# Direct detection for Cygno

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# Outline

- Direct detection phenomenology

  Spin dependent, Spin independent

- Directionality opportunities

  Coherent elastic neutrino nucleus scattering, dark matter properties, boosted dark matter, …

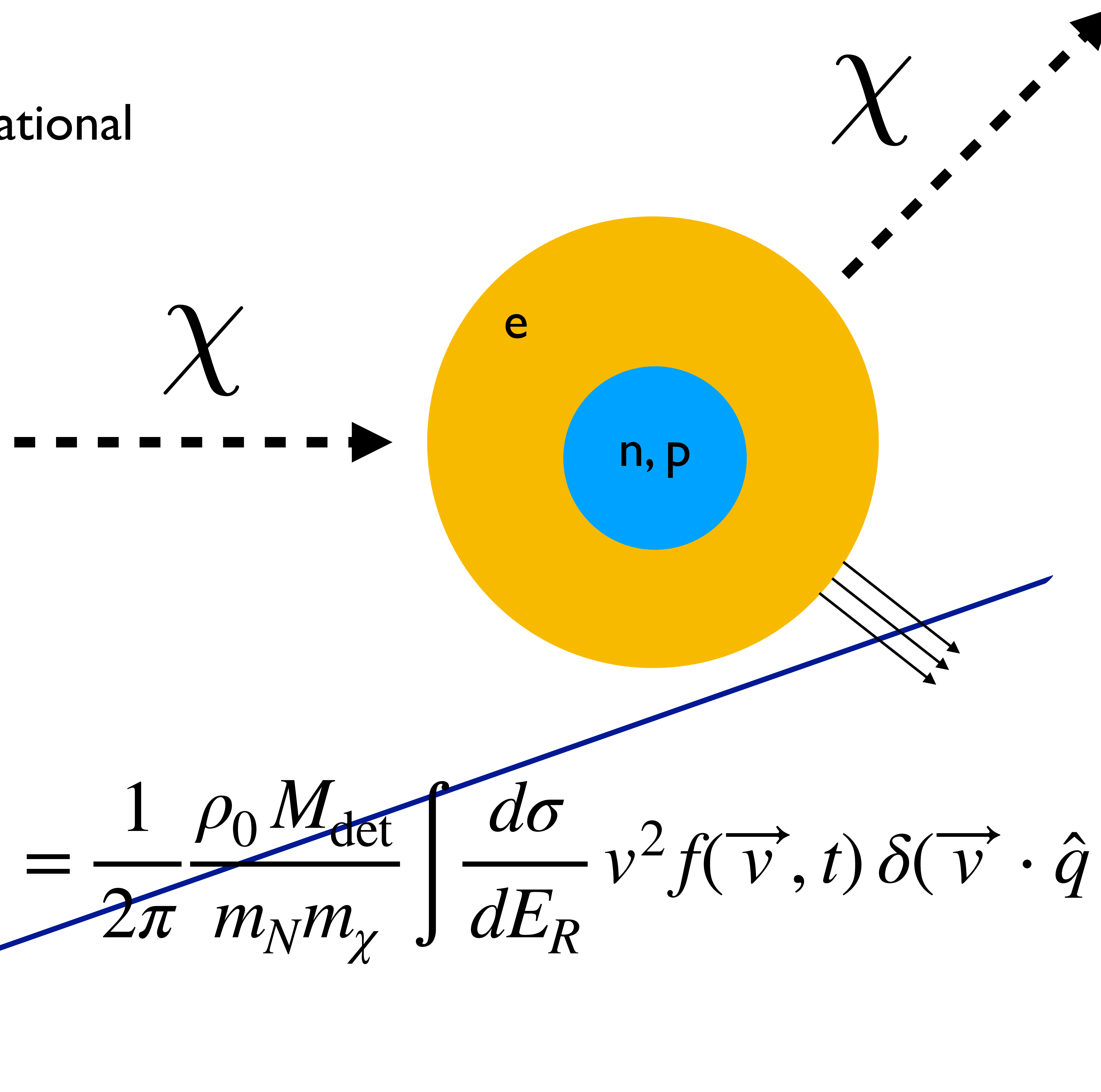
- Migdal Effect

  Migdal effect in nuclear scattering?

# Direct detection phenomenology

# Direct detection phenomenology

*assuming non-gravitational interaction exists




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

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Detector dependence

$m_N$ affects also the cross section

# Direct detection phenomenology

Astrophysical inputs

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particle physics

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Detector dependence

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# Direct detection phenomenology

$$\mathscr{L} \supset \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$
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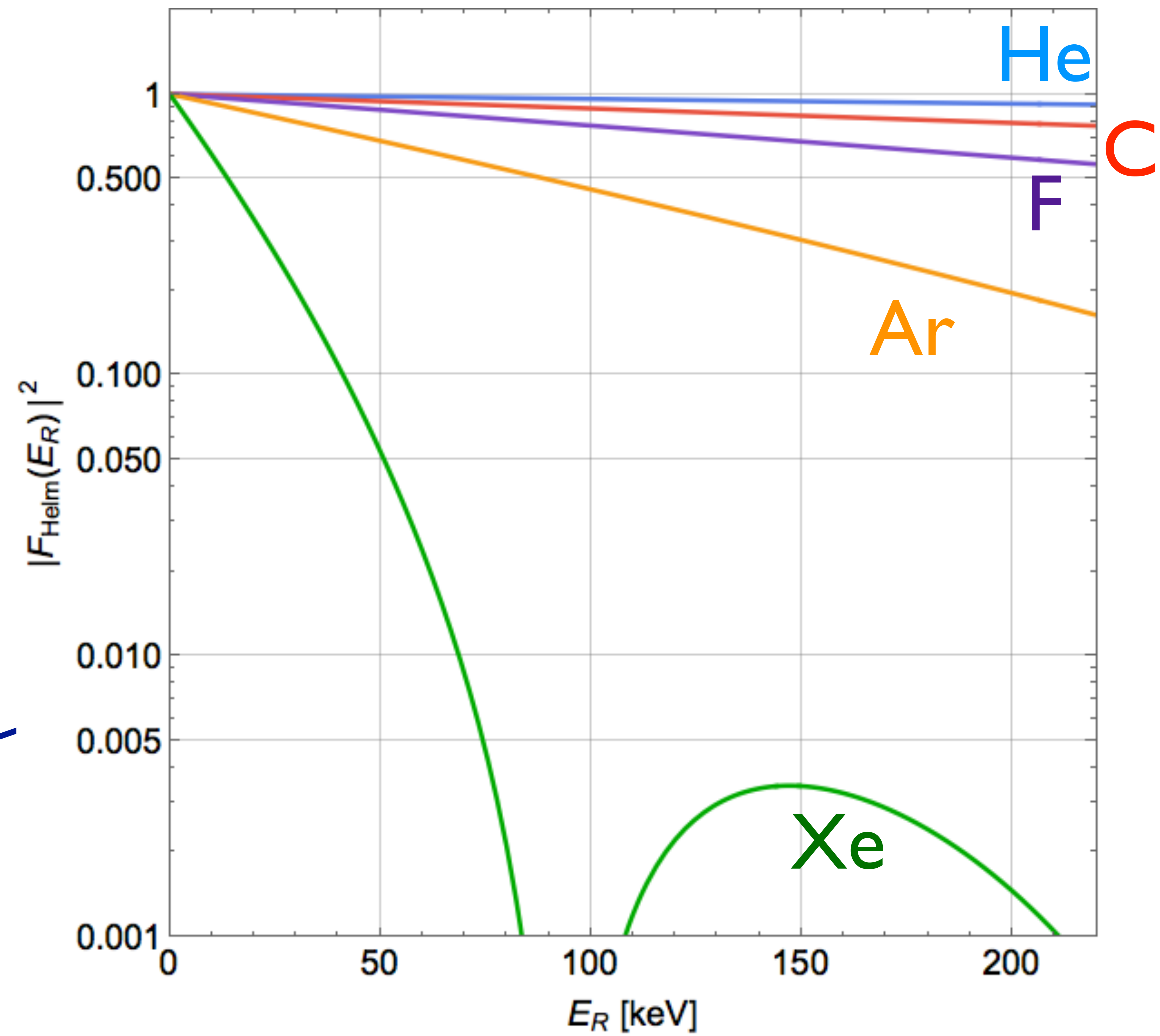
$$\mathscr{L} \supset \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$$

$$\frac{d\sigma}{dE_R}(v, E_R) = \left.\frac{d\sigma}{dE_R}\right|_{SI} + \left.\frac{d\sigma}{dE_R}\right|_{SD}$$

# Direct detection phenomenology

Helm form factor

$$\left.\frac{d\sigma}{dE_R}\right|_{SI} = \frac{m_N\,\sigma_p\,A^2}{2\mu_p^2\,v^2}\,|\,F(E_R)\,|^2$$

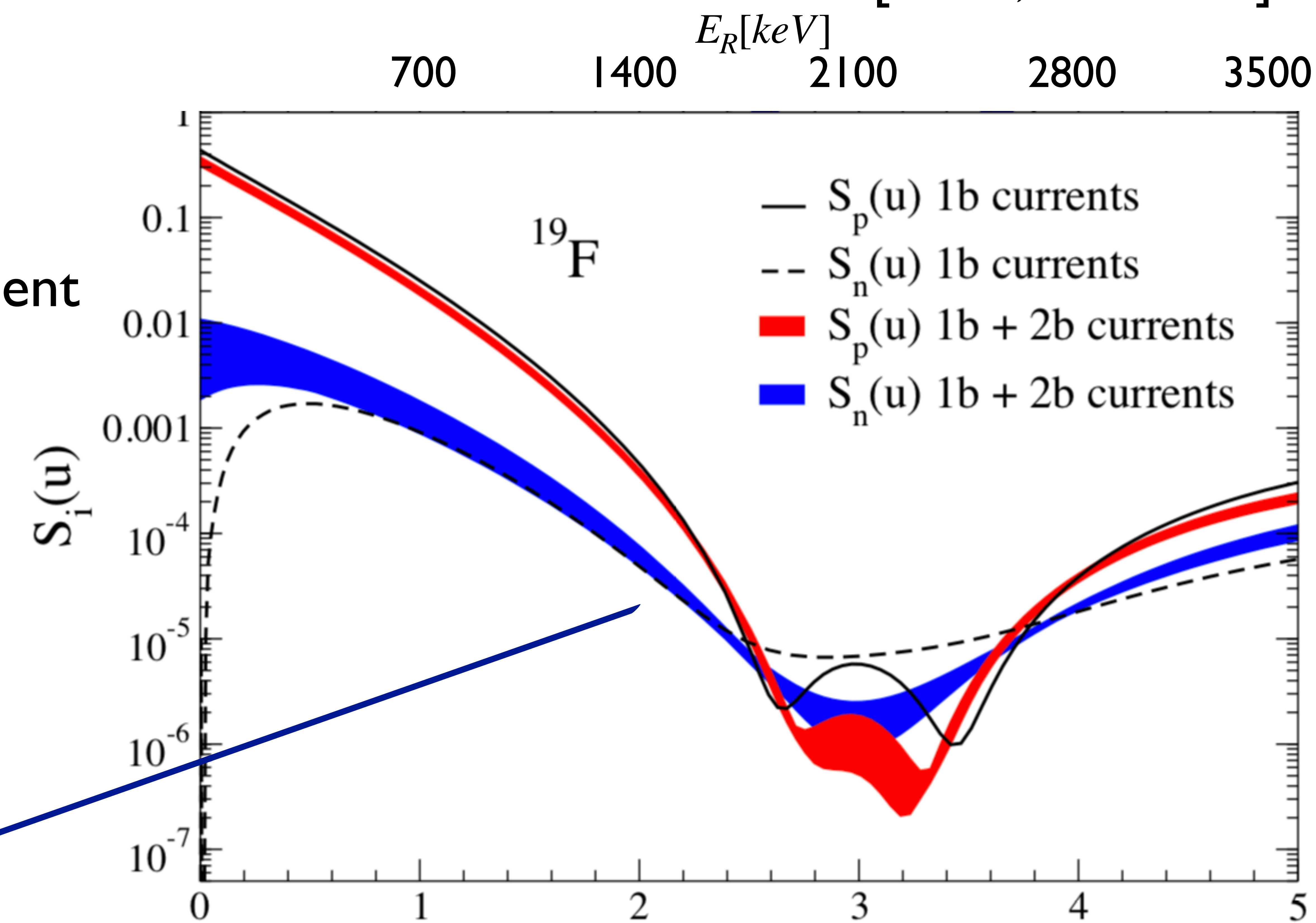


# Direct detection phenomenology

[Klos+, 1304.7684]

$$\left.\frac{d\sigma}{dE_R}\right|_{SD} = \frac{2}{3}\frac{J+1}{J}\frac{m_N\,\sigma_p\,\langle s_p\rangle^2}{\mu_p^2\,v^2}\frac{S_p(E_R)}{S_p(0)}$$

Spin dependent form factor




$$u = \frac{1}{2}q^2b^2$$

| | $\langle s_p\rangle$ | $\langle s_n\rangle$ |
|---|---|---|
| H | 0.5 | 0 |
| He* | 0 | 0 |
| C* | 0 | 0 |
| F | 0.478 | -0.002 |

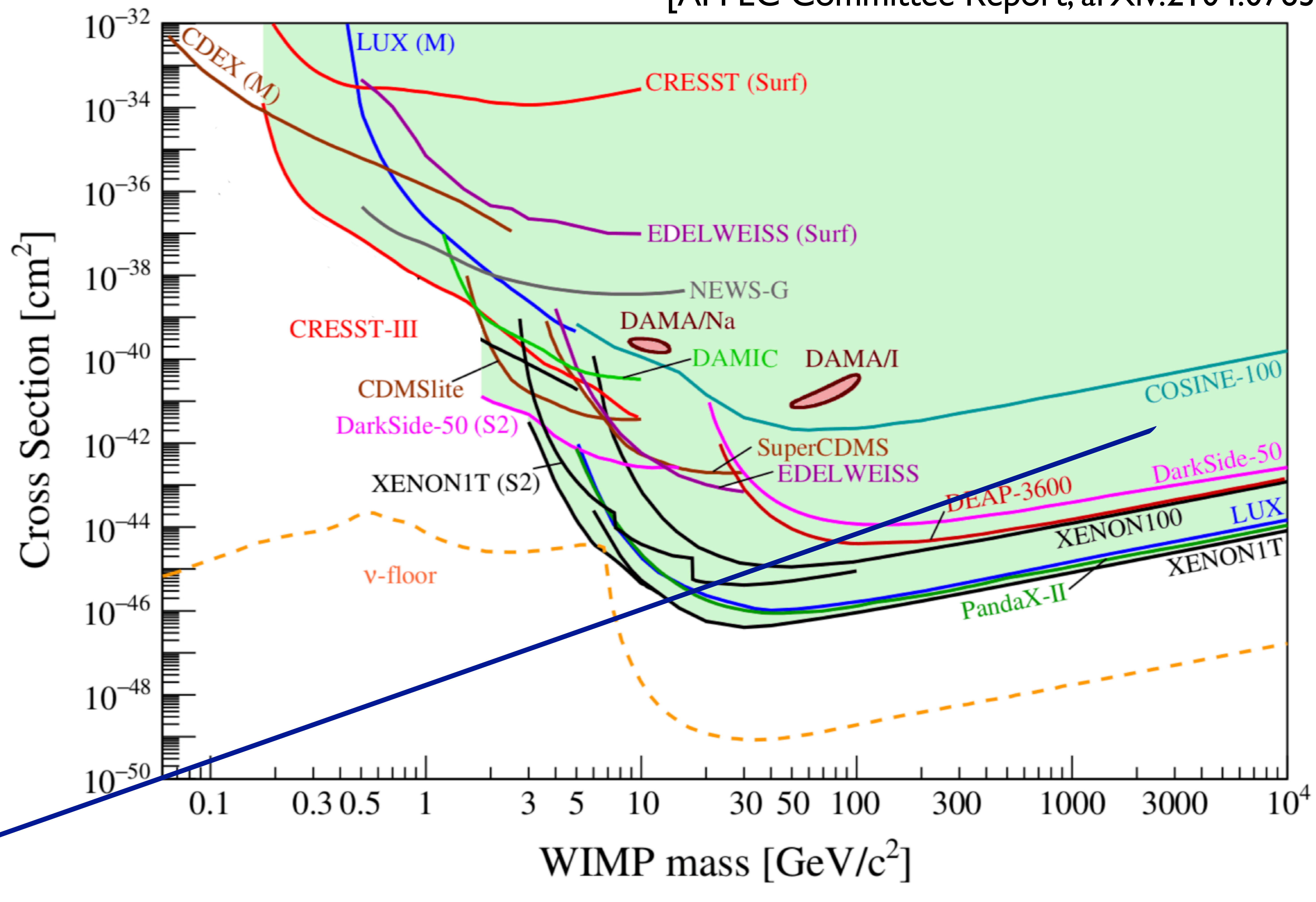
$b \simeq 1.7$ fm

$q^2 = 2\,m_n\,A\,E_R$

* $^3$He and $^{13}$C have $\langle s_n\rangle = 0.552$ and $-0.172$, respectively

# Direct detection phenomenology

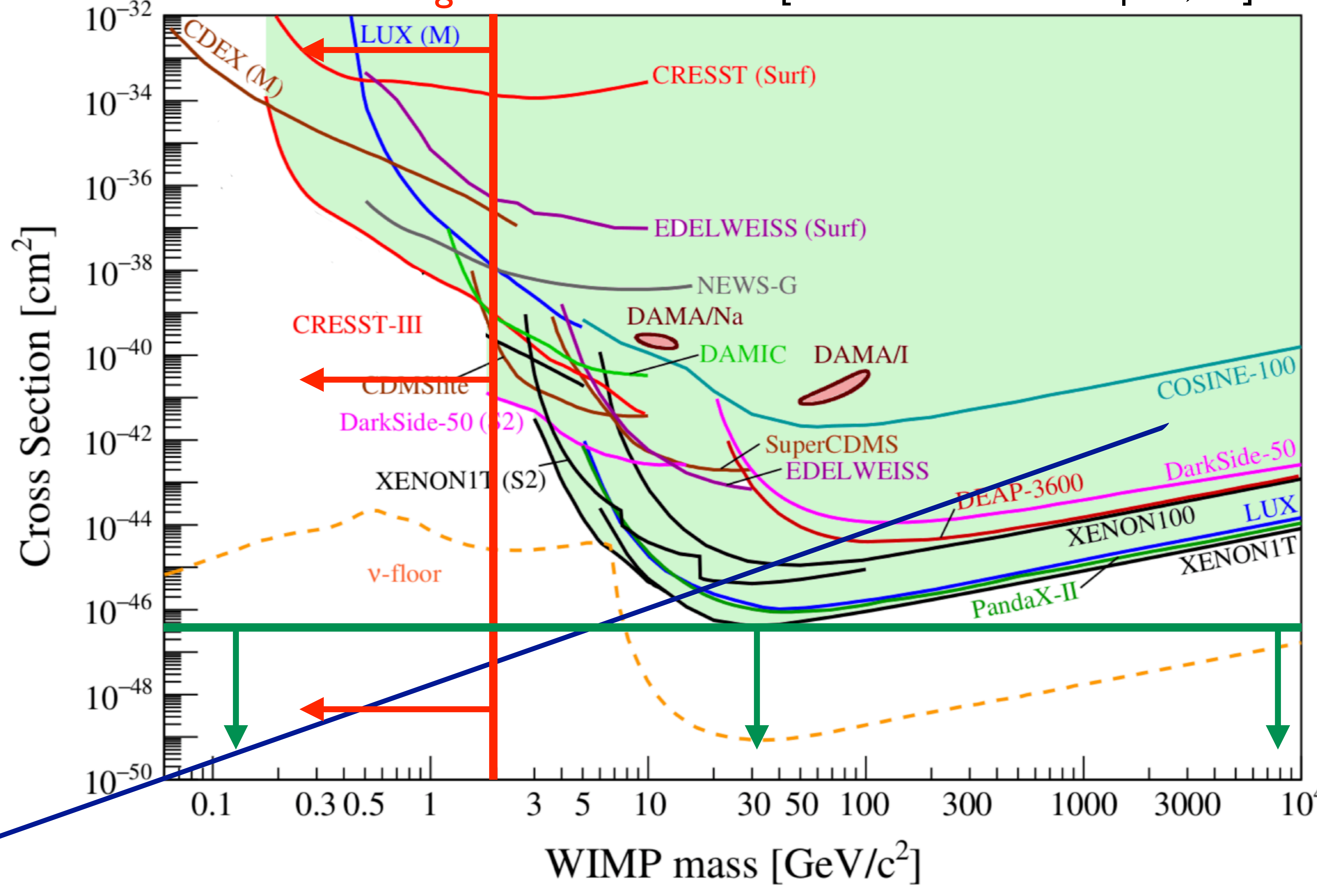
[APPEC Committee Report, arXiv:2104.07634]



# Direct detection phenomenology

Lighter targets, lower threshold, alternative signals

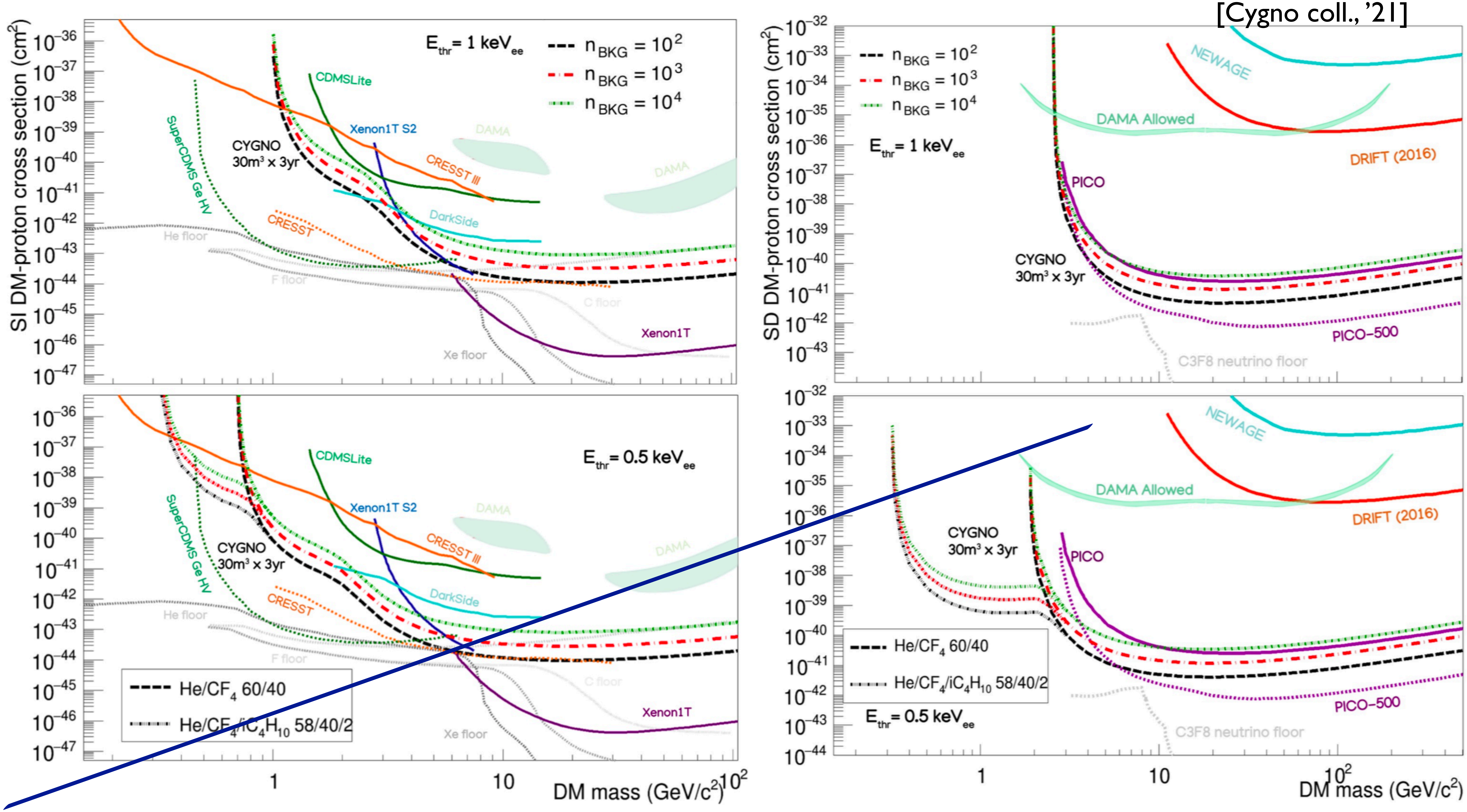
[APPEC Committee Report, '21]




increase exposure or volume of the experiment

# Direct detection phenomenology

[Cygno coll., '21]



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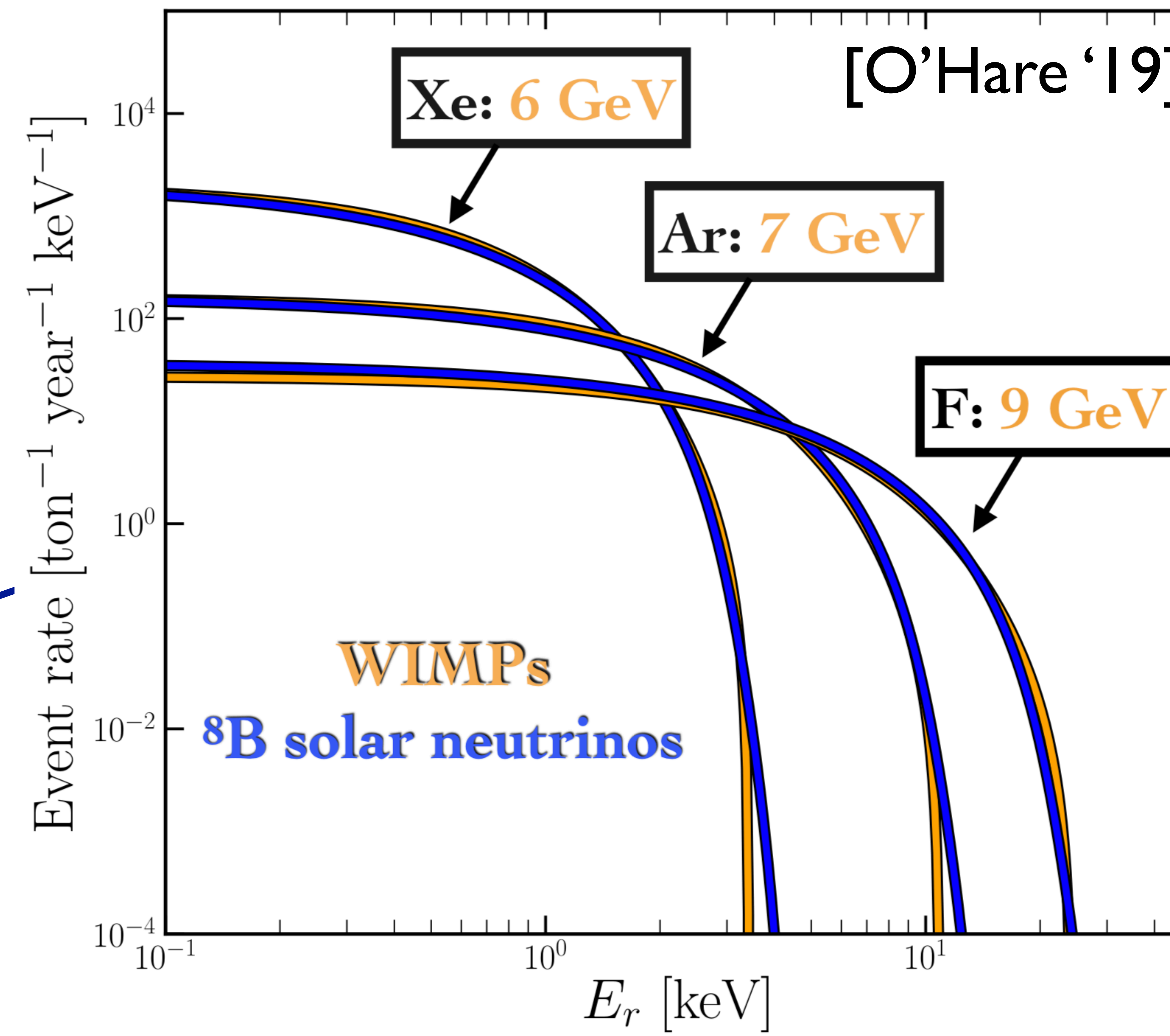
2. Neutrino floor

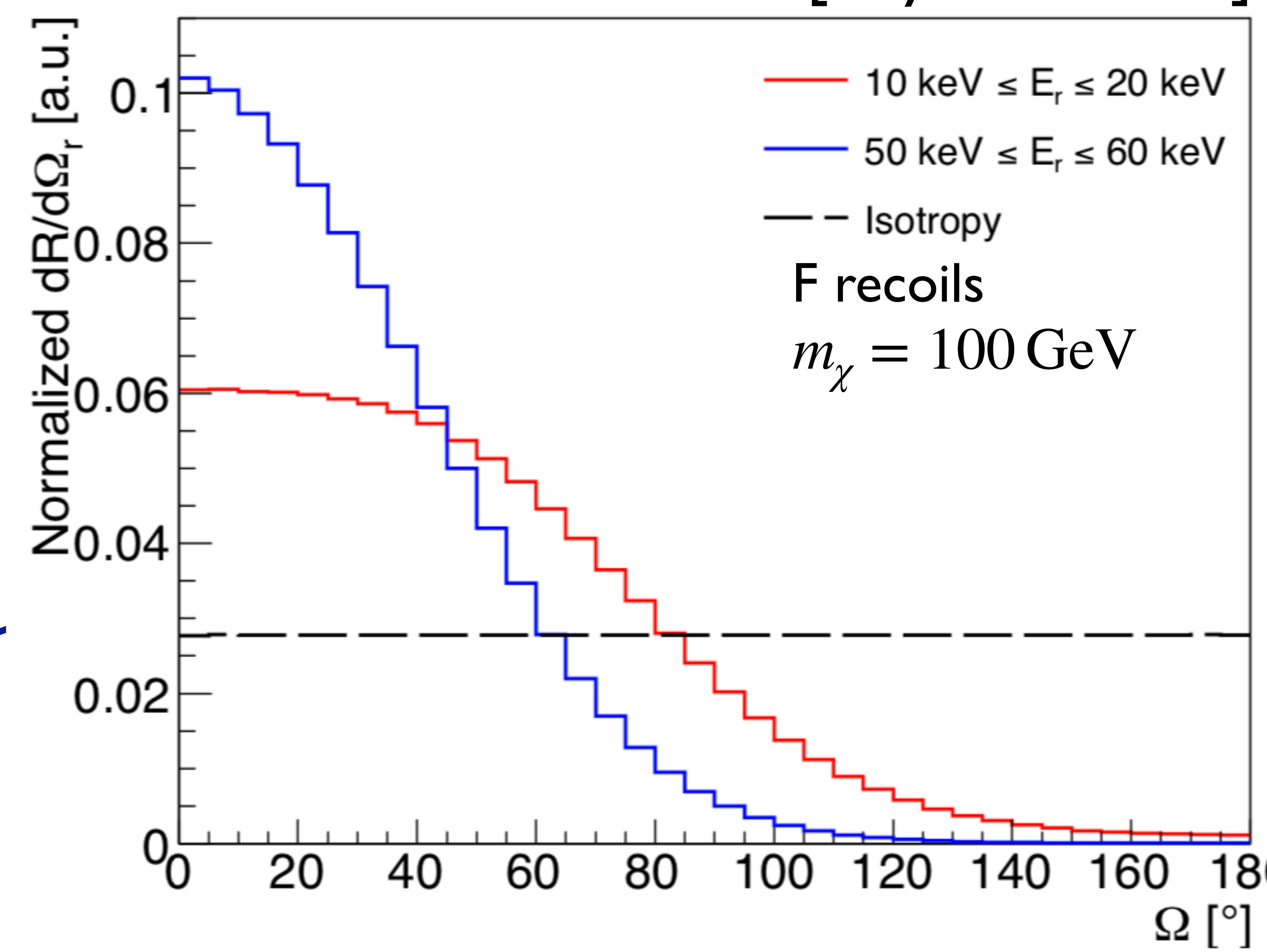


# Directionality opportunities

Solution: directional detection

1. Non isotropic background?

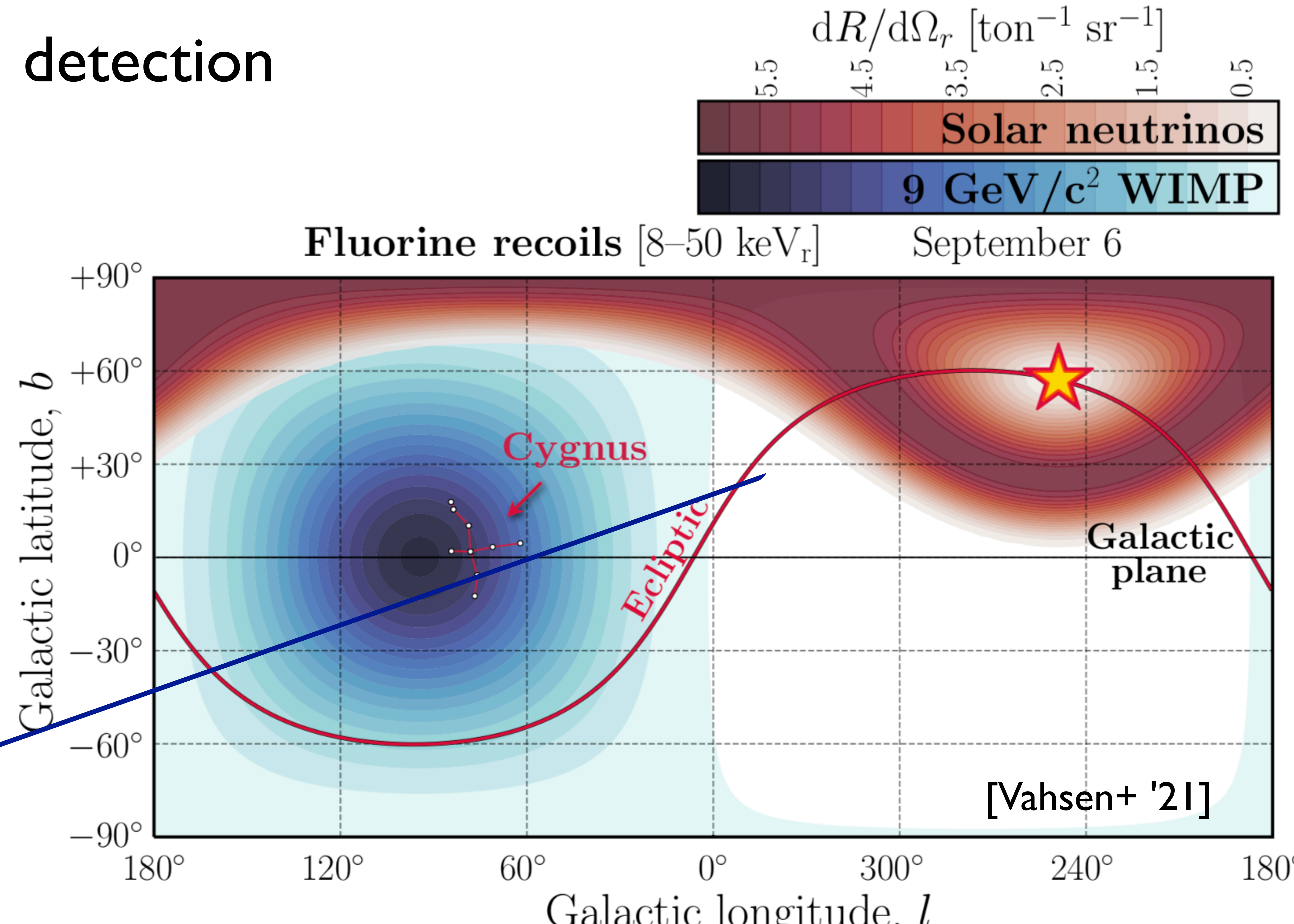
[Mayet et al., '16]



# Directionality opportunities

Solution: directional detection

2. Neutrino floor



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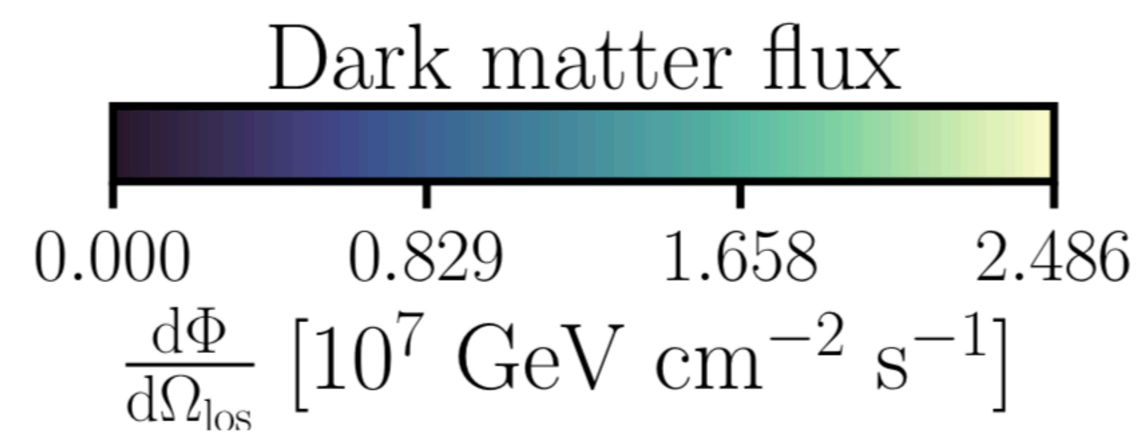


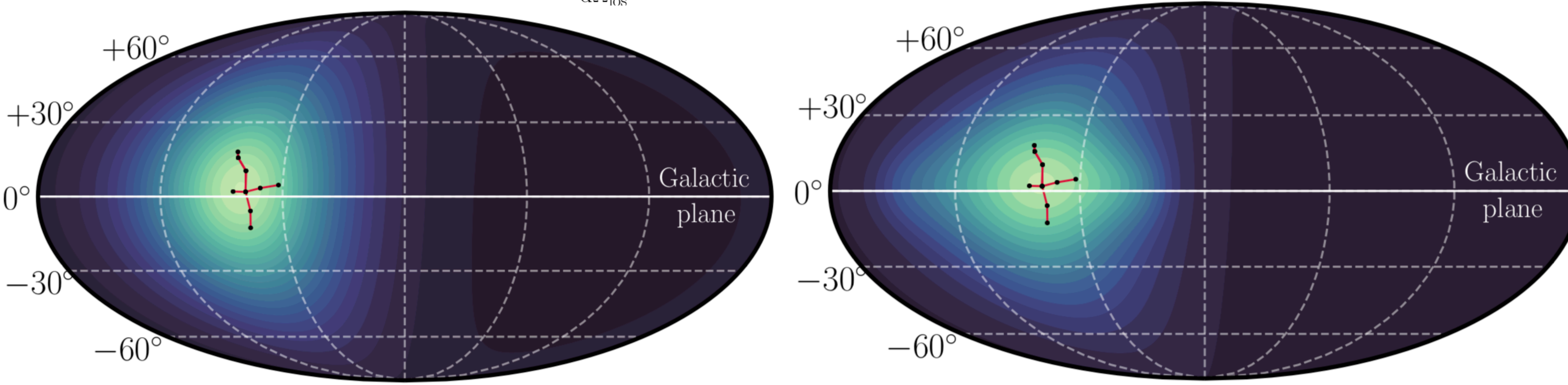


Standard Halo Model DM flux

Standard Halo Model + Gaia Sausage

[Evans+, ’18]

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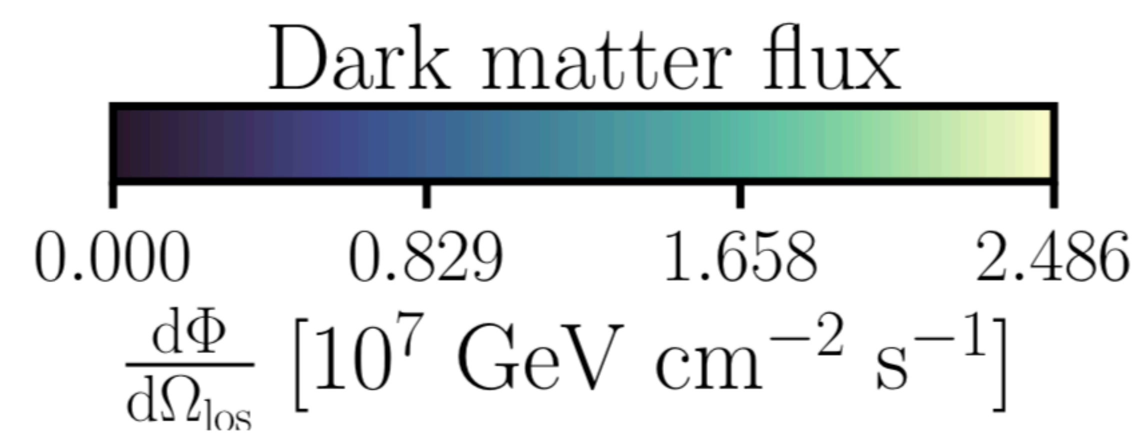
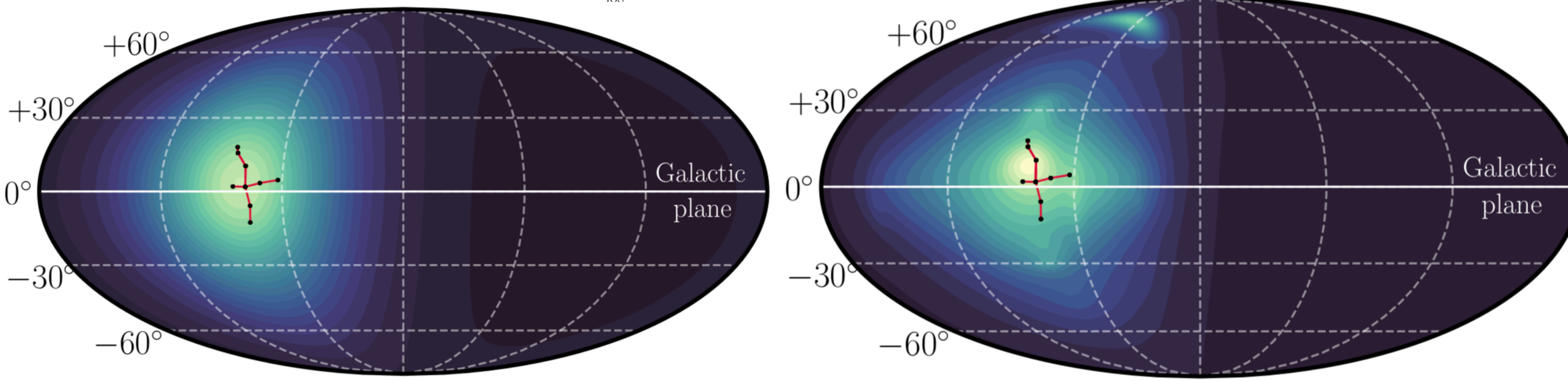


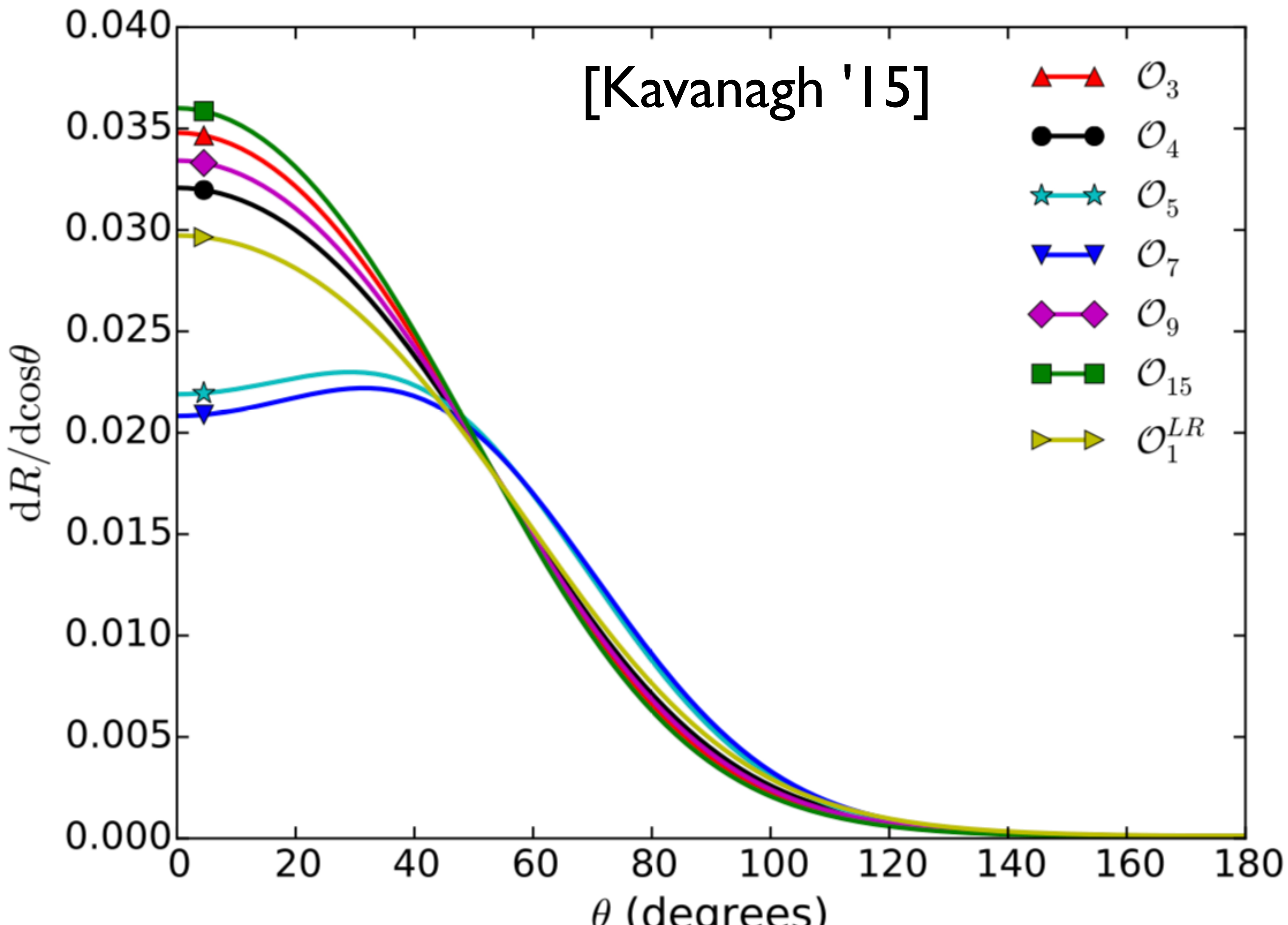

Standard Halo Model DM flux

Standard Halo Model + Gaia Sausage + local substructures [O'Hare+, '19]

# Directionality opportunities

## This assumes that:

- The DM nucleus matrix element does not depend on velocity




$$
\begin{cases}
1 & : \mathcal{O}_1, \mathcal{O}_4\,, \\
v_\perp^2 & : \mathcal{O}_7, \mathcal{O}_8\,, \\
q^2 & : \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12}\,, \\
v_\perp^2 q^2 & : \mathcal{O}_5, \mathcal{O}_{13}, \mathcal{O}_{14}\,, \\
q^4 & : \mathcal{O}_3, \mathcal{O}_6\,, \\
q^4(q^2 + v_\perp^2) & : \mathcal{O}_{15}\,, \\
q^{-4} & : \mathcal{O}_1^{LR}\,.
\end{cases}
$$

# Directionality opportunities

This assumes that:

- There are no fluxes from other directions

Boosted dark matter

1. Cosmic rays up-scattered dark matter
   [Bringmann+ '19, Sala+ '19]
2. Blazar Boosted dark matter
   [Wang+ '21]

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Boosted dark matter

1. Cosmic rays up-scattered dark matter
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   [Wang+ '21]
3. Supernova produced dark matter
   [Baracchini+ '20]

# The Migdal effect

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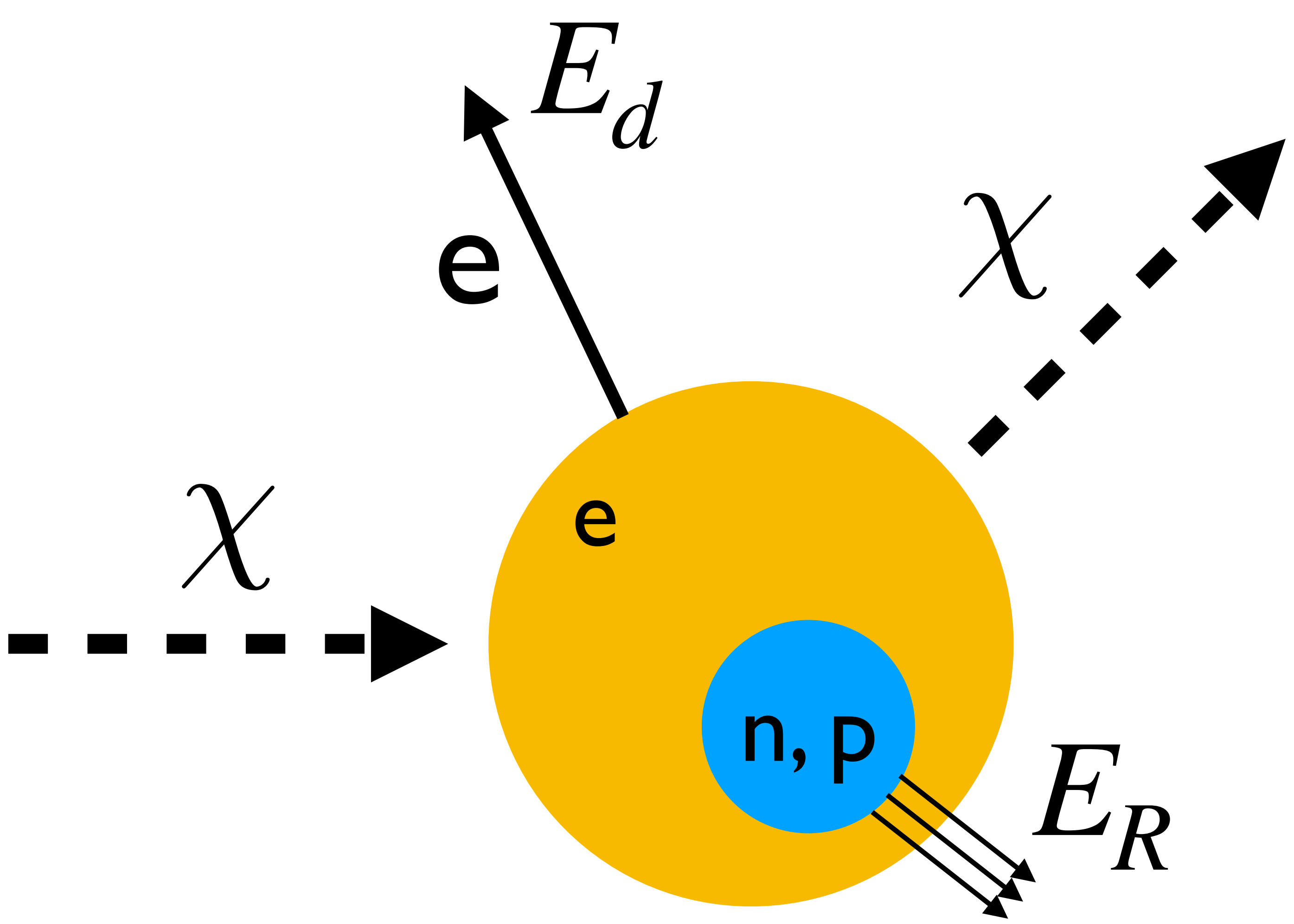

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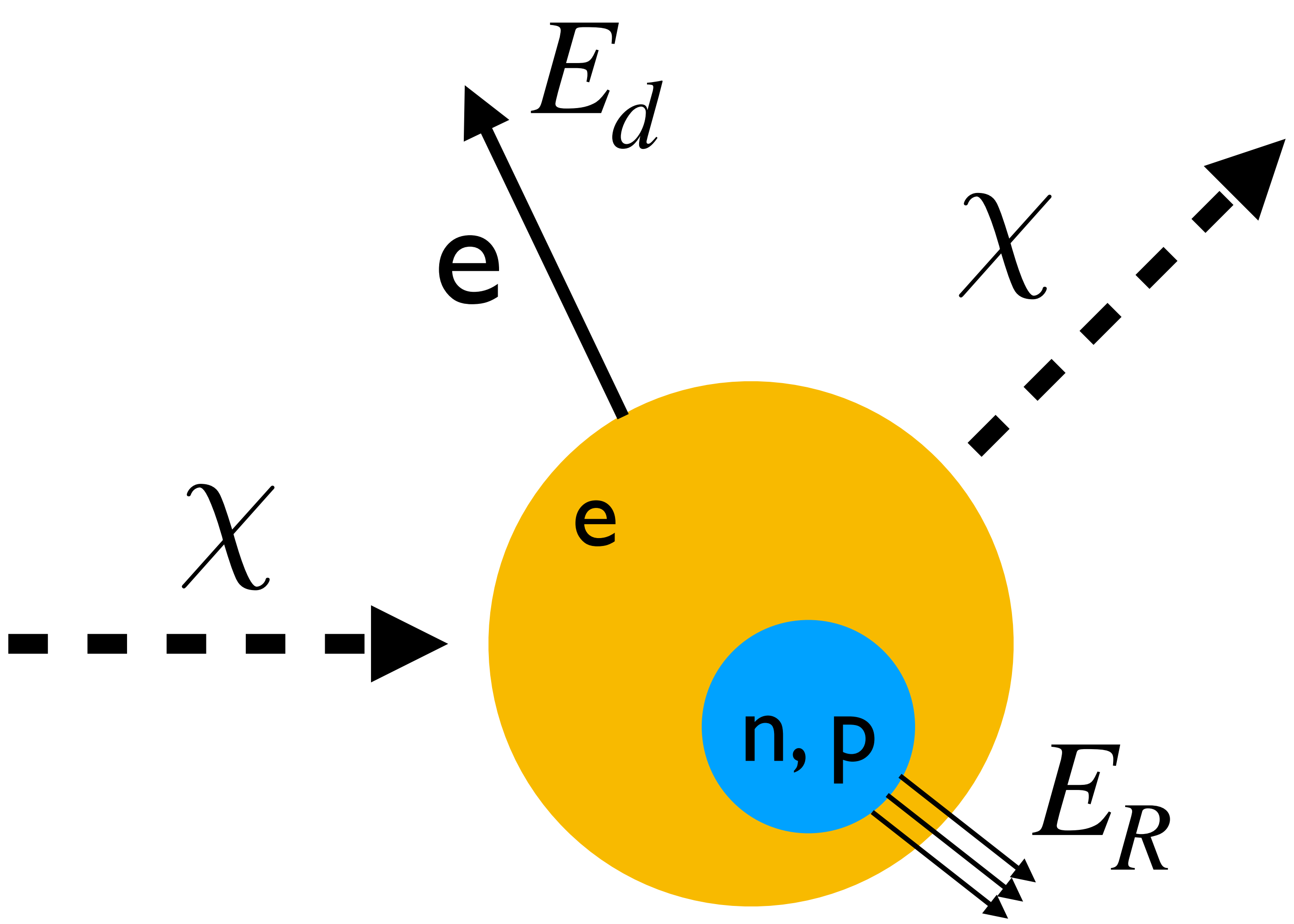


## Kinematics

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

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

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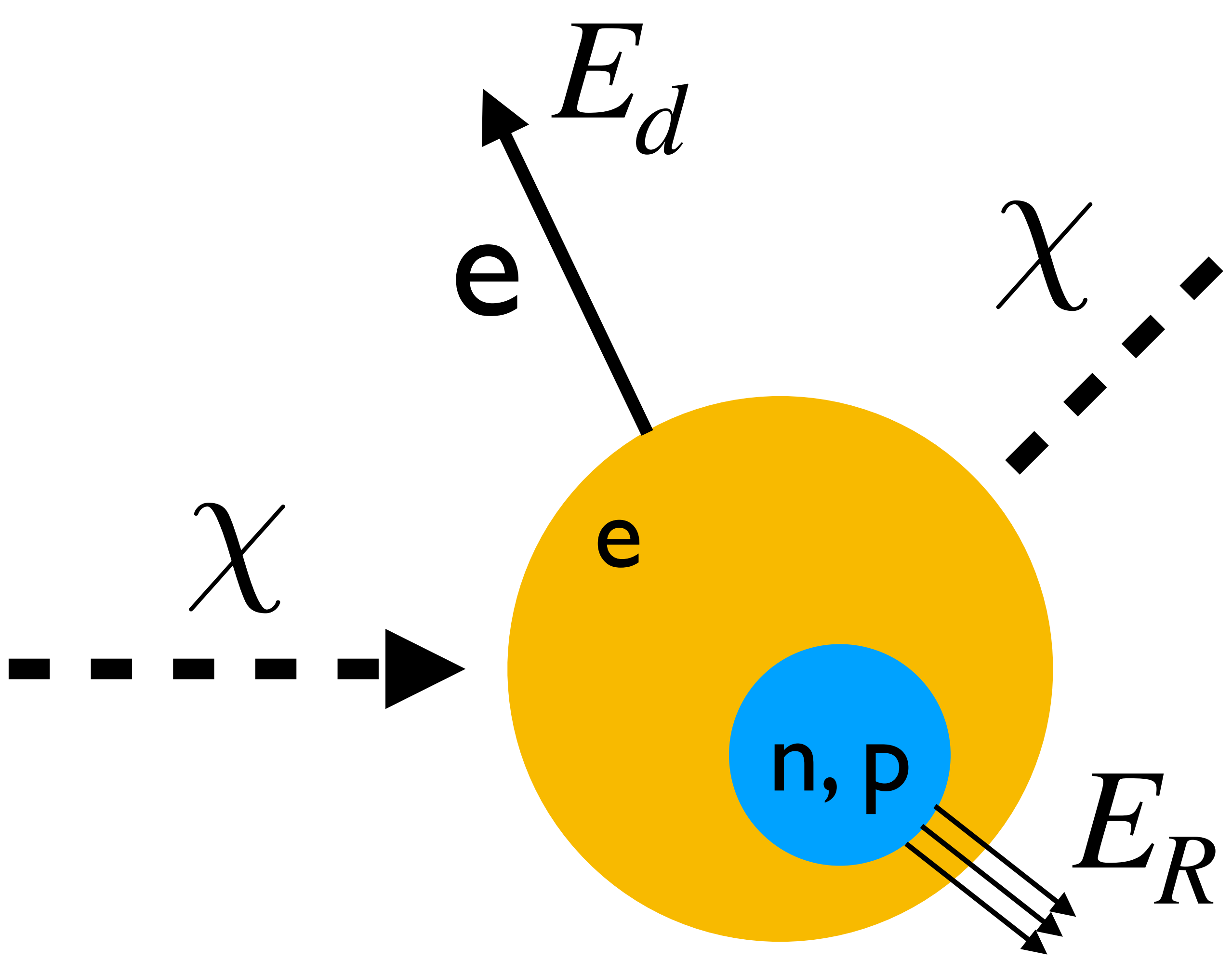


## Kinematics

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

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

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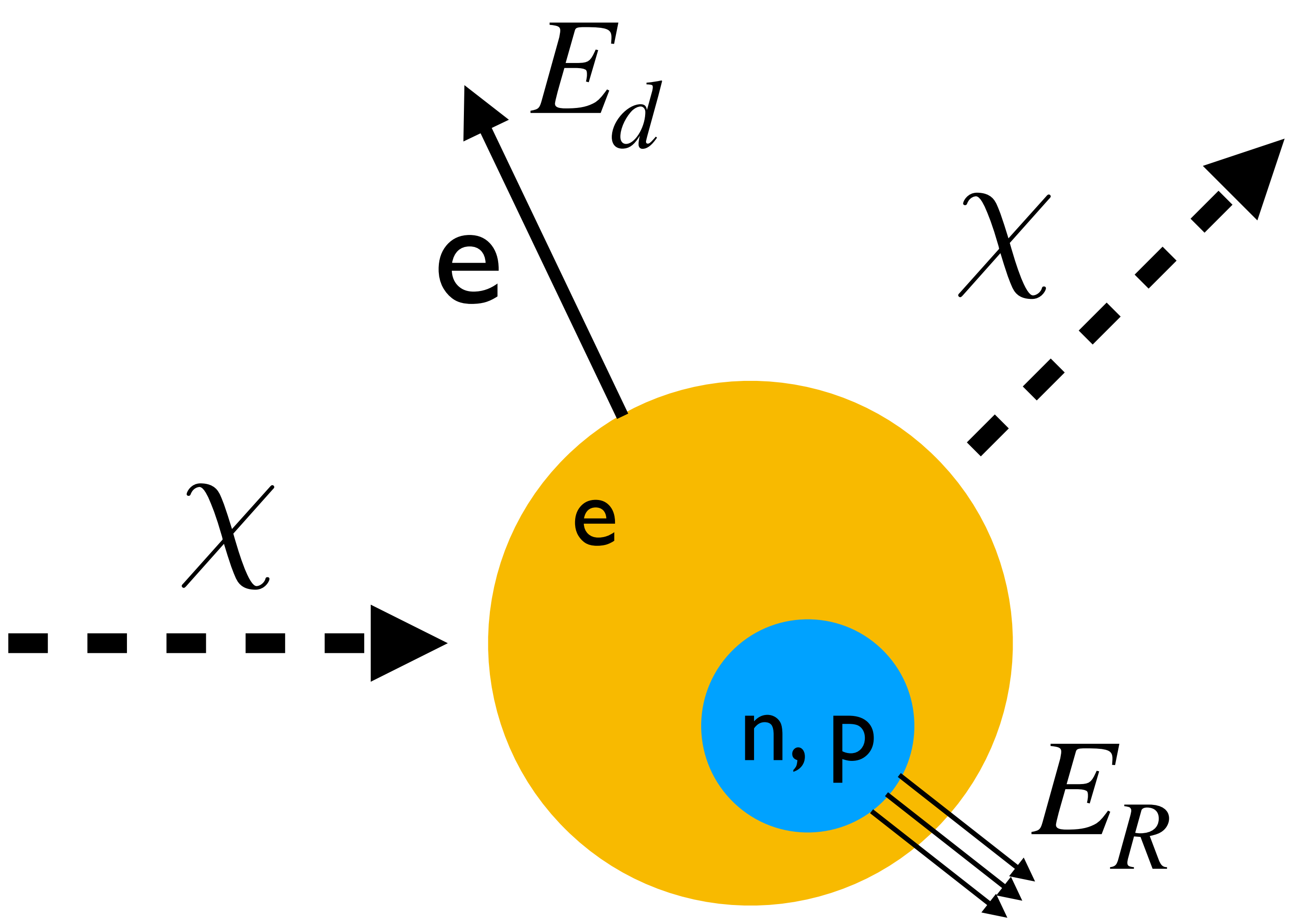


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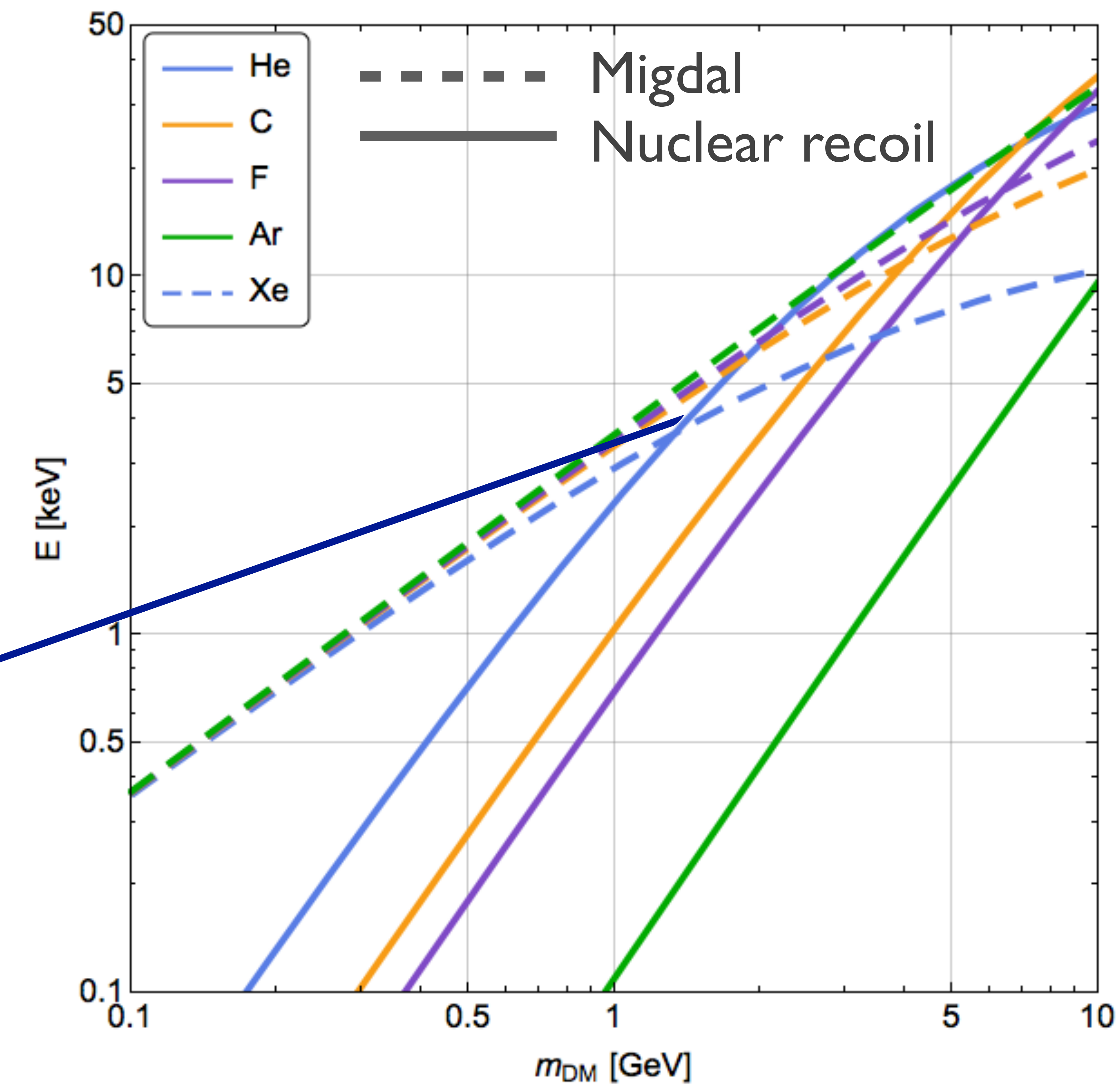


1. Threshold $E \lesssim 1$ keV
2. Sensitivity loss for $m_{DM} \lesssim 2\,\mathrm{GeV}$
3. $E_d^{\max} > E_R^{\max}$ for $m_{DM} \ll m_N$
4. The Migdal effect is sensitive to sub-GeV masses

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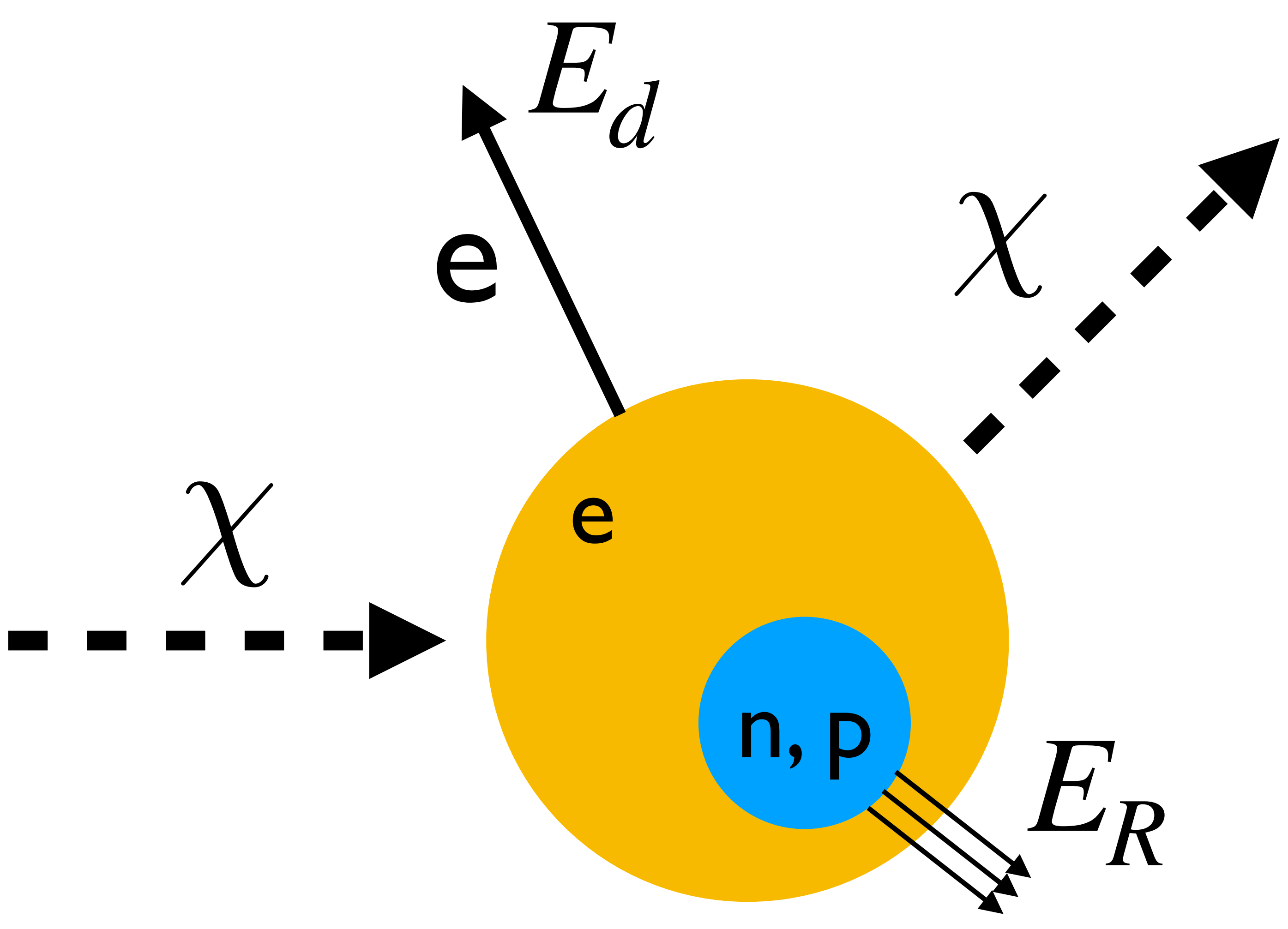


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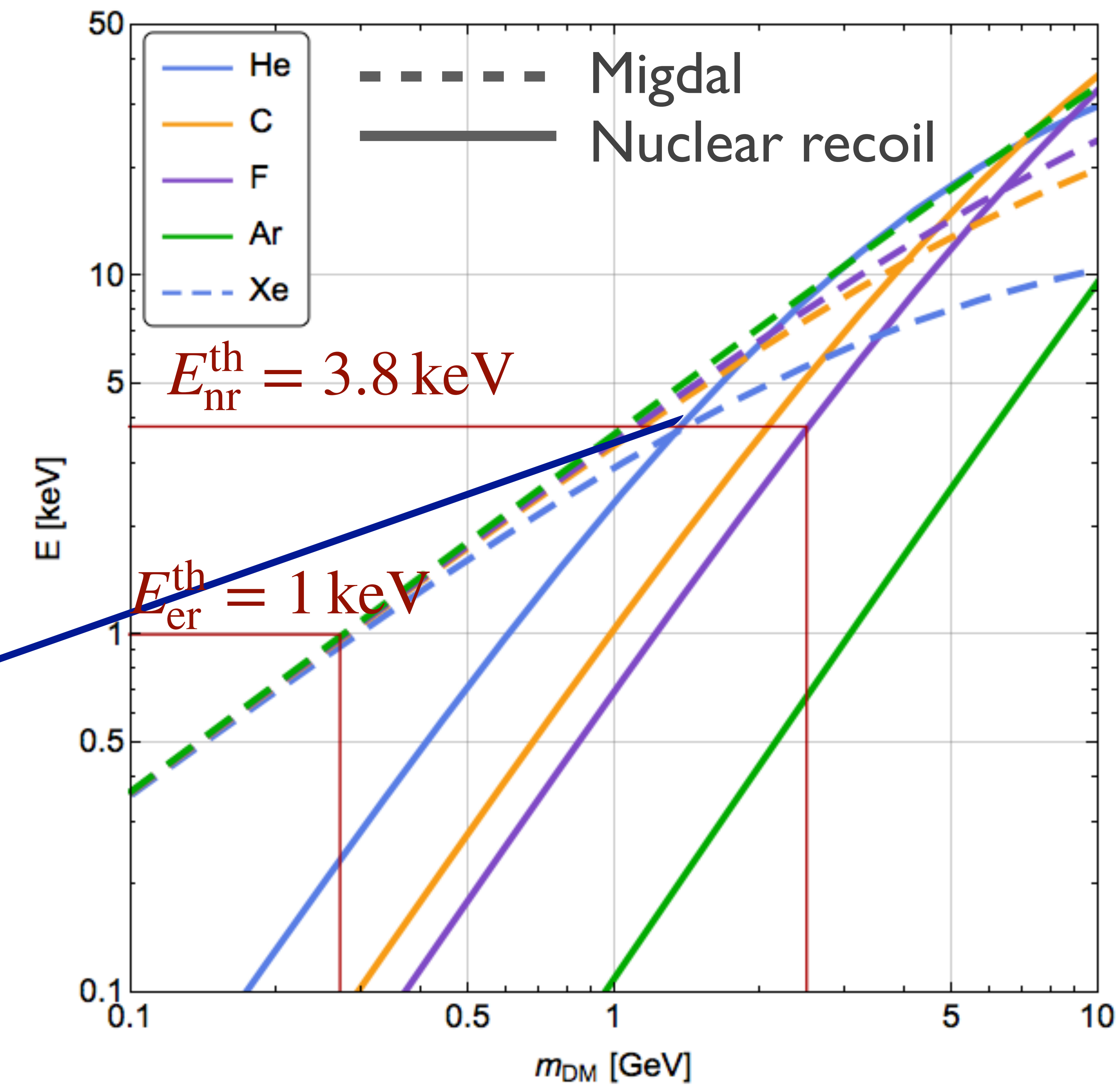


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DM nuclear recoil

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DM nuclear recoil

NR — de-excitation: negligible — ionization rate

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

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DM nuclear recoil

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NR

de-excitation: negligible

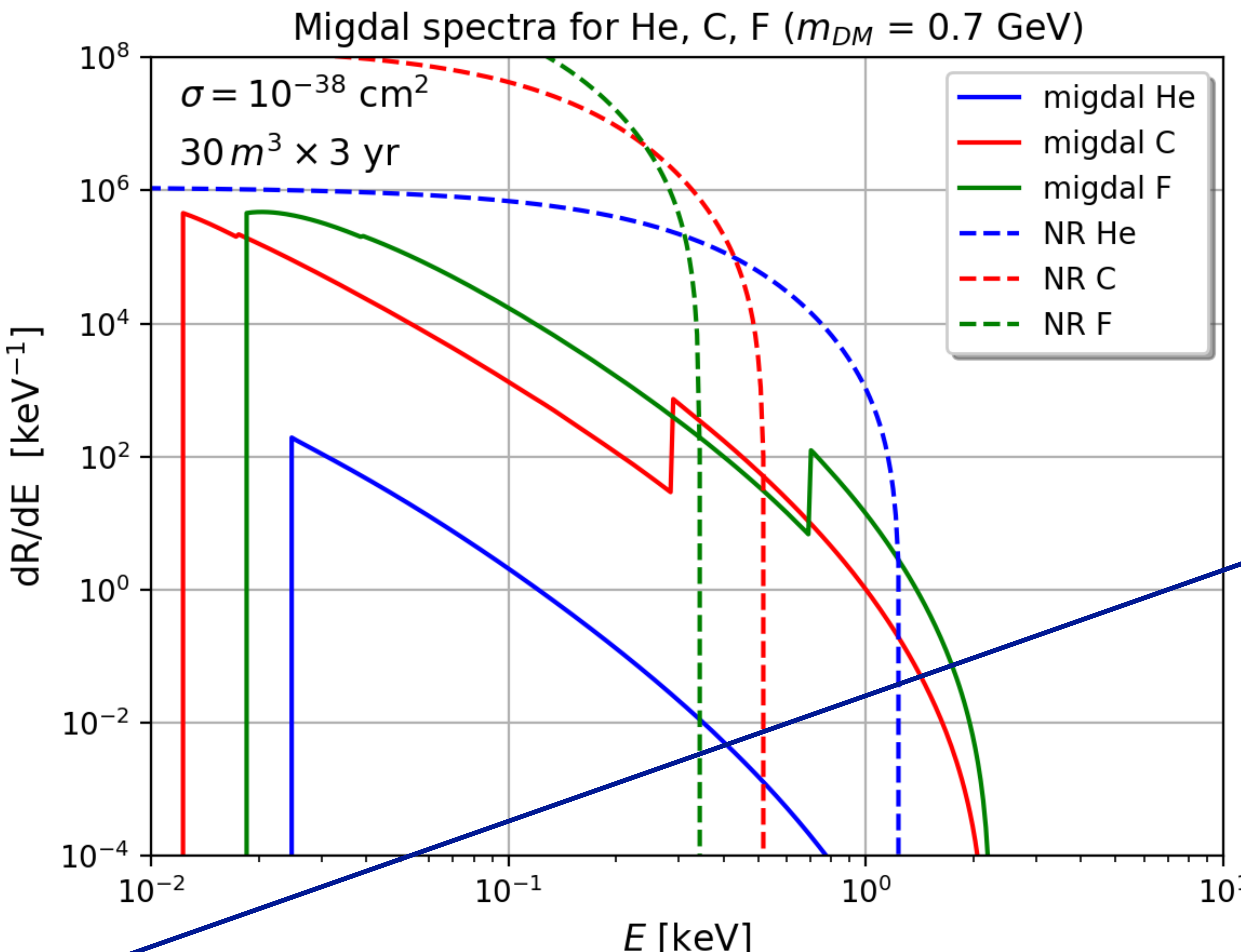
ionization rate

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

Migdal

Computed in [Ibe et al. JHEP03(2018)194] for C, F, Ar, Xe, …
and by GGdC, S. Piacentini and A. Messina [unpublished] for He

# The Migdal effect




[Cygno coll., '21]

Energy thresholds in keV:

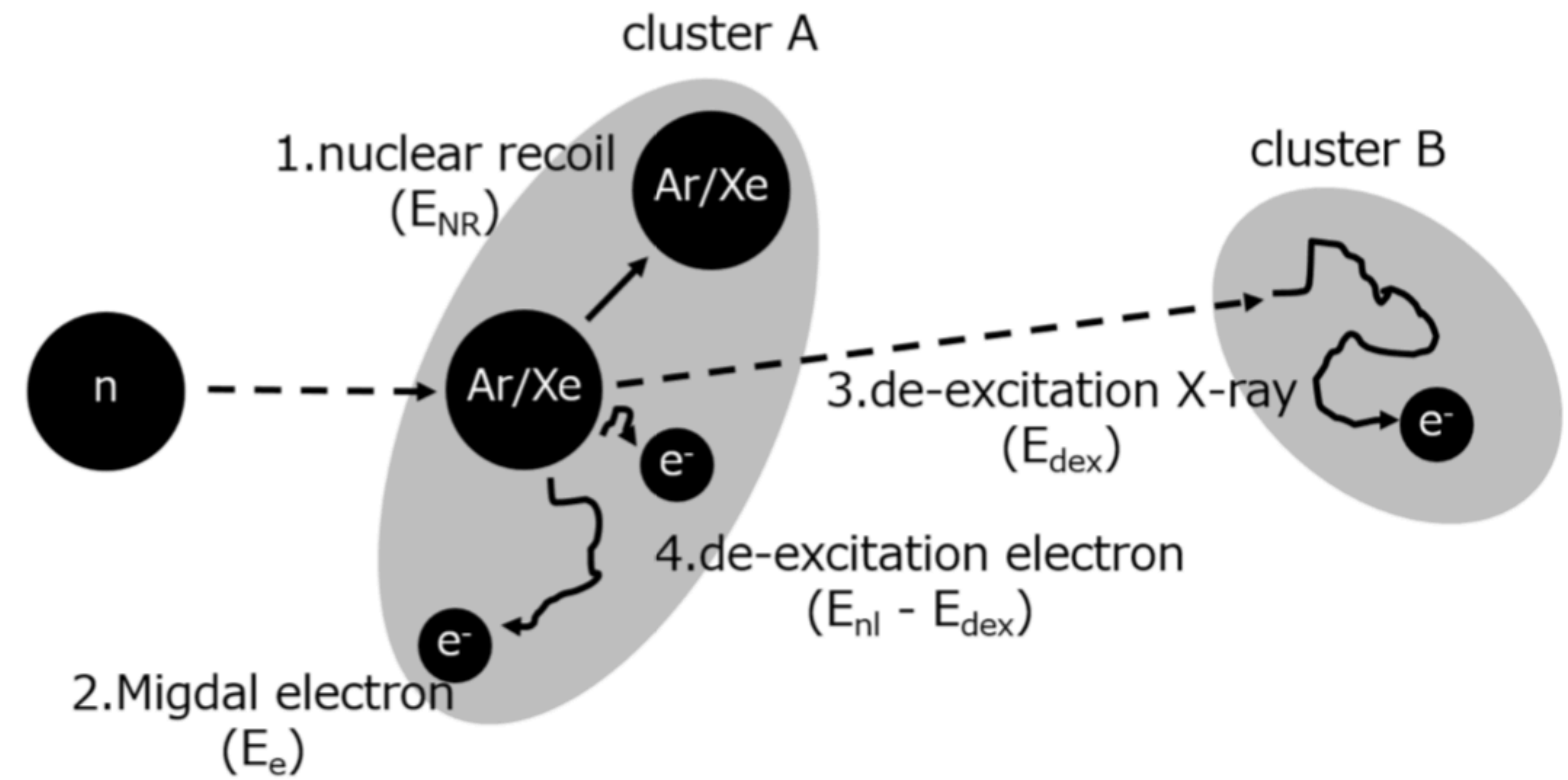
| | | |
|---|---|---|
| $E_{ee}$ | 1.0 | 0.5 |
| $E_{nr}$(He) | 2.1 | 1.2 |
| $E_{nr}$(C) | 3.1 | 1.8 |
| $E_{nr}$(F) | 3.8 | 2.2 |

# Can we measure the Migdal effect in nuclear scattering?

# Possible signatures

1. Neutrons can induce energetic NR;

[Nakamura et al., PTEP 1 (2021) 013C01]



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1. Neutrons can induce energetic NR;
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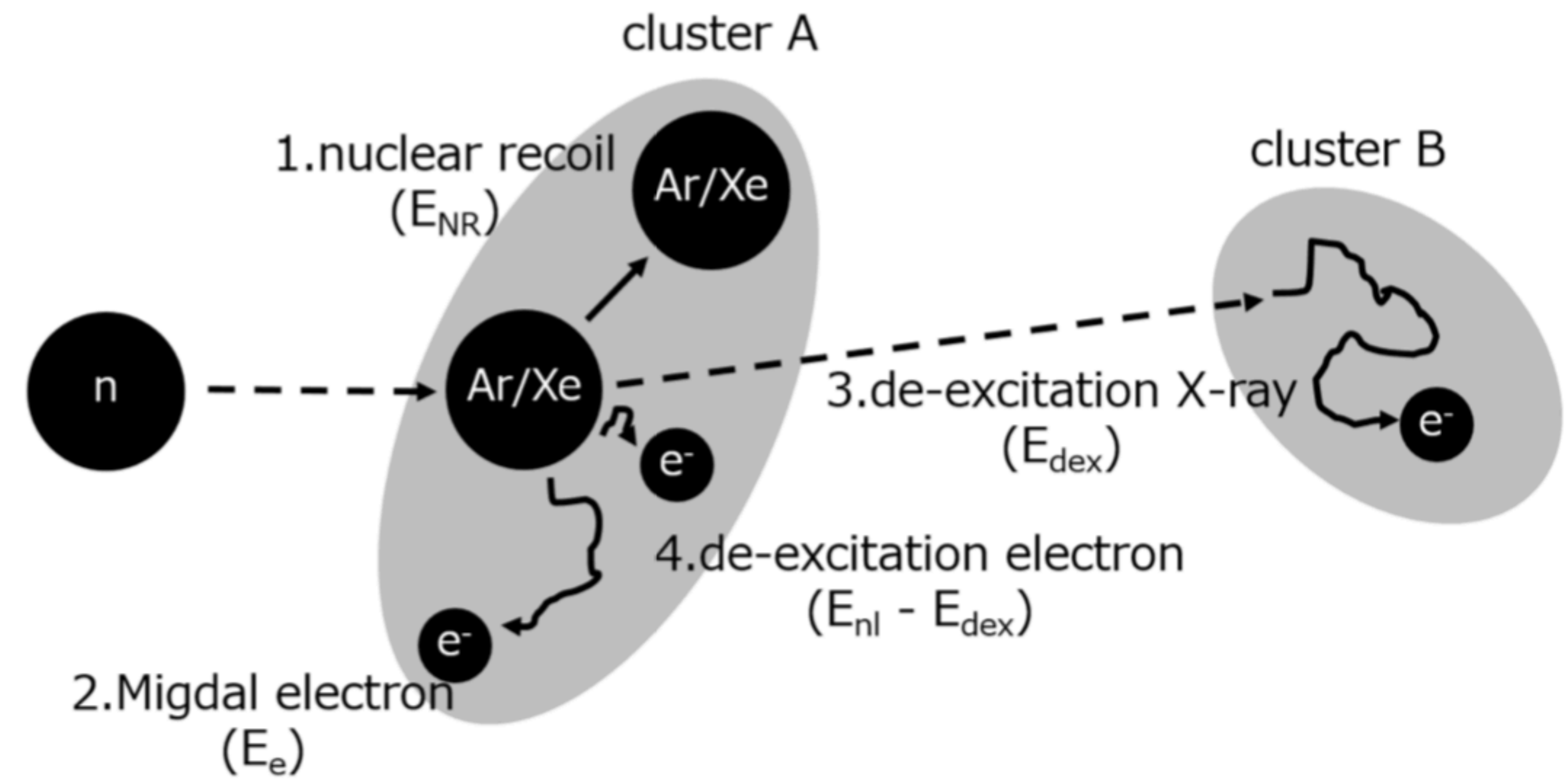

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1. Neutrons can induce energetic NR;
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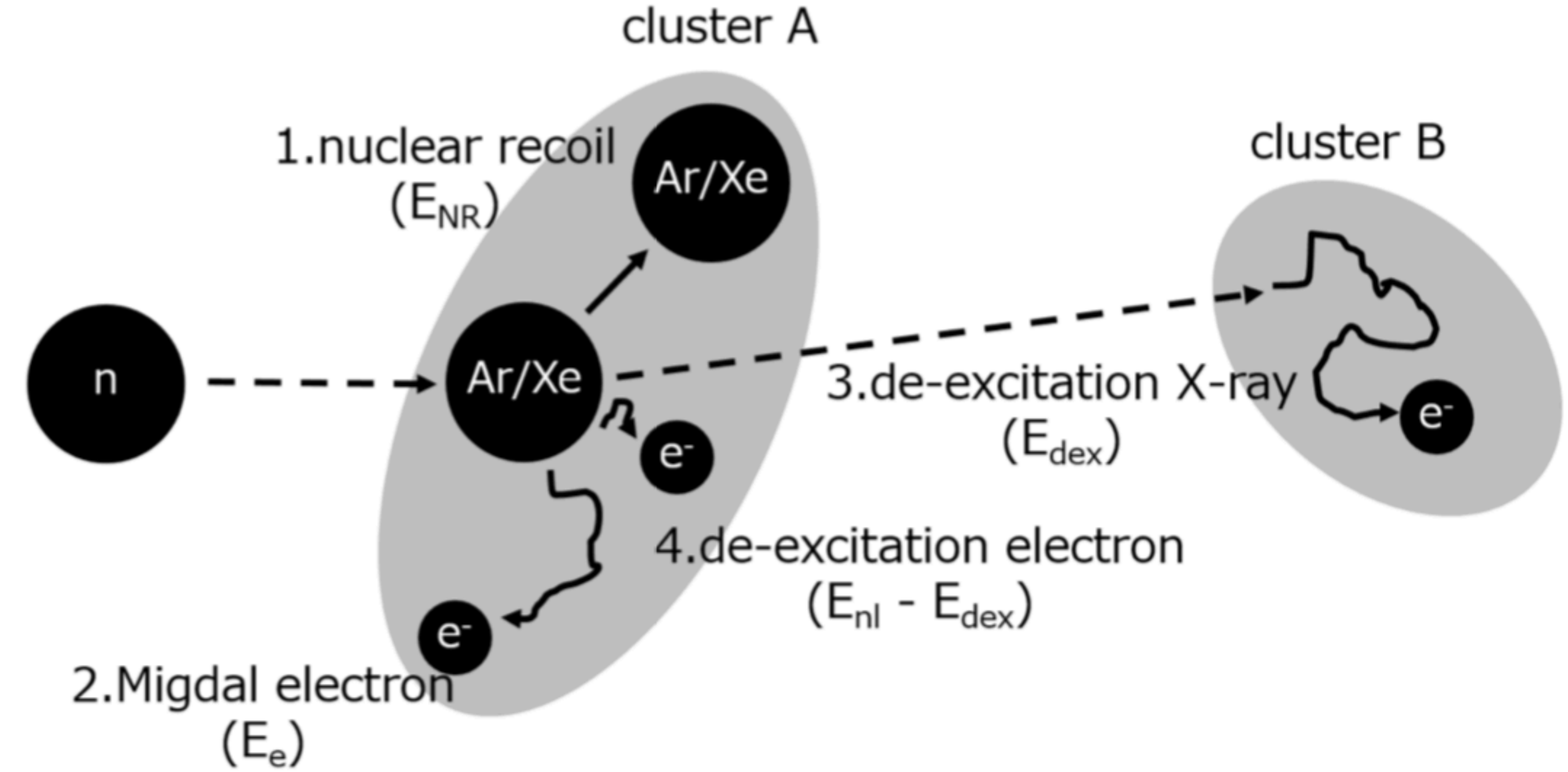

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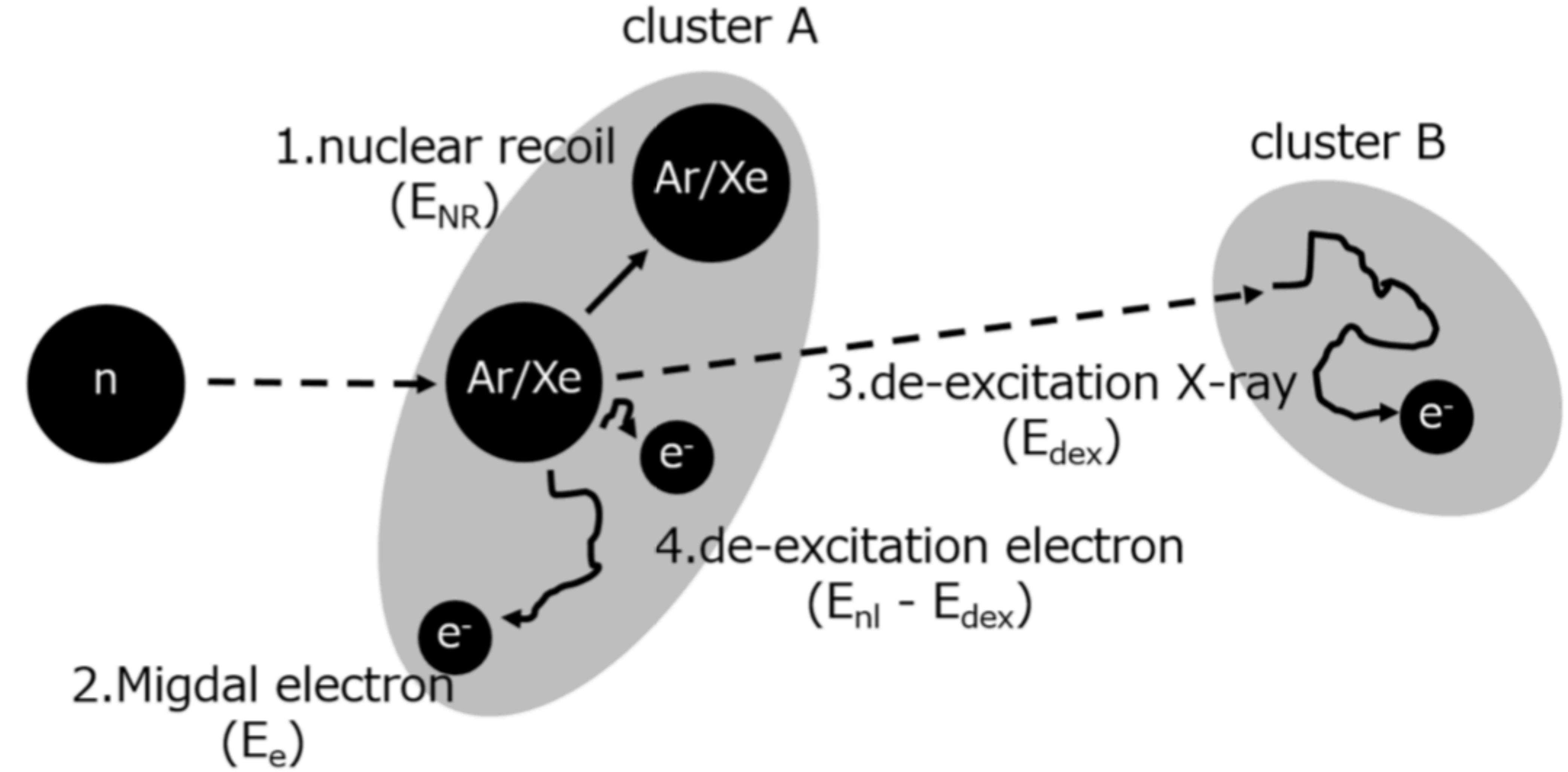
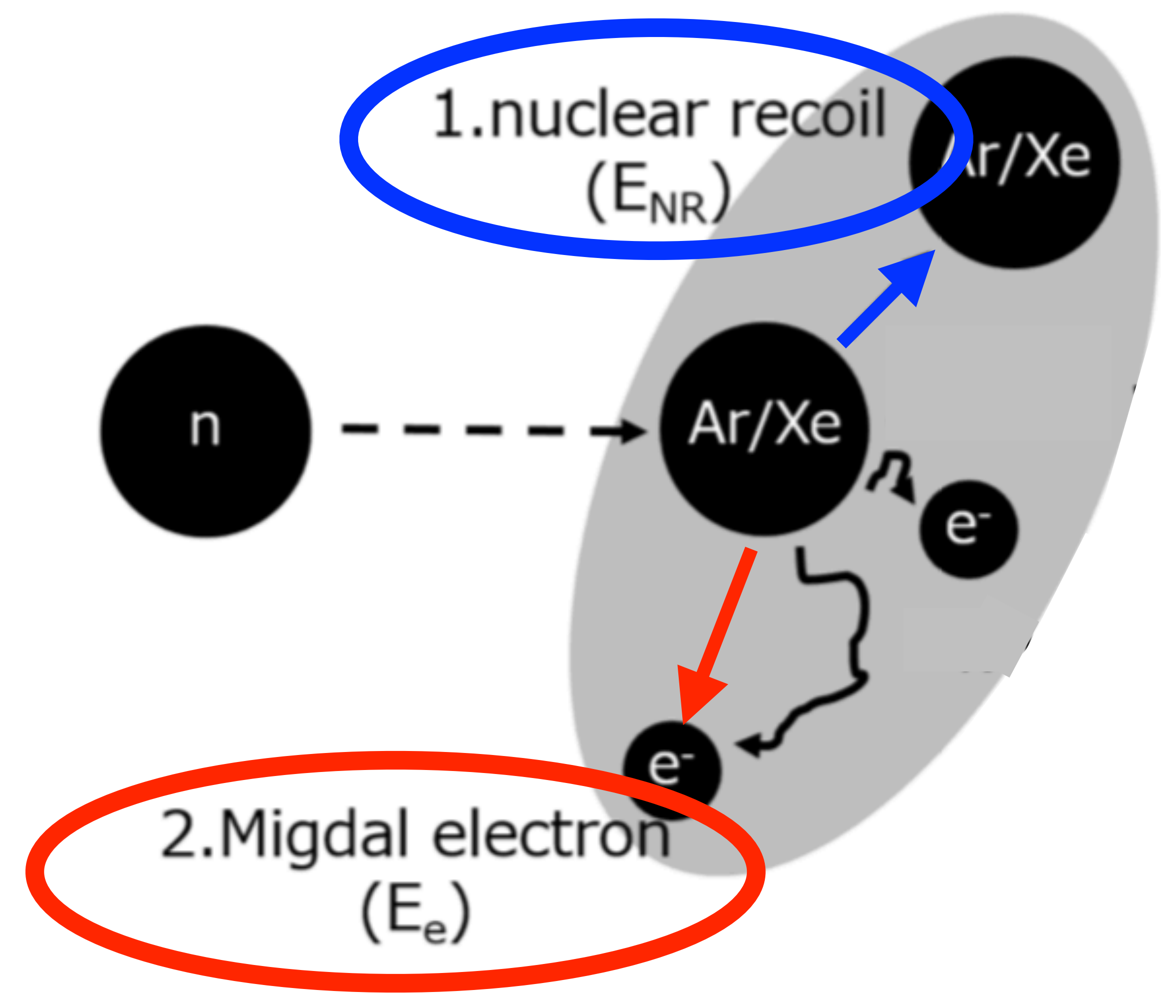
4. The signature is a vertex with an energetic NR and a few keV X-ray absorbed after a few cm;

[Nakamura et al., PTEP 1 (2021) 013C01]



# Possible signatures

Or just detect the Migdal electron exploiting all the atomic shells: it needs to be able to reconstruct a nuclear recoil track and an electron recoil track starting from the same vertex.




Used also to discriminate between signal and background events.

# Experimental opportunity

[Baracchini et al., *Measur.Sci.Tech.* 32 (2021) 2, 025902]

- Cygno Phase 0 TPC (LIME): 50 litres of He/$CF_4$ or Ar/$CF_4$ with very good 3-d tracking capability and resolution both for NR and ER;
- Possibility to exploit available neutron sources at 2.5 MeV and 14 MeV;
- Problems: background

# Experimental opportunity

X-ray signature

$$N_{\text{events}} = N_T \, \Phi \, \sigma_{Ar} \, f_{Ar} \, q_e^2 \, \text{BR}_{\text{Mig}}$$

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X-ray signature

$7.5 \times 10^{23}$

$3.2 \times 10^{-24}\,\mathrm{cm}^2$

$10^{-4} - 10^{-5}$

$$N_{\mathrm{events}} = N_T\, \Phi\, \sigma_{Ar}\, f_{Ar}\, q_e^2\, \mathrm{BR}_{\mathrm{Mig}}$$

Flux for a 2.5 MeV neutron source

$113\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$

$0.14$

Fluorescence yield

$$\frac{2\, m_e^2 E_R}{m_N}$$

# Experimental opportunity

X-ray signature

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Expected absorption length for the X-ray: ~ 3 cm

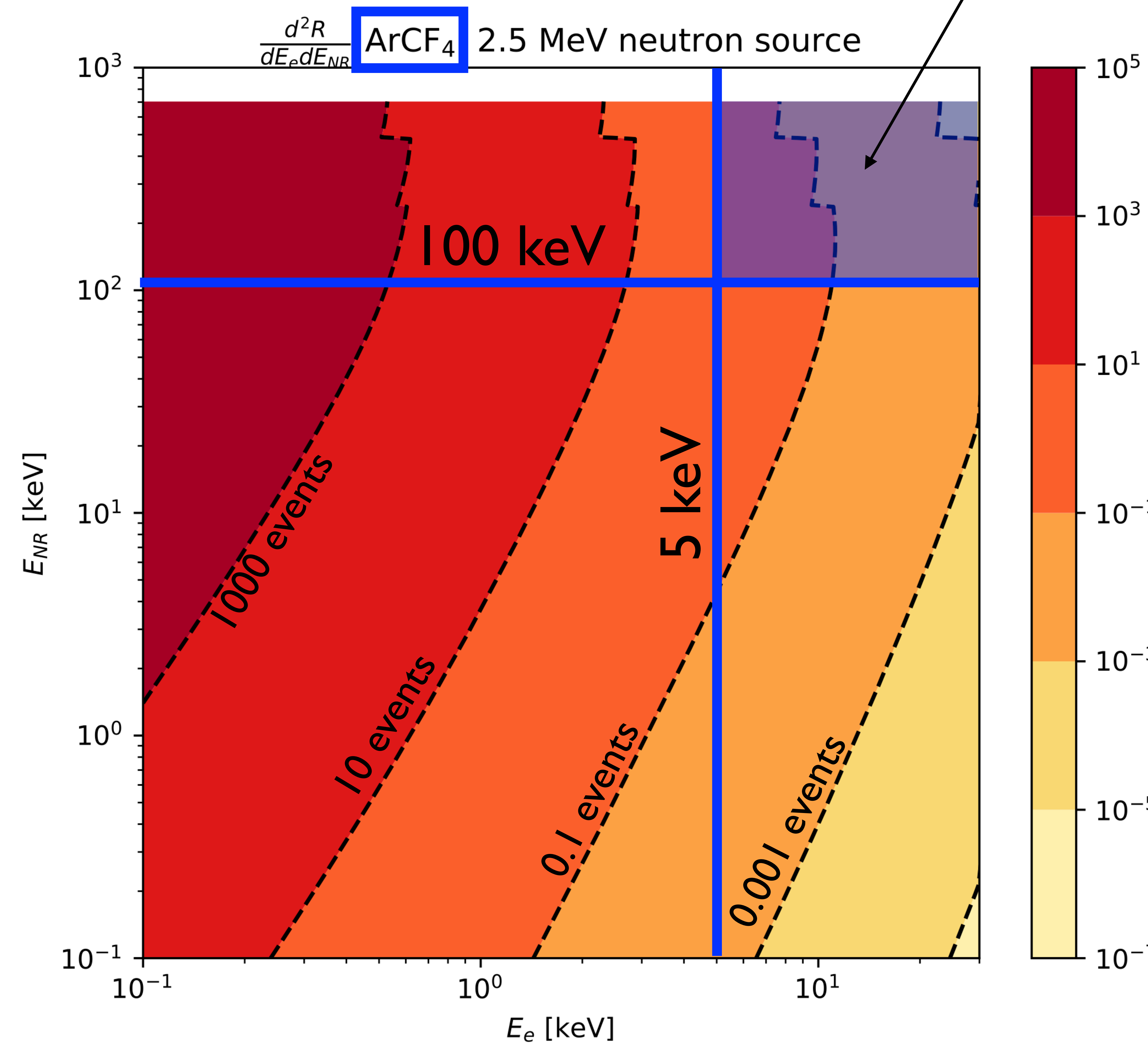
# Experimental opportunity

## Migdal electron signature

- For large $E_{NR}$ good tracking capability down to $E_e \sim 5$ keV.
- Potentially O(100) events per day for a realistic $E_e$ energy threshold of 5 keV (integrating over $E_{NR} > 100$ keV), for a mixture 60:40 of $ArCF_4$;

PRELIMINARY

~600 events/day



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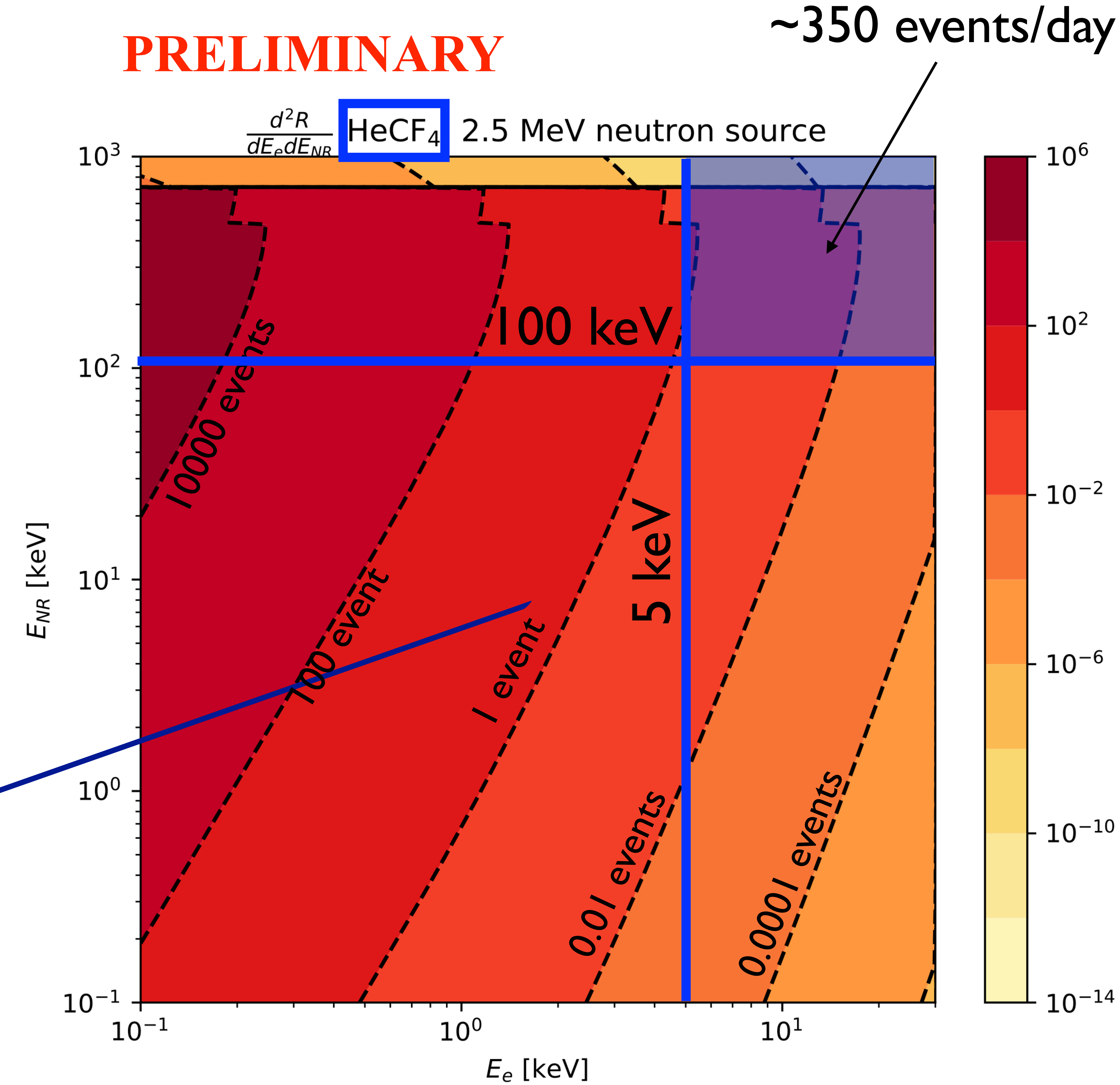

# Conclusions

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- Directional detection experiments are well motivated
- Lots of opportunities: discriminate between DM and background (if DM discovery), neutrino floor studies, possibility to measure deviation from gaussian hypothesis for the DM velocity distribution, boosted DM
- Possible improvement for light DM with the Migdal effect
- Possibility to measure the Migdal effect in nuclear recoils