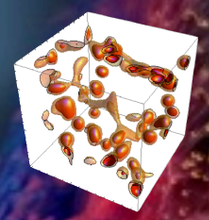
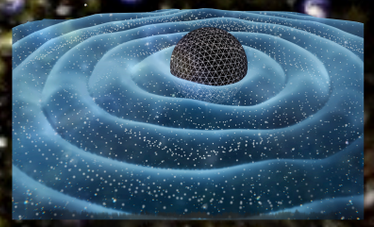
Recent (interesting) alternatives To FIMP/WIMP scenarios



ϕ



Yann Mambrini, IJCLab, Université Paris-Saclay

Dark Matter Day

May 6th 2026

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 !!

Plan

1) Hot dark matter, the neutrino candidate (1966)

2) Cold dark matter, WIMP candidate (1980)

3) Freeze in scenario, FIMP candidate (2010)

4) Freeze in at stronger coupling, FISC (2024)

5) Ultrarelativistic Freeze Out, UFO (2025)

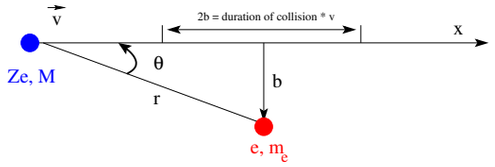


Fig. 5.9 Interaction of a high energy particle of charge Ze with an electron at rest.

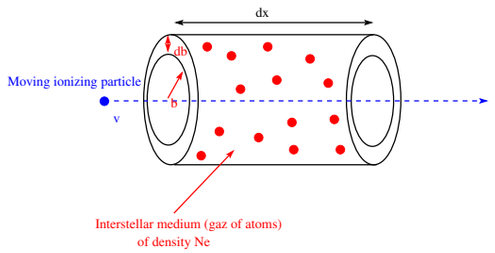


Fig. 5.10 Moving particle in an interstellar medium of density N_e.

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 later 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

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]

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

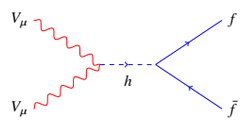
which gives

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

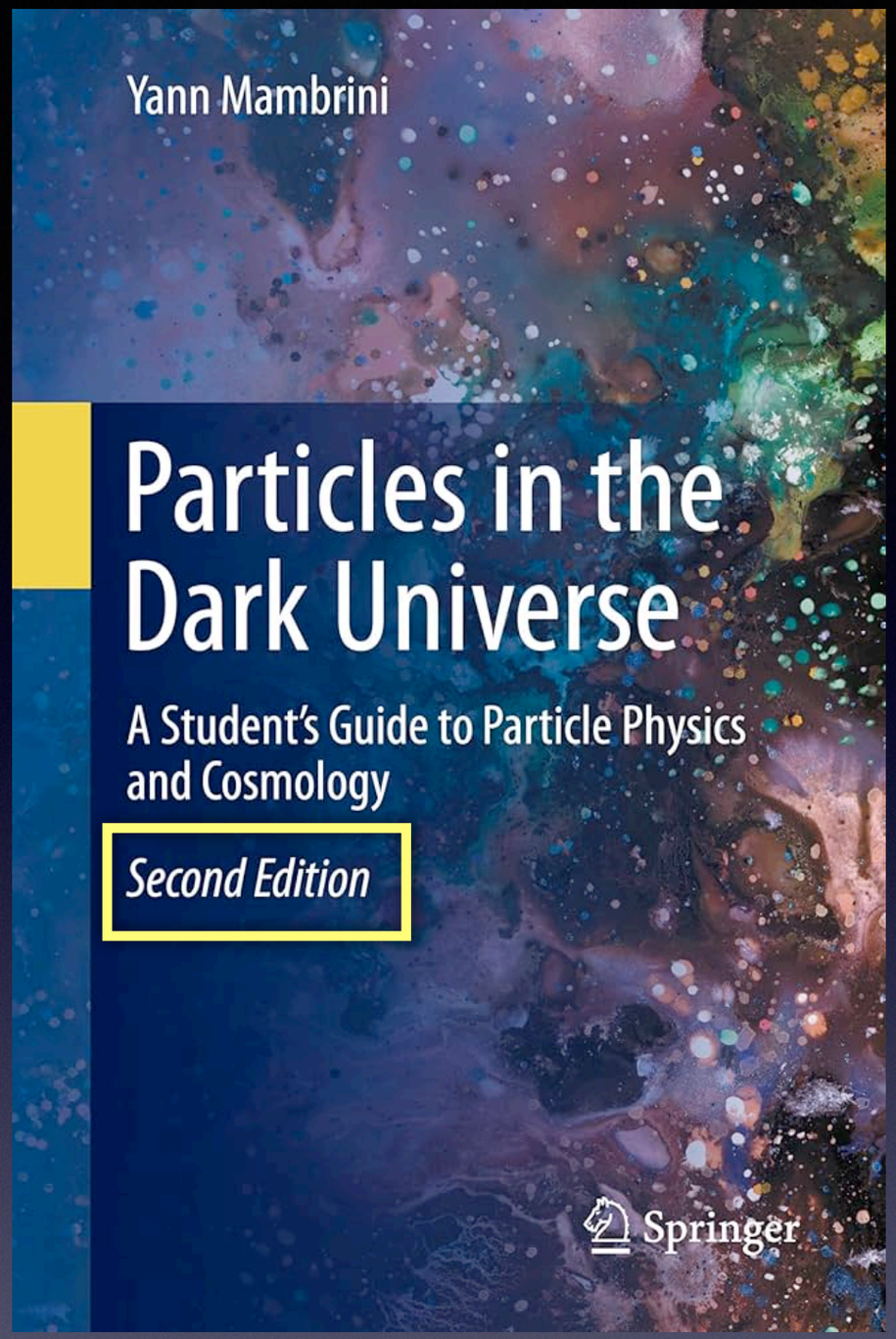
Γ_H being the width of the Higgs boson (including its own decay into SS, see next section). When ones implement this value of $|\mathcal{M}|^2$ into Eq.(B.111) one obtains after simplification

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

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 $\langle\sigma v\rangle^V = \frac{3}{3\times3}\langle\sigma v\rangle^S = \frac{1}{3}\langle\sigma v\rangle^S$. The academical computation for $V_\mu(p_1)V_\mu(p_2) \to f\bar{f}$ gives



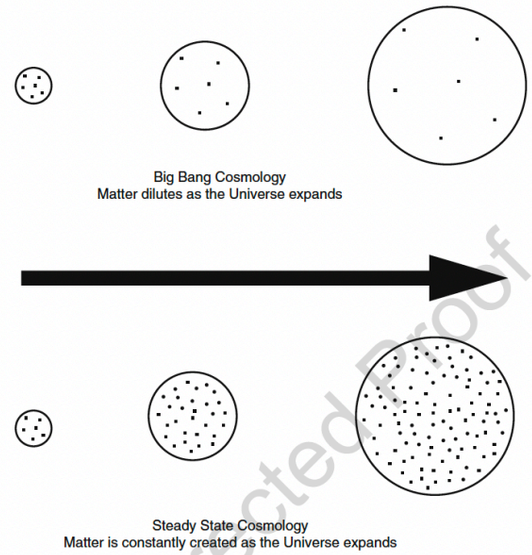


Fig. 2.9 Difference between the Steady State and the Big Bang cosmology

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,

Uncorrected Proof

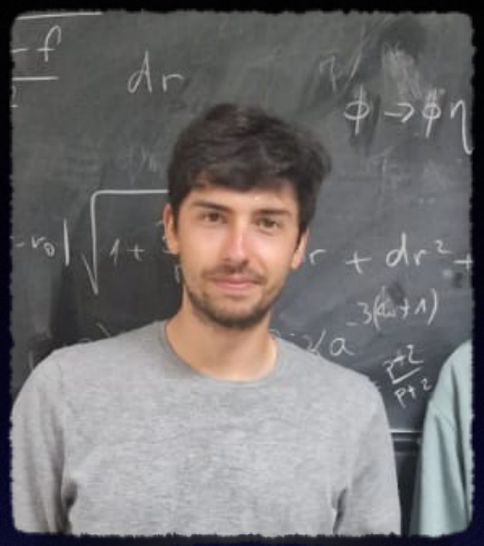
650+ pages, from inflation to dark matter detection.

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

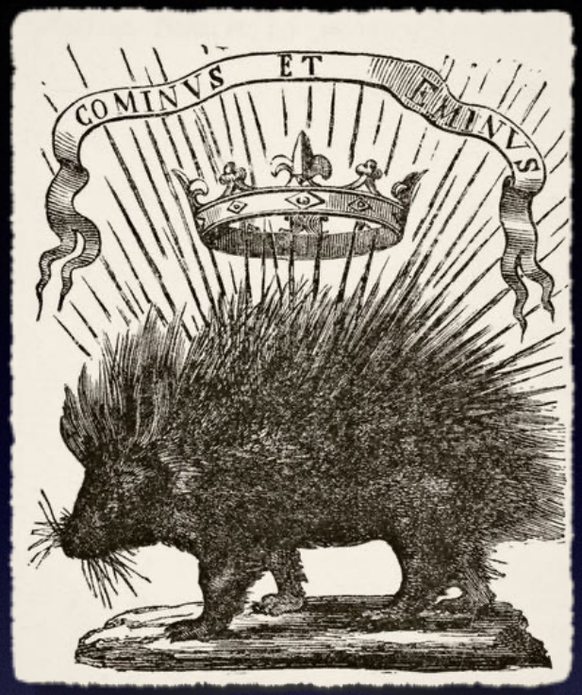
All what is needed to compute cross-sections, relic abundance, and retrace the history of a Dark Universe.

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

students/postdocs :

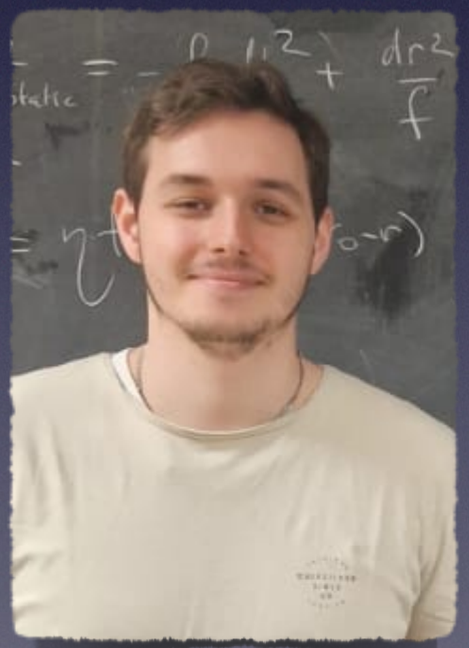


Simon Clery
(TUM, Munchen)





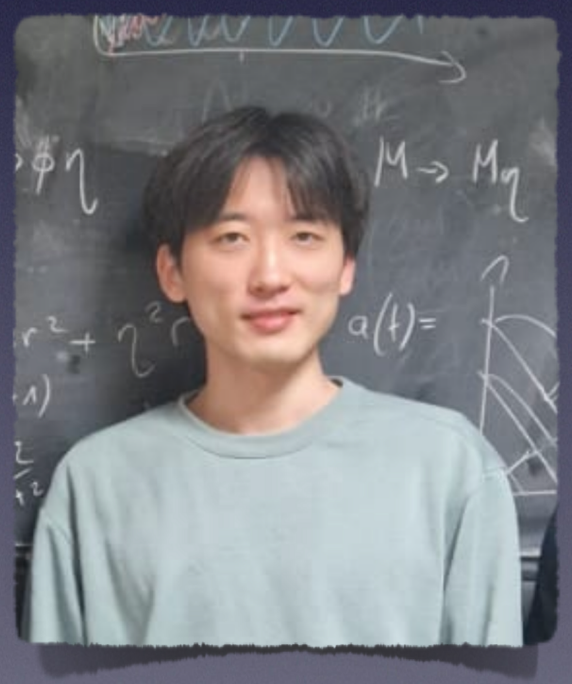
Stephen Henrich
(FITP, Minneapolis)



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]

[1] Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2] Laboratoire de Physique Théorique, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France
[3] Centre de Physique Théorique, Ecole Polytechnique, CNRS, Université Paris-Saclay, 91128 Palaiseau Cedex, France
[4] Department of Physics, University of California, Santa Cruz, 1156 High St, Santa Cruz, CA 95060, USA
[5] Santa Cruz Institute for Particle Physics, Santa Cruz, 1156 High St, Santa Cruz, CA 95060, USA

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]

[1] Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Universita degli Studi di Messina, Via Ferdinando Stagno d'Alcontres 31, I-98166 Messina, Italy
[2]INFN Sezione di Catania, Via Santa Sofia 64, I-95123 Catania, Italy
[3]Departament de Física Quàntica i Astrofísica, Universitat de Barcelona, Martí i Franquès 1, E08028 Barcelona, Spain
[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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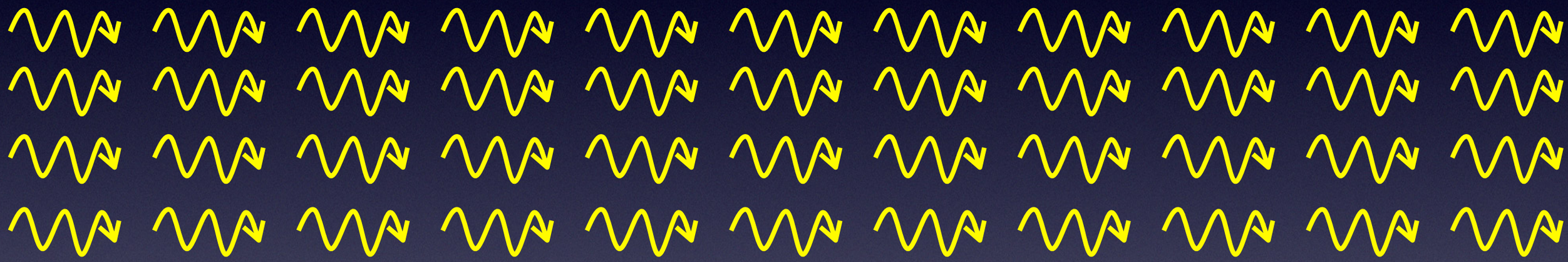


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1 DM particle for ~3 billions photons

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



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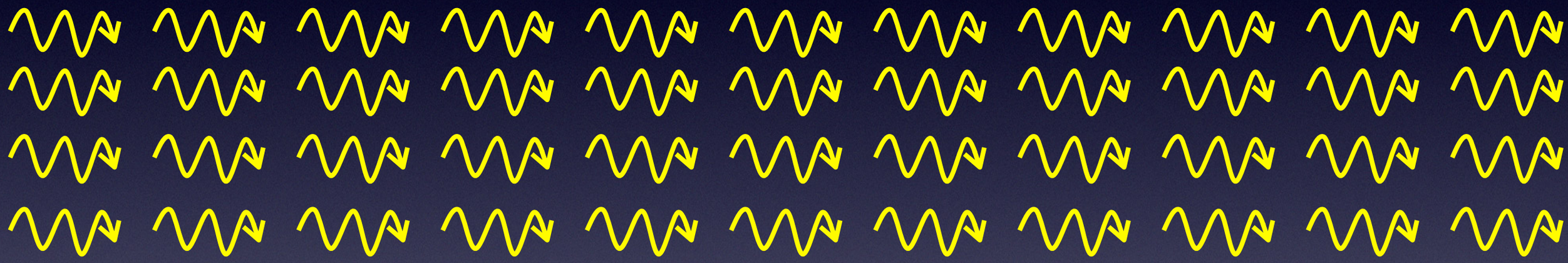


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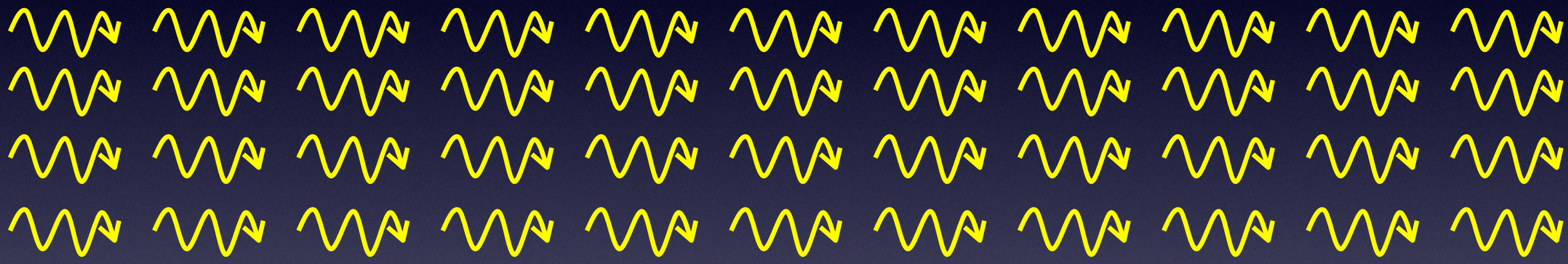


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Some history

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S. S. Gershtein & Ya. B. Zeldovich (1966)

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The mean free path from a 10 eV neutrino is

$$\lambda_{FS}^{NR} \simeq ct_{NR} \sim \frac{1}{H} \sim \frac{M_P}{T_{NR}^2} \sim \frac{M_P}{m_\nu^2}$$ which implies the present *free streaming*

$$\lambda_{FS}^{0} = \lambda_{FS}^{NR}\frac{m_\nu}{T_0} \simeq 10\ \text{Mpc}\left(\frac{10\ \text{eV}}{m_\nu}\right)$$ or minimum mass $10^{15}\ M_\odot$

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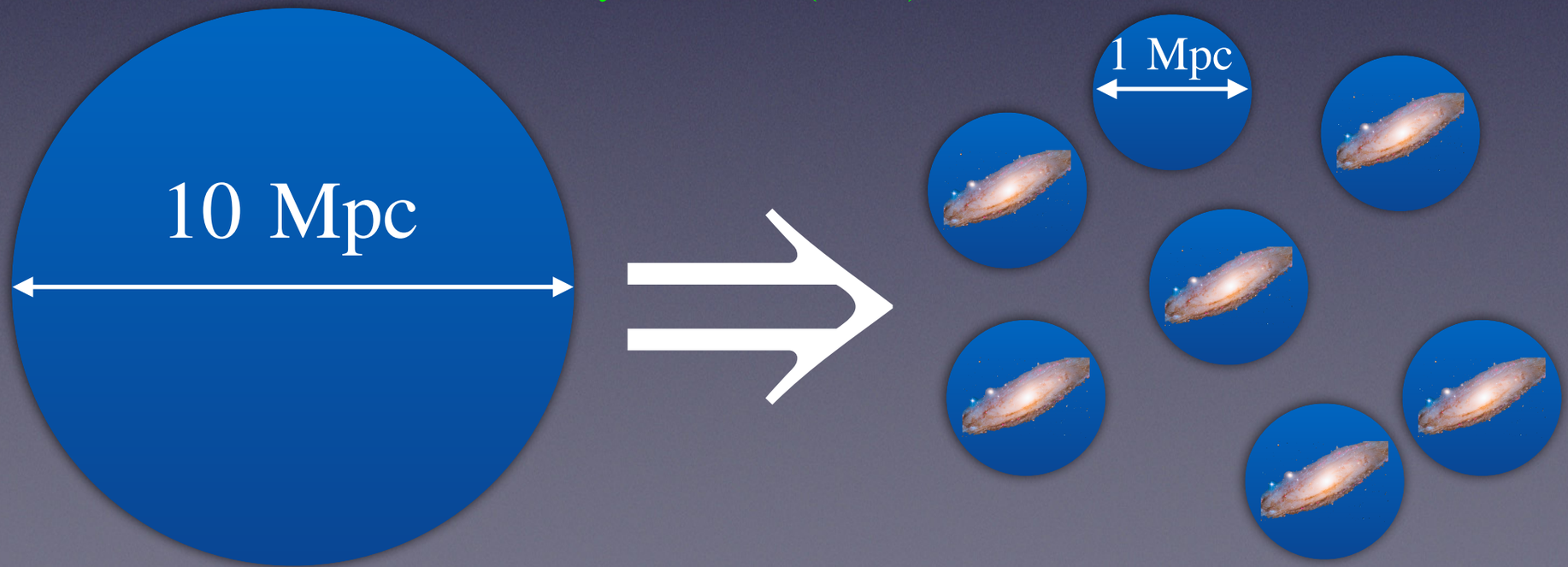
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$n_\nu \simeq$

The mean f

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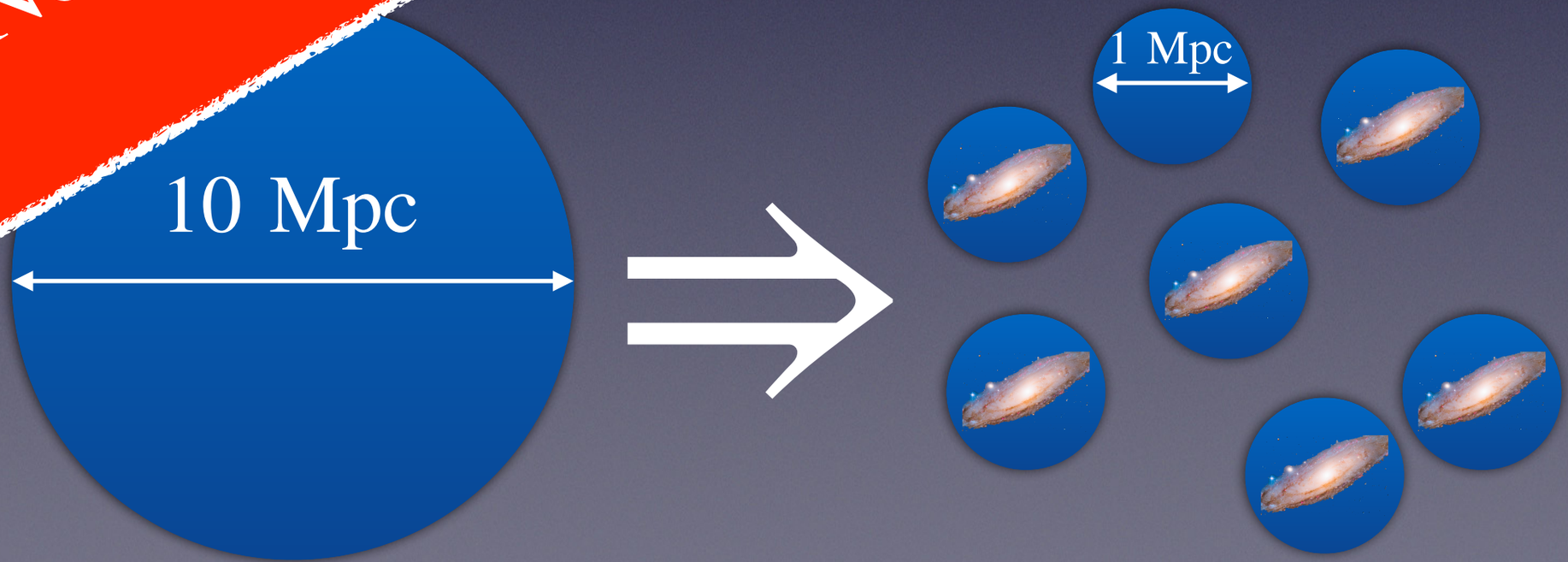
e streaming

Not valid structure formation scenario
Hot DM problem!
Needs an alternative explanation
with heavier DM

20 mum mass $10^{15}\ M_\odot$

the neutrino rest mass »
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$$\frac{\Omega h^2}{0.12} \simeq 10^8 \left(\frac{g_0}{g_*}\right) \frac{n_\chi}{n_\gamma} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)$$

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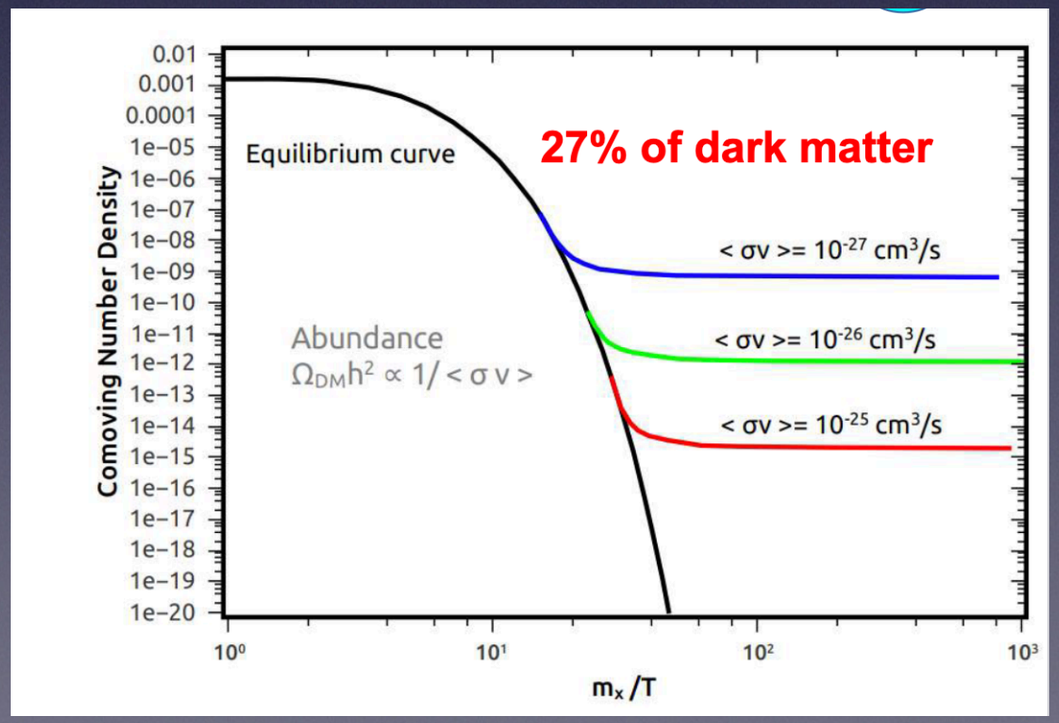
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WIMP miracle :

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

Direct Detection Limits on Dark Matter
Spin-Independent WIMP–Nucleon Cross Section (90% CL)

Z-exchange
$\sigma \sim G_F^2 m_N^2 / 2\pi$
$\approx 1.3 \times 10^{-38}$ **cm²**

Higgs-exchange
$\sigma \approx (f_N m_N m_\chi)^2 / \pi v^2 m_h^4$
$\approx 6.6 \times 10^{-41}$ **cm²**

but…

~ 10^8 × excluded by LZ

DAMIC-M 2025

XENON1T 2018

PandaX-4T

XENONnT 2025

LZ 2025

Experiment / Dataset

- Neutrino fog (indicative)
- XENON1T 2018 (reference)
- PandaX-4T (1.54 t·yr, Jan 2025) min 1.6×10^{-47} cm² @ 40 GeV
- XENONnT SR0+SR1 (3.1 t·yr, Nov 2025) min 1.7×10^{-47} cm² @ 30 GeV
- LZ WS2022+WS2024 (4.2 t·yr, Jul 2025) min 2.2×10^{-48} cm² @ 40 GeV
- LZ low-mass extension (3–9 GeV, Dec 2025)
- PandaX-4T low-mass (2.5–5 GeV, Jul 2025) 1.1×10^{-43} cm² @ 3 GeV
- DAMIC-M 2025 (DM–nucleon, sub-GeV, Si CCD, SNOLAB)
- EW: Z-exchange @ 10 GeV ($\sigma \approx 1.3 \times 10^{-38}$ cm², Goodman & Witten 1985)
- EW: Higgs-exchange @ 10 GeV ($\sigma \approx 6.6 \times 10^{-41}$ cm², Higgs portal)

SI WIMP–nucleon cross section [cm²]

10^{-37}, 10^{-39}, 10^{-41}, 10^{-43}, 10^{-45}, 10^{-47}, 10^{-49}, 10^{-51}

WIMP Mass [GeV/c^2]

10^0, 10^1, 10^2, 10^3, 10^4

LZ: arXiv:2410.17036, arXiv:2512.08065 | XENONnT: arXiv:2502.18005 (PRL 135, 221003, 2025) | PandaX-4T: PRL 134, 011805 (2025); arXiv:2507.11930 | DAMIC-M: DAMIC-M:2025luv
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(Strong) tensions with experiments

but…

DAMIC-M 2025

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LZ: arXiv:2410.17036, arXiv:2512.08065 | XENONnT: arXiv:2502.18005 (PRL 135, 221003, 2025) | PandaX-4T: PRL 134, 011805 (2025); arXiv:2507.11930 | DAMIC-M: DAMIC-M:2025luv
Z-exchange: $\sigma \approx G_F^2 m_N^2 / 2\pi \approx 1.3 \times 10^{-38}$ cm² (Goodman & Witten 1985). Higgs-exchange: $\sigma \approx (f_N m_N m_\chi)^2 / \pi v^2 m_h^4 \approx 6.6 \times 10^{-41}$ cm² (f_N=0.3, m_h=125 GeV).

Plan

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3) Freeze in scenario, FIMP candidate (2010)

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FIMP = Freeze In Massive Particle

or

Feebly Interacting Massive Particle

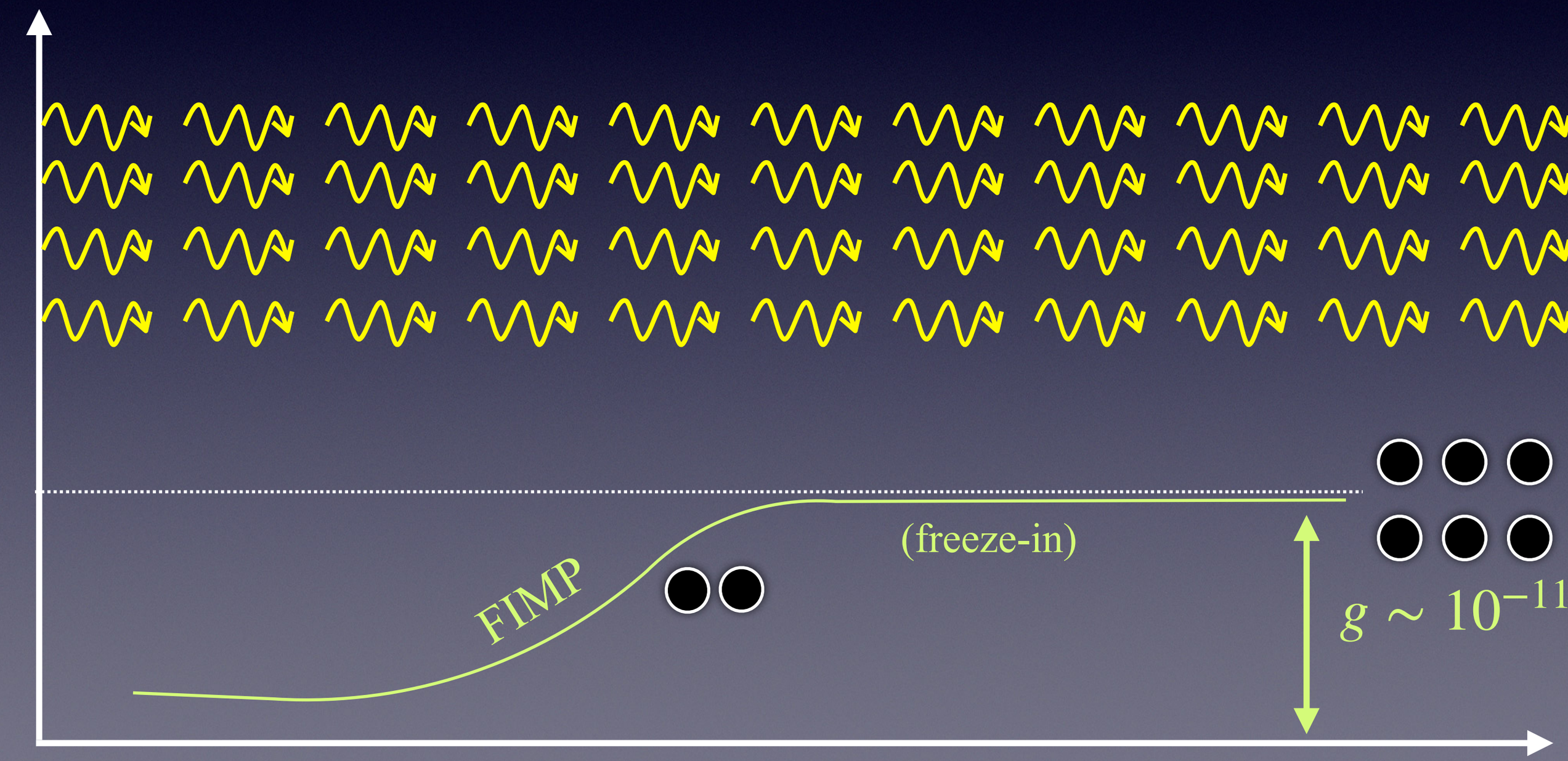
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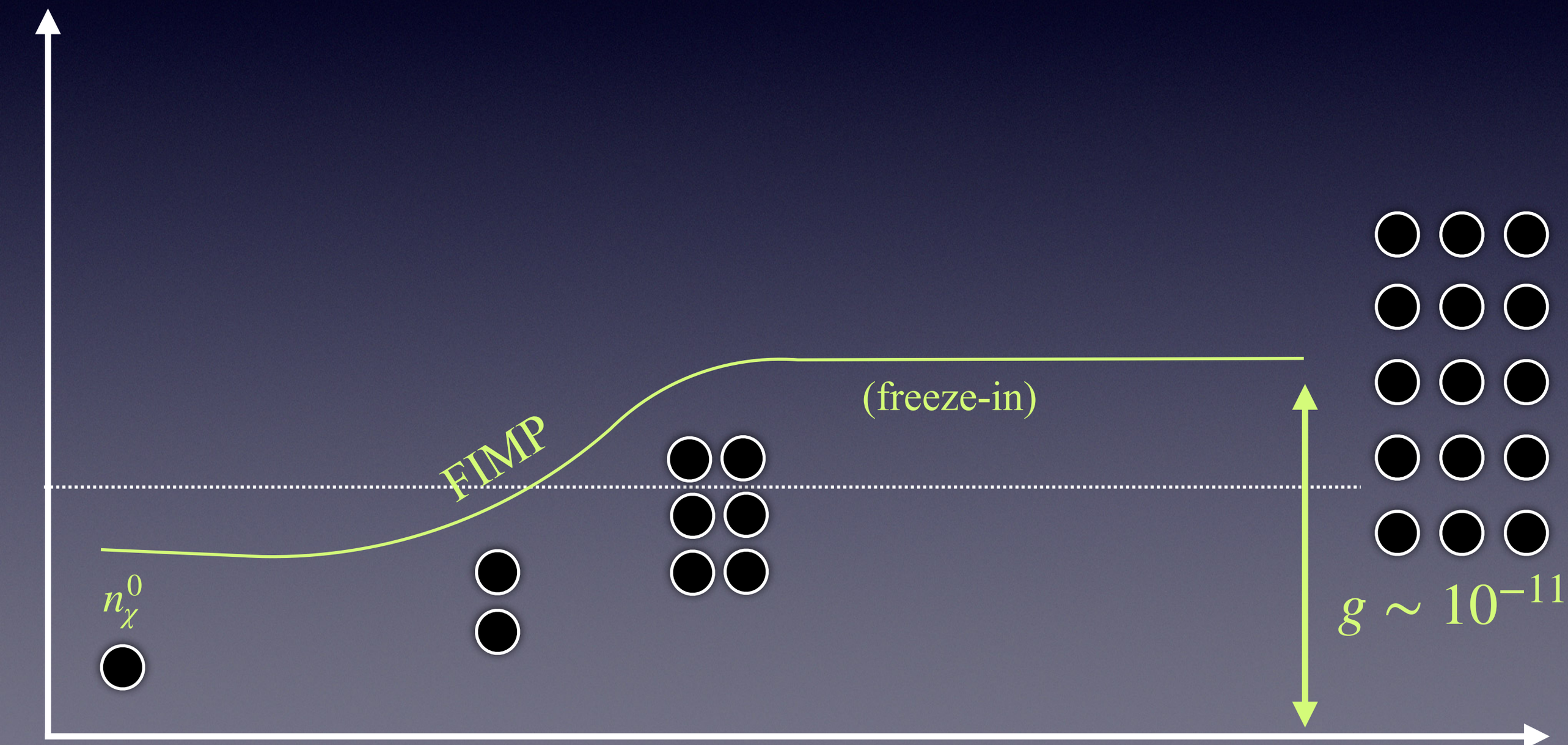
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Problem of the initial condition :

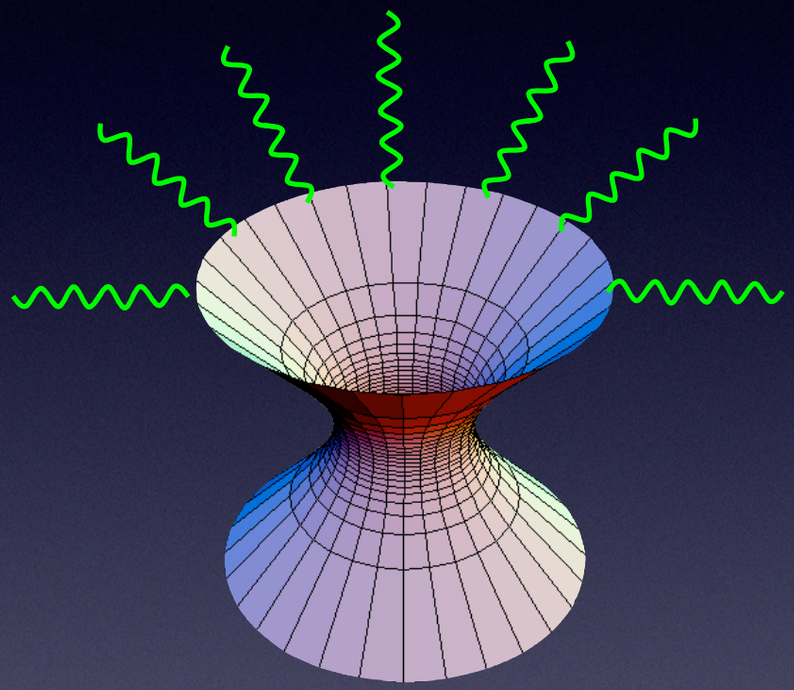
why $n_\chi^0 = 0$?

This issue is *not present* for hot DM or WIMP,
because initial conditions are erased by the thermal equilibrium.
Too feeble coupling + over density!!



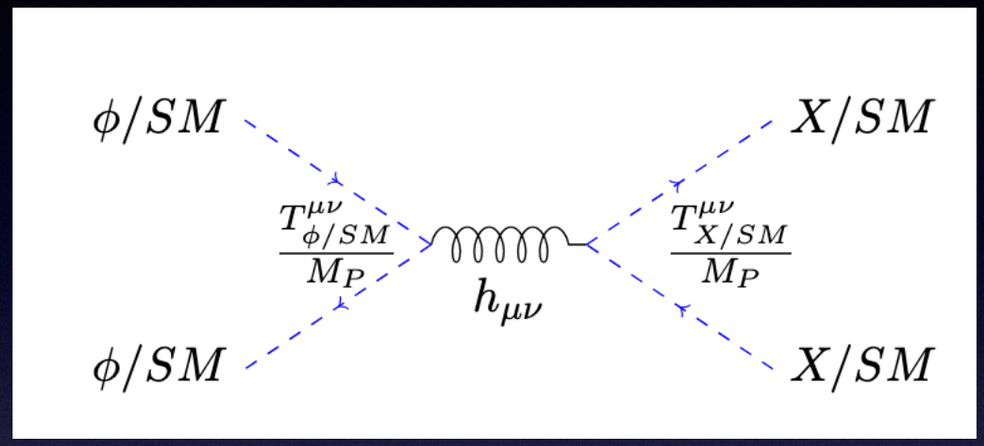
Gravitational production is unavoidable : $n_\chi^0 \neq 0$

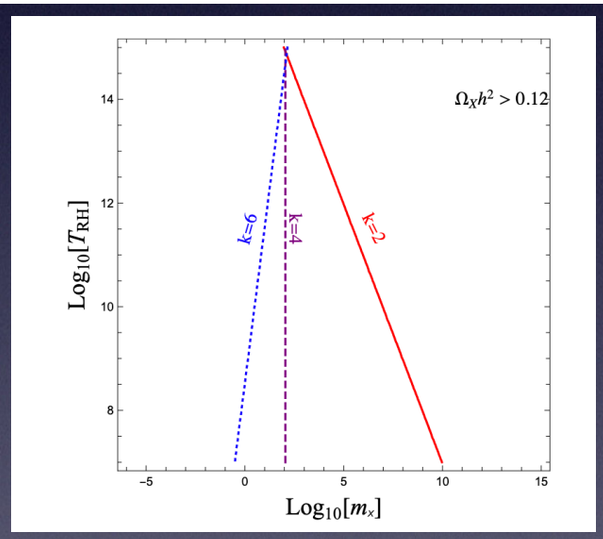
During inflation



De Sitter horizon, $T = \frac{H_{dS}}{2\pi}$

During Reheating

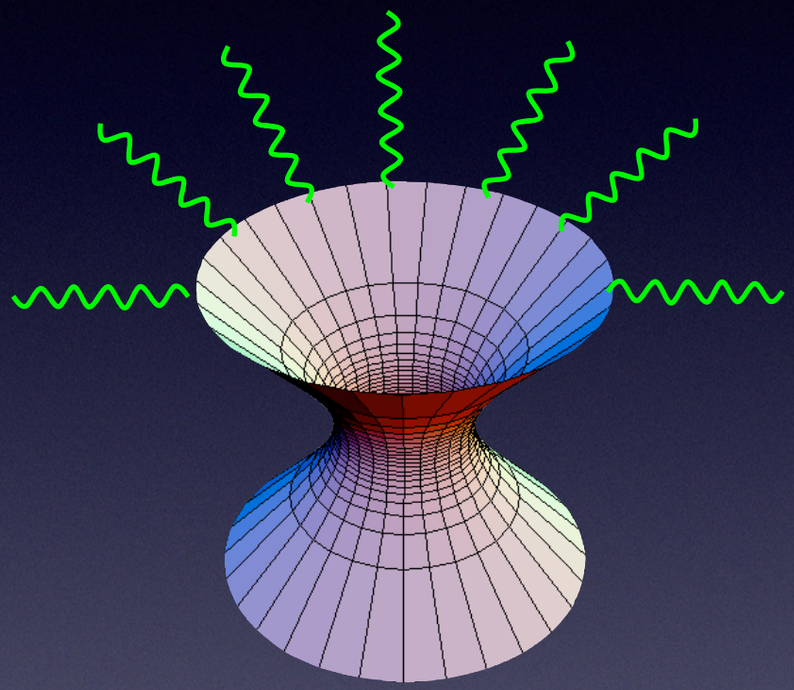




Y. Mambrini and K. A. Olive, Phys. Rev. D **103** (2021)

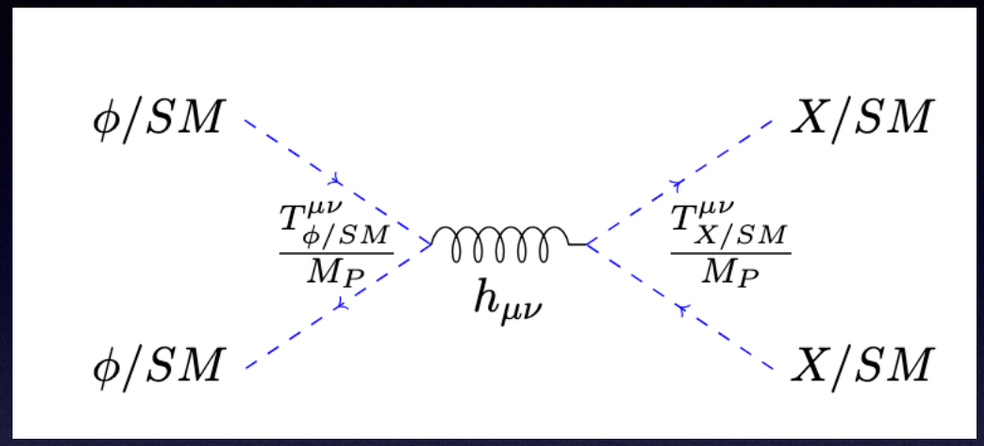
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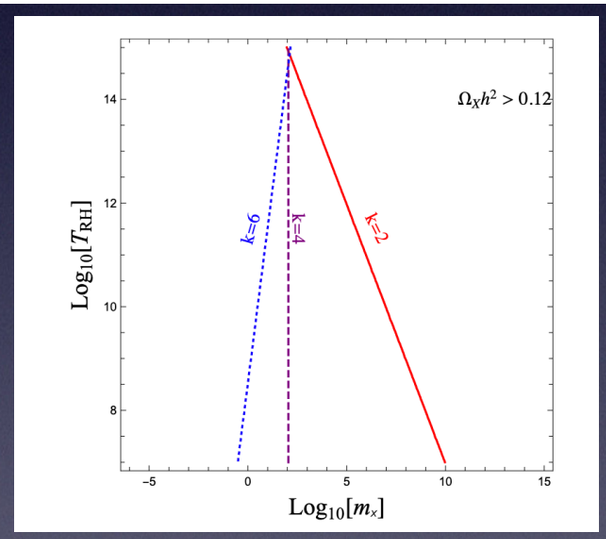
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Y. Mambrini and K. A. Olive, Phys. Rev. D **103** (2021)

Conclusion : FIMP paradigm is not accurate

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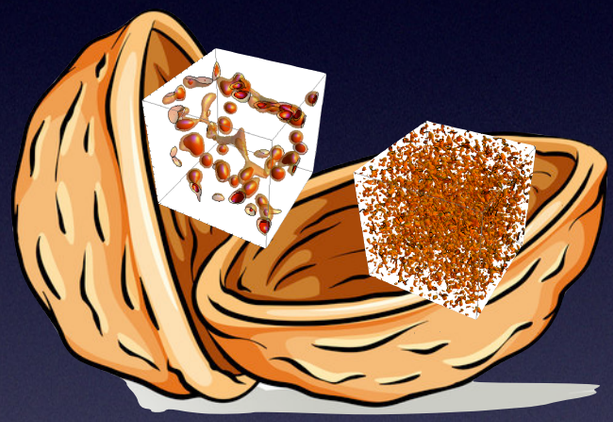
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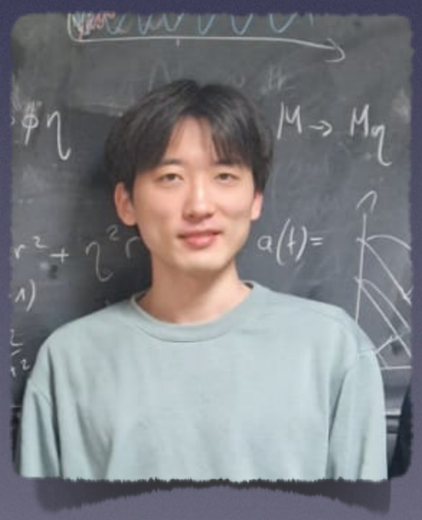
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Common point of all these constructions :
a vanilla (naive?) thermal history of the Universe

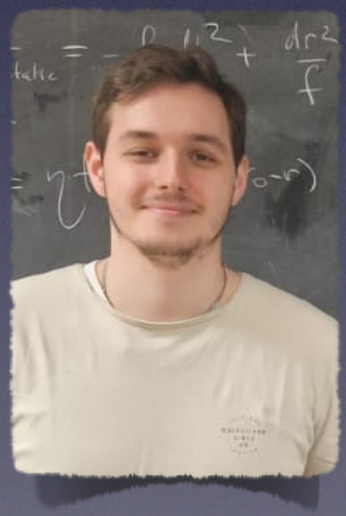
Reheating in a nutshell









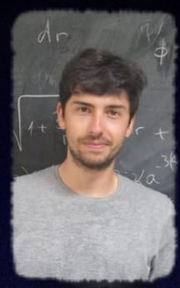


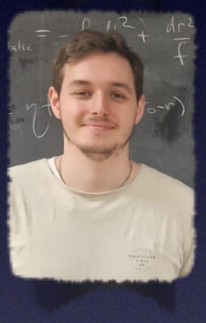
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ϕ

Reheating in a nutshell

Reheating : /ˌriːˈhiːtɪŋ/ *noun*

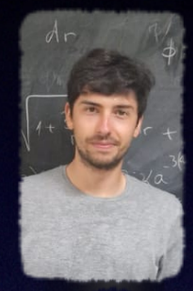
Process of transfer of energy from a de Sitter space to radiation through the oscillations of a *classical homogeneous* field (the inflaton)

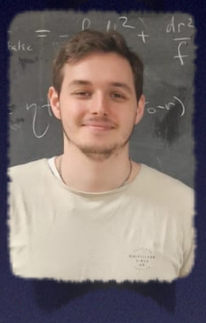


ϕ





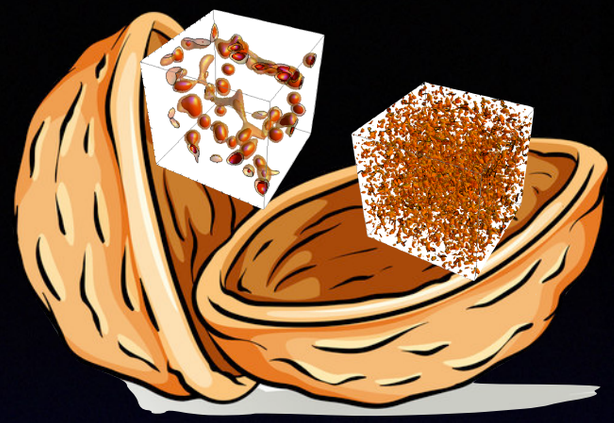




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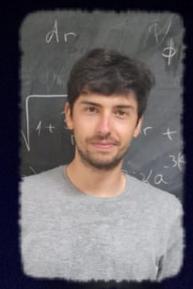
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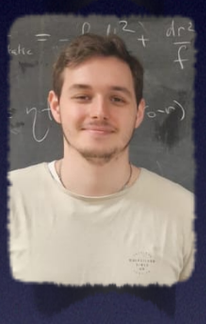
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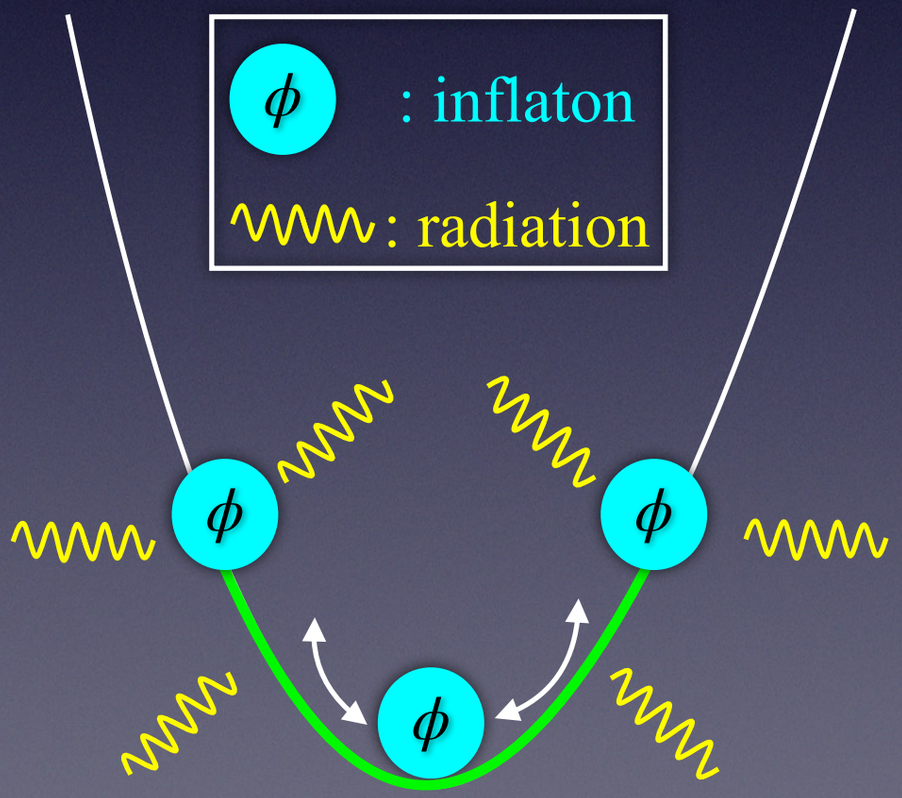


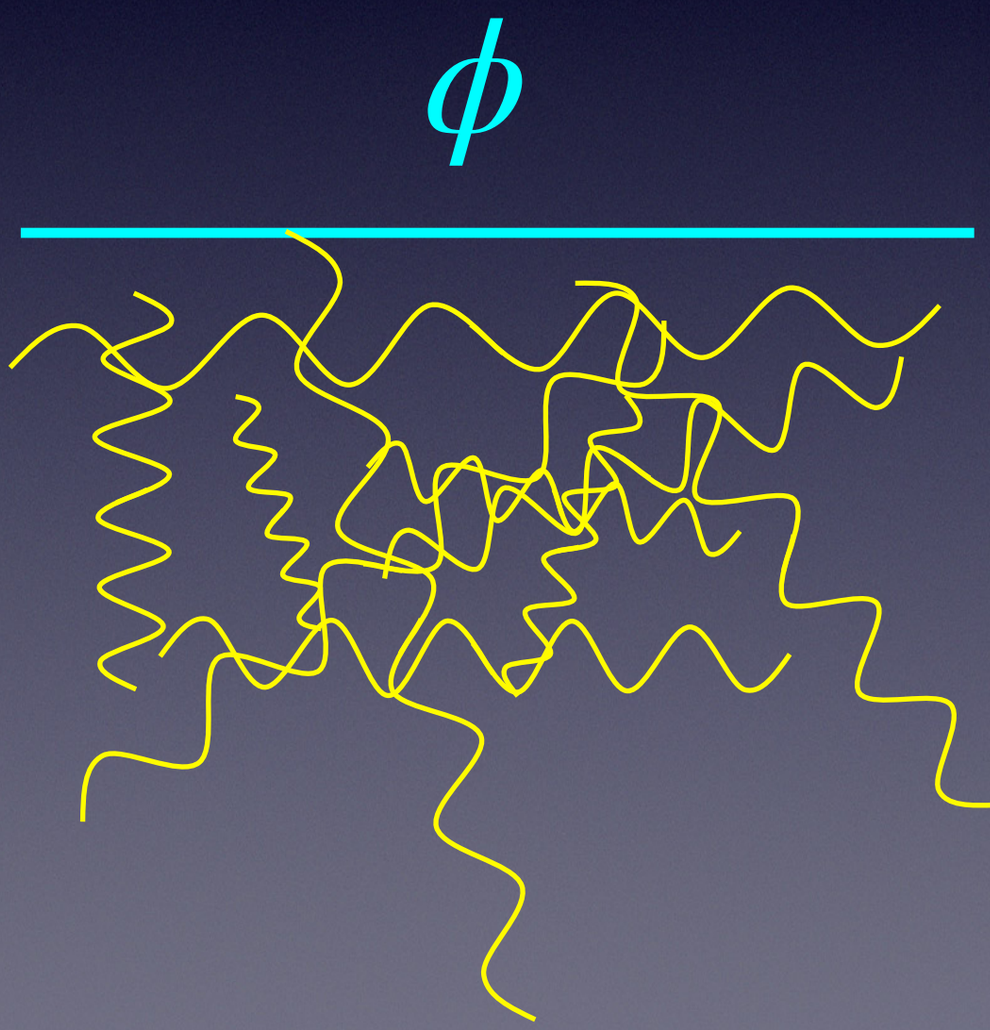












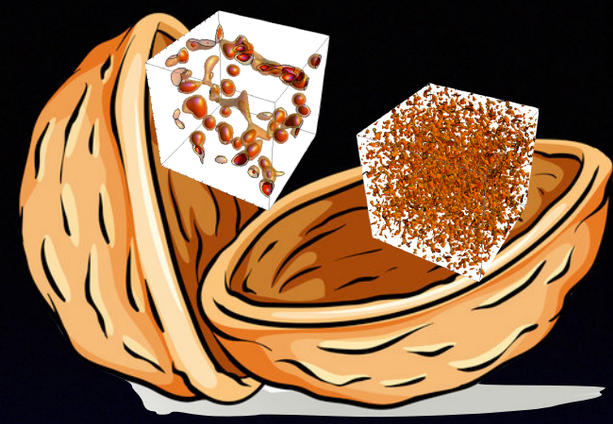
Reheating in a nutshell

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

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

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

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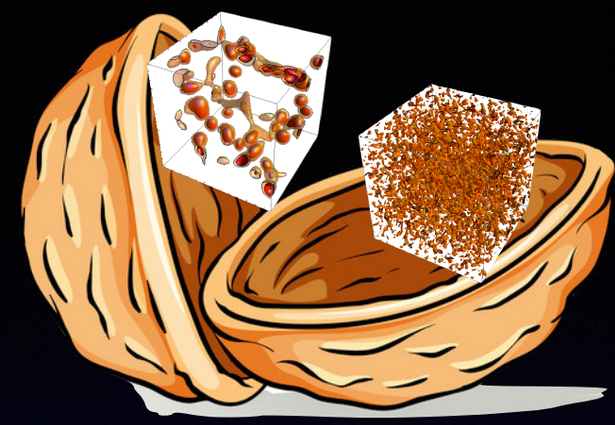
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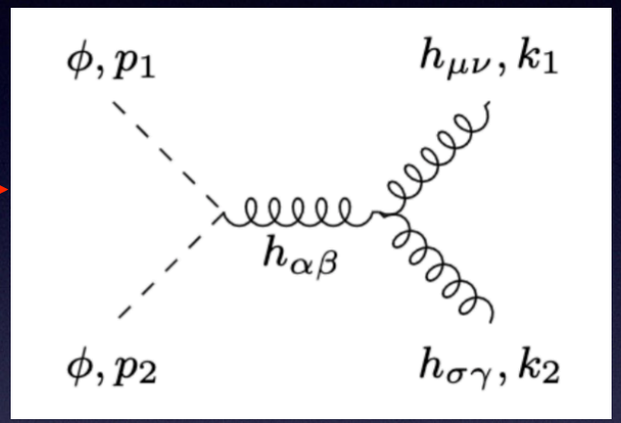
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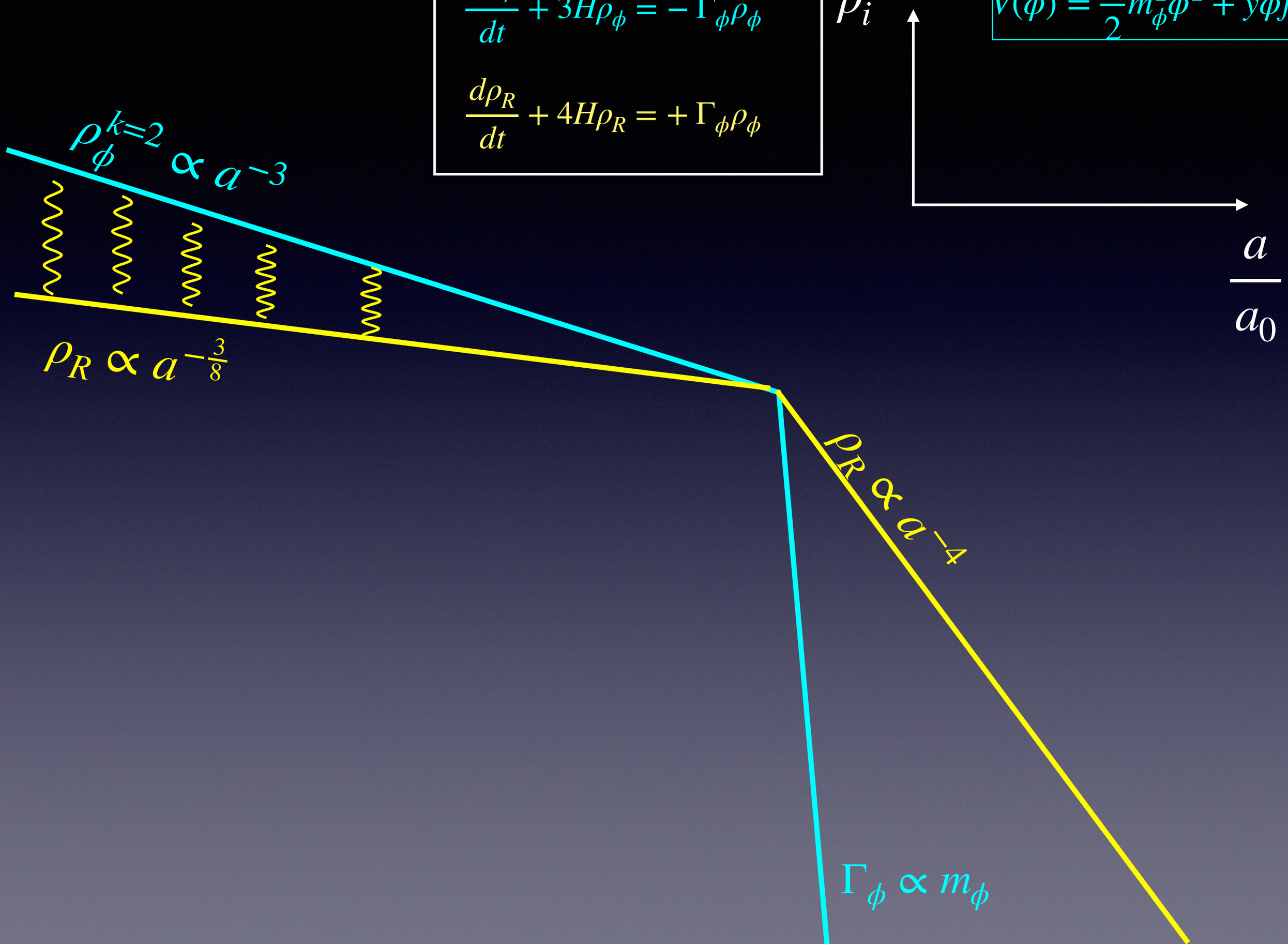


Feynman approach

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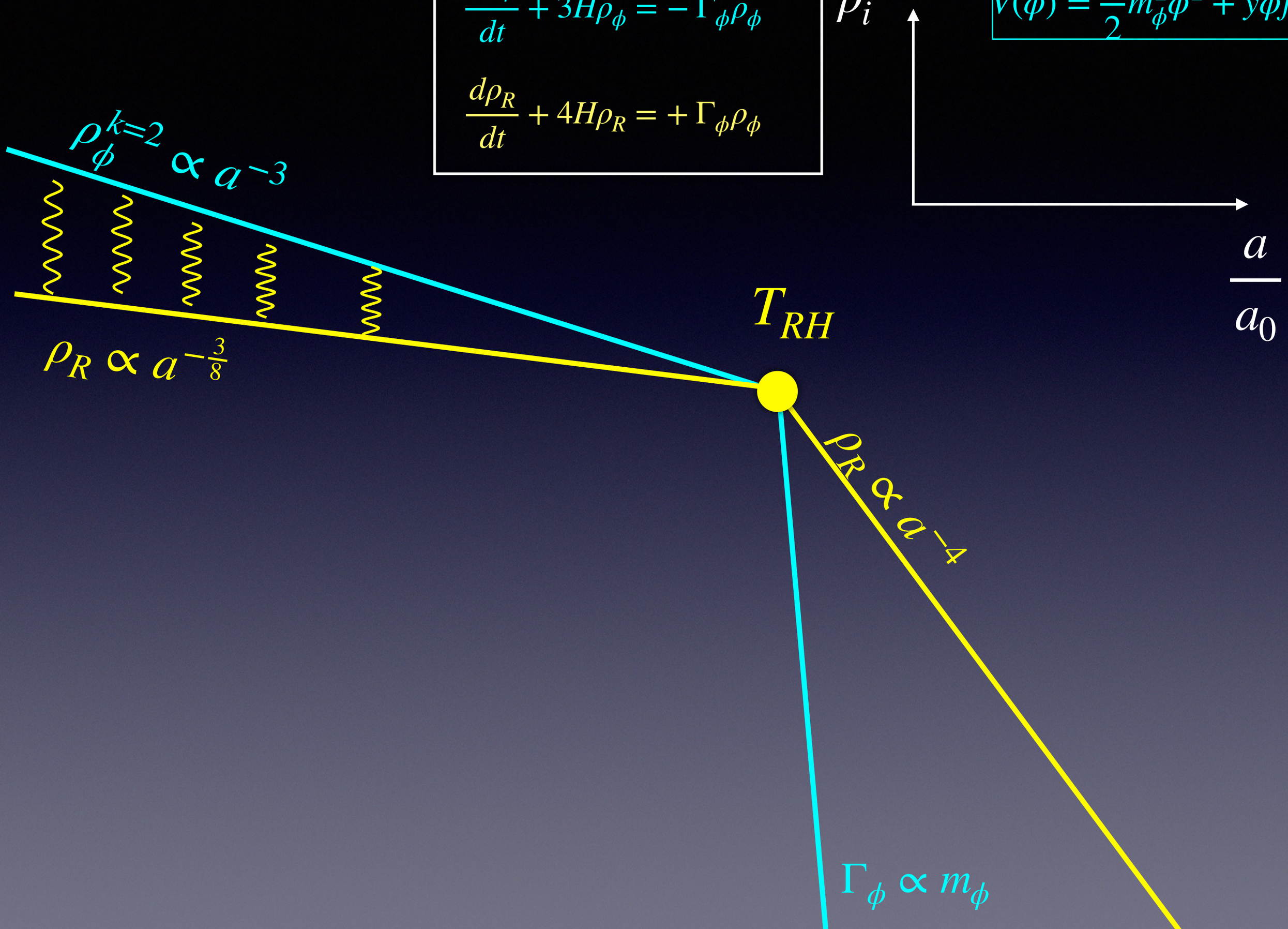
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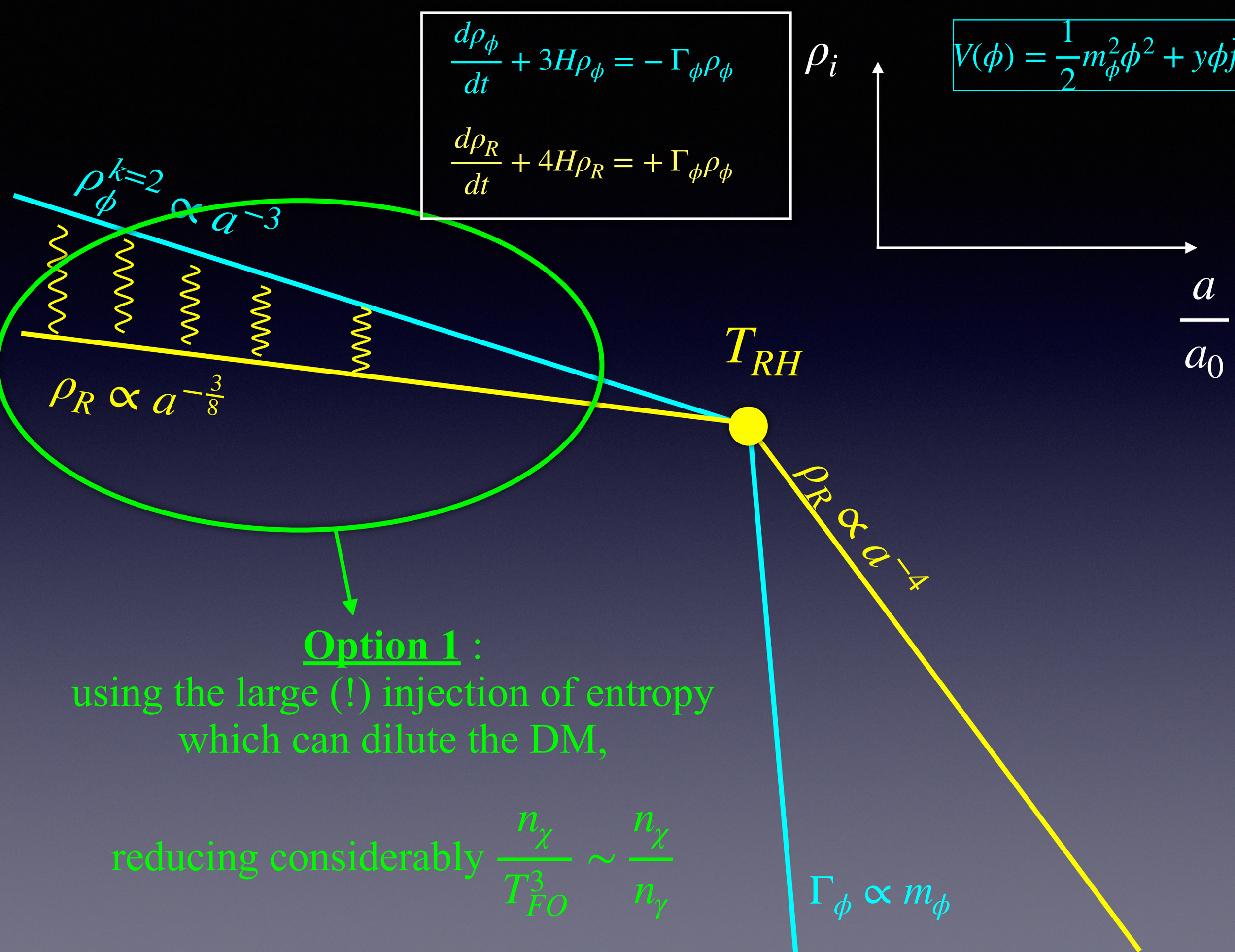
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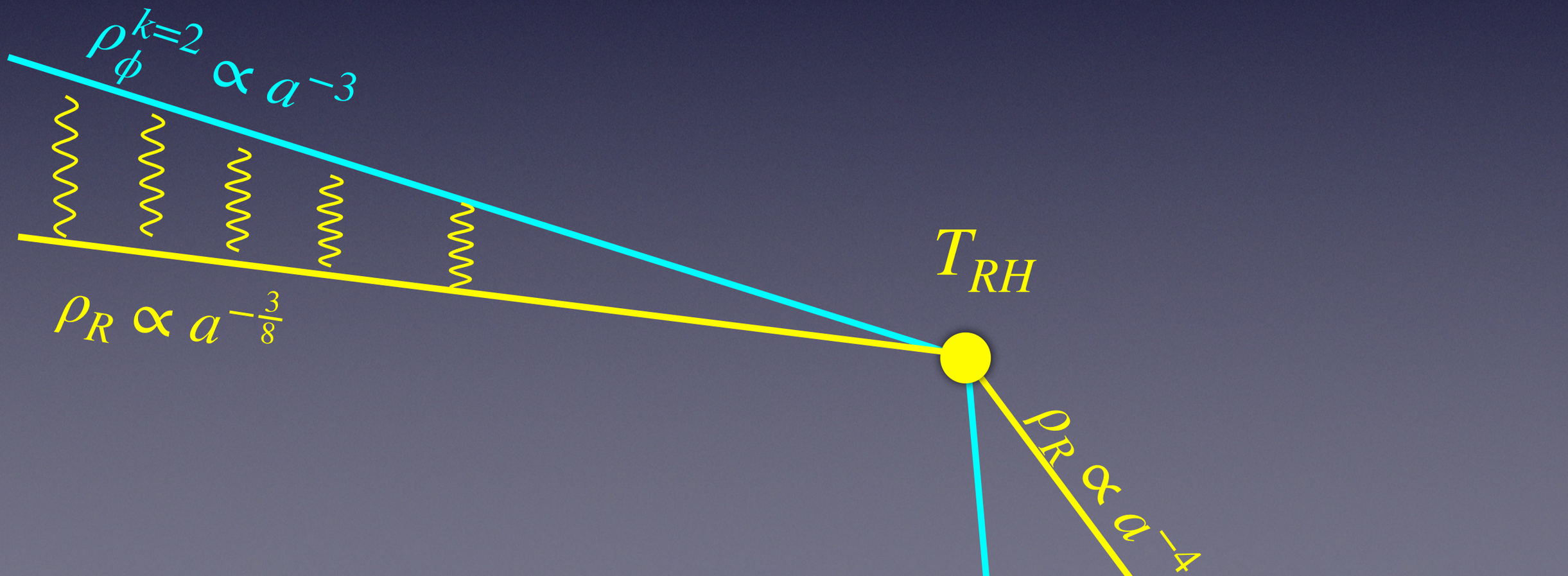
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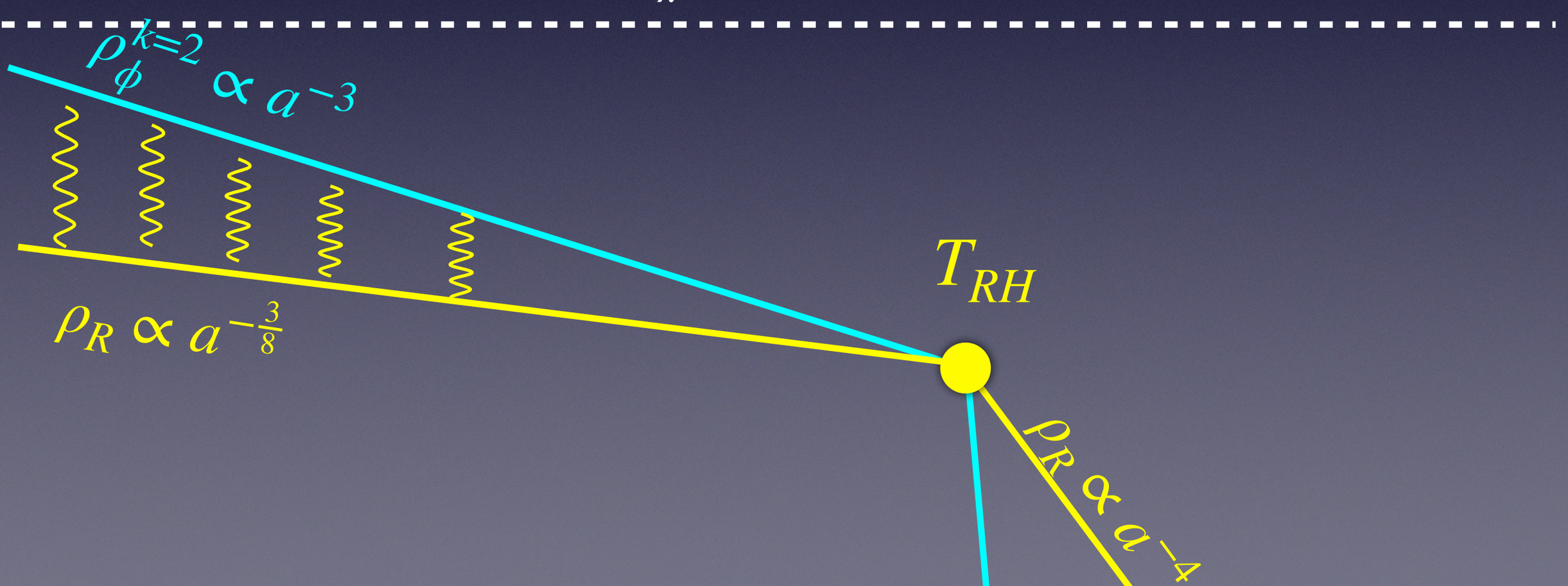
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Option 2 :
DM mass much above
the reheating temperature T_{RH}
(low T_{RH}scenario)

$$\Rightarrow \quad \frac{n_\chi}{n_\gamma} \sim \left(\frac{m_\chi}{T}\right)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}}$$

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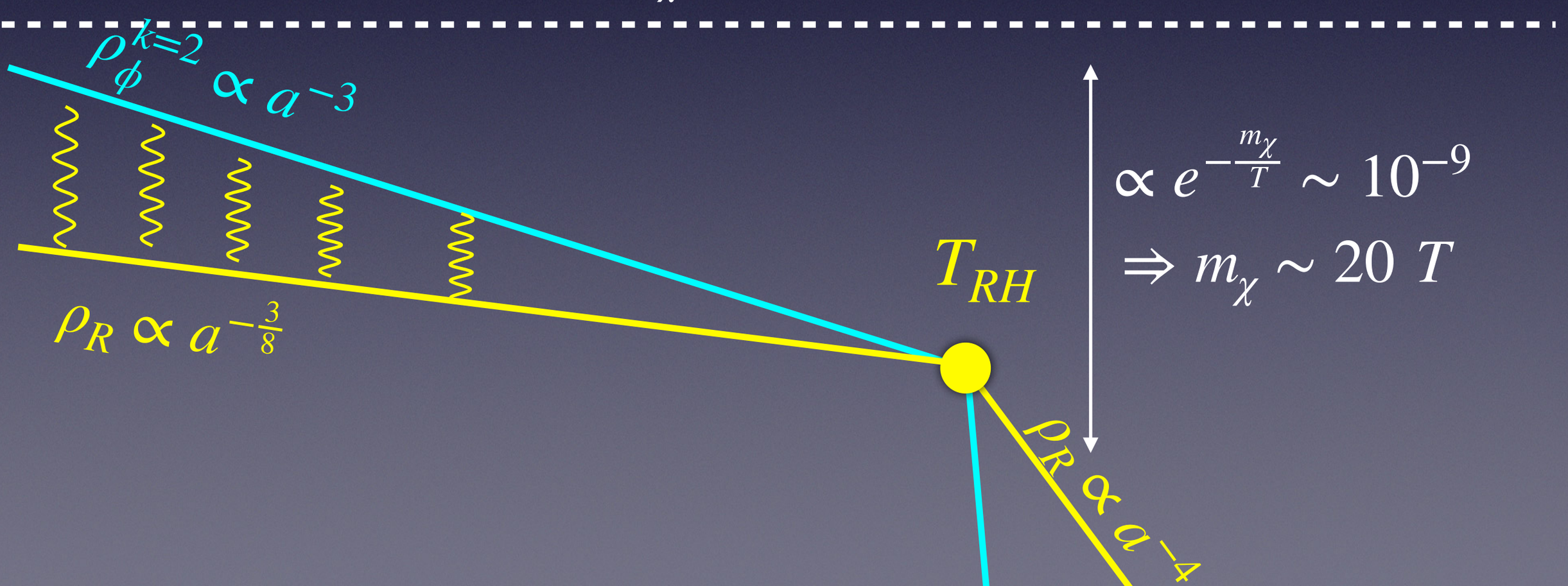
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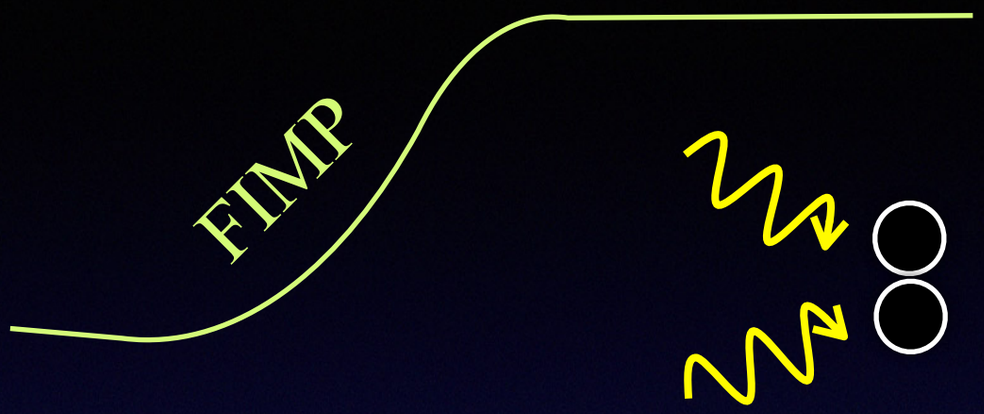


Option 2 :

Freeze In at Stronger Coupling

(FISC; Cosme, Lebedev, 2024)

Freeze In at Stronger Coupling

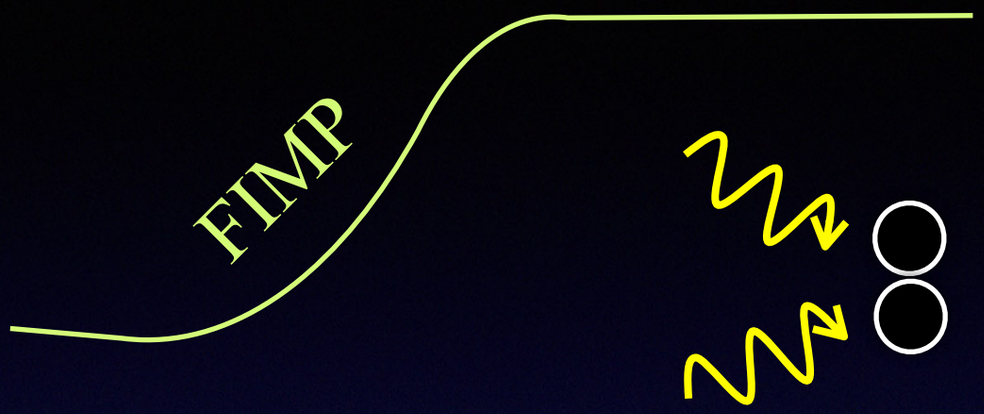


Classical FIMP case :

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

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Freeze In at Stronger Coupling



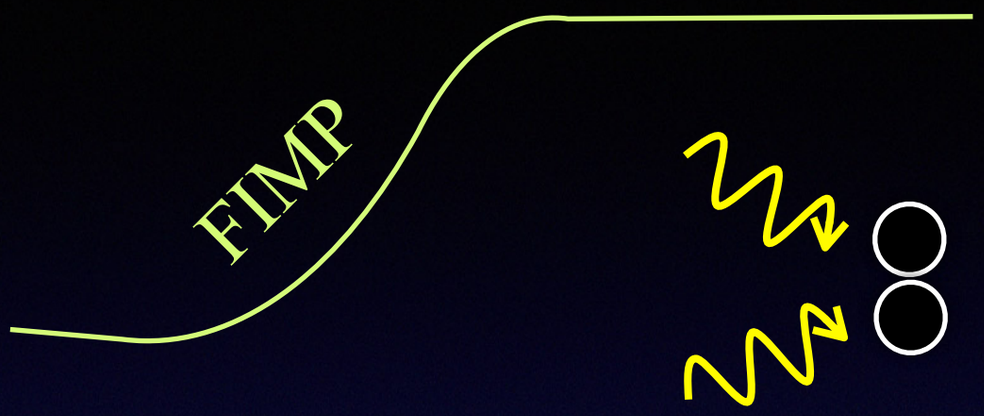
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Freeze In at Stronger Coupling



<u>*Or*</u> :

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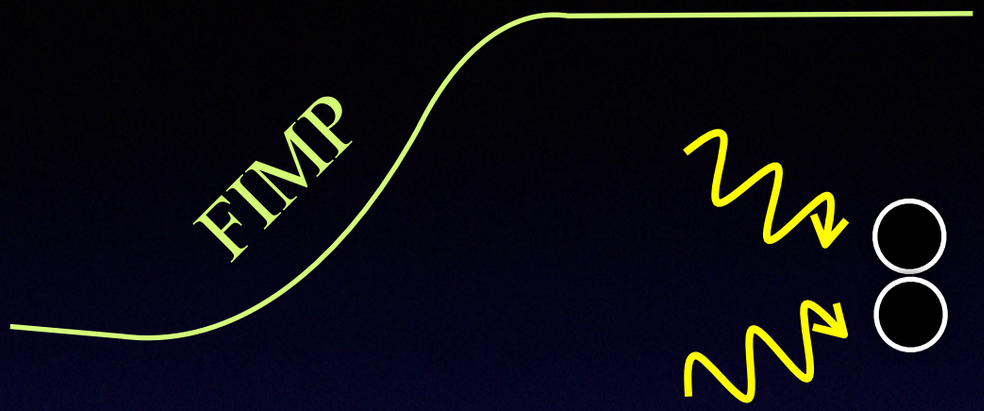
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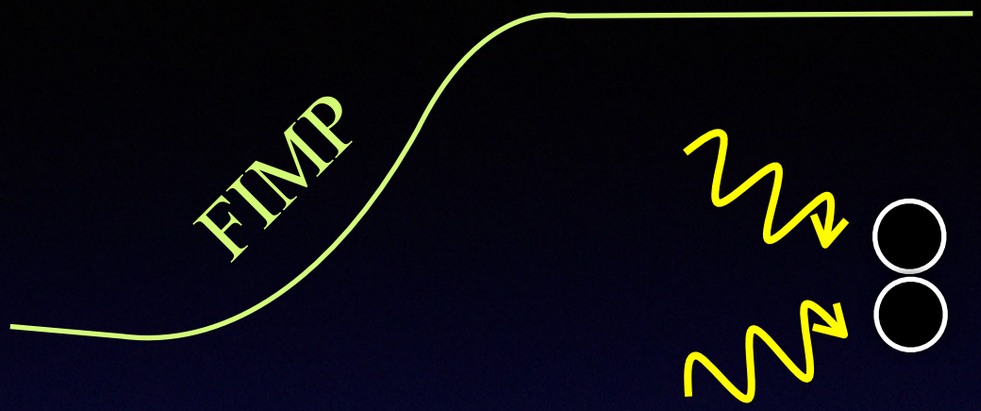
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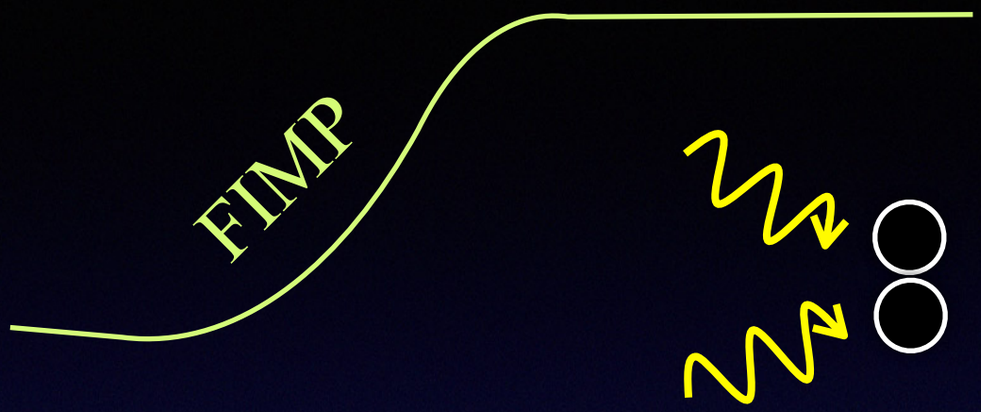
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<u>*Classical*</u> FIMP case :

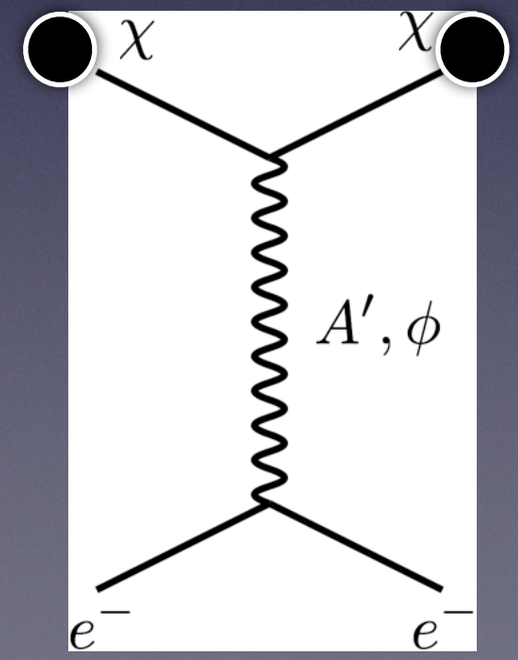
$n_\chi(T_{FO}) = n_\gamma^2 \times [\langle \sigma v \rangle \, H^{-1}]$,

$\langle \sigma v \rangle \simeq 10^{-18} \sigma_{EW} \Rightarrow \dfrac{n_\chi}{n_\gamma} \sim 10^{-9}$

Hard to detect

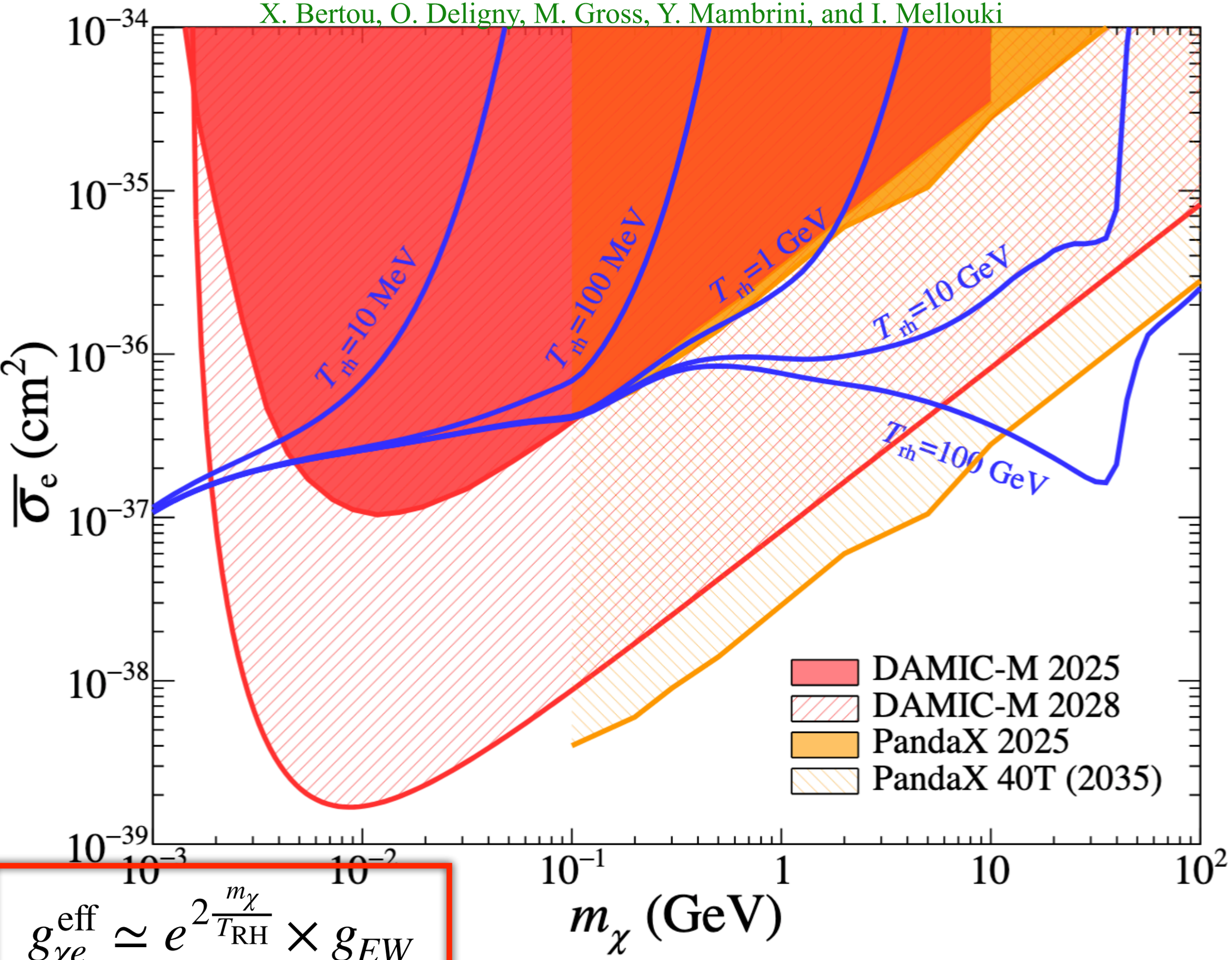
Consequence :

Direct detection possible



« *Next targets of direct-detection experiments sensitive to ultra-light dark photons: freeze-in with stronger couplings and inflaton-seeded freeze-in* »

X. Bertou, O. Deligny, M. Gross, Y. Mambrini, and I. Mellouki



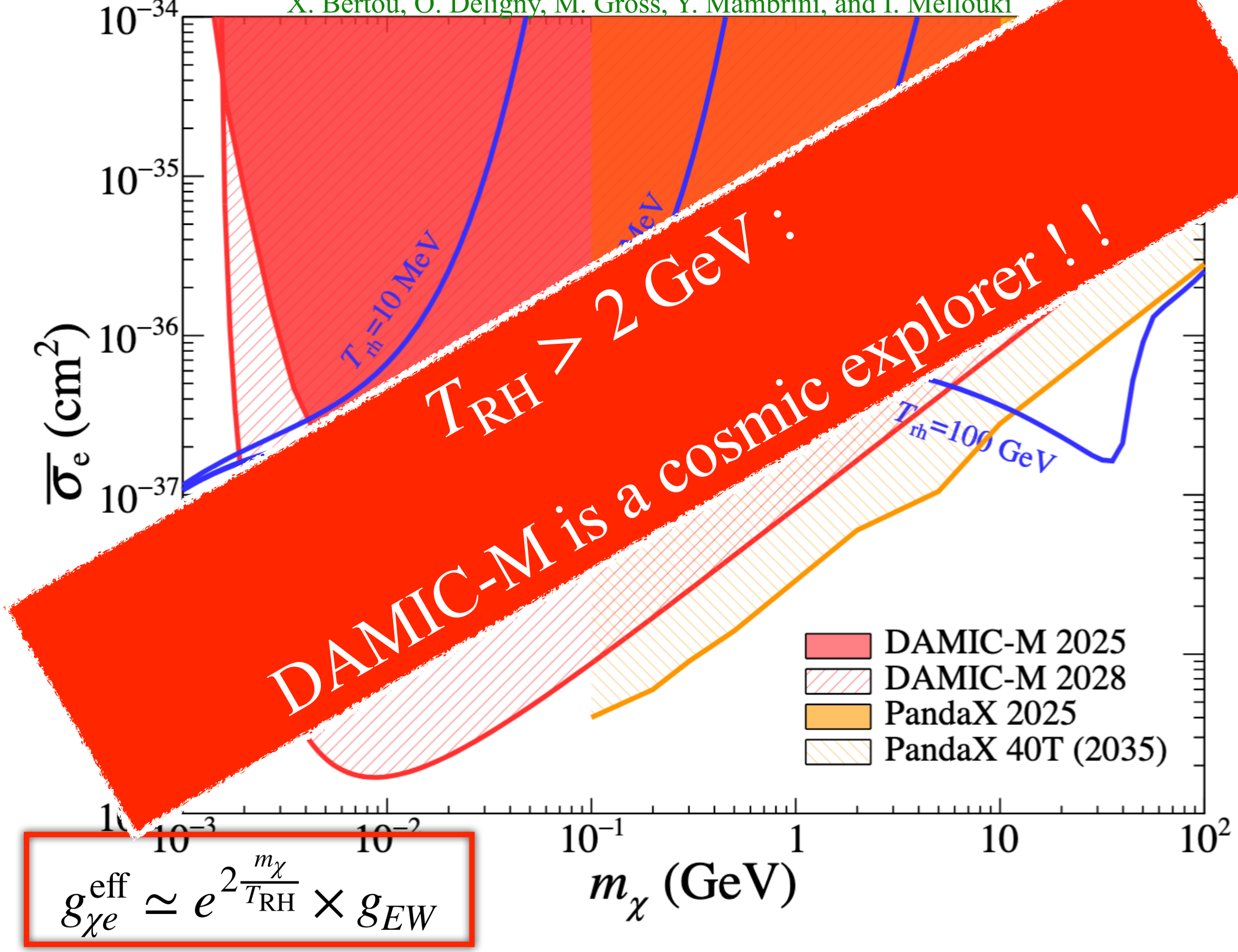
$$g_{\chi e}^{\text{eff}} \simeq e^{2\frac{m_\chi}{T_{\text{RH}}}} \times g_{EW}$$

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$T_{RH} > 2$ GeV :

DAMIC-M is a cosmic explorer ! !



$$g_{\chi e}^{\text{eff}} \simeq e^{2\frac{m_\chi}{T_{\text{RH}}}} \times g_{EW}$$

Plan

1) ~~Hot dark matter~~, ~~the neutrino candidate (1966)~~

2) ~~Cold dark matter~~, ~~WIMP candidate (1980)~~

3) ~~Freeze in scenario~~, ~~FIMP candidate (2010)~~

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Stephen Henrich



Mathieu Gross

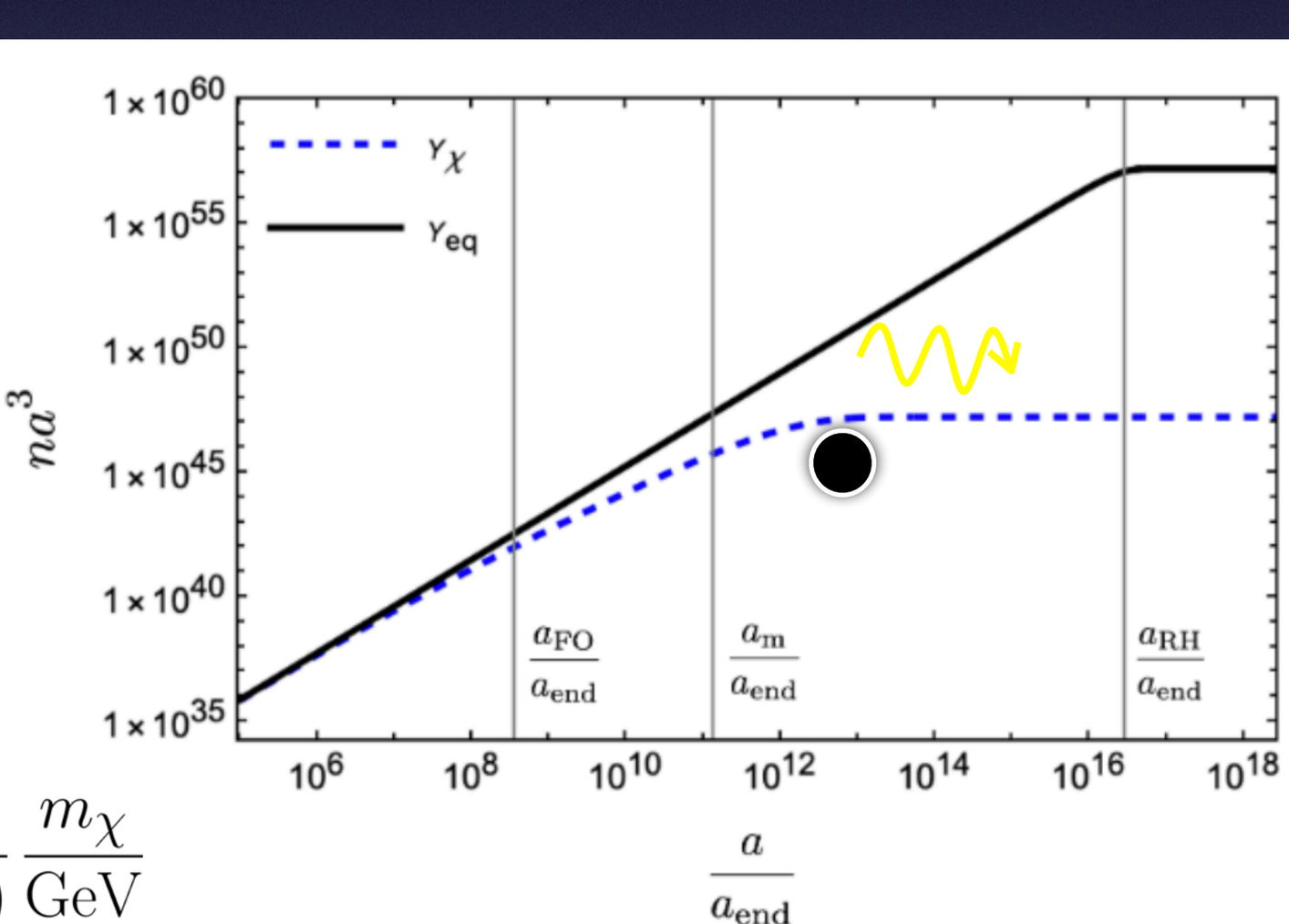
Option 1 :

Ultra-Relativistic Freeze Out

(UFO, 2025)

Ultra-Relativistic Freeze Out

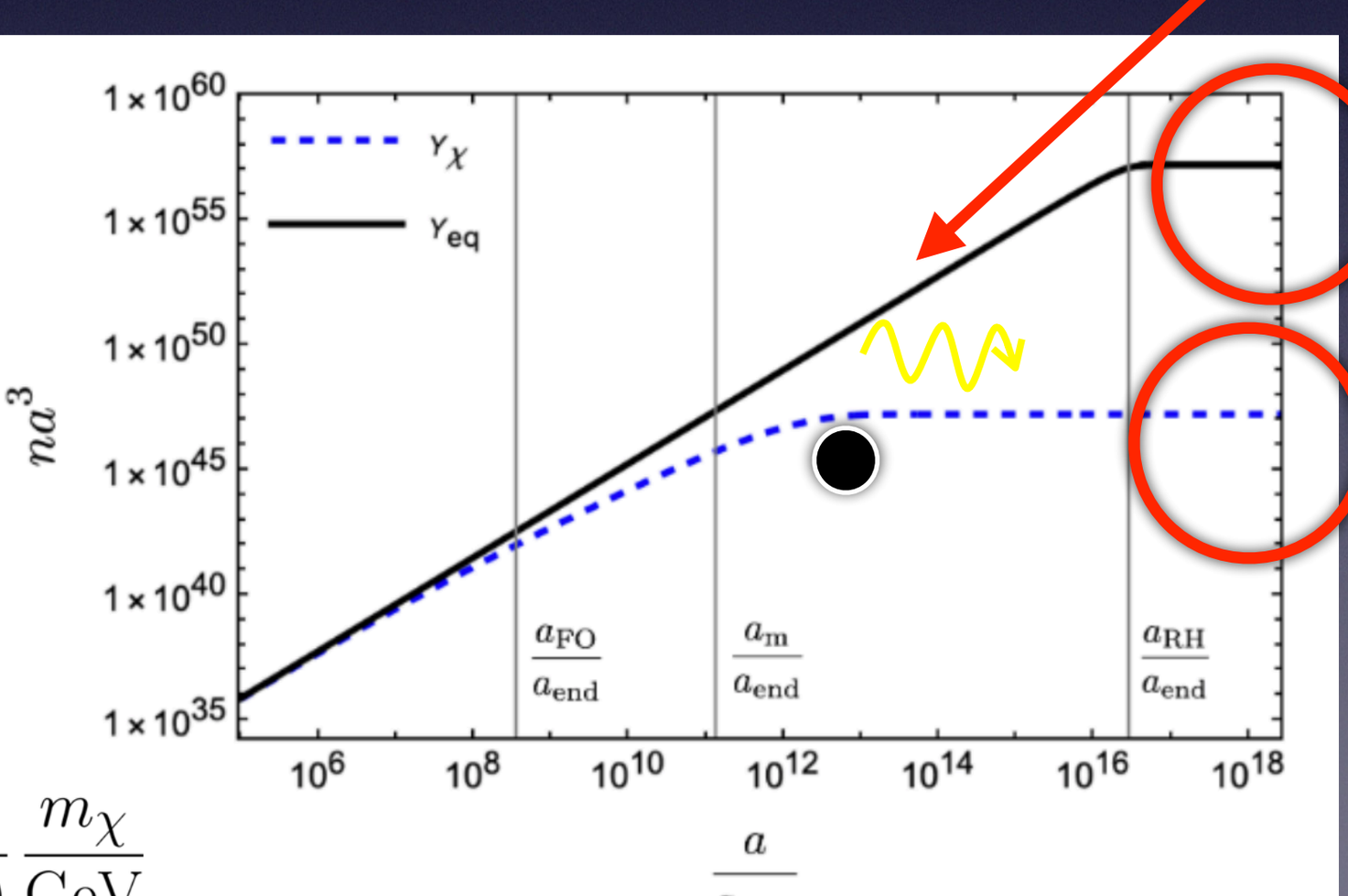
Idea : using the reheating period to *drown* the dark matter in a see of radiation before the radiation domination.



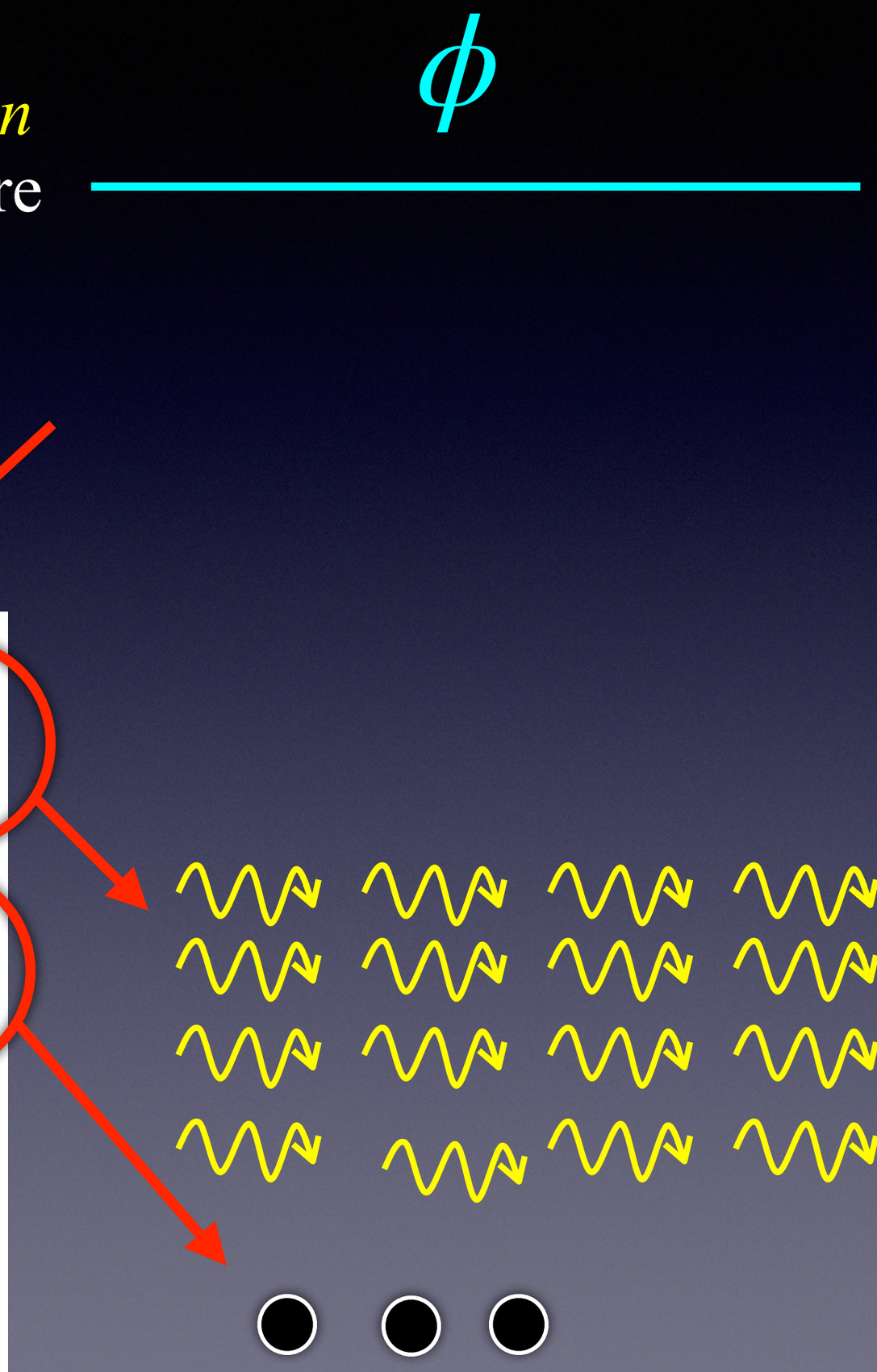
$\frac{m_\chi}{\rm GeV}$

Ultra-Relativistic Freeze Out

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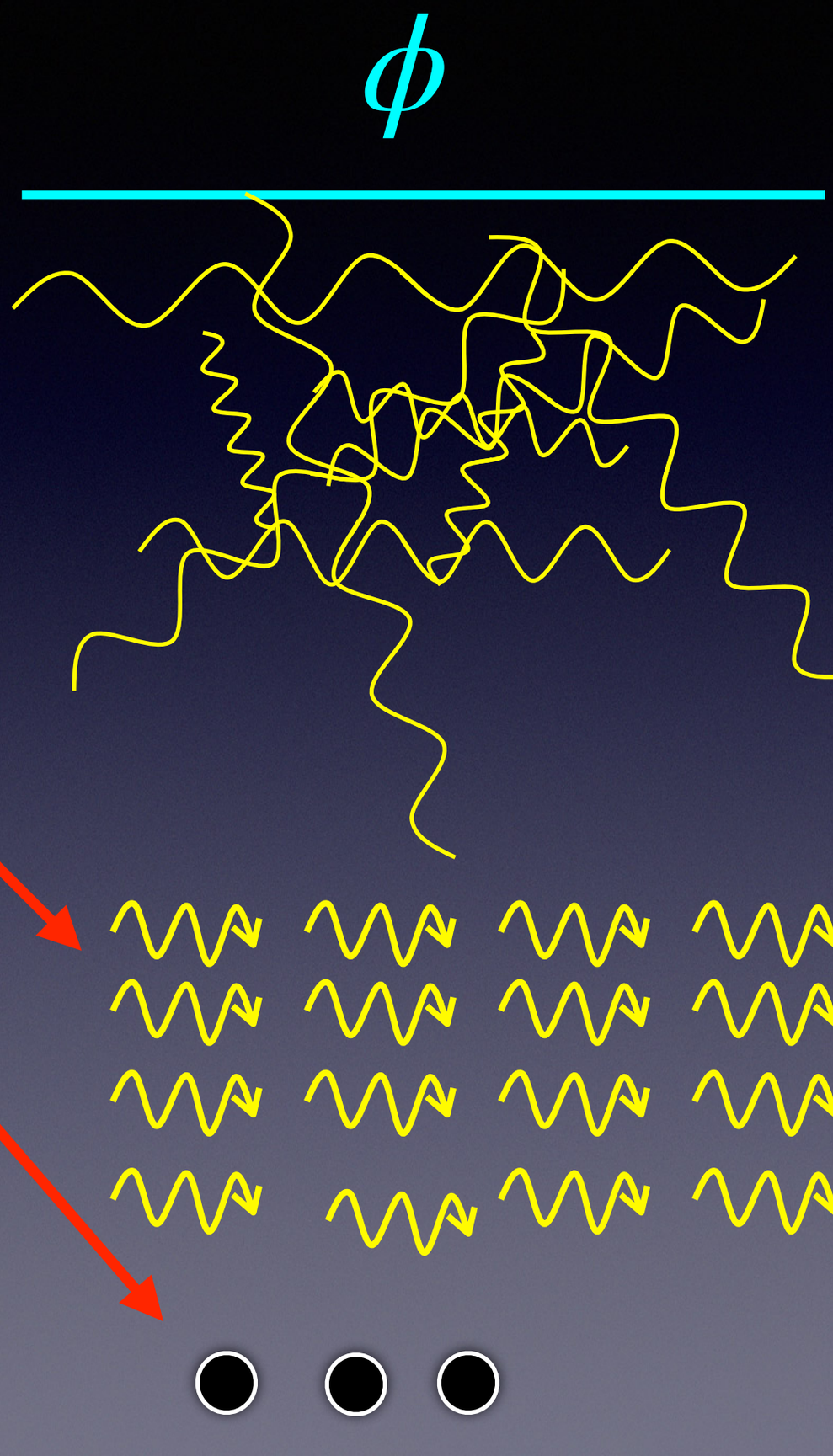


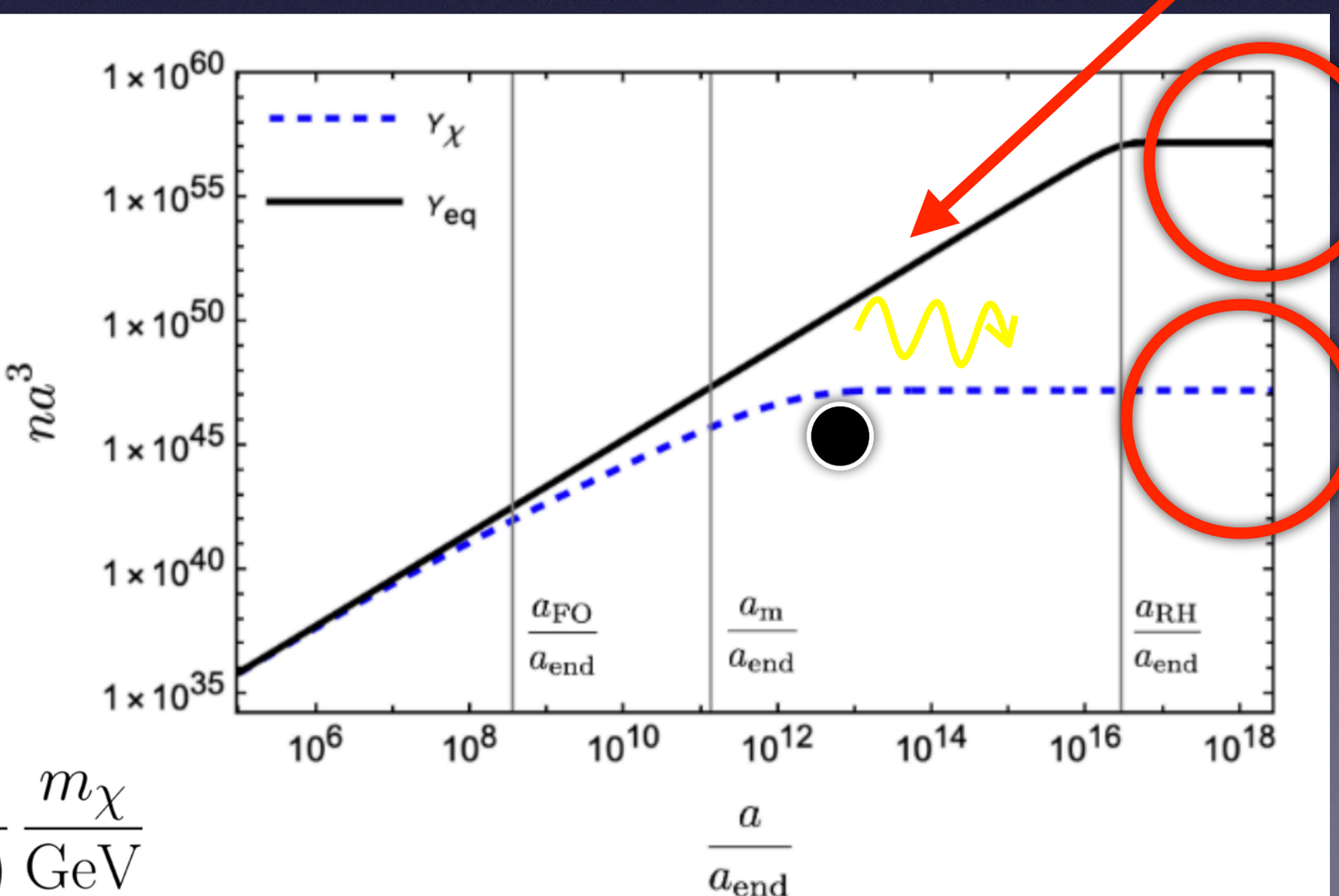
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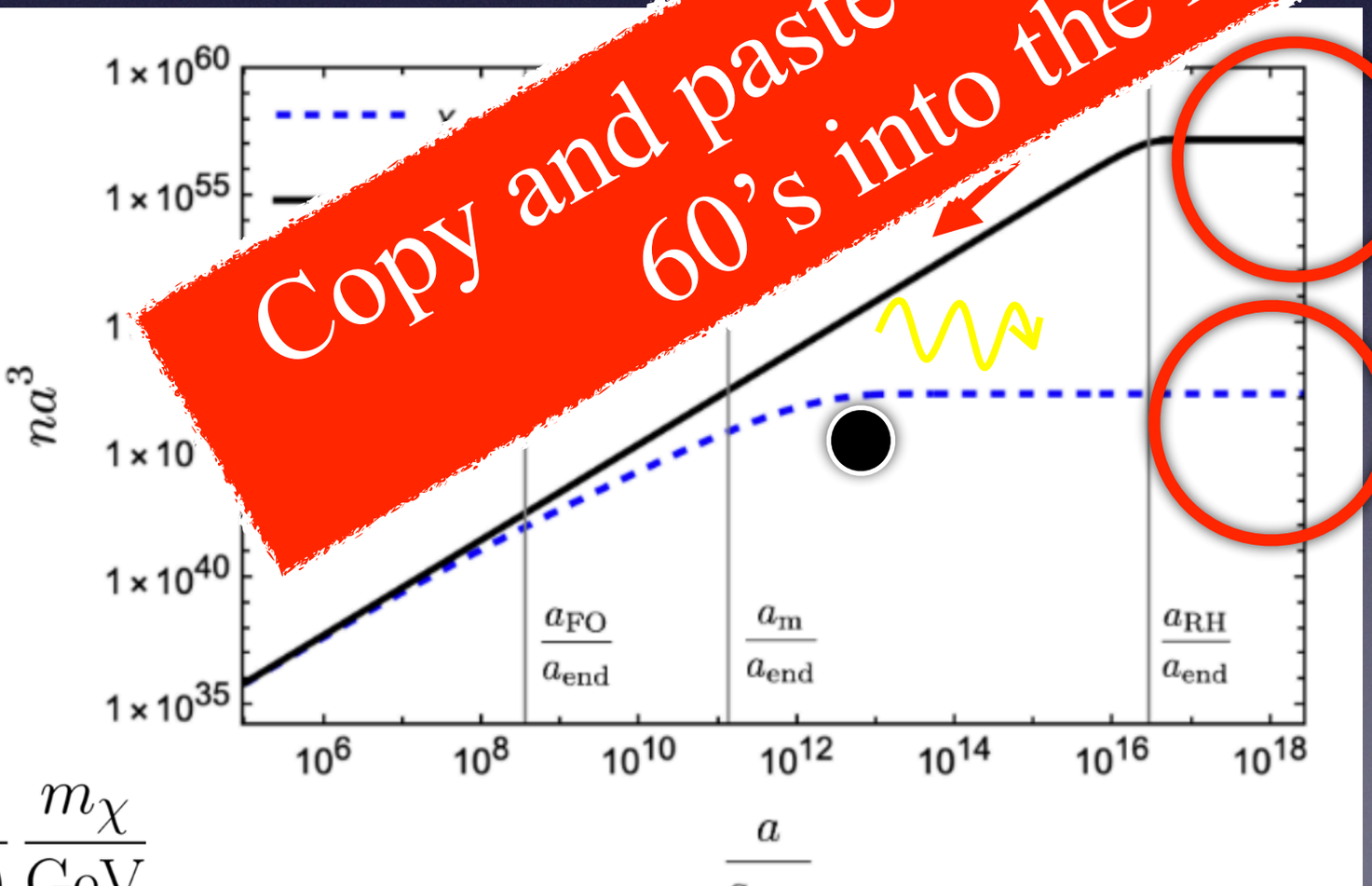


$\frac{m_\chi}{\rm GeV}$

Ultra-Relativistic Freeze Out

Idea : using the reheating period to *drown* the dark matter in a see of radiation before the radiation domination.

Copy and paste the successful ν-story of the 60's into the reheating period



$\frac{m_\chi}{\rm GeV}$

Advantage UFO over FIMP :

« strong » coupling to ensure thermal equilibrium : detectable

Advantage UFO over FISC and FIMP :

no initial condition problem, because DM is in thermal equilibrium before the decoupling. The cosmic history is erased.

Advantage UFO over WIMP :

Possible large coupling but not at EW scale : not excluded by DD experiments

Advantage UFO over $\nu-$DM :

Ultrarelativistic at decoupling time but cold today :
no Lyman-α or structure formation constraints

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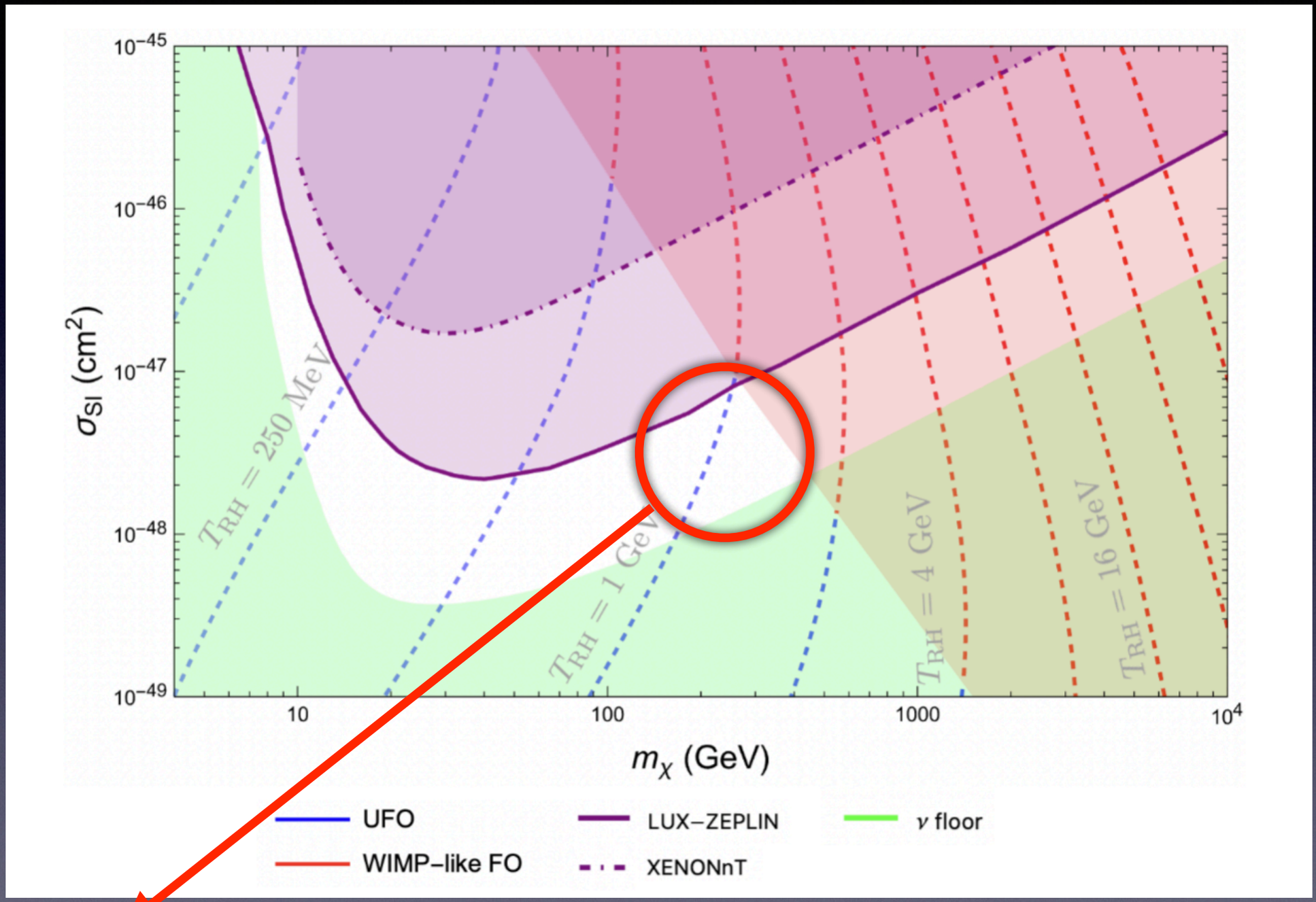
a 10 eV DM stopped very late (at very low T)

Non-relativistic temperature for a UFO DM :

$$T_{\rm NR}^{\rm UFO} \simeq m_{\chi} \times \left(\frac{T_{\rm FO}}{T_{\rm RH}} \right)^{\frac{5}{3}}$$

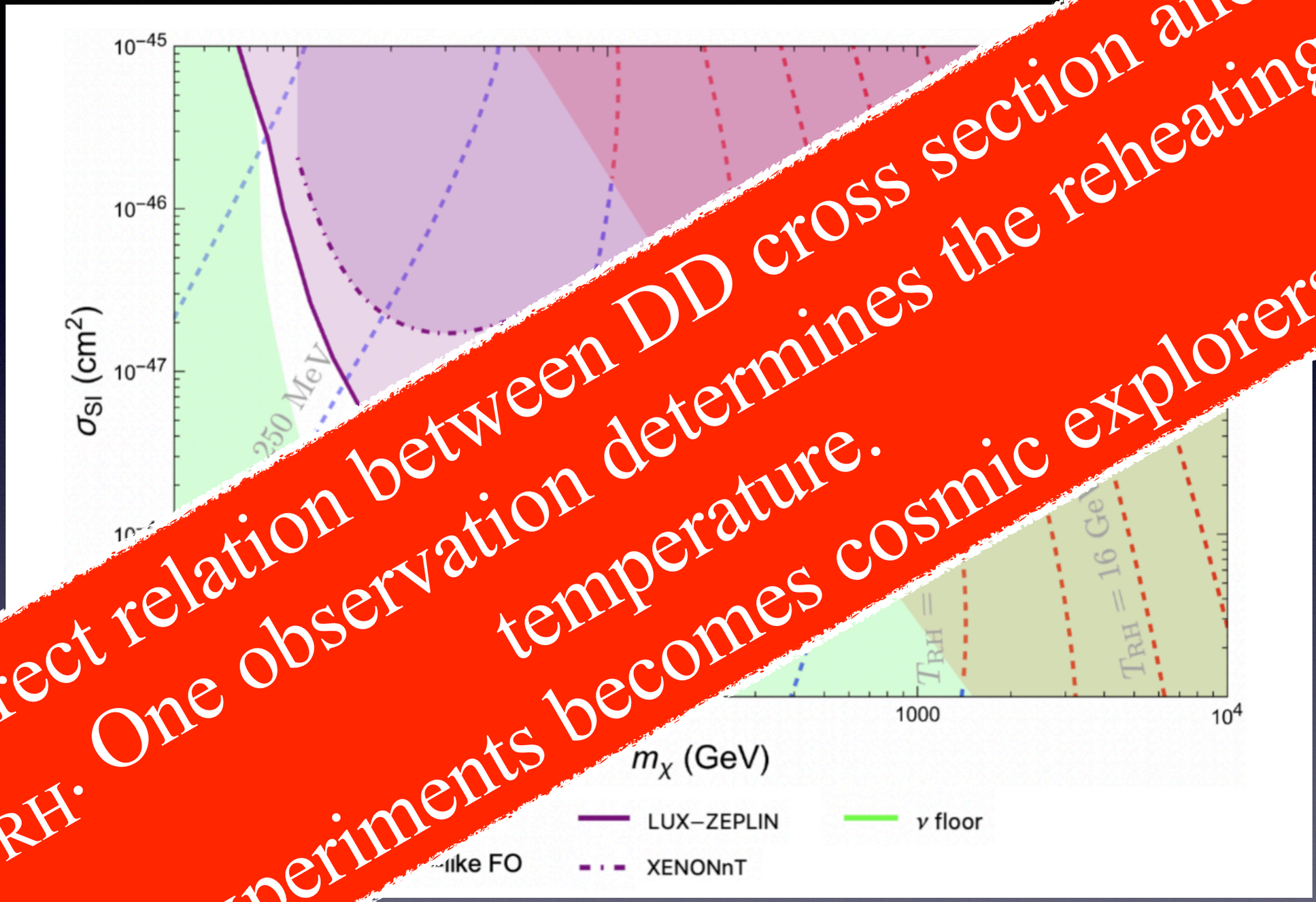
a 10 eV χ stopped very early : small structures ok!

Direct detection prospect for UFO



Strong dependence on T_{RH} which determines how much DM is « drowned »

Direct detection prospect for UFO



Direct relation between DD cross section and T_{RH}: One observation determines the reheating temperature.

DD experiments becomes cosmic explorers ! !

dependence on T_{RH} which determines how much DM is « drowned »

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Conclusion

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

Not seen

WIMP

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

Not visible

FIMP

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

Structures

νFO

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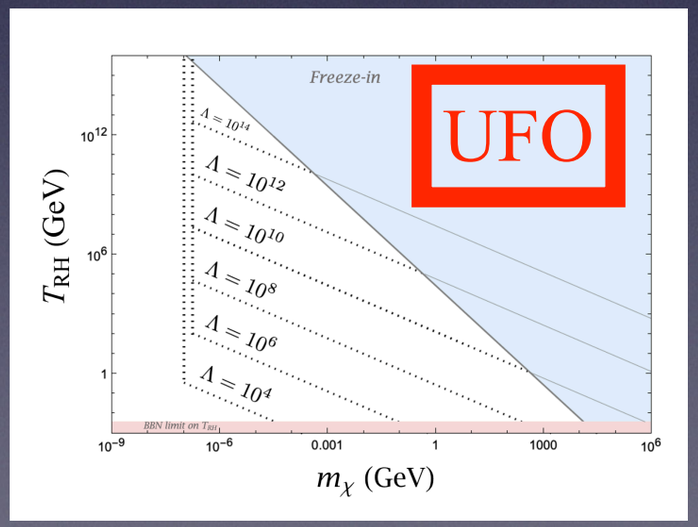
FIMP

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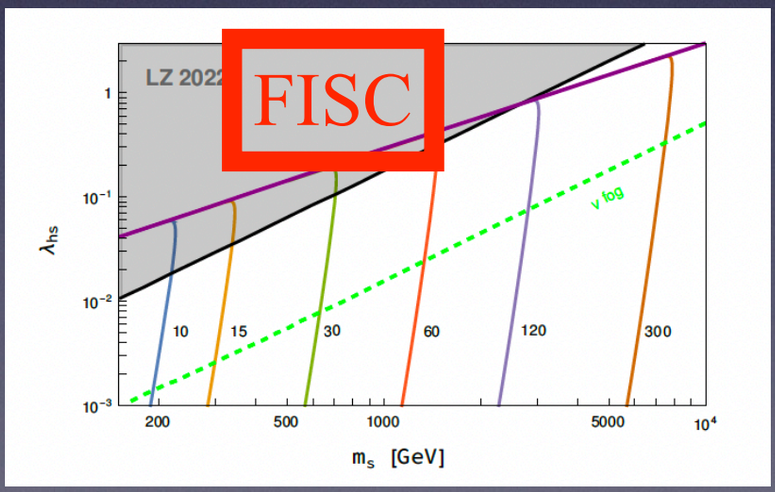
νFO





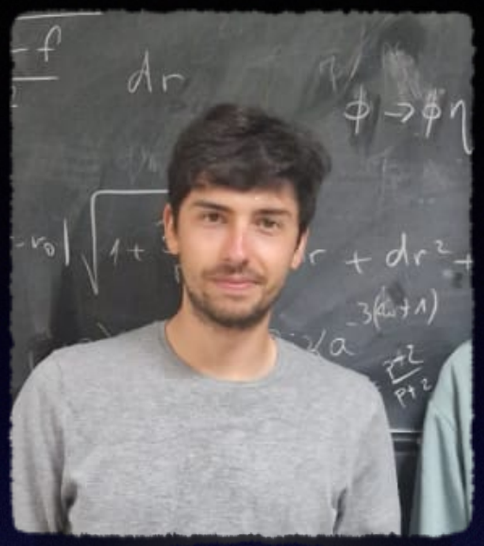
$$\frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{T_{RH}}{T_{FO}}\right)^5 \left(\frac{m_\chi}{10\ \mathrm{eV}}\right)$$



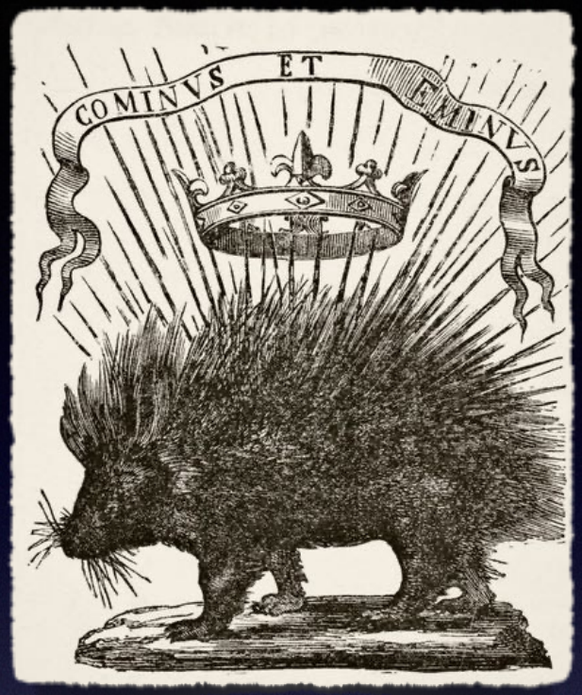


$$\frac{\Omega_\chi h^2}{0.1} \sim \frac{\sigma v}{10^{-9}\ \mathrm{GeV}^{-2}} \left(\frac{e^{\frac{m_\chi}{T_{RH}}}}{10^{-26}}\right) \left(\frac{300\ \mathrm{GeV}}{m_\chi}\right)^4 \left(\frac{T_{RH}}{10\ \mathrm{GeV}}\right)^2$$

Thank you!

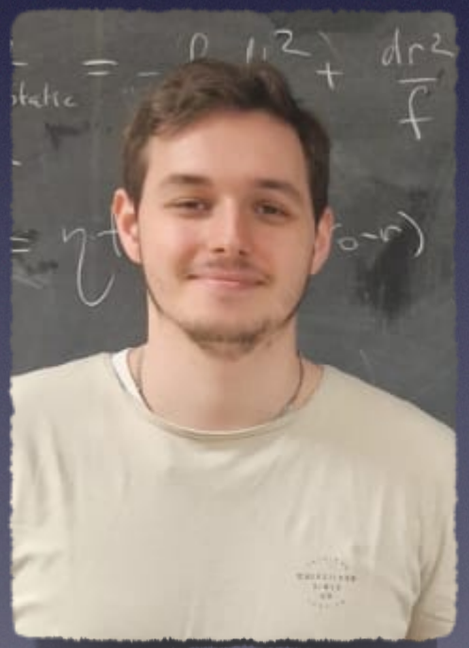


Simon Clery
(TUM, Munchen)





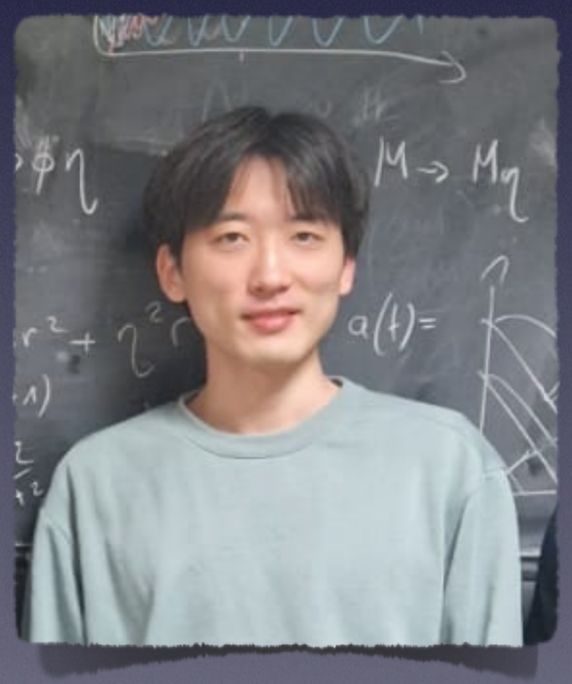
Stephen Henrich
(FITP, Minneapolis)



Mathieu Gross
(Paris-Saclay)



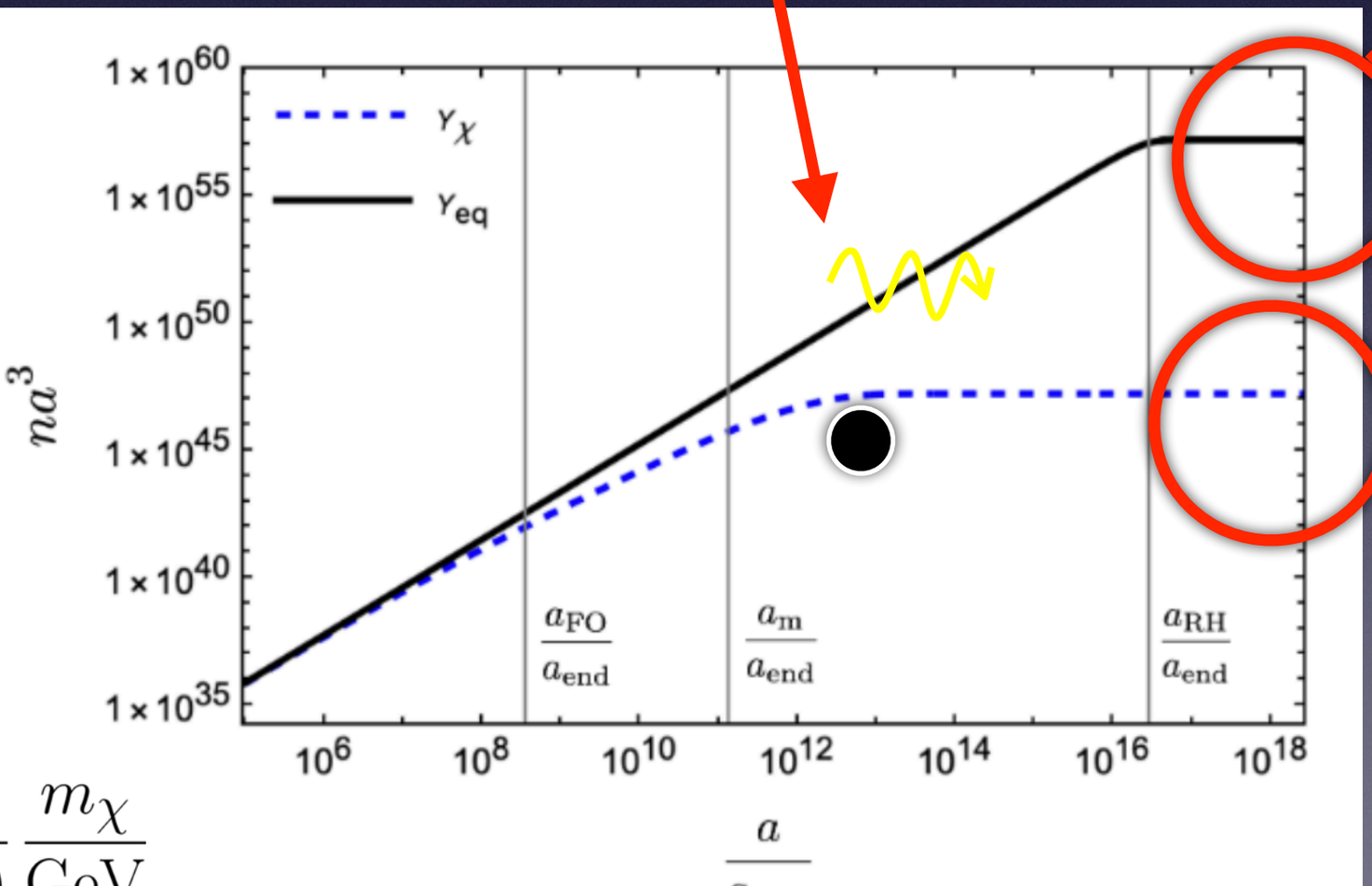
Mathias Pierre
(DESY)



Jong-Hyun Yoon
(CNU, Daejon)

Ultra-Relativistic Freeze Out

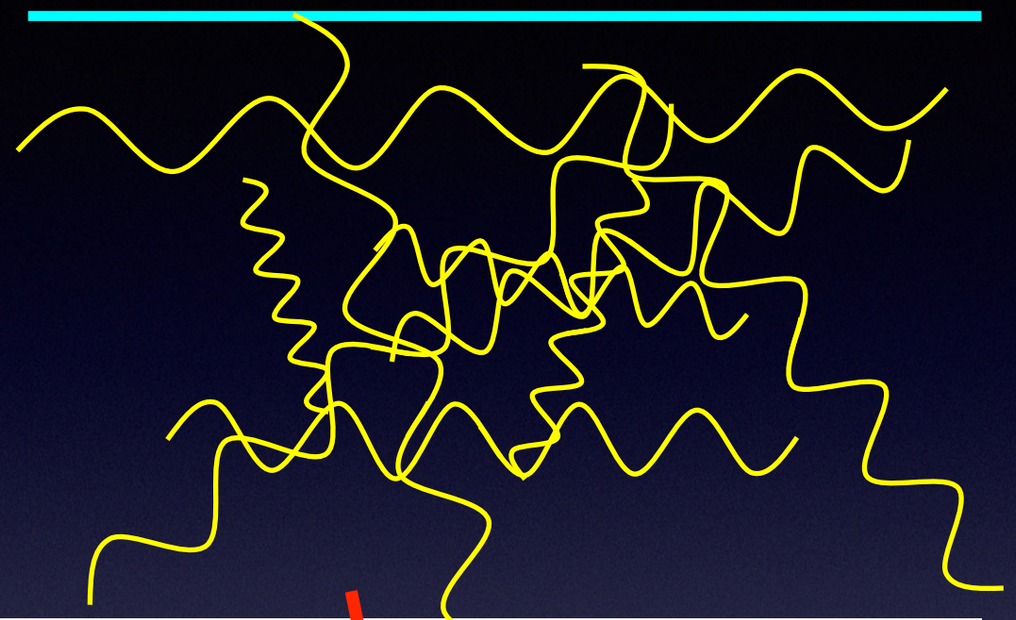
ϕ



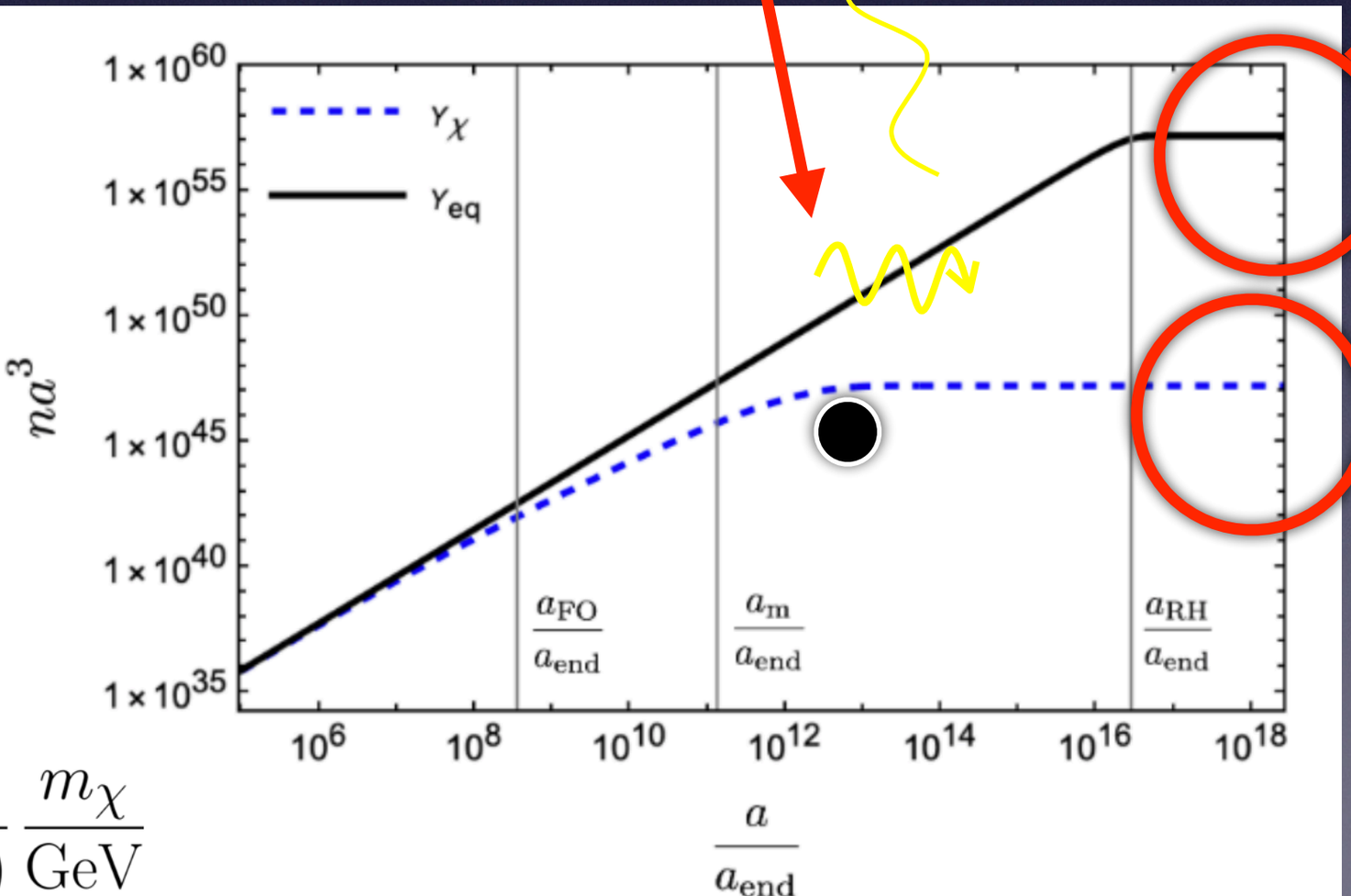
$\frac{m_\chi}{\rm GeV}$

Ultra-Relativistic Freeze Out

ϕ



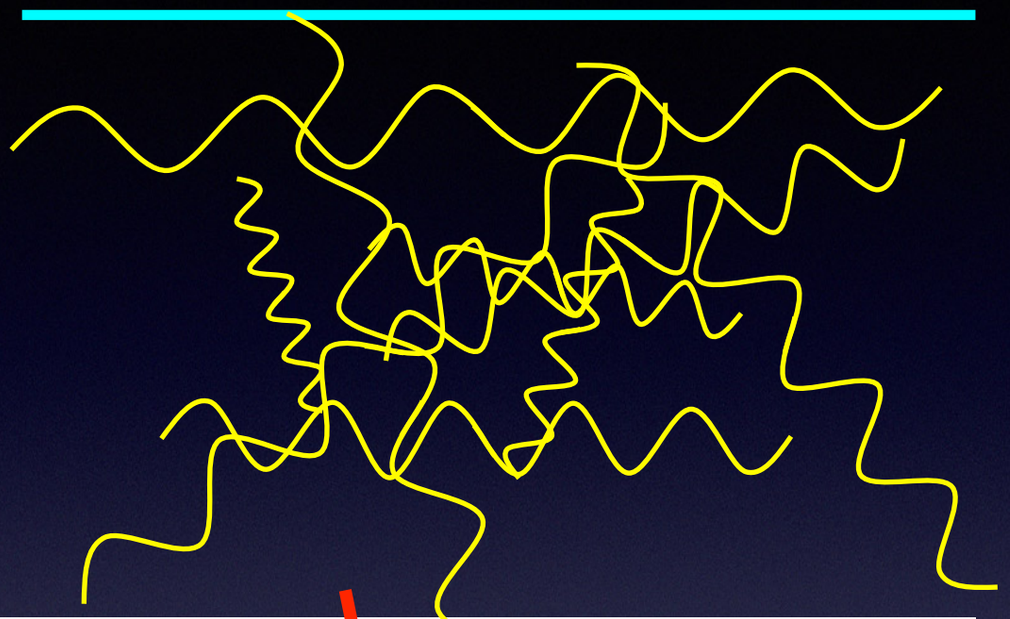




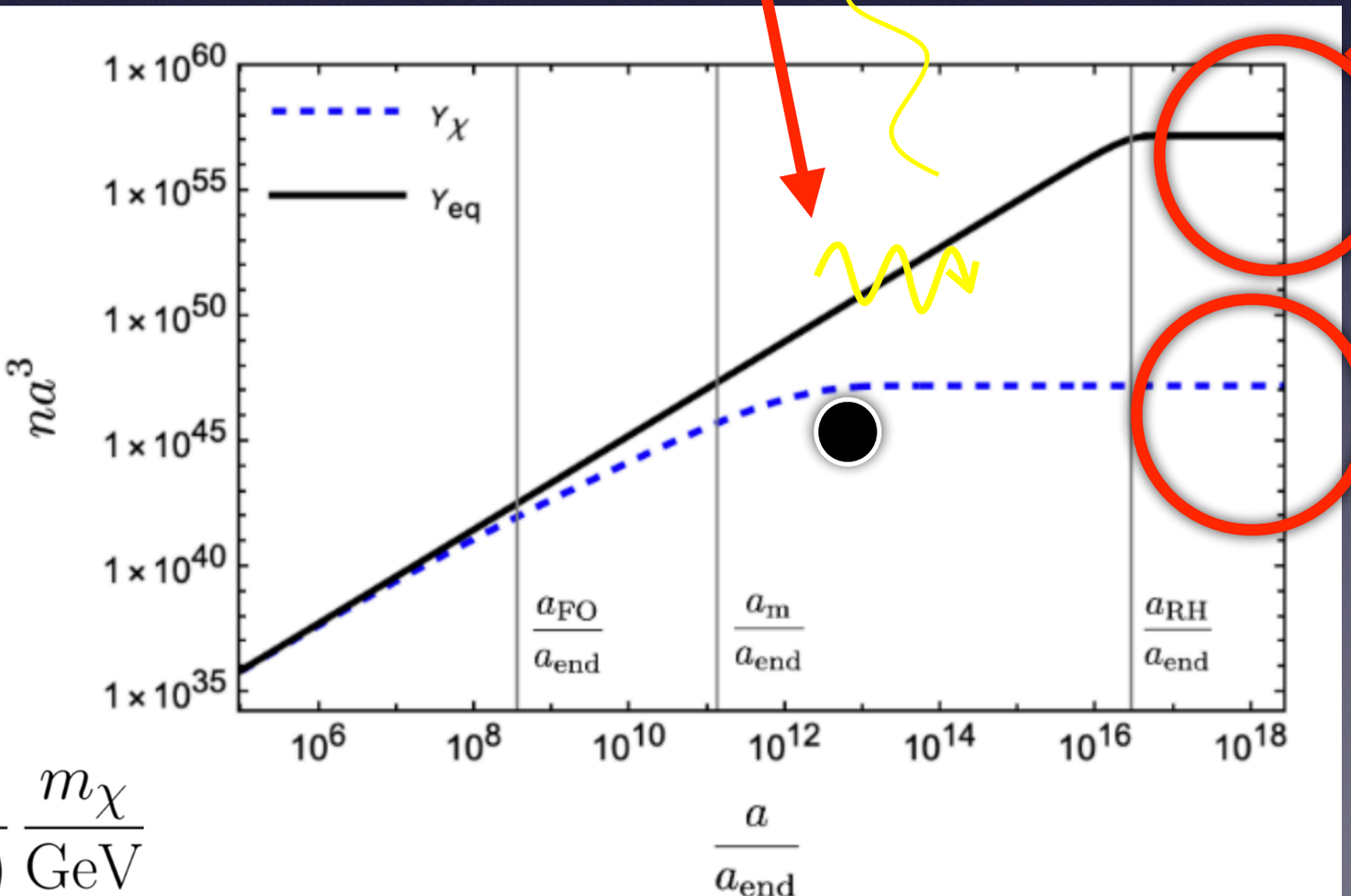
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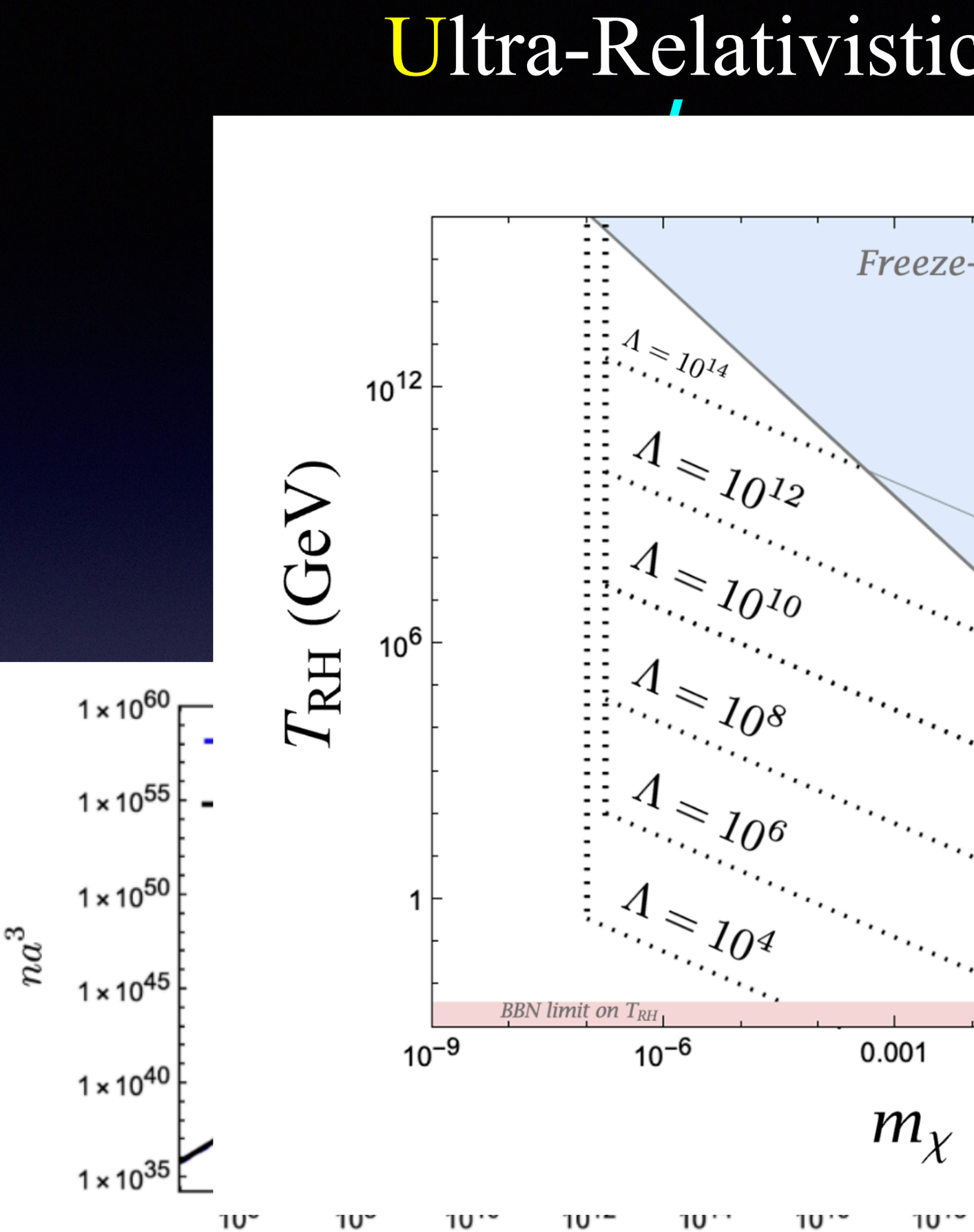


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$\frac{m_\chi}{\text{GeV}}$

Ultra-Relativistic Freeze Out



$$\frac{m_\chi}{\rm GeV}$$

$$\frac{a}{a_{\rm end}}$$

FIMP at stronger coupling (2025)

m_χ ——————————

T_{RH} ....

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

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Olivier Deligny
Xavier Bertou

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DAMIC (2025)

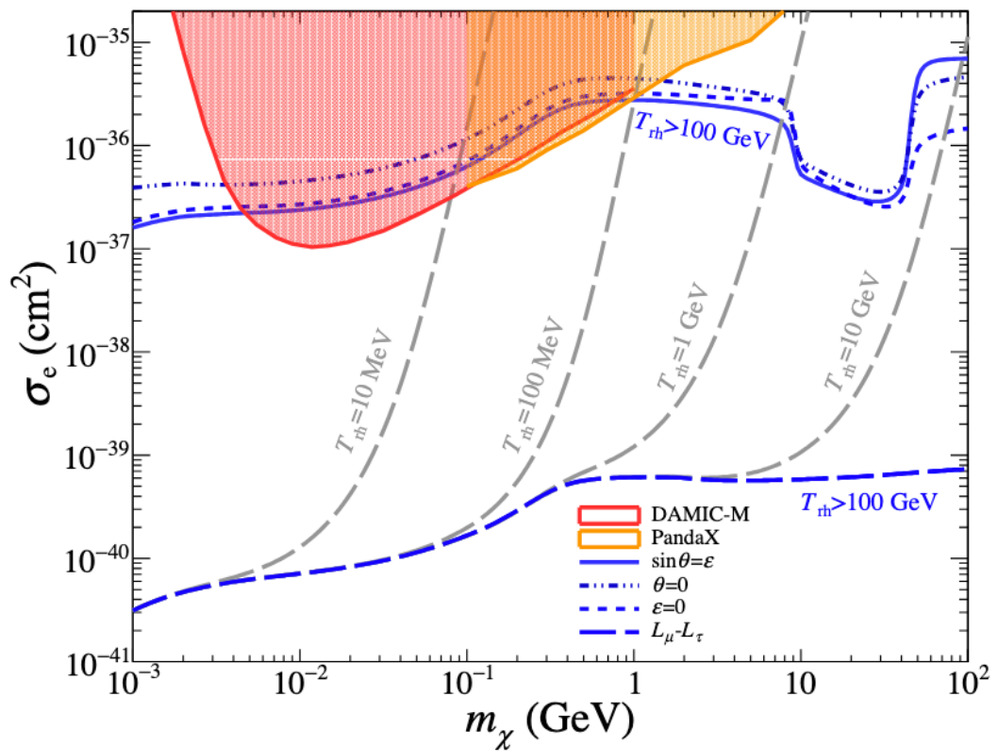


FIG. 1. DM-electron cross section expected for several extra-$U(1)_X$ gauge extension of the SM and various values of reheating temperature as a function of m_χ. The shaded areas stand for the exclusion zones reported by the DAMIC-M and PandaX Collaborations [8, 9].

Olivier Deligny
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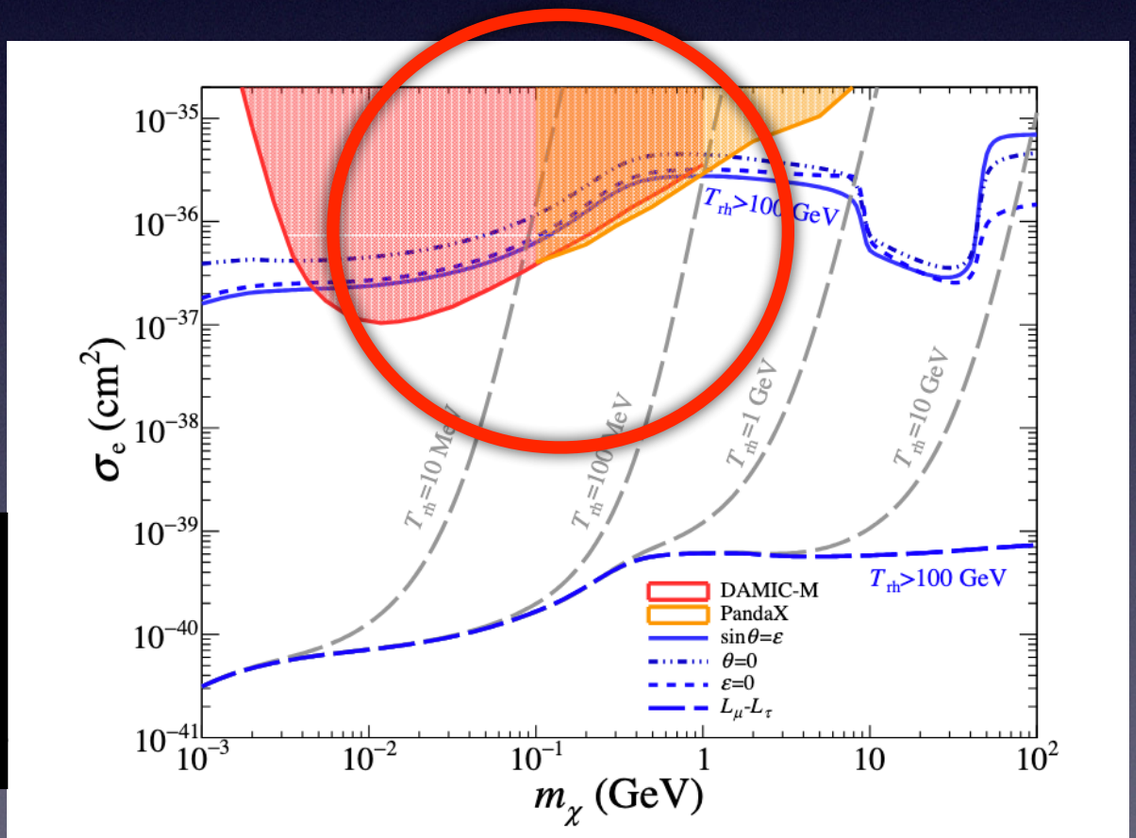


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The cold dark matter (CDM) paradigm

$$\frac{\Omega h^2}{0.12} \simeq 10^8 \left(\frac{g_0}{g_*}\right) \frac{n_\chi}{n_\gamma} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)$$

$$\Updownarrow \quad n_\chi \simeq 10^{-8}\ n_\gamma \left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

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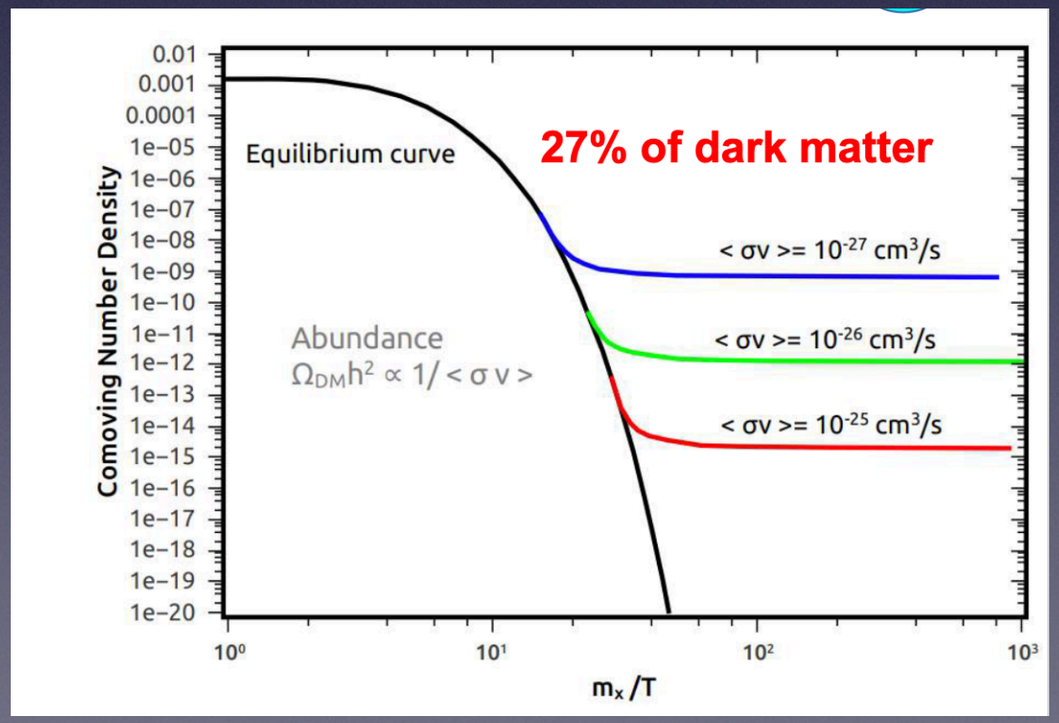
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WIMP miracle :

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

The DM paradigm in a nutshell



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

The DM paradigm in a nutshell

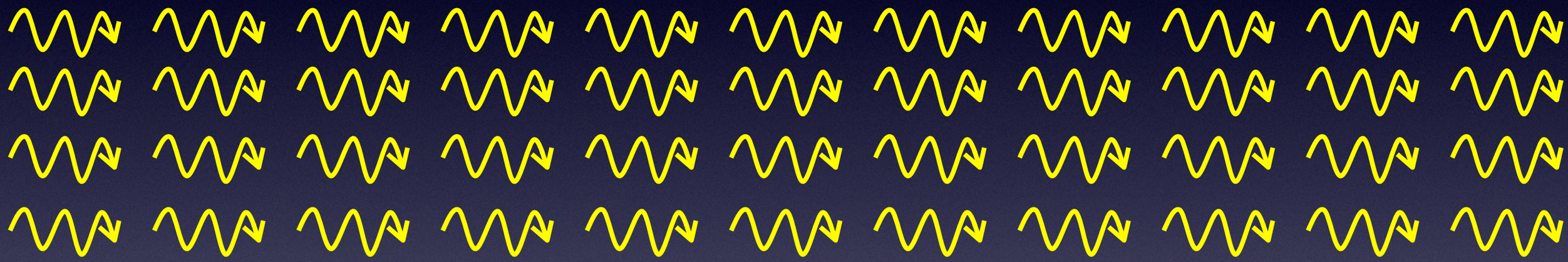


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1 DM particle for ~3 billions photons

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



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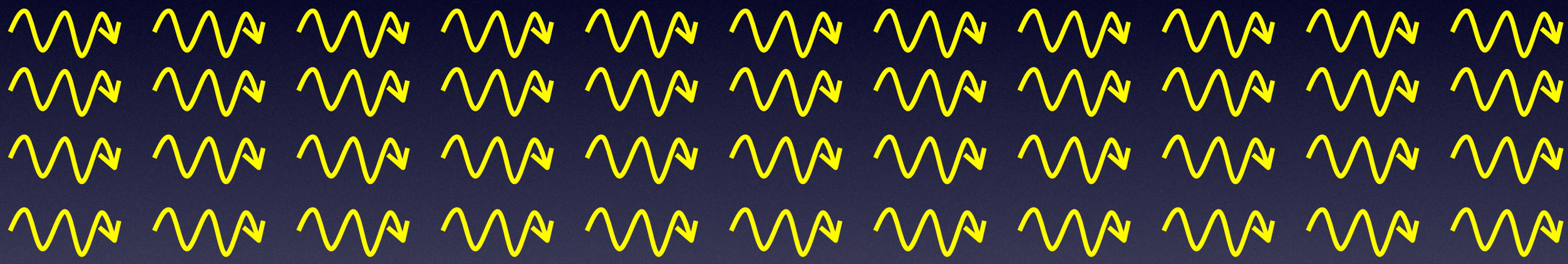


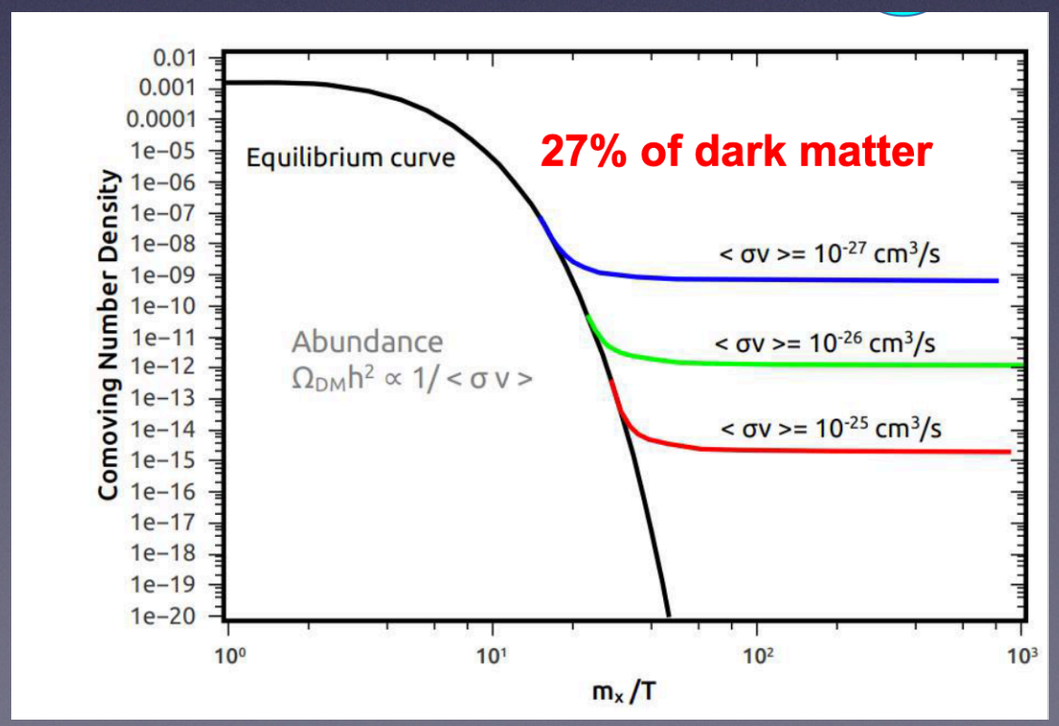
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$$\mathscr{L} = g\,|SM|^2\,|\chi|^2$$

abundance

annihilation

WIMP

freeze-out

$g \sim 0.1$

time= 1/T

$$\mathscr{L} = g\,|SM|^2\,|\chi|^2$$

abundance

WIMP

annihilation

$g \sim 0.1$

(freeze-out)

FIMP

(freeze-in)

$g \sim 10^{-11}$

time= 1/T

$$\mathscr{L} = g\,|SM|^2\,|\chi|^2$$

abundance

WIMP

FIMP

annihilation

(freeze-out)

(freeze-in)

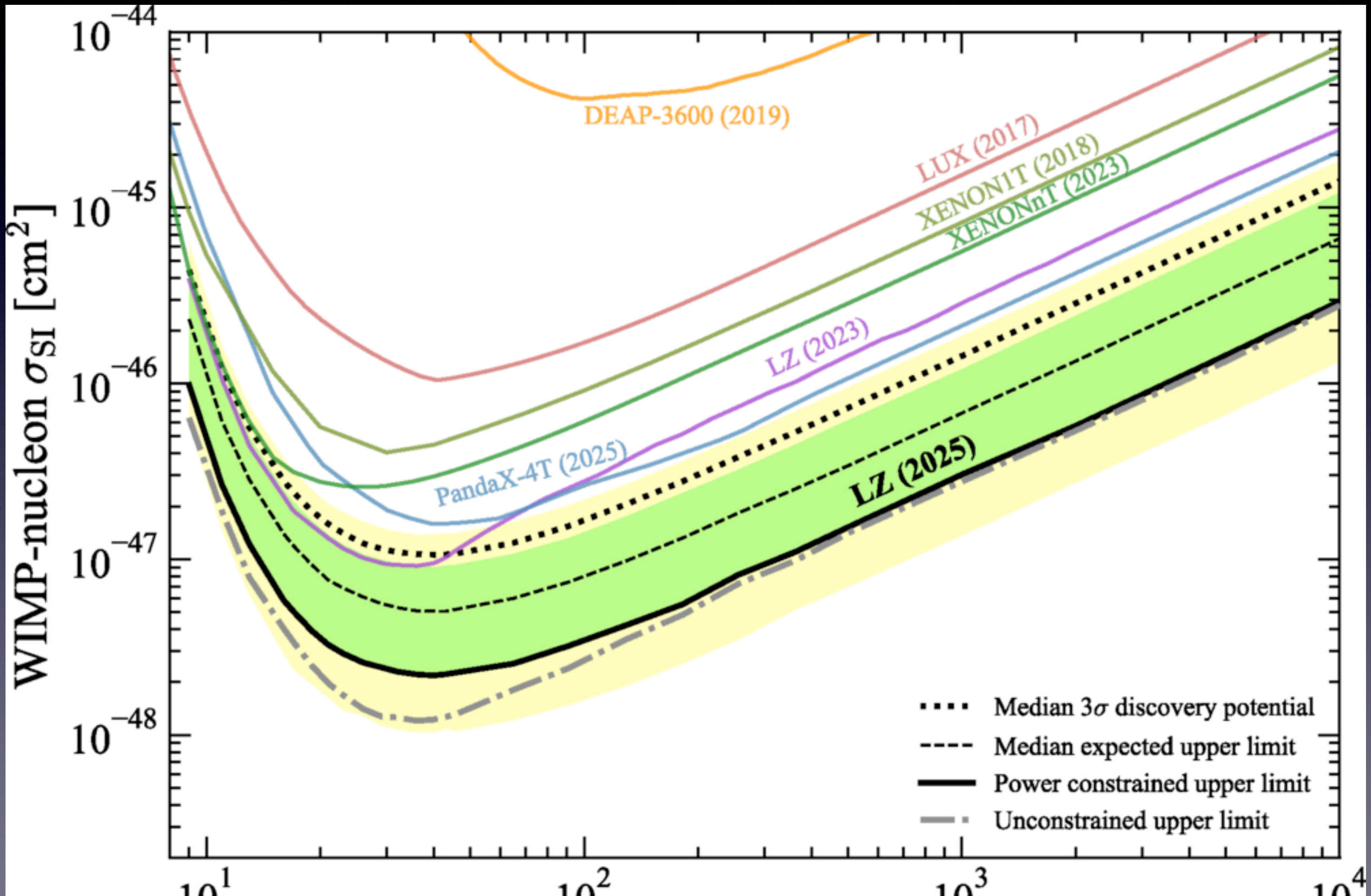
EXCLUDED

Not detectable

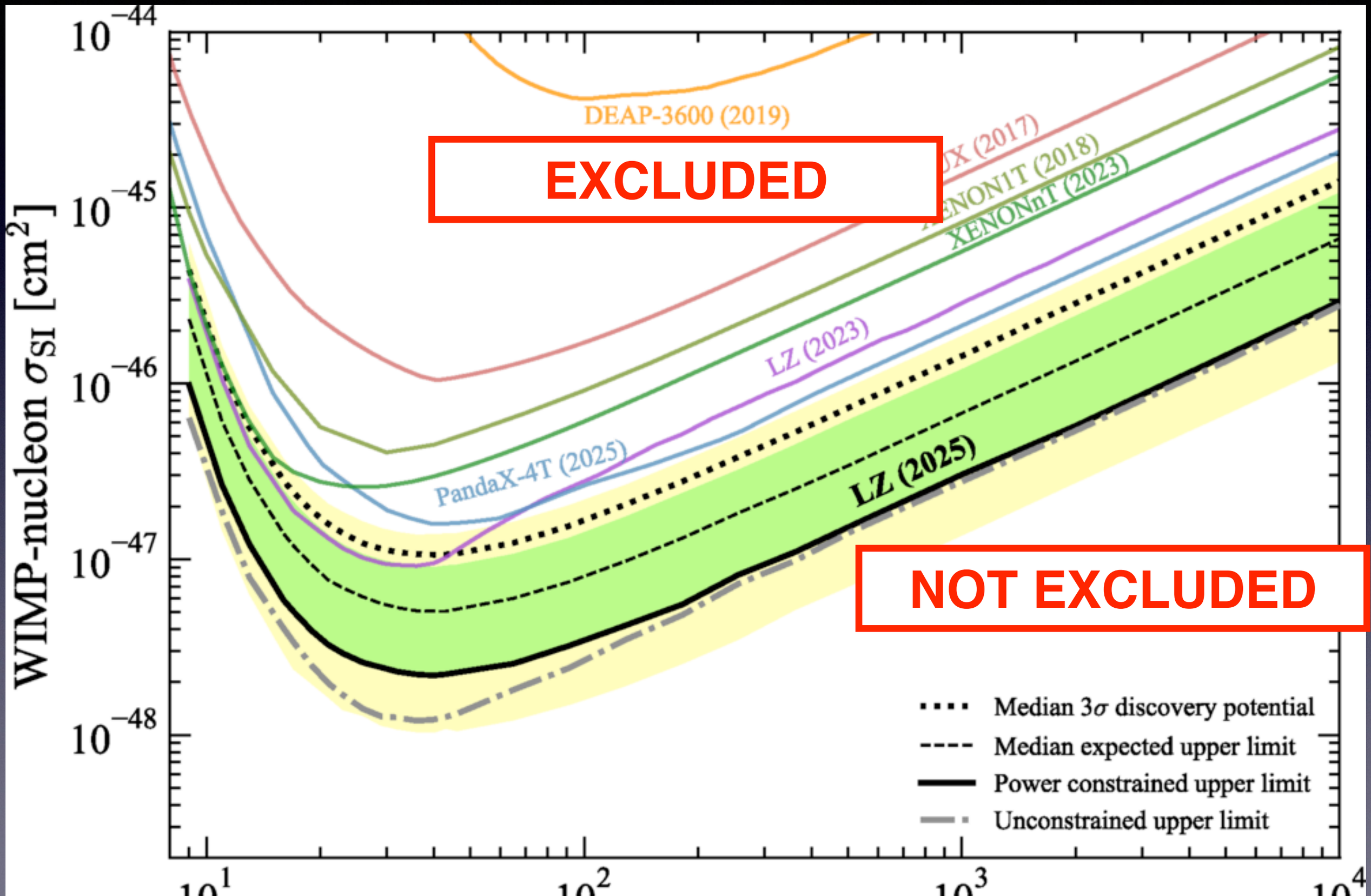
time= 1/Γ

WIMP tensions

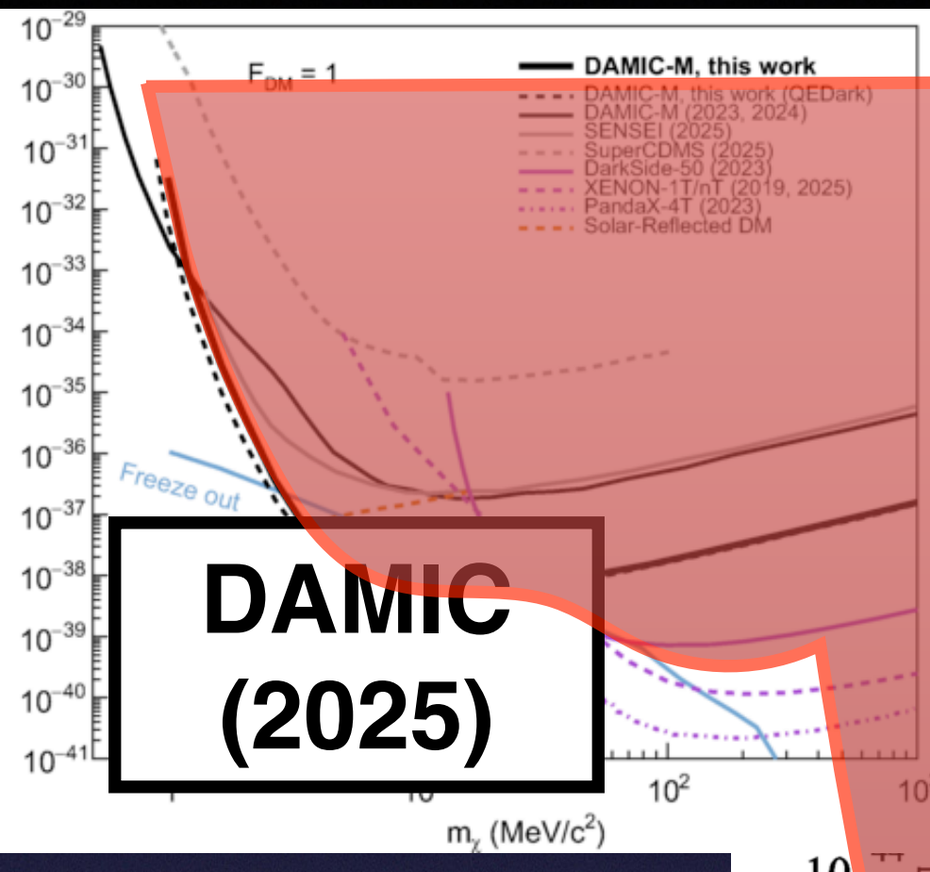
Direct detection of DM



Direct detection of DM

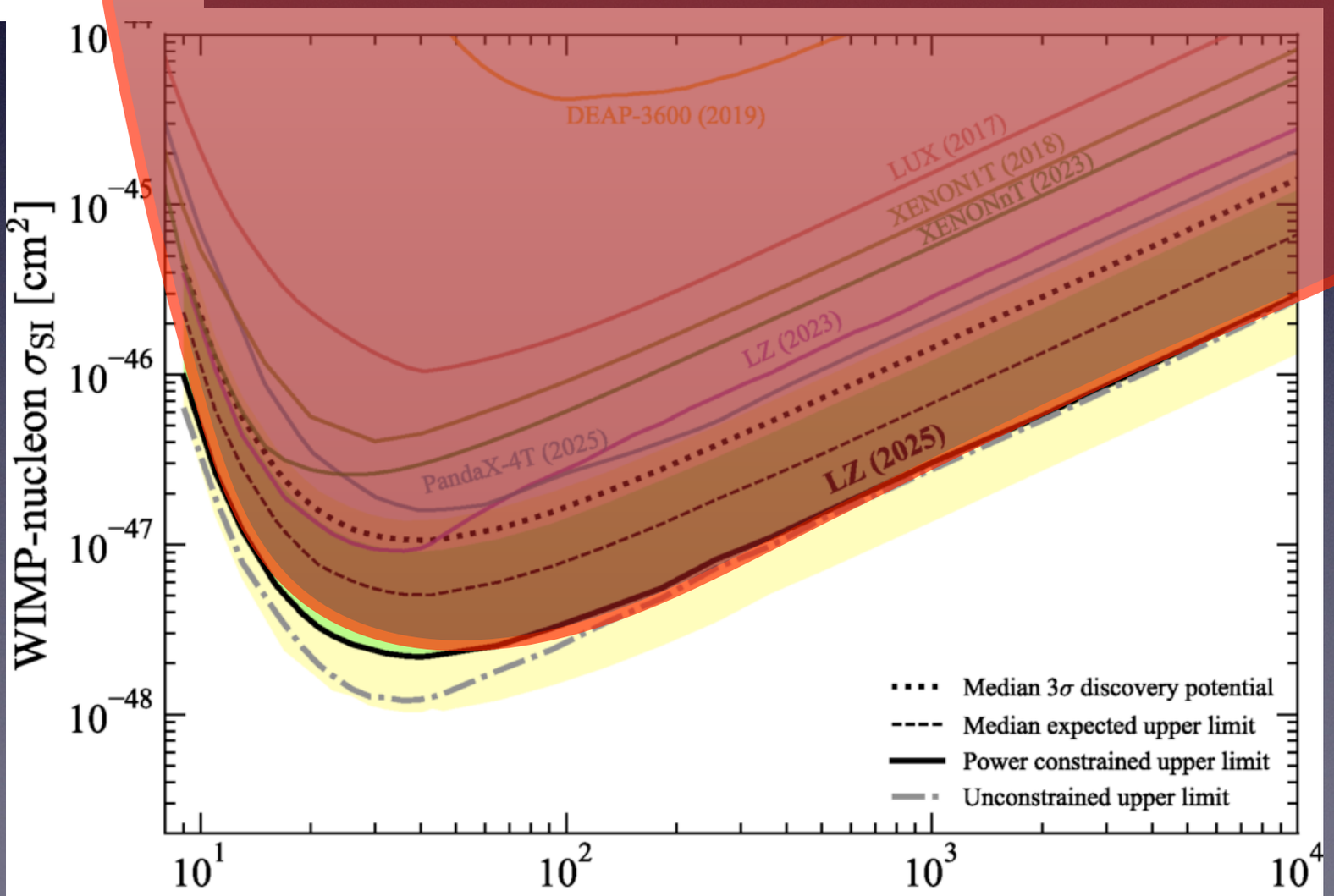


detection of DM



DAMIC (2025)

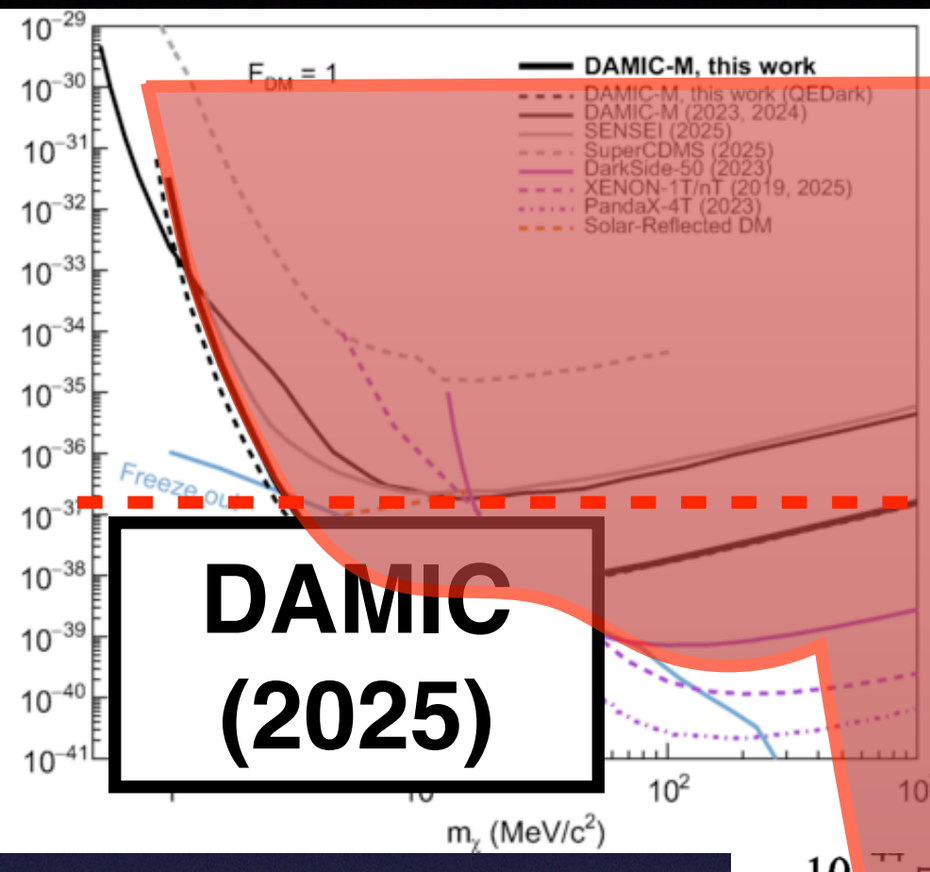
EXCLUDED



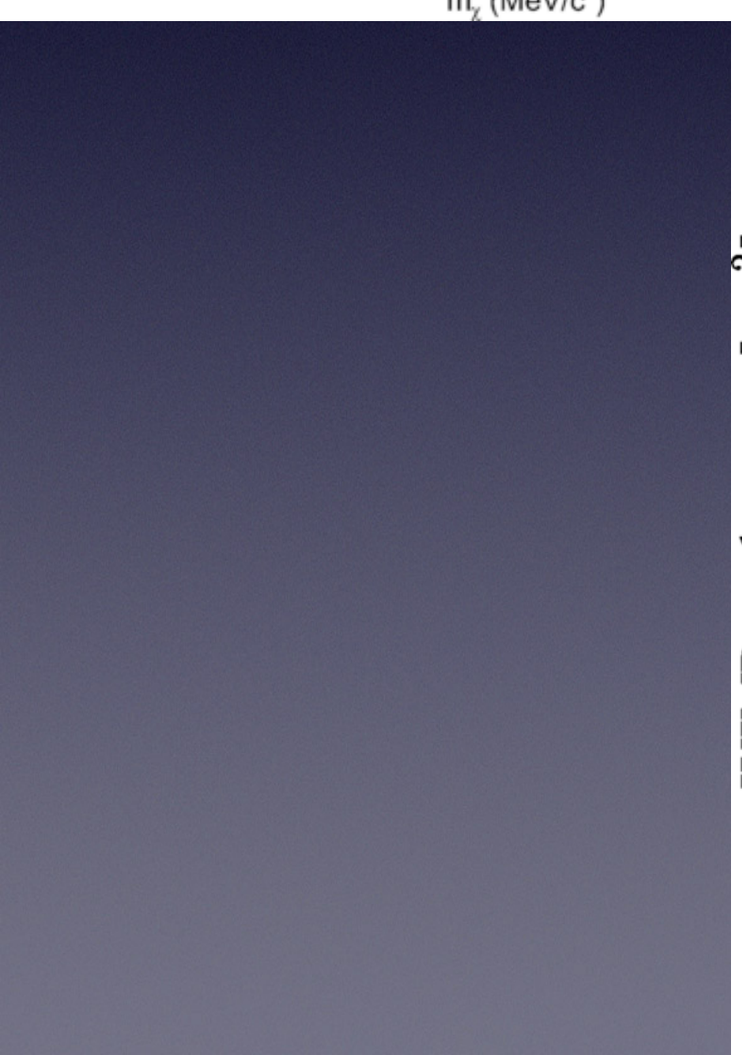
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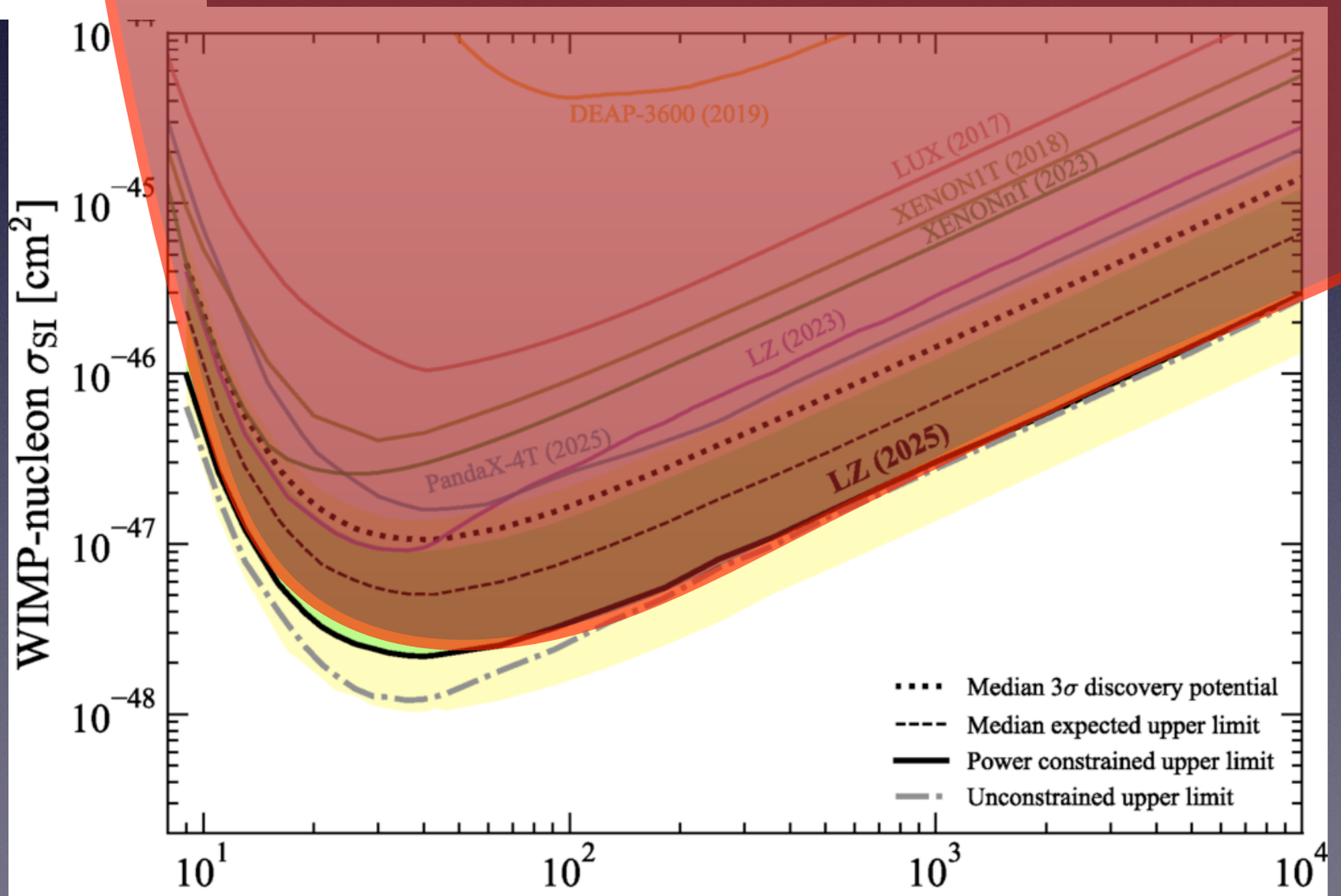
$$\sigma_{EW} \sim 10^{-9}\ \mathrm{GeV}^{-2} \sim 4 \times 10^{-37}\ \mathrm{cm}^2$$

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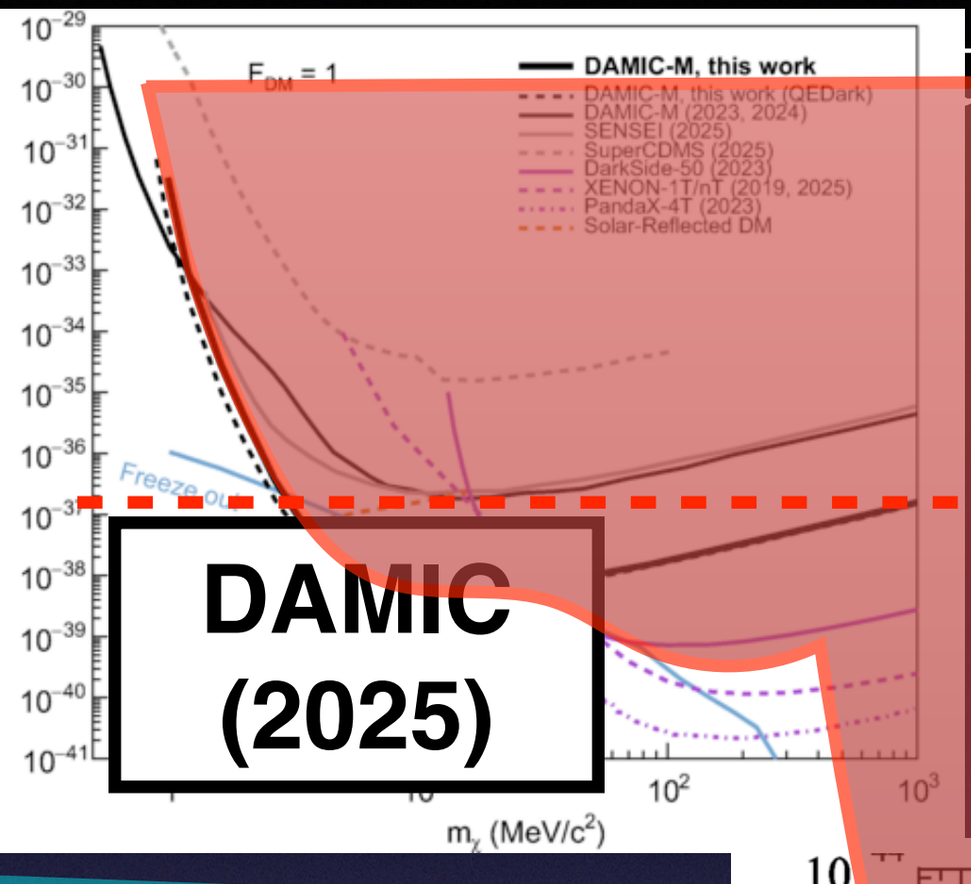




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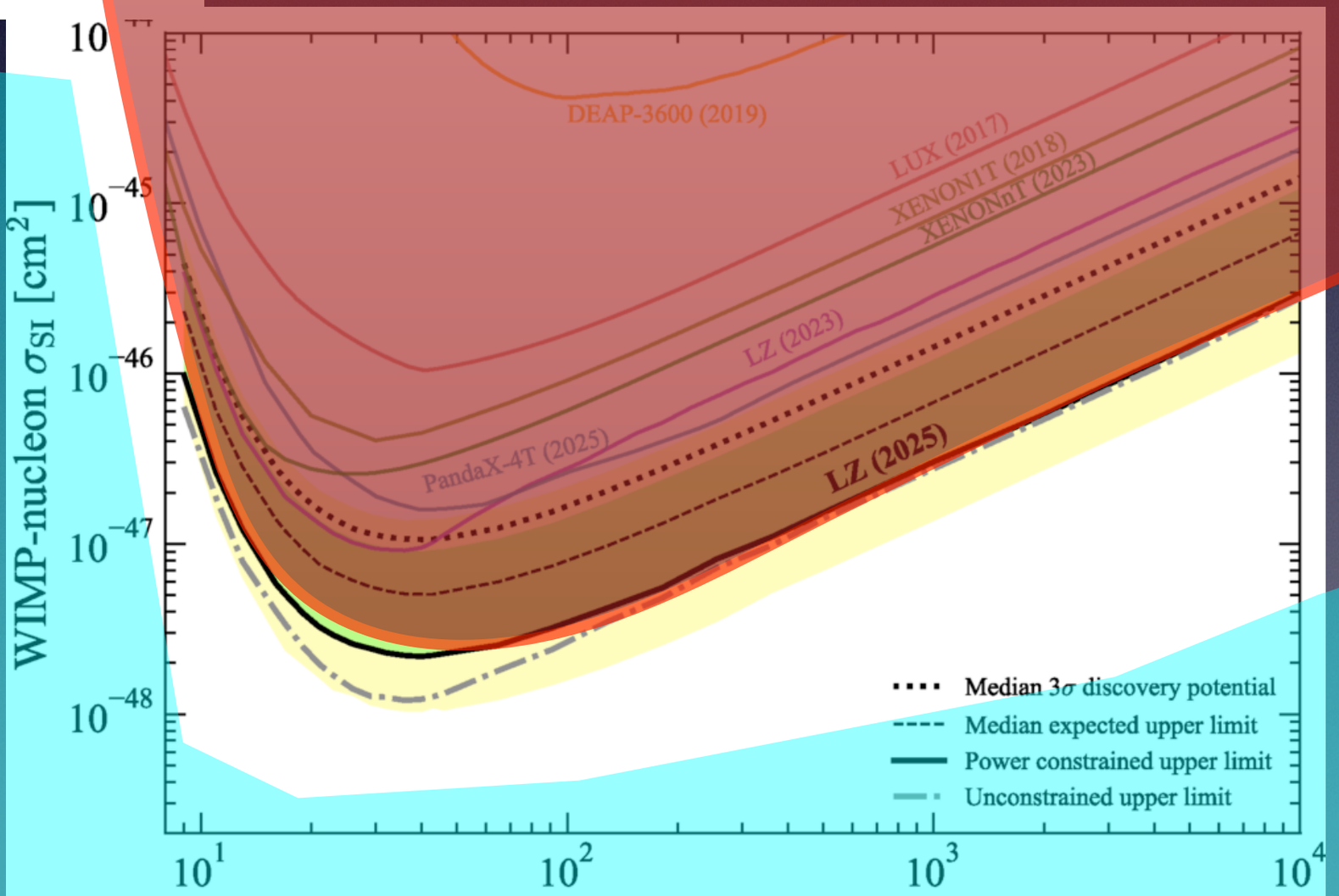
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DAMIC (2025)

Neutrino « fog »

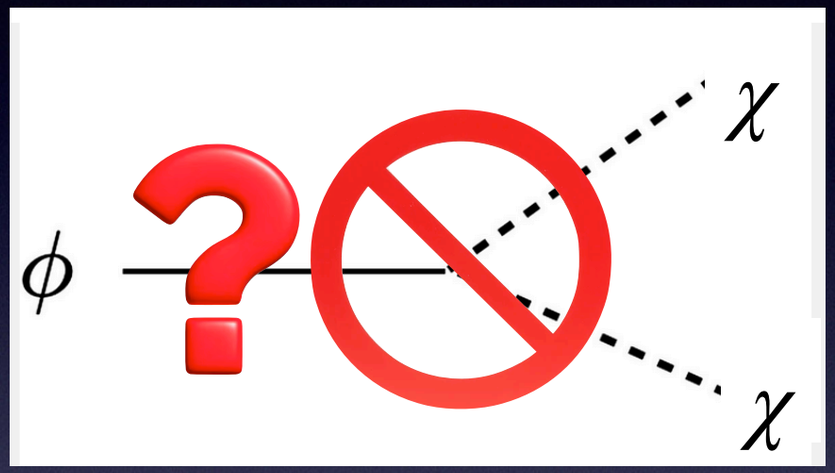


Neglecting the initial production of dark matter is very risky (and surely wrong)*

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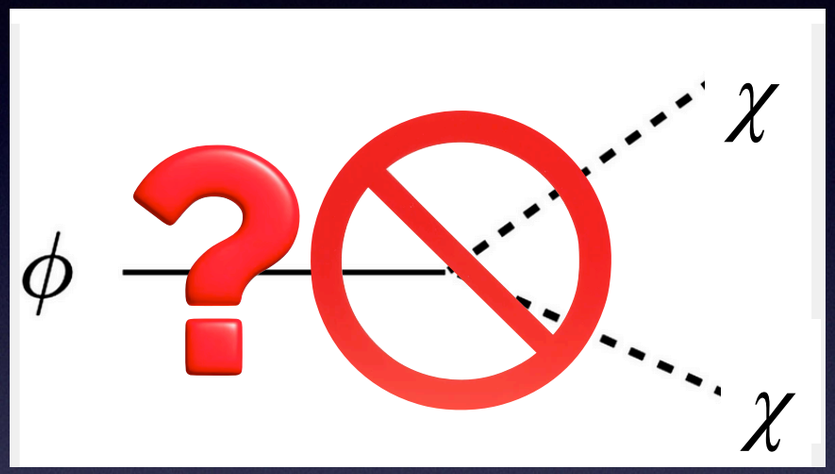
One need to justify why the processus of reheating is « dark-matter blind »
(why the inflaton does not couple to DM?)



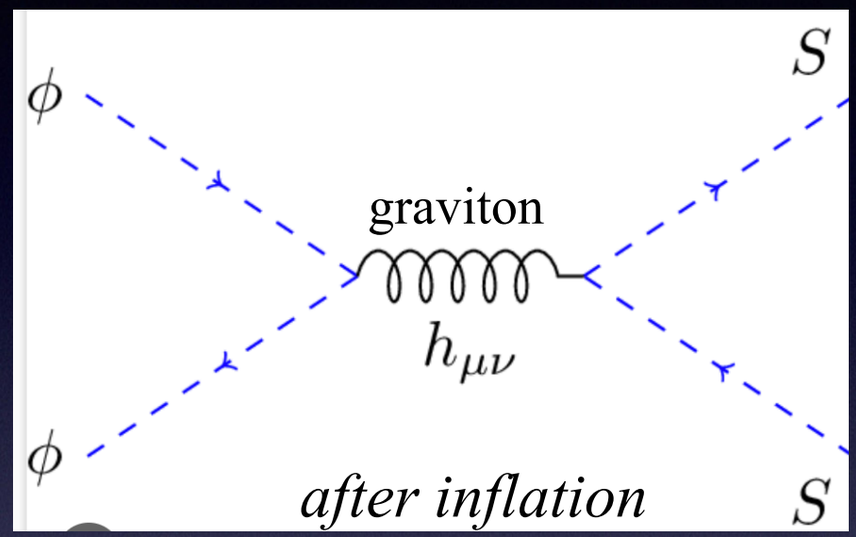
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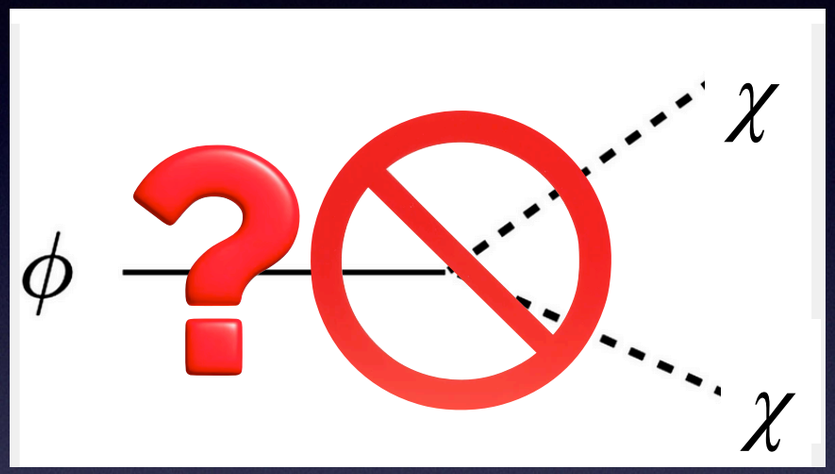
Even in the absence of couplings, gravity produces a large amount of DM by inflaton scattering after inflation…



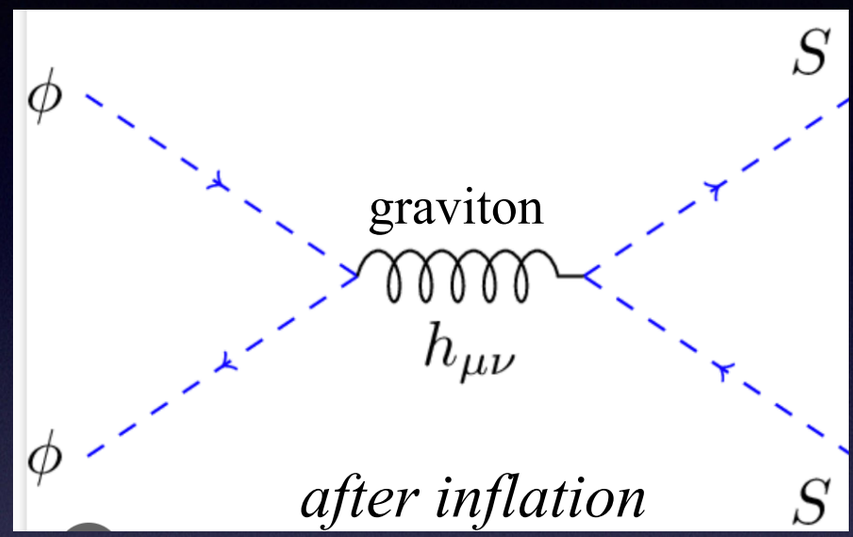
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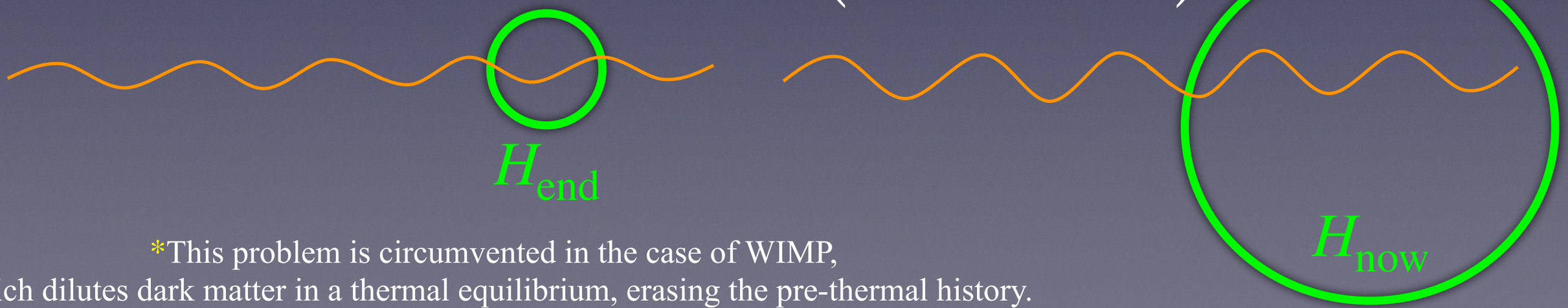


Even in the absence of couplings, gravity produces a large amount of DM by inflaton scattering after inflation…



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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Some numbers

The relic abundance is given by

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

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

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In the case of WIMP,

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

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

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

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



In the case of FIMP, we have

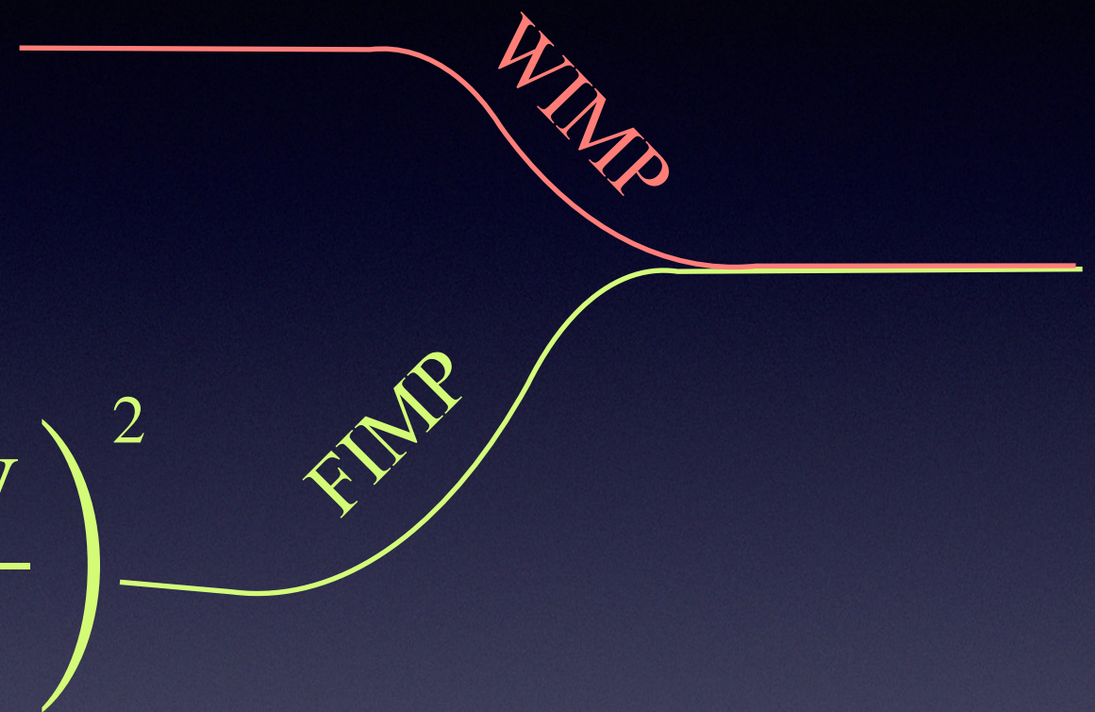
$$n_\chi(T_{FO}) = n_\gamma^2 \langle \sigma v \rangle H^{-1}(T_{FO})$$

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

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

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

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



For the neutrino (relativistic) decoupling, νFO :

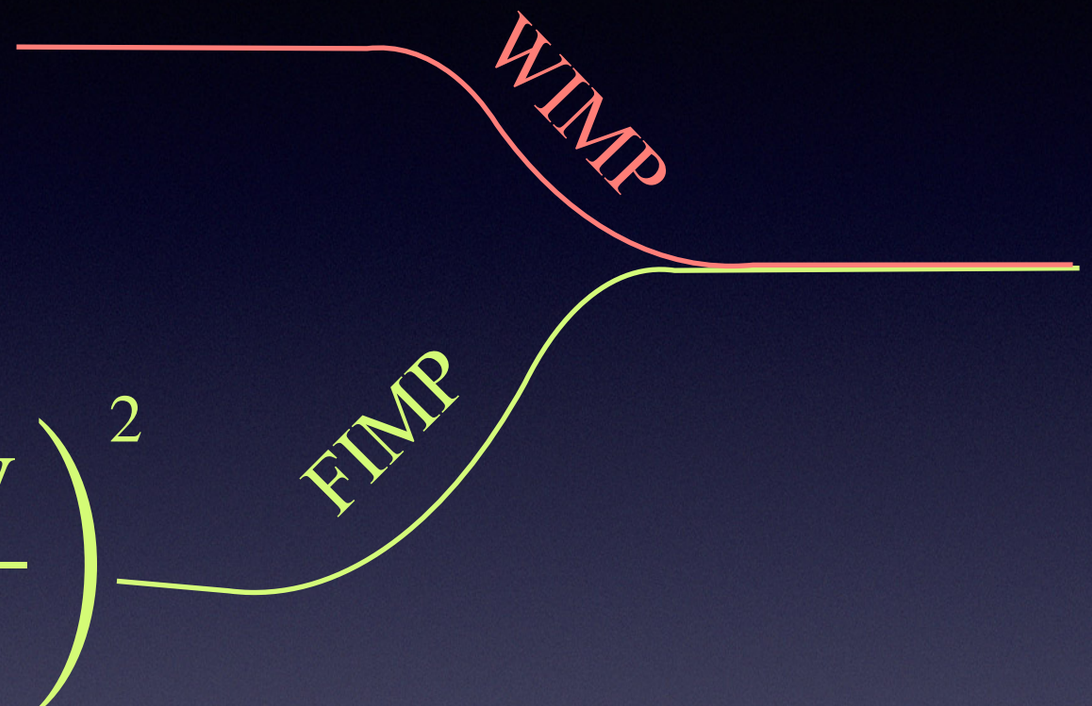
$$n_\chi(T_{FO}) \sim T_{FO}^3 \quad \Rightarrow \quad \frac{\Omega_\chi^{\nu FO} h^2}{0.1} \sim \frac{m_\chi}{10\ \text{eV}}$$

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

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

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

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

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

Not seen

WIMP

FIMP

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

Not visible

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

Structures

σ_χ (GeV^{-2})

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

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

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})

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

10^{-9}

10^{-26}

νFO

Direct detection

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

Neutrino « fog »

Structure

FIMP

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

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