tilde{d}_u - \tilde{d}_d| \lesssim 6 \times 10^{-27}$ cm from the mercury EDM [11] is interpreted as a limit on $\tilde{d}_u(\theta_{\tilde{u}\mu})$ and $\tilde{d}_d(\theta_{\tilde{d}\mu})$ independently, given the distinct CP phases, then the shaded region to the left of each contour is ruled out. For comparison, we have

P Decay

d=6: Enhanced:

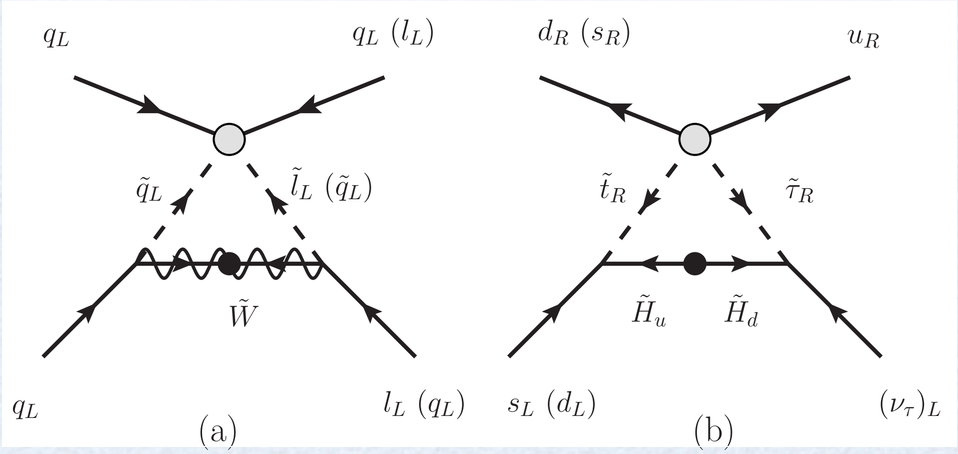
SU(5) gauge bosons lighter

Hall, Nomura
arXiv:1111.4519

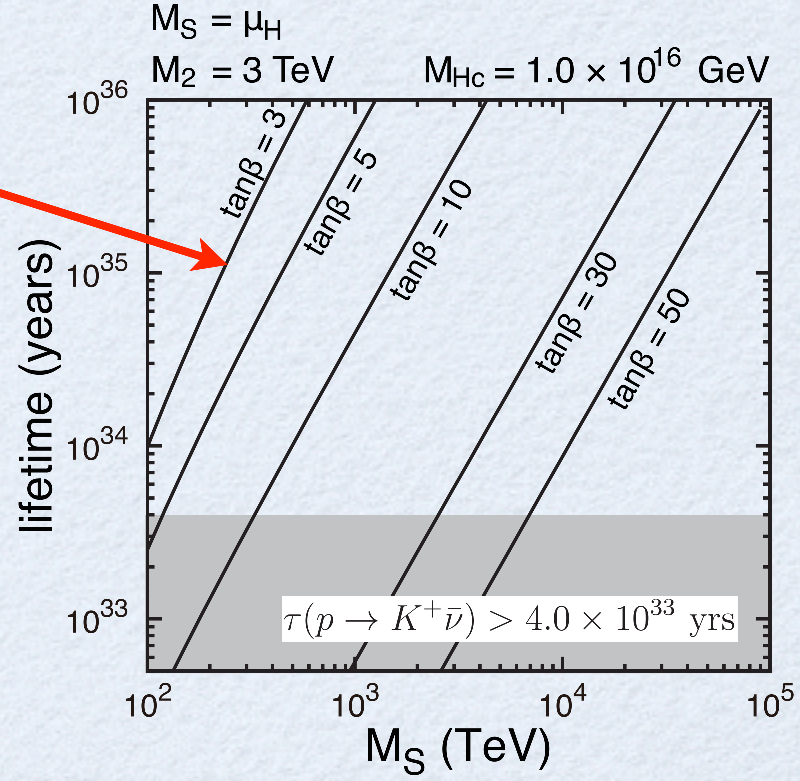
d=5: Minimal SU(5) Alive

squarks and sleptons heavier

Hisano, Kobayashi, Kuwahara, Nagata
arXiv:1304.3651



m_h



Conclusions

Unnatural Susy:

1. TeV-scale superpartners are well-motivated by DM.

2. Signals (collider, DM, flavor) are possible but not guaranteed.

TeV Scale from SUSY Dark Matter

1. The LSP is cosmologically stable
2. $T_R \geq \tilde{m}$
3. No Dilution

(Some) Superpartners at TeV Scale

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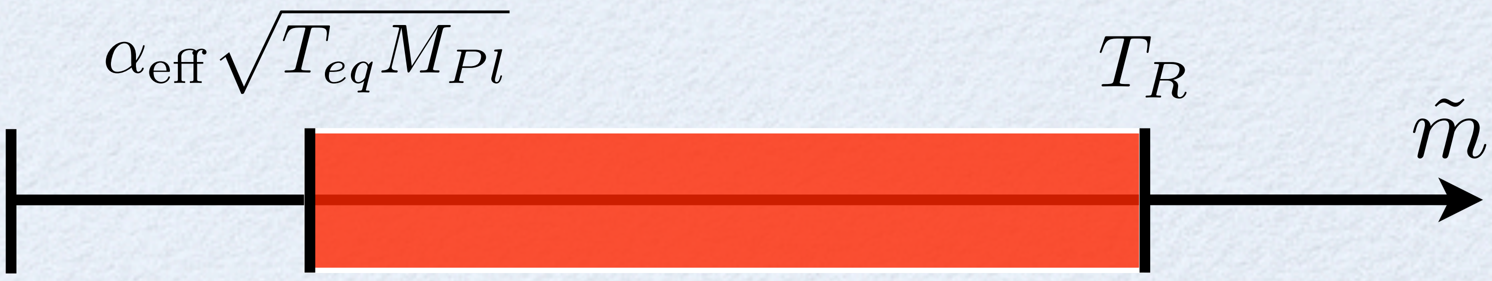
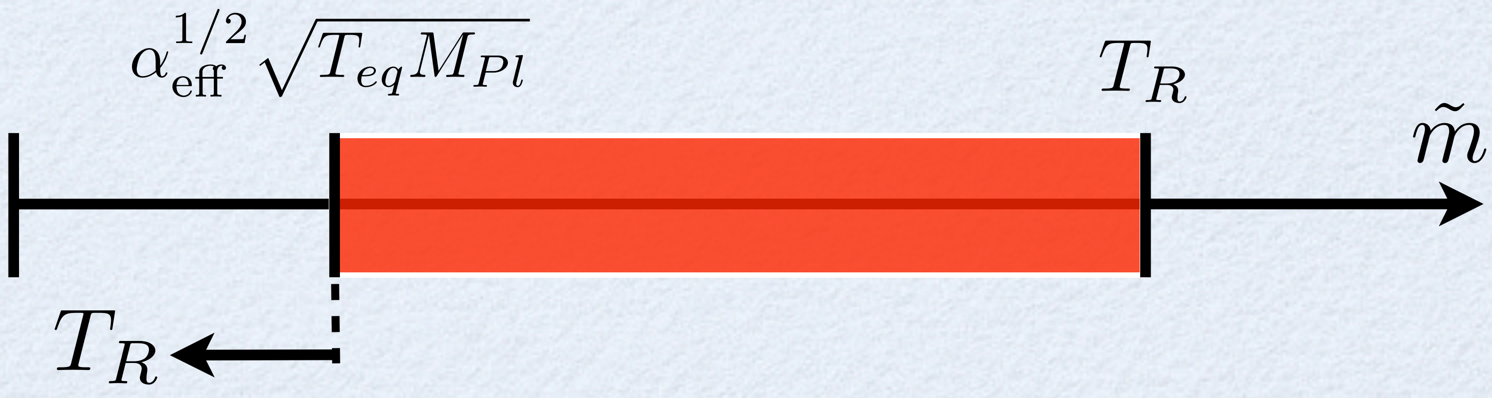
(Some) Superpartners at TeV Scale

$m_{3/2} > \tilde{m}$



$m_{3/2} < \tilde{m}$



Spread Susy: Only Gauginos at TeV Scale

125 GeV Higgs is "effortless"

DM can arise from gravitino decay

$\longrightarrow$ DM lighter than for FO

$\longrightarrow$ Displaced gluino decays

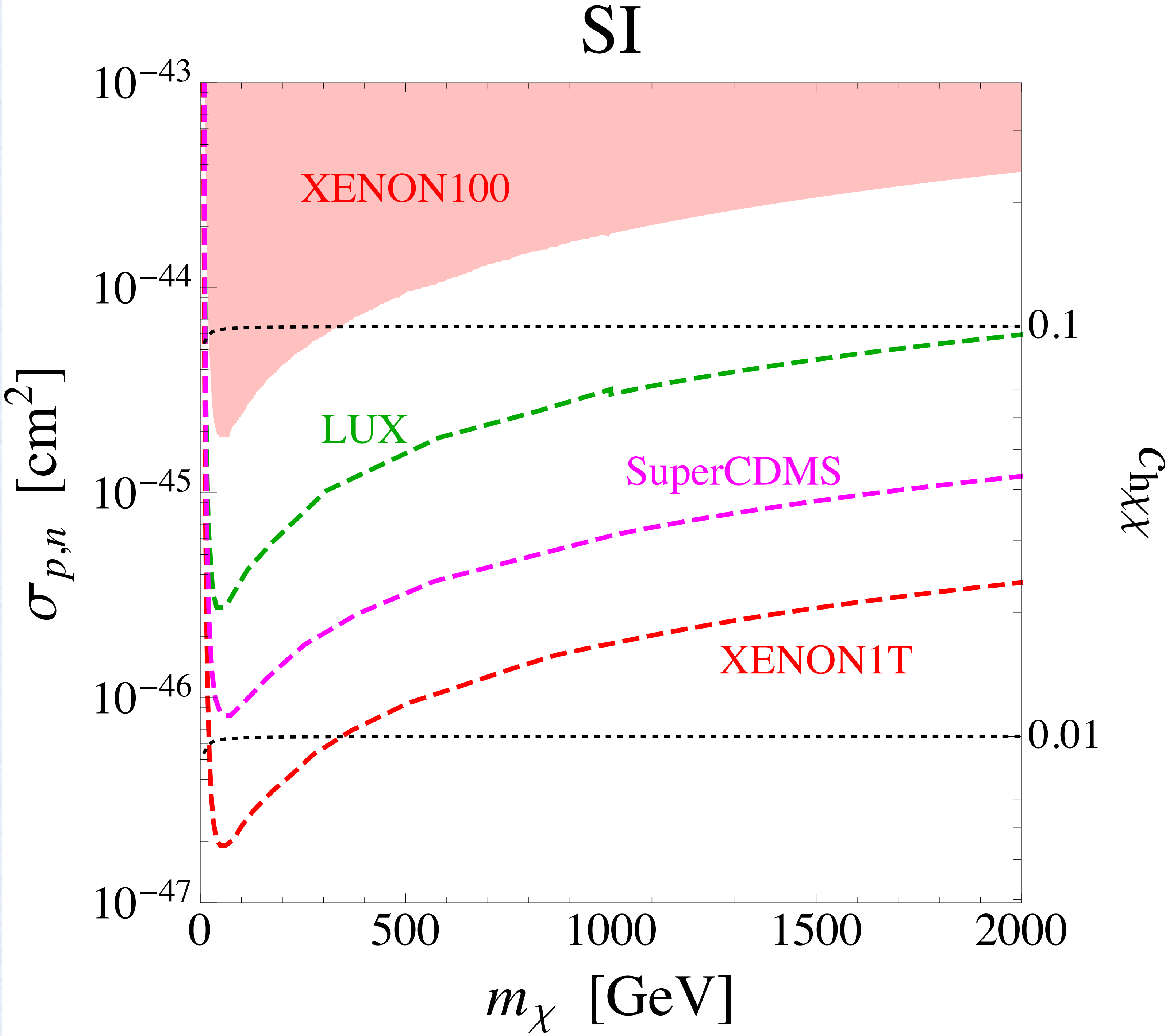
Over-constrained and unique gaugino cascades

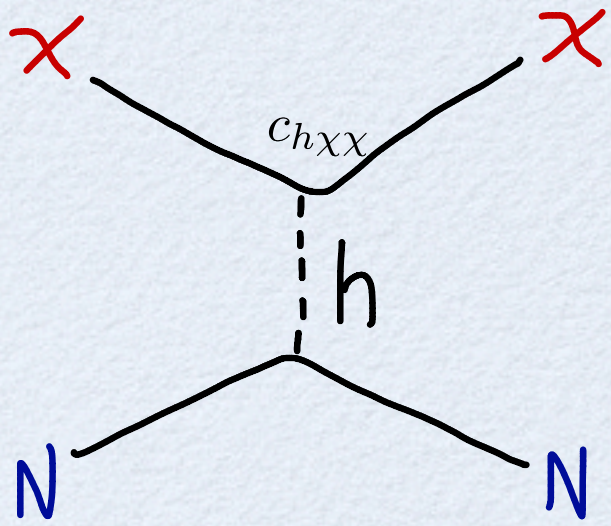
AMS anti-protons are good probe.

Flavor/CP ...

Back-up

Probing the Higgs Coupling



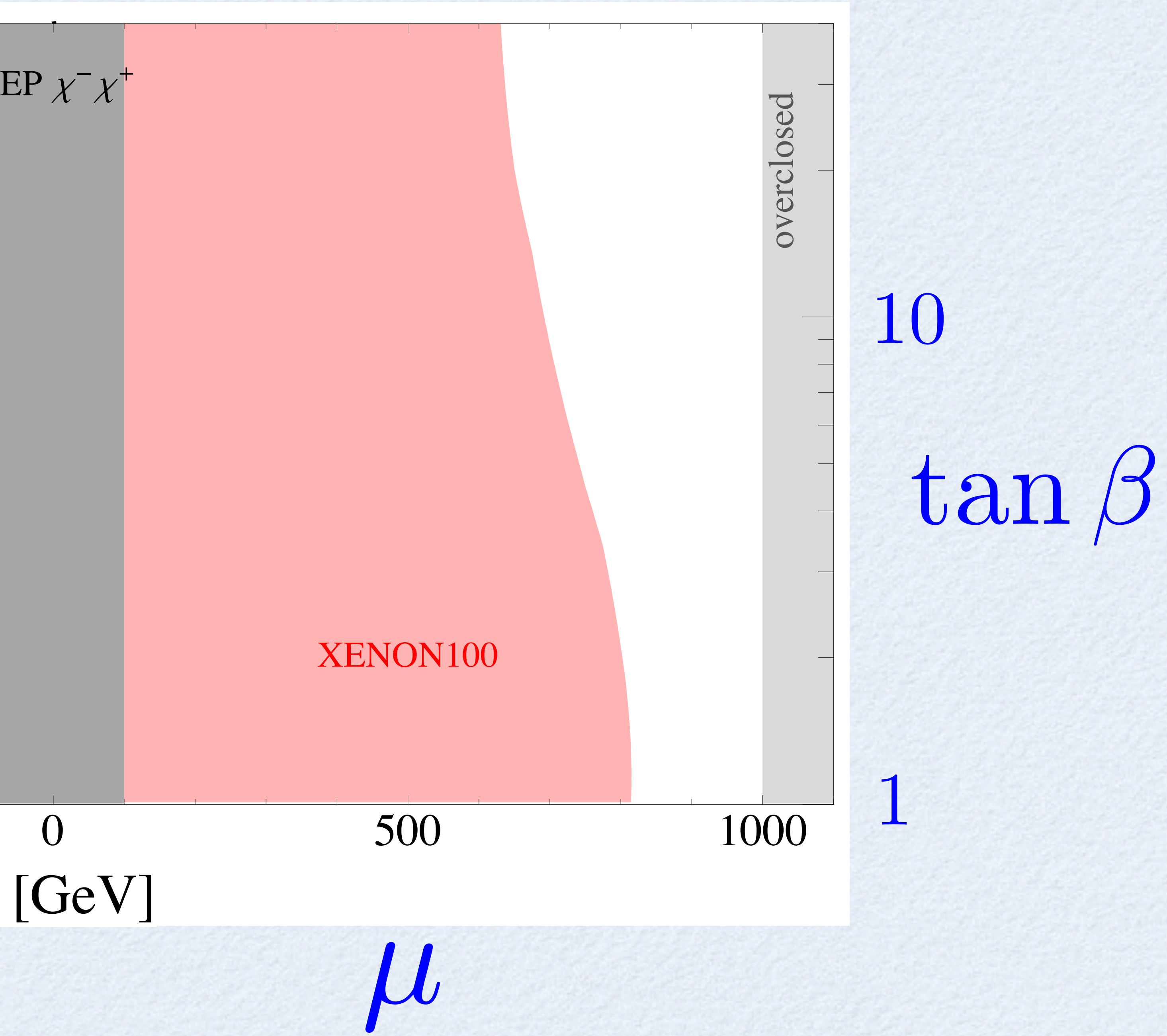


Cliff Cheung, LJH,
David Pinner, Josh Ruderman
arXiv: 1211.4873

Simplified Models

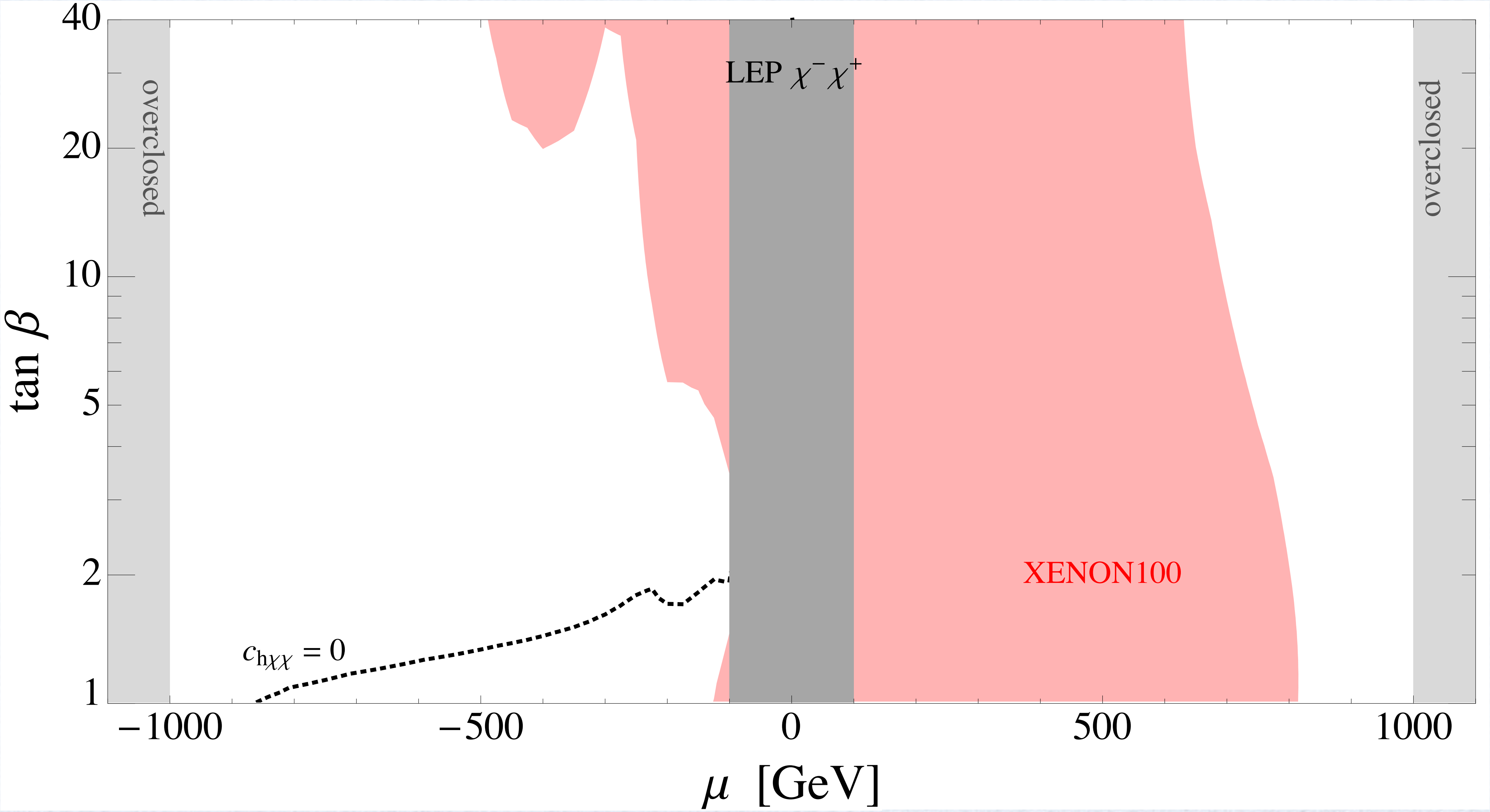
Bino-Higgsino LSP:

Cliff Cheung, LJH,
David Pinner, Josh Ruderman
arXiv: 1211.4873



Almost excluded?

Bino-Higgsino LSP



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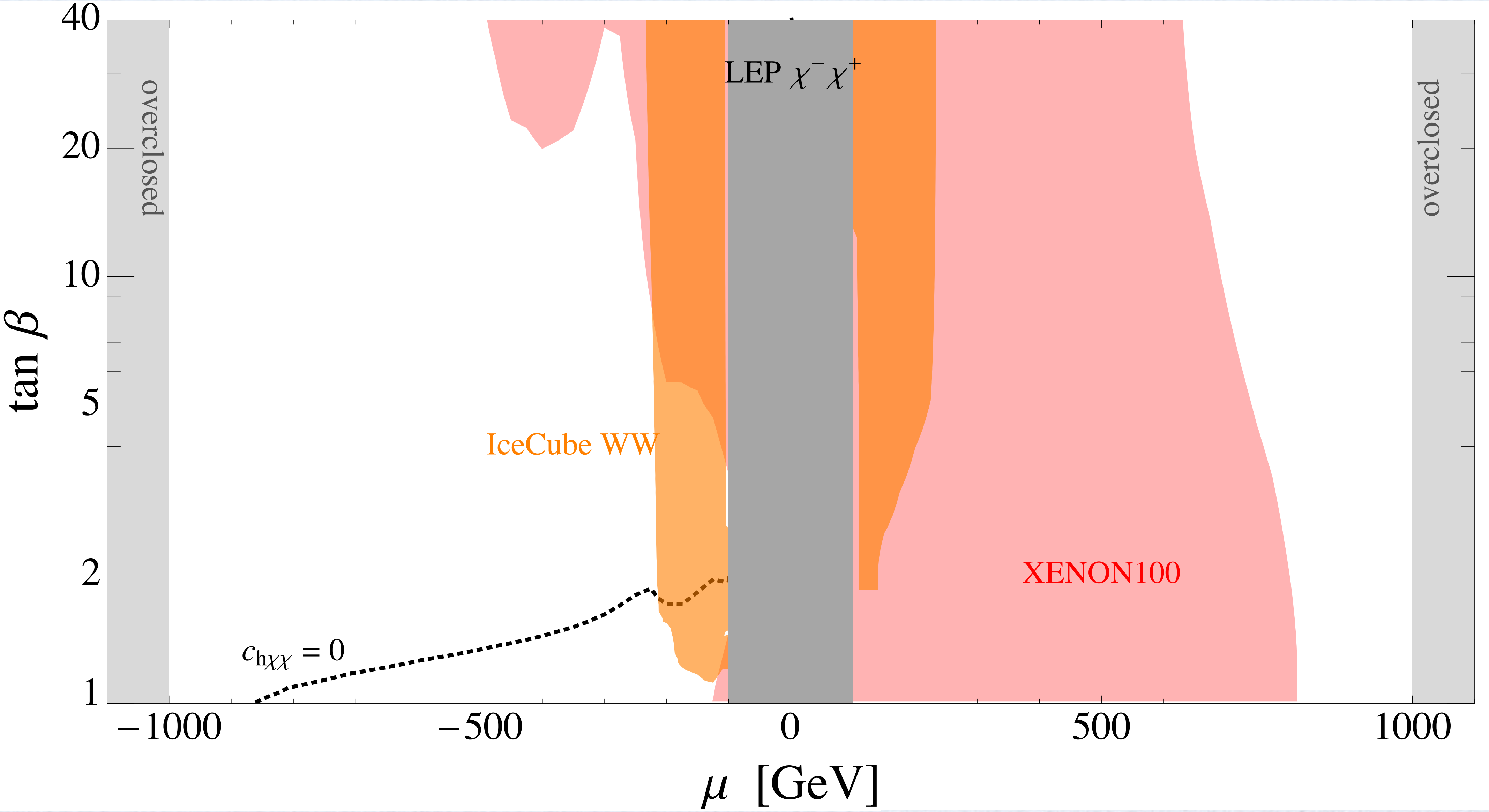
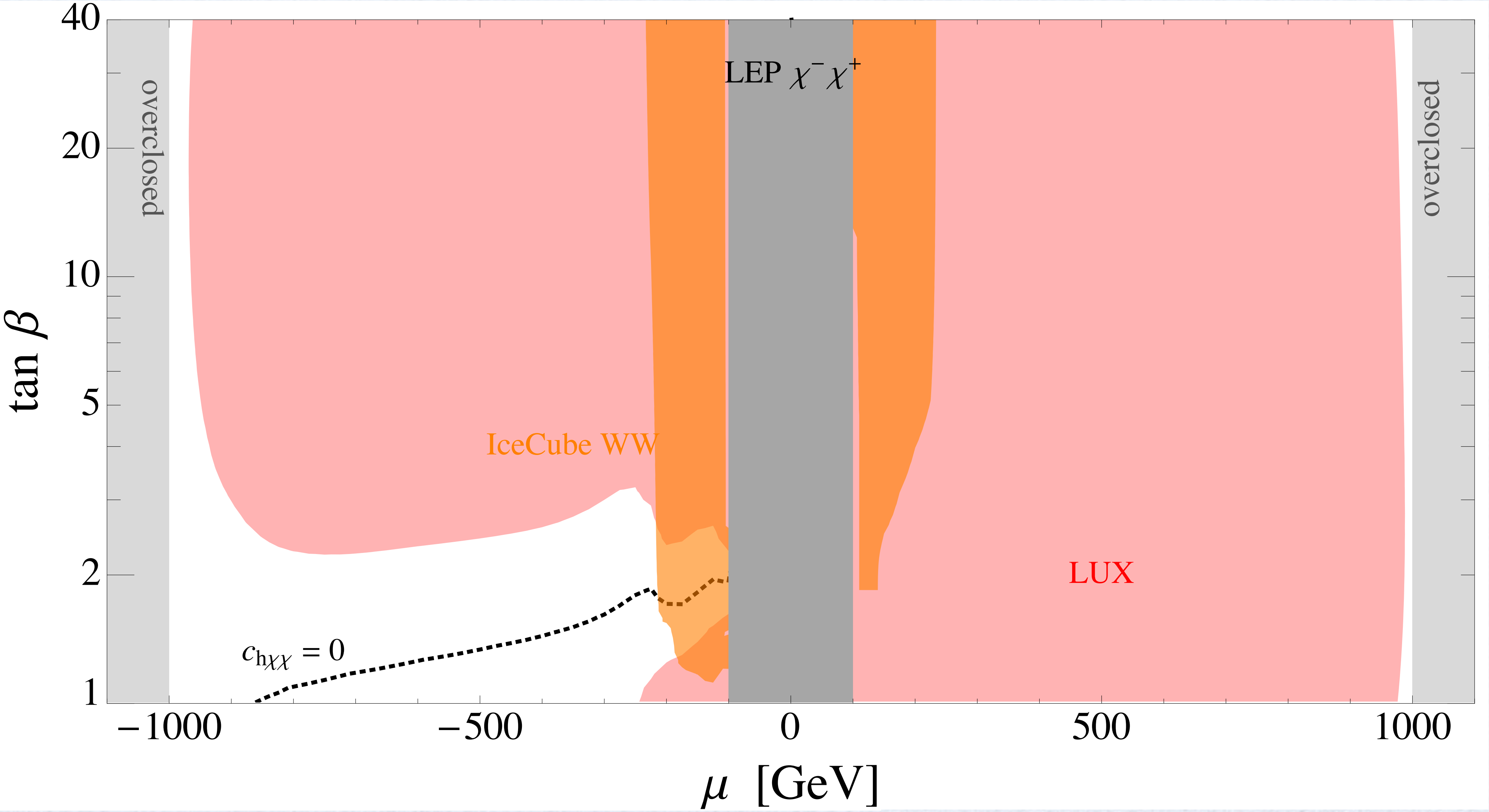
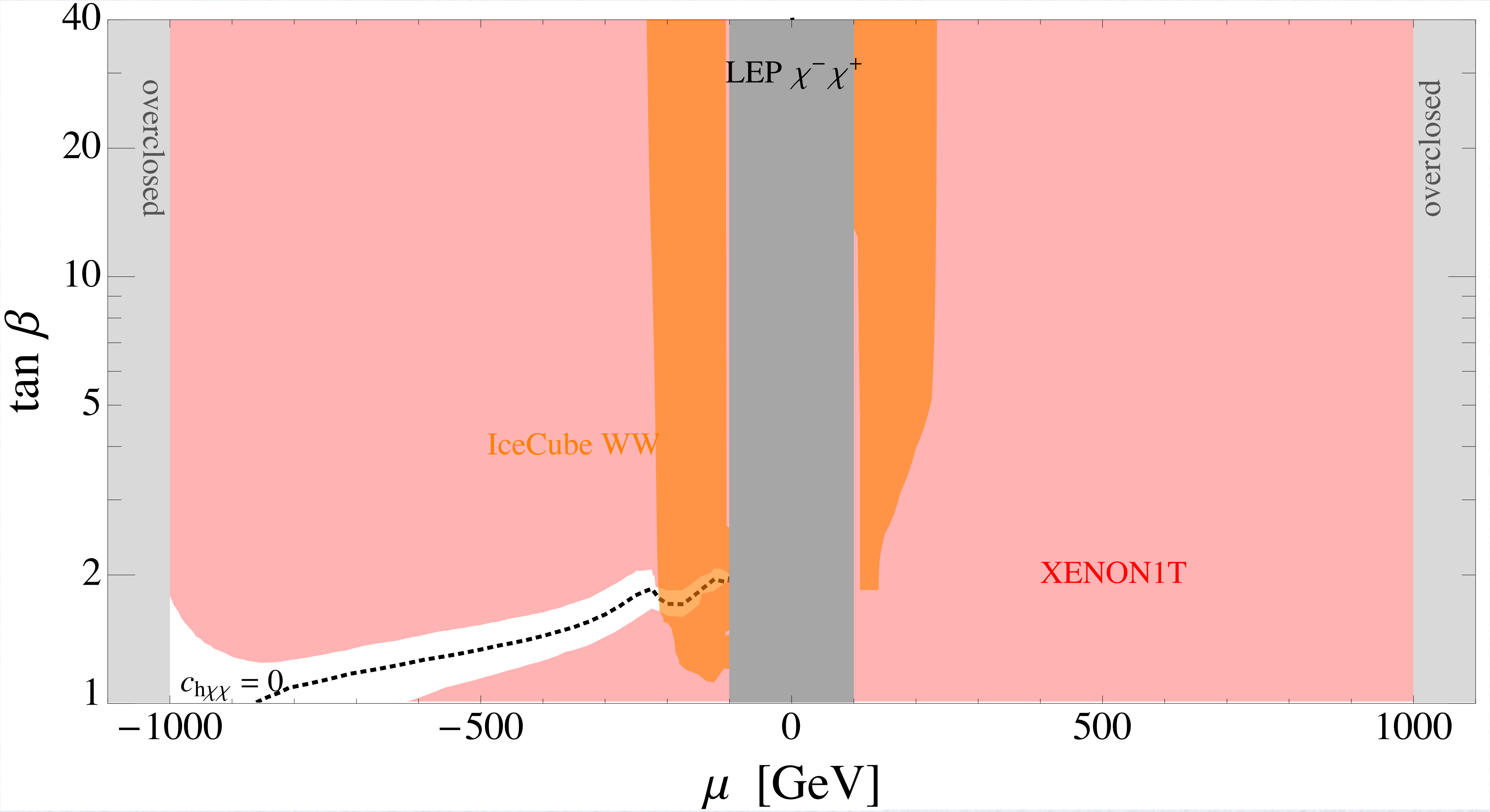
Bino-Higgsino LSP



Bino-Higgsino LSP



Bino-Higgsino LSP



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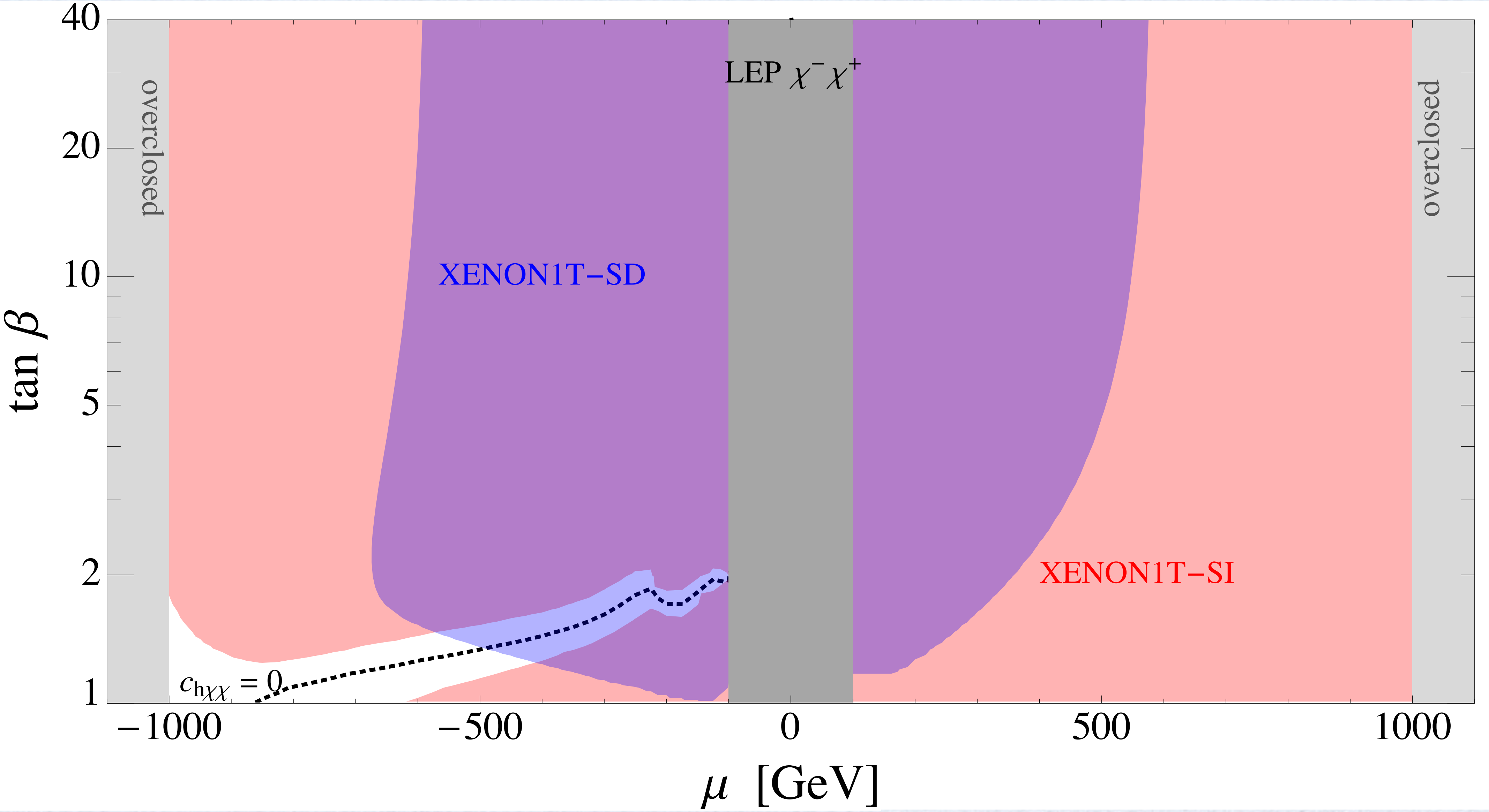
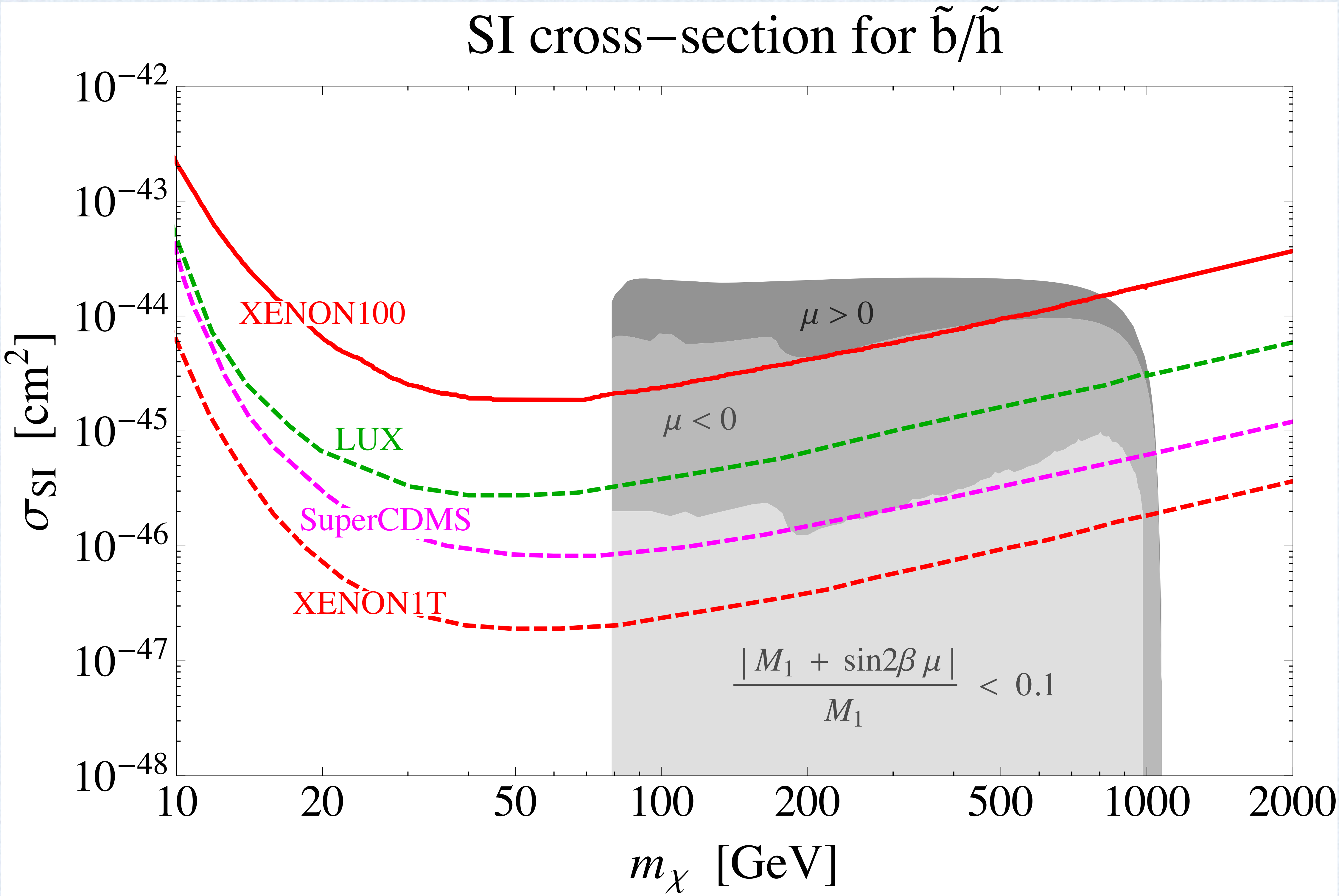


Bino-Higgsino LSP



Cliff Cheung, LJH, David Pinner, Josh Ruderman arXiv: 1211.4873