The First Three Years of the LHC
MITP, Mainz
March 2013

TeV-Scale Superpartners and Dark Matter

Lawrence Hall
University of California, Berkeley

Outline

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

What if
Naturalness Argument
is wrong?

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↓ Is This Robust?

TeV scale
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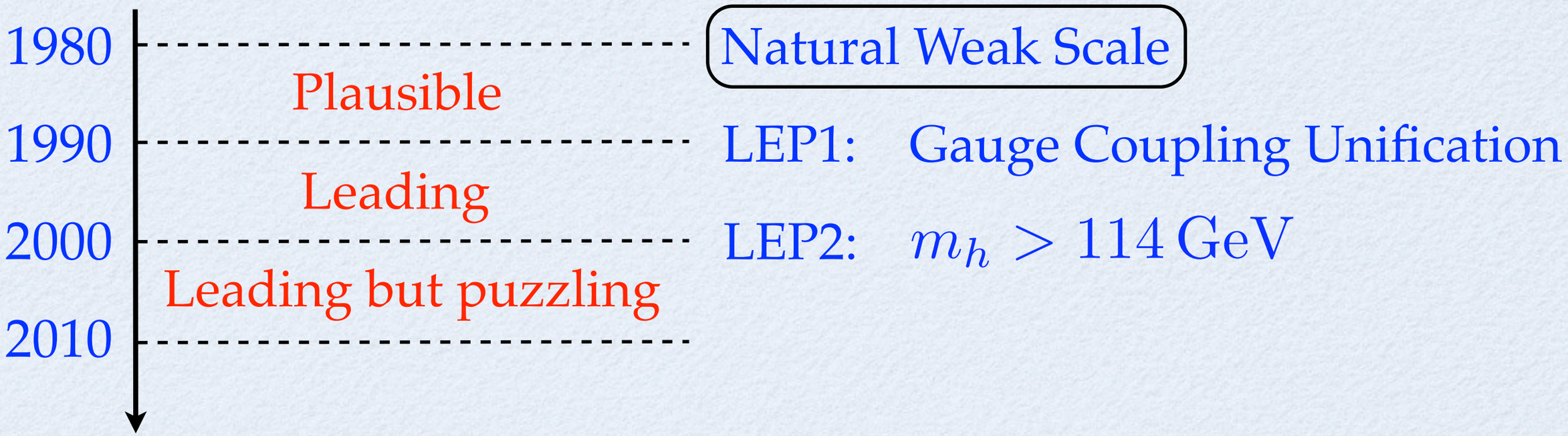
(III)

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

A Third of a Century of Weak Scale Susy



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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$\tilde{m} \sim v$	$\tilde{m} \gg v$

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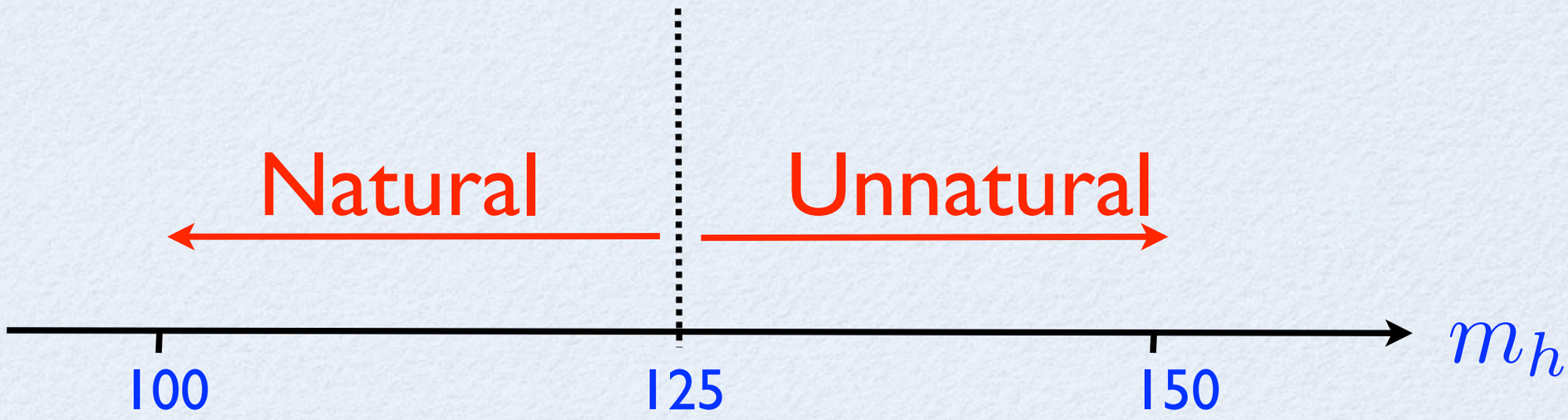

We simply don't know!

Fine-Tuning in the MSSM: 2012

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

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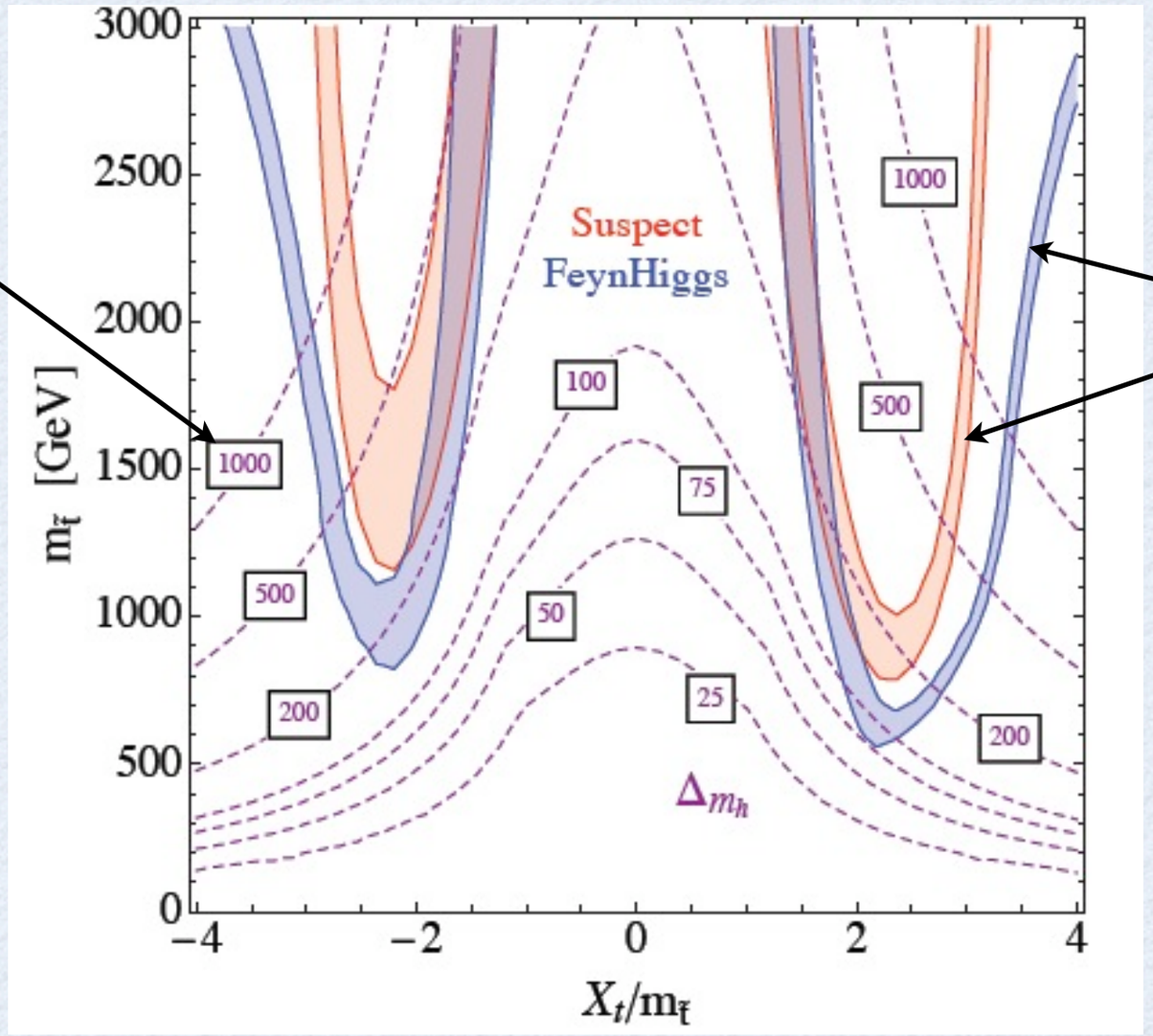
$$\Delta = \frac{\partial \ln m_h}{\partial \ln p}$$



$m_h = 124 - 126$ GeV

David Pinner, Josh Ruderman,
LJH 1112.2703

Minimize Δ

$\tan\beta > 10$

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

messenger scale
of 10 TeV

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

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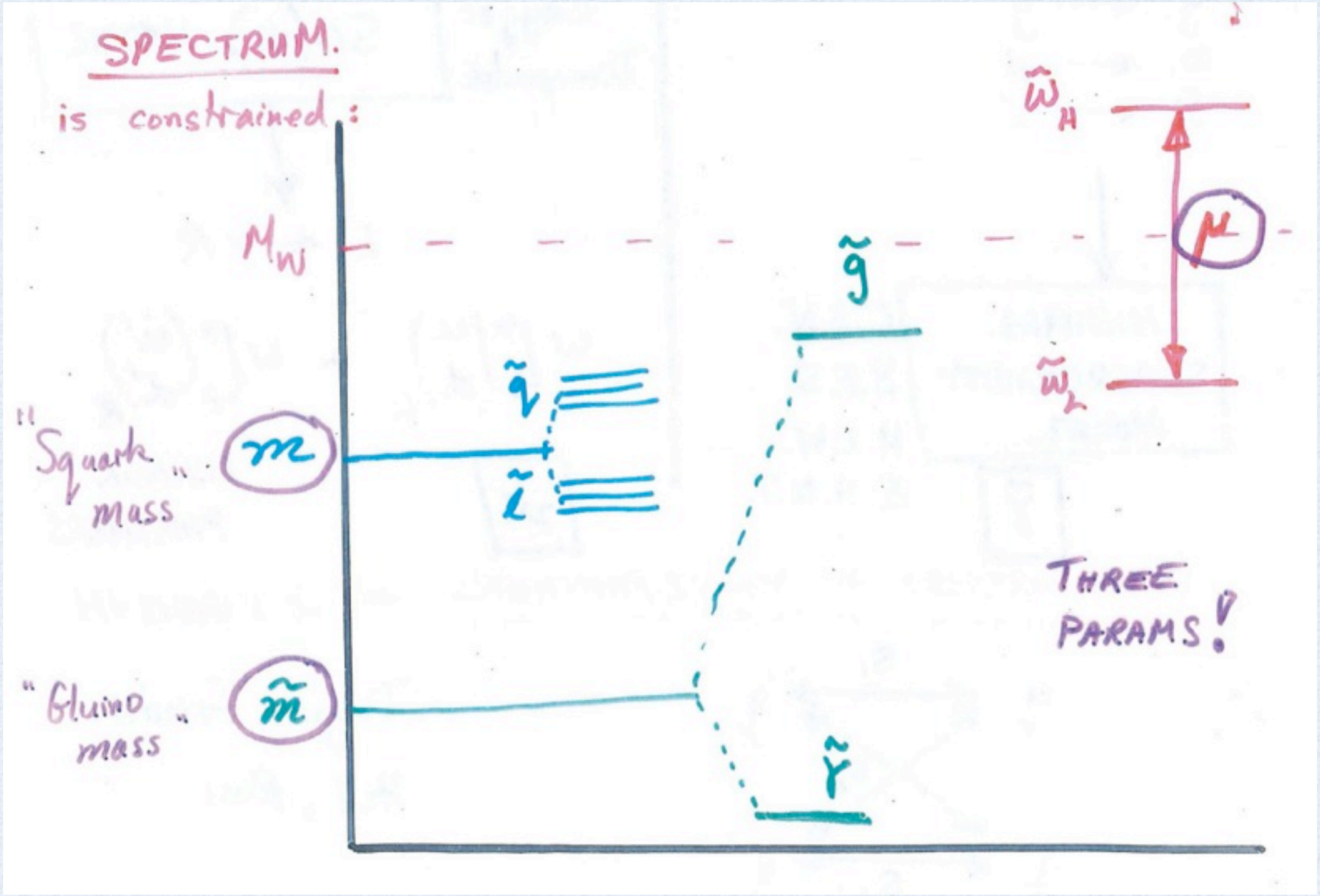
SUSY Spectrum, 1984



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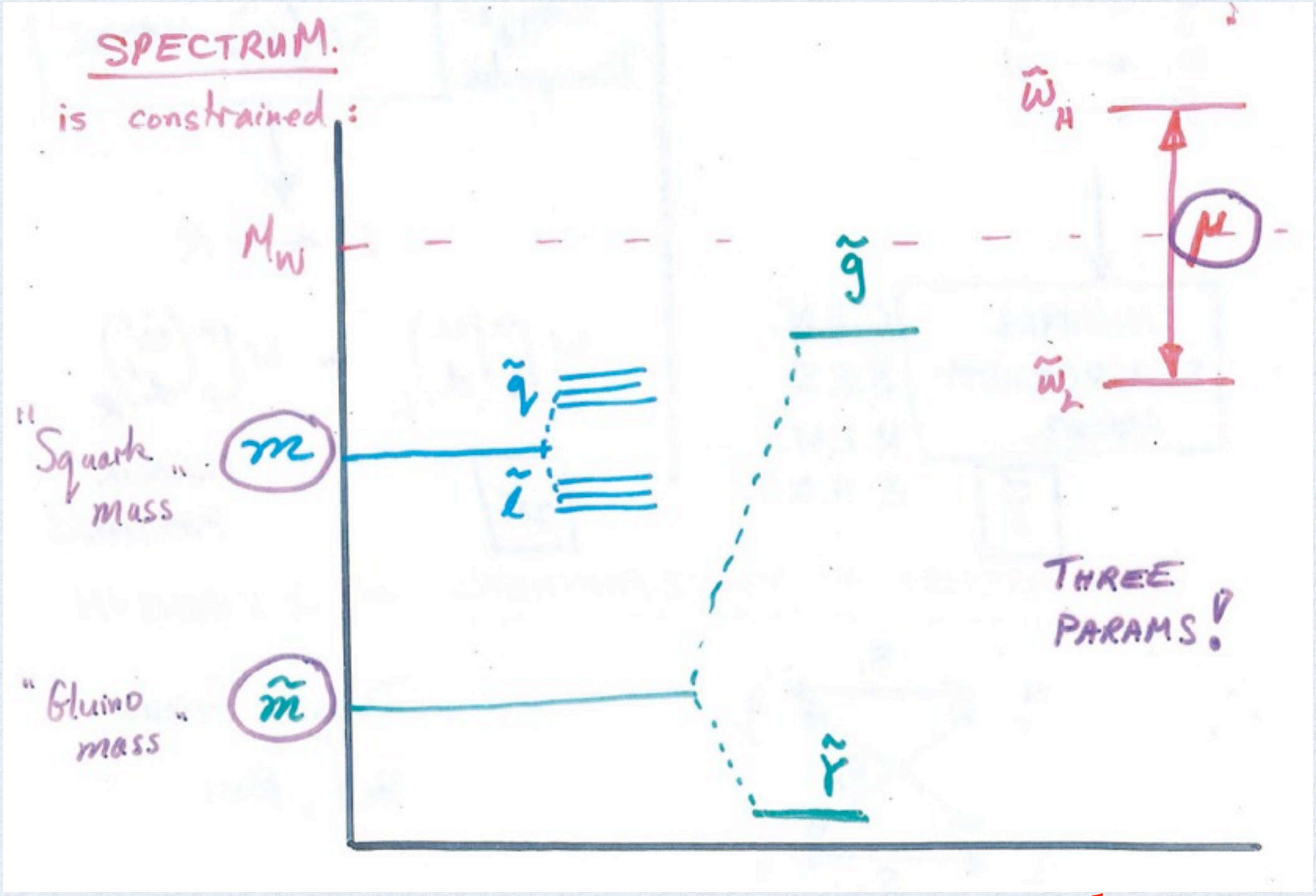
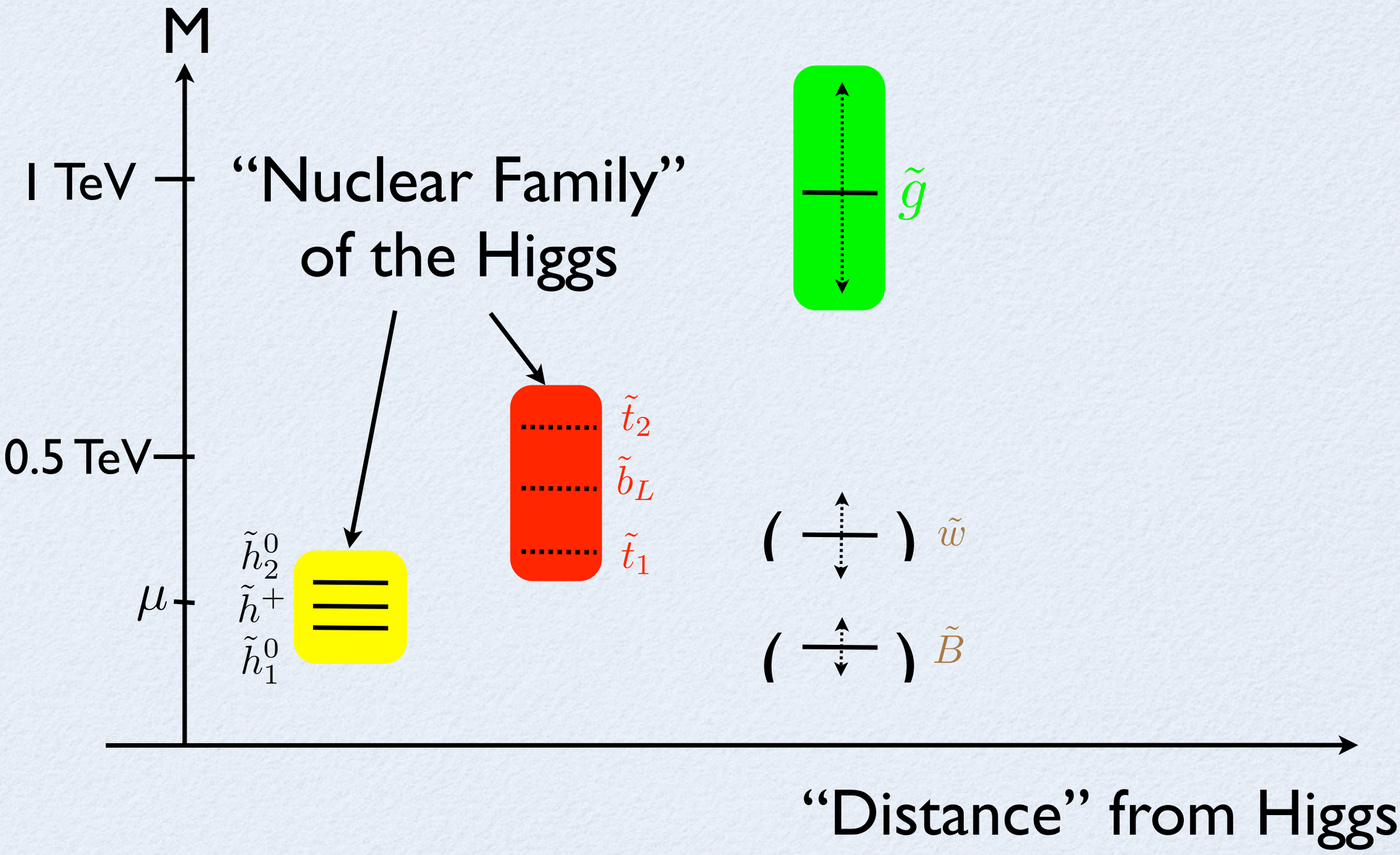


Over 3 decades of susy: seismic shifts!

A Natural Spectrum

Atlas Workshop,Berkeley, Oct 2011



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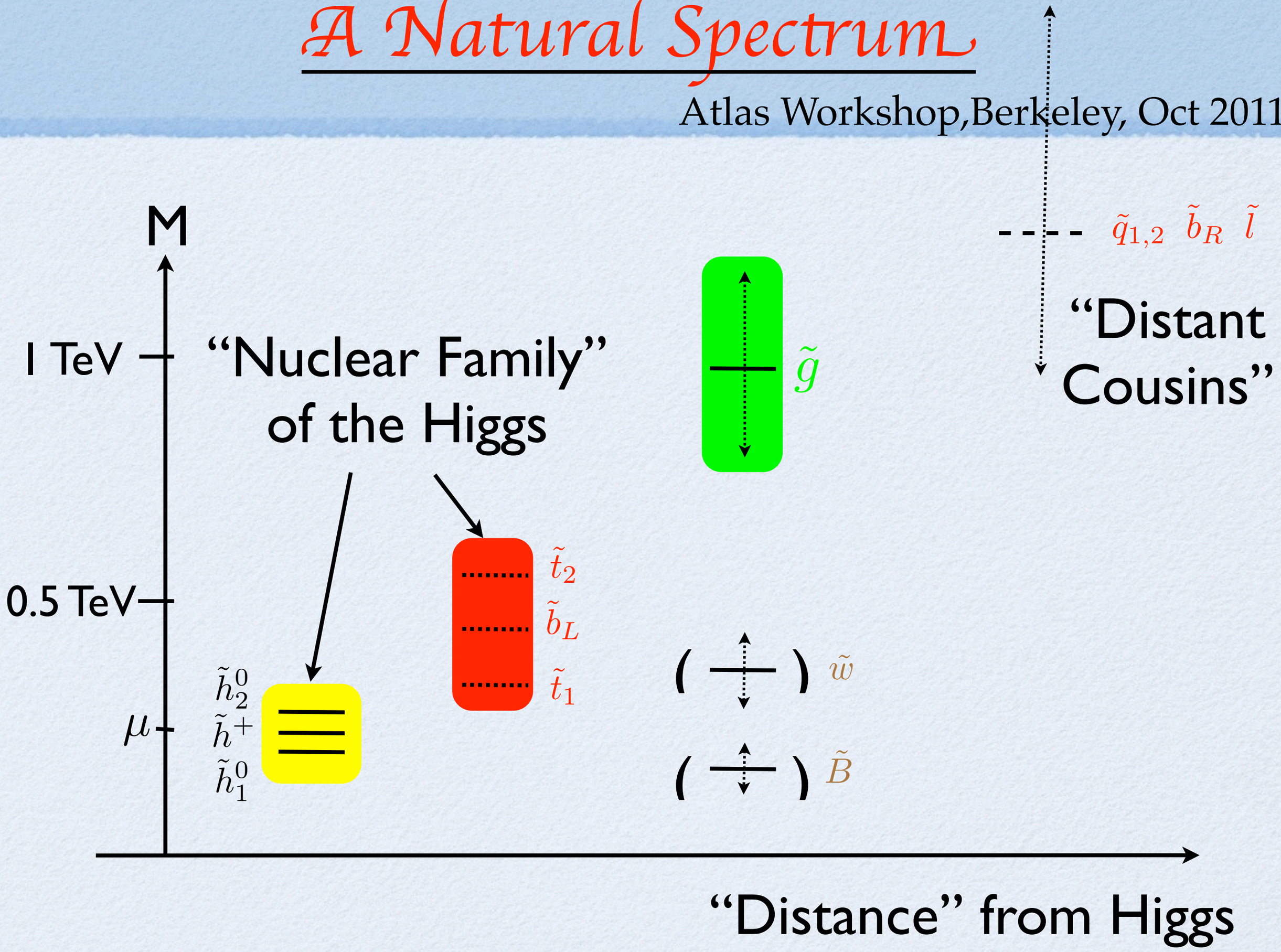

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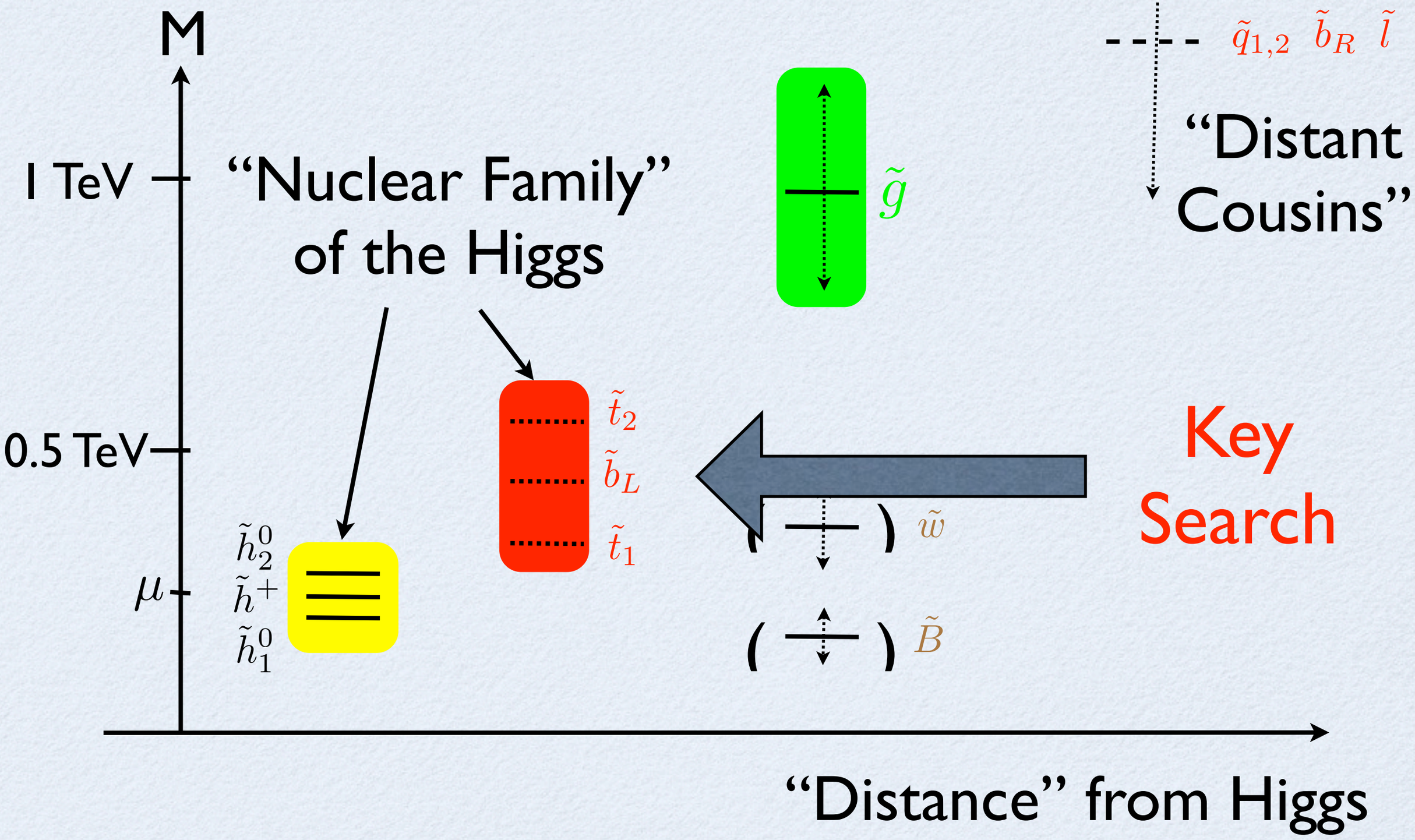
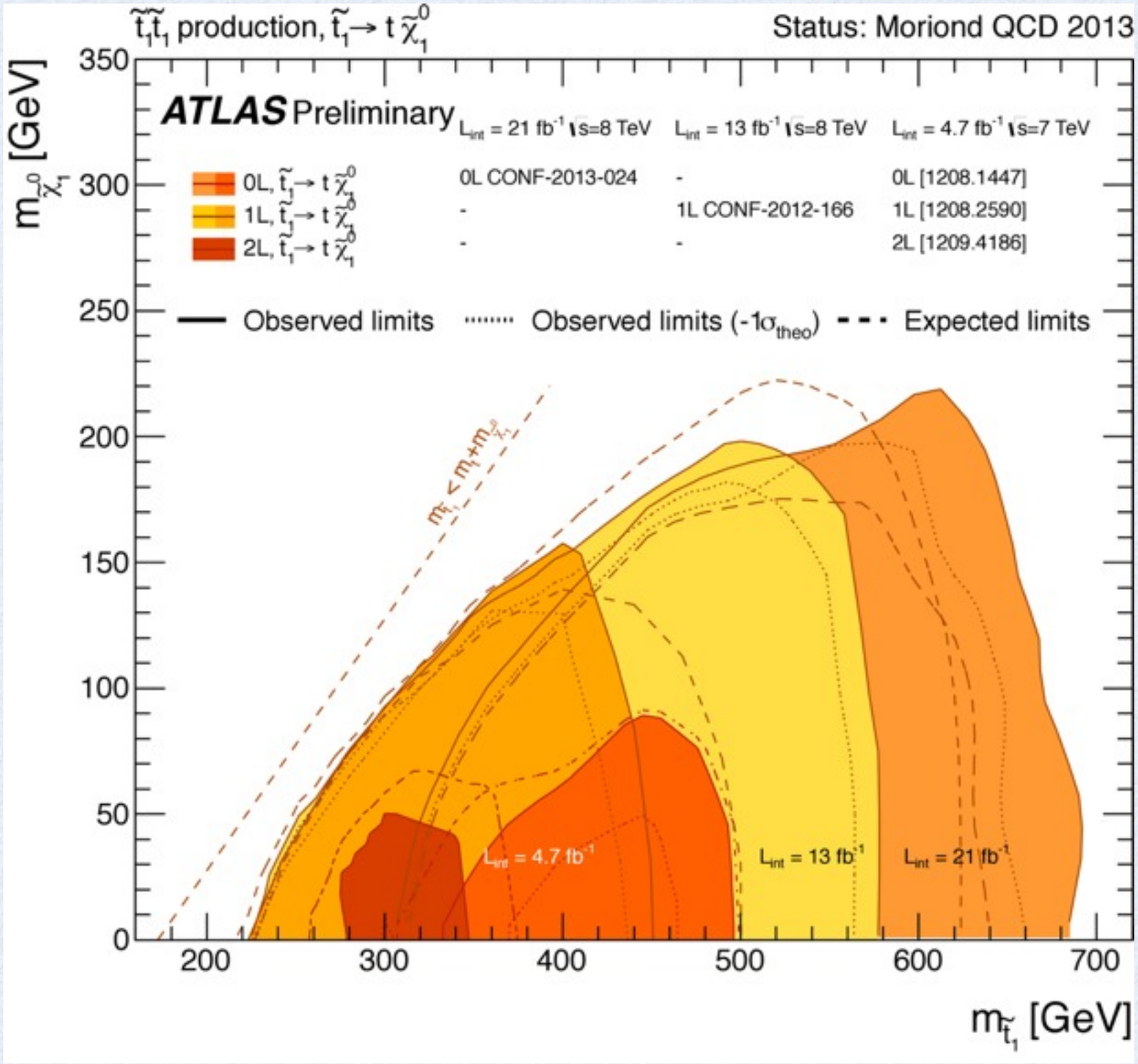


Stop Search with 21 fb^{-1}



Simplified Model
-- care!

The Future of Susy Searches

1980 — Natural Weak Scale

... — ...

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

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2013 .... Leave no stone unturned at LHC for Natural Susy

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Leave no stone unturned
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What if Naturalness is Wrong?

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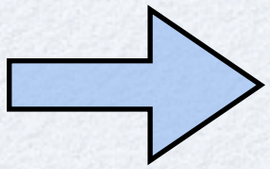
Must rethink SUSY



Back to Basics

Motivations for TeV Scale Susy

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

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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. $T_R \geq \tilde{m}$
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$$m_{LSP} \sim \alpha_{\rm eff} \sqrt{T_{\rm eq} M_{\rm P}} \approx \left(\frac{\alpha_{\rm eff}}{0.01} \right) 1\,{\rm TeV}$$

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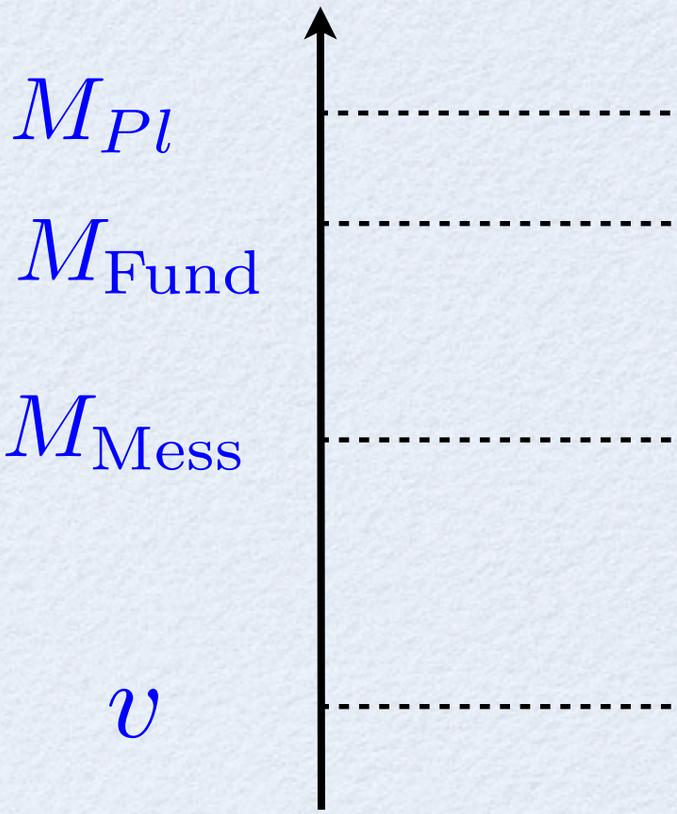
BUT HIDDEN ASSUMPTION

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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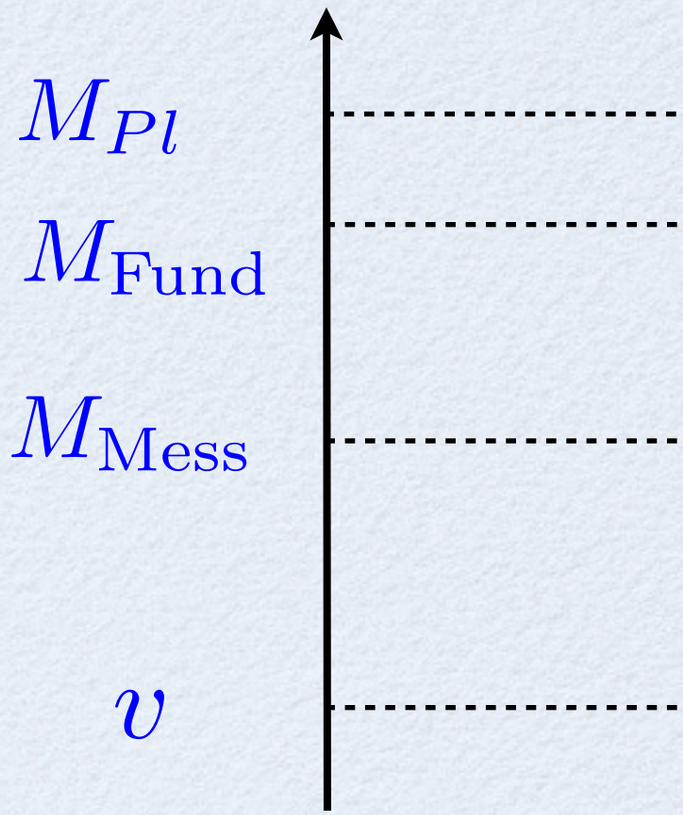

Generic result:

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

$\tilde{G}$ 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

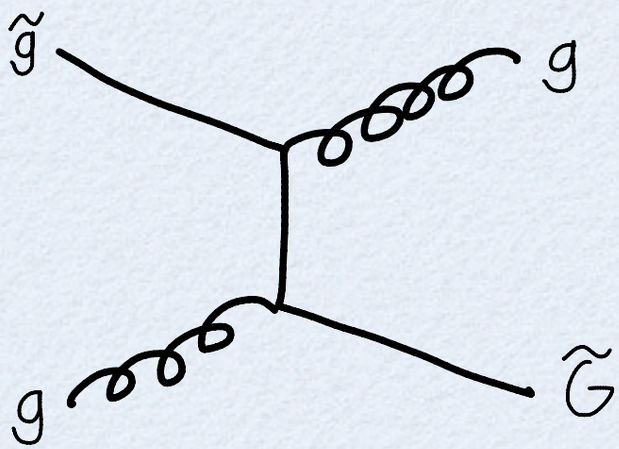
Several processes contribute

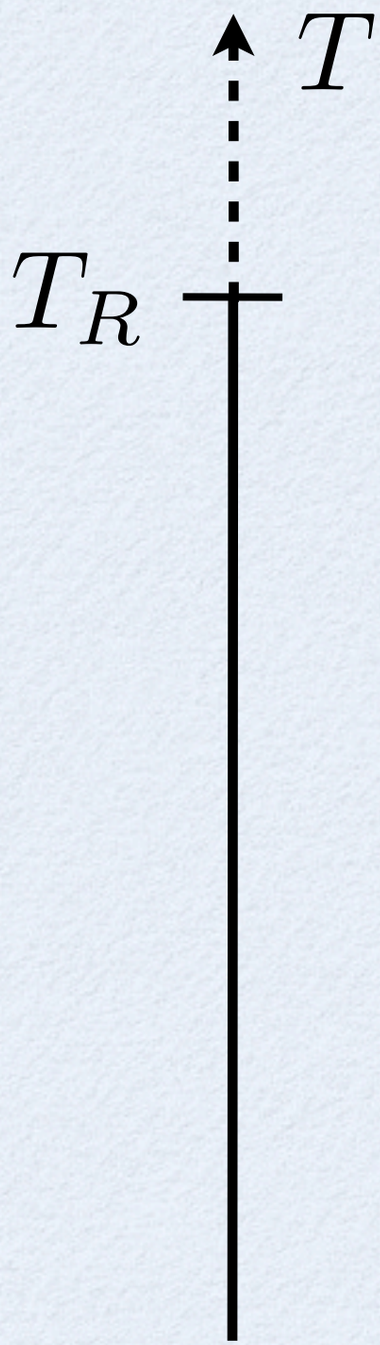
Claim that Gravitino DM also points
to TeV scale superpartners

LJH, Josh Ruderman, Tomer Volansky
arXiv: 1302.2620

UV Scattering

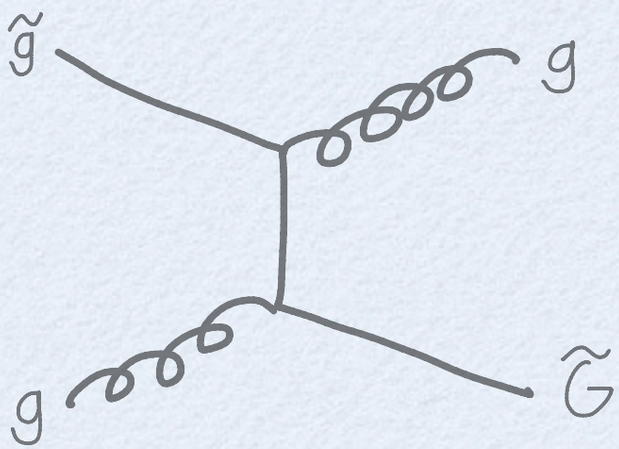
UV scattering

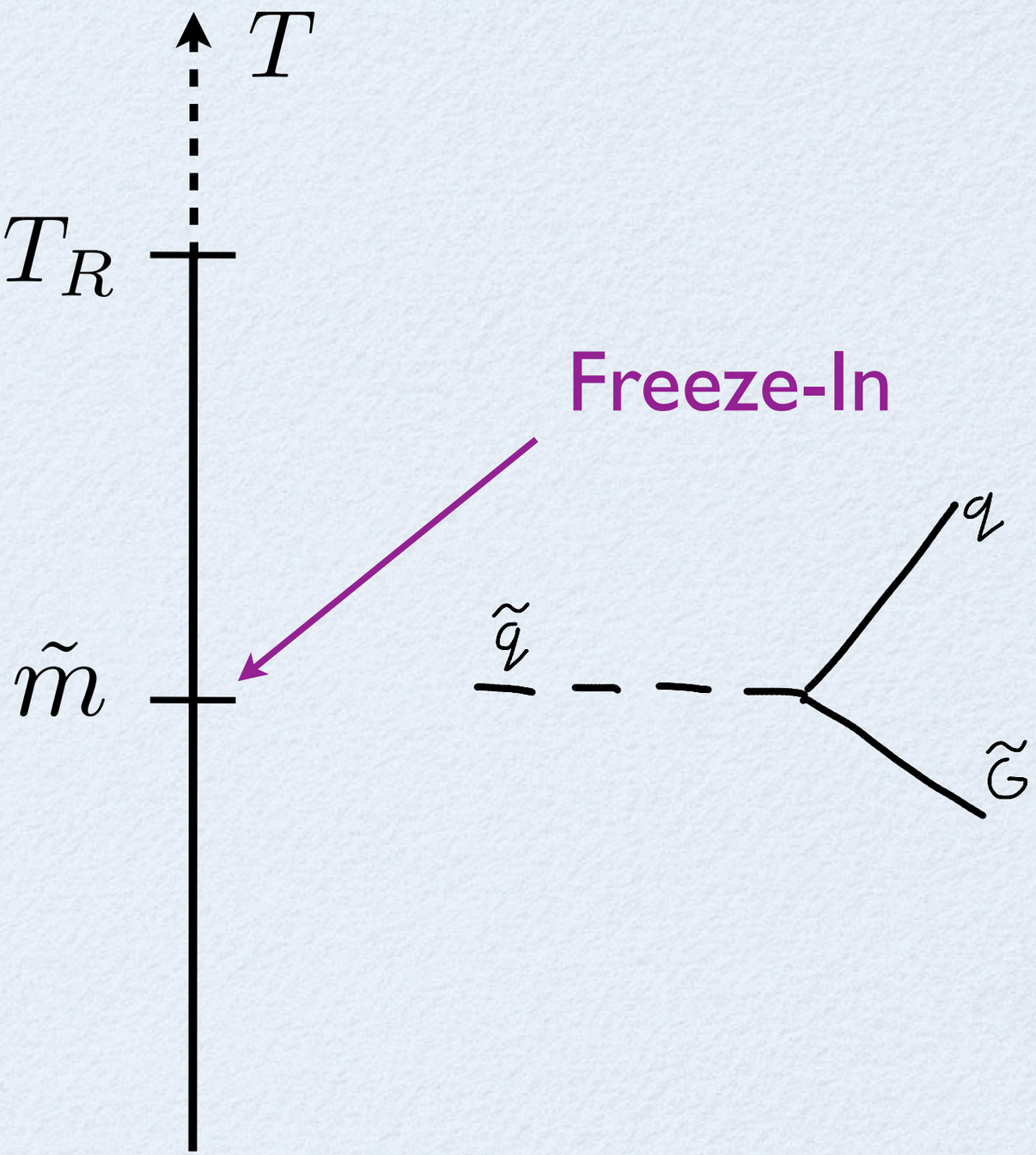




Freeze-In

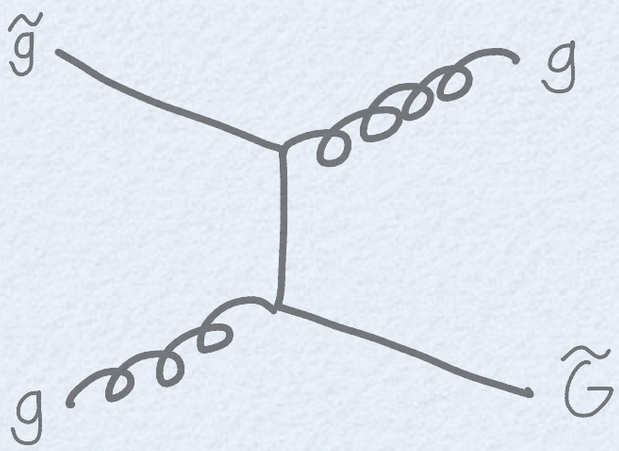
UV scattering

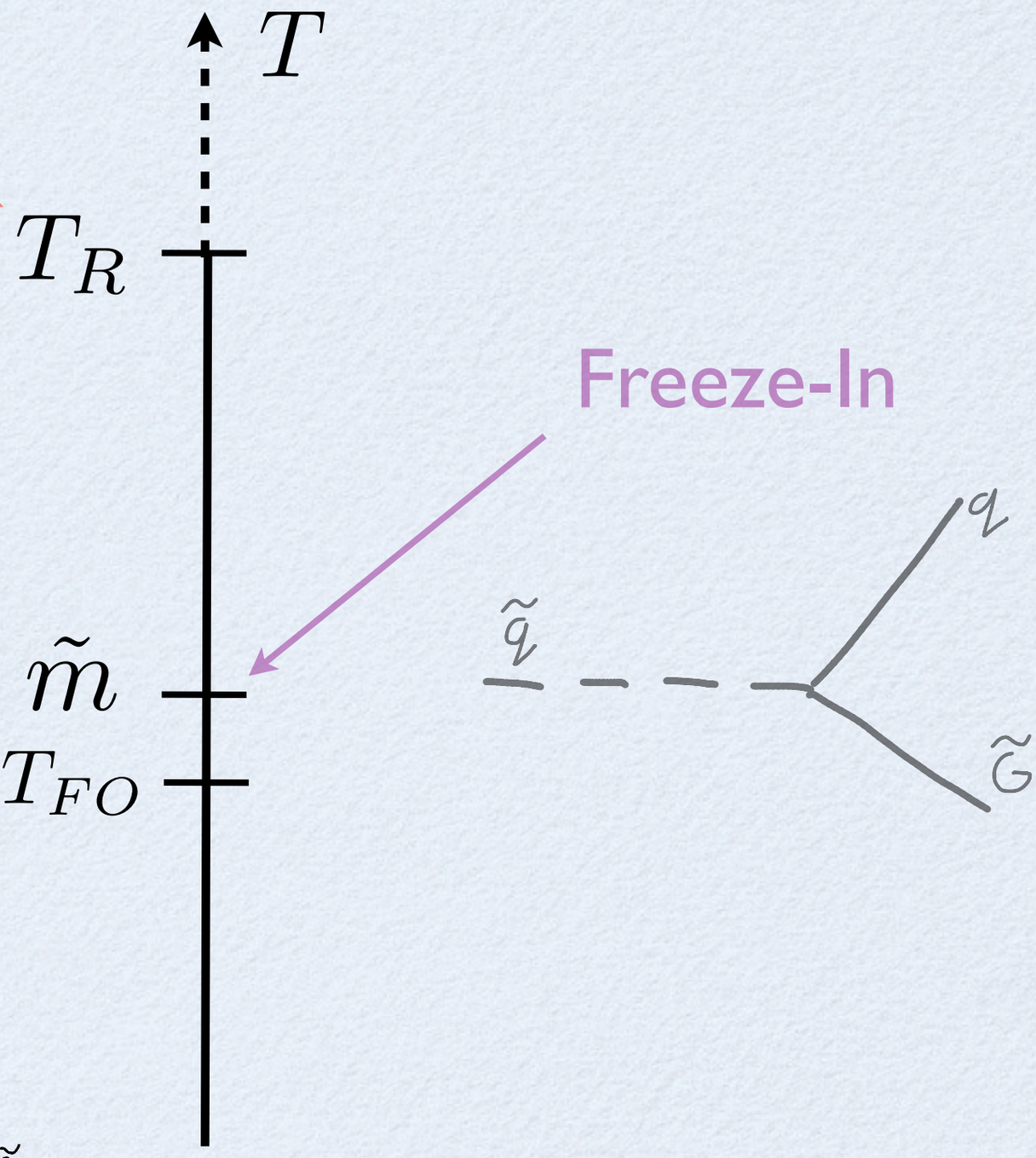




Freeze-Out and Decay

UV scattering





Freeze-In

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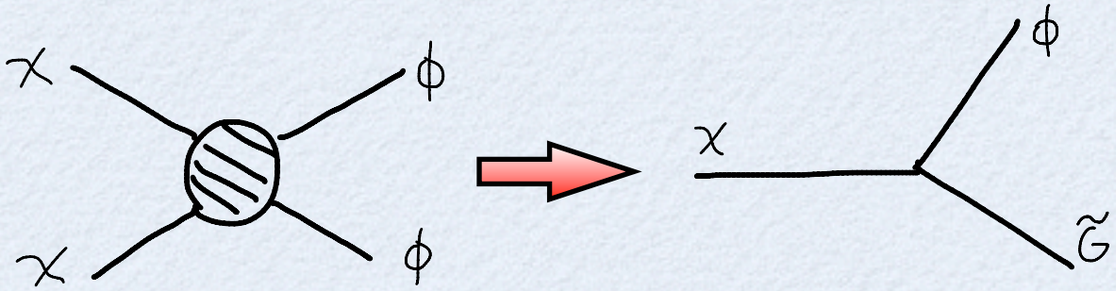
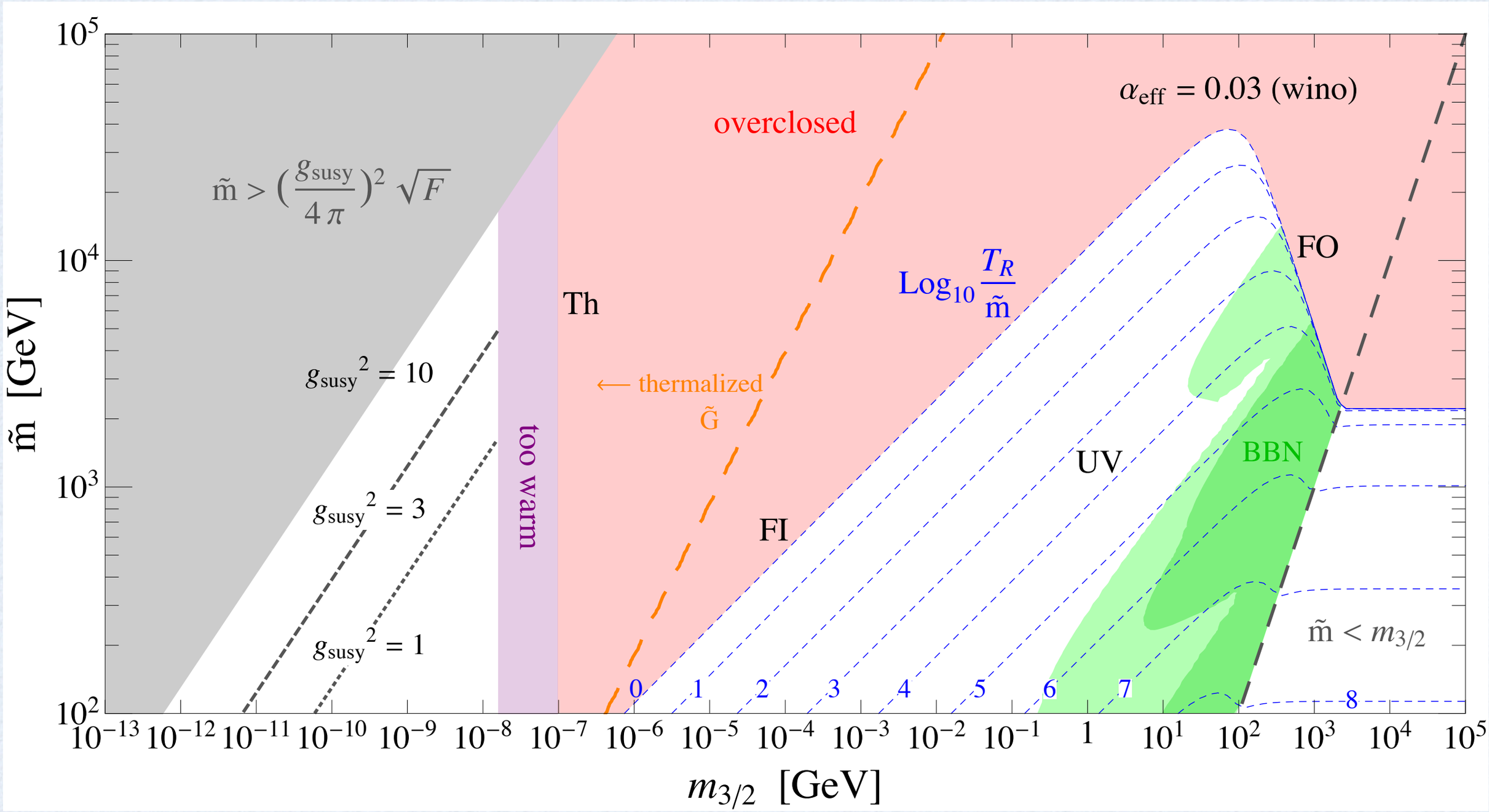


Superpartner Mass Bound



LJH, Josh Ruderman, Tomer Volansky arXiv: 1302.2620

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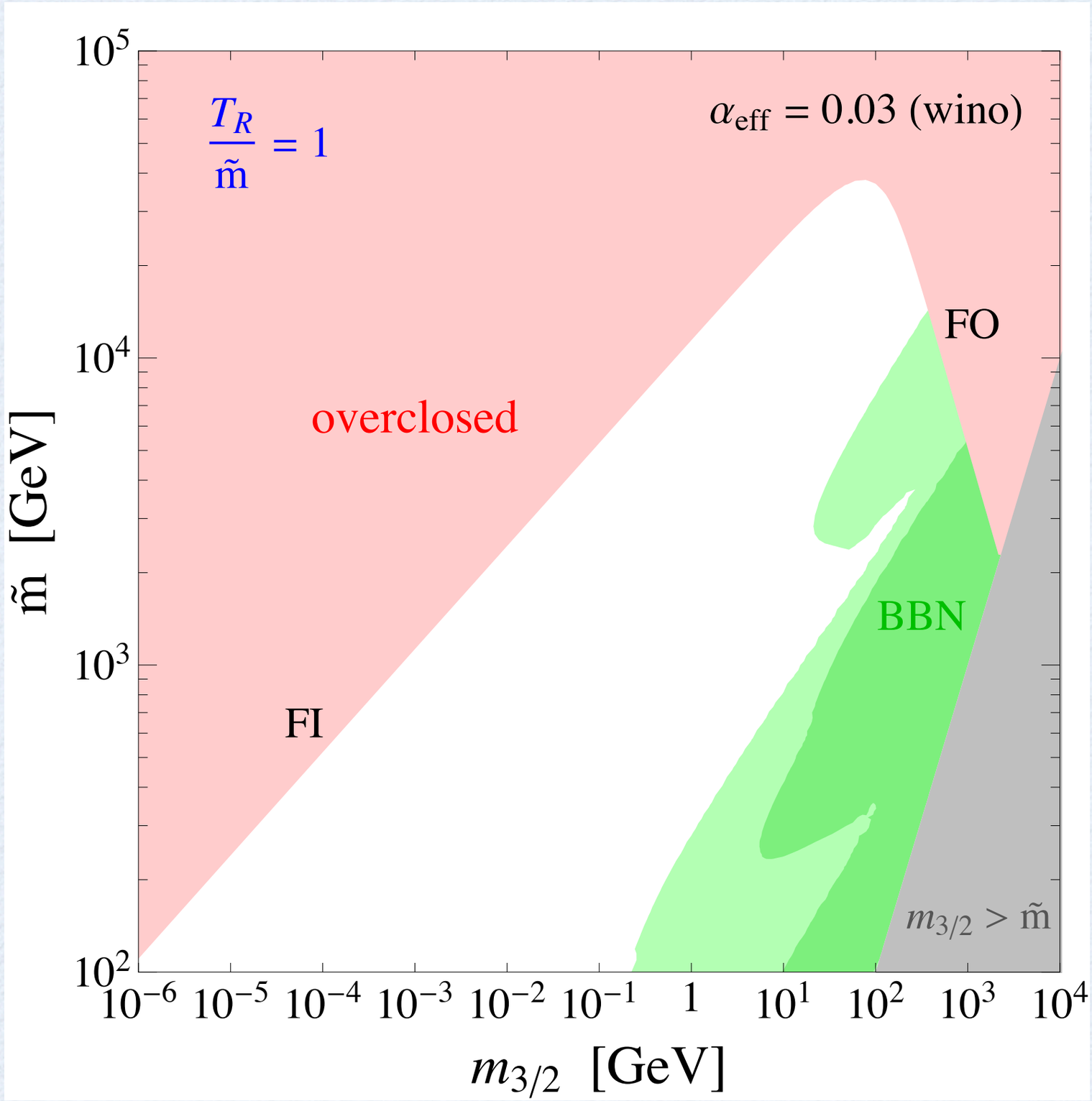
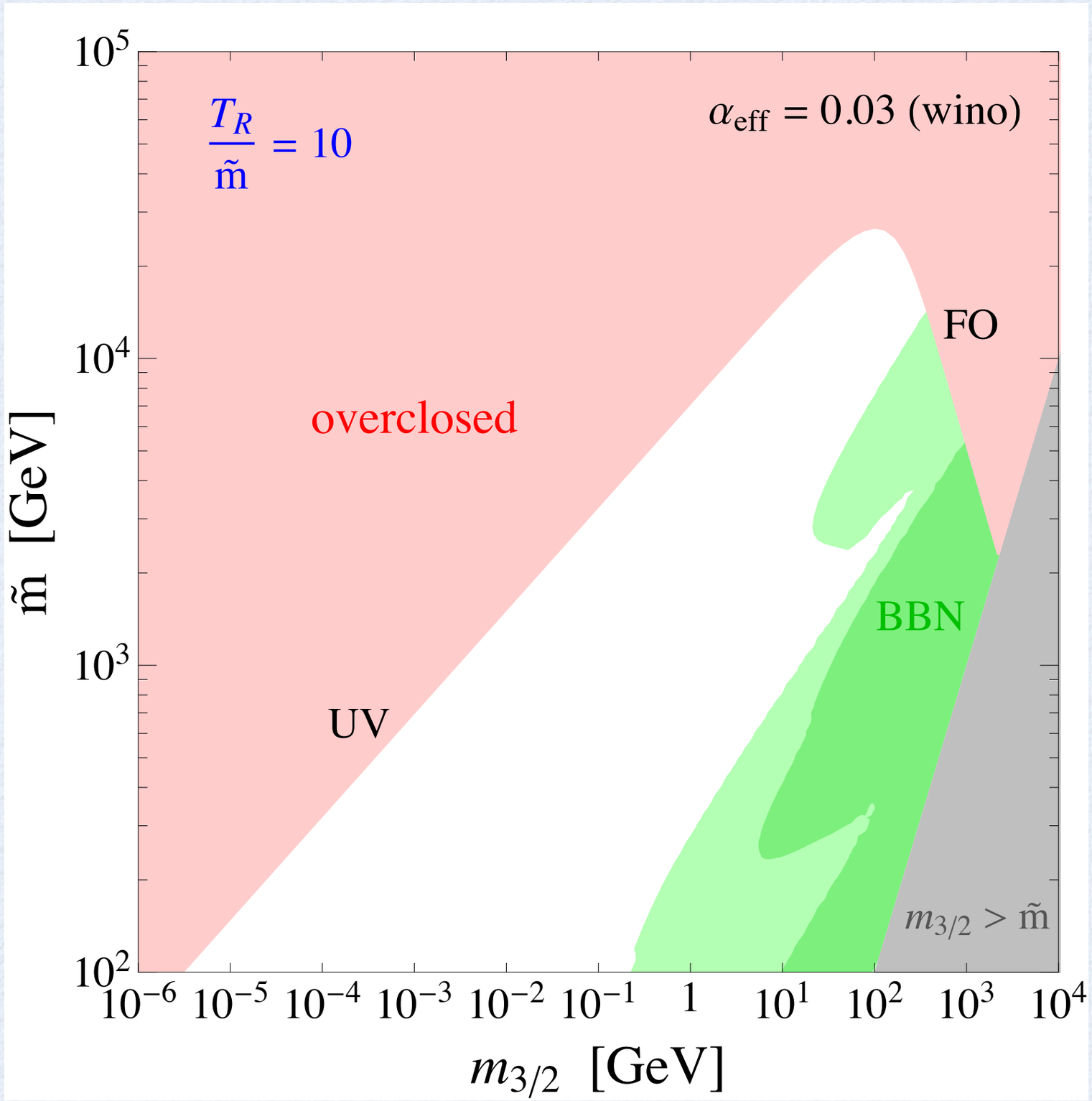


$$\frac{T_R}{\tilde{m}} = 1$$

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

LJH, Josh Ruderman, Tomer Volansky
arXiv: 1302.2620

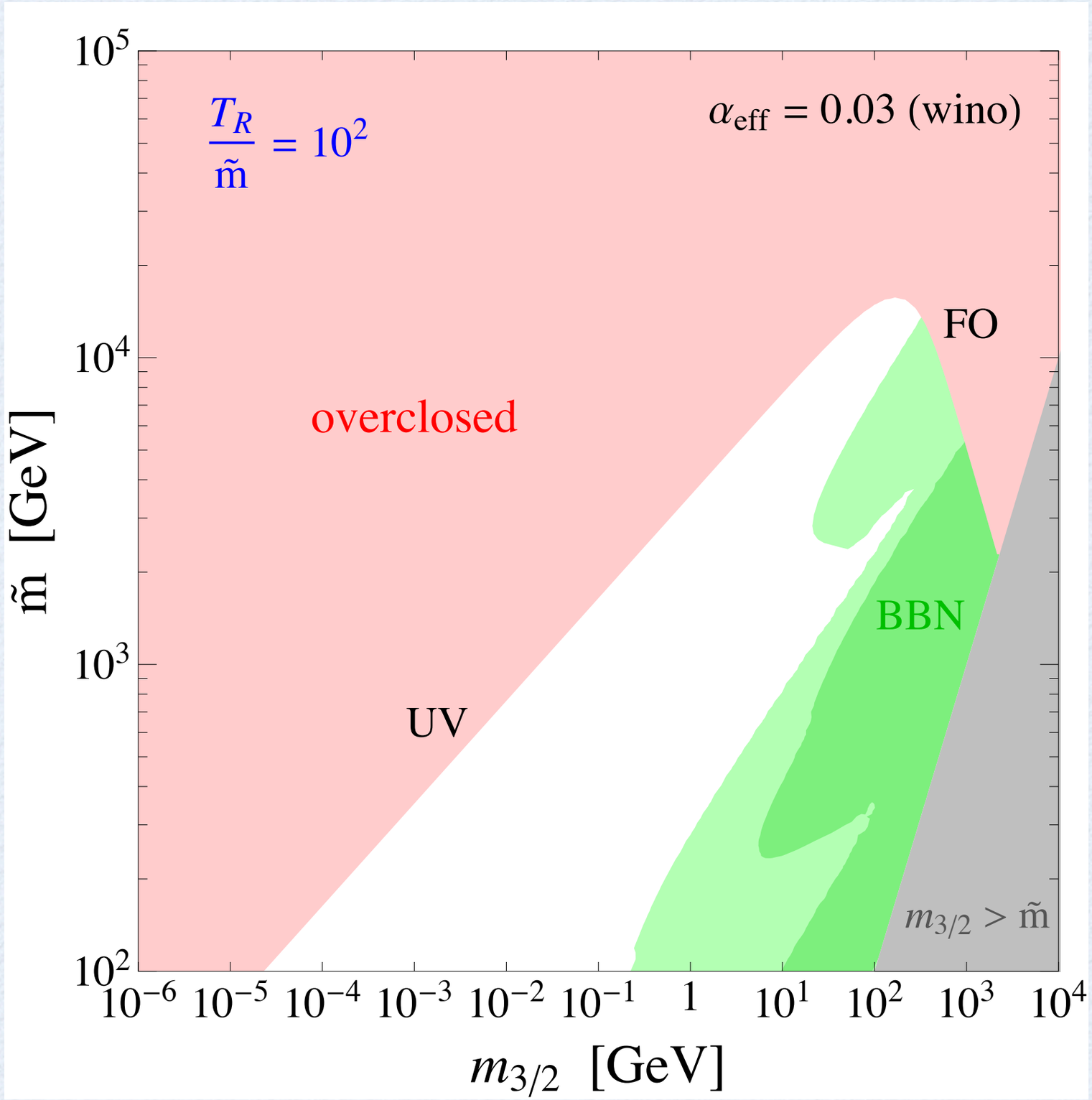
Superpartner Mass Bound



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

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

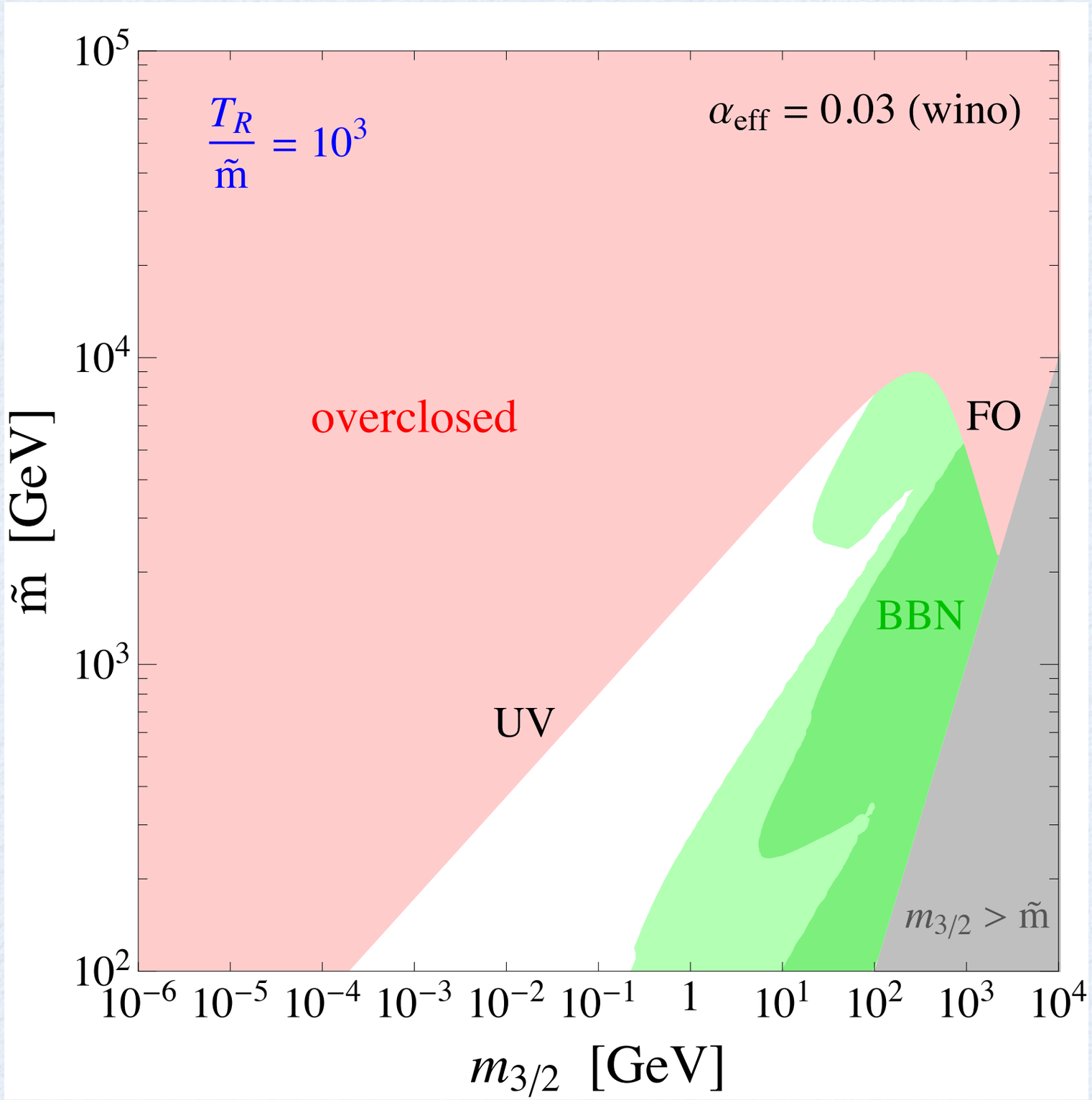
Superpartner Mass Bound



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

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

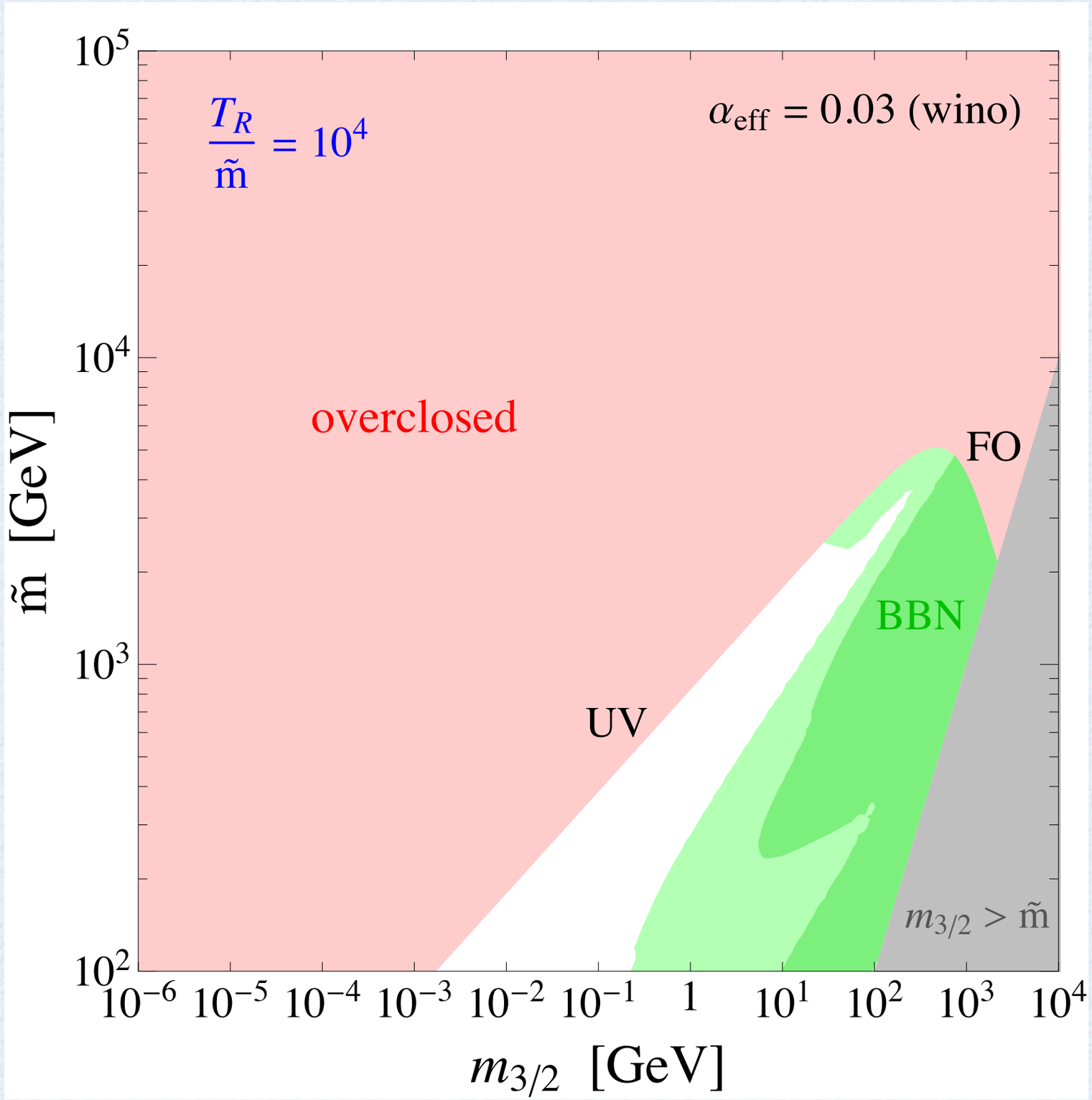
Superpartner Mass Bound



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

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

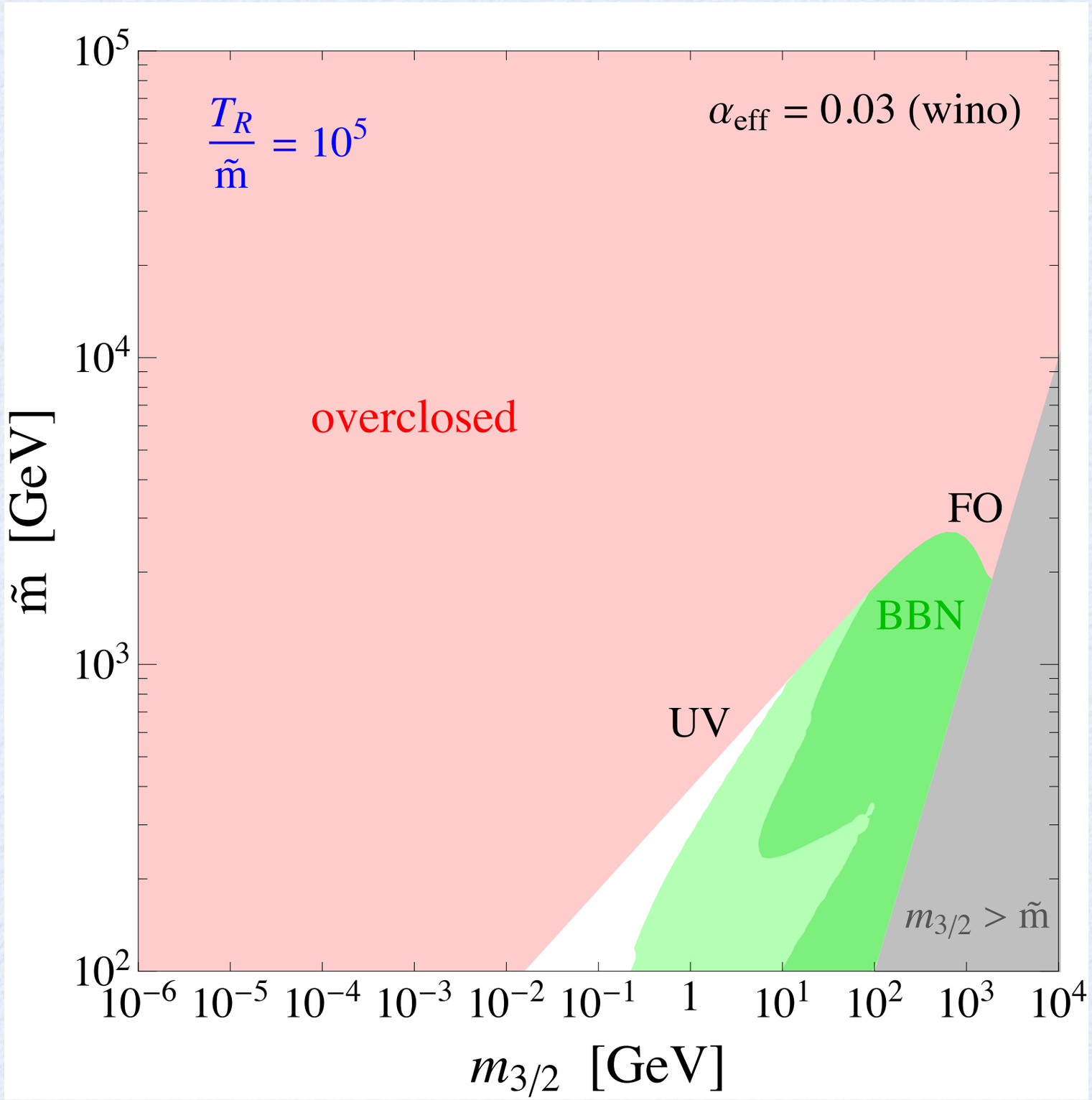
Superpartner Mass Bound



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

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

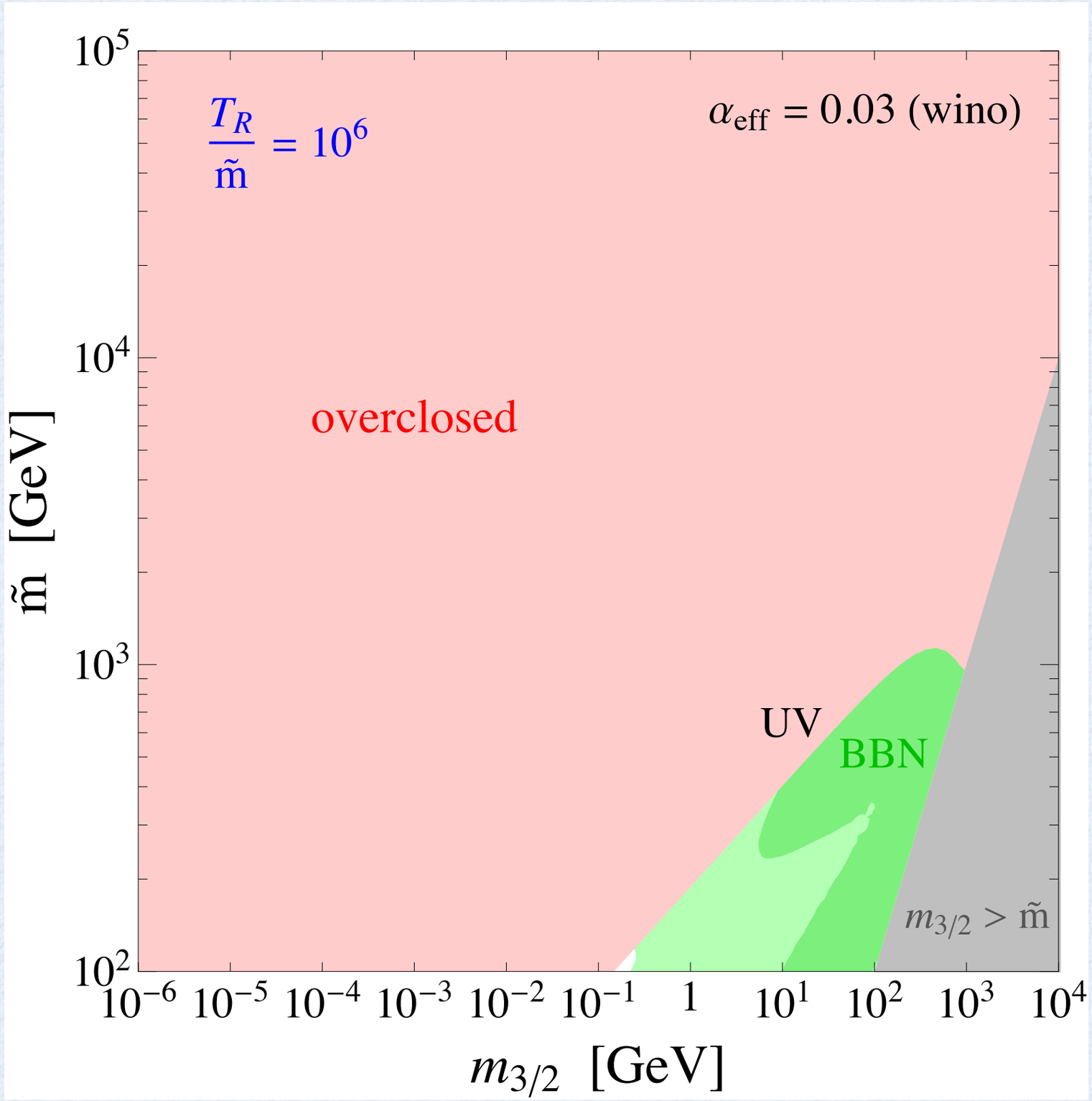
Superpartner Mass Bound



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

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

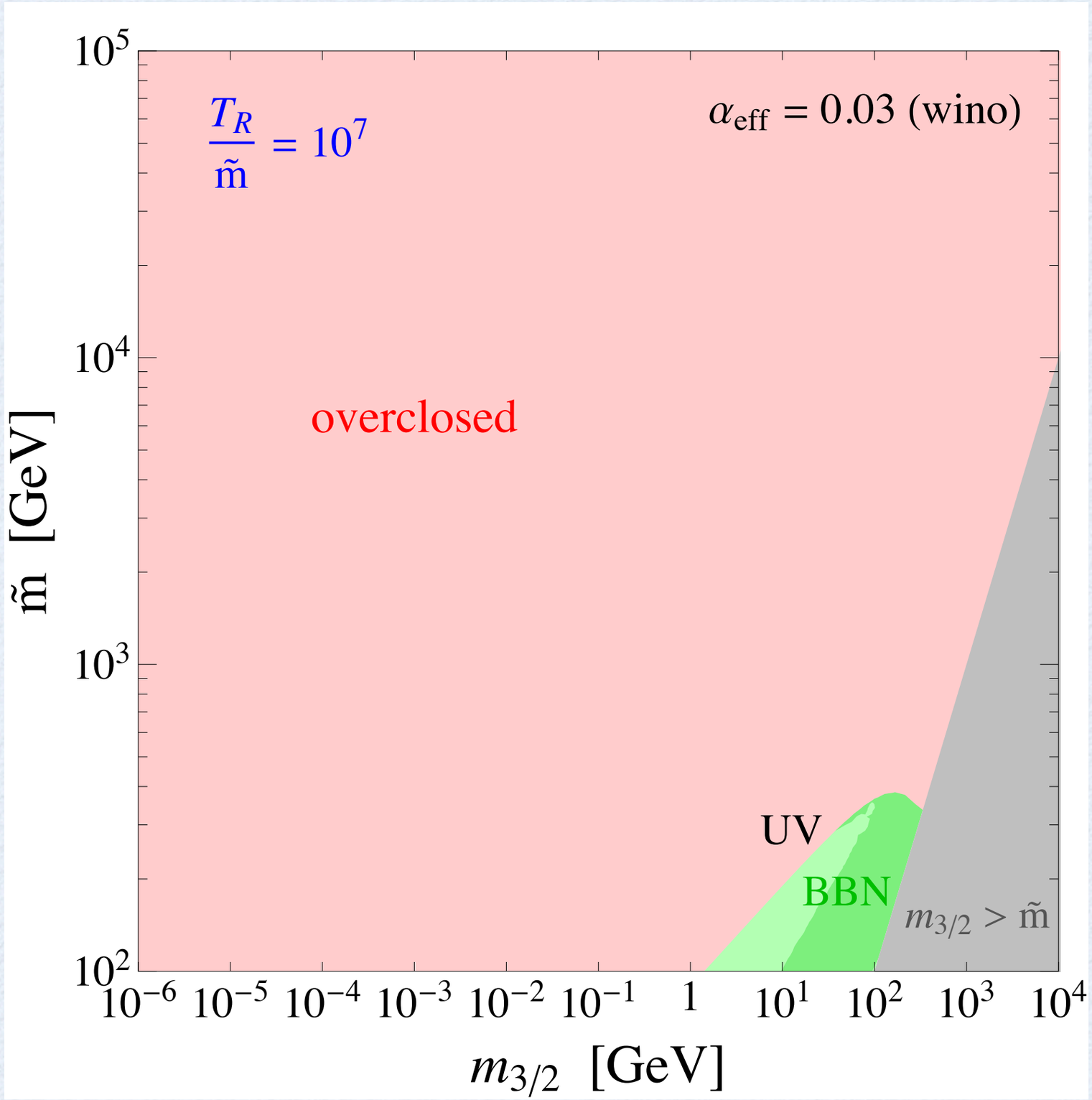
Superpartner Mass Bound



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

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

Superpartner Mass Bound



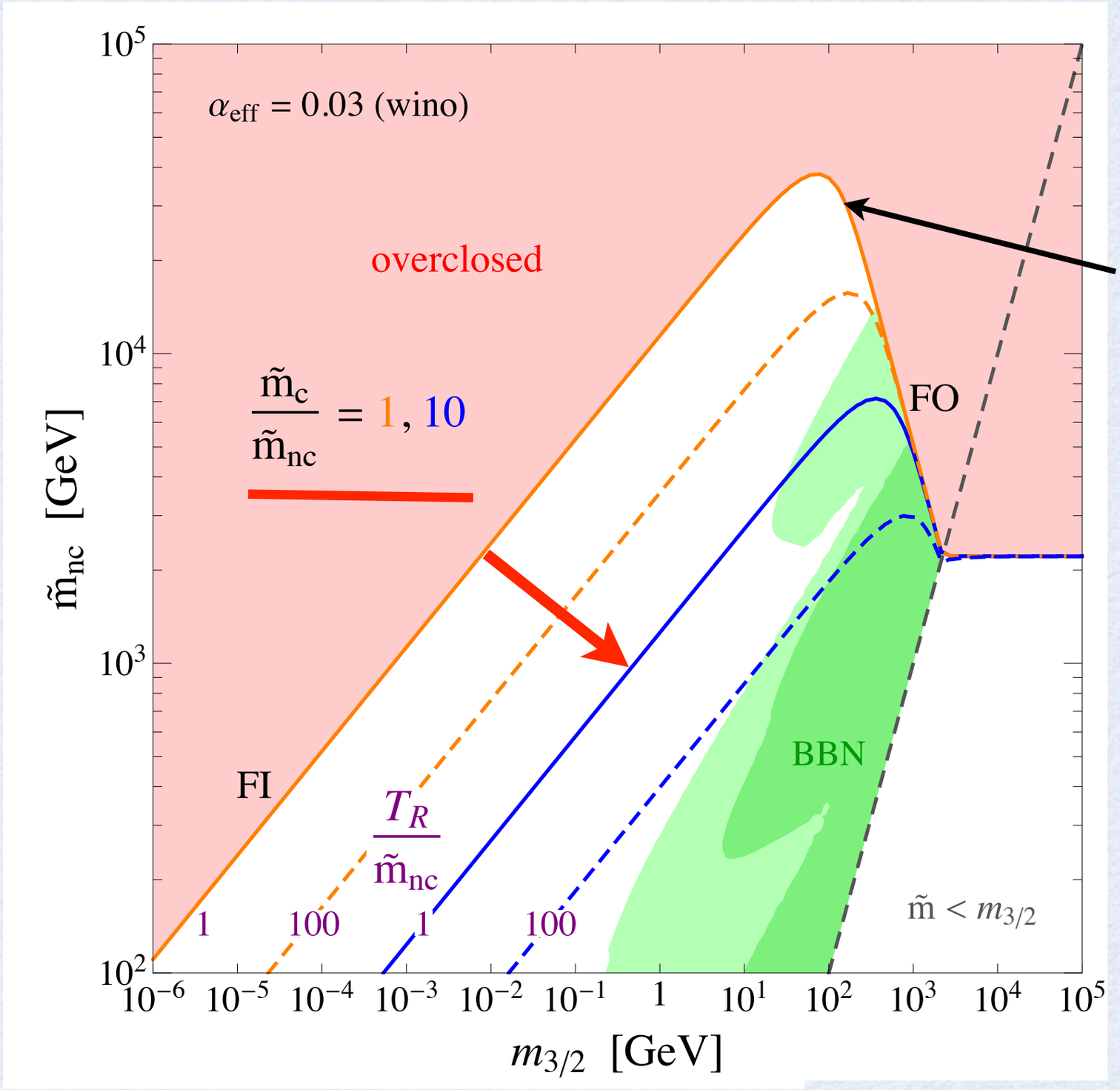
$$\frac{T_R}{\tilde{m}} = 10^7$$

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

Non-Degenerate Susy Spectrum

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

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



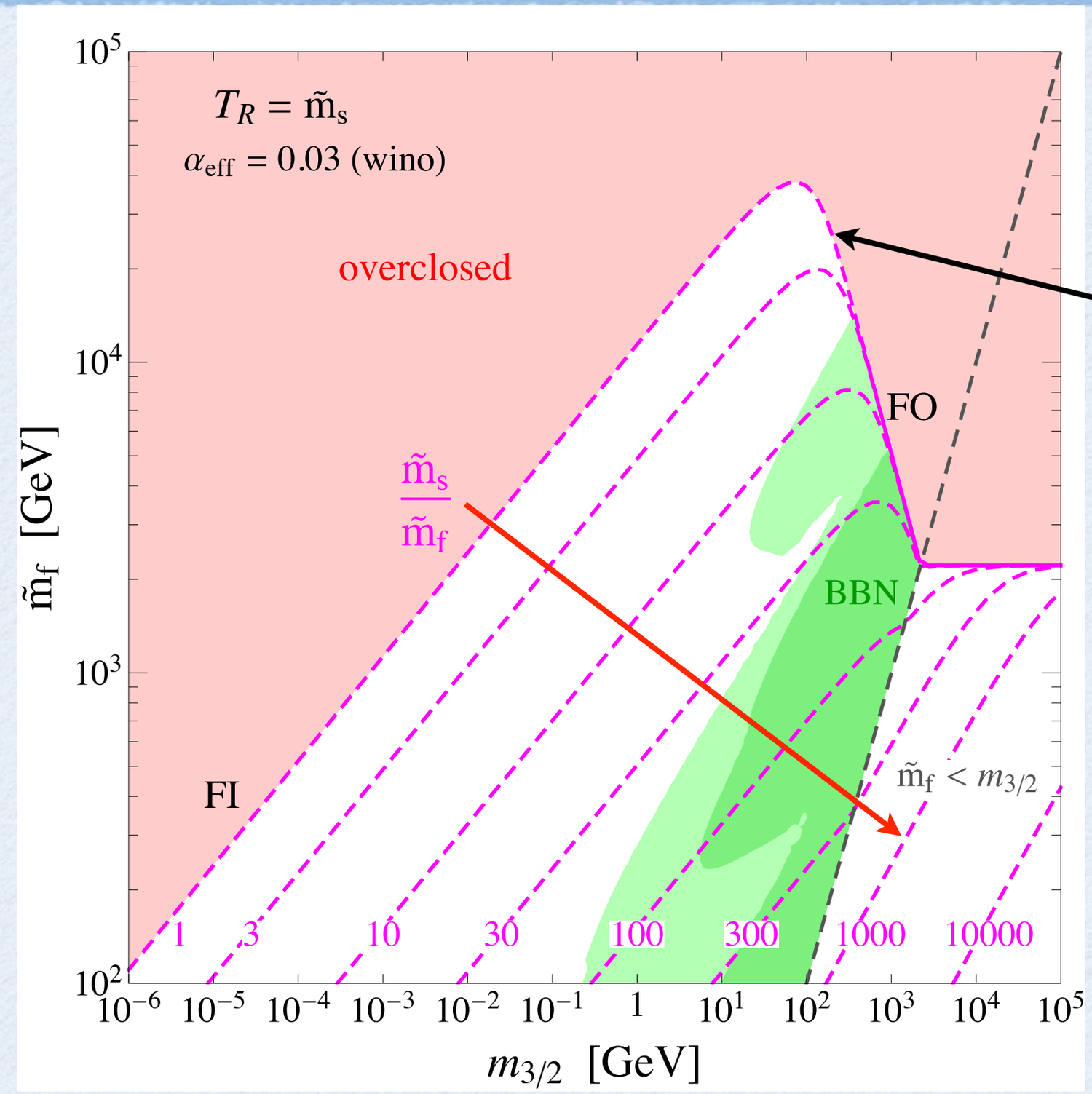
Superpartners degenerate

LJH, Josh Ruderman, Tomer Volansky arXiv: 1302.2620

Split Susy

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

$\tilde{m}_f$



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TeV Scale from SUSY Dark Matter

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

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$m_{3/2} > m$

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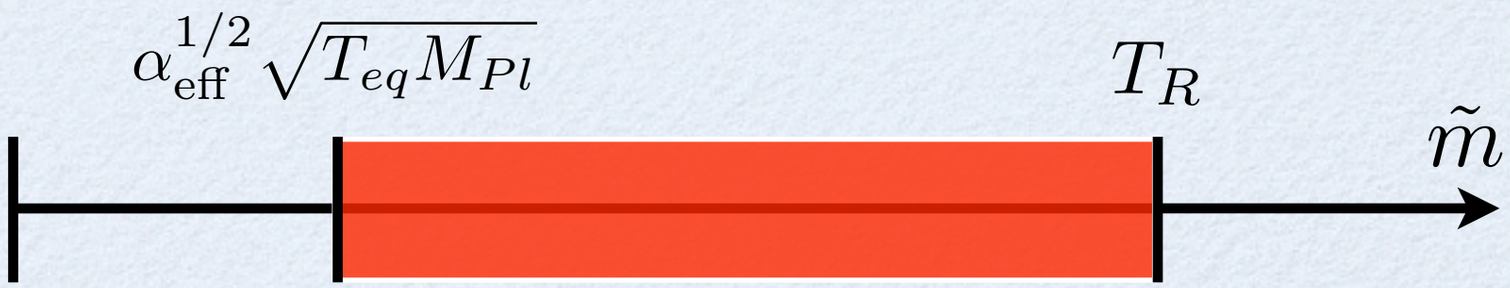

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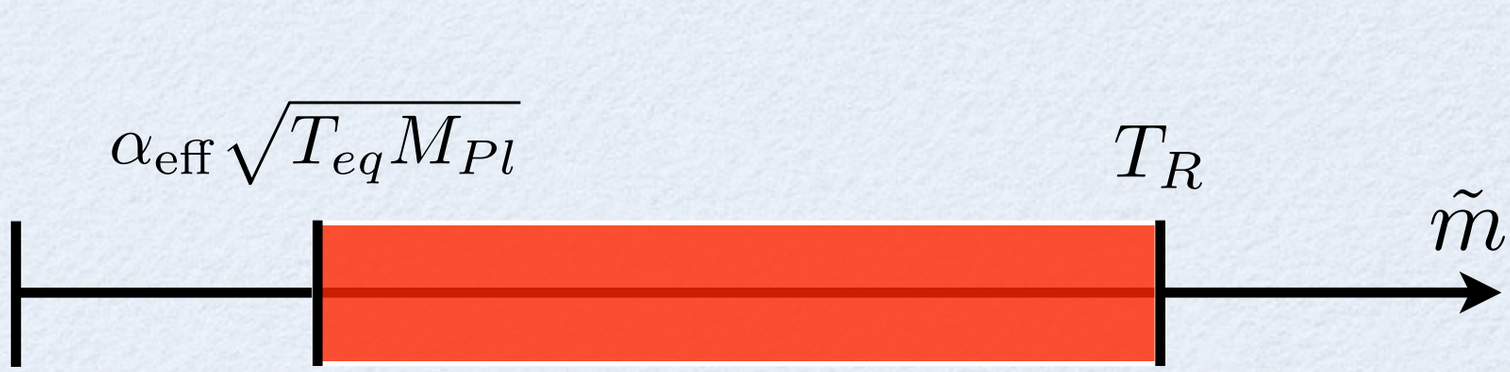

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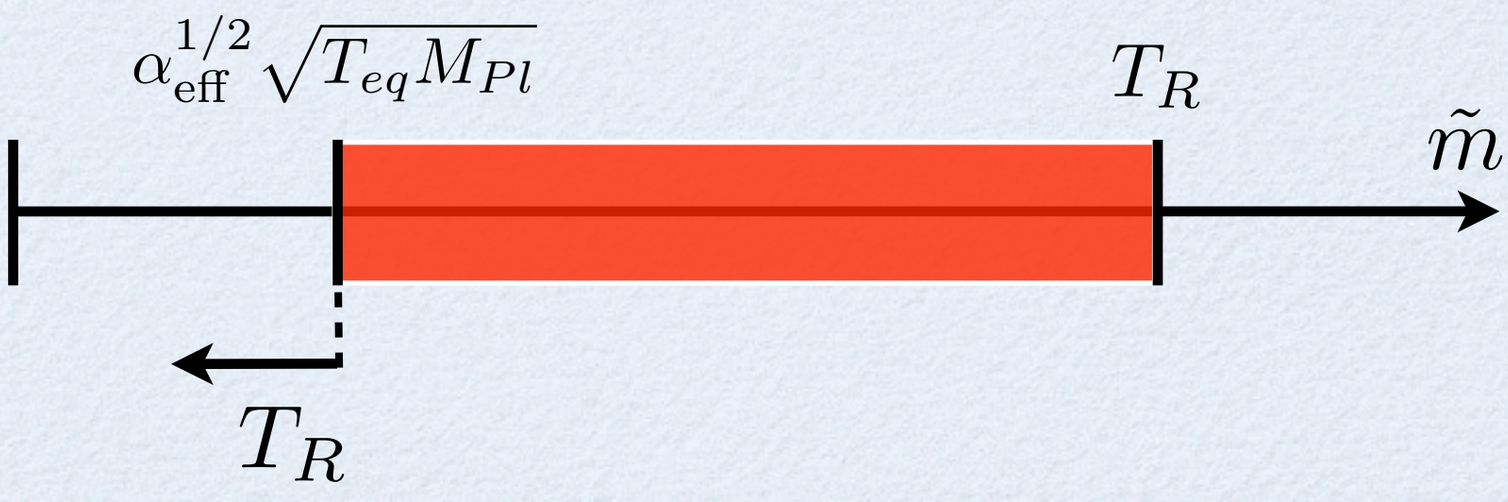

(III) A SUSY Theory for:

125 GeV Higgs

Dark Matter

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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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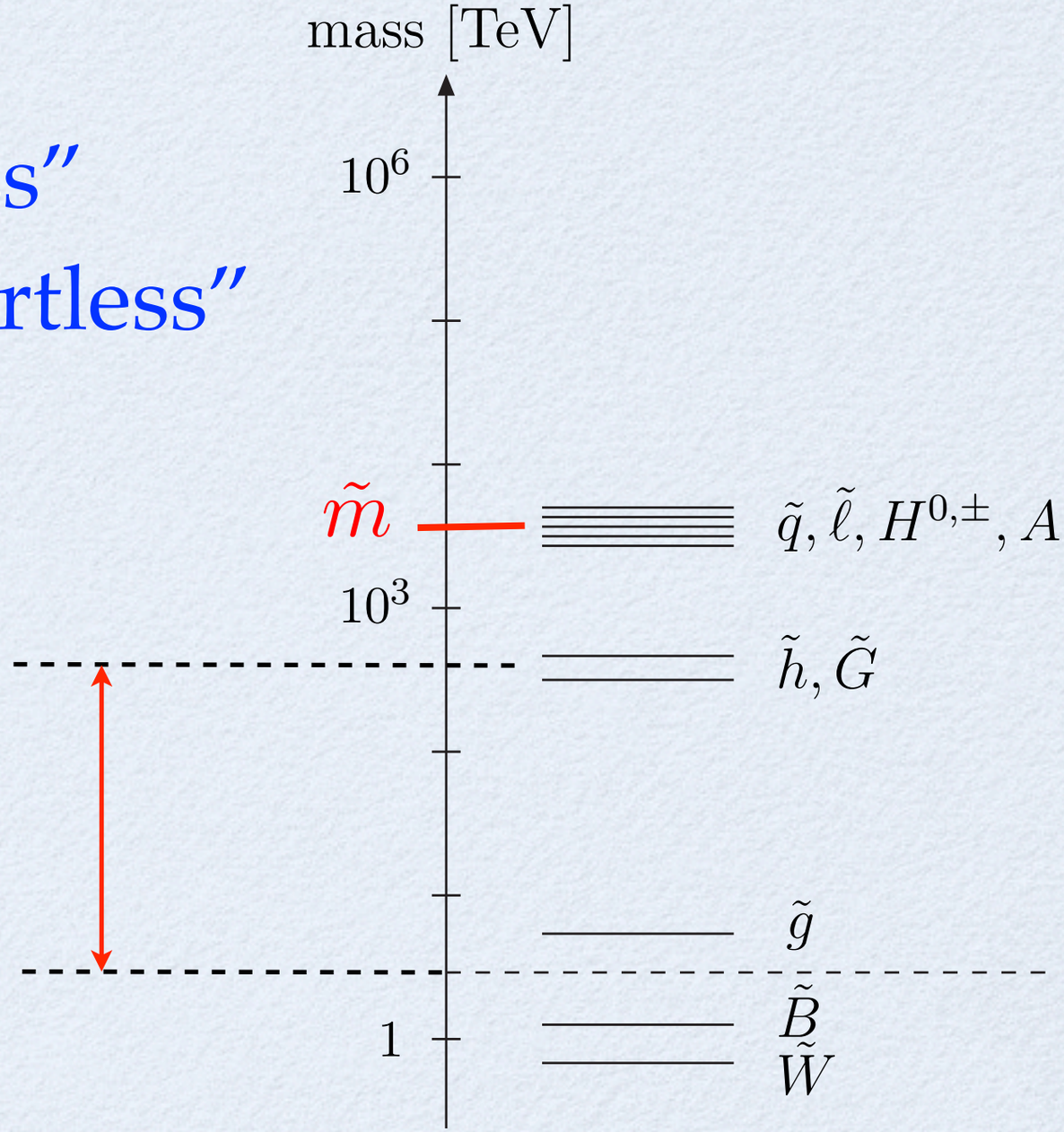
A 1-loop mass hierarchy from Anomaly Mediation

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



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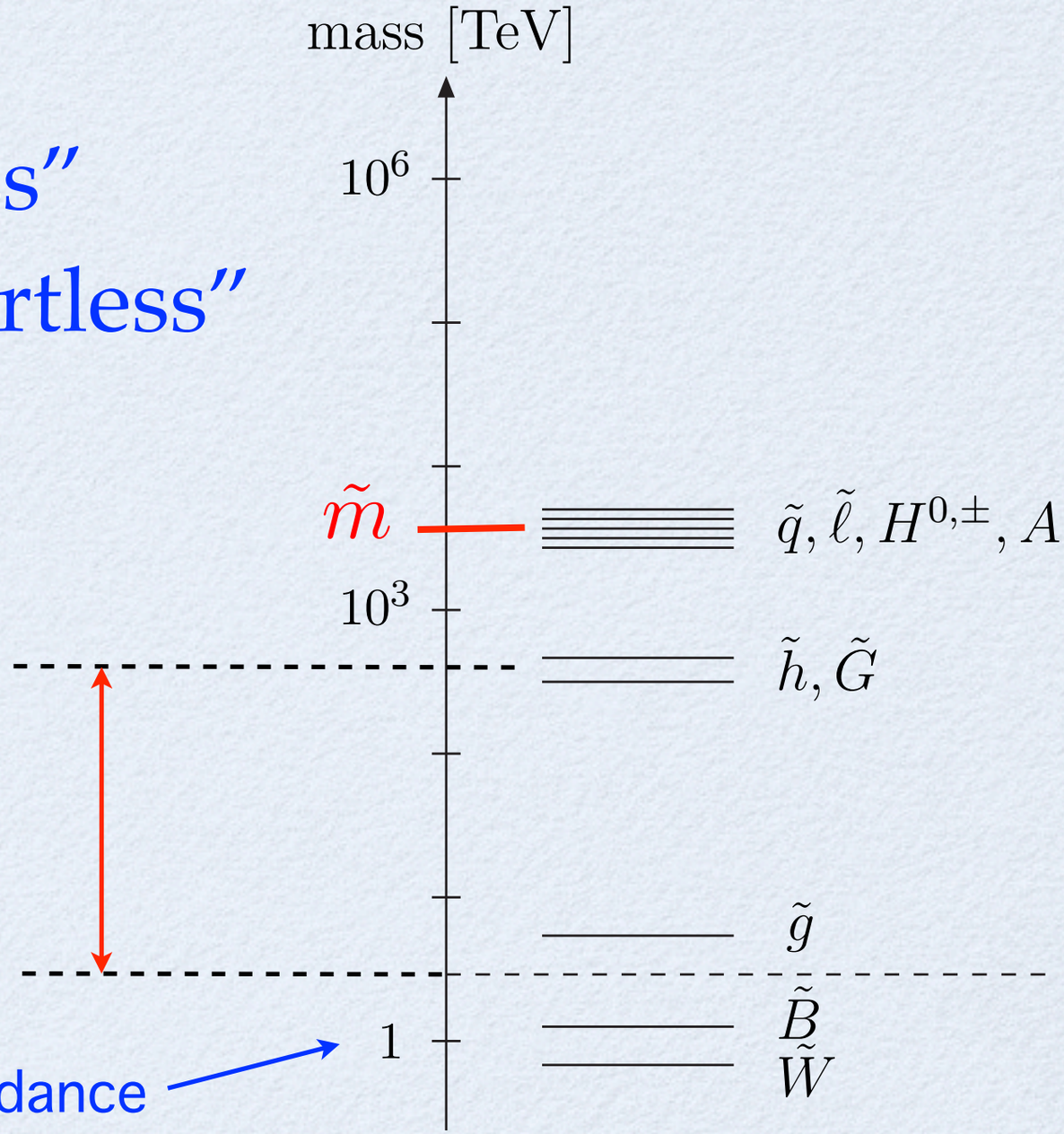

Mass scale normalized by dark matter abundance

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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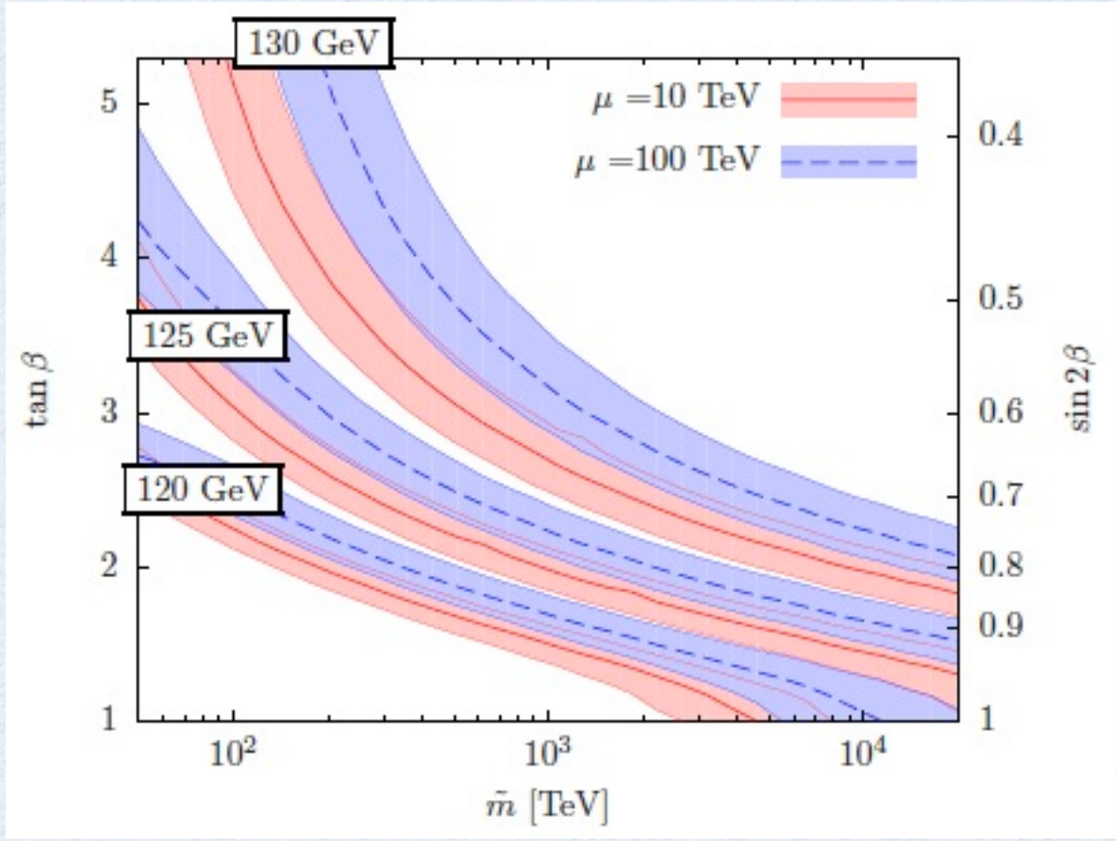
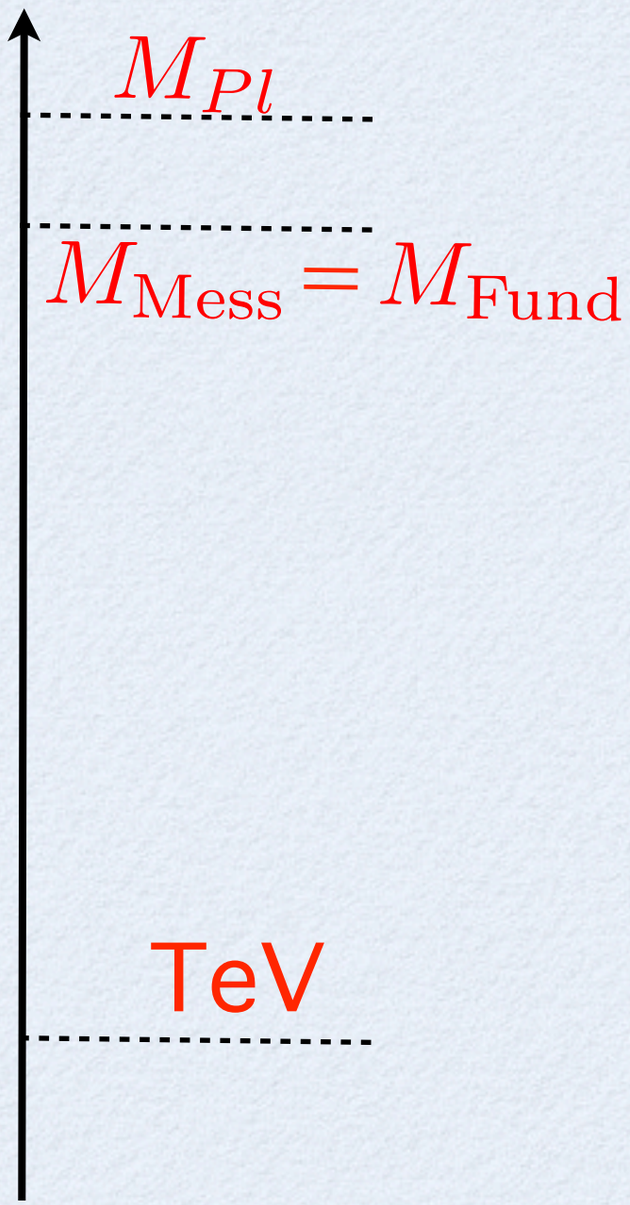


Hall, Nomura, Shirai
arXiv:1210.2395

Mass Scales

Key mass scales



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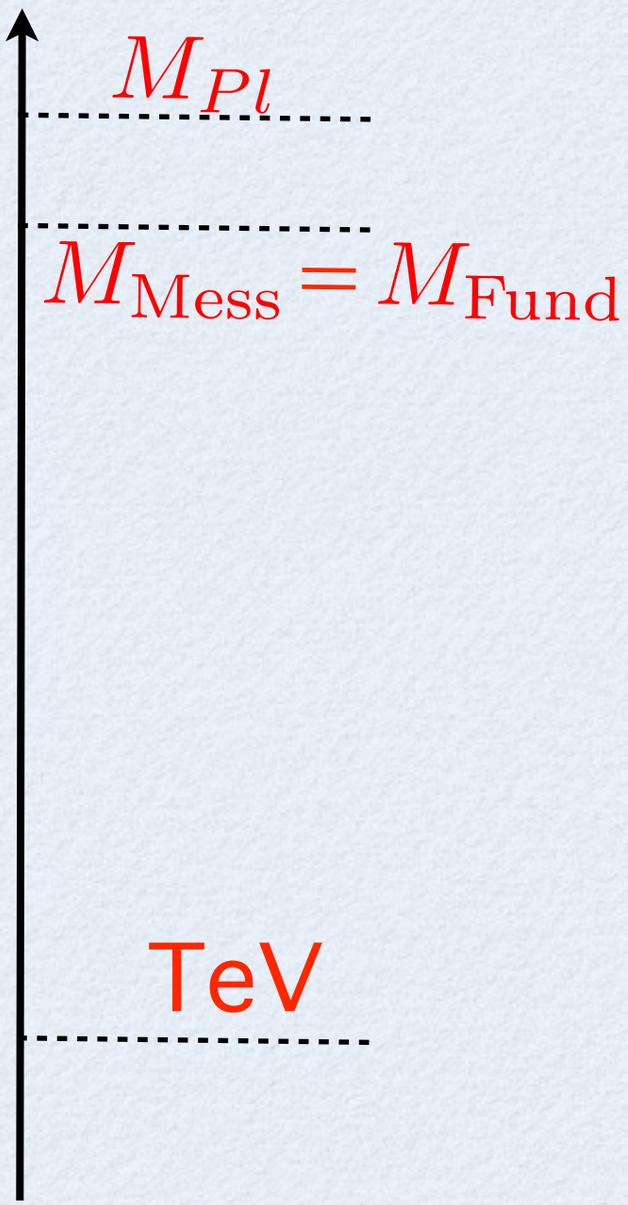
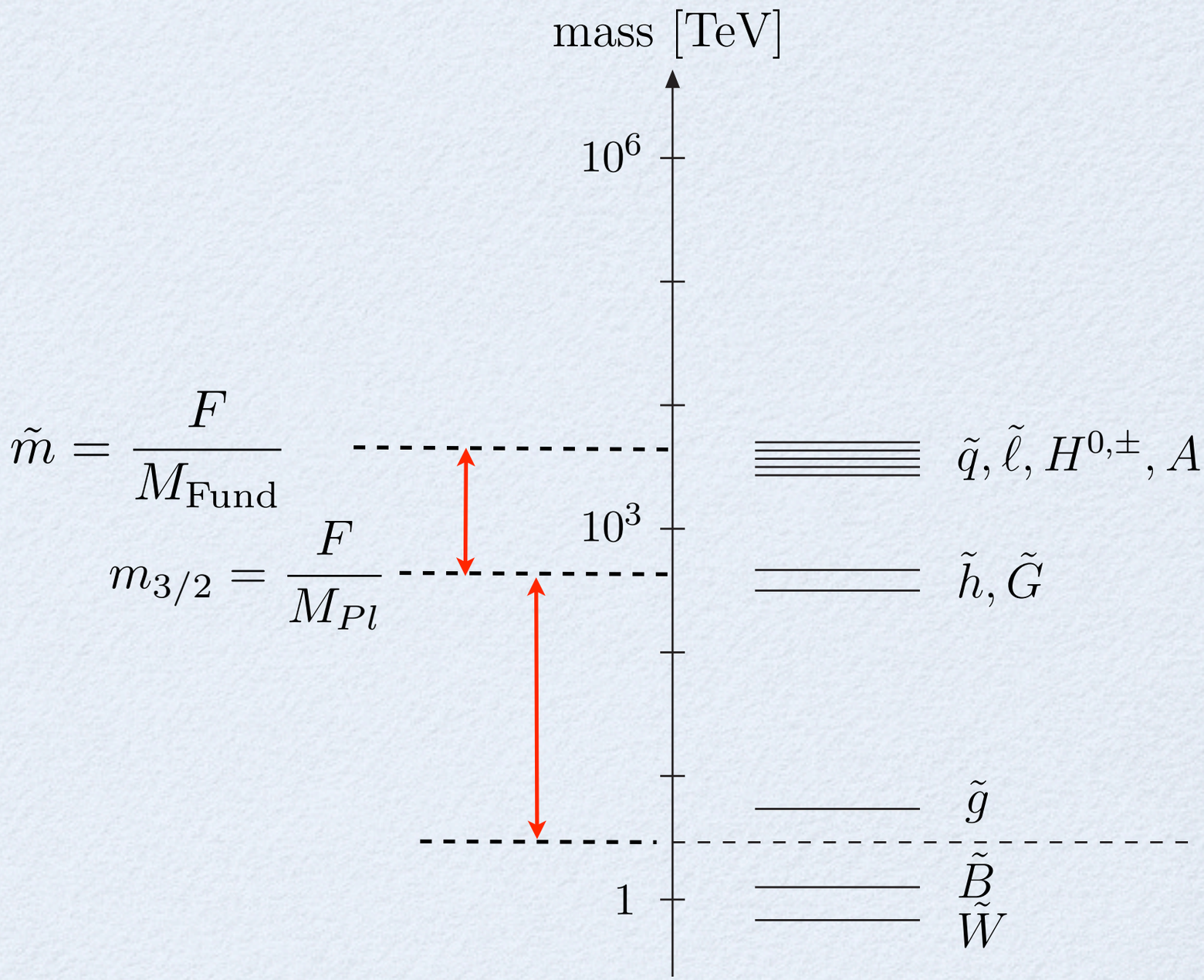


A Spread Susy spectrum



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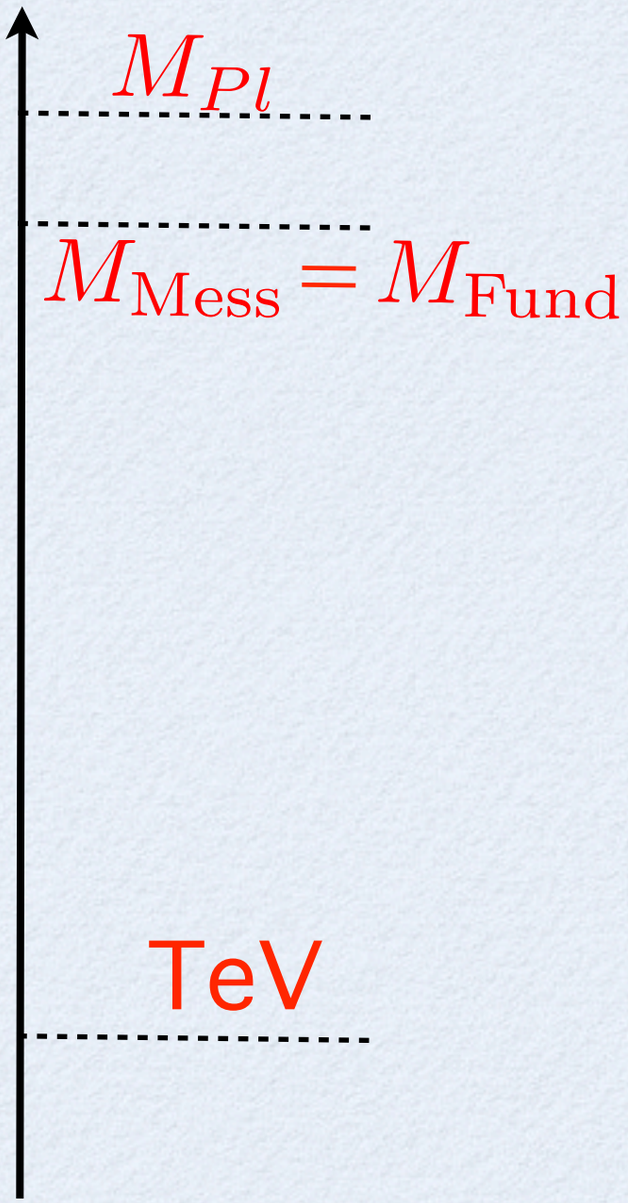
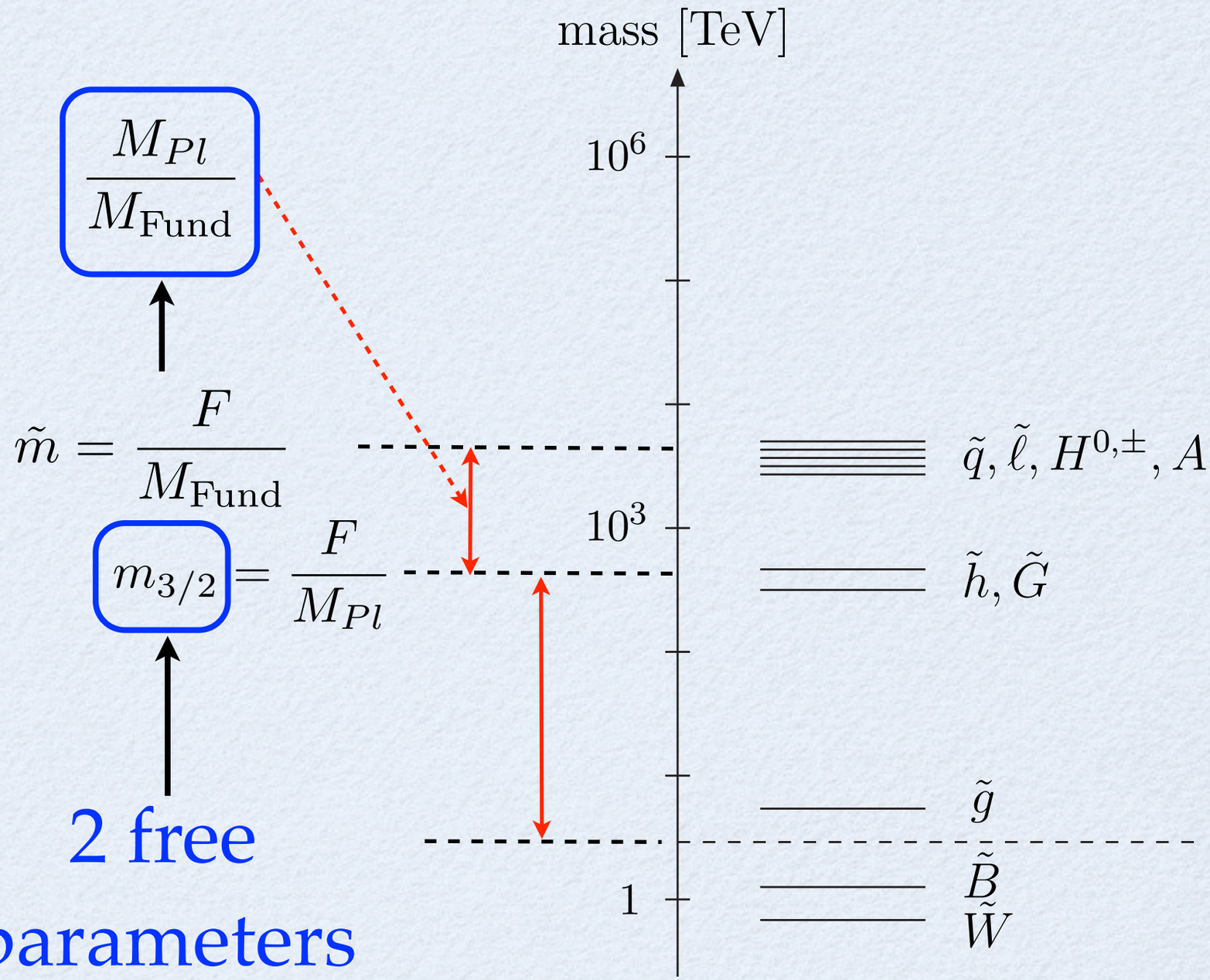
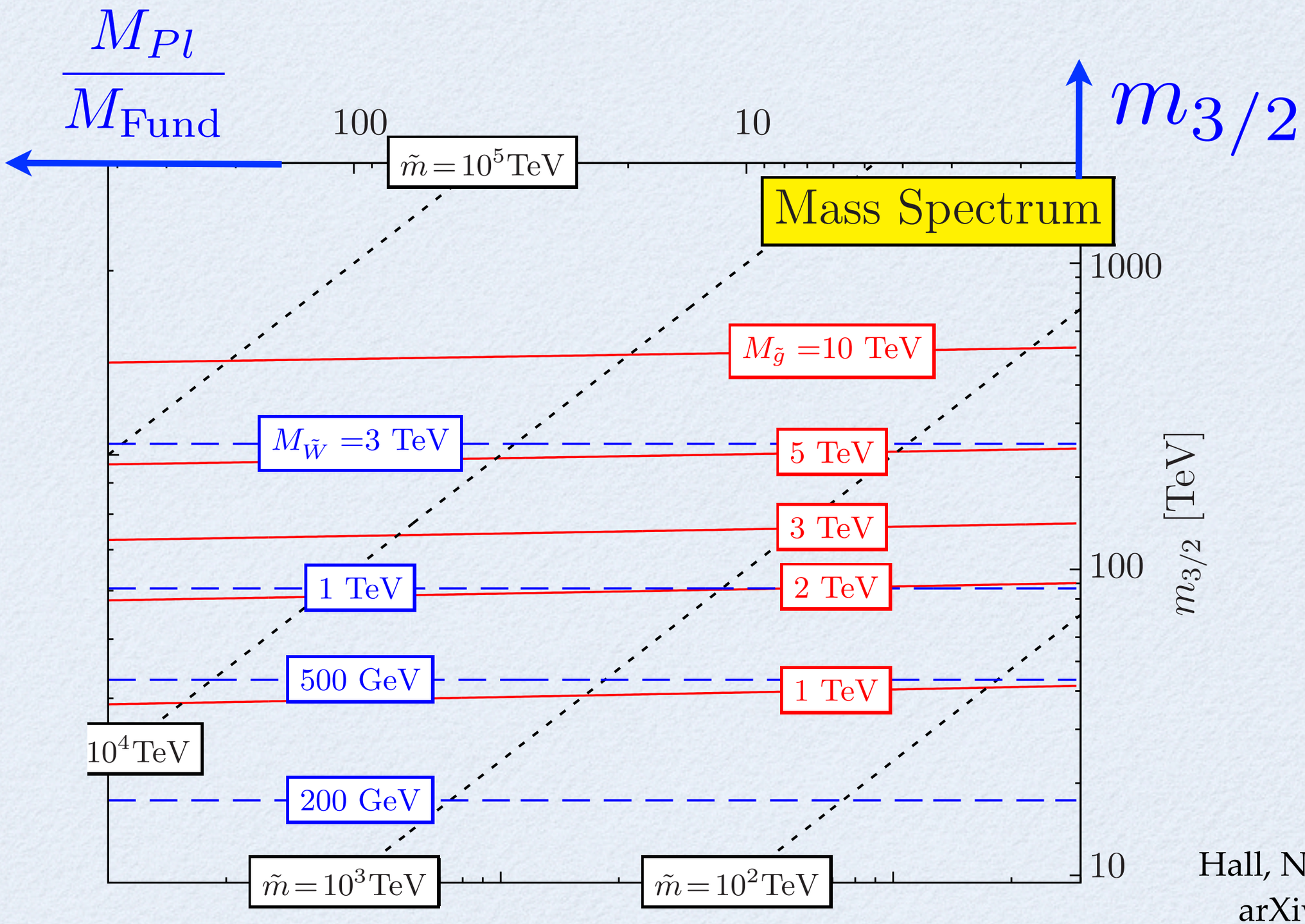
Key mass scales



A Spread Susy spectrum



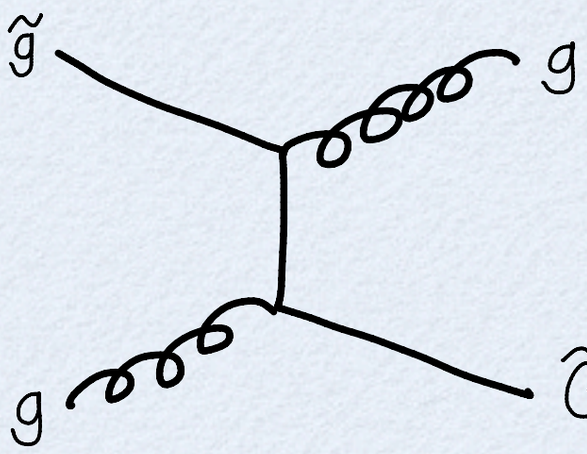
Susy Spectrum



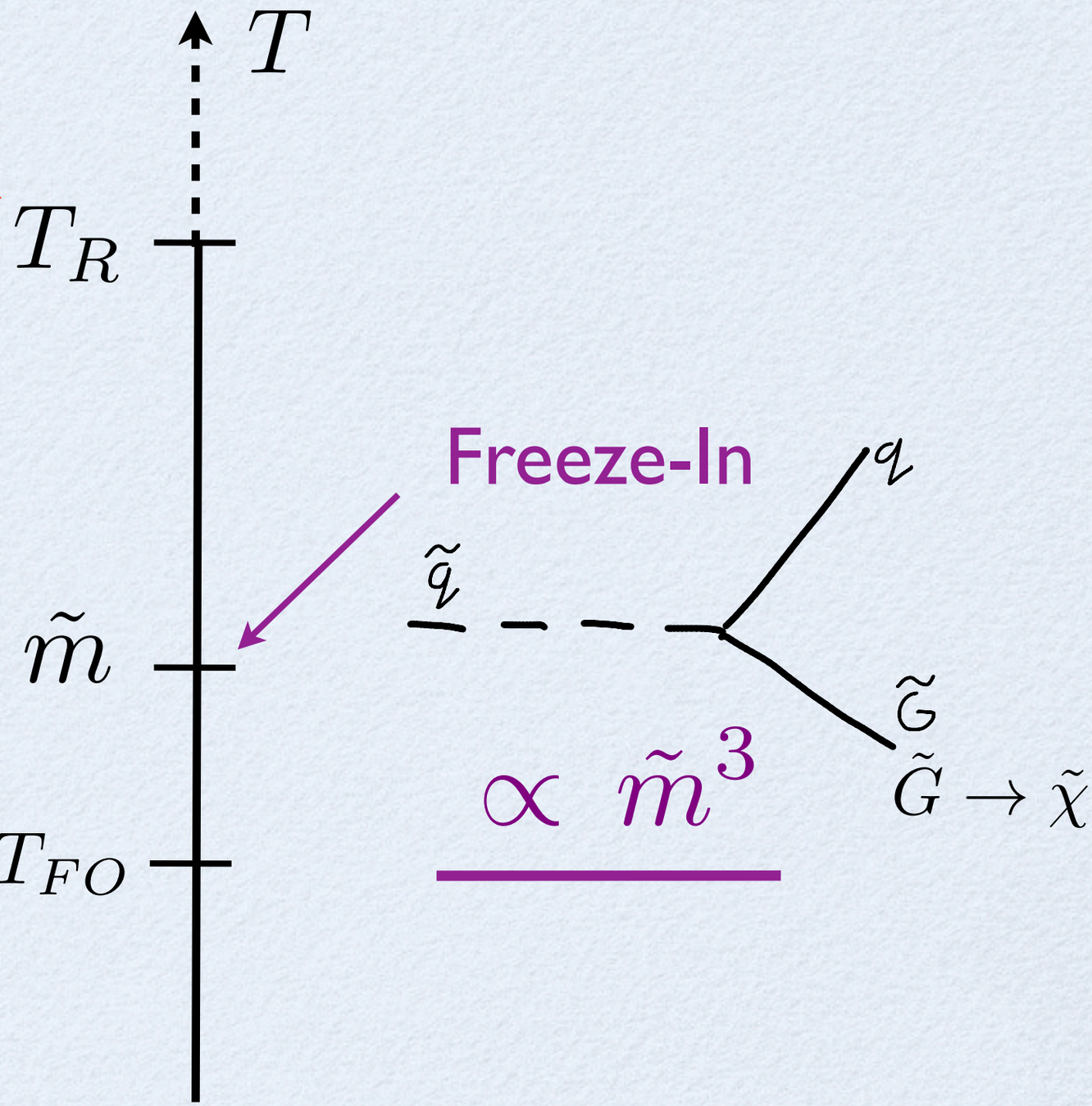
Hall, Nomura, Shirai
arXiv:1210.2395

3 Dark Matter Production Mechanisms

UV scattering



$\tilde{G} \to \tilde{\chi}$

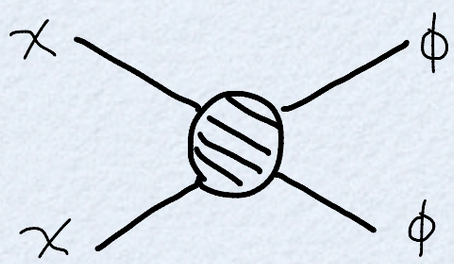


Freeze-In

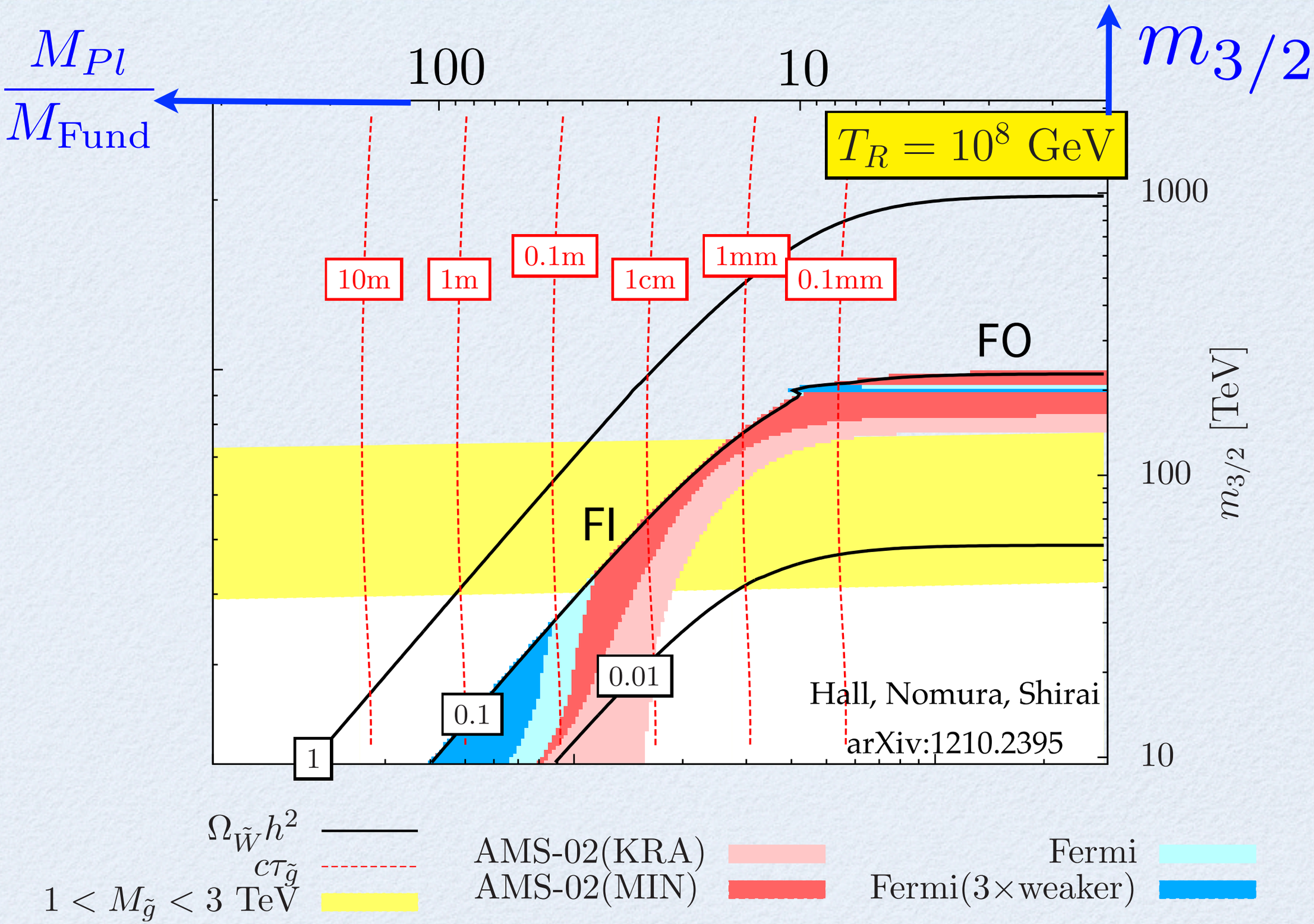
$\tilde{G} \to \tilde{\chi}$

$\propto \tilde{m}^3$

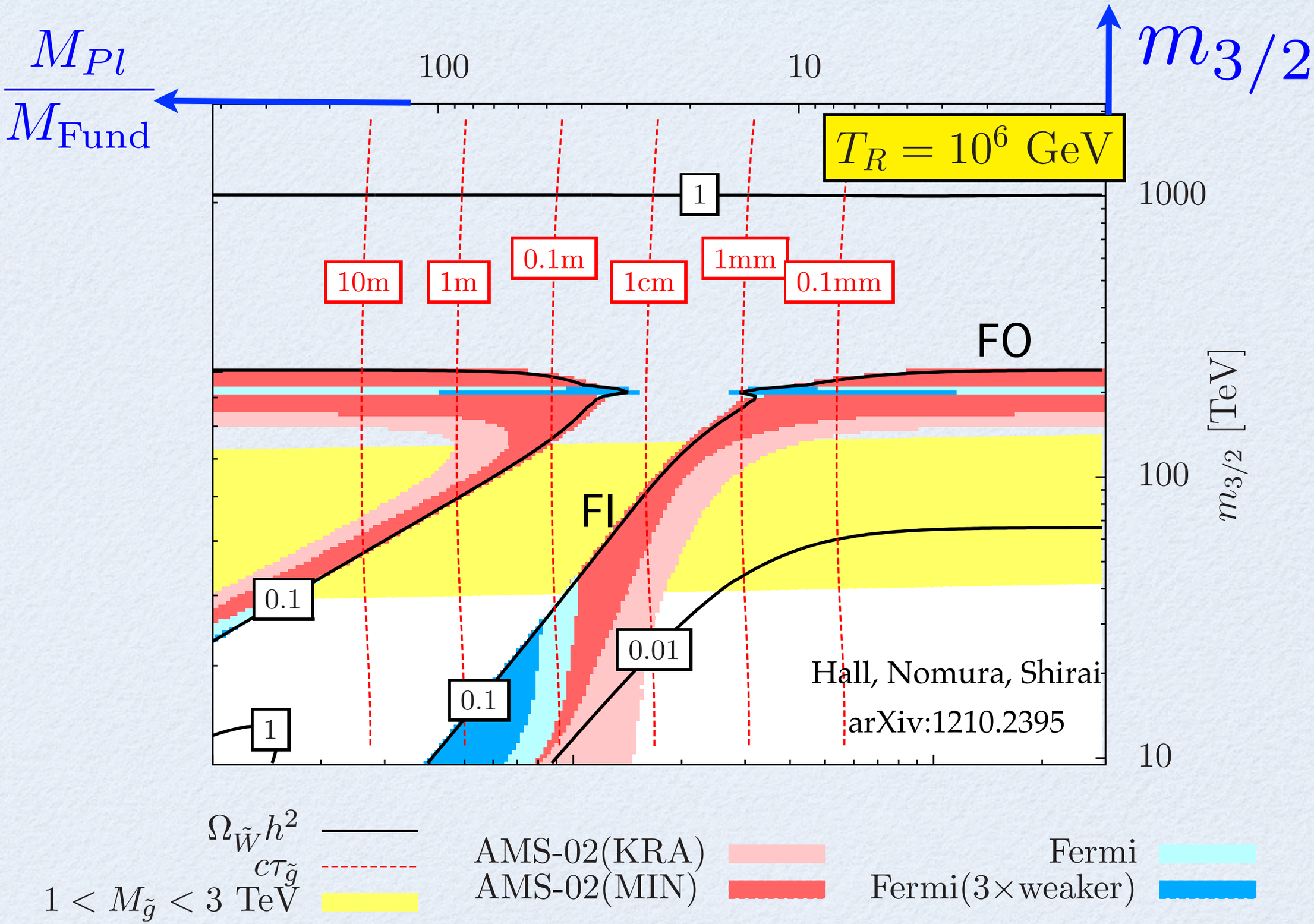
Freeze-Out



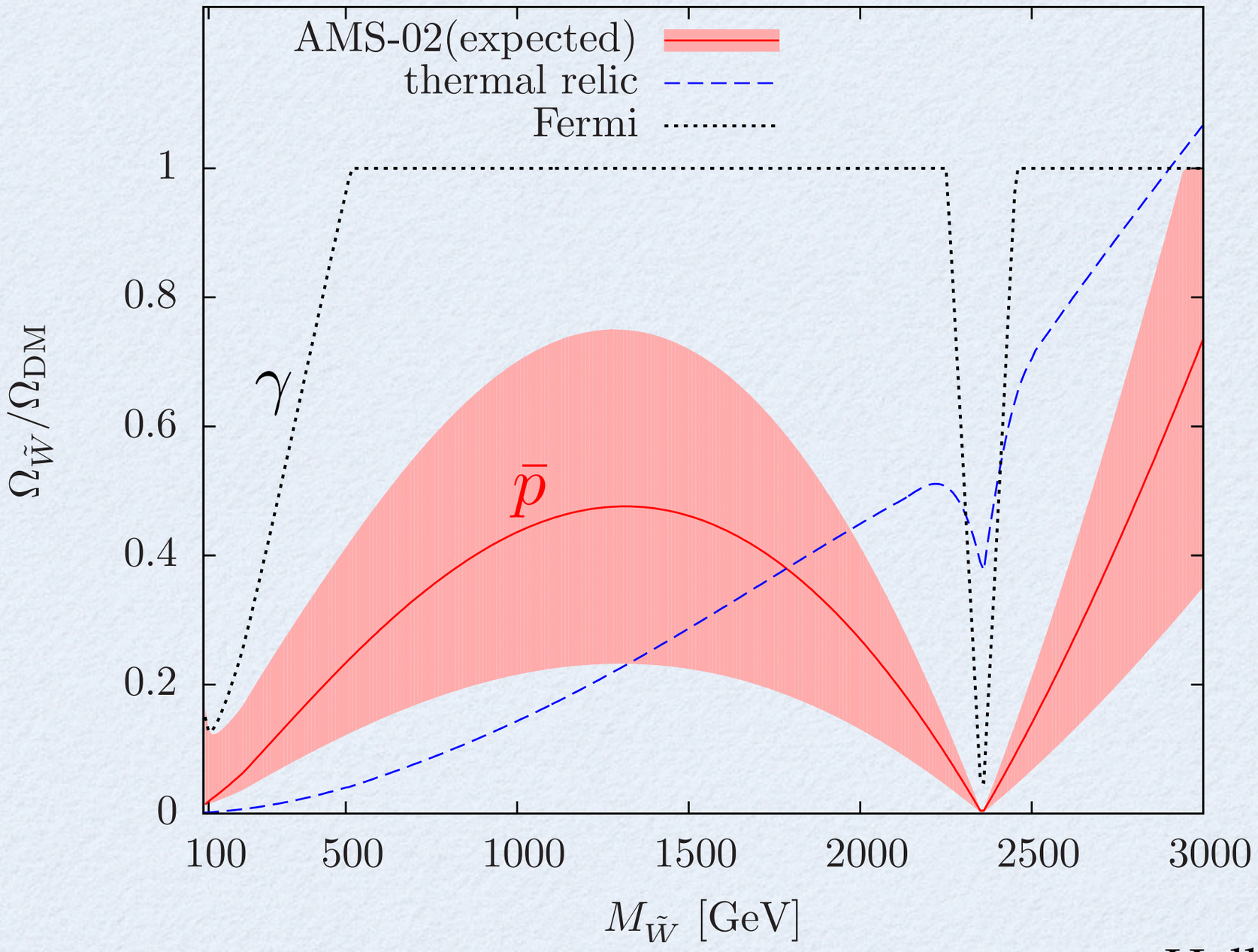
Dark Matter Abundance



Dark Matter Abundance



Indirect Detection of Wino DM



Hall, Nomura, Shirai
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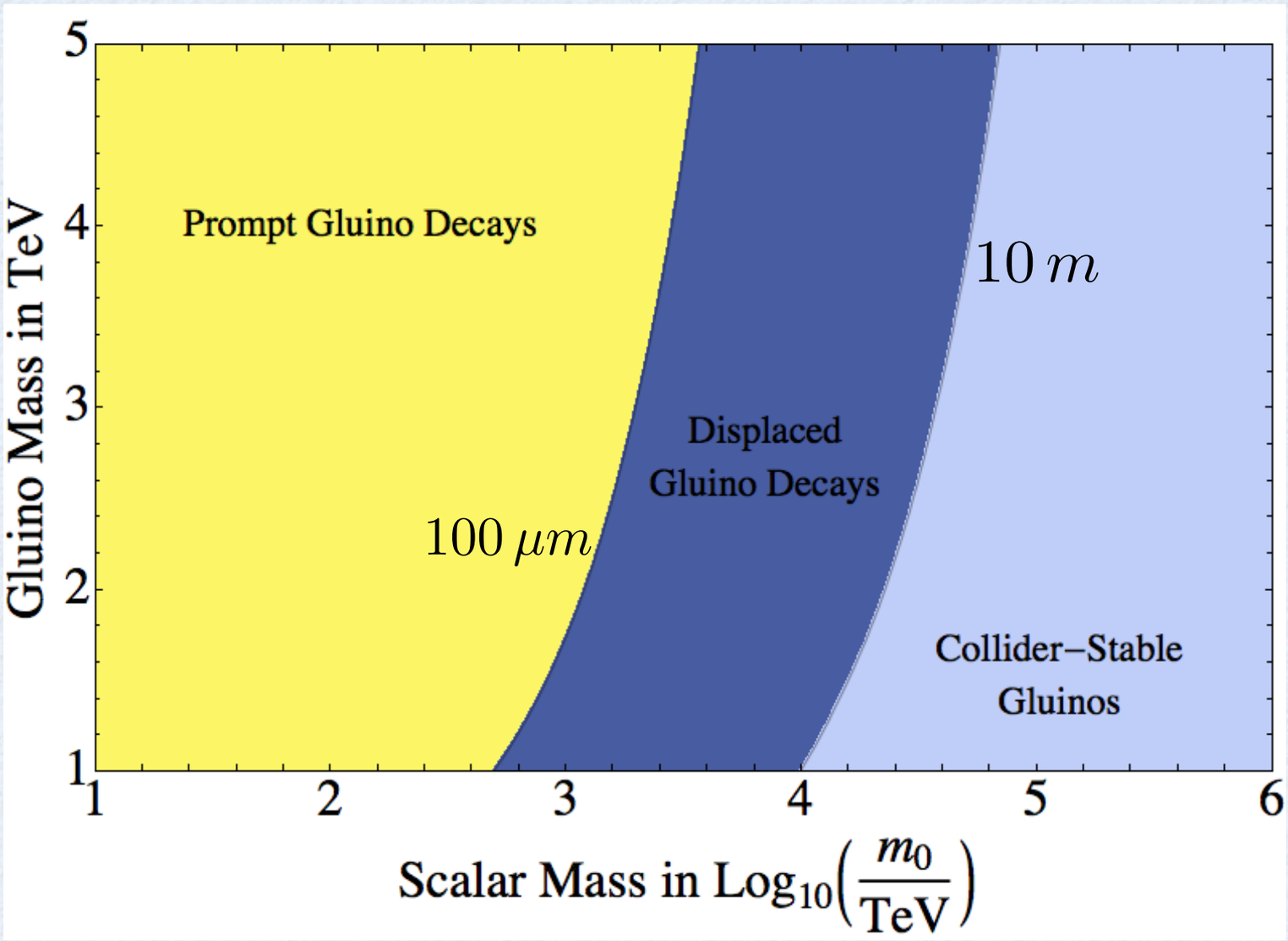
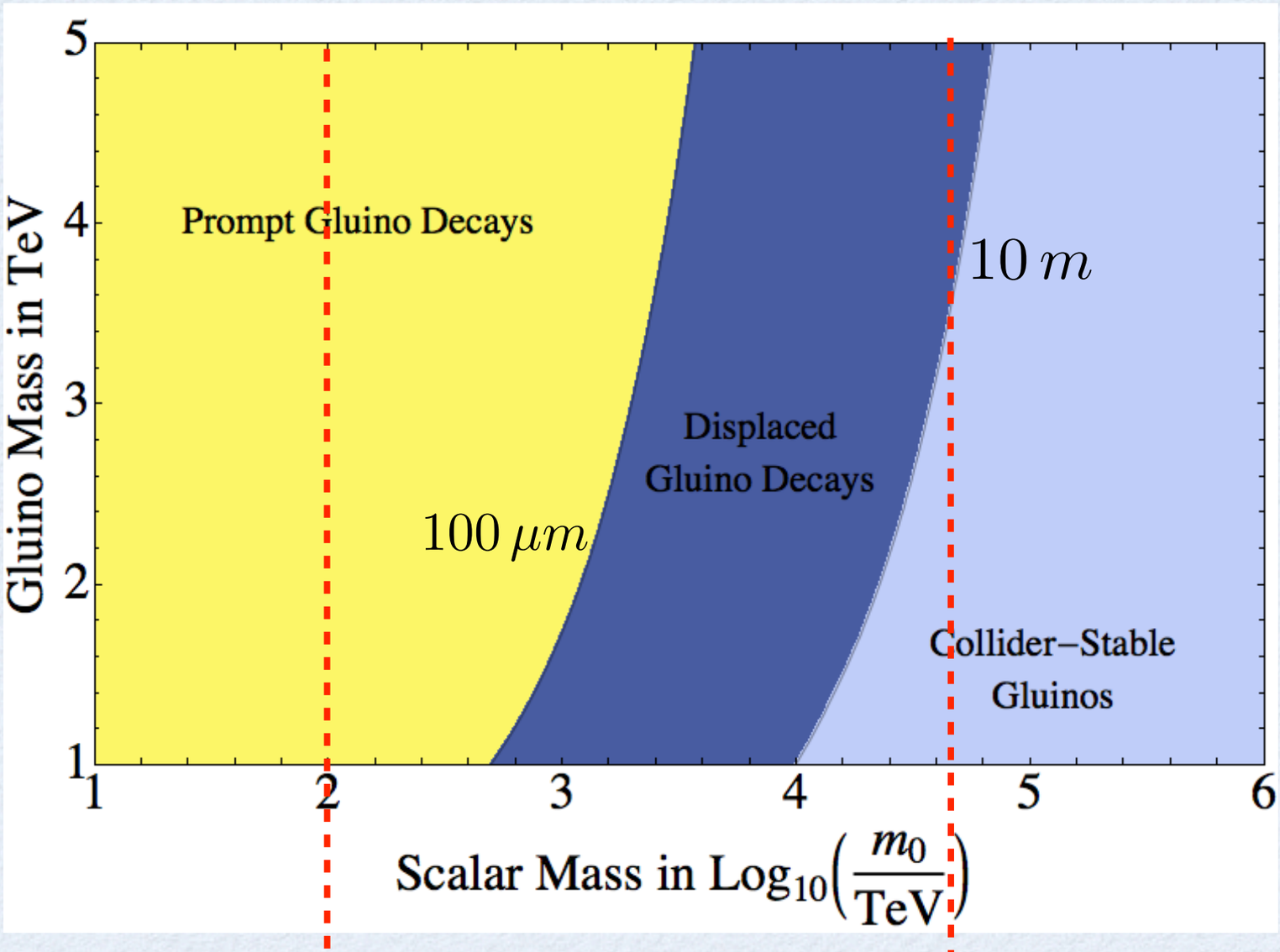
Gluino Pheno



Arvanitaki, Craig, Dimopoulos, Villadoro
arXiv:1210.0555

Gluino Pheno



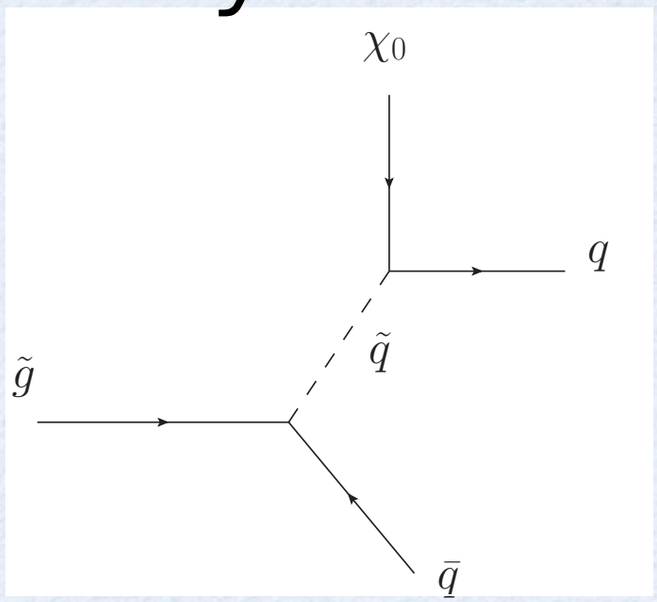
Arvanitaki, Craig, Dimopoulos, Villadoro
arXiv:1210.0555

DM constraint
in Spread

Decay Cascades

Gluino Decays

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



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

only 3 free params

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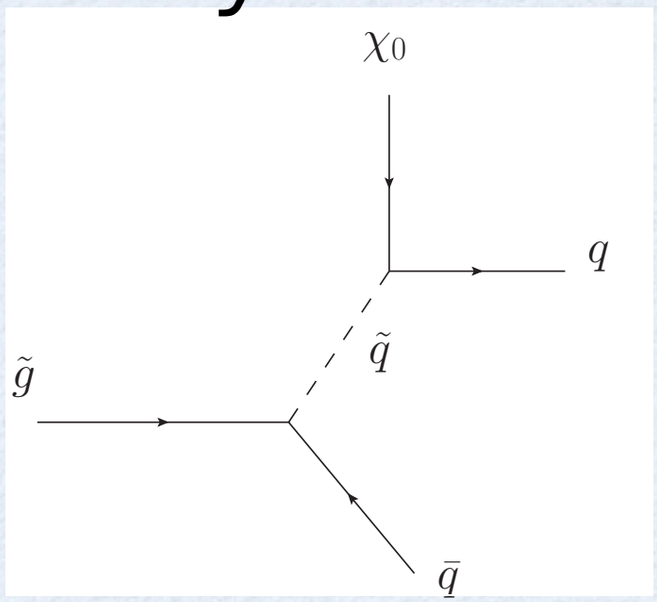

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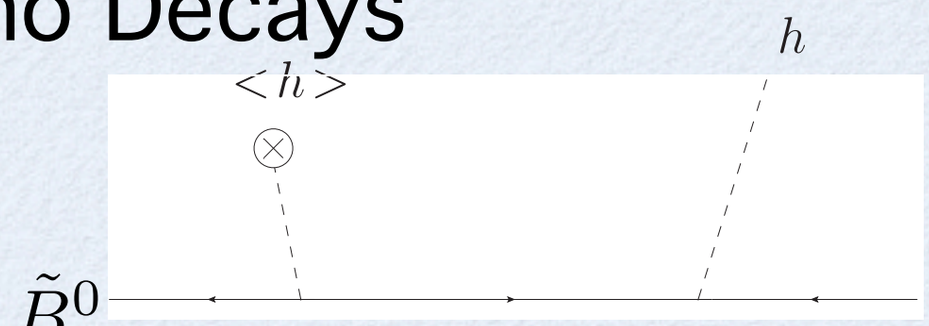
only 3 free params

Bino Decays



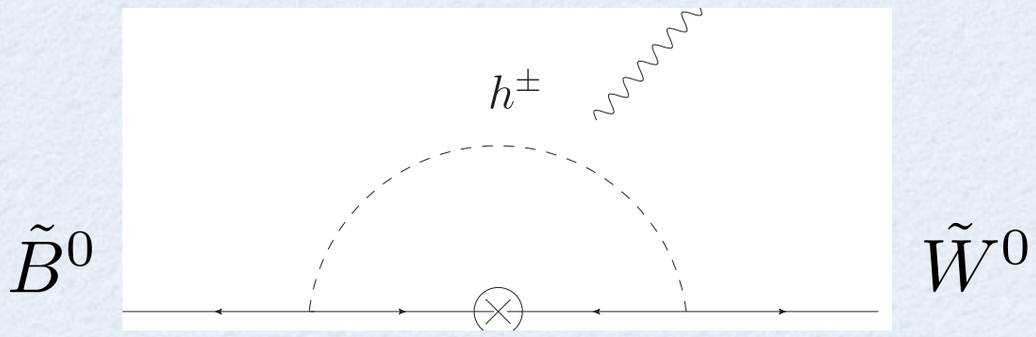
$$\tilde{B}^0 \to \tilde{W}^0 h$$

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

only μ

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

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

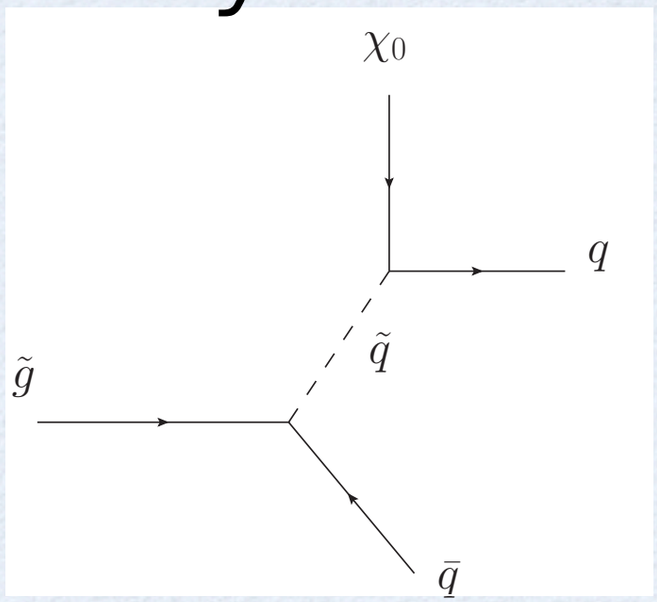


$$\tilde{B}^0 \to \tilde{W}^0 \gamma$$

Decay Cascades

Gluino Decays

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



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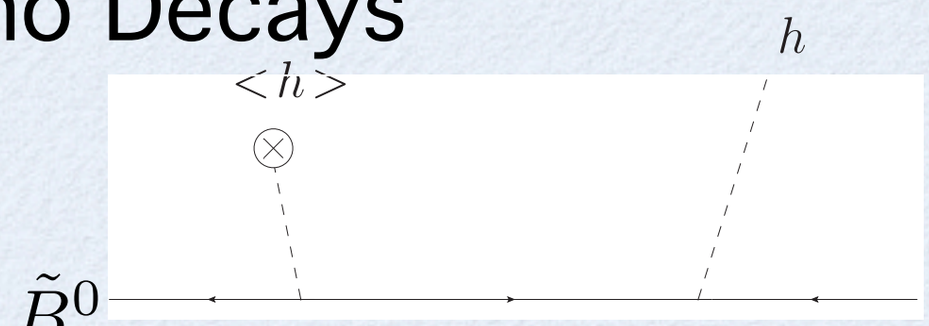
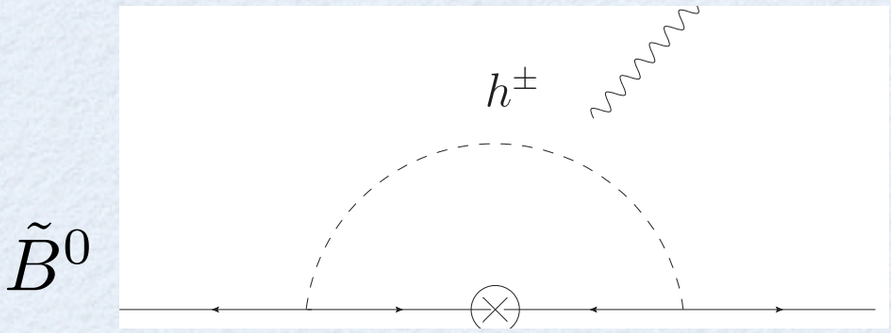
Bino Decays





Wino Decays

$$\tilde{W}^\pm \to \tilde{W}^0\pi^\pm$$
$$\approx 10\,\mathrm{cm}$$

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

only μ

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

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

$h \to \gamma\gamma$

If μ reduced

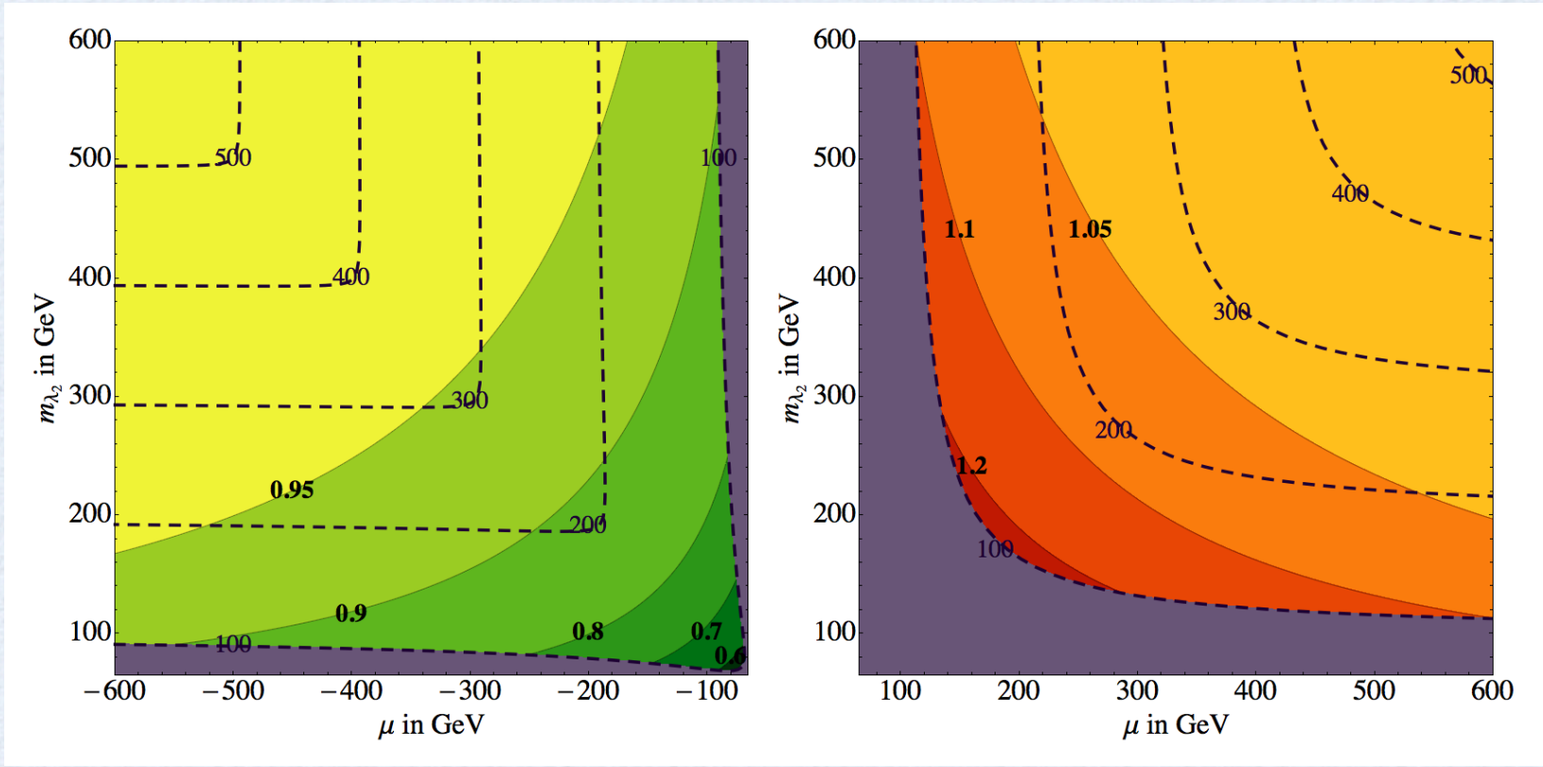


Figure 12: Contours of $\Gamma_{h\to\gamma\gamma}/\Gamma^{SM}_{h\to\gamma\gamma}$ in the higgsino-wino mass plane for $\mu m_{\lambda_2} < 0$ (left) and $\mu m_{\lambda_2} > 0$ (right) with $\tan\beta = 1$. The dashed contours denote the lightest chargino mass in GeV. The purple-shaded region indicates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

Arvanitaki, Craig, Dimopoulos, Villadoro arXiv:1210.0555

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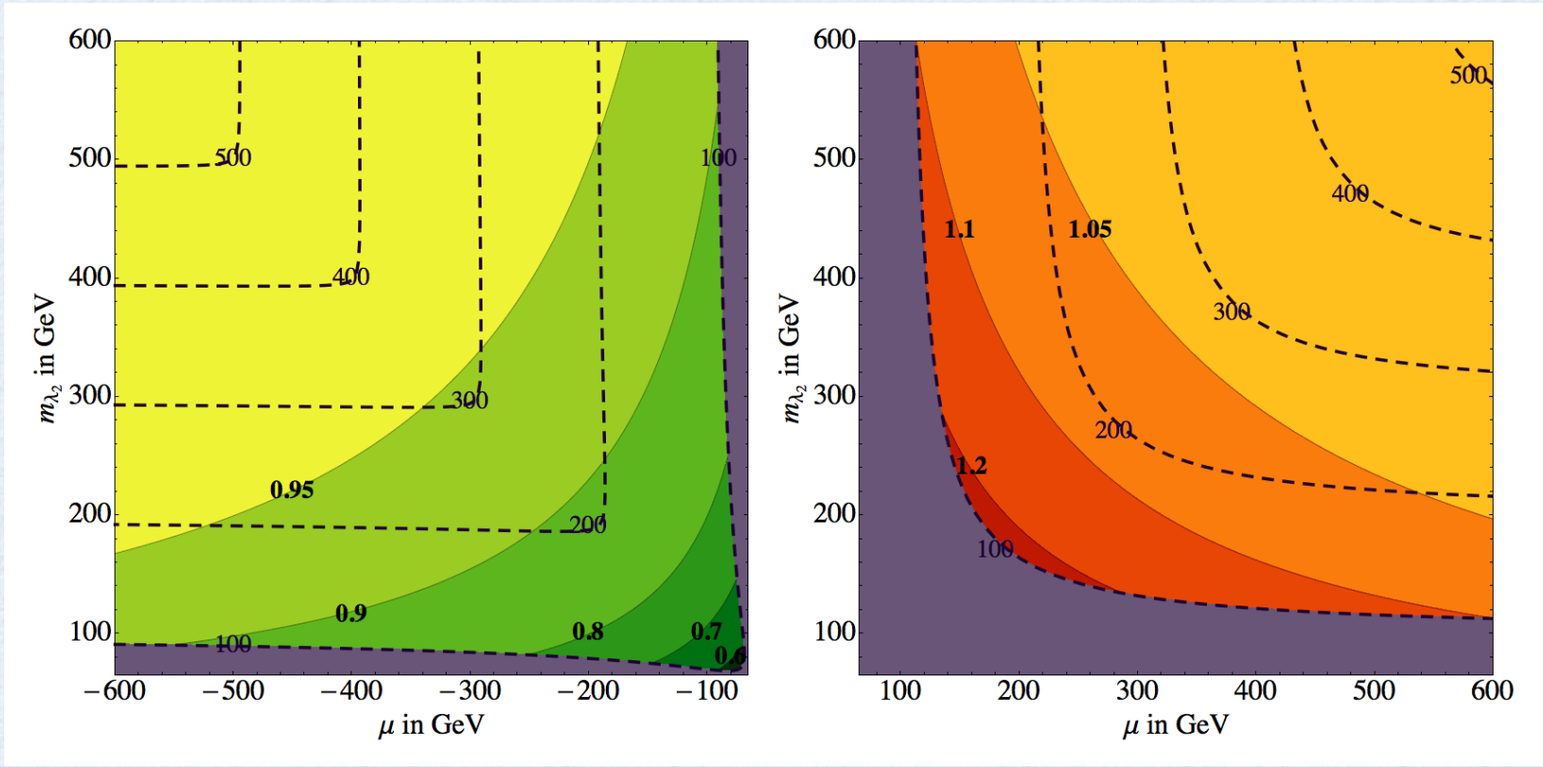

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Arvanitaki, Craig, Dimopoulos, Villadoro
arXiv:1210.0555

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

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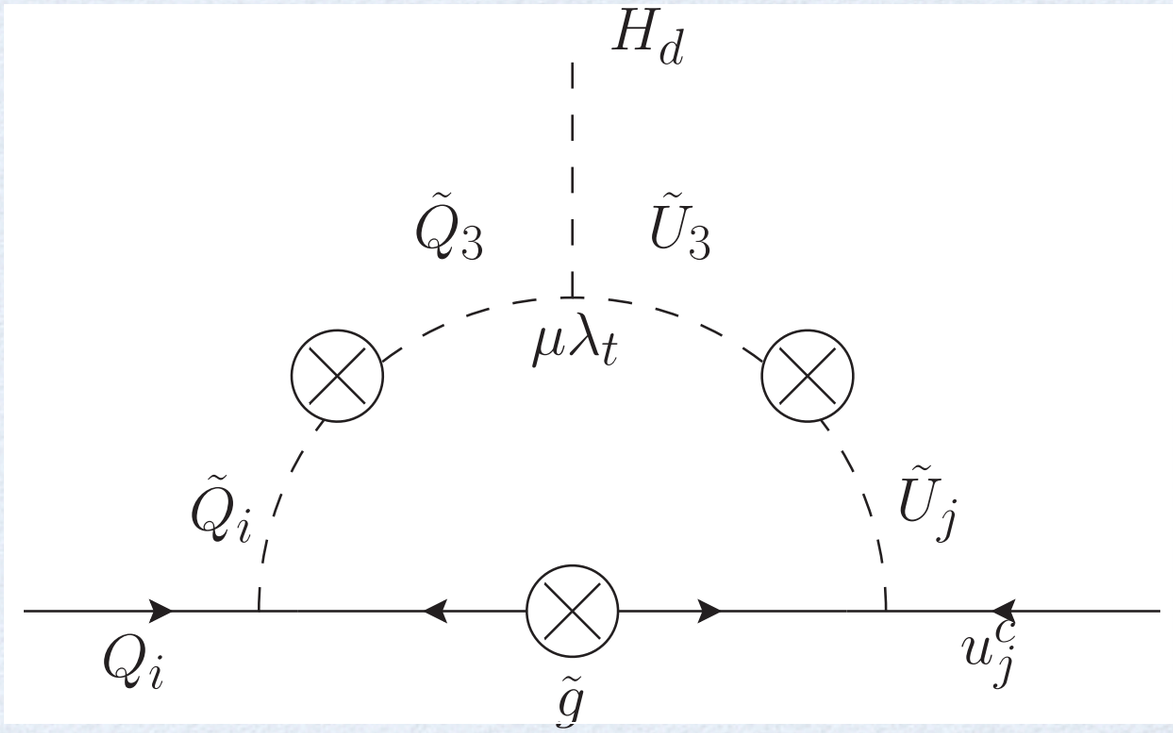
$\tilde{m} \sim 10^3\,\mathrm{TeV}$

Solves susy flavor/CP problem

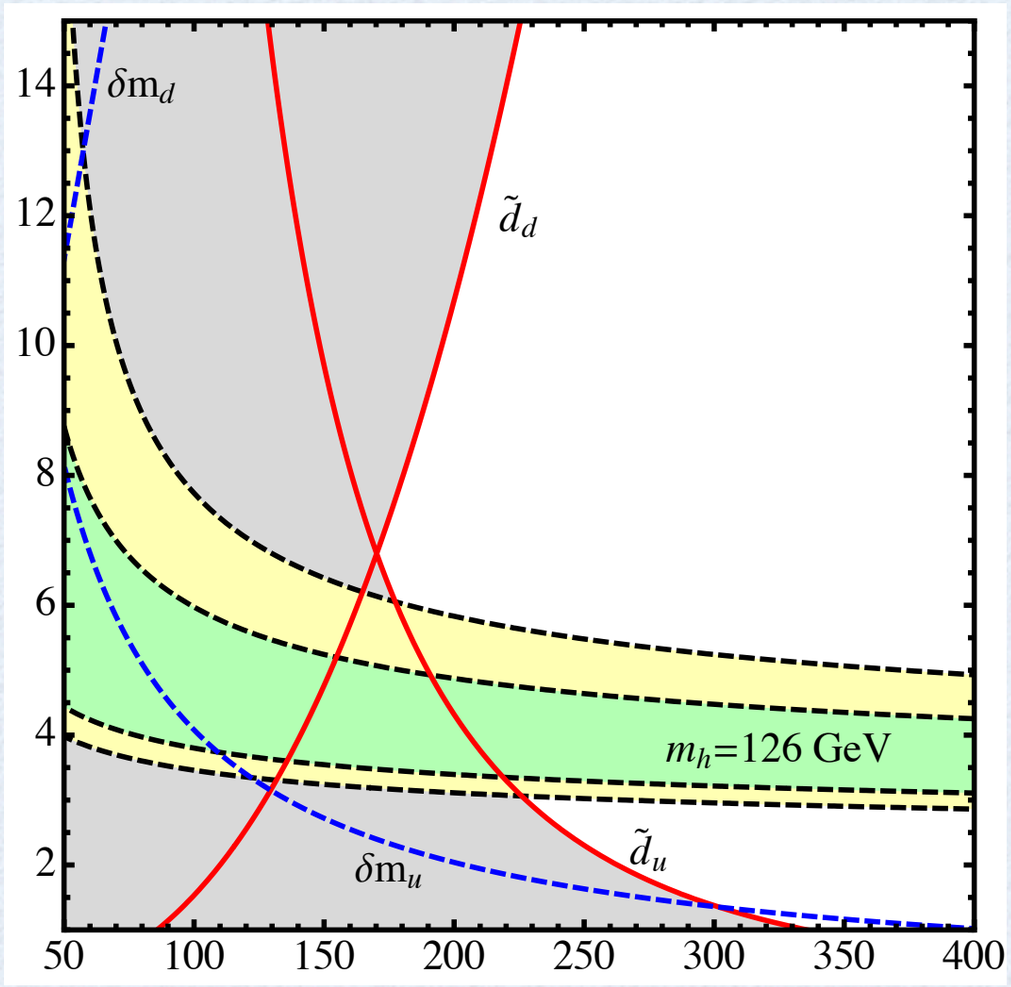
Changes the game of radiative quark and lepton masses



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

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

Nuclear EDMs



McKeen, Pospelov, Ritz
arXiv:1303.1172

FIG. 2. Contours of $\delta m_u = 1\,\mathrm{MeV}$ and $\delta m_d = 2\,\mathrm{MeV}$ (blue, dashed) and $\tilde{d}_q = 6\times10^{-27}$ 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 $|\tilde{d}_u - \tilde{d}_d| \lesssim 6\times10^{-27}$ 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

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

TeV Scale from SUSY Dark Matter

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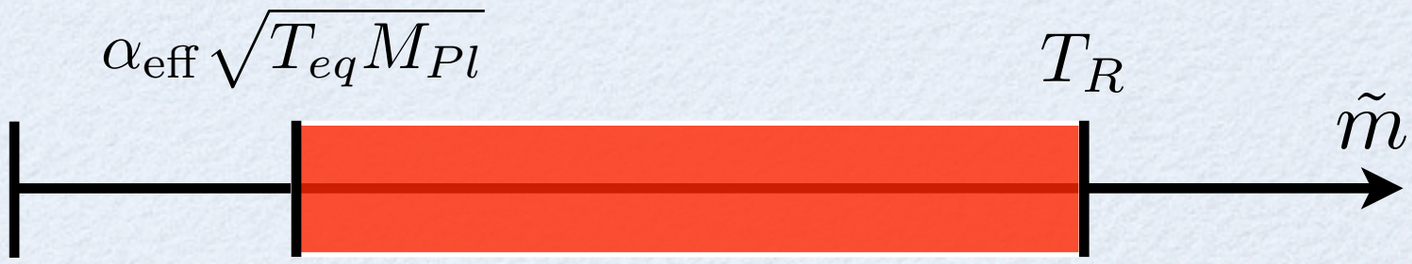
(Some) Superpartners at TeV Scale

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



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

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

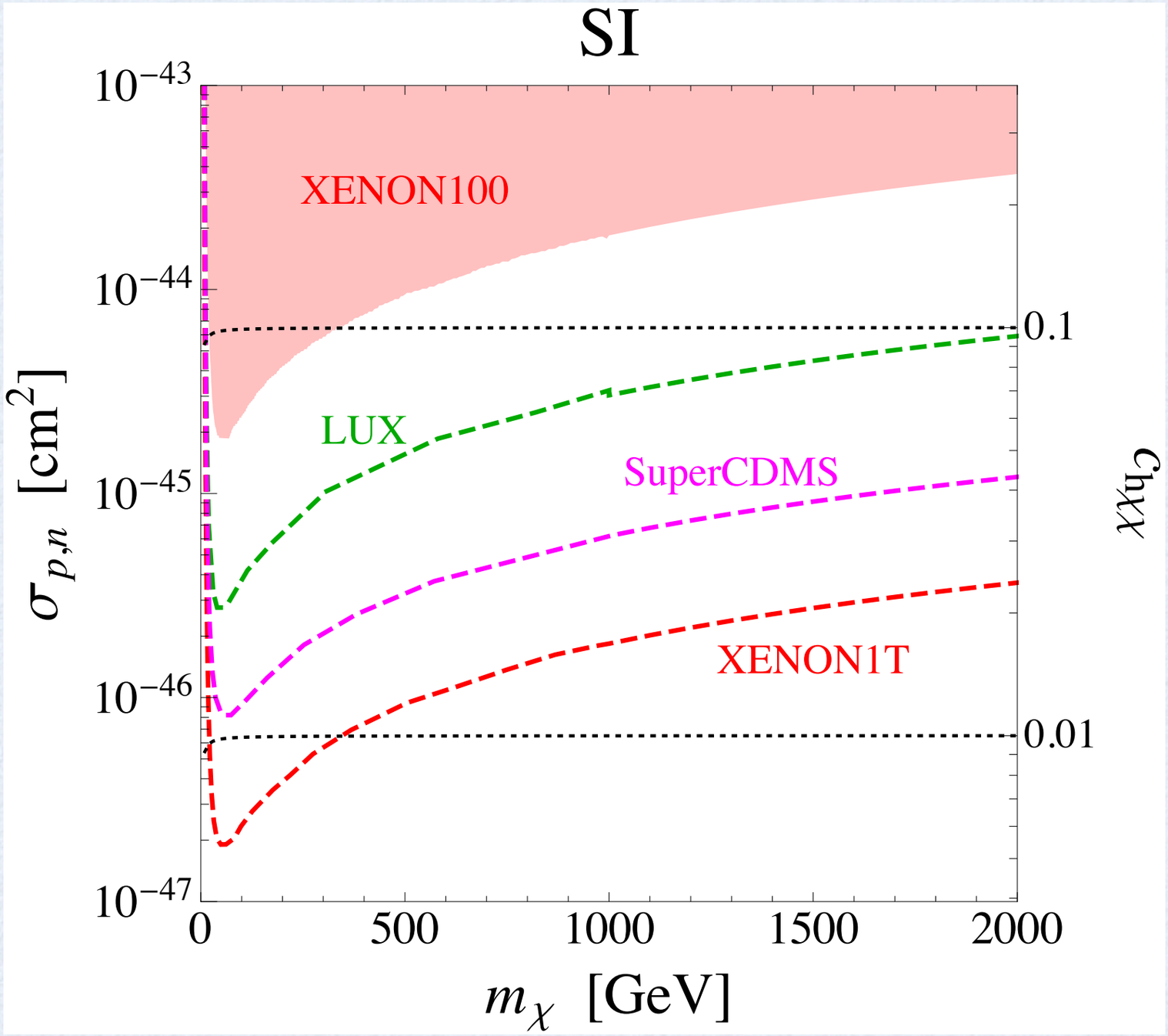
Over-constrained and unique gaugino cascades

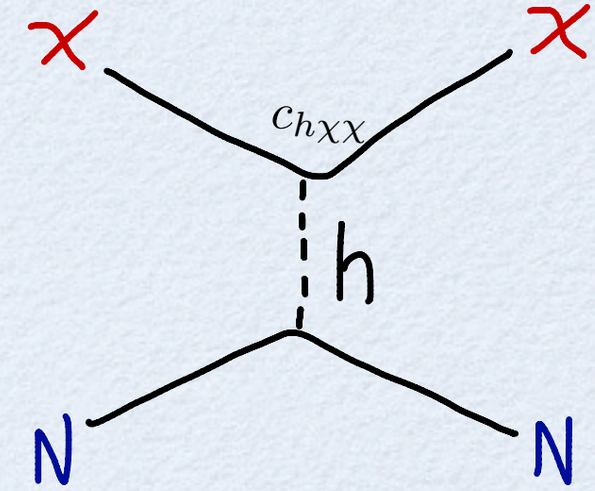
AMS anti-protons are good probe.

Flavor/CP ...

Back-up

Probing the Higgs Coupling



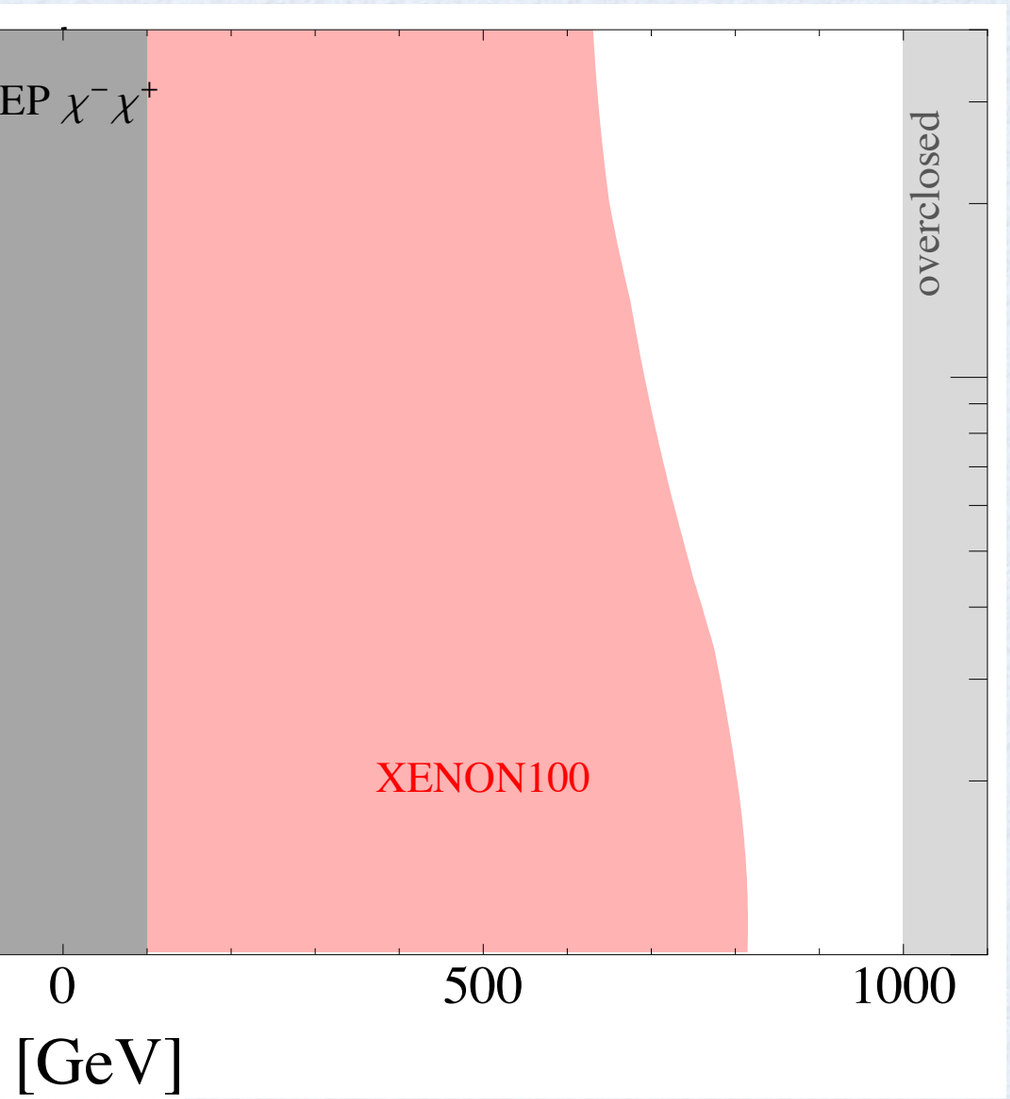


Cliff Cheung, LJH,
David Pinner, Josh Ruderman
arXiv: 1211.4873

Simplified Models

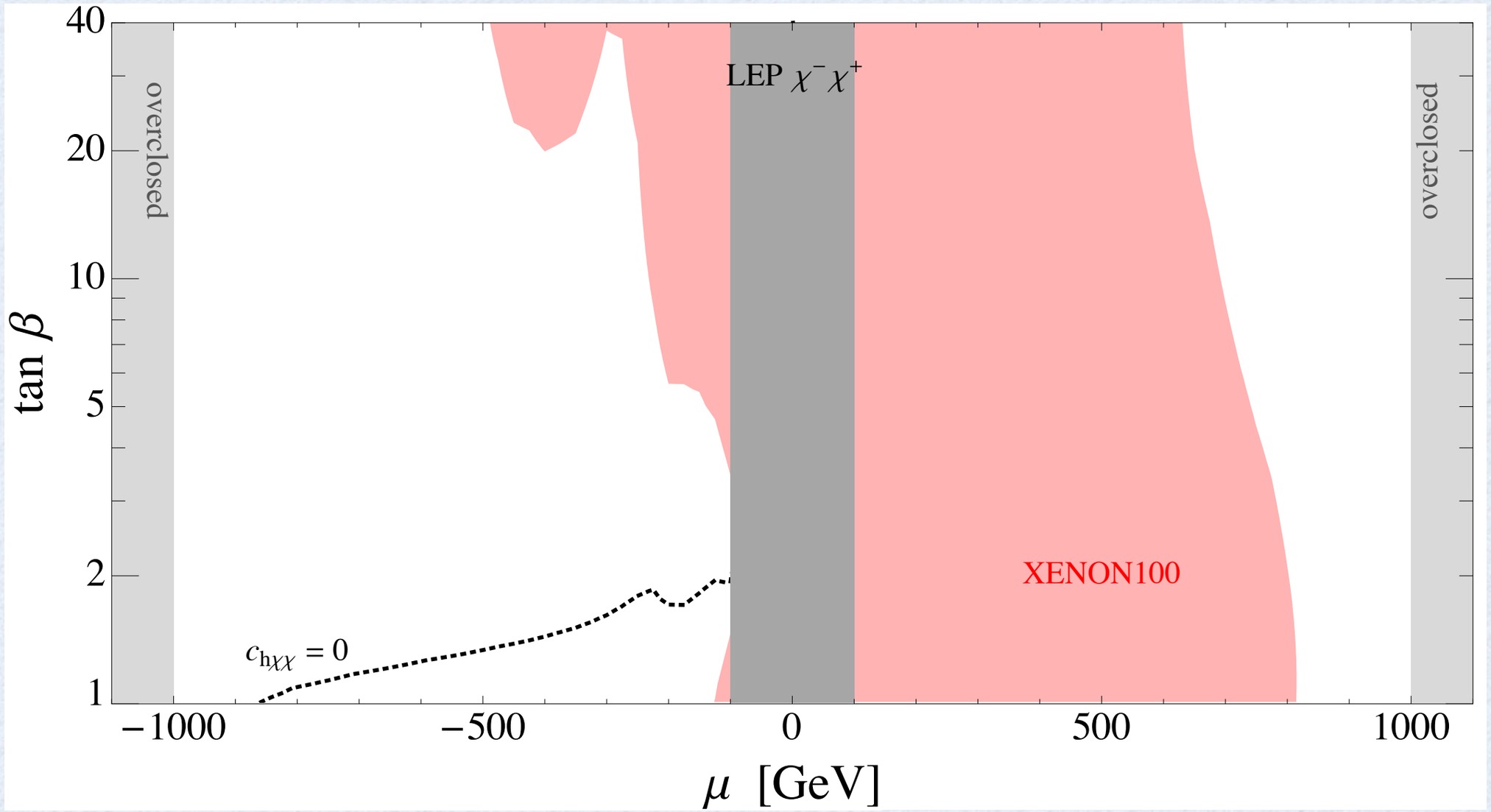
Bino-Higgsino LSP:

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



Almost excluded?

Bino-Higgsino LSP



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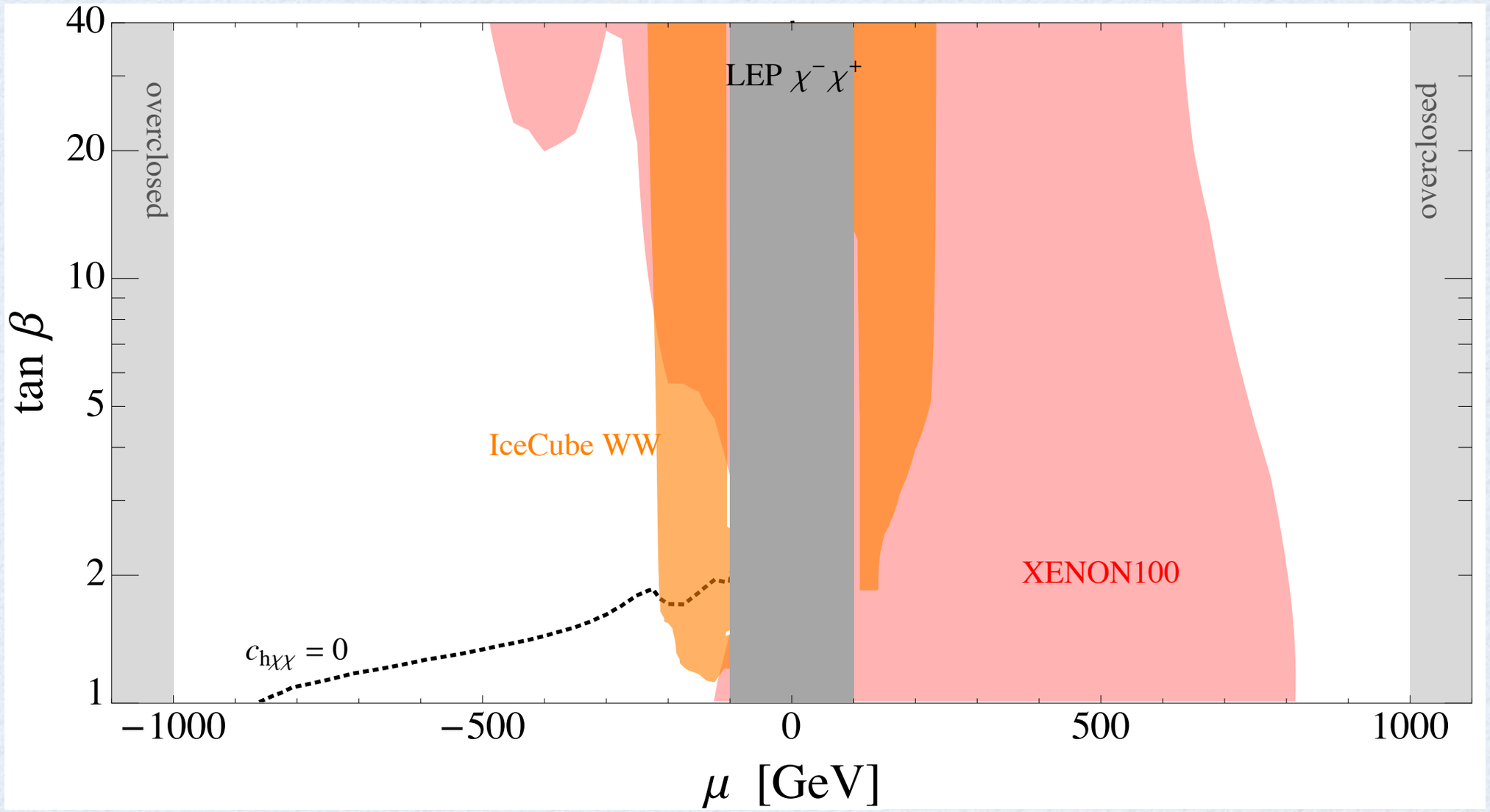
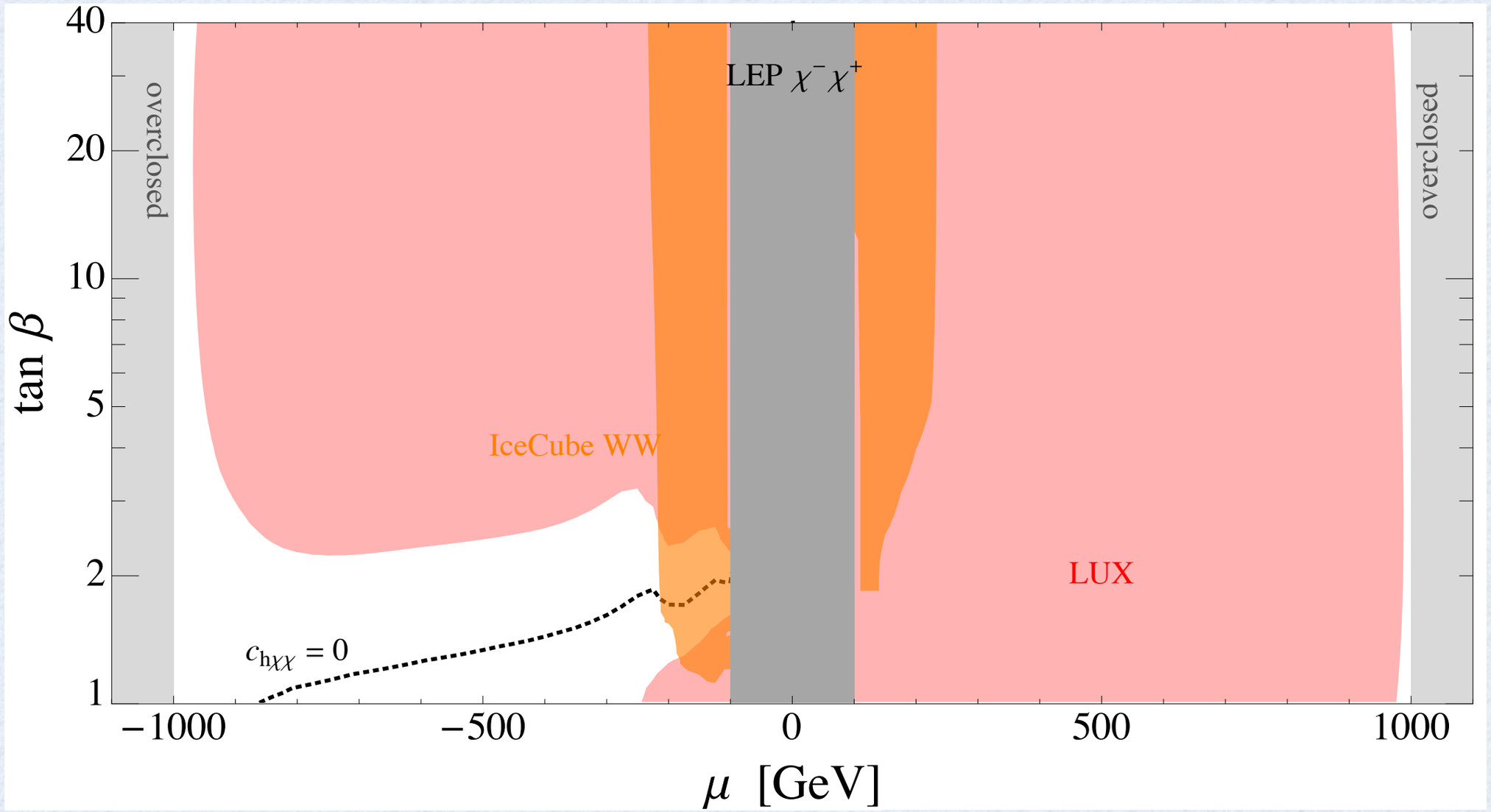
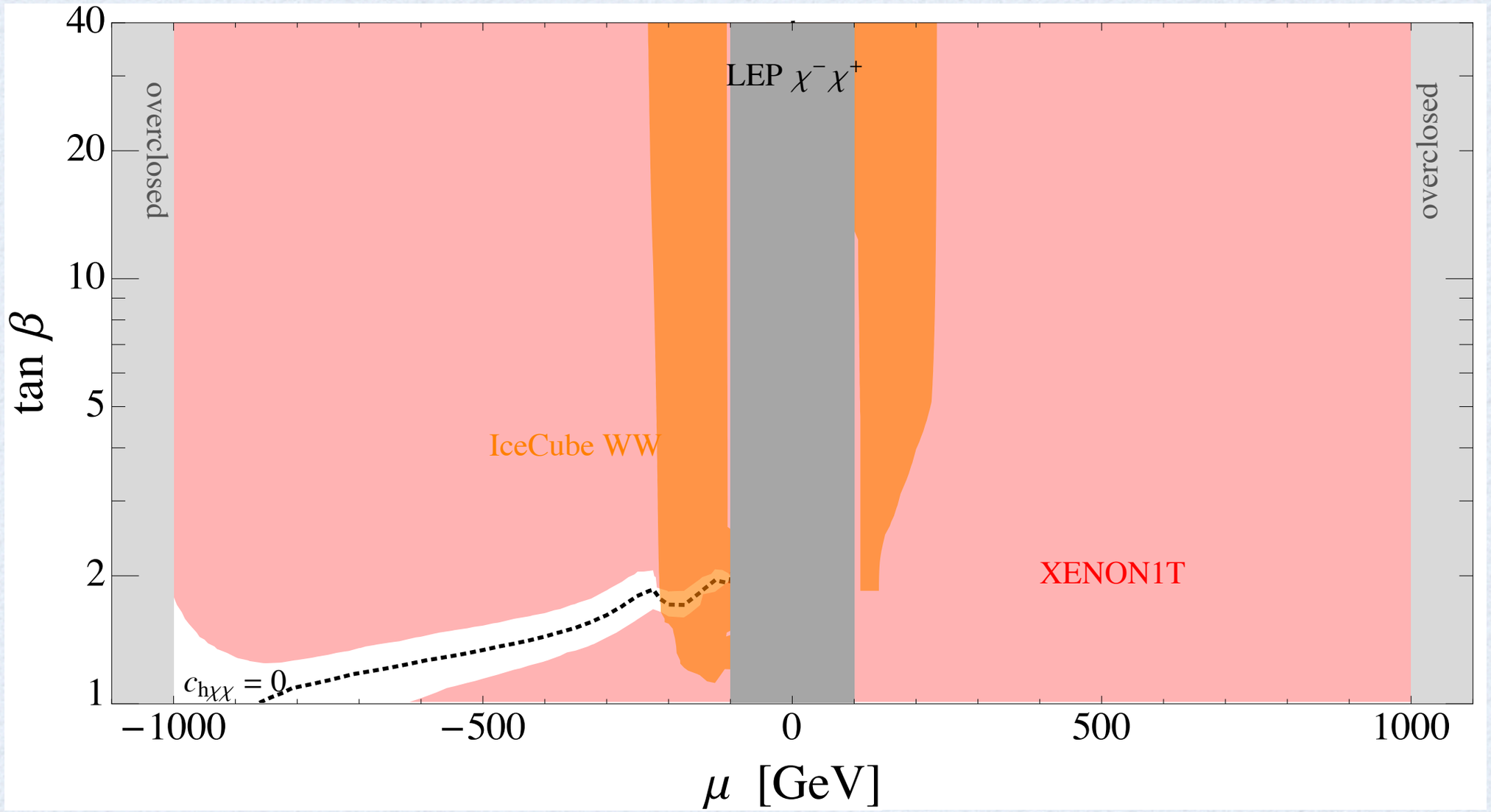
Bino-Higgsino LSP



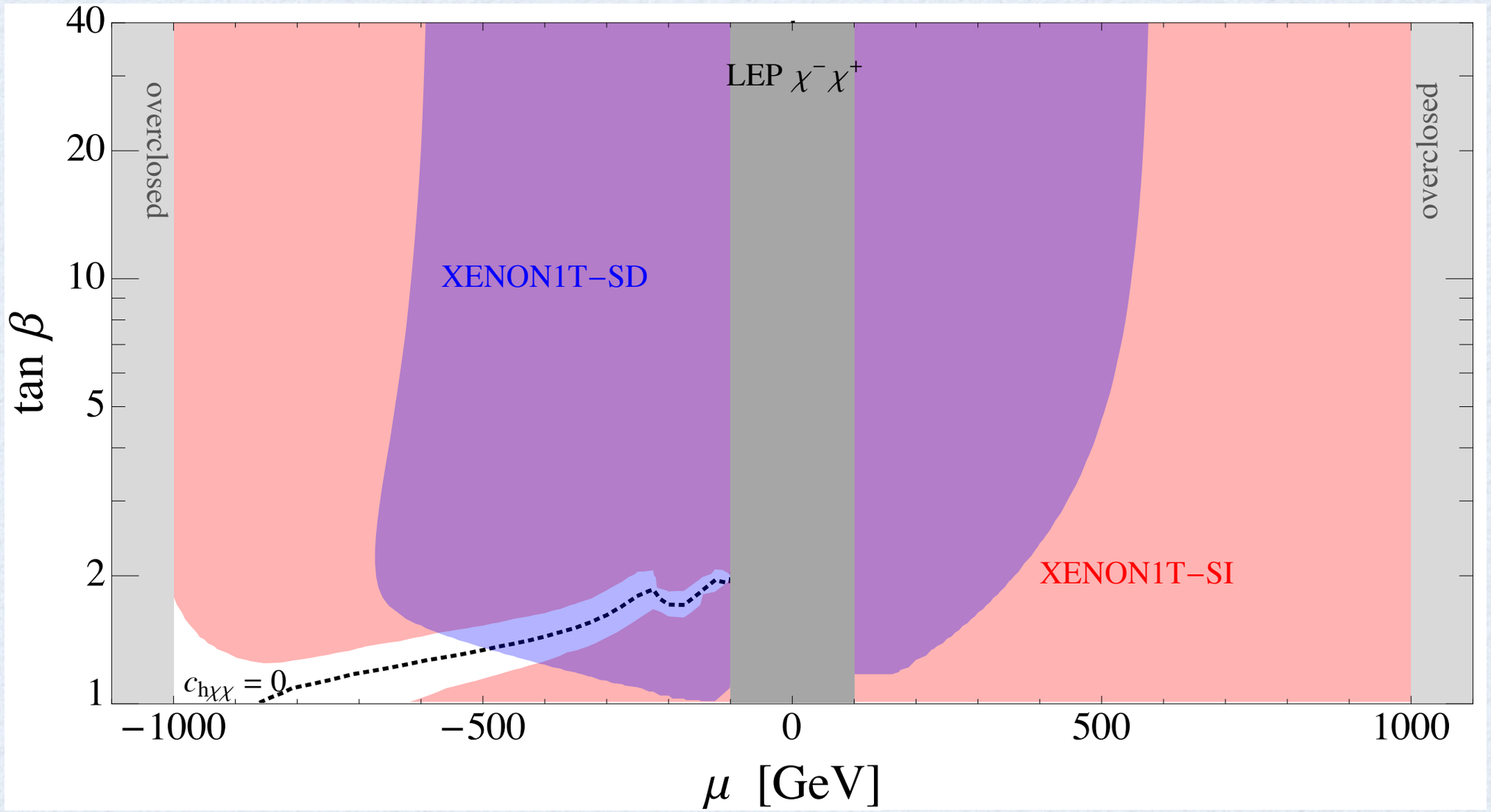
Bino-Higgsino LSP



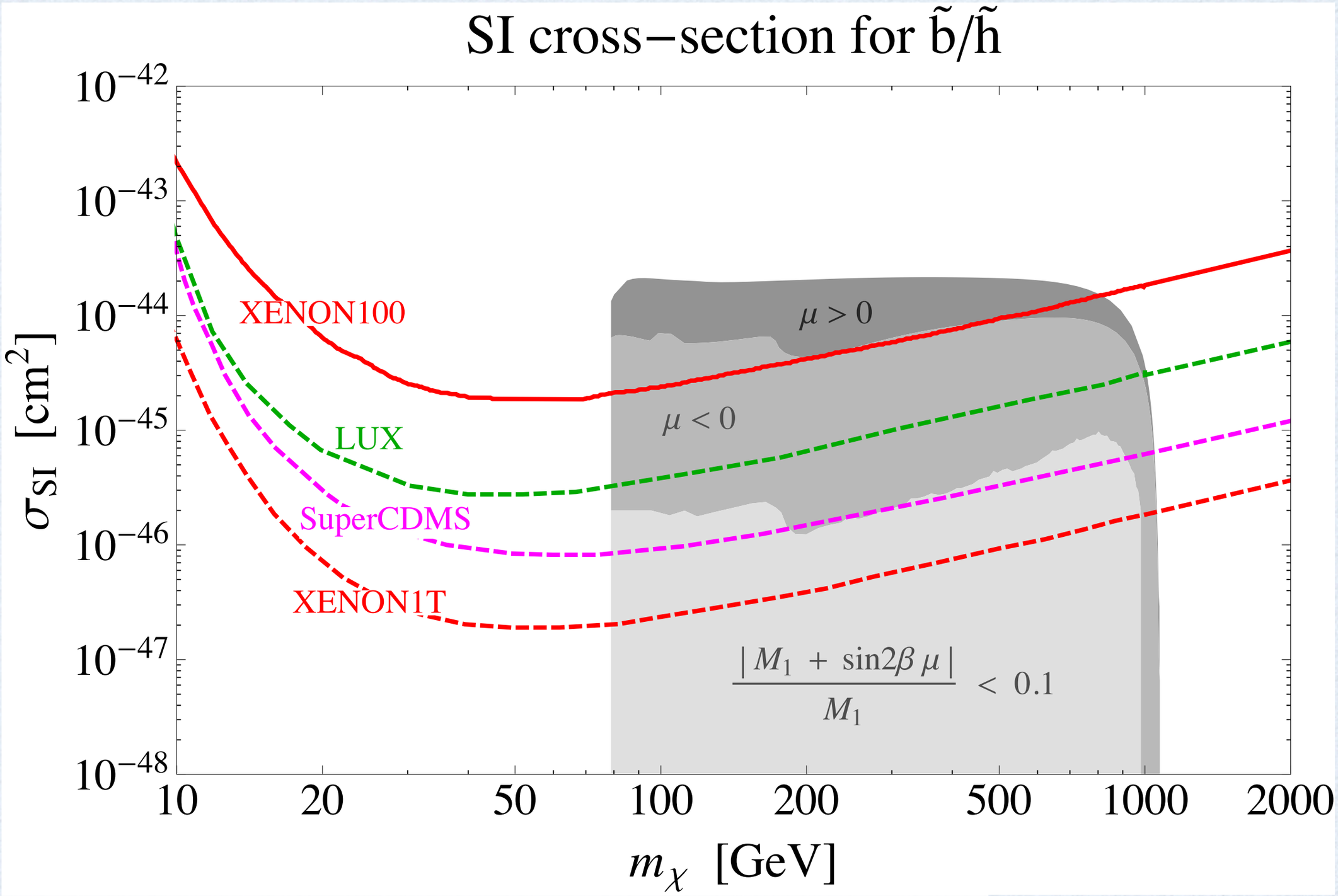
Bino-Higgsino LSP



Bino-Higgsino LSP



Bino-Higgsino LSP



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