Particle Dark Matter

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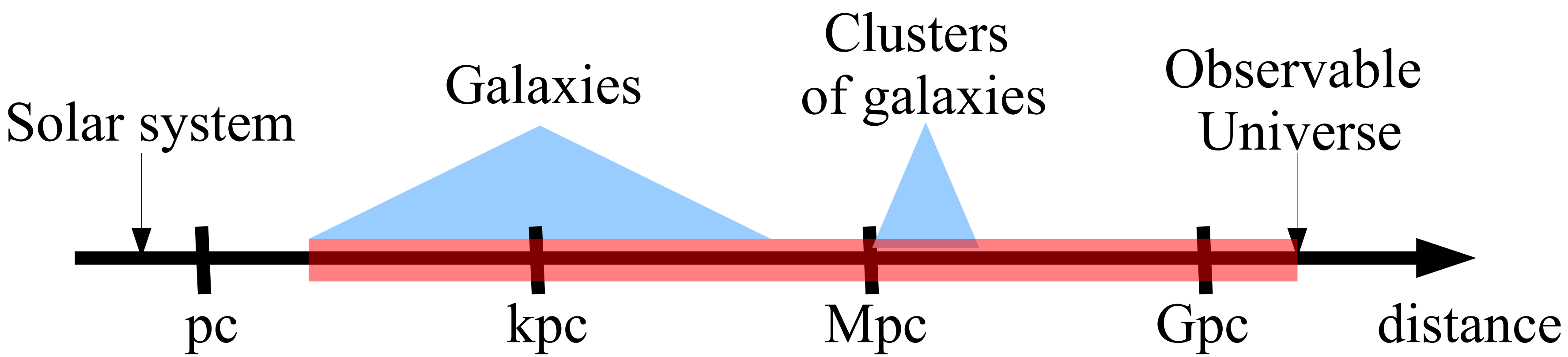
Nagoya
March 2026

There is evidence for dark matter in a wide range of distance scales



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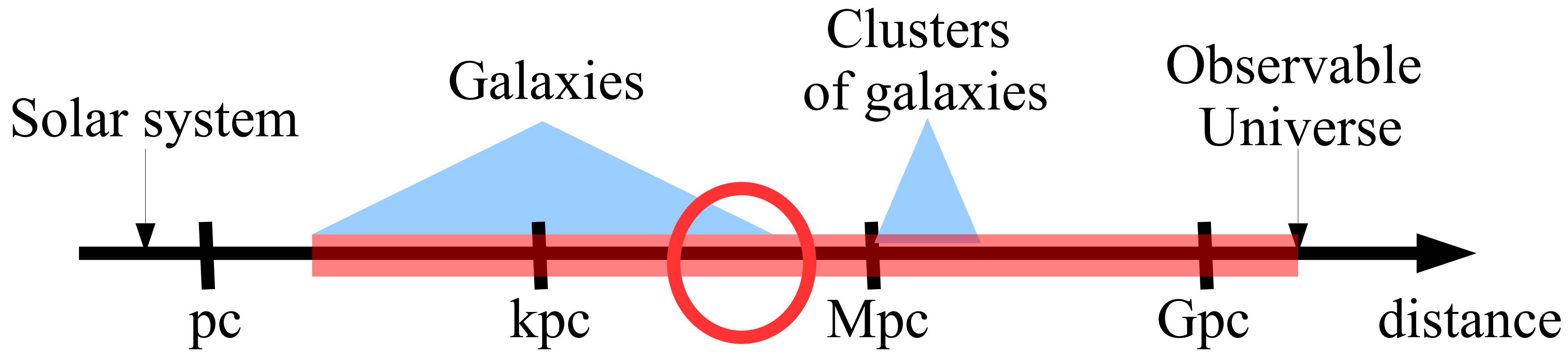

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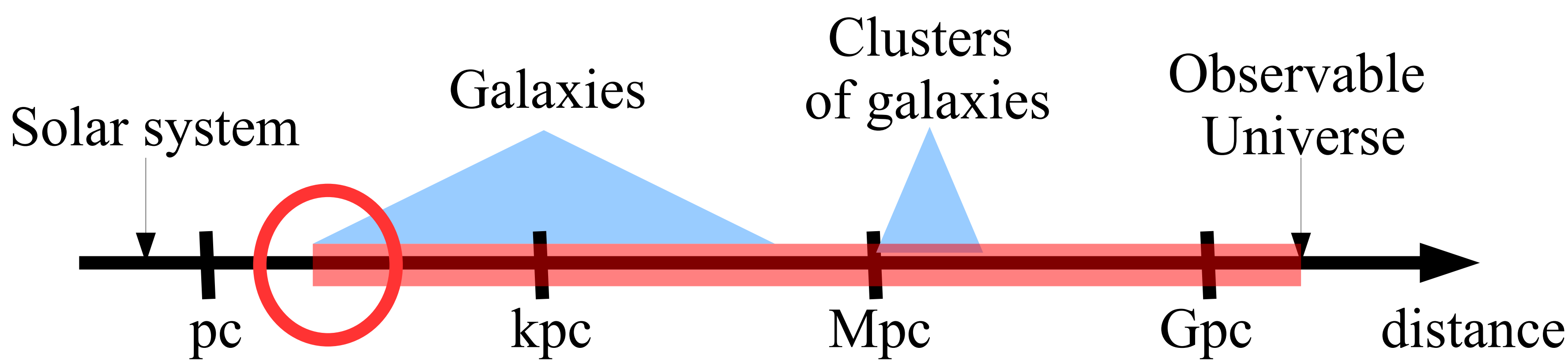
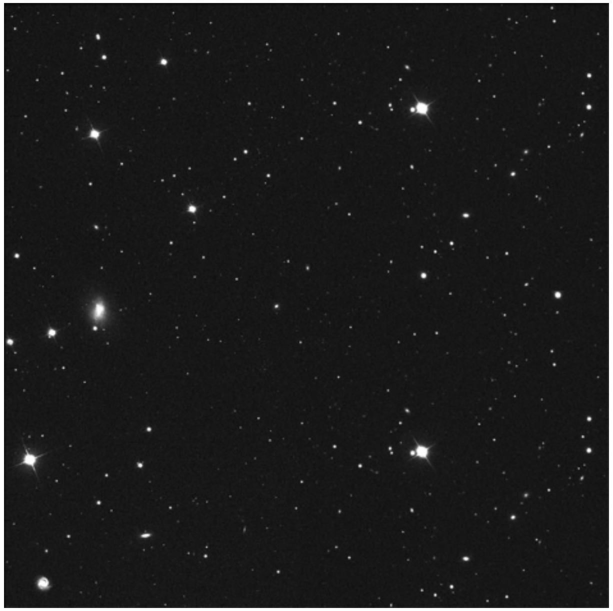
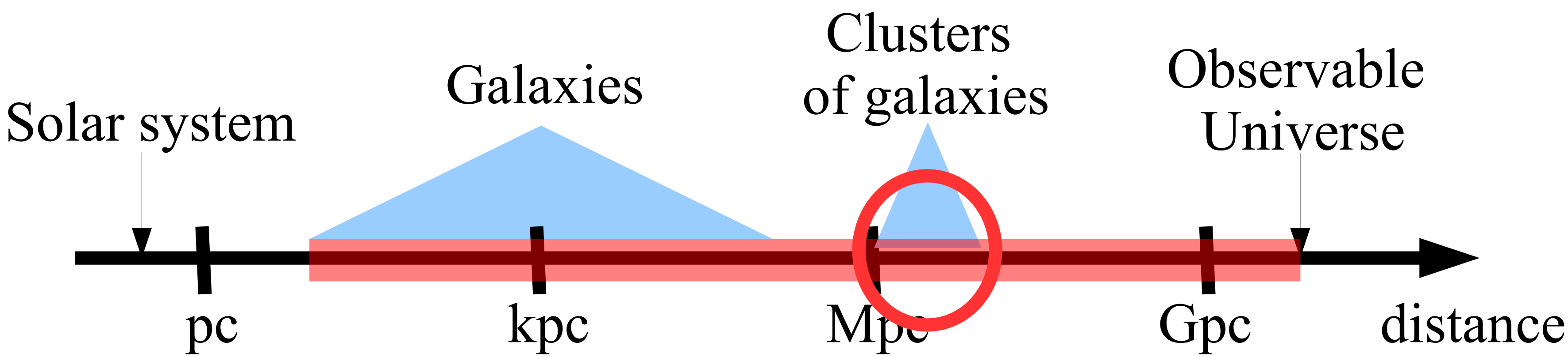
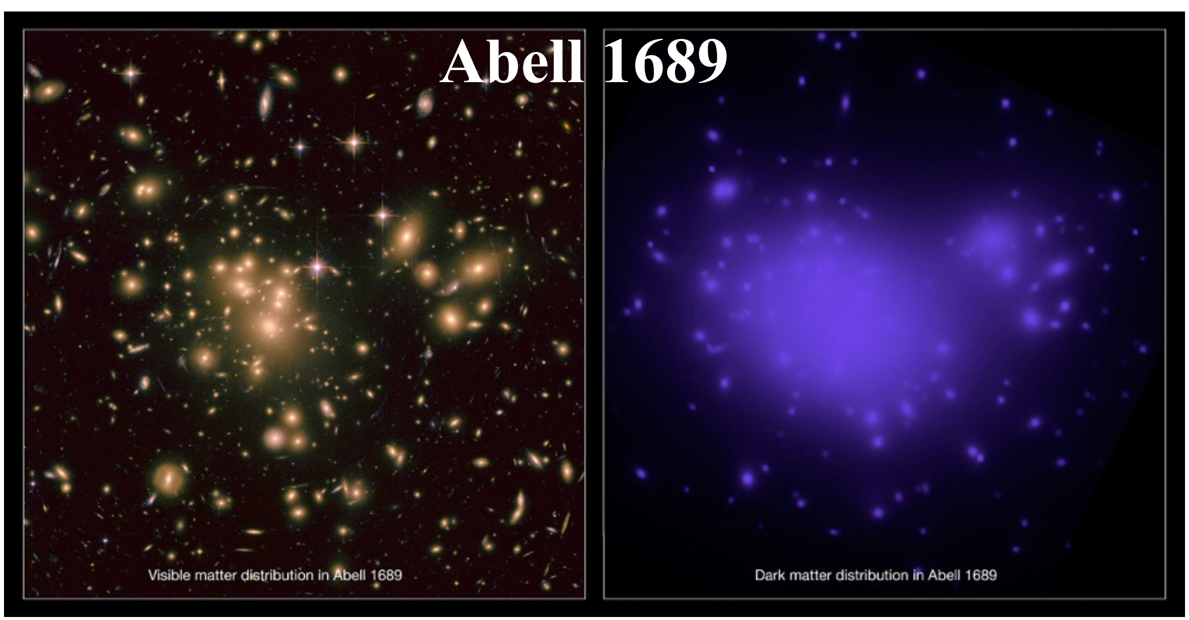




Segue 1

There is evidence for dark matter in a wide range of distance scales





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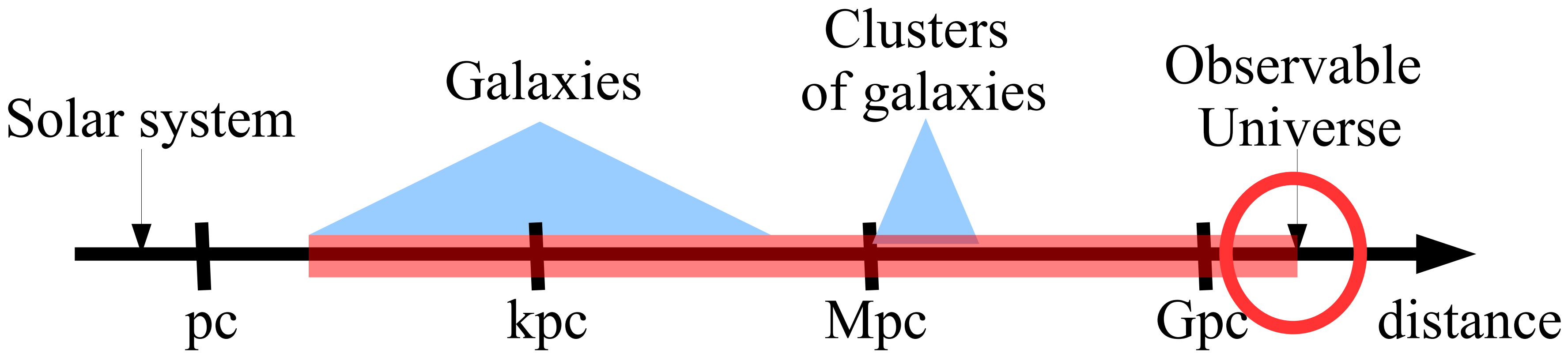

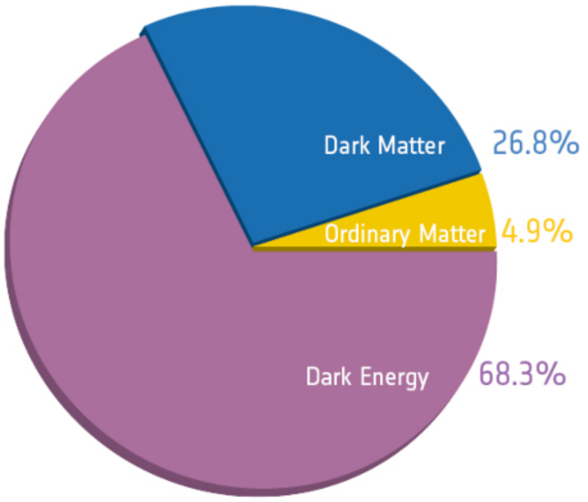

What is dark matter made of?

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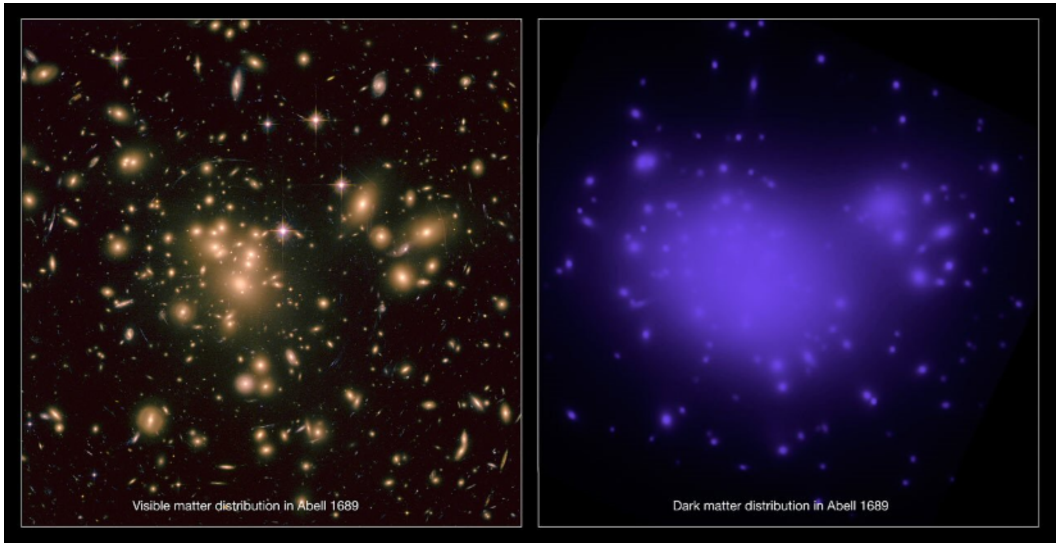

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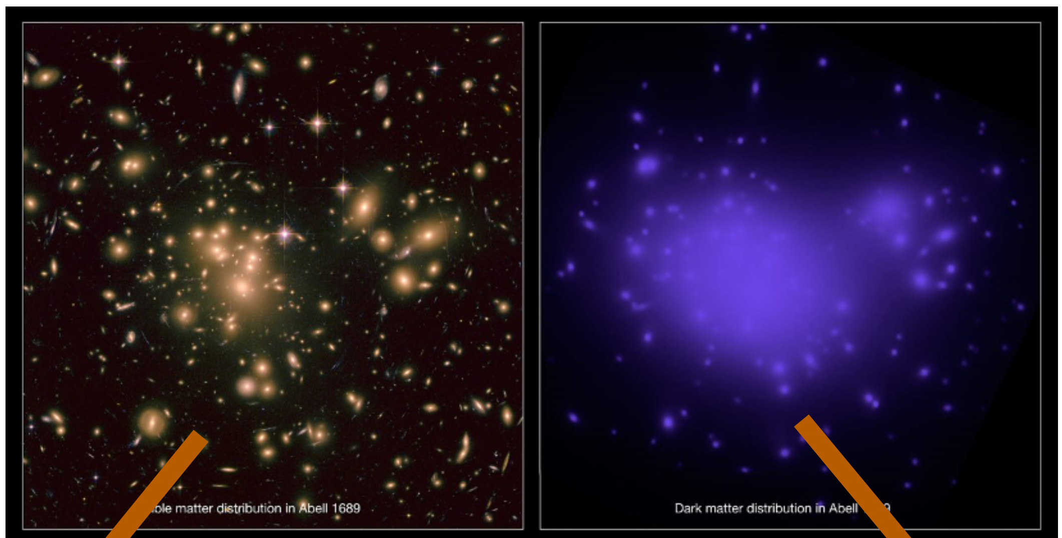
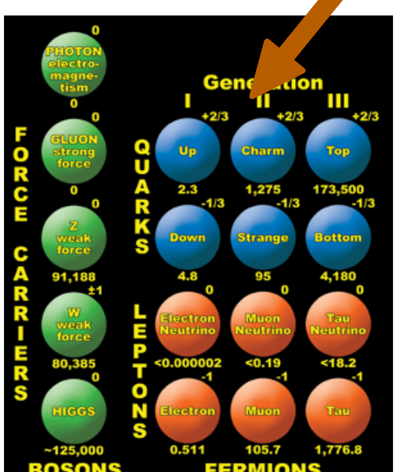
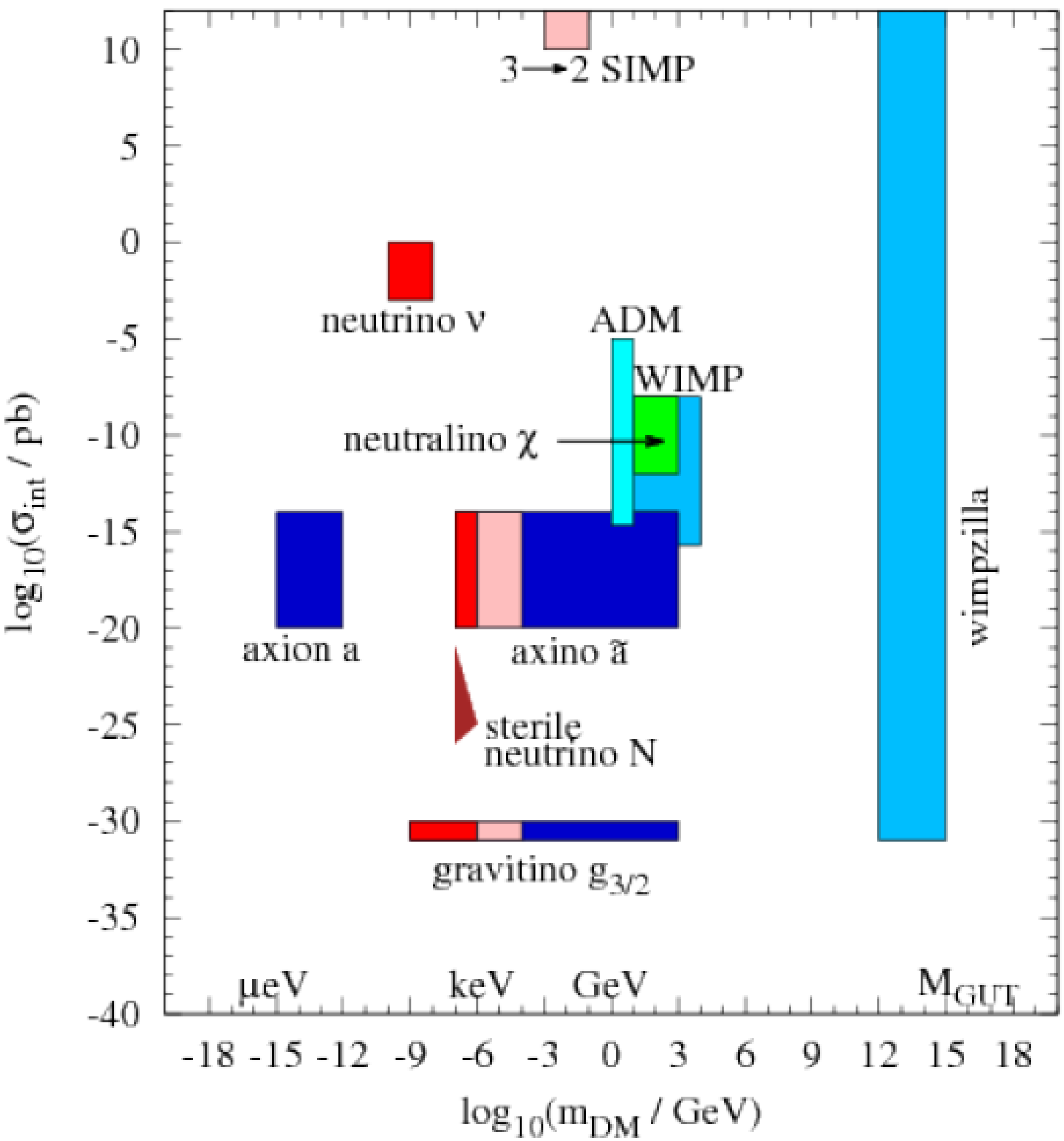




Hypothesis:
Elementary particles,
interacting very weakly
with the Standard Model.

The dark particle zoo



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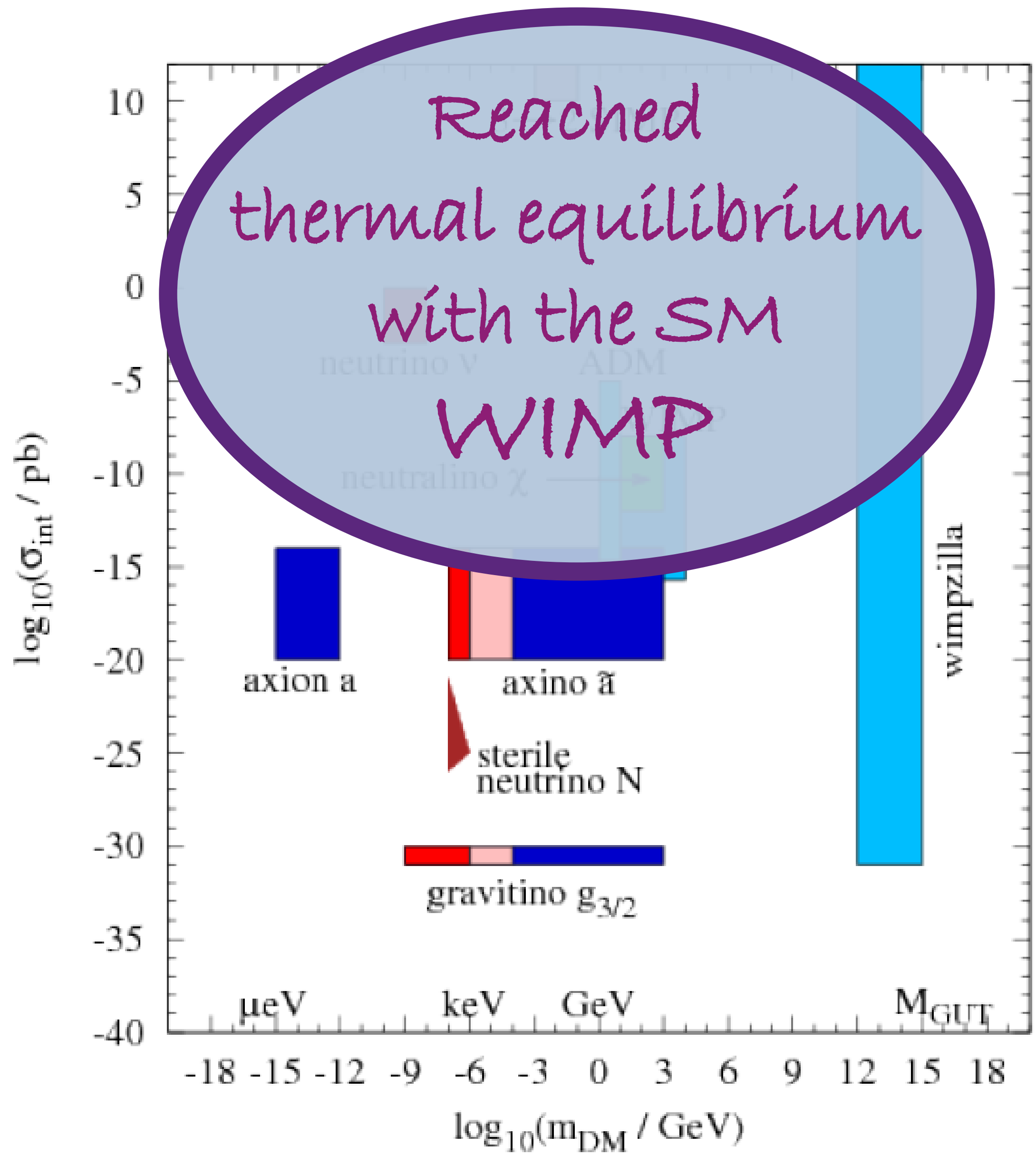

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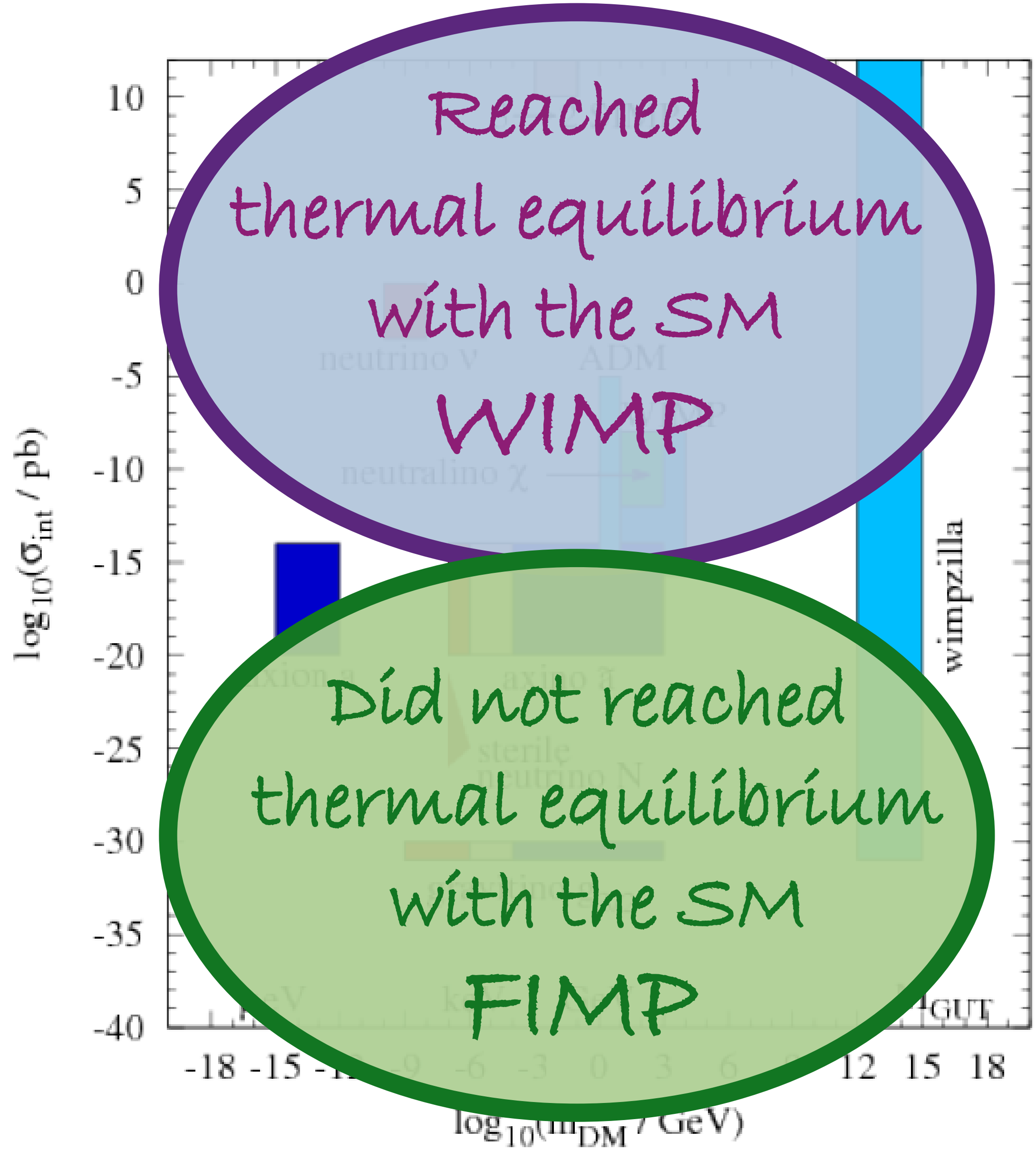
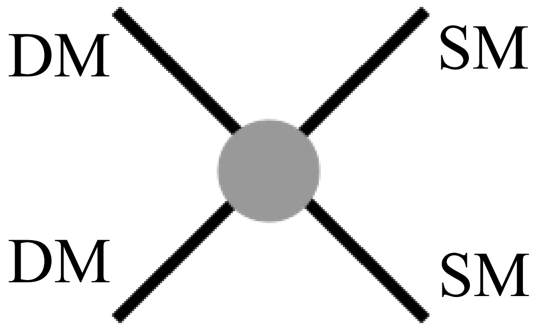


WIMP history (in a nutshell)

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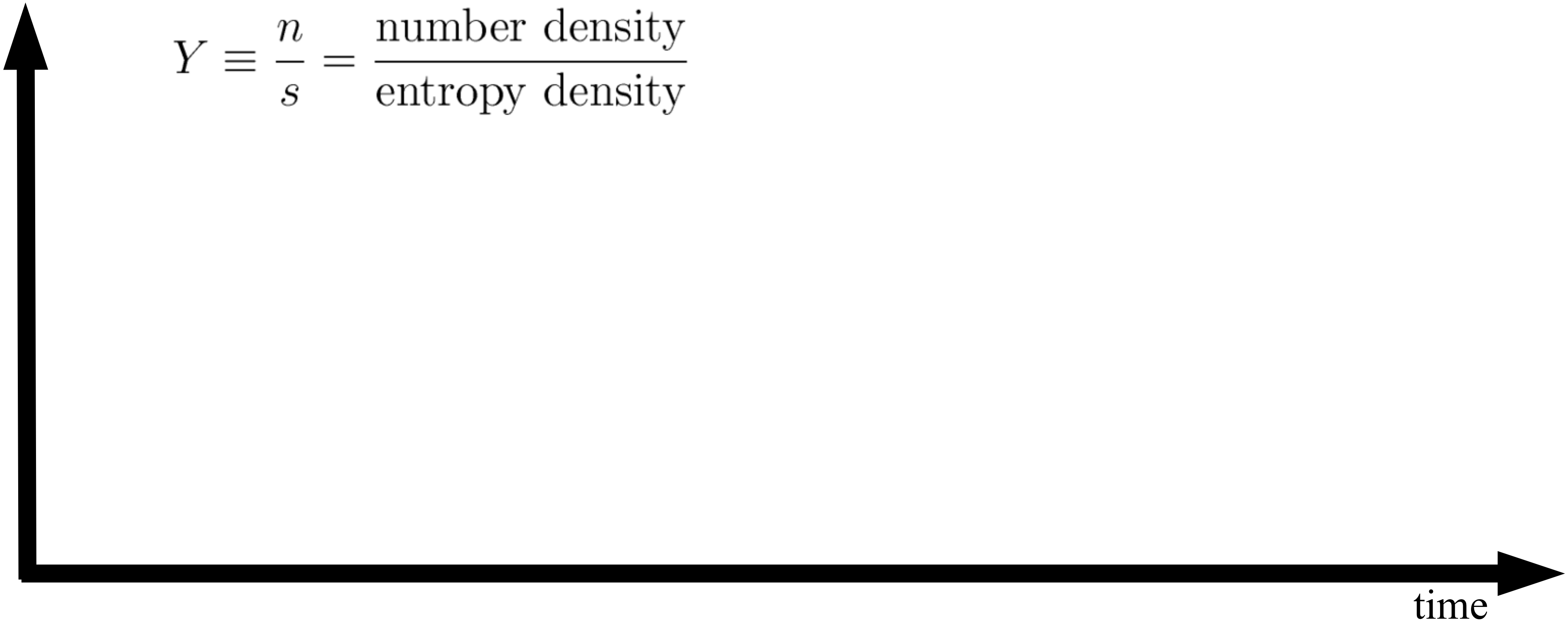
"yield" = number density of DM particles per comoving volume

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



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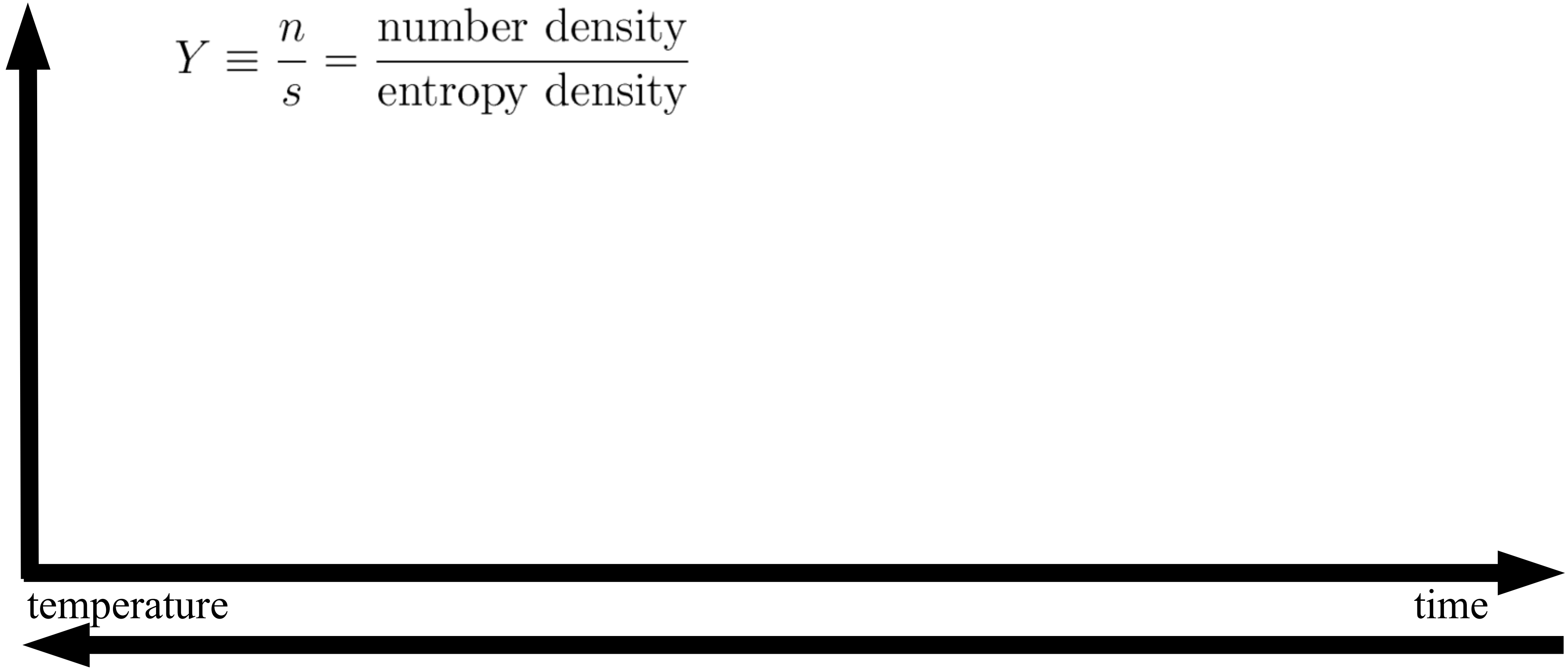

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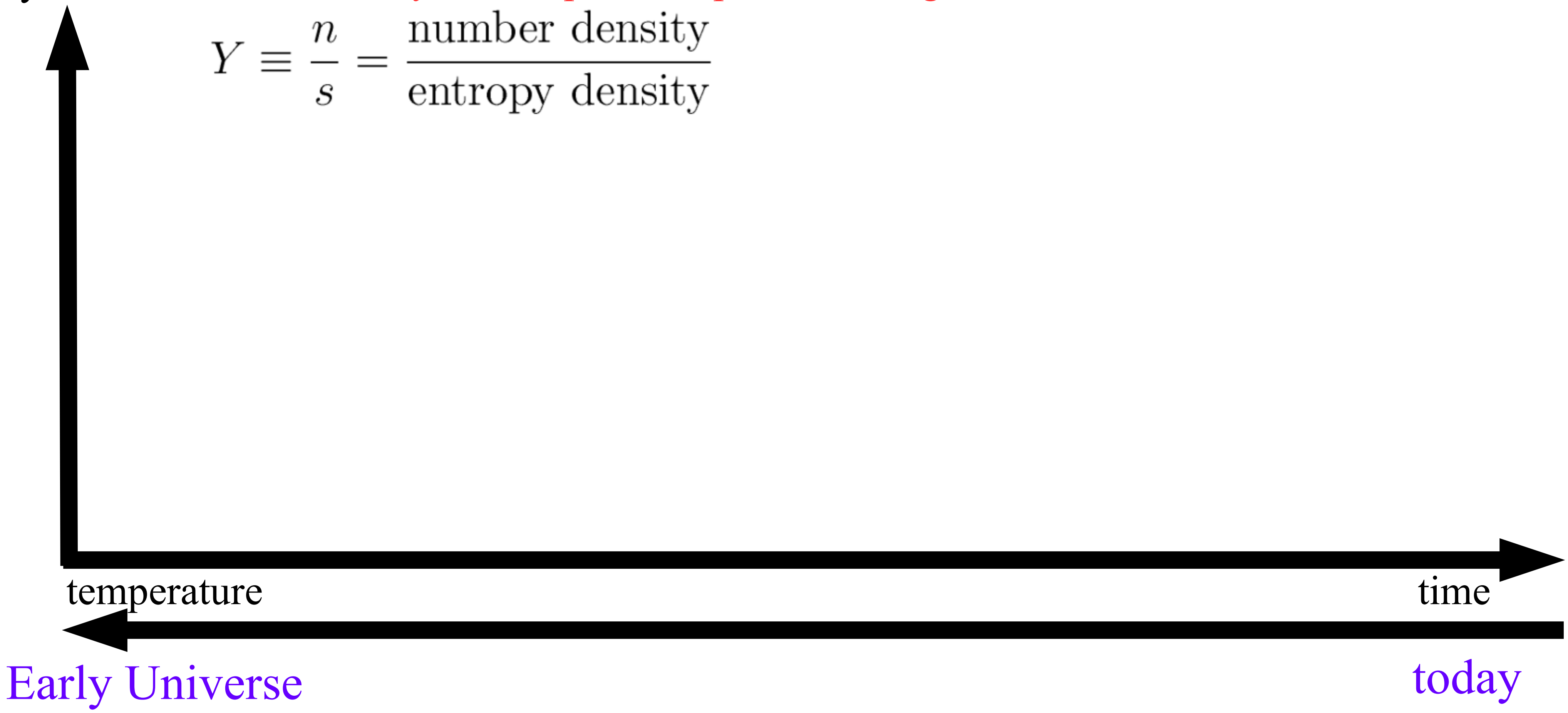

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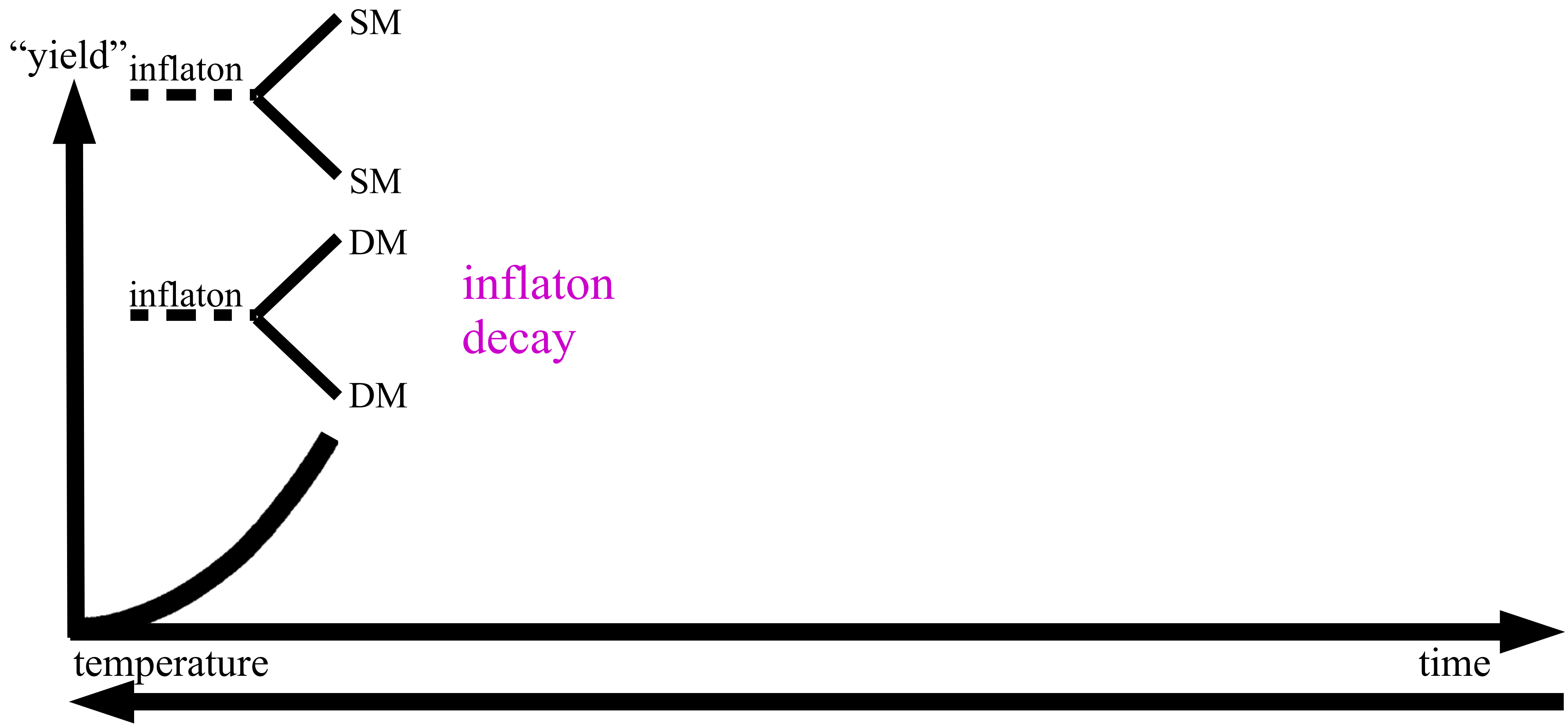

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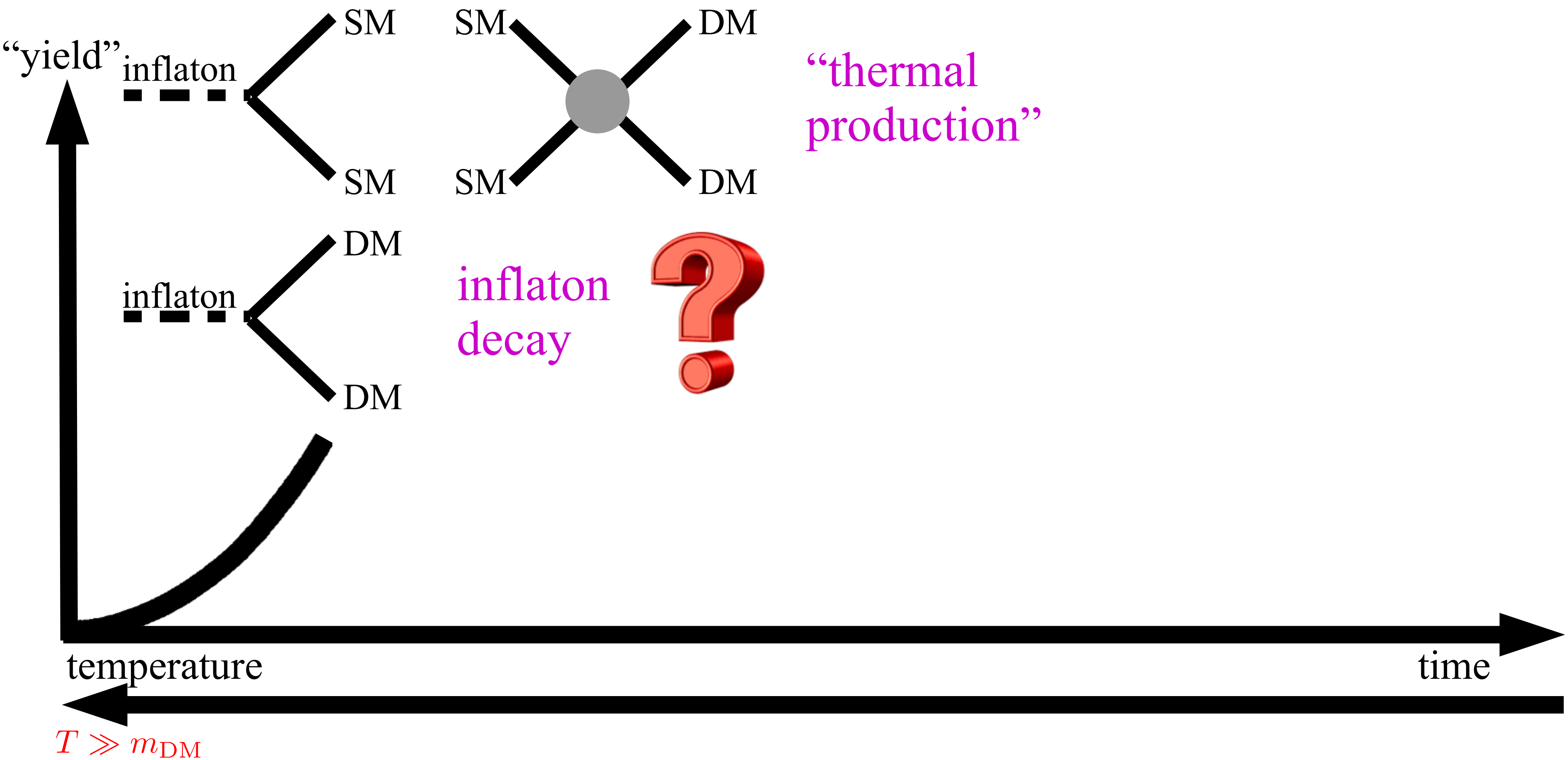
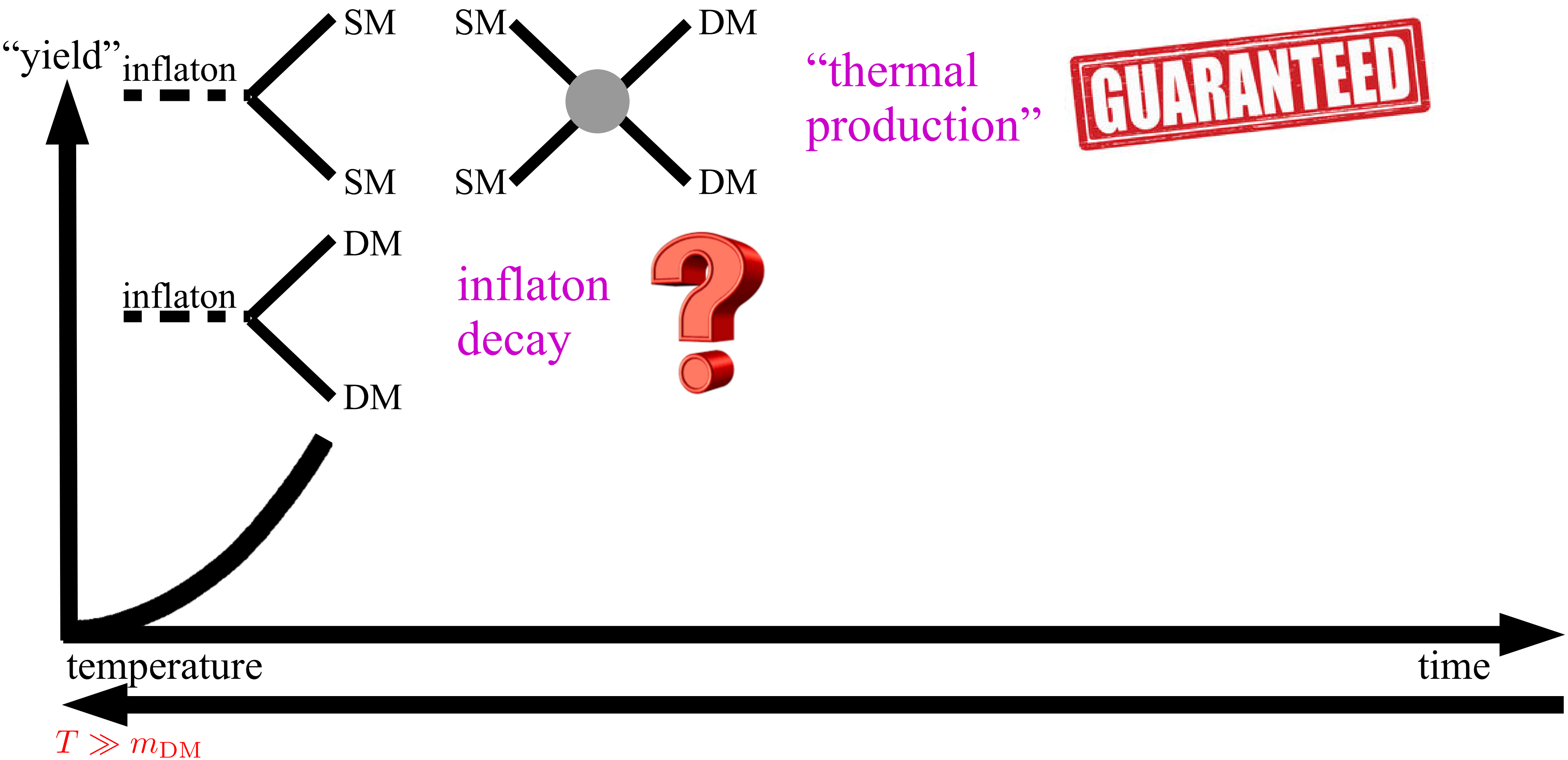


Assume that the temperature of the Universe after reheating was much larger than the DM mass.

WIMP history (in a nutshell)



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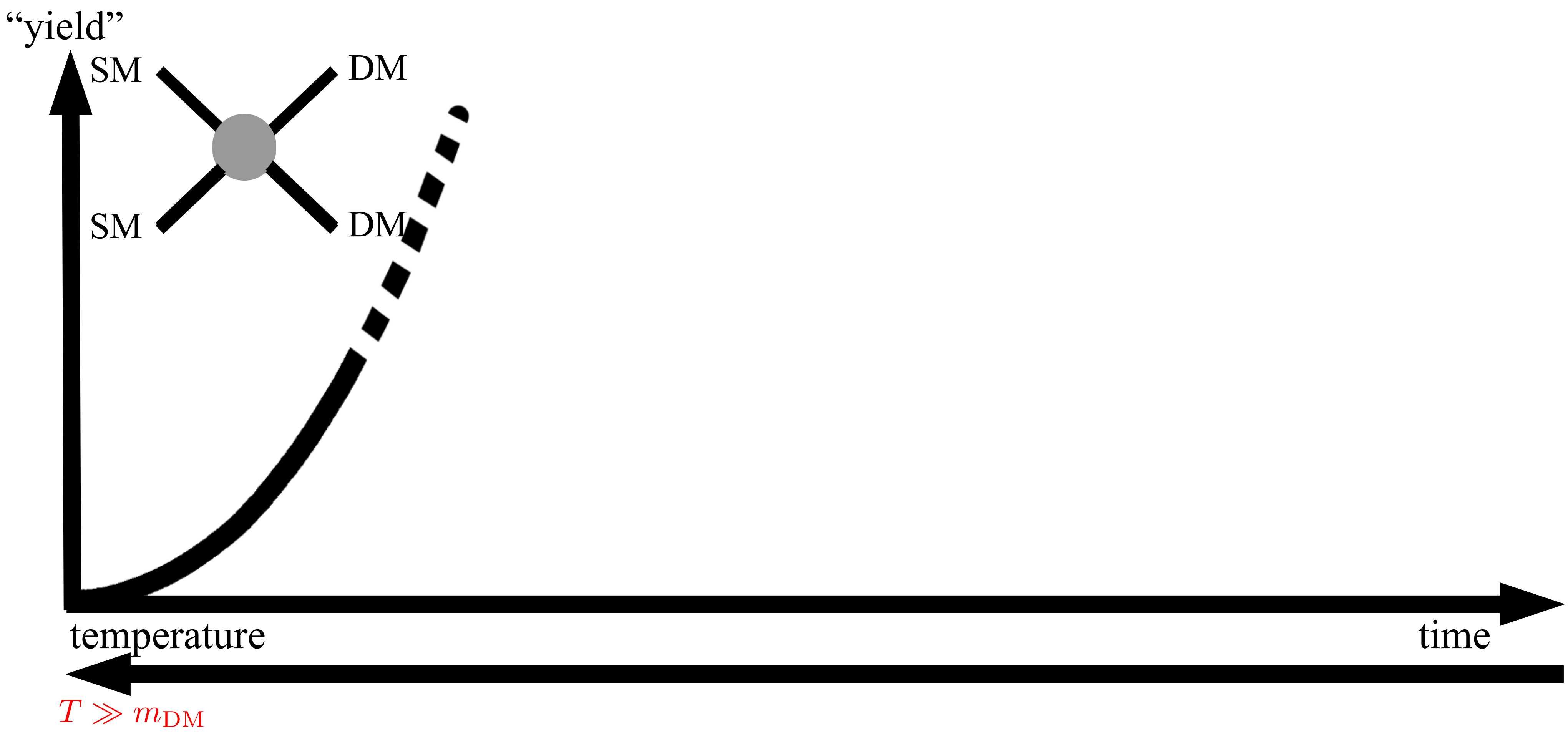

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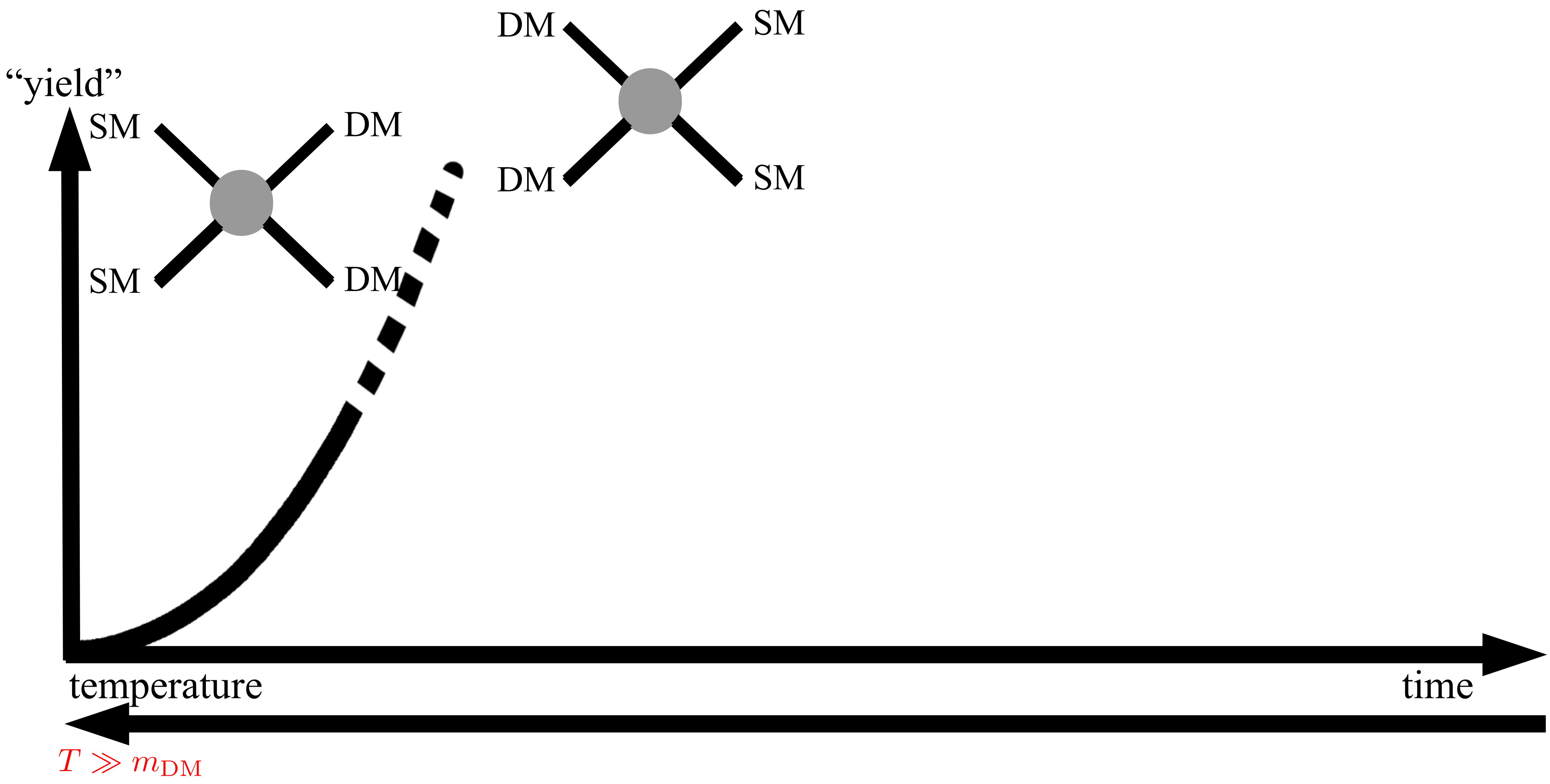

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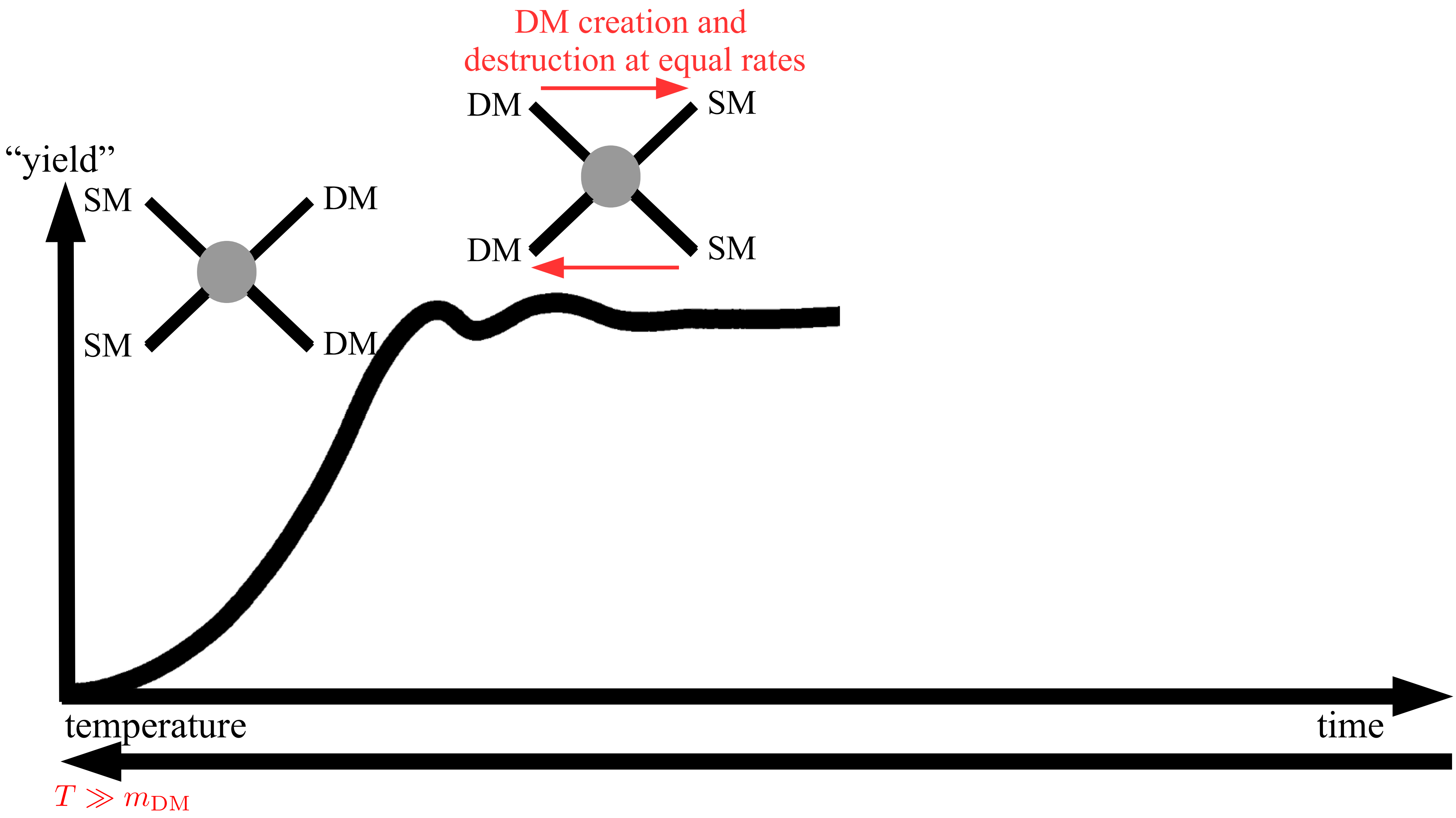

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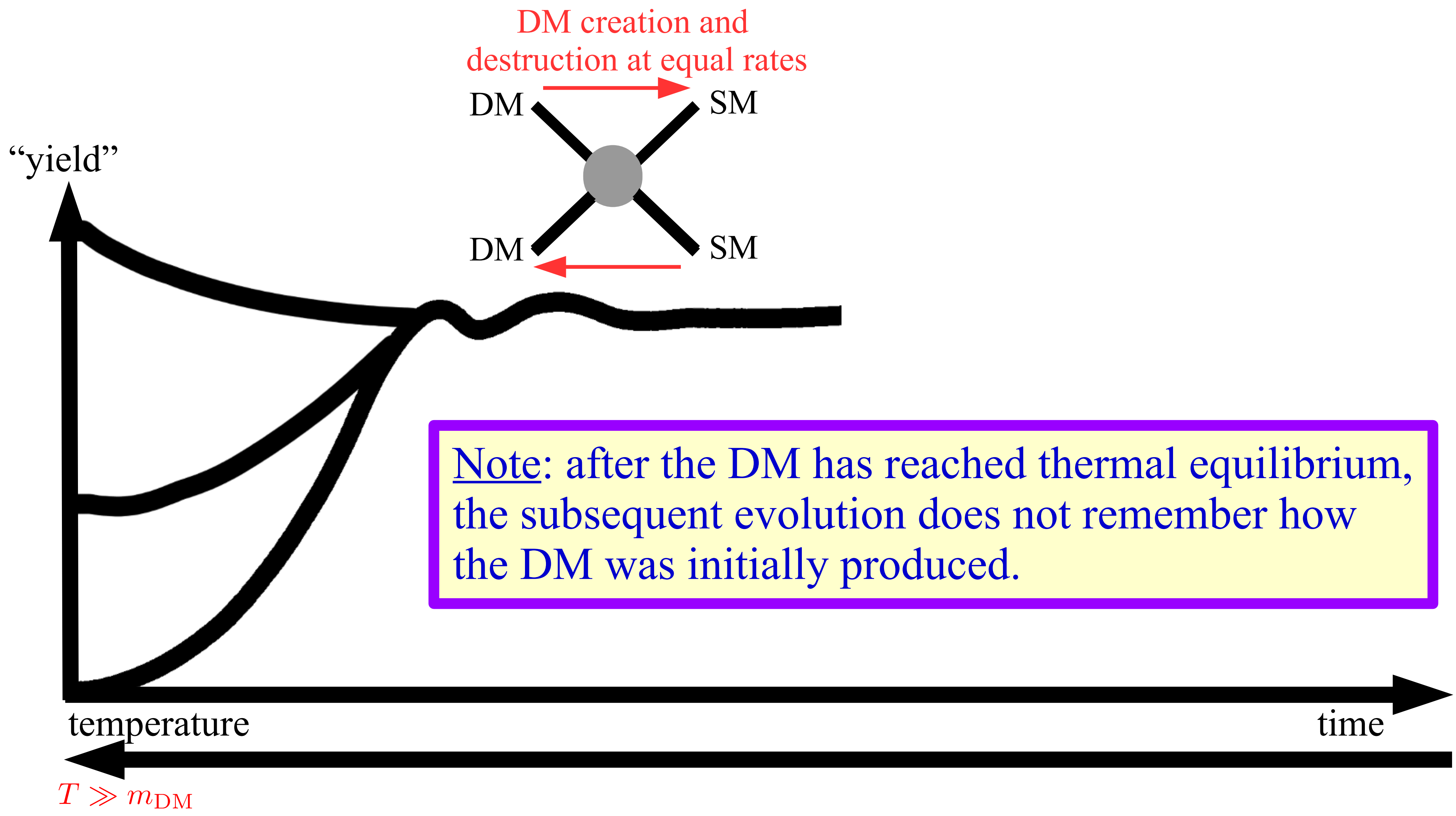
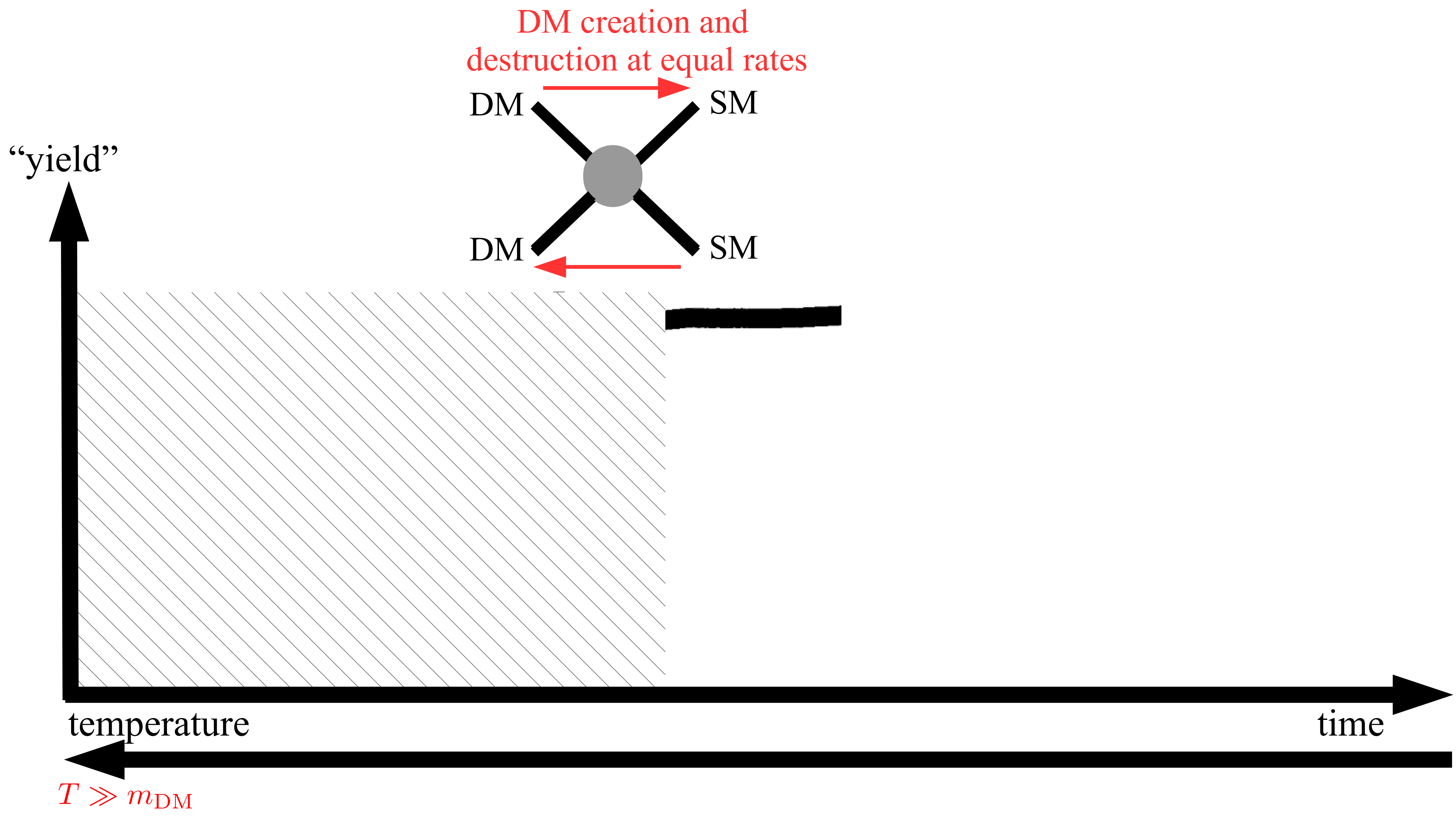


<u>Note</u>: after the DM has reached thermal equilibrium, the subsequent evolution does not remember how the DM was initially produced.

WIMP history (in a nutshell)



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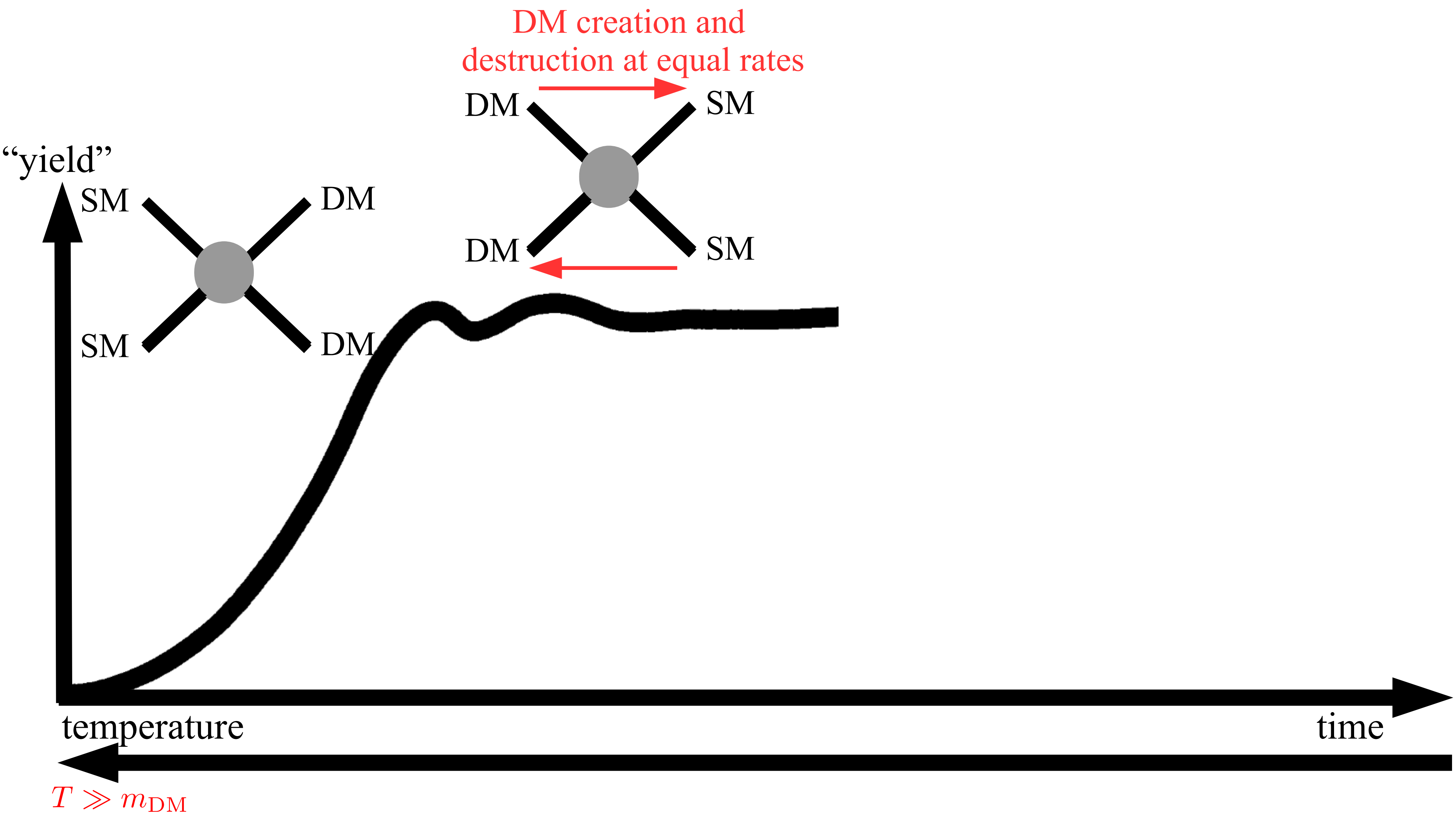

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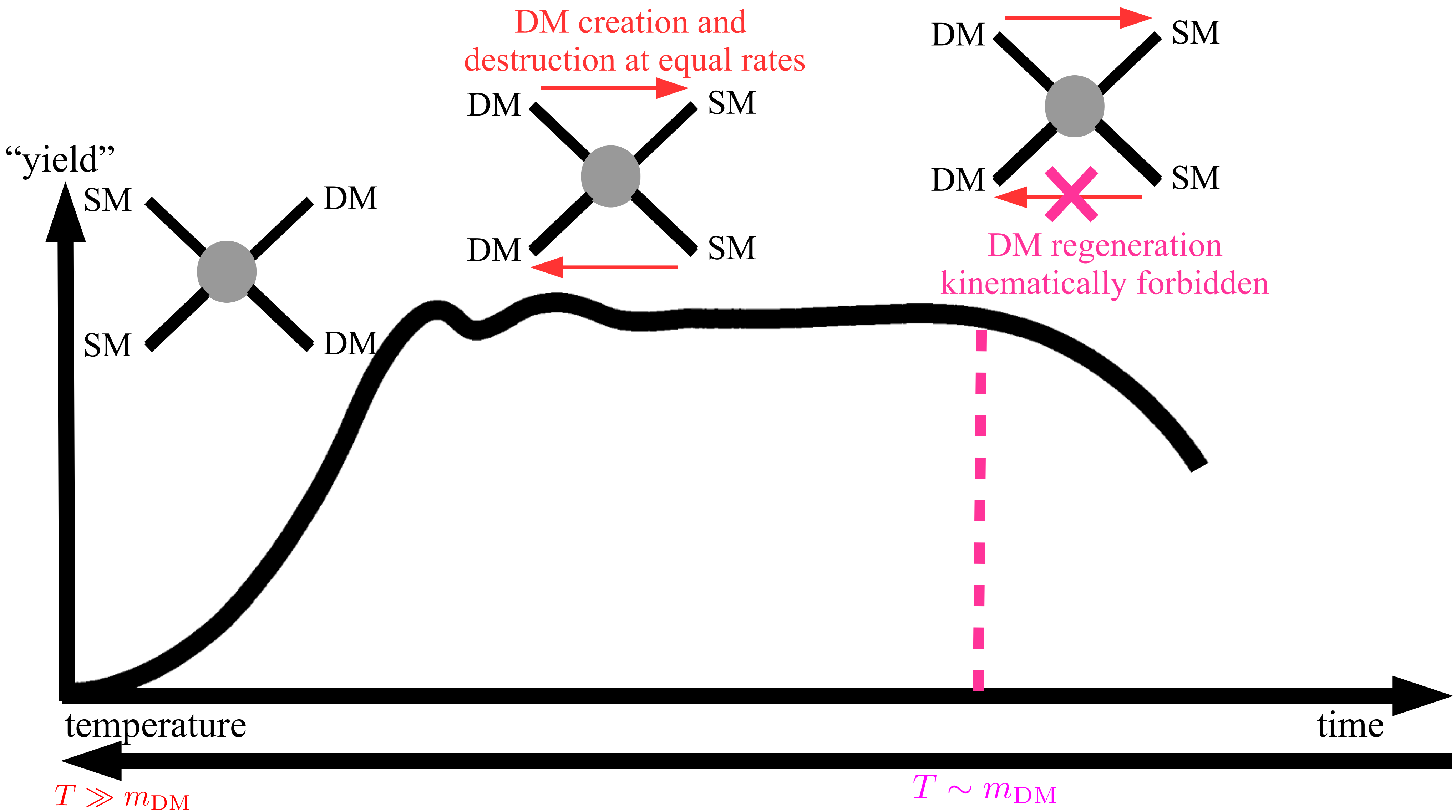

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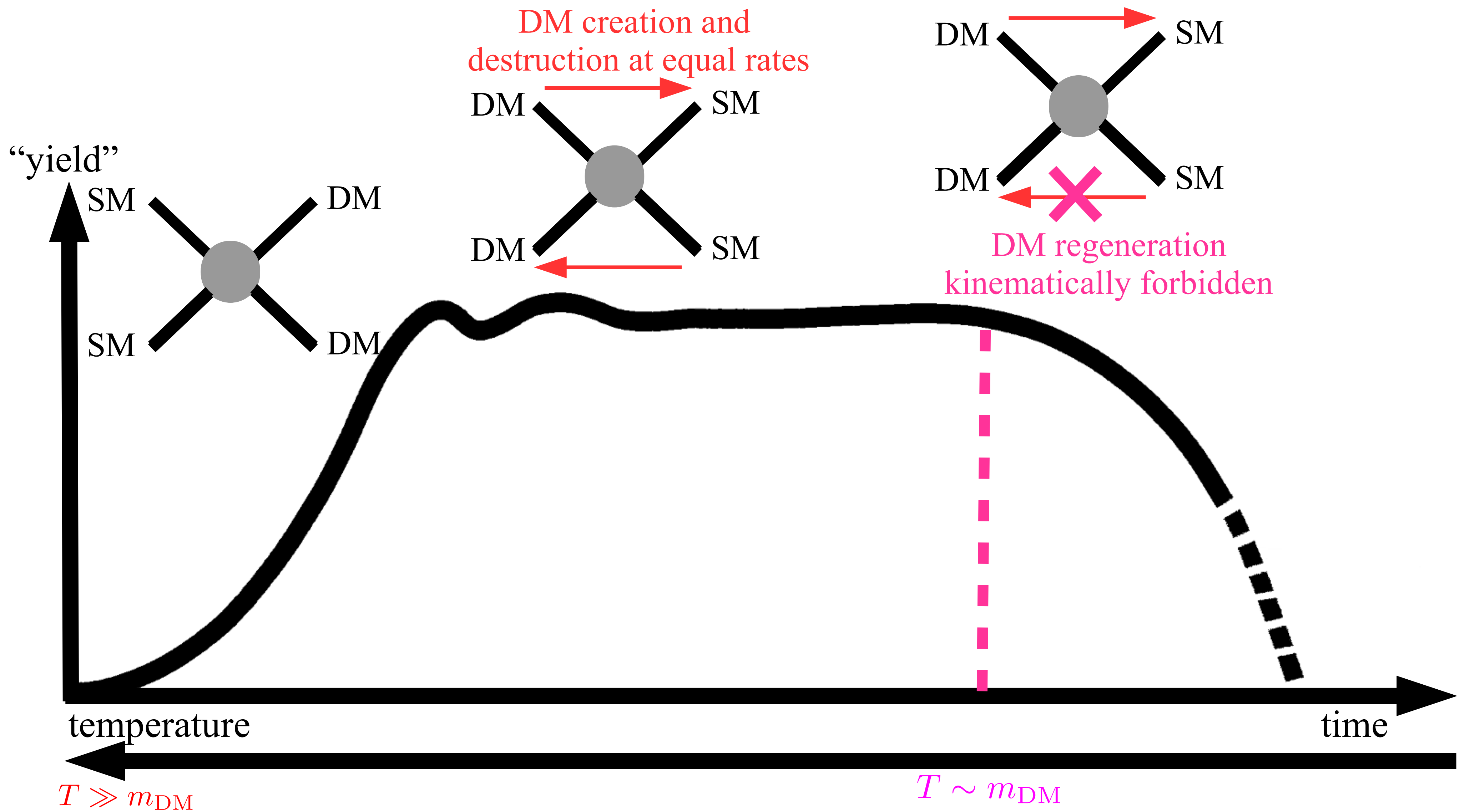

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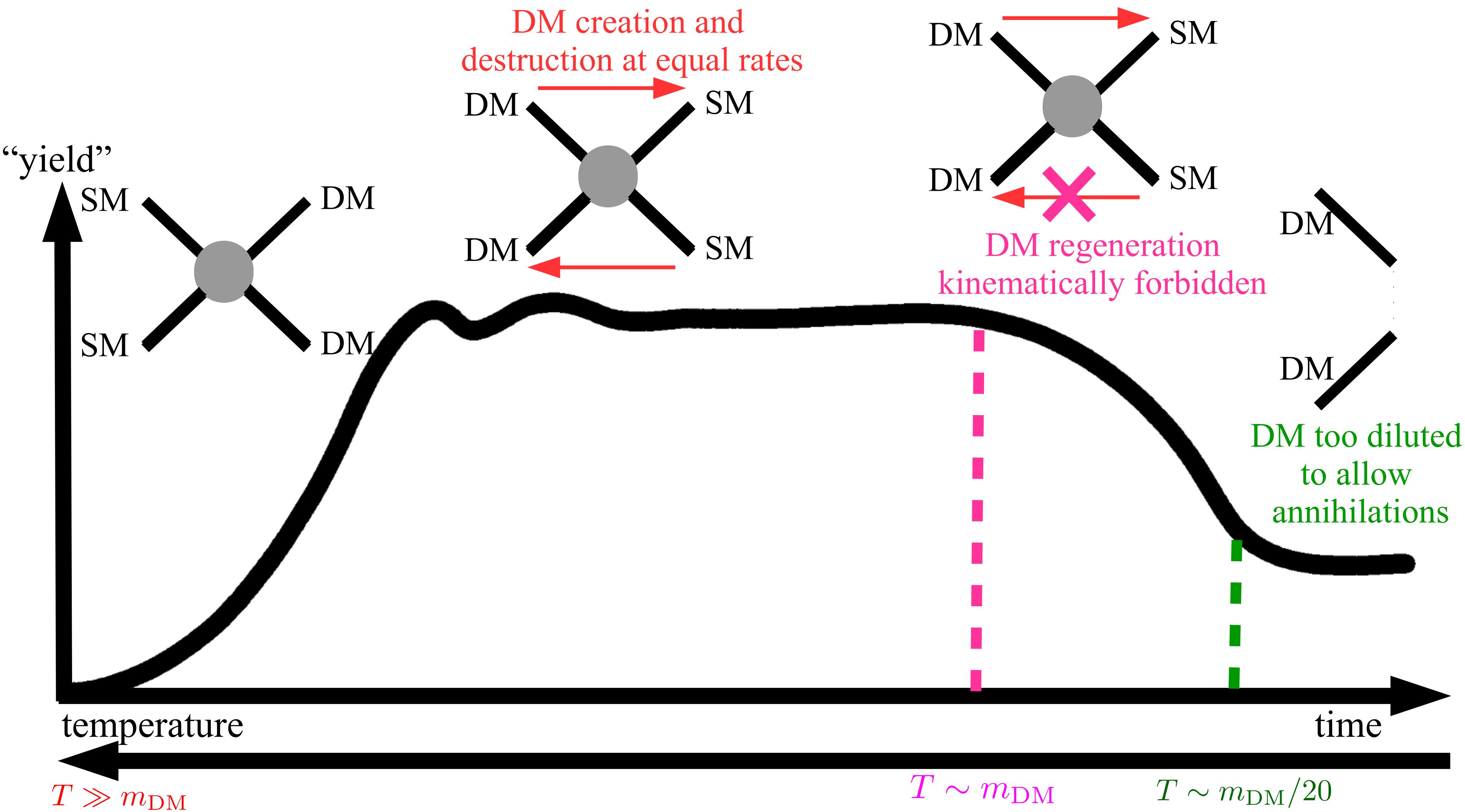

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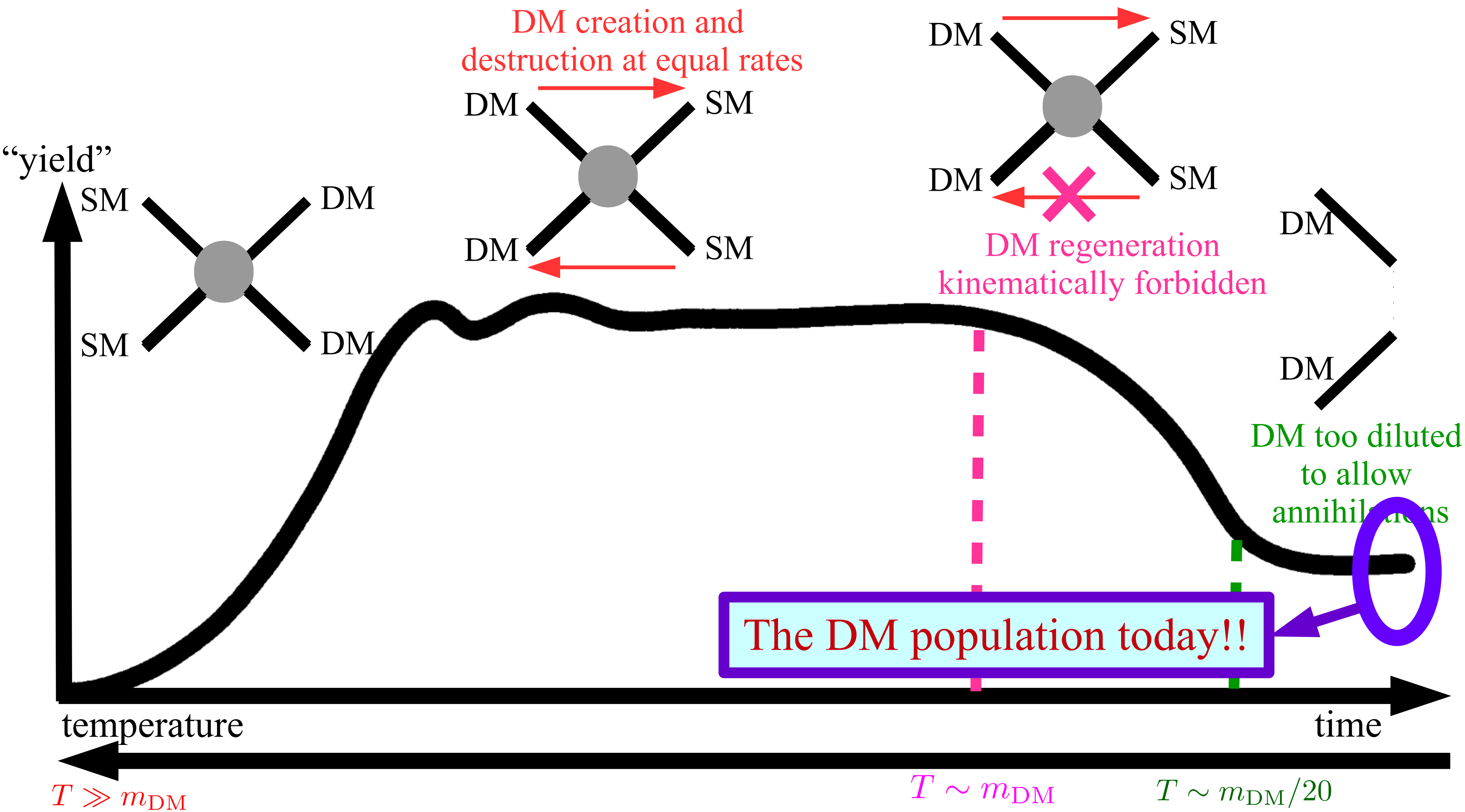

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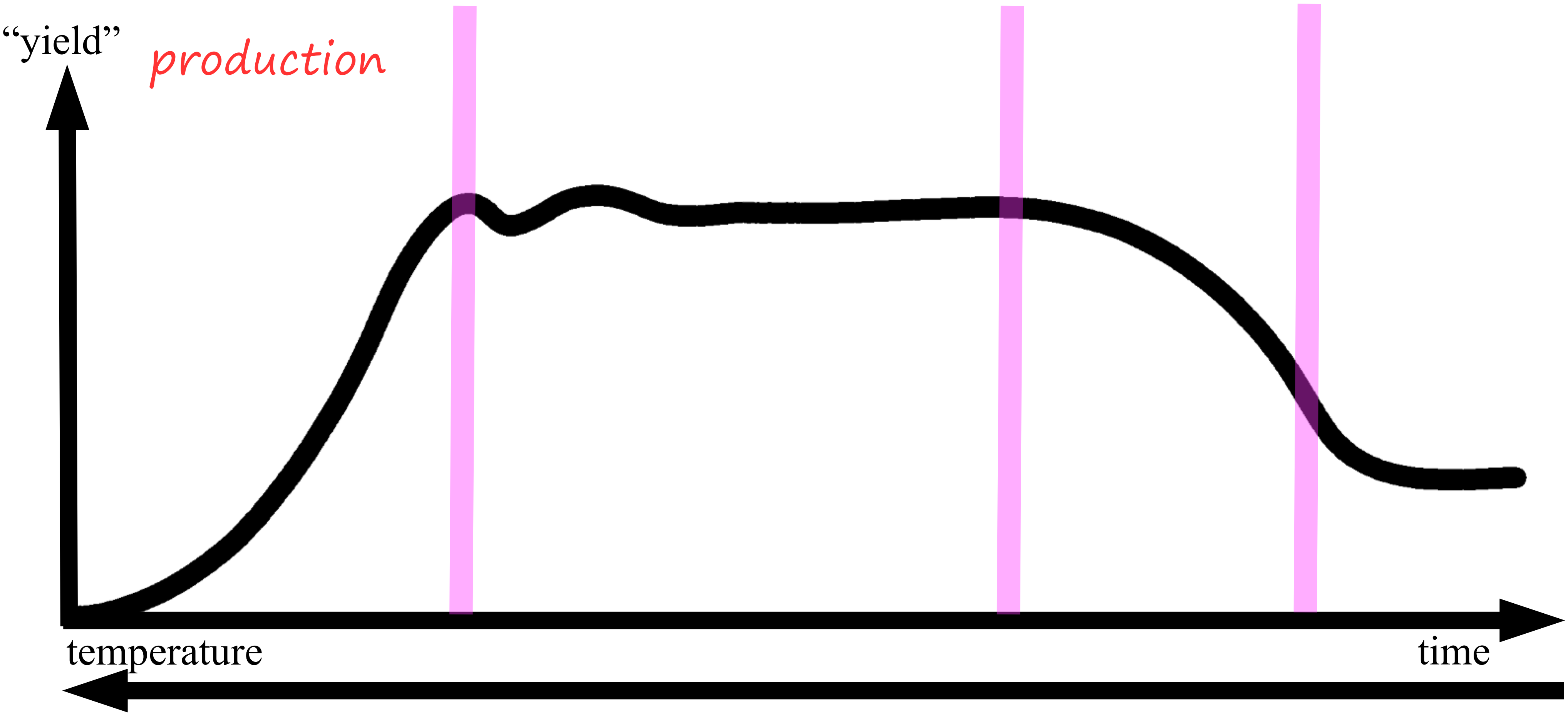

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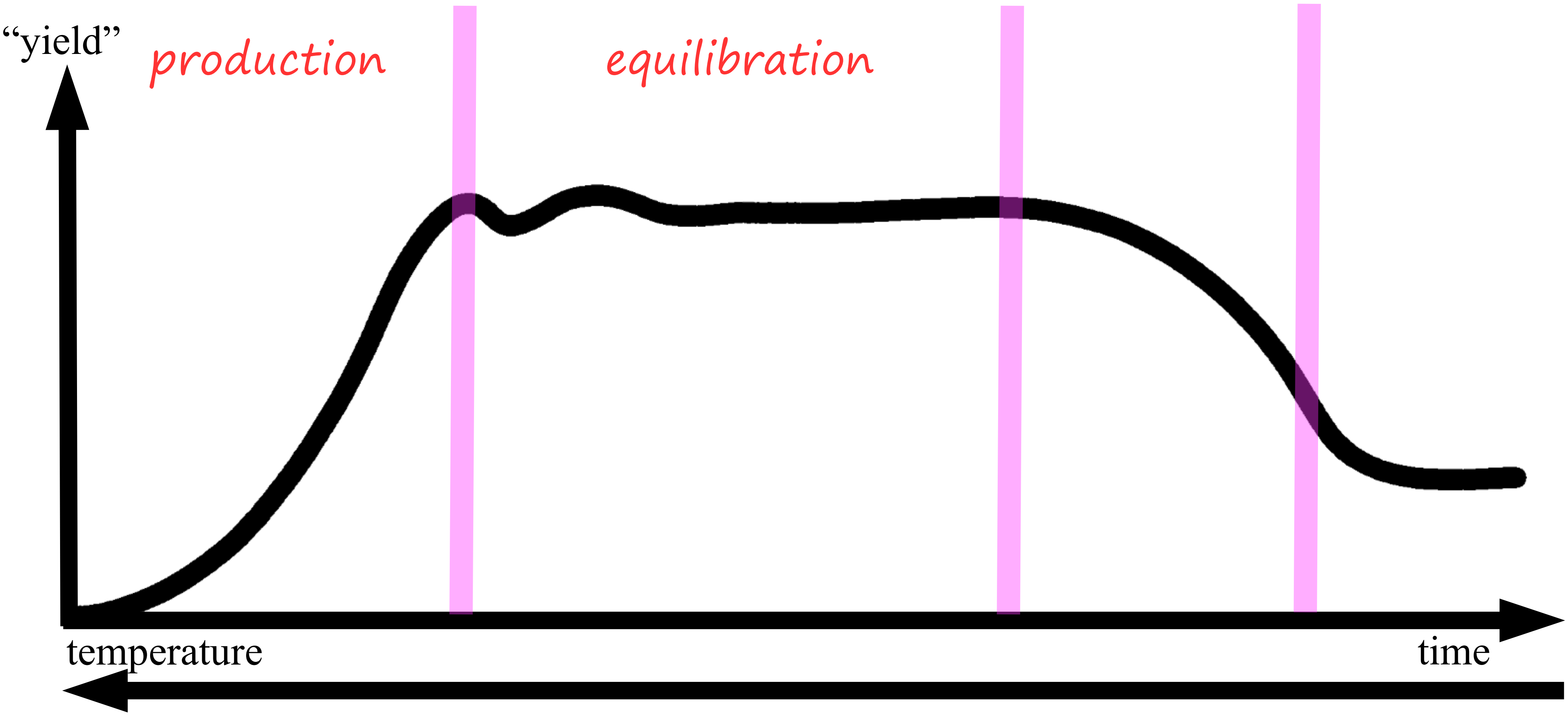

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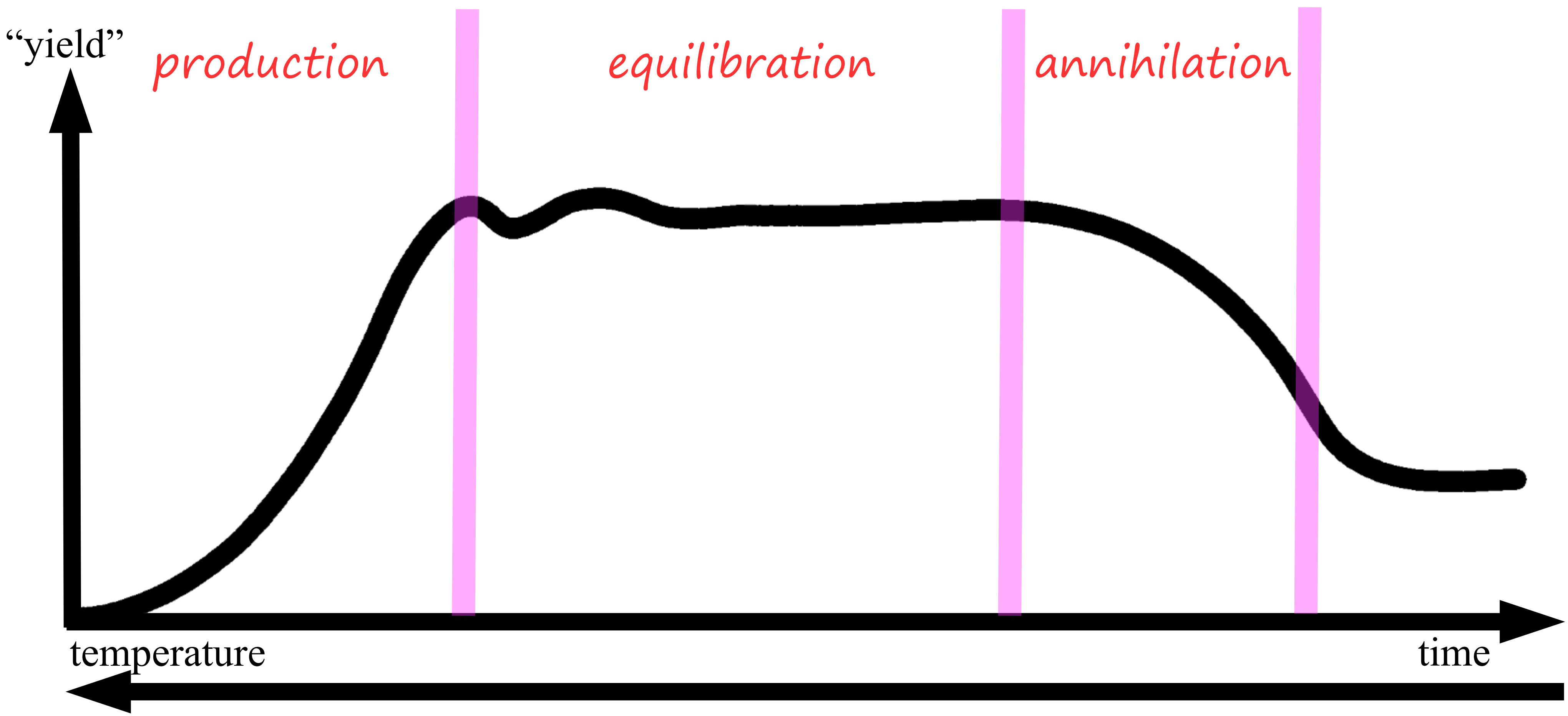

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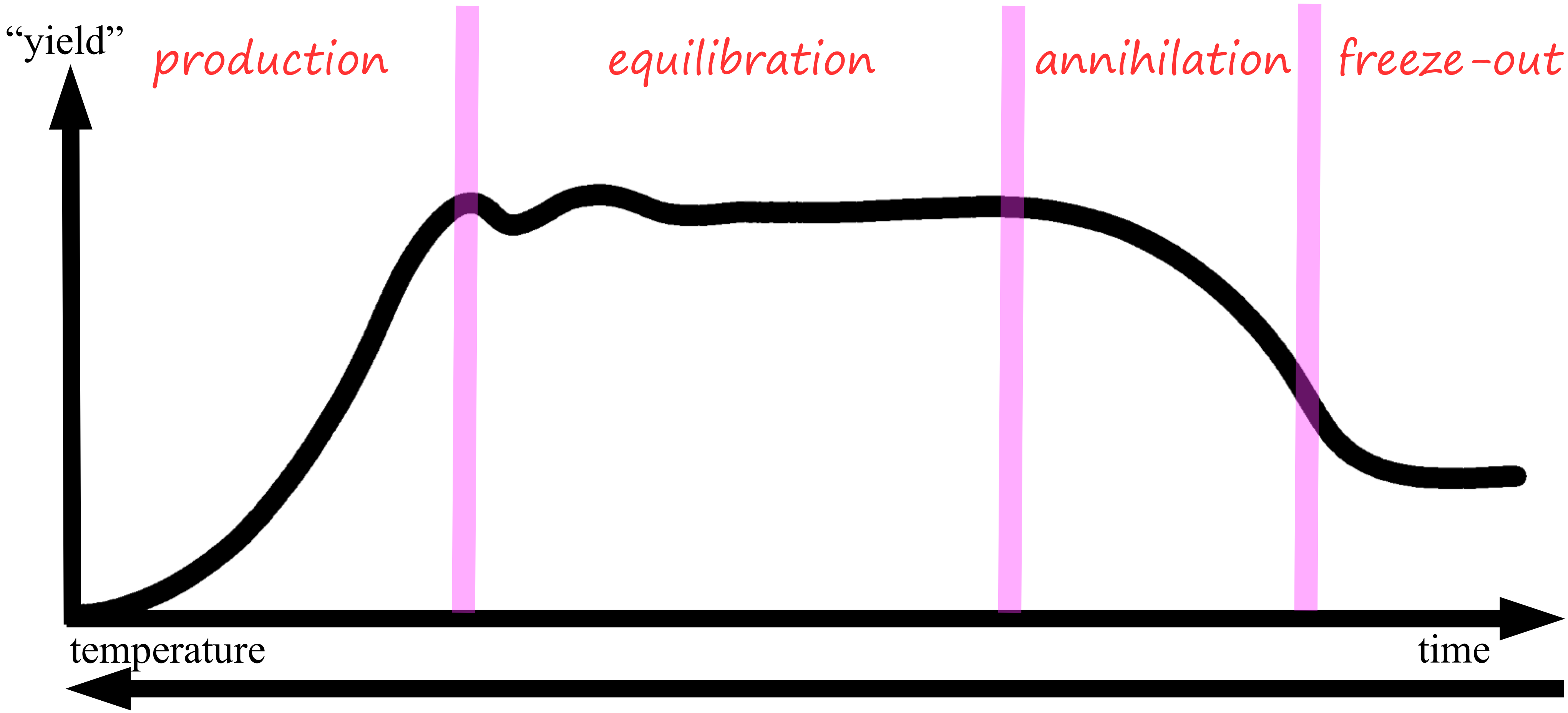
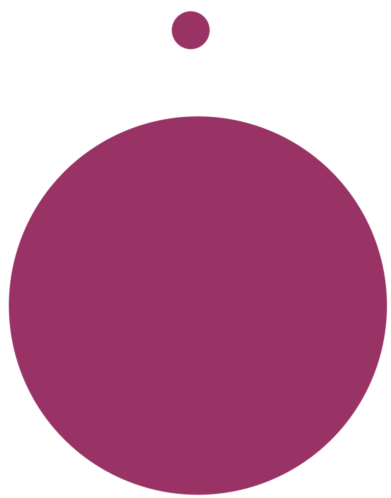


A heuristic view of the freeze-out

The probability of interaction is controlled by the cross-section



Small annihilation rate

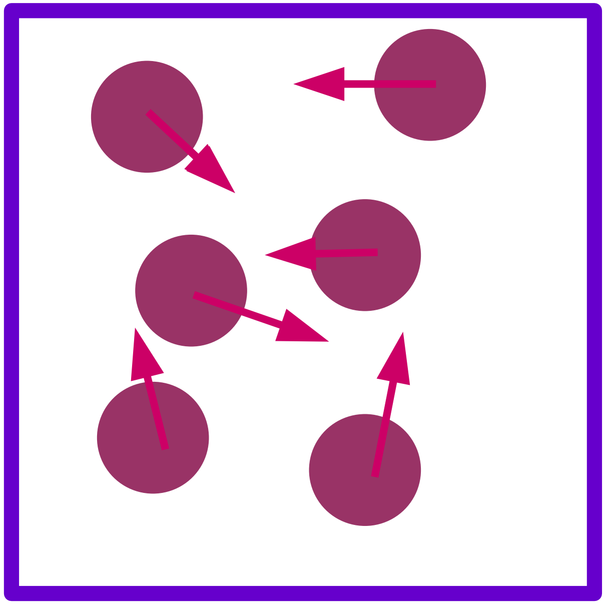
Large annihilation rate

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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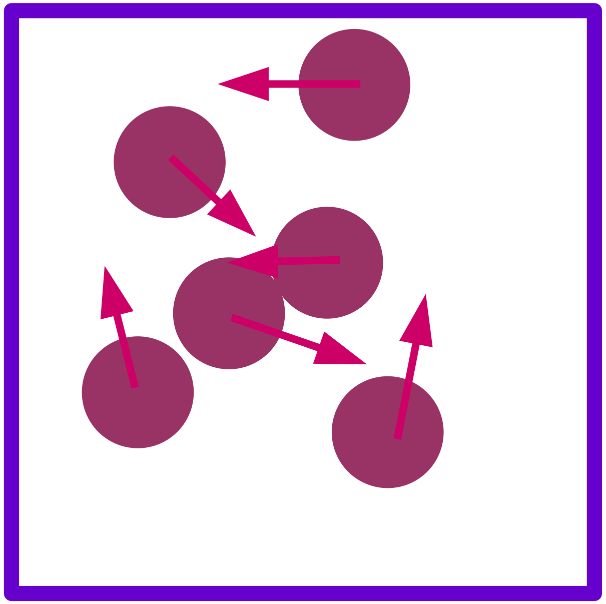

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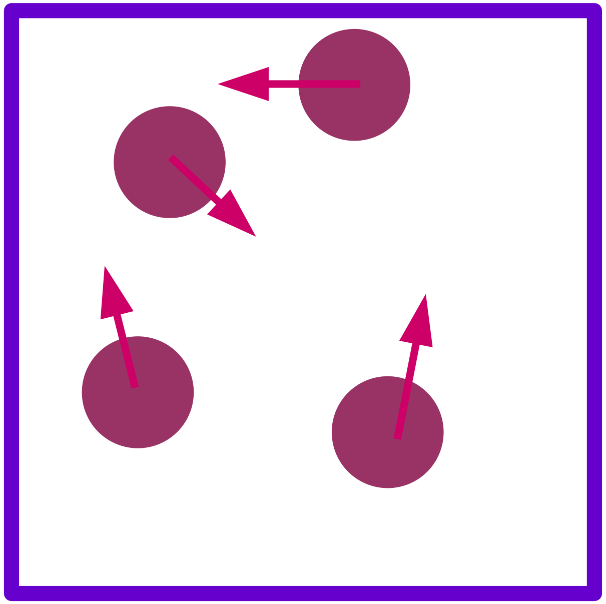

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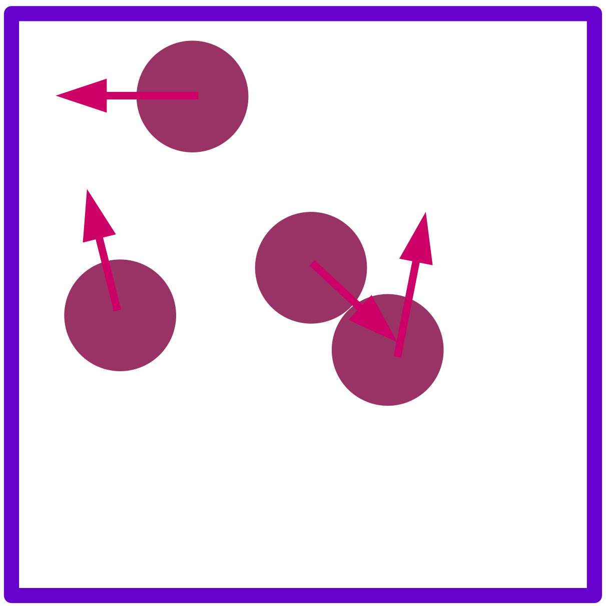

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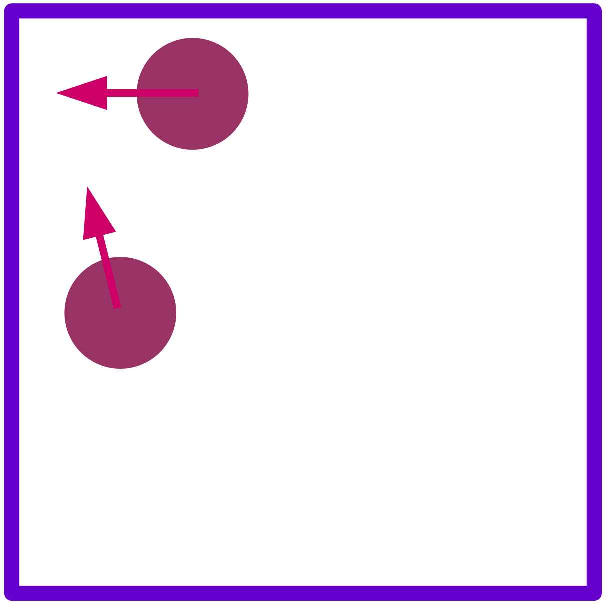

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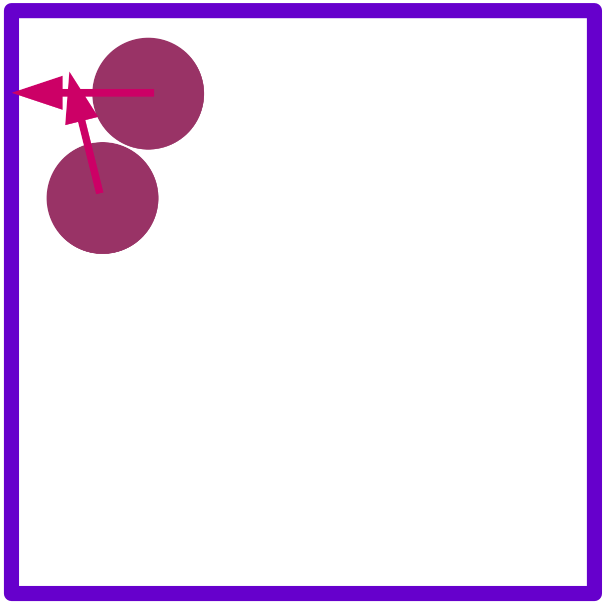

A heuristic view of the freeze-out

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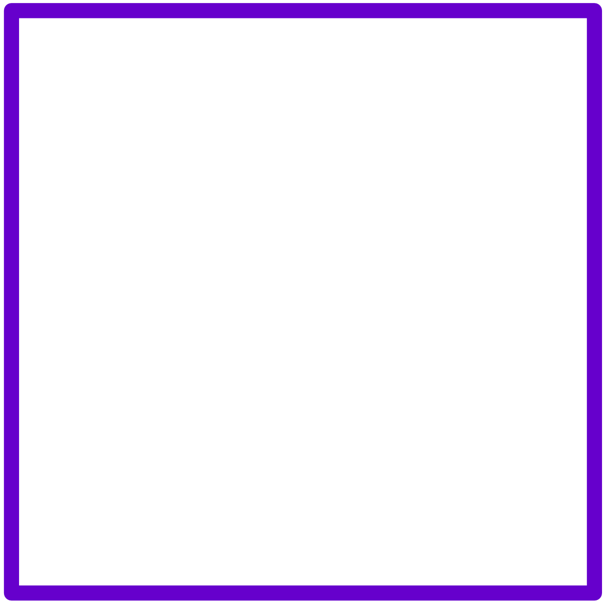
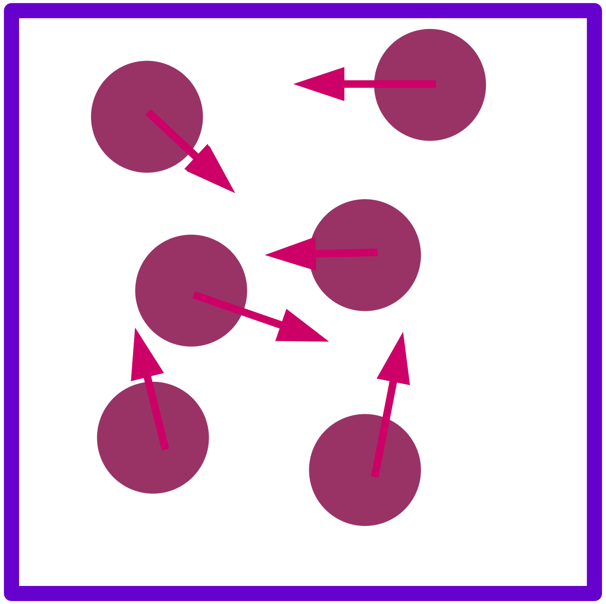
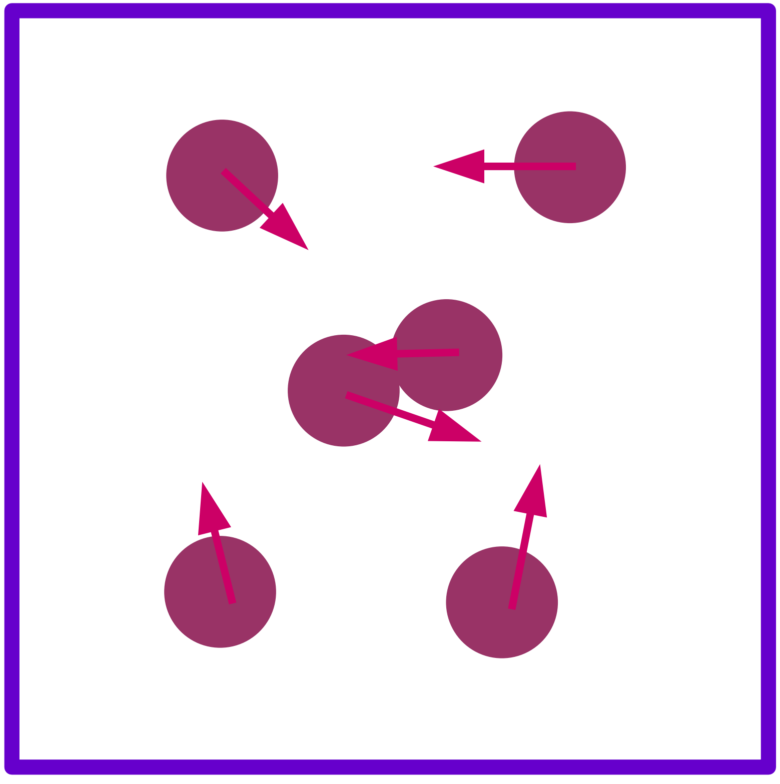


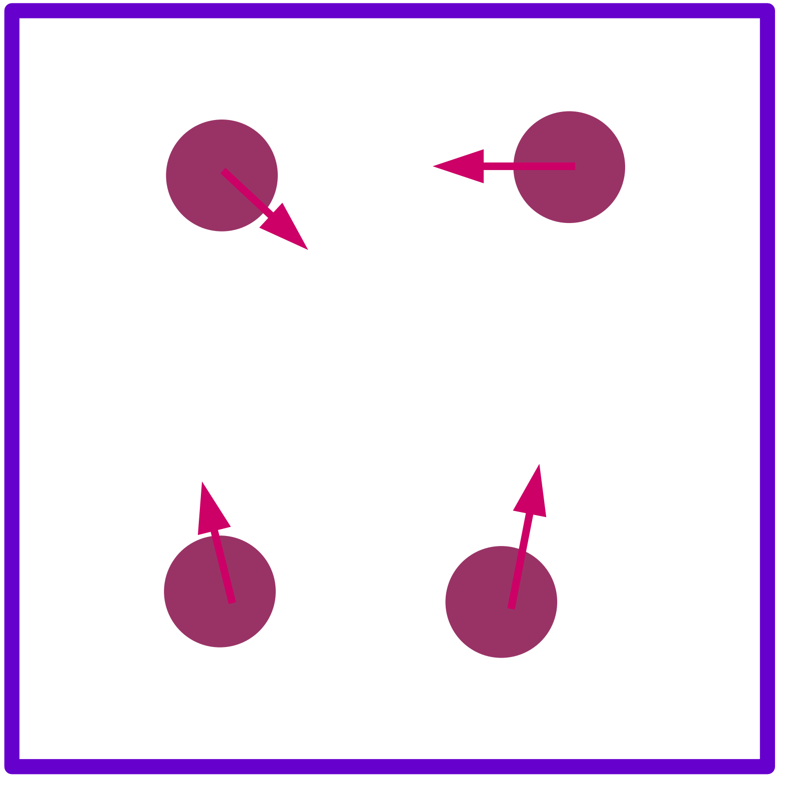
No DM particles at the end!

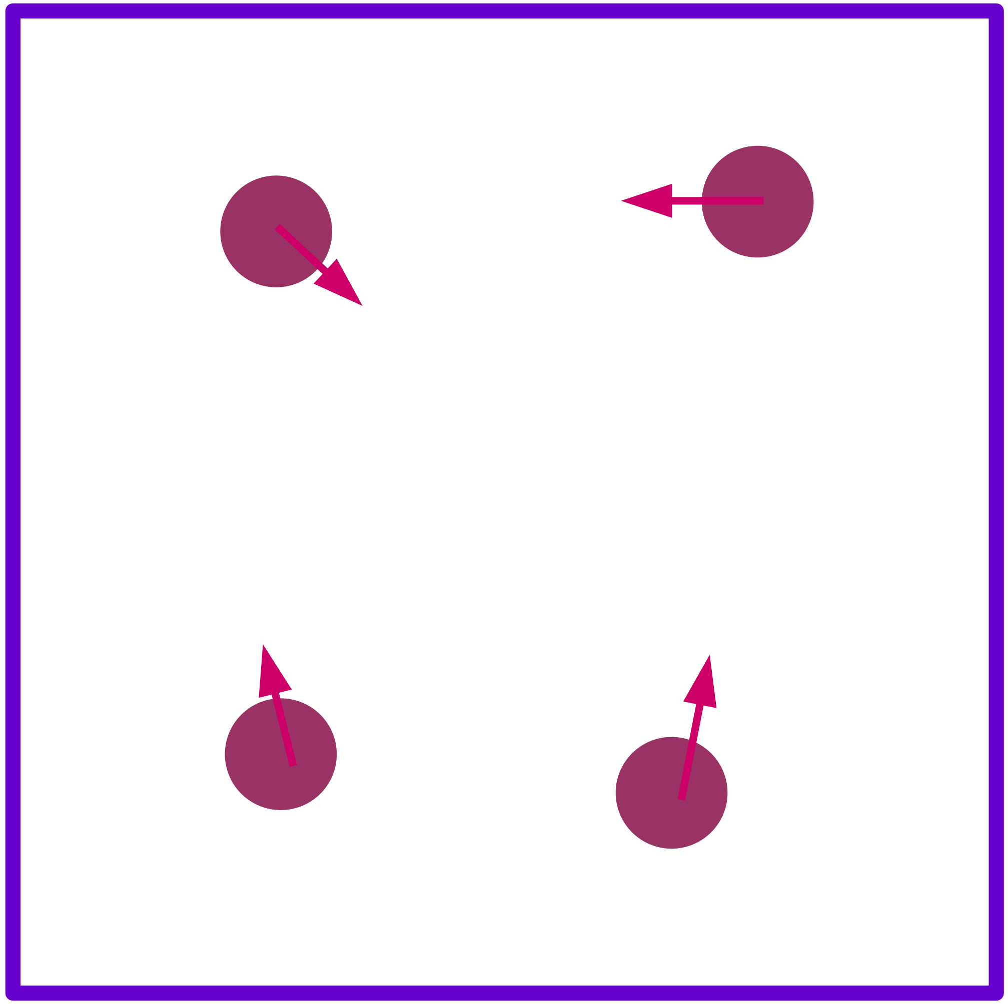
A heuristic view of the freeze-out

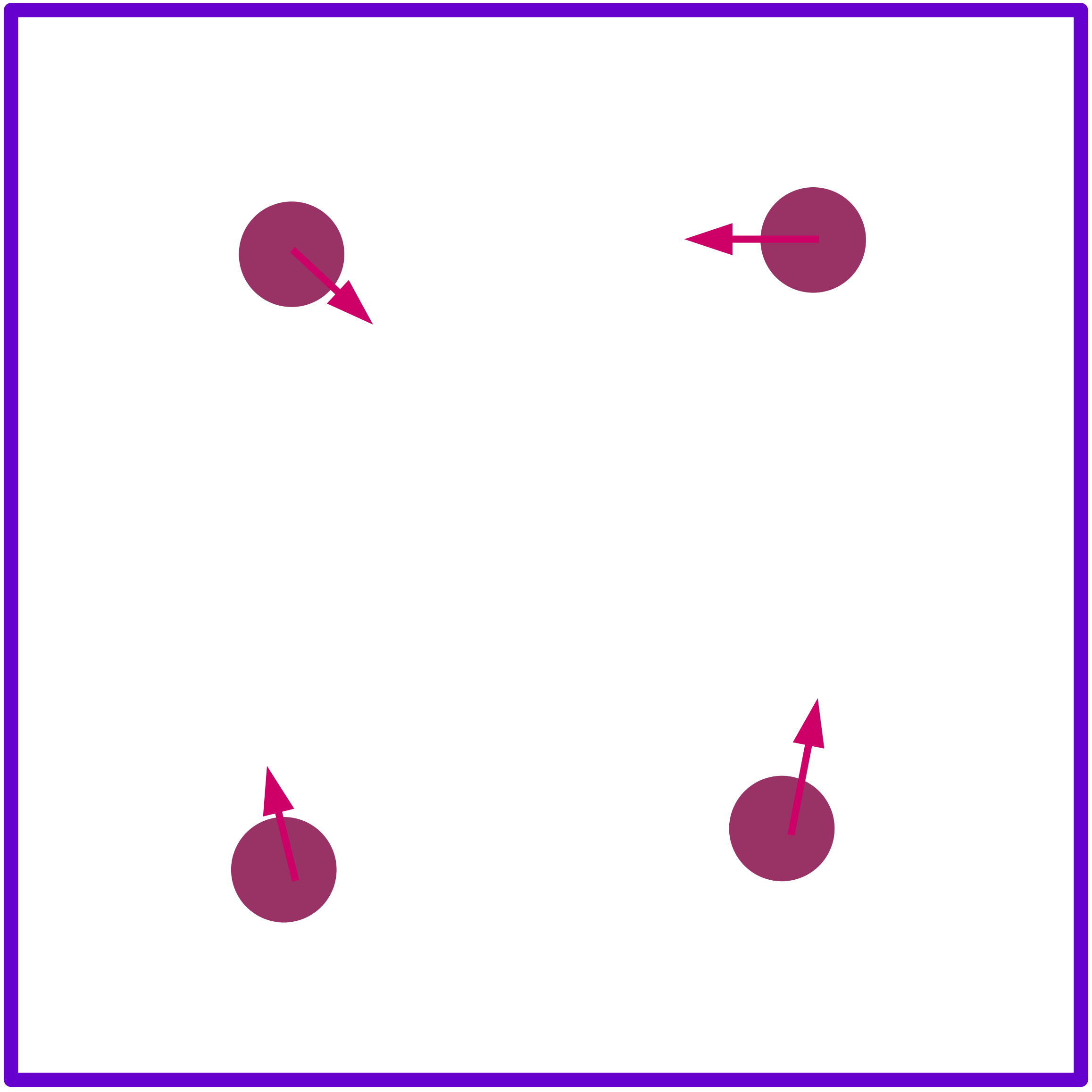
Dark matter population in an expanding Universe





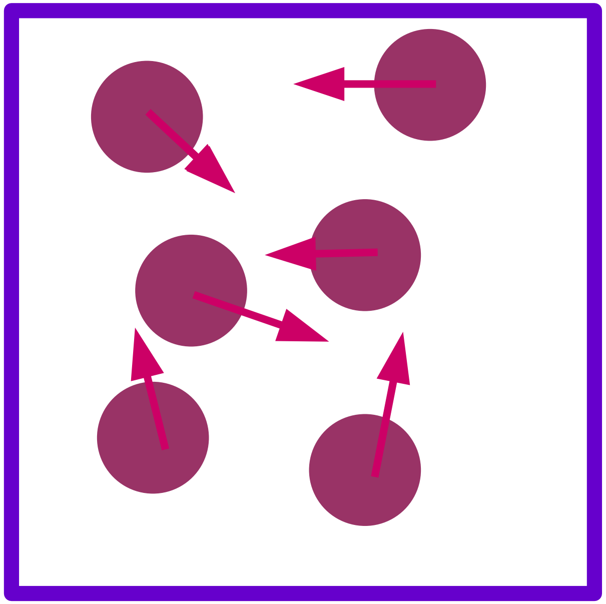






Dark matter particles can no longer annihilate.
The number of dark matter particles "freezes-out"

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



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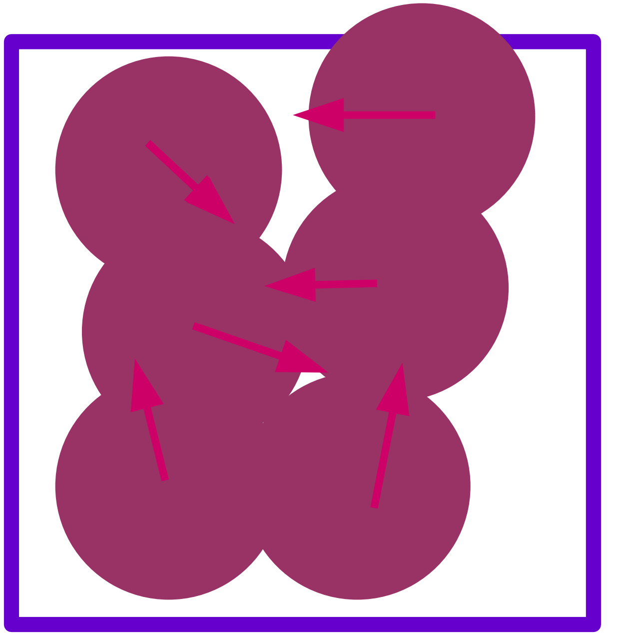

Large annihilation cross section → Small relic abundance

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

Large annihilation cross section → Small relic abundance

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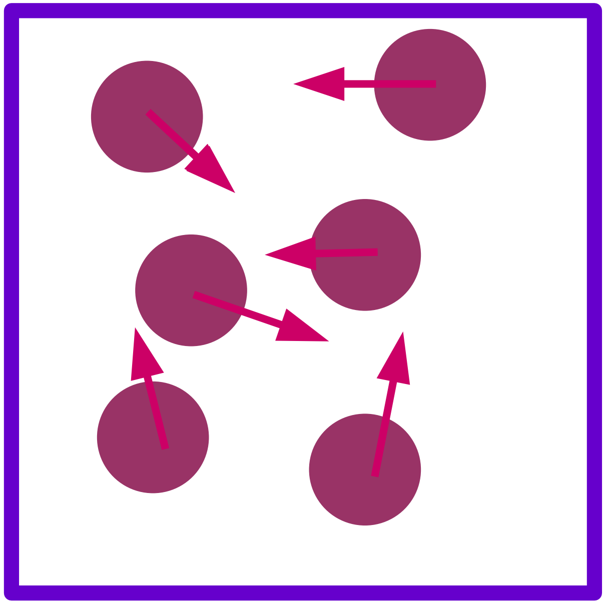
… and on their velocity



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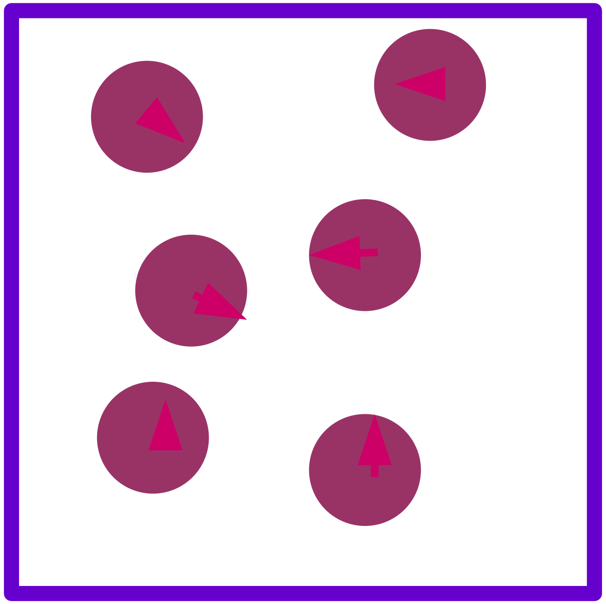

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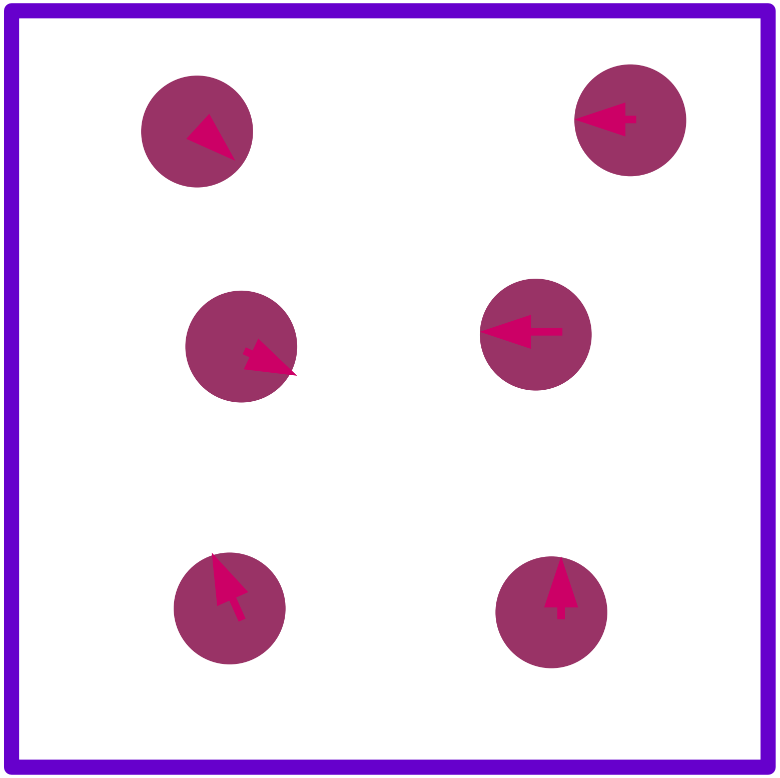


Large velocity → Small relic abundance

Small velocity → Large relic abundance

A heuristic view of the freeze-out

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

The basic tool: the Boltzmann equation

Boltzmann equation: equation that describes the time evolution of the phase space density distribution $f(t, \vec{r}, \vec{p})$:

$$L[f] = C[f]$$

Liouville operator
(time evolution)

Collision term
(creation/destruction of particles in phase space due to annihilations or decays)

The basic tool: the Boltzmann equation

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

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

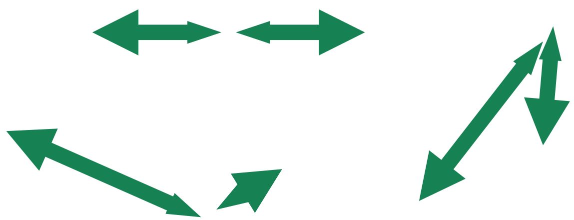
(under some assumptions – see later)

- $n(t)$ number density of DM particles

$$n(t) = \frac{g}{(2\pi)^3}\int d^3p\, f(t,E)$$

- $H(t) \equiv \frac{\dot{a}}{a}$ → Hubble rate

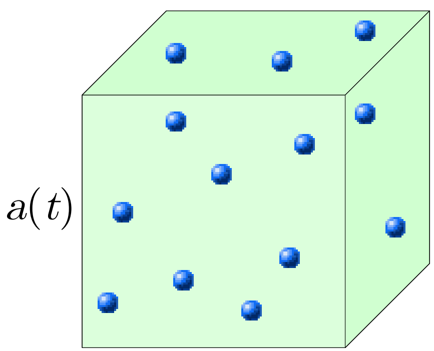
- σ = annihilation cross-section DM DM → SM SM
- v = relative velocity
- ⟨...⟩ = thermal average



Justification

LHS Assume that the collision term vanishes (σ=0)
⇒ number of particles conserved

$$\frac{dN(t)}{dt} = 0$$



$$N(t) = n(t)V(t) = n(t)a(t)^3$$

$$\rightsquigarrow \frac{d}{dt}(na^3) = \dot{n}a^3 + 3na^2\dot{a} = 0$$

$$\Rightarrow a^3(\dot{n} + 3\frac{\dot{a}}{a}n) = 0$$

$$\boxed{\dot{n} + 3Hn = 0 \text{ when } \sigma = 0}$$

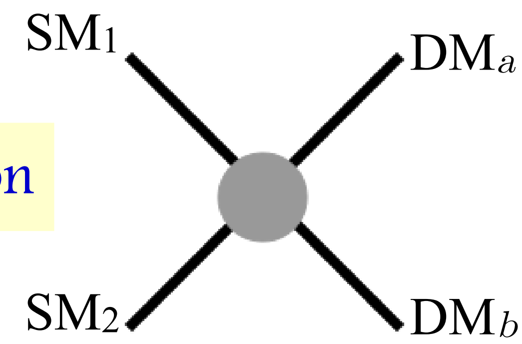
Justification

RHS

Remember:

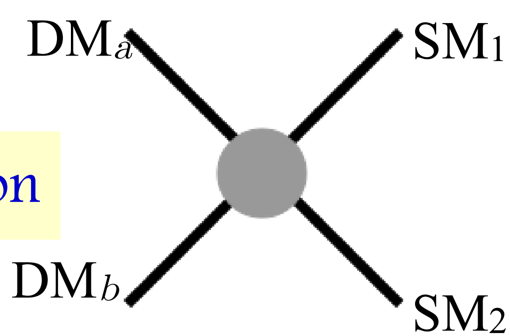
Boltzmann equation: change of n = production - destruction

production



$$\sim \int |\mathcal{M}_{12\to ab}|^2 \, f_1 \, f_2 \, d(\text{phase space})$$

destruction



$$\sim \int |\mathcal{M}_{ab\to 12}|^2 \, f_a \, f_b \, d(\text{phase space})$$

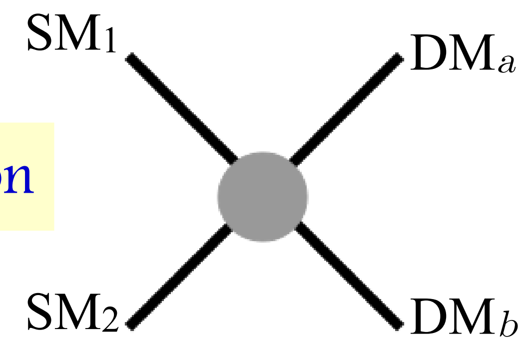
Justification

RHS

Remember:

Boltzmann equation: change of n = production - destruction

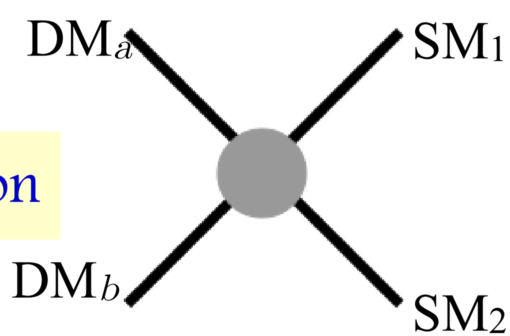
production



$$\sim \int |\mathcal{M}_{12\to ab}|^2 \, f_1 \, f_2 \, d(\text{phase space})$$

Equal if T conserved
(CP conserved)

destruction



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Justification

RHS

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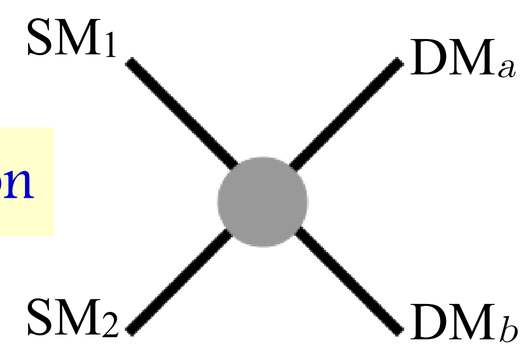
production



$$\sim \int |\mathcal{M}_{12\to ab}|^2 \, f_1 \, f_2 \, d(\text{phase space})$$

Equal if T conserved
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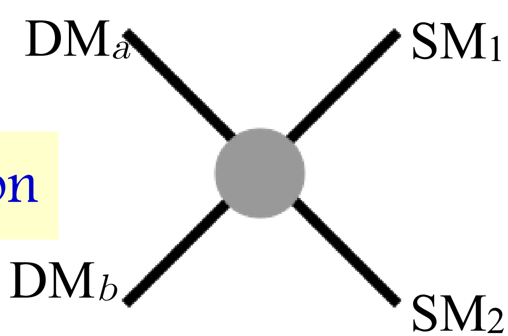
Assumption 1

destruction



$$\sim \int |\mathcal{M}_{ab\to 12}|^2 \, f_a \, f_b \, d(\text{phase space})$$

$$\text{RHS} \sim -\int |\mathcal{M}_{ab\to 12}|^2 \, (f_a \, f_b - f_1 \, f_2) \, d(\text{phase space})$$

Justification

RHS Assume SM particles in thermal equilibrium **Assumption 2**

$$f_1 = f_1^{\text{eq}} = e^{-E_1/T}$$ (Boltzmann distribution)

Justification

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$$f_1 = f_1^{\text{eq}} = e^{-E_1/T} \quad \text{(Boltzmann distribution)}$$

$$\Rightarrow f_1\, f_2 = f_1^{\text{eq}} f_2^{\text{eq}} = e^{-(E_1+E_2)/T} = e^{-(E_a+E_b)/T} = f_a^{\text{eq}} f_b^{\text{eq}}$$

$$\Rightarrow \text{RHS} \sim -\int |\mathcal{M}_{ab\to 12}|^2 \left(f_a\, f_b - f_a^{\text{eq}} f_b^{\text{eq}}\right) d(\text{phase space})$$

Justification

RHS Assume SM particles in thermal equilibrium **Assumption 2**

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$$\Rightarrow f_1 f_2 = f_1^{\rm eq} f_2^{\rm eq} = e^{-(E_1+E_2)/T} = e^{-(E_a+E_b)/T} = f_a^{\rm eq} f_b^{\rm eq}$$

$$\Rightarrow \text{RHS} \sim -\int |\mathcal{M}_{ab\to 12}|^2 \left(f_a f_b - f_a^{\rm eq} f_b^{\rm eq}\right) d(\text{phase space})$$

$$n(t) = \frac{g}{(2\pi)^3}\int d^3p\, f(E,t)$$

$$\sigma = \frac{1}{\text{flux}}\int |\mathcal{M}|^2 d\text{LIPS}$$

$$\text{RHS} = -\langle \sigma v\rangle \left(n_a n_b - n_a^{\rm eq} n_b^{\rm eq}\right)$$

(Full Boltzmann eq: $\dfrac{dn}{dt} + 3Hn = -\langle \sigma v\rangle (n^2 - n_{\rm eq}^2)$)

Solving the Boltzmann equation

Boltzmann equation:

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

Number density reduced by the expansion of the Universe.
Hot to tell whether the dark matter production/destruction is efficient or not?

Solving the Boltzmann equation

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Number density reduced by the expansion of the Universe.
Hot to tell whether the dark matter production/destruction is efficient or not?

Define "yield": $$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

If no entropy production, $$\frac{dS}{dt} = 0 = \frac{d}{dt}(a^3 s) = a^3(\dot{s} + 3Hs)$$

$$\rightsquigarrow \dot{s} + 3Hs = 0$$

Solving the Boltzmann equation

Boltzmann equation:

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

Number density reduced by the expansion of the Universe.
Hot to tell whether the dark matter production/destruction is efficient or not?

Define "yield": $$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

Time evolution of the yield:

$$\frac{dY}{dt} = \frac{1}{s^2}(\dot{n}s - n\dot{s}) = \frac{1}{s^2}(-3Hns - s\langle \sigma v \rangle (n^2 - n_{\rm eq}^2) + n3HS)$$

$$\dot{s} = -3Hs$$

$$\dot{n} = -3Hn - \langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

Solving the Boltzmann equation

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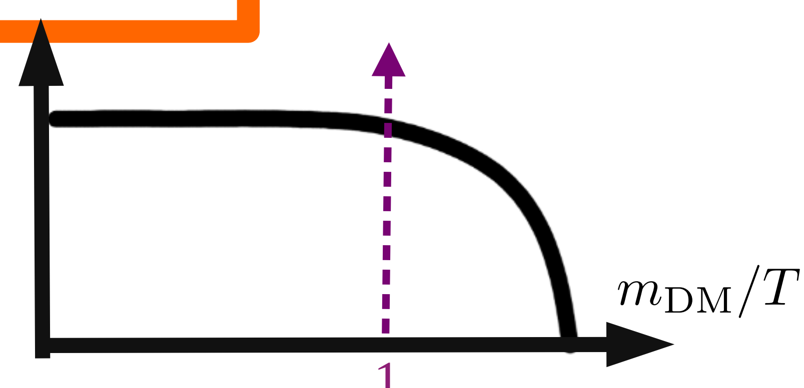
Number density reduced by the expansion of the Universe.
Hot to tell whether the dark matter production/destruction is efficient or not?

Define "yield": $$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

$$\frac{dY}{dt} = -s\langle \sigma v \rangle (Y^2 - Y_{\rm eq}^2)$$

$$Y_{\rm eq} = \begin{cases} \sim \text{constant} & \text{if } T \gg m_{\rm DM} \\ \sim \left(\frac{m_{\rm DM}}{T}\right)^{3/2} e^{-m_{\rm DM}/T} & \text{if } T \ll m_{\rm DM} \end{cases}$$



Solving the Boltzmann equation

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Define "yield": $$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

$$\frac{dY}{dt} = -s\langle\sigma v\rangle(Y^2 - Y_{\rm eq}^2)$$

If $\sigma=0$, then $Y =$ constant

Solving the Boltzmann equation

Boltzmann equation:

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

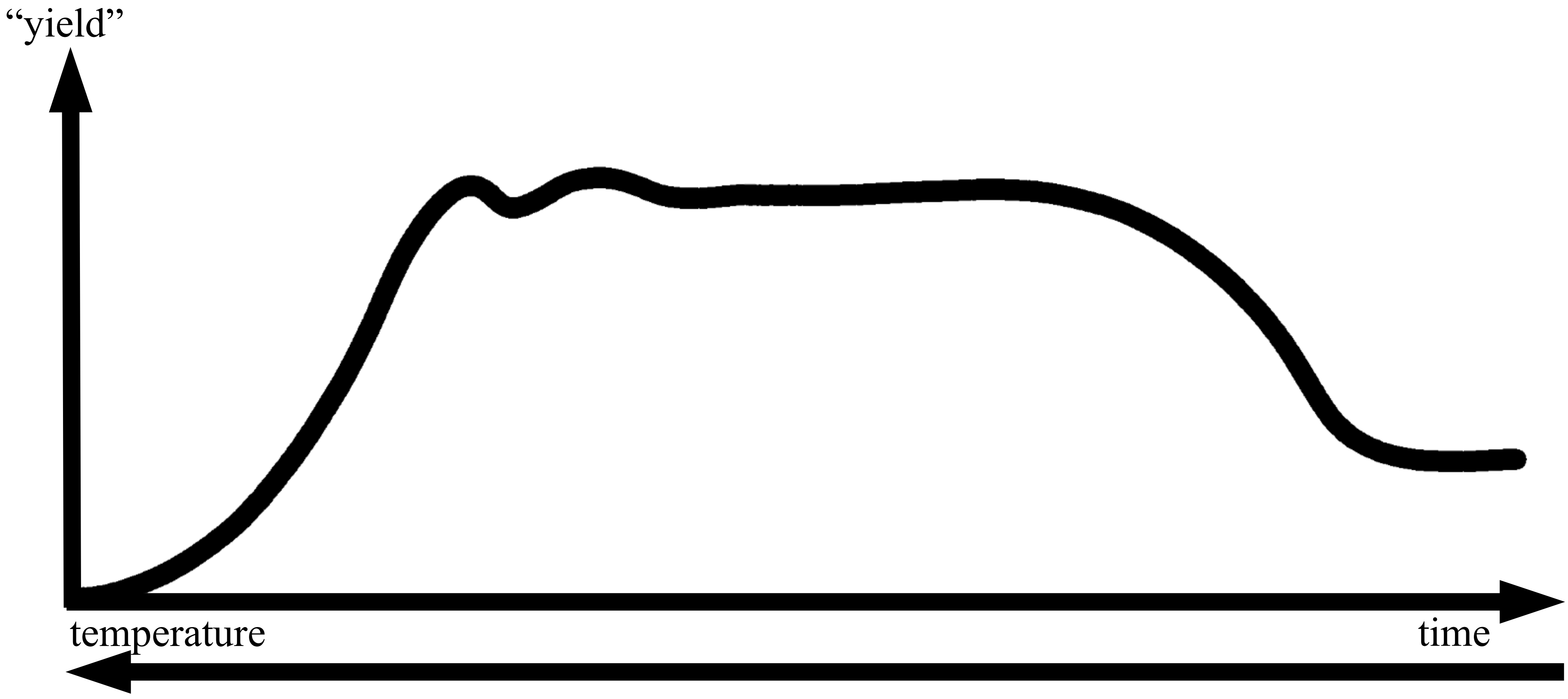
Number density reduced by the expansion of the Universe.
Hot to tell whether the dark matter production/destruction is efficient or not?

Define "yield": $$Y \equiv \frac{n}{s} = \frac{\text{number density}}{\text{entropy density}}$$

Define $x = \dfrac{m_{\rm DM}}{T}$, $\Gamma_{\rm ann} = n_{\rm eq} \langle \sigma v \rangle$

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

WIMP history (in a nutshell)



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WIMP history (in a nutshell)

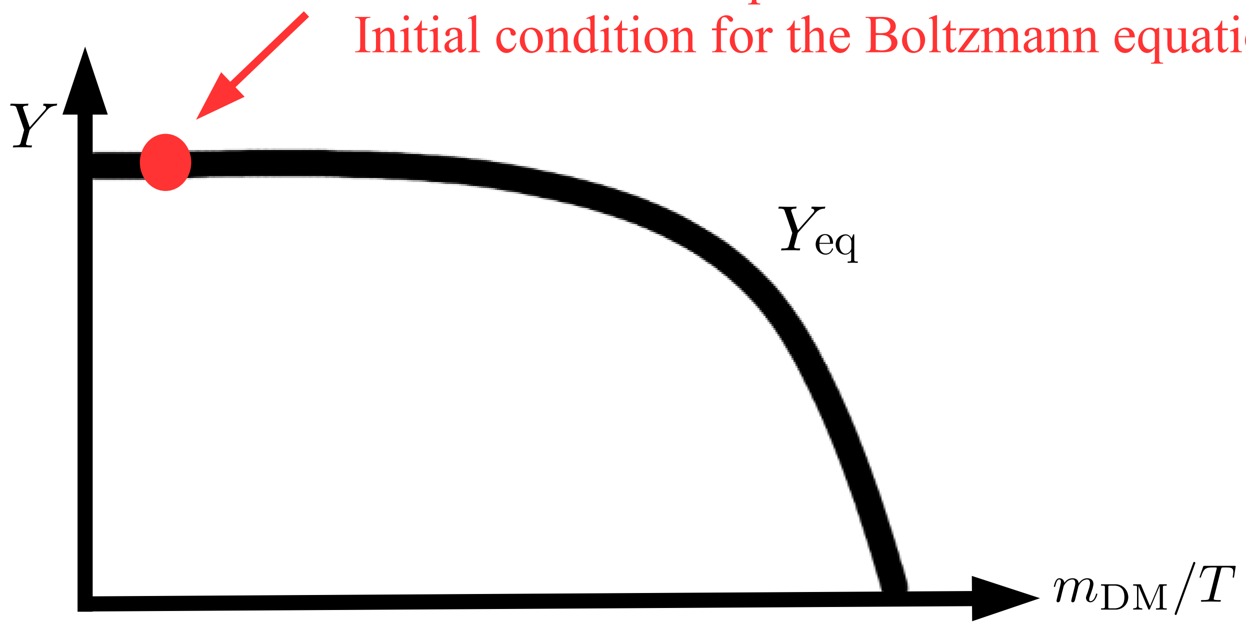
$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm ann}(x)}{H(x)}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right]$$

Qualitative behavior of the solution

1) Solution at very early times ($x \ll 1$, or $T \gg m_{\rm DM}$)

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

Assume that at early times the DM reached thermal equilibrium.
Initial condition for the Boltzmann equation

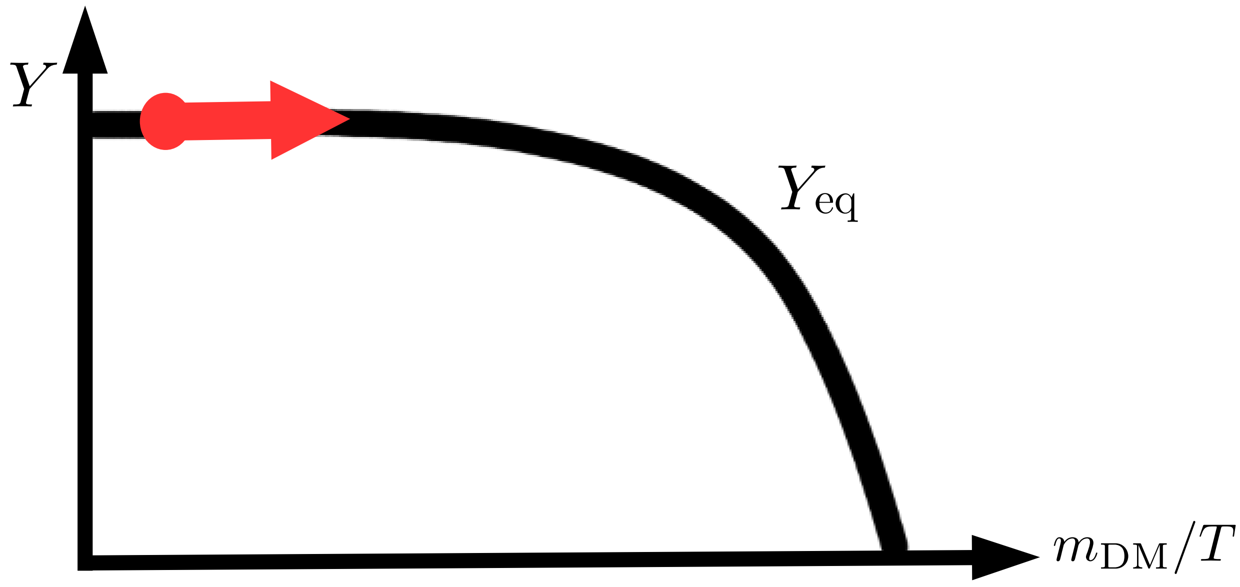


Qualitative behavior of the solution

1) Solution at very early times ($x \ll 1$, or $T \gg m_{\rm DM}$)

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm ann}(x)}{H(x)}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \simeq 0$$

The yield follows the equilibrium distribution

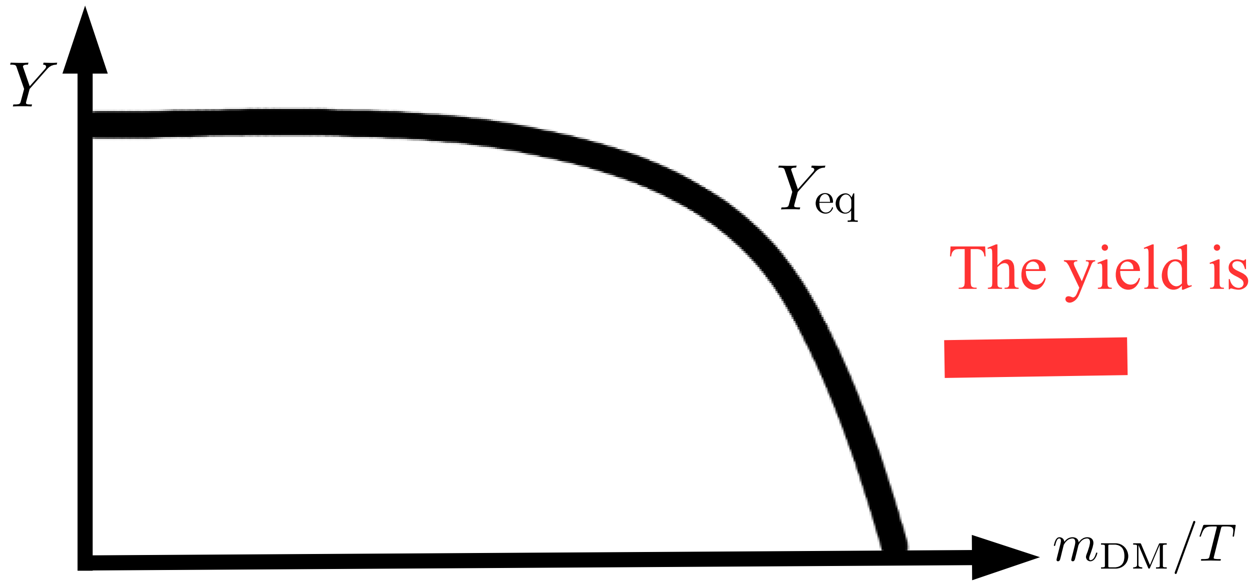


Qualitative behavior of the solution

2) Solution at very early times ($x \gg 1$, or $T \ll m_{\rm DM}$)

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm ann}(x)}{H(x)}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \simeq 0$$

$\Gamma_{\rm ann} = n_{\rm eq}\langle\sigma v\rangle$ small (compared to H)

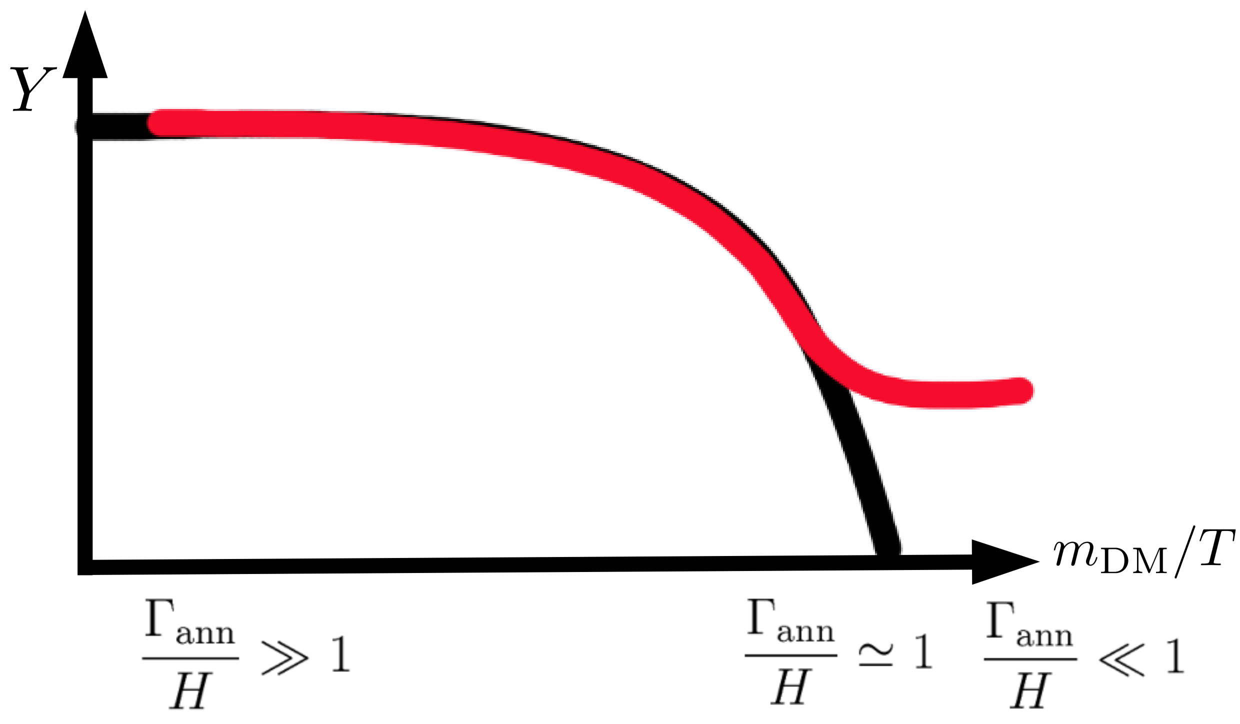


The yield is constant

Qualitative behavior of the solution

3) Extrapolation between the two regimes

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm ann}(x)}{H(x)}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \simeq 0$$



Qualitative behavior of the solution

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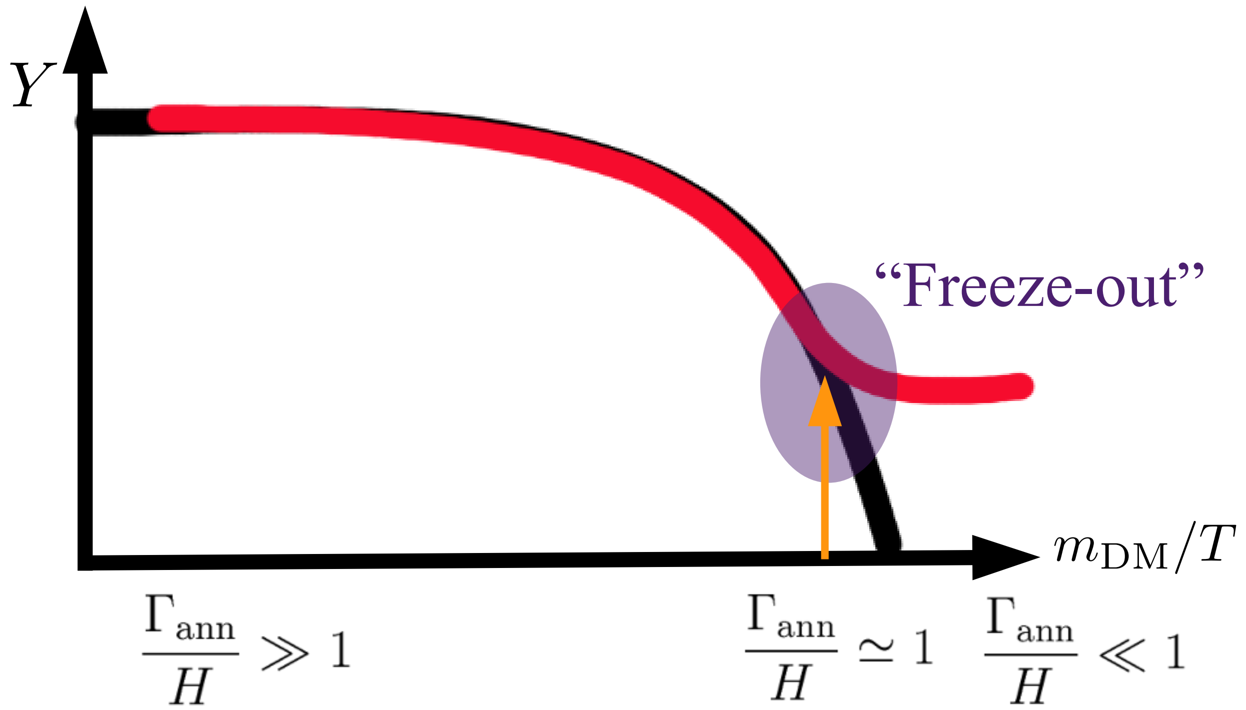
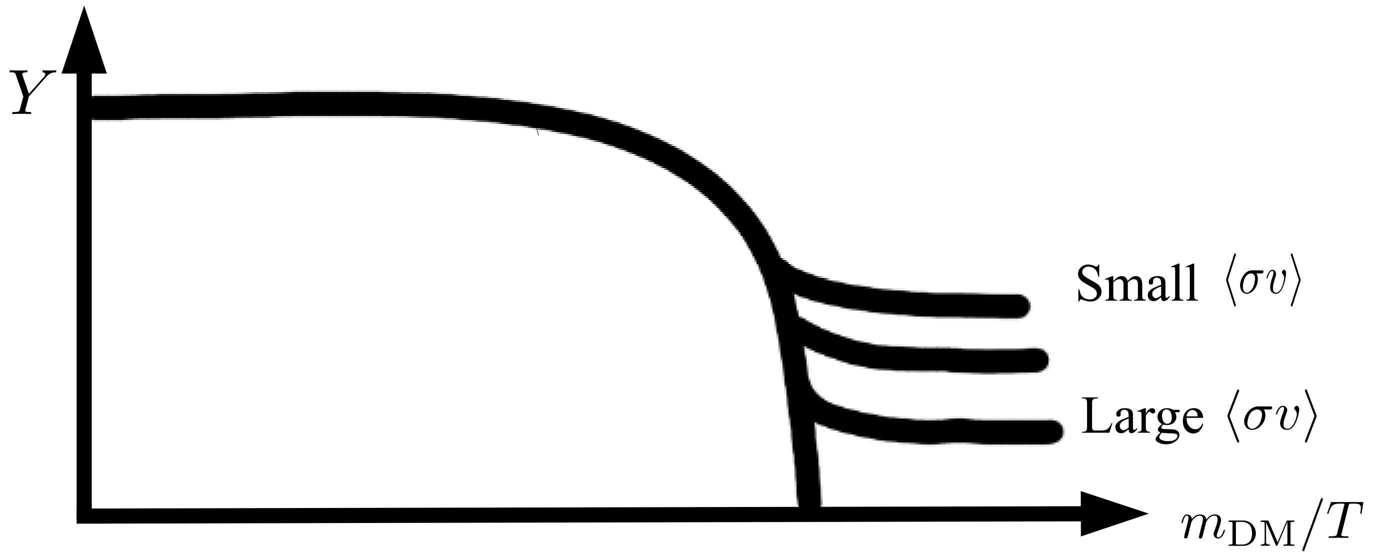


Number density of WIMPs at freeze-out

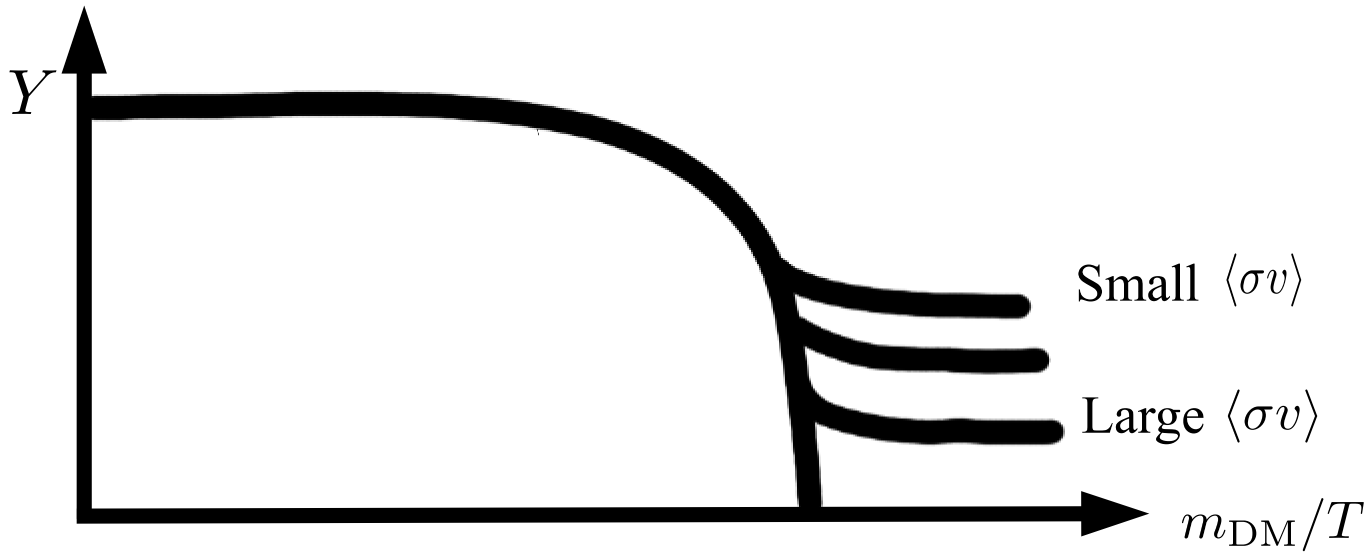
$$n_{\rm eq}(T_{\rm fo}) = \frac{H(T_{\rm fo})}{\langle\sigma v\rangle\big|_{\rm fo}}$$

IMPORTANT: the number density of WIMPs at freeze-out is inversely proportional to the annihilation cross section



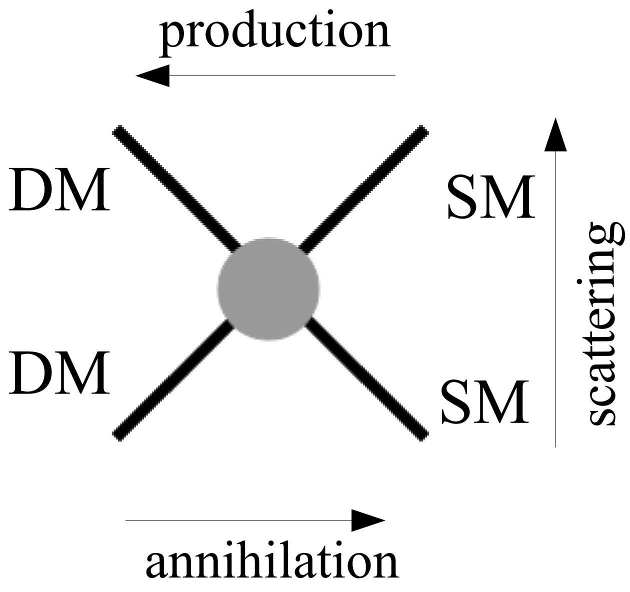
Density parameter of WIMPs today

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



Main results from this part

WIMP dark matter



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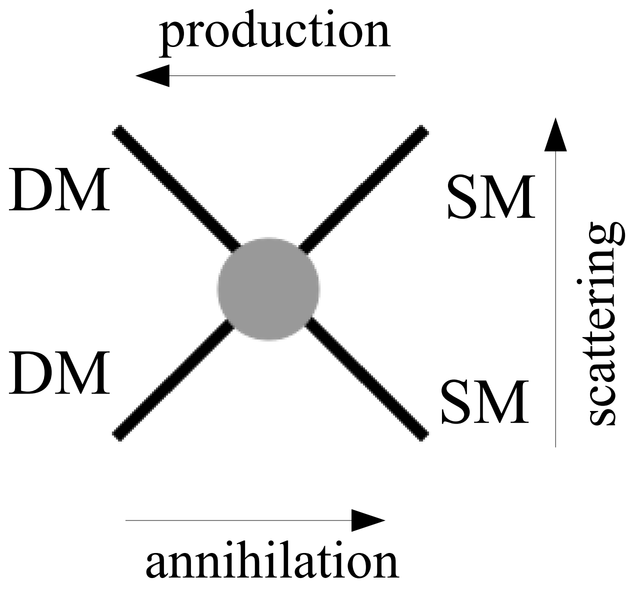
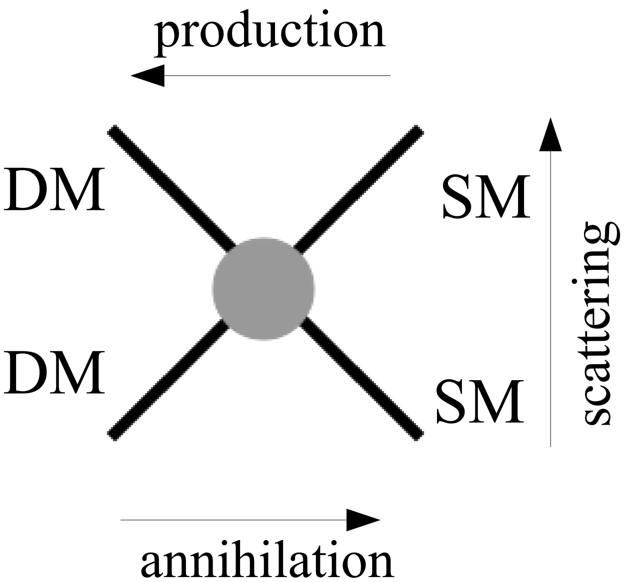


Relic abundance of DM particles

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

Main results from this part

WIMP dark matter



Relic abundance of DM particles

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Correct DM abundance Ωh^2=0.12 if

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

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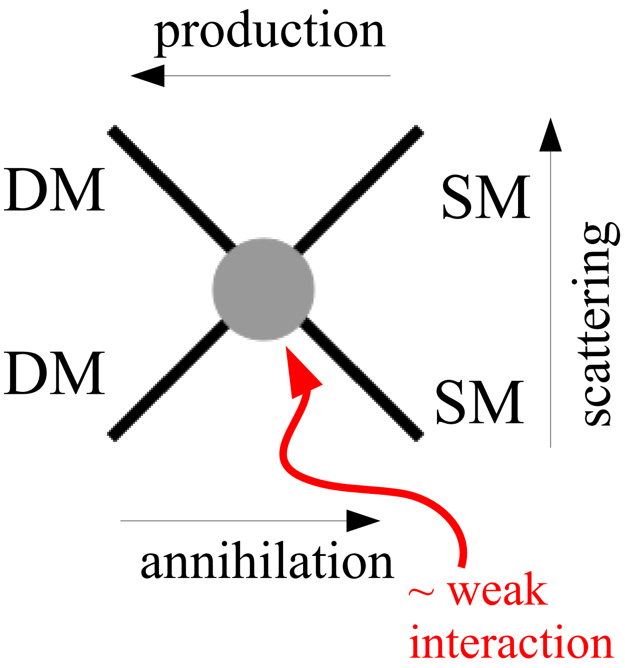

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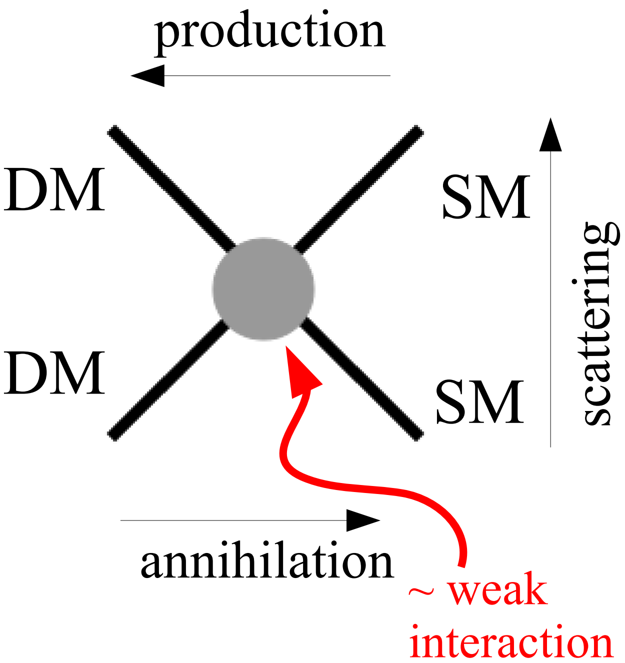

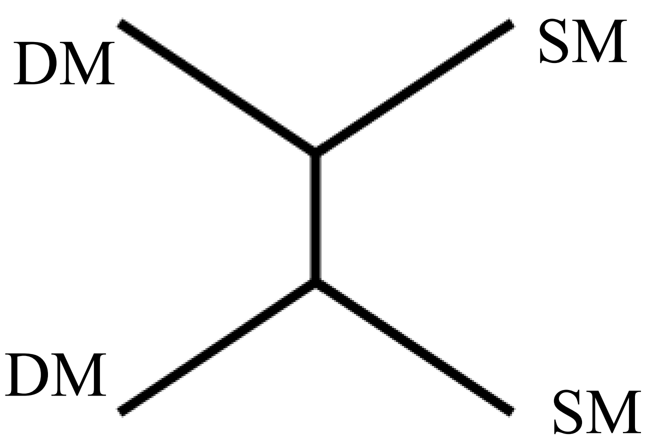

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$$\sigma \sim \frac{g^4}{m_{\mathrm{DM}}^2} = 1\,\mathrm{pb}$$

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

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

LZ

CMS

ATLAS

MAGIC

Xe
XENON
Dark Matter Project

Fermi
Gamma-ray
Space Telescope

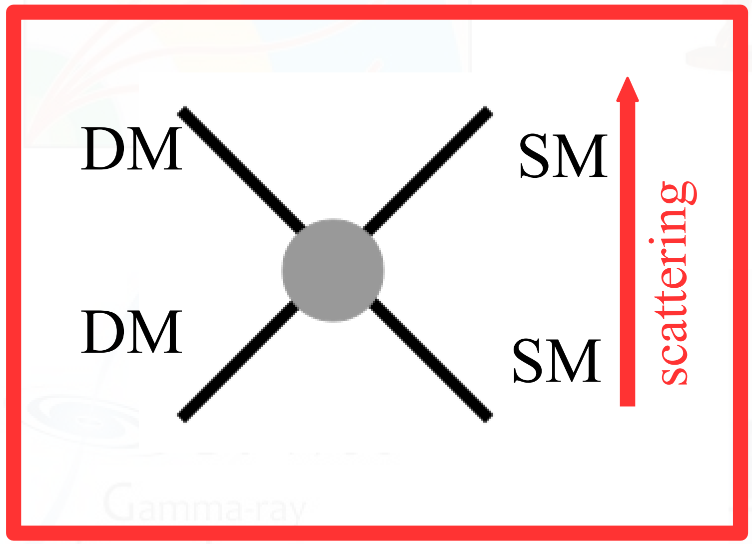
PaMeLa

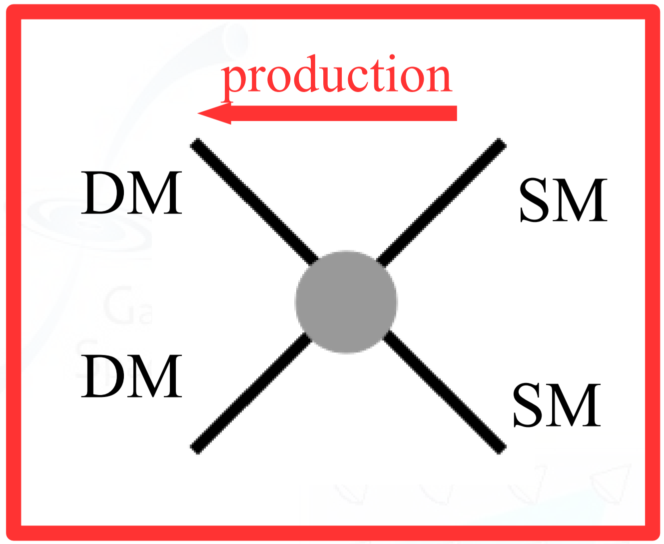
H E S S

Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

VERITAS

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY


DM
DM
SM
SM
scattering


production
DM
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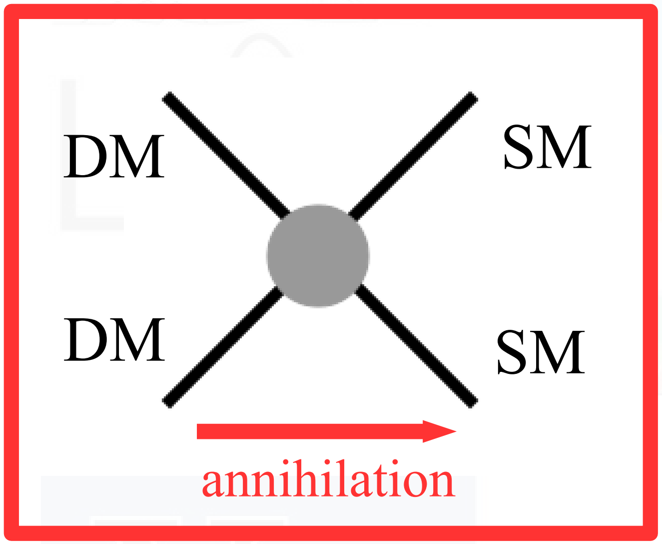
SM
SM



MAGIC

Fermi
Gamma-ray Space Telescope

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H E S S

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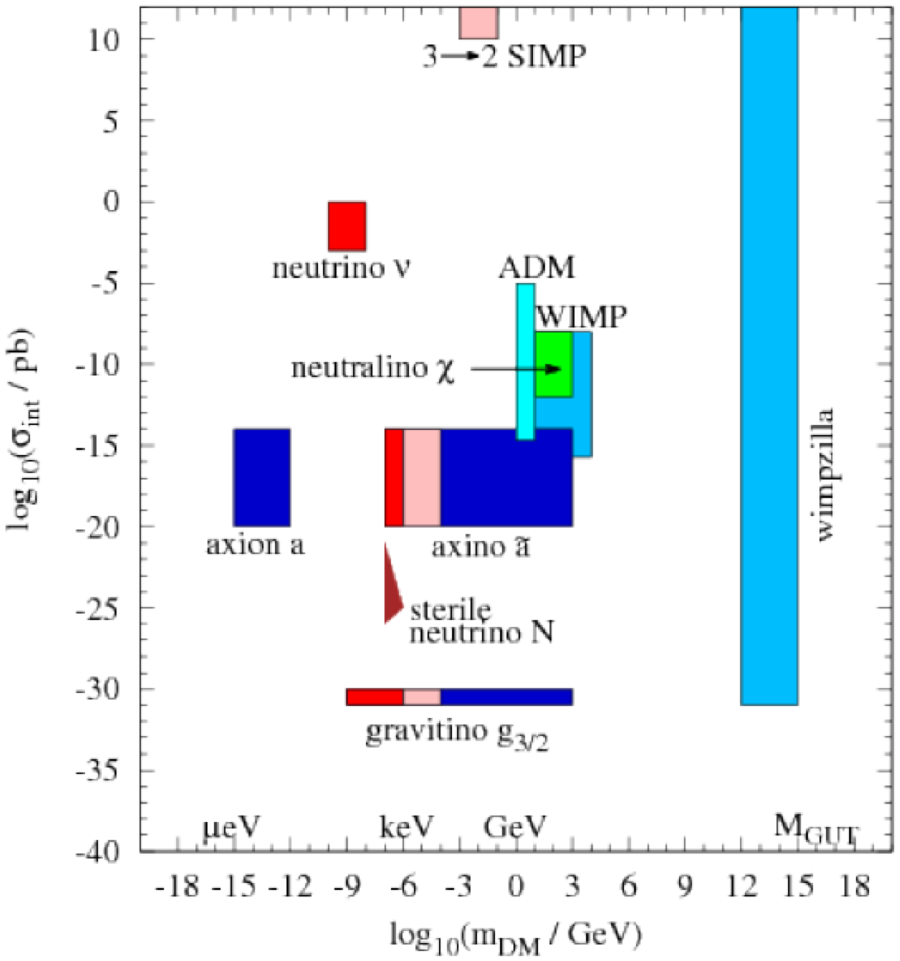
The WIMP zoo



3→2 SIMP
neutrino ν
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WIMP
neutralino χ
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axino ã
sterile
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$\log_{10}(m_{DM}$ / GeV)
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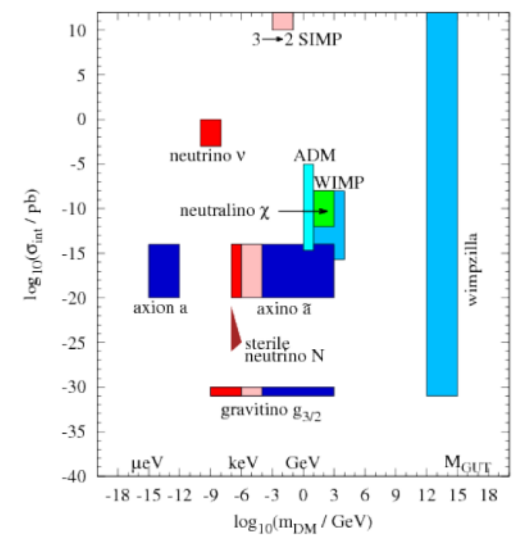
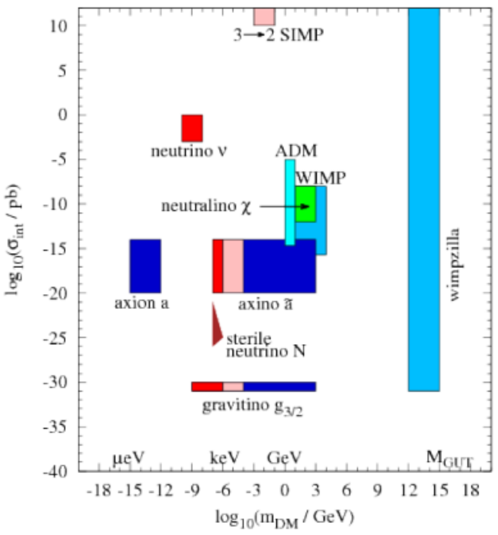
The WIMP zoo

spin



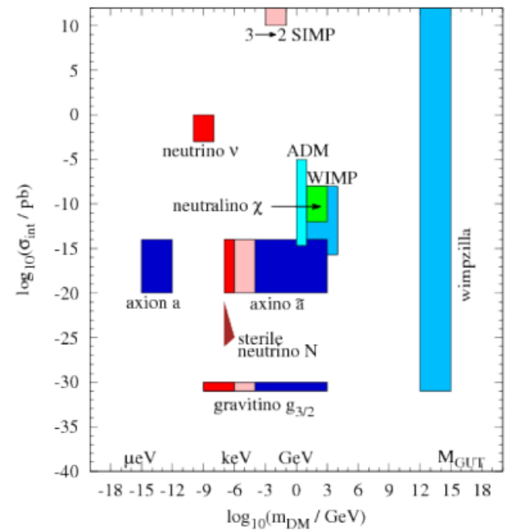
The WIMP zoo



spin

Scattering cross-section off SM particles

The WIMP zoo

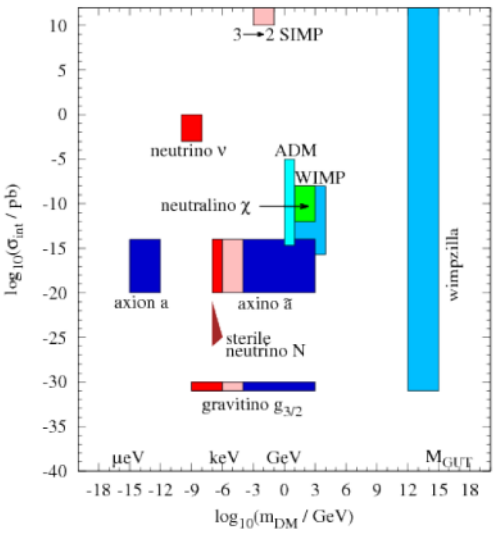


spin

Scattering cross-section off SM particles

Annihilation cross-section into SM particles

The WIMP zoo



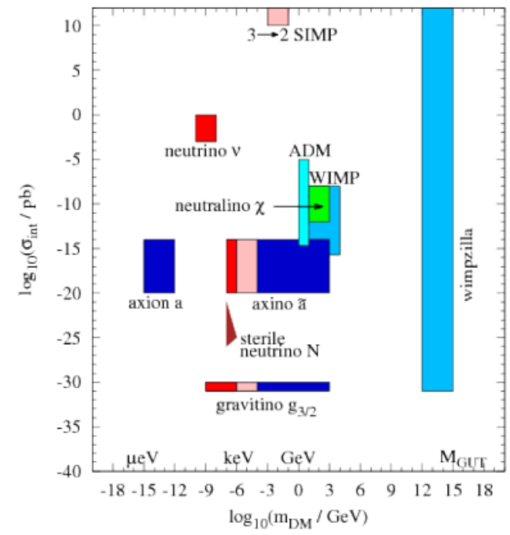
spin

Scattering cross-section off SM particles

Annihilation cross-section into SM particles

Self-coupling

The WIMP zoo



spin

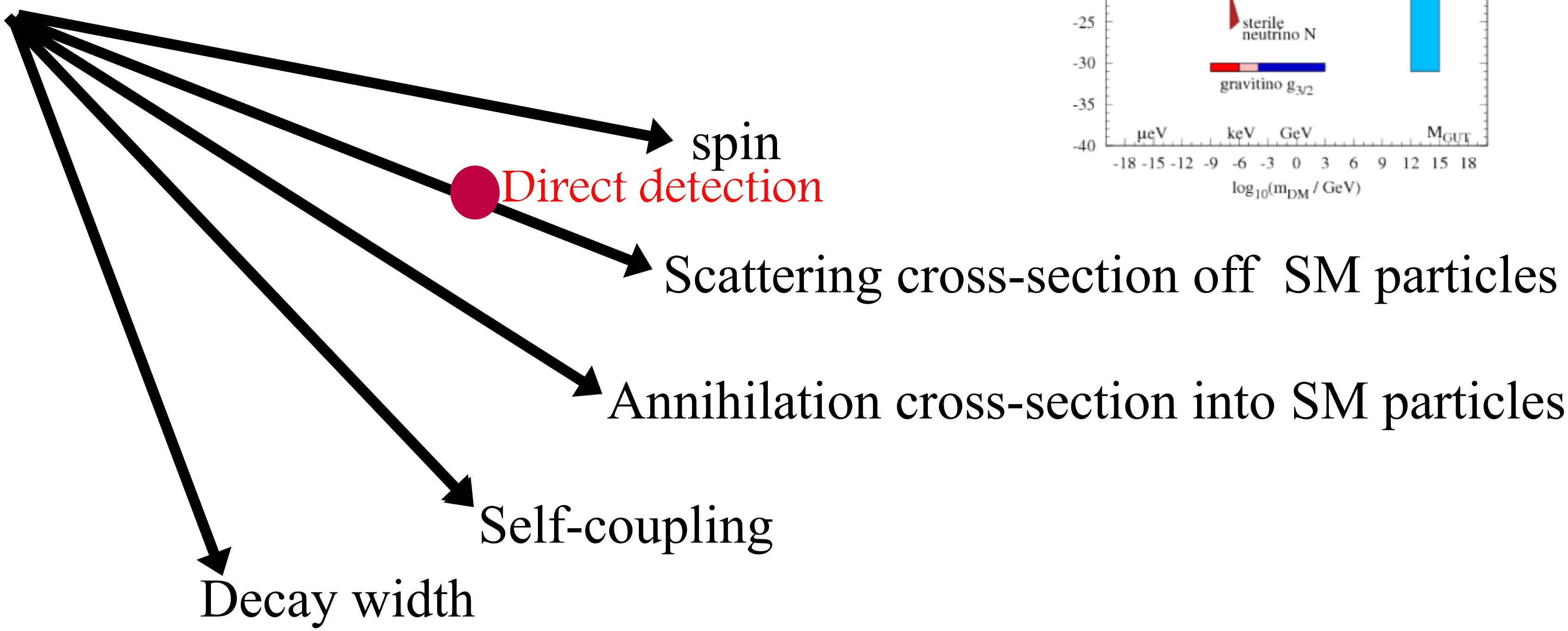
Scattering cross-section off SM particles

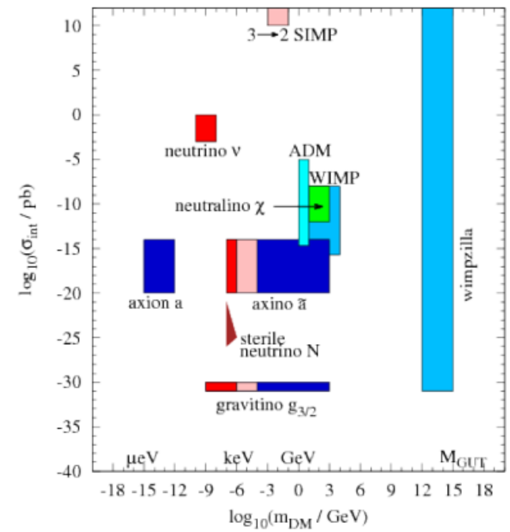
Annihilation cross-section into SM particles

Self-coupling

Decay width

The WIMP zoo


spin
Direct detection
Scattering cross-section off SM particles
Annihilation cross-section into SM particles
Self-coupling
Decay width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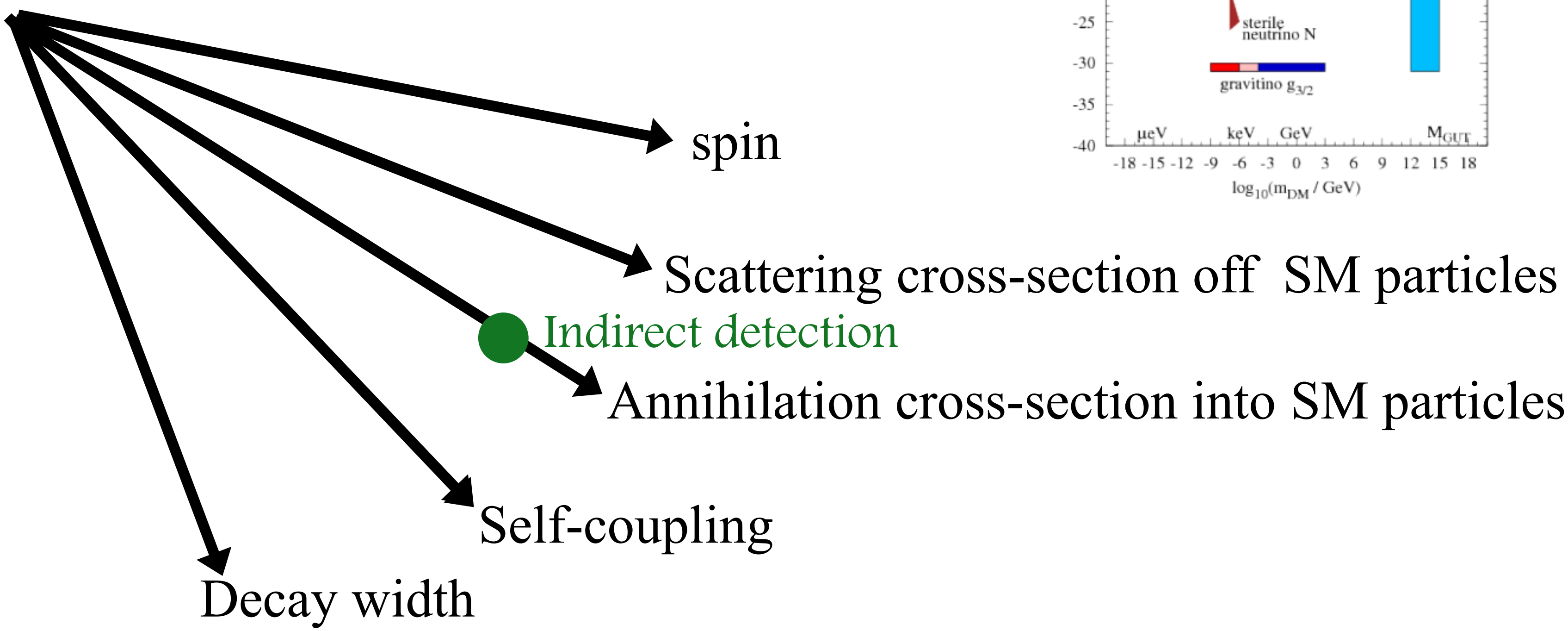
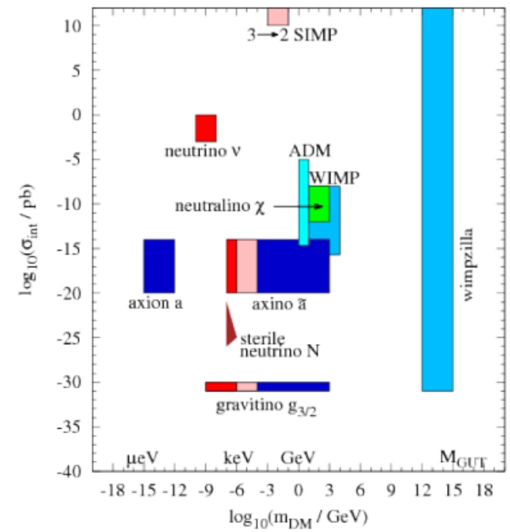
The WIMP zoo


spin
Scattering cross-section off SM particles
Indirect detection
Annihilation cross-section into SM particles
Self-coupling
Decay width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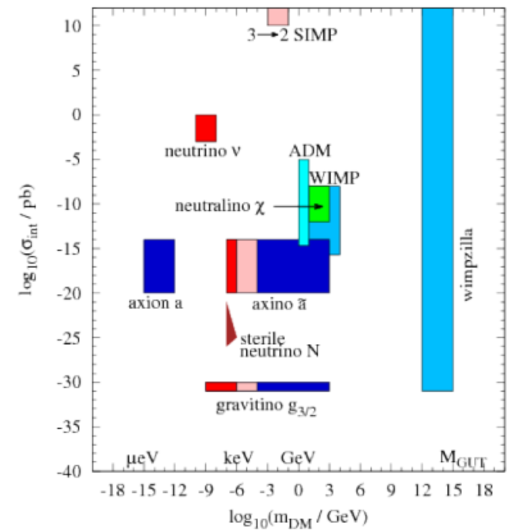
The WIMP zoo



spin

Scattering cross-section off SM particles

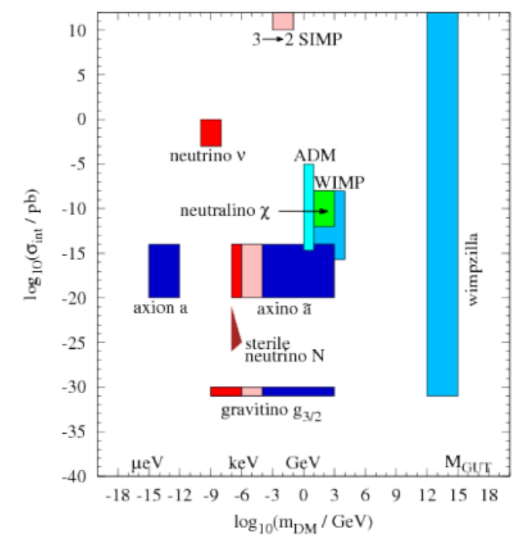
Annihilation cross-section into SM particles

Structure formation

Self-coupling

Decay width

The WIMP zoo



spin

Scattering cross-section off SM particles

Indirect detection

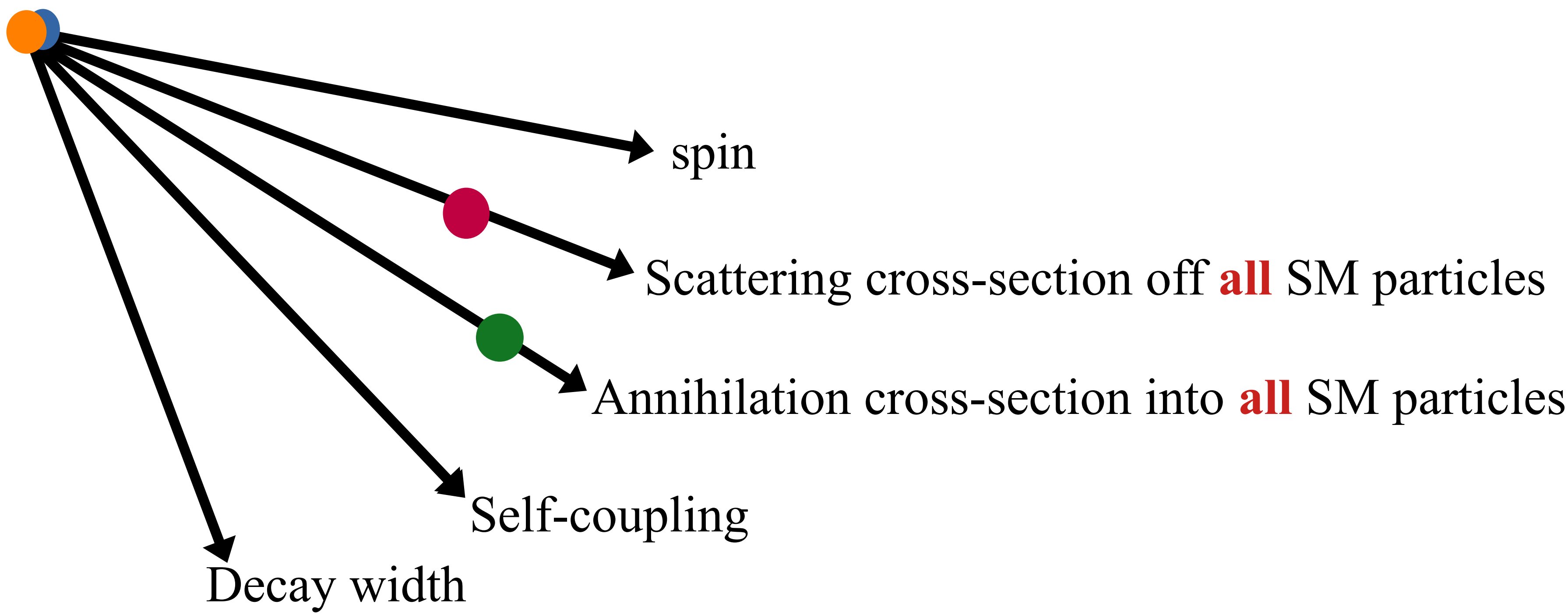
Annihilation cross-section into SM particles

Self-coupling

Decay width

The WIMP zoo

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



The WIMP zoo

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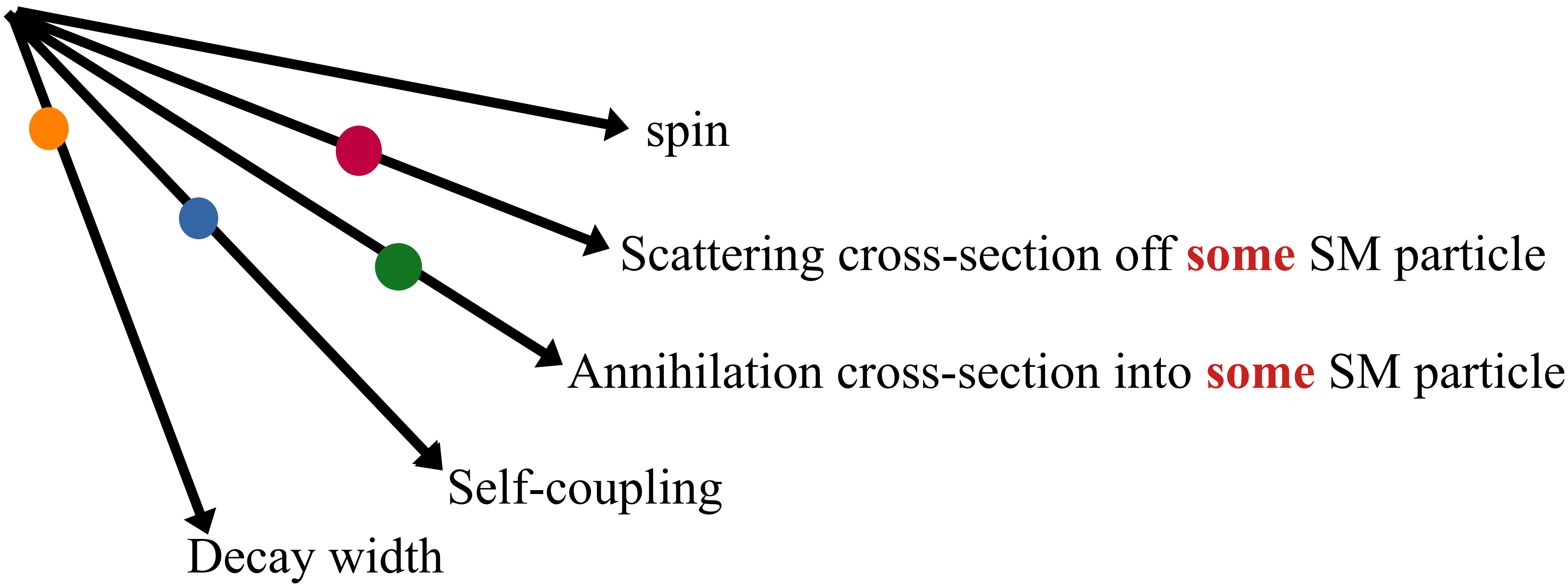

Modern approach:

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

The WIMP zoo

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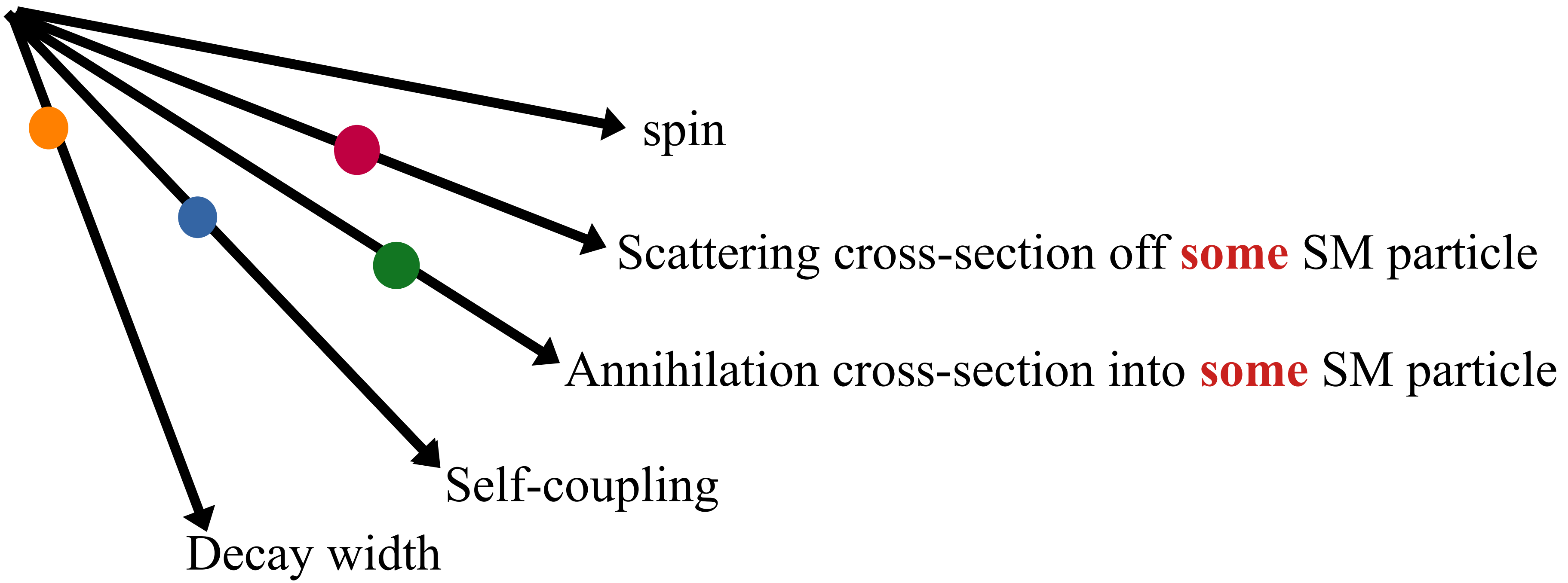
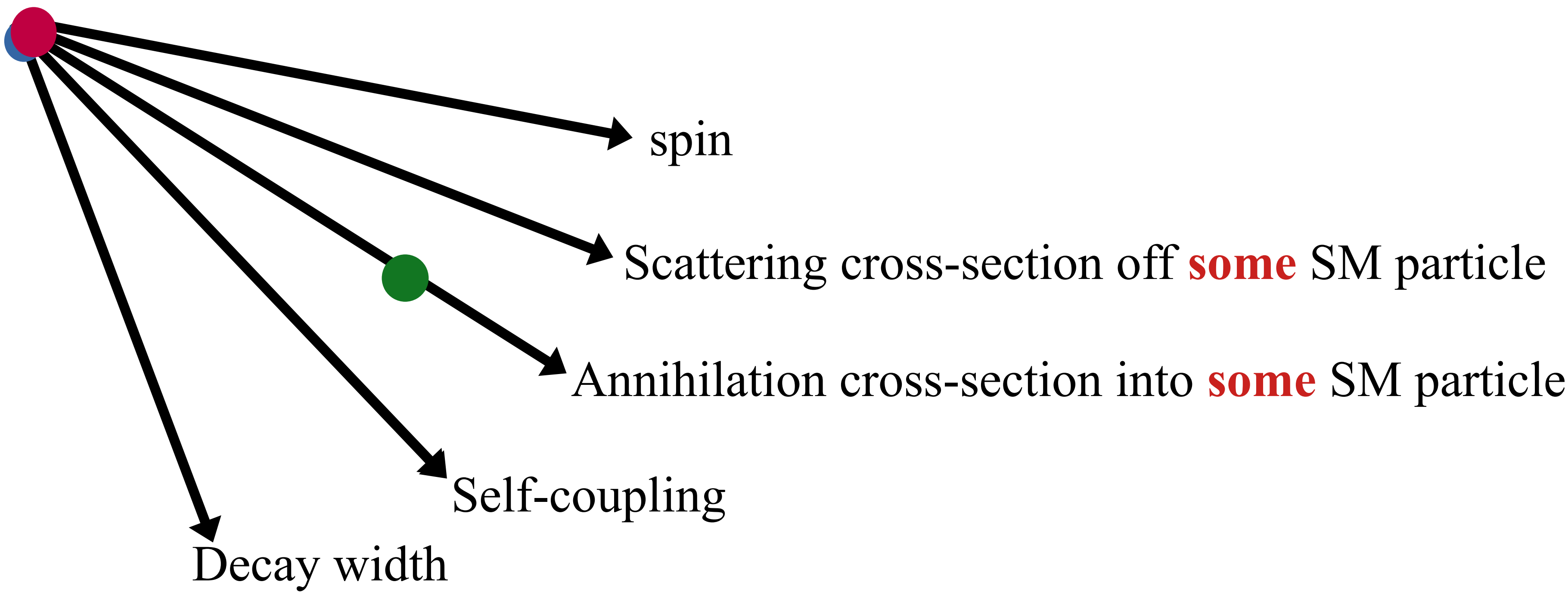


Modern approach:

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

No stone must be left unturned!

Probing the annihilation cross-section

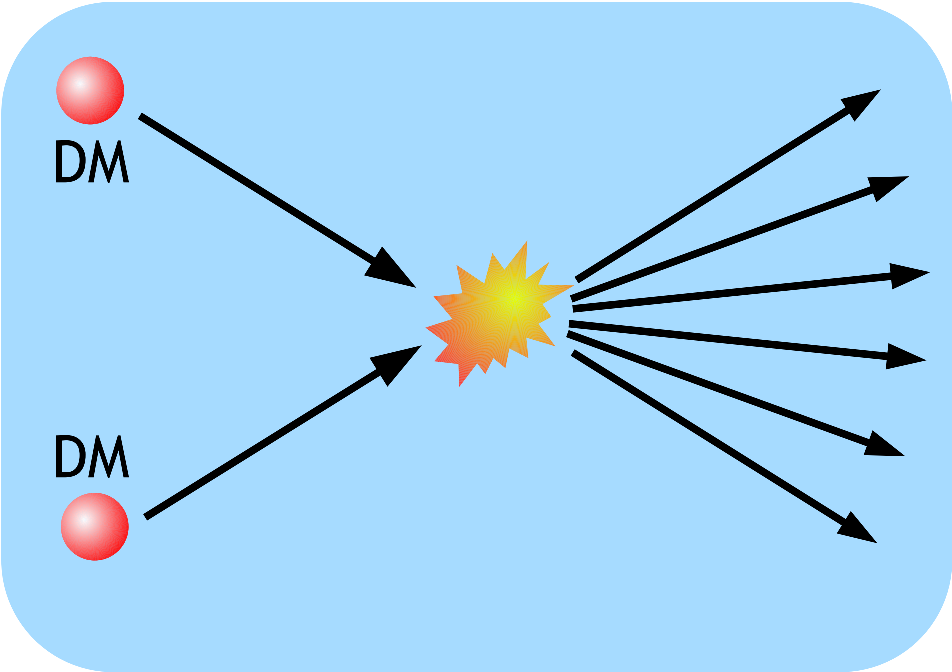


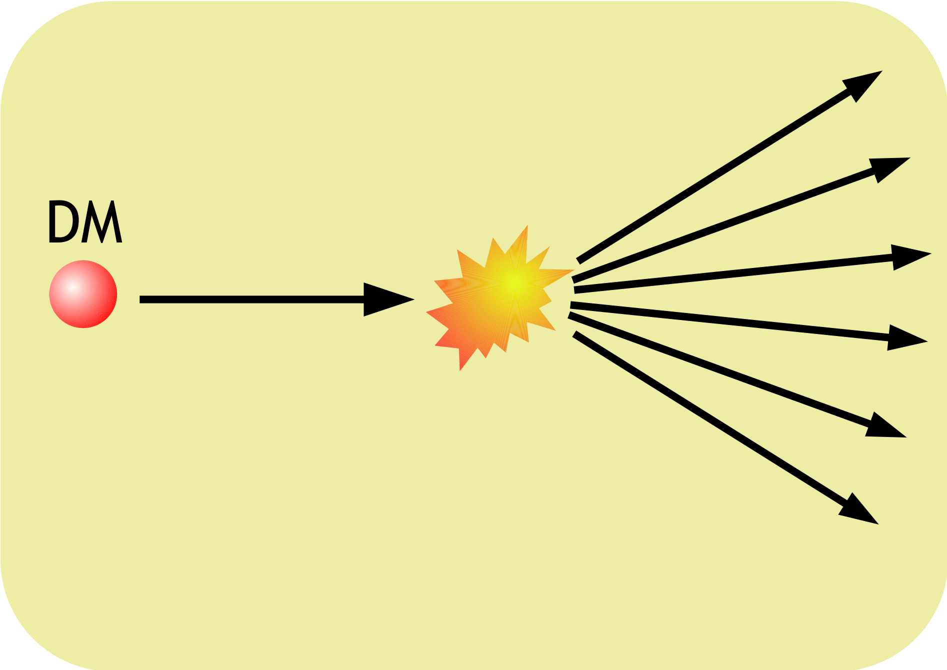
Indirect Dark Matter Searches

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





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.

2) These particles propagate through the galaxy and through the Solar System. Some of them will reach the Earth.

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.

2) These particles propagate through the galaxy and through the Solar System. Some of them will reach the Earth.

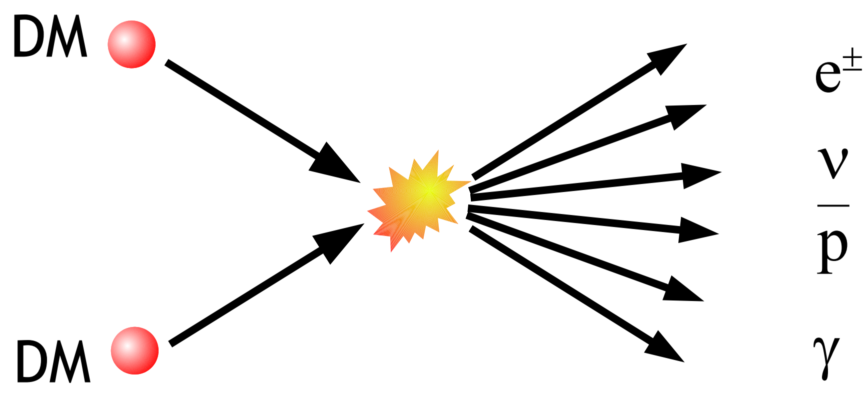
3) The products of the dark matter annihilations or decays are detected together with other particles produced in astrophysical processes (for example, cosmic ray collisions with nuclei in the interstellar medium). The existence of dark matter can then be inferred if there is a significant excess in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

Indirect dark matter searches

Production			Antimatter
Propagation	}	of	{ Gamma-rays
Detection			Neutrinos

Production

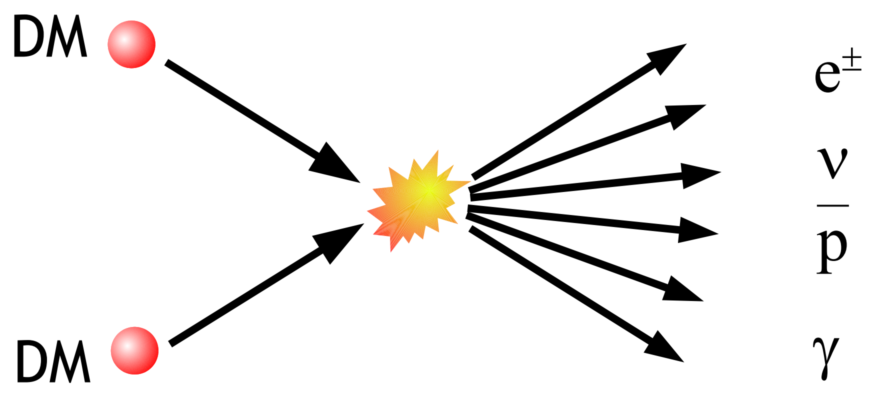
Production of SM particles in DM annihilation



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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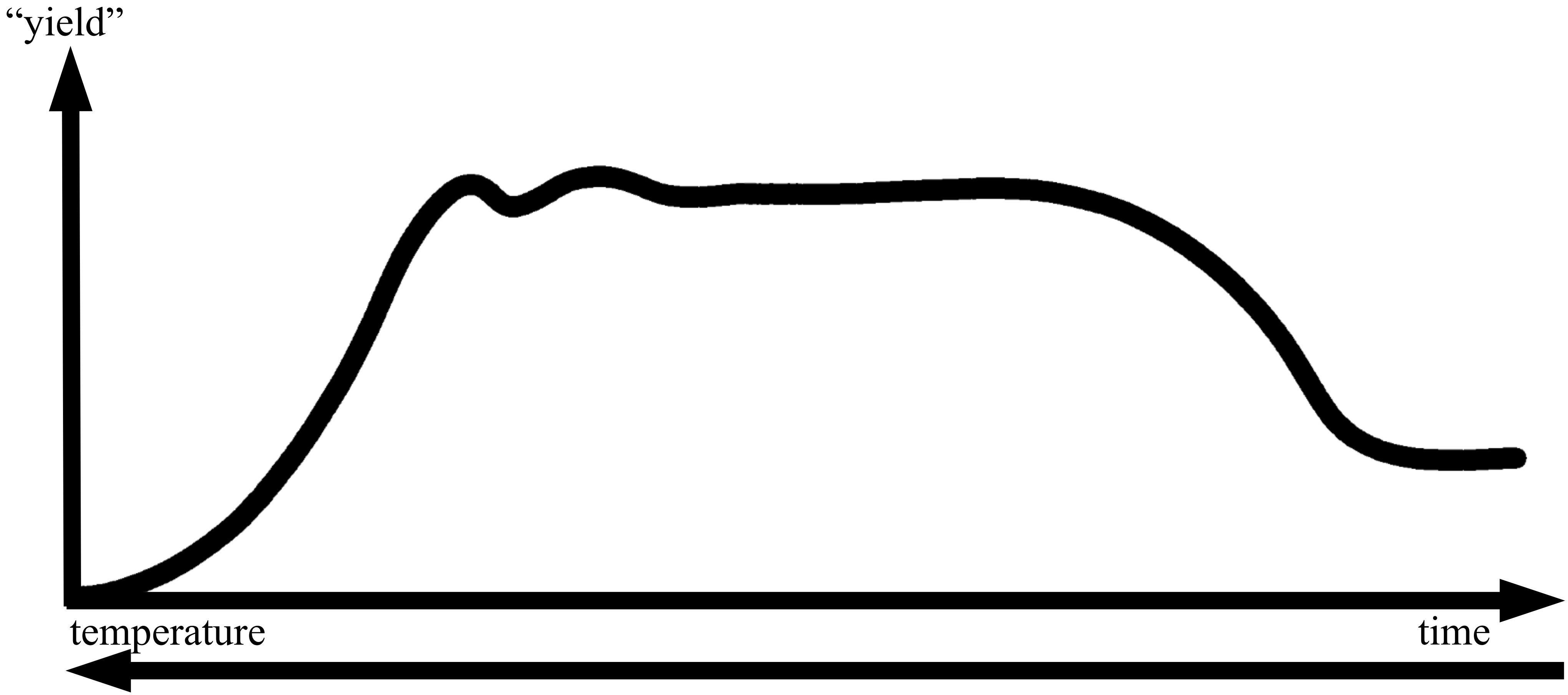
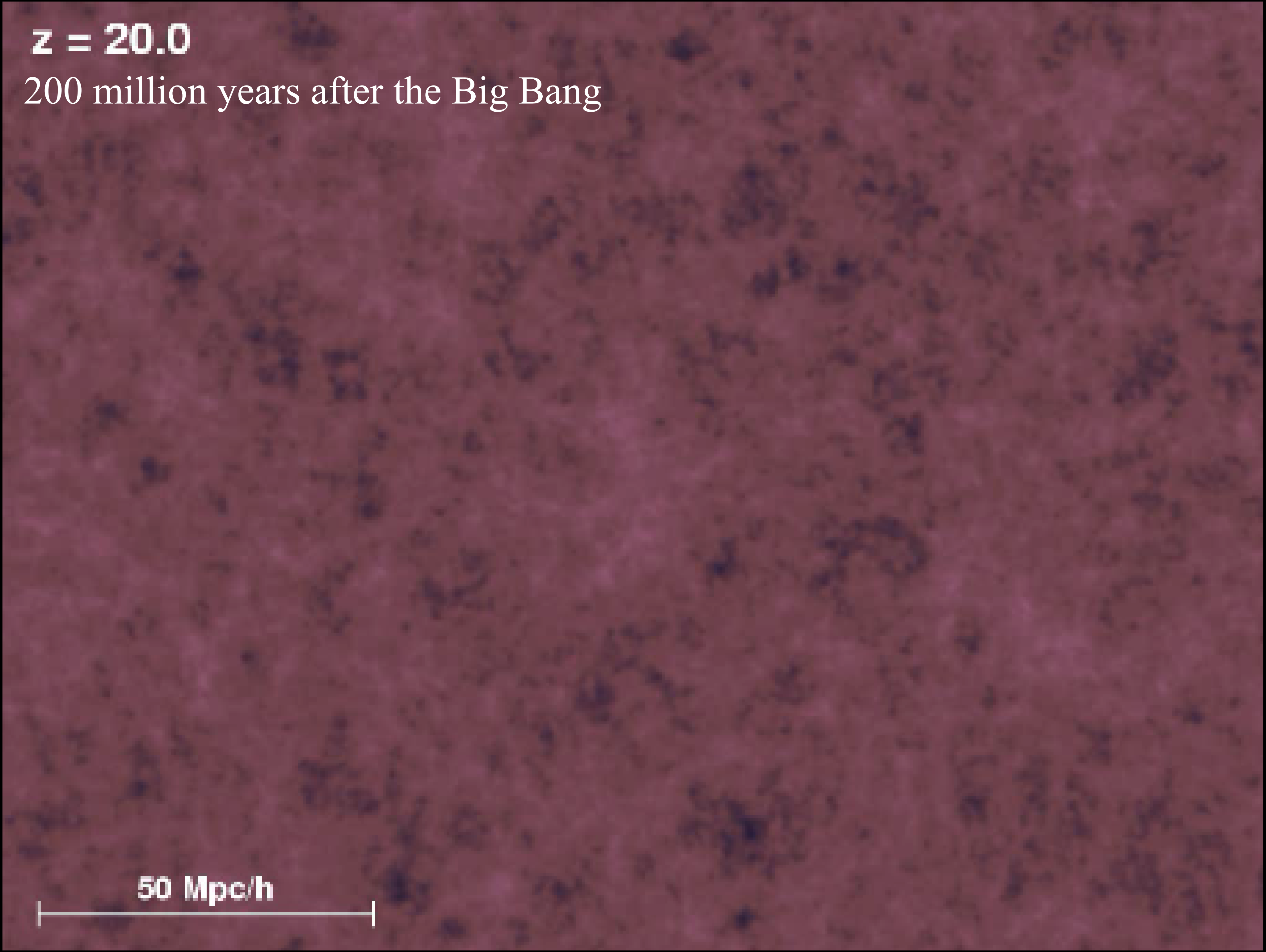
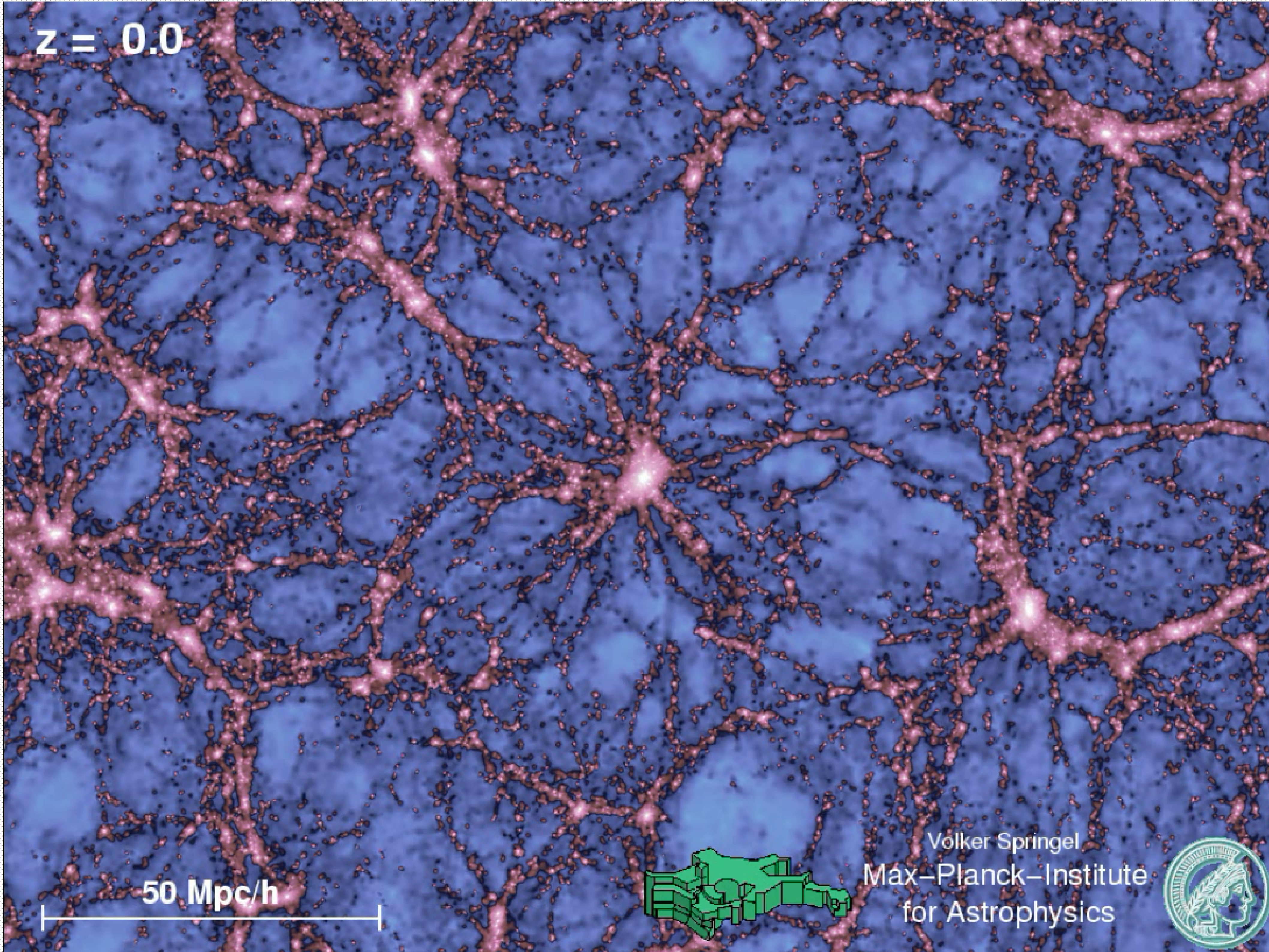
DM density distribution in the MW

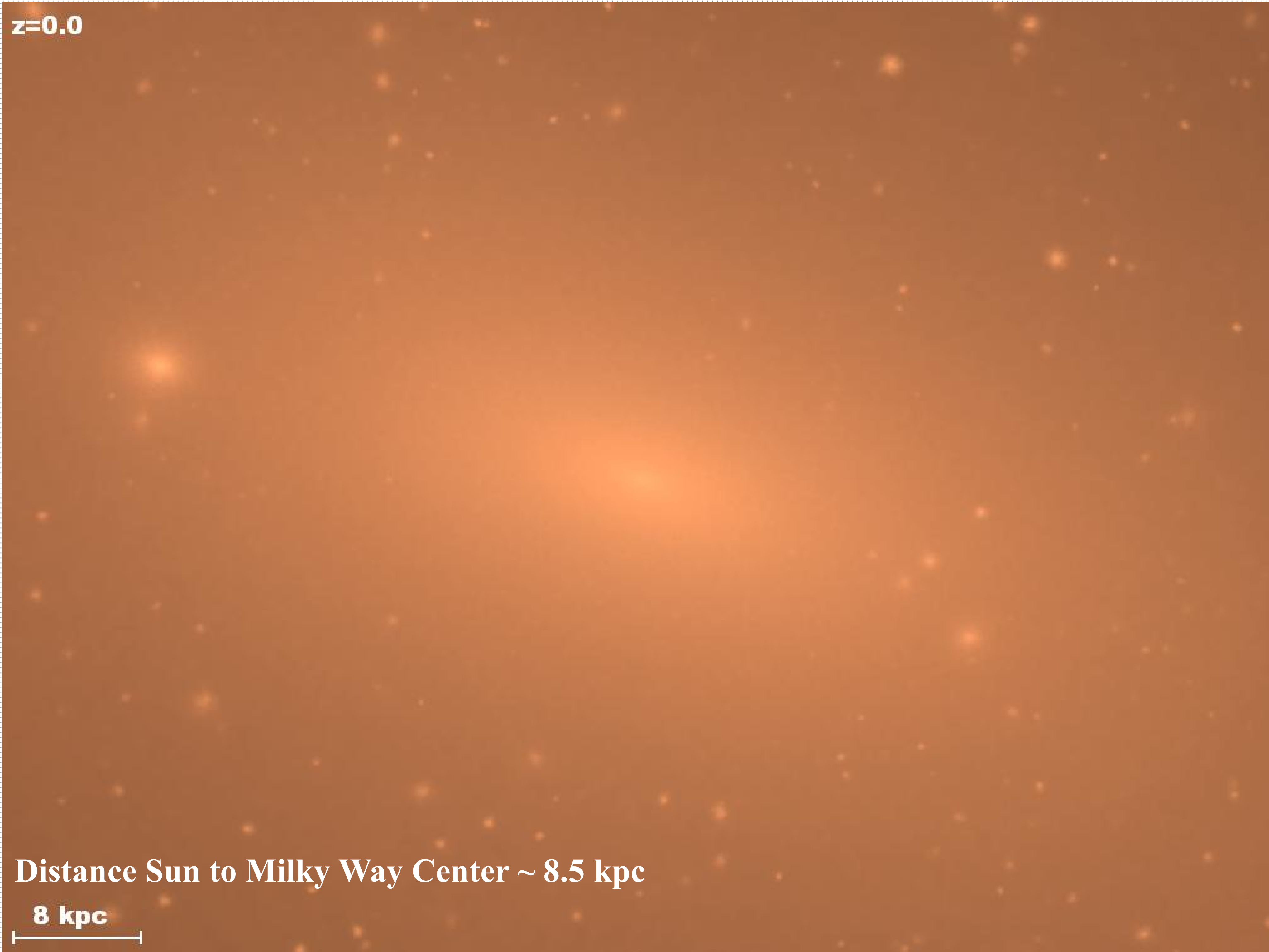
Dark matter distribution



The universe at T~1 GeV

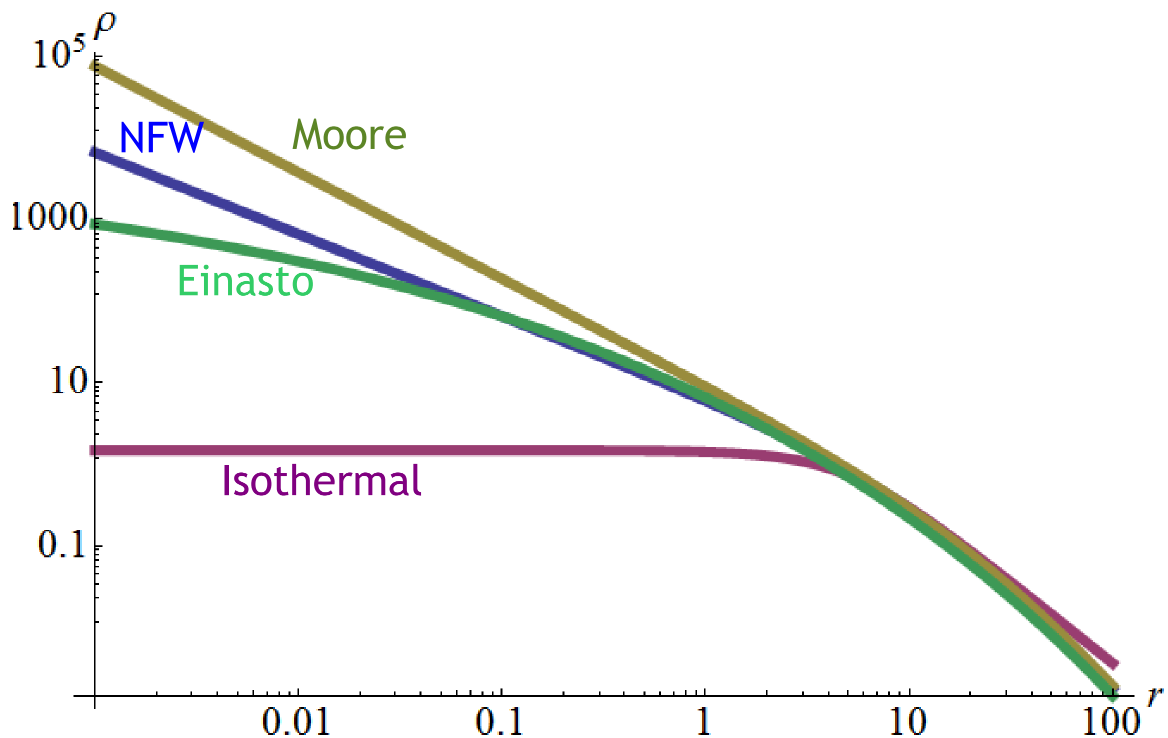

z = 20.0
200 million years after the Big Bang
50 Mpc/h


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

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

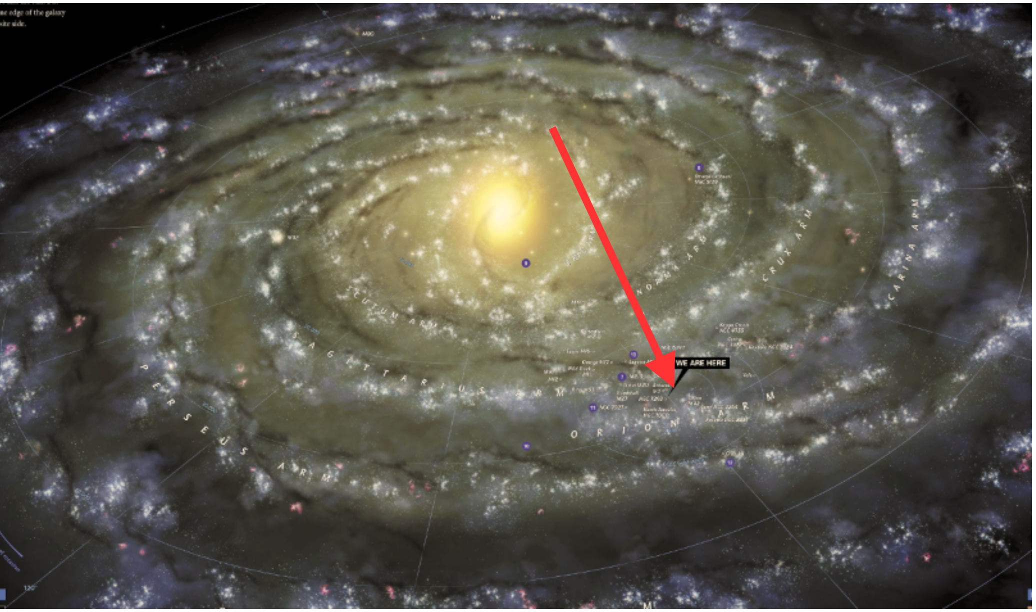
$\alpha = 0.17,\ r_s = 20$ kpc

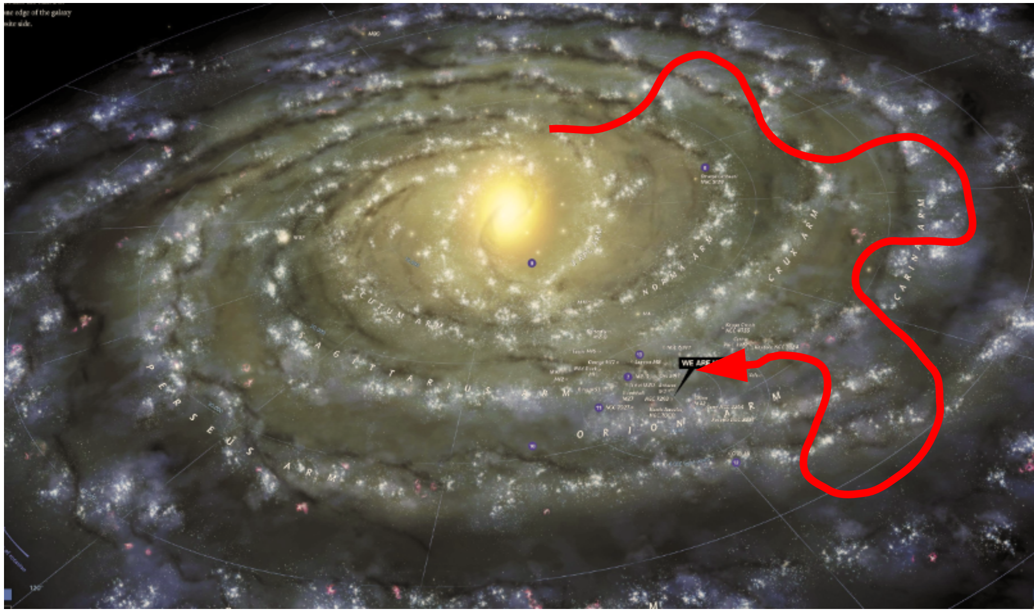
- Normalized such that the local DM density is
  $\rho(r=8.5\ \text{kpc}) = 0.38\ \text{GeV/cm}^3$

Propagation

Propagation of SM particles in the Galaxy

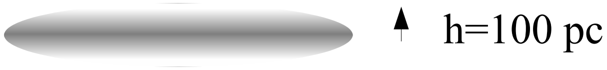
Neutral particles propagate in straight lines practically without losing energy. Charged particles, on the other hand, propagate in a complicated way through the tangled magnetic field of our Galaxy.



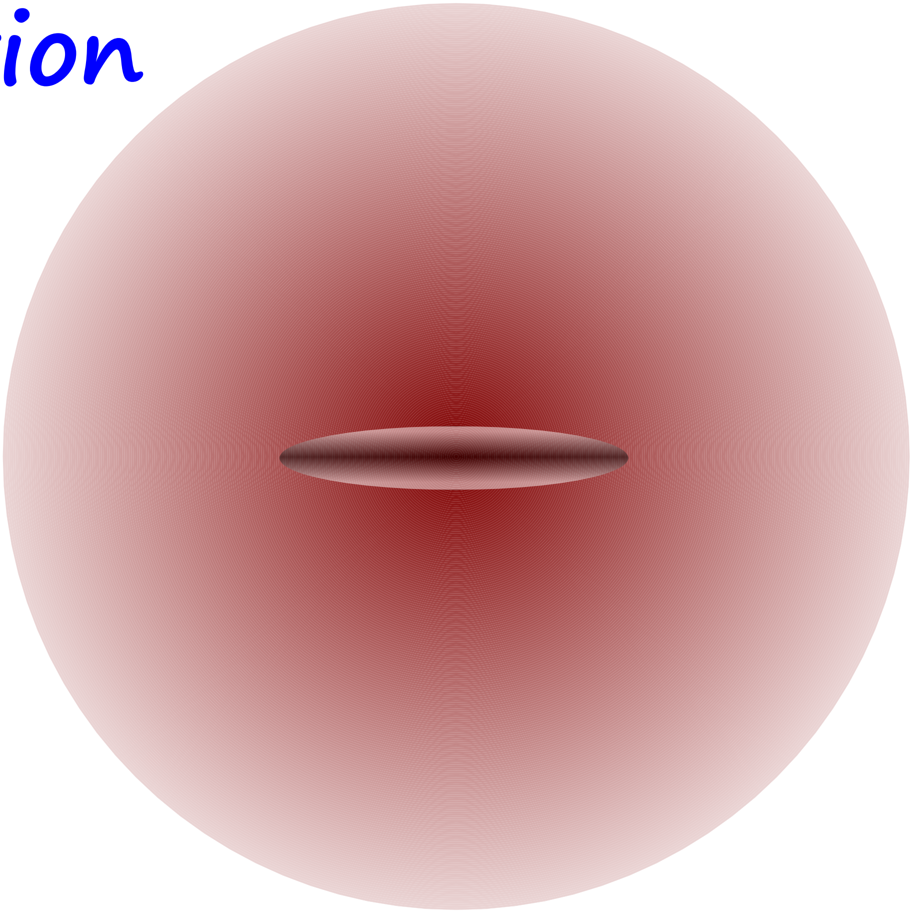


Charged particles

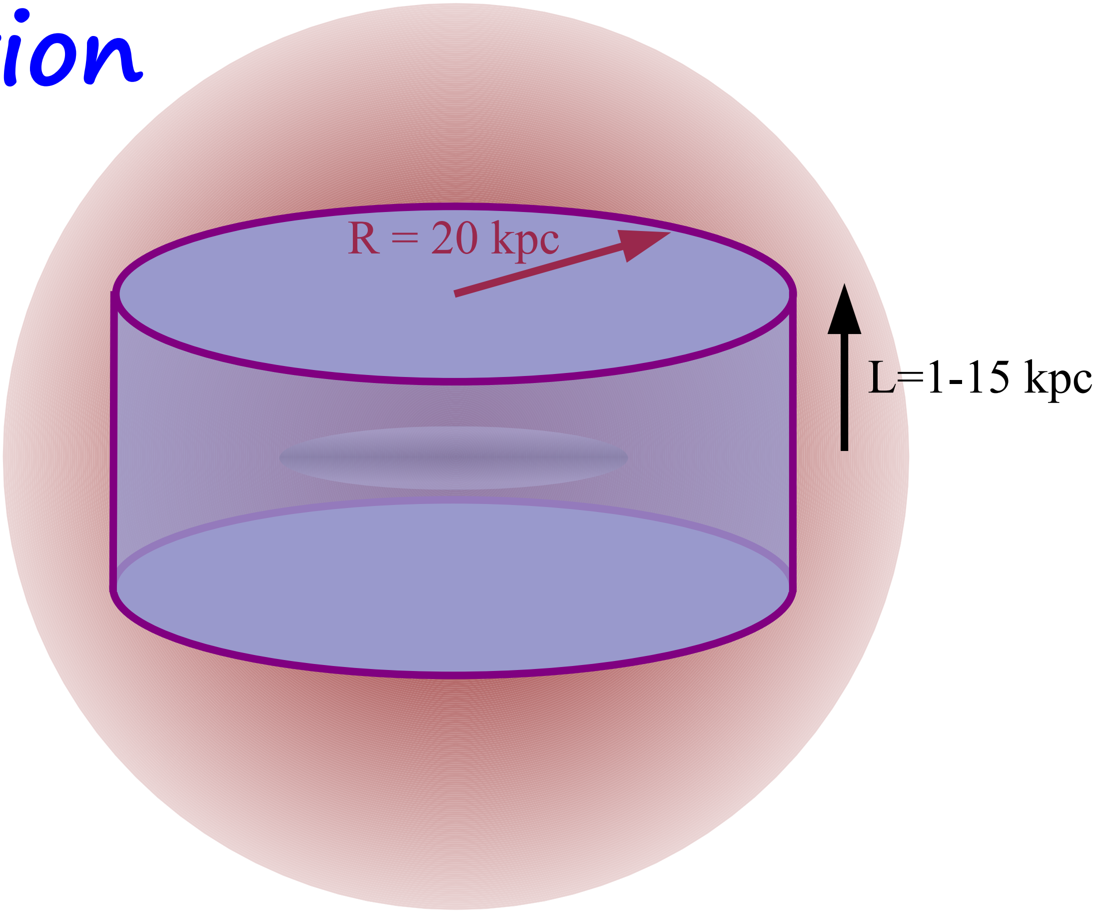
Propagation



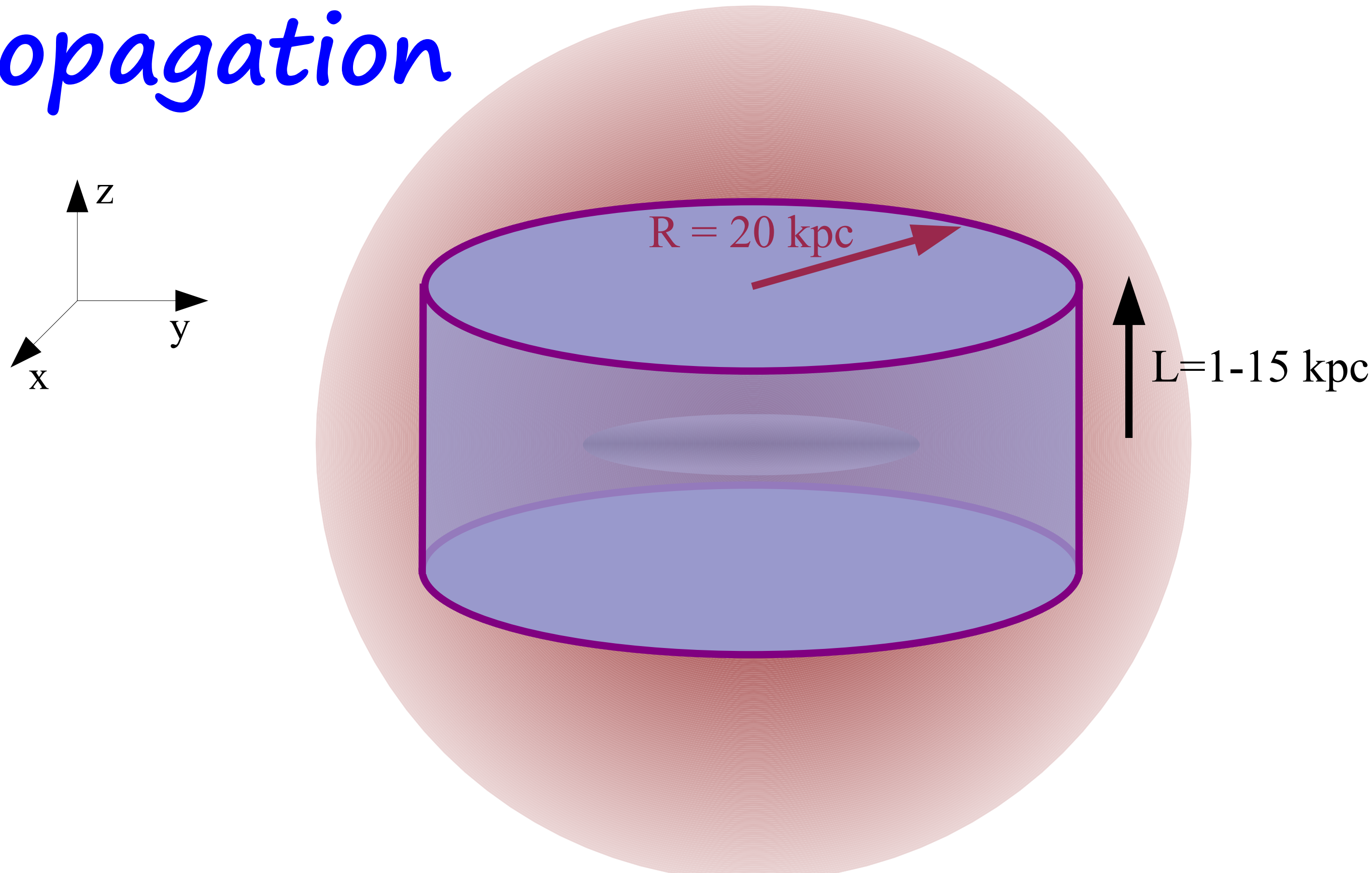
Propagation



Propagation



Propagation



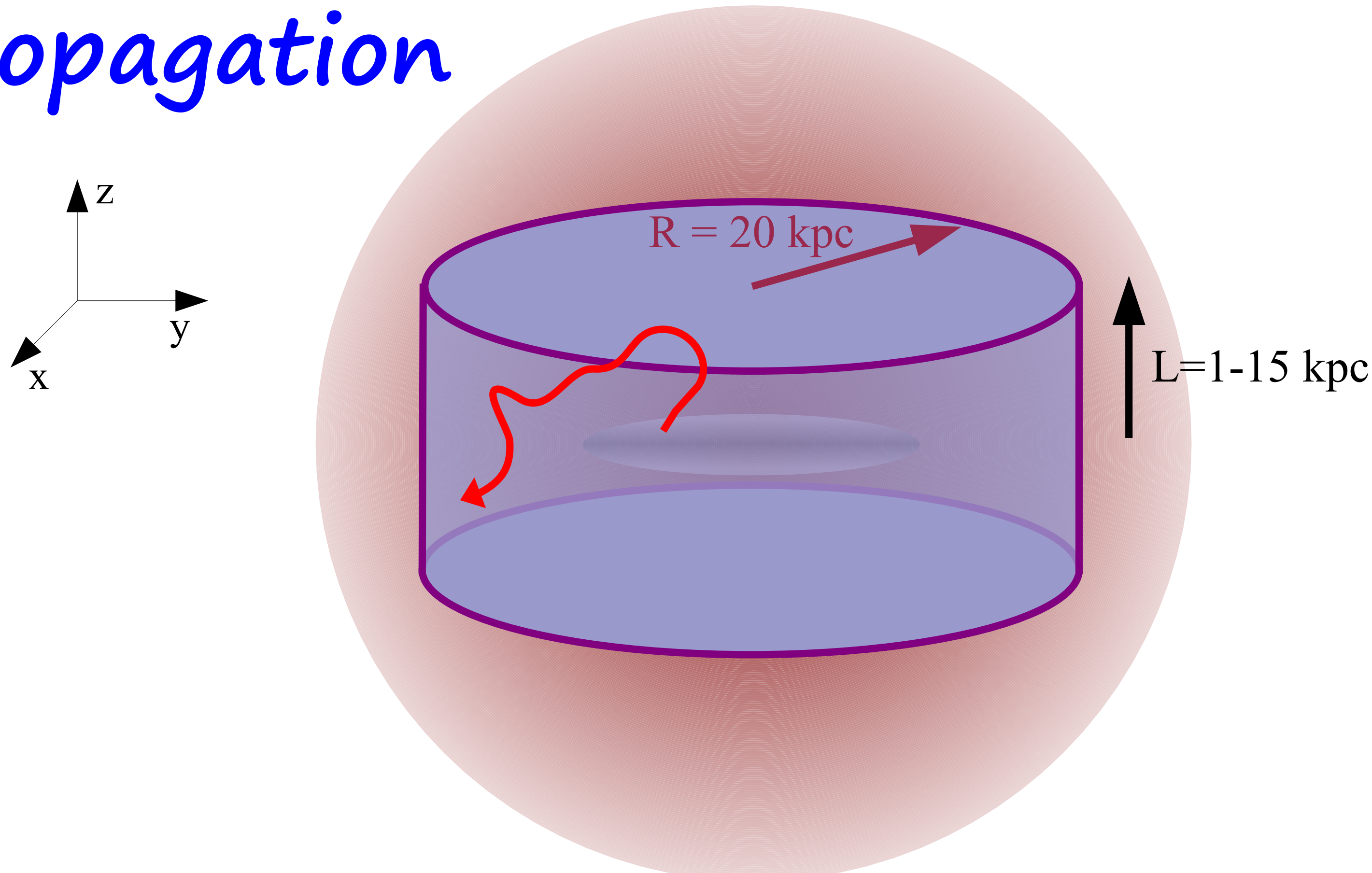
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann}f + Q(T,\vec{r}) \ .$$

f : number density of antiparticles per unit kinetic energy

interstellar antimatter flux:

$$\Phi^{\rm IS}(T) = \frac{dN}{dt\,dS\,dT\,d\Omega} = \frac{v}{4\pi}f(T)$$

Propagation



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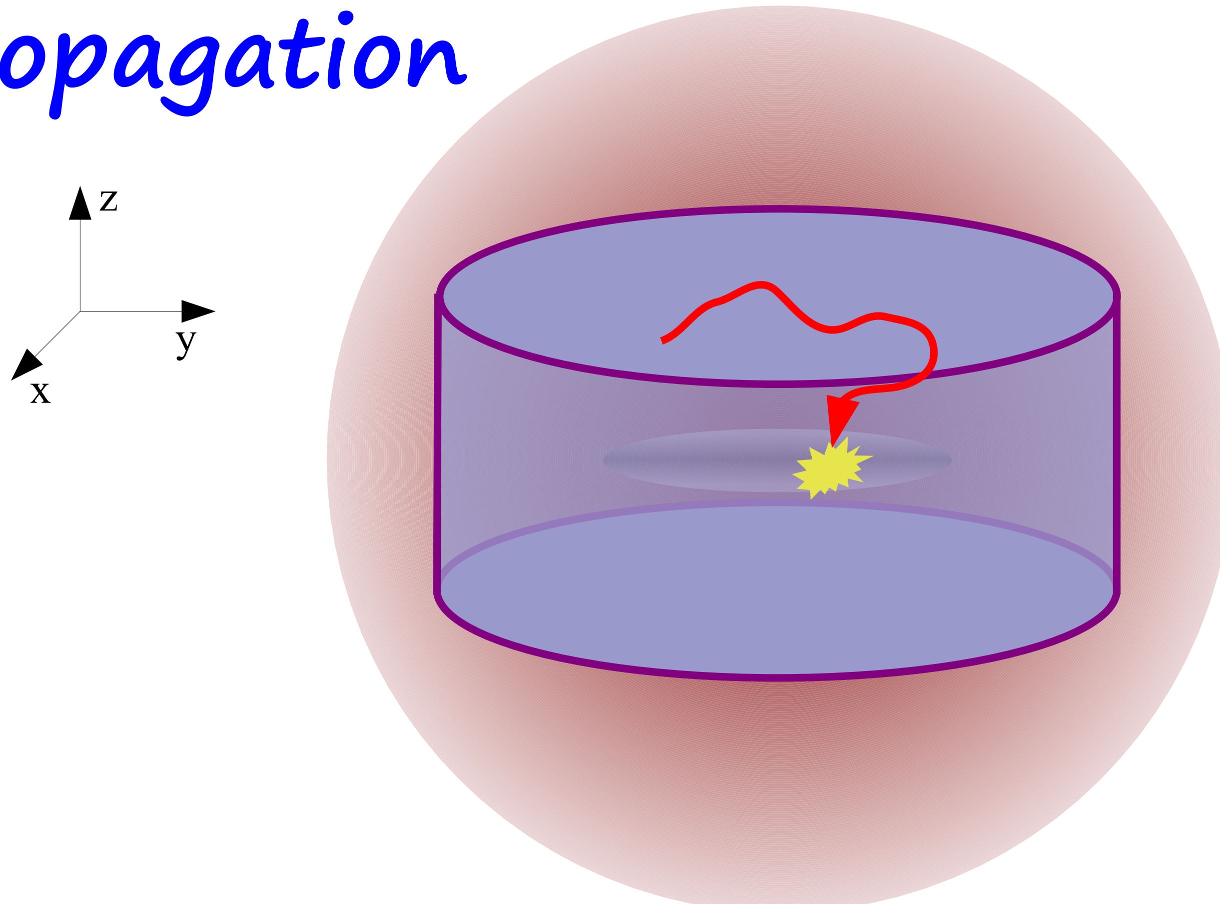
Source term $$Q(T,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_{\text{DM}}^2}\langle\sigma v\rangle\frac{dN}{dT}$$ dark matter annihilation

Propagation



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Annihilation term

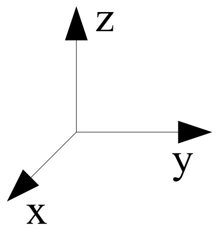
Negligible for positrons.
For antiprotons,

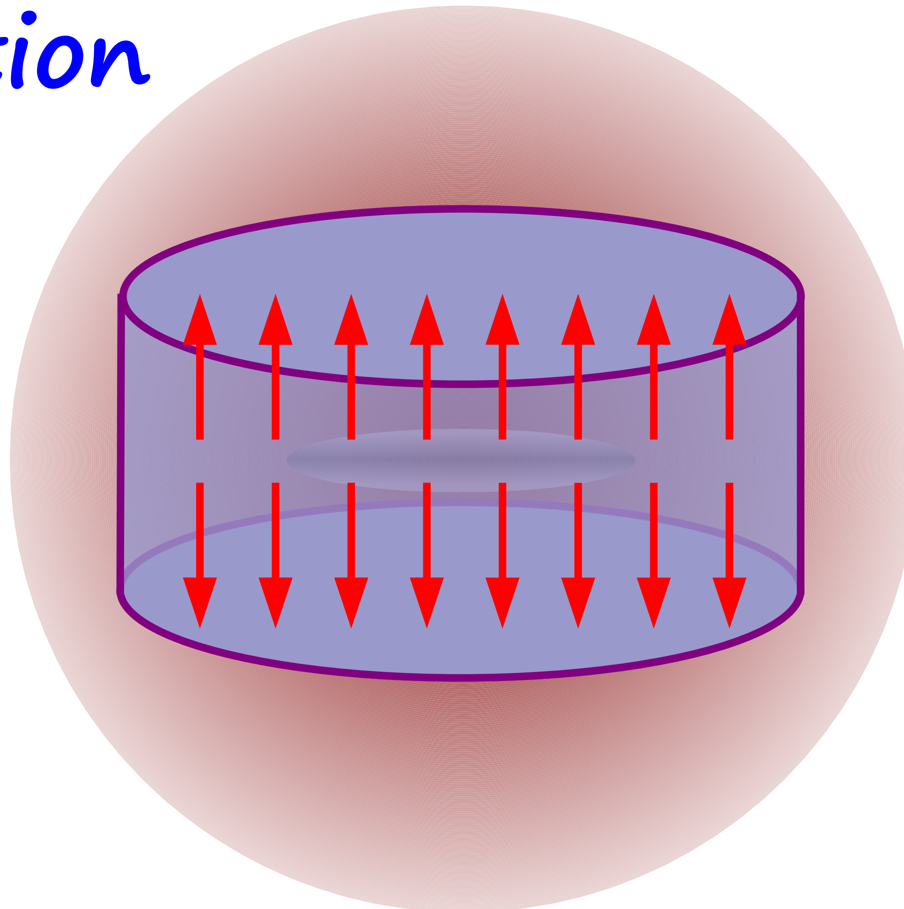
$$\Gamma_{\rm ann} = (n_{\rm H} + 4^{2/3} n_{\rm He})\sigma^{\rm ann}_{\bar{p}p} v_{\bar{p}} \; .$$

$$\sigma^{\rm ann}_{\bar{p}p}(T) = \begin{cases} 661\,(1 + 0.0115\,T^{-0.774} - 0.948\,T^{0.0151})\ {\rm mbarn}\,, & T < 15.5\ {\rm GeV}\,, \\ 36\,T^{-0.5}\ {\rm mbarn}\,, & T \geq 15.5\ {\rm GeV}\,, \end{cases}$$

Tan, Ng

Propagation





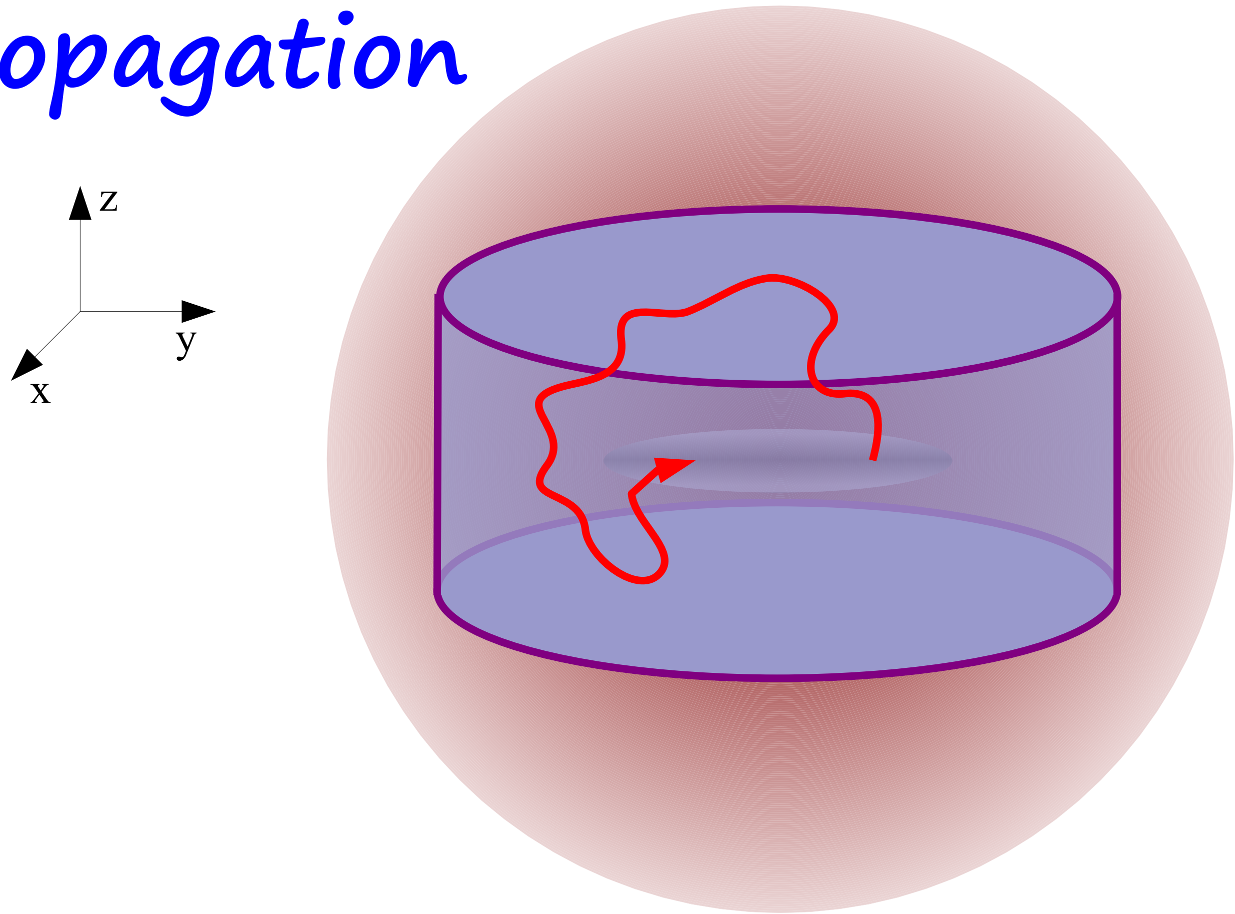
$$0 = \frac{\partial f}{\partial t} = \nabla \cdot [K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla \cdot [\vec{V}_c(\vec{r})f] - 2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r}) \ .$$

Convection term

- Due to the Milky Way galactic wind.
- Drifts particles away from the Galactic disk.
- Difficult to model. Assume:

$$\vec{V}_c(\vec{r}) = V_c \ \mathrm{sign}(z) \ \vec{k}$$

Propagation



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Energy loss term

- Due to inverse Compton scattering on the interstellar radiation field (starlight, thermal radiation of dust, CMB) and synchrotron radiation.
- Negligible for antiprotons and antideuterons
- Can be modelled

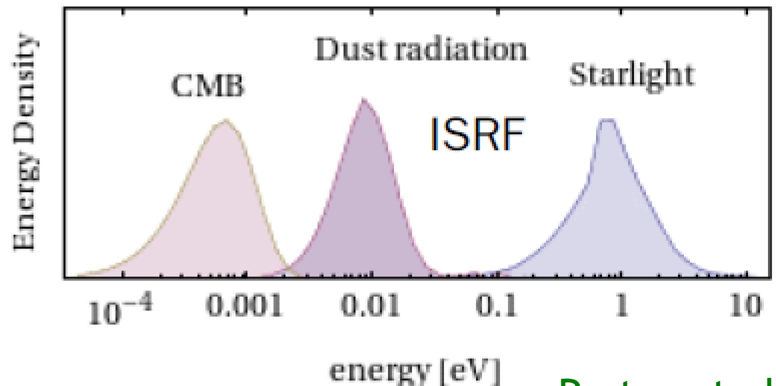
- Energy loss due to Inverse Compton scattering: $e^{+}\gamma \rightarrow e^{+}\gamma$

$$b_{\rm ICS}(E_e,\vec{r}) = \int_0^\infty d\epsilon \int_\epsilon^{E_\gamma^{\max}} dE_\gamma (E_\gamma - \epsilon) \frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} f_{\rm ISRF}(\epsilon,\vec{r})$$

$$\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} = \frac{3}{4}\frac{\sigma_{\rm T}}{\gamma_e^2\,\epsilon} \times \left[2q\ln q + 1 + q - 2q^2 + \frac{1}{2}\frac{(q\Gamma)^2}{1+q\Gamma}(1-q)\right]$$

Number density of photons in ISRF

$\gamma_e = E_e/m_e$ ↔ Lorentz factor.
$\Gamma_e = 4\gamma_e\,\varepsilon/m_e$
$q = E_\gamma/\Gamma(E_e - E_\gamma)$
$\sigma_T = 0.67$ barn ↔ Compton scattering cross section in the Thomson limit.



Porter et al.

- Energy loss due to synchrotron radiation:

$$b_{\rm sync}(E_e,\vec{r}) = \frac{4}{3}\sigma_T \gamma_e^2 \frac{B^2}{2} \qquad B = 6\mu G \exp(-|z|/5{\rm kpc} - r/20{\rm kpc})$$

Approximately $b(E) = \dfrac{E^2}{E_0 \tau_E}$, with $E_0 = 1\,{\rm GeV}$ and $\tau_E = 10^{16}{\rm s}$

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$\gamma_e = E_e/m_e$ ⇒ Lorentz

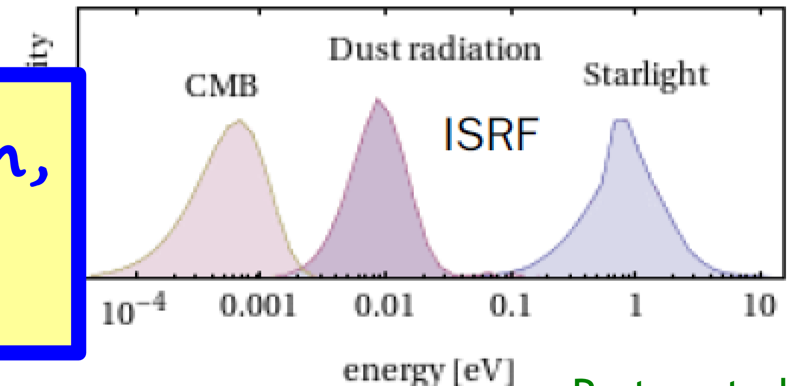
$\Gamma_e = 4\,\gamma_e\,\varepsilon/m_e$

$q = E_\gamma/\Gamma(E_e - E_\gamma)$

$\sigma_T = 0.67$ barn ⇒ Con

in the Thomson limit.

Not very well known, though...



Porter et al.

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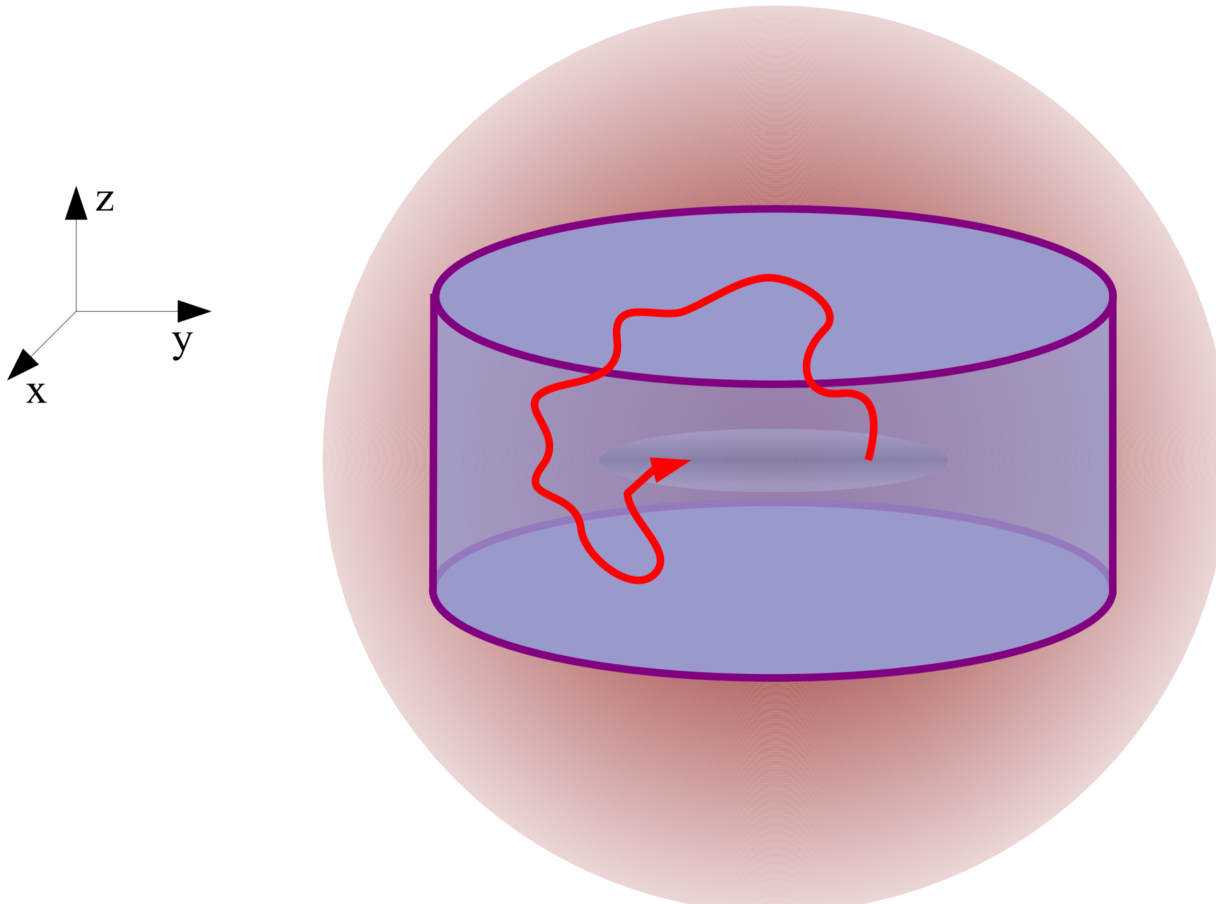

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Diffusion term

- Due to the tangled magnetic field of the Galaxy.
- Difficult to model. Assume

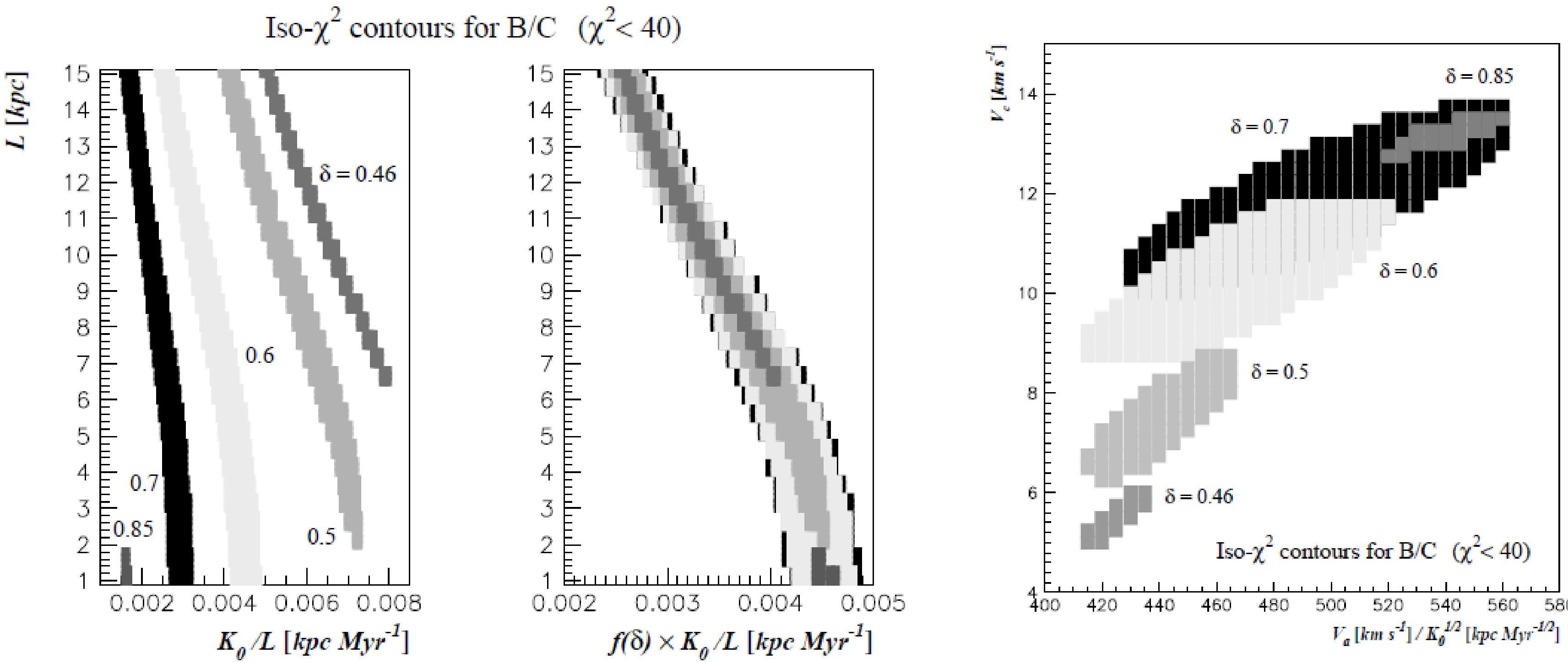
$$K(T) = K_0 \, \beta \, \mathcal{R}^\delta$$

β = velocity
P = rigidity

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

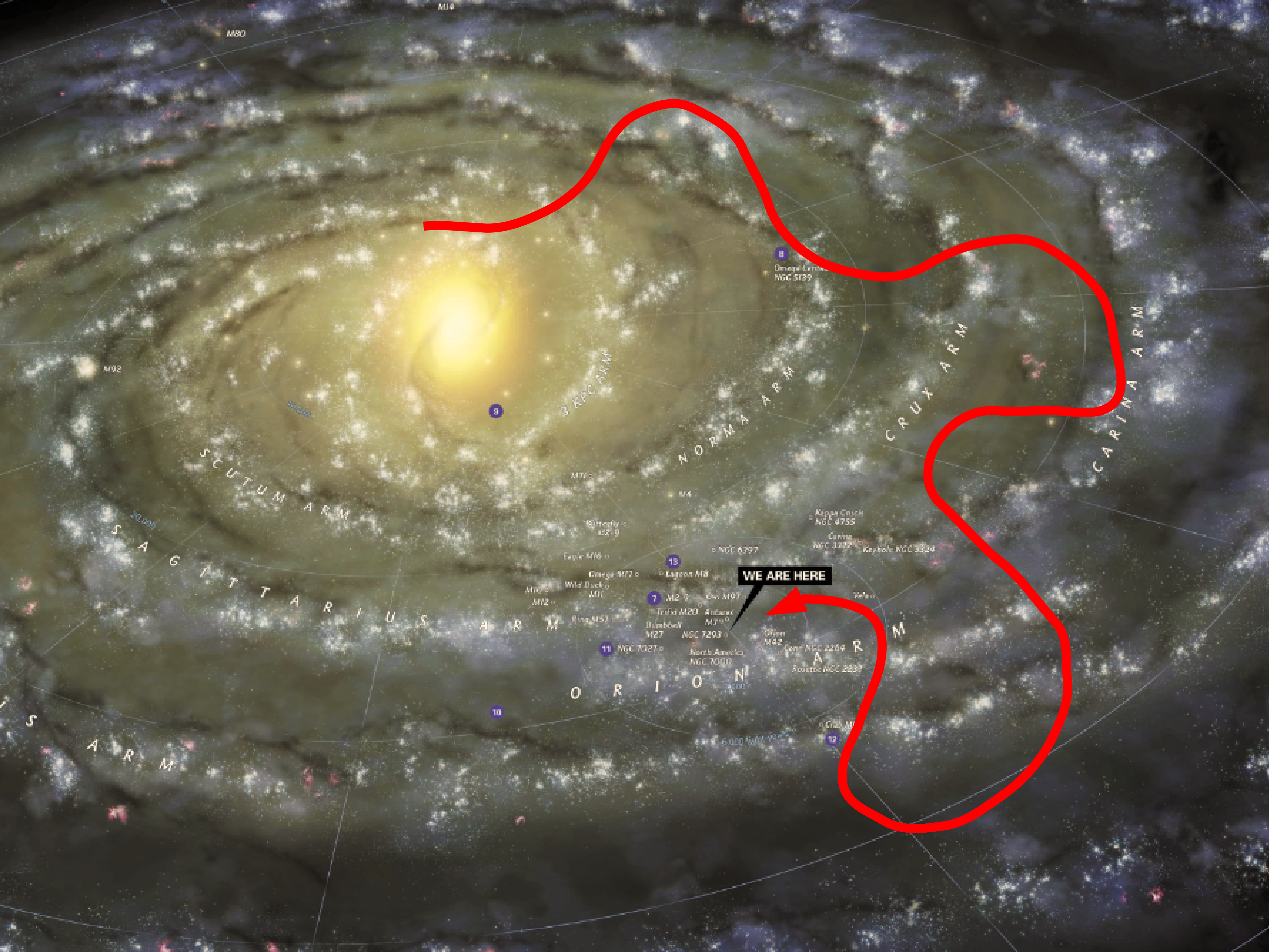
$$K(T) = K_0 \, \beta \, \mathcal{R}^\delta \qquad \qquad \vec{V}_c(\vec{r}) = V_c \; \mathrm{sign}(z) \; \vec{k}$$

K_0, δ, V_c (as well as L) must be determined with measurements of other cosmic ray species (mainly B/C ratio).



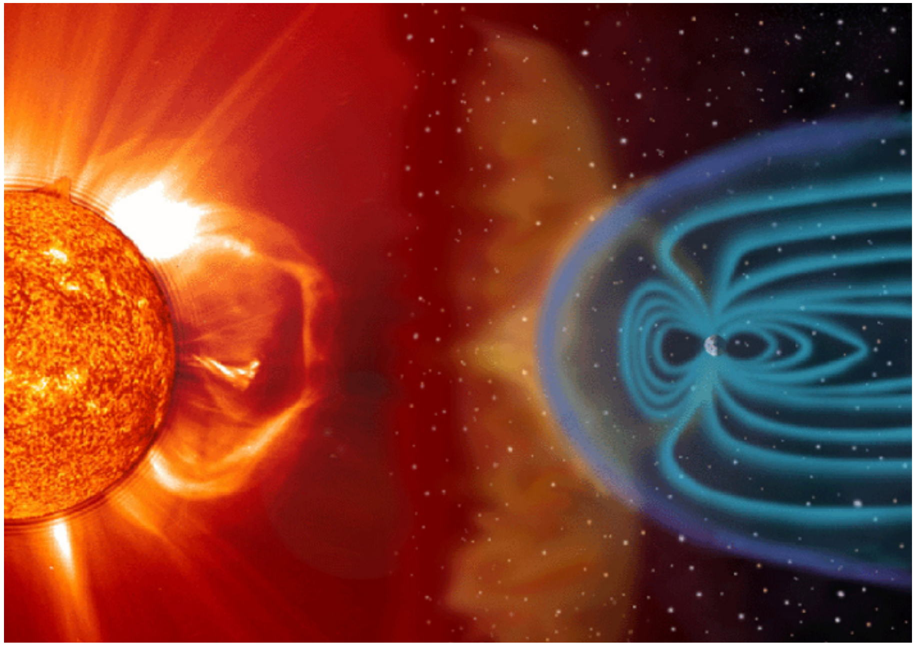
Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Maurin, Donato, Taillet, Salati '01



WE ARE HERE
NORMA ARM
CRUX ARM
CARINA ARM
SCUTUM ARM
SAGITTARIUS ARM
ORION ARM
3 KPC ARM
M80
M92
Omega Centauri NGC 5139
Kappa Crucis NGC 4755
Carina NGC 3372
Keyhole NGC 3324
NGC 6397
Lagoon M8
Omega M17
Eagle M16
Wild Duck M11
M12
Trifid M20
Antares
Ring M57
Dumbbell M27
NGC 7293
NGC 7027
North America NGC 7000
Orion M42
Cone NGC 2264
Rosette NGC 2237
M4

Propagation inside the Solar System



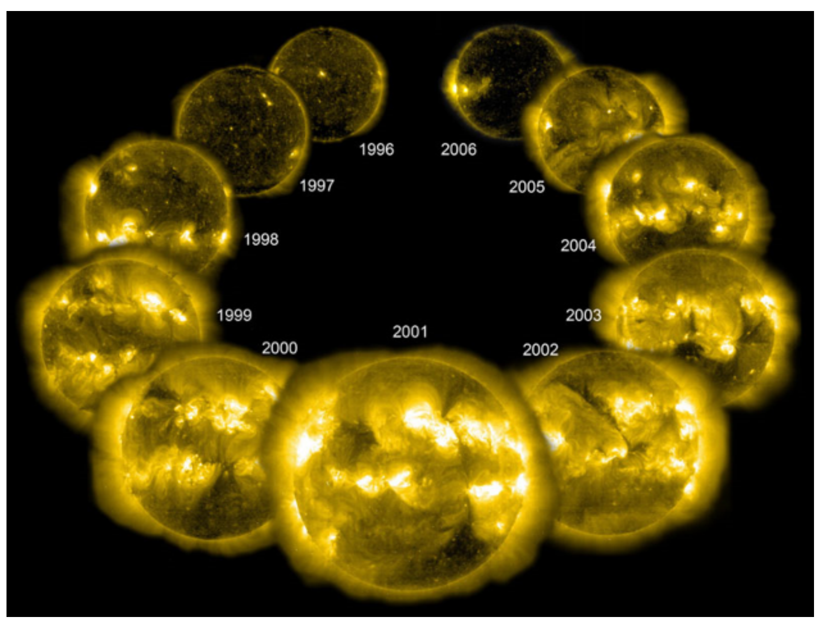
In the "force field approximation",the flux at the top of the atmosphere (TOA) is related to the interstellar flux (IS) by

$$\Phi_{e^\pm}^{\mathrm{TOA}}(E_{\mathrm{TOA}}) = \frac{E_{\mathrm{TOA}}^2}{E_{\mathrm{IS}}^2}\,\Phi_{e^\pm}^{\mathrm{IS}}(E_{\mathrm{IS}})$$

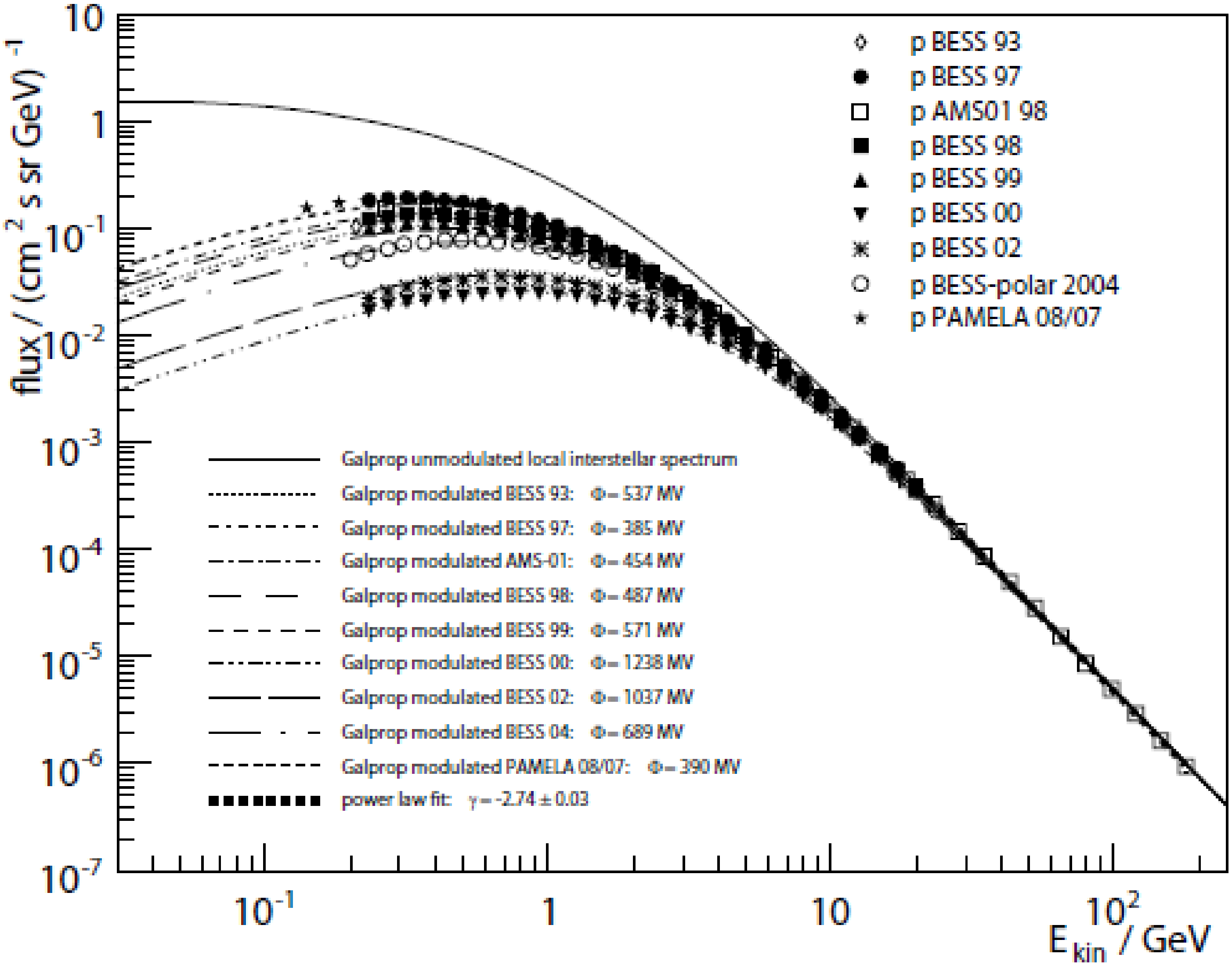
$$E_{\mathrm{IS}} = E_{\mathrm{TOA}} + \phi_F$$

solar modulation parameter

ϕ_F=500 MV – 1.3 GV



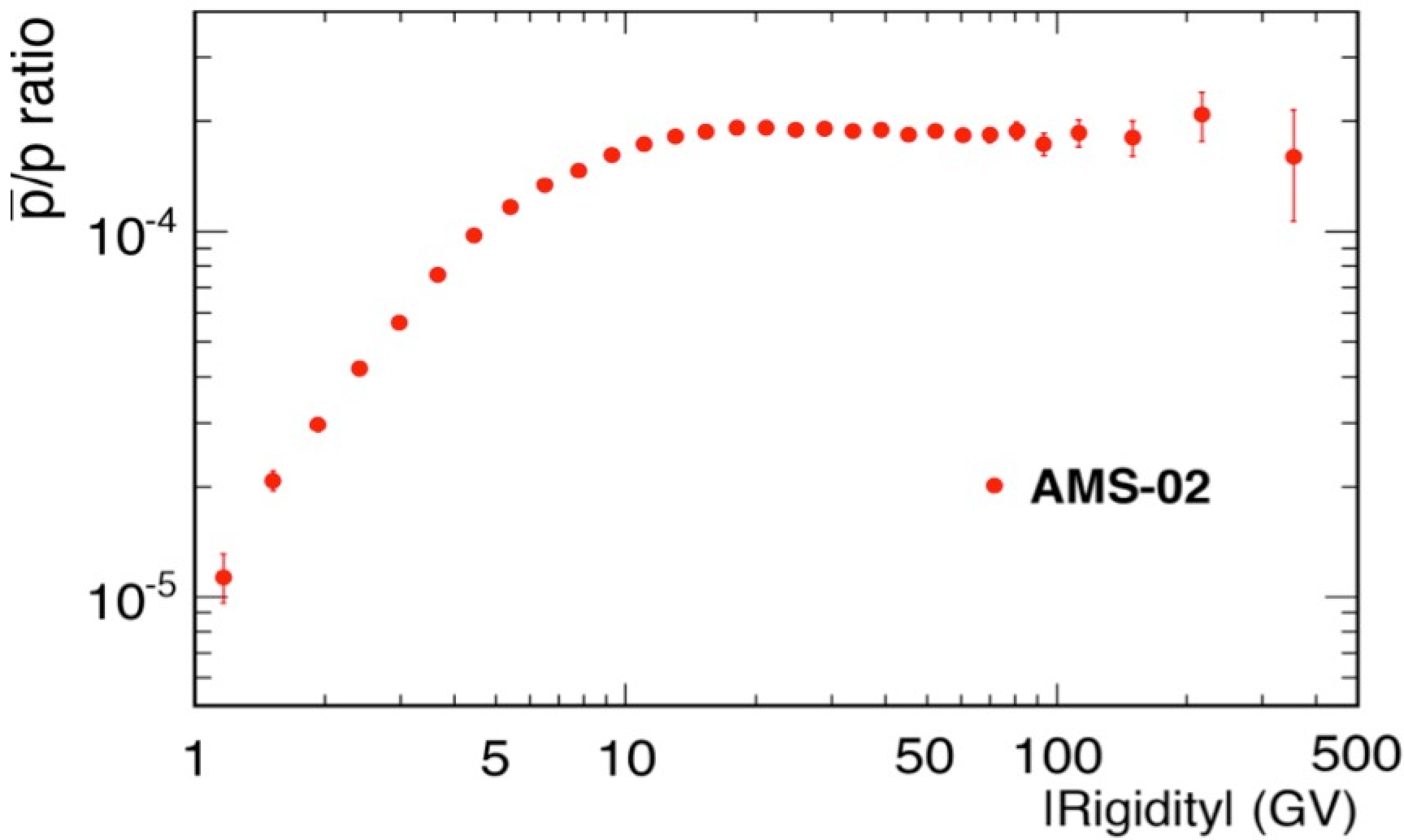
Cosmic ray proton spectrum as measured by BESS, AMS-01 and PAMELA



Gast, Schael '09

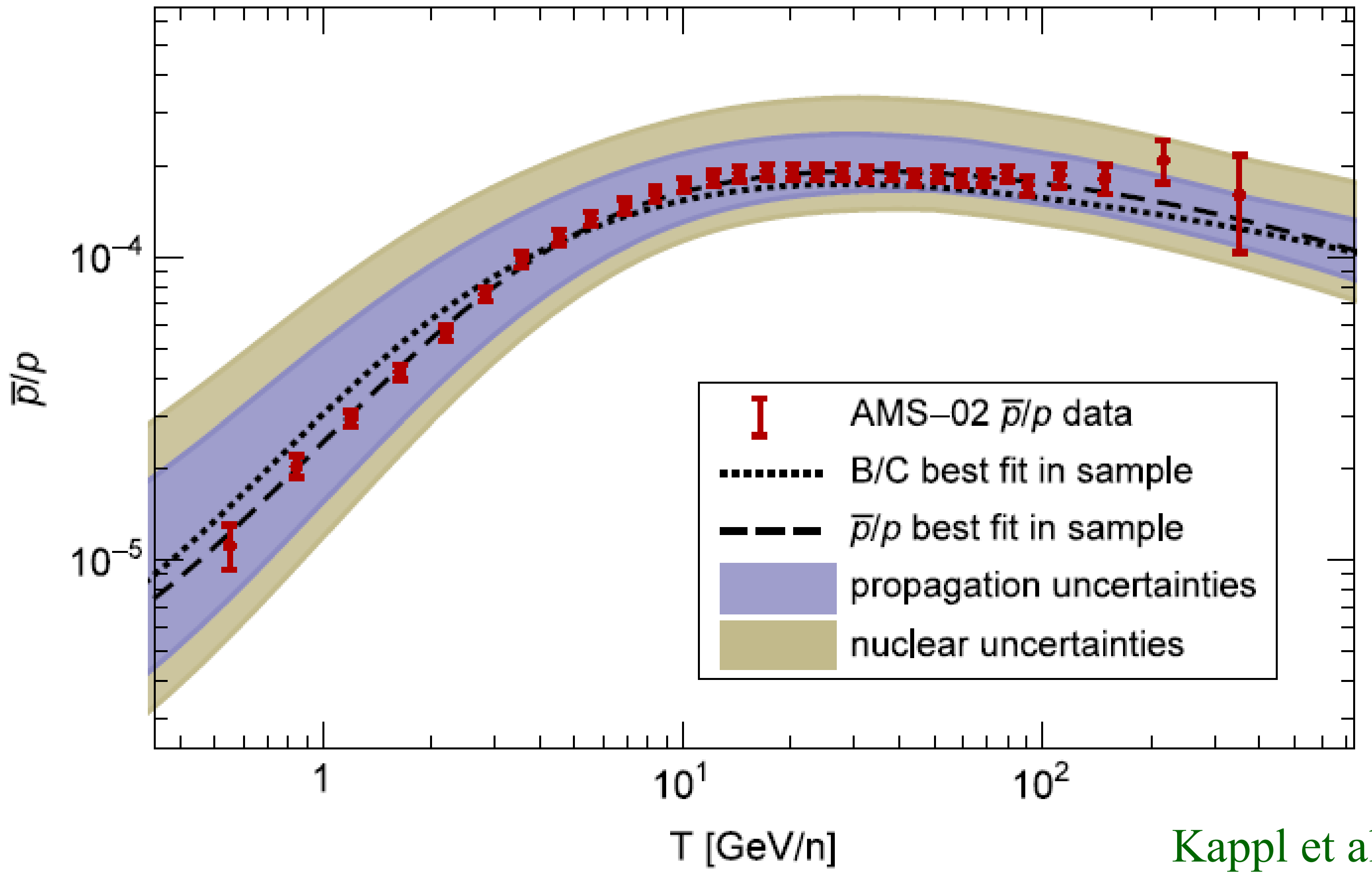
Experimental results

AMS p̄/p results



AMS-02 coll'15

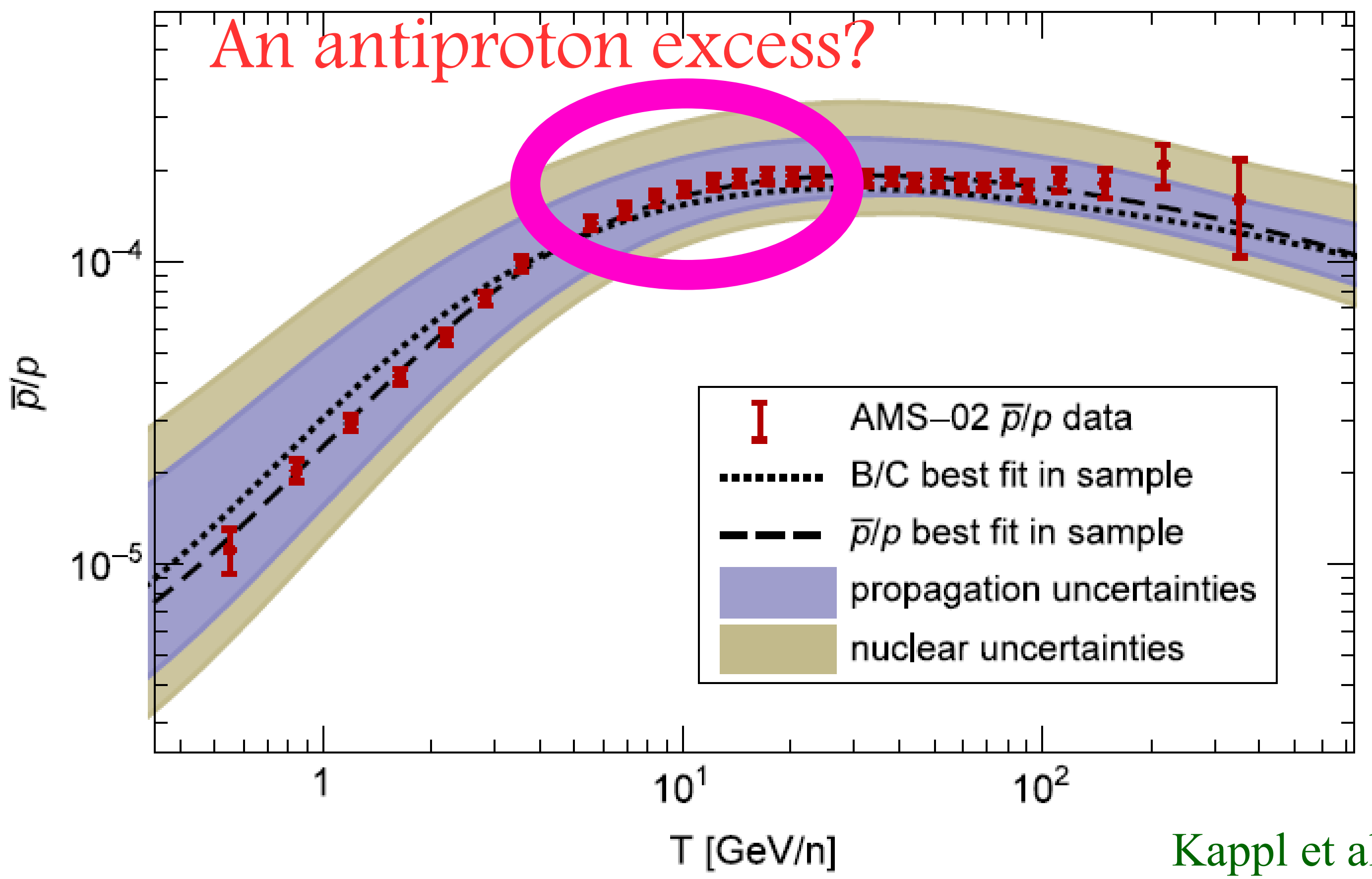
Experimental results



Kappl et al'15

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

Experimental results



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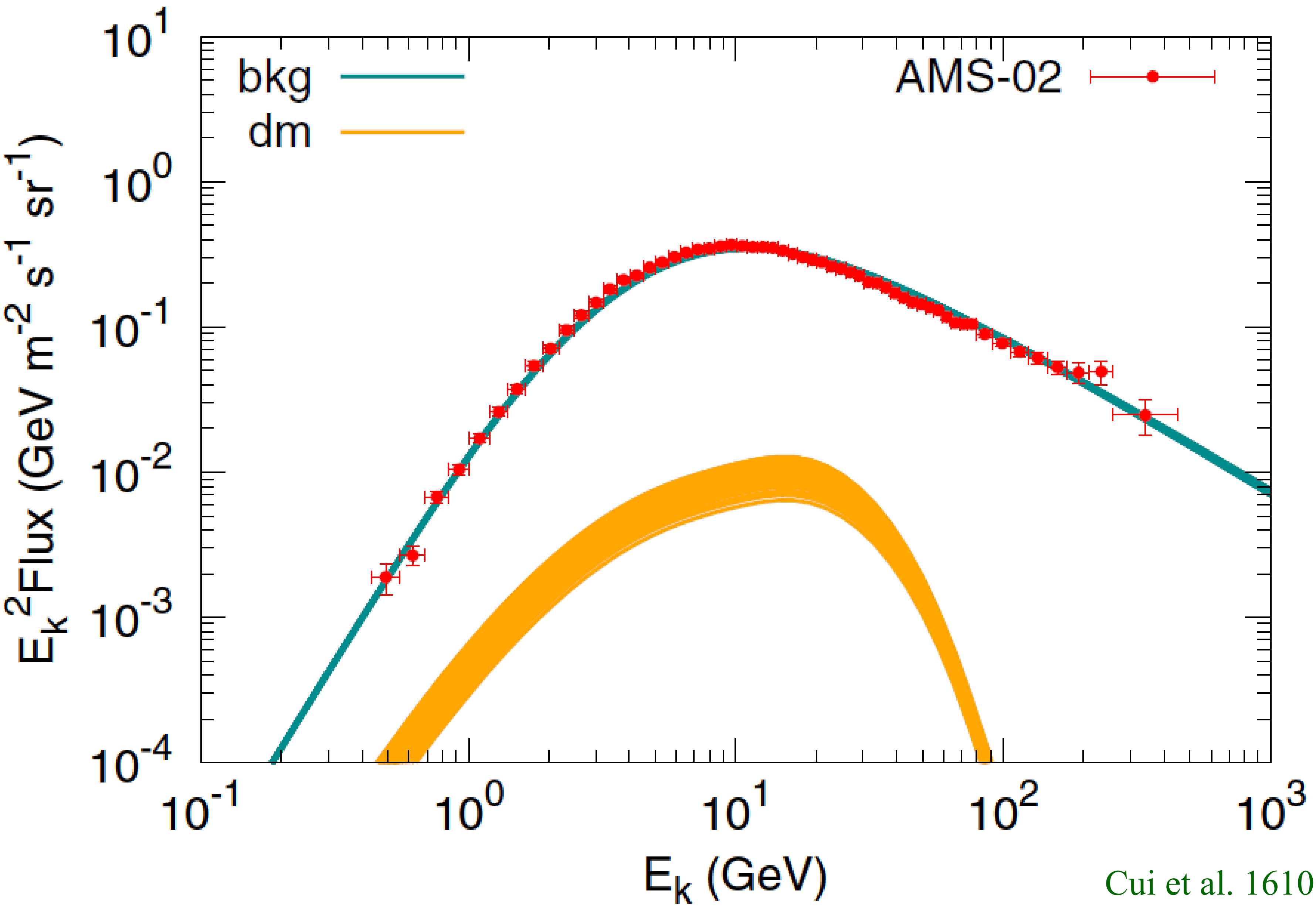
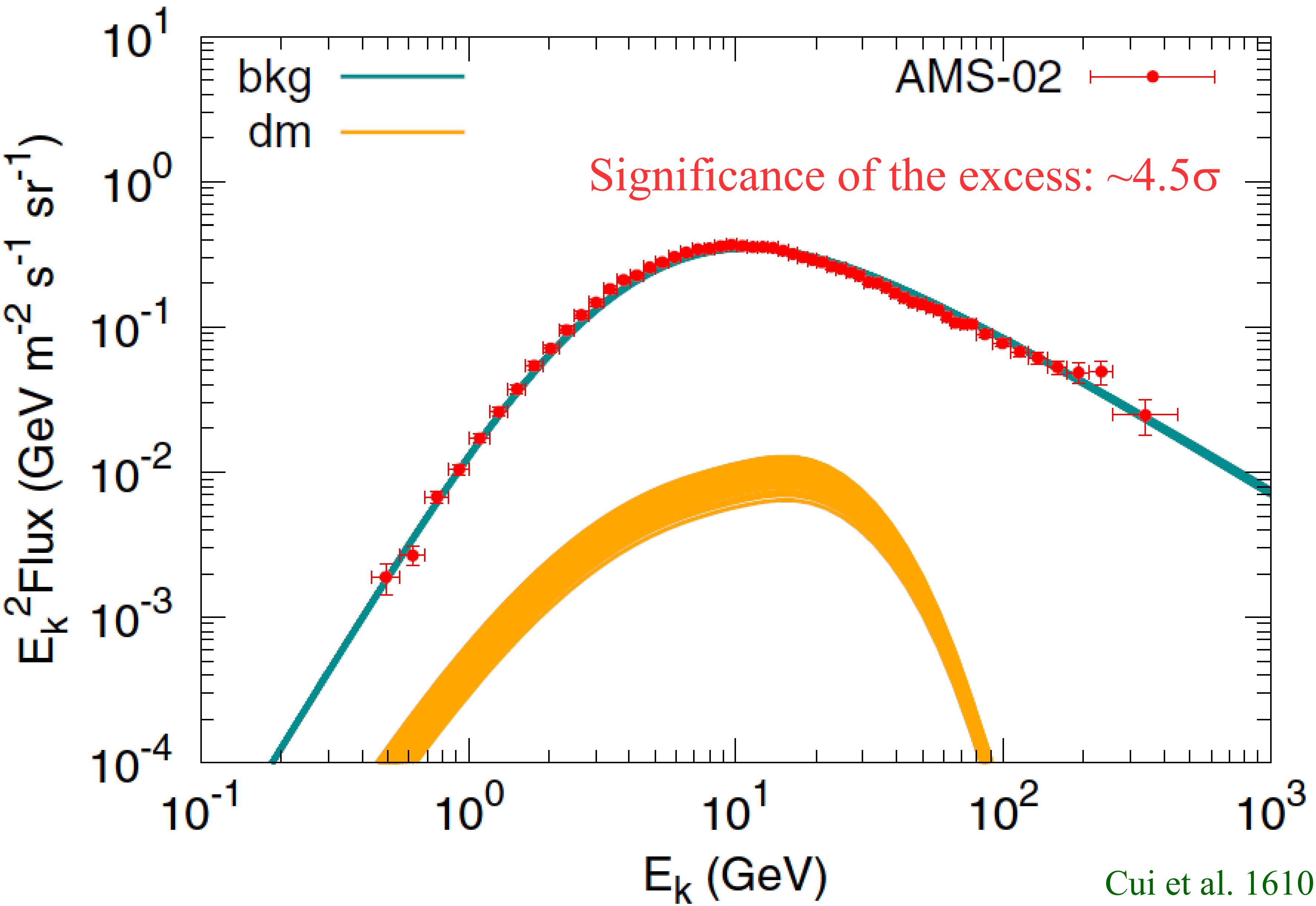
An antiproton excess??



Cui et al. 1610.03840
Cuoco et al. 1610.03071

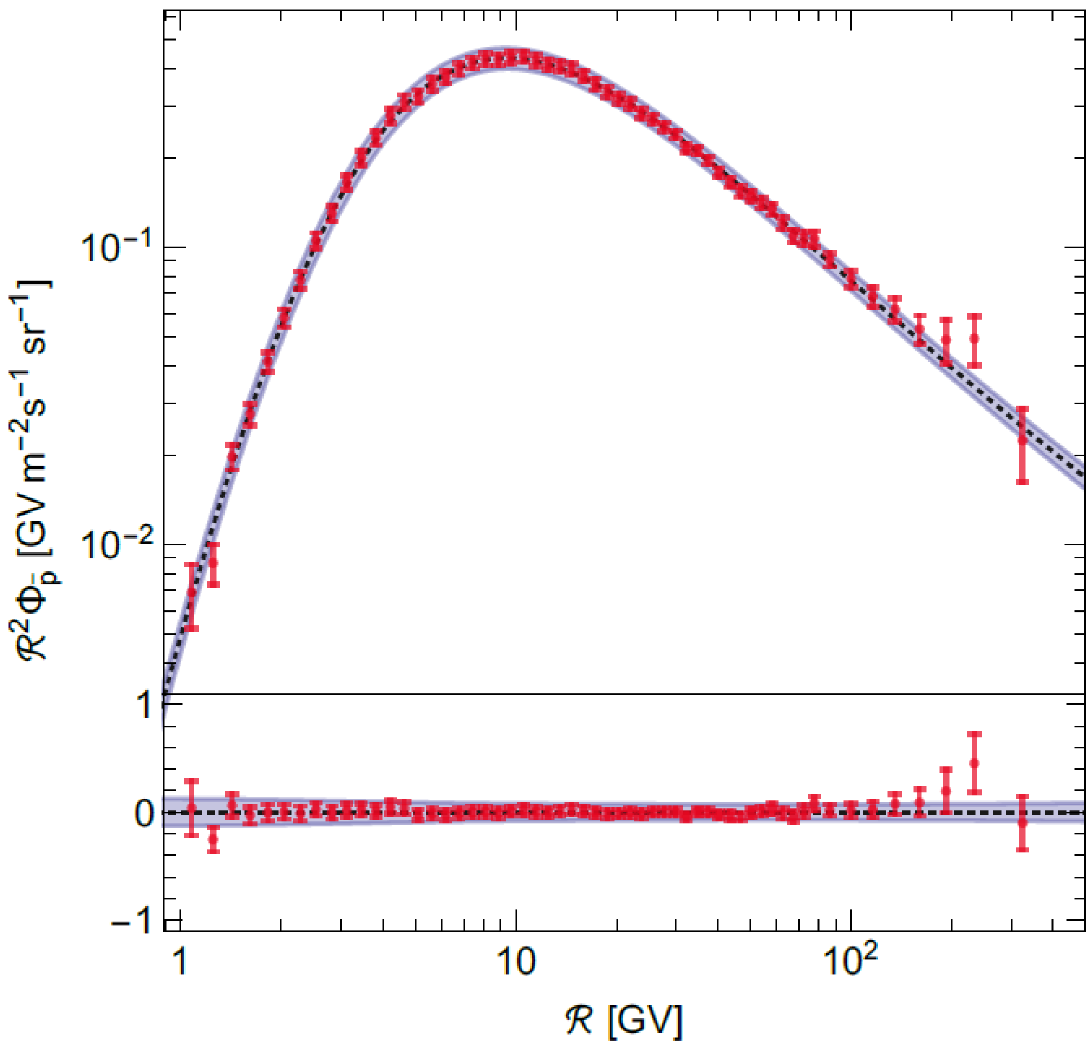
An antiproton excess??



Cui et al. 1610.03840
Cuoco et al. 1610.03071

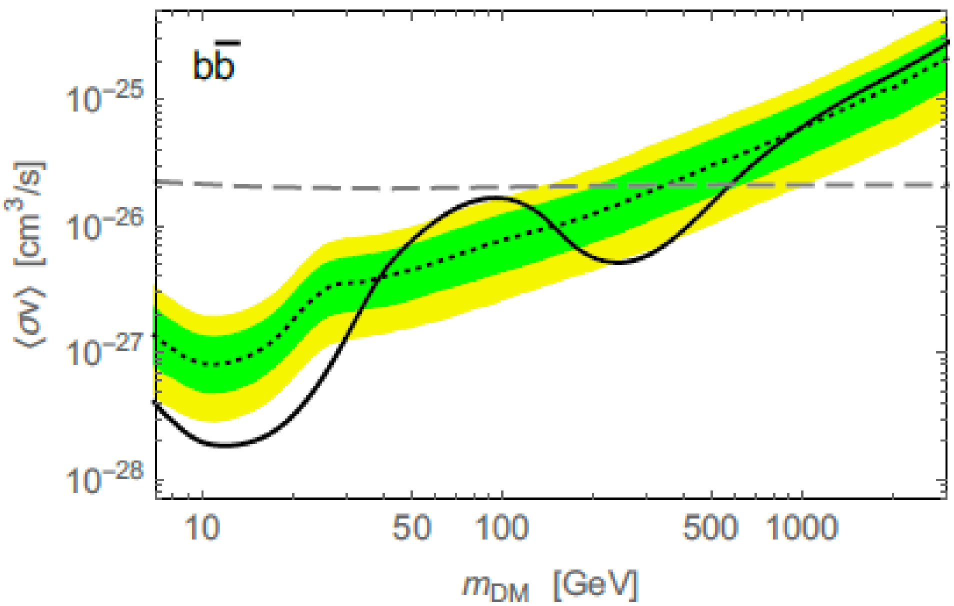
An antiproton excess??

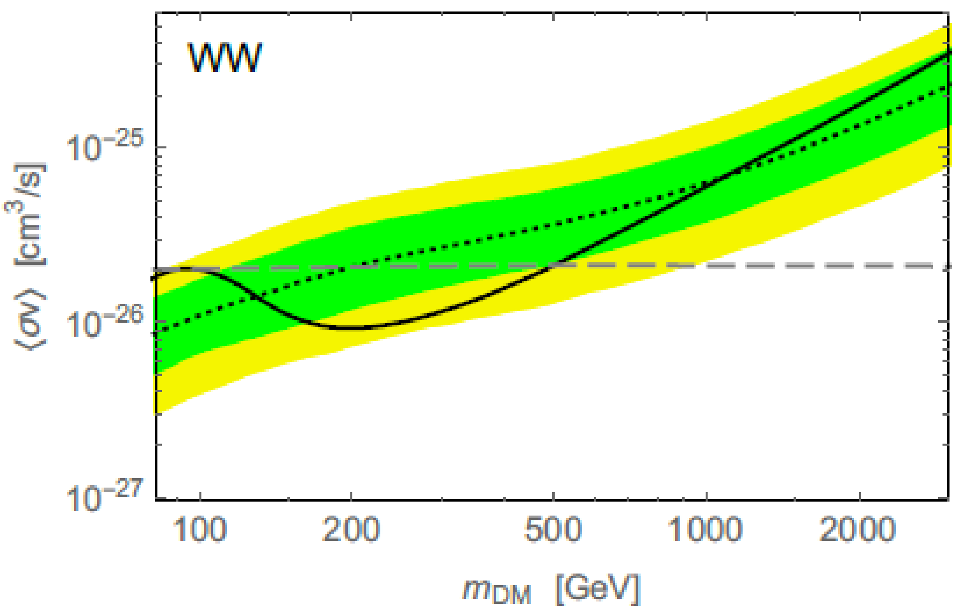
Recent analyses using a large collection of data of antiproton production, and an improved analysis of the propagation uncertainties, lower the significance to 2.2σ.



Reinert, Winkler.
1712.00002

DM constraints from antiproton data





Reinert, Winkler.
1712.00002