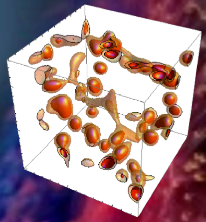
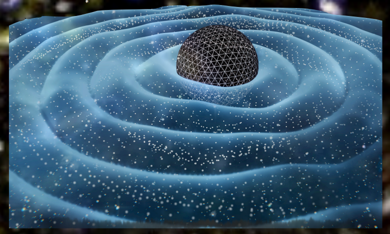
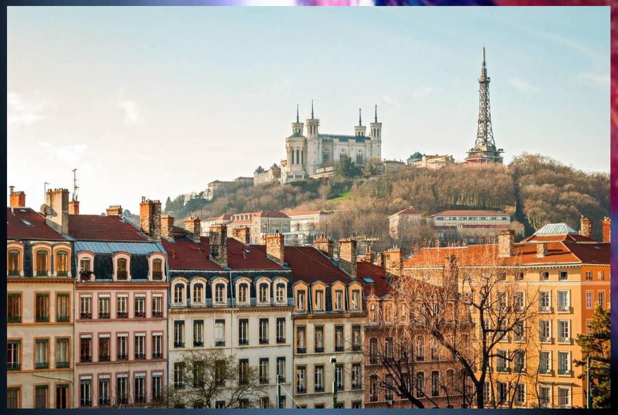
Recent interesting alternatives To FIMP/WIMP scenarios



ϕ





Yann Mambrini, IJCLab, Université Paris-Saclay

Astro@Paris-Saclay

November 7th 2025

Is there a room for an observable

DM $m_\chi \lesssim 100$ GeV ?

Is there a room for an observable

DM $m_\chi \lesssim 100$ GeV ?

Yes !!

5.4 Radiative processes in Astrophysics part I : the non-relativistic case 281

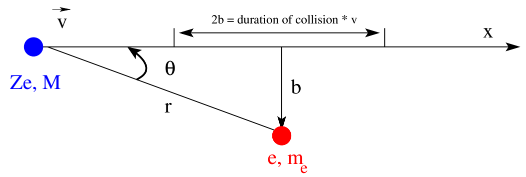


Fig. 5.9 Interaction of a high energy particle of charge Ze with an electron at rest.

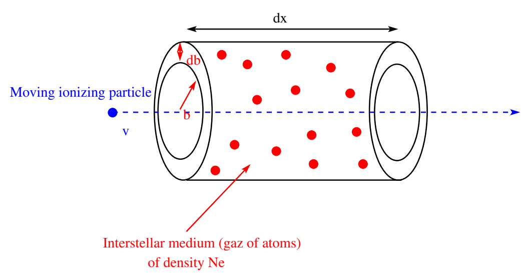


Fig. 5.10 Moving particle in an interstellar medium of density N_e.

distance at which the influence of the traveling particle on the electron is negligible. It corresponds roughly to the time when the orbital period is lower than the typical interaction time. In other words, if the electron takes more time to move around the nucleus than to interact with the moving particle, the electromagnetic influence of the latter becomes weak. If one write τ the interacting time and ν_0 the frequency of the rotating electron in the atom ($\nu_0 = \omega_0/2\pi$), it corresponds to

$$\tau \simeq \frac{2b}{v} < \frac{1}{\nu_0} \;\Rightarrow\; b < \frac{v}{2\nu_0} = b_{max} \tag{5.37}$$

The lower limit b_{min} can be obtained if we suppose, by a quantum treatment and the application of the uncertainty principle, that the maximum energy transfer is $\Delta p_{max} = 2m_e v$ (because as we discussed earlier, the maximum velocity transferred to the electron is $2v$) from $\Delta p \Delta x \gtrsim \hbar$ (Heisenberg principle) we have $\Delta x \gtrsim \hbar/2m_e v$. We can then write

420 B Particle Physics

The two parts of the Lagrangian one needs to compute the scalar annihilation of Dark Matter $SS \to h \to \bar{f} f$ are (see B.235)[9]

$$\mathcal{L}_{HSS} = -\lambda_{HS}\frac{M_W}{2g} hSS \;\to C_{HSS} = -i\frac{\lambda_{HS}M_W}{g}$$
$$\text{and}\;\; \mathcal{L}_{Hff} = -\frac{g m_f}{2M_W} h\bar{f}f \;\to C_{Hff} = -i\frac{g m_f}{2M_W} \tag{B.145}$$

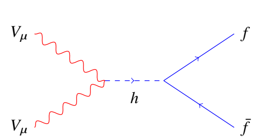
which gives

$$|\mathcal{M}|^2 = \frac{\lambda_{HS}^2 m_f^2 (s/2 - 2m_f^2)}{(s - M_H^2)^2 + \Gamma_H^2 M_H^2} \tag{B.146}$$

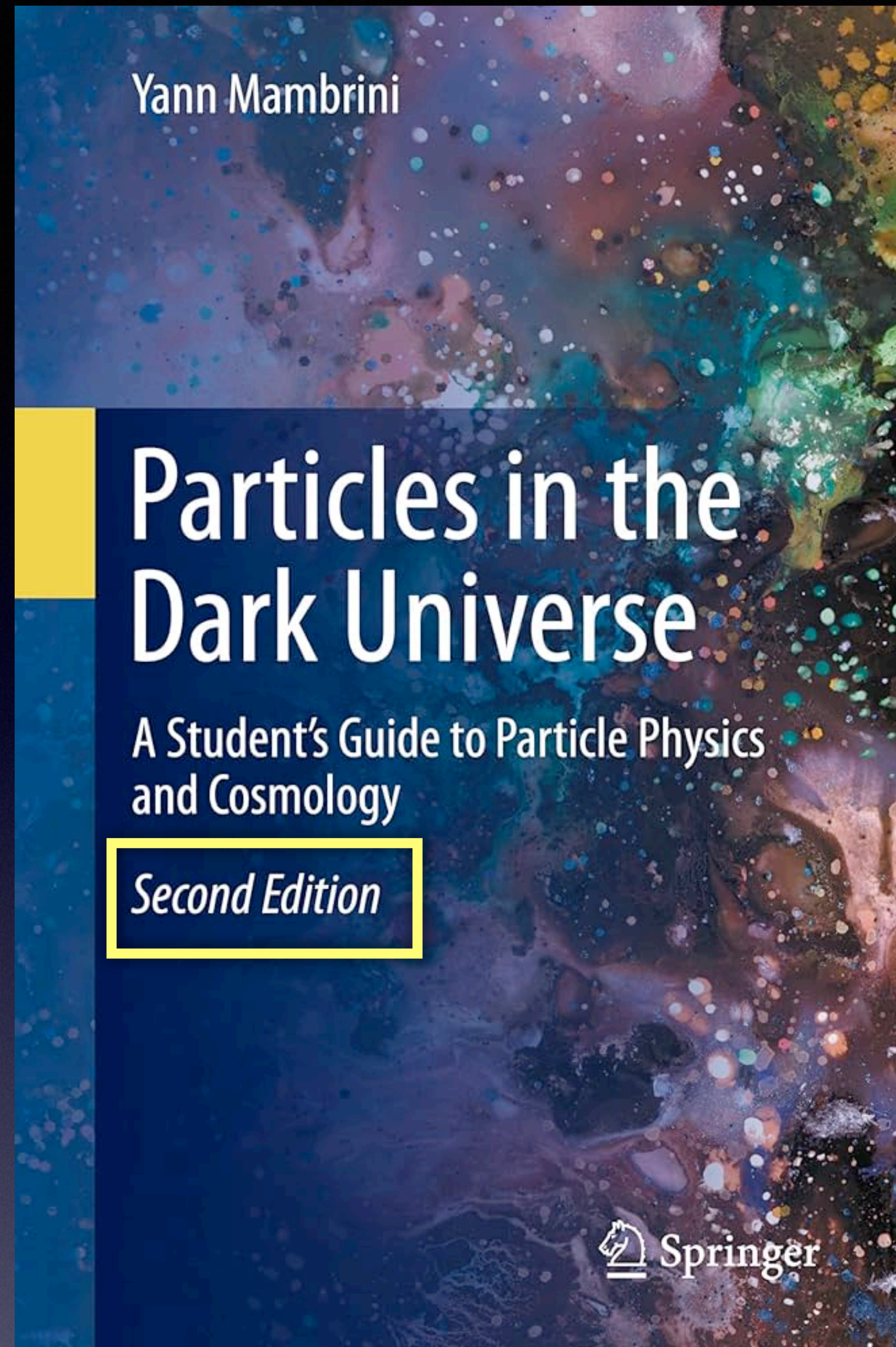
Γ_H being the width of the Higgs boson (including its own decay into SS, see next section). When ones implement this value of $|\mathcal{M}|^2$ into Eq.(B.111) one obtains after simplification

$$\langle\sigma v\rangle^S_{f\bar{f}} = \frac{|\mathcal{M}|^2}{8\pi s}\sqrt{1 - \frac{m_f^2}{M_S^2}} = \frac{\lambda_{HS}^2 (M_S^2 - m_f^2) m_f^2}{16\pi M_S^2 (4M_S^2 - M_H^2)^2}\sqrt{1 - \frac{m_f^2}{M_S^2}}. \tag{B.147}$$

B.4.4.11 Annihilation in the case of vectorial Dark Matter to pairs of fermions



One can compute this annihilation cross section by the normal procedure or noticing that a neutral vectorial dark matter of spin 1 corresponds to 3 degrees of freedom. After averaging on the spin one can then write $\langle\sigma v\rangle^V = \frac{3}{3\times 3}\langle\sigma v\rangle^S = \frac{1}{3}\langle\sigma v\rangle^S$. The academical computation for $V_\mu(p_1)V_\mu(p_2) \to f\bar{f}$ gives



2.1 The Context 77

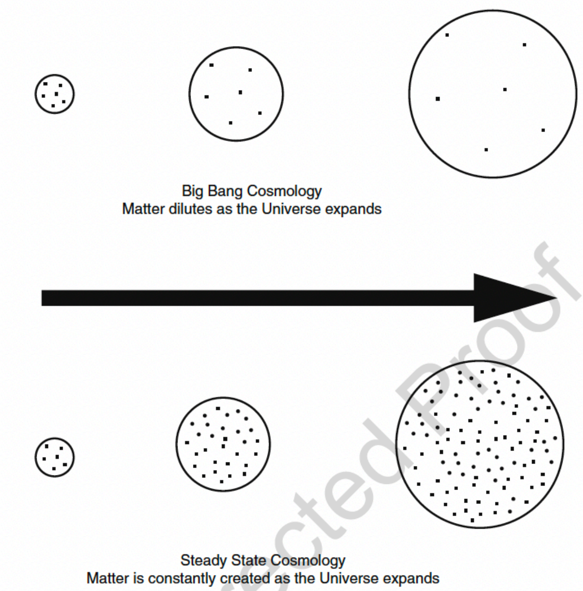


Fig. 2.9 Difference between the Steady State and the Big Bang cosmology

with

$$H_0^2 = \frac{\rho_m}{3M_P^2}. \tag{2.123}$$

and z the redshift being defined by Eq. (2.23). Evolution is therefore similar in every way to a de Sitter type Universe, but with a constant density of matter. It is therefore not possible to distinguish these two models by the flow of a source L_0 at $r = R_0\chi$, which will be redshifted in the same way in both cases

$$L = \frac{L_0}{4\pi r^2(1+z)^2}. \tag{2.124}$$

On the other hand, *the number of sources* is completely different, since in the case of the steady state, the density remaining constant, the number of sources decreases in the past (for a smaller volume, fewer sources) whereas for Big Bang type models,

650+ pages, from inflation to dark matter detection.

2nd edition (+ PBH + unification + history of cosmological models…)

All what is needed to compute cross-sections, relic abundance, and retrace the history of a Dark Universe.

Preface and forewords by K. Olive, J. Peebles and J. Silk

Students/postdocs :

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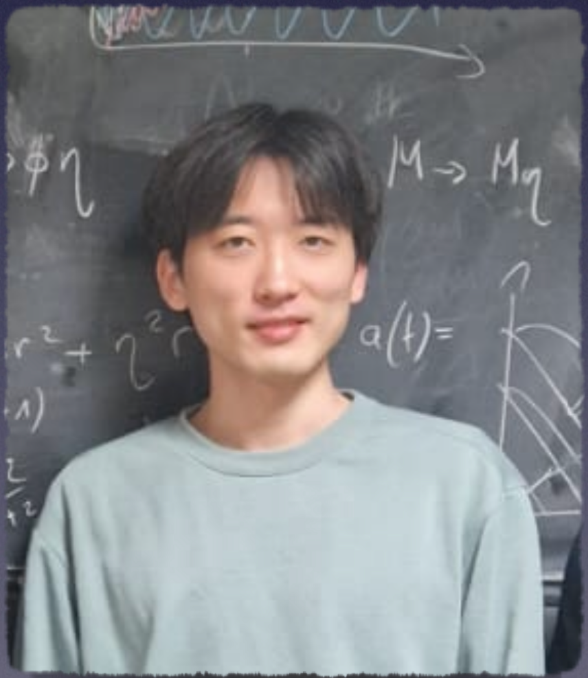
Mathieu Gross
(Paris-Saclay)

Mathias Pierre
(DESY)



Jong-Hyun Yoon
(CNU, Daejon)

DM : State of the art

Eur. Phys. J. C (2018) 78:203
https://doi.org/10.1140/epjc/s10052-018-5662-y

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Review

The waning of the WIMP? A review of models, searches, and constraints

Giorgio Arcadi[1,a], **Maíra Dutra**[2,b], **Pradipta Ghosh**[2,3,c], **Manfred Lindner**[1,d], **Yann Mambrini**[2,e], **Mathias Pierre**[2,f], **Stefano Profumo**[4,5,g], **Farinaldo S. Queiroz**[1,h]

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The Waning of the WIMP: Endgame?

Giorgio Arcadi[a,1,2], **David Cabo-Almeida**[b,1,2,3], **Maíra Dutra**[c,4,5], **Pradipta Ghosh**[d,6], **Manfred Lindner**[e,7], **Yann Mambrini**[f,8], **Jacinto P. Neto**[g,1,9,10], **Mathias Pierre**[h,11], **Stefano Profumo**[i,12,13], **Farinaldo S. Queiroz**[j,9,10,14]

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[4]Astroparticle Physics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, United States of America
[5]NASA Postdoctoral Program Fellow

Based (mainly) on

S. E. Henrich, **Y. Mambrini** and **K. A. Olive**,
``Ultra-relativistic freeze-out: a bridge from WIMPs to FIMPs,''
[arXiv:2511.02117 [hep-ph]].

S. E. Henrich, **M. Gross**, **Y. Mambrini** and **K. A. Olive**,
``Ultra-Relativistic Freeze-Out During Reheating,''
[arXiv:2505.04703 [hep-ph]].

S. E. Henrich, **Y. Mambrini** and **K. A. Olive**,
``Z' portal dark matter from post-inflationary reheating: WIMPs, FIMPs, and UFOs''
[arXiv:2511.xxxxx [hep-ph]].

C. Cosme, F. Costa and **O. Lebedev**,
``Temperature evolution in the Early Universe and freeze-in at stronger coupling,''
[arXiv:2402.04743 [hep-ph]].

G. Belanger, N. Bernal and A. Pukhov,
``Z'-mediated dark matter with low-temperature reheating,''
[arXiv:2412.12303 [hep-ph]].

The DM paradigm in a nutshell

Contrarily to what is sometimes said, the problem of DM is not its *overabundance*, but its *underabundance*.

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1 DM particle for ~3 billions photons

⇒ high annihilation rate required ⇒ **possible detection**

The DM paradigm in a nutshell

Contrarily to what is sometimes said, the problem of DM is not its *overabundance*, but its *underabundance*.

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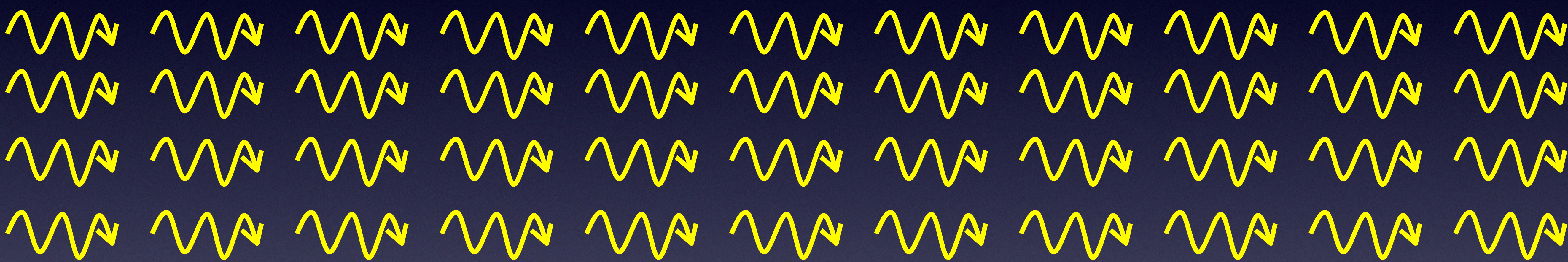
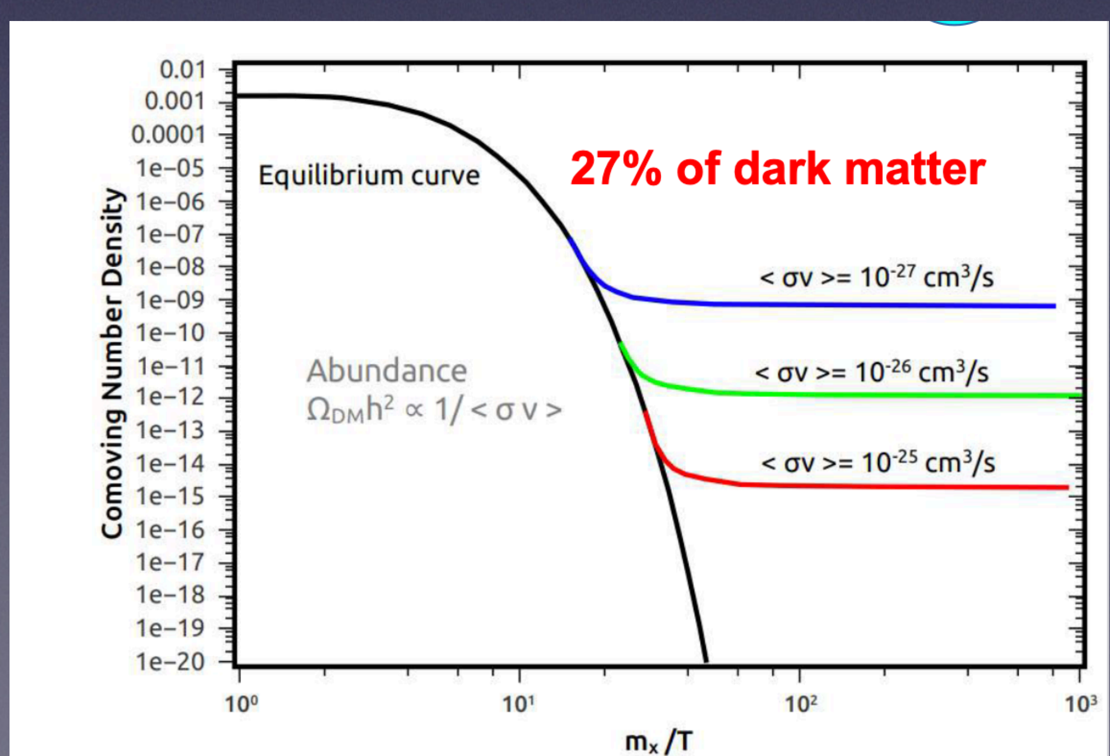
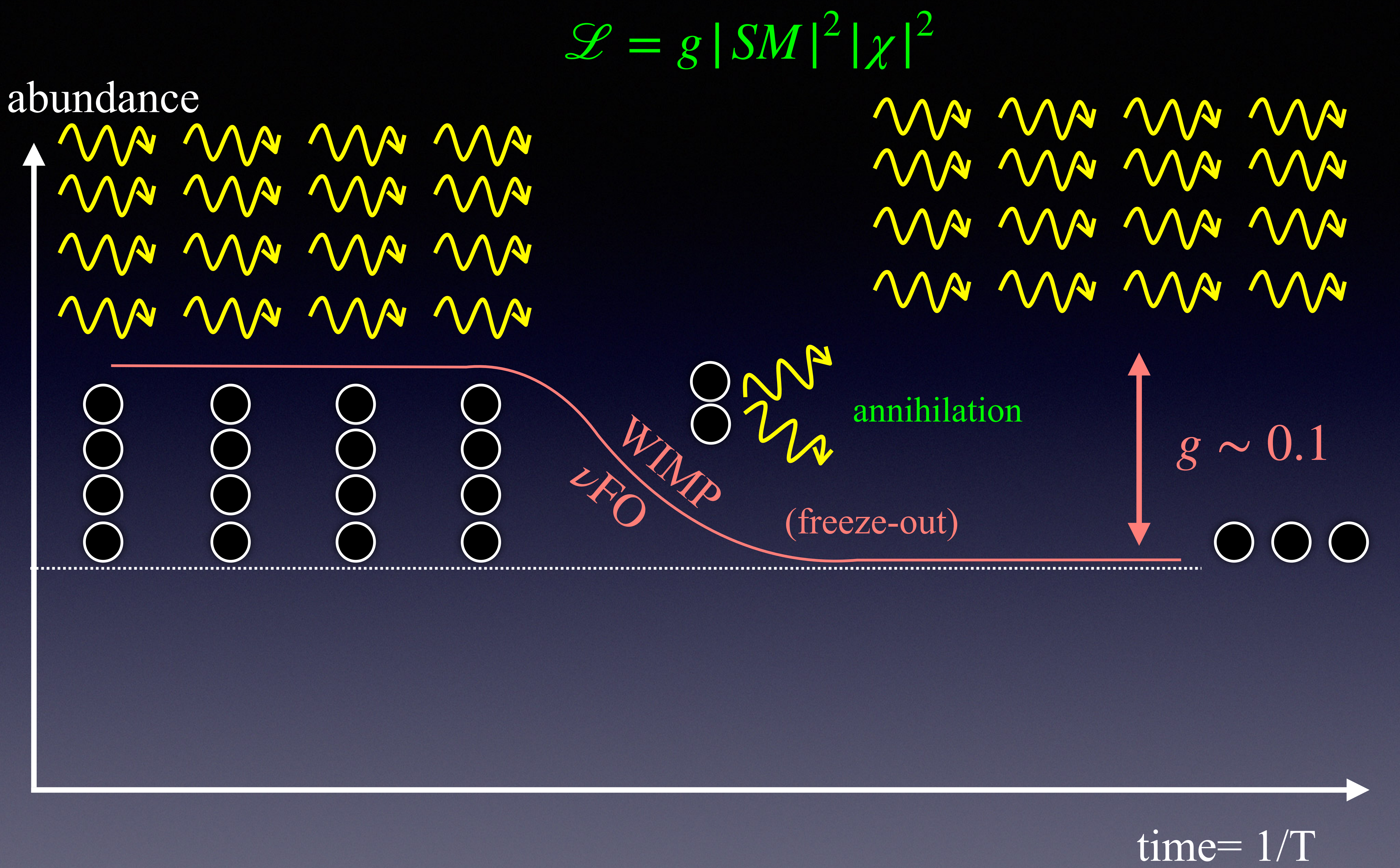


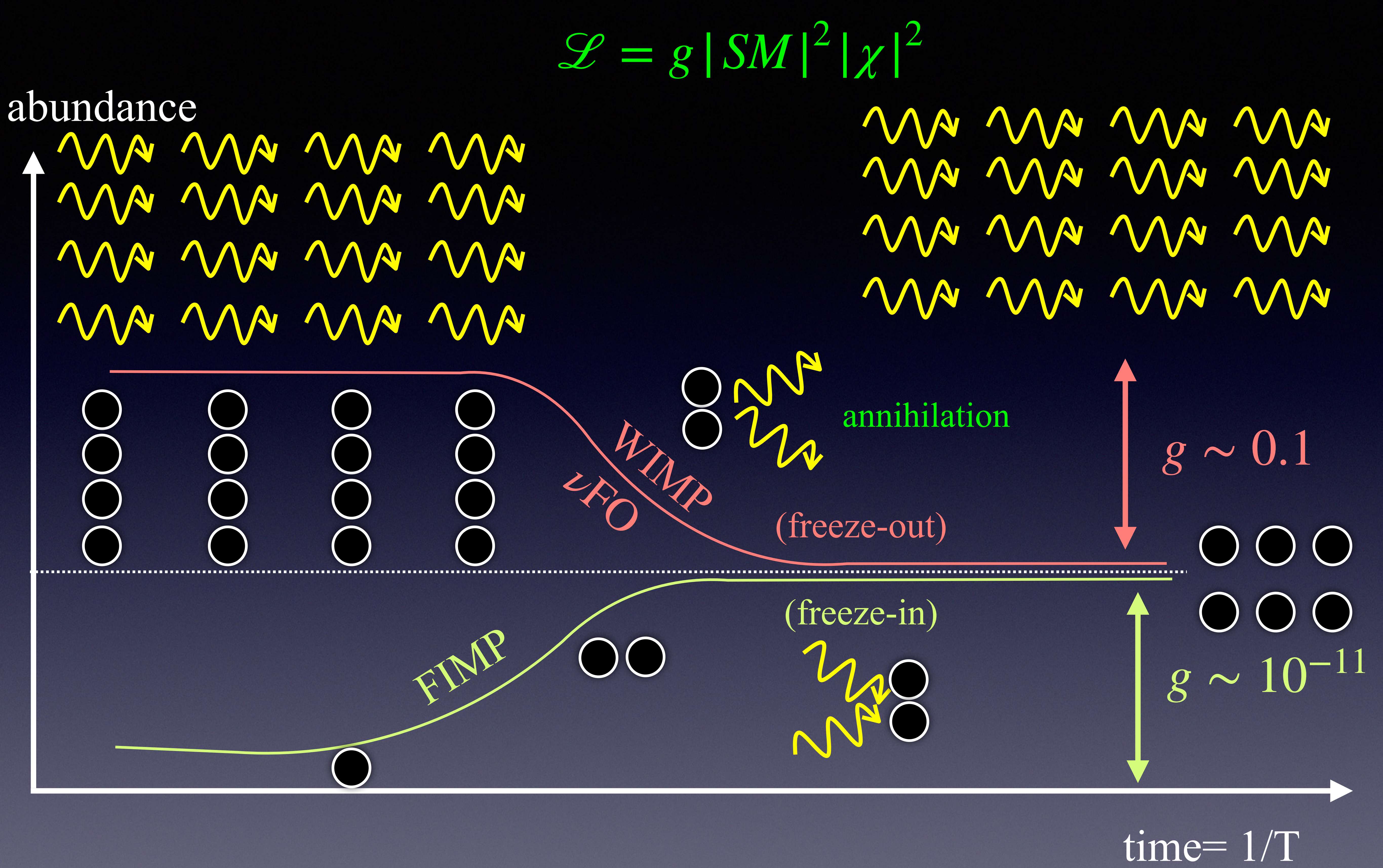


WIMP miracle :

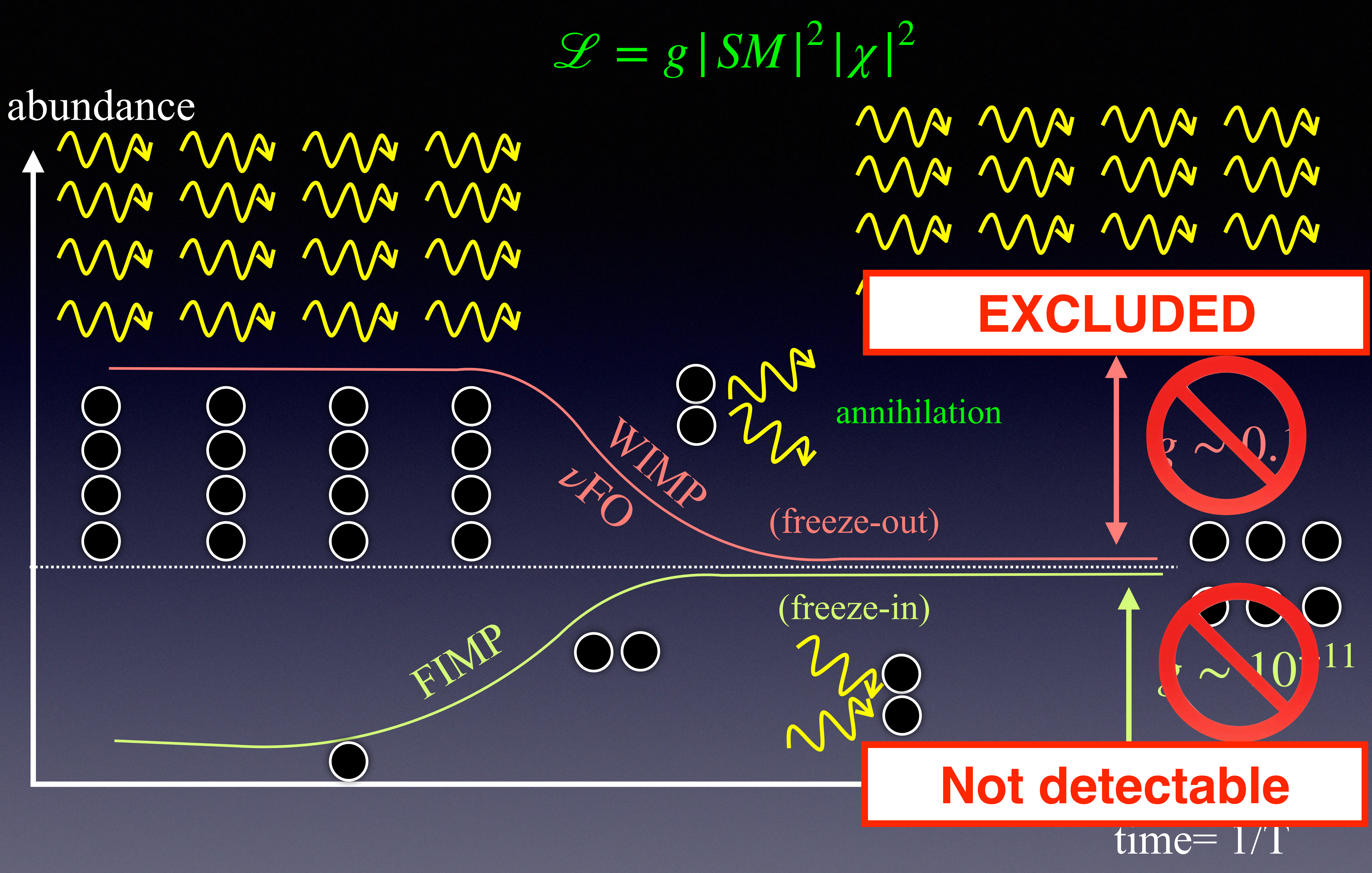
$$\mathscr{L} = g_\chi H^2 \chi^2 \quad \Rightarrow \quad g_\chi \simeq g_{EW}$$



$\mathscr{L} = g\,|SM|^2\,|\chi|^2$
abundance
annihilation
WIMP
νFO
(freeze-out)
$g \sim 0.1$
time= 1/T



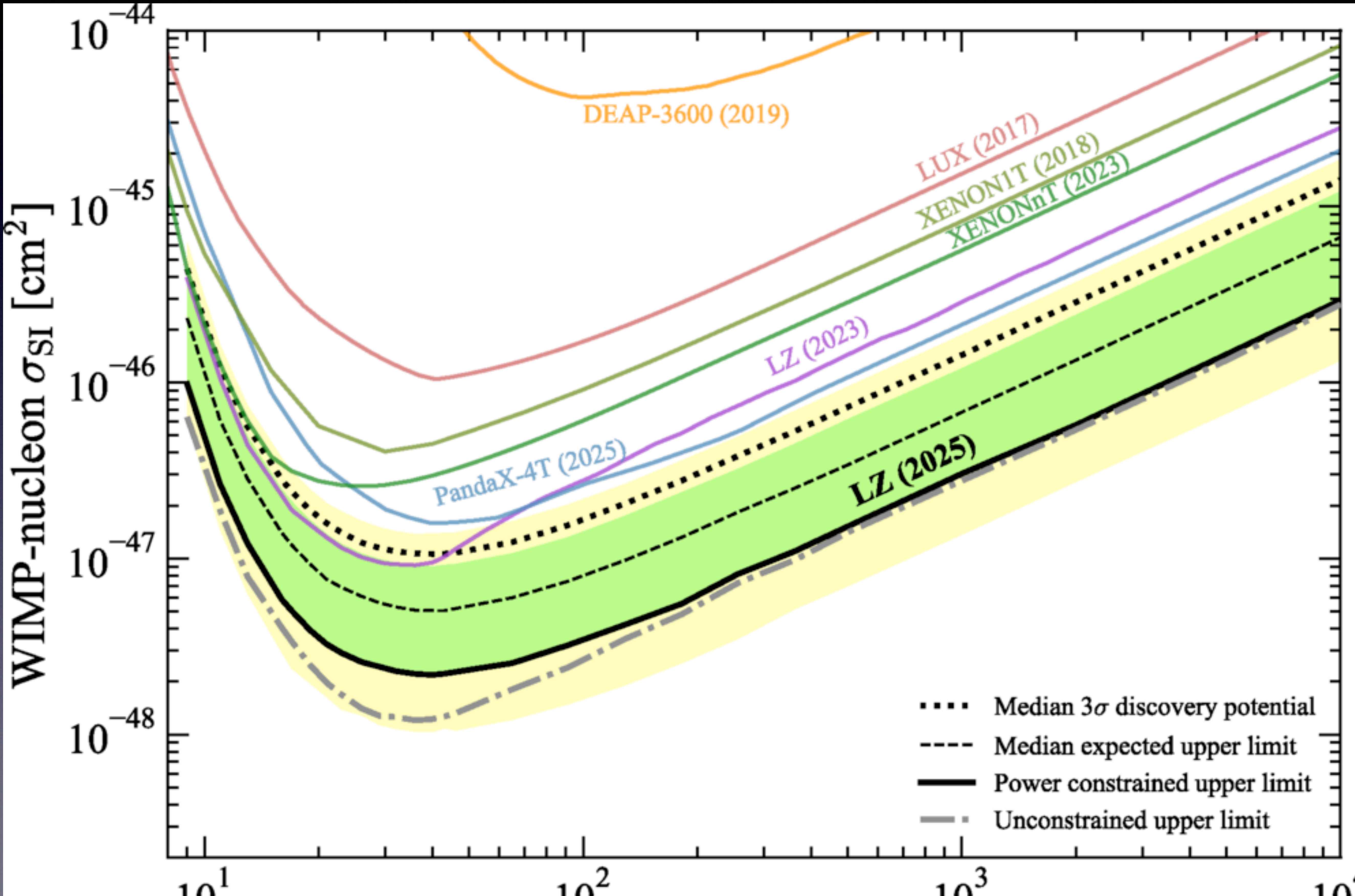
$\mathscr{L} = g\,|SM|^2\,|\chi|^2$
abundance
annihilation
WIMP
νFO
(freeze-out)
$g \sim 0.1$
(freeze-in)
FIMP
$g \sim 10^{-11}$
time= 1/T



$\mathscr{L} = g\,|SM|^2\,|\chi|^2$
abundance
WIMP
νFO
annihilation
(freeze-out)
EXCLUDED
(freeze-in)
FIMP
Not detectable
time= 1/T

WIMP tensions

Direct detection of DM



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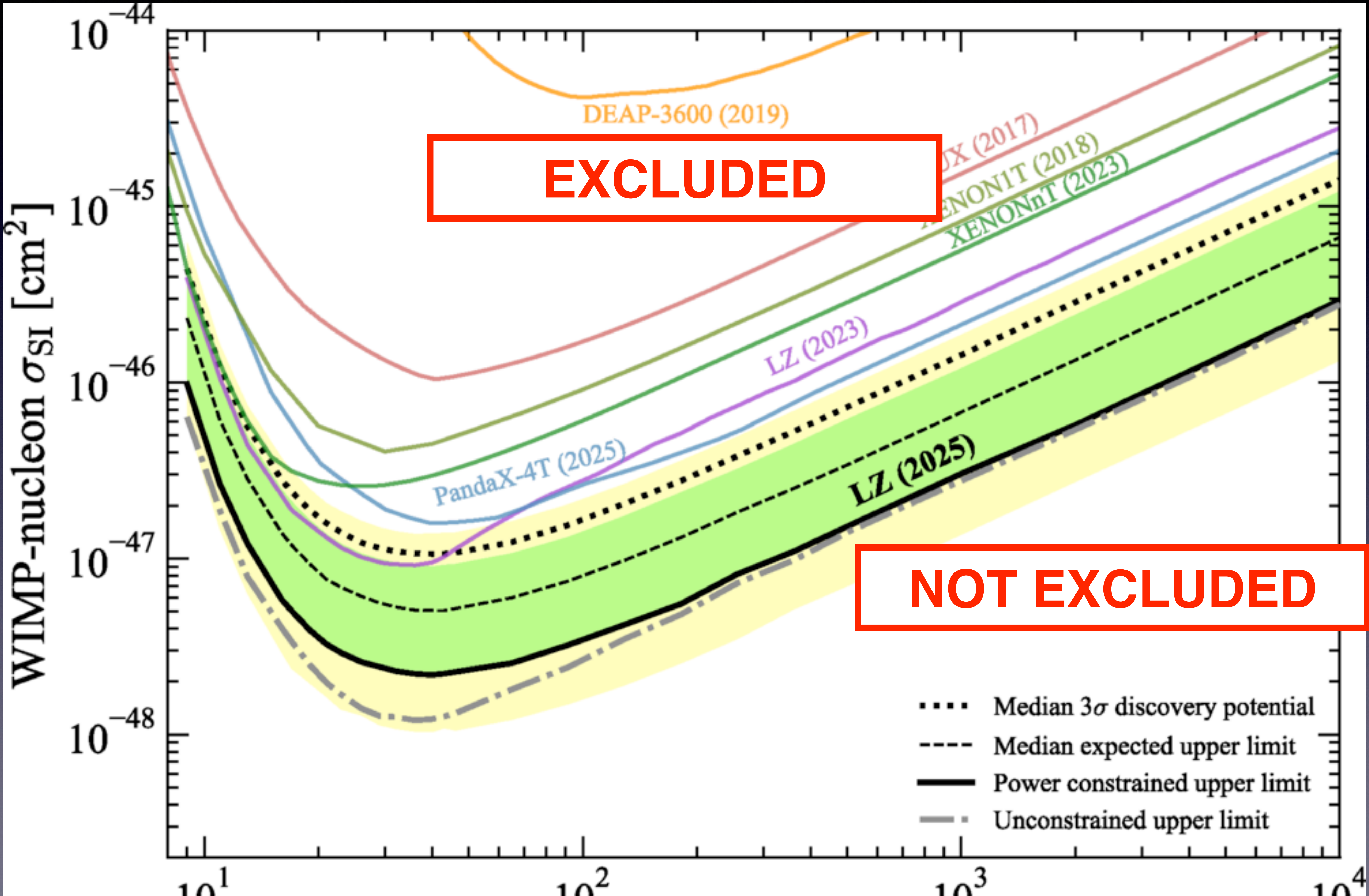
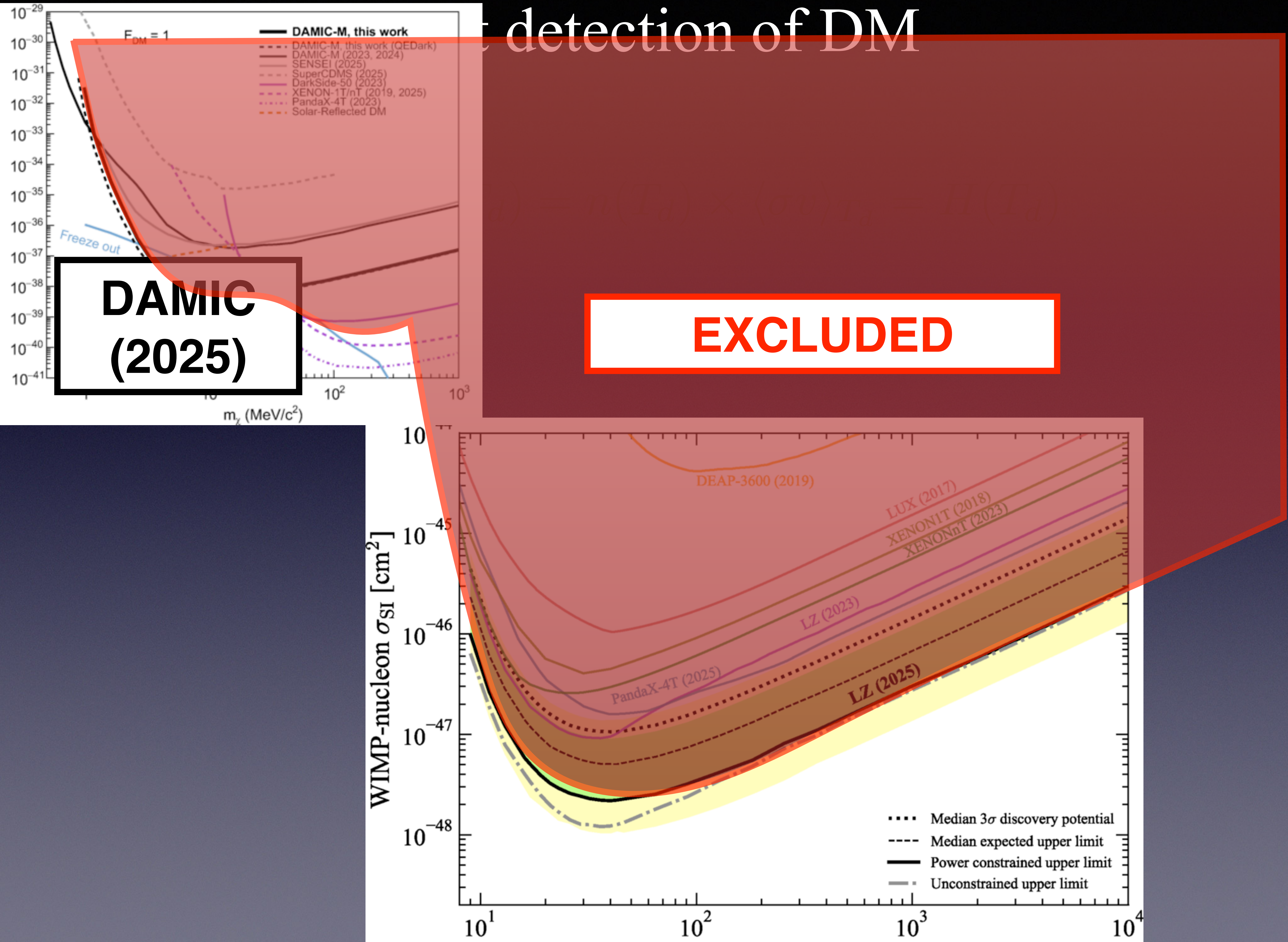


t detection of DM



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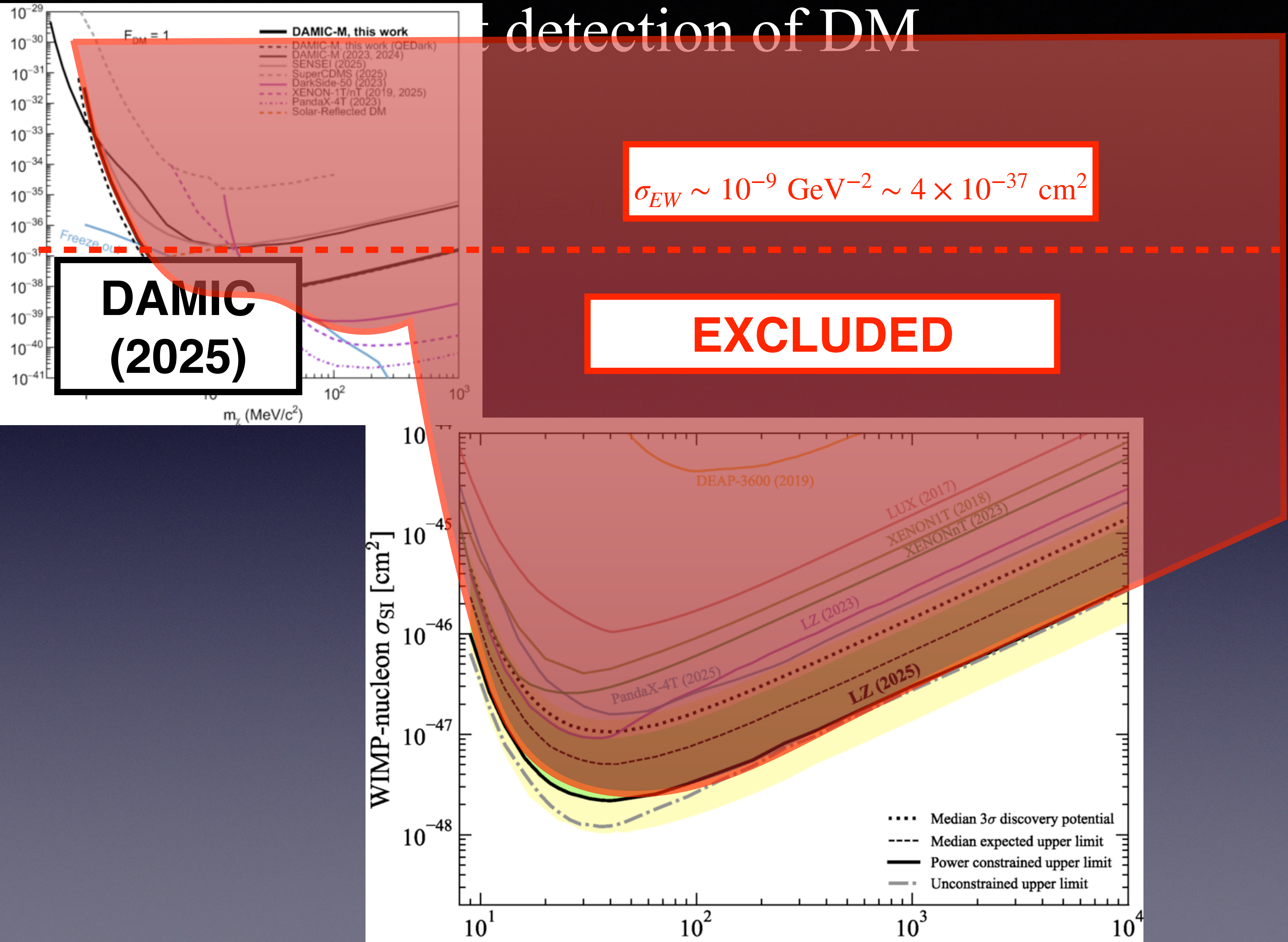
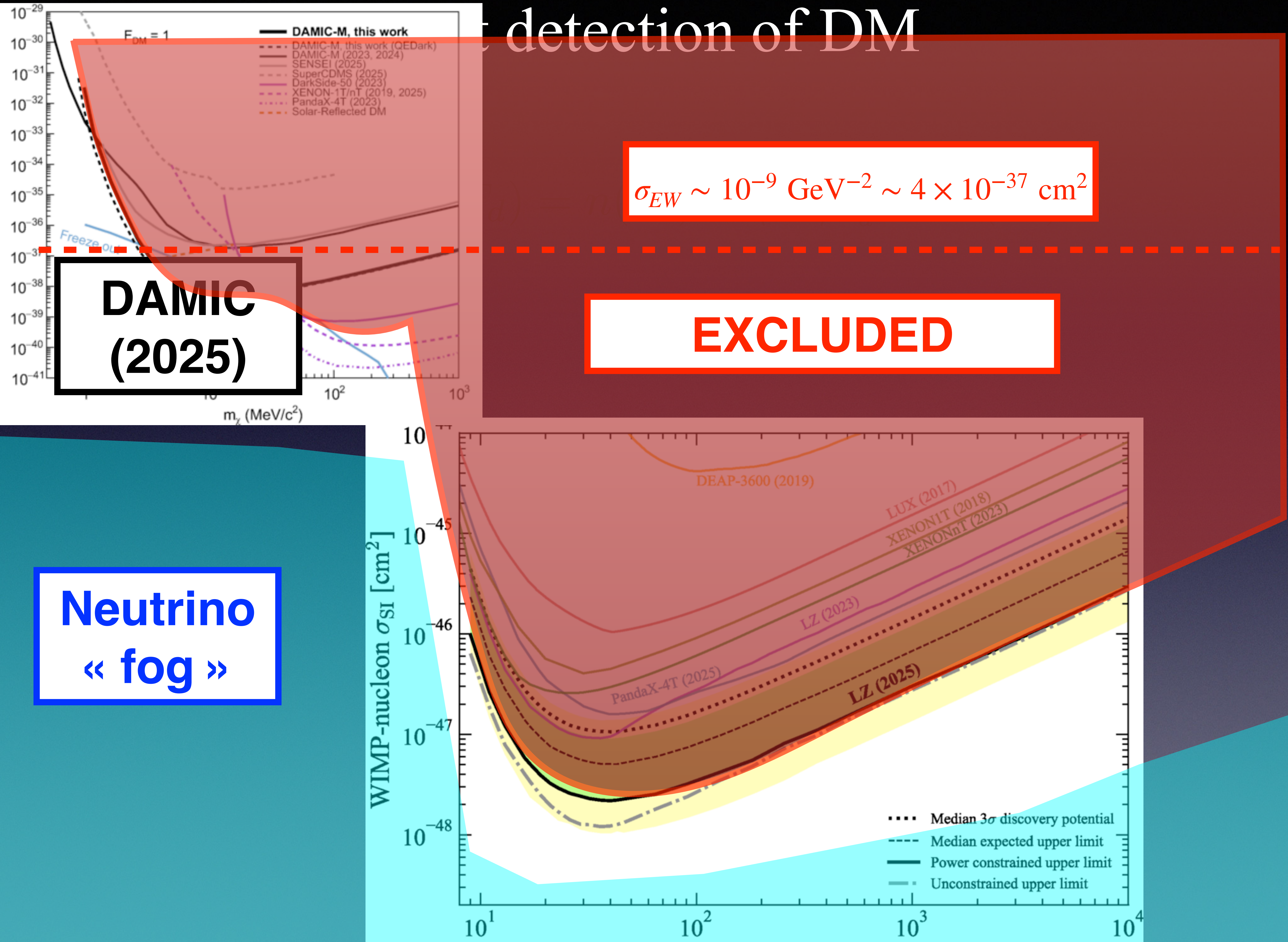


t detection of DM



Neglecting the initial production of dark matter is very risky (and surely wrong)*

*This problem is circumvented in the case of WIMP,
which dilutes dark matter in a thermal equilibrium, erasing the pre-thermal history.

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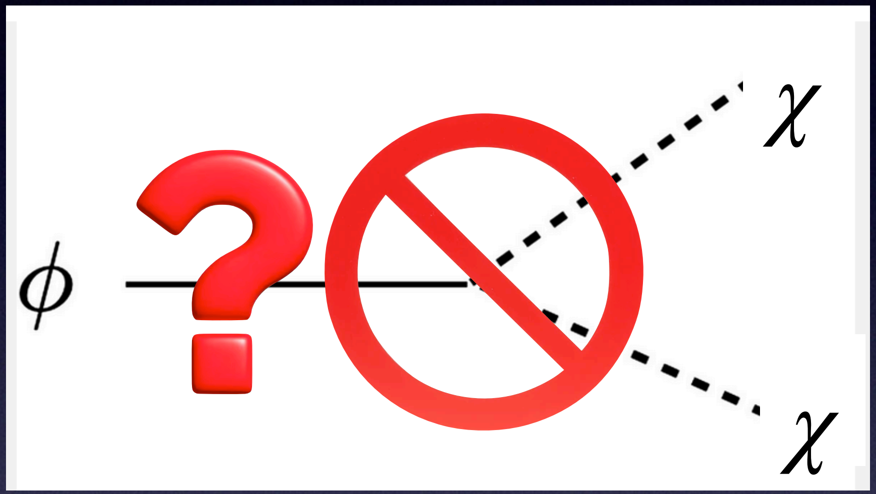
One need to justify why the processus
of reheating is « dark-matter blind »
(why the inflaton does not couple to DM?)



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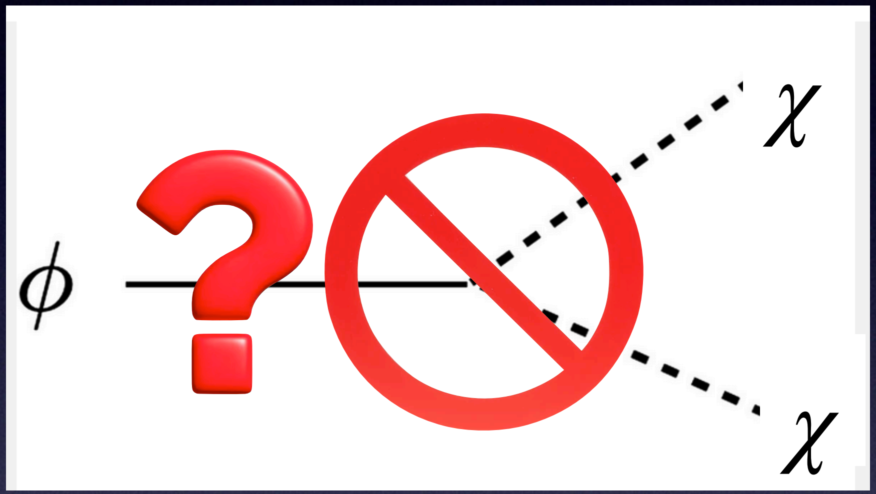
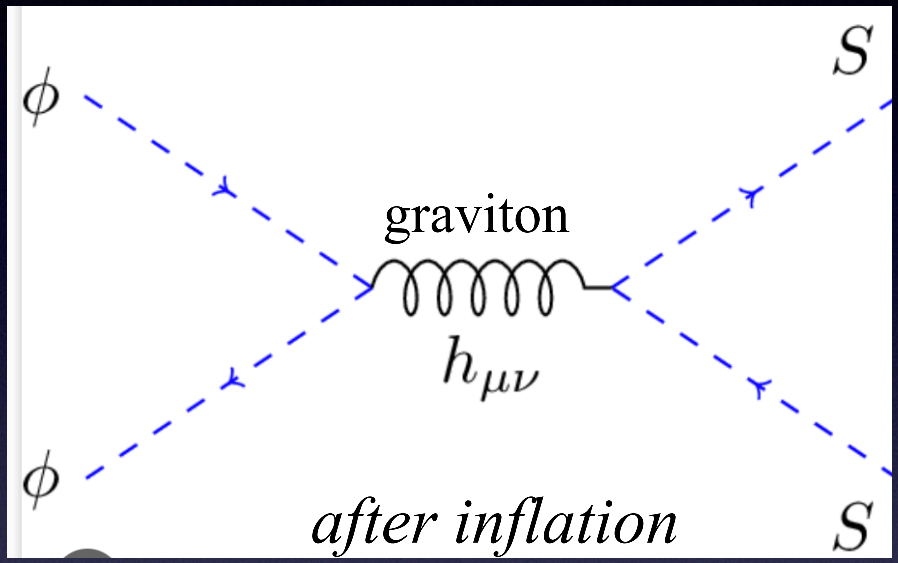


Even in the absence of couplings, gravity produces a large amount of DM by inflaton scattering after inflation…



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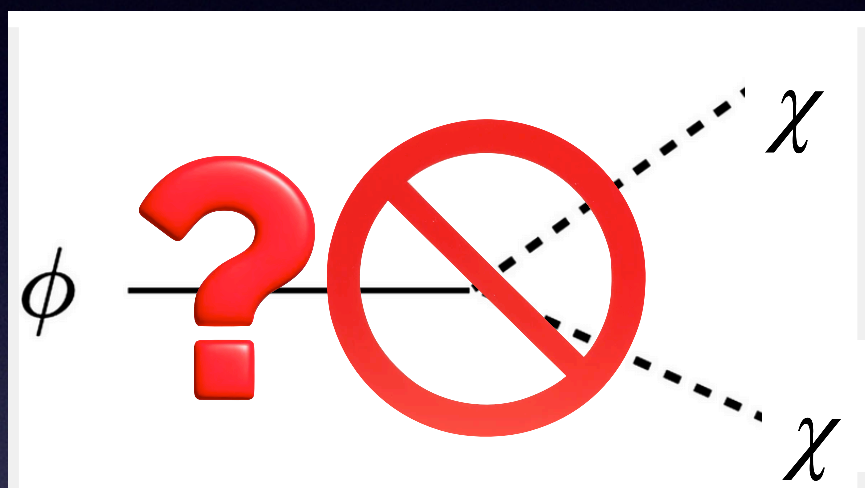

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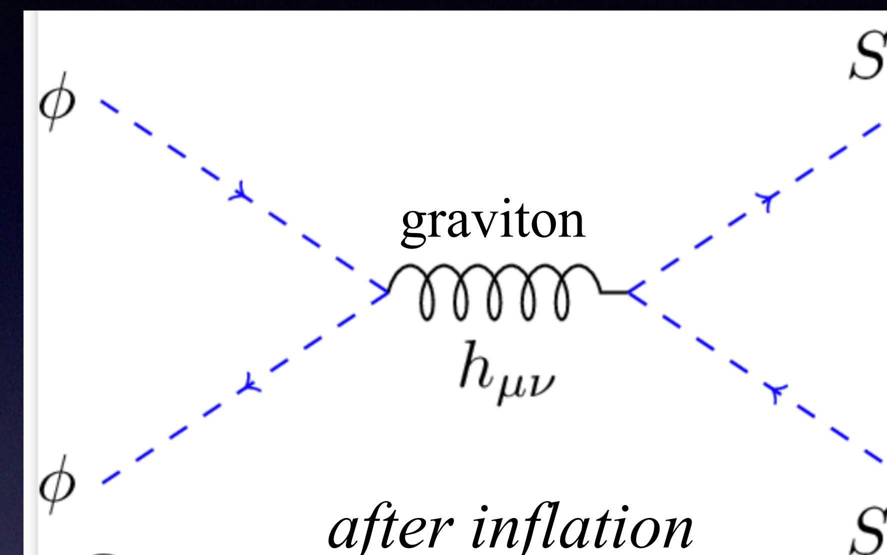
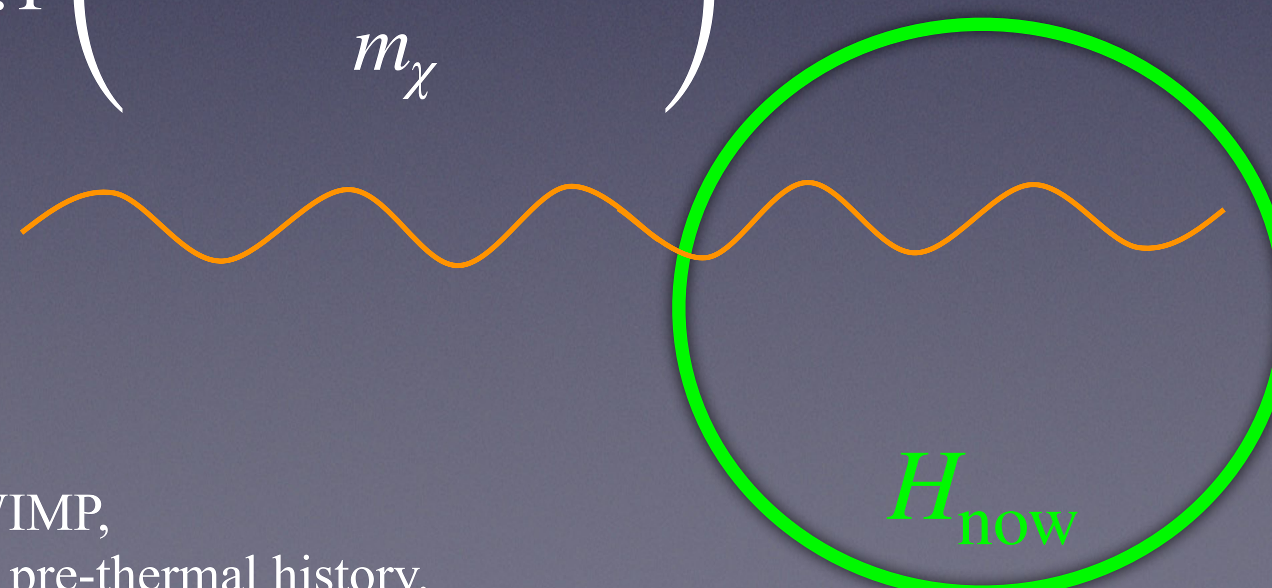


There exist modes which *exited the horizon* during inflation, and are caught back later

$$:\rho_\chi \sim H^2 \quad \Rightarrow \Omega_\chi h^2 \simeq 0.1 \left(\frac{4.3 \times 10^{20}\ \text{GeV}}{m_\chi} \right)$$



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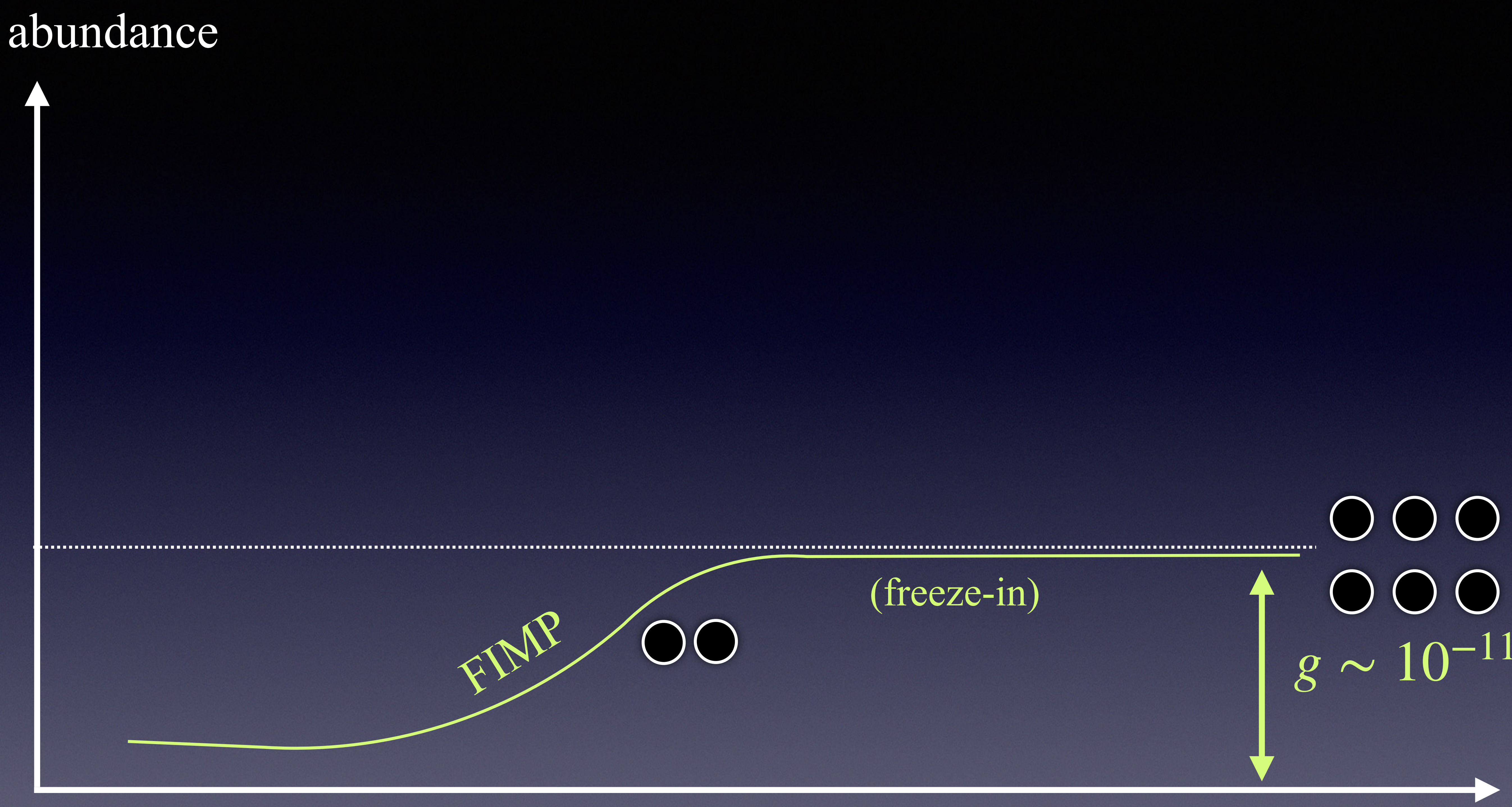
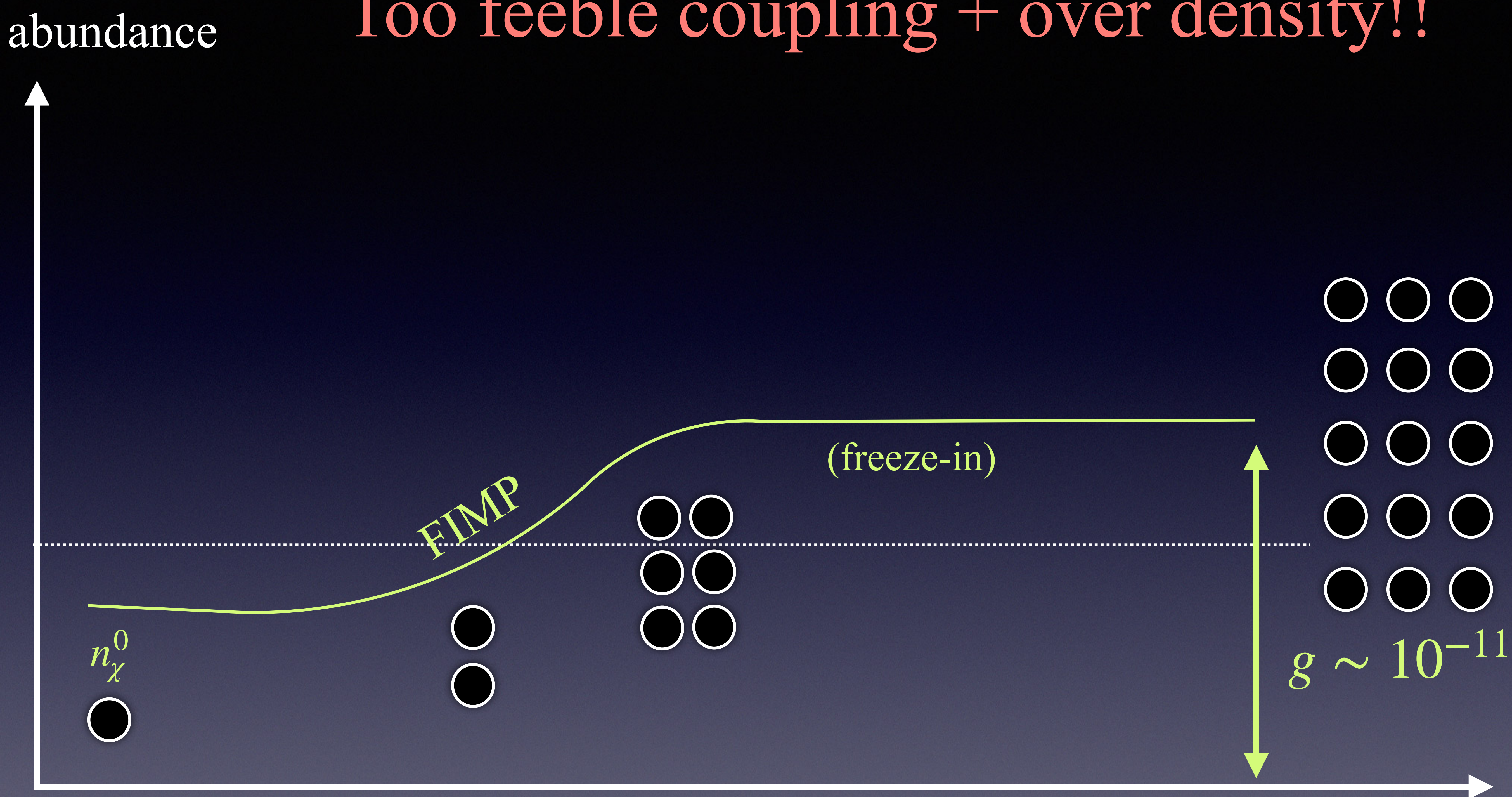

abundance
FIMP
(freeze-in)
$g \sim 10^{-11}$

Too feeble coupling + over density!!



Some numbers

The relic abundance is given by

$$\Omega h^2 = 6 \times 10^6 \times \left(\frac{n_\chi(T_{FO})}{T_{FO}^3} \right) \left(\frac{m_\chi}{1\ \mathrm{GeV}} \right)$$

with T_{FO} the freeze out temperature $\quad n_\gamma(T_{FO}) \sim T_{FO}^3$

The relic abundance is given by

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with T_{FO} the freeze out temperature $\quad n_\gamma(T_{FO}) \sim T_{FO}^3$

In the case of WIMP,

$$n_\chi(T_{FO})\langle \sigma v \rangle = H(T_{FO}) = \frac{T_{FO}^2}{M_P}; T_{FO} \simeq \frac{m_\chi}{30} \quad \Rightarrow \quad \frac{n_\chi}{T_{FO}^3} = \frac{30}{m_\chi M_P \langle \sigma v \rangle}$$

$$\text{or } \frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9} \text{ GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\Omega h^2 = 6 \times 10^6 \times \left(\frac{n_\chi(T_{FO})}{T_{FO}^3} \right) \left(\frac{m_\chi}{1\ \mathrm{GeV}} \right)$$

$$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

In the case of FIMP, we have

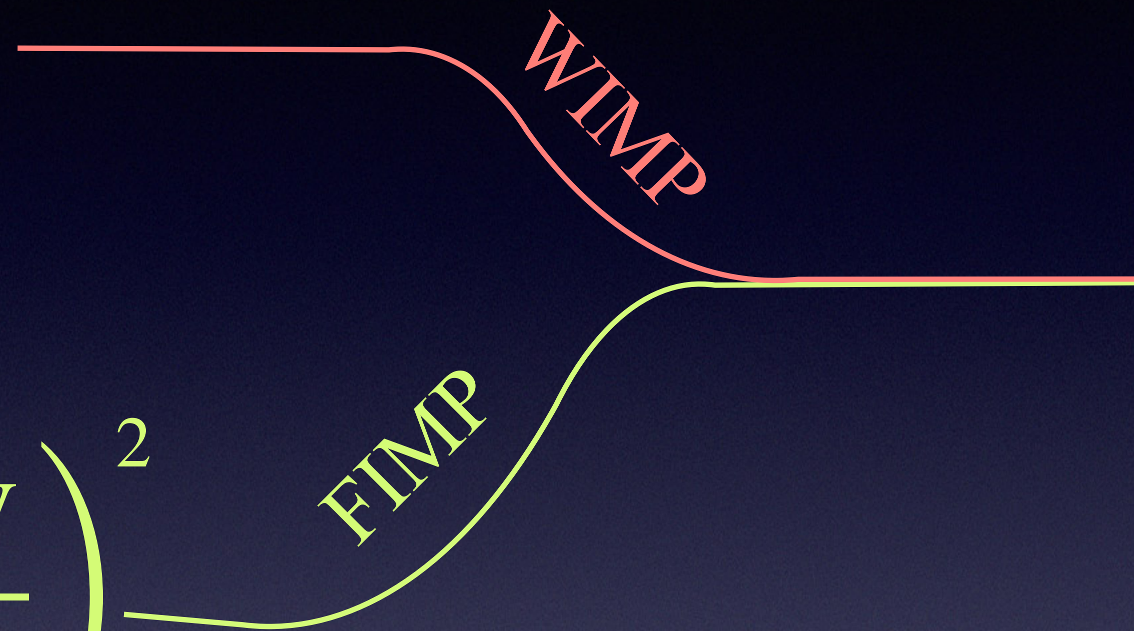
$$n_\chi(T_{FO}) = n_\gamma^2 \langle \sigma v \rangle H^{-1}(T_{FO})$$

$$\Rightarrow \frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{GeV}^{-2}} \right) \left(\frac{1\ \mathrm{GeV}}{m_\chi} \right)^2$$

$$\Omega h^2 = 6 \times 10^6 \times \left(\frac{n_\chi(T_{FO})}{T_{FO}^3} \right) \left(\frac{m_\chi}{1\ \text{GeV}} \right)$$

$$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \text{GeV}^{-2}} \right) \left(\frac{1\ \text{GeV}}{m_\chi} \right)^2$$

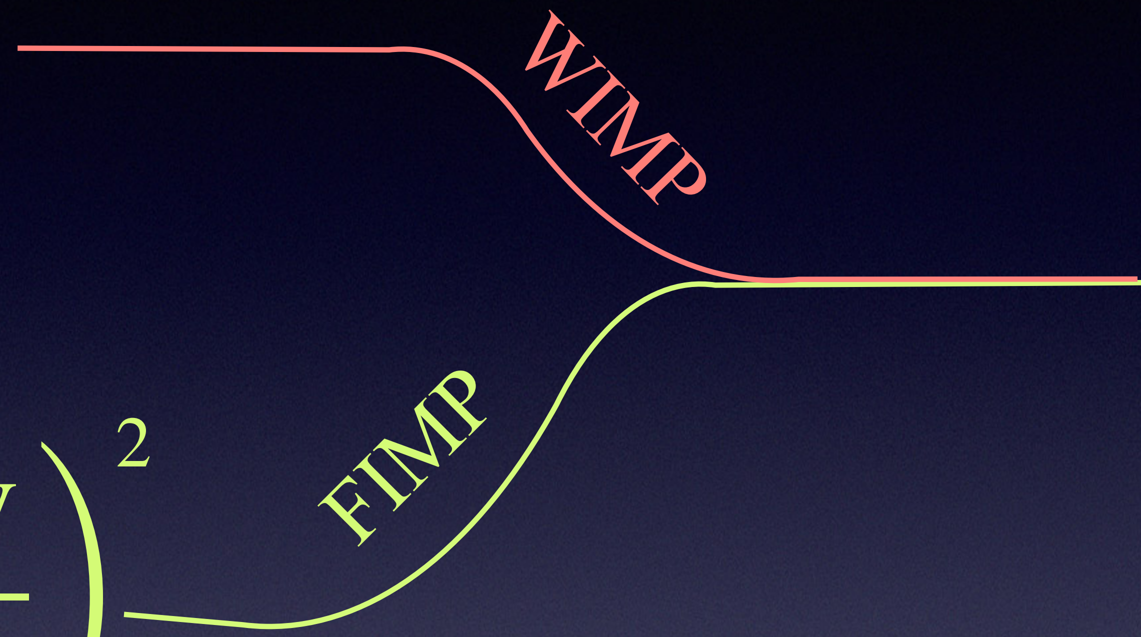


For the neutrino (relativistic) decoupling, νFO :

$$n_\chi(T_{FO}) \sim T_{FO}^3 \quad \Rightarrow \quad \frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10\ \text{eV}}$$

$$\Omega h^2 = 6 \times 10^6 \times \left(\frac{n_\chi(T_{FO})}{T_{FO}^3} \right) \left(\frac{m_\chi}{1 \text{ GeV}} \right)$$

$$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9} \text{ GeV}^{-2}}{\langle \sigma v \rangle}$$



$$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{ GeV}^{-2}} \right) \left(\frac{1 \text{ GeV}}{m_\chi} \right)^2$$

$$\frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10 \text{ eV}}$$

$$\Omega h^2 = 6 \times 10^6 \times \left(\frac{n_\chi(T_{FO})}{T_{FO}^3} \right) \left(\frac{m_\chi}{1\ \mathrm{GeV}} \right)$$

$$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

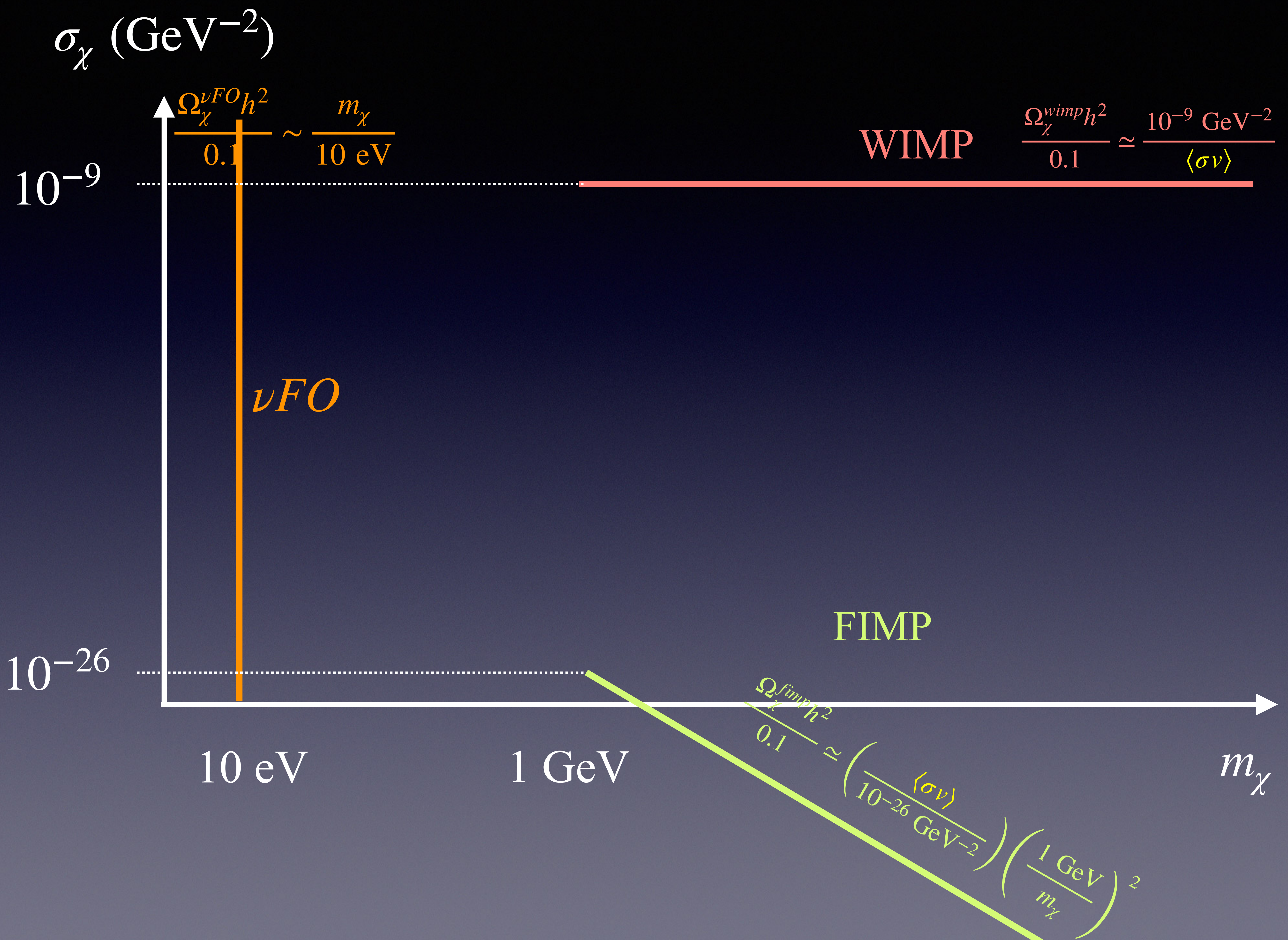
Not seen

$$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{GeV}^{-2}} \right) \left(\frac{1\ \mathrm{GeV}}{m_\chi} \right)^2$$

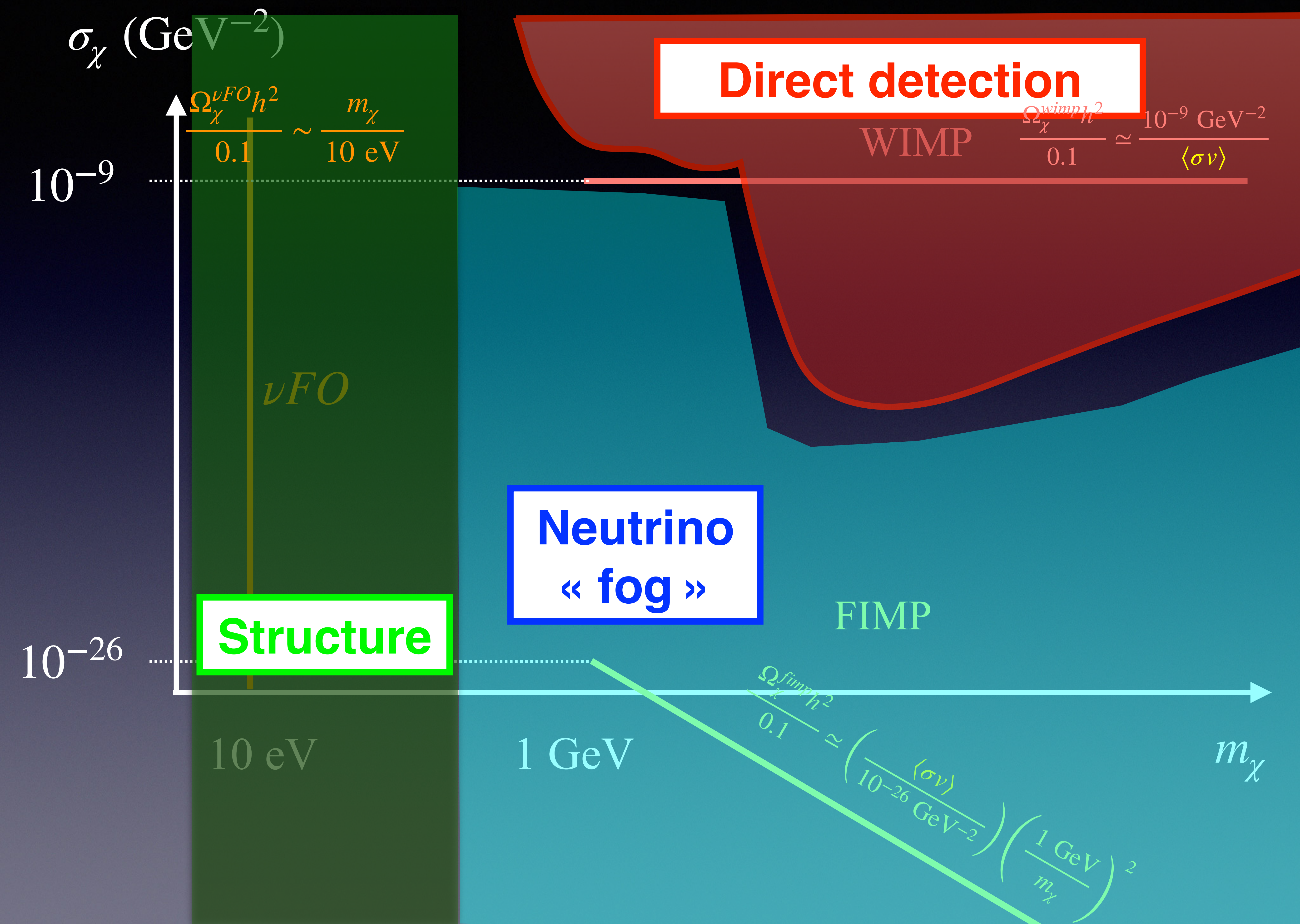
Not visible

$$\frac{\Omega_\chi^{DFO} h^2}{0.1} \sim \frac{m_\chi}{10\ \mathrm{eV}}$$

Structures



σ_χ (GeV^{-2})
$\frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10\ \text{eV}}$
WIMP
$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$
10^{-9}
νFO
FIMP
10^{-26}
$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \text{GeV}^{-2}}\right)\left(\frac{1\ \text{GeV}}{m_\chi}\right)^2$
10 eV
1 GeV
m_χ



σ_χ (GeV^{-2})
Direct detection
$\frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10\ \text{eV}}$
WIMP
$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$
10^{-9}
νFO
Neutrino « fog »
FIMP
Structure
10^{-26}
$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \text{GeV}^{-2}}\right)\left(\frac{1\ \text{GeV}}{m_\chi}\right)^2$
10 eV
1 GeV
m_χ

Alternative

(détectable and not excluded)

scénarios

Alternative

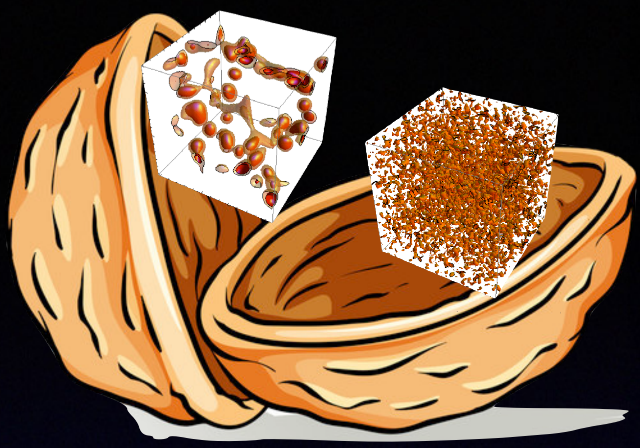
(détectable and not excluded)

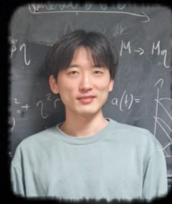
scénarios

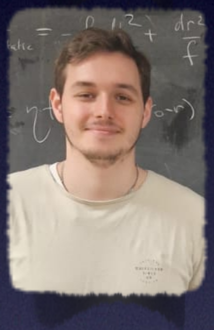
Need to understand better the
pré-radiative era :

the Reheating

Reheating in a nutshell







ϕ

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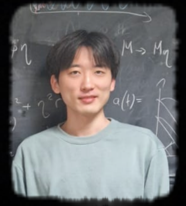
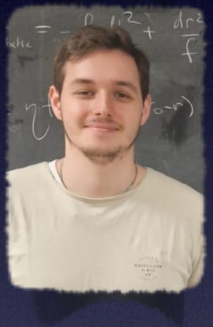


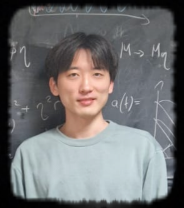


Reheating : /ˌriːˈhiːtɪŋ/ *noun*

Process of transfer of energy from a de Sitter space to radiation through the oscillations of a *classical homogeneous* field (the inflaton)

ϕ

Reheating in a nutshell



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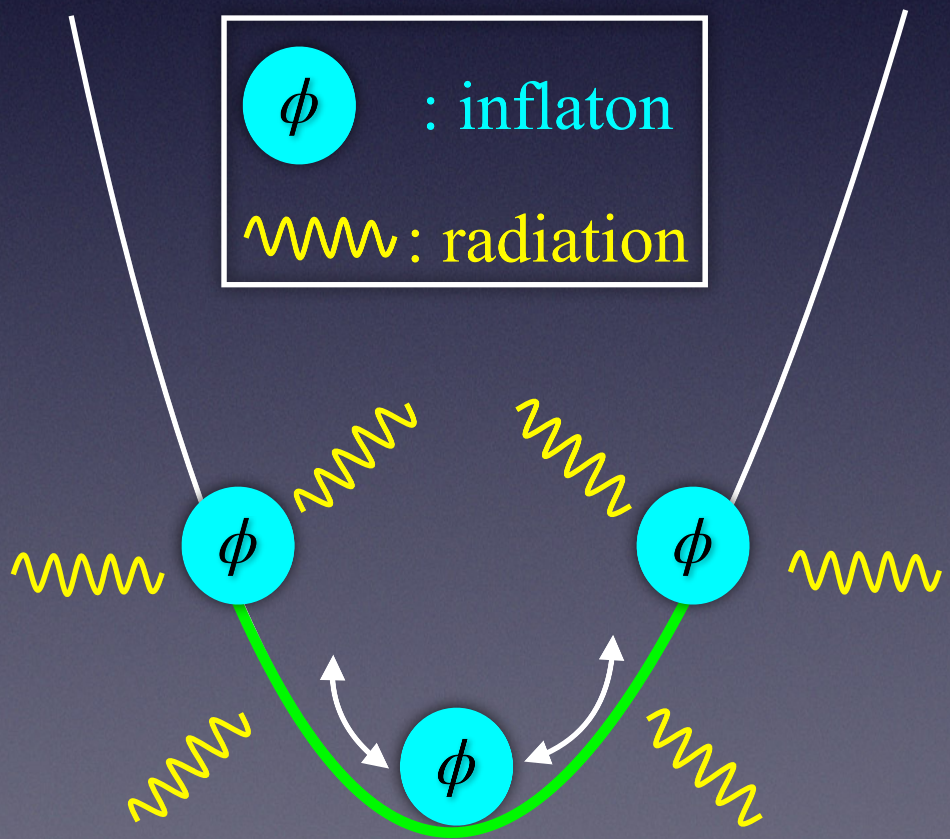
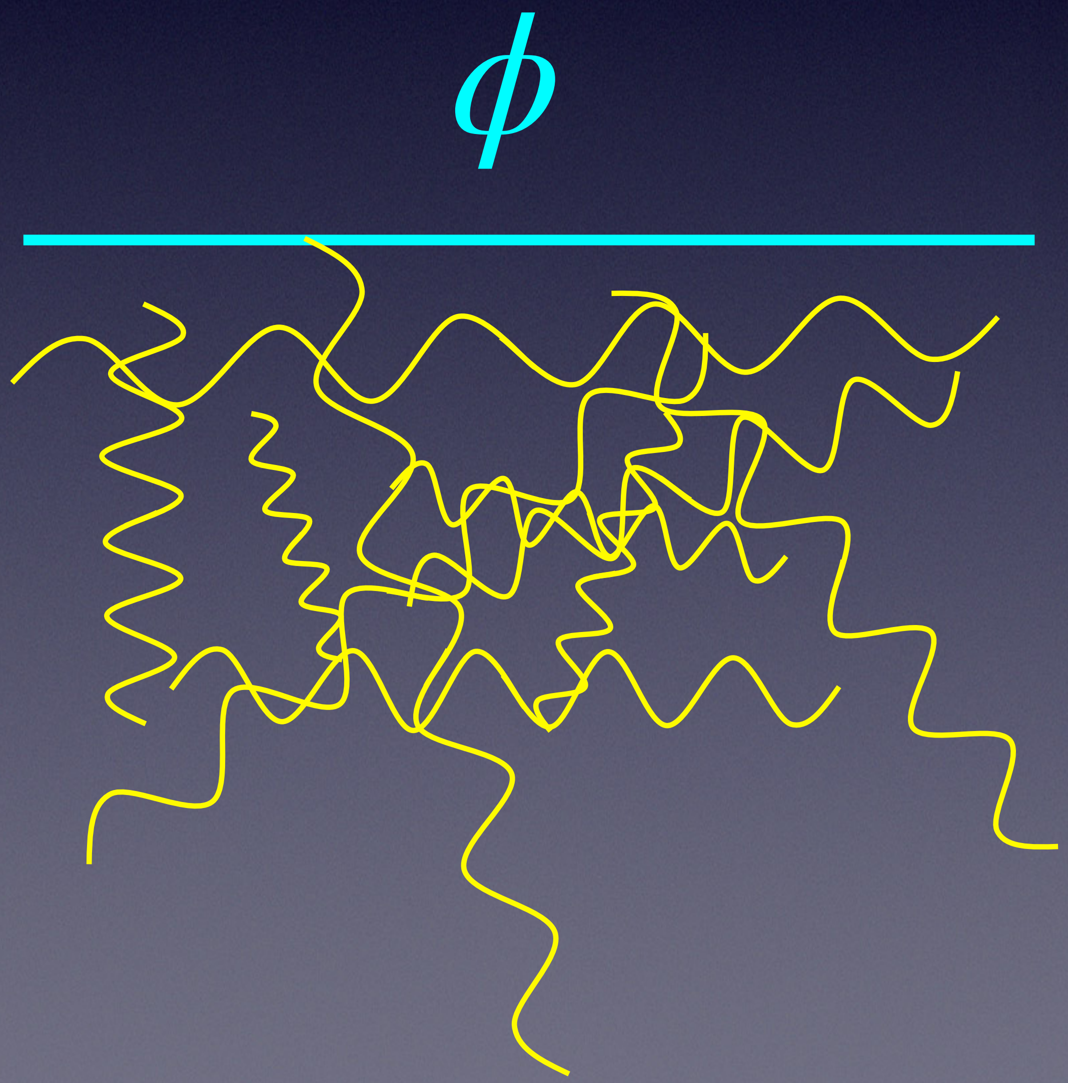
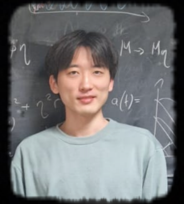




Reheating in a nutshell



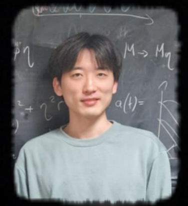
$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi} + V(\phi)$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma_\phi \rho_\phi$$

Reheating in a nutshell



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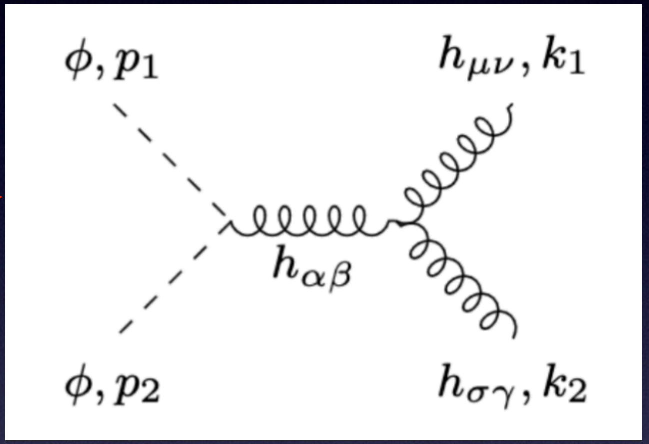
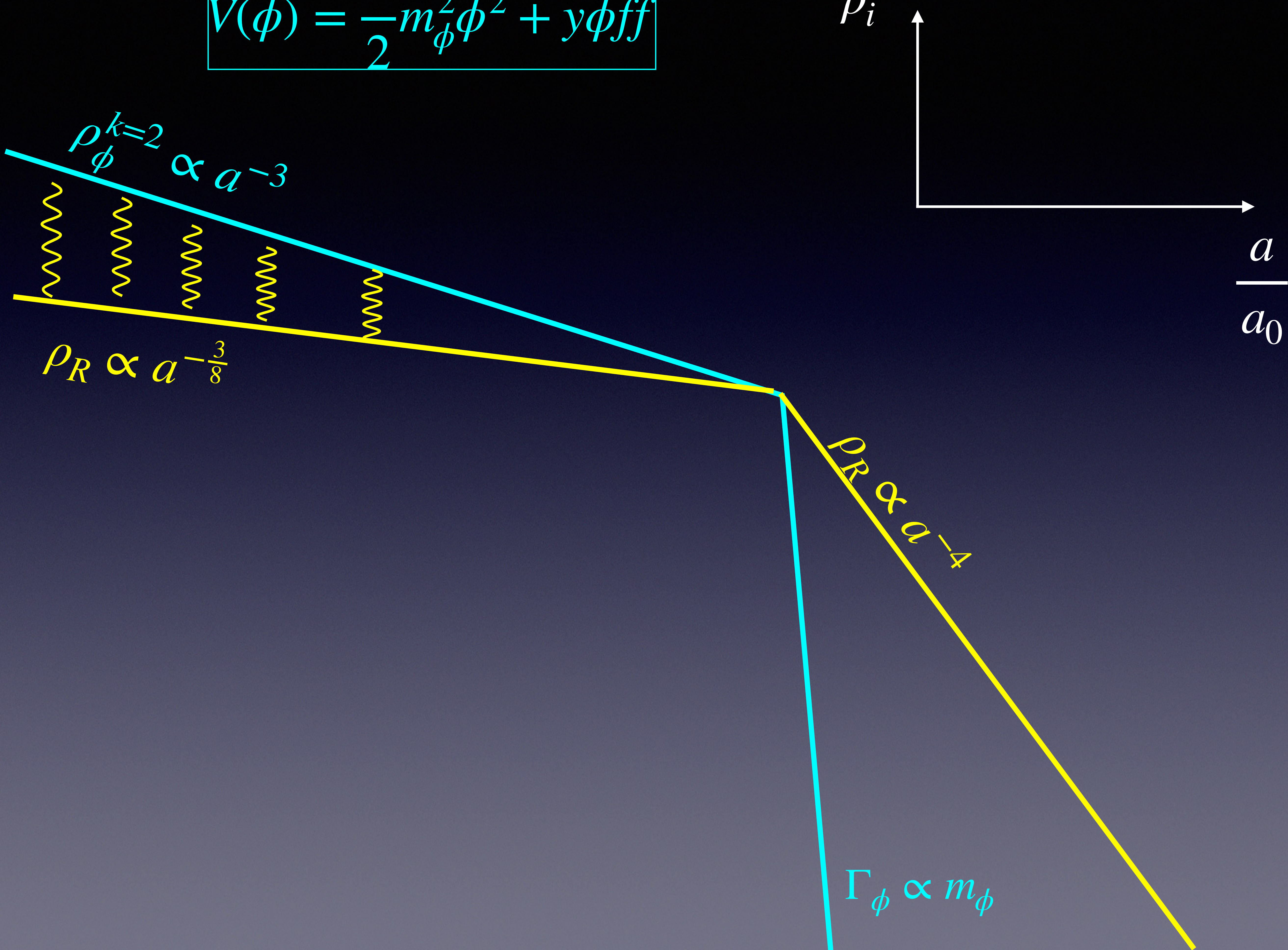


Feynman approach

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + y\phi\bar{f}f$$



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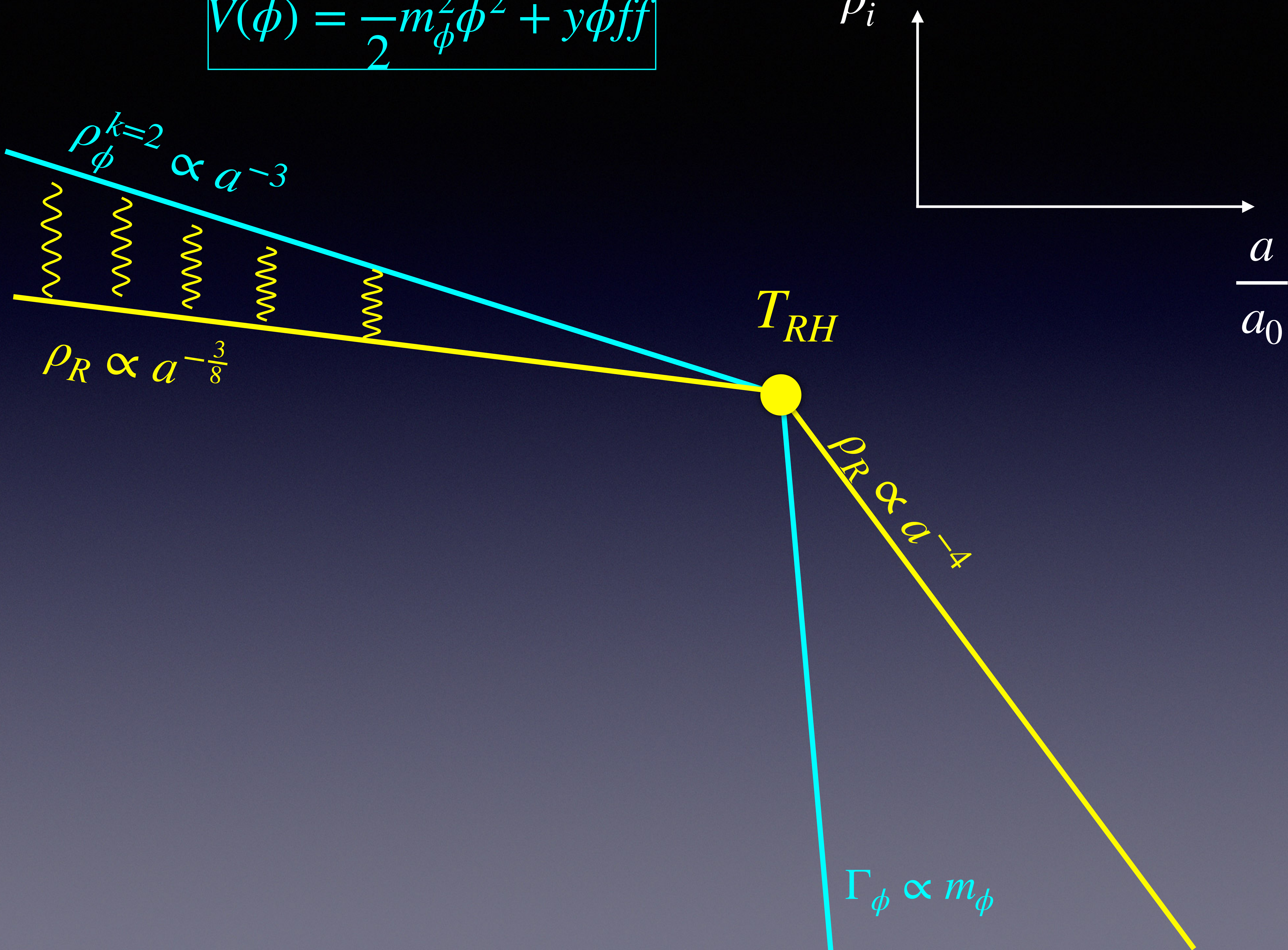
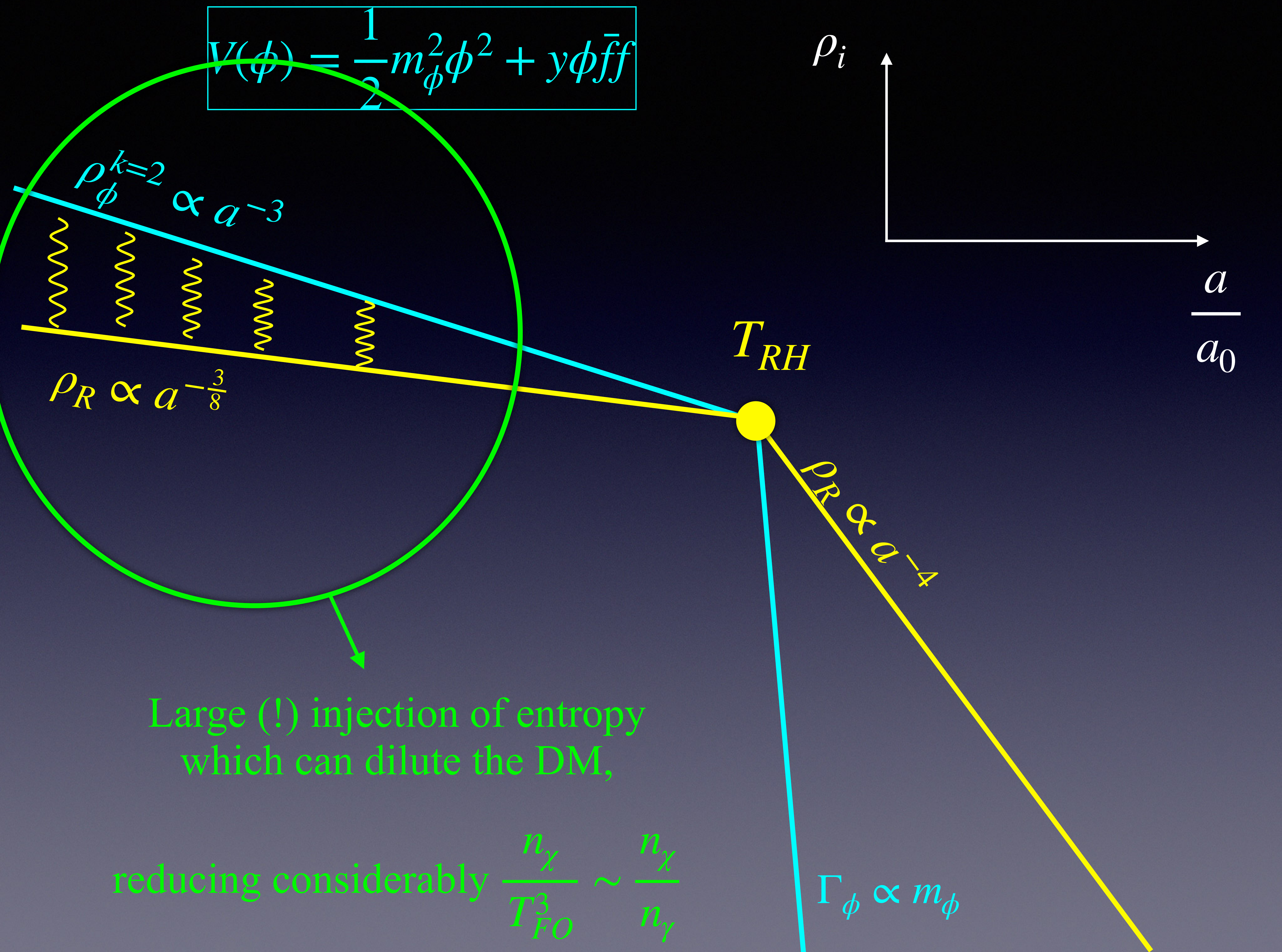



$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + y\phi \bar{f} f$
ρ_i
$\frac{a}{a_0}$
$\rho_\phi^{k=2} \propto a^{-3}$
$\rho_R \propto a^{-\frac{3}{8}}$
T_{RH}
$\rho_R \propto a^{-4}$
$\Gamma_\phi \propto m_\phi$
Large (!) injection of entropy
which can dilute the DM,
reducing considerably $\frac{n_\chi}{T_{FO}^3} \sim \frac{n_\chi}{n_\gamma}$


Stephen Henrich


Mathieu Gross

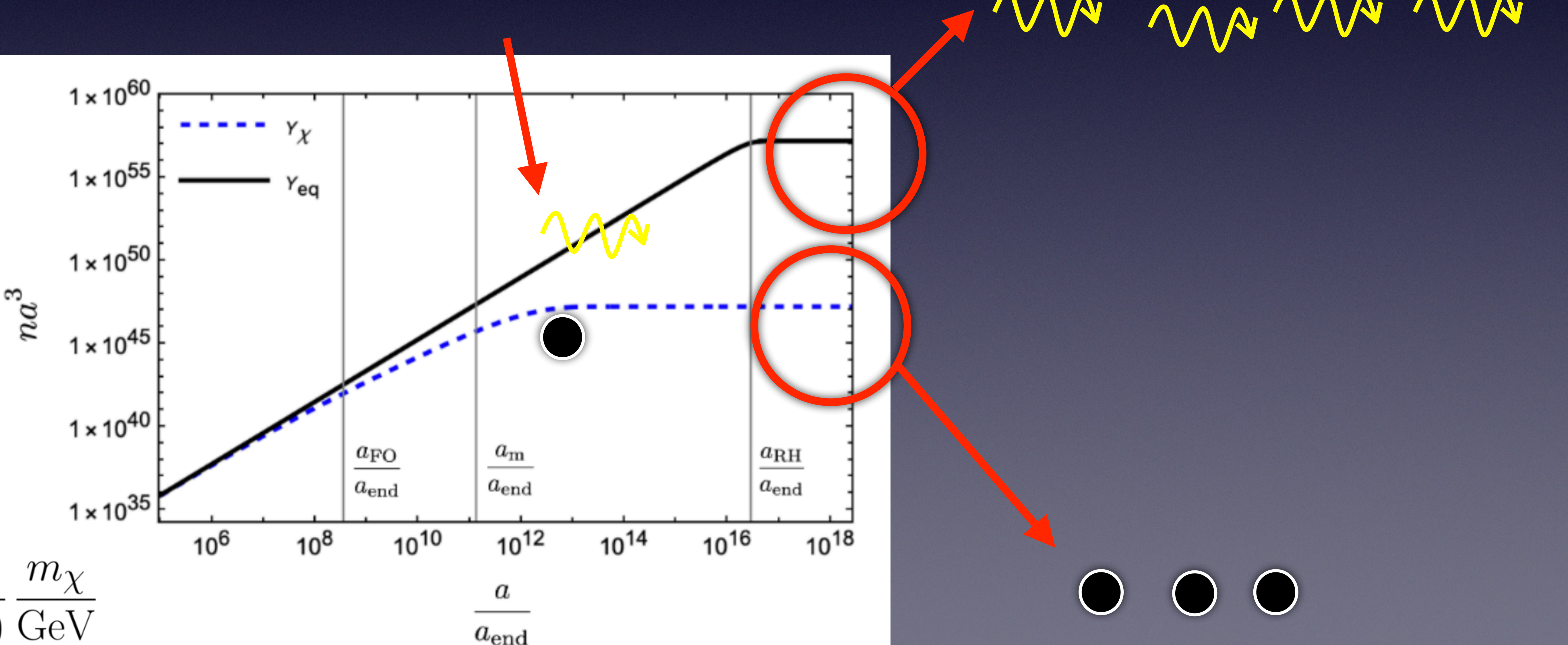
Alternative 1 :

Ultra-Relativistic Freeze Out

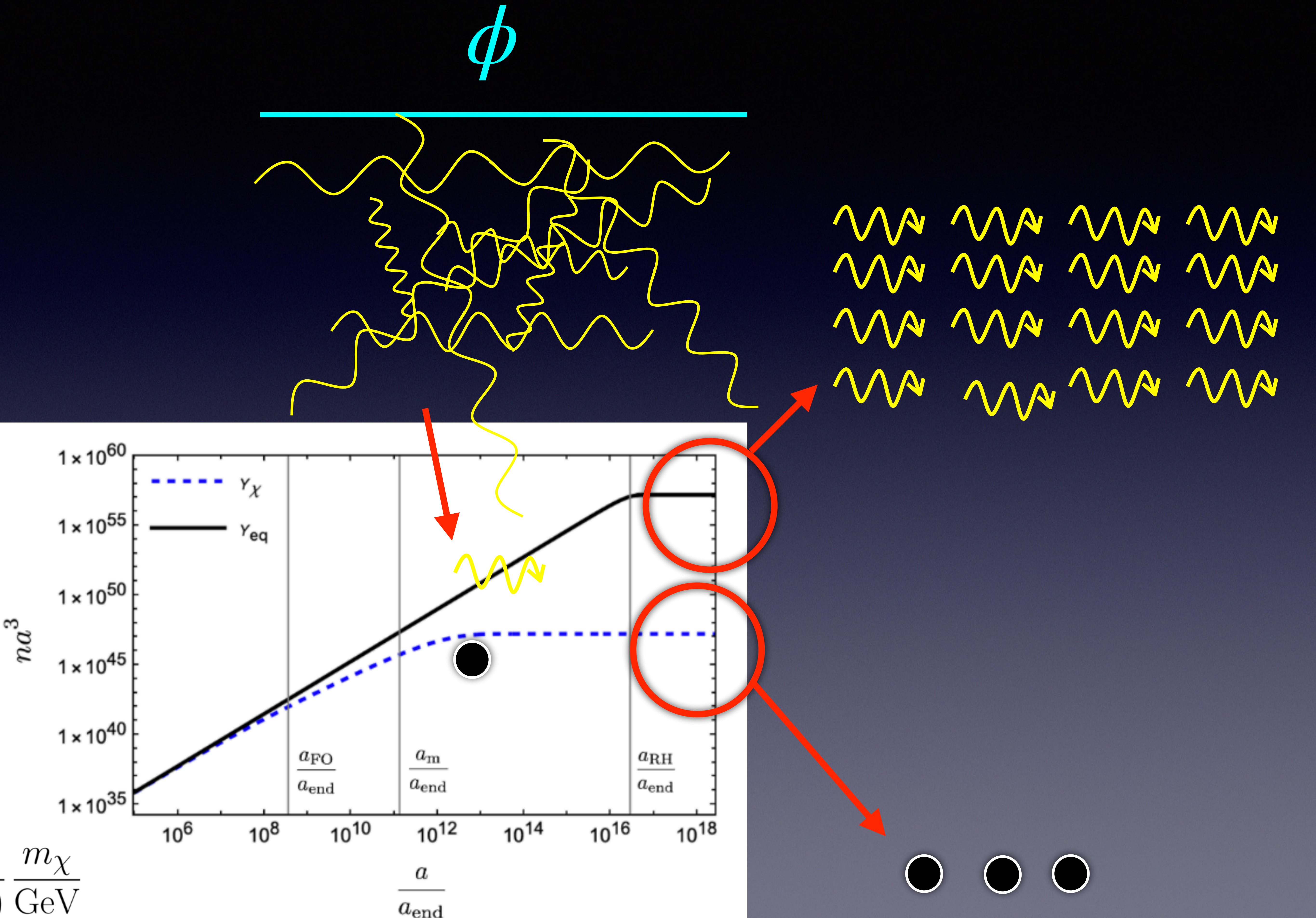
(UFO, 2025)

Ultra-Relativistic Freeze Out

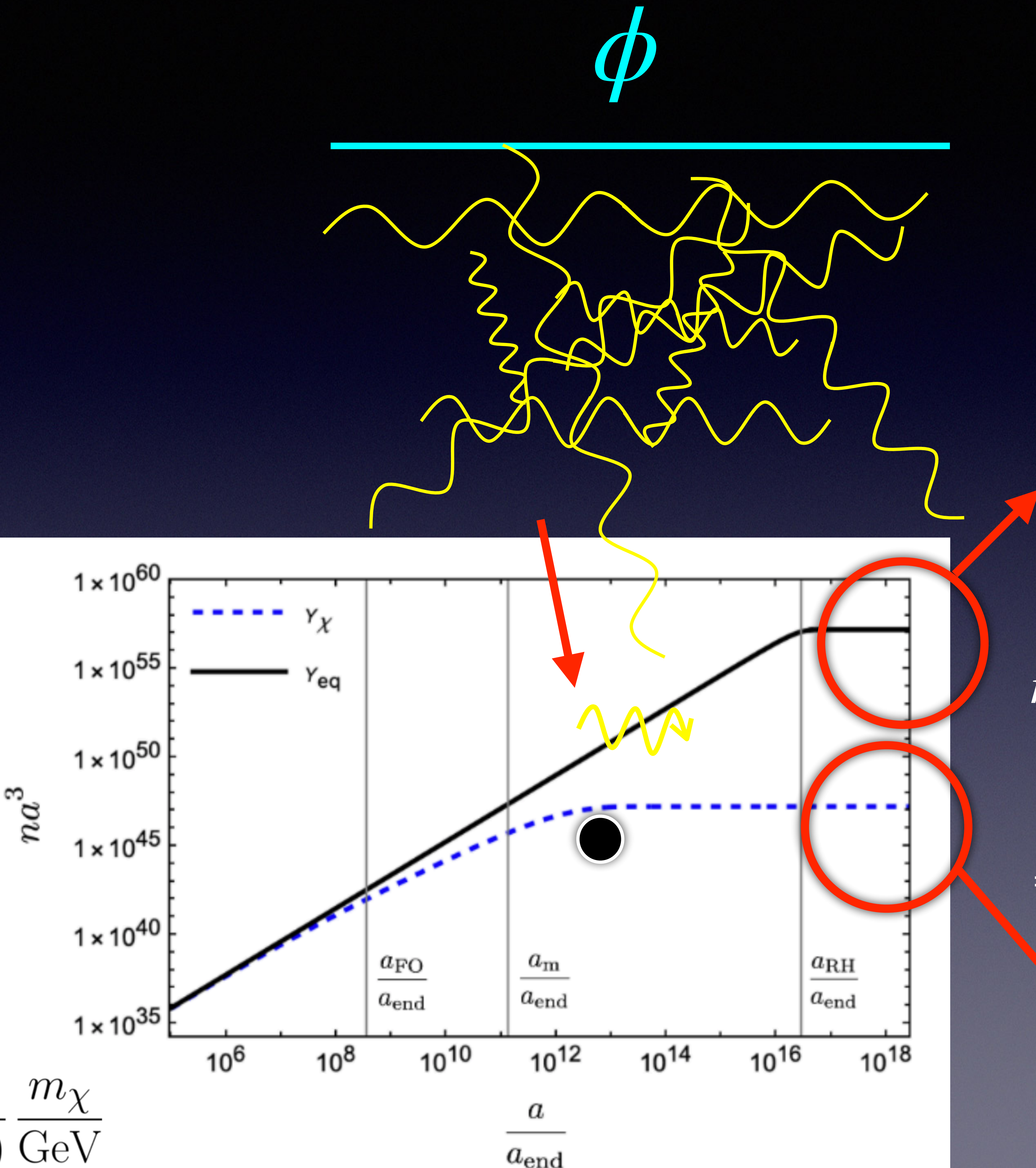
ϕ

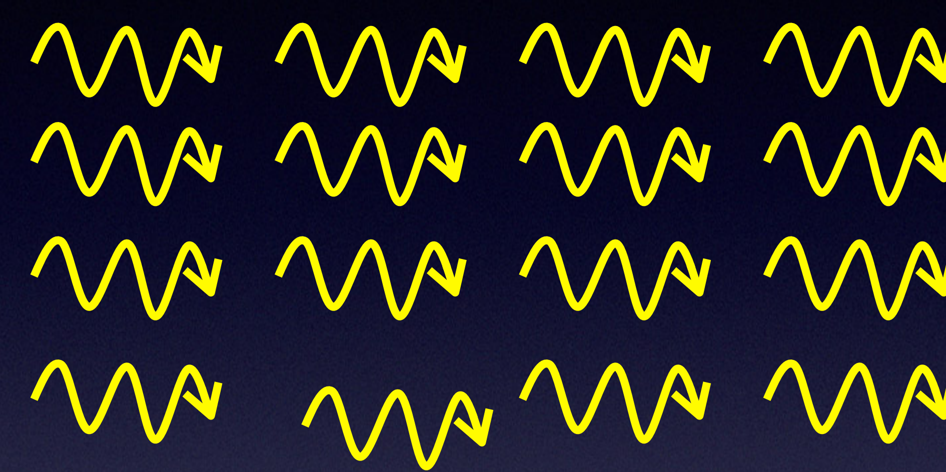


Ultra-Relativistic Freeze Out



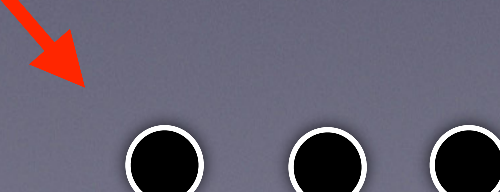
Ultra-Relativistic Freeze Out





$$n_\chi(a_{RH}) = n_\chi(a_{FO})\left(\frac{a_{FO}}{a_{RH}}\right)^3$$

$$\Rightarrow \frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{T_{RH}}{T_{FO}}\right)^5 \left(\frac{m_\chi}{10\ \text{eV}}\right)$$



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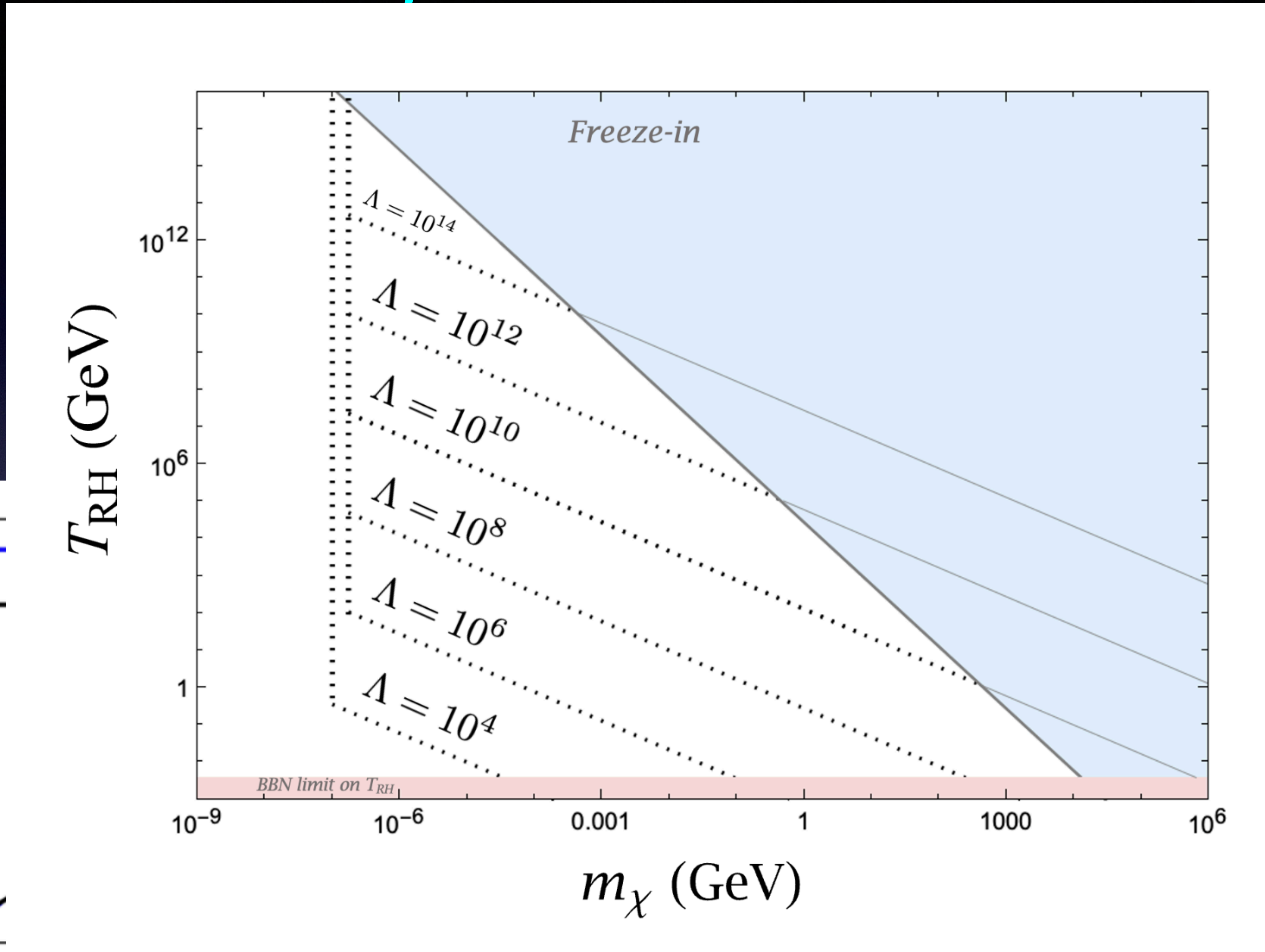

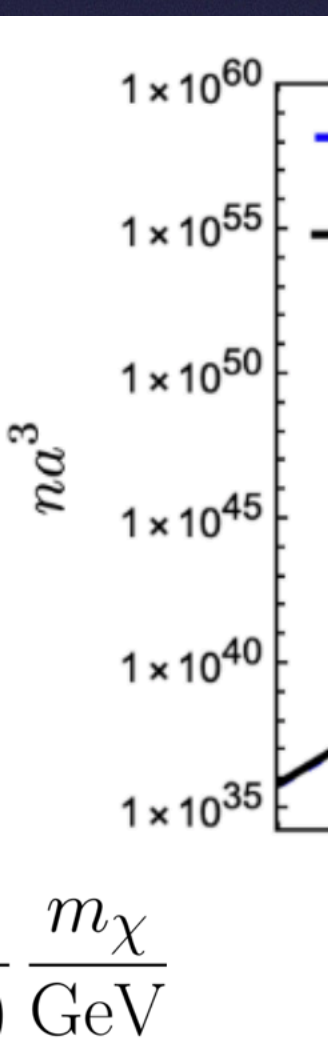

3

Alternative 2 :

Freeze **I**n at **S**tronger **C**oupling

(**FISC**, 2024)

Freeze In at Stronger Coupling

In the « classical » FIMP case, we compute $n_\chi(T_{FO}) = n_\gamma^2 \langle \sigma v \rangle H^{-1}(T_{FO})$, supposing $m_\chi < T$, which implies a feeble cross section $\langle \sigma v \rangle$.

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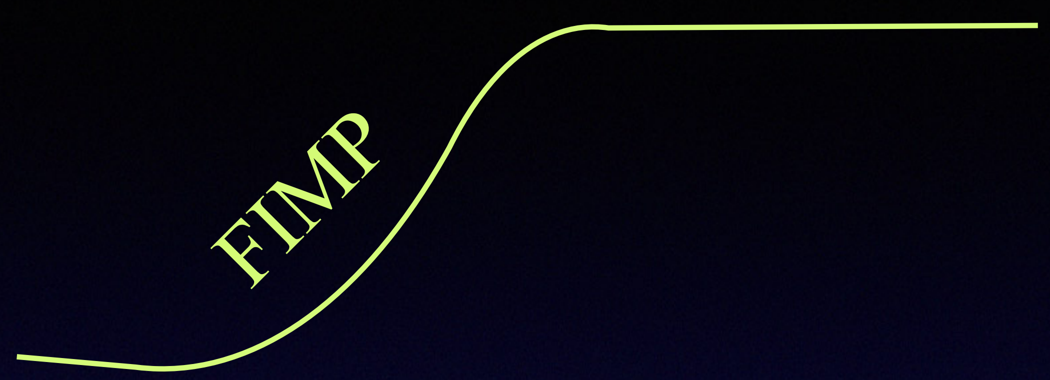

Alternatively, one can suppose $m_\chi > T_{RH} > T$, shifting the weakness of production to Boltzmann's factor of $n_\gamma \sim (m_\chi T)^{\frac{3}{2}}\ e^{-\frac{m_\chi}{T}}$ and no longer $\langle \sigma v \rangle$

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$$\Rightarrow \quad \frac{n_\chi(T_{RH})}{T_{RH}^3} \sim m_\chi^3 \, e^{-2\frac{m_\chi}{T}} \langle \sigma v \rangle \frac{M_P}{T_{RH}^2} \, ,$$

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or,

$$\frac{\Omega_\chi h^2}{0.1} \sim \frac{\sigma v}{10^{-9}\ \mathrm{GeV}^{-2}} \left(\frac{e^{\frac{m_\chi}{T_{RH}}}}{10^{-26}} \right) \left(\frac{300\ \mathrm{GeV}}{m_\chi} \right)^4 \left(\frac{T_{RH}}{10\ \mathrm{GeV}} \right)^2$$

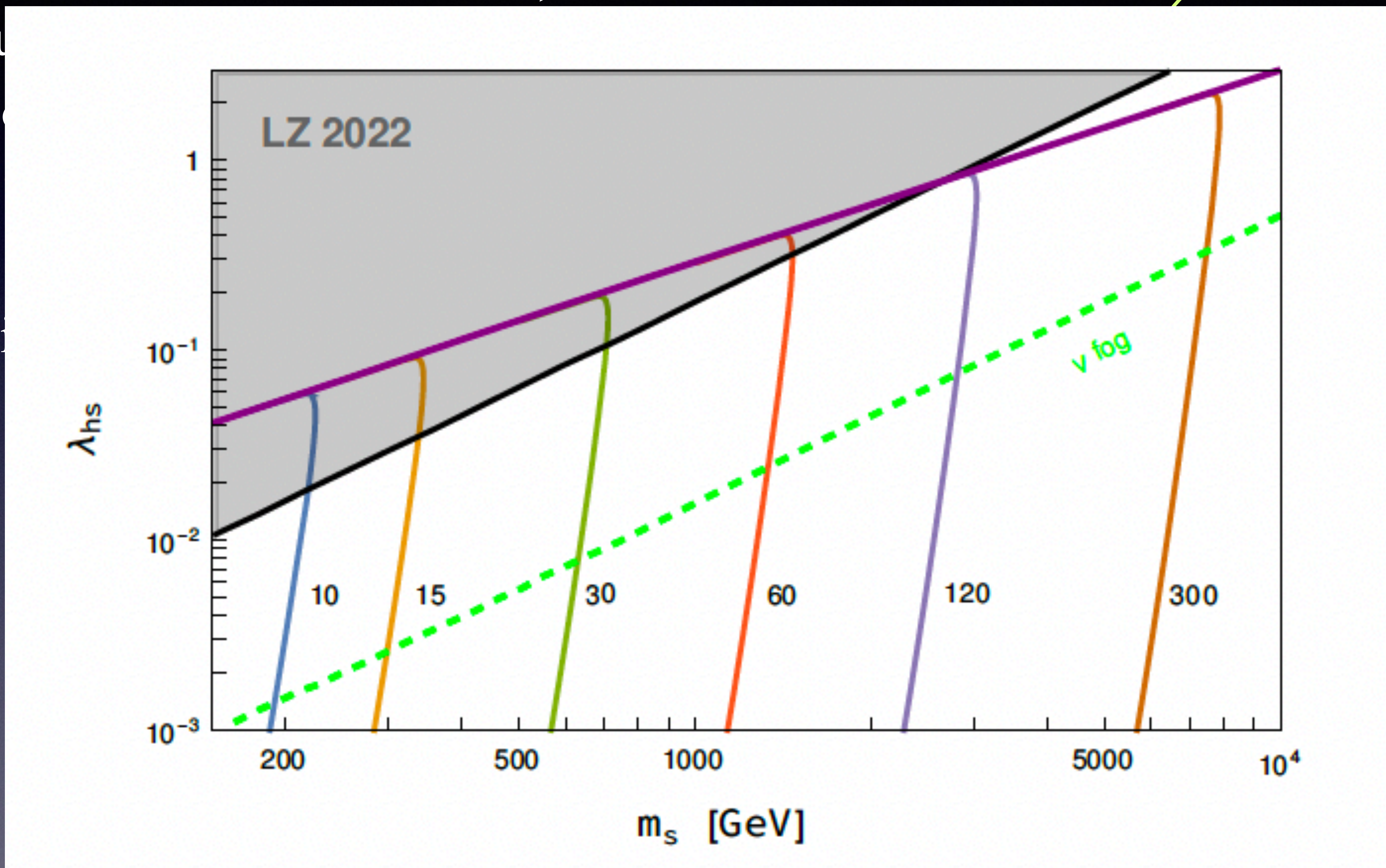
Freeze In at Stronger Coupling

In the « classical » FIMP case, we

compu

supp

Alternati ... duction



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FIMP at stronger coupling (2025)

m_χ

T_{RH}

$$g_{eff} \sim g \times e^{-\frac{m_\chi}{T_{RH}}}$$

$$\Rightarrow g = 0.1,\ m_\chi \sim 10\ T_{RH}$$

Olivier Deligny
Xavier Bertou

FIMP at stronger coupling (2025)

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DAMIC (2025)

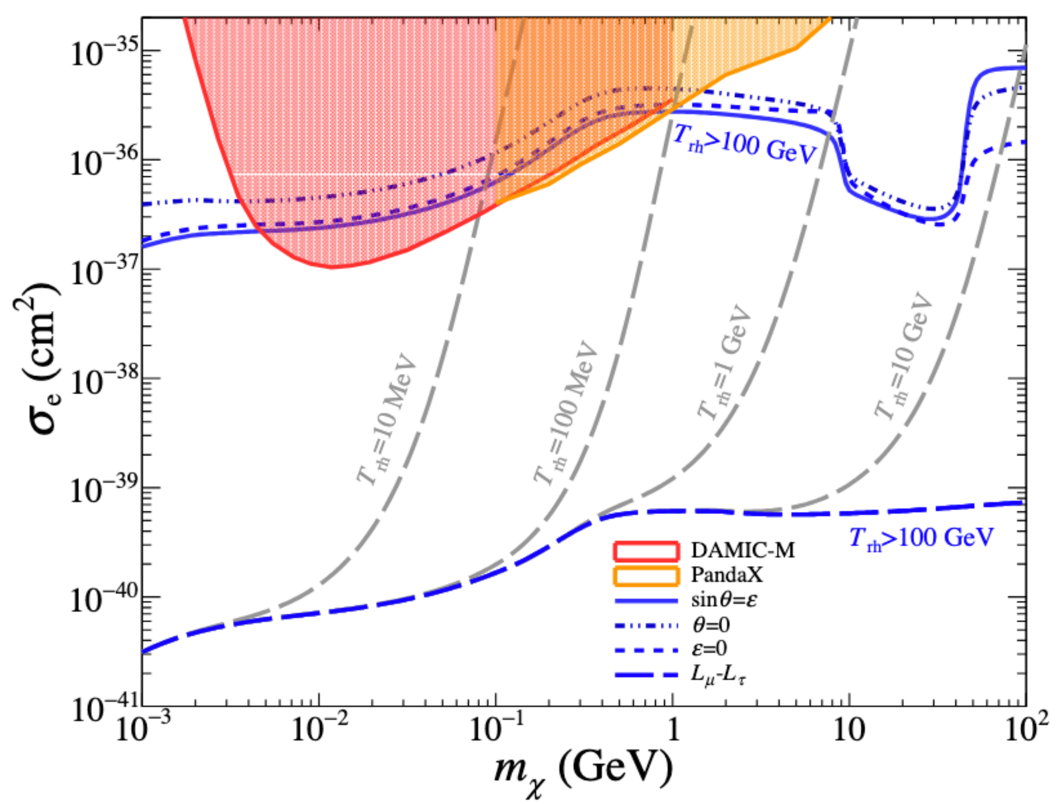

FIG. 1. DM-electron cross section expected for several extra-$U(1)_X$ gauge extension of the SM and various values of reheating temperature as a function of m_χ. The shaded areas stand for the exclusion zones reported by the DAMIC-M and PandaX Collaborations [8, 9].

Olivier Deligny
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FIMP at stronger coupling (2025)

m_χ ————————

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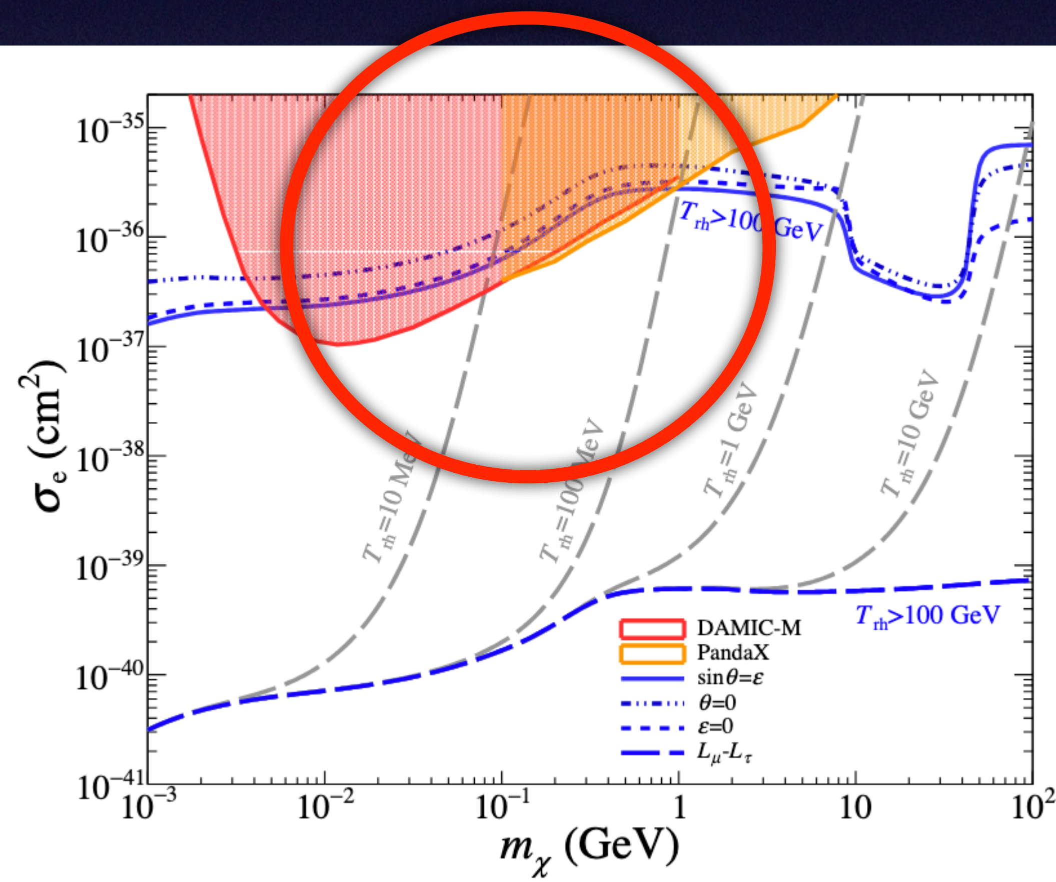

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Olivier Deligny
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Conclusion

$$\frac{\Omega_\chi^{wimp} h^2}{0.1} \simeq \frac{10^{-9}\ \text{GeV}^{-2}}{\langle \sigma v \rangle}$$

Not seen — WIMP

$$\frac{\Omega_\chi^{fimp} h^2}{0.1} \simeq \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \text{GeV}^{-2}} \right) \left(\frac{1\ \text{GeV}}{m_\chi} \right)^2$$

Not visible — FIMP

$$\frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10\ \text{eV}}$$

Structures — νFO

Conclusion

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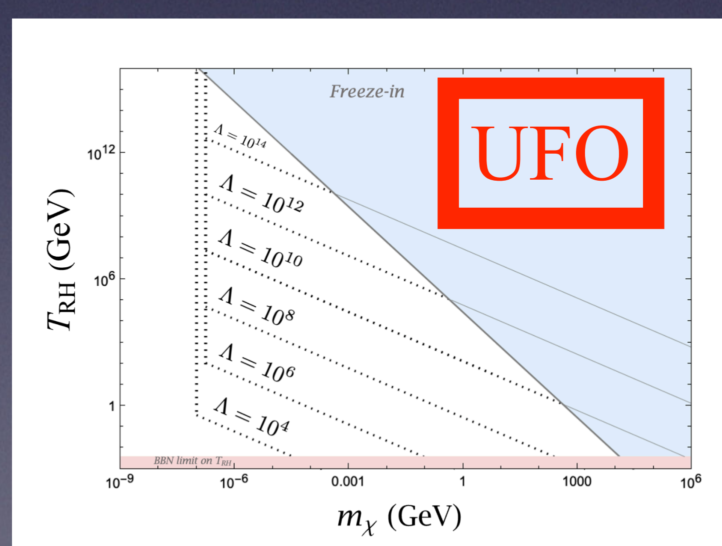

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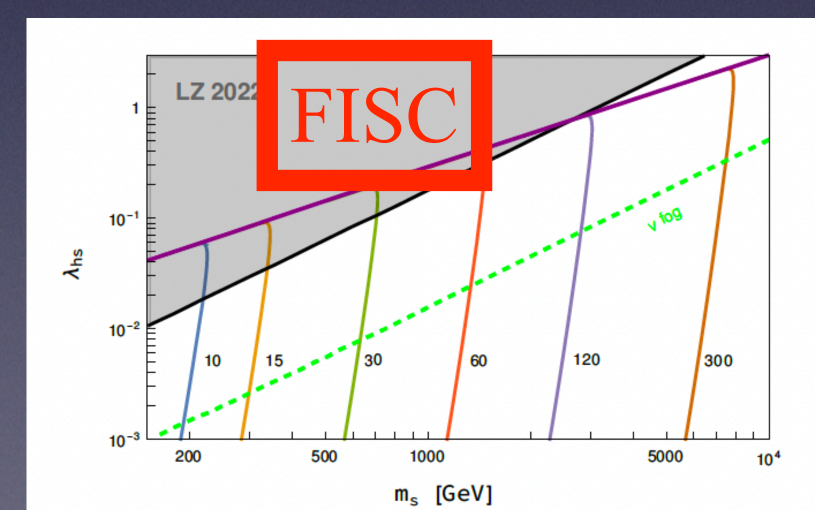

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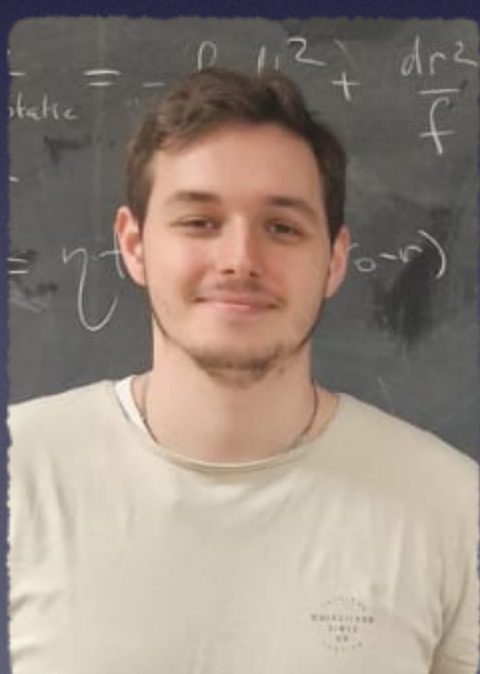
Thank you!

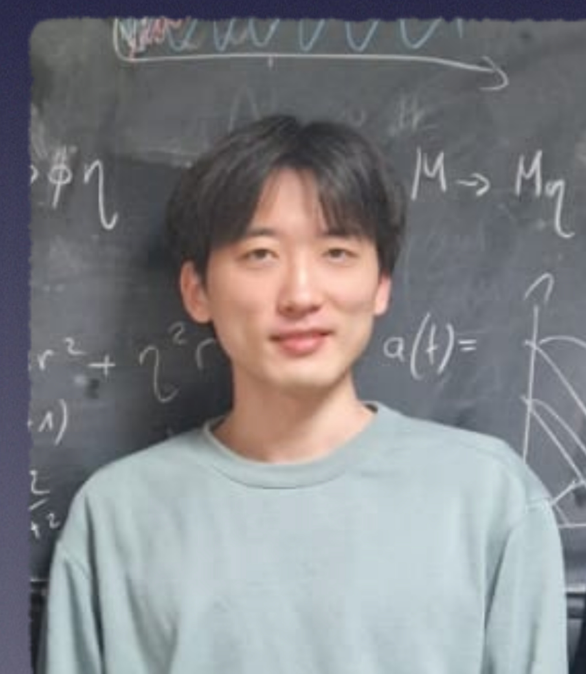
Simon Clery
(TUM, Munchen)

Stephen Henrich
(FITP, Minneapolis)



Mathieu Gross
(Paris-Saclay)

Mathias Pierre
(DESY)



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