WIMP Dark Matter

Alejandro Ibarra

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Fujiyoshida
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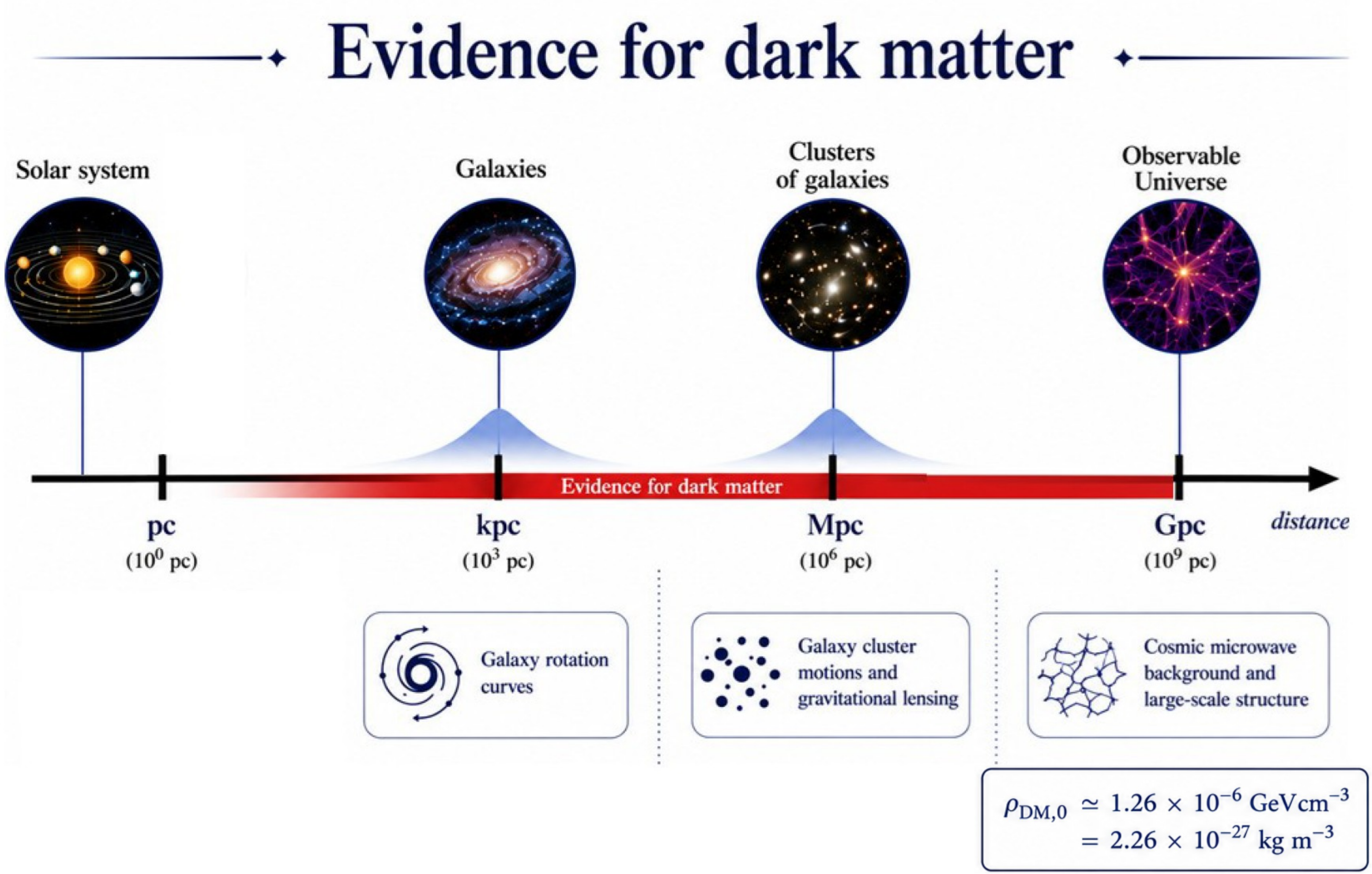
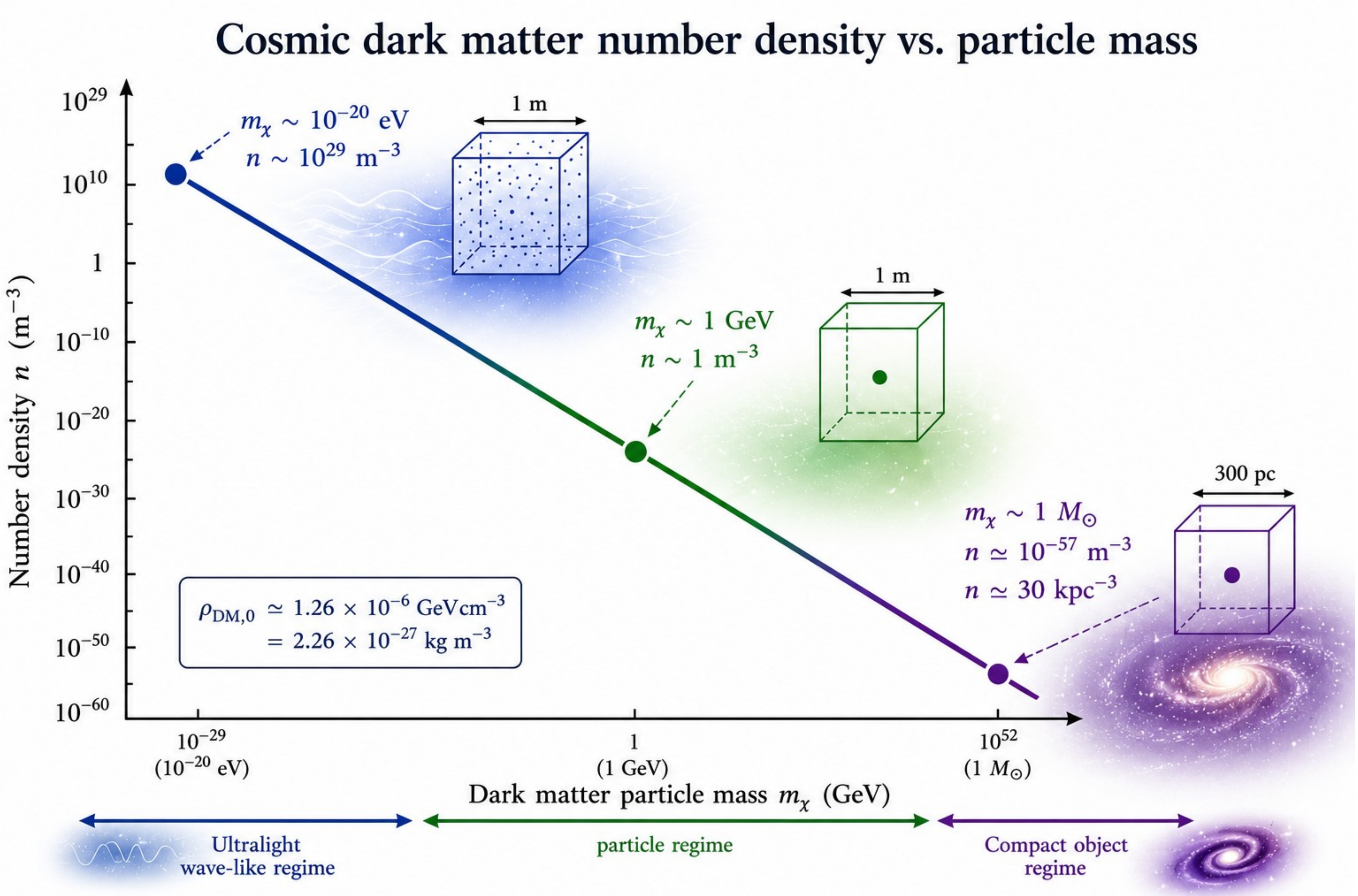


Evidence for dark matter
Solar system
Galaxies
Clusters of galaxies
Observable Universe
Evidence for dark matter
pc
(10^0 pc)
kpc
(10^3 pc)
Mpc
(10^6 pc)
Gpc
(10^9 pc)
distance
Galaxy rotation curves
Galaxy cluster motions and gravitational lensing
Cosmic microwave background and large-scale structure
$\rho_{DM,0} \simeq 1.26 \times 10^{-6}\ \mathrm{GeV cm^{-3}} = 2.26 \times 10^{-27}\ \mathrm{kg\ m^{-3}}$



Cosmic dark matter number density vs. particle mass
10^{29}
10^{10}
1
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
Number density n (m^{-3})
$m_\chi \sim 10^{-20}$ eV
$n \sim 10^{29}$ m^{-3}
1 m
1 m
$m_\chi \sim 1$ GeV
$n \sim 1$ m^{-3}
300 pc
$m_\chi \sim 1\ M_\odot$
$n \simeq 10^{-57}$ m^{-3}
$n \simeq 30$ kpc^{-3}
$\rho_{DM,0} \simeq 1.26 \times 10^{-6}$ GeVcm^{-3}
$= 2.26 \times 10^{-27}$ kg m^{-3}
10^{-29}
(10^{-20} eV)
1
(1 GeV)
10^{52}
(1 $M_\odot$)
Dark matter particle mass m_χ (GeV)
Ultralight
wave-like regime
particle regime
Compact object
regime

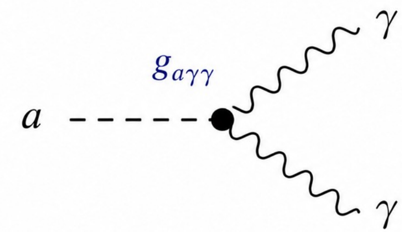
Wave-like dark matter

- Macroscopic de Broglie wavelength

$$\lambda_{\mathrm{dB}} = 1.24\ \mathrm{kpc} \left(\frac{10^{-22}\ \mathrm{eV}}{m_a}\right)\left(\frac{300\ \mathrm{km\,s^{-1}}}{v}\right).$$

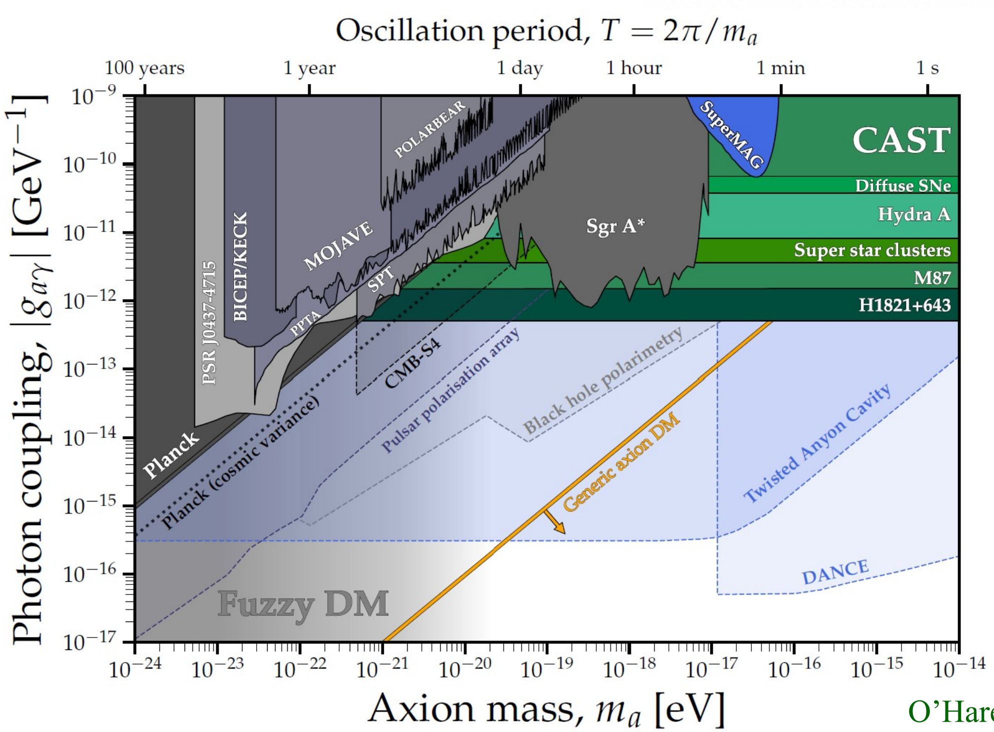
- Dark matter could interact with the Standard Model:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu},$$



- The ULDM field behaves as a coherently oscillating classical field, $a(t) = a_0 \cos(m_a t)$

  $\Rightarrow$ Oscillating electromagnetic effects with frequency $\nu \simeq (1.3\,\mathrm{years})^{-1}\,(m_a/10^{-22}\mathrm{eV})$



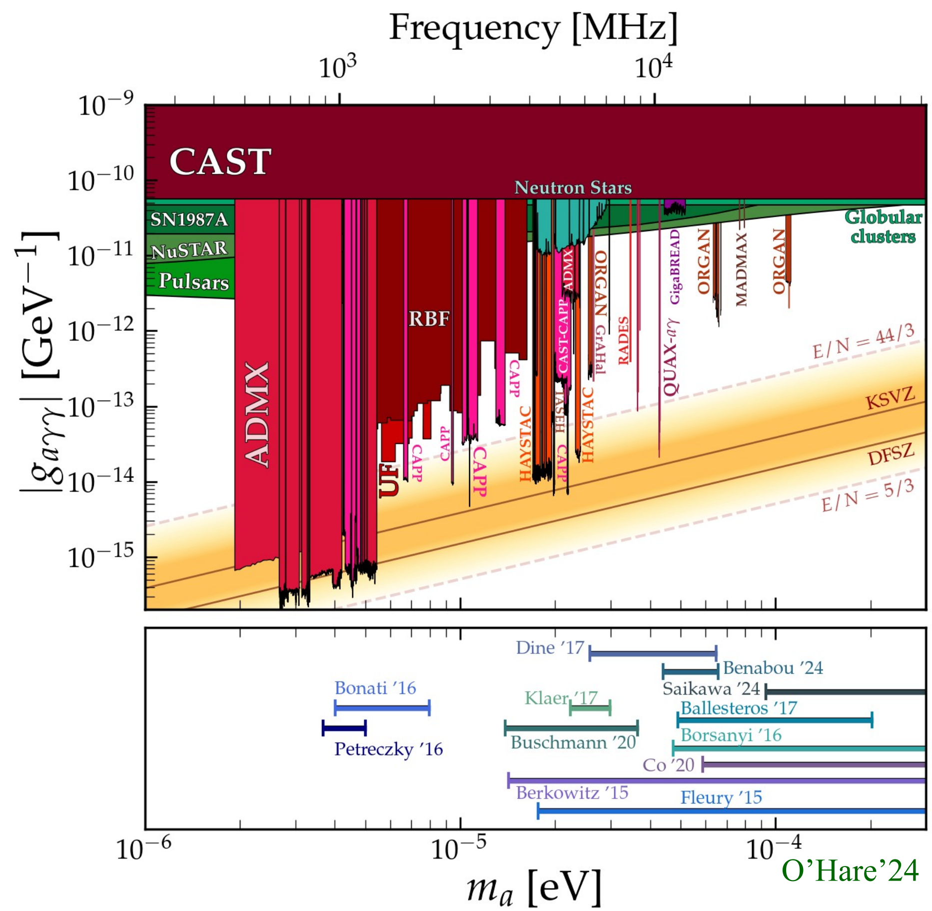
O'Hare'24

Wave-like dark matter: axions

- Models of axion dark matter suggest $m_a \sim 10 - 100\,\mu\text{eV}$ (if the Peccei-Quinn symmetry is broken before inflation; larger if broken after)

$$\nu_a = 2.4\ \text{GHz}\left(\frac{m_a}{10\ \mu\text{eV}}\right).$$

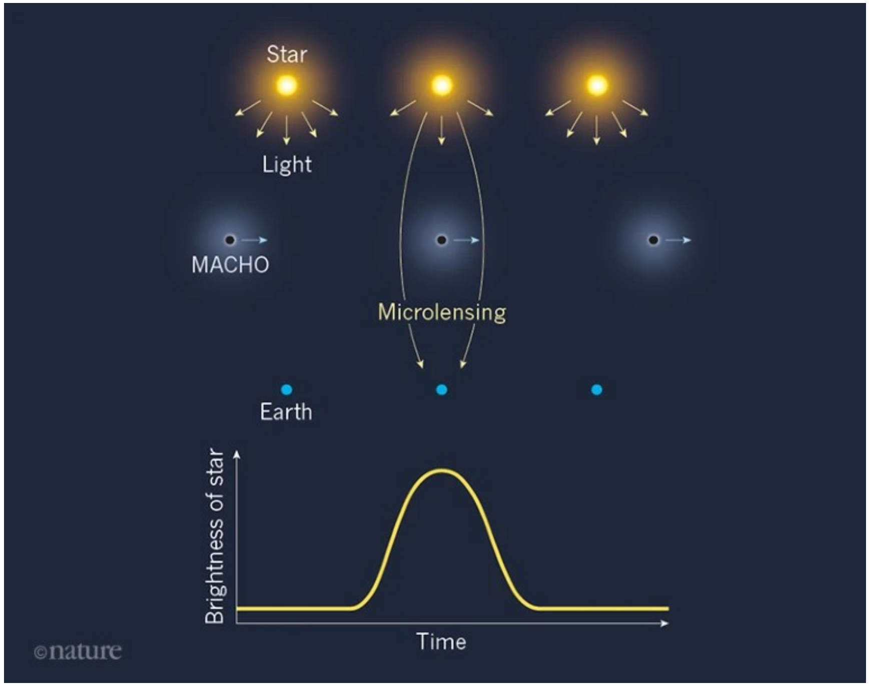
- The axion-photon coupling acts as a source in the Maxwell equations, and amplifies the energy of a cavity with frequency tuned to the axion frequency.



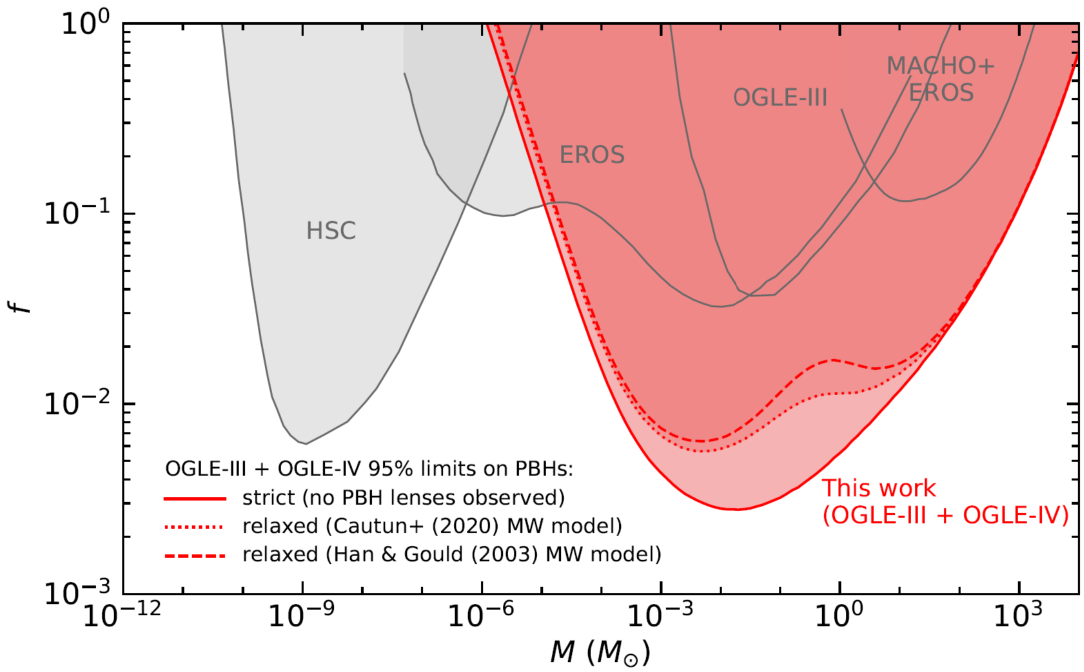
Current experiments start to cover the region favored by axion dark matter models

Macroscopic dark matter

Model independent search strategy: microlensing of the light from distant stars



Pietrzyński '18

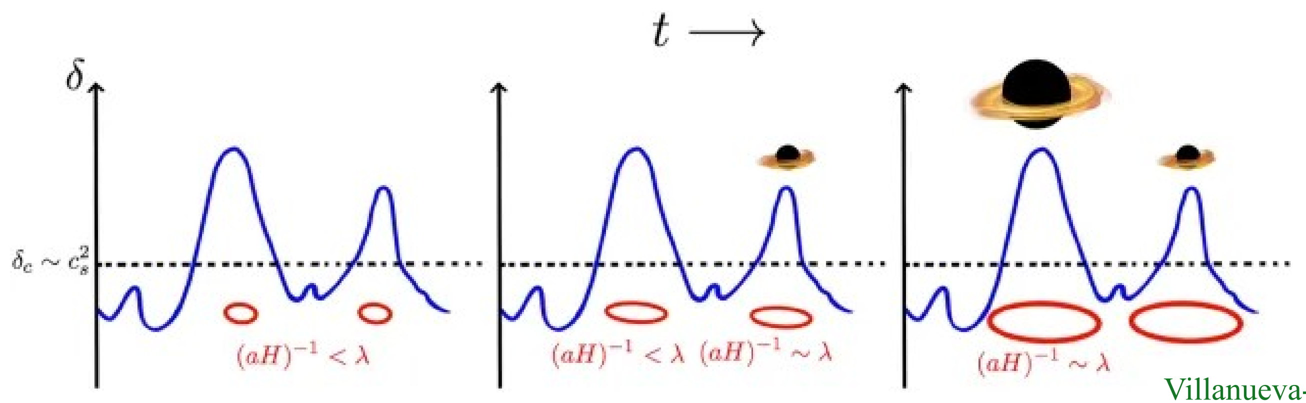


Mroz et al. '24

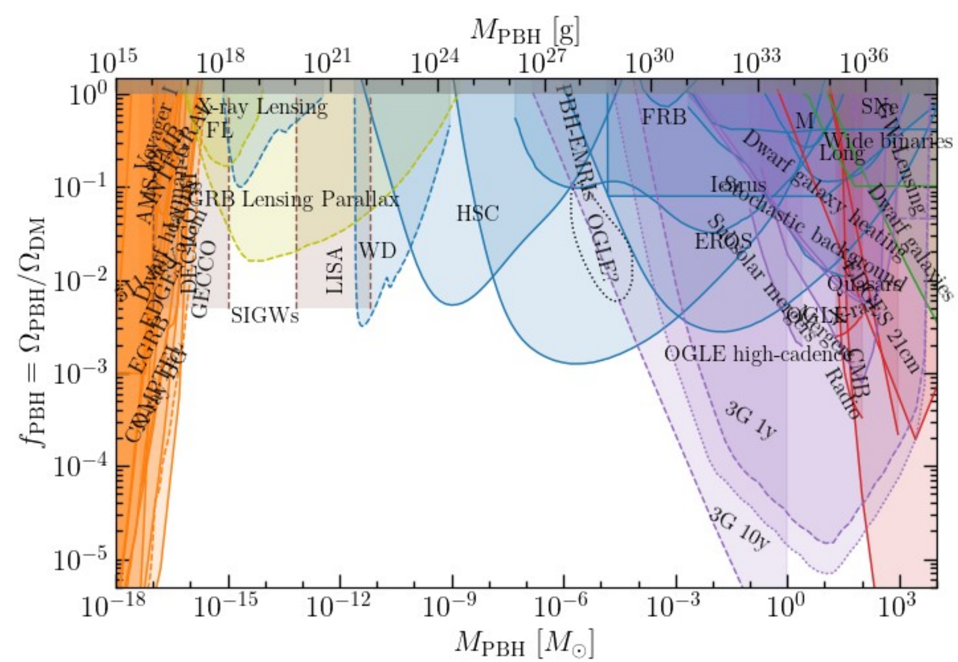
Macroscopic dark matter

Some popular candidates (in the HEP community)

- Primordial black holes Zel'dovich & Novikov ’66, Hawking’71, Carr, Hawking’74



Villanueva-Domingo, Mena, Palomares-Ruiz’21



‣ PBHs are excluded as dominant component of dark matter in large regions of the parameter space.

‣ The region with asteroid mass (10^{17}-10^{22} g) still allowed *if all PBHs had the same mass.* Good prospects to close the window completely.

https://github.com/bradkav/PBHbounds

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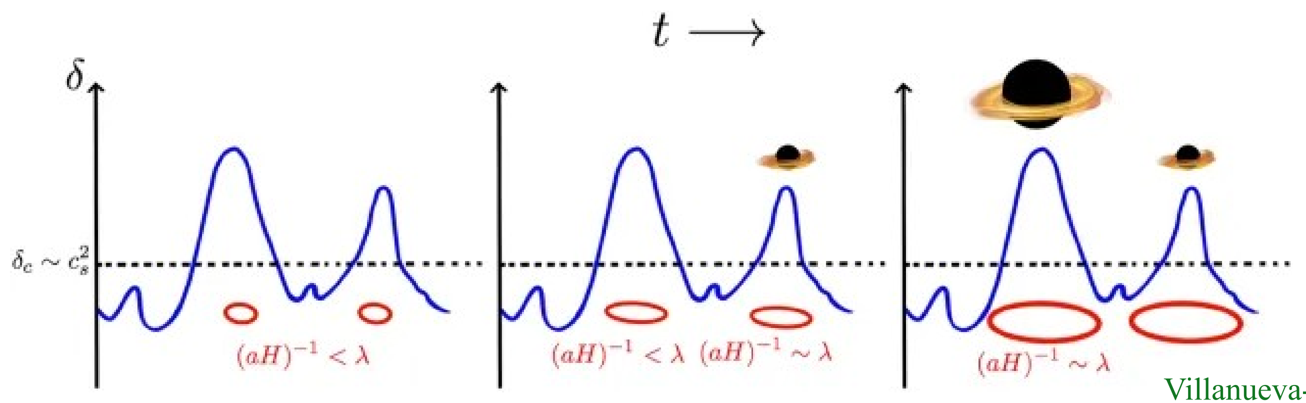
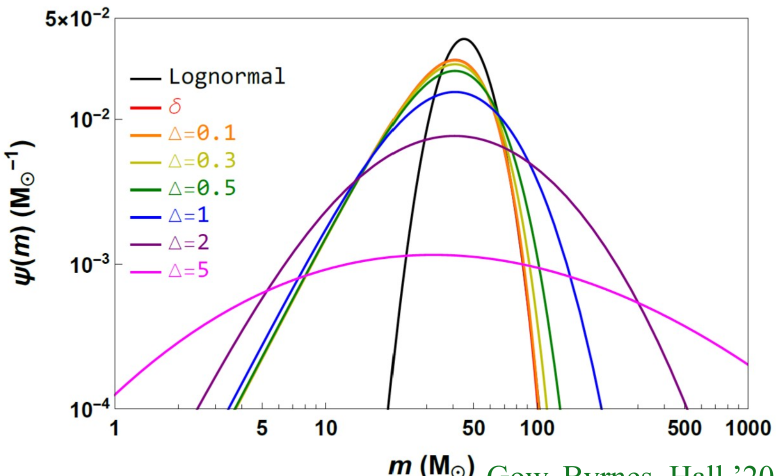
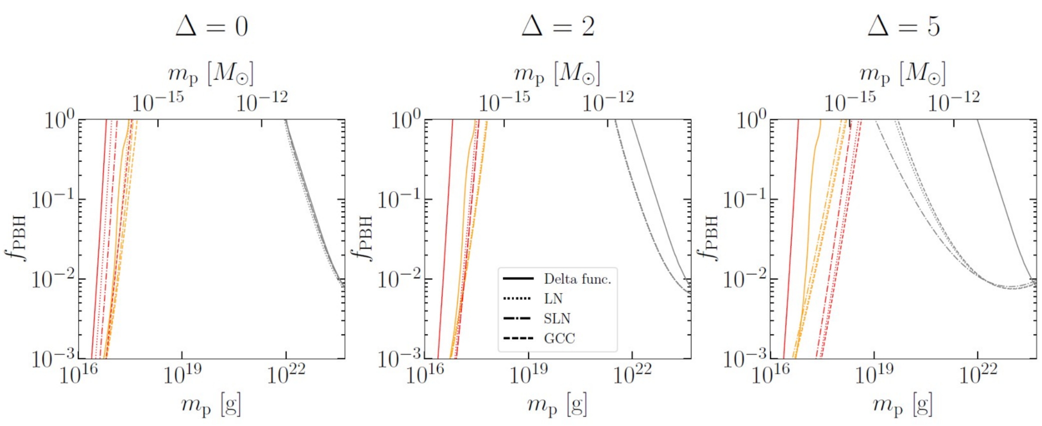


Villanueva-Domingo, Mena, Palomares-Ruiz’21

‣ The PBH mass function is not expected to be exactly monochromatic.



Gow, Byrnes, Hall ’20



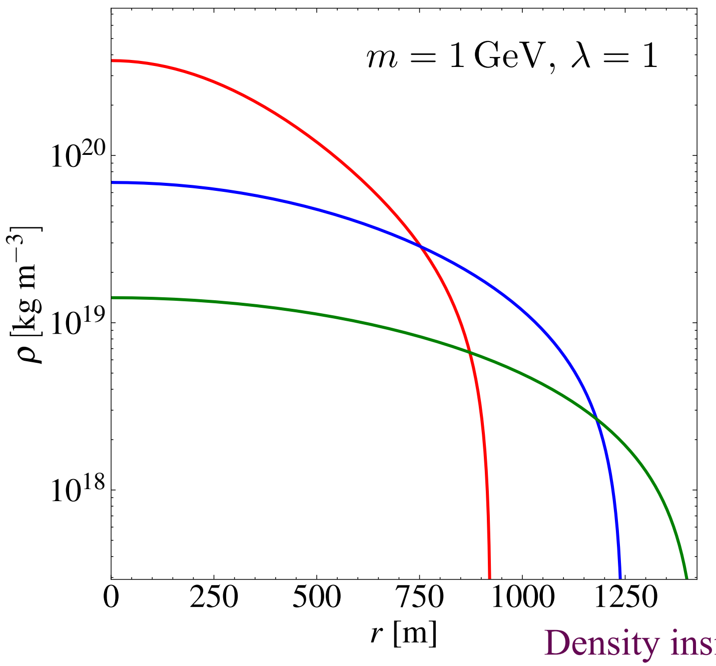
Gorton, Green ’24

Macroscopic dark matter

- Compact dark stars Colpi et al'86
  - Asymmetric dark matter with strong self-interactions (akin to protons).
  - The density profile of dark stars calculable from the Klein-Gordon equation in curved spacetime (for bosonic DM) and the Einstein equations:

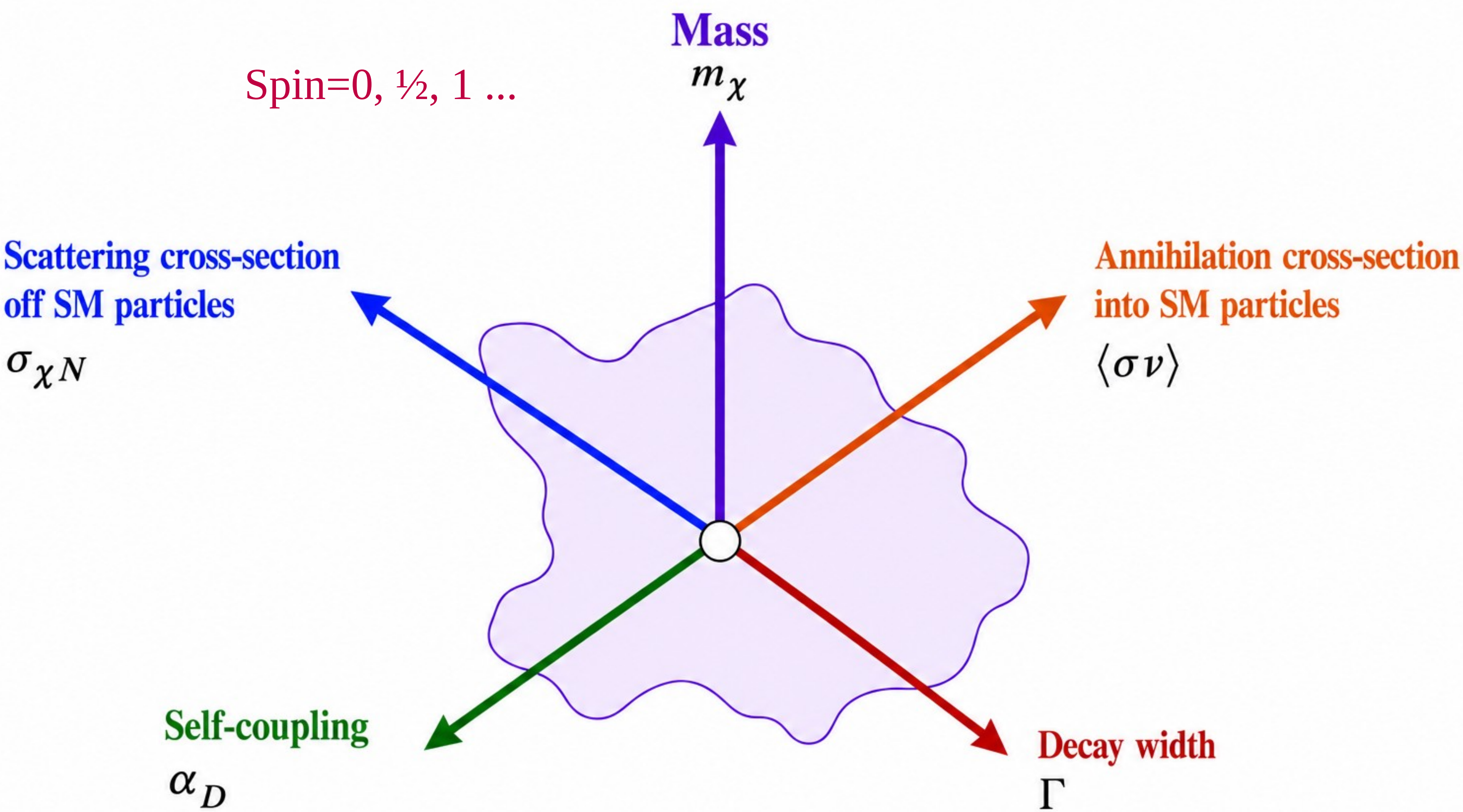
$$g^{\mu\nu}\nabla_\mu\nabla_\nu\phi - m^2\phi - \lambda|\phi|^2\phi = 0$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$$

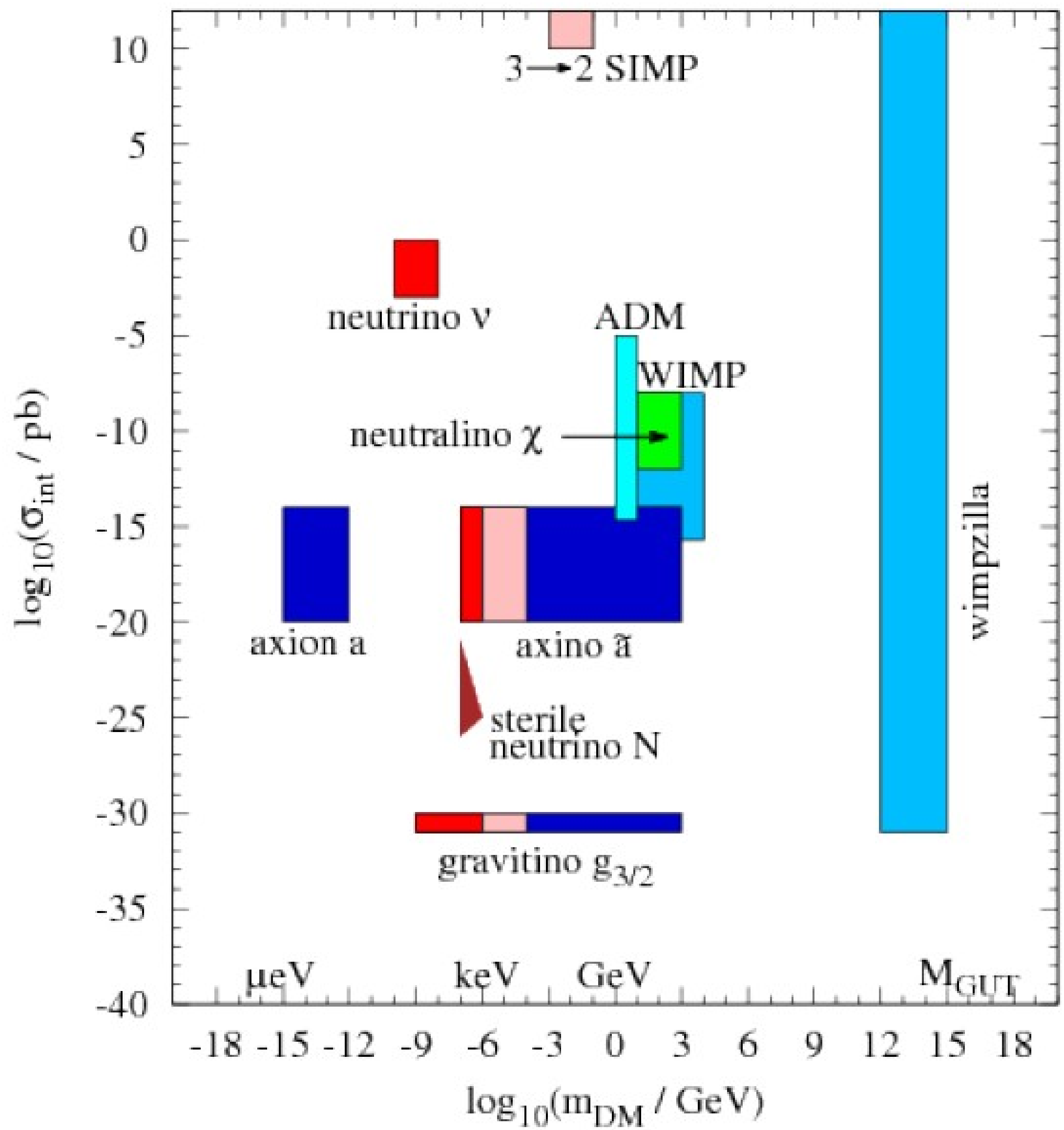


Density inside a neutron star, 10^{18} kg/m^3

Particle Dark Matter Parameter Space



The dark particle zoo



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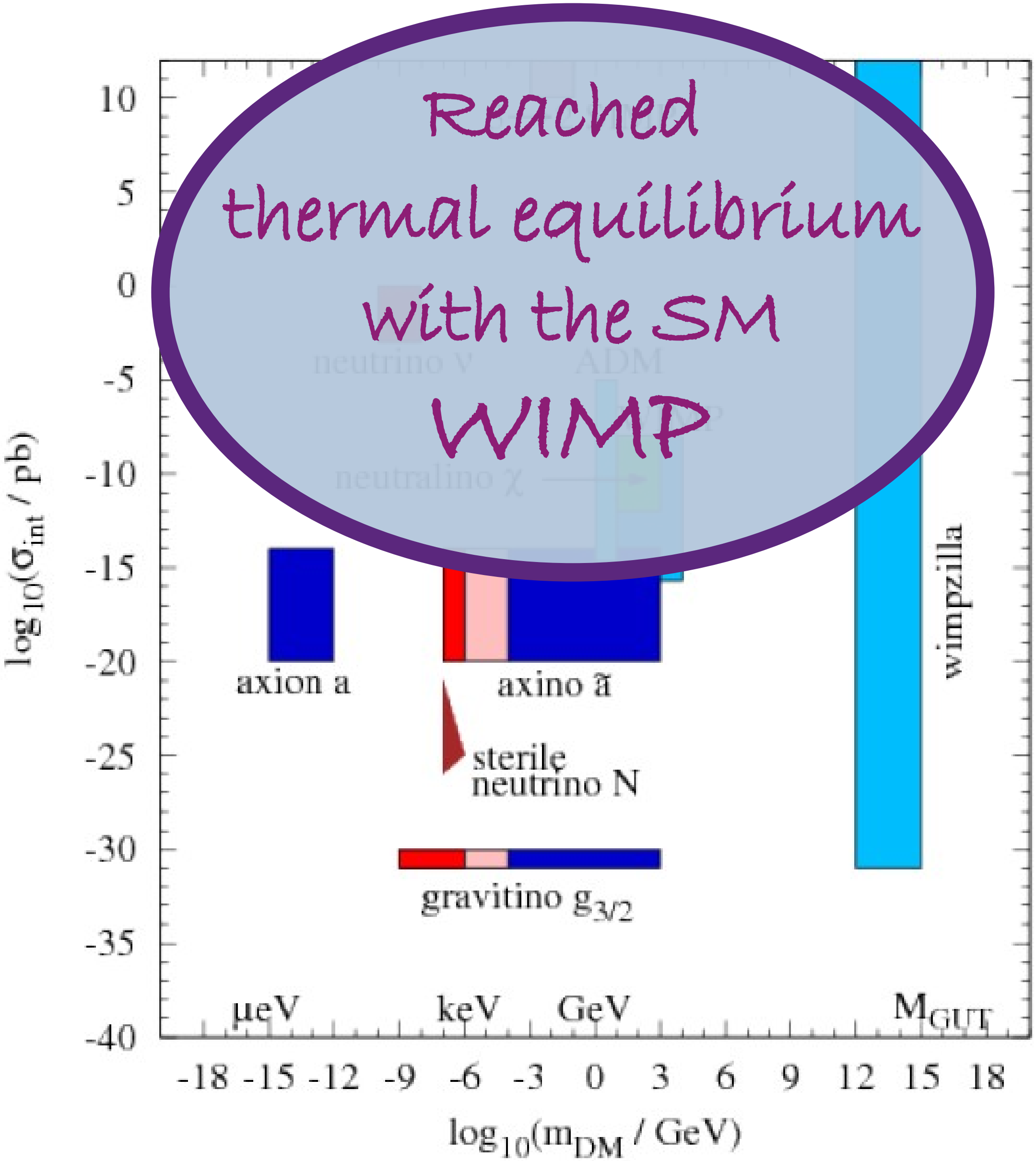

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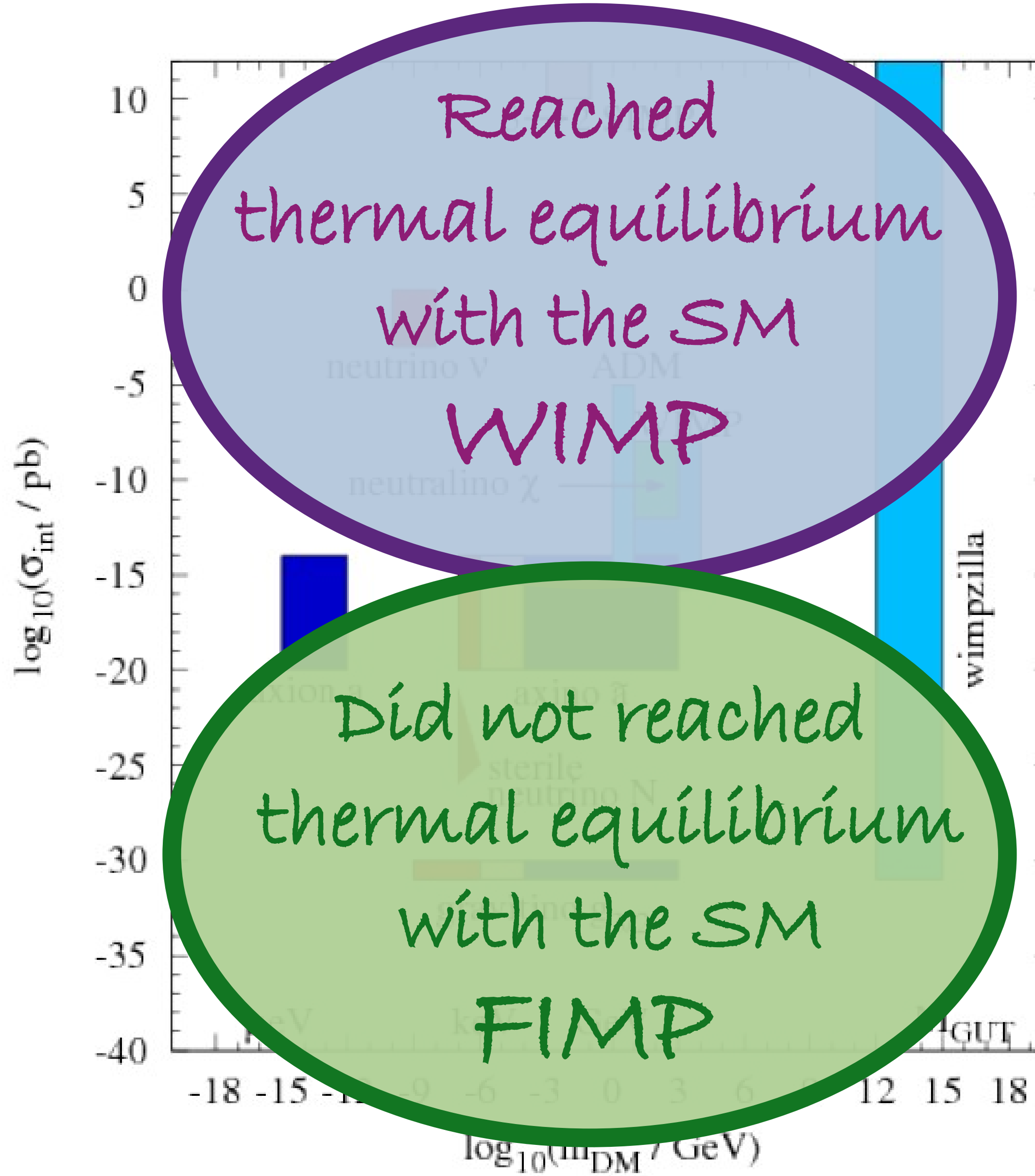
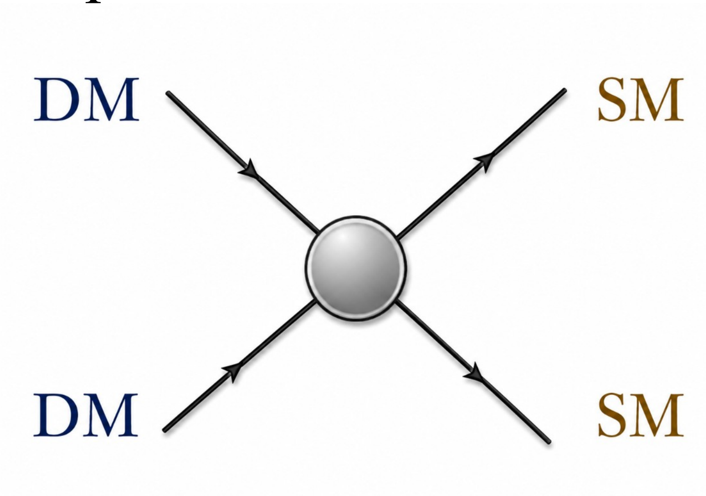


WIMP history (in a nutshell)

Main assumptions on dark matter WIMPs:

1) The WIMP is stable in cosmological timescales.

2) WIMPs interact in pairs with the Standard Model particles



3) The WIMP interaction strength is *large enough* to keep the DM particles in thermal equilibrium with the SM plasma at very high temperatures.

4) The WIMP interaction strength is *small enough* to allow DM particles to chemically decouple from the SM plasma sufficiently early.

WIMP history (in a nutshell)

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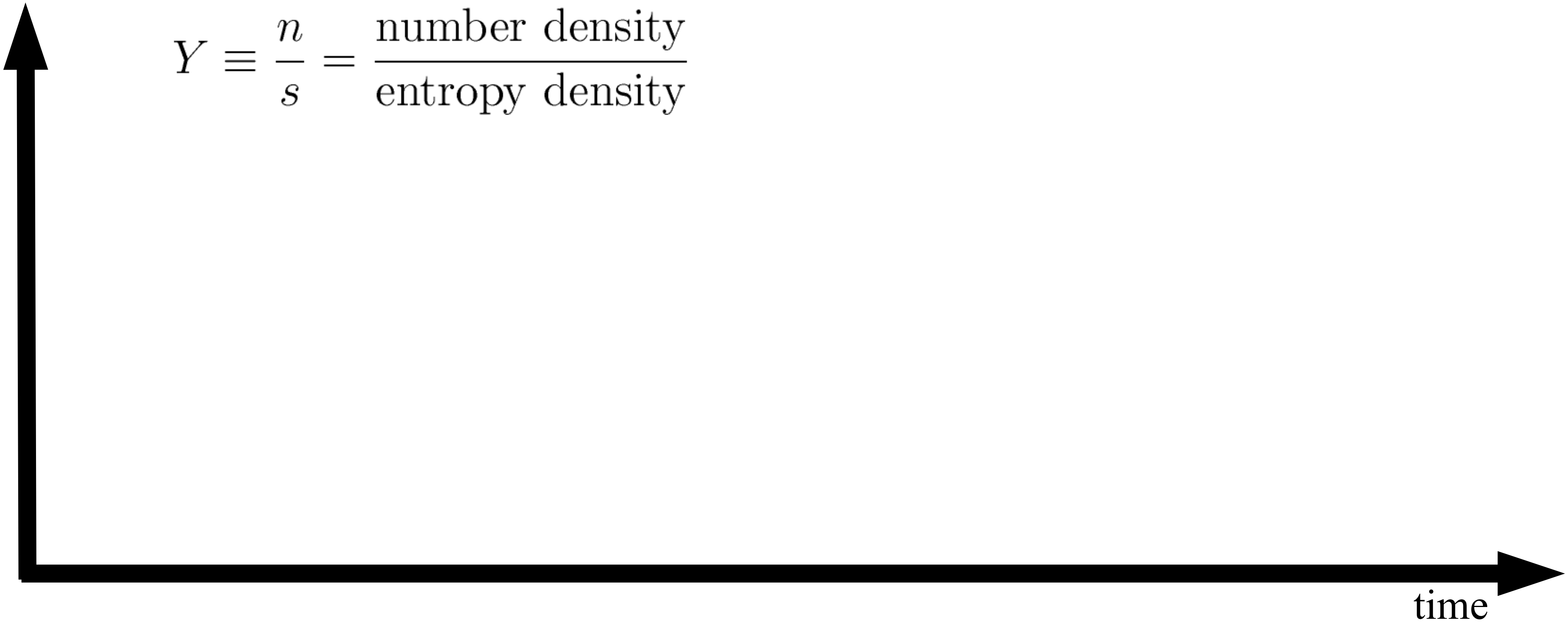
"yield" = number density of DM particles per comoving volume

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



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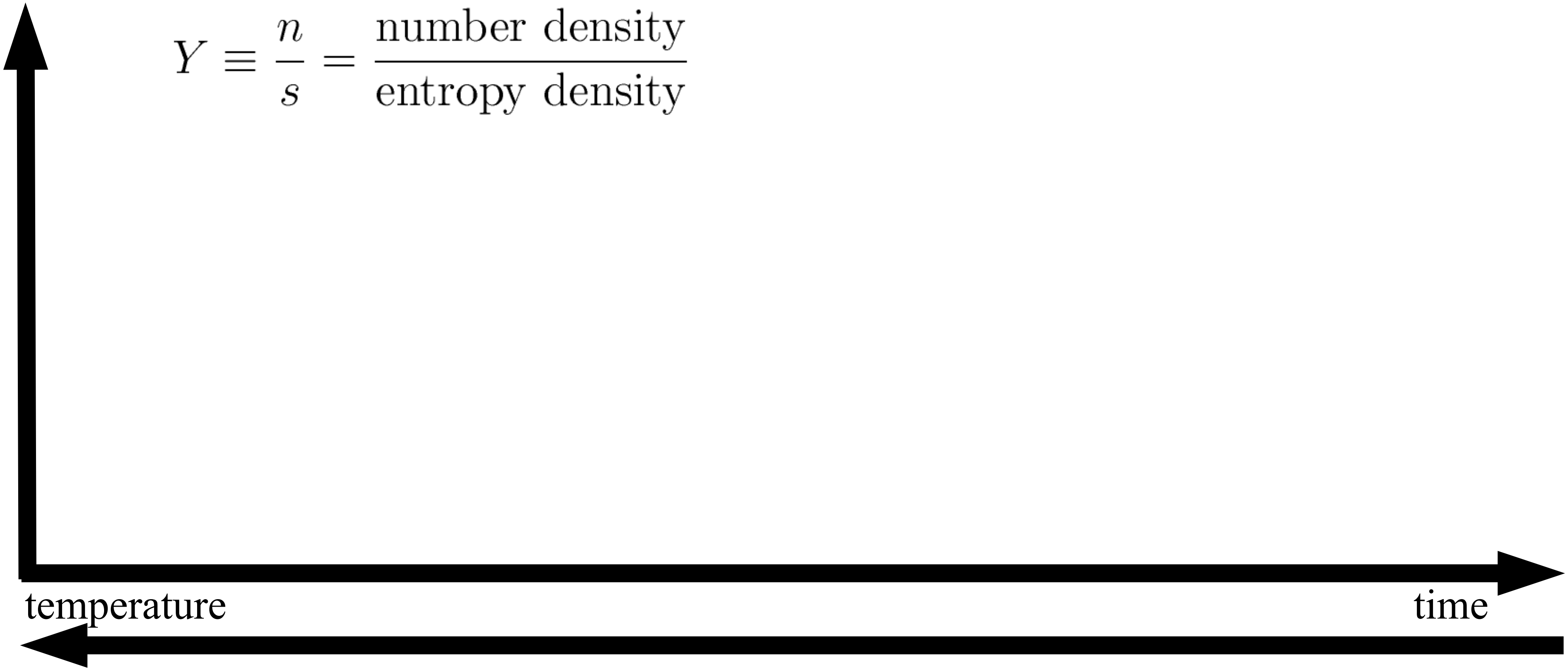

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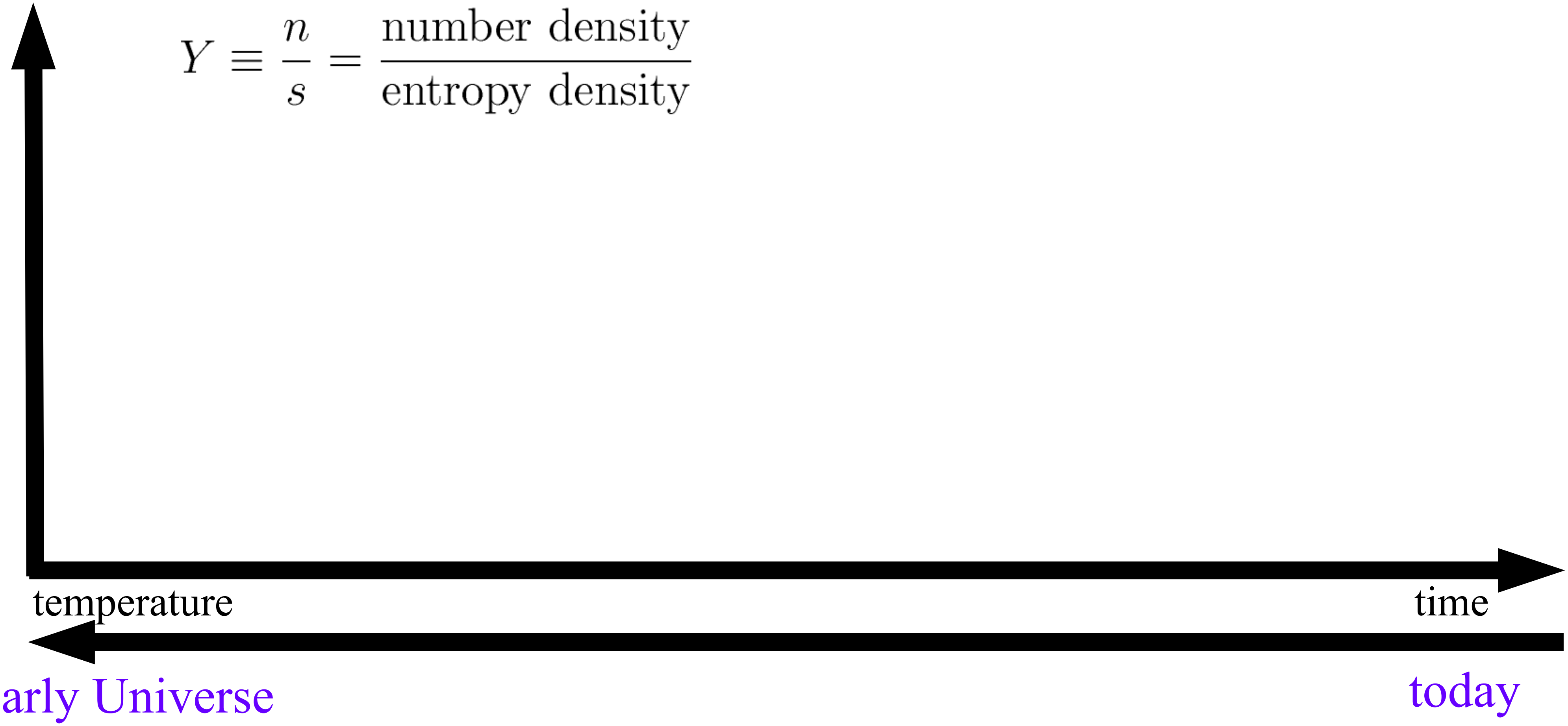

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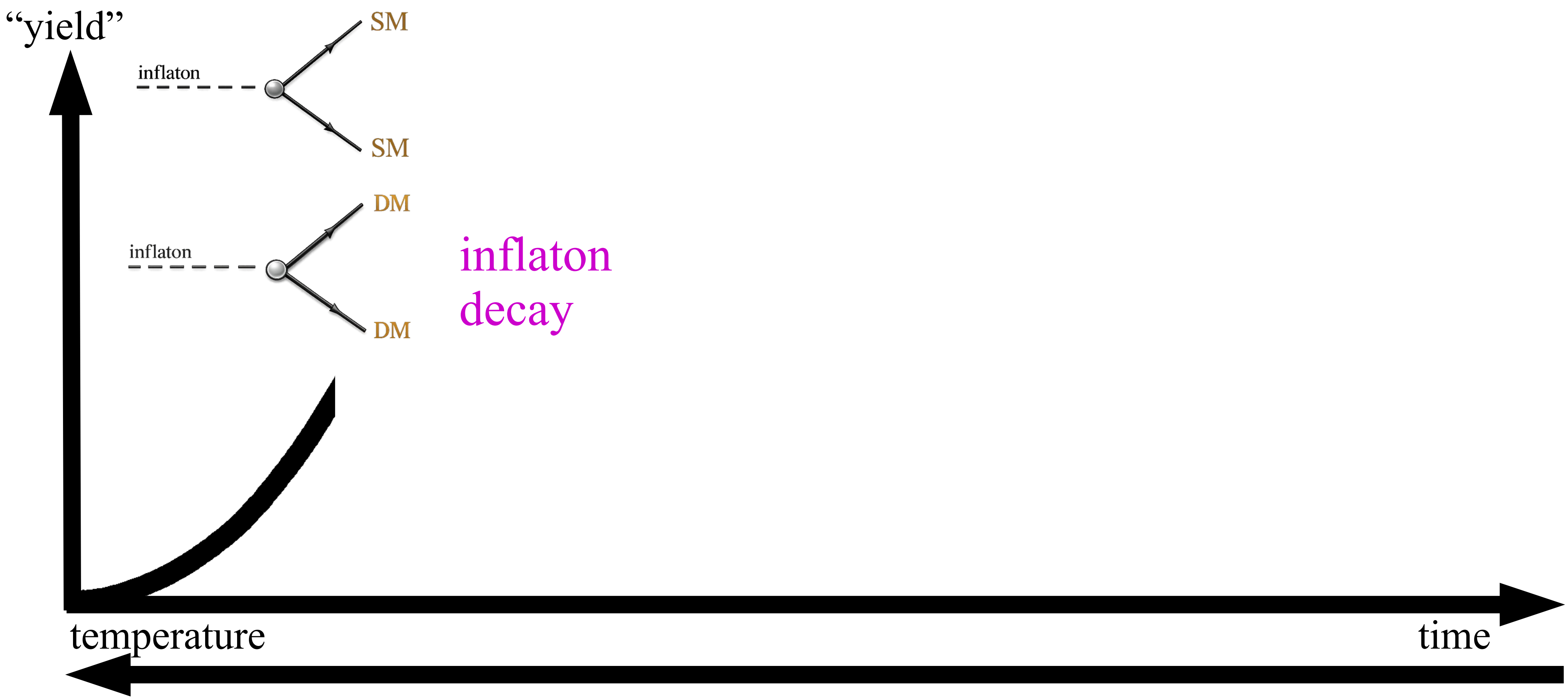

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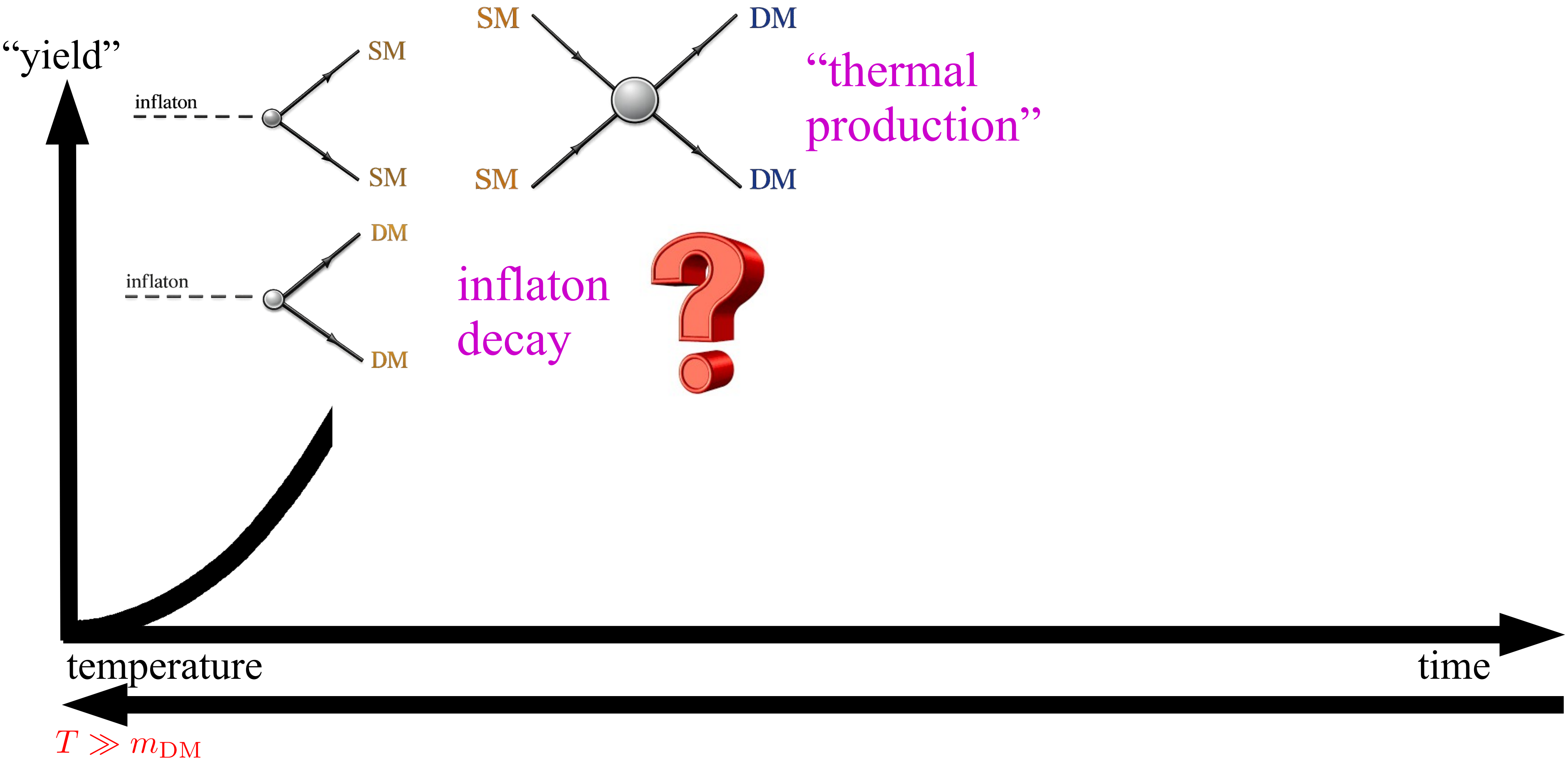
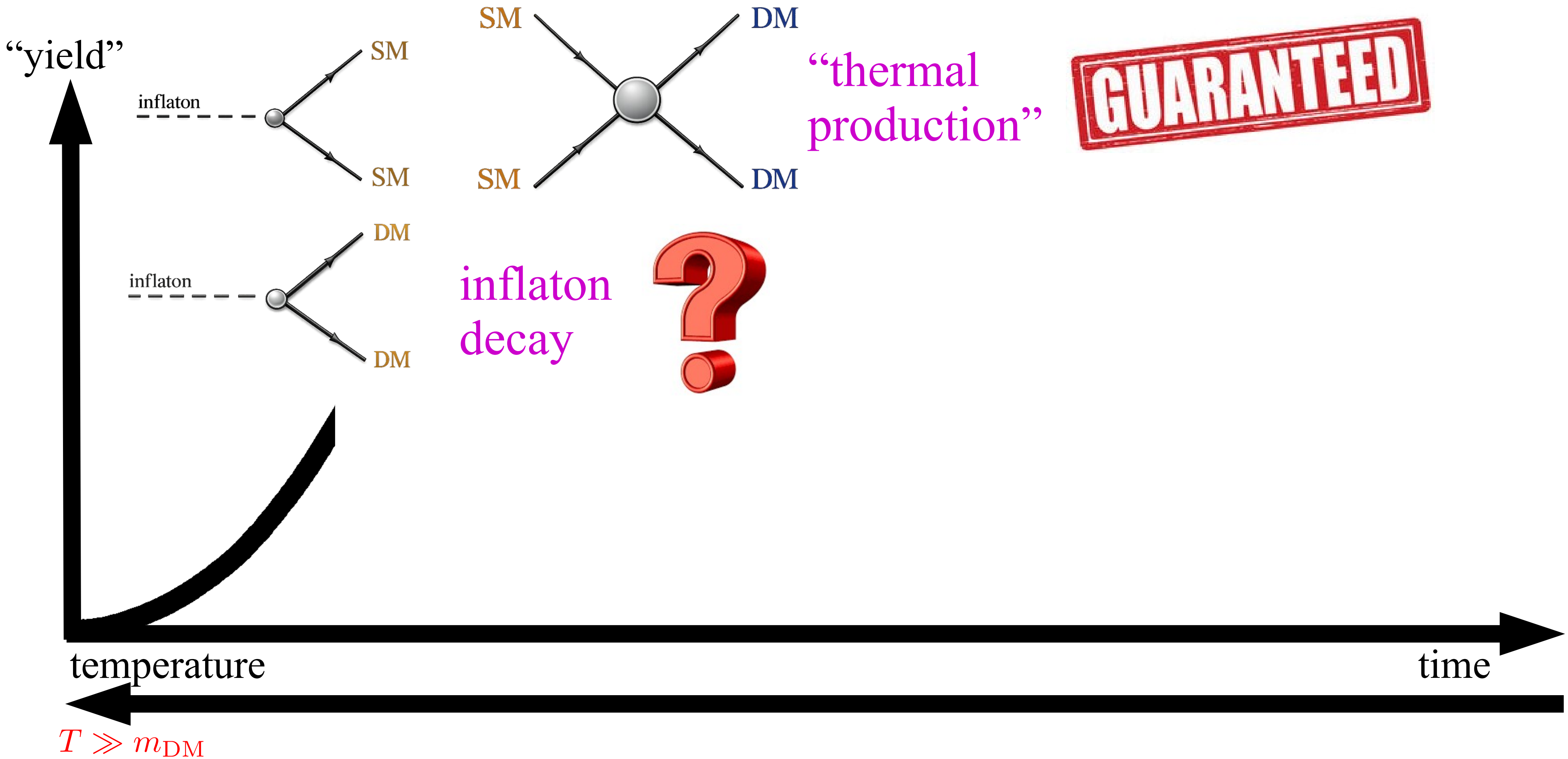


Assume that the temperature of the Universe after reheating was much larger than the DM mass.

WIMP history (in a nutshell)



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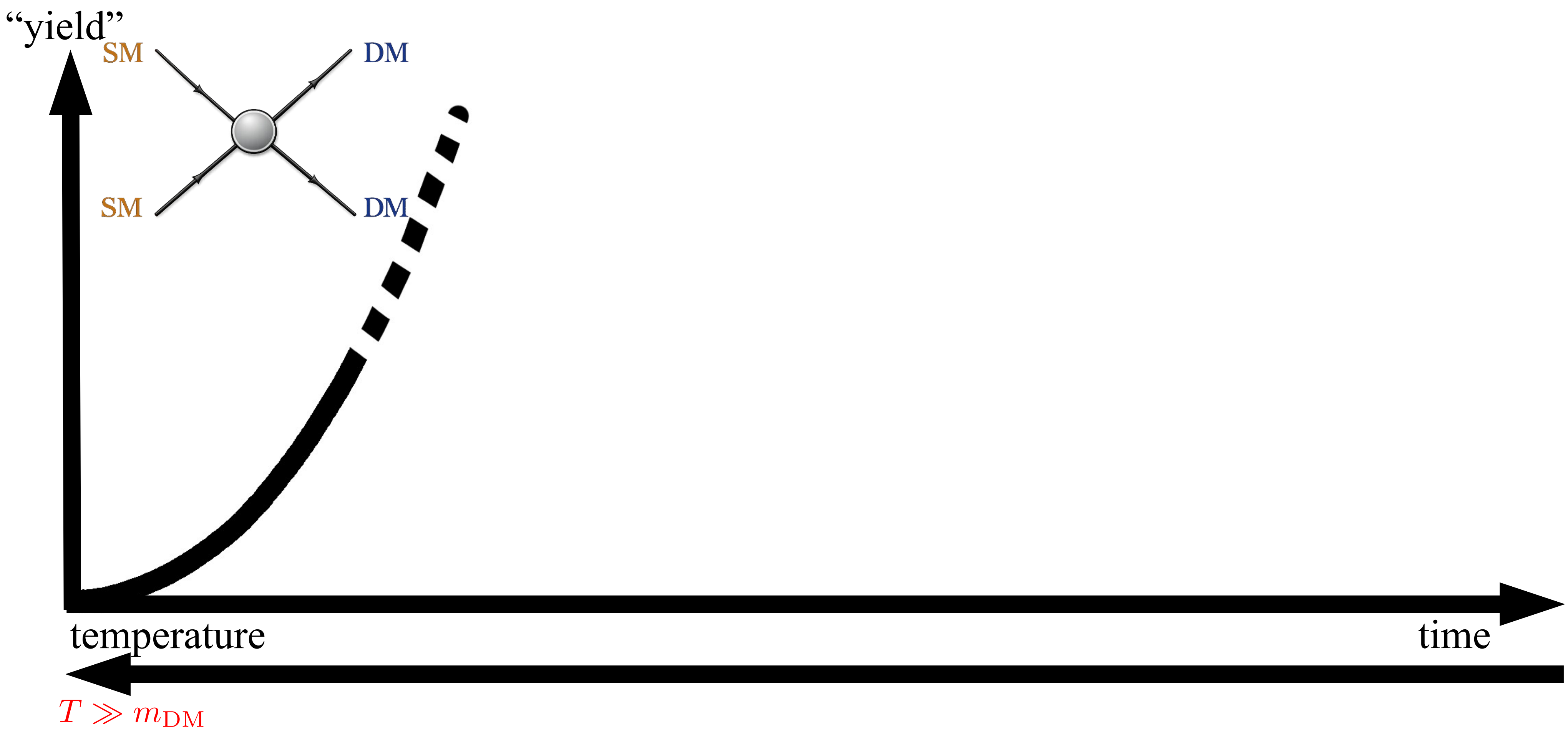

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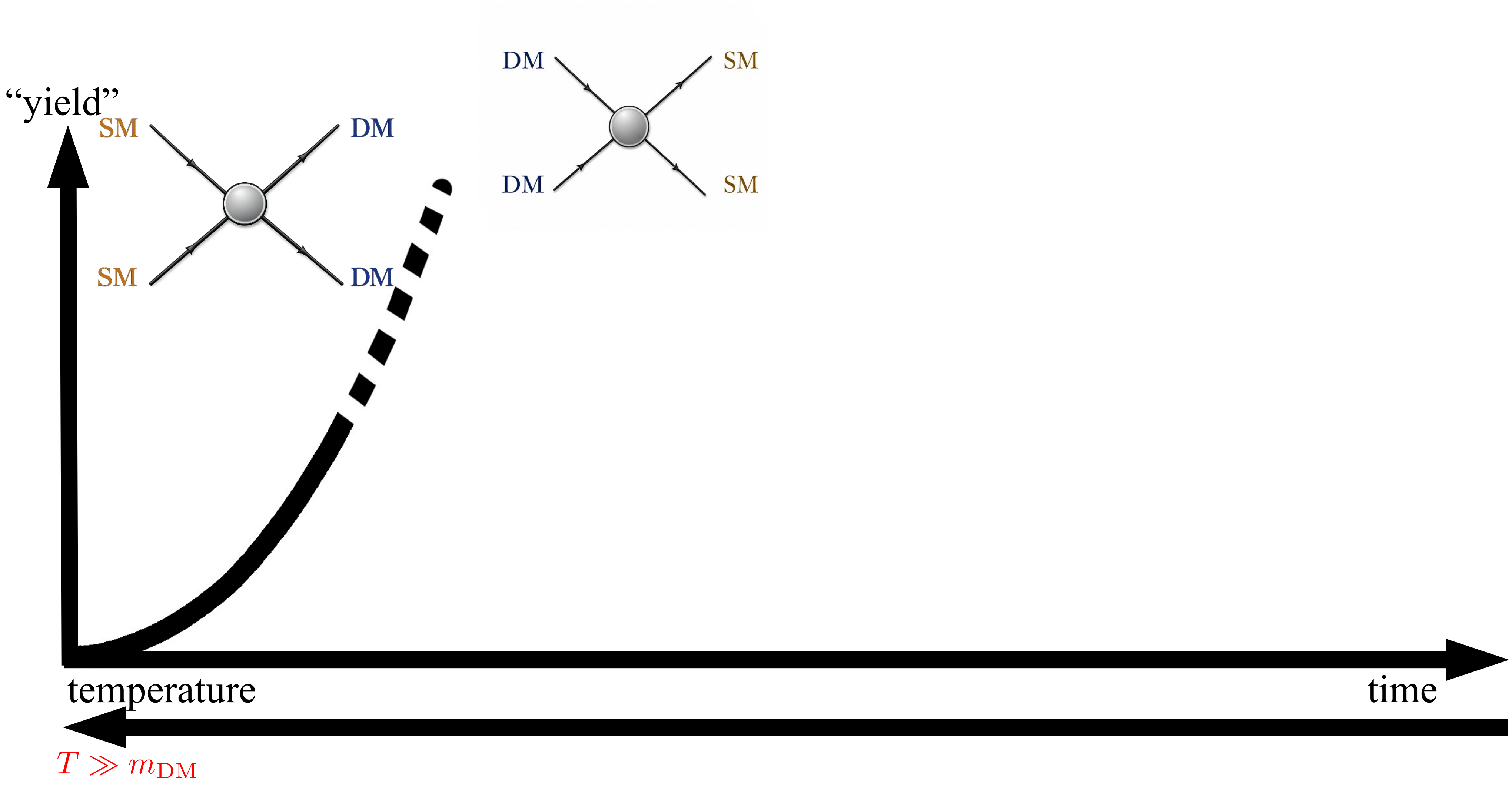

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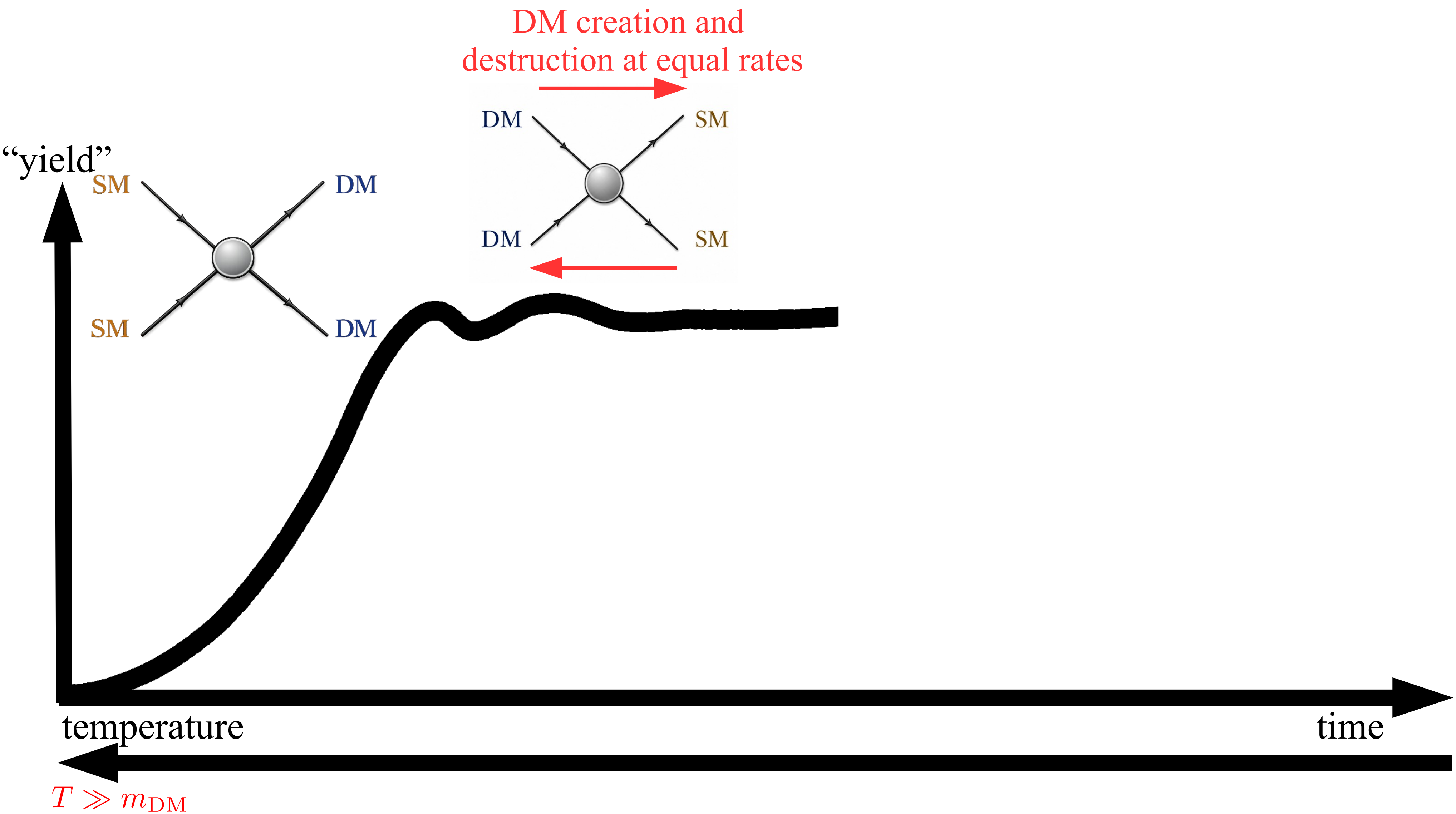

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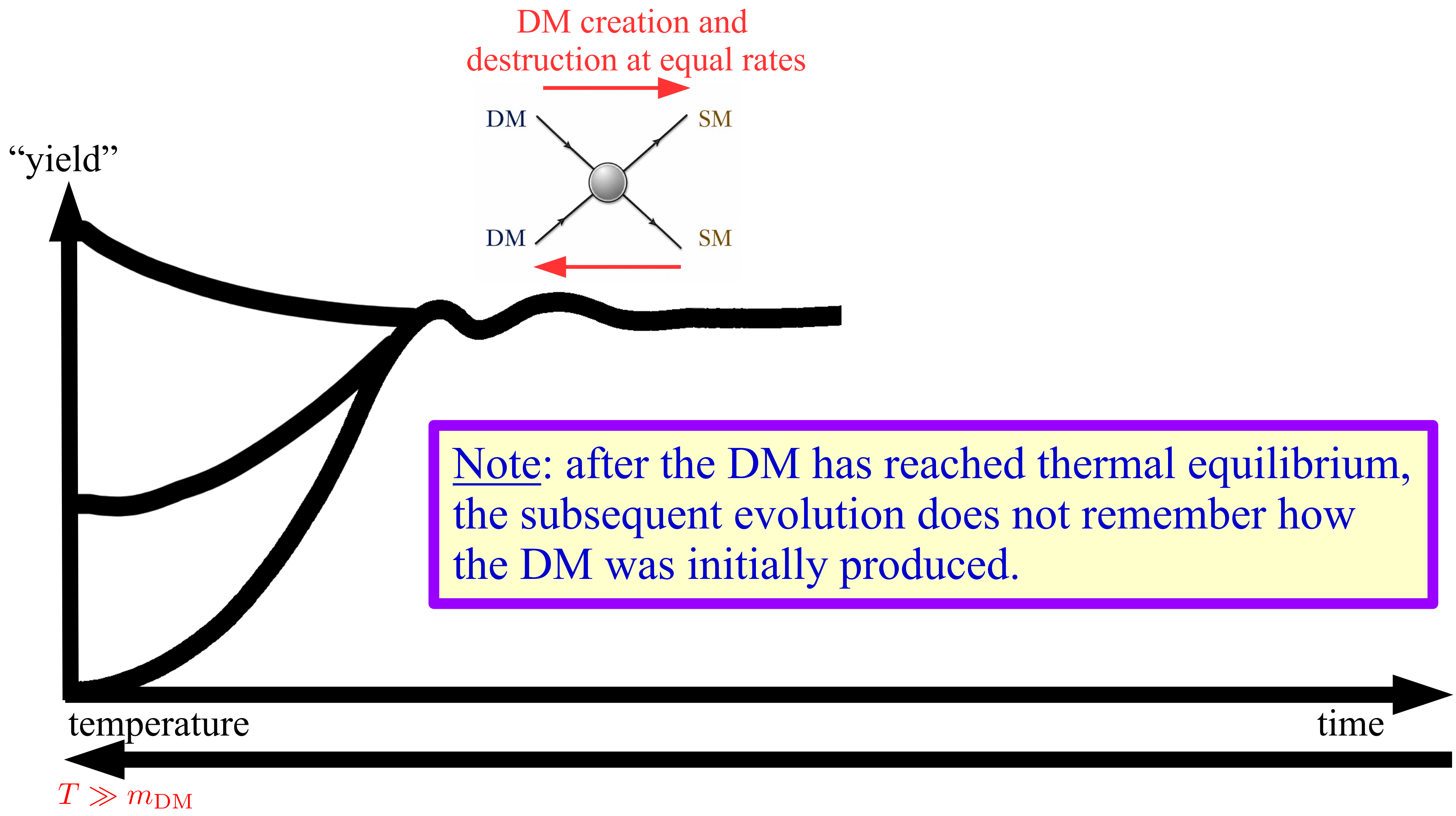
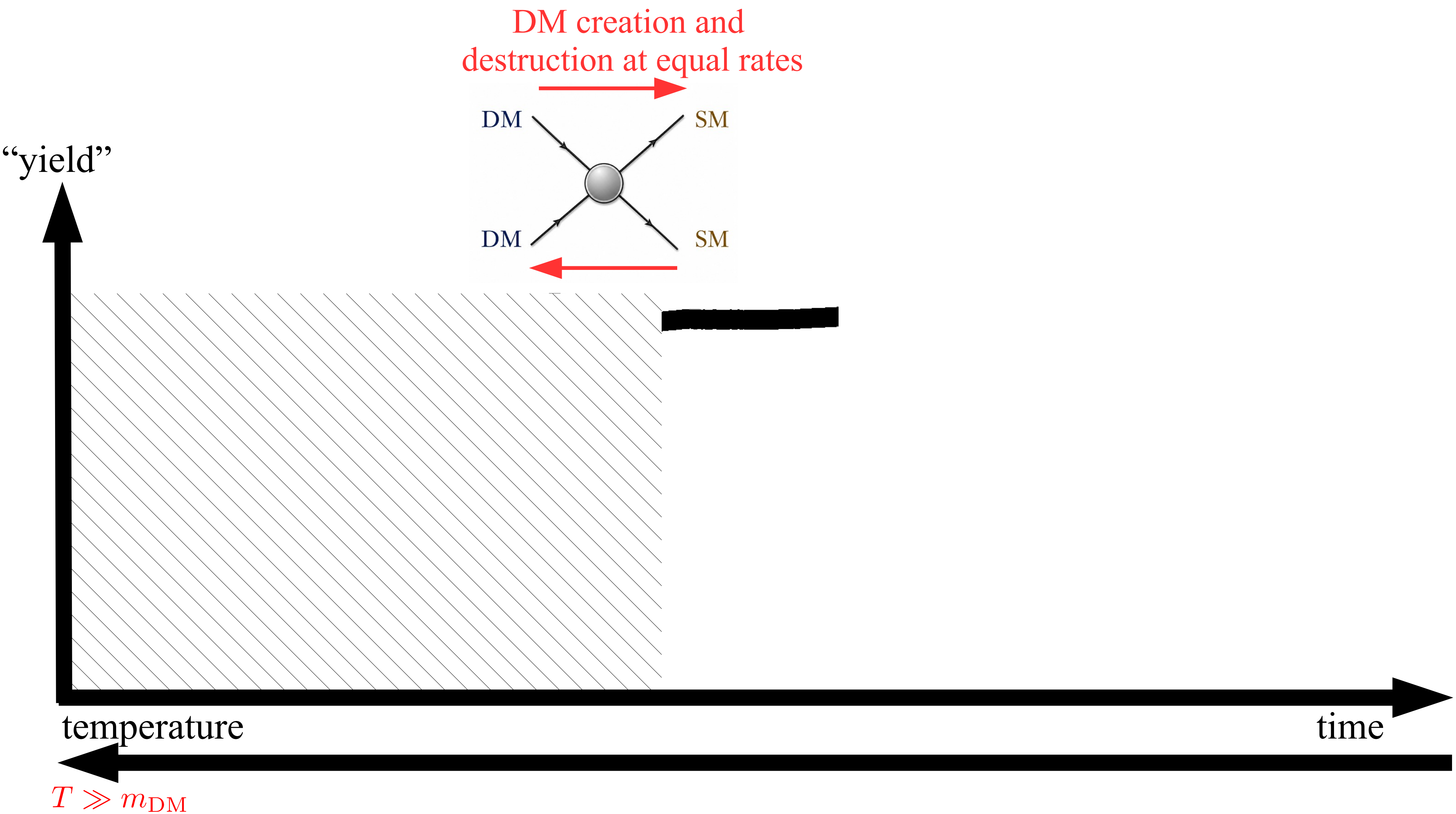


Note: after the DM has reached thermal equilibrium, the subsequent evolution does not remember how the DM was initially produced.

WIMP history (in a nutshell)



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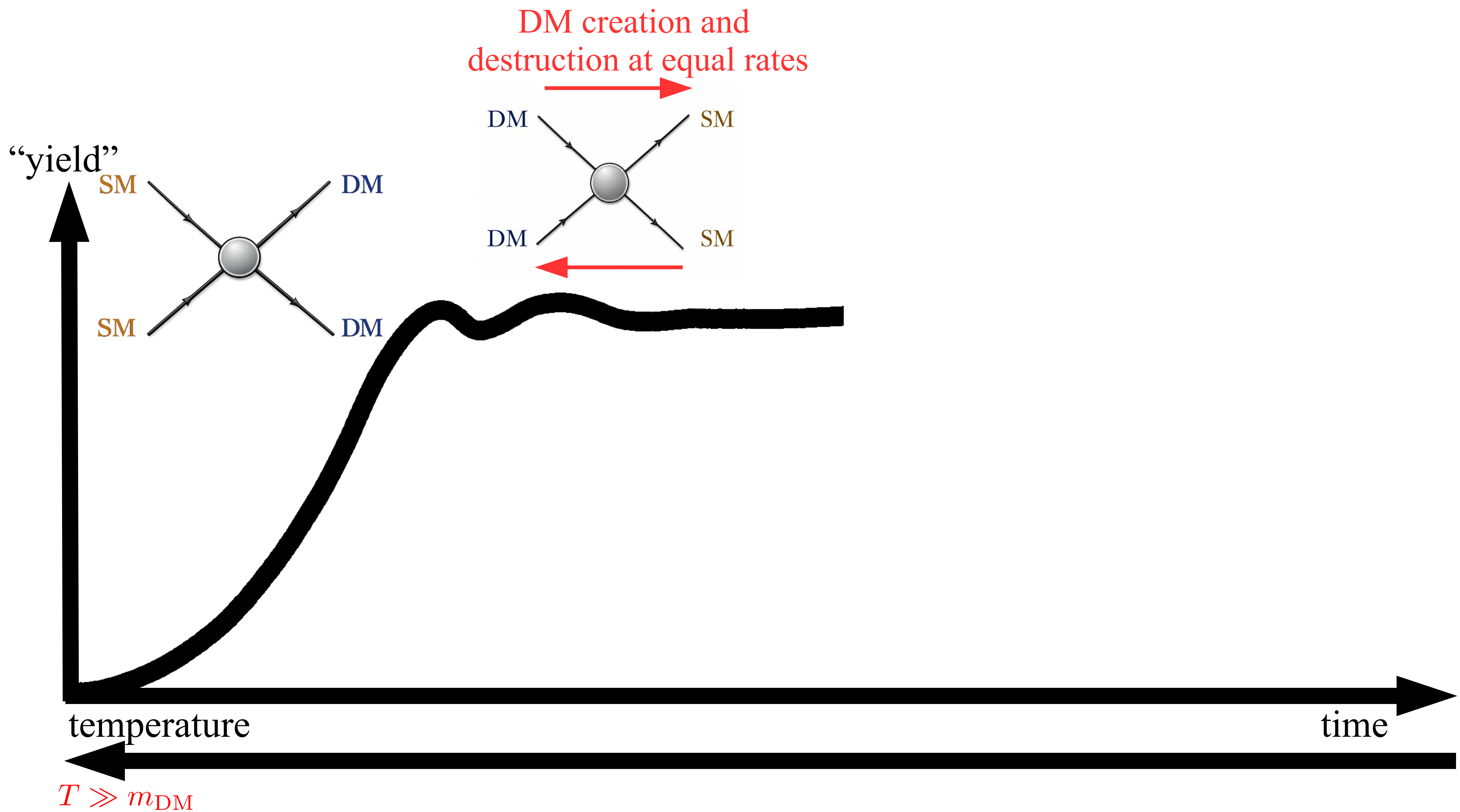

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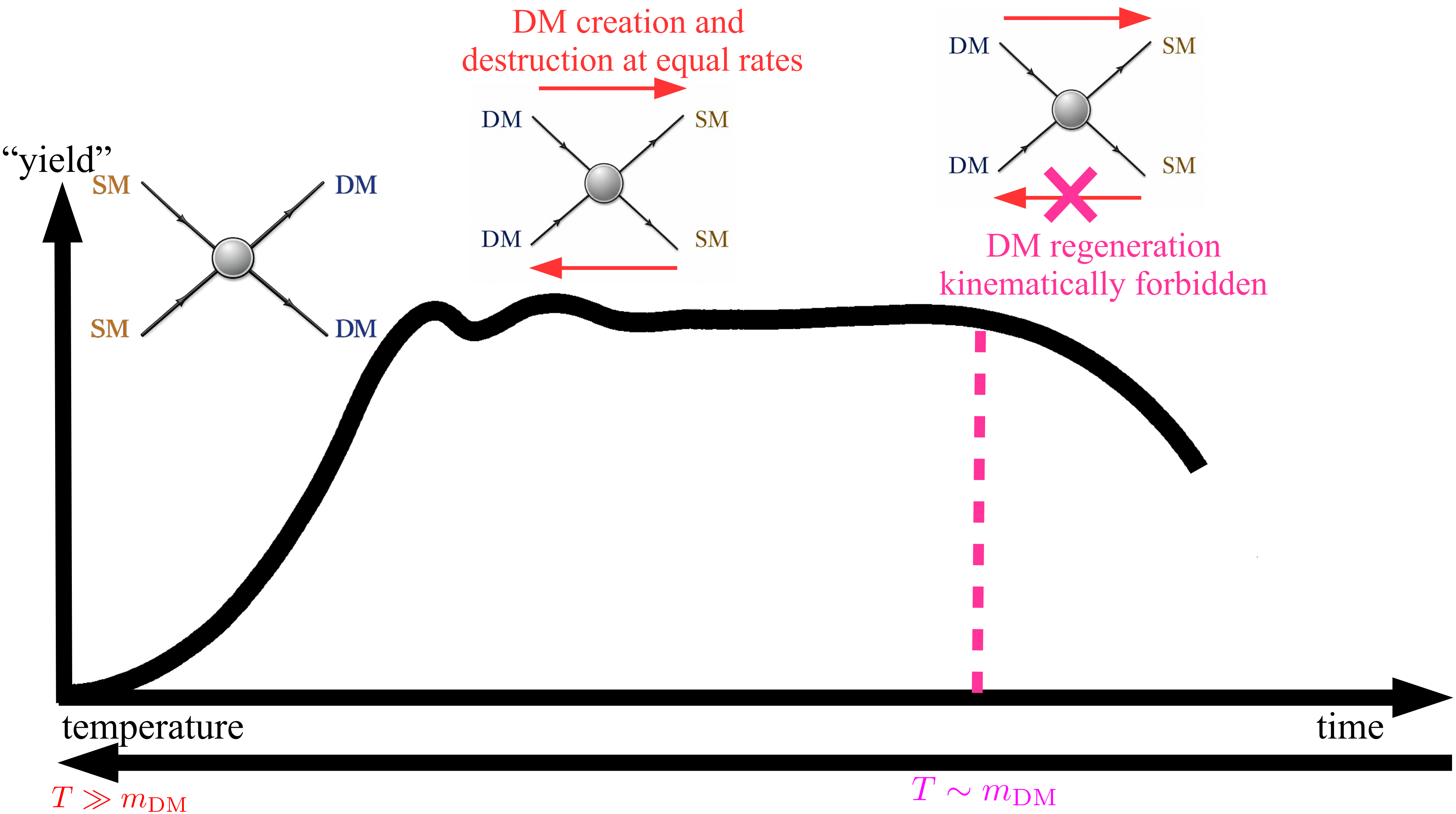

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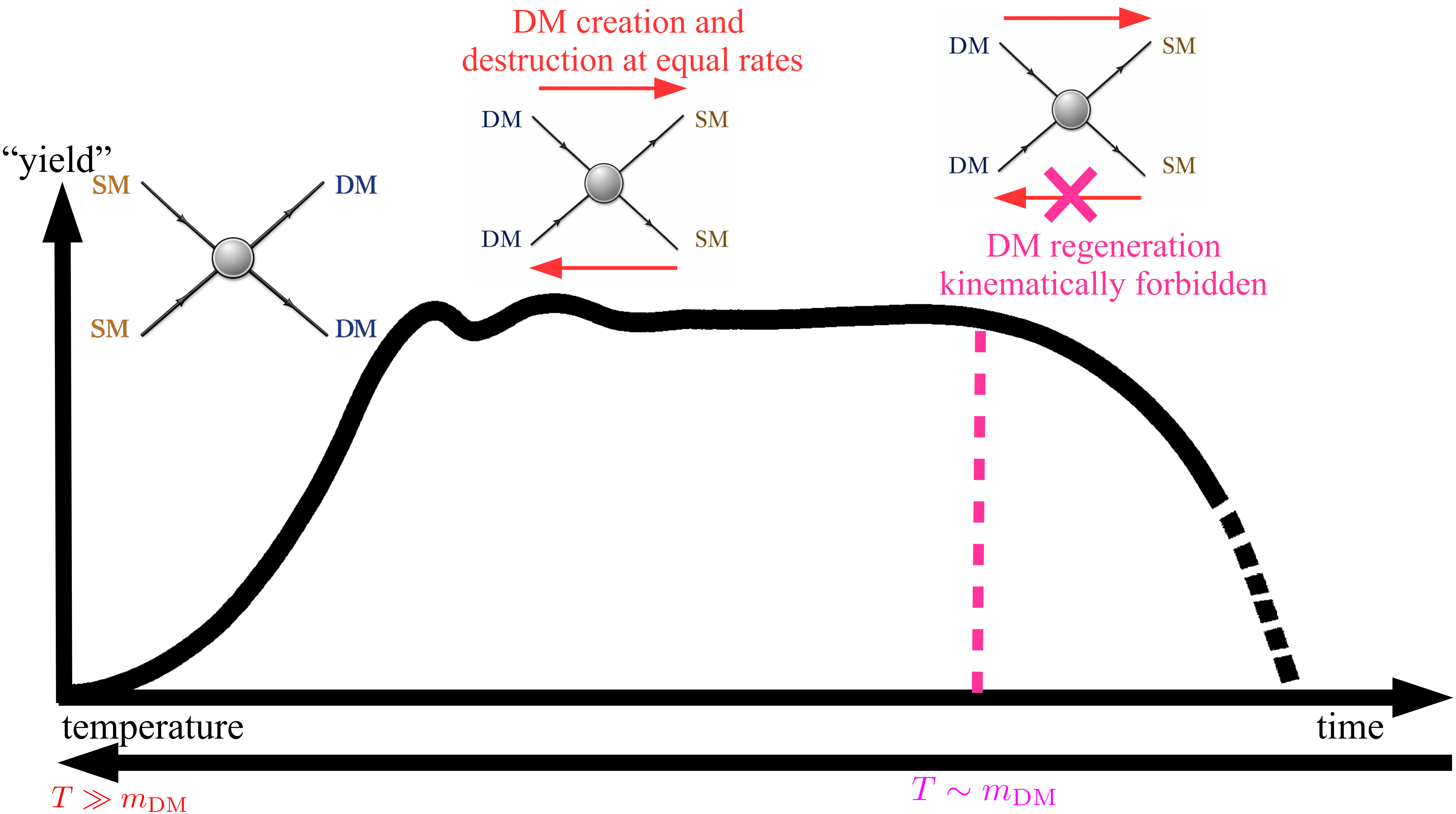

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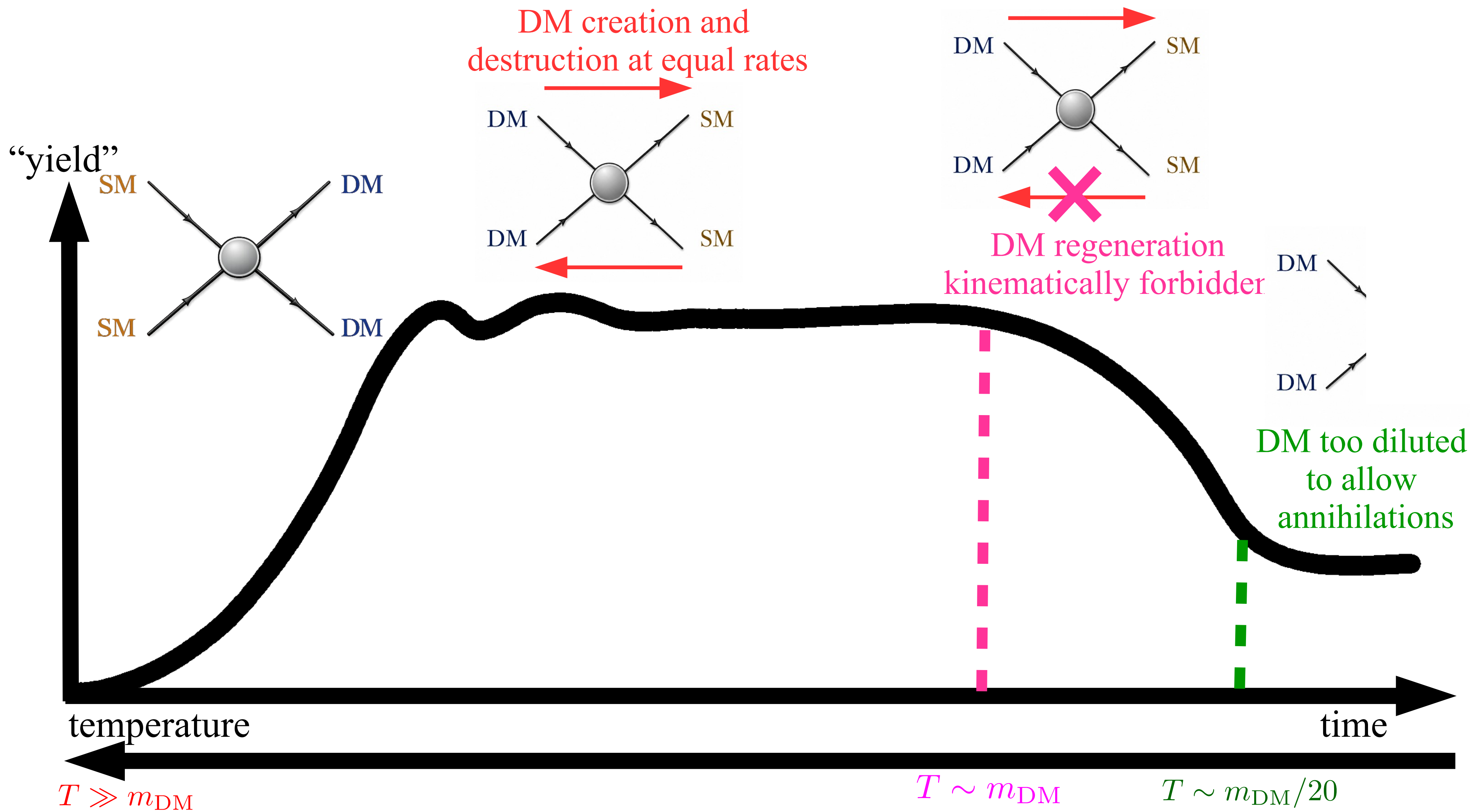

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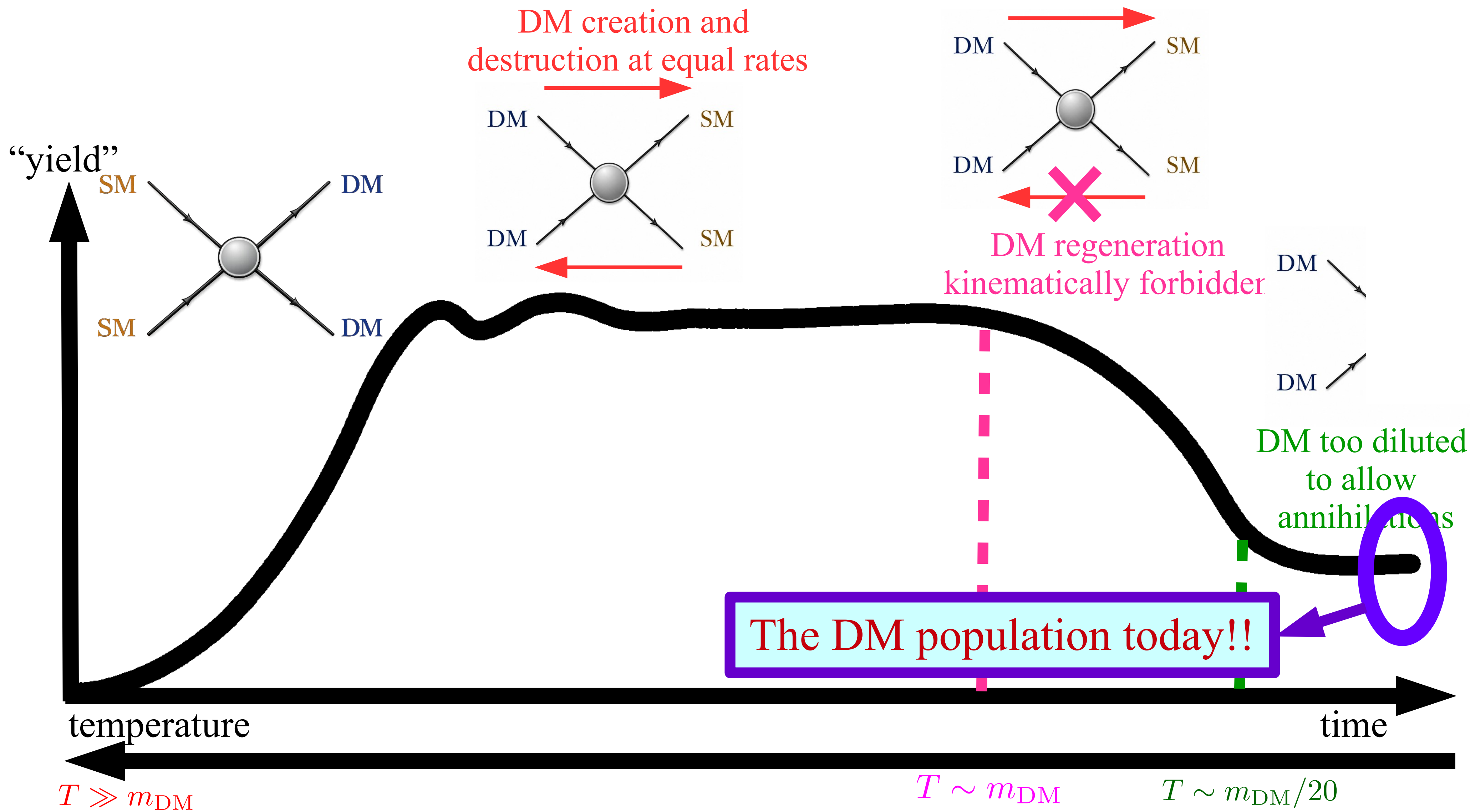

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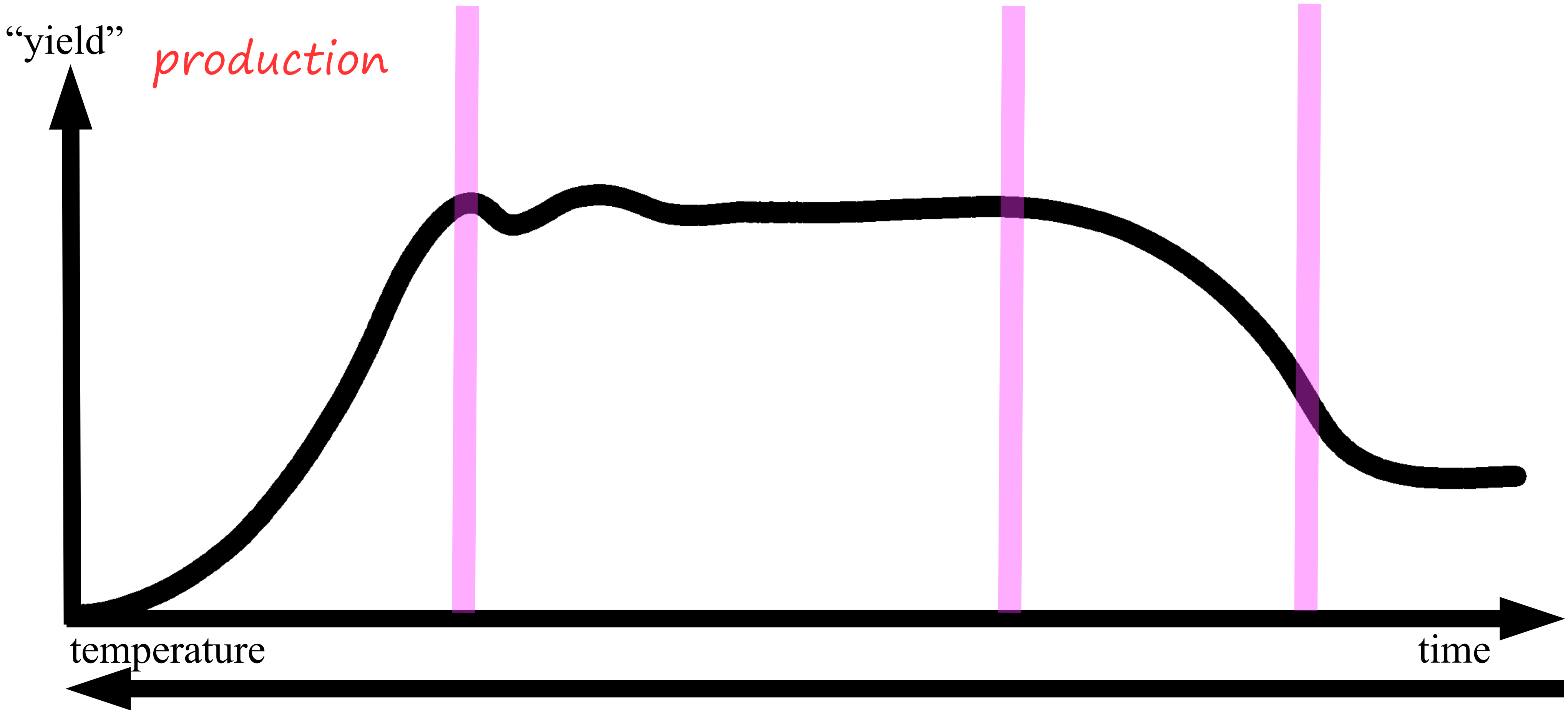

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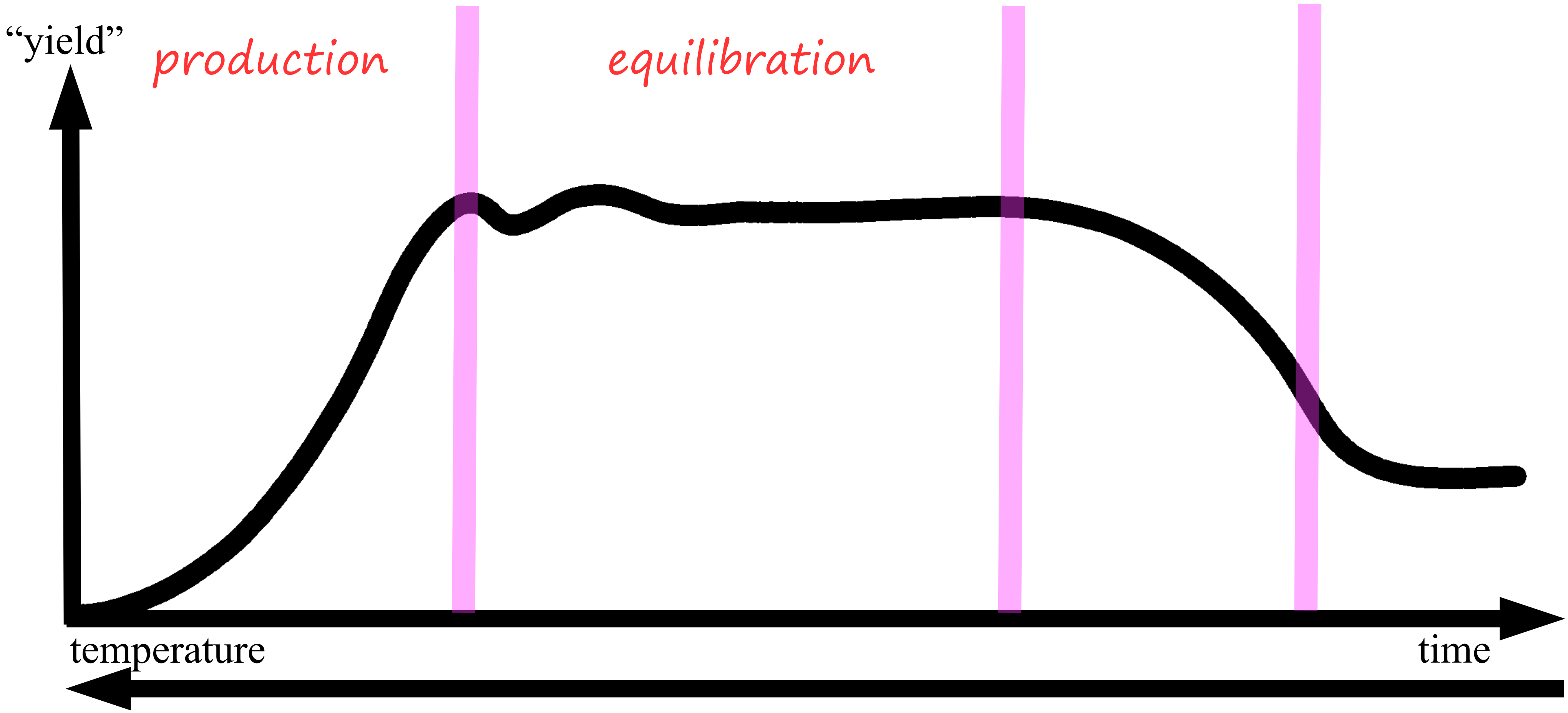

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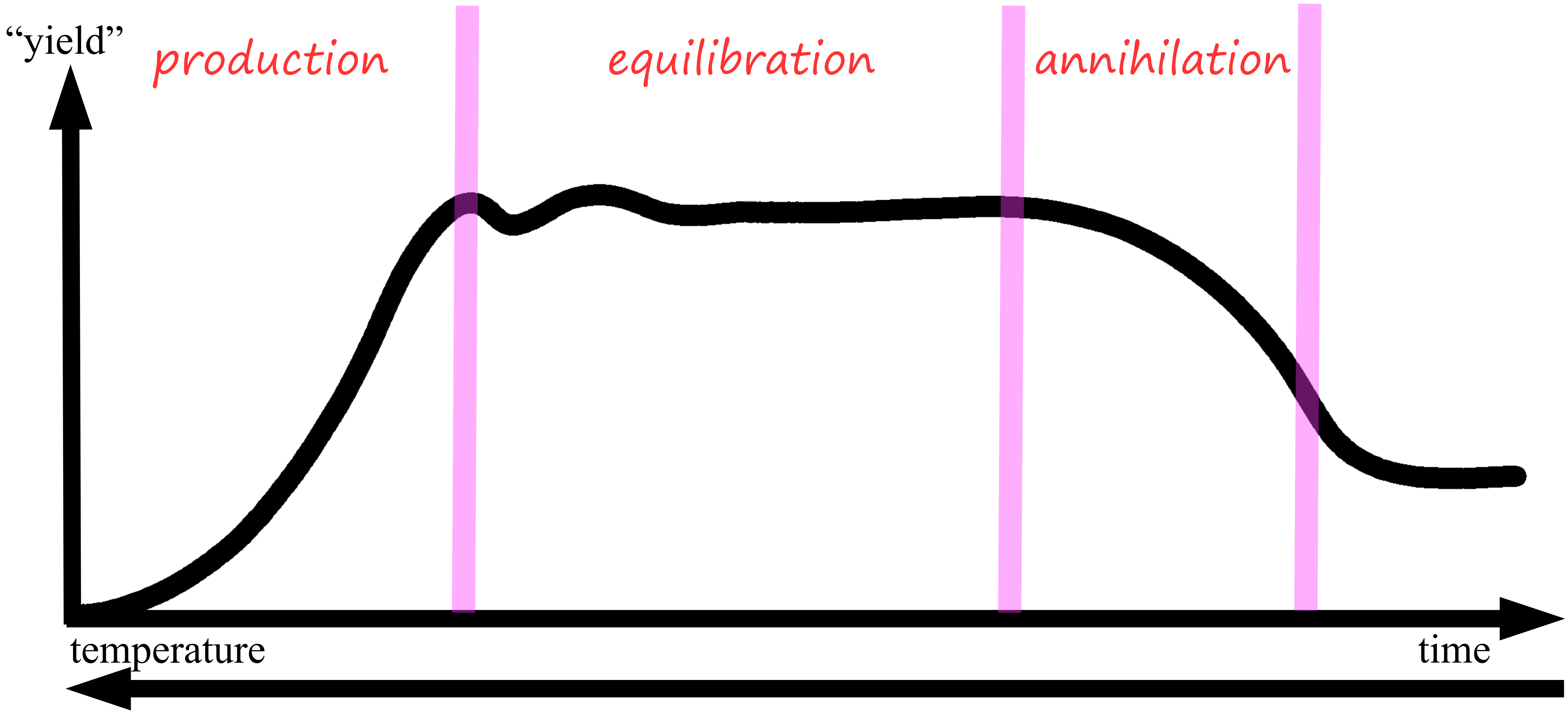

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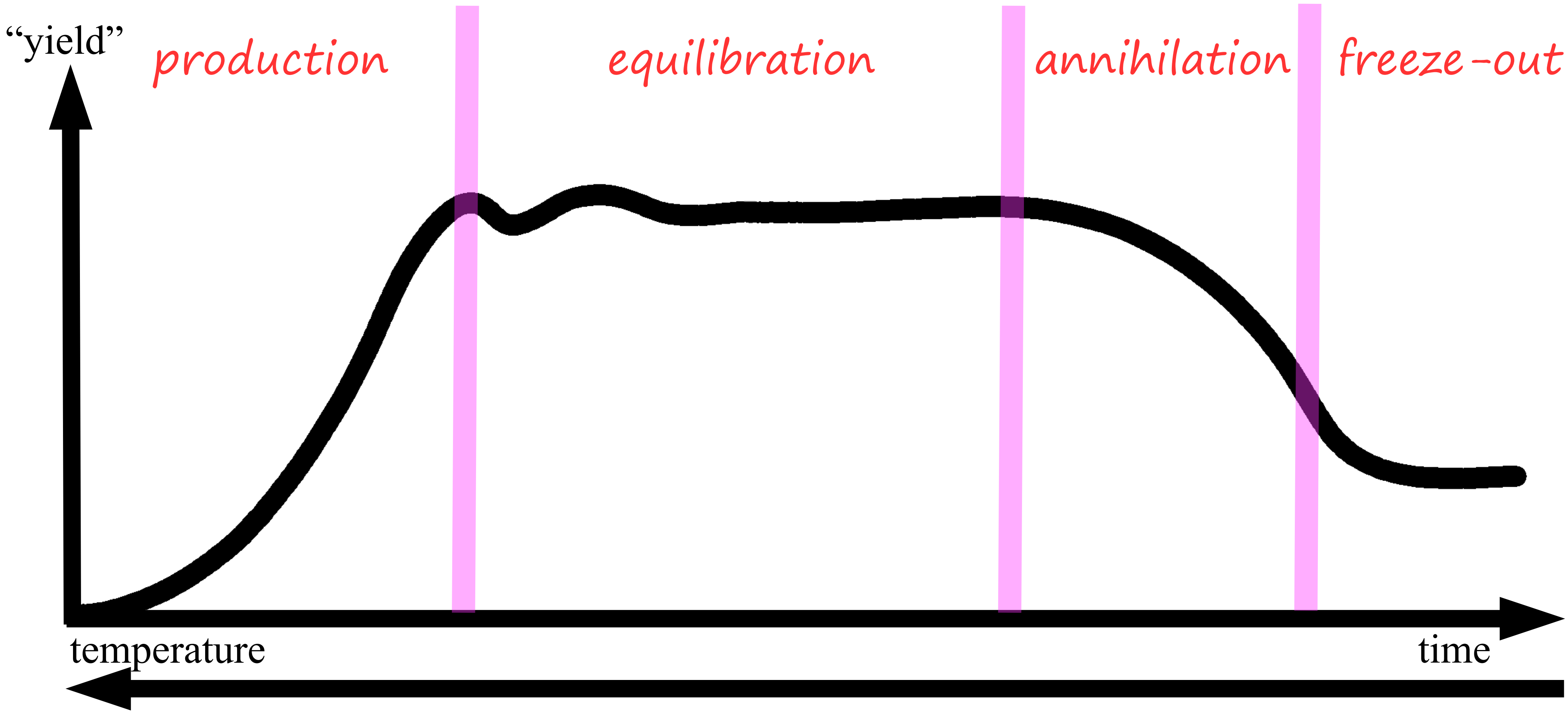
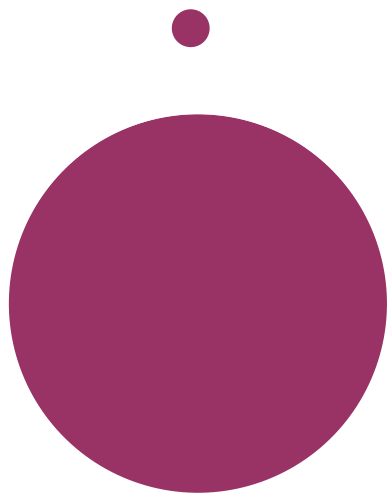


A heuristic view of the freeze-out

The probability of interaction is controlled by the cross-section



Small annihilation rate

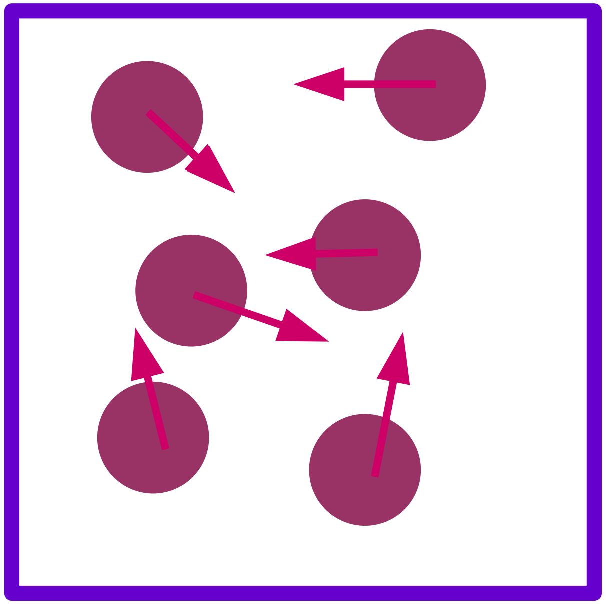
Large annihilation rate

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.

A heuristic view of the freeze-out

Dark matter population in a static Universe



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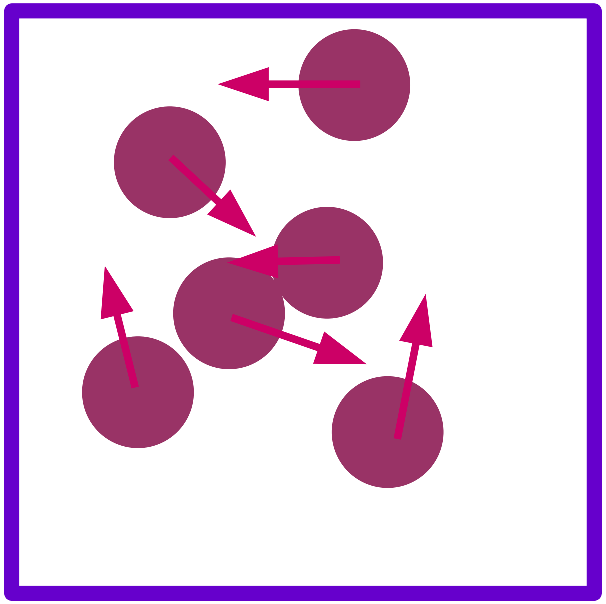

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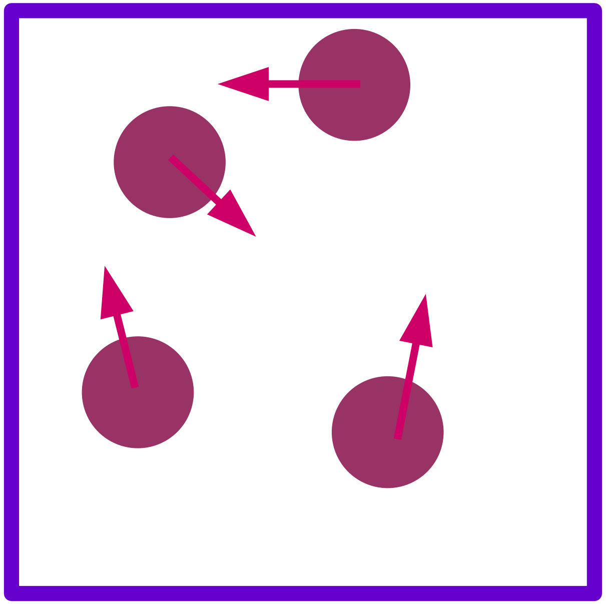

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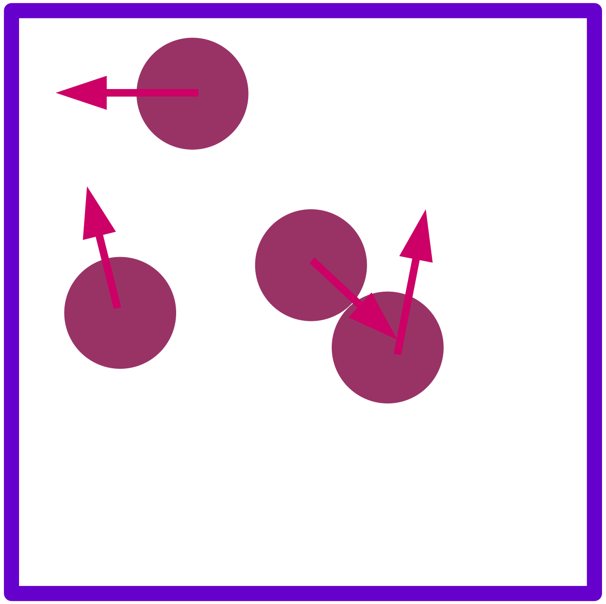

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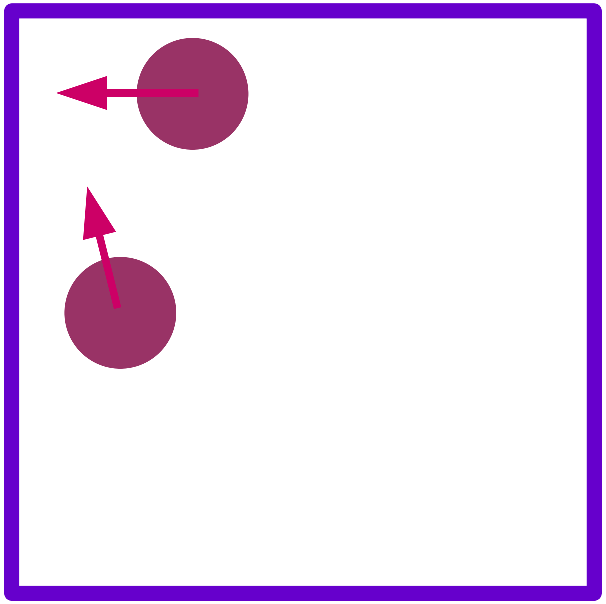

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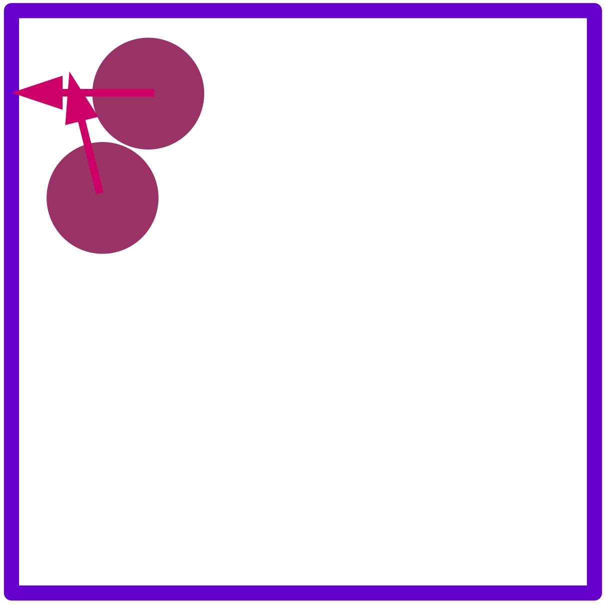

A heuristic view of the freeze-out

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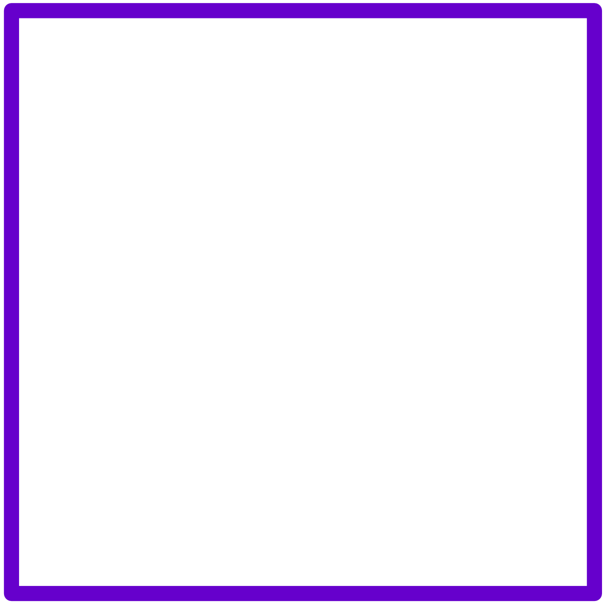
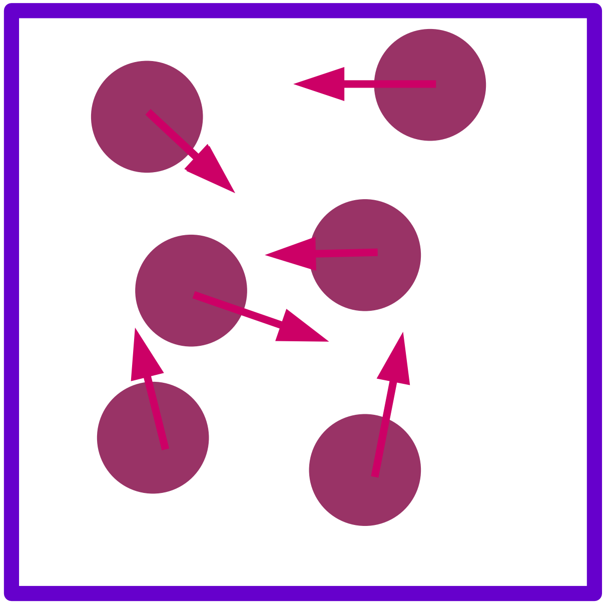
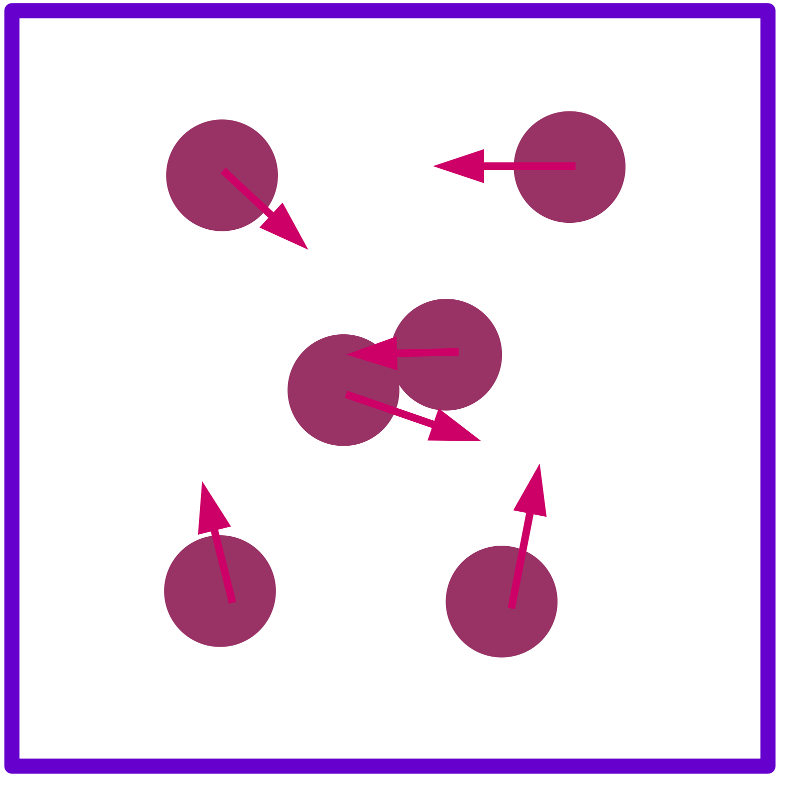


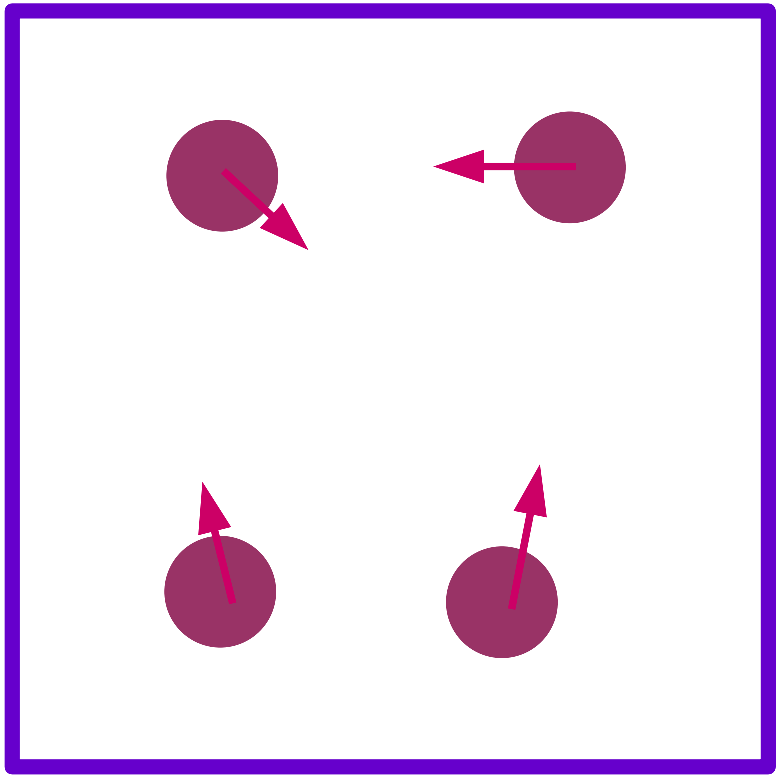
No DM particles at the end!

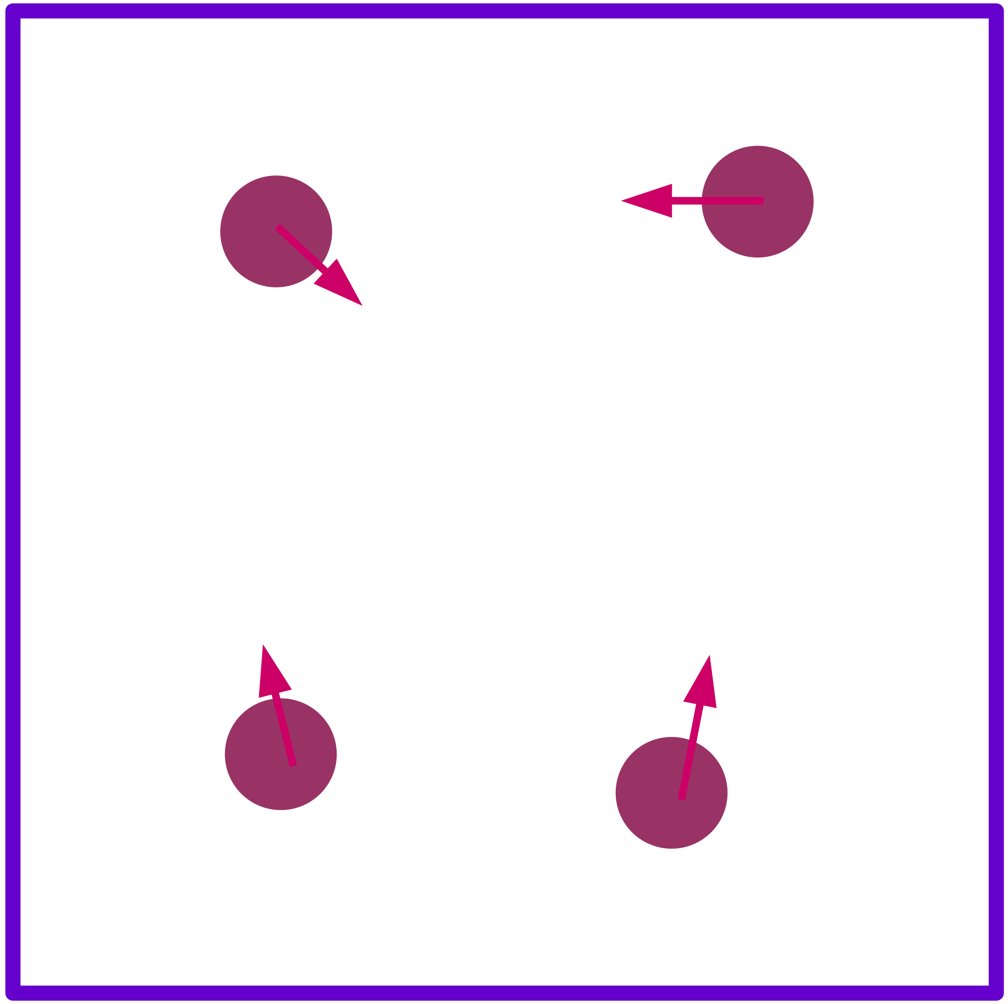
A heuristic view of the freeze-out

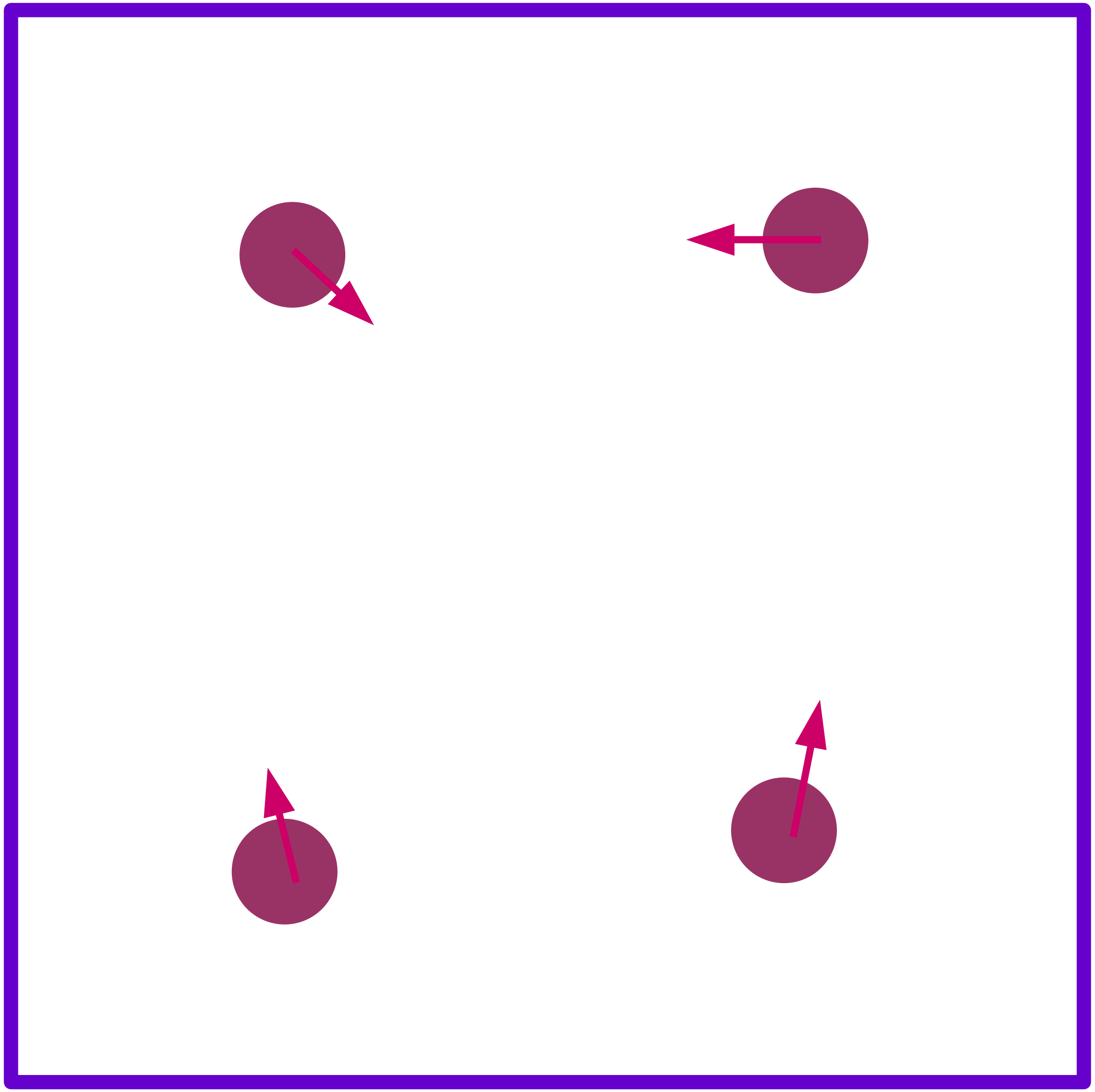
Dark matter population in an expanding Universe





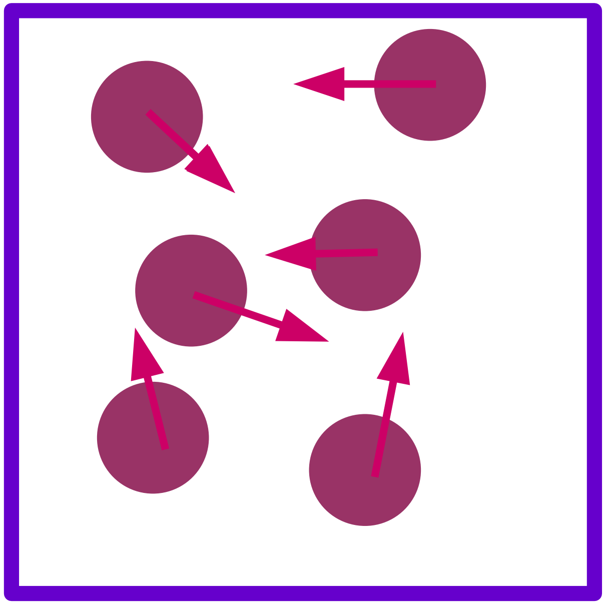




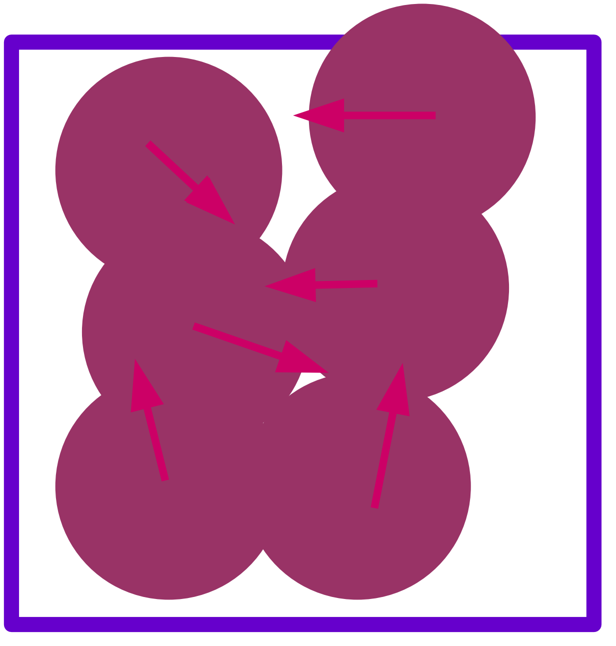


Dark matter particles can no longer annihilate.
The number of dark matter particles “freezes-out”

The *relic abundance* of dark matter particles depends on their annihilation cross section and on their velocity



The *relic abundance* of dark matter particles depends on their annihilation cross section...



Large annihilation cross section → Small relic abundance

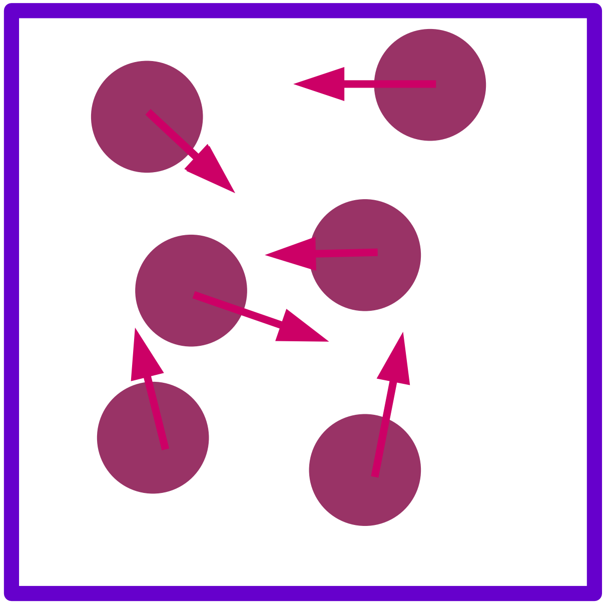
Small annihilation cross section → Large relic abundance

The *relic abundance* of dark matter particles depends on their annihilation cross section...

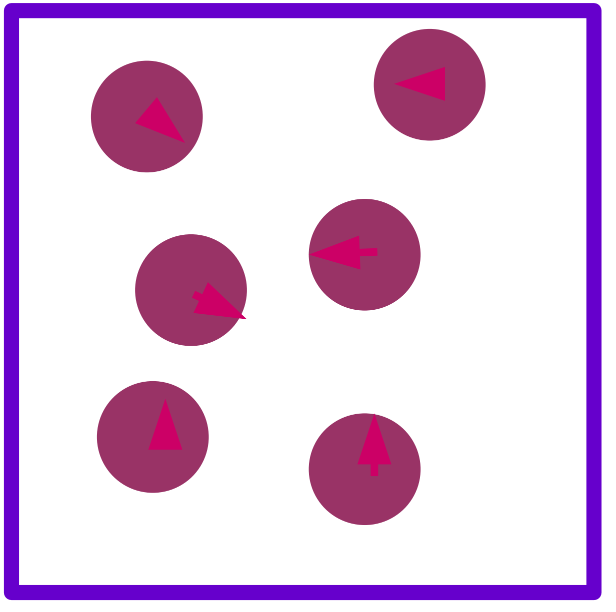
Large annihilation cross section → Small relic abundance

Small annihilation cross section → Large relic abundance

… and on their velocity



… and on their velocity



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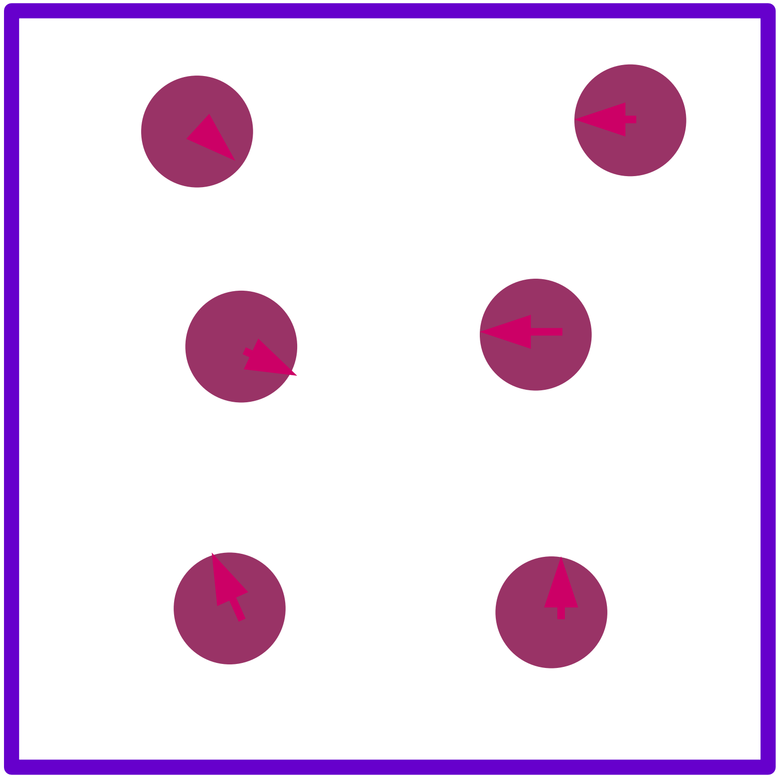


Large velocity → Small relic abundance

Small velocity → Large relic abundance

A heuristic view of the freeze-out

$$\Omega_{\mathrm{DM}} h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

A heuristic view of the freeze-out

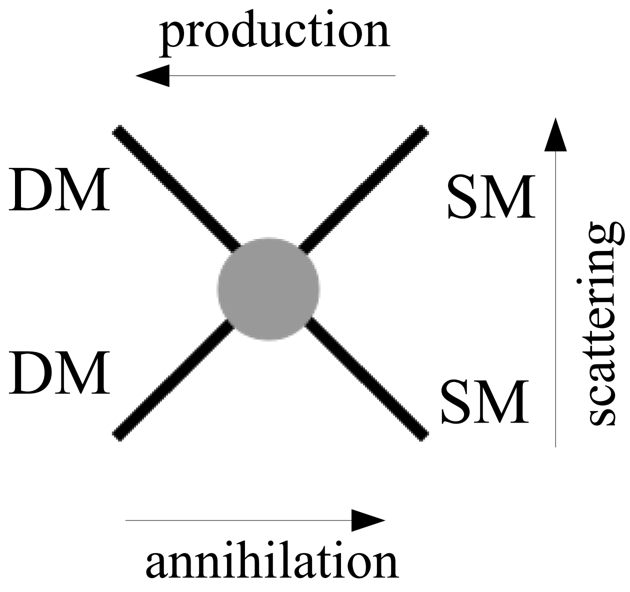
Boltzmann equation for the yield

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm ann}(x)}{H(x)}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right]$$

$$\Omega_{\rm DM} h^2 \simeq \frac{3\times 10^{-27}\,{\rm cm^3 s^{-1}}}{\langle \sigma v \rangle}$$

Main results from this part

WIMP dark matter



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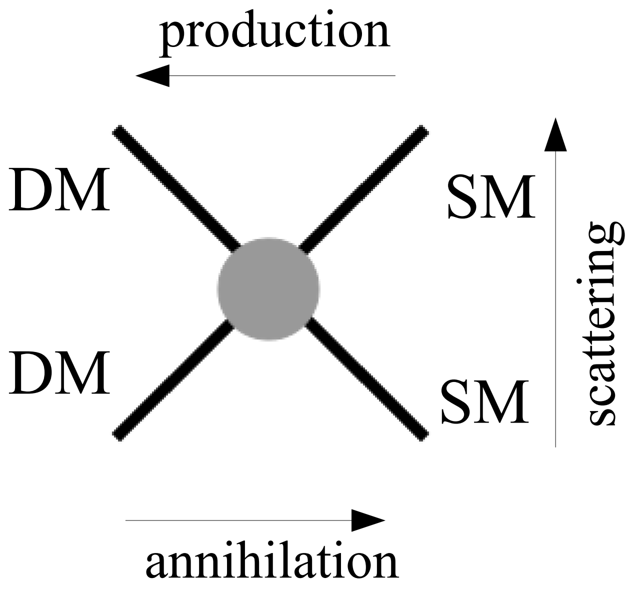

Relic abundance of DM particles

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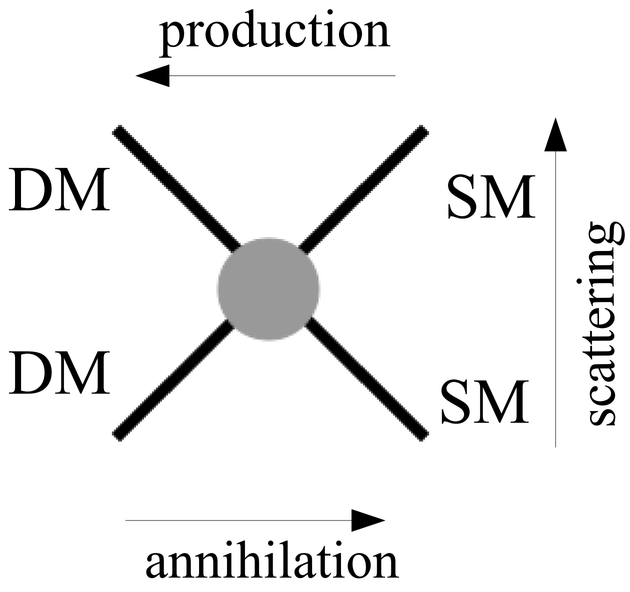

Relic abundance of DM particles

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

Correct DM abundance $\Omega h^2 = 0.12$ if

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

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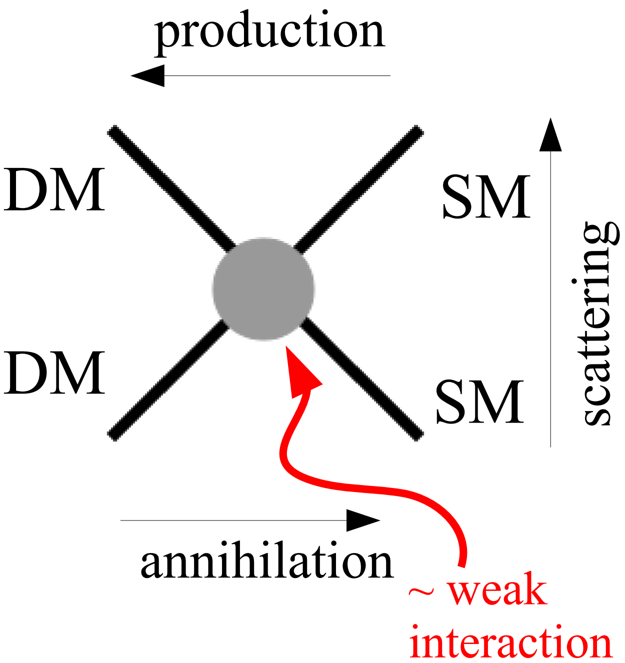

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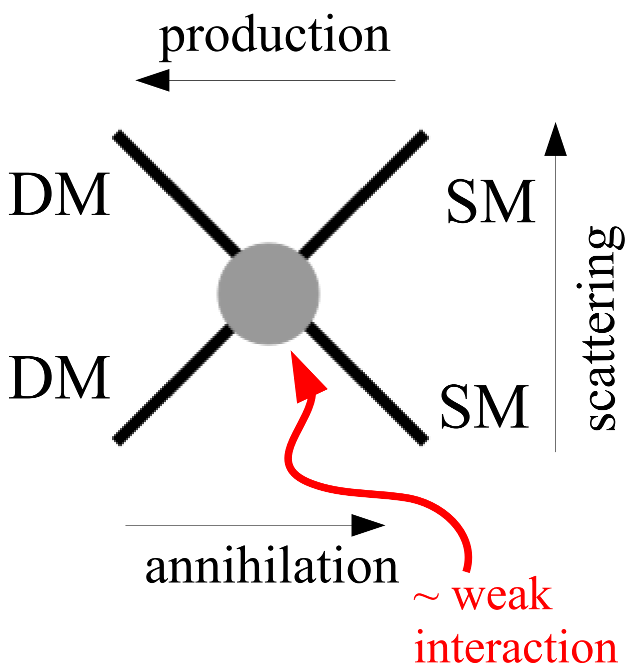

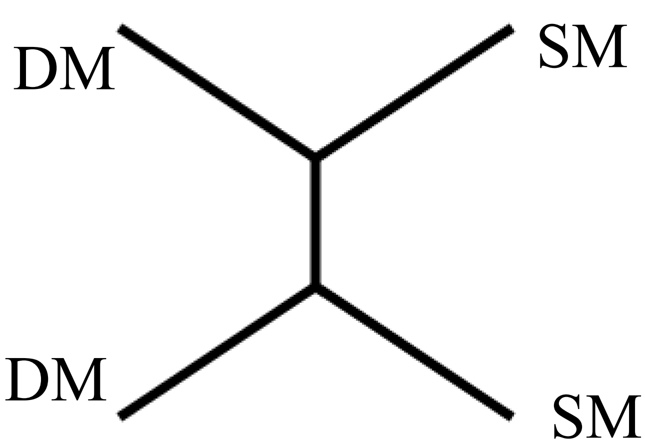

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Correct DM abundance Ωh^2=0.12 if

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

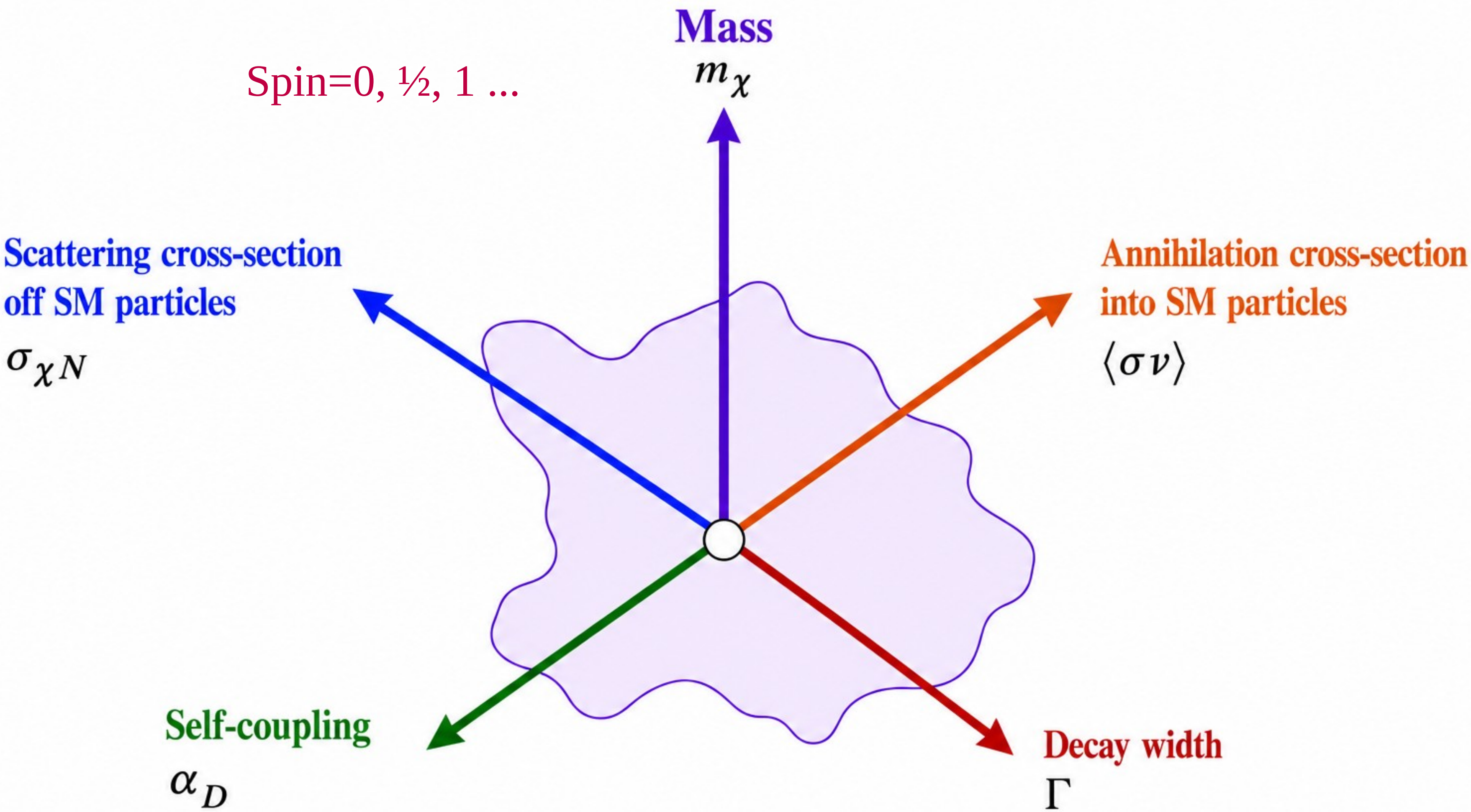
$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

$$m_{\mathrm{DM}} \sim 10\,\mathrm{GeV} - 1\,\mathrm{TeV}$$

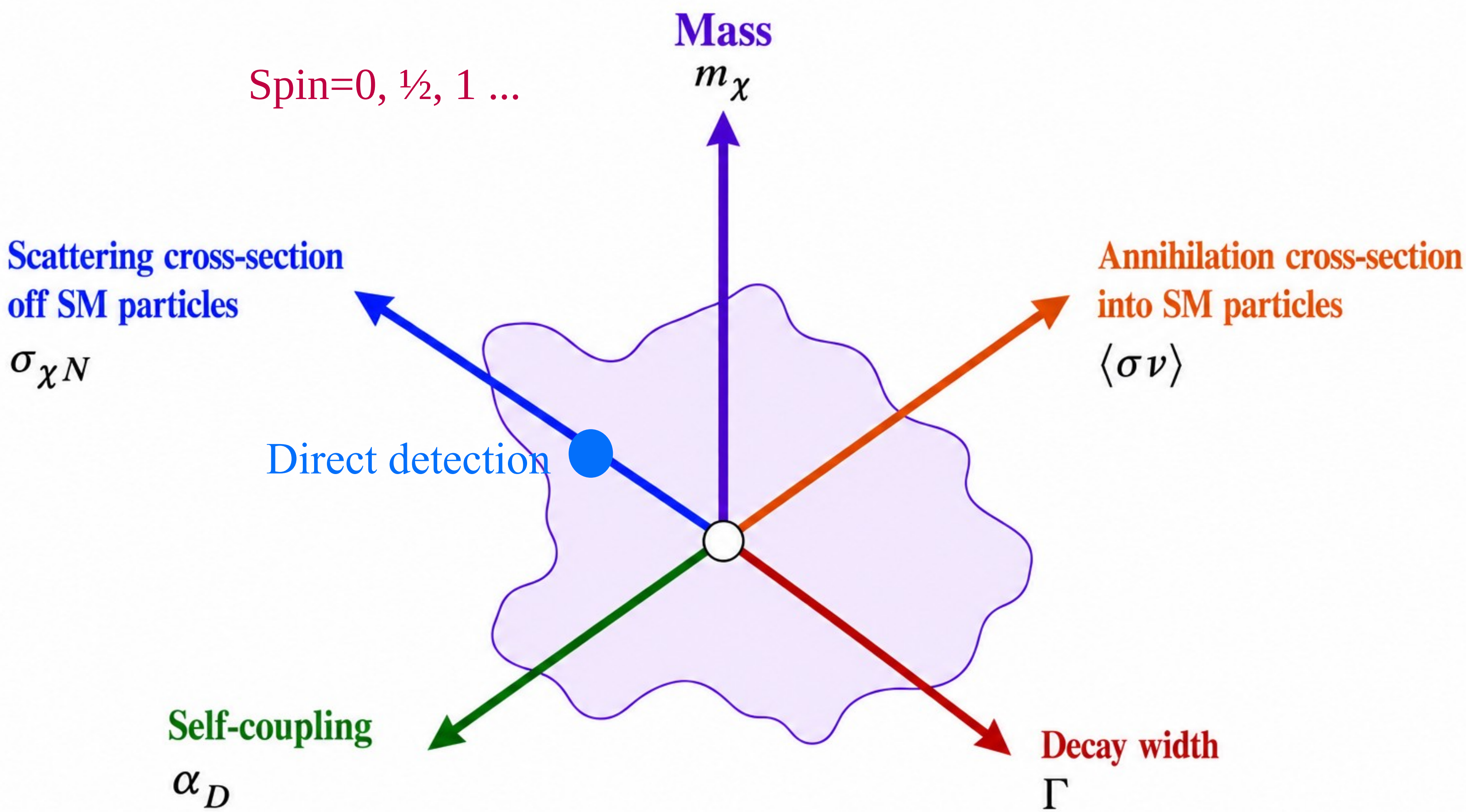
(provided $g \sim g_{\mathrm{weak}} \sim 0.1$)

Particle Dark Matter Parameter Space

Spin=0, ½, 1 ...



Particle Dark Matter Parameter Space



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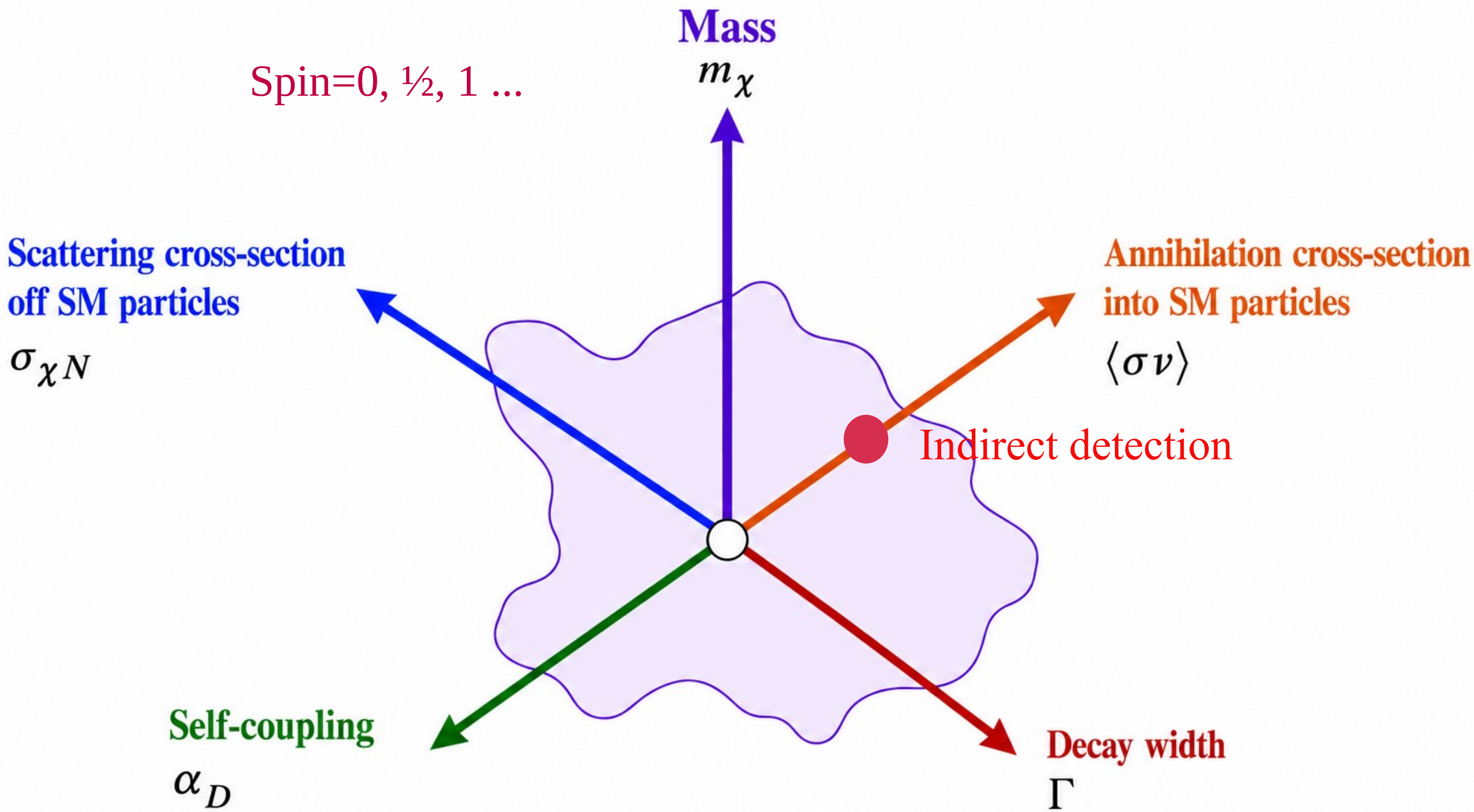
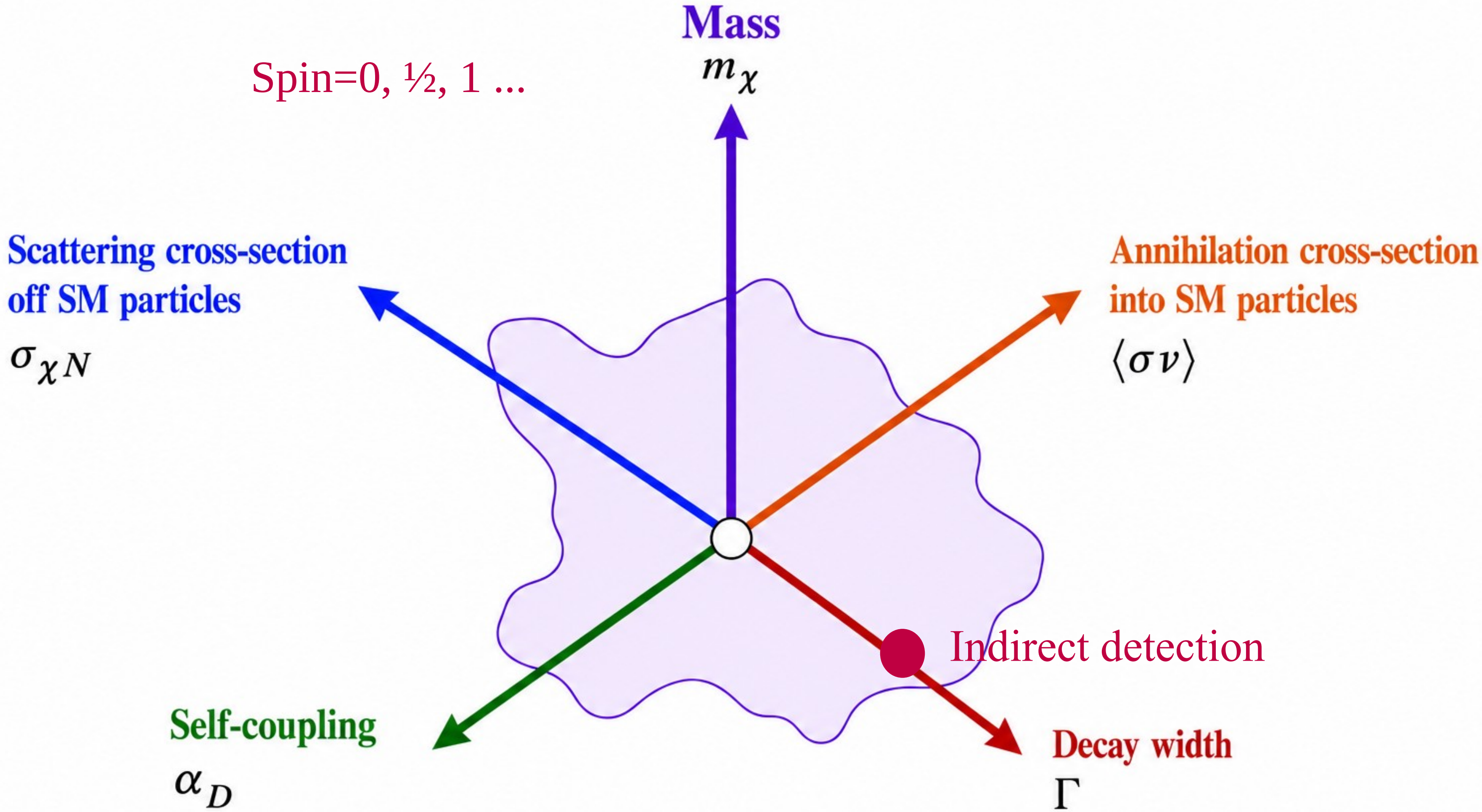
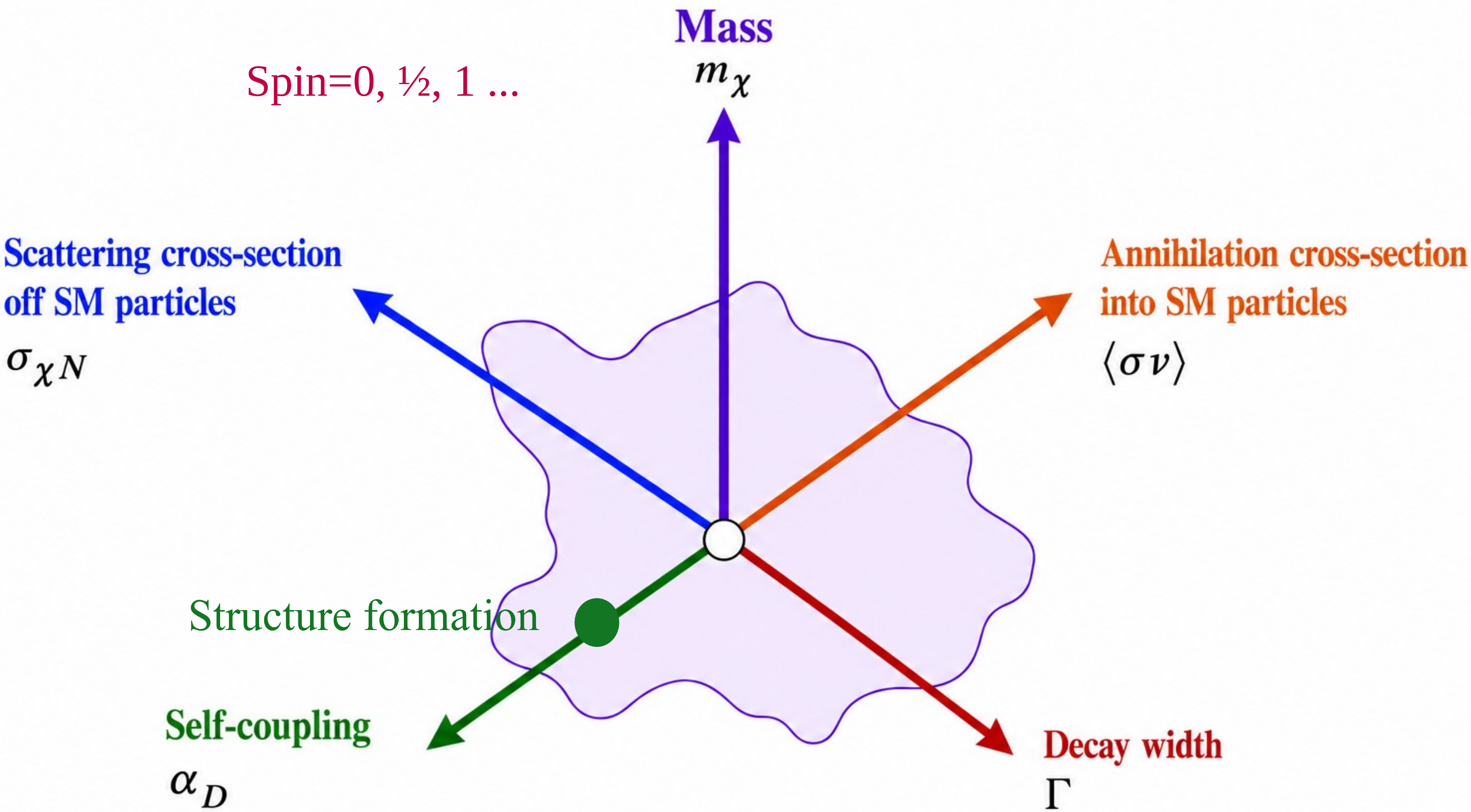


Particle Dark Matter Parameter Space



Particle Dark Matter Parameter Space



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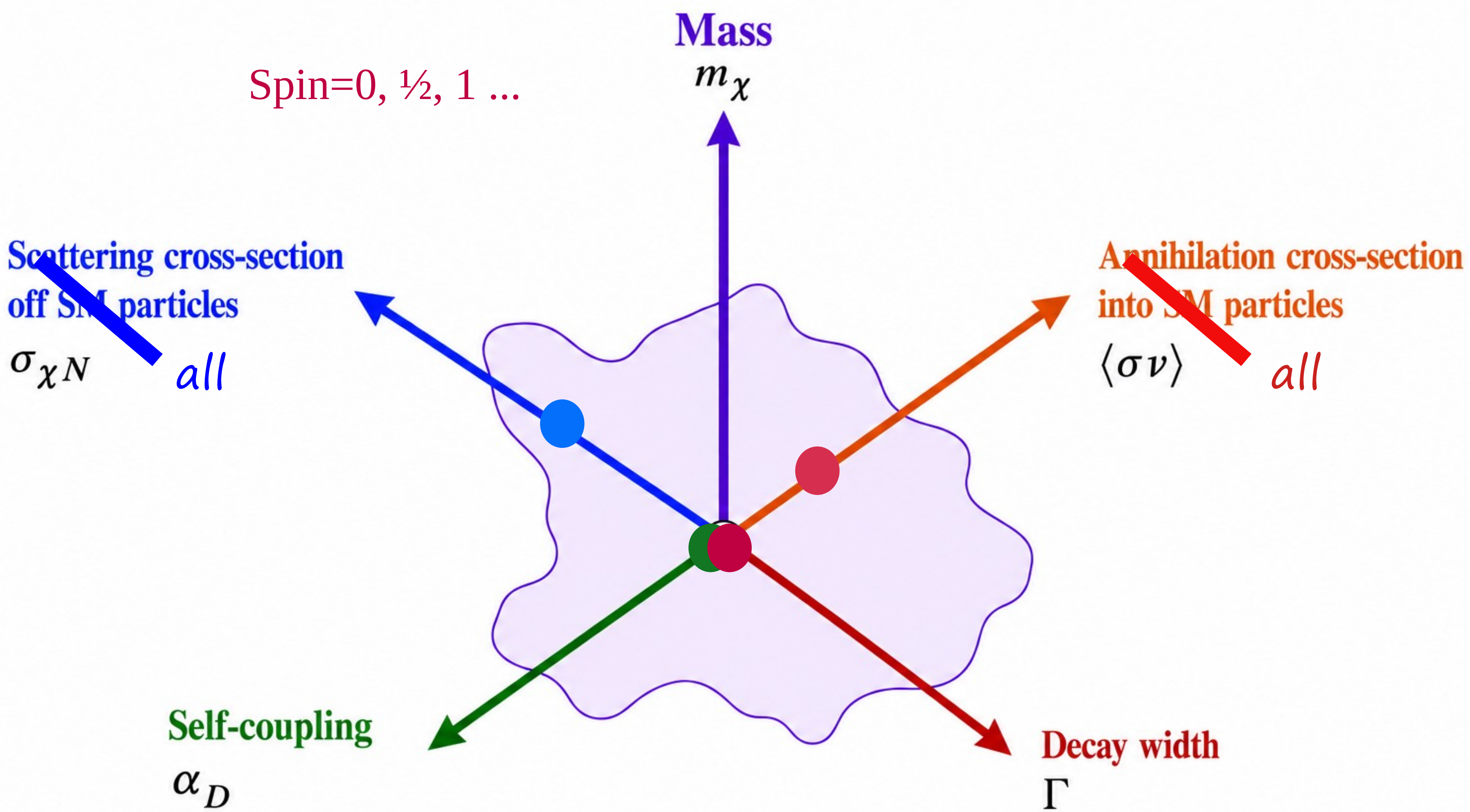
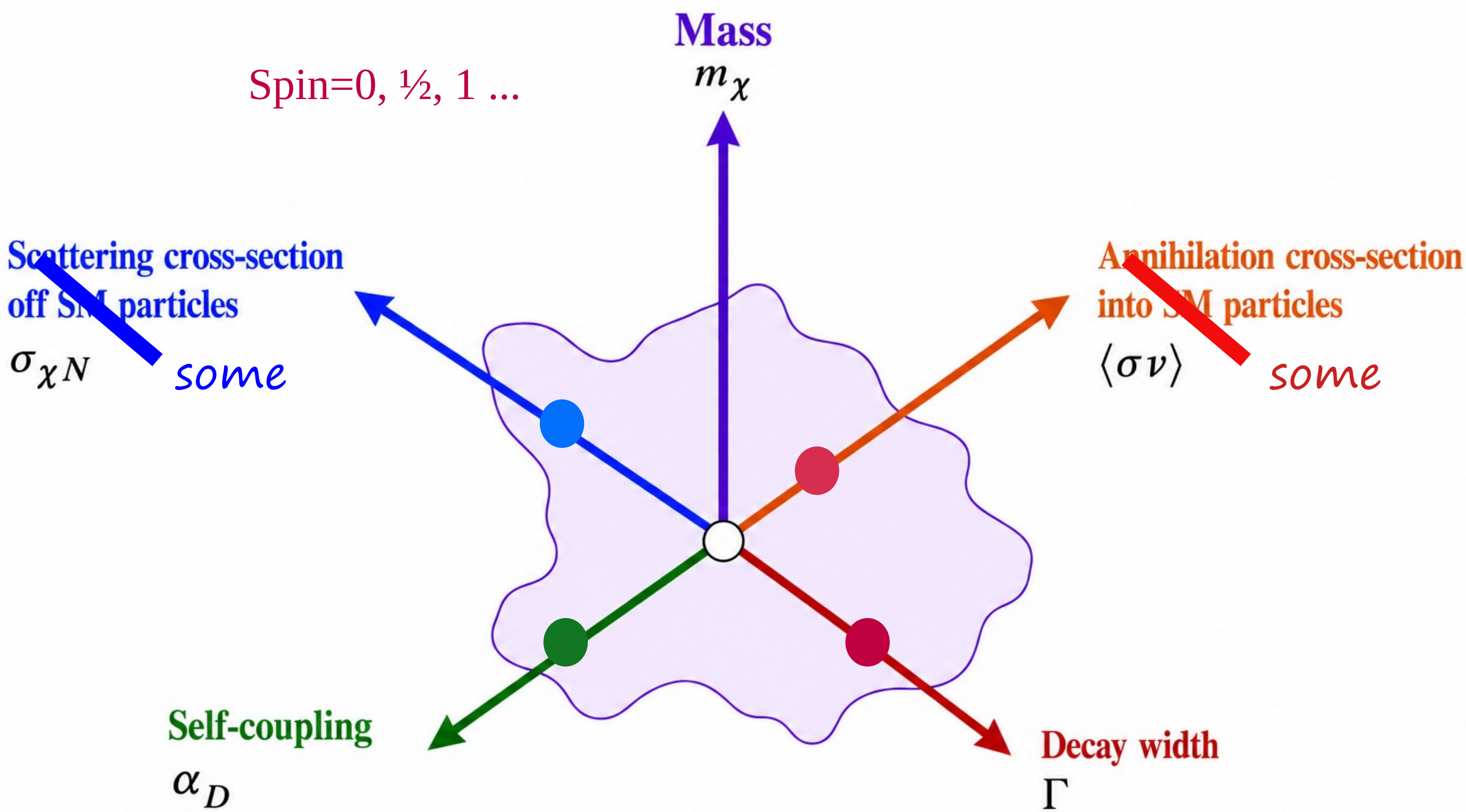


Traditional dark matter searches were optimized to detect the lightest neutralino of the Minimal Supersymmetric Standard Model.

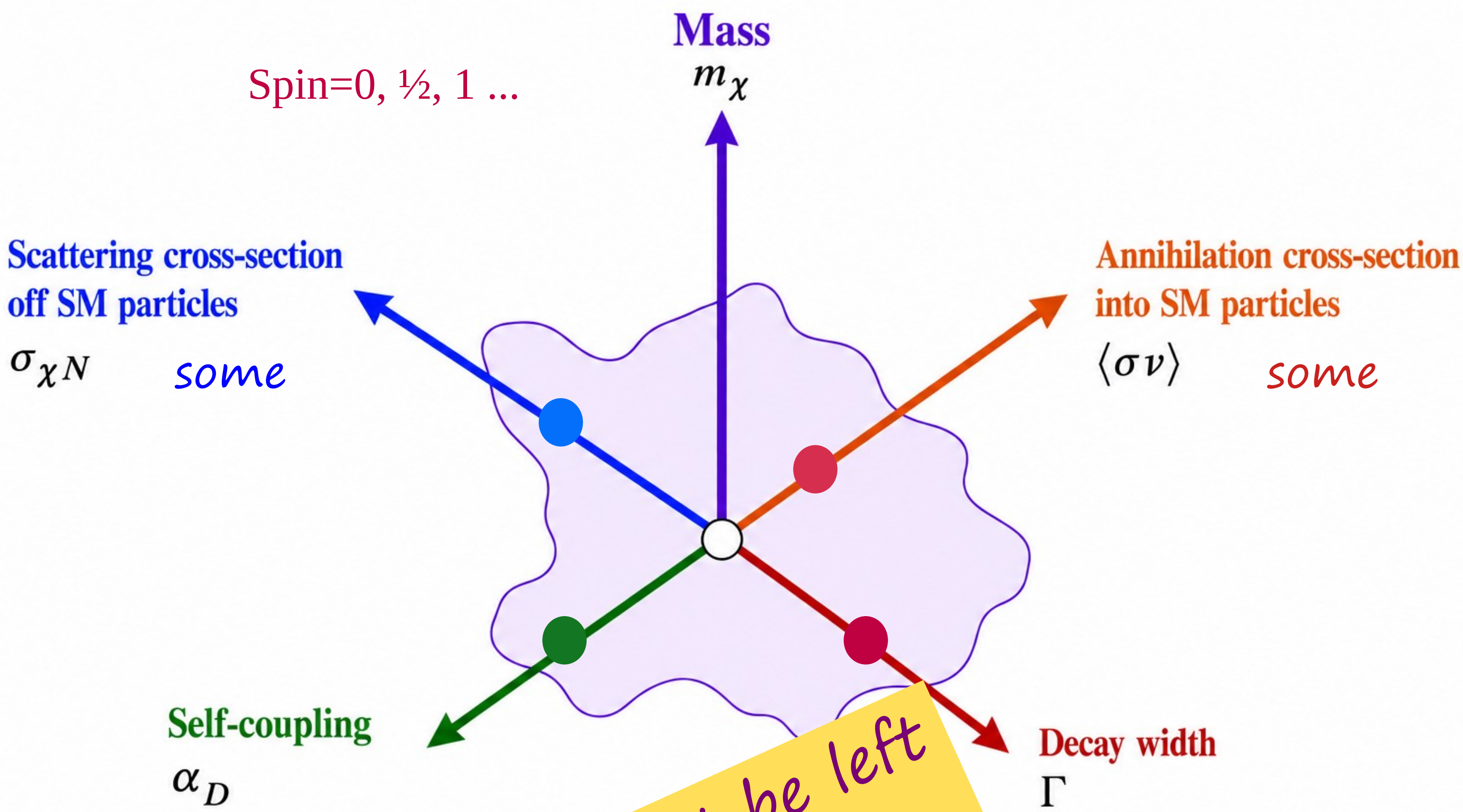
Particle Dark Matter Parameter Space



Modern approach:

- Be agnostic about the model.
- Identify distinct DM signals that allow to explore as much parameter space as possible.

Particle Dark Matter Parameter Space

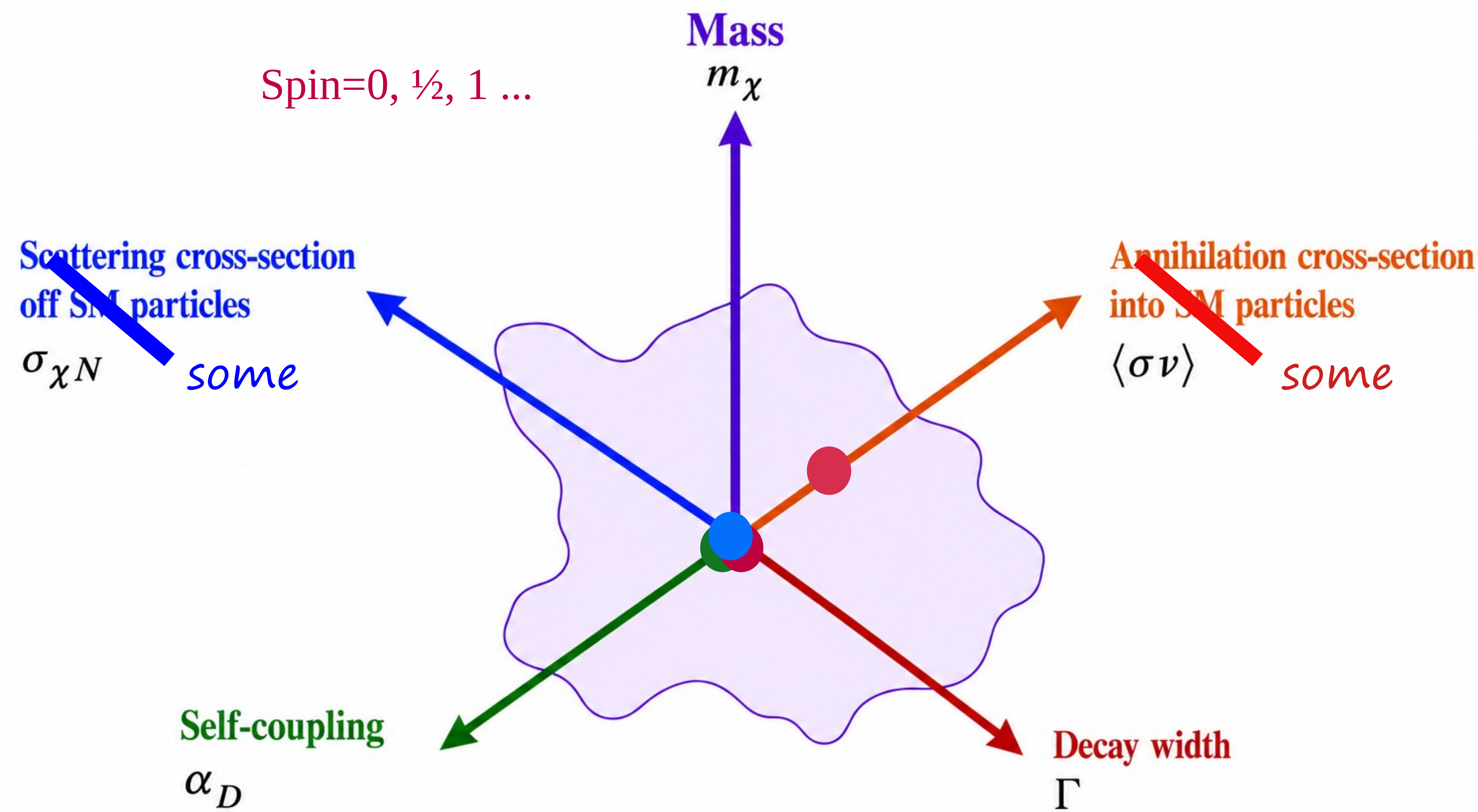


Modern approach:

- Be agnos… …del.
- Iden… …M signals that allow to explore as much parame… …e as possible.

No stone must be left unturned!

Particle Dark Matter Parameter Space

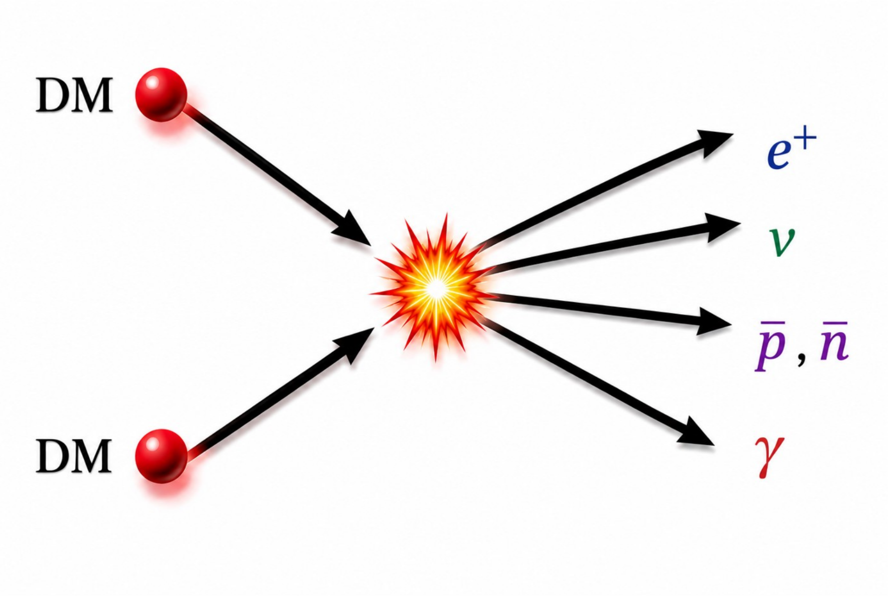


Indirect dark matter searches

Indirect dark matter searches

General idea:

1) Dark matter particles annihilate or decay producing a flux of stable particles: photons, electrons, protons, positrons, antiprotons, (anti-)neutrinos or anti-nuclei



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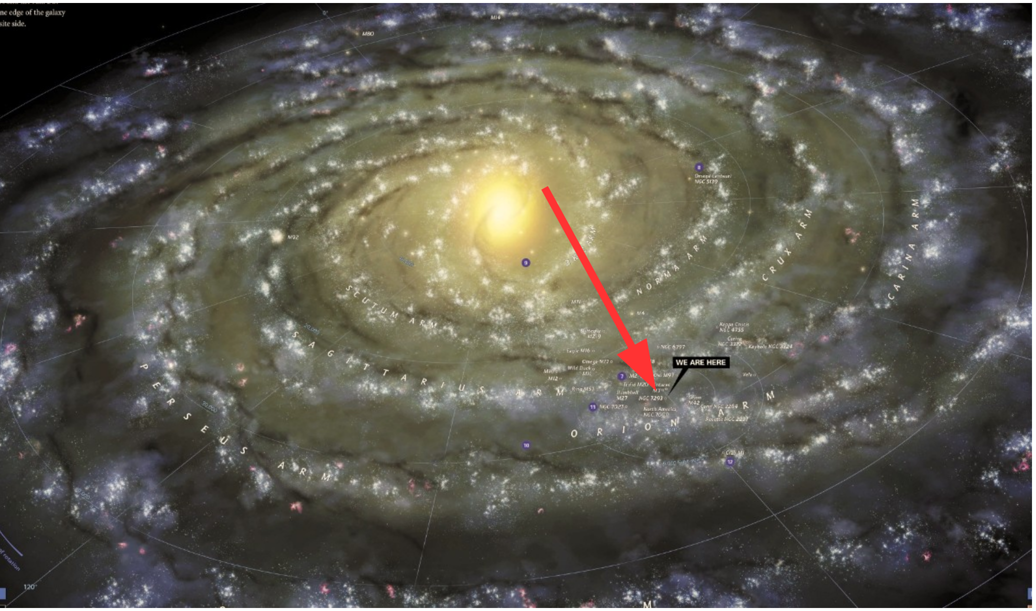

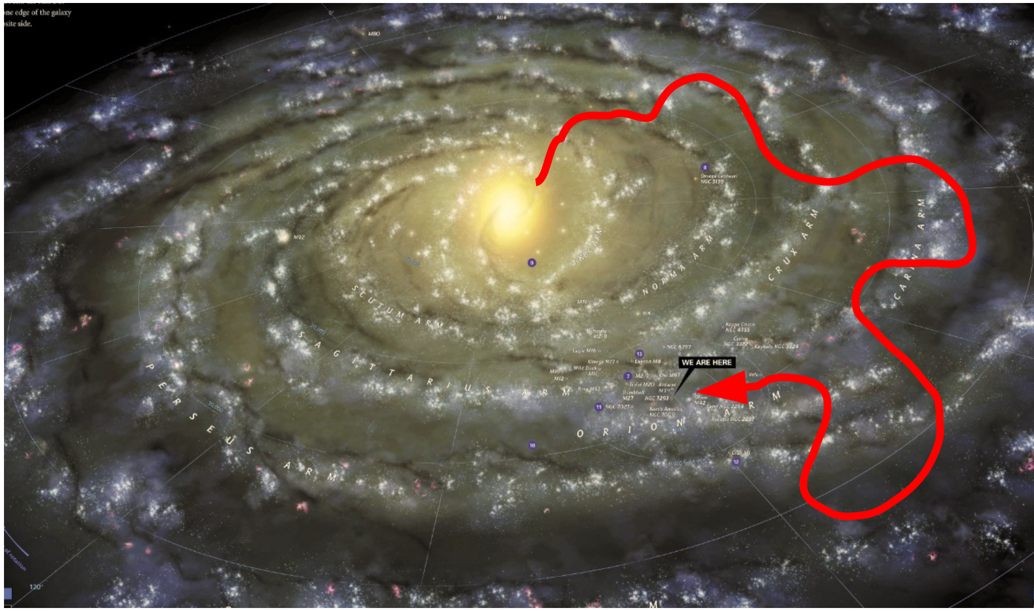

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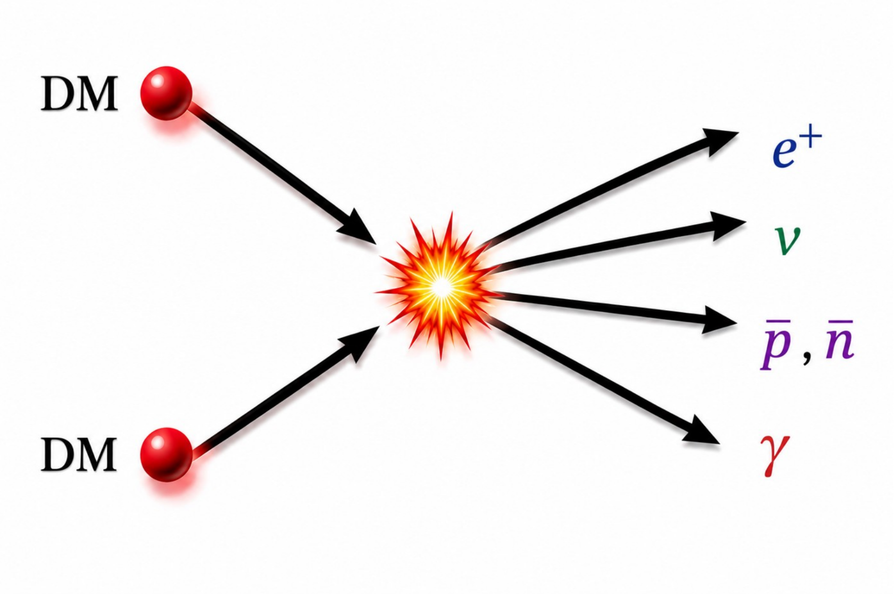
3) The products of the dark matter annihilations or decays are detected together with other particles produced in astrophysical processes (for example, cosmic ray collisions with nuclei in the interstellar medium). The existence of dark matter can then be inferred if there is a significant excess in the fluxes compared to the expected astrophysical backgrounds.

Indirect dark matter searches

Production Propagation Detection	of	Antimatter Gamma-rays Neutrinos

Production

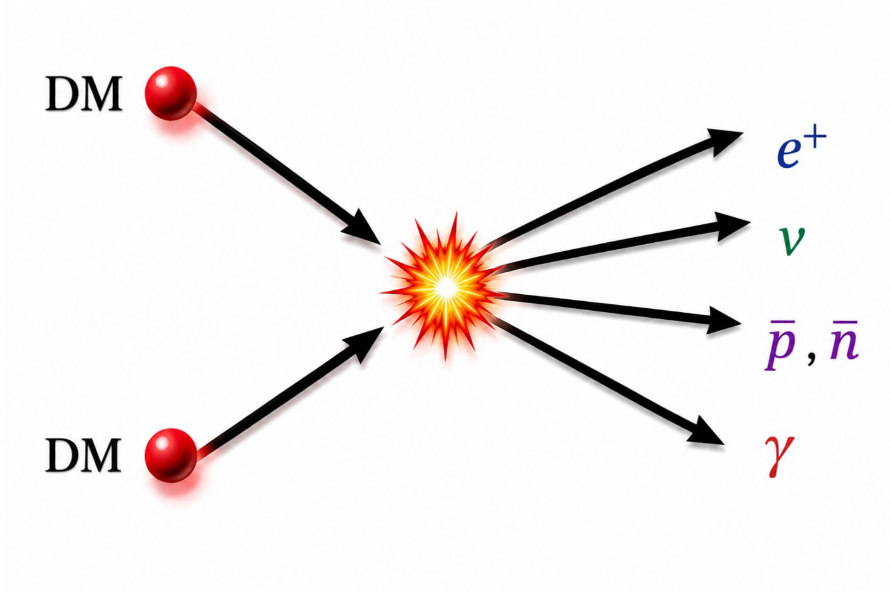
Production of SM particles in DM annihilation



Number of particles of the type "i" produced at the position r per unit time and unit volume:

$$Q(T, \vec{r}) = \frac{1}{2} \frac{\rho_\chi^2(\vec{r})}{m_\chi^2} \sum_i (\sigma v)_i \frac{dN^i}{dT}$$

Production of SM particles in DM annihilation



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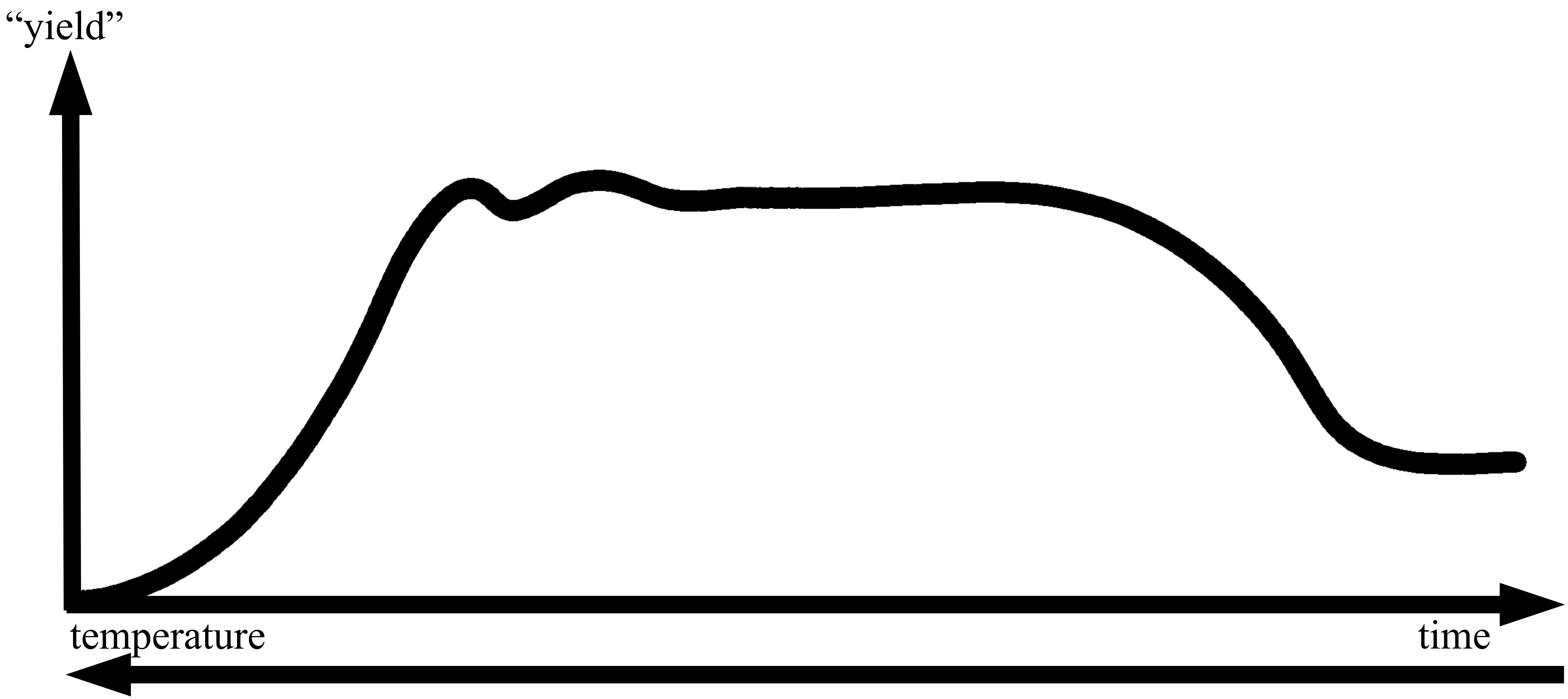
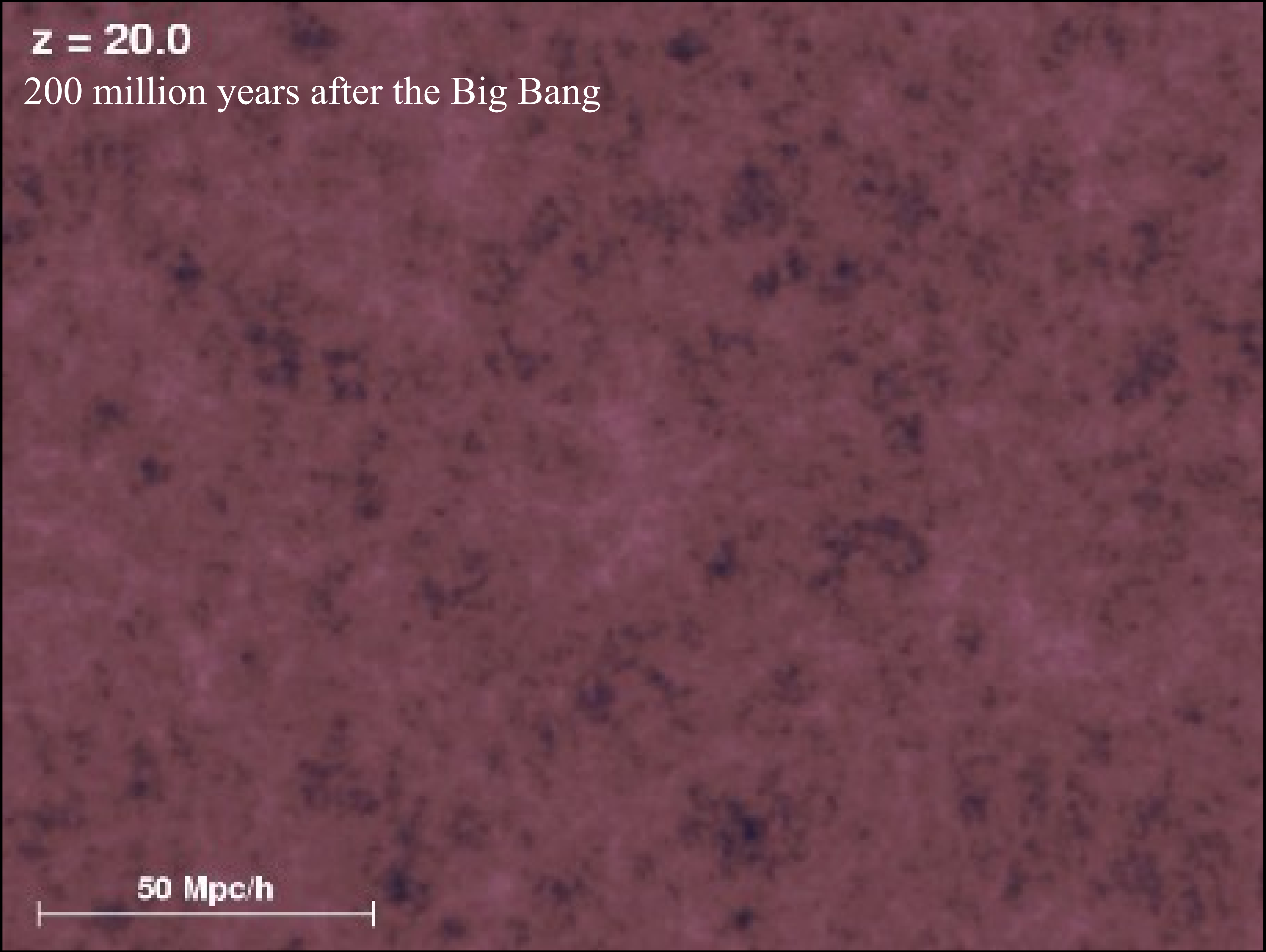
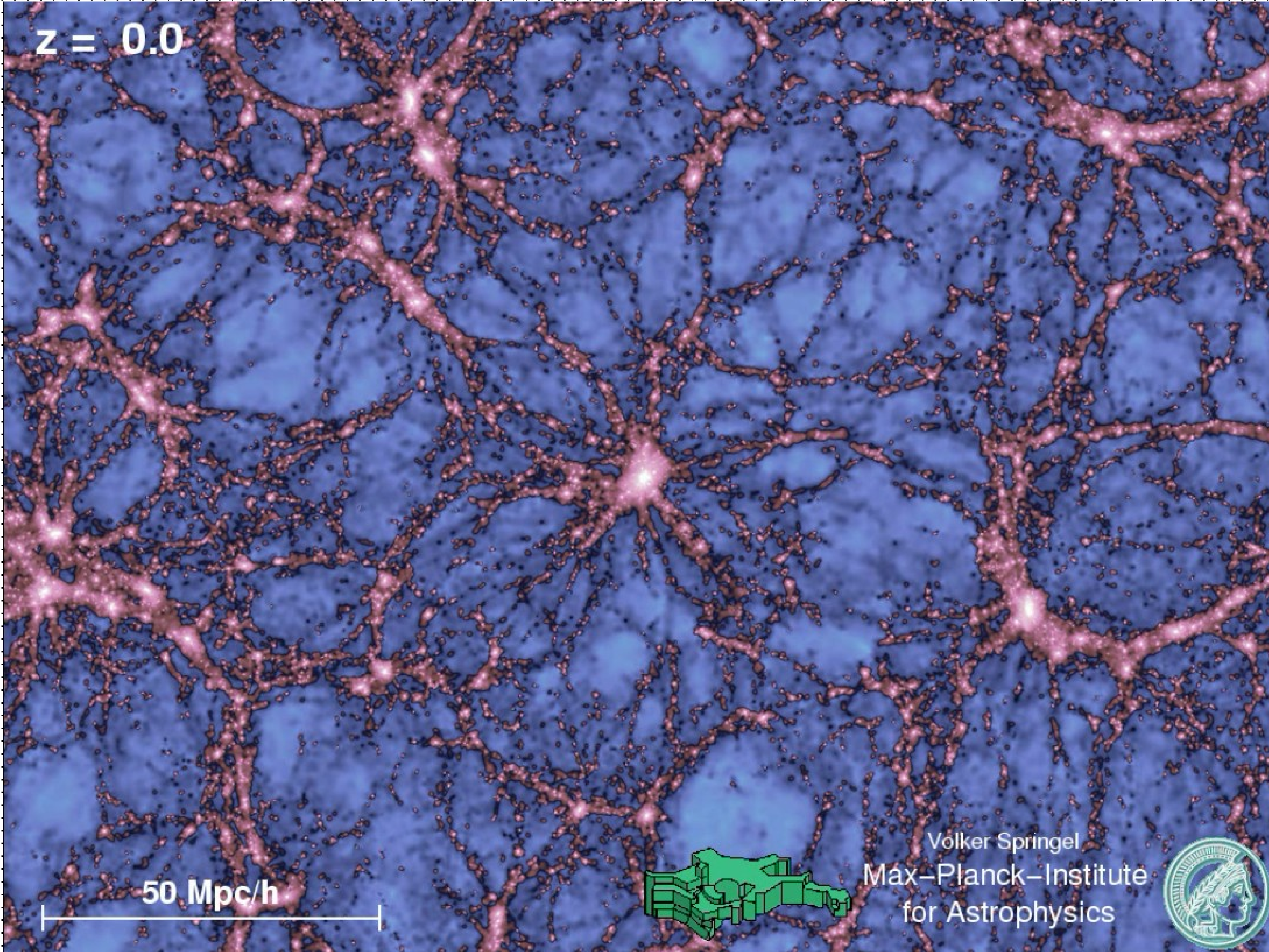
DM density distribution in the MW

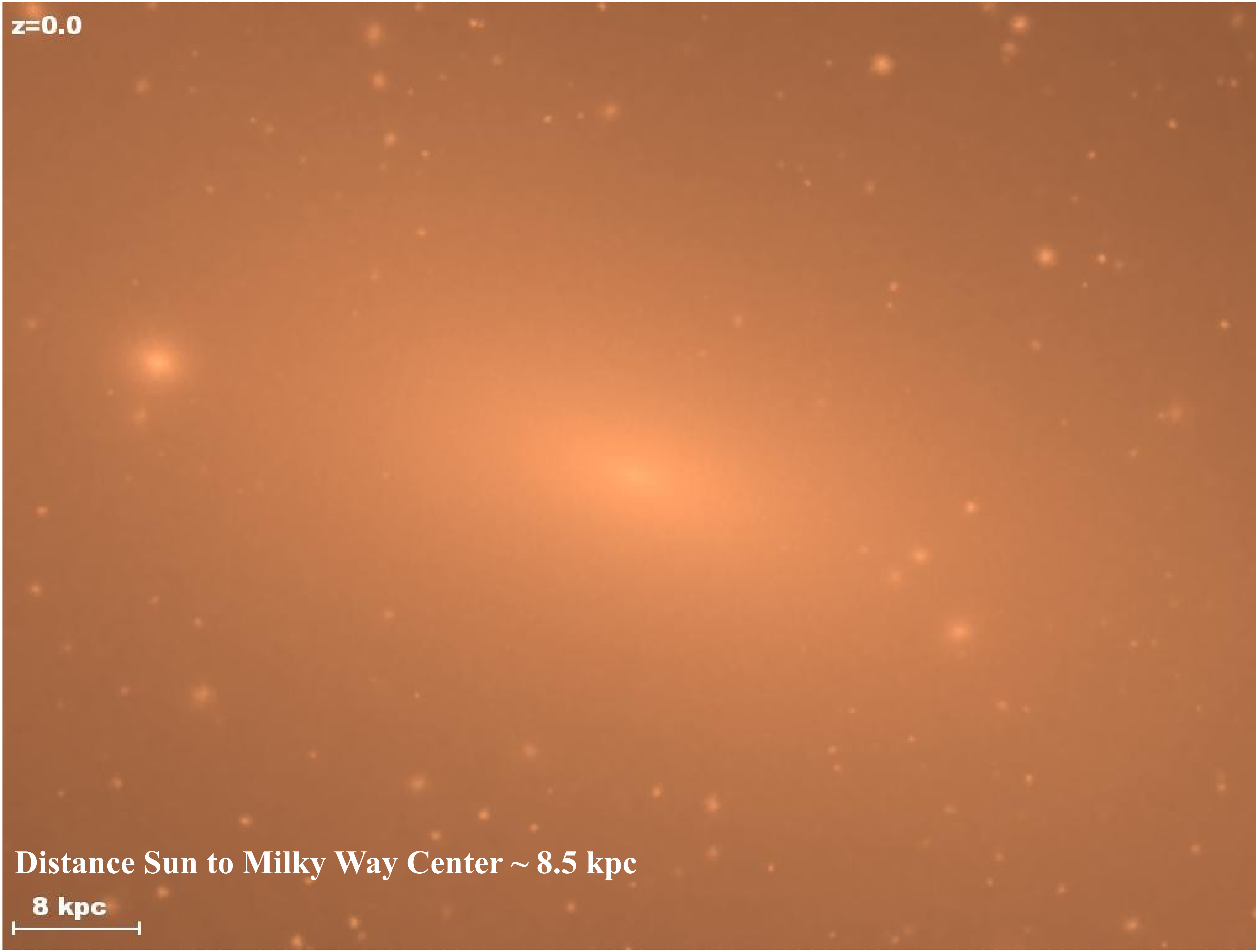
Dark matter distribution



The universe at T~1 GeV

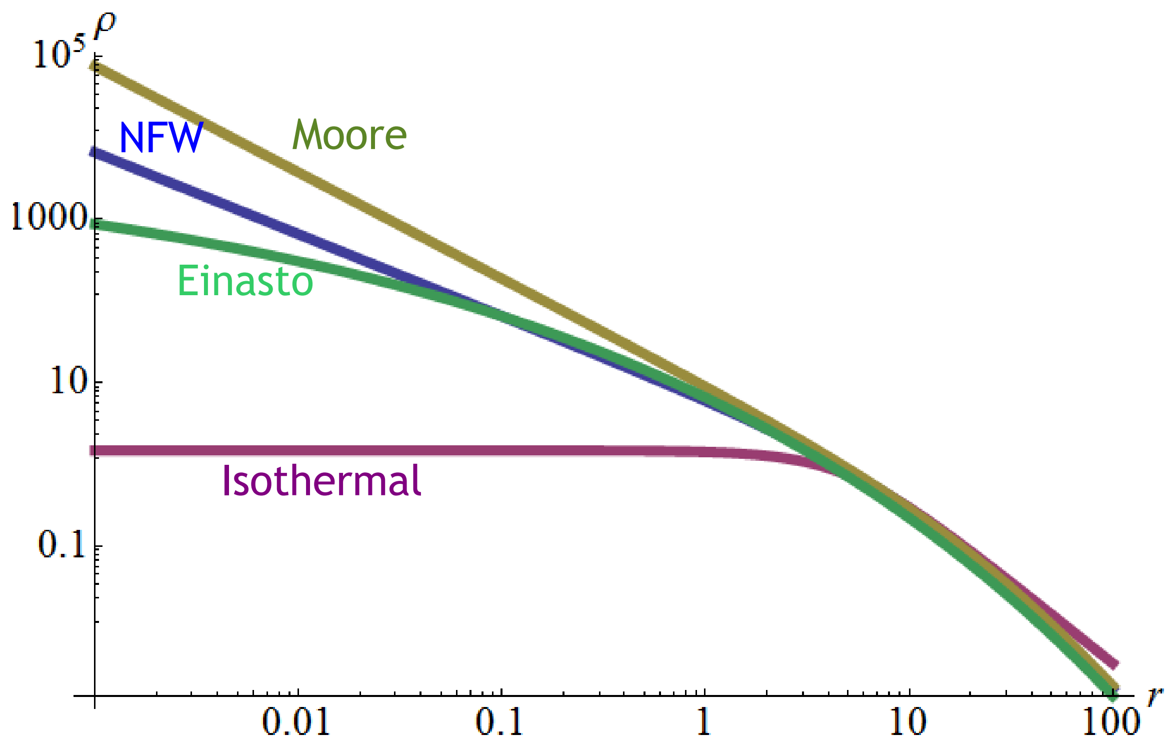

z = 20.0
200 million years after the Big Bang
50 Mpc/h


z = 0.0
50 Mpc/h
Volker Springel
Max–Planck–Institute
for Astrophysics


z=0.0
Distance Sun to Milky Way Center ~ 8.5 kpc
8 kpc

Density distribution of dark matter particles:

- Assume spherical symmetry (in a first approximation).
- Radial distribution:



NFW, Isothermal, Moore

$$\rho(r) = \frac{\rho_0}{(r/r_c)^\gamma [1 + (r/r_c)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Halo model	α	β	γ	r_c (kpc)
Navarro, Frenk, White	1	3	1	20
Isothermal	2	2	0	3.5
Moore	1.5	3	1.5	28

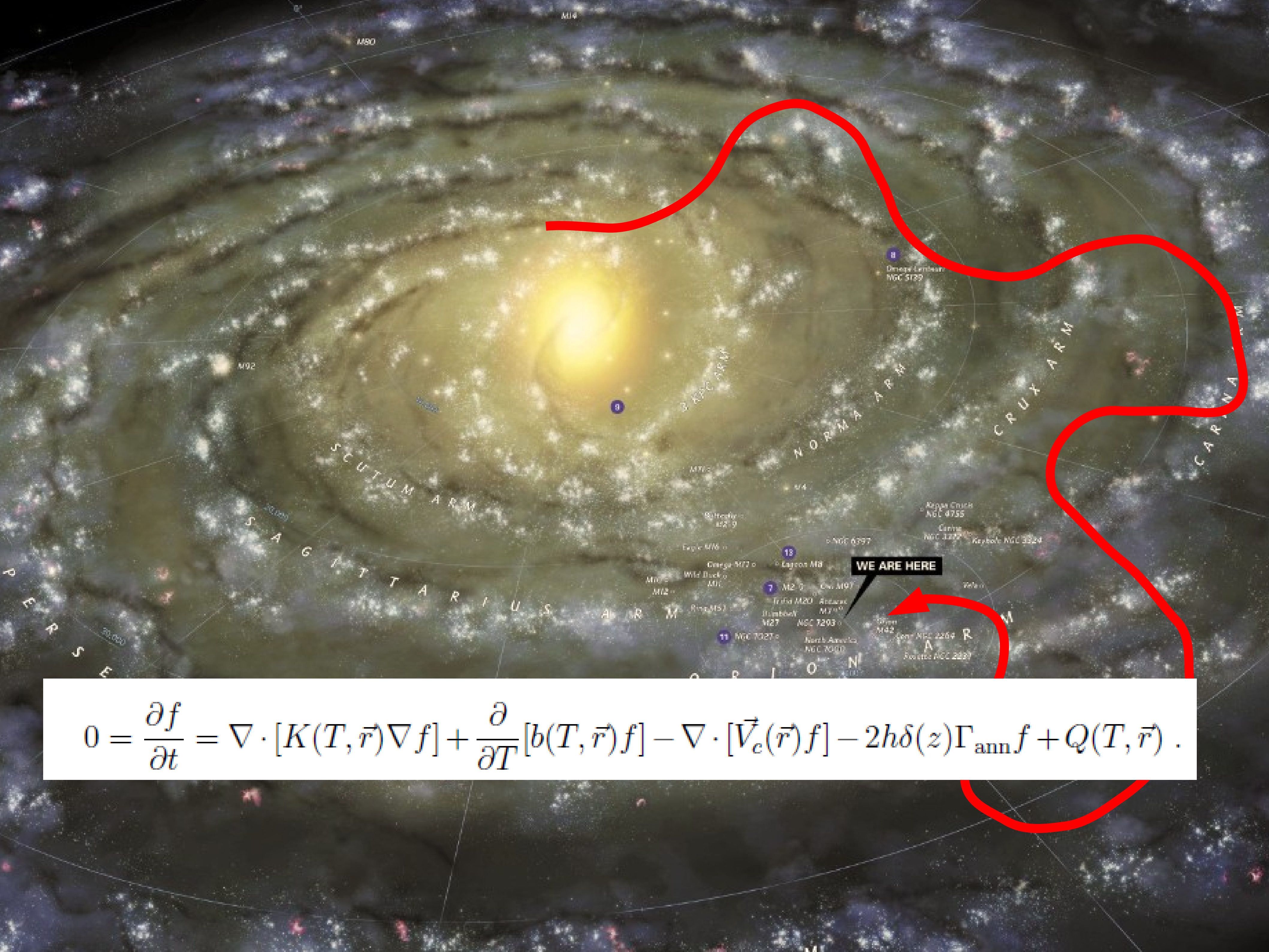
Einasto

$$\rho(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

$\alpha = 0.17,\ r_s = 20$ kpc

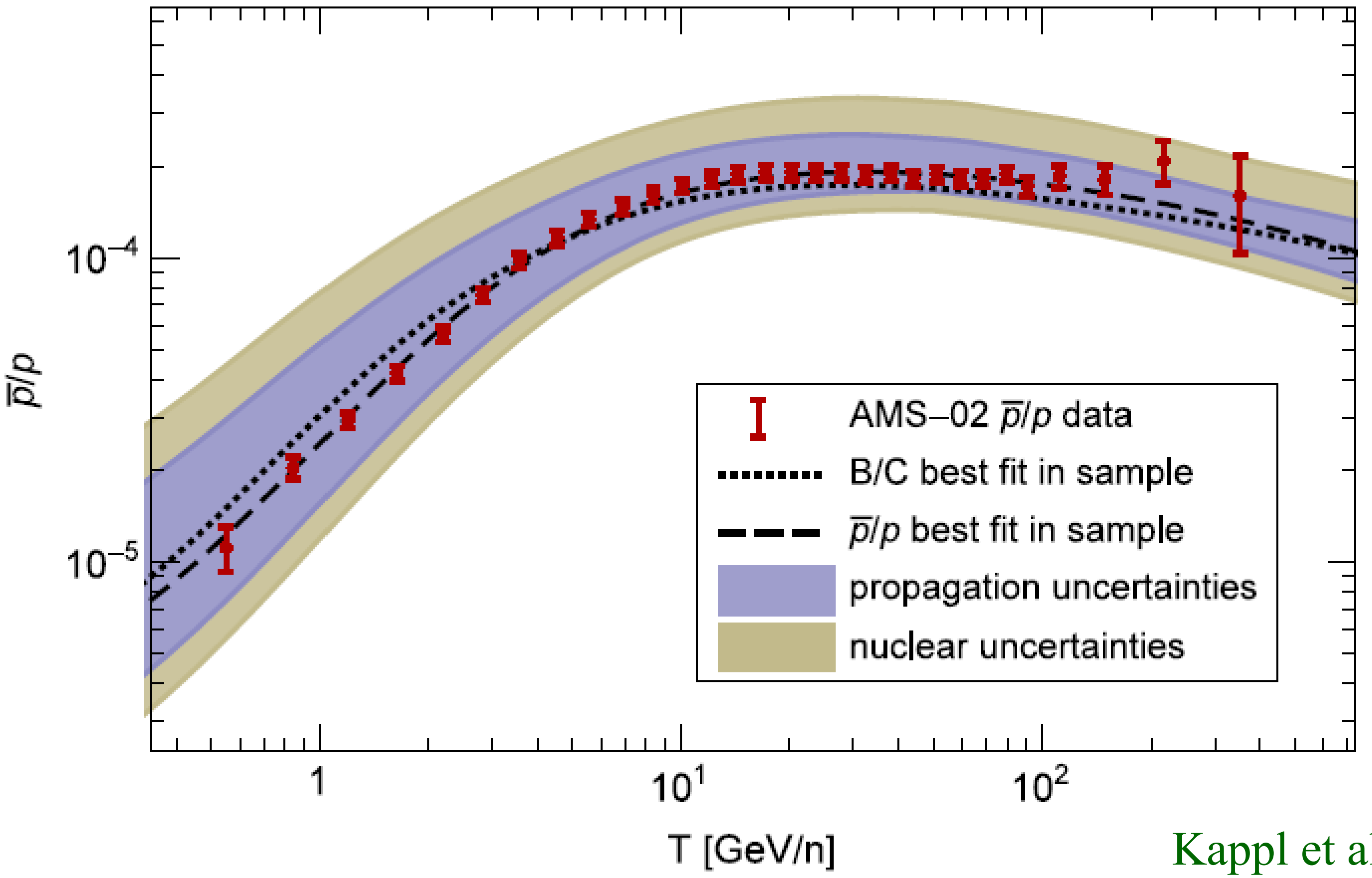
- Normalized such that the local DM density is
  $\rho(r=8.5 \text{ kpc}) = 0.38 \text{ GeV/cm}^3$

Charged particles



$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \ .$$

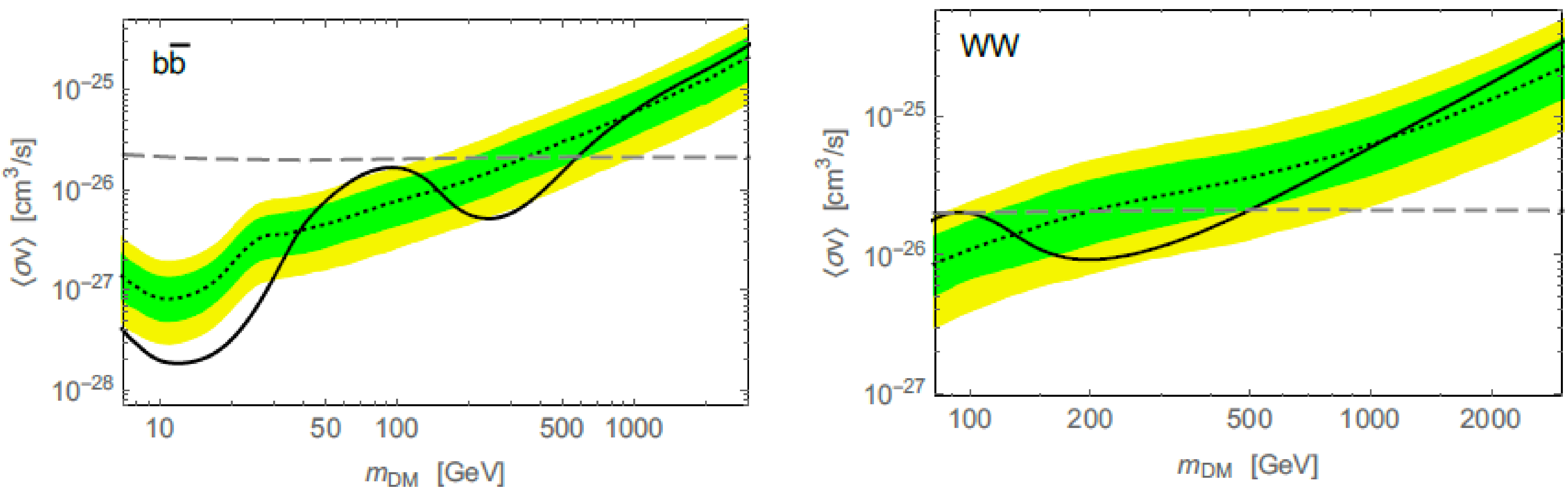
Antiprotons from DM annihilation



Kappl et al'15

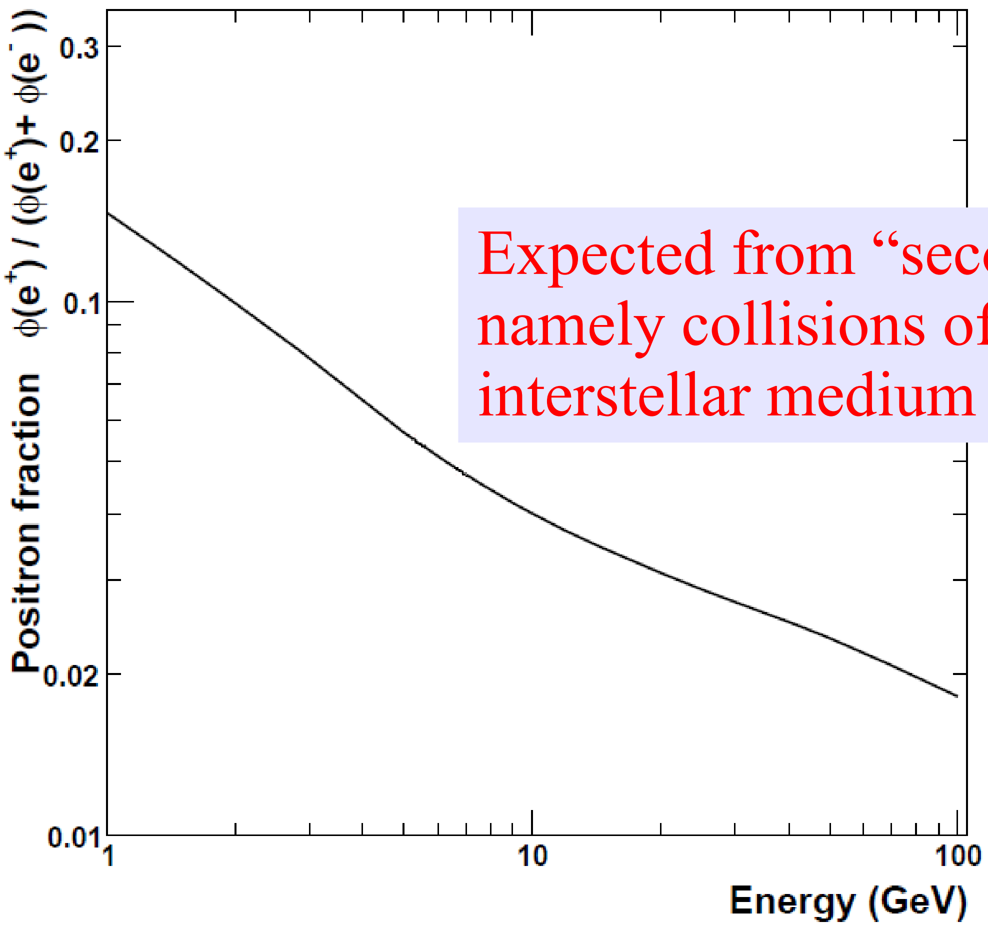
Good qualitative agreement between the measurements and the theoretical predictions from collisions of cosmic rays on the interstellar medium $p\,p \to \bar{p}\,X$

Antiprotons from DM annihilation



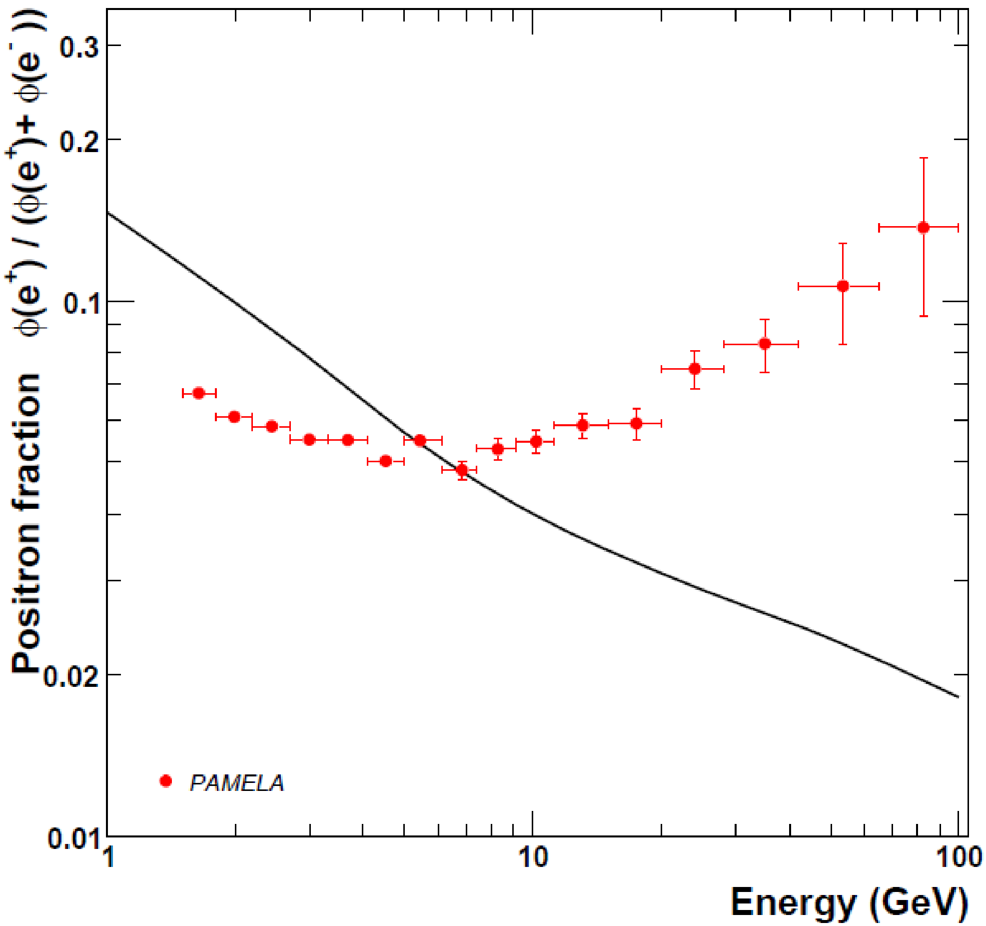
Reinert, Winkler.
1712.00002

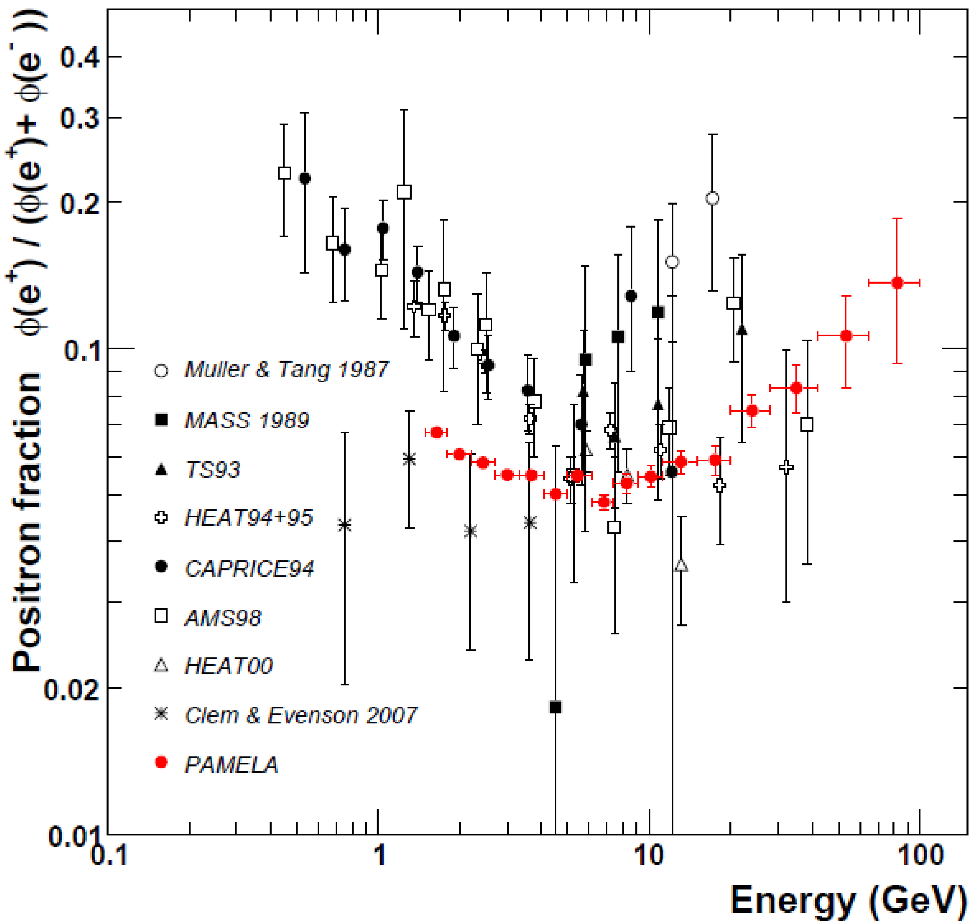
Positrons from DM annihilation



Expected from "secondary production", namely collisions of cosmic rays on the interstellar medium ($p\,p \to e^+ X$).

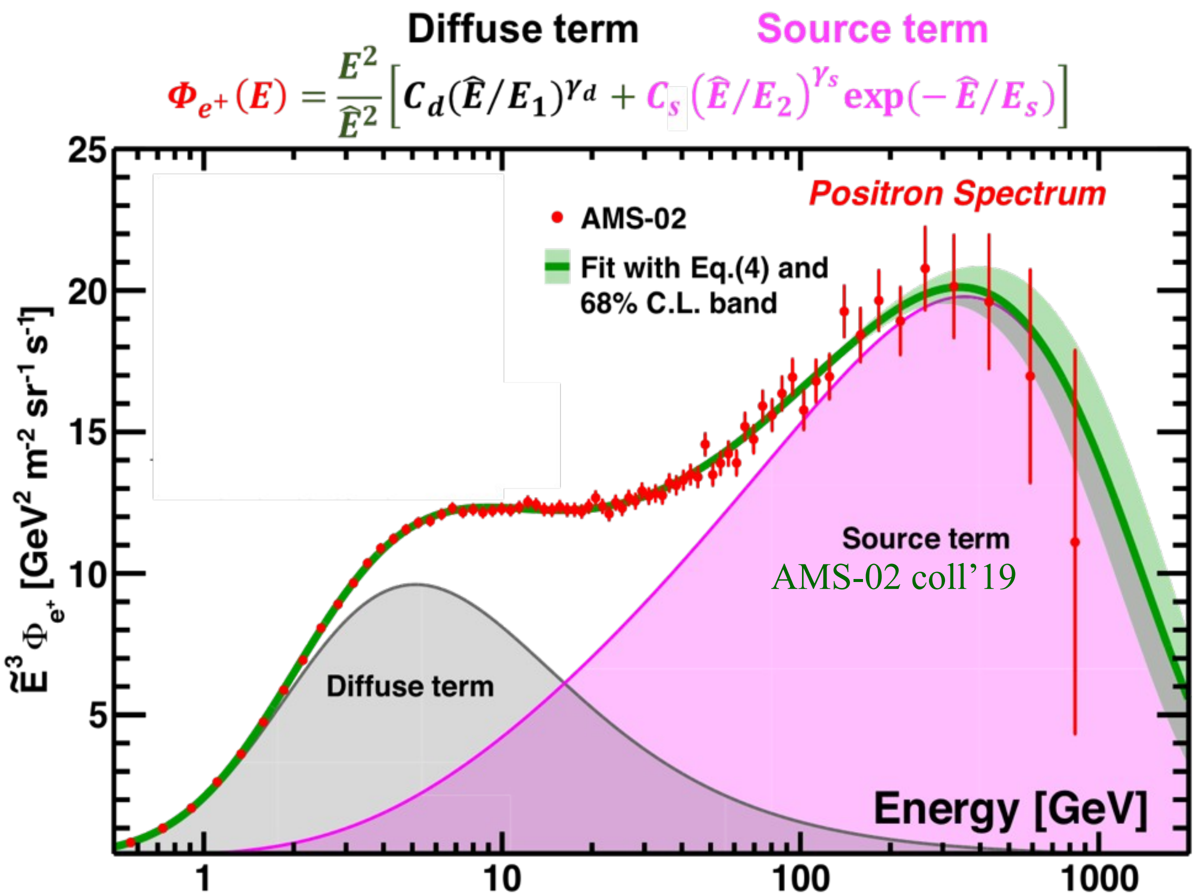
Positrons from DM annihilation





PAMELA coll.
arXiv:0810.4995

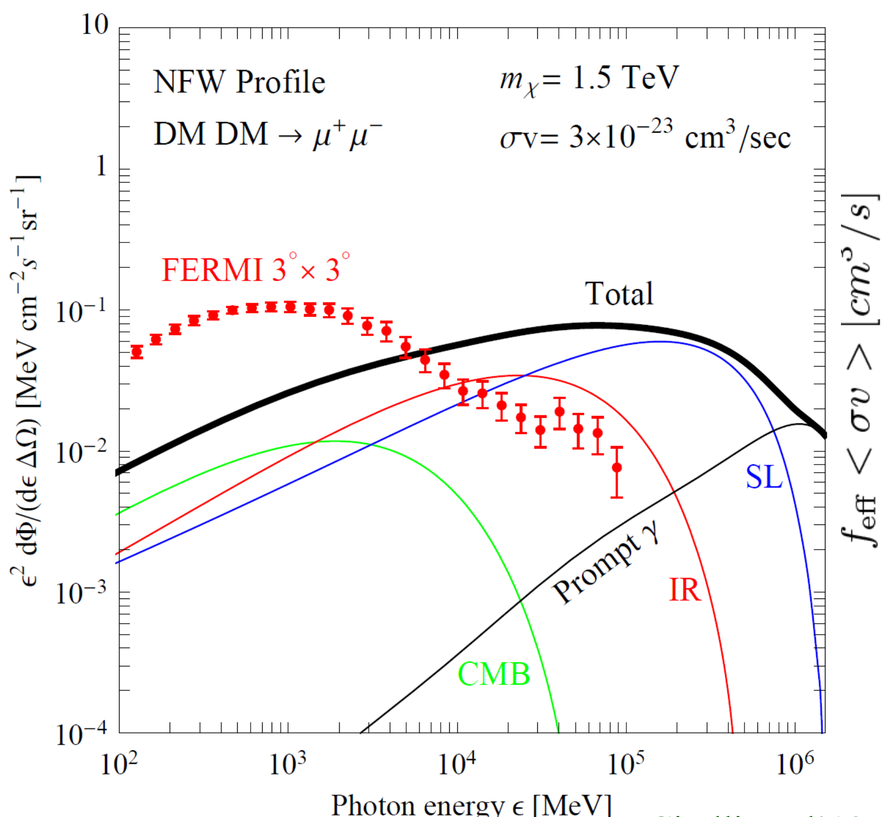
Positrons from DM annihilation



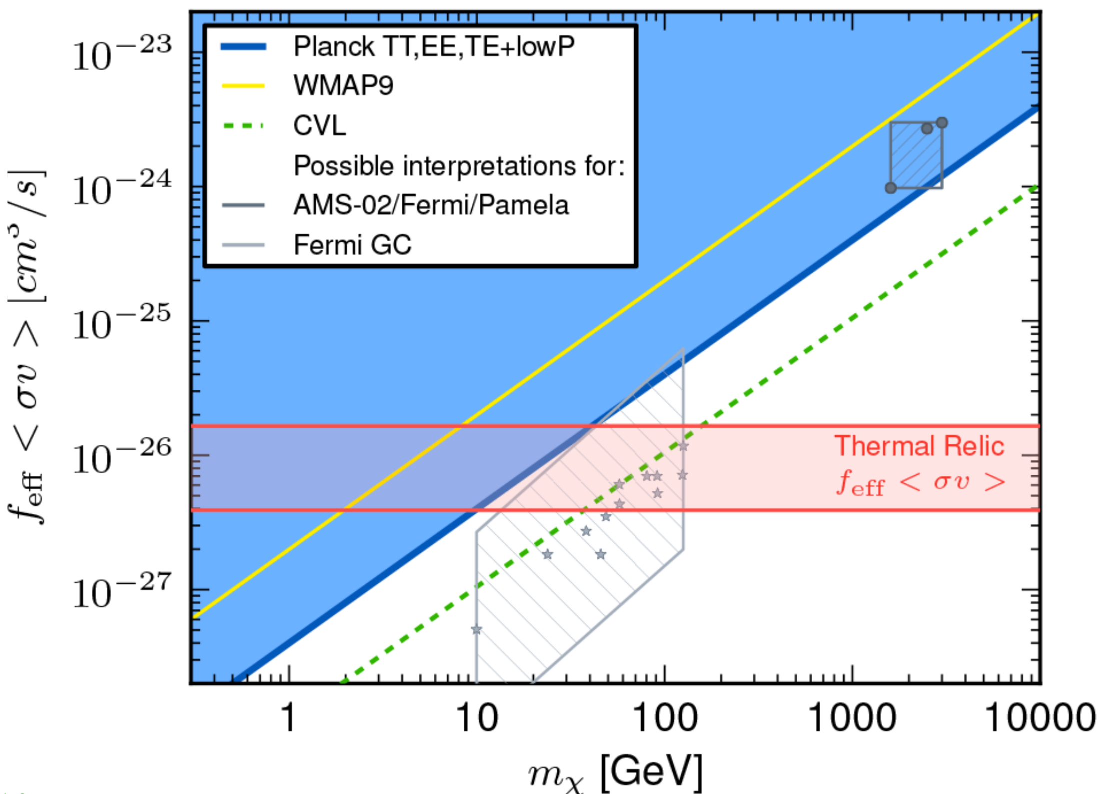
AMS-02 coll'19

Positrons from DM annihilation

Unlikely to be of dark matter origin. The positrons would upscatter ambient photons in the galactic center region to gamma-ray energies, which are not observed. Also, the annihilation would impact the reionization history of the Universe.

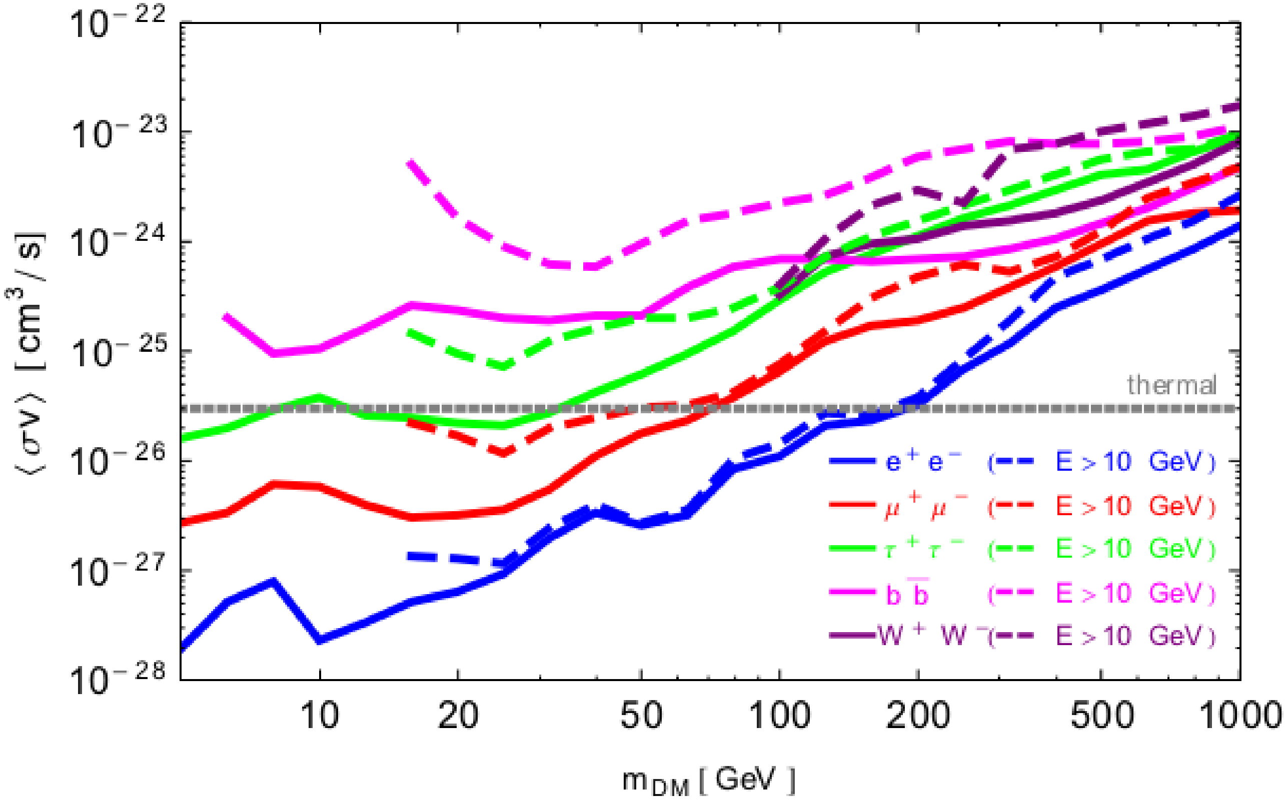


Cirelli et al'19



Planck coll'19

Positrons from DM annihilation



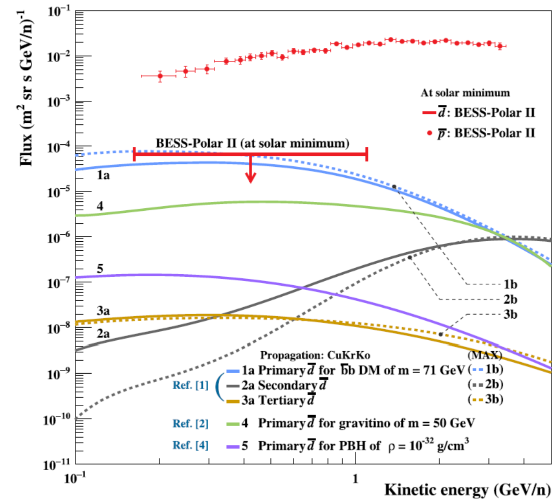
AI, Lamperstorfer, Silk
Bergström et al.

Antinuclei from DM annihilation

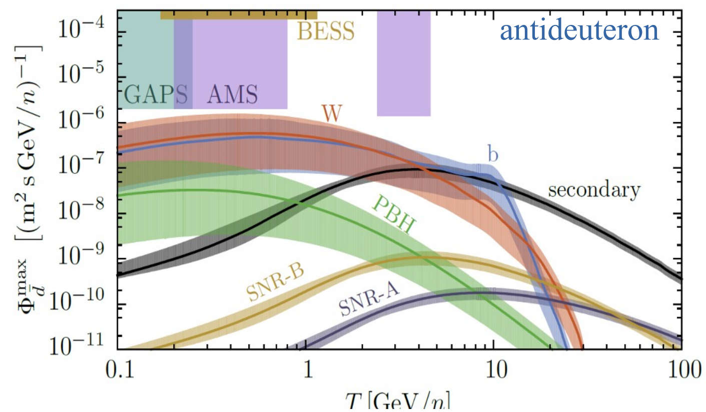
- Antinuclei: Expected from secondary production $p\,p \rightarrow \bar{d}X$

  Correlated to $p\,p \rightarrow \bar{p}X$

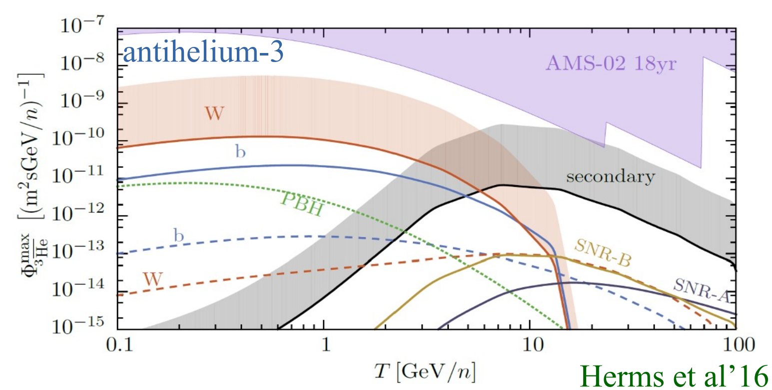
  No antinuclei has been detected in cosmic rays.



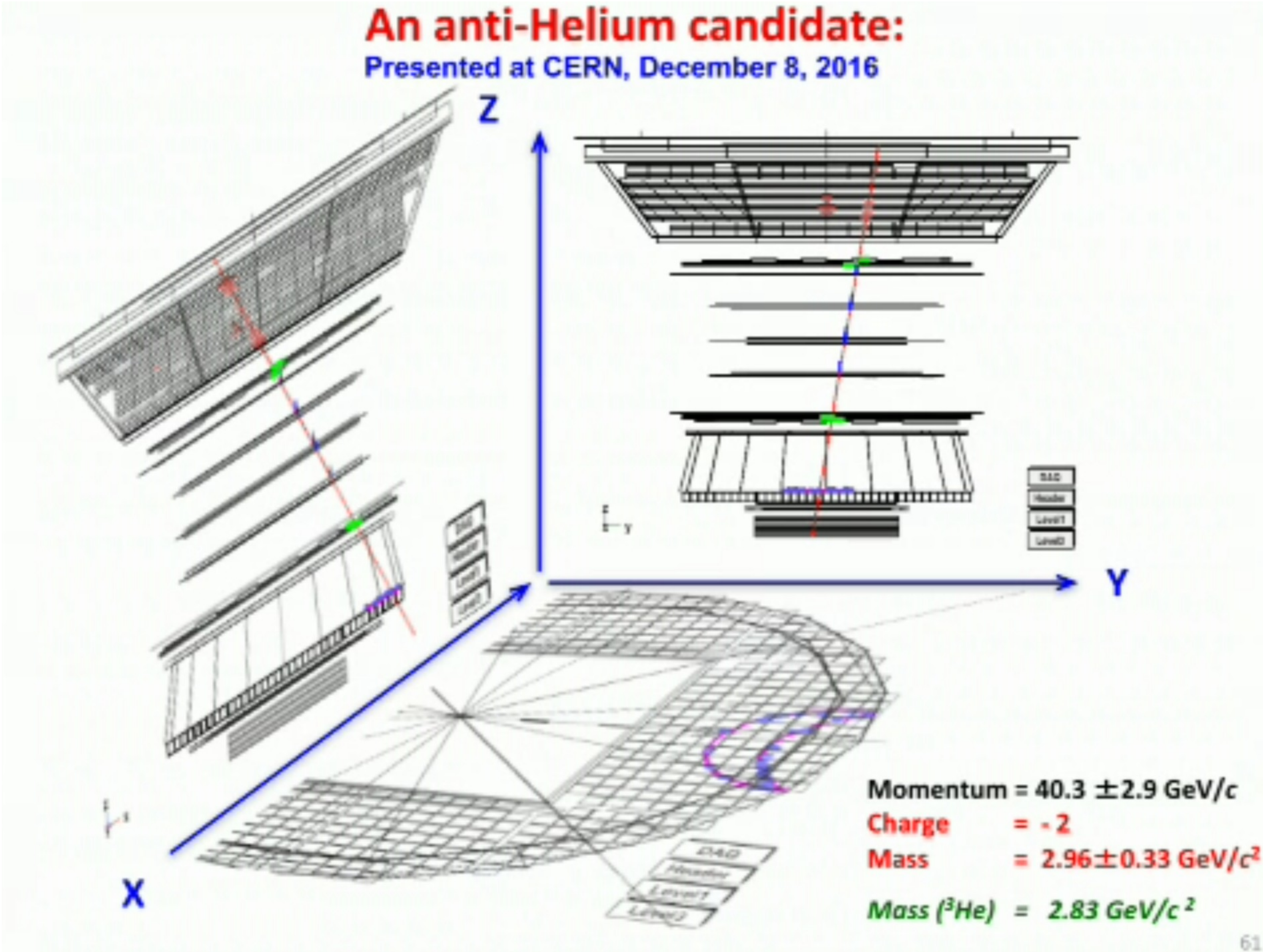
Dark matter annihilations could produce a flux of antinuclei which at low energies is well above the expectations from astrophysics.



Smoking gun for DM detection.



Herms et al'16



Samuel Ting. Talk at CERN. 24th May 2018

To date, we have observed eight events in the mass region from 0 to 10 GeV with Z = –2.

All eight events are in the helium mass region.

All eight events are clean single-track events without additional hits.

All eight events are in the momentum range < 100 GeV/c (where the momentum resolution is better than 10%).

Samuel Ting. Talk at CERN. 24th May 2018