

Light Dark Matter - Existing Limits from Astroparticle Physics, Cosmology and Particle Physics



Kai Schmidt-Hoberg

HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



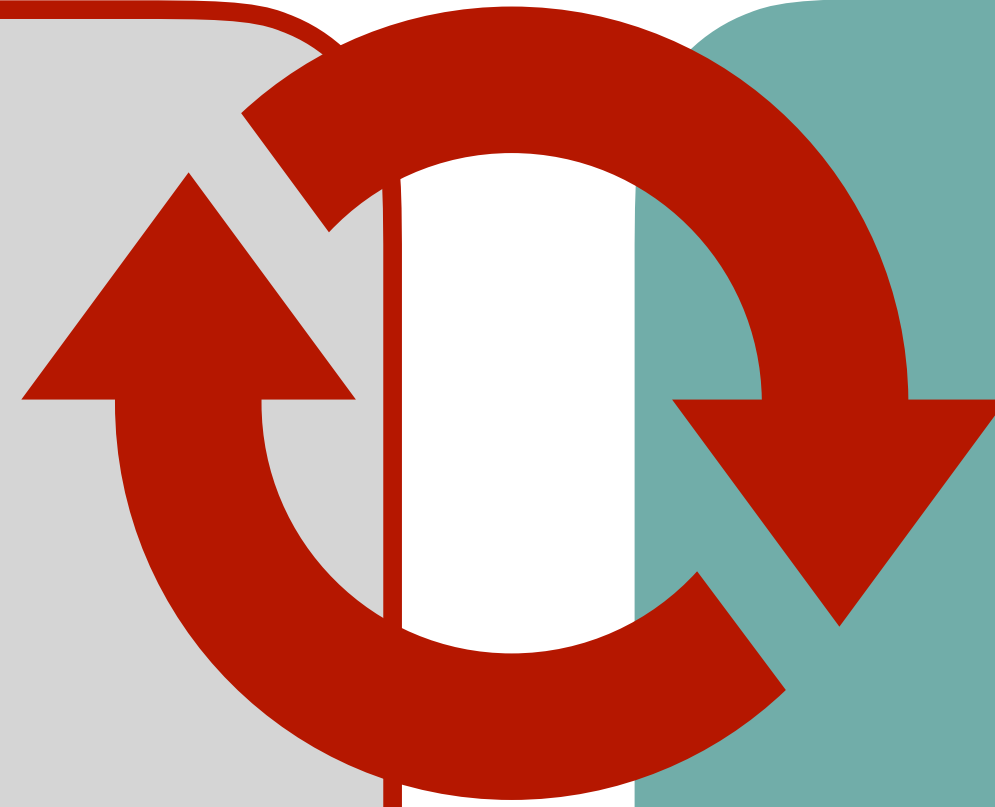
Split overview talks

Part I: Kai

Generic requirements on light DM models

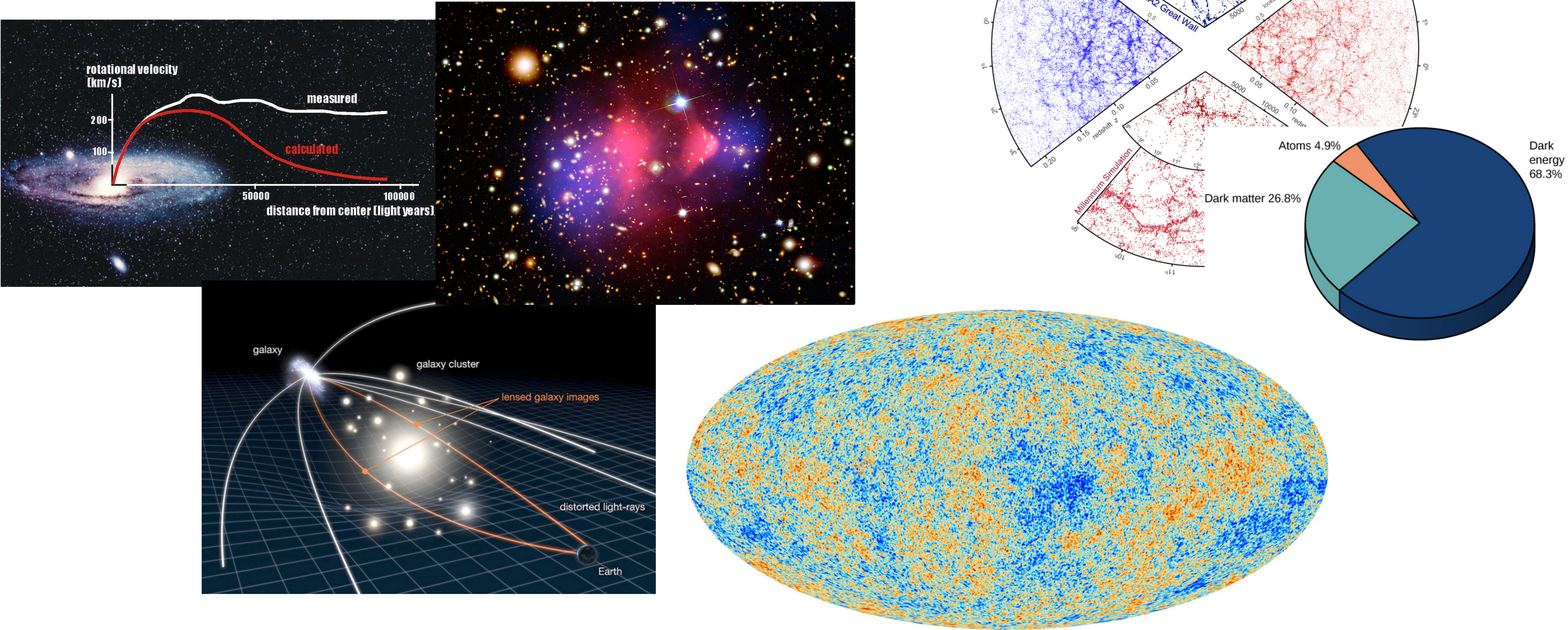
Part II: Patrick

Resulting light DM models



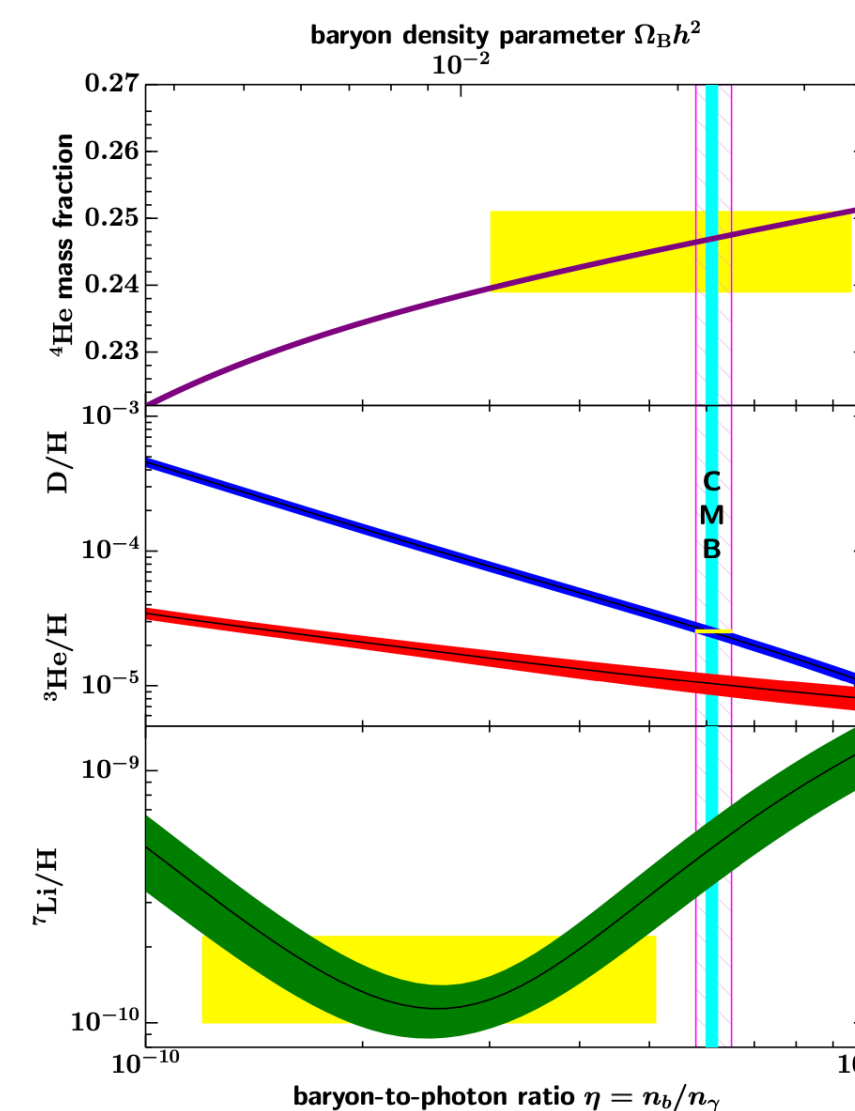
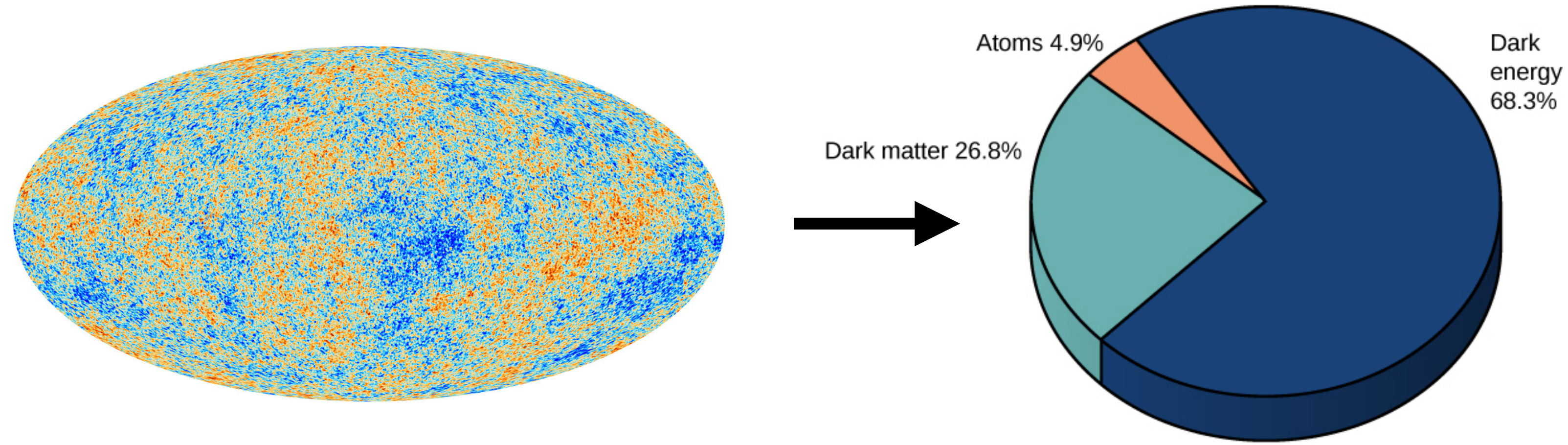
Evidence for dark matter

Compelling evidence for dark matter on **all** astrophysical scales



What do we know?

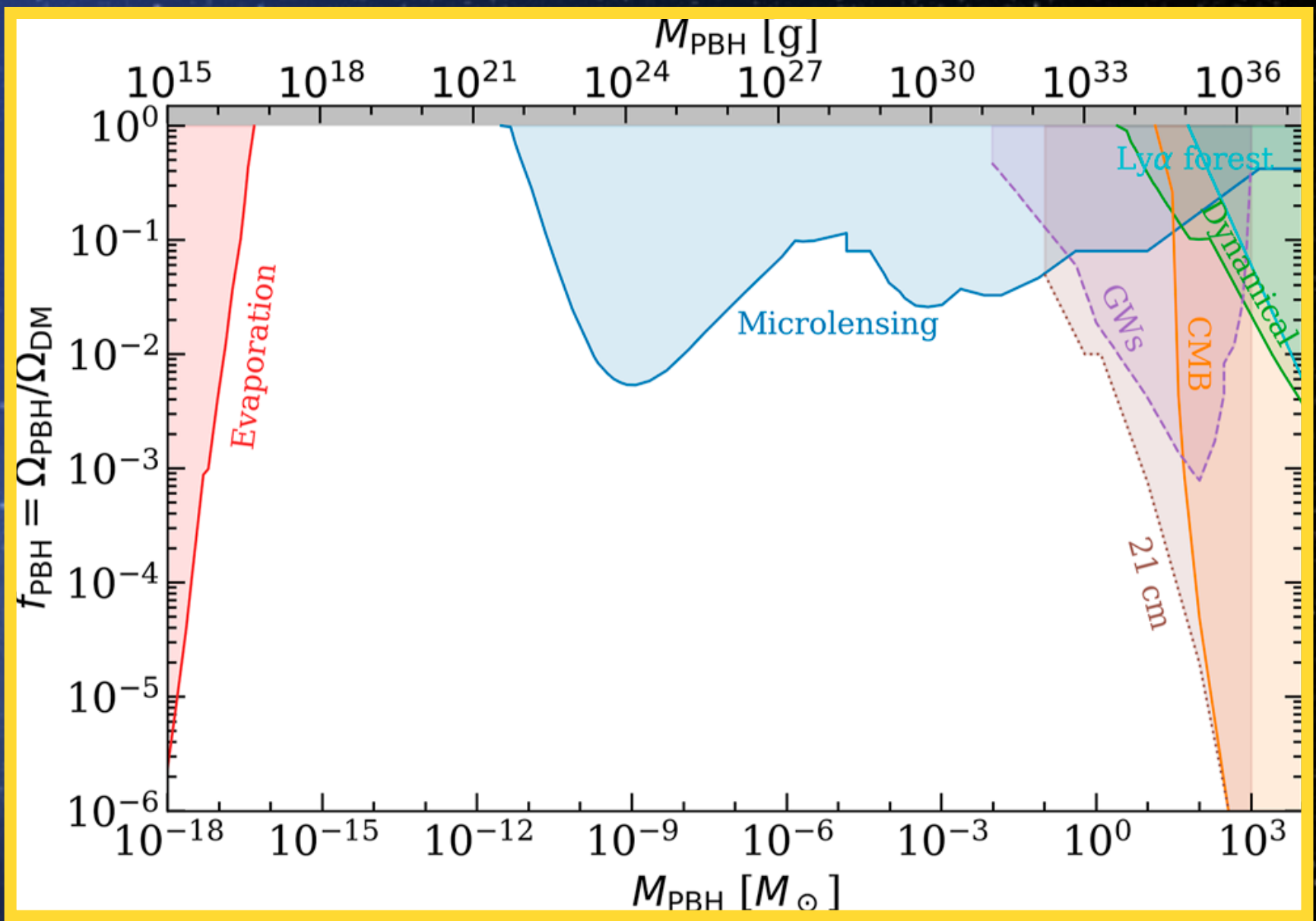
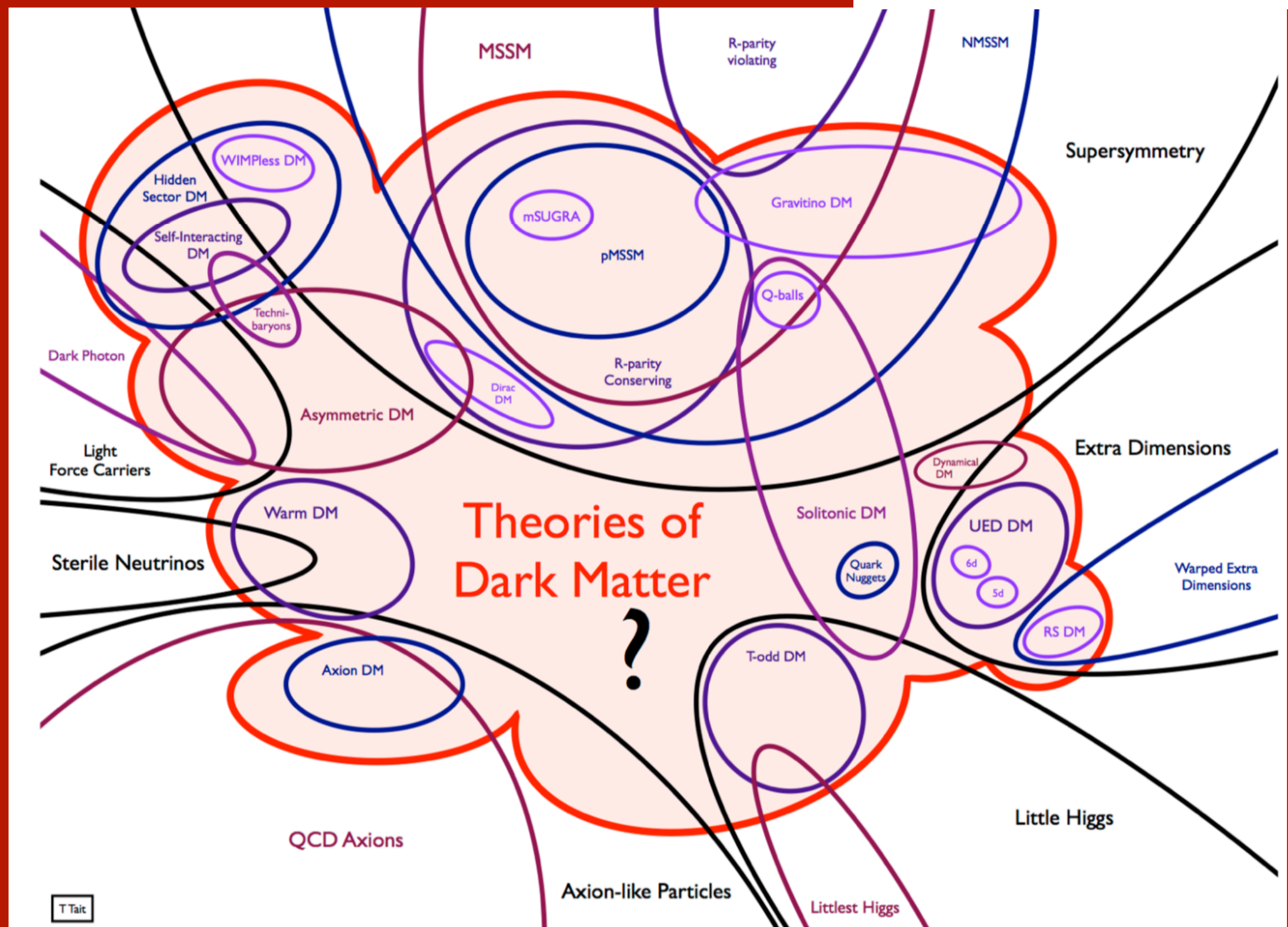
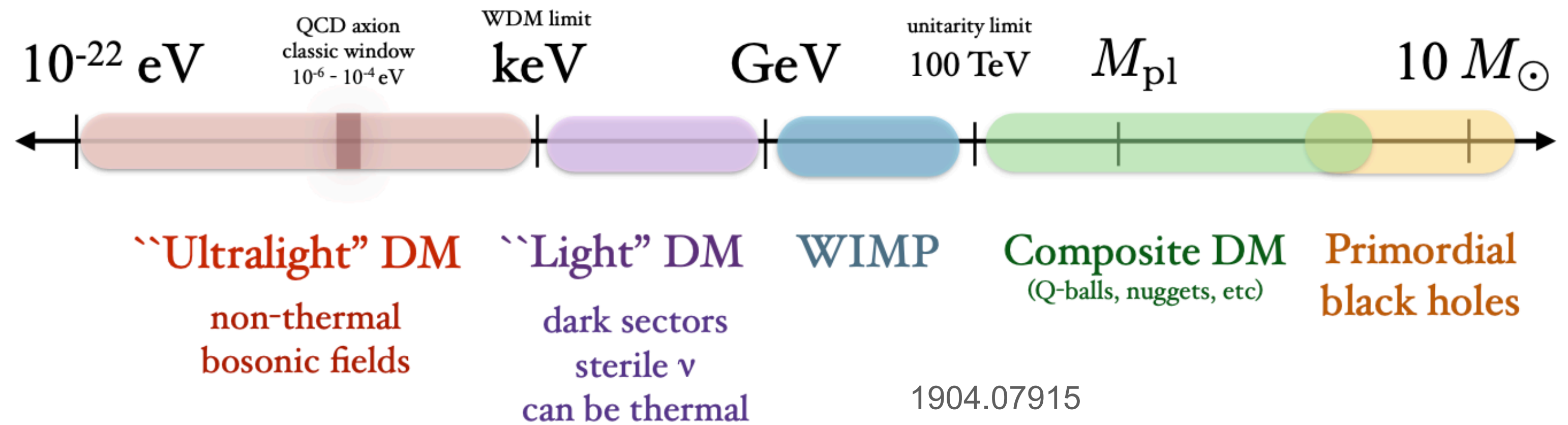
- interacts gravitationally!
- How much: $\Omega \simeq 0.26$
 - already around at CMB times
- **Dark**
 - almost electrically neutral
 - probably colour neutral
- **Stable**
 - sufficiently long-lived
- **Cold**
 - OK with structure formation
- **Non-baryonic**
- **Collisionsless?**
 - well...



this leaves quite some room...

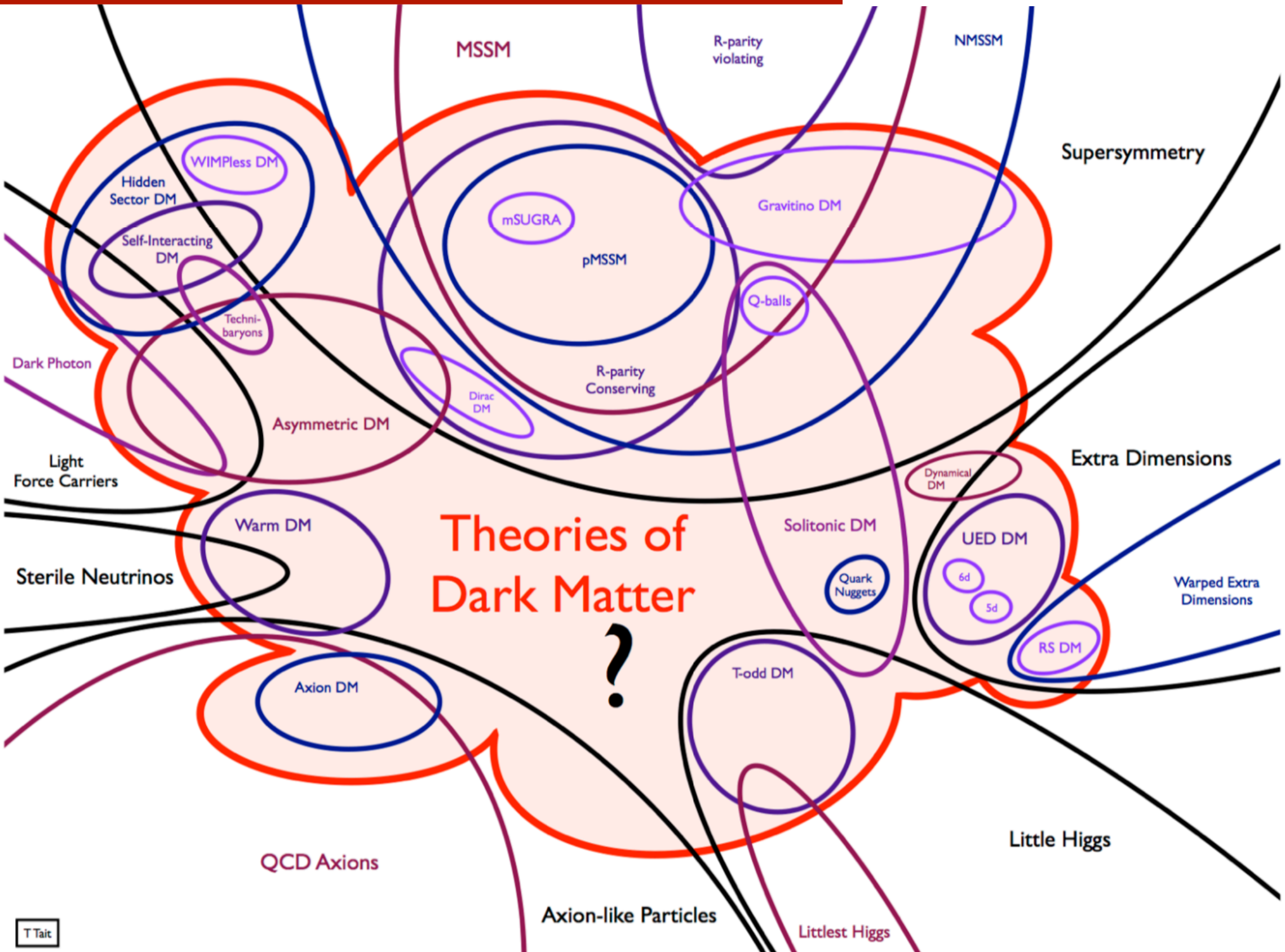
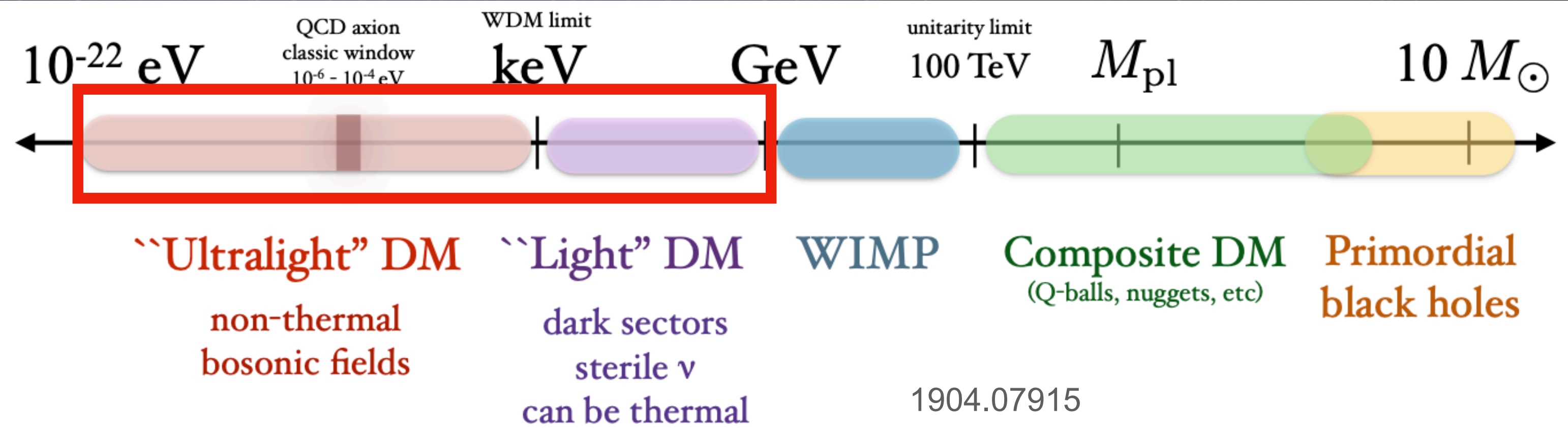
...so what is the nature of dark matter?

Particle dark matter:
huge model space



...so what is the nature of dark matter?

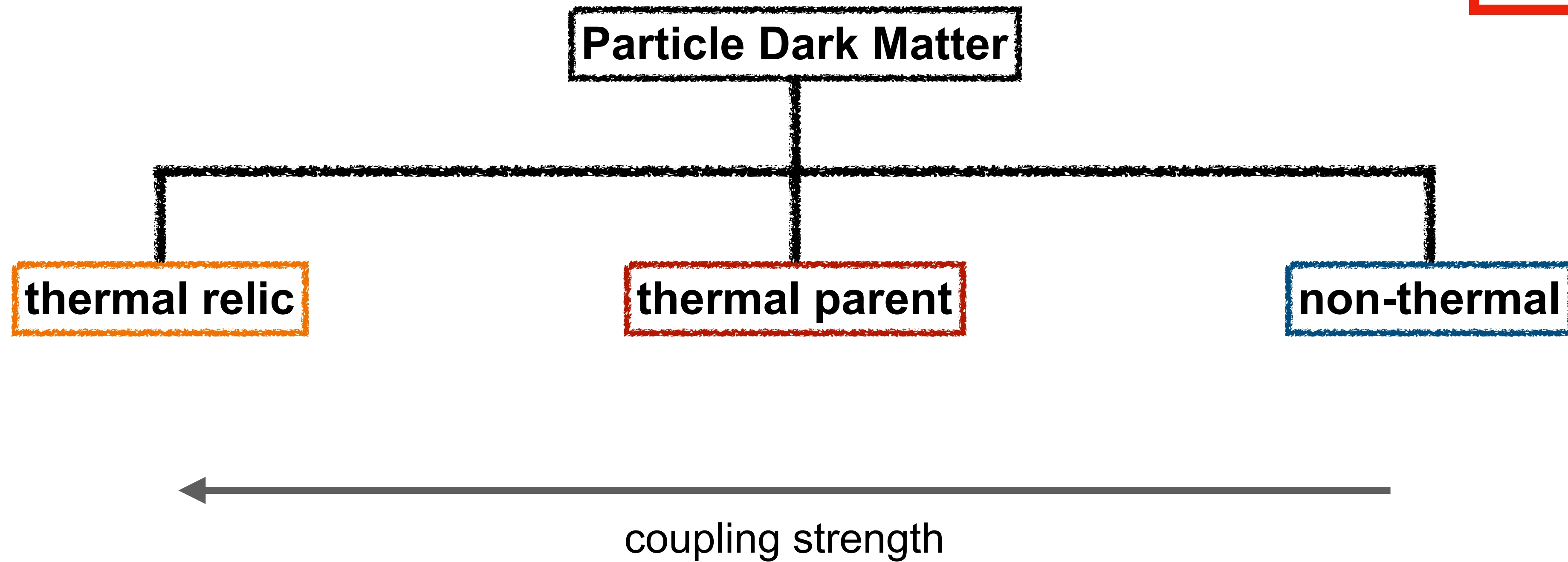
Particle dark matter:
huge model space



today: Light particle dark matter

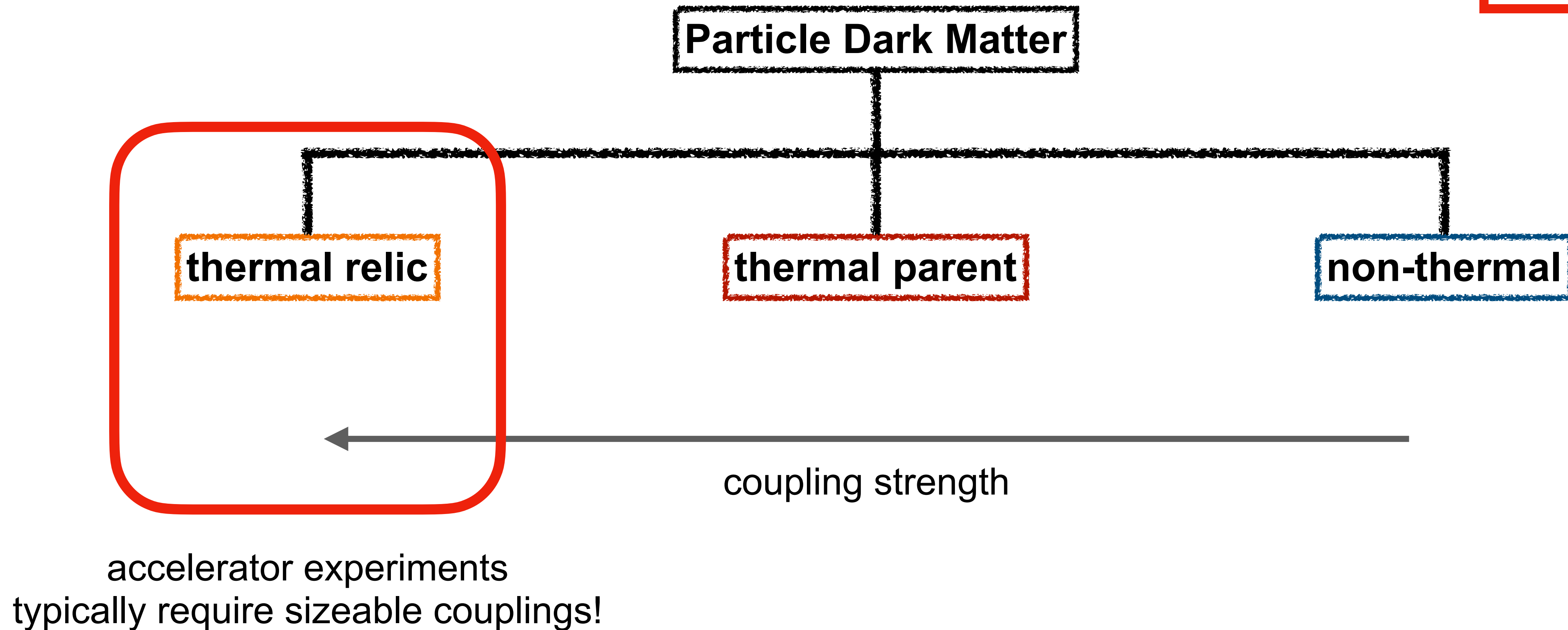
How has Dark Matter been produced?

Patrick's talk

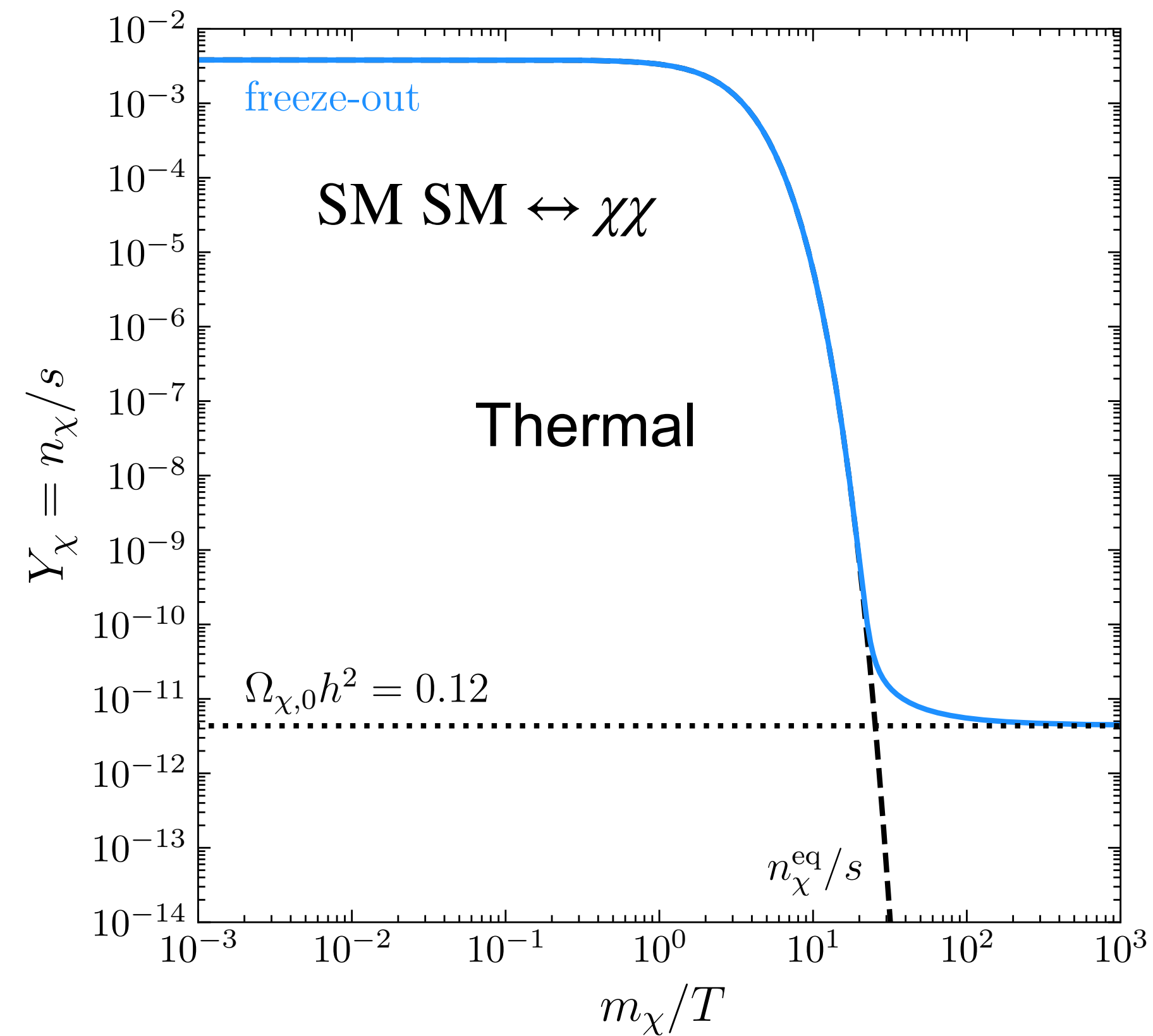


How has Dark Matter been produced?

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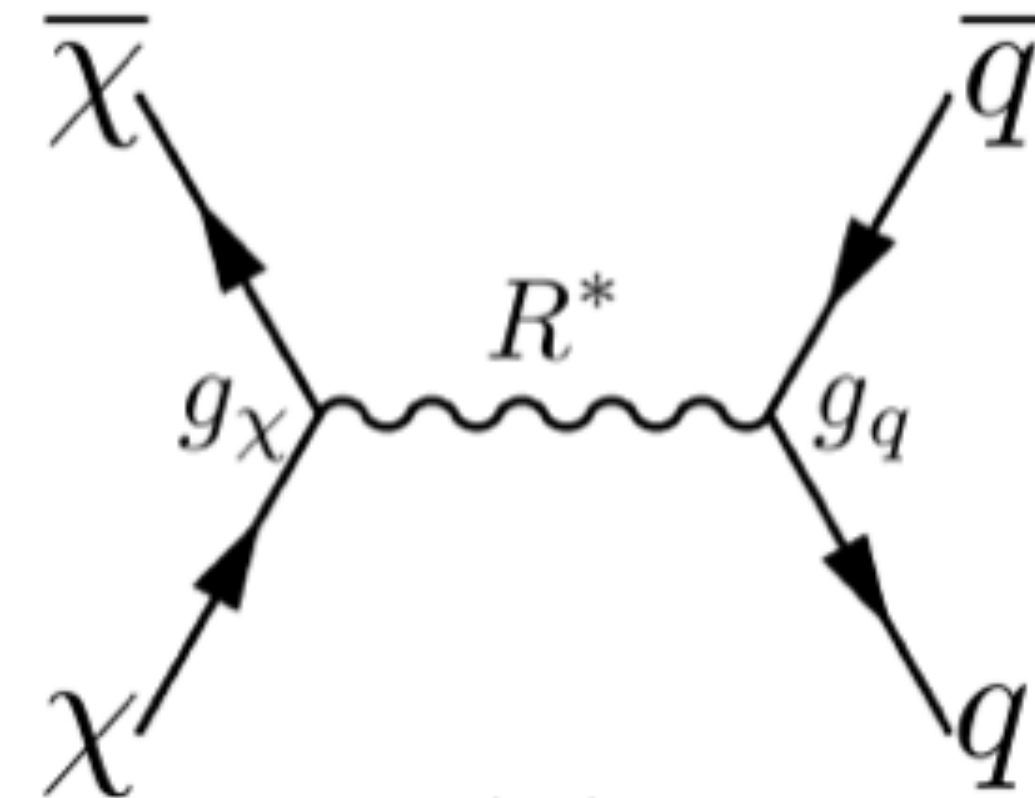


Thermal freeze out

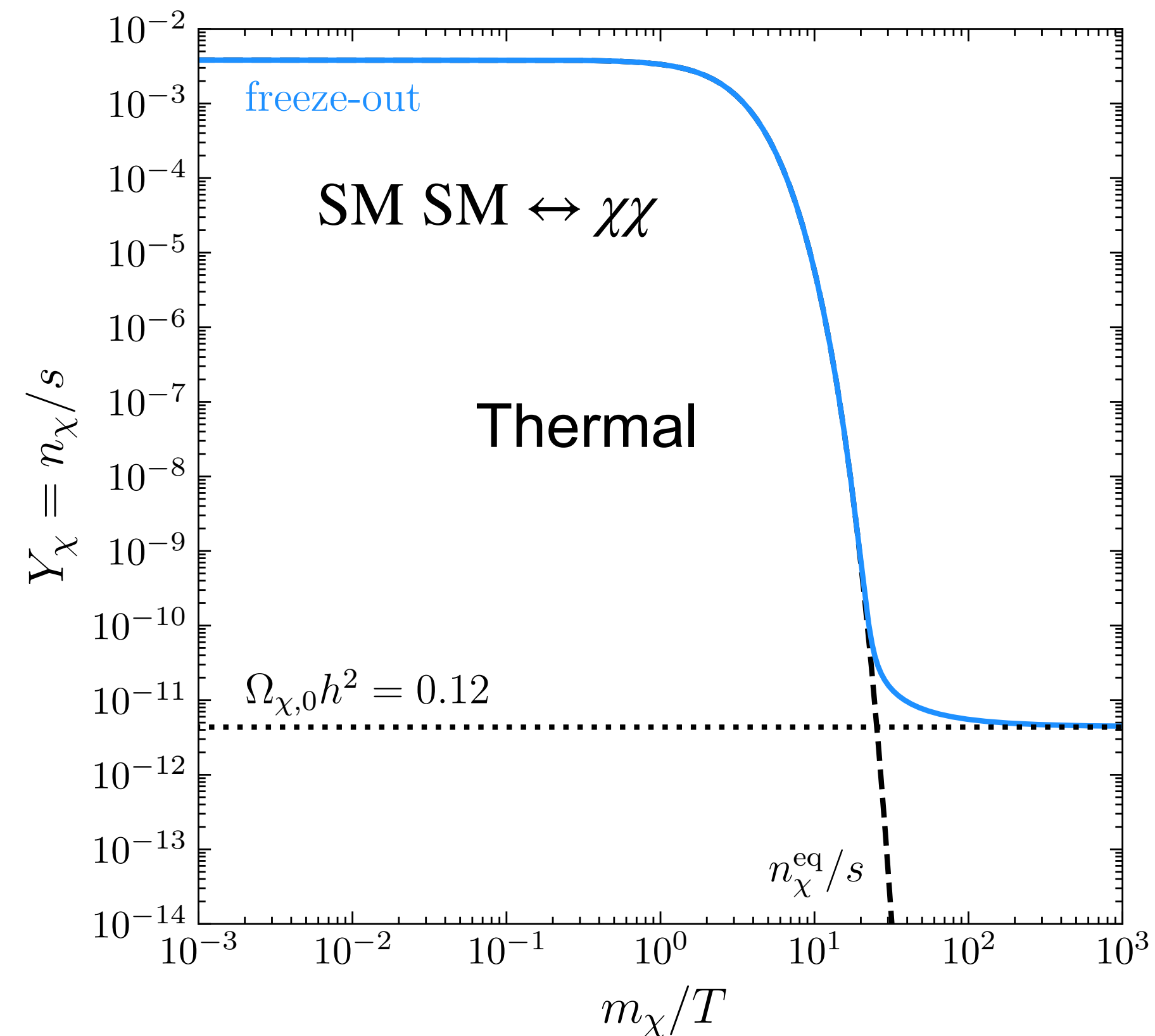


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle (n_\chi^2 - n_{\chi,\text{eq}}^2)$$

1. assume dark matter χ in thermal equilibrium $\chi\chi \rightleftharpoons SM\ SM$
2. Universe cools $\chi\chi \rightarrow SM\ SM$
3. Universe expands $\chi\chi \nrightarrow SM\ SM$



Thermal freeze out



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,\text{eq}}^2)$$

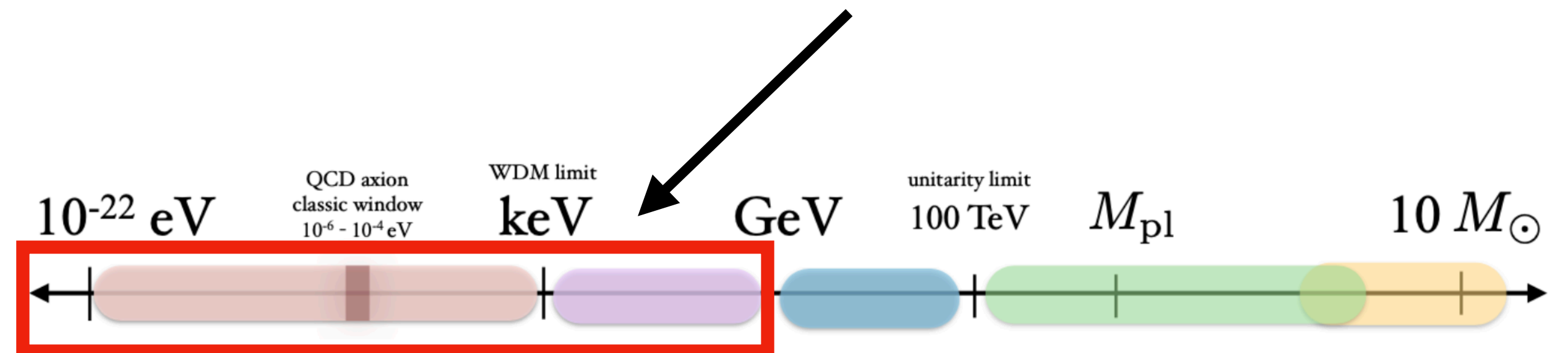
1. assume dark matter χ in thermal equilibrium $\chi\chi \rightleftharpoons SM\ SM$
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Required annihilation cross section?

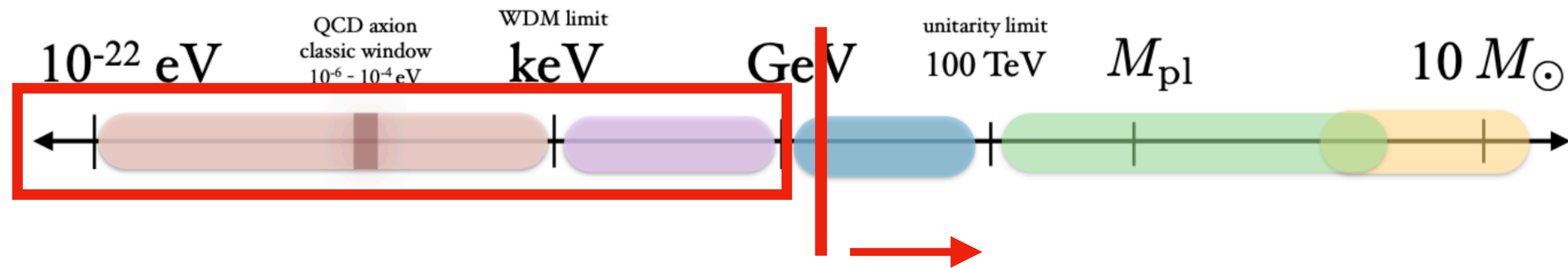
$$\langle\sigma v\rangle \simeq 10^{-26} \frac{\text{cm}^3}{\text{s}}$$

Typical for WEAK interactions and mass $\rightarrow$ WIMP miracle

here: aiming for light (sub-GeV) dark matter



Allowed mass range?

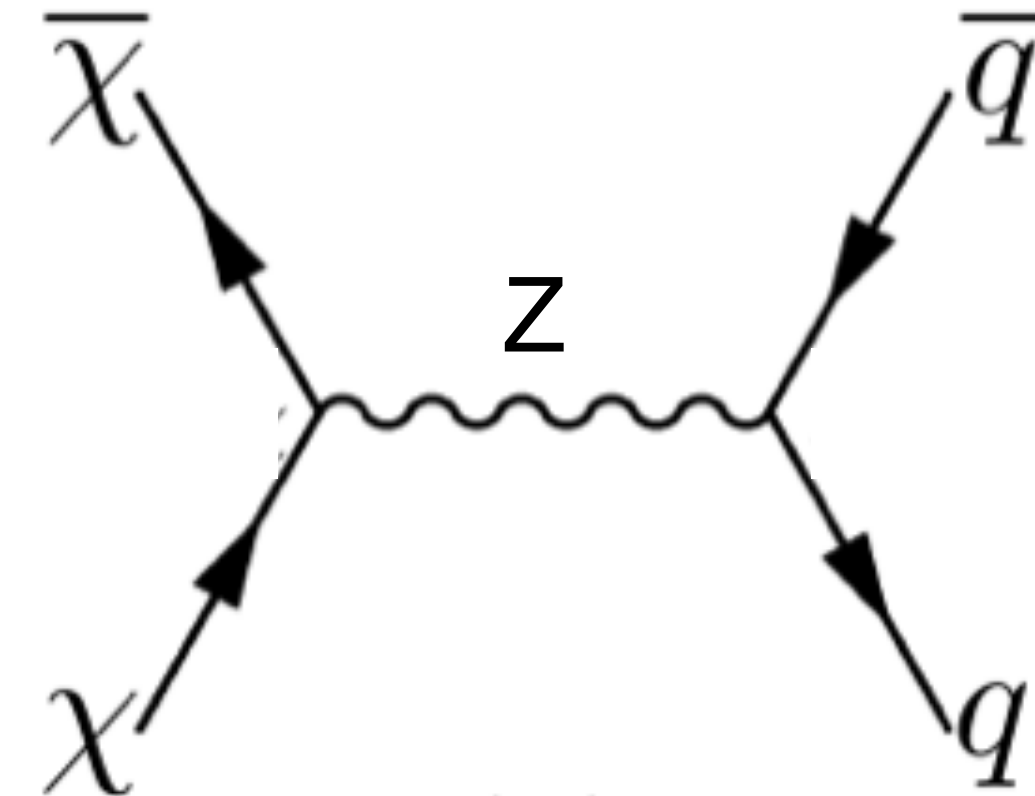


Lee-Weinberg bound

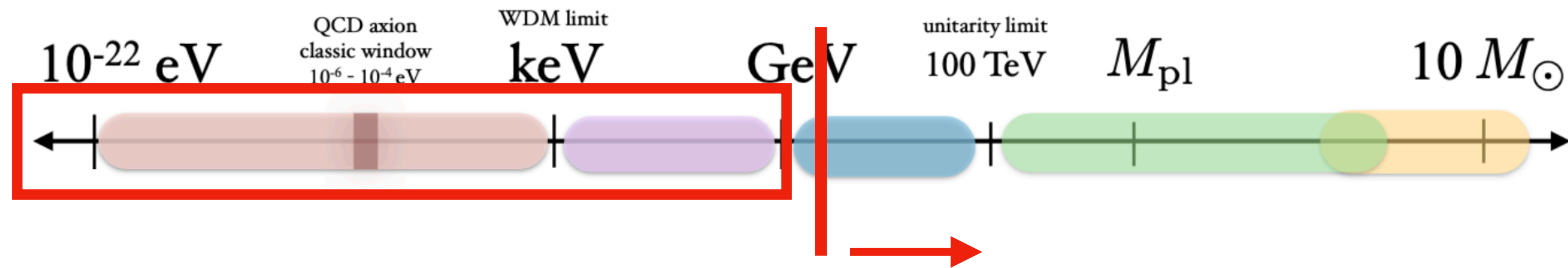
assume: Weak (W,Z) interactions

too much dark matter unless $m_\chi \gtrsim 5 \text{ GeV}$

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4}$$



Allowed mass range?

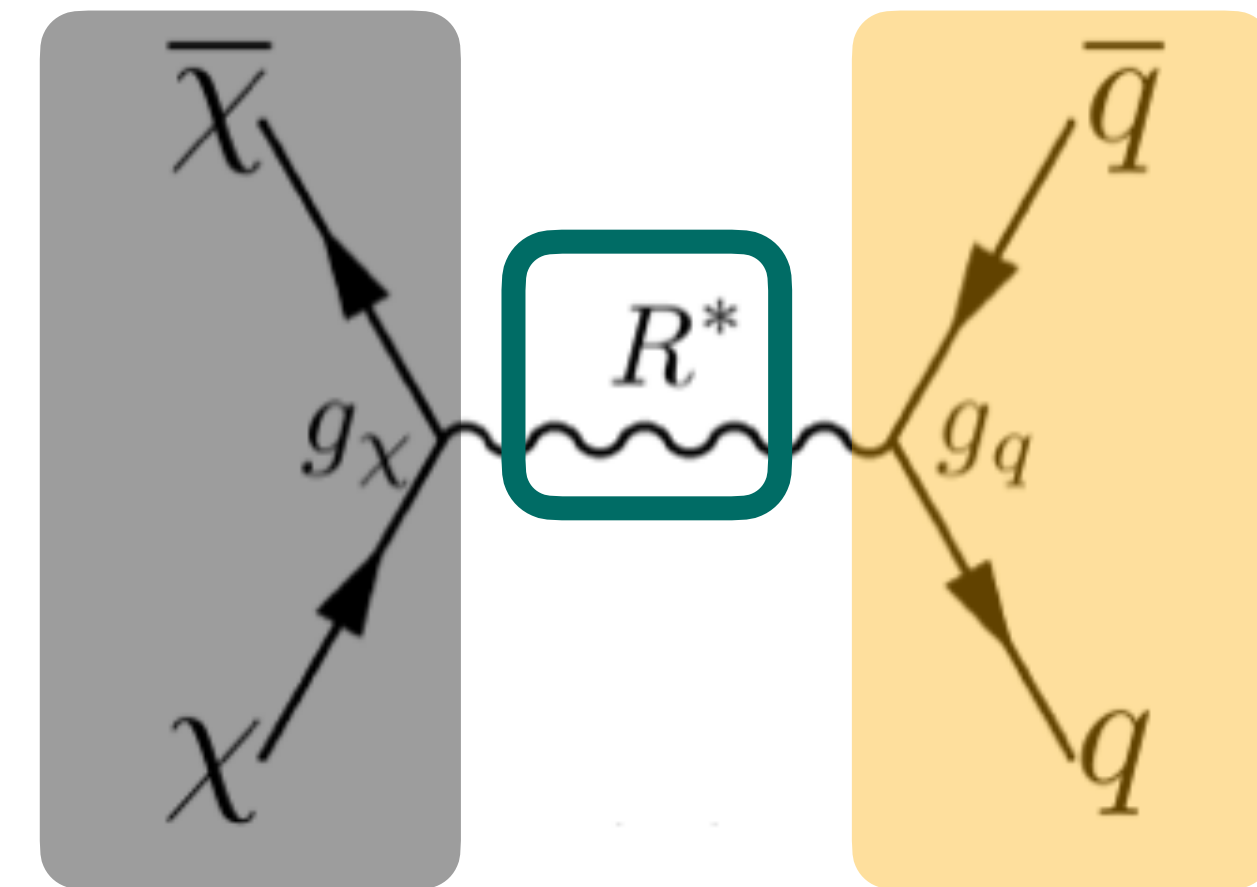


Lee-Weinberg bound

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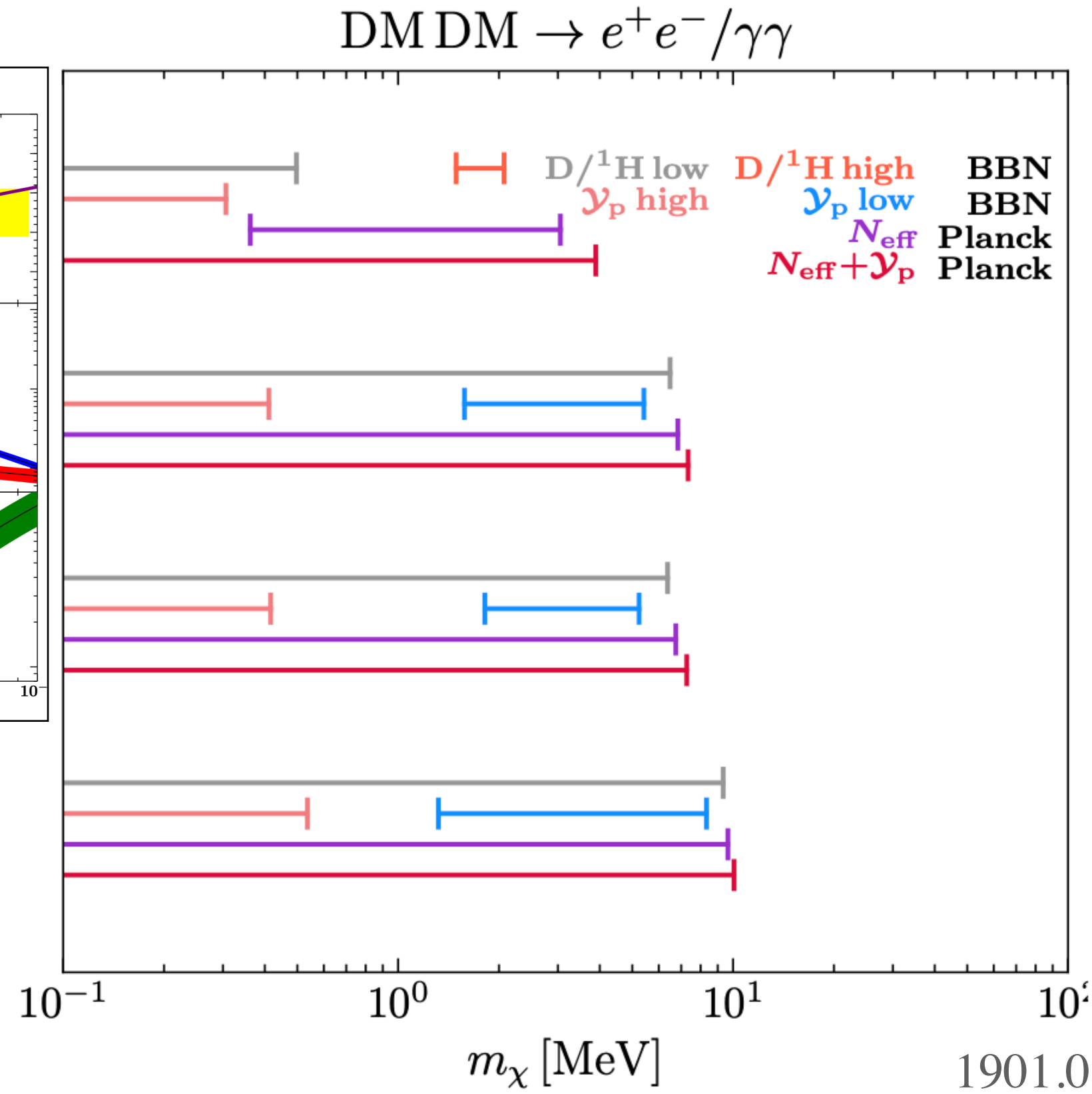
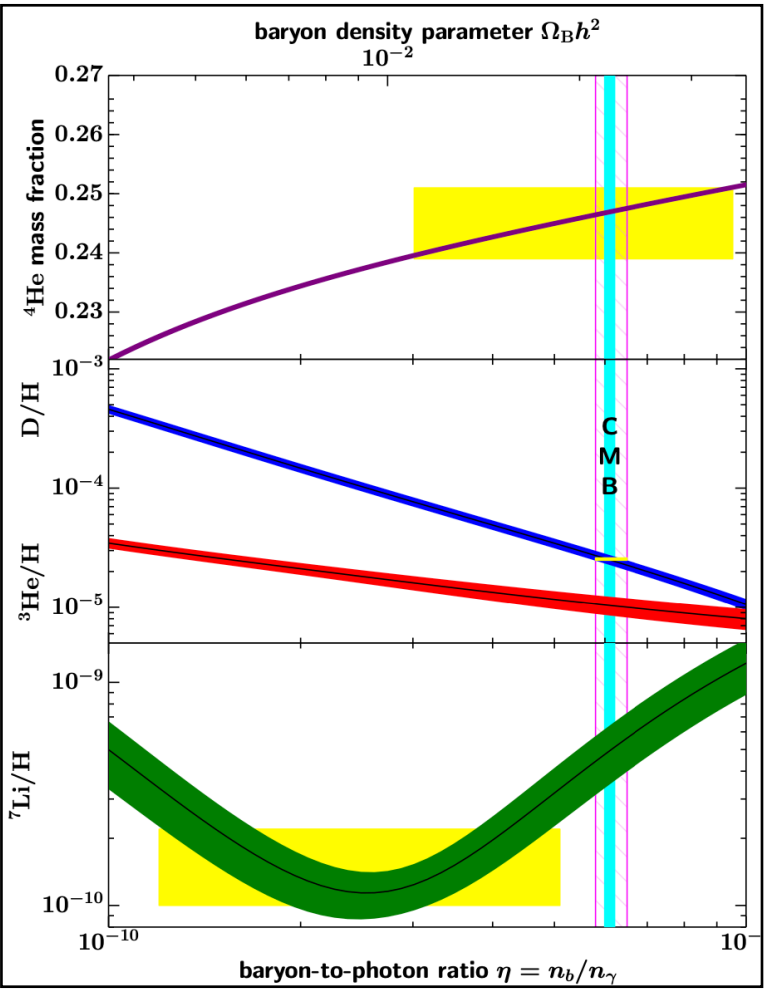
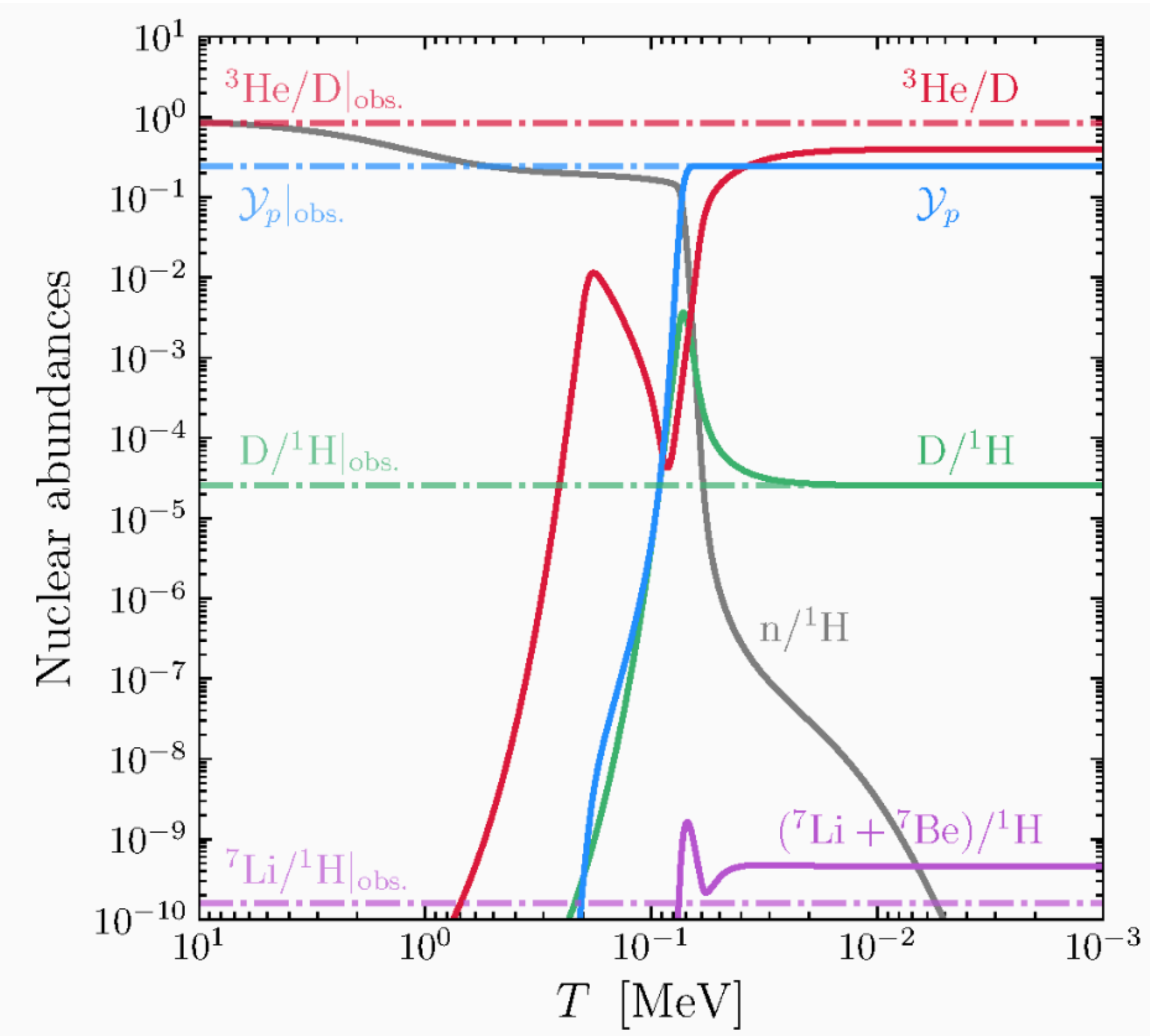
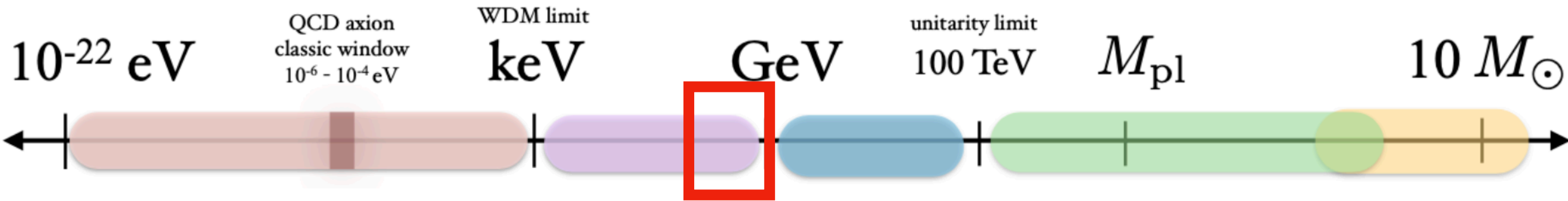
too much dark matter unless $m_{\chi} \gtrsim 5 \text{ GeV}$

need new **mediators** to obtain correct relic for light DM!



Hidden sector!

Allowed mass range?

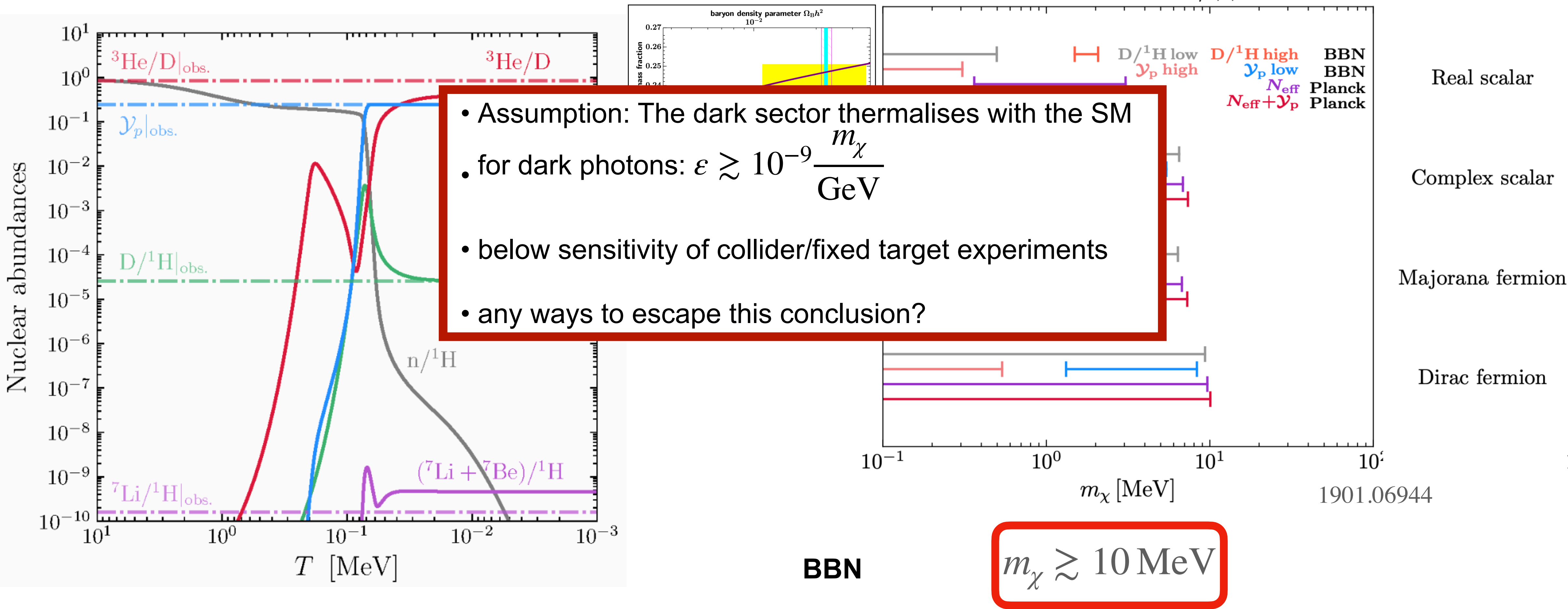
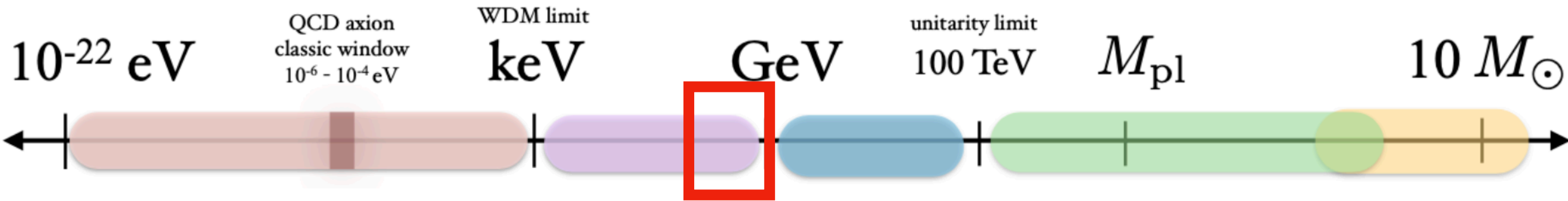


BBN

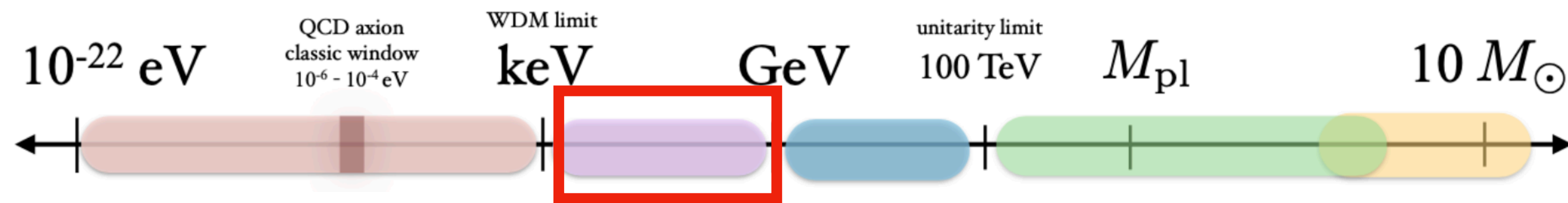
$$m_\chi \gtrsim 10 \text{ MeV}$$

1901.06944

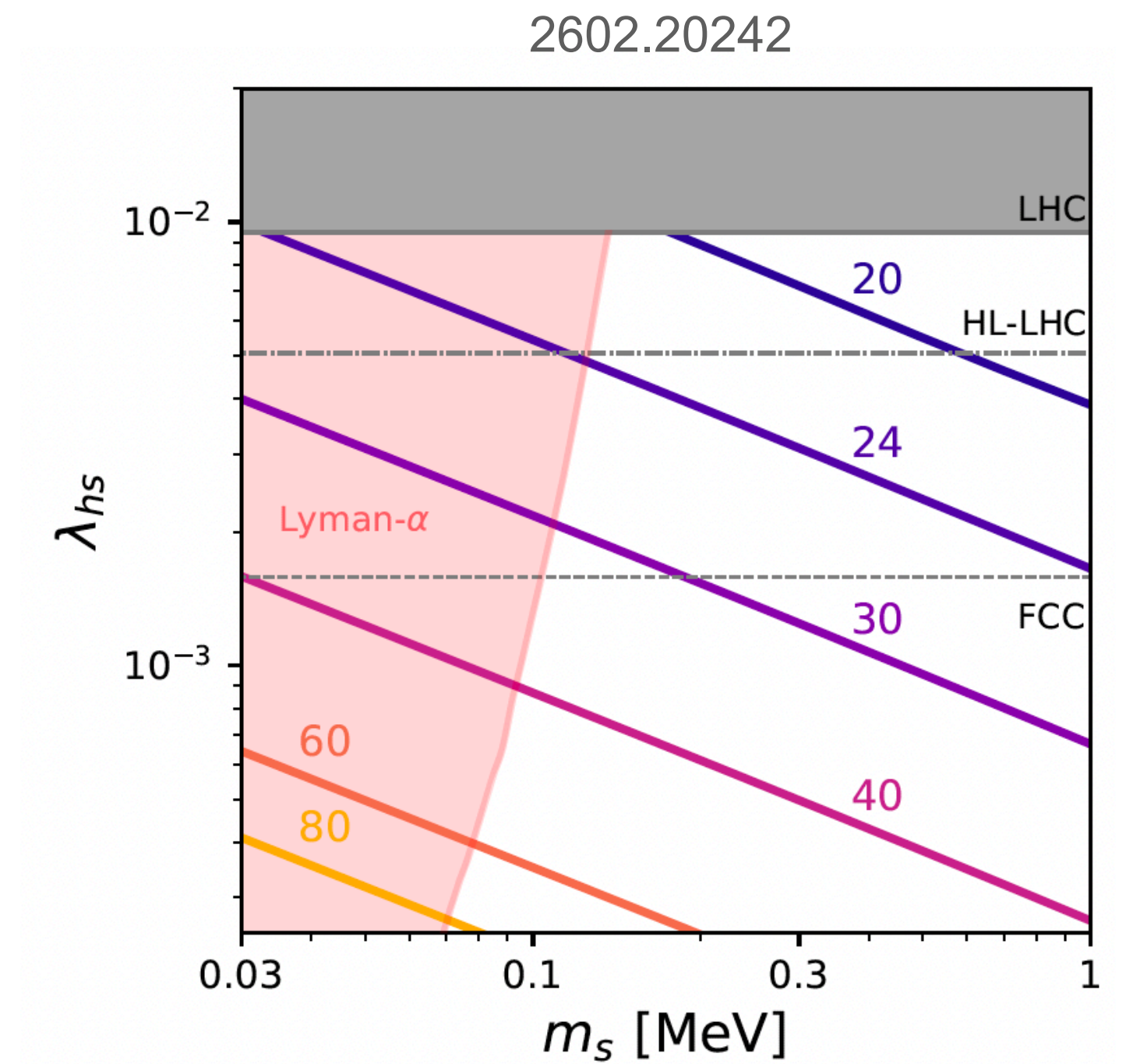
Allowed mass range?



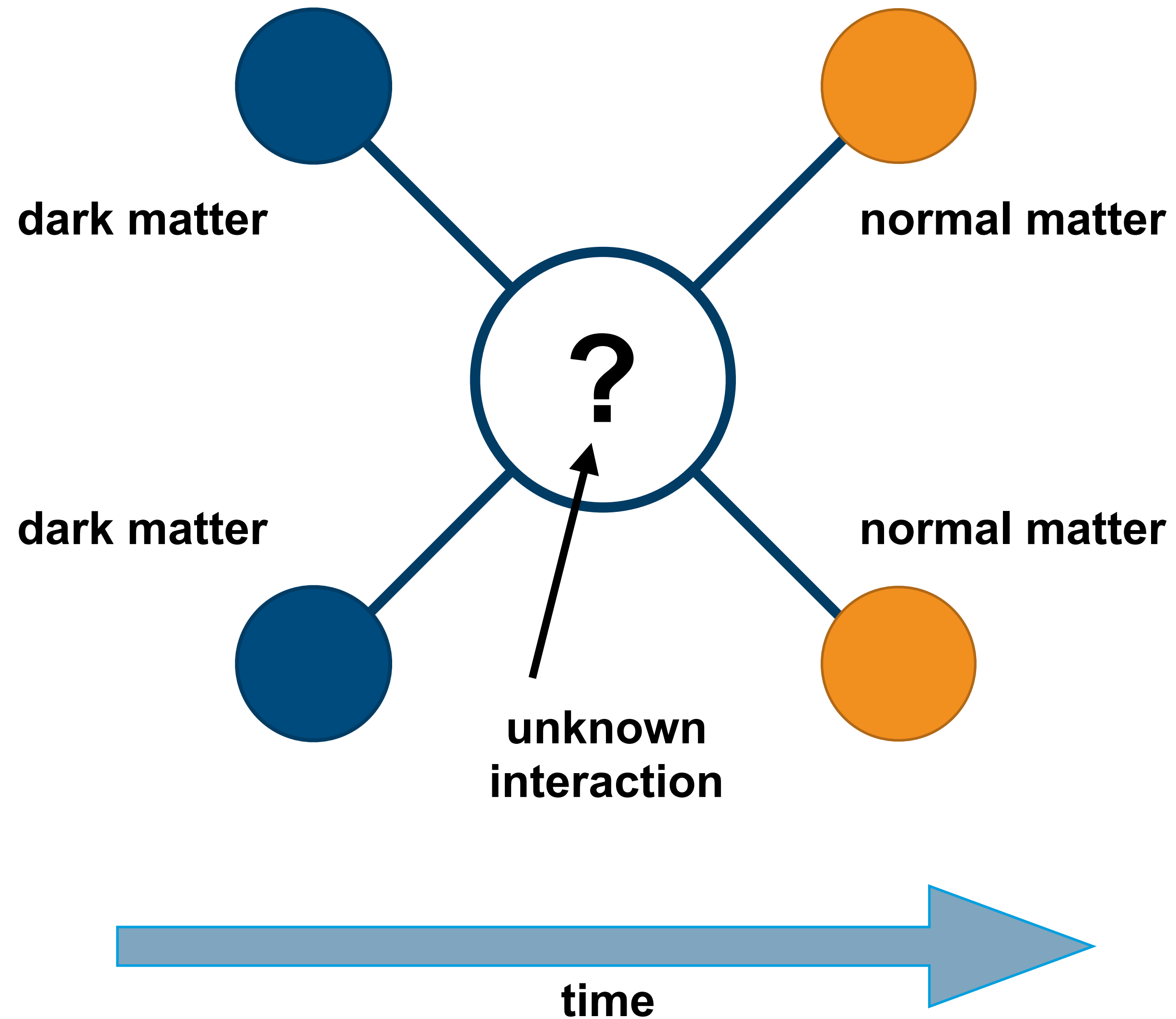
Low reheat temperature



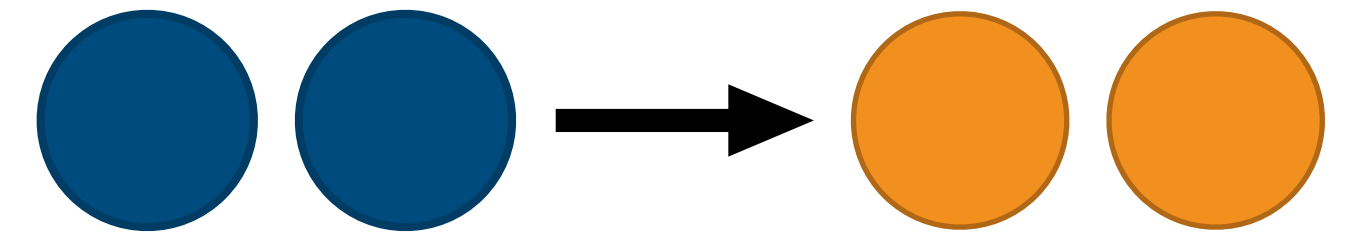
- From BBN we know that the early universe had temperature $T_R \gtrsim 5 \text{ MeV}$
- Difficult to dynamically generate baryon asymmetry (but may be possible)
- For $T_R \lesssim m_{\text{DS}}$ no full thermalisation
- ‘Freeze-in at stronger coupling’ 2306.13061
- Typically warm dark matter bound applies, $m_{\chi} \gtrsim 10 \text{ keV}$



Indirect searches

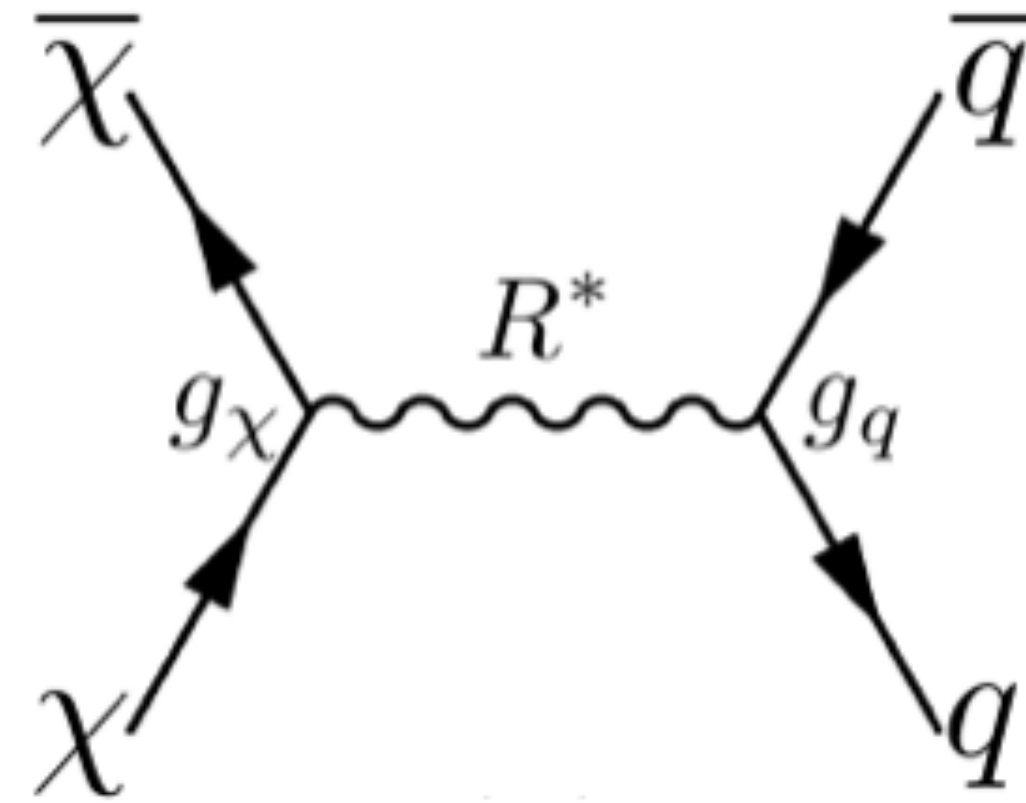


annihilation

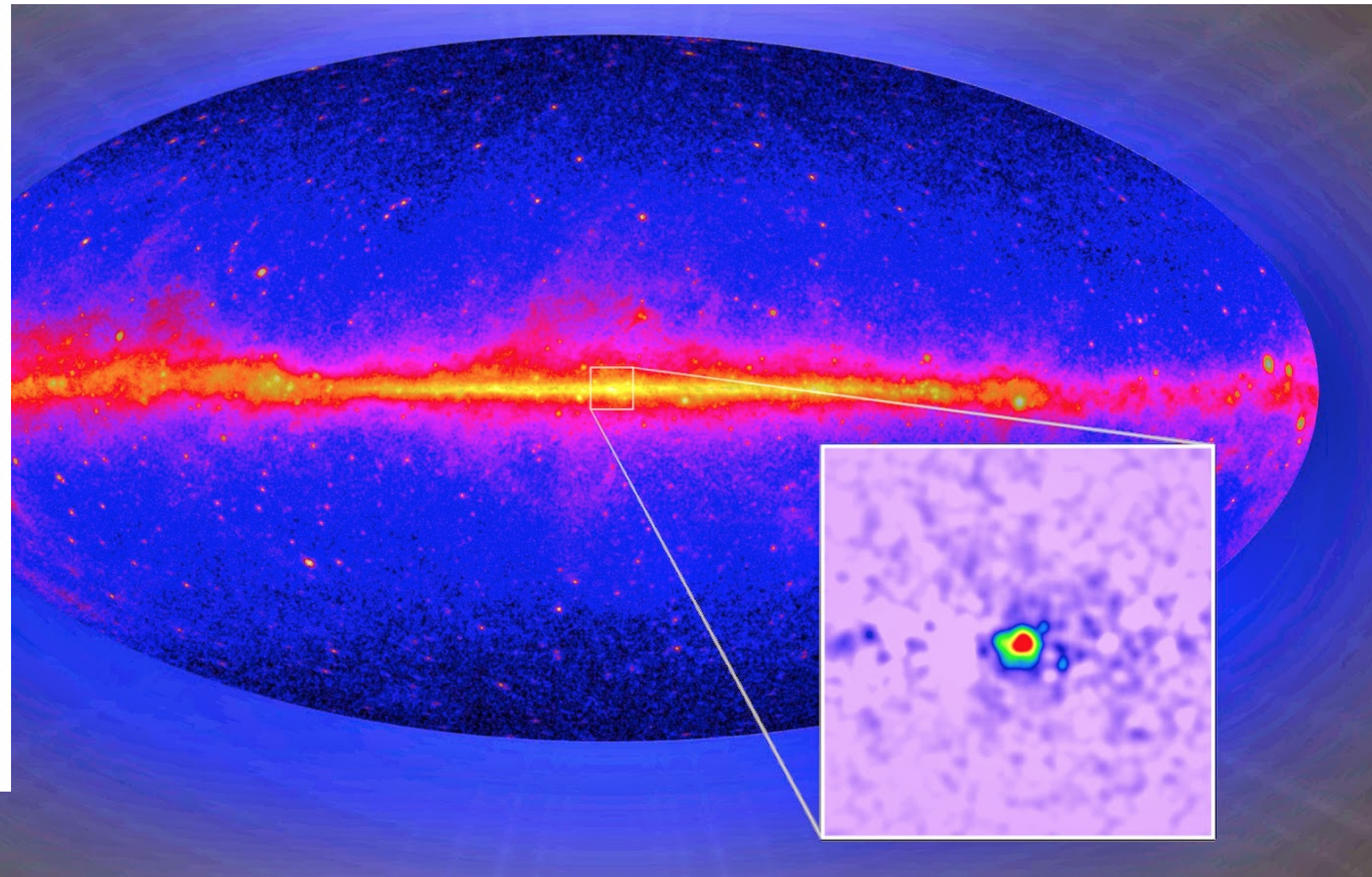
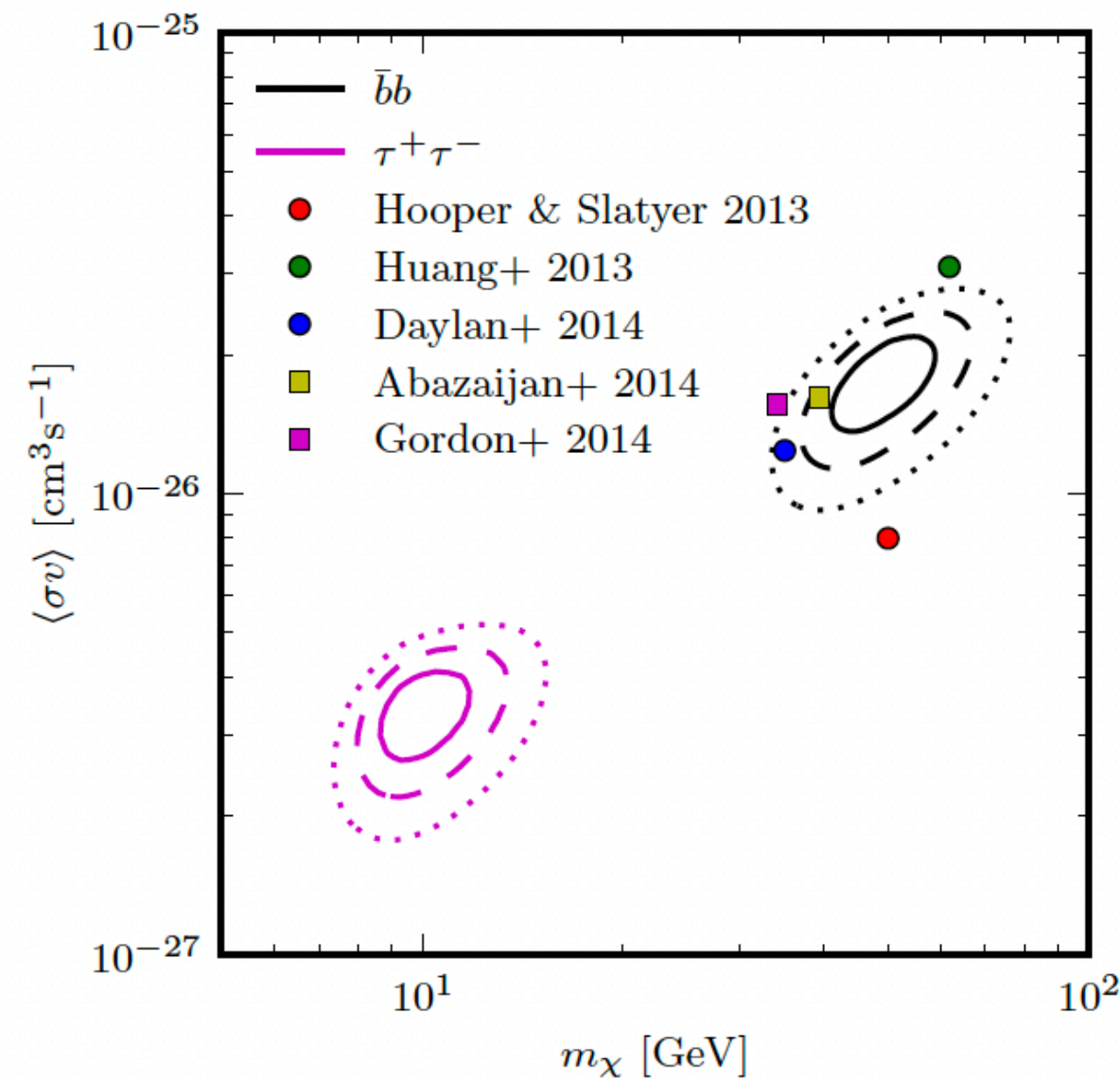
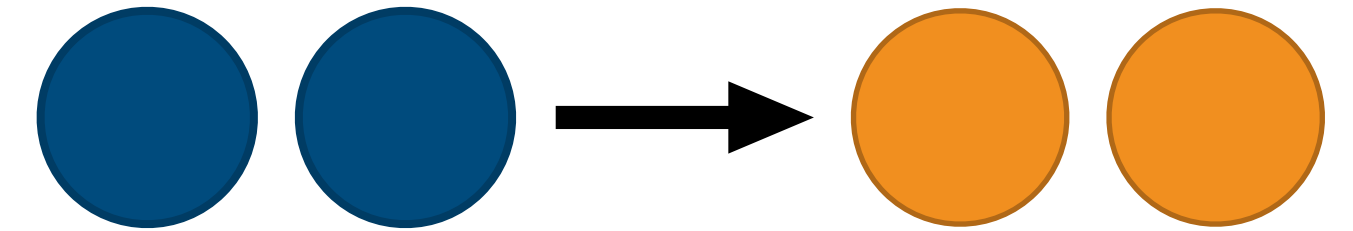


Indirect searches

- Searches with satellites for annihilation signal e.g. from the Galactic centre.
- there are some excesses, but hard to discriminate from astrophysical backgrounds...

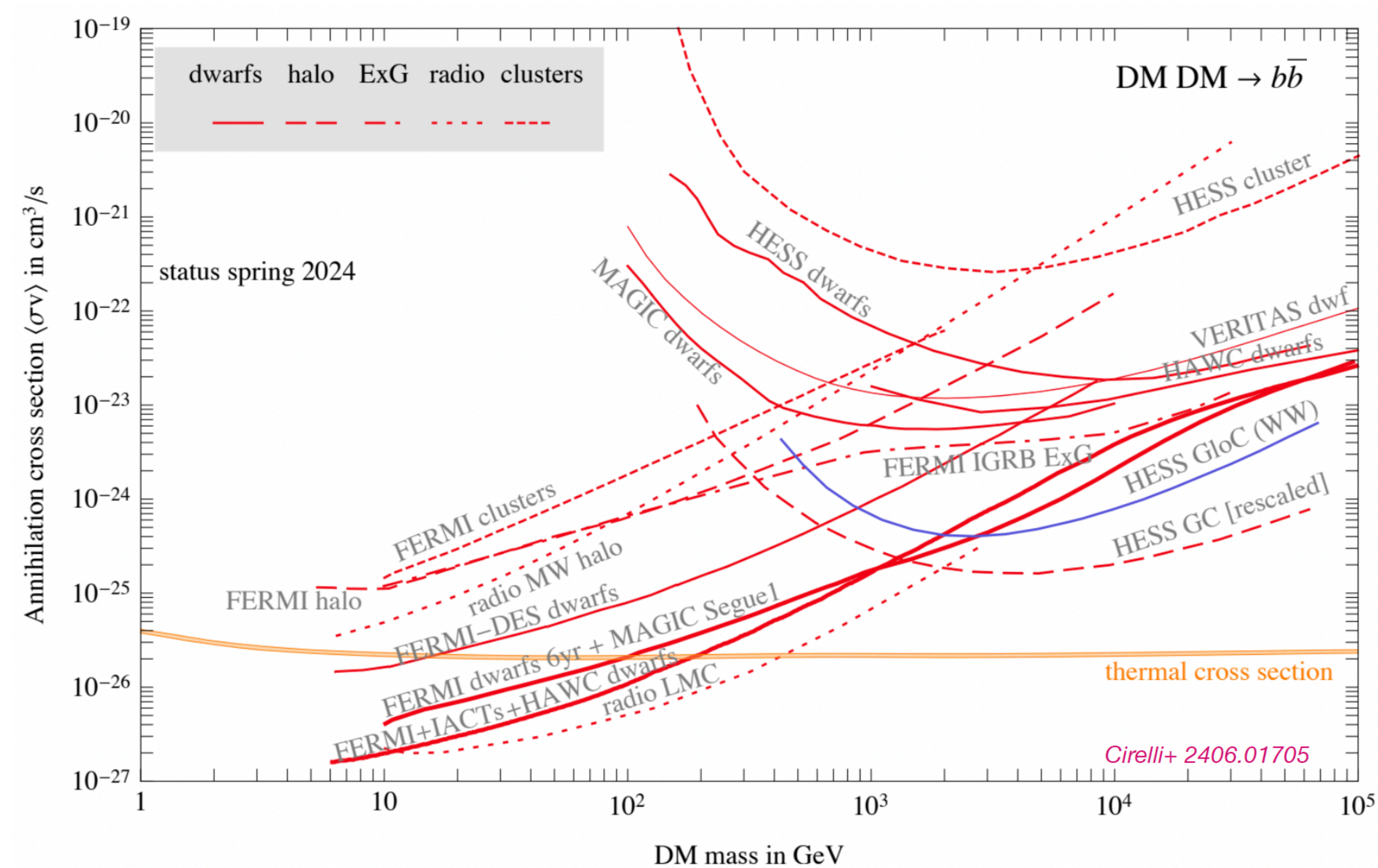


annihilation

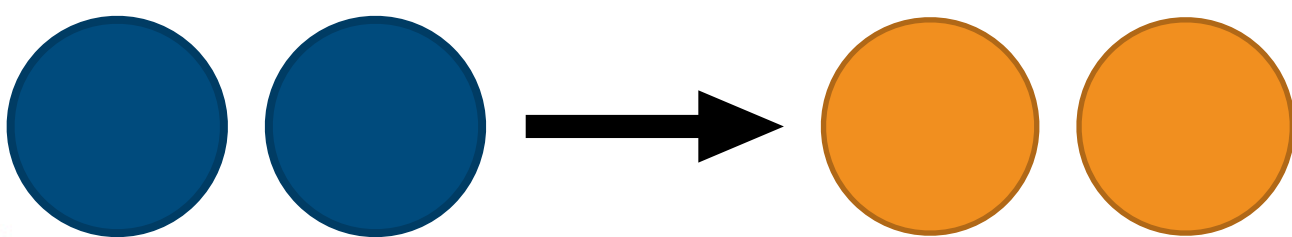


Indirect searches

- Current limits

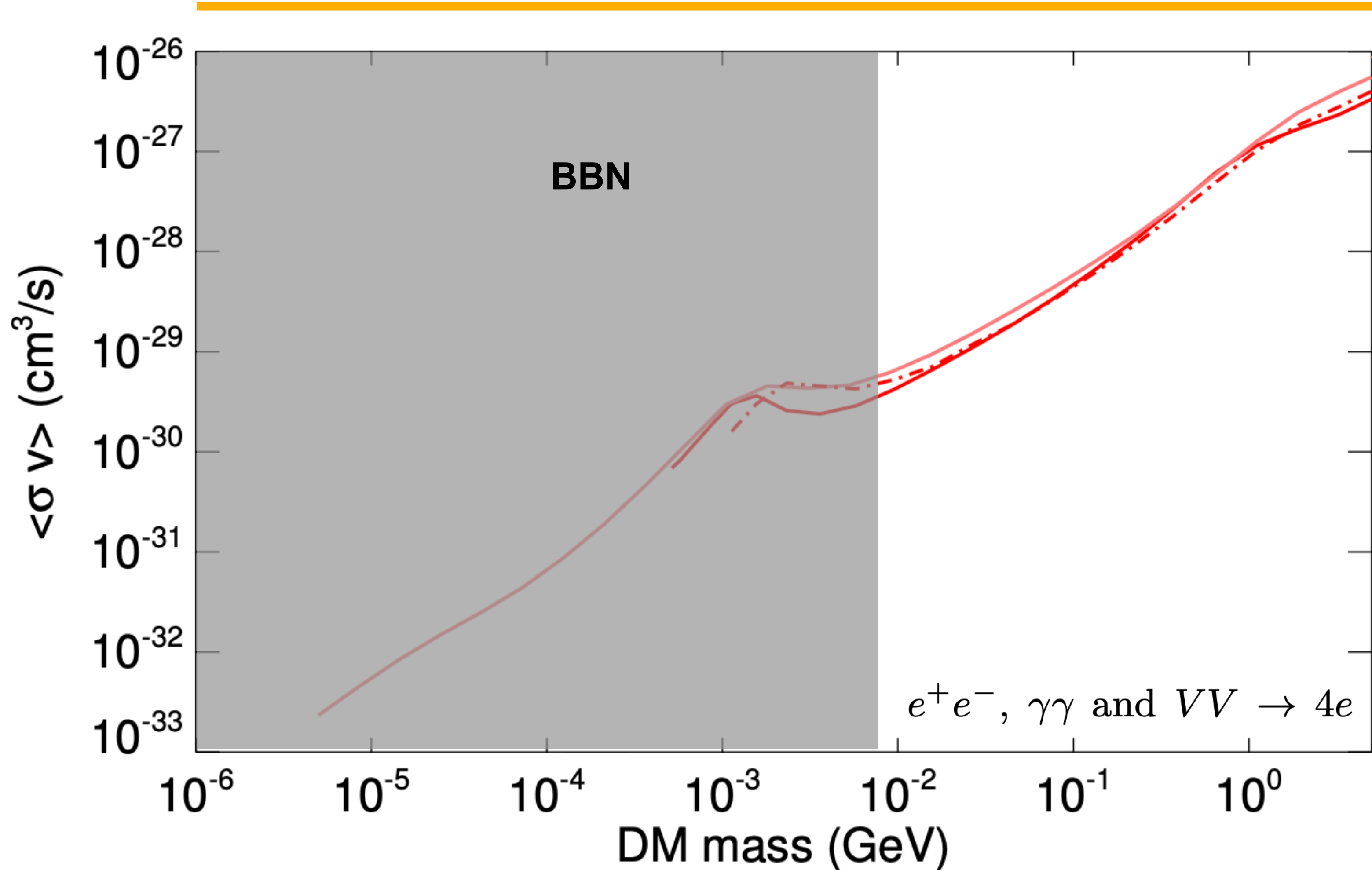
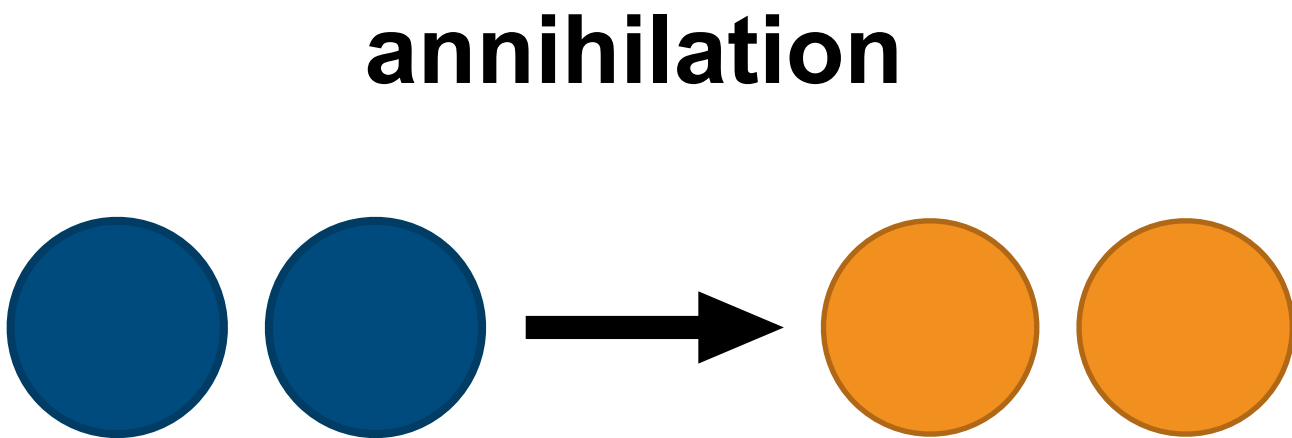
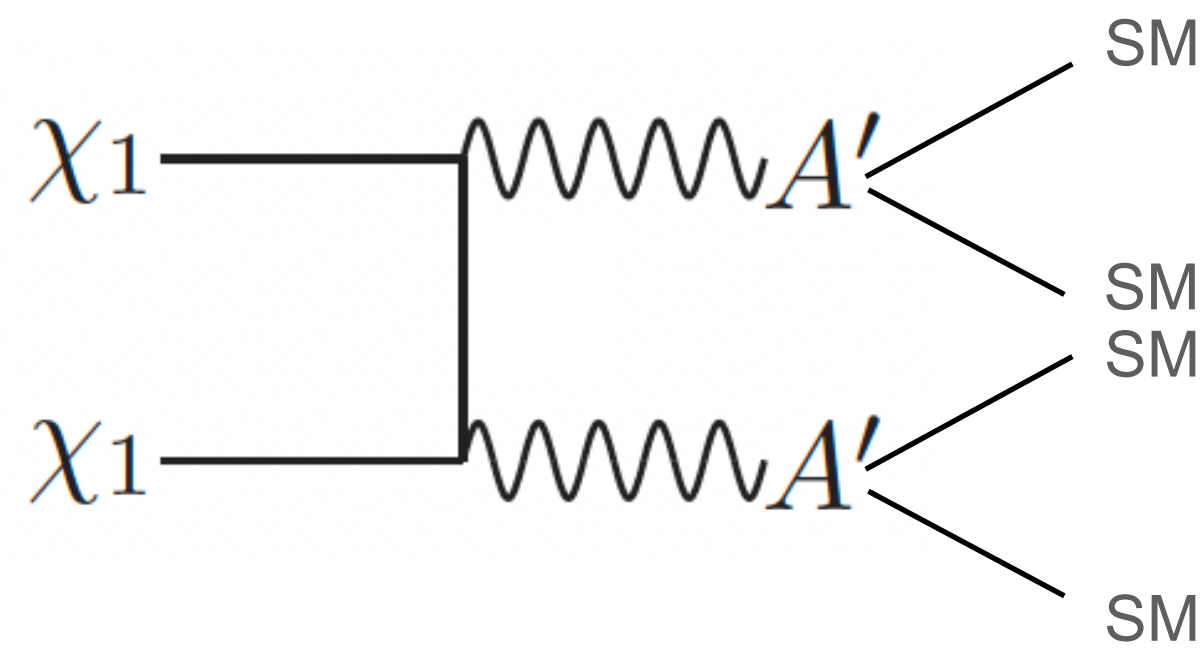


annihilation

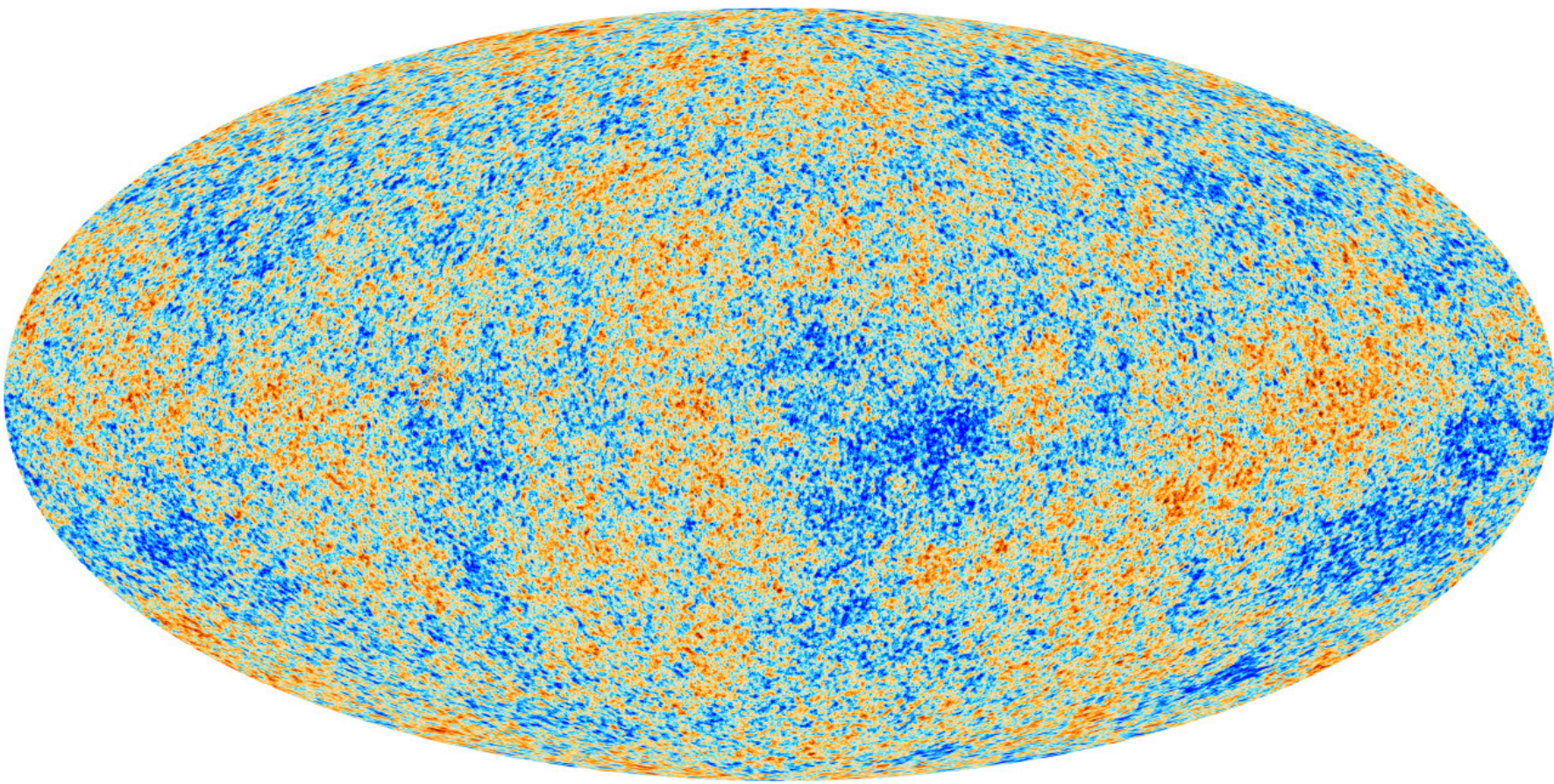


Indirect searches

- Current limits



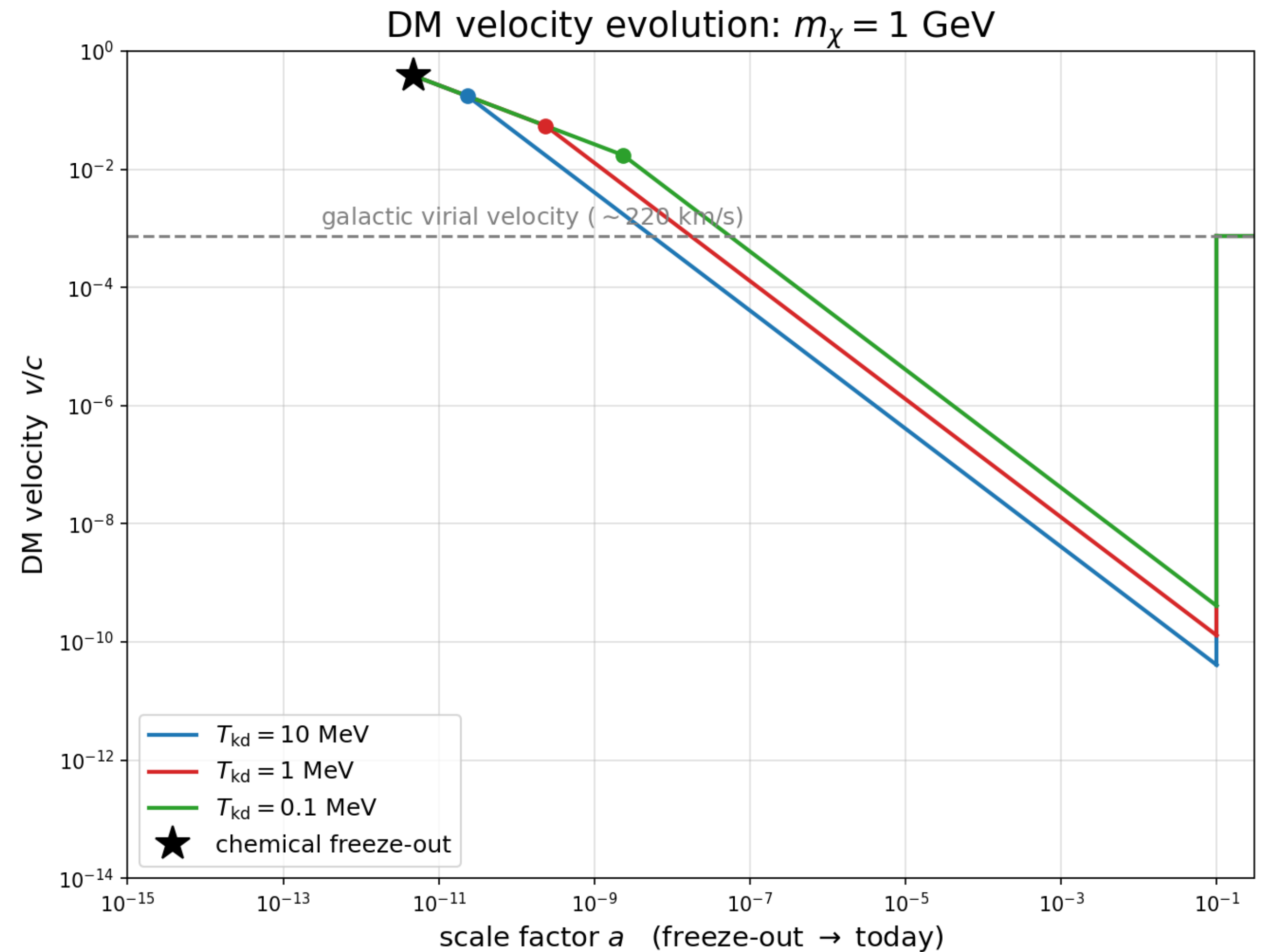
electromagnetic energy injection can re-ionise neutral atoms and thereby affect the CMB



Velocity dependence of annihilation

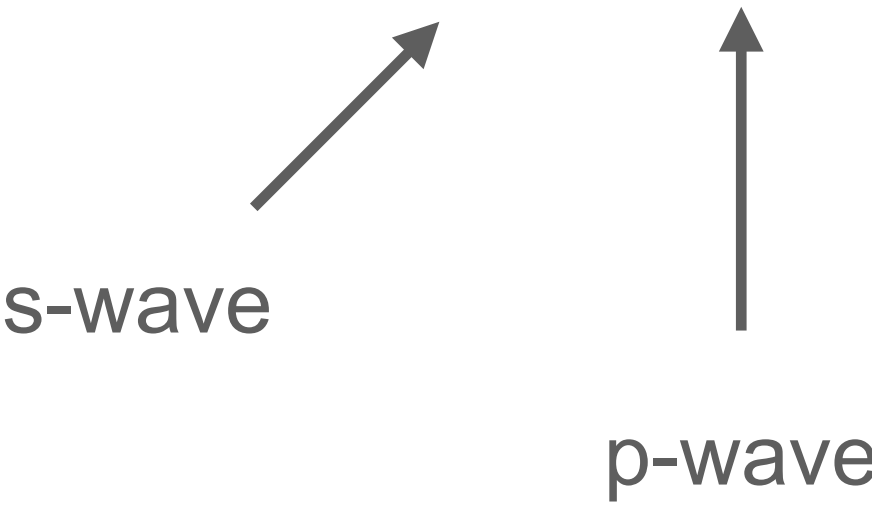
- Freeze-out happens at temperature close to the mass
→ relativistic
- velocities decrease subsequently
- constraints/observations typically at much smaller velocities,
- virialised halo $v \simeq 10^{-4} - 10^{-3}$
- CMB $v \simeq 10^{-8}$
- Need not be the same cross section!

depends on underlying particle physics model!



Suppression of annihilation signals for light DM

- velocity suppression (p-wave)

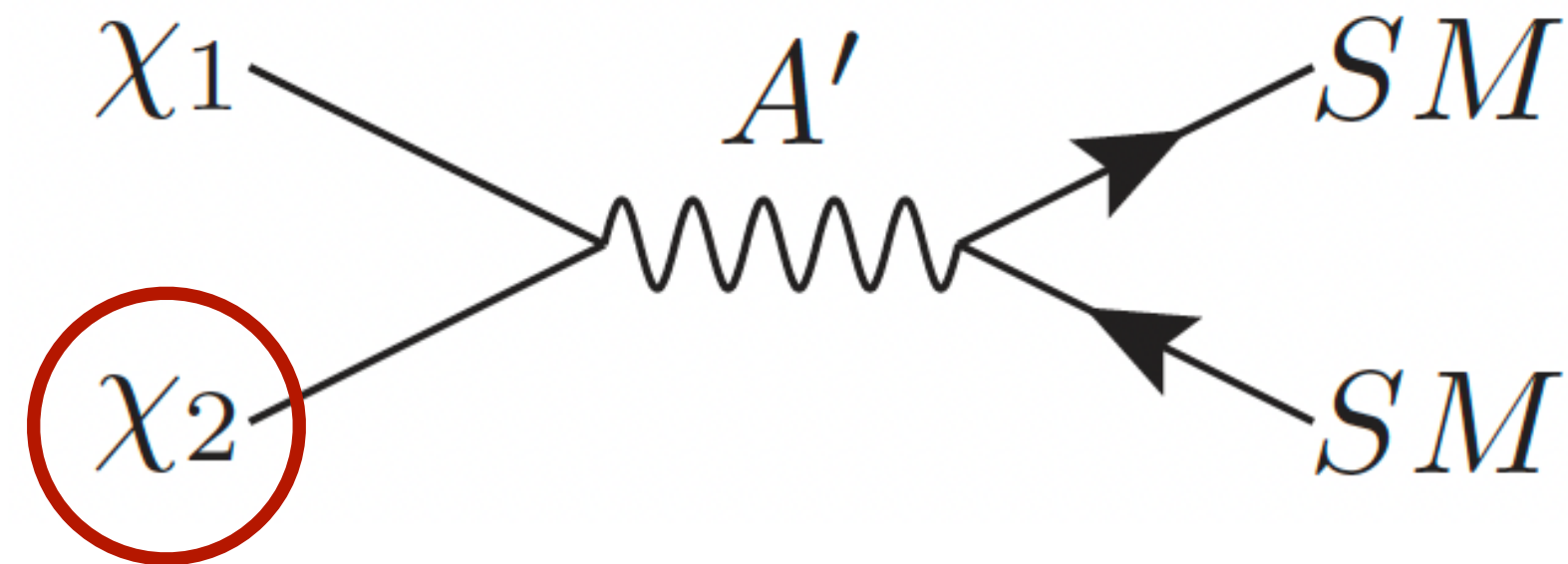
$$\langle \sigma v \rangle \simeq a + bv^2 + \mathcal{O}(v^4)$$


s-wave

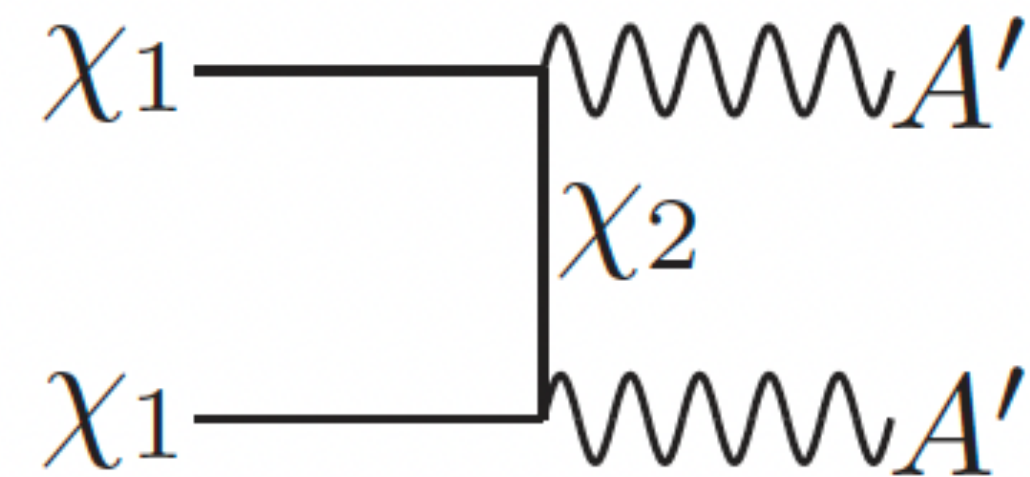
p-wave

Suppression of annihilation signals for light DM

- velocity suppression (p-wave) ✓
- inelastic DM



decays, no longer present at late times



(but does not need to be suppressed for light mediators)

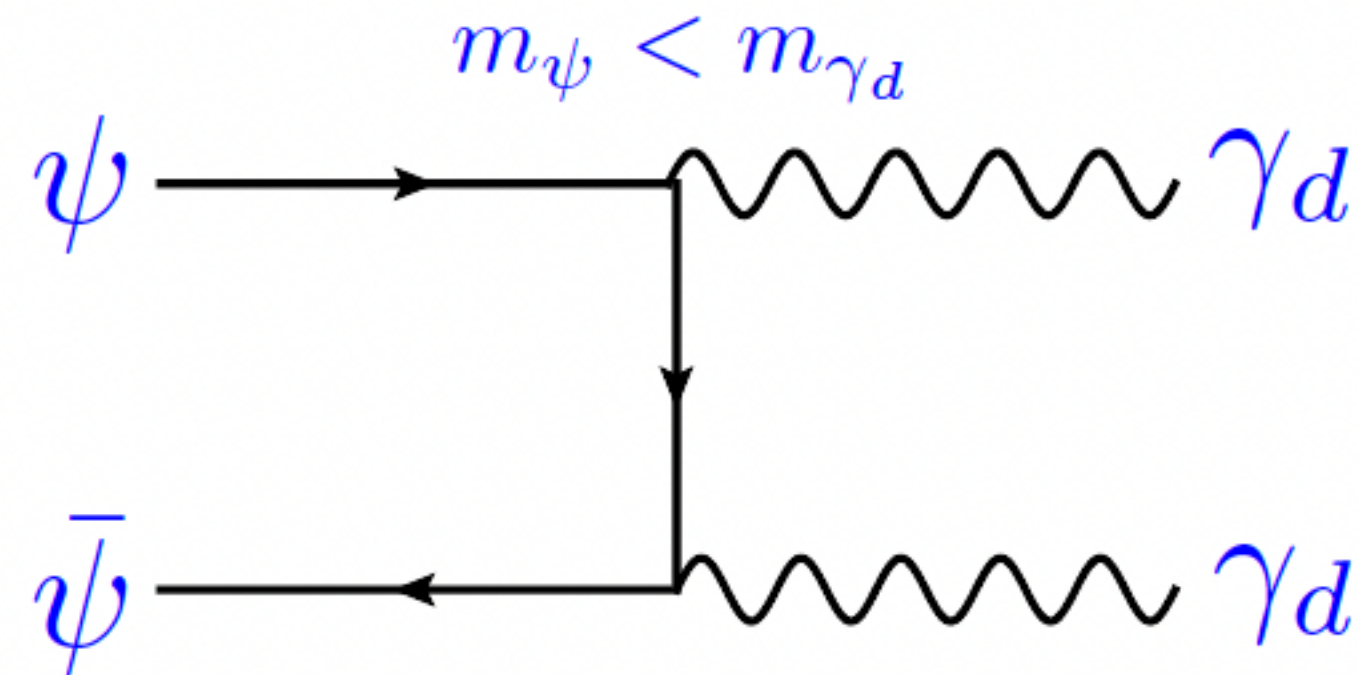
Suppression of annihilation signals for light DM

- velocity suppression (p-wave)
- inelastic DM
- Forbidden DM



1505.07107

1) forbidden annihilations:



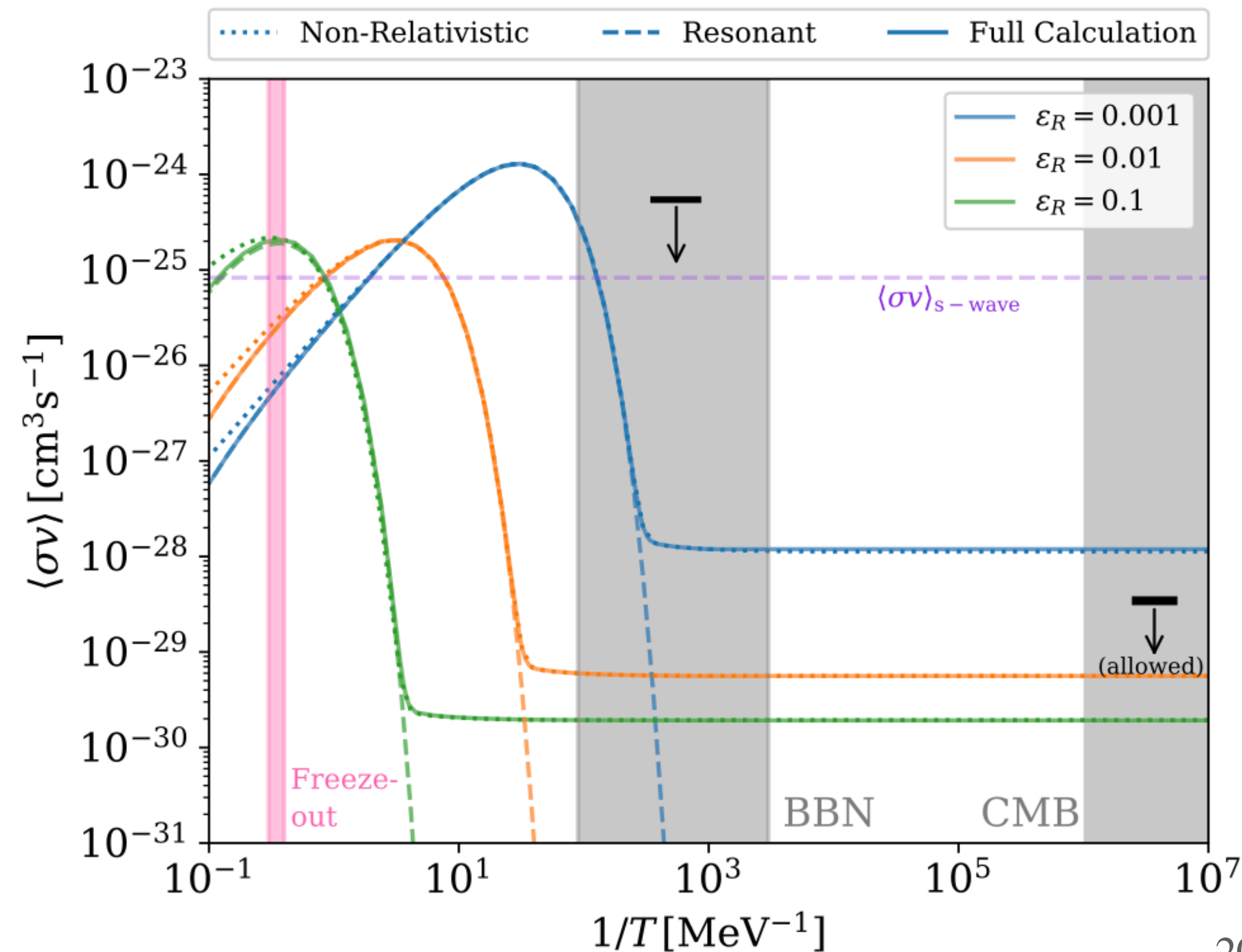
kinetic energy only sufficient for large velocities

Suppression of annihilation signals for light DM

- velocity suppression (p-wave)
- inelastic DM
- Forbidden DM
- resonance at freeze-out



$$\epsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2}$$

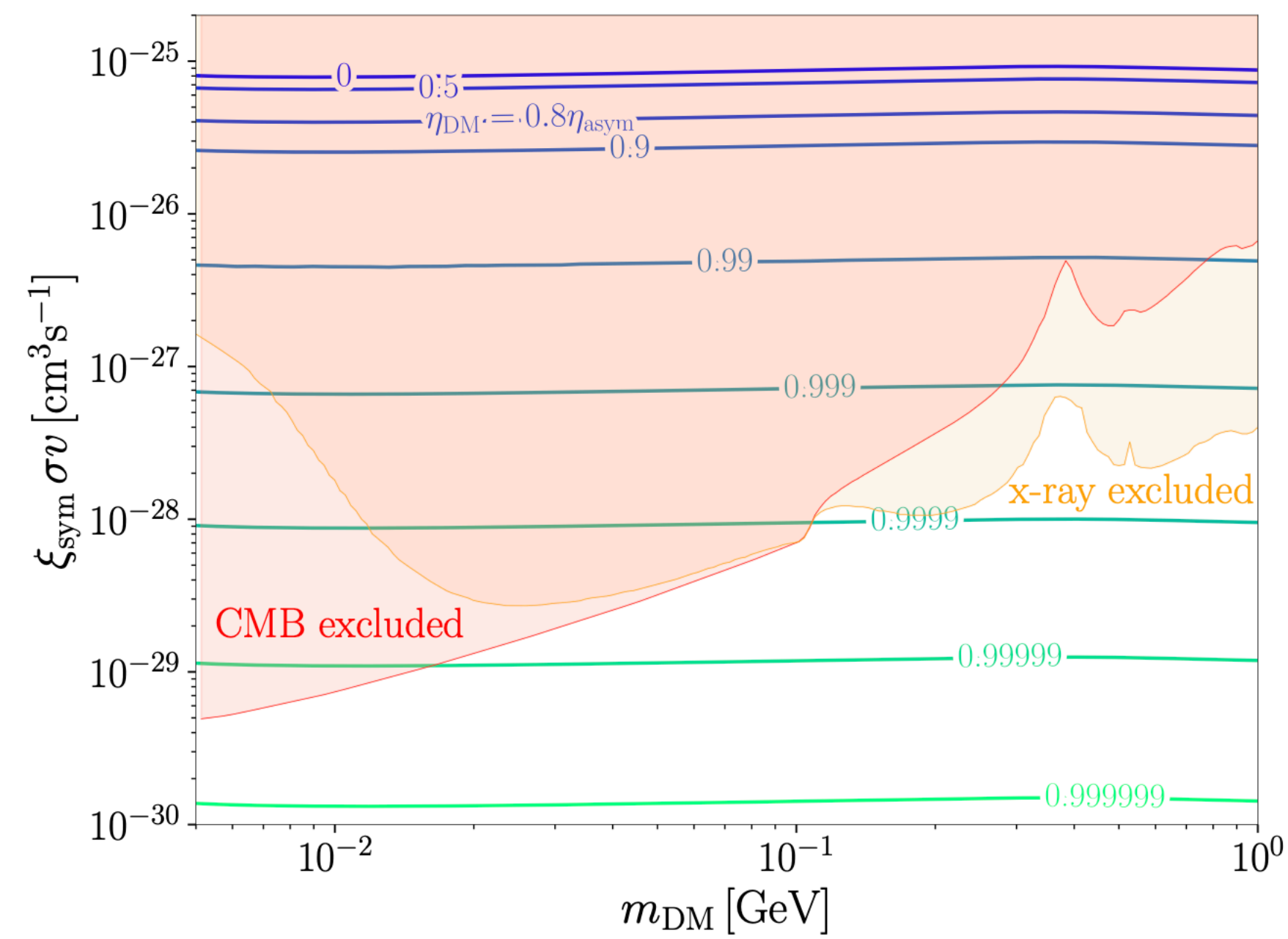


Suppression of annihilation signals for light DM

- velocity suppression (p-wave)
- inelastic DM
- Forbidden DM
- resonance at freeze-out
- asymmetric dark matter



$$\eta_{\text{DM}} \equiv \frac{n_{\chi} - n_{\bar{\chi}}}{s}$$



Suppression of annihilation signals for light DM

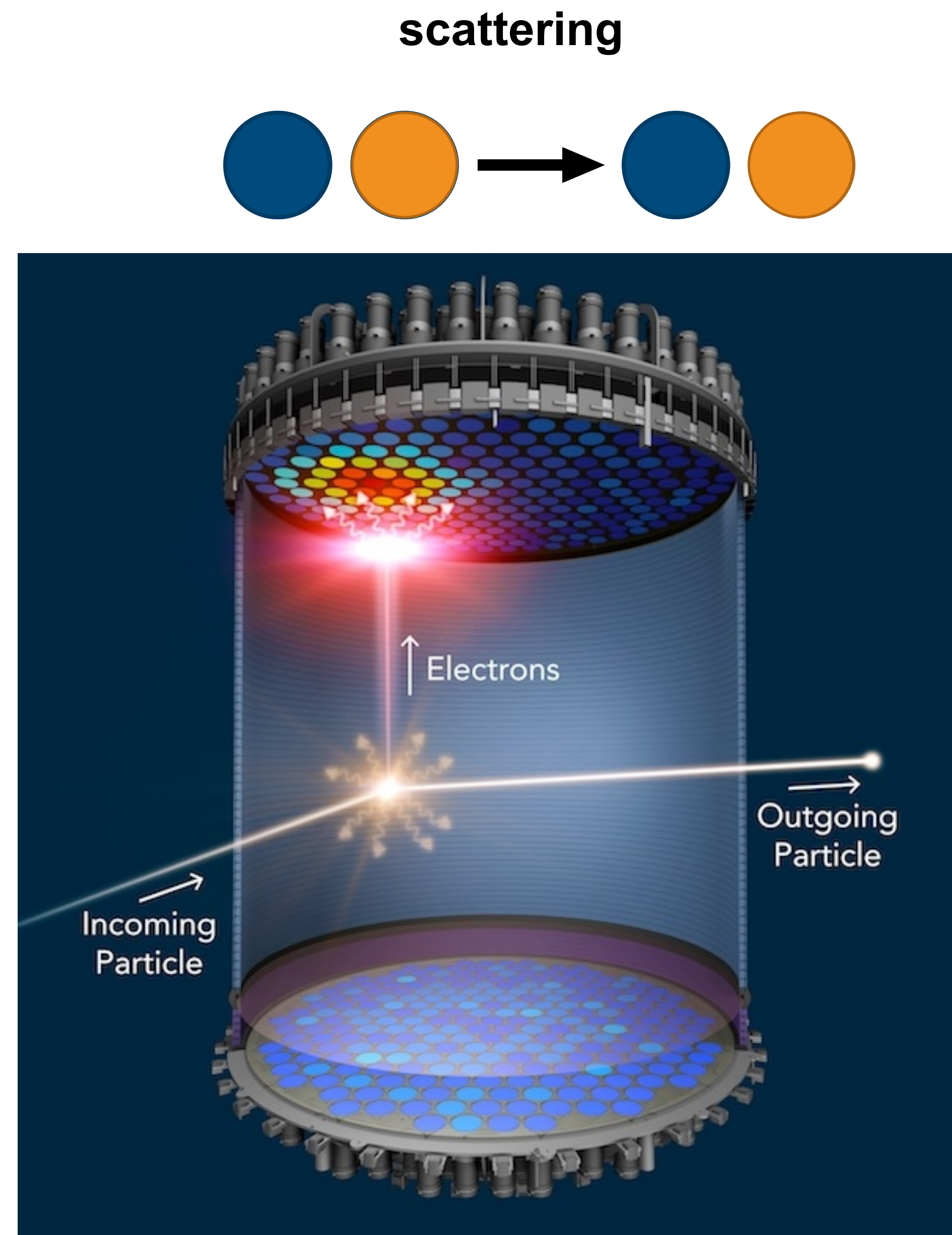
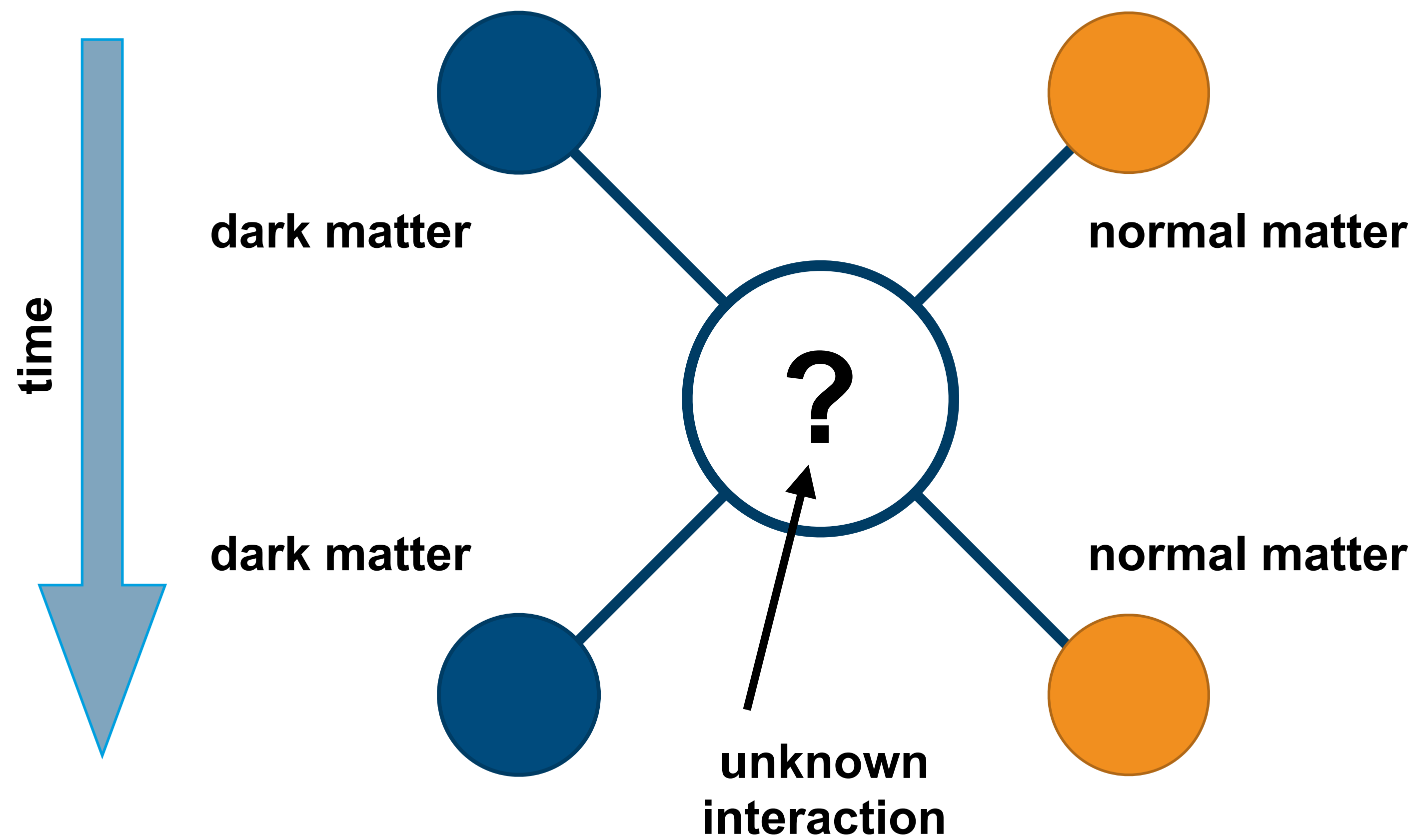
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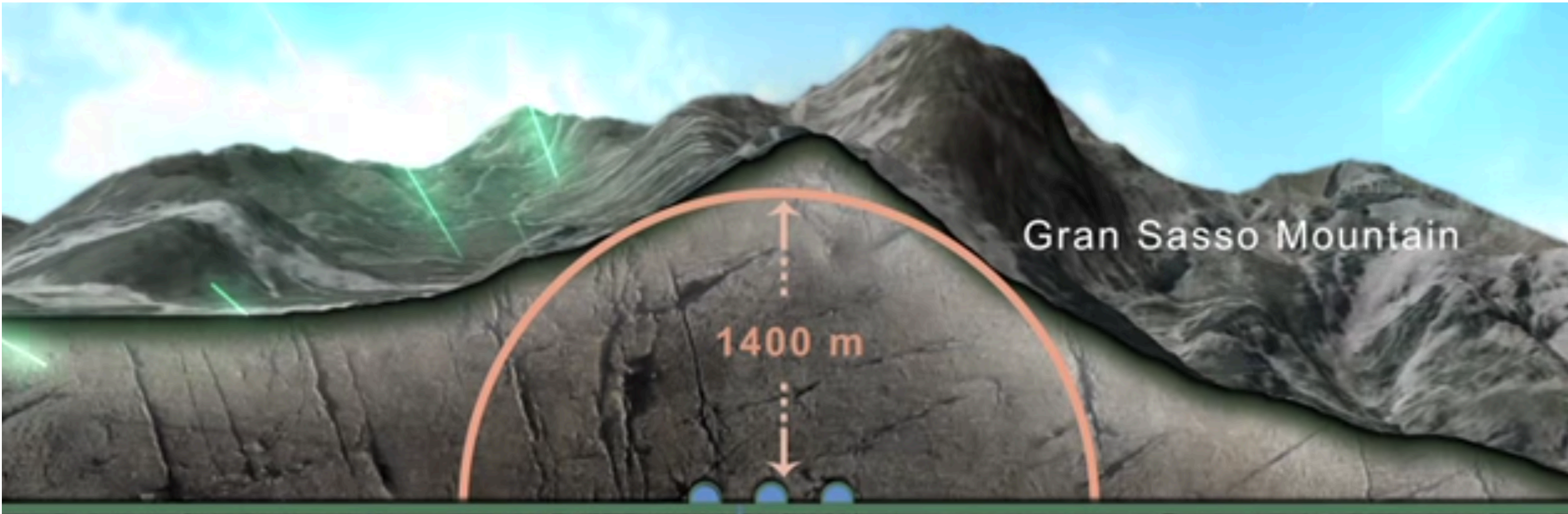
Summary of requirements:

- new light mediators
- $10 \text{ MeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$
- suppressed annihilations for $v \ll 1$

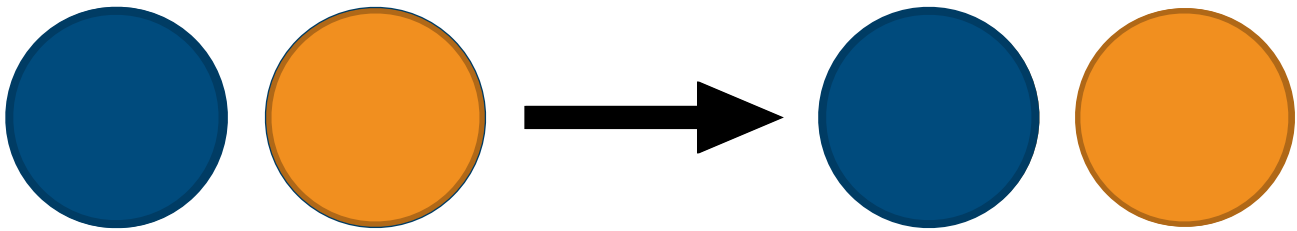
WIMP searches



Direct searches



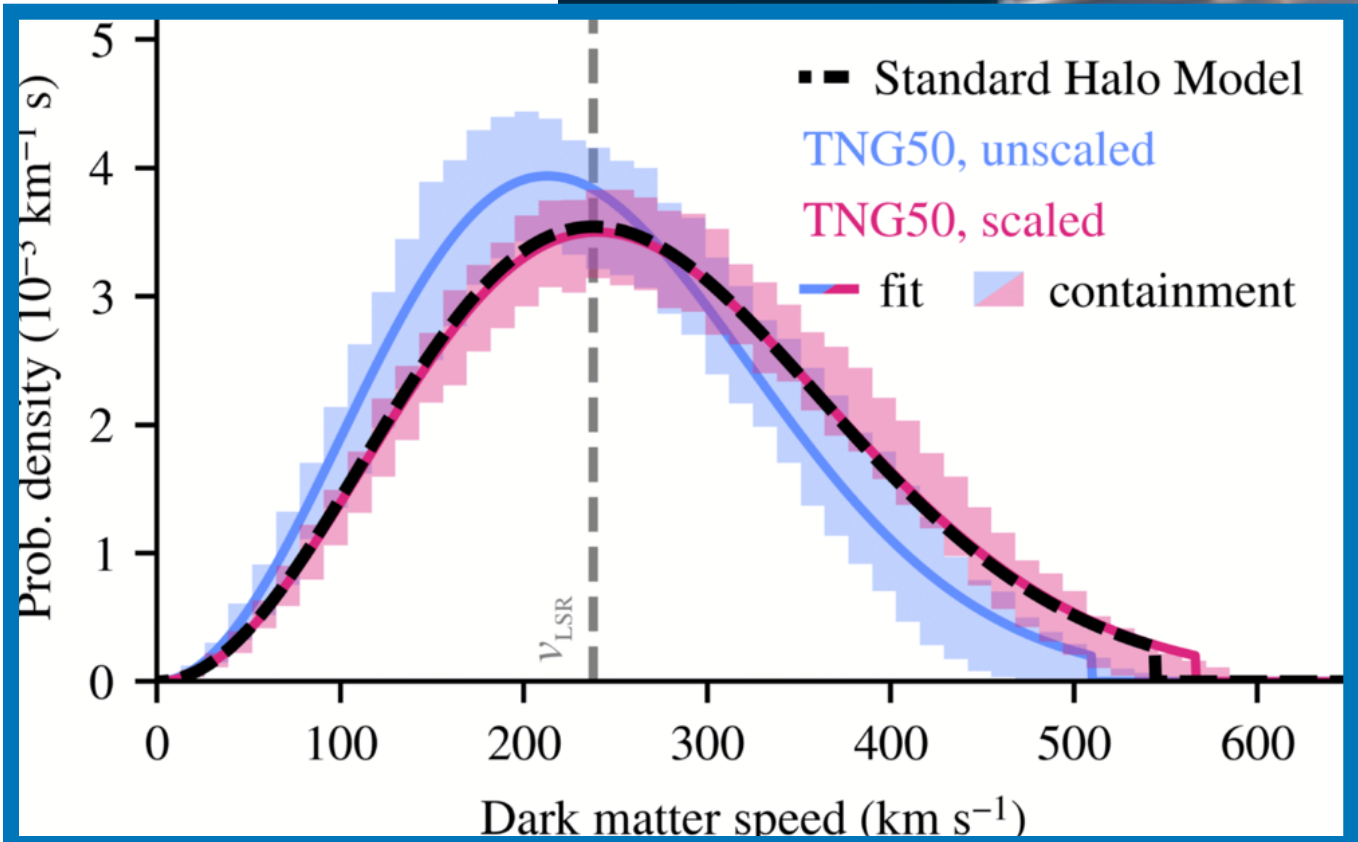
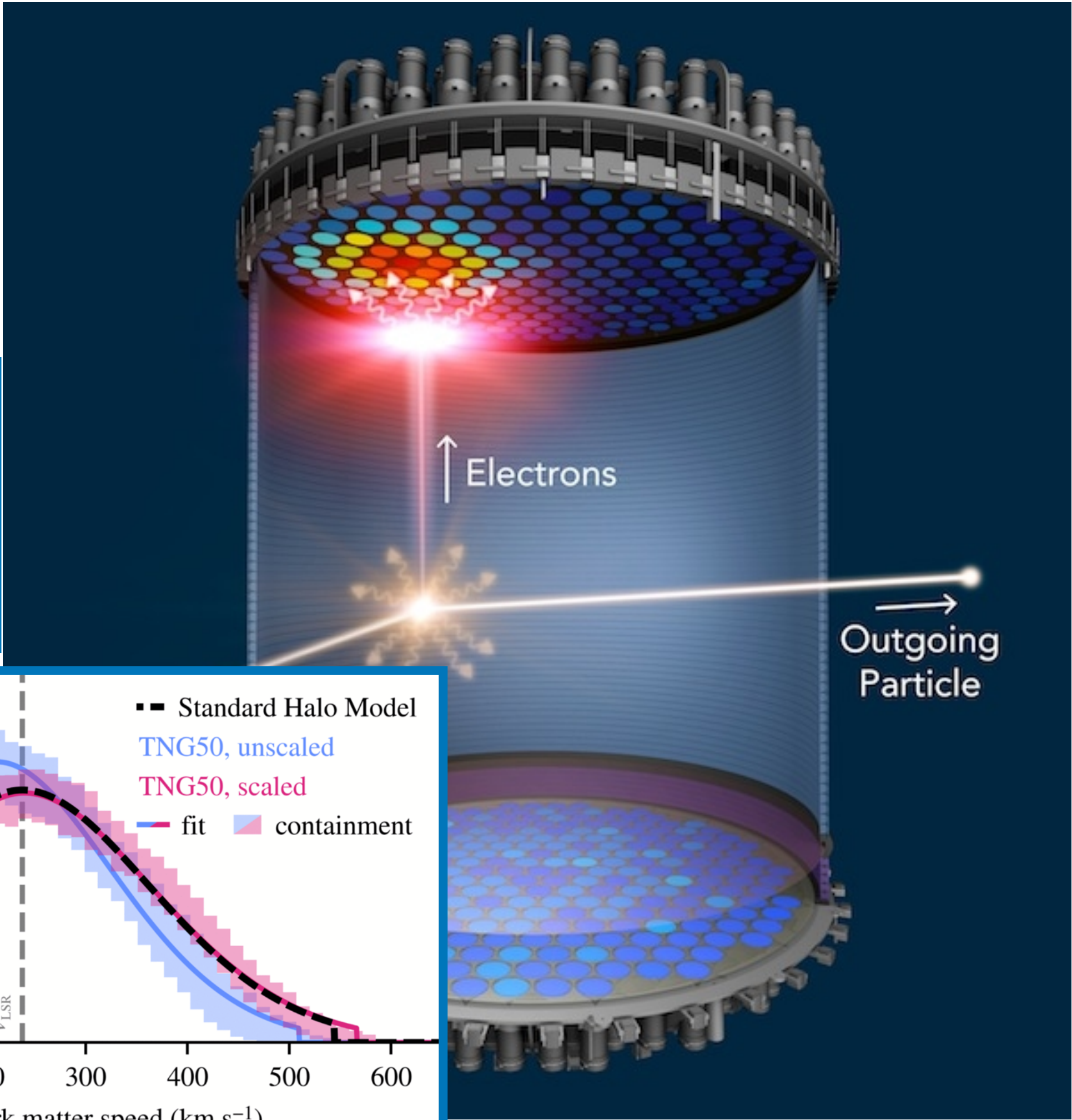
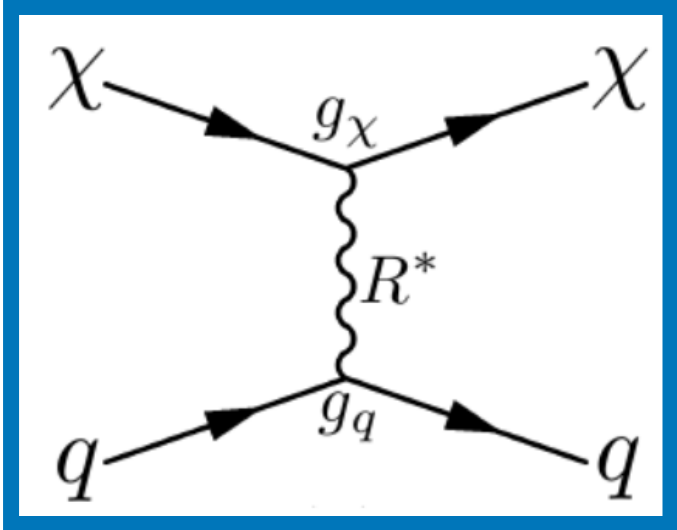
scattering



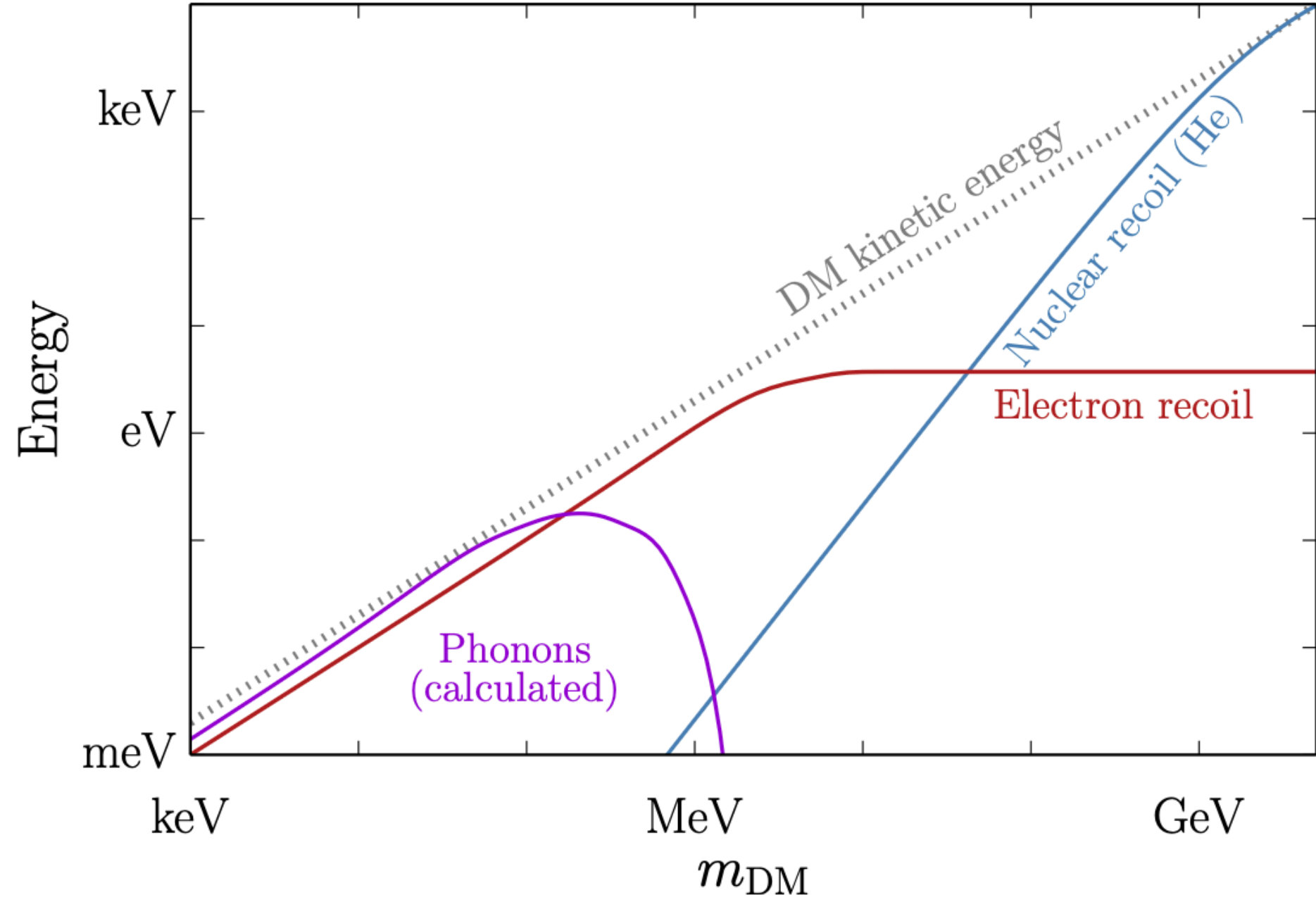
- Searches deep underground to minimise background
- very rare event (~much less than 1 event per kg per year)
- scattering rate and recoil spectrum depends on underlying **particle physics** and **local DM halo**

$$\frac{dR}{dE_R} = \frac{\rho}{m_N m_\chi} \int_{v_{\min}}^{\infty} v f(v + v_E(t)) \frac{d\sigma}{dE_R} d^3v$$

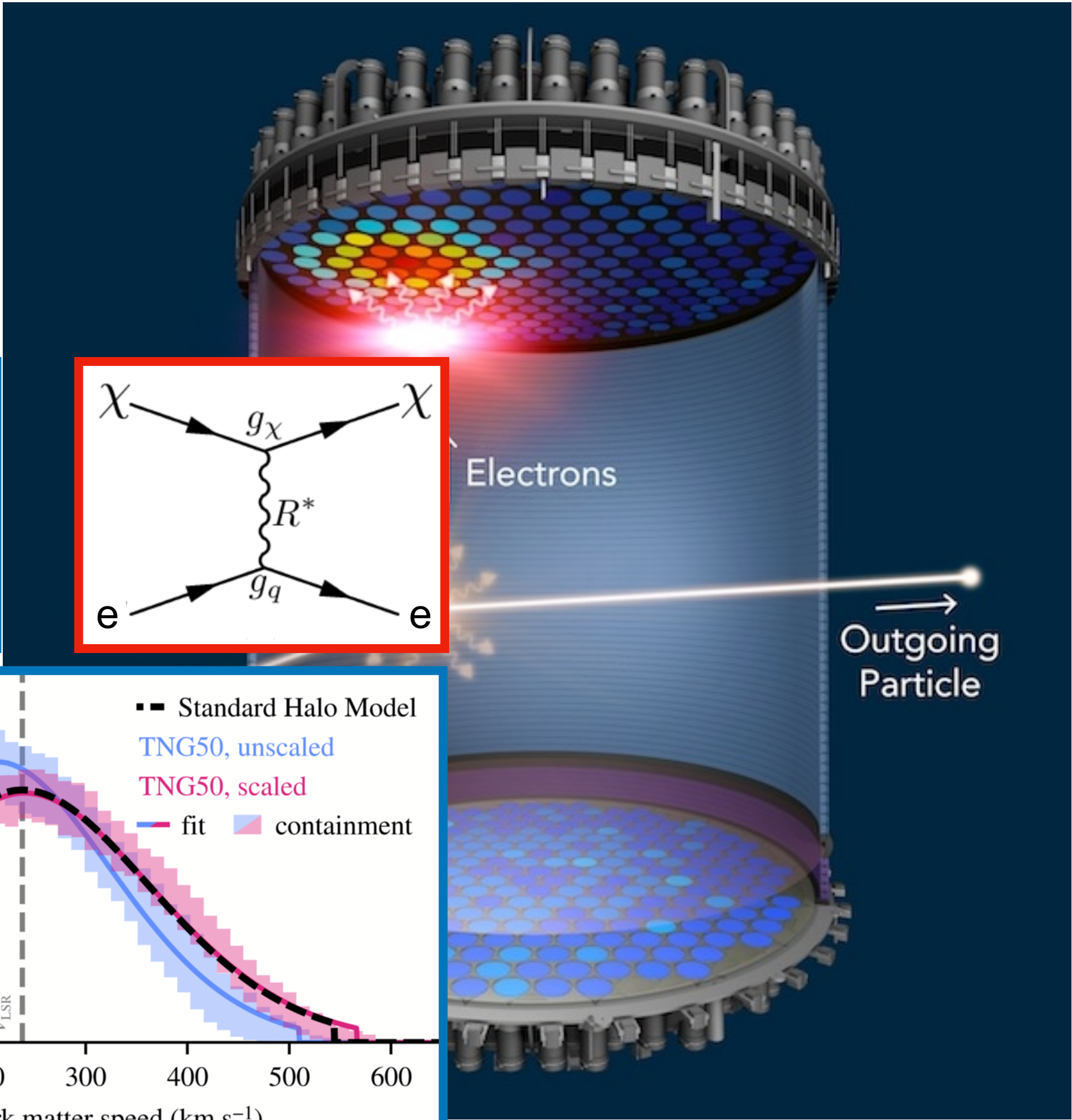
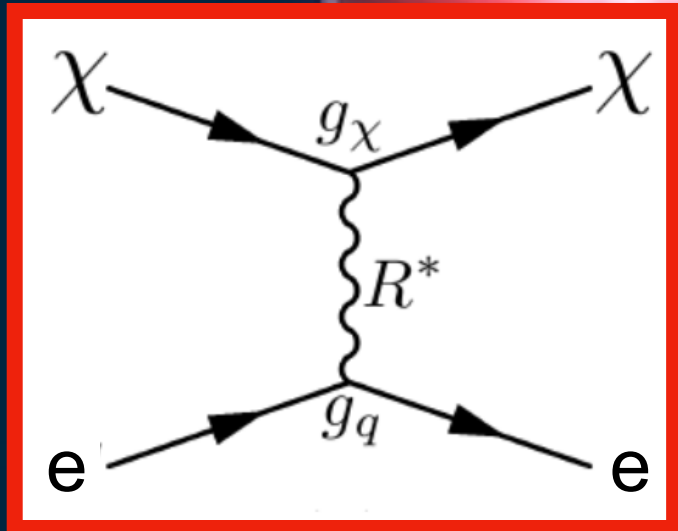
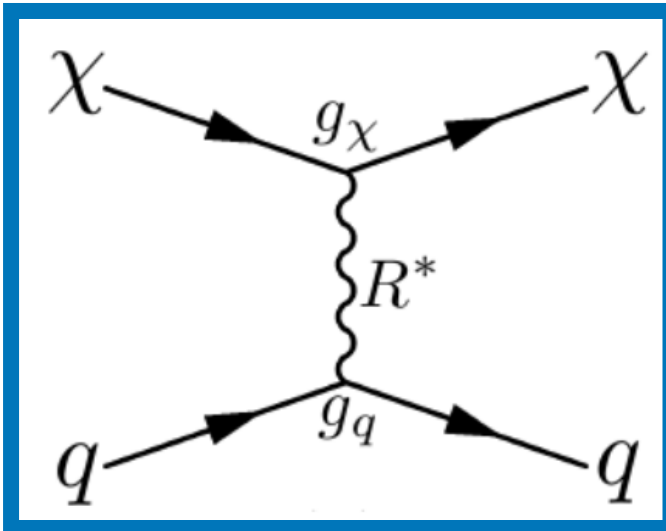
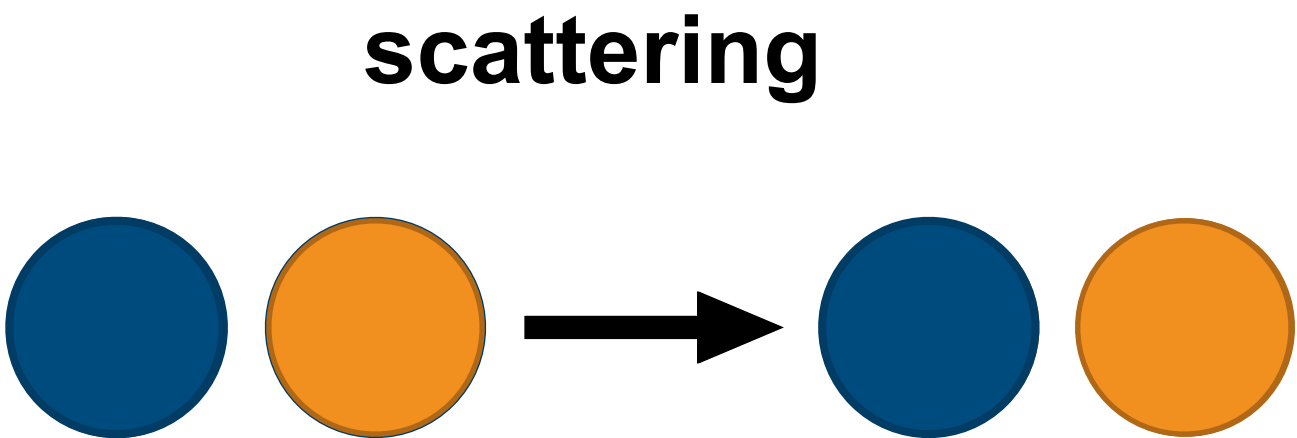
$$\sigma \propto g_\chi^2 g_q^2$$



Scattering kinematics



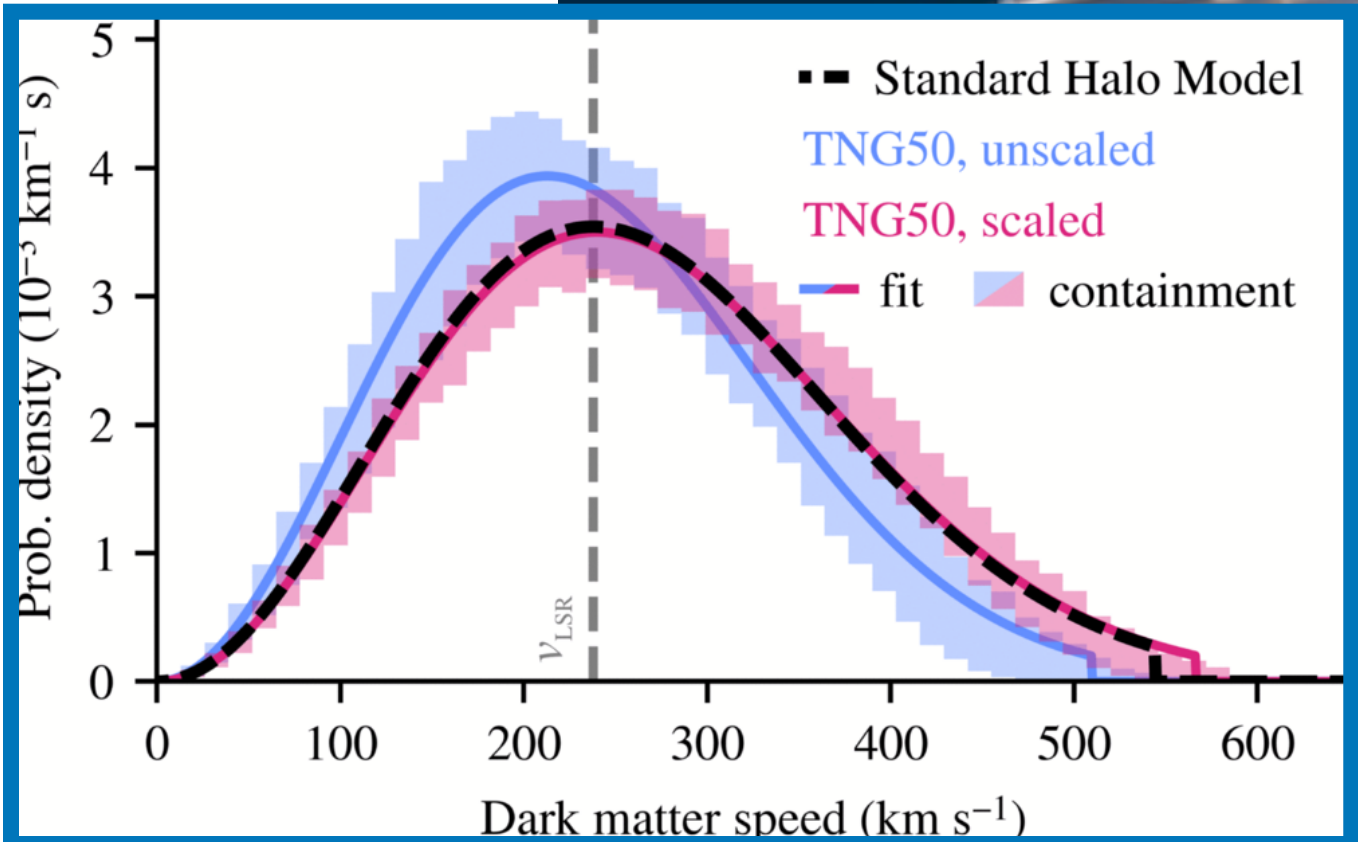
$$\frac{E_{\text{max}}}{\frac{1}{2}m_{\chi}v^2} = \frac{4m_{\chi}m_T}{(m_{\chi} + m_T)^2}$$



$$\frac{dR}{dE_R} = \frac{\rho}{m_N m_{\chi}} \int_{v_{\text{min}}}^{\infty} v f(\mathbf{v} + \mathbf{v}_E(t)) \frac{d\sigma}{dE_R} d^3v$$

$$v_{\text{min}}(E_R) = \sqrt{\frac{m_N E_R}{2 \mu_{N\chi}^2}}$$

minimal v to obtain recoil with energy E_R for elastic scattering



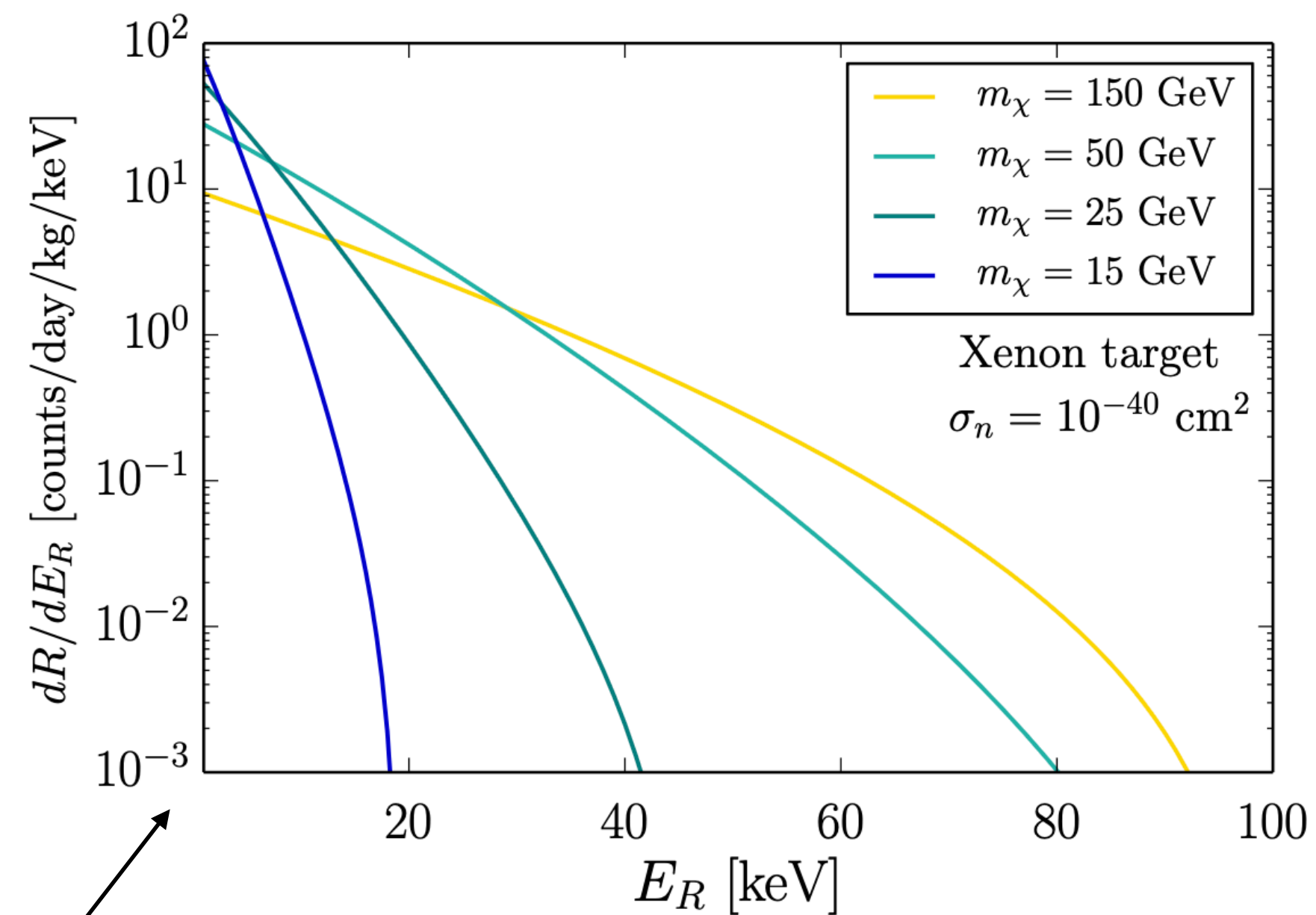
Nuclear scatterings

- vanilla case: spin independent elastic nuclear scatterings

$$\frac{d\sigma}{dE_R} = \frac{\sigma_0 m_N}{2\mu_{\chi N}^2 v^2} \boxed{F^2(E_R)} \quad \sigma_0^{SI} = \frac{4\mu_{\chi N}^2}{\pi} \left[Zf_p + (A - Z)f_n \right]^2$$

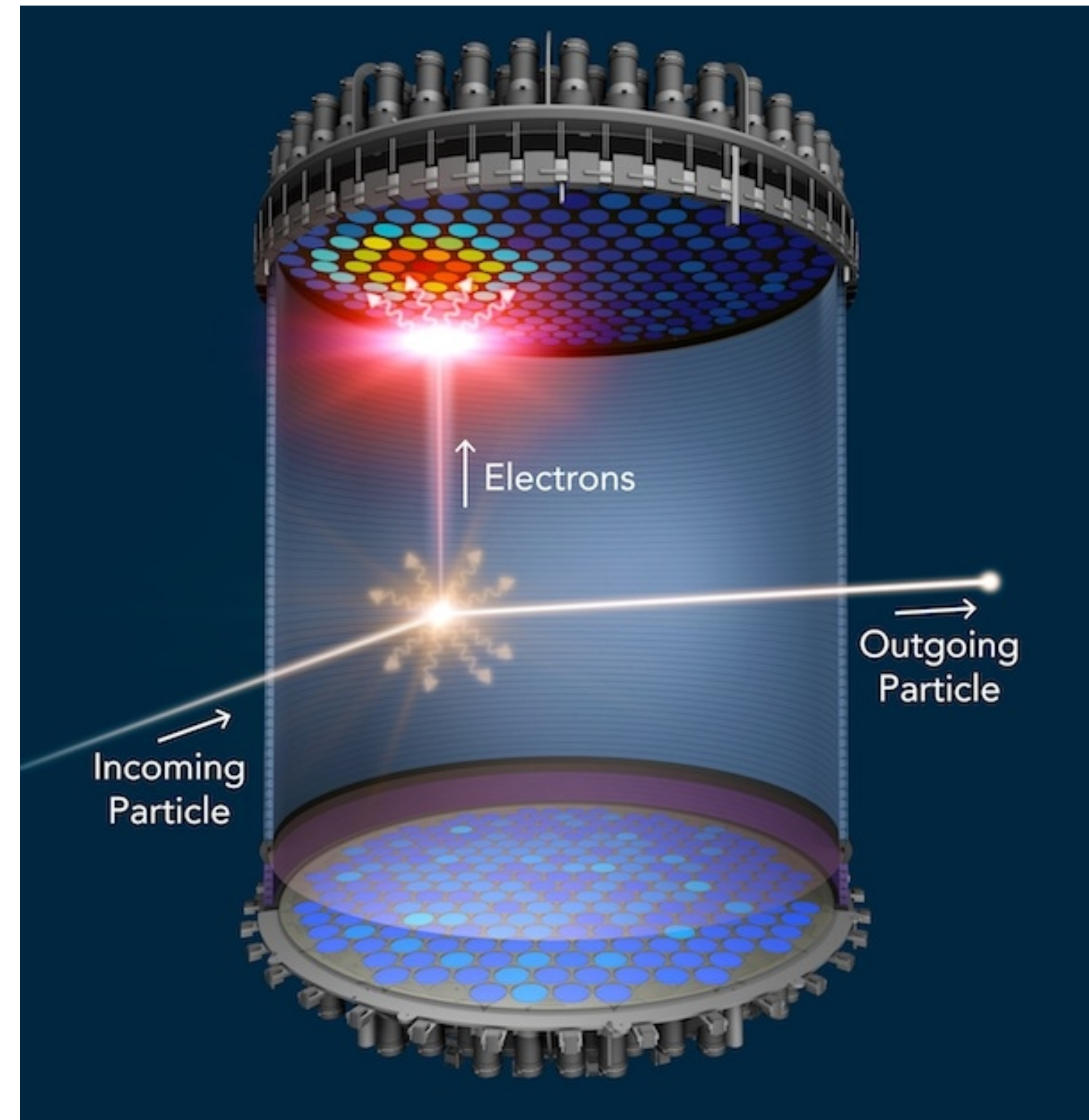
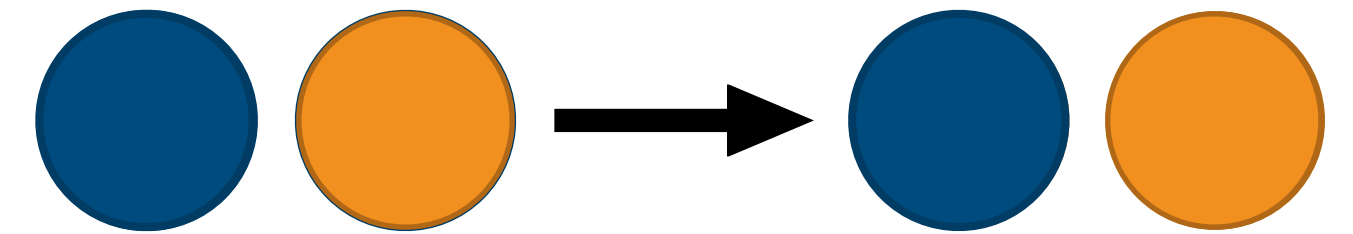
nuclear physics

coherent enhancement



energy threshold

scattering



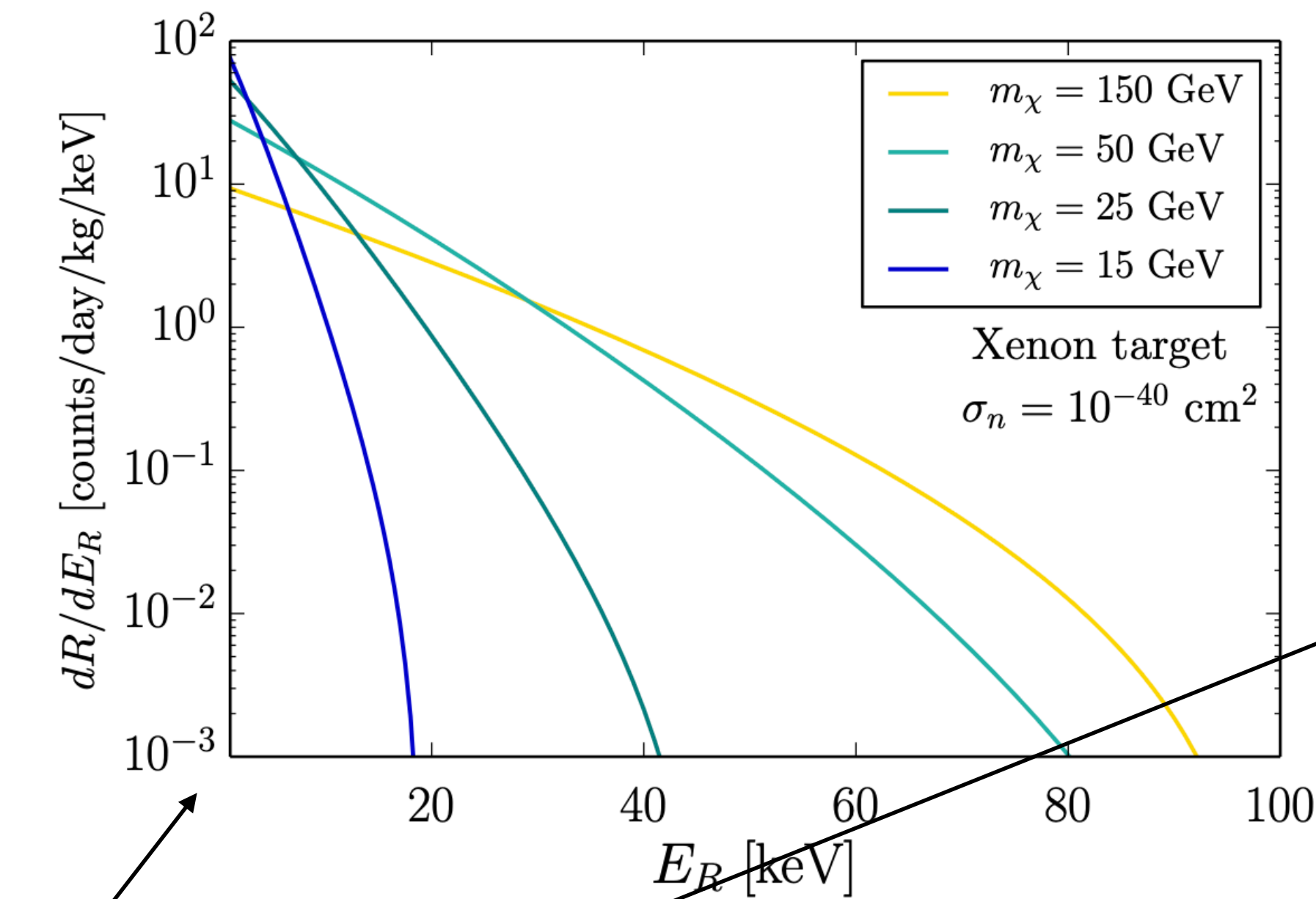
Direct searches

- vanilla case: spin independent elastic nuclear scatterings

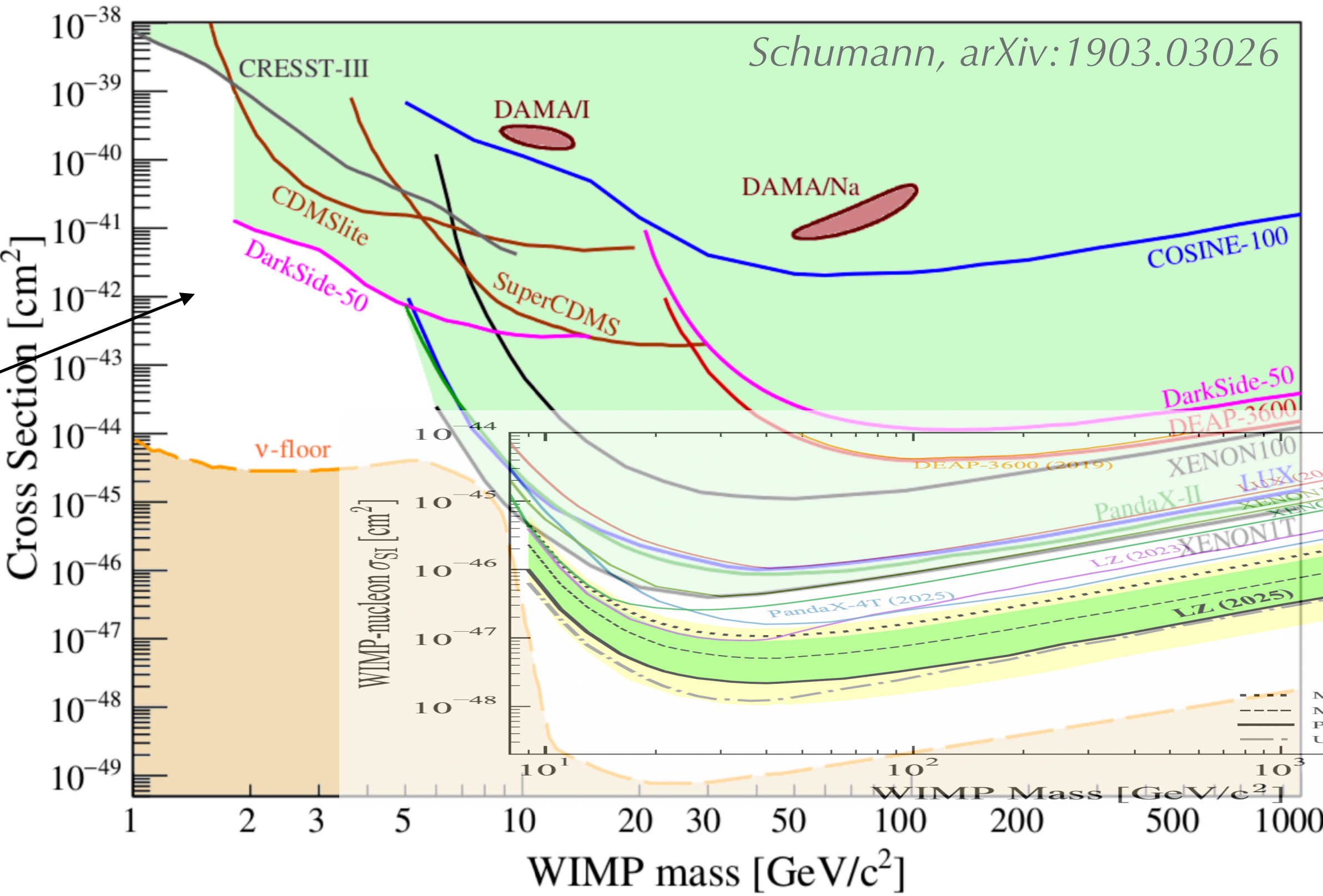
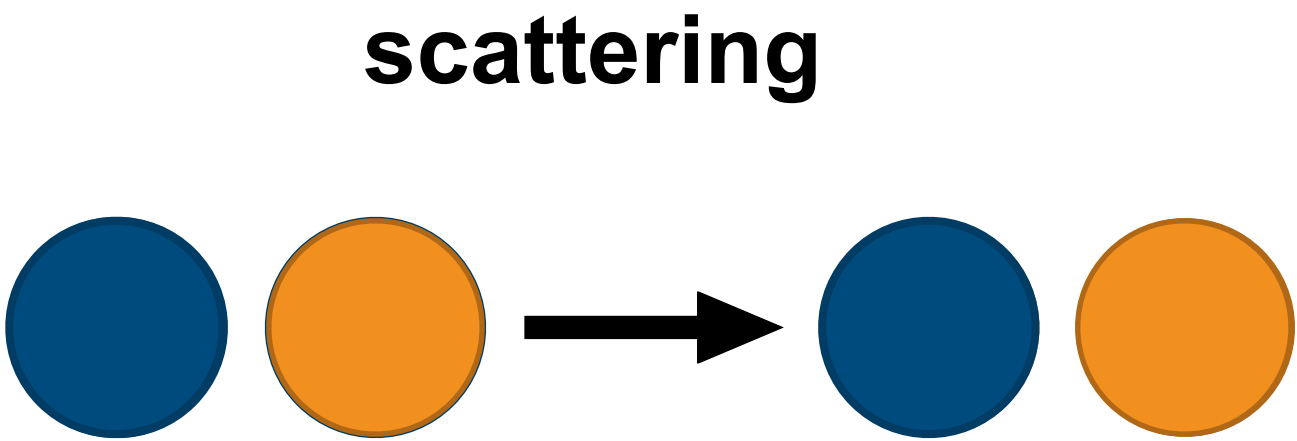
nuclear physics

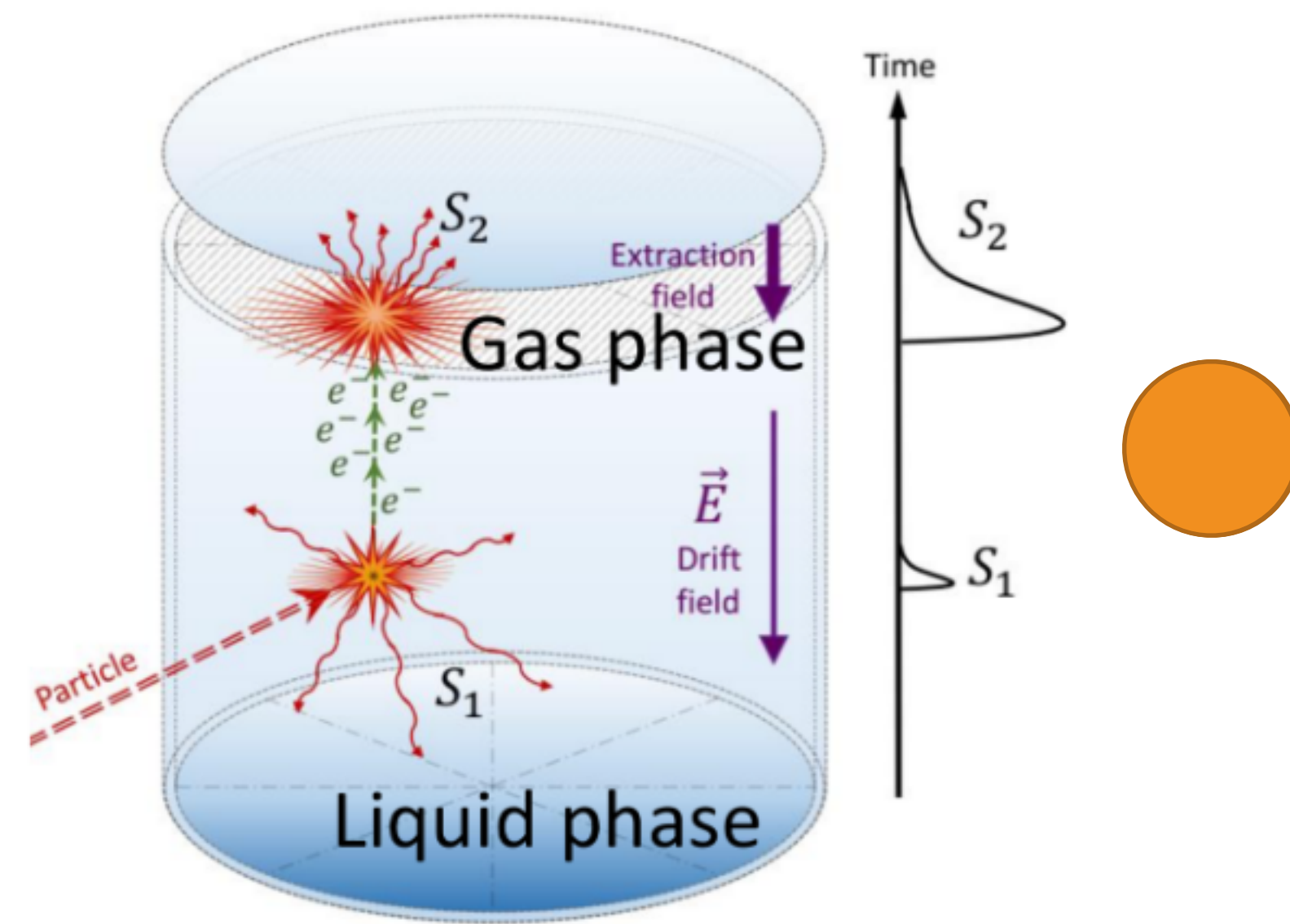
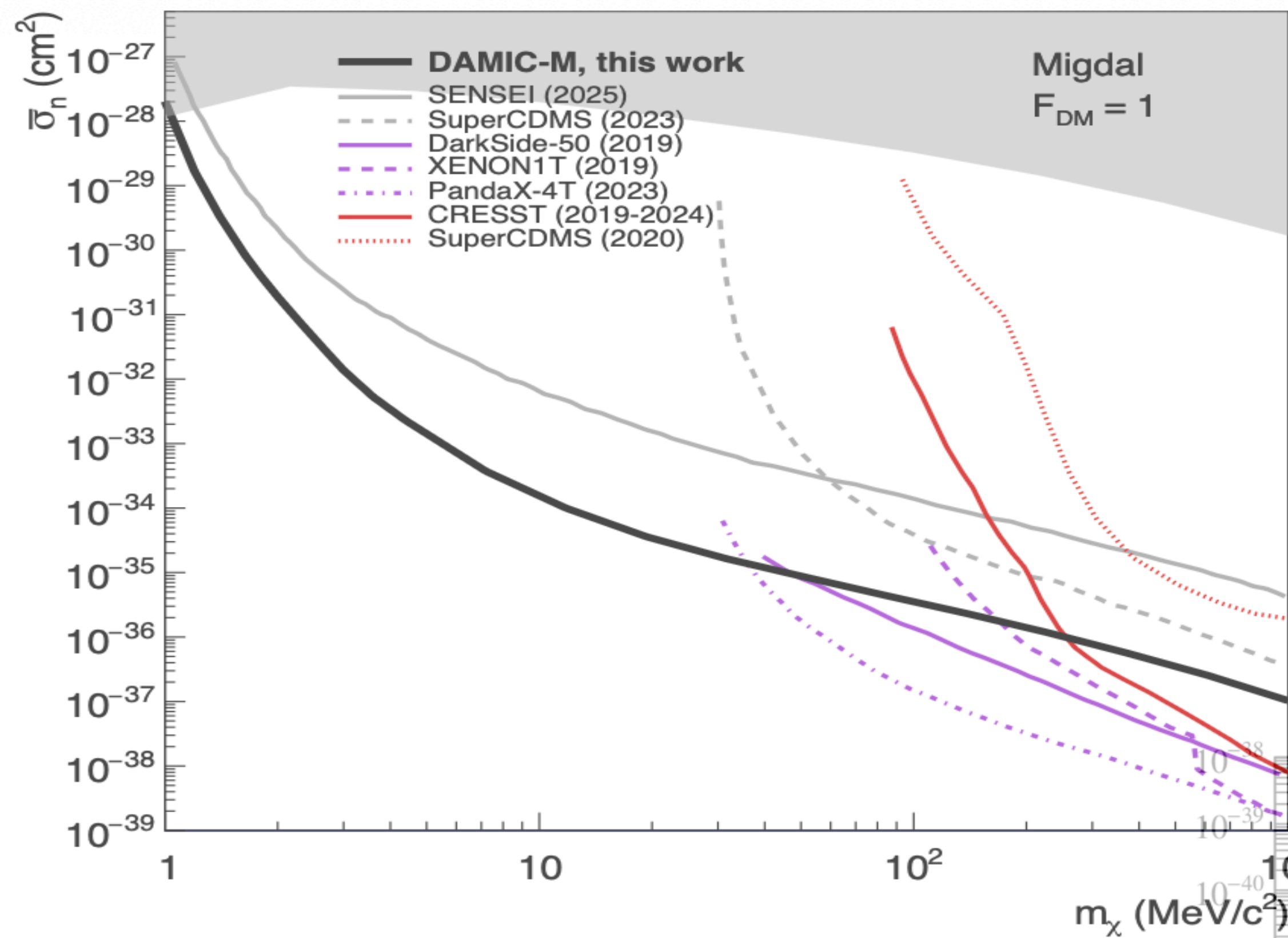
$$\frac{d\sigma}{dE_R} = \frac{\sigma_0 m_N}{2\mu_{\chi N}^2 v^2} F^2(E_R) \quad \sigma_0^{SI} = \frac{4\mu_{\chi N}^2}{\pi} \left[Zf_p + (A - Z)f_n \right]^2$$

coherent enhancement



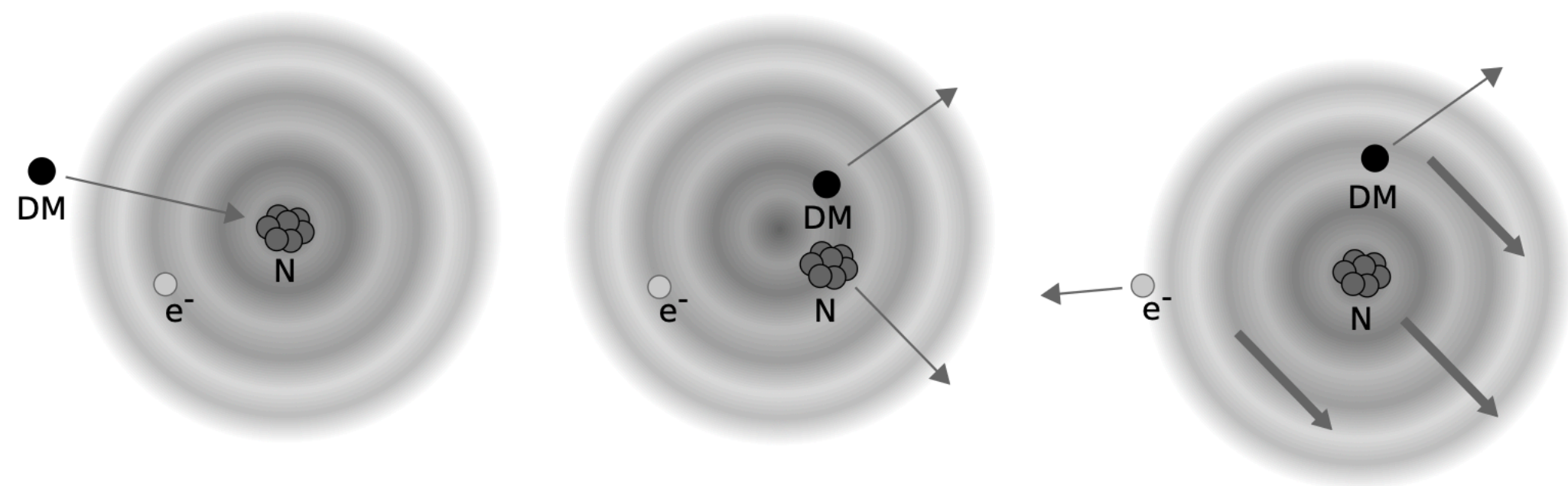
energy threshold



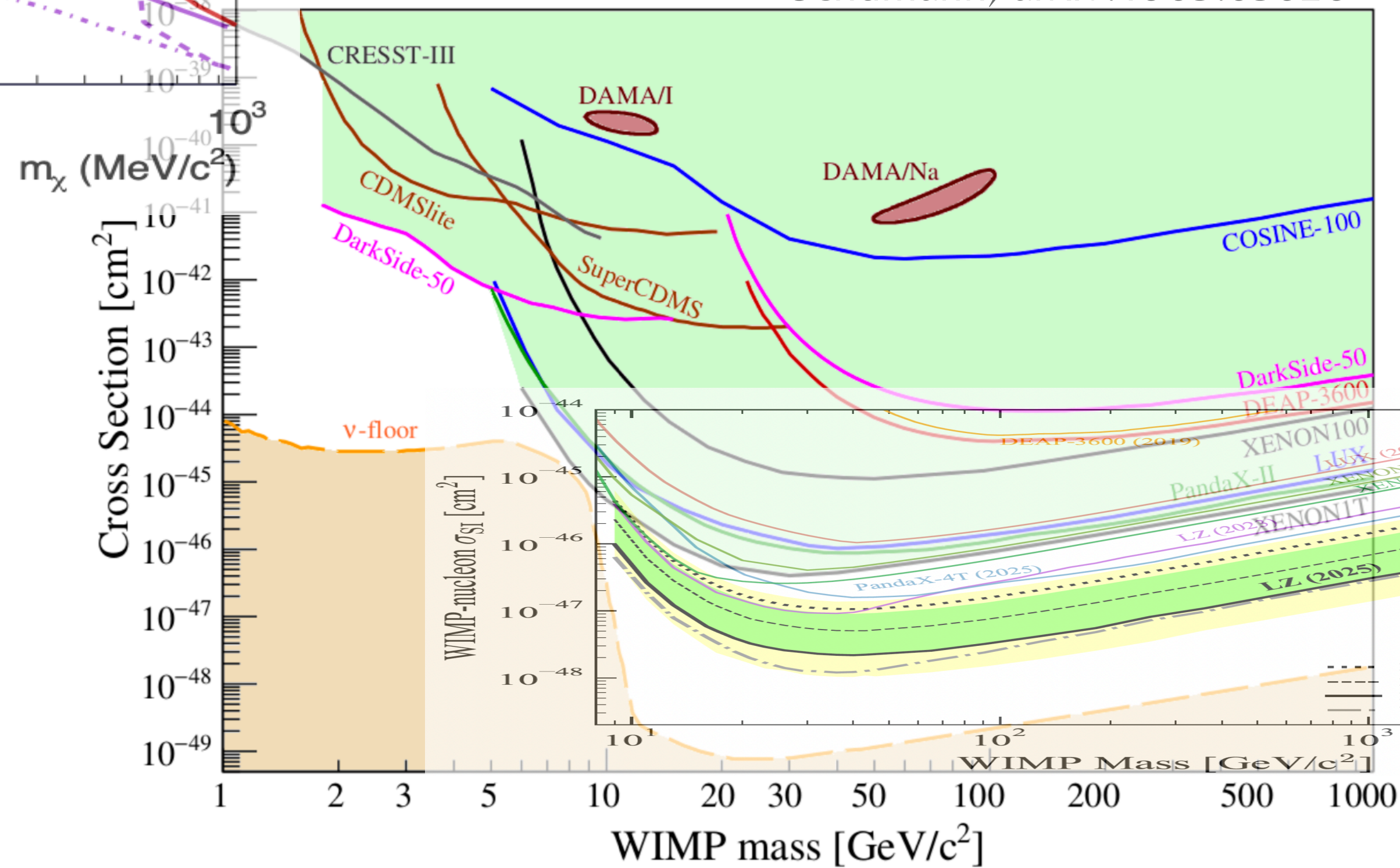


Schumann, arXiv:1903.03026

Migdal effect: inelastic scattering



1711.09906



Many Operators

- Many other interactions possible, most are suppressed...

$$\mathcal{L}_{\text{int}} = \mathcal{O}_\chi \bar{\chi} \bar{N} N,$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N,$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp \right),$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N \right),$$

$$\mathcal{O}_{11}^N = - \left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N,$$

$$\mathcal{O}_{13}^N = - \left(\vec{S}_\chi \cdot \vec{v}_\perp \right) \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_2^N = \left(v_\perp \right)^2 \mathbb{1}_\chi \mathbb{1}_N,$$

$$\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N,$$

$$\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right)$$

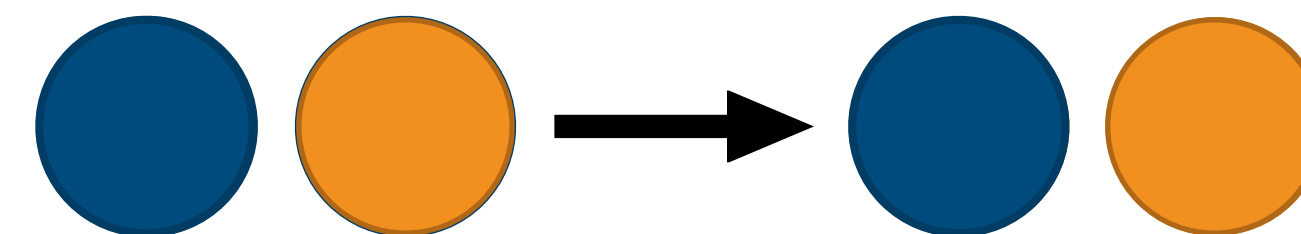
$$\mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp \right) \mathbb{1}_N,$$

$$\mathcal{O}_{10}^N = - \mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp \right),$$

$$\mathcal{O}_{14}^N = - \left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \vec{v}_\perp \right)$$

scattering



Index	Relativistic Operator	Nonrelativistic Limit $\times \frac{1}{4m_N m_\chi}$	$\sum_i c_i \mathcal{O}_i$
1	$\bar{\chi} 2 \chi 1 \bar{N} N$	$\mathbb{1}_\chi \mathbb{1}_N$	$\mathcal{O}_1$
2	$i \bar{\chi} 2 \chi 1 \bar{N} \gamma^5 N$	$i \frac{\vec{q}}{m_N} \cdot \vec{S}_N$	$\mathcal{O}_{10}$
3	$i \bar{\chi} 2 \gamma^5 \chi 1 \bar{N} N$	$-i \frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi$	$-\frac{m_N}{m_\chi} \mathcal{O}_{11}$
4	$\bar{\chi} 2 \gamma^5 \chi 1 \bar{N} \gamma^5 N$	$-(\frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$	$-\frac{m_N}{m_\chi} \mathcal{O}_6$
5	$\bar{\chi} 2 \gamma^\mu \chi 1 \bar{N} \gamma_\mu N$	$\mathbb{1}_\chi \mathbb{1}_N$	$\mathcal{O}_1$
6	$\bar{\chi} 2 \gamma^\mu \chi 1 \bar{N} i \sigma_{\mu\nu} \frac{q^\nu}{m_M} N$	$\frac{ \vec{q} ^2}{2m_N m_M} \mathbb{1}_\chi \mathbb{1}_N$ $+2 \left(\frac{\vec{q}}{m_\chi} \times \vec{S}_\chi + i \vec{v}_{\text{inel}}^\perp \right) \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$\frac{ \vec{q} ^2}{2m_N m_M} \left(\mathcal{O}_1 + \frac{4m_N}{m_\chi} \mathcal{O}_4 \right)$ $-\frac{2m_N}{m_M} \left(\frac{m_N}{m_\chi} \mathcal{O}_6 + \mathcal{O}_3 \right)$
7	$\bar{\chi} 2 \gamma^\mu \chi 1 \bar{N} \gamma_\mu \gamma^5 N$	$-2 \vec{S}_N \cdot (\vec{v}_{\text{inel}}^\perp - \frac{\delta}{ \vec{q} ^2} \vec{q})$ $+2i \vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_\chi})$	$-2 \left(\mathcal{O}_7 + i \frac{m_N \delta}{ \vec{q} ^2} \mathcal{O}_{10} - \frac{m_N}{m_\chi} \mathcal{O}_9 \right)$
8	$i \bar{\chi} 2 \gamma^\mu \chi 1 \bar{N} i \sigma_{\mu\nu} \frac{q^\nu}{m_M} \gamma^5 N$	$2i \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$\frac{2m_N}{m_M} \mathcal{O}_{10}$
9	$\bar{\chi} 2 i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi 1 \bar{N} \gamma_\mu N$	$-\frac{ \vec{q} ^2}{2m_\chi m_M} \mathbb{1}_\chi \mathbb{1}_N$ $-2 \left(\frac{\vec{q}}{m_N} \times \vec{S}_N + i \vec{v}_{\text{inel}}^\perp \right) \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right)$	$-\frac{ \vec{q} ^2}{2m_\chi m_M} \left(\mathcal{O}_1 + \frac{4m_\chi}{m_N} \mathcal{O}_4 \right)$ $+\frac{2m_N}{m_M} (\mathcal{O}_6 + \mathcal{O}_5)$
10	$\bar{\chi} 2 i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi 1 \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} N$	$4 \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$\frac{4m_N^2}{m_M^2} \left(\frac{ \vec{q} ^2}{m_N^2} \mathcal{O}_4 - \mathcal{O}_6 \right)$
11	$\bar{\chi} 2 i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi 1 \bar{N} \gamma_\mu \gamma^5 N$	$4i \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \cdot \vec{S}_N$	$\frac{4m_N}{m_M} \mathcal{O}_9$
12	$i \bar{\chi} 2 i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi 1 \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} \gamma^5 N$	$-\left[i \frac{ \vec{q} ^2}{m_\chi m_M} - 4 \vec{v}_{\text{inel}}^\perp \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \right] \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$-\frac{ \vec{q} ^2}{m_M^2} \left(\frac{m_N}{m_\chi} \mathcal{O}_{10} + 4 \mathcal{O}_{12} \right)$ $-\frac{4m_N^2}{m_M^2} \mathcal{O}_{15}$
13	$\bar{\chi} 2 \gamma^\mu \gamma^5 \chi 1 \bar{N} \gamma_\mu N$	$2 \left(\vec{v}_{\text{inel}}^\perp - \frac{\delta}{ \vec{q} ^2} \vec{q} \right) \cdot \vec{S}_\chi$ $+2i \vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N} \right)$	$2 \left(\mathcal{O}_8 + \mathcal{O}_9 + i \frac{m_N \delta}{ \vec{q} ^2} \mathcal{O}_{11} \right)$
14	$\bar{\chi} 2 \gamma^\mu \gamma^5 \chi 1 \bar{N} i \sigma_{\mu\nu} \frac{q^\nu}{m_M} N$	$4i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$-\frac{4m_N}{m_M} \mathcal{O}_9$
15	$\bar{\chi} 2 \gamma^\mu \gamma^5 \chi 1 \bar{N} \gamma_\mu \gamma^5 N$	$-4 \vec{S}_\chi \cdot \vec{S}_N$	$-4 \mathcal{O}_4$

Spin-dependent nuclear

- spin-dependent scatterings (no coherent enhancements, but no further suppression)
- different for p and n

$$\mathcal{L}_{\text{int}} = \mathcal{O} \chi \bar{\chi} \bar{N} N$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N,$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi (\vec{S}_N \cdot \vec{v}_\perp),$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N \right),$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N,$$

$$\mathcal{O}_{13}^N = -\left(\vec{S}_\chi \cdot \vec{v}_\perp \right) \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_2^N = (v_\perp)^2 \mathbb{1}_\chi \mathbb{1}_N,$$

$$\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N,$$

$$\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right)$$

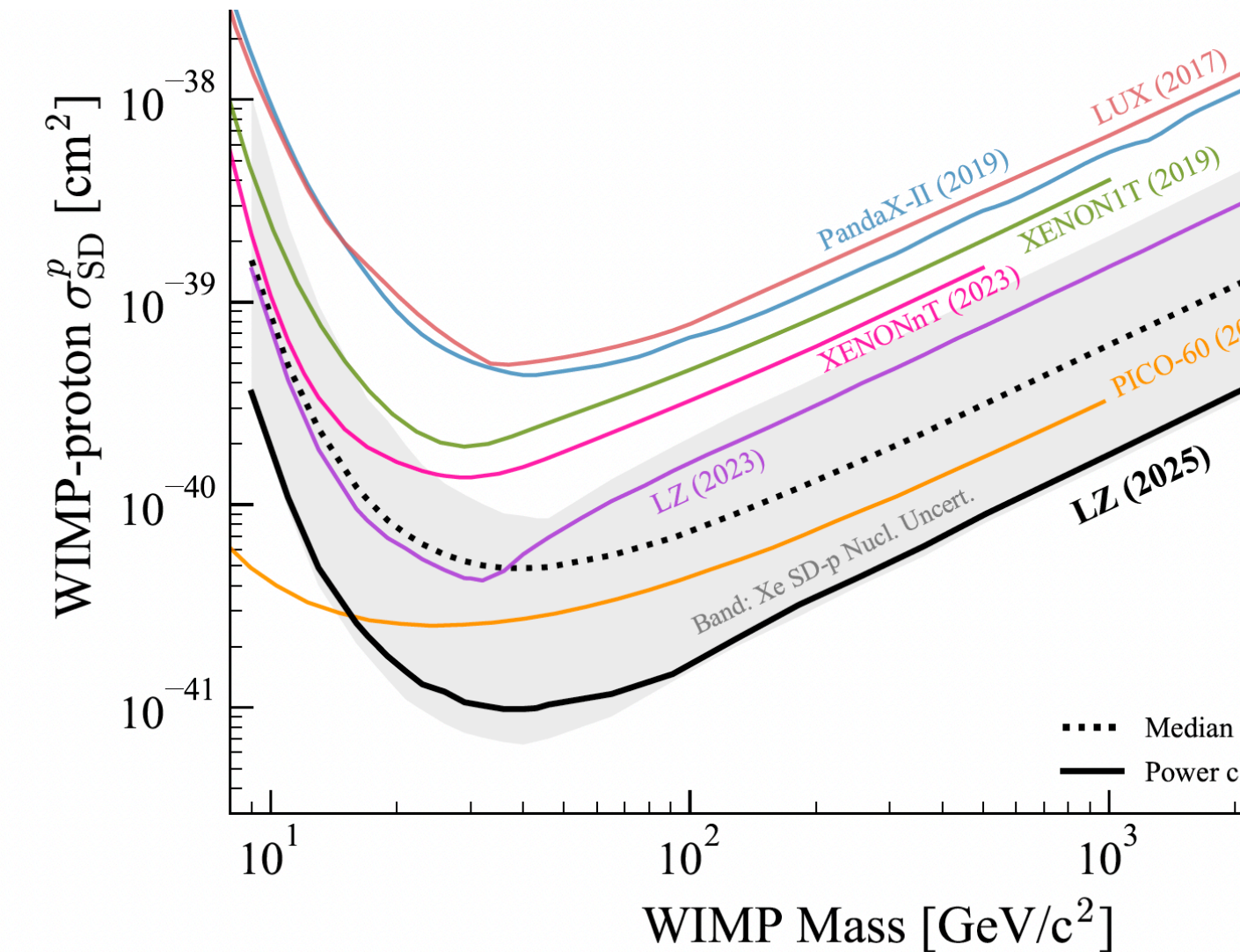
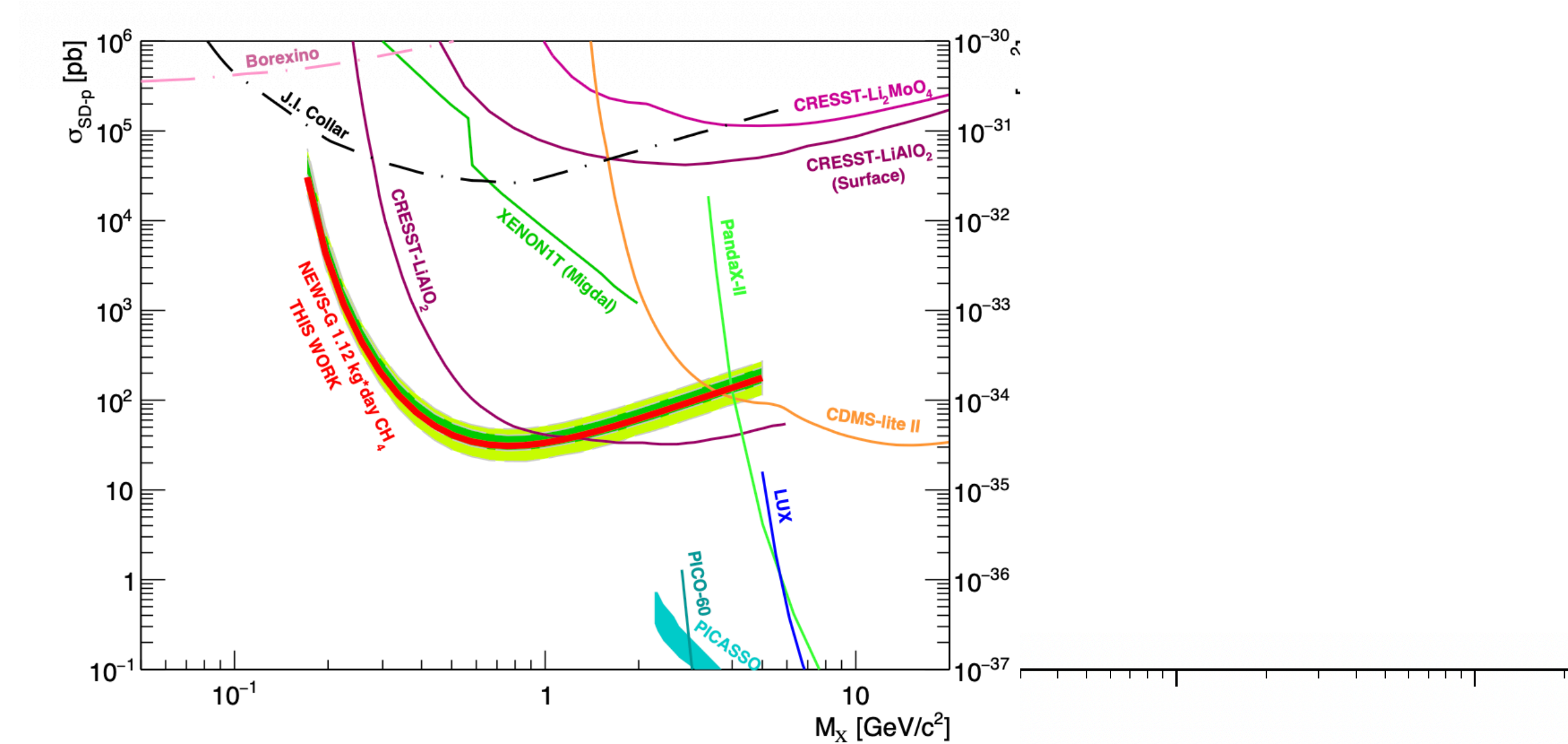
$$\mathcal{O}_8^N = (\vec{S}_\chi \cdot \vec{v}_\perp) \mathbb{1}_N,$$

$$\mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right),$$

$$\mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp \right),$$

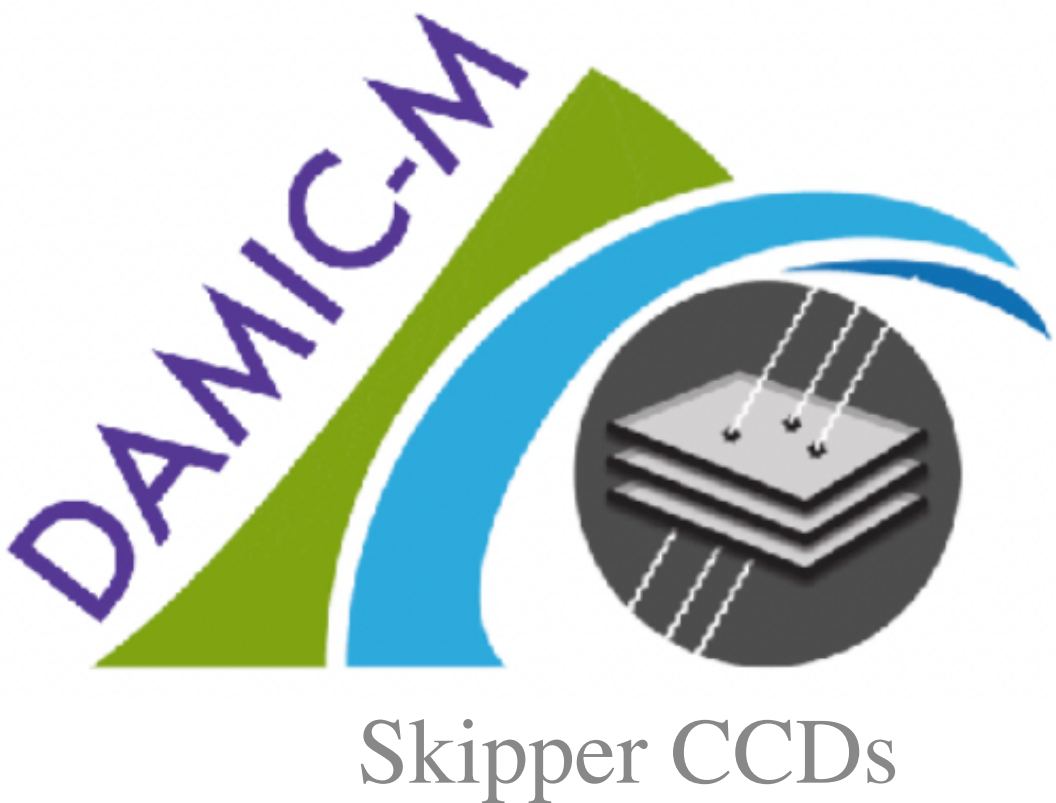
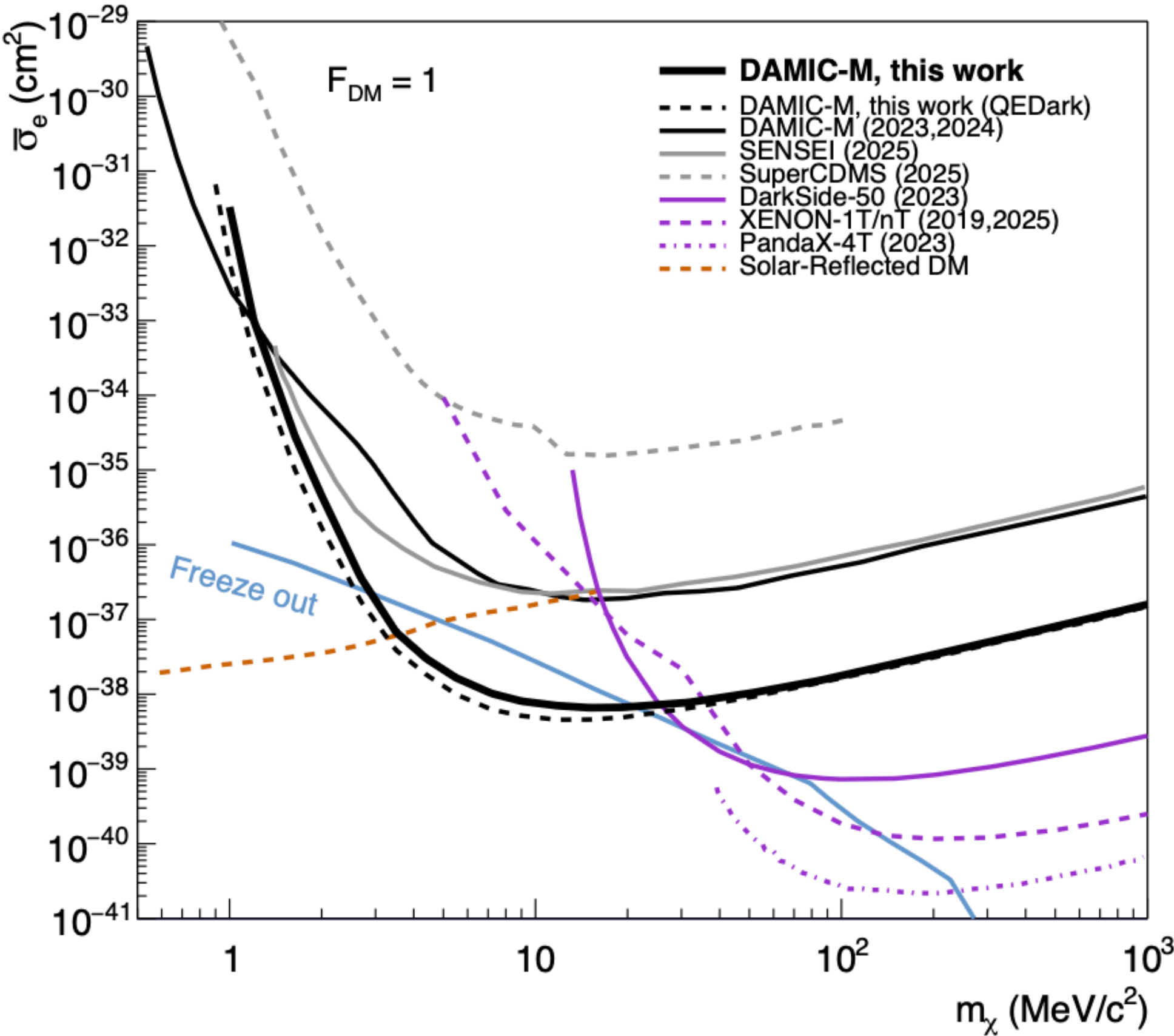
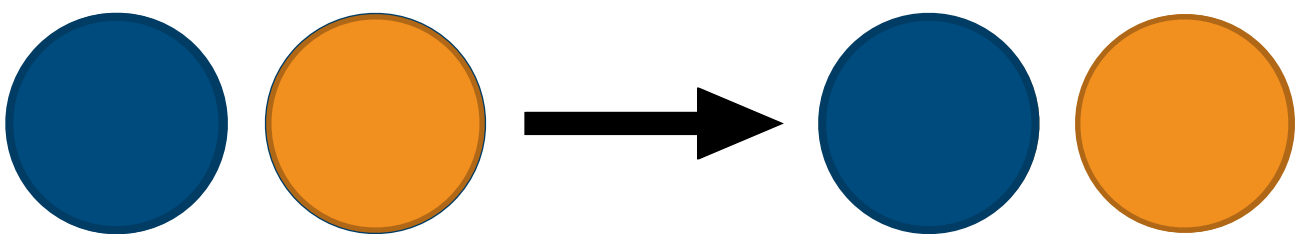
$$\mathcal{O}_{14}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) (\vec{S}_N \cdot \vec{v}_\perp)$$

NEWS-G target consists of
114g of methane CH_4 (gas)



Scattering on electrons

scattering



New LZ result

- **New LZ result:** one event with large recoil energy
- can't be 'standard' spin-independent elastic scattering
- spin-dependent scattering still OK

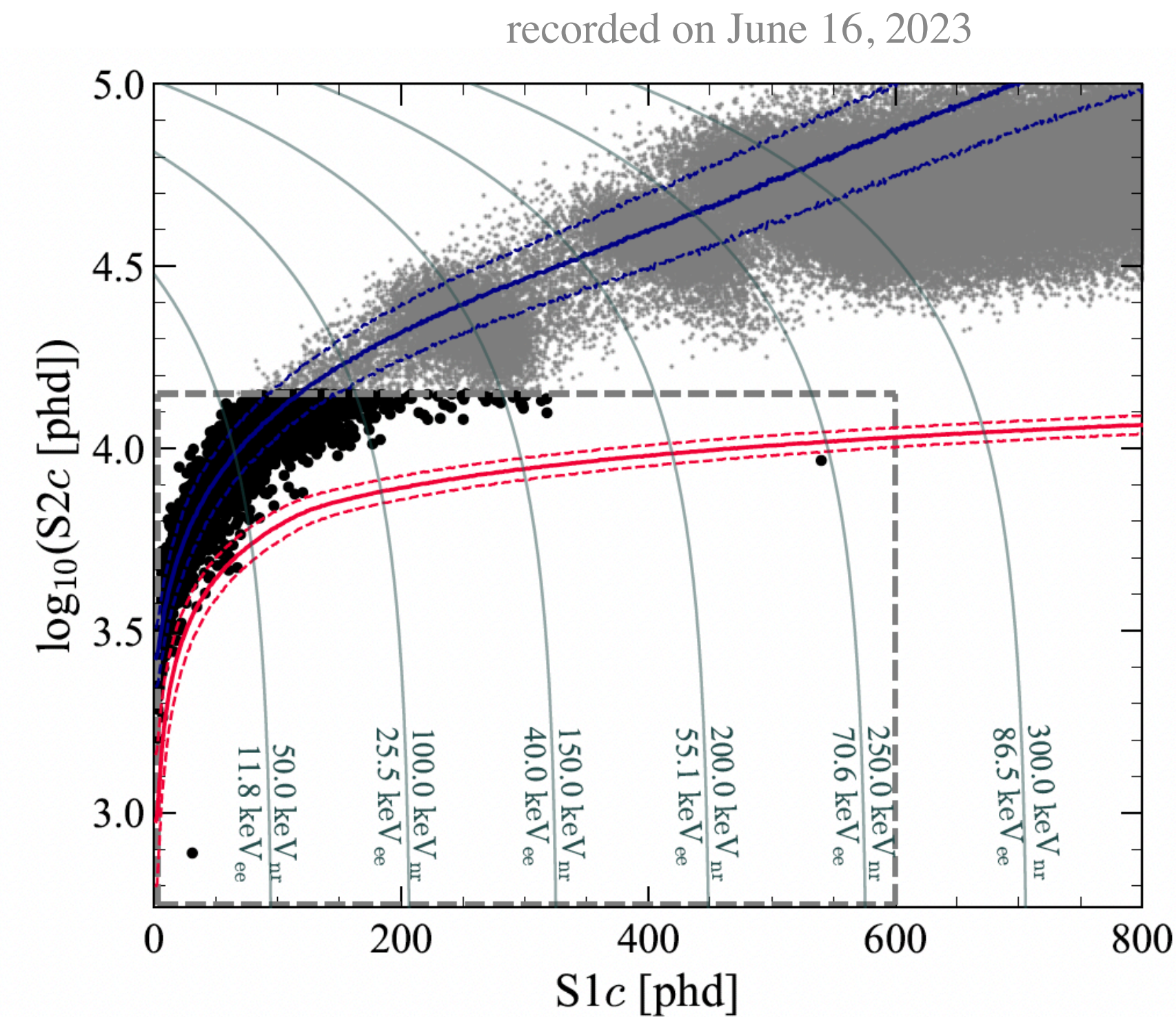
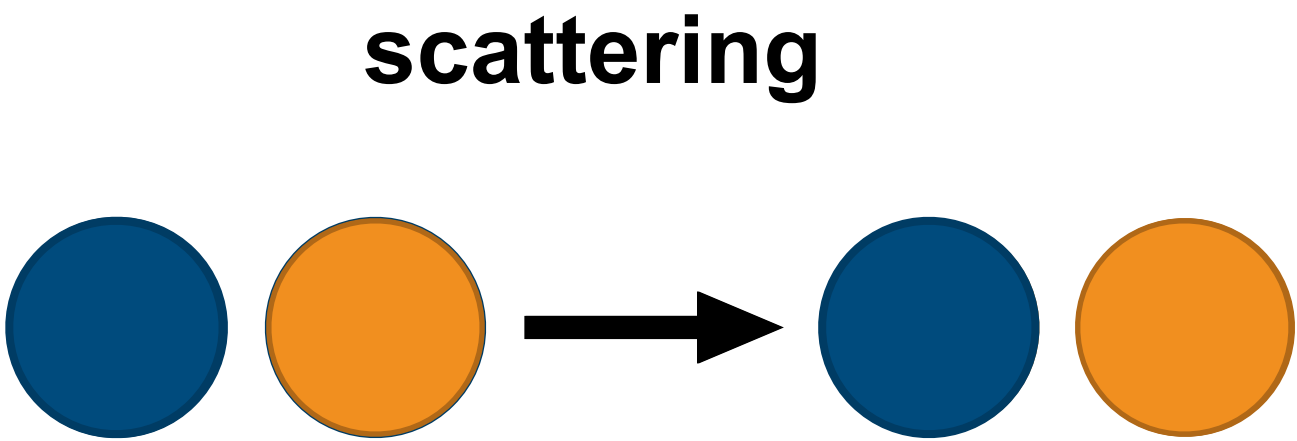
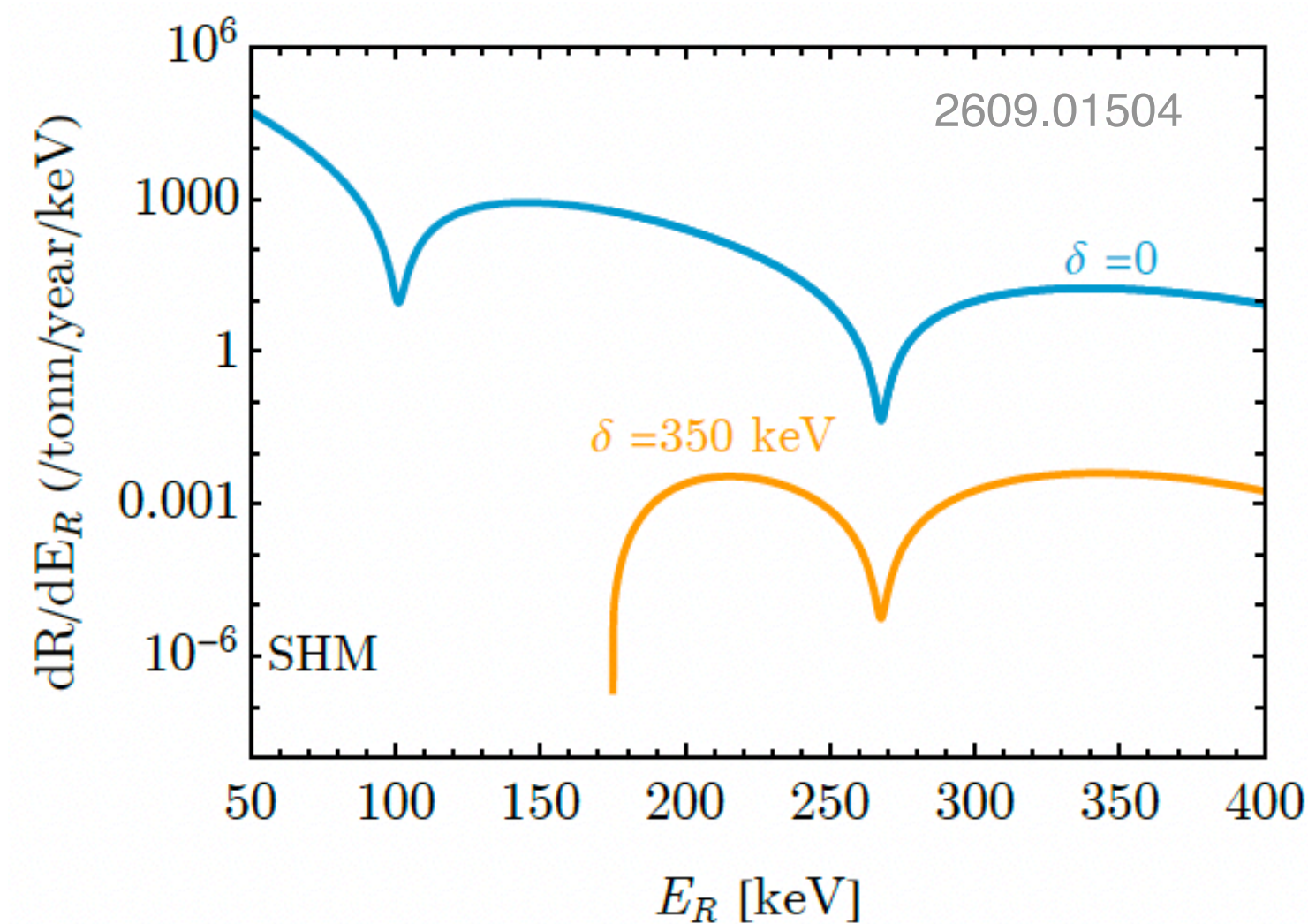
Inelastic dark matter?

Idea: have two dark matter states with small mass splitting
(can be natural)

Requires up scattering in direct detection

$$v_{\min} = \frac{1}{\sqrt{2m_N E_R}} \left| \frac{m_N E_R}{\mu_N} + \delta \right|$$

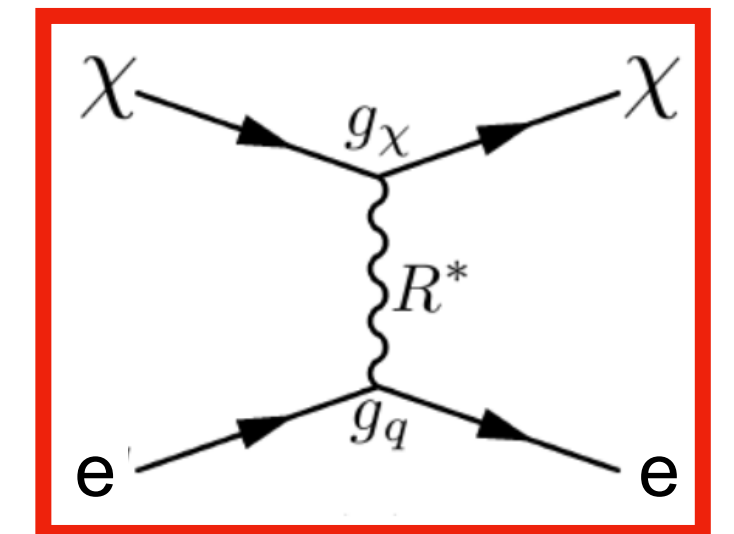
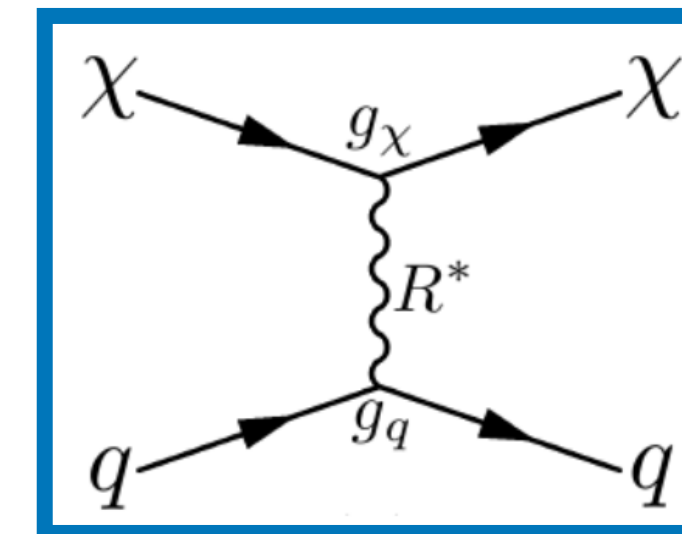
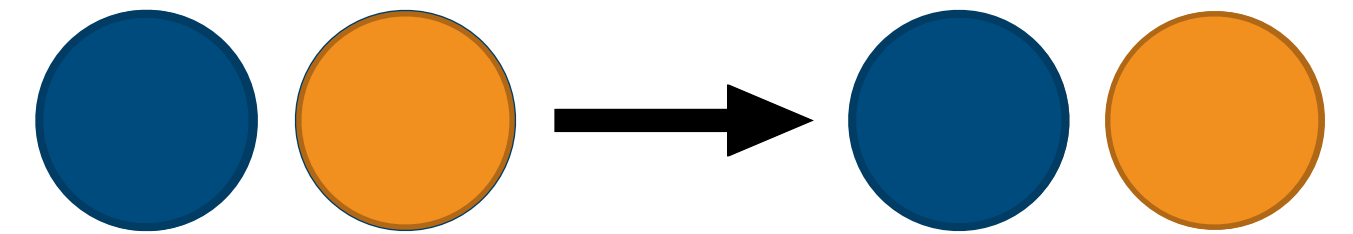
but: requires mass $\gtrsim 80$ GeV for scattering from halo
so: boosted inelastic?



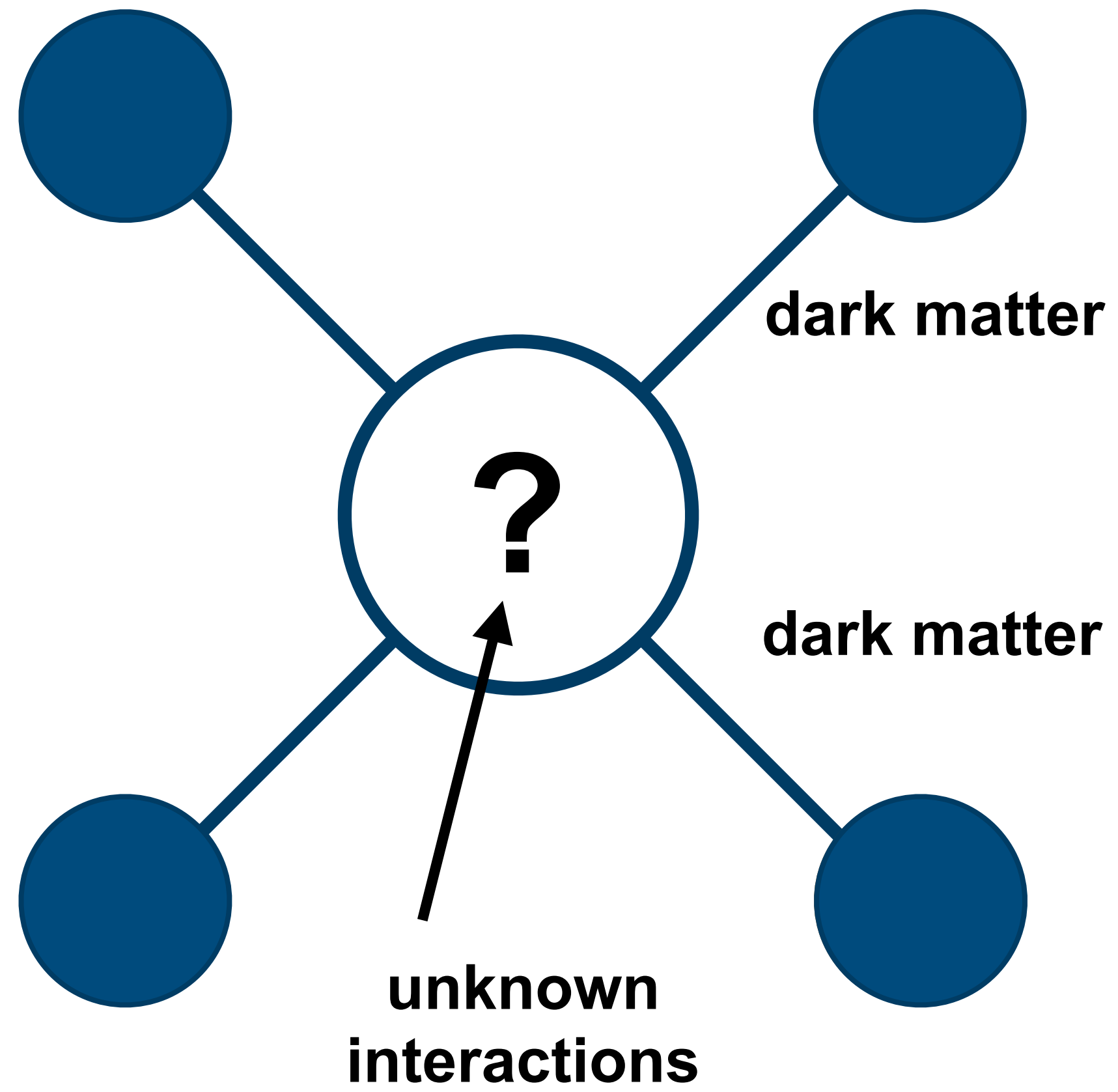
Summary direct detection

- complementary constraints, limits scale as
 $\sigma \propto g_\chi^2 g_{\text{SM}}^2$
- depend on which operator is present in NR limit
- Need to compare at model level!
- Note: Light mediators induce extra momentum dependence from propagator

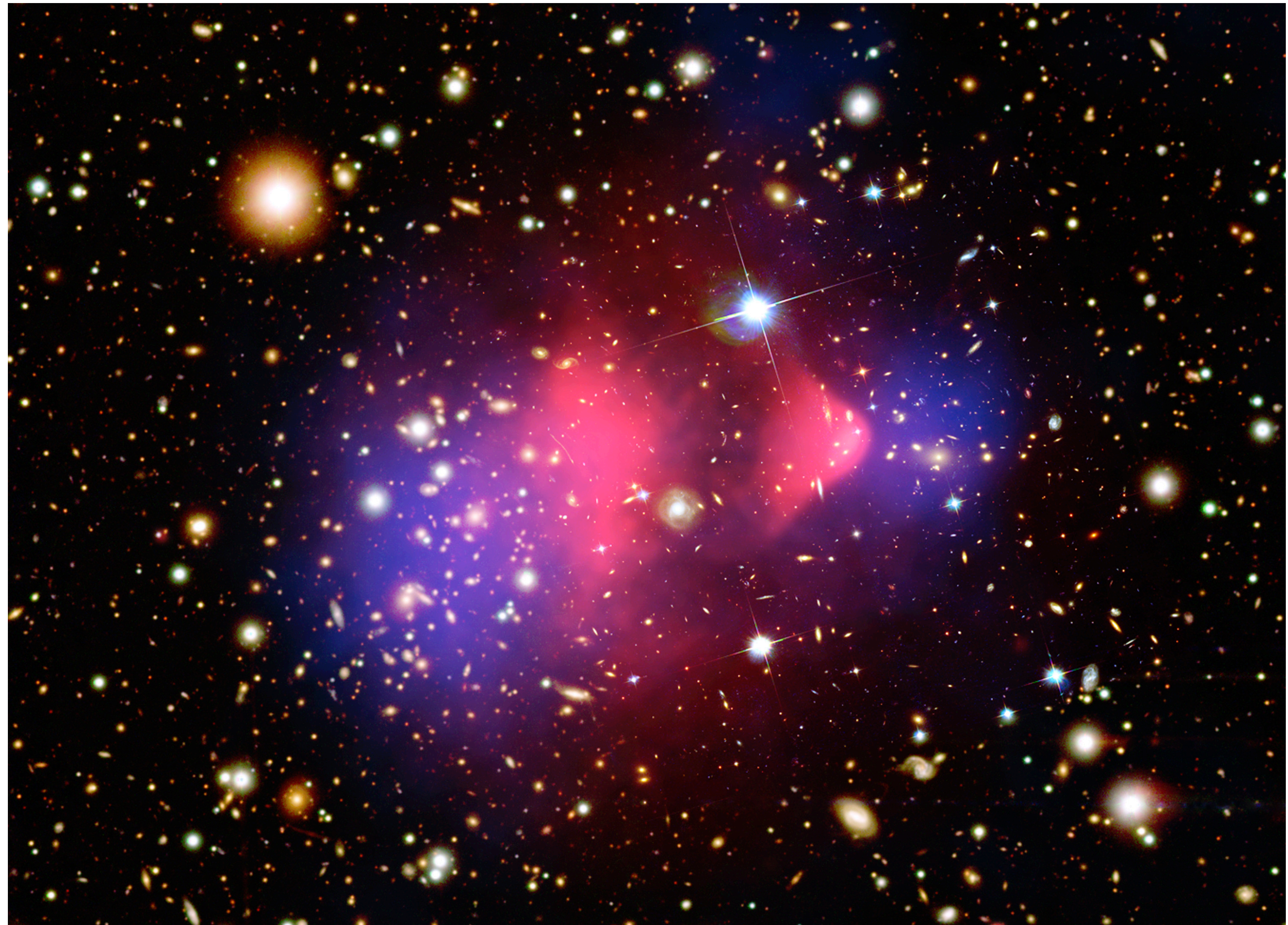
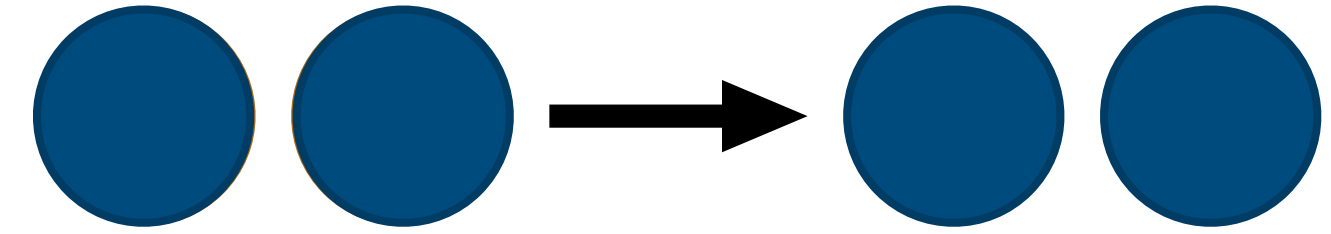
scattering



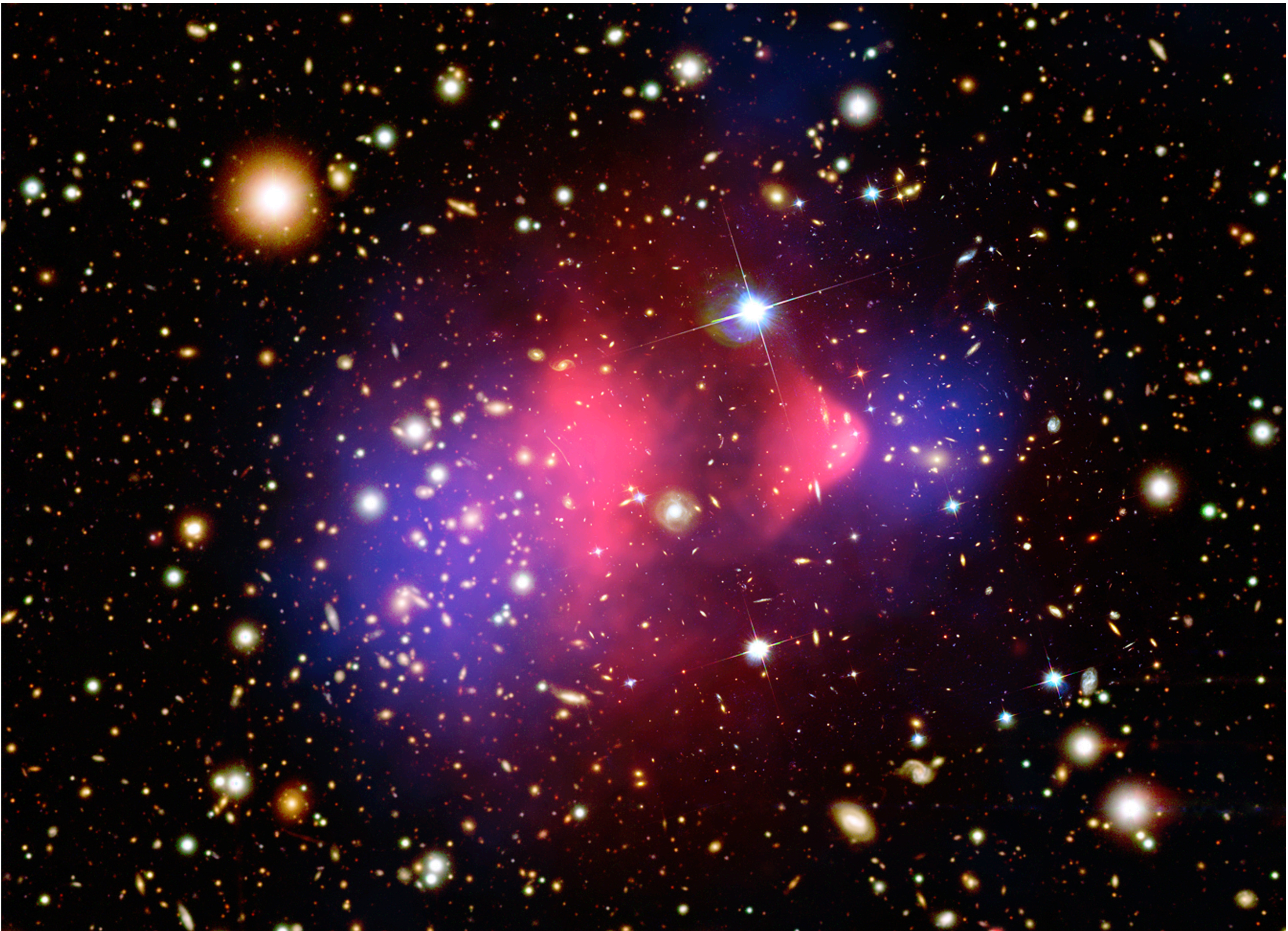
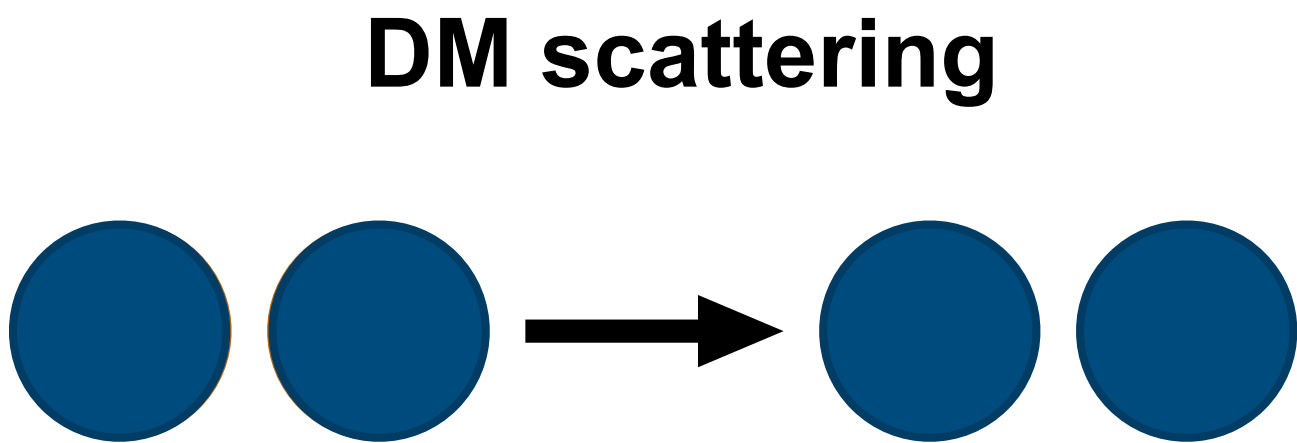
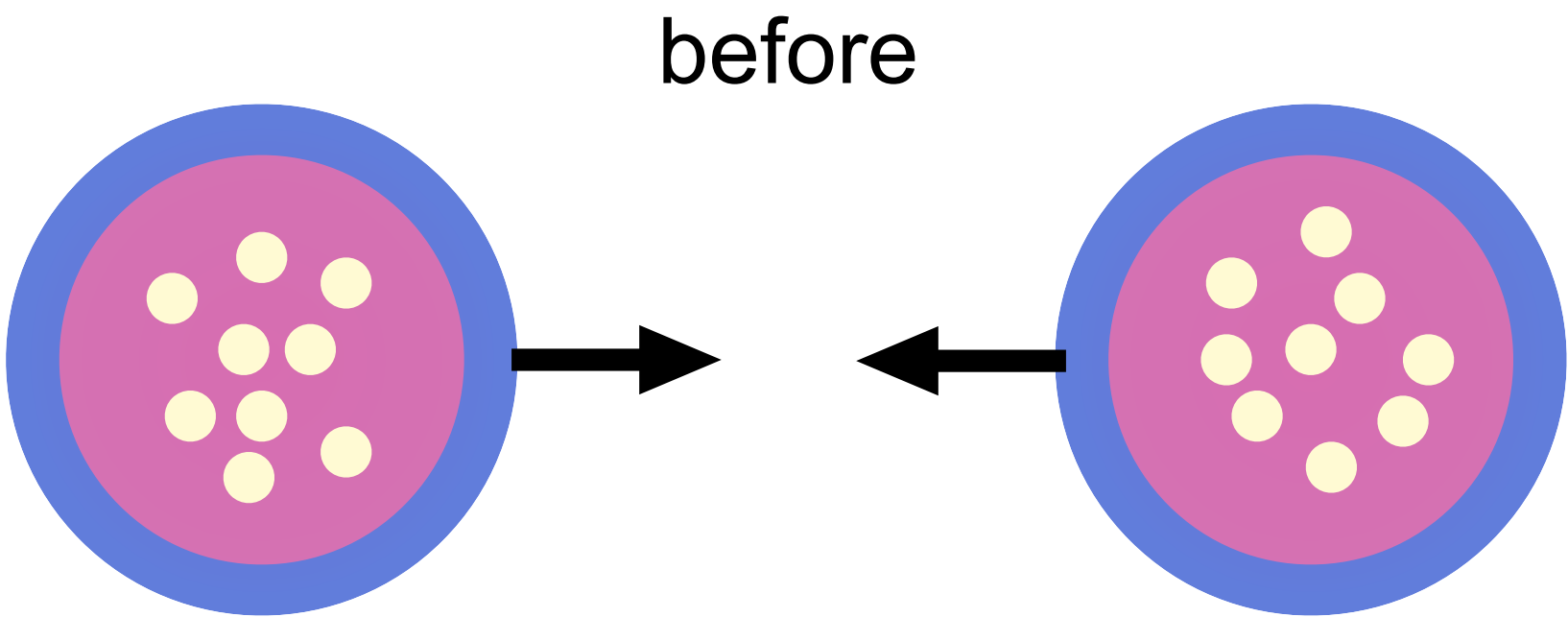
DM self-interactions



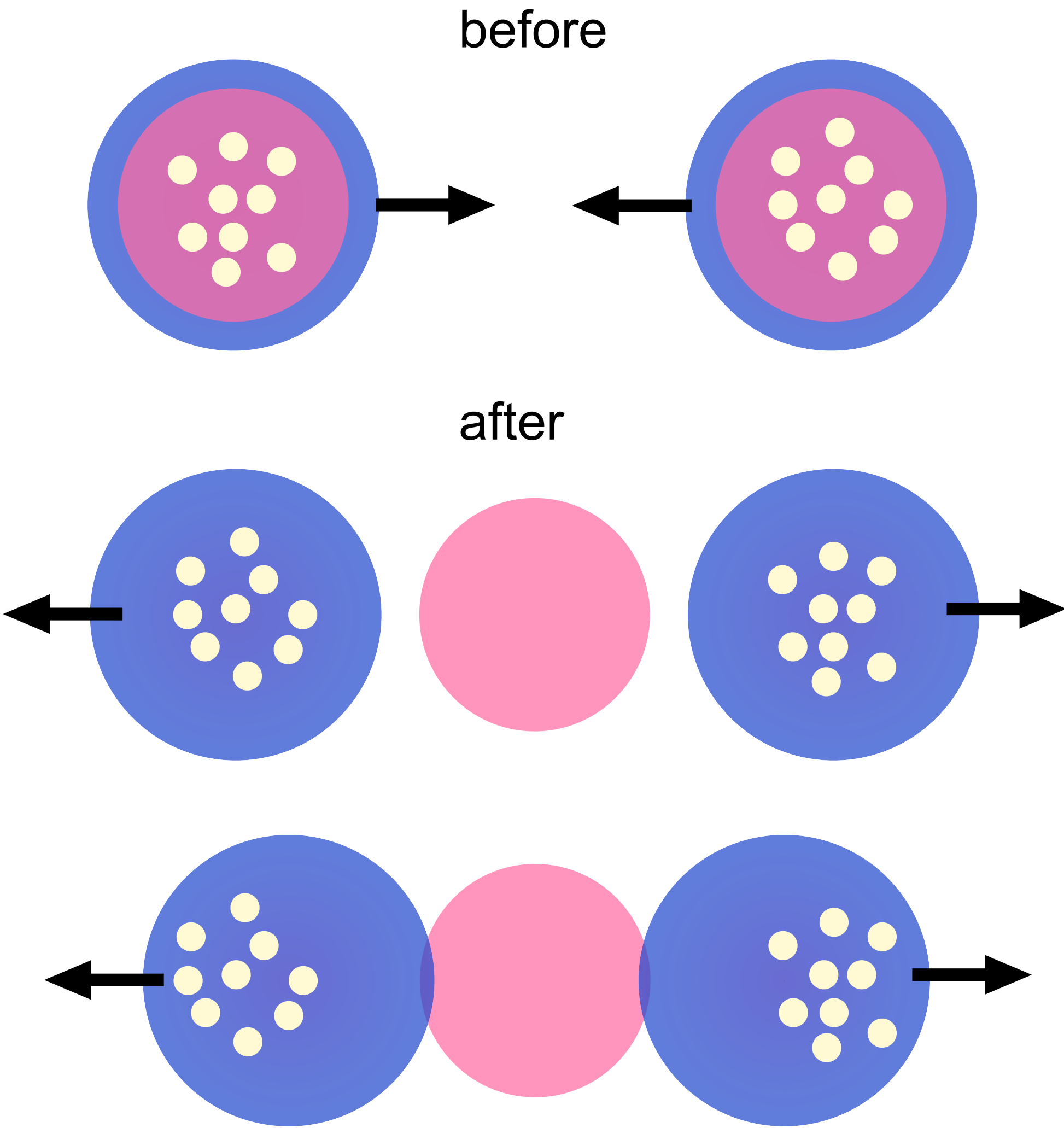
DM scattering



DM self-interactions

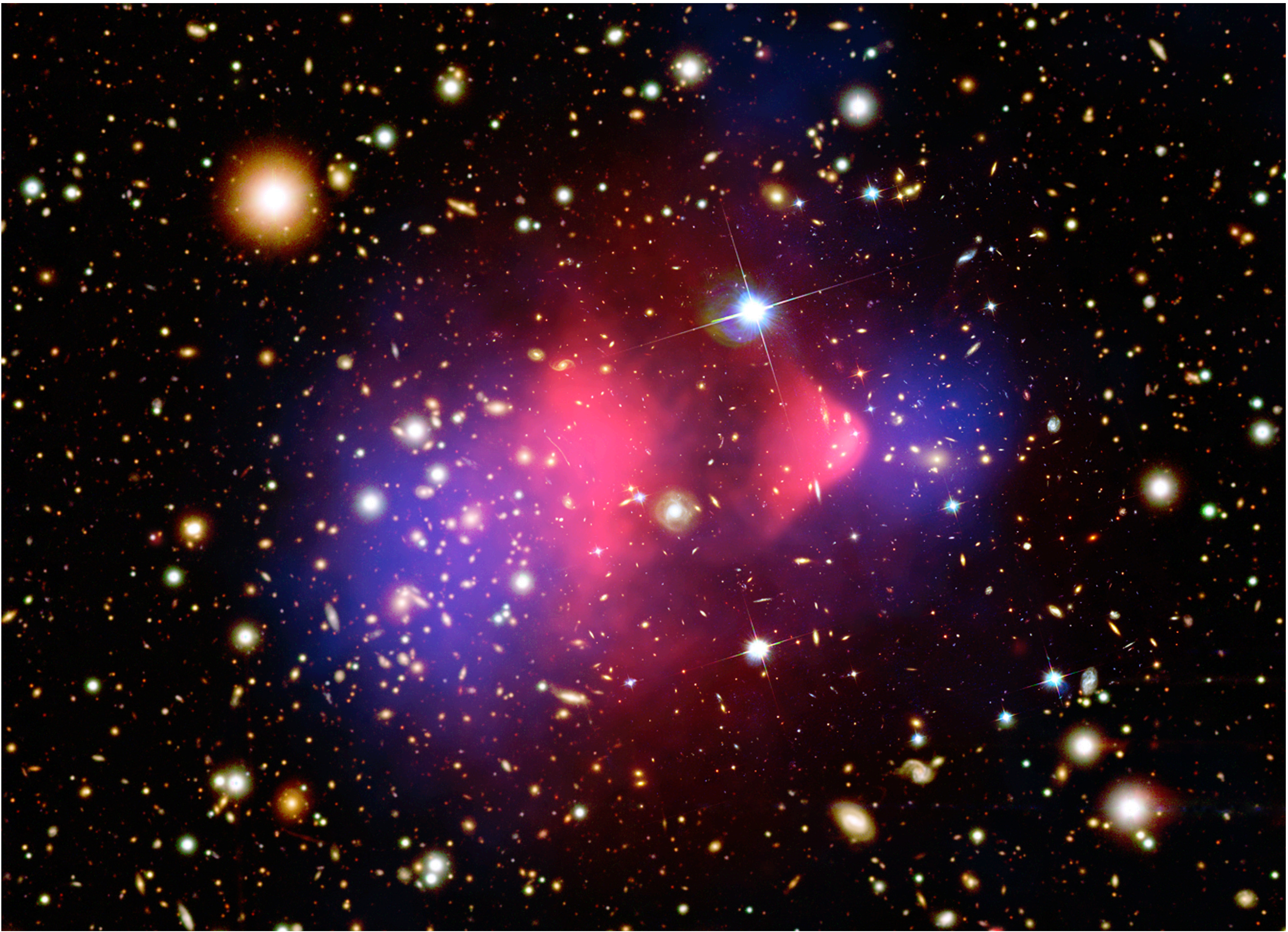
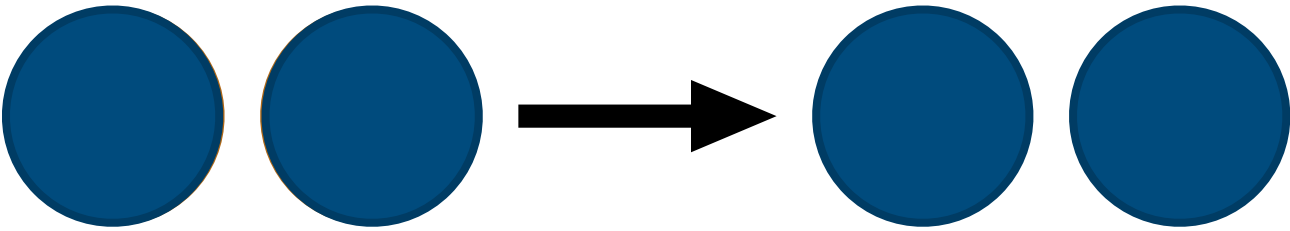


DM self-interactions



$$\sigma_T/m_\chi \lesssim 1\text{barn/GeV}$$

DM scattering

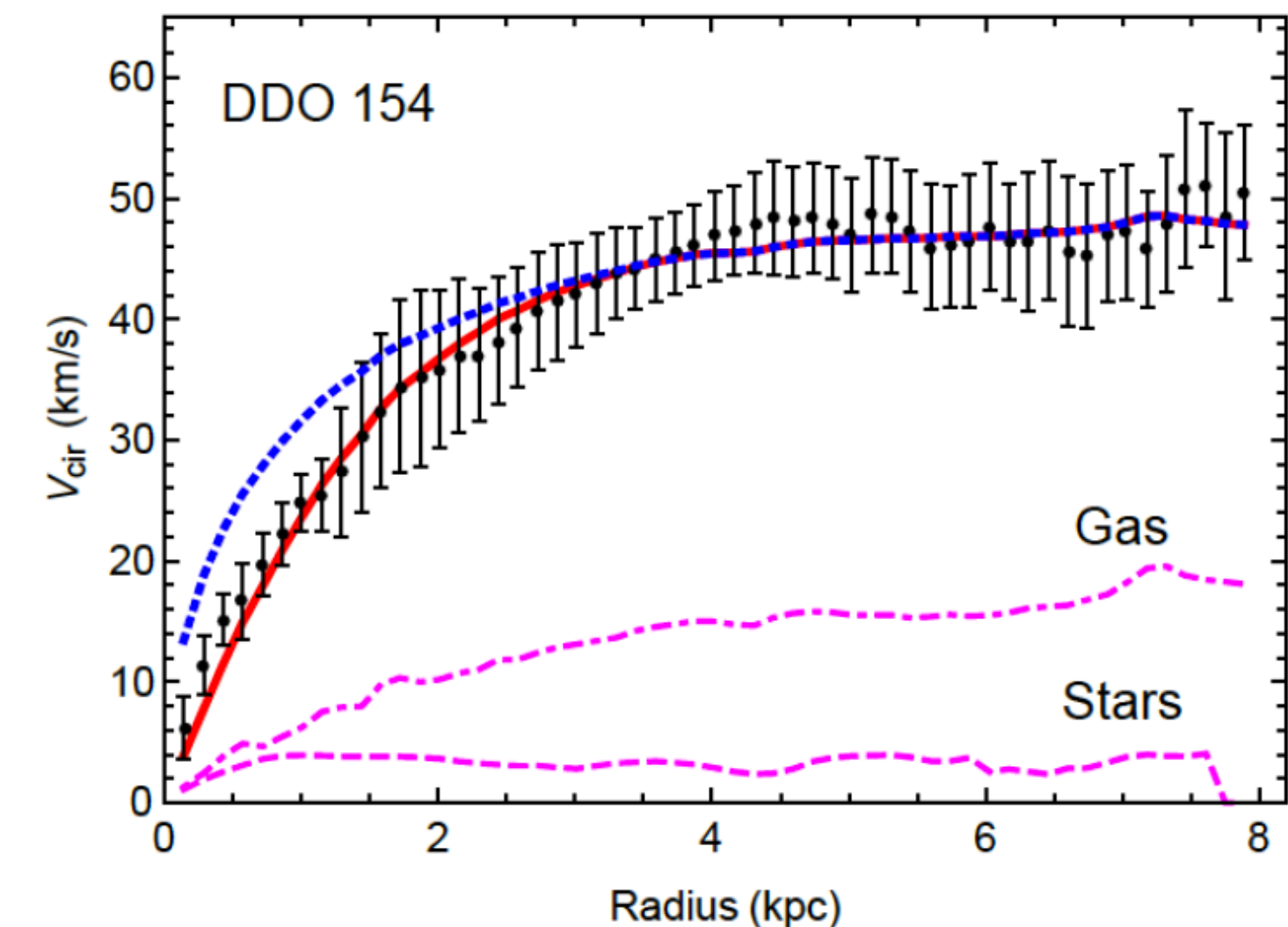
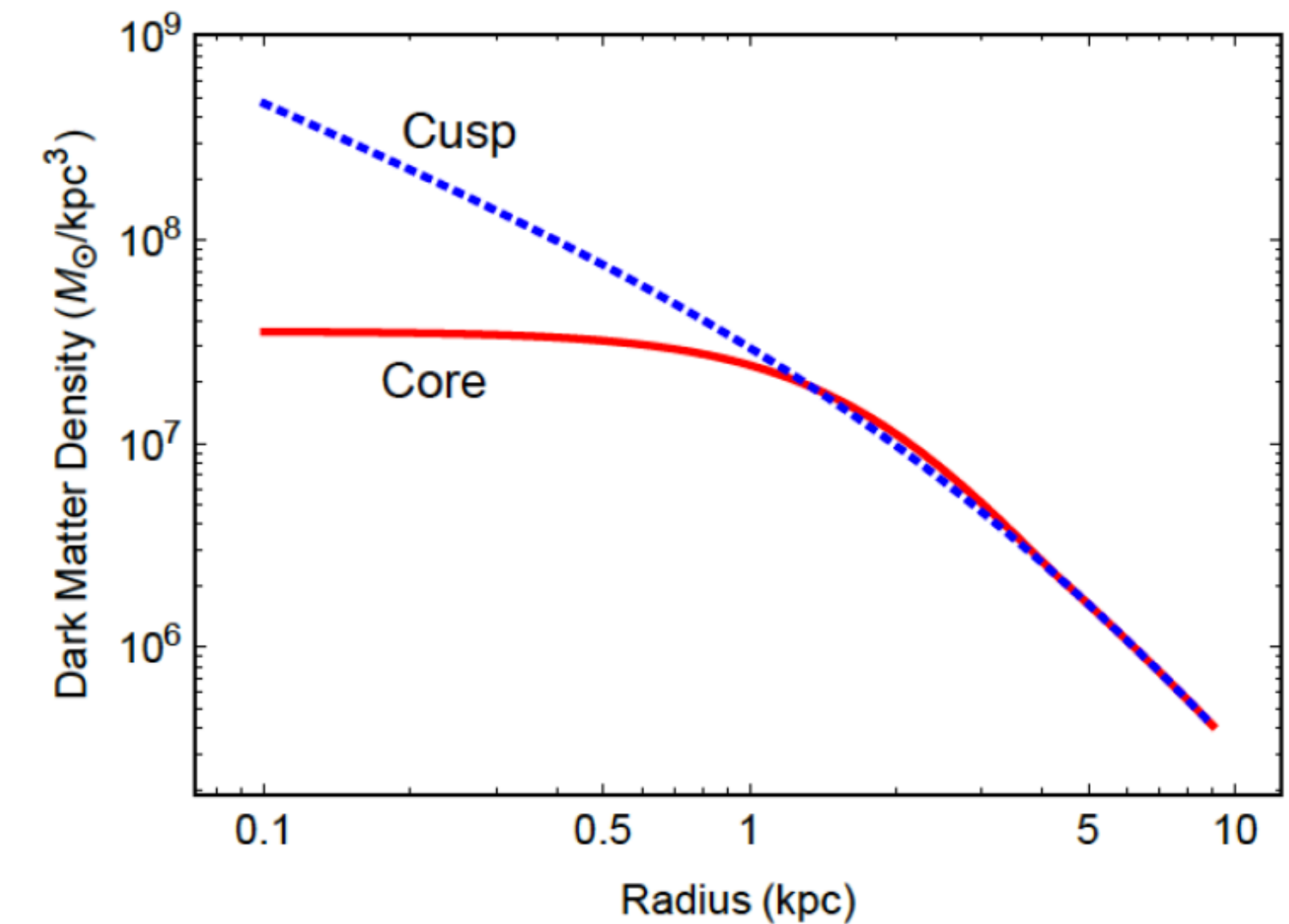
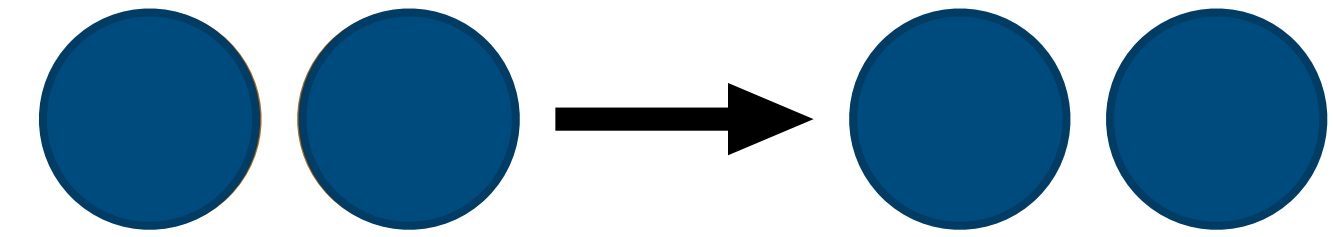


DM self-interactions interesting

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales
 - cusp- vs. core problem
 - ...
- relevant quantity

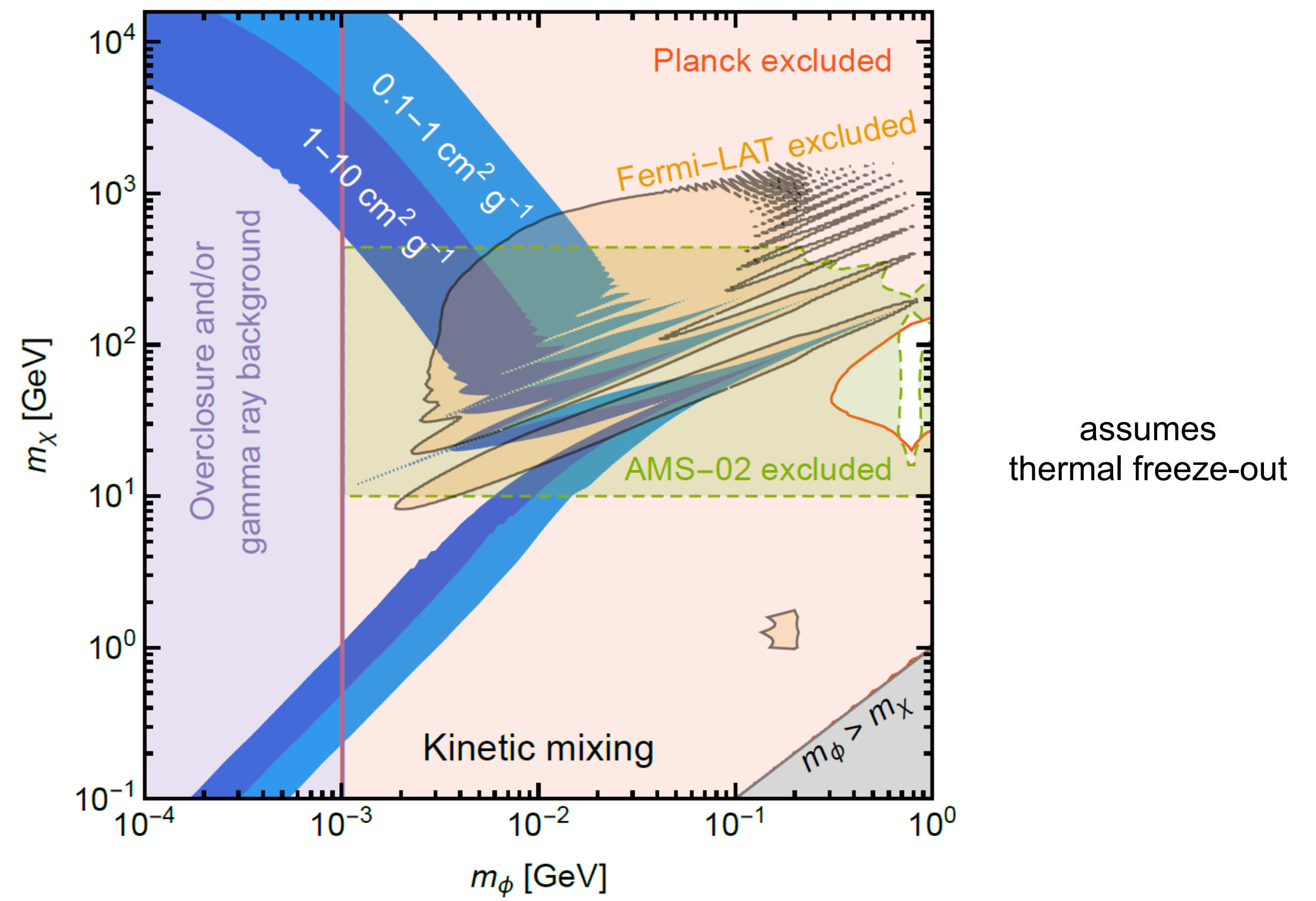
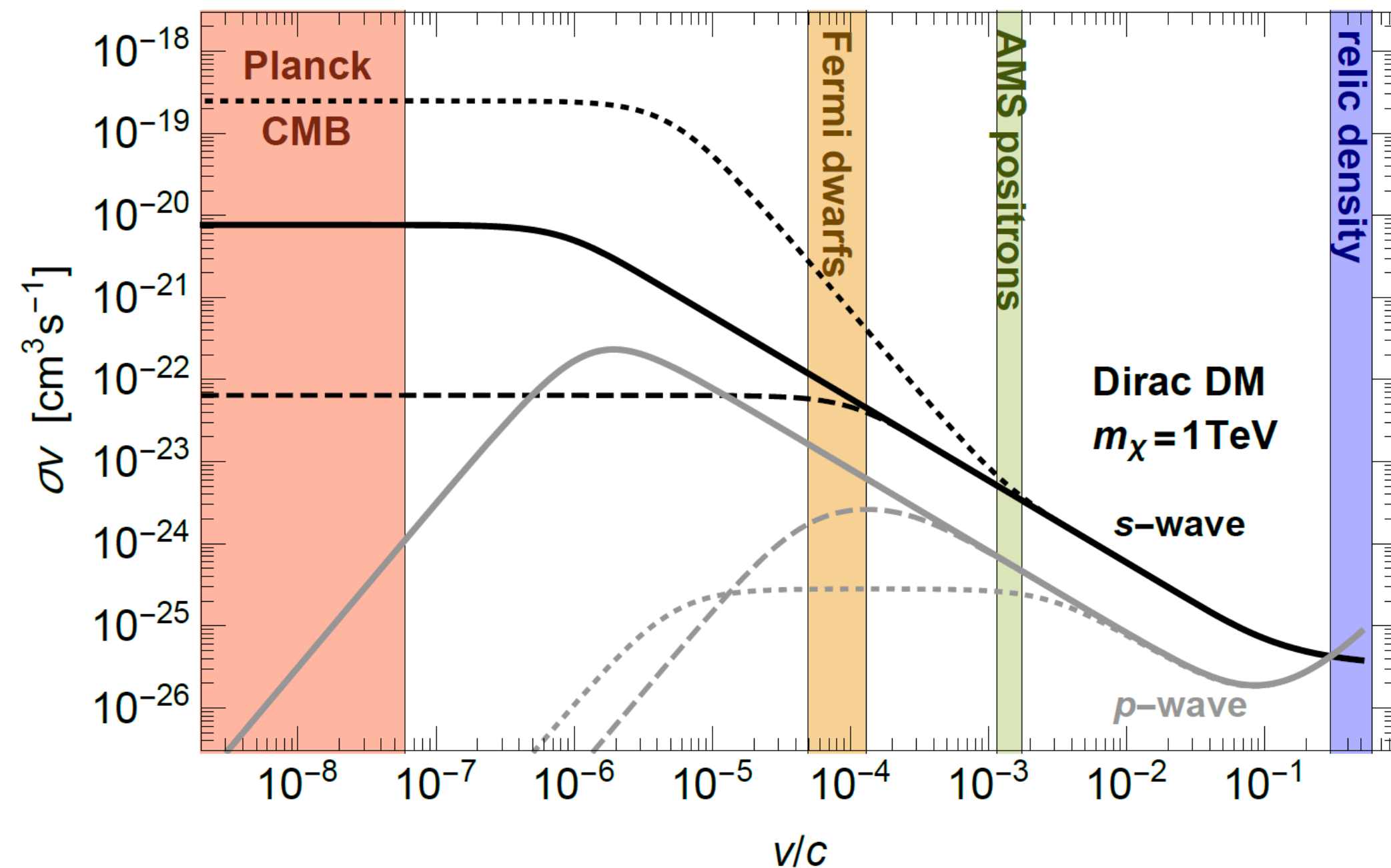
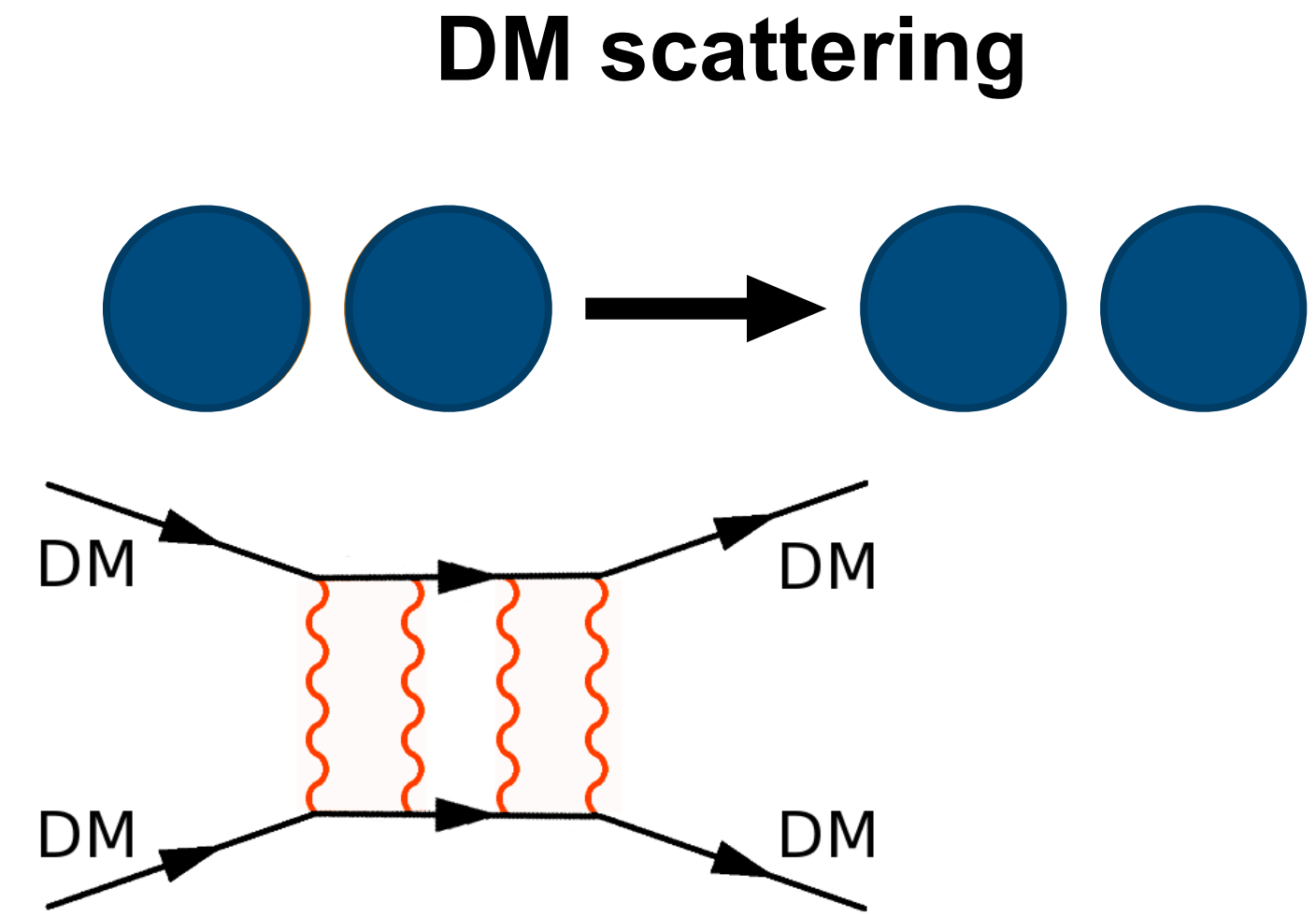
$$\sigma_T/m_\chi \lesssim 1\text{barn/GeV}$$

DM scattering

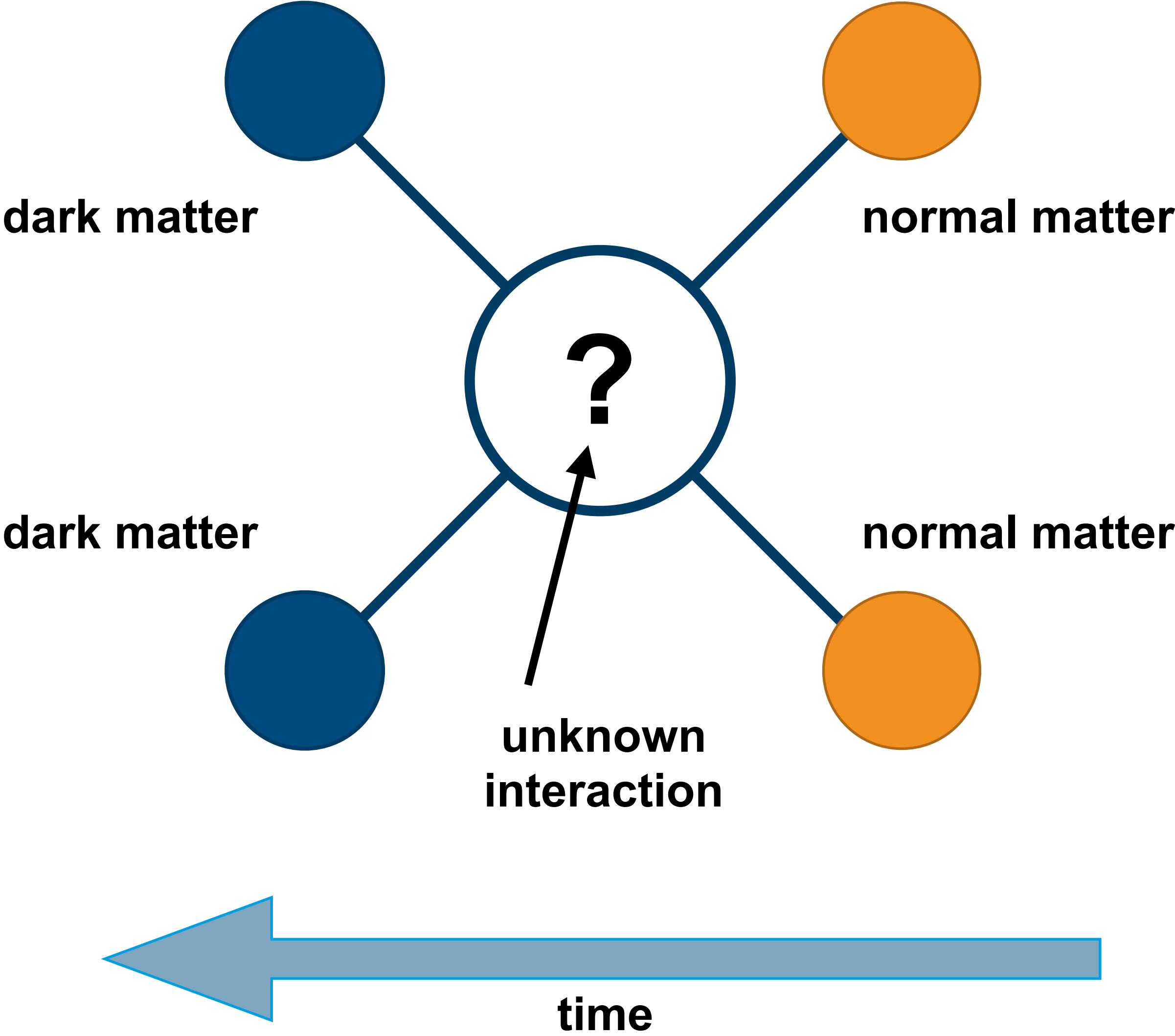


DM self-interactions interesting

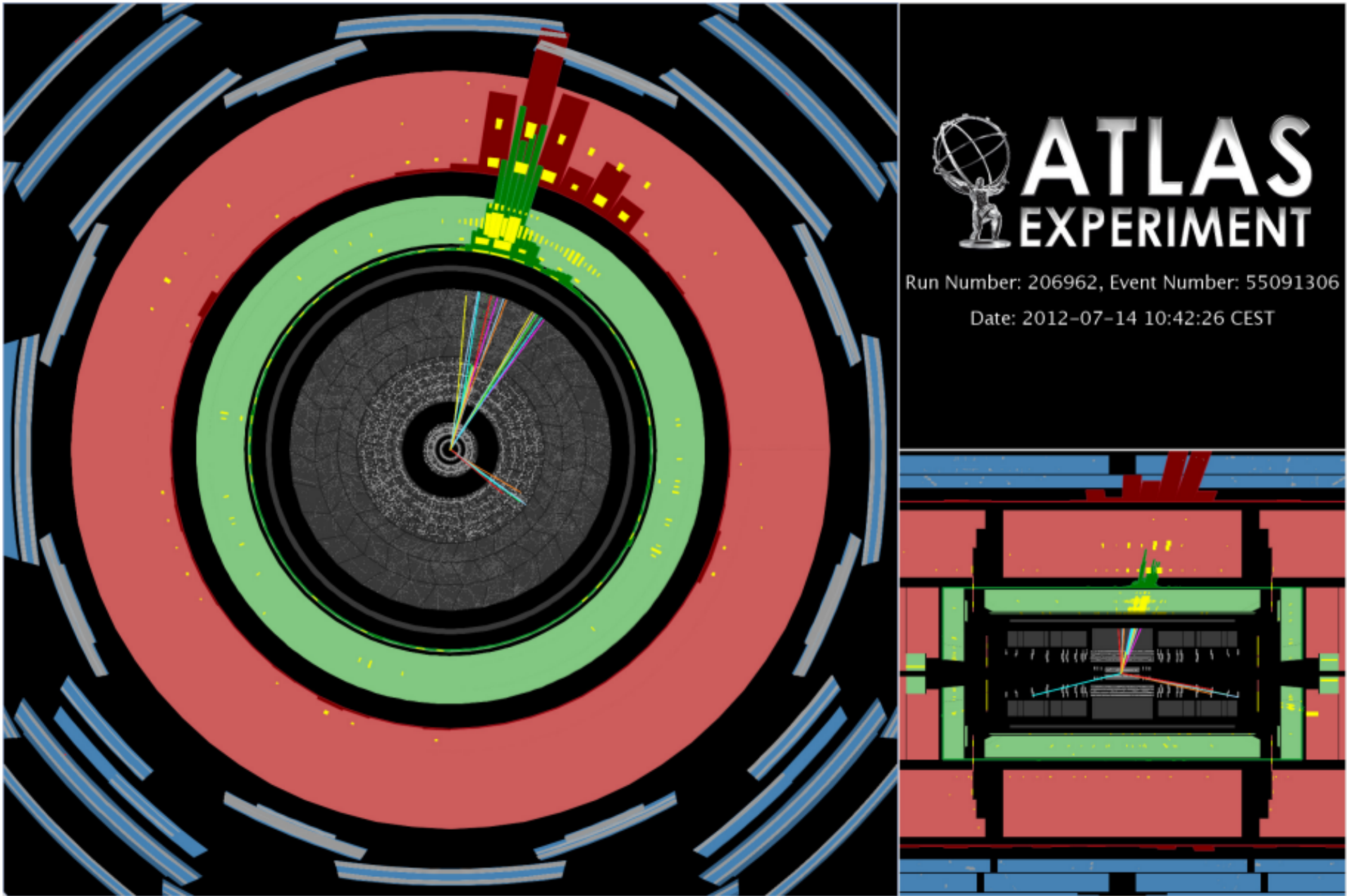
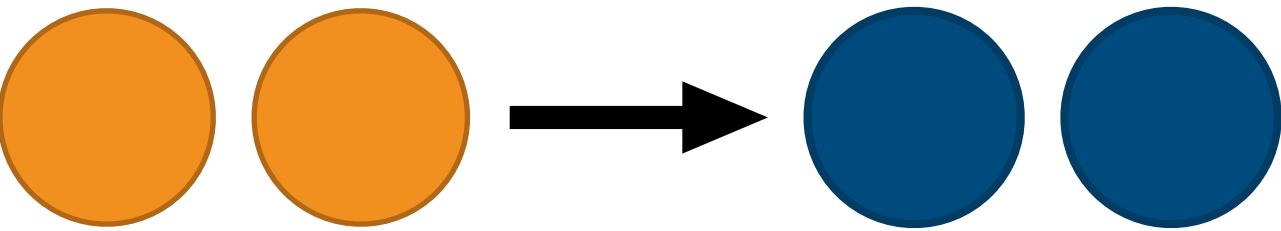
- $\sigma_T/m_\chi \simeq 1 \text{ b/GeV}$ actually possible with light mediators
- non-perturbative effects due to multiple mediator exchange enhance DM self-interactions
- but also Sommerfeld enhancement $\rightarrow$ constraints



Dark matter at colliders

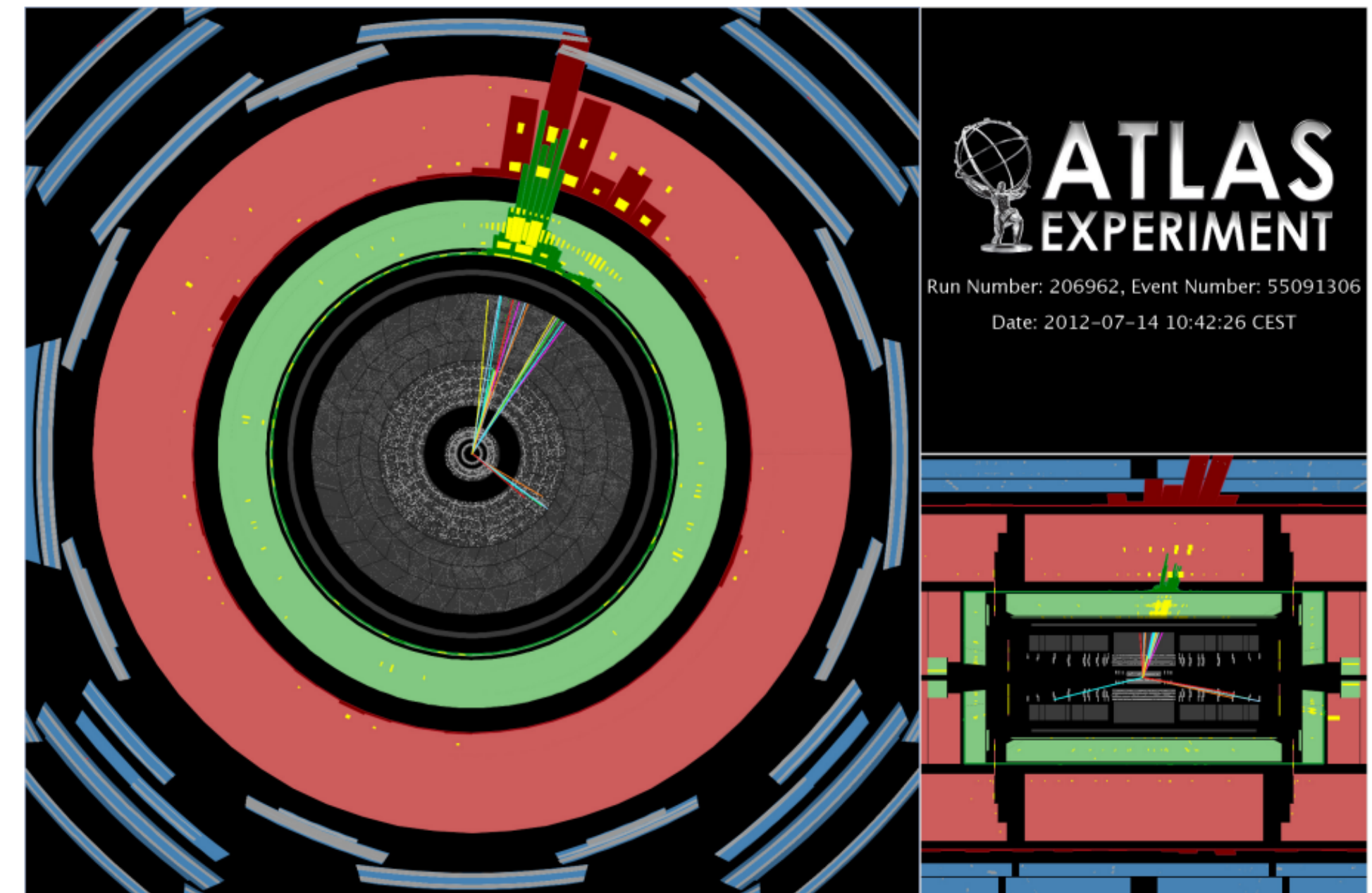
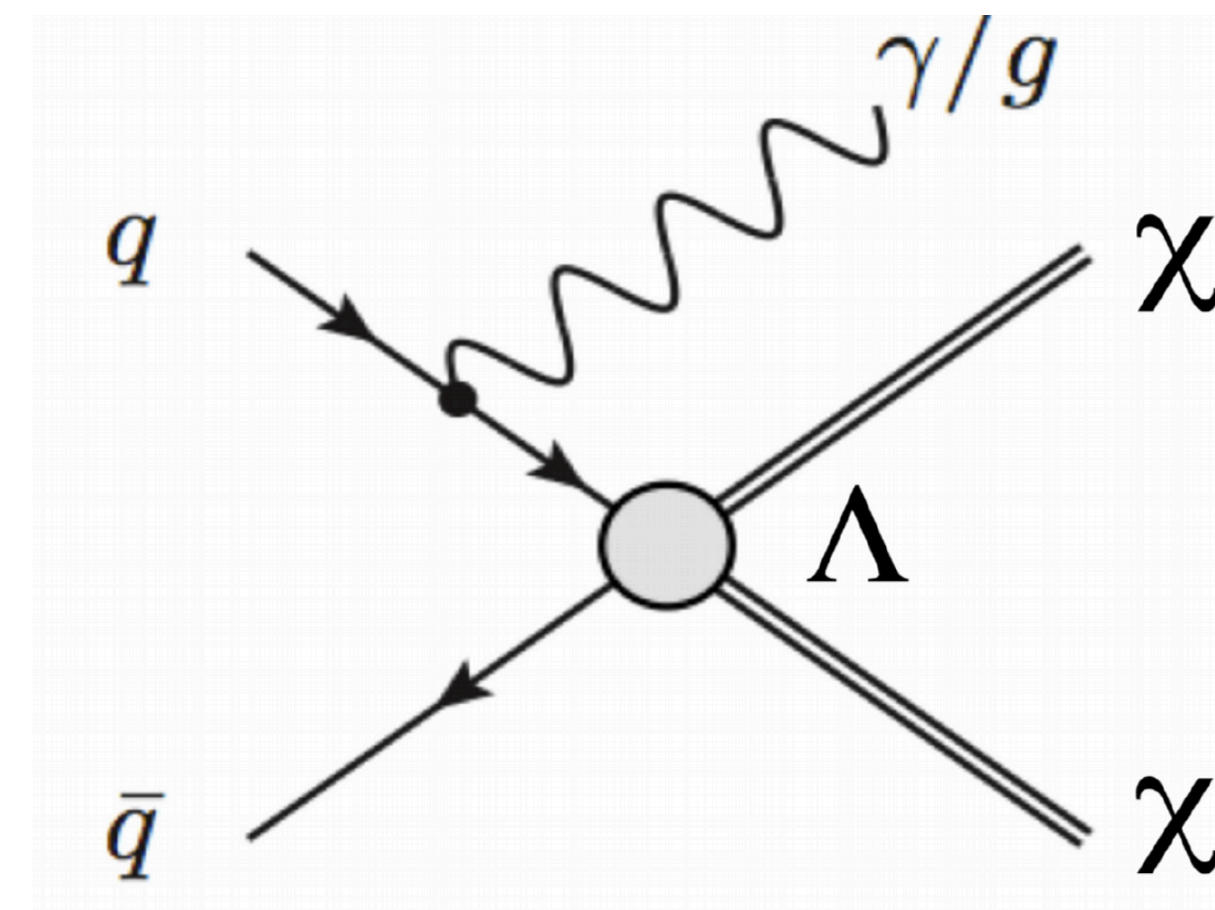


DM production



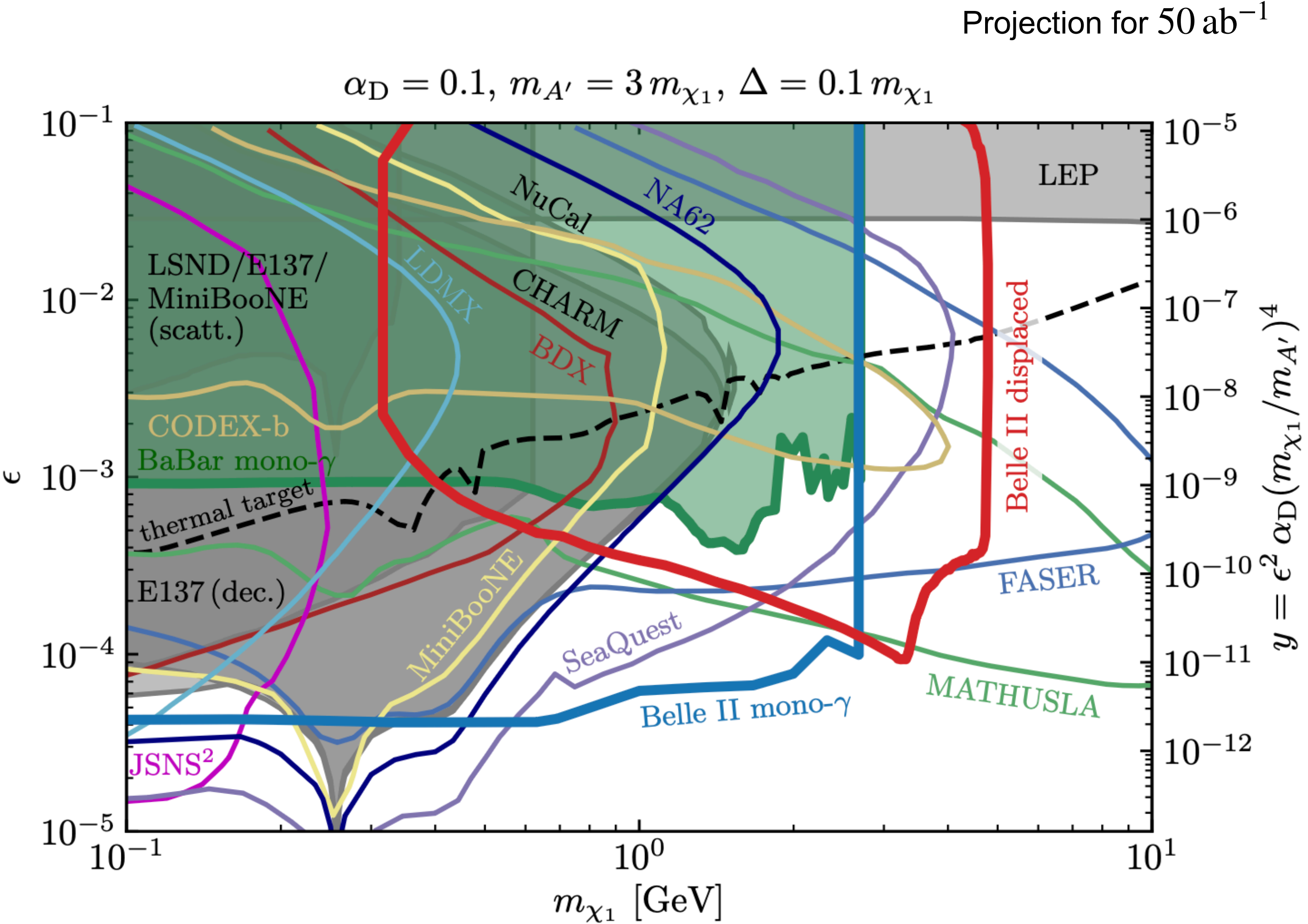
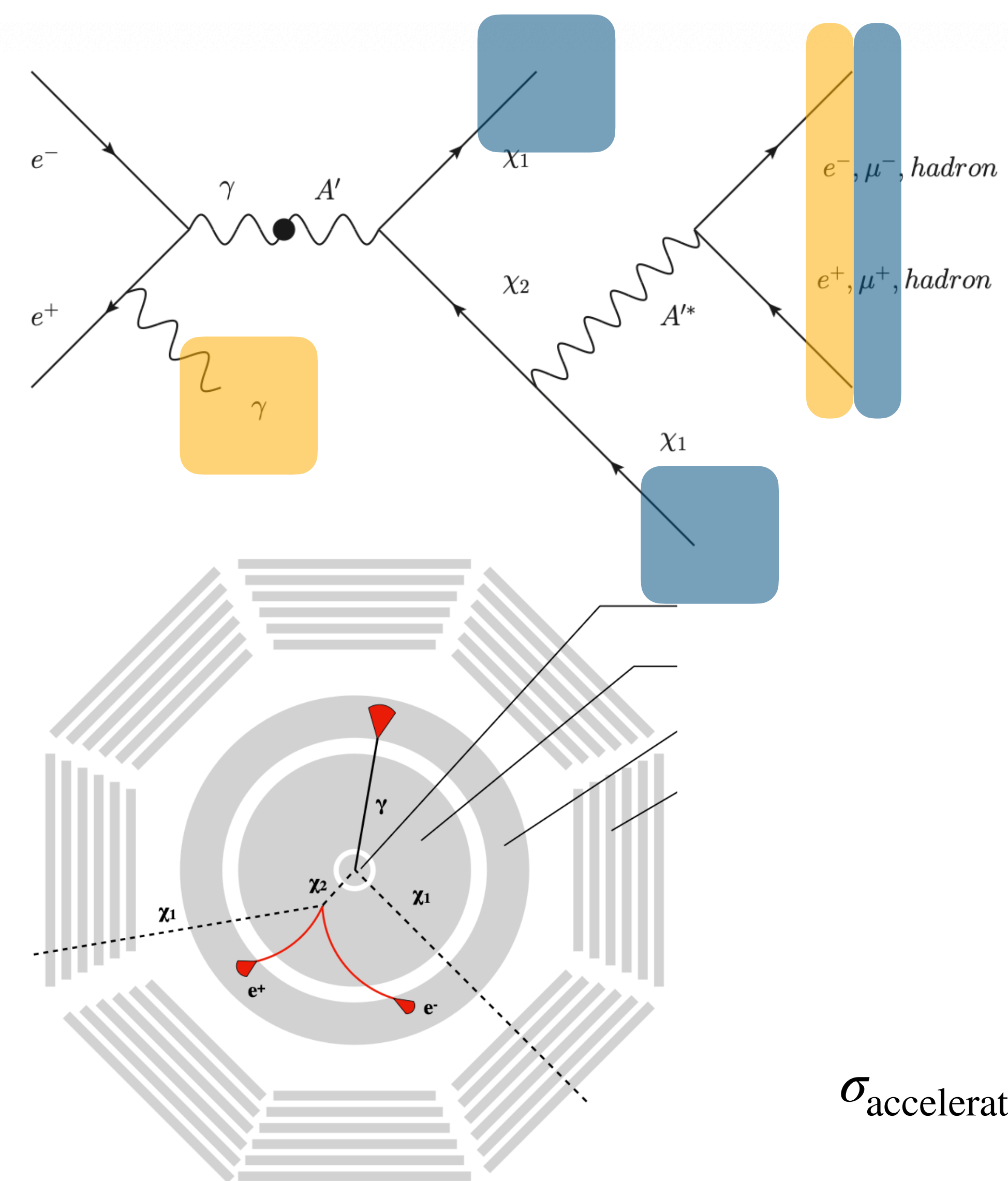
Dark matter at colliders

- Problem with dark matter: leaves no signal in detector
- Vanilla signal: mono-X
- but cannot use effective description — need models



Dark matter at colliders

just one example for Belle II



$$\sigma_{\text{accelerator}} \propto g_{\text{SM}}^2$$

1911.03176

Summary and wishlist for Patrick

- new light mediators
- $10 \text{ MeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$
- suppressed annihilations for $v \ll 1$

complementarity of searches

$$\sigma_{\text{accelerator}} \propto g_{\text{SM}}^2$$

$$\sigma_{\text{ann}} \propto g_{\text{SM}}^2 g_\chi^2 \quad \text{or} \quad g_\chi^4$$

$$\sigma_{\text{DD}} \propto g_{\text{SM}}^2 g_\chi^2$$

$$\sigma_{\text{SIDM}} \propto g_\chi^4$$



Thank you!