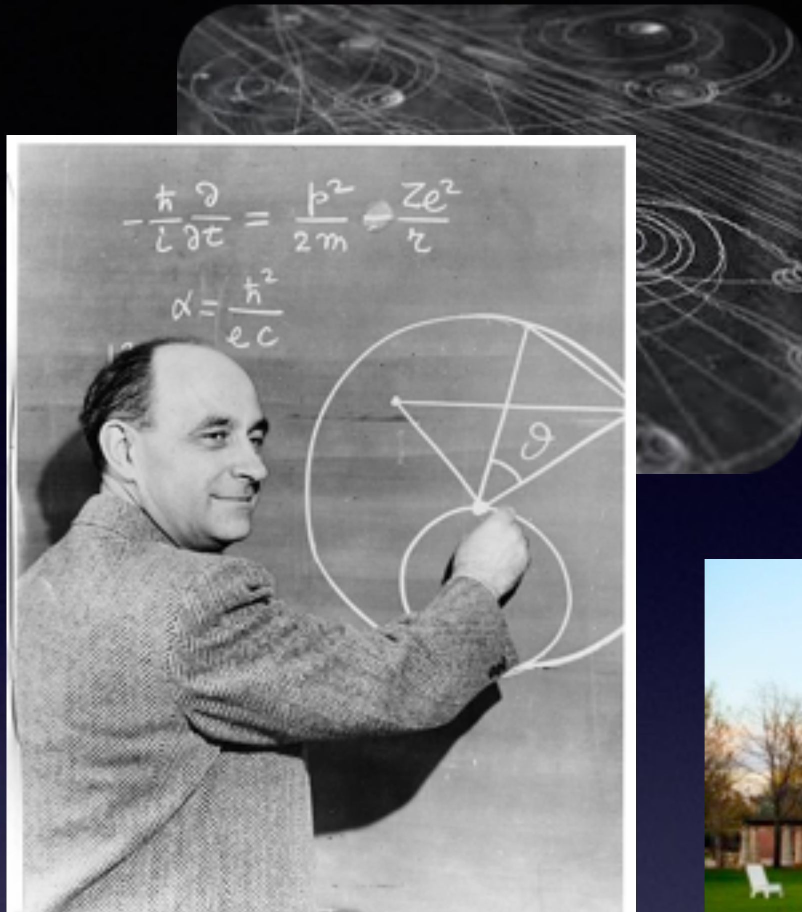
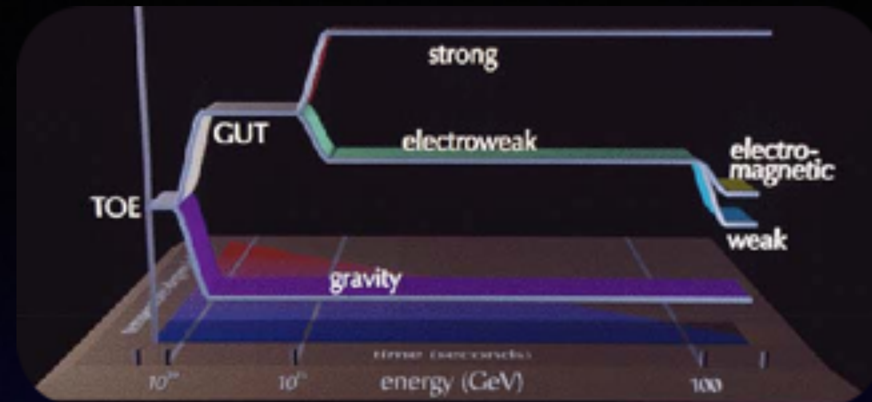
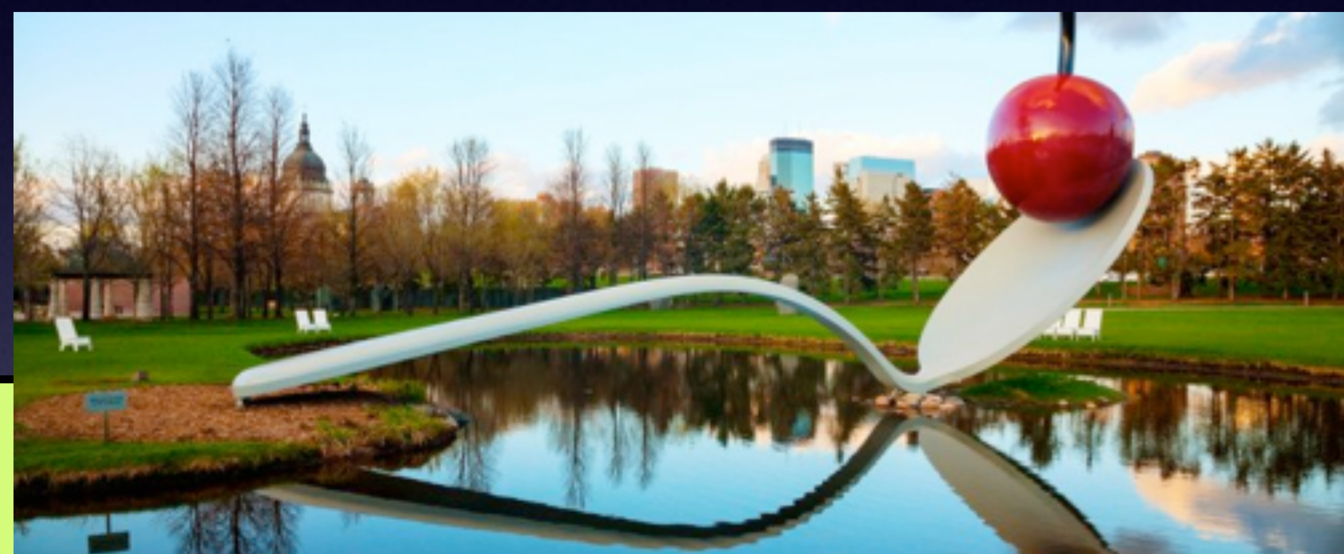
Minimal model of gravitino DM







« Never underestimate the joy people derive from hearing something they already know.»
E. Fermi

« Ok, let's go for a beer»
K.A. Olive

Yann Mambrini,

University of Paris-Saclay

in collaboration with K. Benakli, Y. Chen E. Dudas and K.A. Olive

http://www.ymambrini.com/My_World/Physics.html

Olive fest, May 19th 2017, Minneapolis

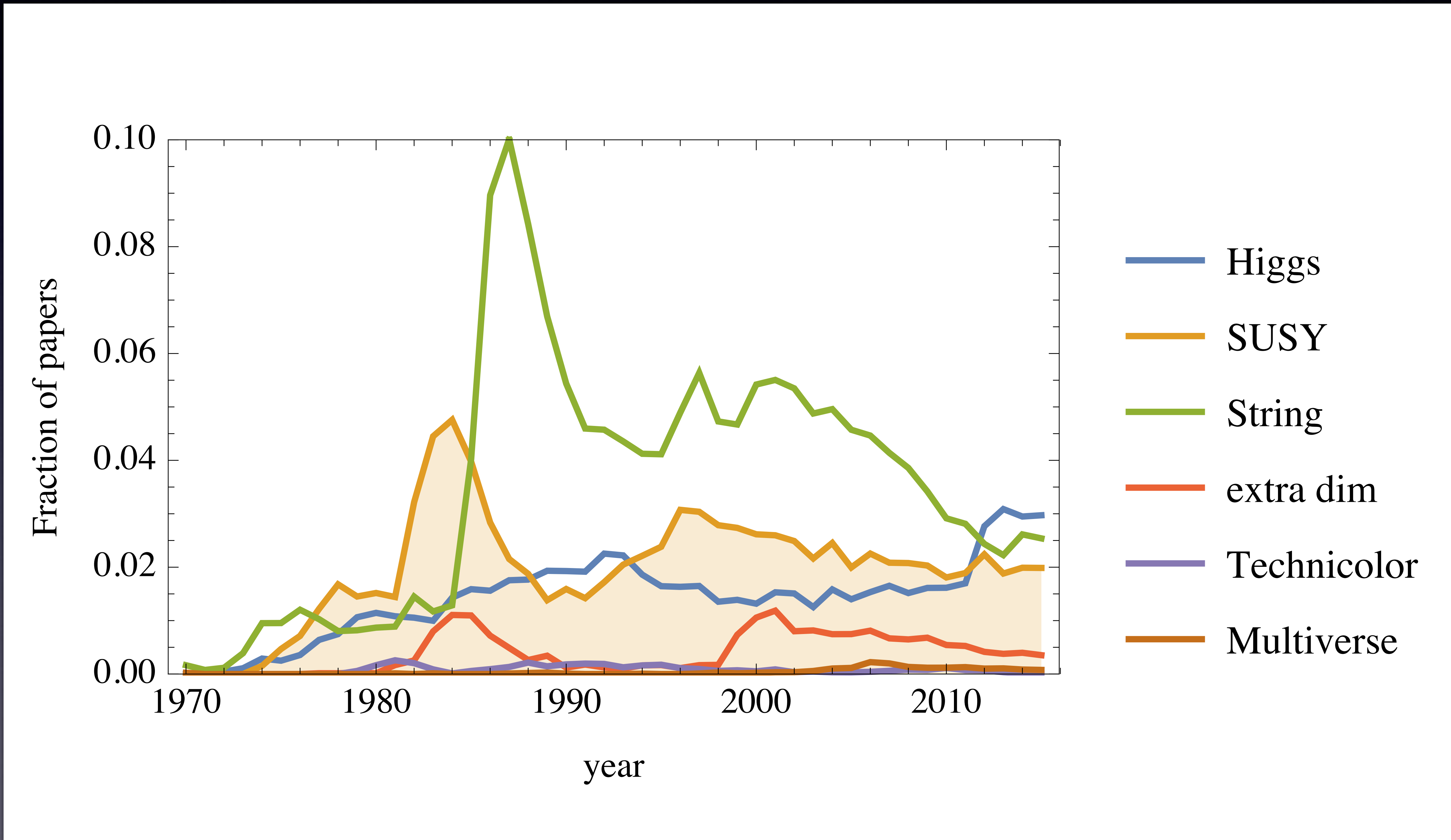
E. Dudas, Y.M. and K.A. Olive, arXiv:1704.03008

K. Benakli, Y. Chen, E. Dudas and Y.M. Phys.Rev. D95 (2017) no.9, 095002

A la mémoire de Pierre Binetruy

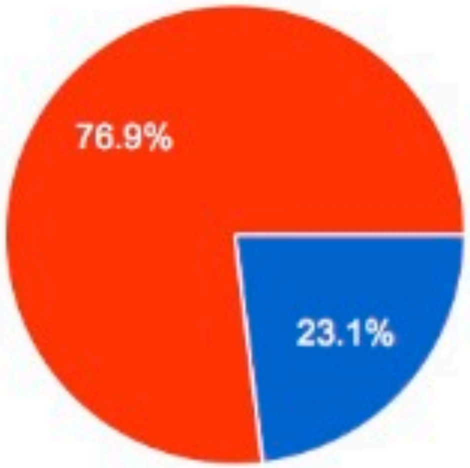
Is SUSY dark matter alive?

Is SUSY alive (and well)?
Not so well, but at least still popular..



Pool at IFT workshop, September 2016

Will dark matter (either WIMP, axions or other) be detected in the next fifteen years?



No	**12**	23.1%
Yes	**40**	76.9%

At least optimism…

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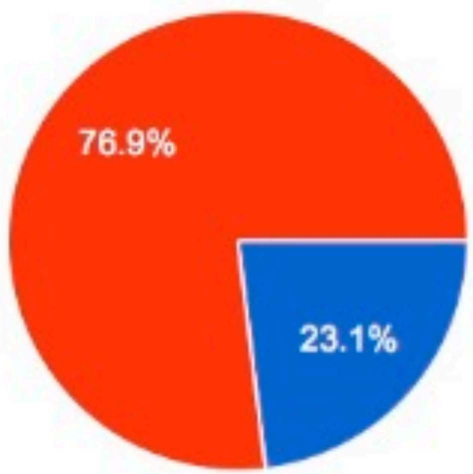
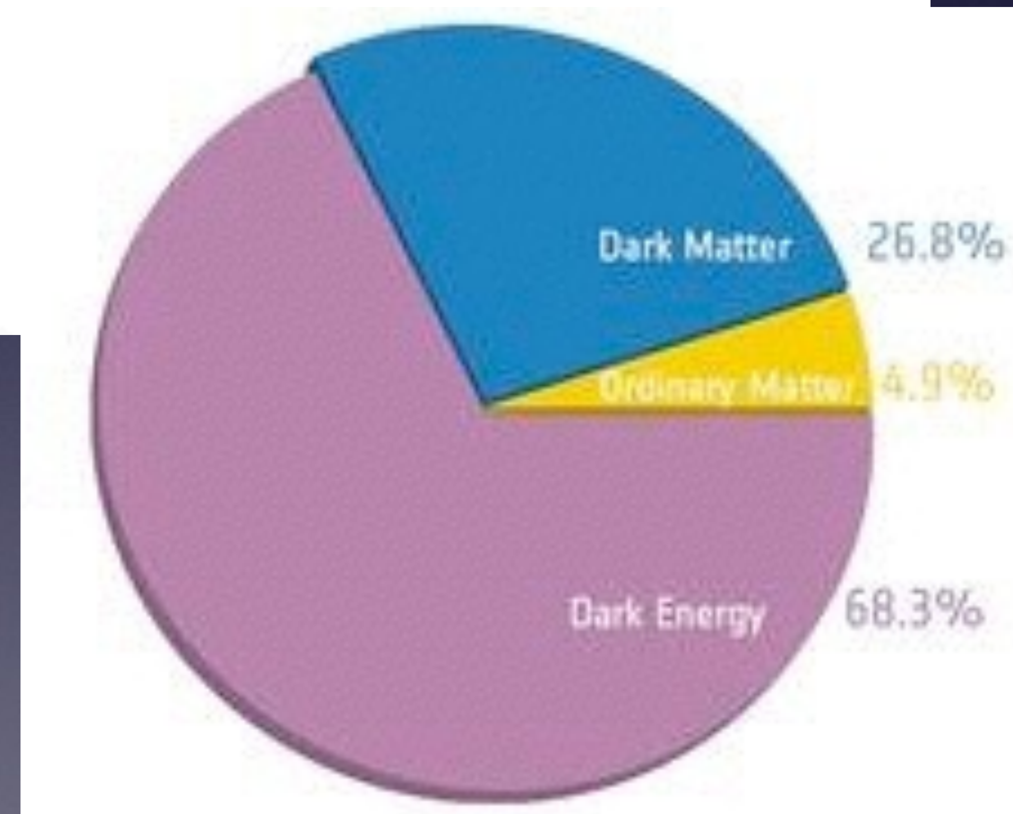




At least optimism…

H. Pagels and J.R. Primack, Phys. Rev. Lett. 48 (1982) 223

The Gravitino Dark Matter

The gravitino was in fact the first candidate to be proposed as a dark matter, before the neutralino by Pagels and Primack in 1982*

Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

Heinz Pagels
The Rockefeller University, New York, New York 10021

and

Joel R. Primack
Physics Department, University of California, Santa Cruz, California 95064

(Received 17 August 1981)

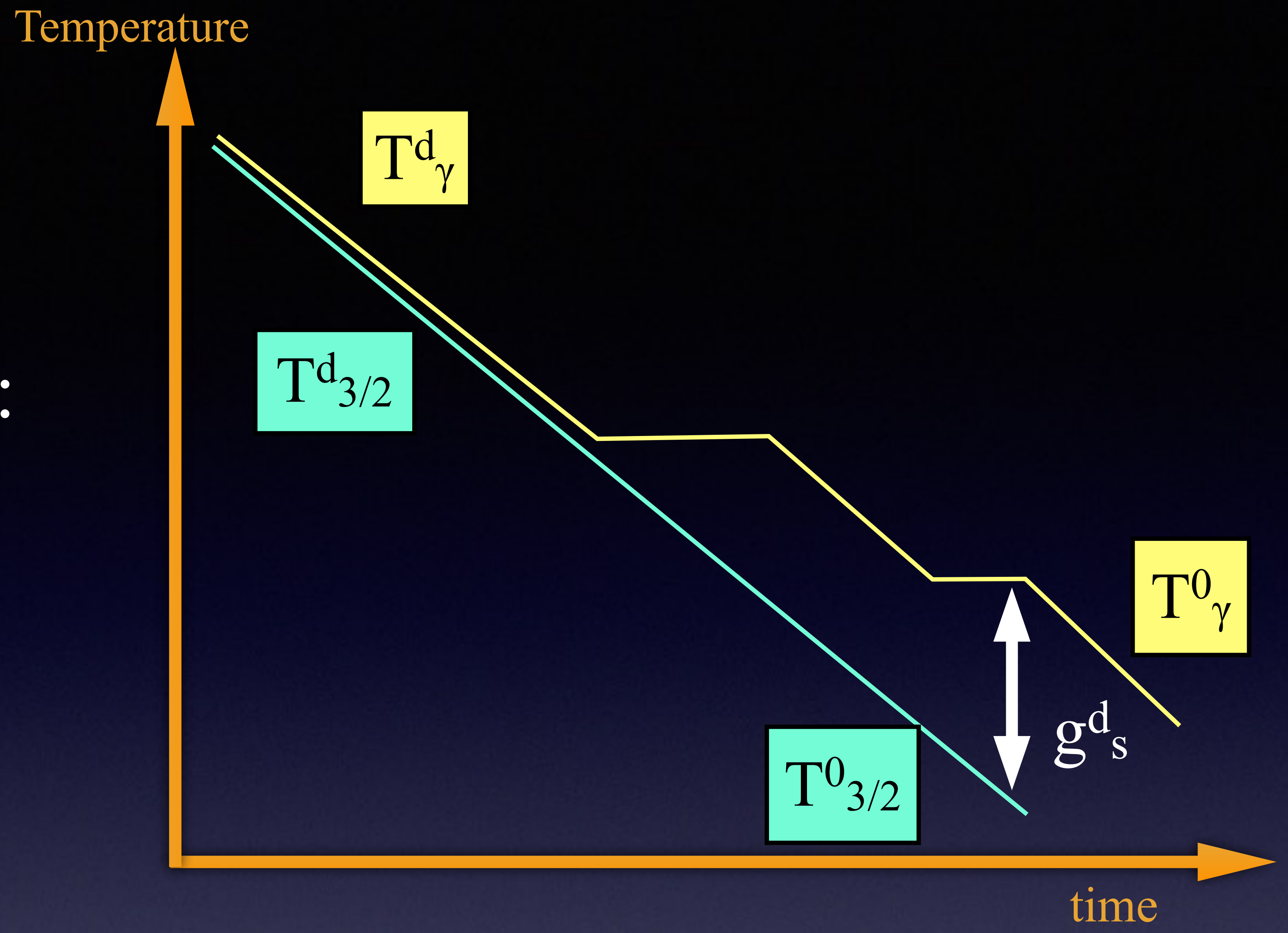
that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter F satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and

This implies that dynamical features associated with supersymmetry must appear in the teraelectronvolt energy range and possibly at much lower energies. The GUT desert must be populated.

*and notes by P. Fayet, in the Proceeding 16th Rencontres de Moriond, march 1981

Same computation than for the neutrino decoupling:

$S_{before} = S_{after}$



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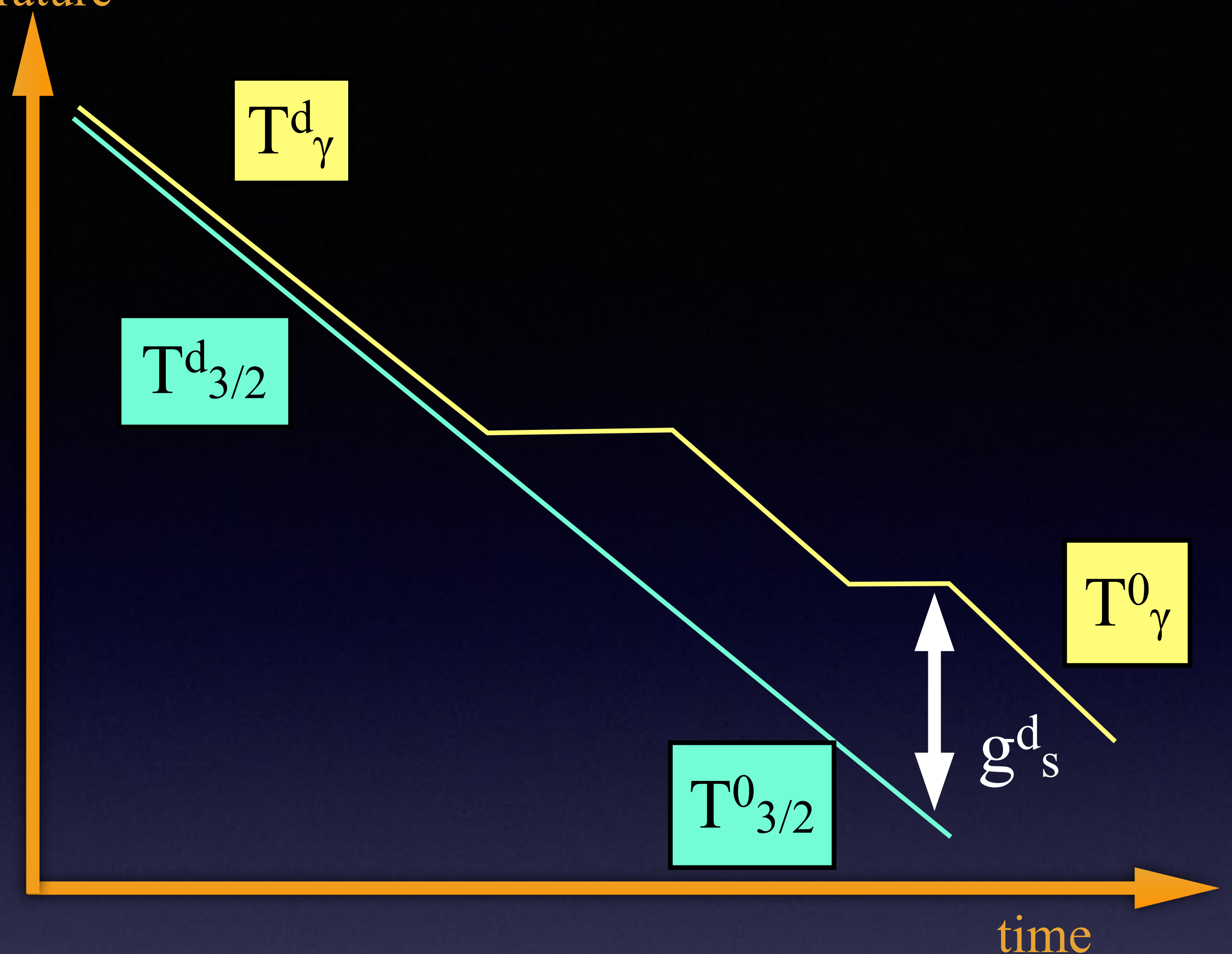

$S_{\text{before}} = S_{\text{after}}$

$$g^d_{s+3/2} \times (T^d_{3/2})^3 \times V(T^d_{3/2}) = \left[4 \times \frac{7}{8} \times (T^0_{3/2})^3 + 3 \times 2 \times \frac{7}{8}(T^0_\nu)^3 + 2 \times (T^0_\gamma)^3\right] \times V(T^0_\gamma)$$

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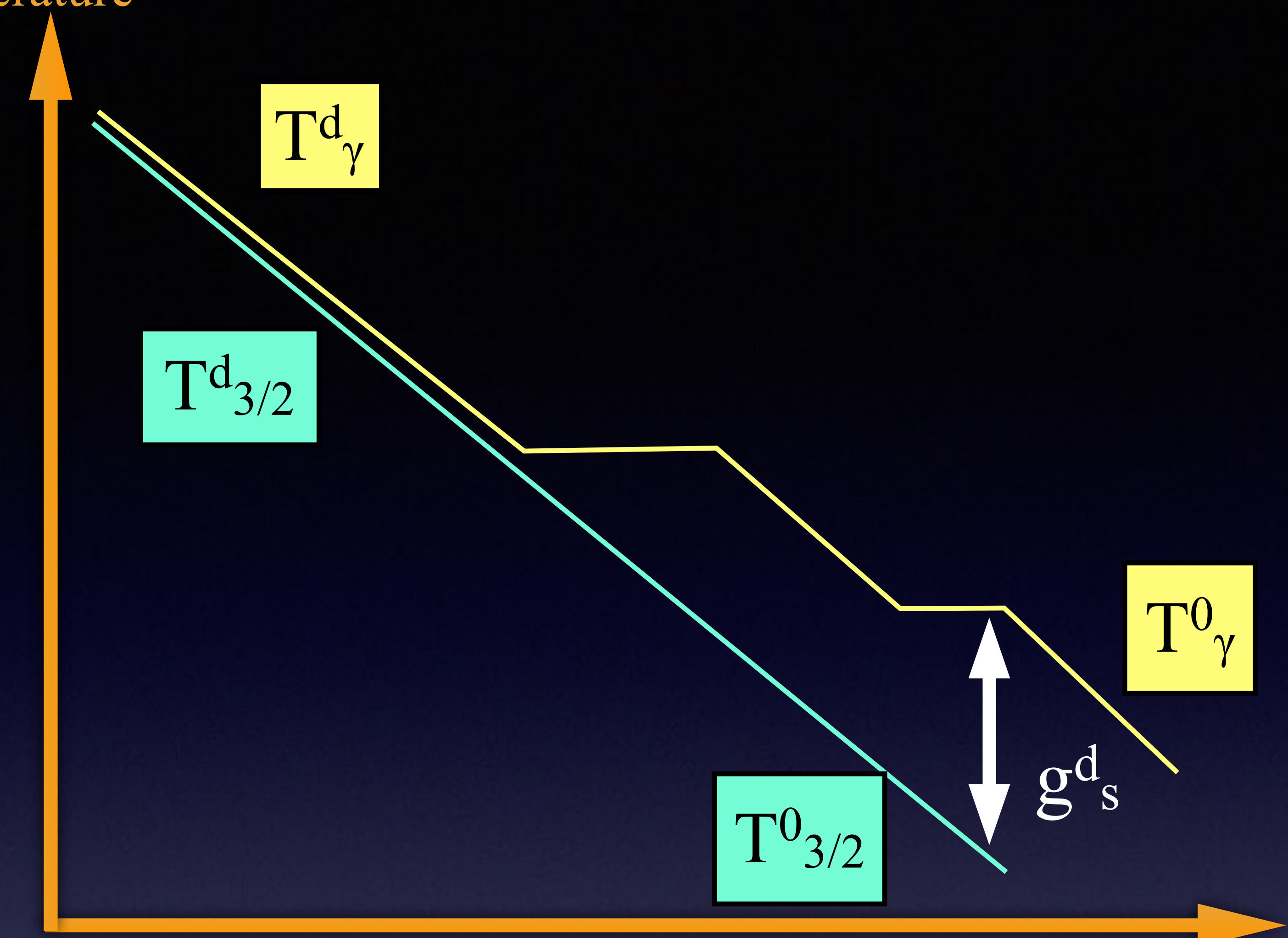

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$$(T^0_{3/2})^3 = \frac{1}{g^d_s}\frac{43}{11}(T^0_\gamma)^3 \quad \Rightarrow \quad \Omega h^2 = \frac{\rho_{3/2}}{\rho^0_c} \simeq \frac{210}{g^d_s}\left(\frac{m_{3/2}}{1\ \mathrm{keV}}\right) \lesssim 0.1 \quad \Rightarrow \quad m_{3/2} \lesssim 100\ \mathrm{eV} \quad [g^d_s \lesssim 200]^*$$

*$m_{3/2} < 1$ keV in the Pagels-Primack case because they took $h^2=1$ and $\Omega < 1$

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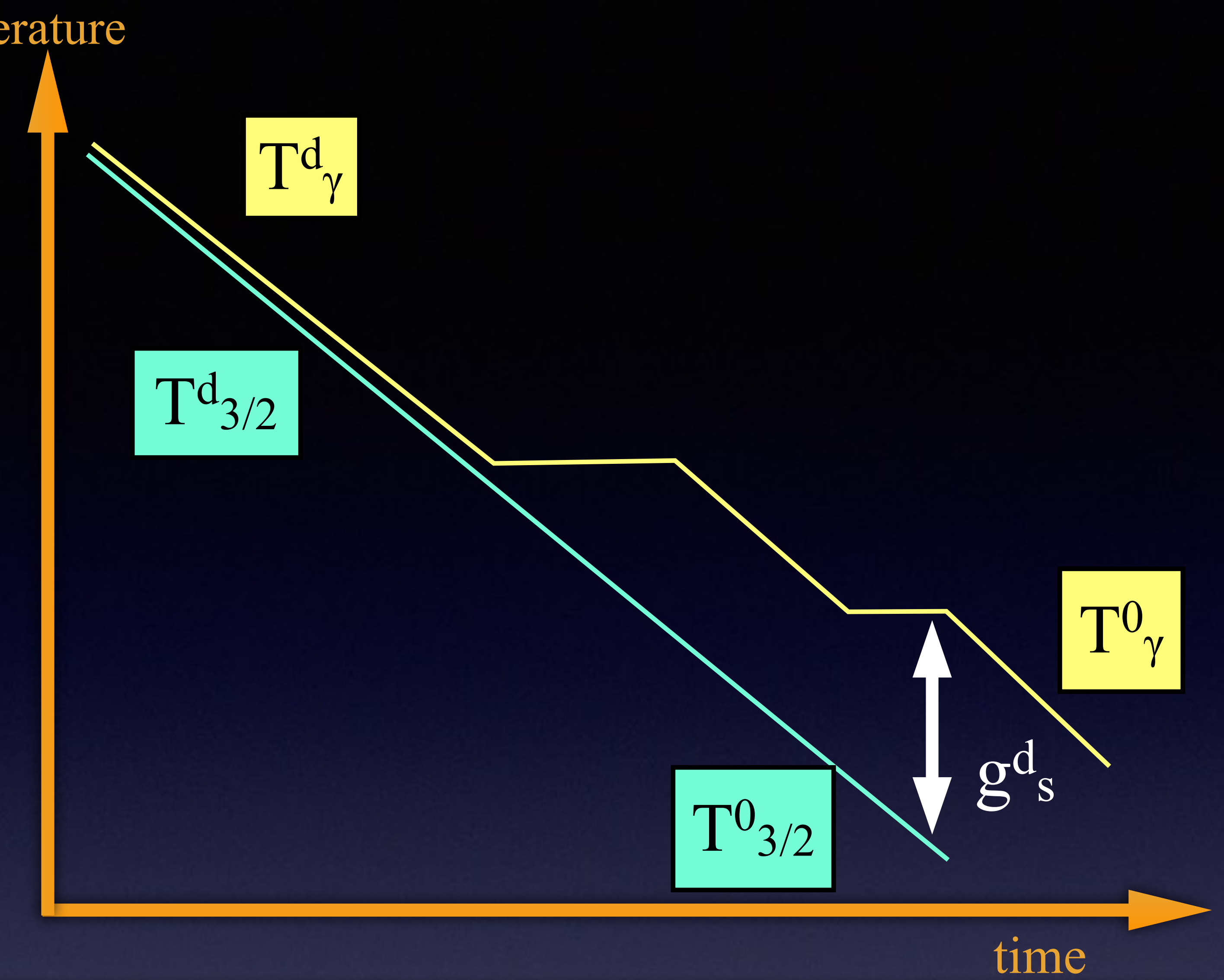

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Fundamental hypothesis: the gravitino has been in thermal equilibrium with the primordial plasma after reheating.

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But….

Main hypothesis is that the gravitino was, after reheating, in thermal equilibrium with the primordial plasma.

Weinberg then proposed 6 month latter a scenario with an unstable gravitino, to allow heavier masses and higher SUSY breaking scale.

Asking for its lifetime $\tau_{3/2} < 1$ second to avoid BBN issues, he obtains

Cosmological Constraints on the Scale of Supersymmetry Breaking

Steven Weinberg
Department of Physics, University of Texas, Austin, Texas 78712
(Received 9 March 1982)

The gravitino must be either light enough so that ambient gravitinos would not produce too large a cosmic deceleration, or heavy enough so that almost all gravitinos would have decayed before the time of helium synthesis. The second alternative is shown to allow supersymmetry-breaking scales above a model-dependent lower bound of 10^{11} to 10^{16} GeV.

$$\Gamma_{3/2} = \alpha_3 \frac{m_{3/2}^3}{M_{\rm Pl}} \; ; \quad \tau_{3/2} < 1 \; s \quad \Rightarrow \quad m_{3/2} > 10 \text{ TeV} \quad \Rightarrow \quad \sqrt{F} \simeq \sqrt{m_{3/2} M_{\rm Pl}} \gtrsim 10^{11} \text{ GeV}$$

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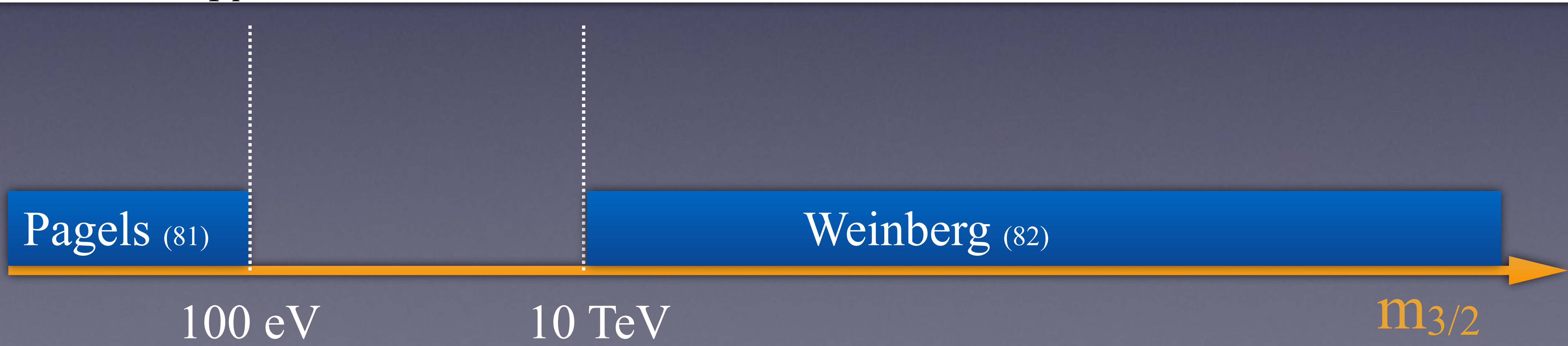

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IS IT EASY TO SAVE THE GRAVITINO?

M.Yu. KHLOPOV
Institute of Applied Mathematics, Moscow 125047, USSR

and

A.D. LINDE
Lebedev Physical Institute, Moscow 117924, USSR

Received 21 December 1983

$$dY_{3/2}/dt \sim \alpha N(T) T^3/m_P , \quad (1)$$

where $N(T) \sim 10^{+2}$ is the effective number of degrees of freedom (the number of particle species with masses $M \lesssim T$). It follows from (1) that if after inflation the universe reheats up to the temperature $T = T_R$, then the gravitino abundance grows practically from zero value up to

$$Y_{3/2} \sim \alpha \sqrt{N(T_R)}\, T_R/m_P \sim 10^{-1}\, T_R/m_P . \quad (2)$$

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M.Y. Khlopov, A.D. Linde; Phys.Lett. 138B (1984) 265-268

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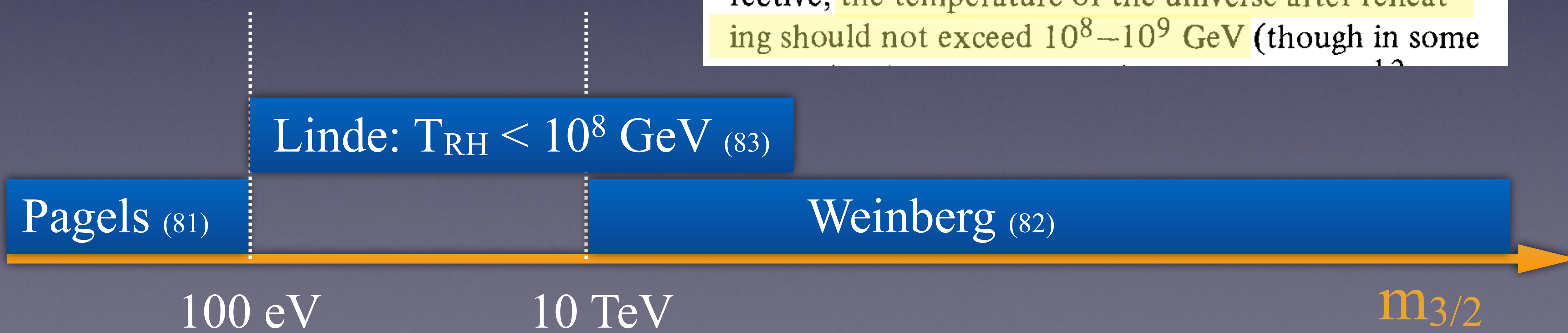


M.Y. Khlopov, A.D. Linde; Phys.Lett. 138B (1984) 265-268

AFTER PRIMORDIAL INFLATION

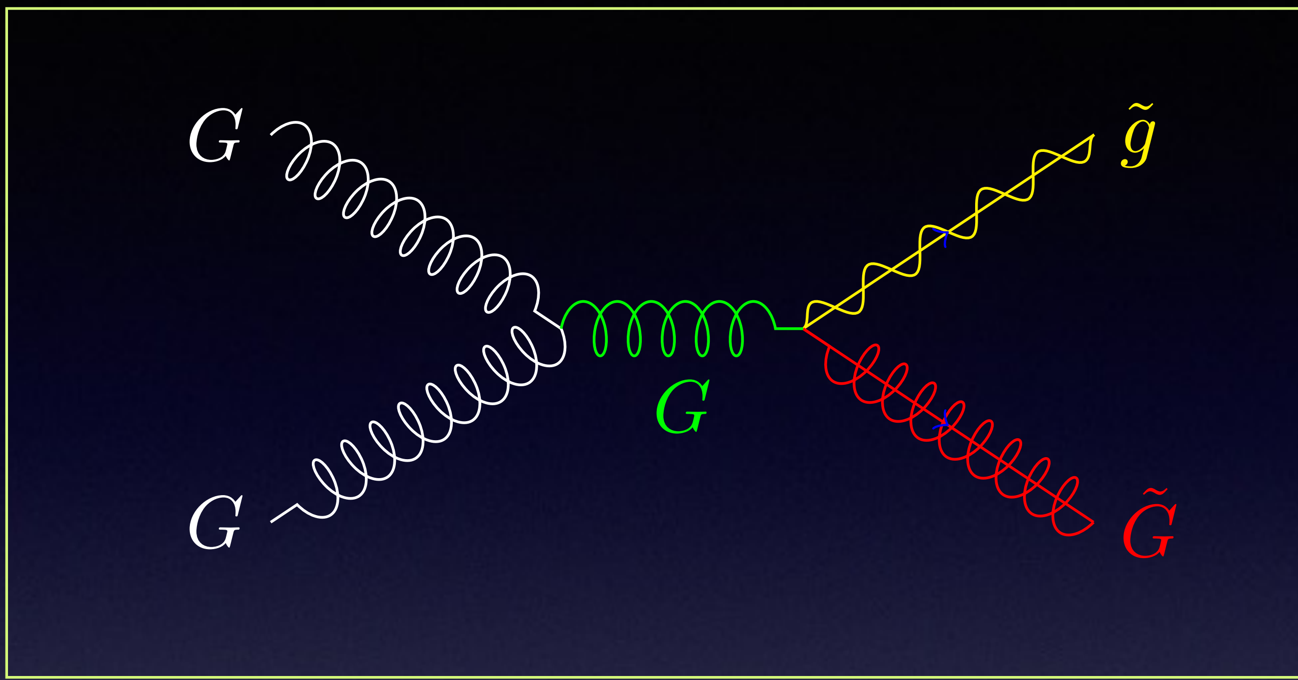
D.V. Nanopoulos, K.A. Olive
and
M. Srednicki

CERN -- Geneva

ABSTRACT

We consider the history of the early Universe in the locally supersymmetric model we have previously discussed. We pay particular attention to the requirement of converting the quanta of the field which drives primordial inflation (inflatons) to ordinary particles which can produce the cosmological baryon asymmetry without producing too many gravitinos. An inflaton mass of about 10^{13} GeV (a natural value in our model) produces a completely acceptable scenario.

Ellis, Kim and Nanopoulos (84) then considered for the first time the dominant process (in fact, they listed 10 processes)



COSMOLOGICAL GRAVITINO REGENERATION AND DECAY

John Ellis, Jihn E. Kim*) and D.V. Nanopoulos

CERN - Geneva

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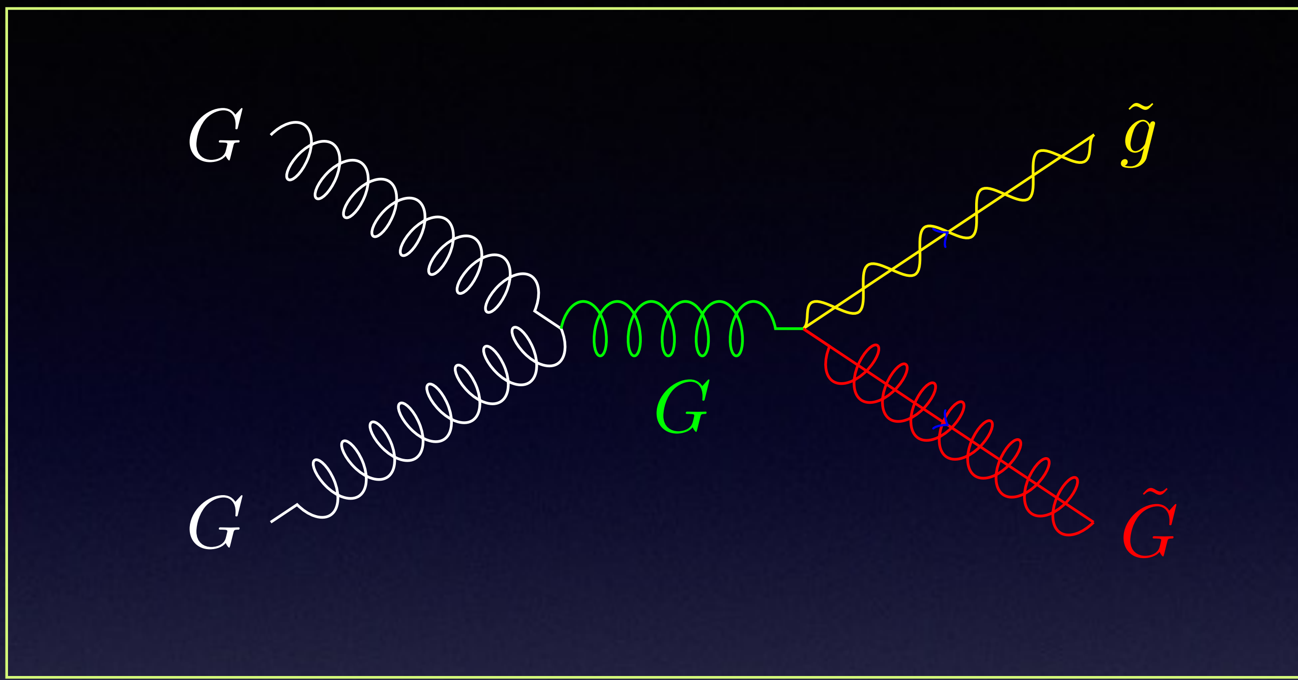

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But just the transverse degree of freedom (spin +/-3/2)

$$\mathcal{L} = \frac{1}{4M_{\rm Pl}} \bar{\psi}^{\alpha} \gamma_{\alpha} [\gamma^{\mu}, \gamma^{\nu}] \, \tilde{G} \, G_{\mu\nu}$$

gravitino gluino gluon

They obtained $T_{RH} < 10^9$ - 10^{10} GeV

Then, Moroi, Murayama and Yamaguchi proposed to look at the goldstino population. This is the « scattering process »

gluon

$$\boxed{\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu\psi} \quad \mathcal{L} = \frac{i m_{\tilde{G}}}{8\sqrt{6}\, m_{3/2}\, M_{Pl}}\bar{\psi}\,[\gamma_\mu, \gamma_\nu]\tilde{G}\, G_{\mu\nu}$$

gluino

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T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

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gluon

gluino

gravitino

Cosmological constraints when the gravitino is the lightest superparticle are studied. From the condition that the relic gravitinos should not overclose the universe, the upper bound on the reheating temperature of the universe is found to be 10^2–10^{10} GeV in a range of gravitino mass 10^{-5}–10 GeV. Furthermore, if the decay of the next-to-the-lightest superparticle produces sizable high energy photons, constraints from the light element (D, ^{3}He, ^{4}He) photodestruction exclude a range of the gravitino mass.

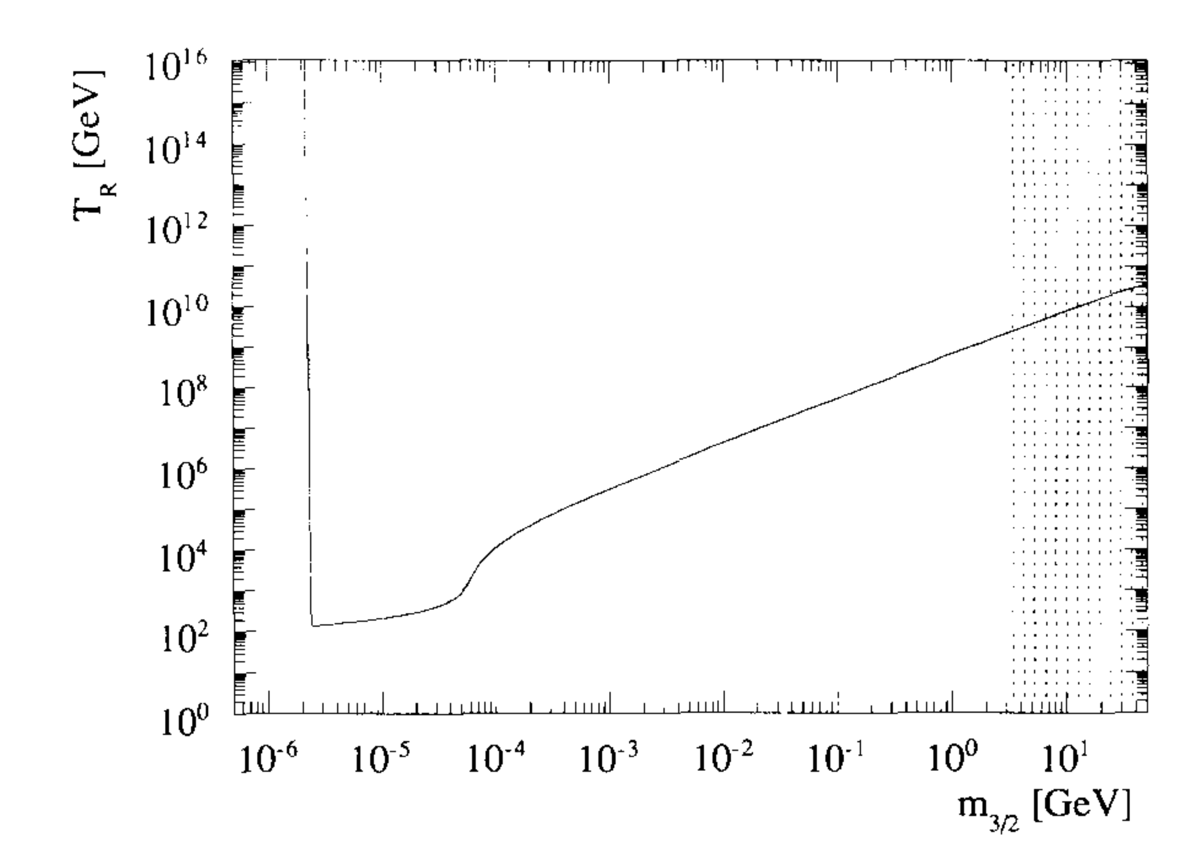
Cosmological constraints on the light stable gravitino

T. Moroi [1], H. Murayama
Department of Physics, Tohoku University, Sendai 980, Japan

and

Masahiro Yamaguchi
Department of Physics, College of General Education, Tohoku University, Sendai 980, Japan

$$\Omega_{3/2}h^2 \sim 0.3\left(\frac{1\ \text{GeV}}{m_{3/2}}\right)\left(\frac{T_{\rm RH}}{10^{10}\ \text{GeV}}\right)\sum\left(\frac{m_{\tilde{G}}}{100\ \text{GeV}}\right)^2$$

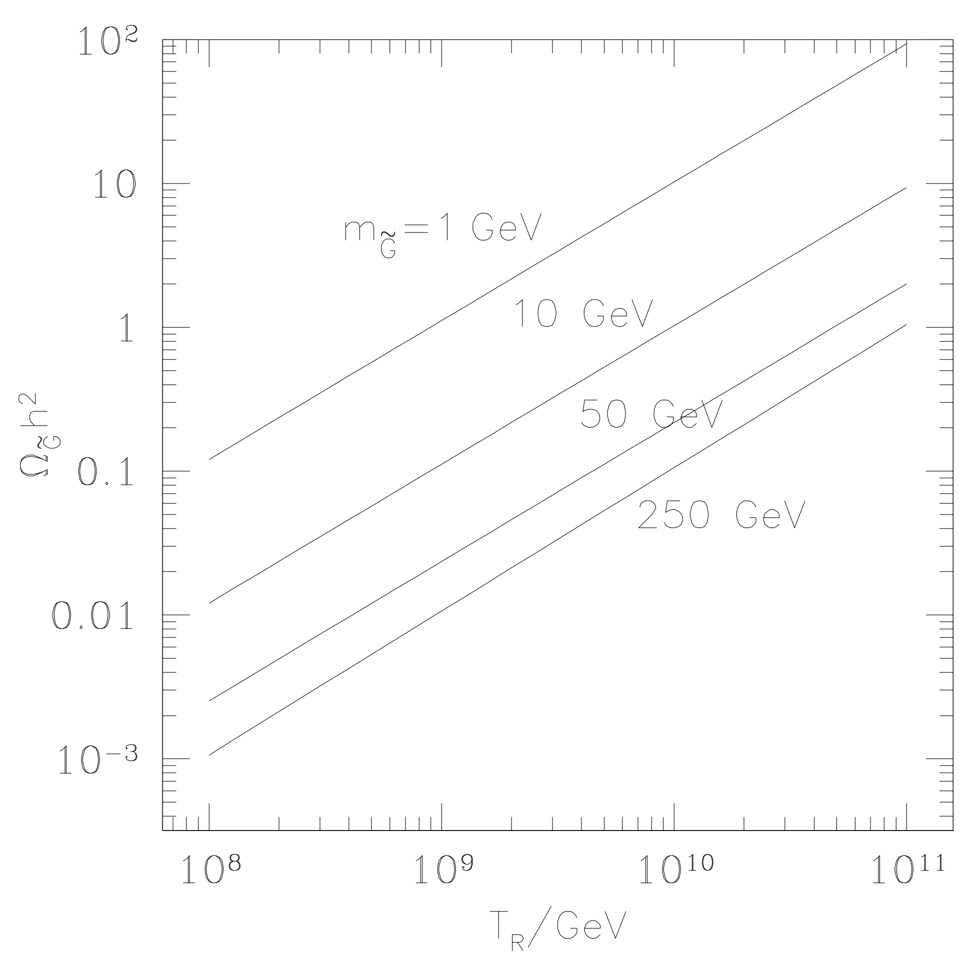


T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

All summarized and completed (loop level) by Bolz, Brandenburg and Buchmuller

Thermal Production of Gravitinos

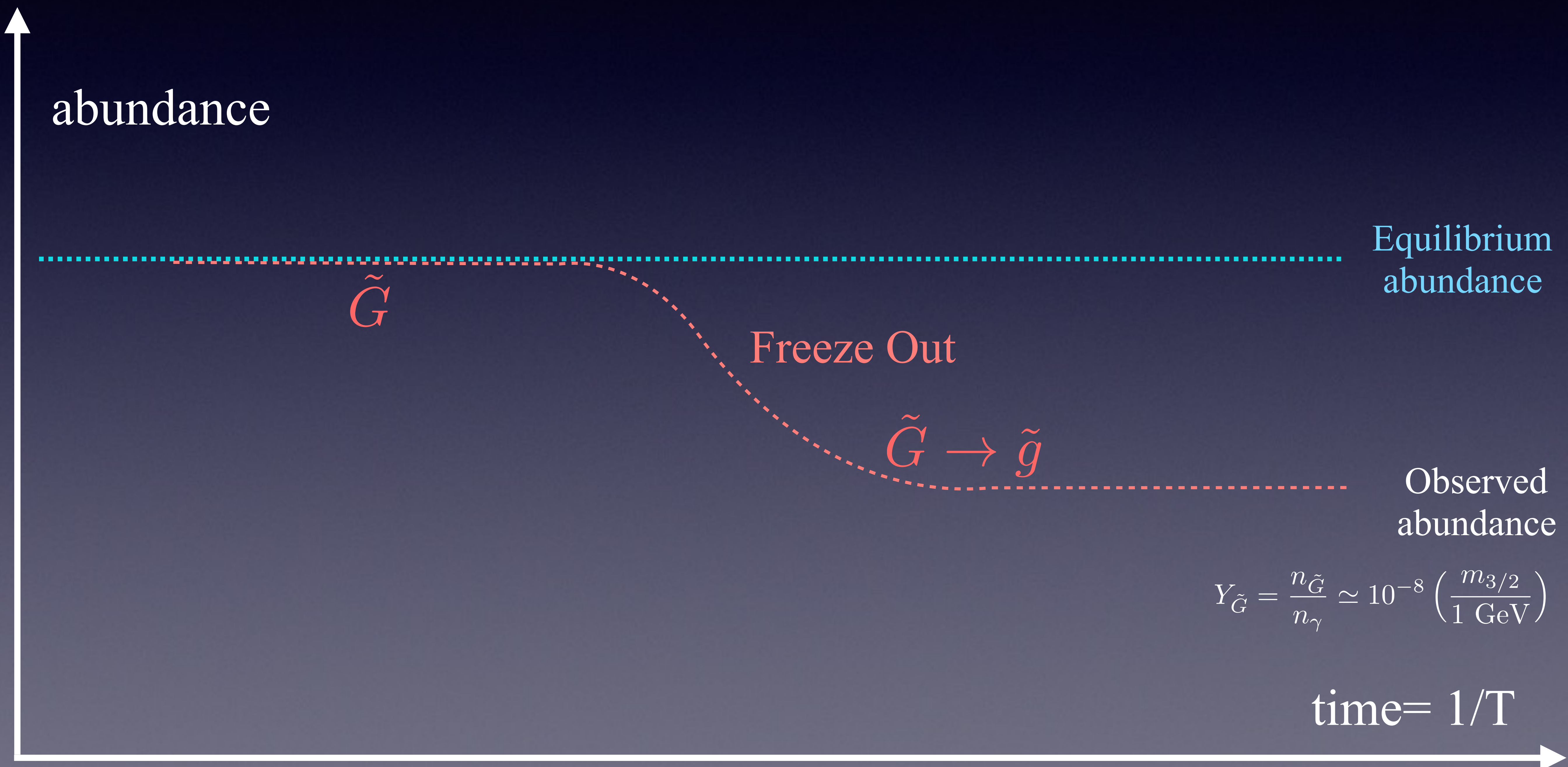
M. Bolz, A. Brandenburg, W. Buchmüller



M. Bolz, A. Brandenburg, W. Buchmuller; Nucl.Phys .**B606** : 518-544, 2001

The Freeze Out process

The Freeze Out (FO) process is the mechanism describing the population of gravitino through the decay of the Next to Lightest Supersymmetric Particle (NLSP) into gravitino, once the NLSP is out of equilibrium. The NLSP can be a sfermion or a neutralino.



J.L. Feng, S. Su and F. Takayama, Phys. Rev. D70 075019 (2004)

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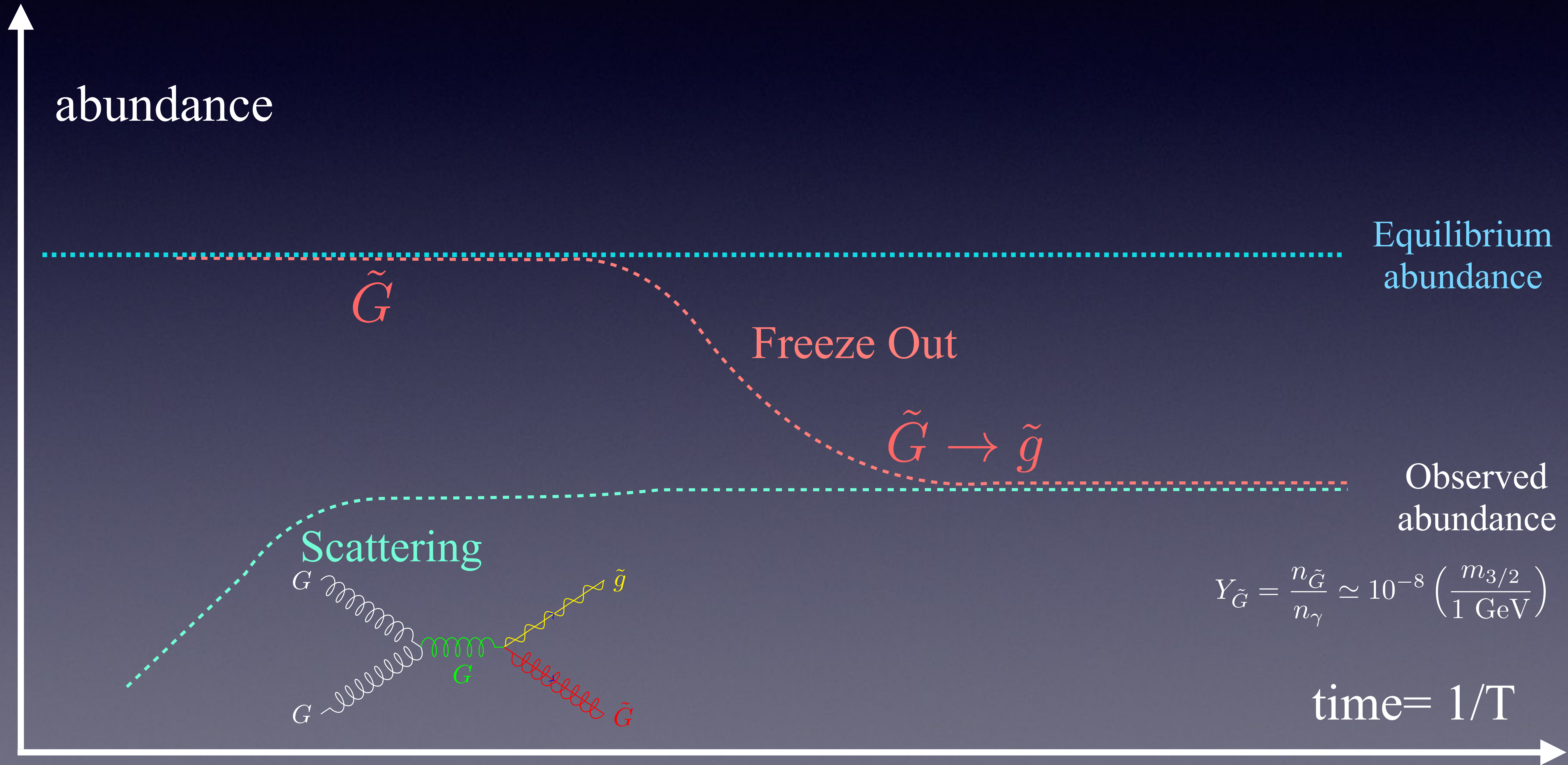

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$$\Omega_{3/2}^{FO} = \Omega_{\tilde{G}} \times \frac{m_{3/2}}{m_{\tilde{G}}} \propto \frac{1}{\langle \sigma v \rangle} \frac{m_{3/2}}{m_{\tilde{G}}} \simeq \frac{1}{\alpha_3} m_{\tilde{G}} \times m_{3/2}$$

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$$\Omega_{3/2}^{\mathrm{scat}} \propto \frac{T_{RH} m_{\tilde{G}}^2}{m_{3/2}} \quad \Rightarrow \quad \Omega_{3/2} \propto \frac{T_{RH} m_{\tilde{G}}^2}{m_{3/2}} + m_{\tilde{G}} \times m_{3/2}$$

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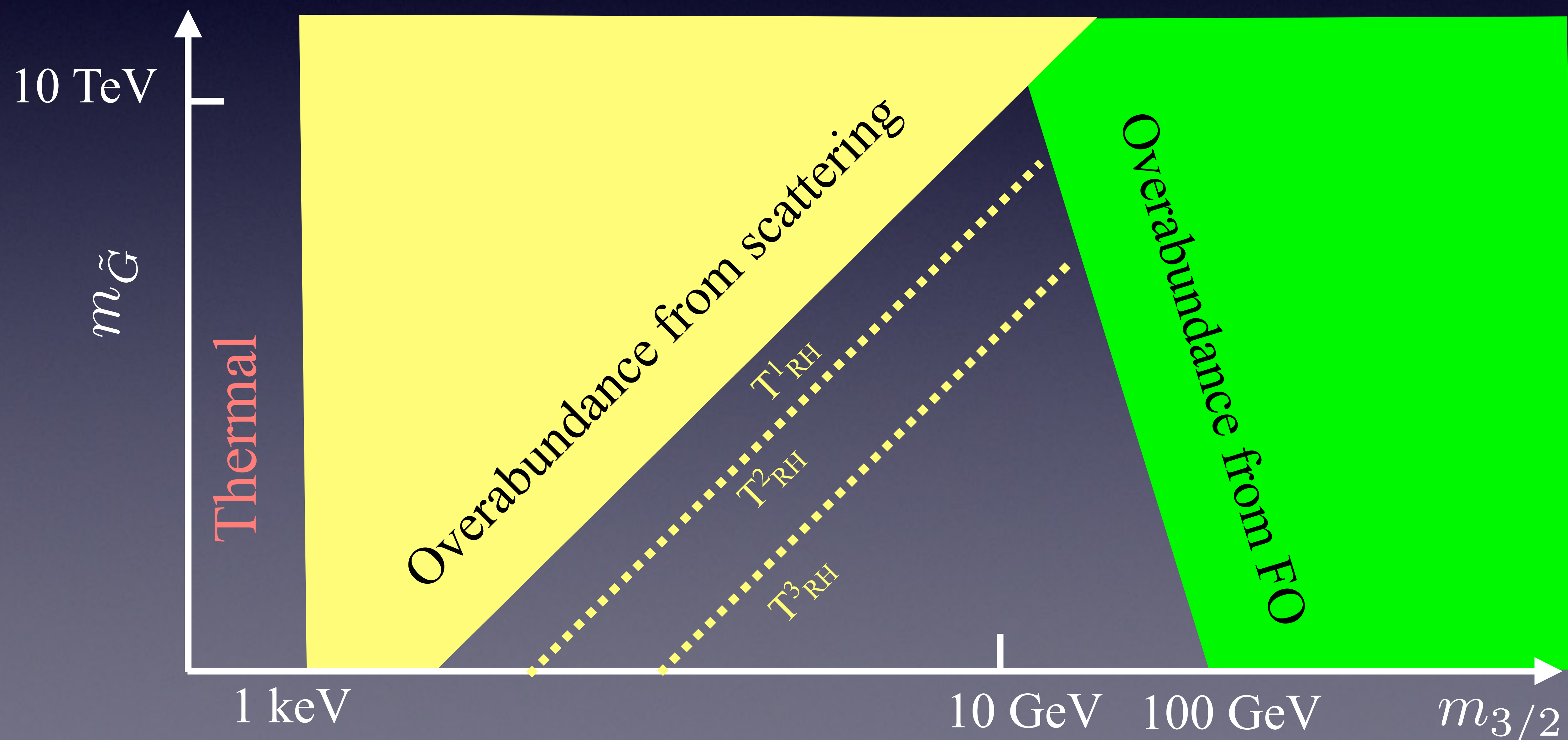

A new paradigm?

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All the computation of relic abundance of gravitino until now has been based on the hypothesis of the gravitino [Pagels] and/or SUSY partners [FO, FI] have been in thermal equilibrium with the primordial plasma or at least are produced by pair with the gravitino [Scattering].

In all case, SUSY spectrum needs to be lower than the reheating temperature:

$M_{SUSY} < T_{RH}$.

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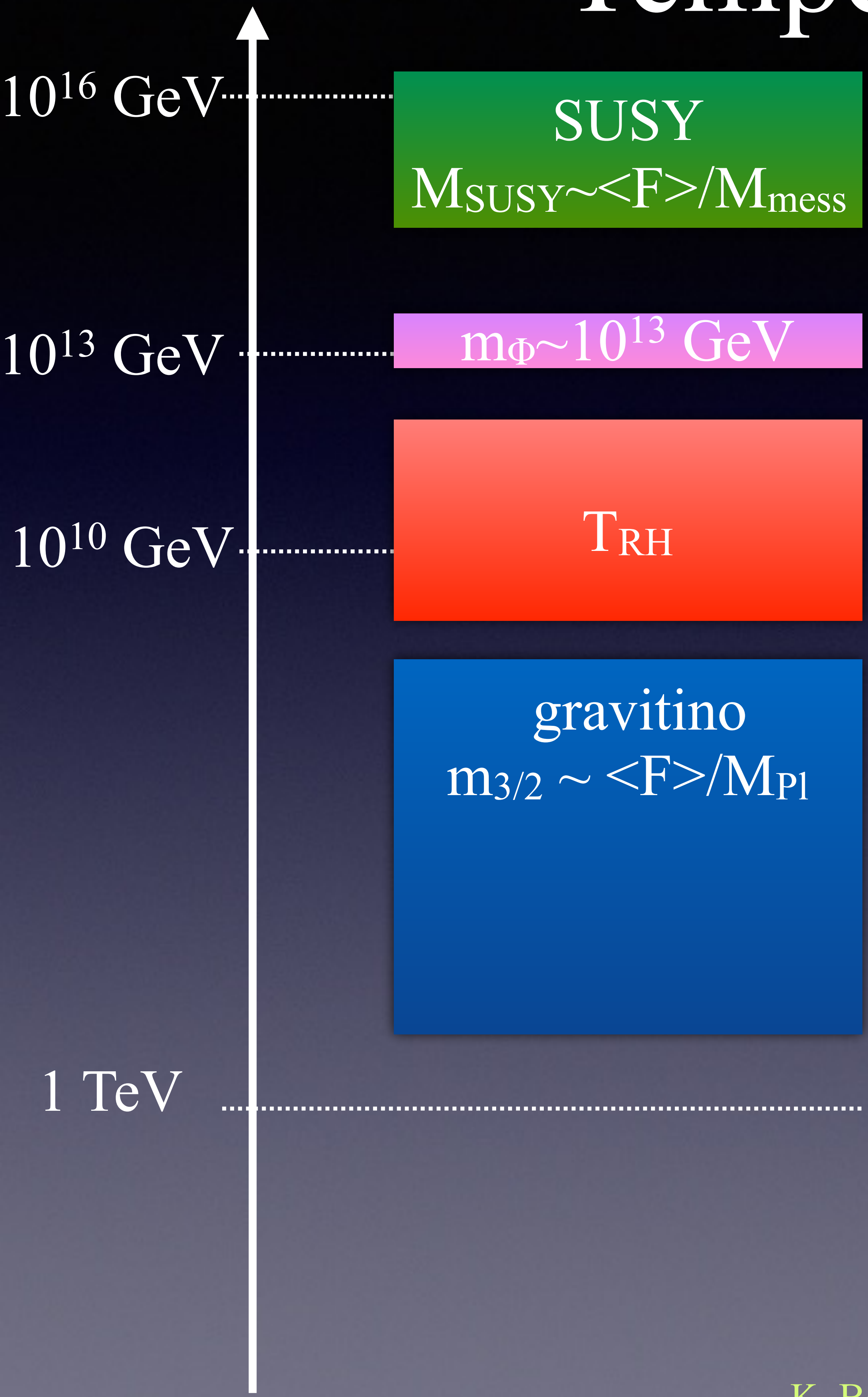
What is happening if we change the pradigm, settling as a minimal (reasonable) hypothesis:

$M_{SUSY} > M_{inflaton} = M_{\Phi}$

Temperature scale



E. Dudas, Y.M. and K.A. Olive, arXiv:1704.03008

K. Benakli, Y. Chen, E. Dudas and Y.M. Phys.Rev. D95 (2017) no.9, 095002

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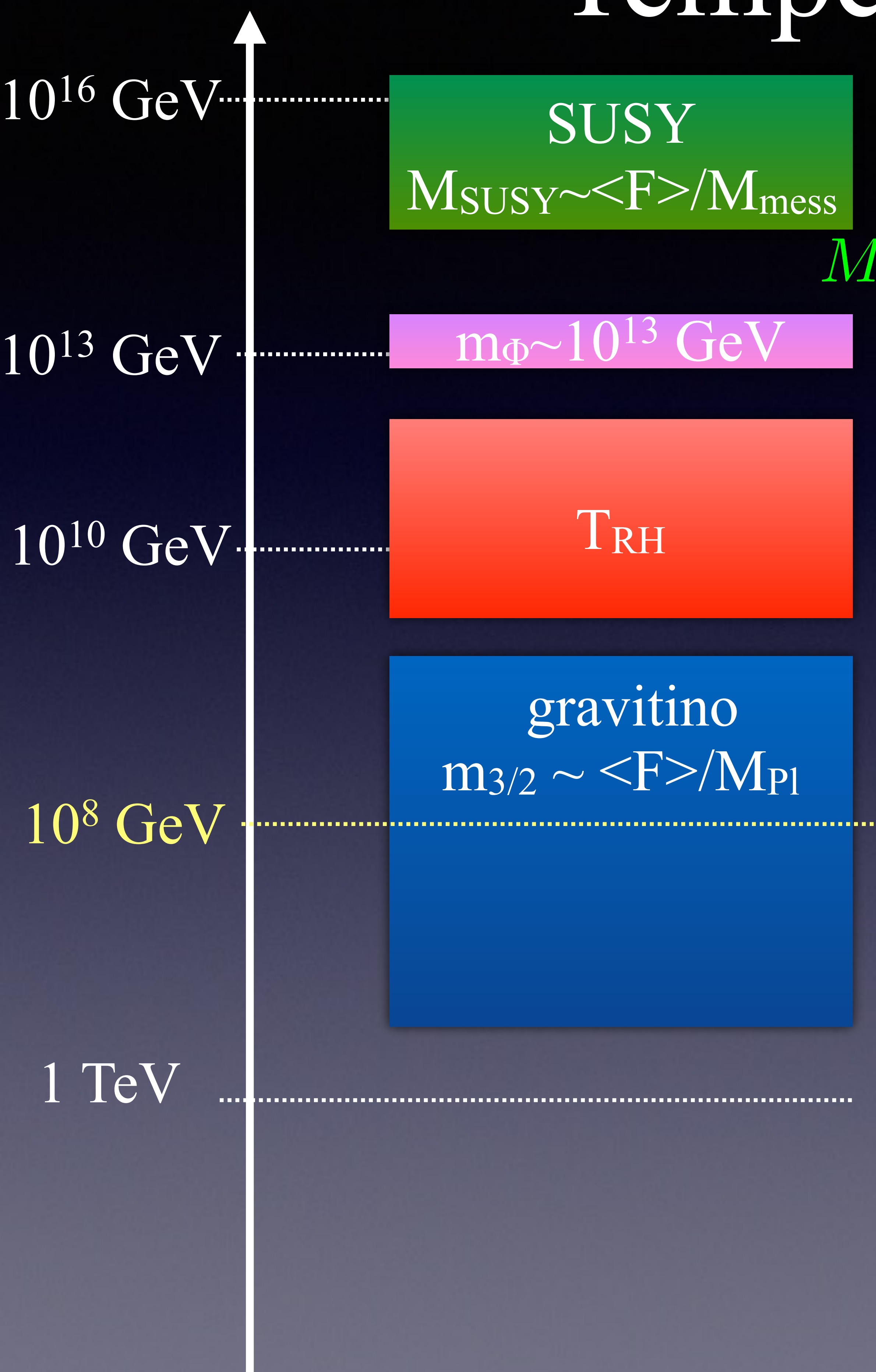


$$M_{SUSY} = \frac{F}{M_{mess}} > m_\phi \;, M_{mess} > M_{SUSY}$$

$$\Rightarrow F > m_\phi^2 \;, \;\text{with}\; m_\phi \sim 3 \times 10^{13}\;\text{GeV}$$

$$\Rightarrow m_{3/2} = \frac{F}{M_{Pl}} \gtrsim 0.2\;\text{EeV}$$

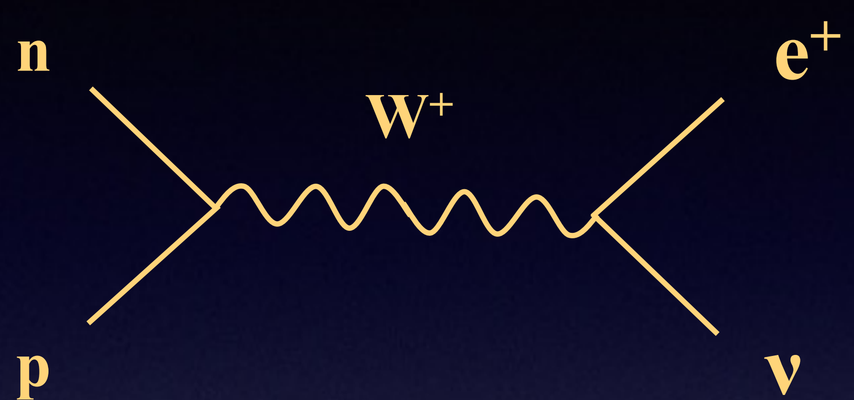
The simple hypothesis $M_{SUSY} > m_\Phi$ gives already a lower bound on gravitino mass of $\sim 10^8$ GeV

E. Dudas, Y.M. and K.A. Olive, arXiv:1704.03008
K. Benakli, Y. Chen, E. Dudas and Y.M. Phys.Rev. D95 (2017) no.9, 095002

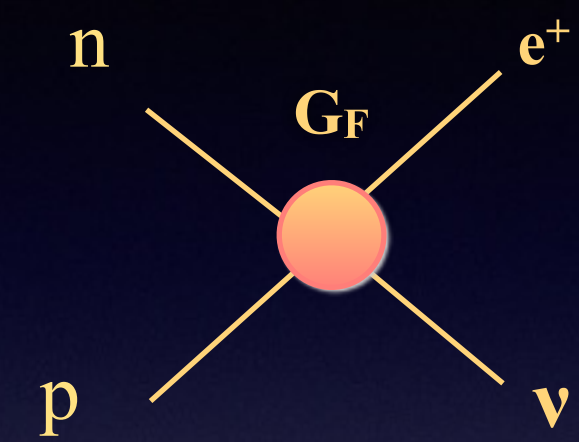
How to produce gravitino?

Directly from the thermal bath

Another (« a la Fermi ») point of view



$M_W >> E$



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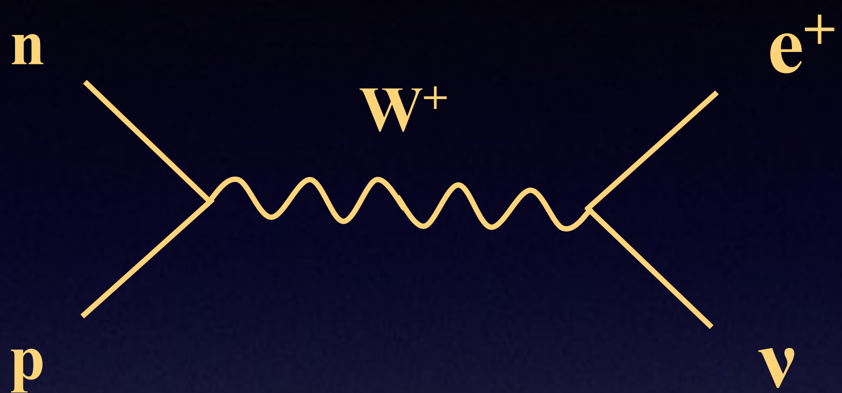

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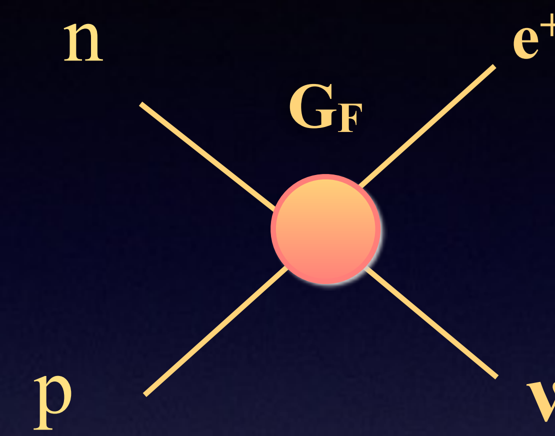

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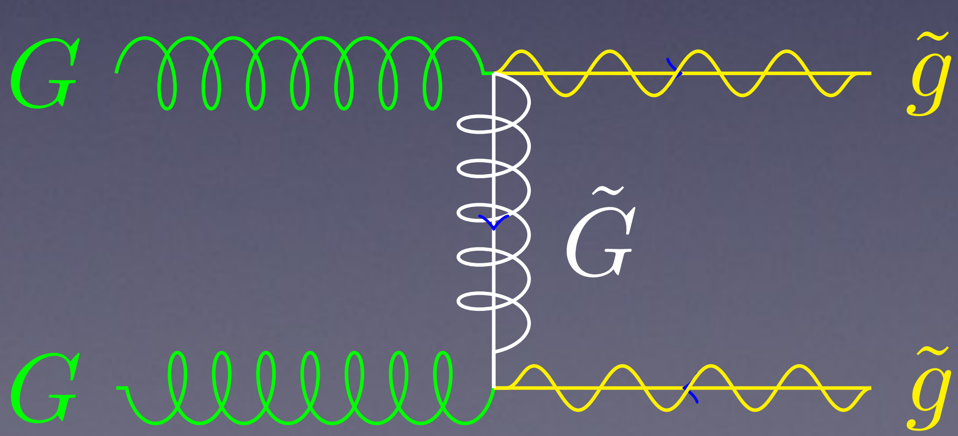
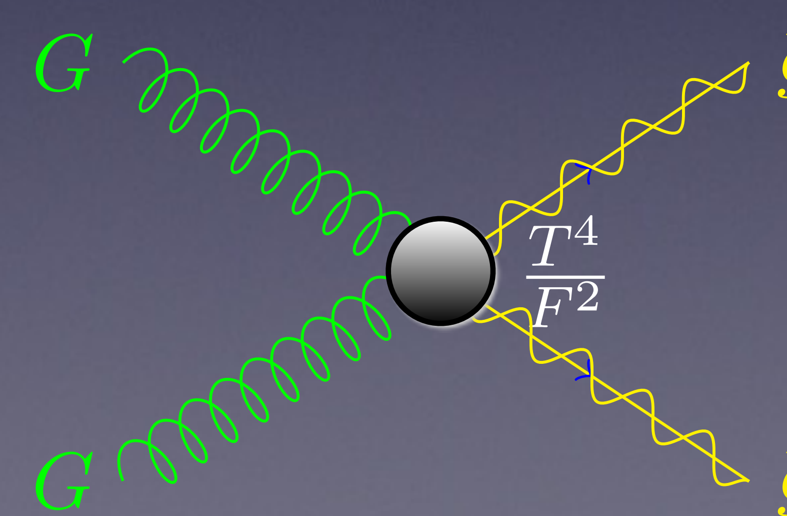


$M_{\tilde{G}} >> E$



Generating the interactions

One can deduce the vierbein of the theory, just from the hypothesis that the longitudinal part of the gravitino is the goldstino of the SUSY transformation*

$$e_m^a \;=\; \delta_m^a - \frac{i}{2F^2}\partial_m G\sigma^a\bar{G} + \frac{i}{2F^2}G\sigma^a\partial_m\bar{G} \;,$$

$$L_{2G} = \frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu},$$

I. Antoniadis, E. Dudas, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

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Which gives the Lagrangian between the SM and the goldstino

$$\begin{aligned}
&\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\mu H\partial_\nu H^\dagger),\\
&\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times\\
&(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),\\
&\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi}, \qquad (10)
\end{aligned}$$

Notice how the Lagrangian has suppressed coupling ($1/F^2$) and strong energy/temperature dependance

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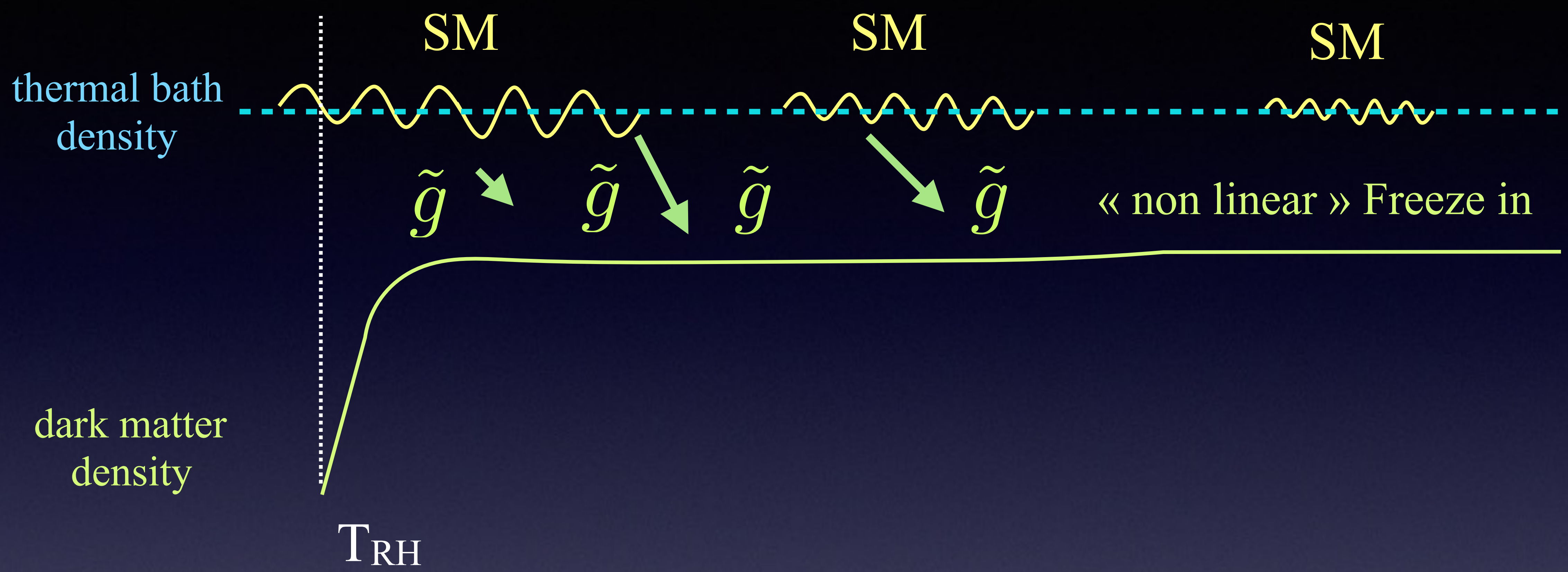
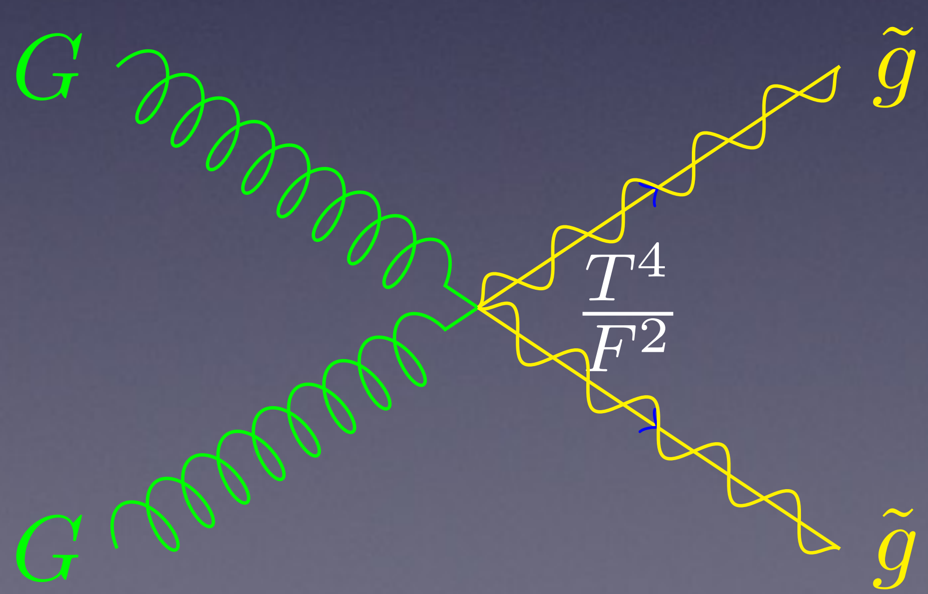
The freeze-in mechanism

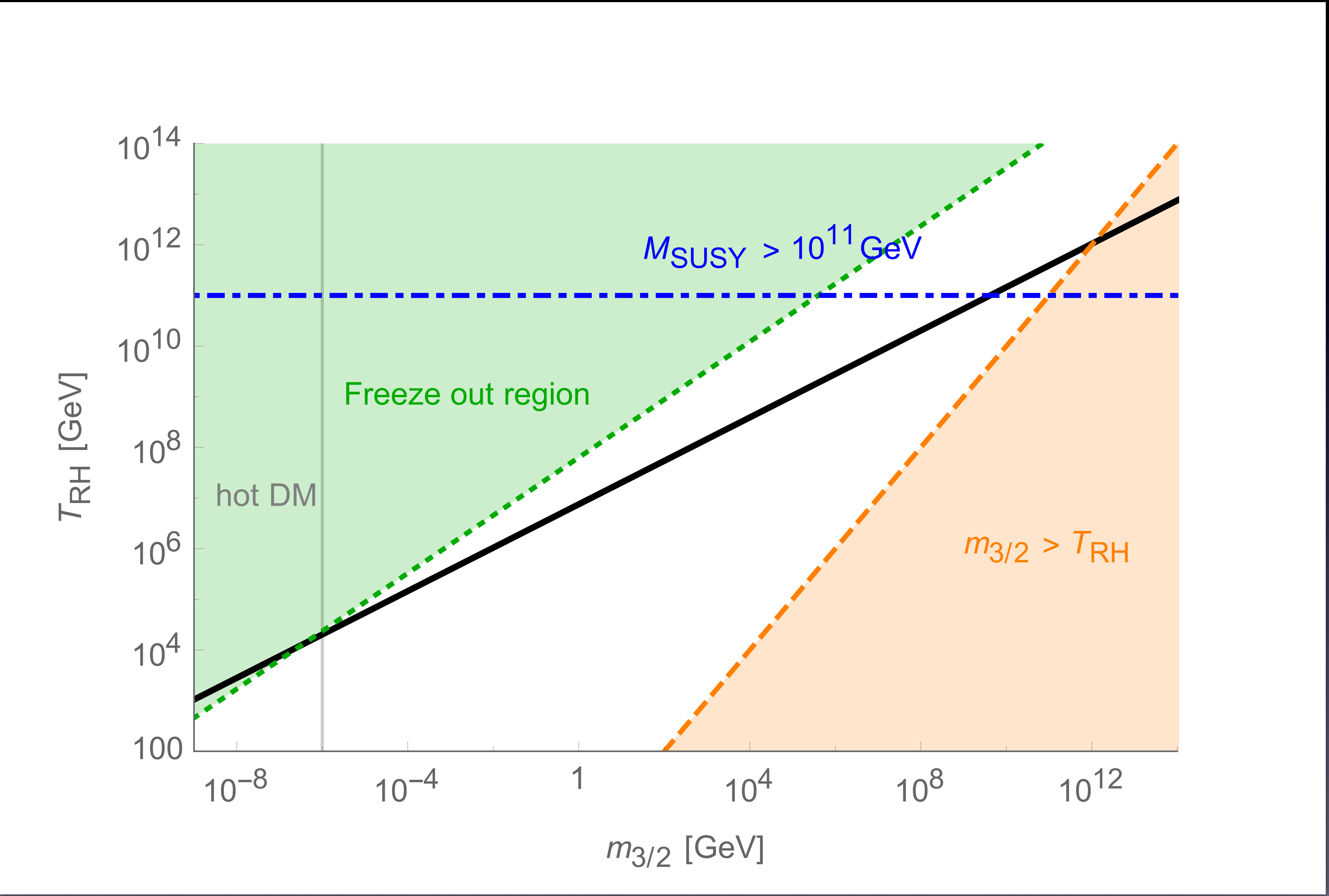




$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{RH}}{2.0 \times 10^{10}\ \mathrm{GeV}}\right)^7$$

K. Benakli, Y. Chen, E. Dudas and Y.M. arXiv:1701.06574

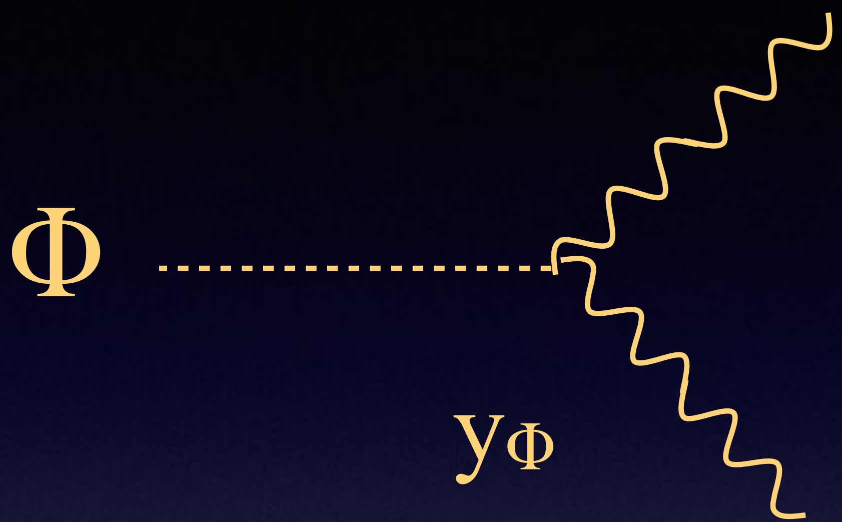
The Freeze-In mechanism (FI)



K. Benakli, Y. Chen, E. Dudas and Y.M. arXiv:1701.06574

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \text{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\text{RH}}}{5.4\times 10^7\ \text{GeV}}\right)^7$$

Including inflaton decay



$$T_{RH} = \left(\frac{10}{g_s}\right)^{1/4} \left(\frac{2\Gamma_\phi\ M_P}{\pi\ c}\right)^{1/2} = 0.55\,\frac{y_\phi}{2\pi}\left(\frac{m_\phi\ M_P}{c}\right)^{1/2}$$

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E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574

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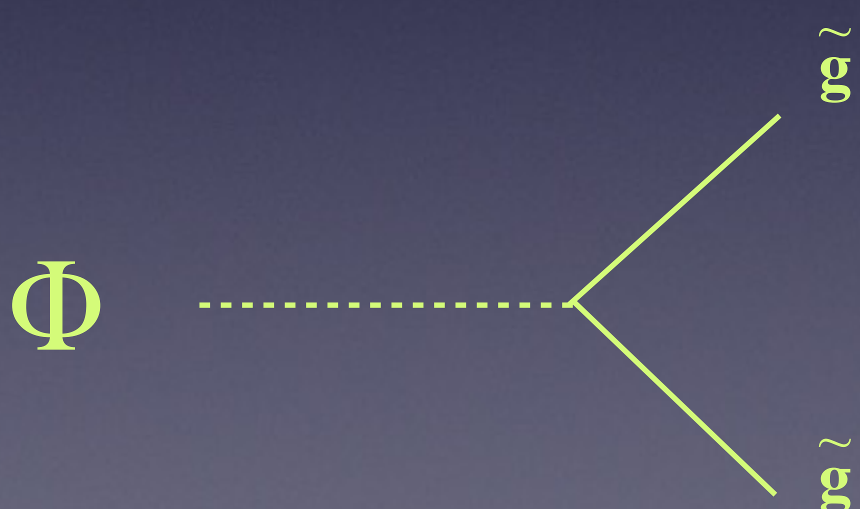
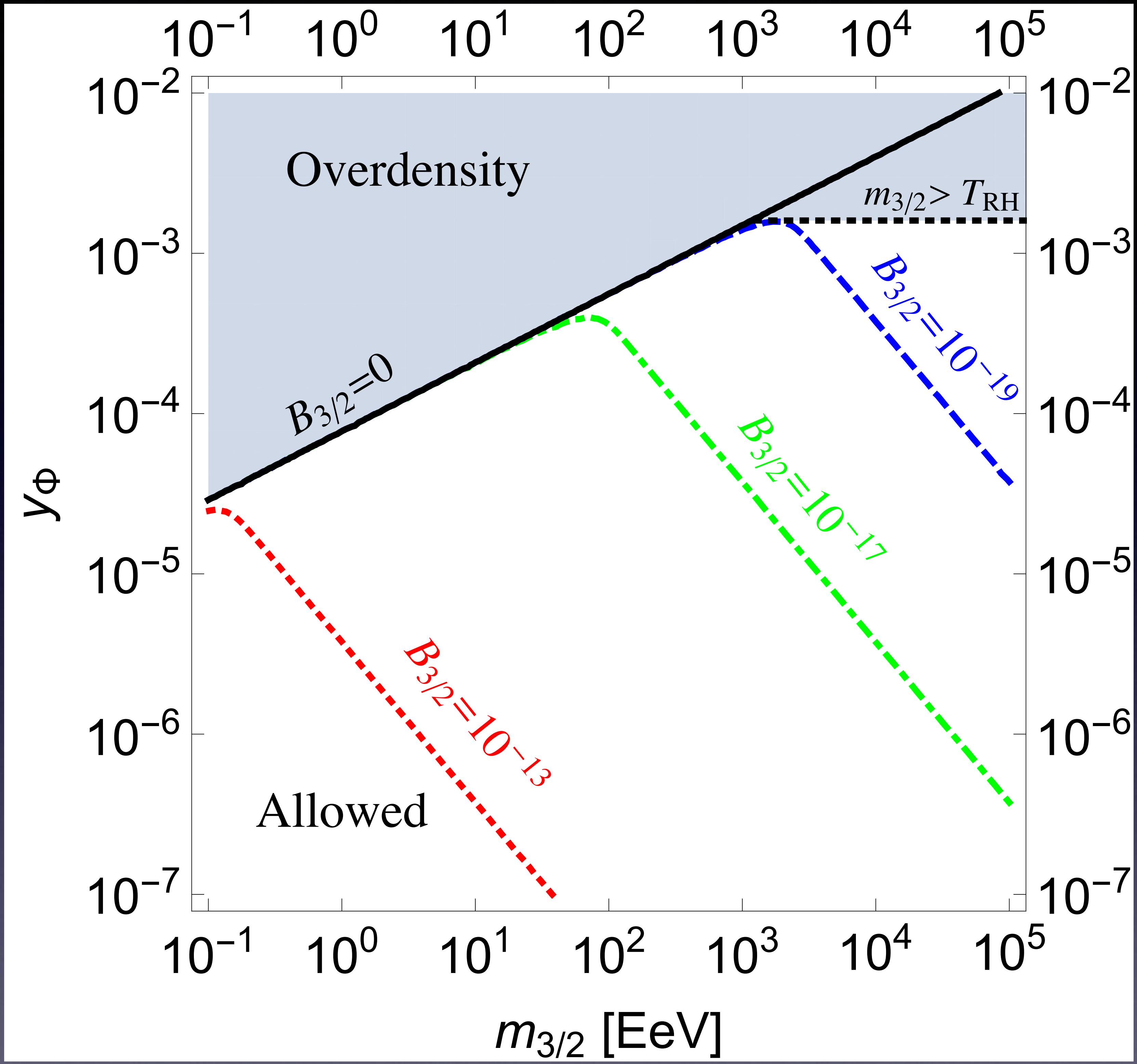


$$\Omega^{decay}_{3/2}h^2 = 0.11\left(\frac{B_{3/2}}{1.3\times 10^{-13}}\right)\left(\frac{y_\phi}{2.9\times 10^{-5}}\right) \times \left(\frac{m_{3/2}}{0.1 \text{ EeV}}\right)\left(\frac{3\times 10^{13} \text{ GeV}}{m_\phi}\right)^{1/2}$$

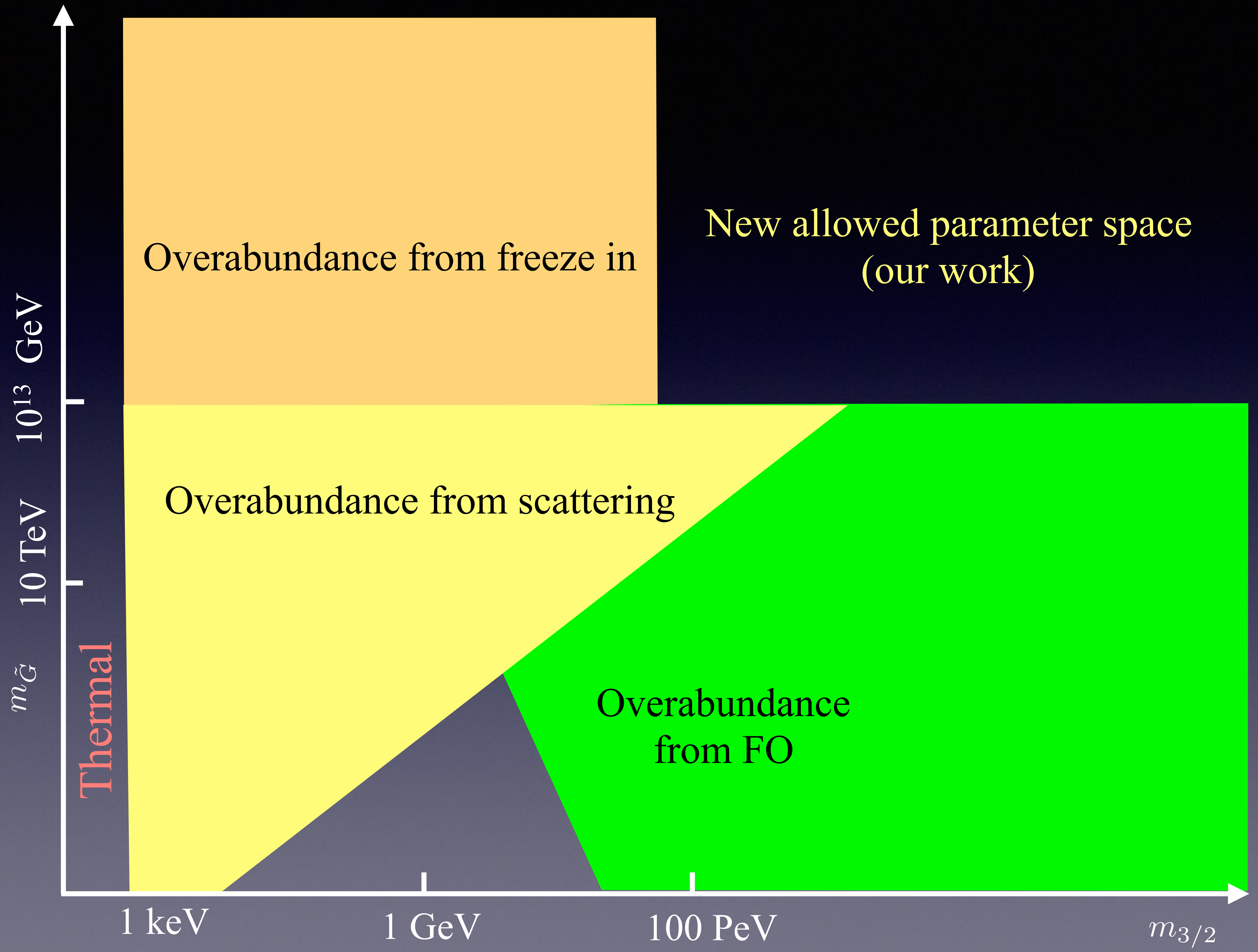
$B_{3/2} = \Gamma_{3/2}/\Gamma_\phi$

E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574



Conclusion: EeV gravitino is compatible with inflationary scenario and DM constraints.

E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574



Overabundance from freeze in
New allowed parameter space
(our work)
Overabundance from scattering
Overabundance
from FO
Thermal
10^{13} GeV
10 TeV
$m_{\tilde{G}}$
1 keV
1 GeV
100 PeV
$m_{3/2}$

Subject: now I am depressed... ;-)

From: "Sven Heinemeyer" <heinemey@mail.cern.ch>

Date: Wed, April 12, 2017 2:06 pm

To: "Keith Olive" <olive@physics.umn.edu> (less)
"Yann Mambrini" <yann.mambrini@th.u-psud.fr>

Conclusion and perspective

Conclusion and perspective

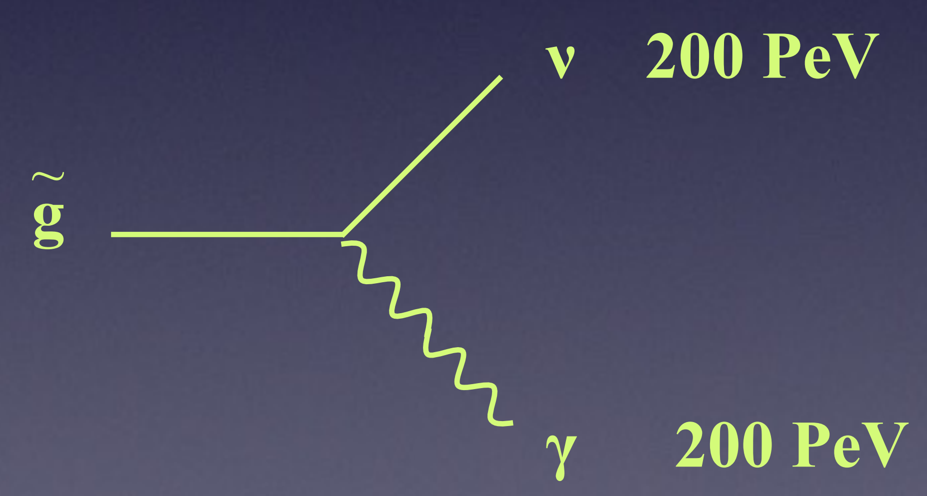
A new Pandora box opened

Conclusion and perspective

A new Pandora box opened

A smoking gun signal

K.A. Olive et al., work in progress



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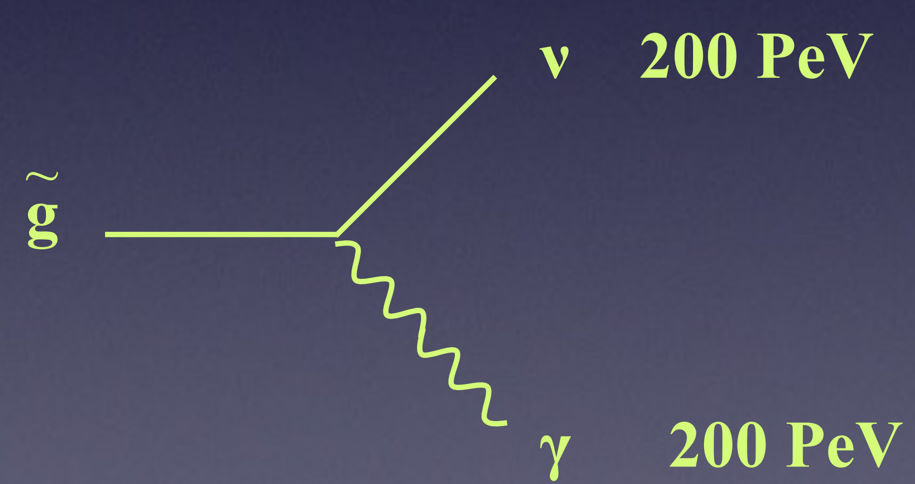

Need for a UV construction

K.A. Olive et al., work in progress

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D.V. Volkov and V.P. Akulov, Phys. Lett. **B 46** (1973) 109

I. Antoniadis, **E. Dudas**, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

E. Dudas, **Y.M.** and **K.A. Olive**, arXiv:1704.03008

K. Benakli, Y. Chen, **E. Dudas** and **Y.M.** Phys.Rev. D95 (2017) no.9, 095002


Keith, we love you!!

Backslides

Cheung et al.* showed in 2011 that the Freeze In (FI) process of gravitino production through the decay of sparticles still in thermal equilibrium should render the Universe overdense if

$T_{RH} > M_{susy}$.

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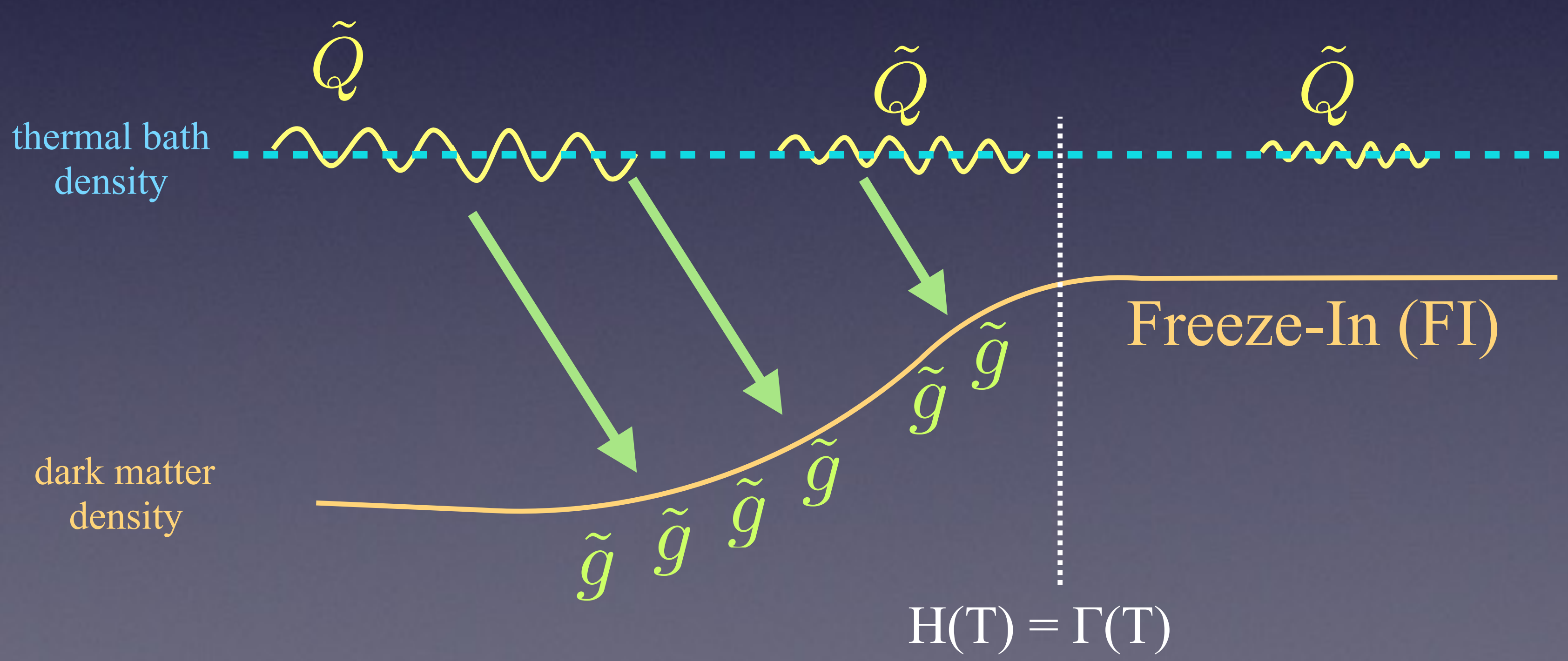
The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation ($H > \Gamma$)



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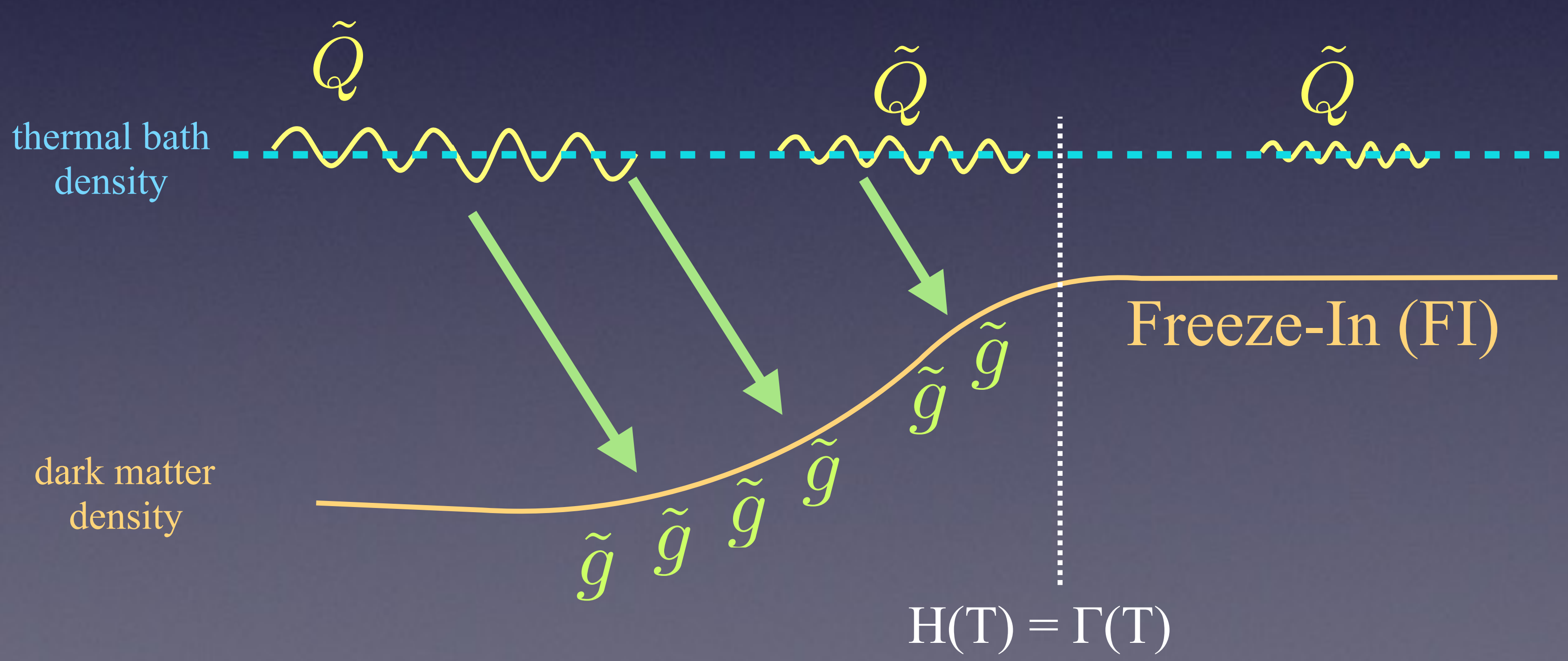

$$\Omega_{3/2}^{decay} h^2 \propto \frac{\sum M_{\tilde{Q}}^3}{m_{3/2} M_{Pl}}$$

but decay will compete with scattering

C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

If the gravitino cannot be produced by the thermalization of the primordial plasma, how can it be present in the Universe?

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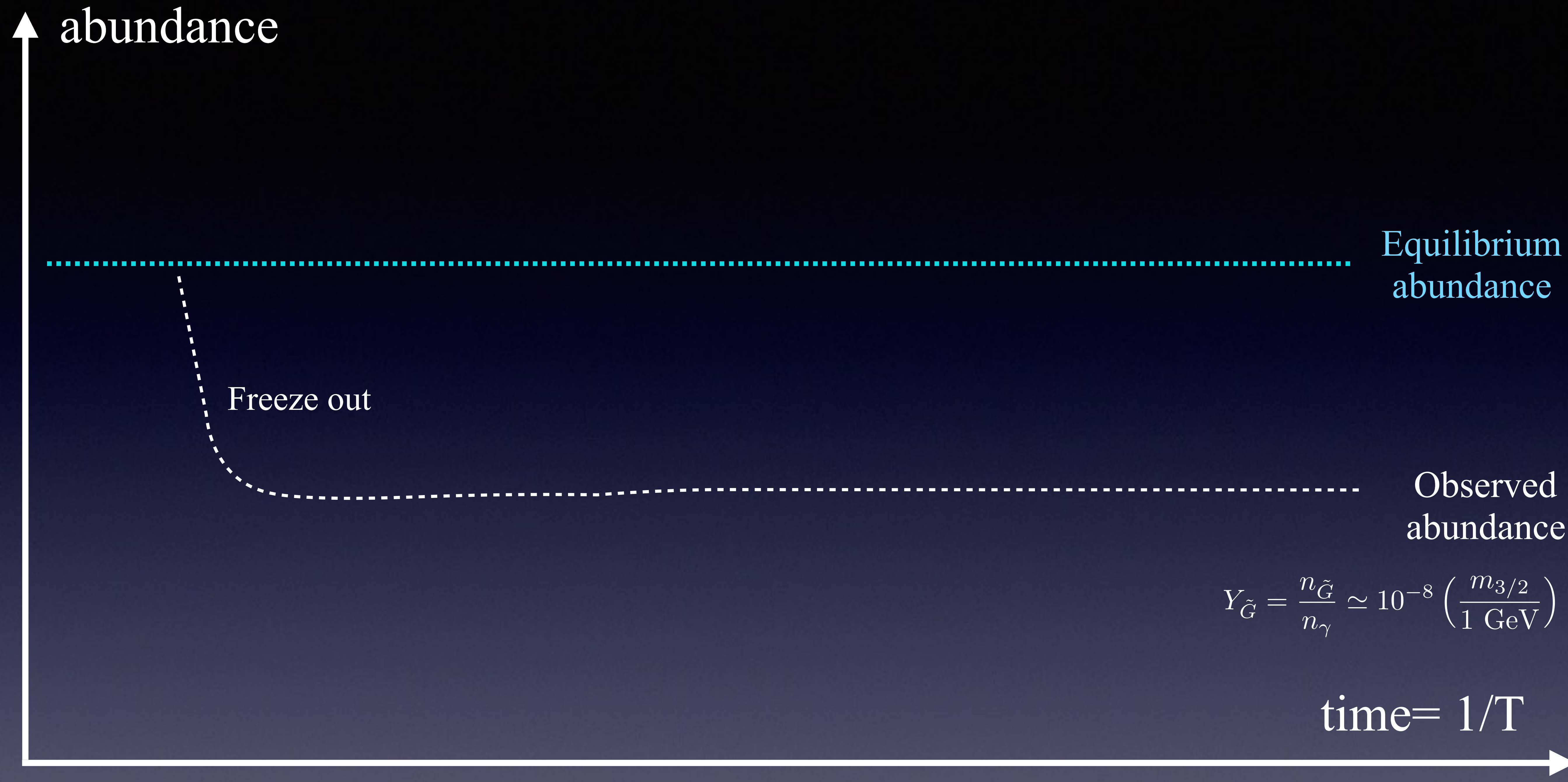
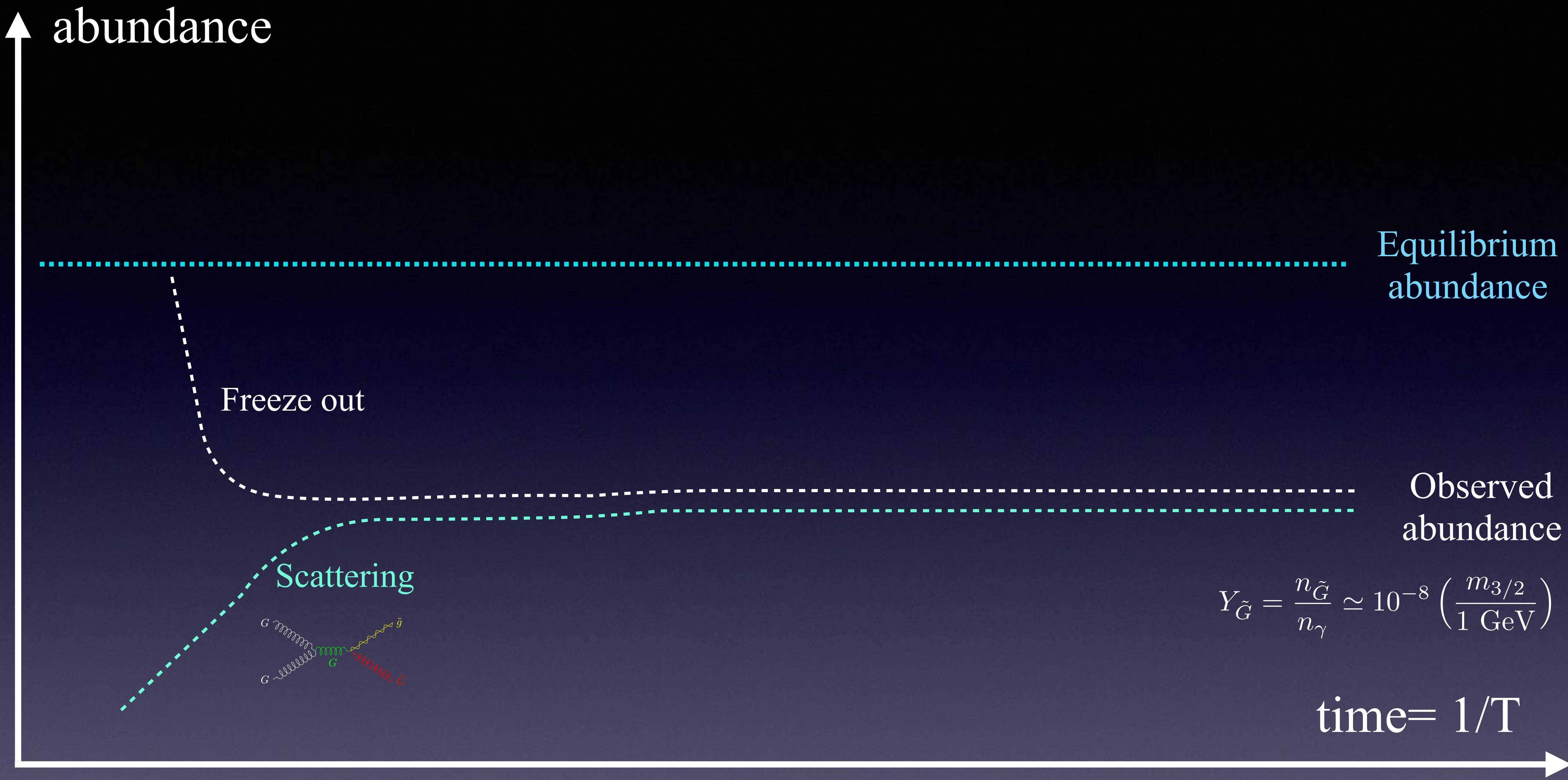
Several mechanisms can enter in the game: **scattering** of thermal particles, or **decays** of heavier supersymmetric partners or through the **freeze in** mechanism. However, the constraints are still quite severe on the gravitino mass if one wants to avoid its overabundance.


abundance
Equilibrium
abundance
Freeze out
Observed
abundance
$Y_{\tilde{G}} = \frac{n_{\tilde{G}}}{n_\gamma} \simeq 10^{-8} \left(\frac{m_{3/2}}{1\ \mathrm{GeV}} \right)$
time= 1/T


abundance
Equilibrium abundance
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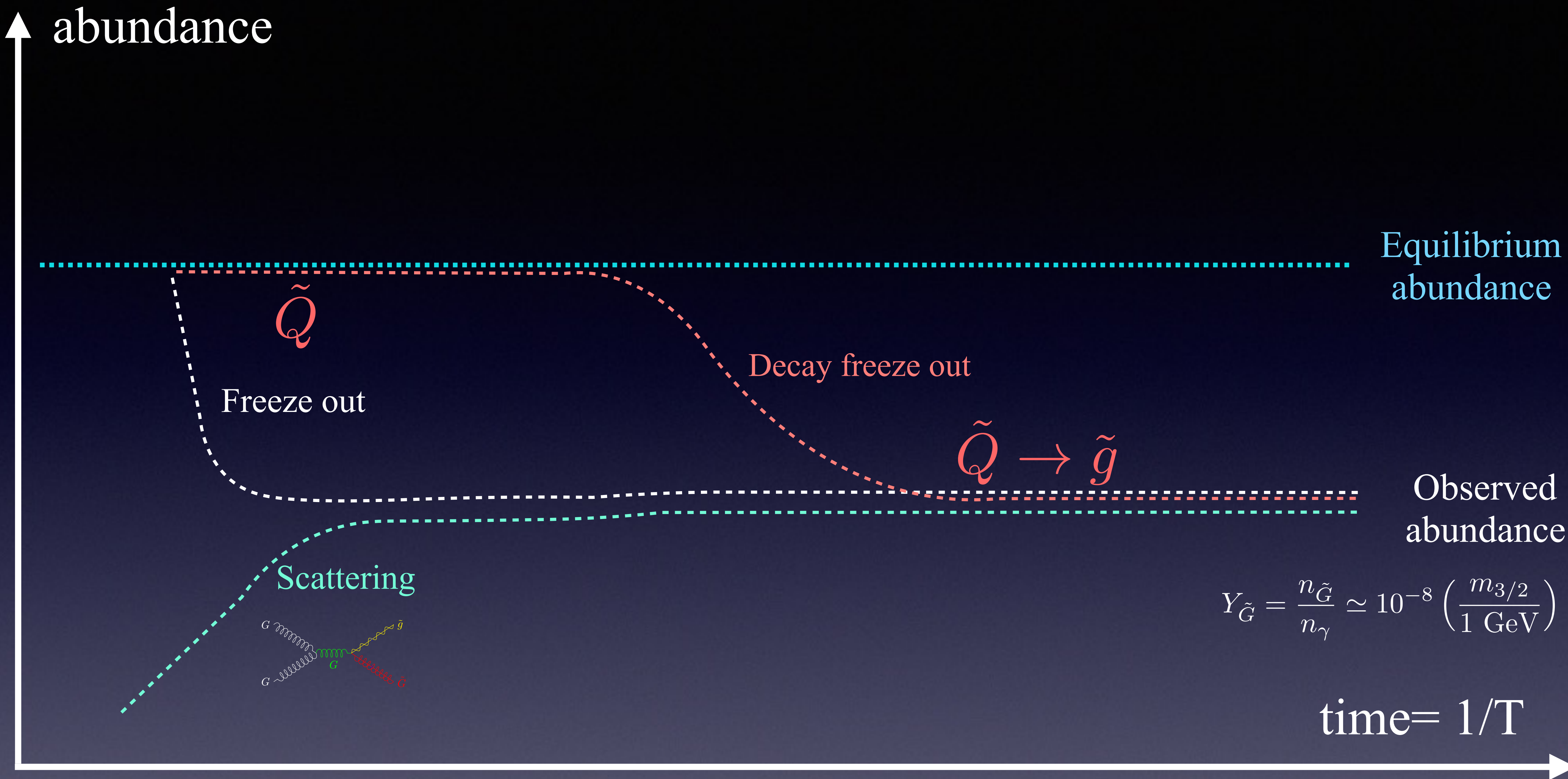
abundance
Equilibrium abundance
$\tilde{Q}$
Freeze out
Decay freeze out
$\tilde{Q} \to \tilde{g}$
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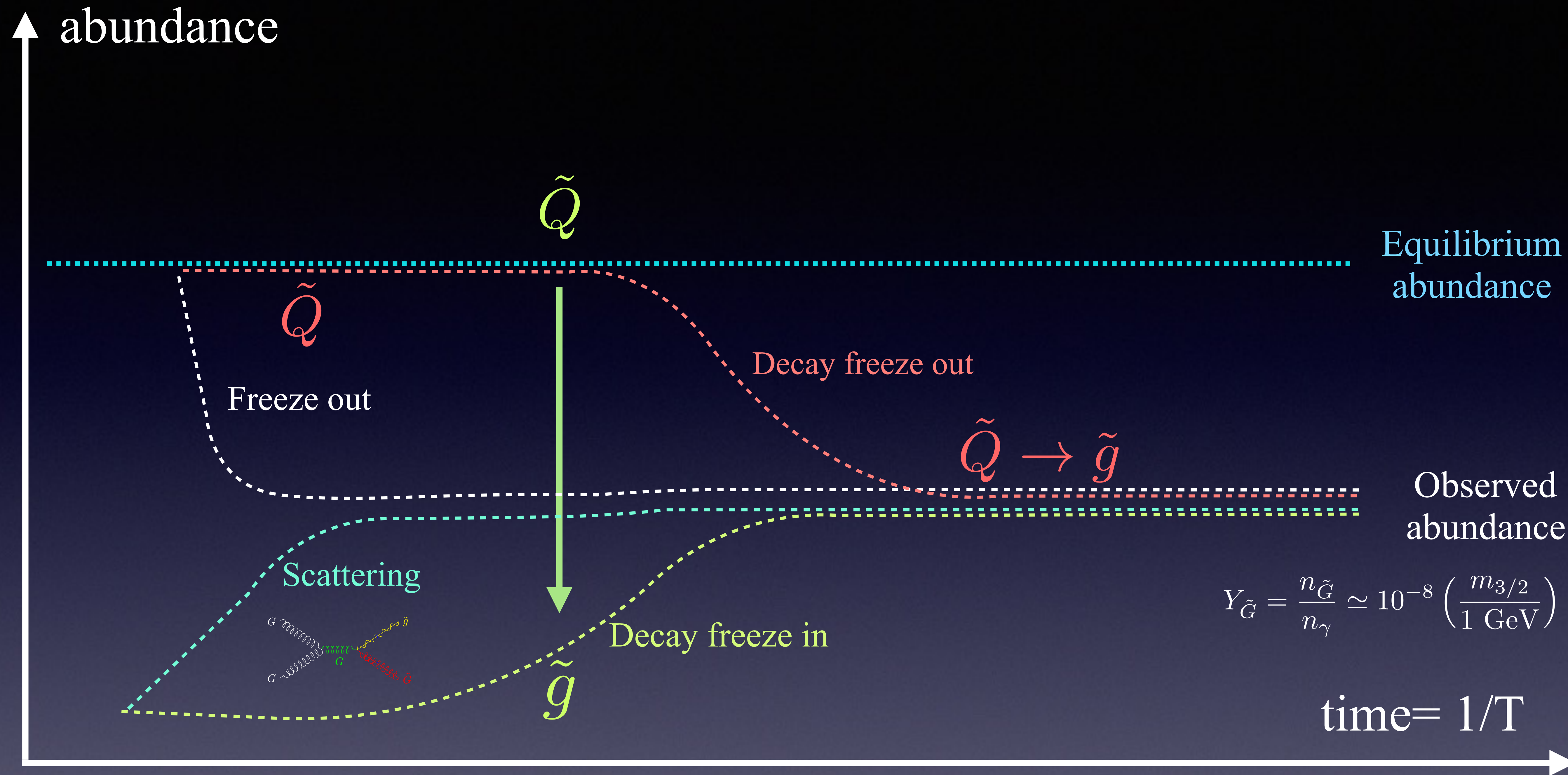

abundance
$\tilde{Q}$
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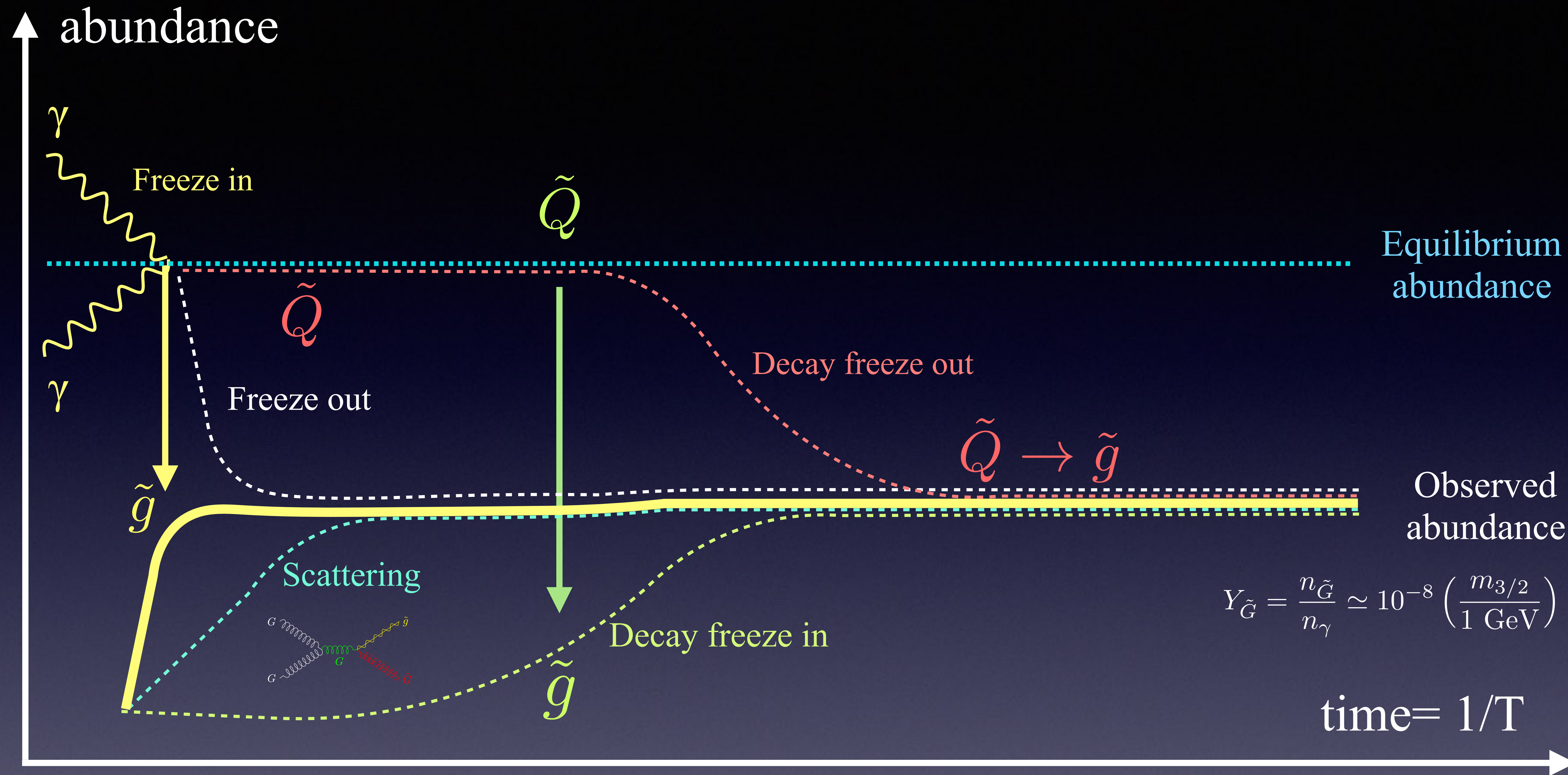
Decay freeze in
$\tilde{g}$
time= 1/T



abundance
γ
Freeze in
$\tilde{Q}$
Equilibrium abundance
$\tilde{Q}$
Decay freeze out
γ
Freeze out
$\tilde{Q} \to \tilde{g}$
$\tilde{g}$
Observed abundance
Scattering
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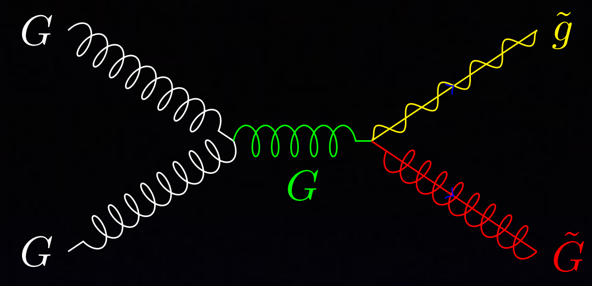
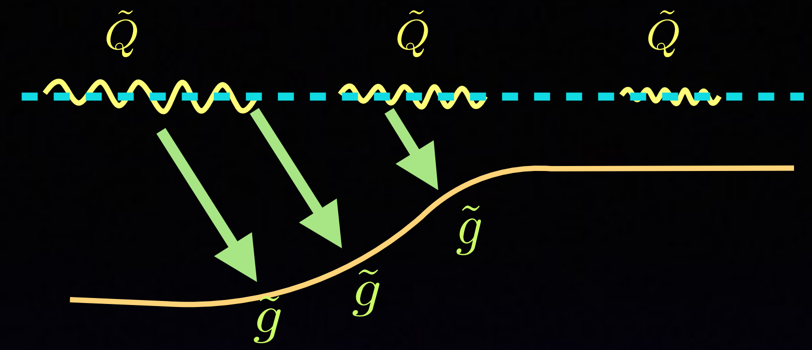
Decay freeze in
$\tilde{g}$
time= 1/T

Add a slide about decay NLSP and BBN
(Stefen..)





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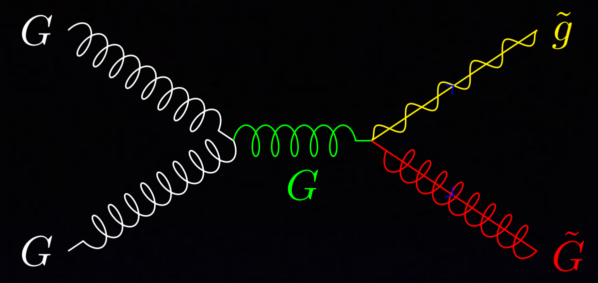
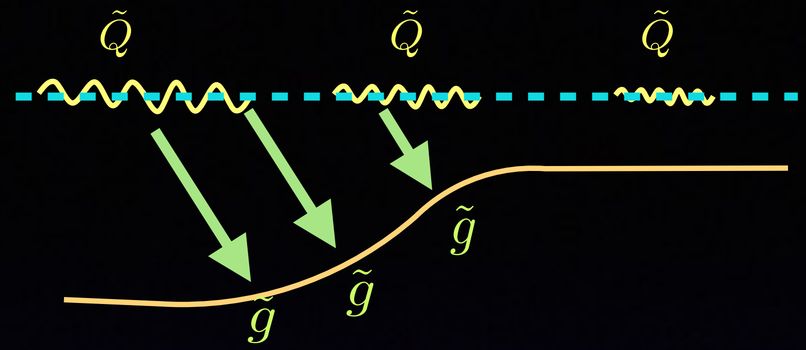
C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)





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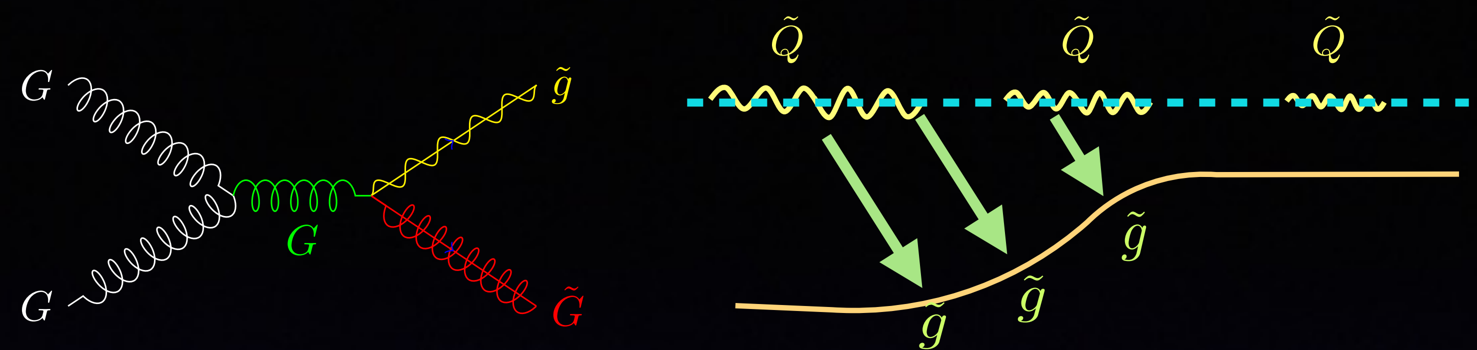
If $\quad T_{RH}M_{\tilde{Q}}^2 \ < \ m_{\tilde{G}}^3$

Then, the relic abundance is given by the decay modes and quickly over-densify the Universe, unless $T_{RH} < M_{susy}$, in which case only the exponential queue of the SUSY distribution plays a role.

C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)



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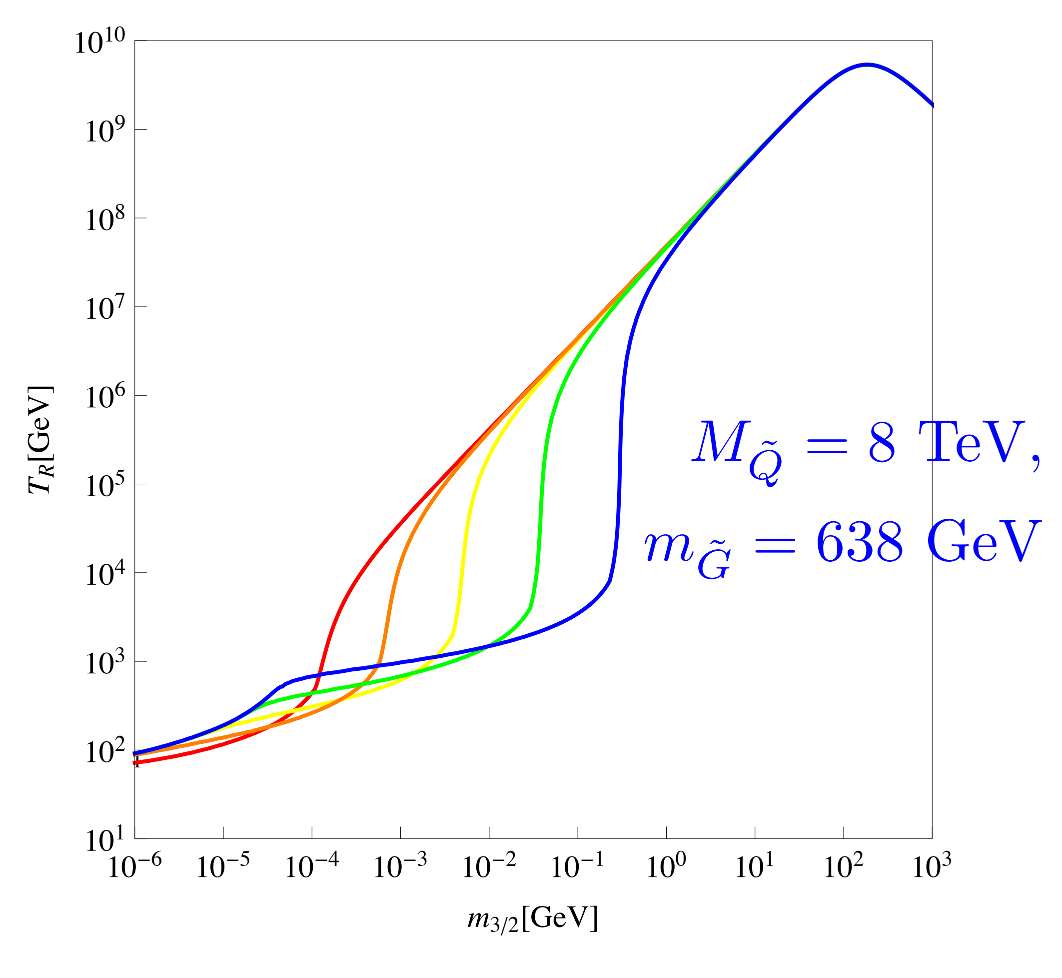
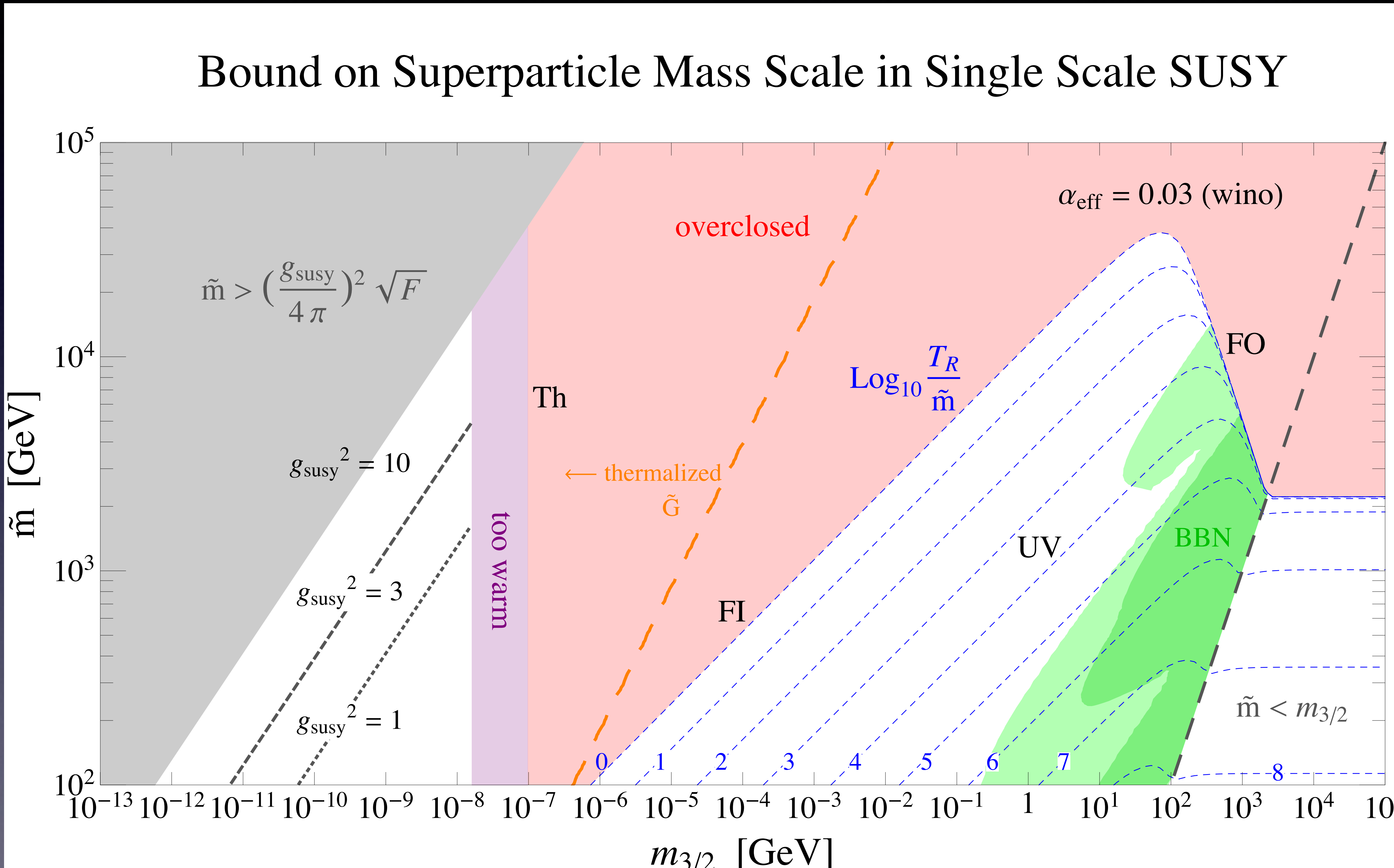


C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

Add a slide about freeze out production
(see references in paper of Volansky or Arcadi 1507.05584)

Add a comment on that plot Tell that BBN constraint restrict a lot (m less than GeV scale) Tell later that this is NOT our case.



L. J. Hall, J. T. Ruderman and T. Volansky, JHEP **1502** (2015) 094

Now, let's turn around the paradigm

Let's suppose that instead of working with such low (and inconvenient) reheating temperature below the SUSY scale, it is the SUSY scale which is pushed much above the reheating temperature.

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*Except in a narrow region where $M_{susy} \sim T_{RH}$ as we will see

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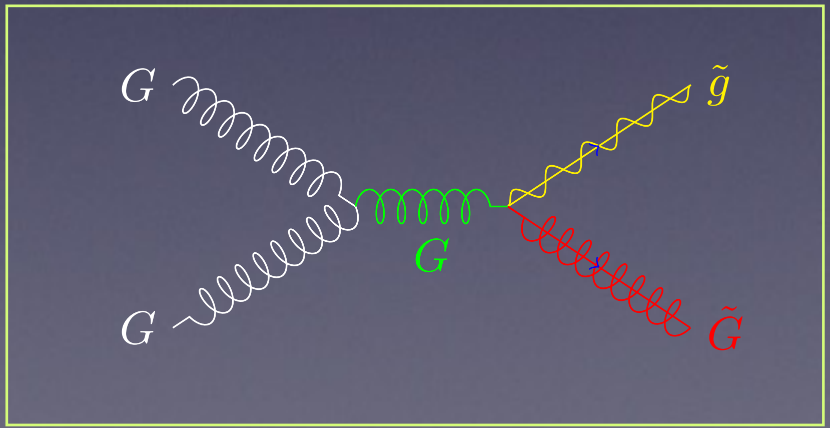
But, in the meantime, we also kinematically forbid the scattering production:



So how to produce the gravitino?

*Except in a narrow region where $M_{susy} \sim T_{RH}$ as we will see

By a freeze in mechanism sourced in the Thermal bath

Indeed, while the SUSY sector is not anymore in equilibrium with the thermal bath (and never was), there is still a possibility to produce gravitino through its vierbein (direct) coupling of its goldstino part to the SM.

This model by its simplicity and naturalness can be considered as « a minimal model of gravitino dark matter »

K. Benakli, Y. Chen, E. Dudas, Y.M. 1701.xxxx

The scales in game

SUGRA reminder

$$V = F^2 + 1/2\ D^2 \sim F^2$$

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}}, \quad M_{SUSY} = \frac{F}{\Lambda_{mess}}$$

Once <F> and/or <D> acquire a *vev*, SUSY is broken and generates gravitino mass. The breaking is then mediated to the SUSY sectors by *messengers* to generate the SUSY spectrum

$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY} \lesssim \sqrt{F} \lesssim \Lambda_{mess} \ll M_{Pl}$$

The low energy spectrum is then only the SM + the gravitino

Generating the interactions

One can deduce the vierbein of the theory, just from the hypothesis that the longitudinal part of the gravitino is the goldstino of the SUSY transformation*

$$e_m^a \;=\; \delta_m^a - \frac{i}{2F^2}\partial_m G\sigma^a\bar{G} + \frac{i}{2F^2}G\sigma^a\partial_m\bar{G} \ ,$$

$$L_{2G} = \frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu},$$

I. Antoniadis, E. Dudas, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

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&(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),\\
&\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi}, \qquad (10)
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Notice how the Lagrangian has suppressed coupling ($1/F^2$) and strong energy/temperature dependance

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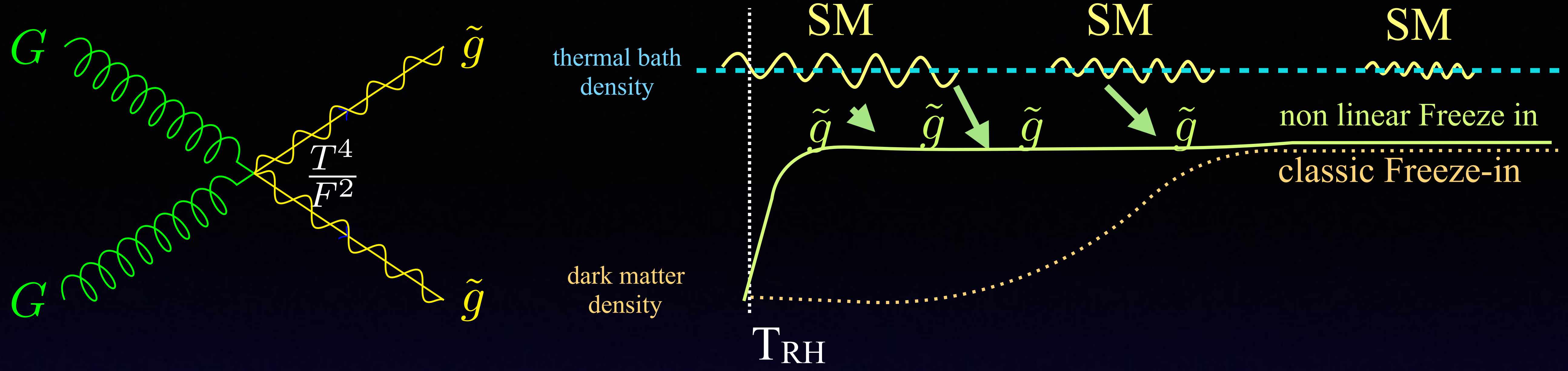
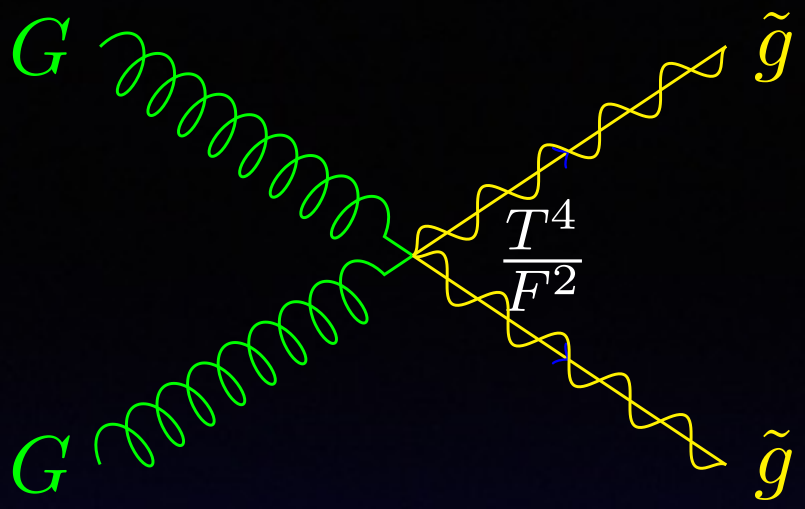
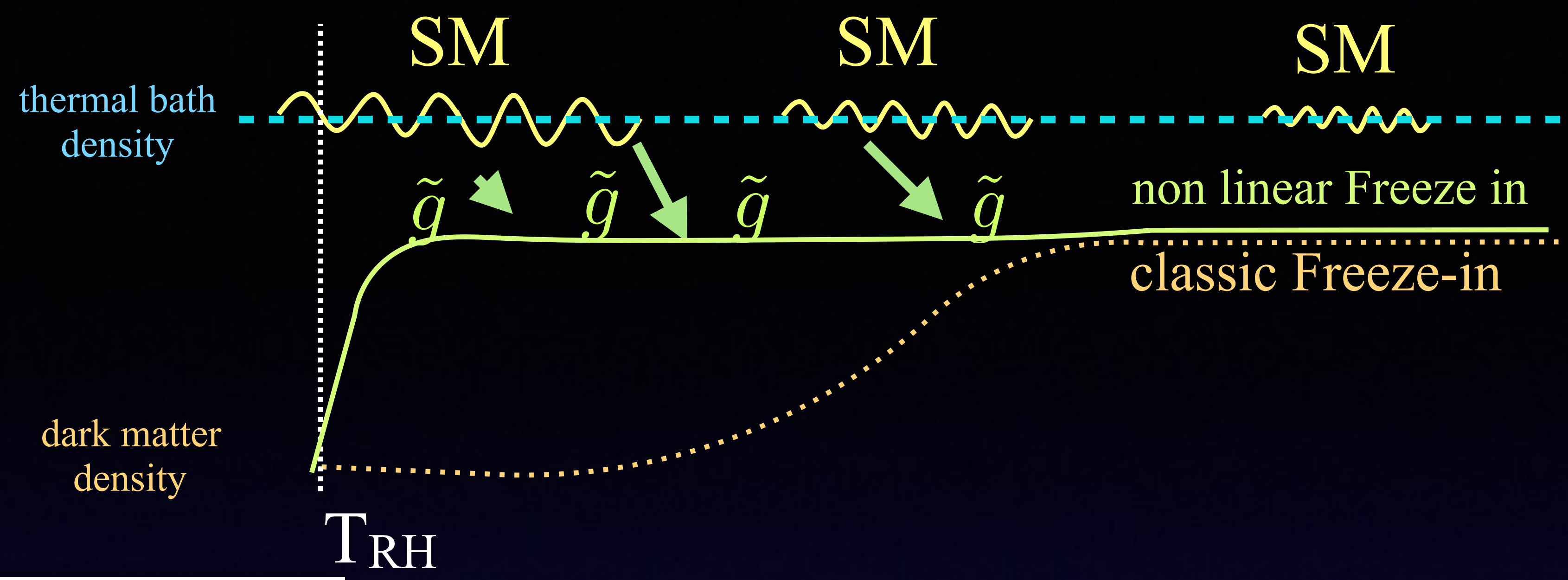
Add a slide about microscopic interpretation
(Keith idea)

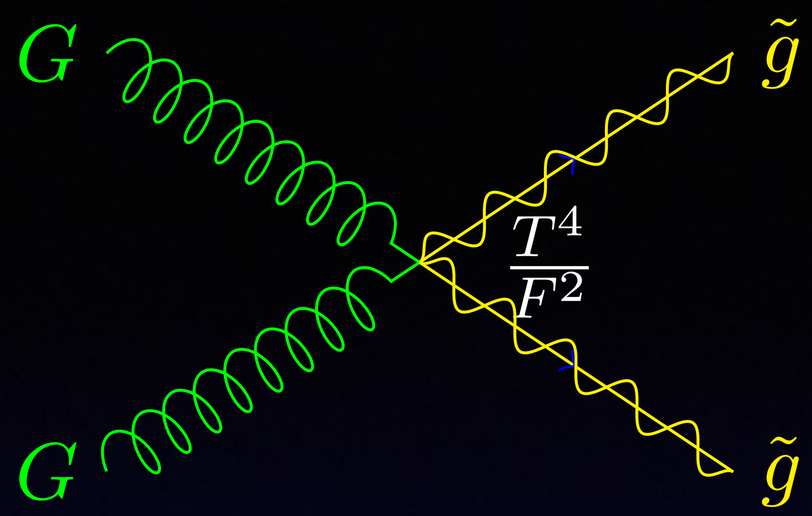


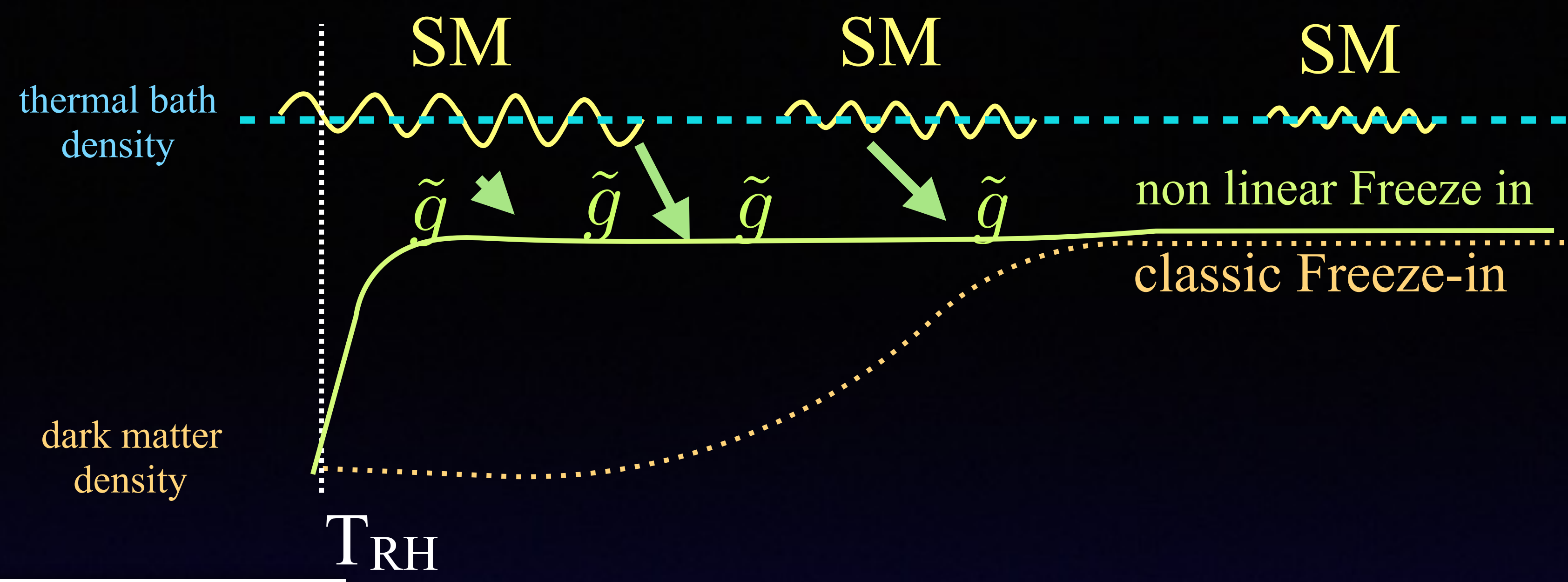
G
G
$\tilde{g}$
$\tilde{g}$
$\frac{T^4}{F^2}$
thermal bath density
SM
SM
SM
$\tilde{g}$
$\tilde{g}$
$\tilde{g}$
$\tilde{g}$
non linear Freeze in
classic Freeze-in
dark matter density
T_{RH}





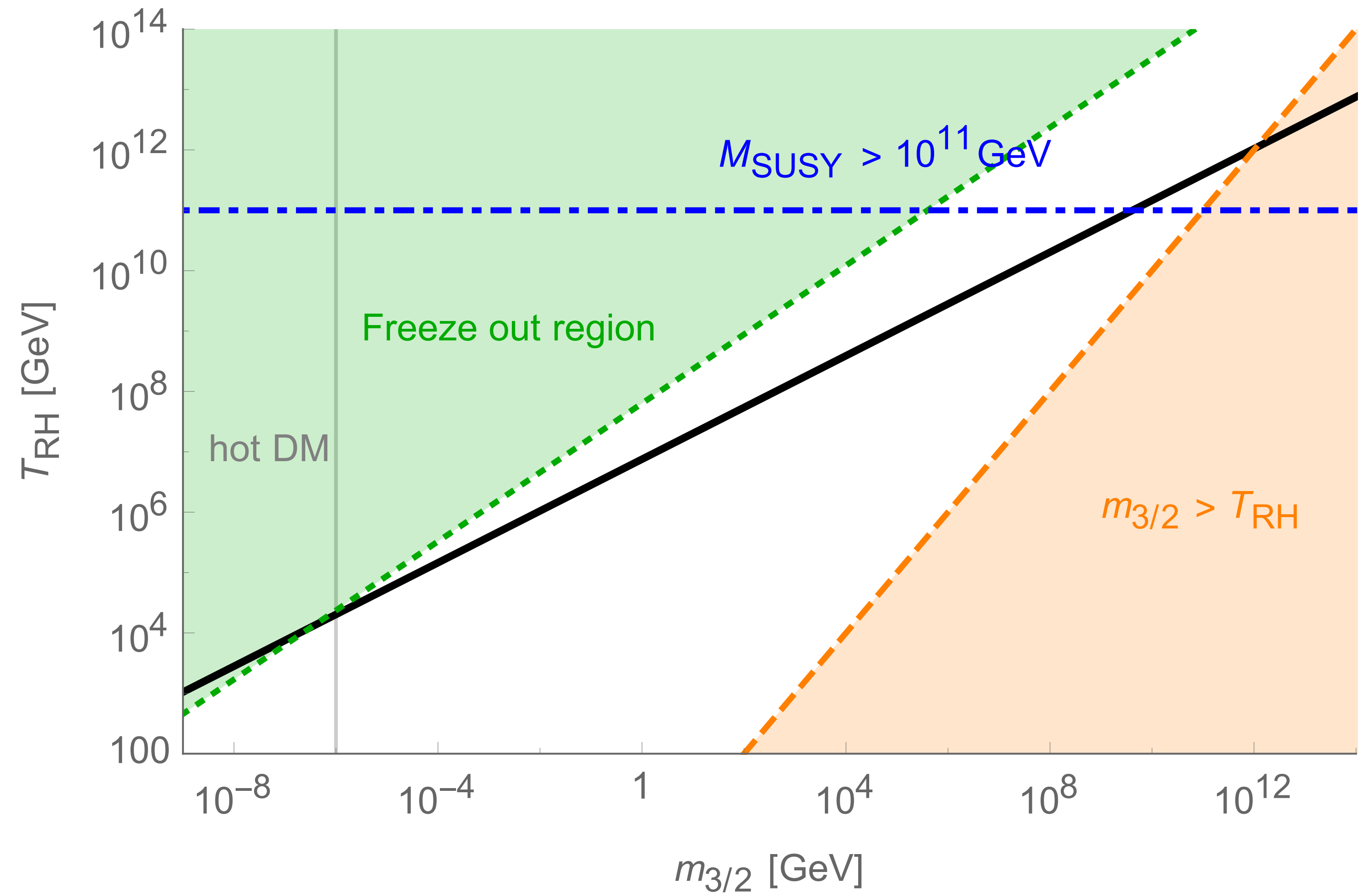
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\mathrm{RH}}}{5.4\times 10^7\ \mathrm{GeV}}\right)^7$$





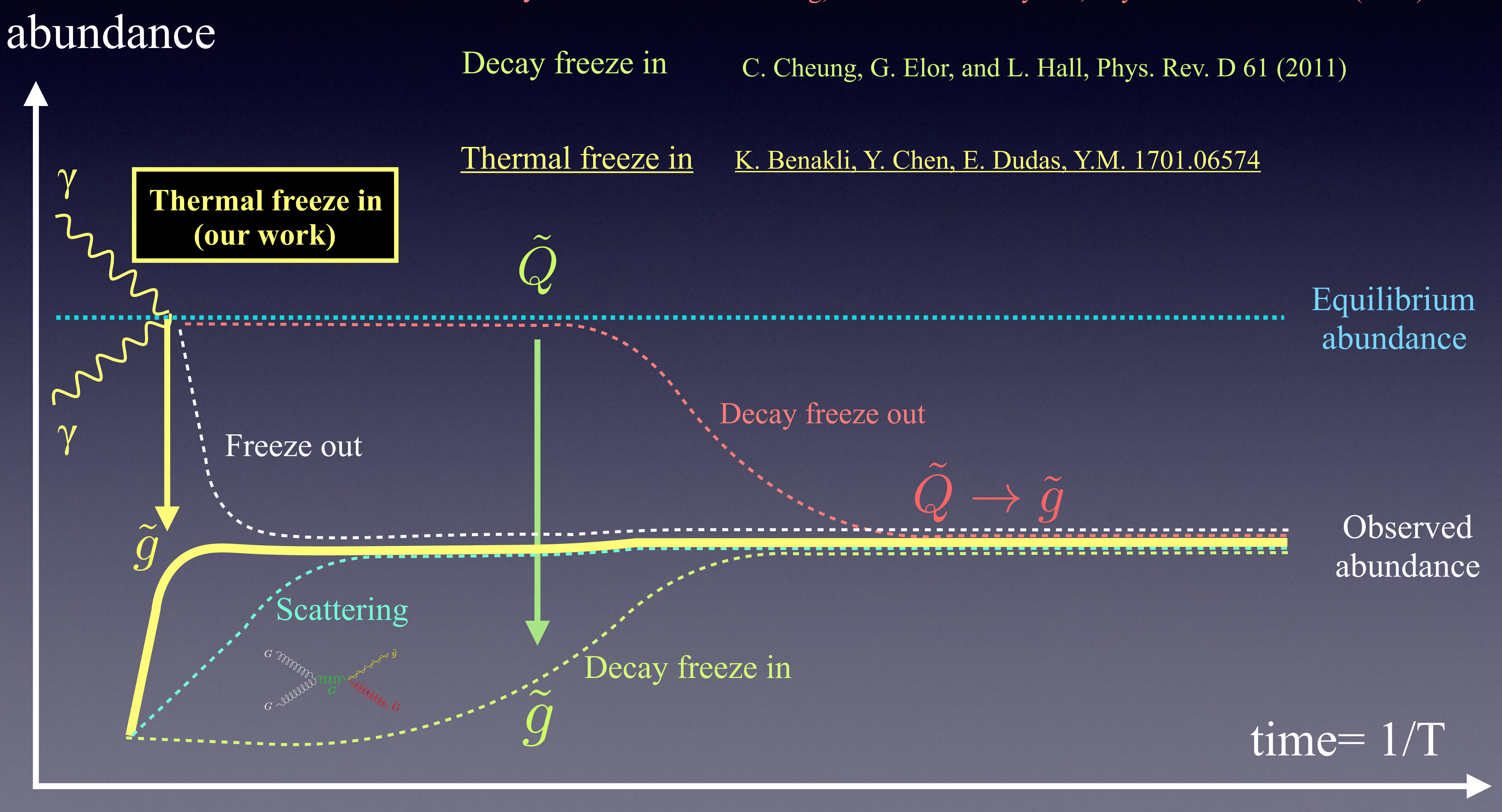
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \text{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\text{RH}}}{5.4\times 10^7\ \text{GeV}}\right)^7$$

Heavy gravitino is compatible with high T_{RH} and no LHC SUSY signals while still giving the right amount of relic abundance.

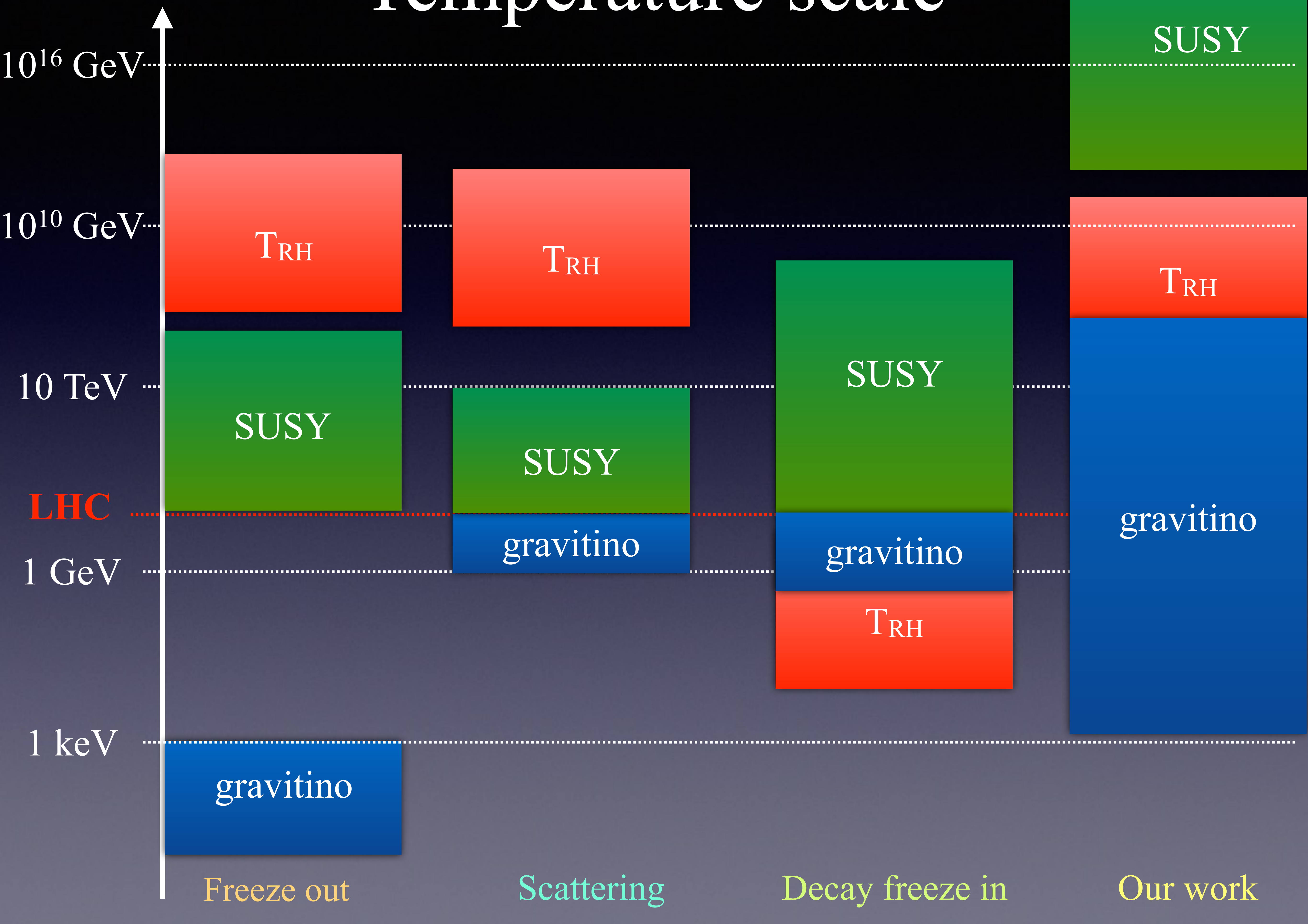


Summary: populating the Universe with gravitino

Freeze out	H. Pagels and J.R. Primack, Phys. Rev. Lett. 48 (1982) 223
Scattering	T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)
Decay freeze out	J.L. Feng, S. Su and F. Takayama, Phys. Rev. **D70** 075019 (2004)
Decay freeze in	C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)
Thermal freeze in	K. Benakli, Y. Chen, E. Dudas, Y.M. 1701.06574



Temperature scale



pré-conclusion

« To the great disappointment of many, experimental searches at the LHC so far have found no evidence for the superpartners predicted by N = 1 supersymmetry. However, there is no reason to give up on the idea of supersymmetry as such, since the refutation of low-energy supersymmetry would only mean that the most simple-minded way of implementing this idea does not work. Indeed, the initial excitement about supersymmetry in the 1970s had nothing to do with the hierarchy problem, but rather because it offered a way to circumvent the so-called Coleman–Mandula no-go theorem – a beautiful possibility that is precisely not realised by the models currently being tested at the LHC. »

H. Nicolai, CERN courier Jan. 2017

Conclusion

We built the simplest low energy SUSY extension, where the only light super partner is the gravitino, whereas SUSY scale is pushed above the reheating temperature.

Through its goldstino component, the gravitino still couples (very weakly) to the standard model, and allows for the right amount of dark matter through a thermal freeze in mechanism.

That a minimal model of gravitino dark matter.

Talk Jussieu

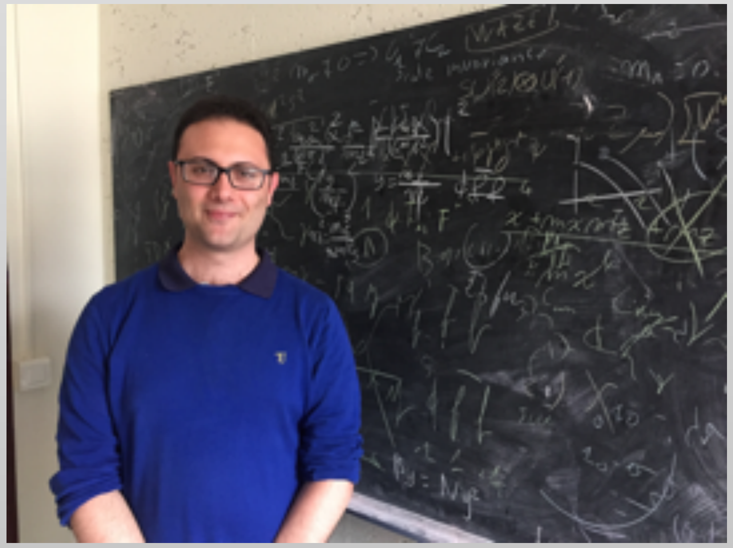
Who really did the job

Maira Dutra

Yifan Chen

Mathias Pierre

Pradipta Ghosh



Giorgio Arcadi

Farinaldo Queiroz

The first DM paper

Henri Poincaré

Contrarily to the common belief, the first time the word « dark matter » is proposed in a scientific paper is not Oort in 1932 but Poincaré in 1906. Indeed, Lord Kelvin in 1904 had the genius to apply the kinetic theory of gas recently elaborated, to the galactic structures in his Baltimore lecture (*molecular dynamics and the wave theory of light*). Poincaré was impressed by this idea and computed the amount of stars in the Milky way necessary to explain the velocity of our sun one observes nowadays.

THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

equation of living forces. We thus find that this velocity is proportional to the radius of the sphere and to the square root of its density. If the mass of this sphere were that of the Sun and its radius that of the terrestrial orbit, it is easy to see that this velocity would be that of the Earth in its orbit. In the case that we have supposed, the mass of the Sun should be distributed in a sphere with a radius one million times larger, this radius being the distance of the nearest stars; the density is then 10^{18} times less; now the velocities are of the same order, hence it must be that the radius is 10^9 times greater, that is one thousand times the distance of the nearest stars, which would make about one thousand millions of stars in the Milky Way.

ence might long remain unknown? Very well then, that which Lord Kelvin's method would give us would be the total number of stars including the dark ones; since his number is comparable to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter.

Using the viral theorem, Poincaré computed first the density of stars around the sun, then supposing it constant, the radius of the sun to the galactic center, and then the number of stars in the Milky Way (~10^9) corresponding to the observations, thus discrediting the existence of dark matter, or dark stars.

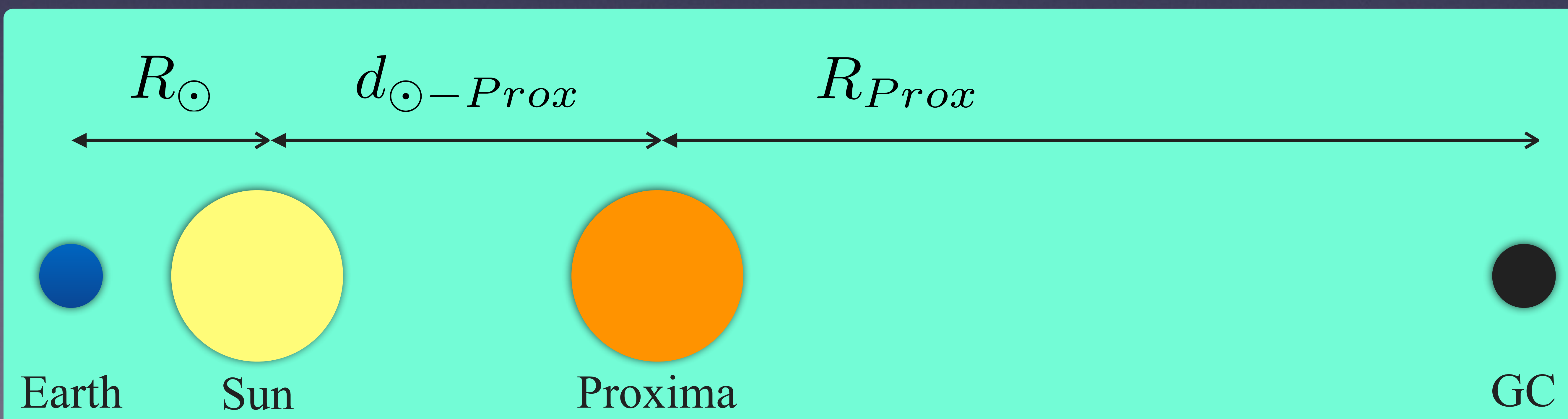
$$v(R) \propto R\sqrt{\rho}$$

$$\frac{v_{earth}(R_\odot)}{v_{sun}(R_{Prox})} = \frac{R_\odot}{R_{Prox}}\frac{\sqrt{\rho_\odot}}{\sqrt{\rho_{Prox}}}$$

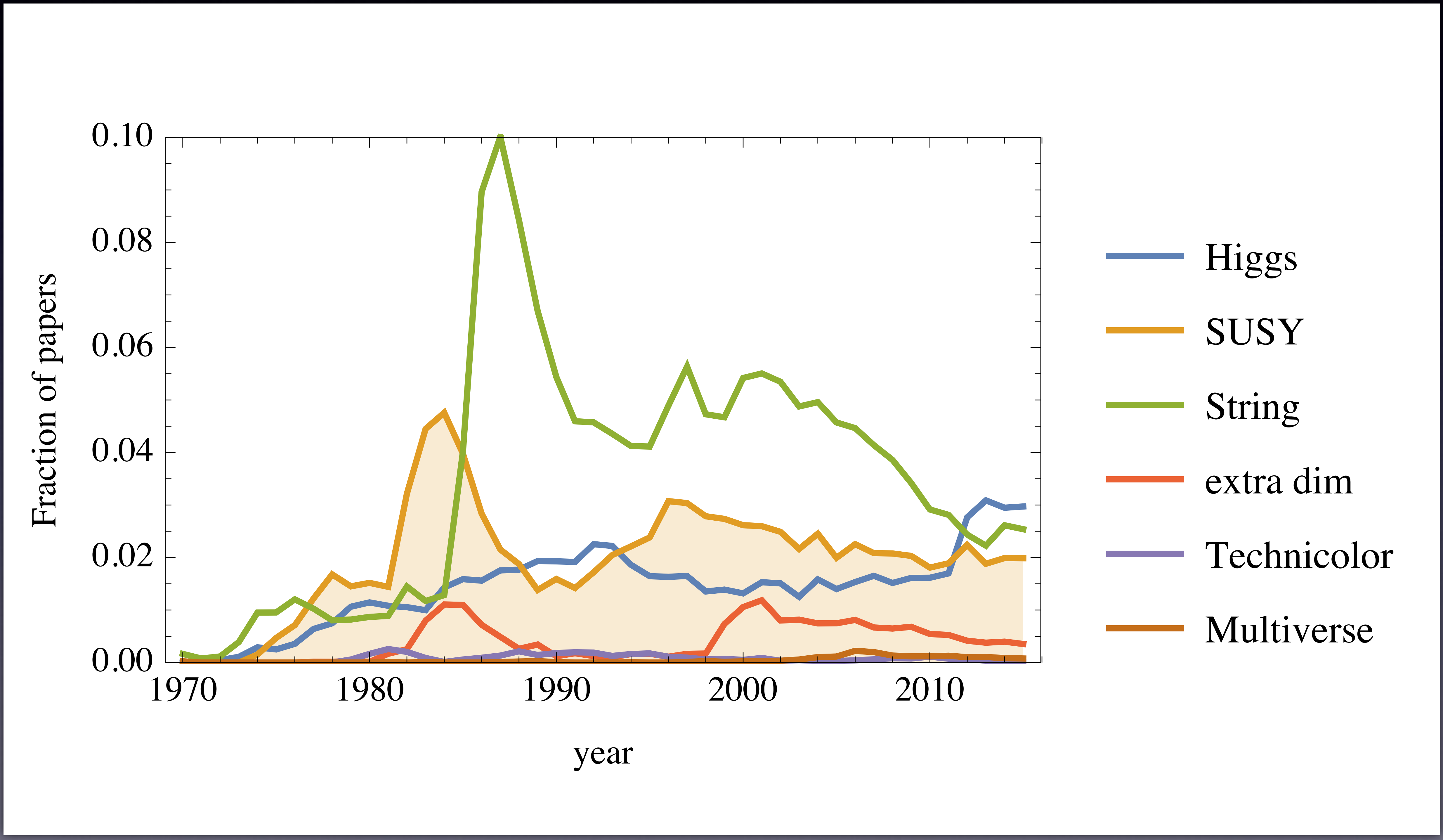
$$d_{Prox-\odot} = 10^6 R_\odot \quad \Rightarrow \quad \rho_{Prox} = 10^{-18}\rho_\odot$$

$$v_{earth} \simeq v_{sun} \quad \Rightarrow R_{Prox} = 10^9 R_\odot$$

$$\Rightarrow N_{stars} = \rho_{Prox} \times R^3_{Prox} \simeq 10^9$$



Is SUSY alive (and well)? Not so well, but at least still popular..



SUSY and dark matter

SUSY has 2 « natural » dark matter candidates:

- The neutralino, $\tilde{\chi}_1^0$ (60% of the SUSY DM papers on spires)
- The gravitino, $\tilde{g}$ (49% of the SUSY DM papers)

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The neutralino is a mixed between Bino, Wino, and Higgsinos:

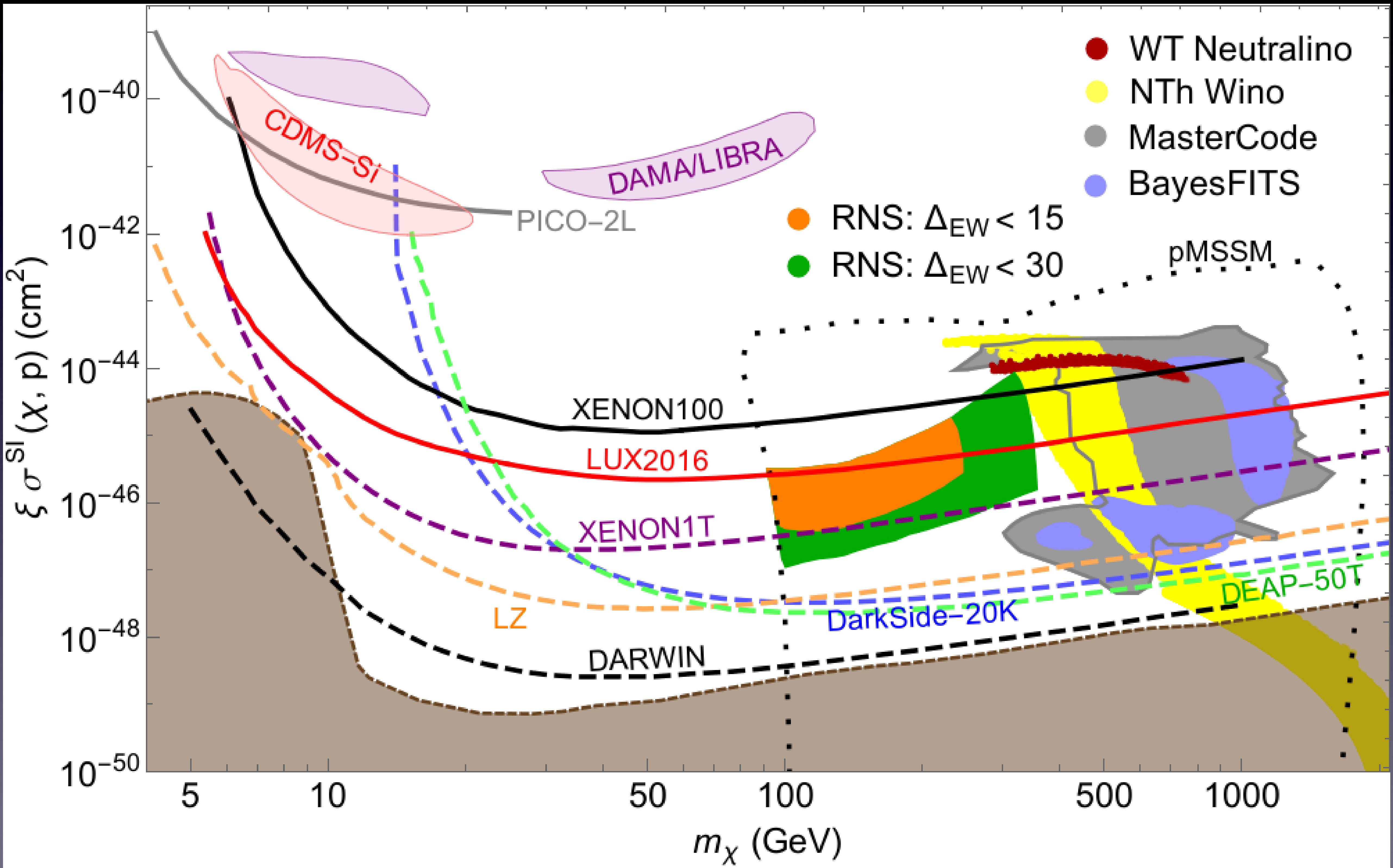
$$\chi_1^0 = c_B\tilde{B} + c_1\tilde{H}_1 + c_2\tilde{H}_2 + c_W\tilde{W}$$

well tempered

non thermal wino

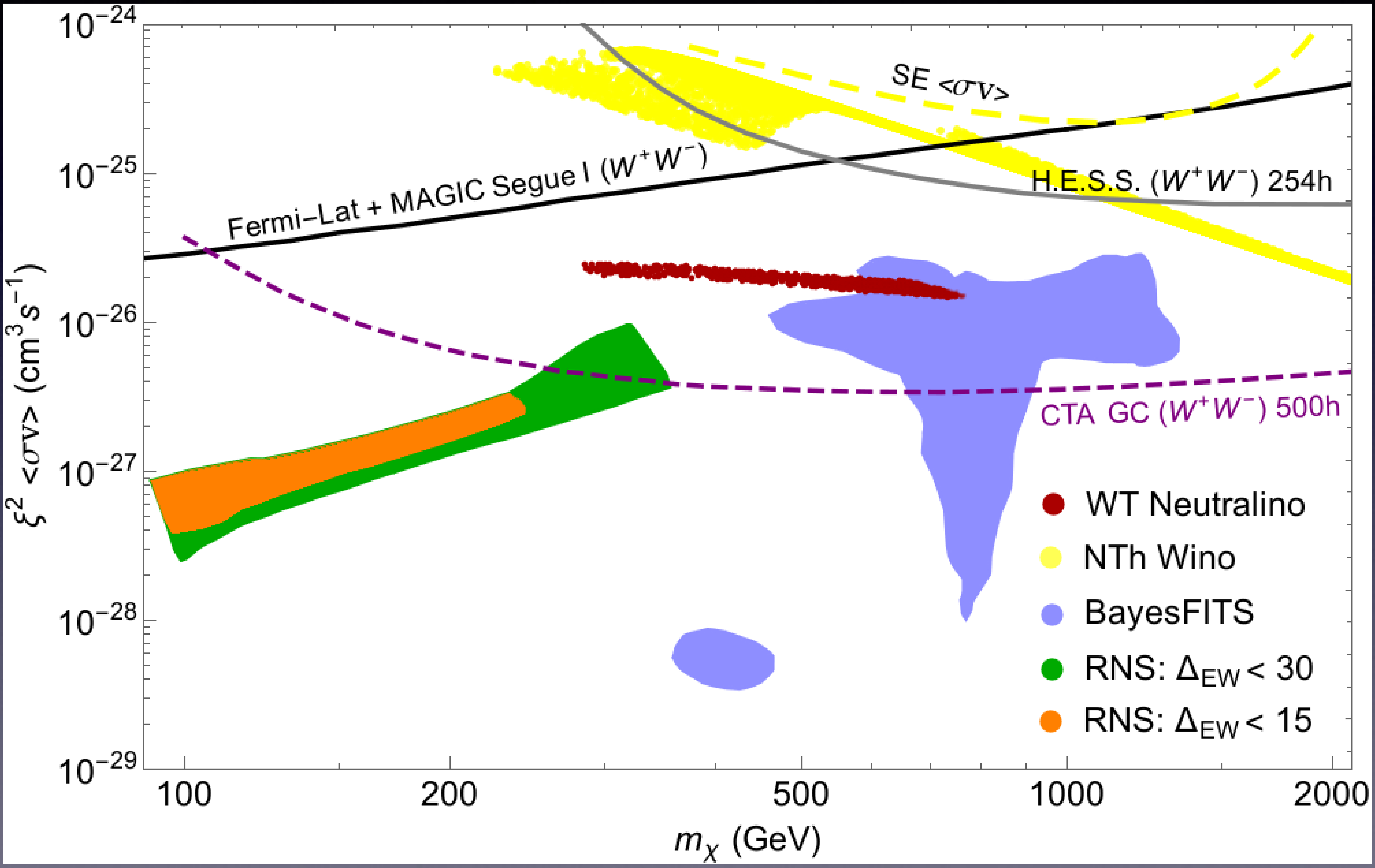
In this sense, he has all the characteristic of a WIMP, and as a consequence suffers from the same constraints listed before

Spin Independant Direct Detection



Baer et al. 1609.06735

Indirect Detection



Baer et al. 1609.06735

The gravitino dark matter

The gravitino was in fact the first candidate to be proposed as a dark matter, before the neutralino by Pagels and Primack in 1982

H. Pagels and J.R. Primack, Phys. Rev. Lett. 48 (1982) 223

It is indeed a completely natural candidate, with the problematic issue of its non-detectability, especially when R-parity is conserved (no smoking gun decay modes)

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However, at first sight, if one supposed that it thermalized and decoupled quite early in the Universe (due to its reduced coupling to the Standard model), its mass is (naively) restricted to ~ keV (the « Cowsik-Mc Clelland analog of the neutrino):

$$\boxed{\Omega_{3/2} = \frac{n_{3/2} m_{3/2}}{\rho_c^0} \simeq \frac{n_\gamma \times \left(\frac{2}{g_*^{MSSM}}\right) m_{3/2}}{10^{-5} h^2 \ \mathrm{GeV/cm^{-3}}} \simeq \frac{0.1}{h^2} \left(\frac{m_{3/2}}{300 \ \mathrm{eV}}\right)}$$

which is excluded by Tremaine Gunn/structure formation bounds

If the gravitino cannot be produced by the thermalization of the primordial plasma, how can it be present in the Universe?

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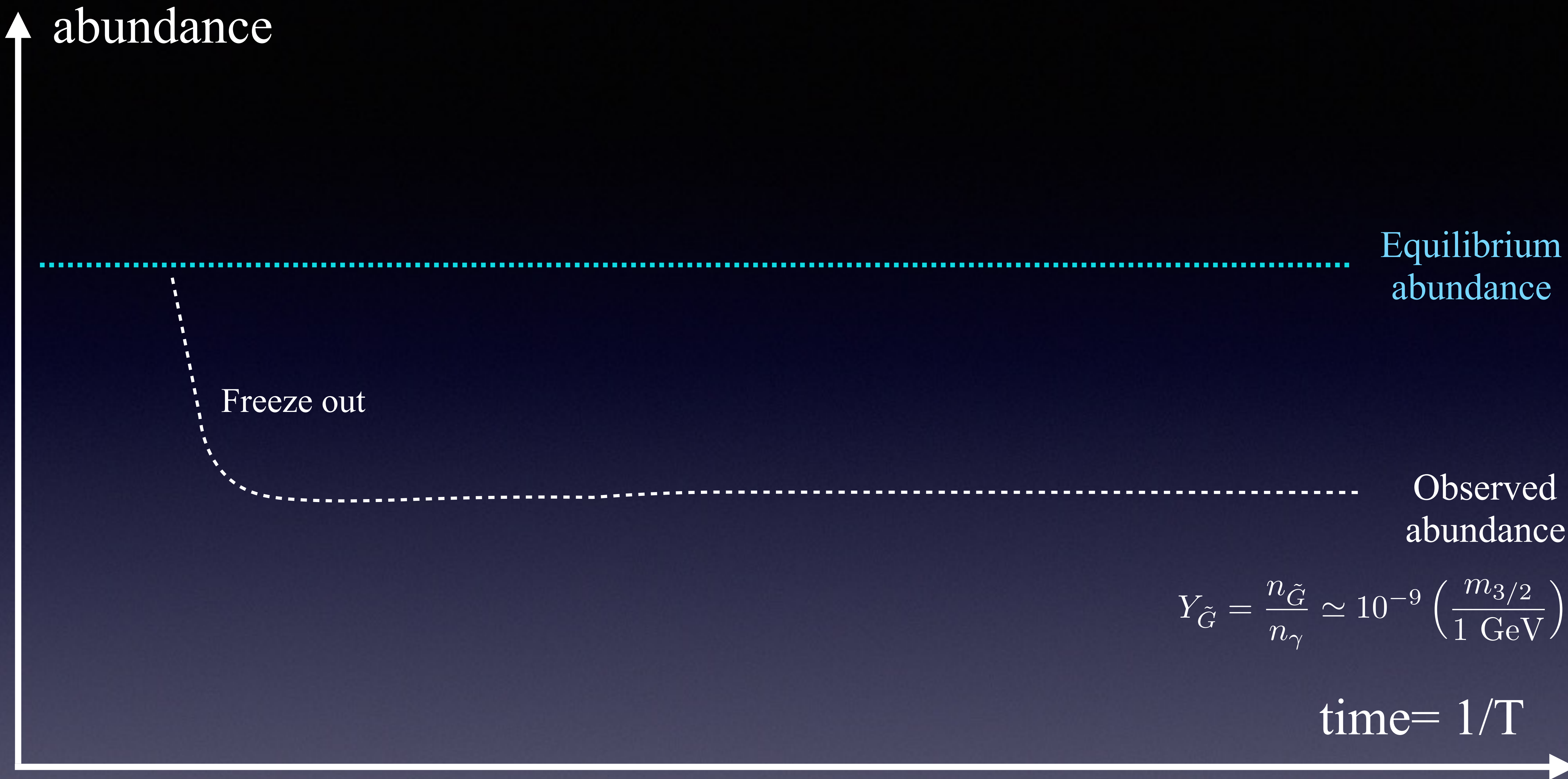
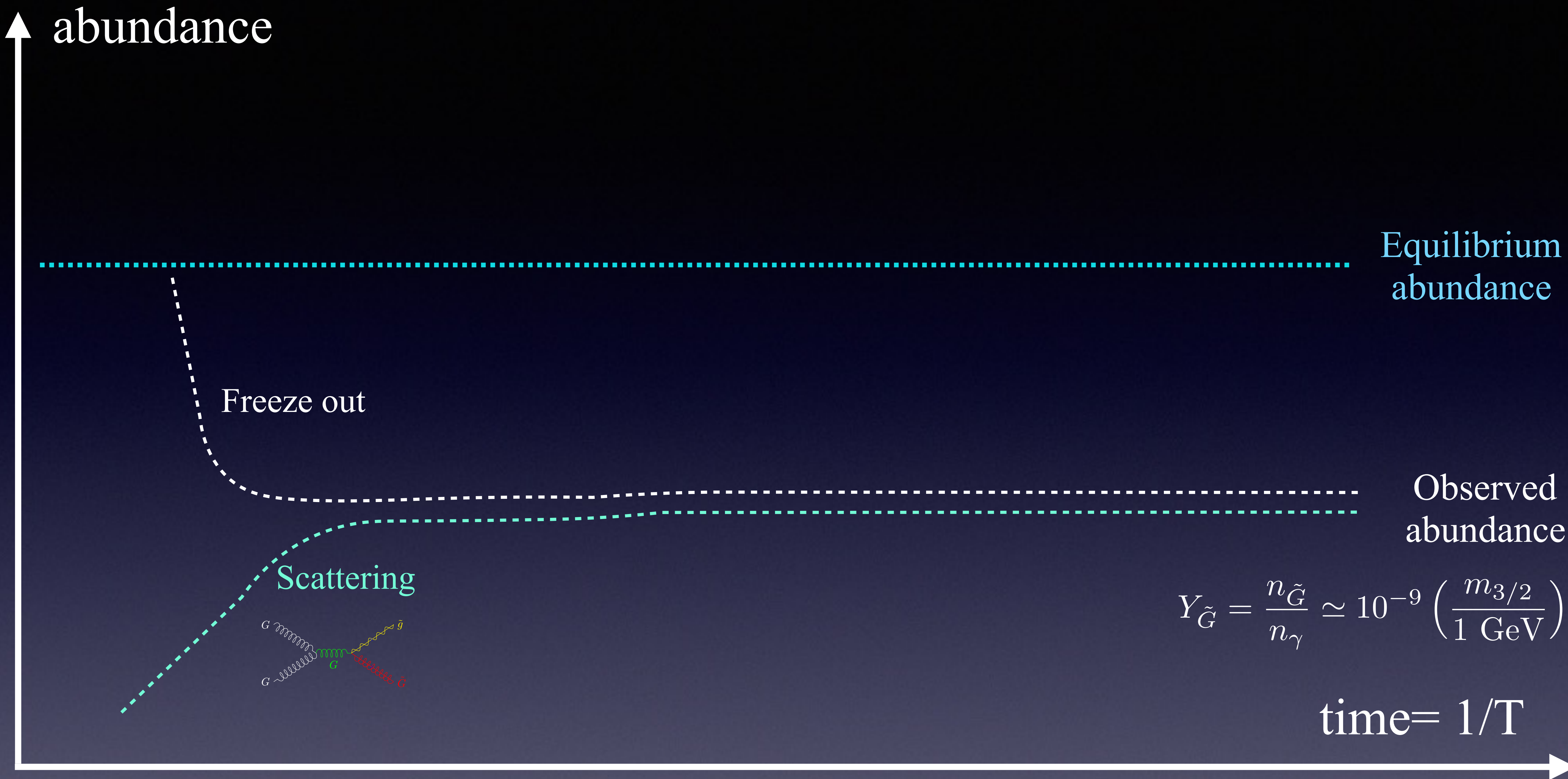
Several mechanisms can enter in the game: **scattering** of thermal particles, or **decays** of heavier supersymmetric partners or through the **freeze in** mechanism. However, the constraints are still quite severe on the gravitino mass if one wants to avoid its overabundance.


abundance
Equilibrium abundance
Freeze out
Observed abundance
$Y_{\tilde{G}} = \frac{n_{\tilde{G}}}{n_\gamma} \simeq 10^{-9} \left(\frac{m_{3/2}}{1 \text{ GeV}} \right)$
time= 1/T


abundance
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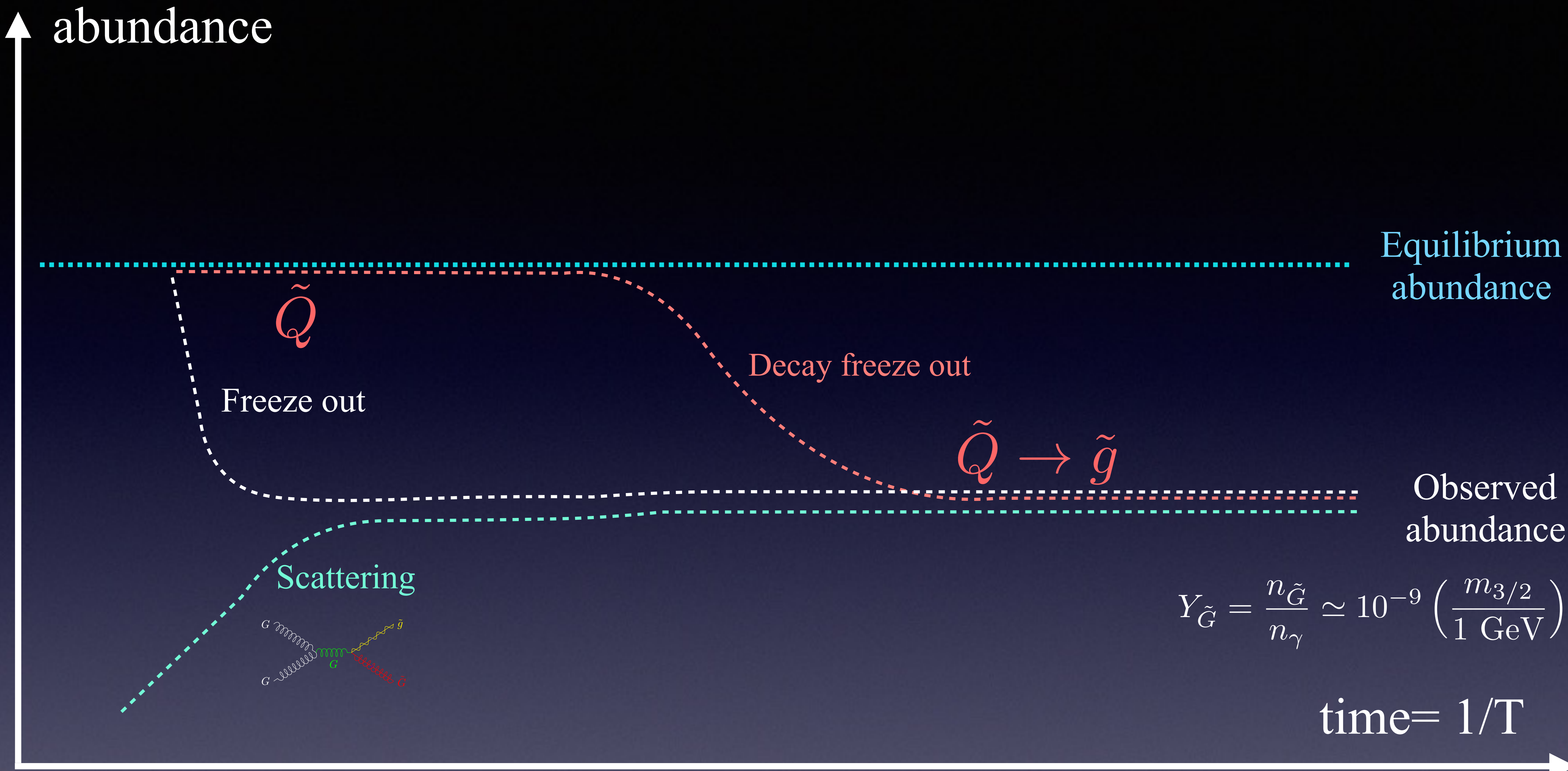

abundance
Equilibrium abundance
$\tilde{Q}$
Freeze out
Decay freeze out
$\tilde{Q} \to \tilde{g}$
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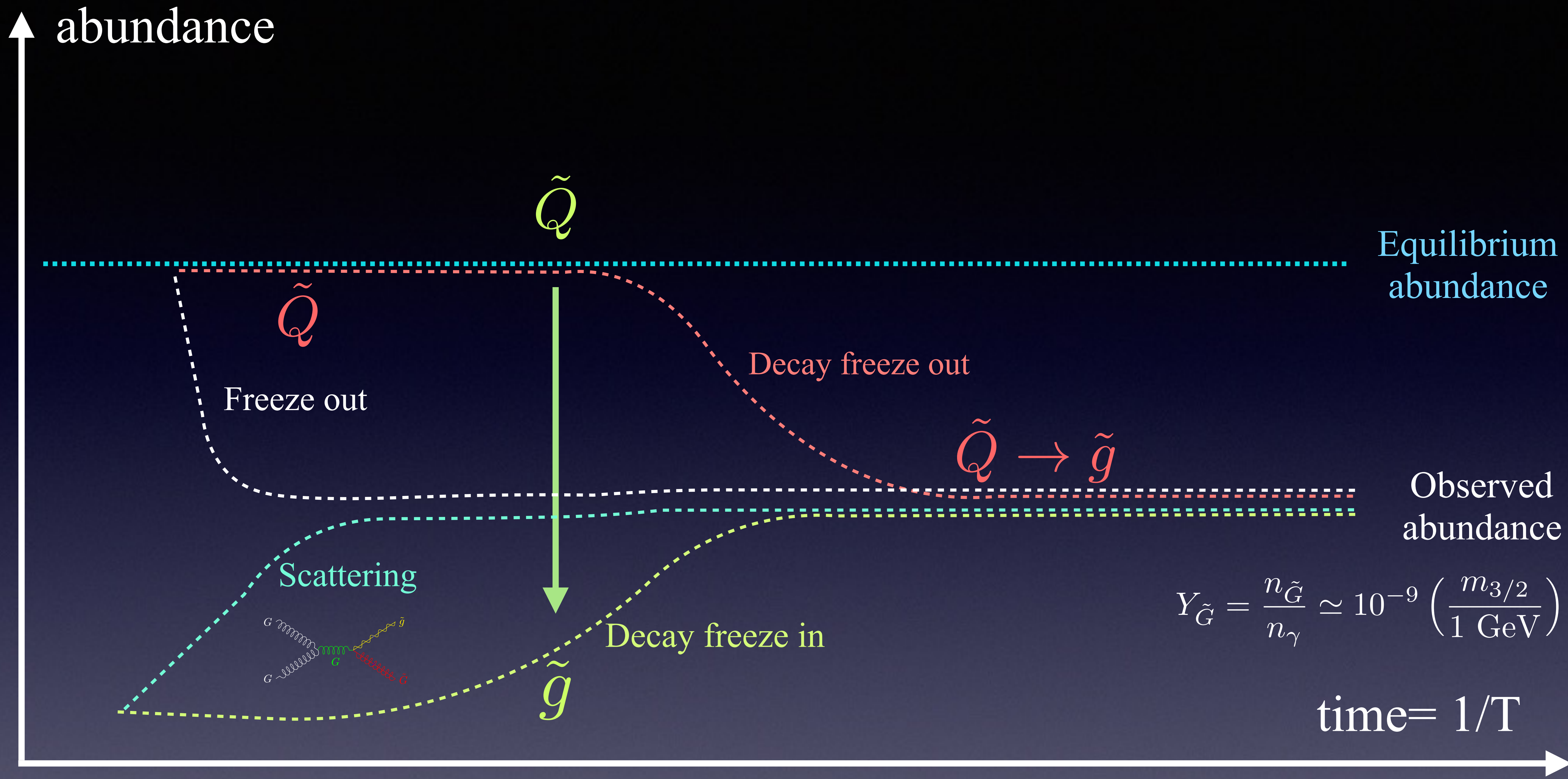
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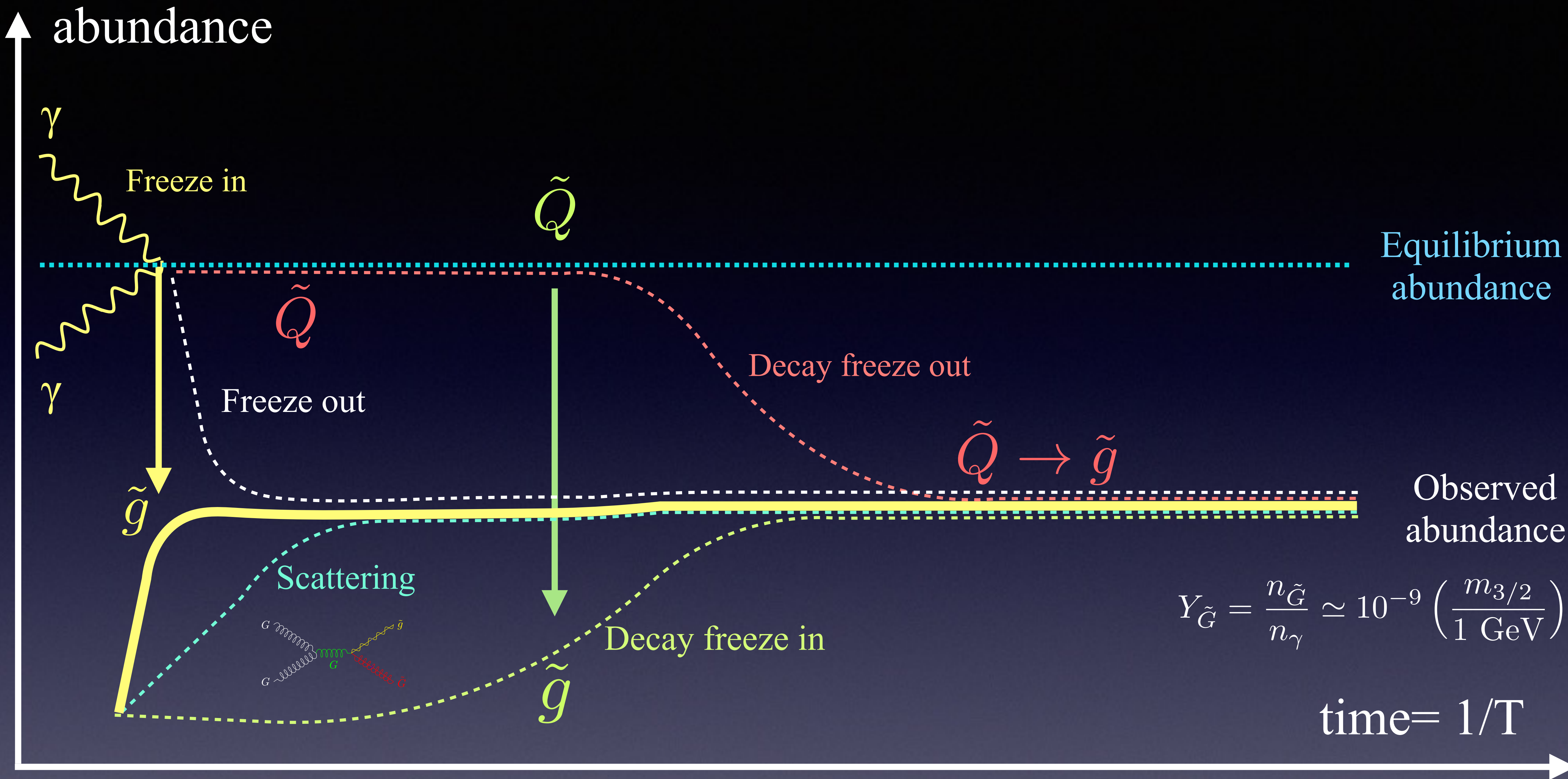
abundance
γ
Freeze in
$\tilde{Q}$
Equilibrium
abundance
$\tilde{Q}$
Decay freeze out
γ
Freeze out
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$\tilde{g}$
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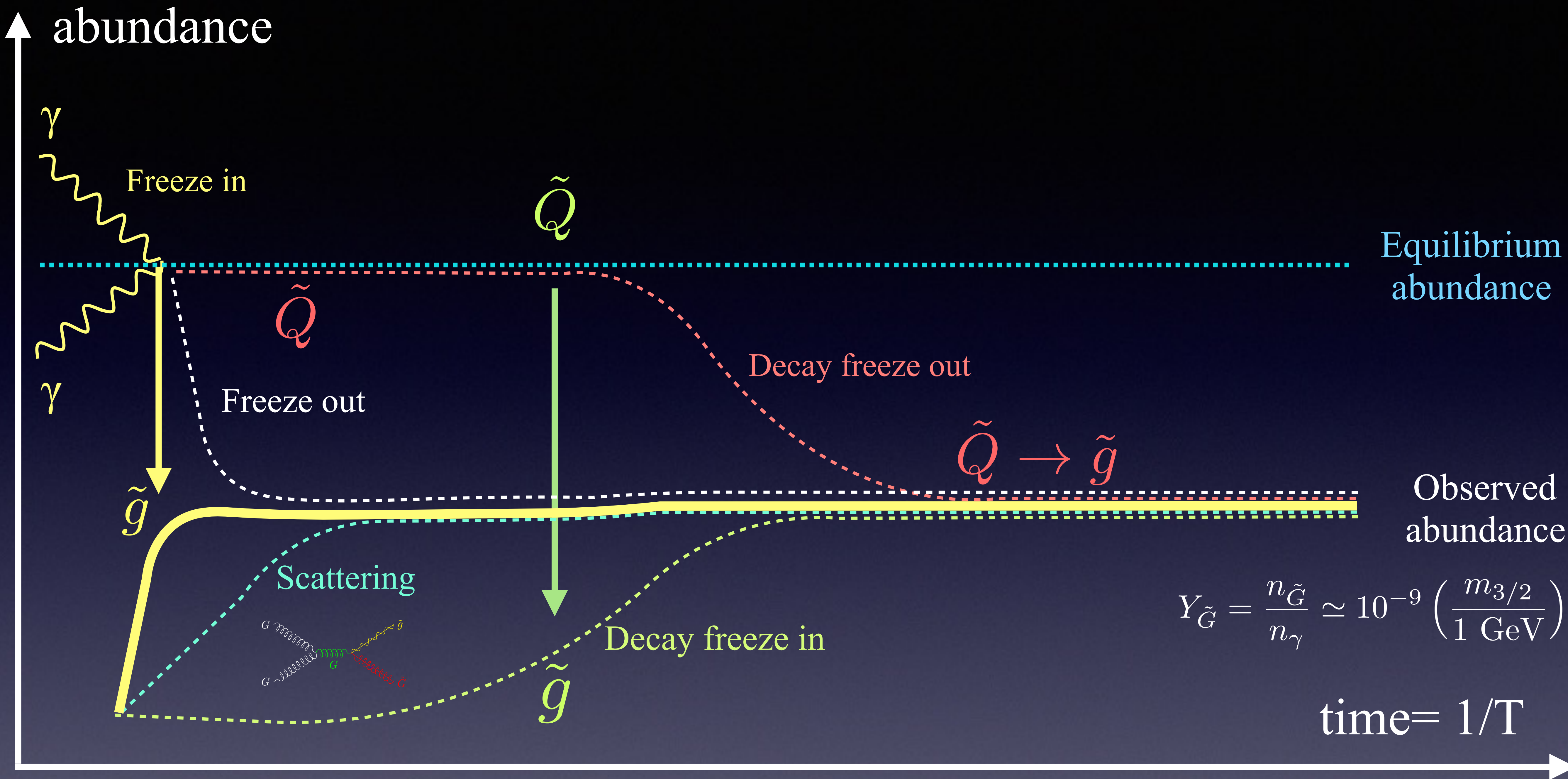
$\tilde{g}$
time= 1/T



$$\boxed{\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{Sc} + \Omega_{\tilde{G}}^{dFO} + \Omega_{\tilde{G}}^{dFI} + \Omega_{\tilde{G}}^{FI}}$$

The scattering process

..In 1993, Moroi, Murayama and Yamaguchi take the goldstino interaction to compute its production rate through SM scattering

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In gauge symmetry, where the transformation parameter **θ** (phase of the Higgs), which represent the (would be) massless goldstone mode of the theory is eaten to give the longitudinal mode of the gauge boson. By analogy, in supergravity (local supersymmetry), the would be fermionic goldstone (goldstino) **ψ** is eaten by the gauge field to give mass to the gravitino (SuperHiggs mechanism)

$$H = he^{i\frac{\theta}{f}} \quad \Rightarrow \quad B_\mu \sim i\frac{1}{f}\partial_\mu\theta$$

$$\boxed{\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu\psi}$$

with $m_{3/2} = \dfrac{< F >}{\sqrt{3}M_{Pl}}$

<F> being the breaking scale of SUSY

$\boxed{\text{The coupling is fixed by the symmetry (breaking)}}$

T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

… one can then compute the relic abundance of the gravitino, repopulated by the scattering of SM particles in the thermal bath:

$$\mathcal{L} = \frac{i m_{\tilde{G}}}{8\sqrt{6}\, m_{3/2}\, M_{Pl}} \bar{\psi}\, [\gamma_\mu, \gamma_\nu] \tilde{G}\; G_{\mu\nu}$$

gravitino

gluino

gluon

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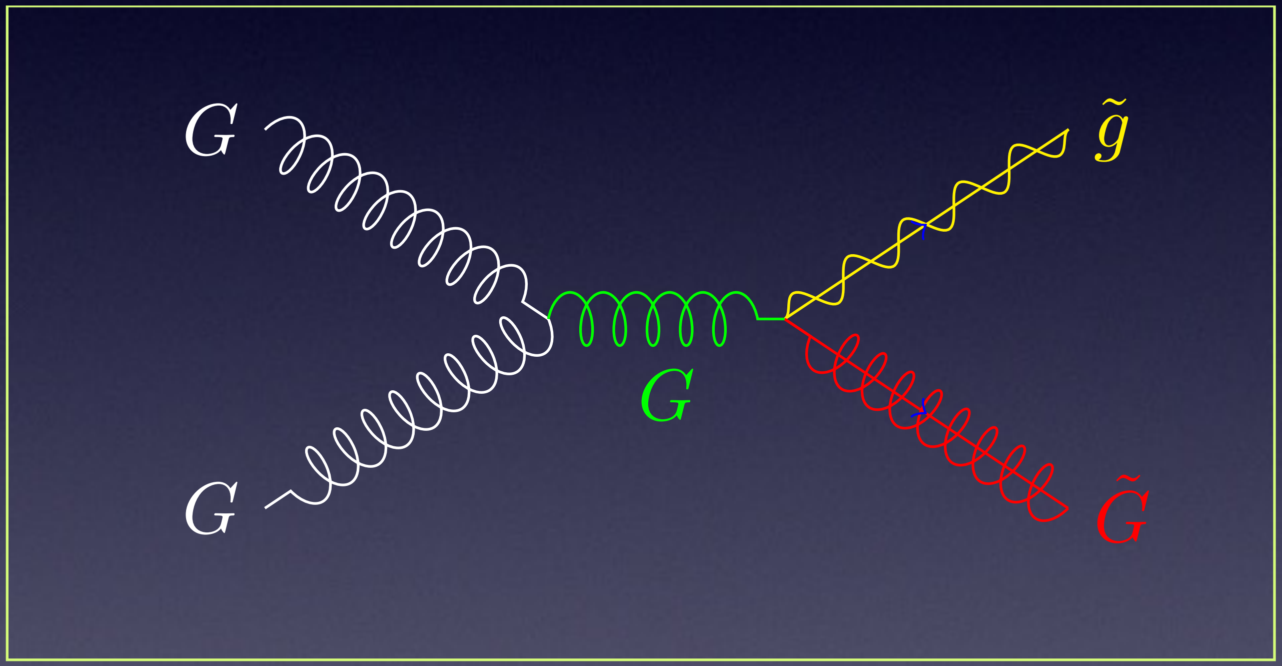

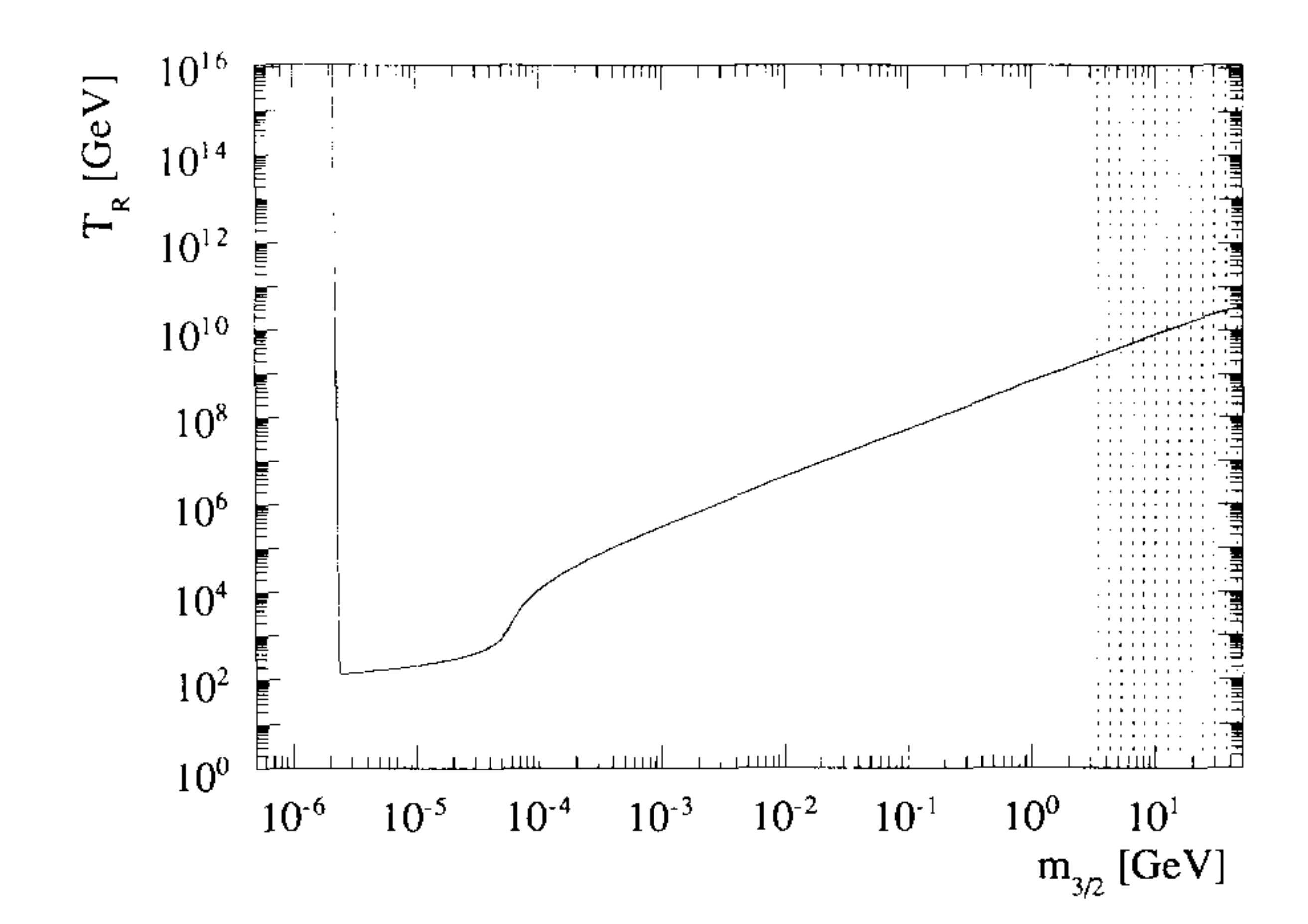

$$\Omega_{3/2}h^2 \sim 0.3 \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_{\mathrm{RH}}}{10^{10}\ \mathrm{GeV}}\right)\sum\left(\frac{m_{\tilde{G}}}{100\ \mathrm{GeV}}\right)^2$$

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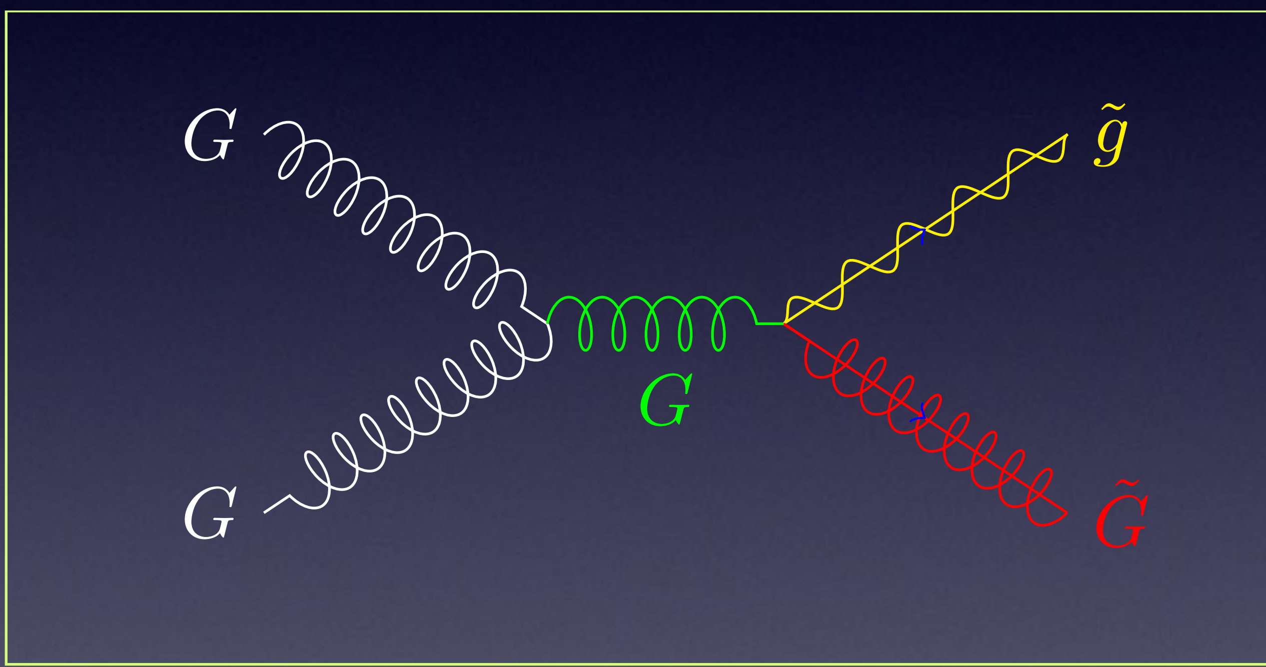
gravitino gluino gluon



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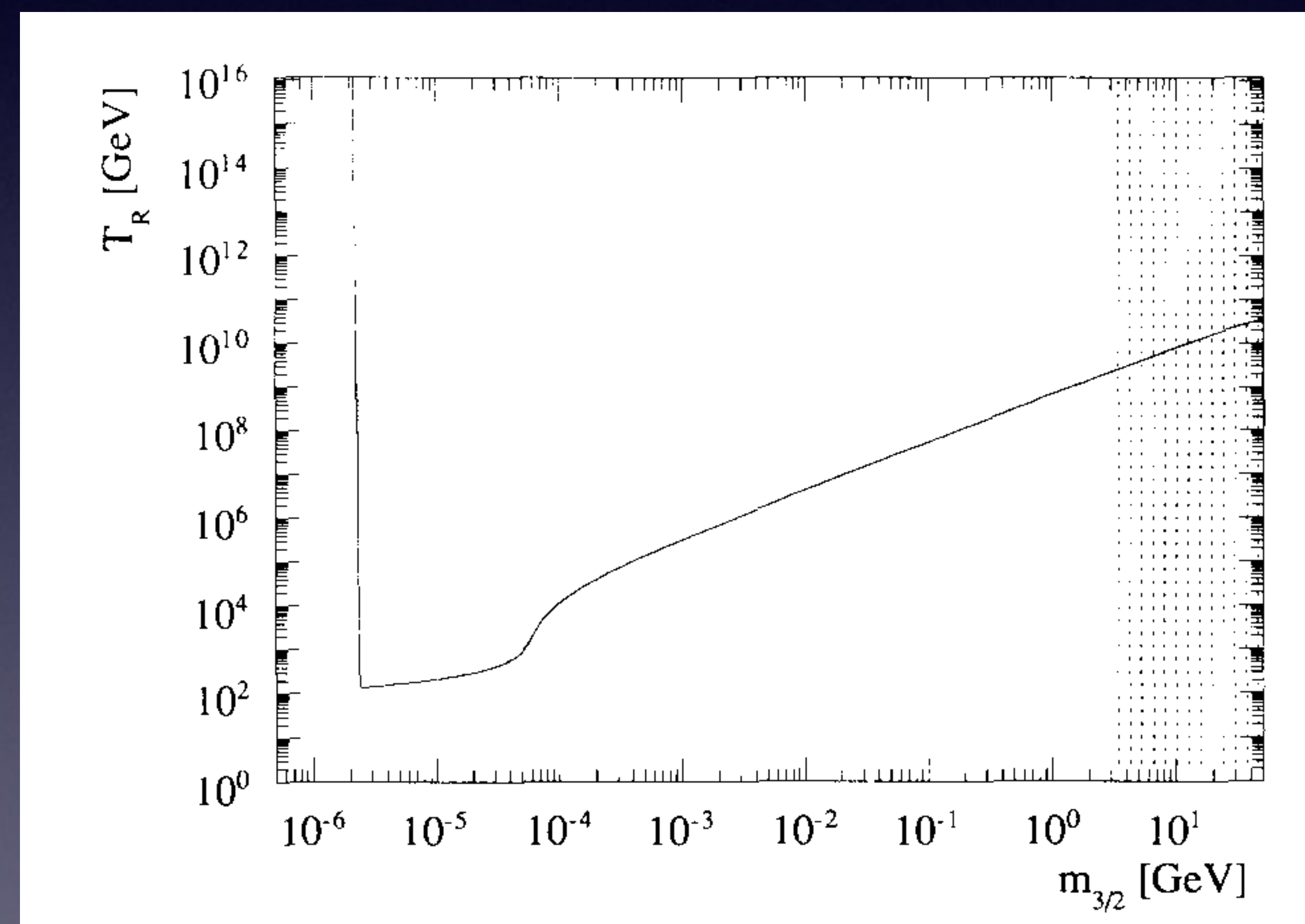

The thermal scattering has reopened a cosmologically viable window ($m_{3/2}$ > 1 keV) but..

The freeze out process

The freeze out process is the mechanism describing the population of gravitino through the decay of the Next to Lightest Supersymmetric Particle (NLSP) into gravitino, once the NLSP is out of equilibrium. The NLSP can be a sfermion or a neutralino. We will take the neutralino case for illustration

See Keith’ paper of 1983

Add a slide about decay NLSP and BBN
(Stefen..)

.. non-discovery of gluino at LHC pushes lower bound on gluino masses, and thus upper bound on T_{RH} of $\sim 10^7$ GeV which can be problematic for some leptogenesis scenario.

But, even in this case…

Cheung et al.* showed in 2011 that the freeze in process of gravitino production through the decay of sparticles still in thermal equilibrium should render the Universe overdense if $T_{RH} > M_{susy}$.

*C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

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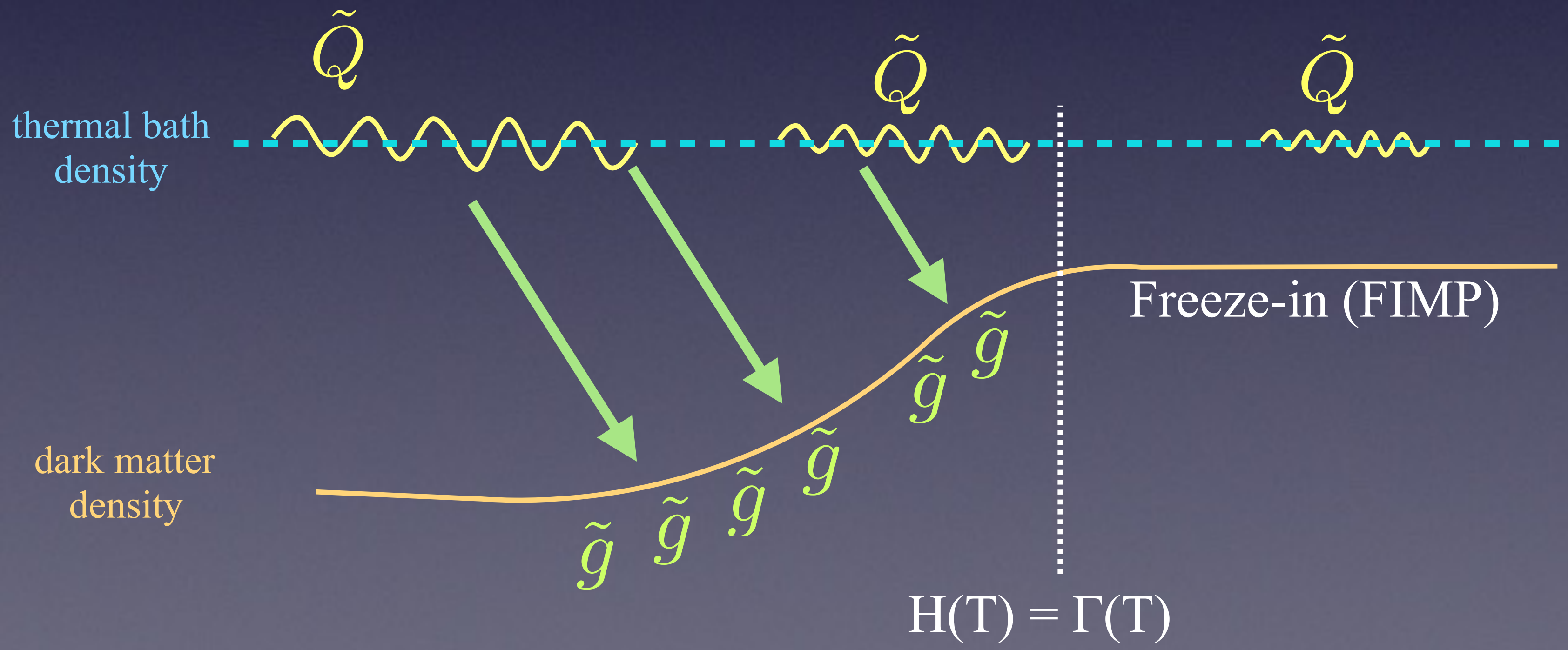
The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation ($H > \Gamma$)



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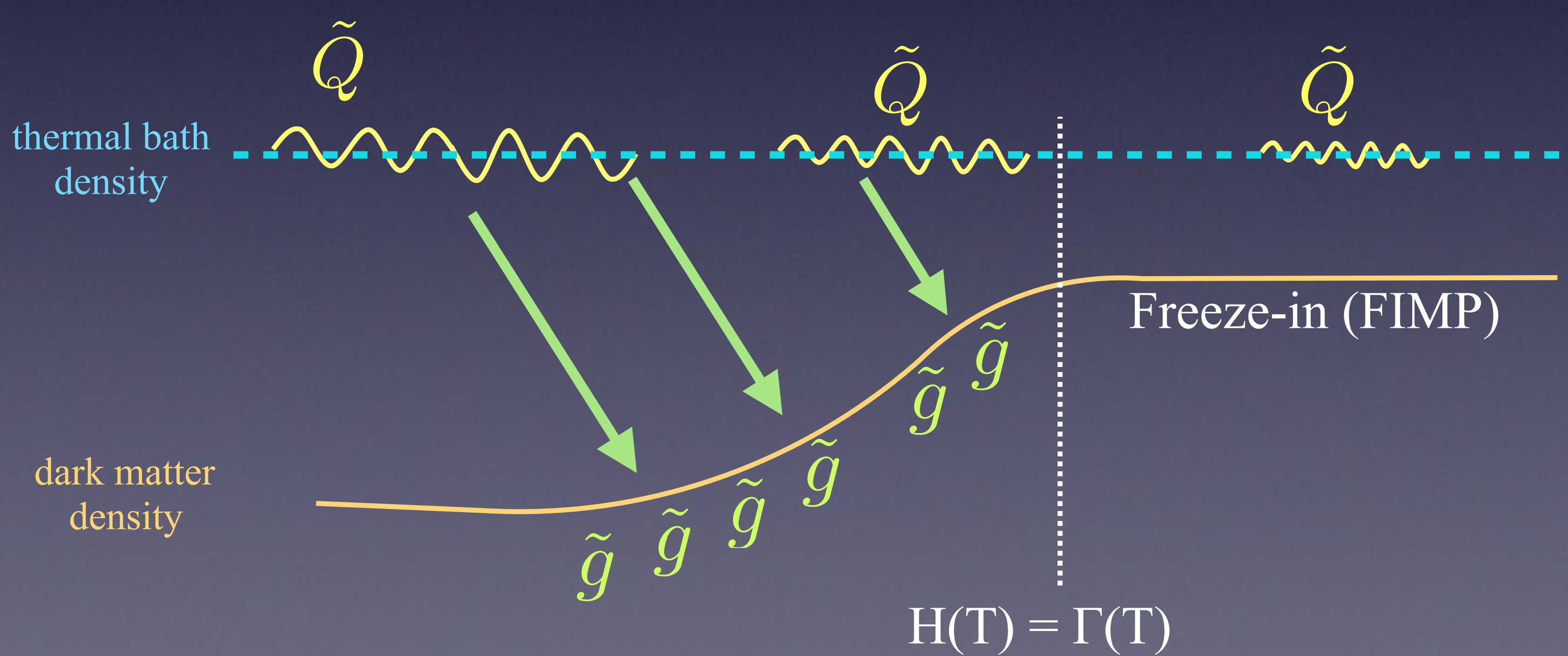
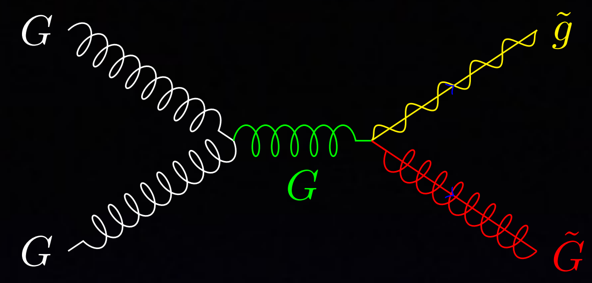
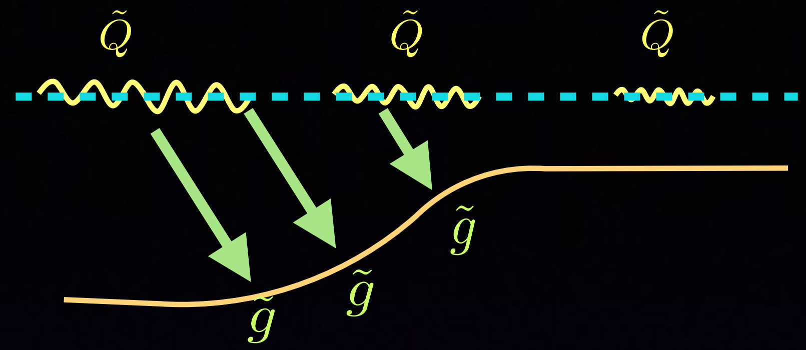


$$\Omega_{3/2}^{decay} h^2 \propto \frac{\sum M_{\tilde{Q}}^3}{m_{3/2} M_{Pl}}$$

but decay will compete with scattering

*C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)





$$\Omega_{3/2}h^2 = \Omega_{3/2}^{scat}h^2 + \Omega_{3/2}^{decay}h^2 \propto \frac{T_{RH}\sum m_{\tilde{G}^2}}{m_{3/2}^2 M_{Pl}} + \frac{\sum M_{\tilde{Q}}^3}{m_{3/2}^2 M_{Pl}}$$

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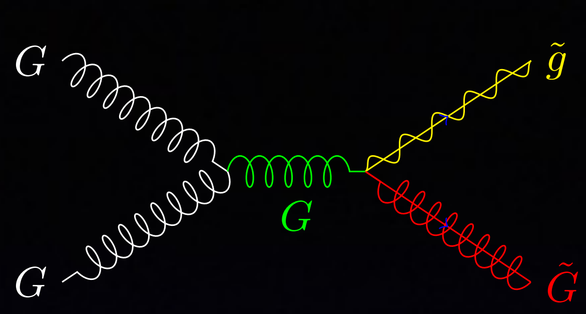

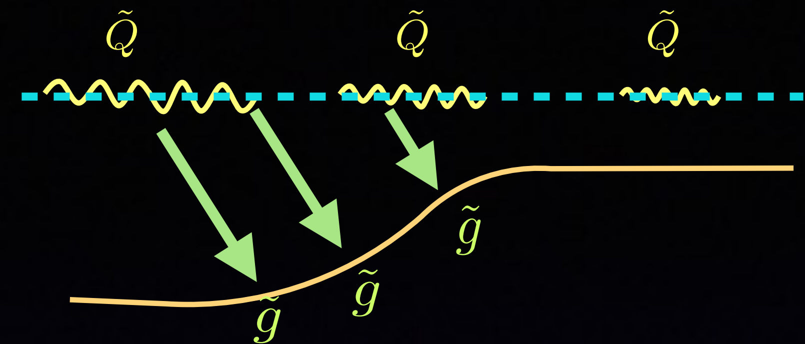

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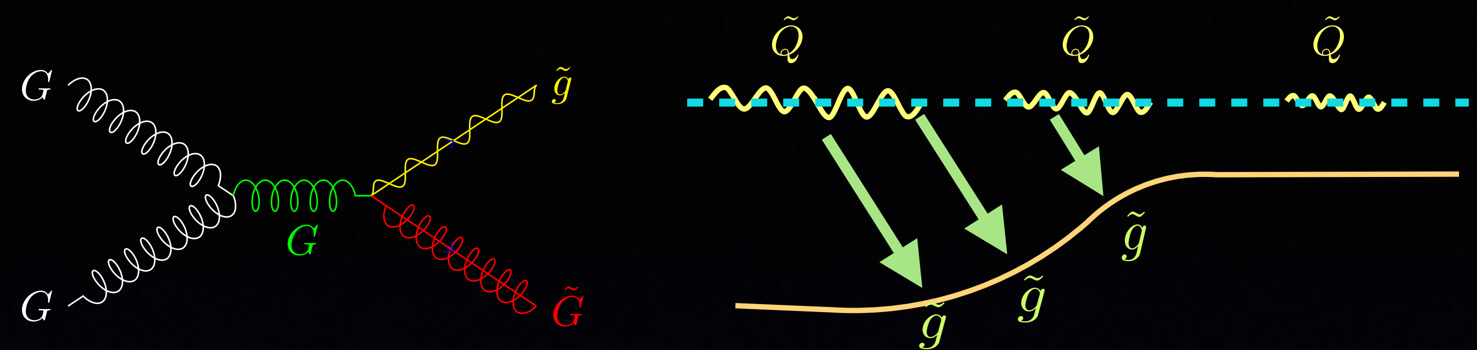
If $\quad T_{RH} M_{\tilde{Q}}^2 \; < \; m_{\tilde{G}}^3$

Then, the relic abundance is given by the decay modes and quickly over-densify the Universe, unless $T_{RH} < M_{susy}$, in which case only the exponential queue of the SUSY distribution plays a role.

C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)



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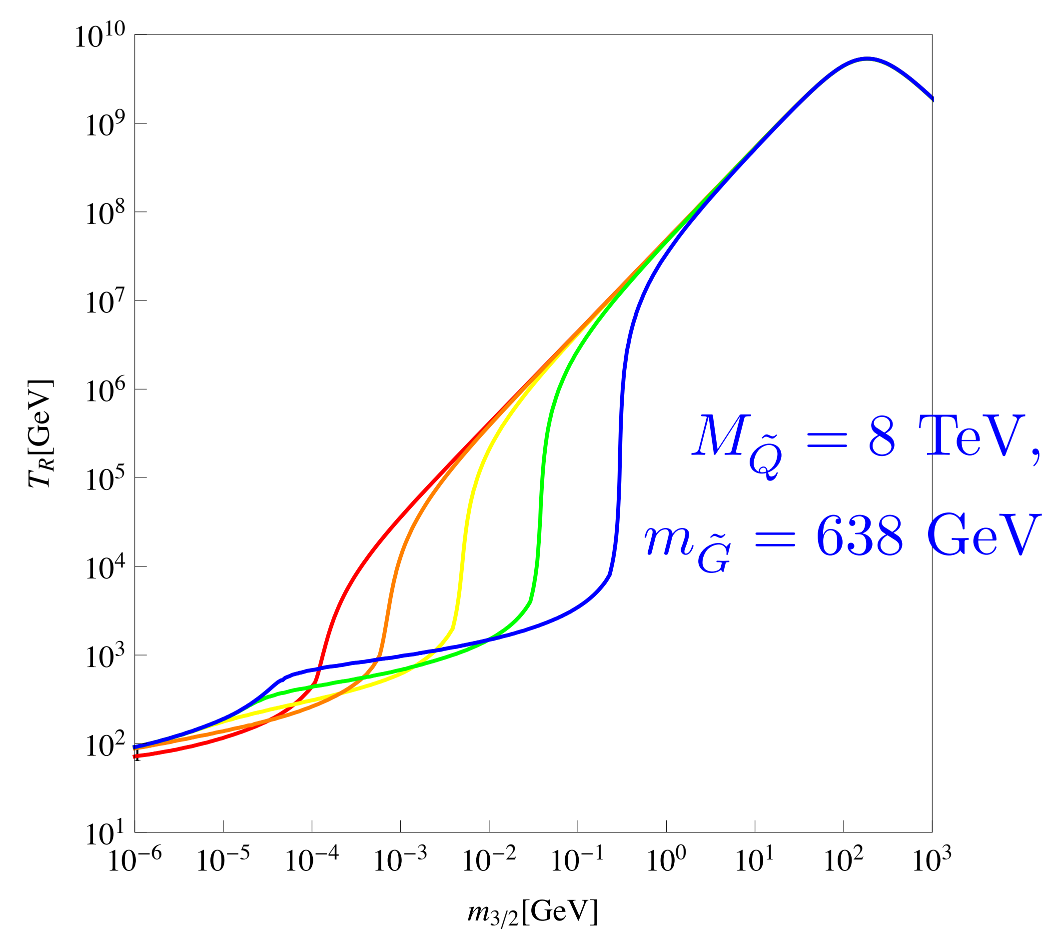

C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

```
H^2 = \left( \frac{\dot a}{a} \right)^2 = \frac{8 \pi G}{3} \rho_{rad}(T) = \frac{8 \pi G}{3} \frac{\pi^2}{15} T^4
\\
aT = \mathrm{cste} ~~~~ \Rightarrow ~~~~ \frac{da}{a} = - \frac{dT}{T}
\\
\frac{dT}{T^3}= -\sqrt{\frac{8 \pi^3 G}{45}} dt ~~~~\Rightarrow ~~~~ t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32
\pi^3}} \simeq 0.2 \frac{M_{PL}}{T^2}
\\
t \simeq 3 \times 10^{27}~\mathrm{GeV^{-1}} \sim 200 ~\mathrm{seconds}
\\
n(t_D) \sigma v ~ t_D \simeq 1 ~~~~\Rightarrow n(t_D) \simeq \frac{1}{\sigma v t_D}
\\
v = \sqrt{\frac{3 T_D}{m_p}}\times c \simeq 5 \times 10^8 ~\mathrm{cm ~s^{-1}}
\\
T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9~\mathrm{K})}\right)^{1/3} 10^9~\mathrm{K} = \left( \frac{10^{-30}}
{1.78 \times 10^{-6}~\mathrm{g/cm^3}} \right)^{1/3}10^9~\mathrm{K} \simeq 8 ~\mathrm{K}


\psi_\mu \sim i \sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu \psi

H = h e^{i \frac{\theta}{<H>}} ~~\Rightarrow ~~ W_\mu = i \frac{1}{<H>} \partial_\mu \theta

\mathrm{with}~~ m_{3/2} = \frac{<F>}{\sqrt{3}M_{Pl}}

{\cal L} = \frac{i m_{\tilde G}}{8 \sqrt{6}~ m_{3/2} ~ M_{Pl}} {\color{yellow} \bar\psi} ~  [\gamma_\mu, \gamma_\nu]
{\color{red} \tilde G} ~ {\color{green} G_{\mu \nu}}


\Omega_{3/2} h^2 \sim 0.3 \left( \frac{1 ~\mathrm{GeV}}{m_{3/2}} \right) \left( \frac{T_{\mathrm{RH}}}{10^{10}~
\mathrm{GeV}} \right) \sum
\left( \frac{m_{\tilde G}}{100~\mathrm{GeV}} \right)^2


\Omega_{3/2} h^2 = {\color{yellow} \Omega_{3/2}^{scat} h^2 } + {\color{red}\Omega_{3/2}^{decay} h^2} ~~ \propto~~
{\color{yellow} \frac{T_{RH}\sum  m_{\tilde G^2}}{m_{3/2}^2 M_{Pl}}} +{\color{red} \frac{ \sum M^3_{\tilde Q}}
{m^2_{3/2} M_{Pl}} }
```

The equations

n_{e^-} + n_{e^+} = n_{\nu} + n_{\bar \nu} = \frac{3}{2} n_{\gamma}

n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}

\frac{\ddot a}{a} = - \frac{4 \pi G}{3} \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c

n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v \rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}

\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f \langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }

\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26 \times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1
~~~~~~~~
\Rightarrow \langle \sigma v \rangle > 10^{-9} h^{-2} ~\mathrm{GeV^{-2}}

\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}

\frac{dY_{a}}{dx_s} =\left(\frac{45}{g_* \pi} \right)^{3/2} \frac{1}{4 \pi^2} \frac{M_P}{m_{a}^5}x_s^4 R

{\color{white} \chi^0_1=} {\color{red} c_B \tilde B + c_1 \tilde H_1 + c_2 \tilde H_2} {\color{yellow} + c_W \tilde W}

The equations

Y_{\tilde G} = \frac{n_{\tilde G}}{n_\gamma} \simeq 10^{-8} \left(\frac{m_{3/2}}{1 ~ \mathrm{GeV}} \right)

```
g_{s+3/2}^d \times (T_{3/2}^d)^3 \times V(T^d_{3/2}) = \left[ 4 \times \frac{7}{8} \times (T_{3/2}^0)^3 + 3 \times 2
\times \frac{7}{8}(T_\nu^0)^3 + 2 \times (T_\gamma^0)^3 \right] \times V(T_\gamma^0)

(T_{3/2}^0)^3 = \frac{1}{g^d_s}\frac{43}{11}(T_\gamma^0)^3 ~~\Rightarrow  ~~ \Omega h^2 = \frac{\rho_{3/2}}
{\rho_c^0} \simeq \frac{210}{g_s^d} \left(\frac{m_{3/2}}{1~\mathrm{keV}} \right) \lesssim 1 ~~ \Rightarrow ~~m_{3/2}
\lesssim 100 ~\mathrm{eV} ~~[g^d_s \lesssim 200]

\Gamma_{3/2}= \alpha_{3} \frac{m_{3/2}^3}{M_{\mathrm{Pl}}} ~; ~~\tau_{3/2} < 1~s ~~  \Rightarrow ~~ m_{3/2} > 10~
\mathrm{TeV} ~~\Rightarrow ~~ \sqrt{F} \simeq \sqrt{ m_{3/2} M_{\mathrm{Pl}}} \gtrsim 10^{11}~\mathrm{GeV}

{\color{yellow} X + \tilde \gamma \rightarrow X + \tilde g}

{\cal L}
=\frac{1}{4 M_{\mathrm{Pl}}}
{\color{yellow} \bar{\psi}^\alpha} \gamma_\alpha[\gamma^\mu,\gamma^\nu ] ~{\color{red} \tilde G} ~{\color{green}
G_{\mu \nu}}

\psi_\mu \sim i \sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \psi

{\color{green} \Omega^{FO}_{3/2} = \Omega_{\tilde G} \times \frac{m_{3/2}}{m_{\tilde G}} \propto \frac{1}{\langle
\sigma v \rangle} \frac{m_{3/2}}{m_{\tilde G}} \simeq \frac{1}{\alpha_3} m_{\tilde G} \times m_{3/2}}

{\color{yellow} \Omega_{3/2}^{\mathrm{scat}} \propto \frac{T_{RH} m_{\tilde G}^2}{m_{3/2}} }~~\Rightarrow ~~
\Omega_{3/2} \propto ~ {\color{yellow} \frac{T_{RH} m_{\tilde G}^2}{m_{3/2}}} +{\color{green} m_{\tilde G} \times
m_{3/2}}
```