MeV-GeV direct detection overview

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Outline

- Introduction
  DM hints
  (Theory) DM challenges

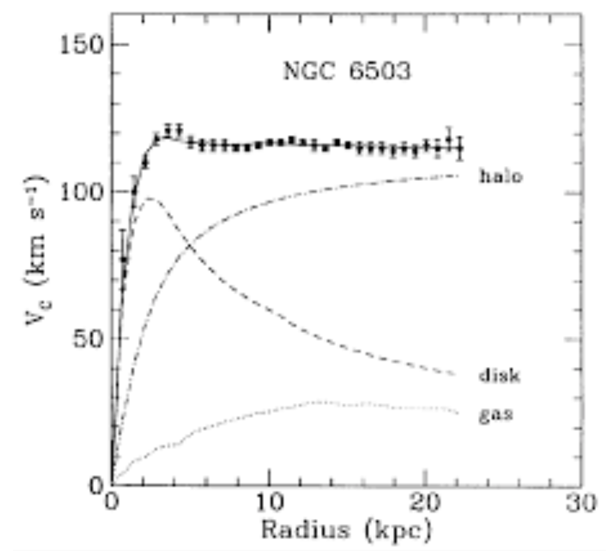
- Direct detection phenomenology
  Migdal effect
  Cosmic ray boosted dark matter
  Blazar boosted dark matter

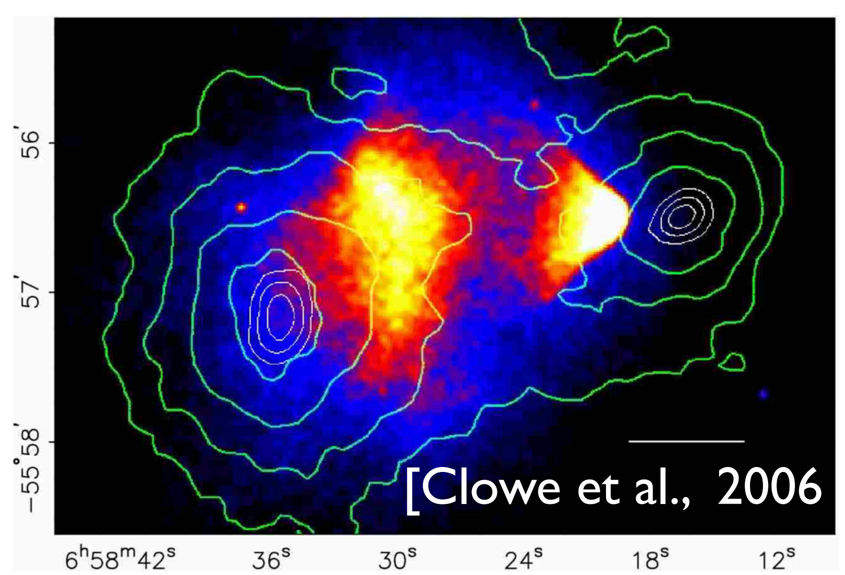
- Conclusions

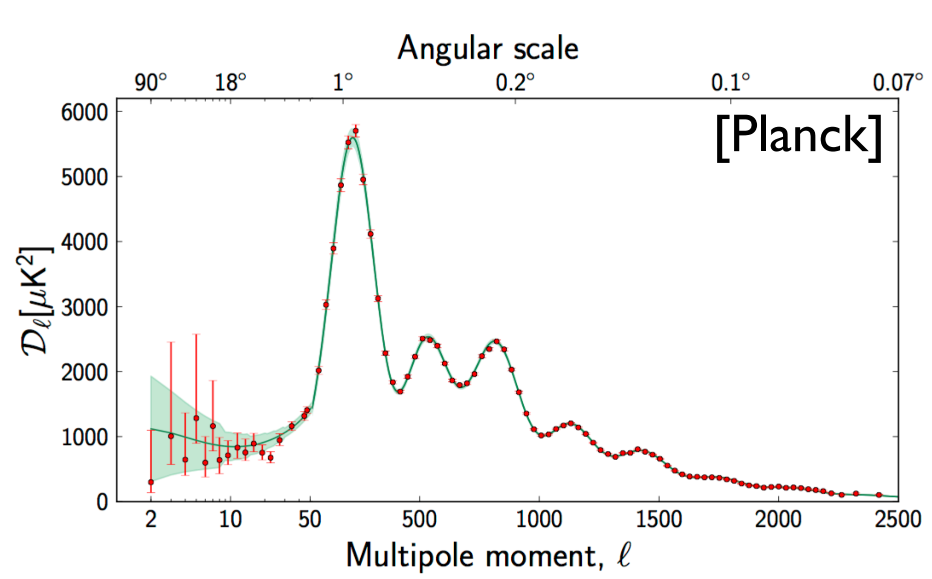
Introduction

What is the universe made of?

Observations







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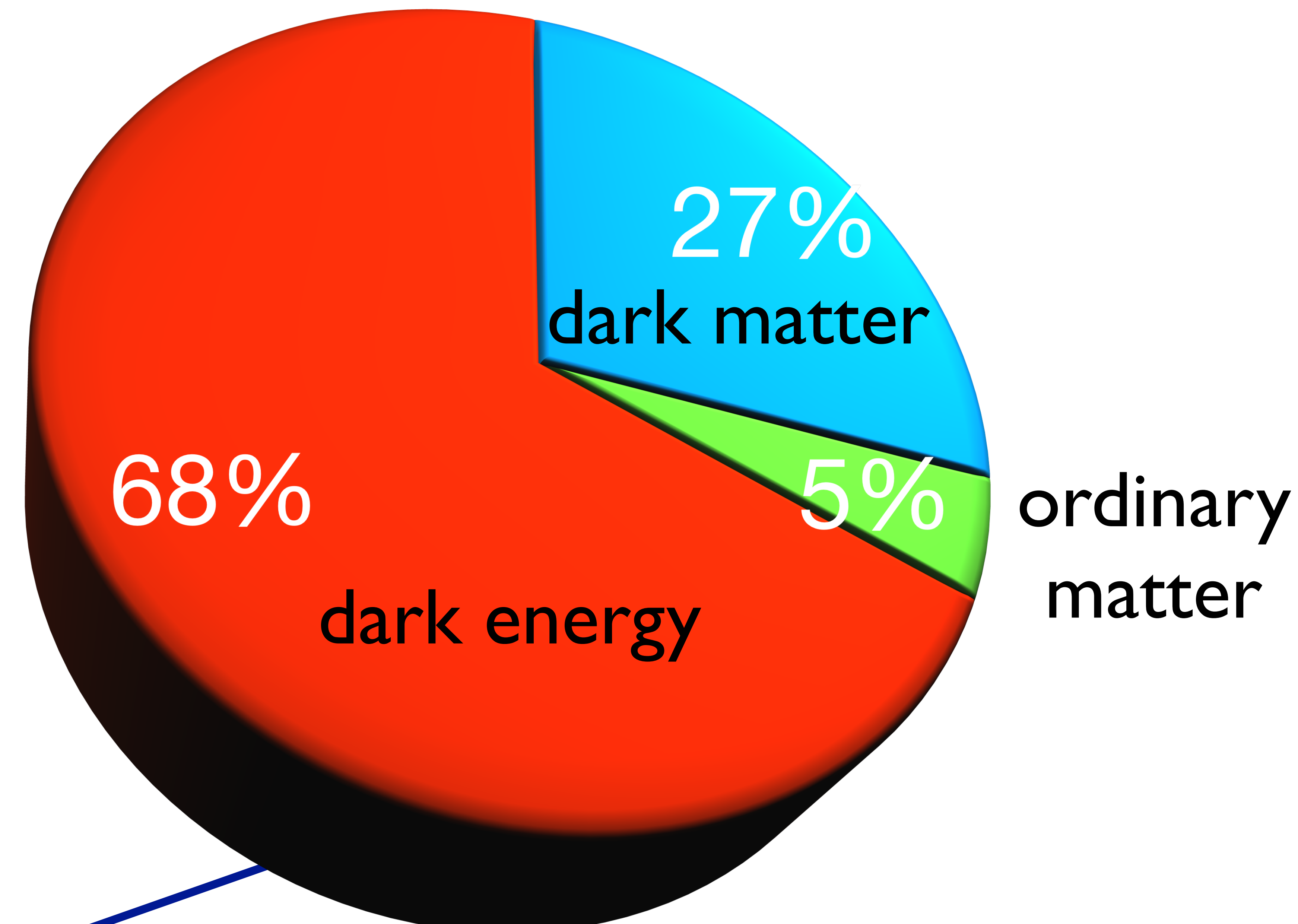

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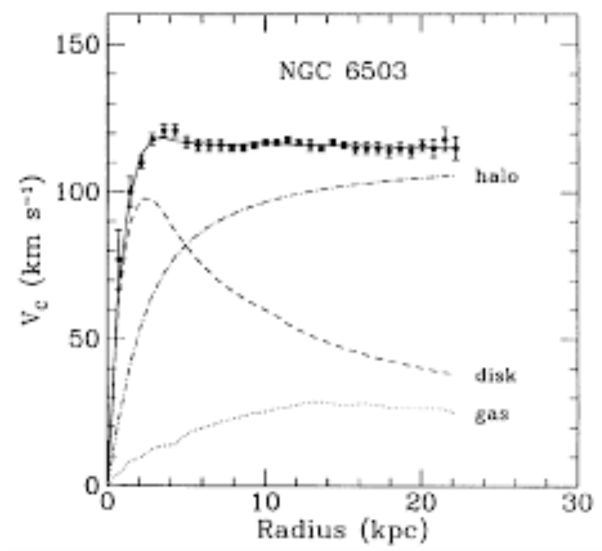

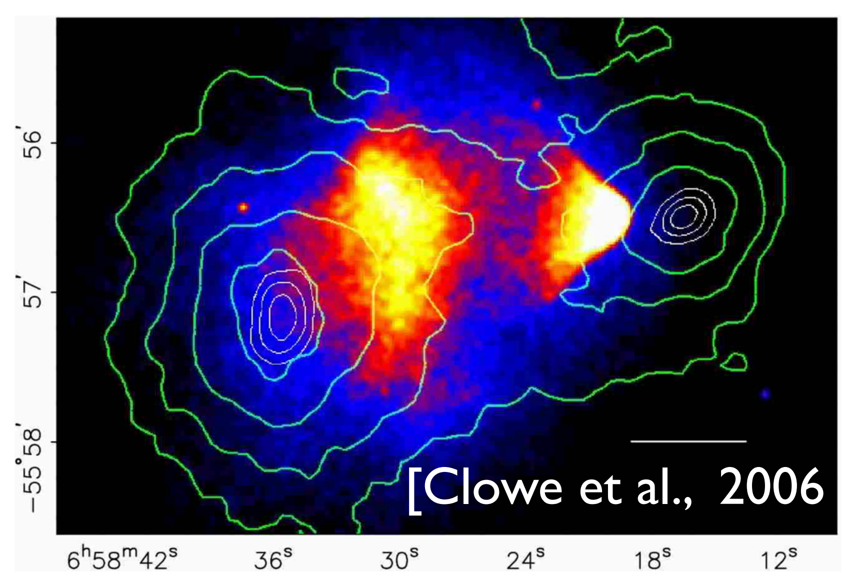

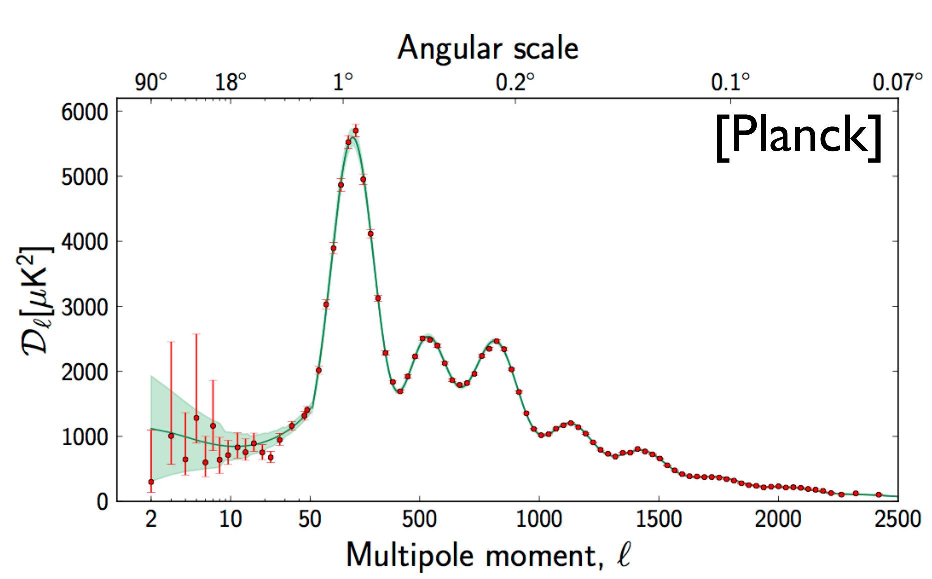

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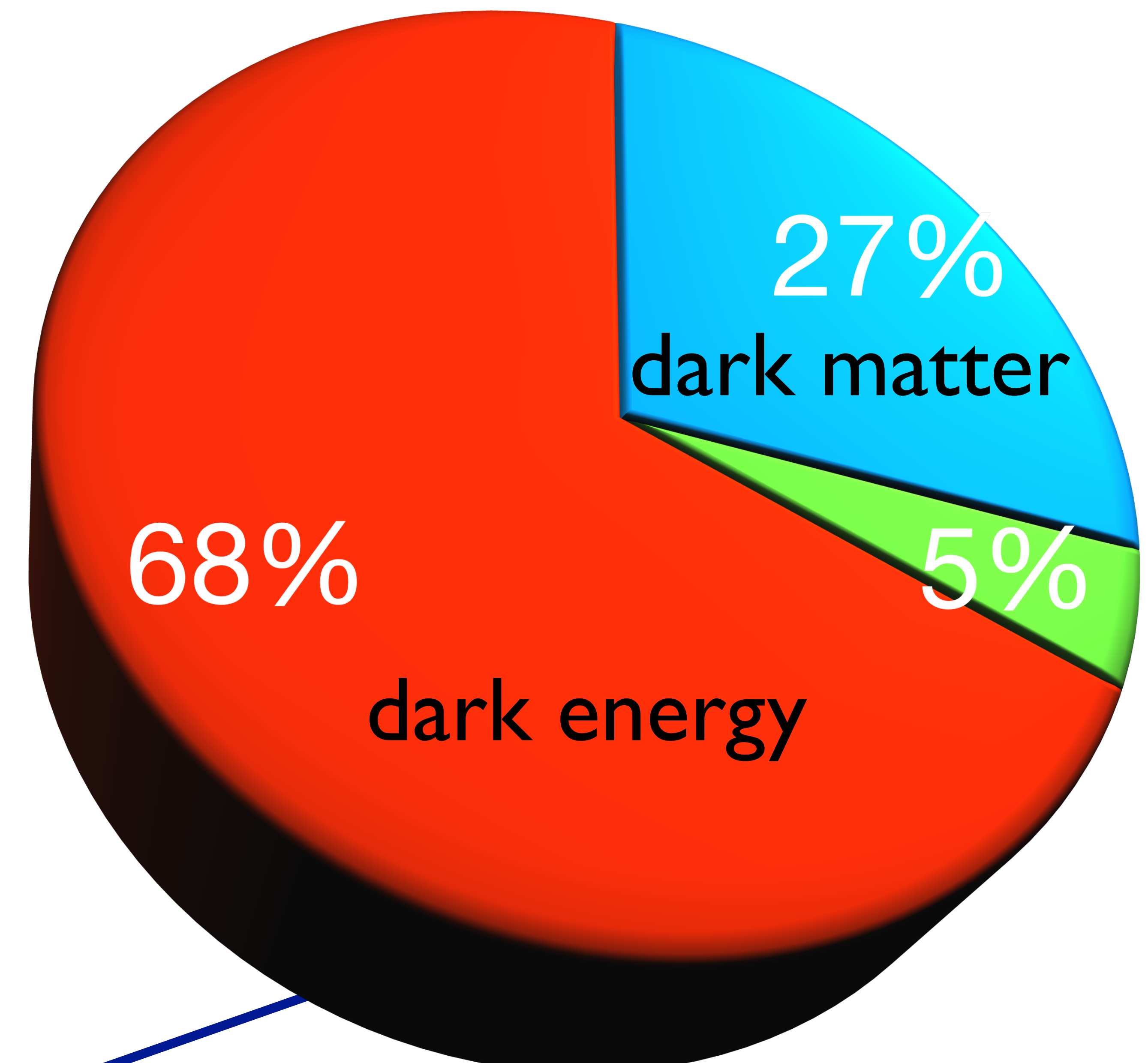
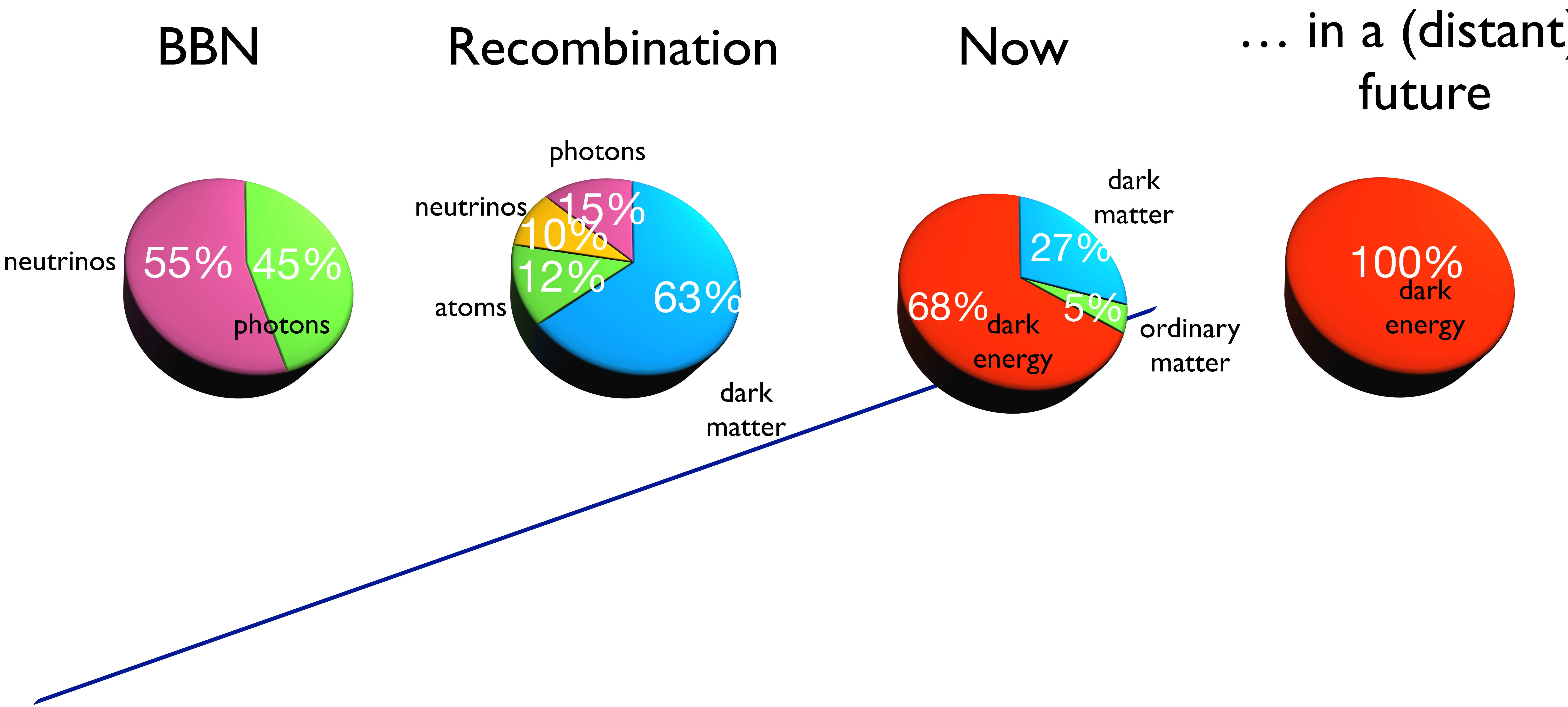


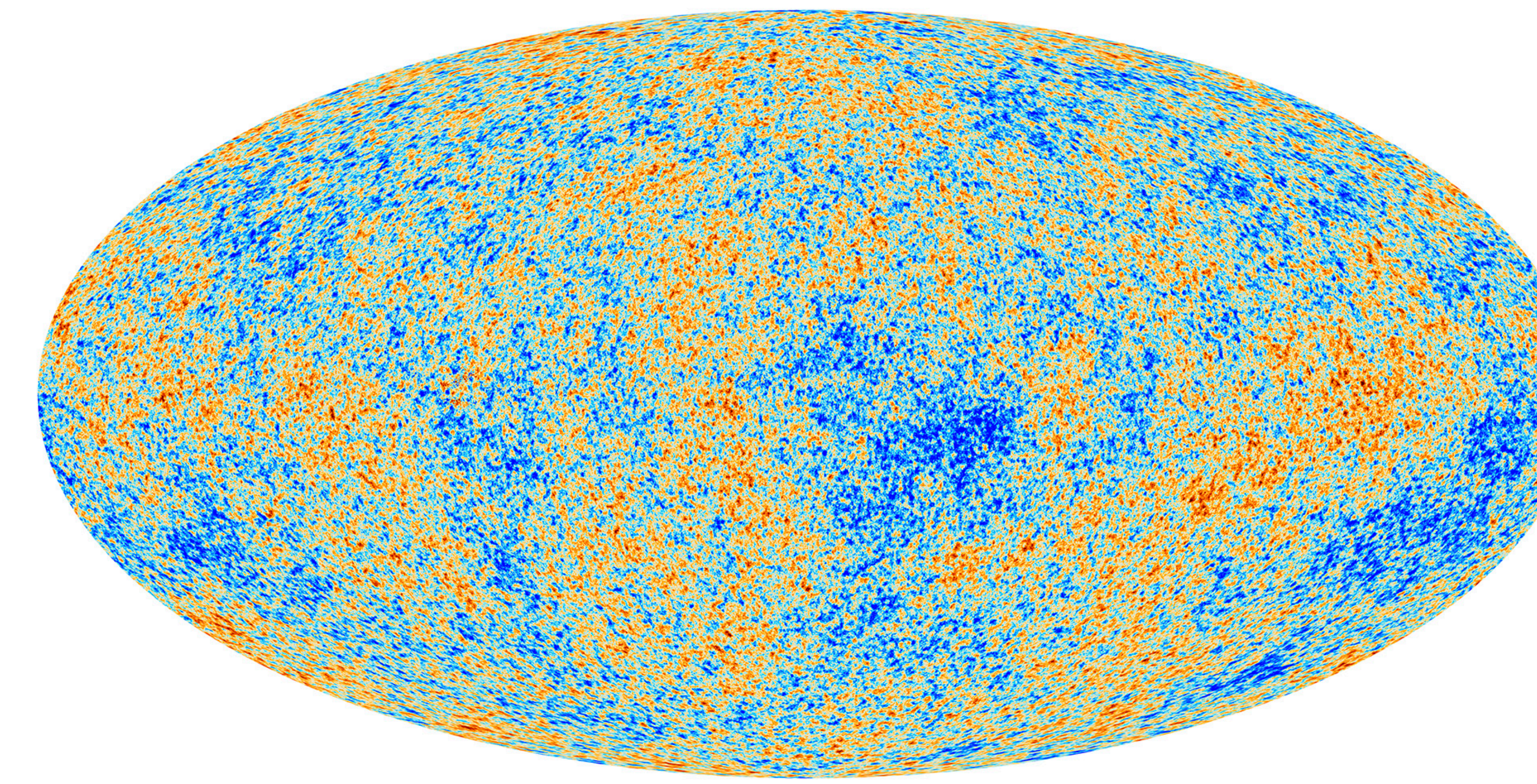
ordinary matter

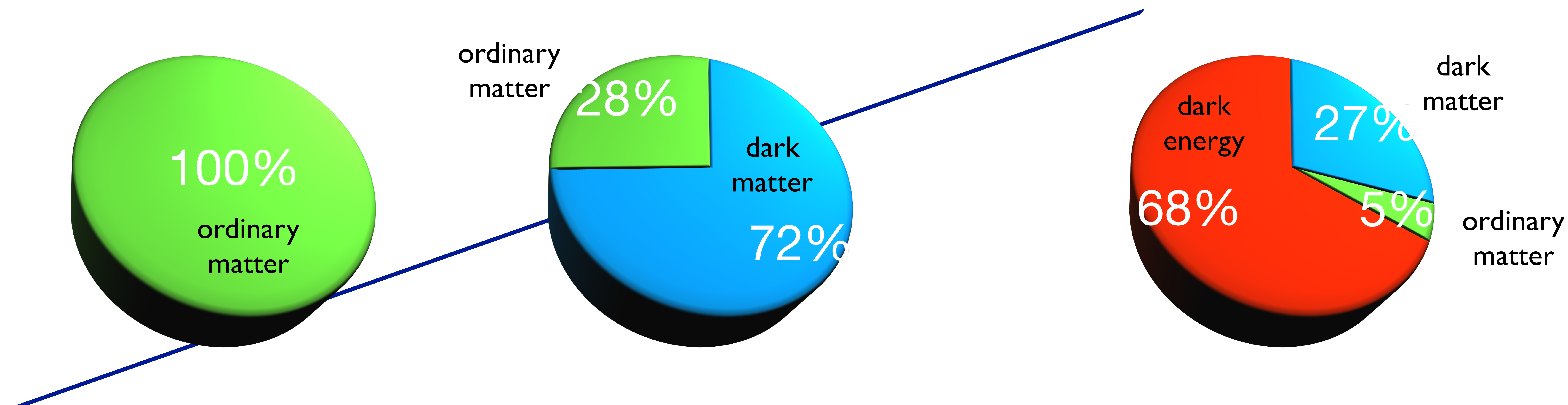
valid now and at large scales

What was the universe made of?



What is the universe made of?





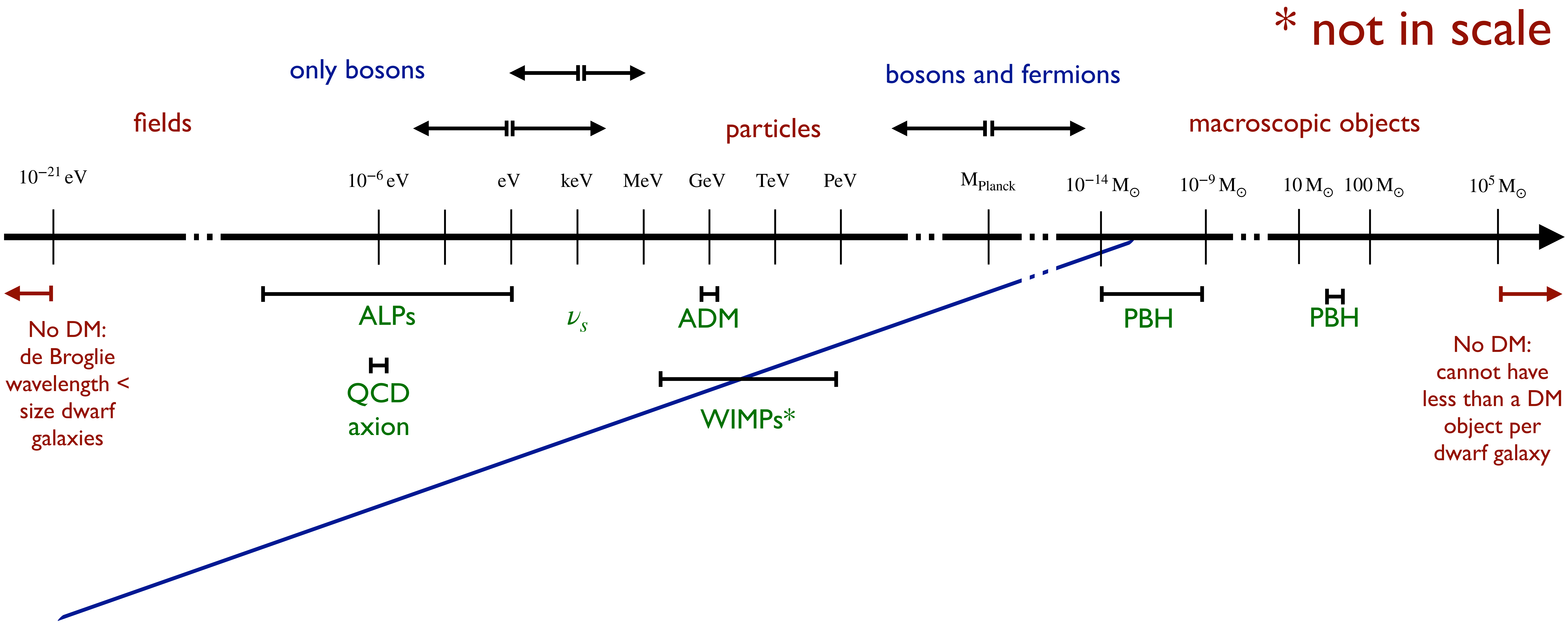
Can X be the DM?

A DM candidate must:

1. match the measured relic density;
2. be cold;
3. be neutral;
4. be consistent with BBN;
5. leave stellar evolution unchanged.

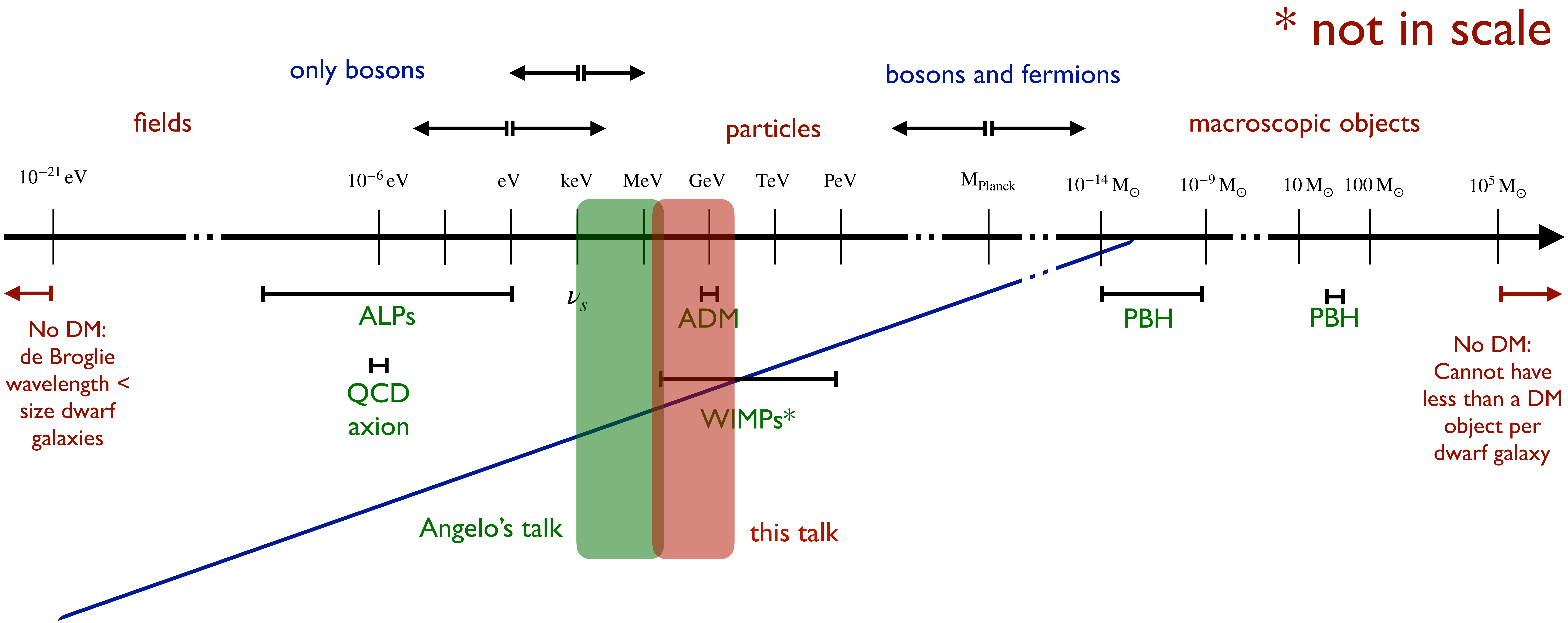
Challenge

We do not know what to search for



Challenges

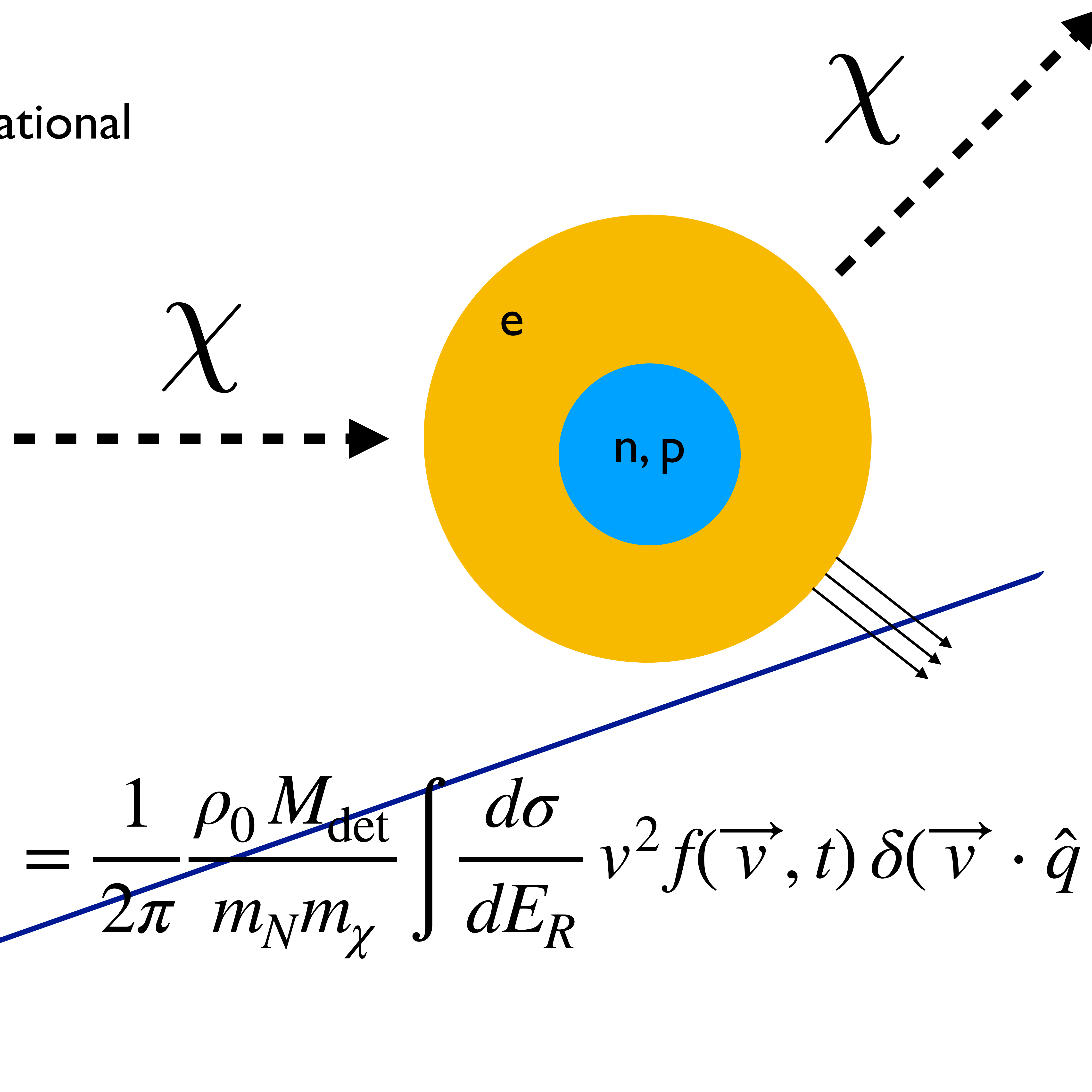
We do not know what to search for



Direct detection phenomenology

Direct detection phenomenology

*assuming non-gravitational interaction exists



$$\frac{d^2R_{\rm nr}}{dE_R\, d\Omega_R} = \frac{1}{2\pi}\frac{\rho_0 M_{\rm det}}{m_N m_\chi}\int \frac{d\sigma}{dE_R} v^2 f(\overrightarrow{v}, t)\, \delta(\overrightarrow{v}\cdot \hat{q} - v_{\rm min})\, d^3v$$

Direct detection phenomenology

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Detector dependence

m_N affects also the cross section

Direct detection phenomenology

Astrophysical inputs

$$\frac{d^2R_{\rm nr}}{dE_R\, d\Omega_R} = \frac{1}{2\pi} \frac{\rho_0 M_{\rm det}}{m_N m_\chi} \int \frac{d\sigma}{dE_R} v^2 f(\overrightarrow{v}, t)\, \delta(\overrightarrow{v} \cdot \hat{q} - v_{\rm min})\, d^3v$$

Detector dependence

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Direct detection phenomenology

particle physics

Astrophysical inputs

$$\frac{d^2 R_{\rm nr}}{dE_R\, d\Omega_R} = \frac{1}{2\pi} \frac{\rho_0 M_{\rm det}}{m_N m_\chi} \int \frac{d\sigma}{dE_R} v^2 f(\overrightarrow{v}, t)\, \delta(\overrightarrow{v} \cdot \hat{q} - v_{\rm min})\, d^3 v$$

Detector dependence

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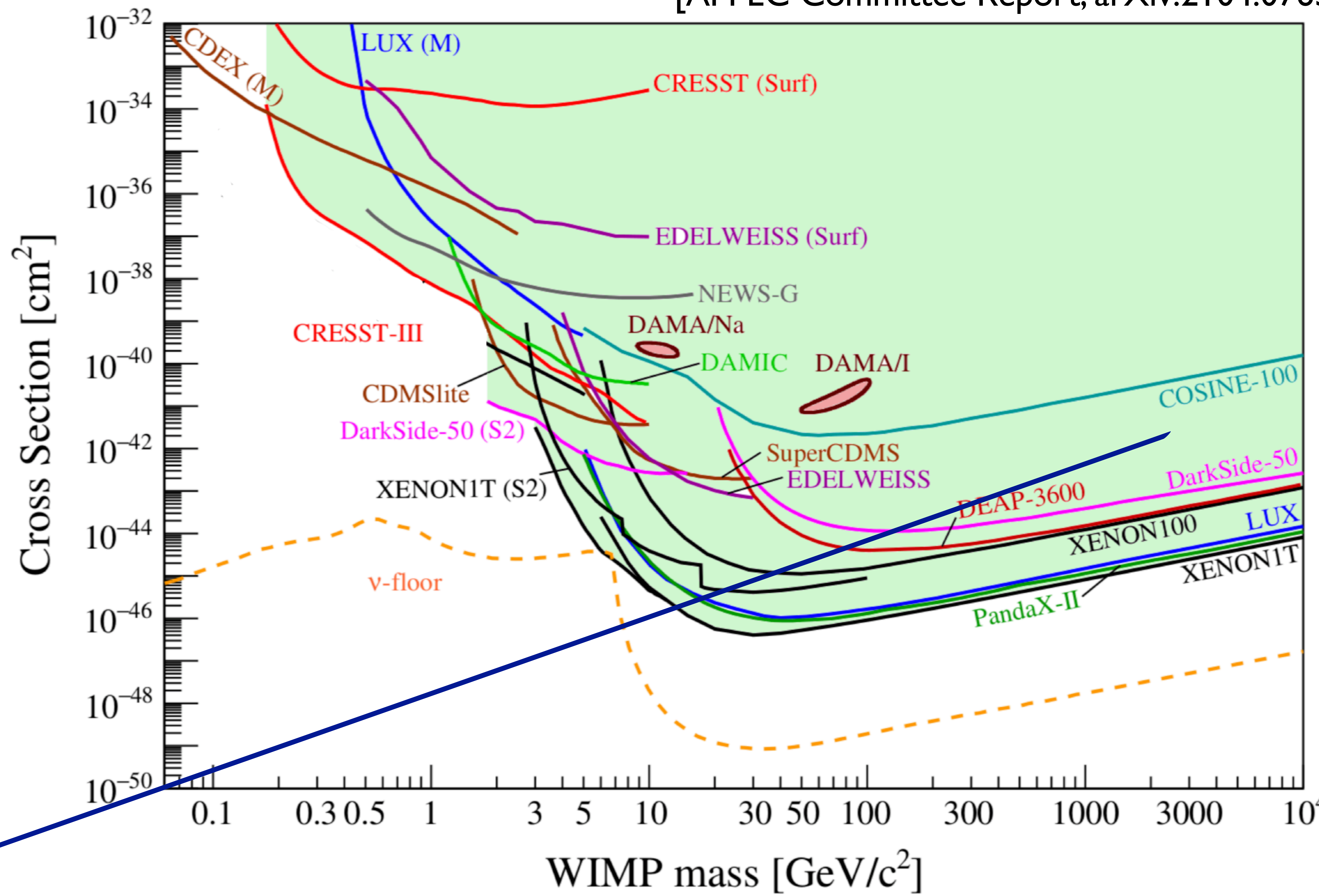
Direct detection phenomenology

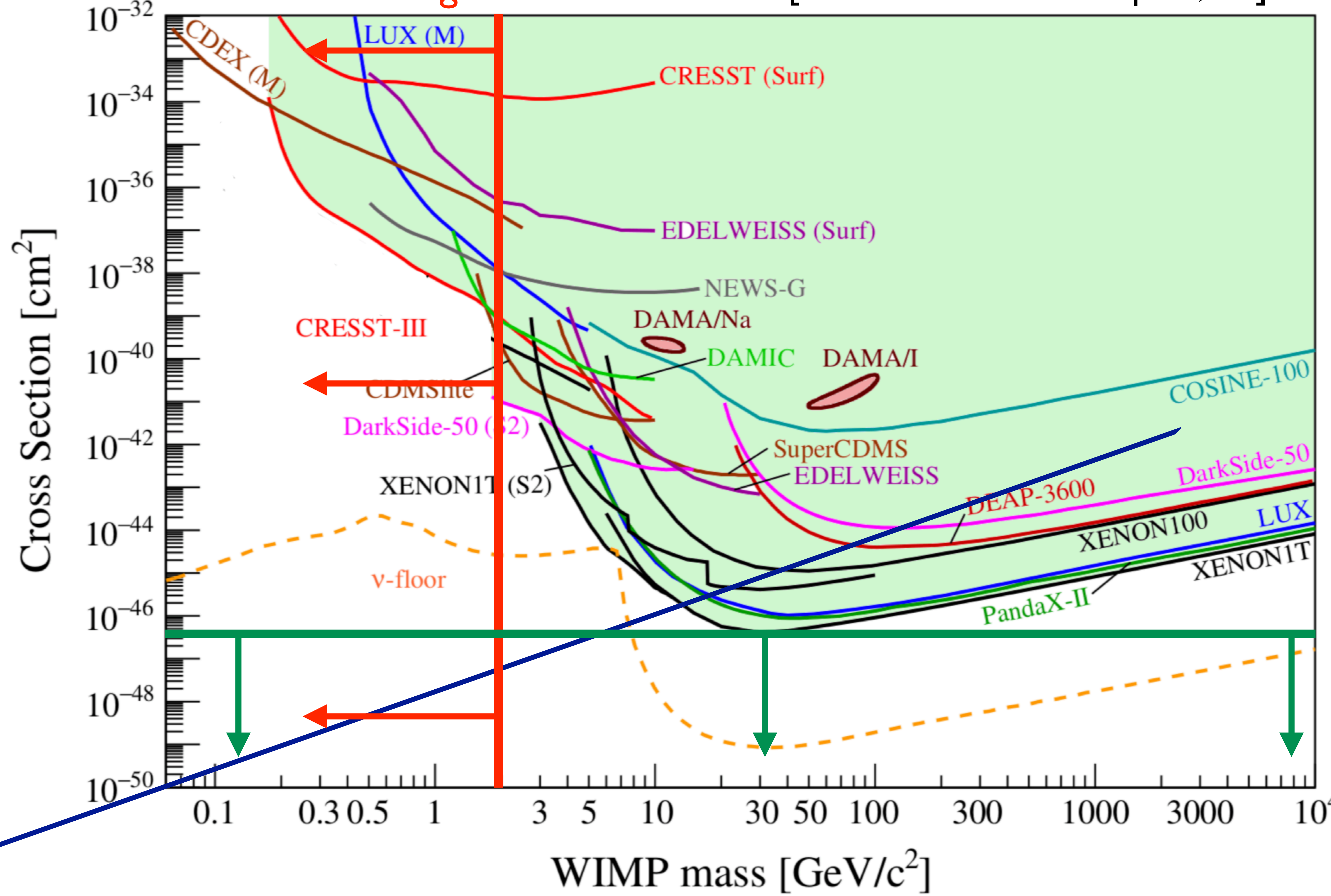
[APPEC Committee Report, arXiv:2104.07634]



Direct detection phenomenology

Lighter targets,
lower thresholds,
alternative signals

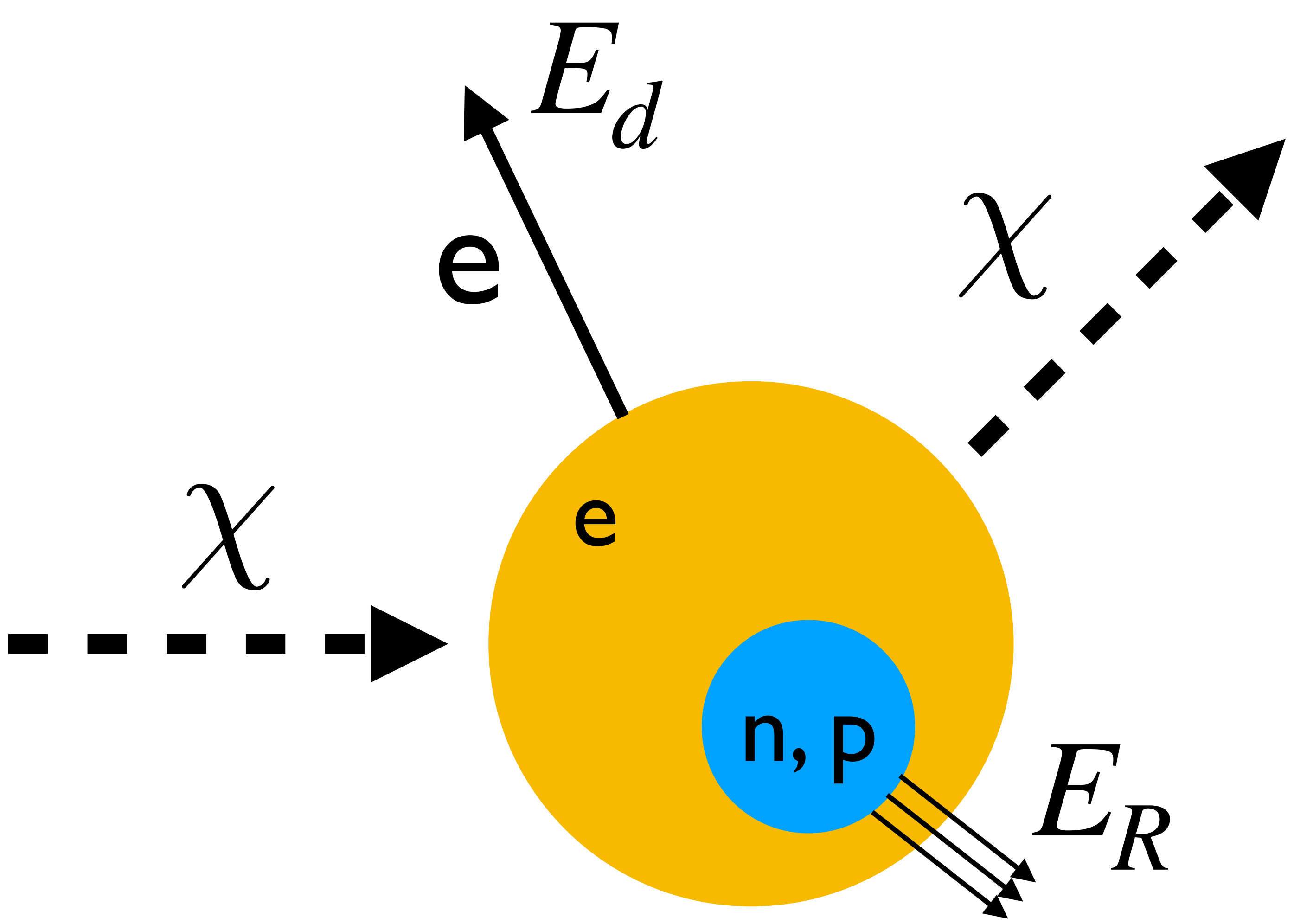
[APPEC Committee Report, '21]



increase exposure or volume of the experiment

The Migdal effect

The Migdal effect



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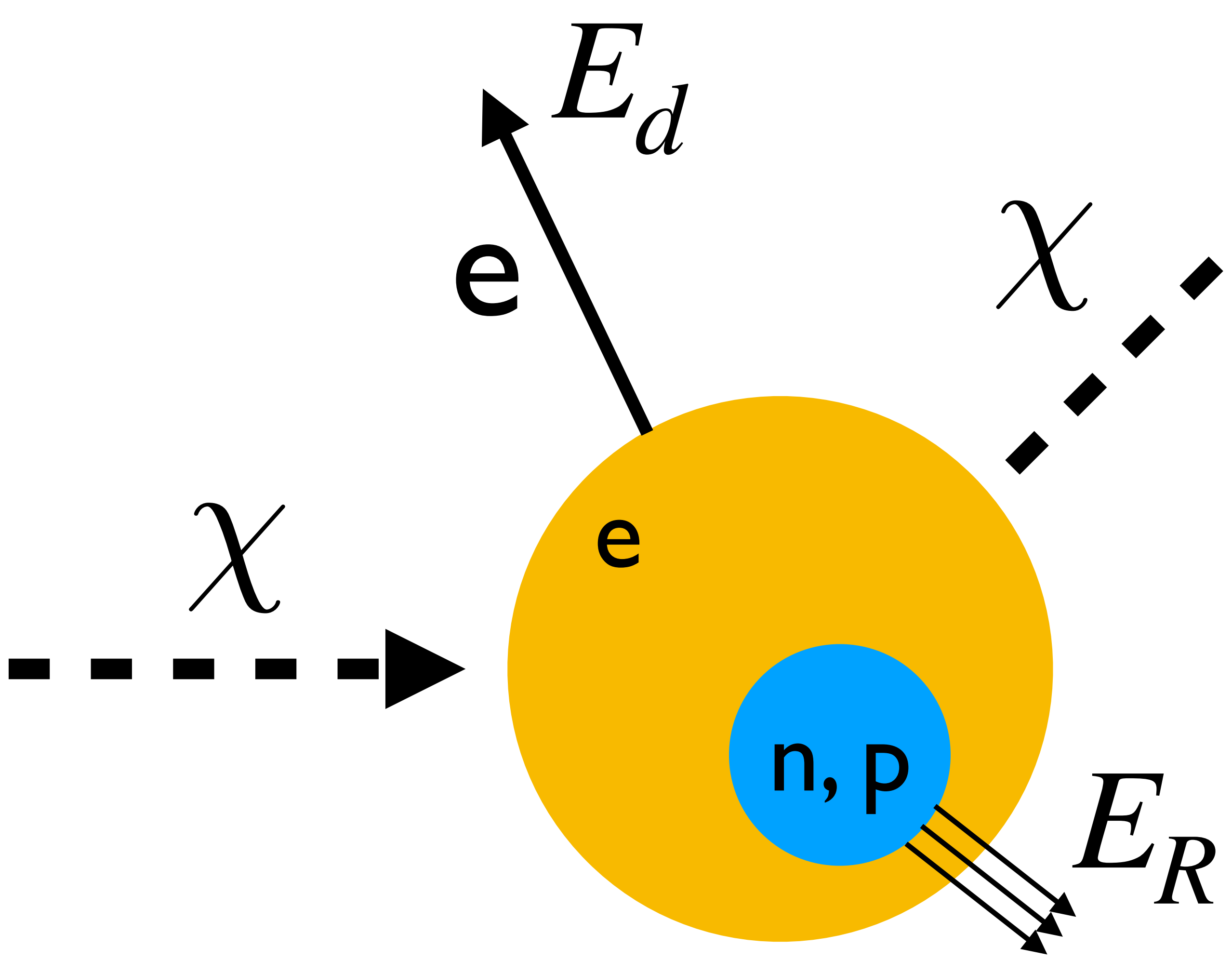
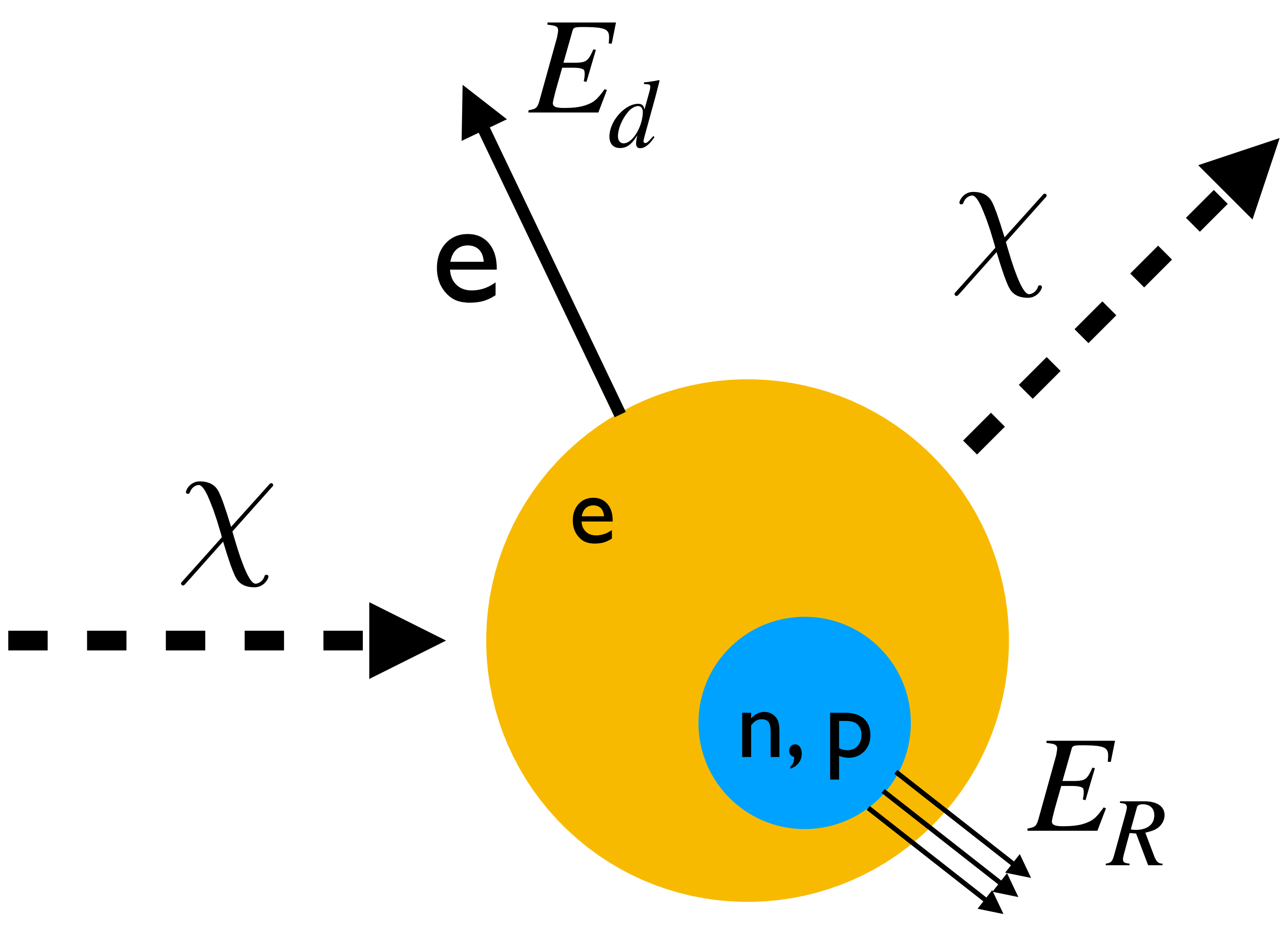


Kinematics

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} + \frac{E_d}{\sqrt{2 m_N E_R}}$$

$$E_R^{\max} = \frac{2\,\mu_N^2\,v_{\max}^2}{m_N} \qquad E_d^{\max} = \frac{\mu_N\,v_{\max}^2}{2}$$

The Migdal effect



Kinematics

Nuclear recoil energy

Electron detected energy

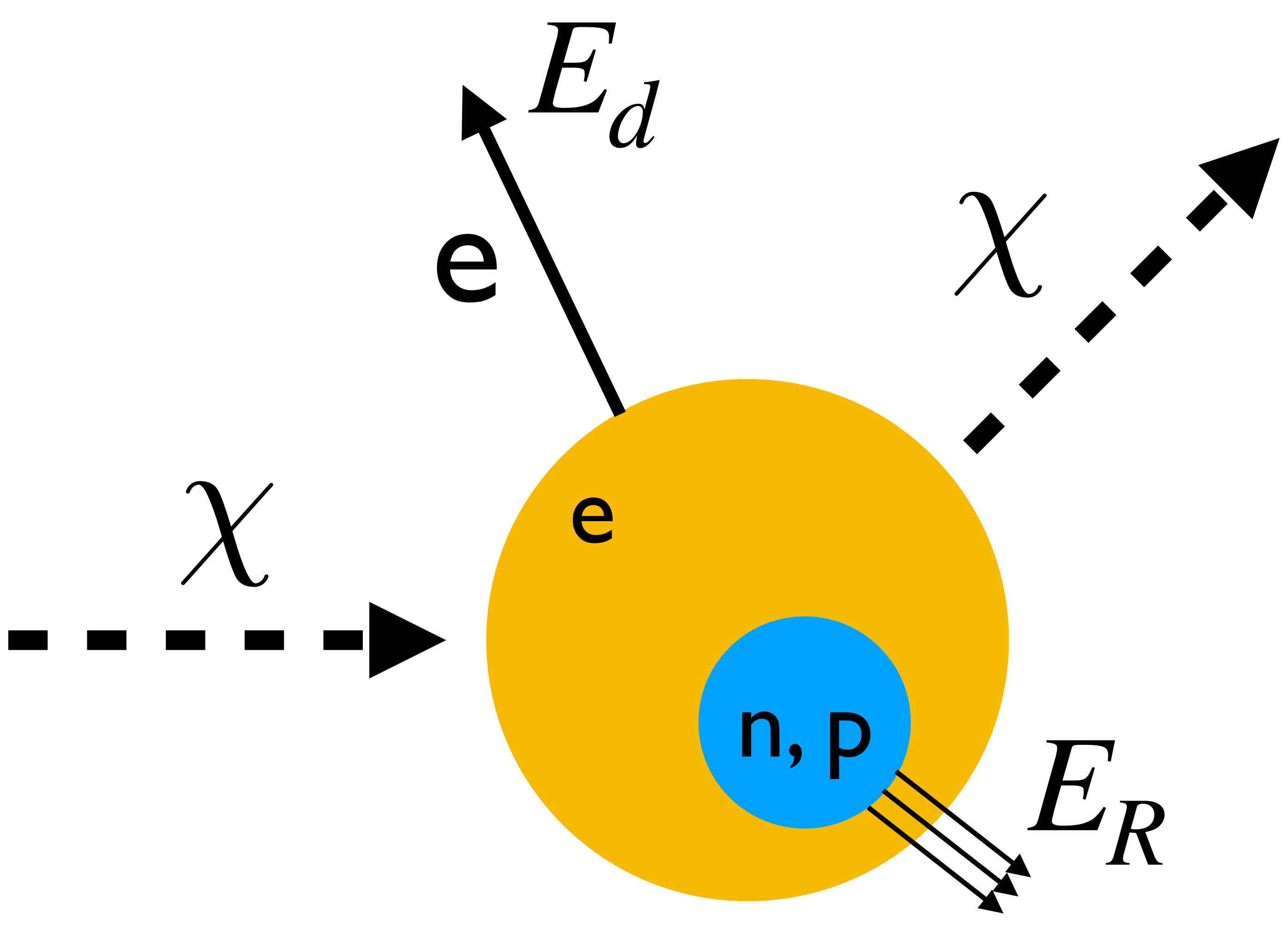
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} + \frac{E_d}{\sqrt{2 m_N E_R}}$$

DM-nucleus reduced mass

nucleus mass

$$E_R^{\max} = \frac{2\,\mu_N^2\, v_{\max}^2}{m_N} \qquad E_d^{\max} = \frac{\mu_N\, v_{\max}^2}{2}$$

The Migdal effect



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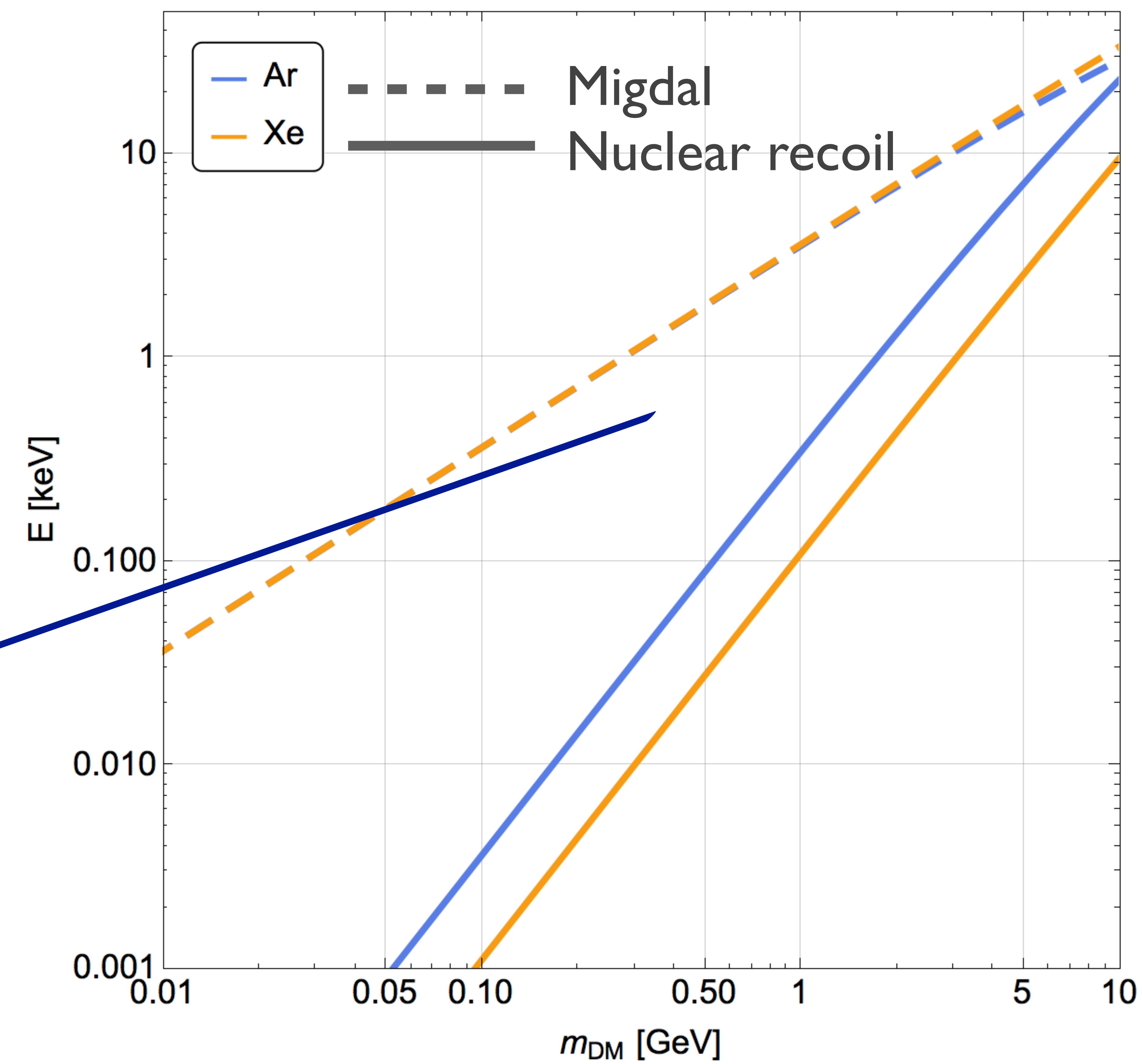
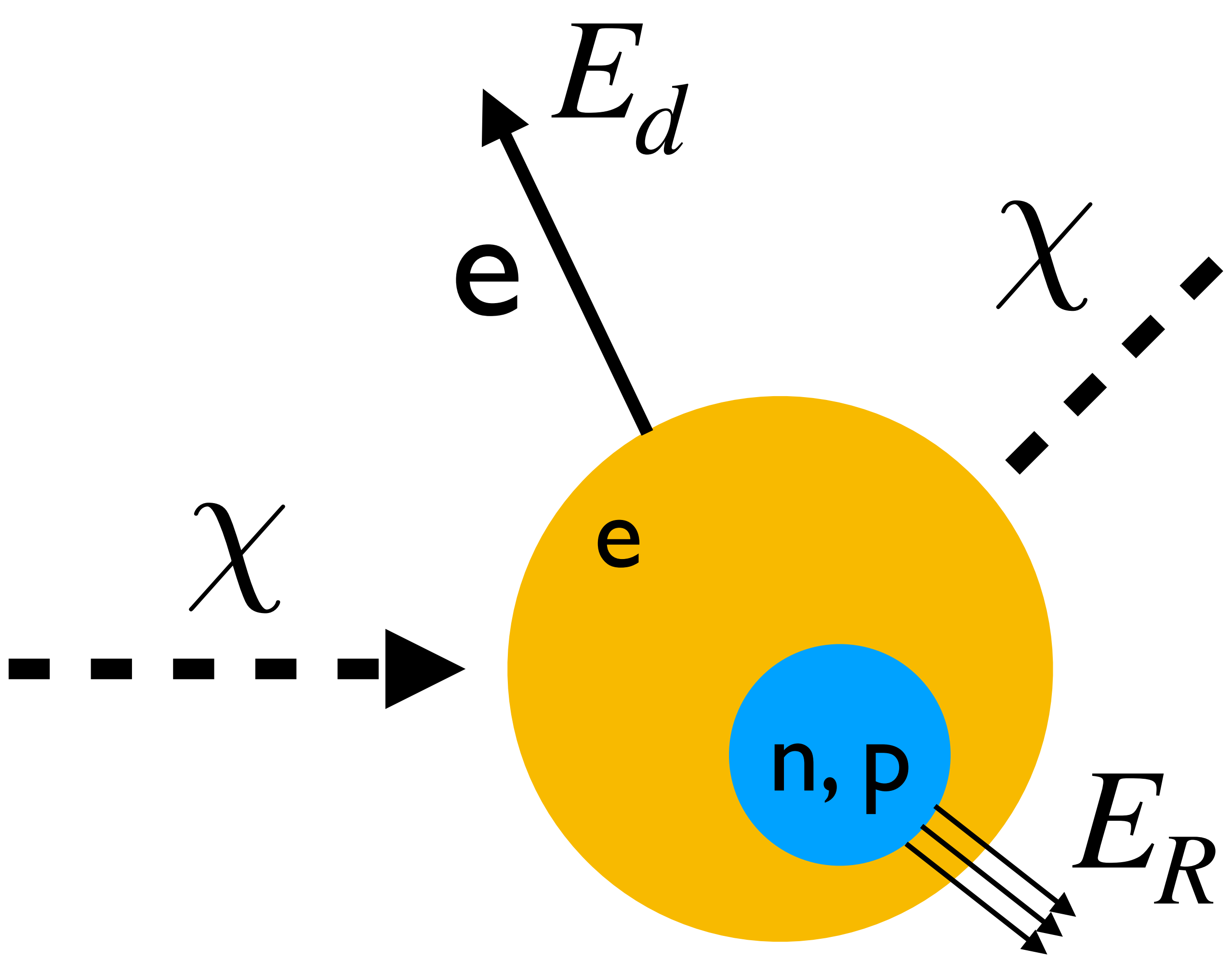


1. Threshold $E \lesssim 1$ keV
2. Sensitivity loss for $m_{DM} \lesssim 2\,\text{GeV}$
3. $E_d^{\max} > E_R^{\max}$ for $m_{DM} \ll m_N$
4. The Migdal effect is sensitive to sub-GeV masses

The Migdal effect



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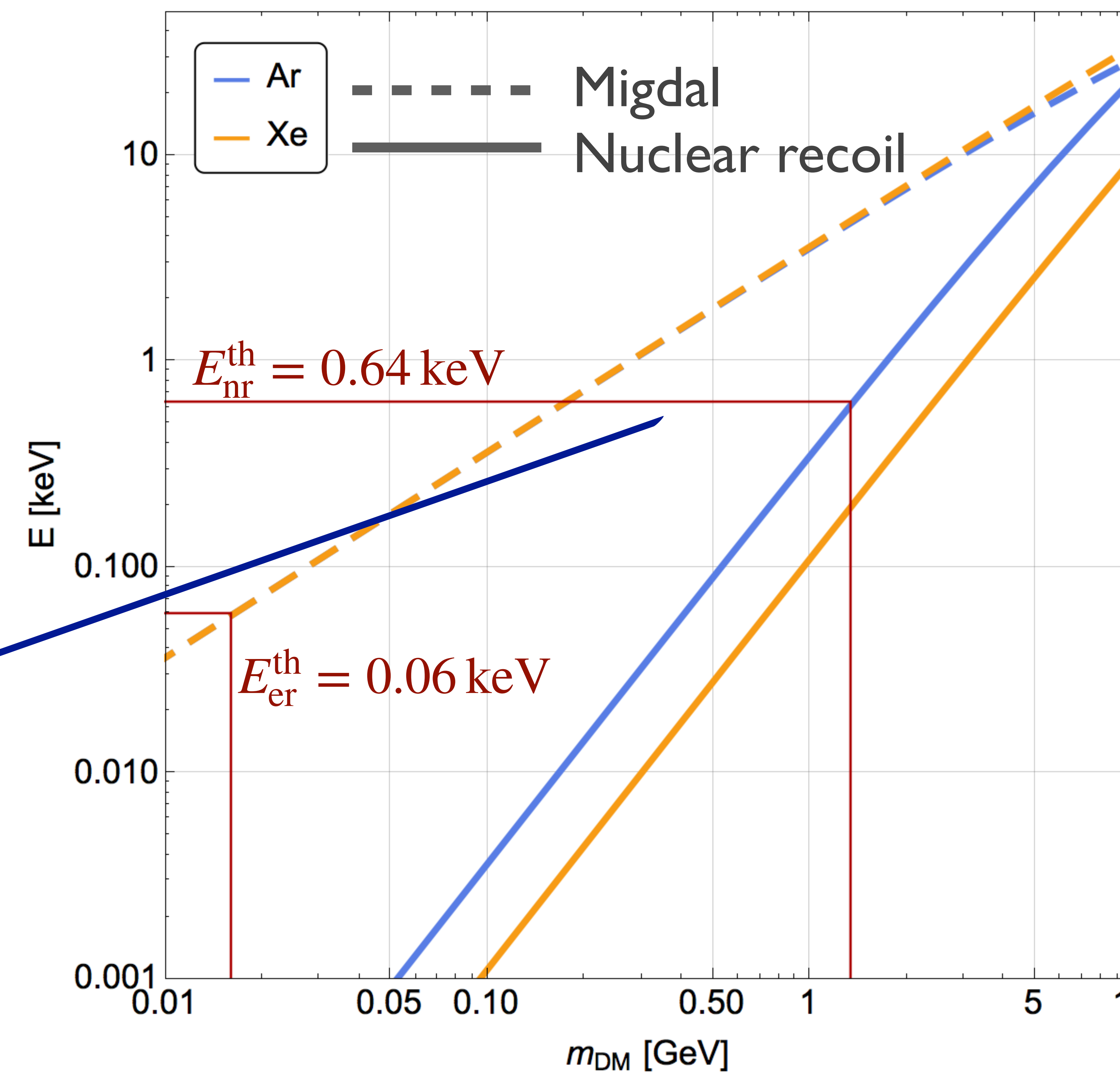

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The Migdal effect

$$\frac{d^3R_{\rm mig}}{dE_R\, dE_e\, dv} = \frac{d^2R_{\rm nr}}{dE_R\, dv}\,|\,Z(E_R, E_e)\,|^2$$

The Migdal effect

$$\frac{d^3R_{\text{mig}}}{dE_R\, dE_e\, dv} = \frac{d^2R_{\text{nr}}}{dE_R\, dv} |Z(E_R, E_e)|^2$$

DM nuclear recoil

The Migdal effect

$$\frac{d^3R_{\rm mig}}{dE_R\,dE_e\,dv} = \frac{d^2R_{\rm nr}}{dE_R\,dv}|Z(E_R,E_e)|^2$$

DM nuclear recoil

$$|Z(E_R,E_e)|^2 \simeq 1 + |Z_{\rm de}|^2 + |Z_{\rm ion}|^2$$

NR

de-excitation: negligible

ionization rate

The Migdal effect

$$\frac{d^3R_{\text{mig}}}{dE_R\,dE_e\,dv} = \frac{d^2R_{\text{nr}}}{dE_R\,dv}\,|Z(E_R,E_e)|^2$$

DM nuclear recoil

$$|Z(E_R,E_e)|^2 \simeq 1 + |Z_{\text{de}}|^2 + |Z_{\text{ion}}|^2$$

NR

de-excitation: negligible

ionization rate

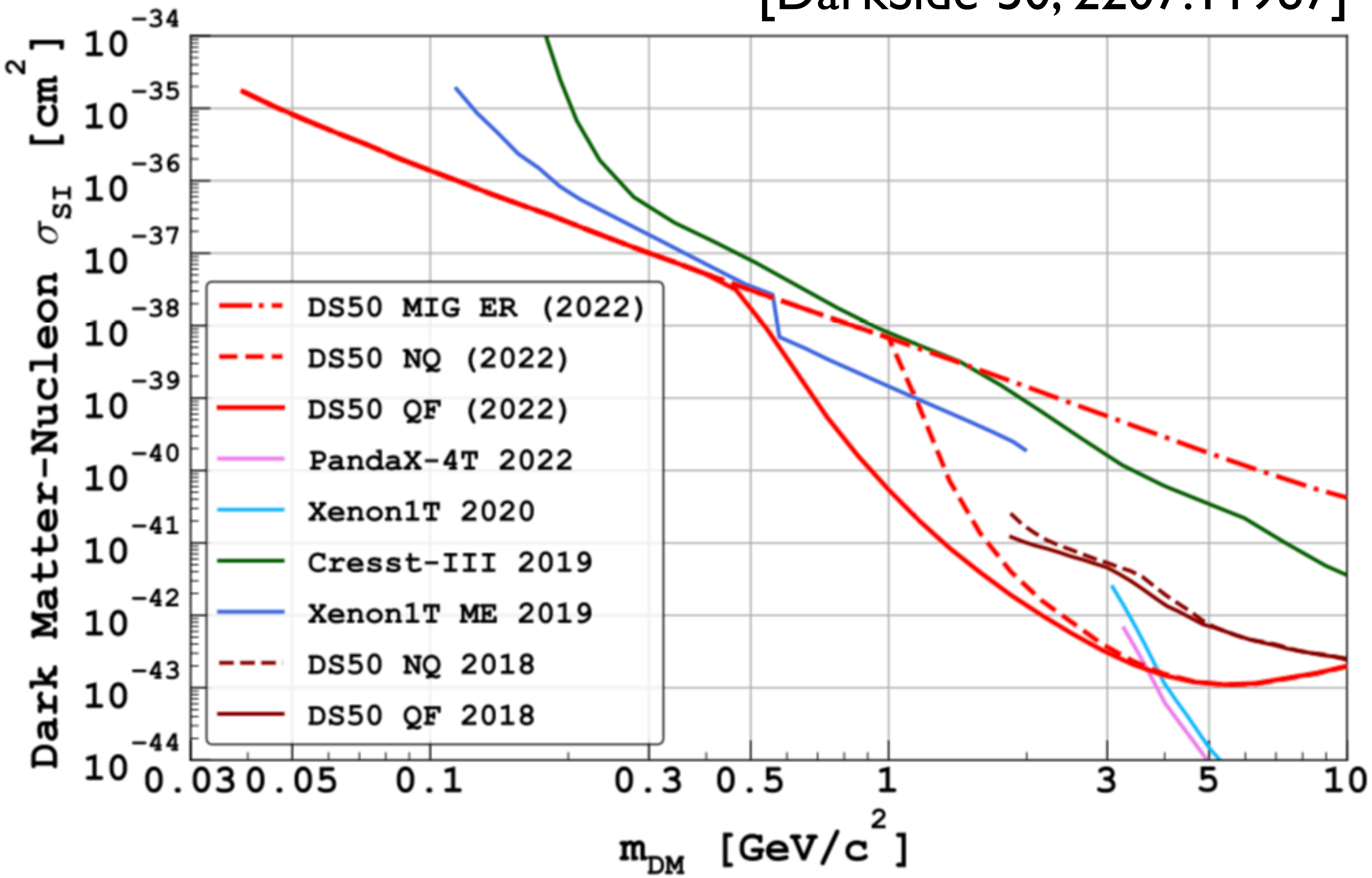
$$|Z_{\text{ion}}(E_R,E_e)|^2 = \frac{1}{2\pi}\sum_{n,\ell}\int dE_e \frac{dp^c_{q_e}(n\ell \to E_e)}{dE_e}$$

Migdal

Computed in [Ibe et al. JHEP03(2018)194] for C, F, Ar, Xe, …,
see also [Cox et al., 2208.12222]

The Migdal effect

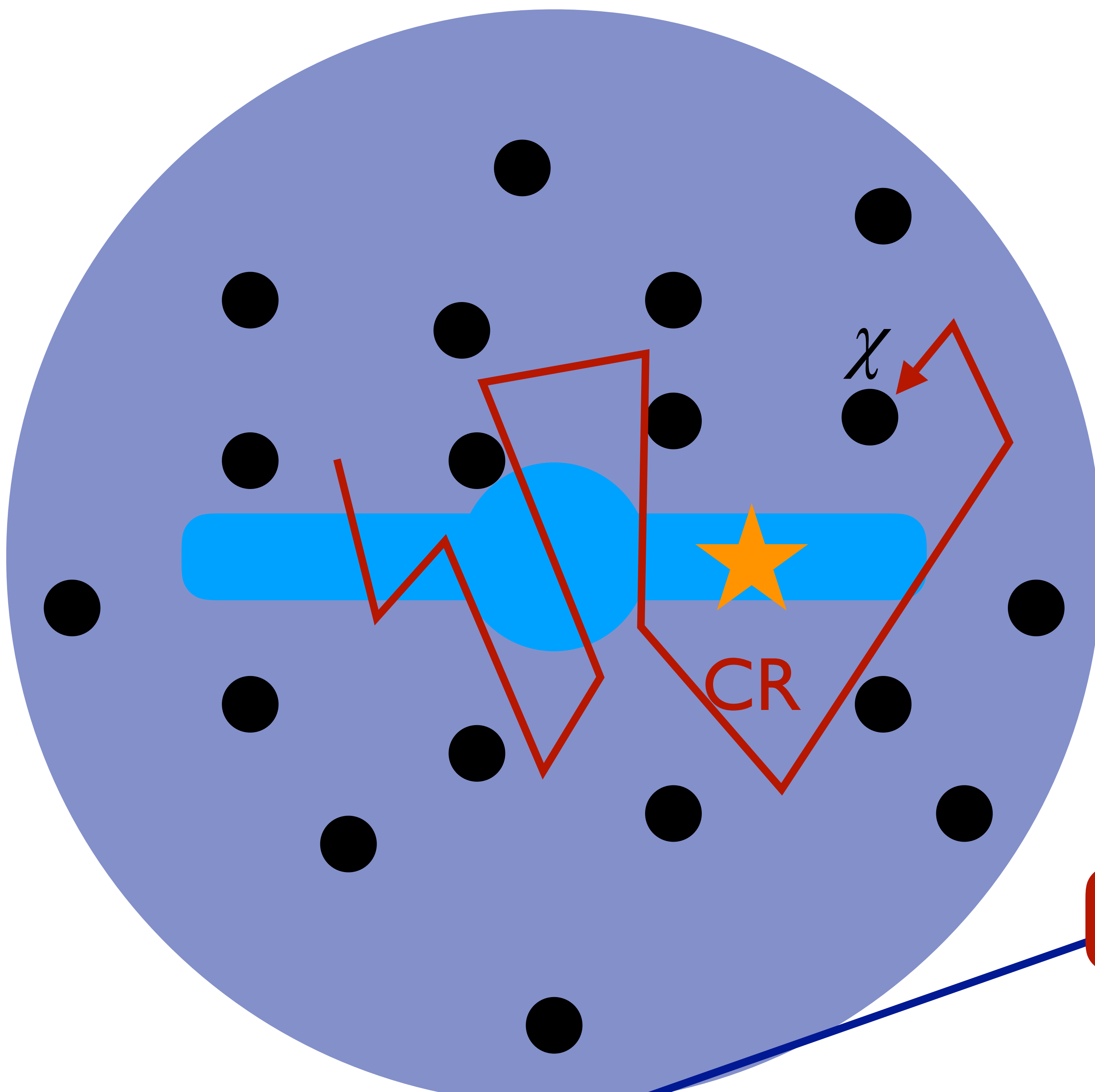
[DarkSide-50, 2207.11967]



Boosted Dark Matter

Cosmic Ray boosted DM

[Bringmann and Pospelov, 1810.10543]



New isotropic component of DM extending to higher energies

DM density as a function of the distance to the galactic centre

CR flux as a function of the distance to the galactic centre

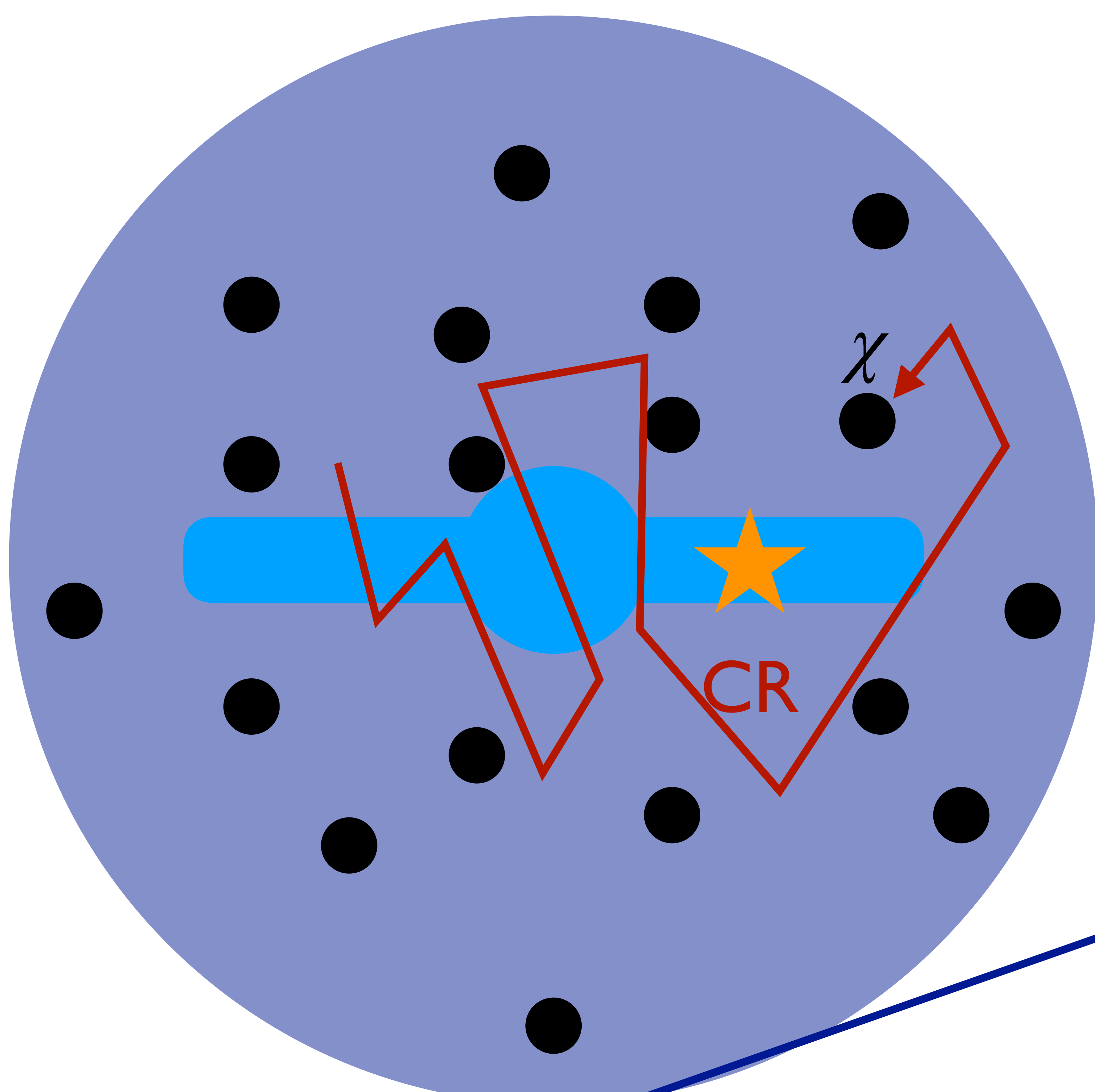
$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{l.o.s.} d\ell \, \sigma_{\chi i} \frac{\rho}{m_\chi} \frac{d\Phi_i}{dT_i}$$

Denotes the CR

CR-DM cross section

Cosmic Ray boosted DM

[Bringmann and Pospelov, 1810.10543]



New isotropic component of DM extending to higher energies

Local interstellar CR flux

Local DM density

$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{l.o.s.} d\ell\, \sigma_{\chi i} \frac{\rho}{m_\chi} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_\chi^{\rm local}}{m_\chi} \frac{d\Phi_i^{LIS}}{dT_i} D_{\rm eff}$$

Denotes the CR

CR-DM cross section

Effective distance parametrizing uncertainty from l.o.s. integration

Cosmic Ray boosted DM

Production

Form factor

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff} \frac{\rho_\chi^{\rm local}}{m_\chi} \sum_i \sigma_{\chi i} F_i^2(2m_\chi T_\chi) \int_{T_i^{\rm min}}^{\infty} \frac{dT_i}{T_\chi^{\rm max}(T_i)} \frac{d\Phi_i^{LIS}}{dT_i}$$

$$i = \{\rm p, He, \dots\}$$

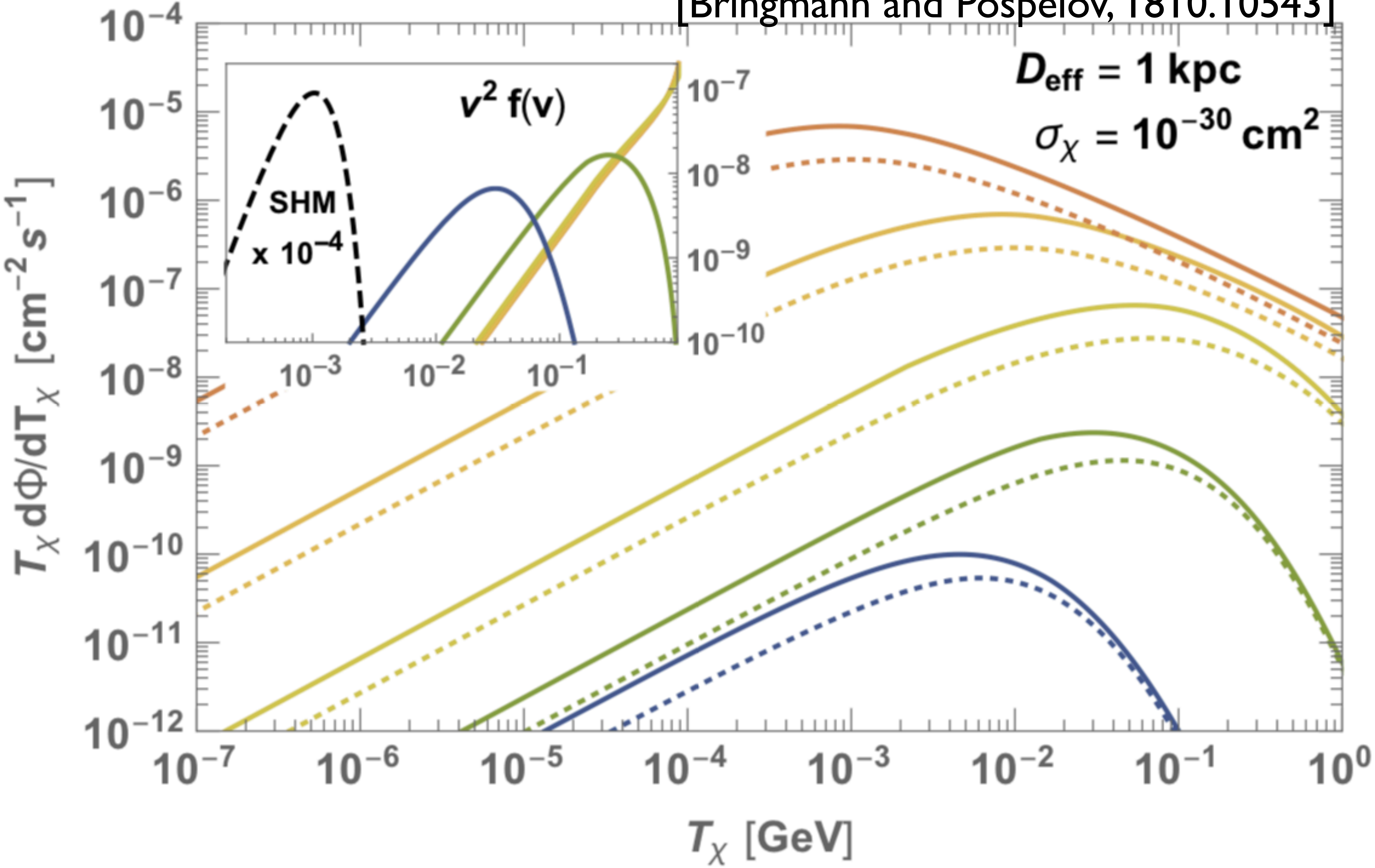
$$T_\chi^{\rm max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2/(2m_\chi)}$$

additional terms compared to the non-relativistic expression

Cosmic Ray boosted DM

Production

[Bringmann and Pospelov, 1810.10543]



Only proton

Proton + He

from top to bottom:
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV

Cosmic Ray boosted DM

Earth attenuation

Easily solvable if it does not depend on the form factor

$$\frac{d\sigma_{\chi N}}{dT_r} = \frac{\sigma_{\chi N}}{T_r^{\max}} F^2(T_r)$$

Solve energy loss equation

$$\frac{dT_\chi}{dz} = -\sum_N n_N \int_0^{T_r^{\max}} \frac{d\sigma_{\chi N}}{dT_r} T_r \, dT_r$$

to obtain flux at the detector depth

$$\frac{d\Phi_\chi}{dT_\chi^z} = \left(\frac{dT_\chi}{dT_\chi^z}\right) \frac{d\Phi_\chi}{dT_\chi} = \frac{4m_\chi^2 e^{z/\ell}}{(2m_\chi + T_\chi^z - T_\chi^z e^{z/\ell})^2} \frac{d\Phi_\chi}{dT_\chi}$$

where the mean free path is

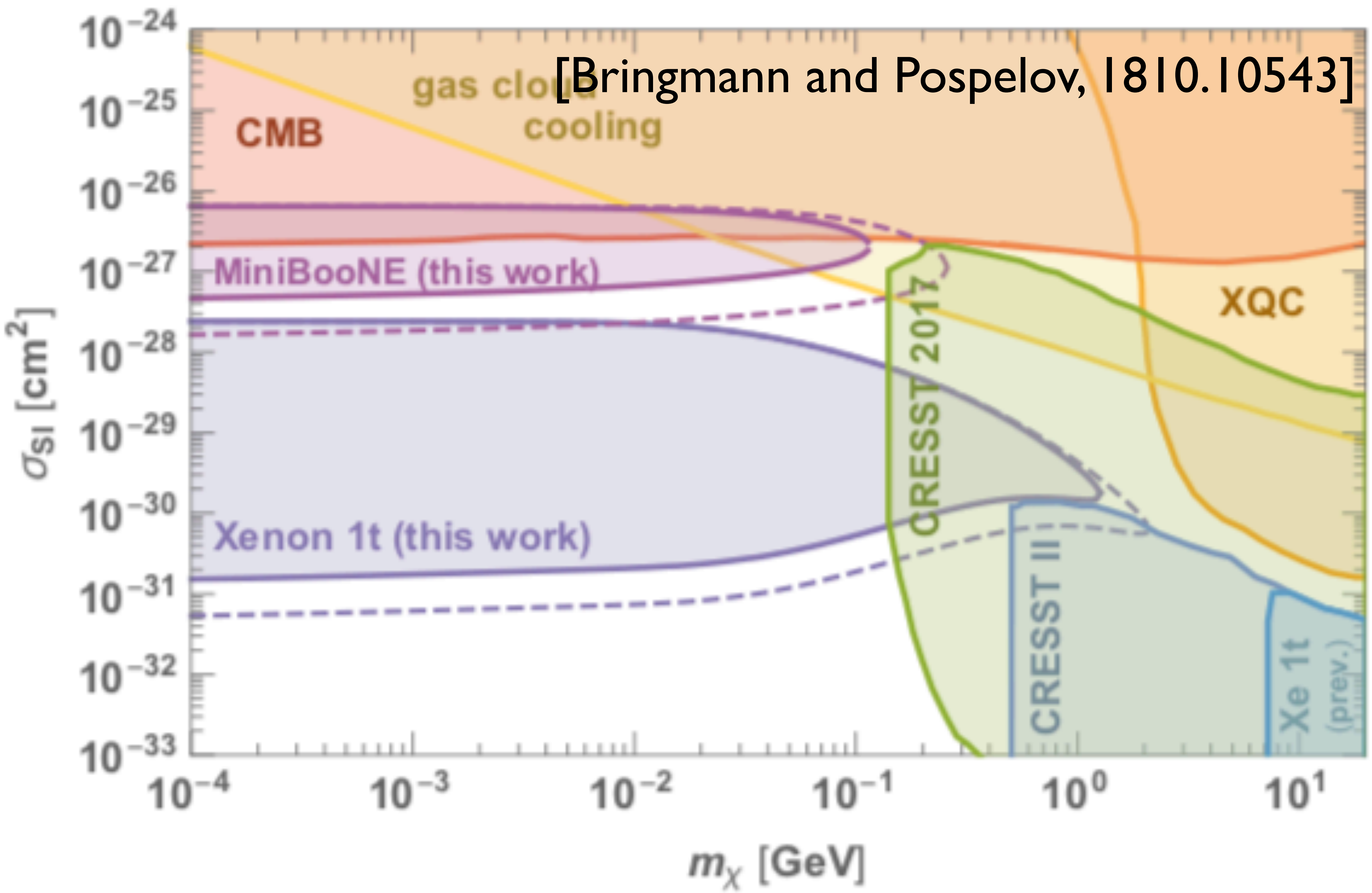
$$\ell^{-1} \equiv \sum_N n_N \, \sigma_{\chi N} \frac{2\, m_N m_\chi}{(m_N + m_\chi)^2}$$

Cosmic Ray boosted DM

Detection

$$\frac{d\Gamma_N}{dT_N} = \int_{T_\chi^{\min}}^{\infty} dT_\chi \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi} = \sigma_{\chi N} F_N^2(2m_N T_N)\int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T_N^{\max}}\frac{d\Phi_\chi}{dT_\chi}$$

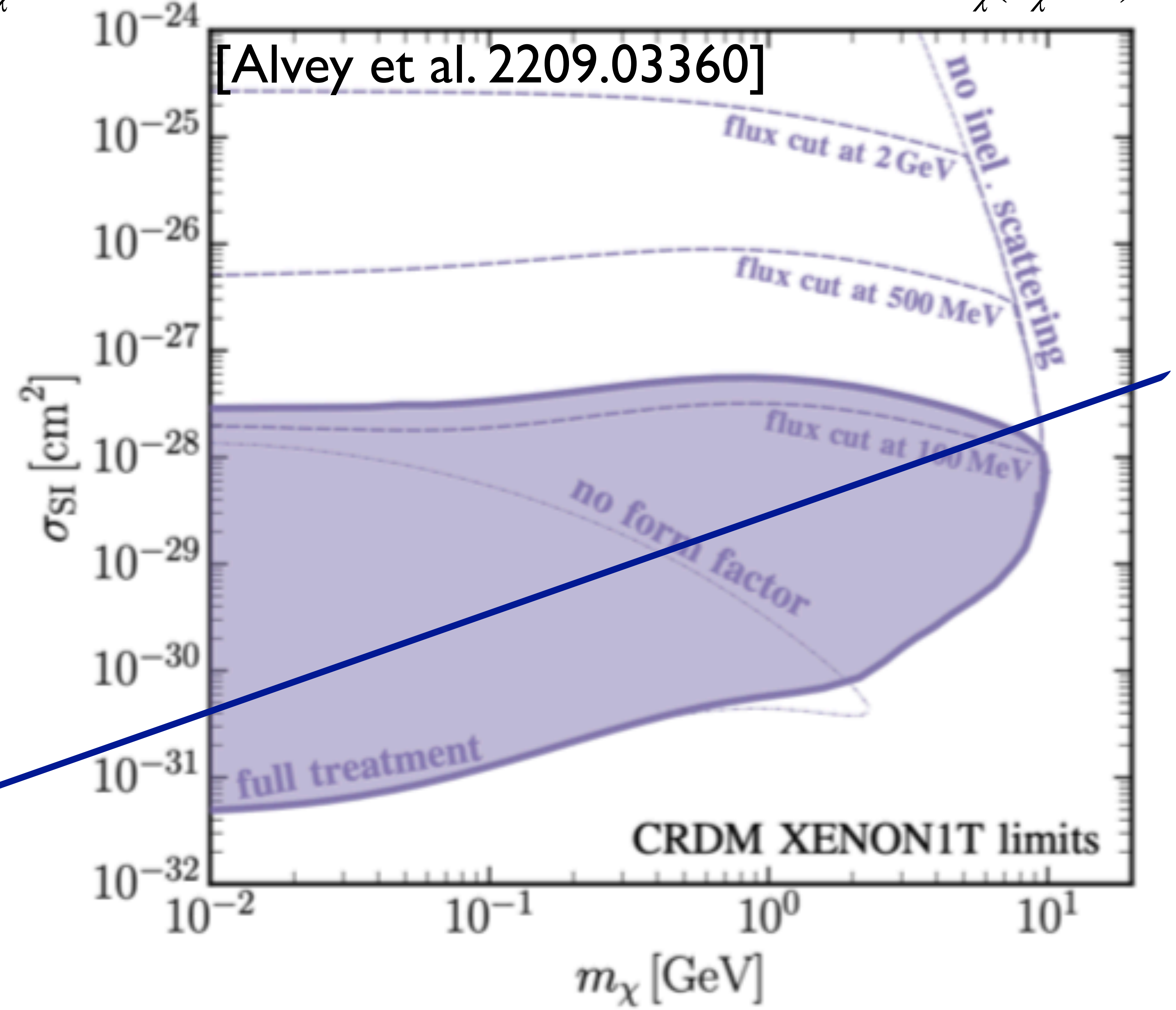
Assuming no form factor in the Earth attenuation



Cosmic Ray boosted DM

Detection

$$\frac{d\Gamma_N}{dT_N} = \int_{T_\chi^{\min}}^{\infty} dT_\chi \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi} = \sigma_{\chi N} F_N^2(2m_N T_N) \int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T_N^{\max}} \frac{d\Phi_\chi}{dT_\chi}$$

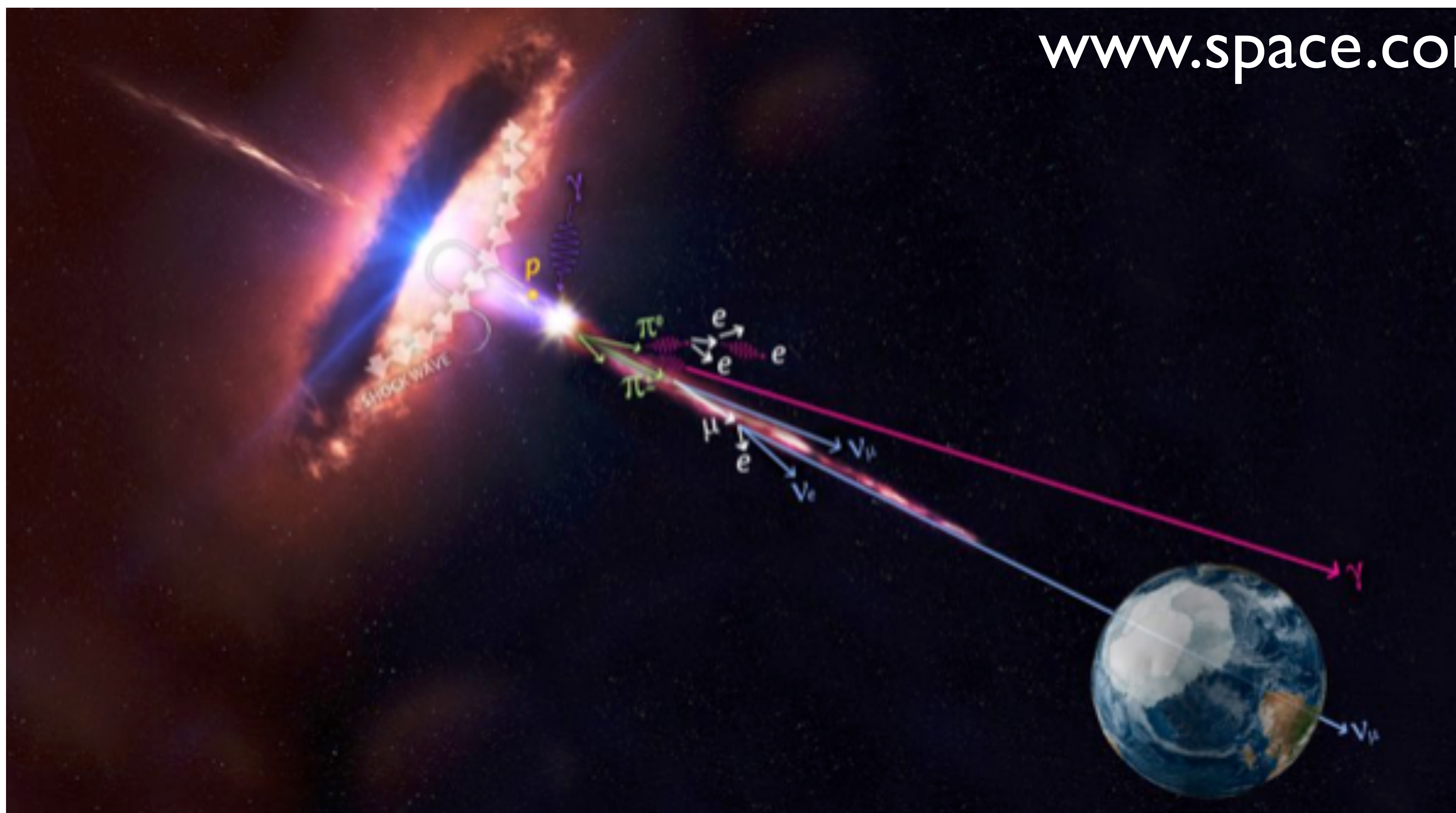


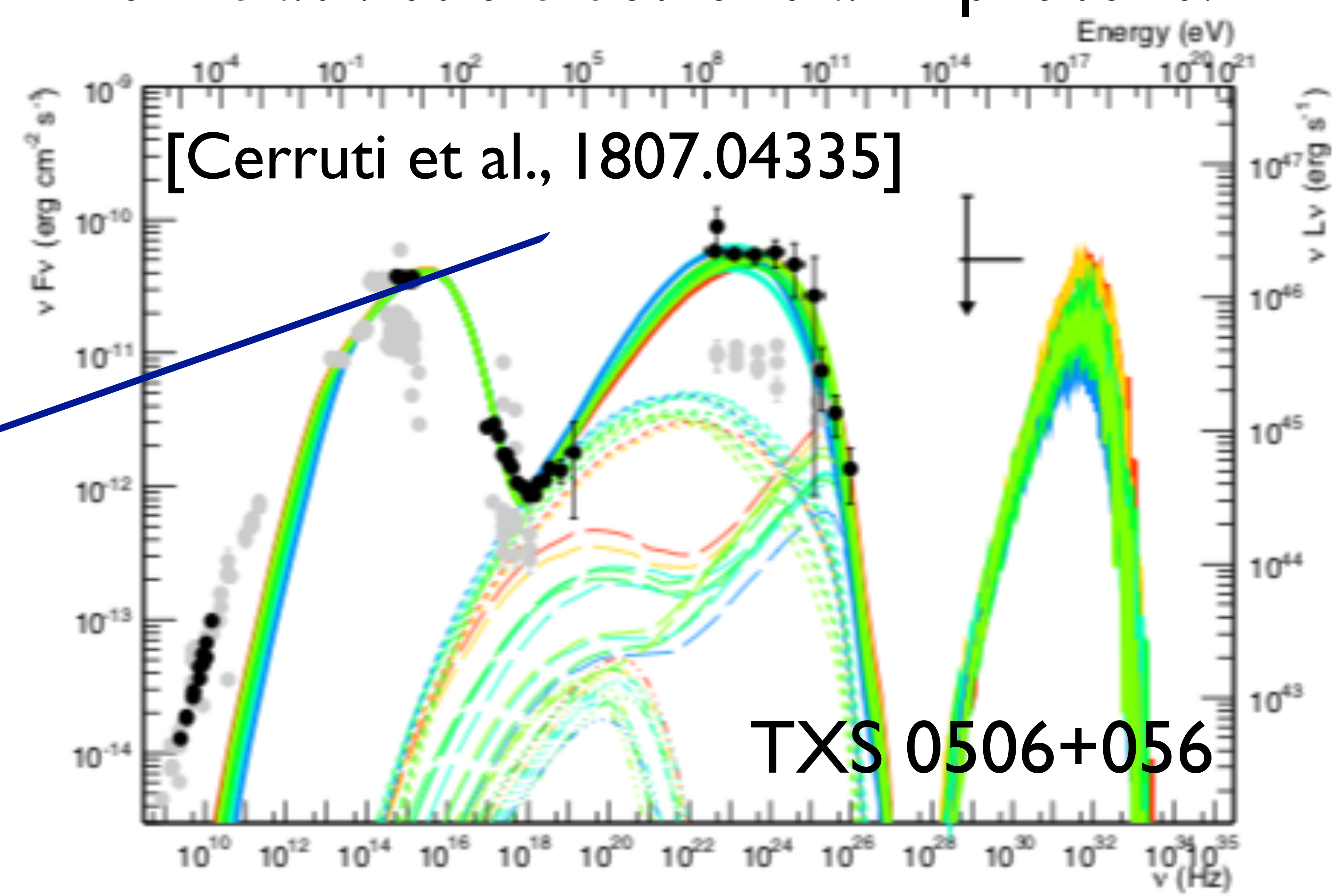
Assuming form factors in the Earth attenuation and taking into account inelastic scattering at high recoil energies.

Blazar boosted DM

[Granelli et al., 2111.13644]

Blazars are AGNs pointing to Earth. The BH at their center accrete ordinary matter and focus DM. They emit a back to back paired jet of relativistic electrons and protons.





Blazar boosted DM

Blazar boosted dark matter at Earth:

$$\Sigma_{\rm DM} \equiv \int_{r_{\rm min}}^{r} \rho_{\rm DM}(r')dr'$$

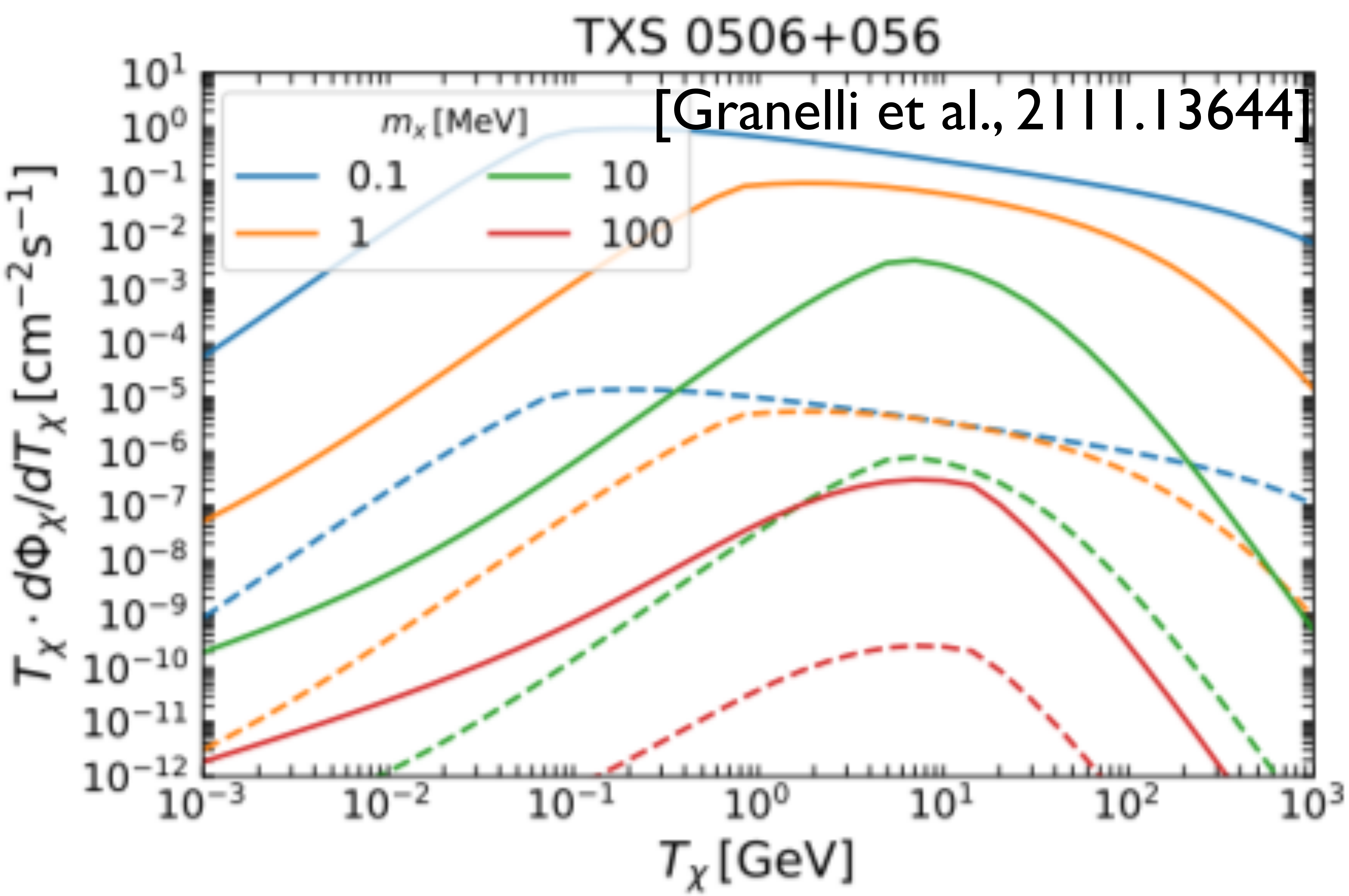
Differential cross section

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{\Sigma_{\rm DM}^{\rm tot}}{m_\chi d_L^2} \int_{T_j^{\rm min}}^{T_j^{\rm max}} dT_j \frac{d\sigma_{\chi p}}{dT_\chi} \frac{d\Gamma_j}{dT_j d\Omega}$$

proton spectrum

Luminosity distance

Blazar boosted DM

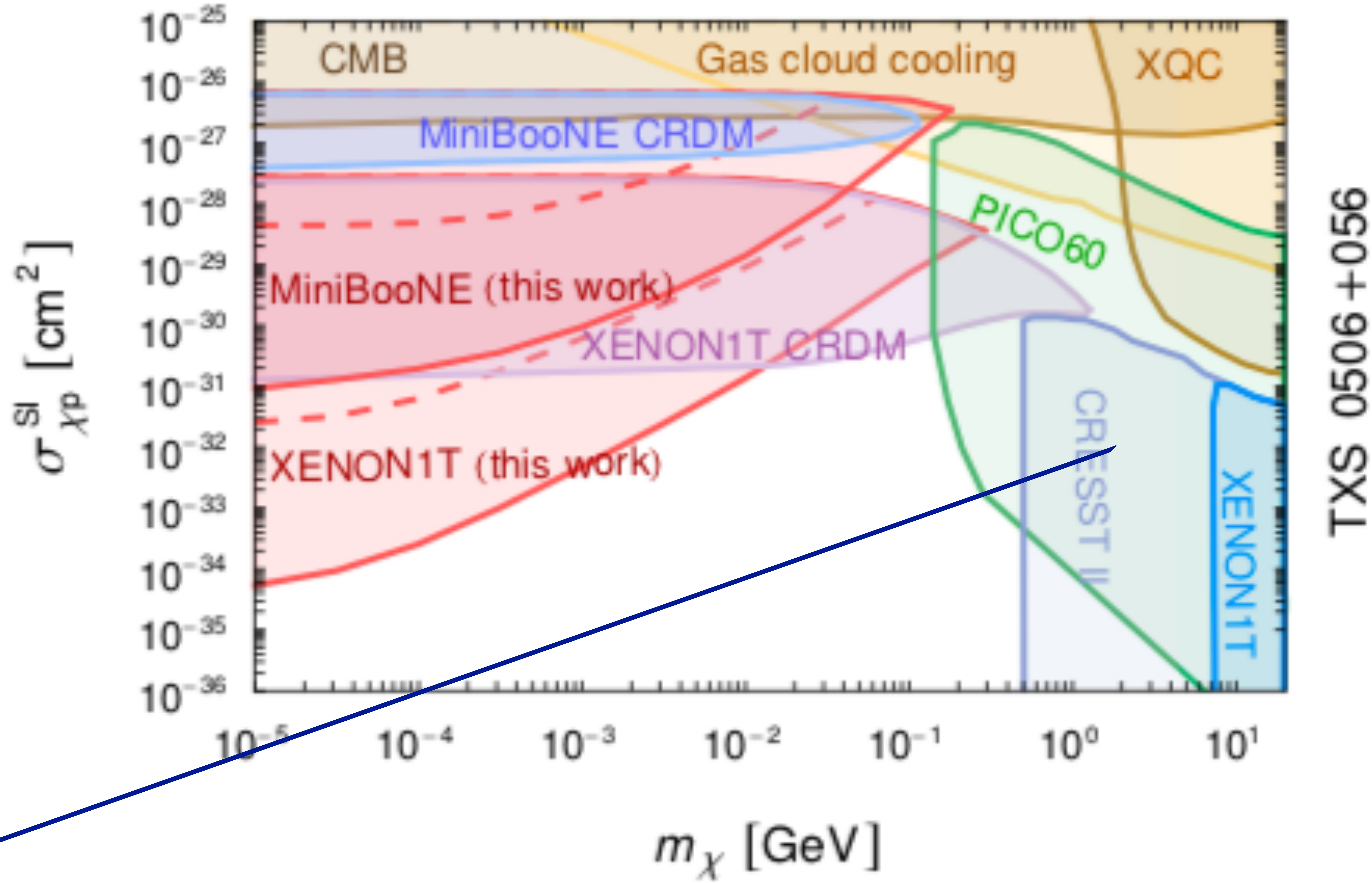


Different assumptions on the DM profile:

- - - - - - $\langle \sigma v \rangle_0 = 0$

——— $\langle \sigma v \rangle_0 = 10^{-28}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$

Blazar boosted DM



Conclusions

Conclusions

- Many hints of the DM existence but where to look for it? We should look everywhere.
- Below the GeV standard direct detection searches are insensitive.
- For the MeV- GeV range one needs to rely on alternative signals: Migdal effect and boosted DM.
- What about $\lesssim$MeV range? See Angelo's talk.