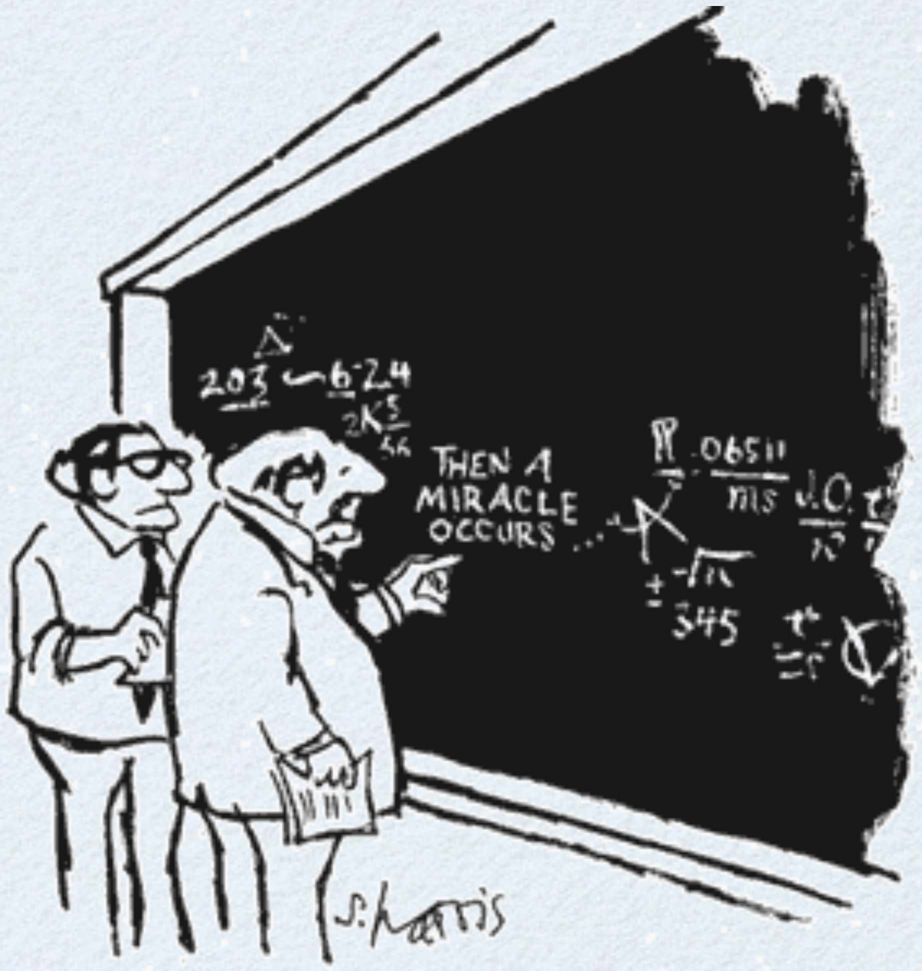
Gravitino Miracle

Josh Ruderman
UC Berkeley

@GGI, July 12, 2013



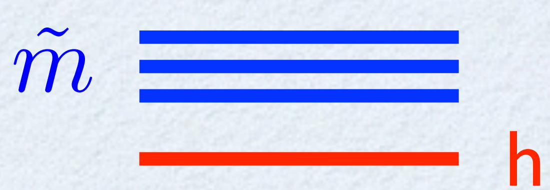
Lawrence Hall, JTR, Tomer Volansky, 1302.2620

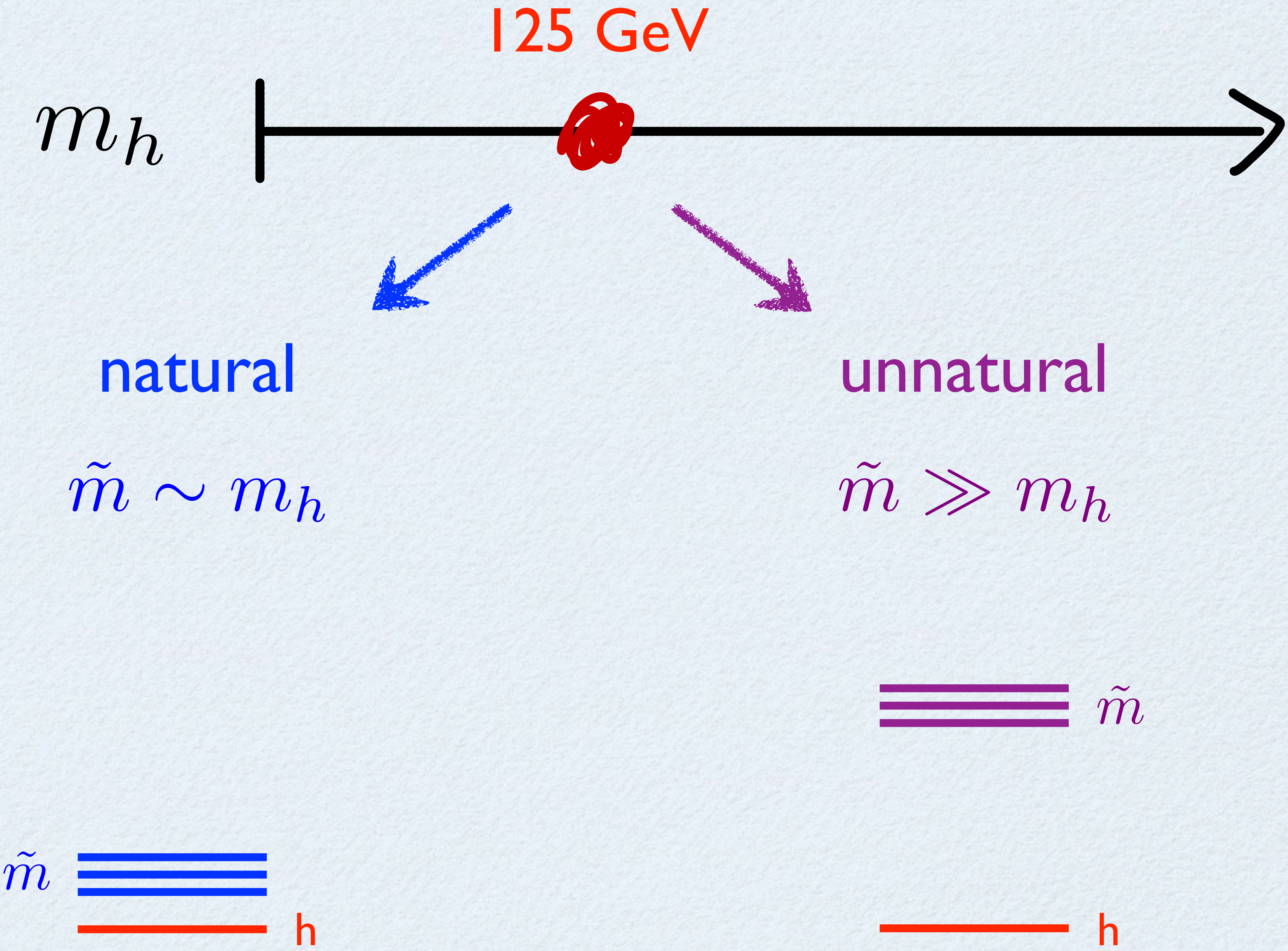
$$m_h \longmapsto$$


125 GeV
m_h

natural

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



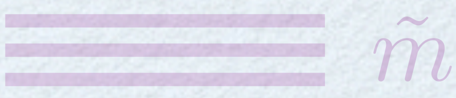

125 GeV
m_h
natural
unnatural
$\tilde{m} \sim m_h$
$\tilde{m} \gg m_h$
$\tilde{m}$
h
$\tilde{m}$
h

natural

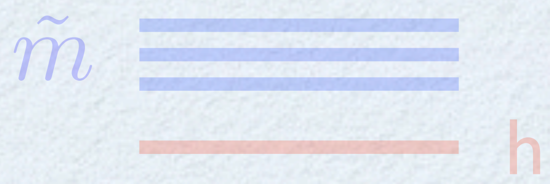
$$\tilde{m} \sim m_h$$

unnatural

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



For this talk, I am agnostic about naturalness.



a finely tuned world?

- what is $\tilde{m}$?

a finely tuned world?

- what is $\tilde{m}$?

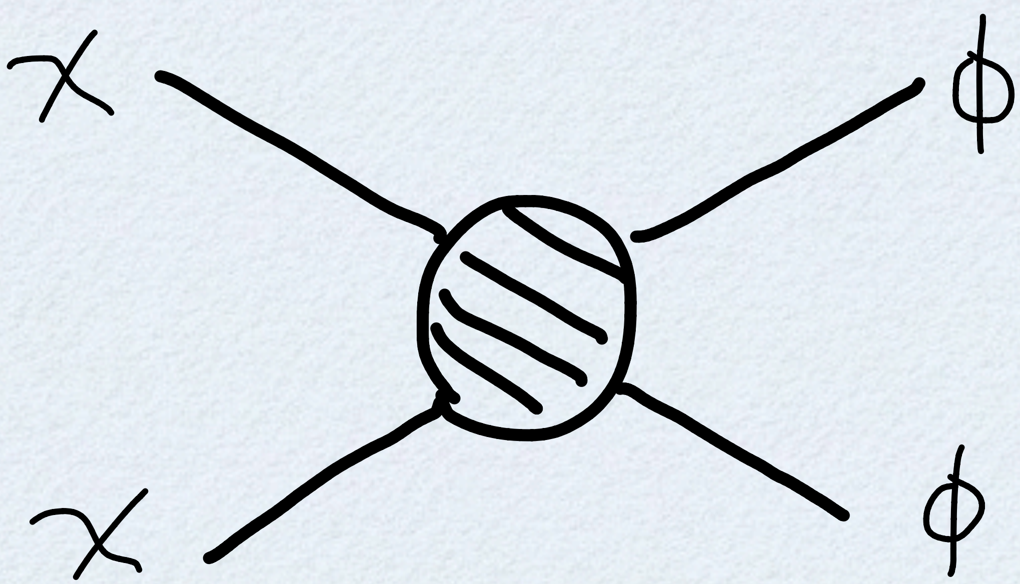
cosmological constraints on $\tilde{m}$?

plan

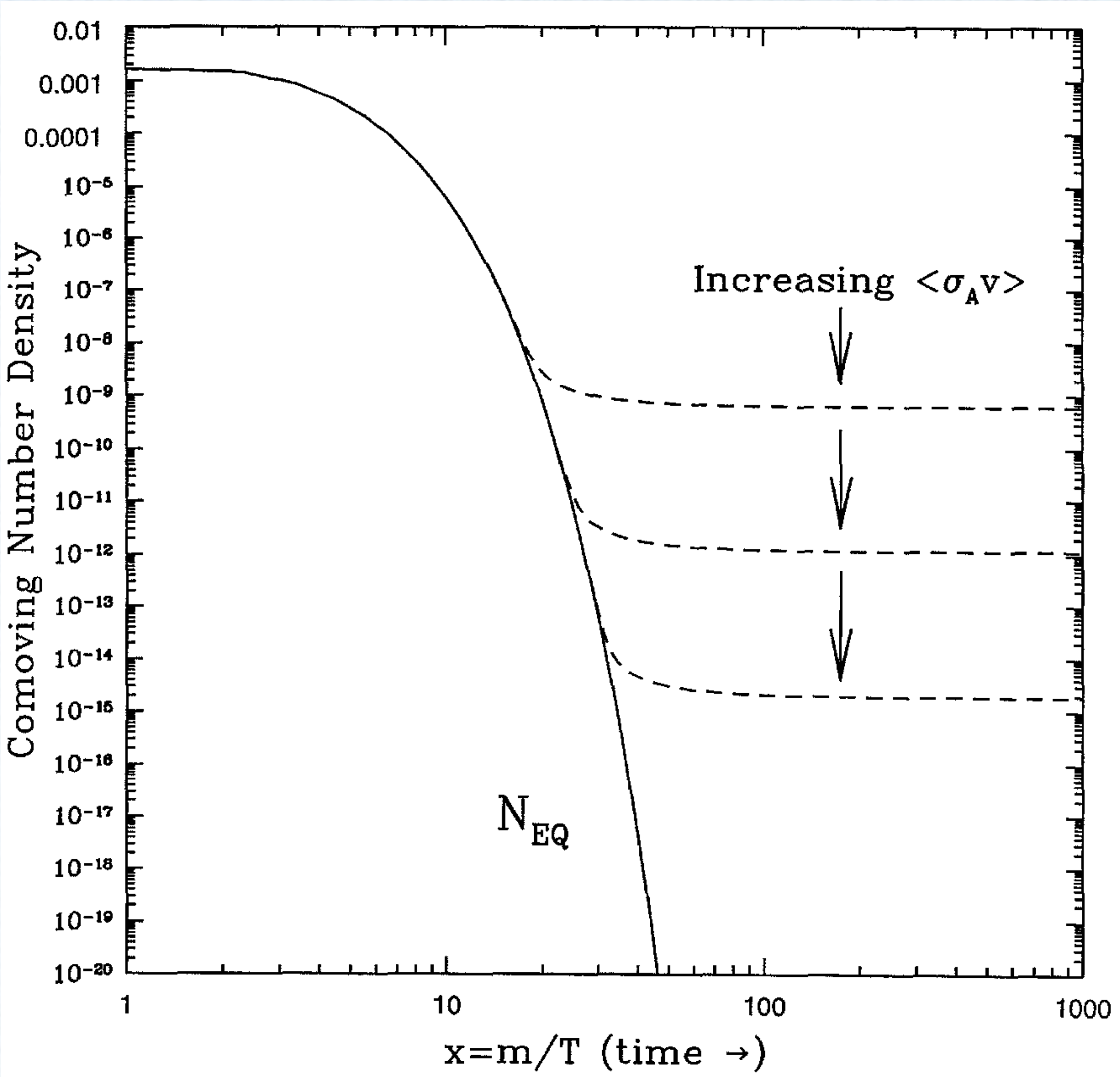
1. WIMP miracle
2. gravitino miracle
3. split with gravitino LSP

WIMP miracle

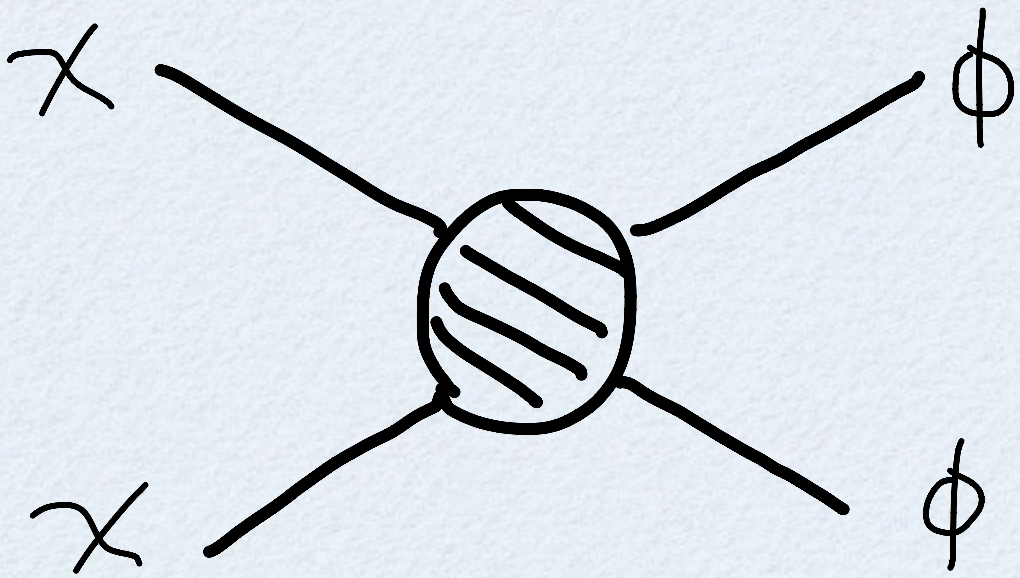
WIMP miracle



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



WIMP miracle



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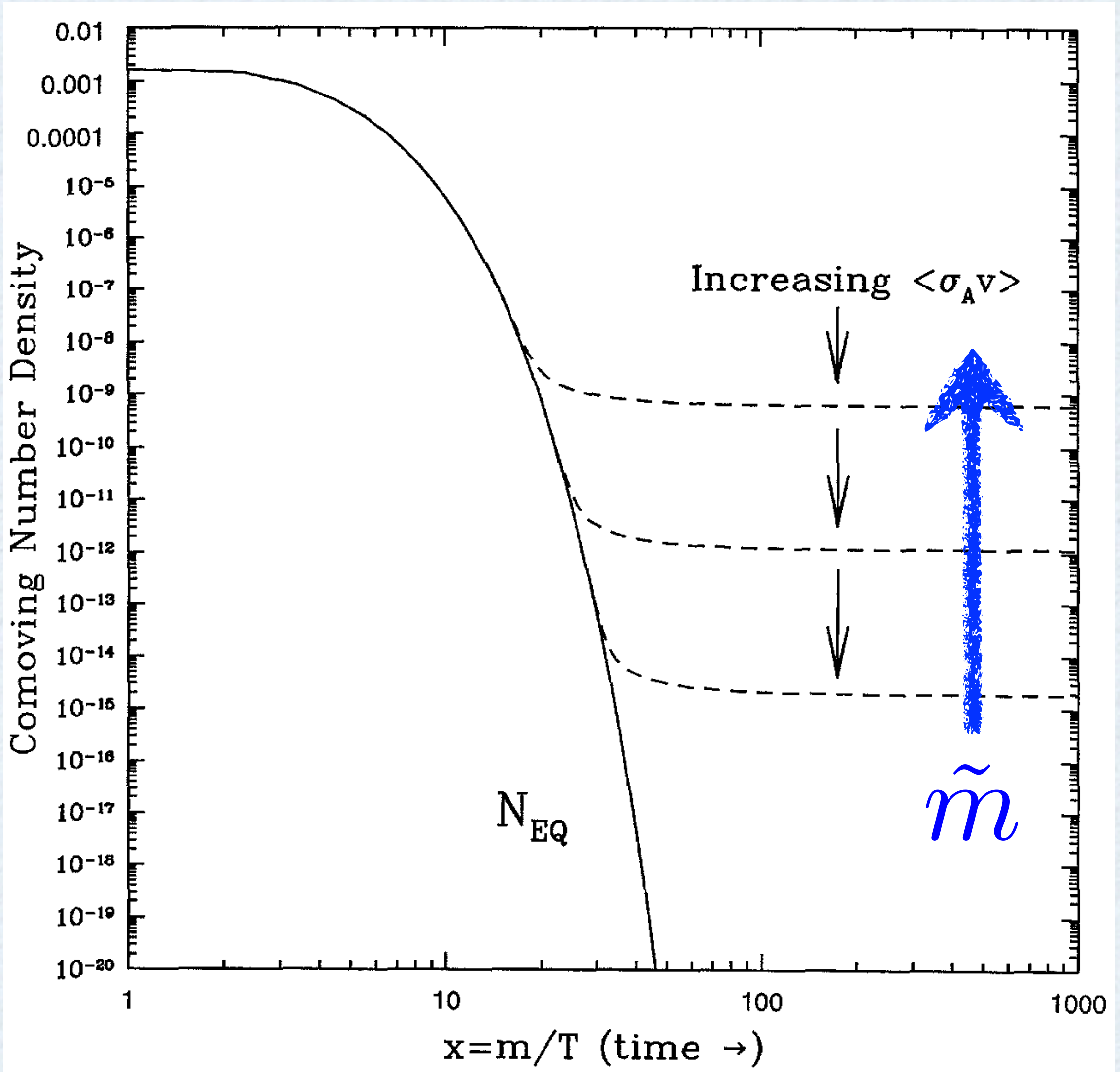
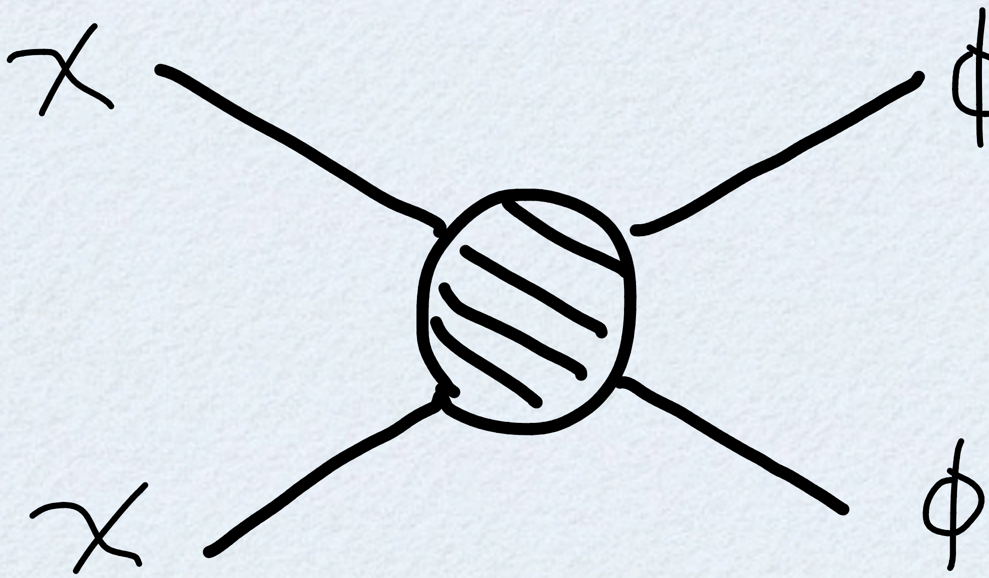


WIMP miracle



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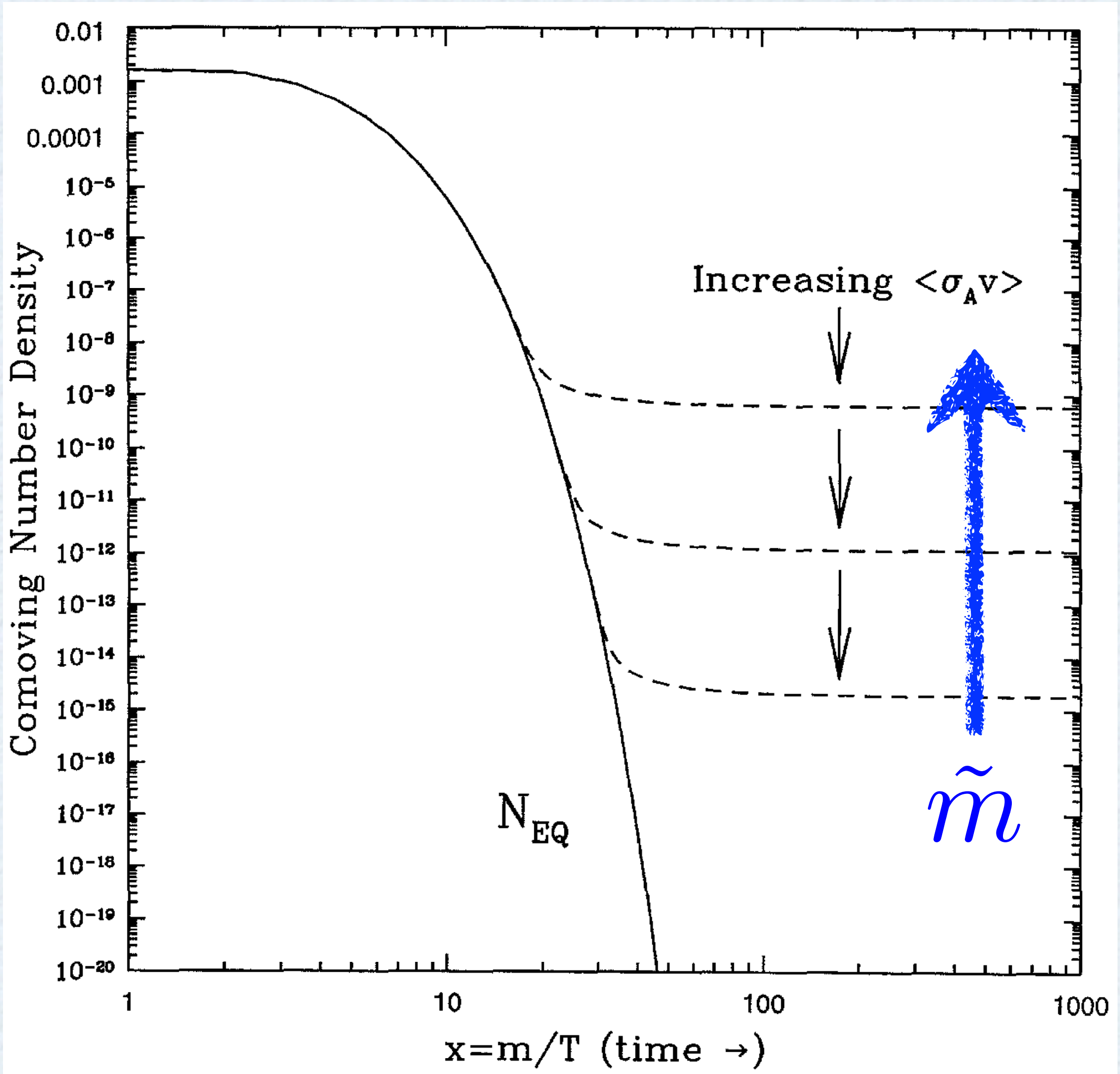
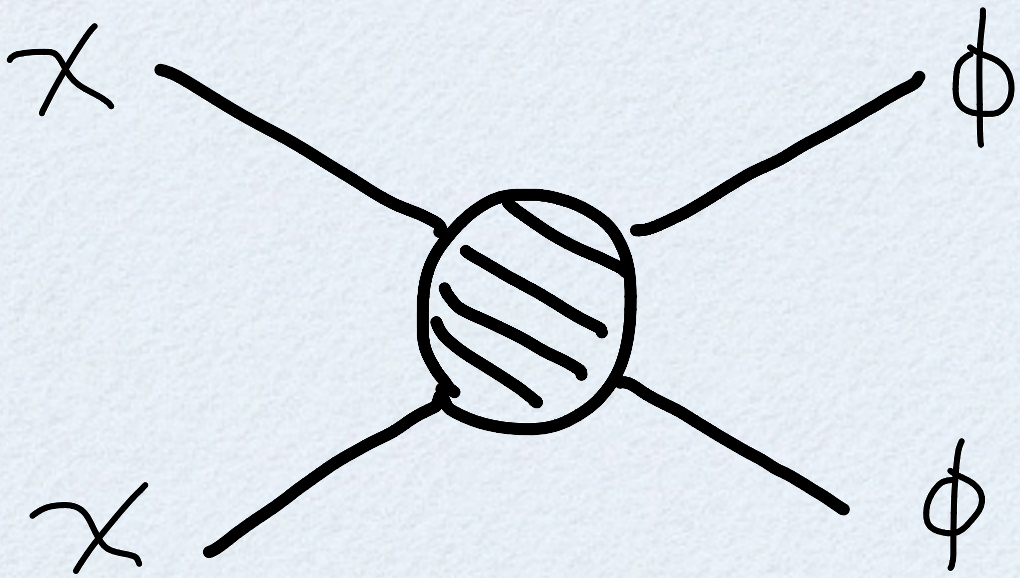
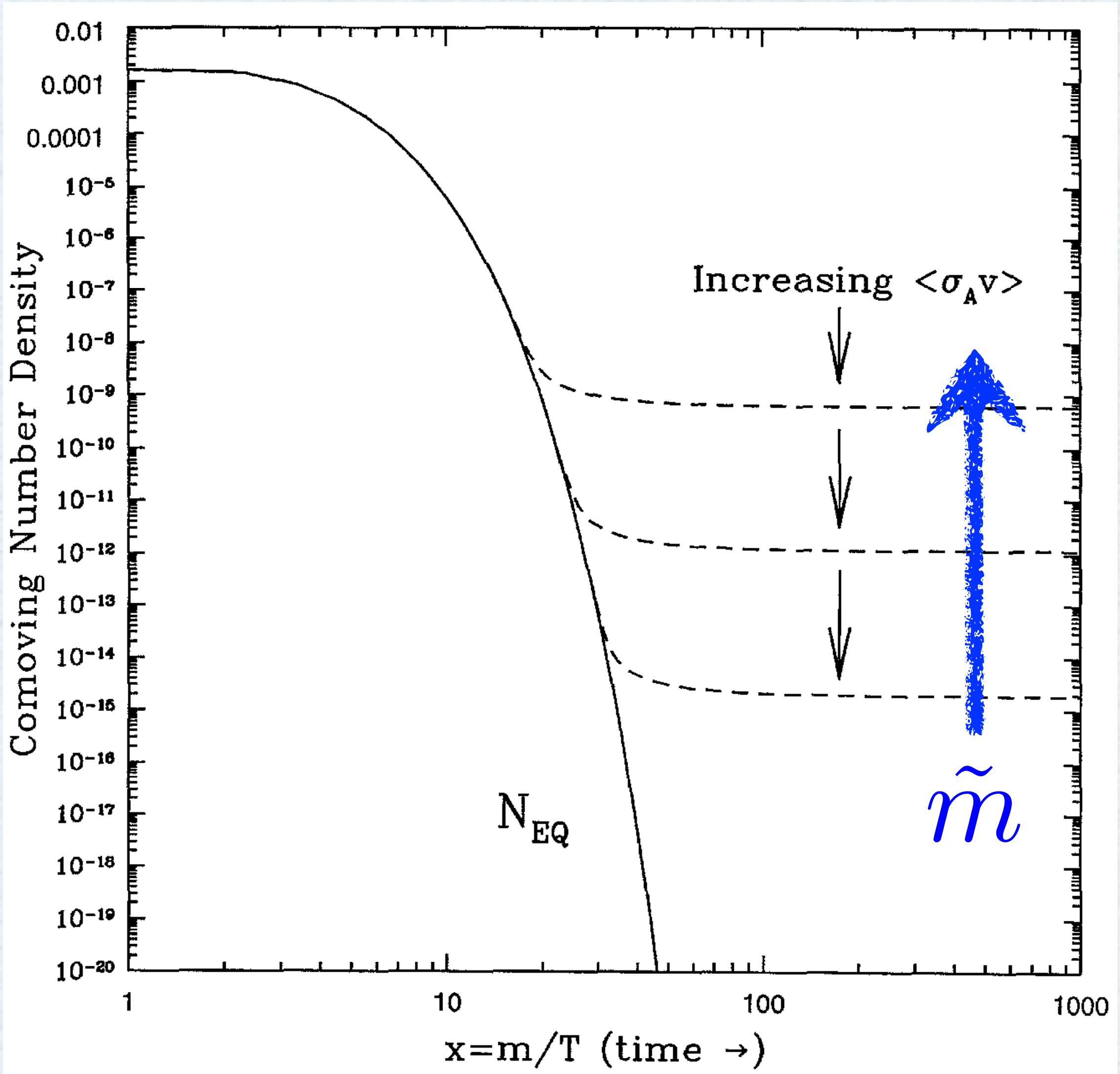


$$Y_{FO} \equiv \frac{n_{FO}}{s} \qquad \tilde{m}\, Y_{FO} \leq T_{eq}$$

WIMP miracle





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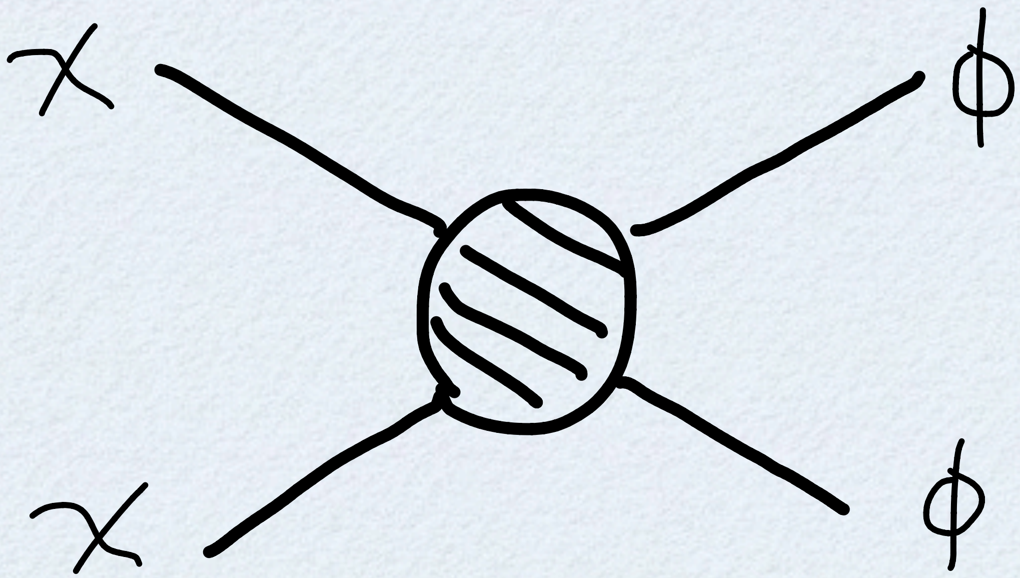
$$Y_{FO} \equiv \frac{n_{FO}}{s} \qquad \tilde{m}\, Y_{FO} \leq T_{eq}$$

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

WIMP miracle



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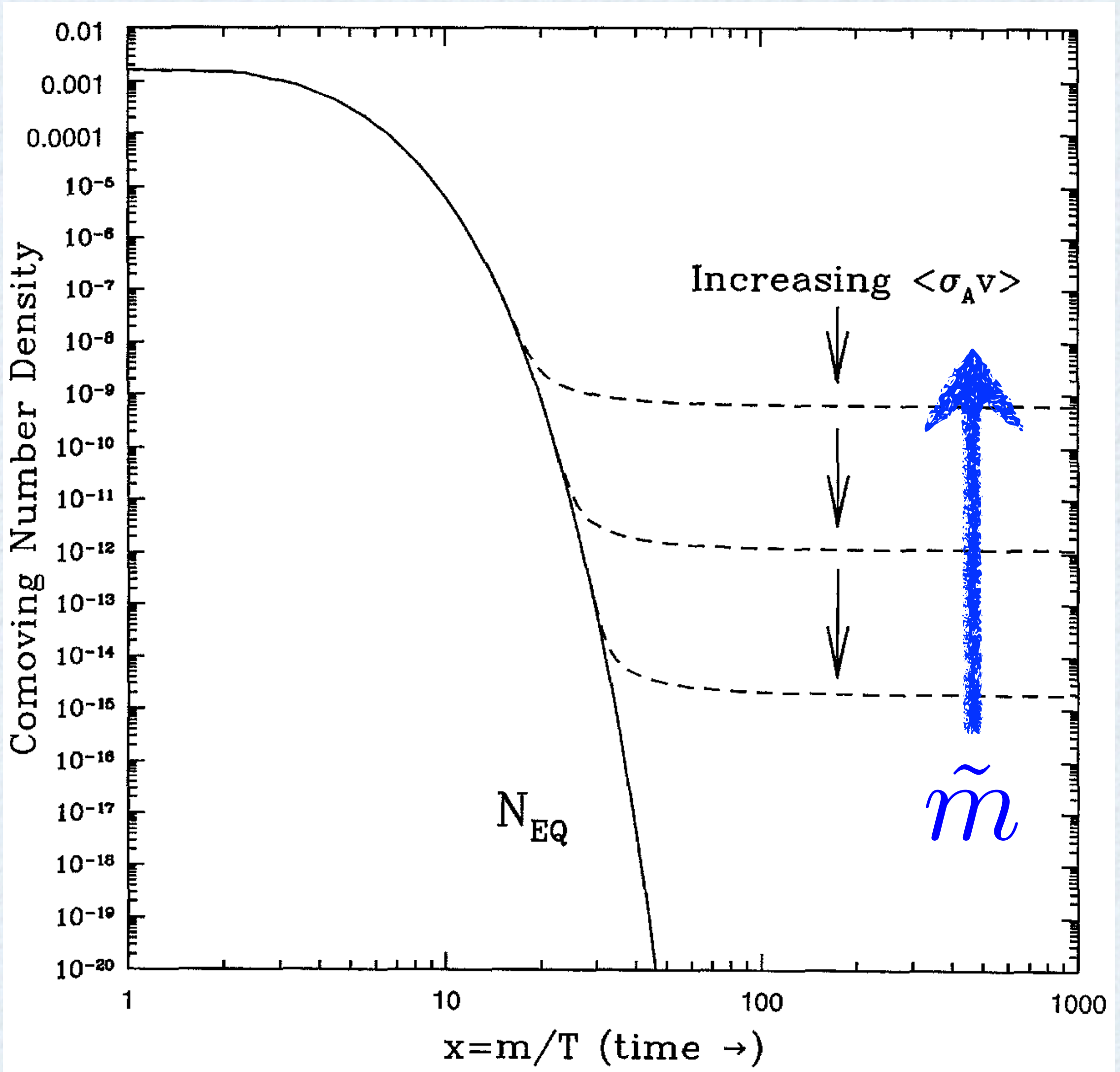

$$Y_{FO} \equiv \frac{n_{FO}}{s}$$

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

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

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

WIMP miracle

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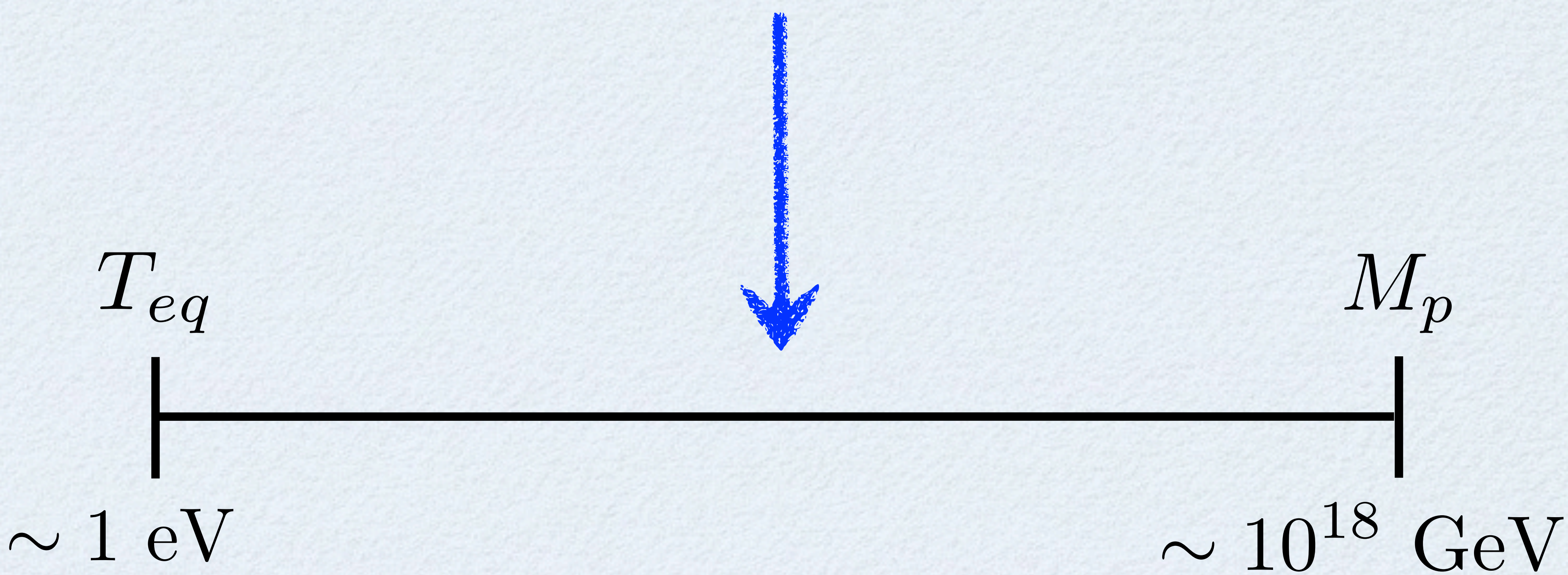

$$\sqrt{T_{eq} M_p} \approx 60 \text{ TeV}$$

WIMP miracle

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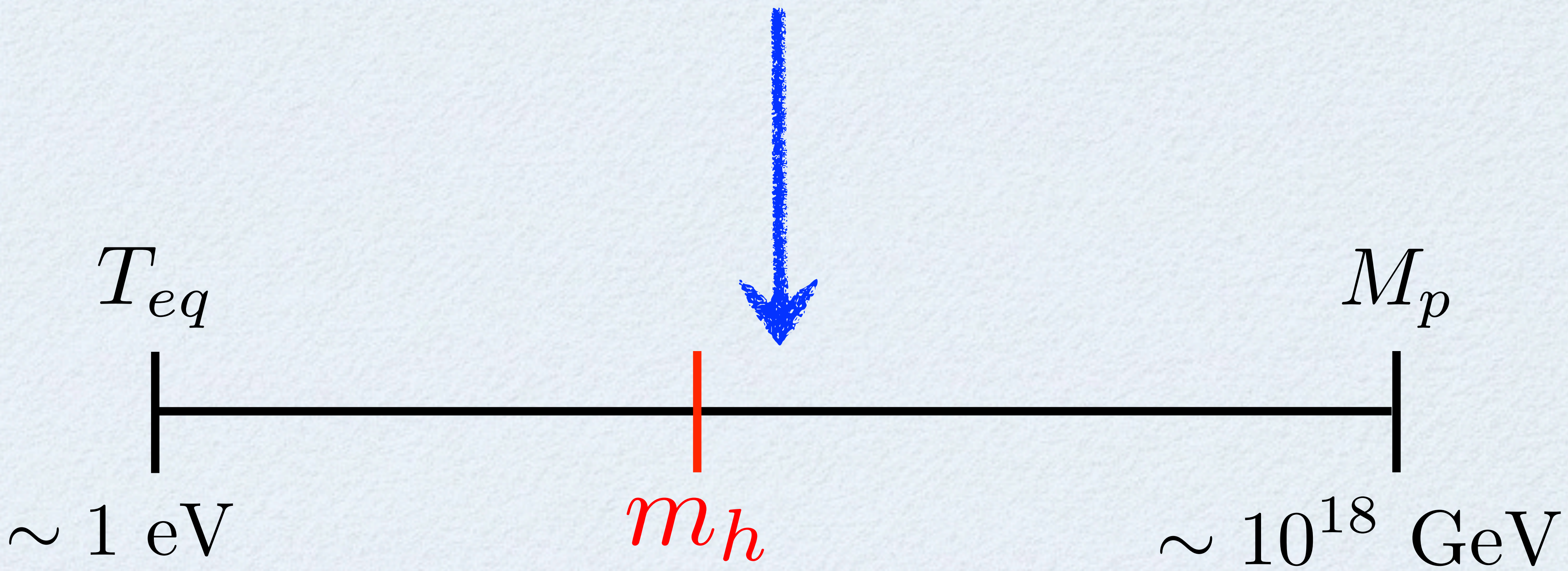

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WIMP miracle

applied to SUSY:

- mass scale of LSP is tied to the weak scale
  - Goldberg, 1983

WIMP miracle

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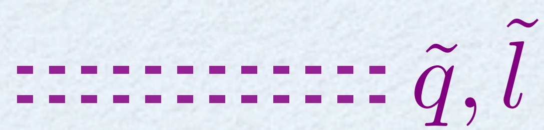
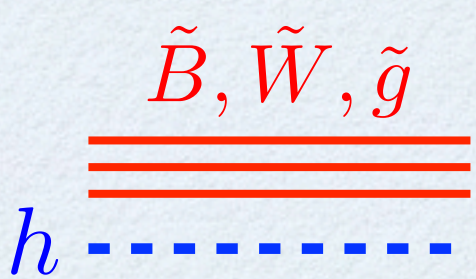
- in Split SUSY, invoked to keep fermions near weak scale





• 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

• Arkani-Hamed, Dimopoulos 2004

- but 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. $T_R > \tilde{m}$

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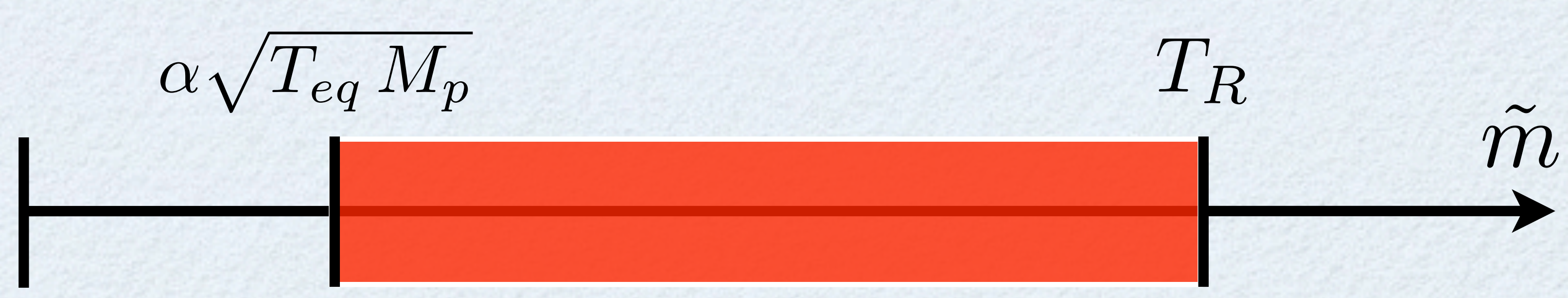

WIMP miracle

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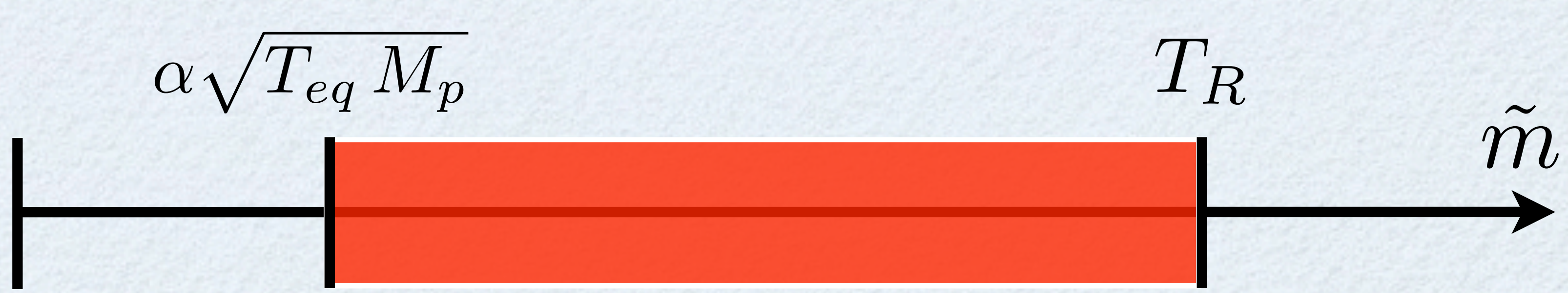

WIMP miracle

key assumptions:

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2. $T_R > \tilde{m}$
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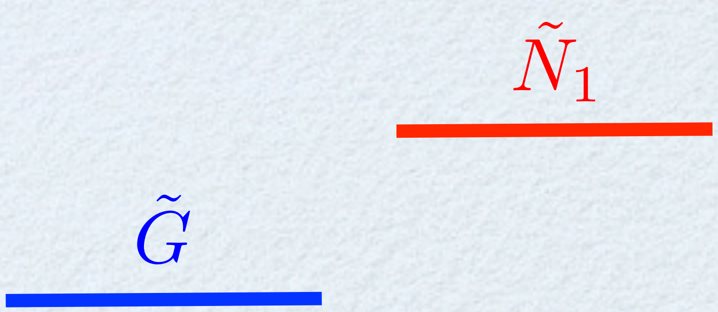
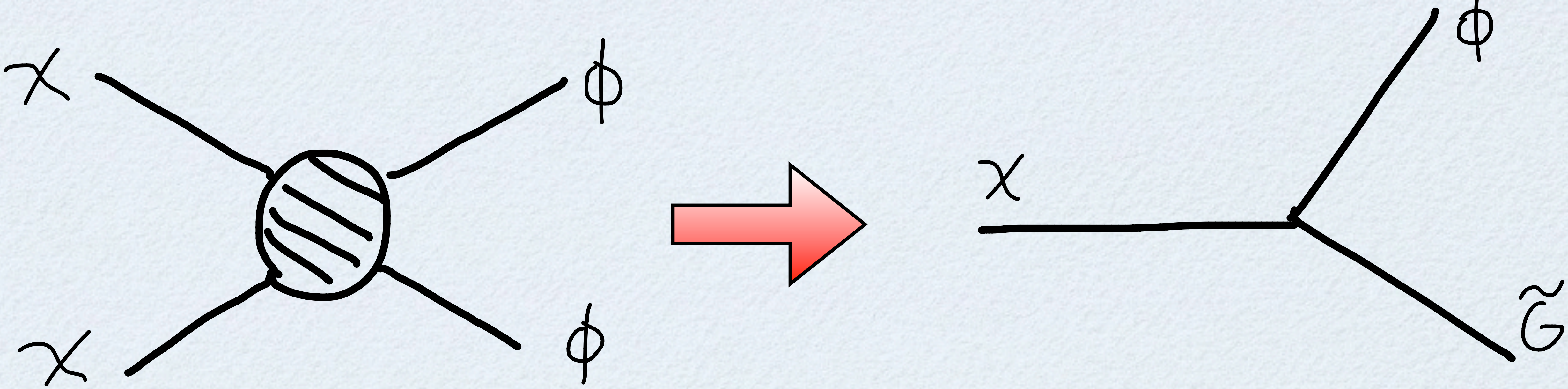
4. LSP reaches equilibrium

what about gravitino LSP?



gravitino miracle

gravitino loophole?

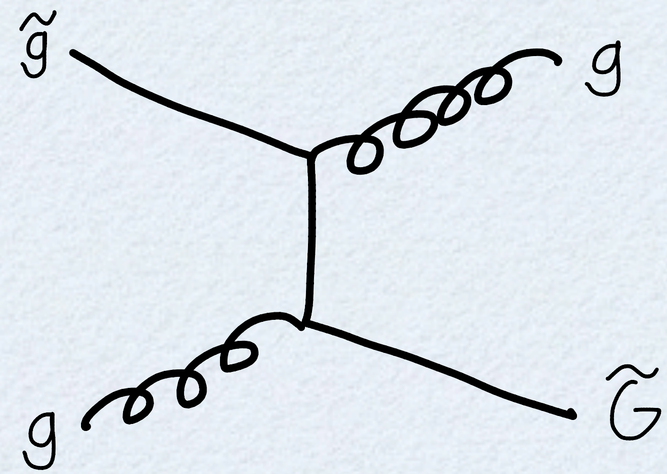


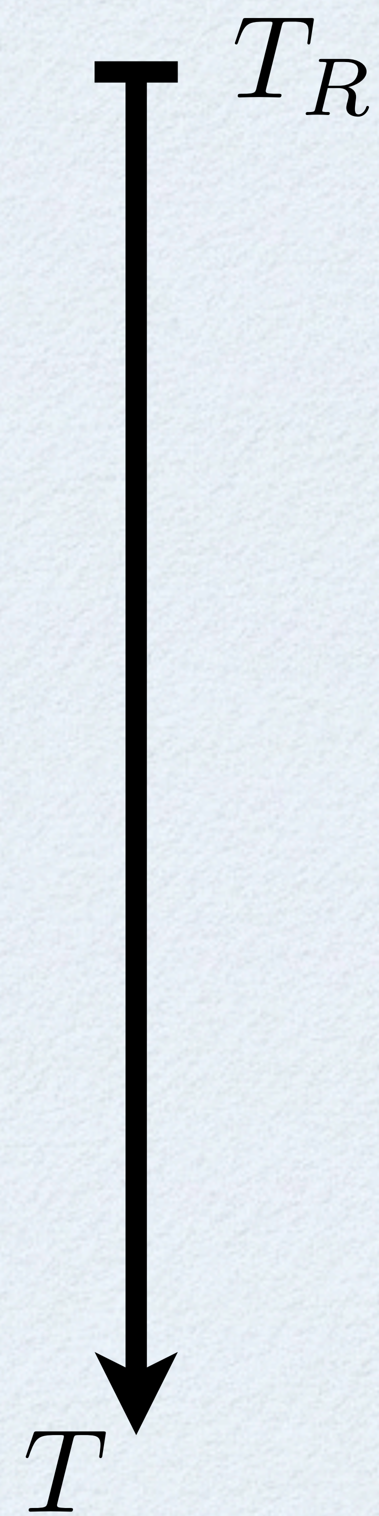
$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\mathrm{NLSP}}}\,\Omega_{\mathrm{NLSP}}$$

gravitino production

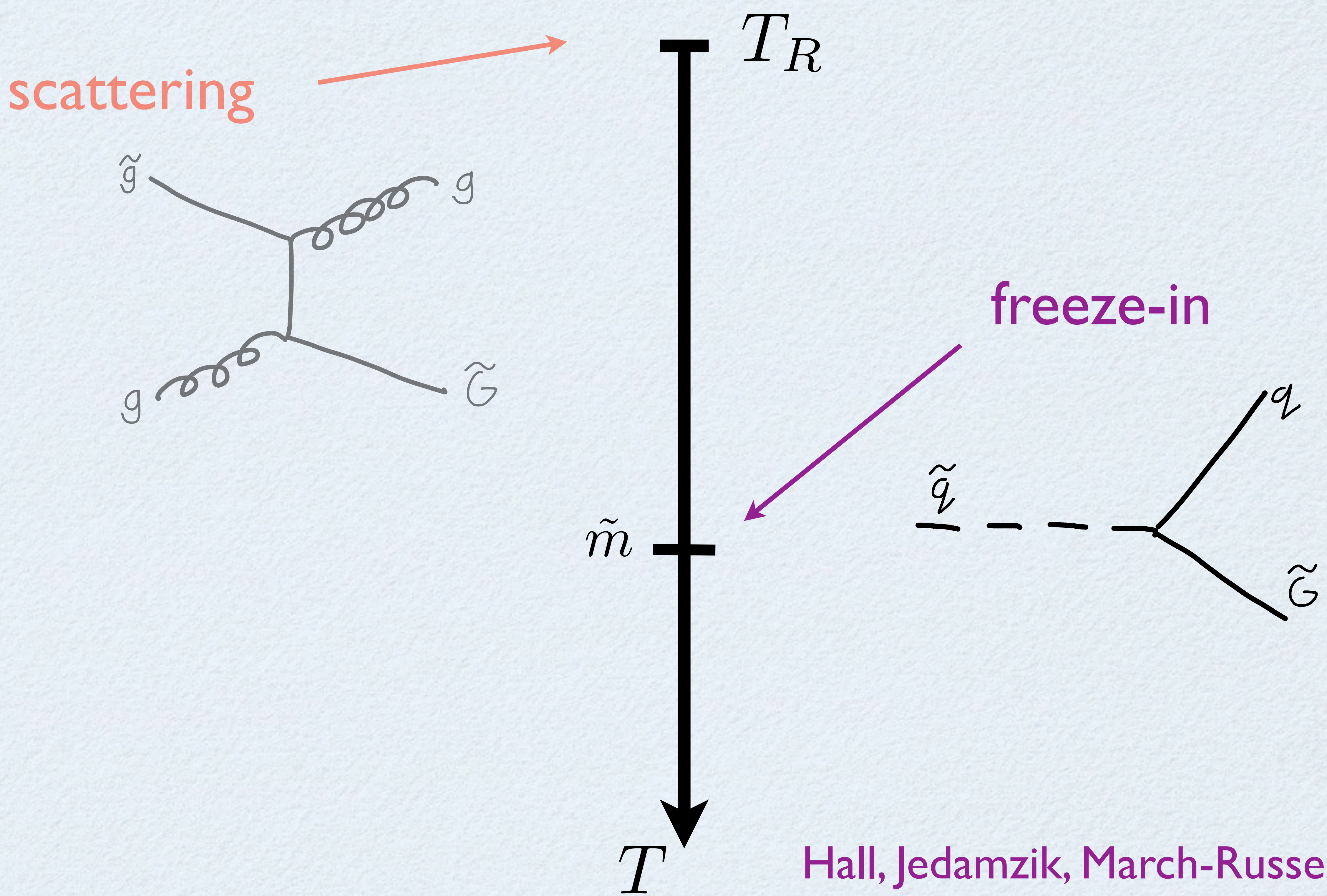
gravitino production

scattering



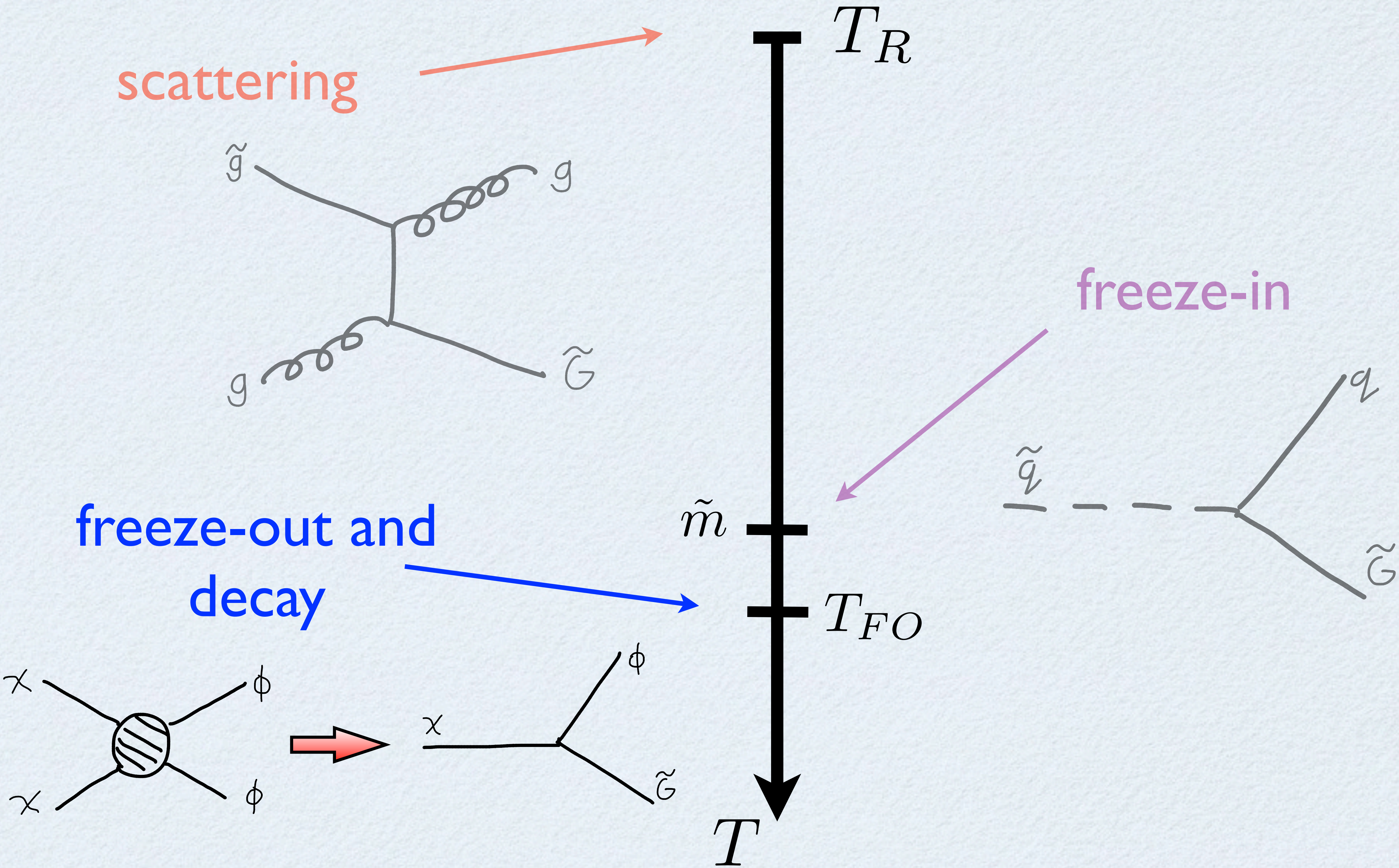


gravitino production



Hall, Jedamzik, March-Russell,
West, 0911.1120

gravitino production



gravitino production

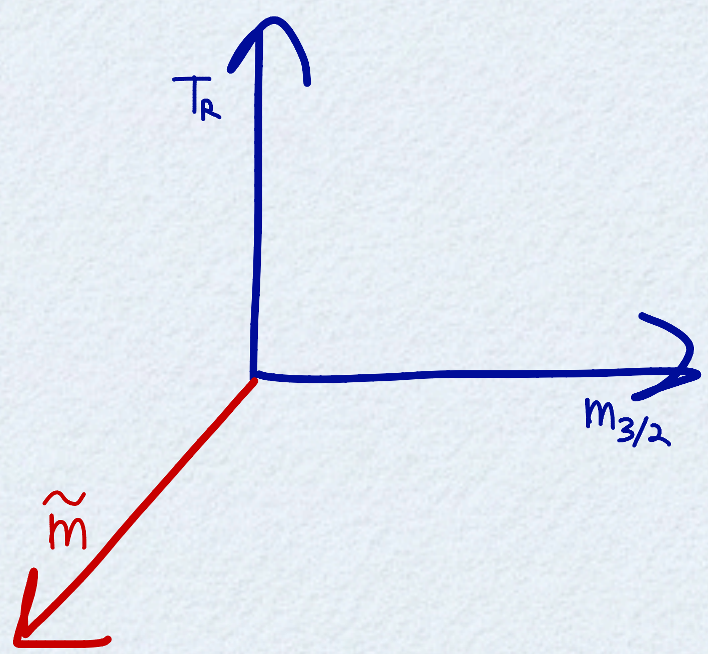
when is: $\Omega_{3/2} \le \Omega_{obs}$?

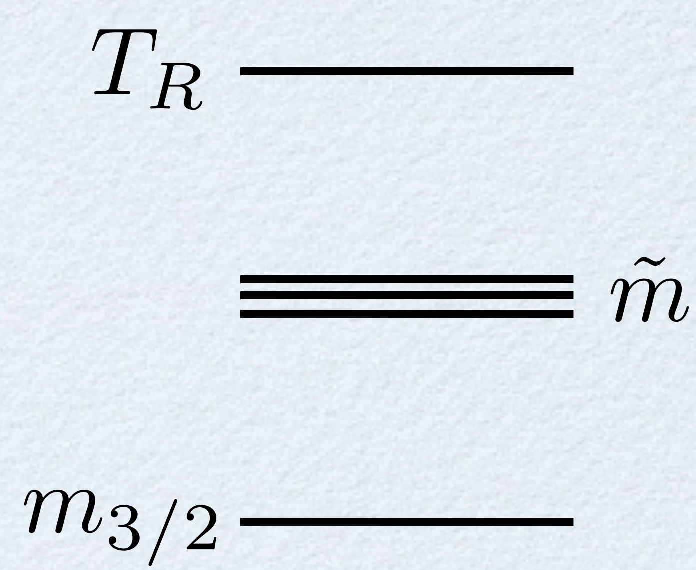
gravitino production

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

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	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

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constrains reheat temperature

$$T_R \lesssim 10^9 \ \text{GeV}$$

when $\tilde{m} \sim \ \text{TeV}$

Moroi, Murayama, Yamaguchi 1993

gravitino production

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

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what about constraining $\tilde{m}$?

gravitino production

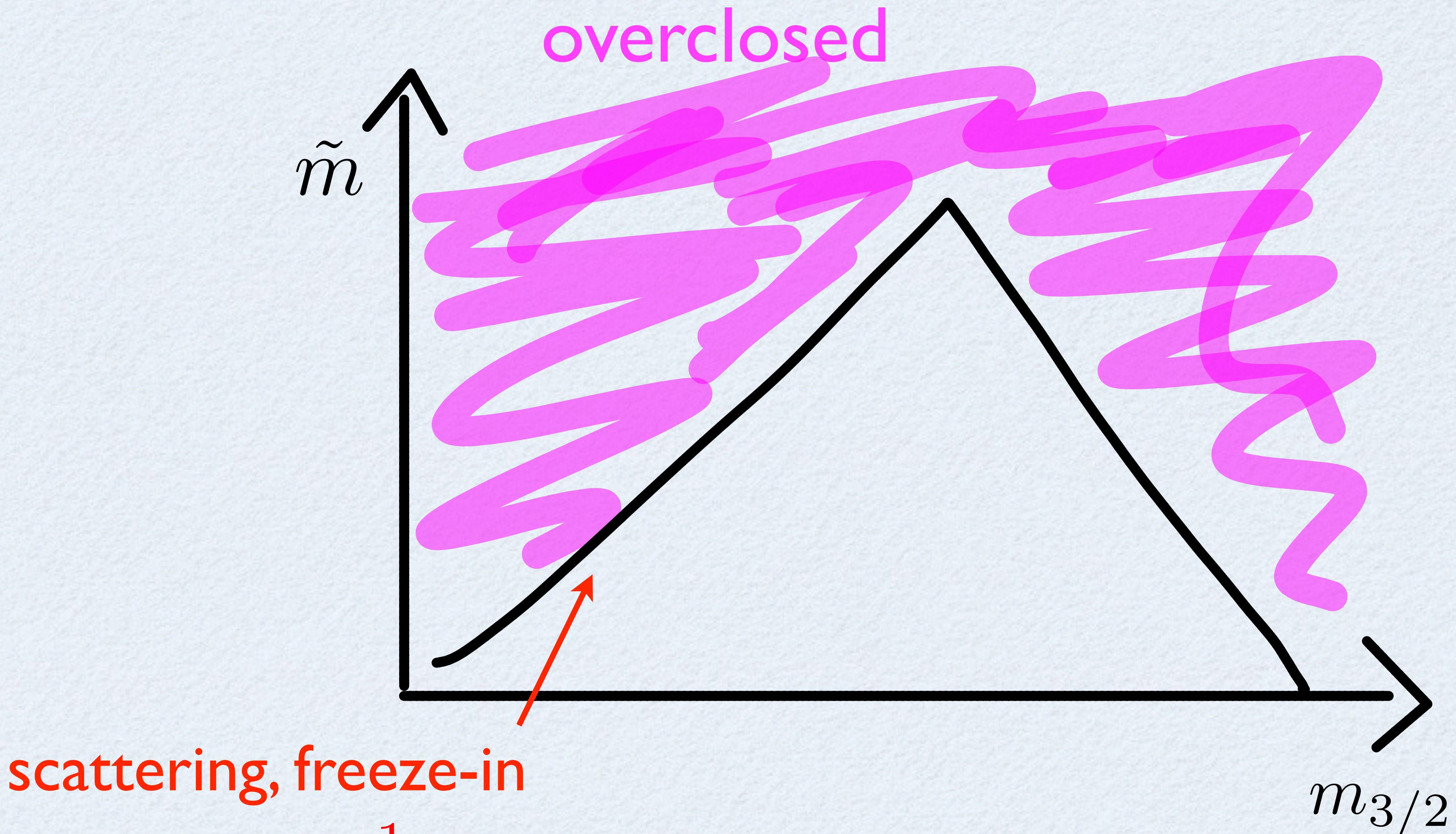
$$m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq}$$

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

different gravitino mass dependence

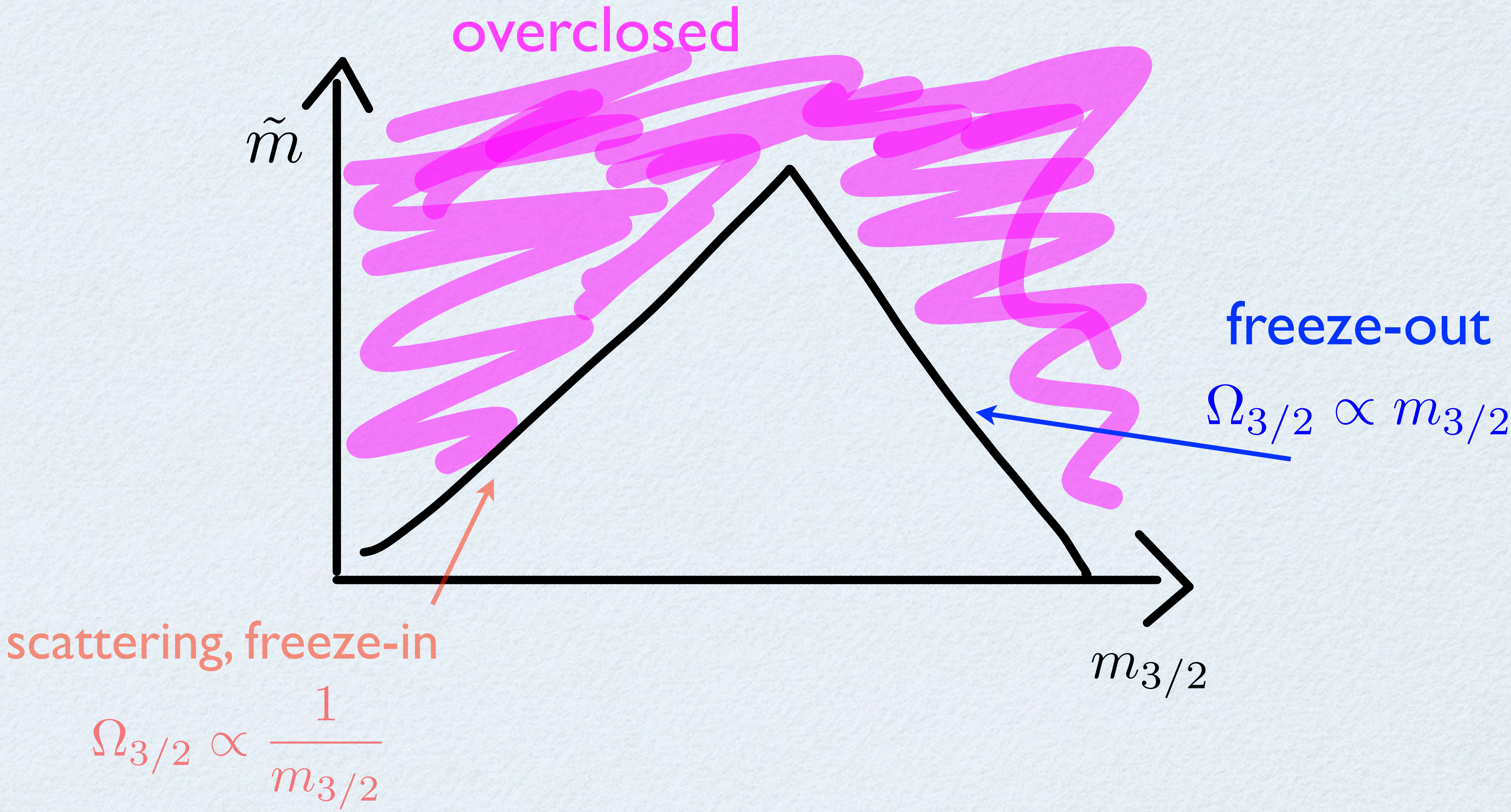
a bound with gravitino LSP

a bound with gravitino LSP

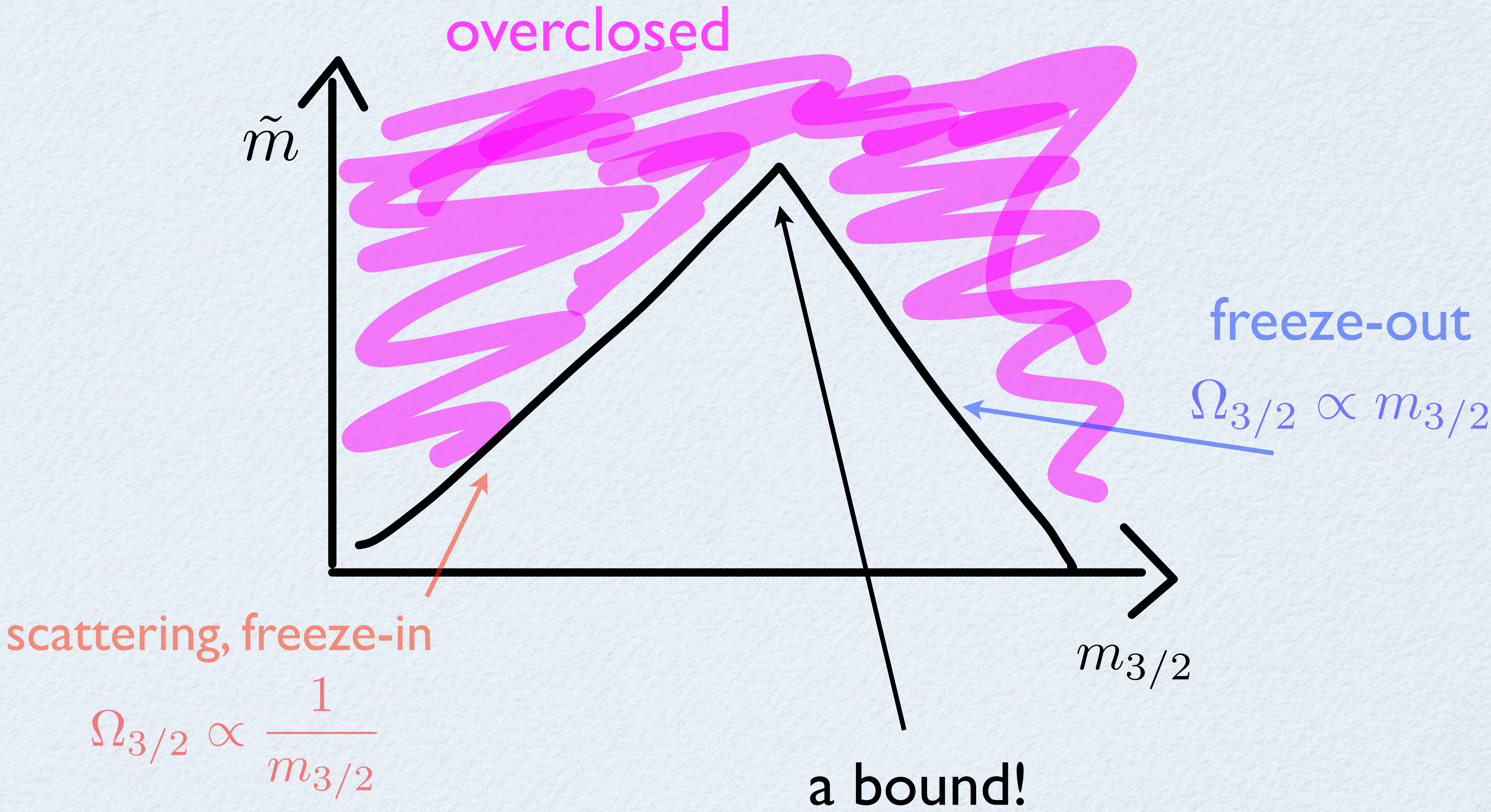


$$\Omega_{3/2} \propto \frac{1}{m_{3/2}}$$

a bound with gravitino LSP



a bound with gravitino LSP



the bound

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

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

the bound

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abundance
minimized when:

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

the bound

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

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abundance minimized when:

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

the bound

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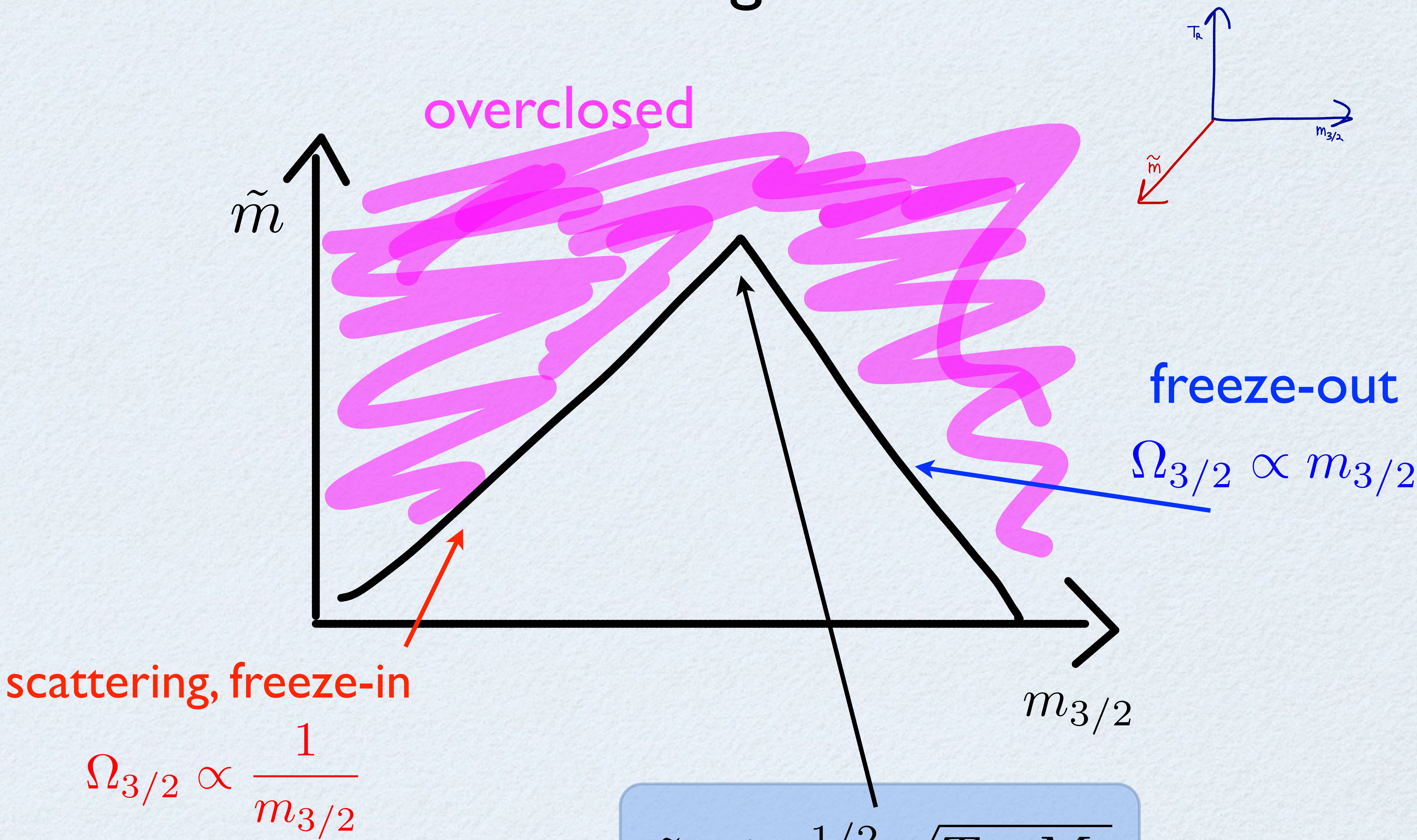
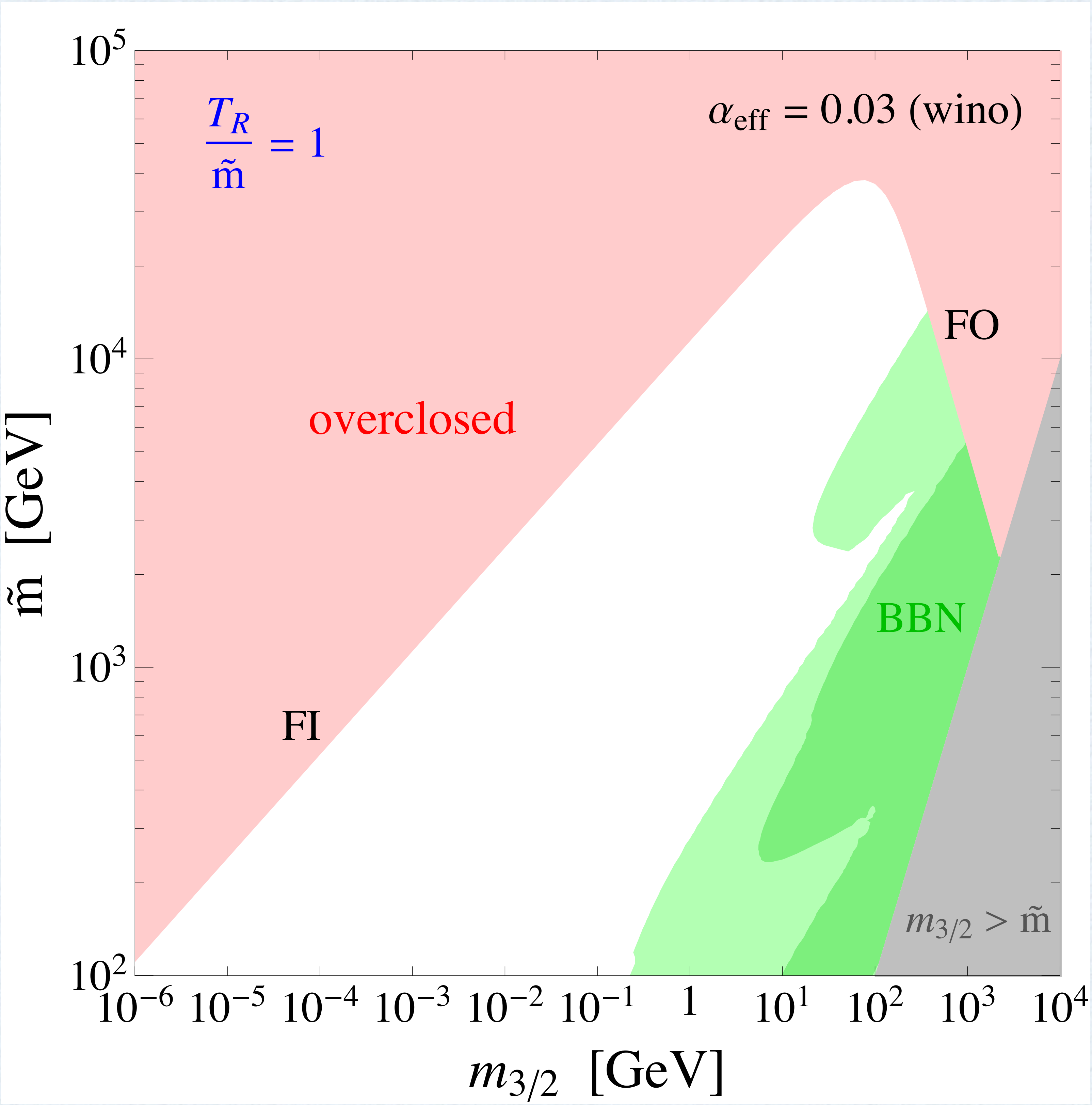
$$\boxed{\tilde{m} \leq \alpha^{1/2} \sqrt{T_{eq} \, M_p}}$$

a bound with gravitino LSP



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

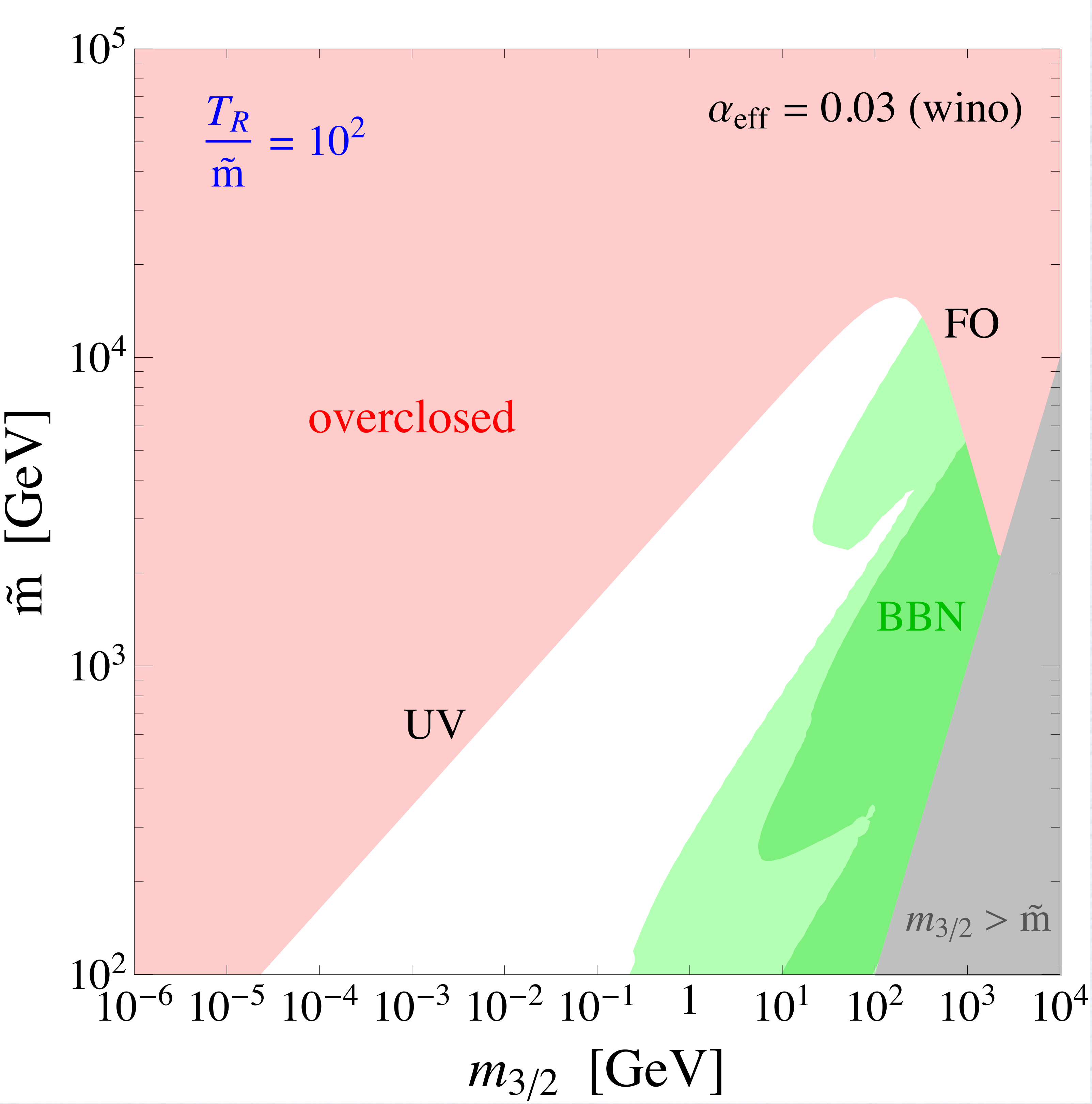
numerics



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

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

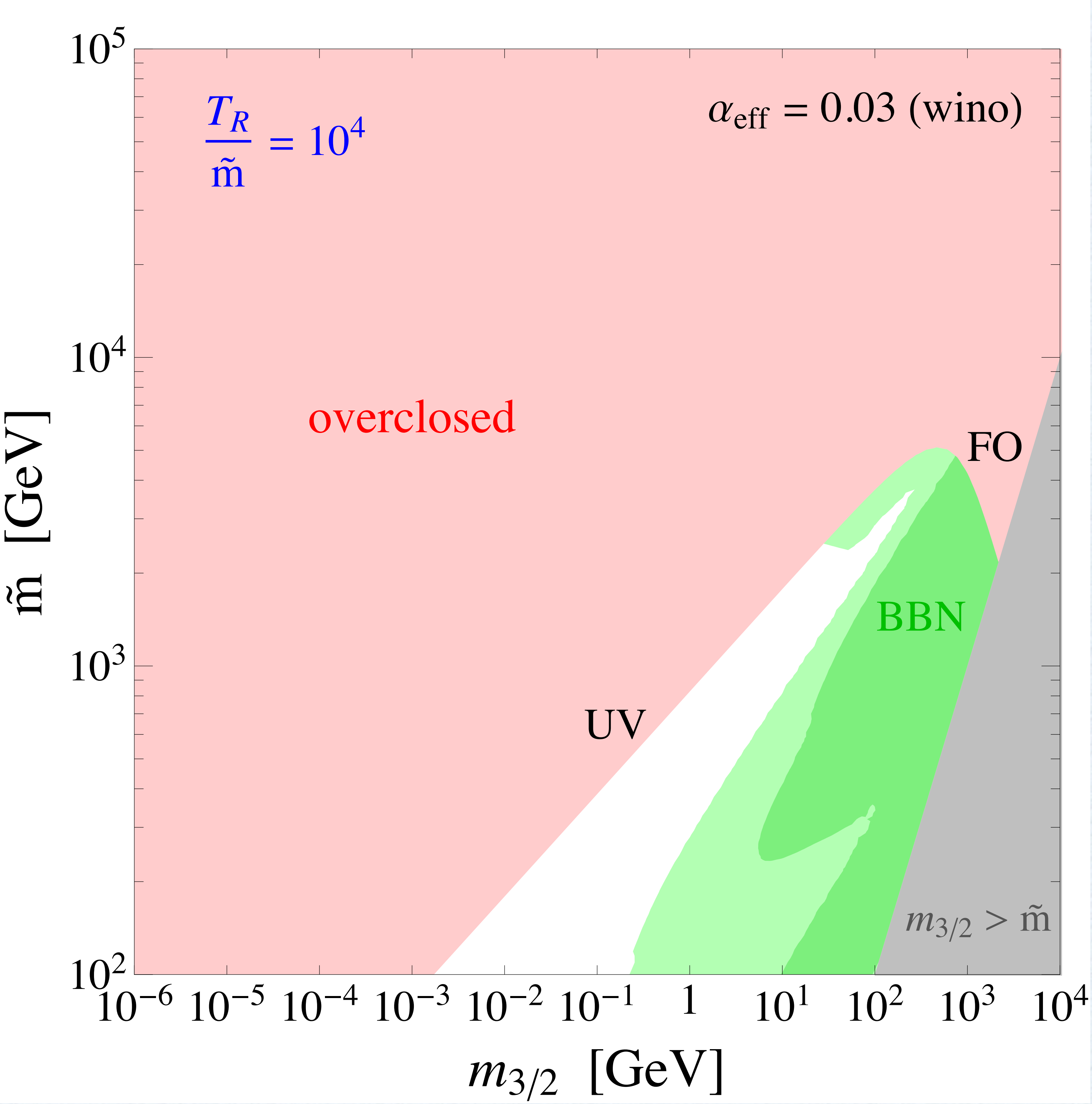
numerics



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

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

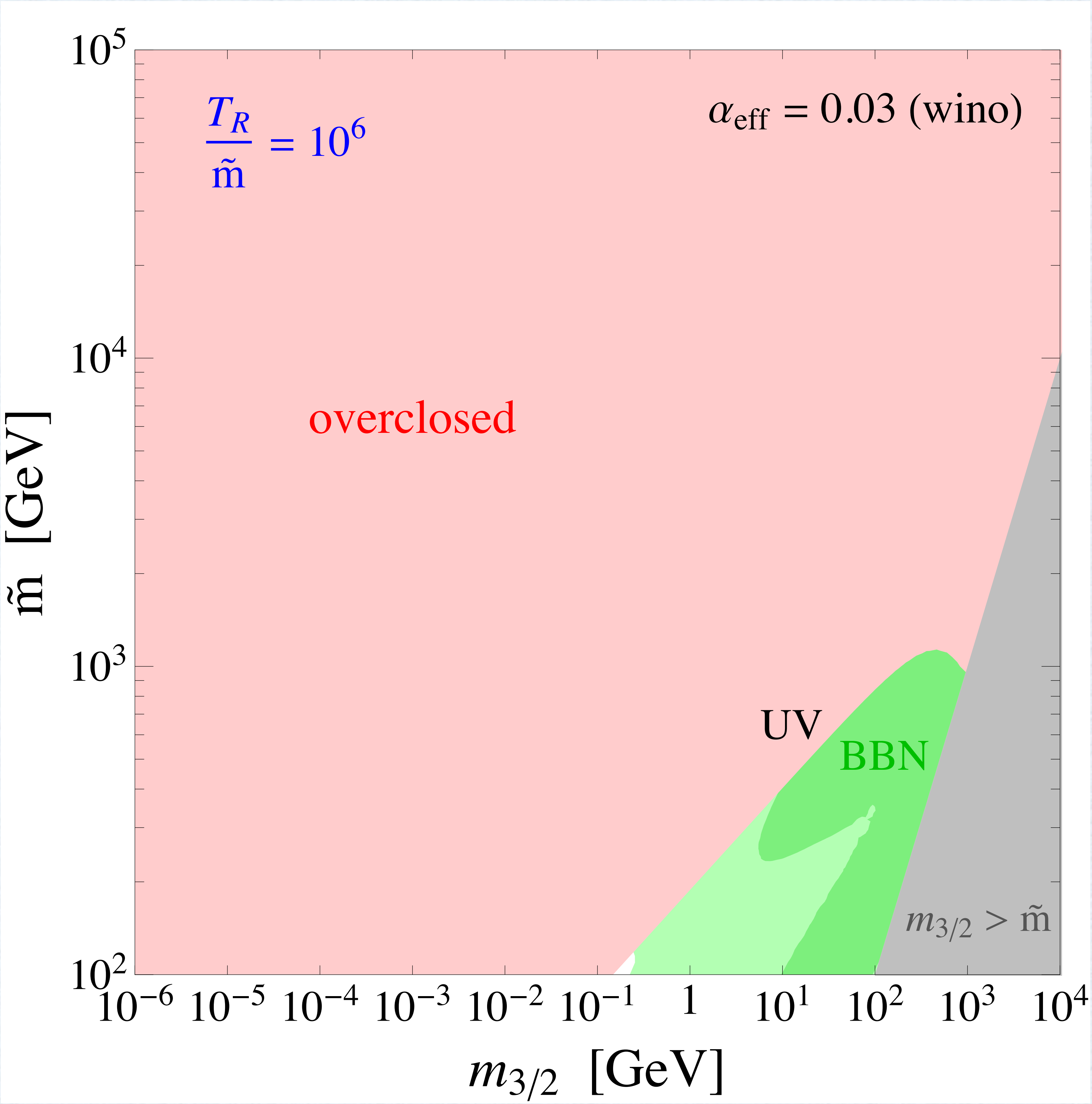
numerics



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

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

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: $Y_{UV} \sim \mathcal{O}(1)$

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

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- overclosure bound

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

- Pagels, Primack 1982

thermalized gravitinos

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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

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

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

thermalized gravitinos

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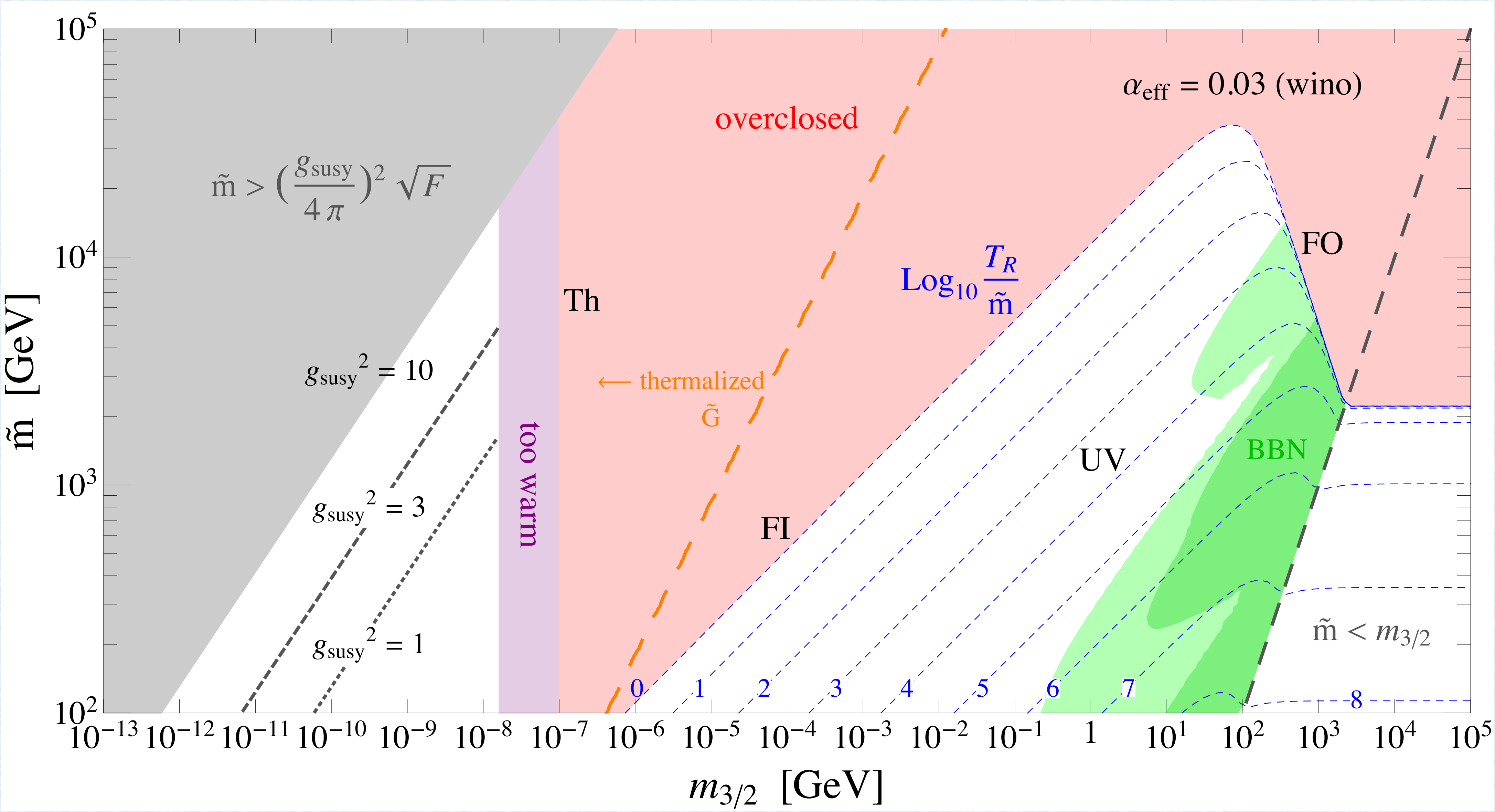
$$\tilde{m} = \left(\frac{g_{\rm susy}}{4\pi}\right)^2 \sqrt{F}$$

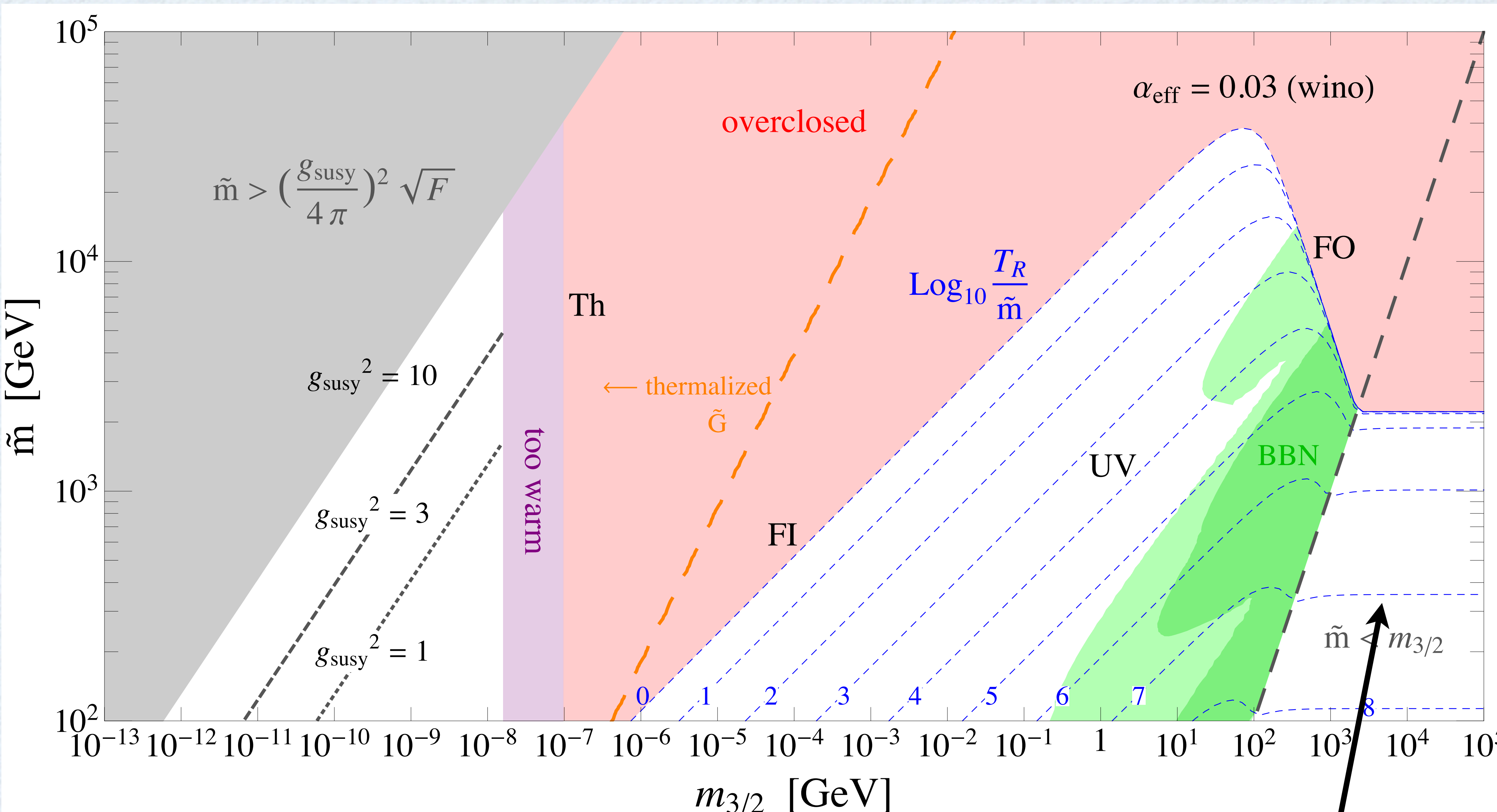
- parametrically,

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

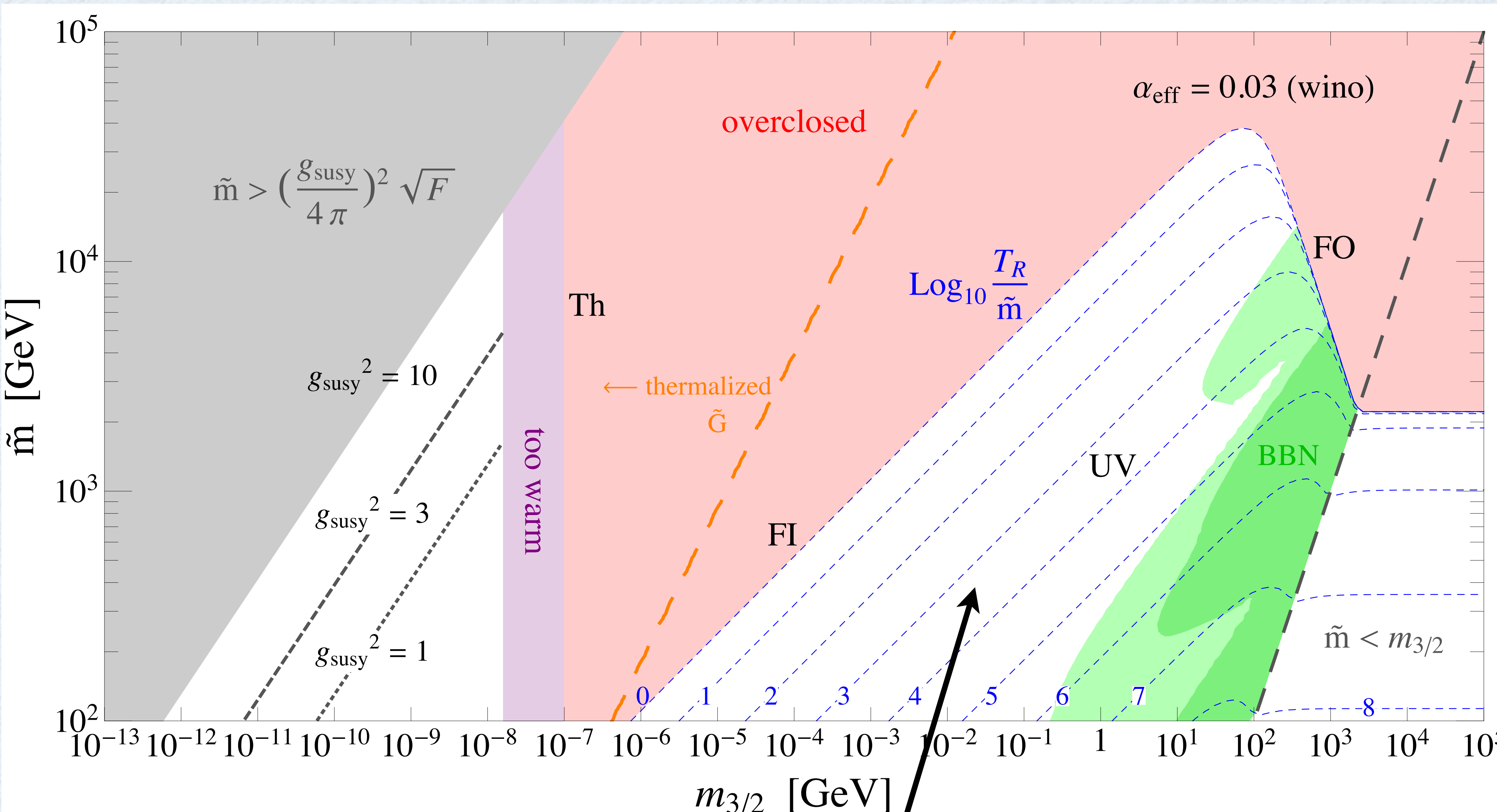
$$F \leq T_{eq}\, M_p \quad \Rightarrow \quad \boxed{\tilde{m} \leq \left(\frac{g_{\rm susy}}{4\pi}\right)^2 \sqrt{T_{eq}\, M_p}}$$



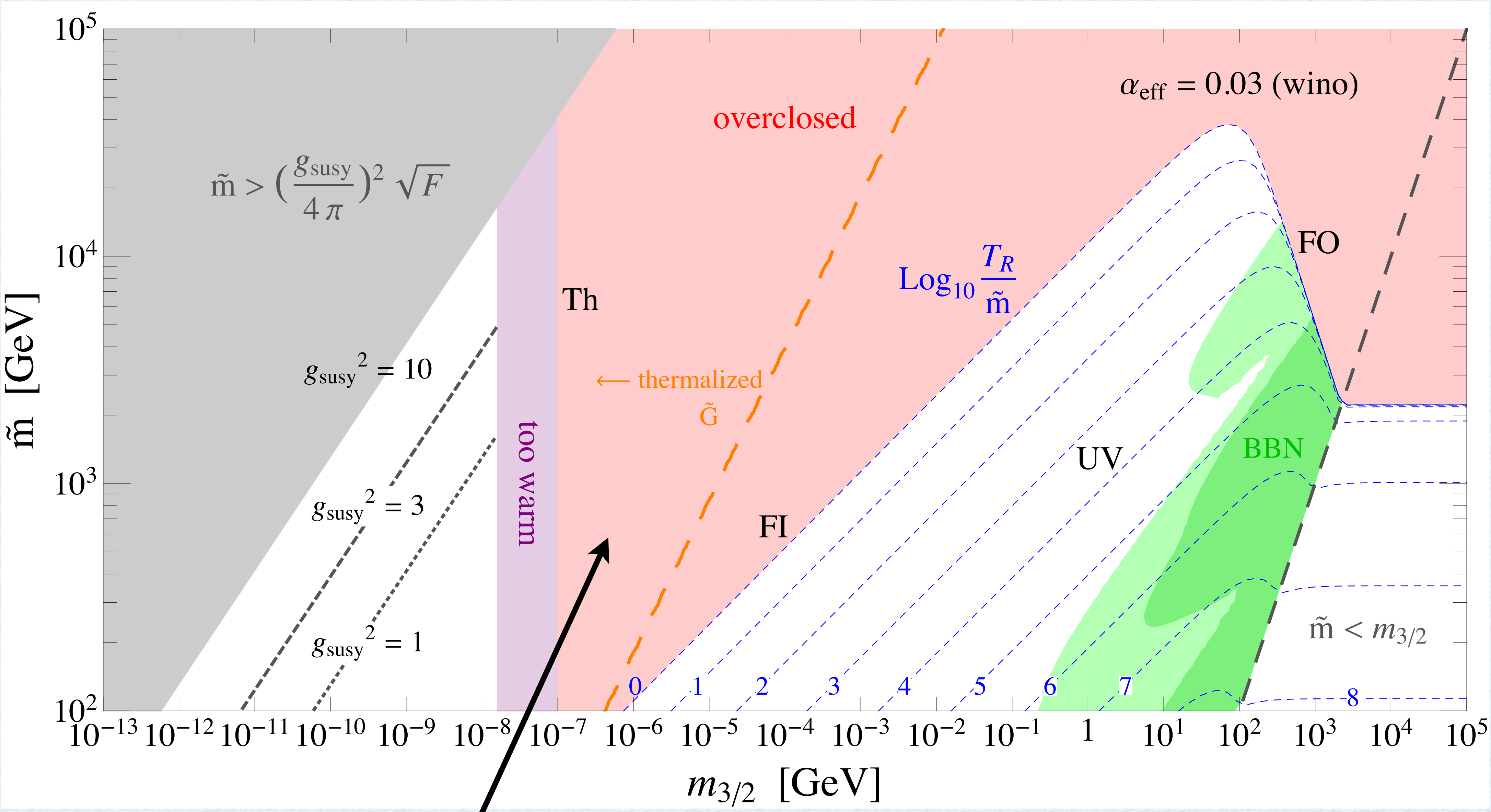
$\tilde{m} > (\frac{g_{susy}}{4\pi})^2 \sqrt{F}$
overclosed
$\alpha_{eff} = 0.03$ (wino)
$Log_{10} \frac{T_R}{\tilde{m}}$
Th
FO
too warm
$g_{susy}{}^2 = 10$
$g_{susy}{}^2 = 3$
$g_{susy}{}^2 = 1$
⟵ thermalized $\tilde{G}$
FI
UV
BBN
$\tilde{m} < m_{3/2}$
0
1
2
3
4
5
6
7
8
$\tilde{m}$ [GeV]
$m_{3/2}$ [GeV]



SM-superpartner LSP

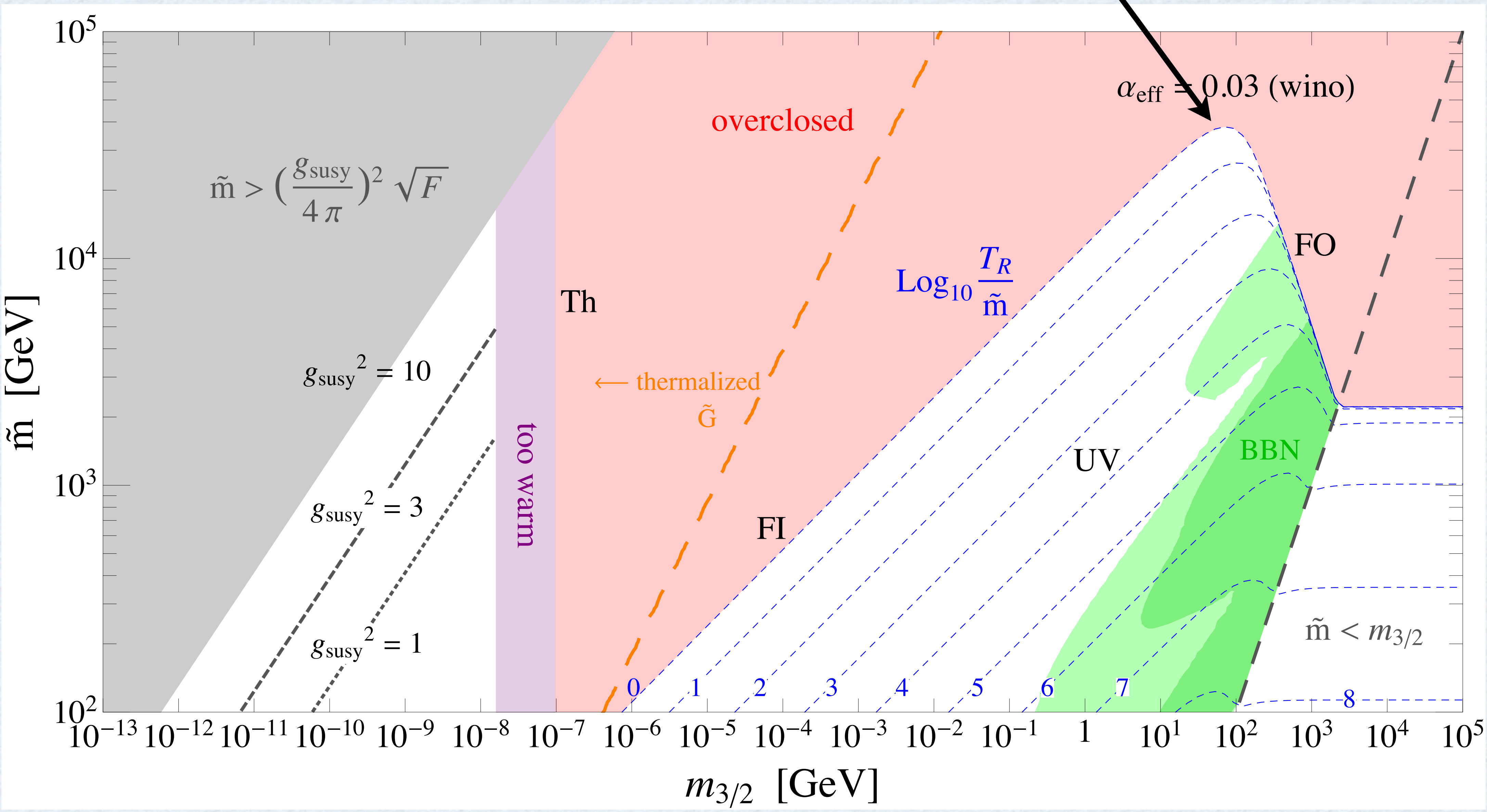


non-thermal gravitino LSP



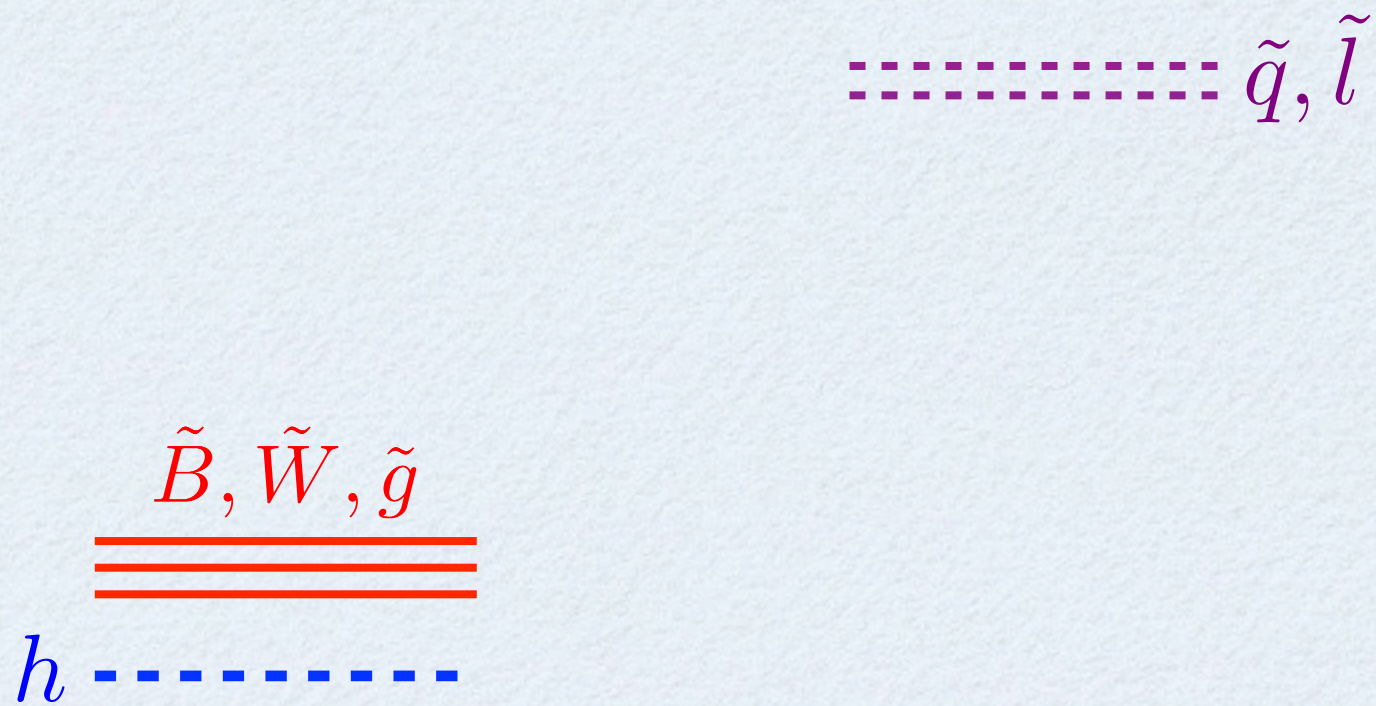
thermal gravitino LSP

$\tilde{m} \leq 40$ TeV

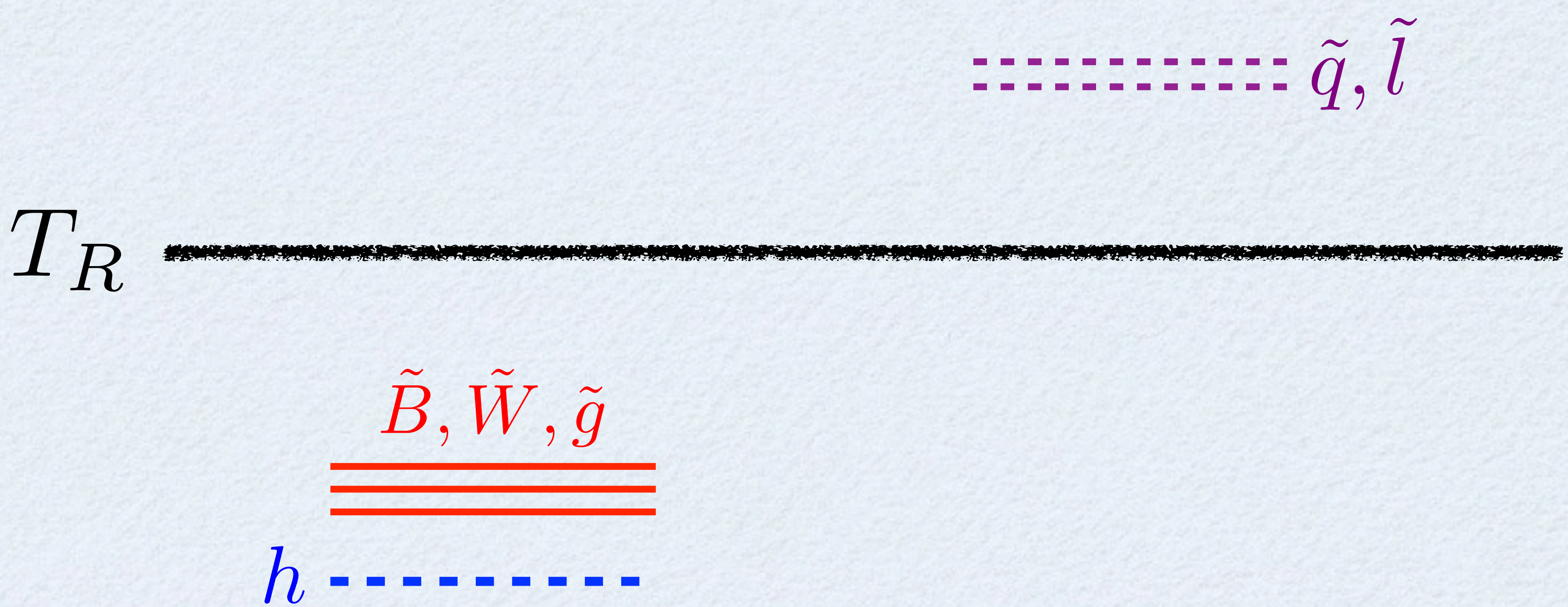


split with gravitino LSP

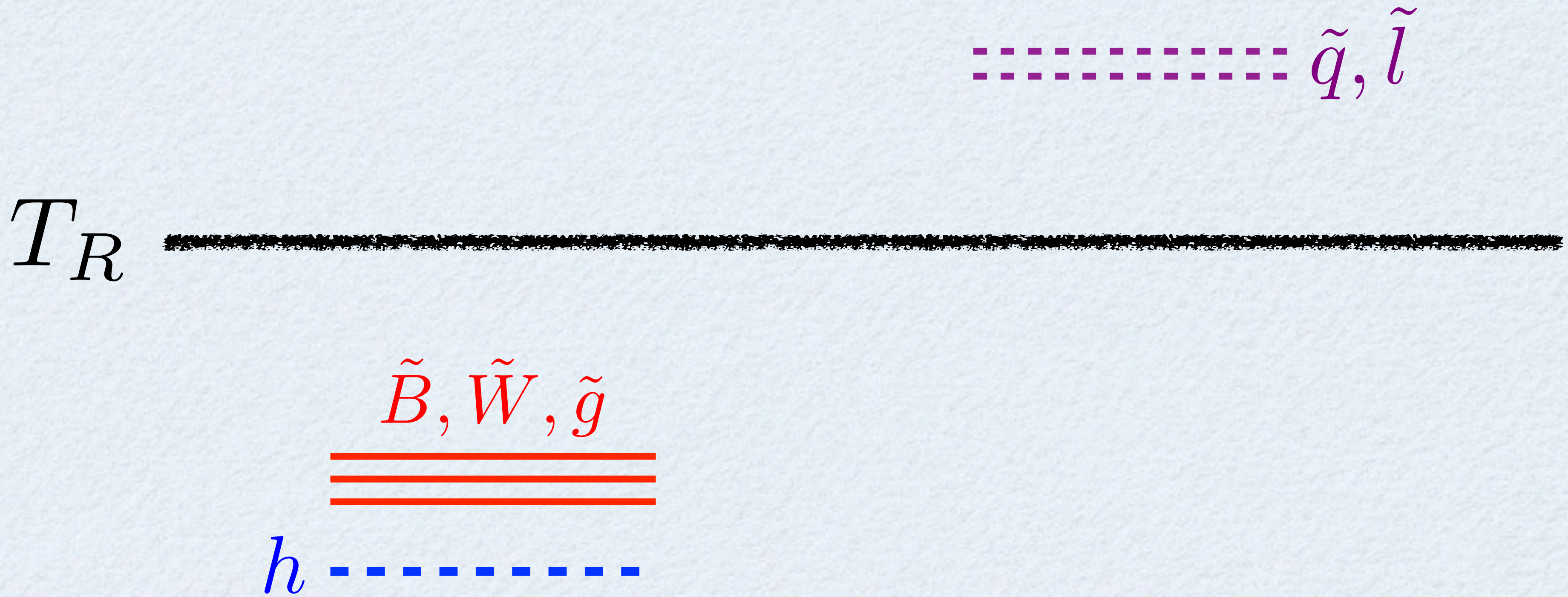
split



split

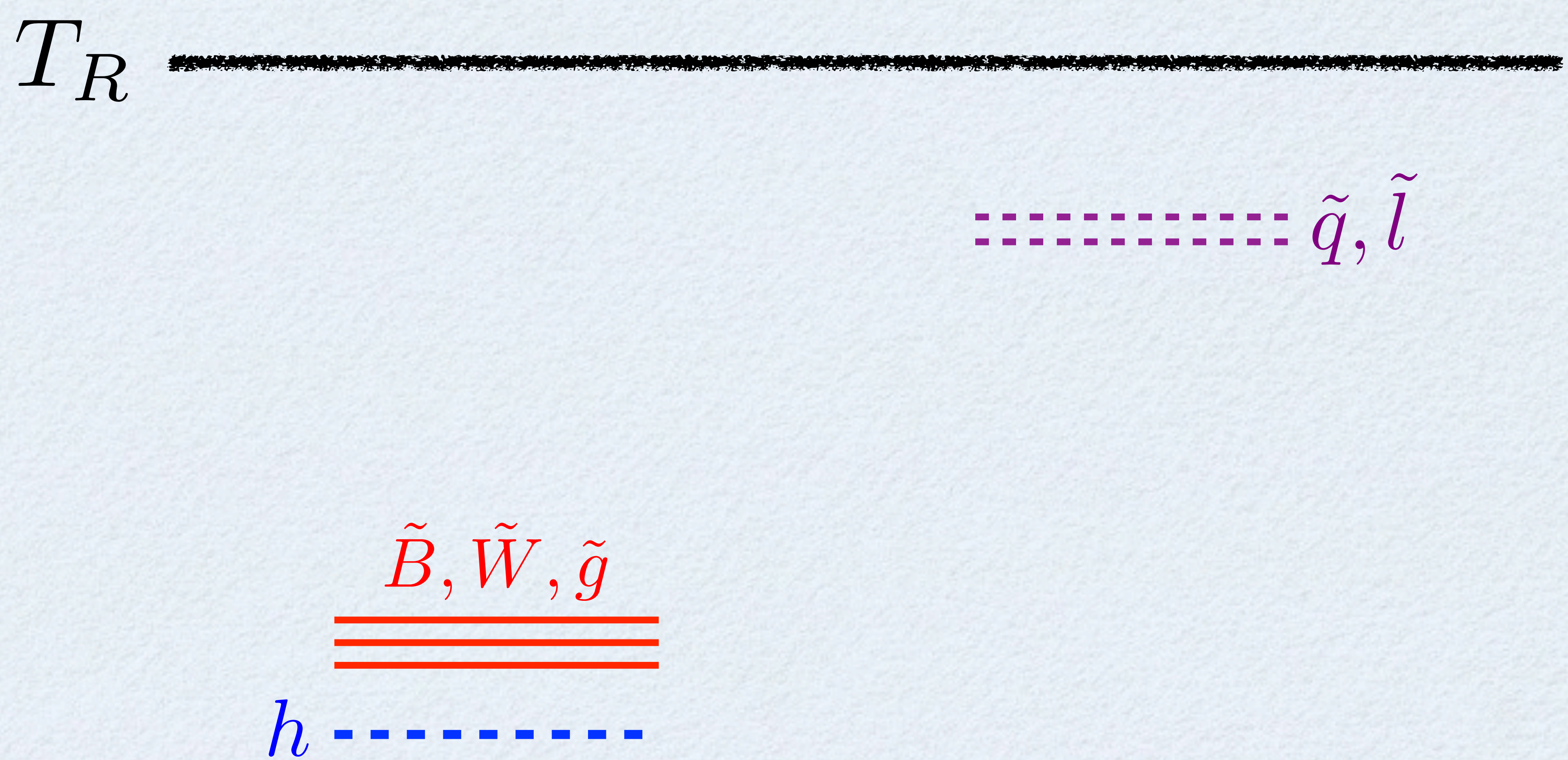


split



- 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

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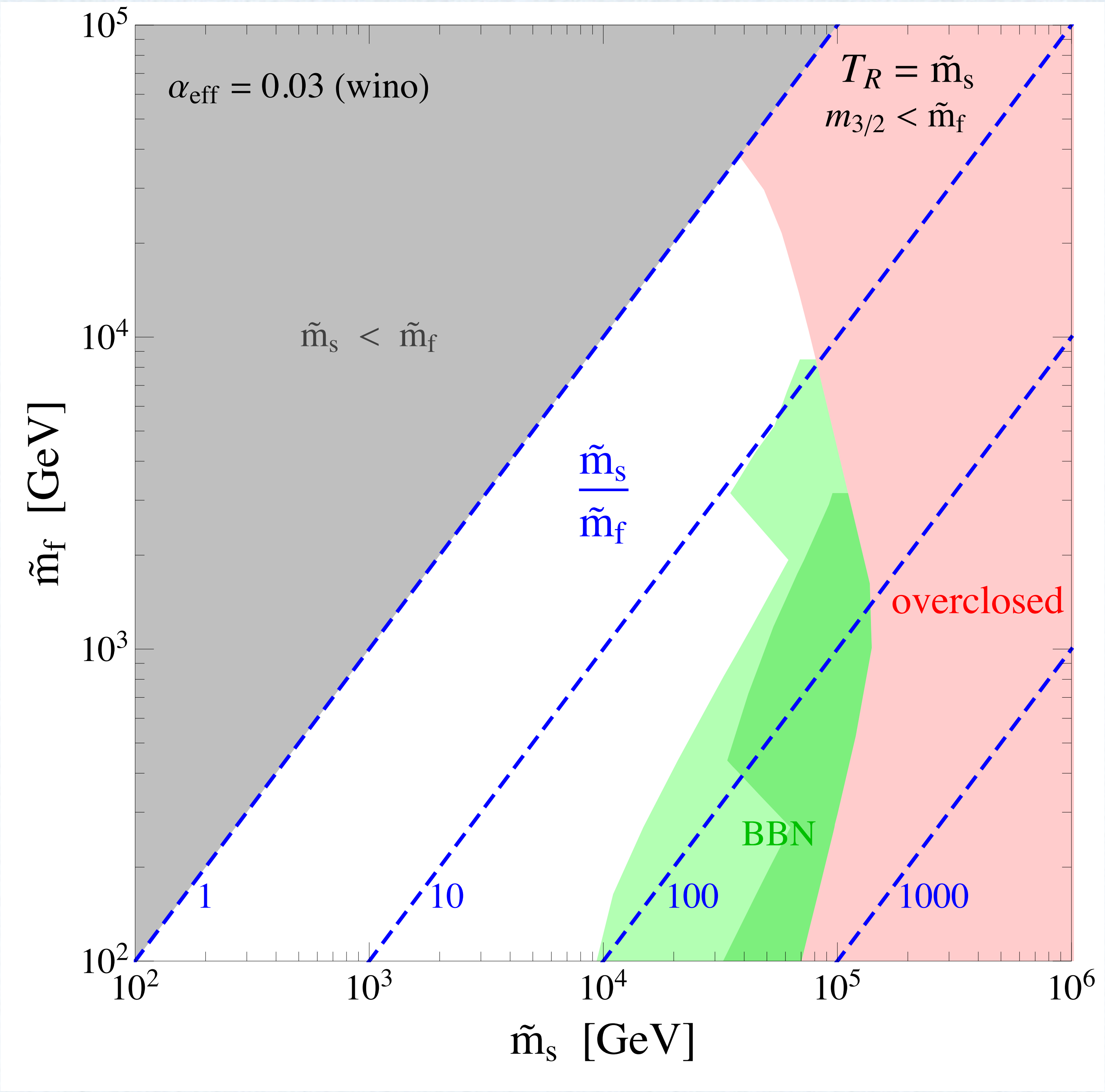
enhanced by large scalar mass

constraint on splitting

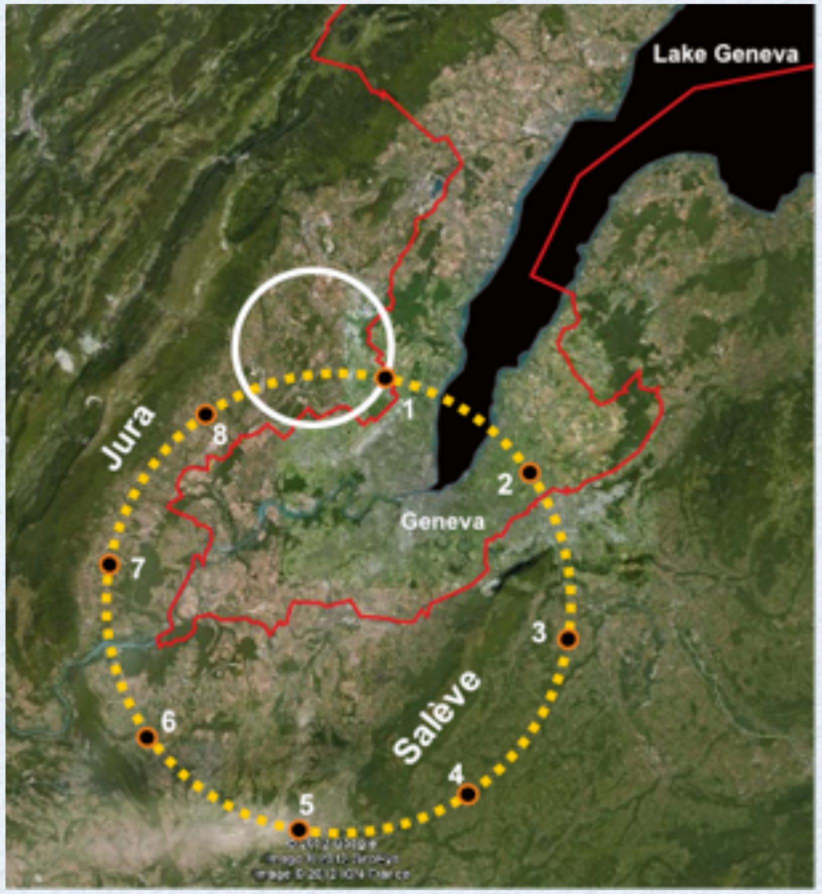


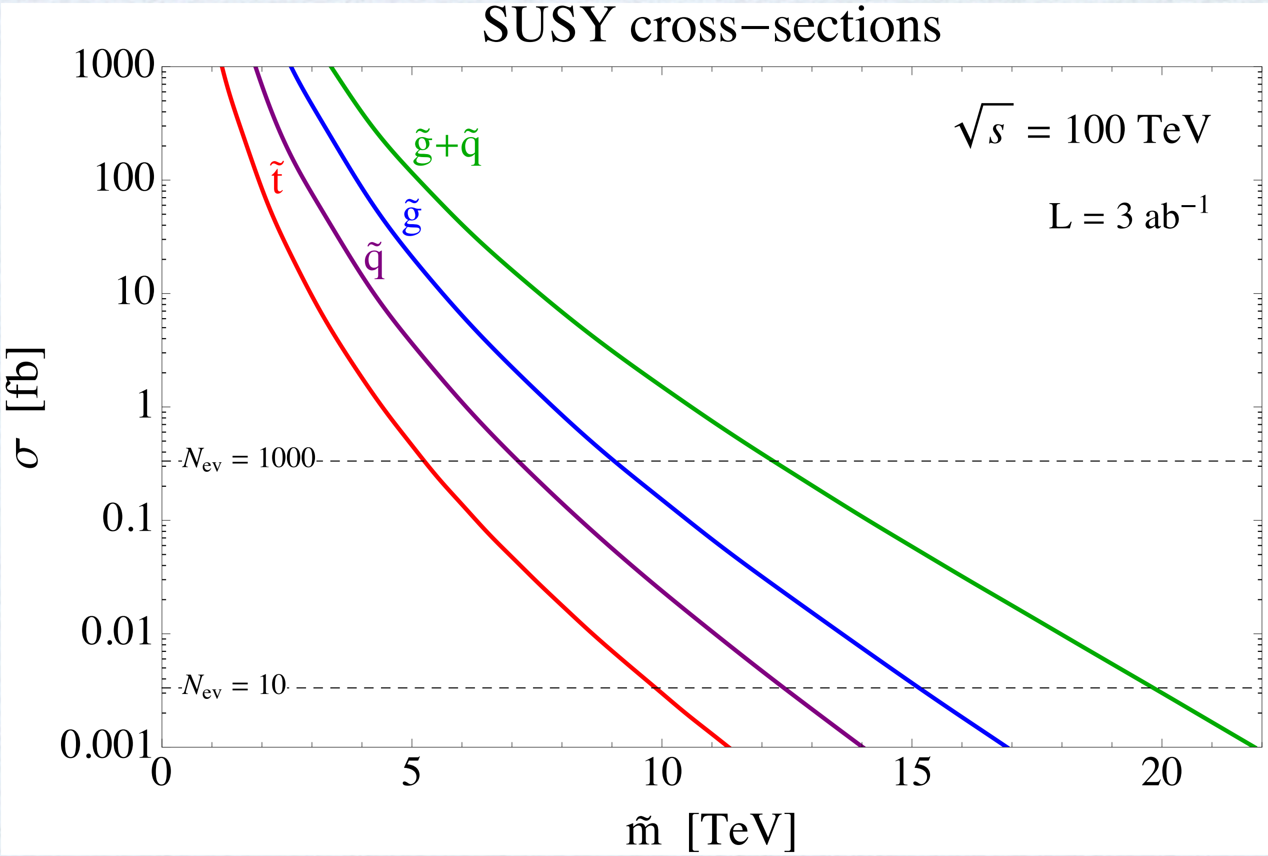
$$\frac{\tilde{m}_s}{\tilde{m}_f} \lesssim 100$$

future of energy frontier?

a 100 TeV collider would probe most of the cosmologically interesting region

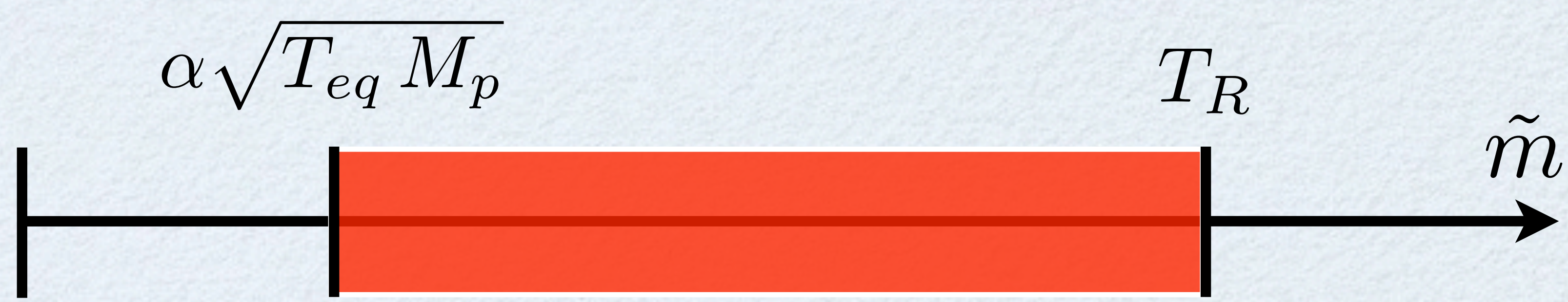
$$\sqrt{T_{eq} M_p} \approx 60 \text{ TeV}$$





conclusions

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



conclusions

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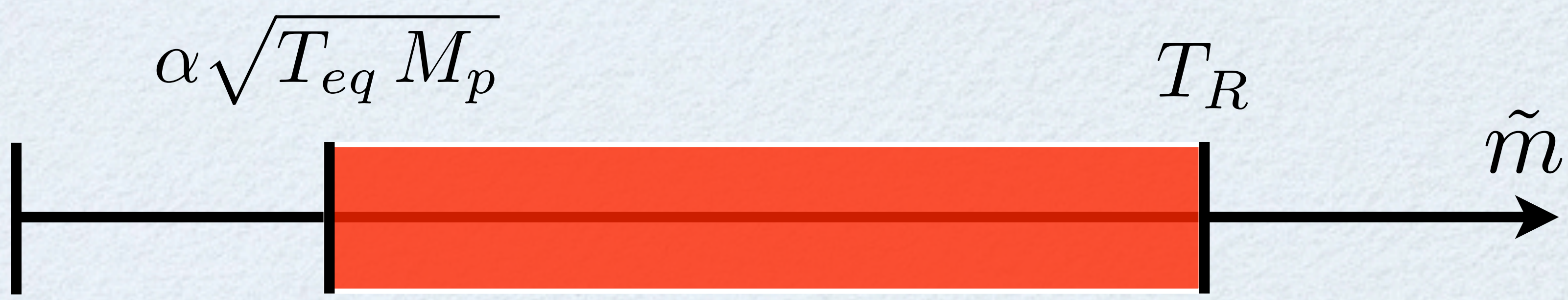
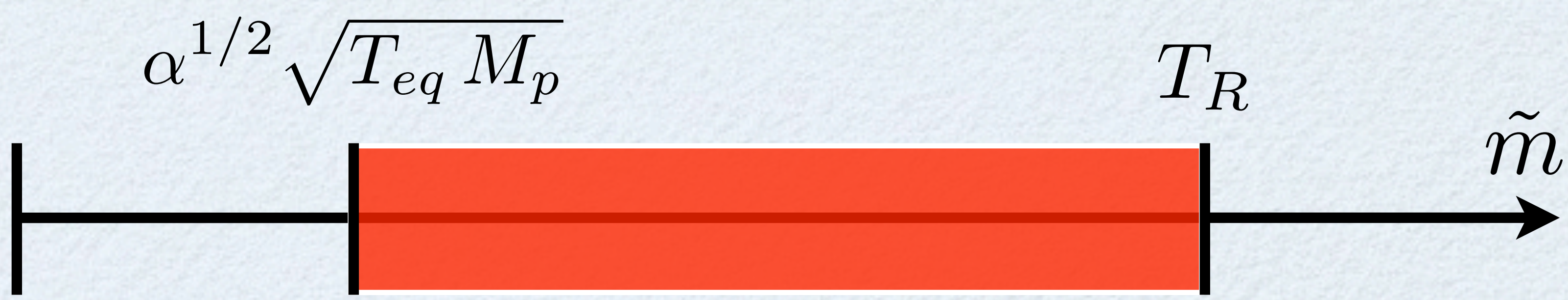


$m_{3/2} < \tilde{m}$

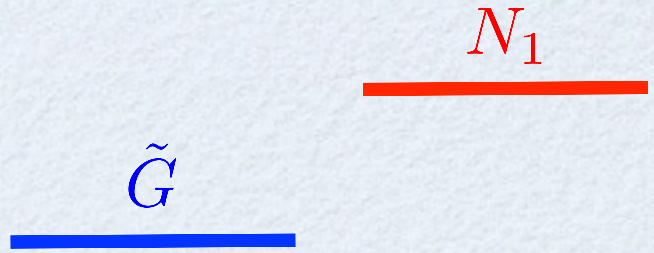


backup

gravitino primer

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

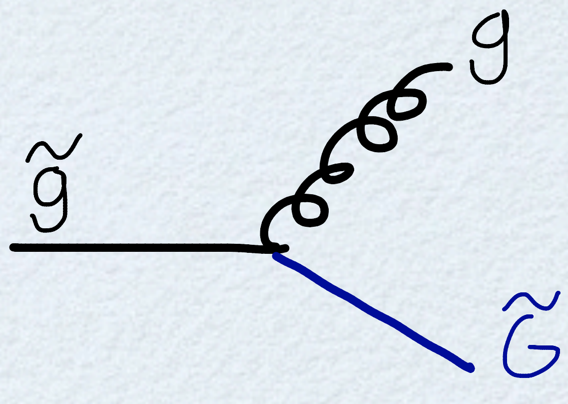
$$M < M_p$$



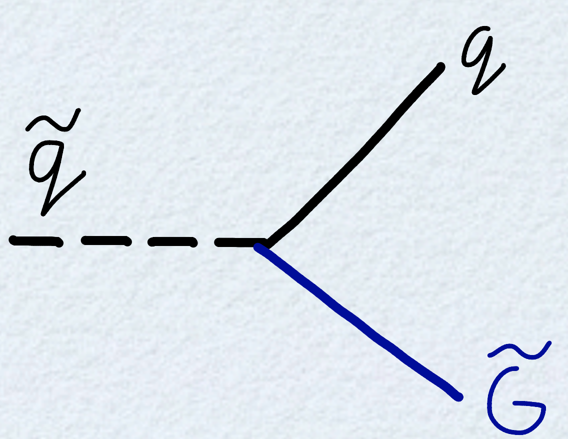
$$\tilde{m} = \frac{F}{M}$$

$$\frac{1}{F} J^{\mu}_{Q}\, \partial_\mu \tilde{G}$$

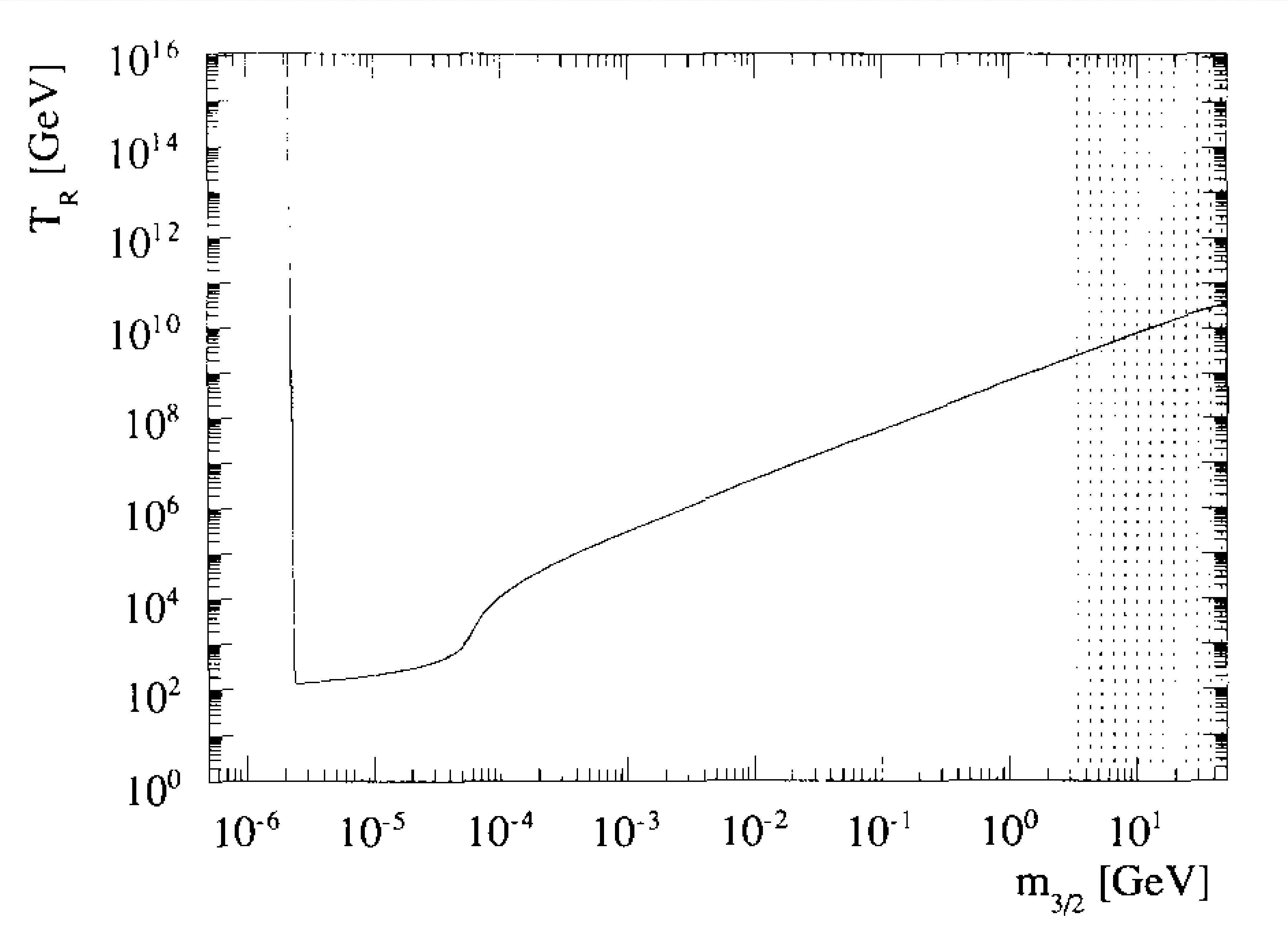
$$\frac{1}{F}\frac{m_\lambda}{4\sqrt{2}}\, \bar{\lambda}\, \sigma^{\mu\nu} F_{\mu\nu}\, \tilde{G}$$



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



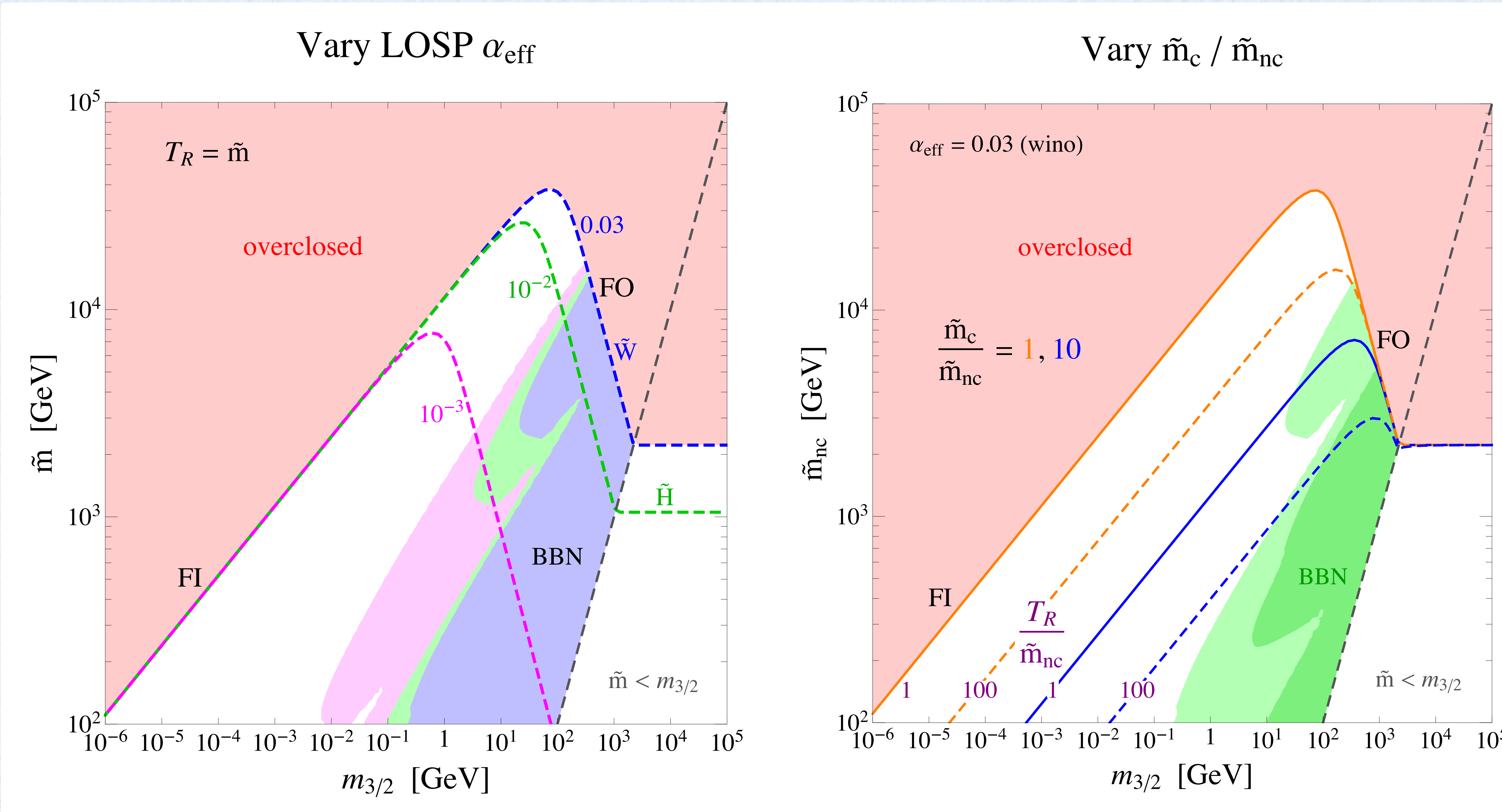
constraining the reheat temperature



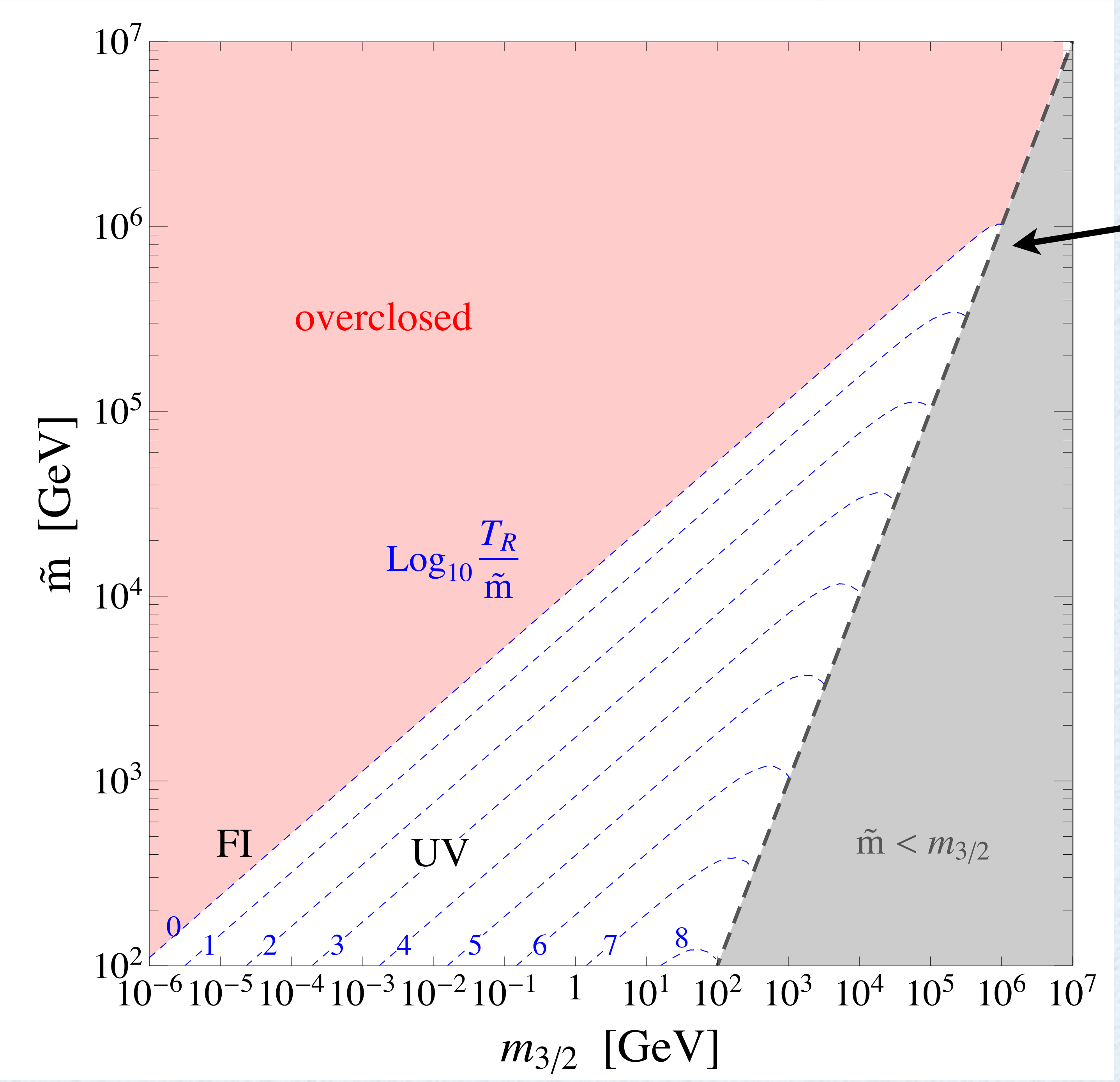
$$m_{\tilde{q}} = 1 \text{ TeV}$$
$$M_1 = 50 \text{ GeV}$$

Moroi, Murayama, Yamaguchi 1993

variations on gravitino bound



no freeze-out and decay



$\tilde{m} \lesssim 1000\ \mathrm{TeV}$