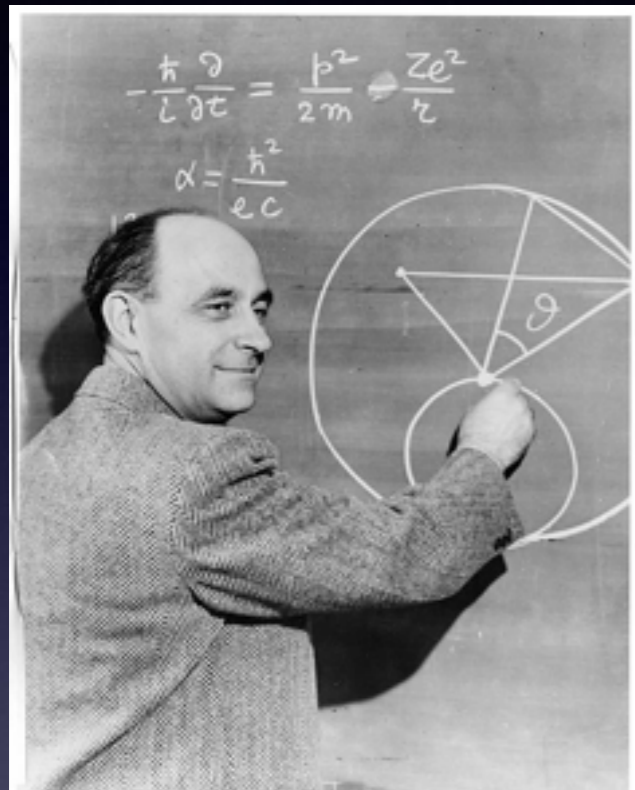


Dark Matter and Early Universe Cosmology



« 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

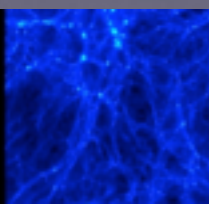
http://www.ymambrini.com/My_World/Physics.html

2017 IDPASC annual workshop : Frontiers of Dark Matter research

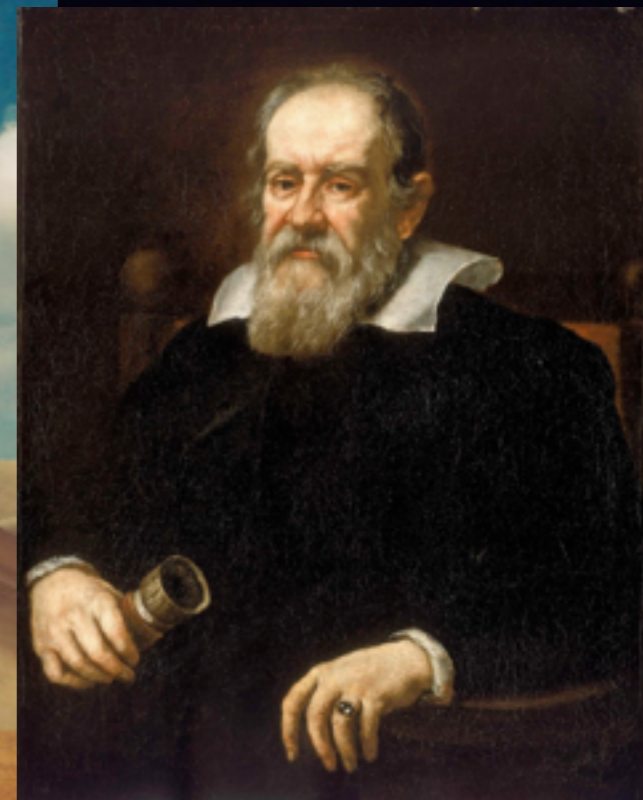
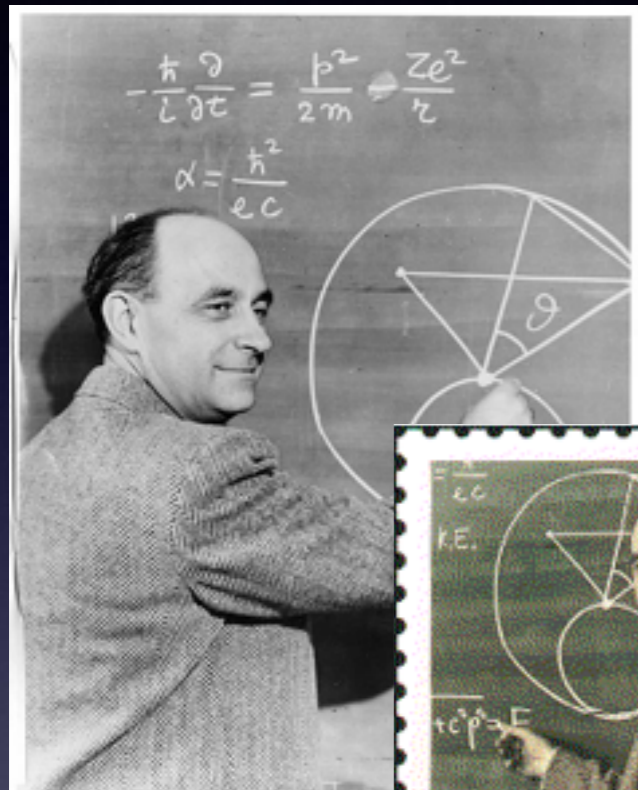
Maira Dutra, Mathias Pierre, Yann Mambrini, work in progress



MultiDark
Multimessenger Approach
for Dark Matter Detection



Dark Matter and Early Universe Cosmology



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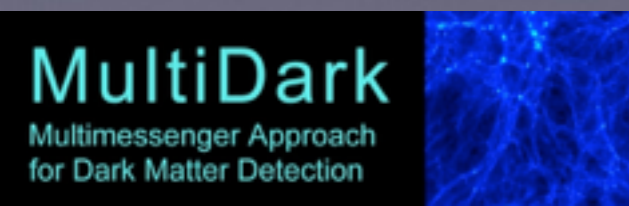
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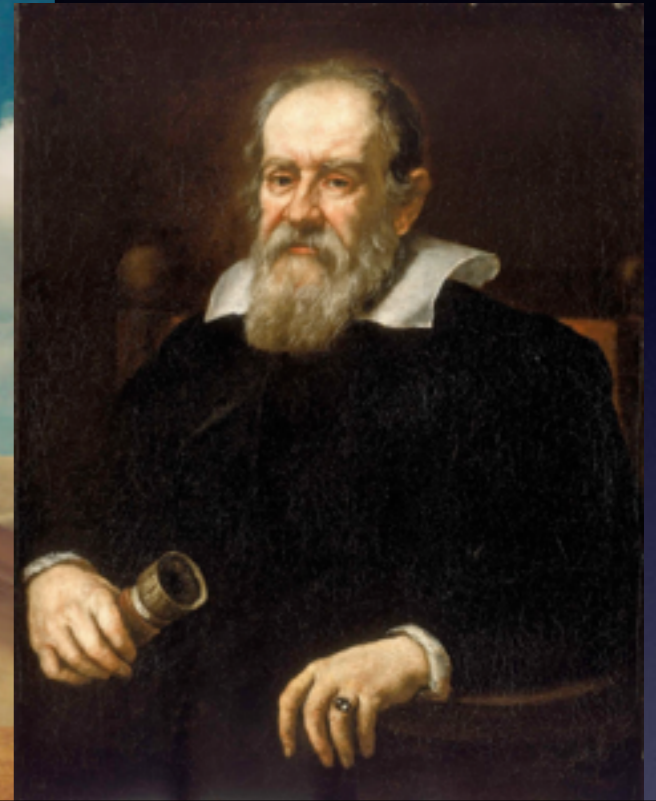
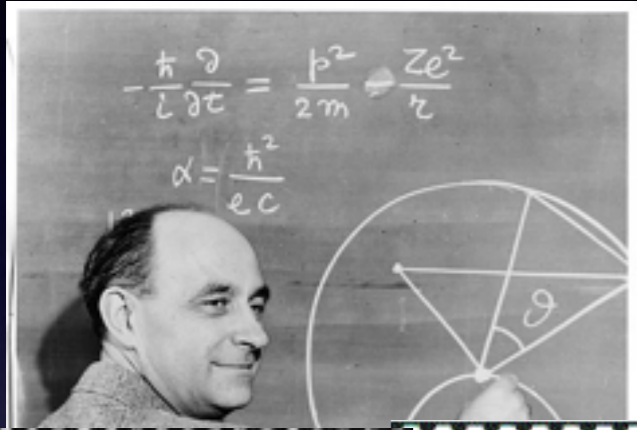
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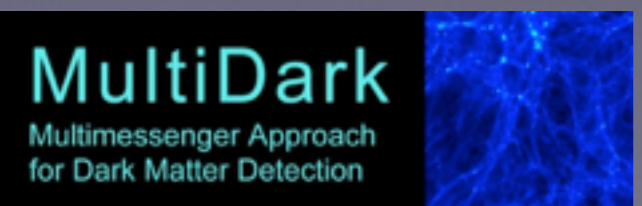


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I appreciate a talk when:

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..



« The **I**nternational **D**octorate Network in **P**article Physics, **A**strophysics and **C**osmology (**IDPASC**) is an interdisciplinary network whose purpose is to create new high-level experts in the fields of **P**article Physics, **A**strophysics and **C**osmology. »



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** ($\sim 10^9$) corresponding to the observations, thus **discrediting** the existence of dark matter, or dark stars.

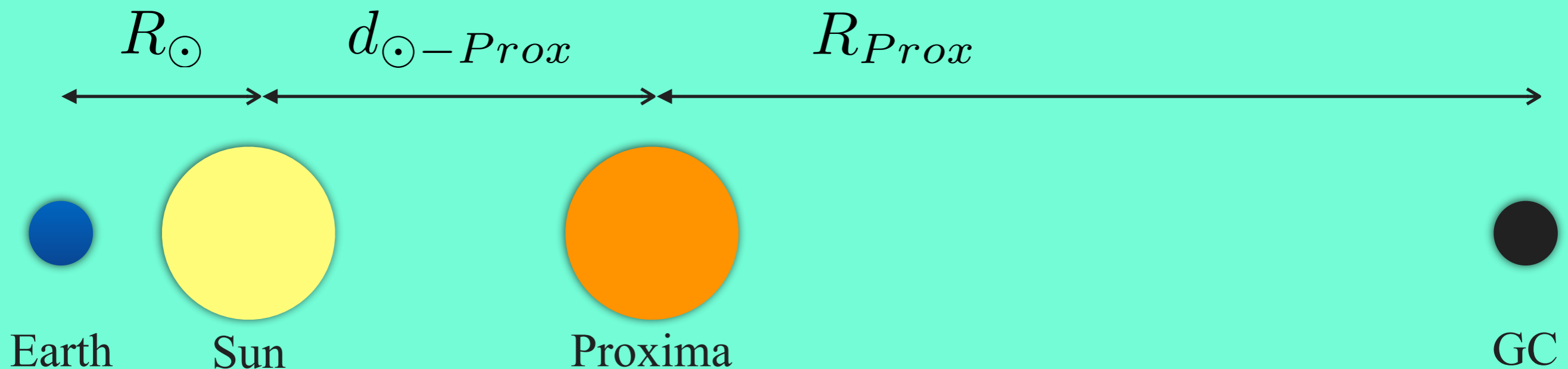
$$v(R) \propto R\sqrt{\rho}$$

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

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

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

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



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

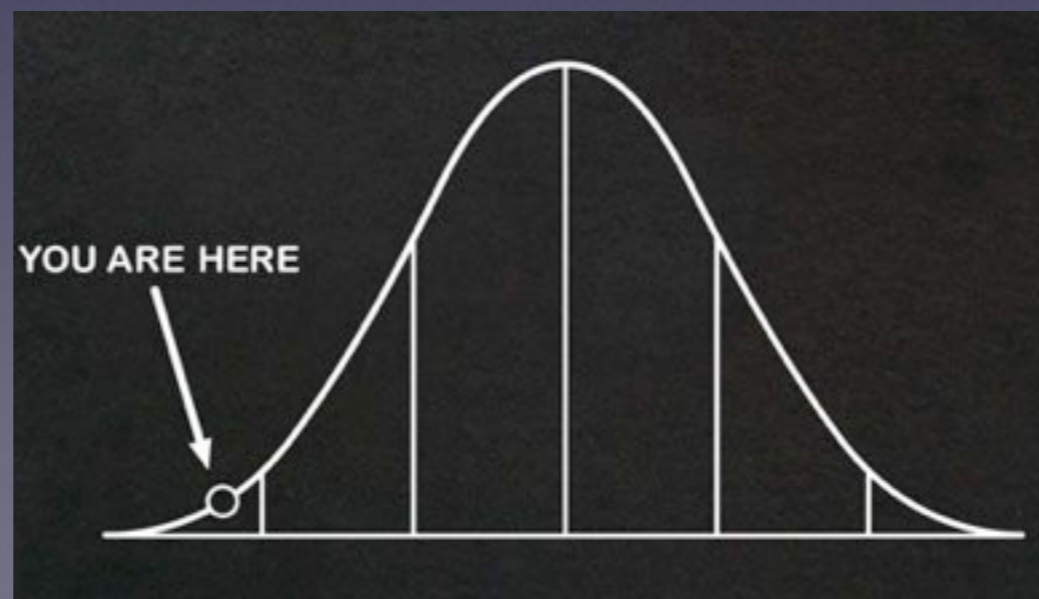
Inflaton portal

gravitino DM in High Scale SUSY

Conclusion

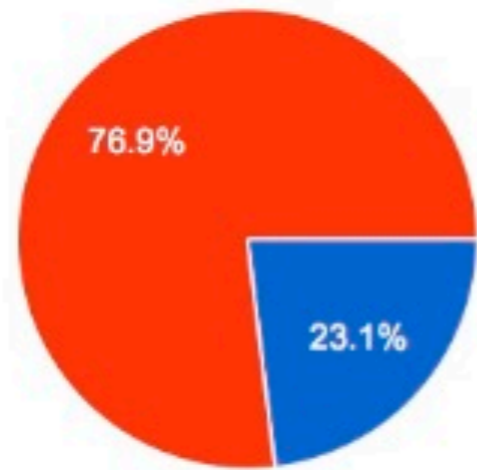
if time is left

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?

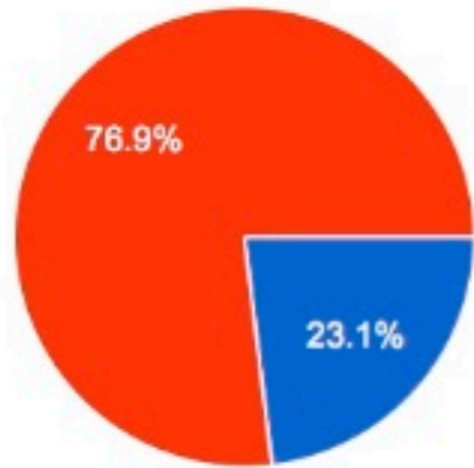


No	12	23.1%
Yes	40	76.9%

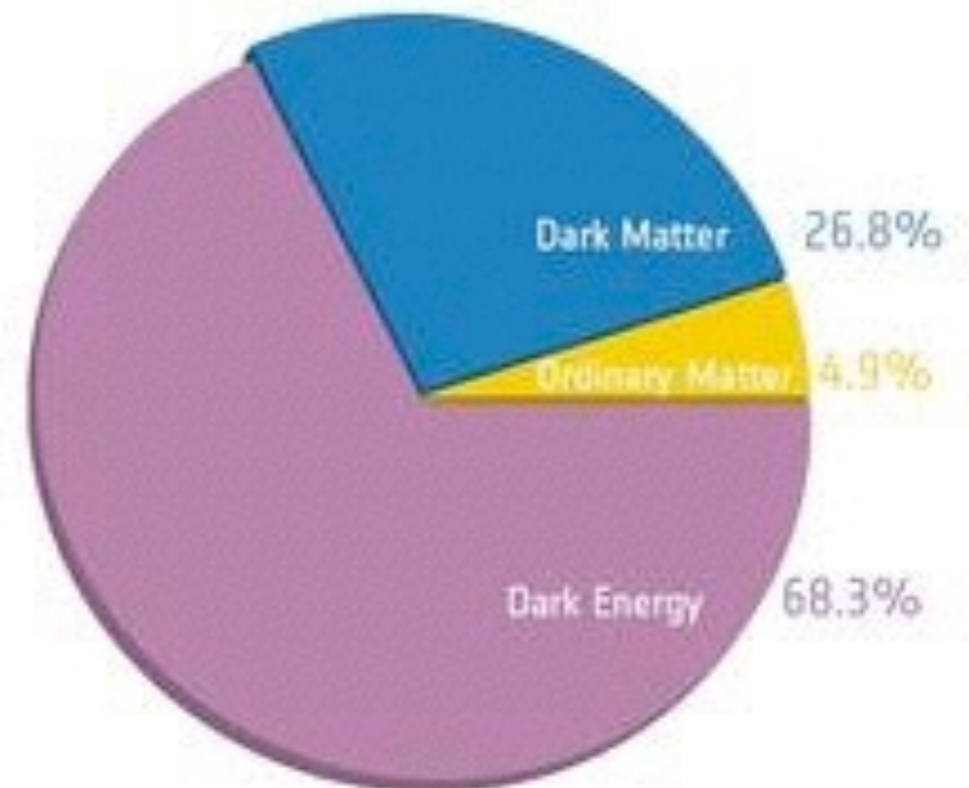
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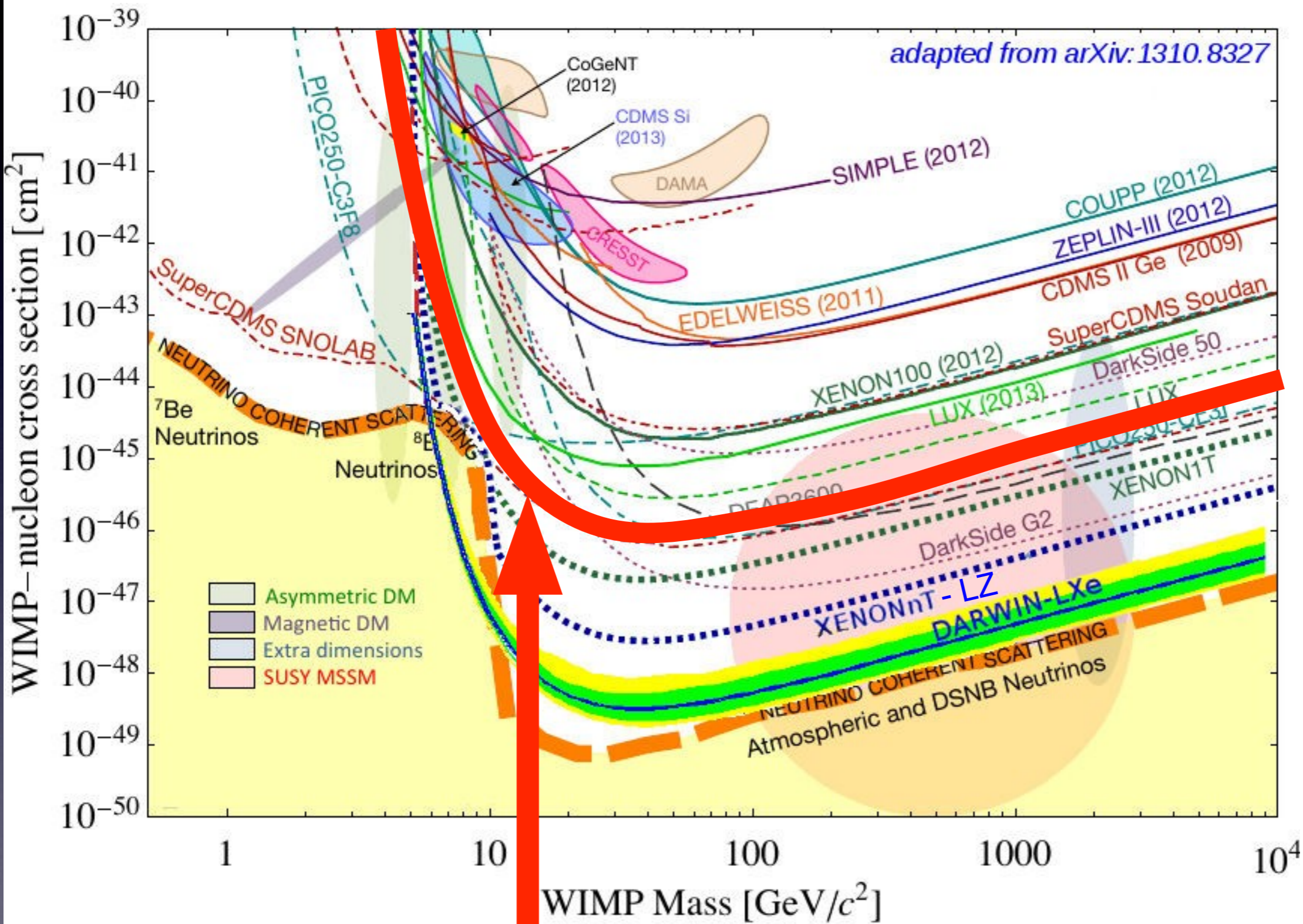


At least optimism...

1

The direct detection race

Perspectives

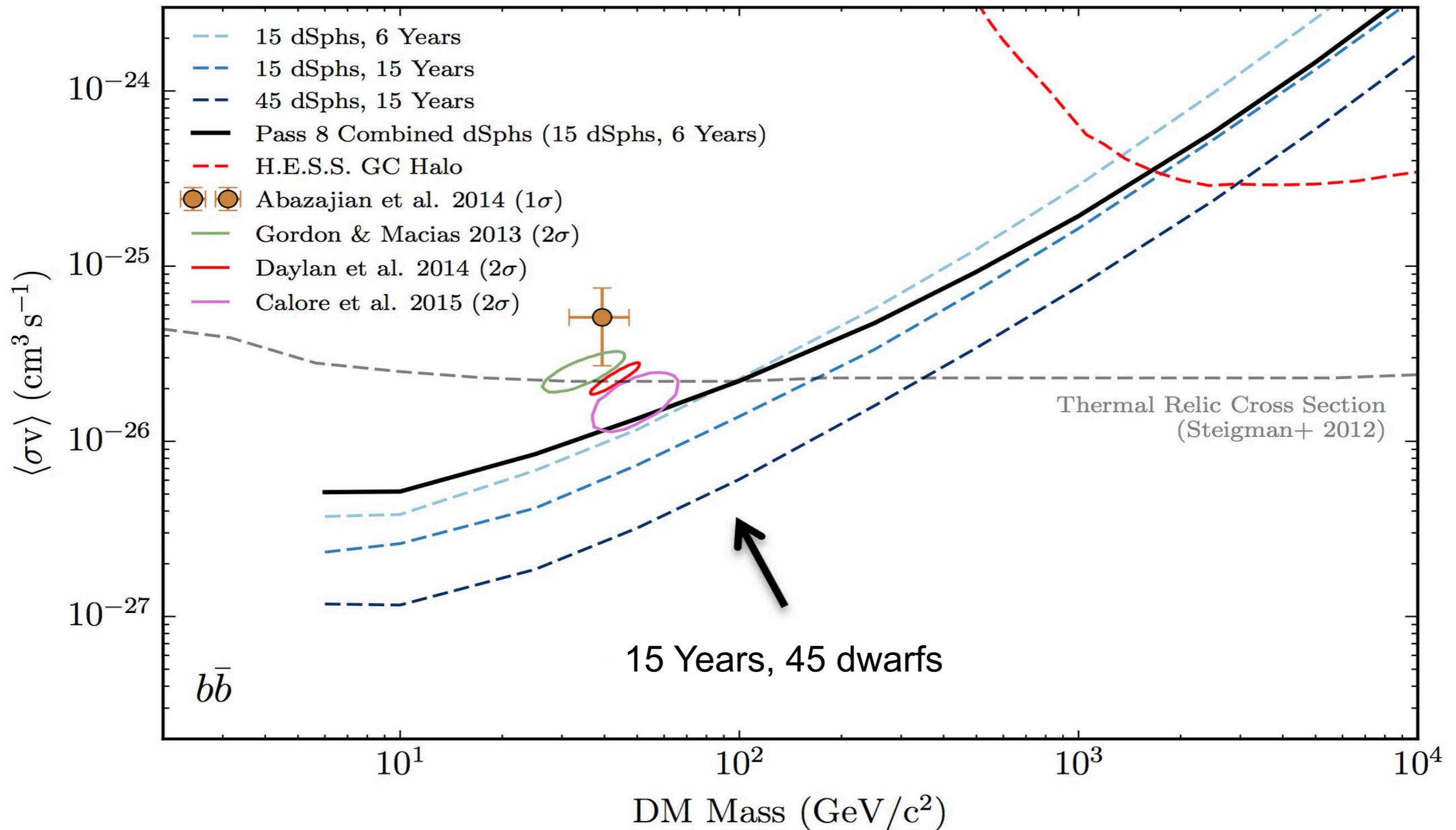


XENON 1T (2017); arXiv:1705.06655 + PandaX-II (2017); arXiv:1708.06917

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 $\sigma < 10^{-46} \text{ cm}^2 \sim 10^{-18} \text{ GeV}^{-2}$

What do we expect for a WIMP*:



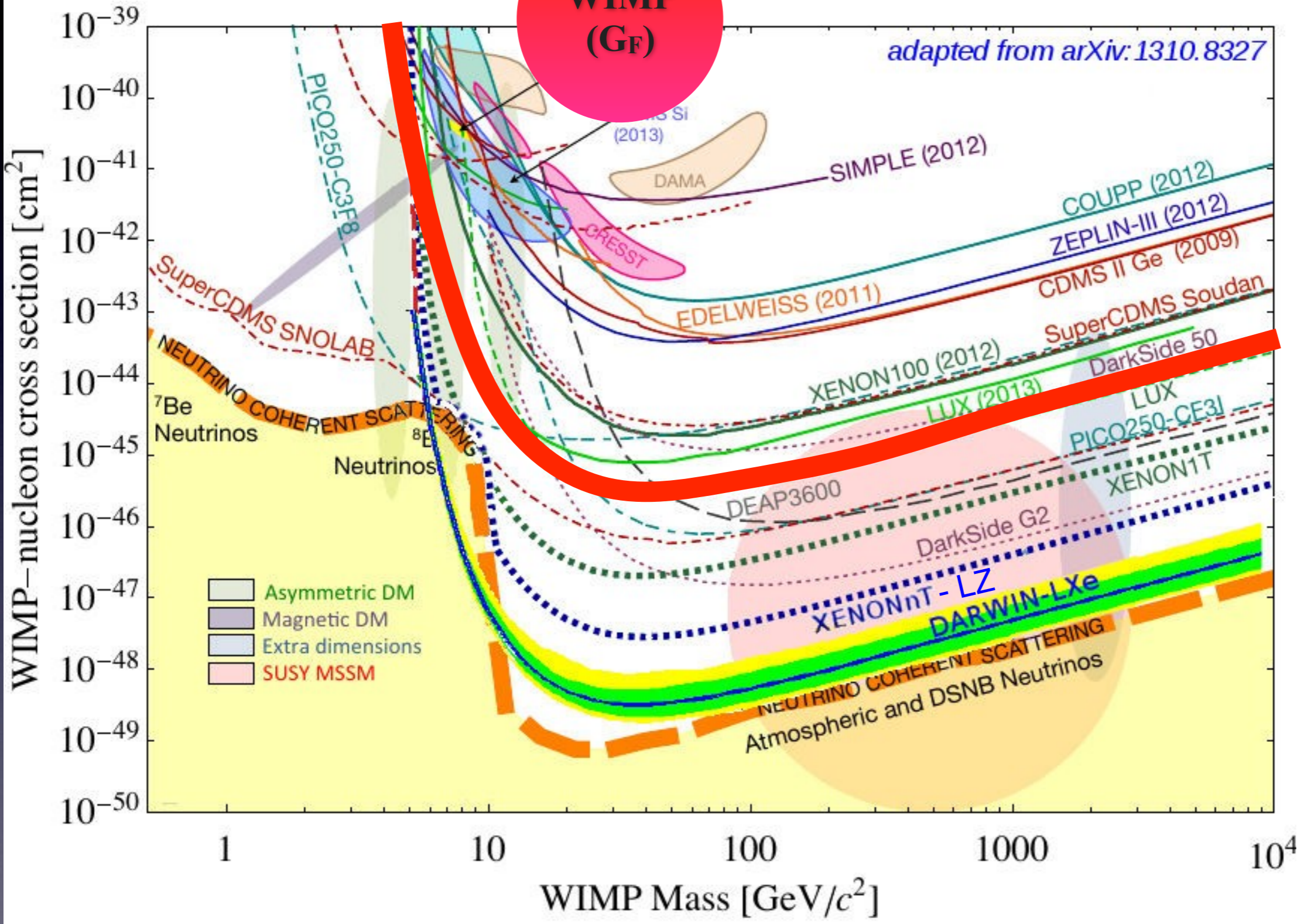
$$\begin{aligned} \sigma_{EW}(\chi p \rightarrow \chi p) &\simeq G_F^2 m_\chi^2 \\ &\simeq \frac{g_2^2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1 \text{ GeV}} \right)^2 \end{aligned}$$

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

Perspectives

**WIMP
(G_F)**

adapted from arXiv:1310.8327



Why are we so attached to
WIMP-like particle?

The WIMP miracle !



The Boltzmann equation

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

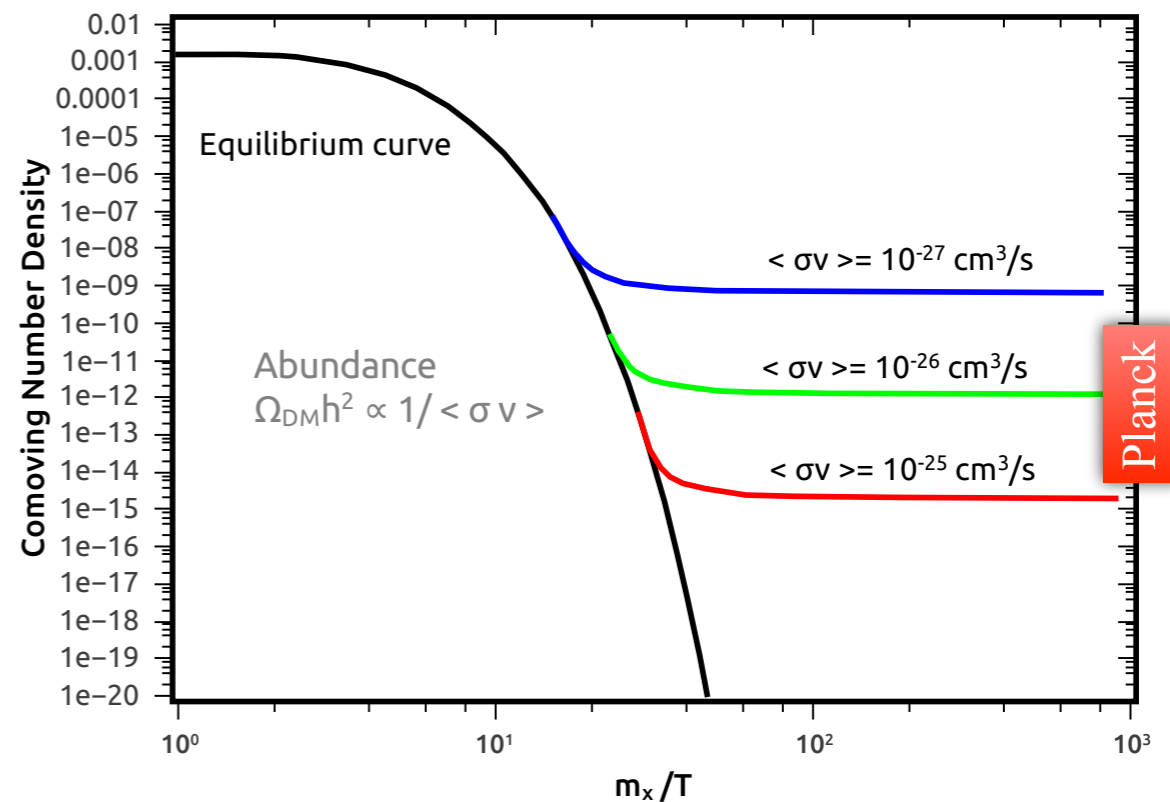
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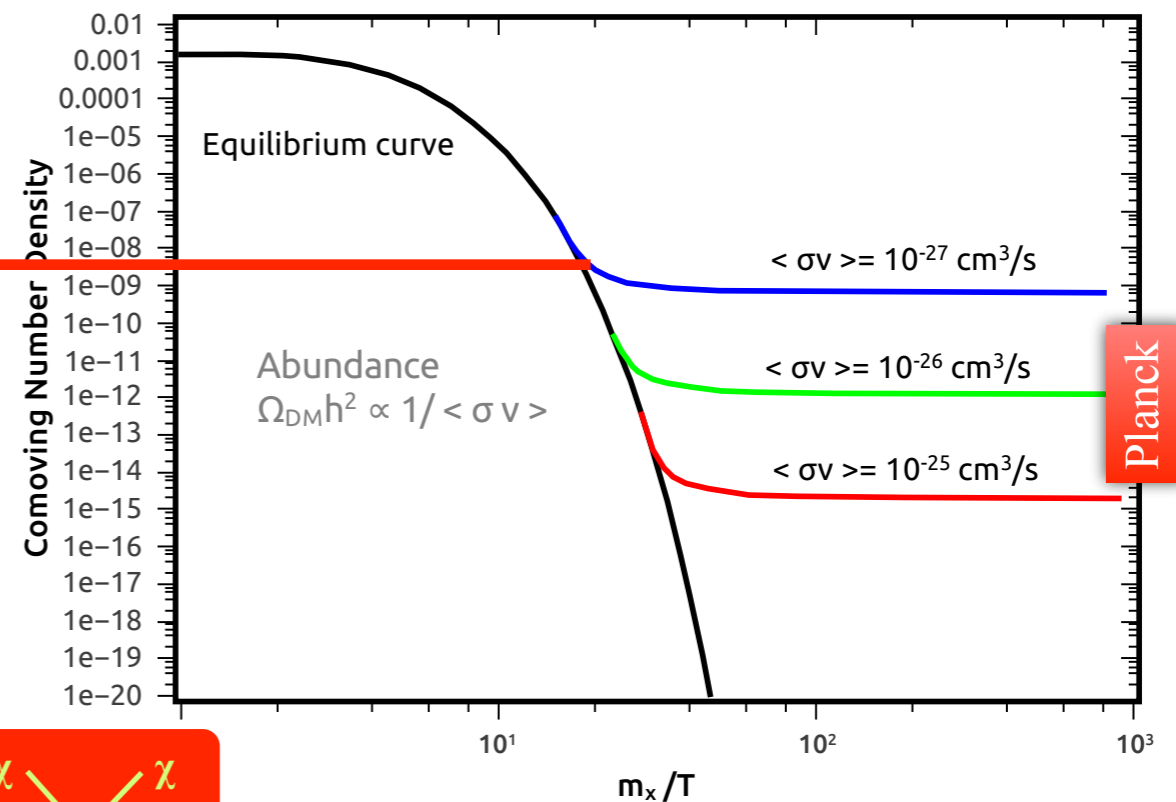
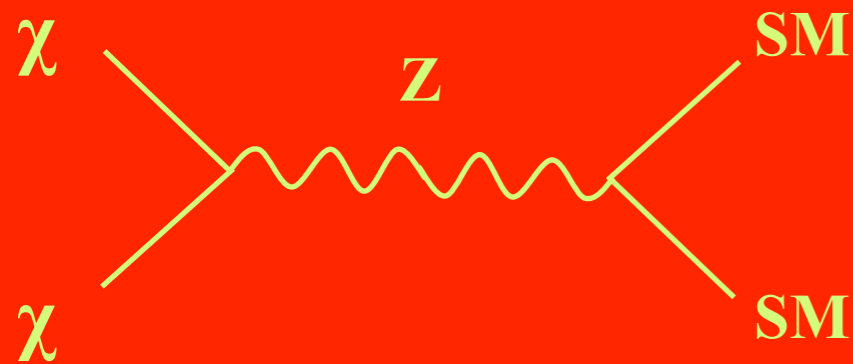


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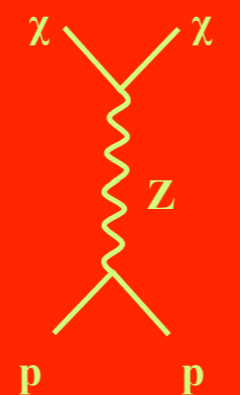
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One needs a phase of depletion of dark matter, annihilating to SM to avoid the overabundance. Can we deplete it without even coupling to the SM, and thus avoiding the direct detection conflict?



What is happening if one releases one hypothesis?

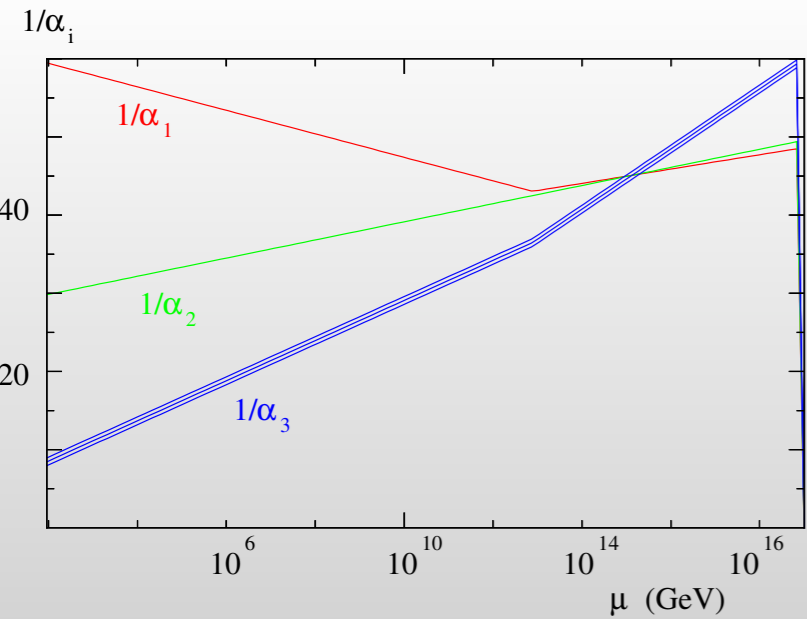
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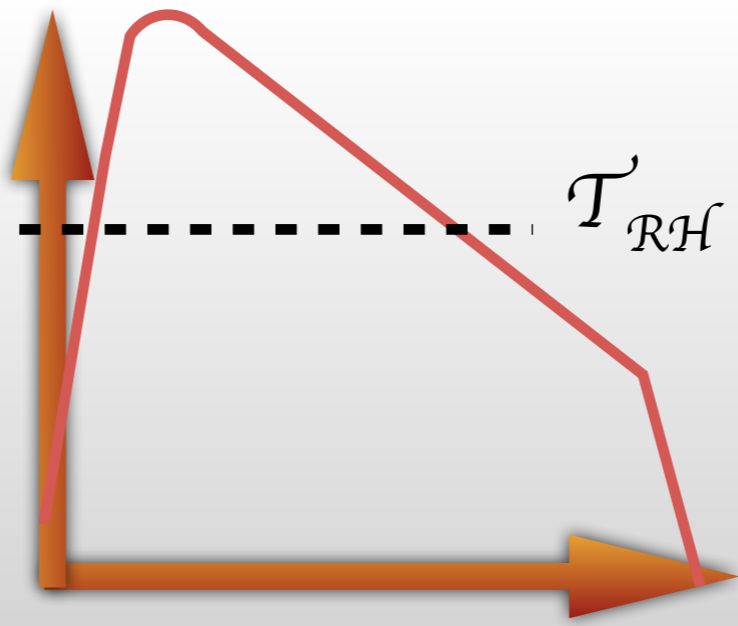
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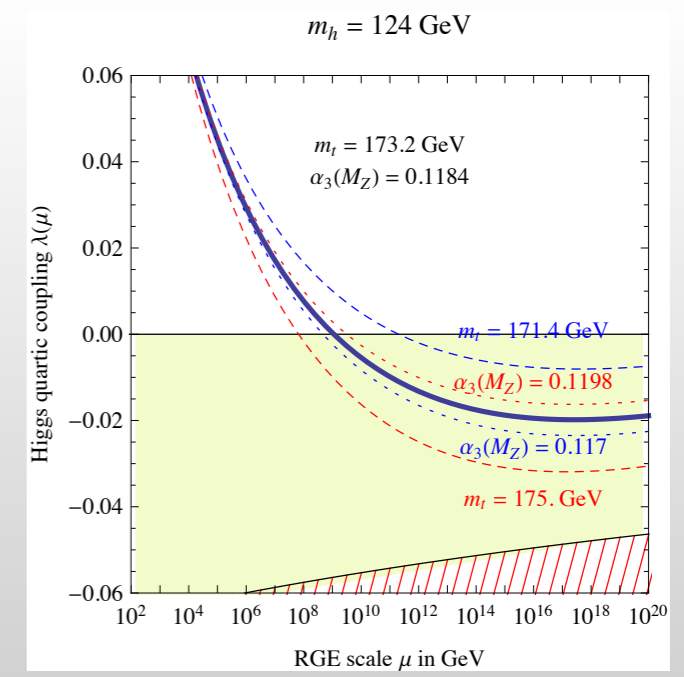
In other words, both sector are secluded or by
tiny couplings (of the order of y_v)
or by massive particles
(of the order of intermediate scale, 10^{10} GeV)



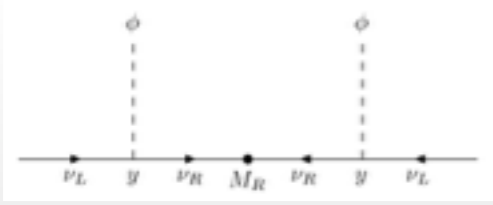
Unification :
Intermediate scale $\sim 10^{10}$ GeV



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



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



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

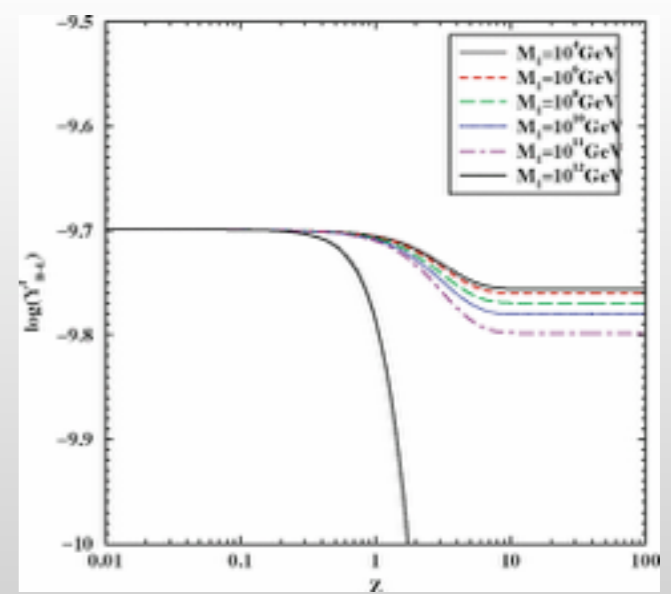
$$\mathcal{L}_\nu = -\left(\frac{1}{2}M^R + \frac{ih}{\sqrt{2}}A\right)\bar{\nu}_R^c\nu_R - \frac{y_{LR}}{\sqrt{2}}\bar{\nu}_L H\nu_R + h.c.$$

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

See-saw mechanism with ν_R :
 $m_\nu = 0.1$ eV $\Rightarrow M^R \sim 10^{10}$ 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

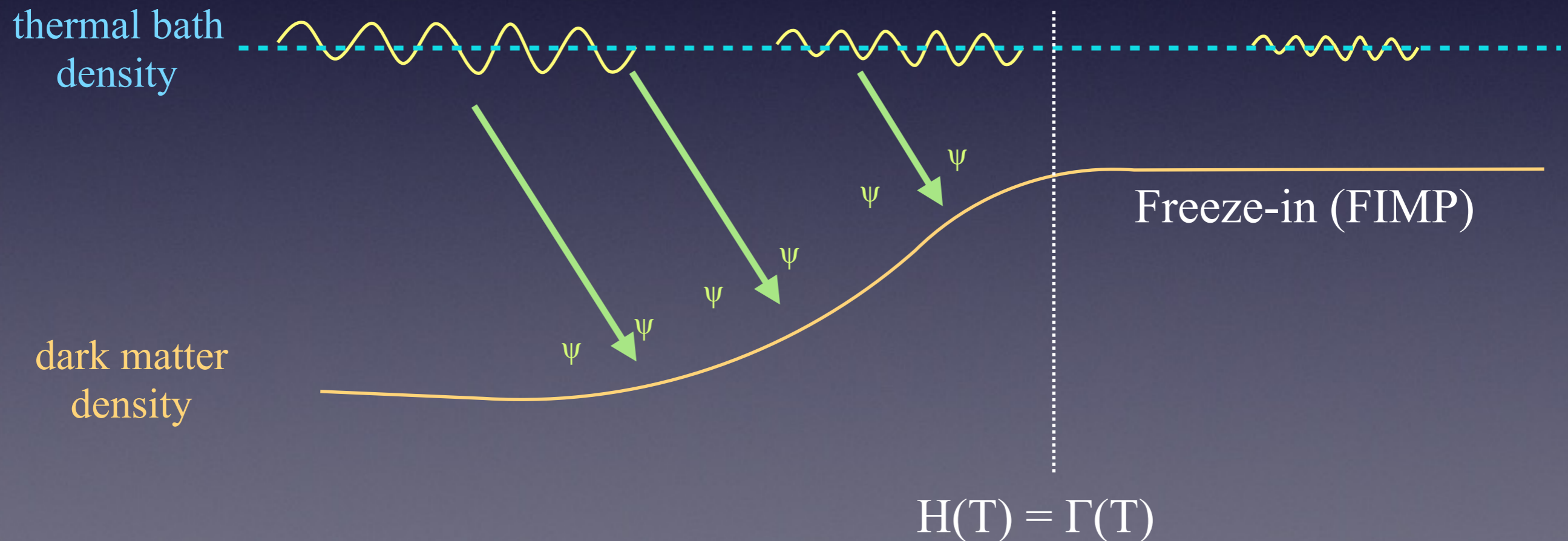


Leptogenesis/baryogenesis
 $\mu \sim 10^{10}$ GeV

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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3) Both cases

Computing a relic abundance

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

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

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

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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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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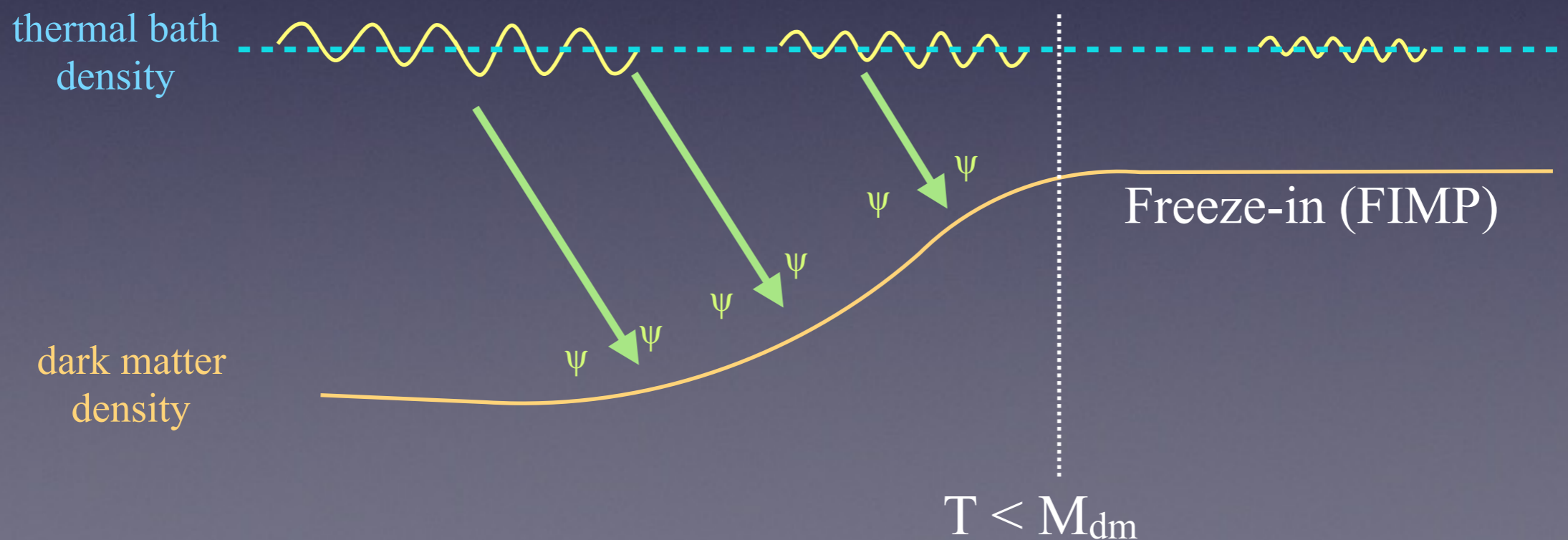
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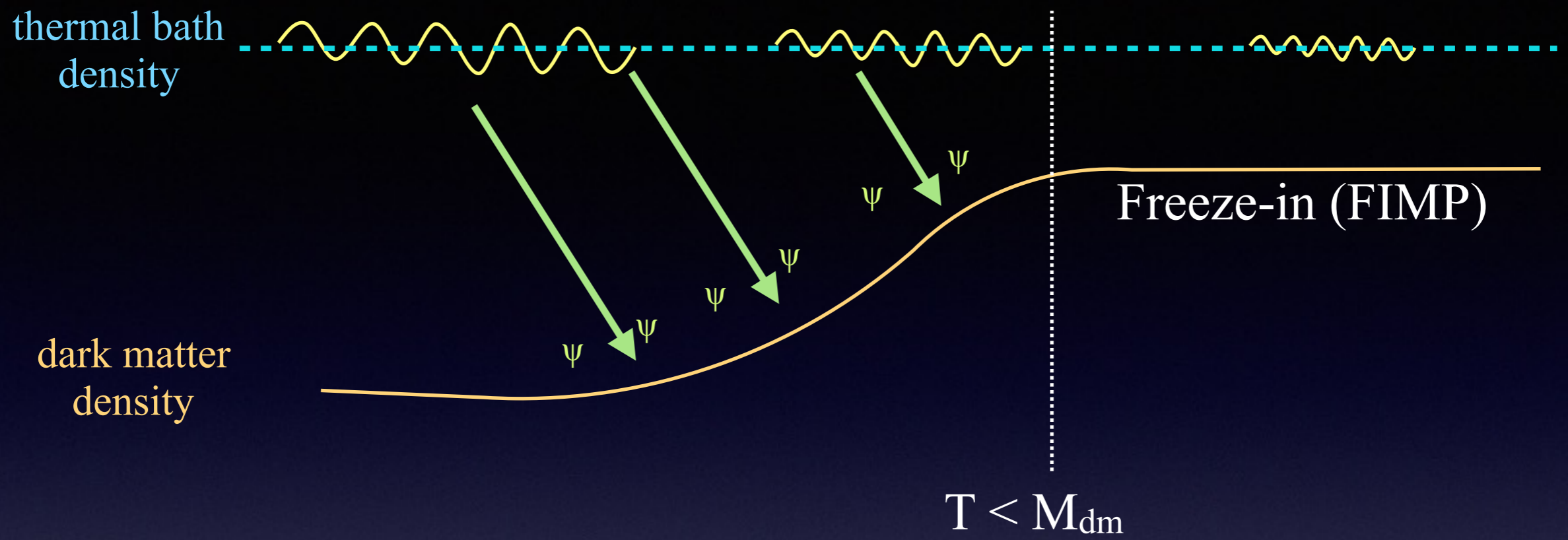
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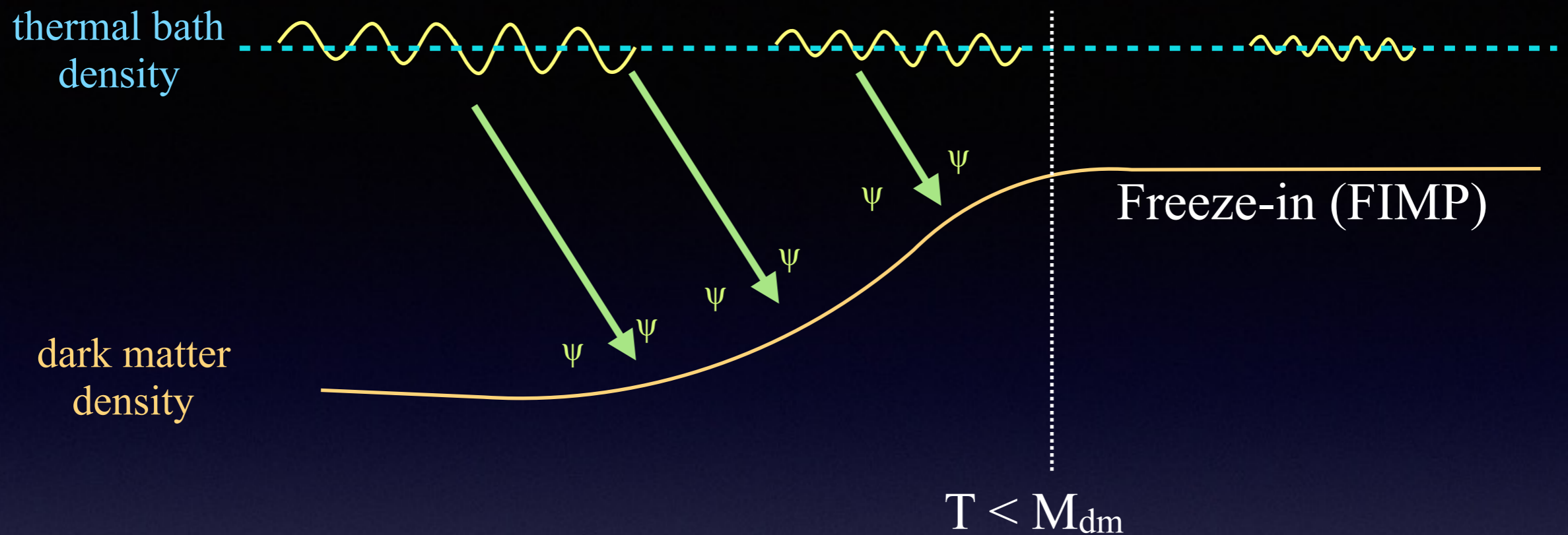
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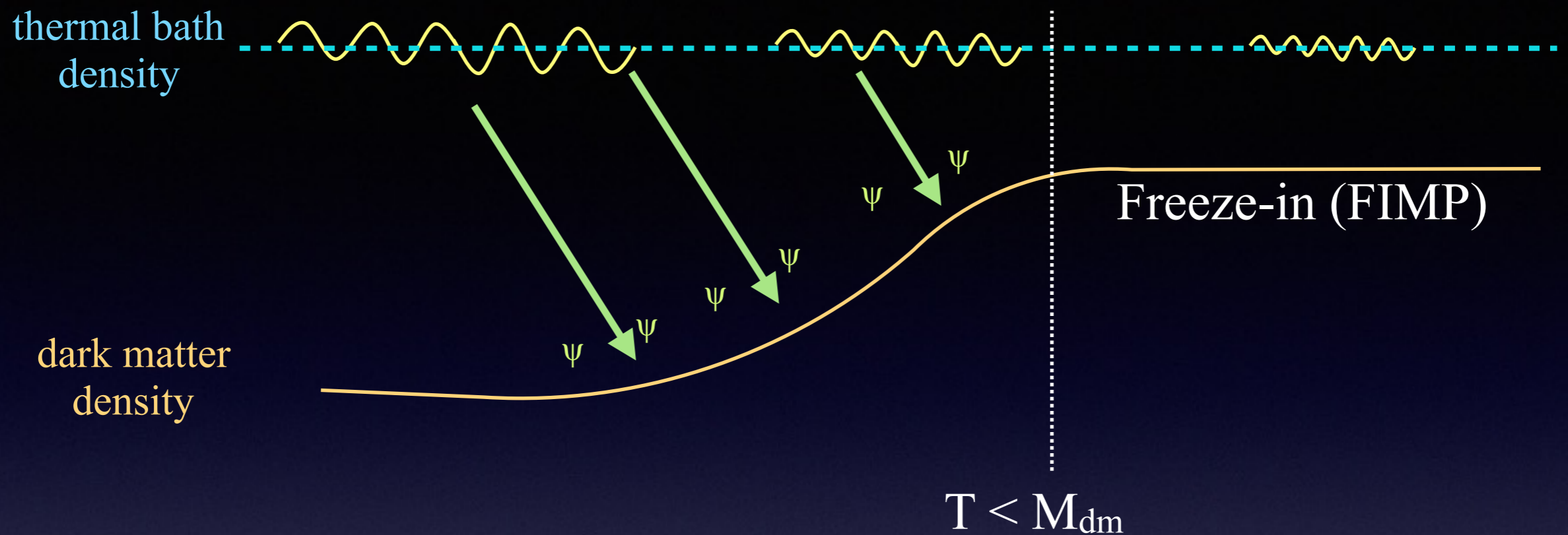






The main production is at late time (low temperature) so Maxwell Boltzman approximation is valid $(e^{E_i/T} - 1) \sim e^{E_i/T}$





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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 $\sim 10^{-11}$ 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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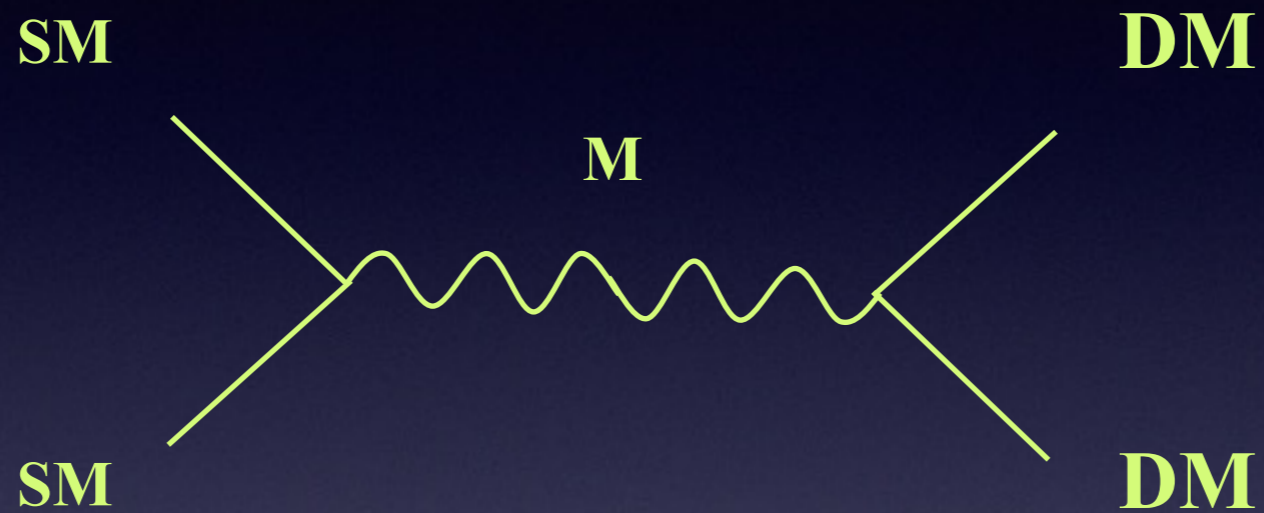
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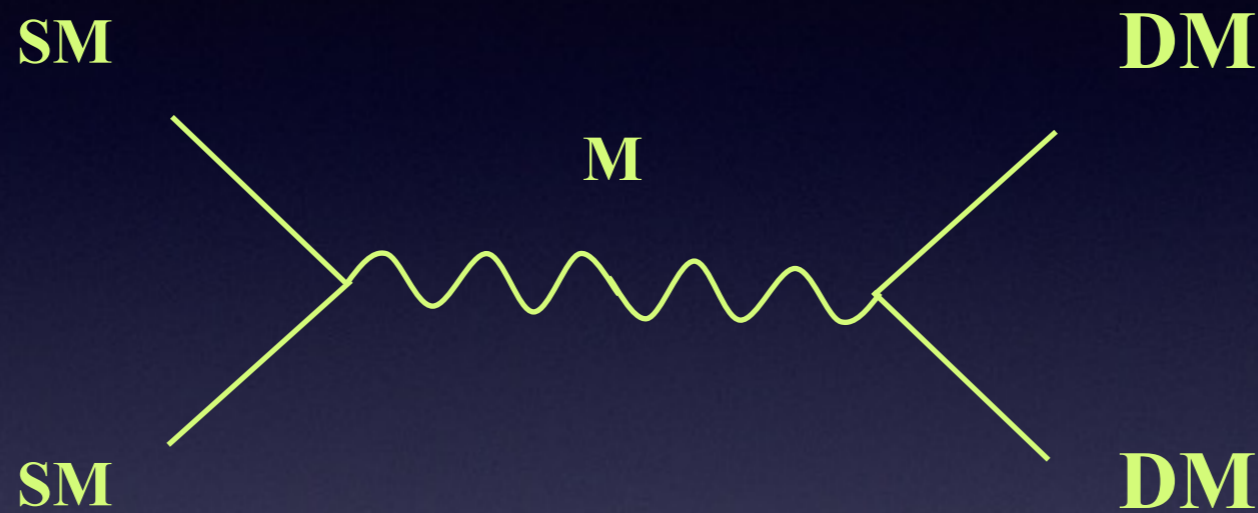
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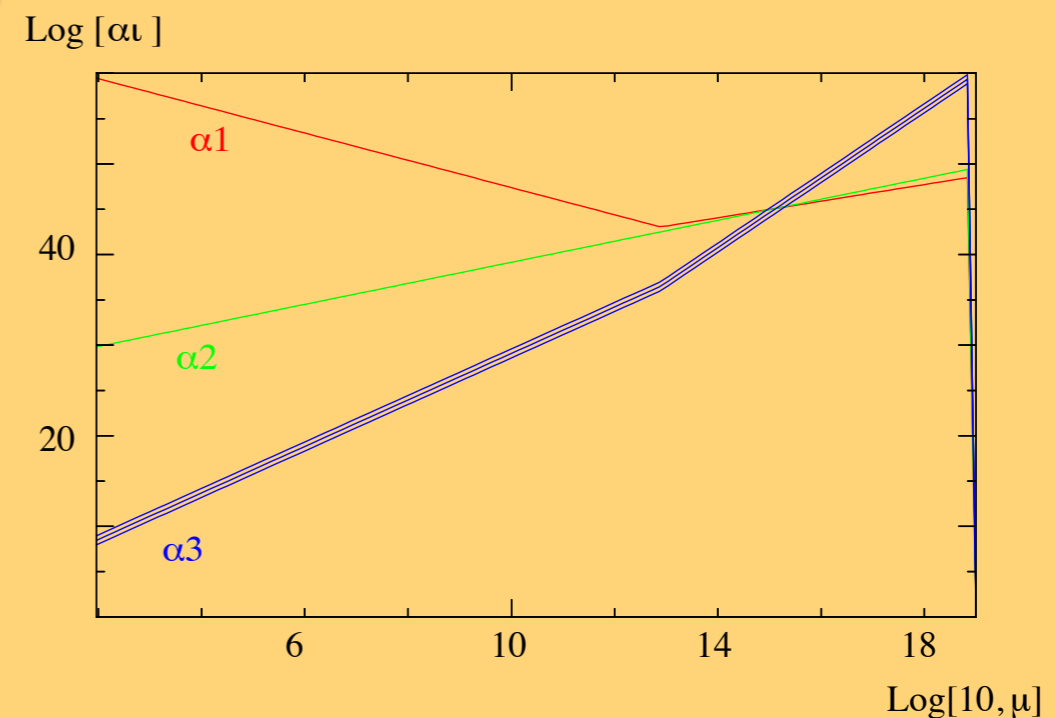
$$\mathcal{M} = \lambda \frac{s}{p^2 - M_M^2} \simeq \lambda \frac{s}{M_M^2} \Rightarrow R(T) \sim \frac{T^8}{M_M^4}$$

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

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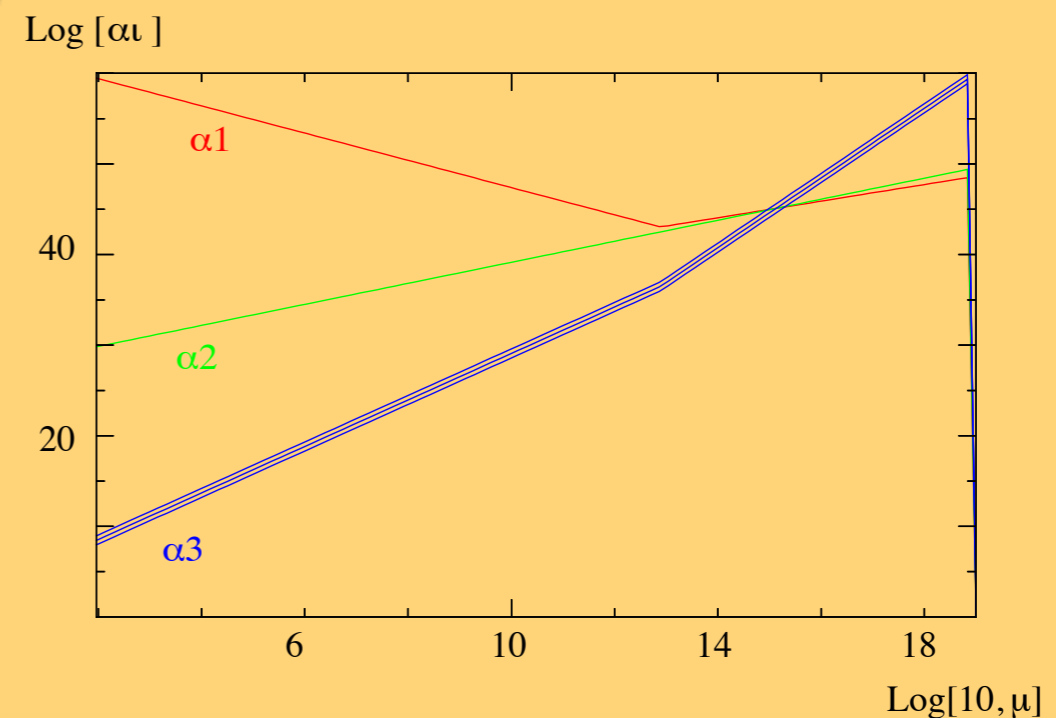
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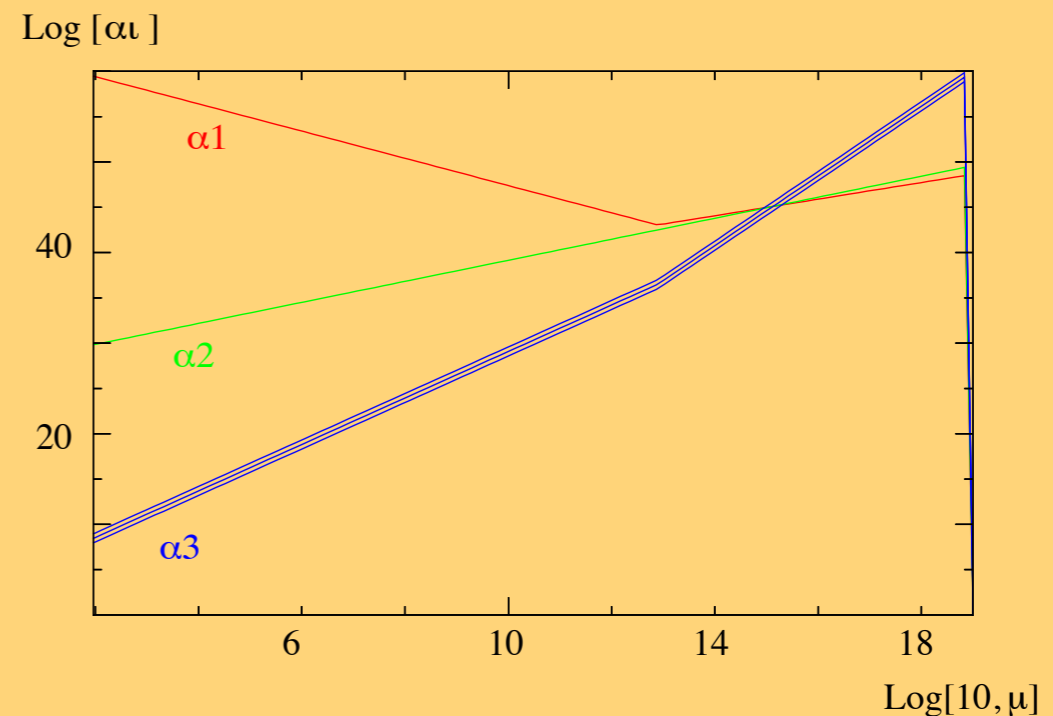


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Can we talk about a « FIMP miracle »?

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 .



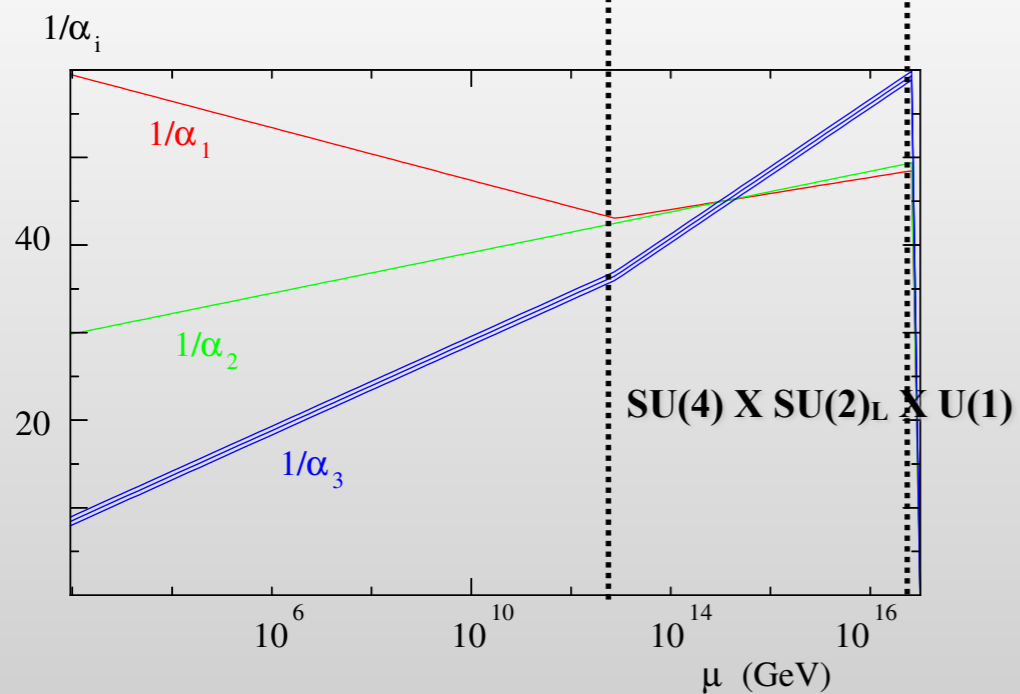
Example : SO(10) and ν_R

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 ($\sim 10^{10}$ GeV) scale provides then the best framework for a natural see-saw mechanism (natural means $y_\nu \sim 1$)

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

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

SU(3)_c X SU(2)_L X U(1)_R SO(10)



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

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

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

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

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

	$SO(10) \rightarrow \mathcal{G} \times [\text{Higgs}]$	$M_{\text{int}}(\text{GeV})$	$T_{RH}(\text{GeV})$
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

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

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

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

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Strong dependance on reheating

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Naturally large reheating temperature

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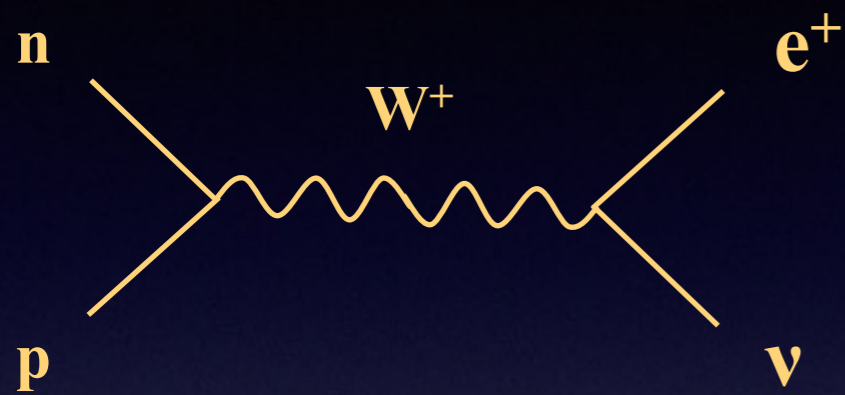
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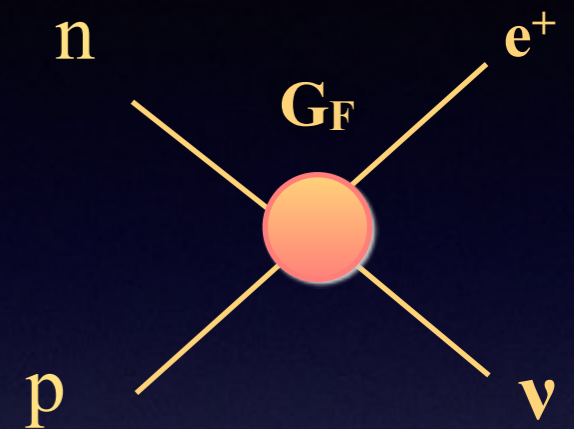


Moreover, the fact that the process is dominant at high temperature, one cannot neglect the statistical factor $(e^{E_i/T} - 1)$

Example : gravitino DM and High Scale SUSY

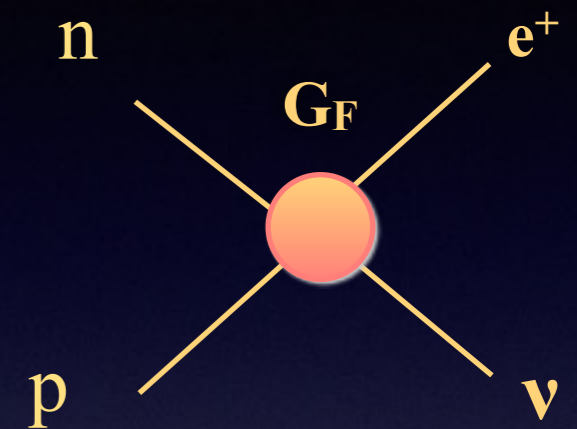
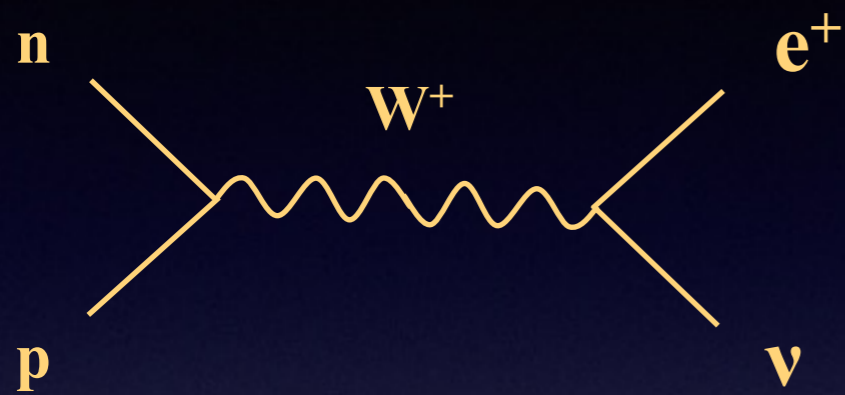


$$M_W \gg E$$

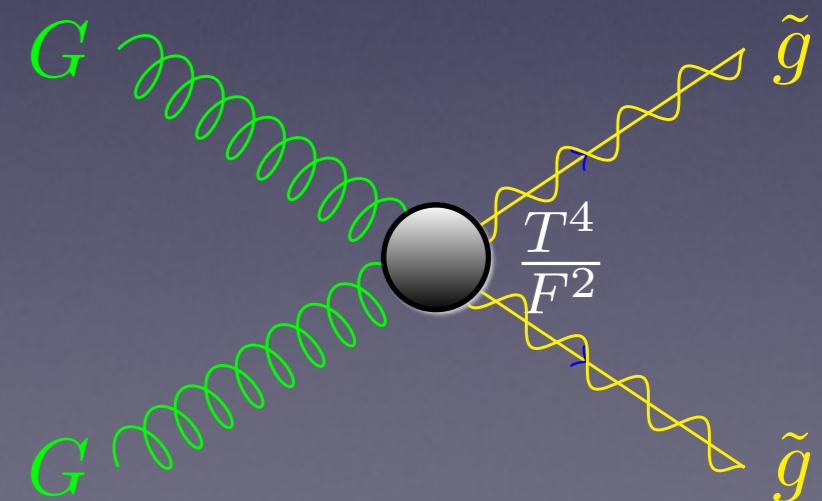
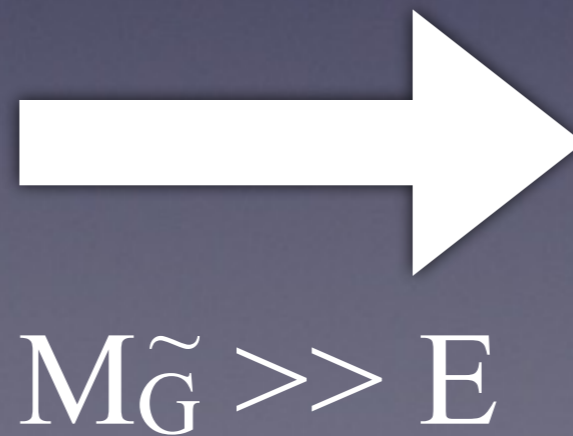
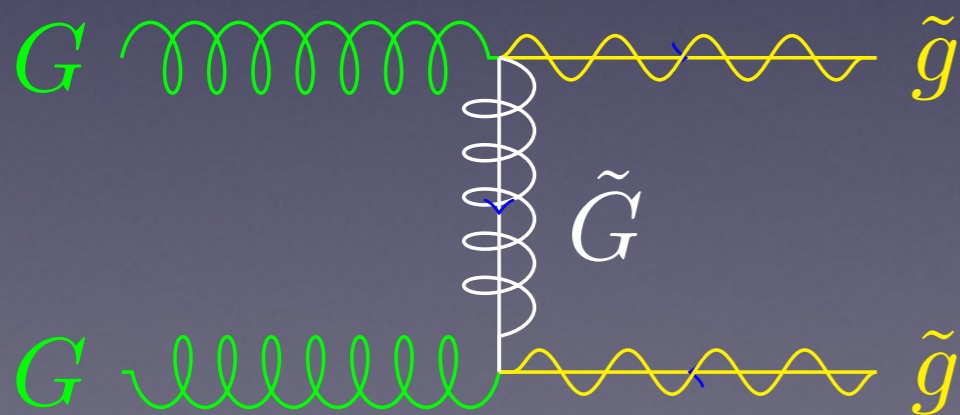


$$G_F = 10^{-5} \text{ GeV}^{-2}$$

Example : gravitino DM and High Scale SUSY



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



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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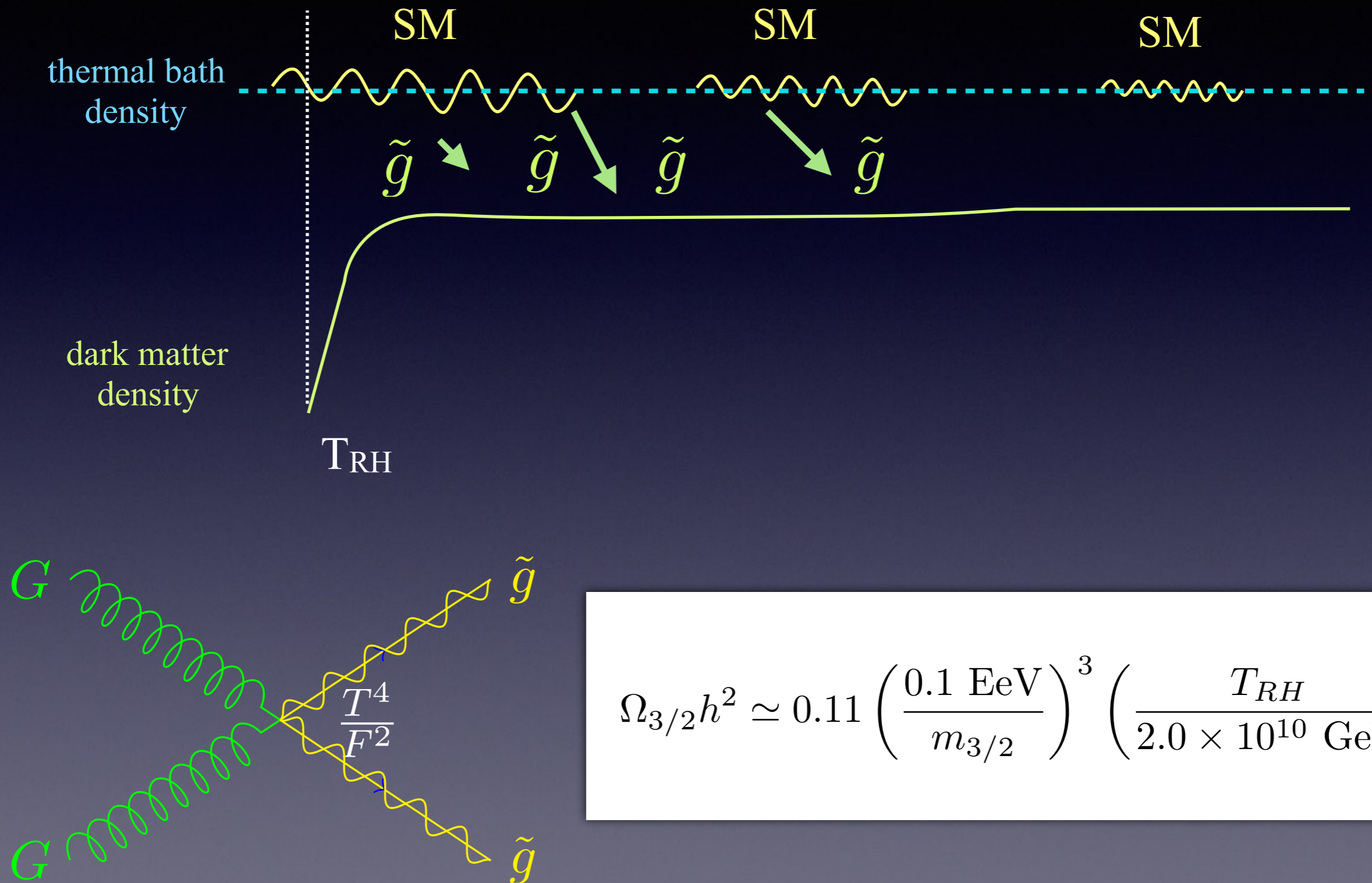
Which gives the Lagrangian between the SM and the goldstino

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

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

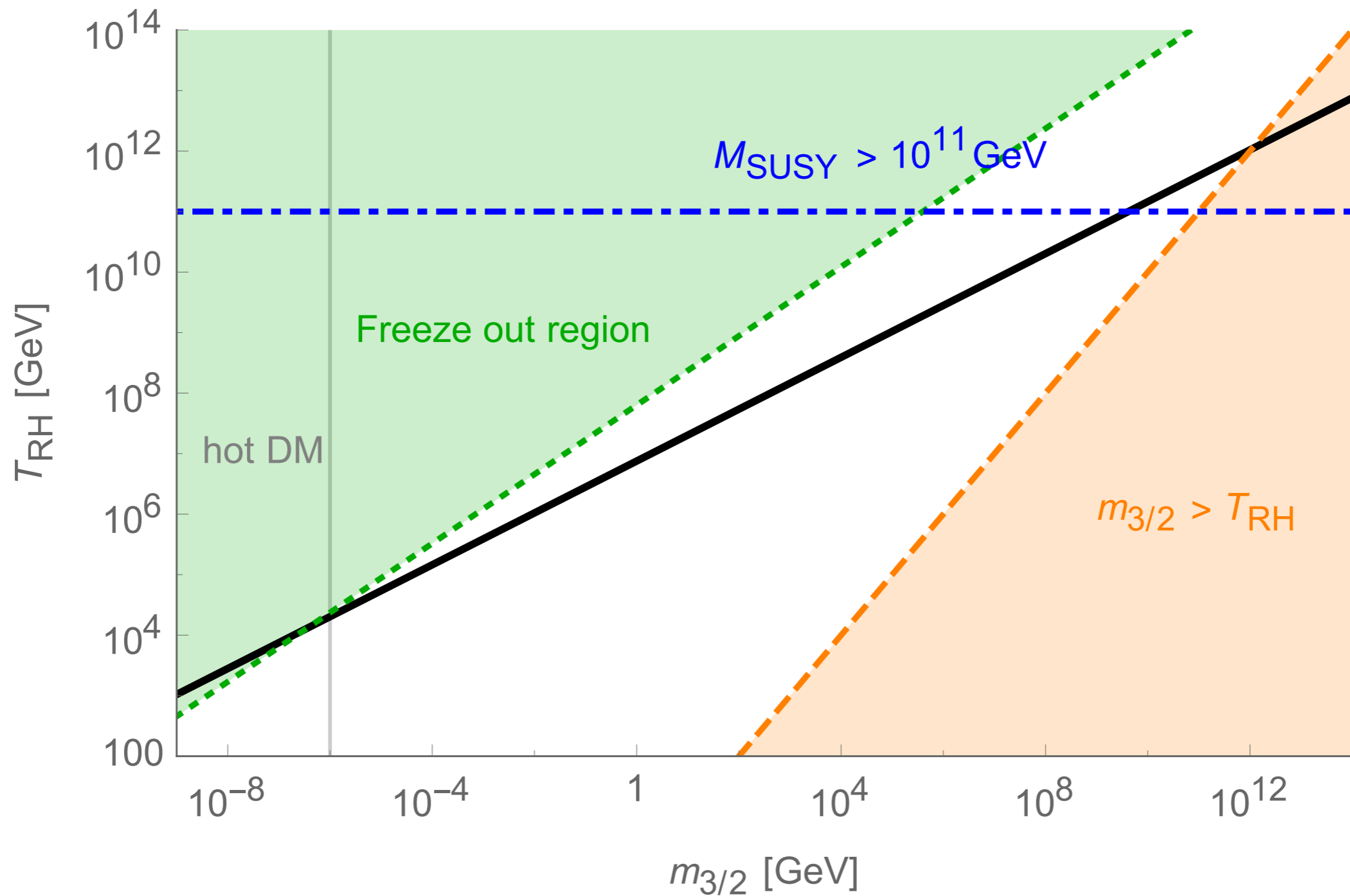
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The production mechanism



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

The Freeze-In mechanism (FI)



Including inflaton decay

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

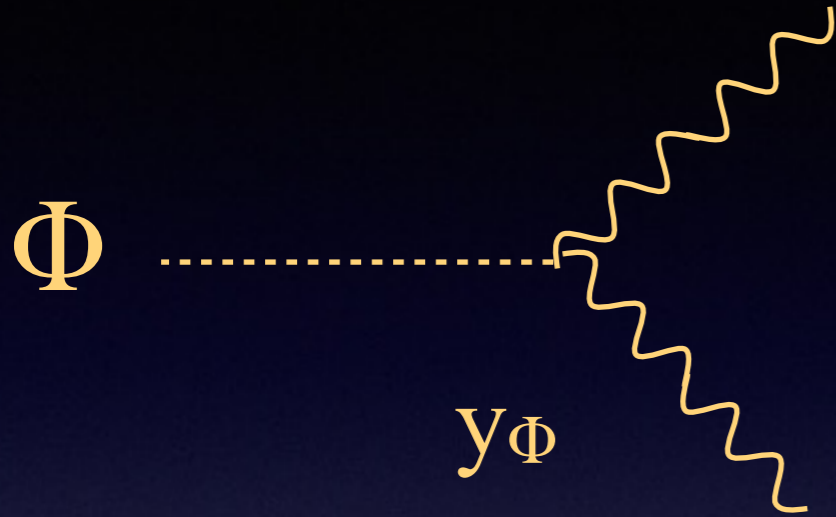


$$T_{RH} = \left(\frac{10}{g_s} \right)^{1/4} \left(\frac{2\Gamma_\phi M_P}{\pi c} \right)^{1/2} = 0.55 \frac{y_\phi}{2\pi} \left(\frac{m_\phi M_P}{c} \right)^{1/2}$$

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

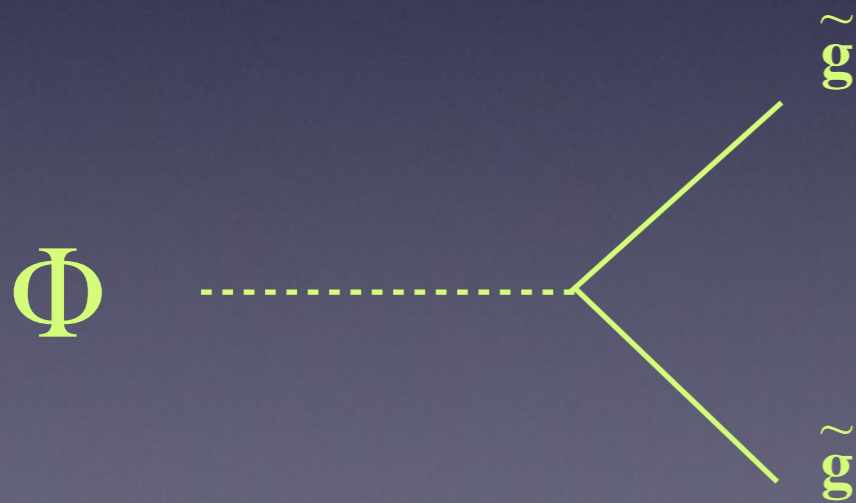
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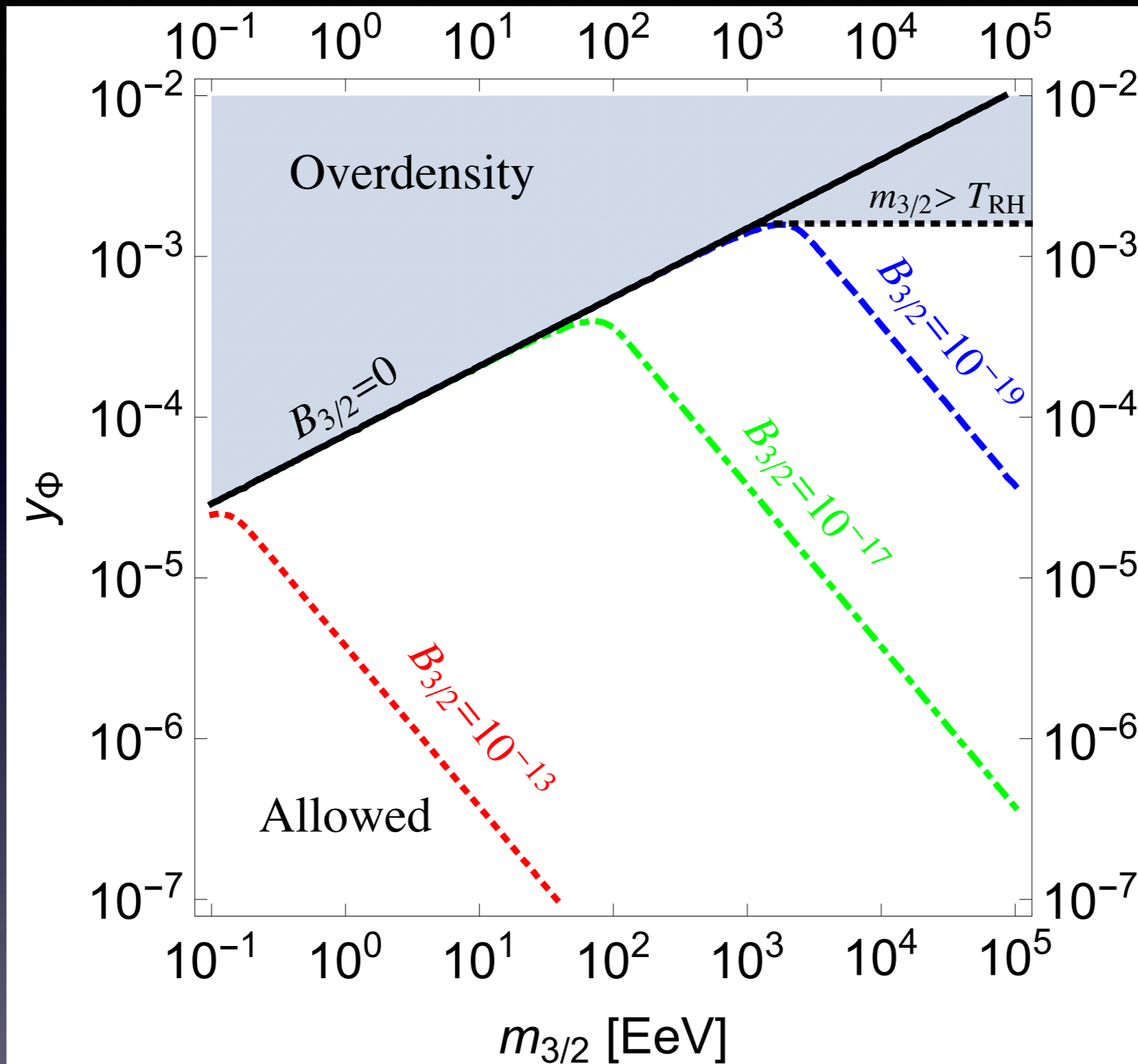
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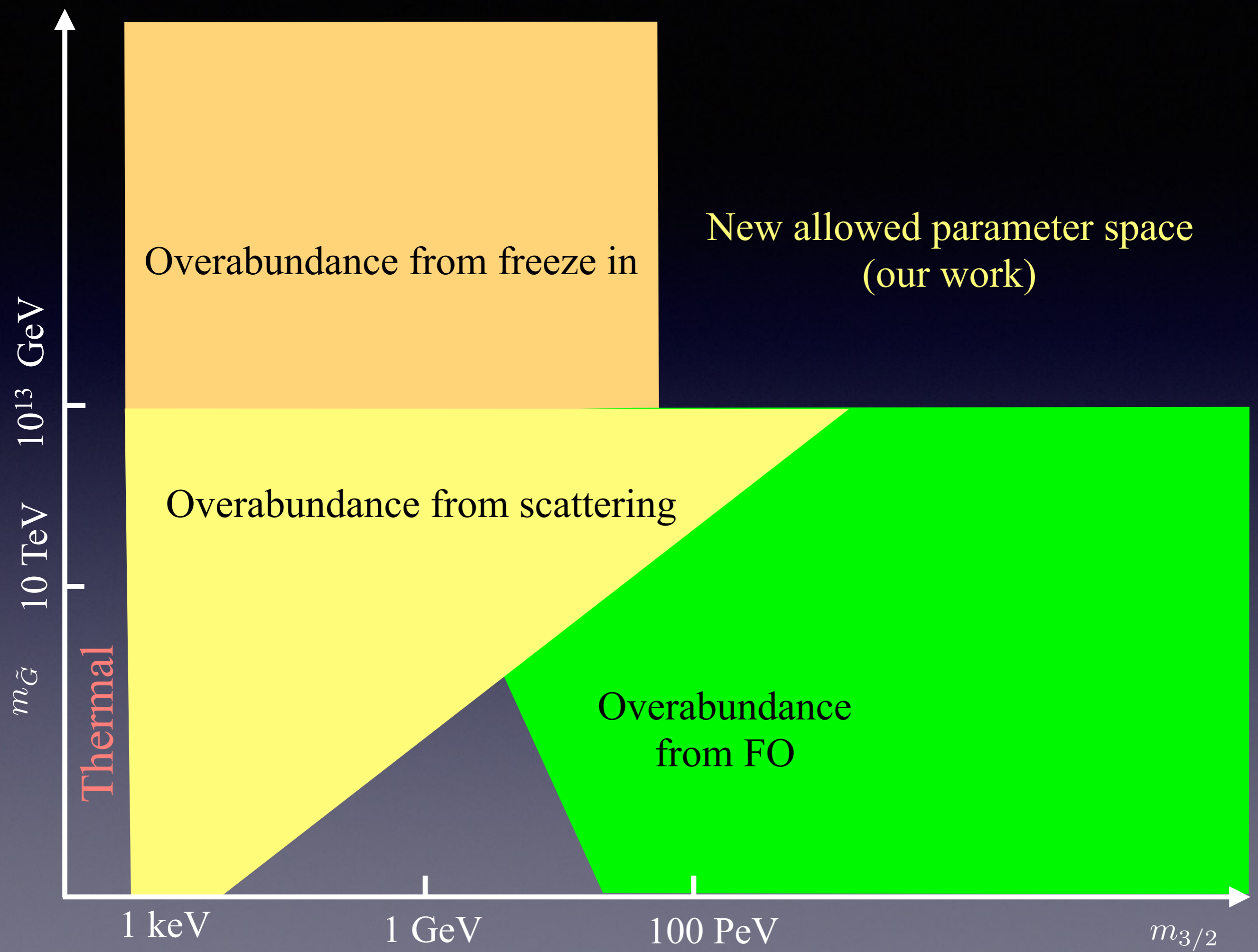


$$\Omega_{3/2}^{decay} h^2 = 0.11 \left(\frac{B_{3/2}}{1.3 \times 10^{-13}} \right) \left(\frac{y_\phi}{2.9 \times 10^{-5}} \right) \times \left(\frac{m_{3/2}}{0.1 \text{ EeV}} \right) \left(\frac{3 \times 10^{13} \text{ GeV}}{m_\phi} \right)^{1/2}$$

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



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



Overabundance from freeze in

New allowed parameter space
(our work)

Overabundance from scattering

Overabundance
from FO

Thermal

1 keV

1 GeV

100 PeV

$m_{3/2}$

$m_{\tilde{g}}$

10^{13} GeV

10 TeV

Message to the string
« inspired » theorist, or
supergravitymen :

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BE NOT AFRAID.

Message to the string « inspired » theorist, or supergravitymen :

Indeed, no need to add an *anti-D3
branes at the tip of a Klebanov-
Strassler throat à la KKL'T (sic!)*
to justify a TeV SUSY mass scale.

A SUSY mass scale at the energy
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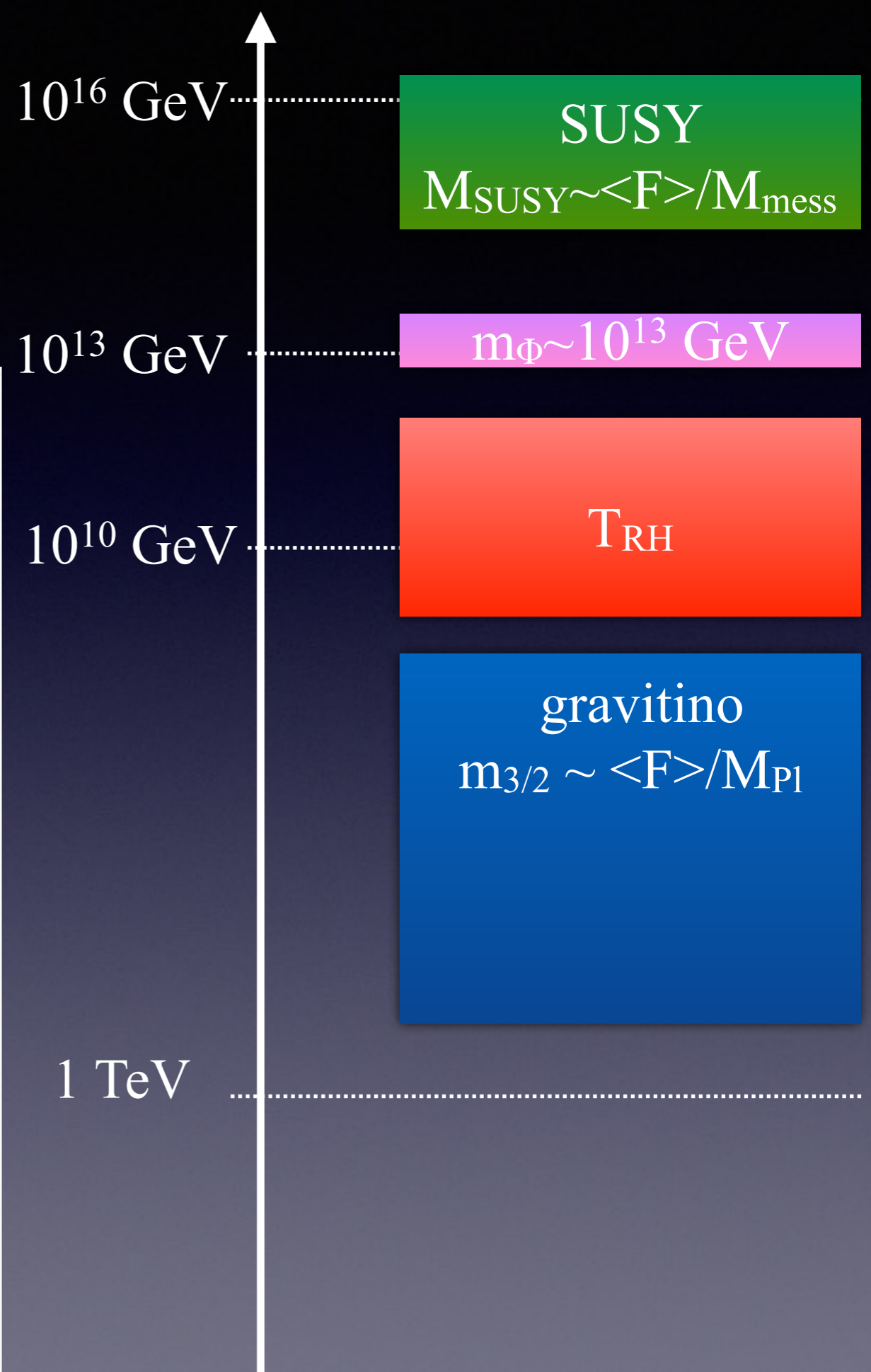
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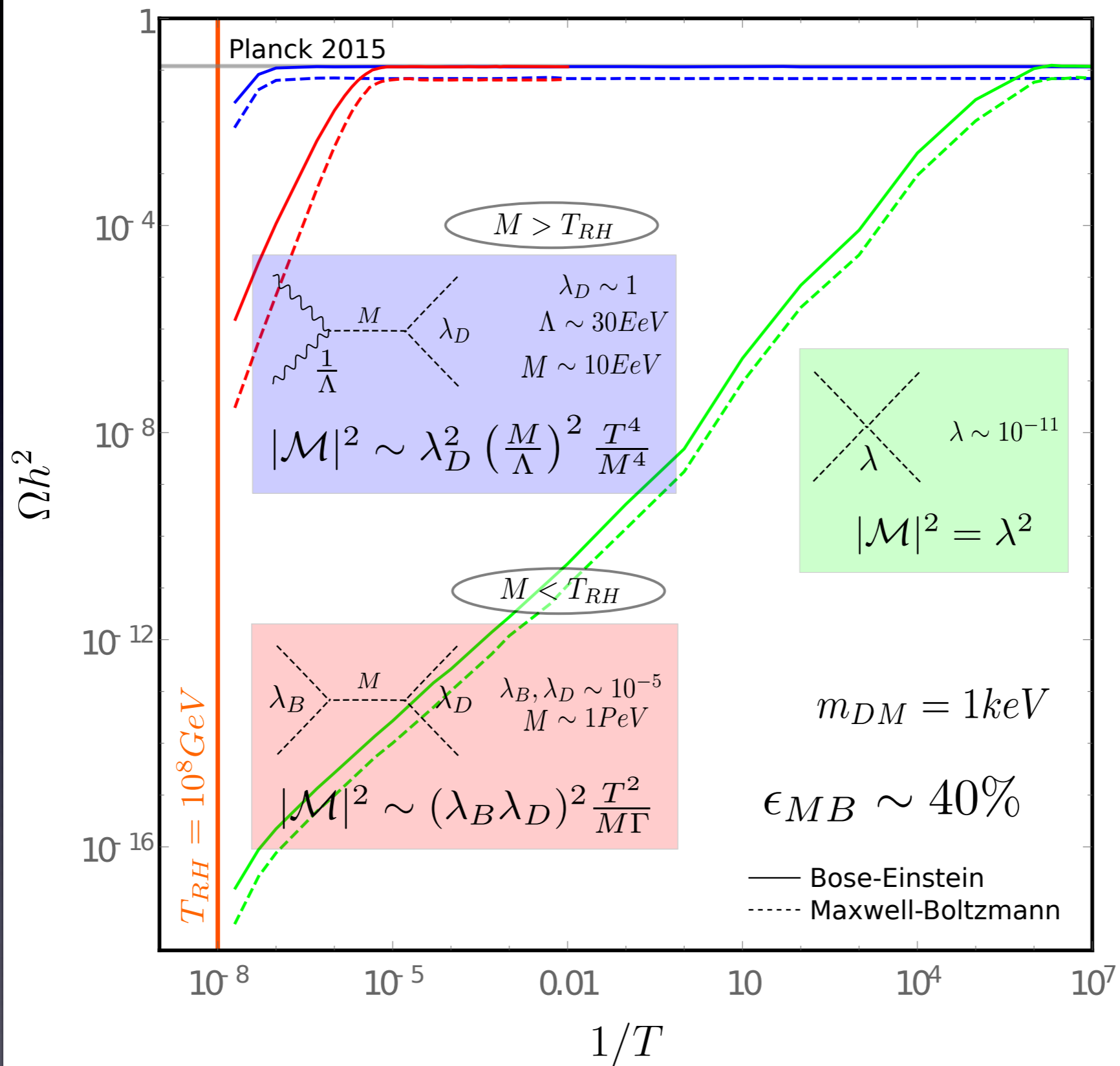
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Summary



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}

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

Indeed, the maximum temperature is not T_{RH}

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

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

Boltzmann equation for the decaying Inflaton

Boltzmann equation for the Radiation

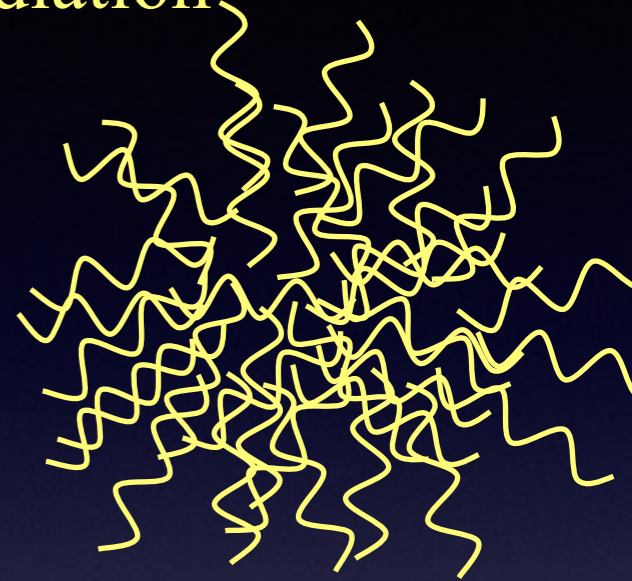
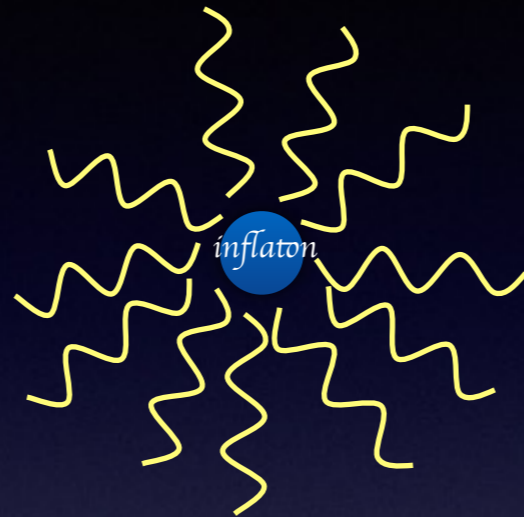
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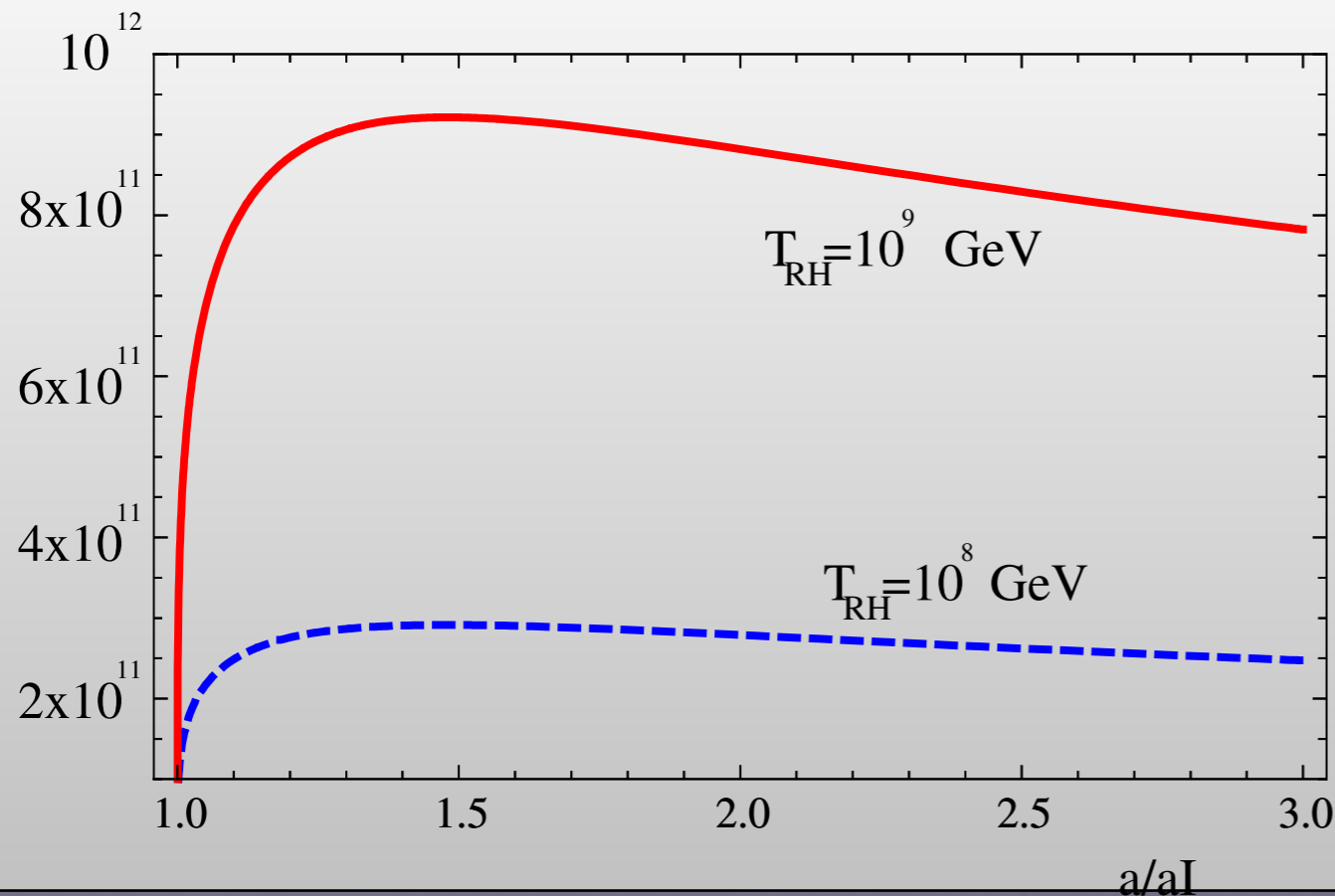
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Boltzmann equation for the decaying Inflaton

Boltzmann equation for the Radiation



T (GeV)



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

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.

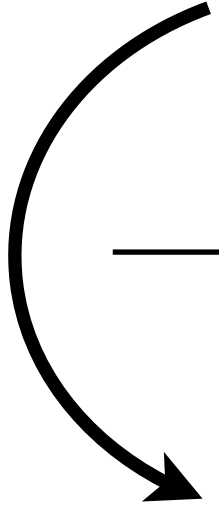
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$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi\rho_\phi = 0$$

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

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

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


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

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

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

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

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

R_χ^n does not depends on λ or M (!!)

Example, for $n=6$

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

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

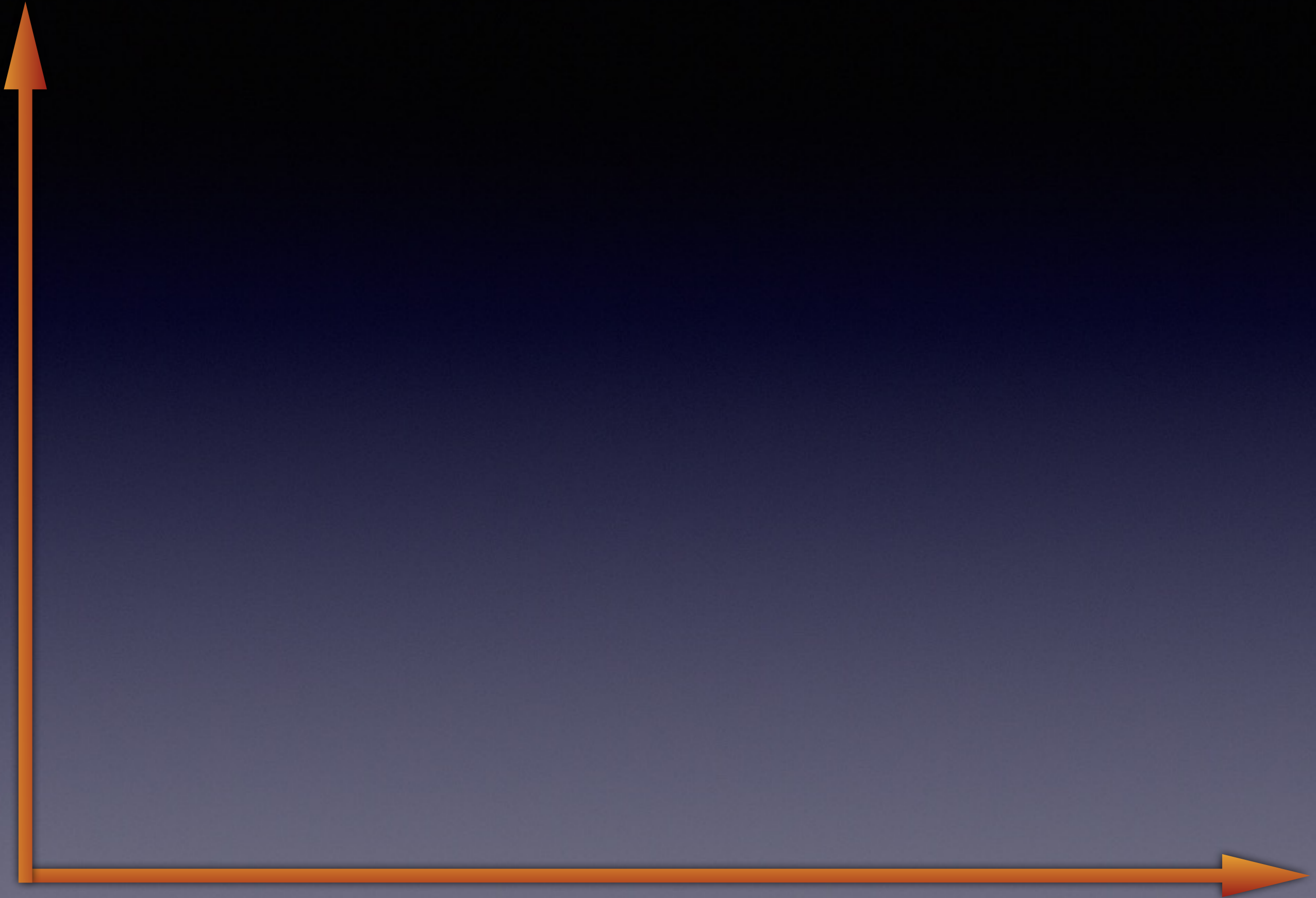
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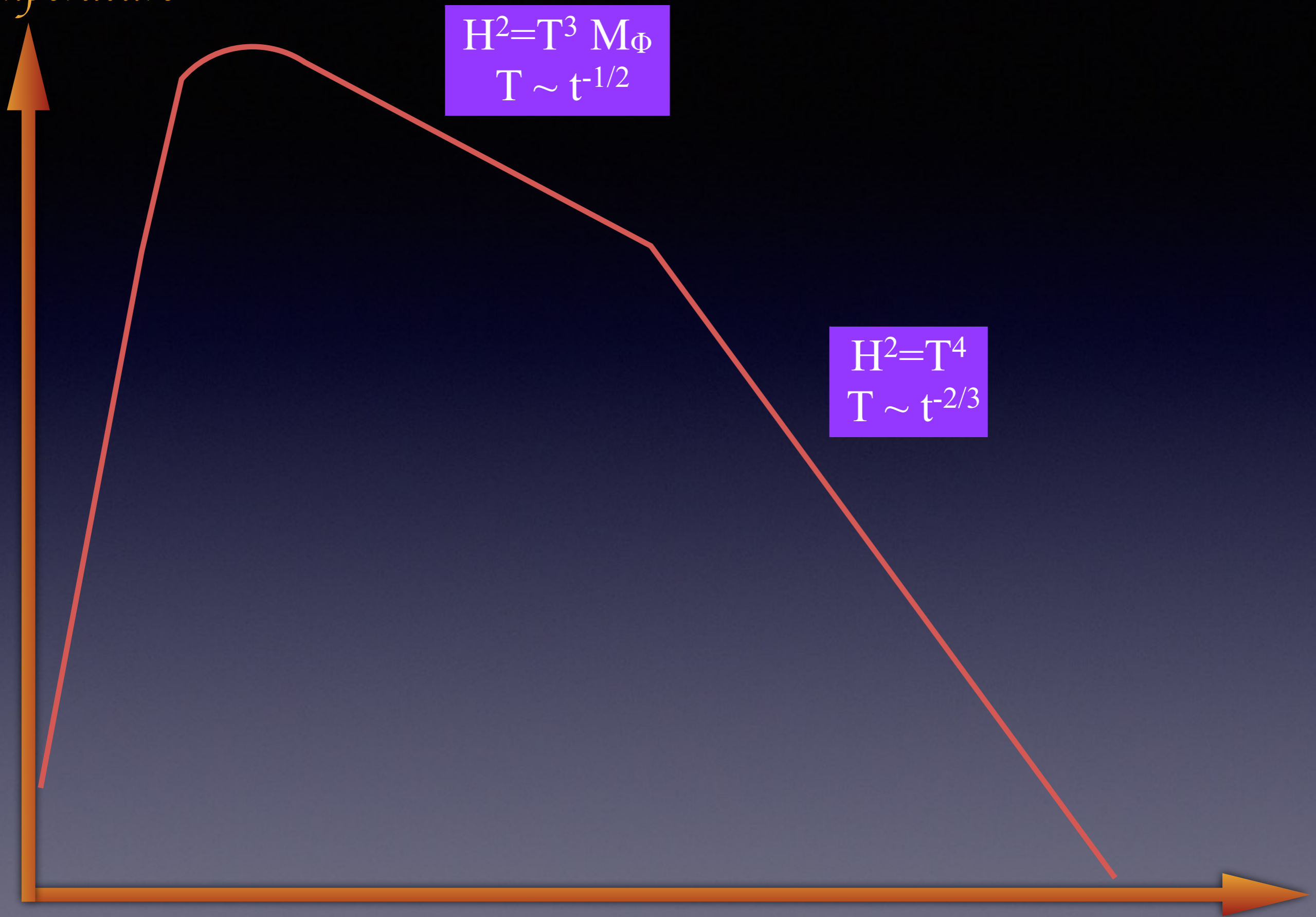
99.996 % of the dark matter is produced before reheating!!!

Temperature



time

Temperature



Temperature

$$H^2 = T^3 M_\Phi$$
$$T \sim t^{-1/2}$$

T_{RH}

$$H^2 = T^4$$
$$T \sim t^{-2/3}$$



time

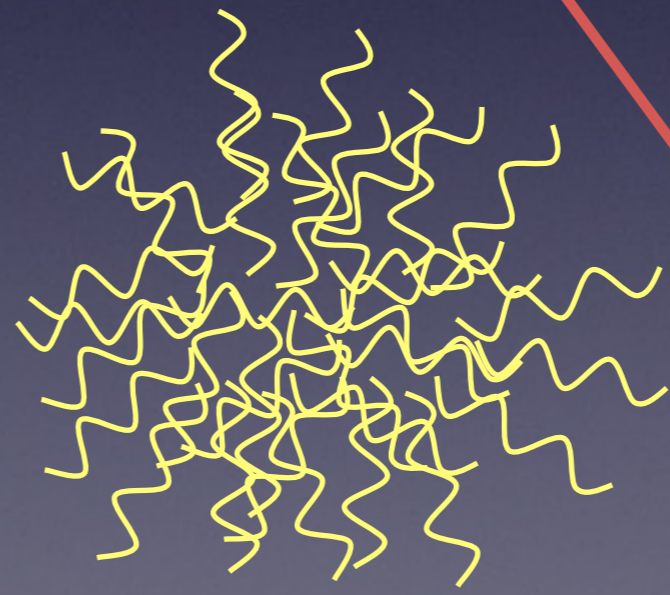
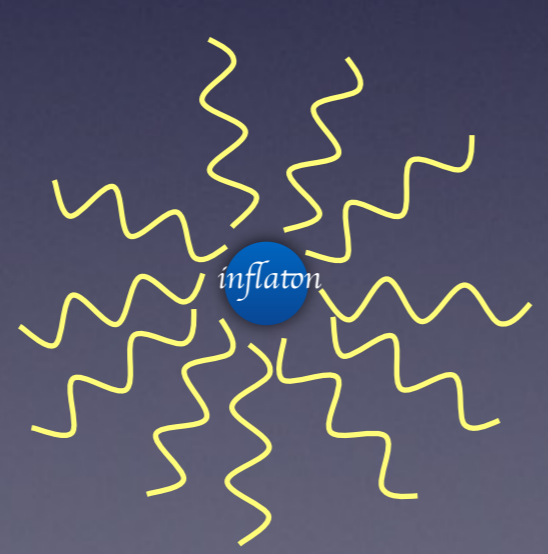
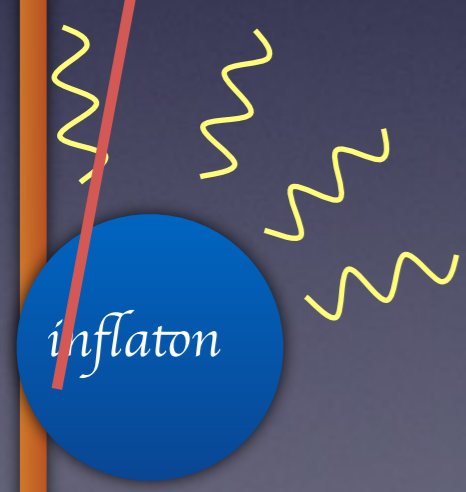
Temperature

$$H^2 = T^3 M_\Phi$$
$$T \sim t^{-1/2}$$

T_{RH}

DM production
10% if $\sigma \sim s / M^4$
50% if $\sigma \sim s^2 / M^6$
99.996% if $\sigma \sim s^3 / M^8$

$$H^2 = T^4$$
$$T \sim t^{-2/3}$$



time

Conclusion 1

be very careful when dealing with
non-thermal scenario

!!!!!!!

Conclusion 2

Conclusion 2

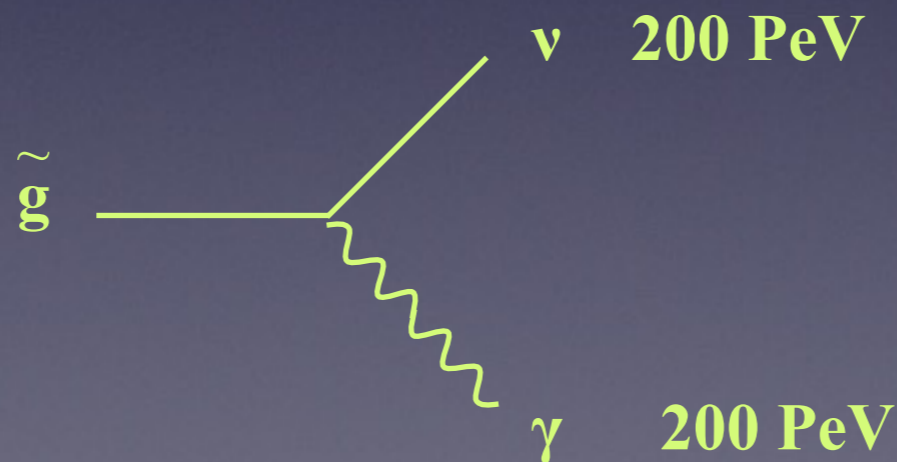
« And what is the signature of such models? »

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



Messages to keep in mind

Salviati:

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

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