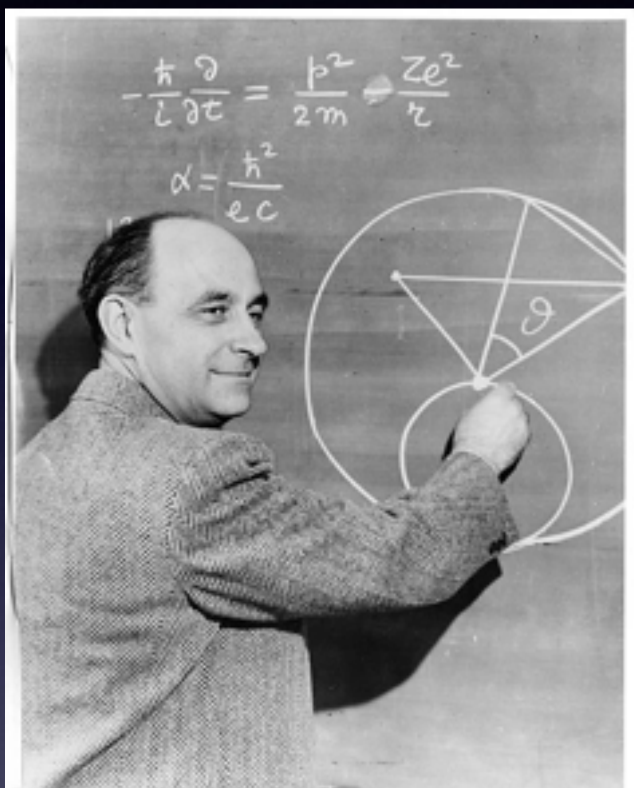
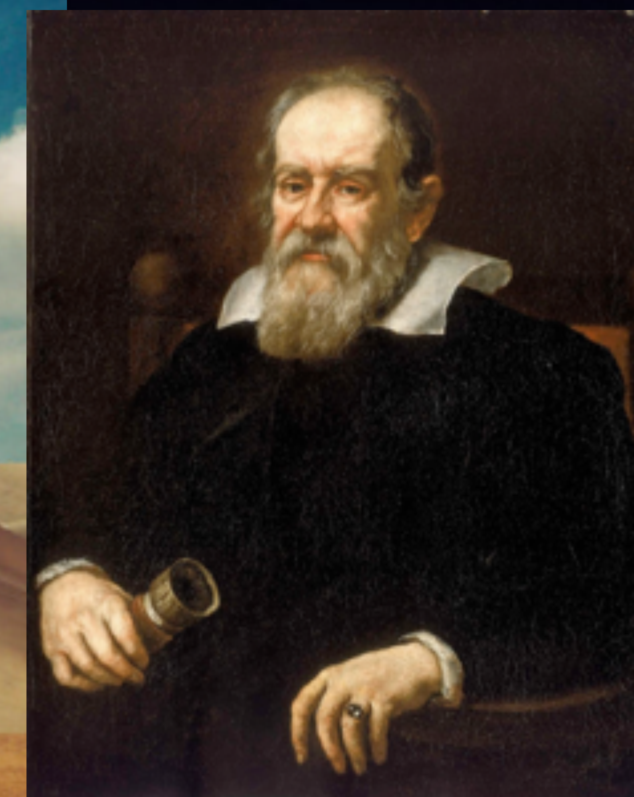
Dark Matter and Early Universe Cosmology





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

« I have never met a man so ignorant that I could not learn something from him»
G. Galilei

Yann Mambrini

University of Paris-Saclay

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

GGI conference, « Collider Physics and the Cosmos », 9th of October 2017

Maira Dutra, Mathias Pierre, Yann Mambrini, work in progress

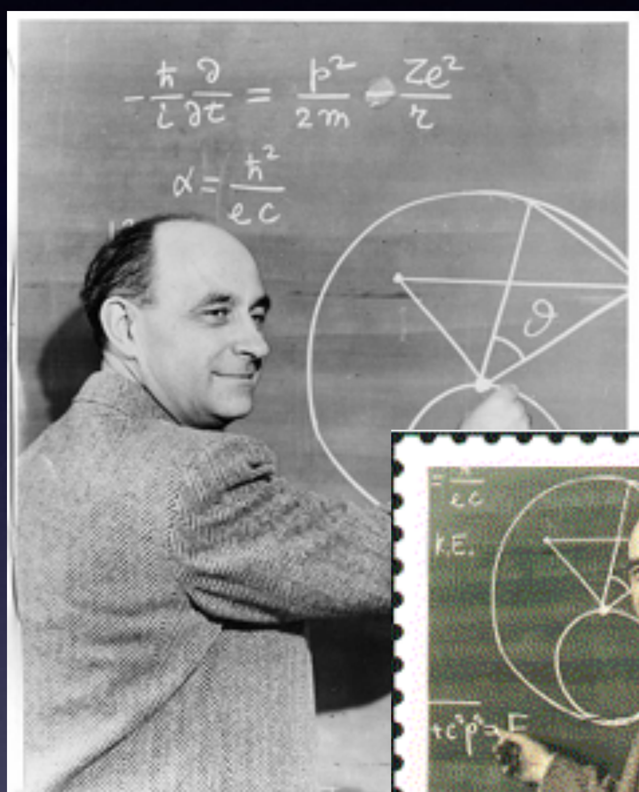
P2IO

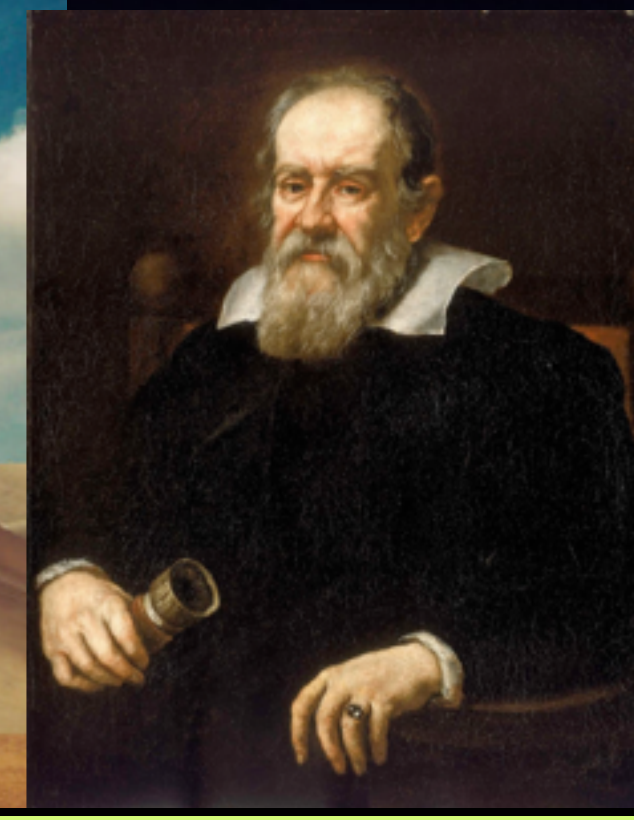
MultiDark
Multimessenger Approach for Dark Matter Detection

cnrs

LPT Orsay

Dark Matter and Early Universe Cosmology





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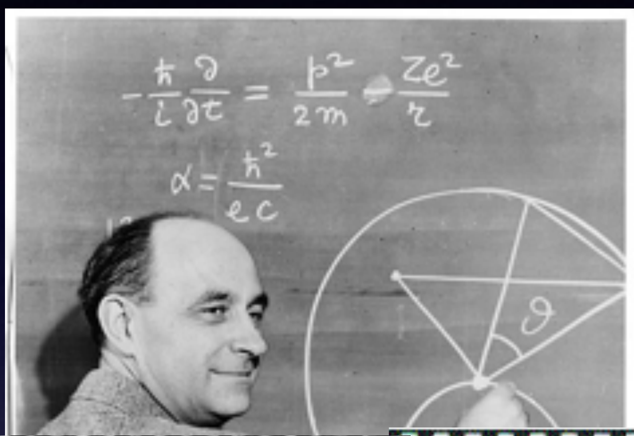

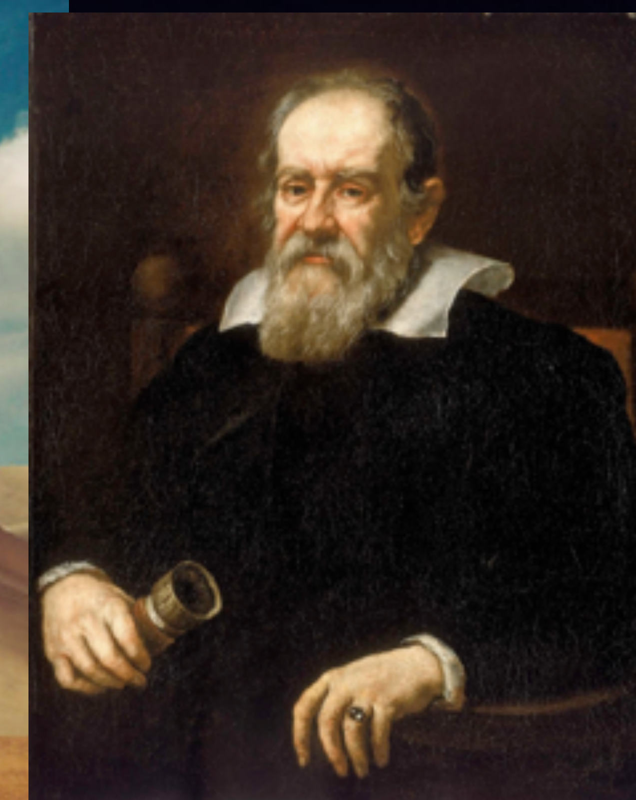

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I appreciate a talk when:

1) I learn something new
or
2) I understand something new
or
3) I hear something I know already

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I hope you will appreciate mine then..

Pierre Binetruy

Whatever is the length of your talk, never try to give more than 3 messages

Pierre Binetruy

Henri Poincaré

The first DM paper

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.

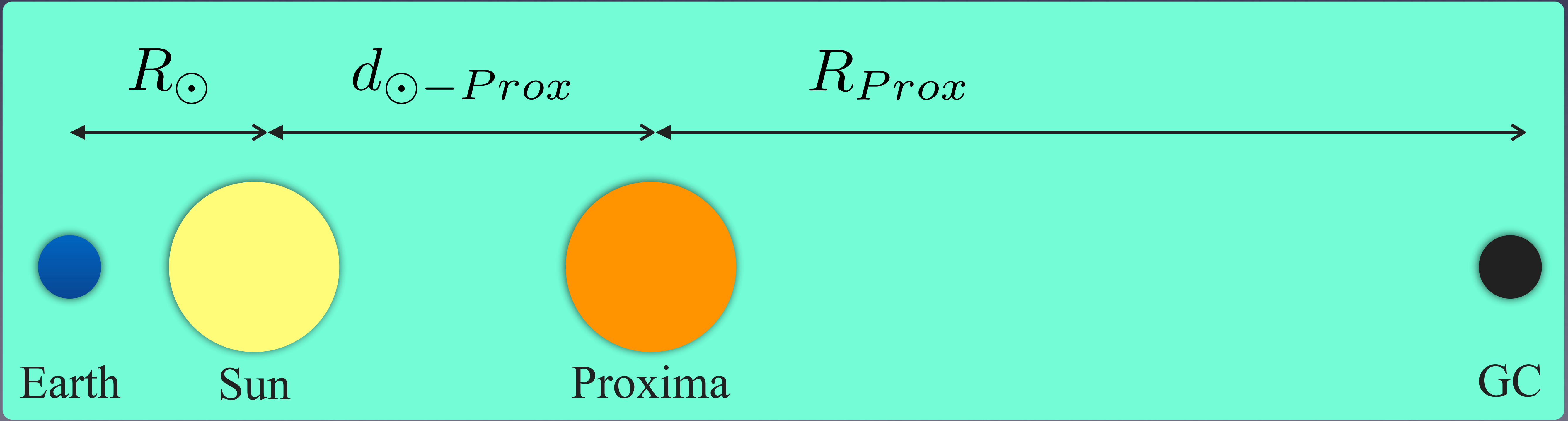
$$v(R) \propto R\sqrt{\rho}$$

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

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

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

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



Plan

Where are we?

The detection and WIMP status

Where should we go?

Alternative early-cosmology scenario
DM production enhancement at early stage [pre-heating]

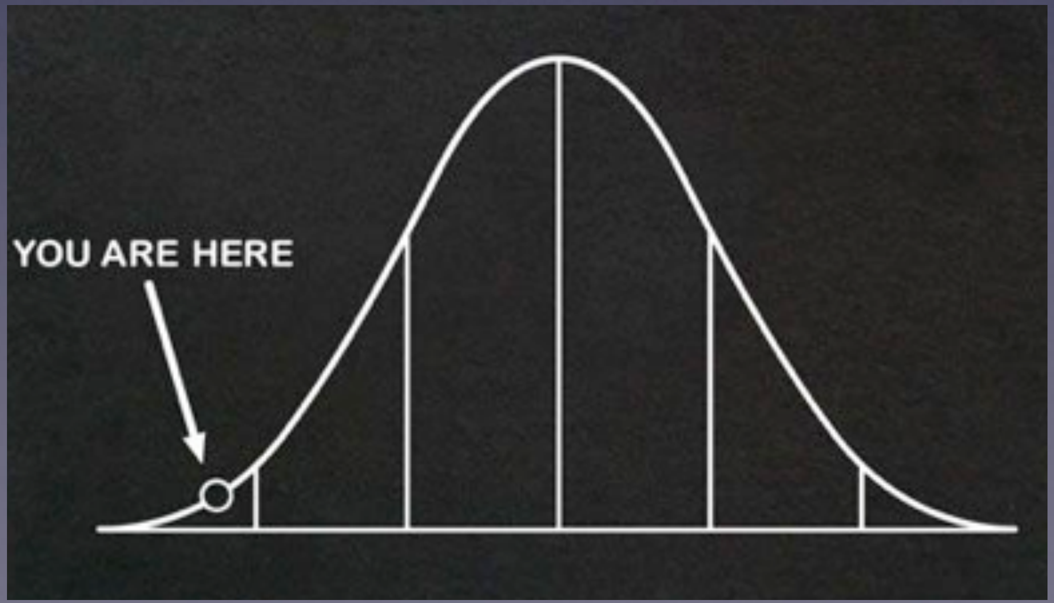
Applications

SO(10)/E6 models
Inflaton portal
gravitino DM in High Scale SUSY

Conclusion

if time is left

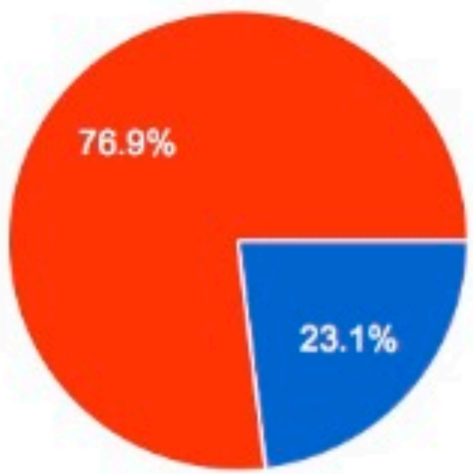
Where are we now?



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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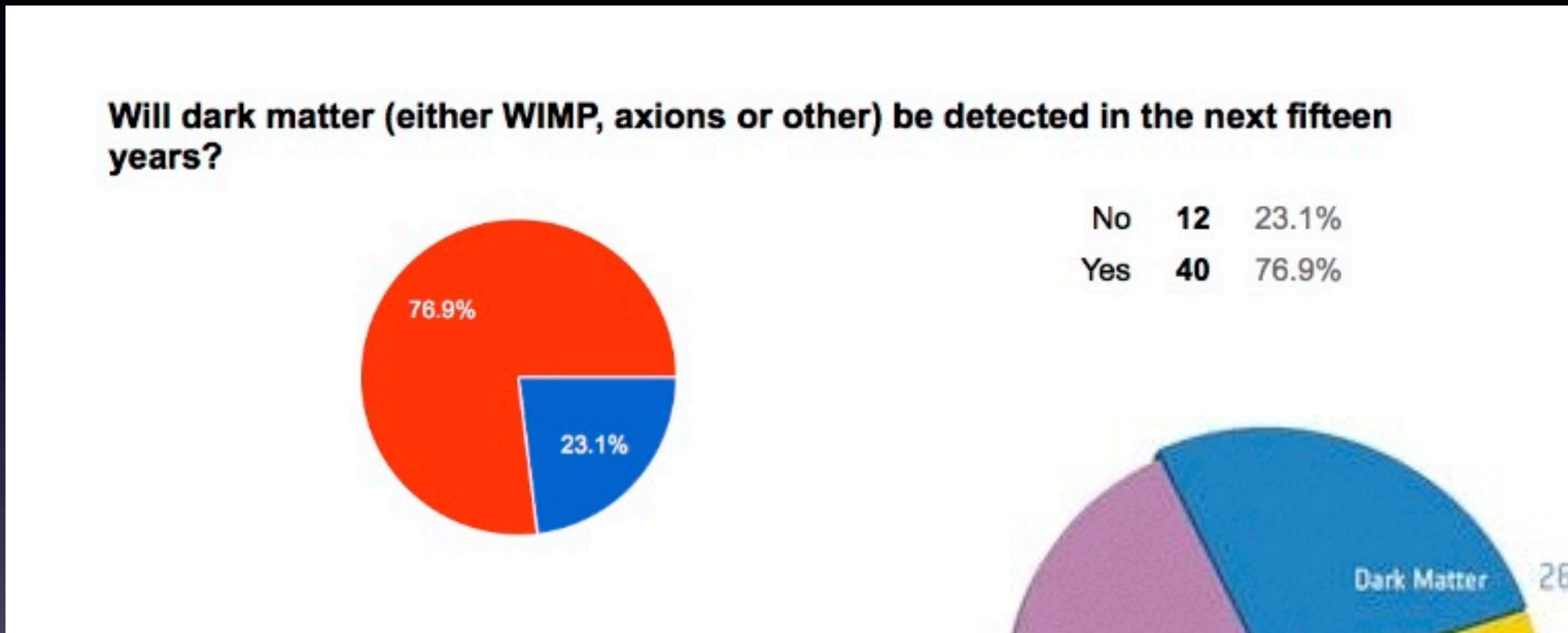
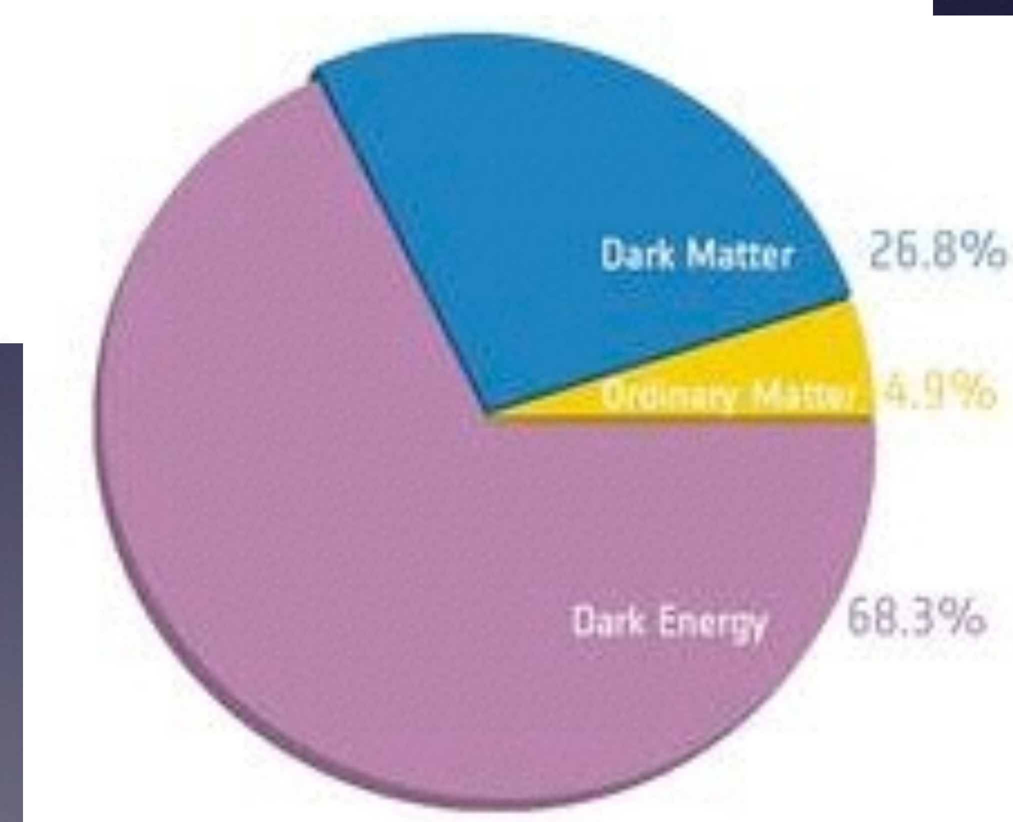


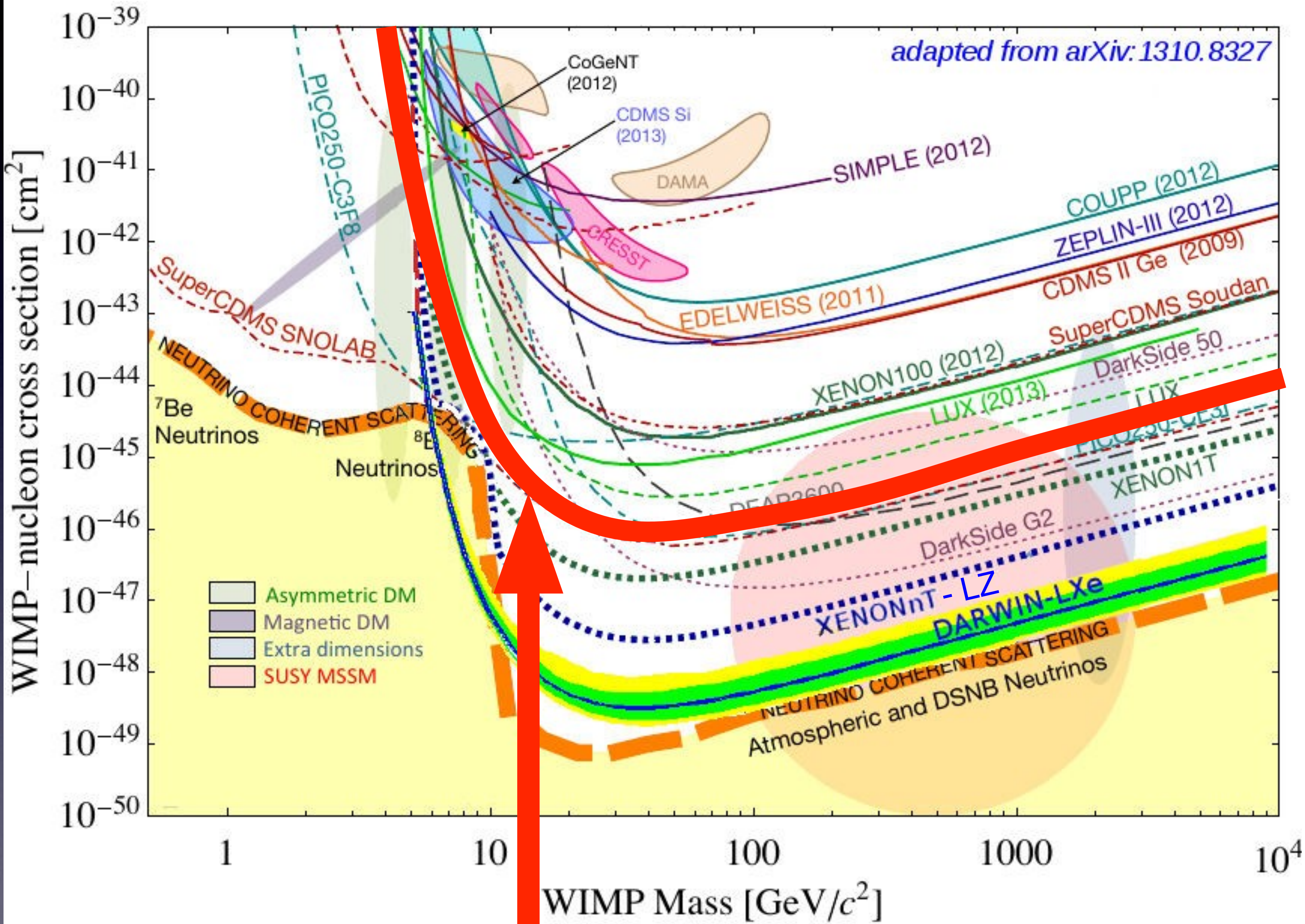


At least optimism…

1

The direct detection race

Perspectives

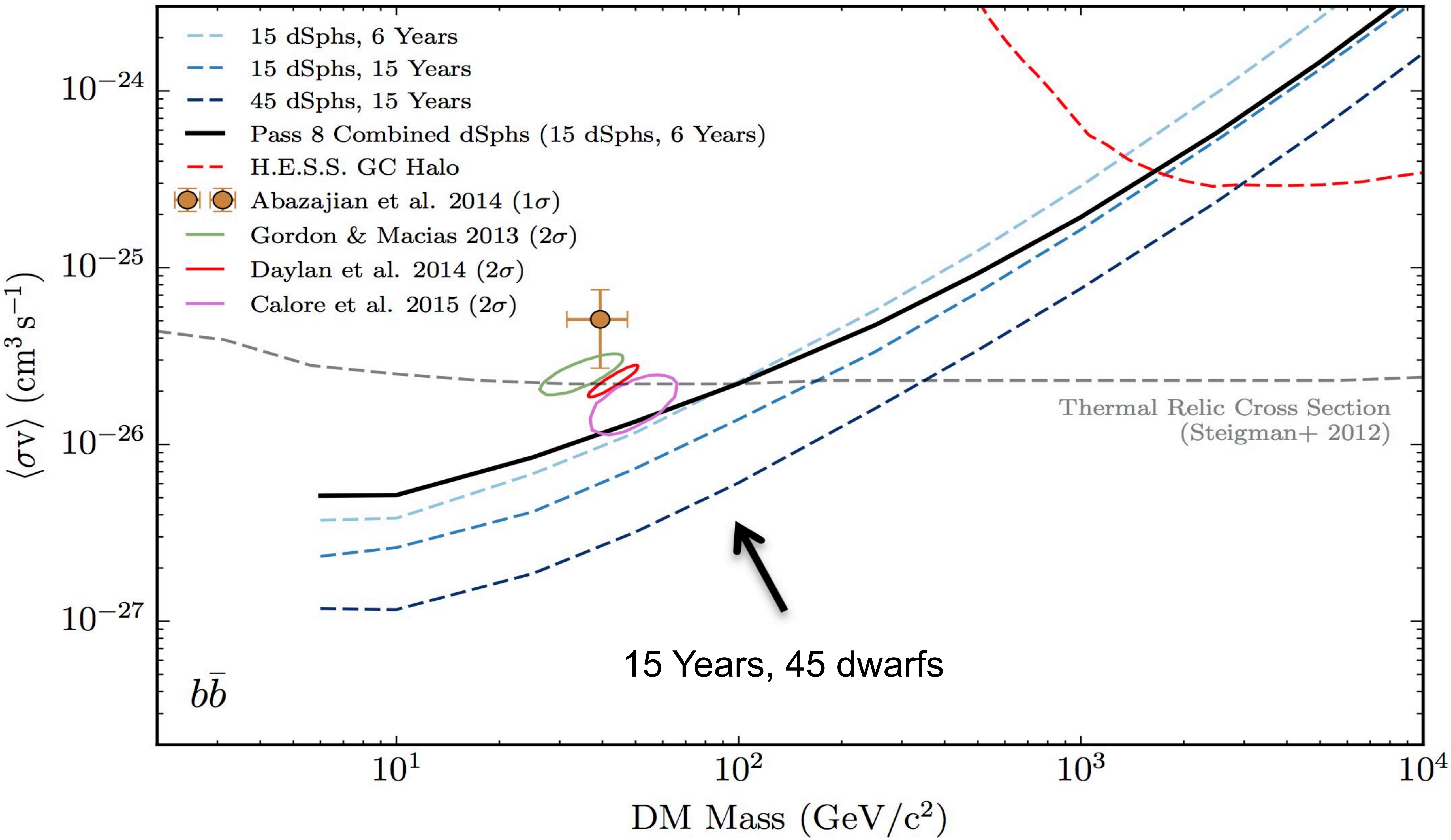


XENON 1T (2017); arXiv:1705.06655 + PandaX-II (2017); arXiv:1708.06917

2

The indirect detection status

DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



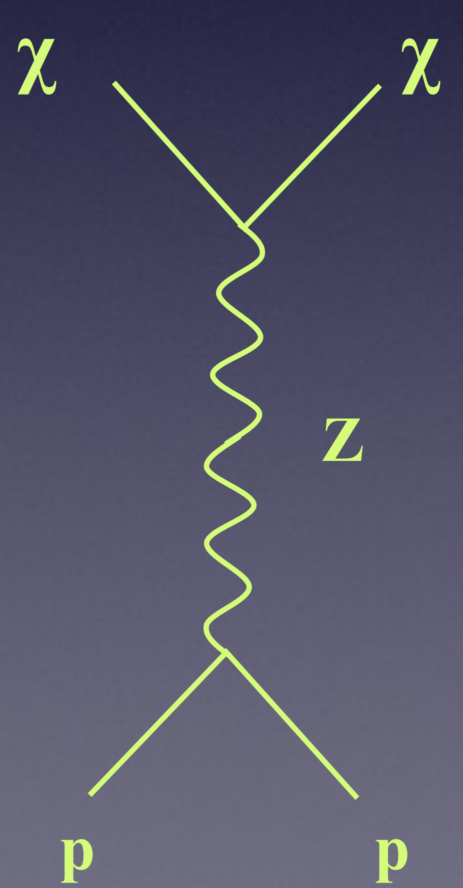
E. Charles et.al, Phy Rep. 636 2016, arXiv:1605.02016

Latest result by FERMI in May: nothing

Conclusion

The **non-observation** of any signal at direct and indirect detection experiments constrains the interaction cross section DM-SM to values below $\sigma < 10^{-46}$ cm^2 ~ 10^{-18} GeV^{-2}

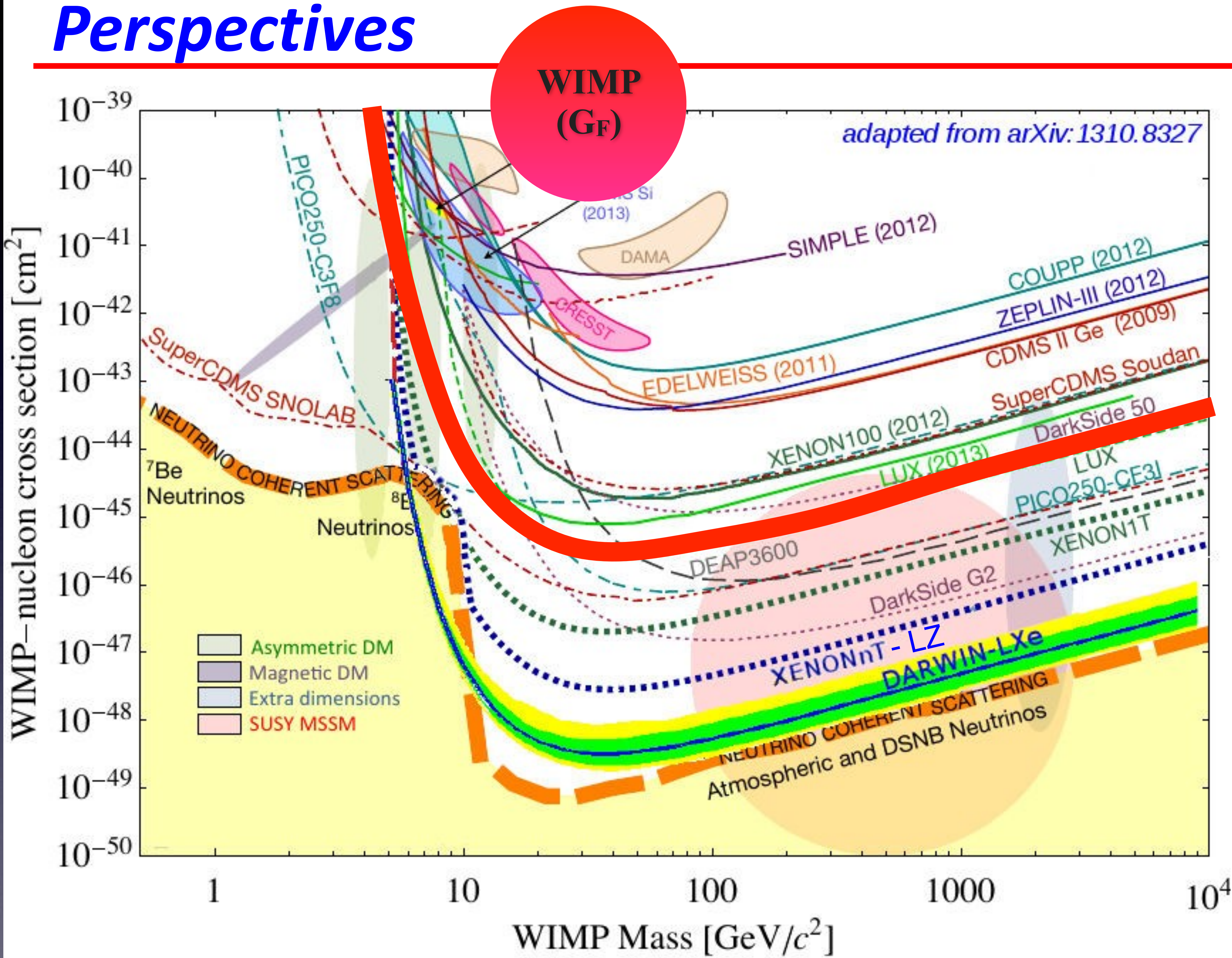
What do we expect for a WIMP*:



$$\sigma_{EW}(\chi\, p \to \chi\, p) \simeq G_F^2 m_\chi^2$$
$$\simeq \frac{g_2^2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^2$$

*Not valid if one exchanges the Higgs or a Z’

Perspectives



Why are we so attached to WIMP-like particle?

The WIMP miracle !

The Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)$$

$$\Omega_A h^2 \simeq \frac{0.17}{\frac{\langle \sigma v \rangle}{(1.2\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})}}$$

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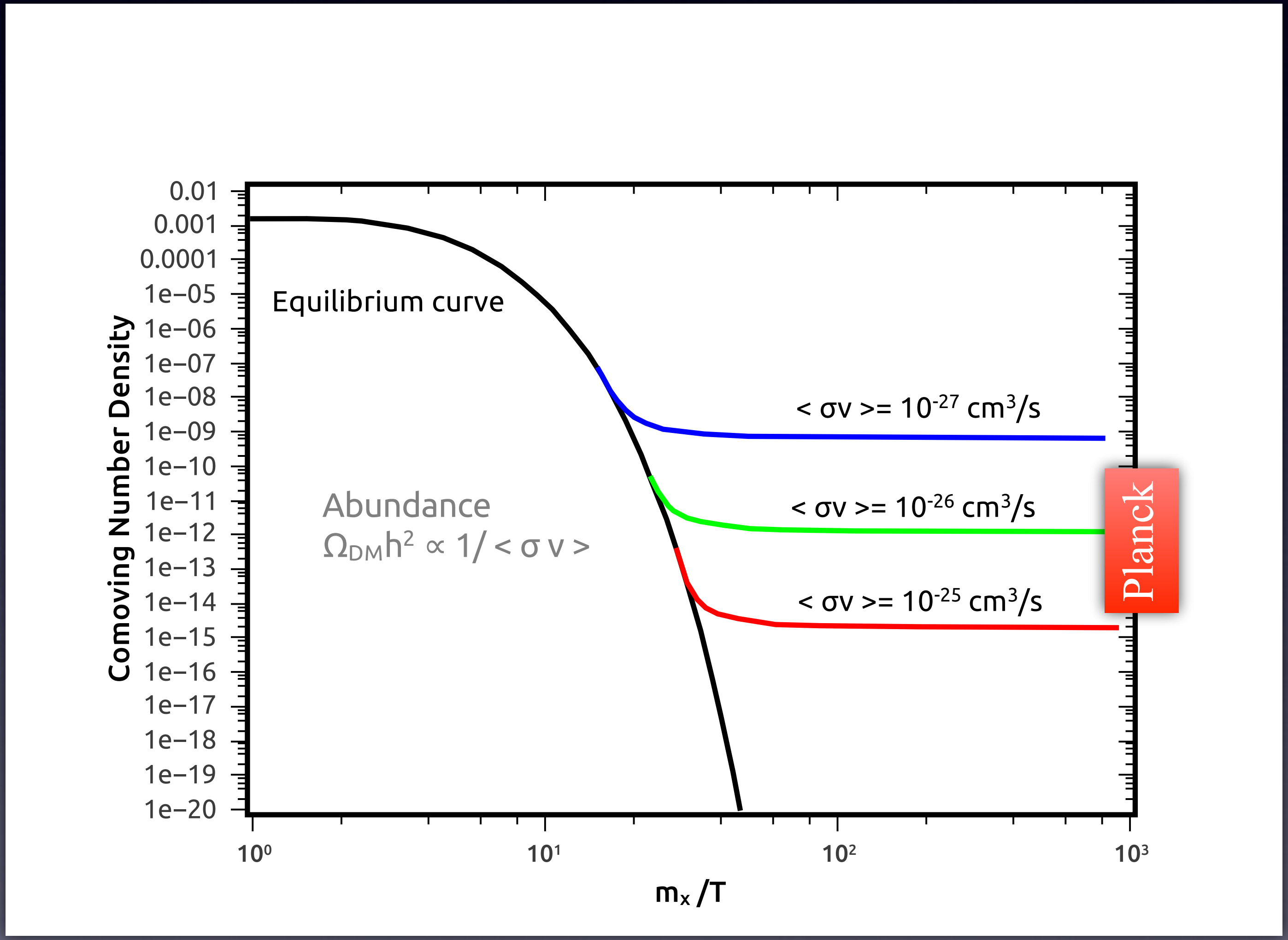

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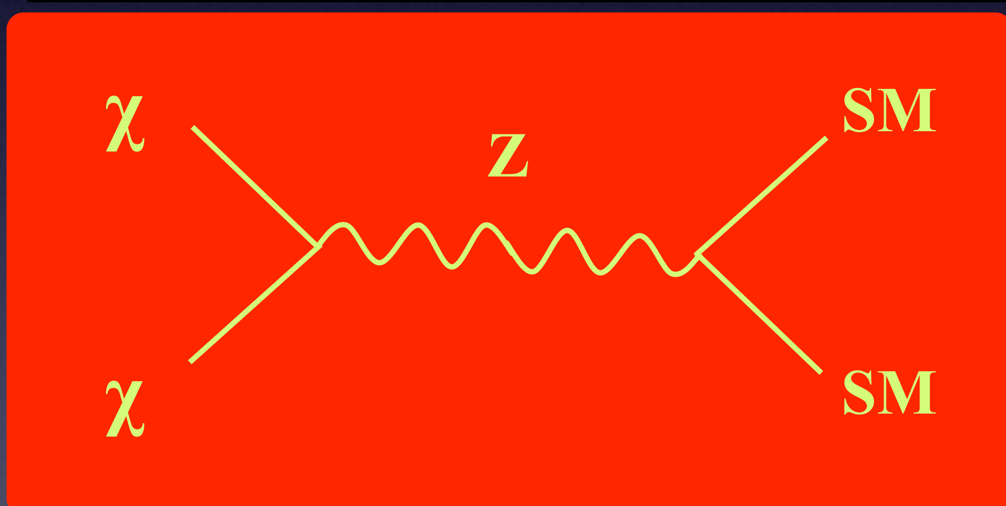
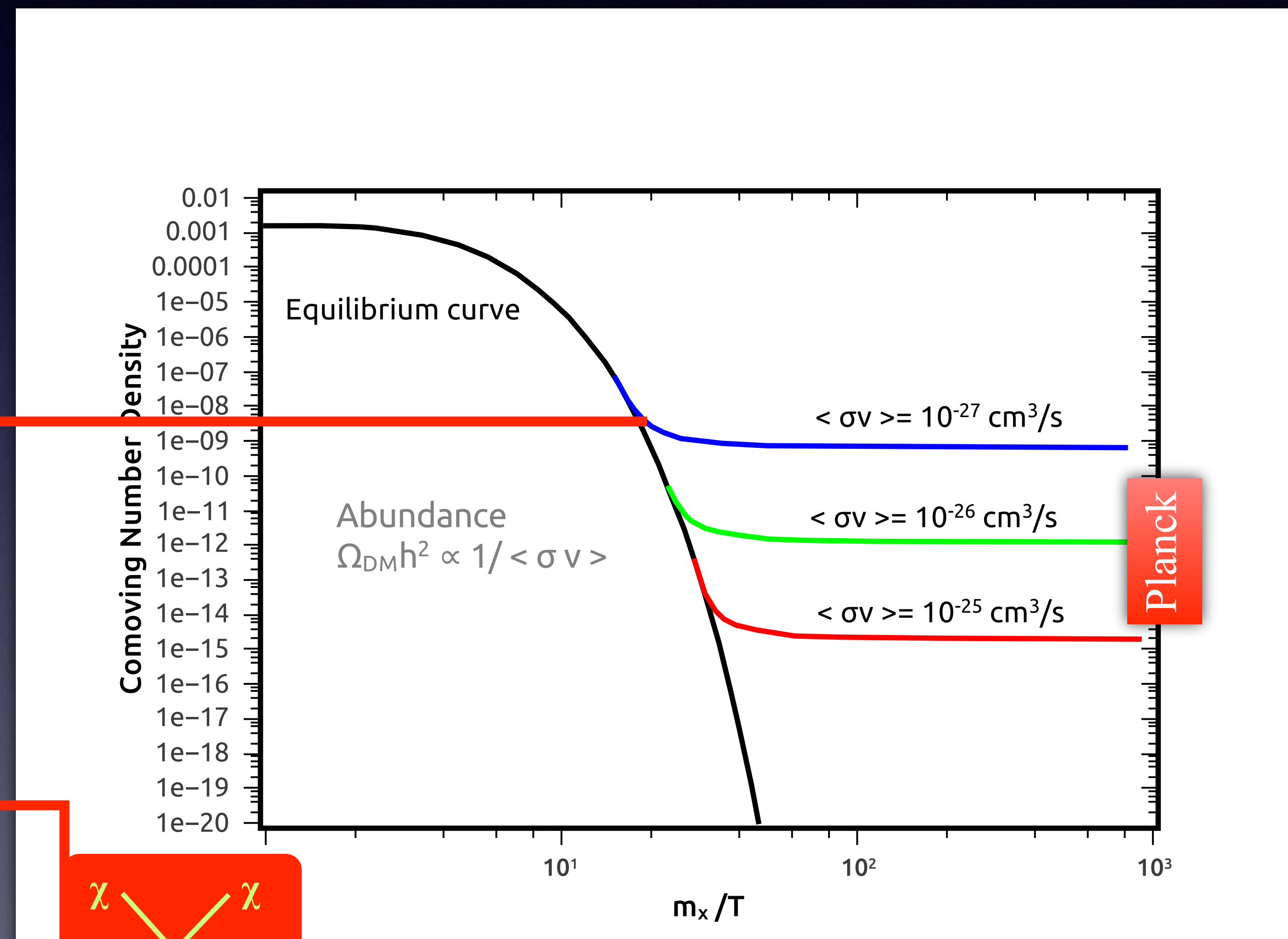
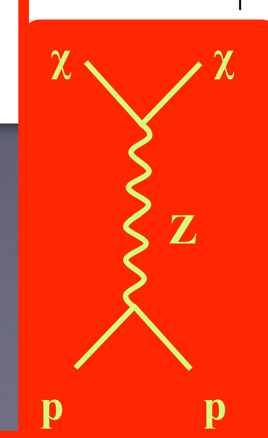




One needs a phase of depletion of dark matter, annihilating to SM to avoid the overabundance. Can we deplete it without even coupling to the SM, and thus avoiding the direct detection conflict?



What is happening if one releases one hypothesis?

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Let suppose the dark matter
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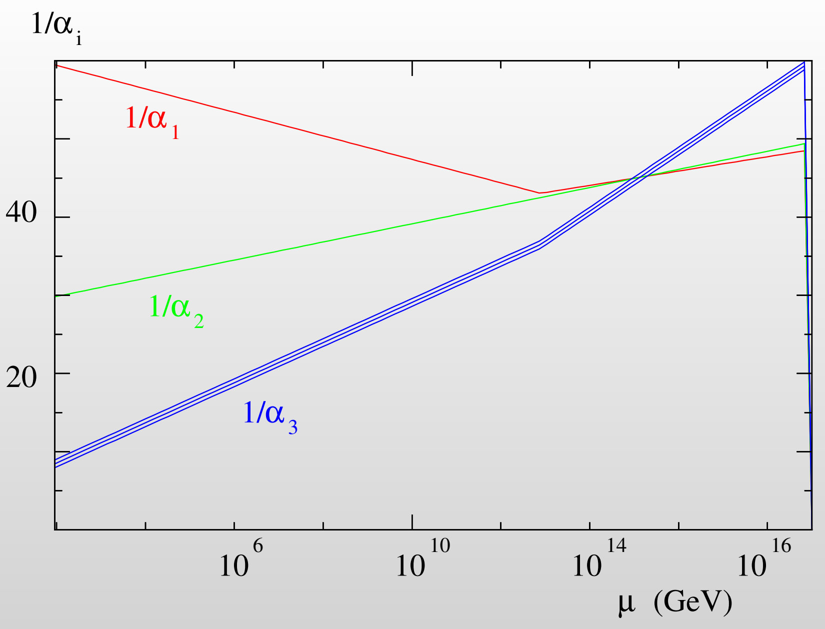
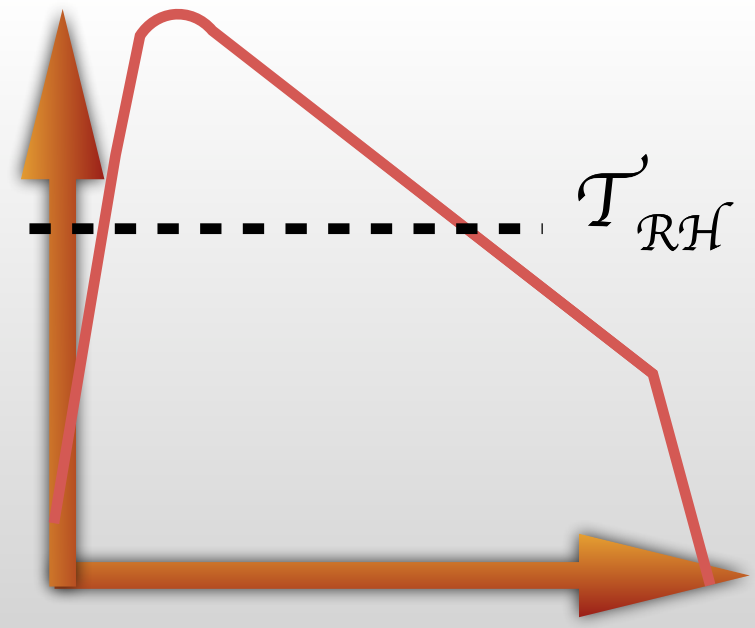
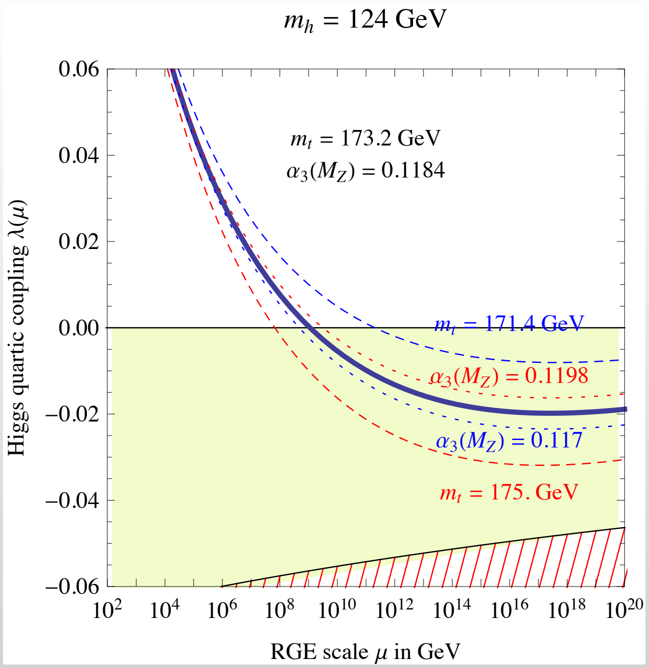
In other words, both sector are secluded or by tiny couplings (of the order of y_ν)
or by massive particles
(of the order of intermediate scale, 10^{10} GeV)



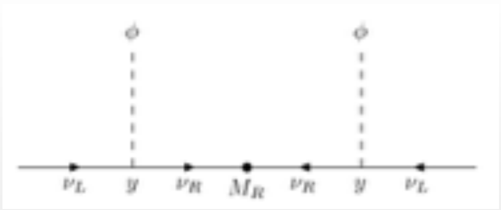
Unification :
Intermediate scale ~ 10^{10} GeV



Reheating process:
$T_{RH} \sim 10^{10}$ GeV



Higgs quartic coupling
$\mu \sim 10^{10}$ GeV



$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M^R \end{pmatrix}$$

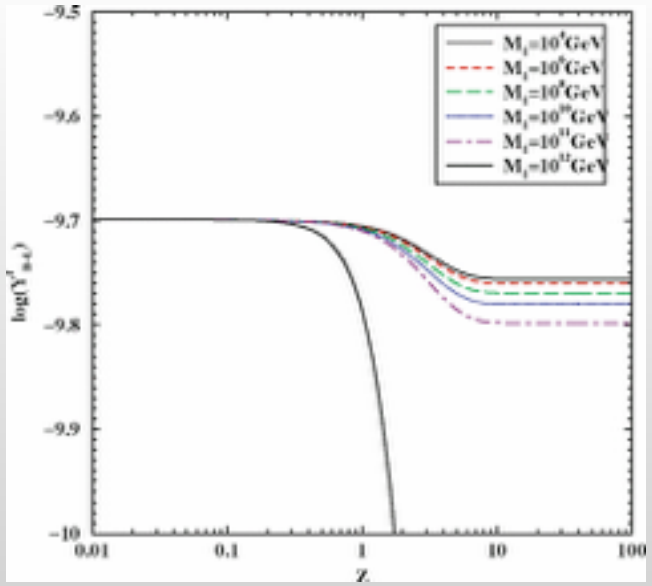
$$\mathcal{L}_\nu = -(\frac{1}{2}M^R + \frac{ih}{\sqrt{2}}A)\bar{\nu}_R^c \nu_R - \frac{y_{LR}}{\sqrt{2}}\bar{\nu}_L H \nu_R + h.c.$$

$$m_1 = \frac{1}{2}\left[M^R - \sqrt{(M^R)^2 + 4m_D^2}\right] \simeq -\frac{m_D^2}{M^R} \simeq -\frac{y_{LR}^2 v_H^2}{2M^R}$$

See-saw mechanism with ν_R:
m_ν=0.1 eV => $M^R \sim 10^{10}$ GeV

Motivations for an intermediate mass scale

« Unification is one thing, and stability [in Northeast Asia] is another thing. »
Kim Dae Jung, president of South Korea



Leptogenesis/baryogenesis
$\mu \sim 10^{10}$ GeV

Early cosmology scenario

The dark matter is « slowly » produced from the thermal bath from annihilation of SM particles. It freezes « in the process » of reaching thermal equilibrium

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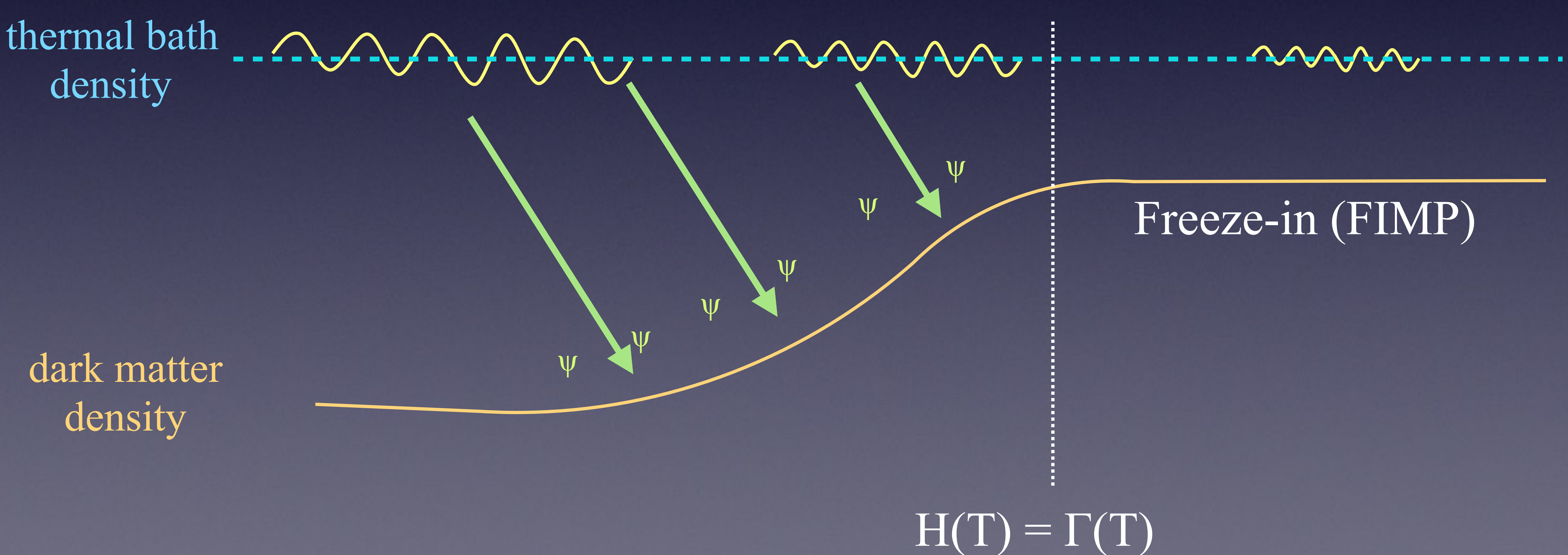

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3) Both cases

Computing a relic abundance

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$$\frac{dn}{dt} = \langle \sigma v \rangle n_\gamma^2 = R \quad \Rightarrow \quad \frac{dY}{dT} = \frac{R(T)}{H\ T\ s}$$

$$\text{with} \quad H(T) = 1.66\ g_*(T) \frac{T^2}{M_{Pl}} \quad \text{and} \quad s = \frac{2\pi^2}{45} g_*(T)\ T^3$$

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$$R(T) = \int \frac{E_1 dE_1 E_2 dE_2\ d\cos\theta_{12}}{(e^{E1/T} - 1)(e^{E_2/T} - 1)} \int \frac{|\mathcal{M}|^2_{\gamma\gamma\to\psi\psi}}{1024\pi^6} d\Omega$$

The jungle of freeze-in processes

The dependence on the temperature of the rate R(T) is completely model-dependent and generates
very different results.

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1) Classical case

Hall, Jedamzik, March-Russell, West; 0911.1120

$$|\mathcal{M}|^2 = \lambda^2 \quad \Rightarrow \quad R(T) \propto \lambda^2\ T^4 \quad \Rightarrow \quad \Omega h^2 \simeq 0.1 \left(\frac{\lambda}{10^{-11}} \right)^2$$

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Remark: the dark matter mass do not appear. The process is achieved once the temperature reaches M_{dm}. i.e., when the thermal bath is not able anymore to produce it kinematicaly.

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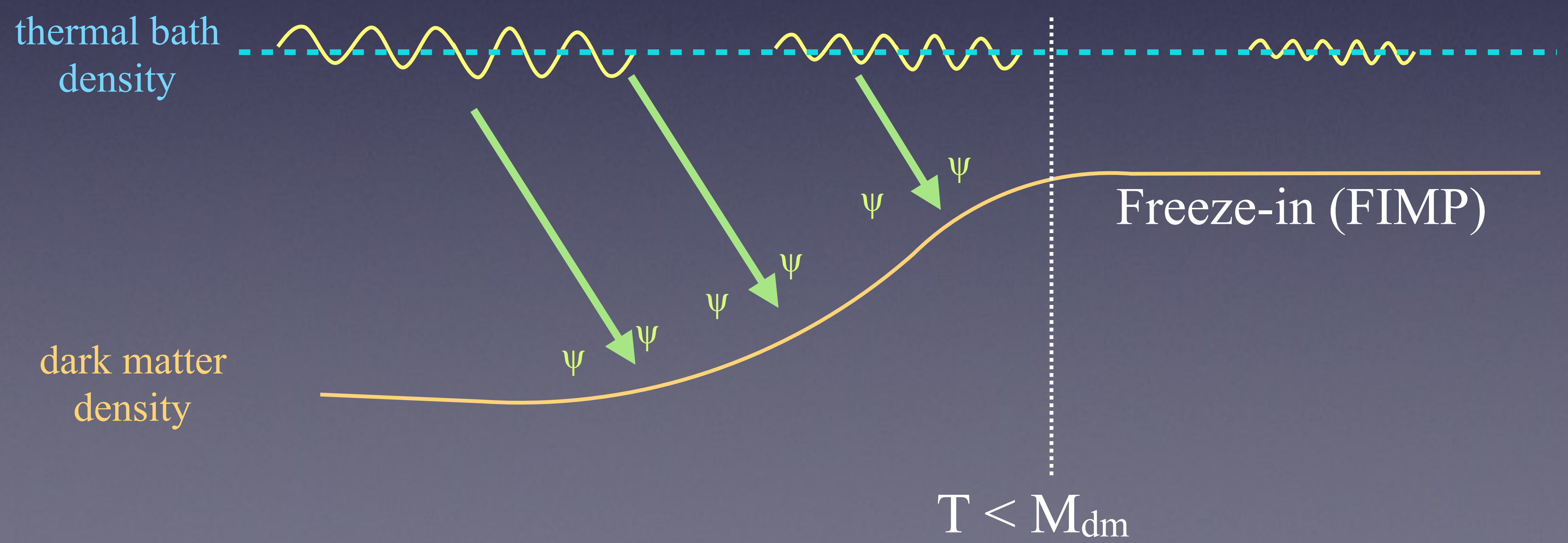
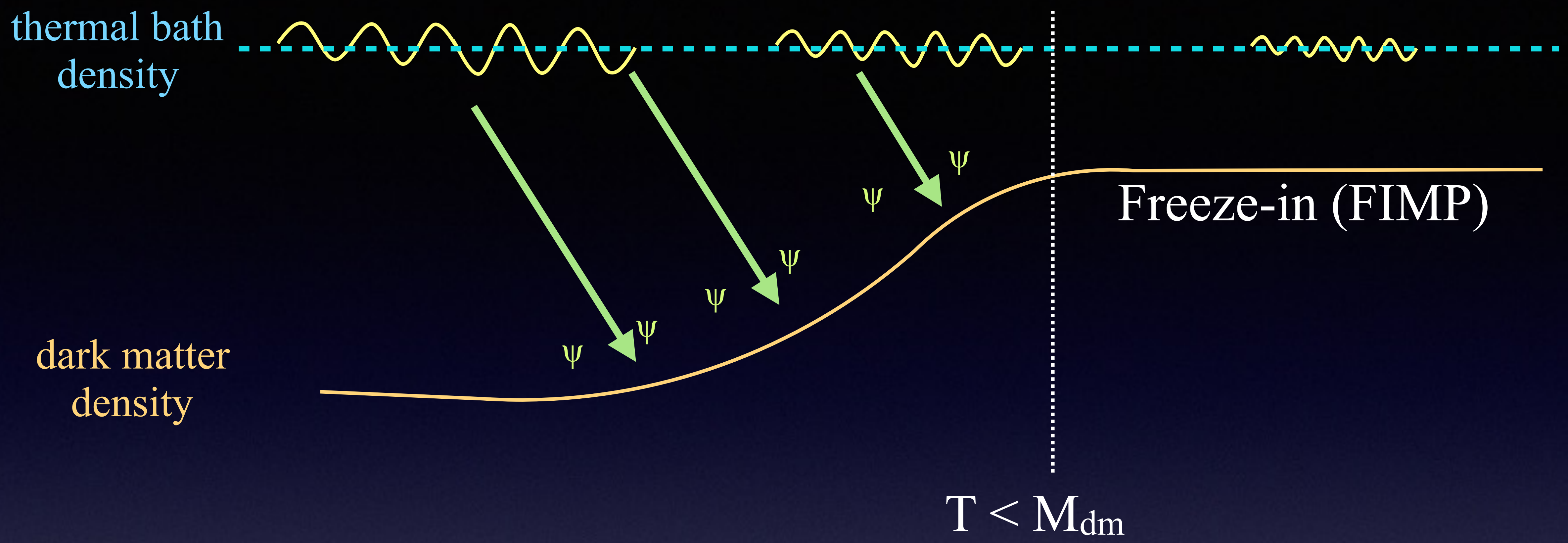
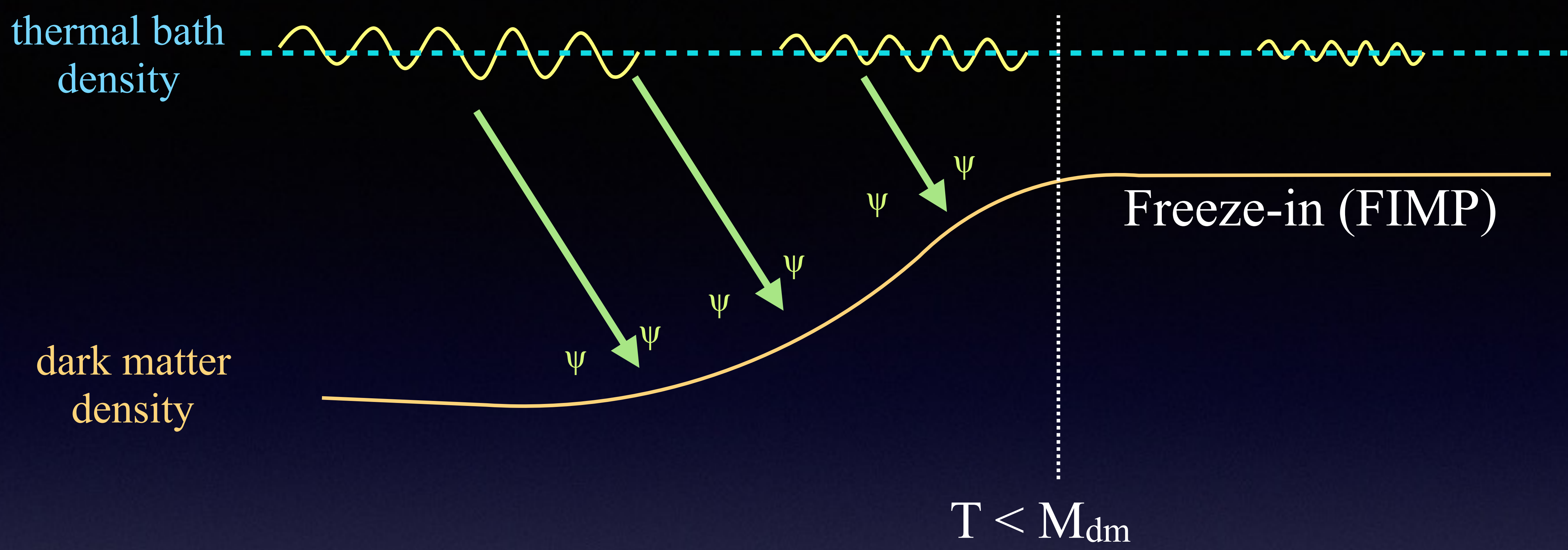
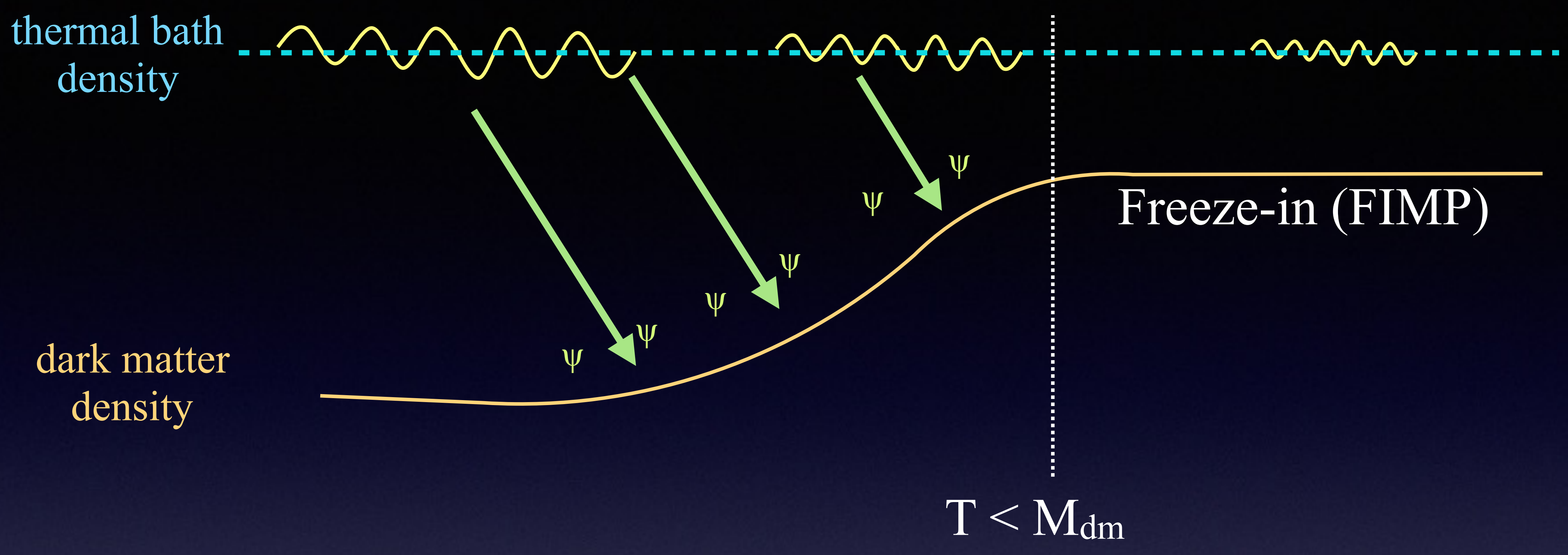



thermal bath density
ψ
ψ
ψ
ψ
ψ
ψ
Freeze-in (FIMP)
dark matter density
T < M_dm



The main production is at late time (low temperature) so Maxwell Boltzman approximation is valid $(e^{Ei/T} - 1) \sim e^{Ei/T}$



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this correspond to the exchange of a light mediator, coupling very feebly with the SM:

$$\mathcal{M} = \lambda \frac{s}{p^2 - m^2}$$

Naturalness?

$$\Omega h^2 \simeq 0.1 \left(\frac{\lambda}{10^{-11}} \right)^2$$

How natural is a ~10^{-11} coupling?
Can we find a setup where FIMP is natural?
and discuss about a « FIMP miracle » paradigm

$$\frac{dY}{dT} = \frac{R(T)}{H\ T\ s}$$

2) Heavy mediator case

Y. M., K.A. Olive, J. Quevillon and B. Zaldivar; **Phys.Rev.Lett. 110 (2013)** [arXiv:1302.4438]

Y. M., N. Nagata, K.A. Olive, J. Quevillon and J. Zheng; **Phys.Rev. D91 (2015)** [arXiv:1502.06929]

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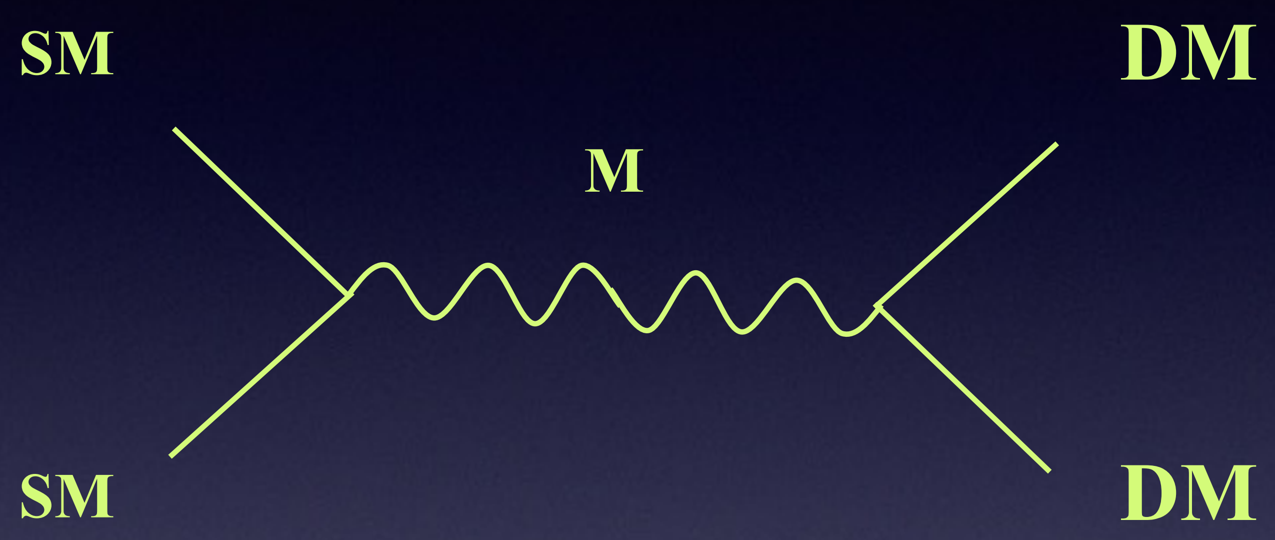

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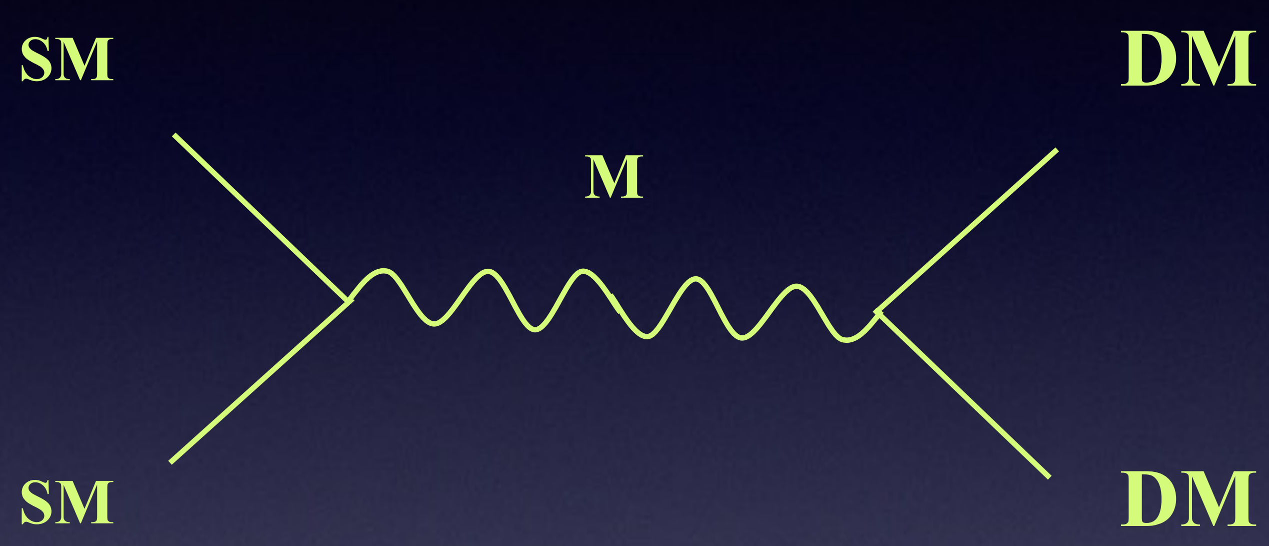

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$$\Rightarrow \quad \Omega h^2 = 0.1\ \lambda^2 \left(\frac{M_{dm}}{1\ \text{TeV}}\right) \left(\frac{T_{RH}}{10^{10}\ \text{GeV}}\right)^3 \left(\frac{10^{10}}{M_M}\right)^4$$

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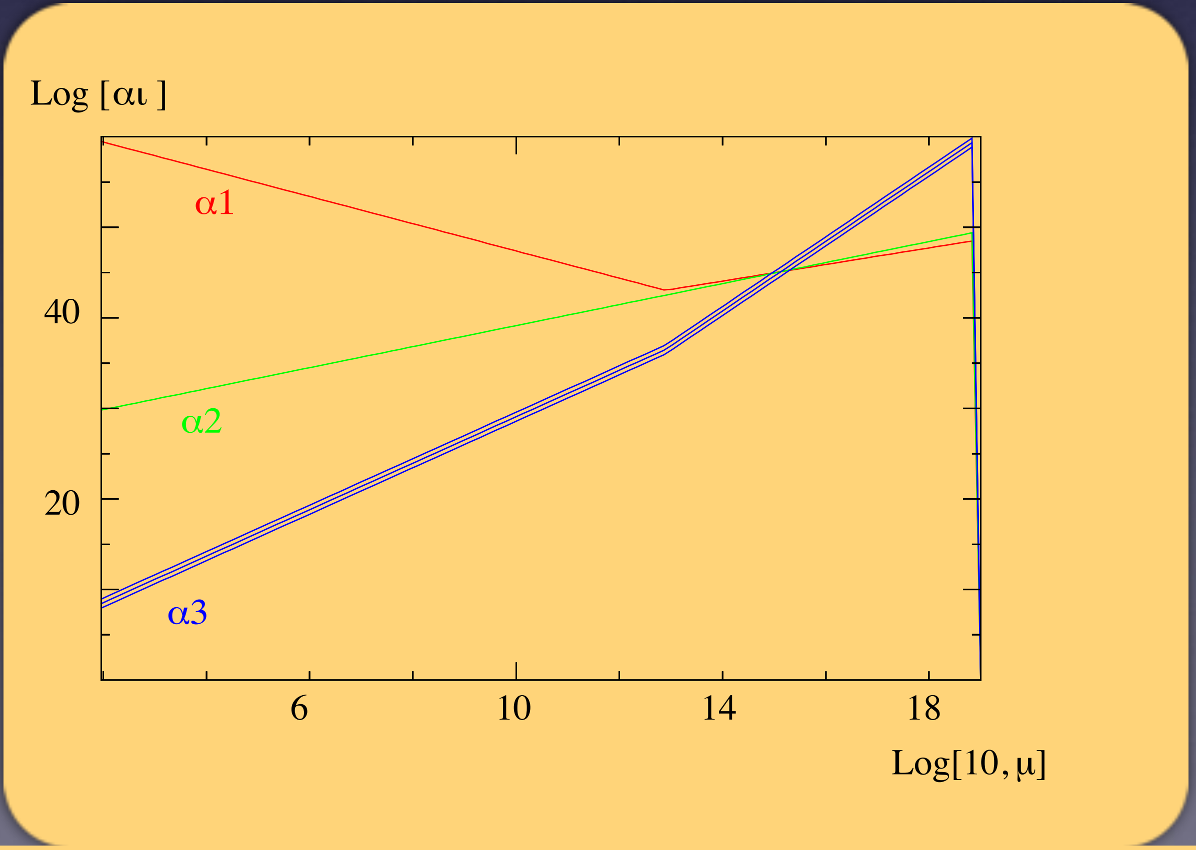
We transformed a « non natural » tiny 10^{-11} coupling into a natural intermediate mass 10^{10} GeV, appearing in any SO(10), E6.. unification scheme .



Y. M., N. Nagata, K.A. Olive, J. Quevillon and J. Zheng; arXiv:1502.06929

$$\Rightarrow \quad \Omega h^2 = 0.1 \, \lambda^2 \left(\frac{M_{dm}}{1 \text{ TeV}}\right) \left(\frac{T_{RH}}{10^{10} \text{ GeV}}\right)^3 \left(\frac{10^{10}}{M_M}\right)^4$$

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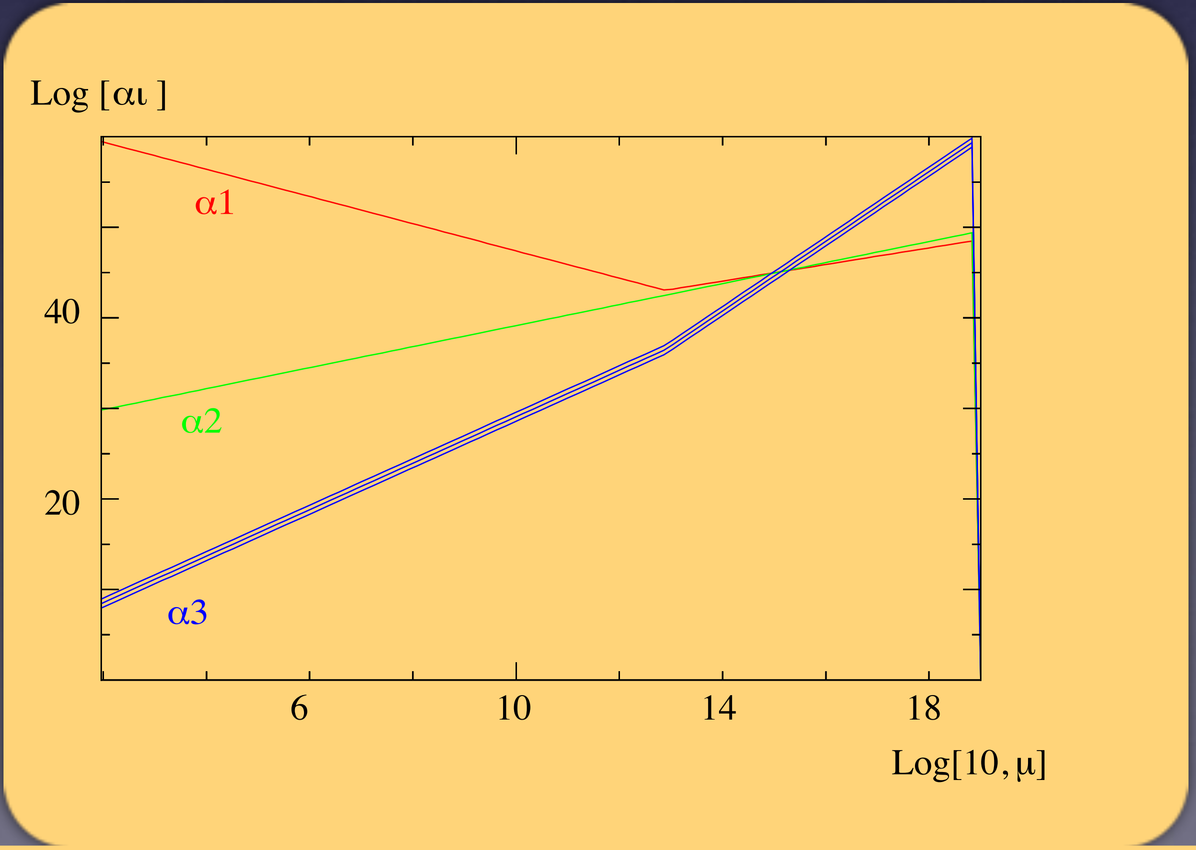

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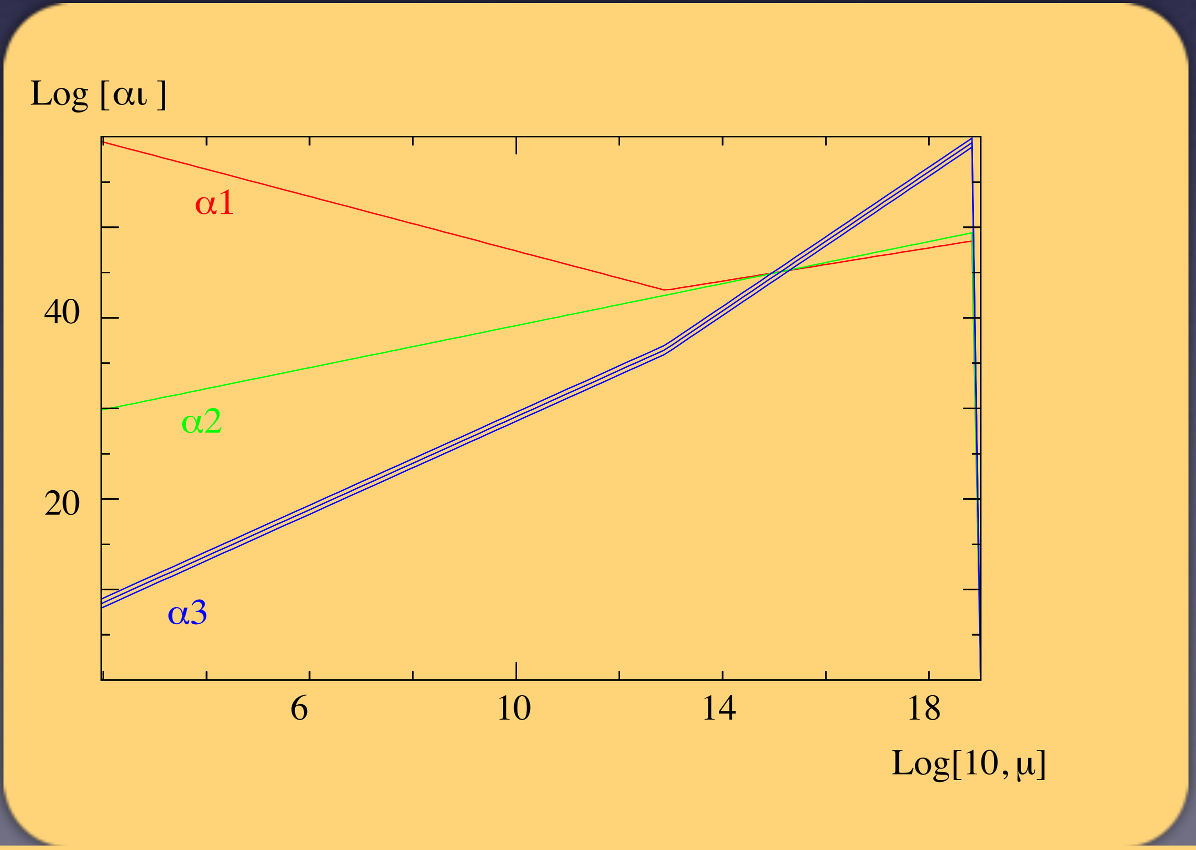


Can we talk about a « FIMP miracle »?

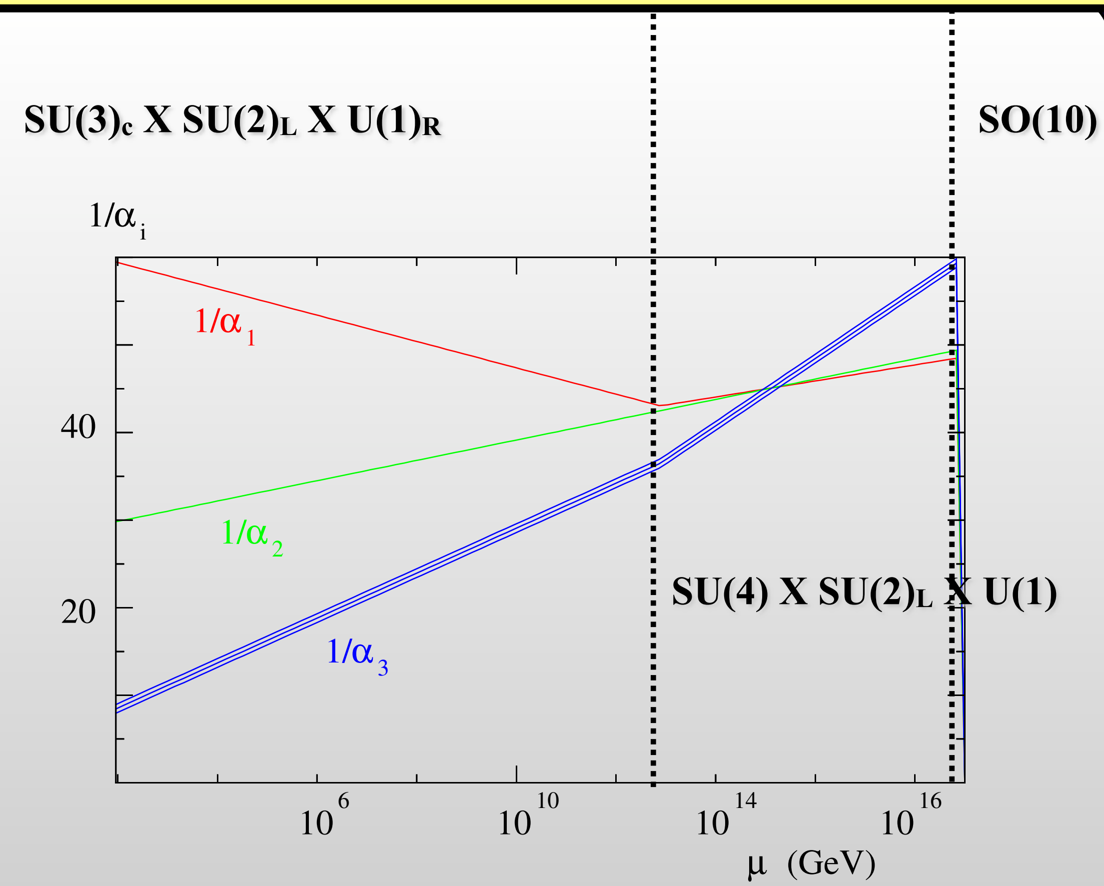
Y. M., N. Nagata, K.A. Olive, J. Quevillon and J. Zheng; arXiv:1502.06929

Example : SO(10) and ν_R

The SO(10) spinor in the 16 representation naturally embed a ***right handed neutrino*** ν_R. The breaking of SO(10) into an *intermediate group*, at an intermediate (~10^{10} GeV) scale provides then the best framework for a natural see-saw mechanism (natural means $y_\nu \sim 1$)

$$\Rightarrow \quad \Omega h^2 = 0.1\,\lambda^2 \left(\frac{M_{dm}}{1\ \text{TeV}}\right)\left(\frac{T_{RH}}{10^{10}\ \text{GeV}}\right)^3\left(\frac{10^{10}}{M_M}\right)^4$$

As a free bonus, one also obtain unification at GUT scale!



Asking for unification imposes the intermediate scale (~10^{10} GeV) and leads to natural see-saw

$$SO(10) \longrightarrow G_{\text{int}} \longrightarrow G_{\text{SM}} \otimes \mathbb{Z}_N$$

$$\mathcal{L}_Y = \frac{g}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{10} + \frac{h}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{126}$$

$$M^R = h\langle\mathbf{126}\rangle$$

TABLE I. Possible breaking schemes of SO(10).

	$SO(10) \to \mathcal{G} \times$ [Higgs]	M_{int}(GeV)	T_{RH}(GeV)
A	$4 \times 2_L \times 1_R$ [**16**]	$10^{12.9}$	3×10^9
A	$4 \times 2_L \times 1_R$ [**126**]	$10^{11.8}$	1×10^8
B	$4 \times 2_L \times 2_R$ [**16**]	$10^{14.4}$	3×10^{11}
B	$4 \times 2_L \times 2_R$ [**126**]	$10^{13.8}$	5×10^{10}
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**16**]	$10^{10.6}$	3×10^6
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**126**]	$10^{8.6}$	6×10^3

Y. M., K.A. Olive, J. Quevillon and B. Zaldivar; **Phys.Rev.Lett. 110 (2013)** [arXiv:1302.4438]

$$\frac{dY}{dT} = \frac{R(T)}{H\ T\ s}$$

3) Heavy mediator case+ tiny coupling case

K. Benakli, Y. Chen, E. Dudas and Y. M.; Phys.Rev. D95 (2017) [arXiv:1701.06574]

E. Dudas, Y. M. and K. Olive; Phys.Rev.Lett. 119 (2017) [arXiv:1704.03008]

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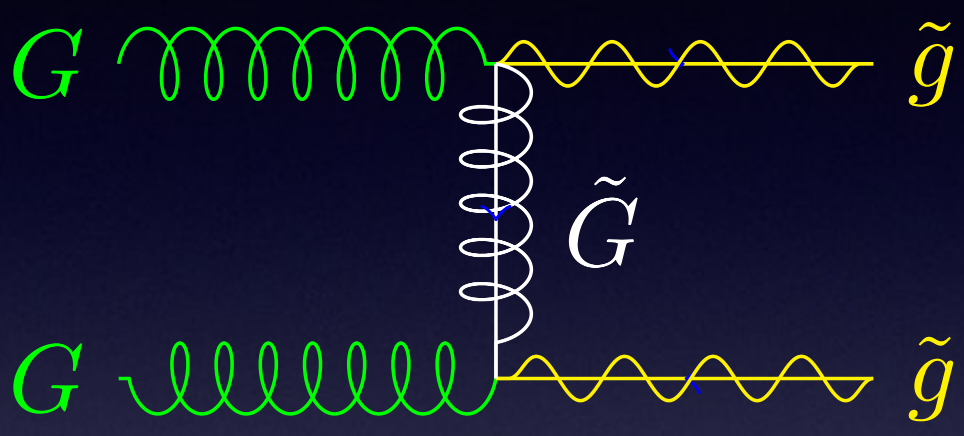
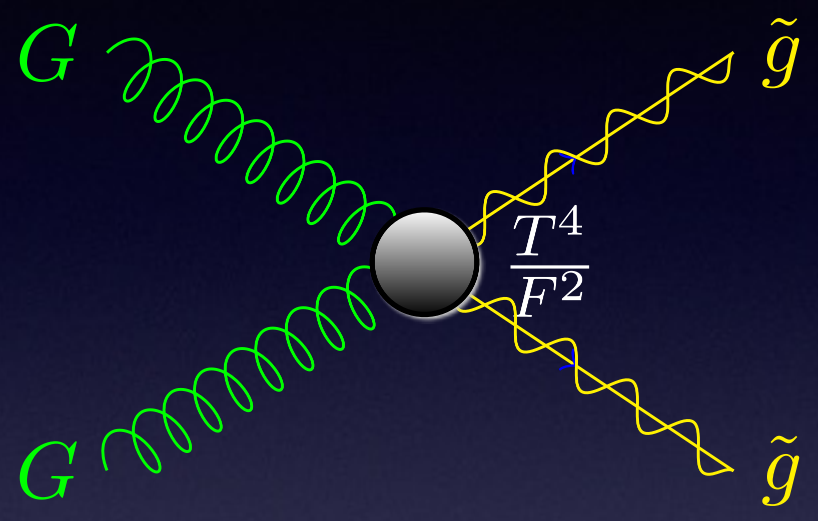


$M_{\tilde{G}} >> E$



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$$\mathcal{M} = \frac{1}{M_{Pl}^2} \frac{T^4}{M_{SUSY}^2} \quad \Rightarrow \quad R(T) \sim \frac{T^{12}}{M_{Pl}^4 M_{SUSY}^4}$$

$$\Rightarrow \quad \Omega h^2 = 0.1 \left(\frac{T_{RH}}{10^{10}\ \text{GeV}} \right)^7 \left(\frac{0.1\ \text{Eev}}{M_{dm}} \right)^3$$

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Strong dependance on reheating

$$\Omega h^2 = 0.1 \left(\frac{T_{RH}}{10^{10}\ \mathrm{GeV}}\right)^7 \left(\frac{0.1\ \mathrm{Eev}}{M_{dm}}\right)^3$$

Naturally large reheating temperature

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The large power-dependance on temperature suggests that all the dark matter is produced at the beginning of the reheating, not at late time as in classical FIMP case. This is a « fast » freeze-in process.

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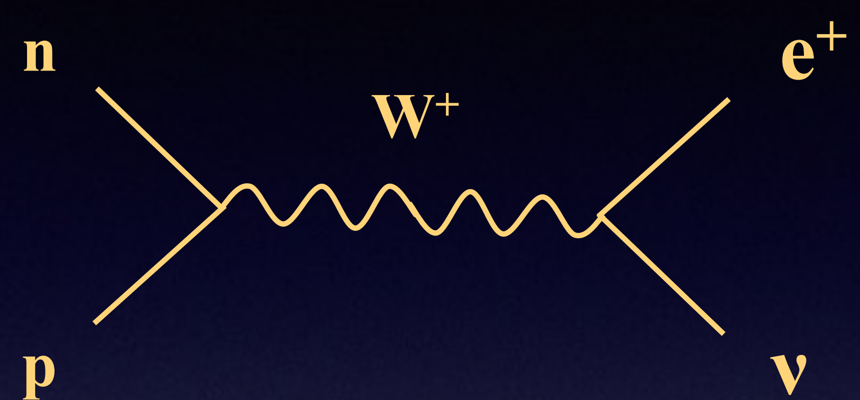
Moreover, the fact that the process is dominant at high temperature, one cannot neglect the statistical factor (eEi/T -1)

Example : gravitino DM and High Scale SUSY



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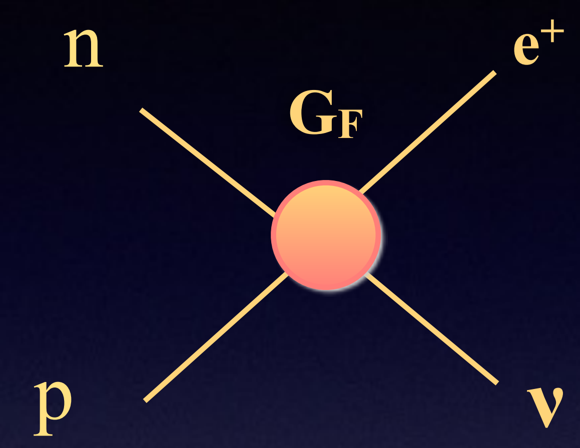

$G_F = 10^{-5}\ GeV^{-2}$

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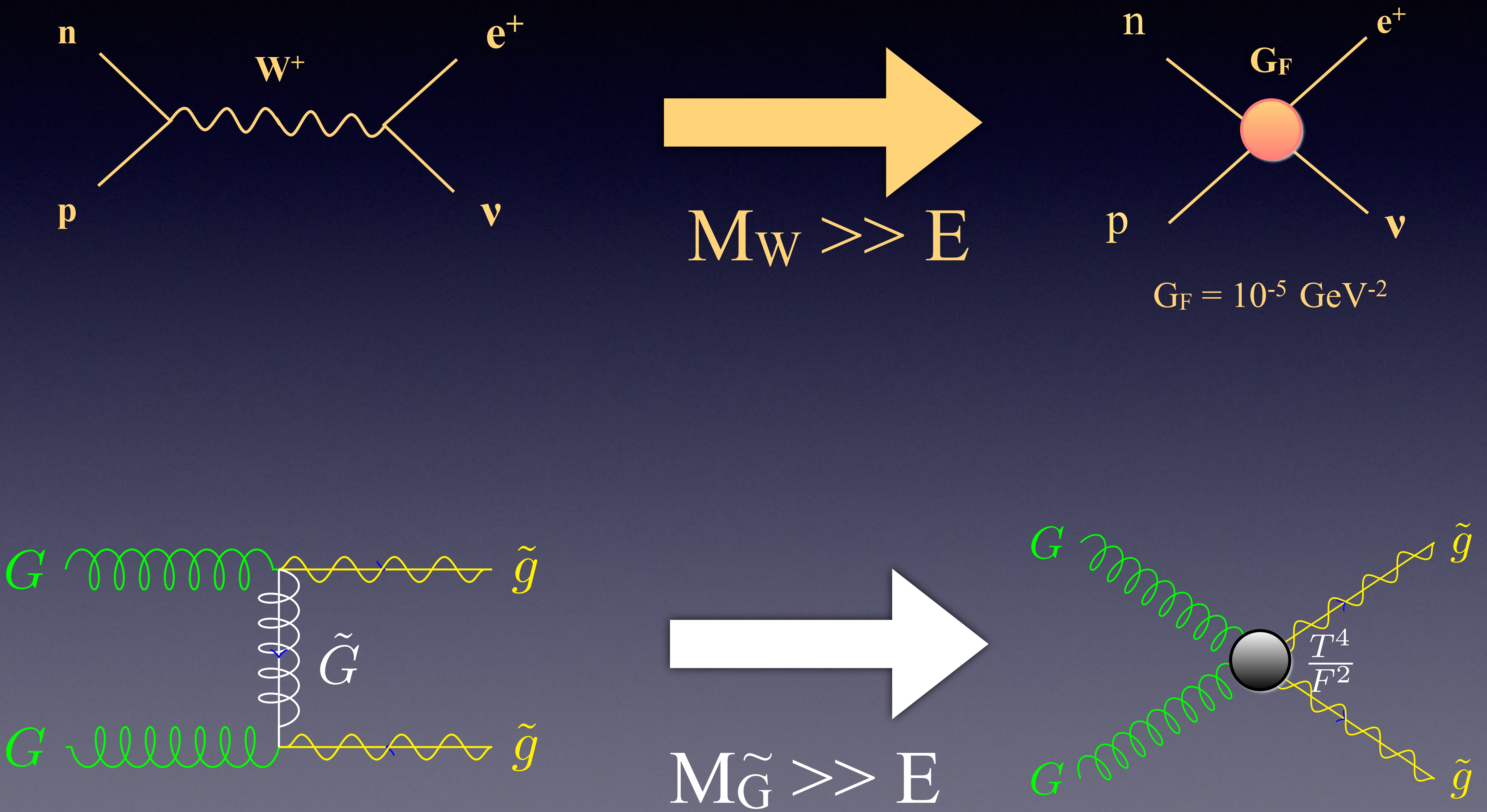

Generating the interactions

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

* see the incredibly modern article « Is the Neutrino a Goldstone particle » by D.V. Volkov and V.P. Akulov,Phys. Lett. **B 46** (1973) 109

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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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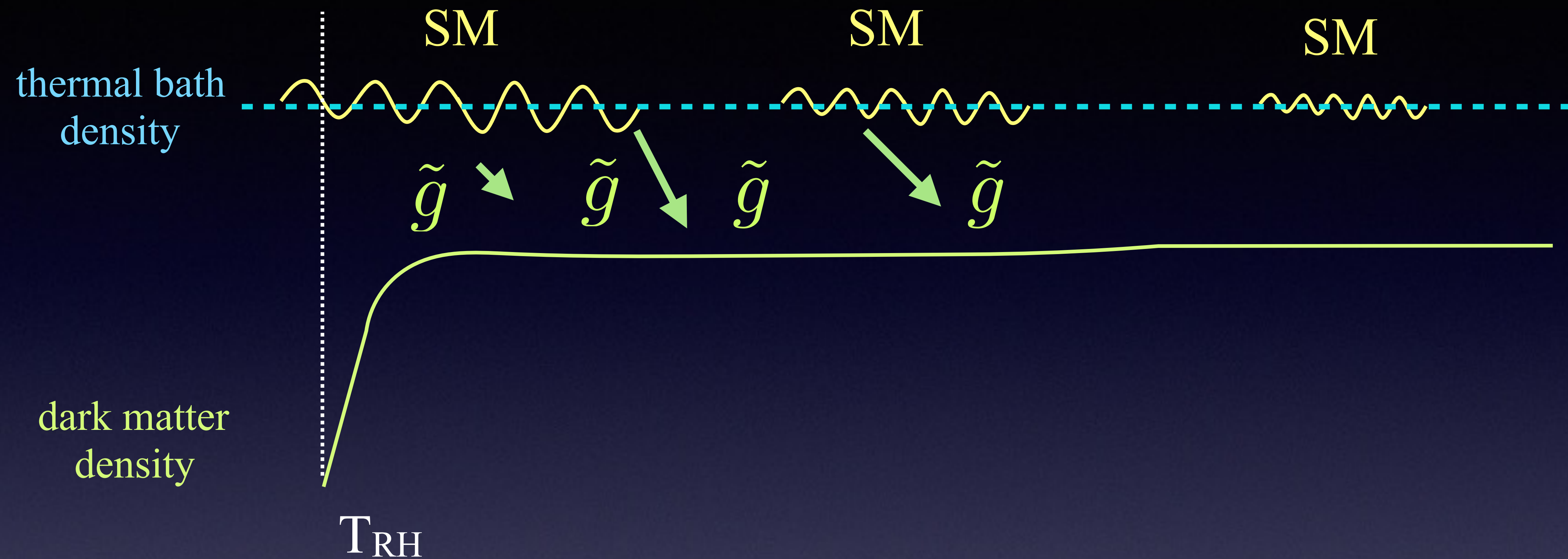
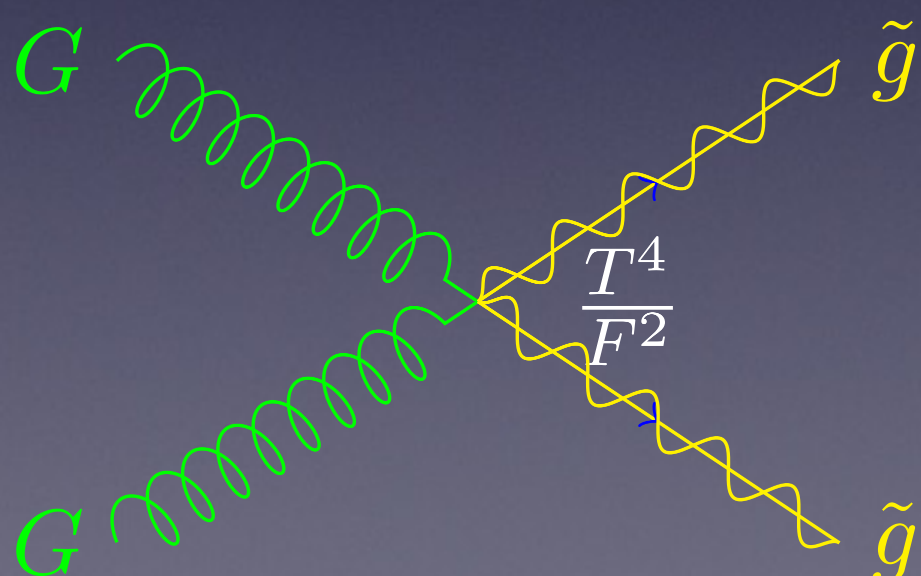
The production mechanism

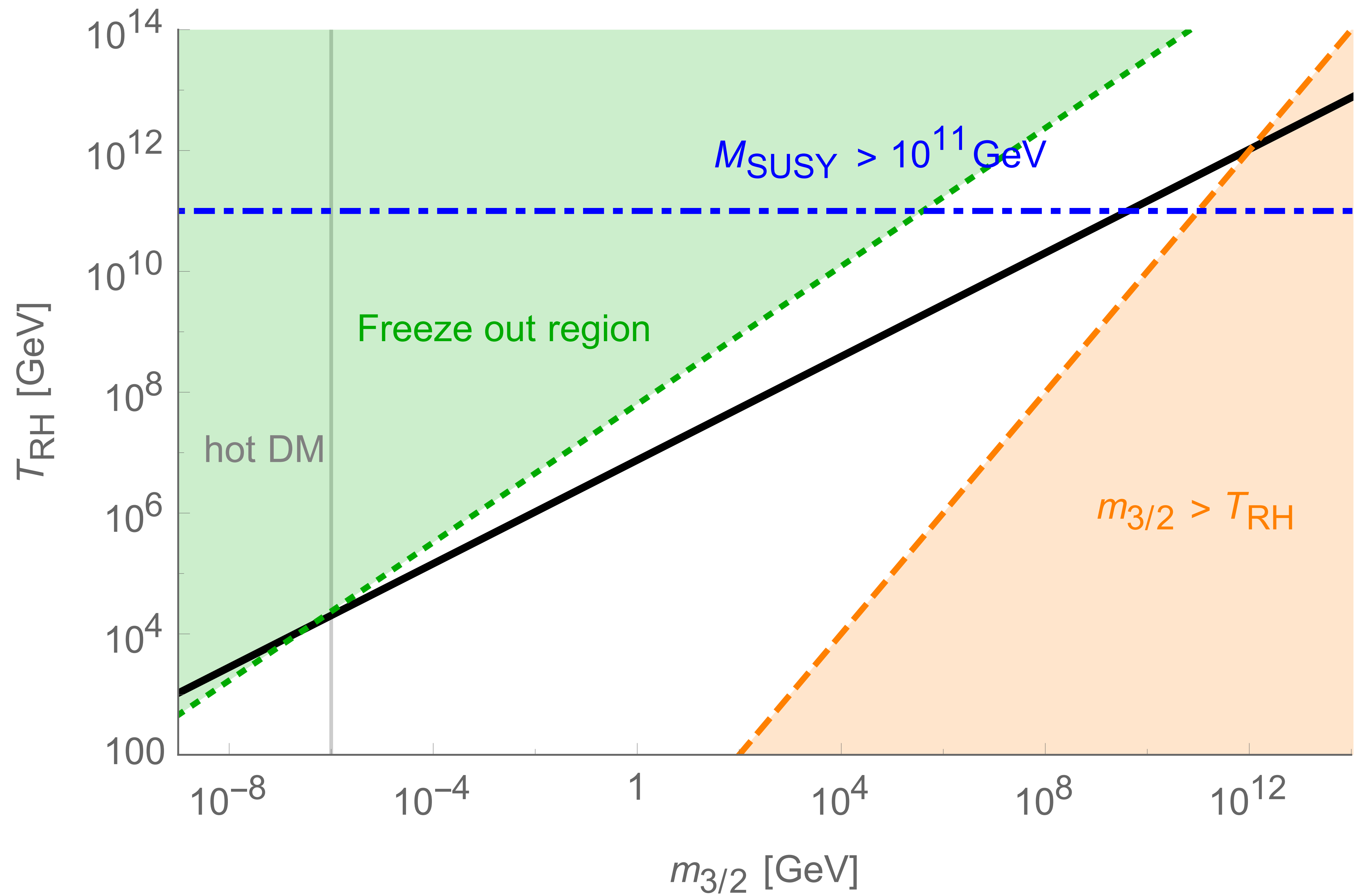




$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1 \text{ EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{RH}}{2.0 \times 10^{10} \text{ GeV}}\right)^7$$

K. Benakli, Y. Chen, E. Dudas and Y. M.; Phys.Rev. D95 (2017) [arXiv:1701.06574]

The Freeze-In mechanism (FI)



K. Benakli, Y. Chen, E. Dudas and Y. M.; Phys.Rev. D95 (2017) [arXiv:1701.06574]

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

Including inflaton decay

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

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{m_\phi}{3\times 10^{13}\mathrm{GeV}}\right)^{7/2} \left(\frac{y_\phi}{2.9\times 10^{-5}}\right)^7$$

E. Dudas, Y. M. and K. Olive; Phys.Rev.Lett. 119 (2017) [arXiv:1704.03008]

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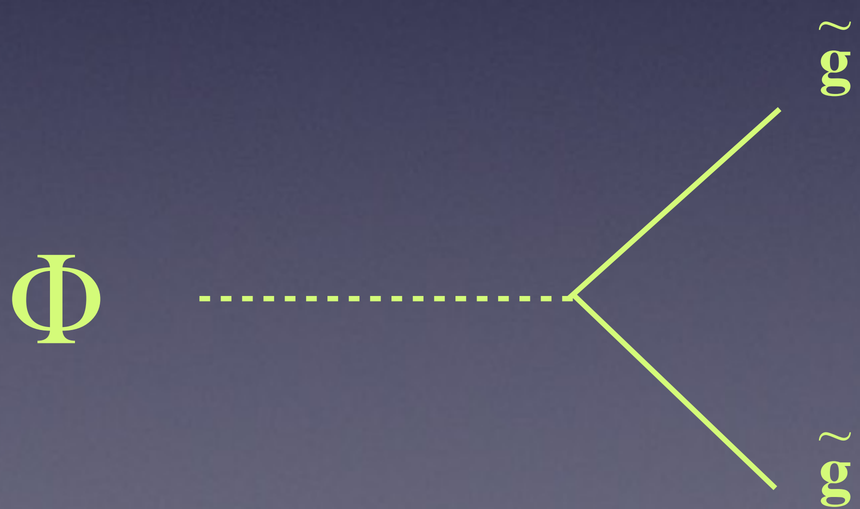
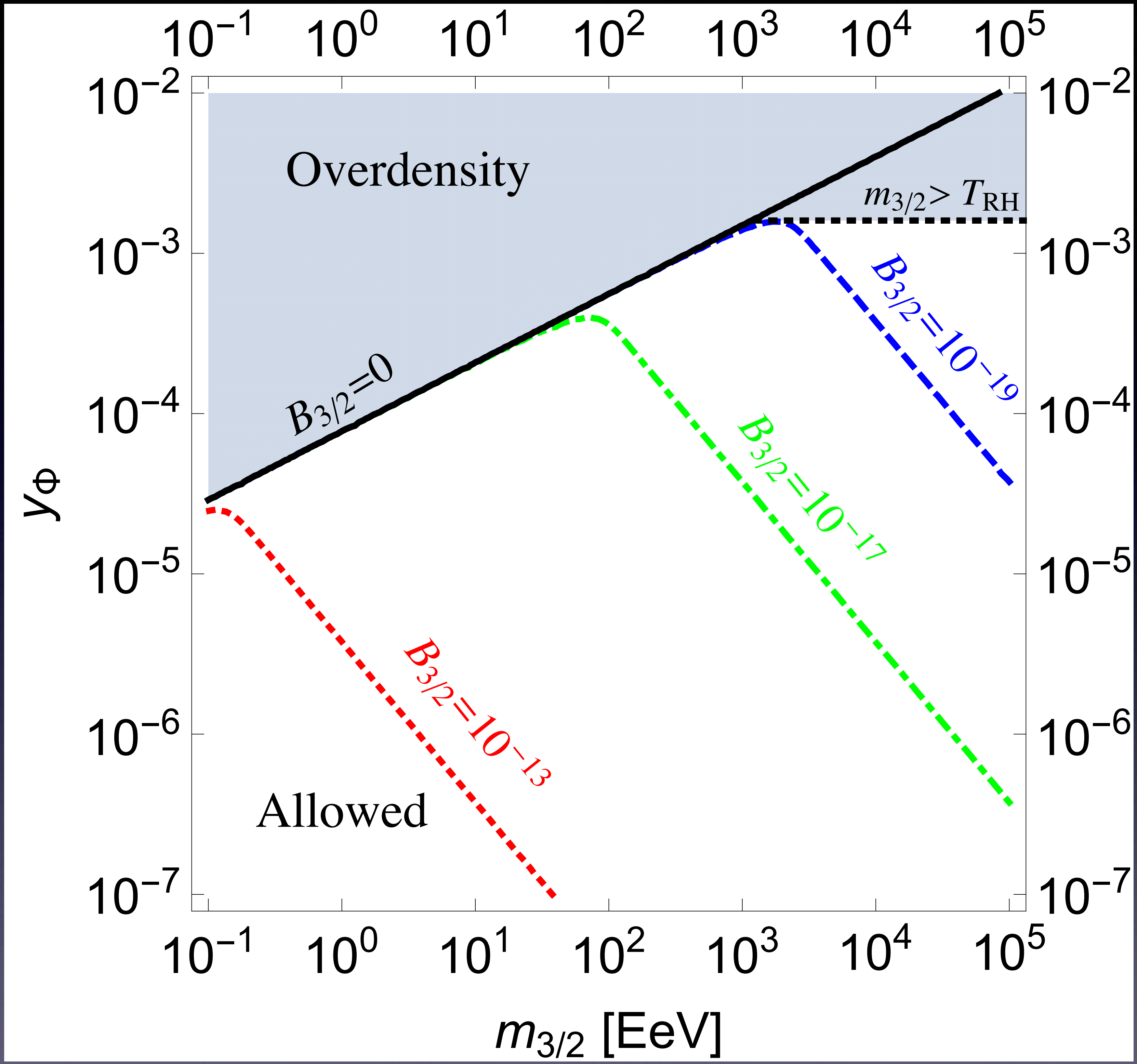


$$\Omega^{decay}_{3/2}h^2 = 0.11\left(\frac{B_{3/2}}{1.3\times 10^{-13}}\right)\left(\frac{y_\phi}{2.9\times 10^{-5}}\right) \times \left(\frac{m_{3/2}}{0.1\ \text{EeV}}\right)\left(\frac{3\times 10^{13}\ \text{GeV}}{m_\phi}\right)^{1/2}$$

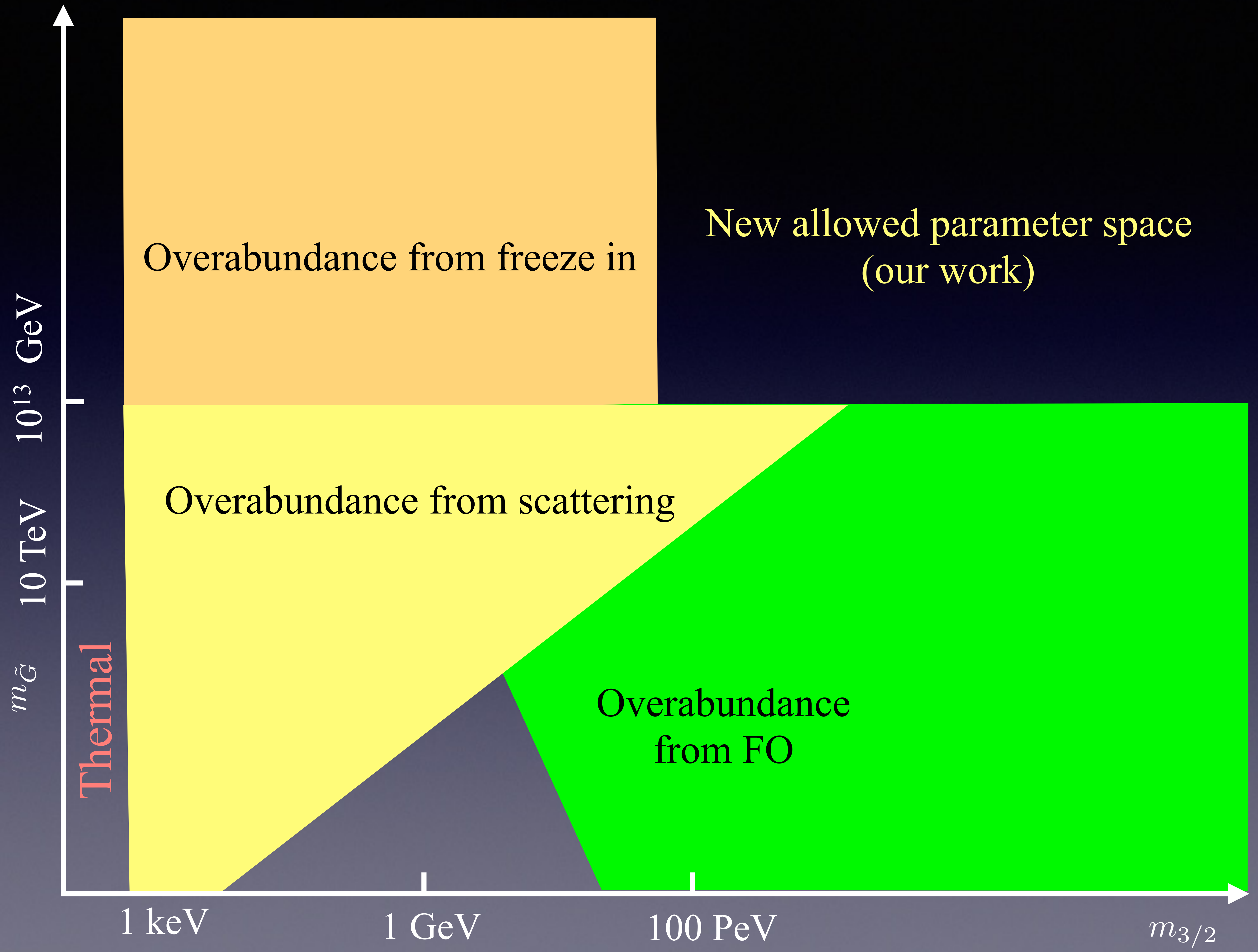
$$B_{3/2} = \Gamma_{3/2}/\Gamma_\phi$$

E. Dudas, Y. M. and K. Olive; Phys.Rev.Lett. 119 (2017) [arXiv:1704.03008]



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

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


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

Message to the string « inspired » theorist, or super$_{\text{gravity}}$men :

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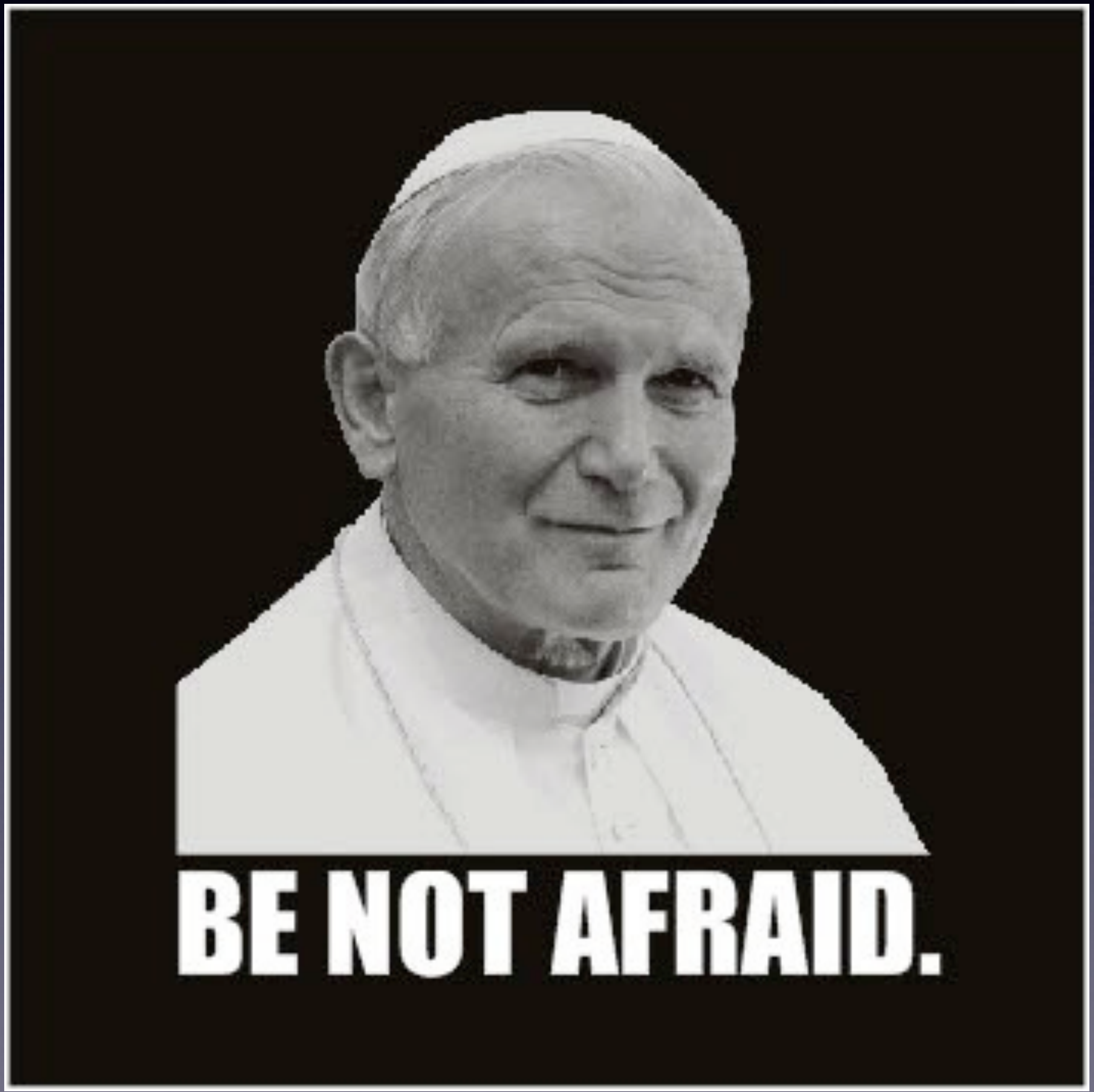

Message to the string « inspired » theorist, or super$_{\text{gravity}}$men :

Indeed, no need to add an *anti-D3 branes at the tip of a Klebanov-Strassler throat à la KKLT (sic!)* to justify a TeV SUSY mass scale.

A SUSY mass scale at the energy of the SUSY breaking scale (of the order of intermediate/string scale) is natural (cf. the Higgs mechanism) AND provide you a reliable gravitino dark matter.

BE NOT AFRAID.

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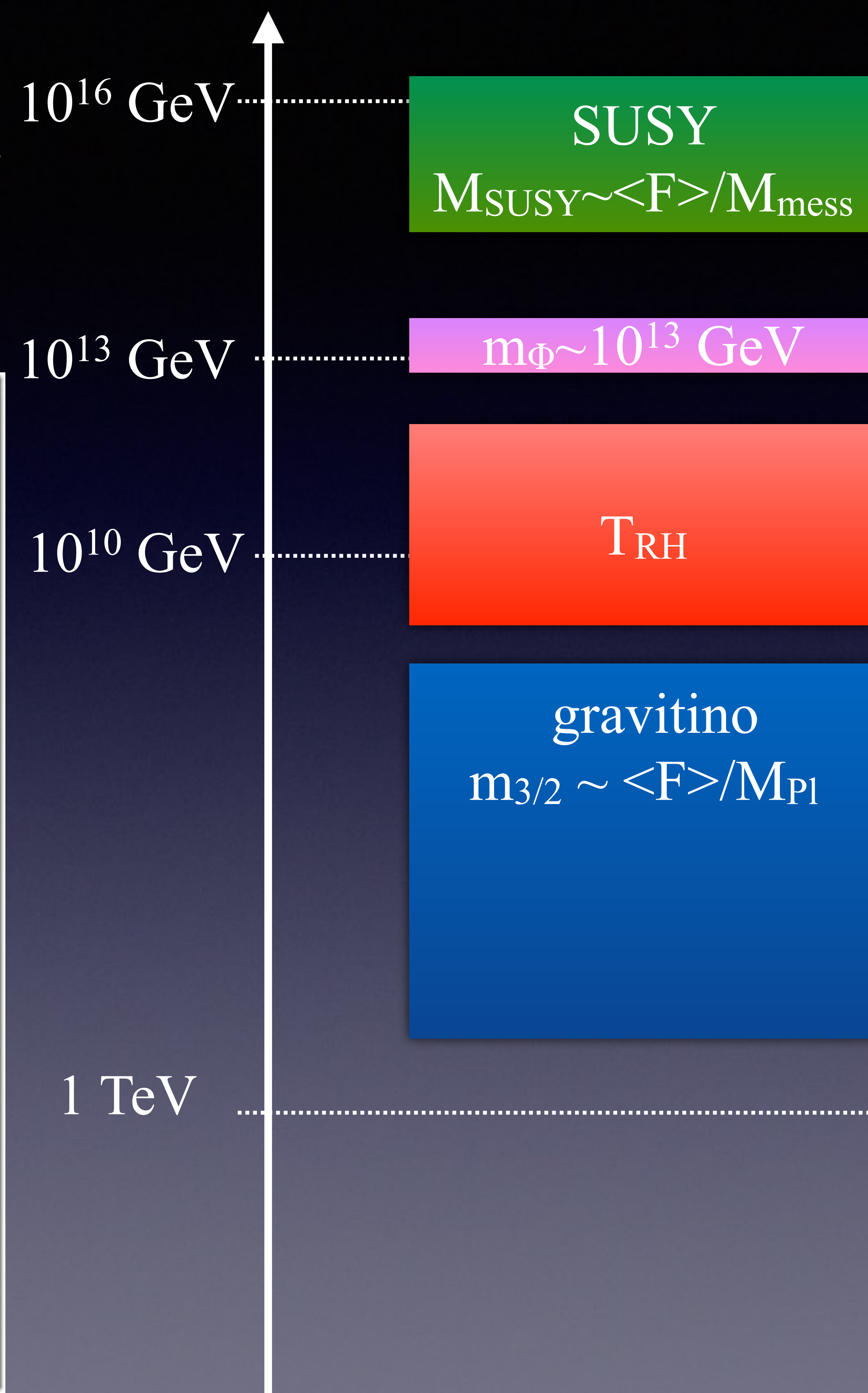
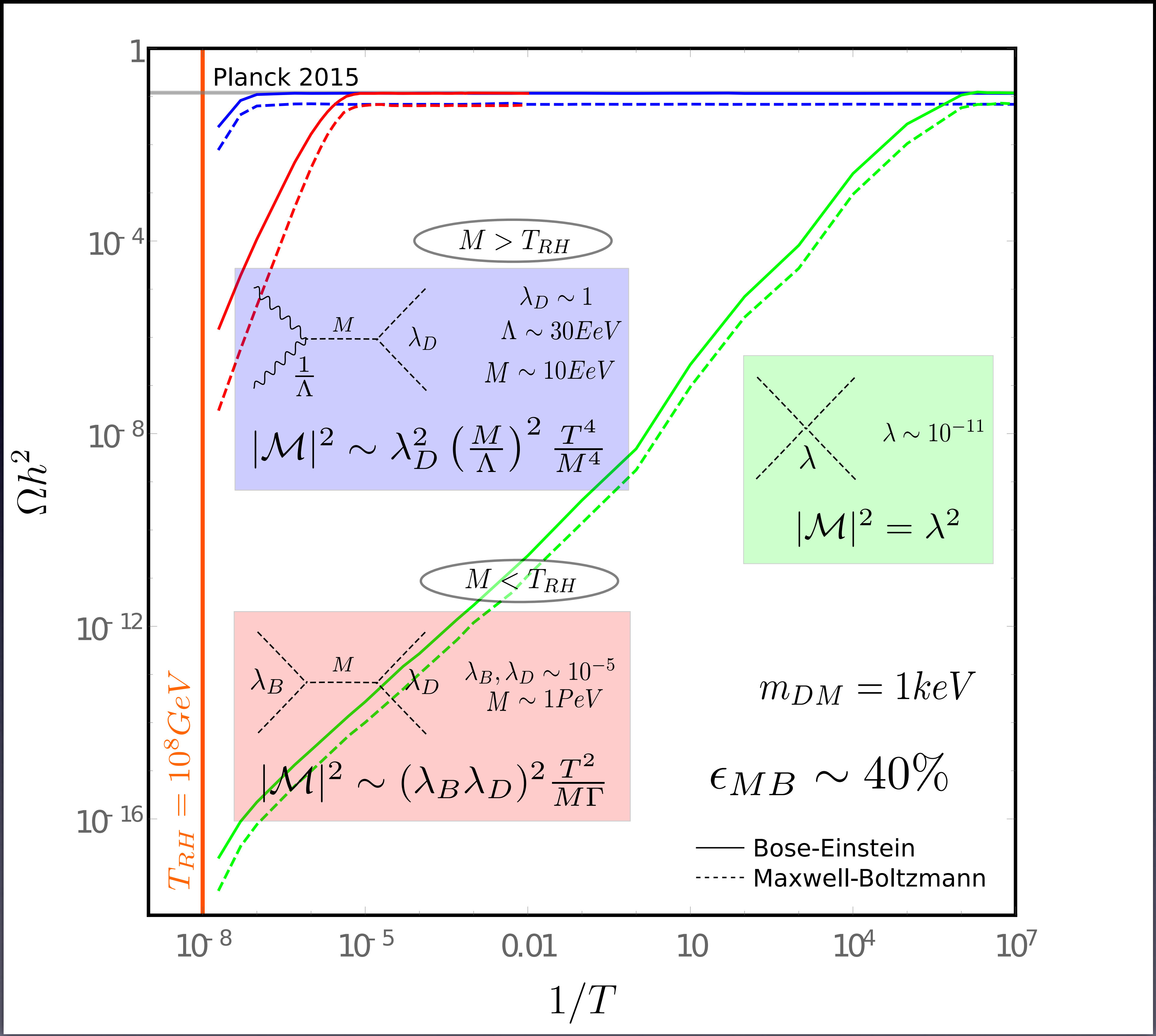


Summary


Planck 2015
$M > T_{RH}$
$\lambda_D \sim 1$
$\Lambda \sim 30 EeV$
$M \sim 10 EeV$
M
λ_D
$\frac{1}{\Lambda}$
$|\mathcal{M}|^2 \sim \lambda_D^2 \left(\frac{M}{\Lambda}\right)^2 \frac{T^4}{M^4}$
$\lambda \sim 10^{-11}$
λ
$|\mathcal{M}|^2 = \lambda^2$
$M < T_{RH}$
λ_B
M
λ_D
$\lambda_B, \lambda_D \sim 10^{-5}$
$M \sim 1 PeV$
$|\mathcal{M}|^2 \sim (\lambda_B \lambda_D)^2 \frac{T^2}{M\Gamma}$
$m_{DM} = 1 keV$
$\epsilon_{MB} \sim 40\%$
Bose-Einstein
Maxwell-Boltzmann
$T_{RH} = 10^8 GeV$
Ωh^2
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-8}
10^{-5}
0.01
10
10^4
10^7
$1/T$

However, the story does not stop there..

Indeed, when the production rates develops a strong dependance on the temperature (as it is the case for the gravitino), one should check what was produced before the reheating, while the Universe was still dominated by the matter (inflaton), but temperature was higher than T_{RH}

M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]

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In other words, one should compare the total DM production releasing the hypothesis of instantaneous reheating

M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]

Indeed, the maximum temperature is not T_{RH}

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$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0$$

Boltzmann equation for the decaying Inflaton

$$\dot{\rho}_\gamma + 4H\rho_\gamma - \Gamma_\phi \rho_\phi = 0$$

Boltzmann equation for the Radiation

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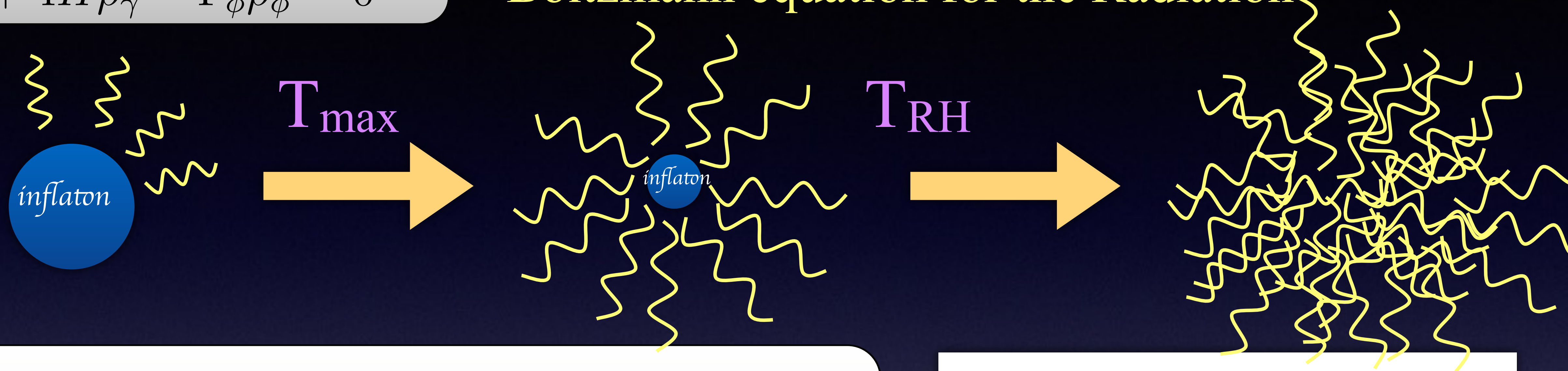

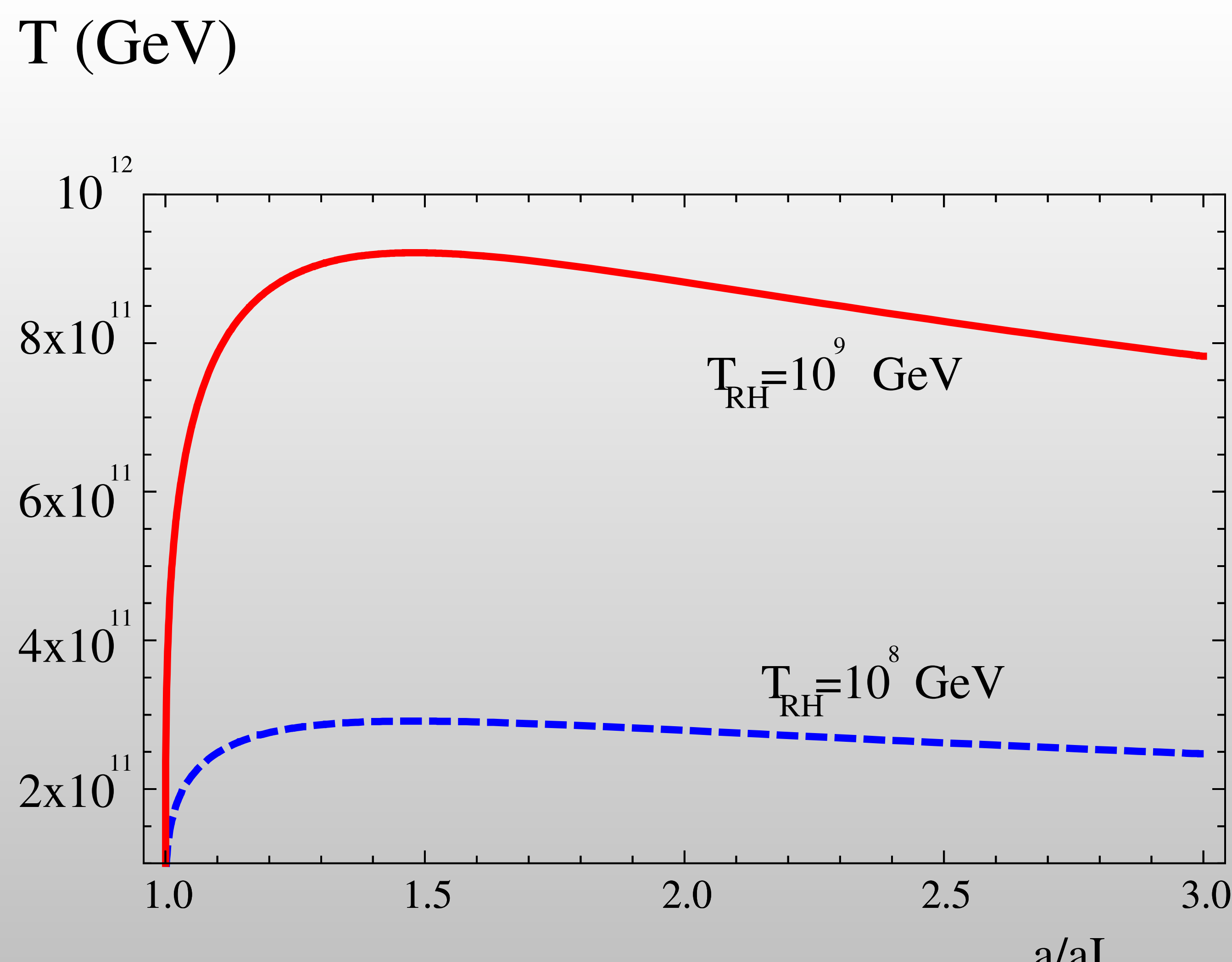

$$T_{\max} \simeq 0.5 \left(\frac{m_\phi}{\Gamma_\phi}\right)^{1/4} T_{RH}$$

With T_{RH} defined by

$\rho_\Phi (T_{RH}) = \rho_\gamma (T_{RH})$

$$T_{RH} = \left(\frac{40}{g_{RH}\pi^2}\right)^{1/4} \left(\frac{\Gamma_\phi M_P}{c}\right)^{1/2}$$

Adding the production of dark « matter » renders the system is a little bit more complex.

$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0$$

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$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0$$

$$\dot{\rho}_\gamma + 4H\rho_\gamma - \Gamma_\phi \rho_\phi = 0$$

$$\dot{n}_\chi + 3Hn_\chi + \langle\sigma|v|\rangle \left[n_\chi^2 - (n_\chi^{\rm eq})^2\right] = 0$$

$$\rho_\phi + \rho_\gamma = 3\, M_P^2\, H^2$$

$$\dot{Y}_\chi + 3\left(H + \frac{\dot{T}}{T}\right) Y_\chi = g_\chi^2 \langle\sigma|v|\rangle n_{\rm rad}$$

with $Y_\chi\,(T) \equiv \frac{n_\chi(T)}{n_{\rm rad}(T)}$

If one defines R_χ^n as $Y/Y_{inst.}$ one obtains

$$R_\chi^{(n)}(T) \equiv \frac{Y_\chi^{(n)}(T)}{Y_{\chi,\mathrm{instant.}}} \simeq f(n) \begin{cases} \frac{8}{5}\left(\frac{n+1}{6-n}\right), & n<6 \\ \frac{56}{5}\ln\left(\frac{T_{\max}}{T_{RH}}\right), & n=6 \\ \frac{8}{5}\left(\frac{n+1}{n-6}\right)\left(\frac{T_{\max}}{T_{RH}}\right)^{n-6}, & n>6 \end{cases},$$

---

with $\langle\sigma|v|\rangle = \frac{\lambda T^n}{\pi M^{n+2}}$

R_χ^n does not depends on λ or M (!!)

Exemple, for n=6

$$\langle\sigma|v|\rangle = \frac{\lambda T^n}{\pi M^{n+2}}$$

$$R_\chi \simeq \frac{56}{5}\ln\left(\frac{T_{\max}}{T_{RH}}\right), \qquad R_\chi \sim 25.7$$

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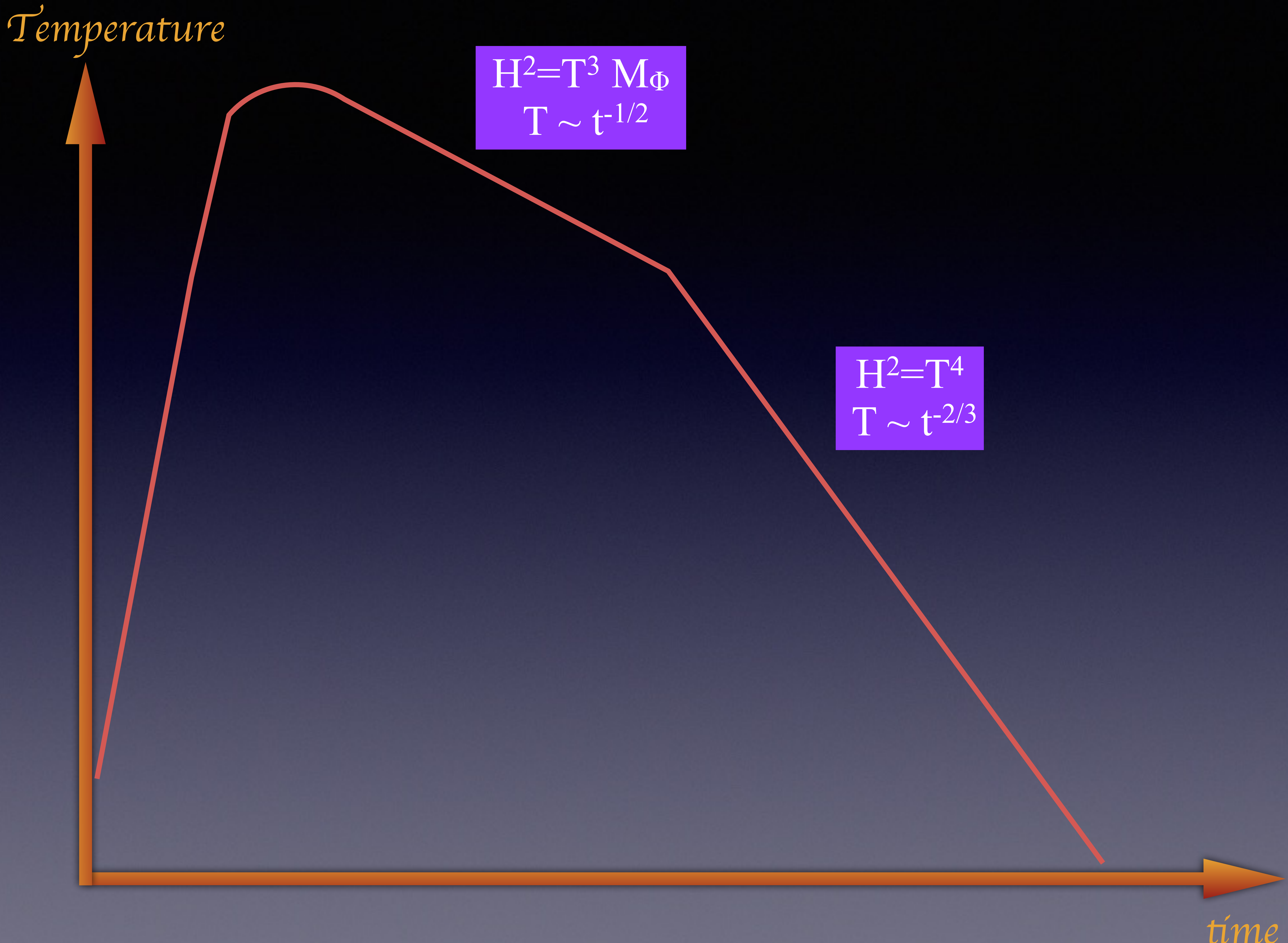
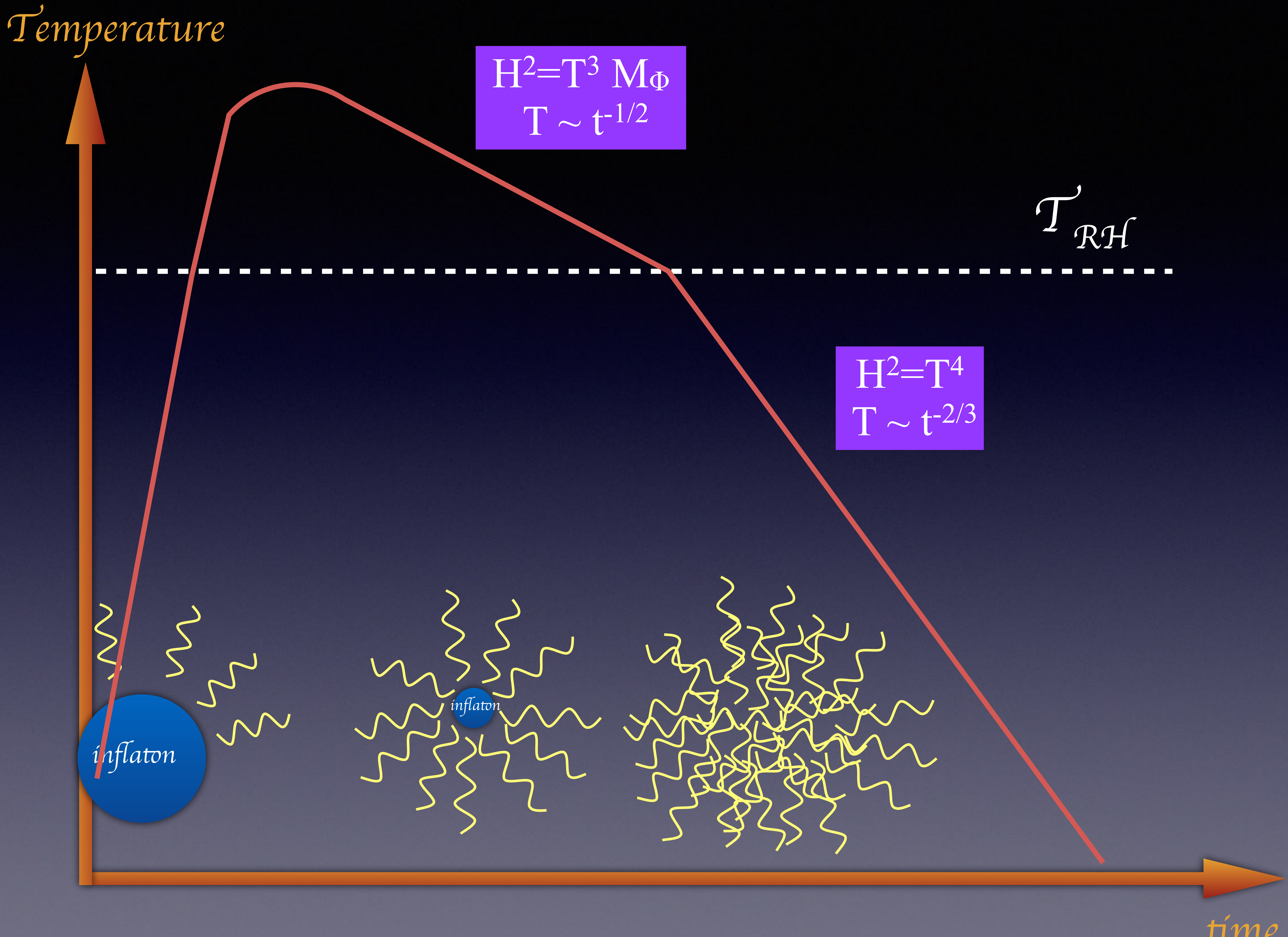
99.996 % of the dark matter is produced before reheating!!!

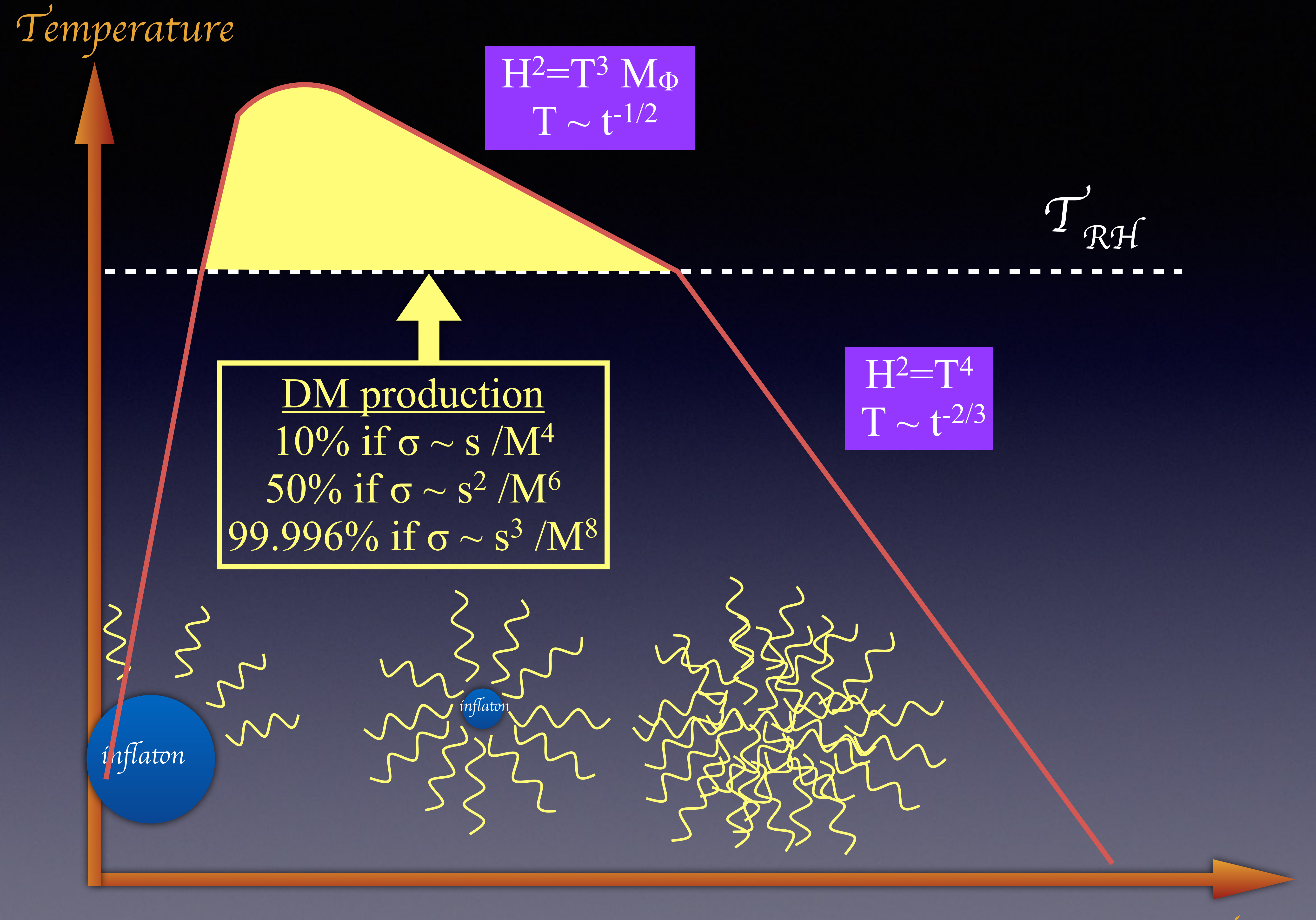
M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]



M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]



M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]



M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]

Conclusion 1

be very carful when dealing with non-thermal scenario

!!!!!!!

Conclusion 2

Conclusion 2

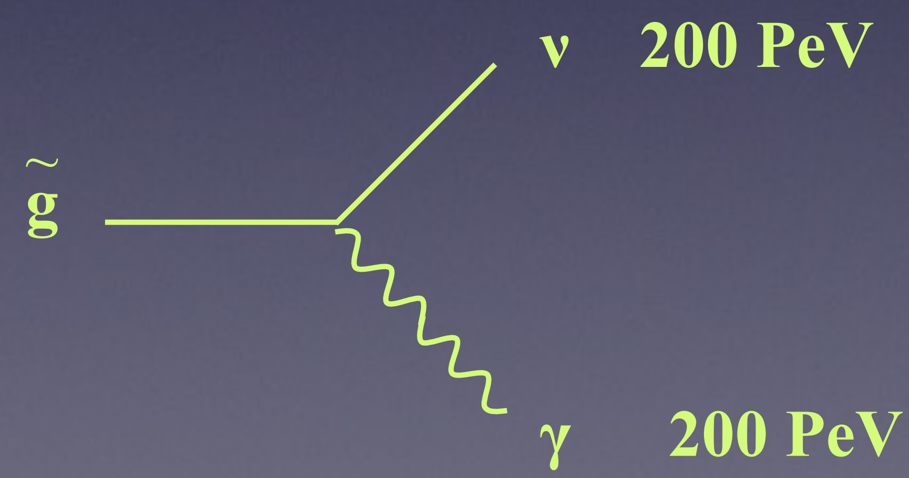
« And what is the signature of such models? »

Conclusion 2

« And what is the signature of such models? »

A smoking gun signal (CTA? HAWK?)

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



Conclusion 2

Conclusion 2

What are your 3 messages?

Messages to keep in mind

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Salviati:
Did you know that the first dark matter computation in the Universe was made by Poincare himself in 1906?

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Simplicius:
And I also recently noticed that secluding a sector by an intermediate scale leads to a miracle

Messages to keep in mind

Salviati:
Did you know that the first dark matter computation in the Universe was made by Poincare himself in 1906?

Simplicius:
And I also recently noticed that secluding a sector by an intermediate scale leads to a miracle

Sagredo:
Yes, but be careful in the Early Universe when dealing with high energy processes