Sterile neutrino dark matter

Sterile neutrinos as dark matter

Simplest scenario accounting for the dark matter of the Universe

- One new particle, ν_s
- No new symmetries
- Two new parameters: m_{DM}, θ_{as}.

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③ The existence of a lepton asymmetry can resonantly enhance the dark matter production, via the MSW mechanism.

Sterile neutrinos as dark matter

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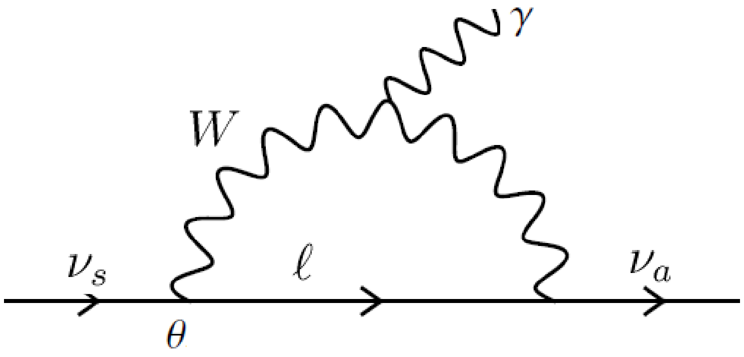
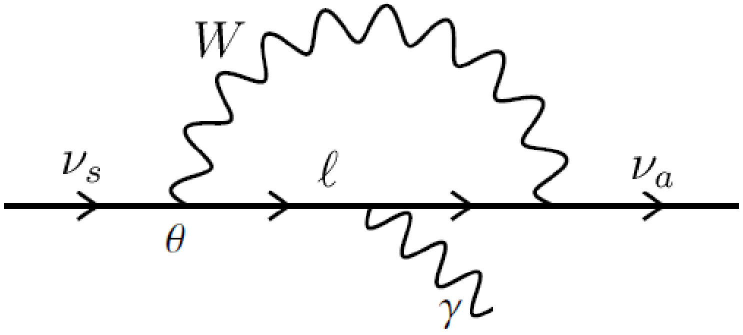
⑤ Sterile neutrinos are not absolutely stable





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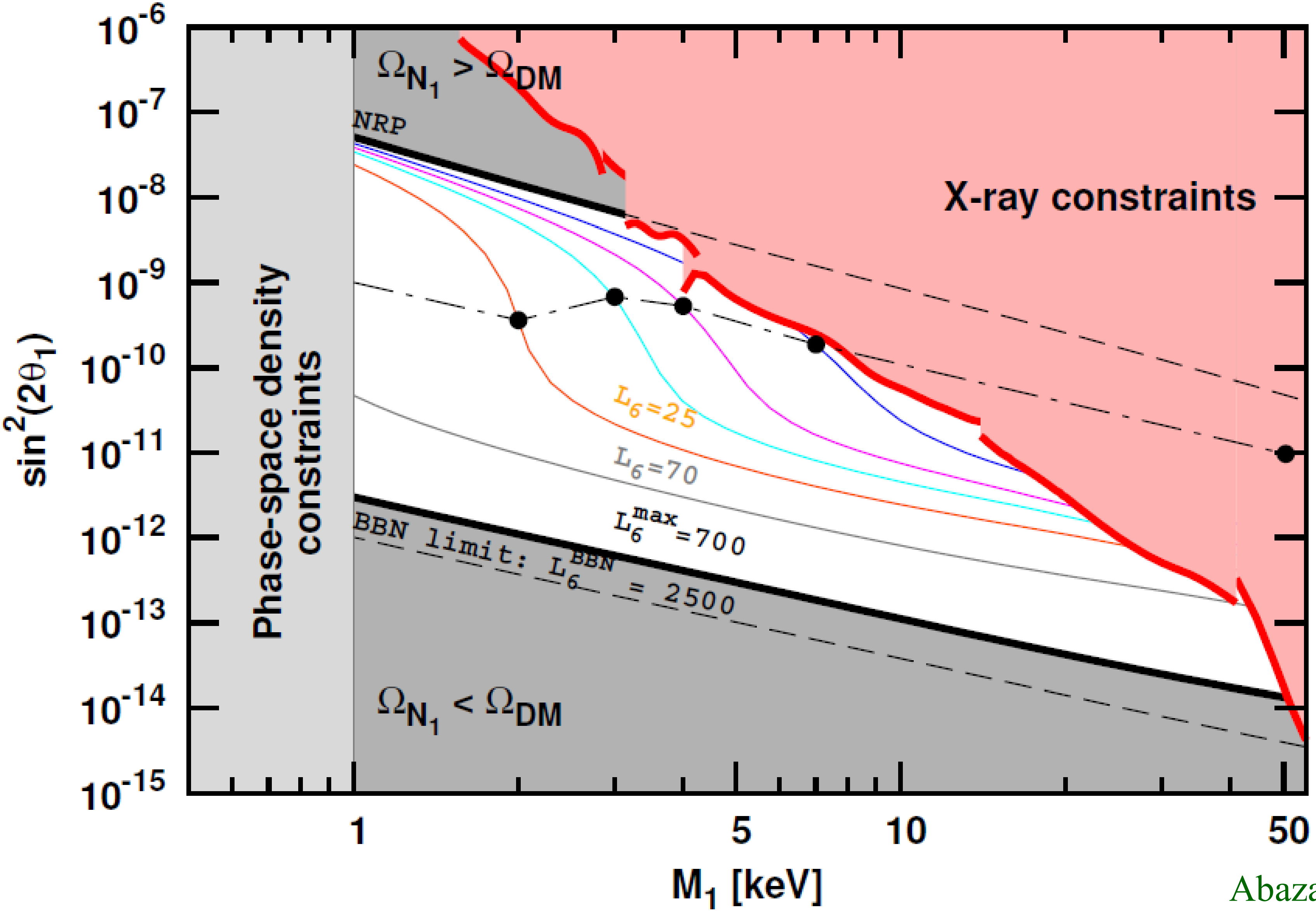

Abazajian et al.
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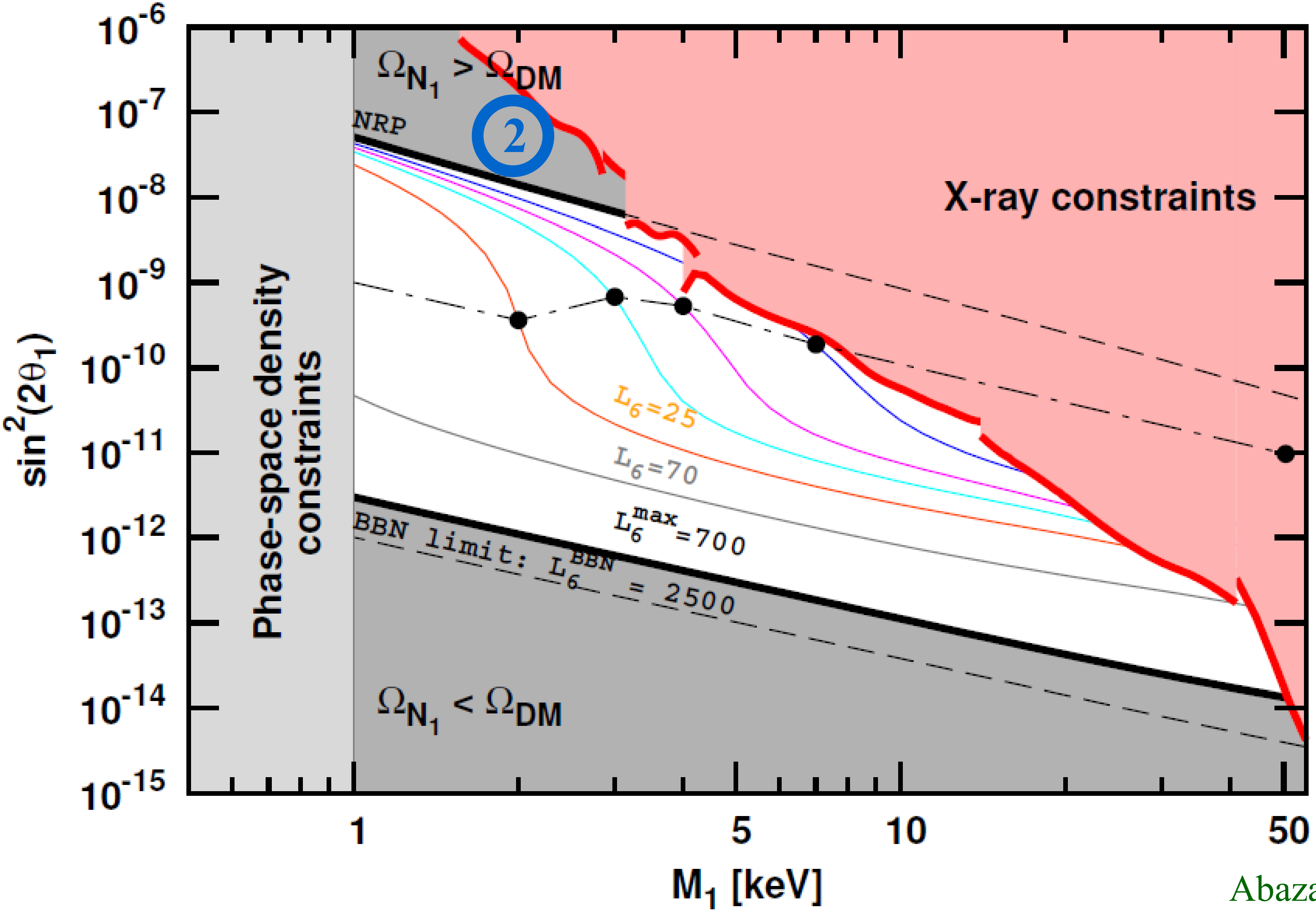

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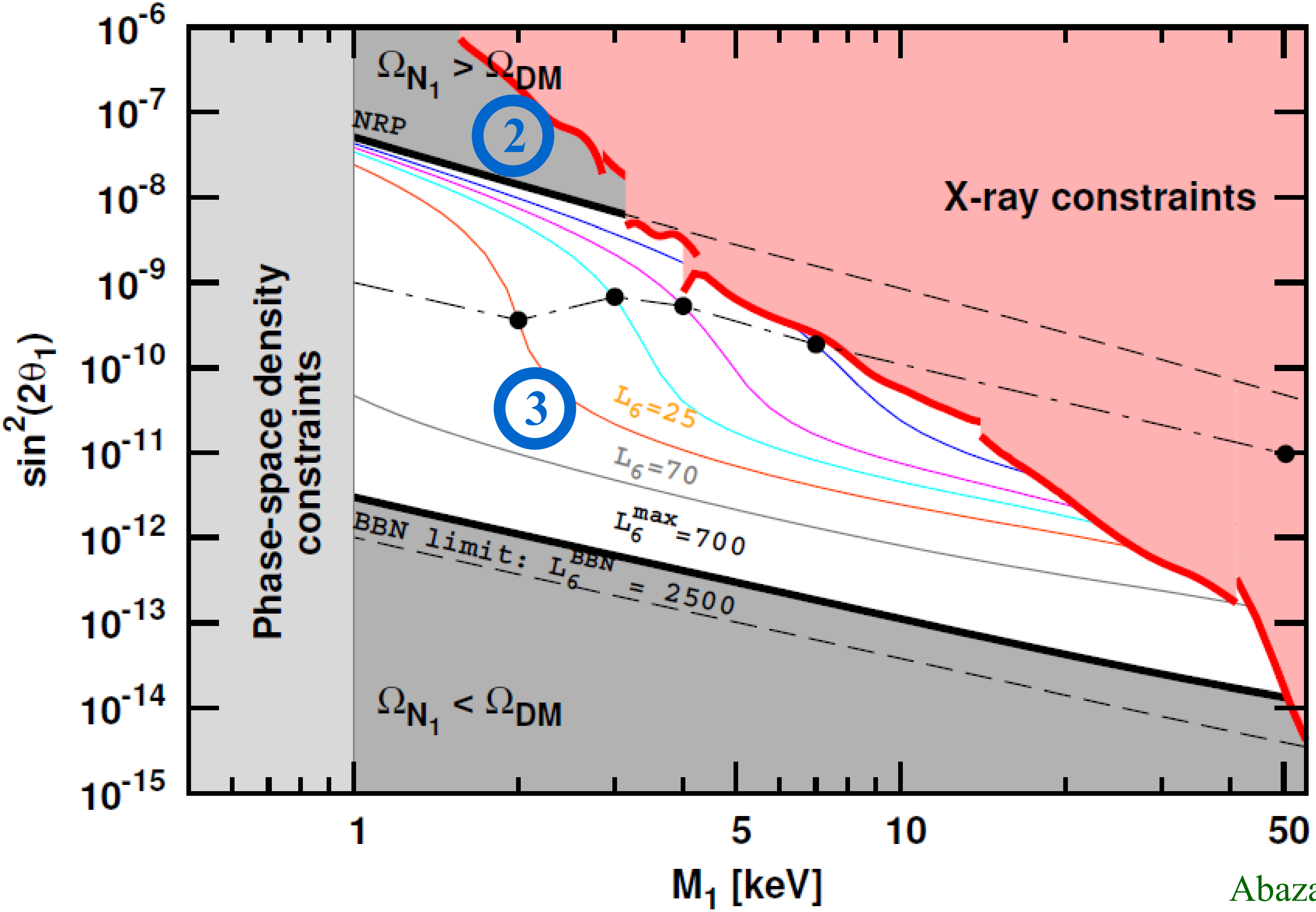

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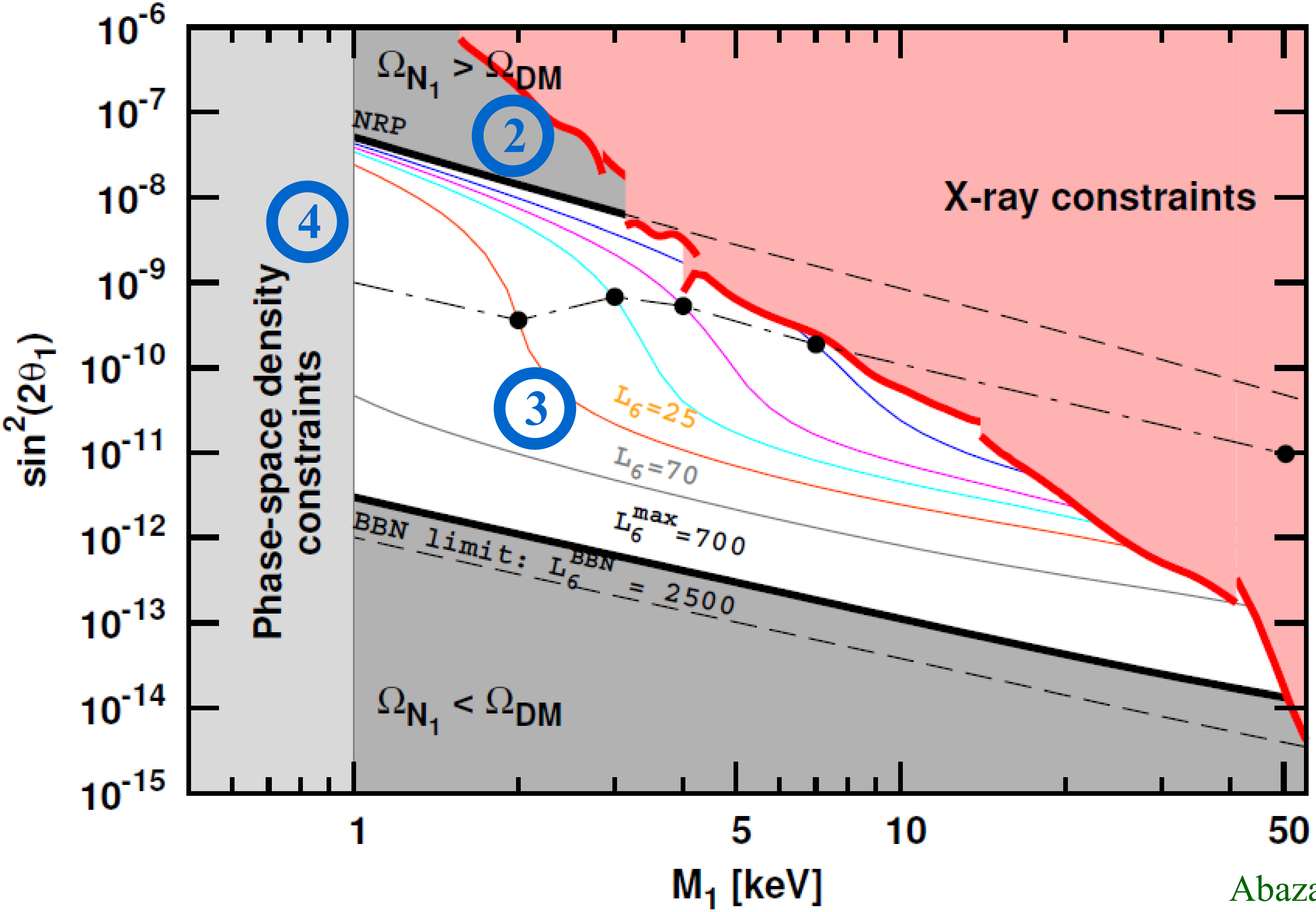

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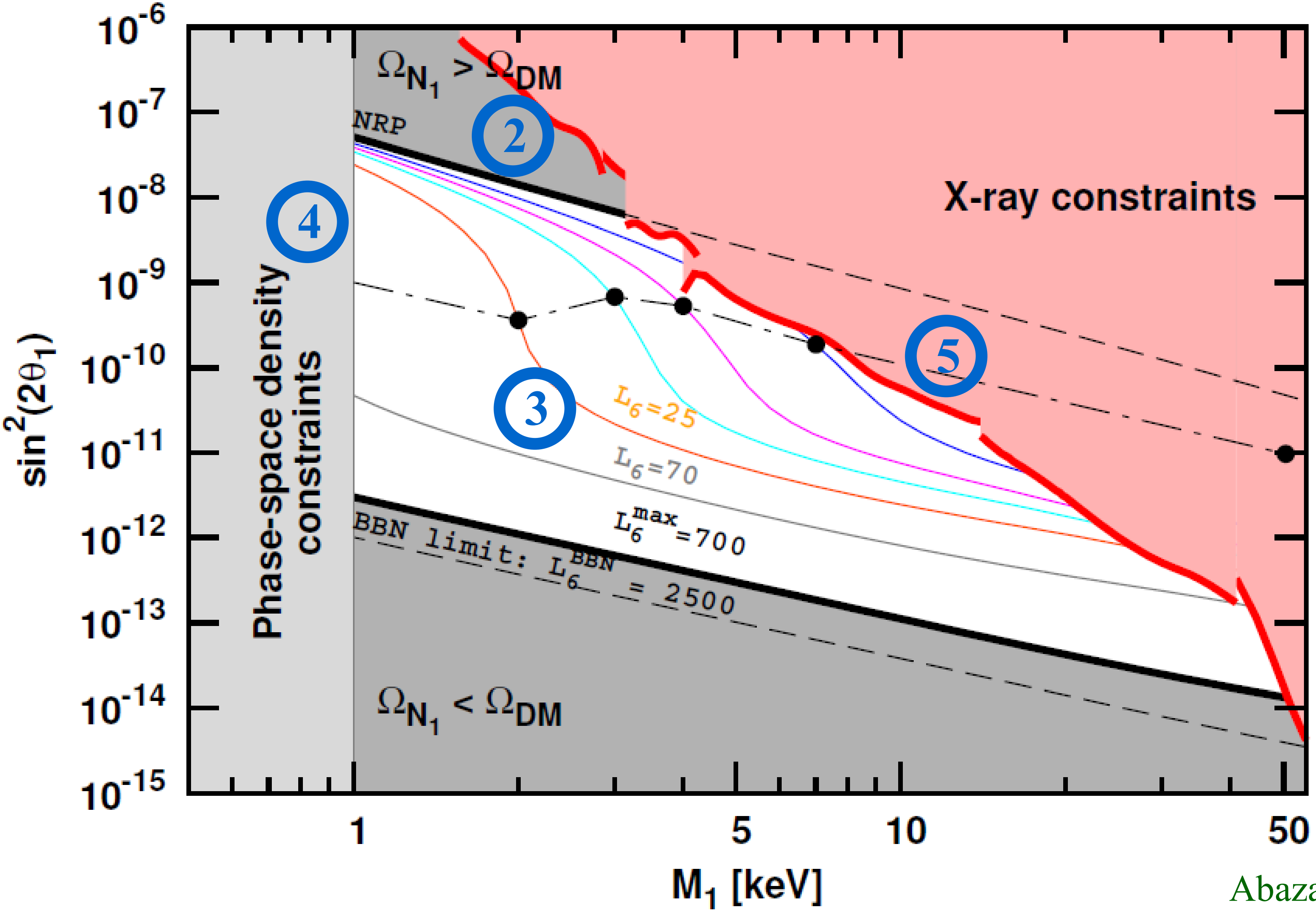

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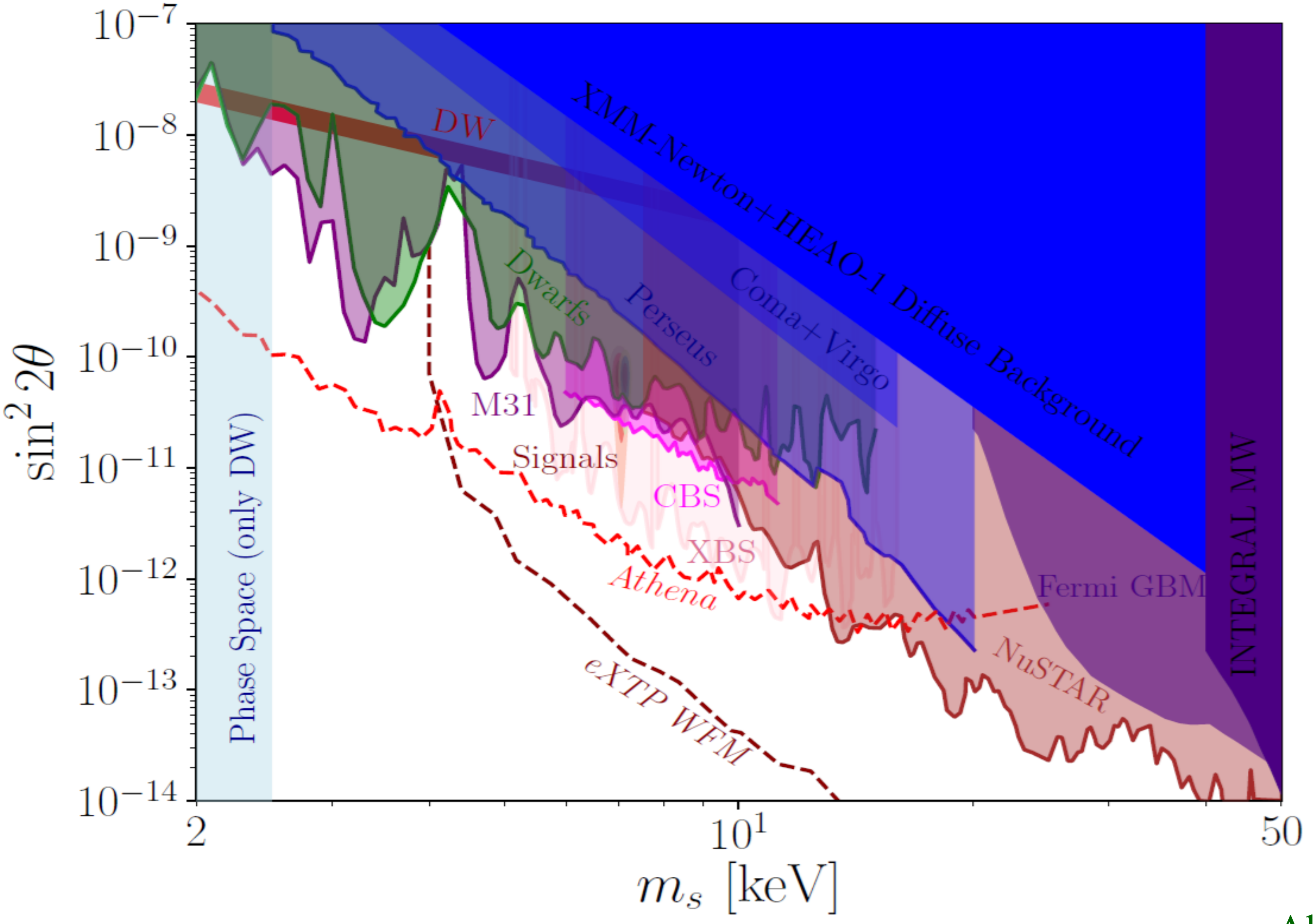
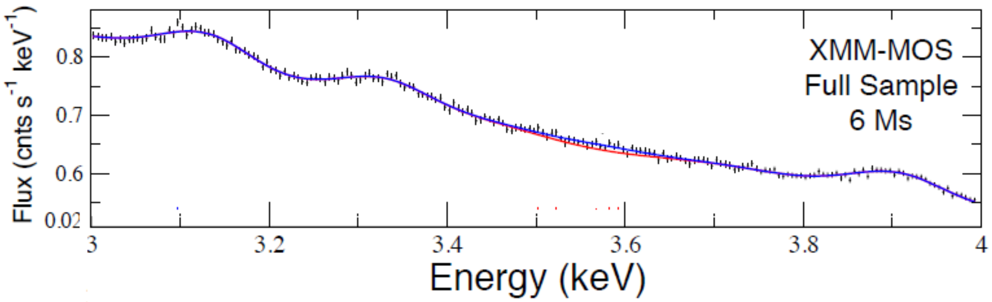


Abazajian’21

Sterile neutrinos as dark matter

Hints for an unidentified X-ray line signal

Bulbul et al, 1402.2301



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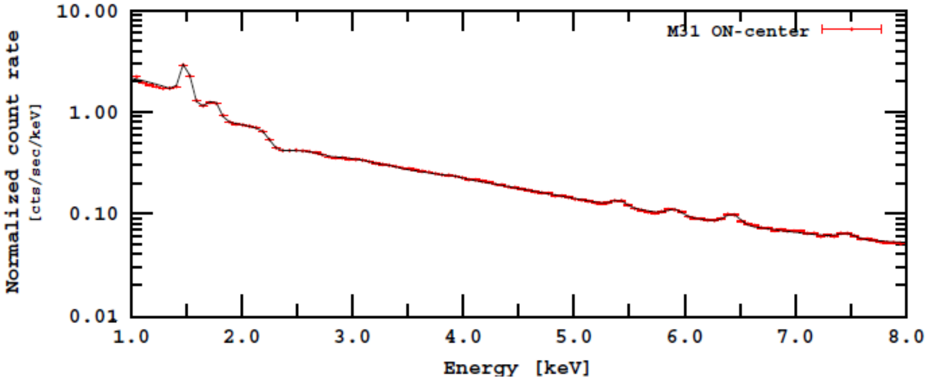

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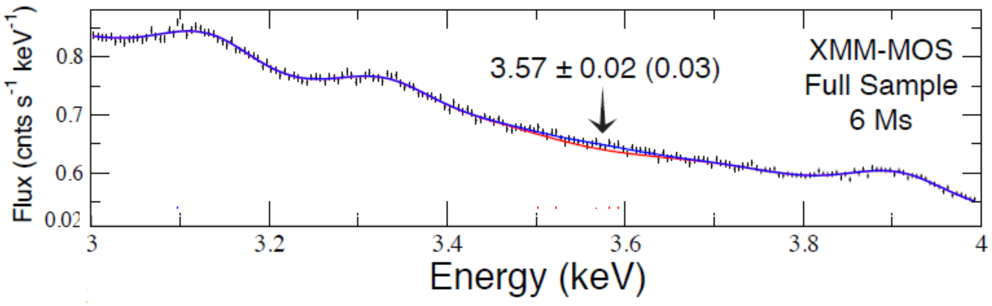

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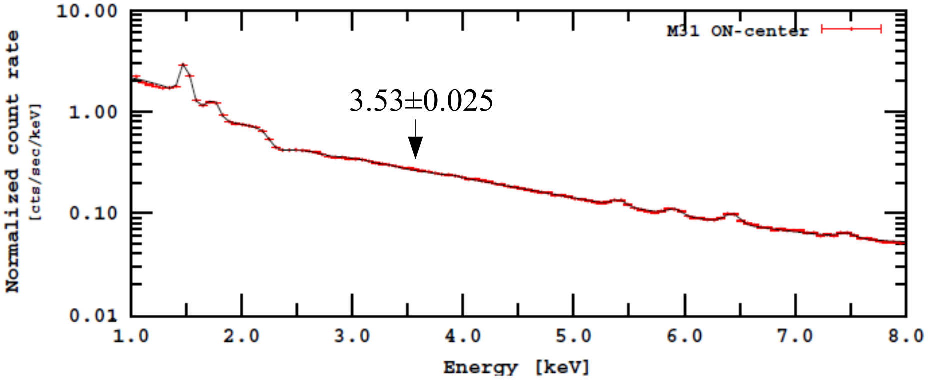

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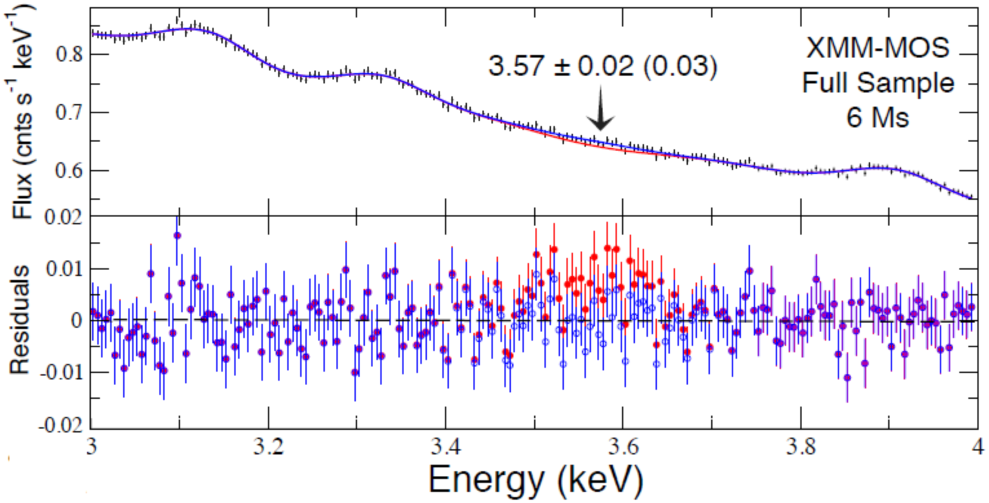

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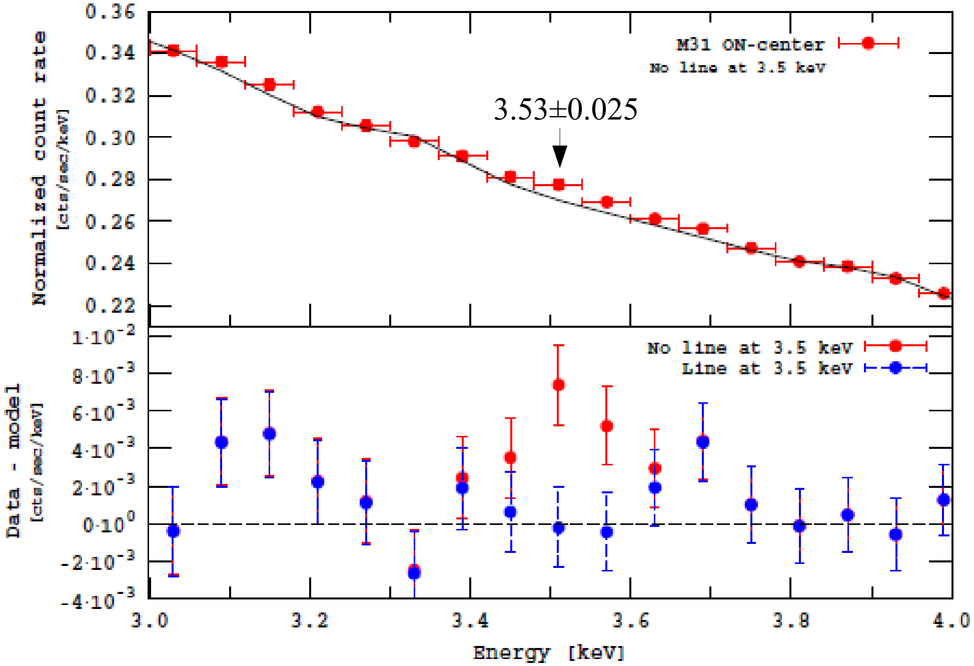

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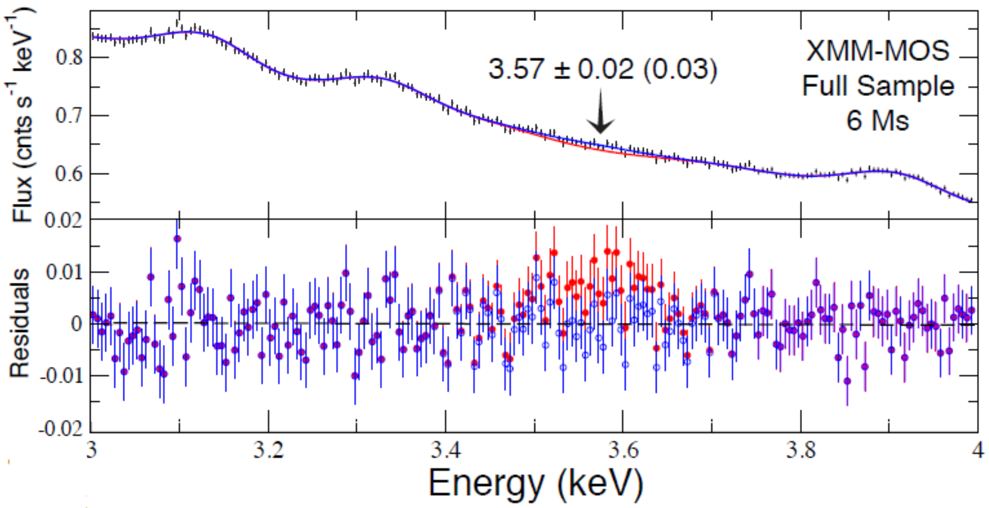

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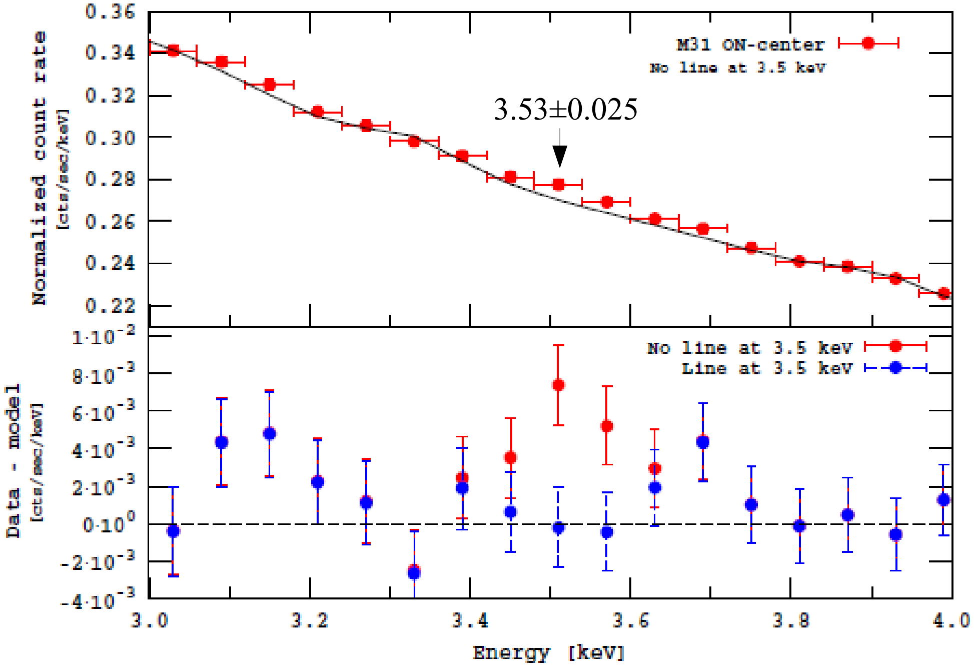

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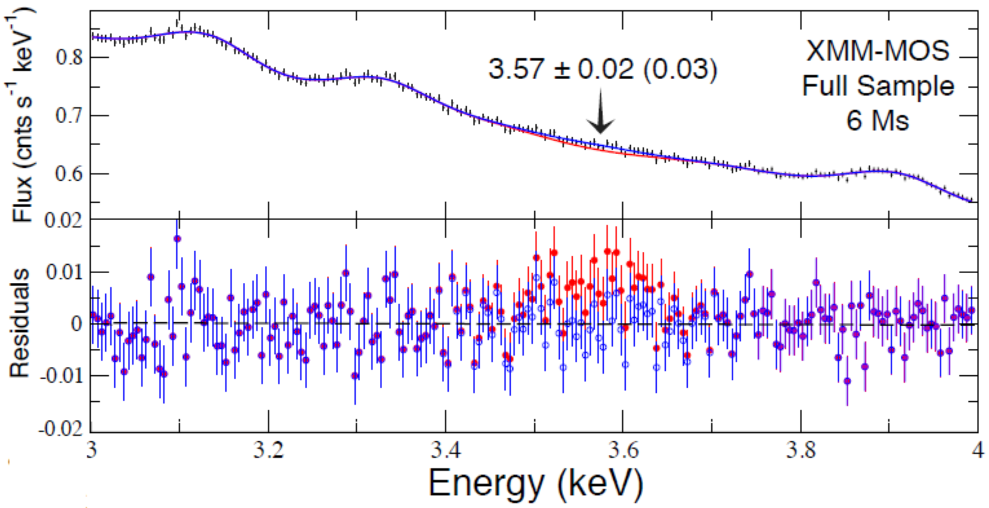

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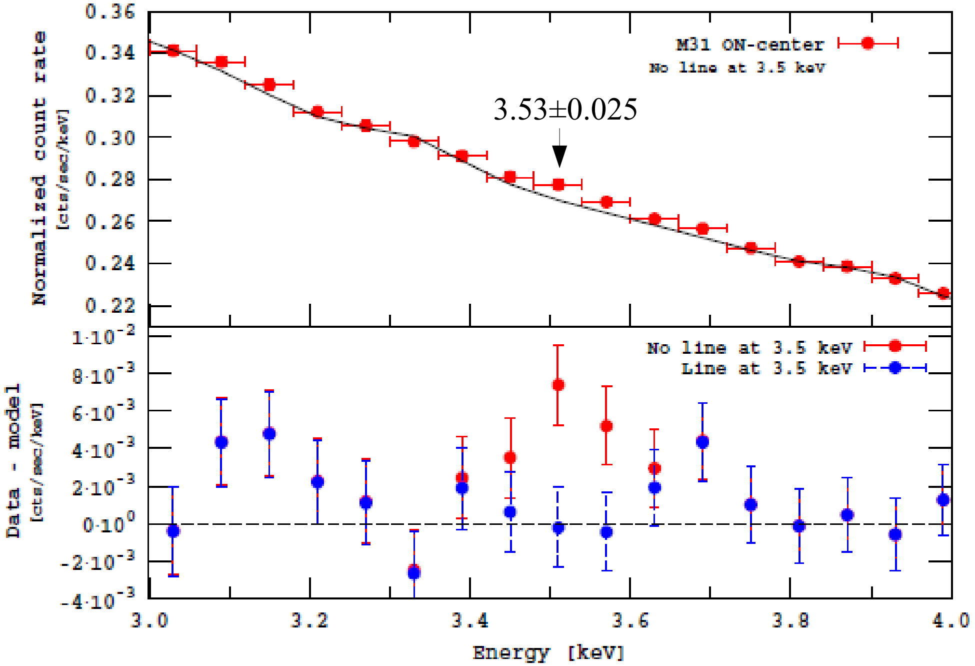


- Not observed in the deep "blank sky" dataset. Probably not instrumental.
- Observed in different datasets at different redshifts.
- Atomic origin not demonstrated: candidate atomic lines expected to be much fainter.
- Originated by sterile neutrino decay?

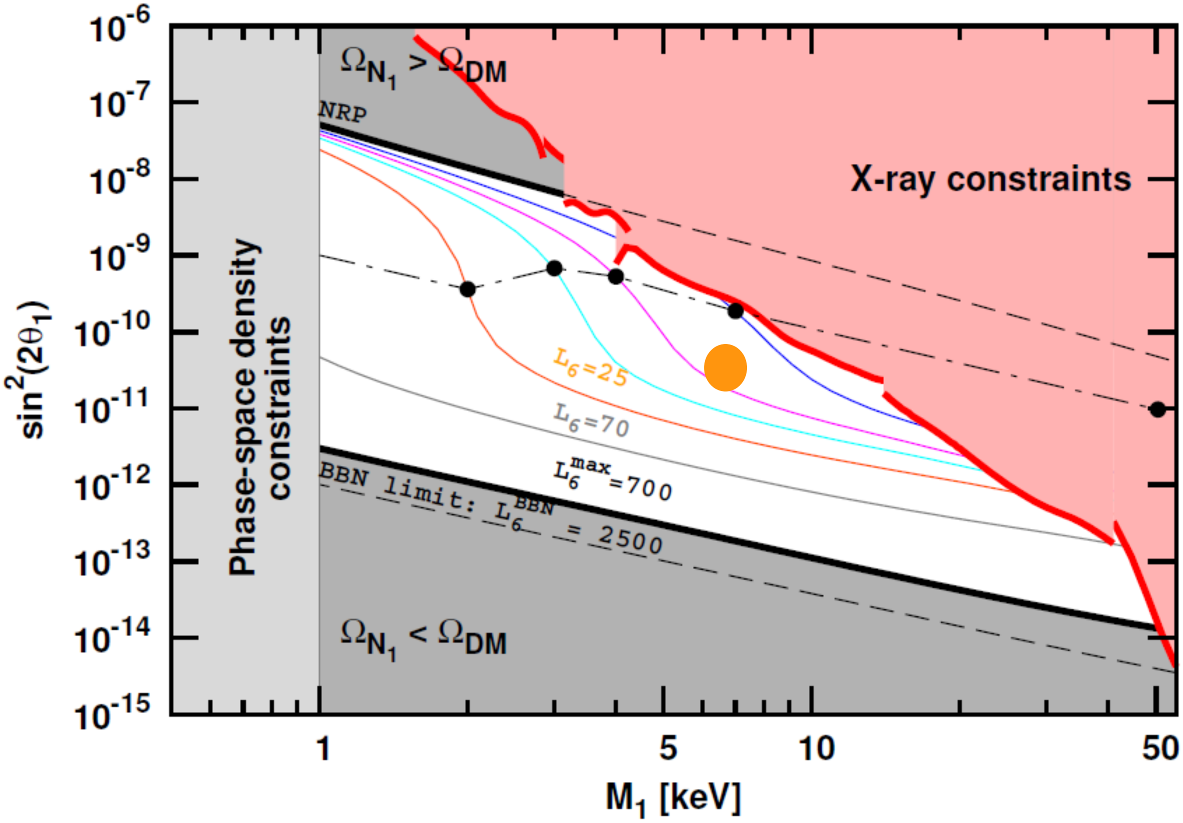
Sterile neutrinos as dark matter

Bulbul et al, 1402.2301

$$m_{\rm DM} = 7.1\,{\rm keV}$$
$$\sin^2 2\theta \approx 7\times10^{-11}$$

Boyarsky al, 1402.4119

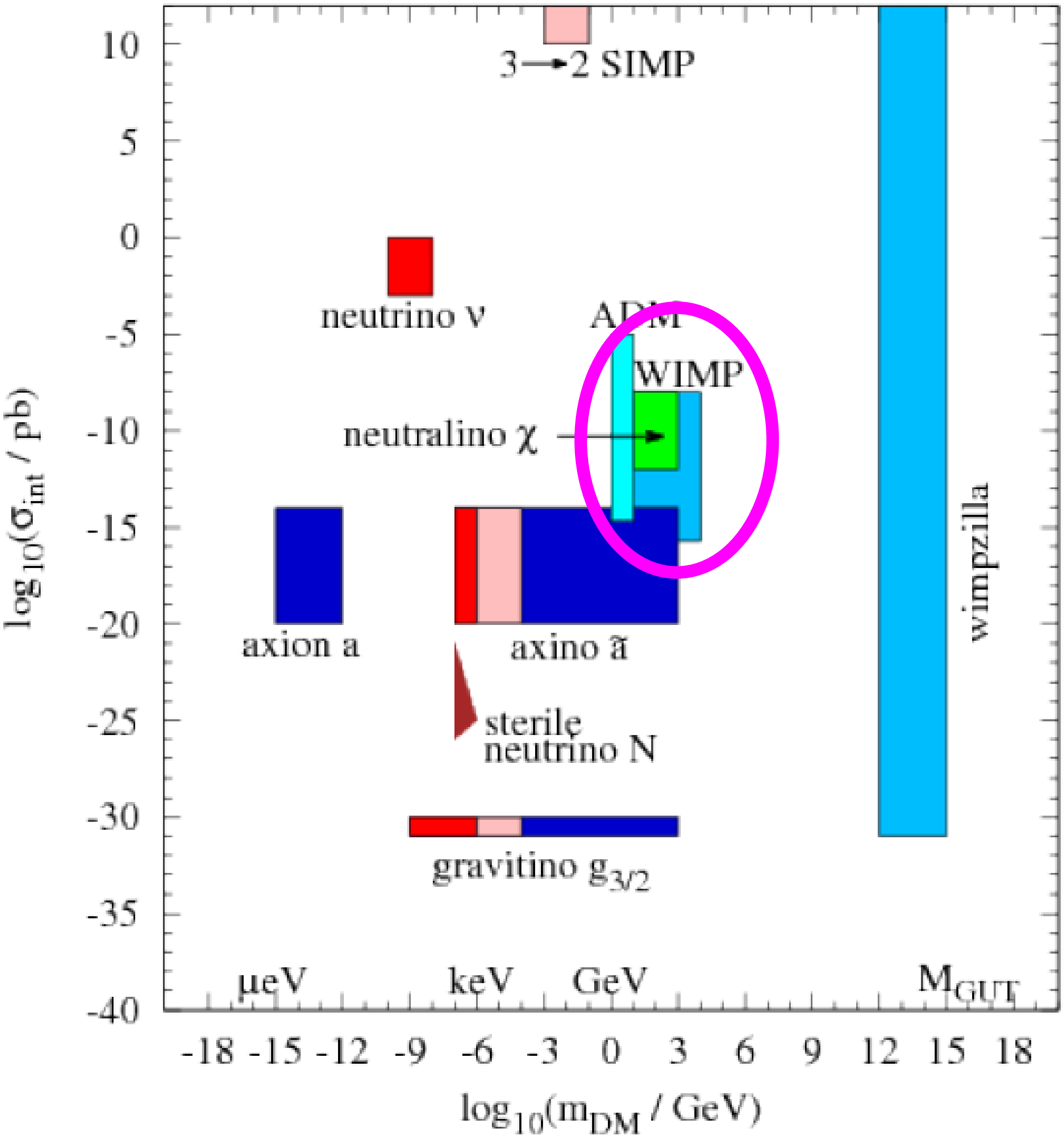
$$m_{\rm DM} = 7.06\pm0.05\,{\rm keV}$$
$$\sin^2 2\theta = (2.2-20)\times10^{-11}$$



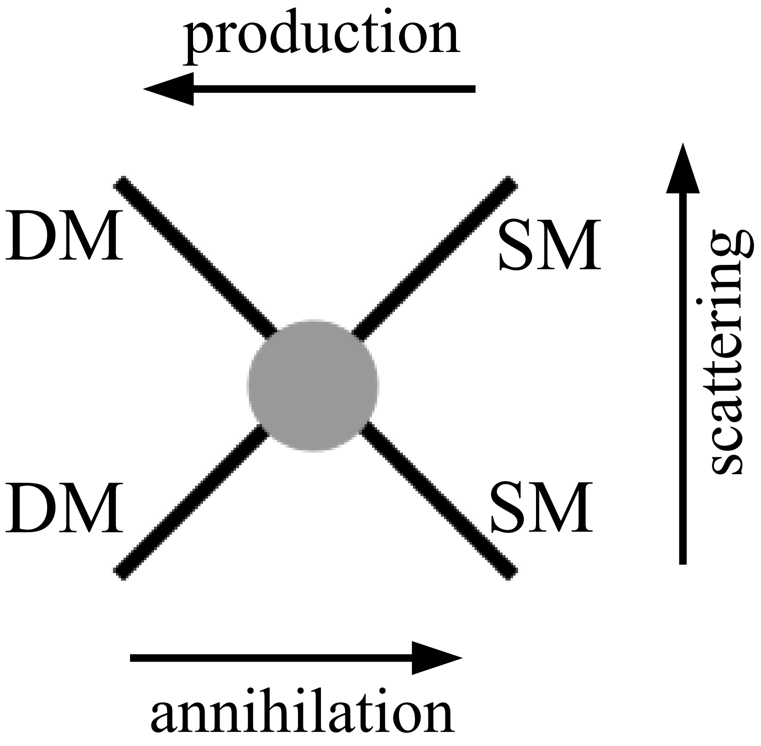
Requires nL/s ~ 10^{-5} (compared to nB/s ~ 10^{-10})

The future Athena mission will hopefully clarify the nature of this line.

WIMP
dark matter


3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
axion a
axino ã
sterile neutrino N
gravitino $g_{3/2}$
wimpzilla
μeV
keV
GeV
M_{GUT}
$\log_{10}(\sigma_{int}$ / pb)
$\log_{10}(m_{DM}$ / GeV)
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18

The freeze-out mechanism



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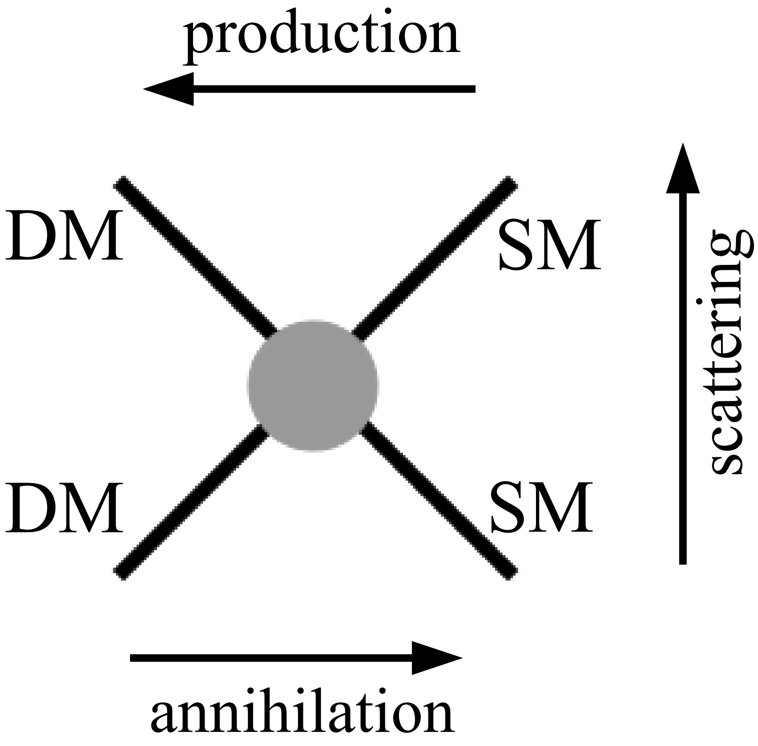
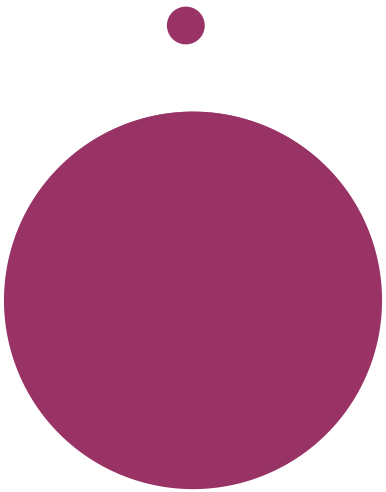


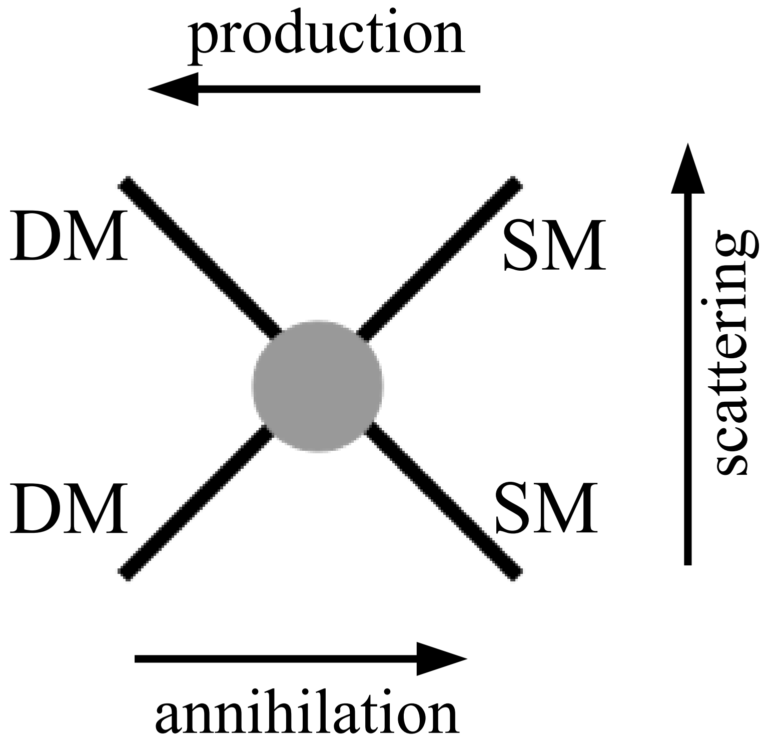
The probability of interaction controlled by the cross-section



Small interaction rate

Large interaction rate

The freeze-out mechanism

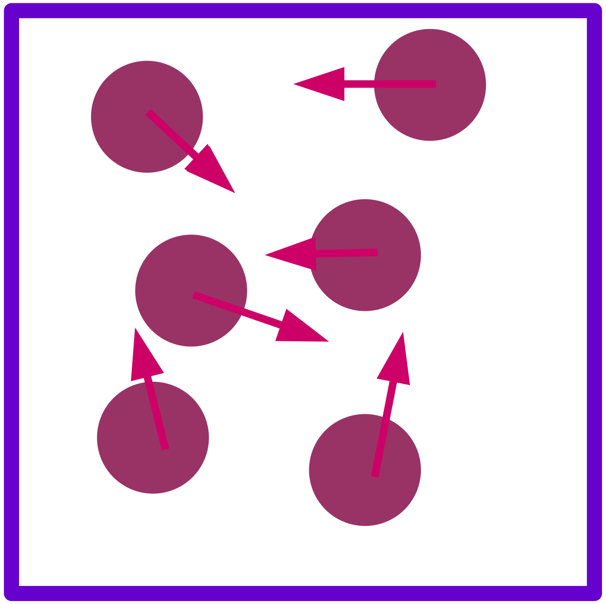


At very high temperatures,
dark matter particles are annihilated
and regenerated at the same rate.

However, at low temperatures,
the Standard Model particles do not
have enough kinetic energy to
regenerate DM particles, and DM
particles can only annihilate.

The subsequent evolution of the dark
matter number density depends
crucially on the fact that our Universe
is expanding.

Dark matter population in a static Universe



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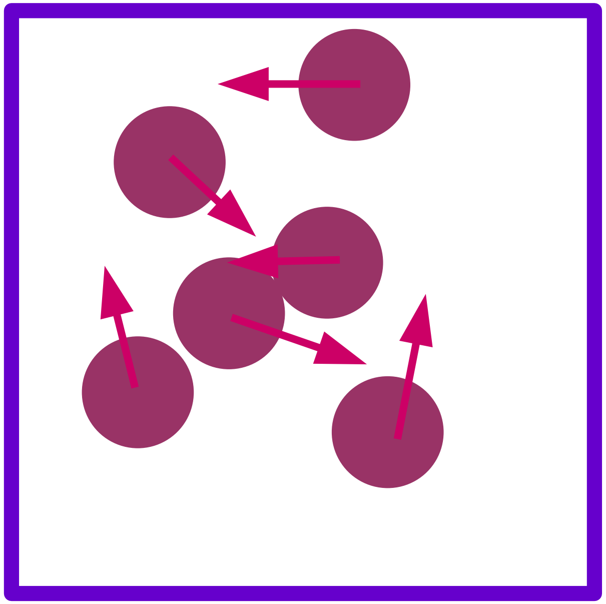

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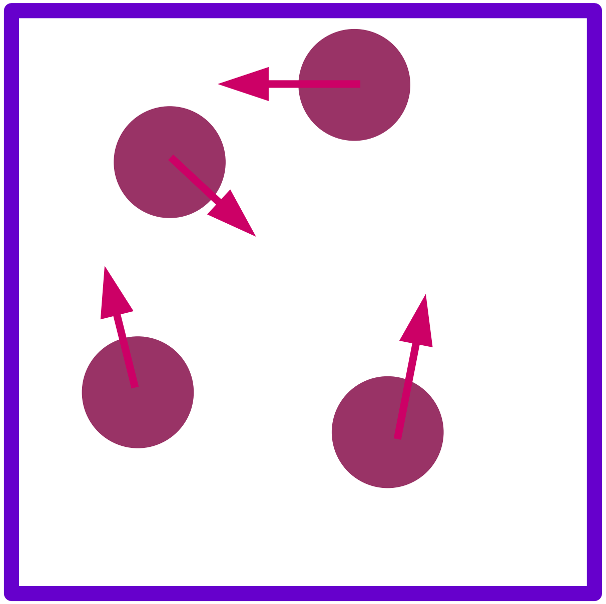

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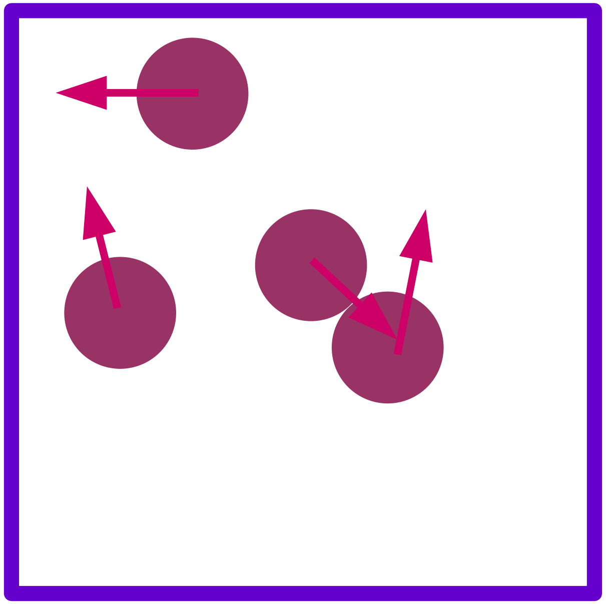

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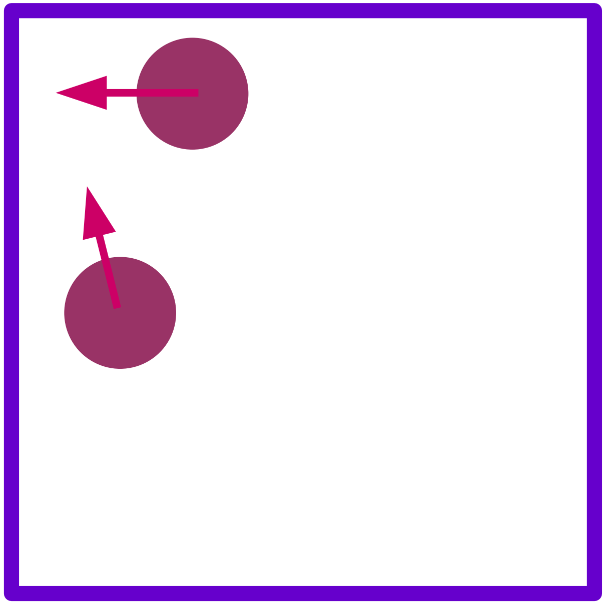

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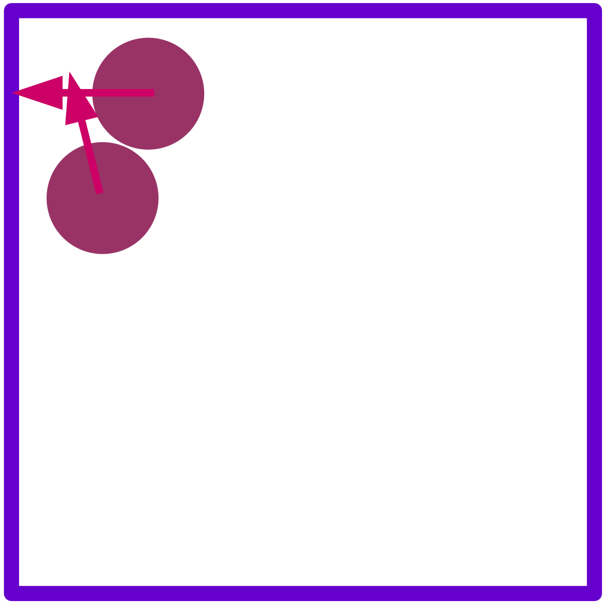
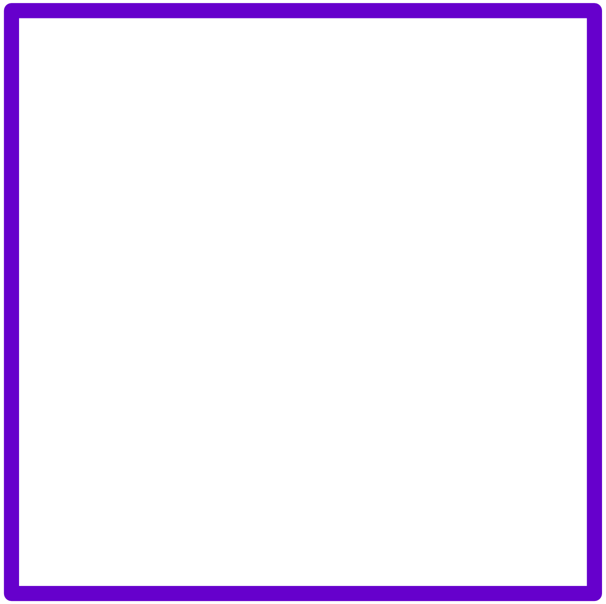
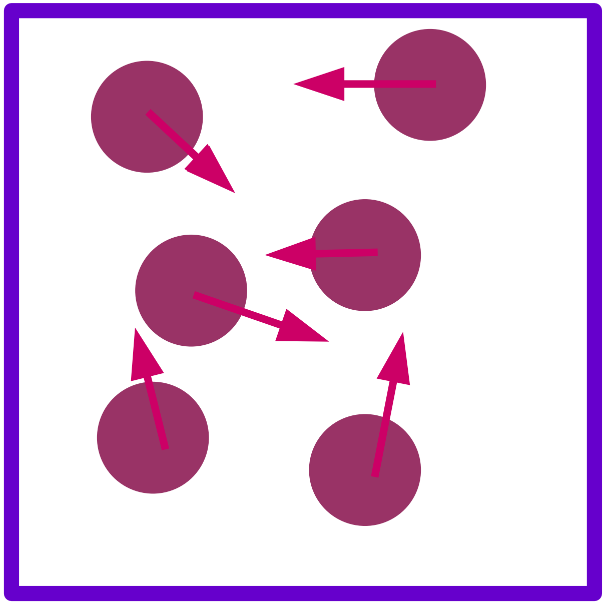


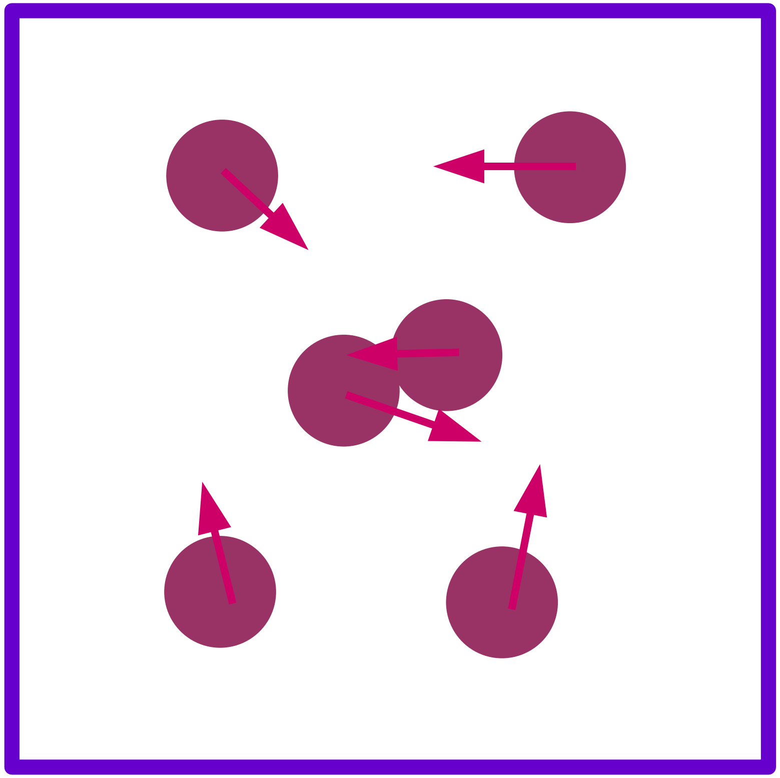
Dark matter population in a static Universe

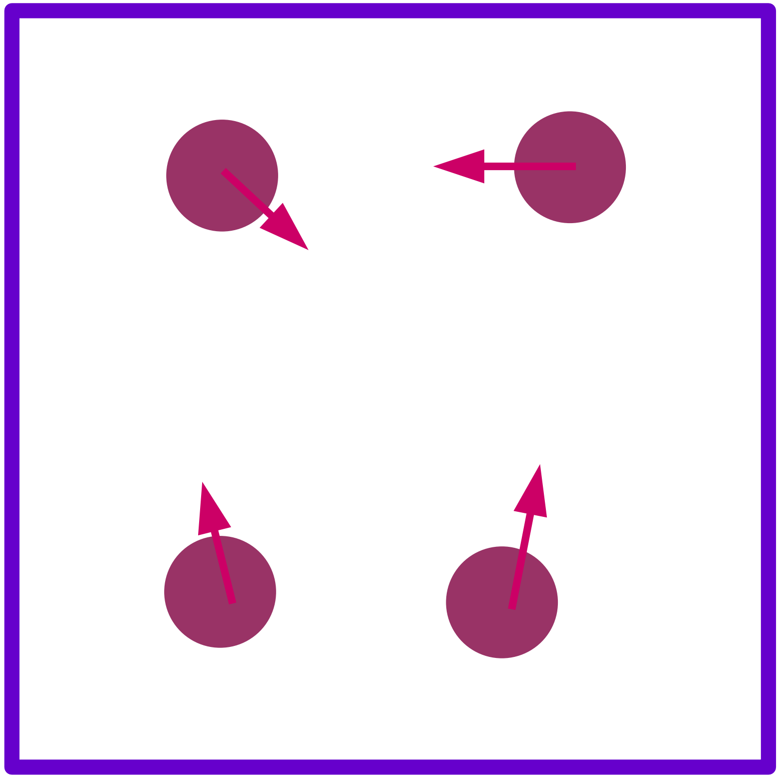


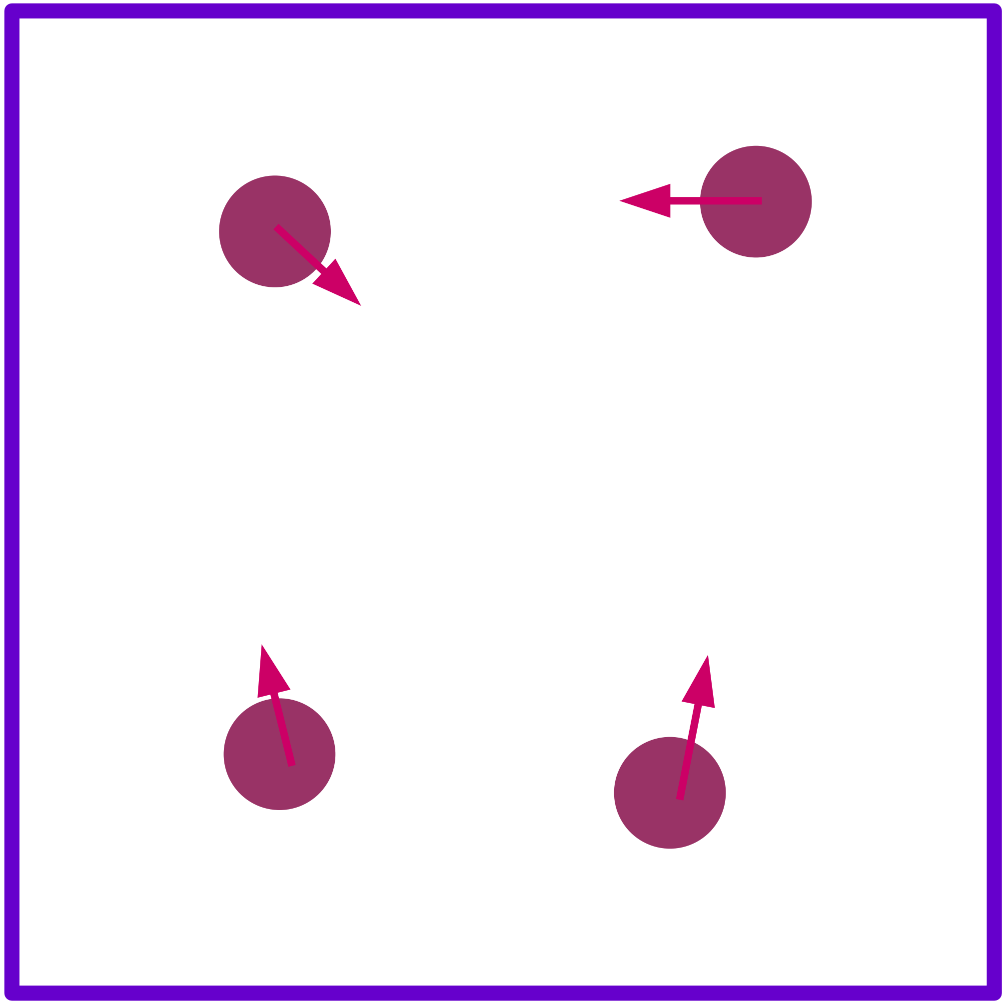
No DM particles at present times!

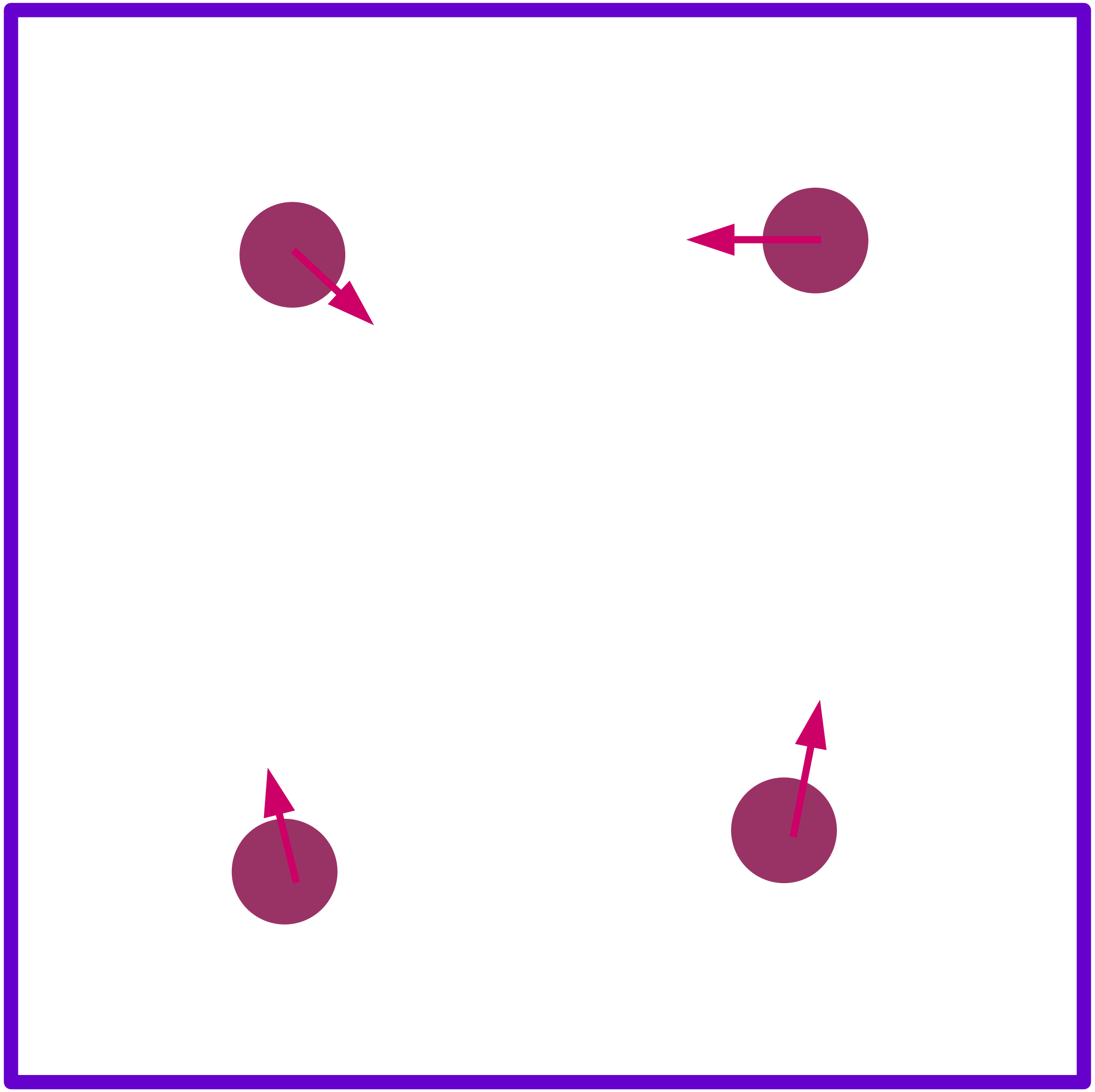
Dark matter population in an expanding Universe





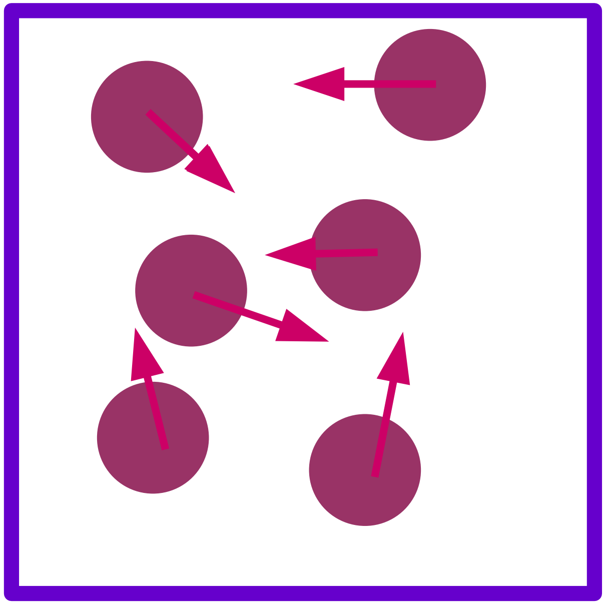






Dark matter particles can no longer annihilate.
The number of dark matter particles "freezes-out"

The “relic abundance” of dark matter particles depends on their annihilation cross section and on their relative velocity



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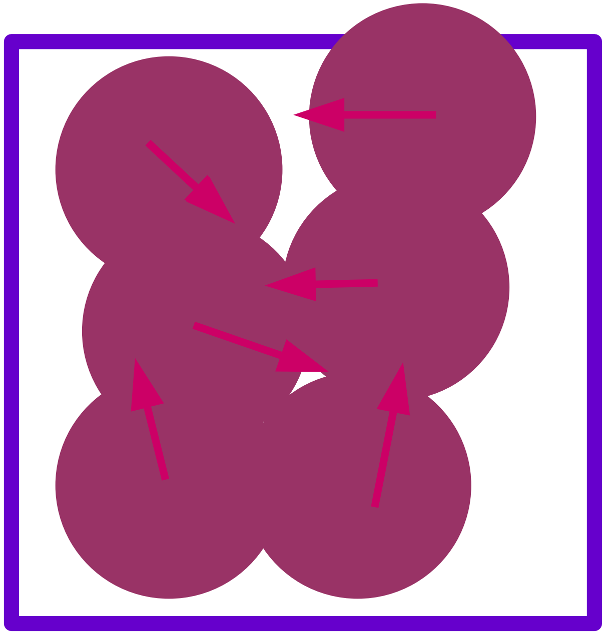

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Large annihilation cross section → Small relic abundance
Small annihilation cross section → Large relic abundance

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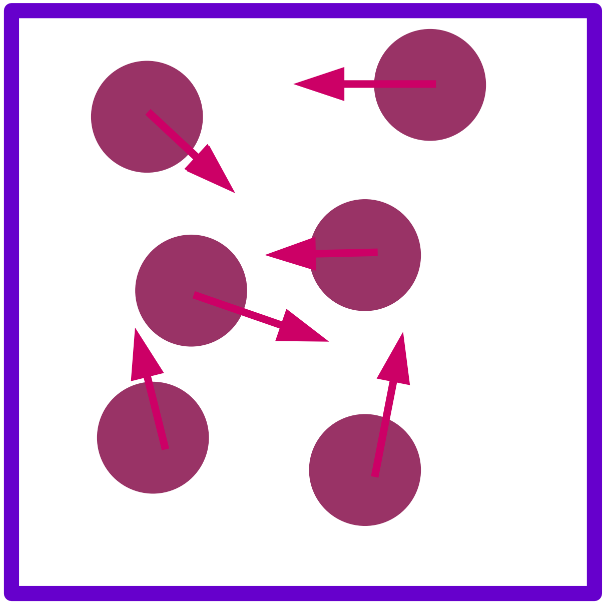

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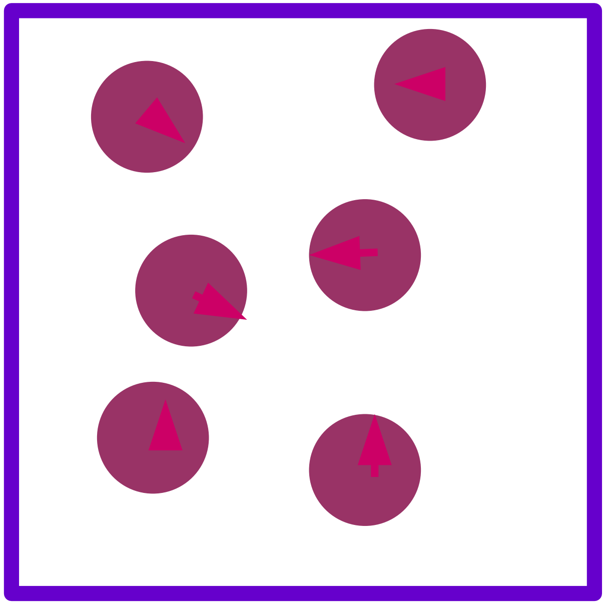

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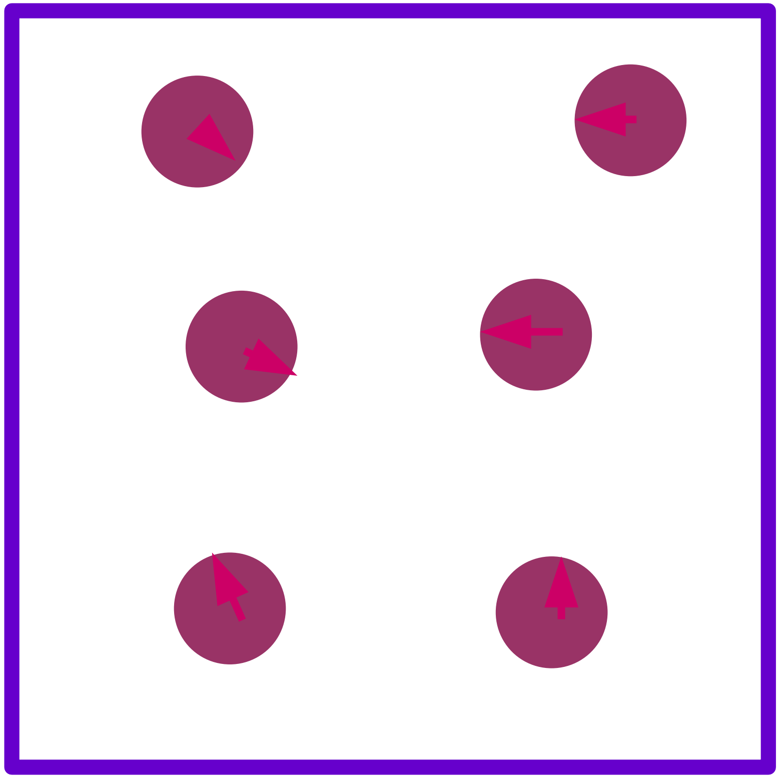


Small velocity → Large relic abundance
Large velocity → Small relic abundance

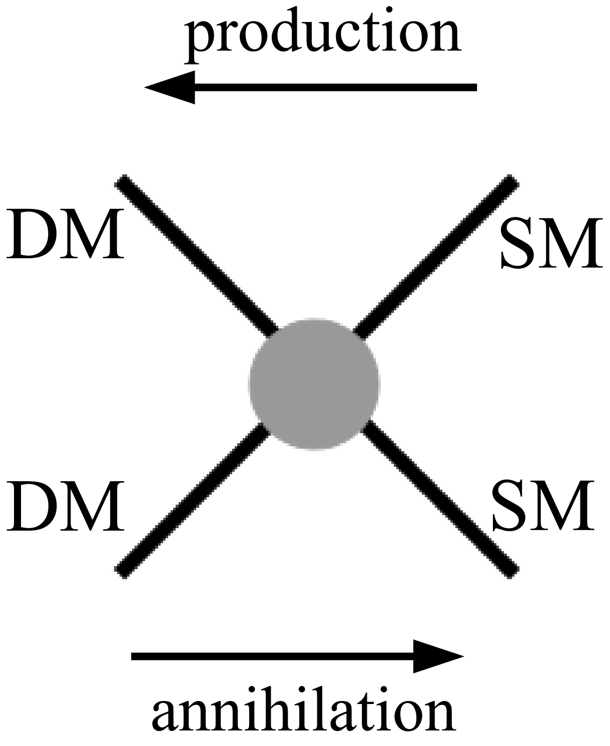
$$n_{\mathrm{DM}}\Big|_{\mathrm{f.o.}} \propto \frac{1}{\sigma v}$$

The basic tool: the Boltzmann equation

Boltzmann equation for the dark matter number density in an expanding Universe:

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

change of n = production - destruction



WIMP history (in a nutshell)

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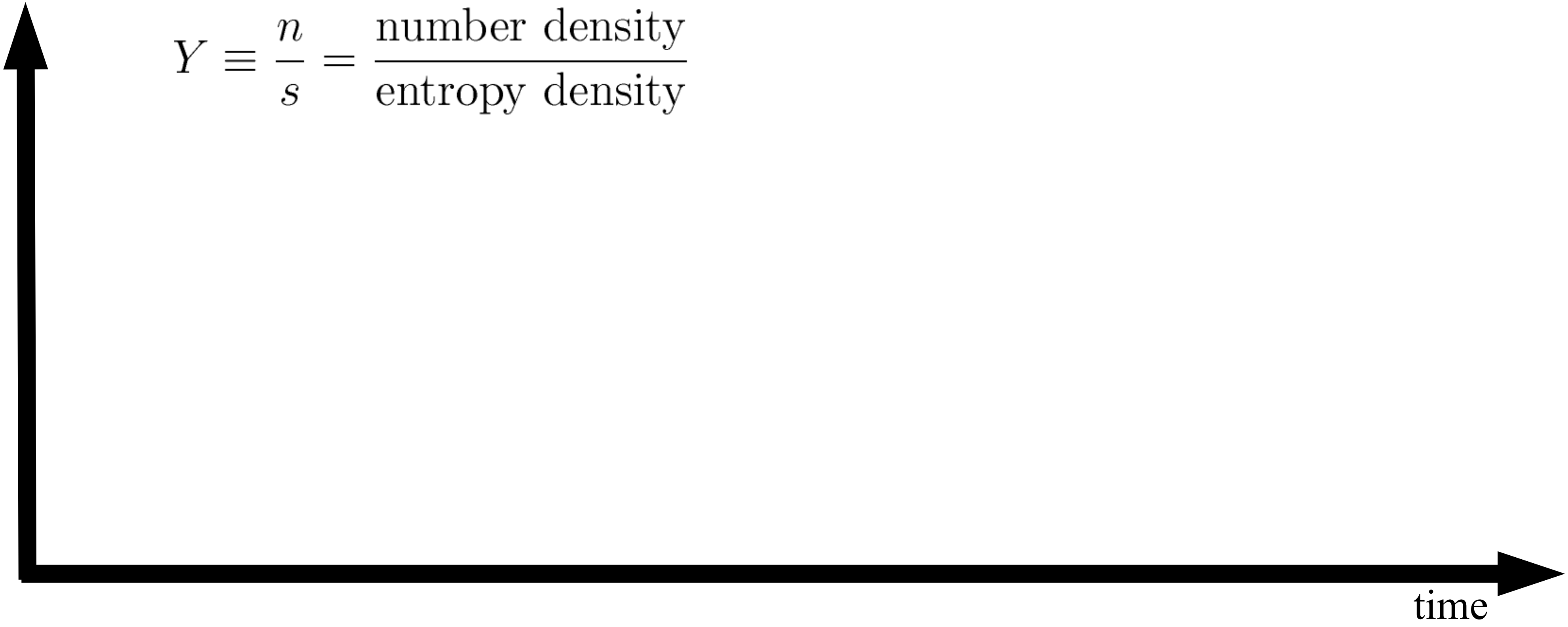

“yield” = number density of DM particles per comoving volume

$$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

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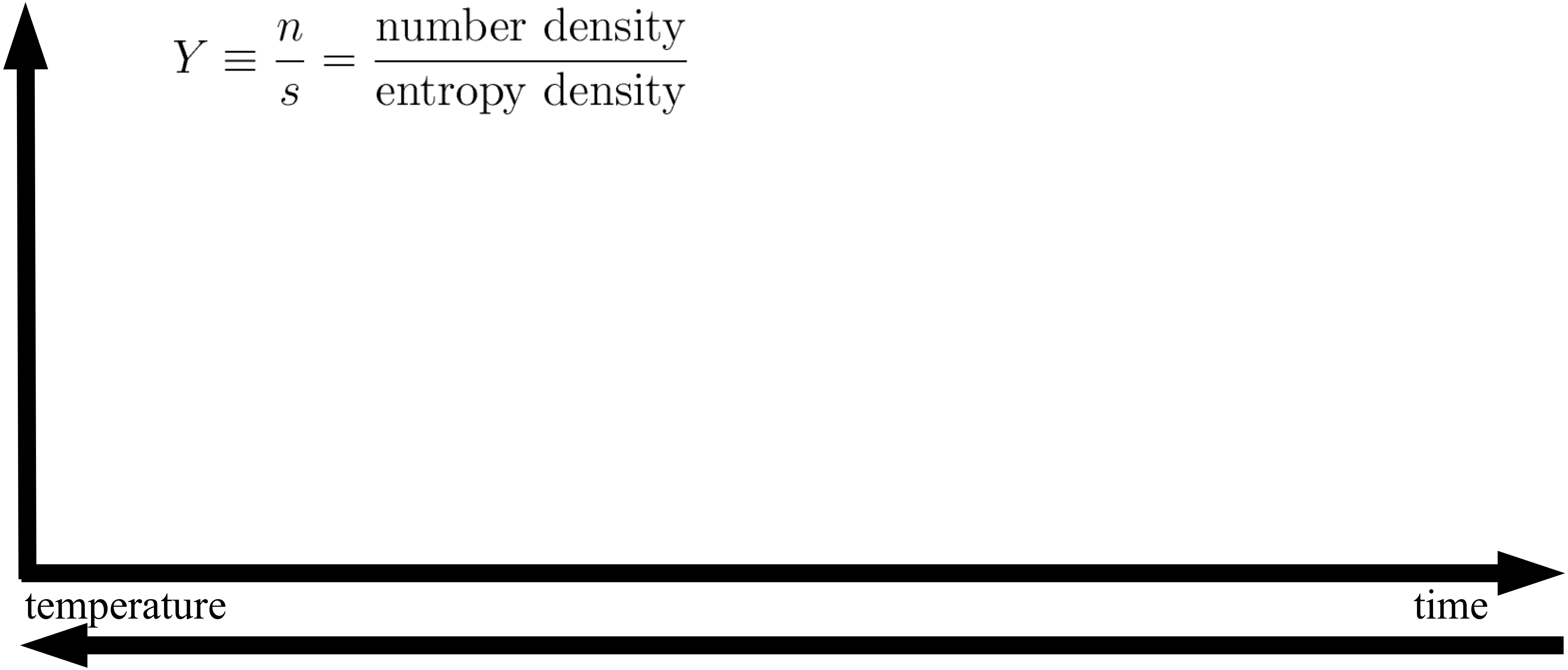

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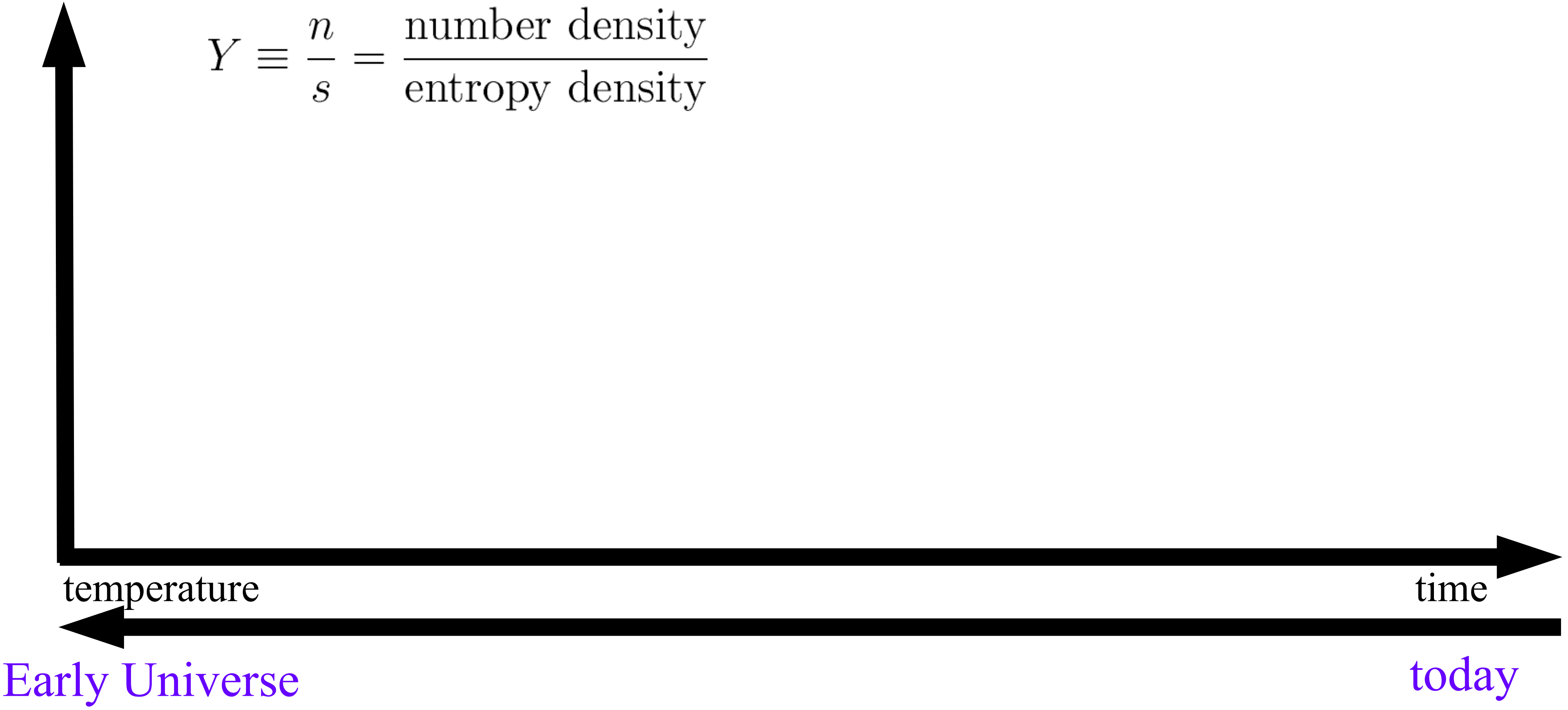
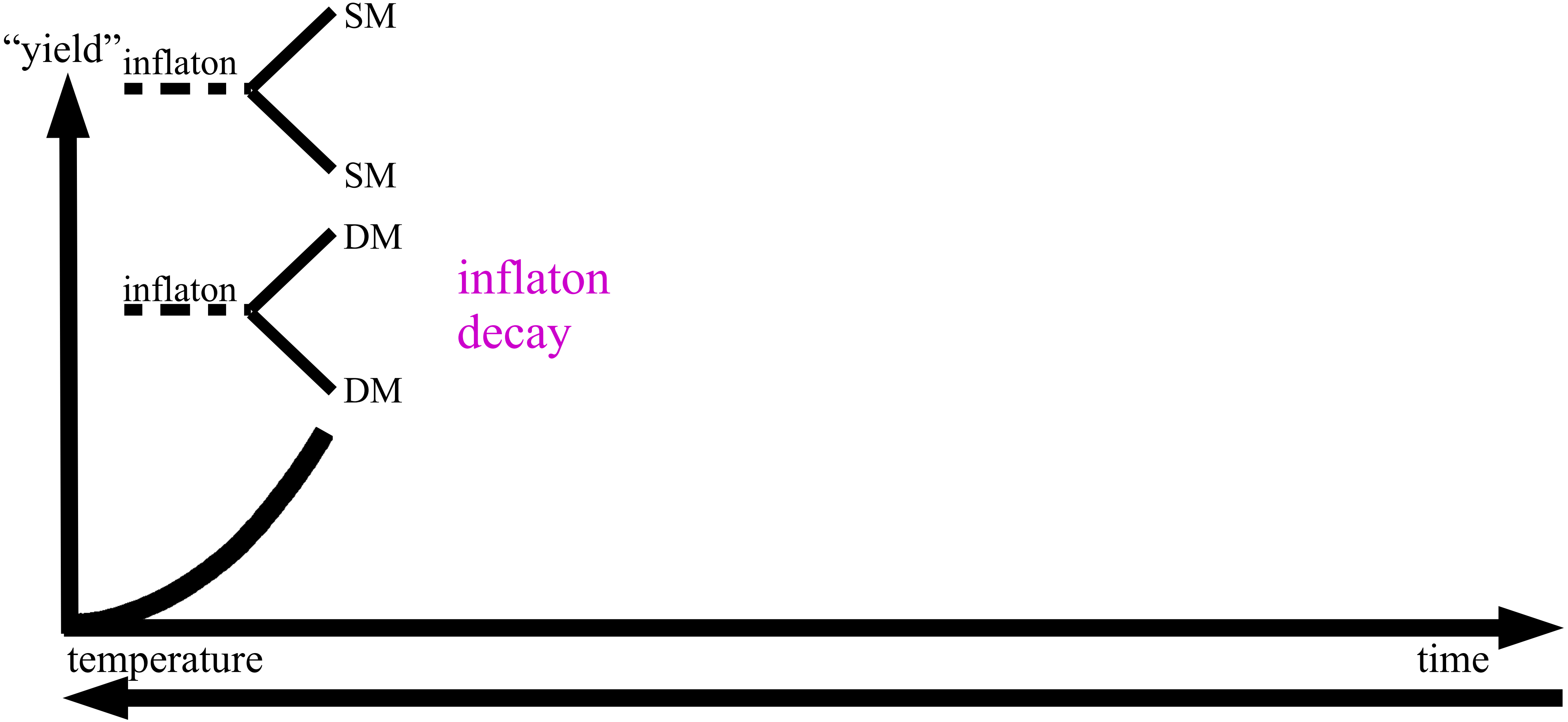


WIMP history (in a nutshell)

End of inflation

WIMP history (in a nutshell)



“yield”

inflaton

SM

SM

inflaton

DM

DM

inflaton
decay

temperature

time

WIMP history (in a nutshell)

“yield”

inflaton

SM

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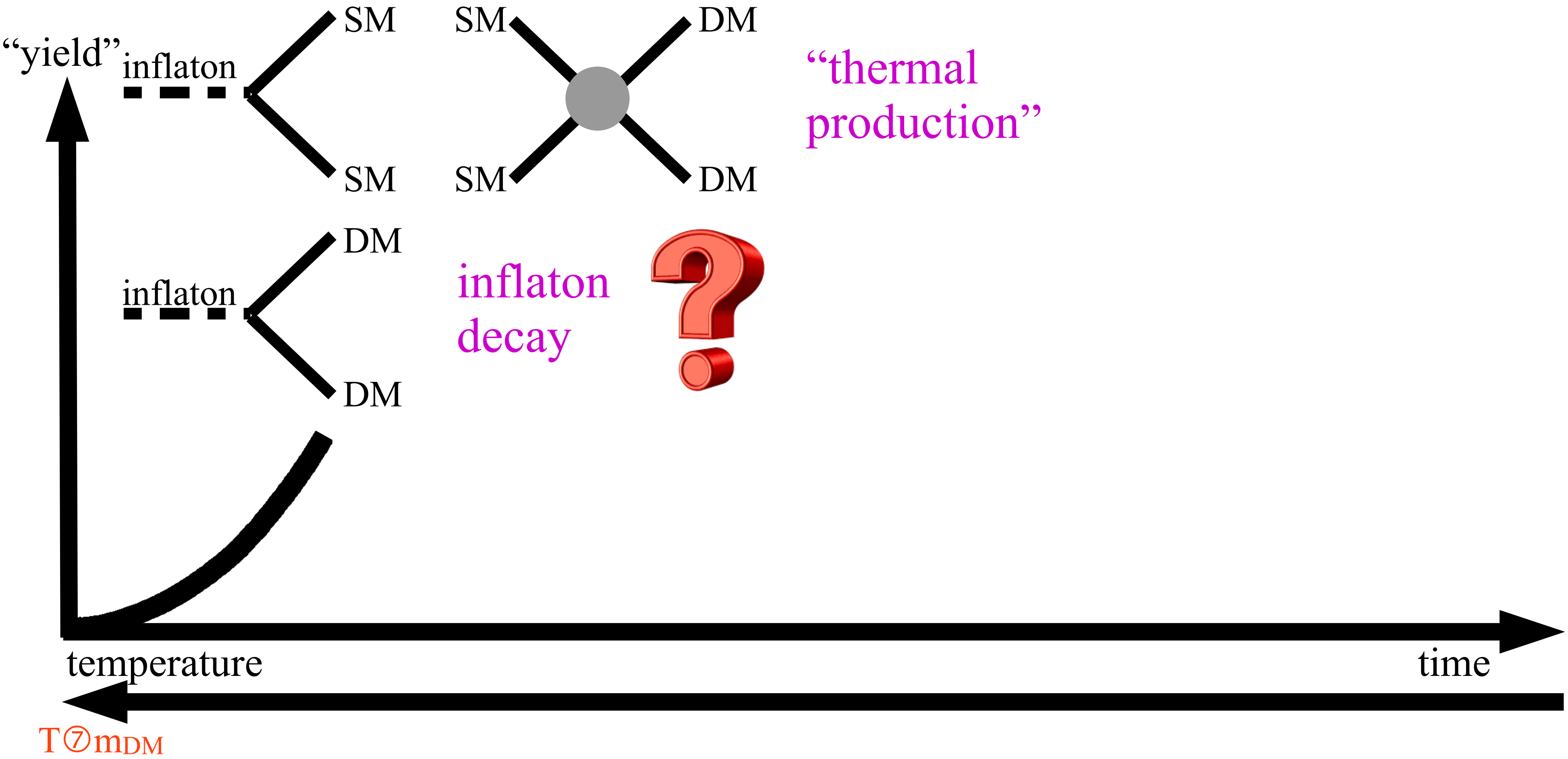


“yield”

inflaton

SM

SM

SM

SM

DM

DM

“thermal production”

inflaton

DM

DM

inflaton decay

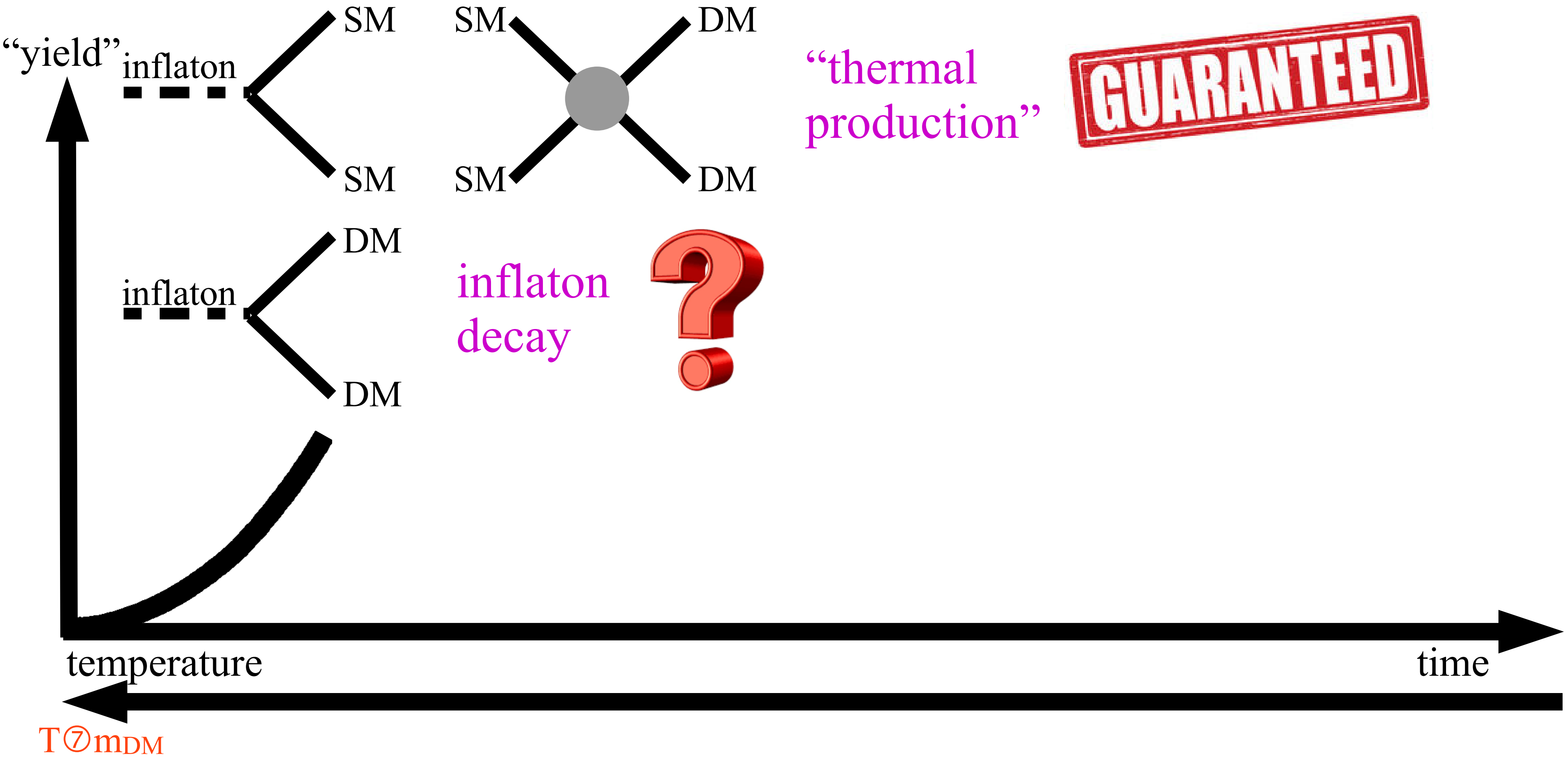
temperature

time

T⑦m_{DM}

Assume that the temperature of the Universe after reheating was much larger than the DM mass.

WIMP history (in a nutshell)



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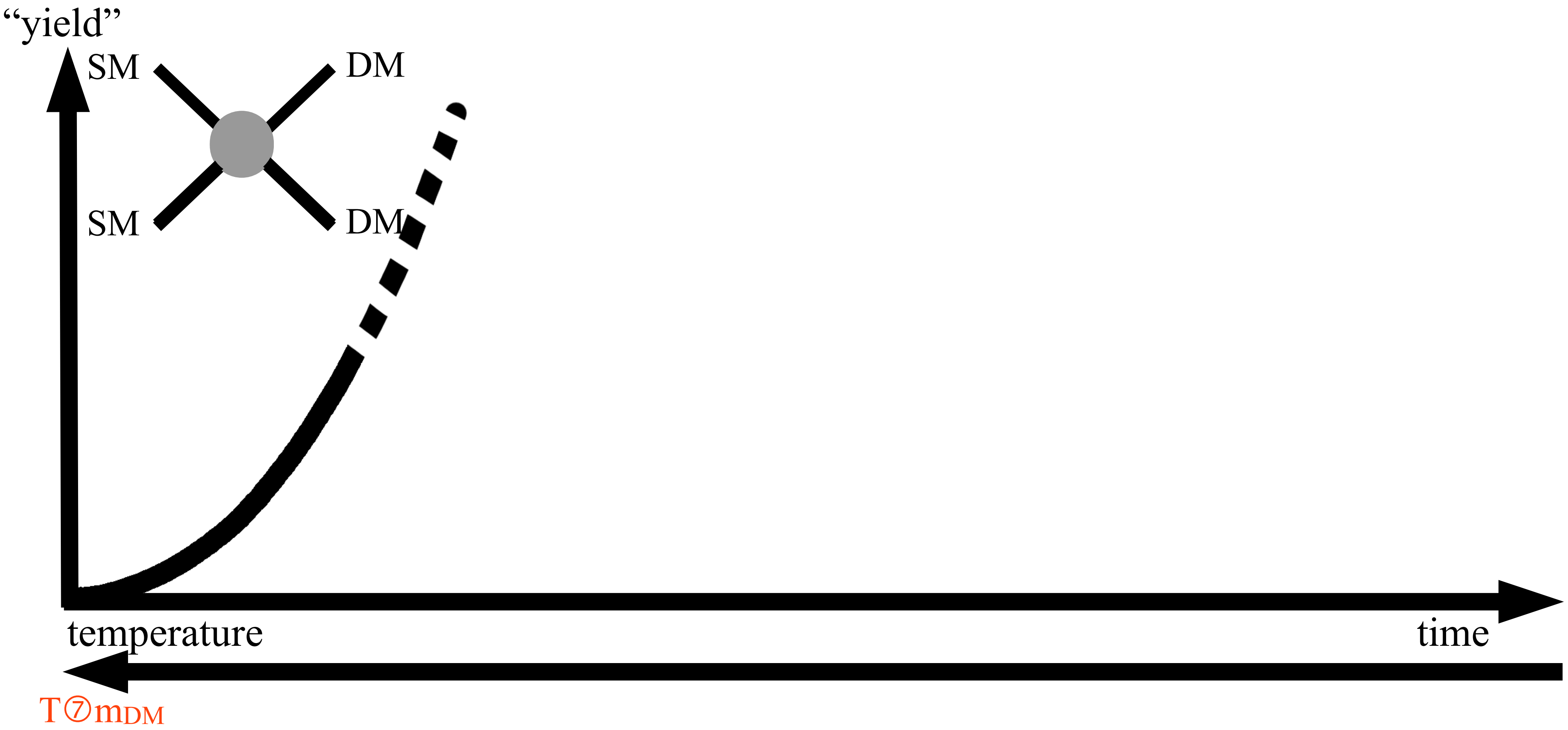

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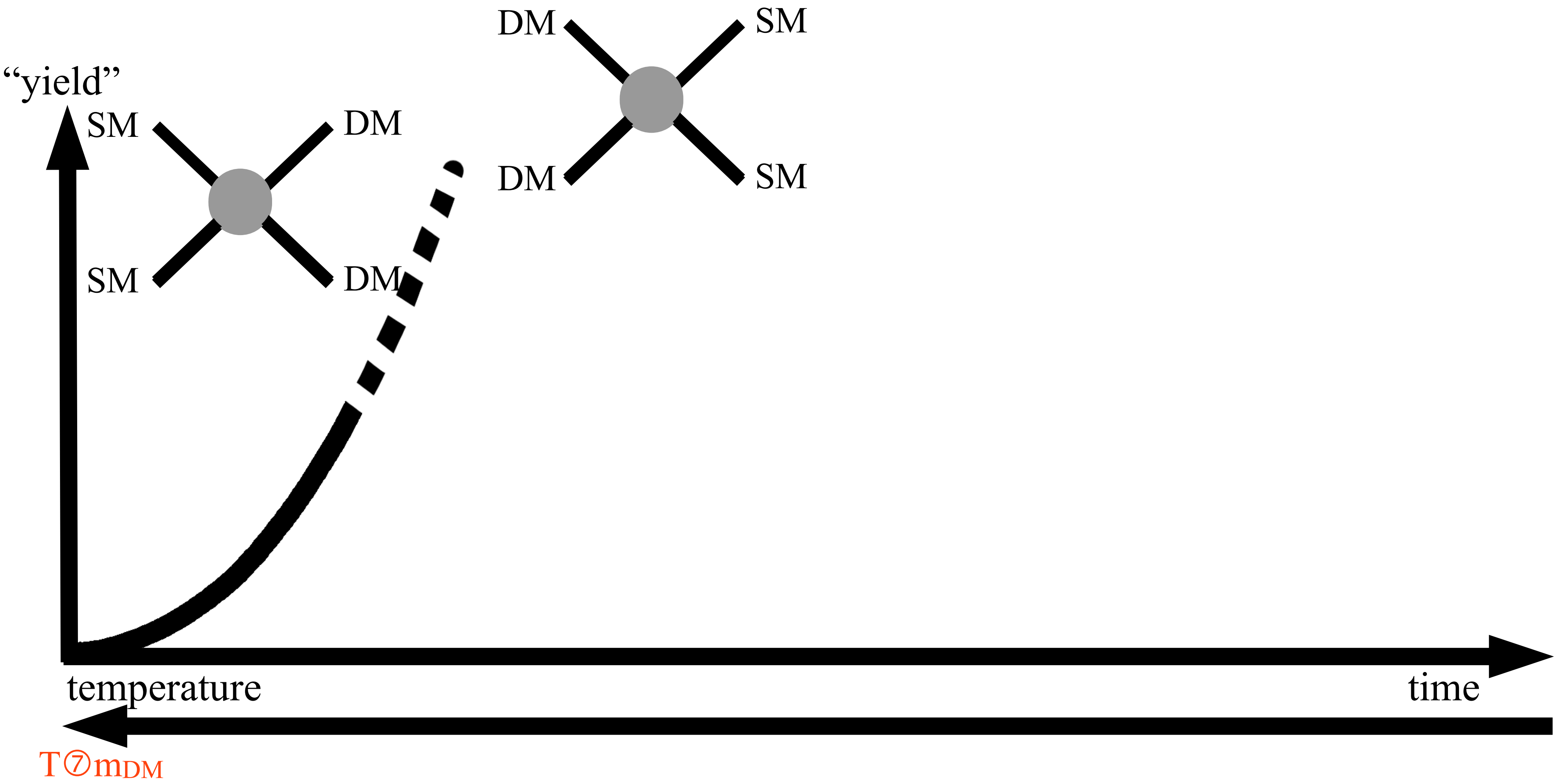

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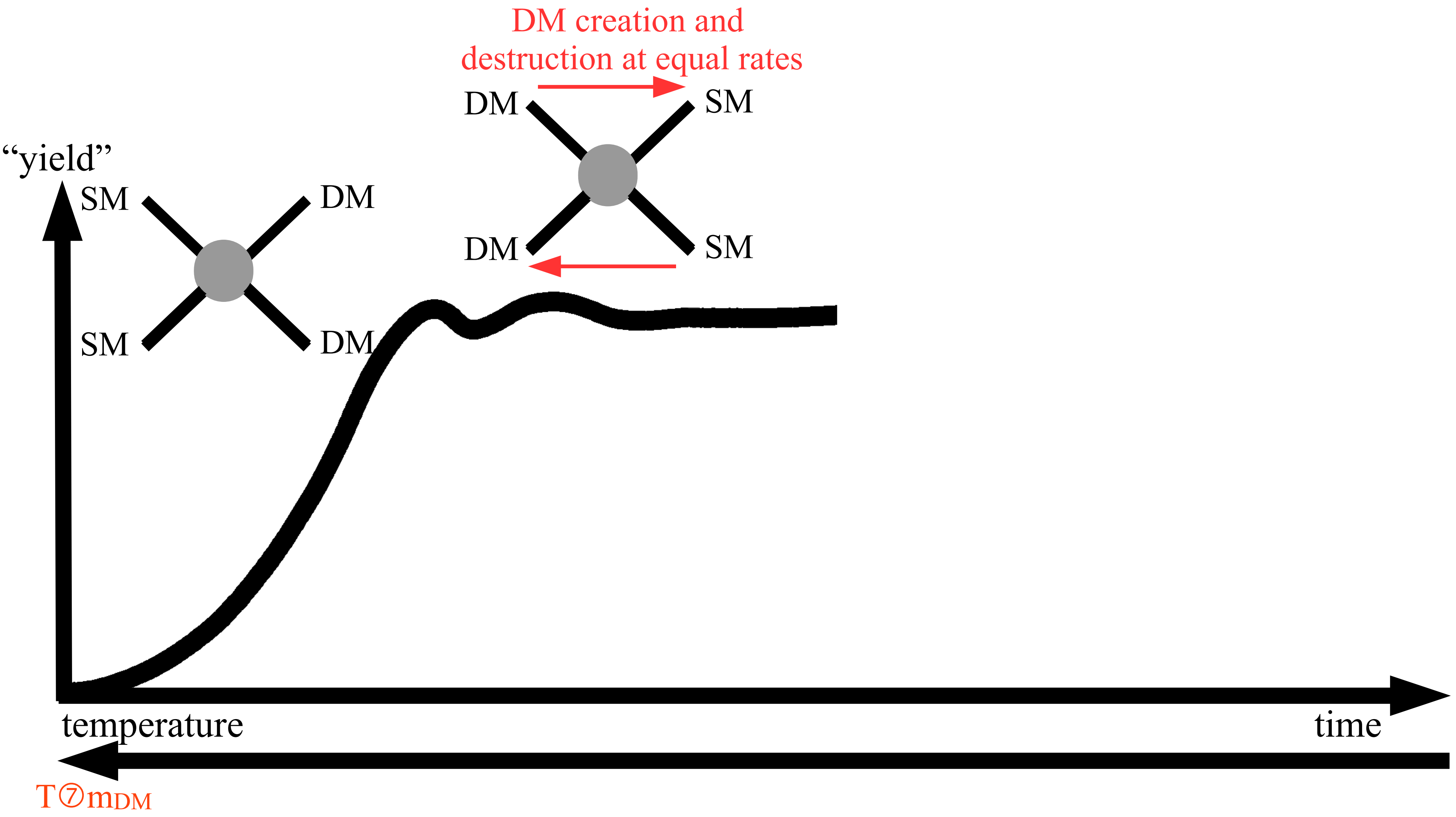
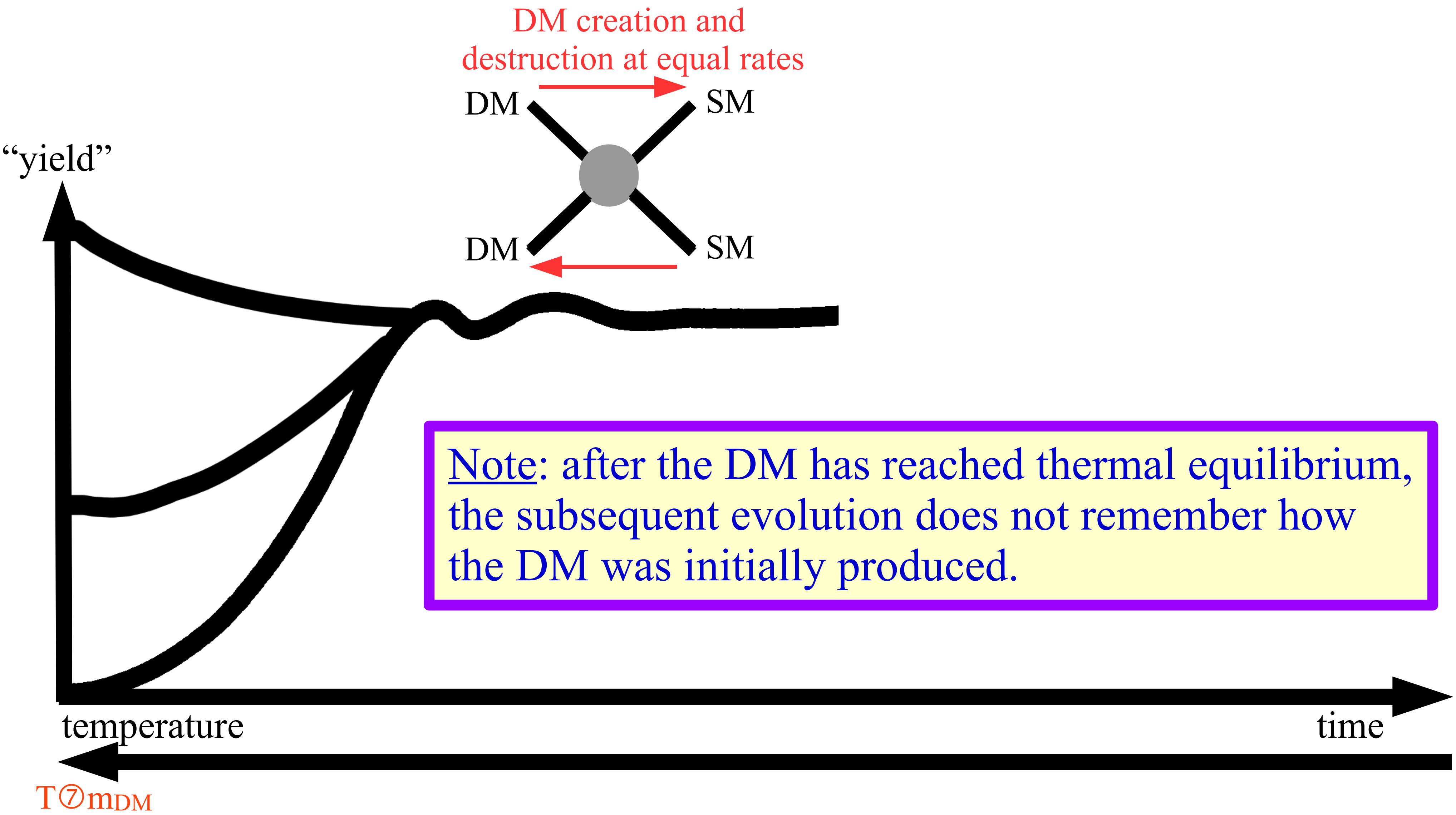


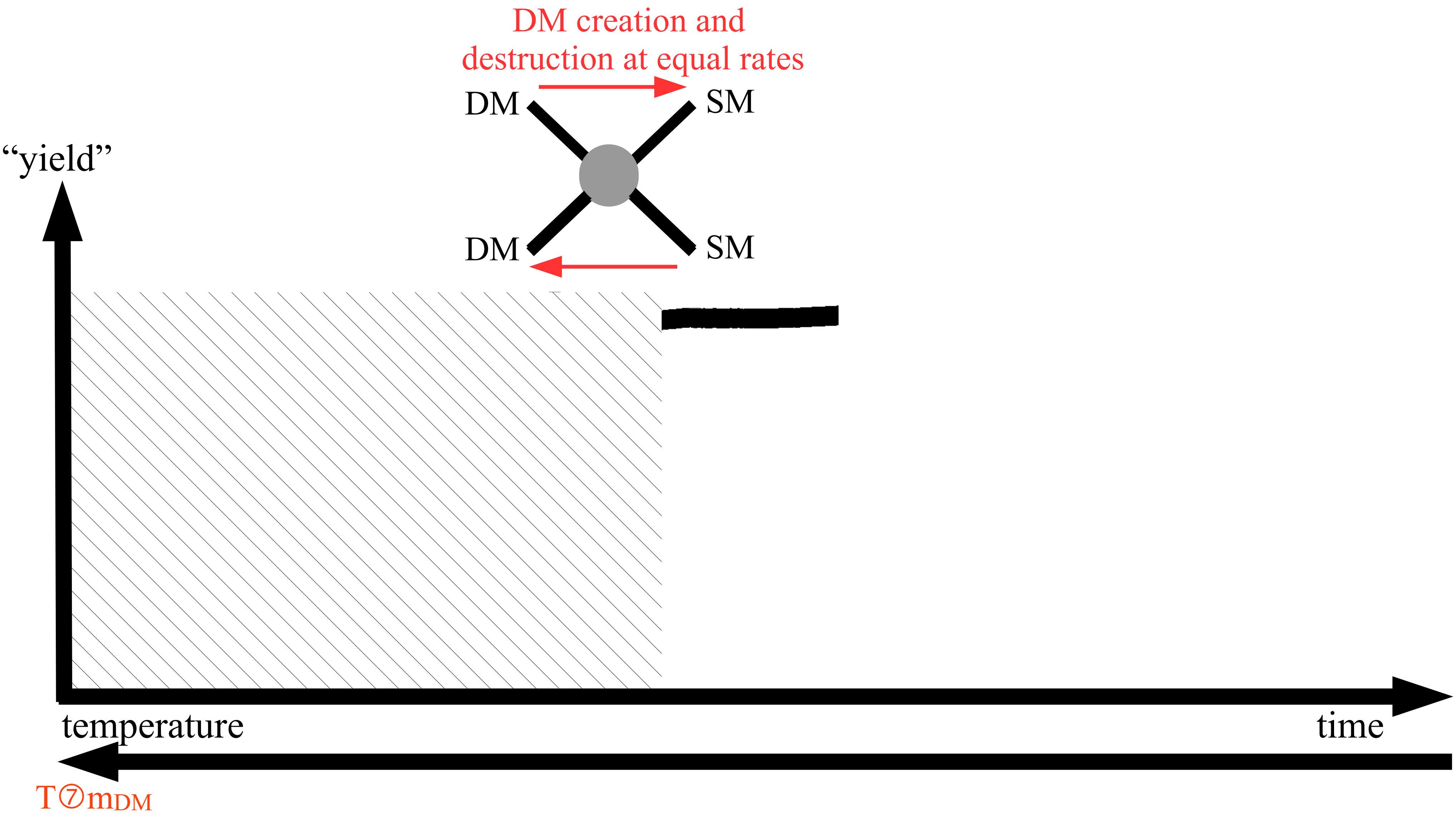
DM creation and destruction at equal rates

WIMP history (in a nutshell)



<u>Note</u>: after the DM has reached thermal equilibrium, the subsequent evolution does not remember how the DM was initially produced.

WIMP history (in a nutshell)



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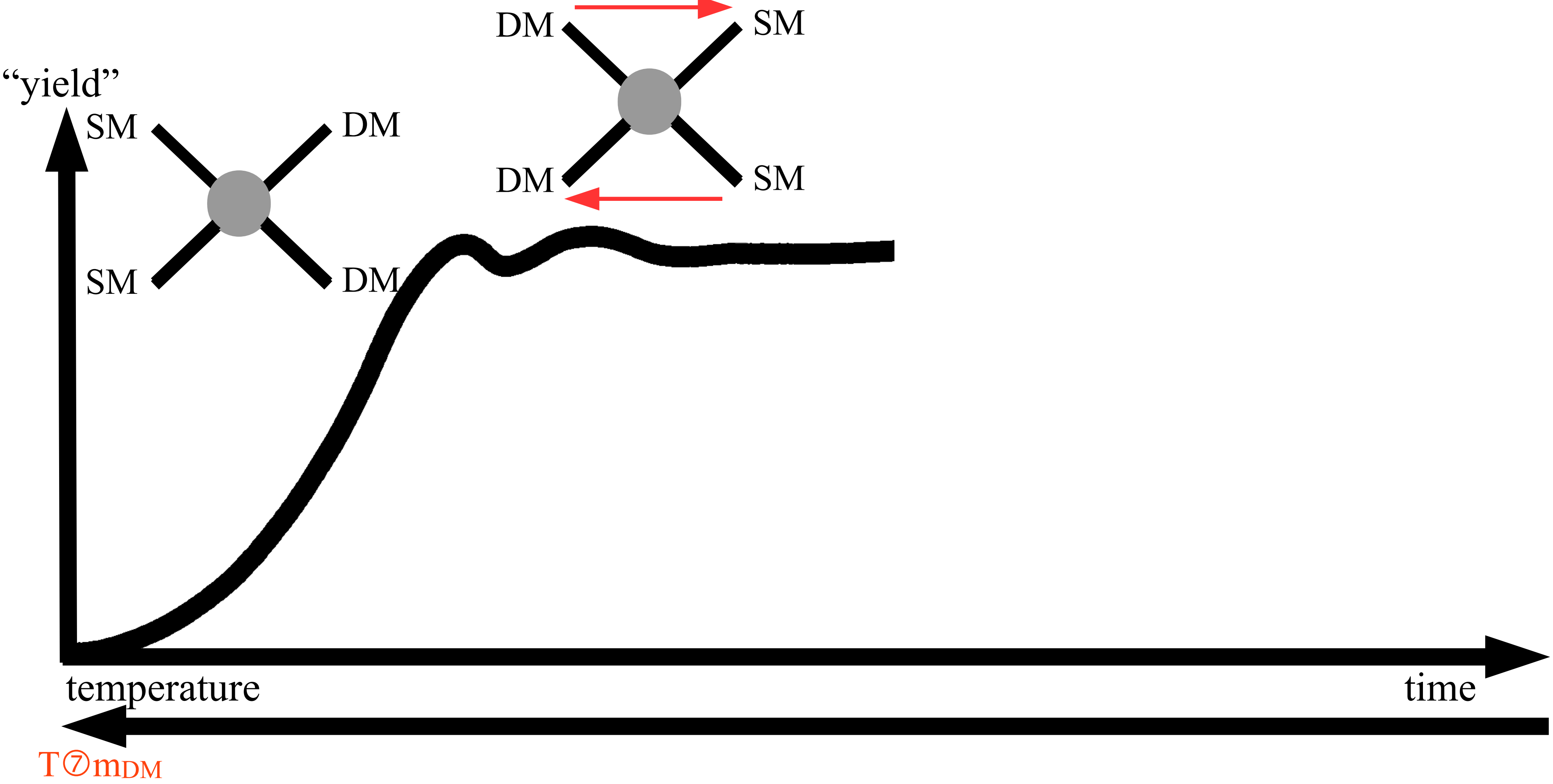
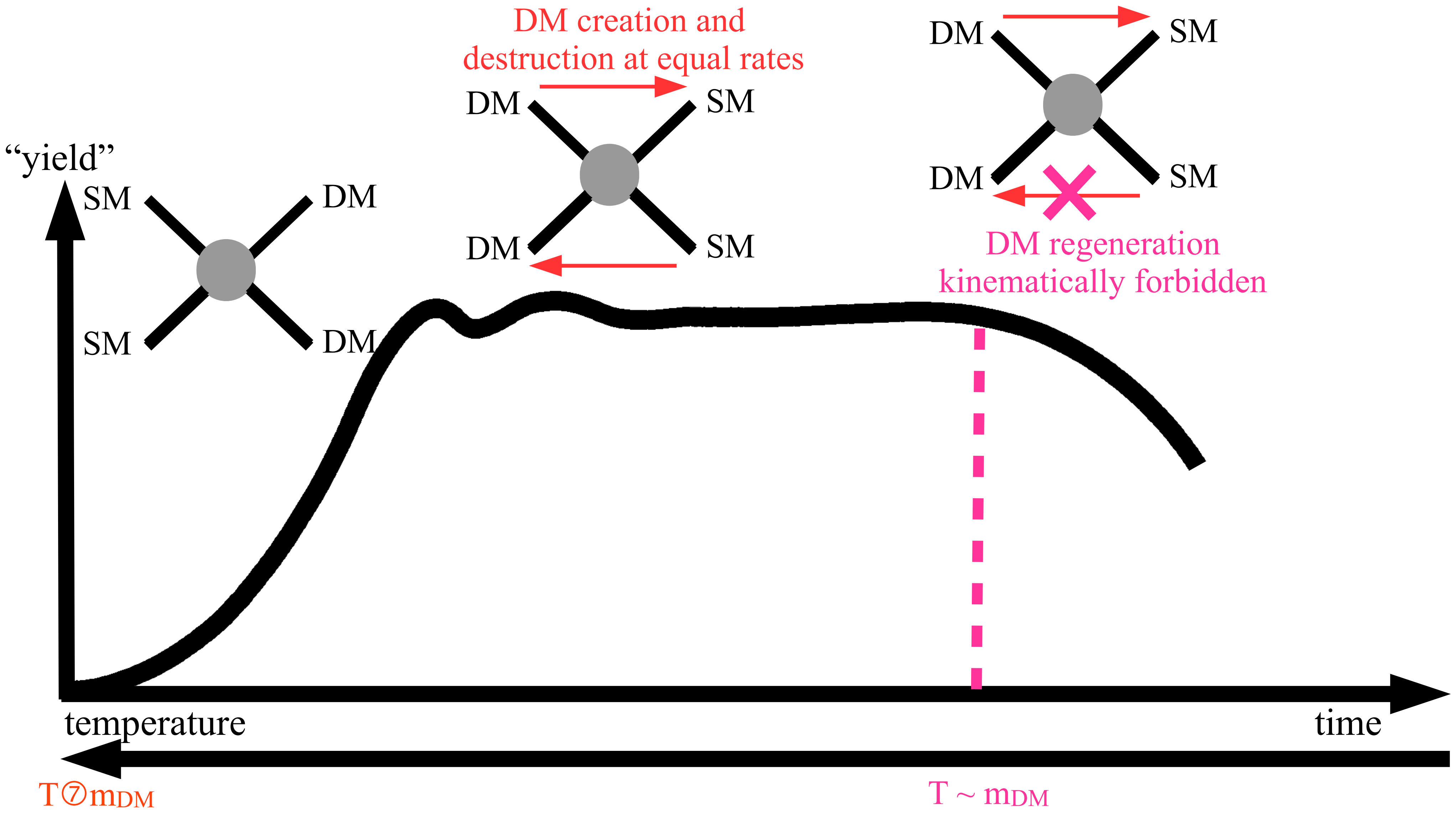


DM creation and destruction at equal rates

WIMP history (in a nutshell)



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DM regeneration kinematically forbidden

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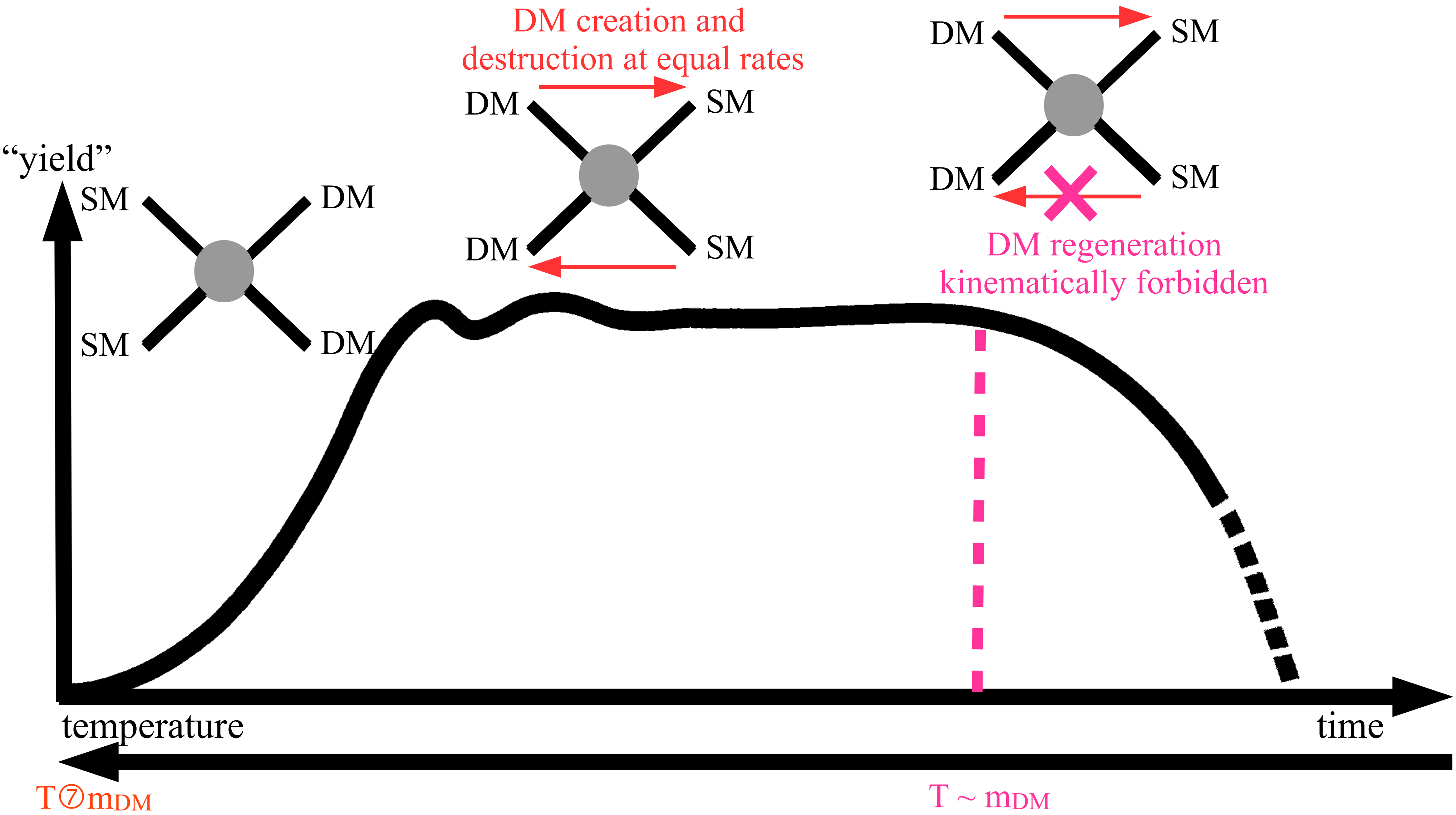

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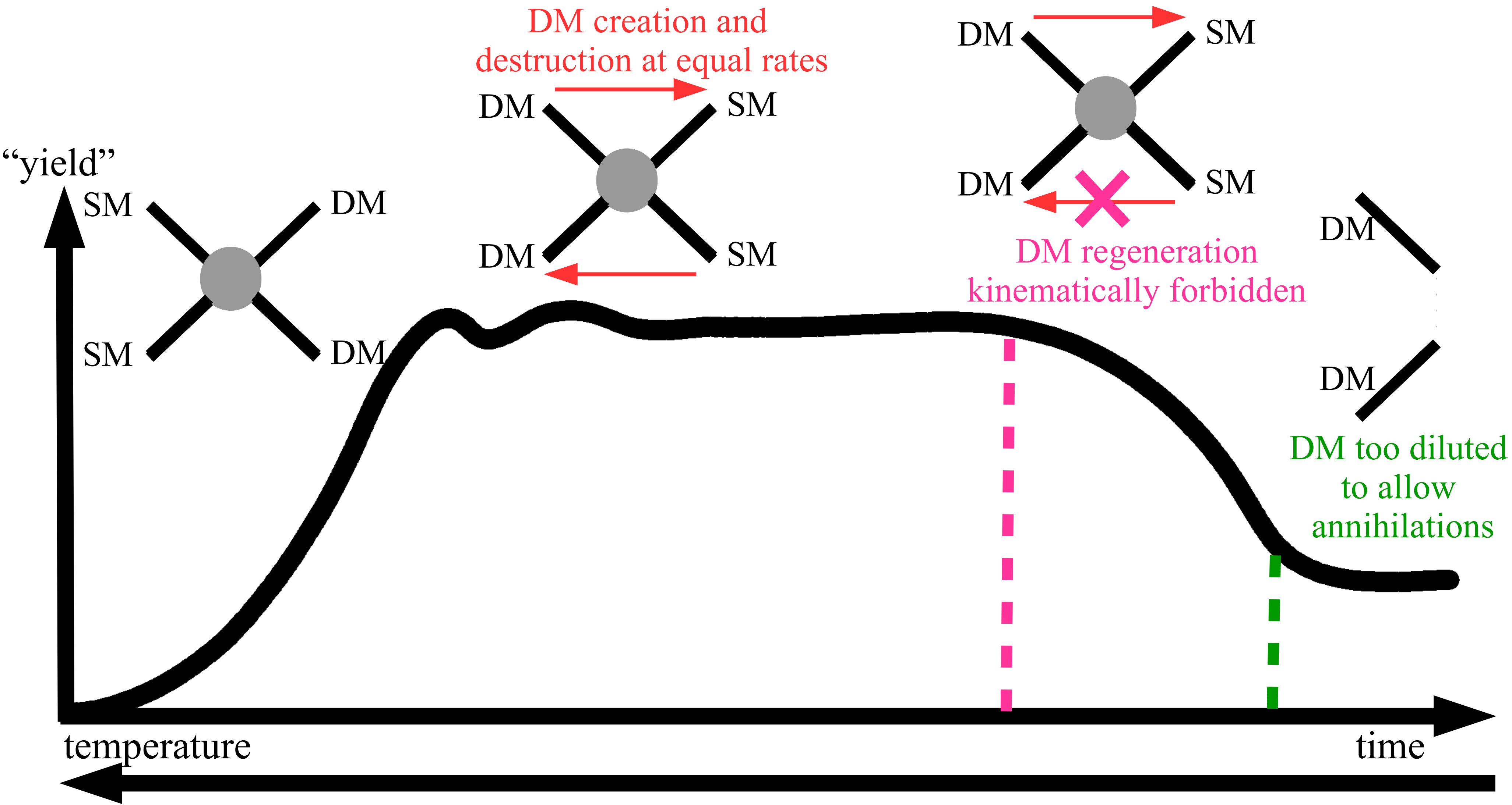

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DM too diluted to allow annihilations

T⑦m_{DM}

$T \sim m_{DM}$

$T \sim m_{DM}/20$

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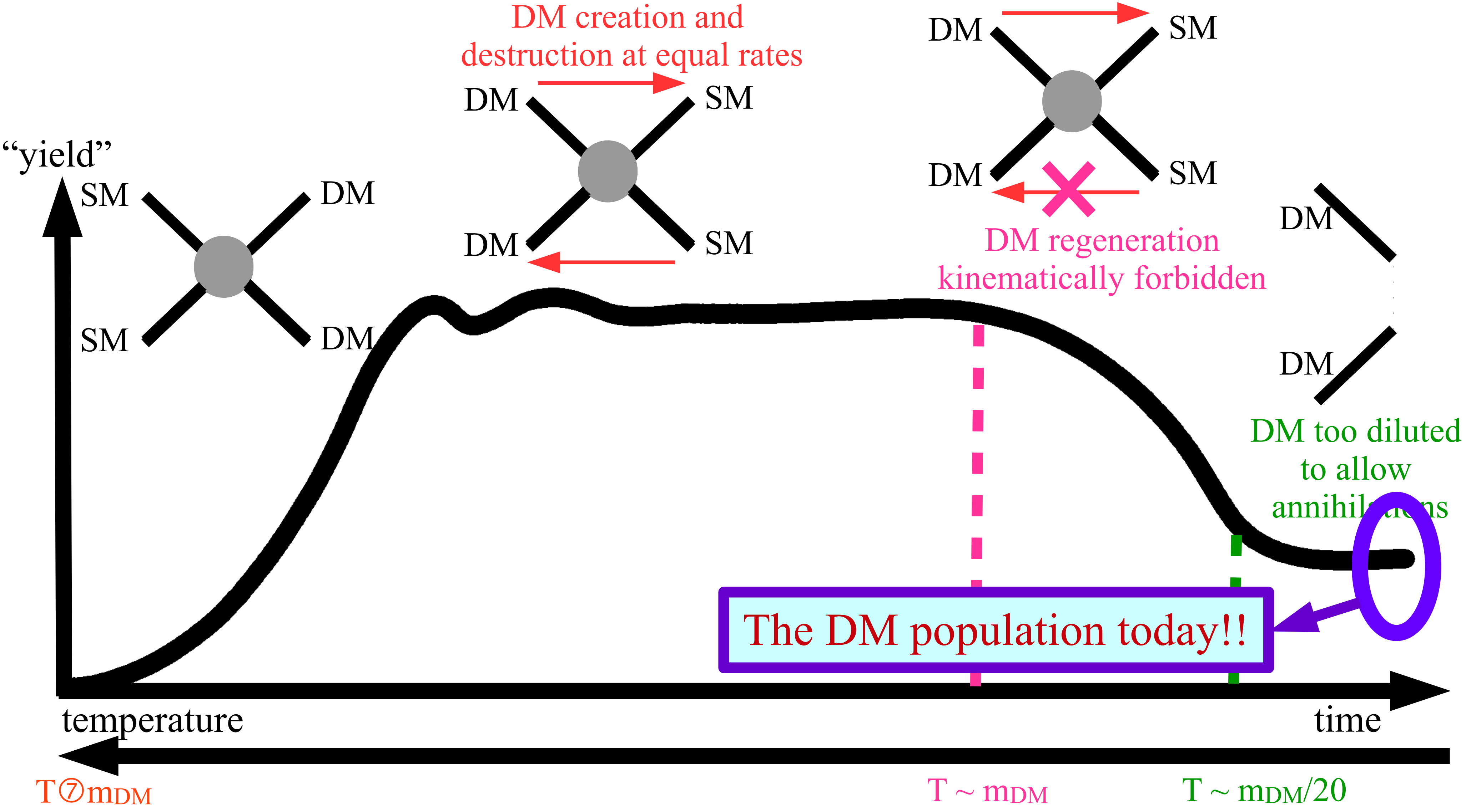

DM creation and destruction at equal rates

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The DM population today!!

T⑦m_{DM}

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$T \sim m_{DM}/20$

$$\begin{array}{c}\text{Fraction of the total}\\ \text{energy of the Universe}\\ \text{in the form of DM}\end{array} \simeq \frac{6 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Correct DM abundance (25% of the total energy of the Universe), if

$$\boxed{\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}$$

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1 pb = 10^{-36} cm^2.
Typical strength of
the weak interactions

Speed of light

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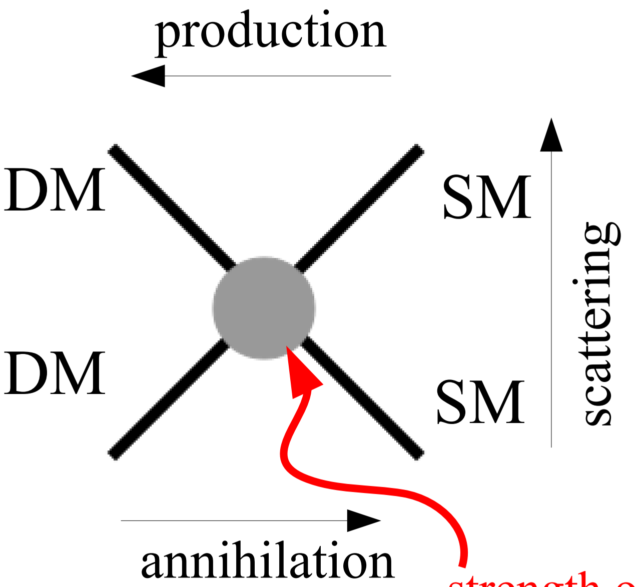

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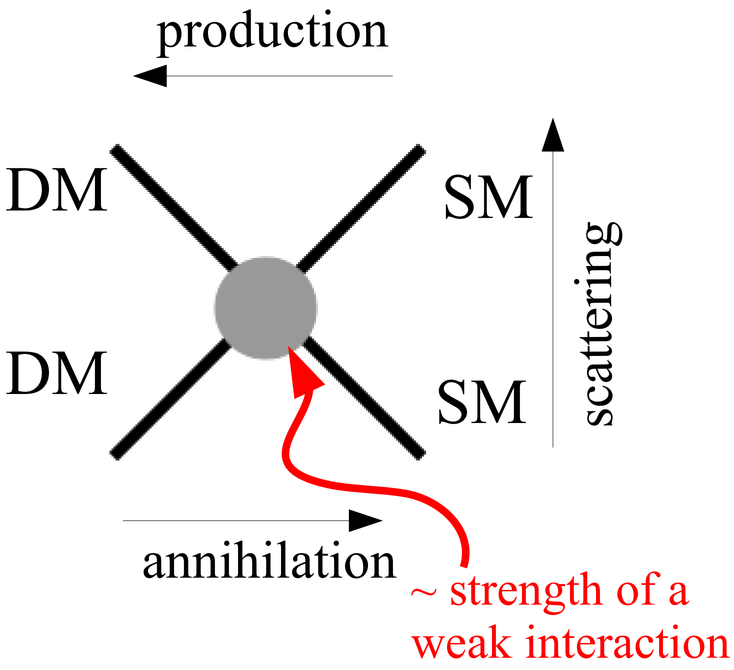

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The dark matter is a Weakly Interacting Massive Particle (WIMP)

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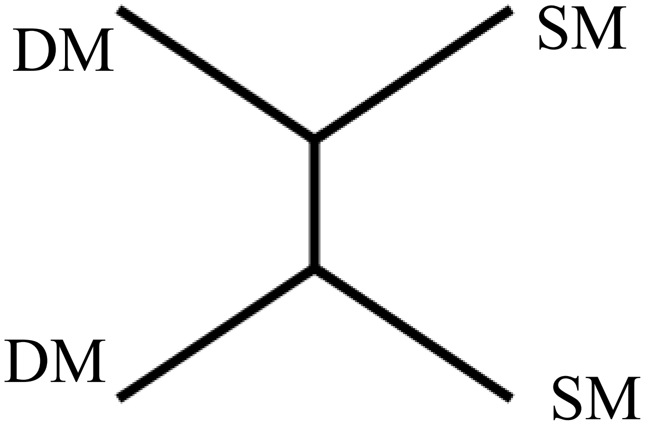


The dark matter is a Weakly Interacting Massive Particle (WIMP)

More numerology:

$$1\,\mathrm{pb} \simeq \frac{(0.1)^4}{(100\,\mathrm{GeV})^2} = \frac{\mathrm{coupling}^4}{\mathrm{mass}^2}$$

The freeze-out mechanism suggests that the WIMP has mass ~ a few GeV – a few TeV and a coupling with ordinary matter ~ 0.1 – 0.01

LUX

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

Fermi
Gamma-ray
Space Telescope

PaMeLa

PandaX

H E S S

Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

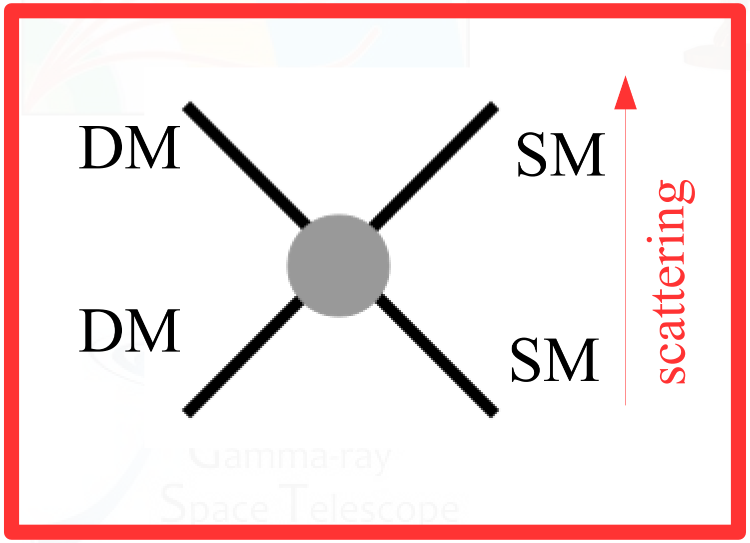
VERITAS

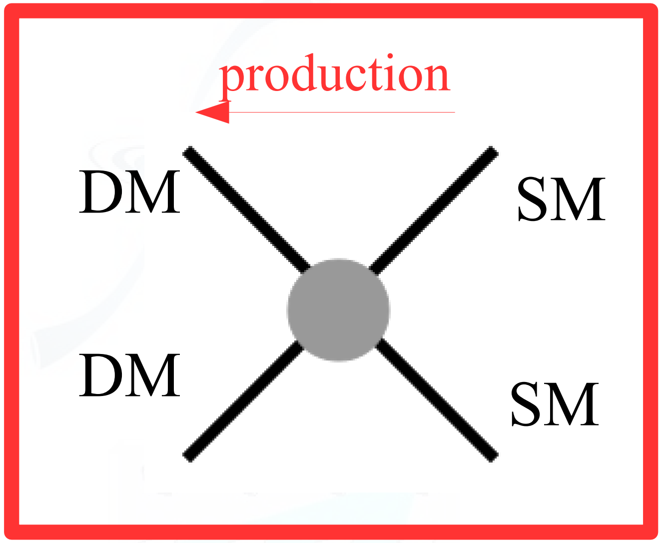
IceCube
SOUTH POLE NEUTRINO OBSERVATORY

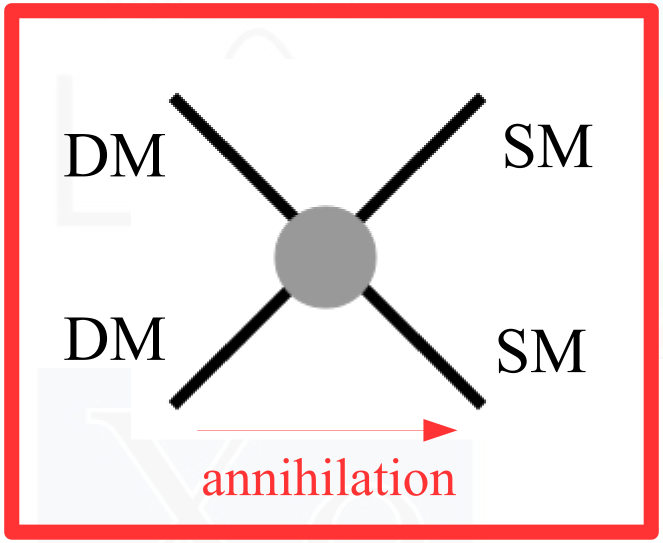
LUX

Xe
XENON
Dark Matter Project

PANDA X




production
DM
DM
SM
SM



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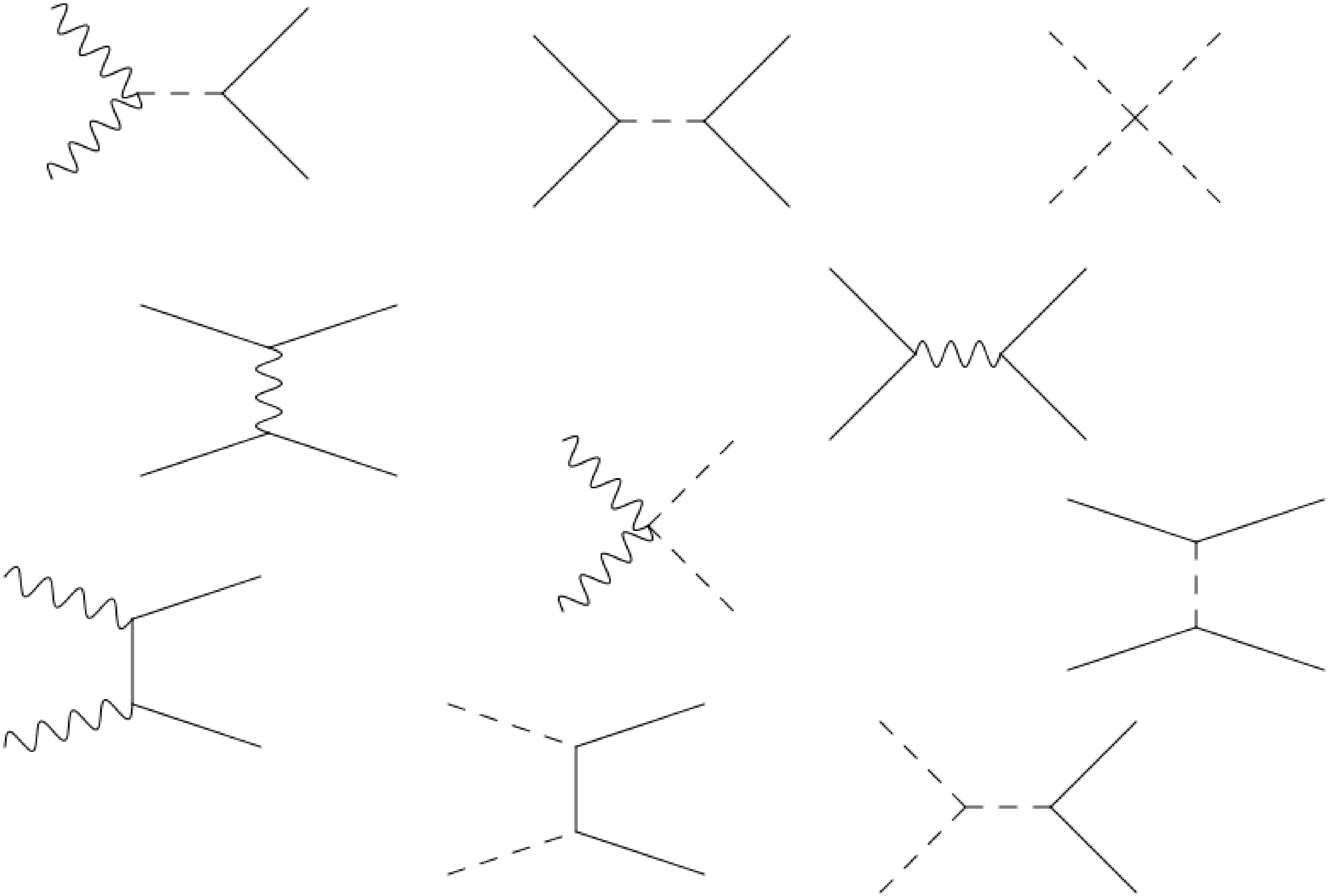
Many possible realizations of the effective interaction

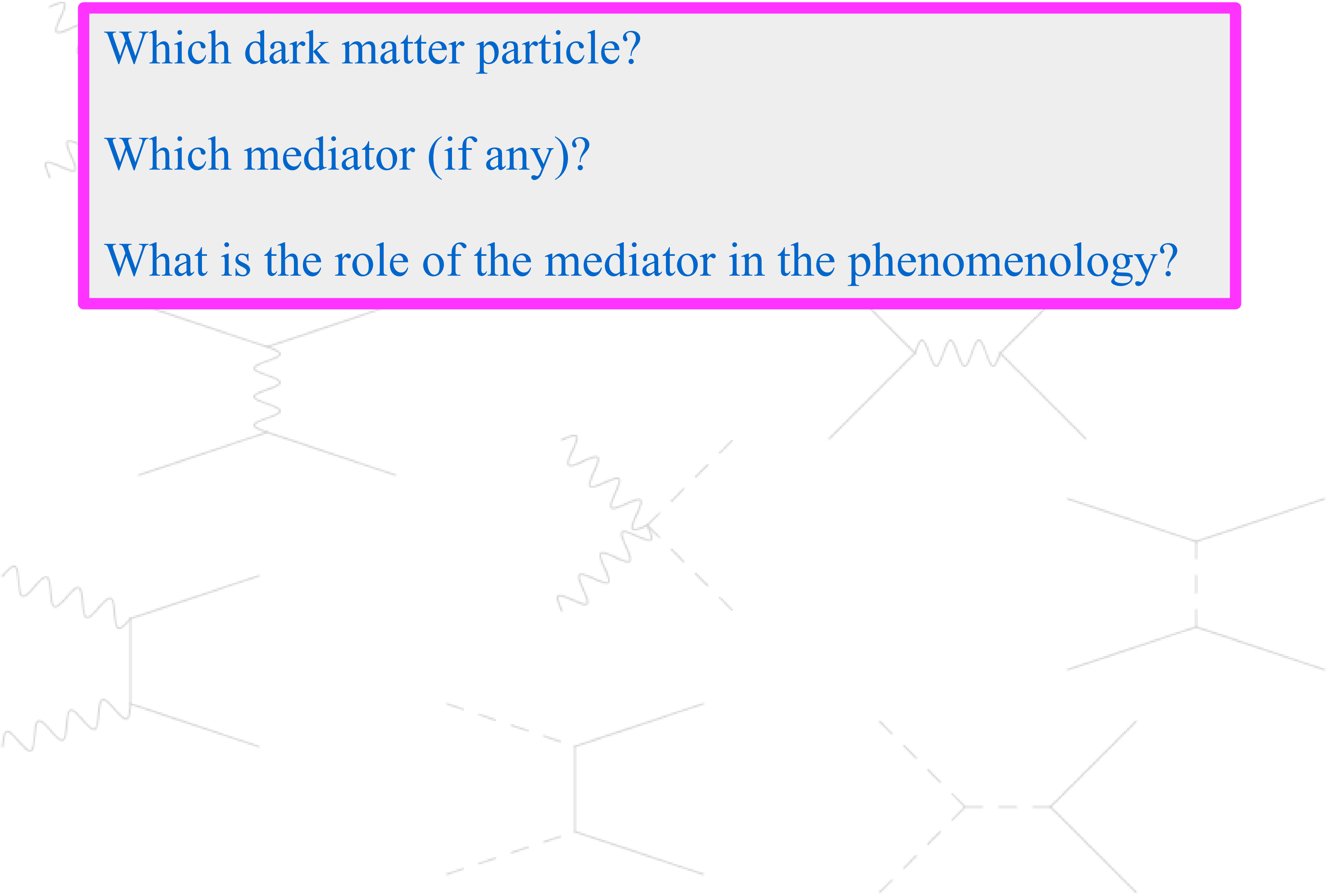


Many possible realizations of the effective interaction

Which dark matter particle?

Which mediator (if any)?

What is the role of the mediator in the phenomenology?



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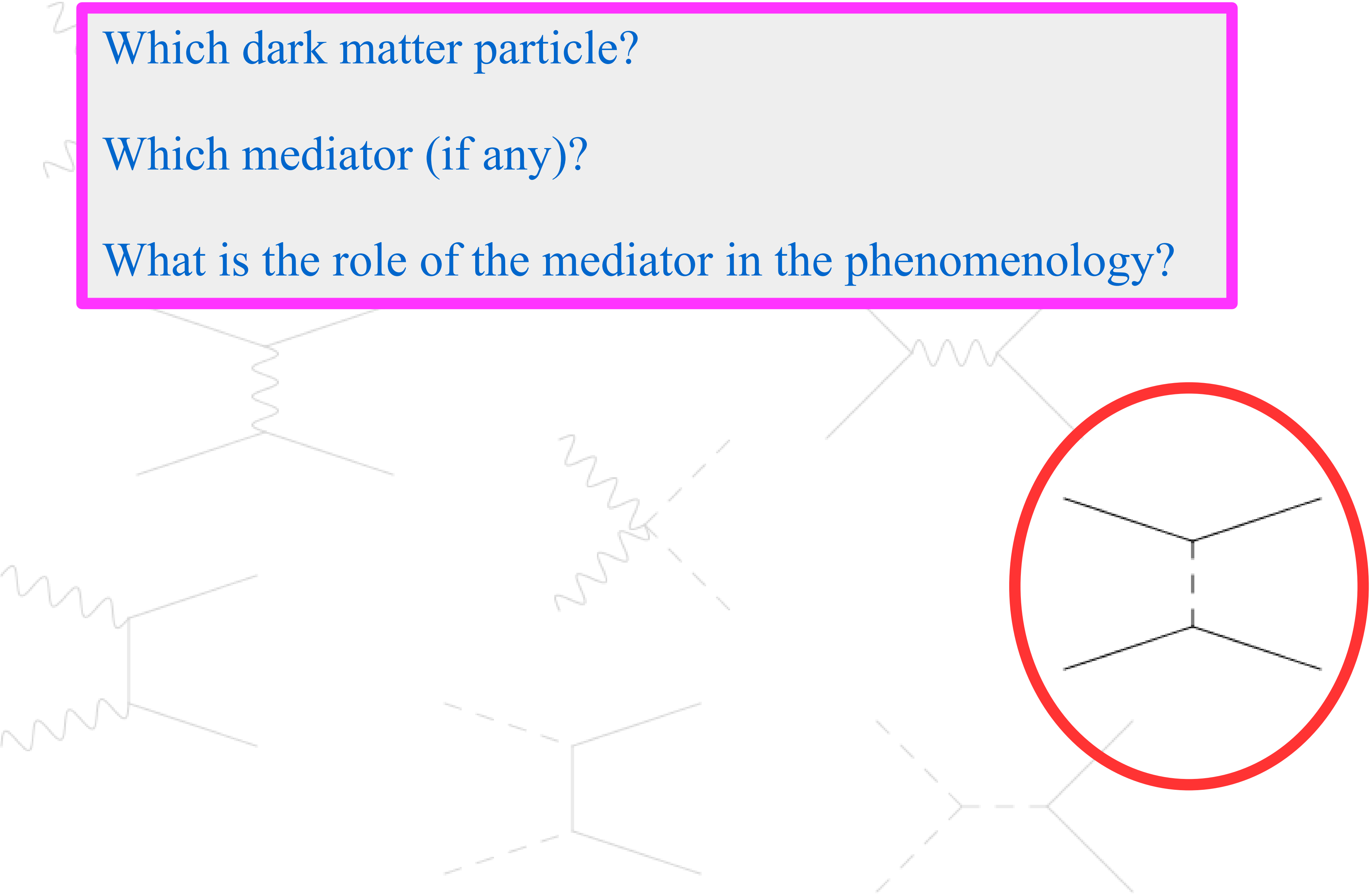


A toy dark matter model

We extend the Standard Model with two new particles;

χ, Majorana fermion, “Dark matter particle”.

η, complex scalar. “Mediator”.

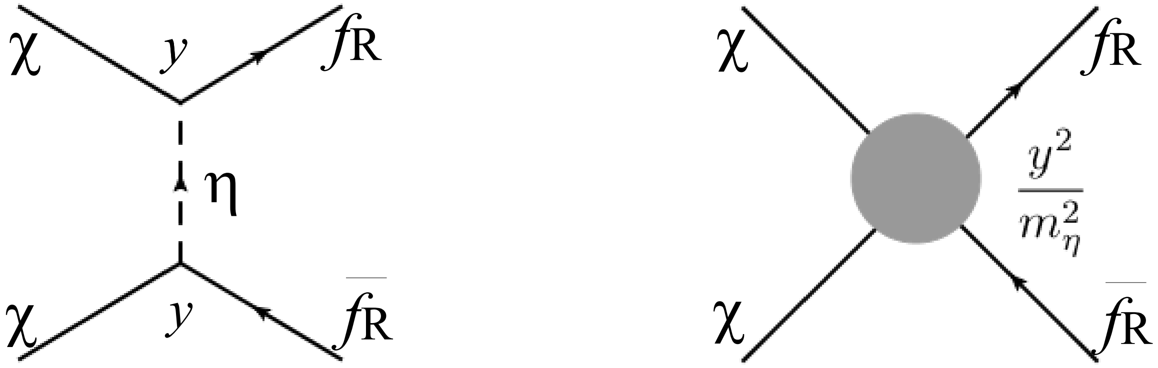
We assume:

1) χ and η are odd under a Z2 symmetry, while the SM particles are even.
2) χ is lighter than η ⇒ η is absolutely stable due to the Z2 symmetry.
3) χ is a singlet under the Standard Model gauge group.
4) η has quantum numbers that allow a Yukawa coupling of χ with one SM fermion (e.g. a right-handed fermion).

$$\begin{aligned}\mathcal{L}_{\rm int}^{\rm fermion} &= -y\bar{\chi} f_R \eta + \text{h.c.}\ , \\ \mathcal{L}_{\rm int}^{\rm scalar} &= -\lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta)\ .\end{aligned}$$

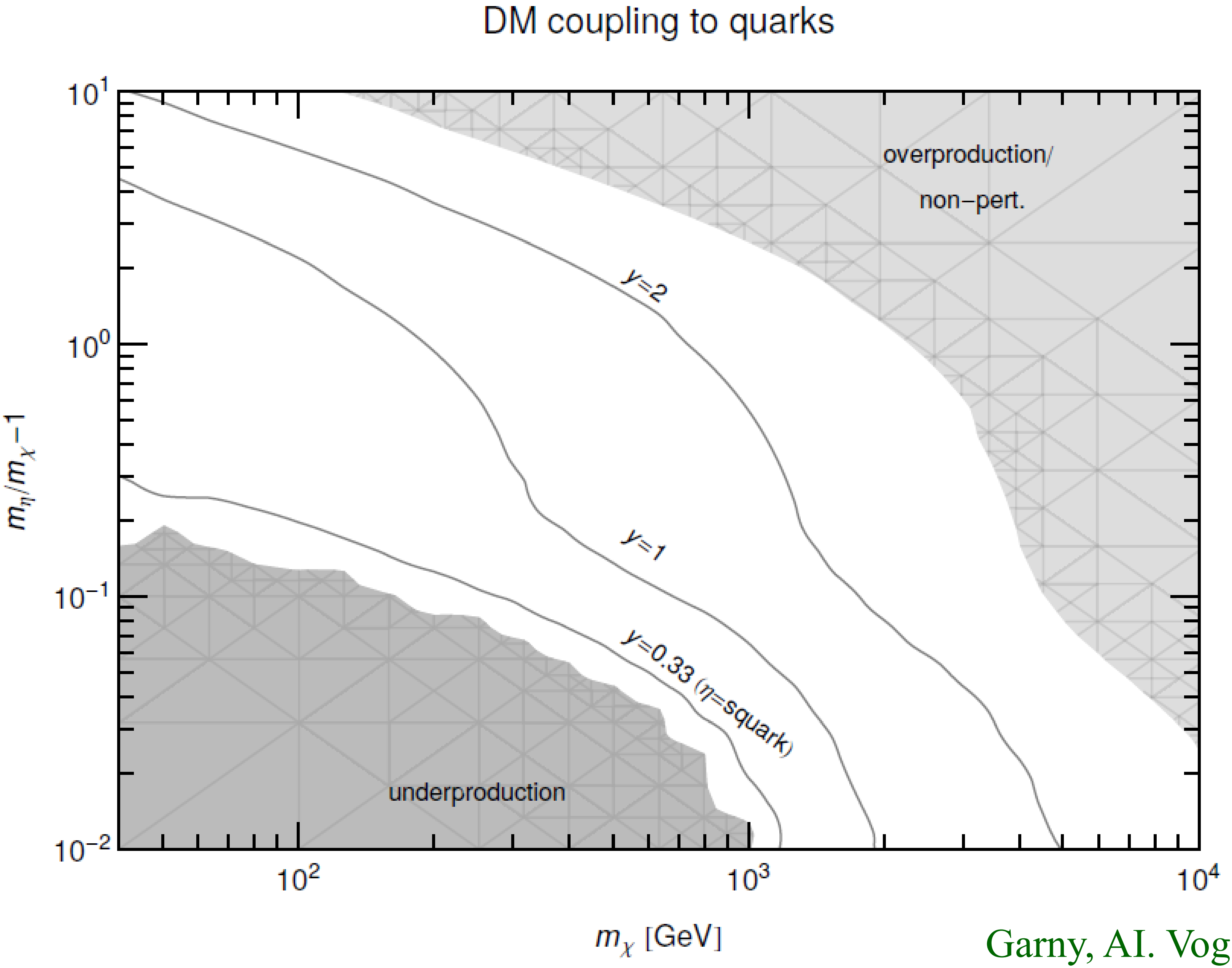
A toy dark matter model

For $m_\eta/m_\chi << 1$, the interaction can be described by a contact term.

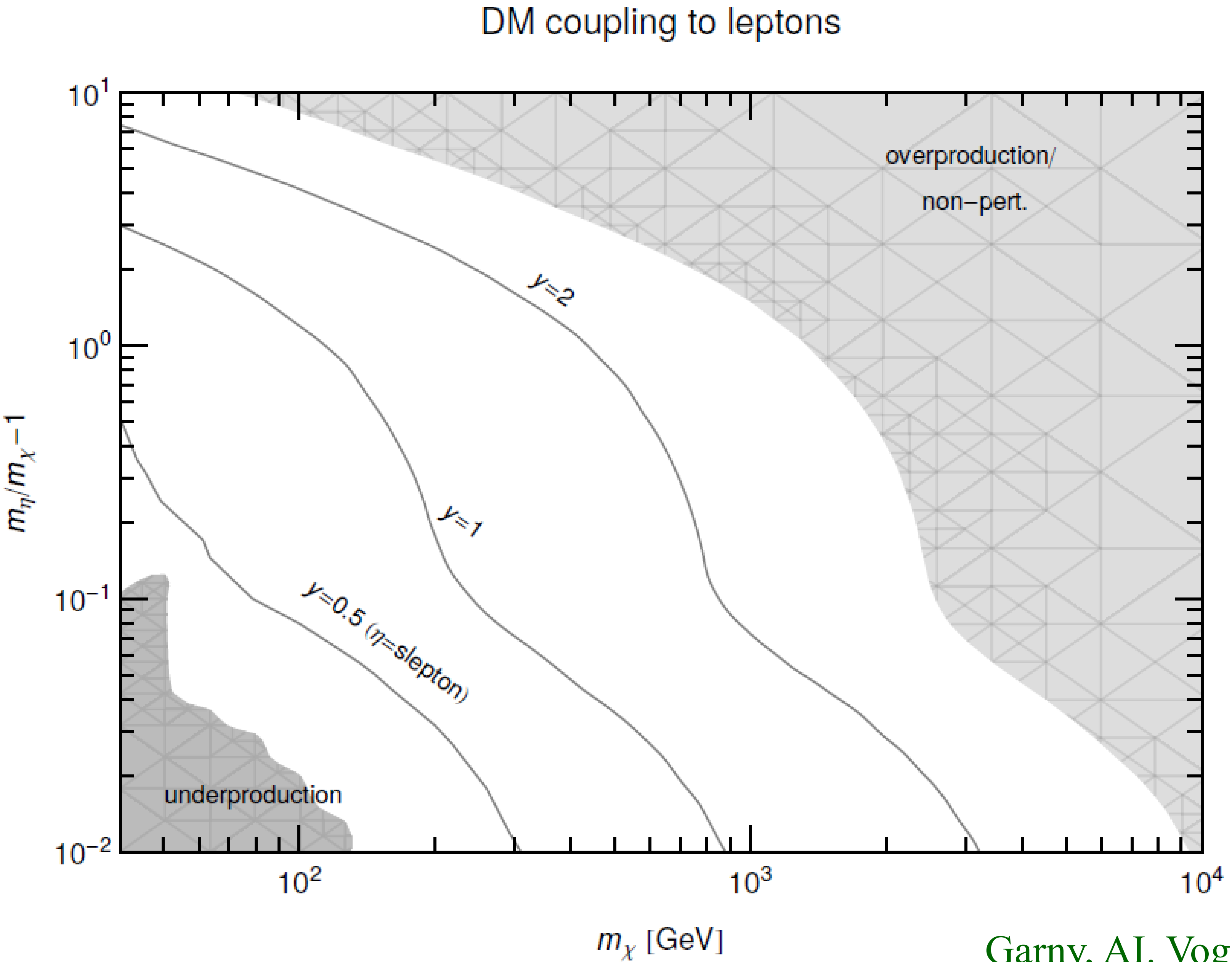


$$\Omega_\chi h^2 \simeq \frac{0.12}{N_c}\left(\frac{1.85}{y}\right)^4\left(\frac{m_\eta}{500\,\mathrm{GeV}}\right)^4\left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{-2}$$

For every dark matter mass, there is always a choice of the coupling and the mediator mass that reproduces the observed DM abundance.



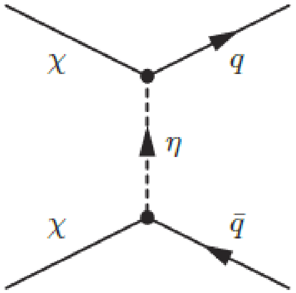
Garny, AI. Vogl,
1503.01500



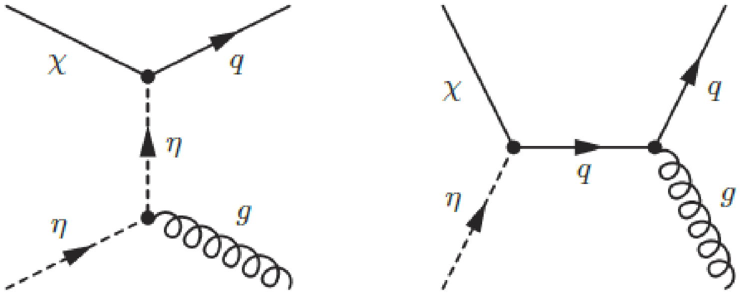
Garny, AI. Vogl,
1503.01500

If the mediator and the dark matter have comparable masses, the mediator is present in the thermal plasma during the epoch of freeze-out.

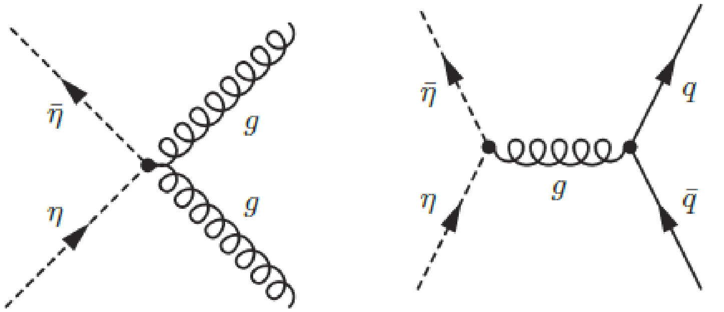
New channels deplete the number of dark matter particles, via “coannihilations”, and lower the dark matter relic abundance. Griest, Seckel '91



$\sim y^4$



$\sim y^2 g^2$



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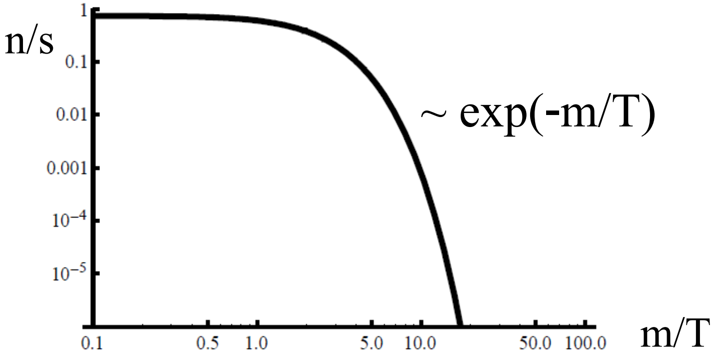

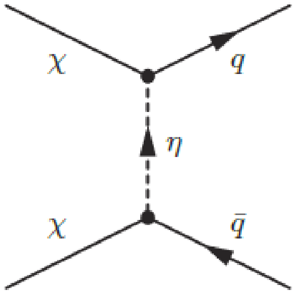

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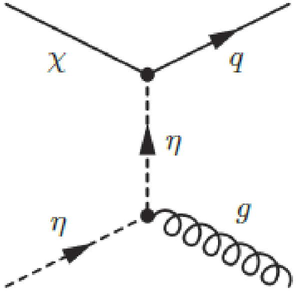

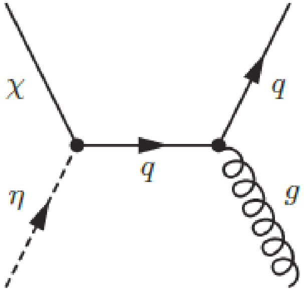

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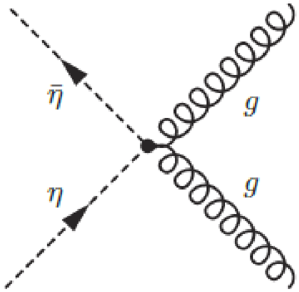
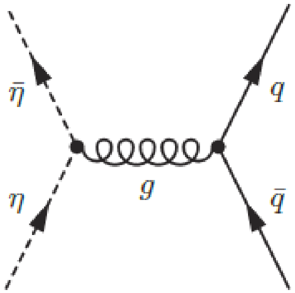
Rate compared to $\chi\chi \to q\bar{q}$ suppressed by

$$\frac{g^2}{y^2}\, e^{-\frac{(m_\eta - m_\chi)}{T}}$$





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If the mediator and the dark matter have comparable masses, the mediator is present in the thermal plasma during the epoch of freeze-out.

New channels deplete the number of dark matter particles, via "coannihilations", and lower the dark matter relic abundance.

$$\sigma_{\rm eff} v \sim \underbrace{\sigma_{\chi\chi} v}_{\frac{y^4}{m_\chi^2} C_{\chi\chi}} + \underbrace{\sigma_{\chi\eta} v \, e^{-\frac{(m_\eta - m_\chi)}{T}}}_{\frac{y^2 g^2}{m_\chi^2} C_{\chi\eta}} + \underbrace{\sigma_{\eta\eta} v \, e^{-\frac{2(m_\eta - m_\chi)}{T}}}_{\frac{g^4}{m_\chi^2} C_{\eta\eta}}$$

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle} \sim \frac{m_\chi^2}{y^4 \langle C_{\chi\chi} \rangle + y^2 g^2 \langle C_{\chi\eta} \rangle + g^4 \langle C_{\eta\eta} \rangle}$$

If the Boltzmann-suppression factor is not very big ($C_{\eta\eta} \neq 0$), the ηη annihilations can lower the DM density below the measured value.

Connecting dark matter and neutrino masses?

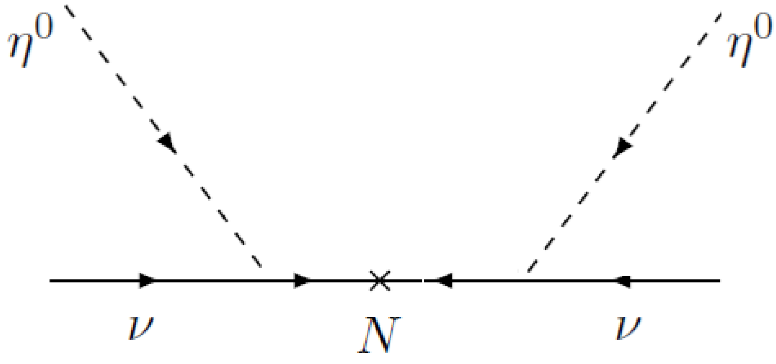
We extend the Standard Model with two new particles;

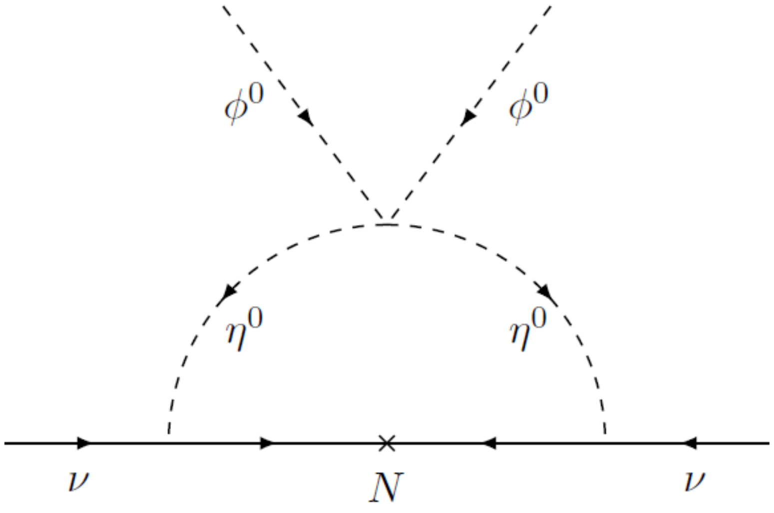
χ, Majorana fermion. Singlet under the SM gauge group. Odd under Z2

η, complex scalar. Same quantum numbers as the SM Higgs. Odd under Z2

$$\mathcal{L}_{\rm int}^{\rm fermion} = -y\overline{L}\eta\chi + {\rm h.c.}$$

$$-\mathcal{L}_{\rm int}^{\rm scalar} = \lambda_3(H^\dagger H)(\eta^\dagger \eta) + \lambda_4(H^\dagger \eta)(\eta^\dagger H) + \frac{1}{2}\lambda_5(\eta^\dagger H)(\eta^\dagger H)$$





$$\mathcal{M}_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{Y_{ik}Y_{jk}M_k}{m_0^2 - M_k^2}\left[1 - \frac{M_k^2}{m_0^2 - M_k^2}\log\frac{m_0^2}{M_k^2}\right]$$

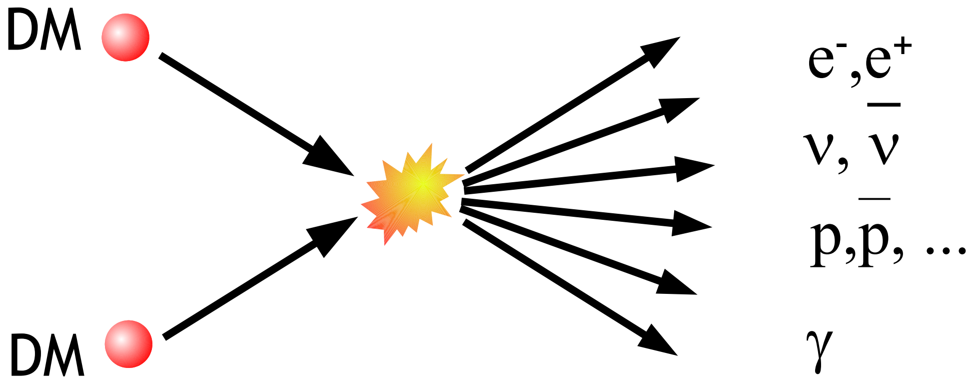
Tao' 96
Ma' 06

Indirect

Dark Matter

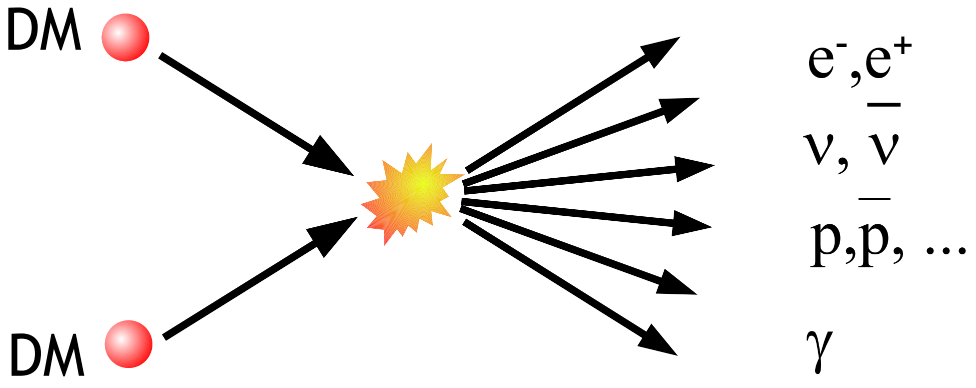
Searches

Indirect dark matter searches



- Dark matter particles annihilate into ordinary particles, such as electrons and positrons, antiprotons, neutrinos, photons…

Indirect dark matter searches



DM

DM

e^-,e^+

$\nu, \bar{\nu}$

$p,\bar{p}$, ...

γ

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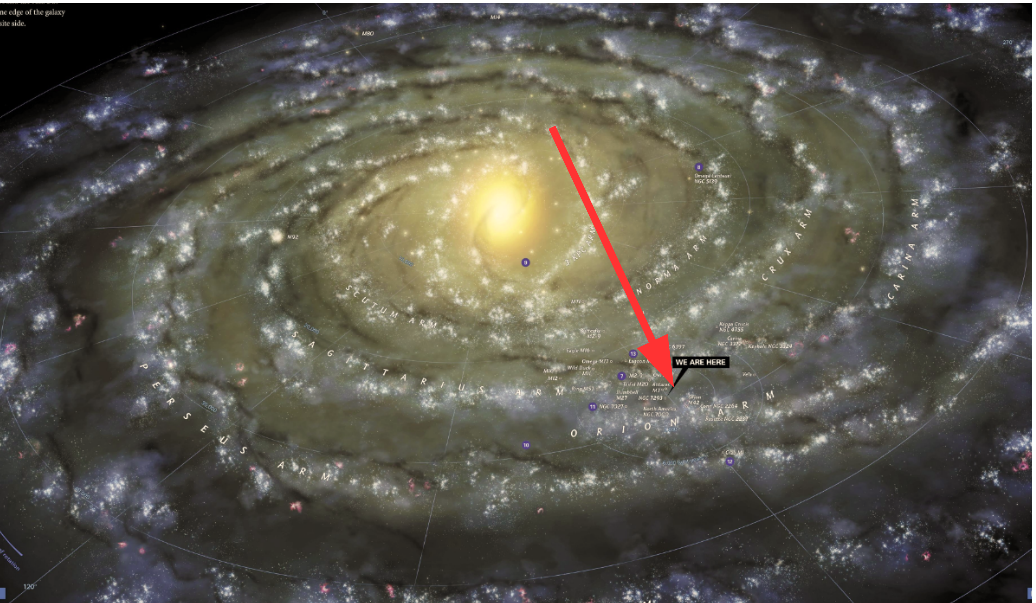
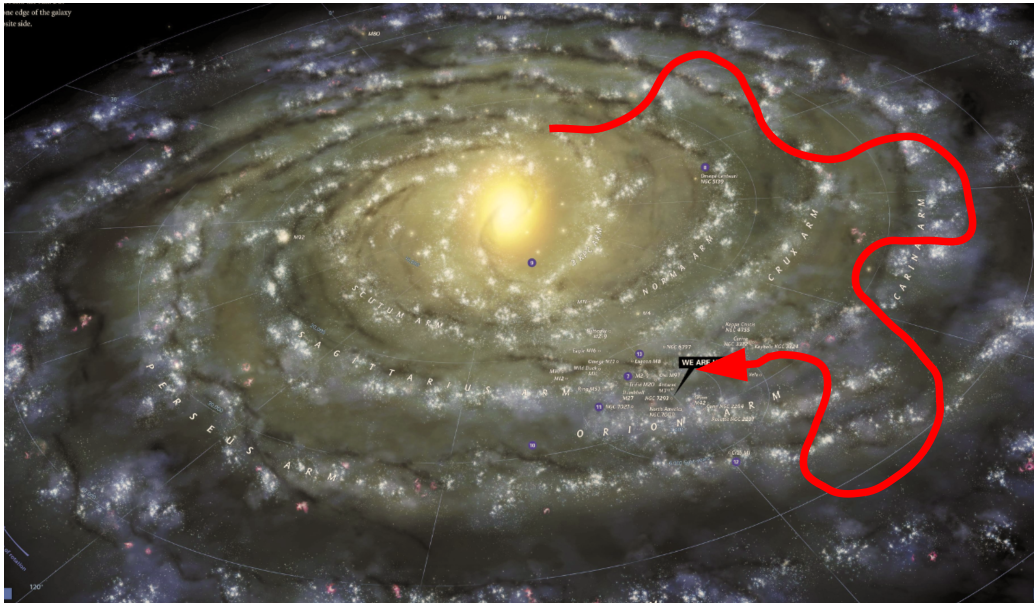
- Neutrinos propagate in the galaxy in straight lines practically without losing energy (in contrast to charged particles).





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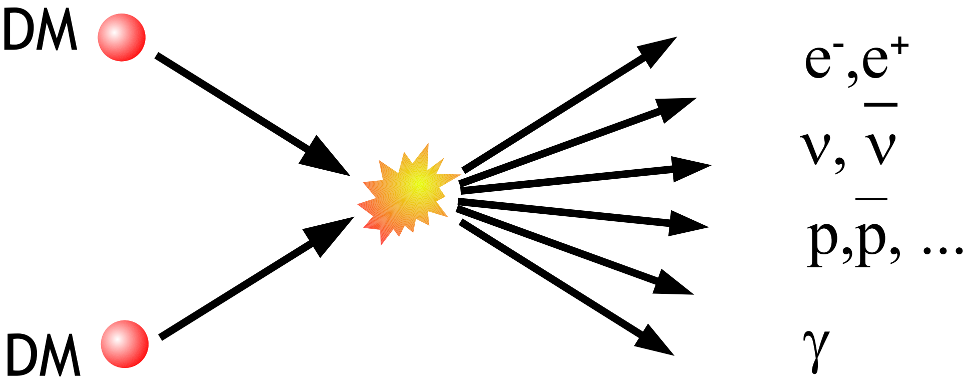

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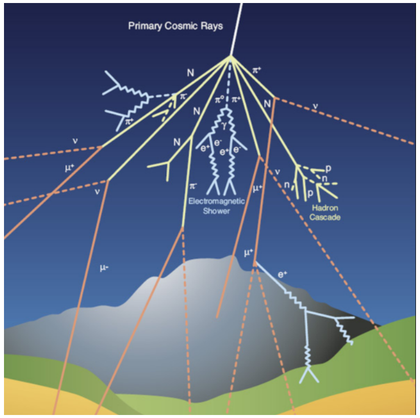

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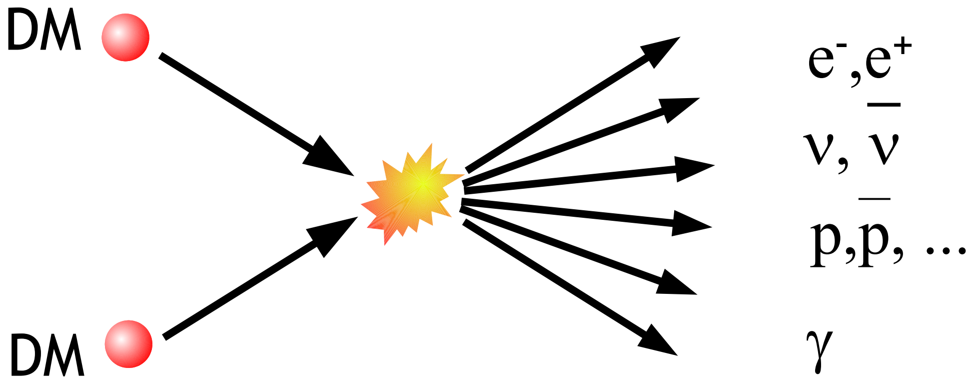

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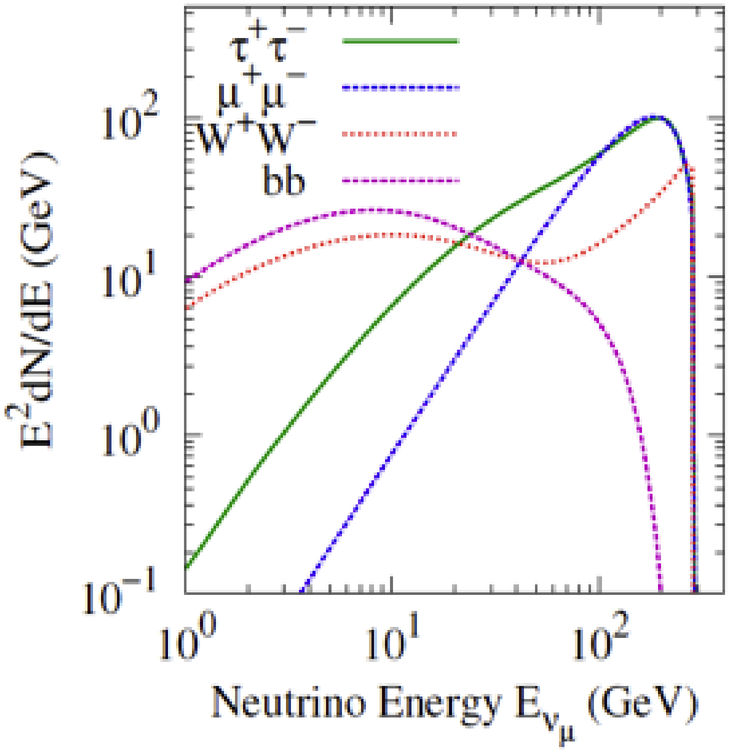
- Neutrinos from DM annihilations arrive to the detector together with neutrinos produced in conventional processes (primarily collisions of cosmic rays with the Earth's atmosphere).
- The existence of dark matter can then be inferred if there is a significant excess in the fluxes compared to the expected backgrounds.

Probing the annihilation cross-section

Neutrinos from dark matter annihilations in the Milky Way halo

$$\frac{dJ_{\rm halo}}{dE_\nu} = \frac{1}{4\pi}\underbrace{\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\nu^f}{dE_\nu}B_f\right]}_{\substack{\text{Source term}\\ \text{(particle physics)}}} \times \underbrace{\int_{\rm l.o.s.}\rho^2(\vec{l})\,d\vec{l}}_{\substack{\text{Line-of-sight integral}\\ \text{(astrophysics)}}}$$



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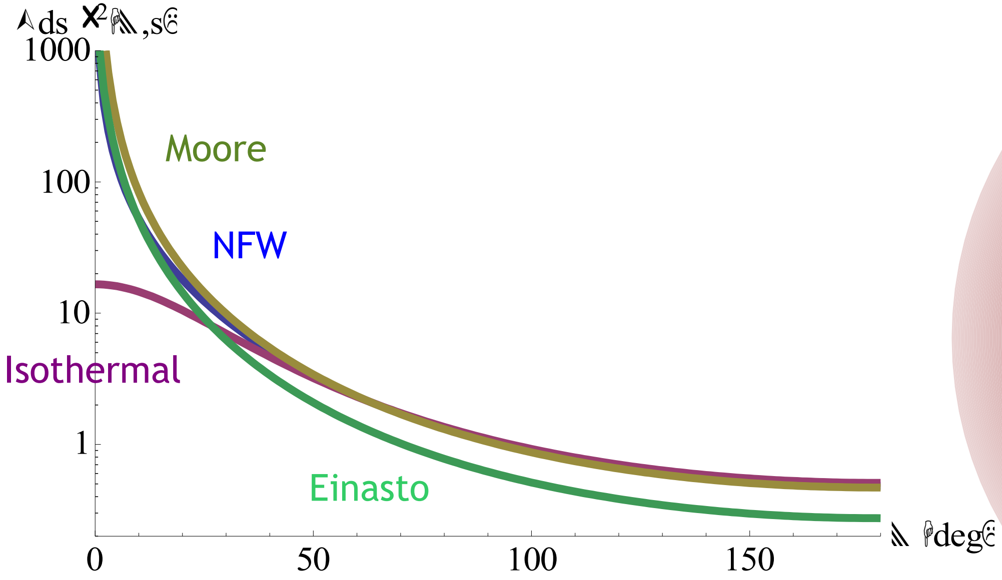

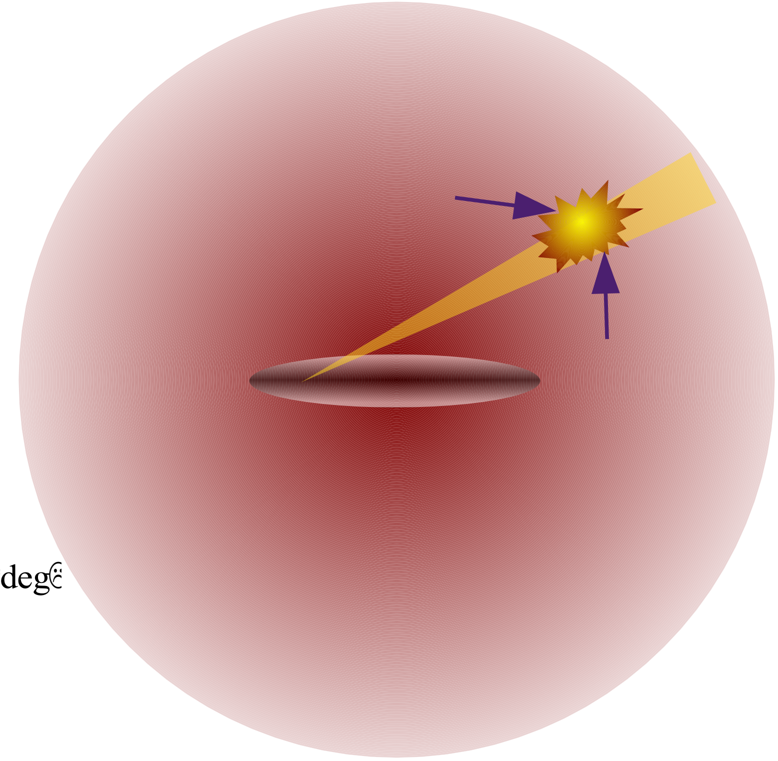

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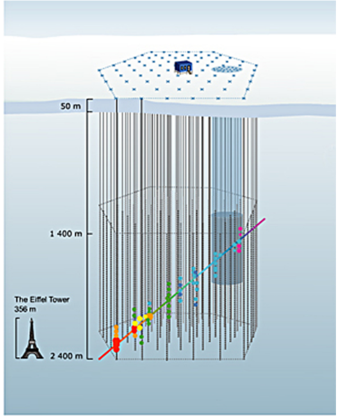
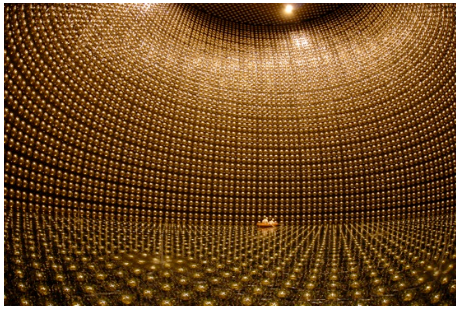
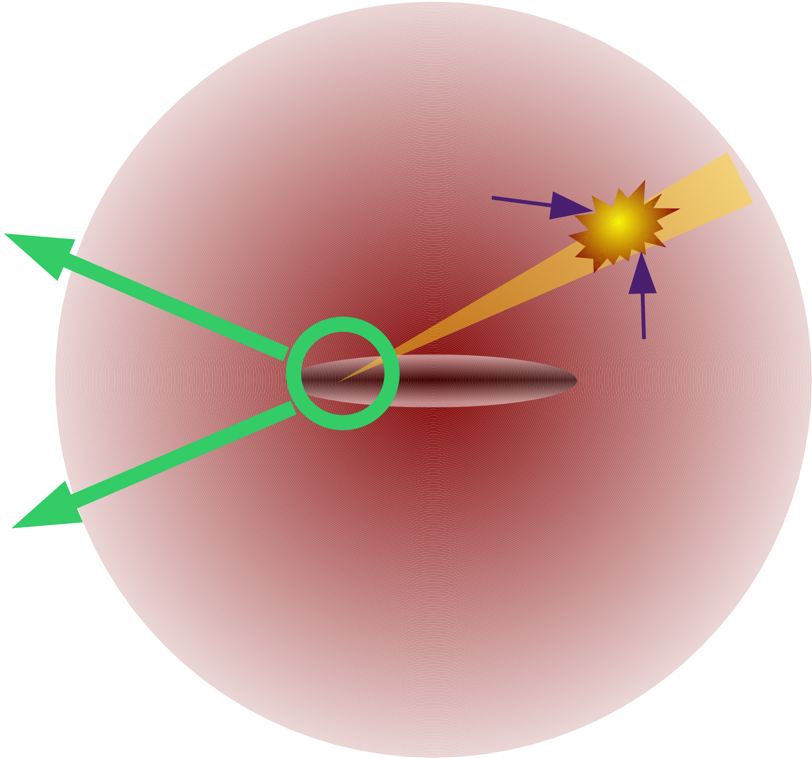
IceCube

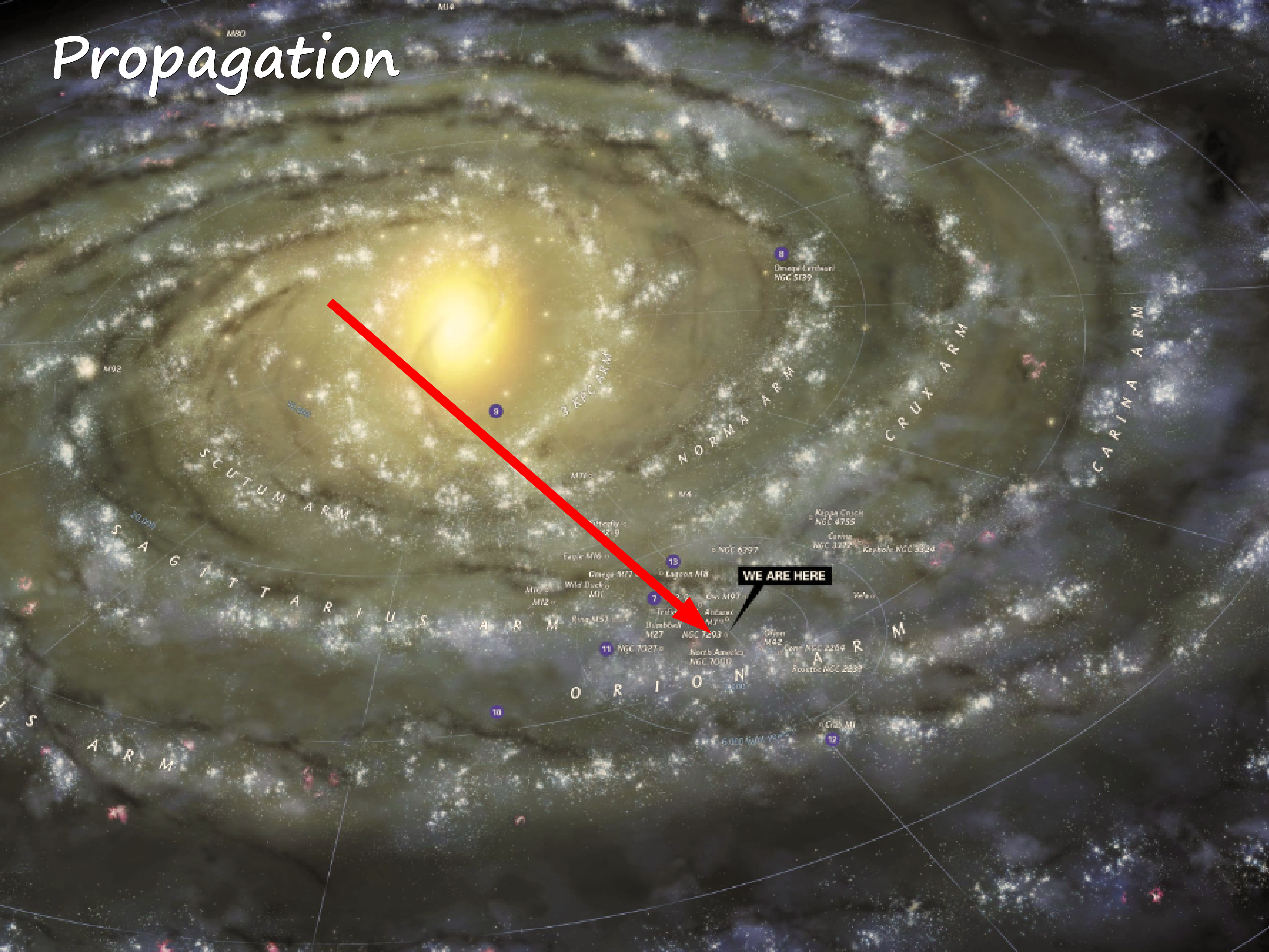


SuperK



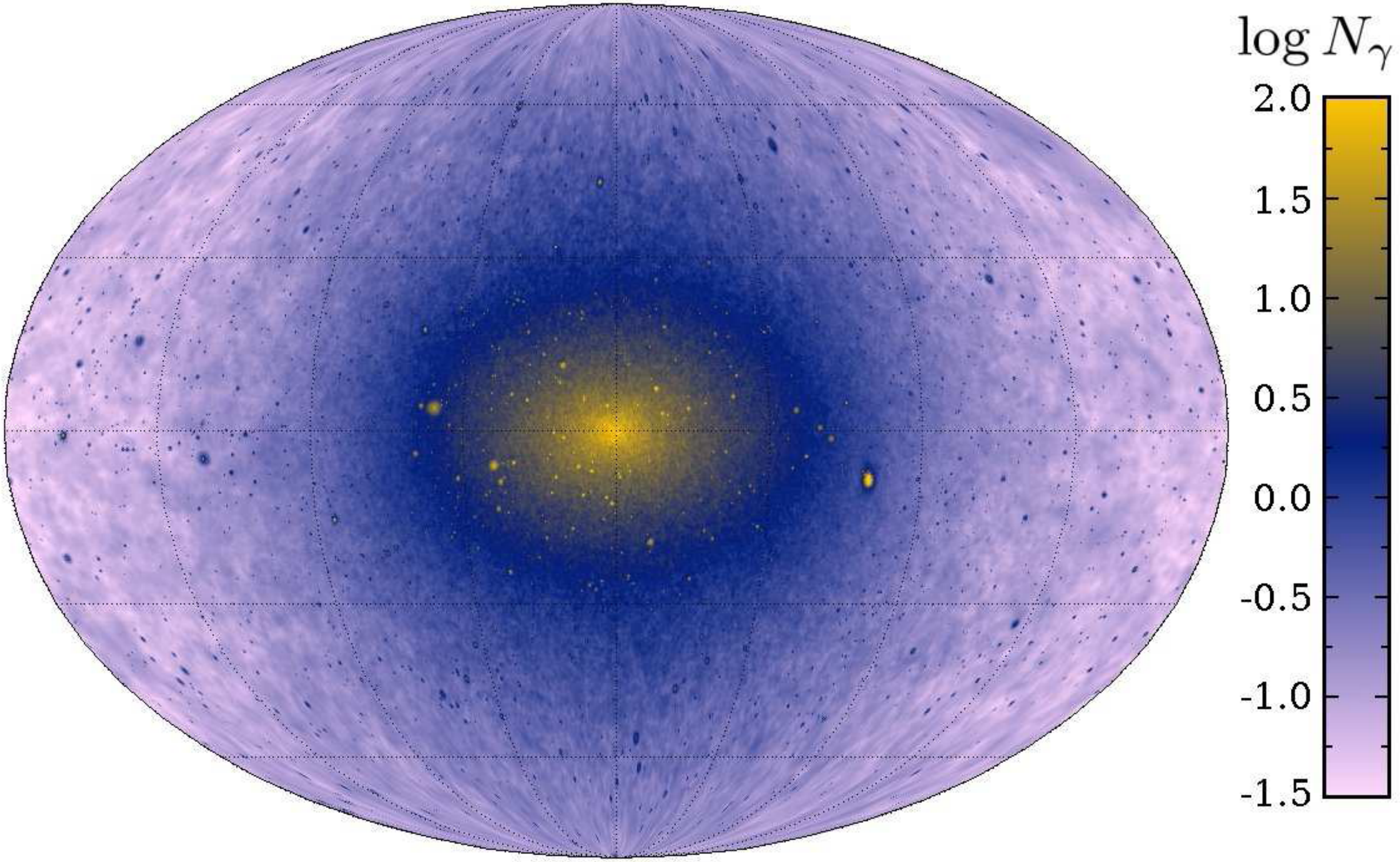


Propagation



Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

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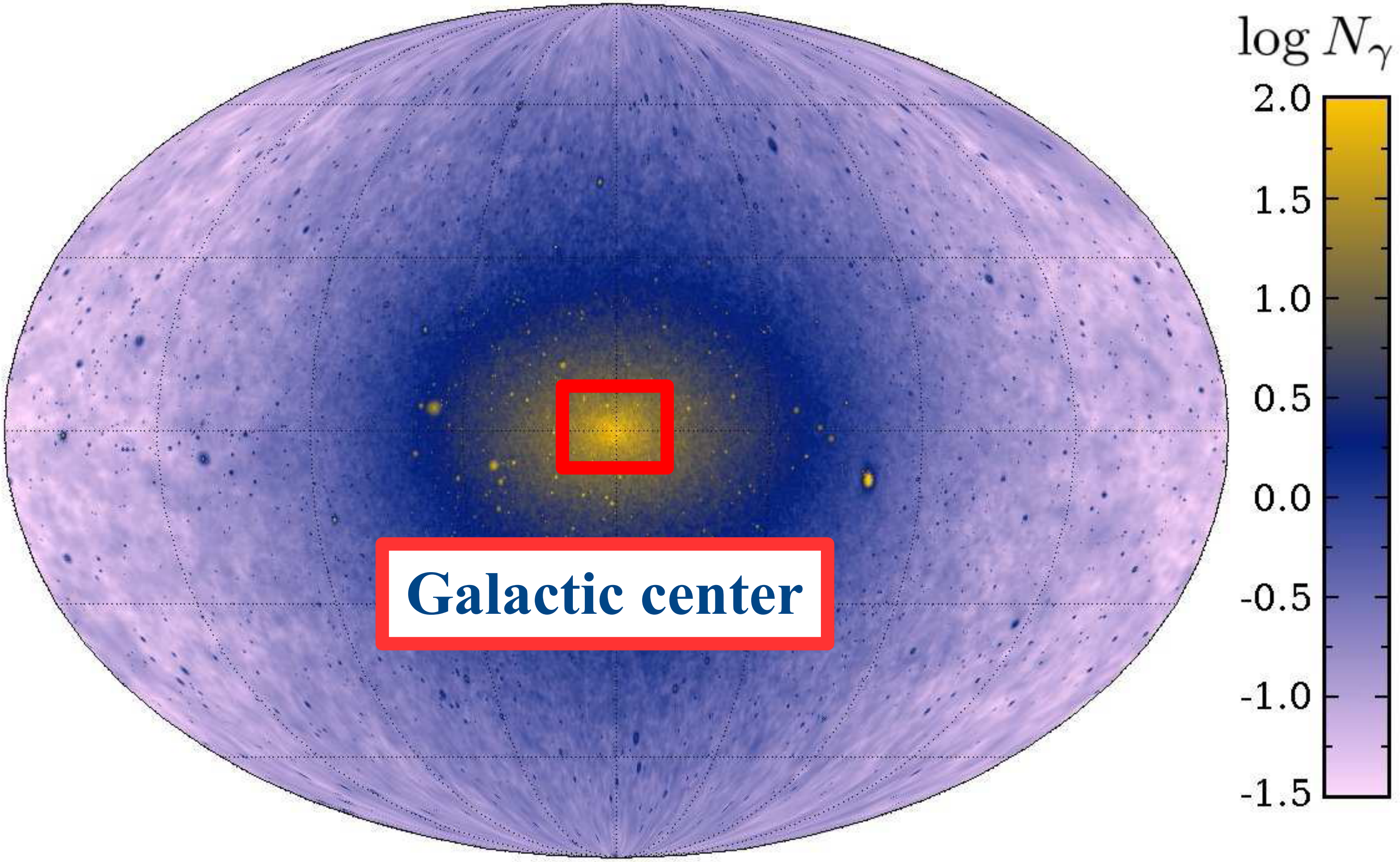

Galactic center

Kuhlen, Diemand, Madau

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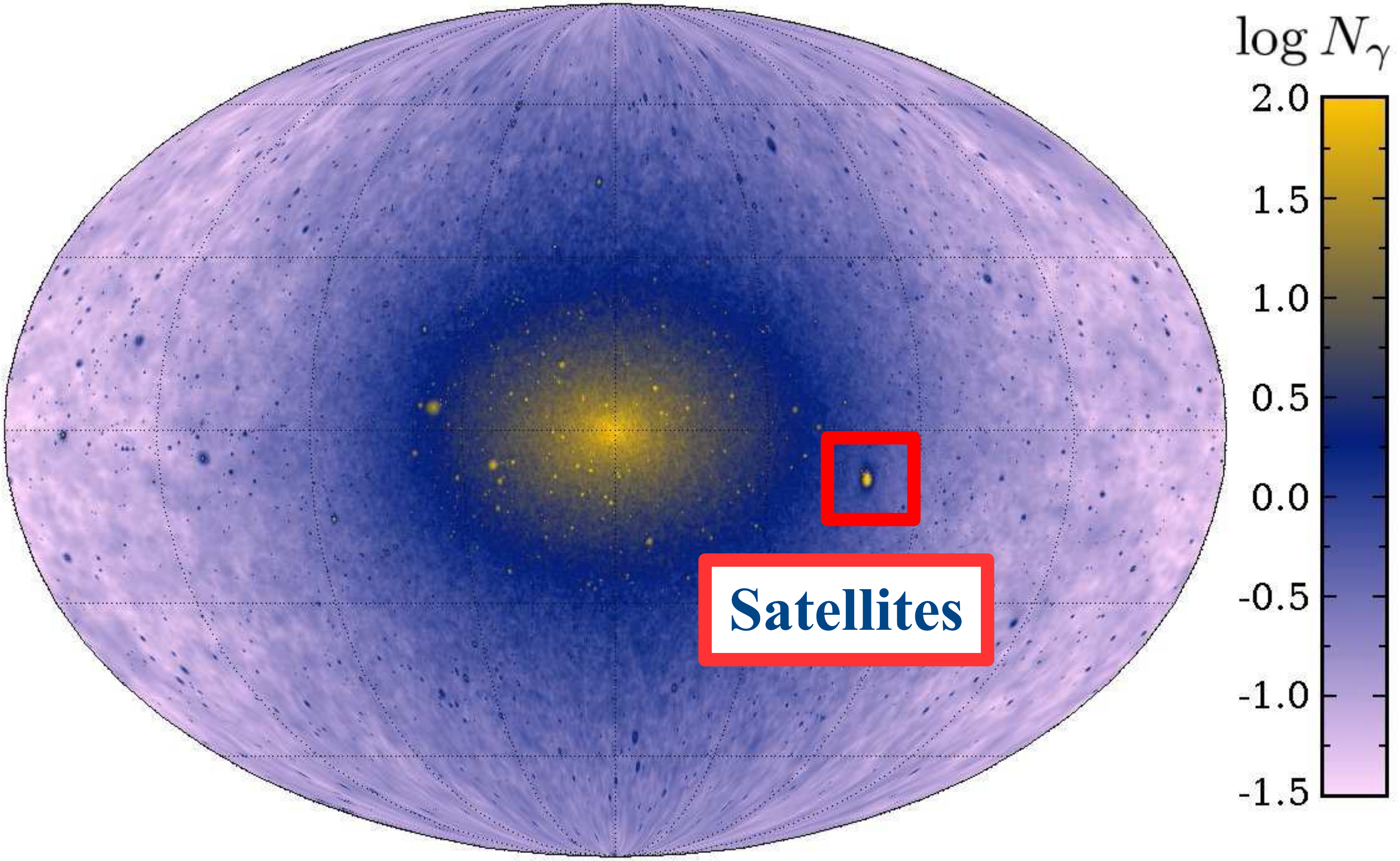
Baltz et al.
arXiv:0806.2911

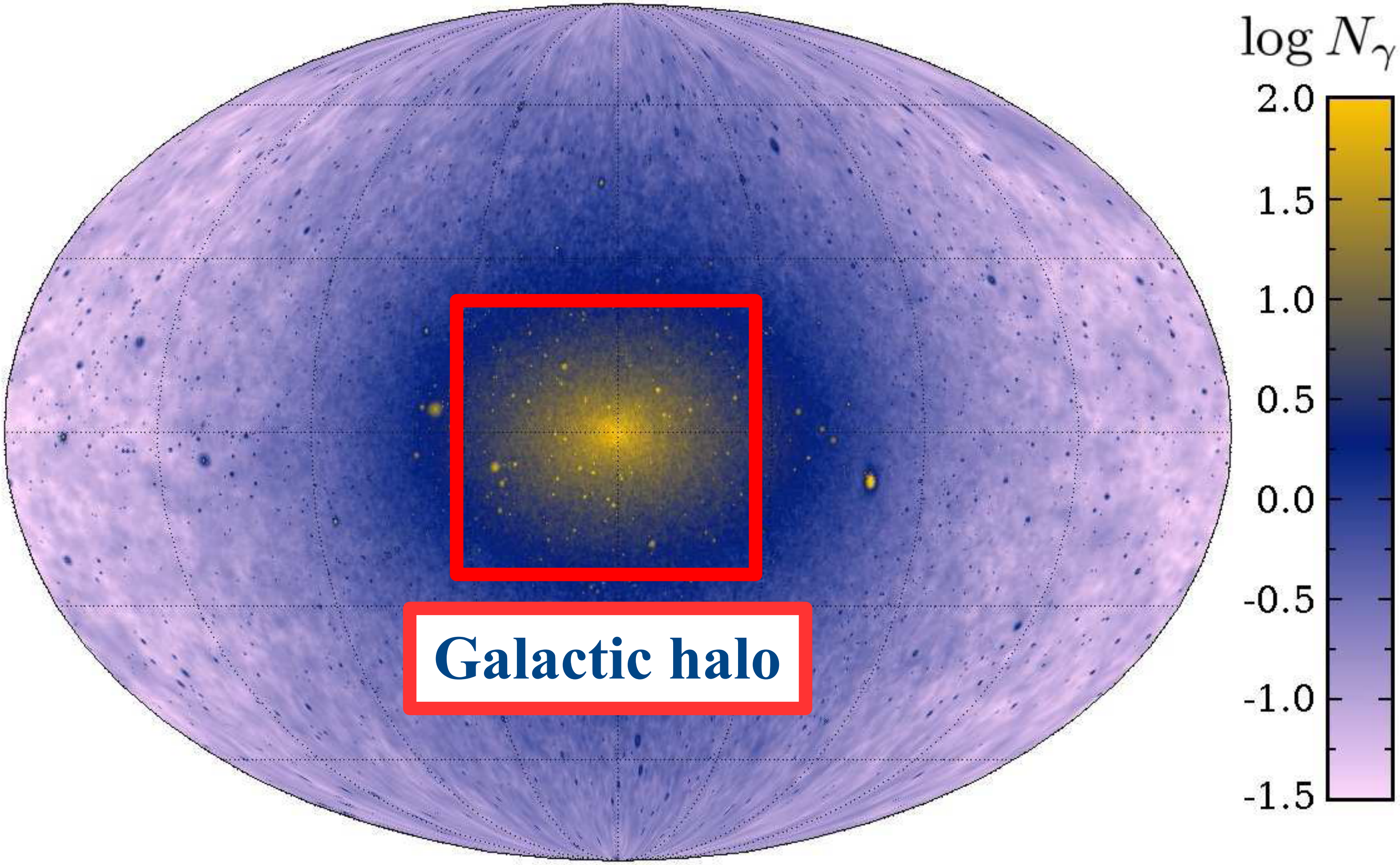


Satellites

Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

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Baltz et al.
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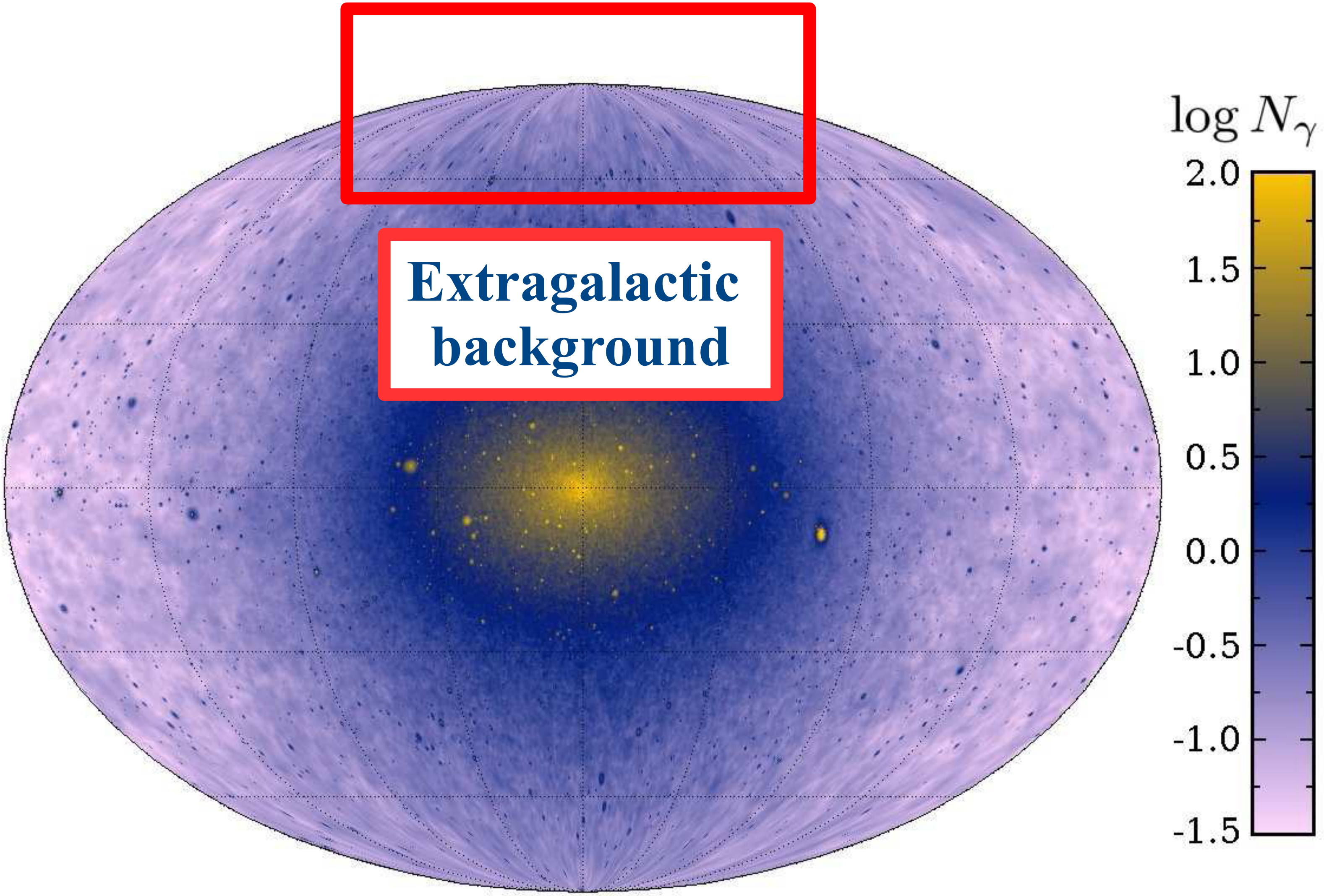

Kuhlen, Diemand, Madau

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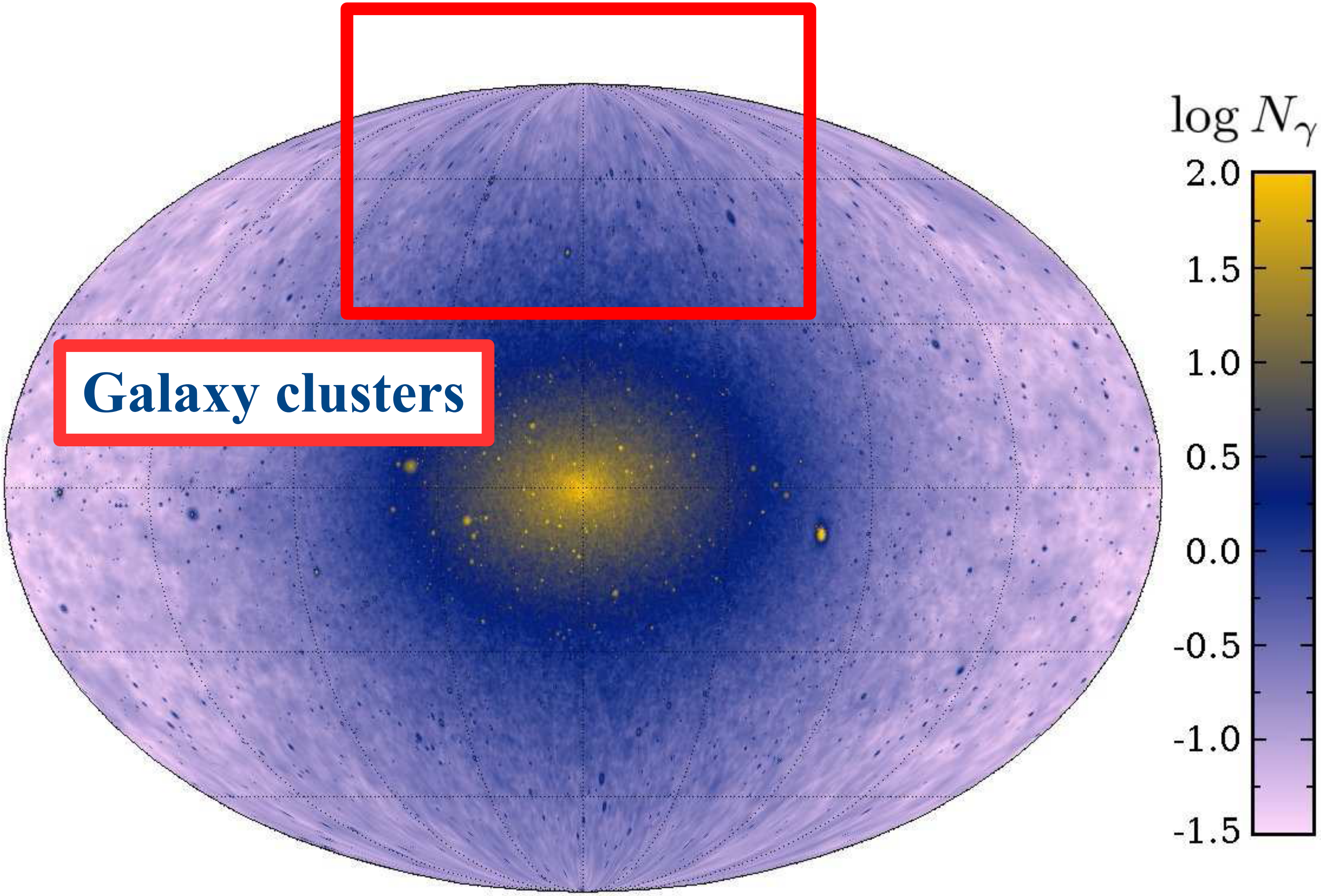
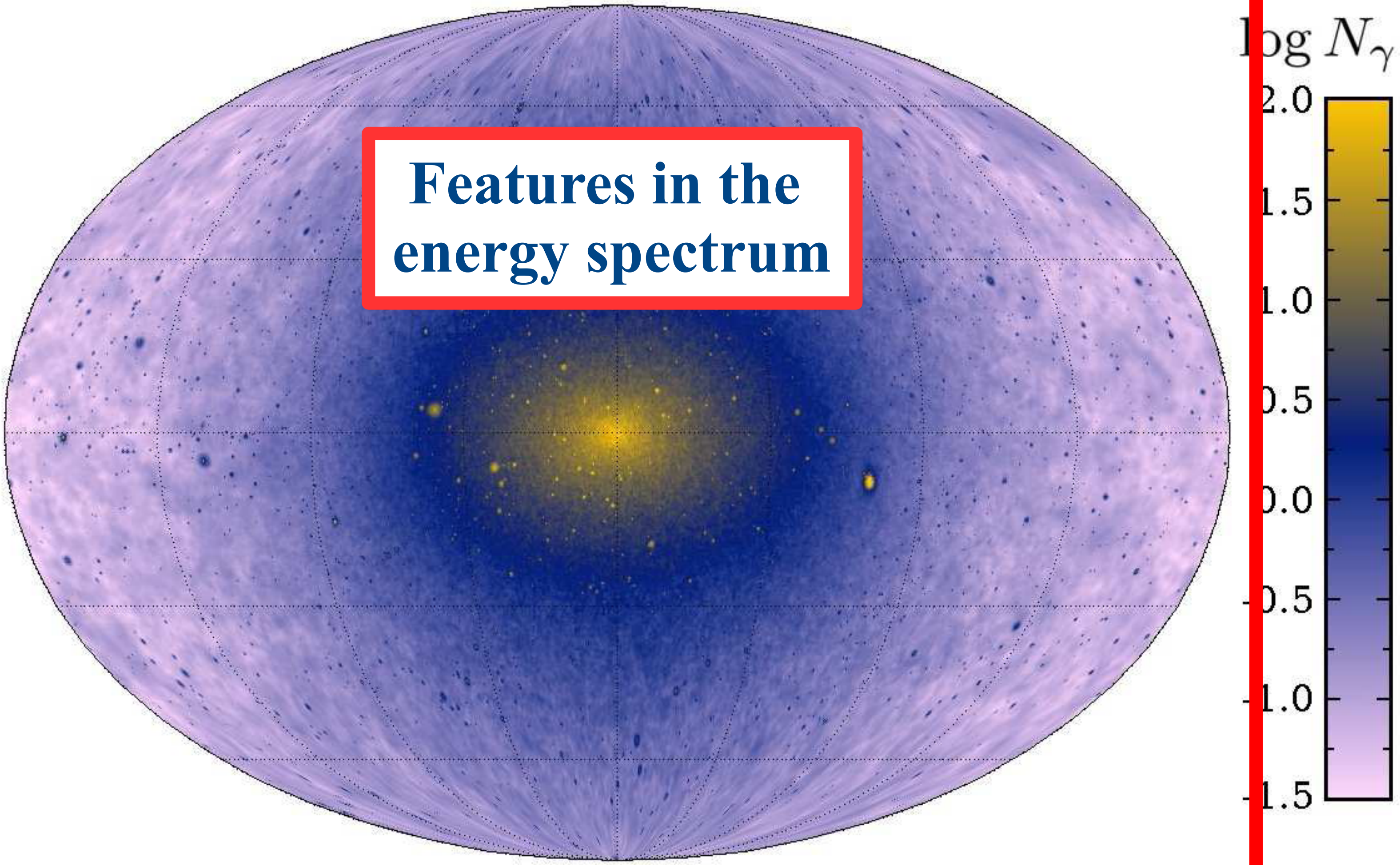


Galaxy clusters

Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911

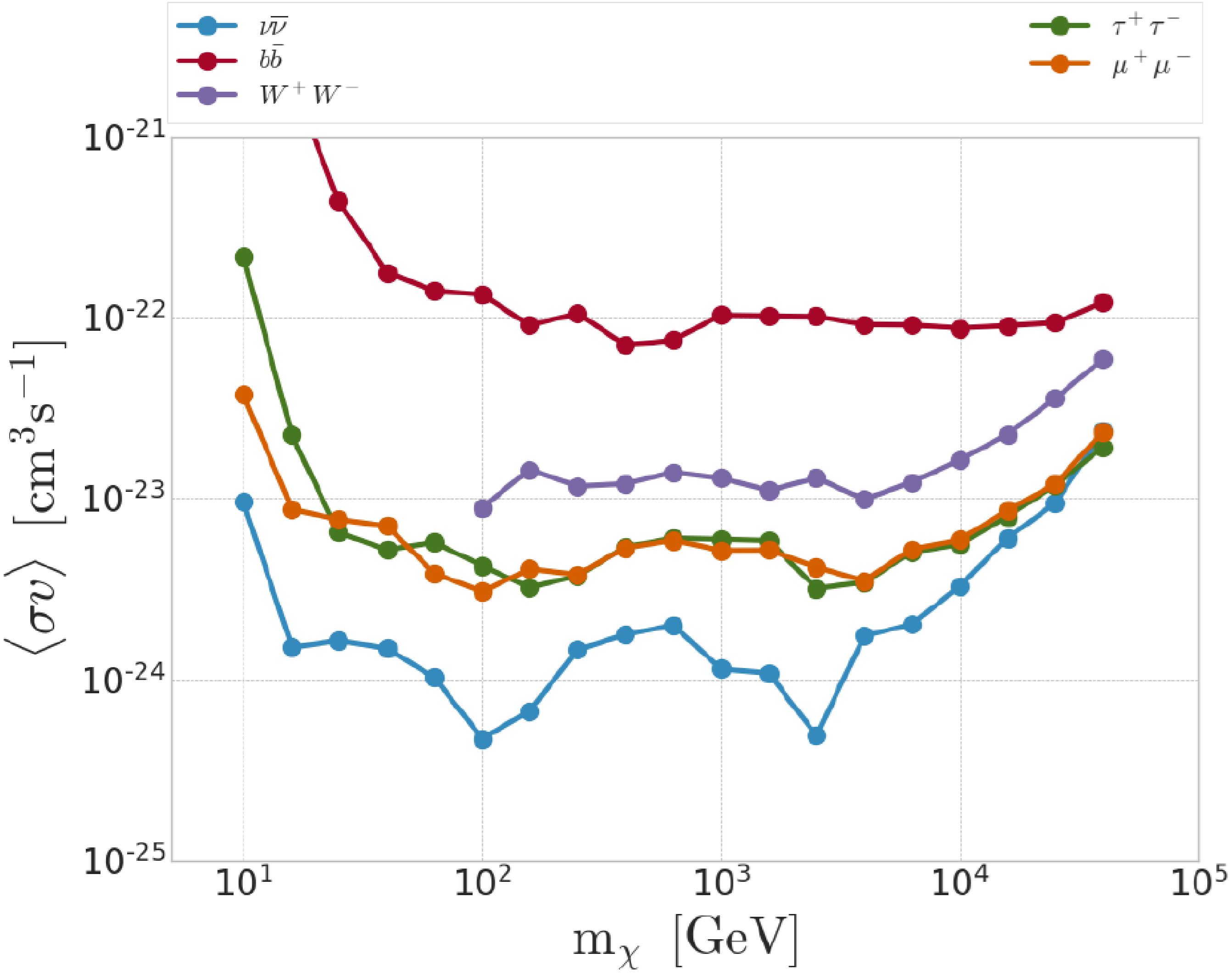


Features in the energy spectrum

Kuhlen, Diemand, Madau

Limits on the annihilation cross-section

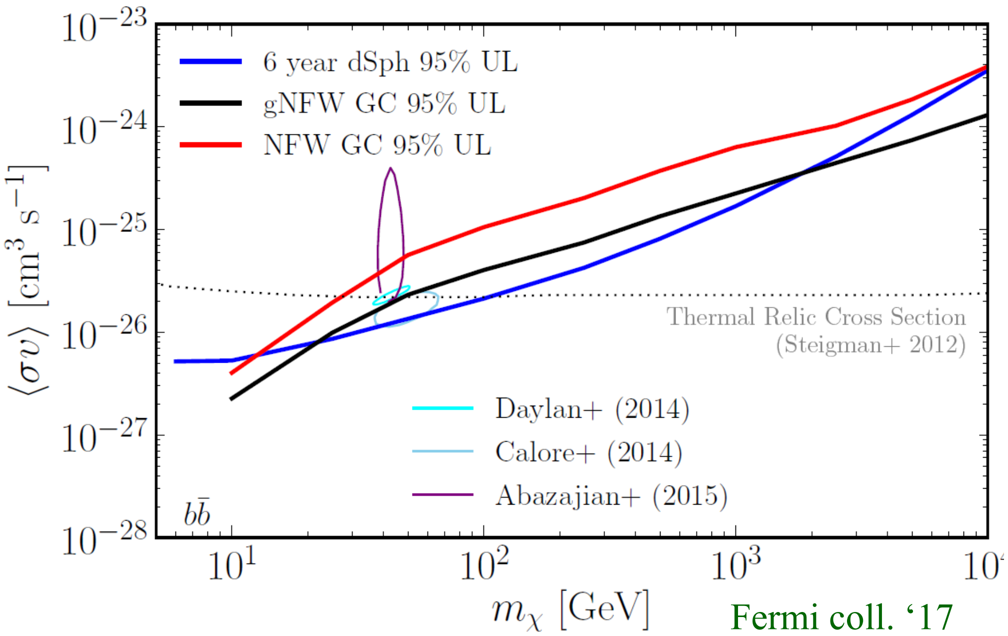
Neutrinos from dark matter annihilations in the Milky Way halo



IceCube 2023

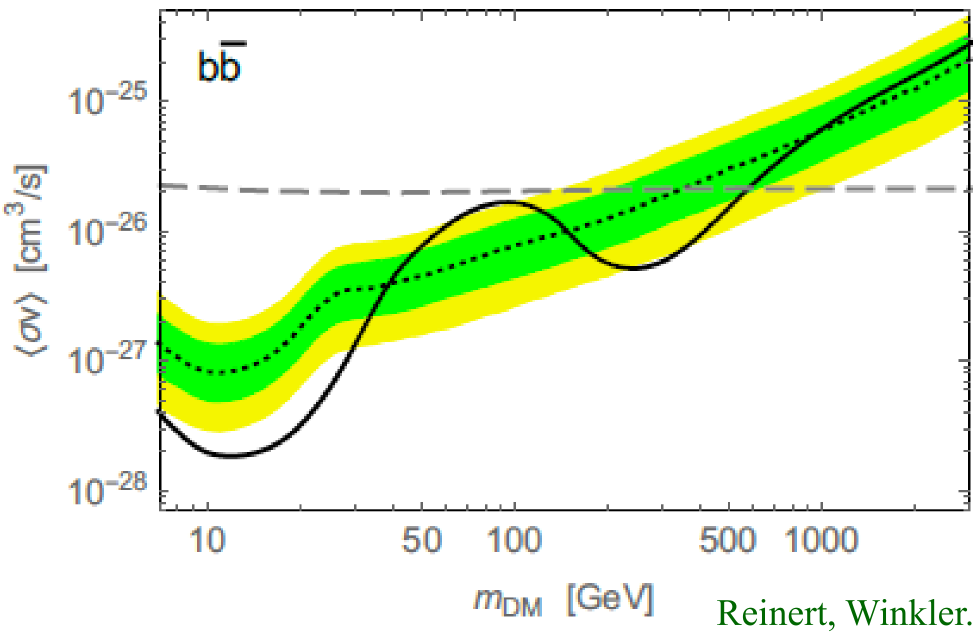
Limits on the annihilation cross-section

gamma-rays from DM annihilations



Fermi coll. '17

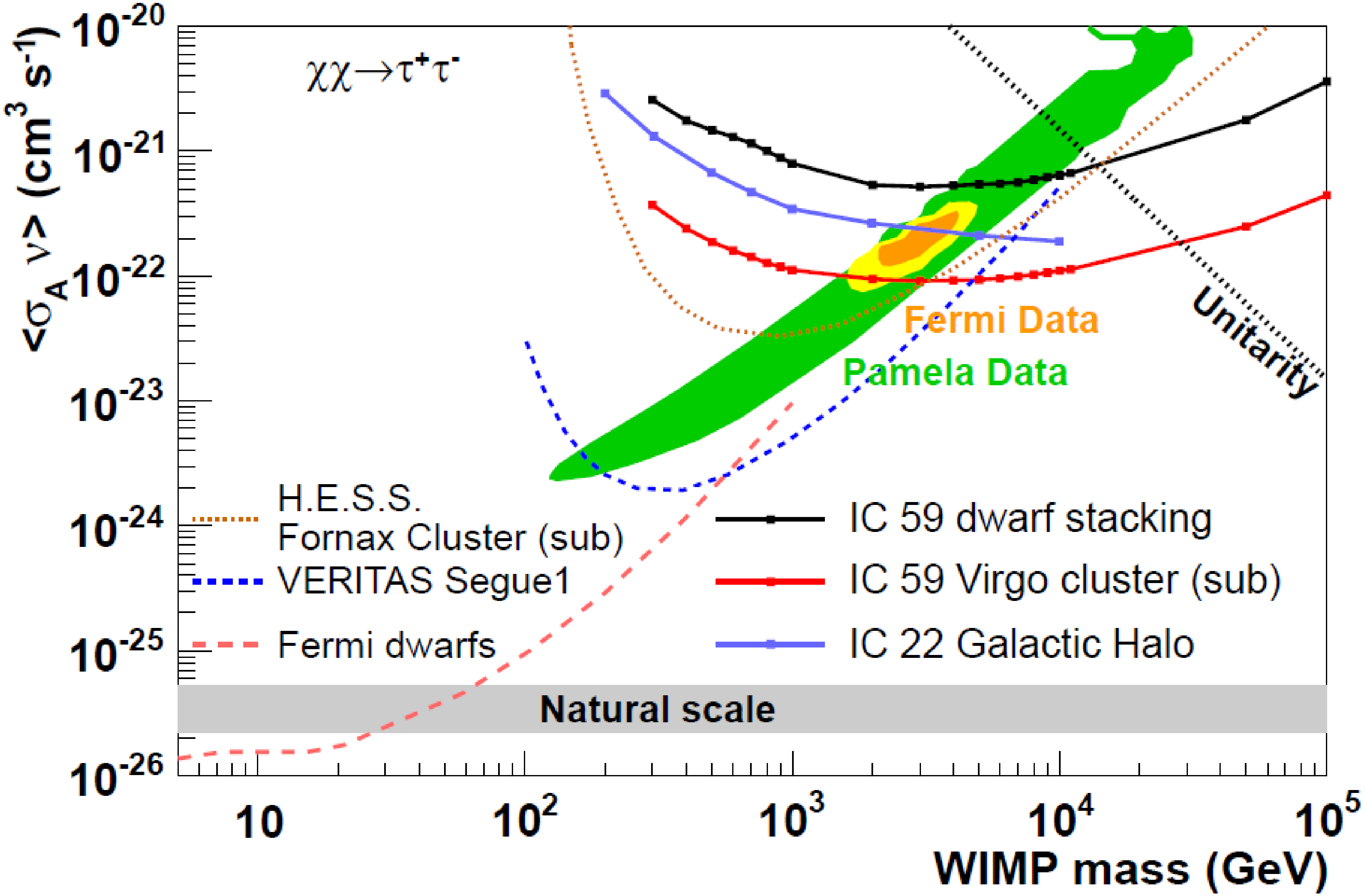
antiprotons from DM annihilations



Reinert, Winkler.
1712.00002

Limits on the annihilation cross-section

Neutrinos from dark matter annihilations in dwarf galaxies & galaxy clusters.



Aartsen et al., arXiv:1307.3473