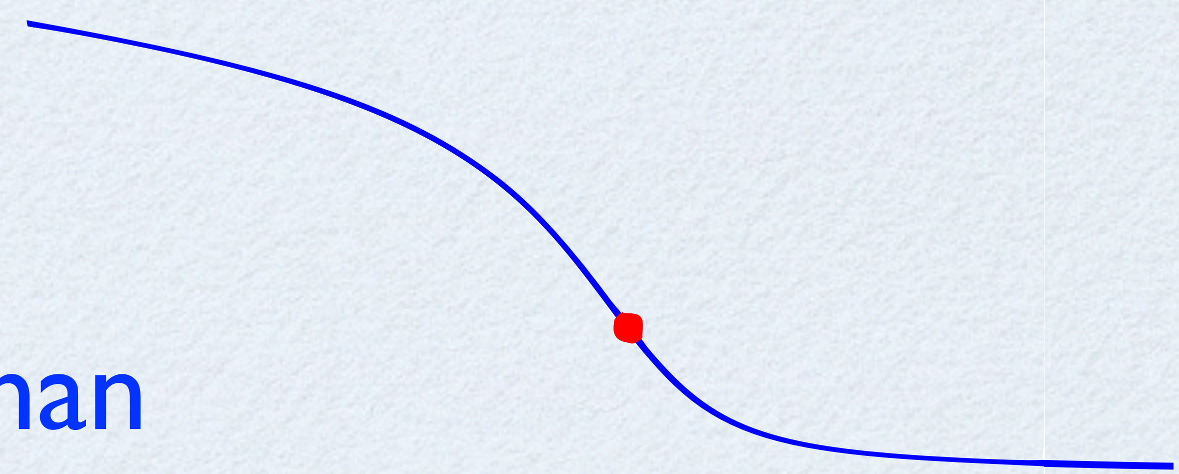
Dark Matters in Supersymmetry



Josh Ruderman
UC Berkeley

@Rutgers, April 22, 2013

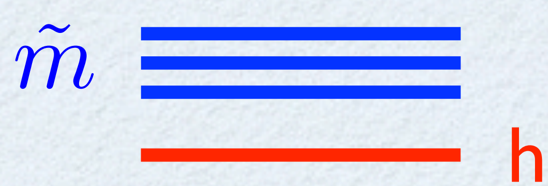
Lawrence Hall, JTR, Tomer Volansky, 1302.2620
Cliff Cheung, Lawrence Hall, David Pinner, JTR 1211.4873

$m_h \longmapsto$


125 GeV
m_h

natural

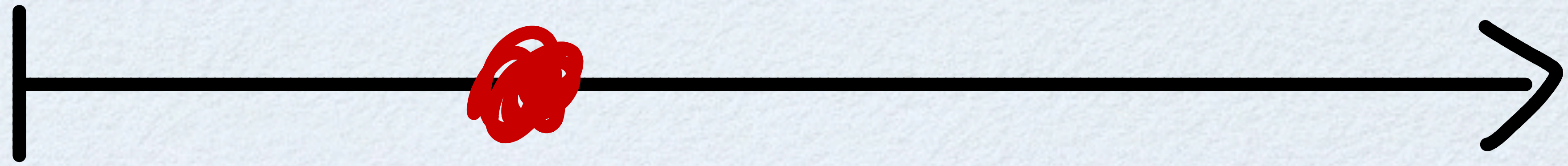
$$\tilde{m} \sim m_h$$



natural	unnatural
$\tilde{m} \sim m_h$	$\tilde{m} \gg m_h$

125 GeV

m_h



natural	unnatural
$\tilde{m} \sim m_h$	$\tilde{m} \gg m_h$

- MSSM 1% tuned
- non-minimal options remain natural

$$\lambda S H_u H_d$$

natural

$\tilde{m} \sim m_h$

unnatural

$\tilde{m} \gg m_h$

- MSSM 1% tuned
- non-minimal options remain natural

$\lambda S H_u H_d$

$\tilde{m}$

h

For this talk, I am agnostic about naturalness.

a finely tuned world?

$$\tilde{m} \gg m_h$$

a finely tuned world?

$$\tilde{m} \gg m_h$$

- what constrains $\tilde{m}$?

a finely tuned world?

$$\tilde{m} \gg m_h$$

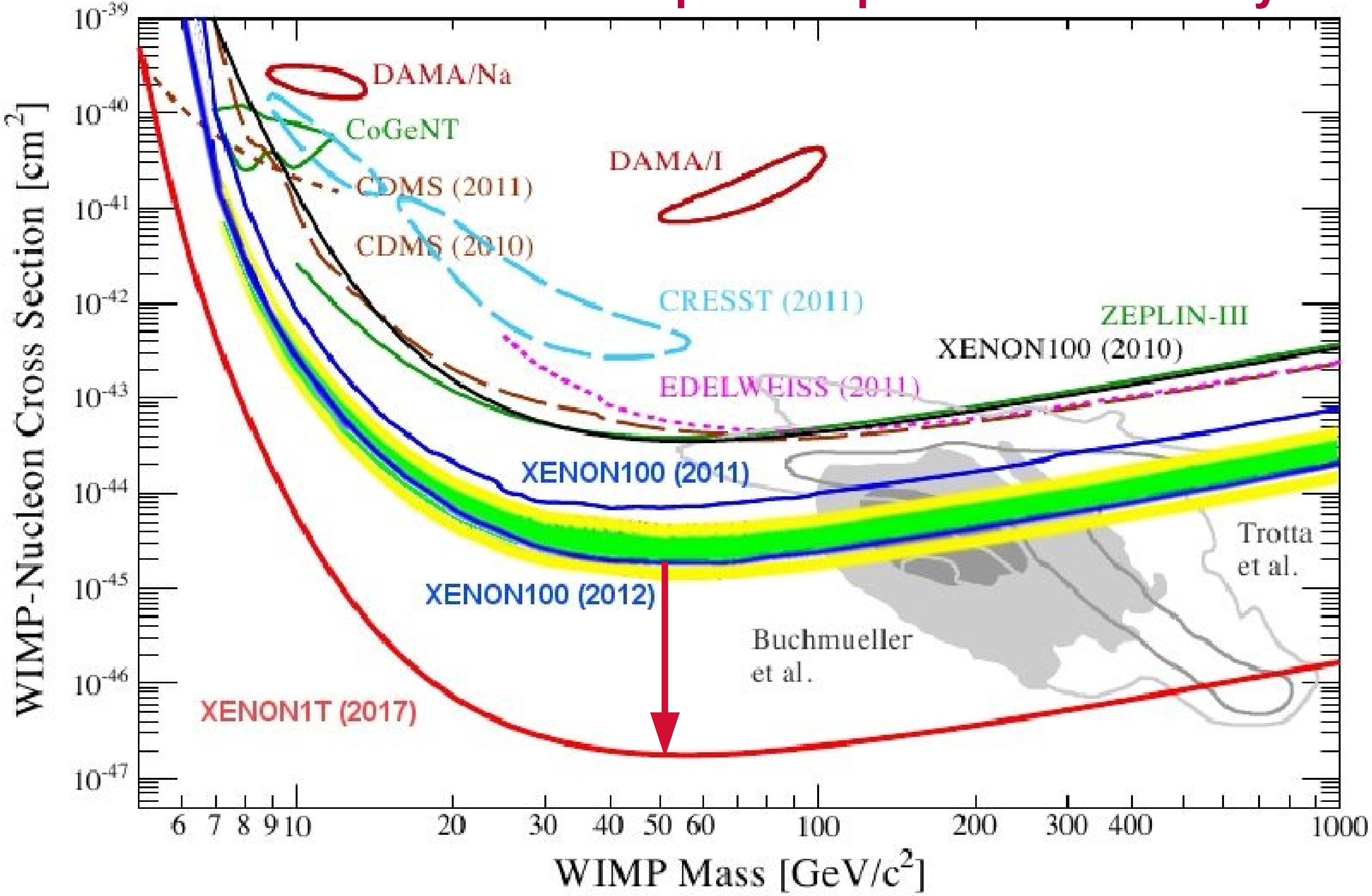
- what constrains $\tilde{m}$?
- what can we measure in experiments?

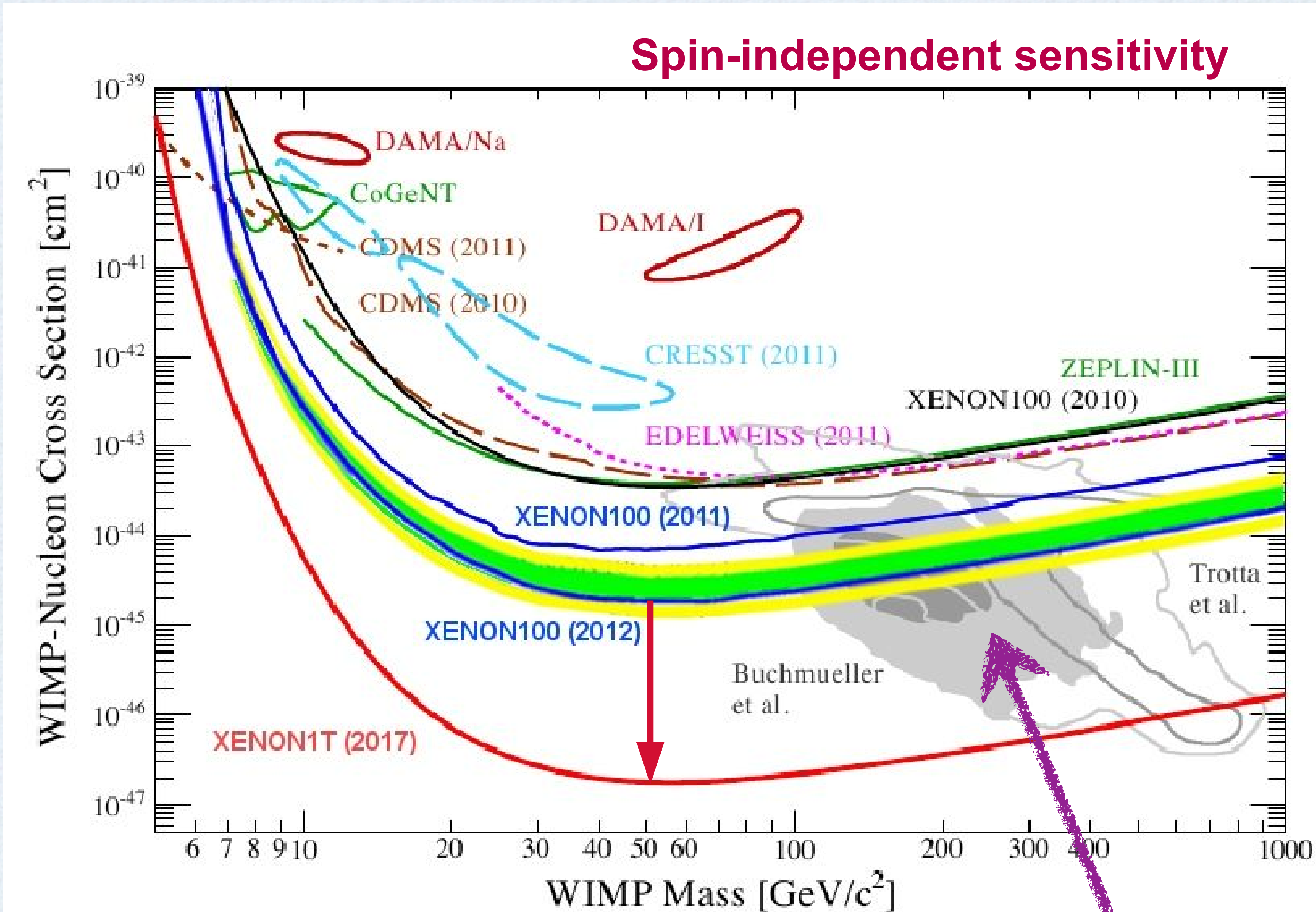
a finely tuned world?

$$\tilde{m} \gg m_h$$

- what constrains $\tilde{m}$?
- what can we measure in experiments?

Spin-independent sensitivity





experimental status of SUSY DM?

the plan

1. gravitino miracle

$\tilde{N}_1$

$\tilde{G}$

2. neutralino DM
vs.
experiment

the plan

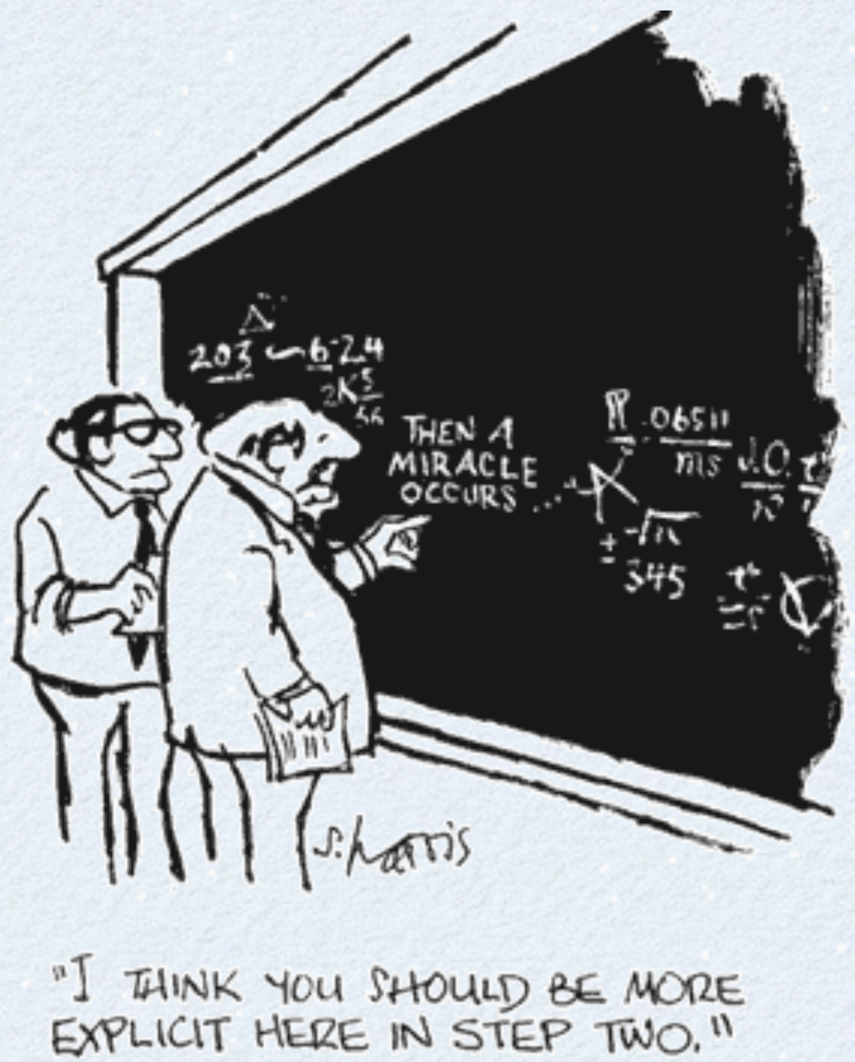
1. gravitino miracle

$\tilde{G}$

$\tilde{N}_1$

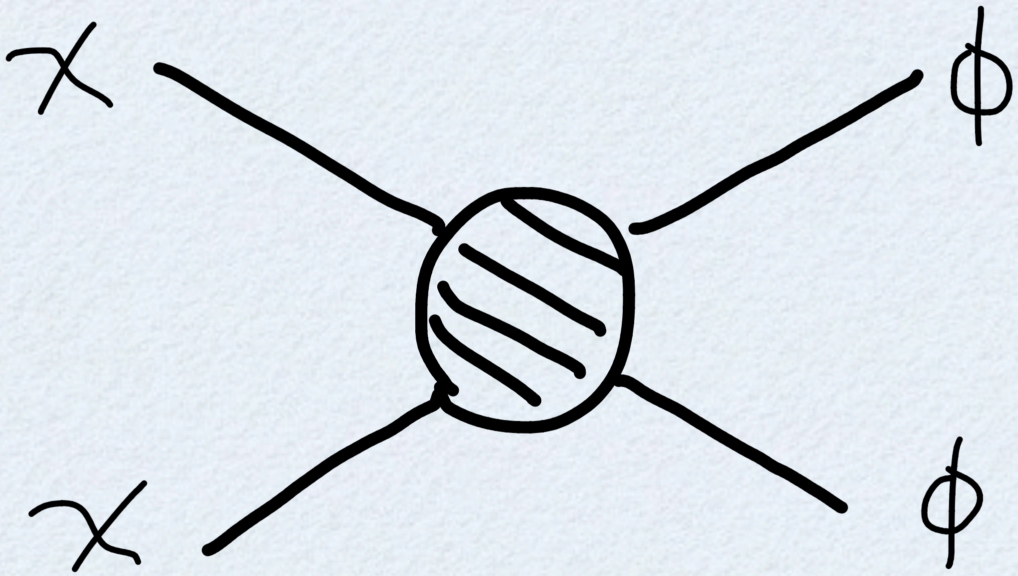
2. neutralino DM
vs.
experiment

Gravitino Miracle

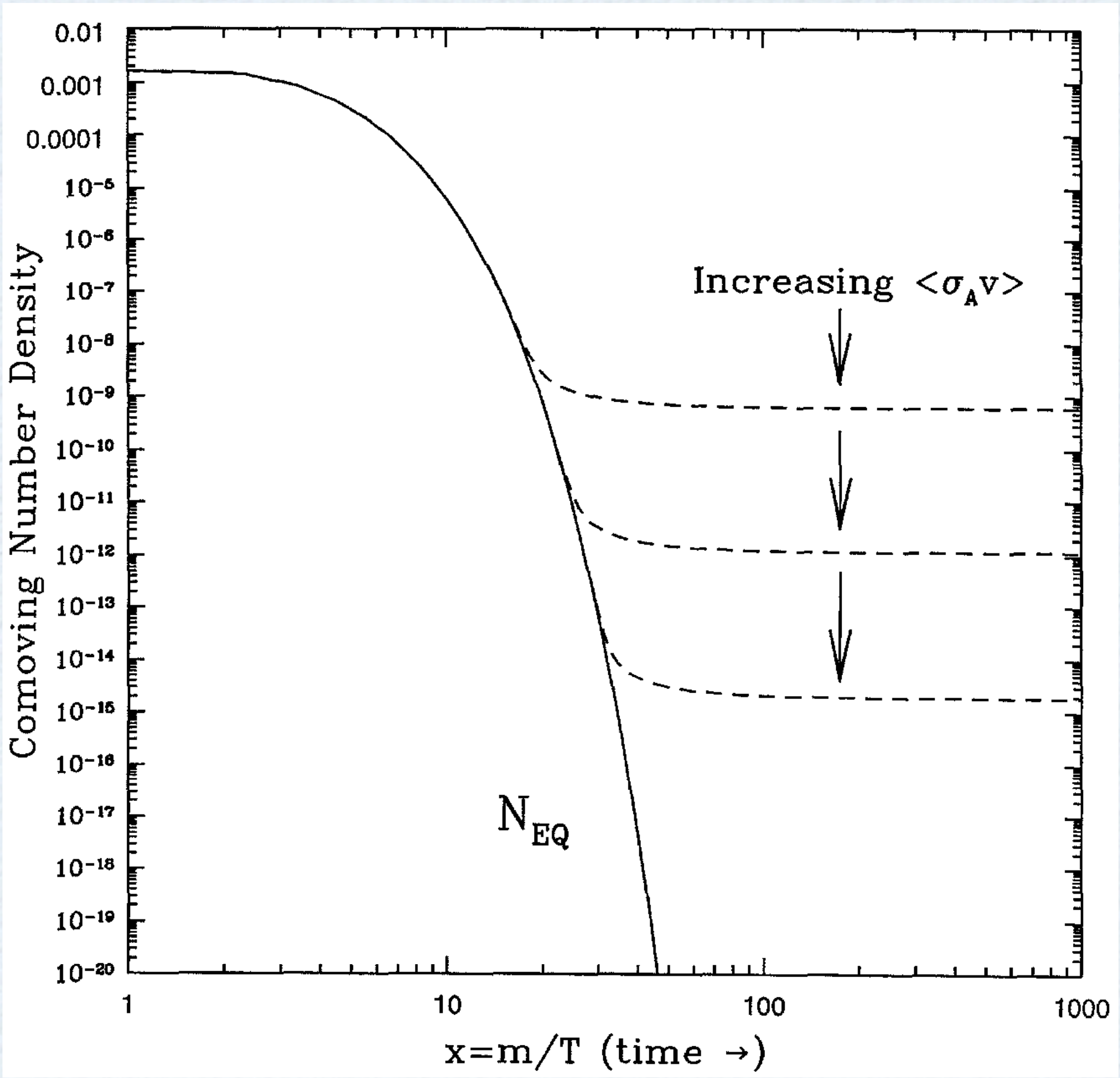


Lawrence Hall, JTR, Tomer Volansky, 1302.2620

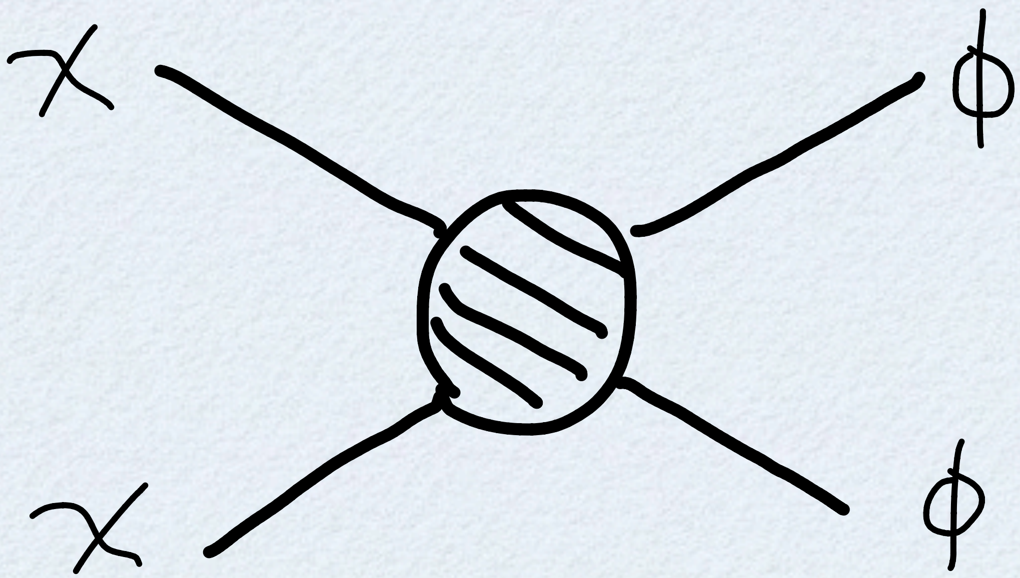
WIMP miracle



$$\langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2}$$



WIMP miracle



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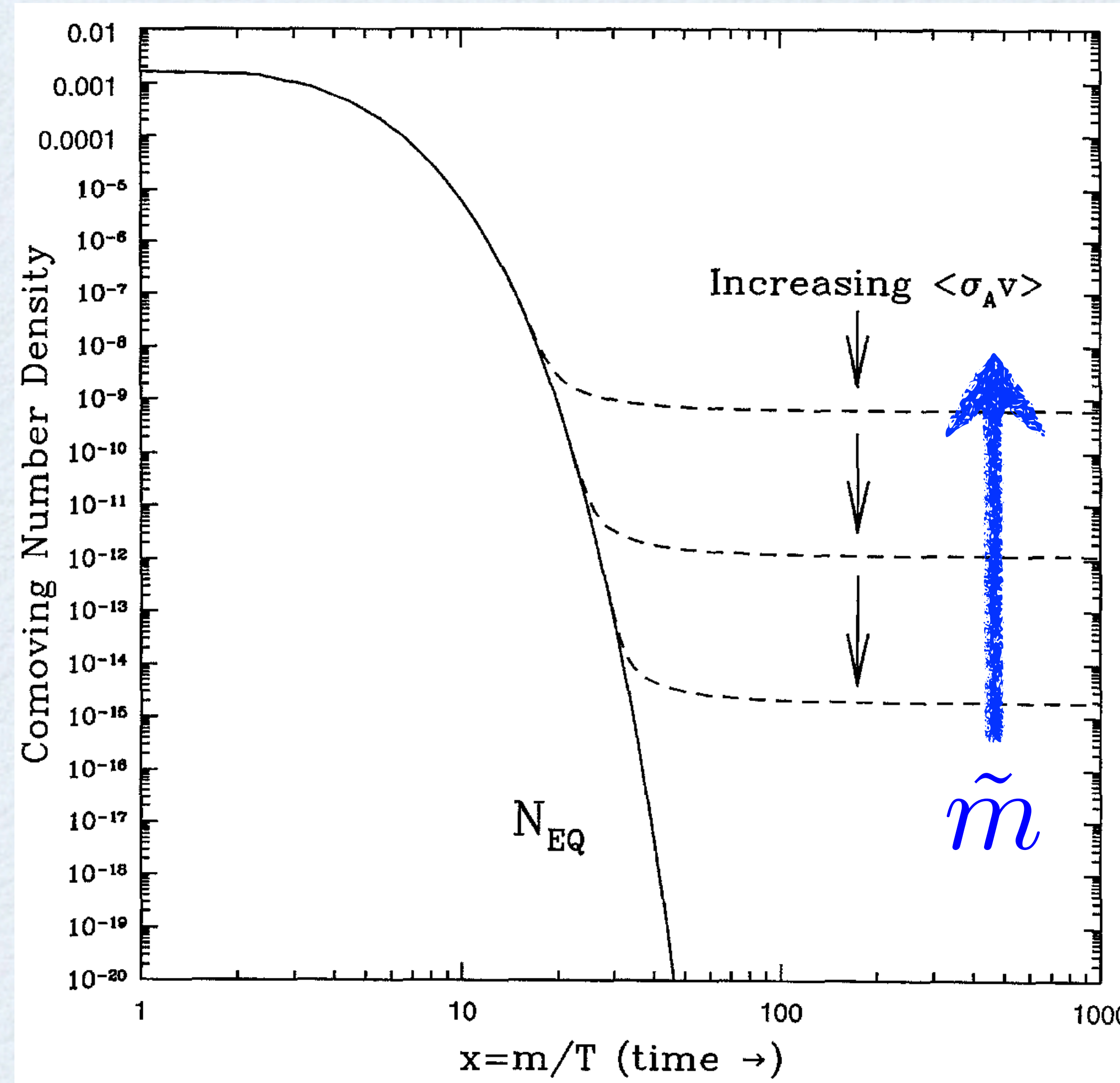
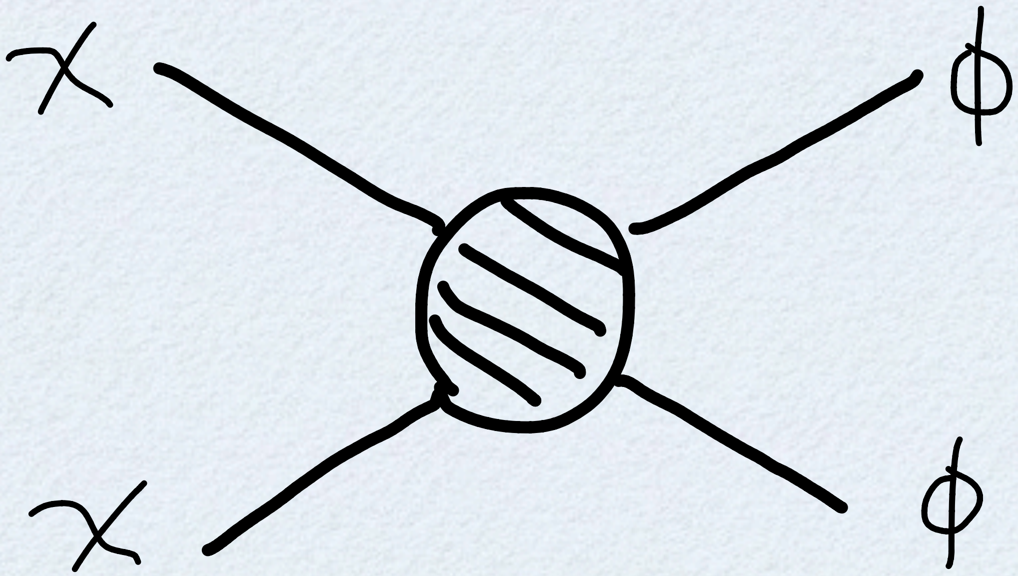


WIMP miracle



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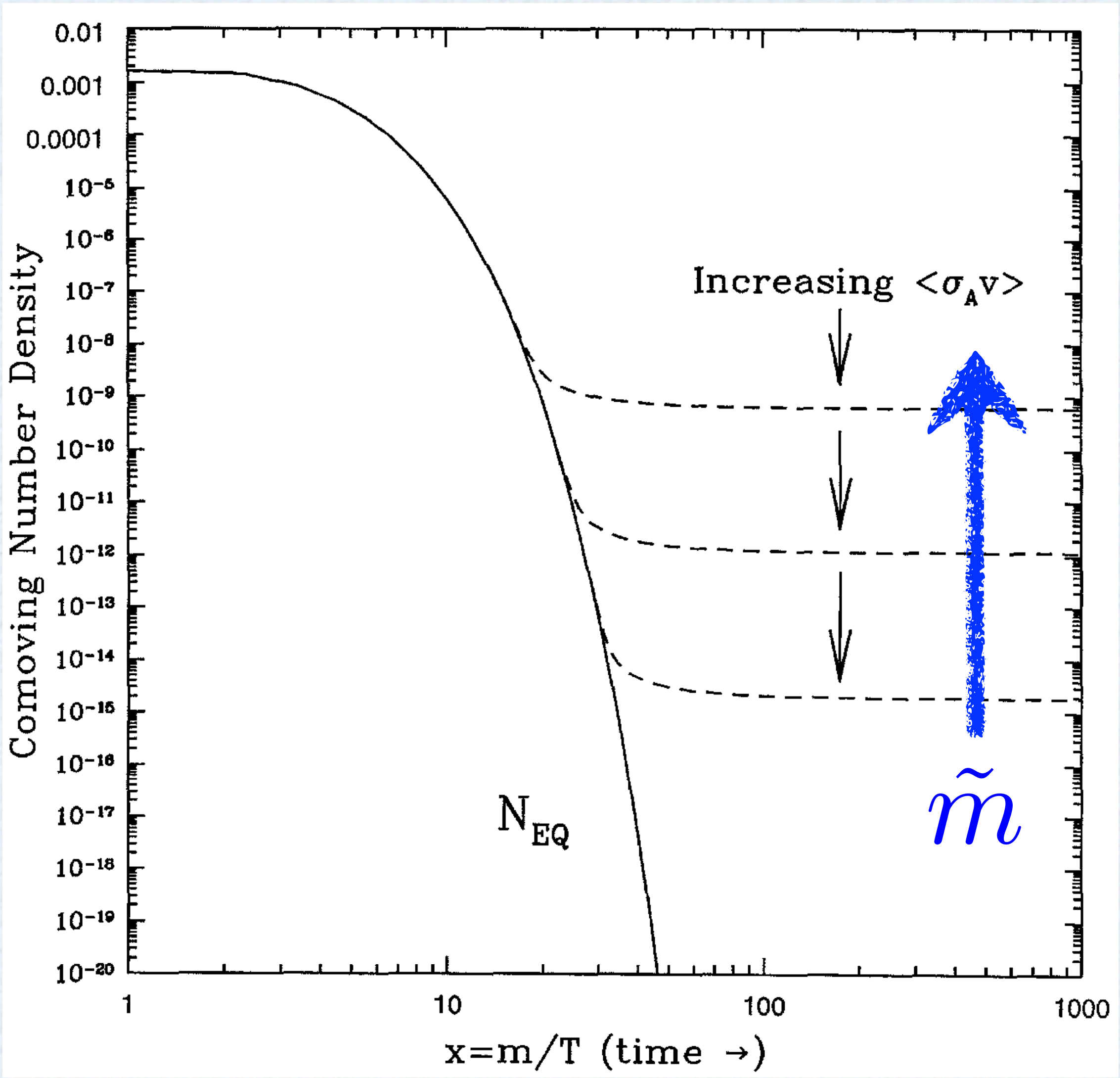
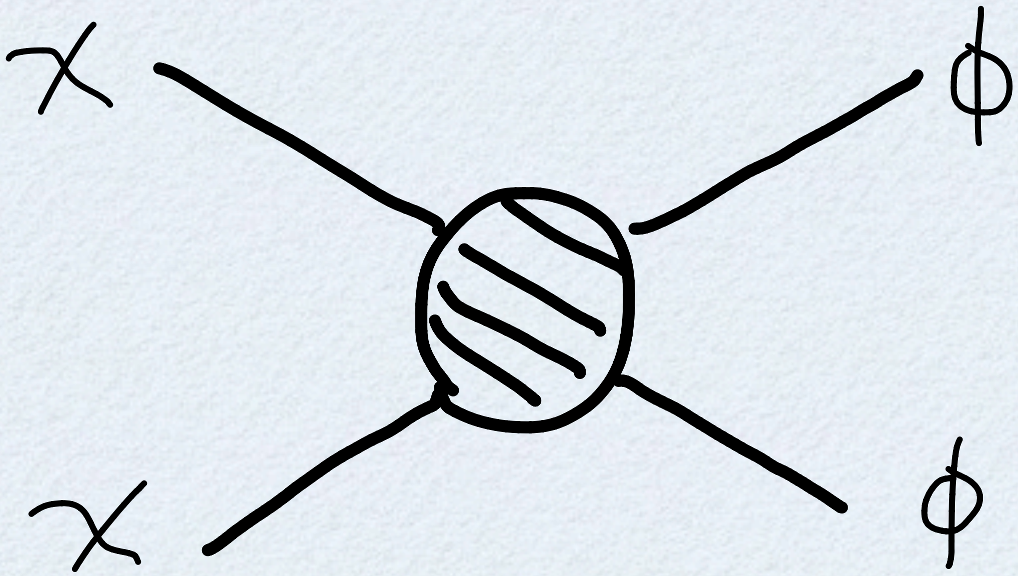
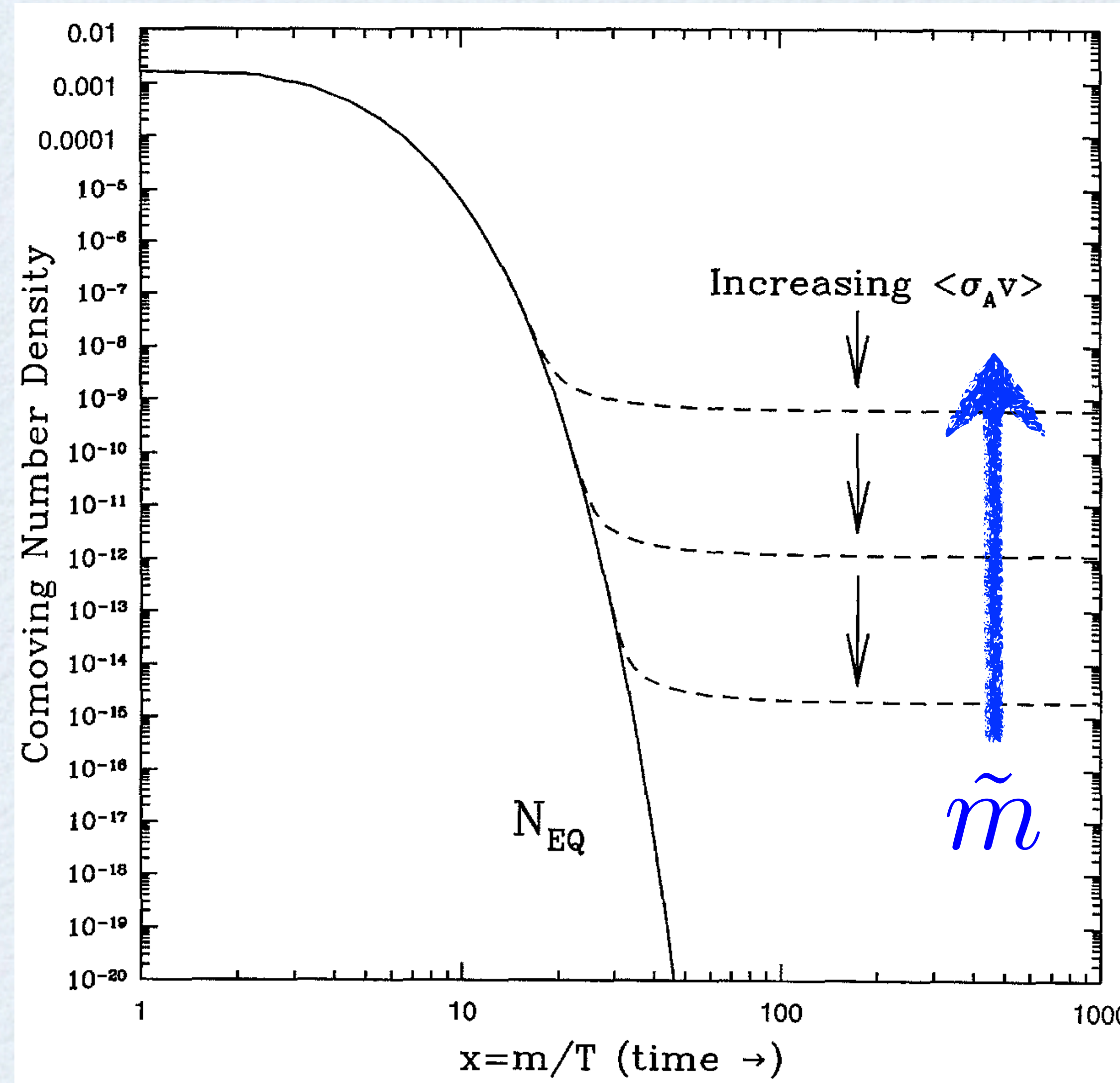


$$\tilde{m}\, Y_{FO} \leq T_{eq}$$

WIMP miracle



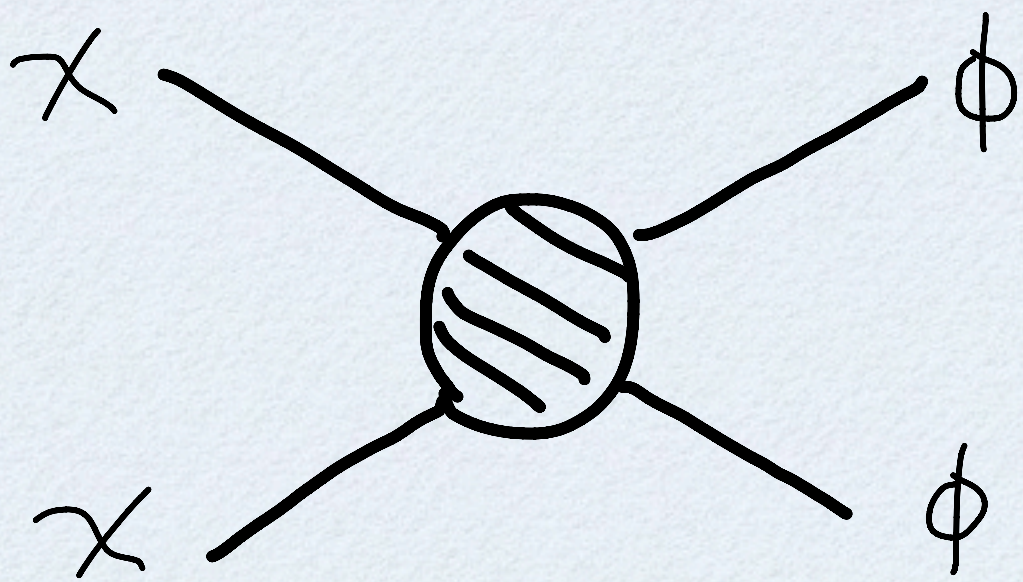


$$\langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2}$$

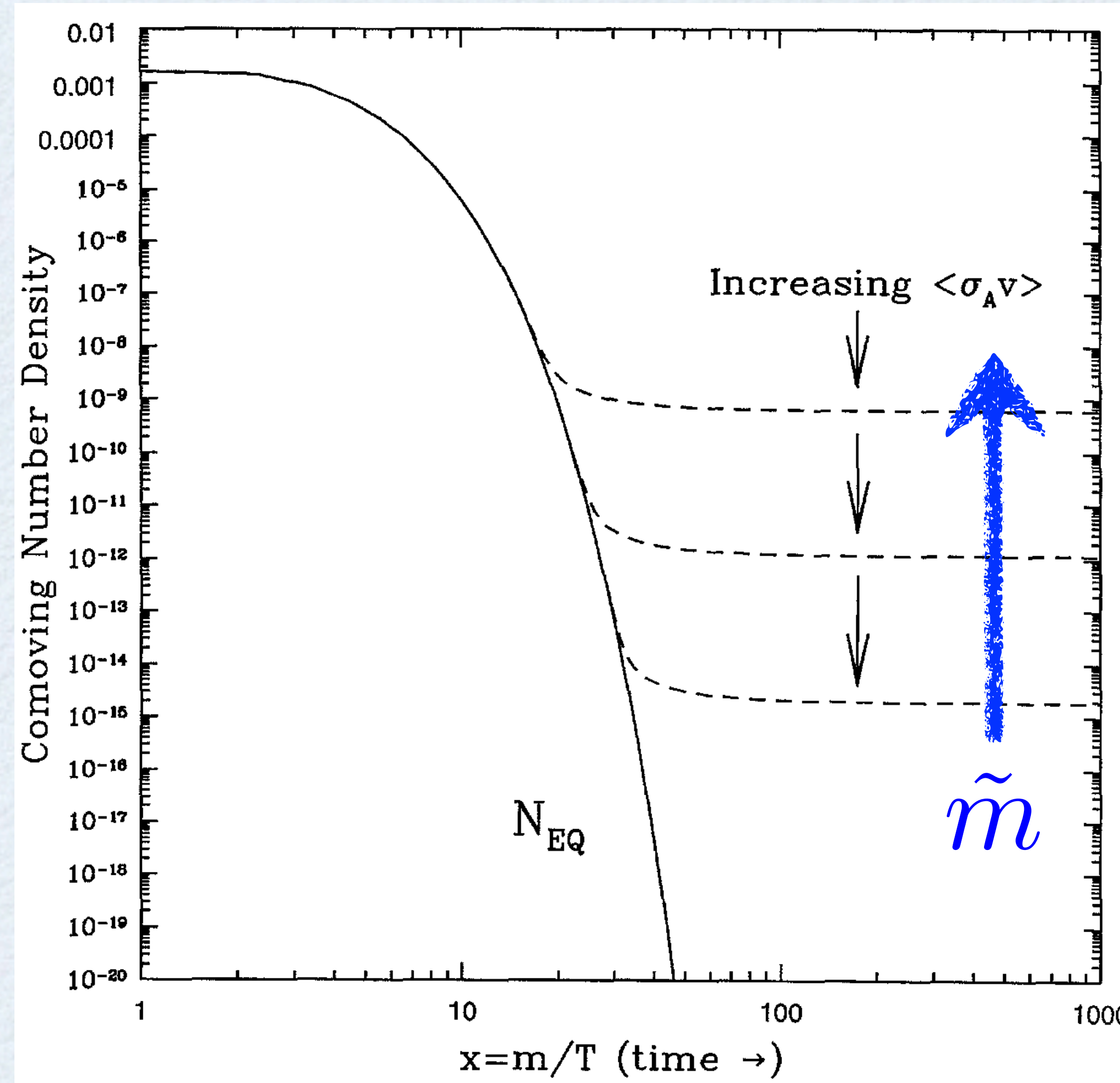
$$\tilde{m}\, Y_{FO} \leq T_{eq}$$

$$Y_{FO} = \frac{n_{FO}}{s} = \frac{1}{M_p \, \langle \sigma v \rangle \, T_{FO}}$$

WIMP miracle



$$\langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2}$$



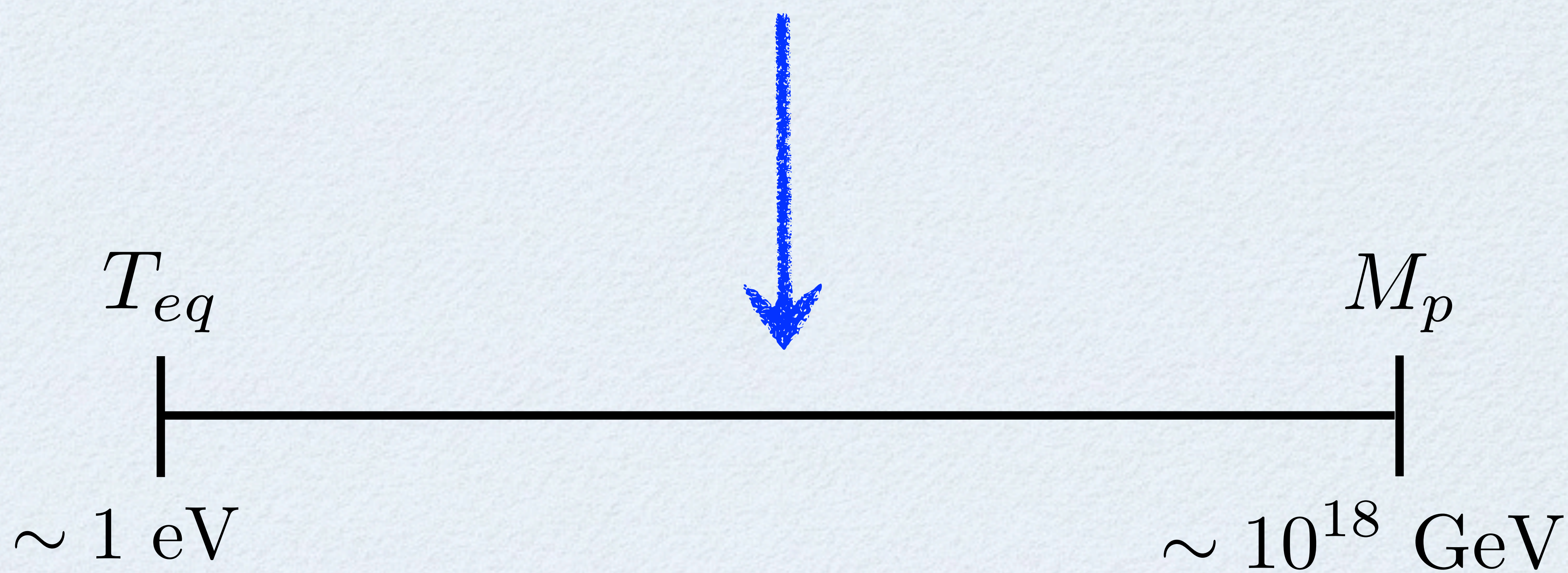
$$\tilde{m}\, Y_{FO} \leq T_{eq}$$

$$Y_{FO} = \frac{n_{FO}}{s} = \frac{1}{M_p \langle \sigma v \rangle T_{FO}}$$

$$\tilde{m} \leq \alpha \sqrt{T_{eq} M_p}$$

WIMP miracle

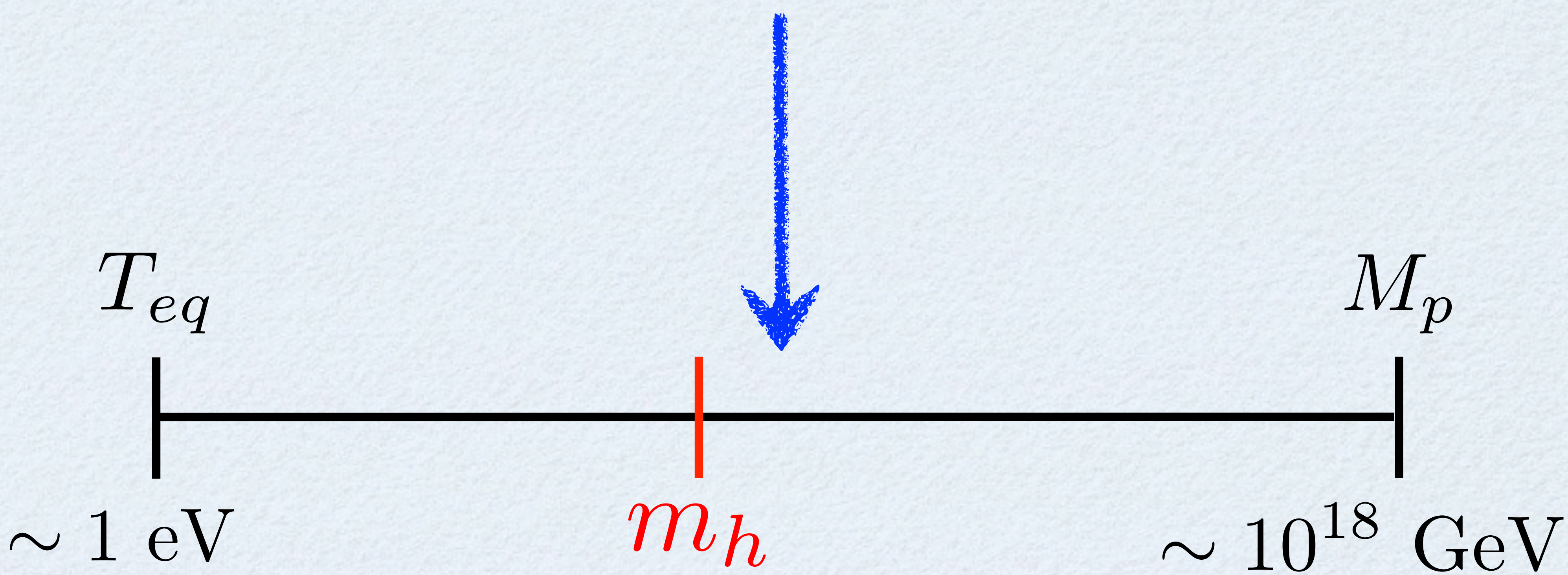
$$\tilde{m} \leq \alpha \sqrt{T_{eq}\, M_p}$$



$$\sqrt{T_{eq} M_p} \approx 60 \text{ TeV}$$

WIMP miracle

$$\tilde{m} \leq \alpha\sqrt{T_{eq}\, M_p}$$



$$\sqrt{T_{eq} M_p} \approx 60\ \mathrm{TeV}$$

WIMP miracle

applied to SUSY:

- mass scale of LSP is tied to the weak scale

•Goldberg, 1983

WIMP miracle

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- in Split SUSY, invoked to keep fermions near weak scale

- Wells, 2003
- Arkani-Hamed, Dimopoulos 2004

WIMP miracle

applied to SUSY:

- mass scale of LSP is tied to the weak scale

•Goldberg, 1983

- in Split SUSY, invoked to keep fermions near weak scale

- Wells, 2003
- Arkani-Hamed, Dimopoulos 2004

- relies on several assumptions!

WIMP miracle

key assumptions:

WIMP miracle

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1. stable LSP (R-parity)

WIMP miracle

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2. $T_R > \tilde{m}$

WIMP miracle

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WIMP miracle

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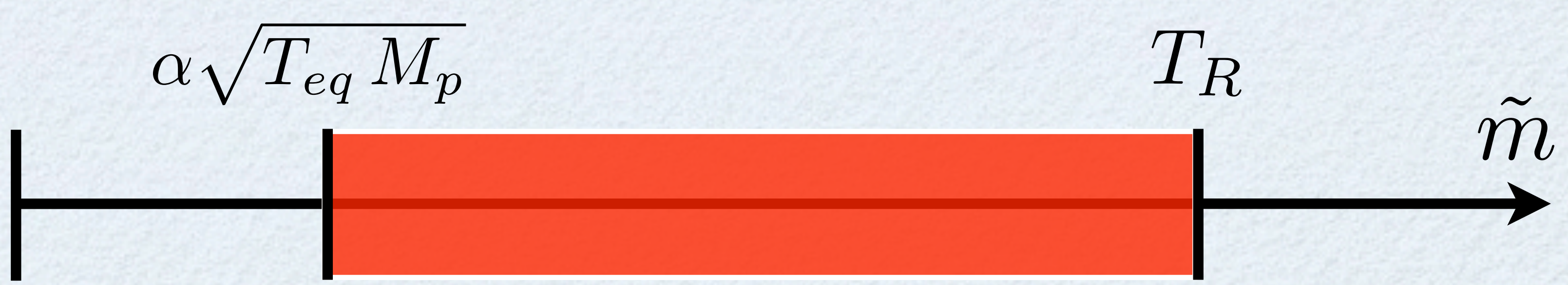

WIMP miracle

key assumptions:

1. stable LSP (R-parity)
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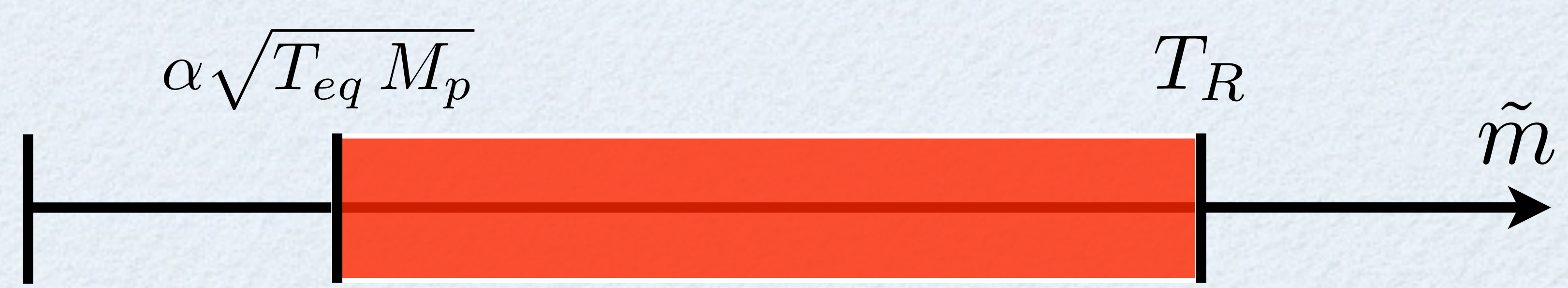
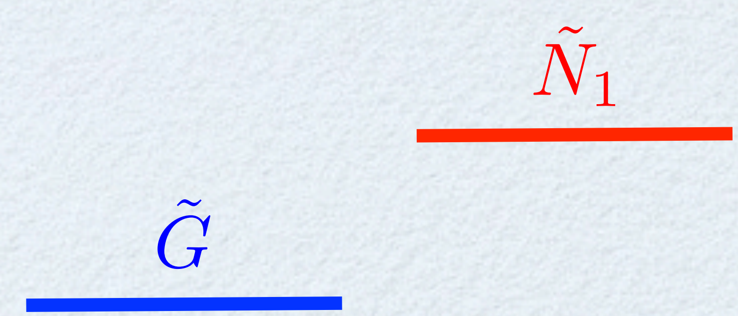


WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. $T_R > \tilde{m}$
3. no dilution
4. LSP reaches equilibrium

what about
gravitino LSP?



gravitino primer

$$m_{3/2} \approx \frac{F}{M_p}$$

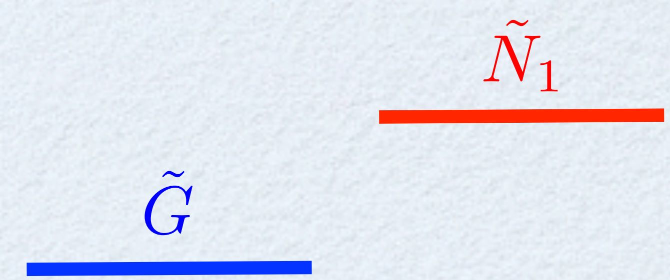
$$\tilde{m} = \frac{F}{M}$$

gravitino primer

$$m_{3/2} \approx \frac{F}{M_p}$$

$$\tilde{m} = \frac{F}{M}$$

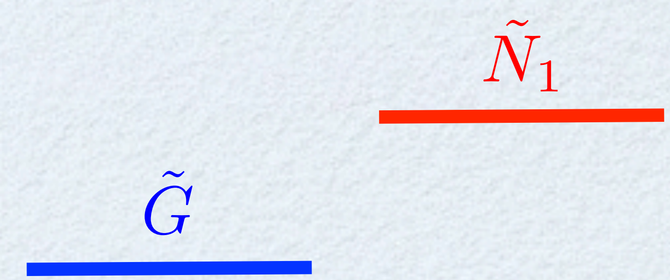
$$M < M_p$$



gravitino primer

$$m_{3/2} \approx \frac{F}{M_p}$$

$$M < M_p$$



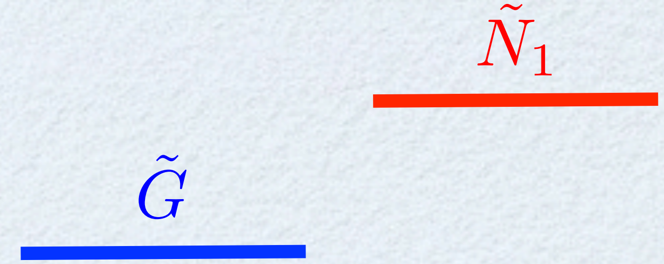
$$\tilde{m} = \frac{F}{M}$$

$$\frac{1}{F} J_Q^\mu \, \partial_\mu \tilde{G}$$

gravitino primer

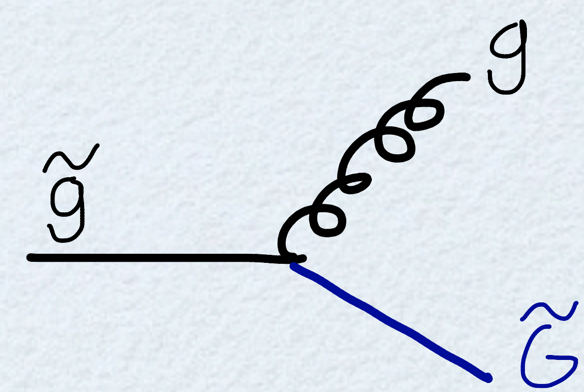
$$m_{3/2} \approx \frac{F}{M_p}$$

$$M < M_p$$



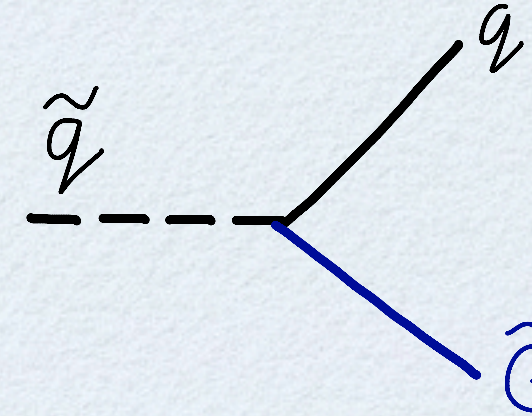
$$\tilde{m} = \frac{F}{M}$$

$$\frac{1}{F}\frac{m_\lambda}{4\sqrt{2}}\,\bar{\lambda}\,\sigma^{\mu\nu}F_{\mu\nu}\,\tilde{G}$$

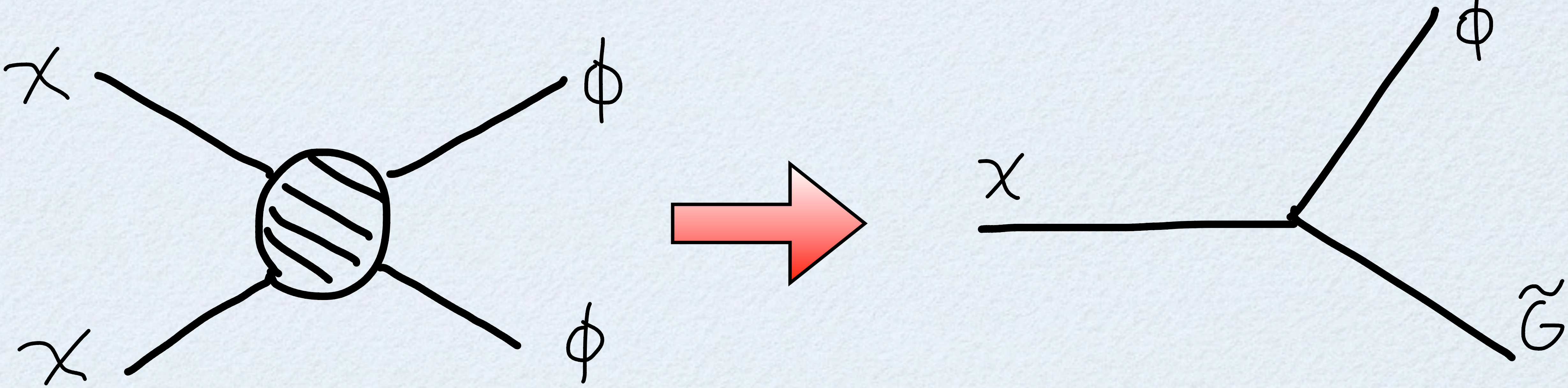


$$\frac{1}{F}J_Q^\mu\,\partial_\mu\tilde{G}$$

$$\frac{1}{F}(m_\psi^2 - m_\phi^2)\,\bar{\psi}_L\phi\,\tilde{G}$$

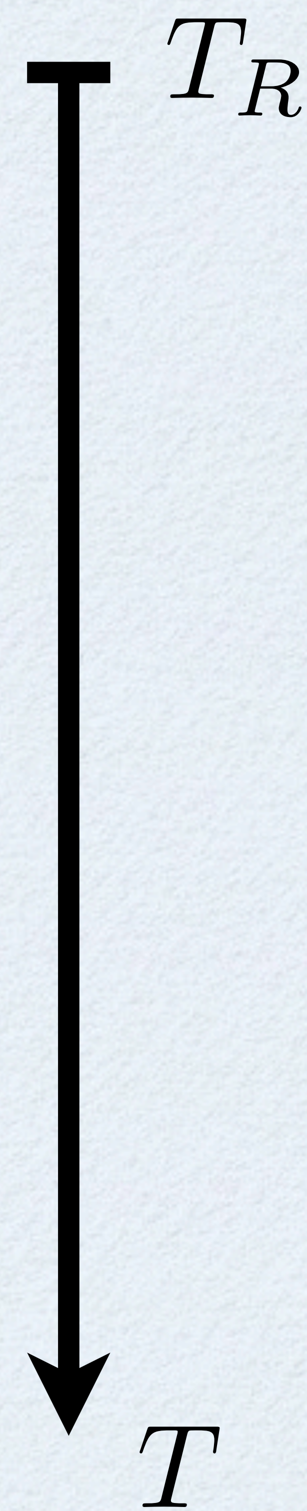


gravitino loophole?



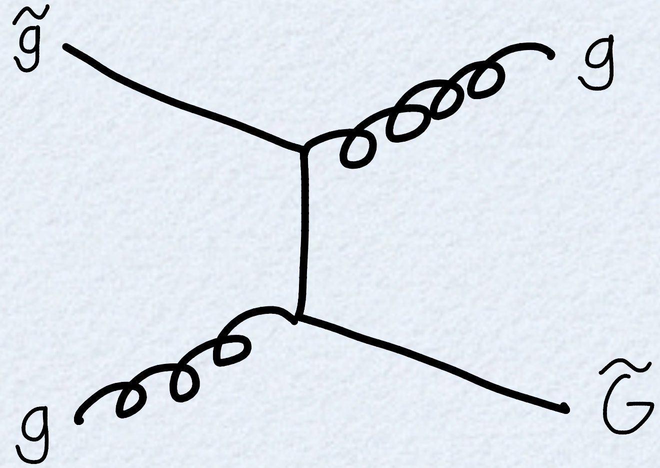
$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\mathrm{NLSP}}}\,\Omega_{\mathrm{NLSP}}$$

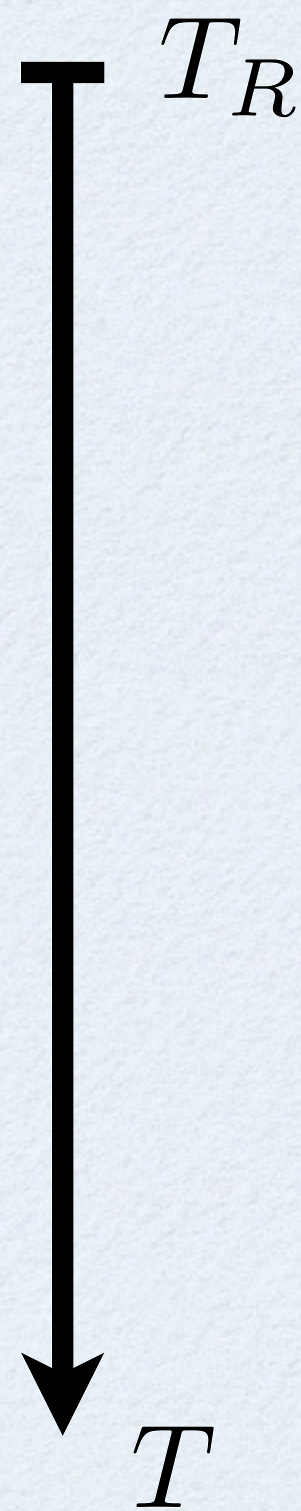
gravitino production



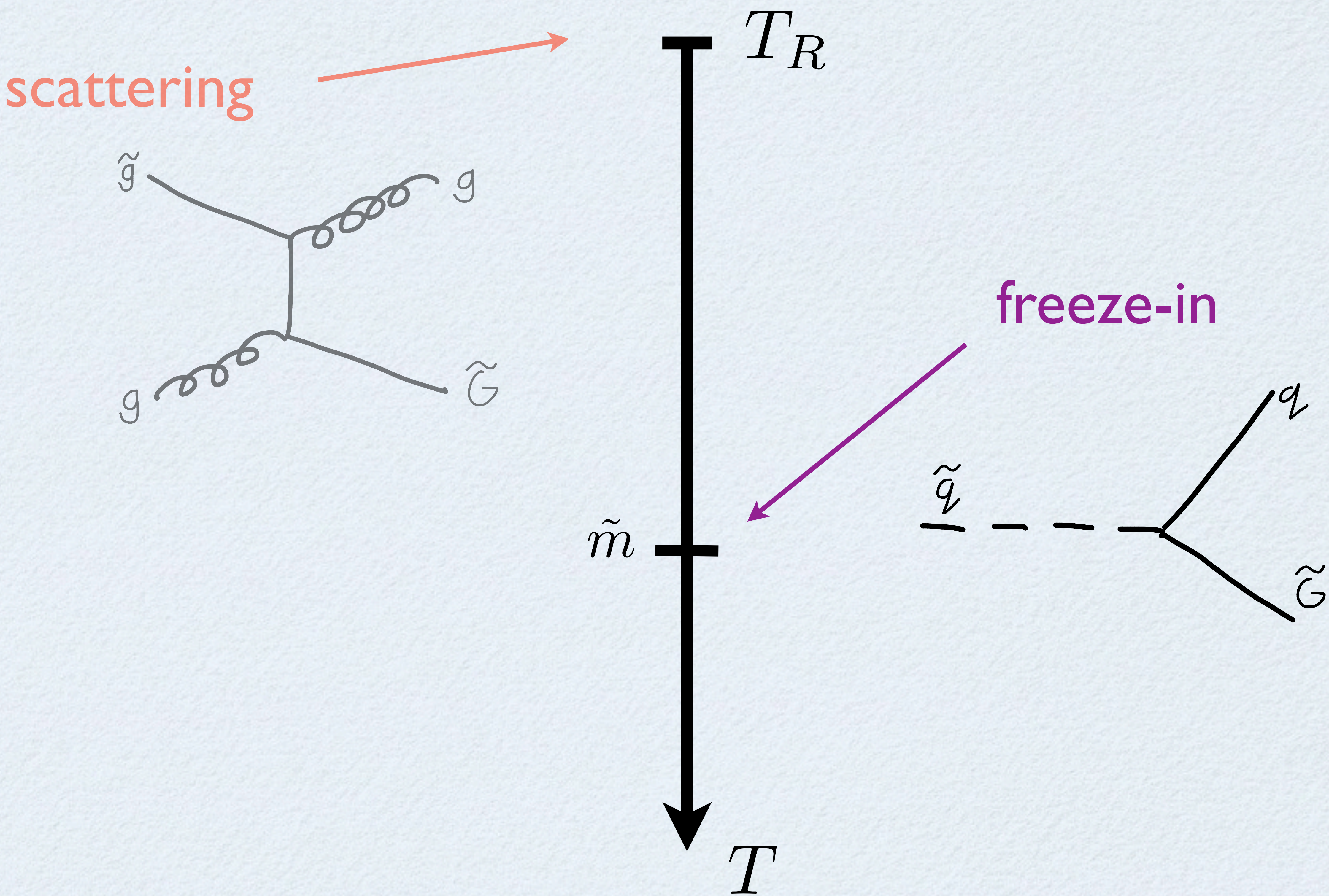
gravitino production

scattering

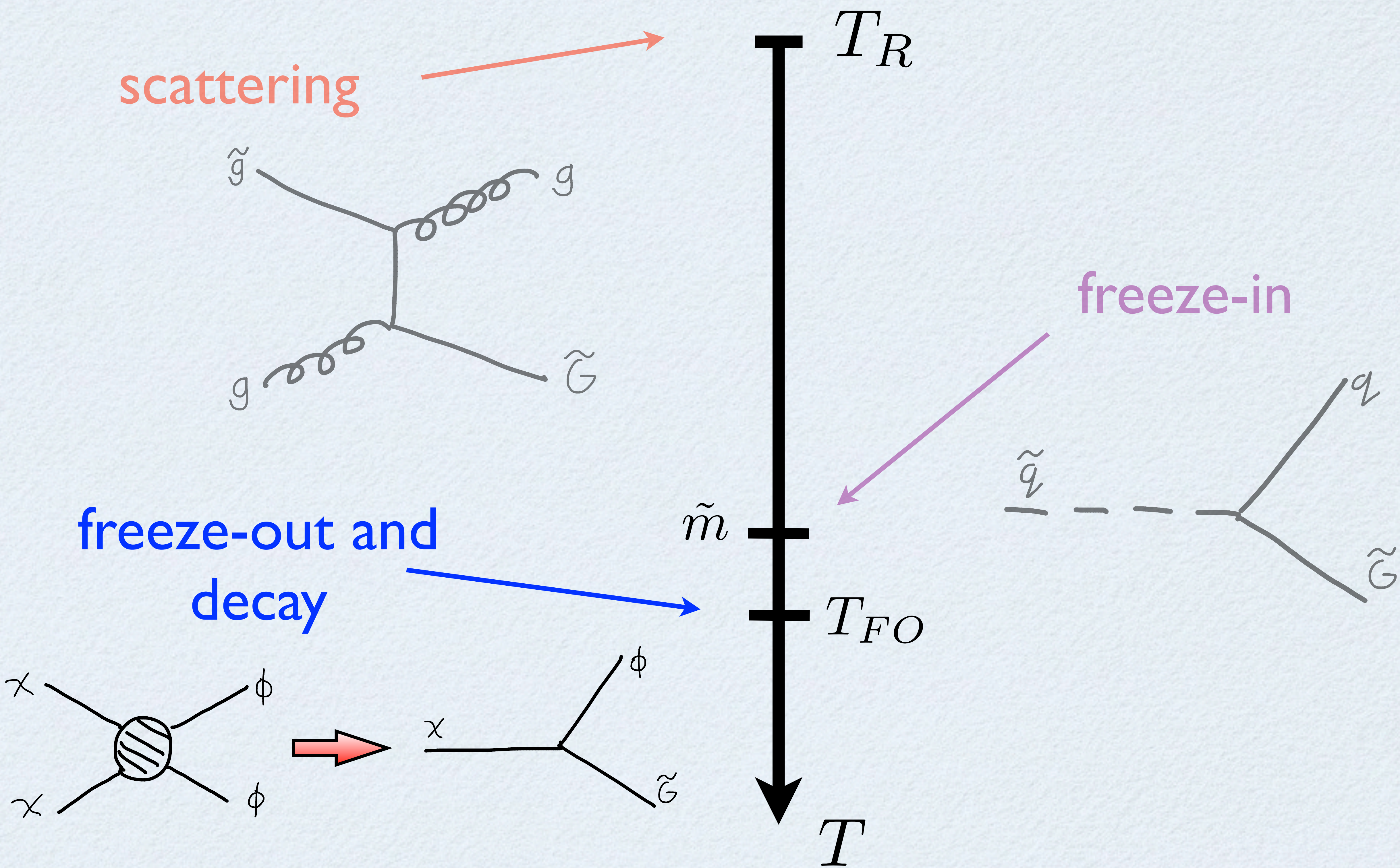




gravitino production



gravitino production



gravitino production

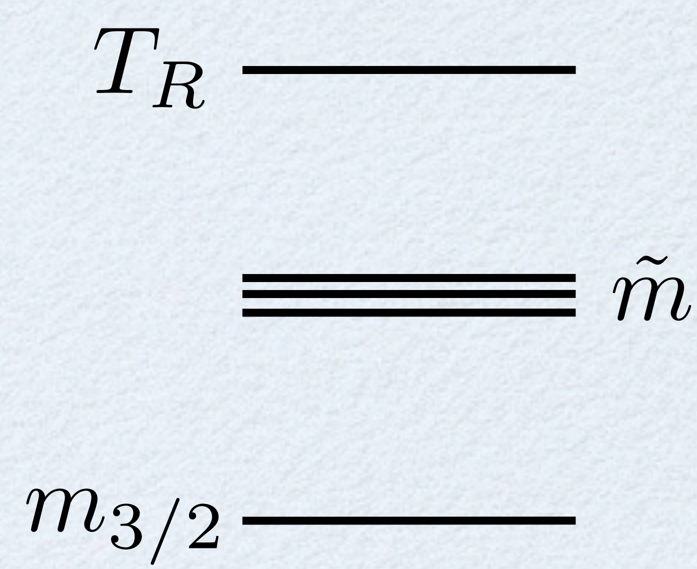
when is: $\Omega_{3/2} \leq \Omega_{obs}$?

gravitino production

when is: $\Omega_{3/2} \leq \Omega_{obs}$?

a simple parameterization:

$\tilde{m},\ m_{3/2},\ T_R$



gravitino production

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

gravitino production

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}}\frac{T_R\,\tilde{m}^2}{M_p}$	$\frac{1}{m_{3/2}}\frac{\tilde{m}^3}{M_p}$	$m_{3/2}\frac{\tilde{m}}{\alpha^2 M_p}$

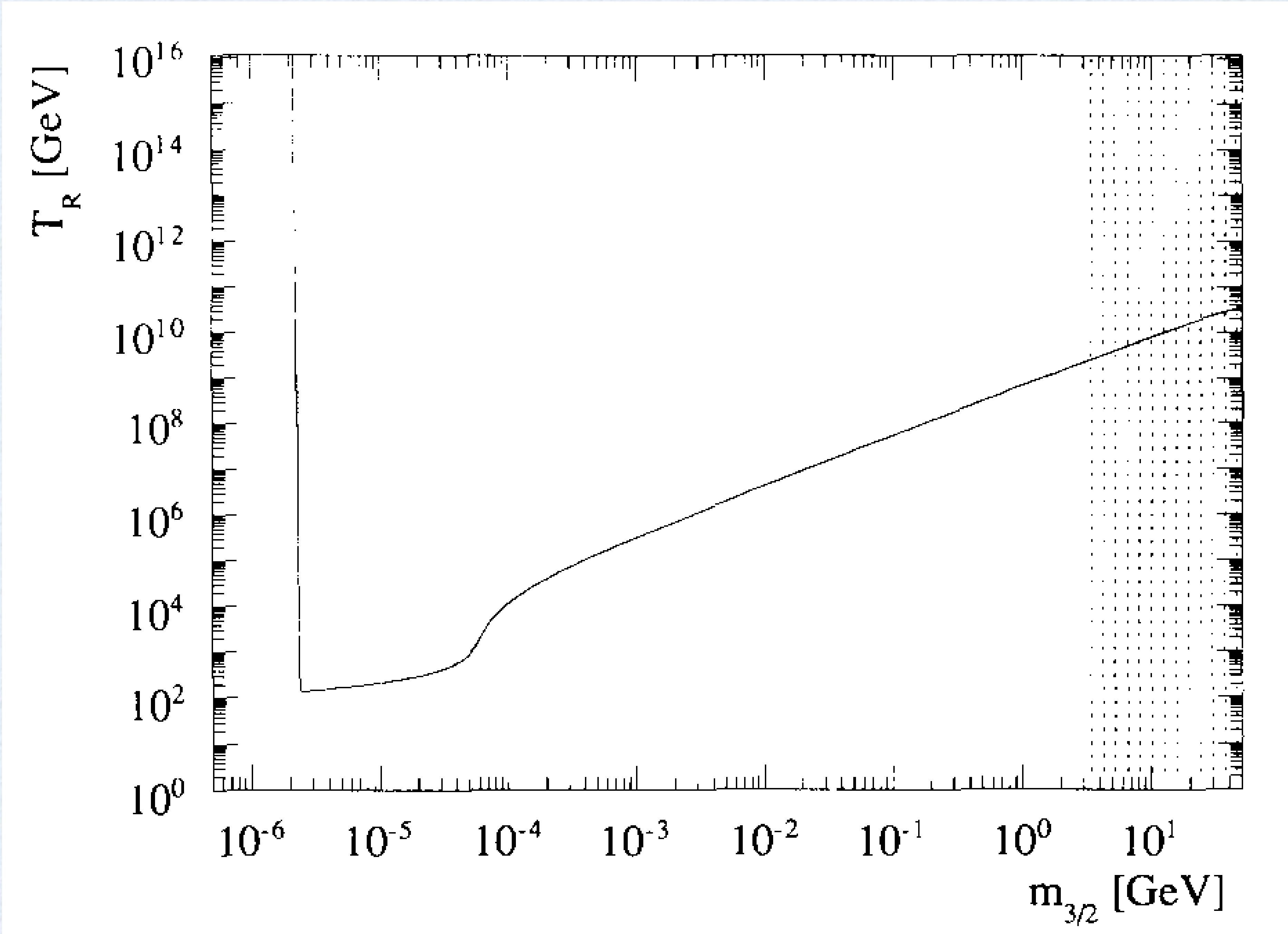
gravitino production

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p}$	$\frac{1}{m_{3/2}} \frac{\tilde{m}^3}{M_p}$	$m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p}$

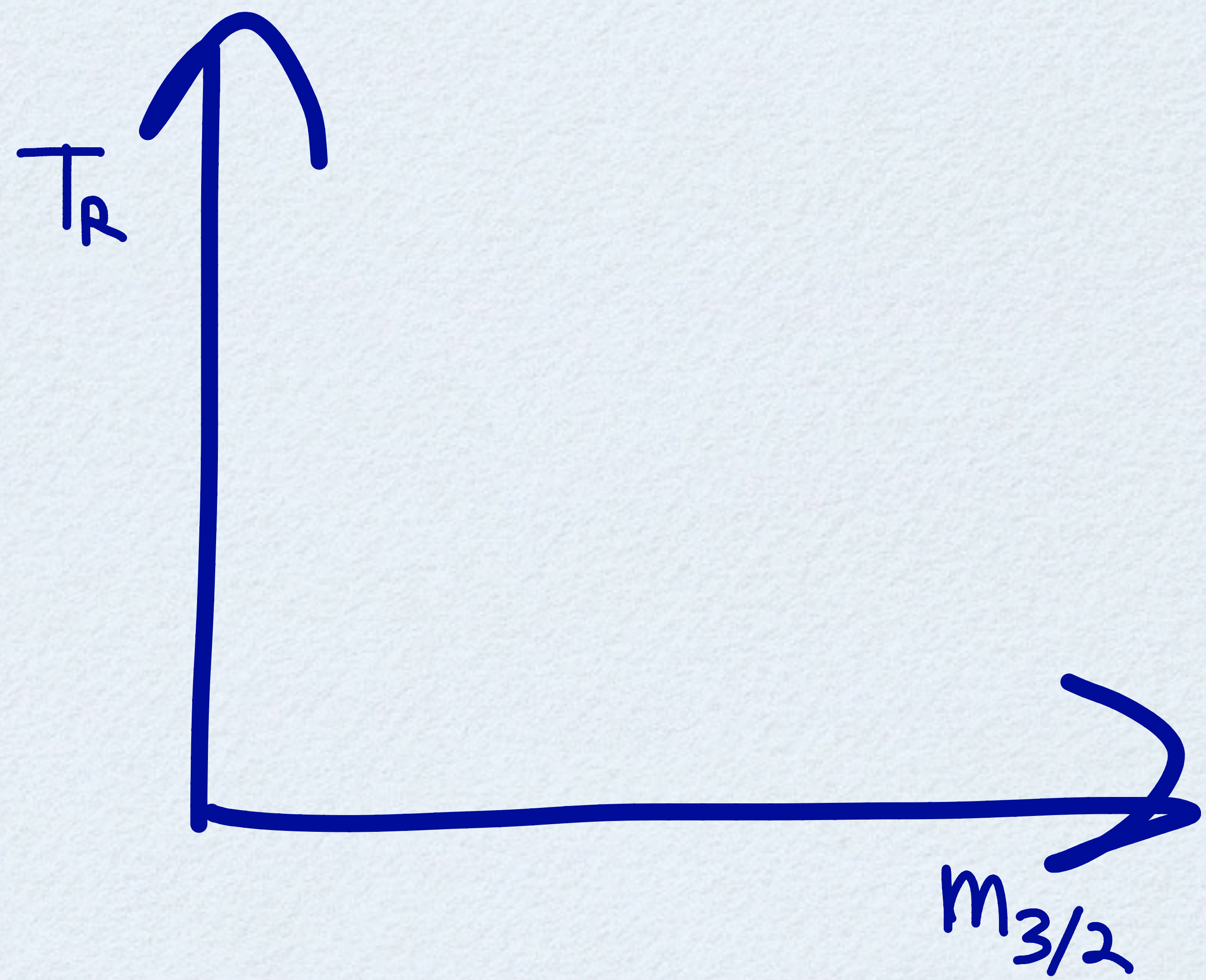
constrains reheat temperature

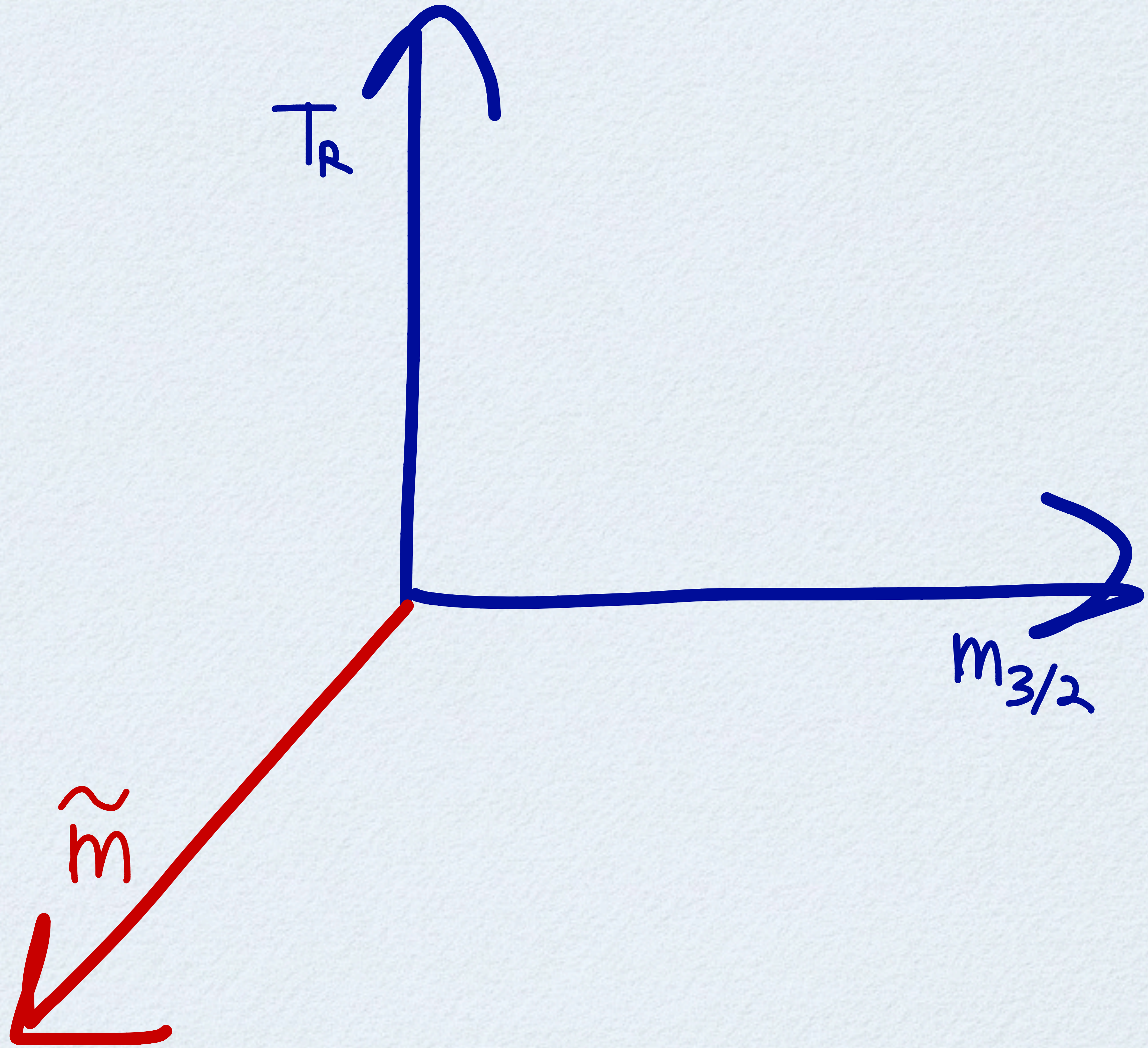
constraining the reheat temperature



$$m_{\tilde{q}} = 1 \text{ TeV}$$
$$M_1 = 50 \text{ GeV}$$

Moroi, Murayama, Yamaguchi 1993


T_R
$m_{3/2}$



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

gravitino production

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
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gravitino production

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}}\frac{T_R\tilde{m}^2}{M_p}$	$\frac{1}{m_{3/2}}\frac{\tilde{m}^3}{M_p}$	$m_{3/2}\frac{\tilde{m}}{\alpha^2 M_p}$

what about constraining $\tilde{m}$?

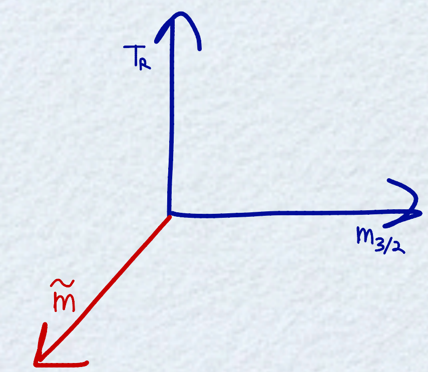
gravitino production

$$\color{red}{m_{3/2}Y_{UV}} + \color{purple}{m_{3/2}Y_{FI}} + \color{blue}{m_{3/2}Y_{FO}} \color{black}{\leq T_{eq}}$$

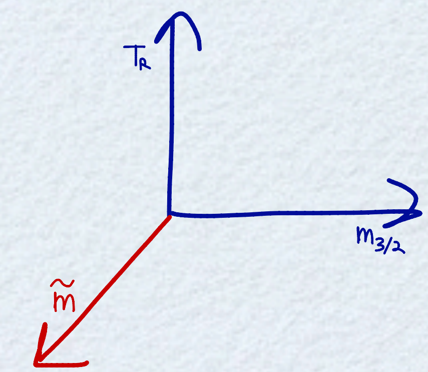
	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\boxed{\frac{1}{m_{3/2}}}\frac{T_R\,\tilde{m}^2}{M_p}$	$\boxed{\frac{1}{m_{3/2}}}\frac{\tilde{m}^3}{M_p}$	$\boxed{m_{3/2}}\frac{\tilde{m}}{\alpha^2 M_p}$

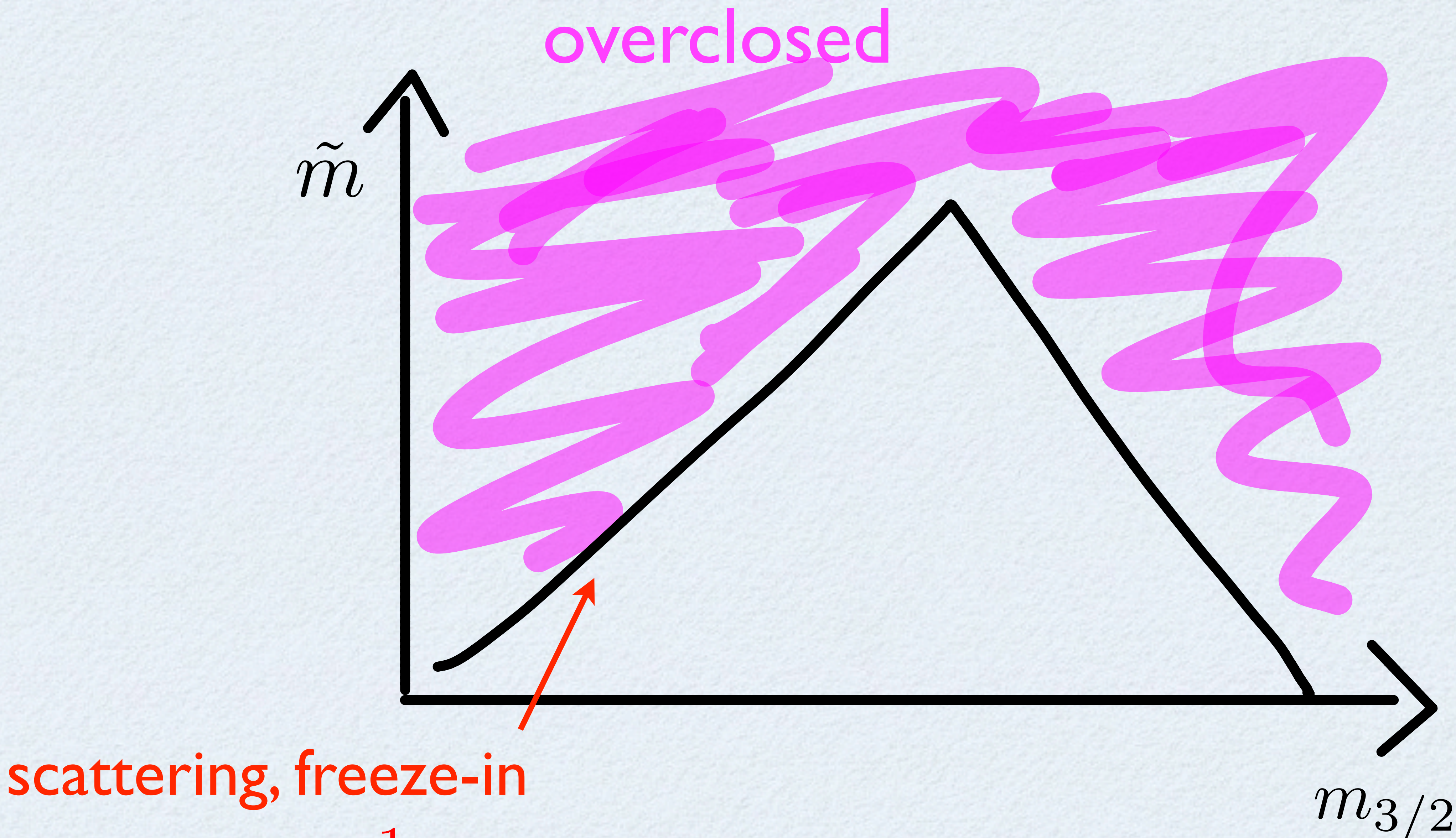
different gravitino mass dependence

a bound with gravitino LSP



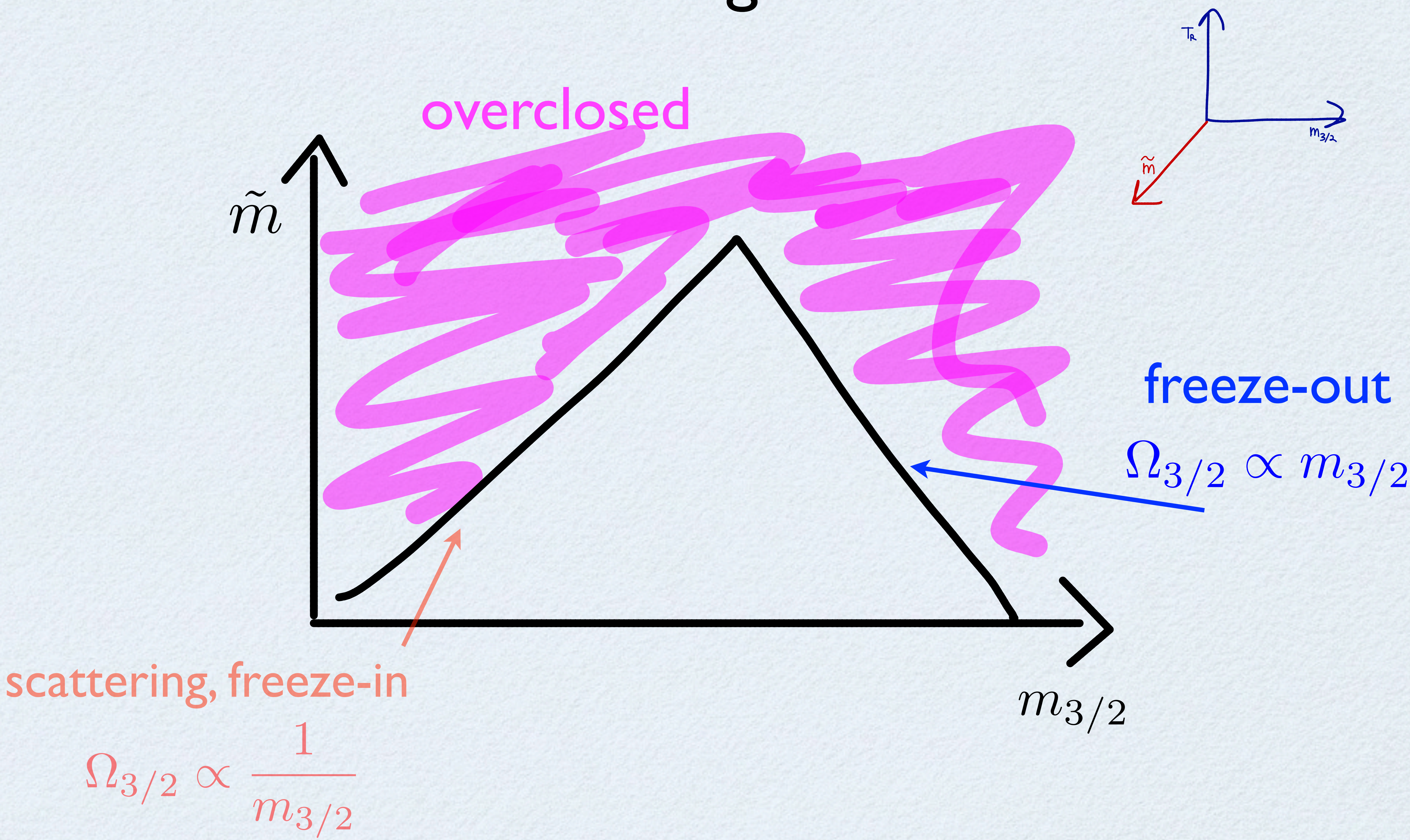
a bound with gravitino LSP



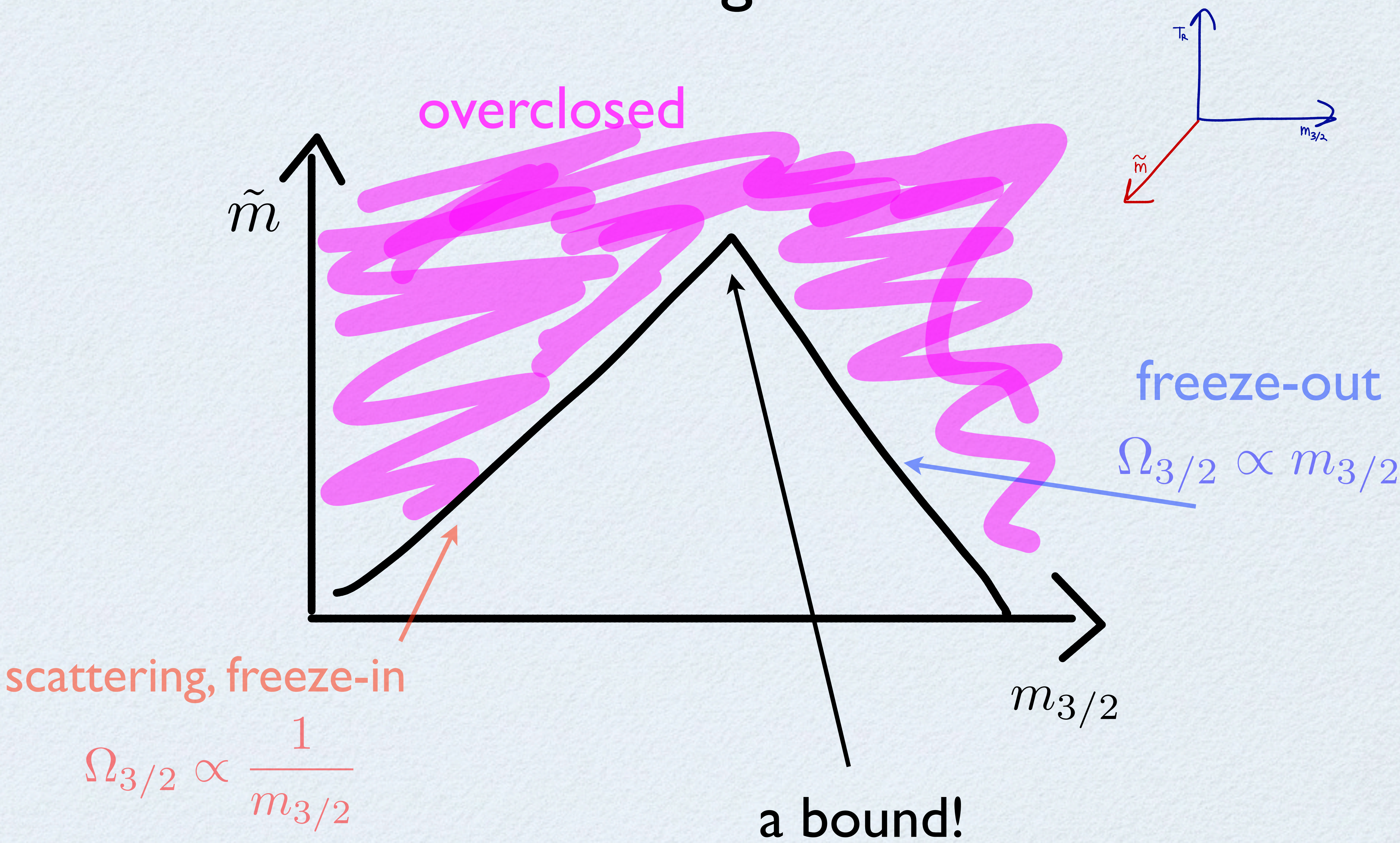


$$\Omega_{3/2} \propto \frac{1}{m_{3/2}}$$

a bound with gravitino LSP



a bound with gravitino LSP



the bound

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FO} \leq T_{eq}$$

the bound

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FO} \leq T_{eq}$$

$$\frac{1}{m_{3/2}}\frac{T_R\,\tilde{m}^2}{M_p} + m_{3/2}\frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq}$$

the bound

$$m_{3/2} Y_{UV} + m_{3/2} Y_{FO} \leq T_{eq}$$

$$\frac{1}{m_{3/2}} \frac{T_R \, \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq}$$

abundance minimized when:

$$m_{3/2} = \left(\frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \, \tilde{m}$$

the bound

$$m_{3/2} Y_{UV} + m_{3/2} Y_{FO} \leq T_{eq}$$

$$\frac{1}{m_{3/2}} \frac{T_R \, \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq}$$

abundance minimized when:

$$m_{3/2} = \left(\frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \, \tilde{m}$$

$$\tilde{m} \leq \left(\frac{T_R}{\tilde{m}} \right)^{-1/4} \alpha^{1/2} \sqrt{T_{eq} M_p}$$

the bound

$$m_{3/2} Y_{UV} + m_{3/2} Y_{FO} \le T_{eq}$$

$$\frac{1}{m_{3/2}} \frac{T_R \, \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \le T_{eq}$$

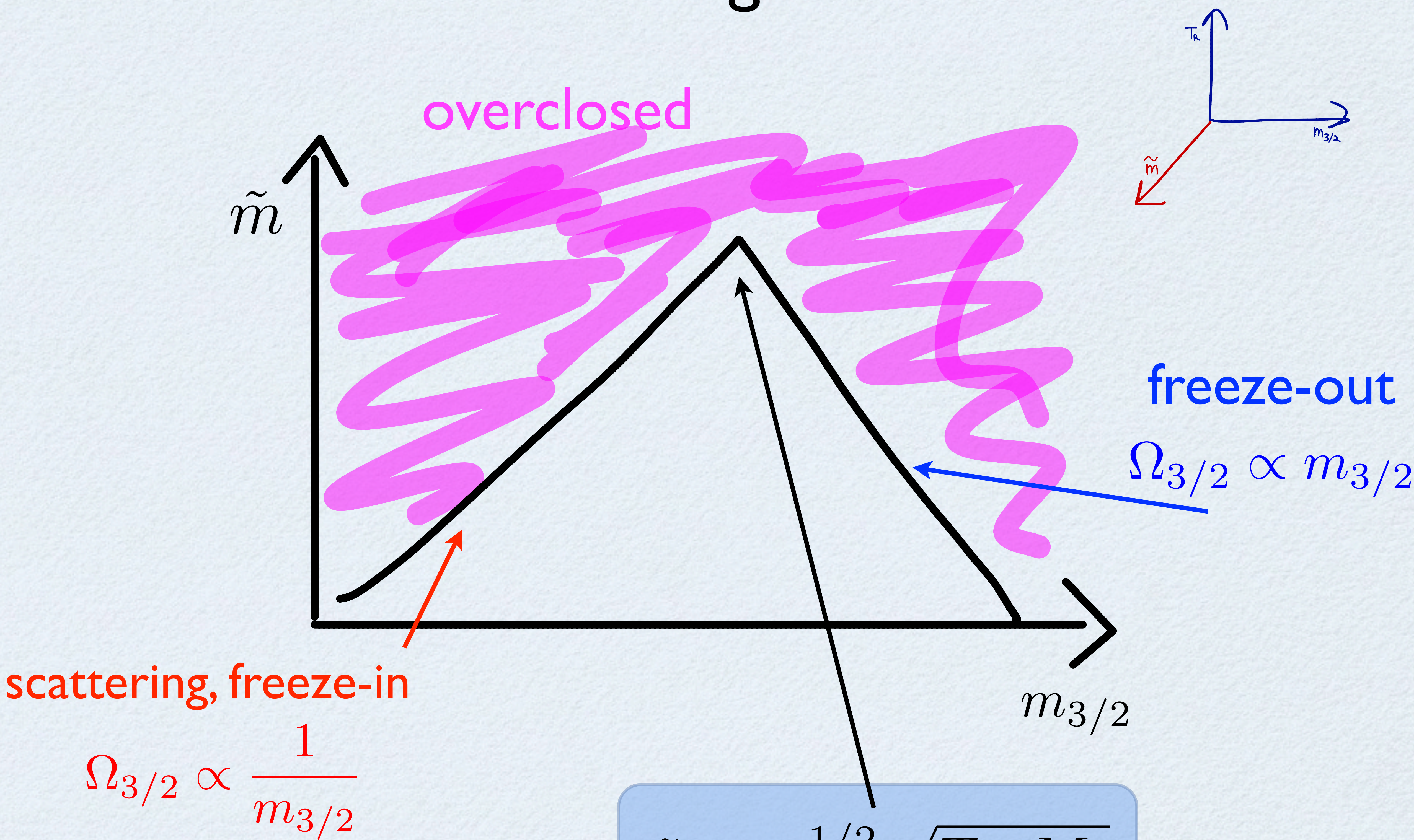
abundance minimized when:

$$m_{3/2} = \left(\frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \, \tilde{m}$$

$$\tilde{m} \le \left(\frac{T_R}{\tilde{m}} \right)^{-1/4} \alpha^{1/2} \sqrt{T_{eq} M_p}$$

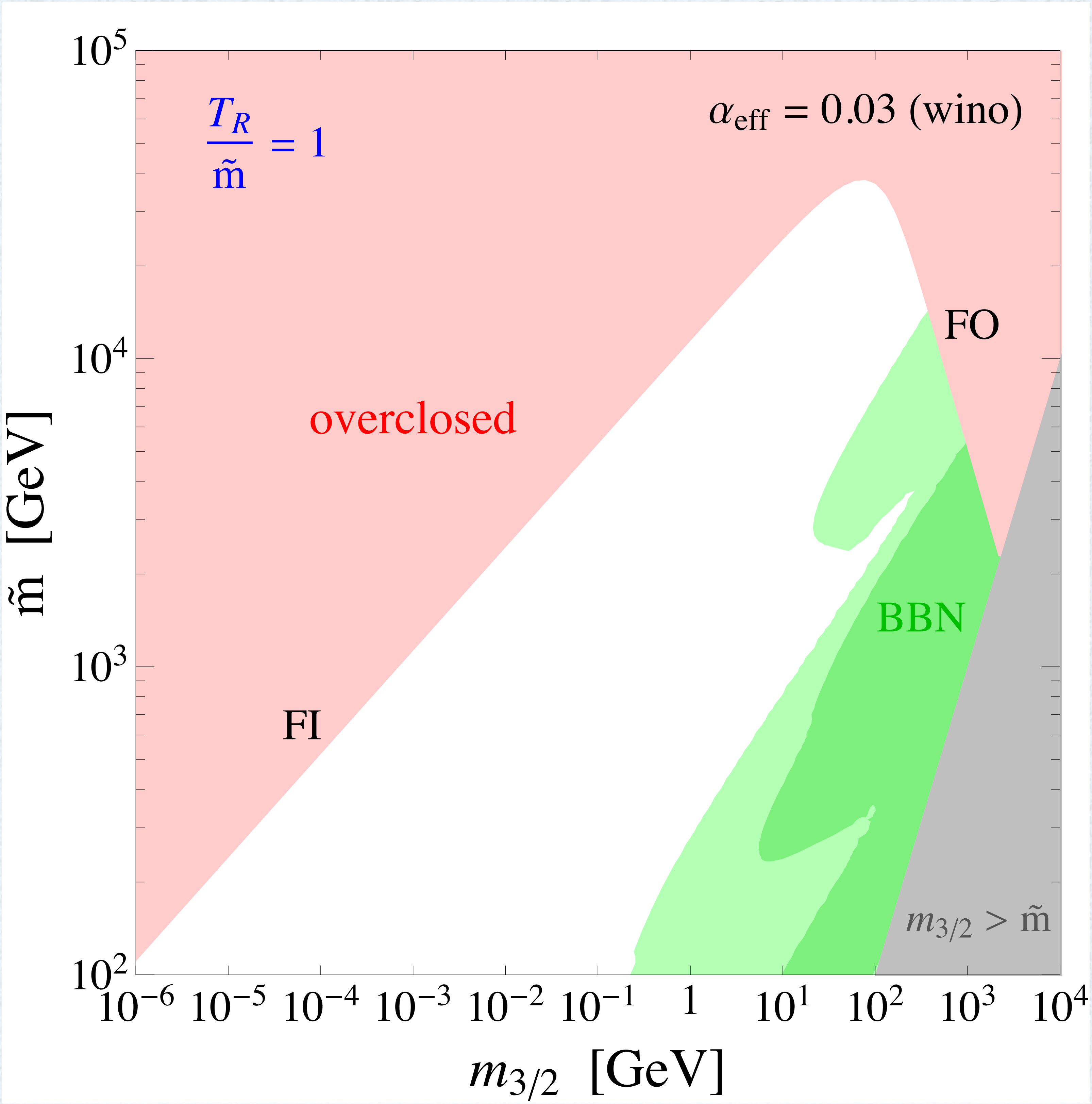
$$\boxed{\tilde{m} \le \alpha^{1/2} \sqrt{T_{eq} \, M_p}}$$

a bound with gravitino LSP



$$\tilde{m} \leq \alpha^{1/2} \sqrt{T_{eq} M_p}$$

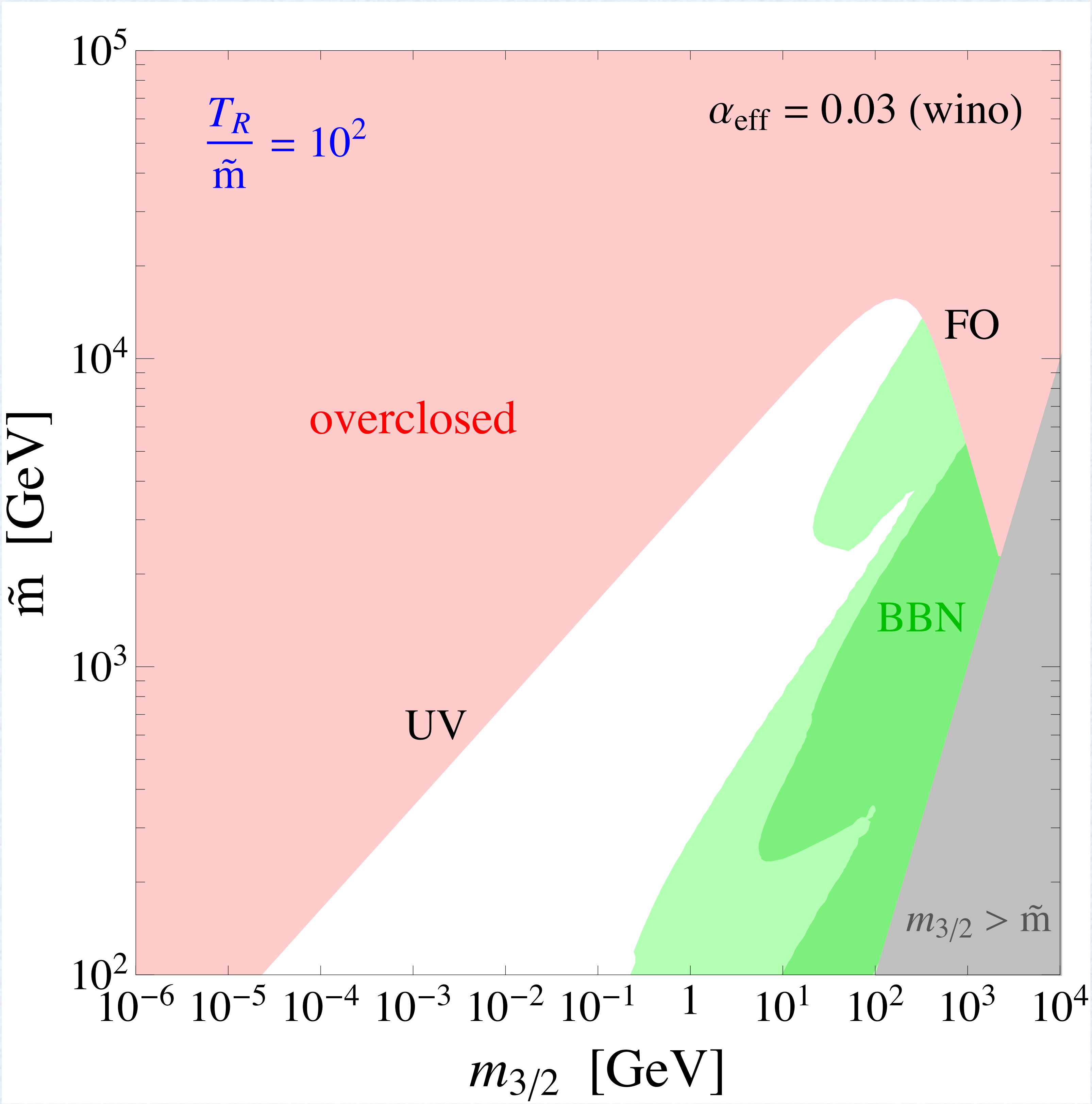
numerics



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

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

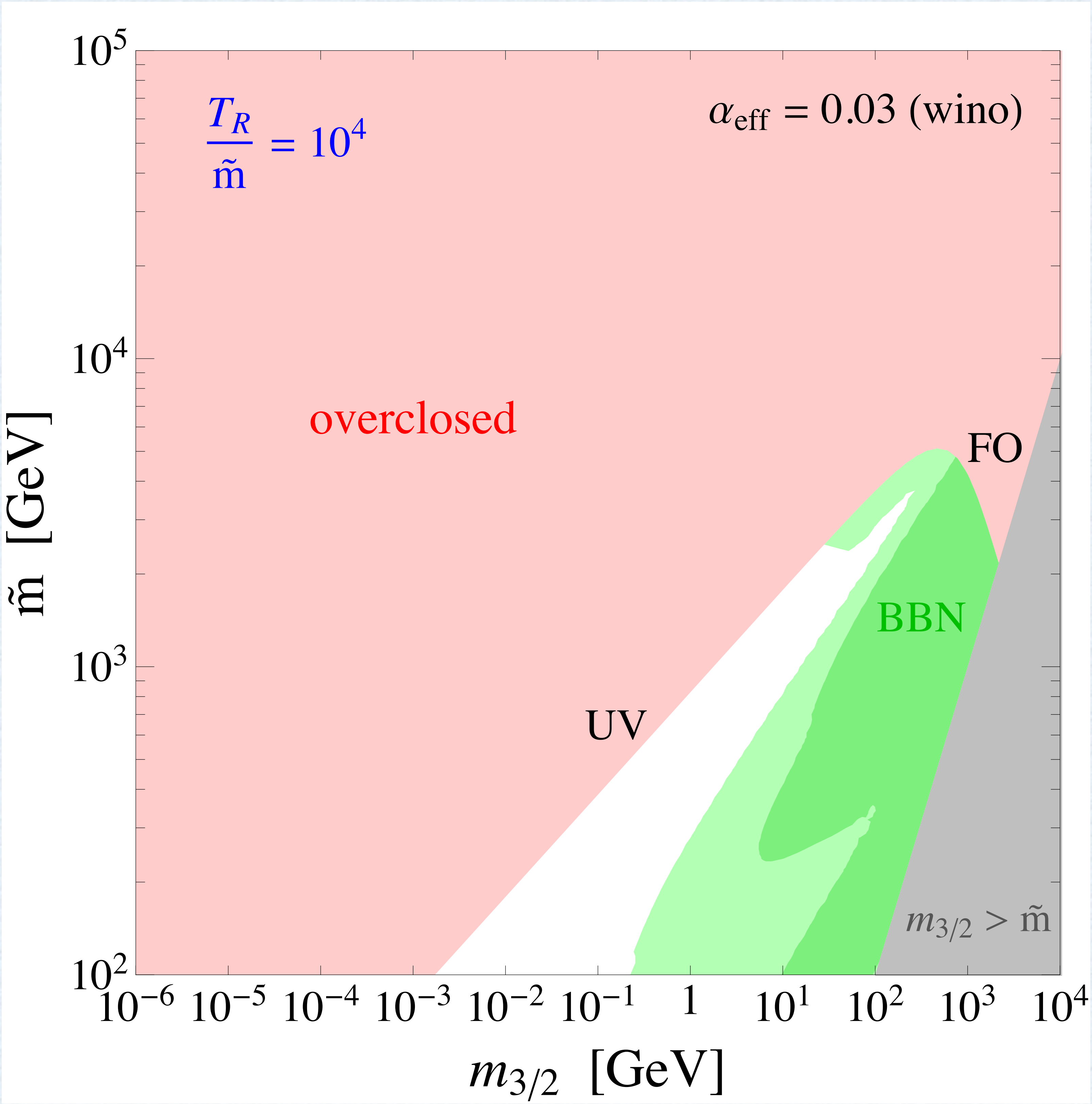
numerics



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

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

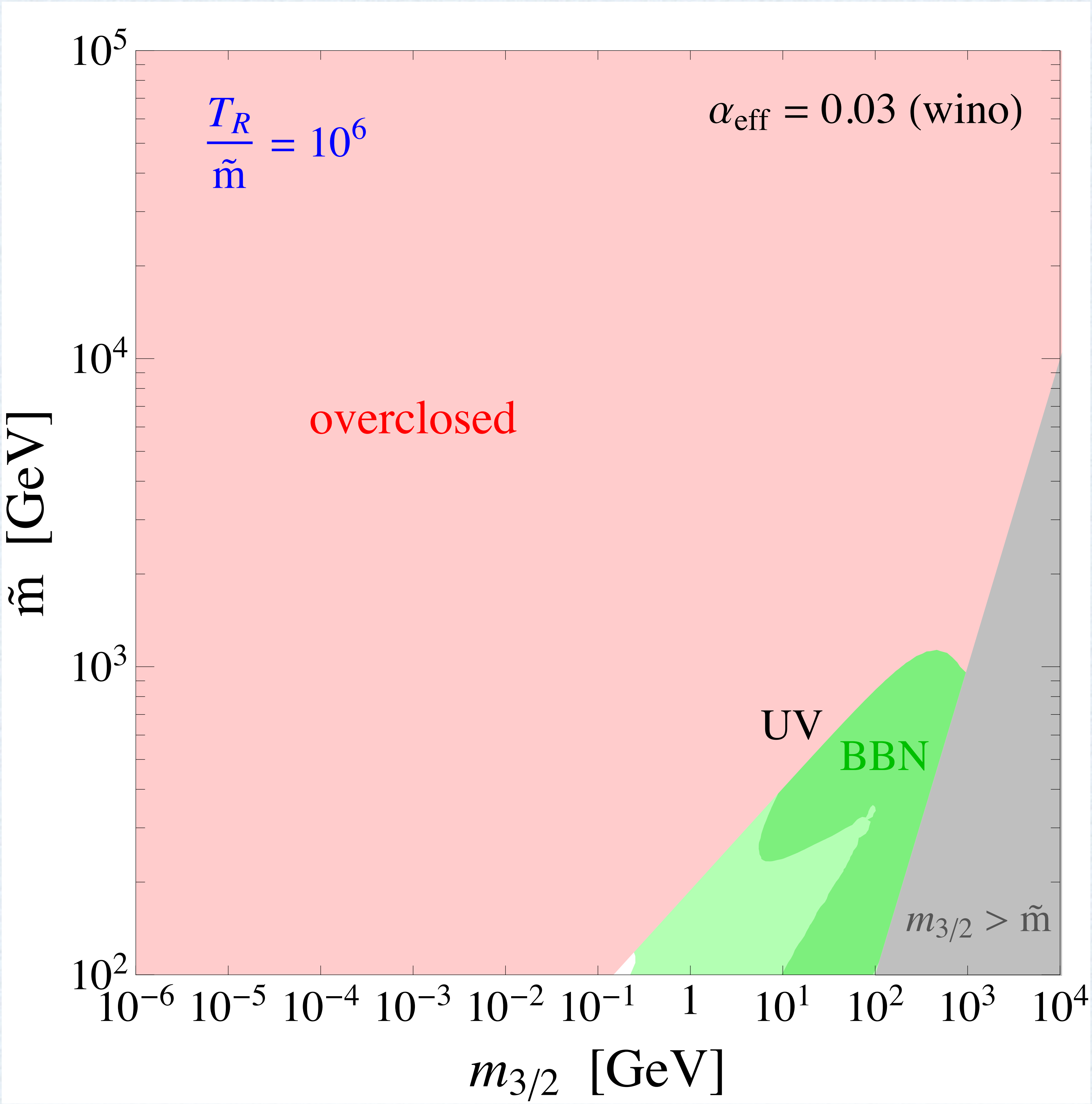
numerics



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

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

numerics



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

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

thermalized gravitinos

- very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

thermalized gravitinos

- very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

$$m_{3/2}^2 \leq \left(\frac{T_R}{\tilde{m}}\right) \frac{\tilde{m}^3}{M_p} \approx \mathrm{keV}^2 \left(\frac{T_R}{\tilde{m}}\right) \left(\frac{\tilde{m}}{100\ \mathrm{GeV}}\right)^3$$

thermalized gravitinos

- very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

$$m_{3/2}^2 \leq \left(\frac{T_R}{\tilde{m}}\right)\frac{\tilde{m}^3}{M_p} \approx \mathrm{keV}^2 \left(\frac{T_R}{\tilde{m}}\right)\left(\frac{\tilde{m}}{100\ \mathrm{GeV}}\right)^3$$

- overclosure bound

$$m_{3/2} \lesssim 100\ \mathrm{eV}$$

  - Pagels, Primack 1982

thermalized gravitinos

- very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

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- overclosure bound

$$m_{3/2} \lesssim 100\ \mathrm{eV}$$

  - Pagels, Primack 1982

- free streaming length:

$$m_{3/2} \lesssim 16\ \mathrm{eV}$$

  - Viel et al., 2005

thermalized gravitinos

- implies low SUSY breaking scale

$$m_{3/2} \lesssim 16 \text{ eV} \quad \Rightarrow \quad \sqrt{F} \lesssim 260 \text{ TeV}$$

$$\tilde{m} = \left(\frac{g_{\text{susy}}}{4\pi}\right)^2 \sqrt{F}$$

thermalized gravitinos

- implies low SUSY breaking scale

$$m_{3/2} \lesssim 16 \text{ eV} \quad \Rightarrow \quad \sqrt{F} \lesssim 260 \text{ TeV}$$

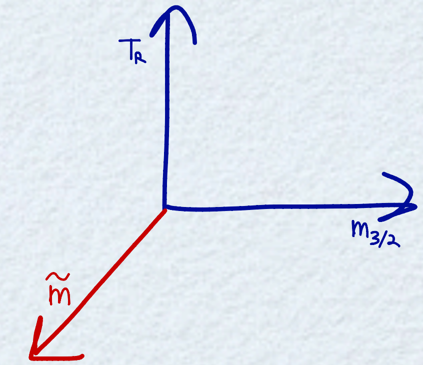
$$\tilde{m} = \left(\frac{g_{\text{susy}}}{4\pi}\right)^2 \sqrt{F}$$

- parametrically,

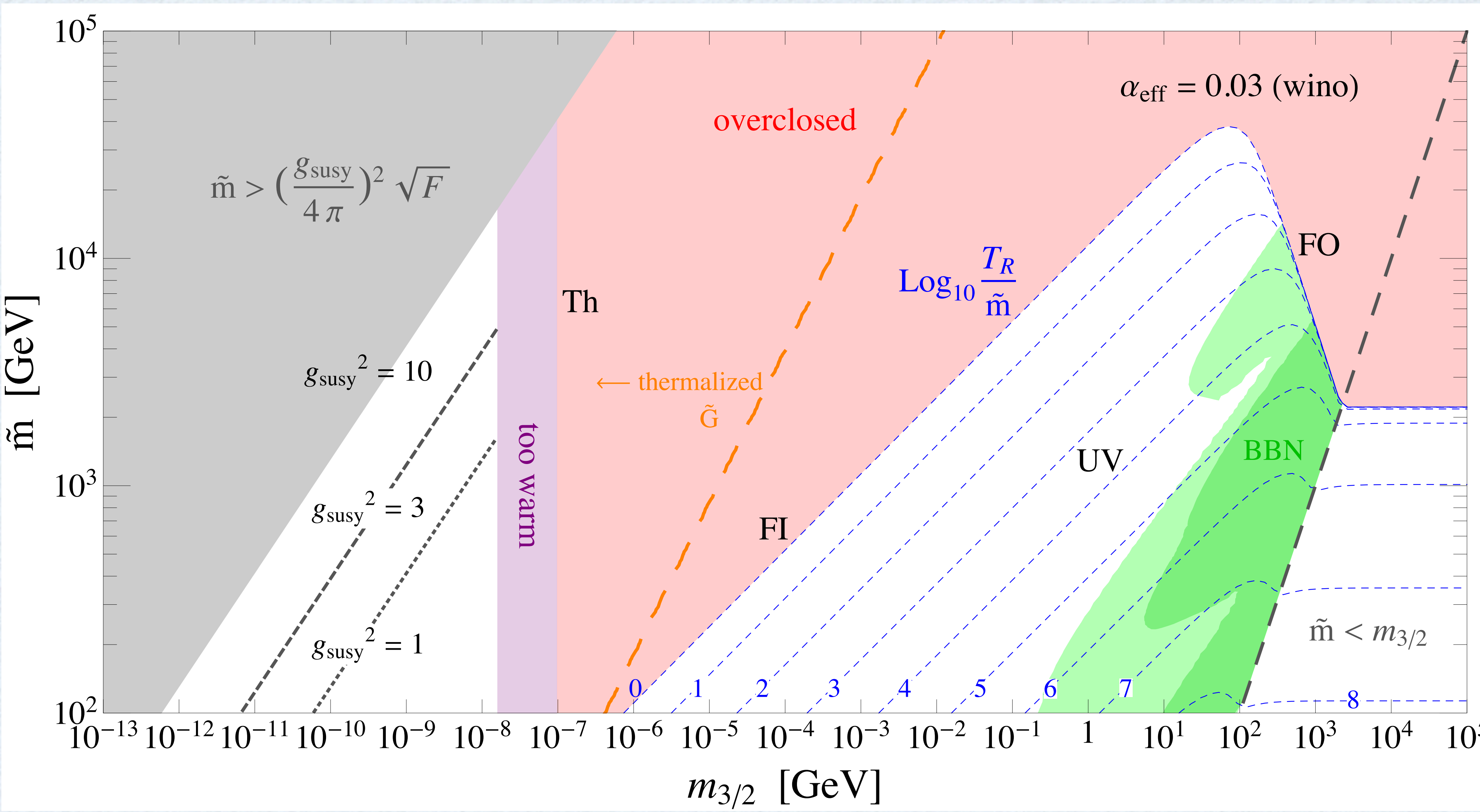
$$m_{3/2} < T_{eq}$$

$$F \leq T_{eq} M_p \quad \Rightarrow \quad \boxed{\tilde{m} \leq \left(\frac{g_{\text{susy}}}{4\pi}\right)^2 \sqrt{T_{eq} M_p}}$$

numerics

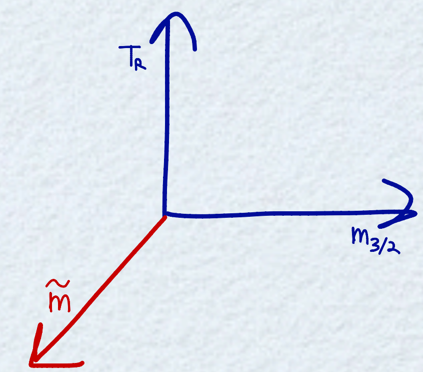


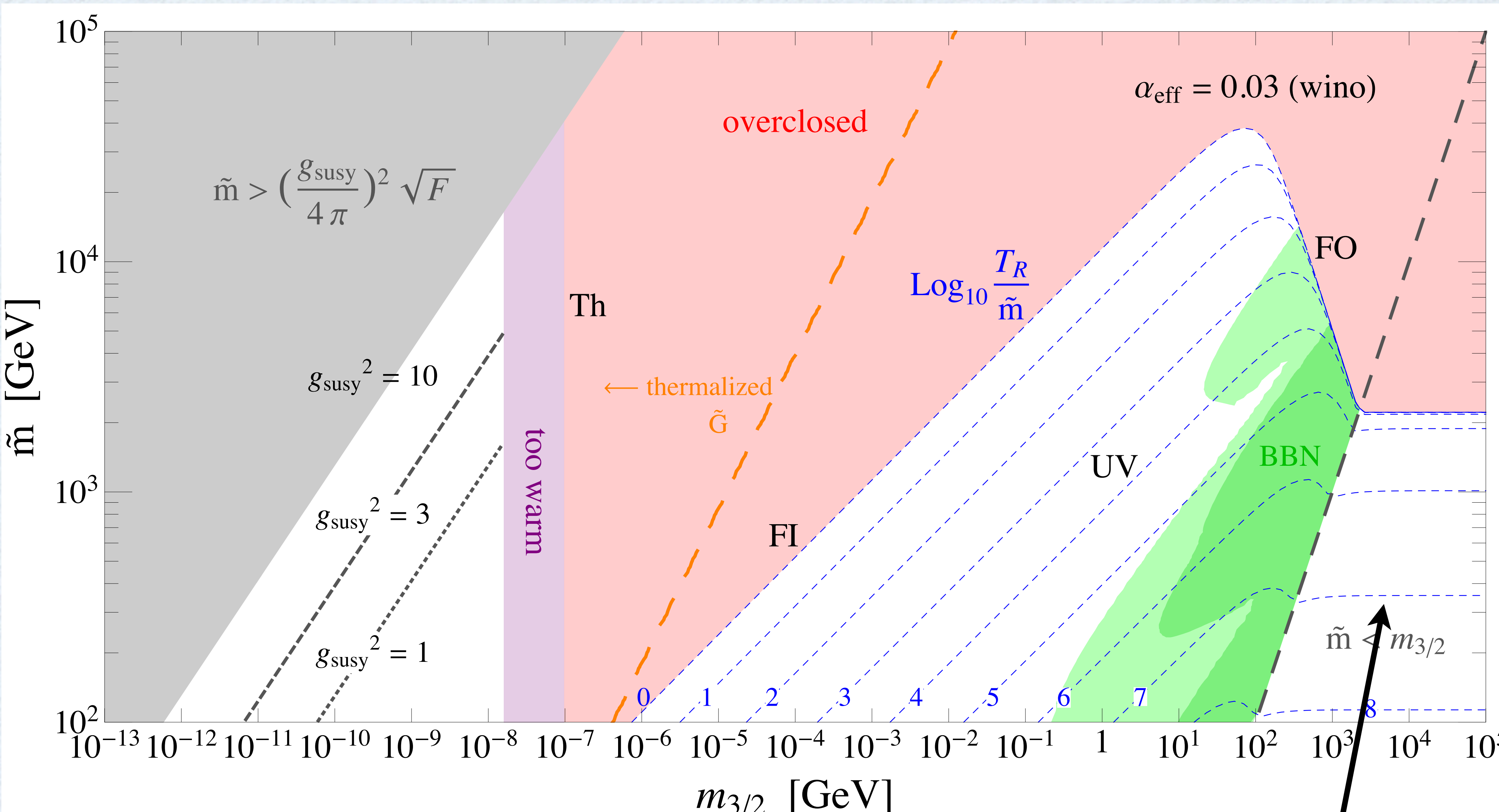
T_R
$m_{3/2}$
$\tilde{m}$



$\alpha_{\text{eff}} = 0.03$ (wino)
overclosed
$\tilde{m} > (\frac{g_{\text{susy}}}{4\pi})^2 \sqrt{F}$
Th
too warm
$g_{\text{susy}}{}^2 = 10$
$g_{\text{susy}}{}^2 = 3$
$g_{\text{susy}}{}^2 = 1$
← thermalized $\tilde{G}$
$\text{Log}_{10} \frac{T_R}{\tilde{m}}$
FO
UV
FI
BBN
$\tilde{m} < m_{3/2}$
0 1 2 3 4 5 6 7 8
$\tilde{m}$ [GeV]
$m_{3/2}$ [GeV]

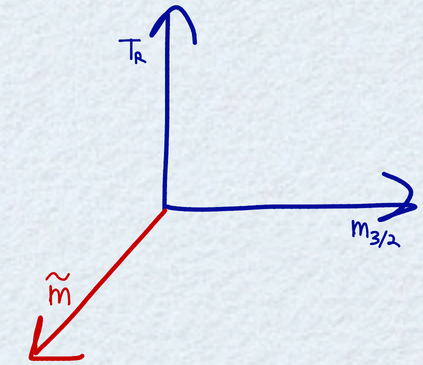
numerics

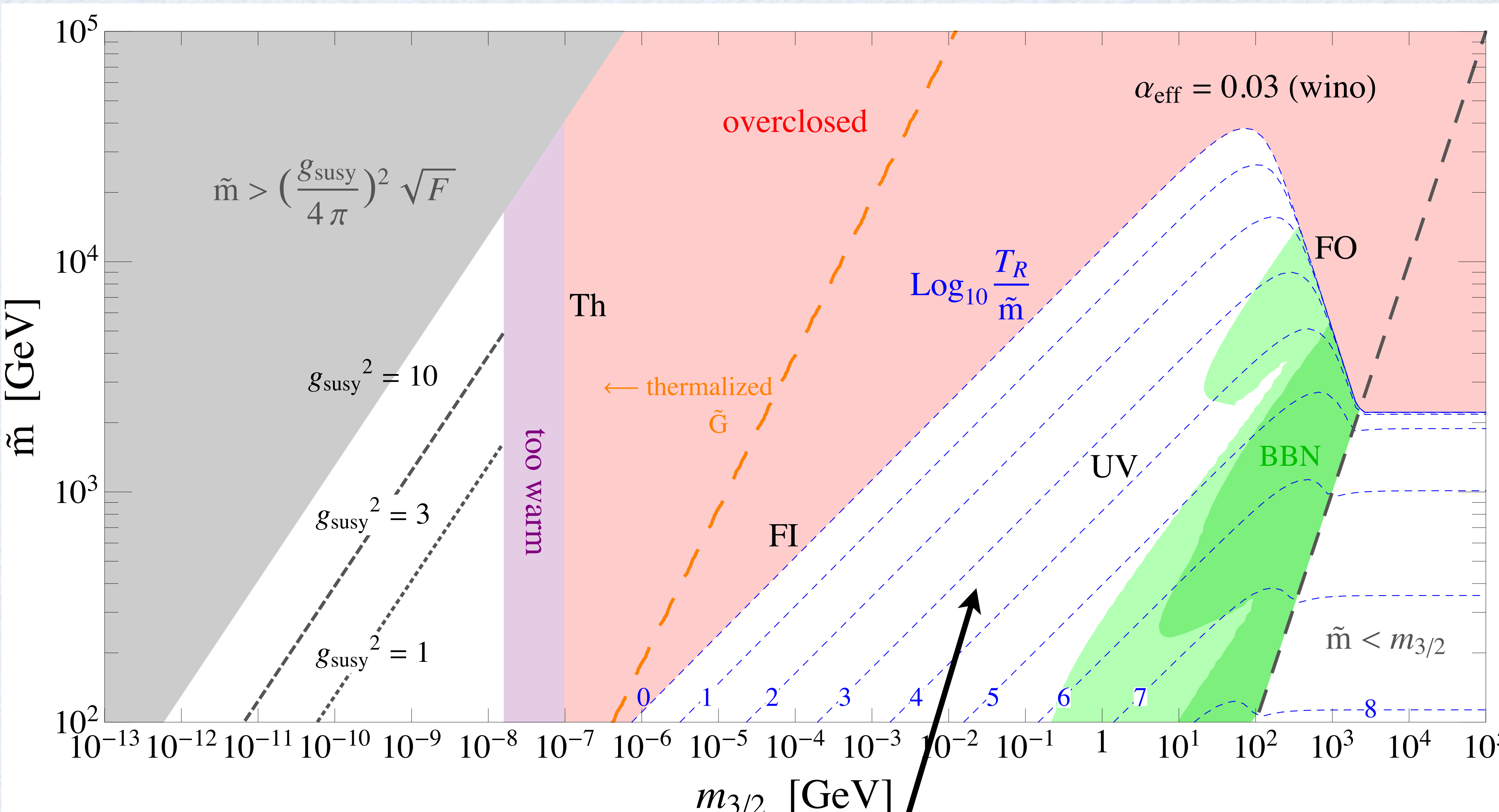




SM-superpartner LSP

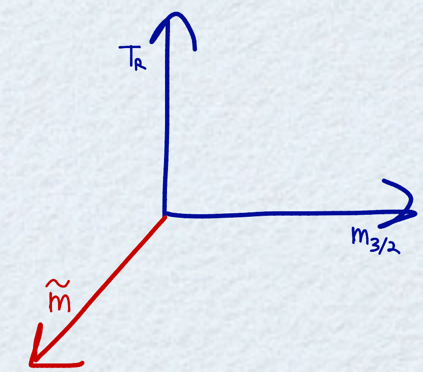
numerics

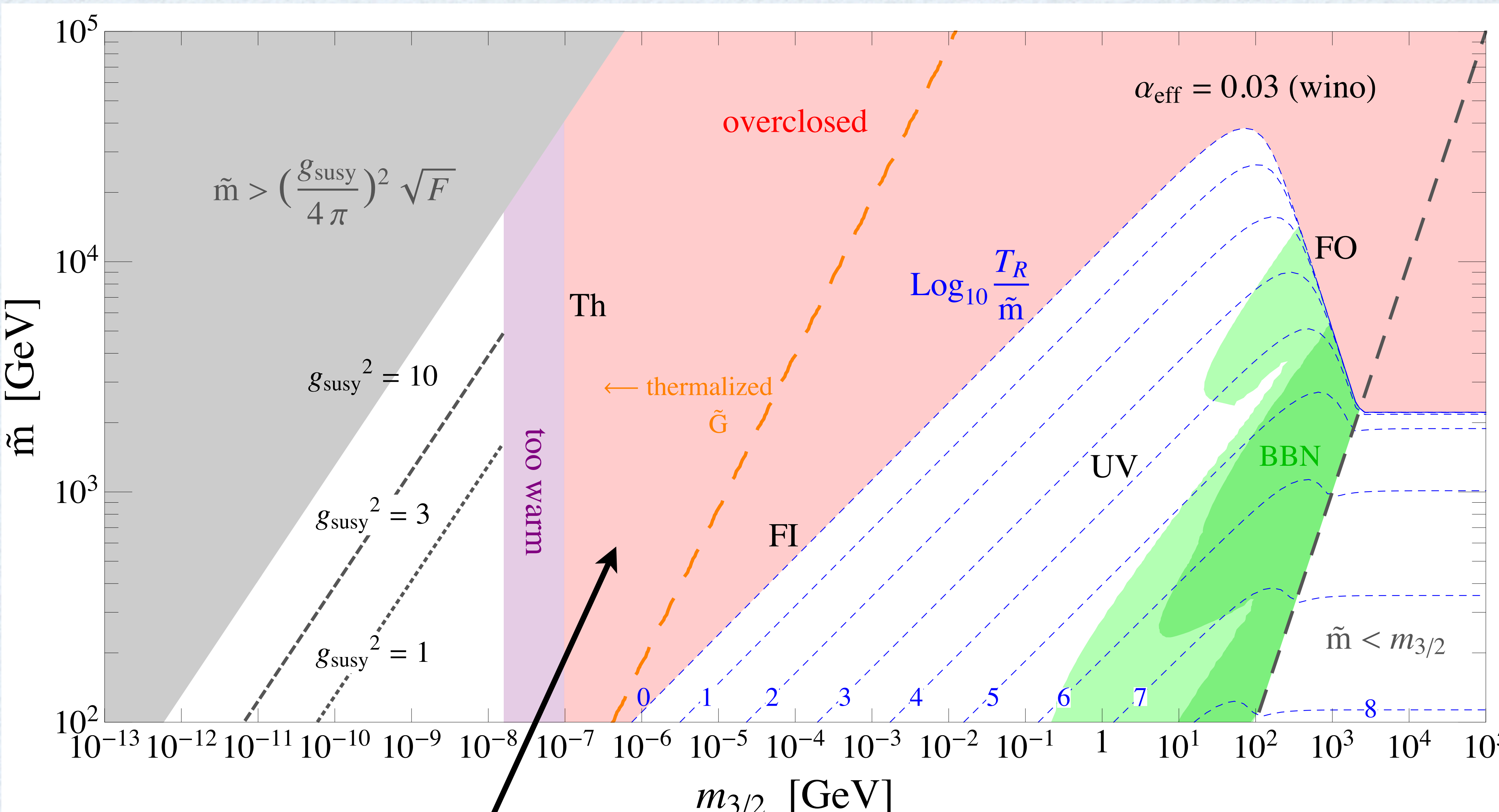




non-thermal gravitino LSP

numerics

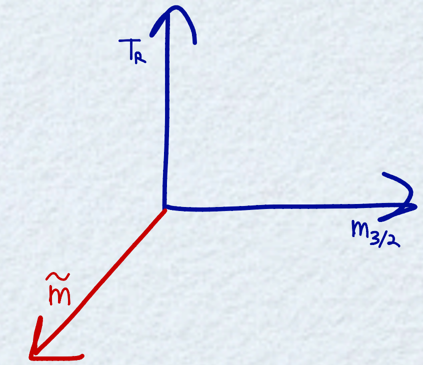


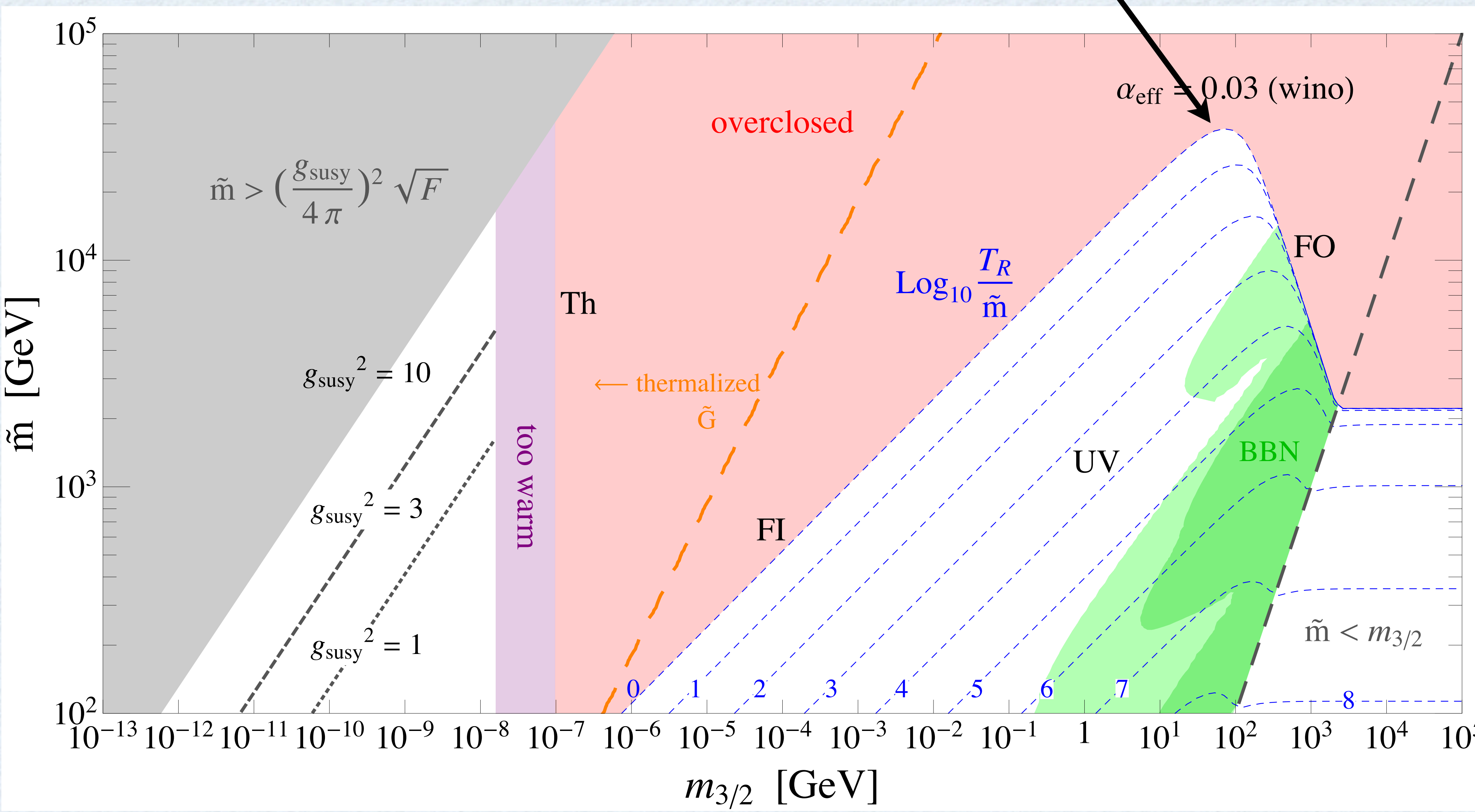


thermal gravitino LSP

numerics

$\tilde{m} \leq 40$ TeV

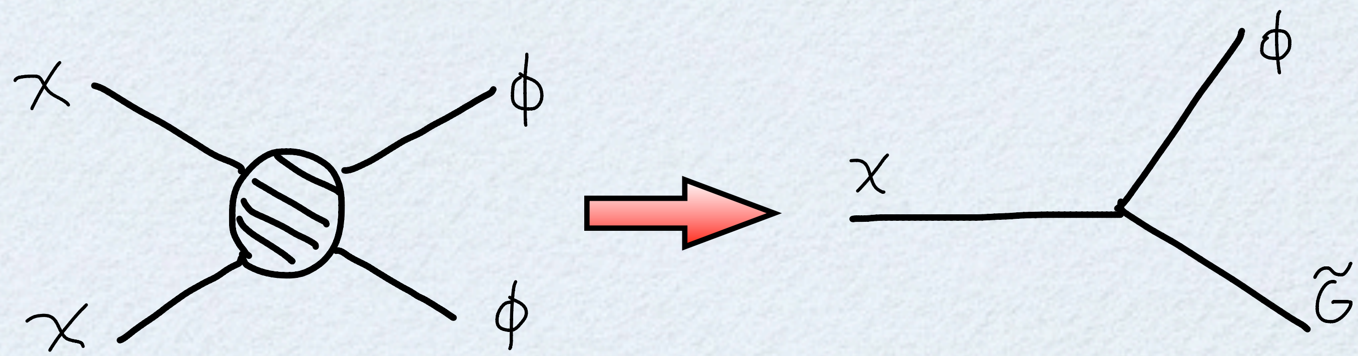




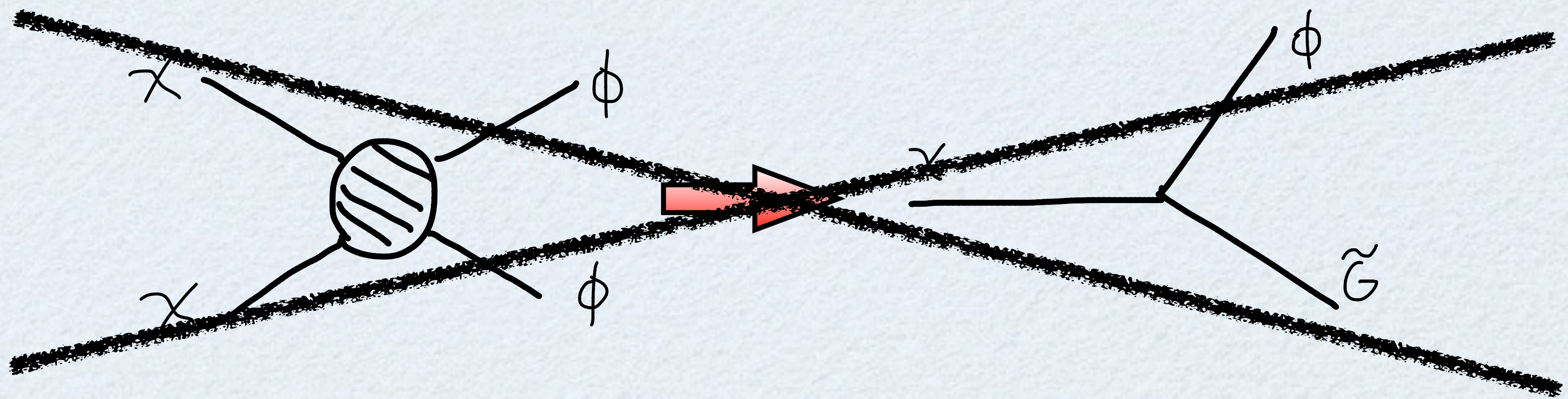
generalizations

1. no freeze-out and decay
2. split SUSY

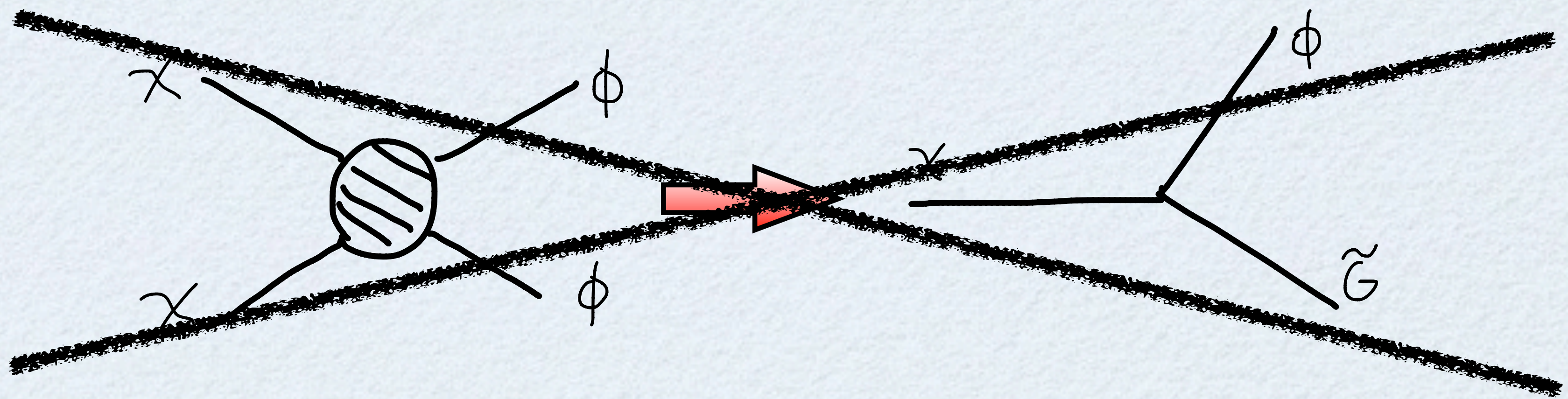
no freeze-out and decay



no freeze-out and decay

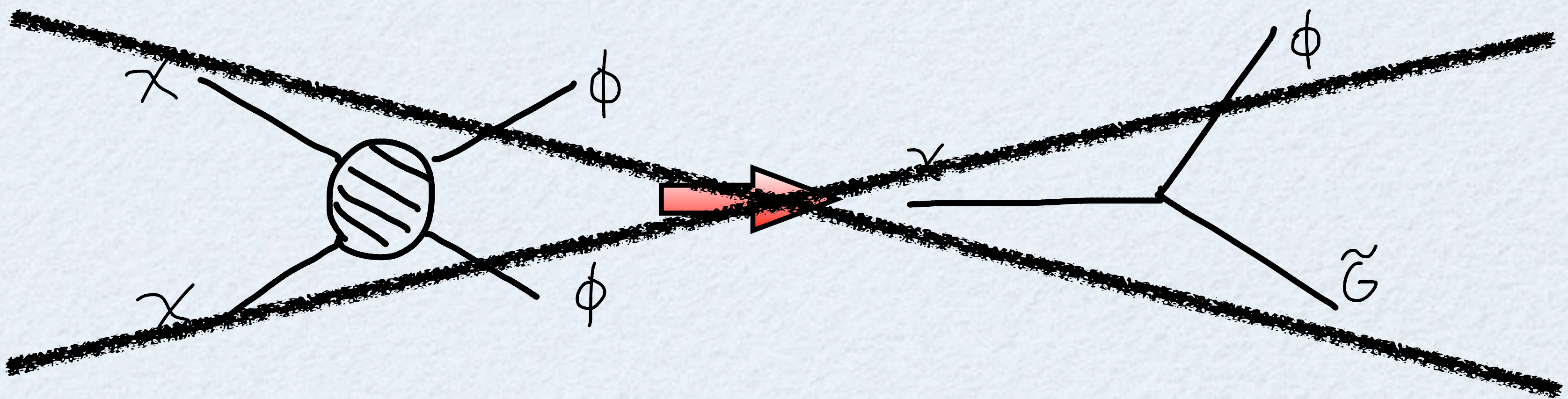


no freeze-out and decay



- RPV
- light hidden sector
- colored LOSP

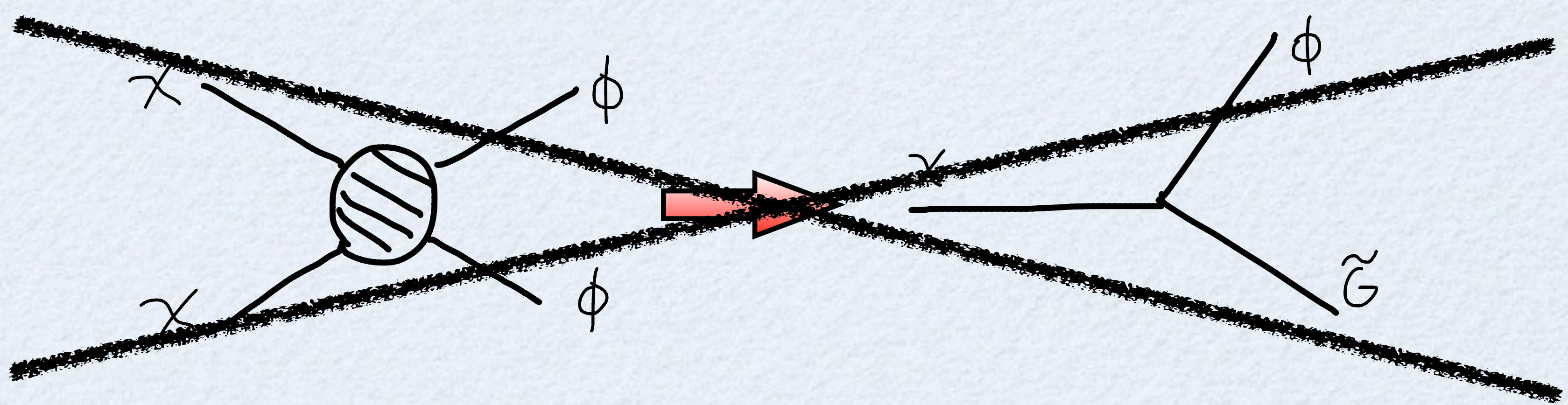
no freeze-out and decay



- RPV
- light hidden sector
- colored LOSP

$$\frac{1}{m_{3/2}} \frac{T_R\,\tilde{m}^2}{M_p} \leq T_{eq}$$

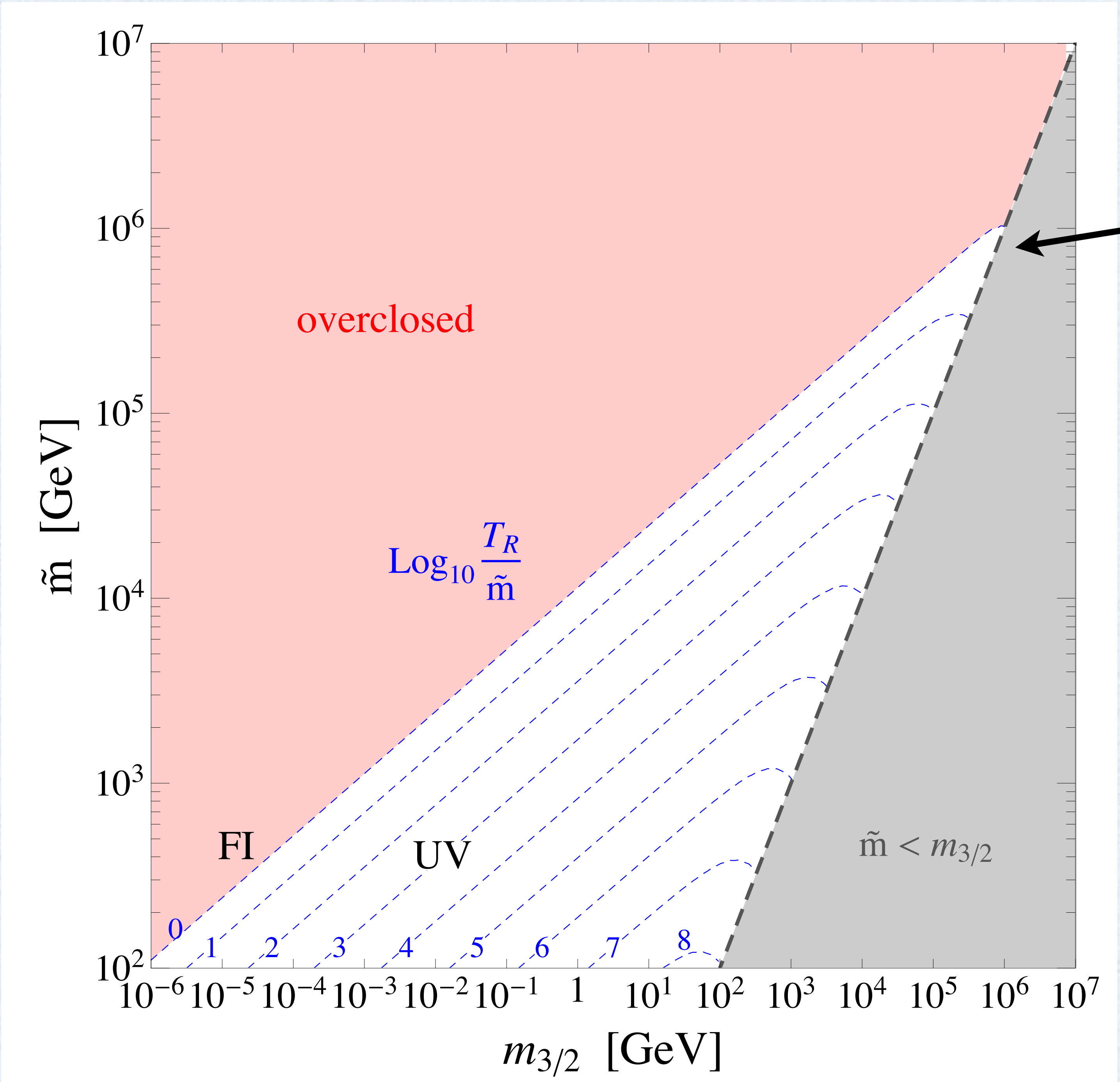
no freeze-out and decay



- RPV
- light hidden sector
- colored LOSP

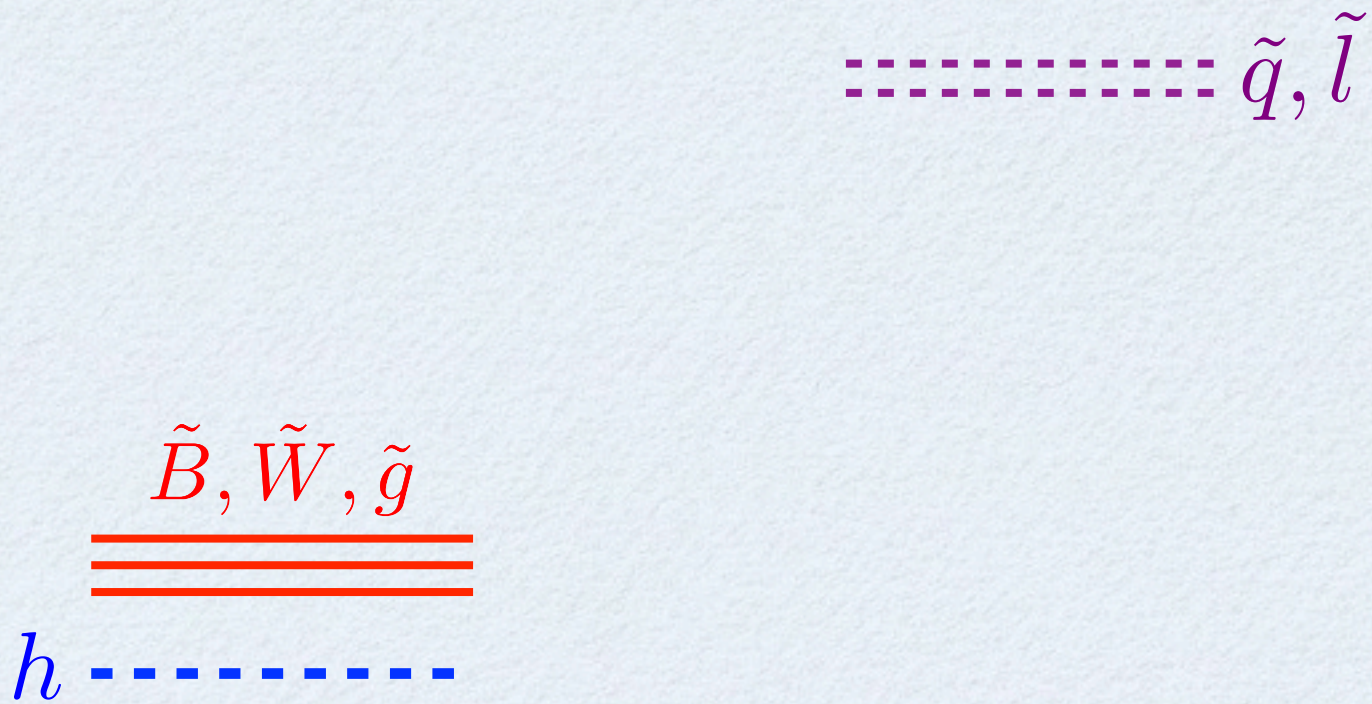
$$\frac{1}{m_{3/2}} \frac{T_R\,\tilde{m}^2}{M_p} \leq T_{eq} \quad \xrightarrow[m_{3/2} < \tilde{m}]{} \quad \boxed{\tilde{m} \leq \left(\frac{T_R}{\tilde{m}}\right)^{-1/2} \sqrt{T_{eq}\,M_p}}$$

no freeze-out and decay

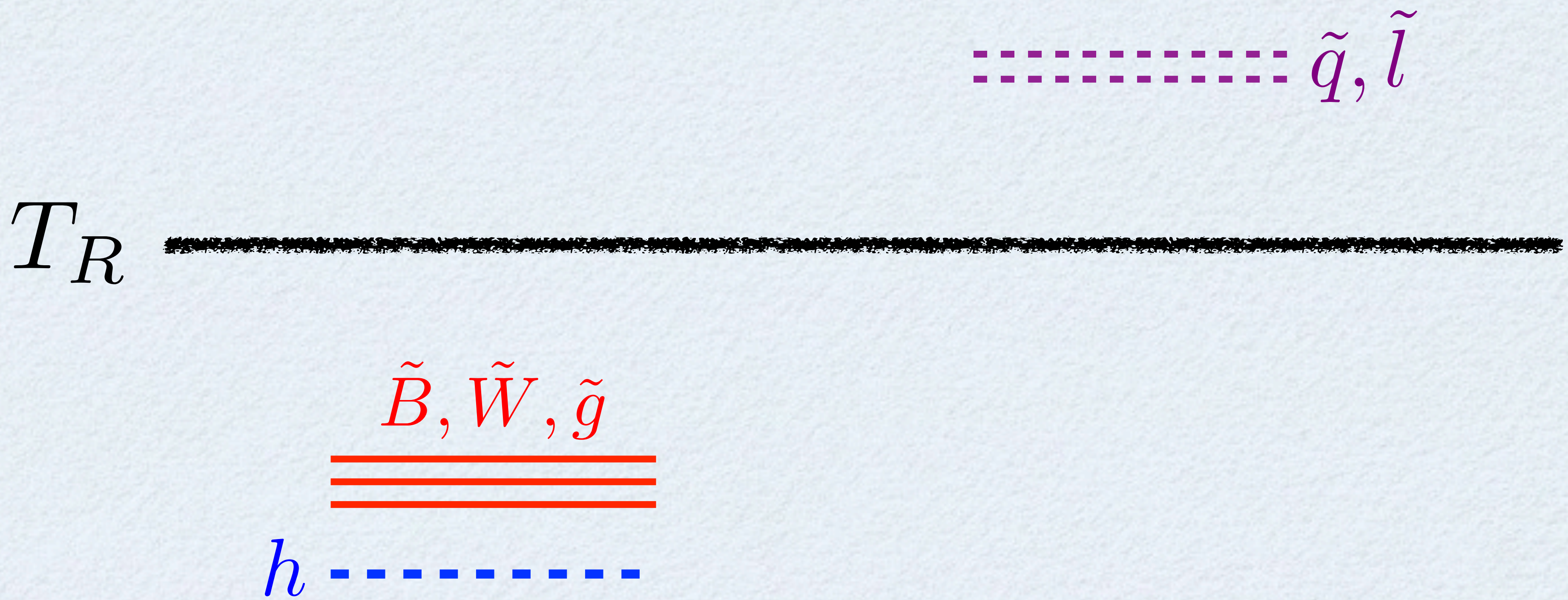


$\tilde{m} \lesssim 1000$ TeV

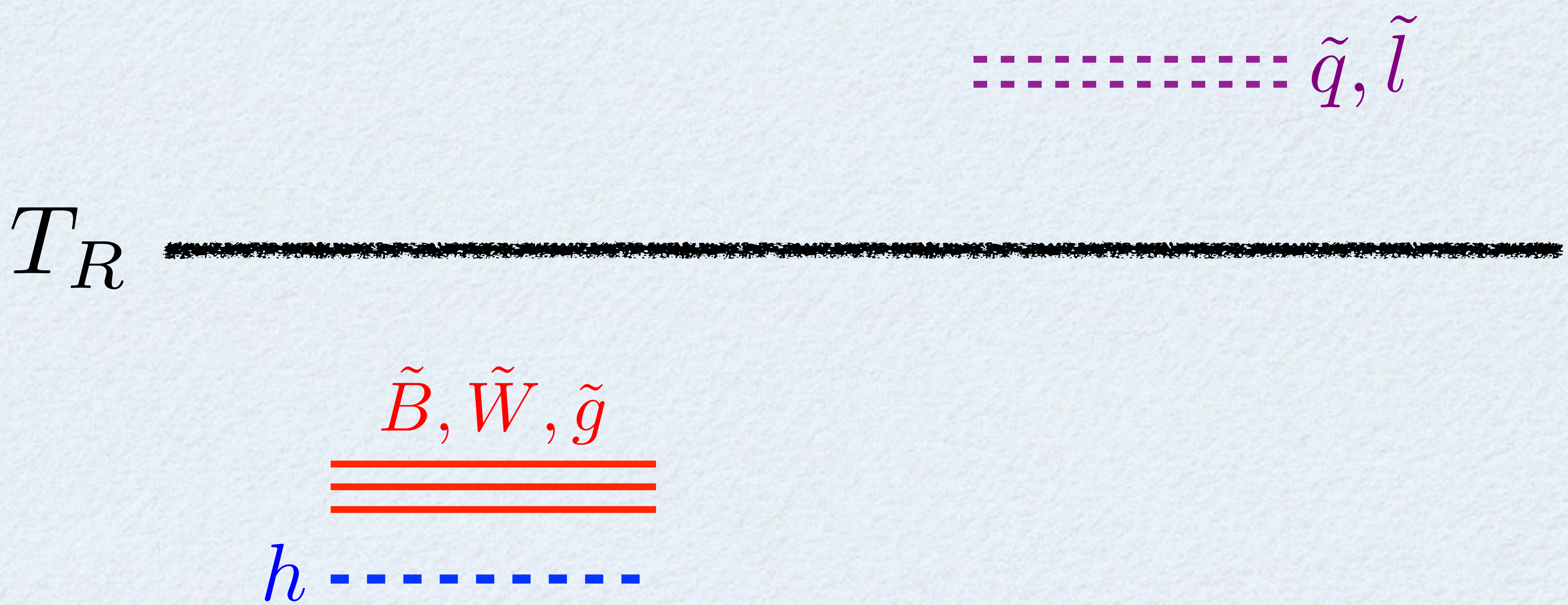
split



split

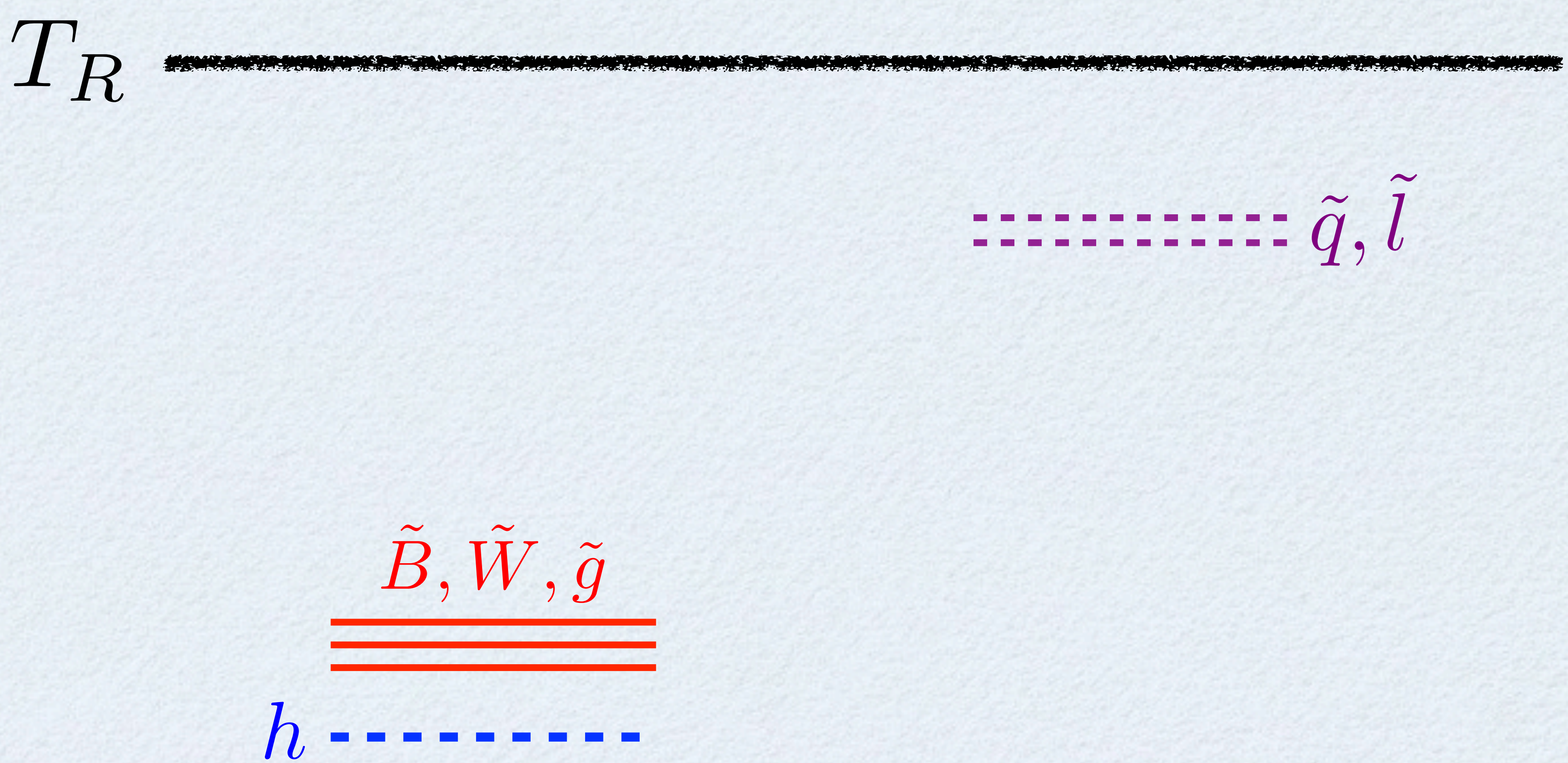


split



- same as above with $\tilde{m} \to m_f$

split



gravitino production in split

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}}\frac{T_R\,\tilde{m}_f^2}{M_p}$	$\frac{1}{m_{3/2}}\frac{\tilde{m}_s^3}{M_p}$	$m_{3/2}\frac{\tilde{m}_f}{\alpha^2 M_p}$

gravitino production in split

$$\color{red}{m_{3/2}Y_{UV}} + \color{purple}{m_{3/2}Y_{FI}} + \color{blue}{m_{3/2}Y_{FO}} \leq T_{eq}$$

	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}}\frac{T_R\,\tilde{m}_f^2}{M_p}$	$\frac{1}{m_{3/2}}\frac{\tilde{m}_s^3}{M_p}$	$m_{3/2}\frac{\tilde{m}_f}{\alpha^2 M_p}$

depends on fermion mass

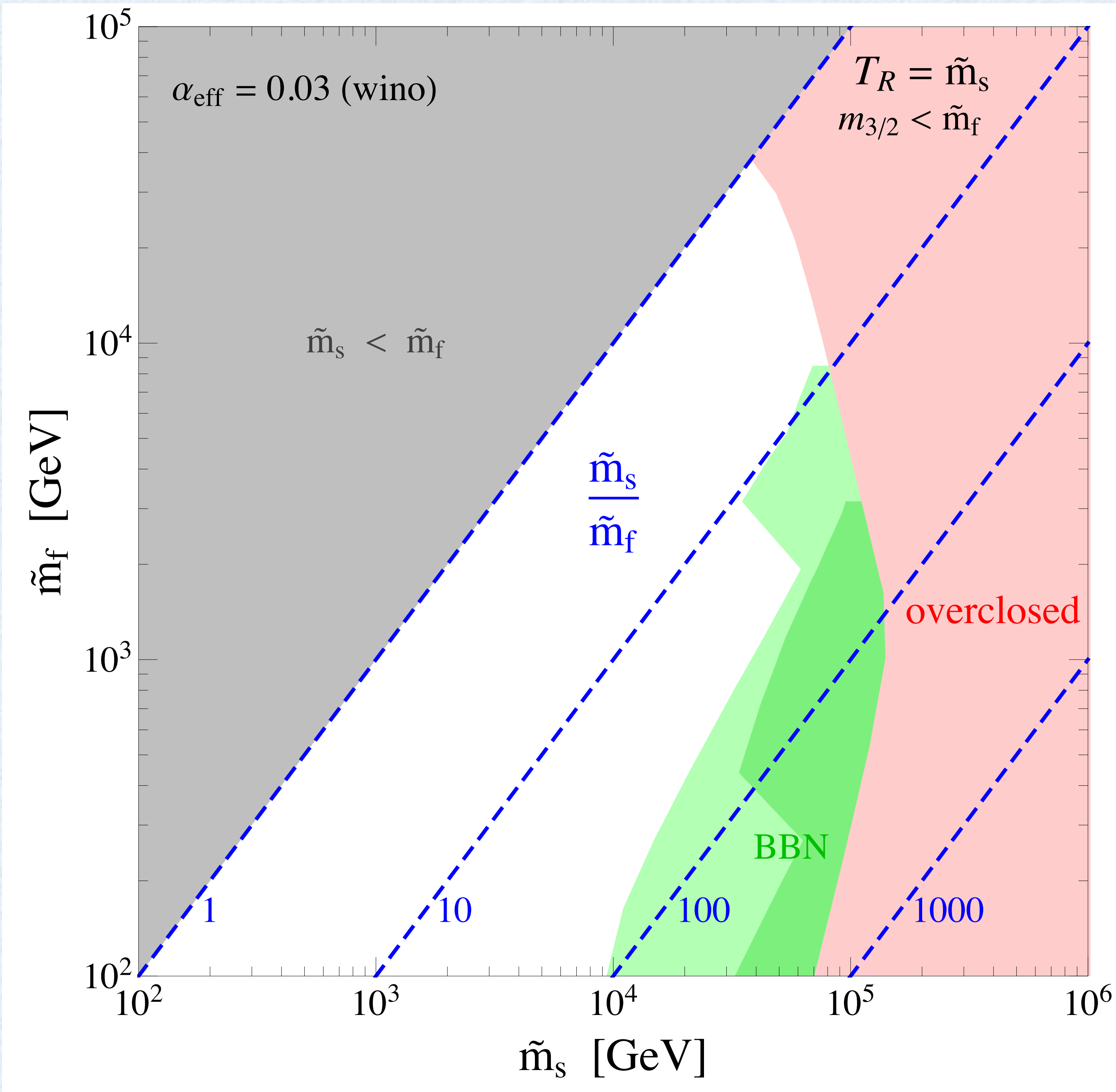
gravitino production in split

$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

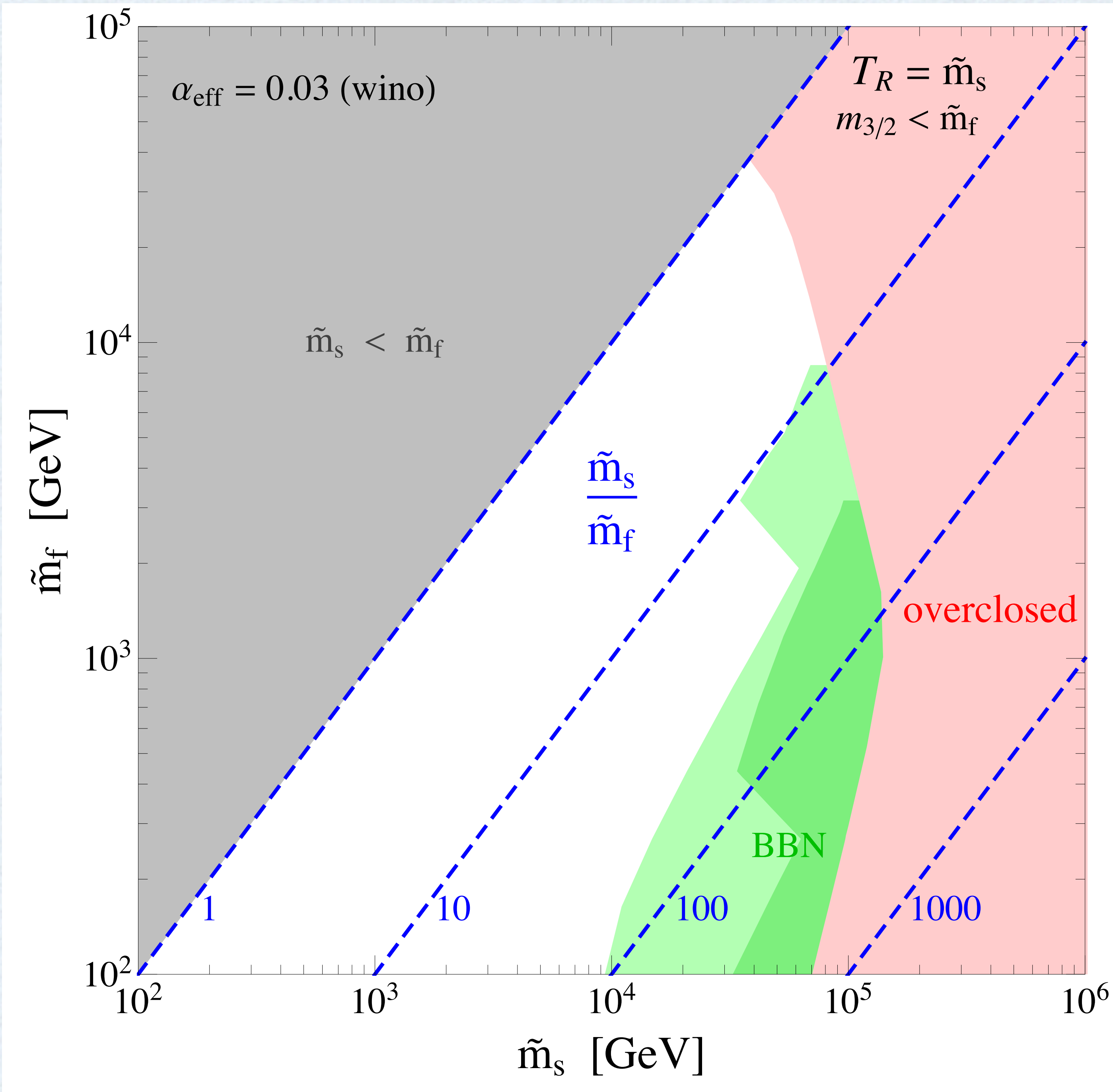
	scattering	freeze-in	freeze-out
$m_{3/2}Y_{3/2}$	$\frac{1}{m_{3/2}} \frac{T_R \tilde{m}_f^2}{M_p}$	$\frac{1}{m_{3/2}} \frac{\tilde{m}_s^3}{M_p}$	$m_{3/2} \frac{\tilde{m}_f}{\alpha^2 M_p}$

enhanced by large scalar mass

constraint on splitting



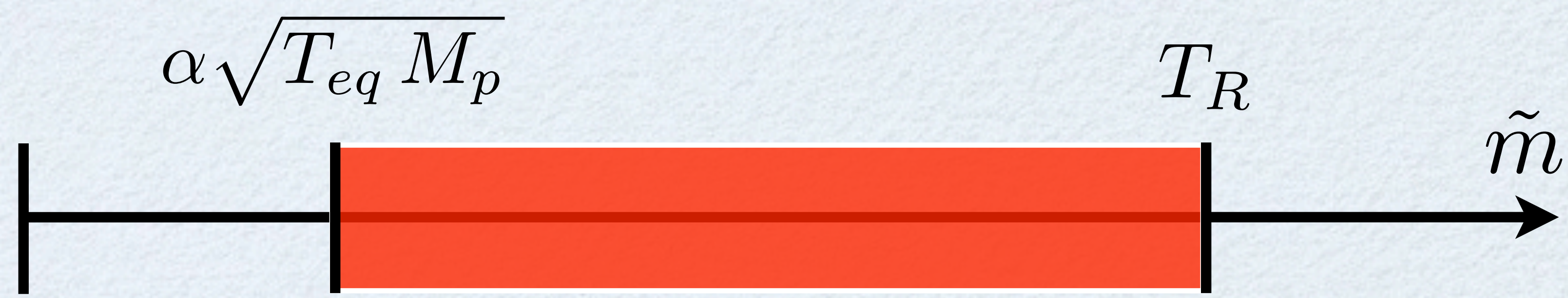
constraint on splitting



$$\frac{\tilde{m}_s}{\tilde{m}_f} \lesssim 100$$

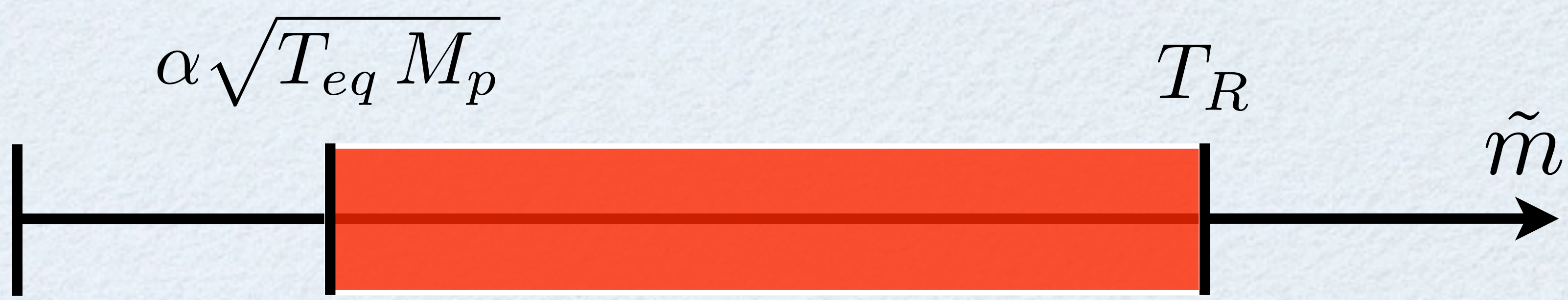
DM and the Weak Scale

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

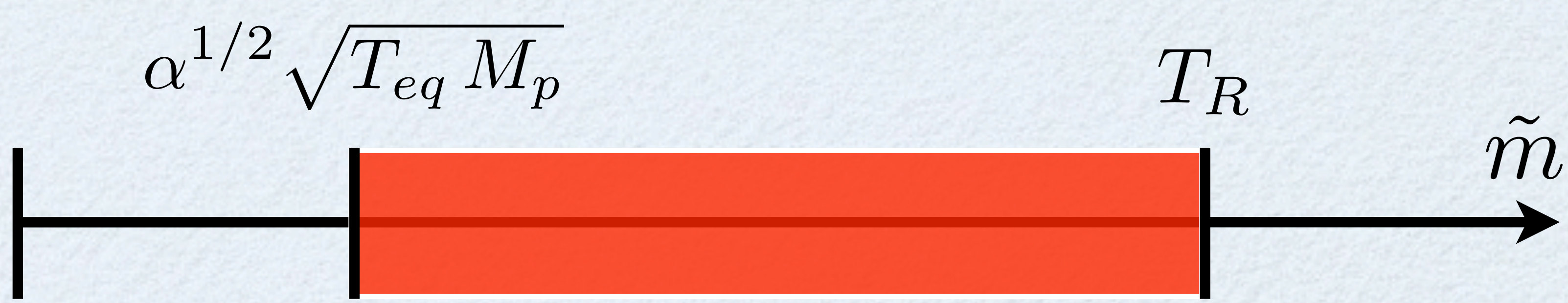


DM and the Weak Scale

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



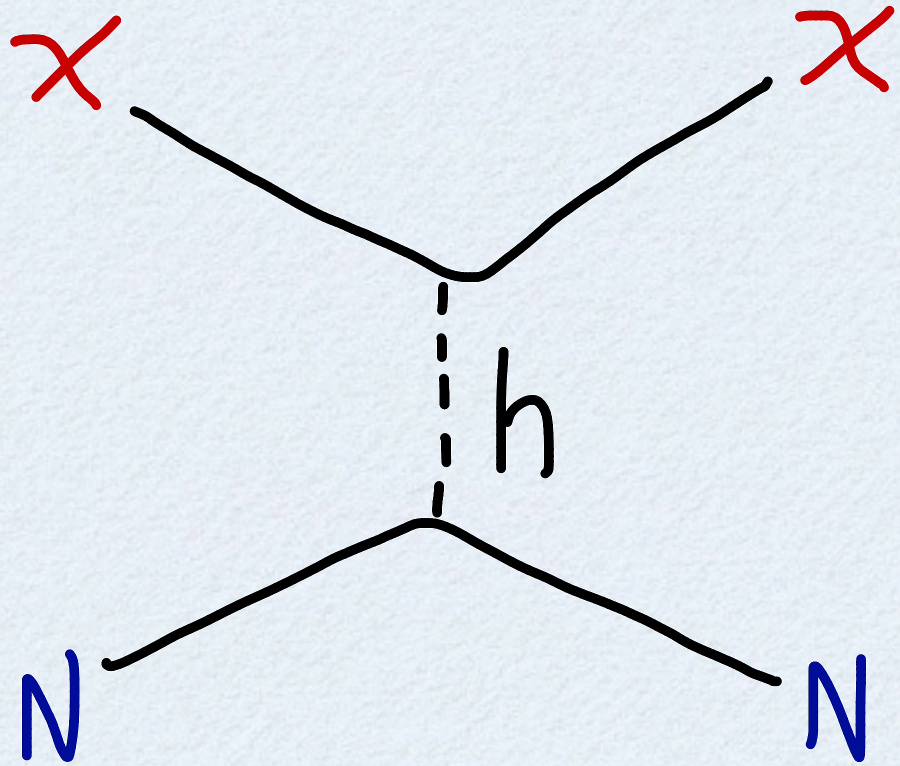
$m_{3/2} < \tilde{m}$

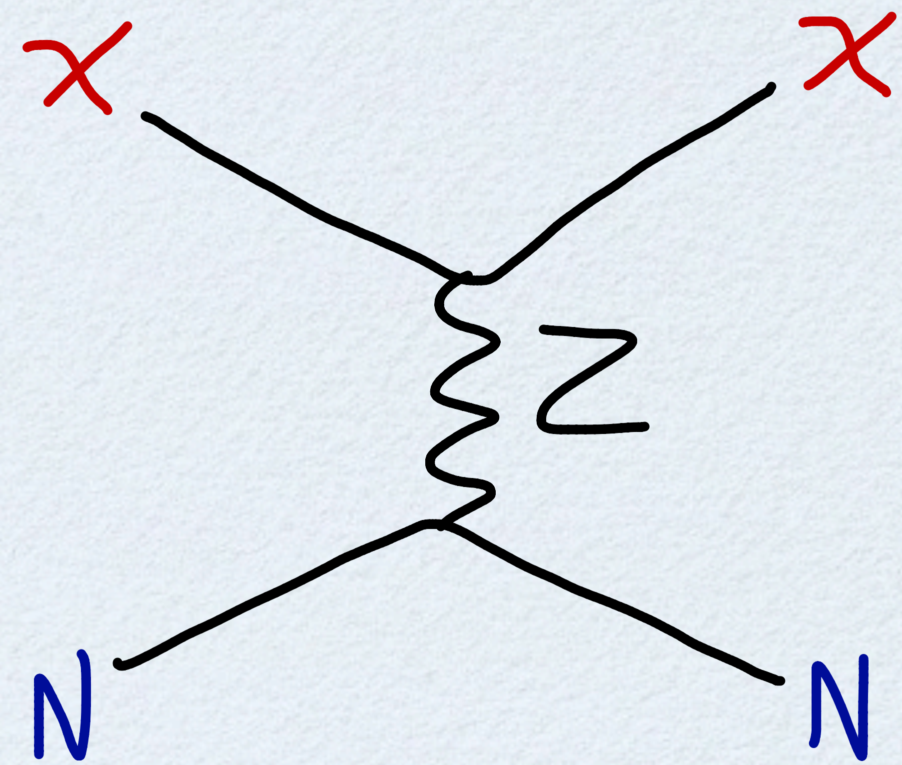


neutralino DM
-v-
experiment

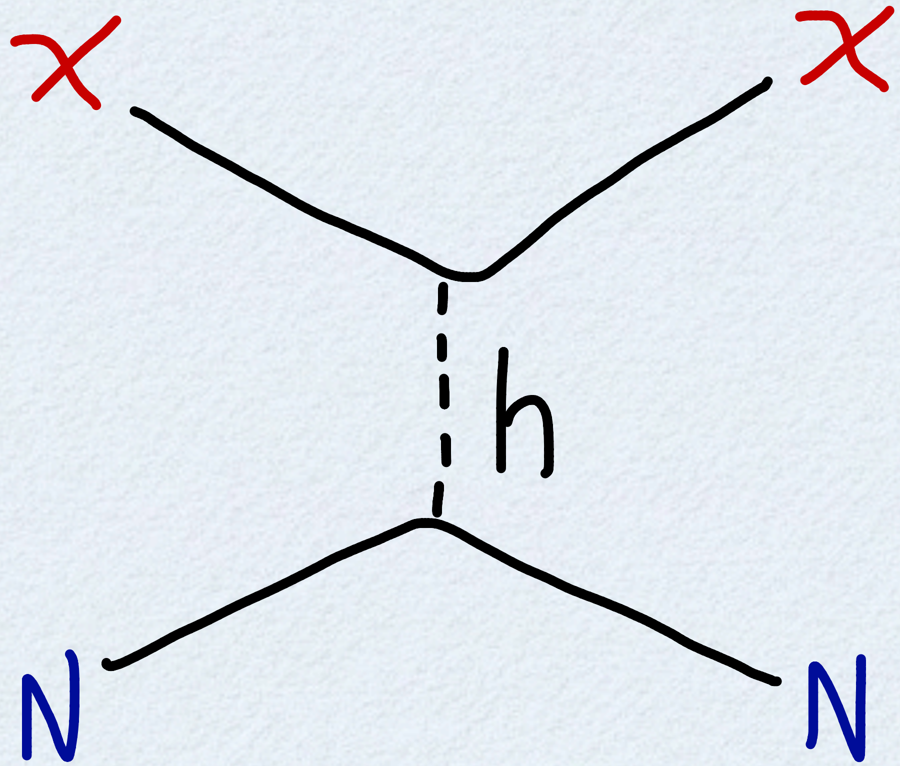
Cliff Cheung, Lawrence Hall, David Pinner, JTR 1211.4873

direct detection



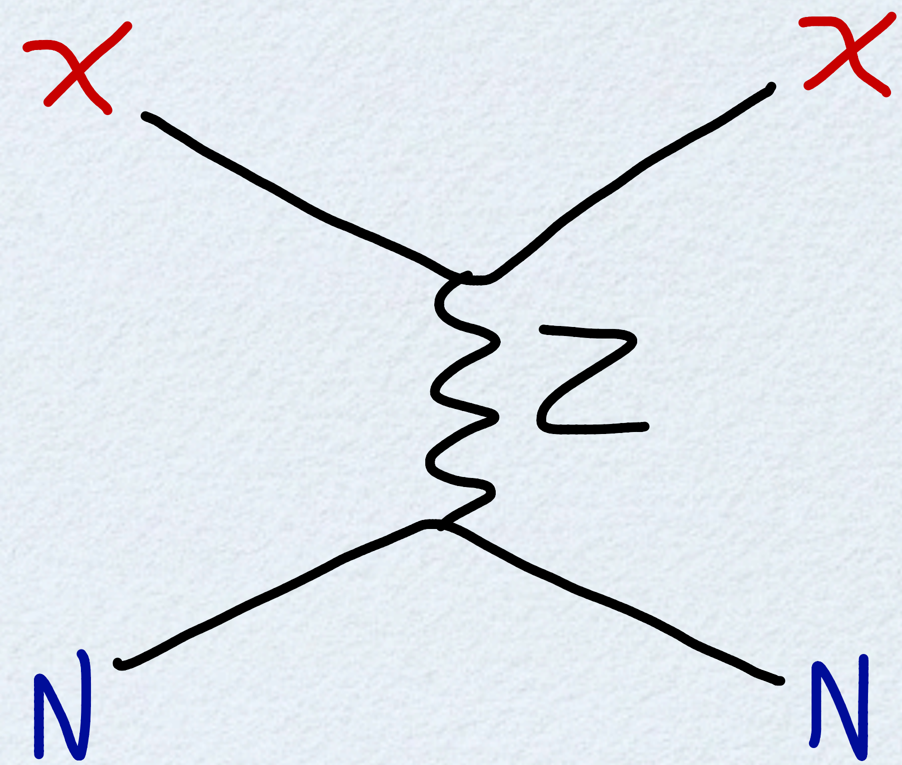


direct detection



spin-independent

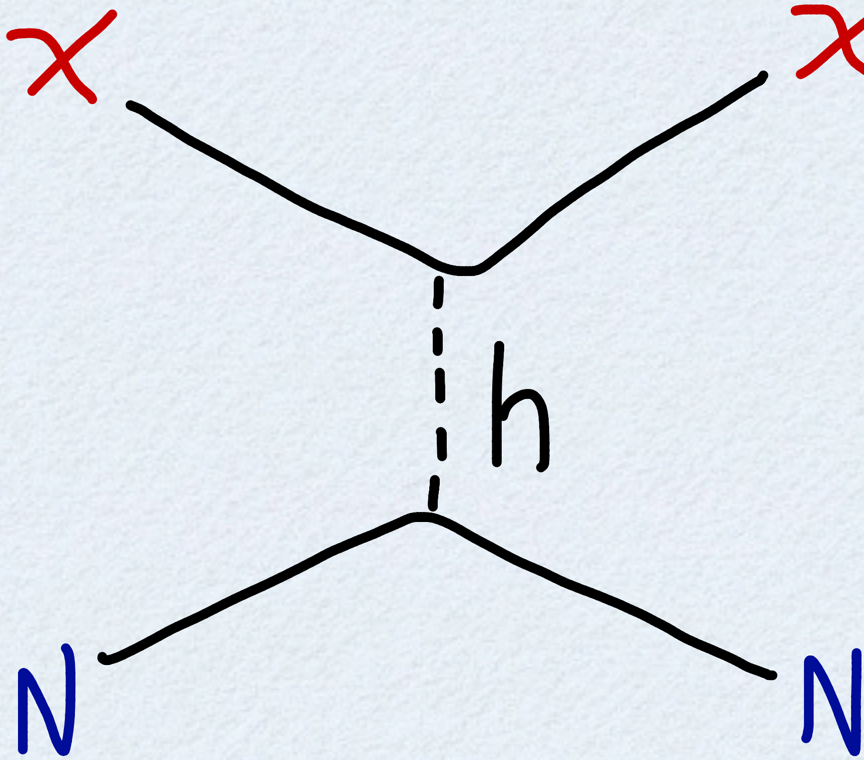
$\bar{\chi}\chi\bar{N}N$



spin-dependent

$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\ \bar{N}\gamma_{\mu}\gamma^{5}N$

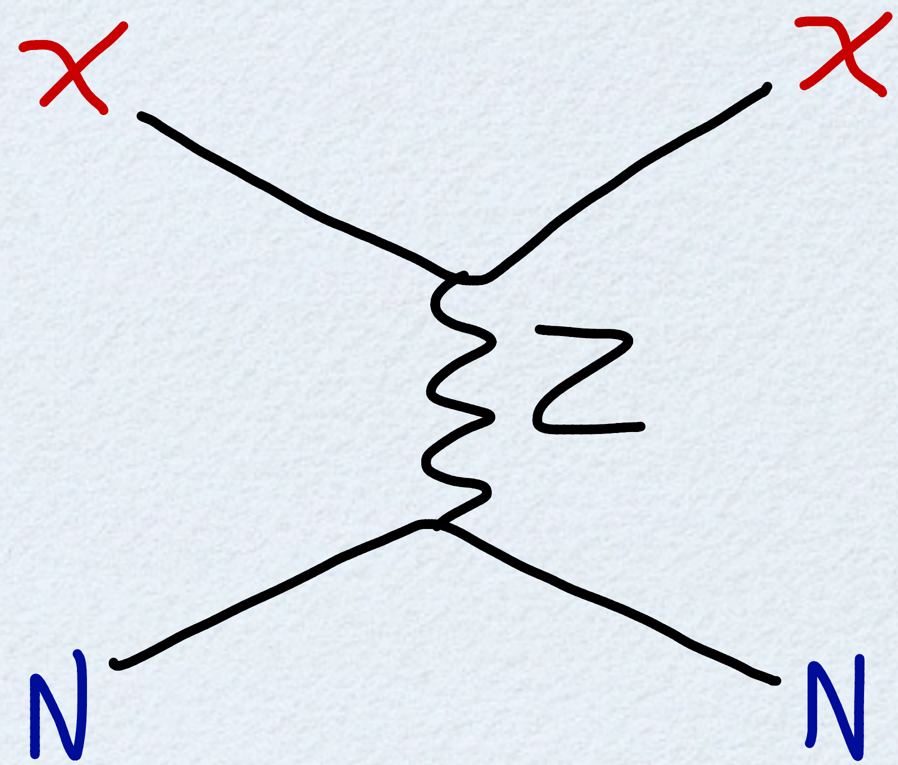
direct detection



spin-independent

$$\bar{\chi}\chi\bar{N}N$$

$$\sigma_{SI} \approx 6 \times 10^{-45}\,\mathrm{cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

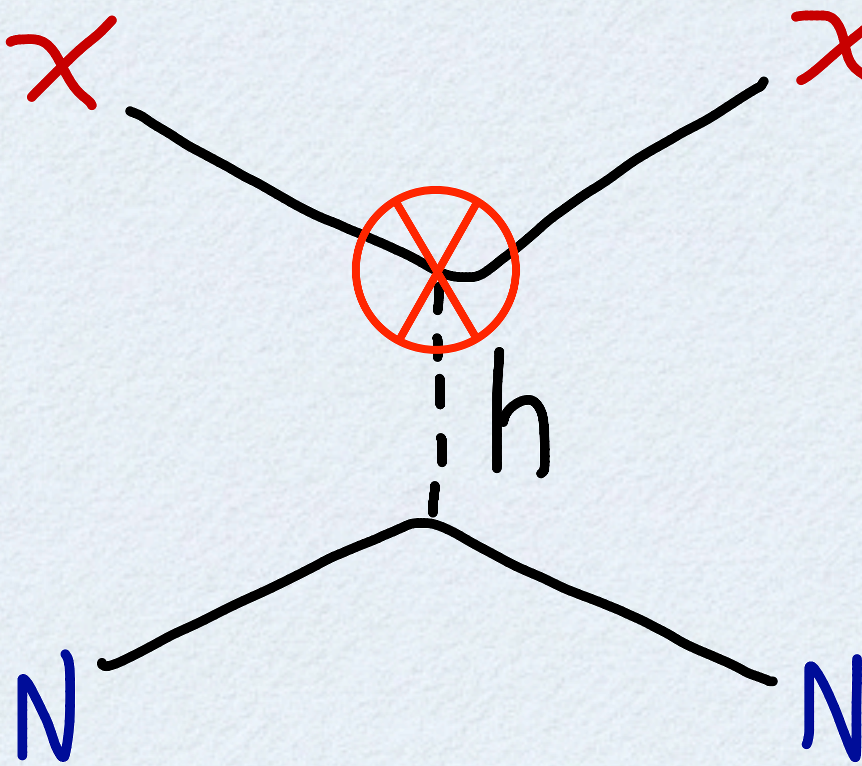


spin-dependent

$$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\ \bar{N}\gamma_{\mu}\gamma^{5}N$$

$$\sigma_{SD} \approx 3 \times 10^{-39}\,\mathrm{cm}^2 \left(\frac{c_{Z\chi\chi}}{0.1}\right)^2$$

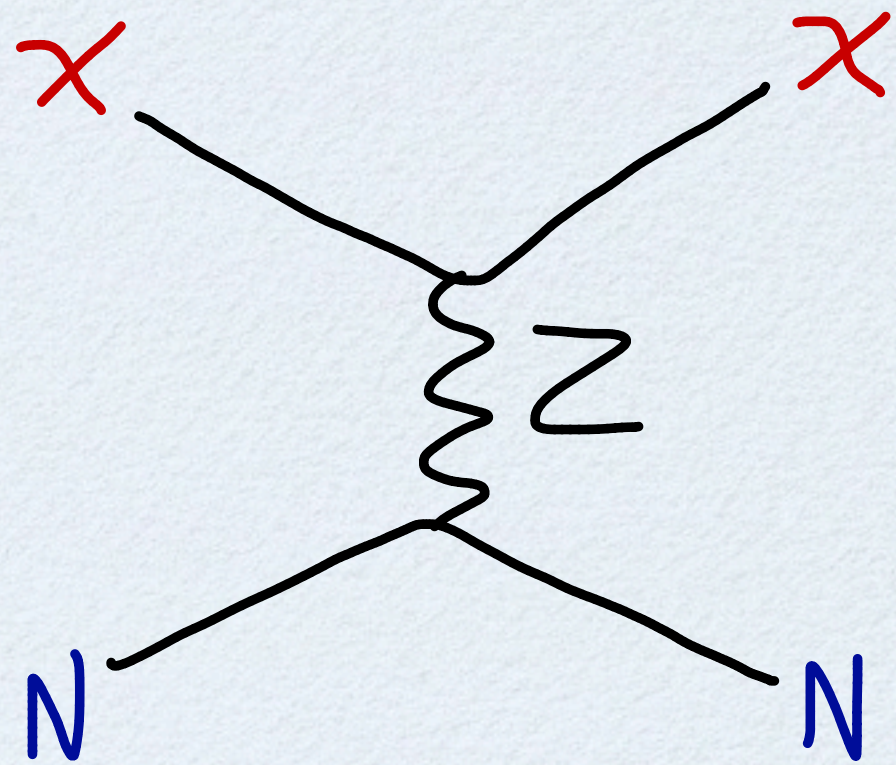
direct detection



spin-independent

$$\bar{\chi}\chi\bar{N}N$$

$$\sigma_{SI} \approx 6 \times 10^{-45}\,\mathrm{cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

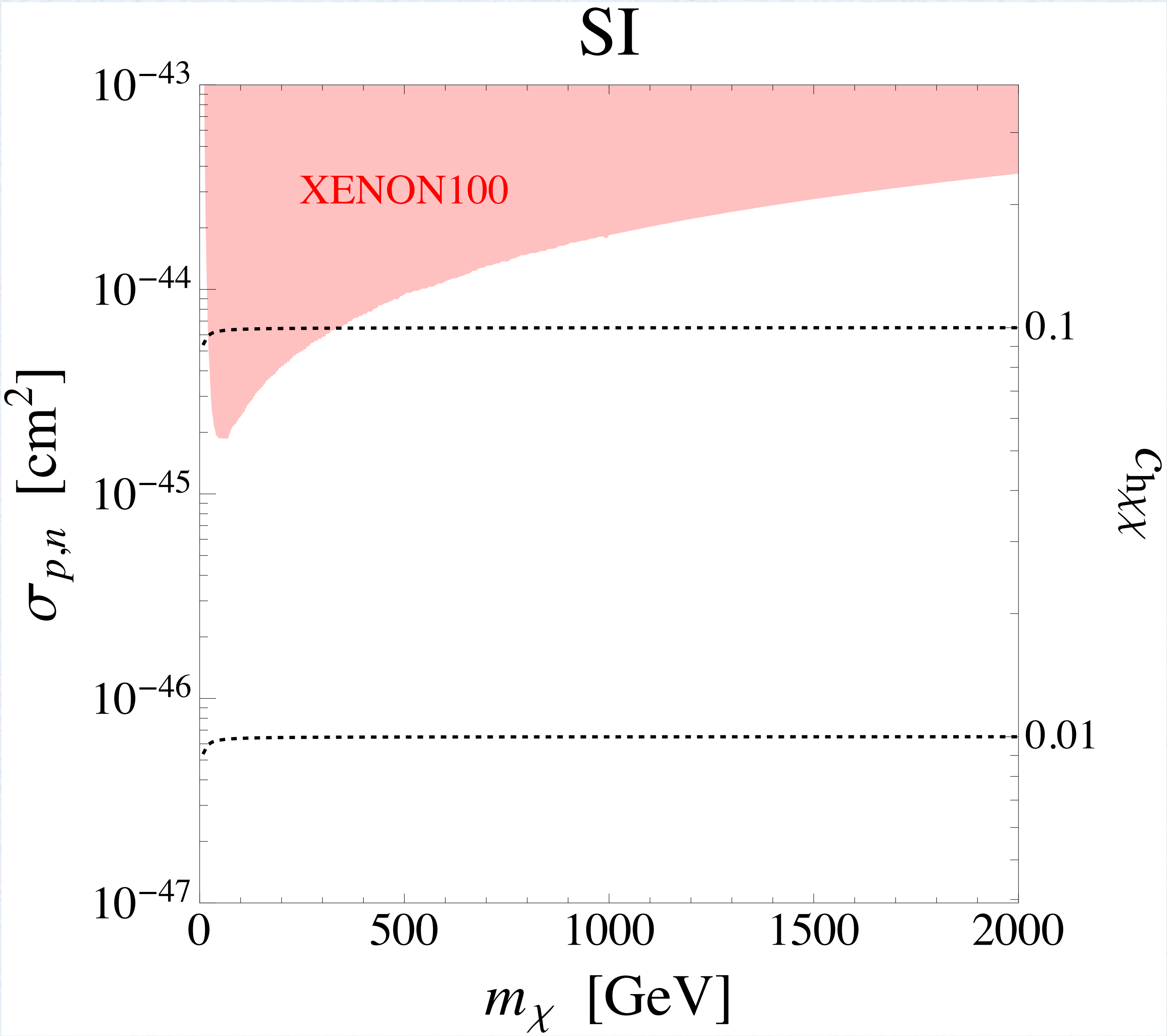


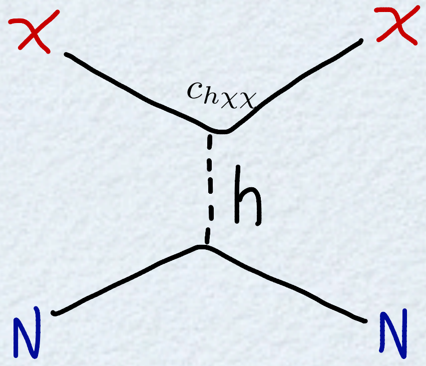
spin-dependent

$$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\ \bar{N}\gamma_{\mu}\gamma^{5}N$$

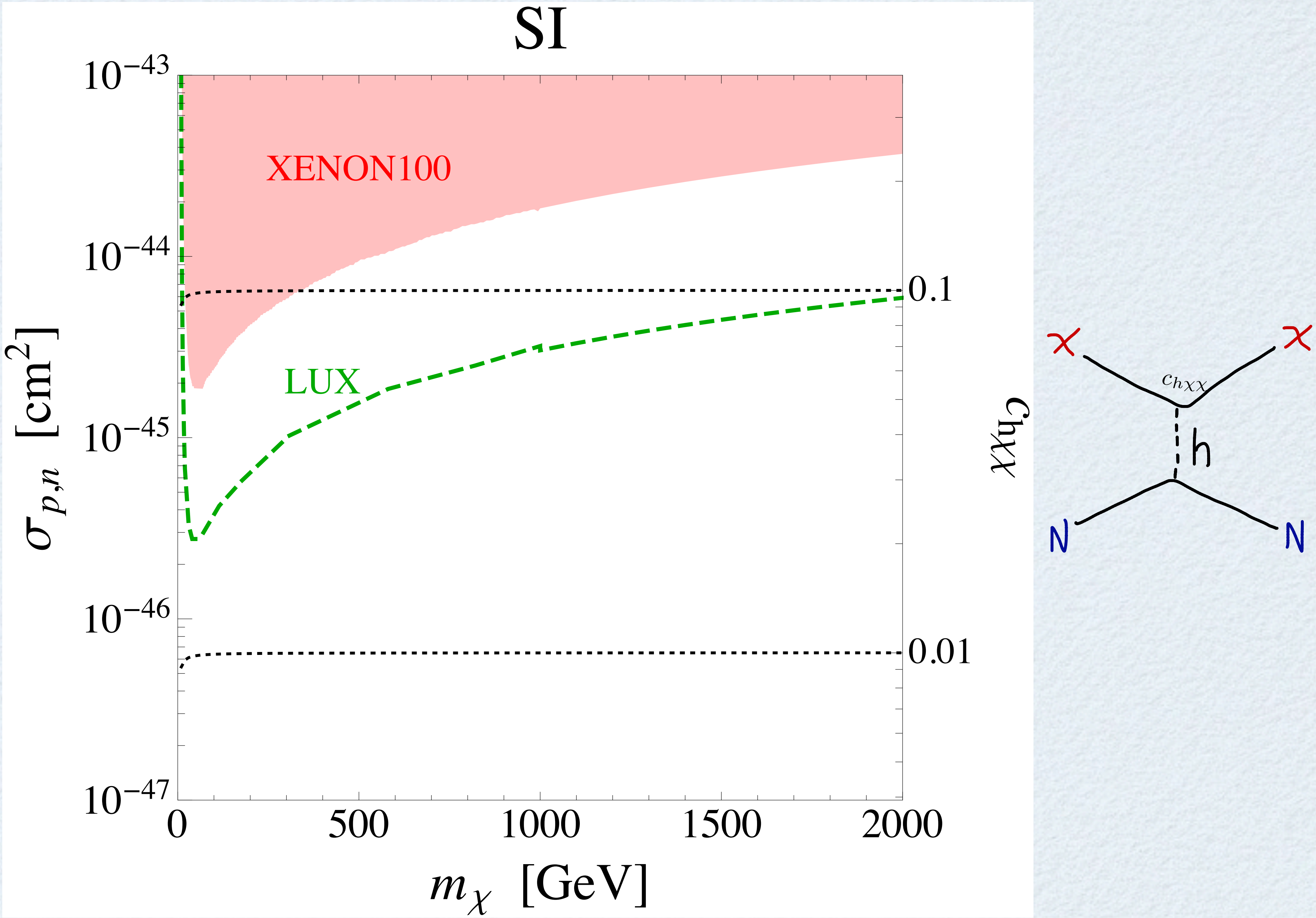
$$\sigma_{SD} \approx 3 \times 10^{-39}\,\mathrm{cm}^2 \left(\frac{c_{Z\chi\chi}}{0.1}\right)^2$$

spin-independent

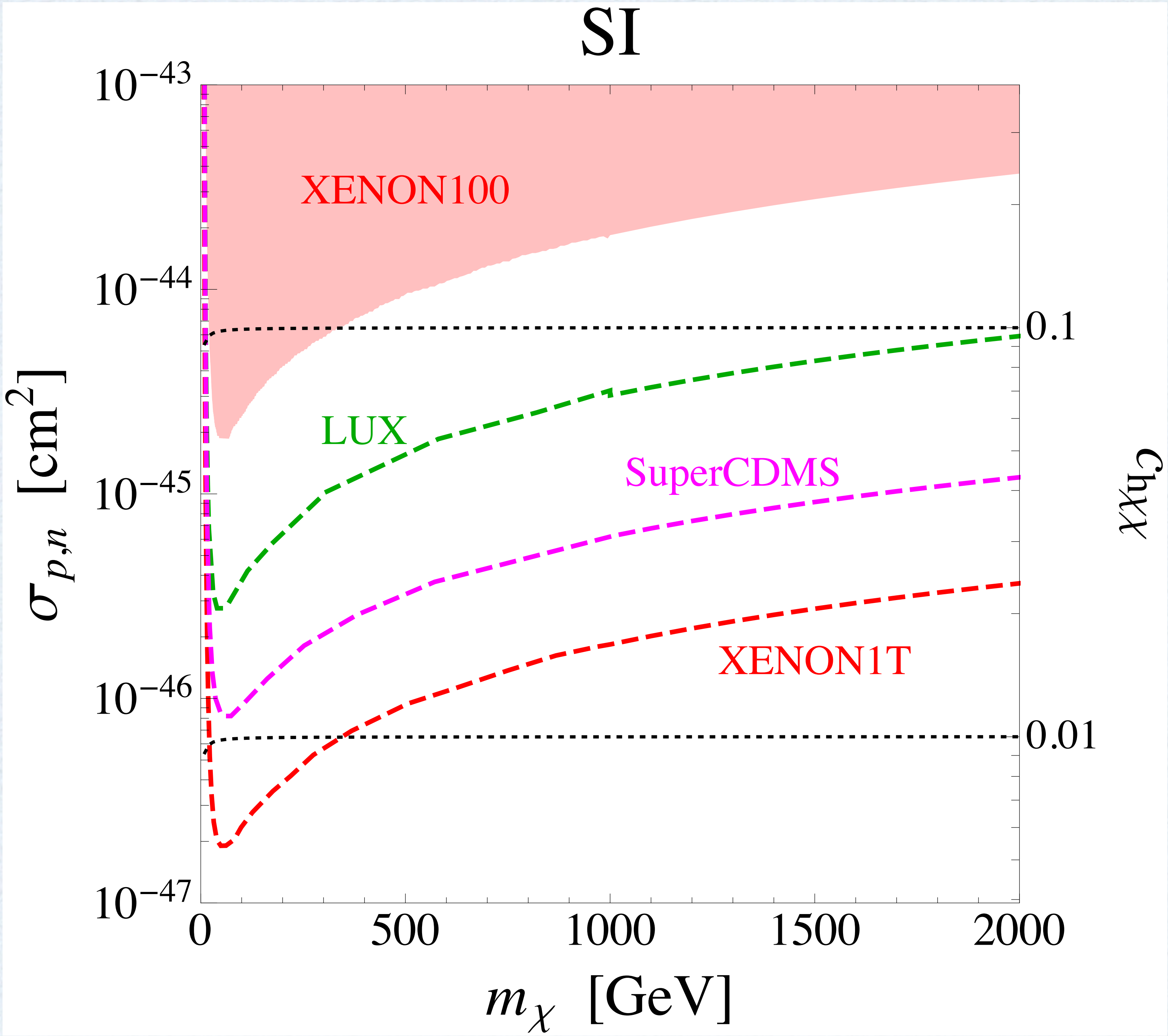


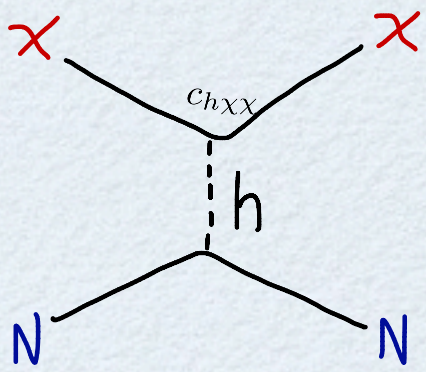


spin-independent

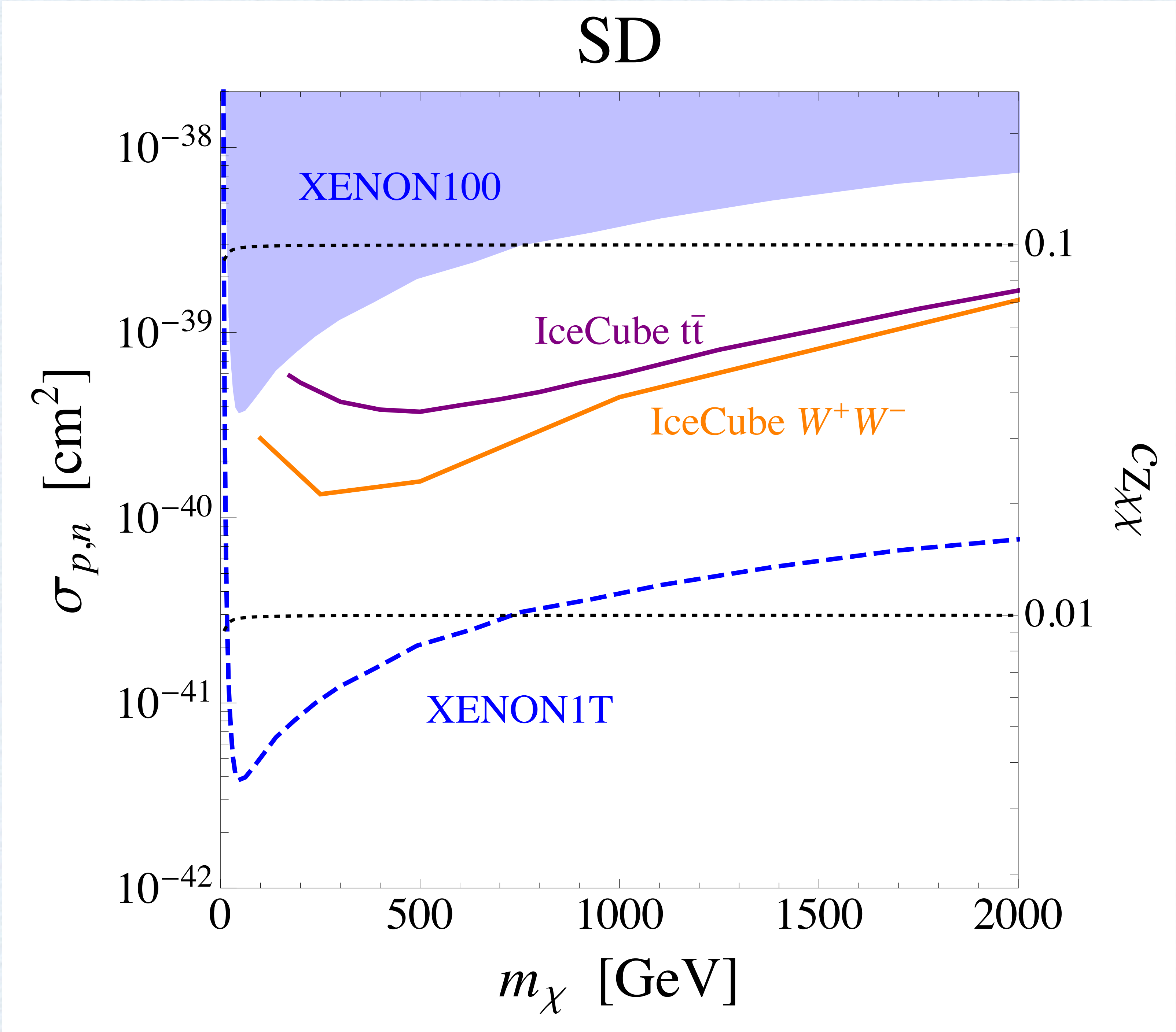


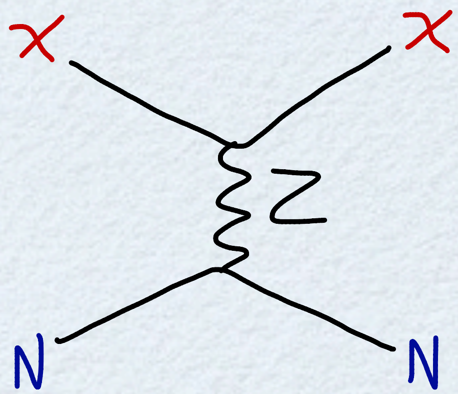
spin-independent



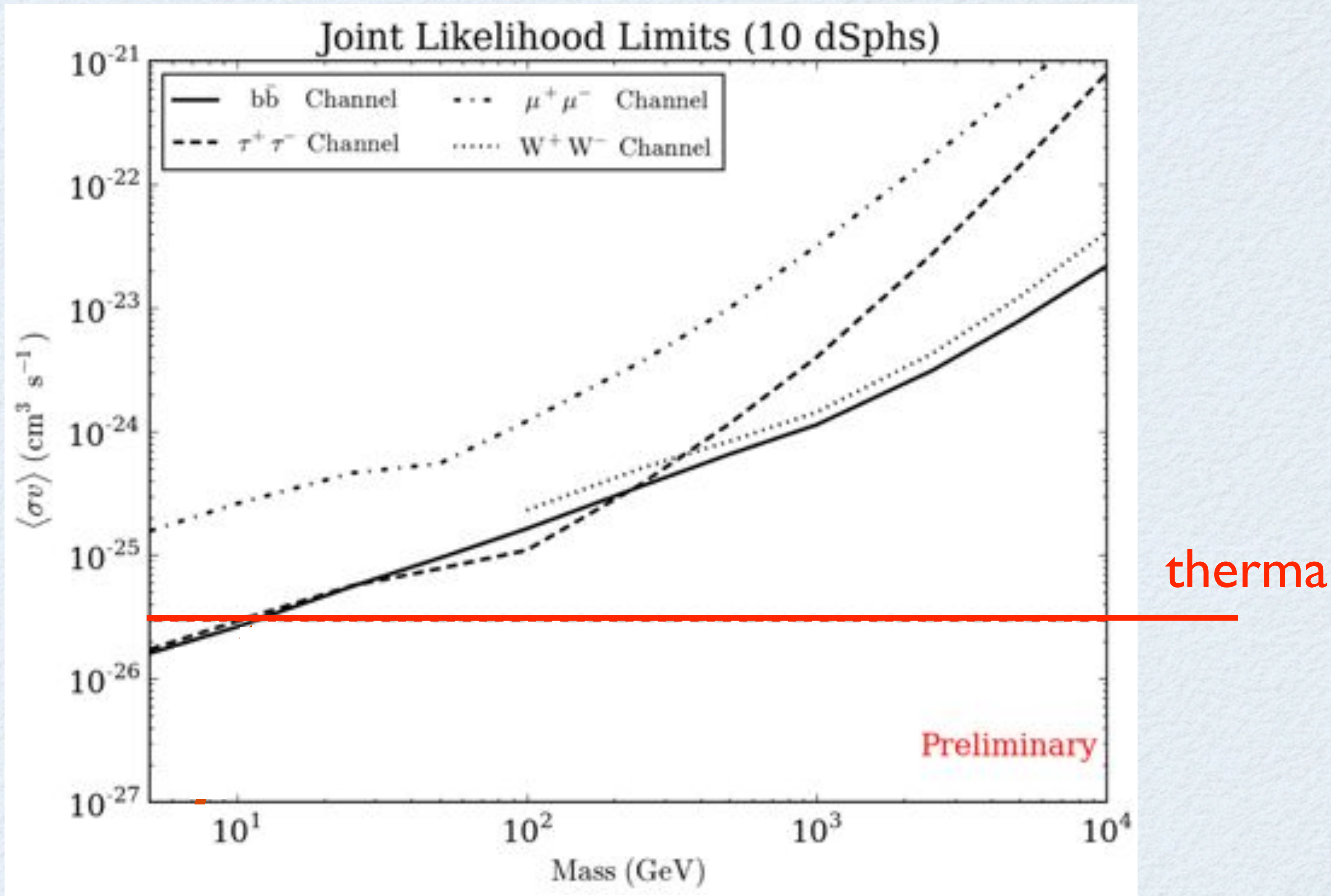


spin-dependent





indirect



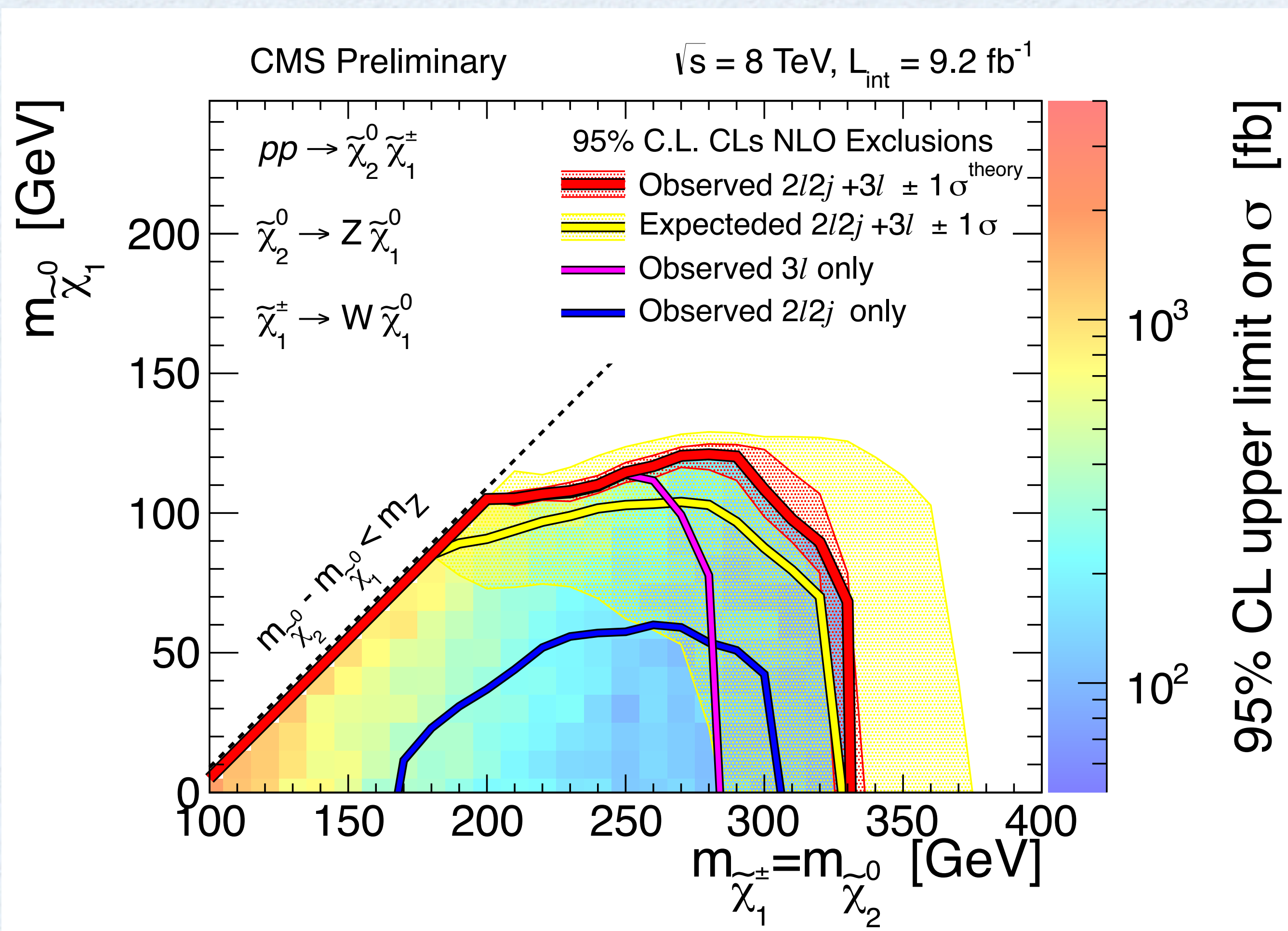
FERMI-LAT 1108.3546

updated in Alex Drlica-Wagner's talk, Fermi Symposium, 11/2012

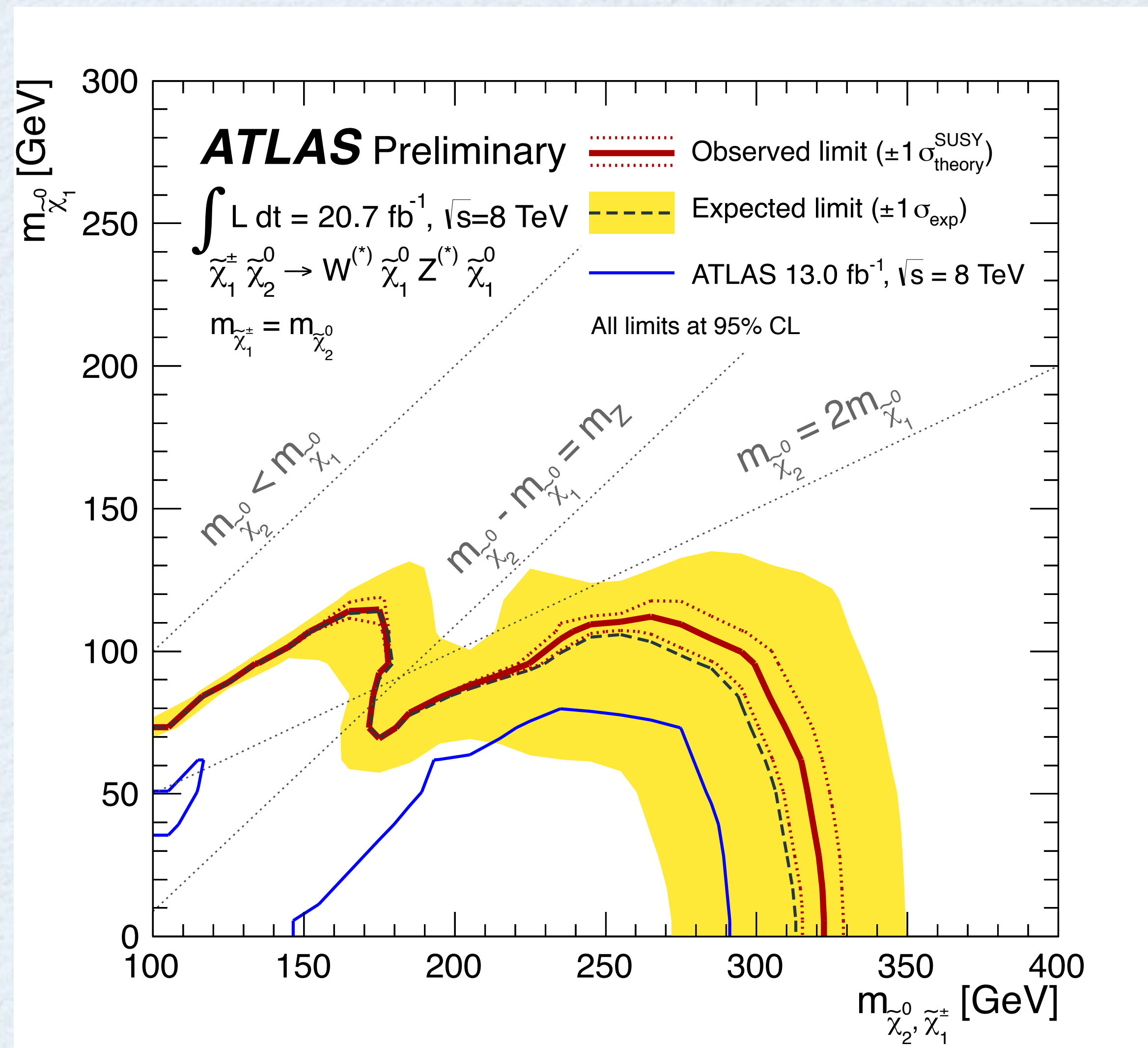
collider

LEP: $\mu, M_2 \gtrsim 100\ \mathrm{GeV}$

CMS



ATLAS



simplified model of neutralino DM

$$SM + \tilde{B}, \tilde{W}, \tilde{H}$$

simplified model of neutralino DM

$$SM + \tilde{B}, \tilde{W}, \tilde{H}$$

- assume scalar superpartners can be decoupled when computing: $\sigma_{\chi N}, \; \Omega$

simplified model of neutralino DM

$$SM + \tilde{B}, \tilde{W}, \tilde{H}$$

- assume scalar superpartners can be decoupled when computing: $\sigma_{\chi N}, \Omega$

- assume CP

simplified model of neutralino DM

$$SM + \tilde{B}, \tilde{W}, \tilde{H}$$

- assume scalar superpartners can be decoupled when computing: $\sigma_{\chi N},\ \Omega$

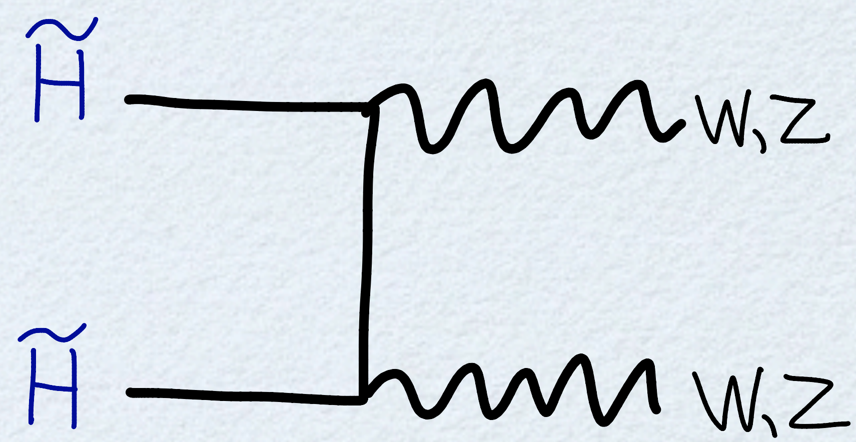
- assume CP

- parameters:

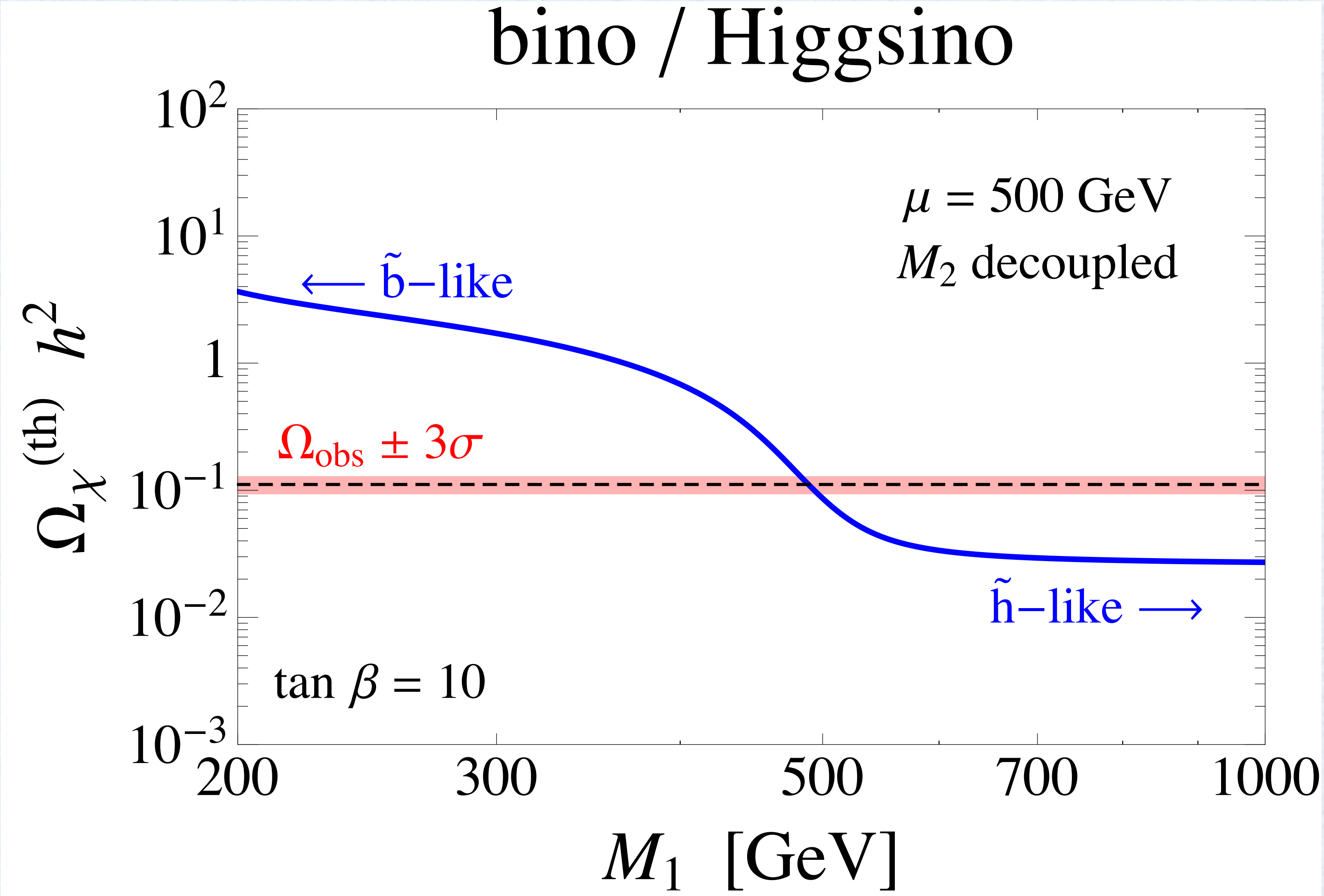
$$\boxed{M_1,\ M_2,\ \mu,\ \tan\beta}$$

thermal DM with pure eigenstates

- bino — overcloses
- higgsino — $m_{\tilde{H}} \approx 1 \text{ TeV}$
- wino — $m_{\tilde{W}} \approx 2.7 \text{ TeV}$

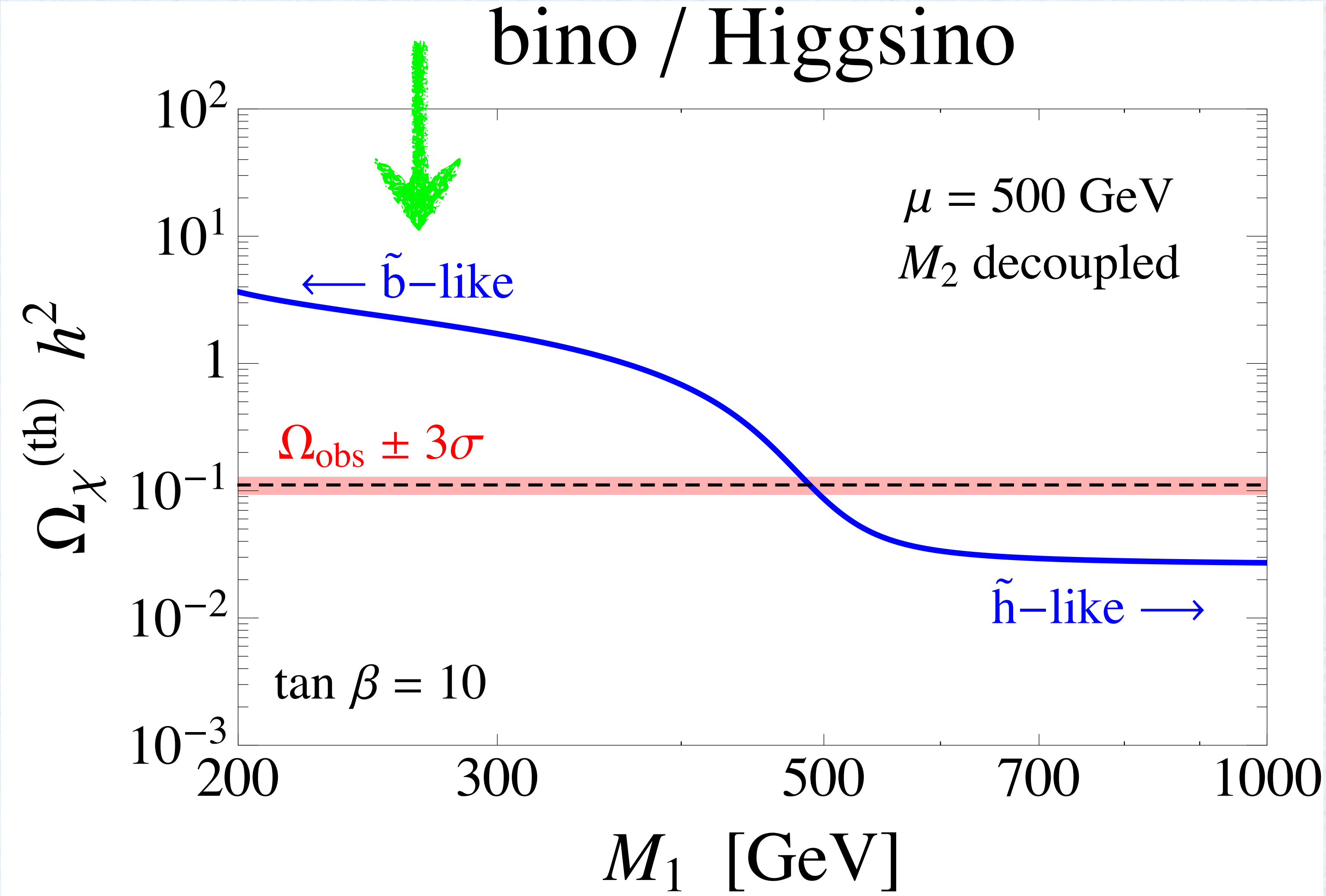


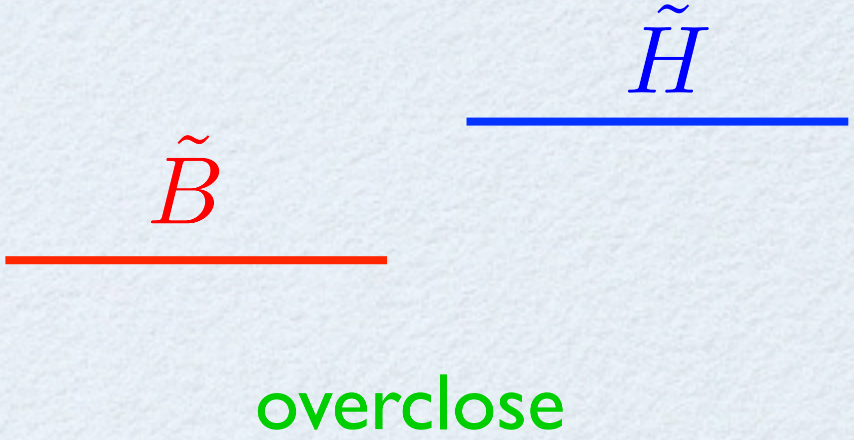
well-tempered neutralino



N. Arkani-Hamed, A. Delgado, G. Giudice 0601041.

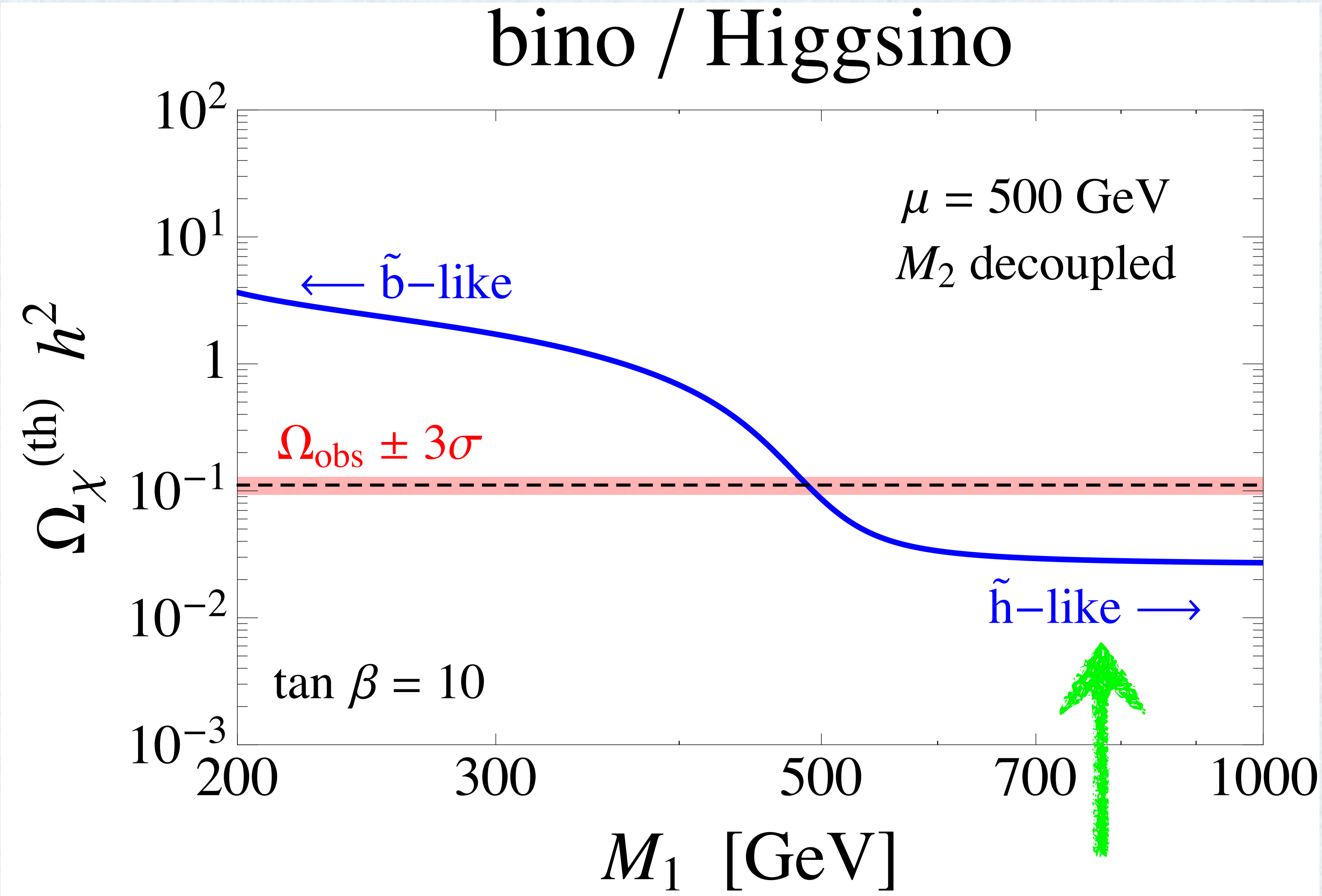
well-tempered neutralino





N. Arkani-Hamed, A. Delgado, G. Giudice 0601041.

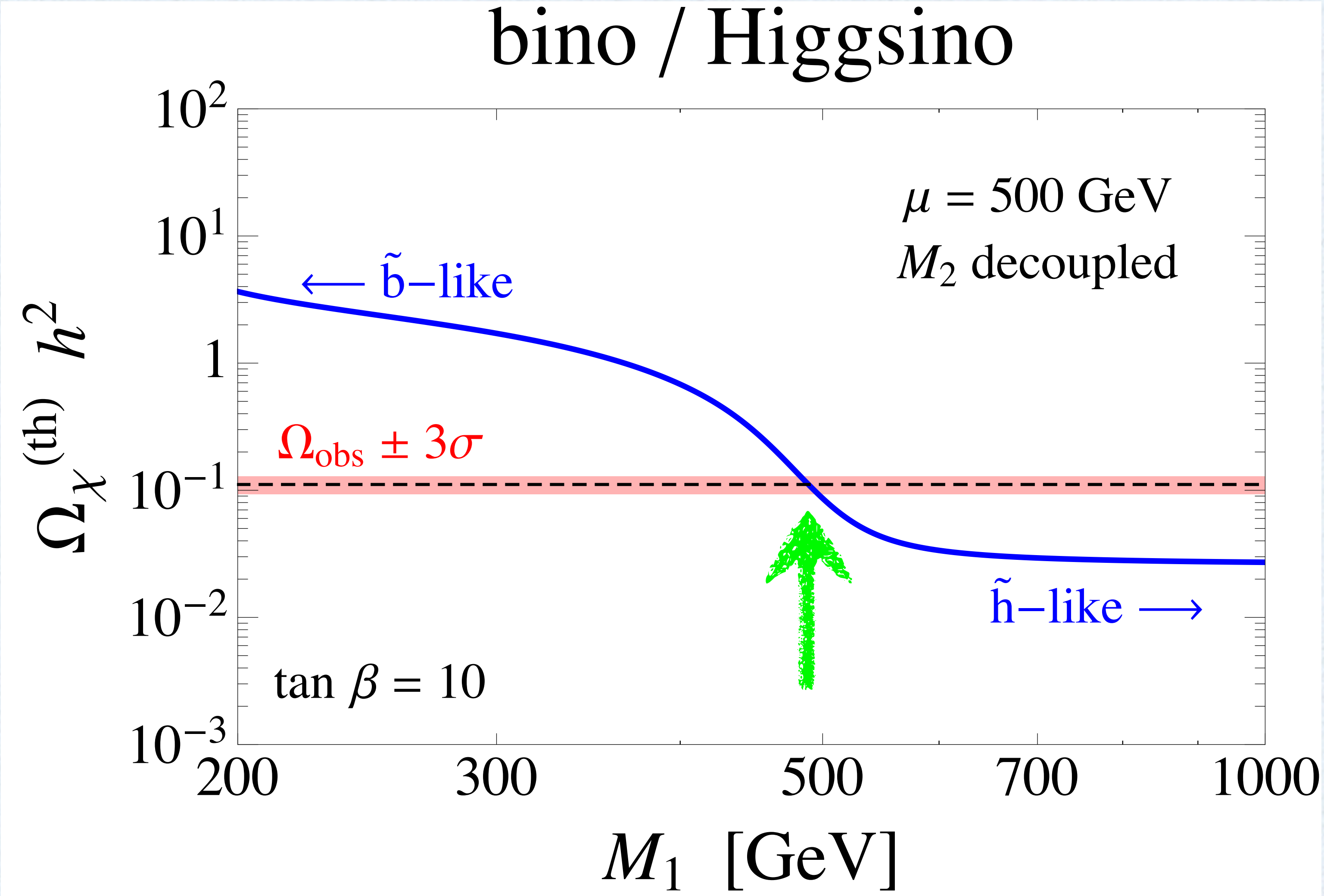
well-tempered neutralino



under-abundant

N. Arkani-Hamed, A. Delgado, G. Giudice 0601041.

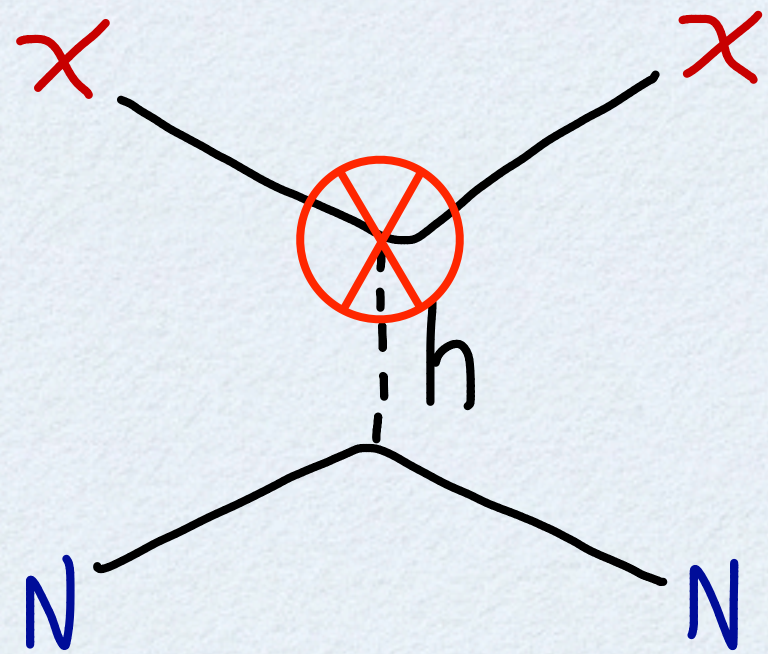
well-tempered neutralino



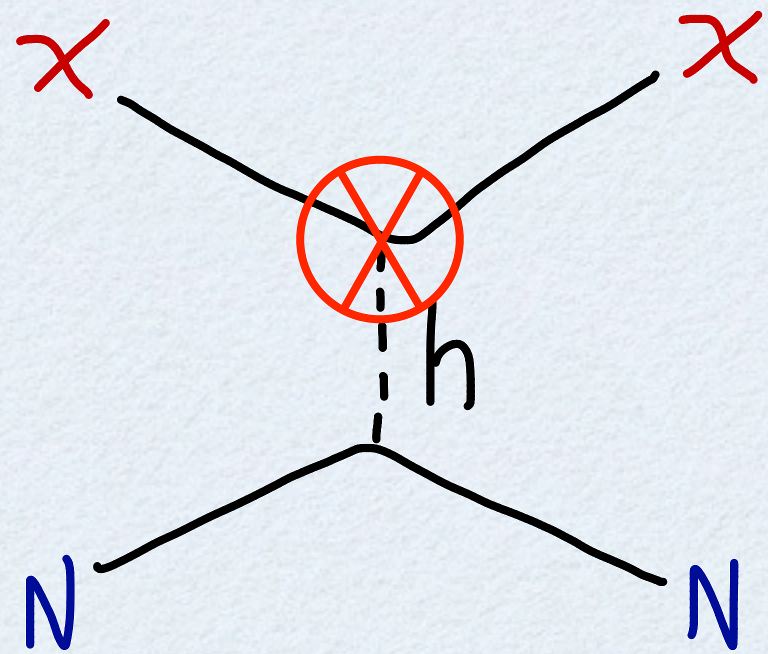
well-tempered

N. Arkani-Hamed, A. Delgado, G. Giudice 0601041.

hidden dark matter



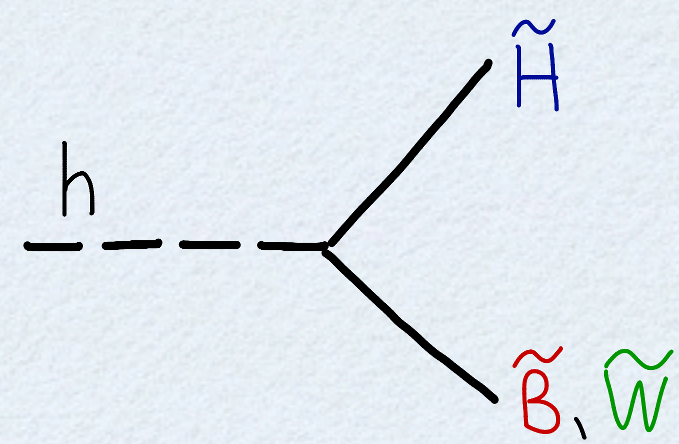
hidden dark matter



1. purity

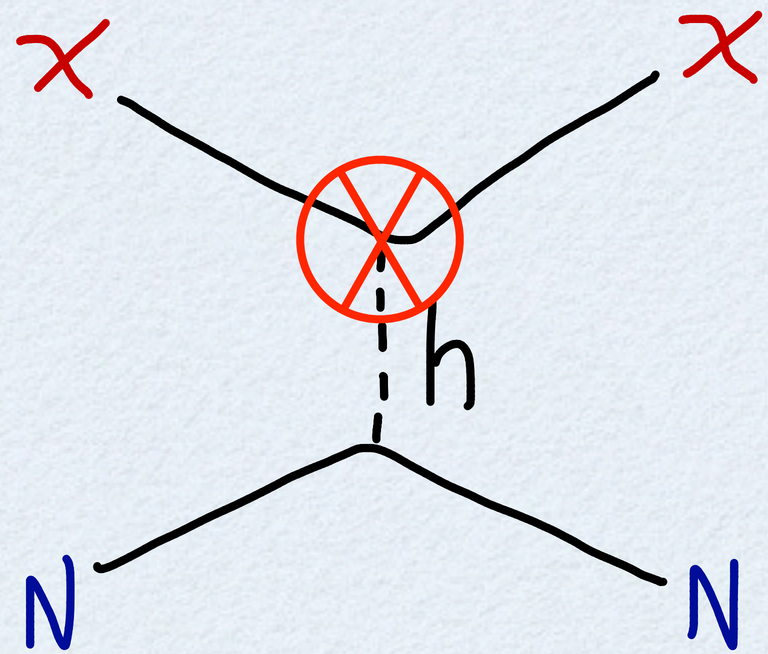
$$\chi \to \tilde{B}, \tilde{W}, \tilde{H}$$

$$c_{h\chi\chi} \to 0$$



decouple higgsinos or gauginos

hidden dark matter



1. purity

$\chi \to \tilde{B}, \tilde{W}, \tilde{H}$

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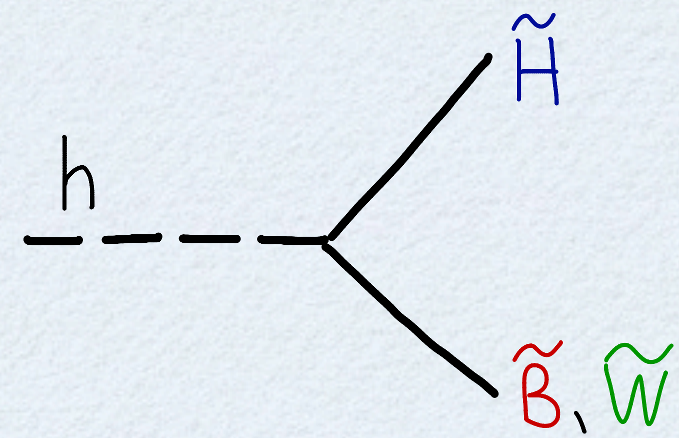


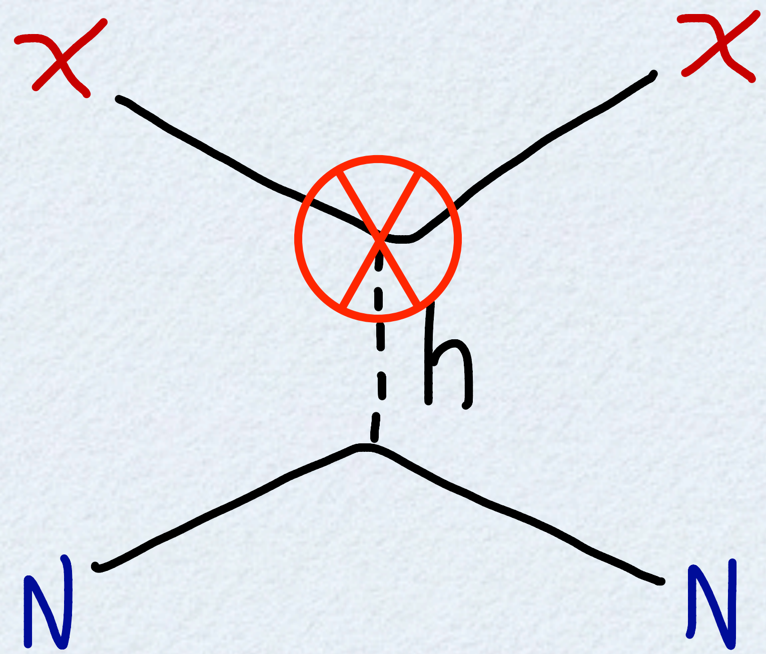
decouple higgsinos or gauginos

2. blindspots

$c_{h\chi\chi} = 0$

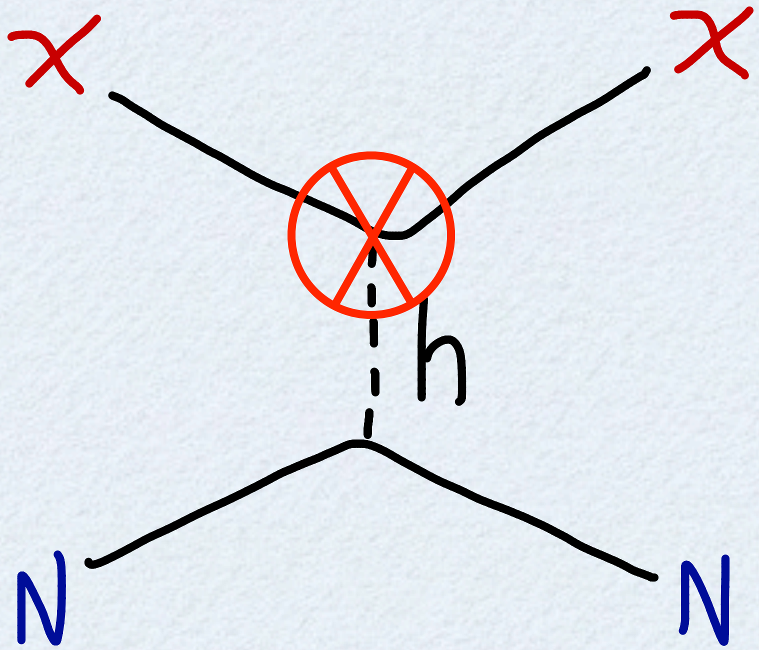
tuned cancellation

blindspots



$$c_{h\chi\chi} = \frac{\partial m_\chi}{\partial v} = 0$$

blindspots



$$c_{h\chi\chi} = \frac{\partial m_\chi}{\partial v} = 0$$

	$\mathbf{m}_\chi$	**condition**	**signs**
bino	M_1	$M_1 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_1/\mu) = -1$
wino	M_2	$M_2 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_2/\mu) = -1$
higgsino	$-\mu$	$\tan\beta = 1$	$\mathrm{sign}(M_{1,2}/\mu) = -1$
bino/wino	M_2	$M_1 = M_2$	$\mathrm{sign}(M_{1,2}/\mu) = -1$

studied in singlet/doublet model by

Cohen, Kearney, Pierce, Tucker-Smith 1109.2604

bino-higgsino

- decouple wino

bino-higgsino

- decouple wino

- parameters

$$\boxed{M_1,\ \mu,\ \tan\beta}$$

bino-higgsino

- decouple wino

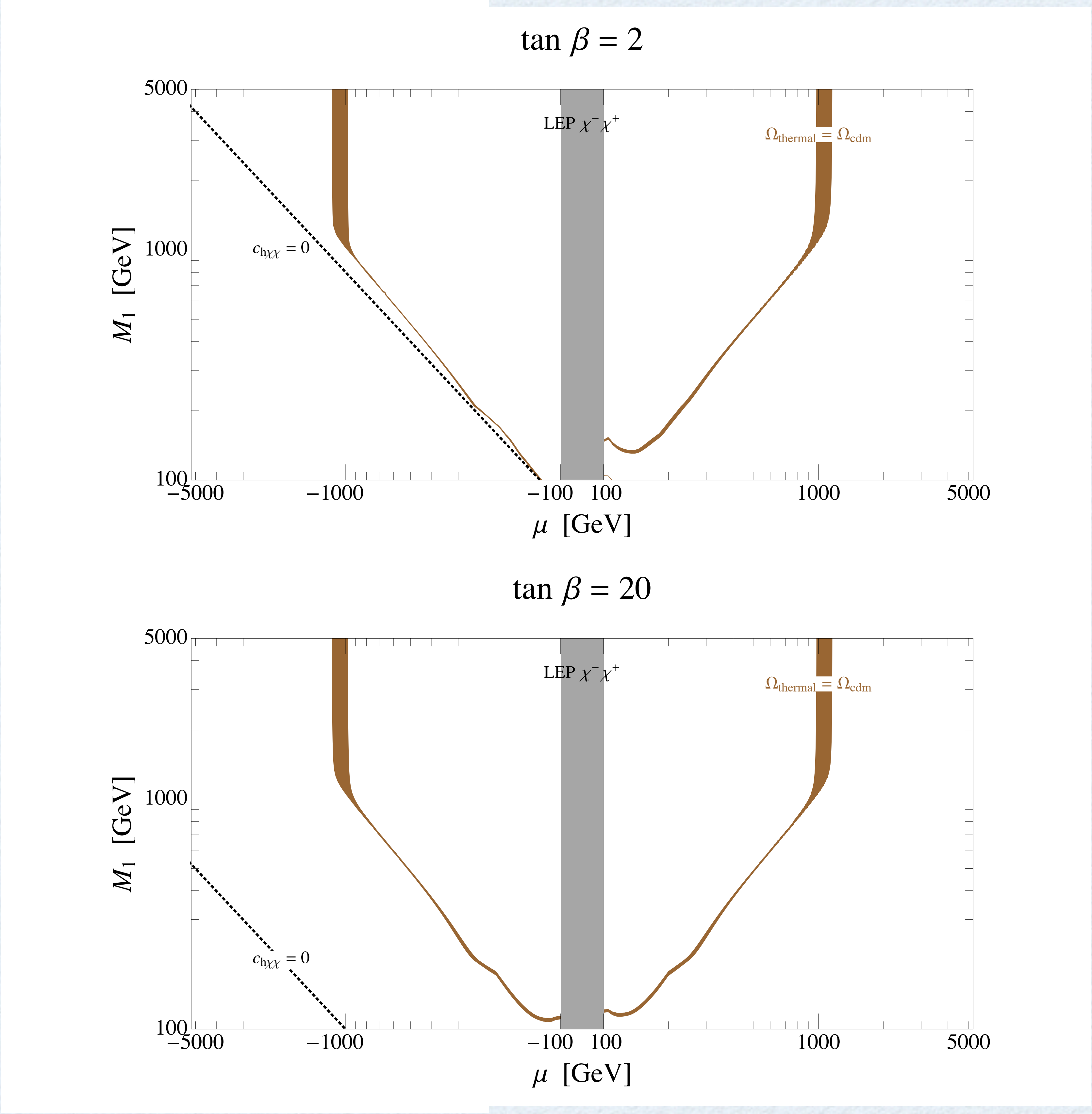
- parameters

$$\boxed{M_1,\ \mu,\ \tan\beta}$$

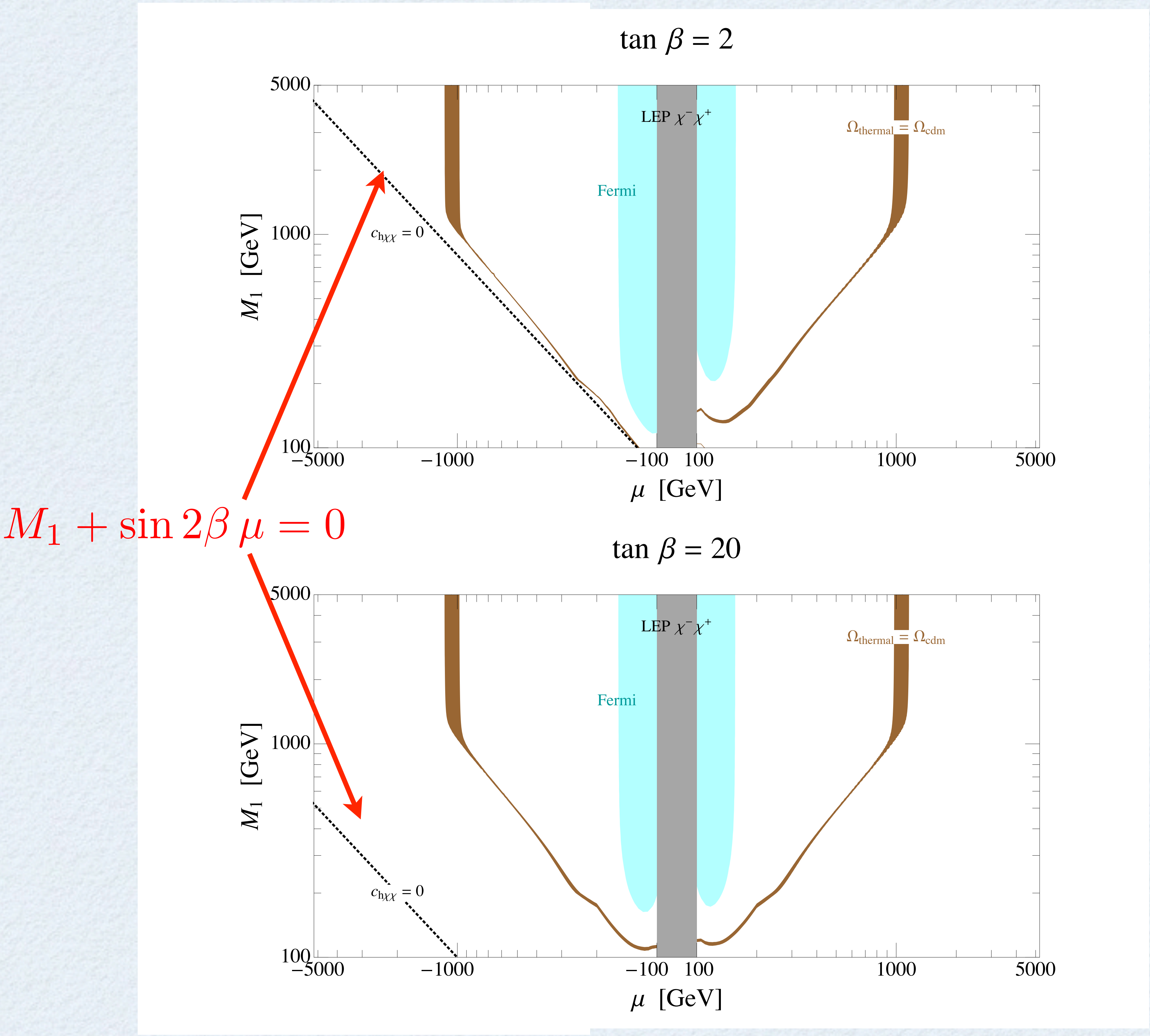
- allow for non-thermal cosmology

$$\Omega_{FO} \neq \Omega_{obs}$$

non-thermal

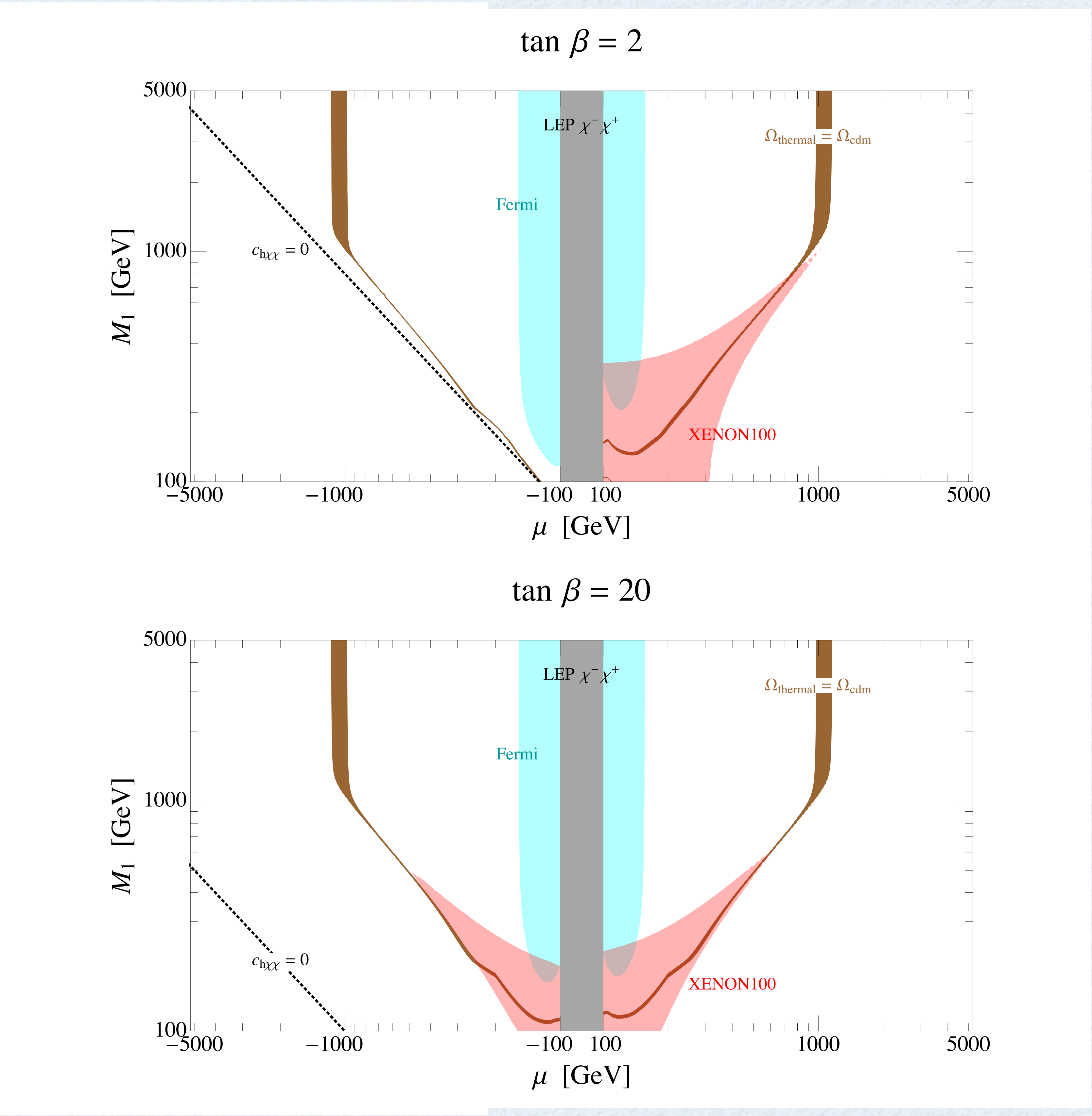

tan β = 2
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
$c_{h\chi\chi} = 0$
M_1 [GeV]
μ [GeV]
5000
1000
100
−5000
−1000
−100
100
1000
5000
tan β = 20
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
$c_{h\chi\chi} = 0$
M_1 [GeV]
μ [GeV]

non-thermal



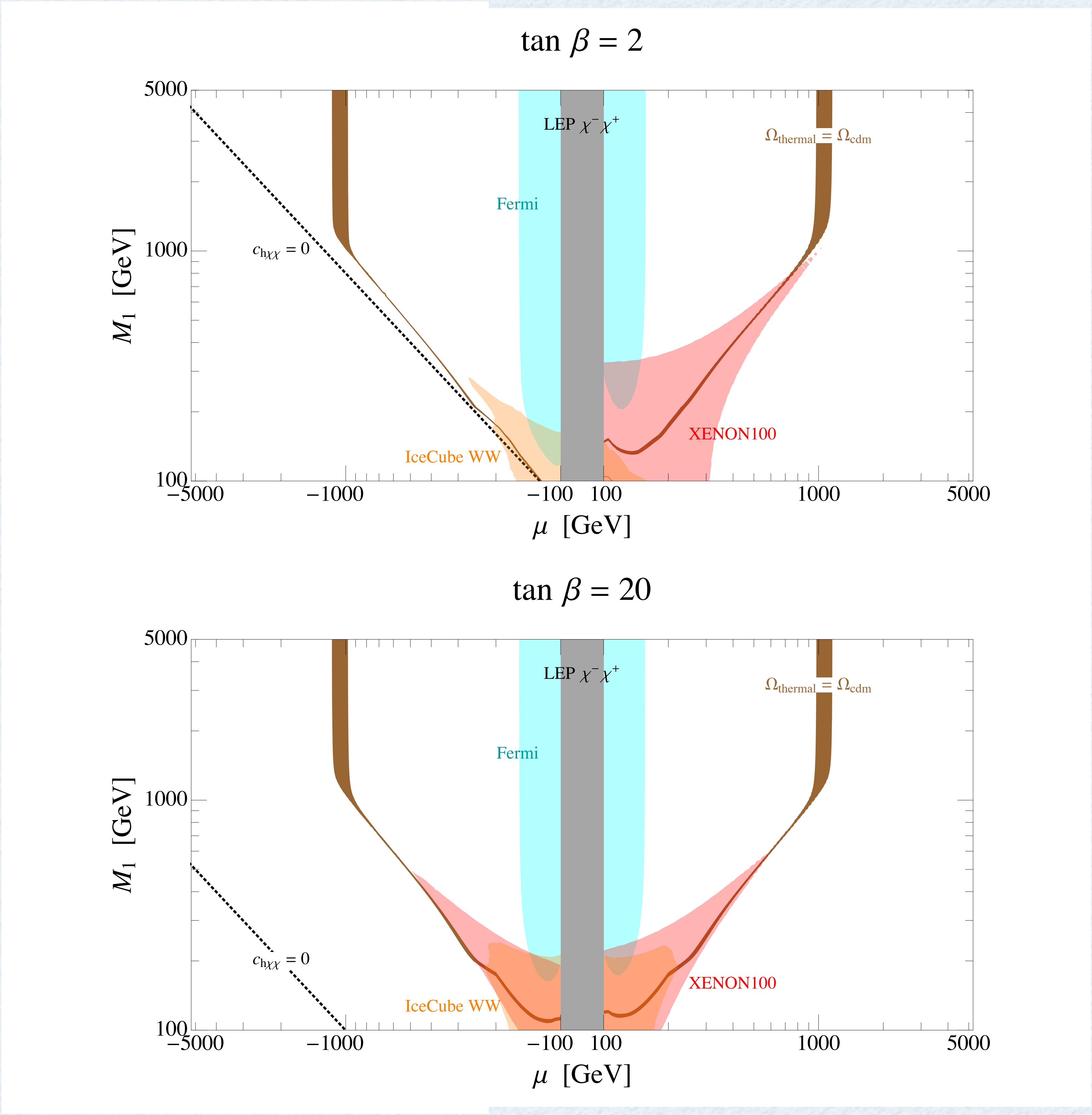
tan β = 2
LEP $\chi^-\chi^+$
$\Omega_{\rm thermal} = \Omega_{\rm cdm}$
Fermi
$c_{h\chi\chi} = 0$
M_1 [GeV]
5000
1000
100
−5000
−1000
−100
100
1000
5000
μ [GeV]
$M_1 + \sin 2\beta\, \mu = 0$
tan β = 20
LEP $\chi^-\chi^+$
$\Omega_{\rm thermal} = \Omega_{\rm cdm}$
Fermi
$c_{h\chi\chi} = 0$
M_1 [GeV]
μ [GeV]

non-thermal



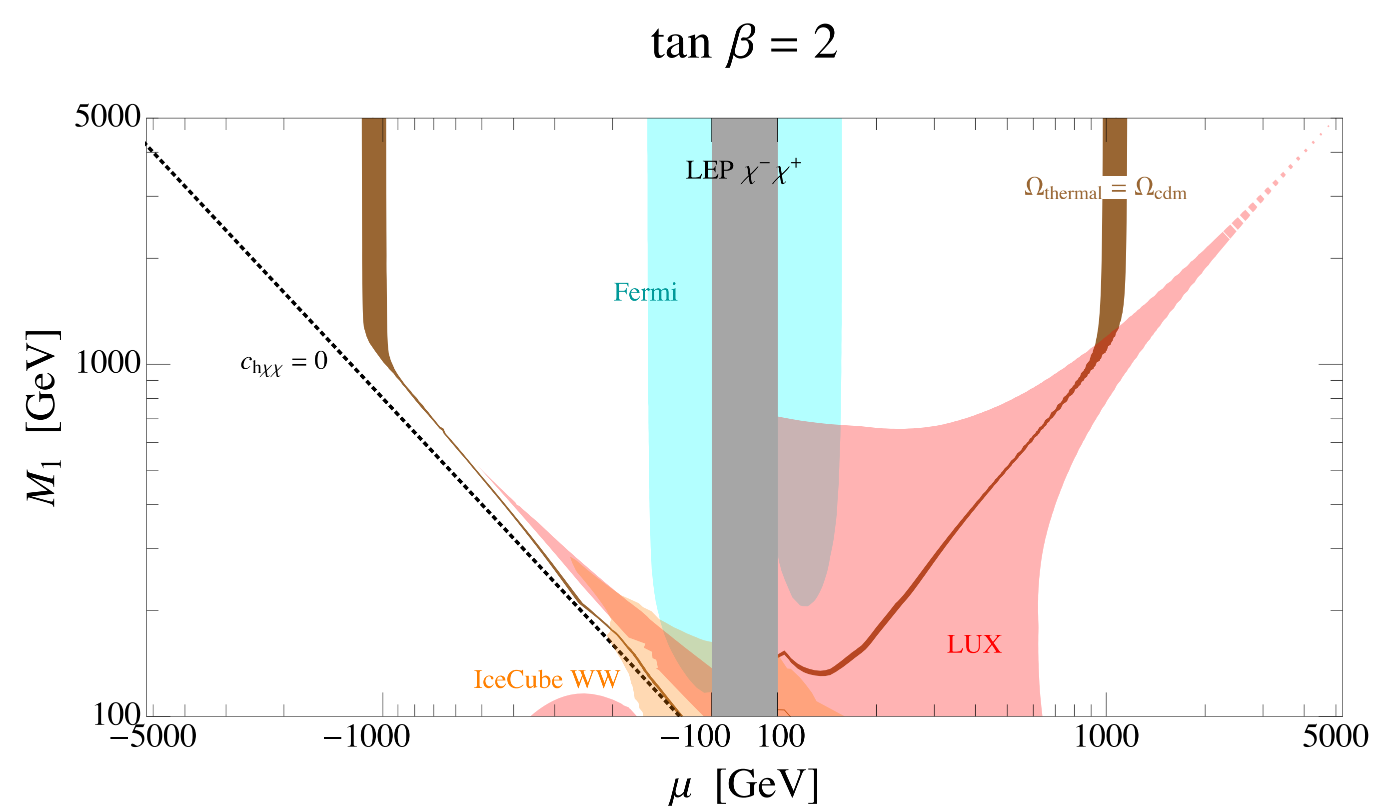
tan β = 2
5000
1000
100
−5000
−1000
−100
100
1000
5000
M_1 [GeV]
μ [GeV]
LEP $\chi^-\chi^+$
Fermi
$\Omega_{\rm thermal} = \Omega_{\rm cdm}$
$c_{h\chi\chi} = 0$
XENON100
tan β = 20

non-thermal

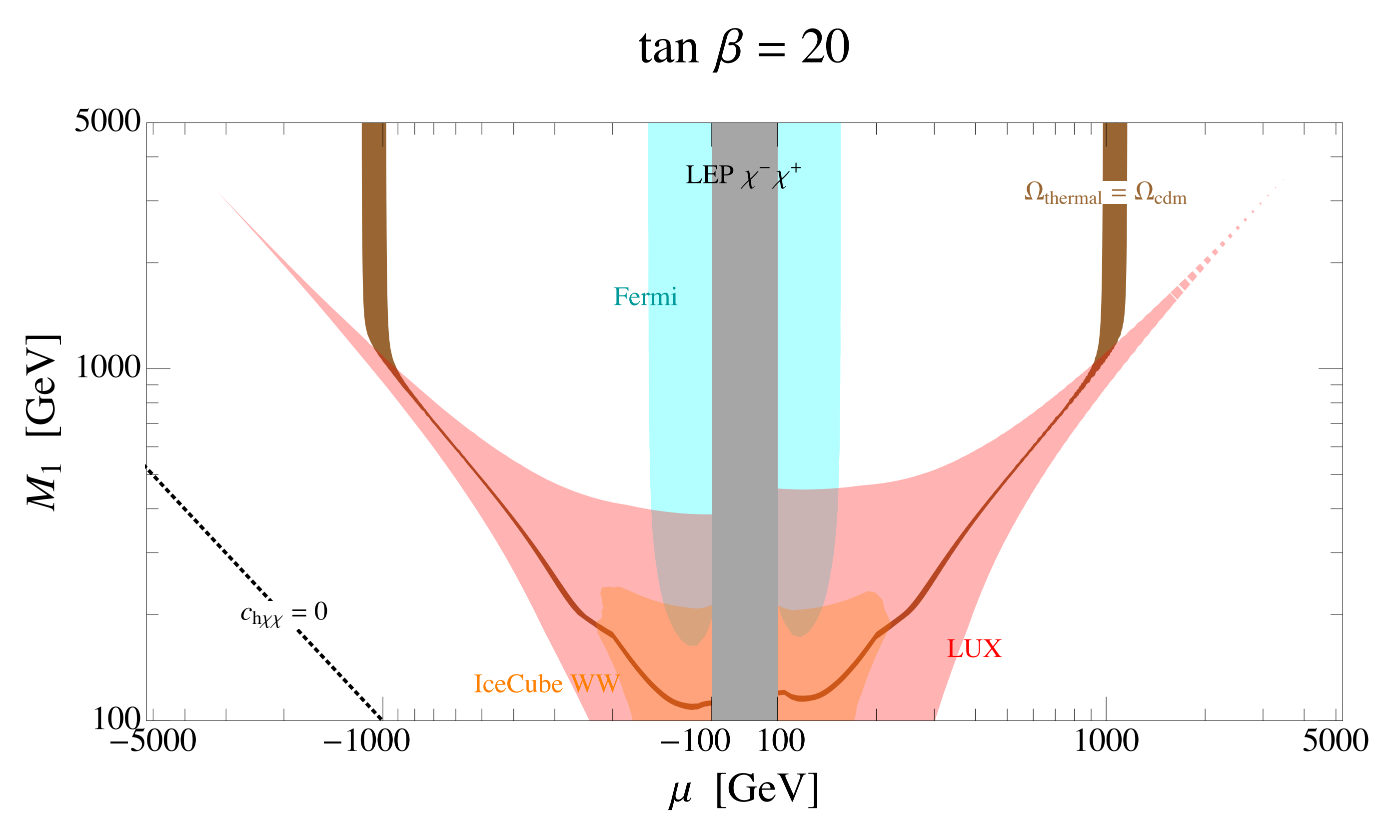


tan β = 2
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
Fermi
$c_{h\chi\chi} = 0$
XENON100
IceCube WW
M_1 [GeV]
μ [GeV]
5000
1000
100
−5000
−1000
−100
100
1000
5000
tan β = 20
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
Fermi
$c_{h\chi\chi} = 0$
XENON100
IceCube WW
M_1 [GeV]
μ [GeV]

non-thermal

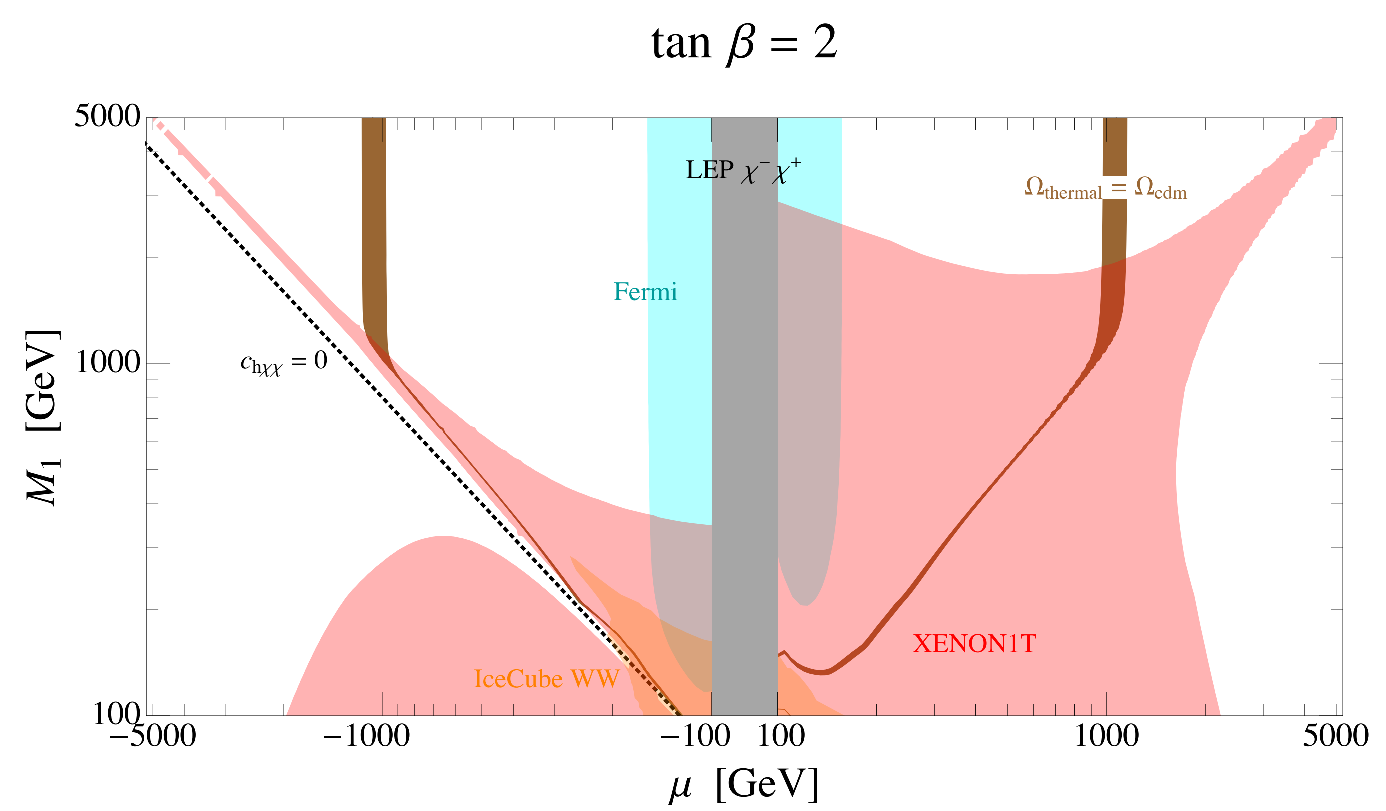


tan β = 2
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
Fermi
$c_{h\chi\chi} = 0$
LUX
IceCube WW
5000
1000
100
M_1 [GeV]
−5000
−1000
−100
100
1000
5000
μ [GeV]

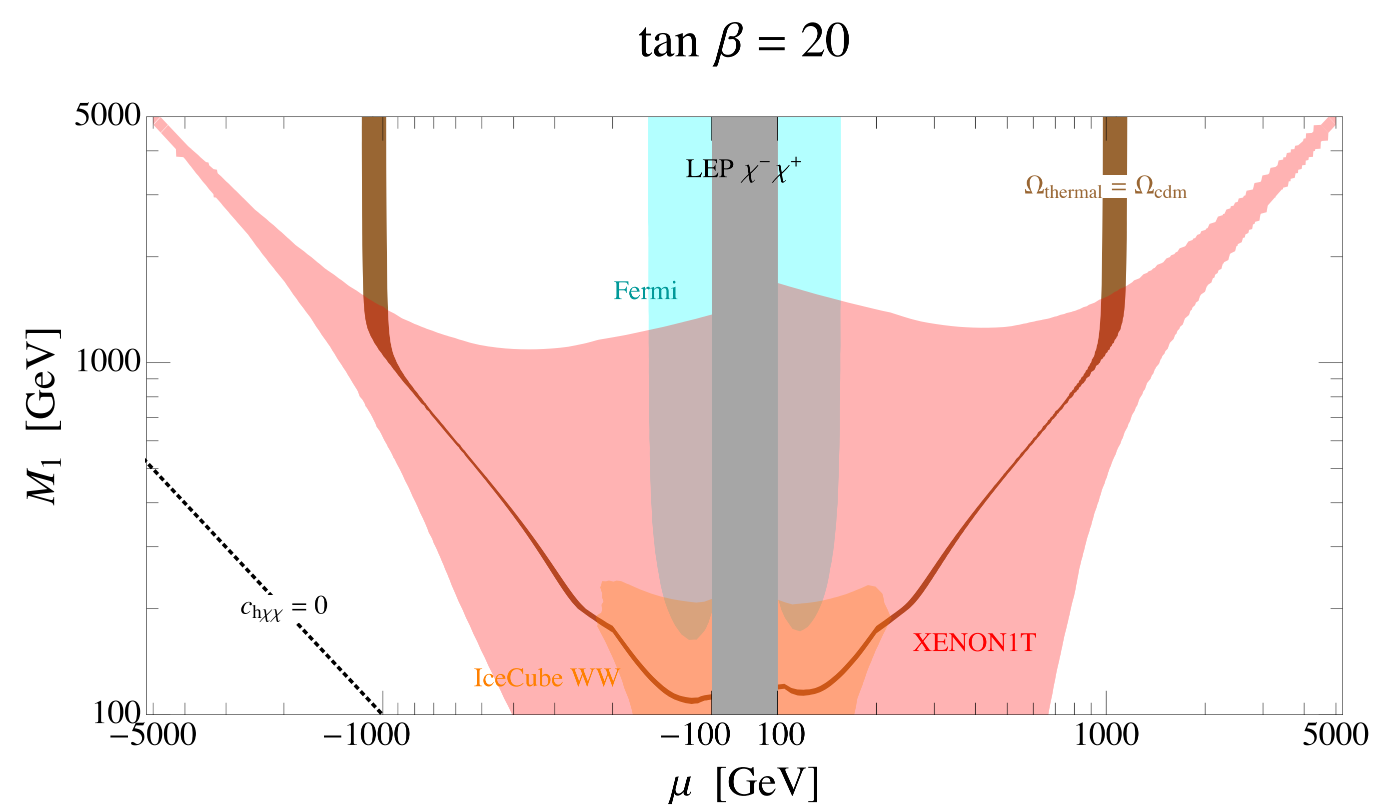


tan β = 20
LEP $\chi^-\chi^+$
$\Omega_{thermal} = \Omega_{cdm}$
Fermi
$c_{h\chi\chi} = 0$
LUX
IceCube WW
5000
1000
100
M_1 [GeV]
−5000
−1000
−100
100
1000
5000
μ [GeV]

non-thermal

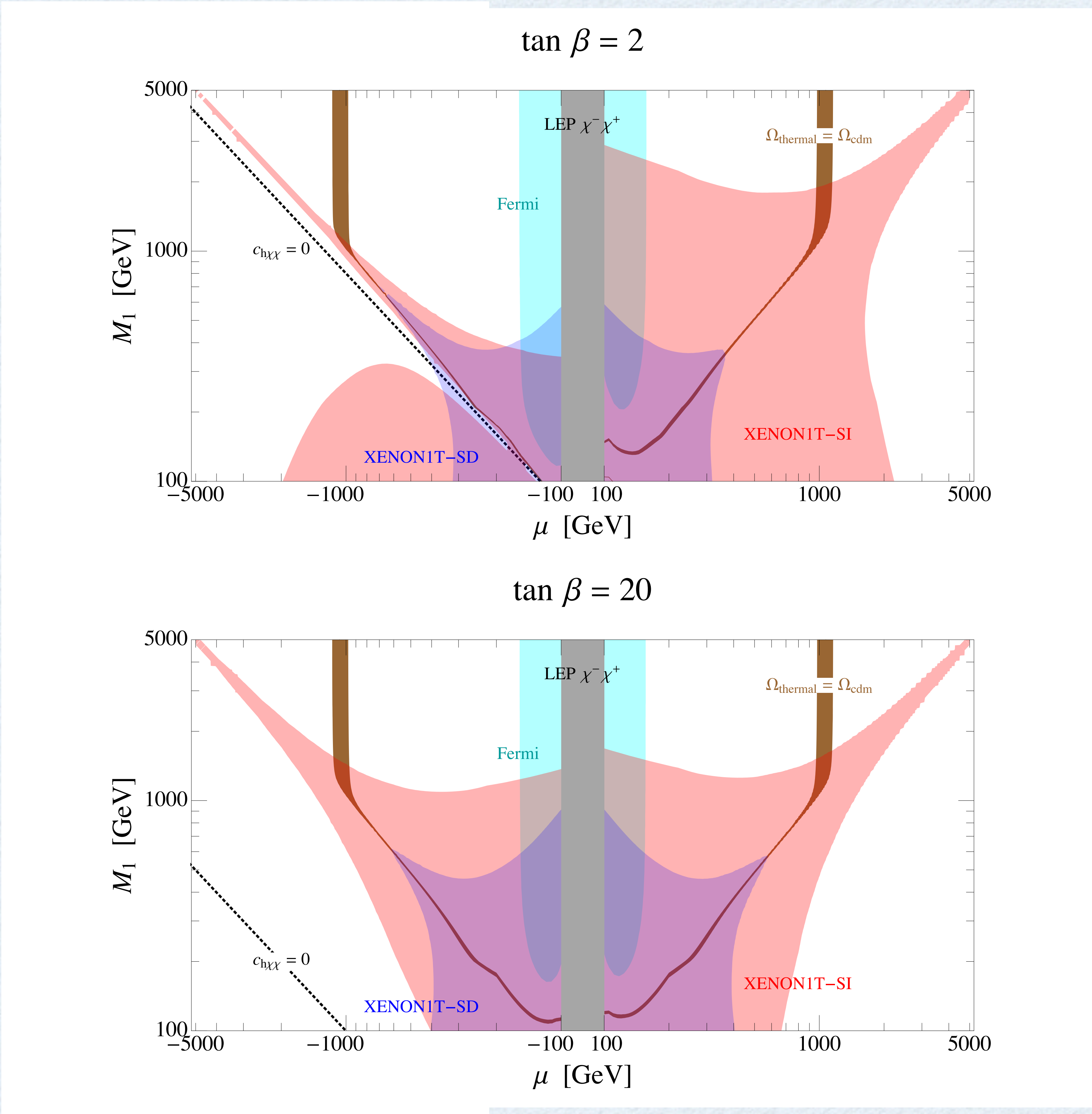


tan β = 2
5000
1000
100
M_1 [GeV]
−5000
−1000
−100
100
1000
5000
μ [GeV]
LEP $\chi^-\chi^+$
Fermi
$c_{h\chi\chi} = 0$
$\Omega_{thermal} = \Omega_{cdm}$
XENON1T
IceCube WW



tan β = 20
5000
1000
100
M_1 [GeV]
−5000
−1000
−100
100
1000
5000
μ [GeV]
LEP $\chi^-\chi^+$
Fermi
$c_{h\chi\chi} = 0$
$\Omega_{thermal} = \Omega_{cdm}$
XENON1T
IceCube WW

non-thermal

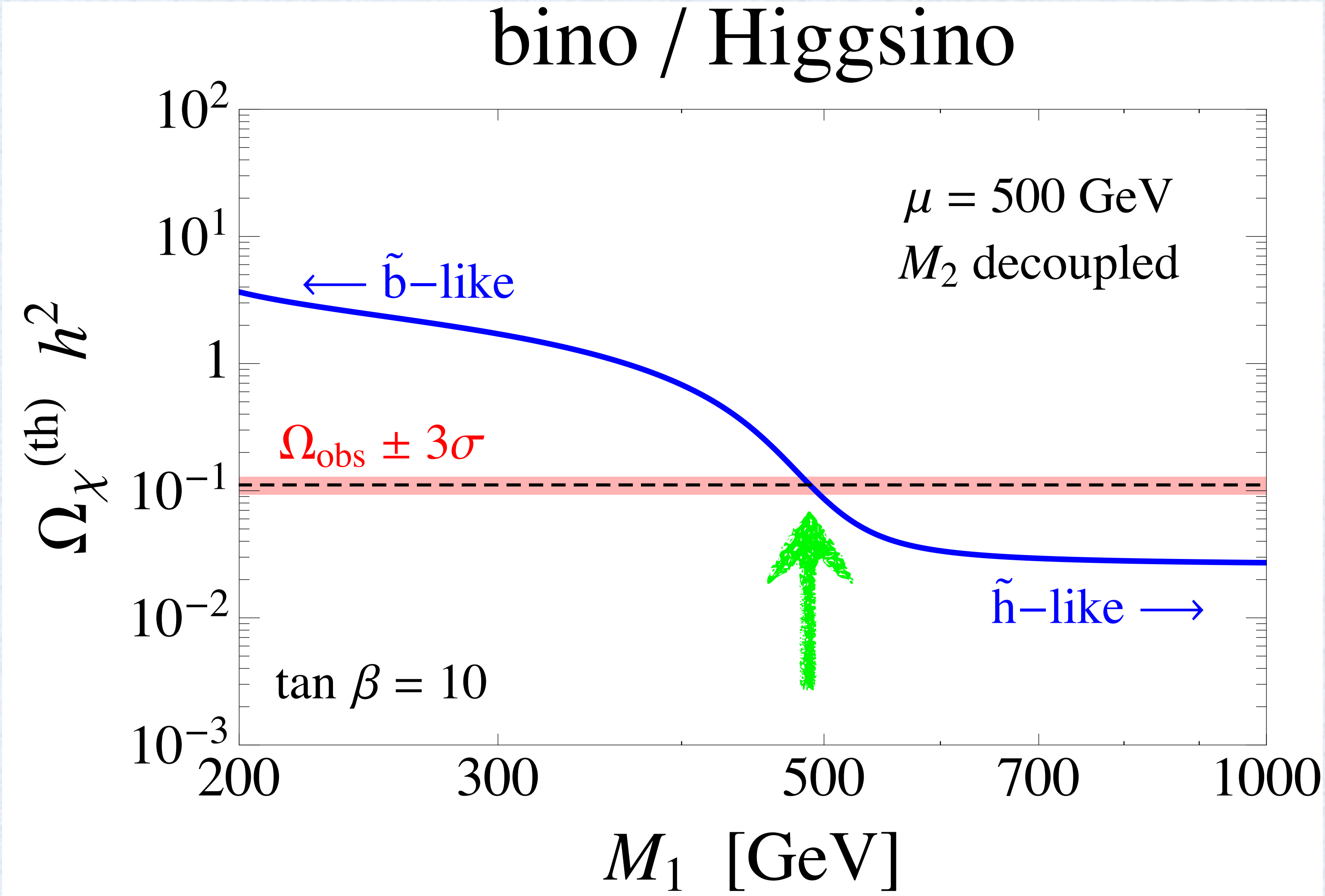

tan β = 2
5000
1000
100
M_1 [GeV]
LEP $\chi^-\chi^+$
Fermi
$\Omega_{\rm thermal} = \Omega_{\rm cdm}$
$c_{h\chi\chi} = 0$
XENON1T−SD
XENON1T−SI
−5000
−1000
−100
100
1000
5000
μ [GeV]
tan β = 20
5000
1000
100
M_1 [GeV]
LEP $\chi^-\chi^+$
Fermi
$\Omega_{\rm thermal} = \Omega_{\rm cdm}$
$c_{h\chi\chi} = 0$
XENON1T−SD
XENON1T−SI
−5000
−1000
−100
100
1000
5000
μ [GeV]

Ω

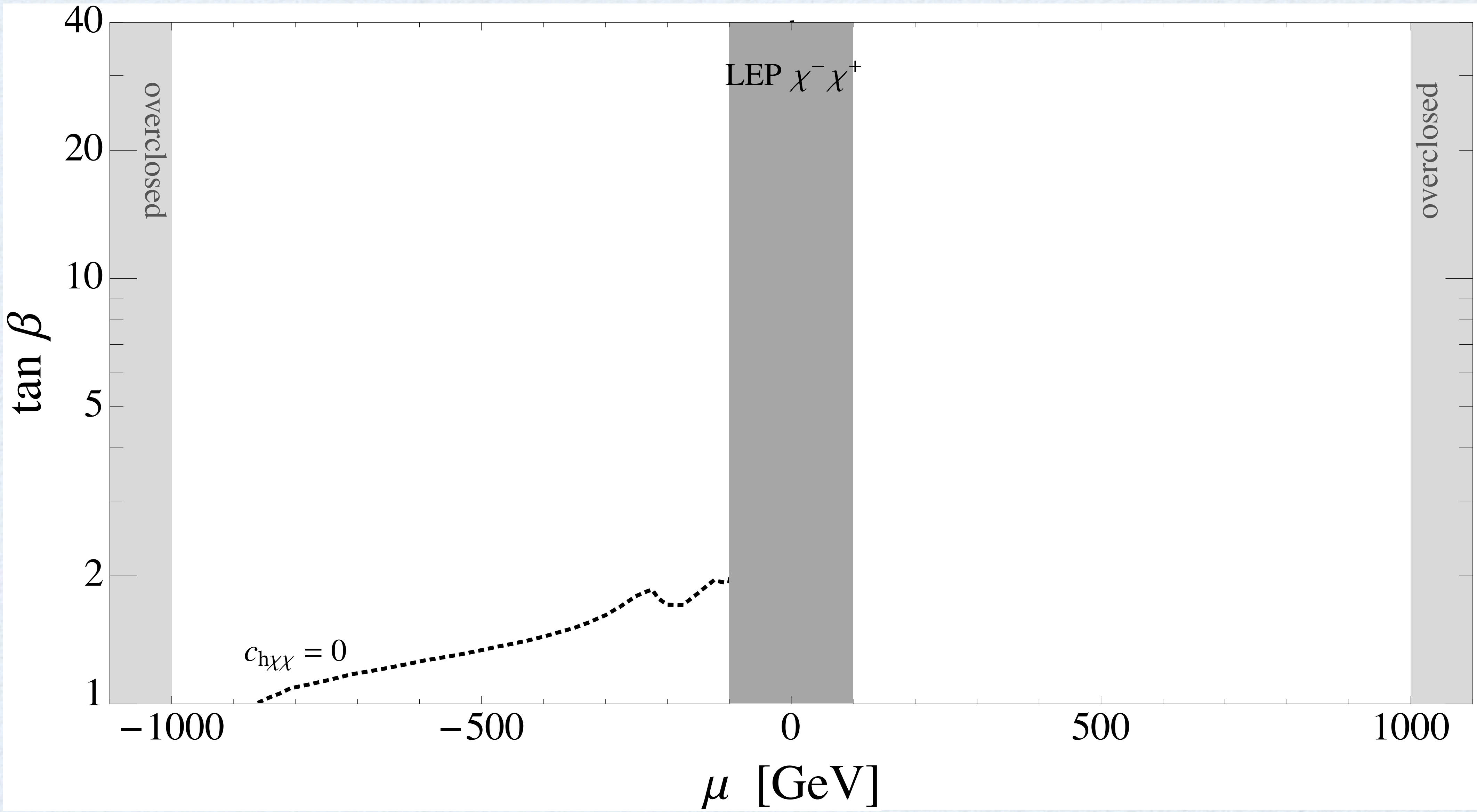
$$\Omega_{FO} = \Omega_{obs}$$

solve for:

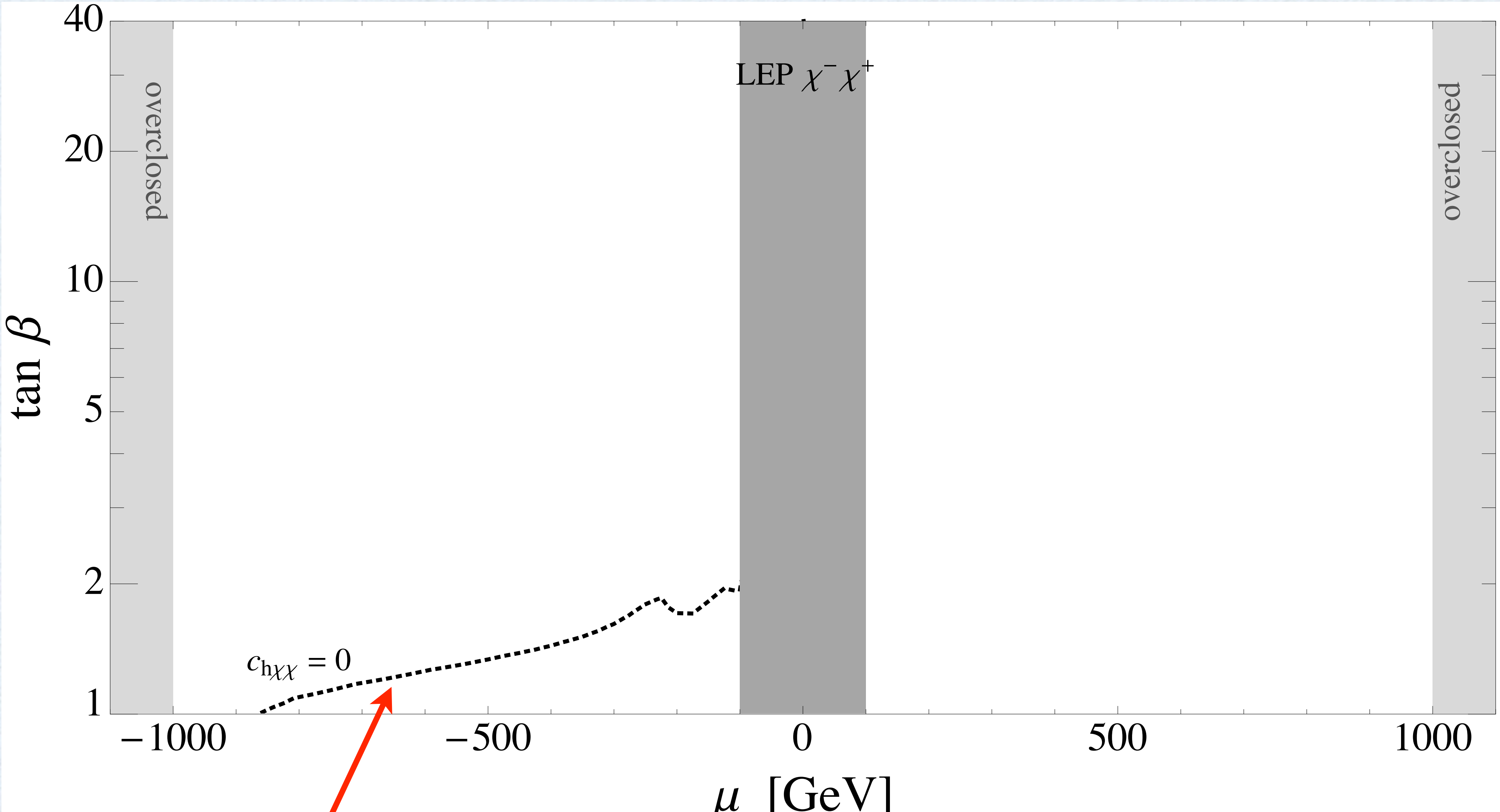
$$M_1\,(\mu, \tan\beta)$$



well-tempered

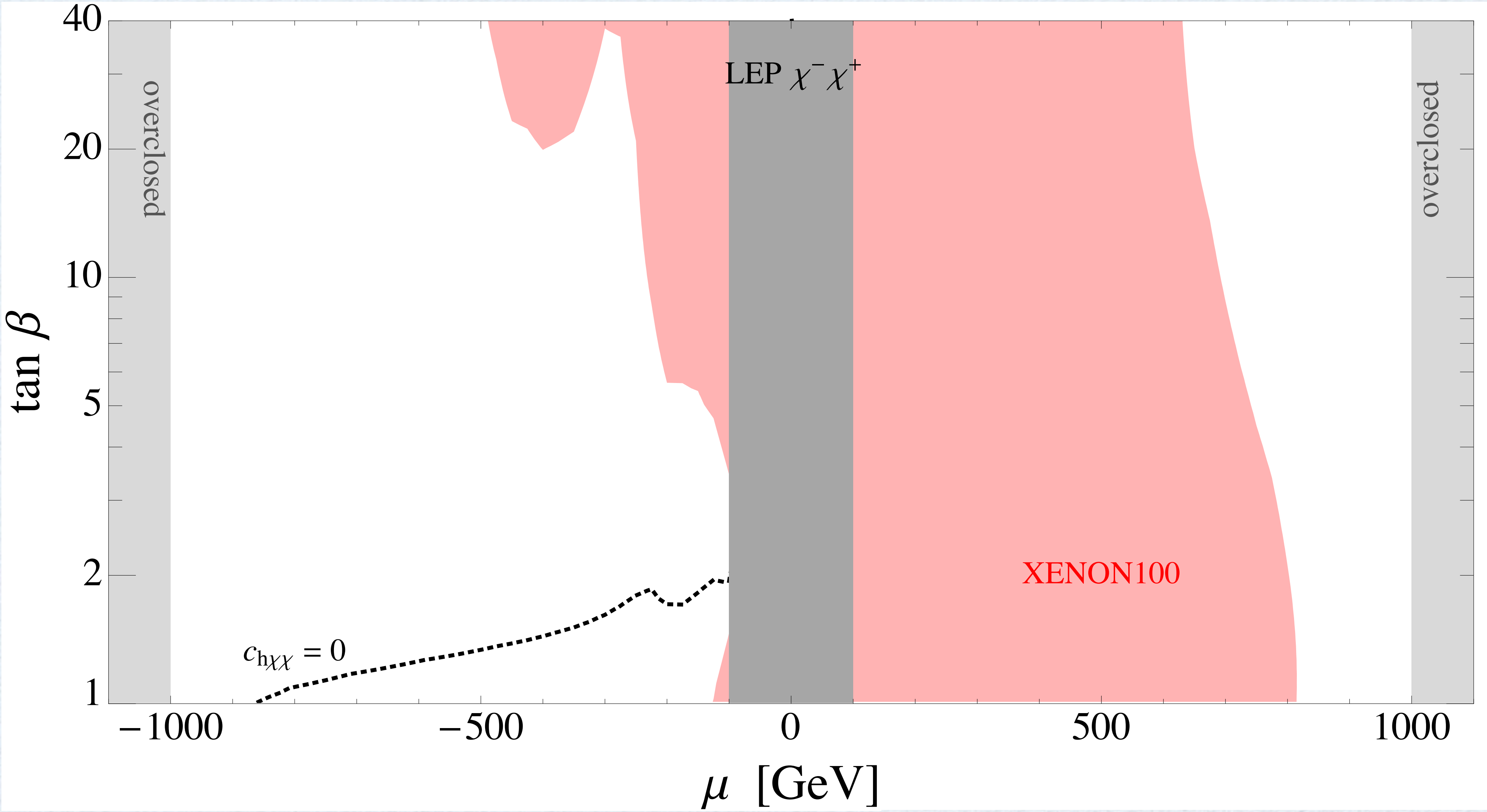


well-tempered

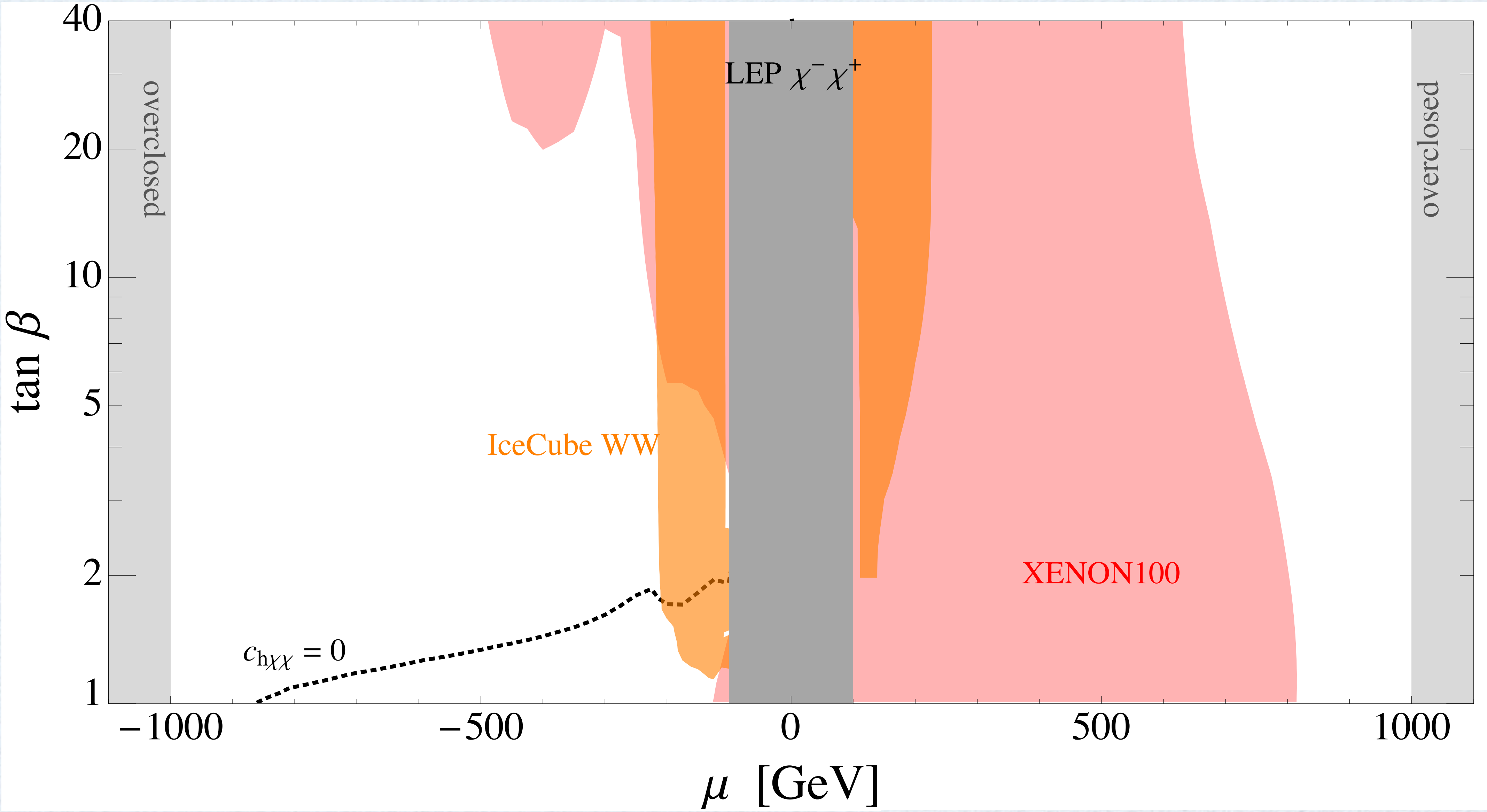


$$M_1 + \sin 2\beta\, \mu = 0$$

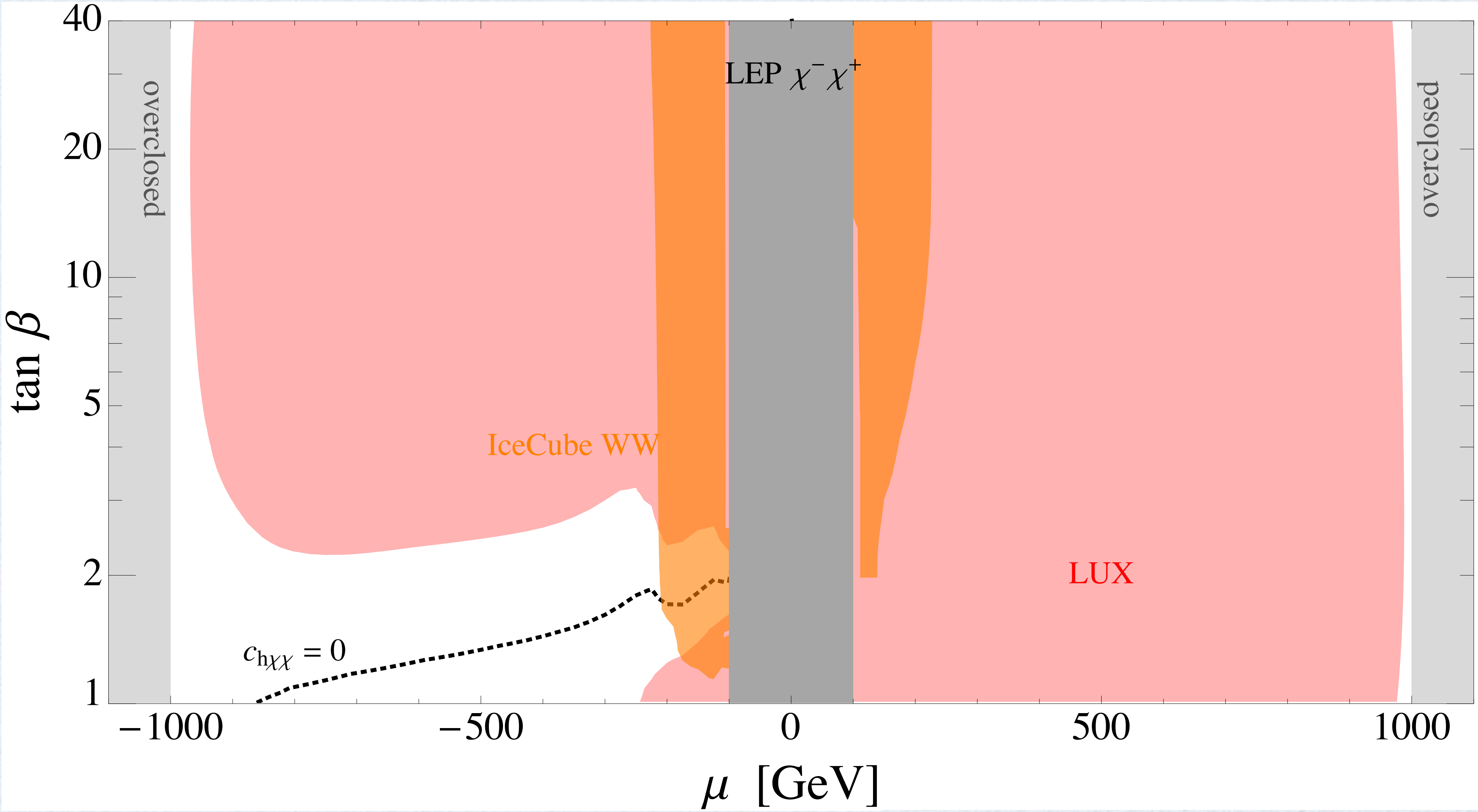
well-tempered



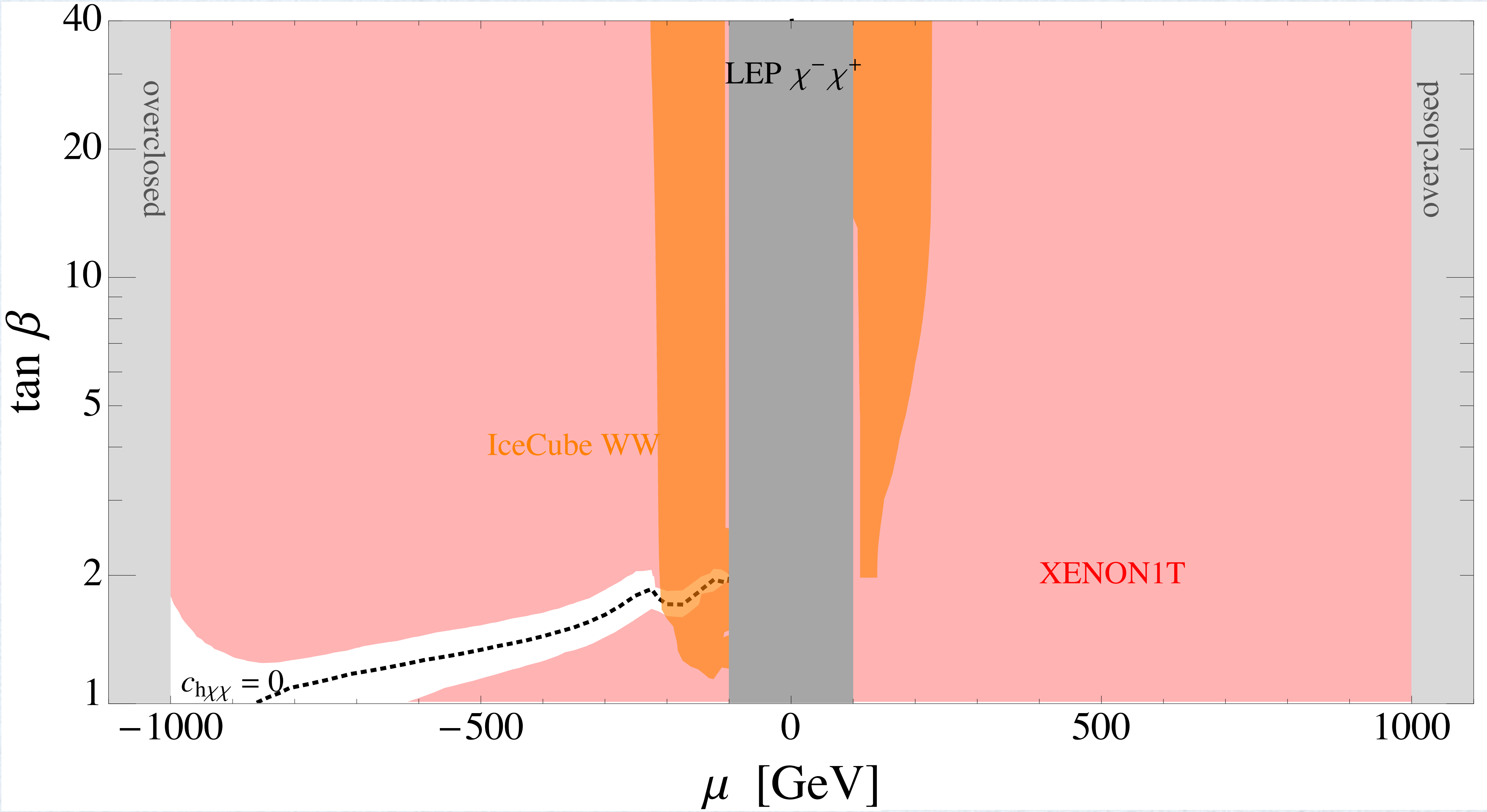
well-tempered



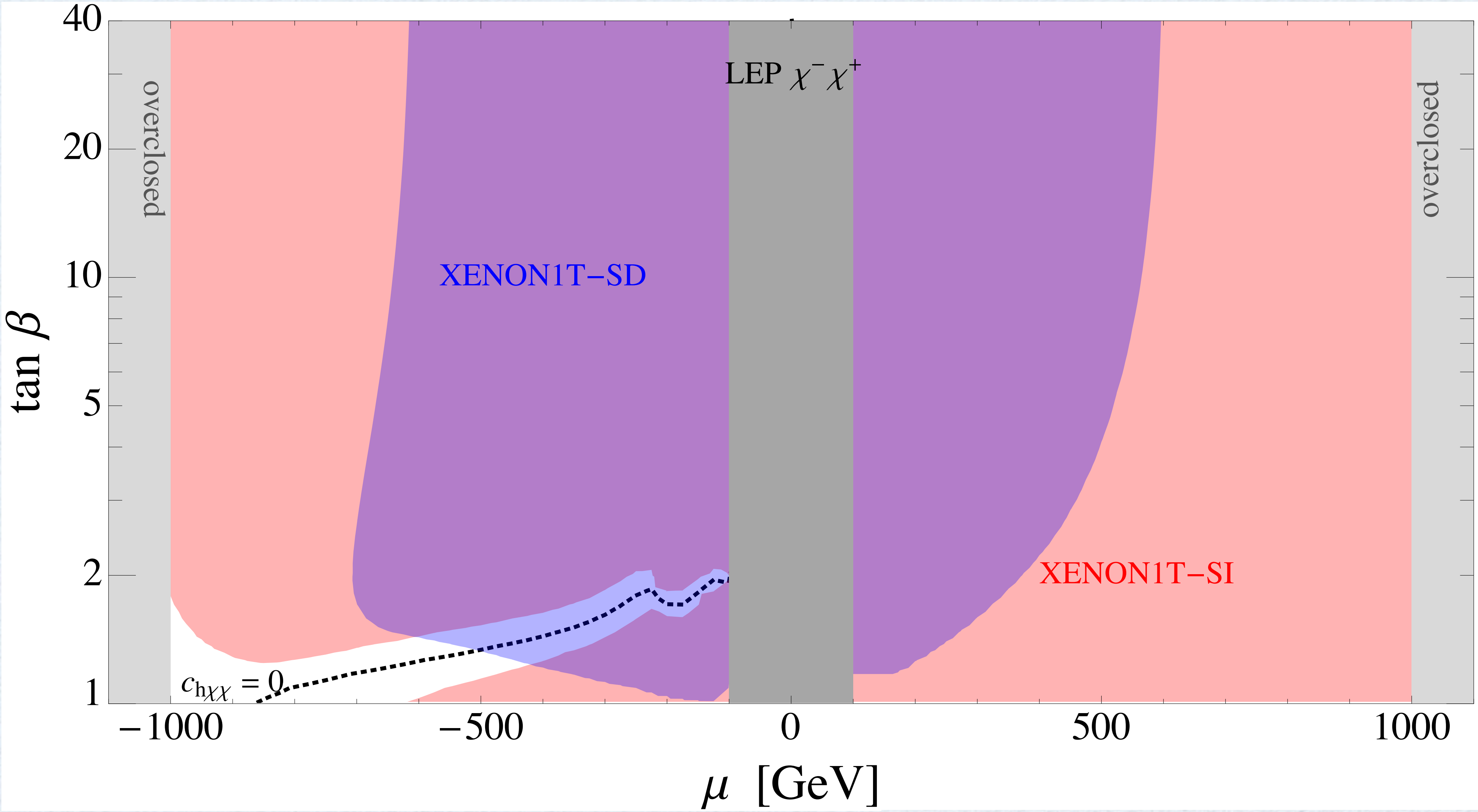
well-tempered



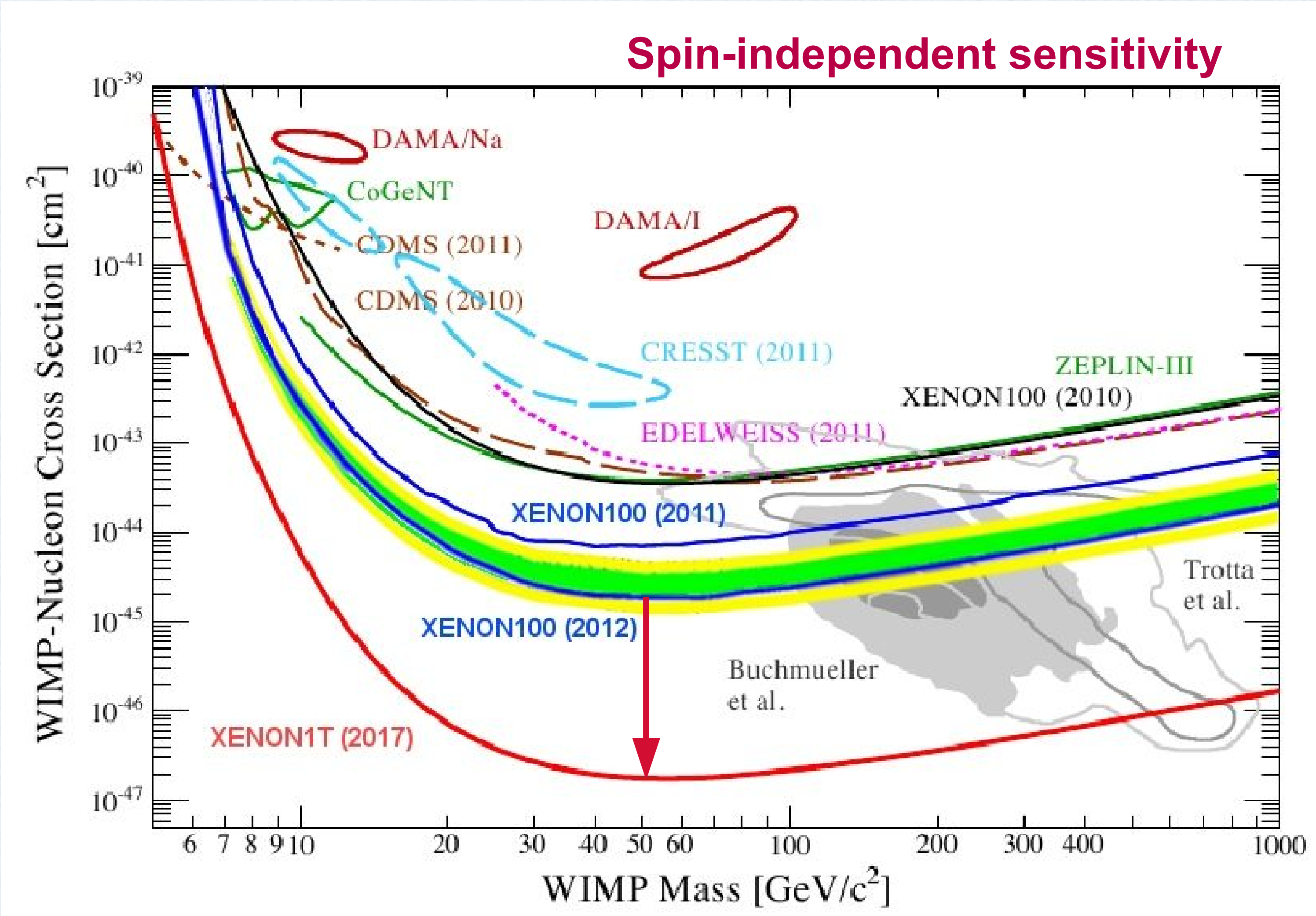
well-tempered



well-tempered

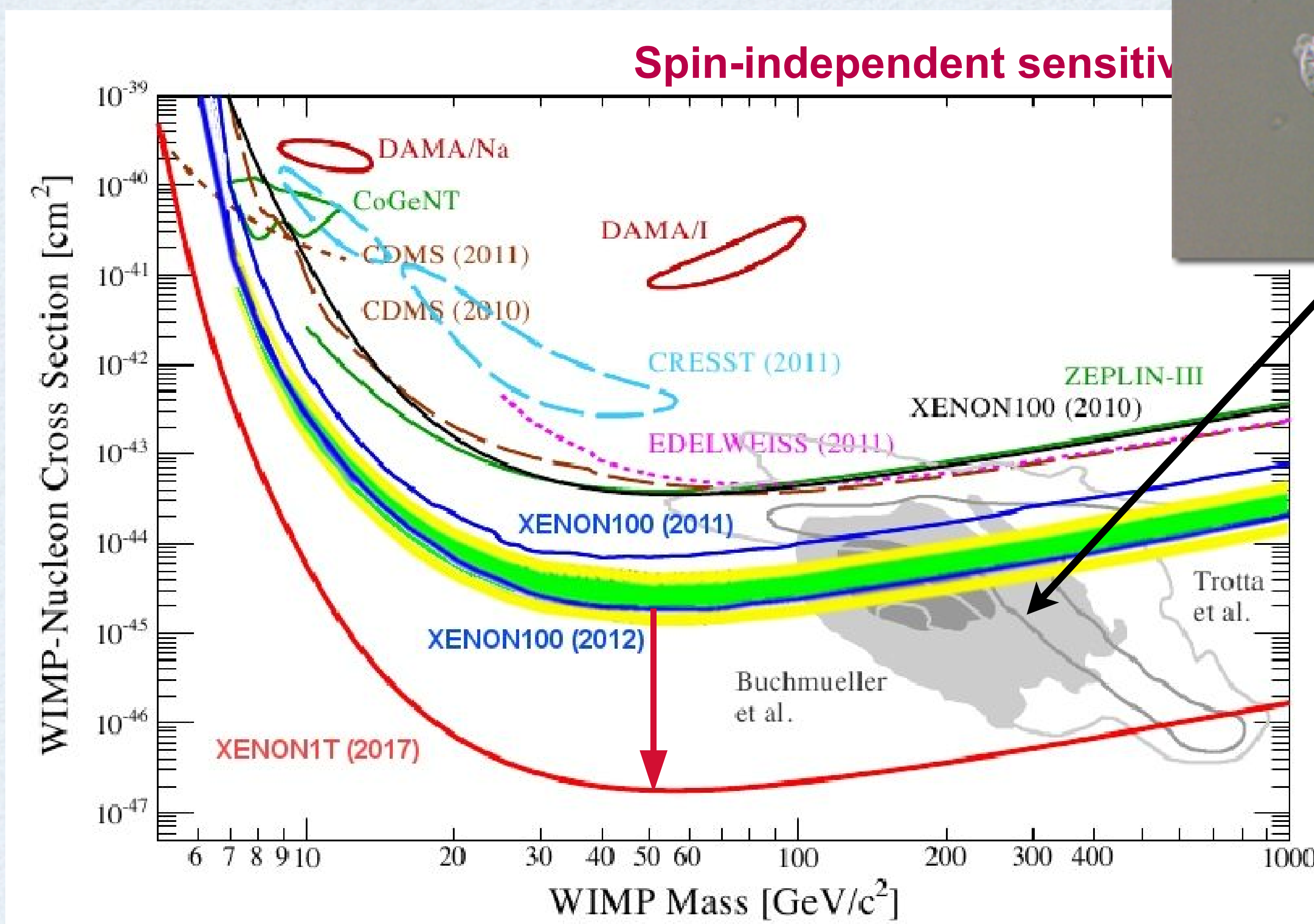


target



Spin-independent sensitivity
DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
CDMS (2010)
CRESST (2011)
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
XENON100 (2011)
XENON100 (2012)
Trotta et al.
Buchmueller et al.
XENON1T (2017)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]

target



Spin-independent sensitiv
DAMA/Na
CoGeNT
CDMS (2011)
CDMS (2010)
DAMA/I
CRESST (2011)
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
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WIMP-Nucleon Cross Section [cm^2]
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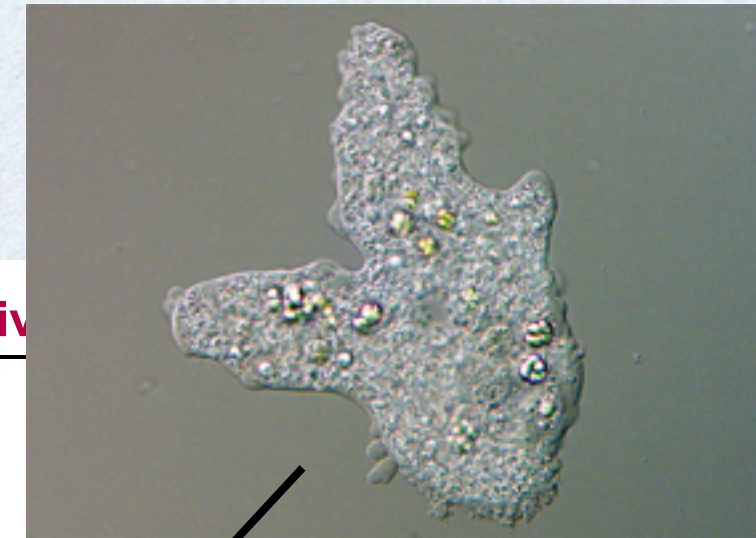
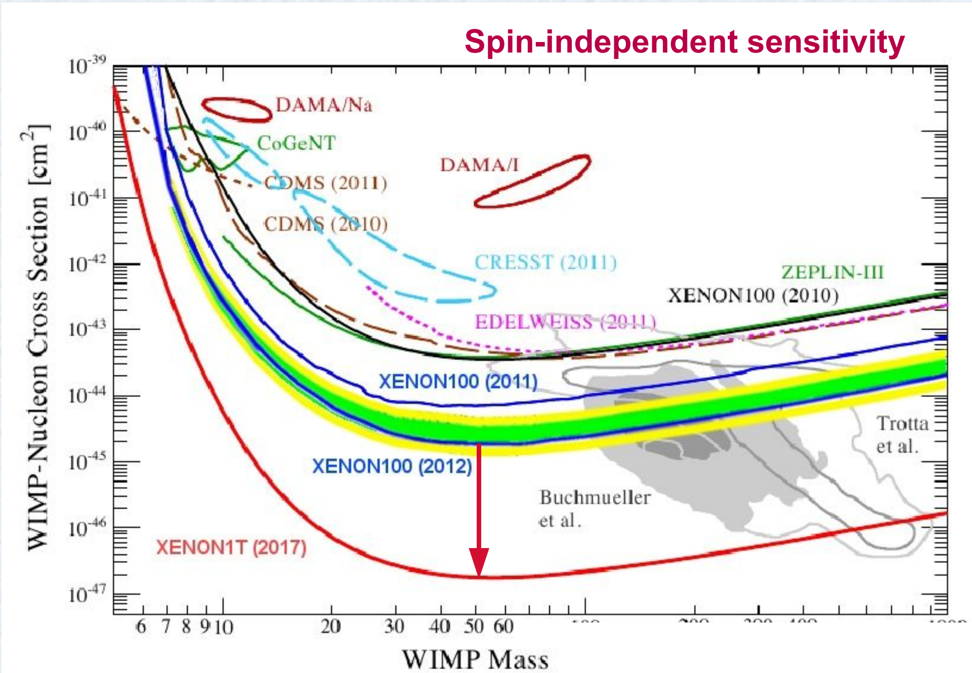


target



Spin-independent sensitivity
WIMP-Nucleon Cross Section [cm^2]
DAMA/Na
CoGeNT
CDMS (2011)
CDMS (2010)
DAMA/I
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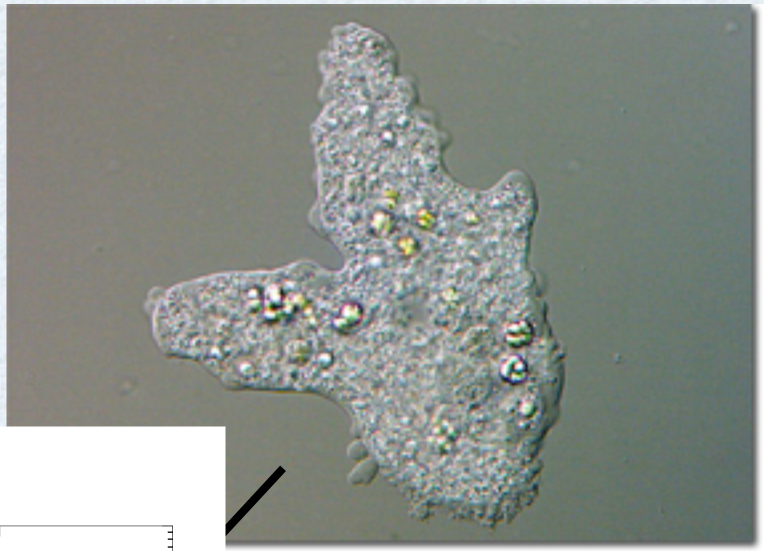
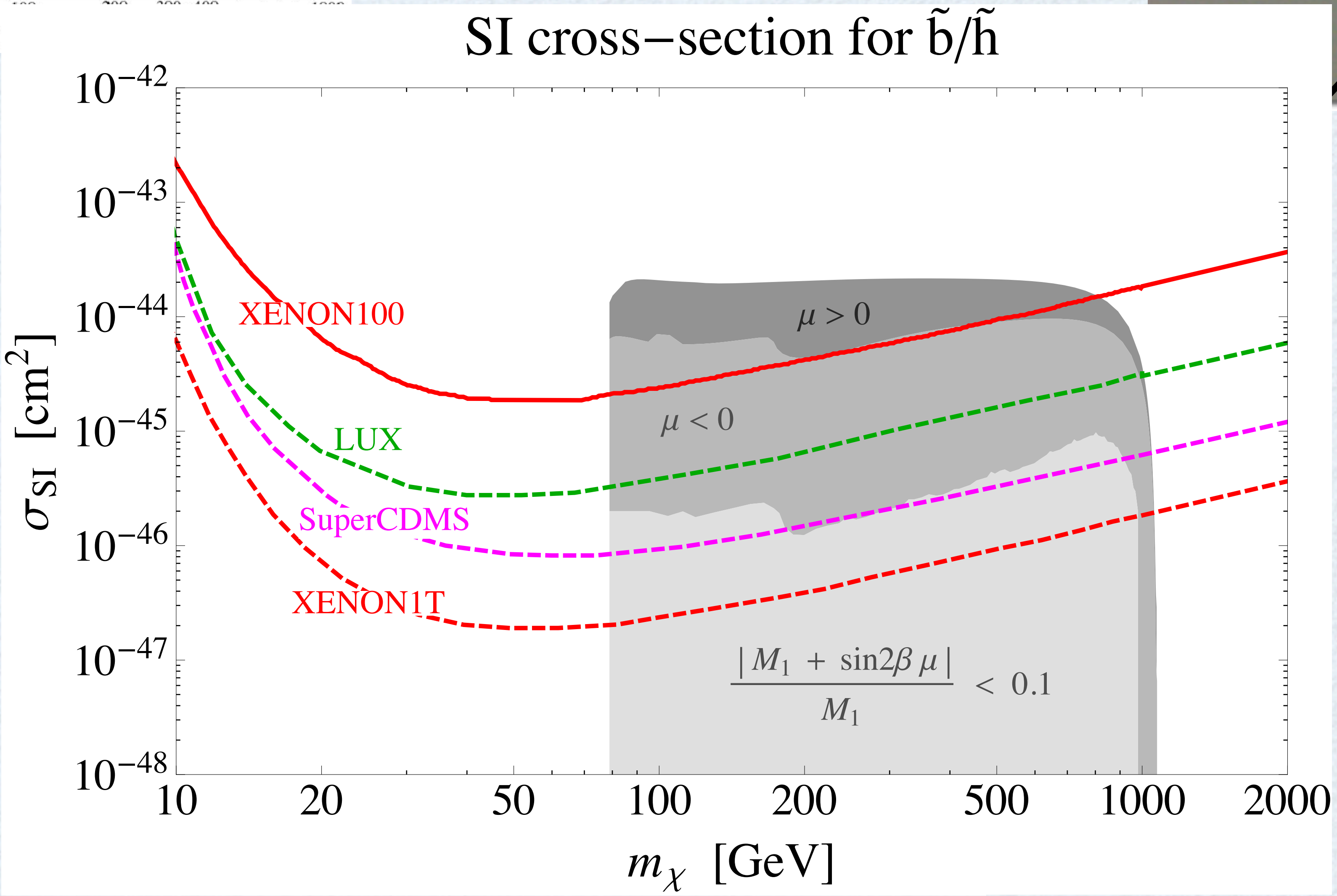
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
XENON100 (2011)
XENON100 (2012)
Trotta et al.
Buchmueller et al.
XENON1T (2017)
WIMP Mass





SI cross−section for $\tilde{b}/\tilde{h}$
σ_{SI} [cm^2]
m_χ [GeV]
XENON100
LUX
SuperCDMS
XENON1T
$\mu > 0$
$\mu < 0$
$\frac{|M_1 + \sin 2\beta\,\mu|}{M_1} < 0.1$

conclusions

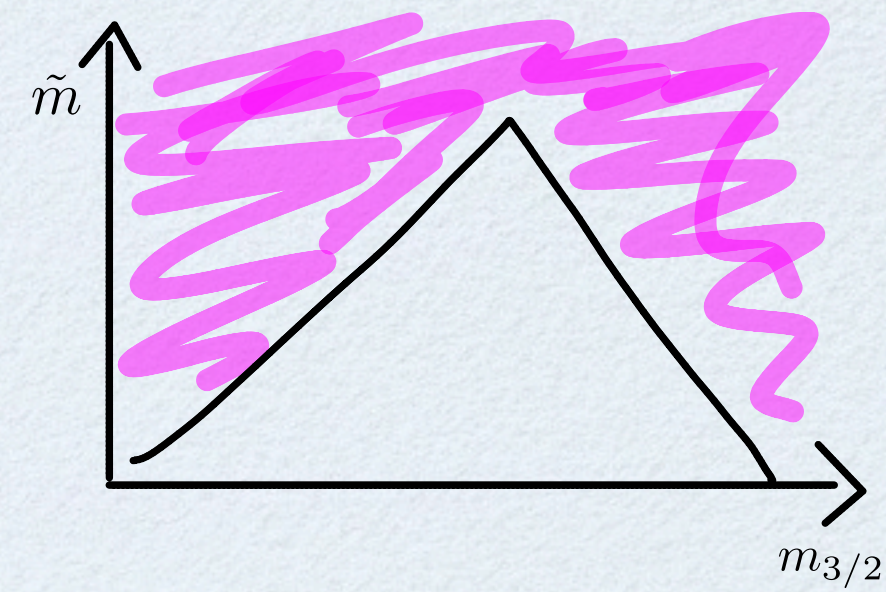
conclusions

- gravitino miracle

$$\tilde{m} < \alpha^n \sqrt{T_{eq}\, M_p}$$

LSP = $\tilde{N}_1$ $\quad n = 1$

LSP = $\tilde{G}$ $\quad n = 1/2$



conclusions

- gravitino miracle

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LSP = $\tilde{N}_1$ $\qquad n = 1$

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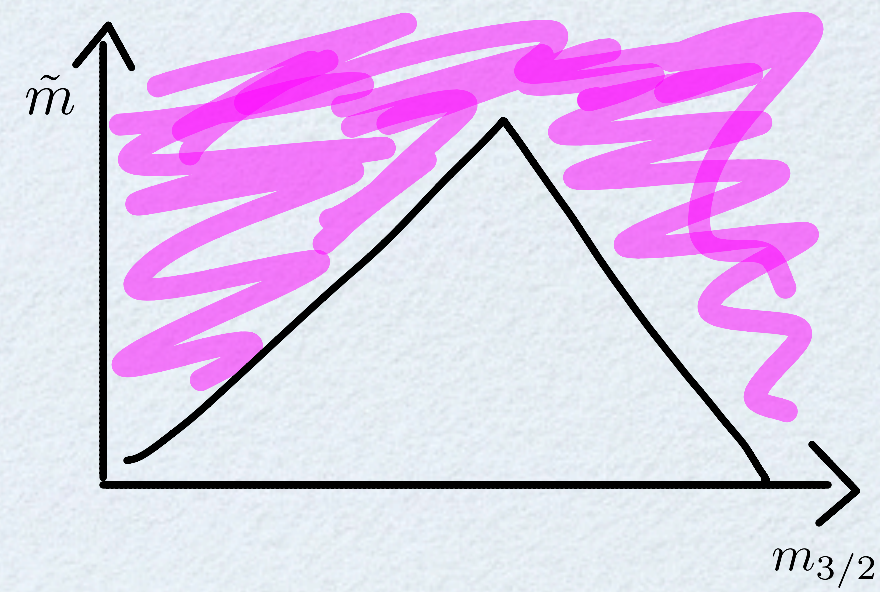

- direct detection is now testing DM-Higgs coupling

conclusions

- gravitino miracle

$$\tilde{m} < \alpha^n \sqrt{T_{eq} M_p}$$

LSP = $\tilde{N}_1$ $\quad n = 1$

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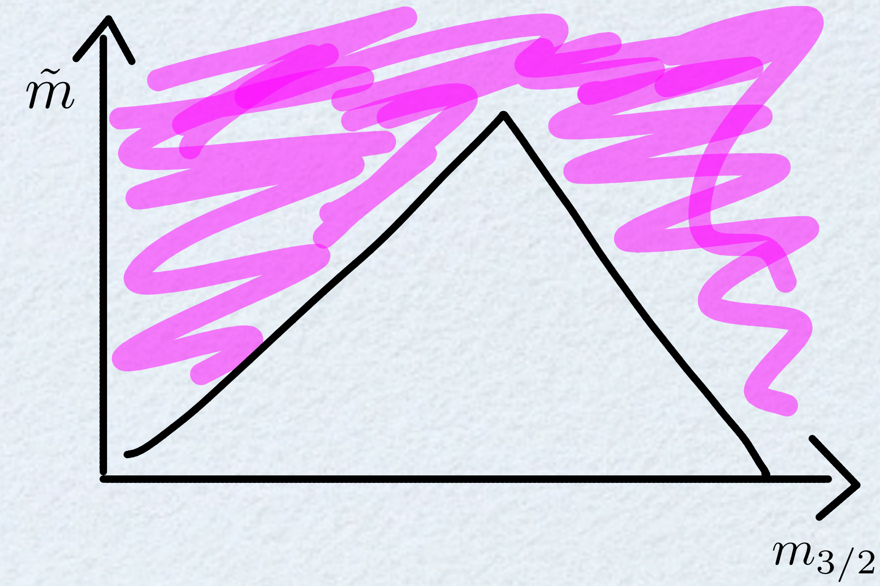
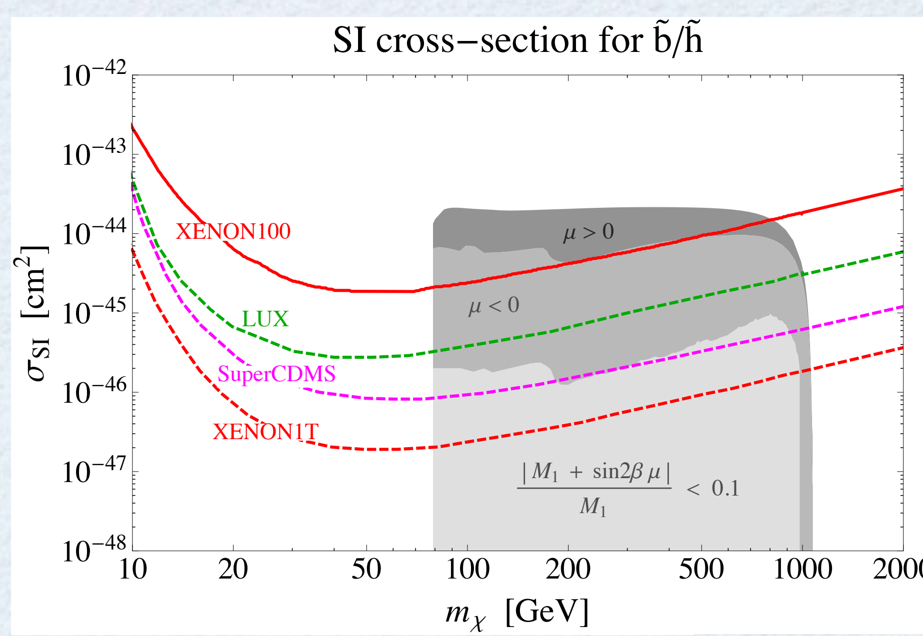


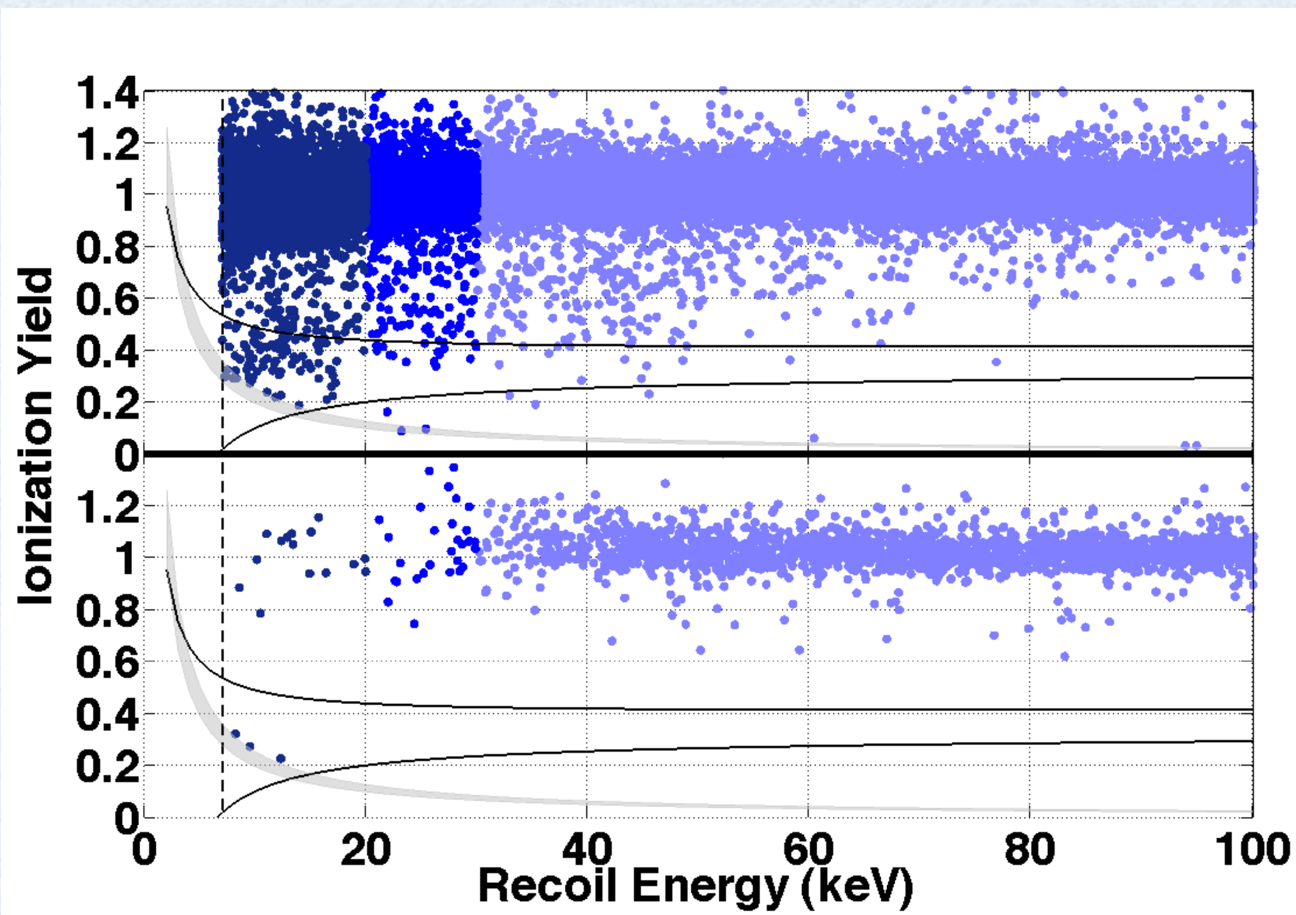
- direct detection is now testing DM-Higgs coupling

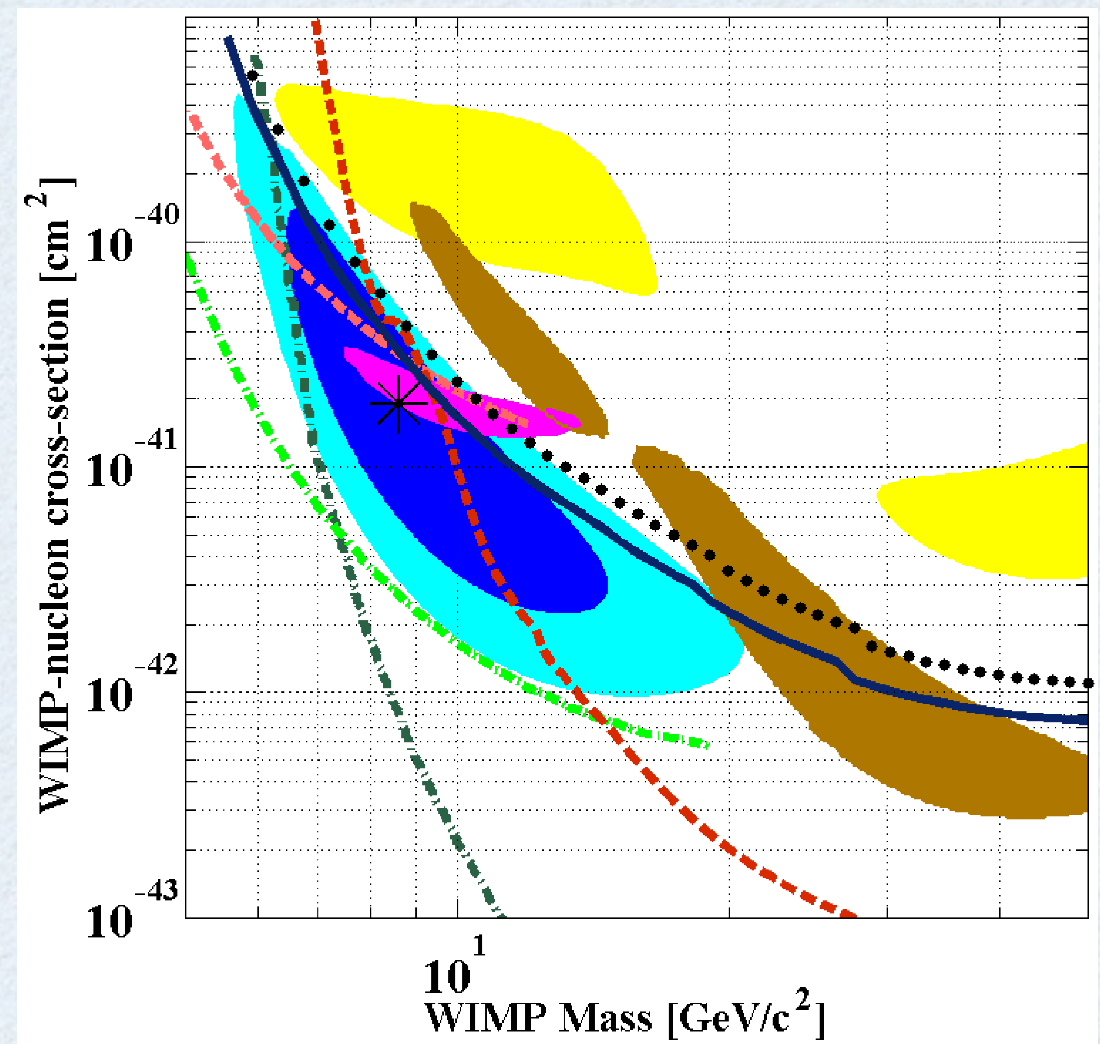
- but there are *blindspots*



backup

CDMS II silicon





gravitino bound

overclosure bound:

$$C_{UV}\,\frac{T_R\tilde{m}^2}{m_{3/2}} + C_{FI}\,\frac{\tilde{m}^3}{m_{3/2}} + C_{FO}\,\frac{\tilde{m}m_{3/2}}{\alpha_{\rm eff}^2} \;\leq\; aM_{\rm Pl}T_{\rm eq}$$

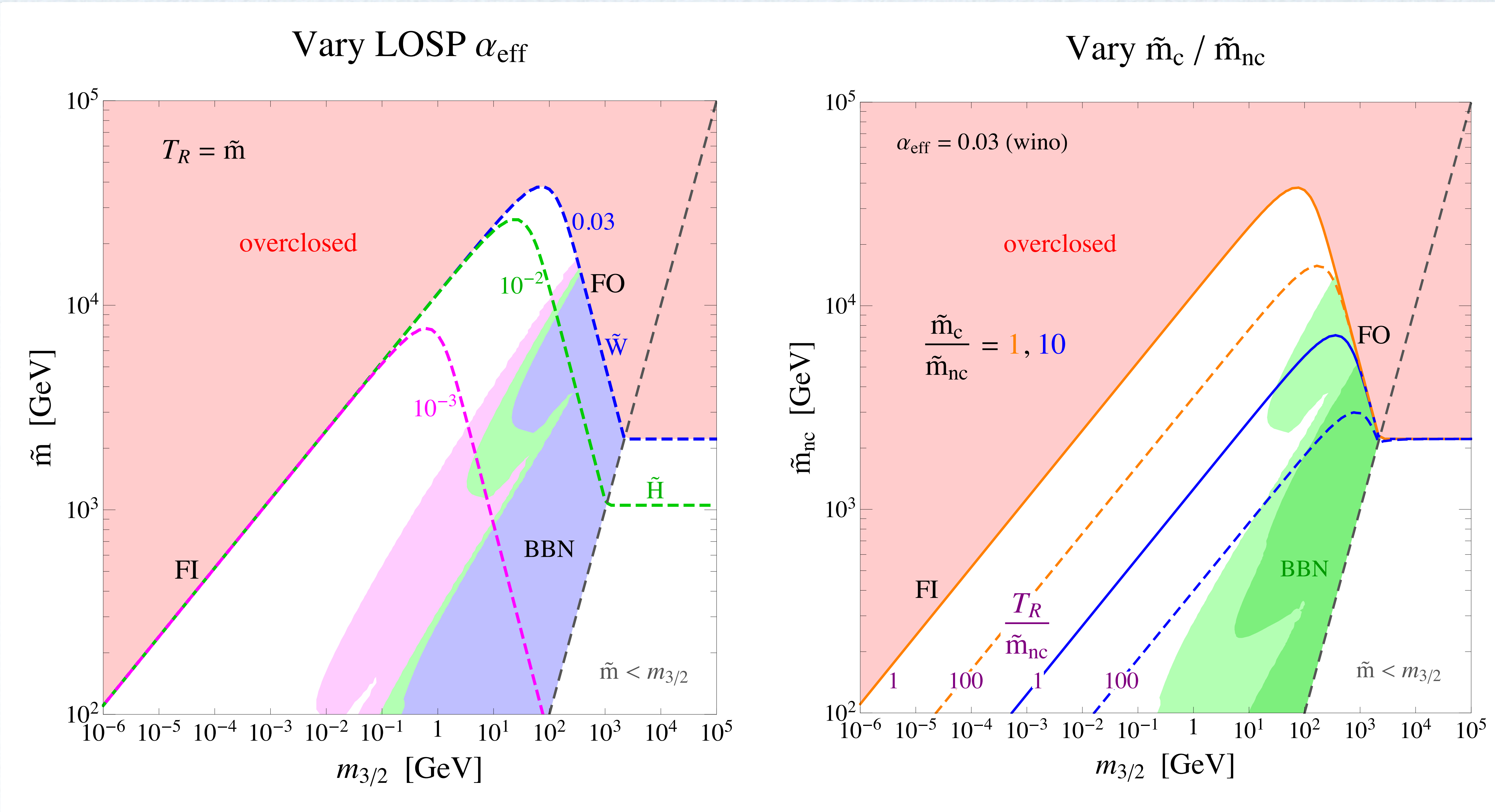
rate coefficients:

$$C_{UV} = \gamma_3\frac{15\sqrt{90}}{2\pi^3 g_*^{3/2}} \qquad C_{FI} \;=\; \frac{405}{2\pi^4}\sqrt{\frac{5}{2}}\frac{1}{g_*^{3/2}}\frac{n_{FI}}{4\pi} \qquad C_{FO} \;=\; \frac{3\sqrt{5}\,x_f}{8\sqrt{2}\,g_*\pi^2}$$

superpartner mass bound: $m_{3/2} = \sqrt{\dfrac{C_D}{C_{FO}}}\,\alpha_{eff}\,\tilde{m}$

$$\tilde{m}^2 \;\leq\; \frac{a/2}{\sqrt{C_{FO}C_D}}\,\alpha_{\rm eff}\,M_{Pl}\,T_{eq} \qquad C_D = C_{UV}(T_R/\tilde{m}) + C_{FI}$$

variations on gravitino bound



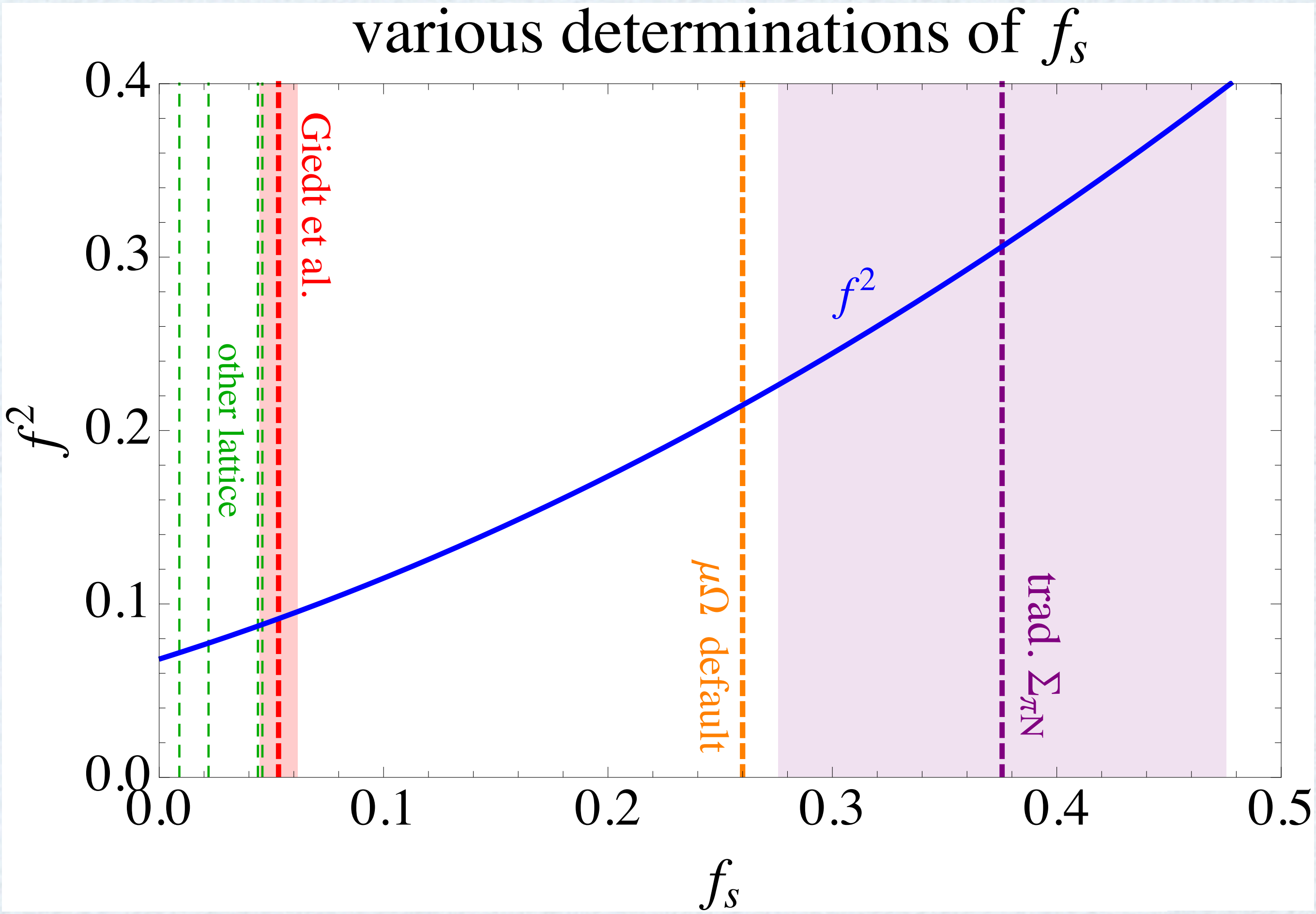
neutralino mass matrix

$$\begin{pmatrix} M_1 & 0 & -\frac{g' \cos\beta}{\sqrt{2}} v & \frac{g' \sin\beta}{\sqrt{2}} v \\ 0 & M_2 & \frac{g \cos\beta}{\sqrt{2}} v & -\frac{g \sin\beta}{\sqrt{2}} v \\ -\frac{g' \cos\beta}{\sqrt{2}} v & \frac{g \cos\beta}{\sqrt{2}} v & 0 & -\mu \\ \frac{g' \sin\beta}{\sqrt{2}} v & -\frac{g \sin\beta}{\sqrt{2}} v & -\mu & 0 \end{pmatrix}$$

strange quark

$$f_q = \frac{m_q}{m_N} \langle N | q\bar{q} | N \rangle \qquad \sigma \propto f^2$$

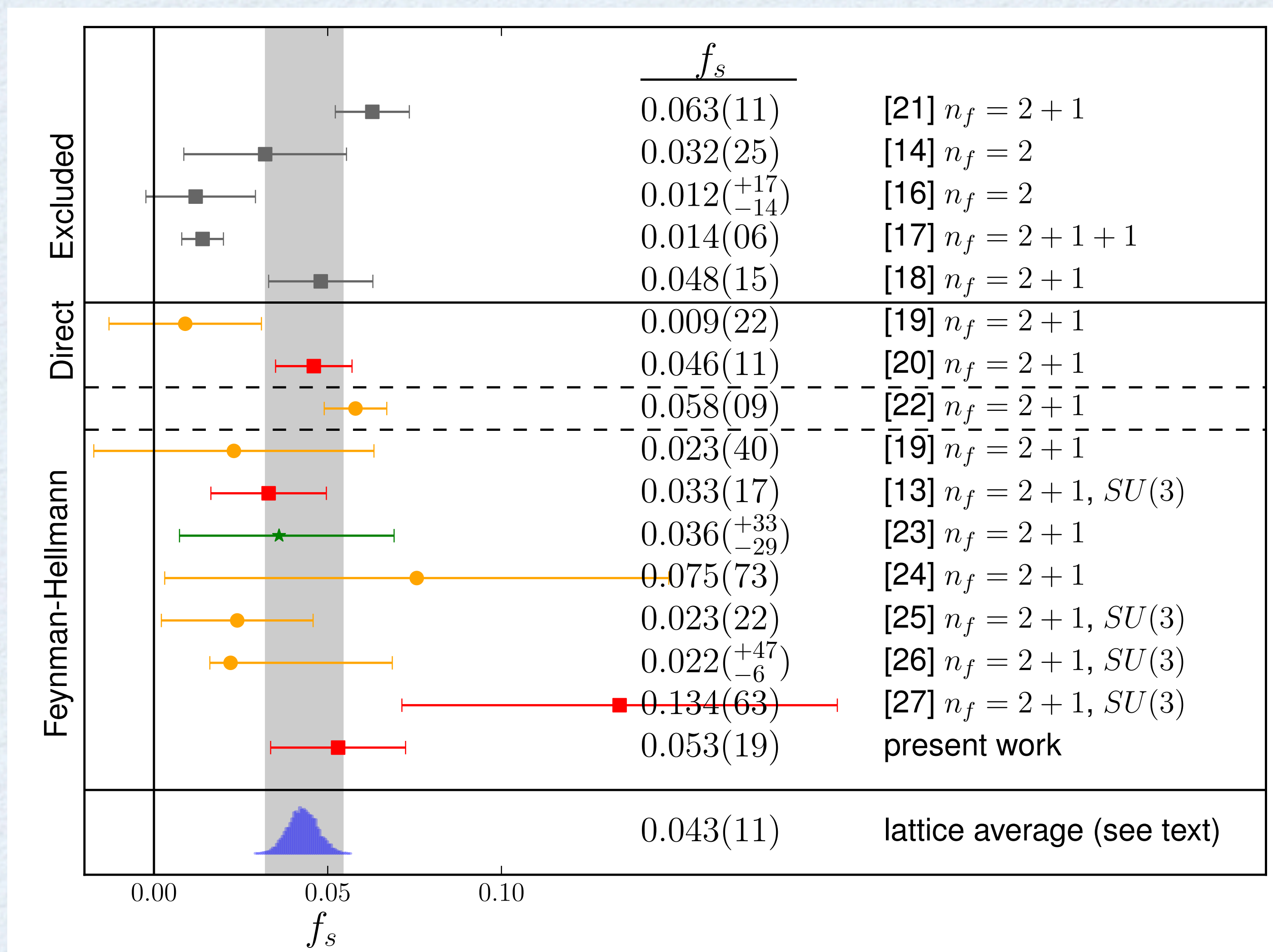
$$f = \Sigma_q f_q$$



strange quark

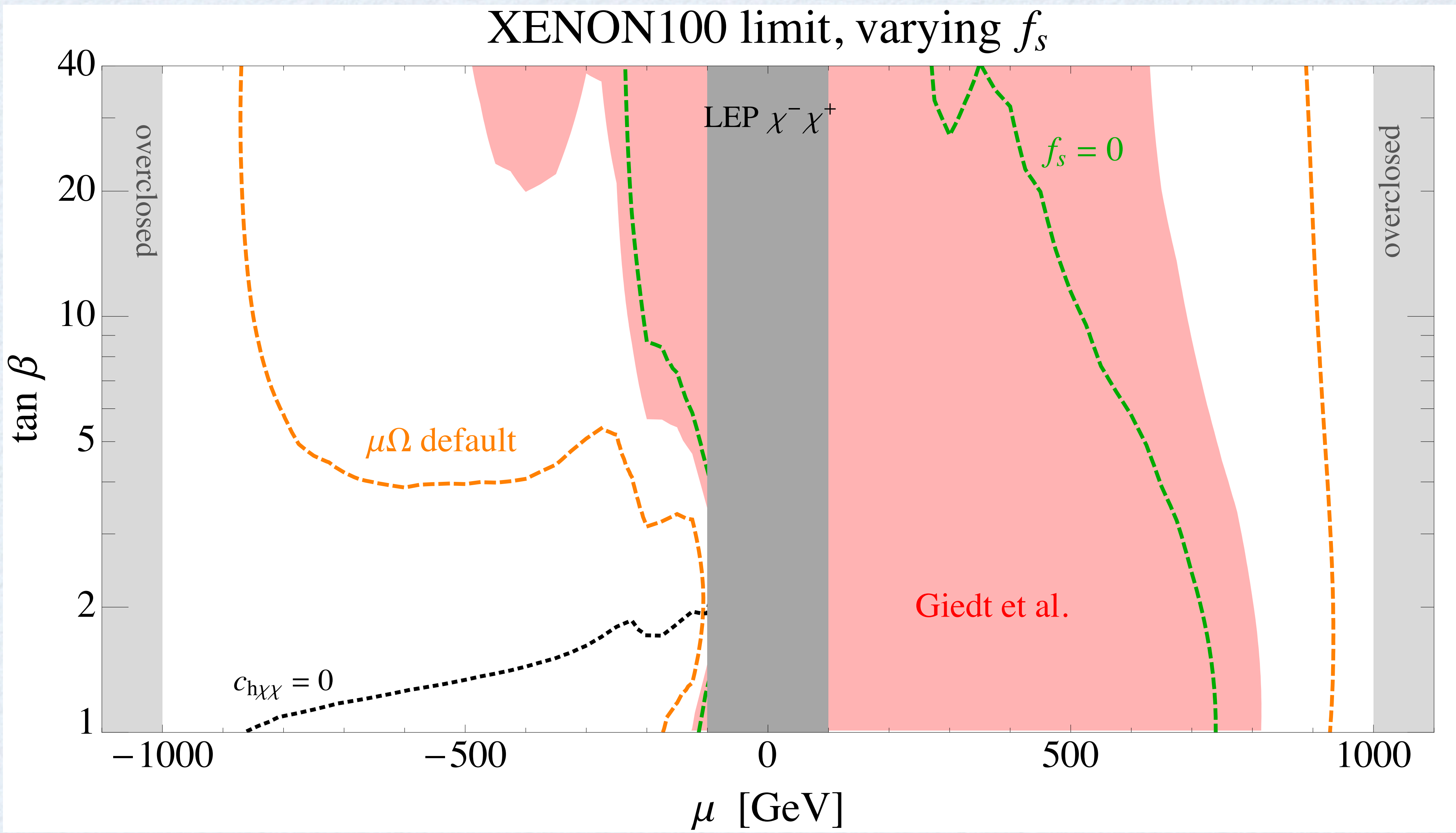
$$f_s = 0.053$$

Giedt, Thomas, Young, 0907.4177

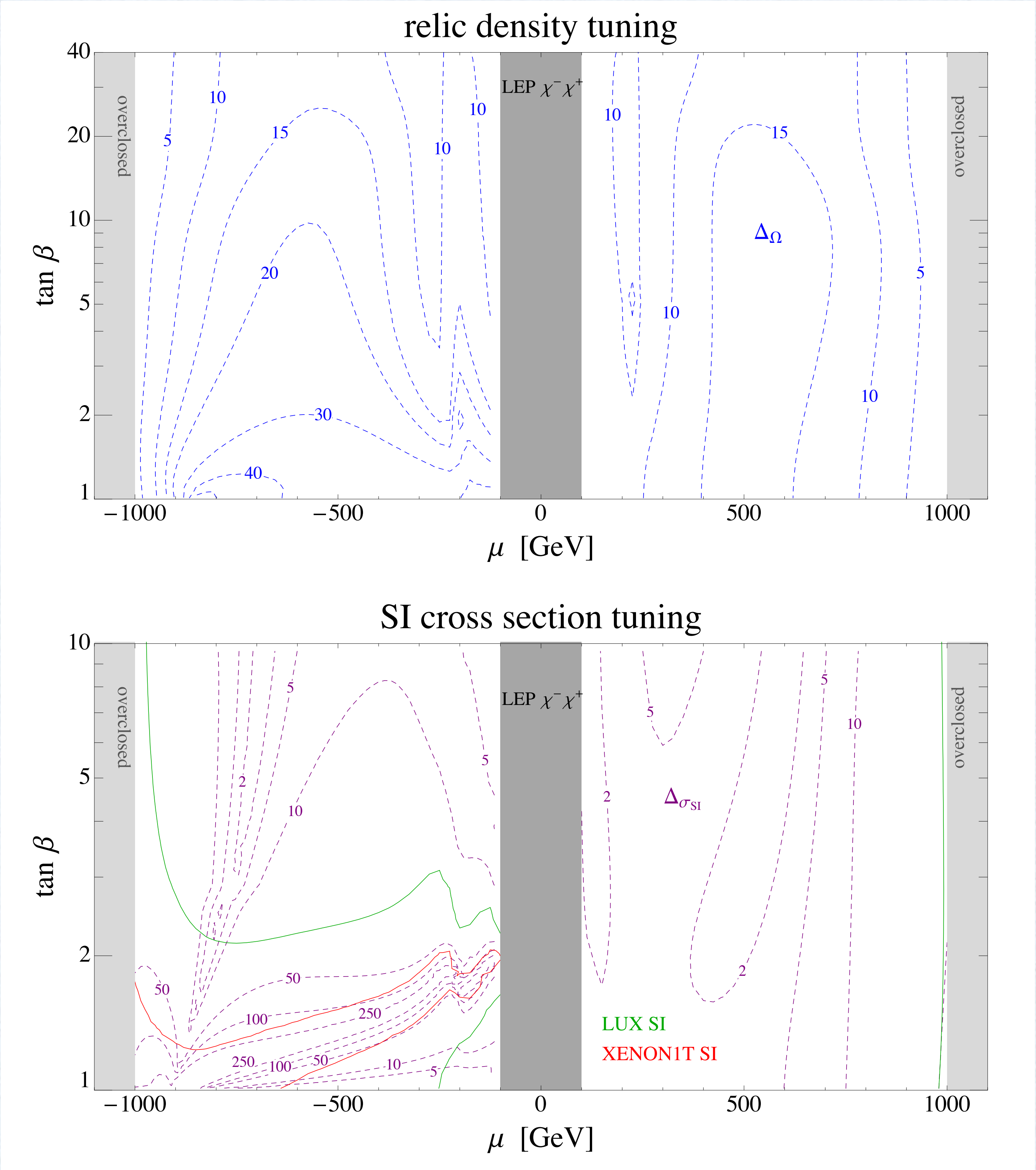


Junnarkar, Walker-Loud 1301.1114

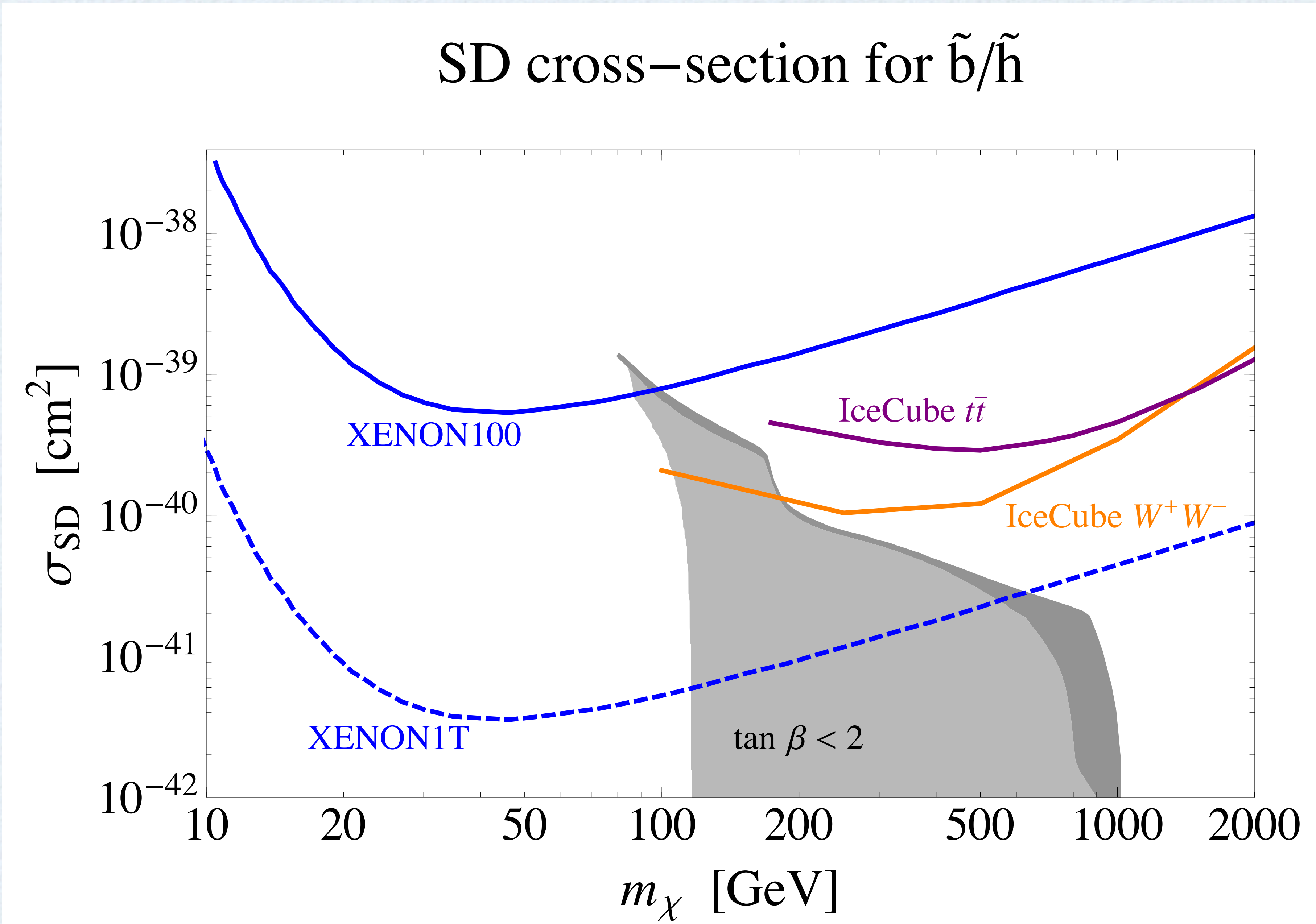
strange quark



tuning



relic density tuning
LEP $\chi^-\chi^+$
overclosed
overclosed
Δ_Ω
tan β
μ [GeV]
SI cross section tuning
LEP $\chi^-\chi^+$
overclosed
overclosed
$\Delta_{\sigma_{SI}}$
LUX SI
XENON1T SI
tan β
μ [GeV]



SD cross−section for b̃/h̃
σ_{SD} [cm^2]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10
20
50
100
200
500
1000
2000
m_χ [GeV]
XENON100
XENON1T
IceCube $t\bar{t}$
IceCube W^+W^-
tan $\beta < 2$

blindspots

$$\mathcal{L} \supset \frac{1}{2} m_\chi (v + h)\ \chi^2 = \frac{1}{2} m_\chi\, \chi^2 + \frac{1}{2} \frac{\partial m_\chi}{\partial v}\, h\, \chi^2 + \ldots$$

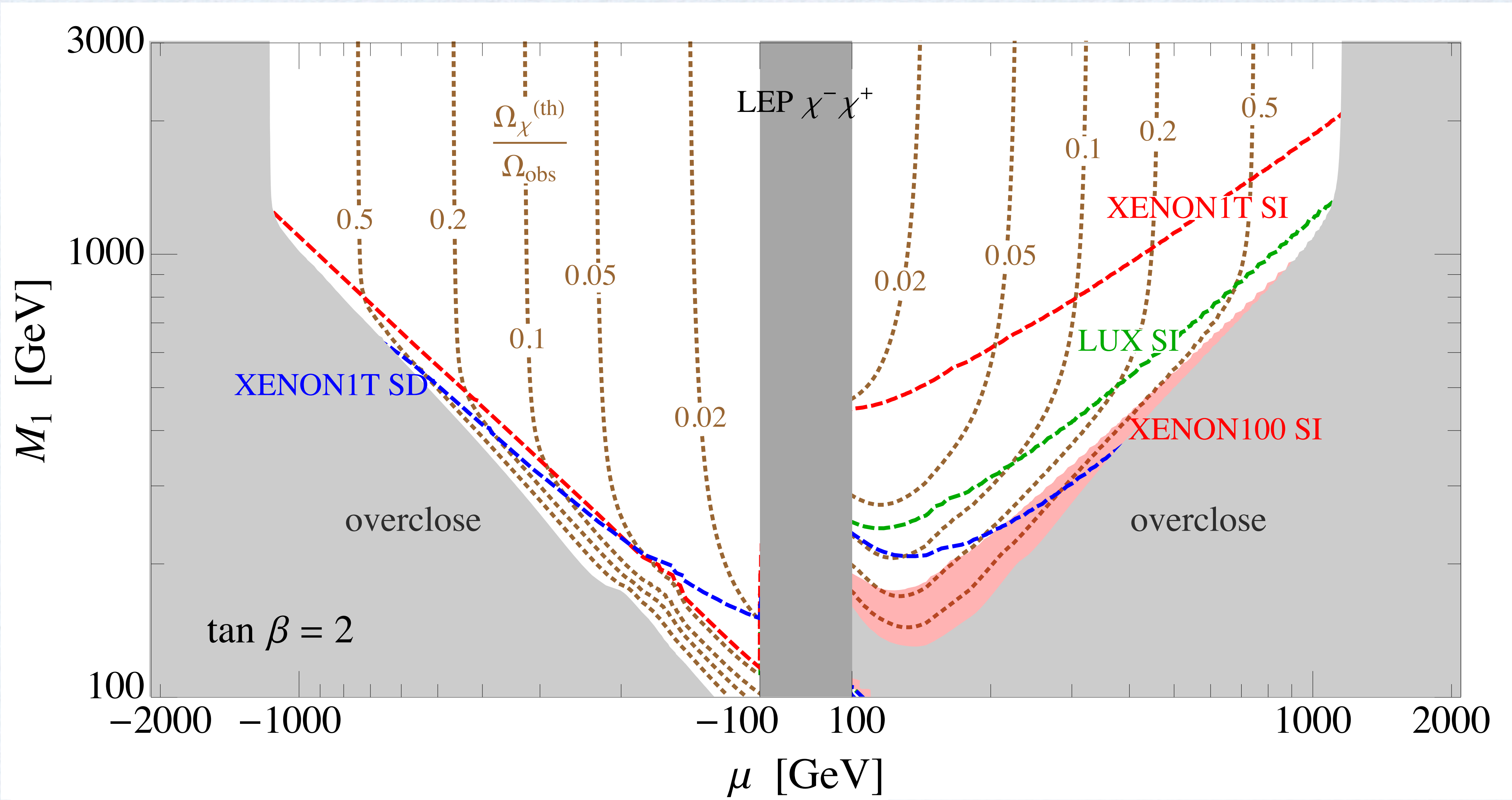
Higgs-DM-DM coupling:

$$c_{h\chi\chi} = \frac{\partial m_\chi}{\partial v} = 0$$

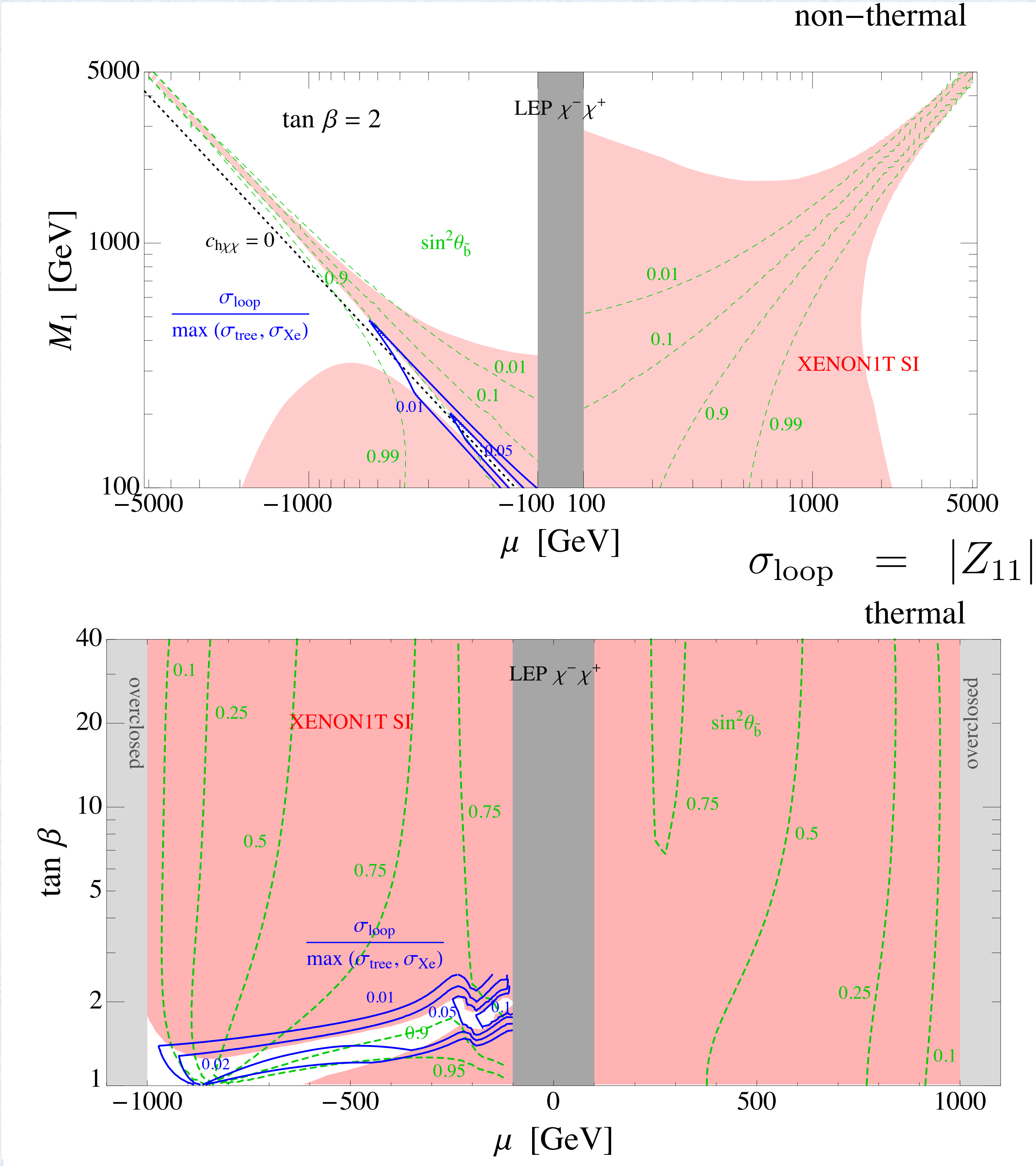
$$\det(M_\chi - \mathbb{1} m_{\chi_i}(v)) \quad = \quad 0$$

$$(m_{\chi_i}(v) + \mu \sin 2\beta) \left(m_{\chi_i}(v) - \frac{1}{2}(M_1 + M_2 + \cos 2\theta_W (M_1 - M_2)) \right) \quad = \quad 0$$

multi-component

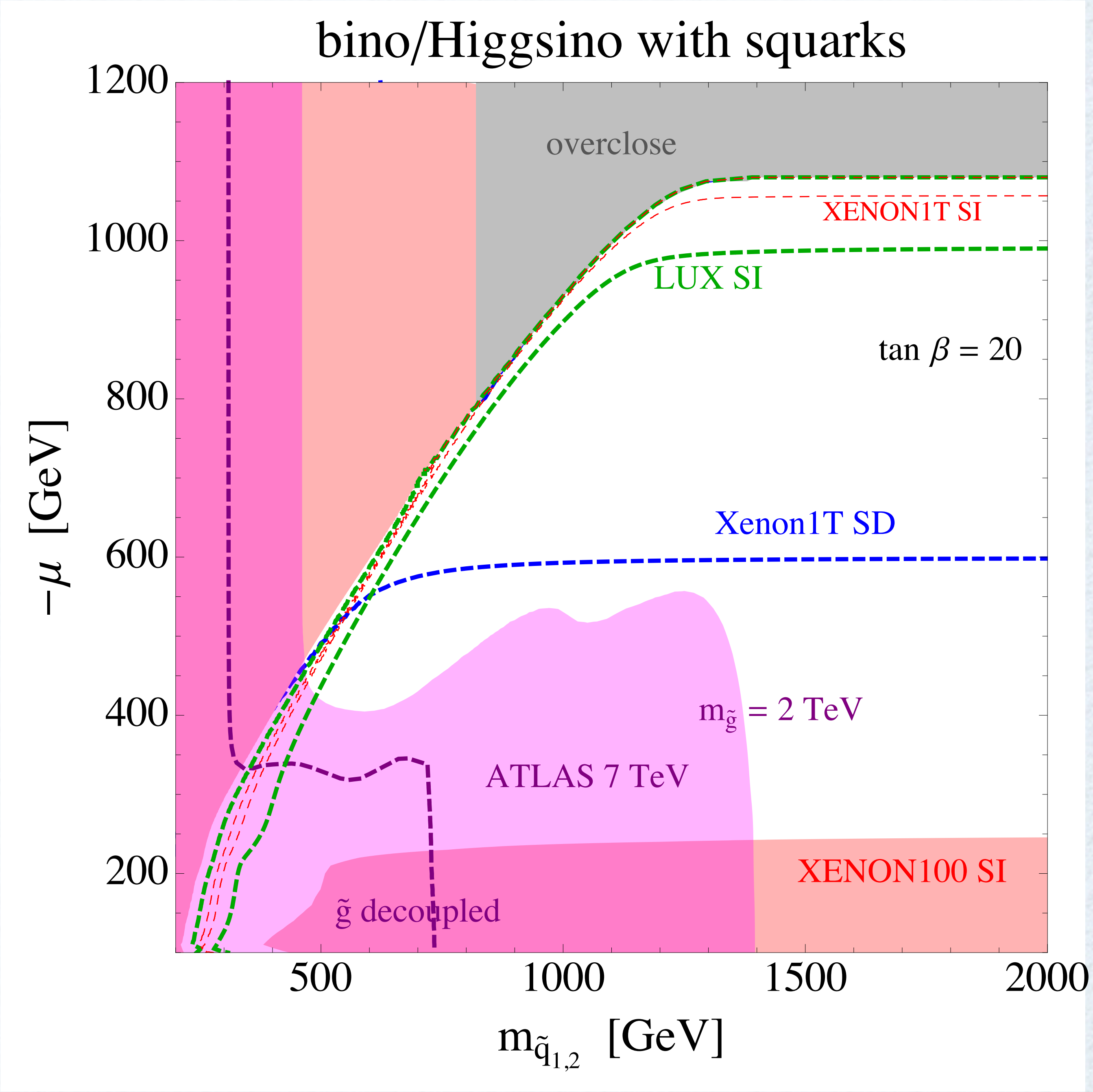


loop

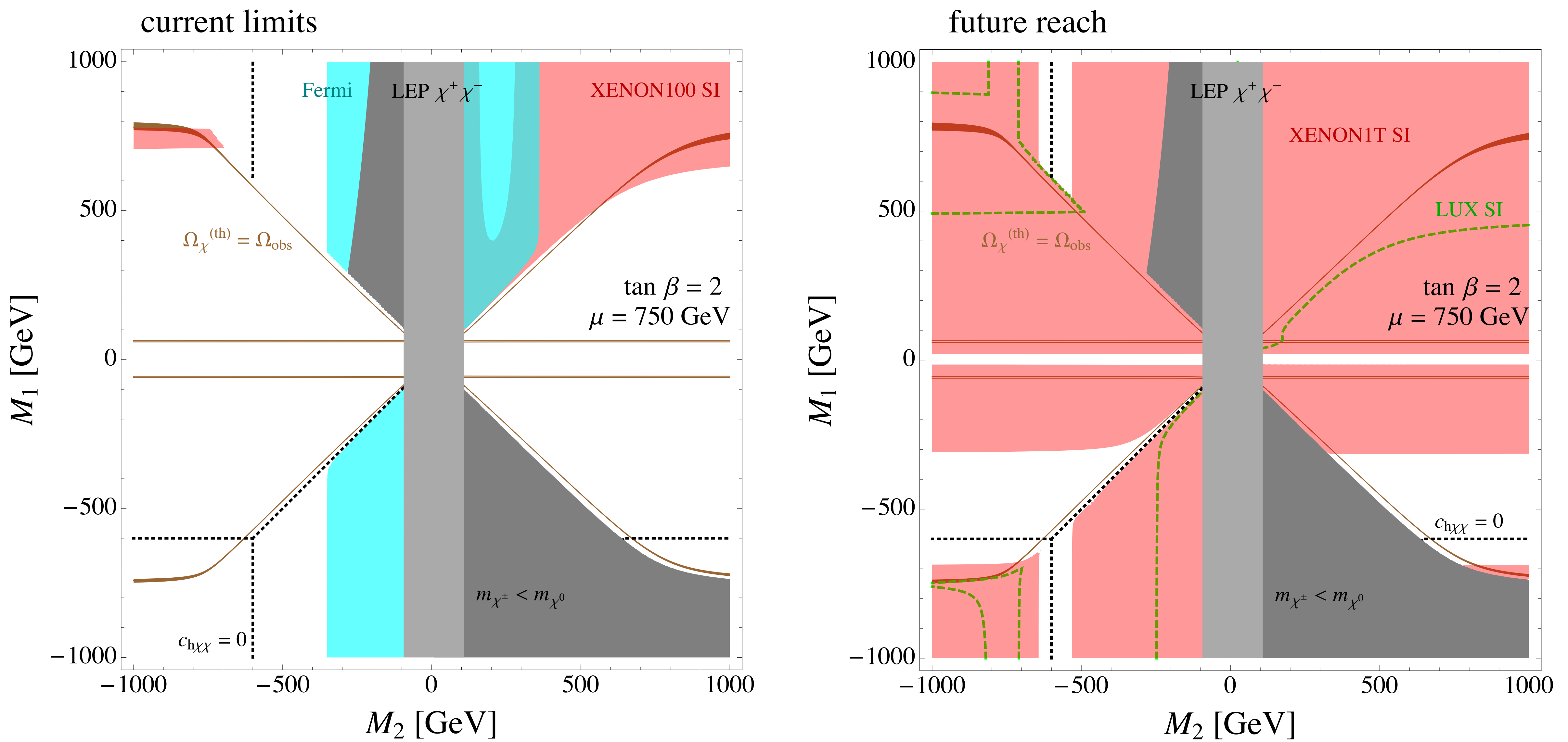


$$\sigma_{\rm loop} \;=\; |Z_{11}|^2(1-|Z_{11}|^2)\times(2\times10^{-47}\ {\rm cm}^2)$$

with squarks



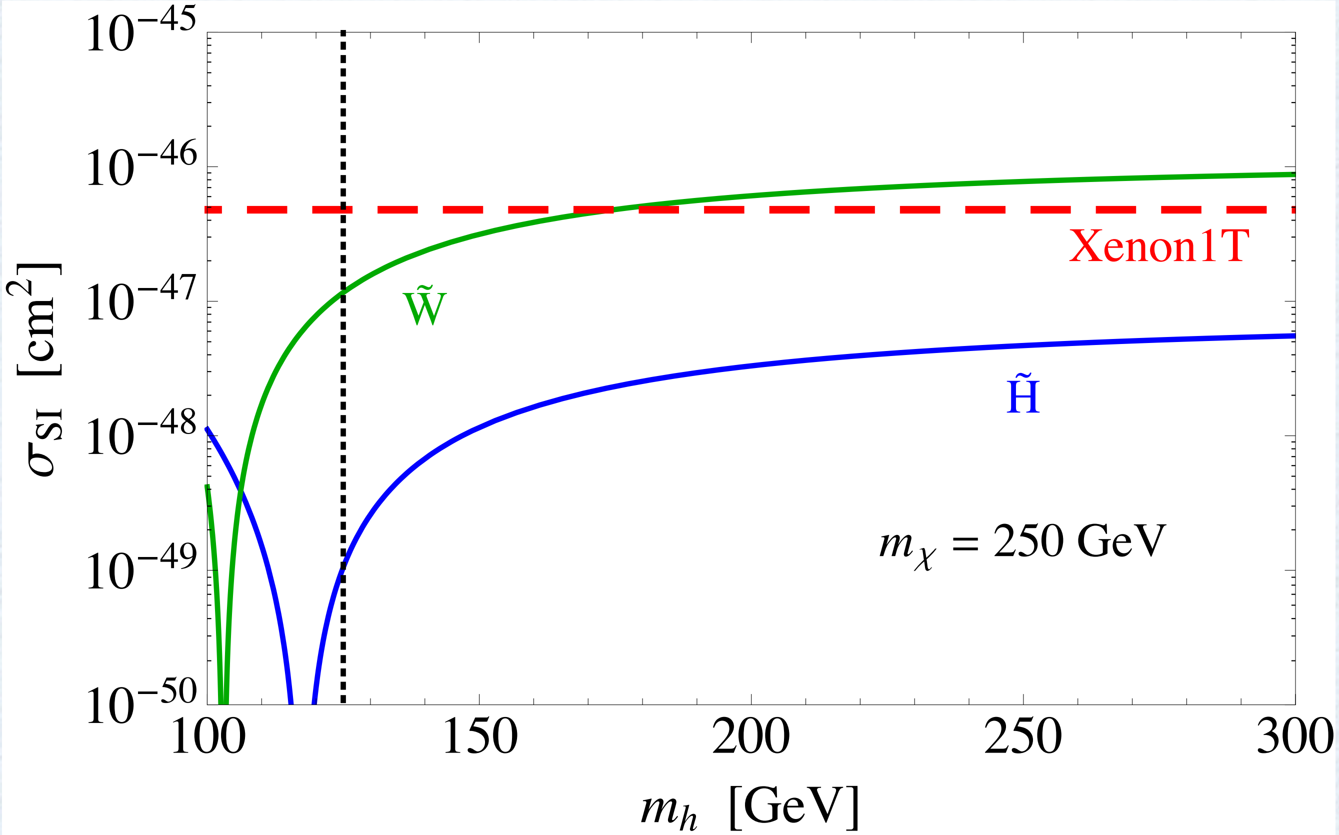
non−thermal $\tilde{B}/\tilde{W}/\tilde{h}$

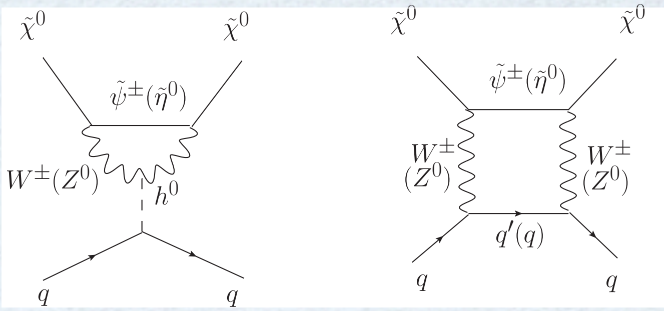


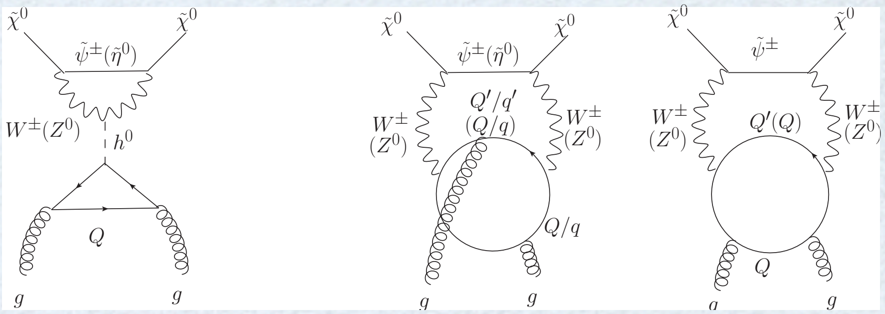
purity

- tree-level Higgs coupling vanishes for pure higgsino or Wino

- loop contribution smaller than expected







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