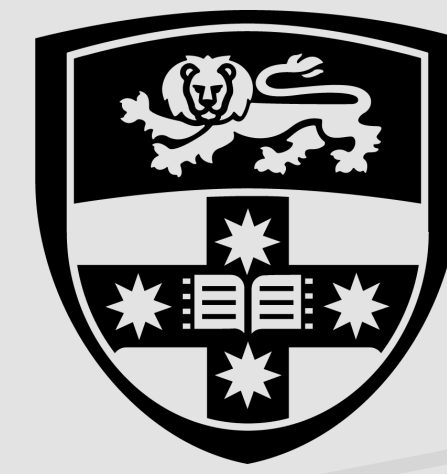
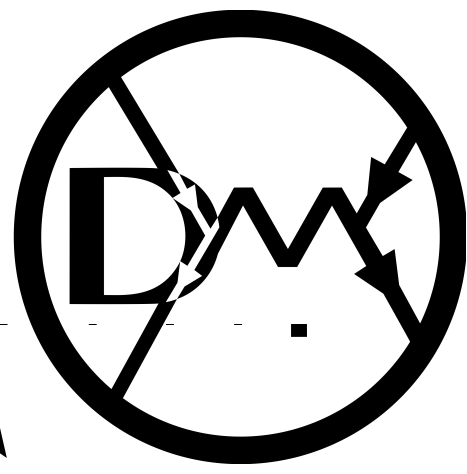
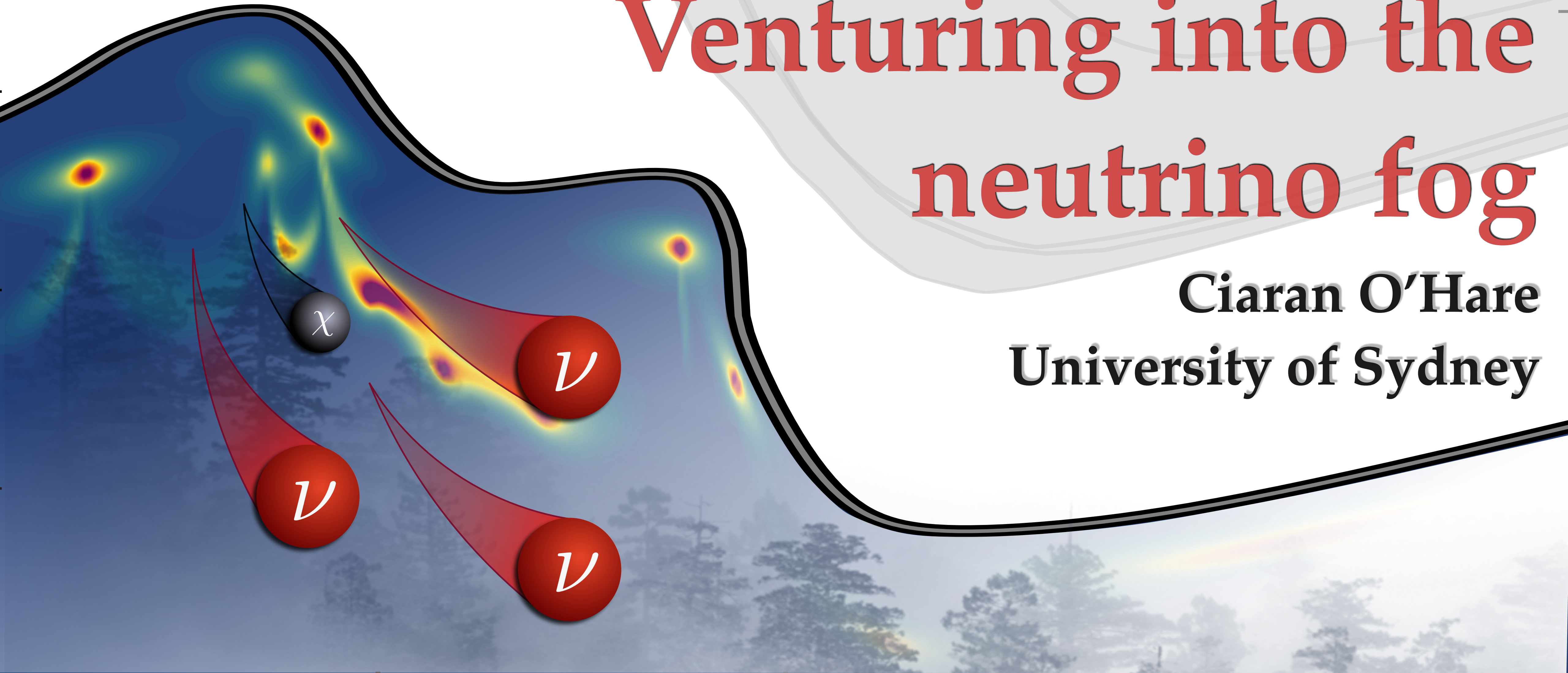




Venturing into the neutrino fog

Ciaran O'Hare
University of Sydney



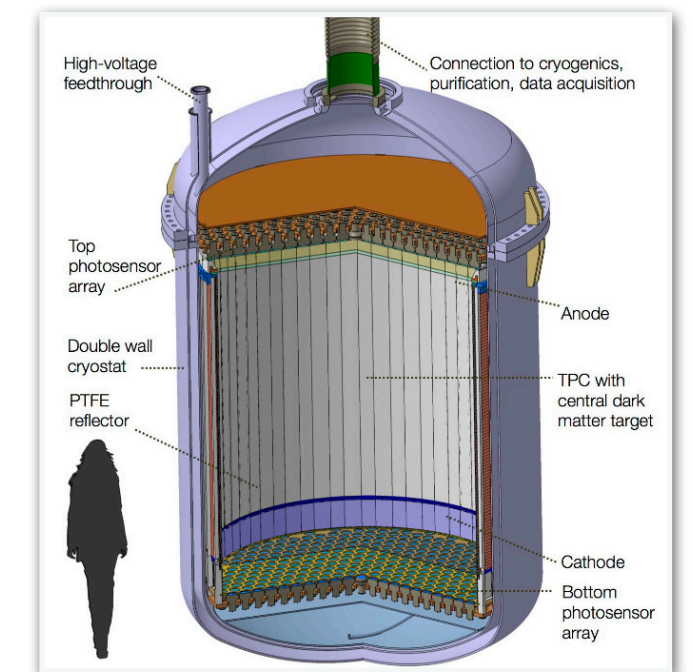
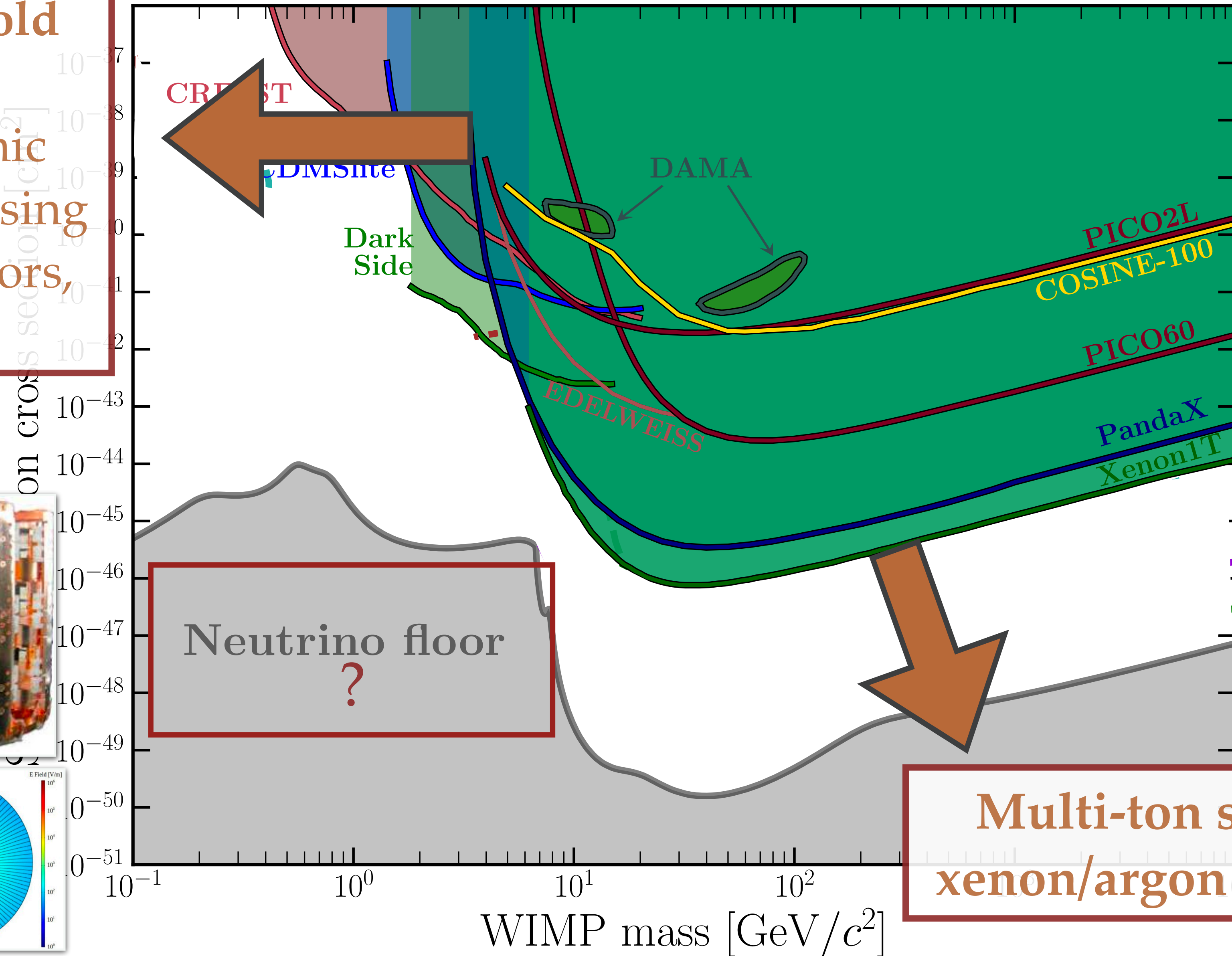
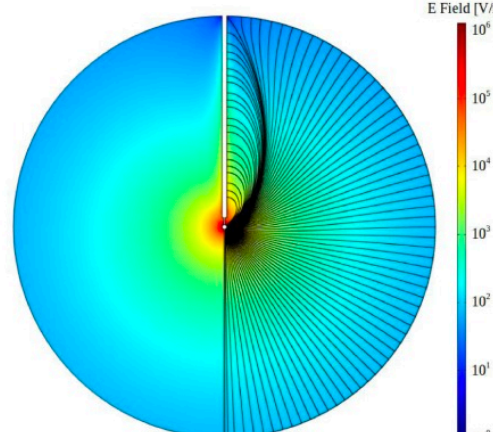
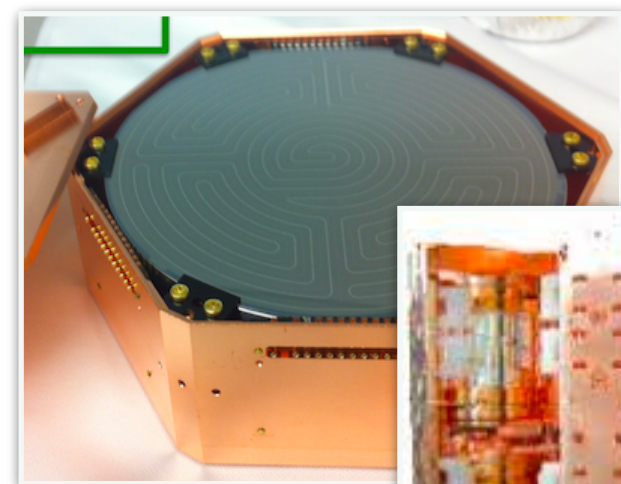
Part 1: What is the neutrino fog

Part 2: How do we deal with it?

Part 3: Can we use it to our advantage?

Status of searches for WIMP-like dark matter via nuclear recoils

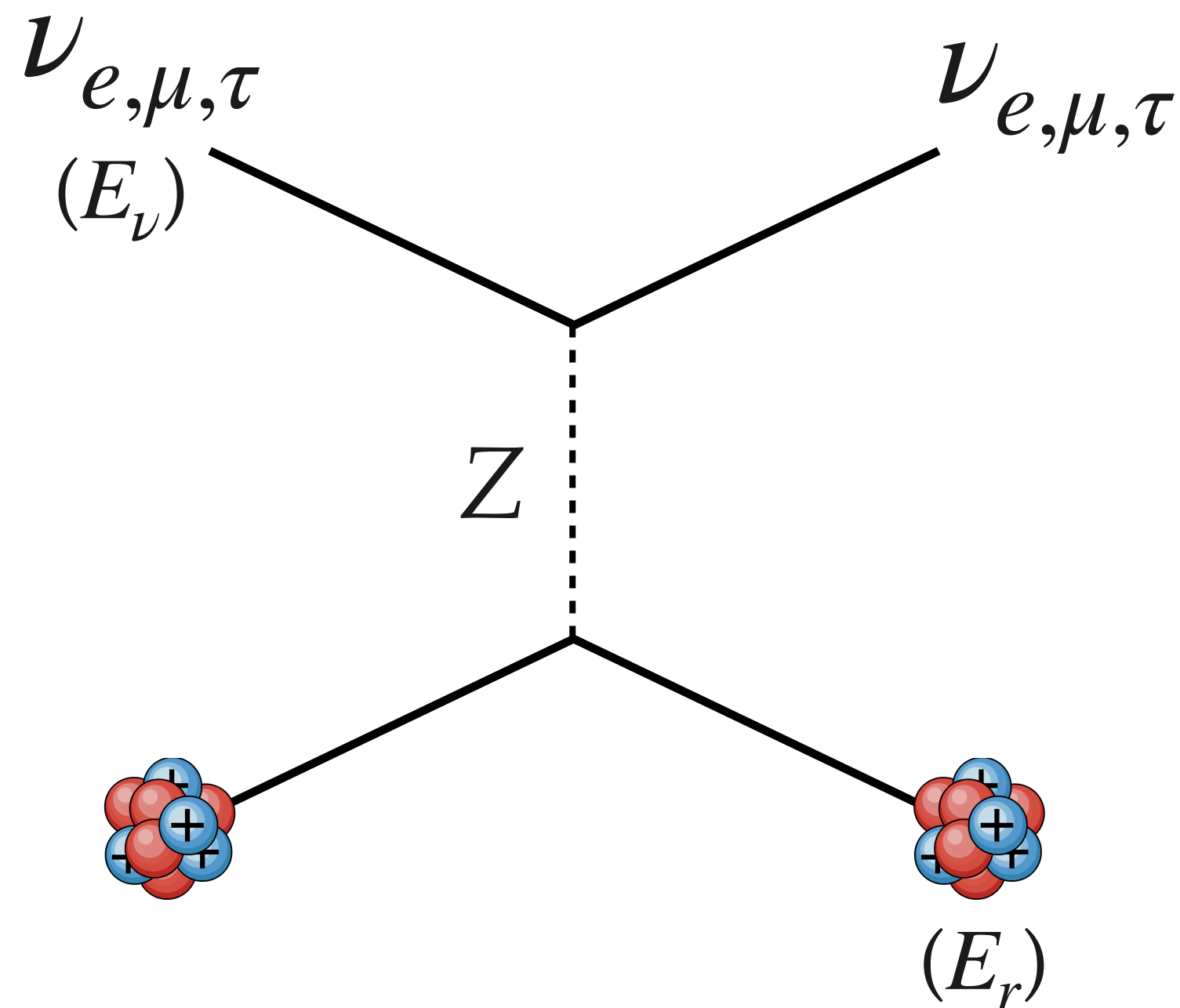
Low threshold
detectors
e.g. cryogenic
scintillators using
semiconductors,
gas SPCs



Multi-ton scale liquid
xenon/argon experiments

Coherent elastic neutrino-nucleus scattering (CEvNS)

Freedman (1974), detected by COHERENT [2003.10630]



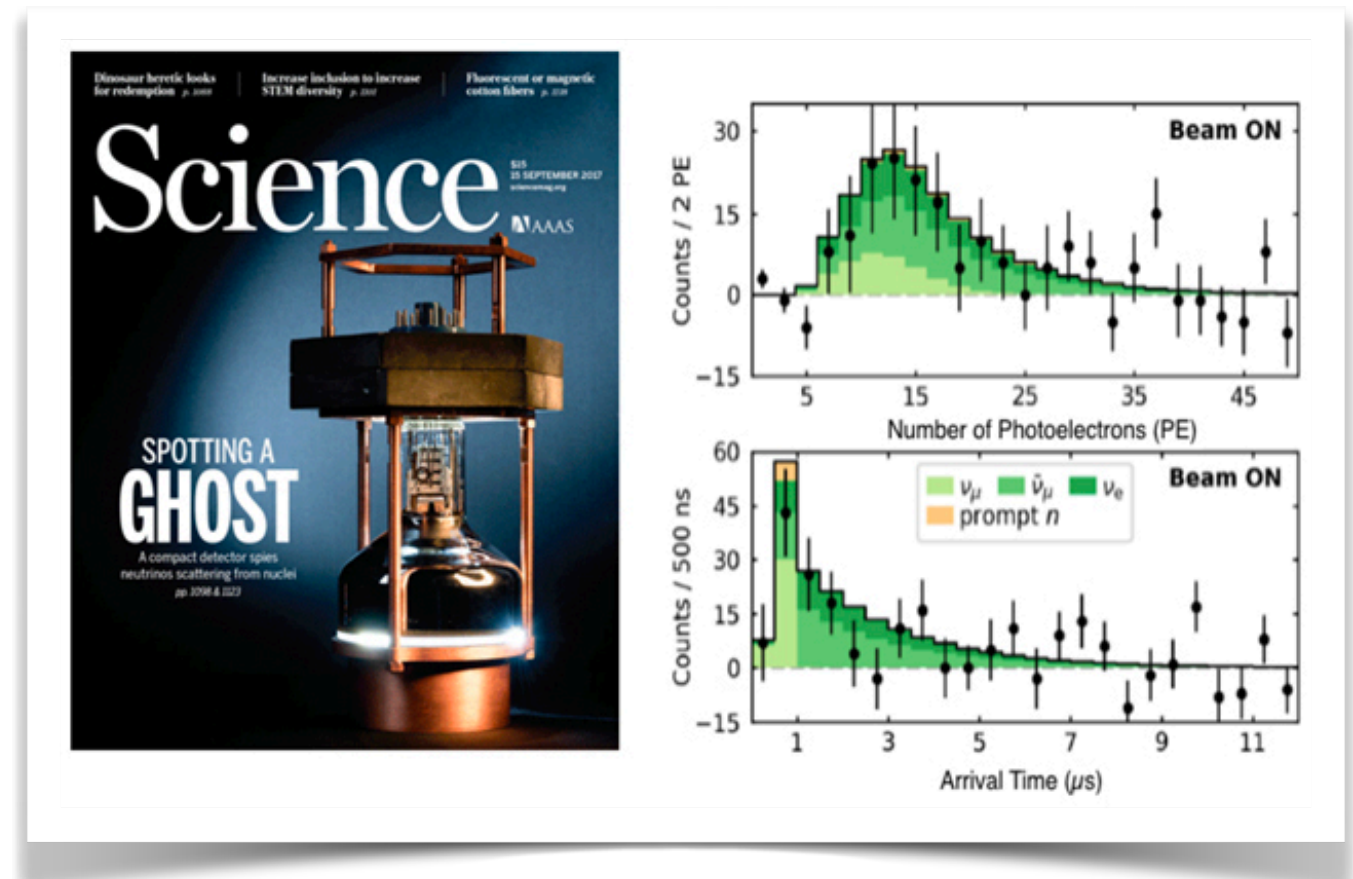
$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} \underbrace{Q_W^2}_{\text{Weak hypercharge}} m_N \left(1 - \frac{m_N E_r}{2E_\nu^2} \right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

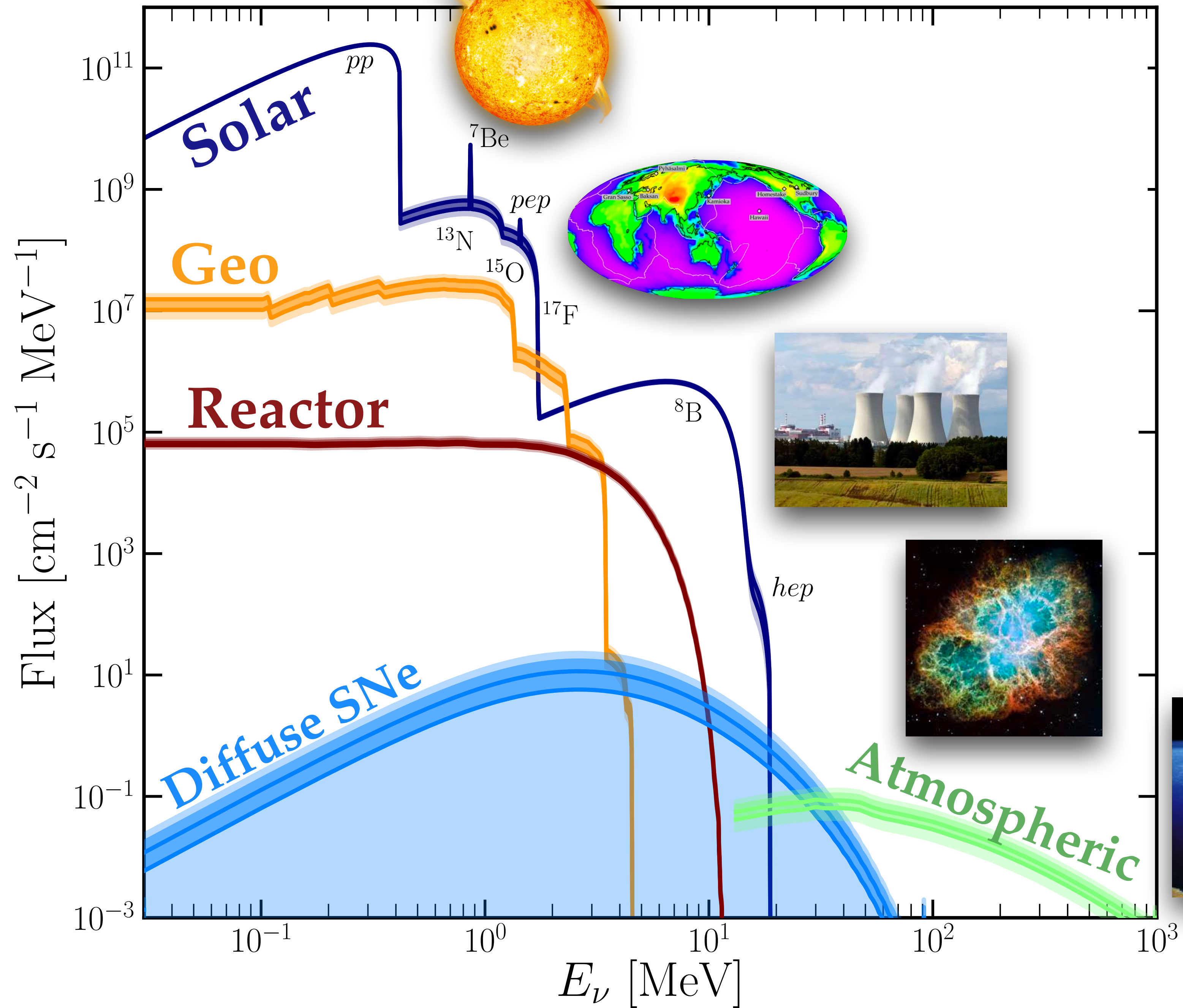
$$E_r \approx \mathcal{O}(10 \text{ keV}) \Rightarrow E_\nu \lesssim \sqrt{\frac{m_N E_r}{2}} \approx 10 \text{ MeV}$$

Neutral current
→ flavour blind

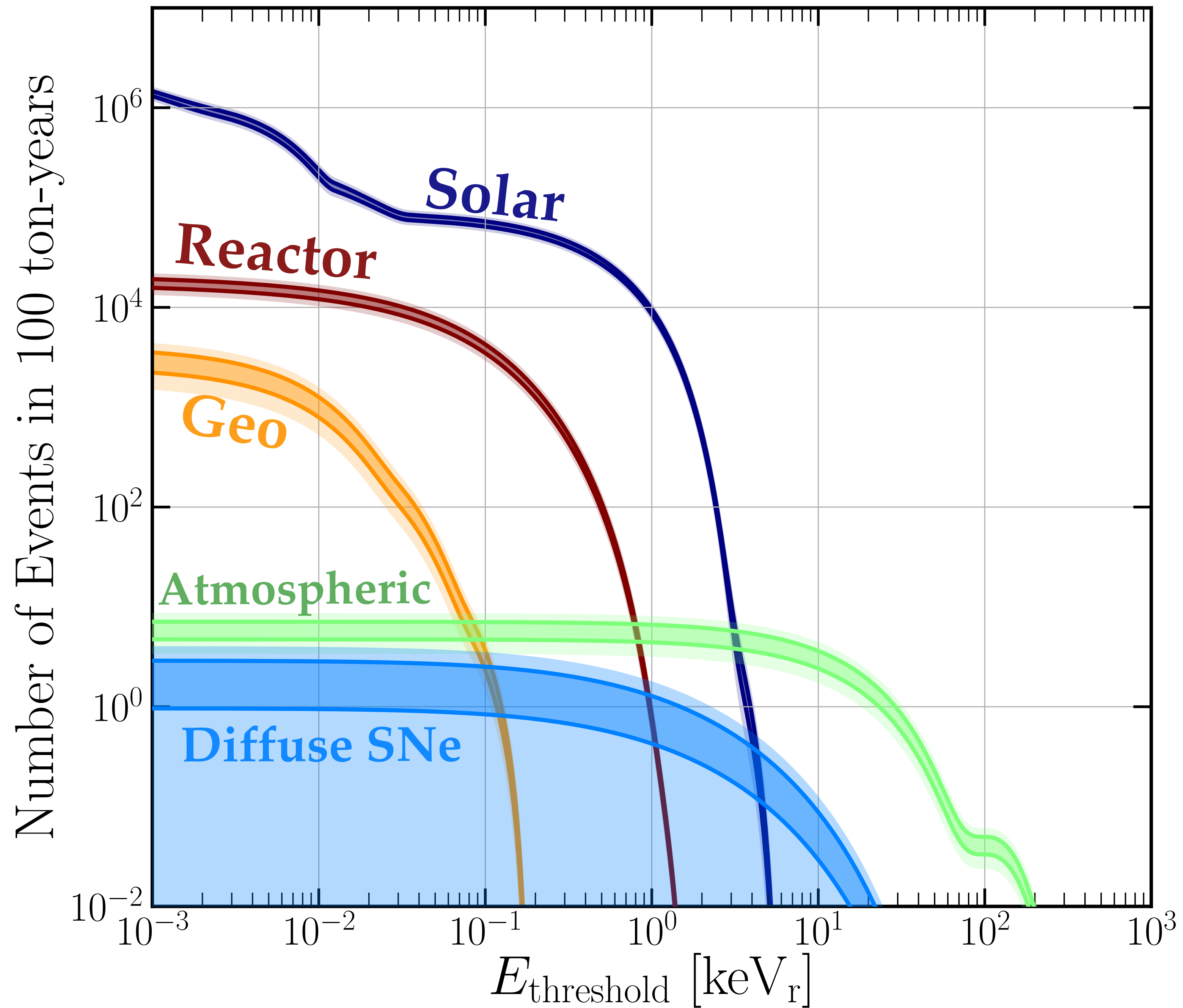
⇒

>10 MeV neutrinos will generate
nuclear recoils in a similar energy
range to $m_\chi \gtrsim \text{GeV}$ dark matter





**Neutrino fluxes relevant for
dark matter searches**

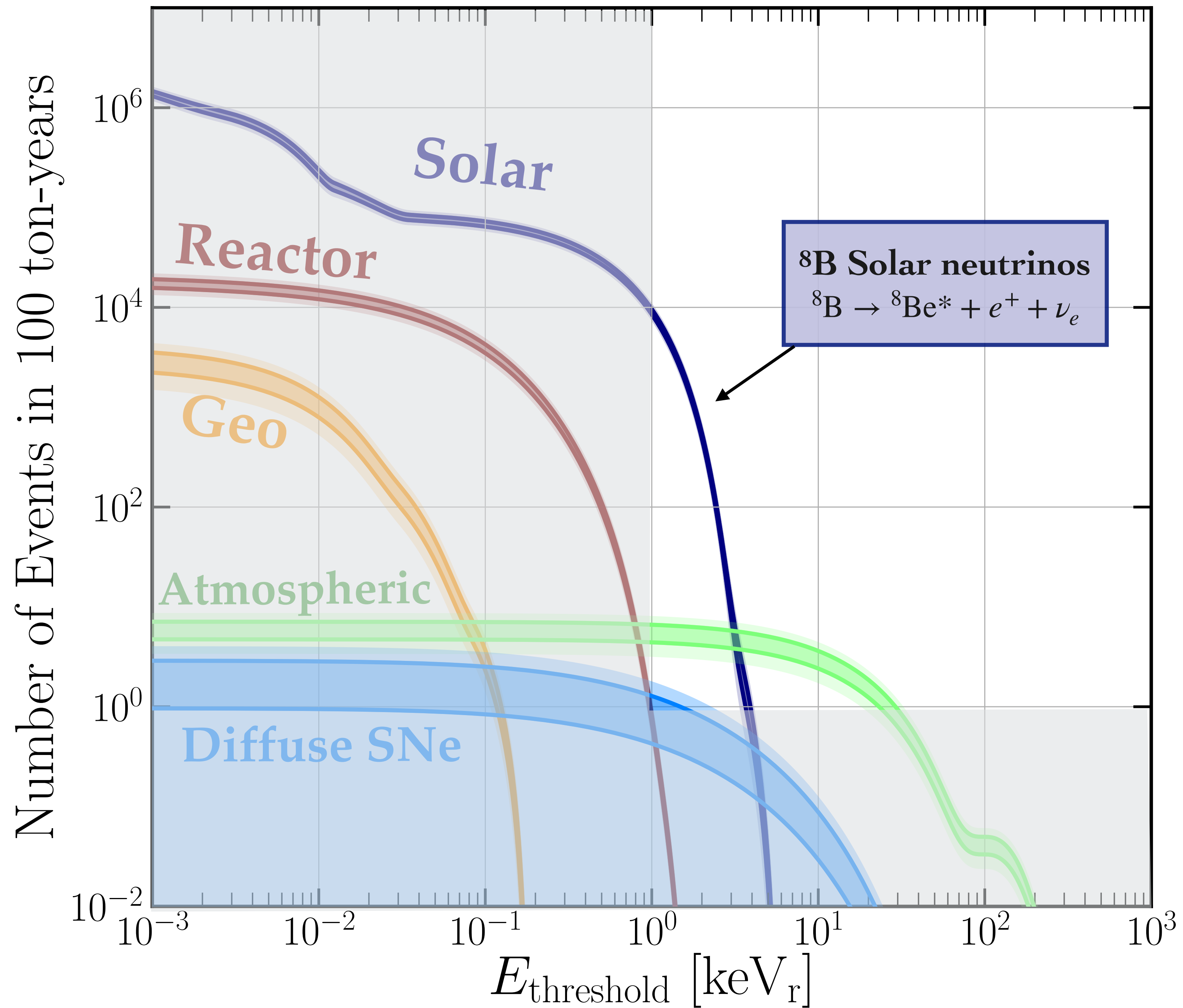


Neutrino fluxes relevant for
dark matter searches



Event rates for a Xe target

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N} \int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu$$

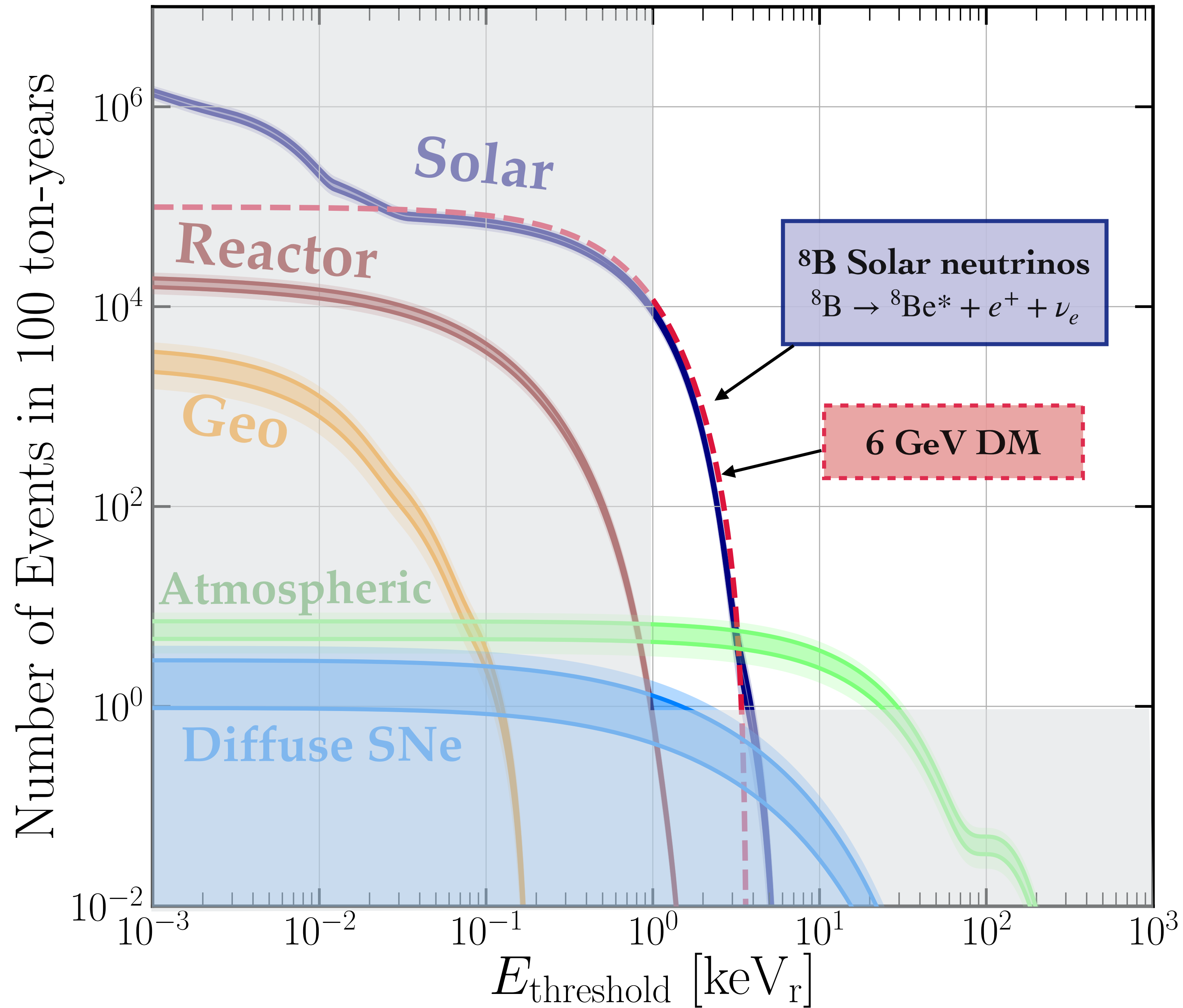


**Neutrino fluxes relevant for
dark matter searches**



Event rates for a Xe target

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N} \int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu$$



Neutrino fluxes relevant for
dark matter searches

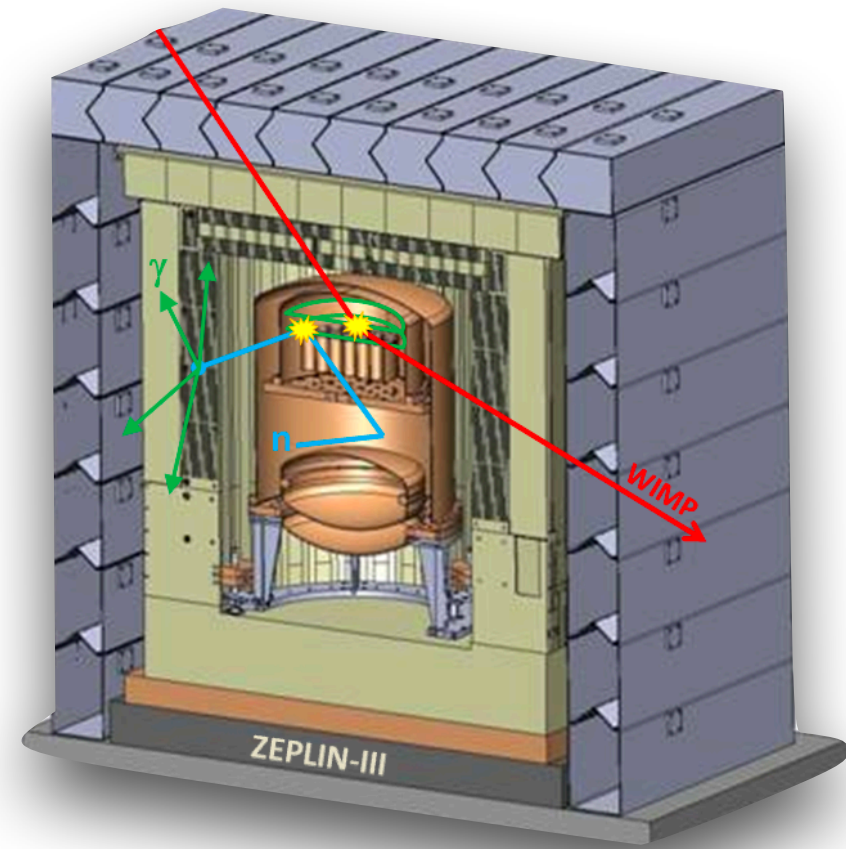


Event rates for a Xe target

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N} \int_{E_\nu^{\min}} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu$$

The “neutrino floor” as it’s usually presented

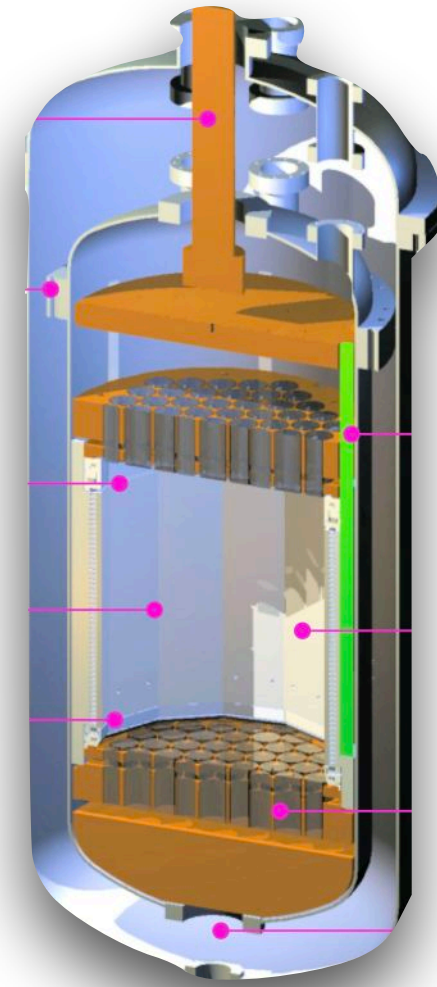
e.g. for LXe TPCs



ZEPLIN~12 kg



XENON100~34 kg



LUX~118 kg



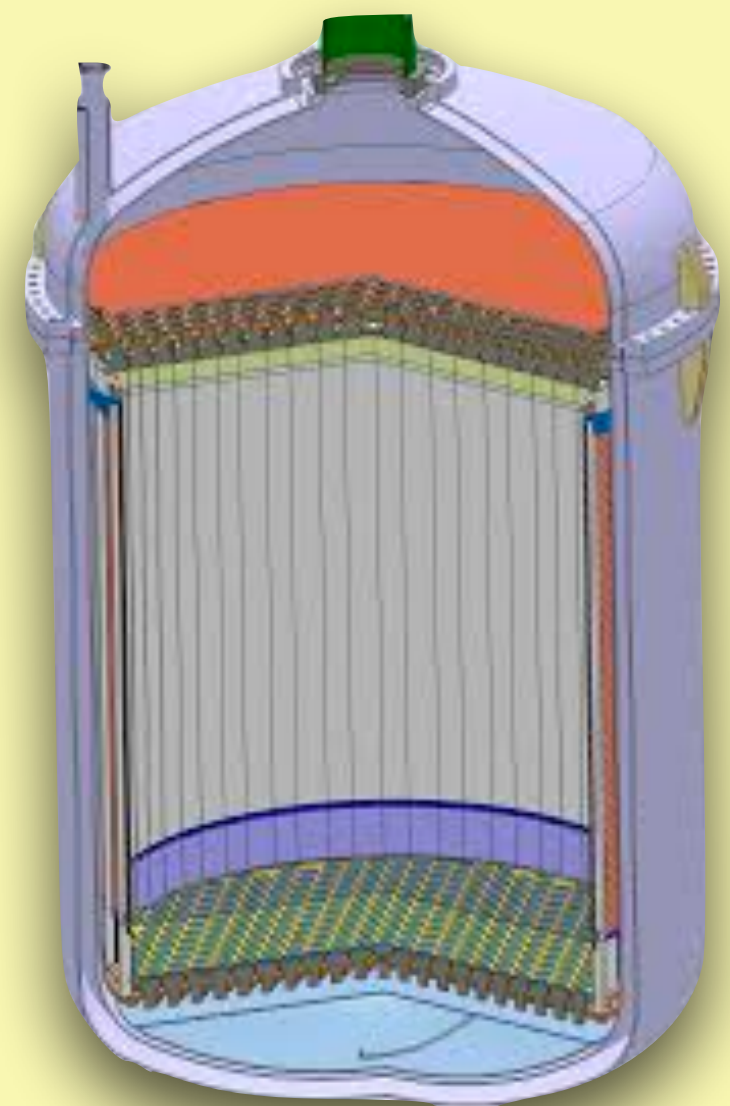
XENON1T~1 ton

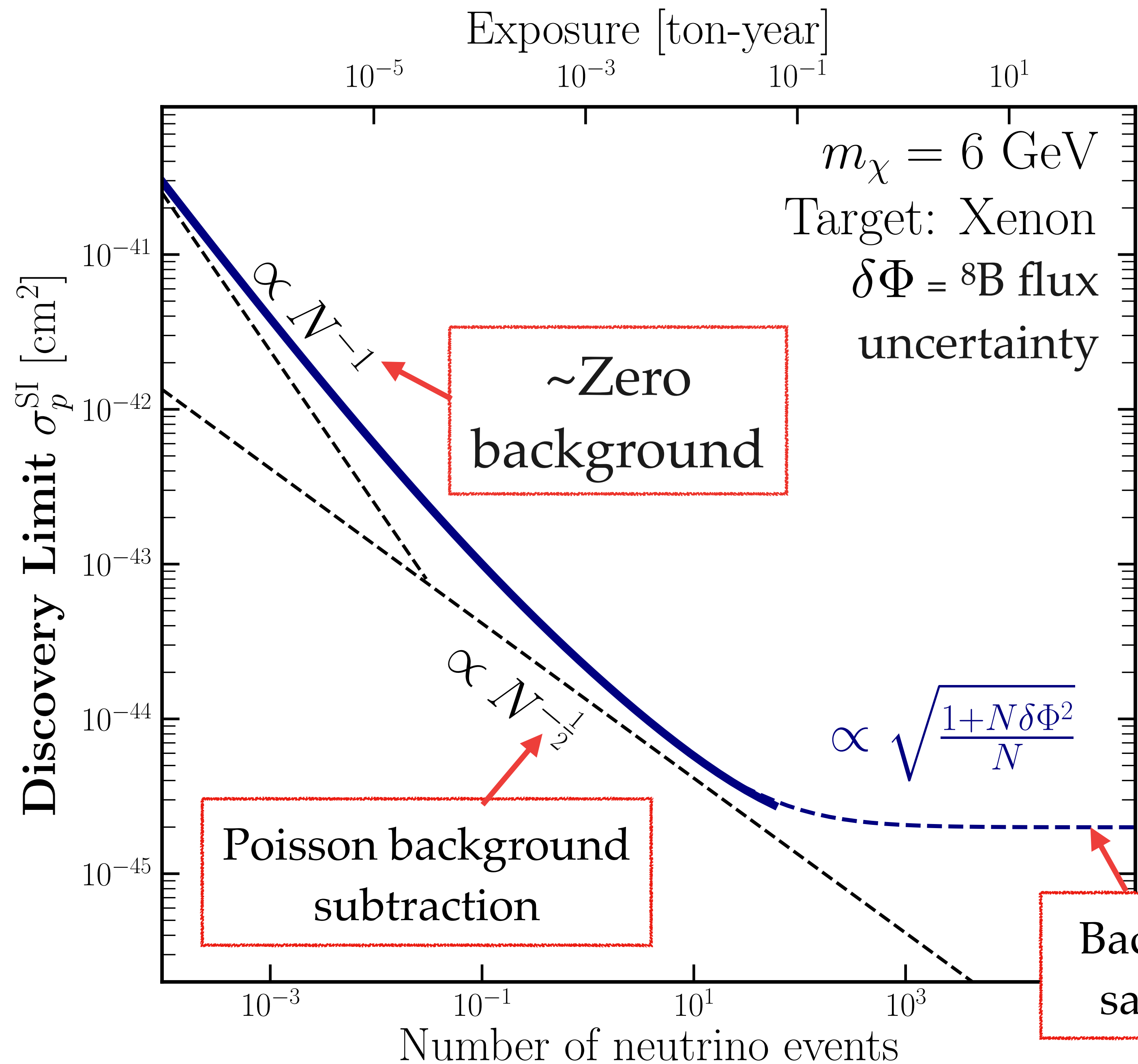
Sensitivity to DM cross sections

Neutrino floor

DARWIN ~ 40 ton?

$CE_{\nu NS} < \text{required DM events}$
 $CE_{\nu NS} > \text{required DM events}$





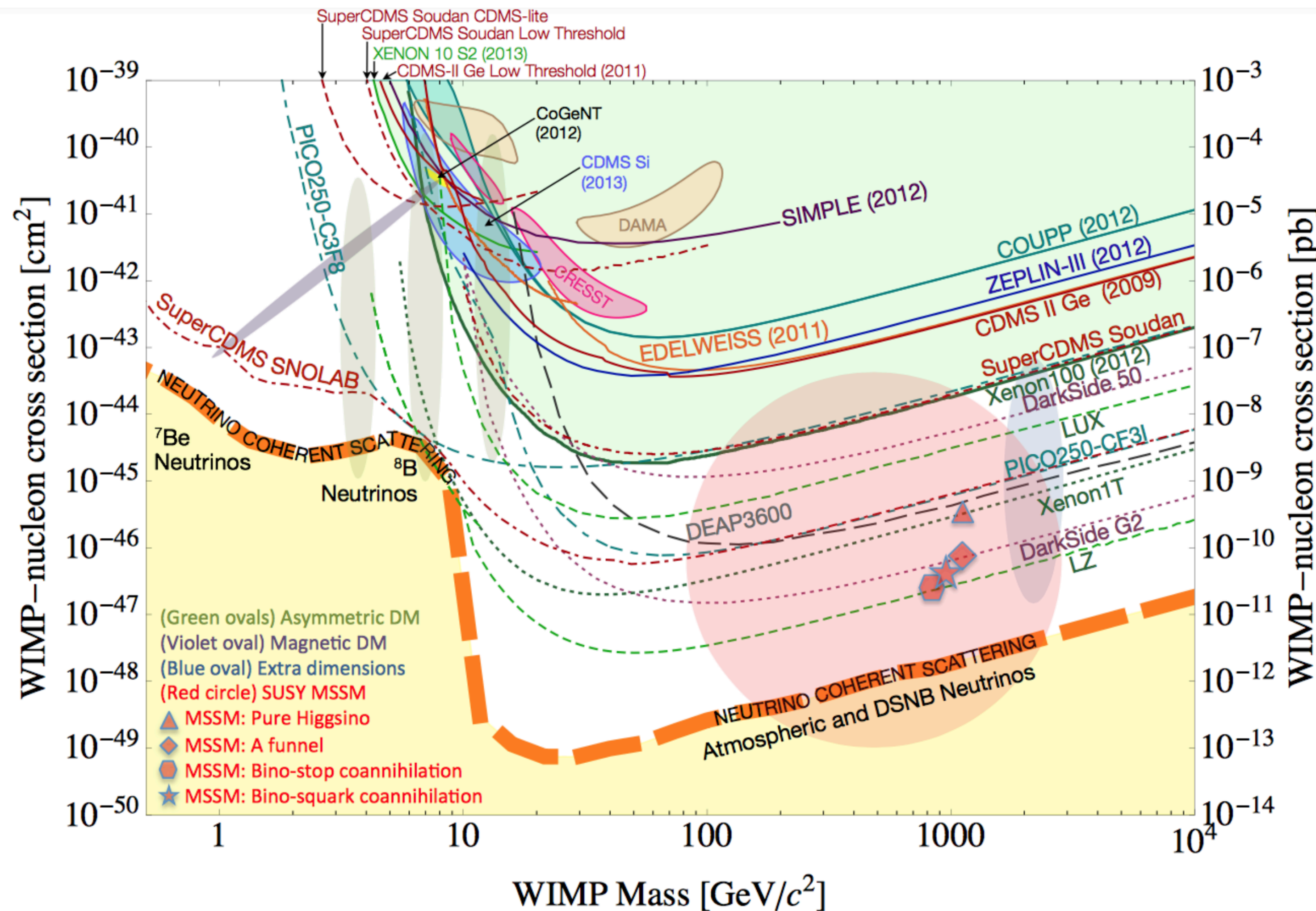
The neutrino “floor”

← Scaling of a DM discovery limit for increasing exposure

→ Experiment can't probe cross sections smaller than those which generate an excess in events smaller than estimated background fluctuations

The neutrino “floor”

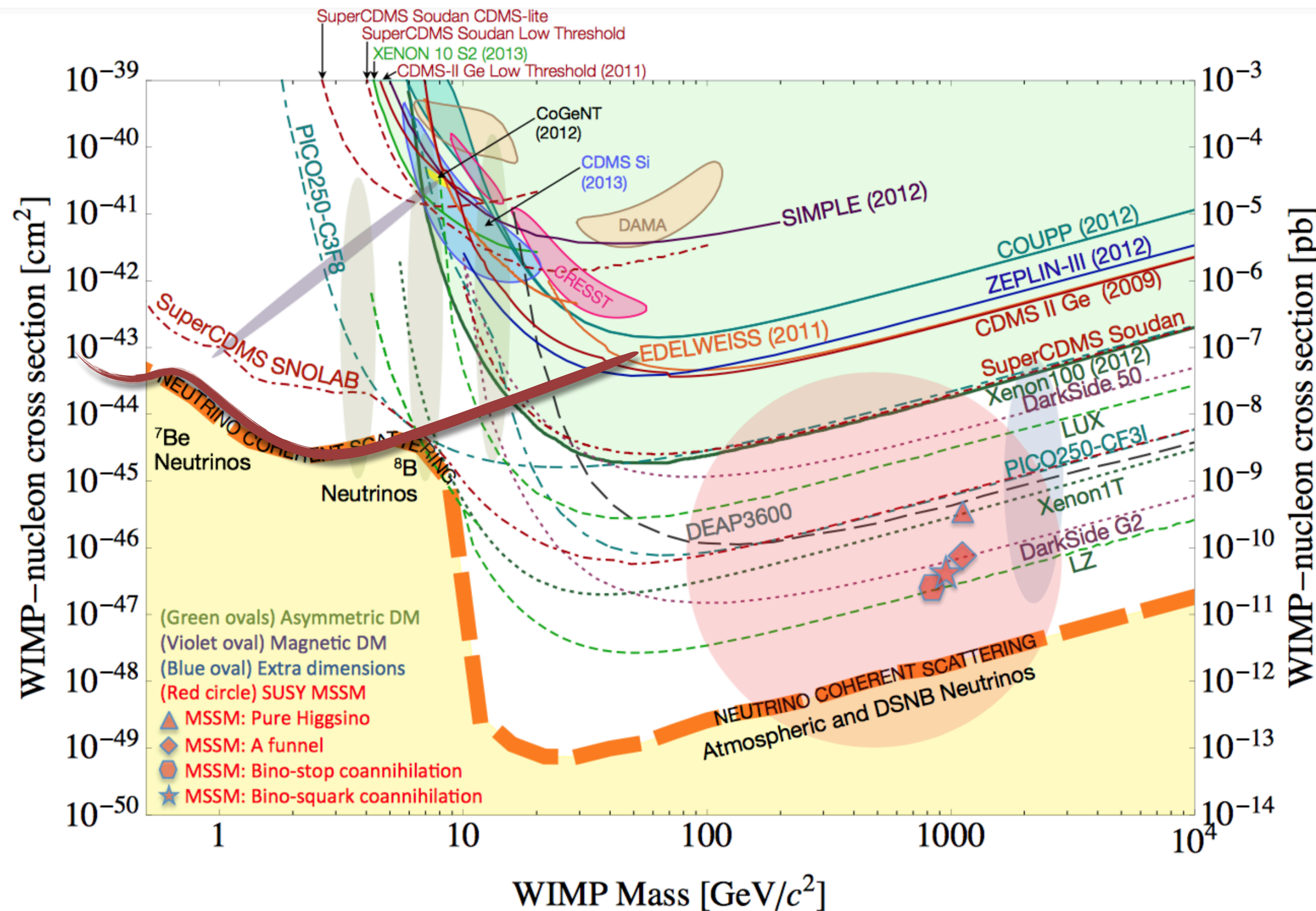
Defined in Billard et al. [1307.5458] and popularised by Snowmass ’13 Cosmic Frontier report [1401.6085]



Interpolation of two
discovery limits
(3σ discovery in 90% of expts)

The neutrino “floor”

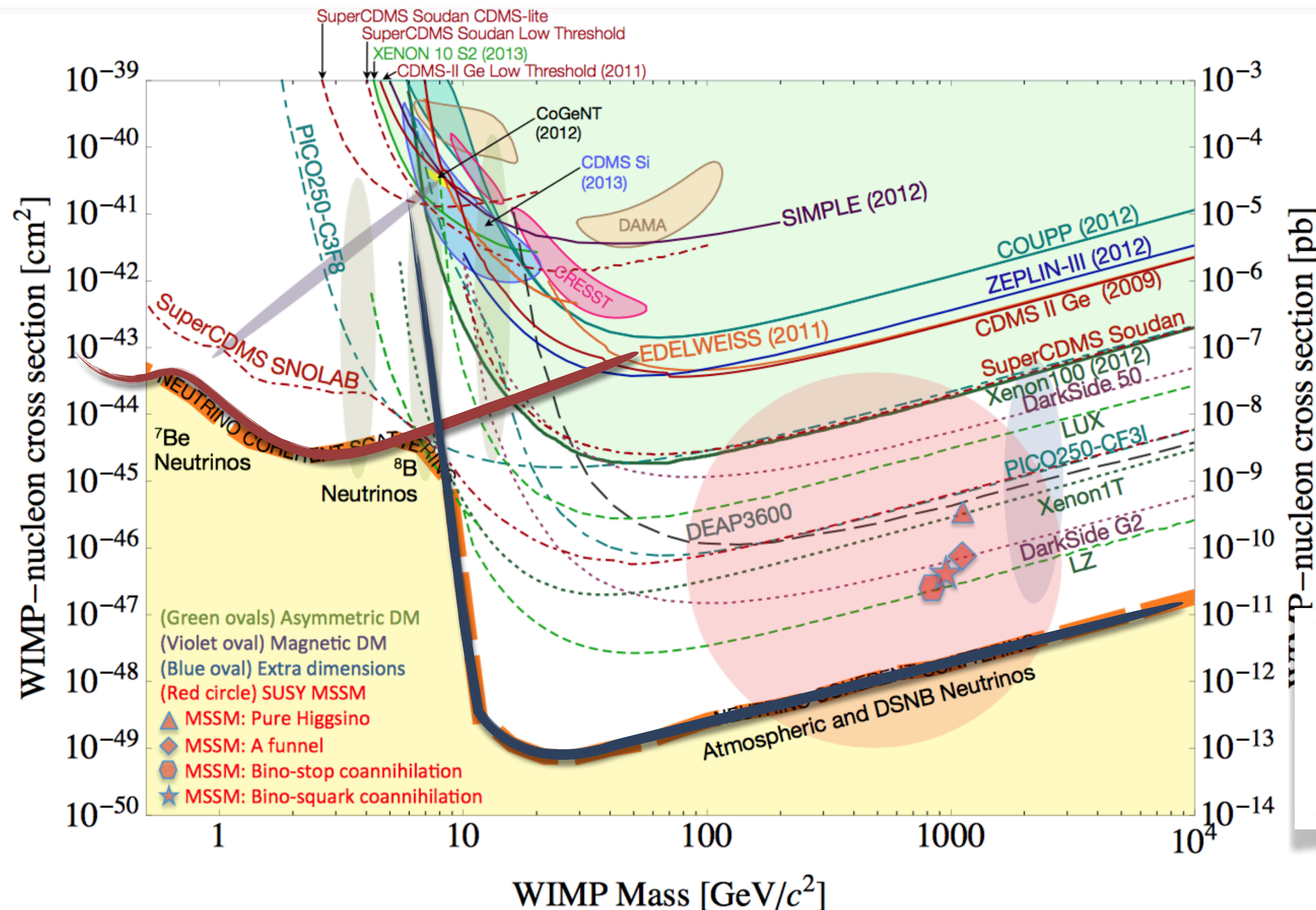
Defined in Billard et al. [1307.5458] and popularised by Snowmass ’13 Cosmic Frontier report [1401.6085]



Interpolation of two
discovery limits
(3σ discovery in 90% of expts)
→ low mass/low threshold
(500 solar neutrino events)

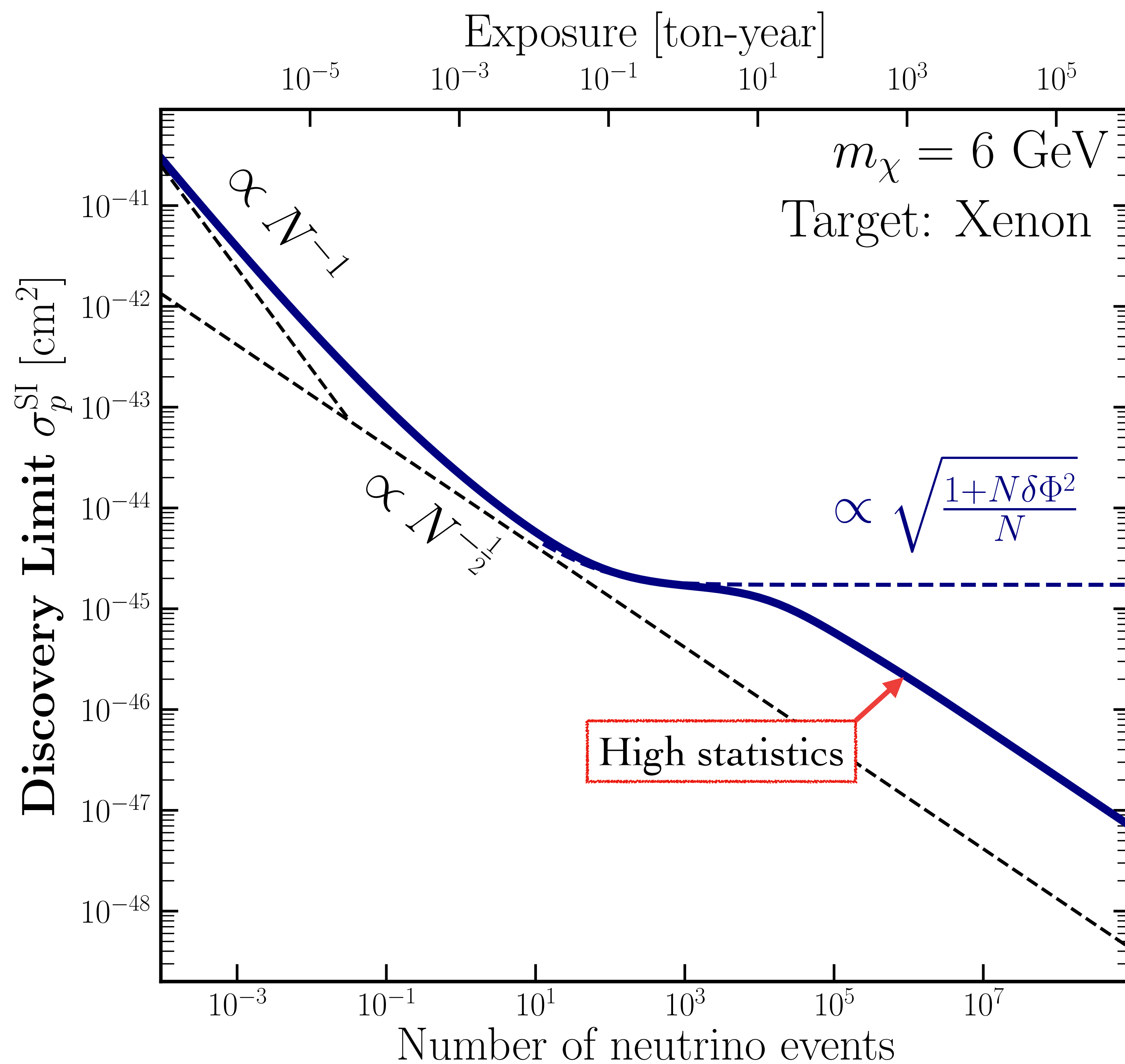
The neutrino “floor”

Defined in Billard et al. [1307.5458] and popularised by Snowmass ’13 Cosmic Frontier report [1401.6085]



Interpolation of two
discovery limits
(3σ discovery in 90% of expts)
→ low mass/low threshold
(500 solar neutrino events)
→ high mass/high threshold
(500 atmospheric events)

To ensure we are well into the systematics limited regime, exposures were increased to obtain 500 neutrino events. This line thus represents a hard lower discovery limit for dark matter experiments. Interestingly, we can denote three distinct features in the discovery limits coming



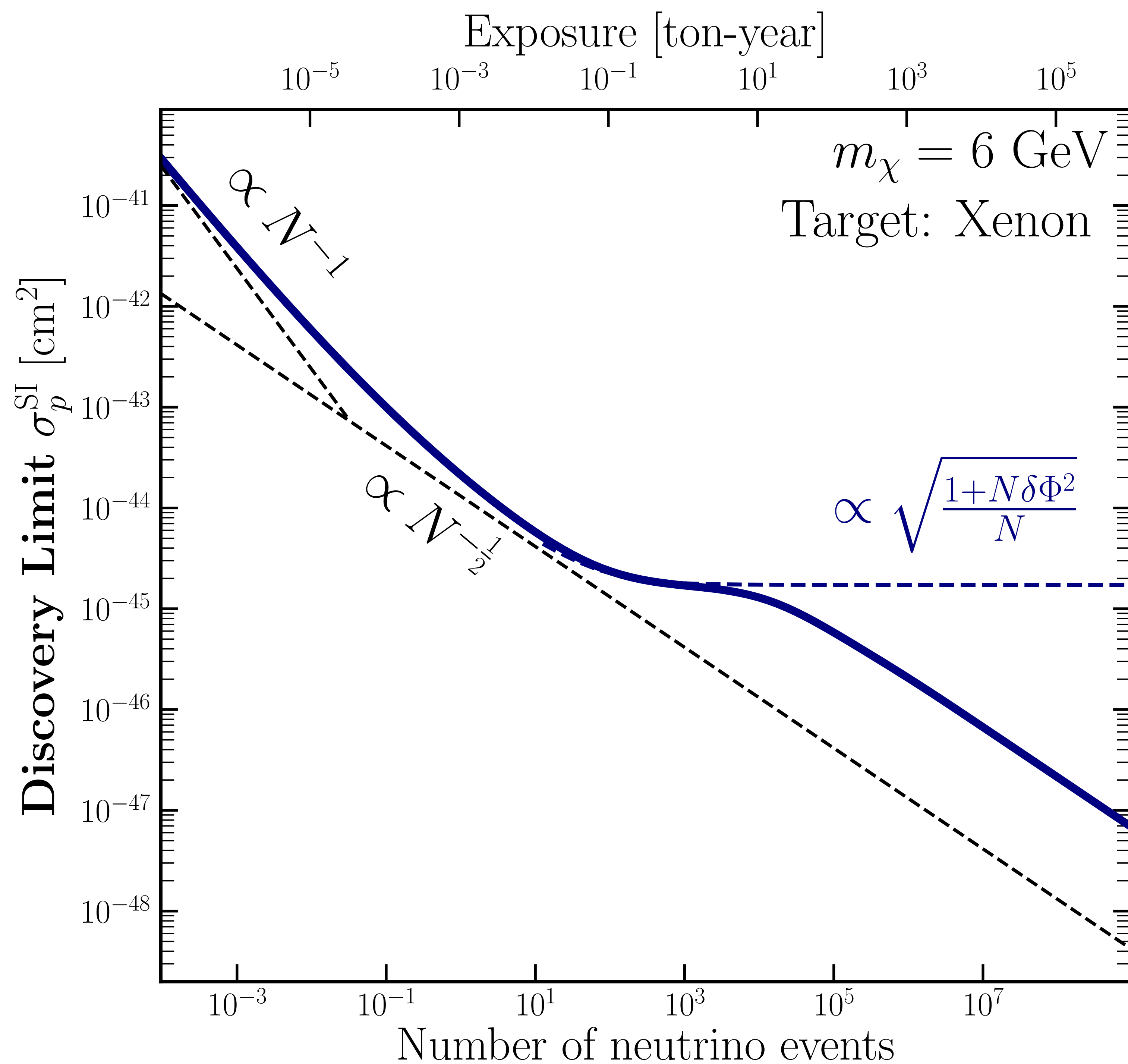
The neutrino “floor”

DM / CEvNS signals not **identical**
 → at high statistics, start to
 discriminate them with spectral
 information

→ **Required**
exposures get very
large, but there is
no hard “floor”

This should not be surprising, HEP experiments deal with backgrounds orders of magnitude larger than their signals all the time. We are in an era where DM experiments are no longer “background free”.

→ Instead of a “floor” beyond which experiments cannot reach, there is a “**fog**” that makes identifying a DM signal more challenging and demands that we understand our background better.



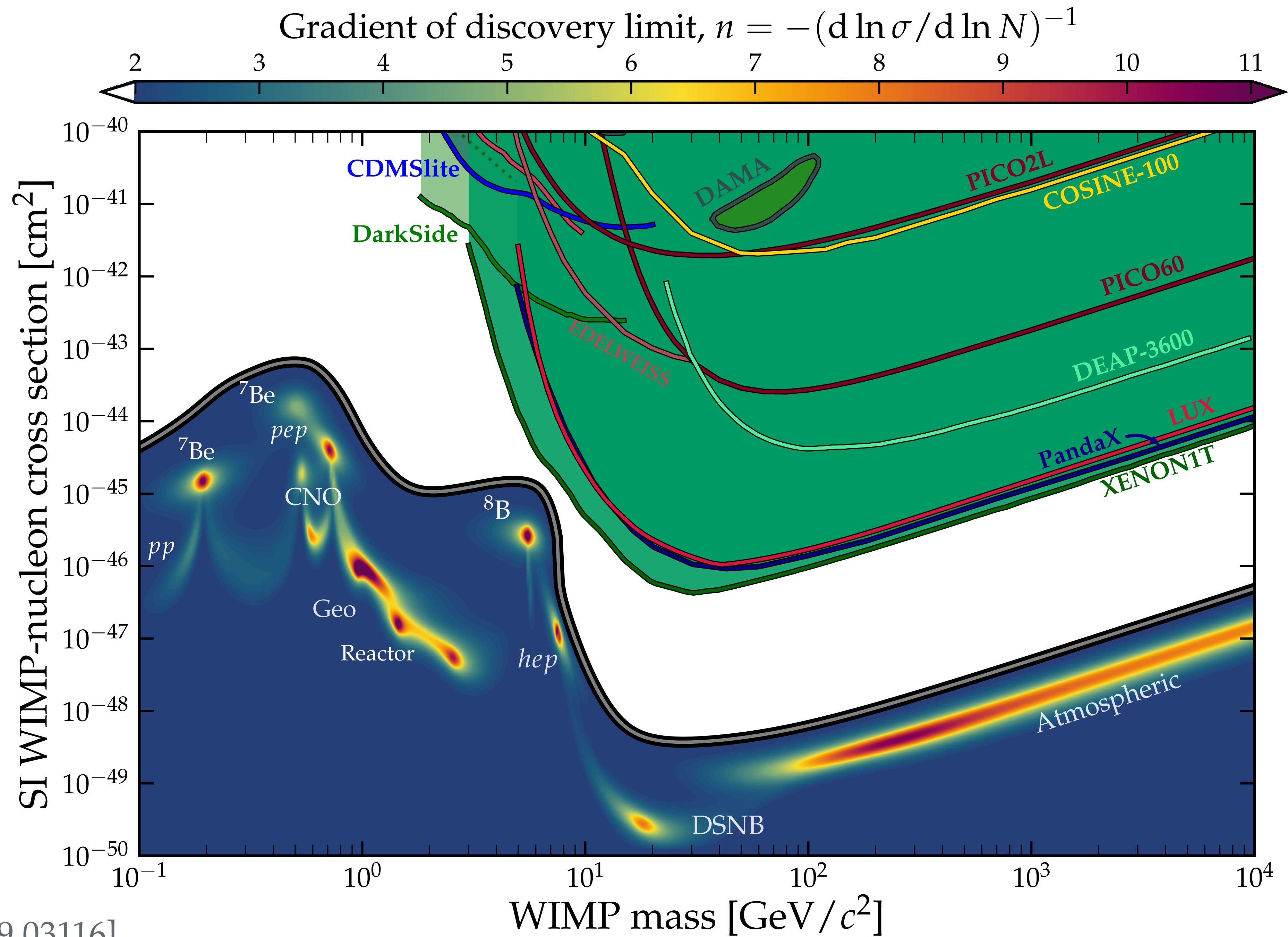
The neutrino fog

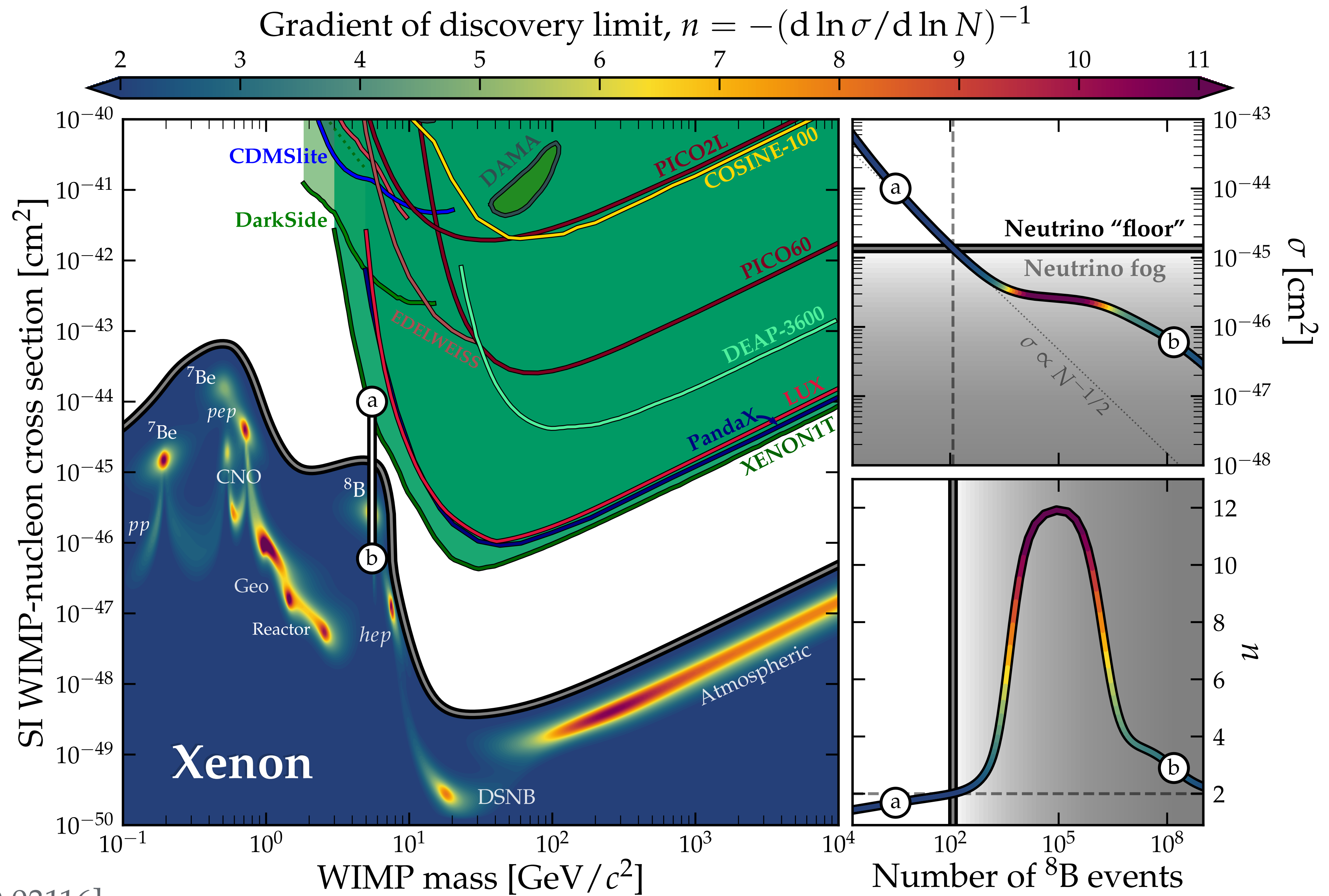
There is no “floor”, but we can give the fog a boundary by looking at where the scaling departs from the Poissonian expectation

Define:

$$n = -(\text{d ln } \sigma / \text{d ln } N)^{-1}$$

So $n = 2$ for Poissonian background subtraction and $n > 2$ for worse than Poissonian

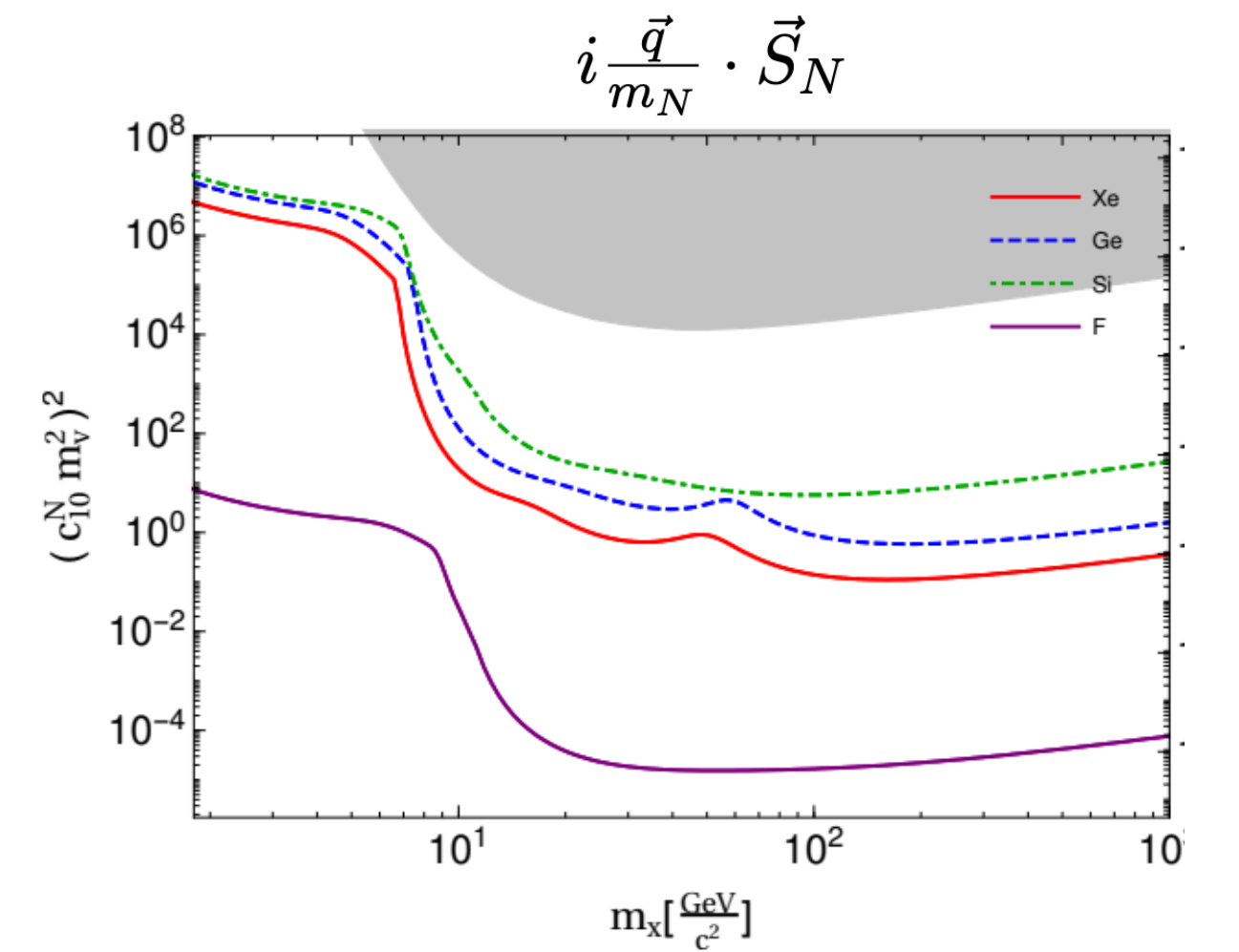
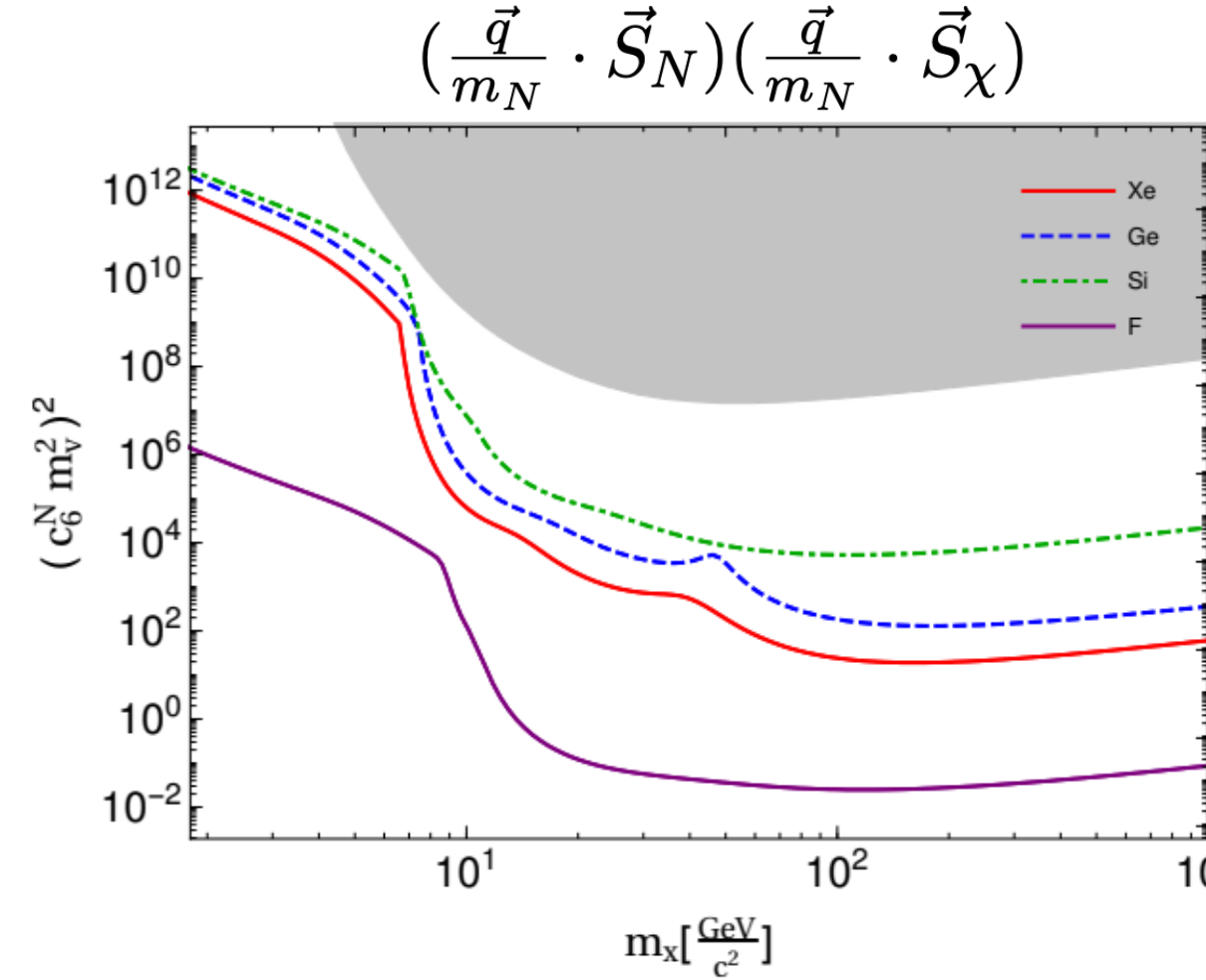
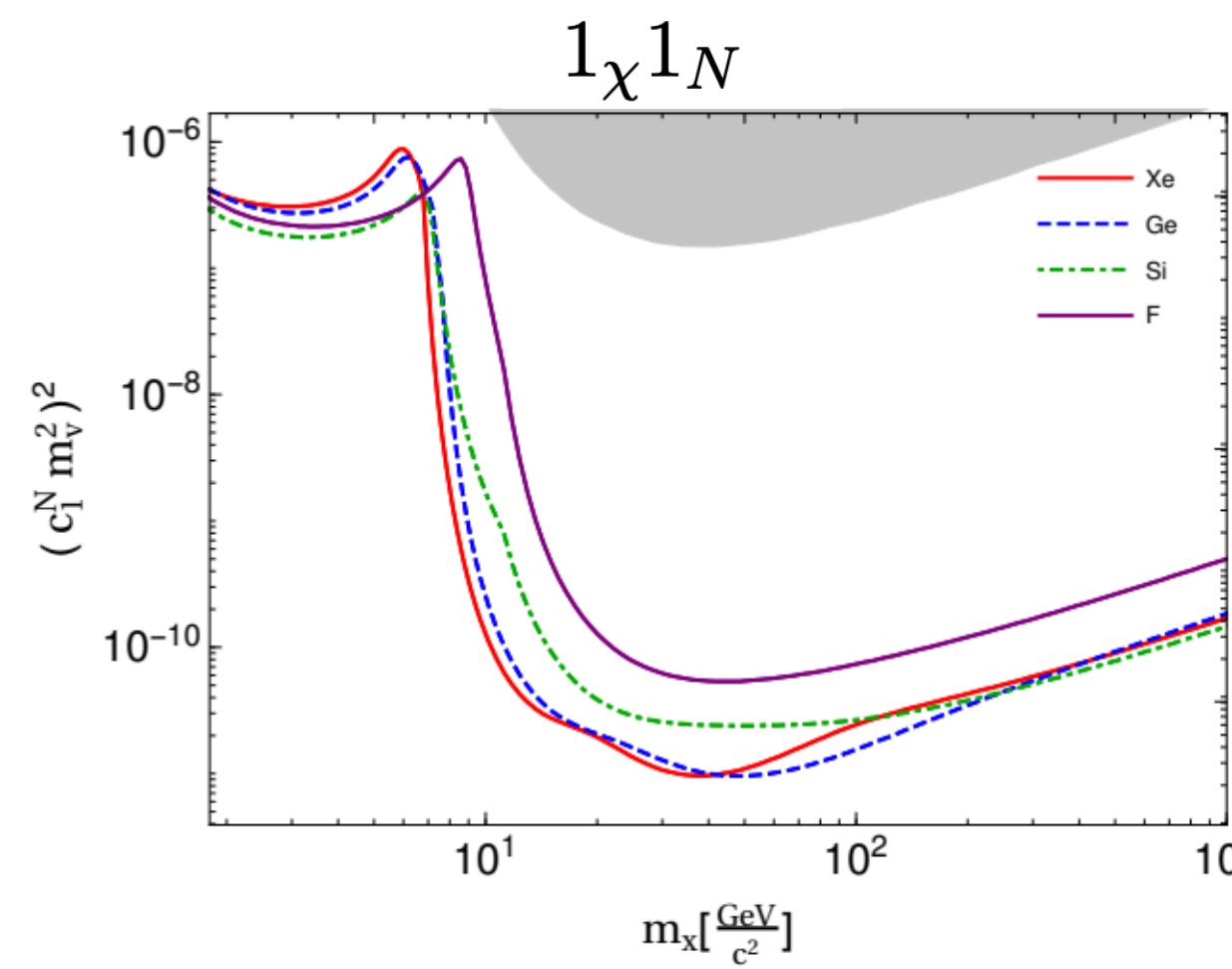




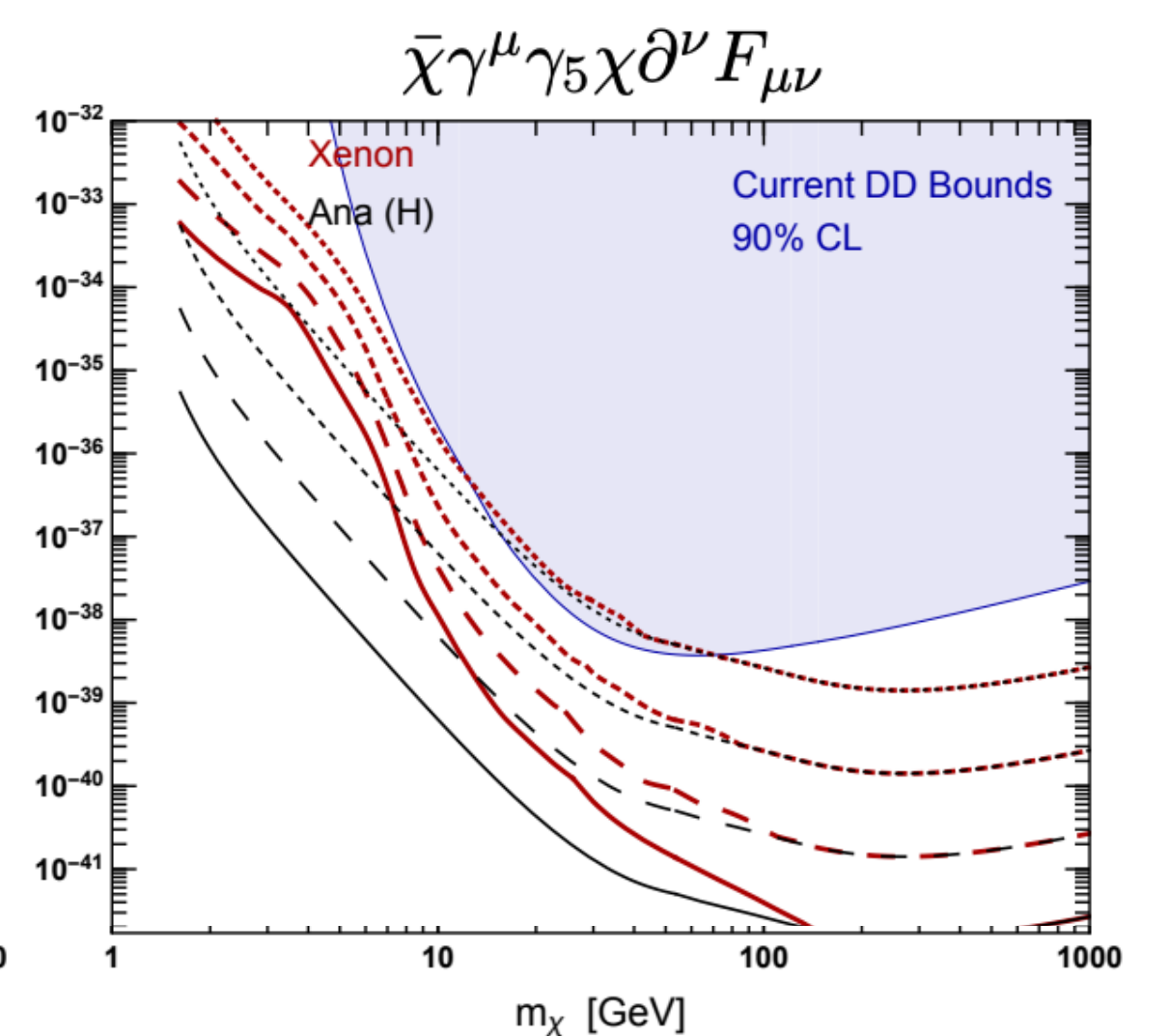
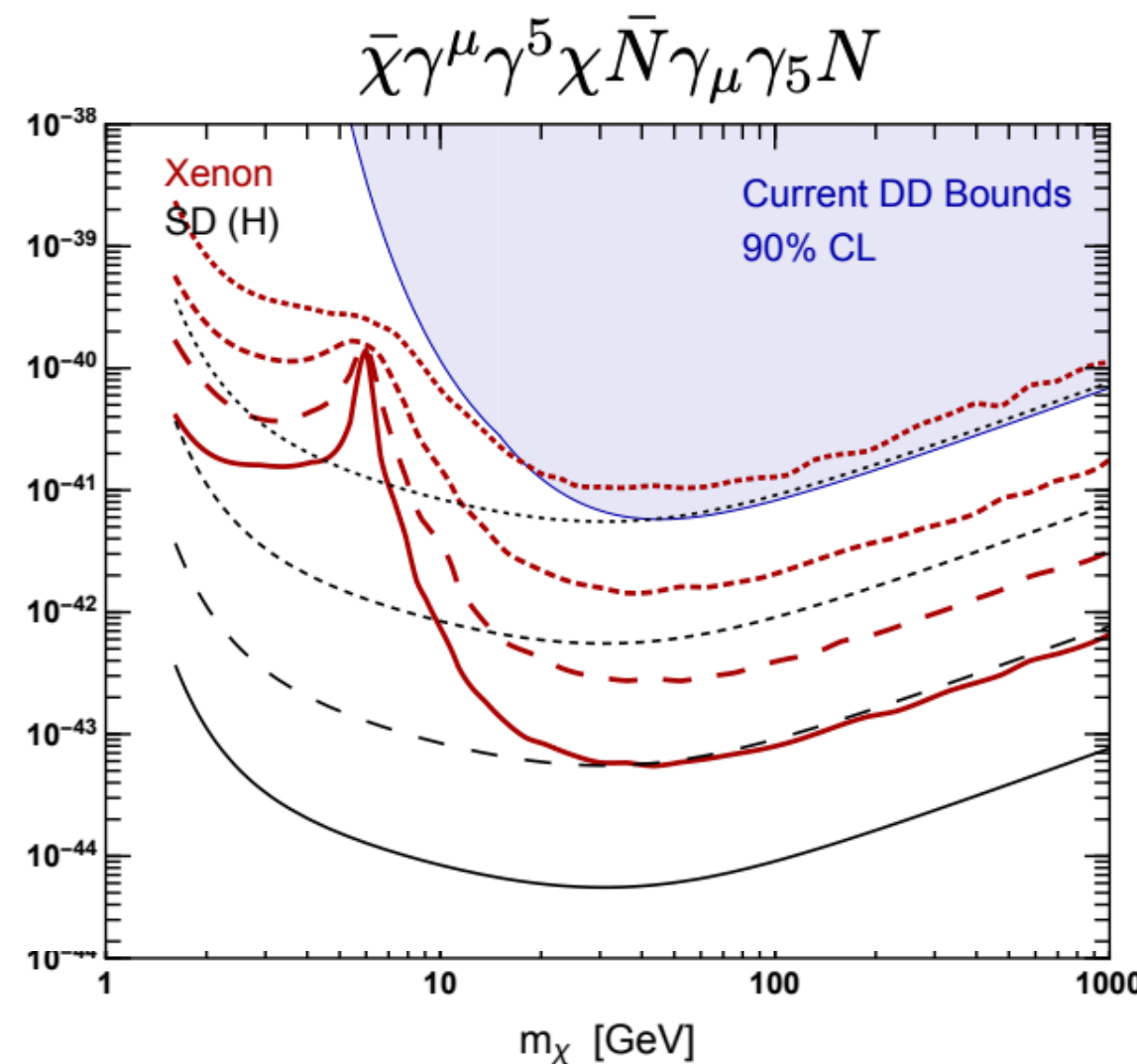
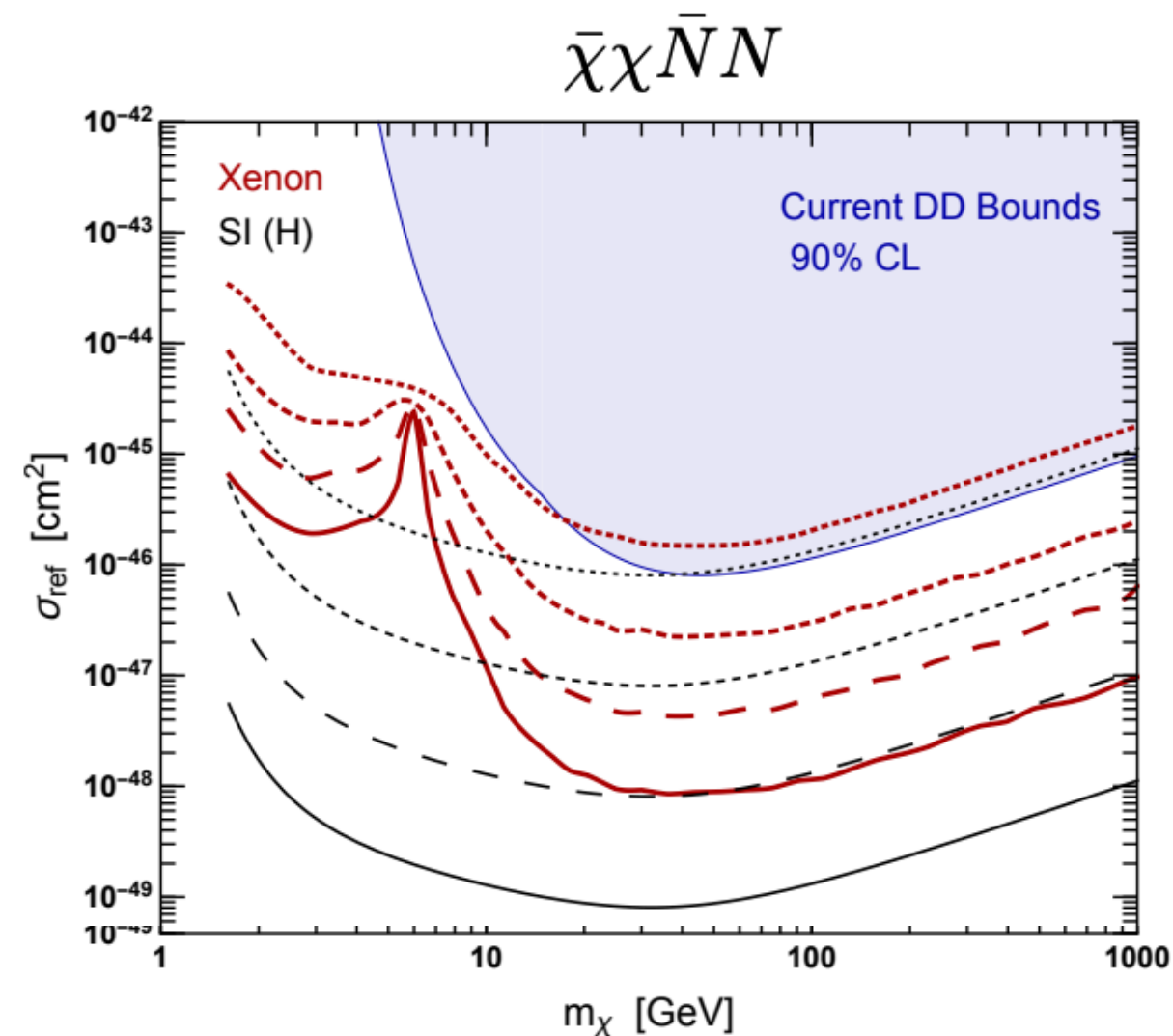
Neutrino “floors” beyond SI

→ Not all possible DM-nucleon interactions suffer same saturation by CEvNS background

Newstead et al.
[1602.05300]
→ Non-rel. EFT
operators



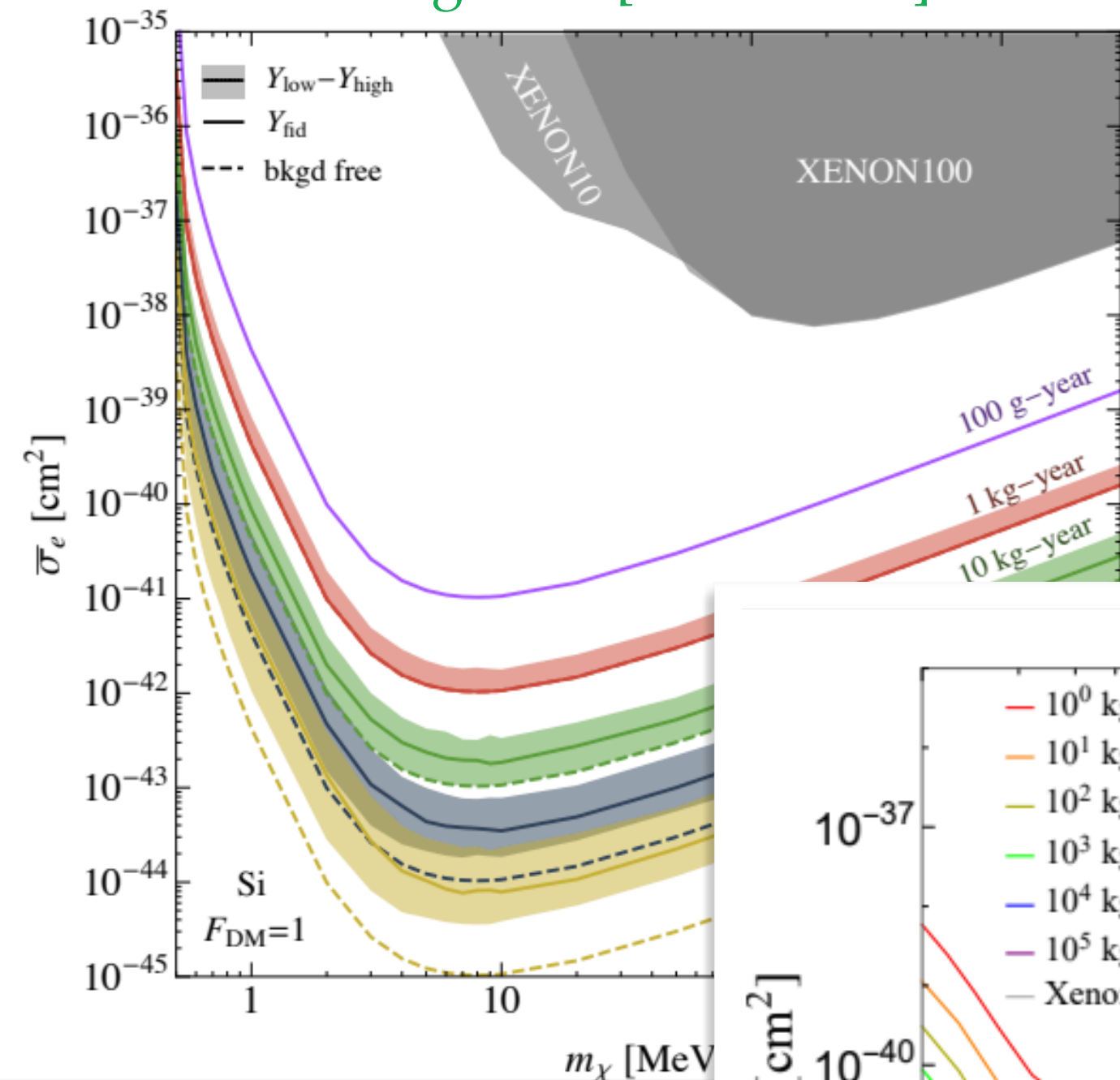
Gelmini et al.
[1804.01638]
→ Various DM
Interaction models



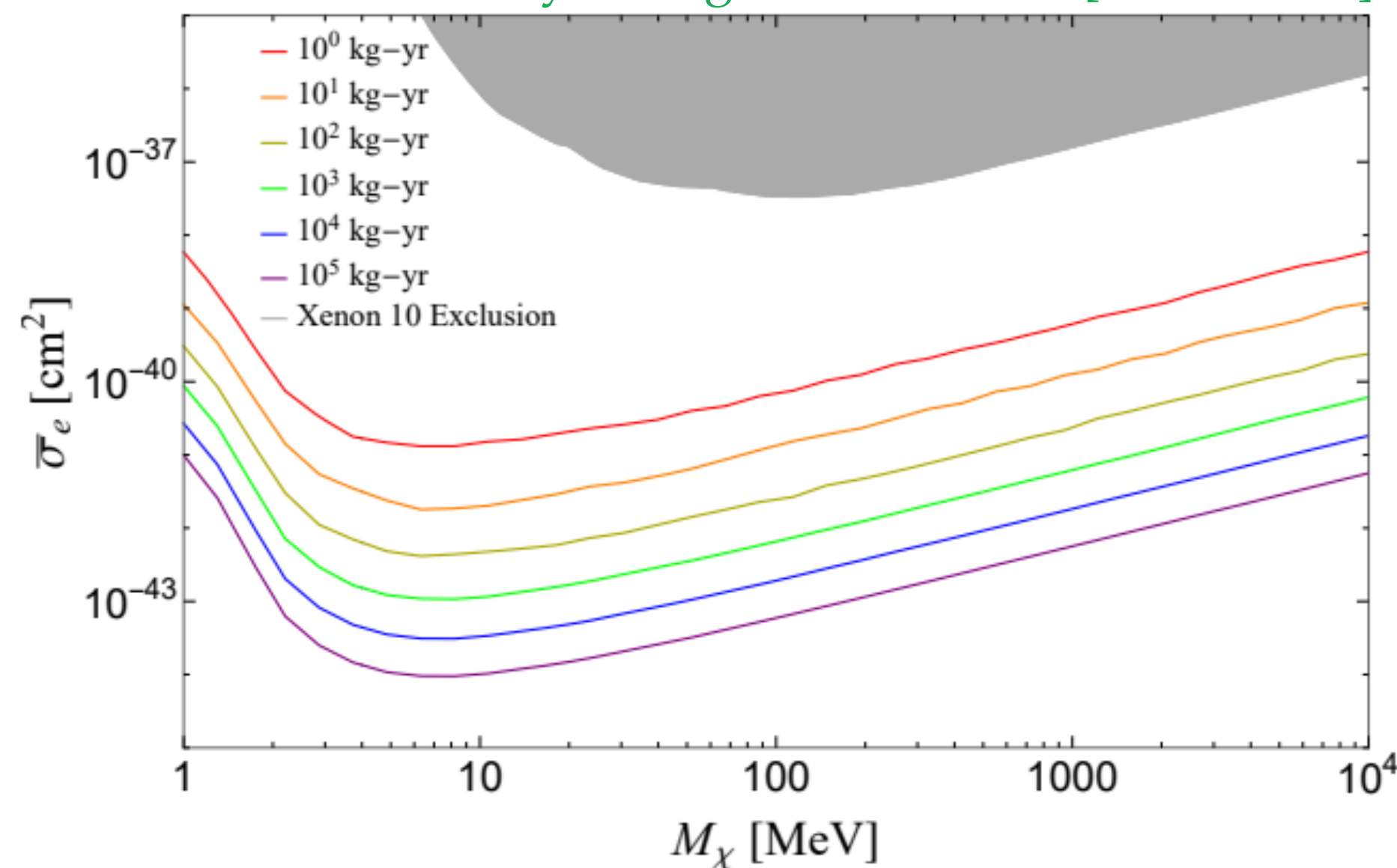
Neutrino “floors” beyond vanilla WIMP DM

DM-electron scattering

Essig et al. [1801.10159]



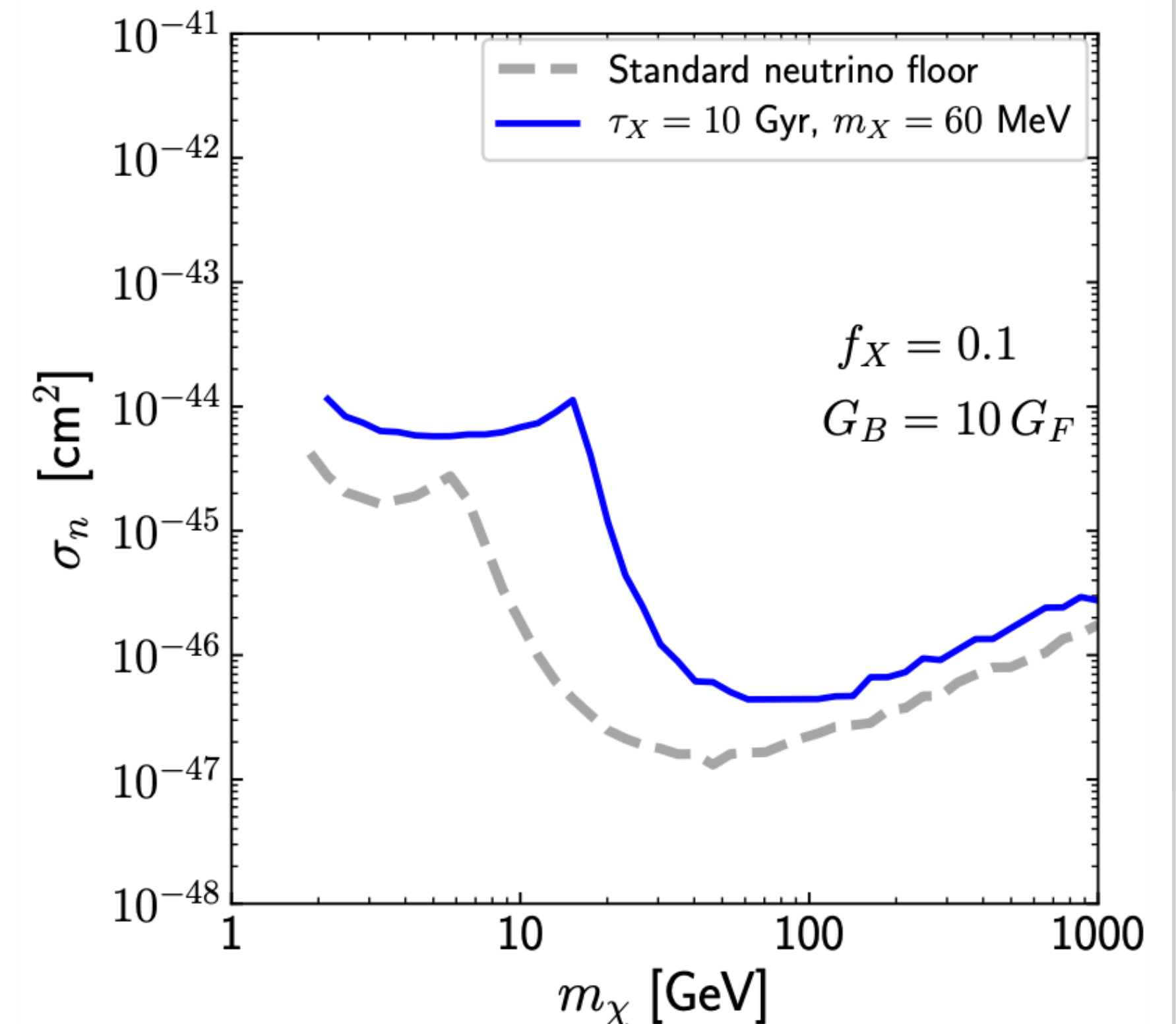
Wyenberg & Shoemaker [1803.08146]



More complicated DM models

DM + dark radiation from DM decay in the form of
SM- ν / sterile- ν

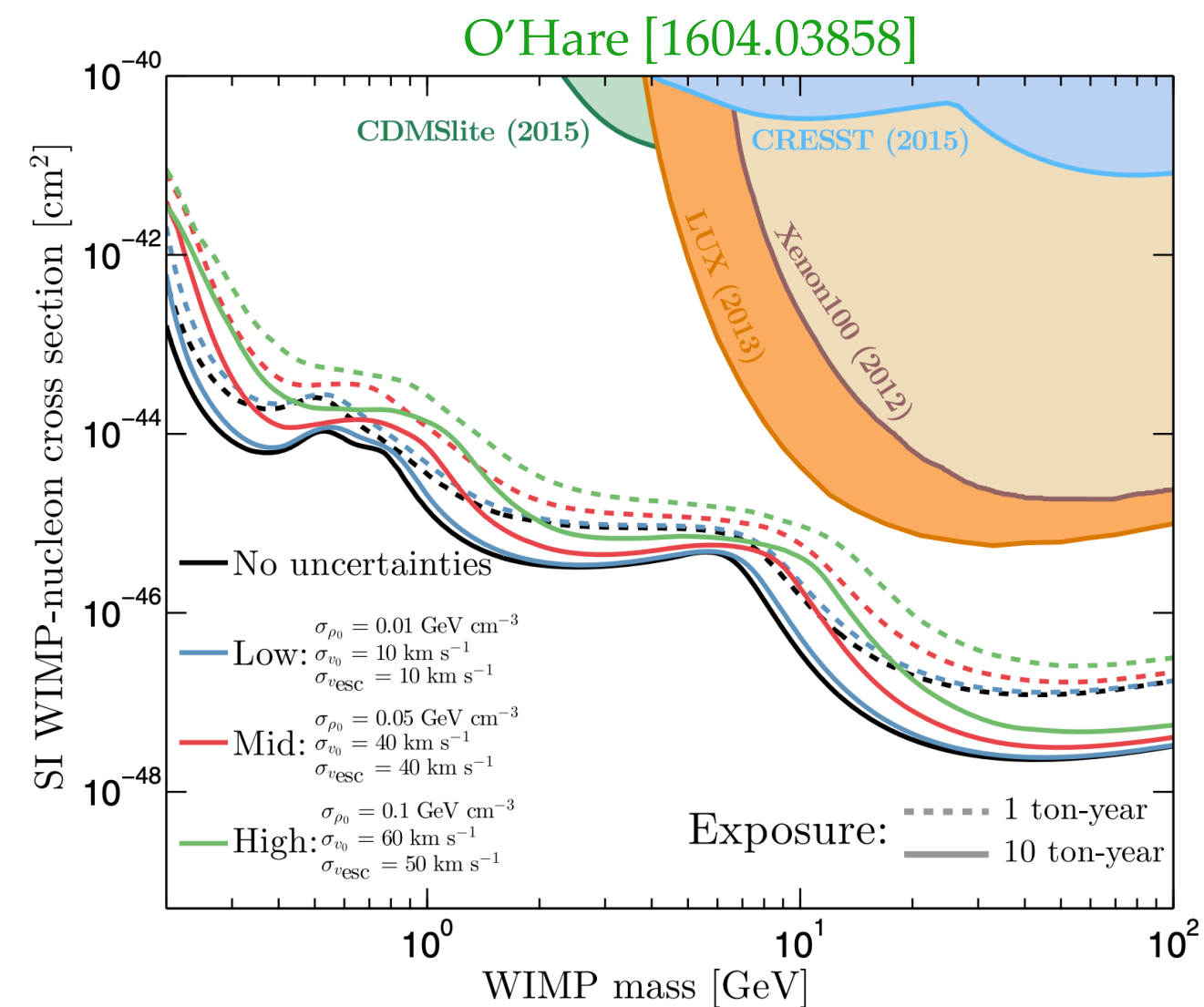
Nikolic et al. [2008.13557]



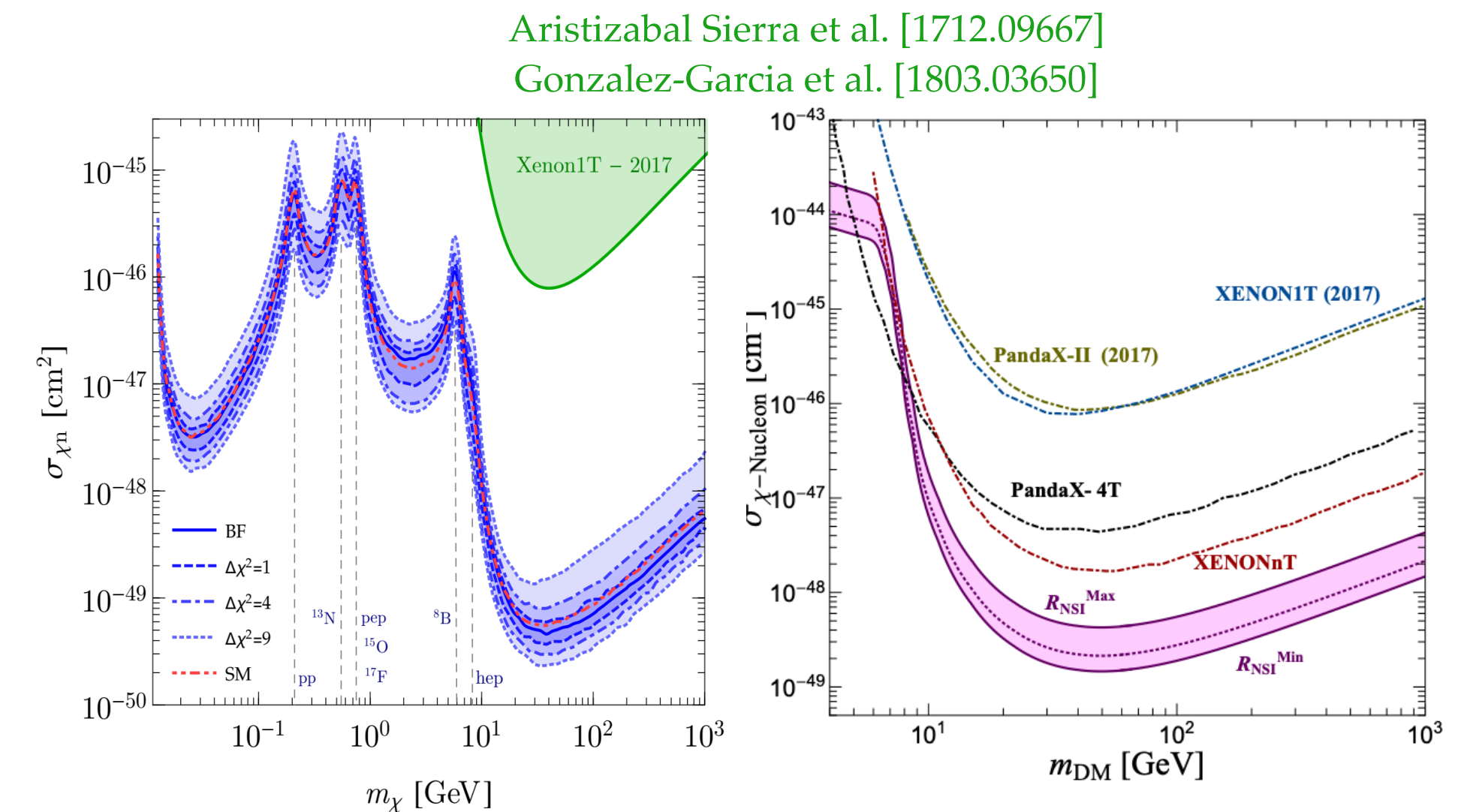
Uncertainties...

Some of these are things we would like to study in experiments

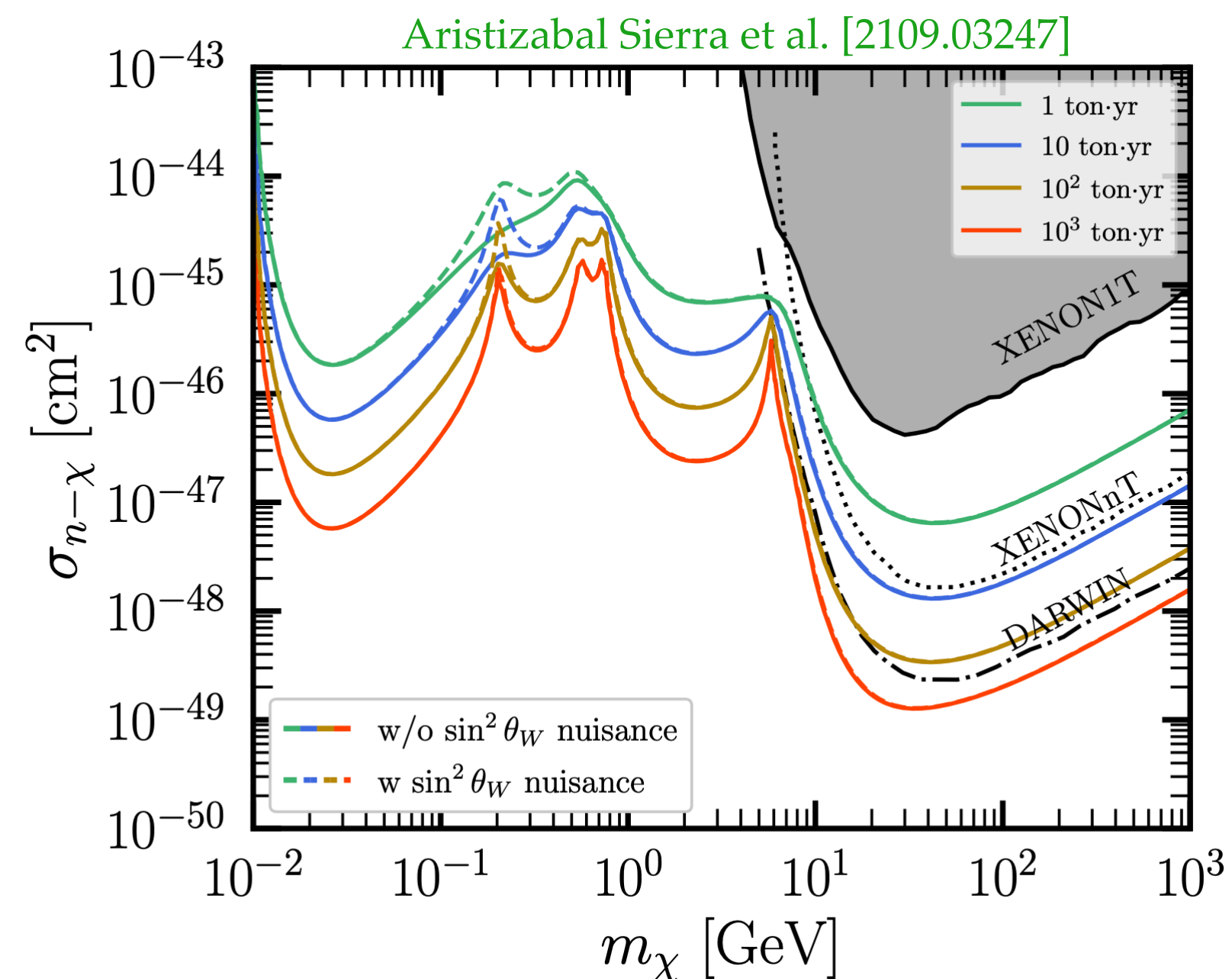
Astrophysical uncertainties



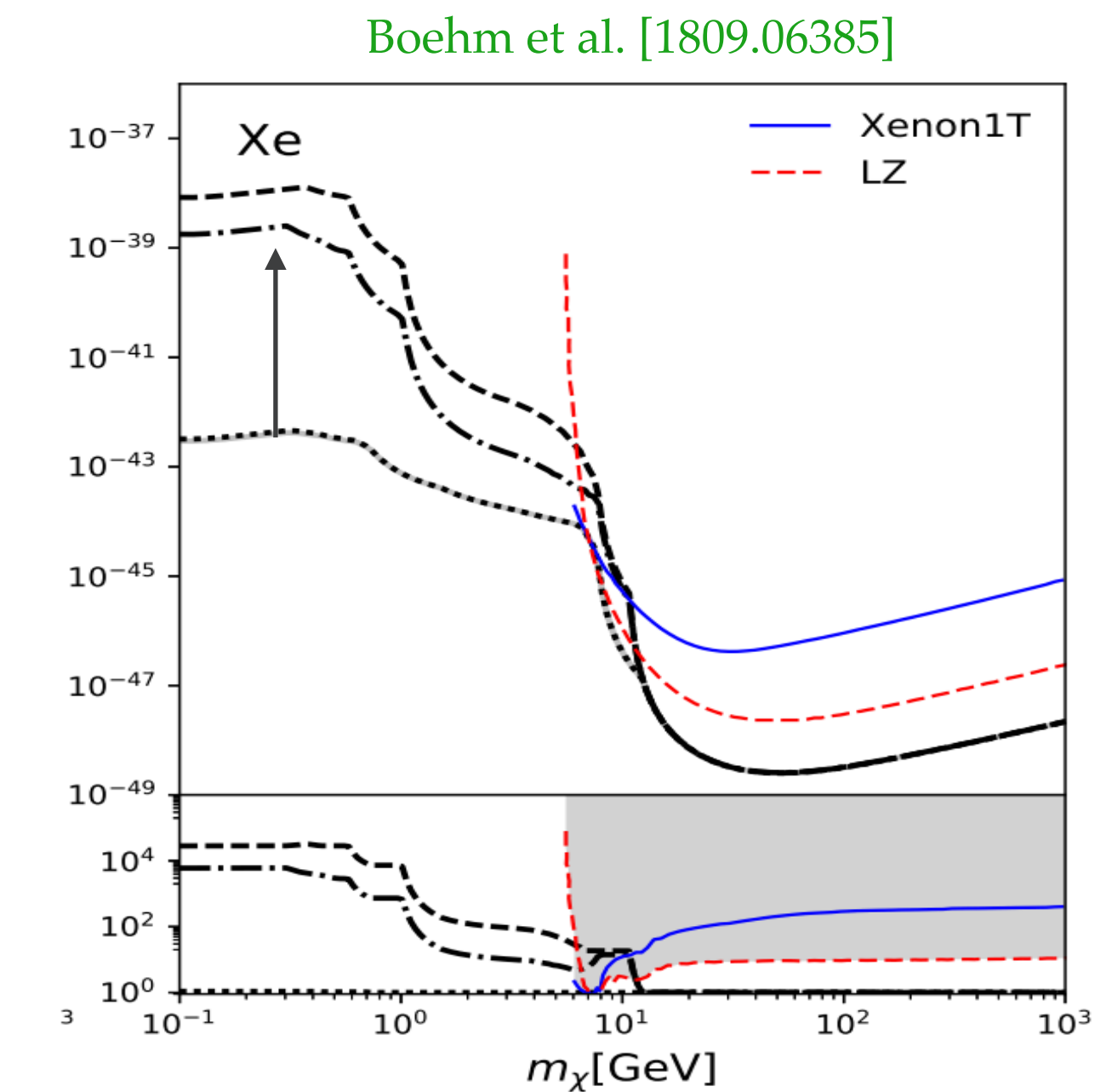
Neutrino non-standard interactions



CEvNS uncertainties



New mediators involved in CEvNS



If we want to..

1. Continue the search for DM *into* the neutrino fog

Reasons to want that: Athron+ [1705.07935], Beskidt+ [1703.01255],
Roskowski+ [1411.5214] , Hisano+[1104.0228], Arcadi+[1711.02110],
Baker+ [1912.02830], Arina+[1912.04008] ...

2. Be able to study both DM and neutrino signals in experiments

Reasons to want that: Harnik+ [1202.6073], Pospelov+ [1103.3261], Franco+[1510.04196],
Schumann+[1506.08309], Strigari [1604.00729], Dent+[1612.06350], Chen+[1610.04177],
Cerdeño+[1604.01025], Dutta+[1901.08876], Lang+[1606.09243], Bertuzzo+[1701.07443],
Dutta+[1705.00661], Aristizabal Sierra+[1712.09667] ...

Then, we need strategies for dealing with the fog

How to venture into the neutrino fog:

5 methods, ordered (sort of) in increasing effectiveness

~~1. Detect *a lot* of events~~

2. Use annual modulation

3. Have multiple target nuclei

4. Improve neutrino flux measurements

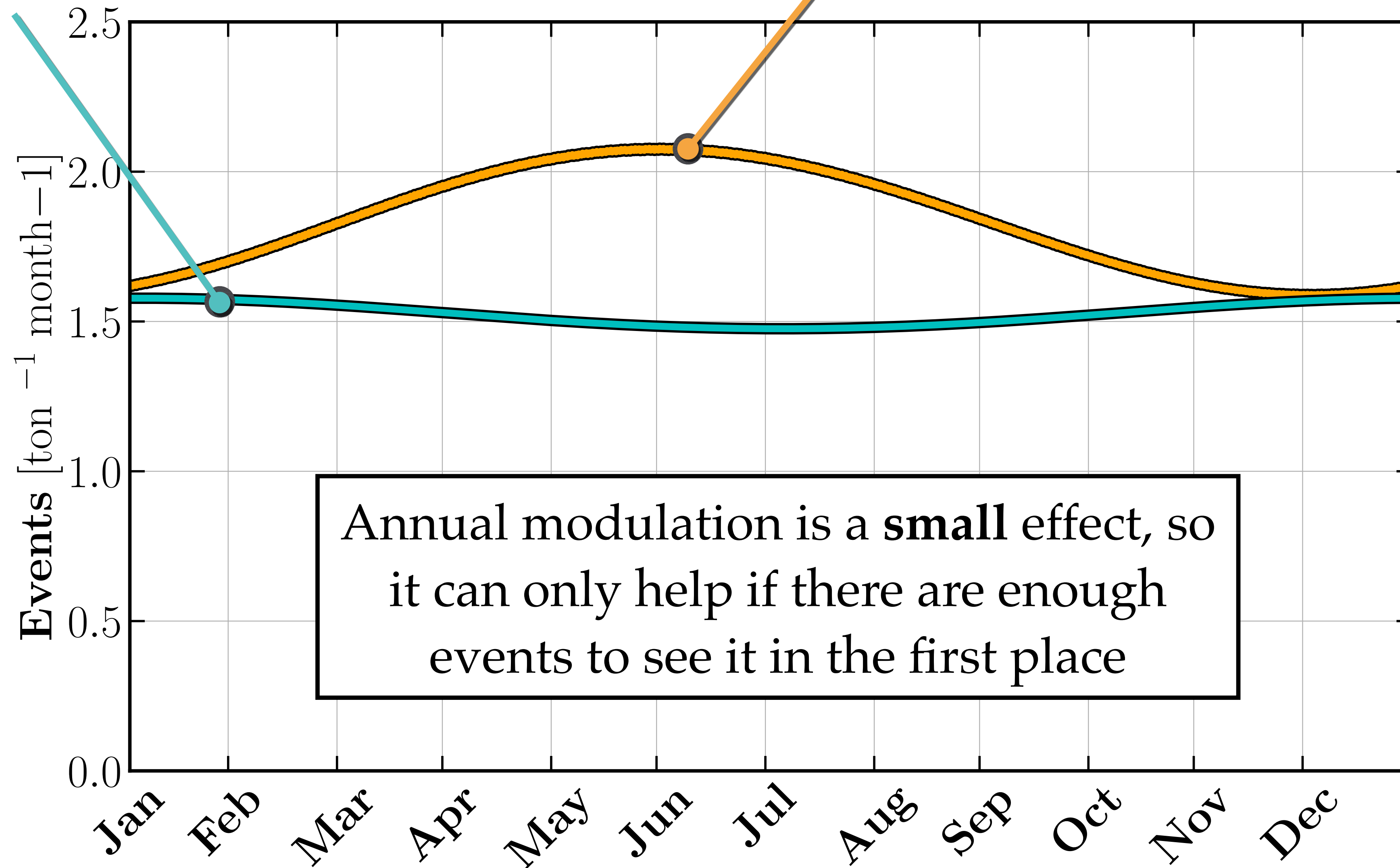
5. Use directional detectors



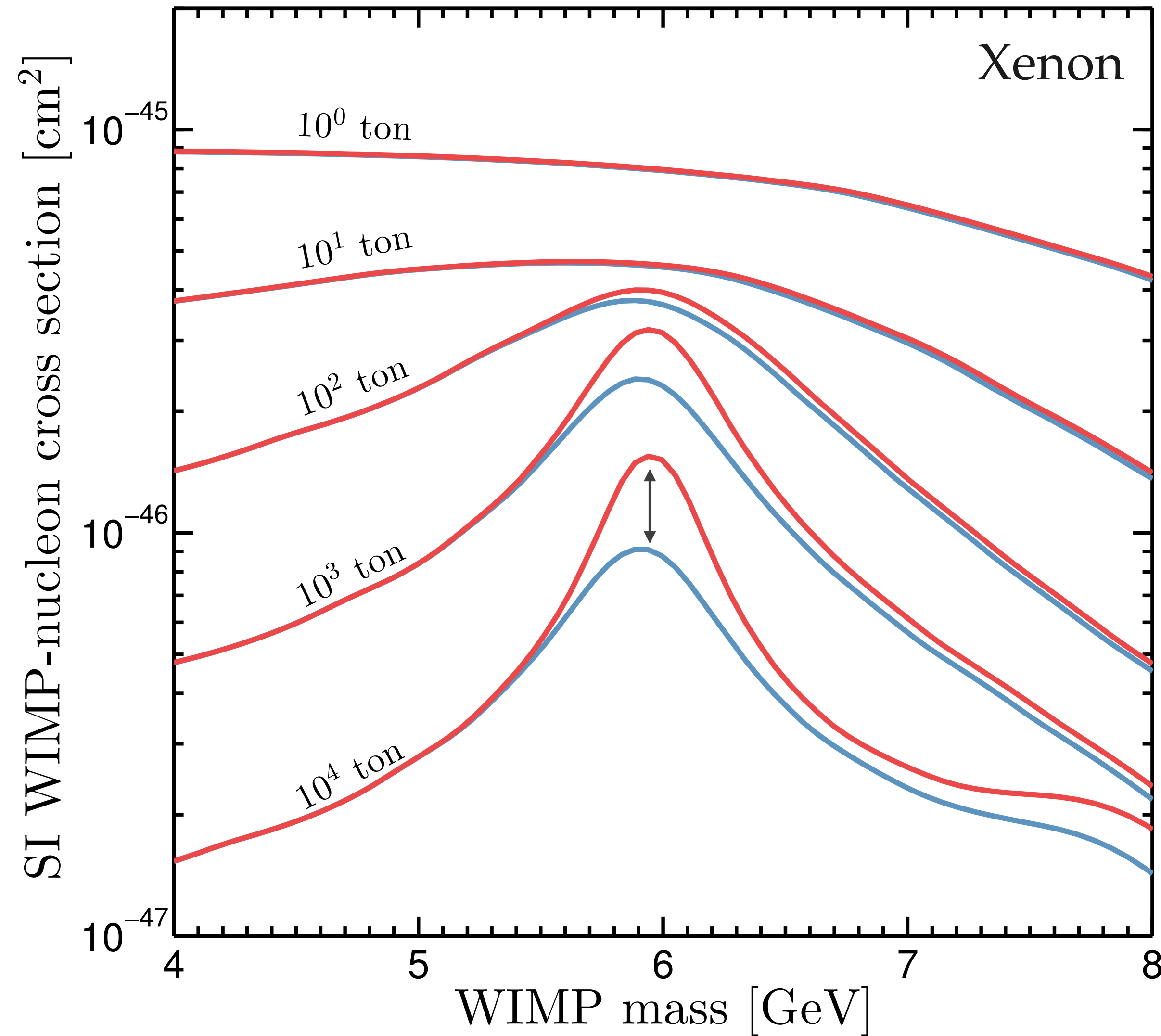
1. Annual modulation

Neutrinos peak in January when Earth is closest to the Sun

DM peaks in June when Earth is facing the DM wind



1. Annual modulation



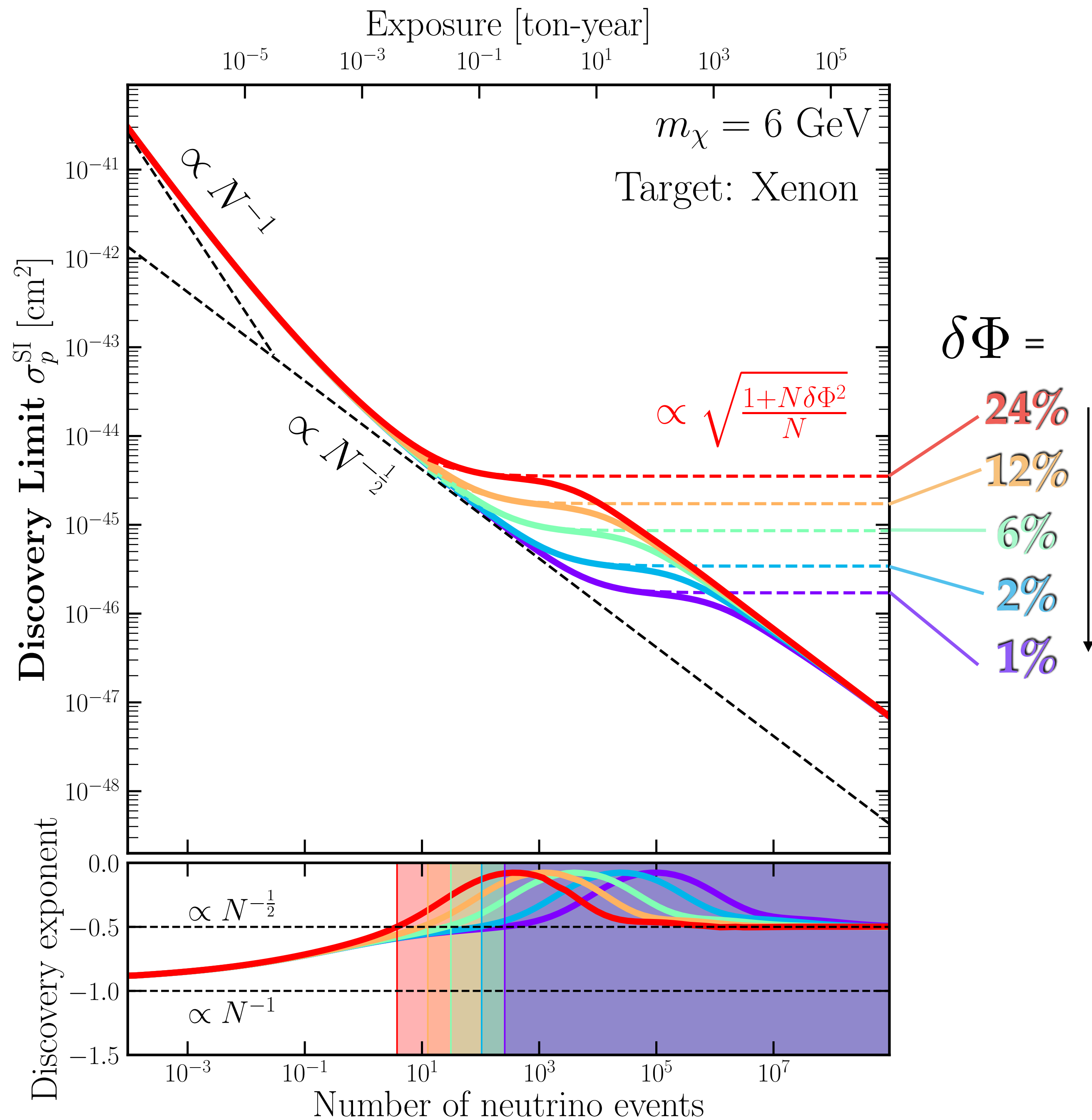
Information used:

Energy only

Energy+Time

Increasing
exposure





2. Flux uncertainties

Better flux measurement, the better
you understand the background
→ boundary of neutrino fog is lower

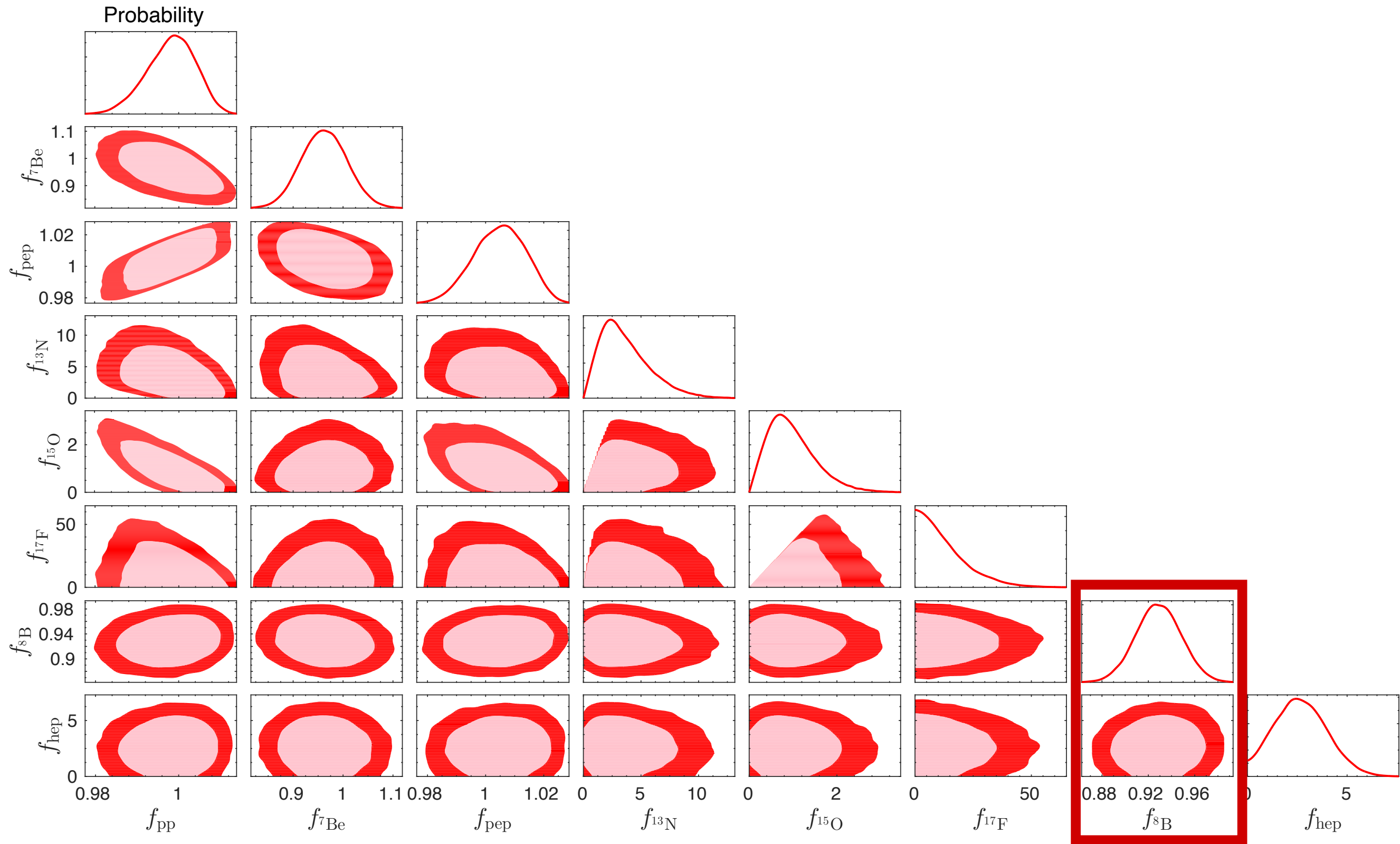
2. Flux uncertainties

ν type		$\Phi(1 \pm \delta\Phi/\Phi) \times 10^n$ [cm ⁻² s ⁻¹]	
Solar	pp	5.98 (1 ± 0.006)	10 ¹⁰
	pep	1.44 (1 ± 0.01)	10 ⁸
	hep	7.98 (1 ± 0.30)	10 ³
	^7Be	4.93 (1 ± 0.06)	10 ⁸
	^7Be	4.50 (1 ± 0.06)	10 ⁹
	^8B	5.16 (1 ± 0.02)	10 ⁶
	^{13}N	2.78 (1 ± 0.15)	10 ⁸
	^{15}O	2.05 (1 ± 0.17)	10 ⁸
	^{17}F	5.29 (1 ± 0.20)	10 ⁶
Geo.	U	4.34(1 ± 0.20)	10 ⁶
	Th	4.23(1 ± 0.25)	10 ⁶
	K	2.05(1 ± 0.17)	10 ⁷
Reactor		3.06(1 ± 0.08)	10 ⁶
DSNB		8.57(1 ± 0.50)	10 ¹
Atmospheric		1.07(1 ± 0.25)	10 ¹

2. Flux uncertainties

ν type		$\Phi(1 \pm \delta\Phi/\Phi)$	$\times 10^n$
		[cm ⁻² s ⁻¹]	
Solar	<i>pp</i>	5.98 (1 ± 0.006)	10 ¹⁰
	<i>pep</i>	1.44 (1 ± 0.01)	10 ⁸
	<i>hep</i>	7.98 (1 ± 0.30)	10 ³
	⁷ Be	4.93 (1 ± 0.06)	10 ⁸
	⁷ Be	4.50 (1 ± 0.06)	10 ⁹
	⁸ B	5.16 (1 ± 0.02)	10 ⁶
	¹³ N	2.78 (1 ± 0.15)	10 ⁸
Geo.	¹⁵ O	2.05 (1 ± 0.17)	10 ⁸
	¹⁷ F	5.29 (1 ± 0.20)	10 ⁶
	U	4.34(1 ± 0.20)	10 ⁶
Geo.	Th	4.23(1 ± 0.25)	10 ⁶
	K	2.05(1 ± 0.17)	10 ⁷
Reactor		3.06(1 ± 0.08)	10 ⁶
DSNB		8.57(1 ± 0.50)	10 ¹
Atmospheric		1.07(1 ± 0.25)	10 ¹

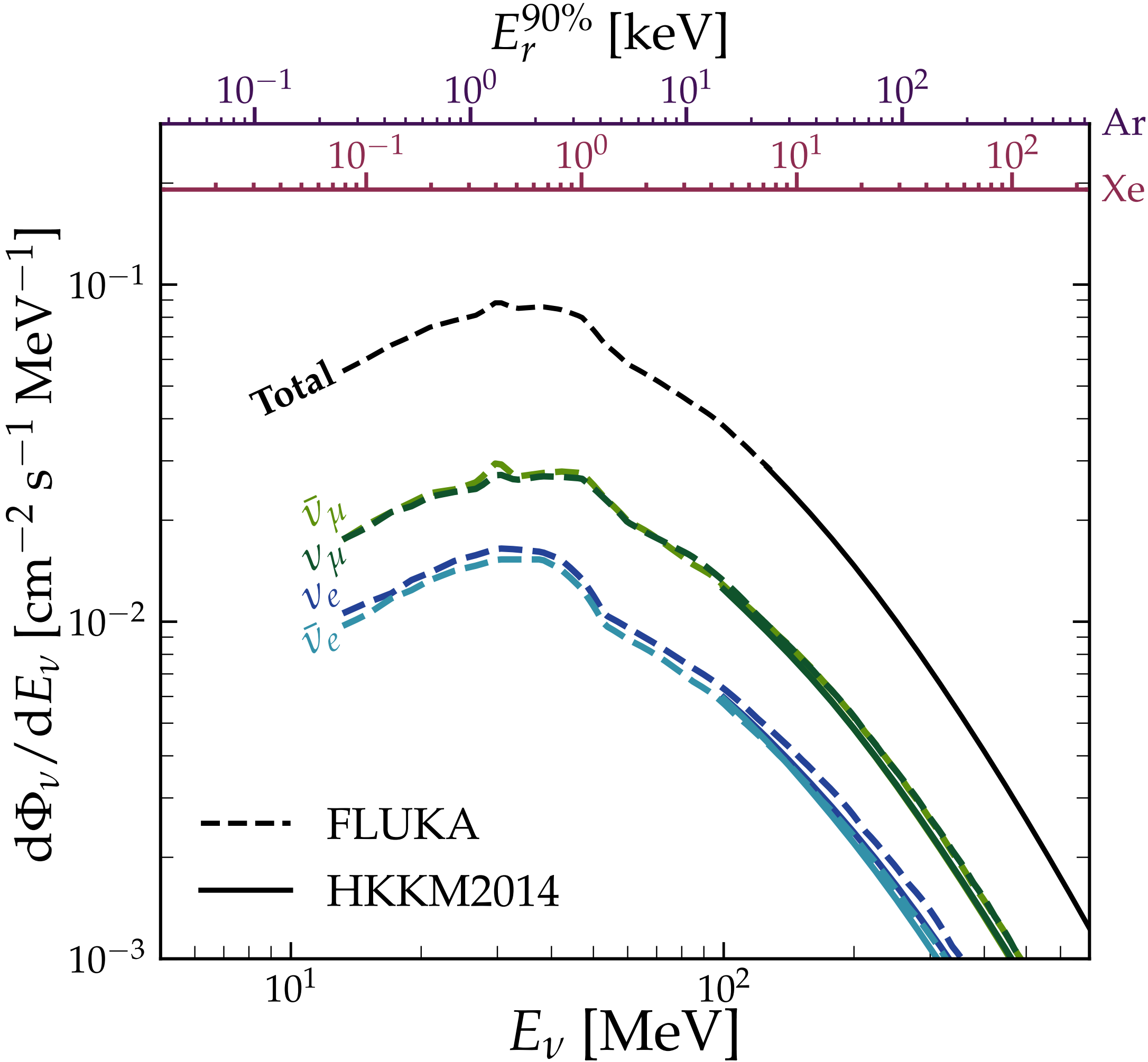
⁸B flux at ~2% (from global fit 1601.00972), so already well-measured. Could improve further with experiments like DUNE, JUNO, Hyper-K, or potential successor to Borexino, all of which will observe large numbers of solar neutrinos



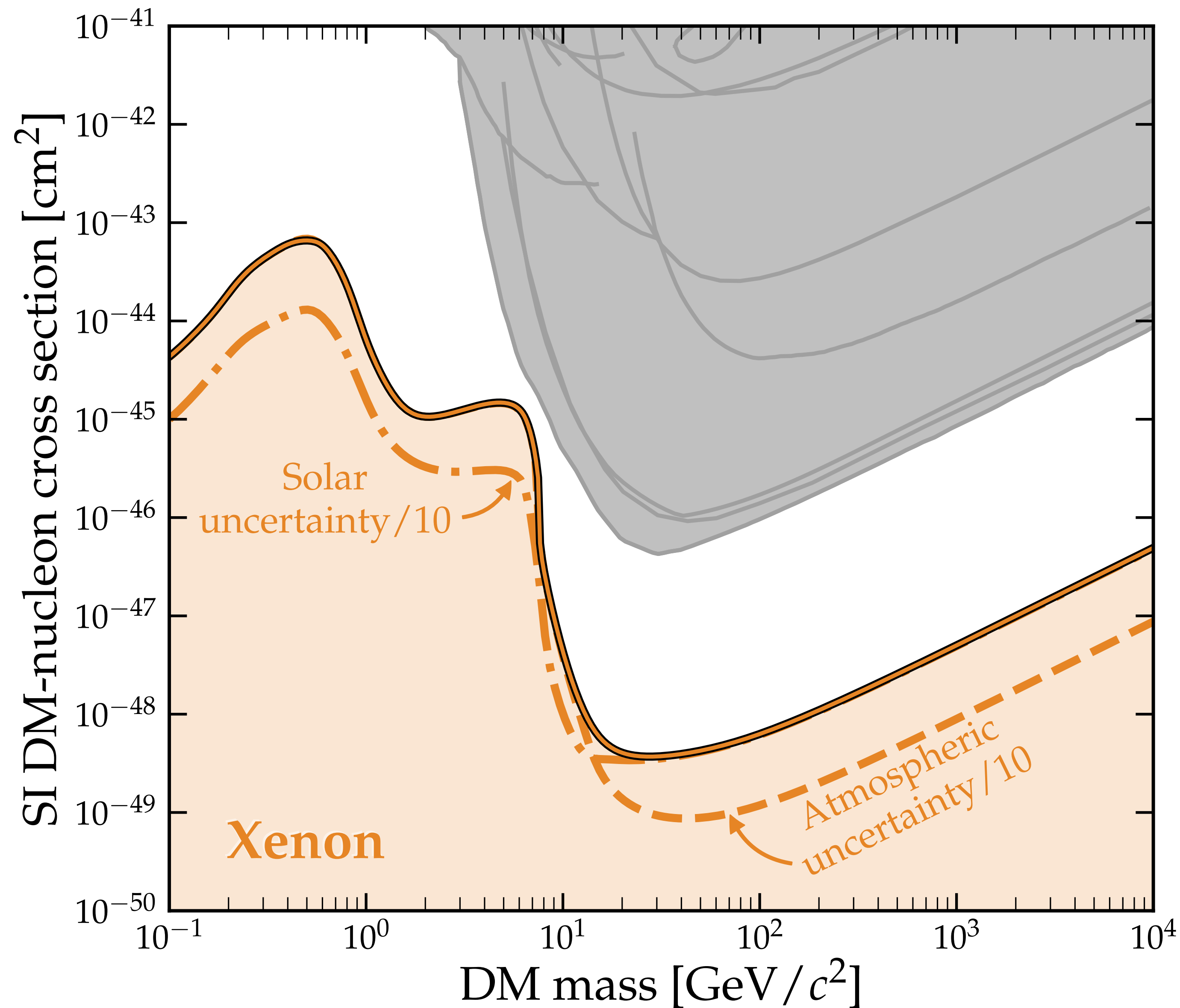
2. Flux uncertainties

ν type		$\Phi(1 \pm \delta\Phi/\Phi) \times 10^n$ [cm ⁻² s ⁻¹]
Solar	<i>pp</i>	5.98 (1 ± 0.006) 10 ¹⁰
	<i>pep</i>	1.44 (1 ± 0.01) 10 ⁸
	<i>hep</i>	7.98 (1 ± 0.30) 10 ³
	⁷ Be	4.93 (1 ± 0.06) 10 ⁸
	⁷ Be	4.50 (1 ± 0.06) 10 ⁹
	⁸ B	5.16 (1 ± 0.02) 10 ⁶
	¹³ N	2.78 (1 ± 0.15) 10 ⁸
	¹⁵ O	2.05 (1 ± 0.17) 10 ⁸
	¹⁷ F	5.29 (1 ± 0.20) 10 ⁶
Geo.	U	4.34(1 ± 0.20) 10 ⁶
	Th	4.23(1 ± 0.25) 10 ⁶
	K	2.05(1 ± 0.17) 10 ⁷
Reactor		3.06(1 ± 0.08) 10 ⁶
DSNB		8.57(1 ± 0.50) 10 ¹
Atmospheric		1.07(1 ± 0.25) 10 ¹

Low-tail of atmospheric flux not yet measured at the relevant energies, 25% uncertainty is advisory, and may improve after its measurement



2. Effect of Flux uncertainties (for illustration only)

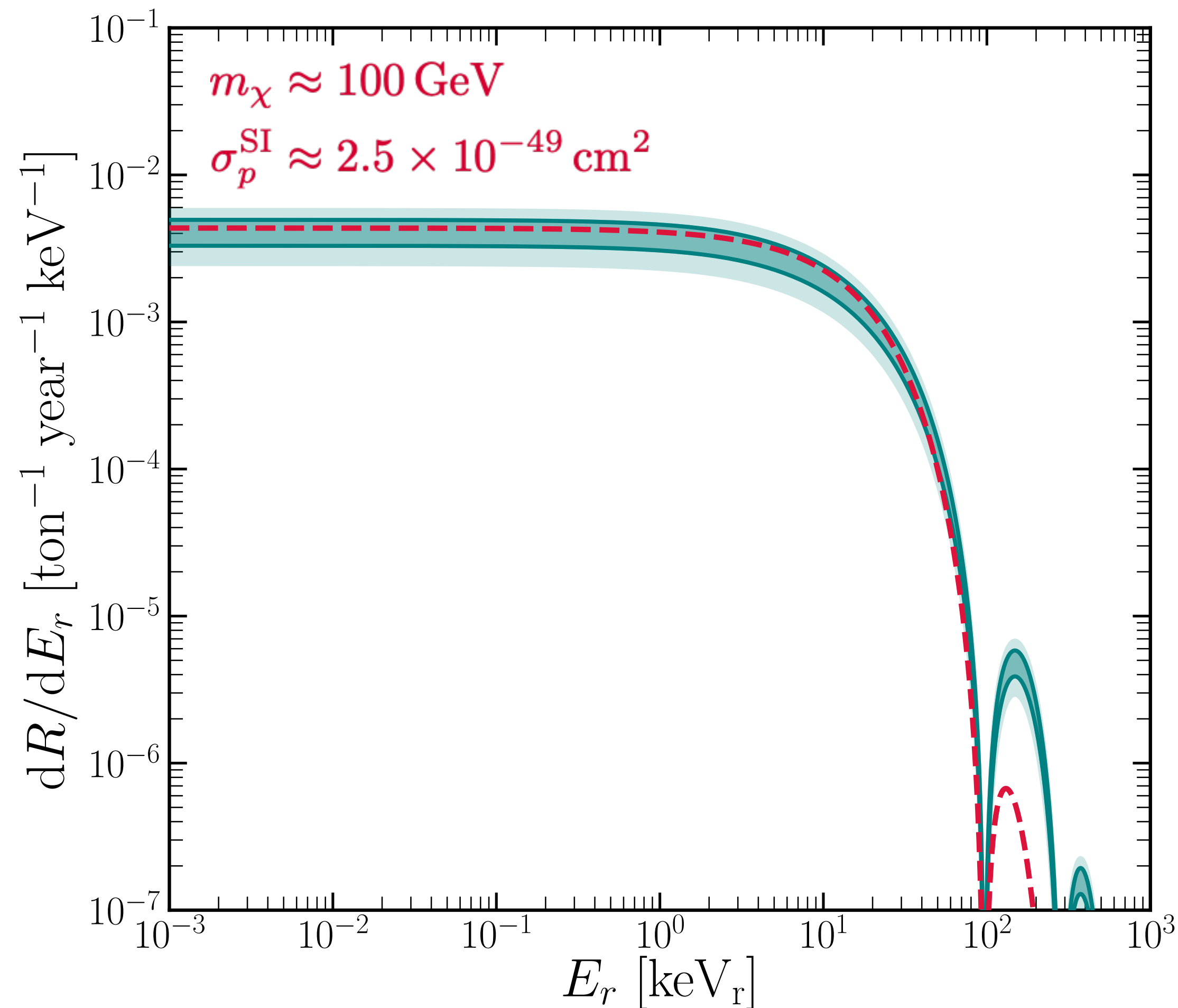


Better flux measurement
→ **enter the neutrino fog at
a lower cross section**

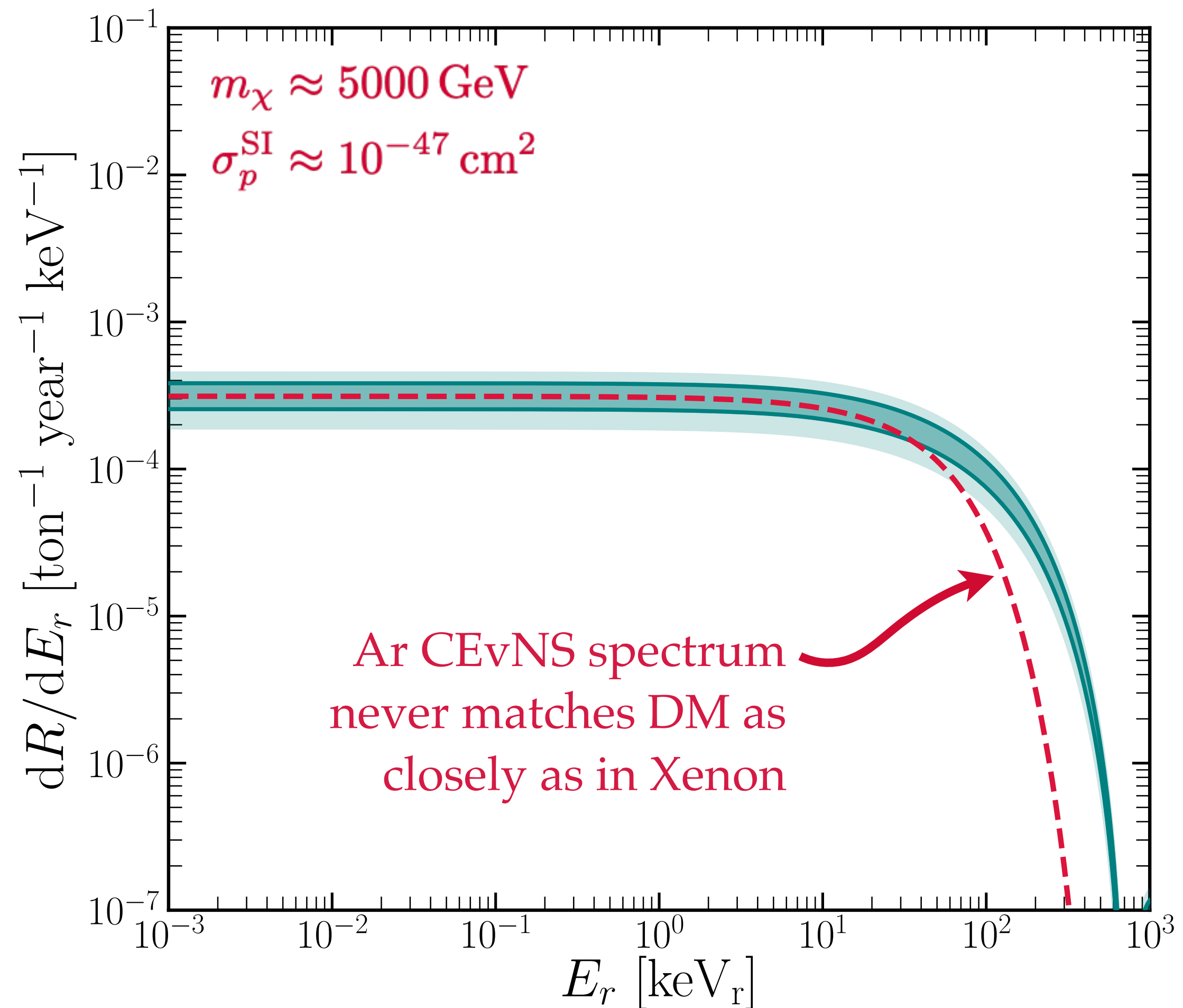
3. Target complementarity: Xe & Ar

High mass (>100 GeV) **DM (SI)** versus **Atmospheric neutrinos**

Xenon

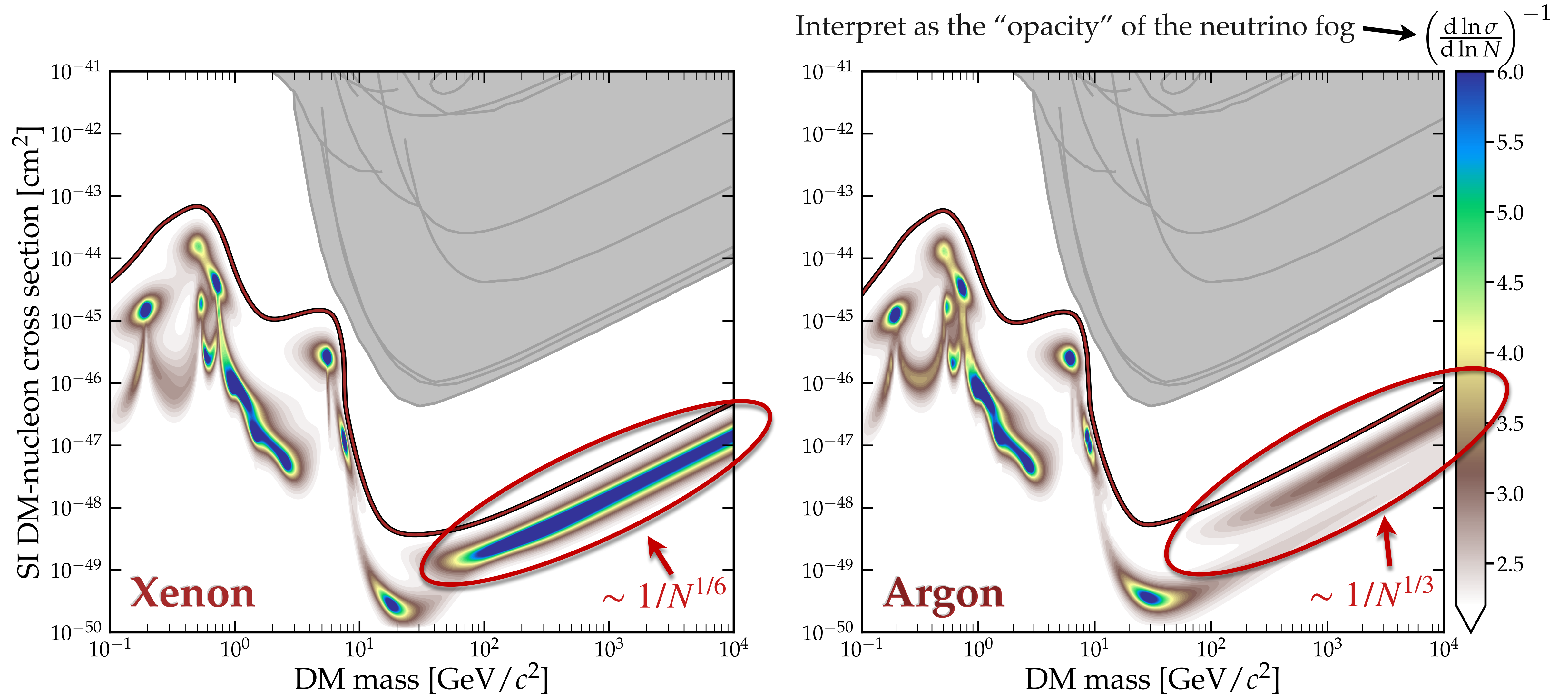


Argon

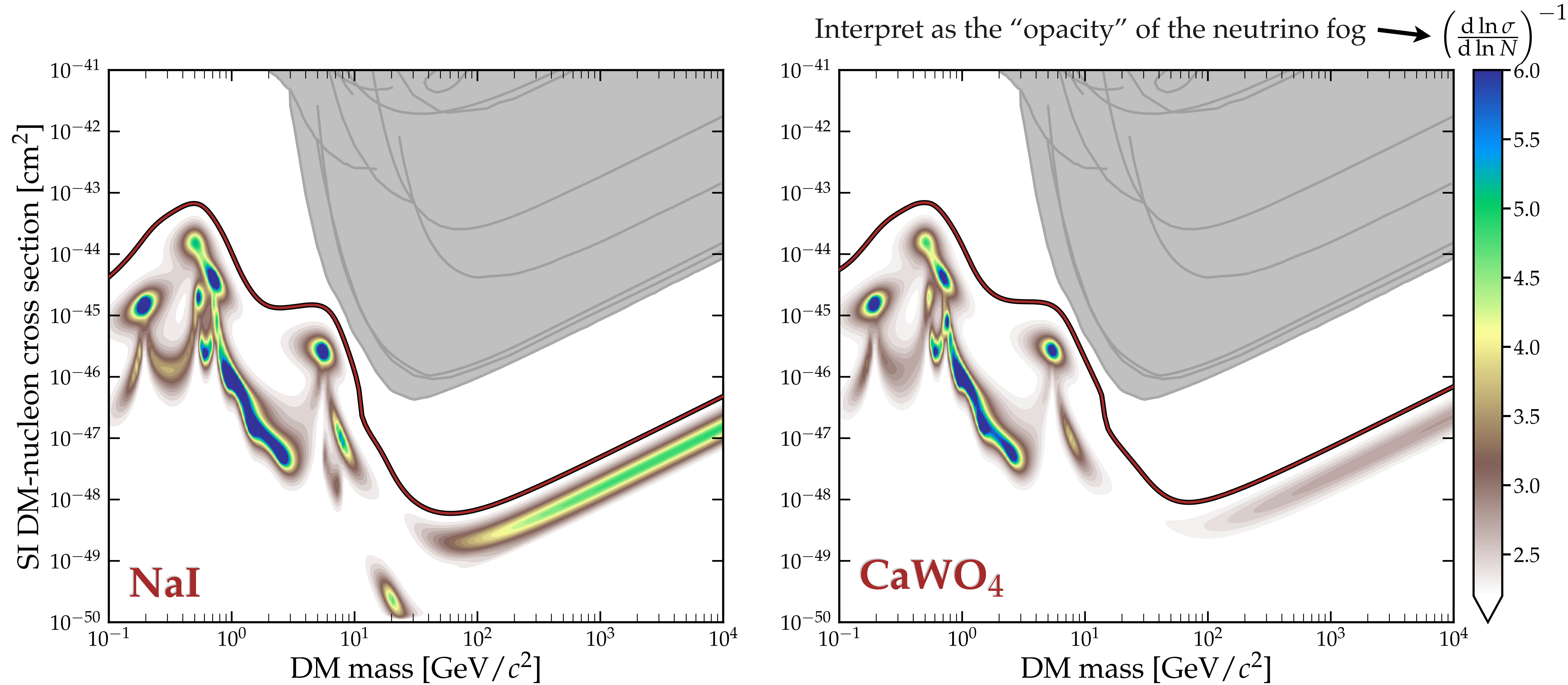


3. Target complementarity: Xe & Ar

High mass (>100 GeV) **DM (SI)** versus **Atmospheric neutrinos**



3. Target complementarity



Ultimate multi-ton Xenon+Argon DM search?

“Standard” strategy: → No WIMP/atmospheric neutrino discrimination attempted

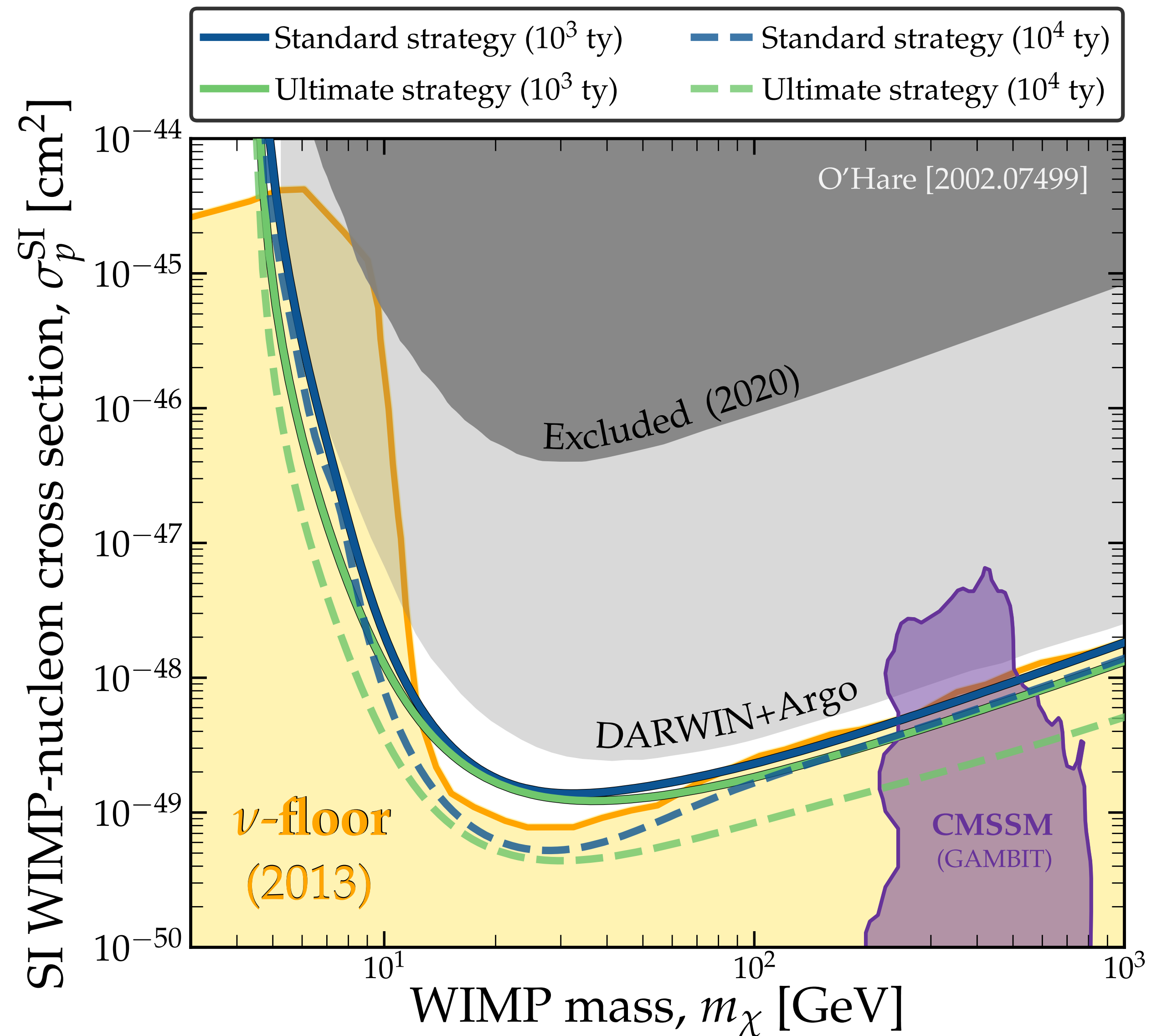
Xenon experiment only

“Ultimate” strategy: → Attempt WIMP/neutrino discrimination

+ Xenon / Argon combined analysis

+ annual modulation

+ Atmospheric neutrino flux uncertainty 25% → 10%
(reasonable expectation for DUNE, JUNO, Hyper-K...)



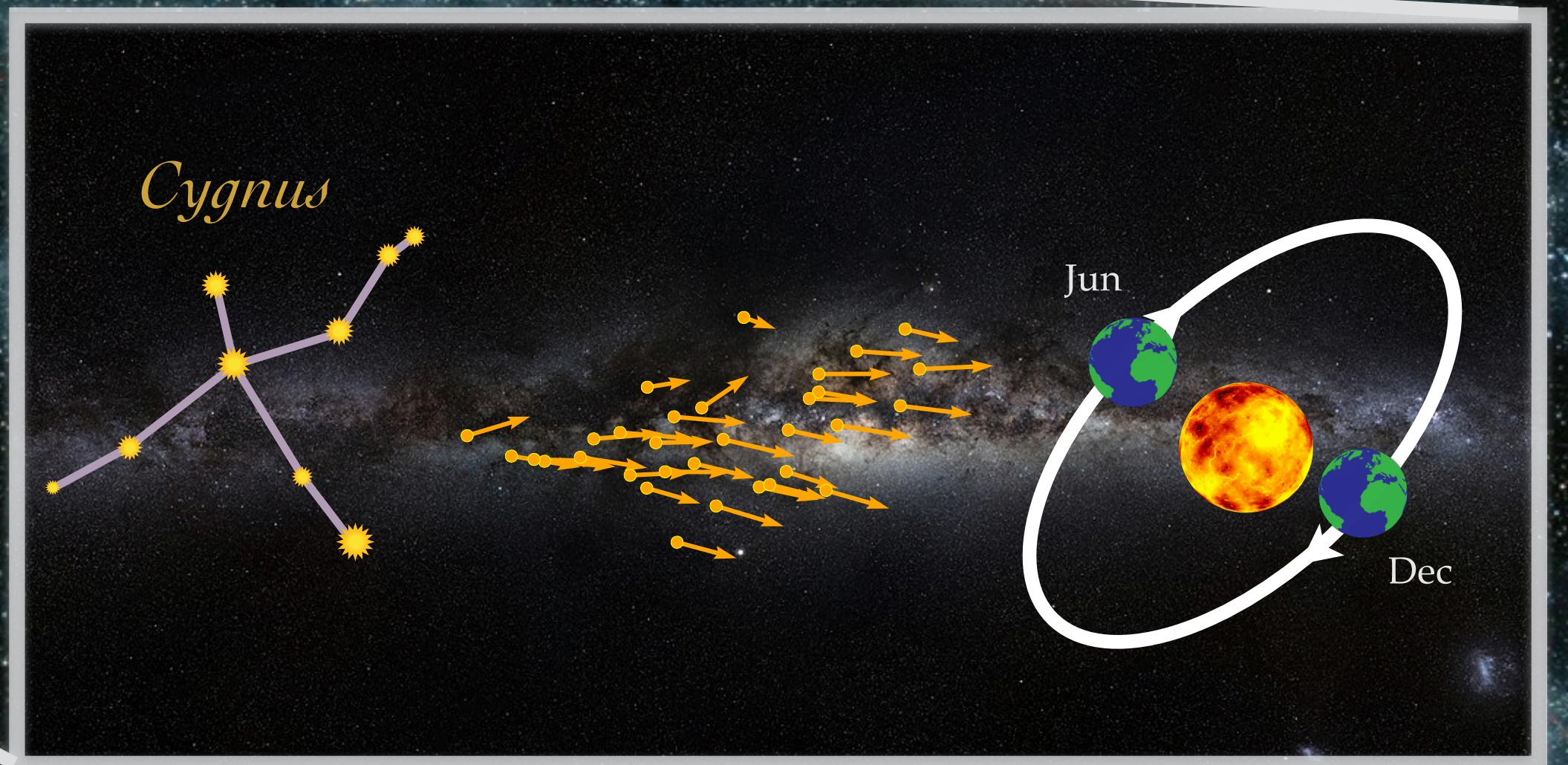
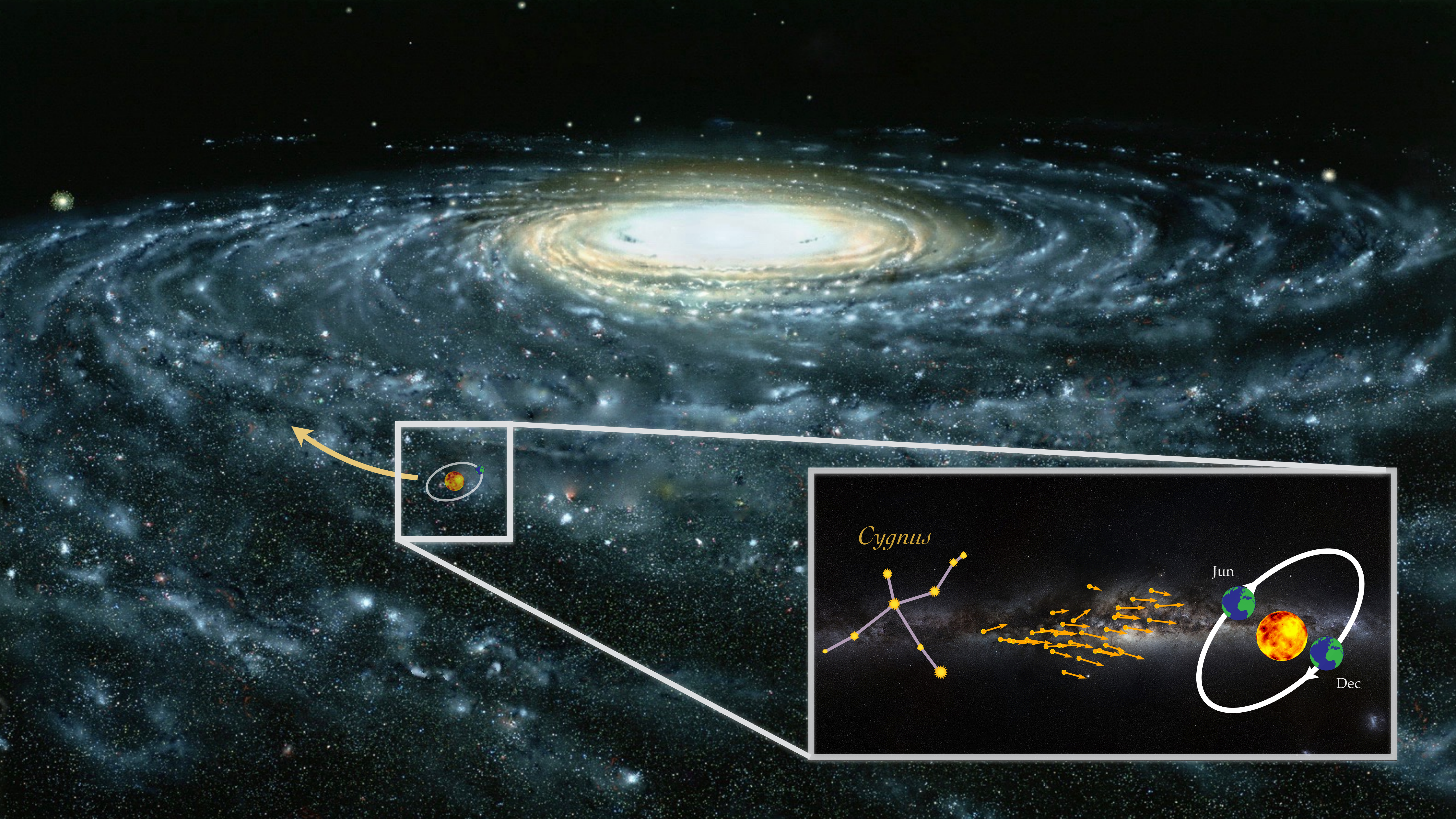
~~Method 1: Detect a lot of events~~

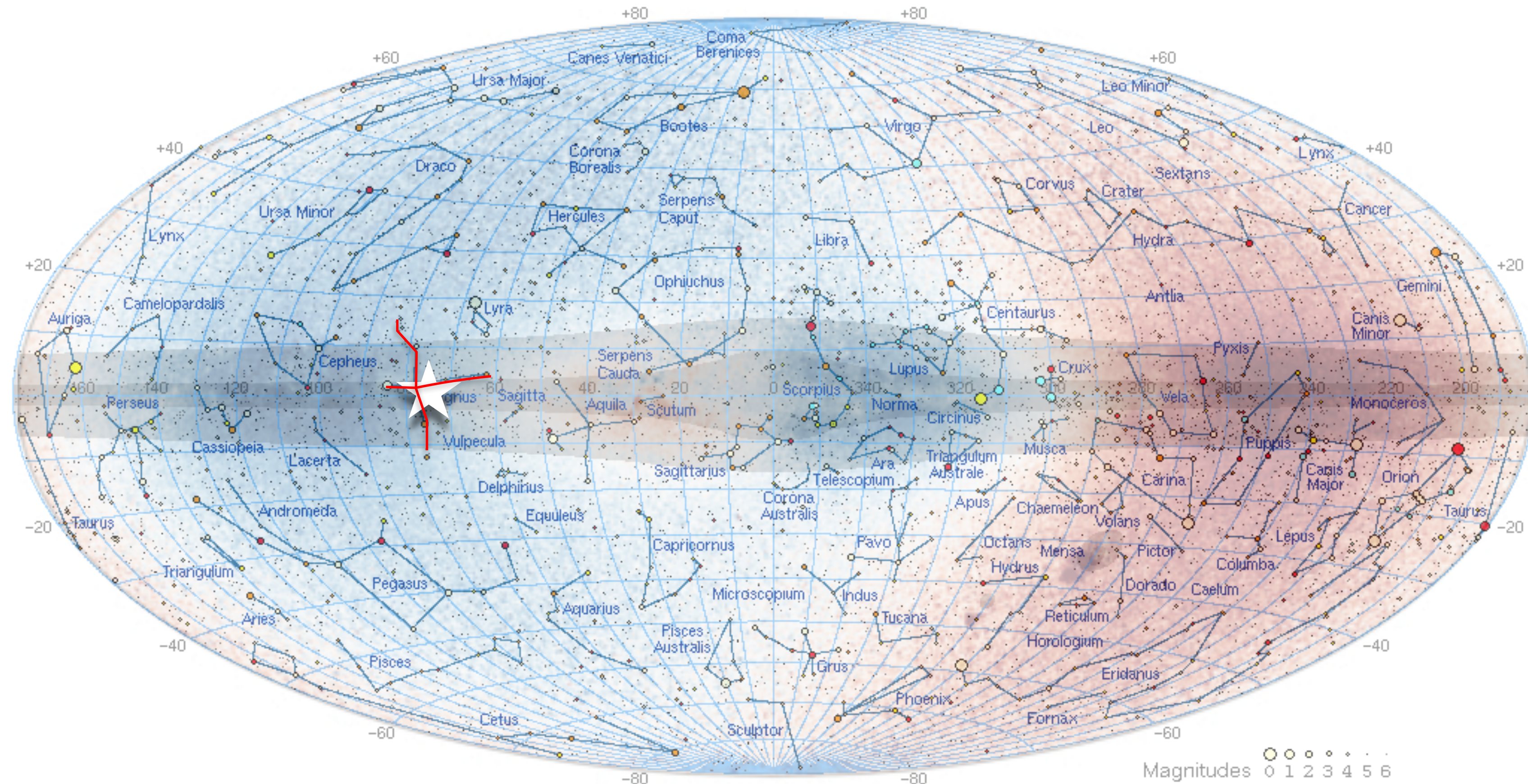
~~Method 2: Improve neutrino flux measurements~~

~~Method 3: Use annual modulation~~

~~Method 4: Use multiple targets~~

To do better we need something that actually distinguishes DM and neutrinos

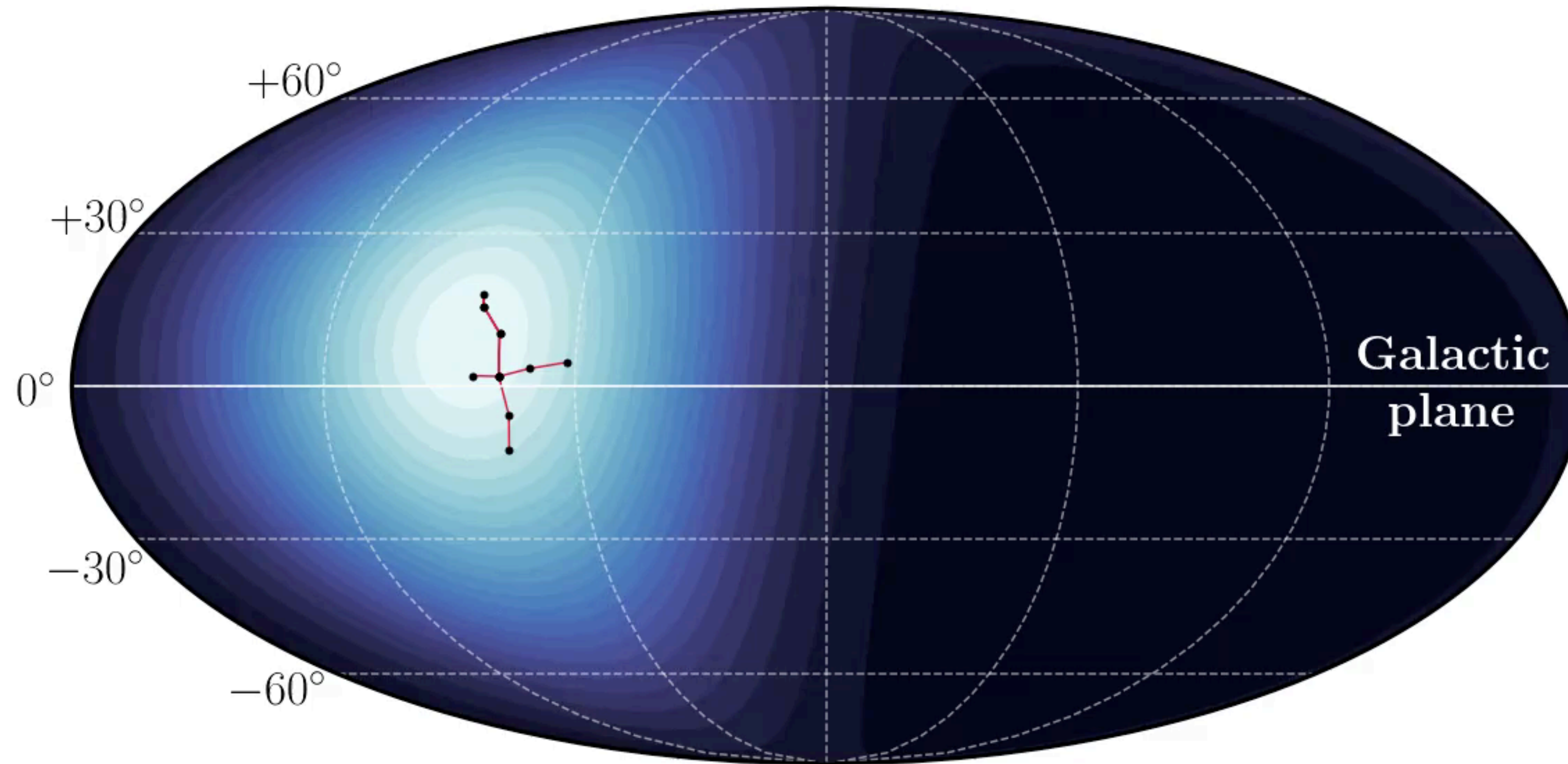




Gaia RVS skymap of line of sight velocities

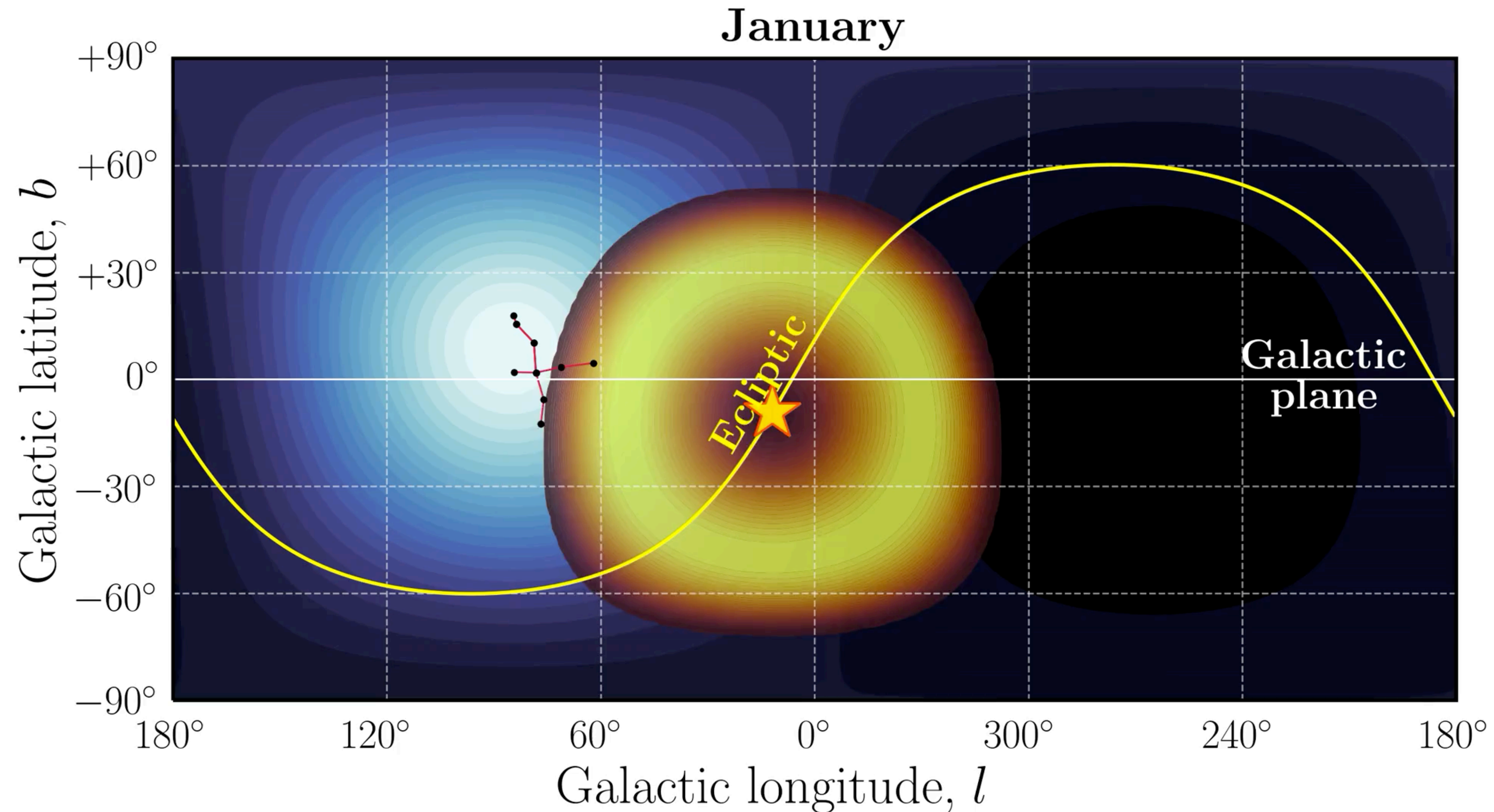
Blue = moving towards us (relatively)

Red = moving away from us



The dark matter flux on Earth is anisotropic and should align with the direction of galactic rotation → a highly characteristic signal that is robust against theoretical and astrophysical uncertainties

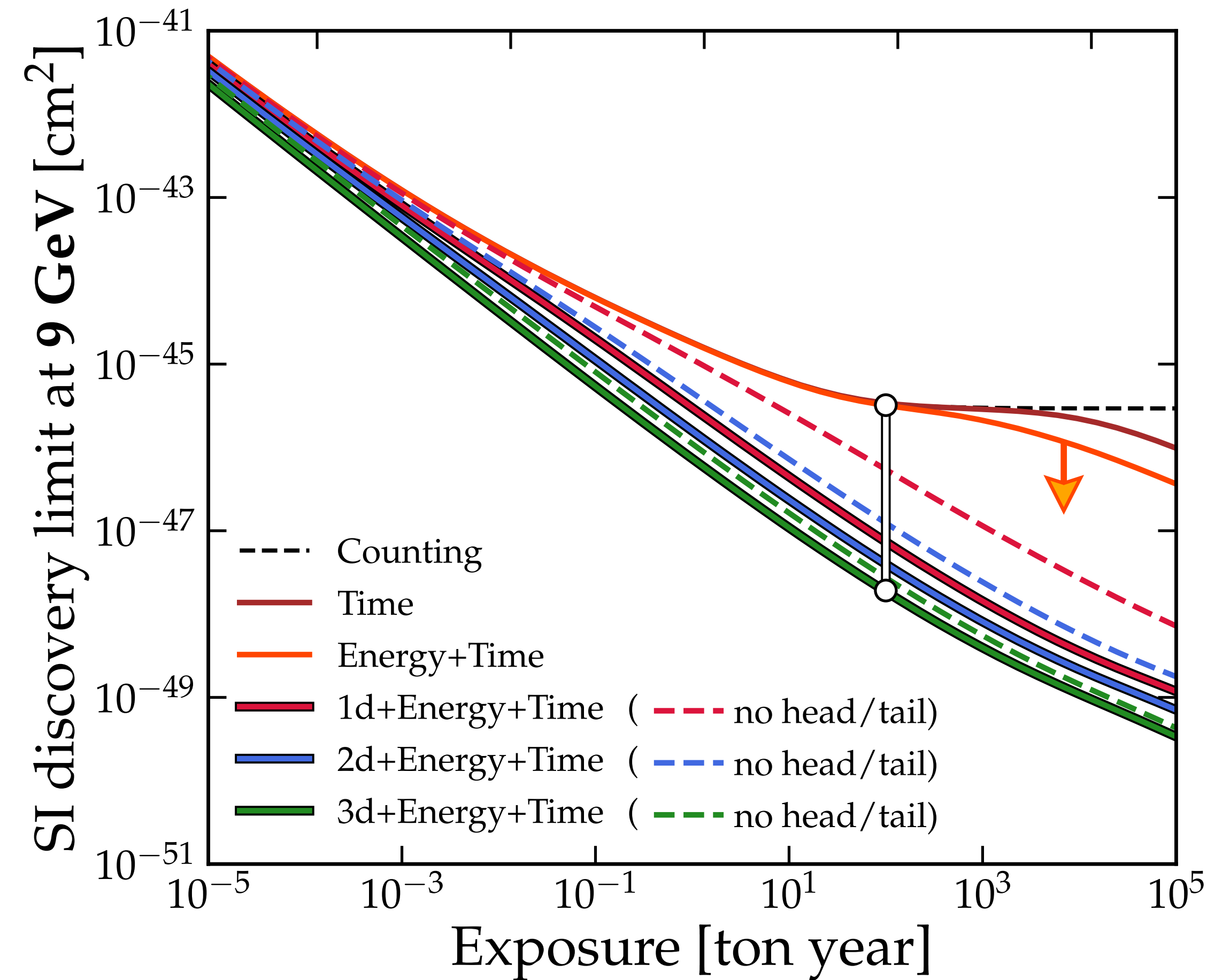
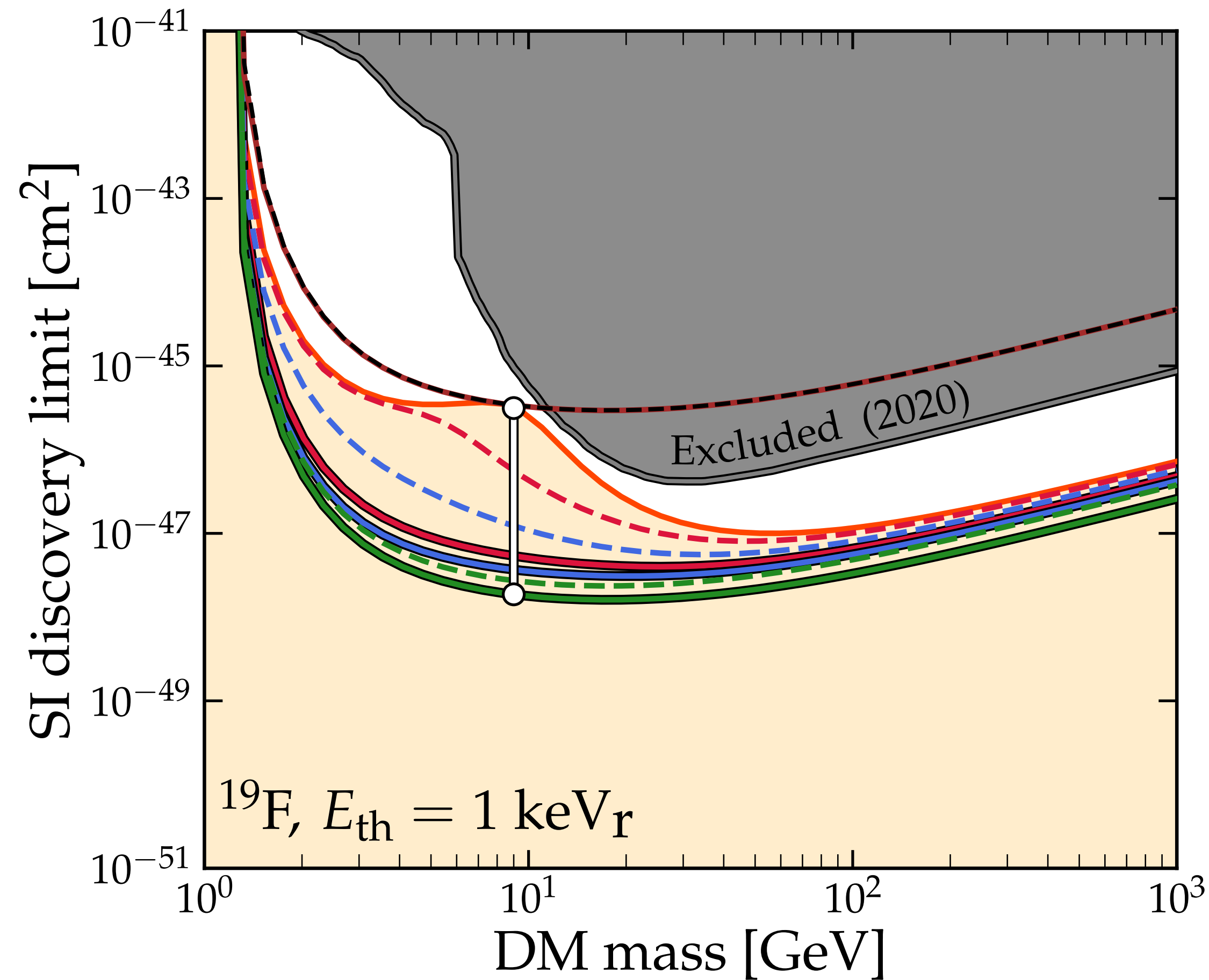
The dark matter flux on Earth is anisotropic and should align with the direction of galactic rotation
→ a highly characteristic signal that is robust against theoretical and astrophysical uncertainties



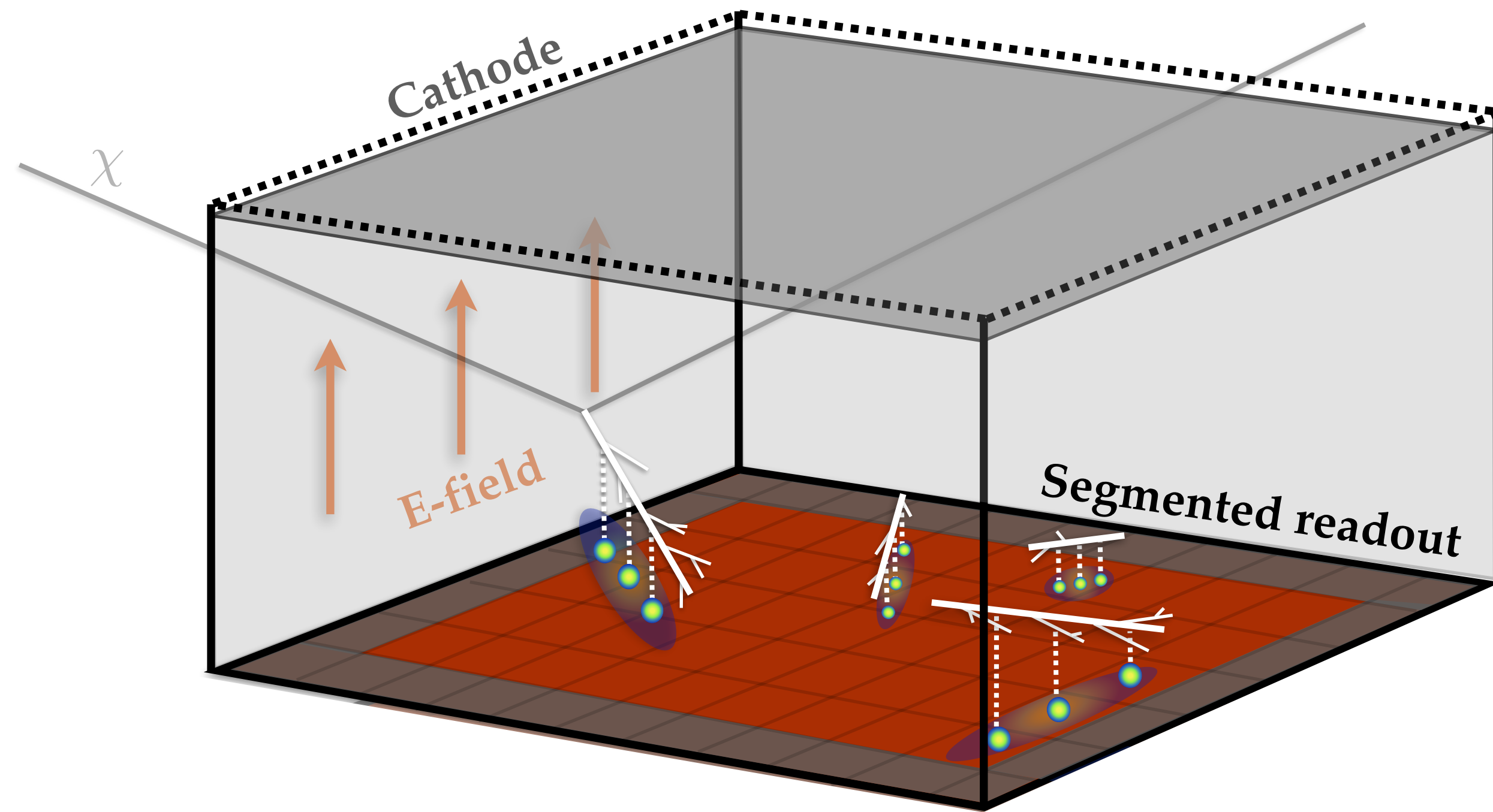
A directional detector should be able to “see through” the neutrino fog

Subtracting the neutrino background with directionality

Simple demonstration based purely on information content



One popular approach: gas time projection chamber



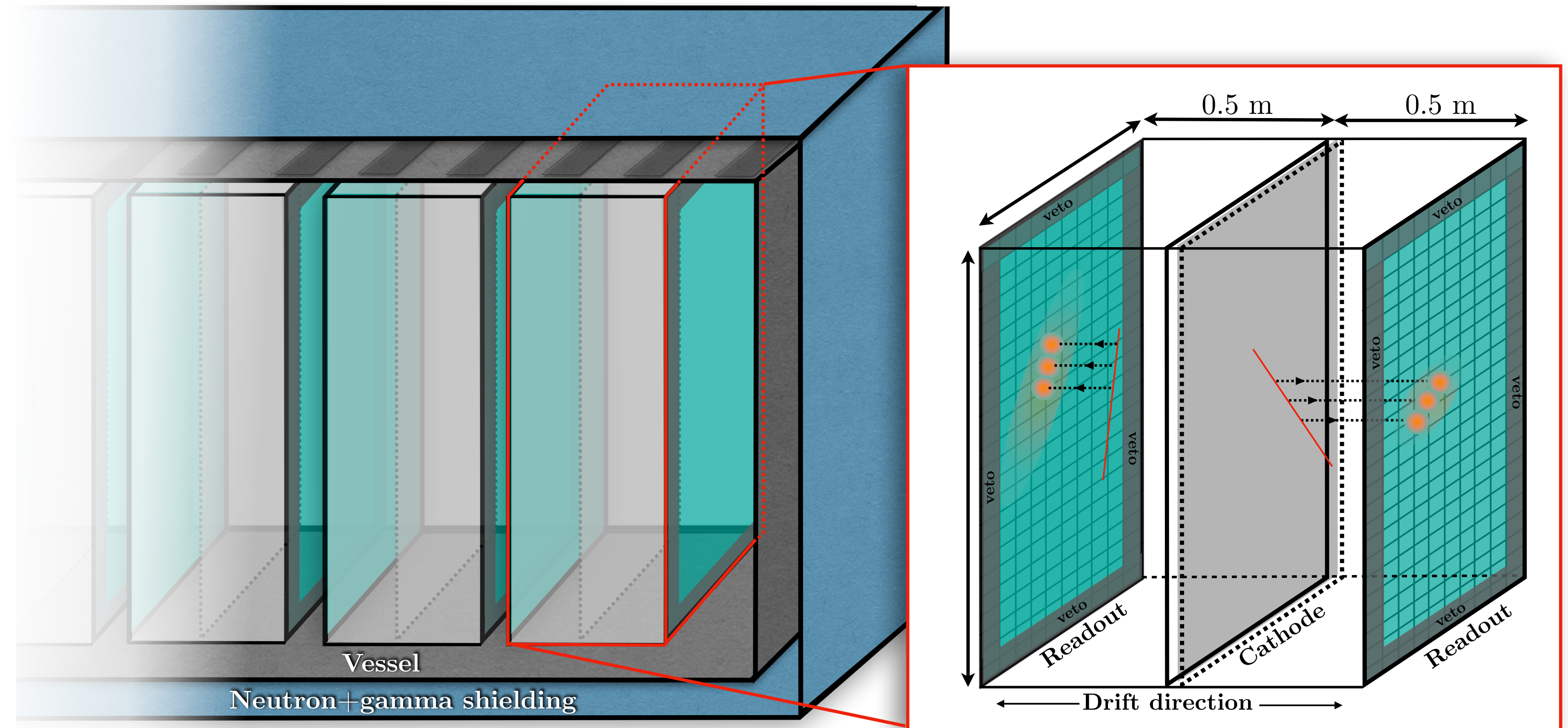
[2008.12587]

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

S. E. Vahsen,¹ C. A. J. O'Hare,² W. A. Lynch,³ N. J. C. Spooner,³ E. Baracchini,^{4,5,6} P. Barbeau,⁷
J. B. R. Battat,⁸ B. Crow,¹ C. Deaconu,⁹ C. Eldridge,³ A. C. Ezeribe,³ M. Ghrear,¹ D. Loomba,¹⁰
K. J. Mack,¹¹ K. Miuchi,¹² F. M. Mouton,³ N. S. Phan,¹³ K. Scholberg,⁷ and T. N. Thorpe^{1,6}

CYGNUS-Nm³

CYGNUS-10 m³ module



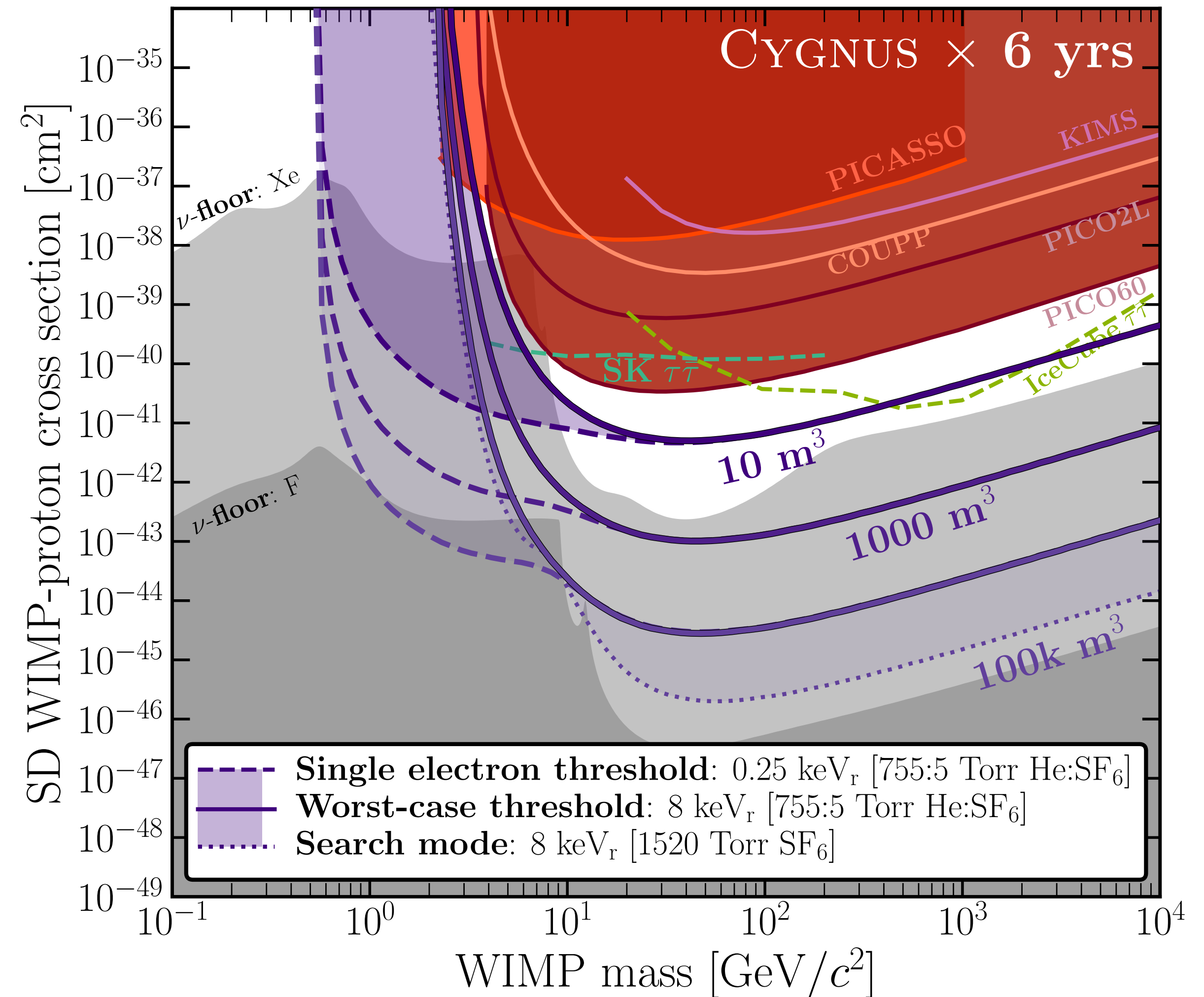
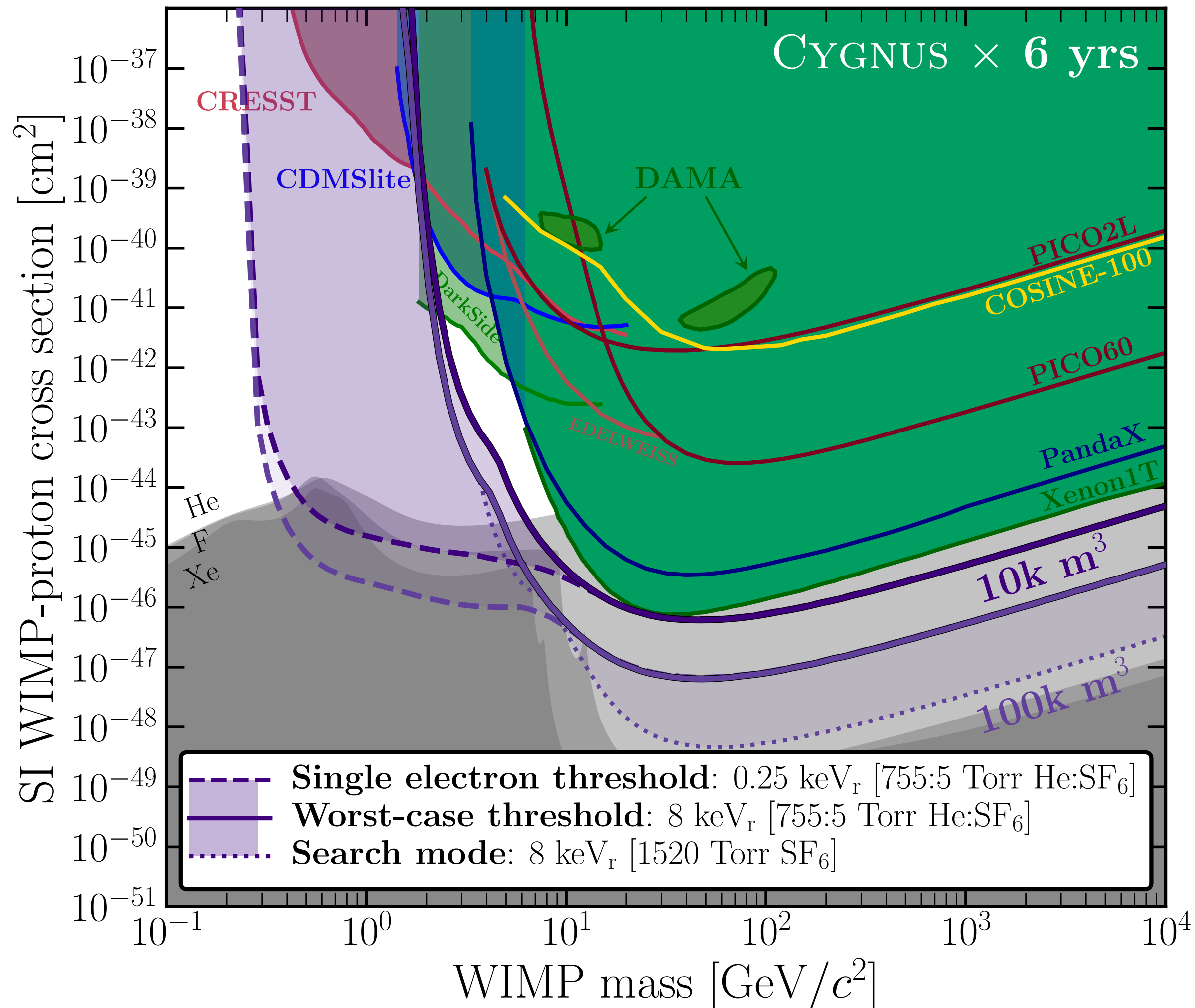
Possible gases:

He, SF₆, CF₄

Can potentially
operate at
atmospheric
pressure and
temperature

Cygnus: projected sensitivity

Target gas, volume, and threshold are still under investigation, but there is scope for world-leading limits even with a 10 m³ scale experiment (~2025–2030)

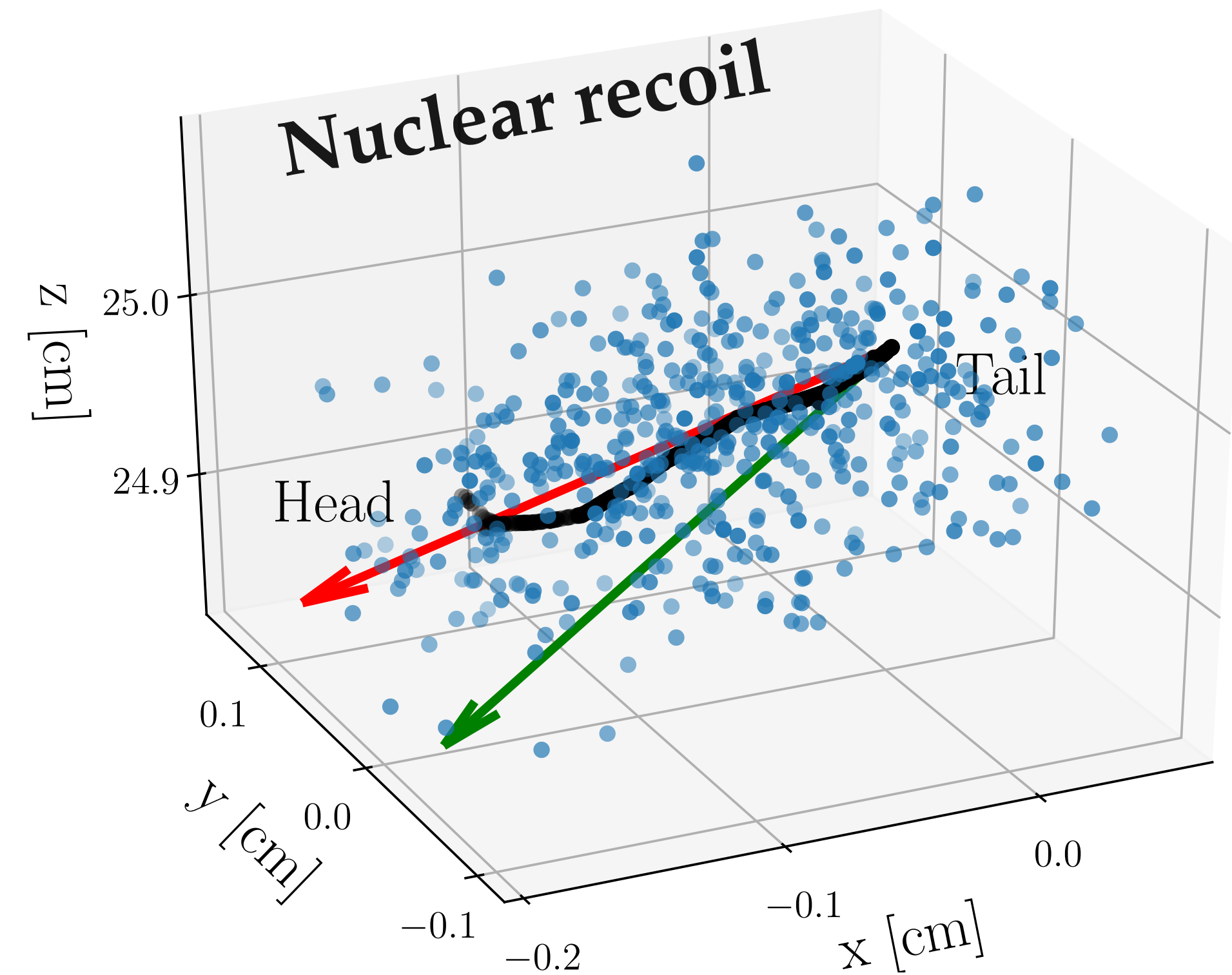
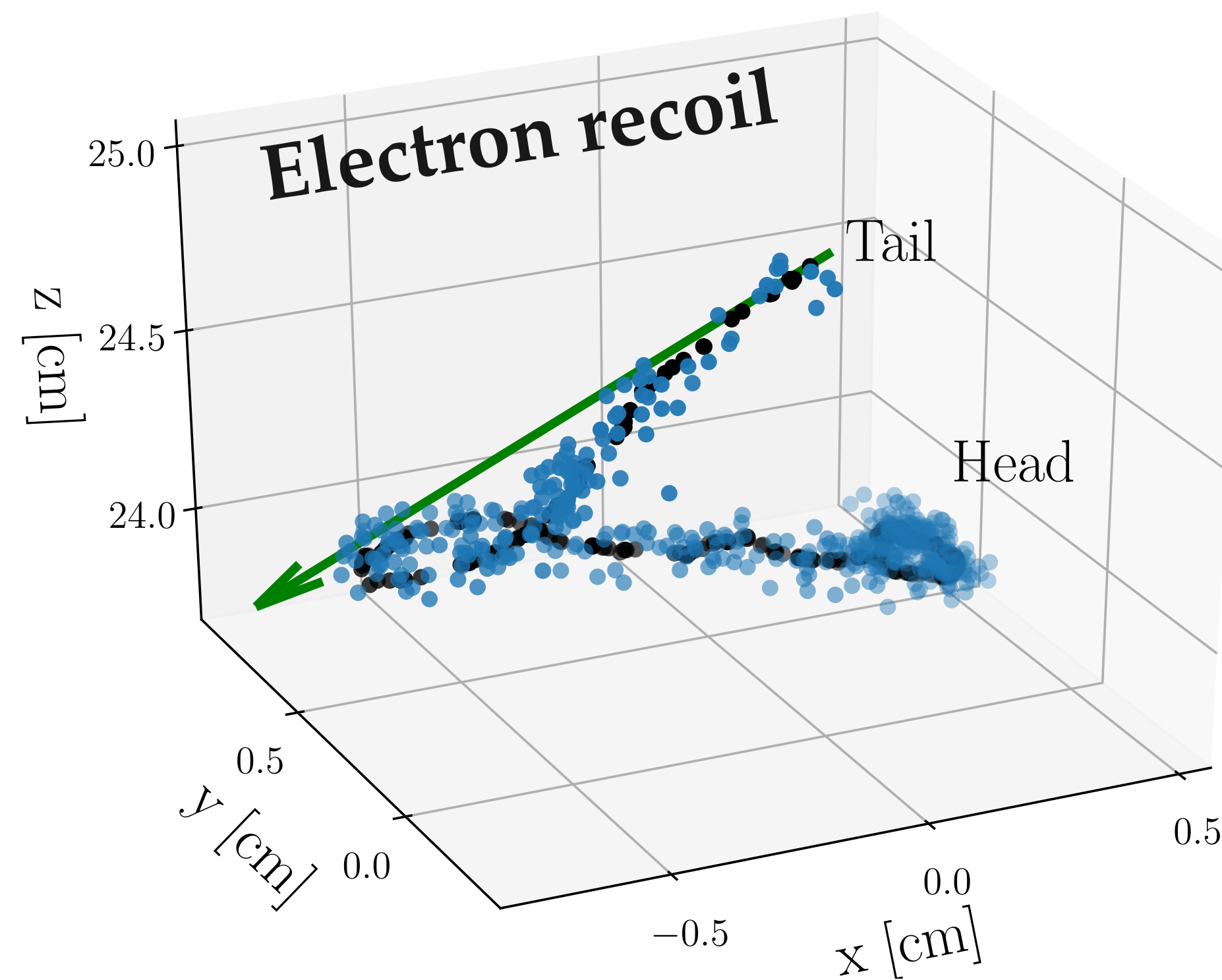


Directionality in TPCs, beyond nuclear recoils

Gas TPCs can measure the directions of both electron recoils and nuclear recoils.

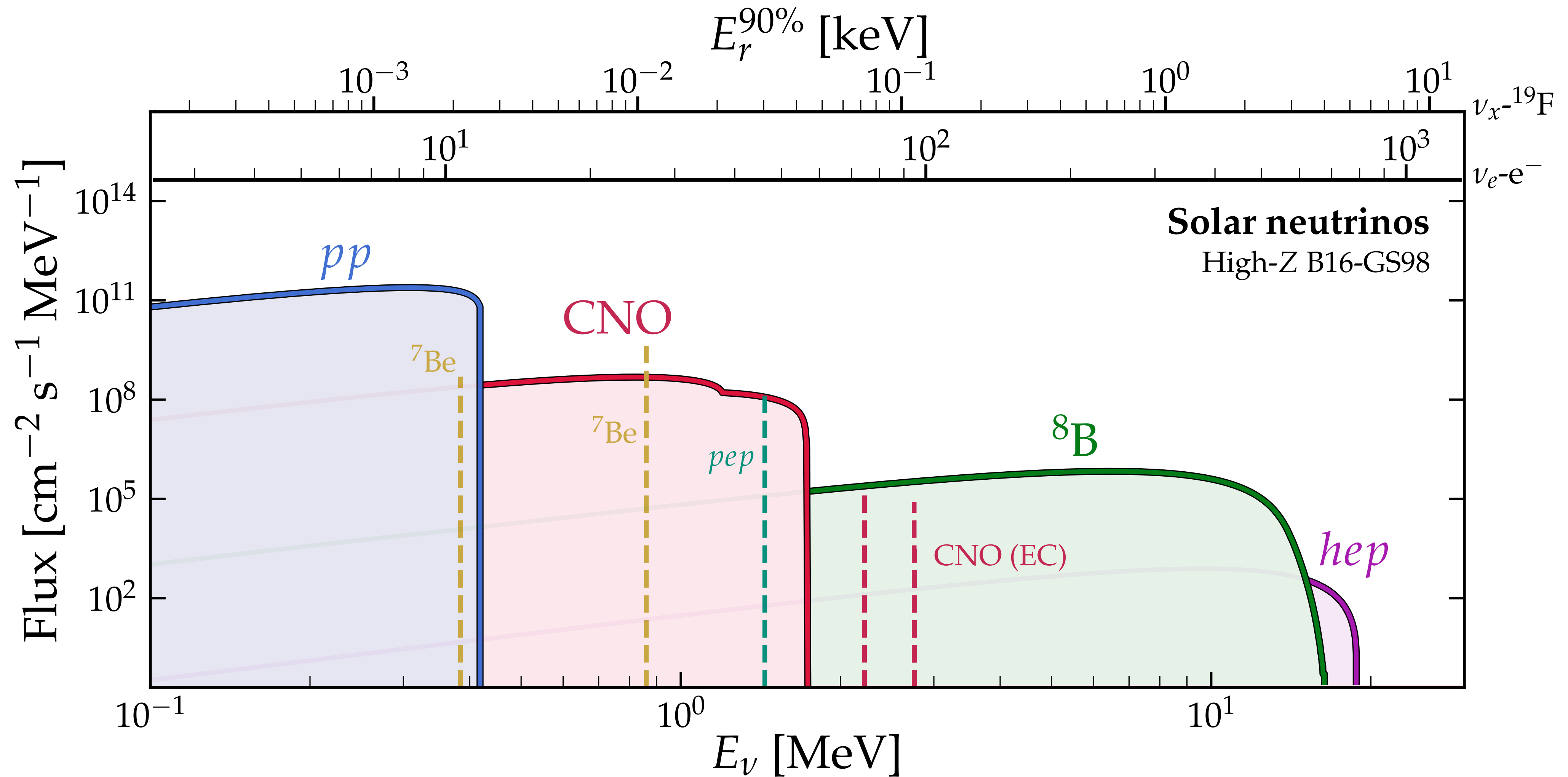
The directionality and track shapes also help distinguish between them

→ Is there other physics we can do?



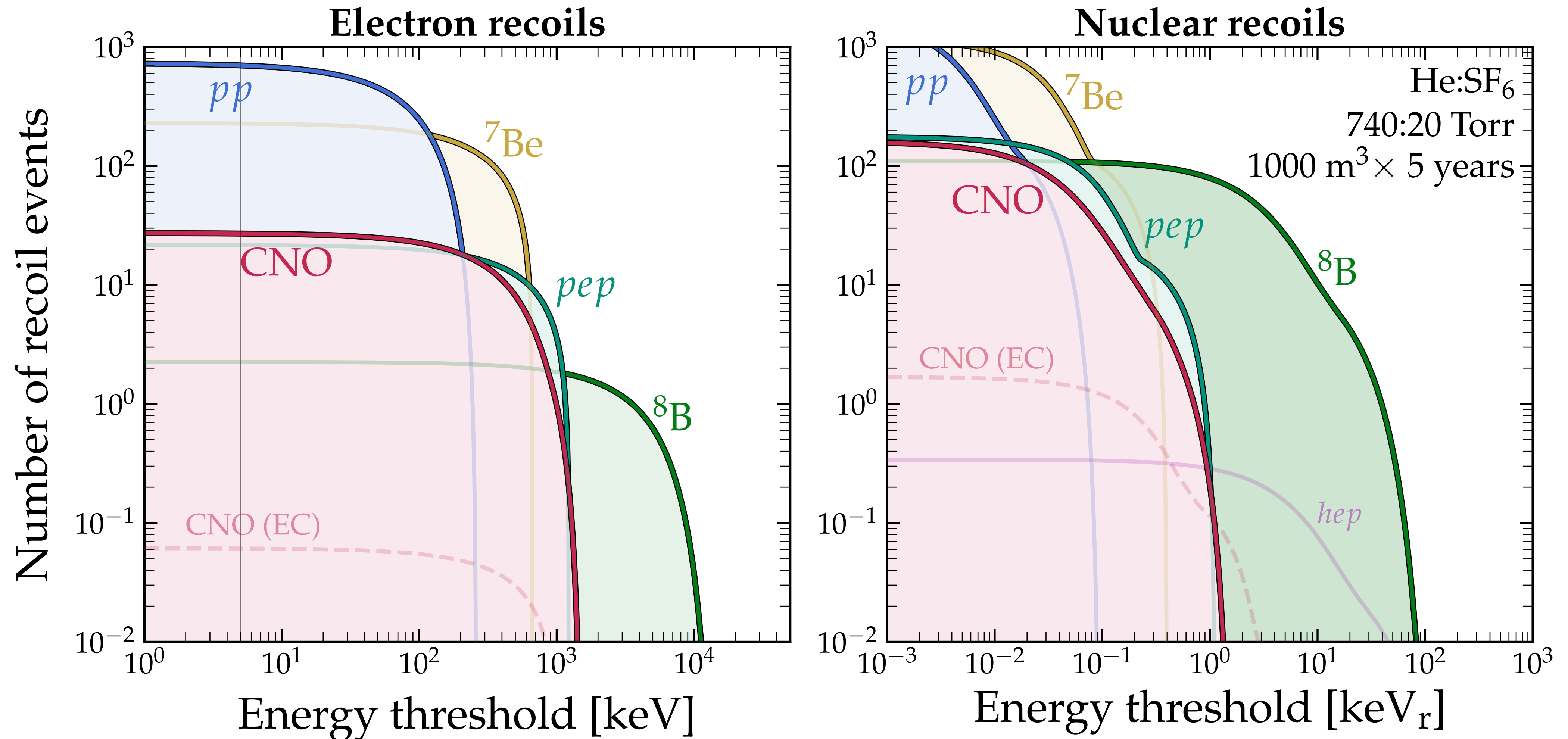
Thinking beyond dark matter

Solar neutrinos can scatter off electrons and nuclei $\rightarrow$ detectors have both!

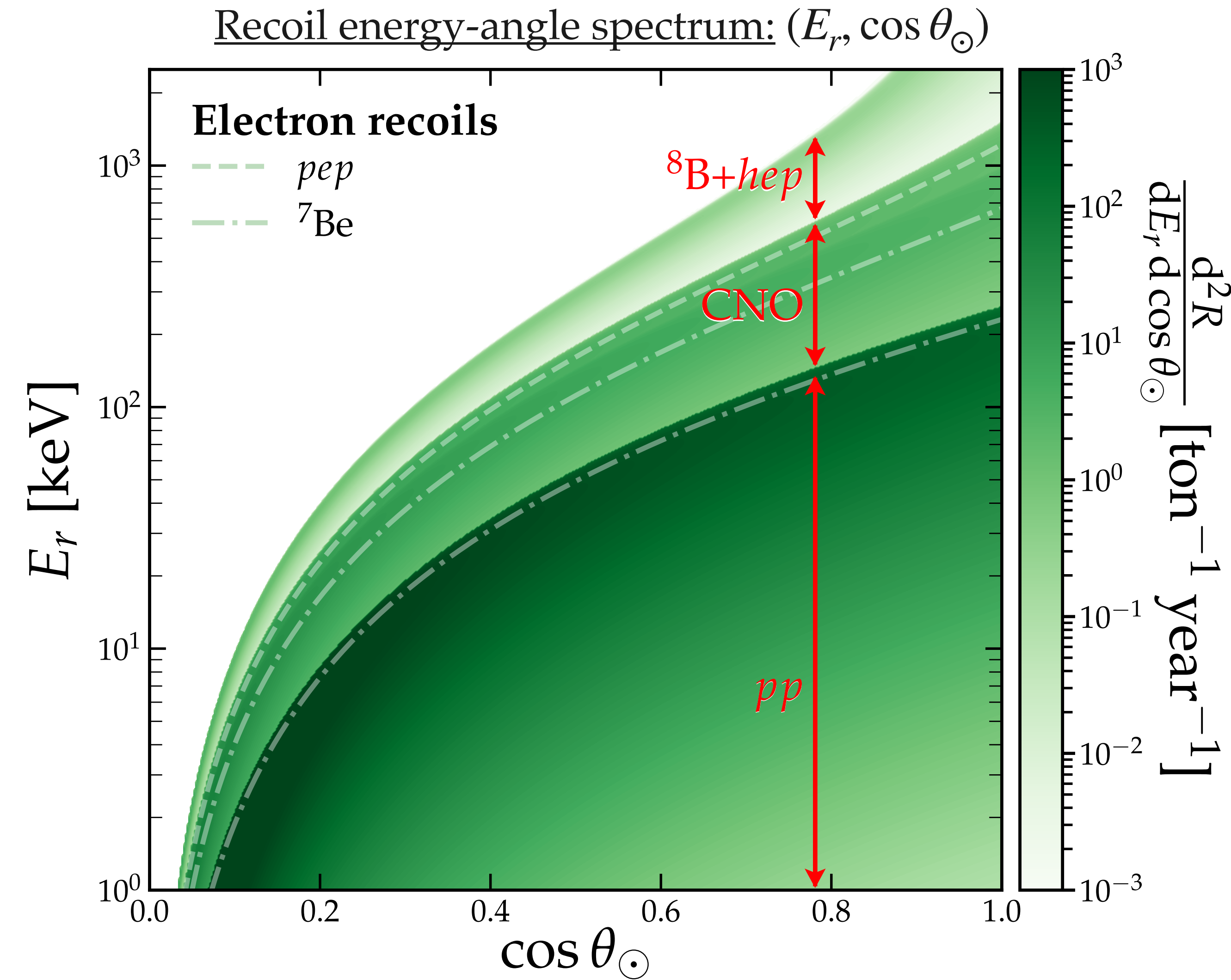


Thinking beyond dark matter

A directional detector could measure the directions of solar neutrino-induced recoils in both electronic and nuclear channels. ERs potentially provide a lot more events than CE ν NS, and at more accessible energies.



CYGNUS for neutrinos?



Given known direction to the Sun, directional information allows one to reconstruct the neutrino energy spectrum event-by-event

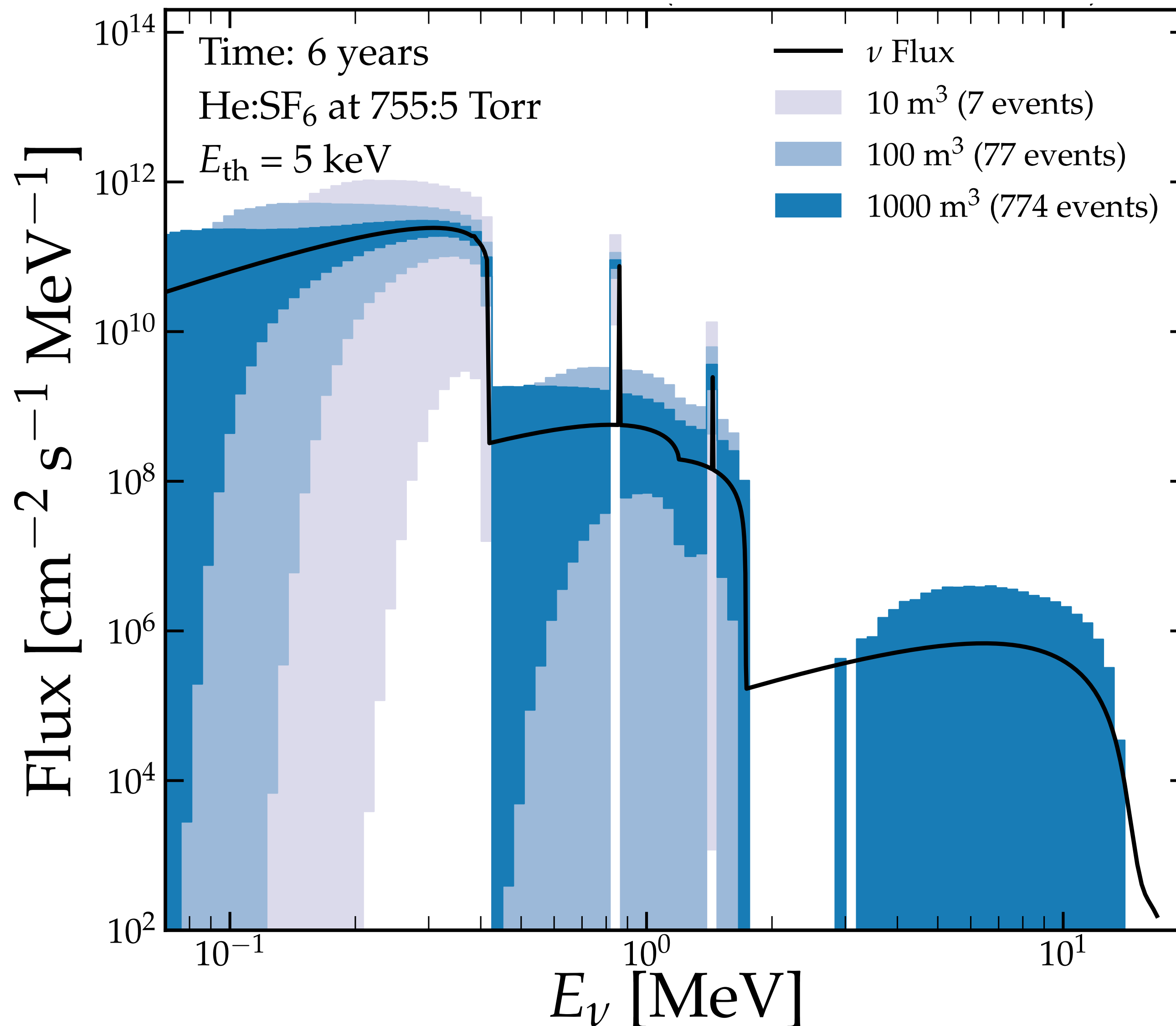
$$\cos \theta_\odot = \hat{\mathbf{q}}_r \cdot \hat{\mathbf{q}}_\odot = \frac{E_\nu + m}{E_\nu} \sqrt{\frac{E_r}{E_r + 2m}}$$

Measure recoil energies and angles



Empirically measure flux, $\Phi(E_\nu)$

The dream: Empirical flux reconstruction



- O(10) m³ accesses only *pp*
- O(100) m³ accesses *pp*, ⁷Be, CNO
- O(1000) m³ access all fluxes except *hep*



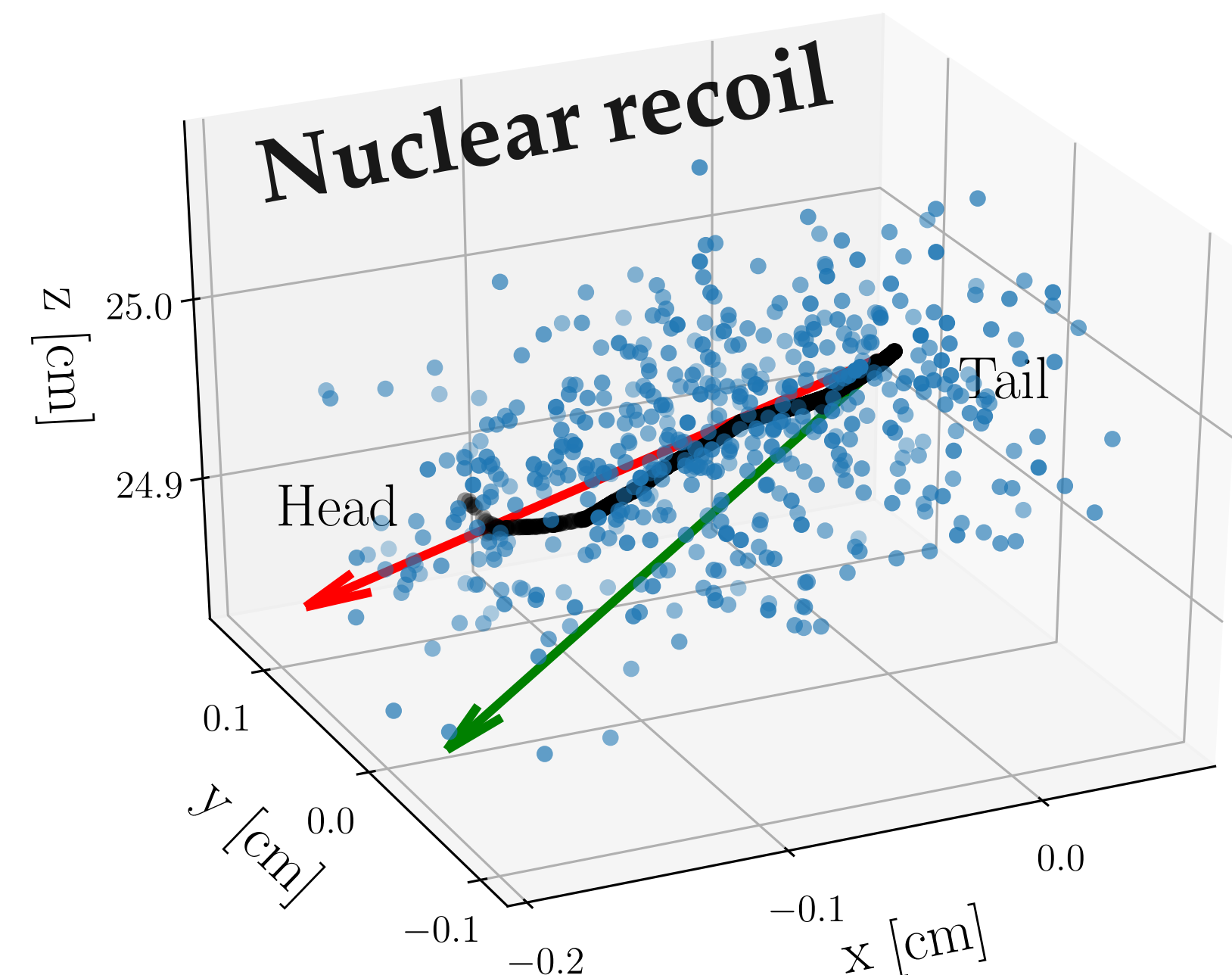
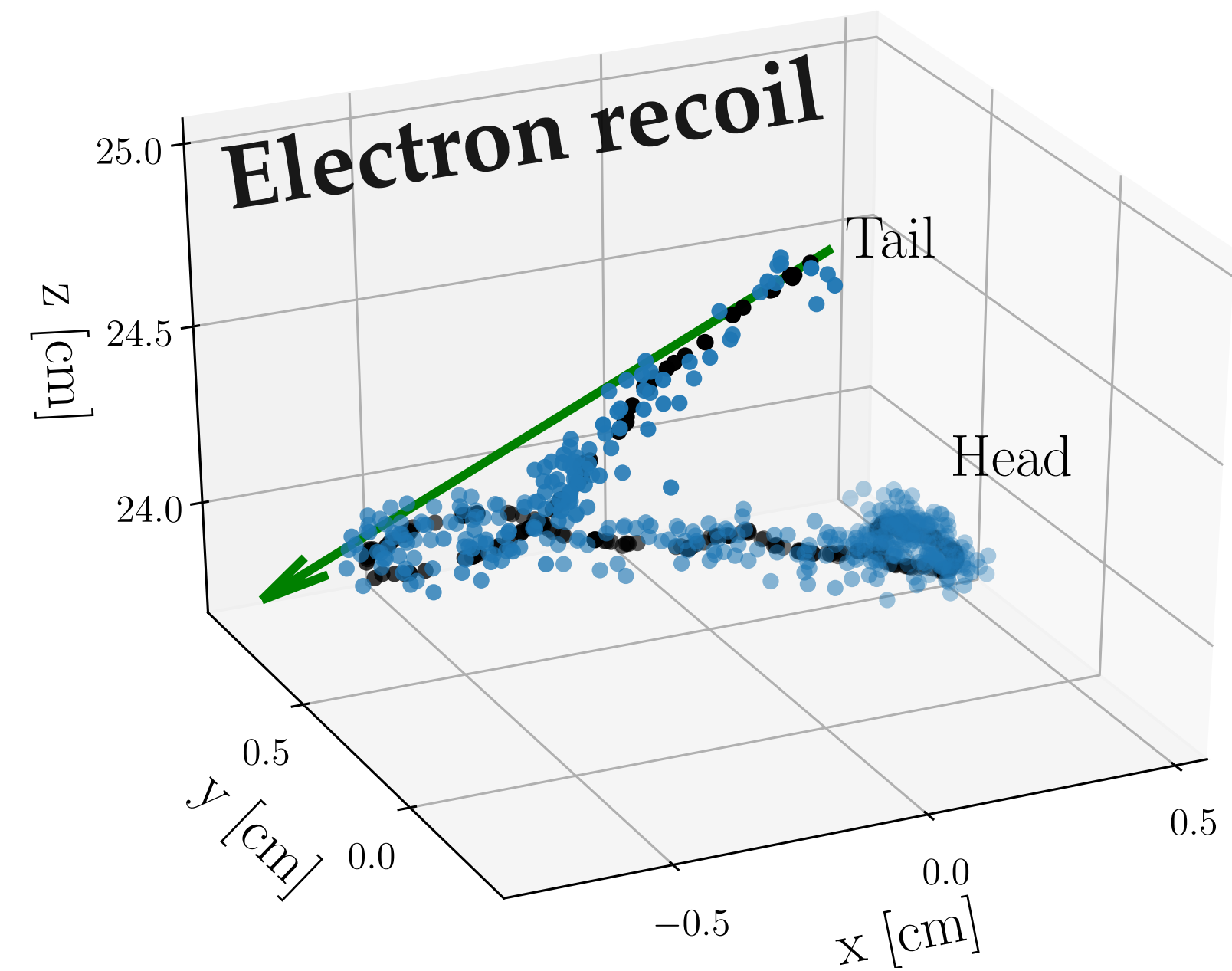
Potentially less in fact. This assumes 755:5 Torr He:SF₆ which is good for ~10 keV NRs but >100 keV ERs may be more tolerant of higher pressures

...Angular performance

Everything gets worse at lower energies:

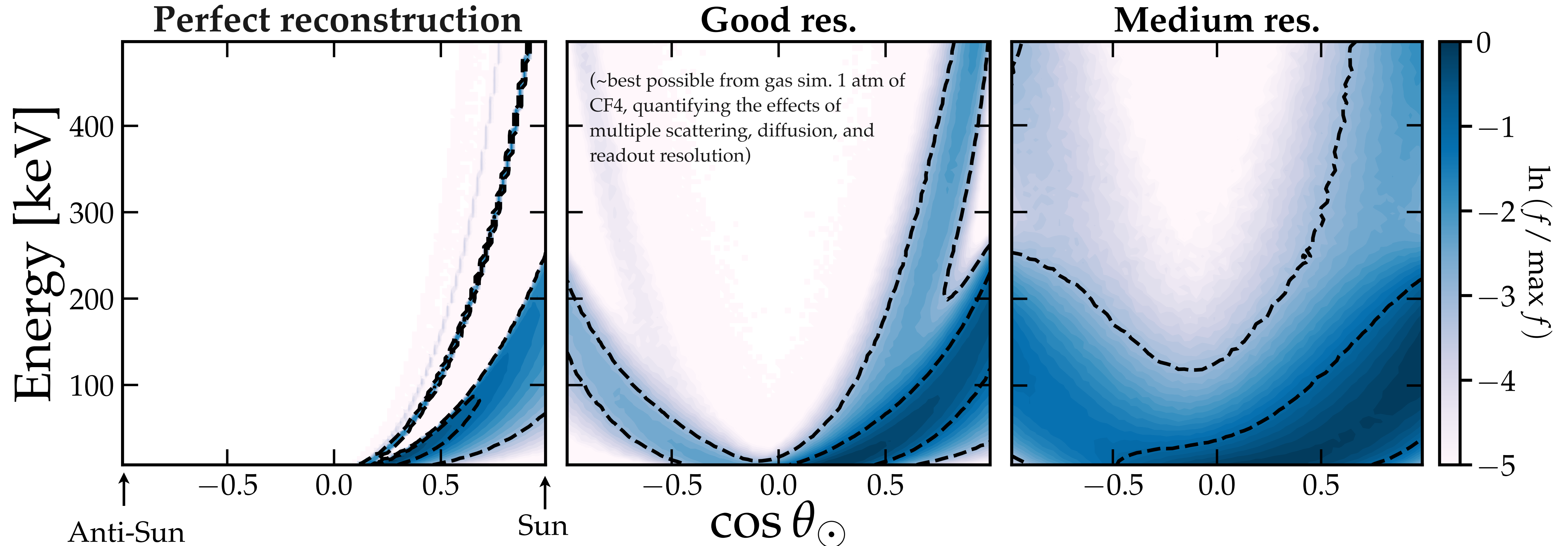
- Decreasing quenching factor, means recoils are harder to detect
- Tracks get shorter $\rightarrow$ harder to measure directions
- Contrast in dE/dx is lower, harder to measure head-tail
- All this makes it harder to distinguish ER/NRs, so worse background rejection

$\rightarrow$ **Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals**



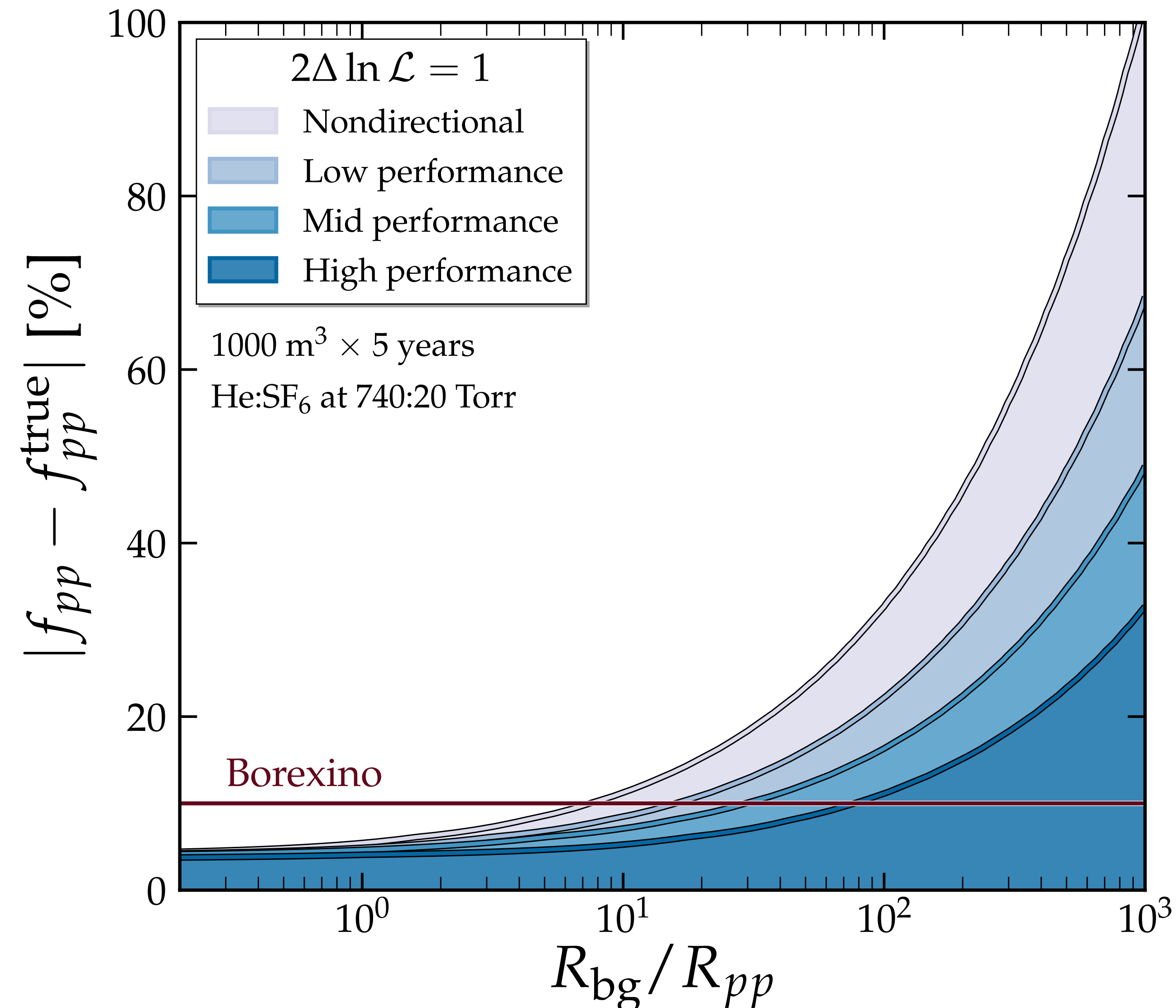
Impact of energy/angular resolution on measuring solar neutrino energies

- **Perfect** reconstruction (for reference purposes)
- **“Good”** resolution, $\sigma/E \sim 5\%$, $\sigma_\theta \sim 15^\circ$ and $\epsilon_{\text{HT}} \sim 0.9$ → close to best possible
- **“Medium”** resolution, $\sigma/E \sim 10\%$, $\sigma_\theta \sim 30^\circ$ and $\epsilon_{\text{HT}} \sim 0.75$ → optimistic



Another key issue → background rate

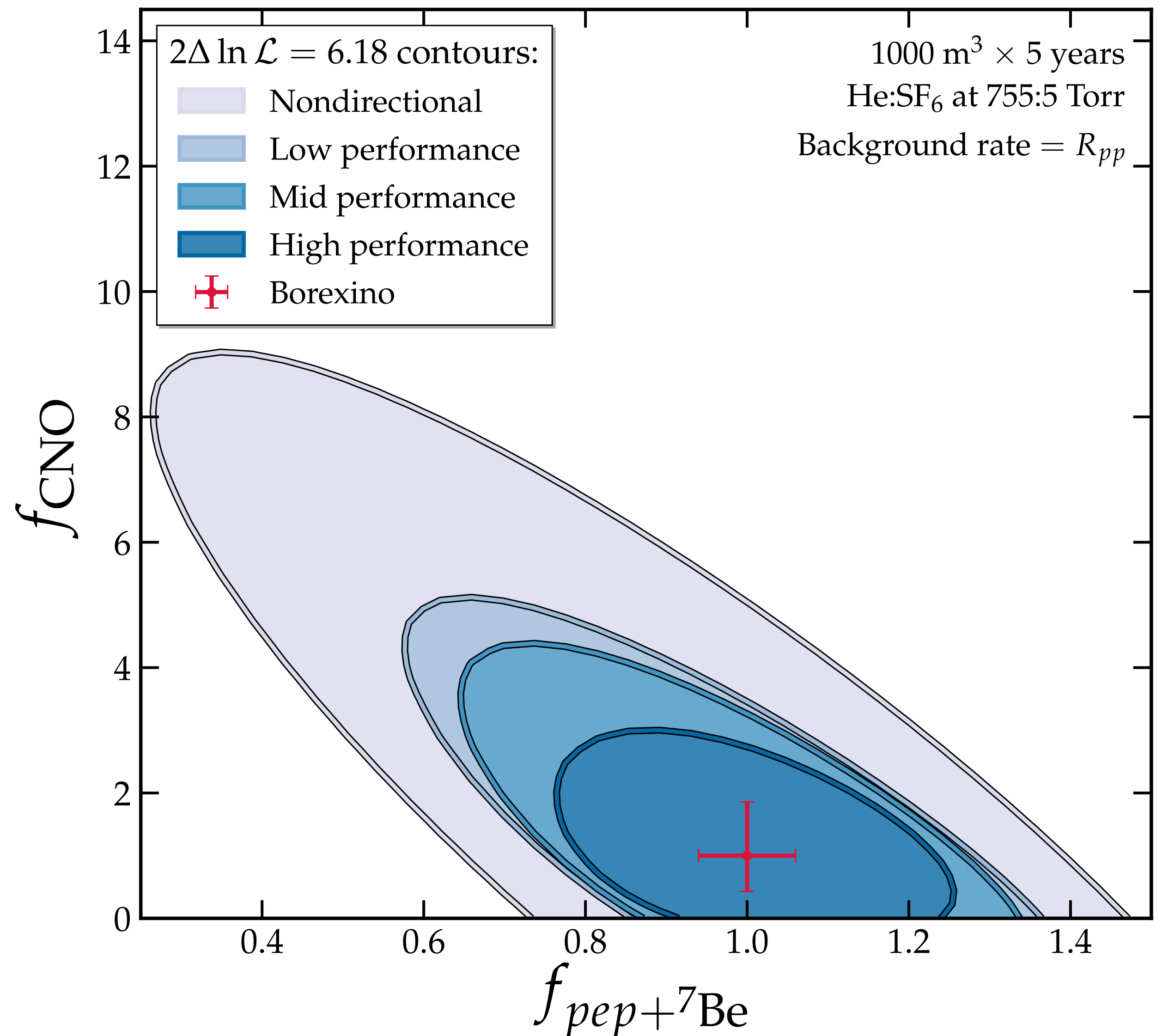
- A directional experiment can tolerate higher background, however Solar neutrino sensitivity (e.g. accuracy of pp flux reconstruction) crucially dependent on size of electron background (which is typically large)
- Using pp ER rate as a reference point, competitive sensitivity achievable even with background ~ 10 – 100 times higher than # neutrinos
- Electron backgrounds at ~ 100 keV energies not well studied in gas TPCs as they are irrelevant for DM, however CYGNO study suggests this is still a little too high



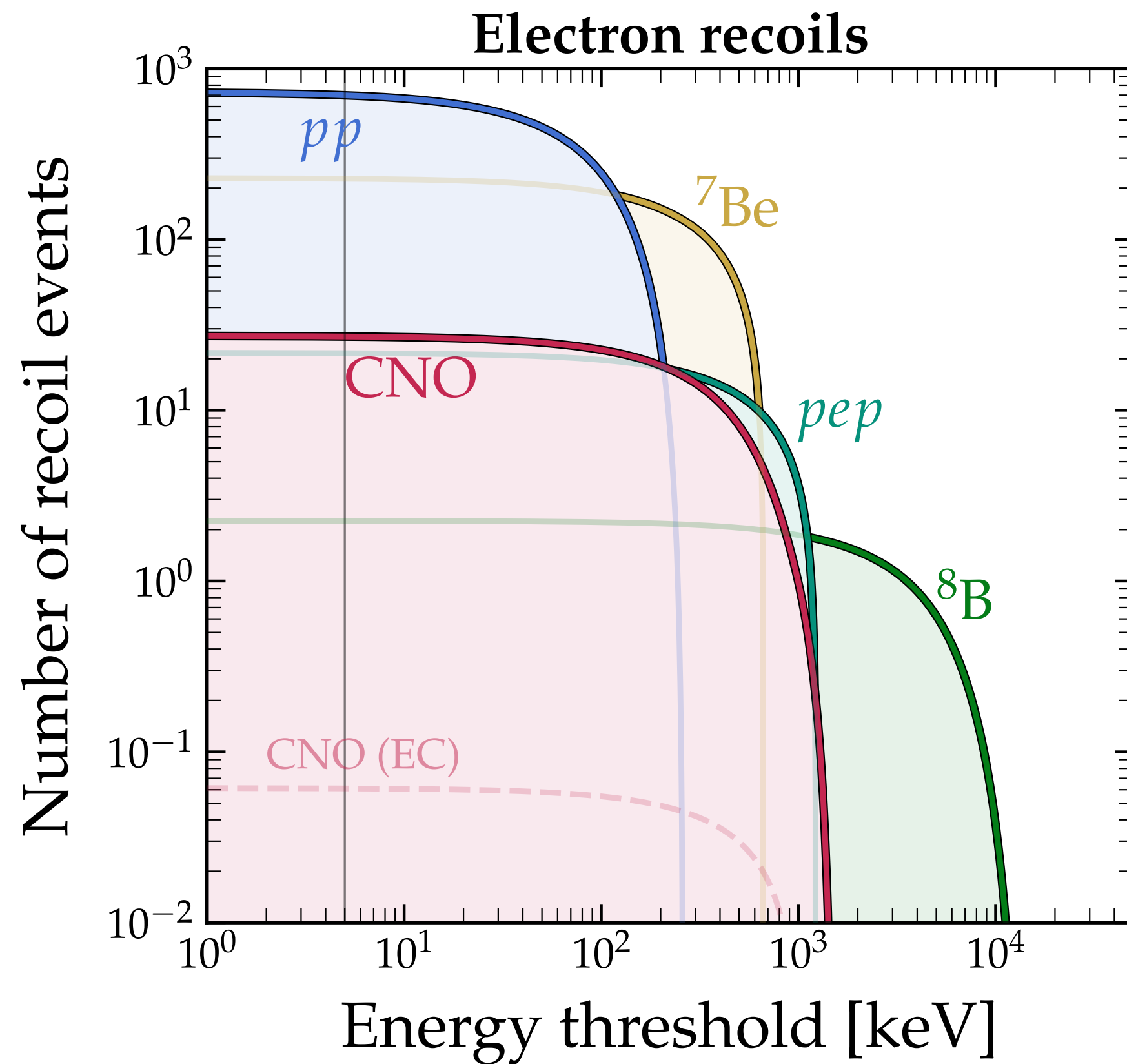
Solar neutrino spectroscopy

- Assuming optimistic configuration: CYGNUS-1000 with a good directional sensitivity on ~ 100 keV ERs, and isotropic backgrounds at a similar level to the neutrino rate

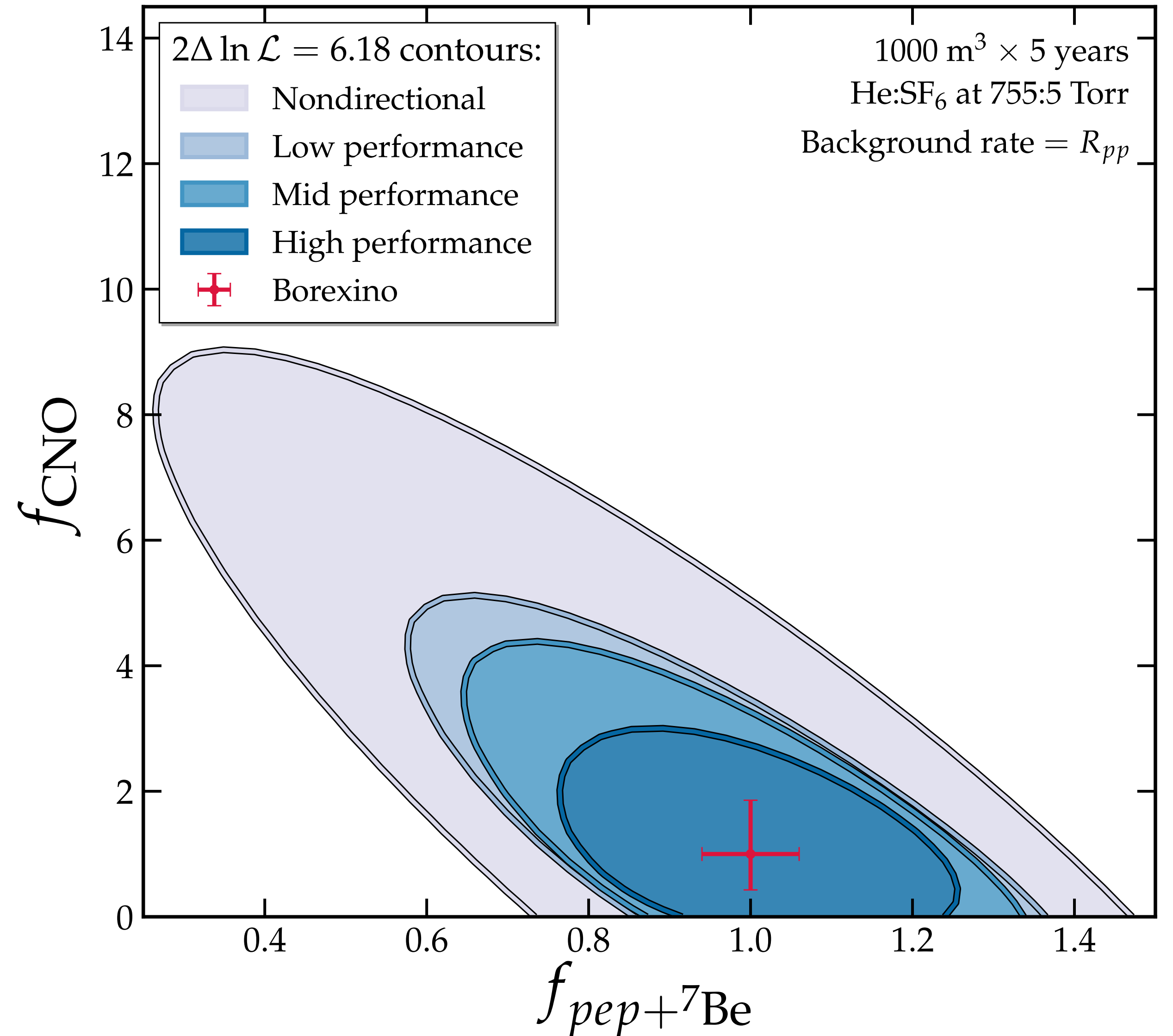
→ Potentially complementary to experiments like Borexino due to the fact that directionality enables reconstruction of fluxes that are degenerate with each other in recoil energy (e.g. CNO vs pep flux)



Solar neutrino spectroscopy

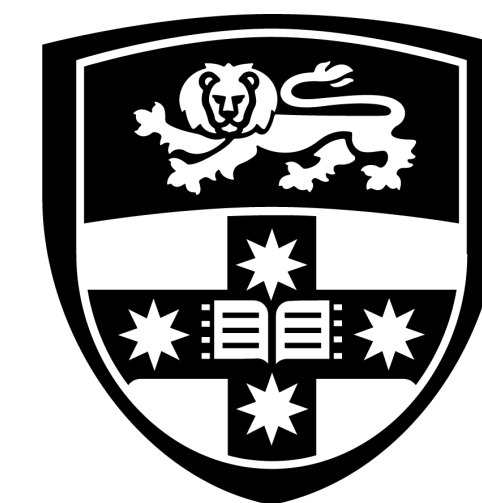


NB: not intending on beating Borexino! These measurements will be complementary, and (hopefully) *in addition* to DM detection



Summary

- The neutrino fog looms.
- Directionality is a smoking gun signature that could be used to most efficiently probe further into the neutrino fog, if it can be realised at scale.
- Cygnus is making steady progress towards a competitive network of modular gas time projection chambers. Important experimental milestones coming in the next few years.
- 3d, time-resolved tracks with head-tail should be the ultimate goal. Any limitations in directionality incur a limitation in the distance you can go through the fog.
- Cygnus could potentially one day serve a dual purpose as a DM and neutrino detector, with the ability to distinguish the two signals



THE UNIVERSITY OF
SYDNEY

Further reading (of my own papers...)

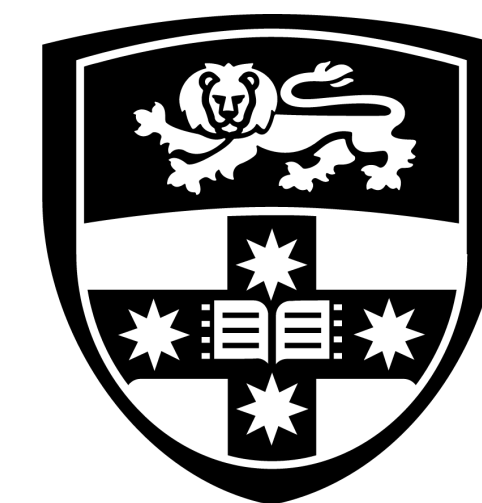
[2102.04596] - a review of directional detection

[2002.07499] - directional detection in Xe / Ar

[2008.12587] - directional detection with gas TPCs

[2105.11949] - directional detection with DNA

[2109.03116] - the neutrino fog



THE UNIVERSITY OF
SYDNEY

Sven E. Vahsen,¹ Ciaran A. J. O'Hare,² and Dinesh Loomba³

¹Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA; email: sevhansen@hawaii.edu
²ARC Centre of Excellence for Dark Matter Particle Physics, The University of Sydney, School of Physics, NSW 2006, Australia; email: ciaran.ohare@sydney.edu.au
³Department of Physics and Astronomy, University of New Mexico, NM 87131, USA, email: dloomba@unm.edu

Annual Review of Nuclear and Particle Science
2021. XX:1–45
This article's doi:
10.1146/annurev-nucl-020821-035016
Copyright © 2021 by Annual Reviews.
All rights reserved

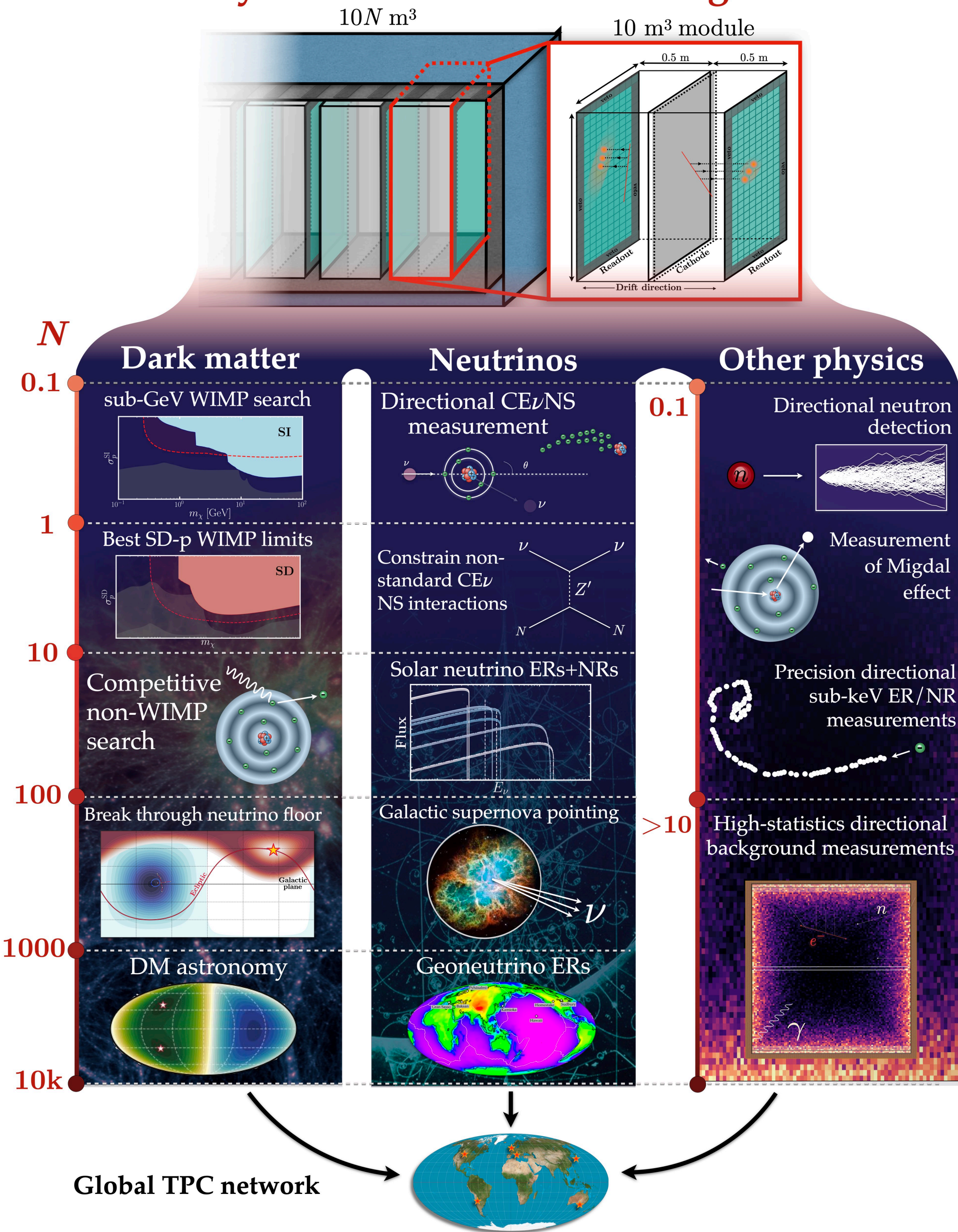
Keywords

nuclear recoils, electron recoils, dark matter, neutrinos, gas time projection chambers, Migdal effect

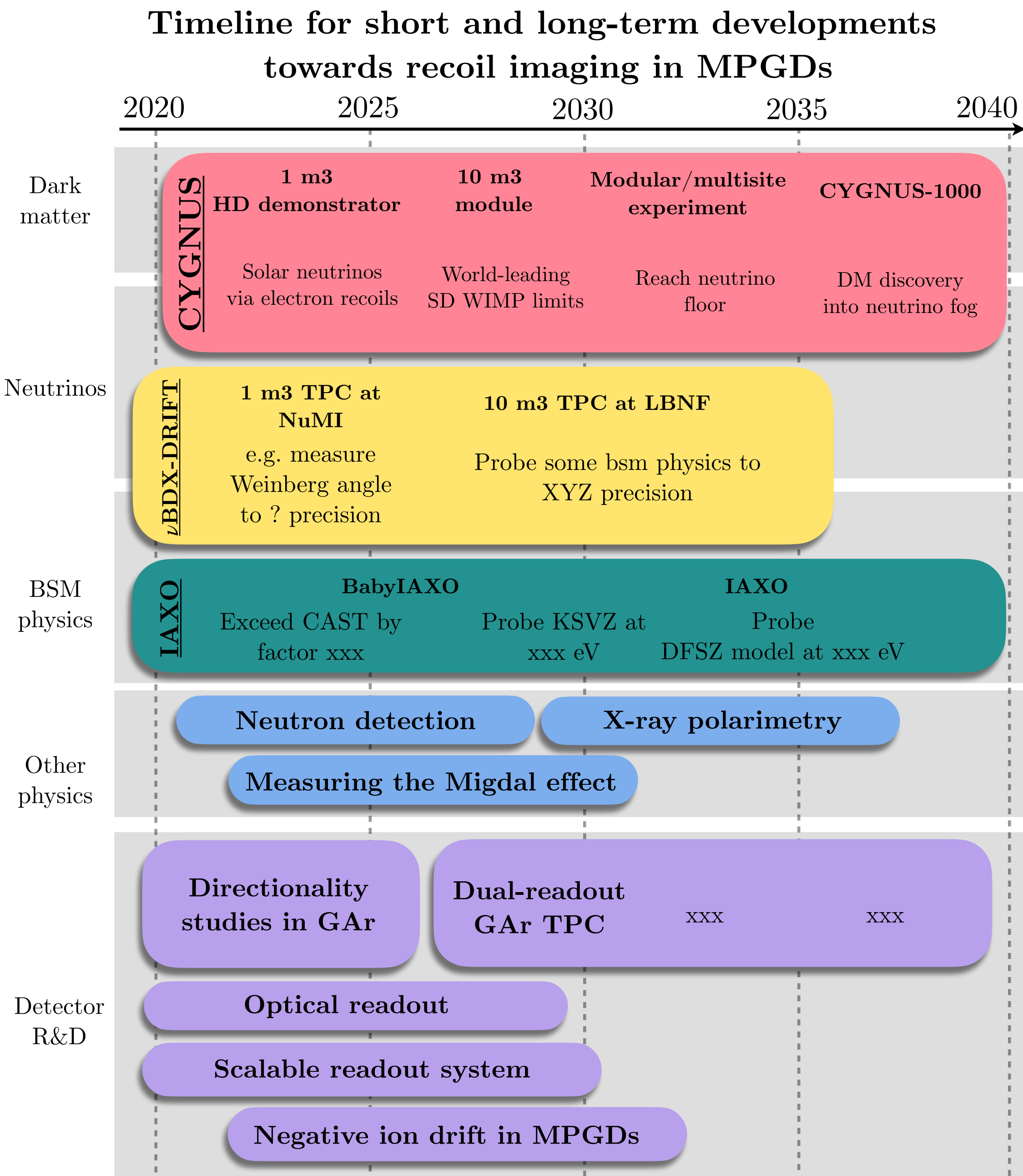
Abstract

Searches for dark matter-induced recoils have made impressive advances in the last few years. Yet the field is confronted by several outstanding problems. First, the inevitable background of solar neutrinos will soon inhibit the conclusive identification of many dark matter models. Second, and more fundamentally, current experiments have no practical way of confirming a detected signal's galactic origin. The concept of directional detection addresses both of these issues while offering opportunities to study novel dark matter and neutrino-related physics. The concept remains experimentally challenging, but gas time projection chambers are an increasingly attractive option, and when properly configured, would allow directional measurements of both nuclear and electron recoils. In this review, we reassess the required detector performance and survey relevant technologies. Fortuitously, the highly-segmented detectors required to achieve good directionality also enable several fundamental and applied physics measurements. We comment on near-term challenges and how the field could be advanced.

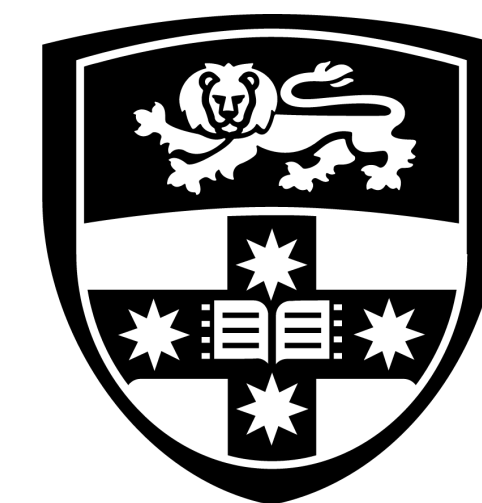
Physics case for a directional gas TPC



Sneak peak...

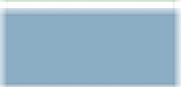
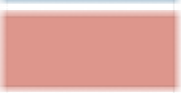


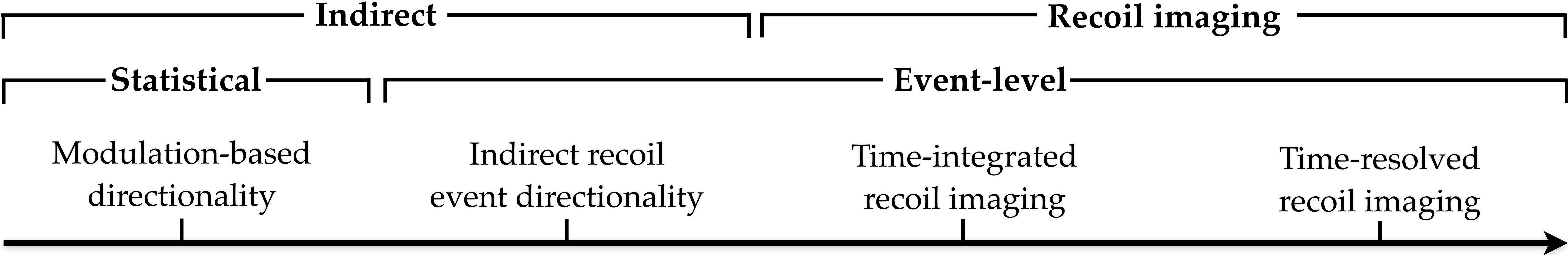
Extra slides



THE UNIVERSITY OF
SYDNEY

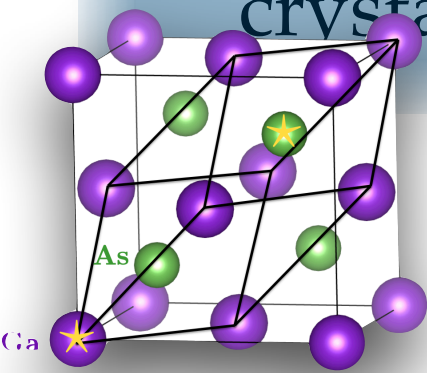
Detector classes by directional information

Demonstrated 
R&D 
Proposed 



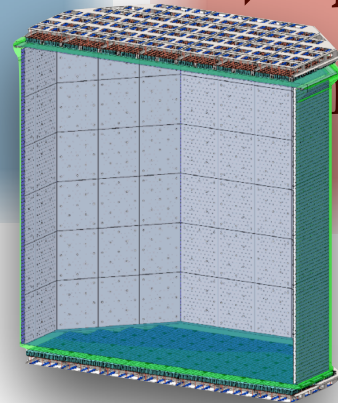
Anisotropic scintillators

- ▶ No event-level directions
- ▶ Exploits modulation of DM with respect to crystal axes



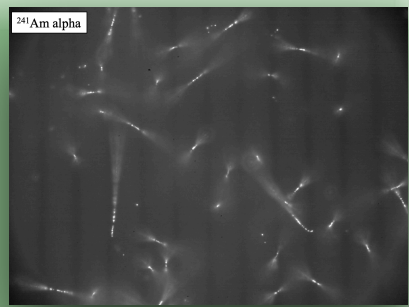
Columnar recombination

- ▶ Event-level 1d directions
- ▶ No head / tail
- ▶ Direction and energy are not independent



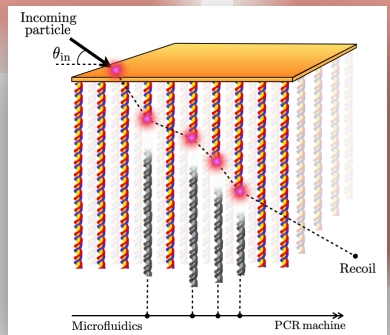
Nuclear emulsions

- ▶ 2d recoil tracks, head / tail
- ▶ No event times information recorded



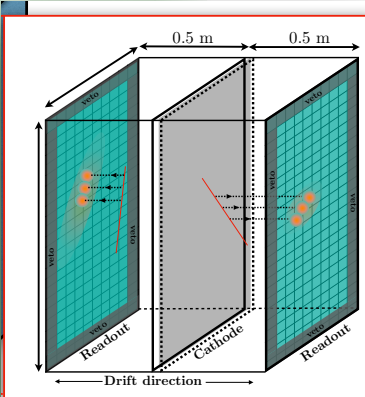
DNA detector

- 3d recoils without head / tail
- No event times recorded



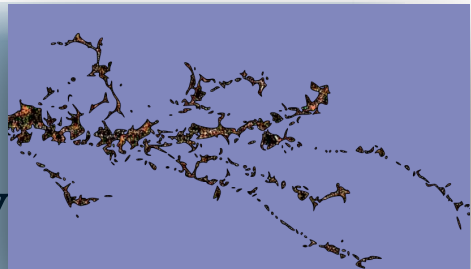
Gas TPC

- ▶ Head / tail measurable
- ▶ 1d, 2d or 3d
- ▶ Independent energy / direction measurement



Crystal defects

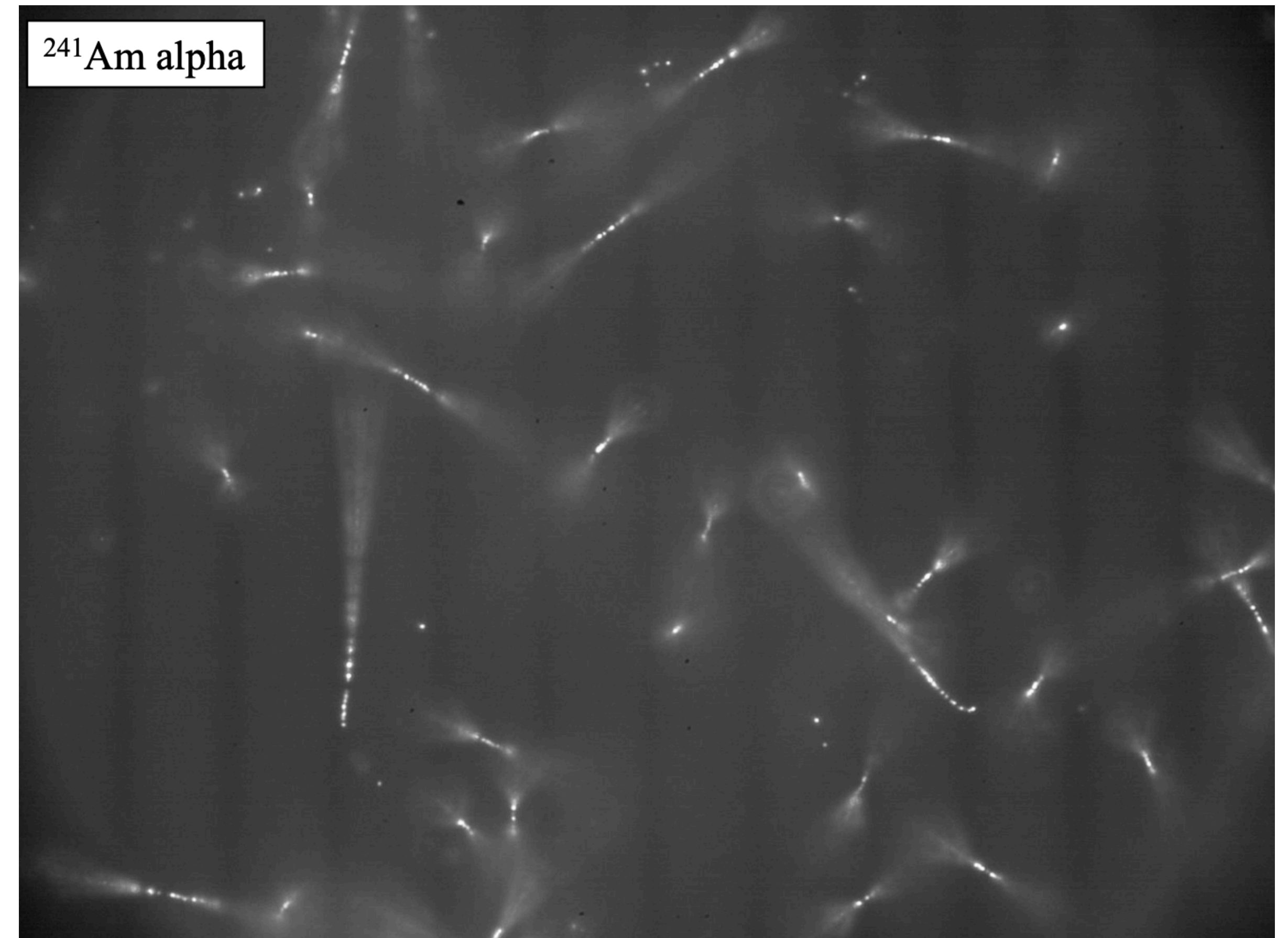
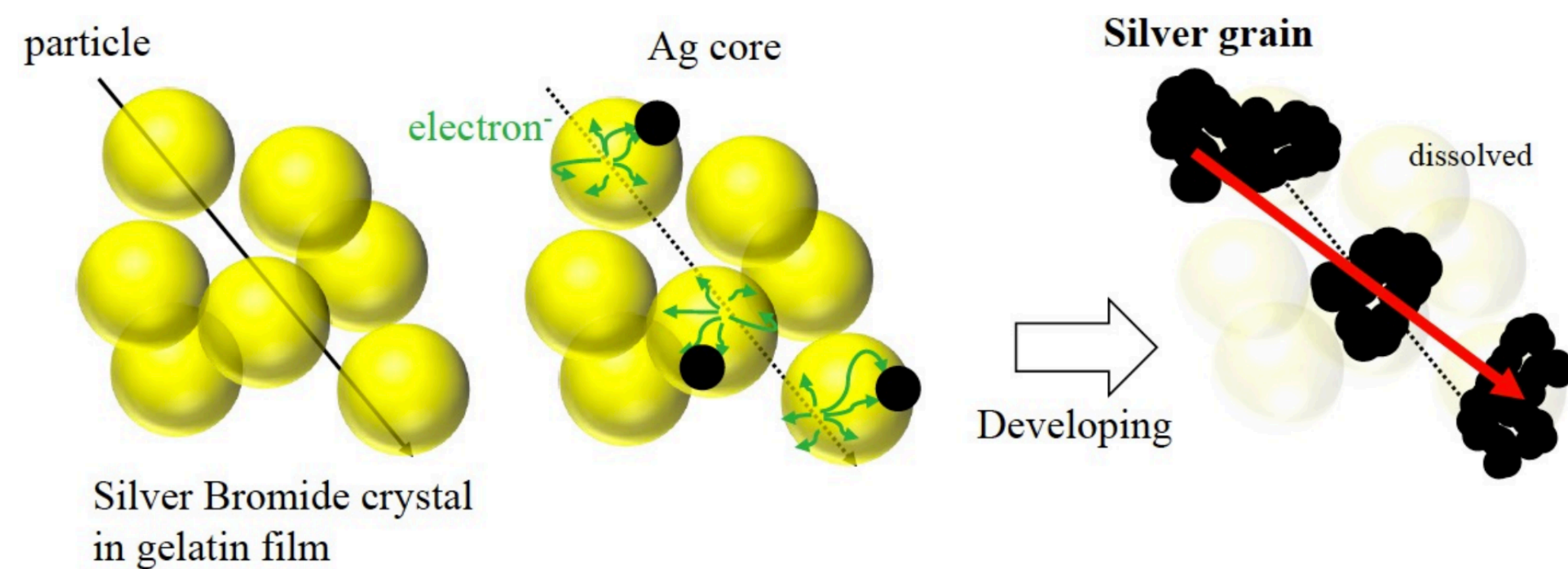
- ▶ 3d track topology
- ▶ Head / tail measurable



Least directionality Distance through the neutrino fog Most directionality

3D tracking in high density targets?

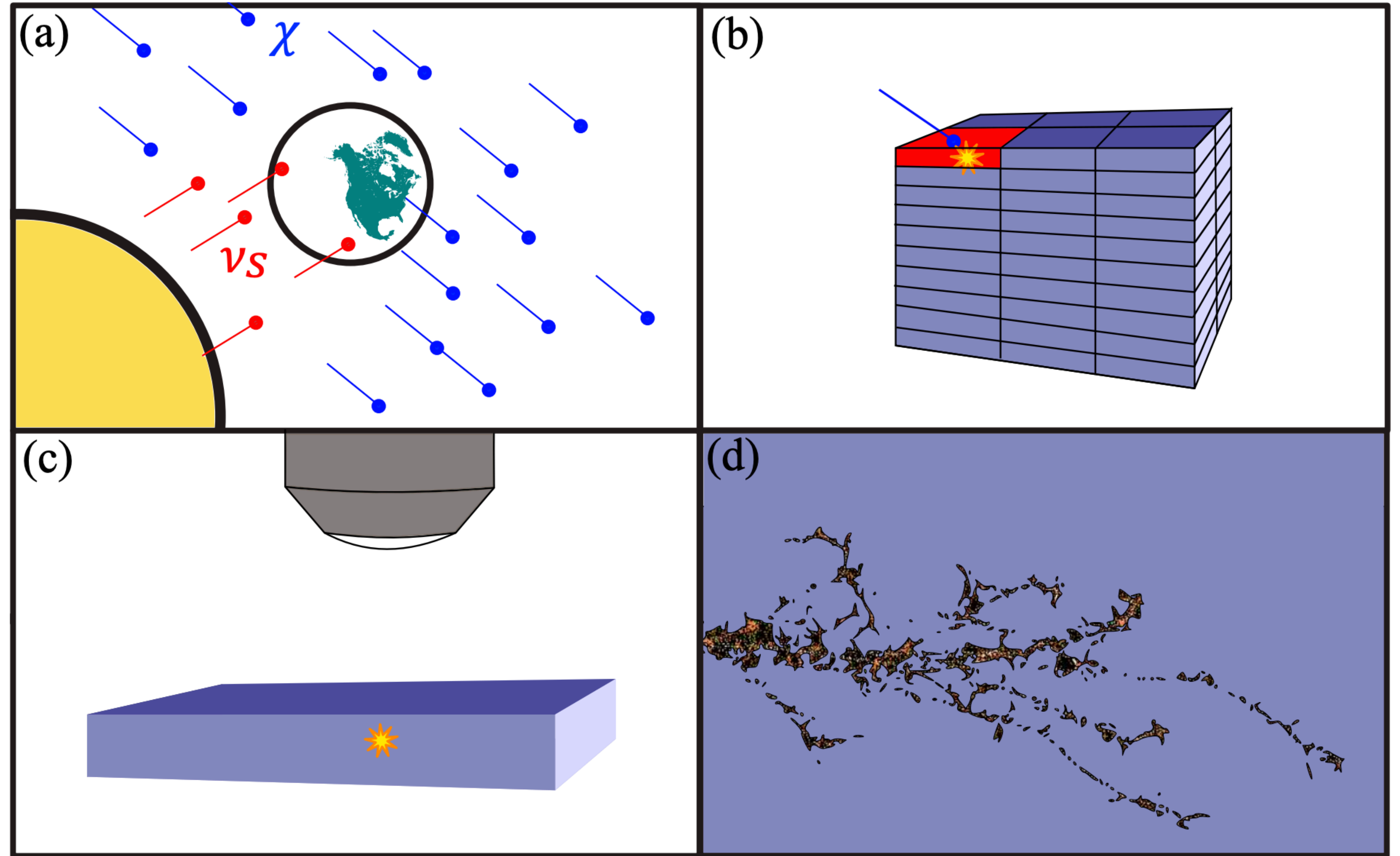
Nuclear emulsions-based
directional detector being pursued
by NEWSdm collaboration
[1604.04199]

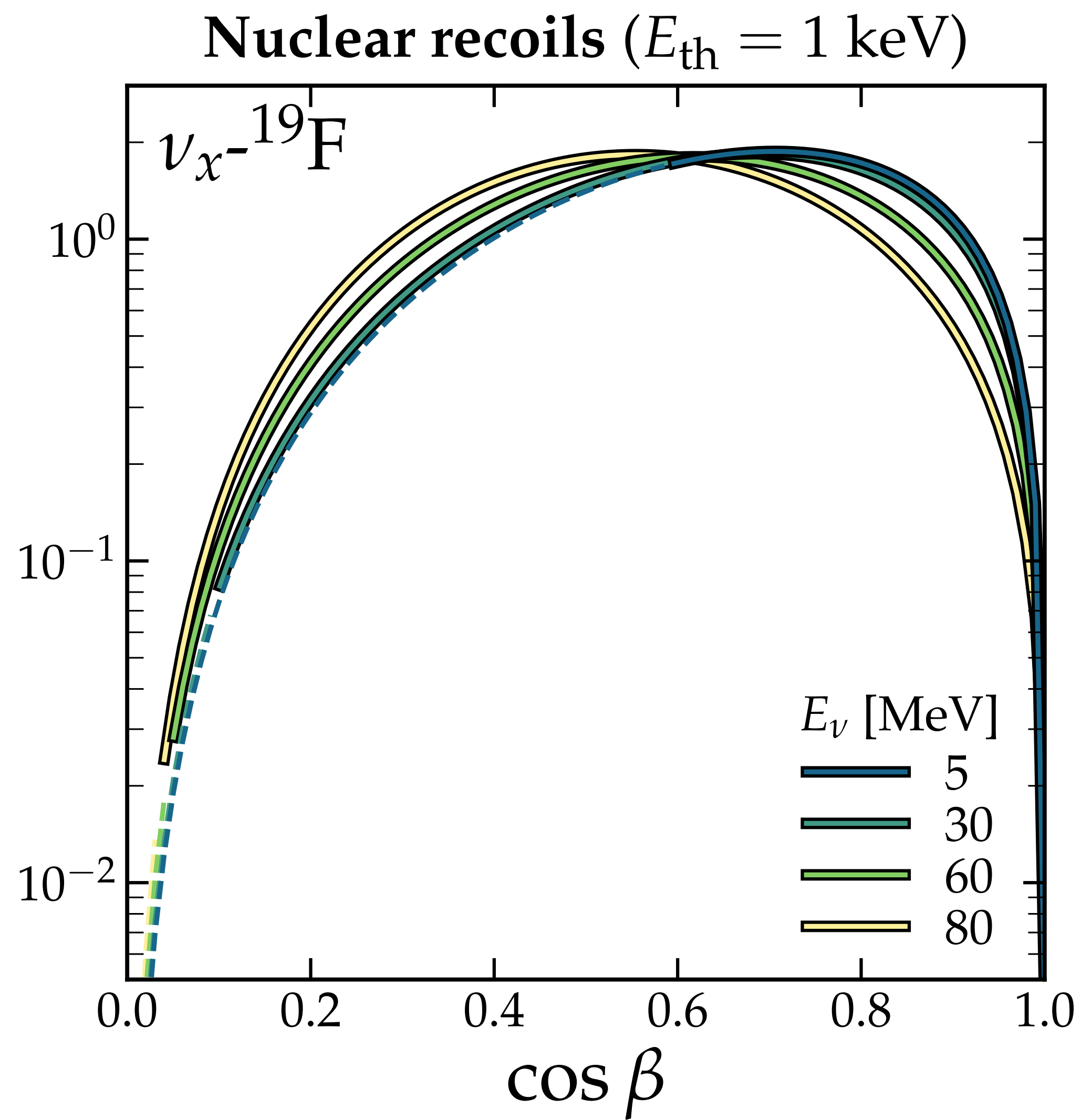
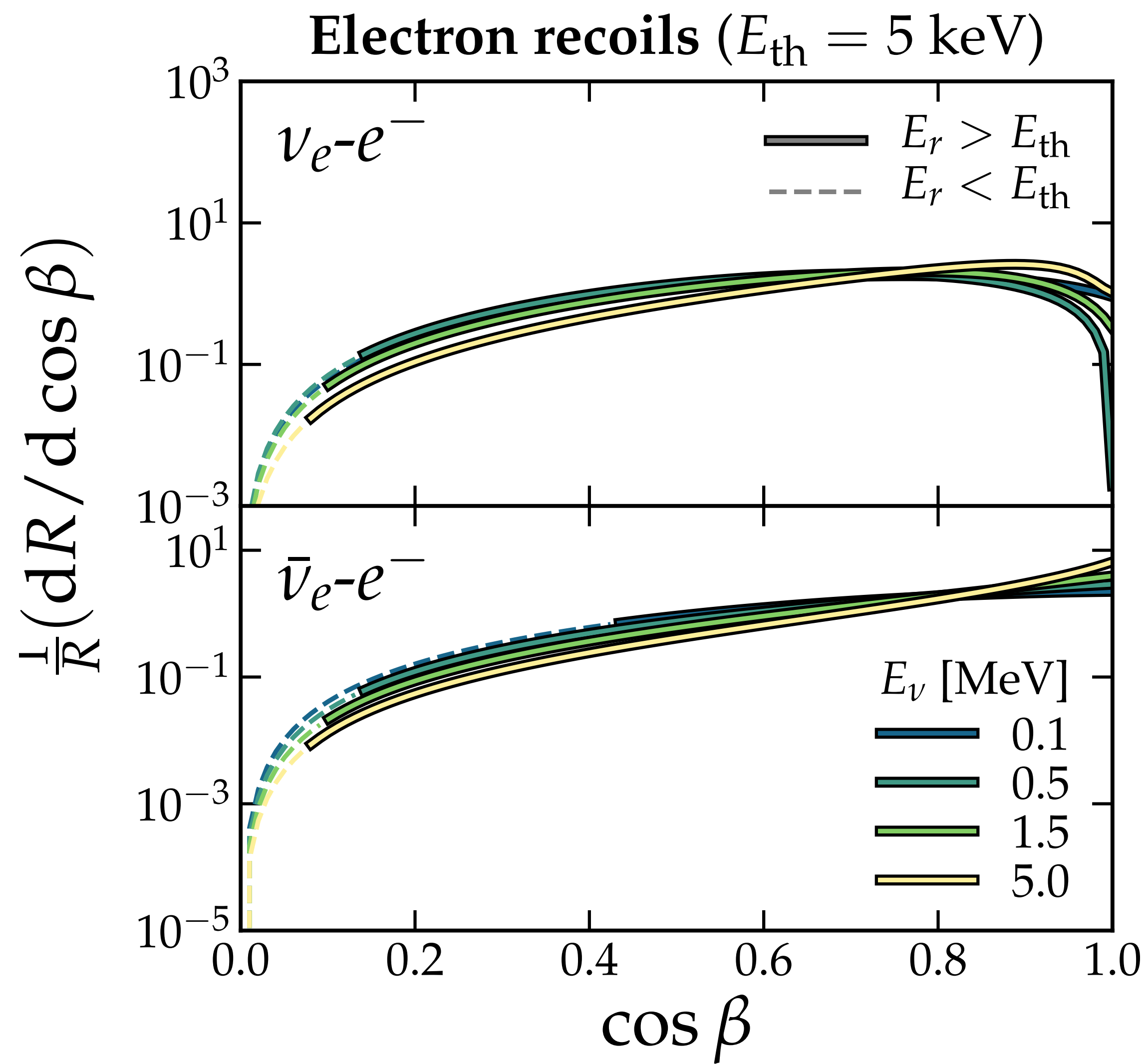


Another idea for a solid target: crystal defect spectroscopy

Marshall+ [2009.01028]

Nitrogen vacancy centres in diamond.
Can spectroscopically interrogate crystal damage to detect tracks

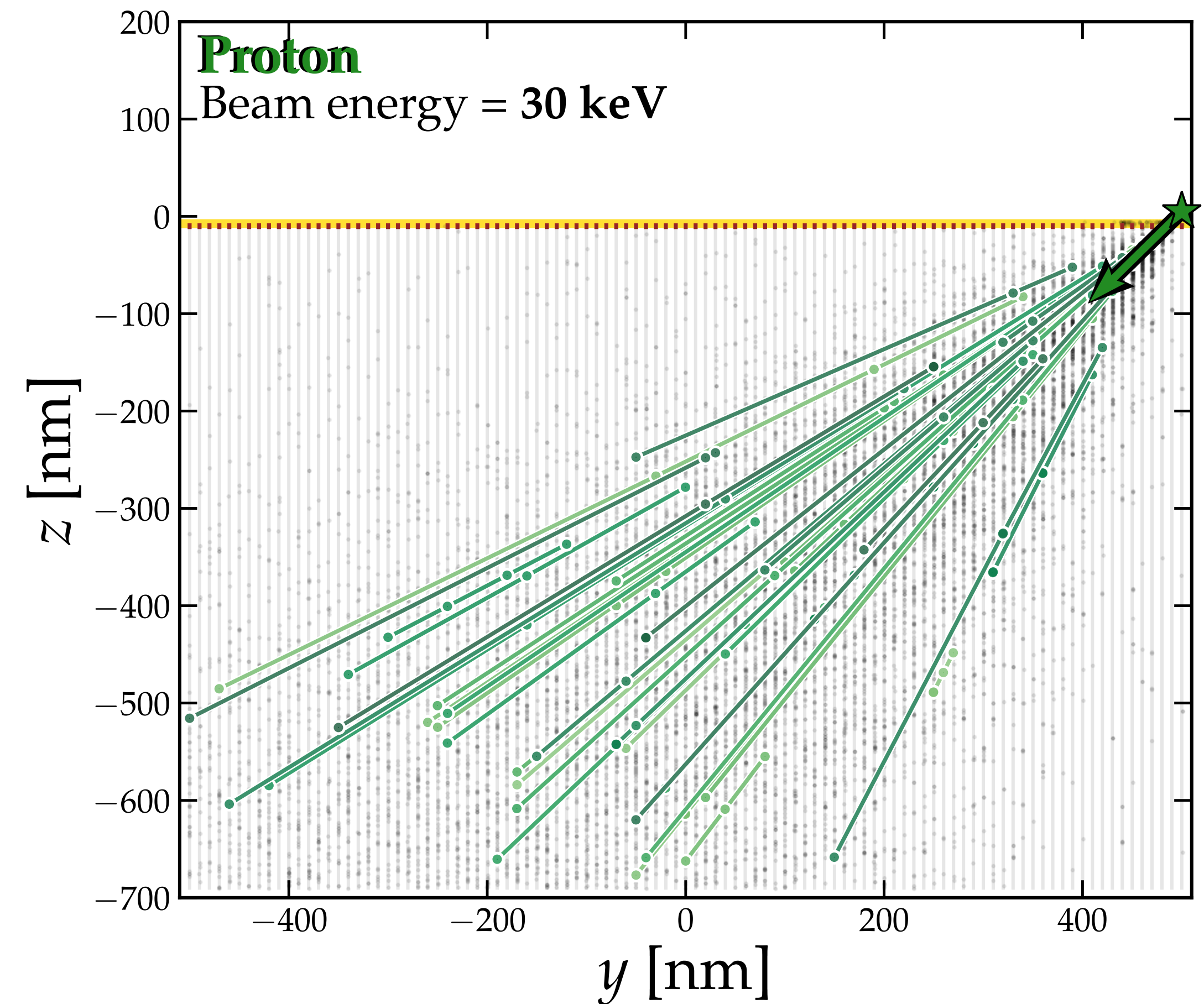
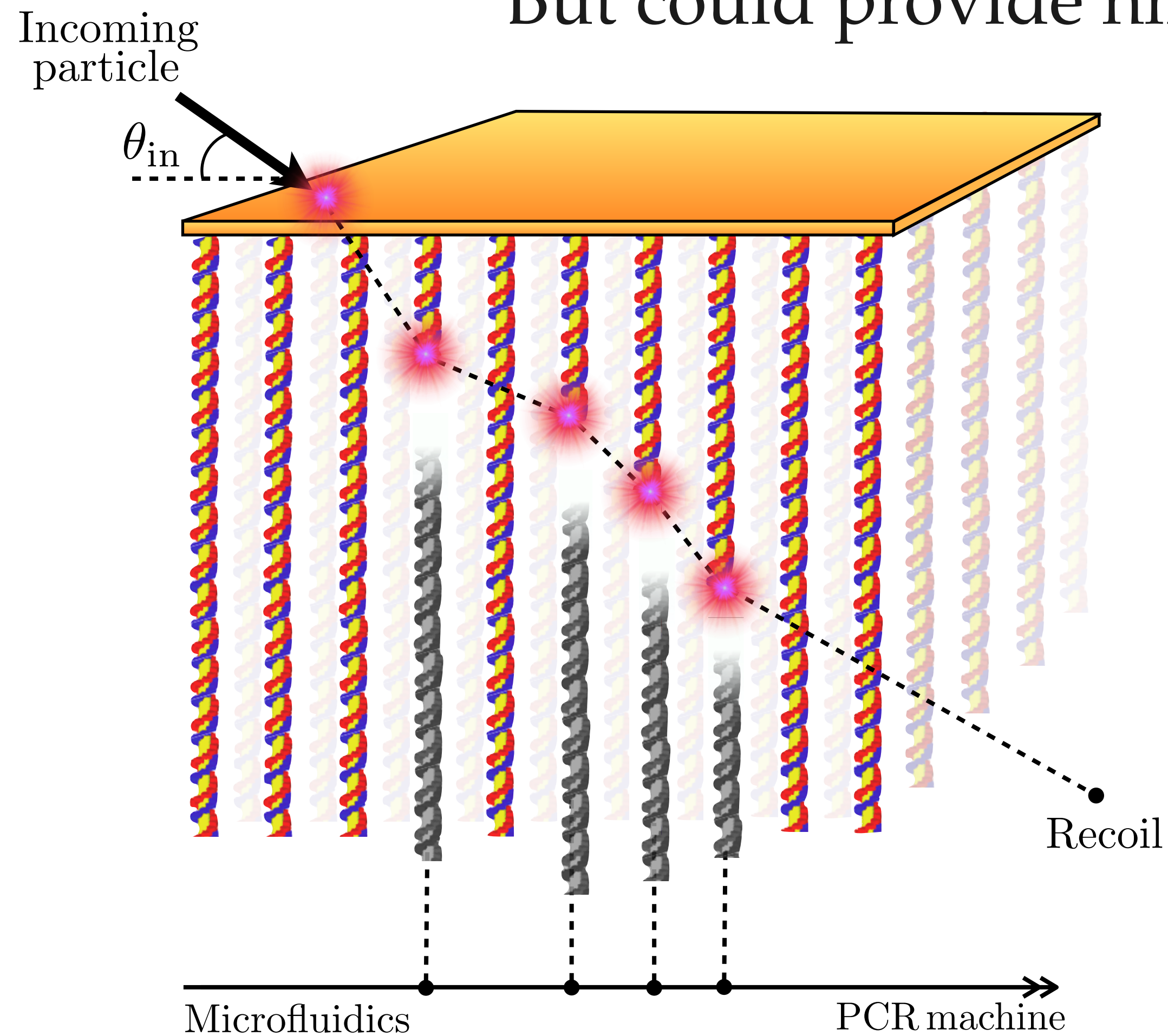




DNA-based directional detector?

Not high-density, so challenging for WIMP-like dark matter.

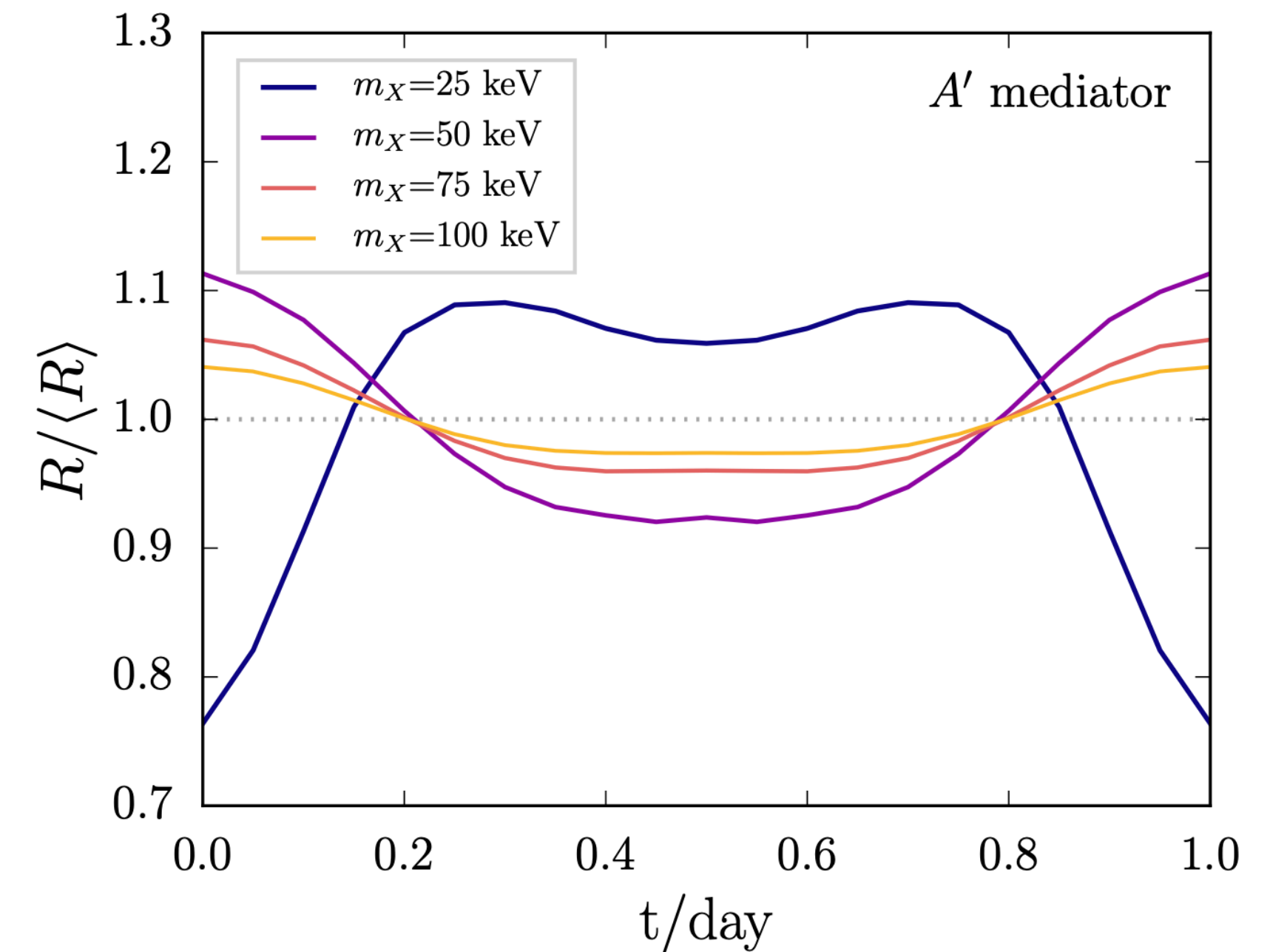
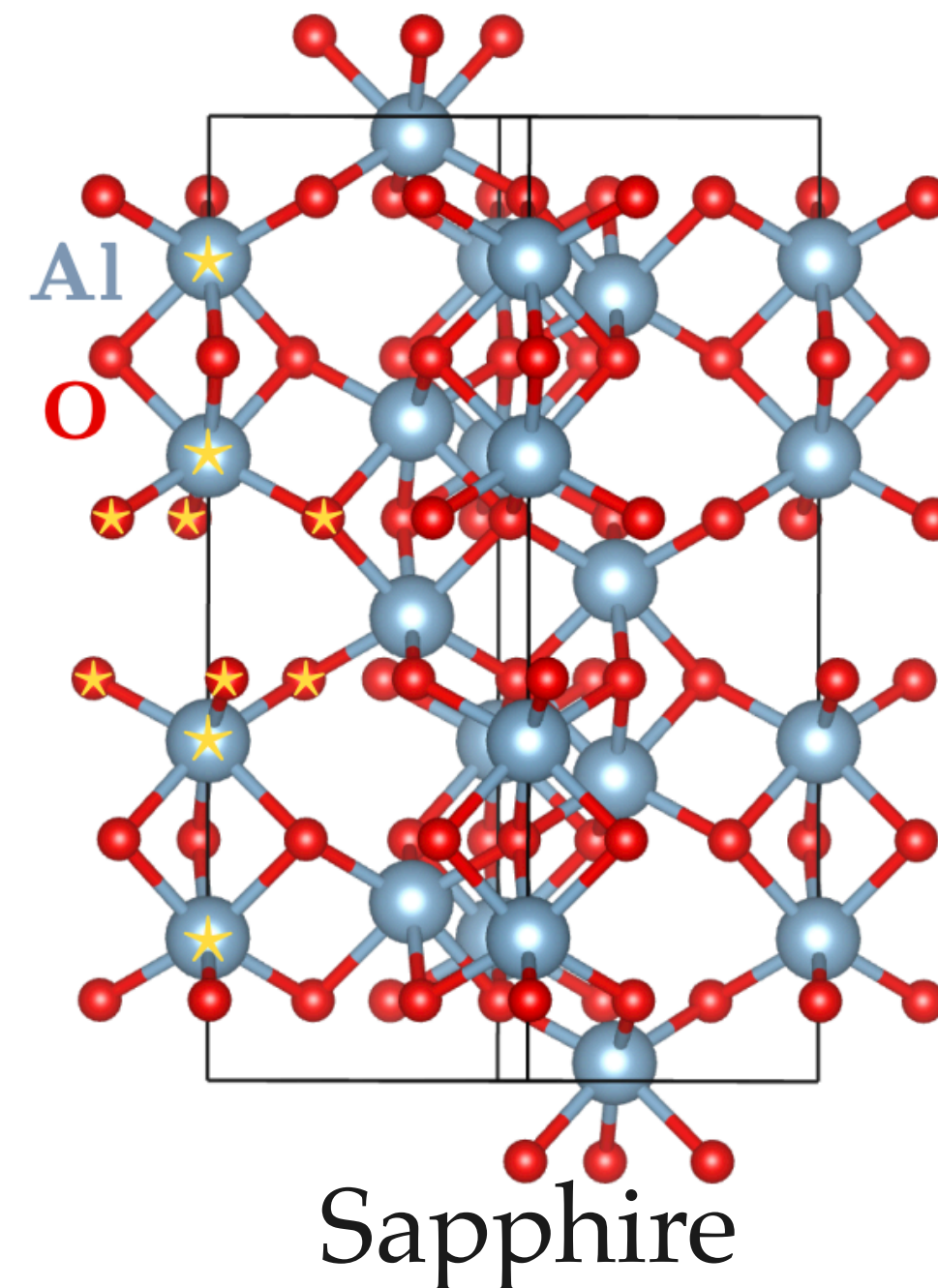
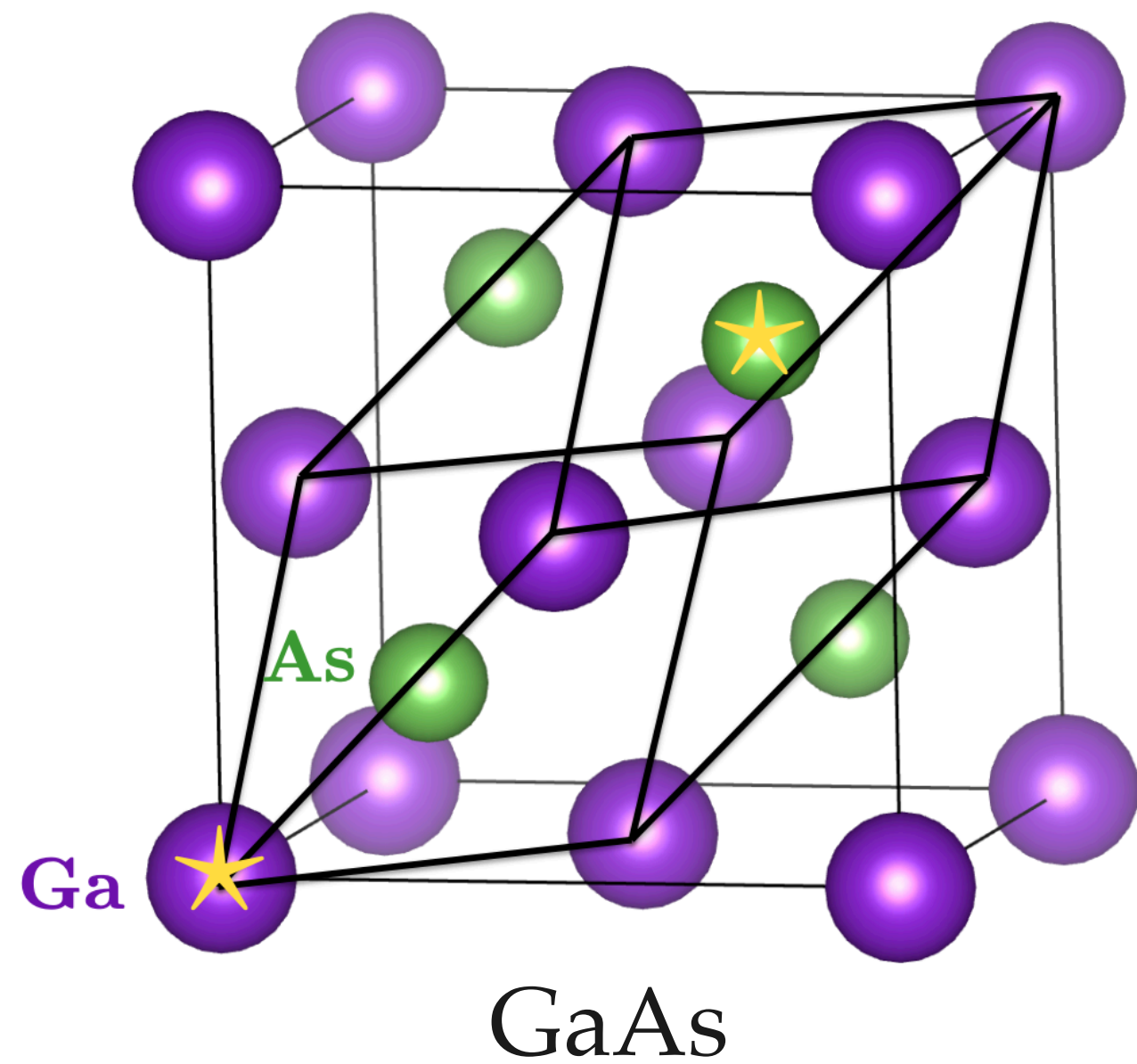
But could provide nm-scale tracking of radiation



Indirect directionality: anisotropic materials

Use some material with an anisotropic response to a DM signal (e.g. via phonons/light)
→ Detect directionality via daily modulation without needing to reconstruct a track in 3D.
Could be an approach for very low mass DM-electron scattering

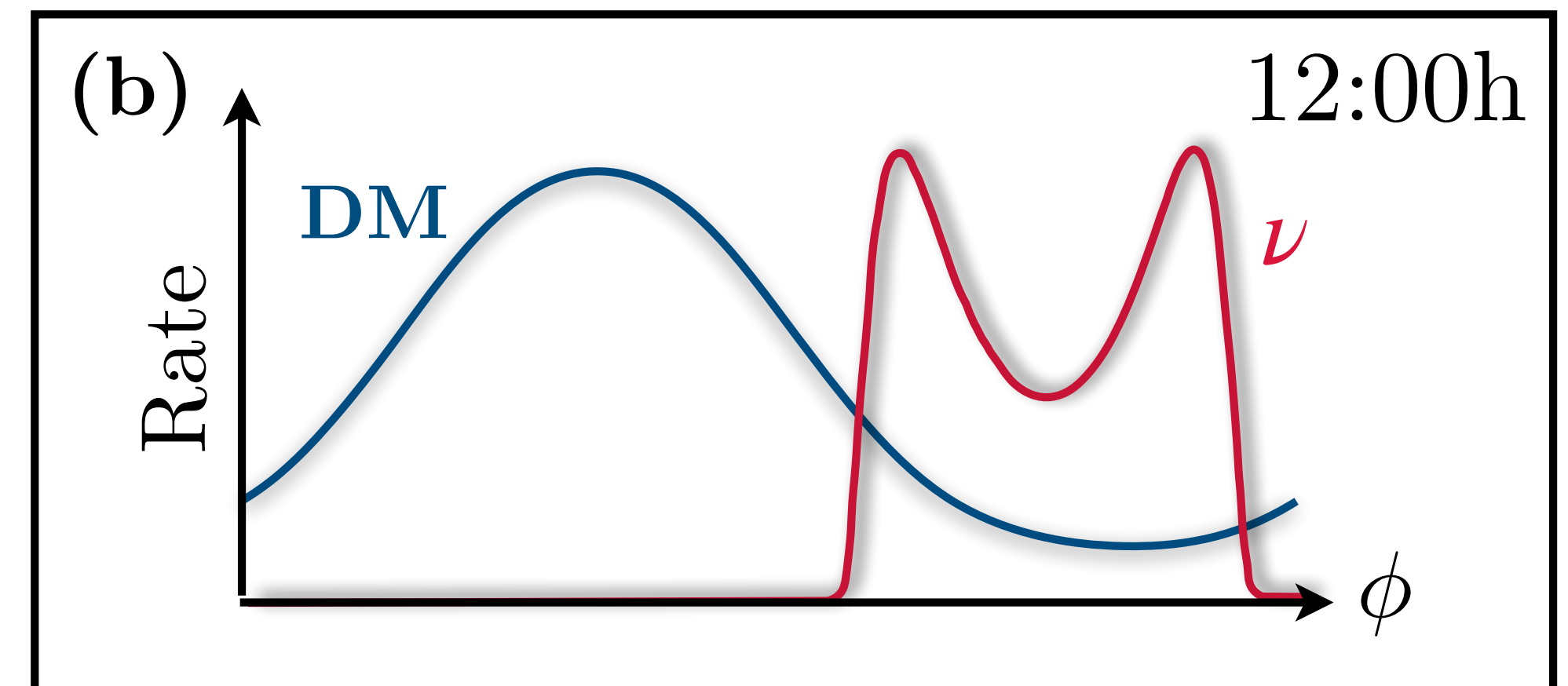
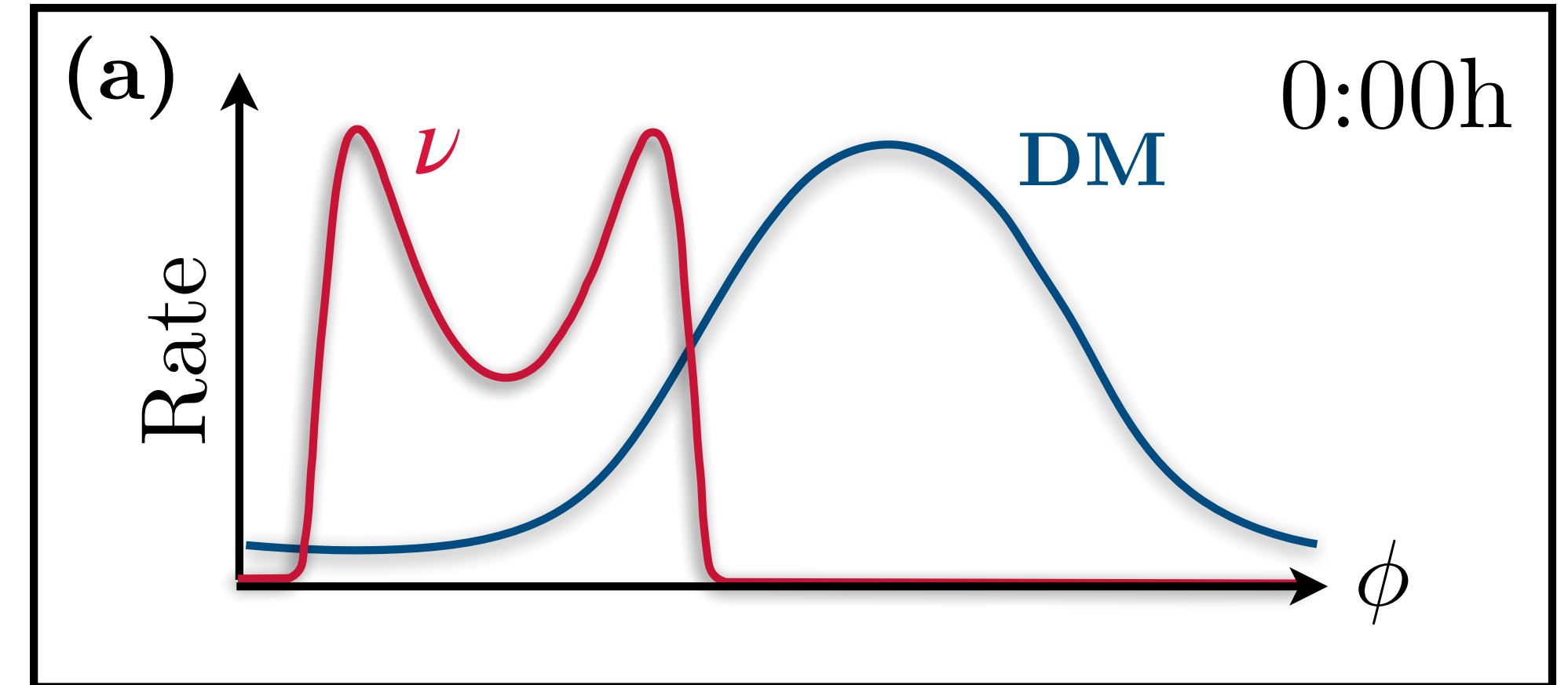
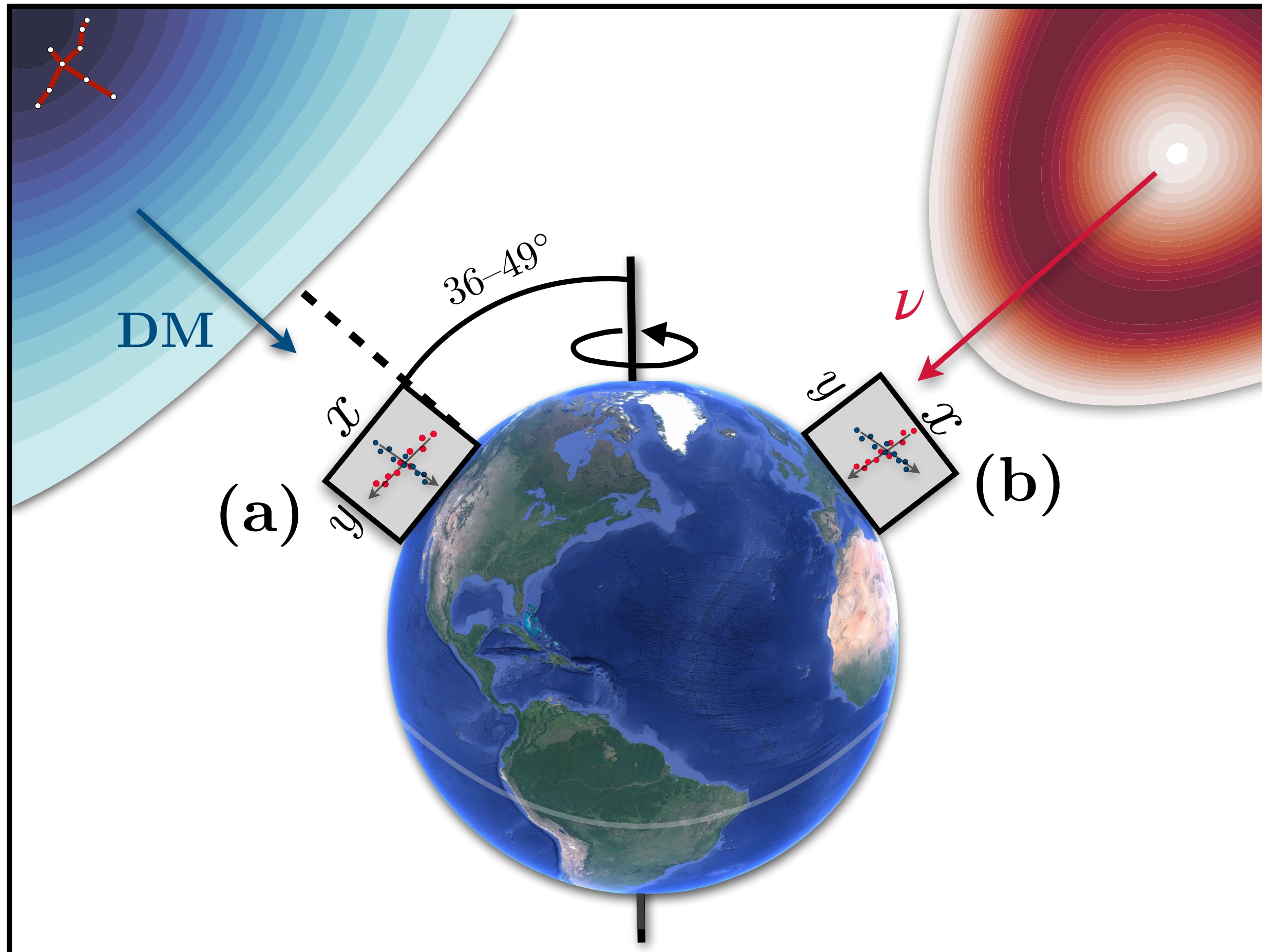
e.g. “Polar materials” Griffin+ [1807.10291]



Important caveat: hard to do event-by-event directionality this way
→ Need to use daily modulation

A different way of seeing directionality: Daily modulation

From the detector's perspective, the galactic dipole signature translates to a sidereal daily modulation in angle $\rightarrow$ this is also a smoking gun

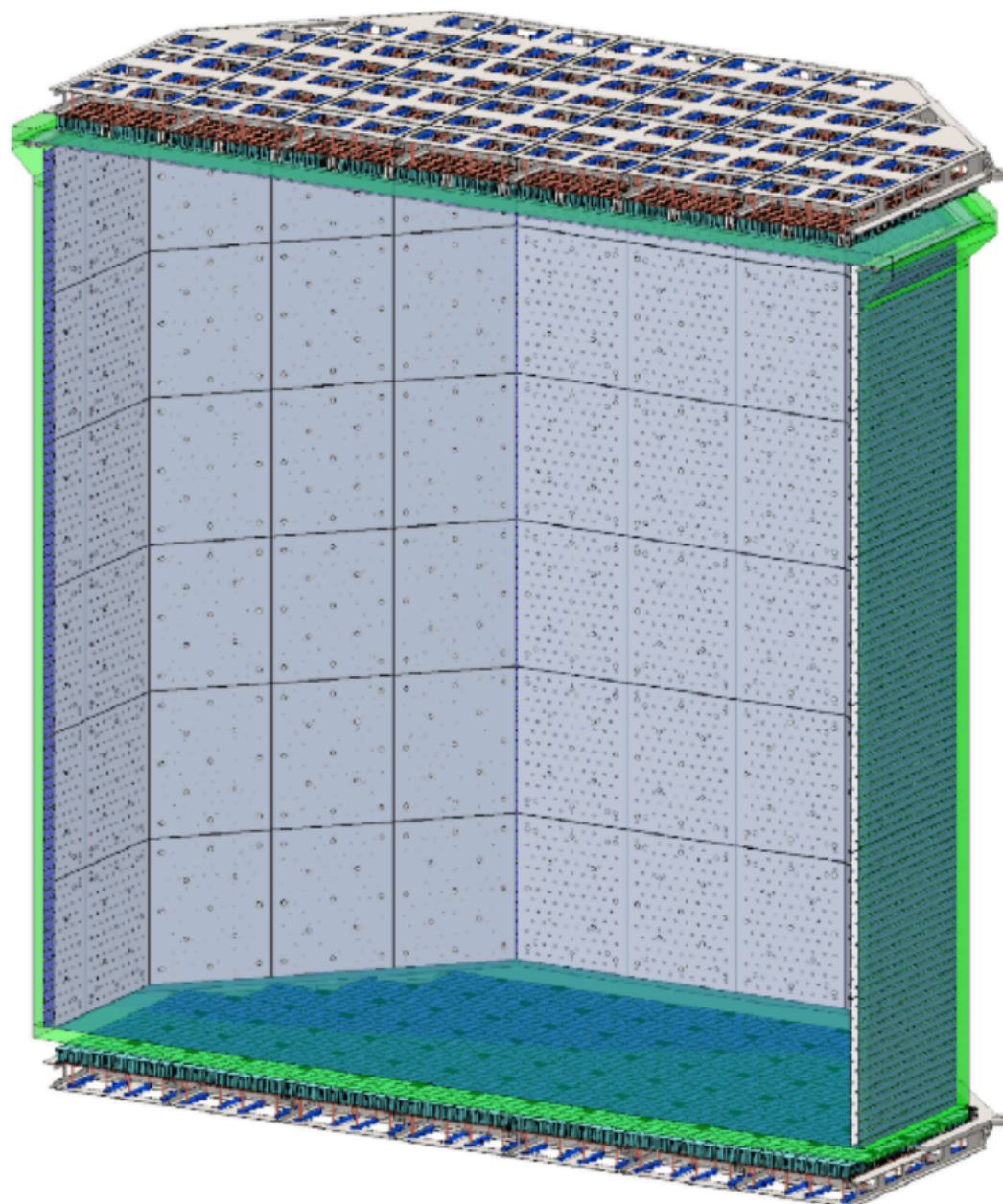


Indirect directionality: columnar recombination

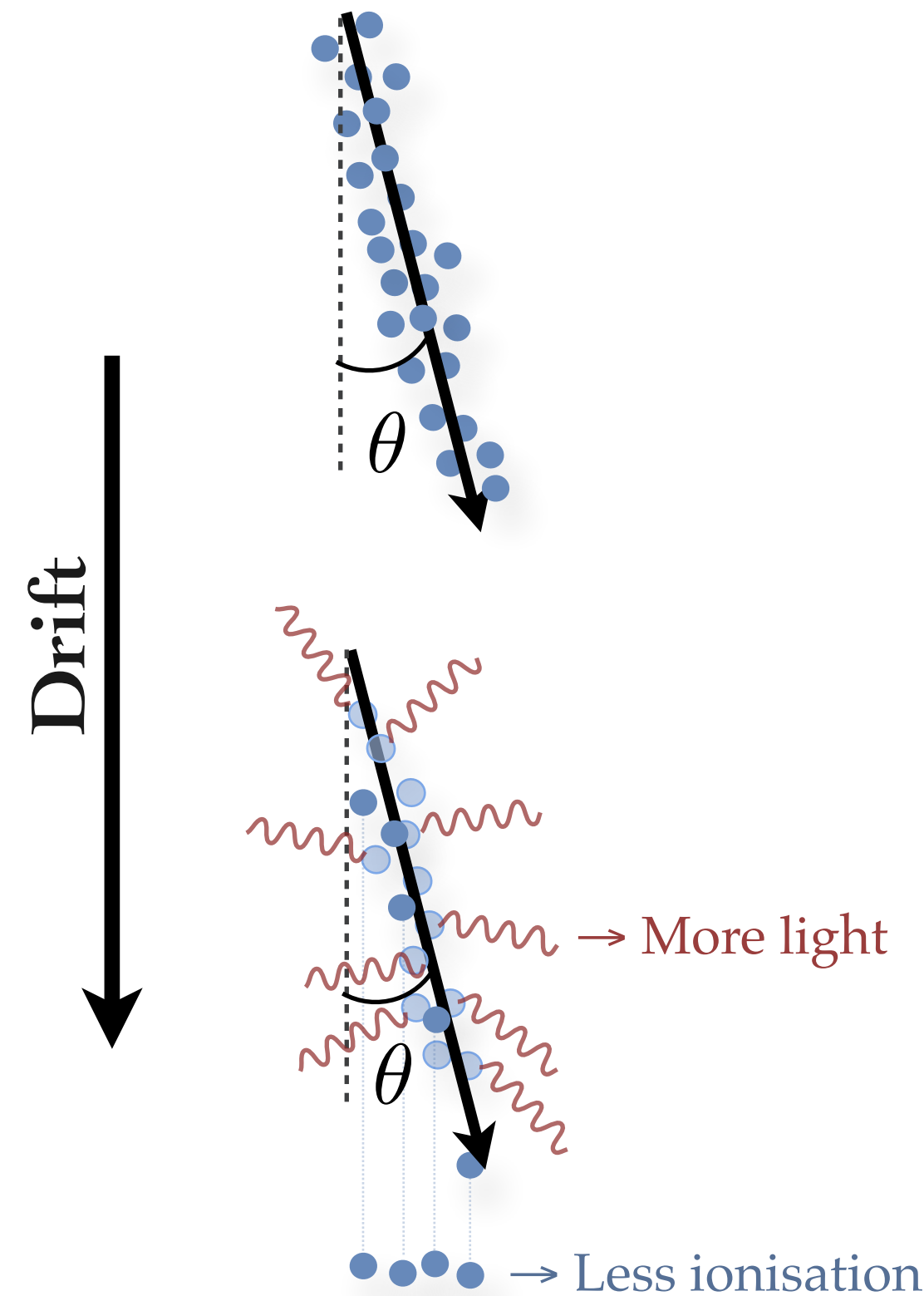
Nygren 2013 J. Phys.: Conf. Ser. 460 012006

→ Possible directional effect where charge/light yield in LXe/LAr depends on angle of recoil w.r.t. electric field

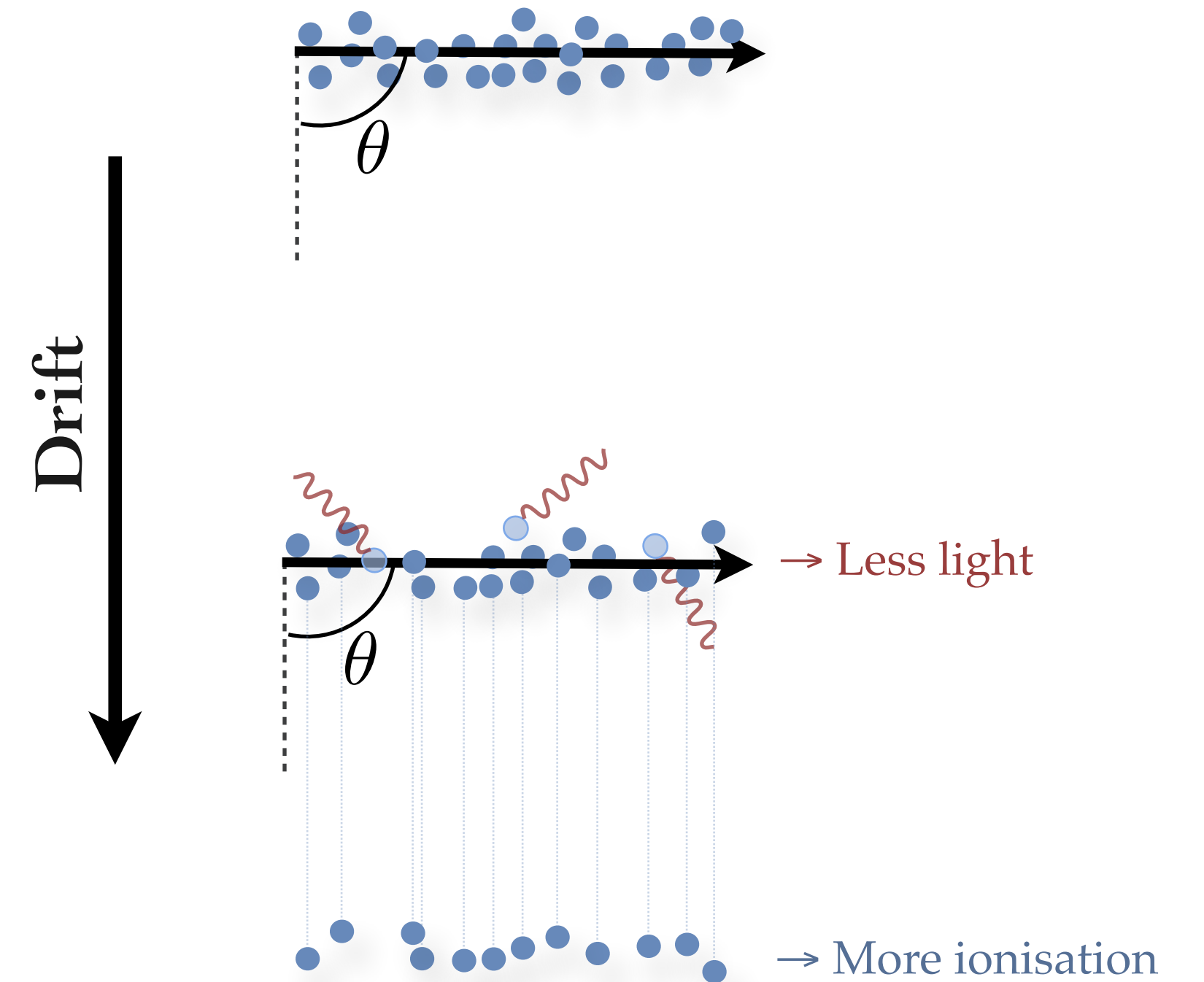
DarkSide-20k. 2024-??



Small drift angles



Large drift angles



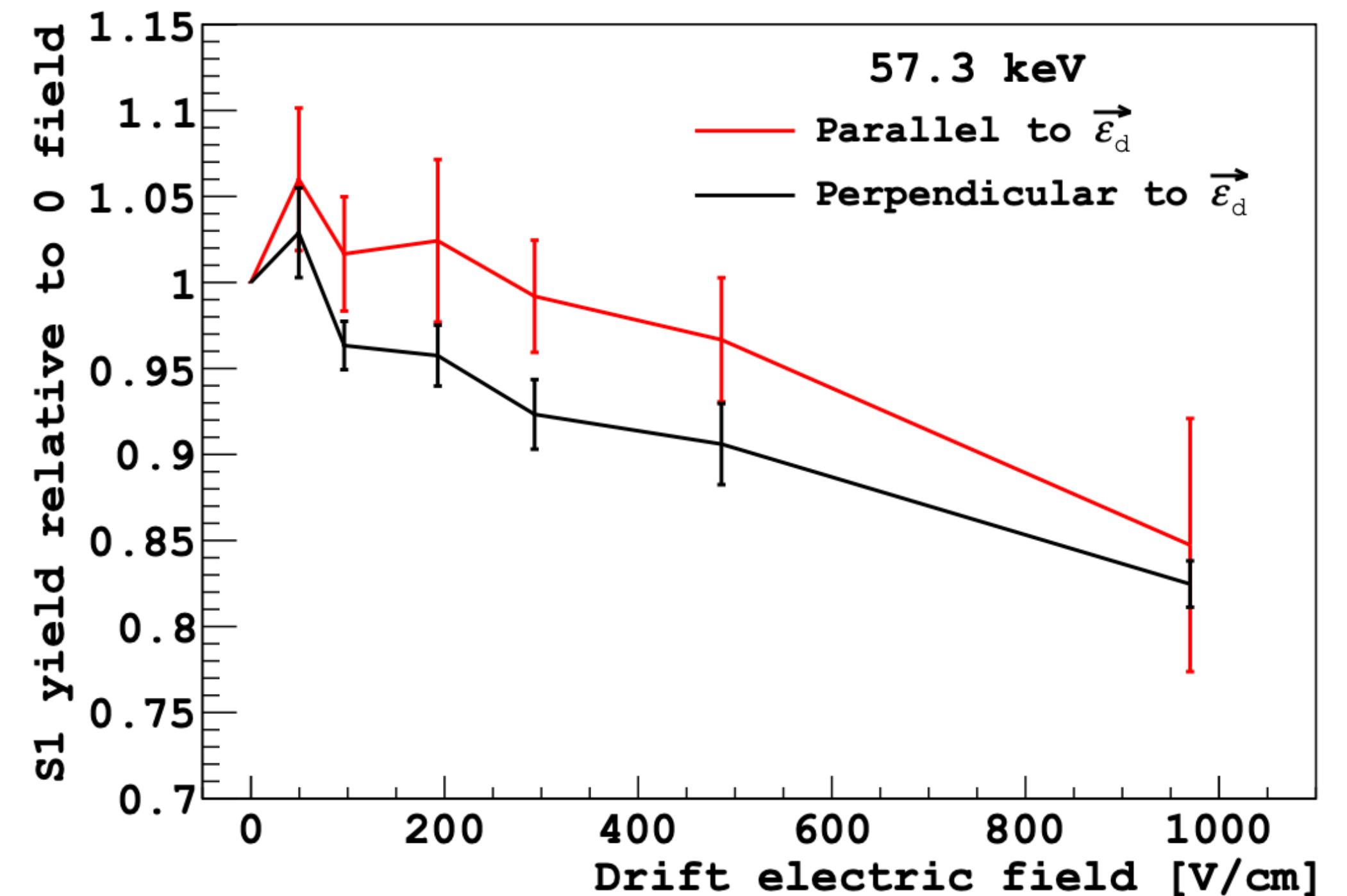
Indirect directionality: columnar recombination

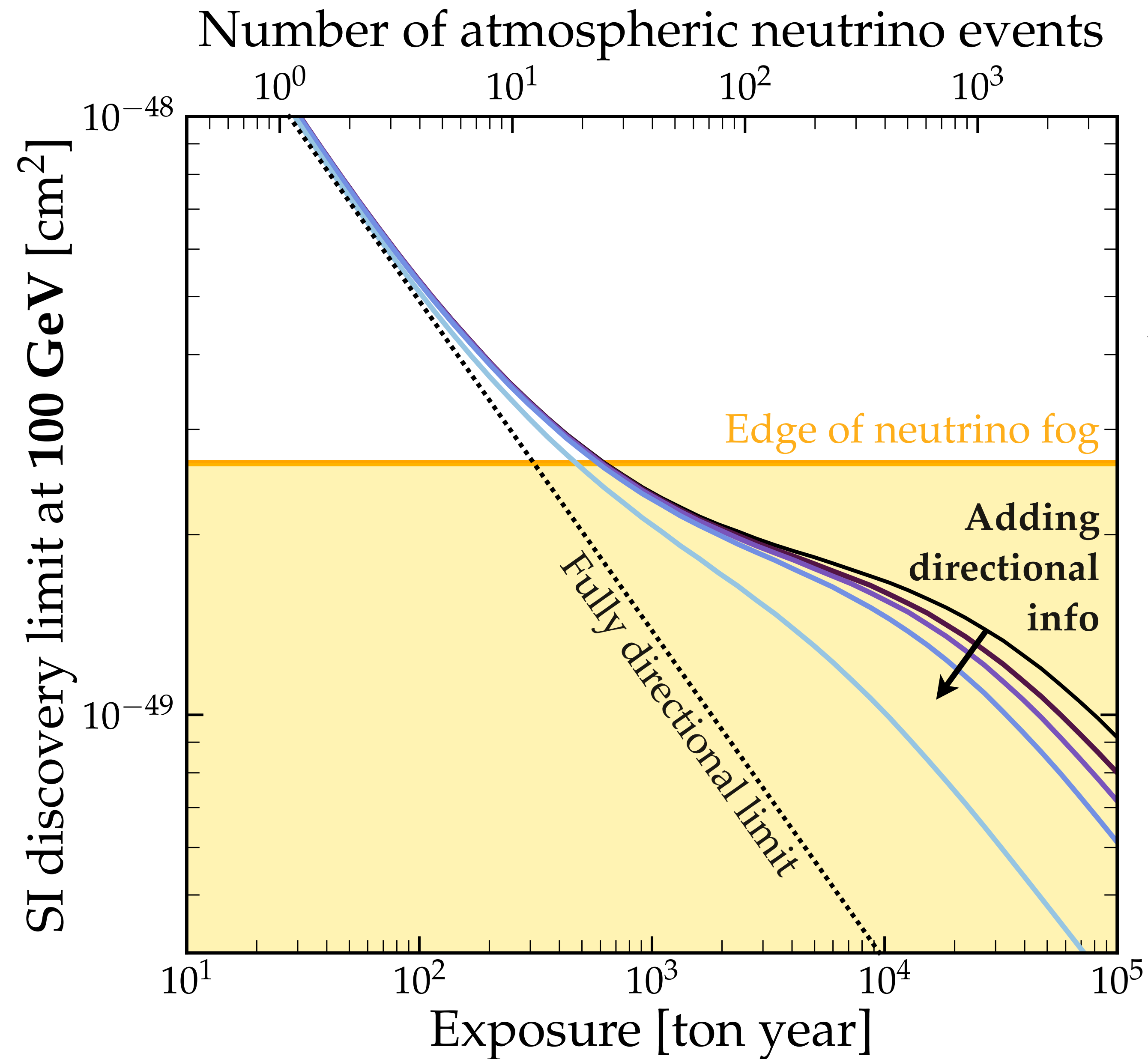
- Possible hint in LAr
- Almost certainly unobservable in LXe (at interesting energies, though GXe is a possibility)

Measurement of scintillation and ionization yield and scintillation pulse shape from nuclear recoils in liquid argon

H. Cao,¹ T. Alexander,^{2,3} A. Aprahamian,⁴ R. Avetisyan,⁴ H. O. Back,¹ A. G. Cocco,⁵ F. DeJongh,³ G. Fiorillo,⁵ C. Galbiati,¹ L. Grandi,⁶ Y. Guardincerri,³ C. Kendziora,³ W. H. Lippincott,³ C. Love,⁷ S. Lyons,⁴ L. Manenti,⁸ C. J. Martoff,⁷ Y. Meng,⁹ D. Montanari,³ P. Mosteiro,¹ D. Olivett,⁷ S. Pordes,³ H. Qian,¹ B. Rossi,^{5,1} R. Saldanha,⁶ S. Sangiorgio,¹⁰ K. Siegl,⁴ S. Y. Strauss,⁴ W. Tan,⁴ J. Tatarowicz,⁷ S. Walker,⁷ H. Wang,⁹ A. W. Watson,⁷ S. Westerdale,¹ and J. Yoo³
(The SCENE Collaboration)

1406.4825



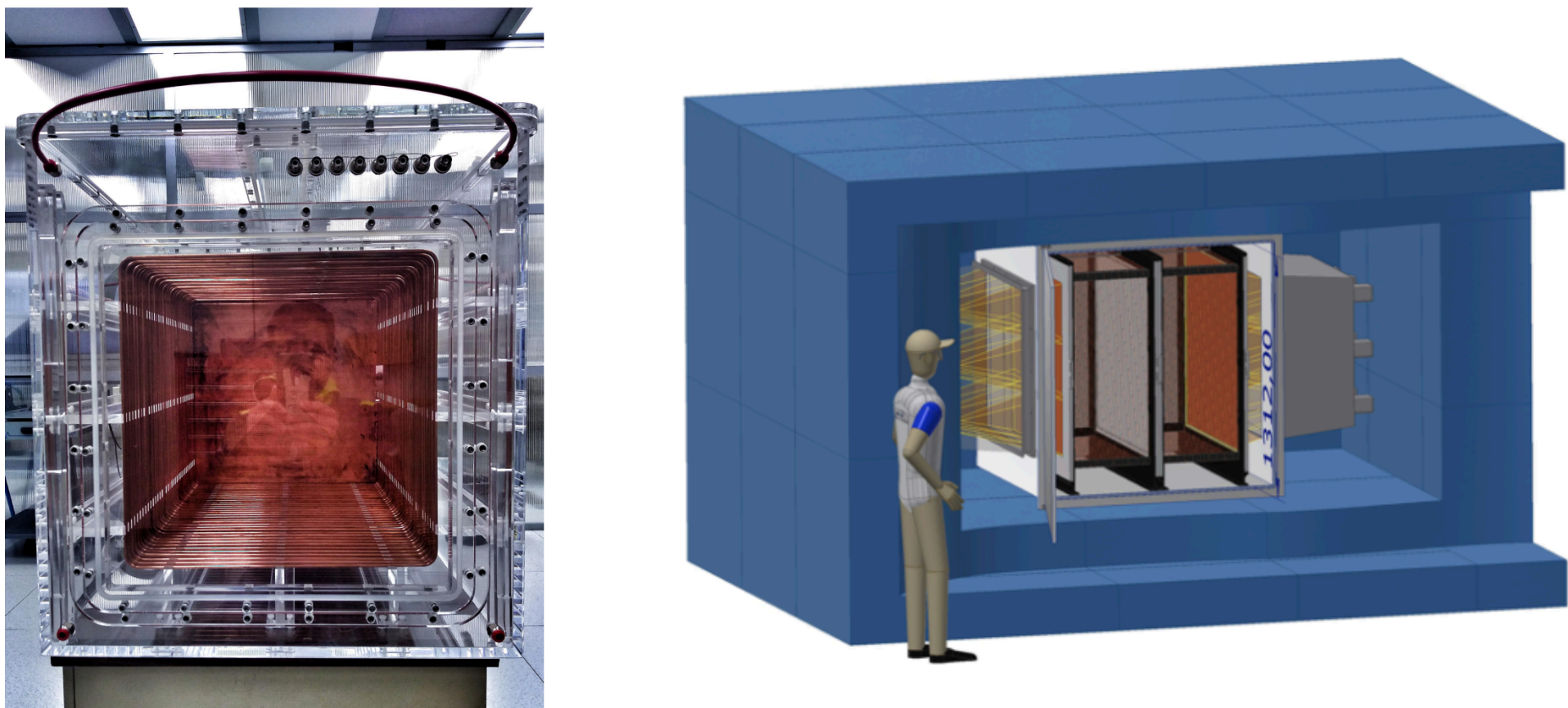


- | | | | |
|-----------------|---|---|------------------------------------|
| No effect | → | — | Nondirectional |
| Realistic | → | — | Stationary, $\mathcal{A} = 0.5$ |
| Optimistic | → | — | Stationary, $\mathcal{A} = 1$ |
| Very optimistic | → | — | Cygnus Tracking, $\mathcal{A} = 1$ |
| Impossible | → | — | Head-Tail, $\mathcal{A} = 1$ |

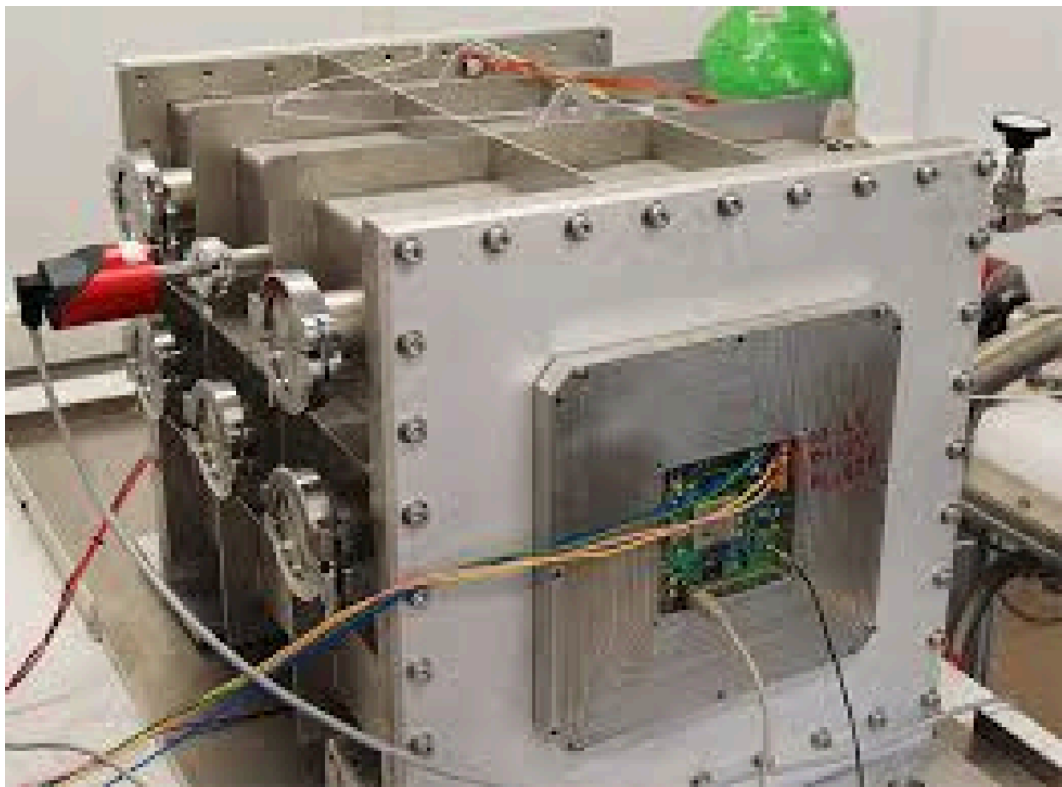
Columnar recombination
doesn't help much, even in
wildly over-optimistic scenario
→ **directionality in liquids
seems unfeasible for now**

More experiments I didn't have time to mention

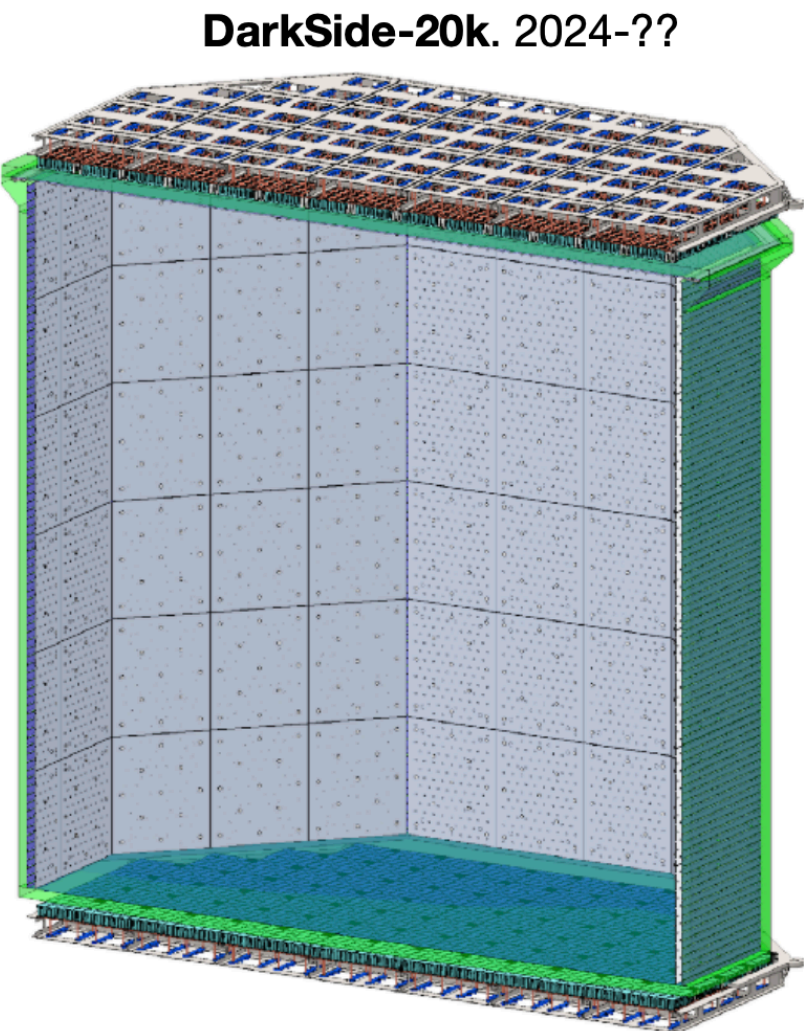
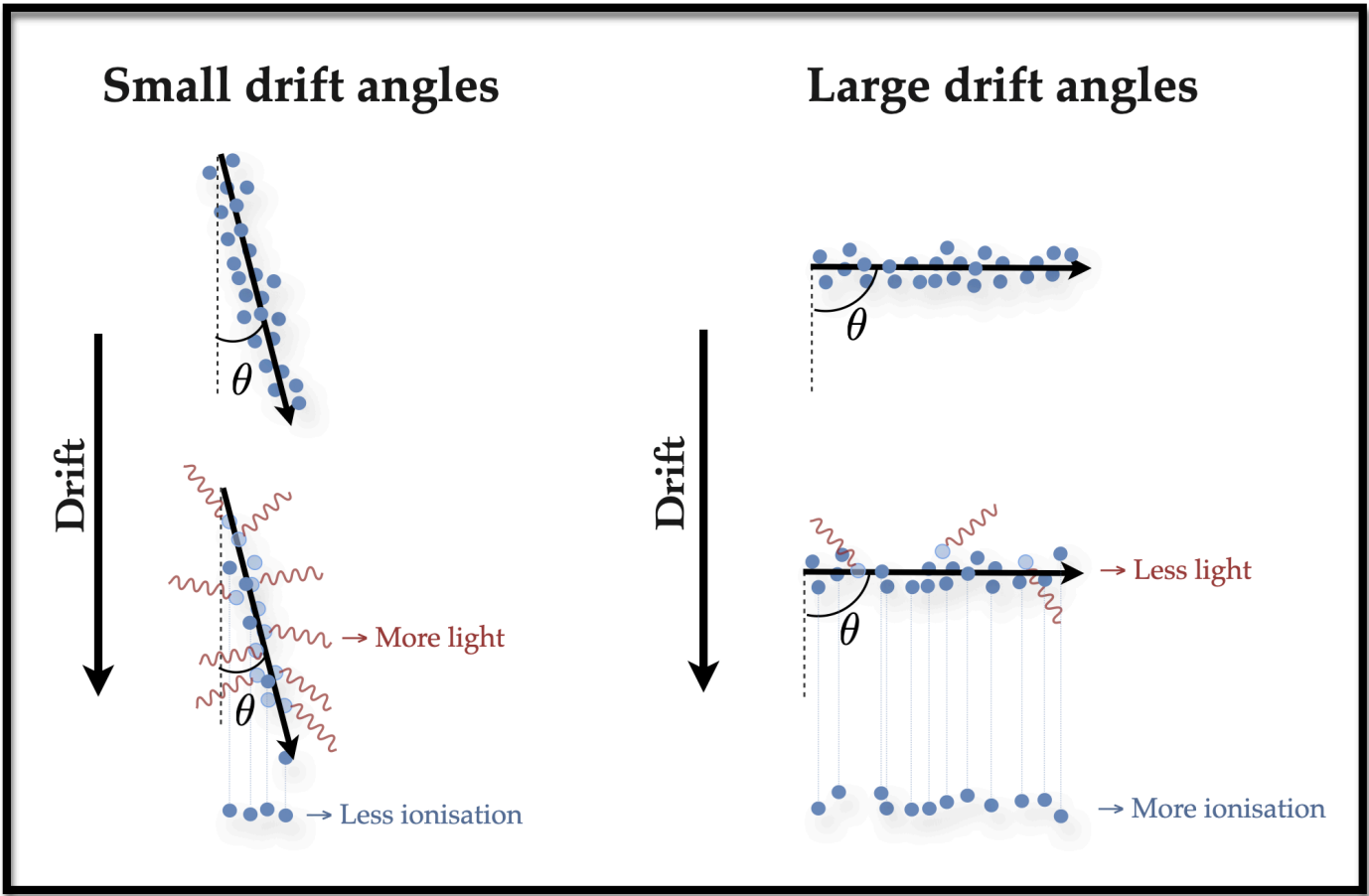
CYGNO (various TPC projects)



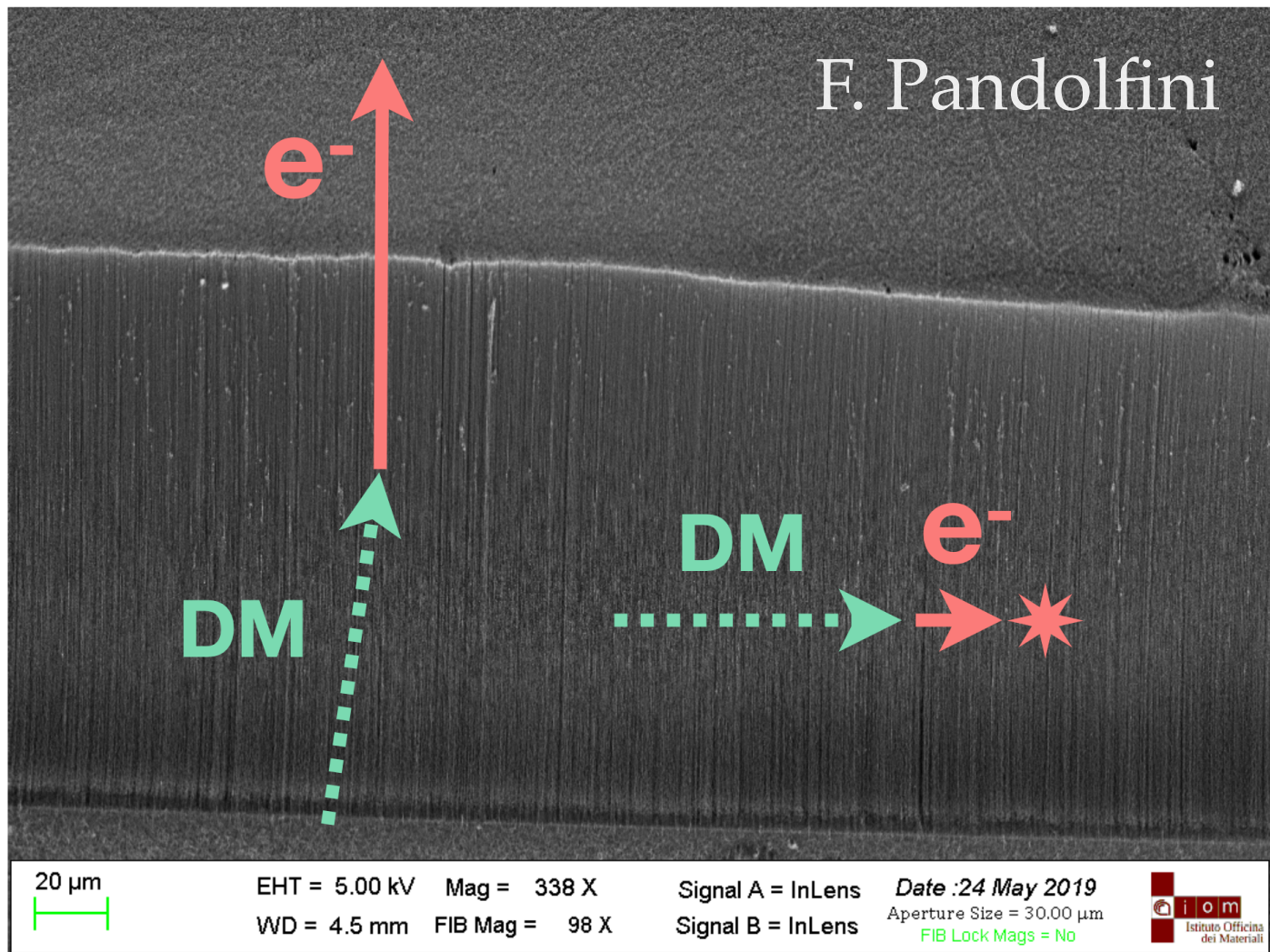
MIMAC (TPC)



ReD/DarkSide (columnar recombination in LAr)

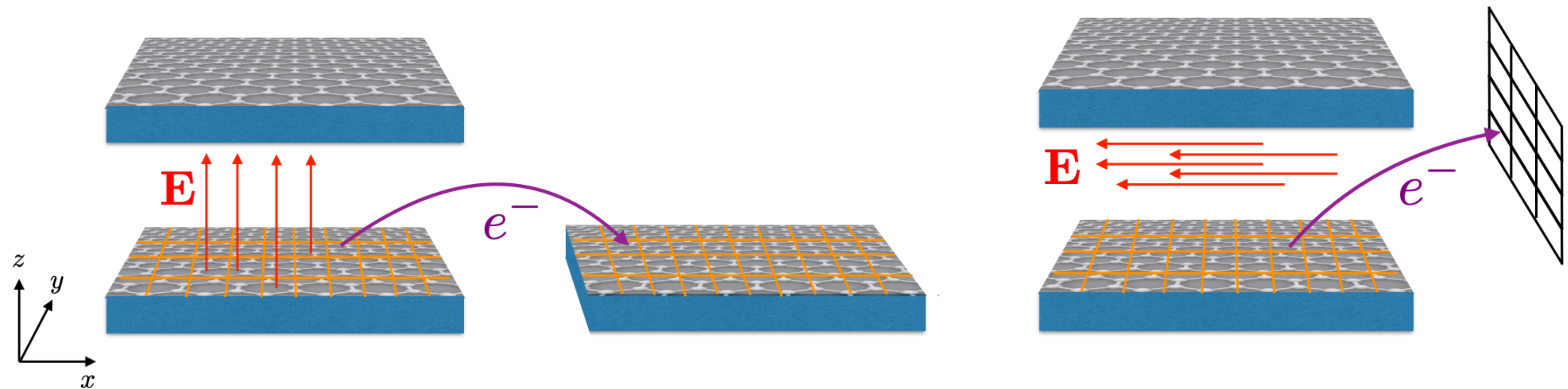
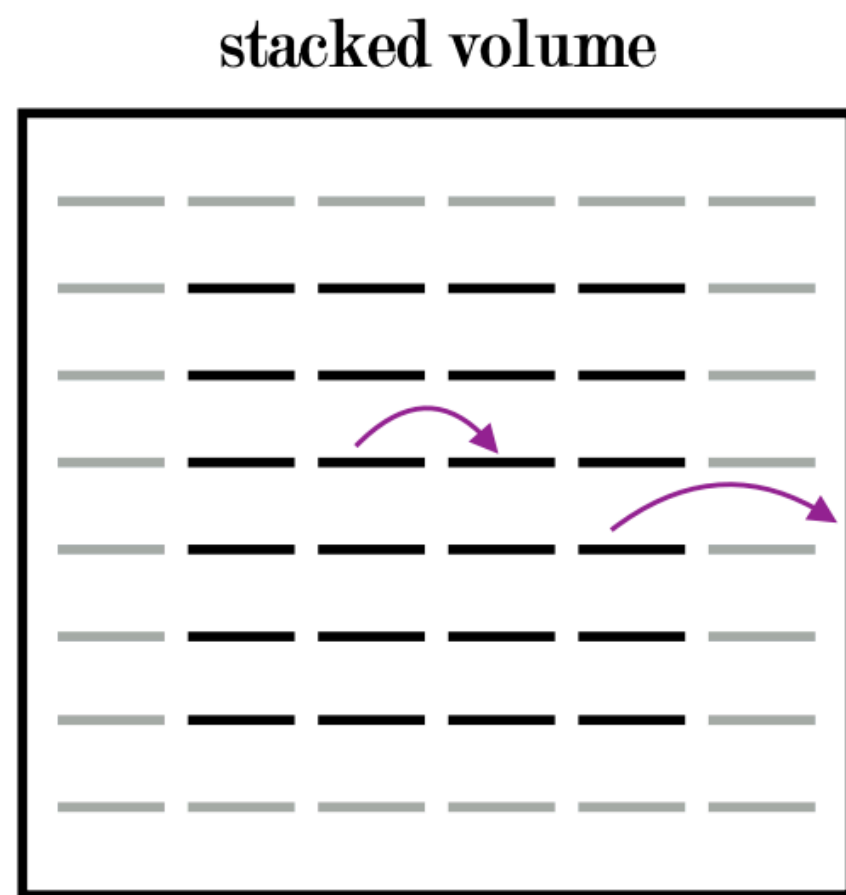


Dark-PMT (Carbon nanotubes)



More concepts for light DM directionality

- Graphene, Hochberg+ [1606.08849]
- Superfluid helium, Caputo+ [2012.01432]
- Anisotropic scintillators (ADAMO project)
- ...



Target gas mixture: 755:5 He+SF₆ at 1 atm.

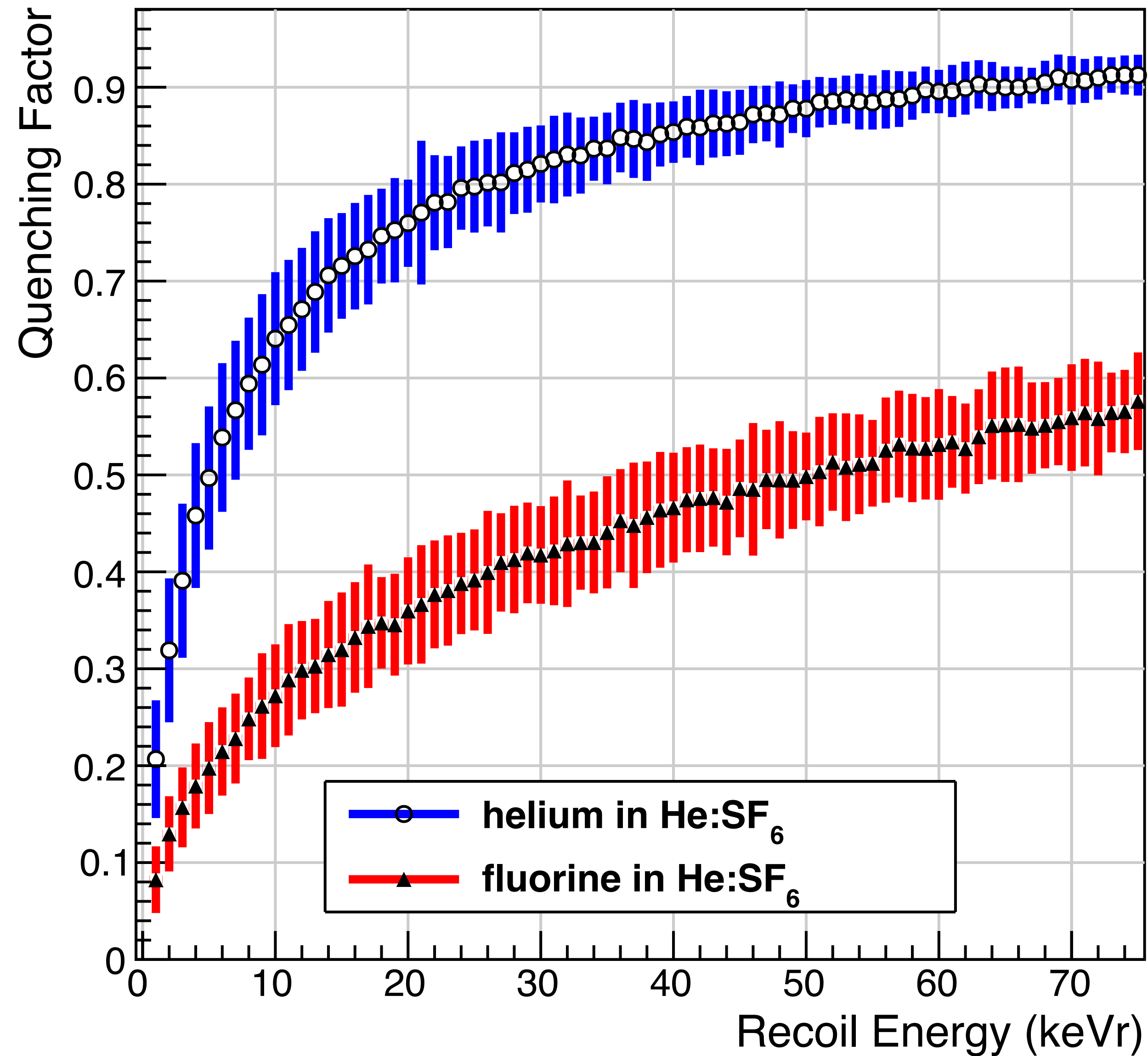
Why SF₆?

- ☑ **Negative ion drift mixture:** drift ions rather than electrons, results in lower diffusion and better track preservation
- ☑ **Minority charge carriers** which can be used to fiducialise the gas volume in the drift direction (z)
- ☑ **¹⁹F has very high $\langle S_p \rangle$** so sets powerful spin dependent WIMP limits (this is why PICO's SD-p limits are so good)

Why He?

- ☑ **Light WIMPs** still give large recoil energies with He: improves the low mass sensitivity
- ☑ **High quenching factor** in gas mixture (>70% above 10 keVr)
- ☑ **Doesn't significantly impact Fluorine tracks**, can be used simultaneously

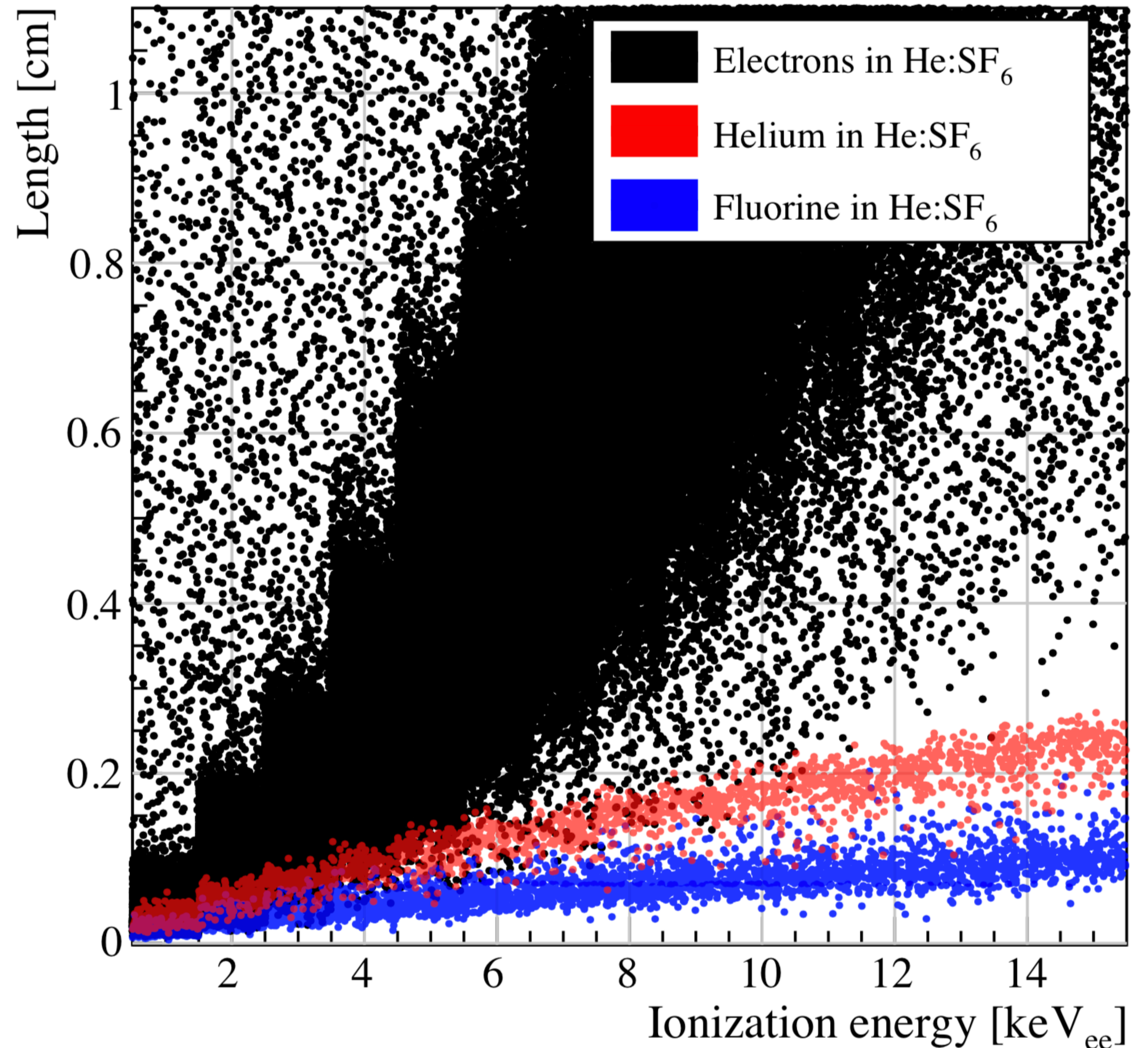
Quenching factors for recoils in 1 atm of He+SF₆



Electron discrimination

- Electrons have much longer tracks than nuclei so can discriminate based on this info.
- Track lengths for recoils in He+SF₆ at 1 atm:

Energy threshold will be based on how low this can be achieved, probably can do a lot better with more sophisticated track fit and comparison metric



Gas mixture	SF ₆	He:SF ₆	He:SF ₆
Pressure [Torr]	20	740:20	755:5
Density [kg/m ³]	0.16	0.32	0.20
W [eV/ion pair]	35.5	38.0	40.0
Trans. diffusion [$\mu\text{m}/\sqrt{\text{cm}}$]	116.2	78.6	78.6
Long. diffusion [$\mu\text{m}/\sqrt{\text{cm}}$]	116.2	78.6	78.6
Drift velocity [mm/ μs]	0.140	0.140	0.140
Mean avalanche gain	9×10^3	9×10^3	9×10^3

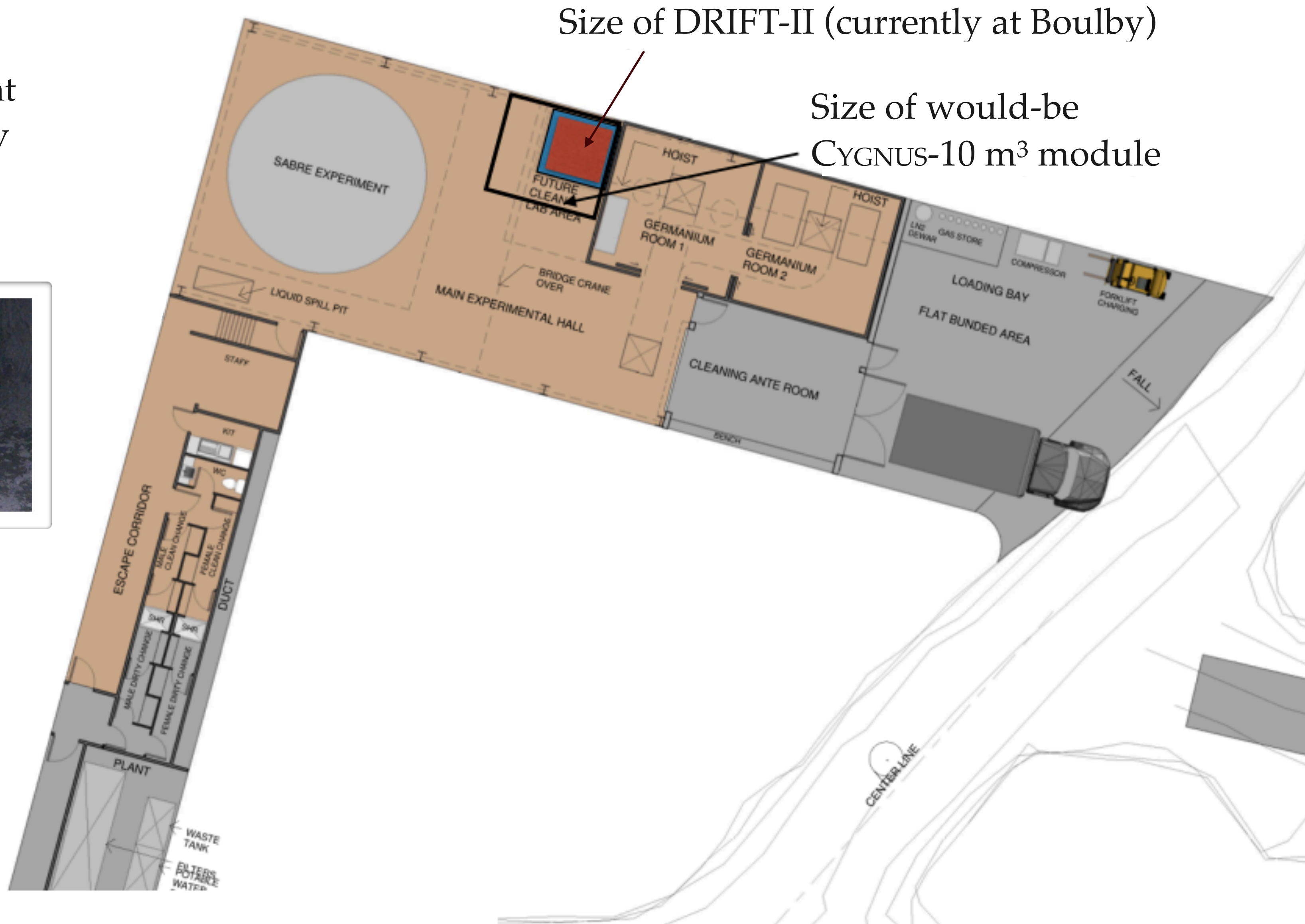
TABLE I. Various gas-dependent parameters assumed in the TPC detector simulation. The values are sourced as follows: the W factor for pure SF₆ is from a measurement with alpha particles [310], while the W factors for the He:SF₆ and He:CF₄ mixtures are calculated using Eq.(1) of Ref. [266]. The diffusion values and drift velocity in 20 Torr of pure SF₆ were measured in Ref. [299]. For the He:SF₆ mixtures, no measurements or reliable simulations exist, so we use the 40 Torr pure SF₆ diffusion from Ref. [299] and then assume the electric field can be adjusted to keep the drift velocity constant. The avalanche gain assumed for pure SF₆ has been achieved with THGEMs in Ref. [311] and triple thin GEMs in Ref. [312], and is also used for He:SF₆ mixtures.

Readout type	Dimensionality	Segmentation ($x \times y$)	Capacitance [pF]	σ_{noise} in 1 μs	Threshold/ σ_{noise}
planar	1d (z)	10 cm $\times$ 10 cm	3000	18000 e^-	3.09
wire	2d (yz)	1 m wires, 2 mm pitch	0.25	800 e^-	4.11
pad	3d (xyz)	3 mm $\times$ 3 mm	0.25	375 e^-	4.77
optical	2d (xyz)	200 μm $\times$ 200 μm	n/a	2 photons	5.77
strip	3d (xyz)	1 m strips, 200 μm pitch	500	2800 e^-	4.61
pixel	3d (xyz)	200 μm $\times$ 200 μm	0.012 - 0.200	42 e^-	5.77

TABLE II. List of readout-specific parameters that are used in the simulation of each technology we consider here. The capacitance, which determines the noise level, is listed as that for a single detector element. For the optical readout, a yield of 7.2×10^{-6} photons per avalanche electron is used to account for the combined effects of photon yield, geometric optical acceptance, optical transparency, and quantum efficiency.

Stawell Underground Physics Laboratory (SUPL)

- ♦ 1.6 km depth, still operational gold mine
- ♦ First underground site in Southern Hemisphere
- ♦ Will host one half of SABRE experiment
- ♦ Cygnus involvement as part of recently formed Centre of Excellence for Dark Matter Particle Physics

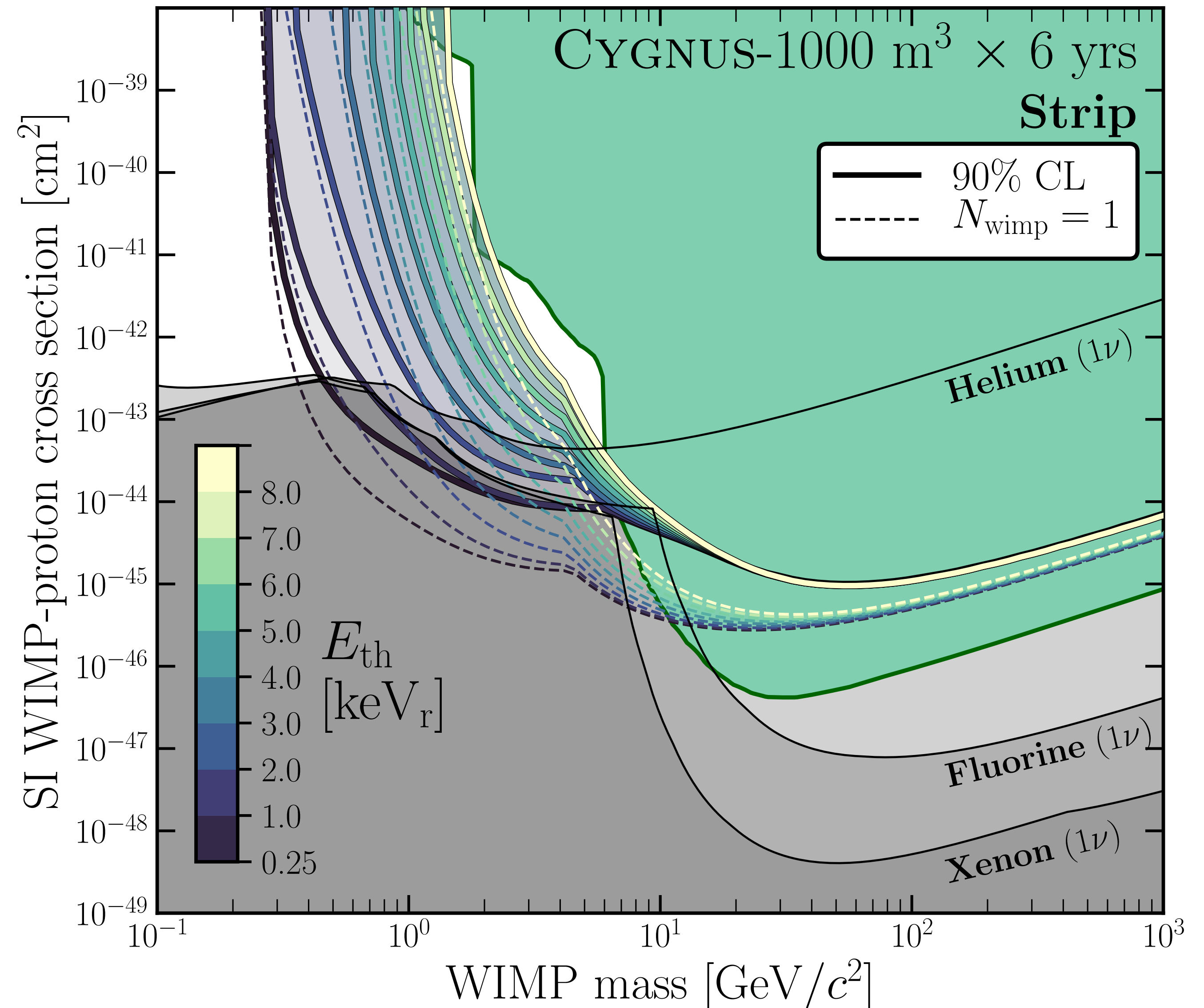


μ -PIC (strip) readout currently looks the best in terms of cost vs. directional sensitivity

A closer look at dependence on threshold:

Threshold:

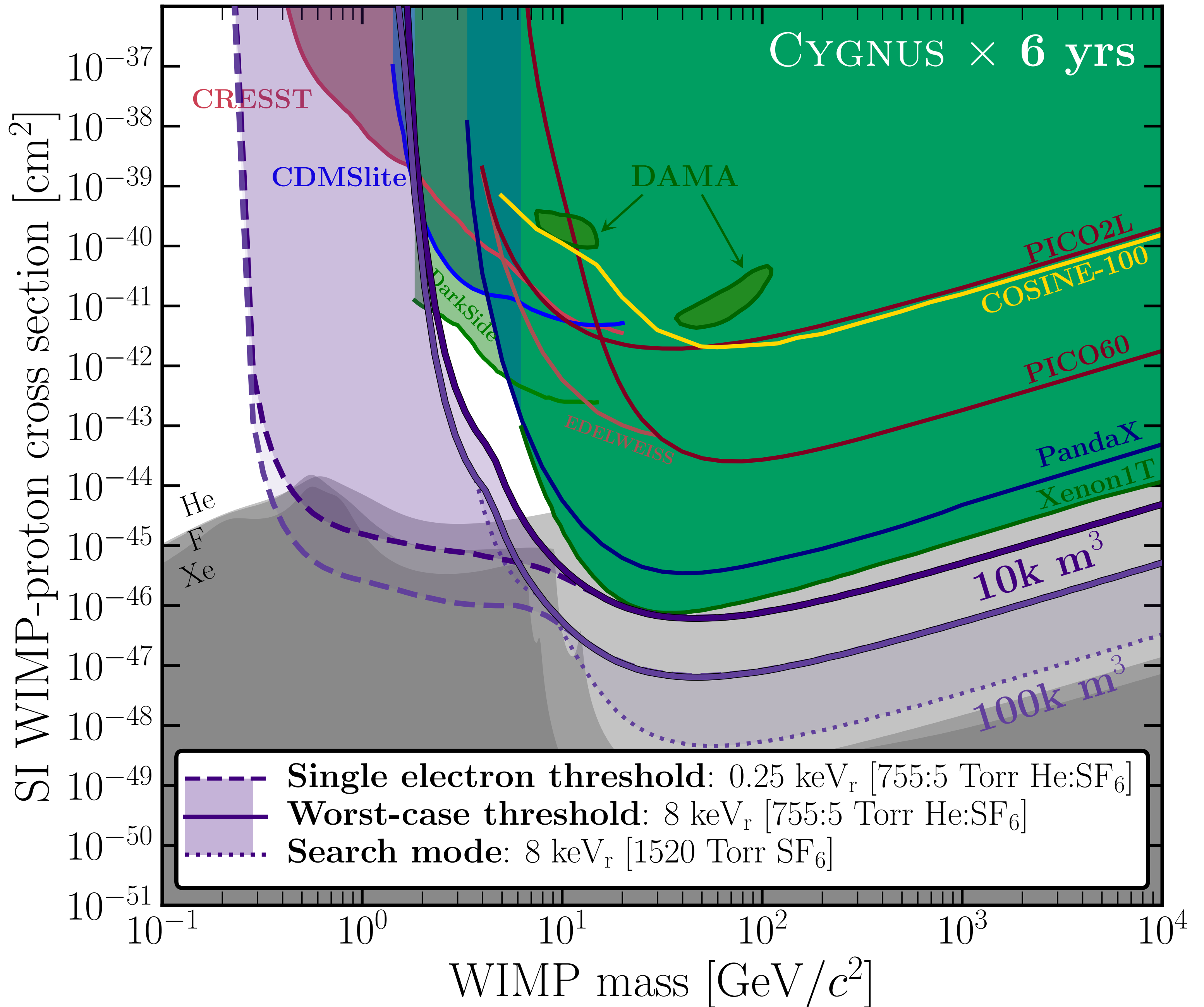
- 8 keVr definitely feasible with simplest electron rejection strategy
- 3 keVr is probably feasible with optimisation of gas, bespoke track fitting algorithms
- 0.25 keVr is theoretical minimum (single electron)



Sensitivity (SI)

→ Window worst/best case threshold
→ Search mode: 1 atm. of SF₆ but no directionality (possible way to extend high mass sensitivity)

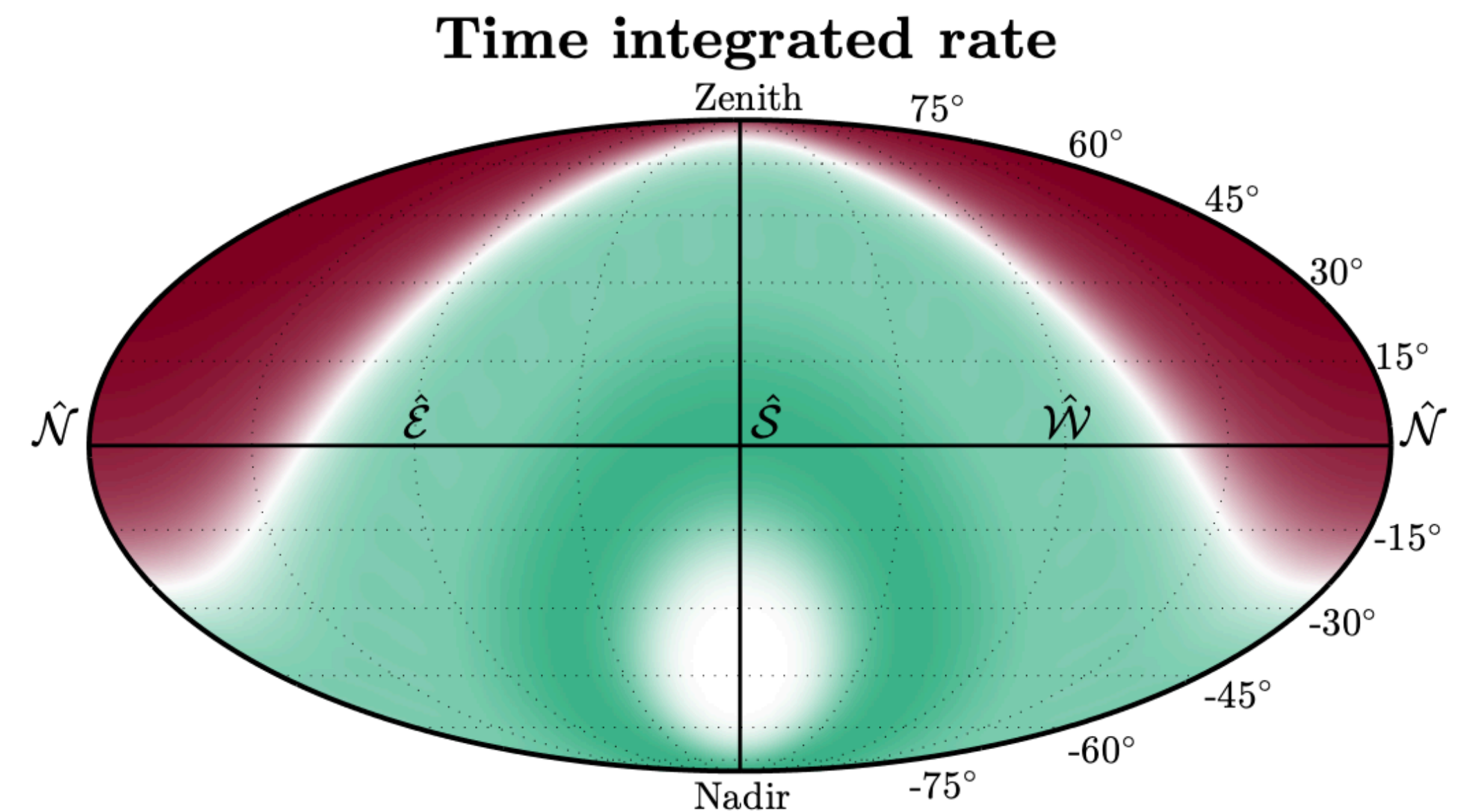
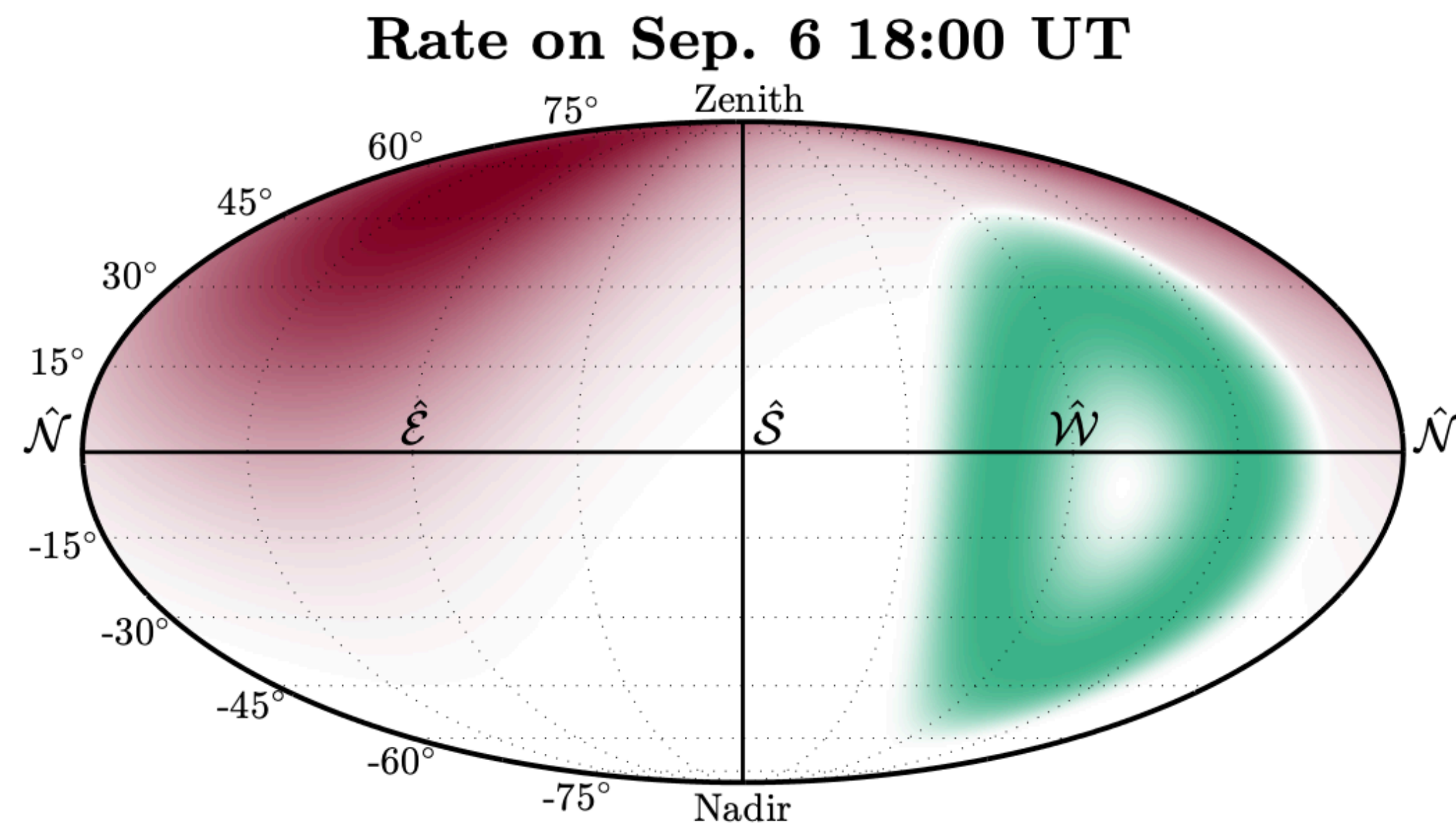
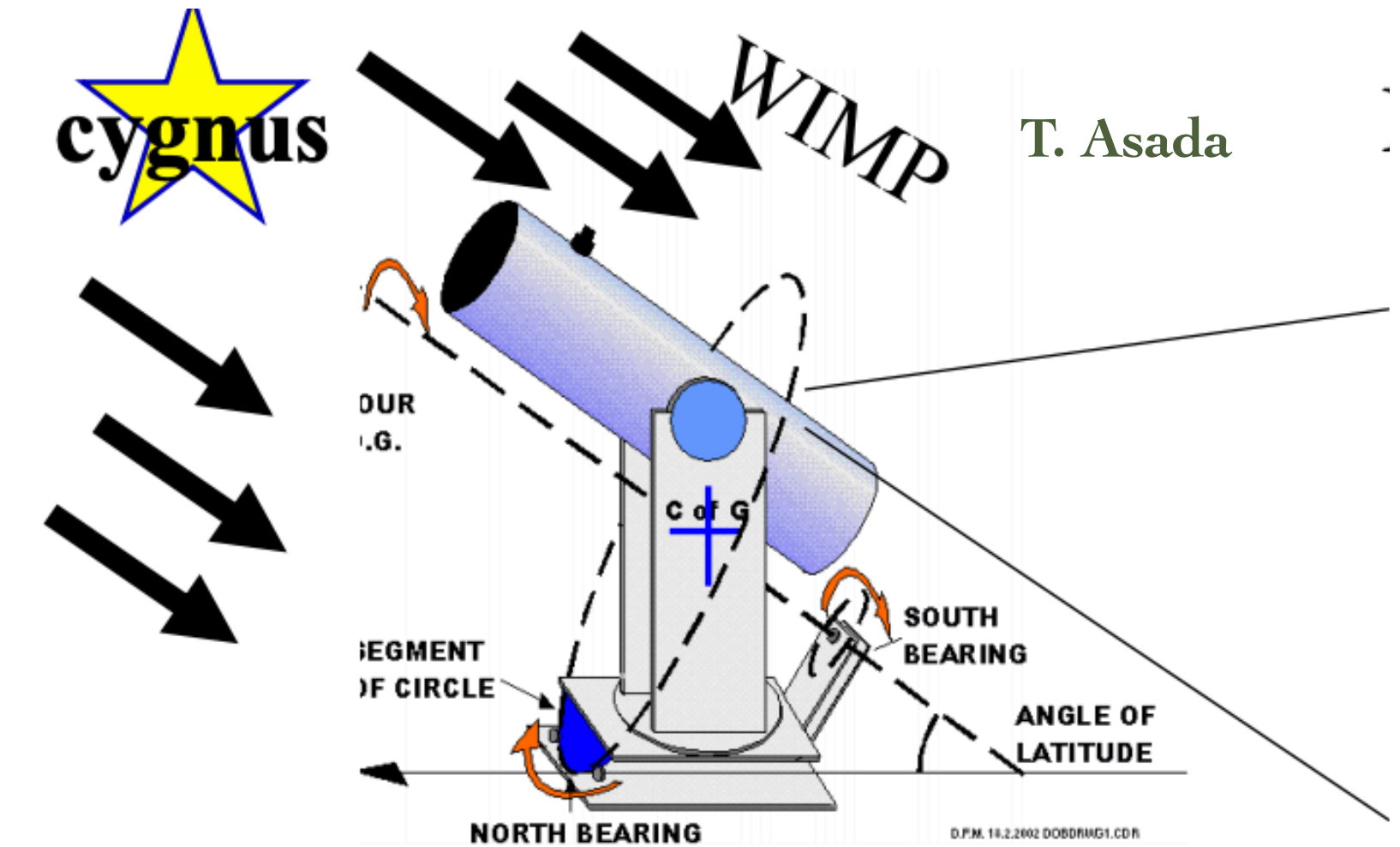
Important note: these limits are true discovery limits, i.e. a signal can be confirmed as DM, so comparison of Cygnus limits with other experiments undersells its potential



Time-integrated directional detection

Experiments like NEWSdm need to develop tracks after exposure

→ rotation of Earth will wash out anisotropy unless some Cygnus-tracking is implemented



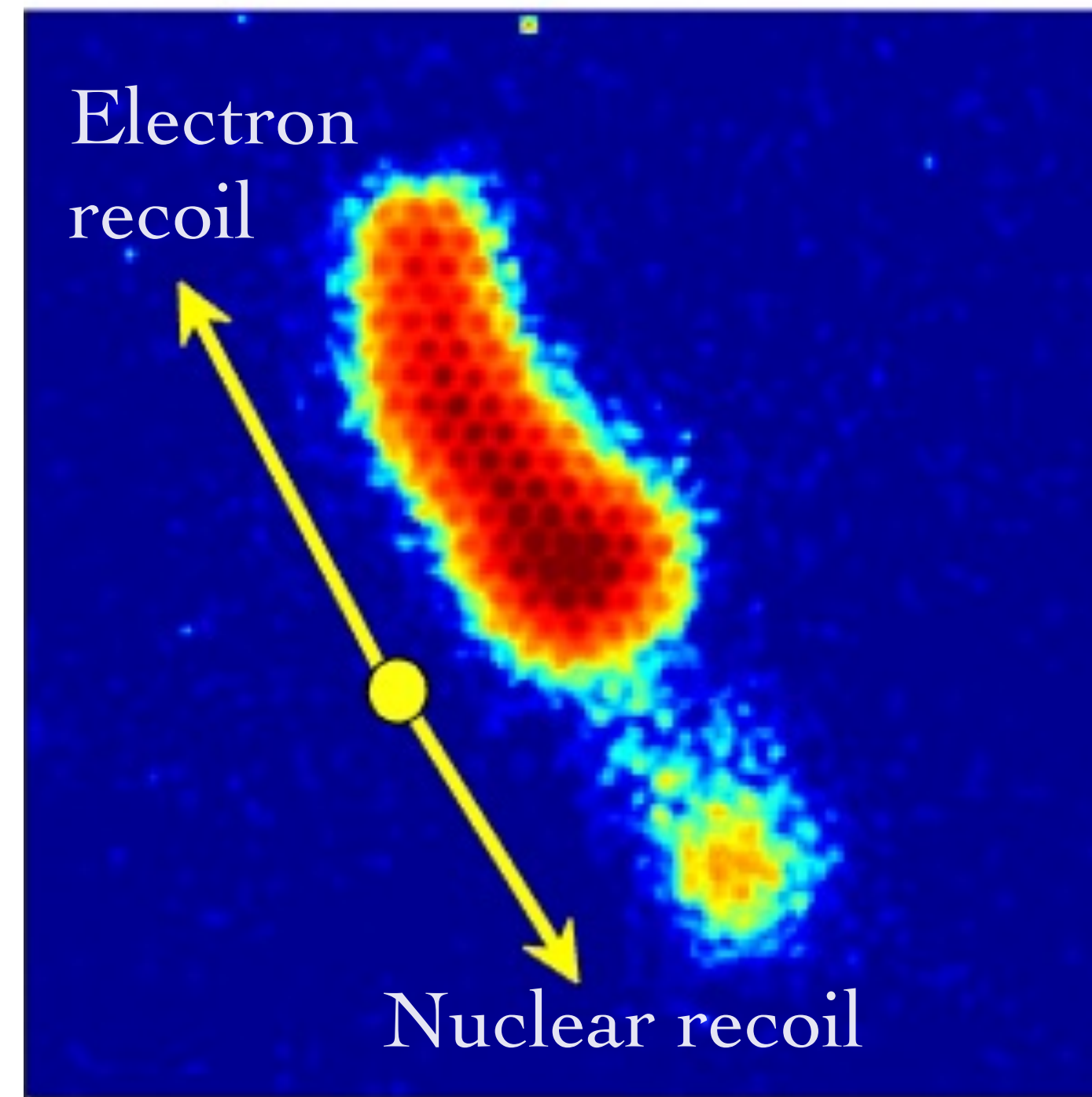
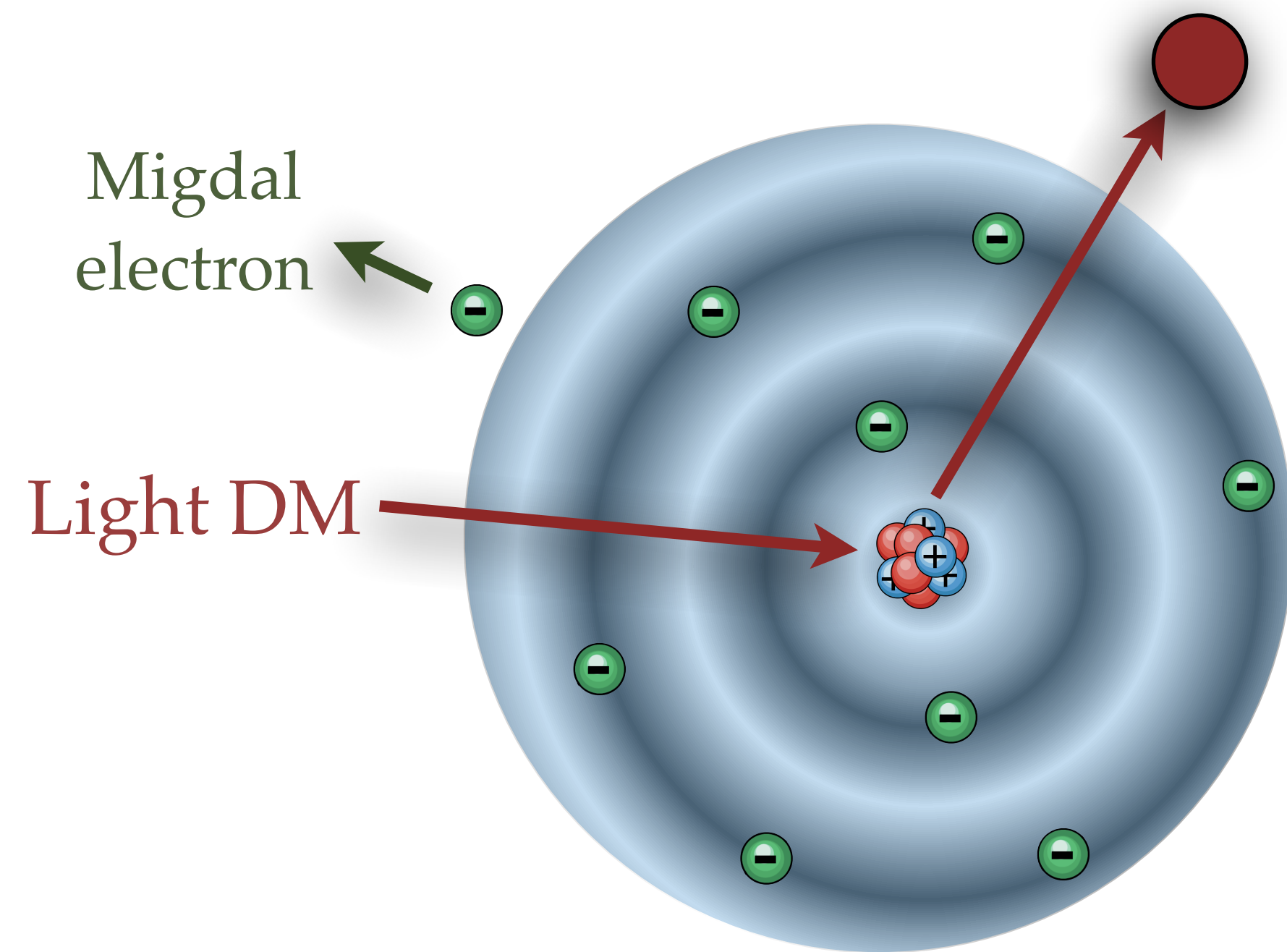
Neutrino events



DM events

General physics: Measurement of the Migdal effect

→ Emission of $\sim\text{keV}$ electron for very low energy NRs. Important for sub-GeV DM searches, but on shaky ground theoretically as it has never been measured

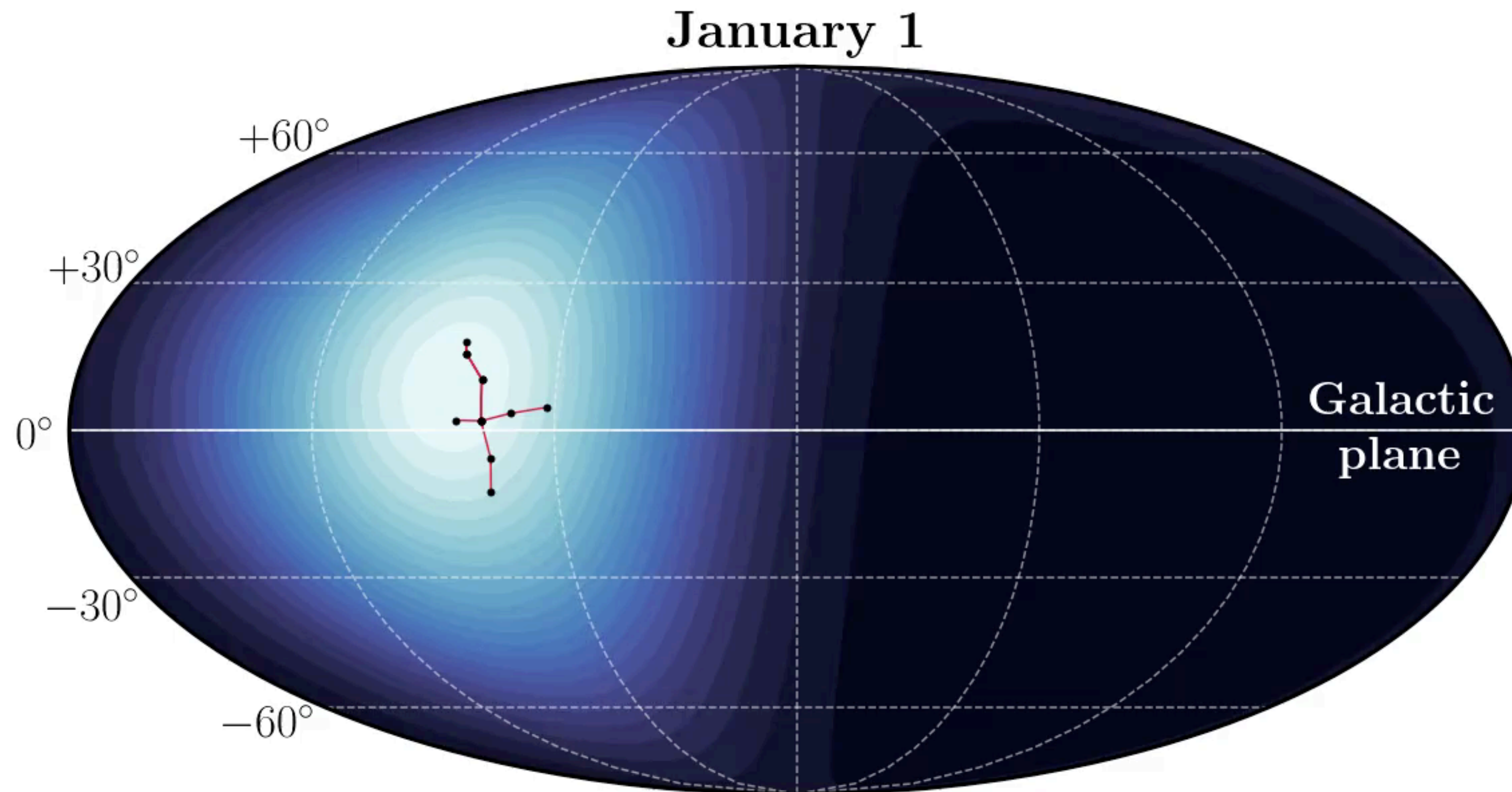


Could be confirmed directionally, using a small-scale TPC!

Based on standard assumptions, what should the signal look like?

→ a **Gaussian** peaking towards **Cygnus**

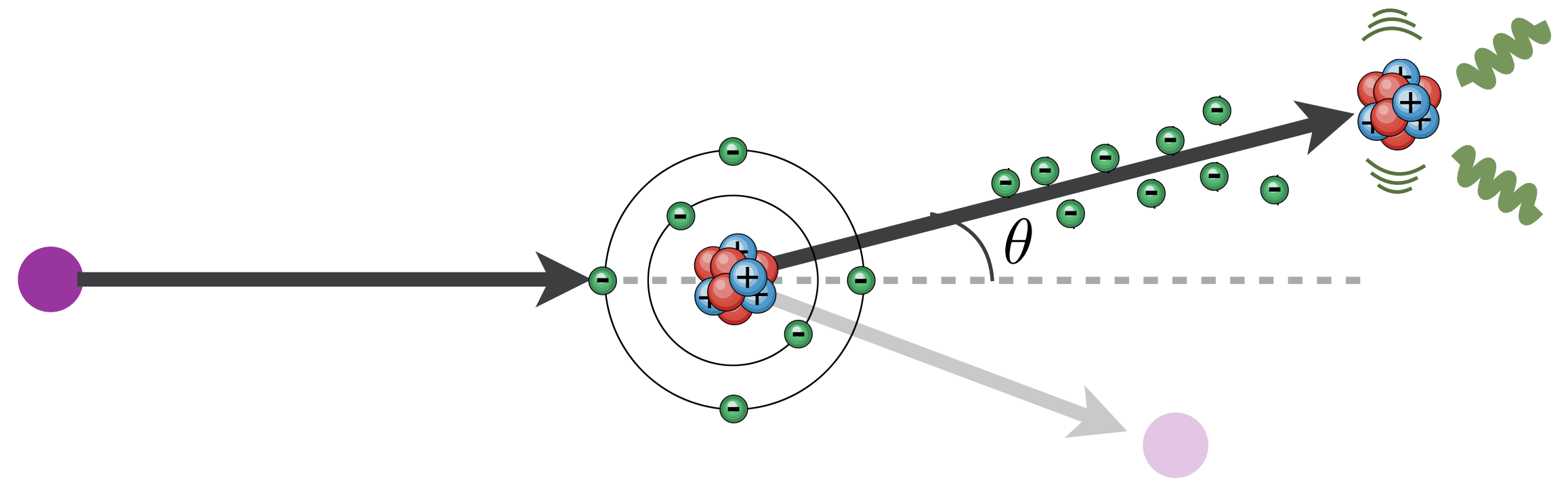
$$\left. \frac{dR(t)}{d \cos \theta} \right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp \left(-\frac{(v_{\min} + v_{\text{lab}}(t) \cos \theta)^2}{2\sigma_v^2} \right)$$



Standard prediction based on a few assumptions

- The DM scatters elastically

↳
$$E_r = \frac{2m_N m_\chi^2}{(m_N + m_\chi)^2} v^2 \cos^2 \theta$$



- The DM velocity distribution is a Gaussian (SHM)

↳
$$f(\mathbf{v}) \sim \exp \left(-\frac{(\mathbf{v} + \mathbf{v}_{\text{lab}})^2}{2\sigma_v^2} \right)$$

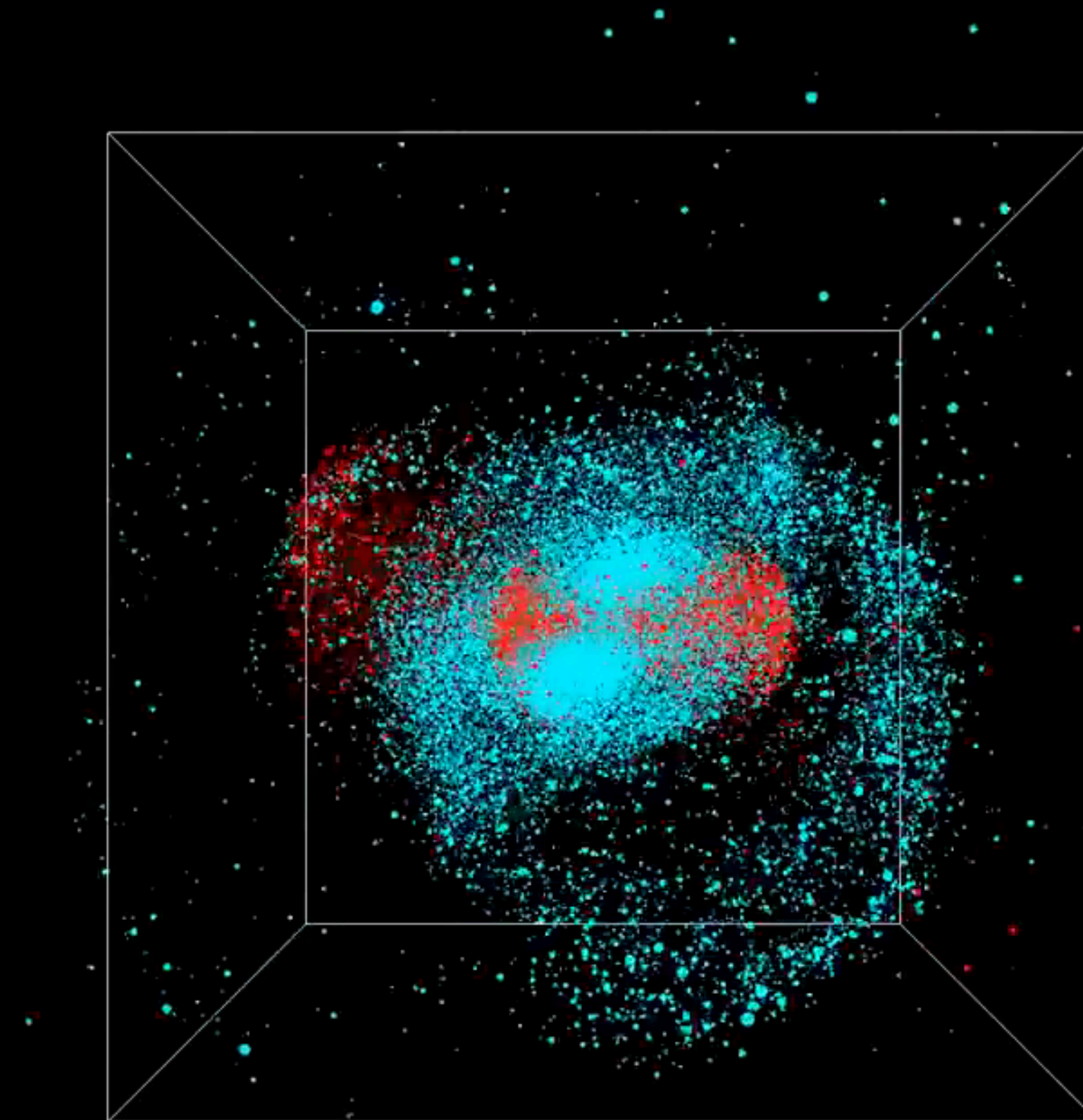
- DM-nucleus matrix element does not depend on velocity

↳
$$\frac{dR}{d\Omega} \sim \int \delta(v \cos \theta - v_{\text{min}}) f(\mathbf{v}) d^3\mathbf{v}$$

Should the DM velocity distribution be a Gaussian?

→ Evidence of significant merger in the MW's history

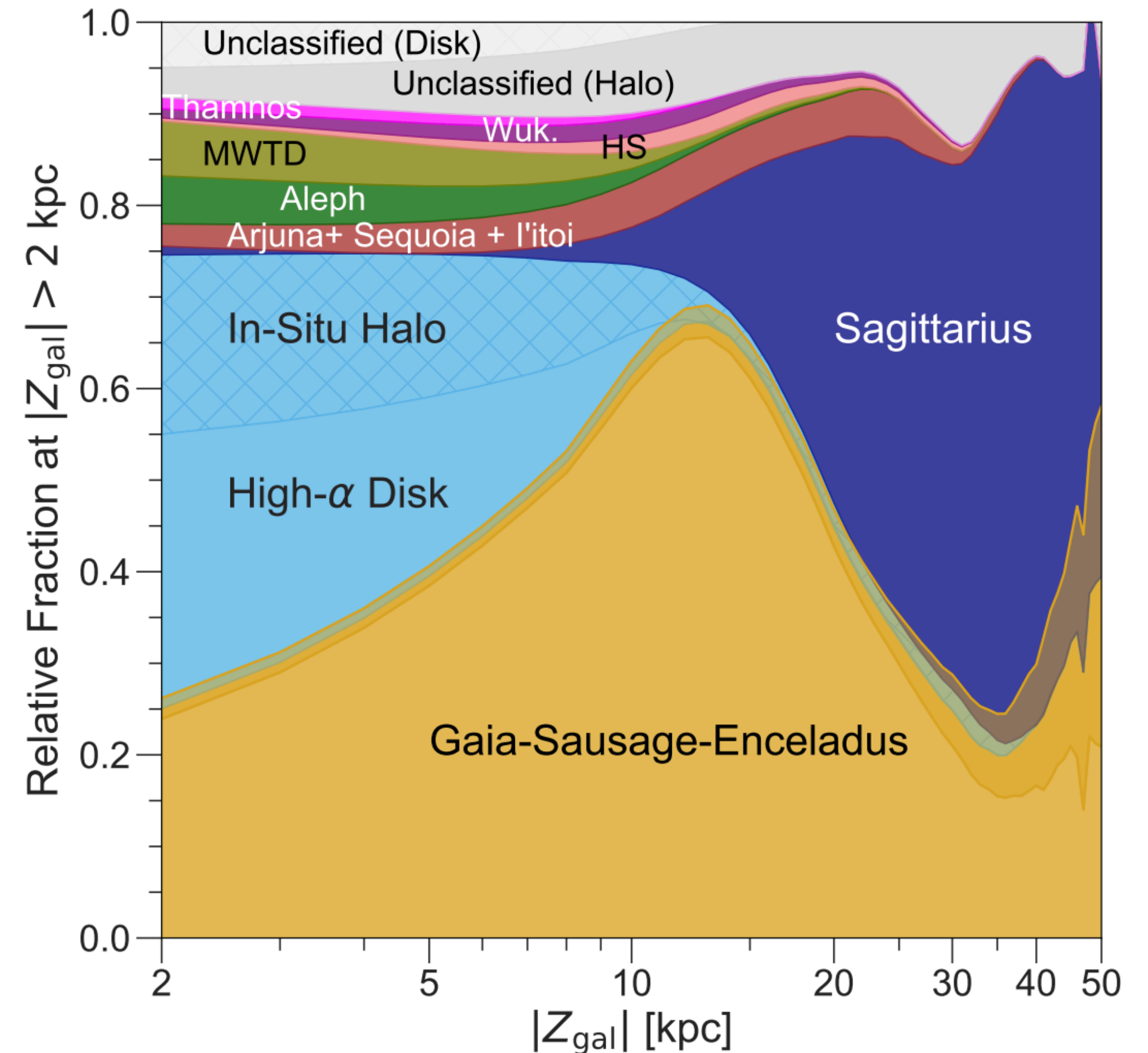
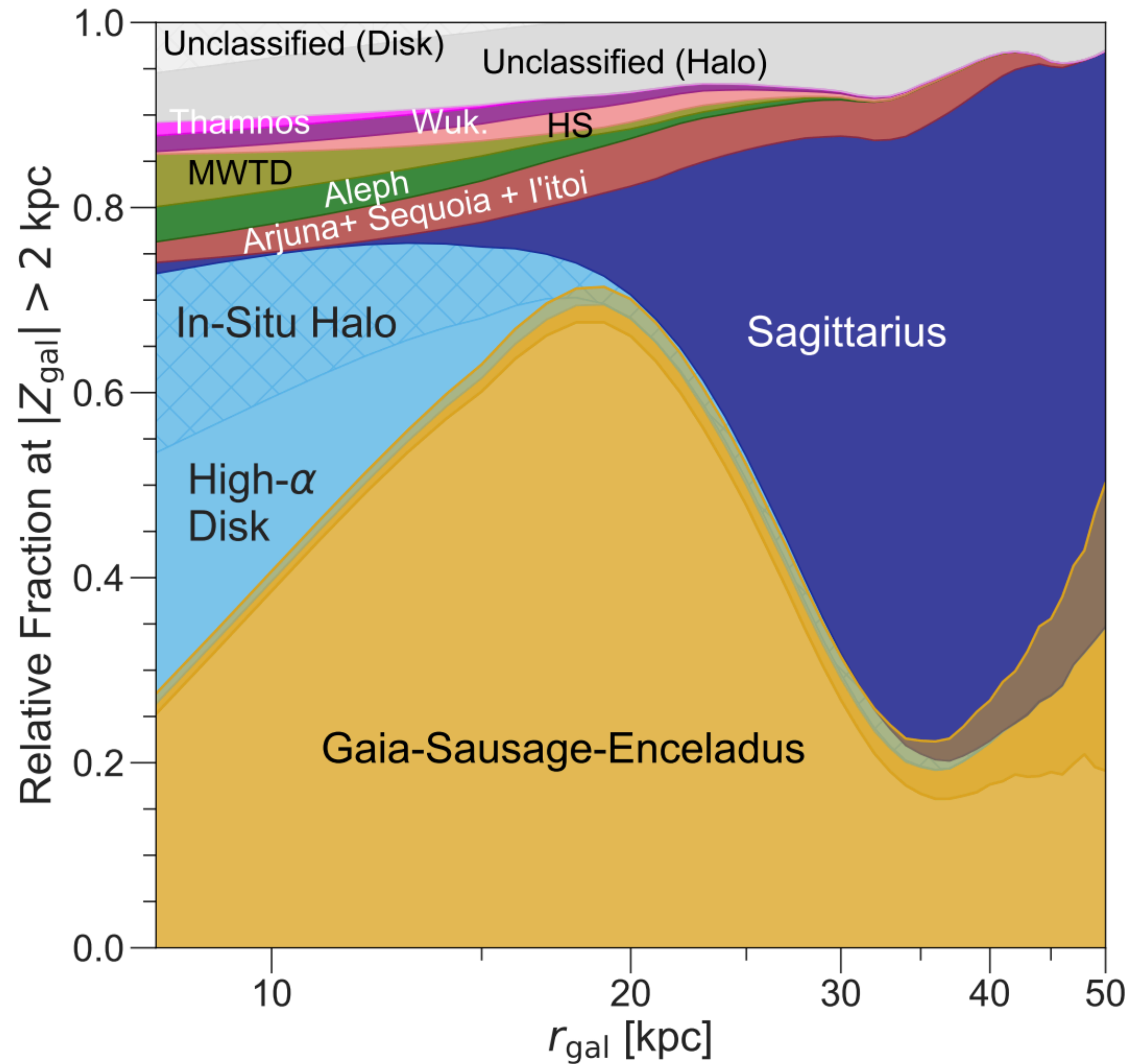
The Gaia Sausage



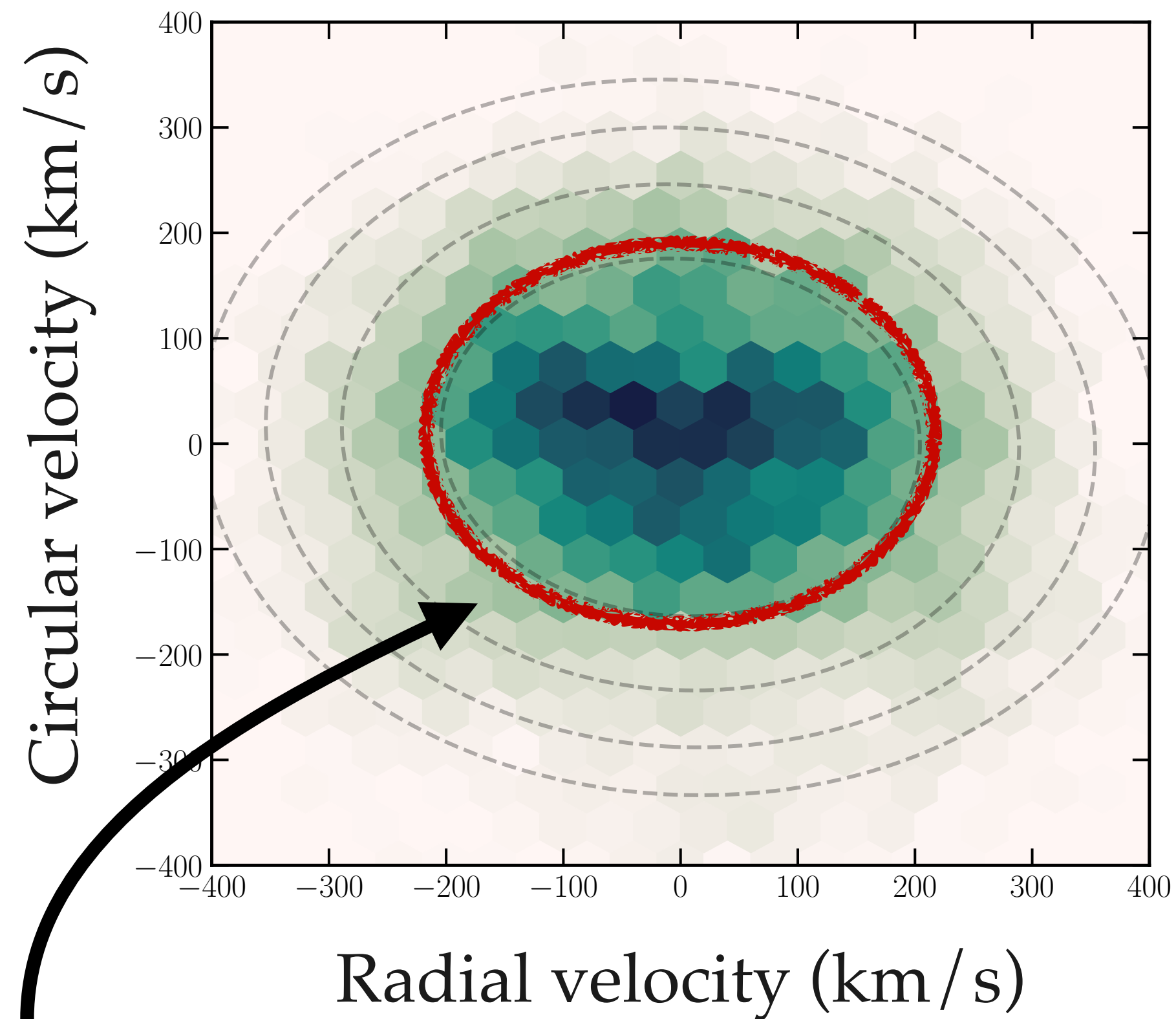
See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

Evidence from the H3 Survey that the Stellar Halo is Entirely Comprised of Substructure

ROHAN P. NAIDU,¹ CHARLIE CONROY,¹ ANA BONACA,¹ BENJAMIN D. JOHNSON,¹ YUAN-SEN TING (丁源森),^{2,3,4,5,*}
NELSON CALDWELL,¹ DENNIS ZARITSKY,⁶ AND PHILLIP A. CARGILE¹



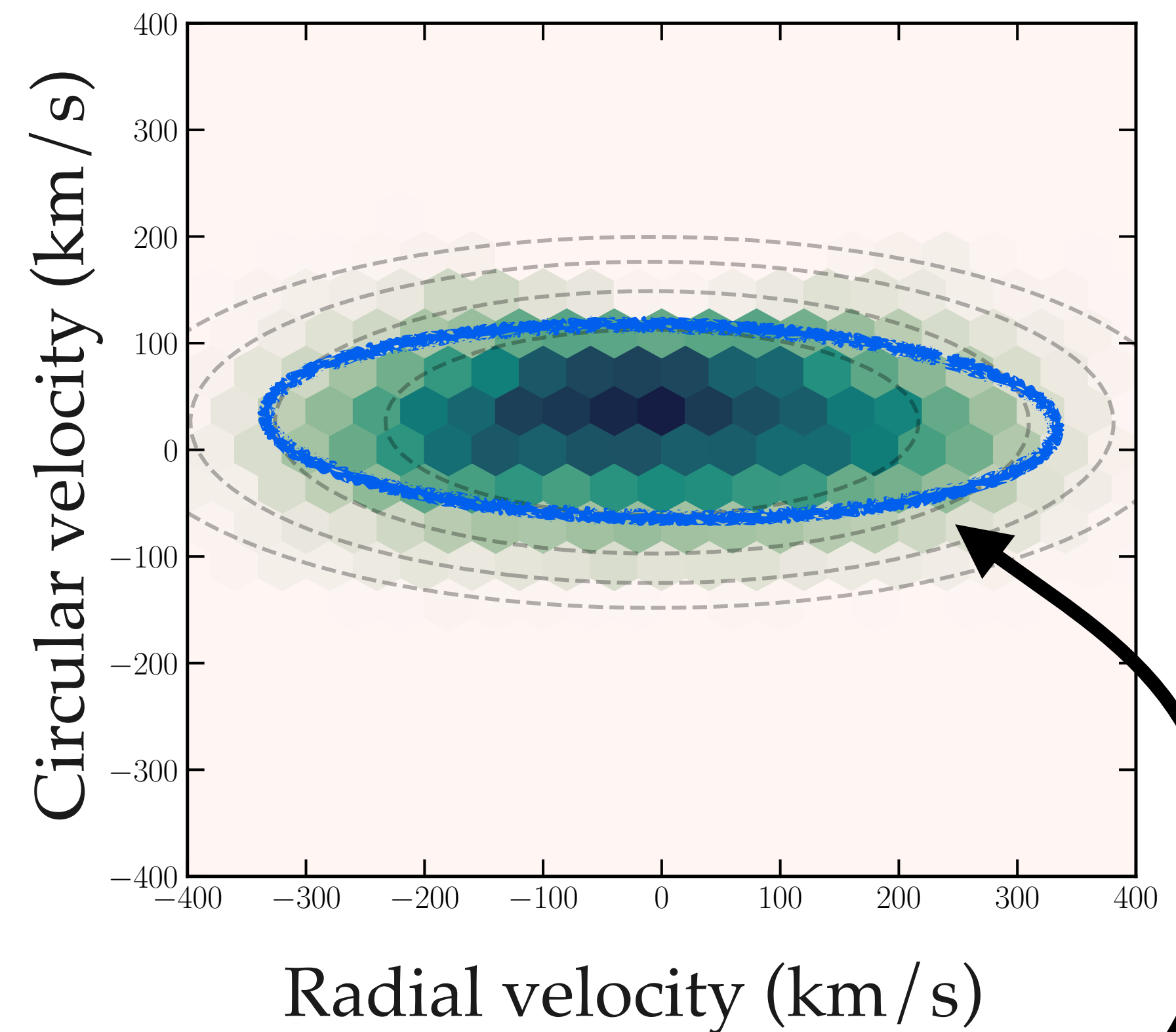
$[\text{Fe}/\text{H}] < -1.5$



“Metal-poor” halo

- Round velocity ellipsoid
- $\sim 30\%$ of main sequence halo sample
- More metal-poor on average

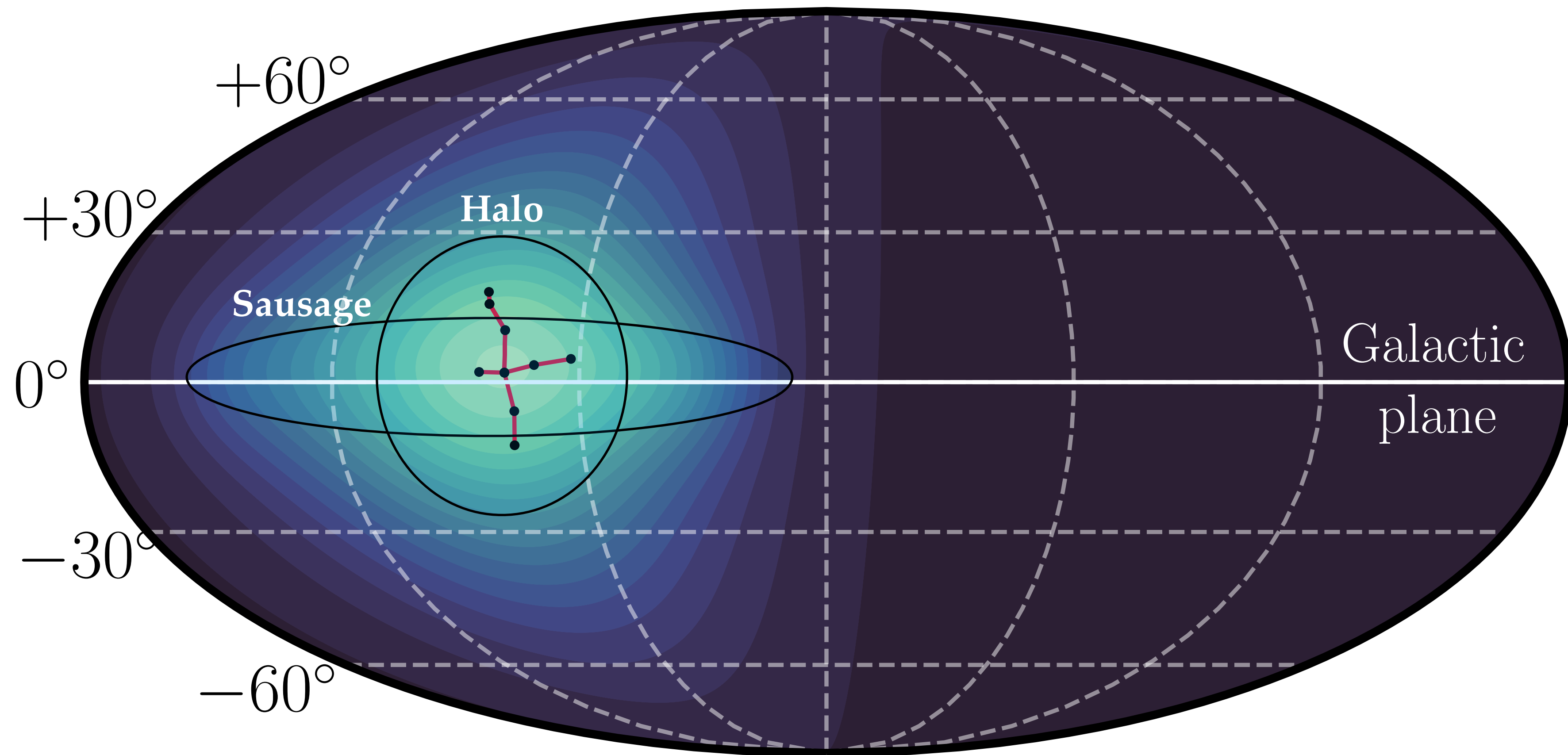
$[\text{Fe}/\text{H}] > -1.5$



“Metal-rich” halo

- Highly eccentric radial orbits
- Dominant contribution $\sim 50\%$
- Characteristic metallicity $[\text{Fe}/\text{H}] = -1.4$

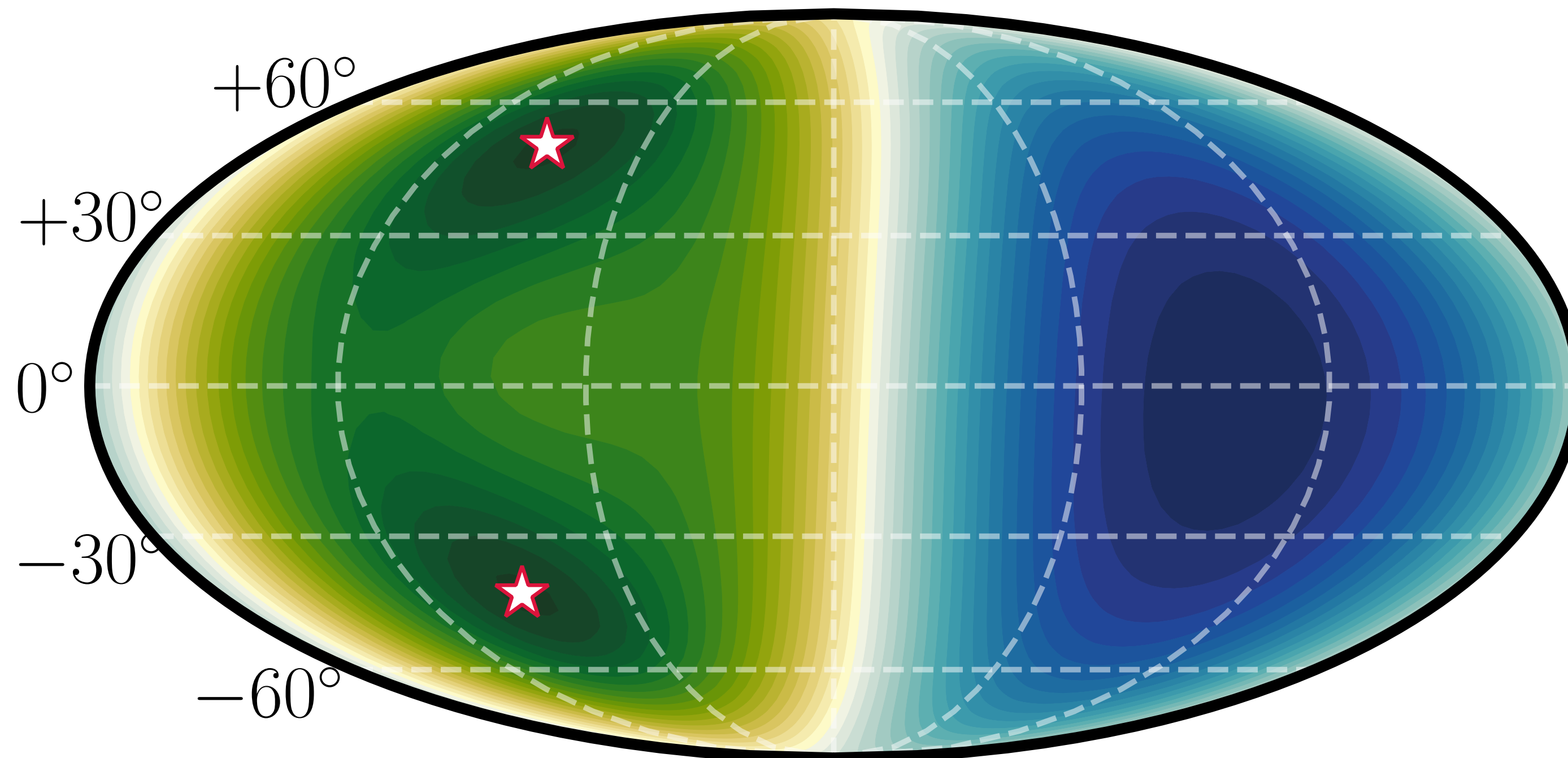
Flux of DM from the Gaia Sausage versus the rest of the halo



The Gaia Sausage gives rise to peaks off center from Cygnus

O'Hare+ [1909.04684]

5 – 10 keV



Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP

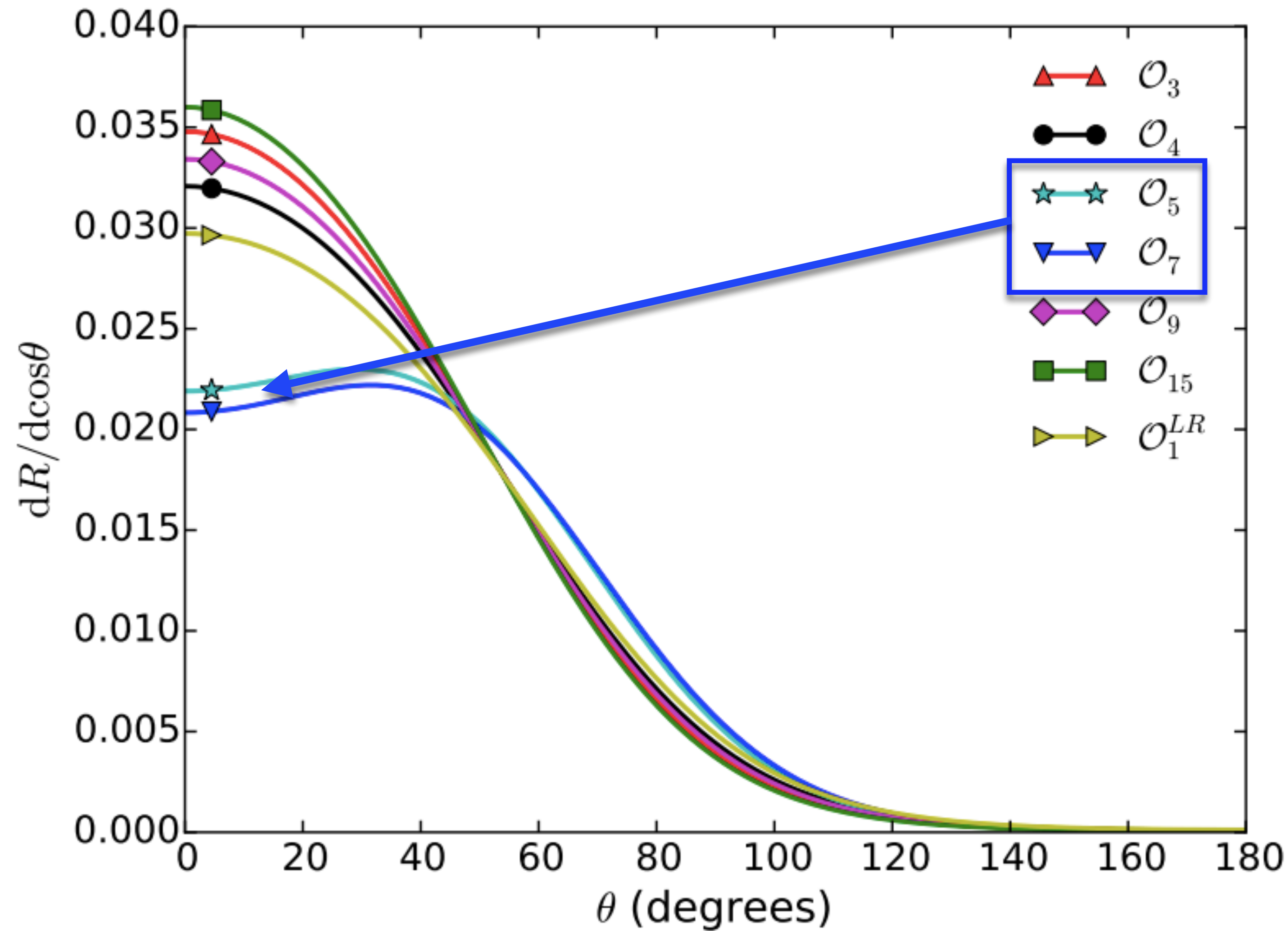
Halo model = SHM + Sausage

Non-relativistic EFT of DM-nucleus interaction

Allows for operators (e.g. $\mathcal{O}_5$, $\mathcal{O}_7$) dependent on transverse velocity:

Kavanagh [1505.07406]

→ Non-Gaussian angular distributions



DNA detector?

New Dark Matter Detectors using DNA or RNA for Nanometer Tracking

Andrzej Drukier,^{1,*} Katherine Freese,^{2,3,†} Alejandro Lopez,^{2,‡} David Spergel,^{4,§} Charles Cantor,^{5,¶} George Church,^{6,**} and Takeshi Sano^{7,††}

¹ *BioTraces Inc., 5660 Oak Tanager Ct., Burke, Va. 22015*

² *Michigan Center for Theoretical Physics, Department of Physics,
University of Michigan, Ann Arbor, MI 48109*

³ *Physics Department, Caltech, Pasadena, CA 91101*

1206.6809

DNA-based particle detector?

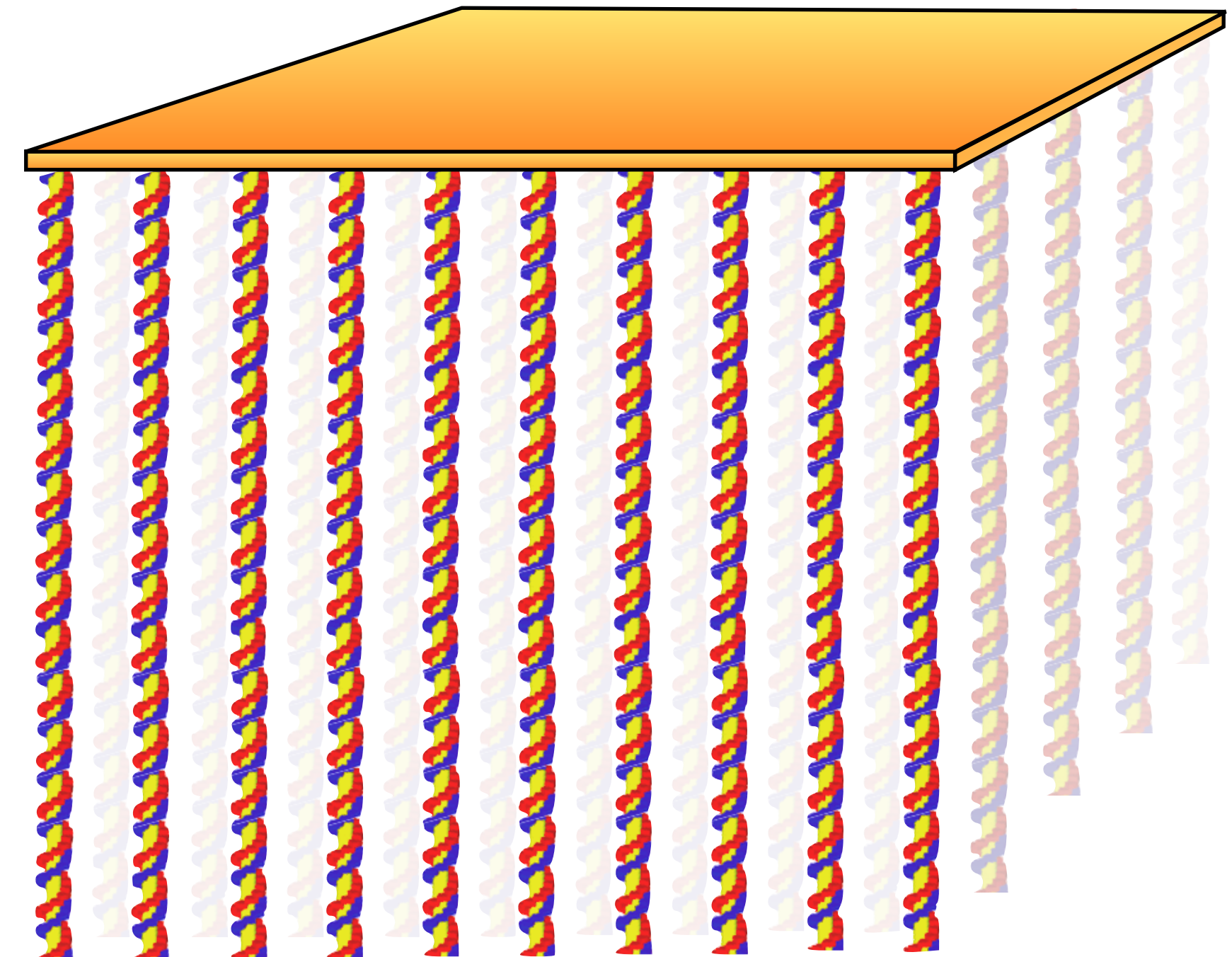
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases



DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

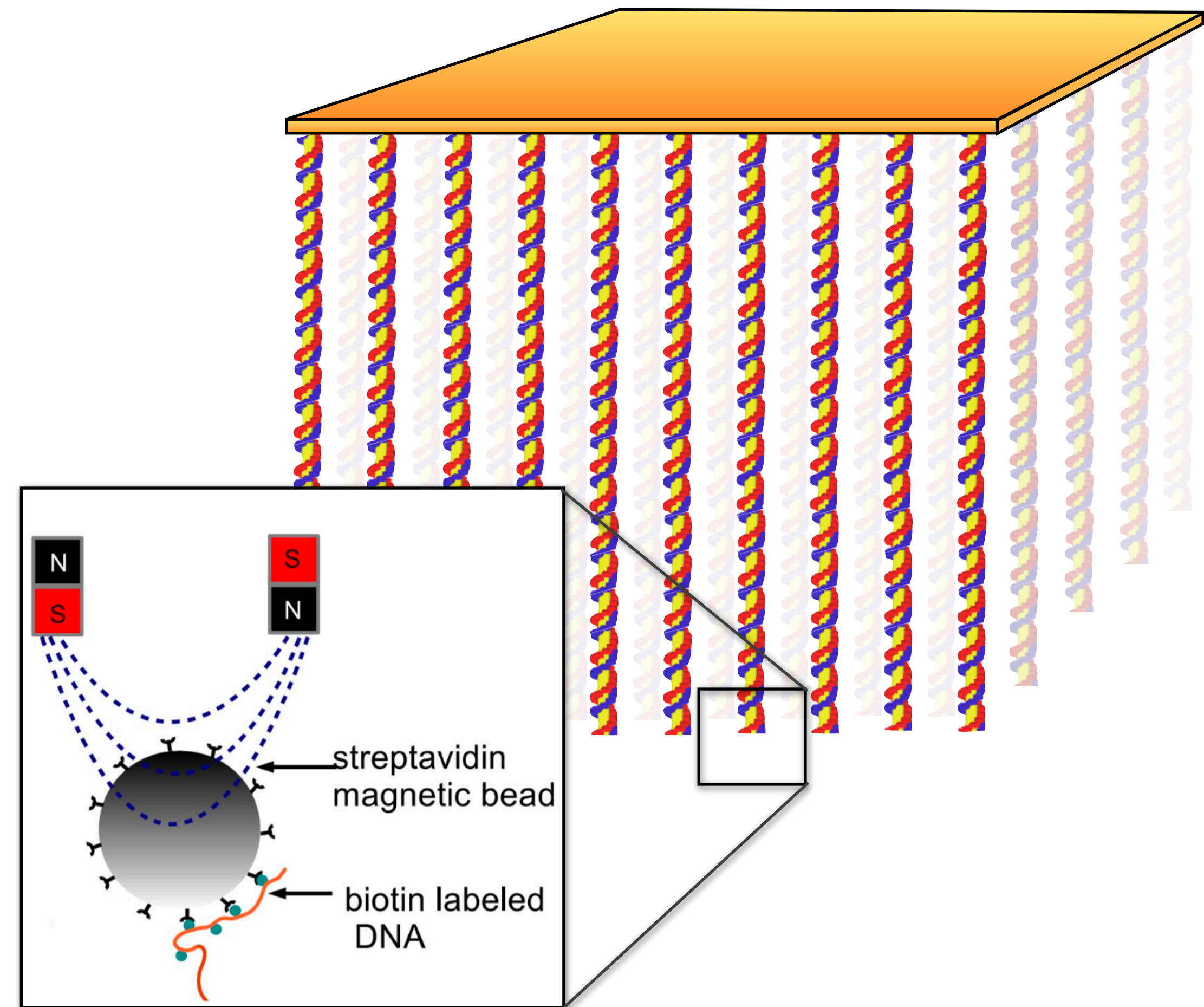


DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand



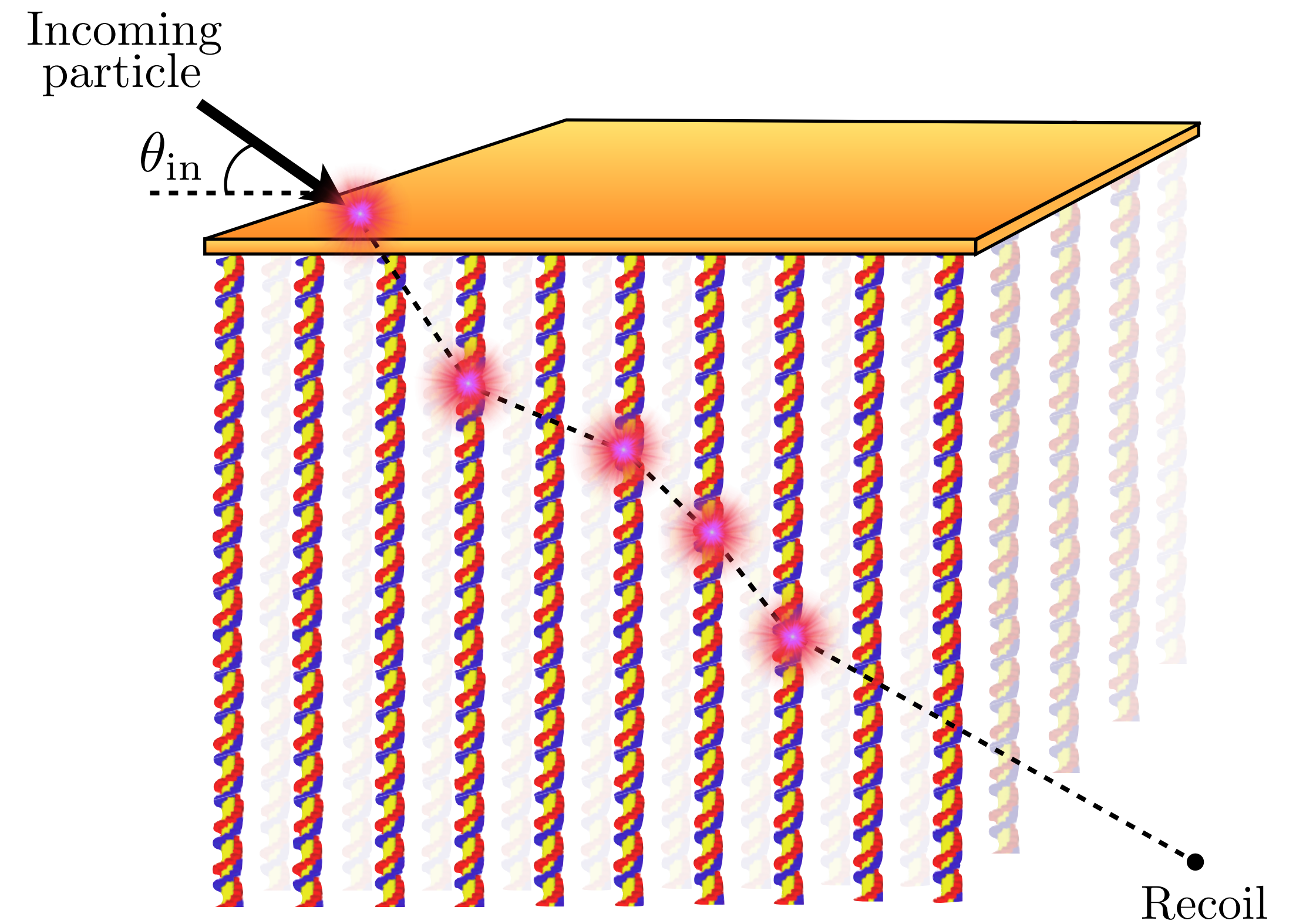
DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases



DNA-based particle detector?

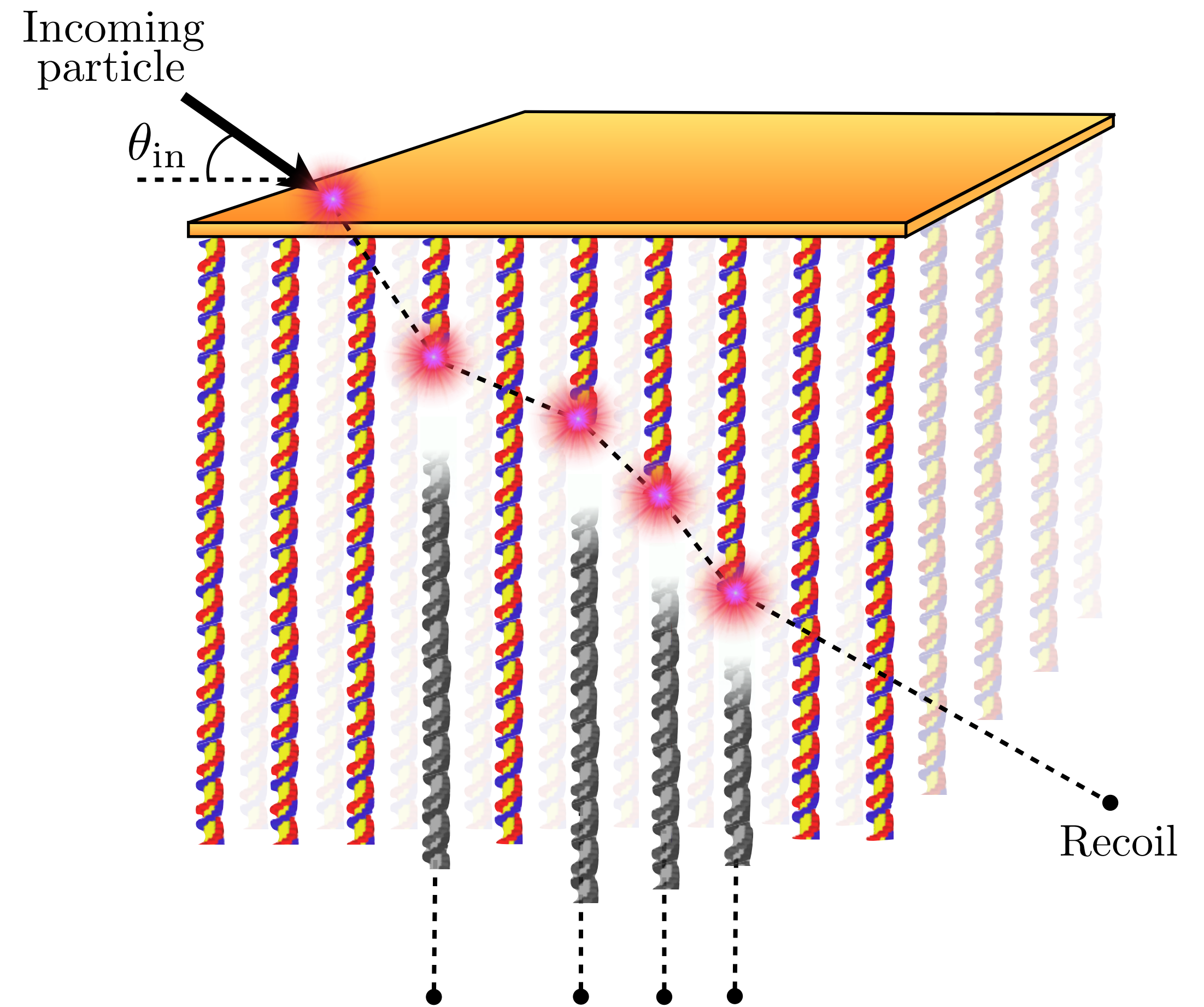
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases

Step 5: Broken strand segments fall down



DNA-based particle detector?

Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

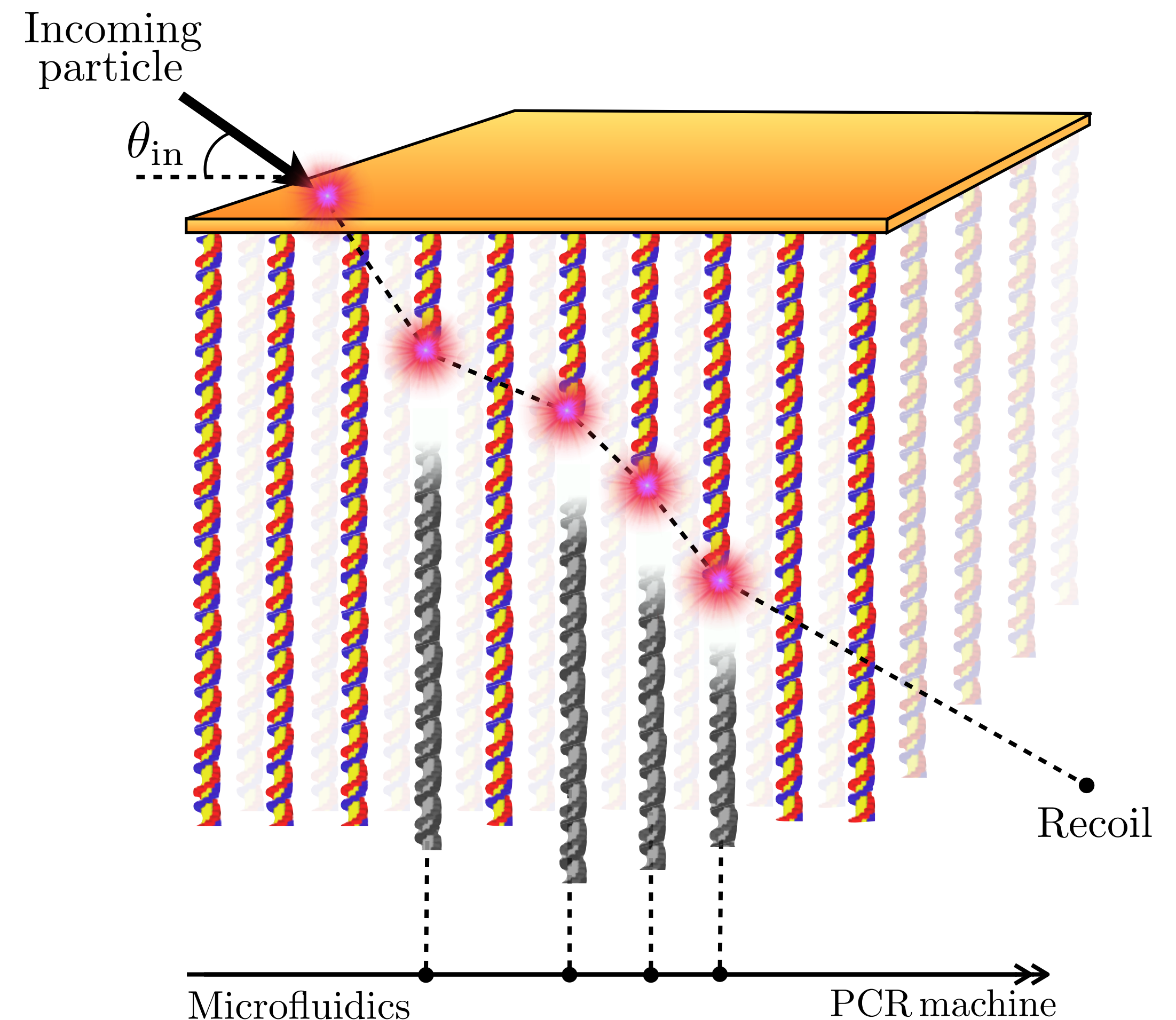
Step 2: Attach them in a regular pattern to a thin substrate made of a high density material

Step 3: Attach a paramagnetic bead to each strand

Step 4: Particles come in and break a sequence of bases

Step 5: Broken strand segments fall down

Step 6: System of microfluidics transports the strand segments to a PCR machine which amplifies them and the original (x,y,z) positions are reconstructed

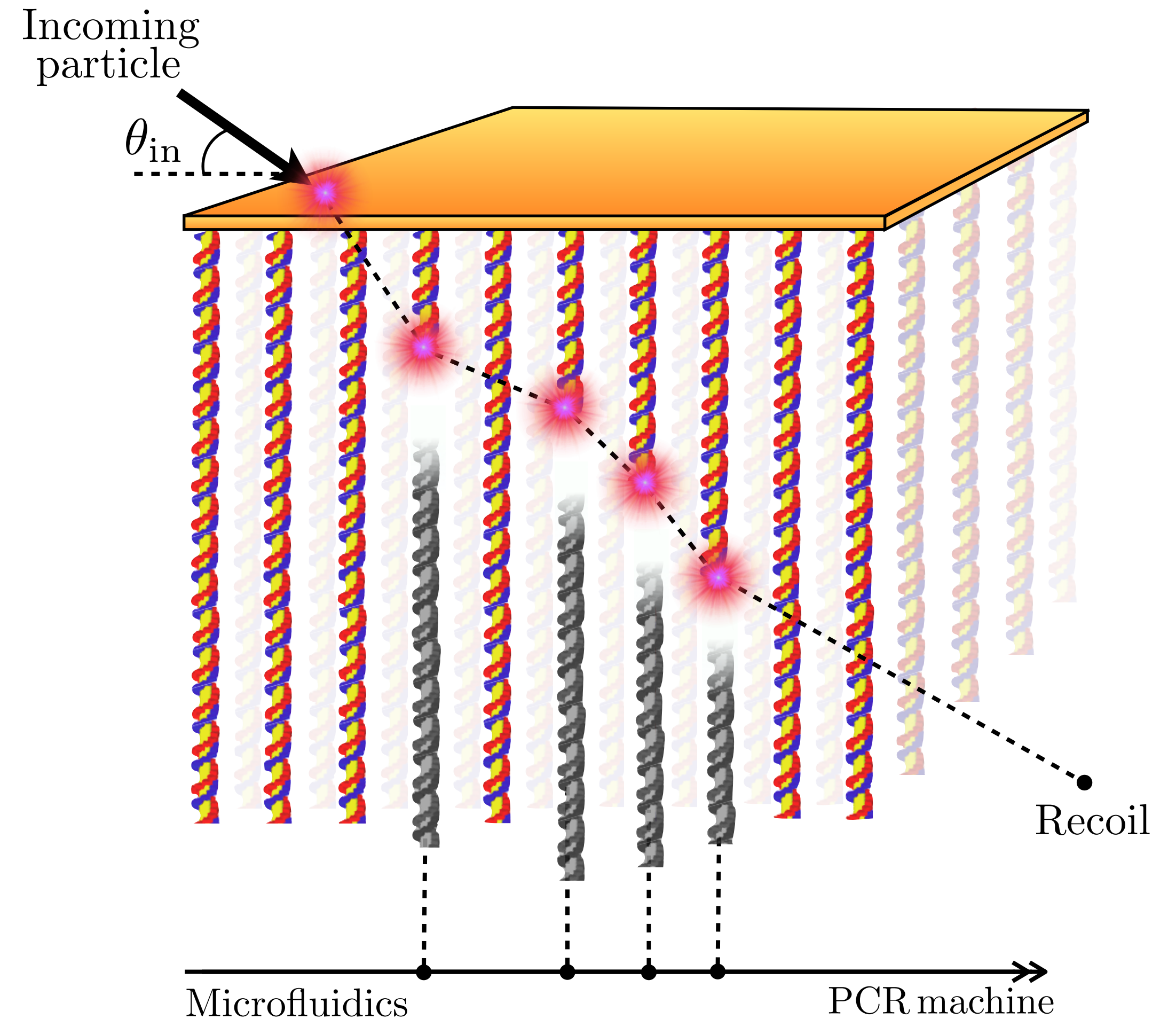


DNA-based particle detector?

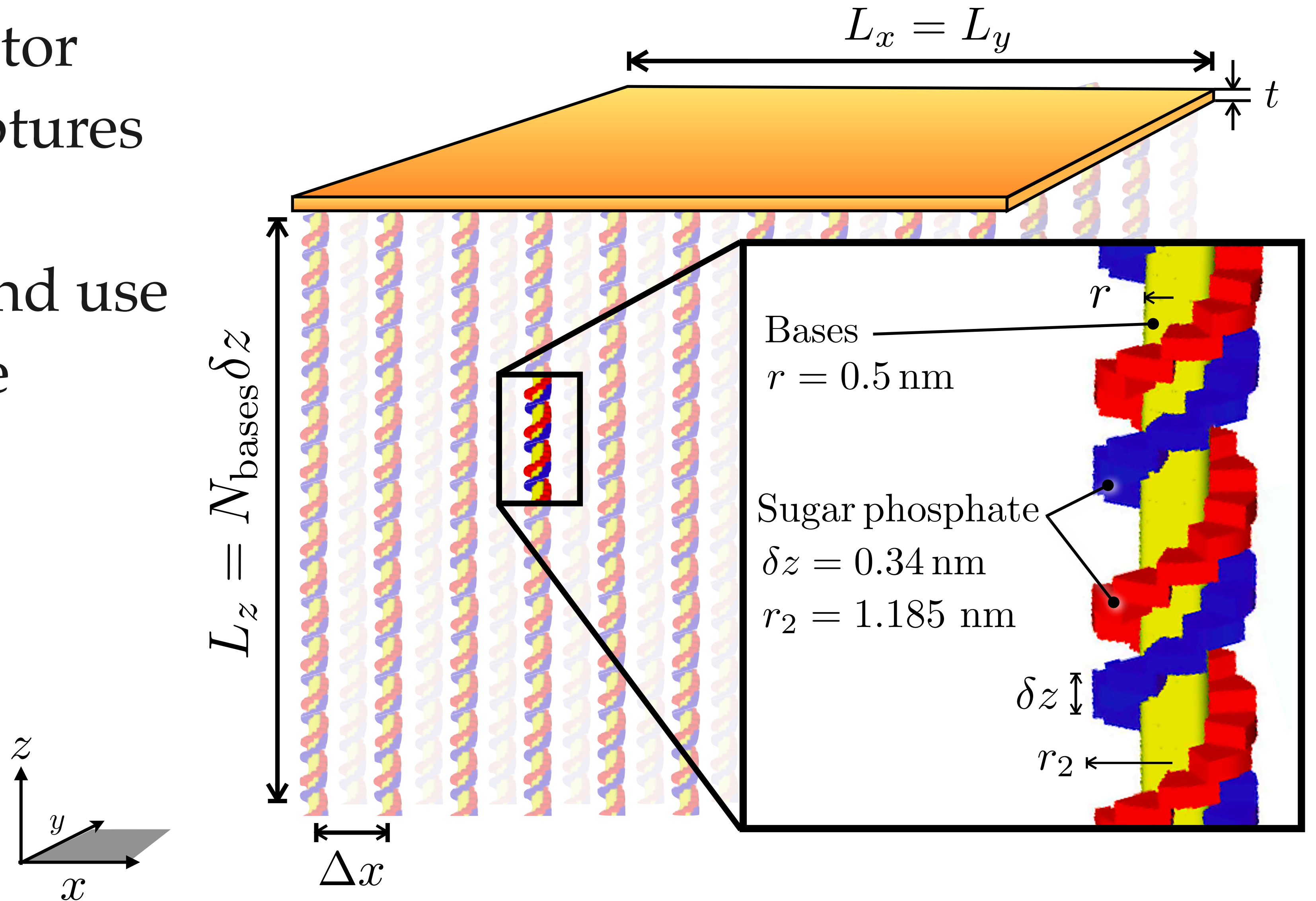
How crazy is it?

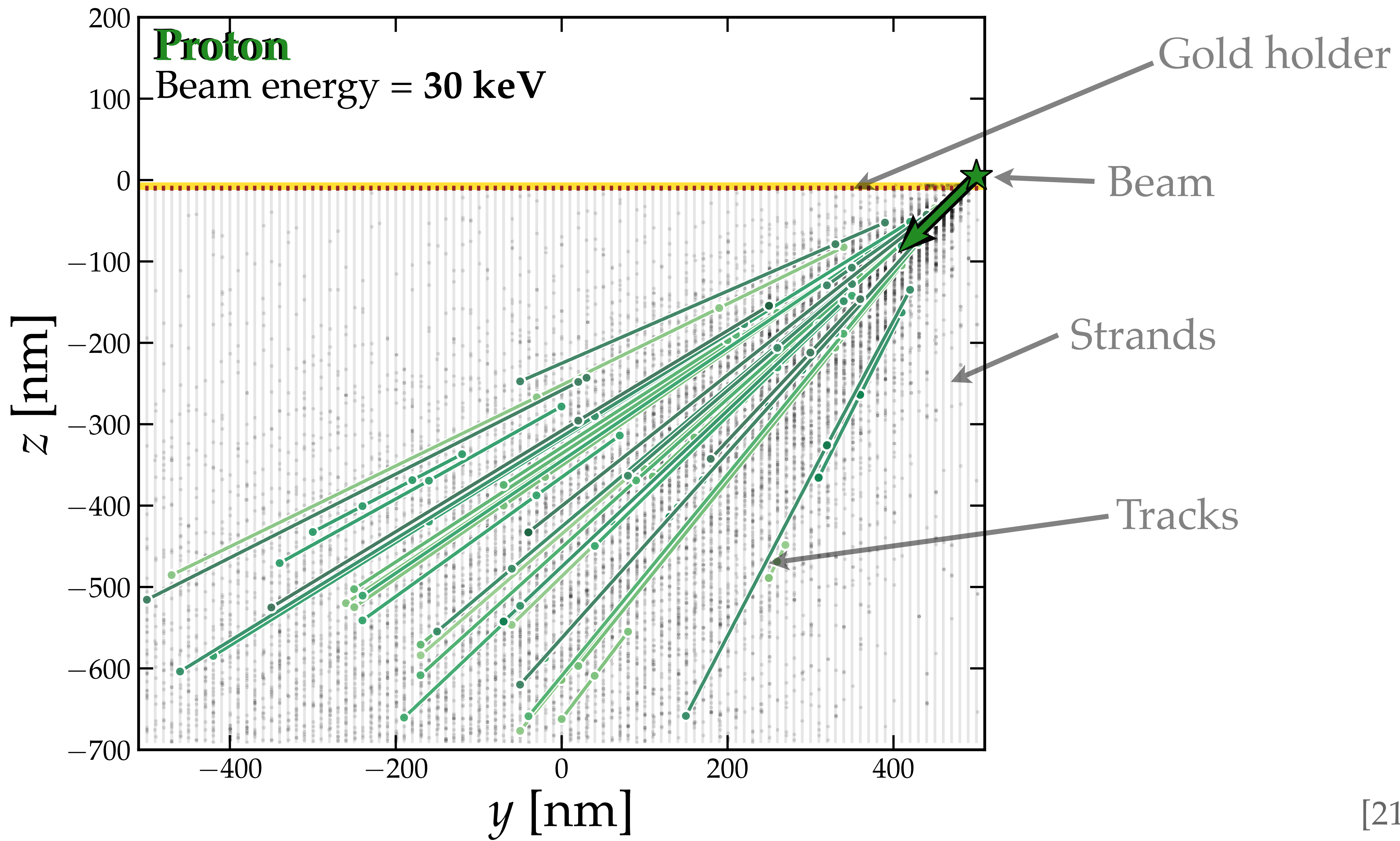
Putting aside the obvious experimental challenge, there is a clear advantage in the context of directional detection

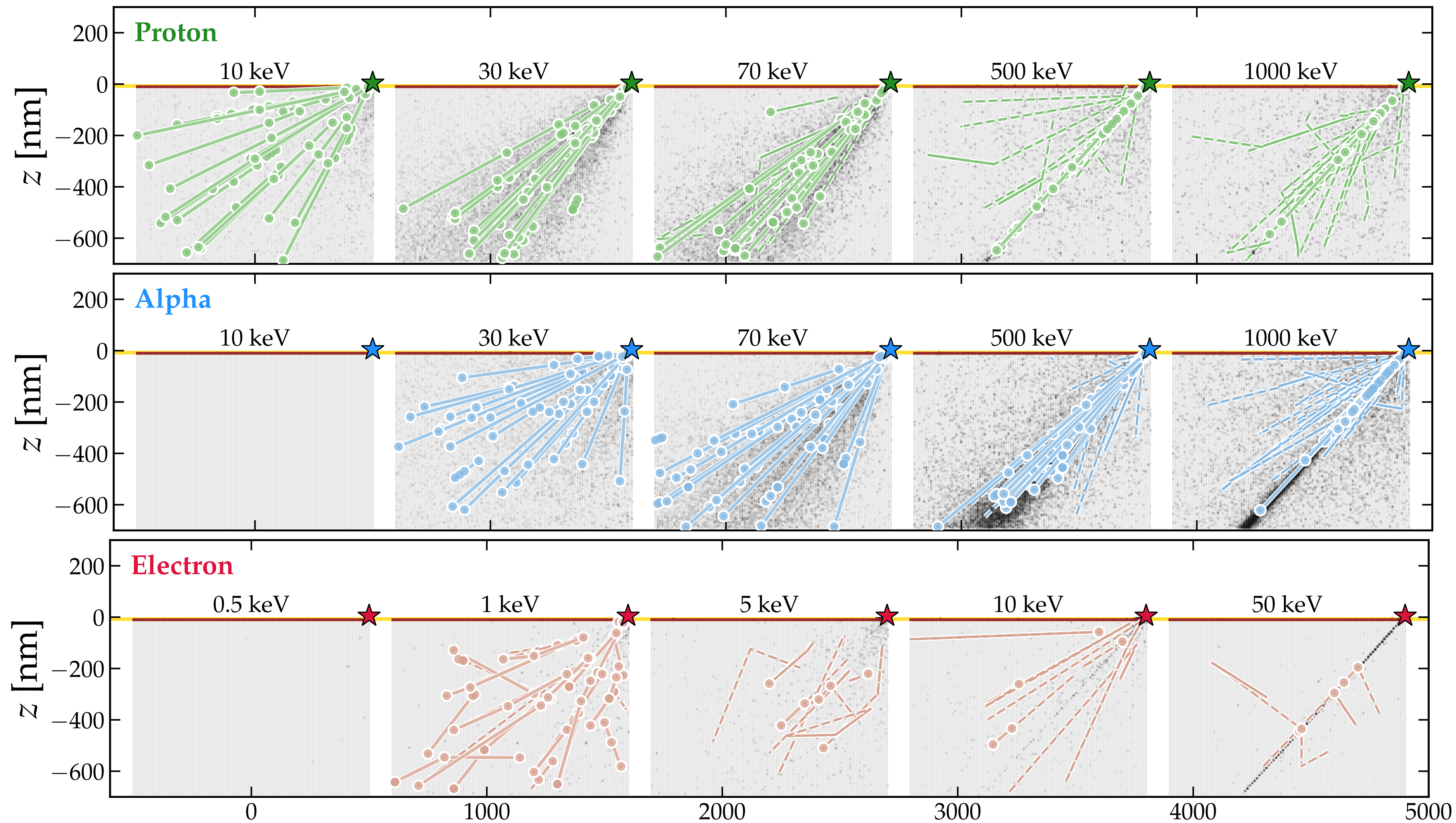
→ No diffusion and no nanoscale interrogation required

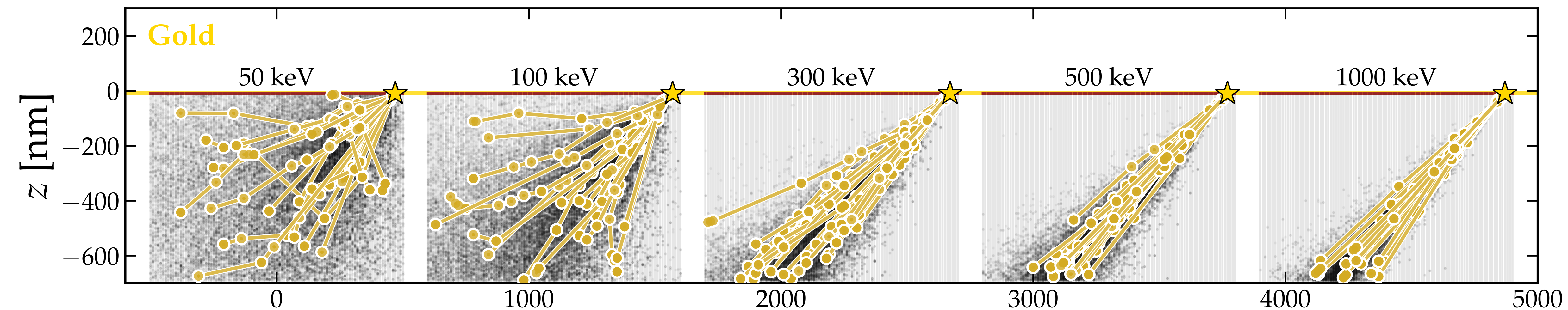
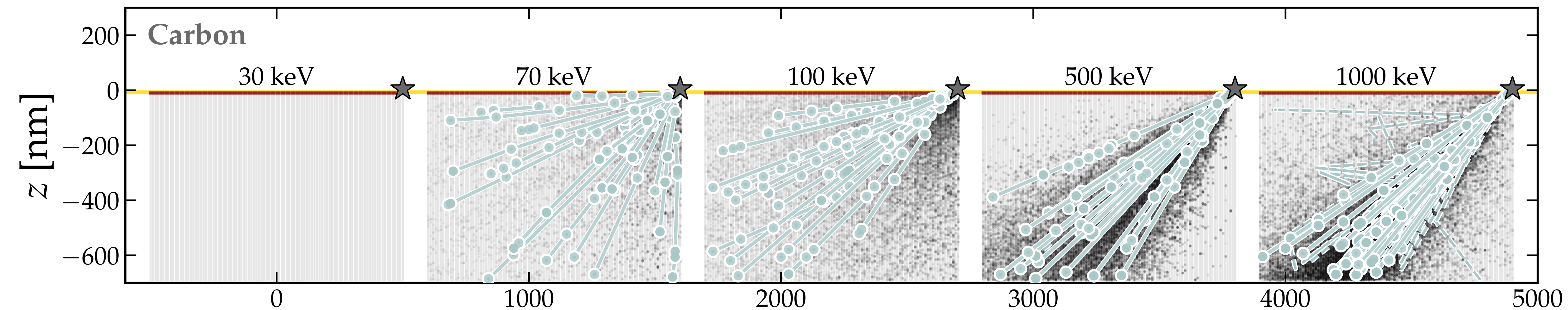


Idea: Lets make a crude model of the detector which roughly captures the geometry and material content and use Geant4 to simulate particle tracks





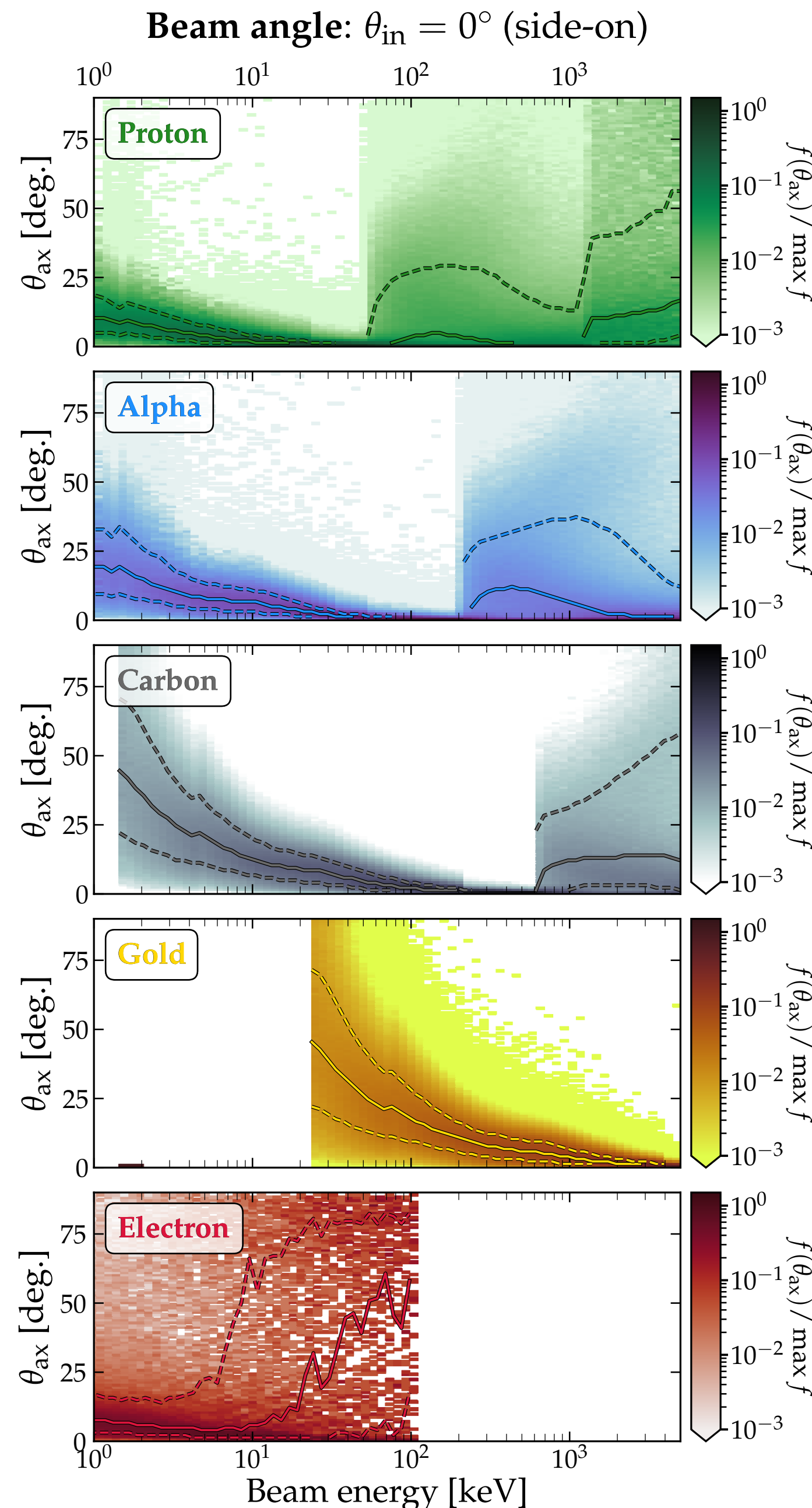




Main conclusions from the μm^3 unit simulation

← Track directions well-preserved. Around 25° angular res. for *initial* recoil direction

- Particle ID and energy reconstruction not really possible, need to look at tracks over many units and measure dE/dx
- Need to find a good purpose for the idea...



Experimental side

- **Detector construction** →
DNA-origamists can make practically anything

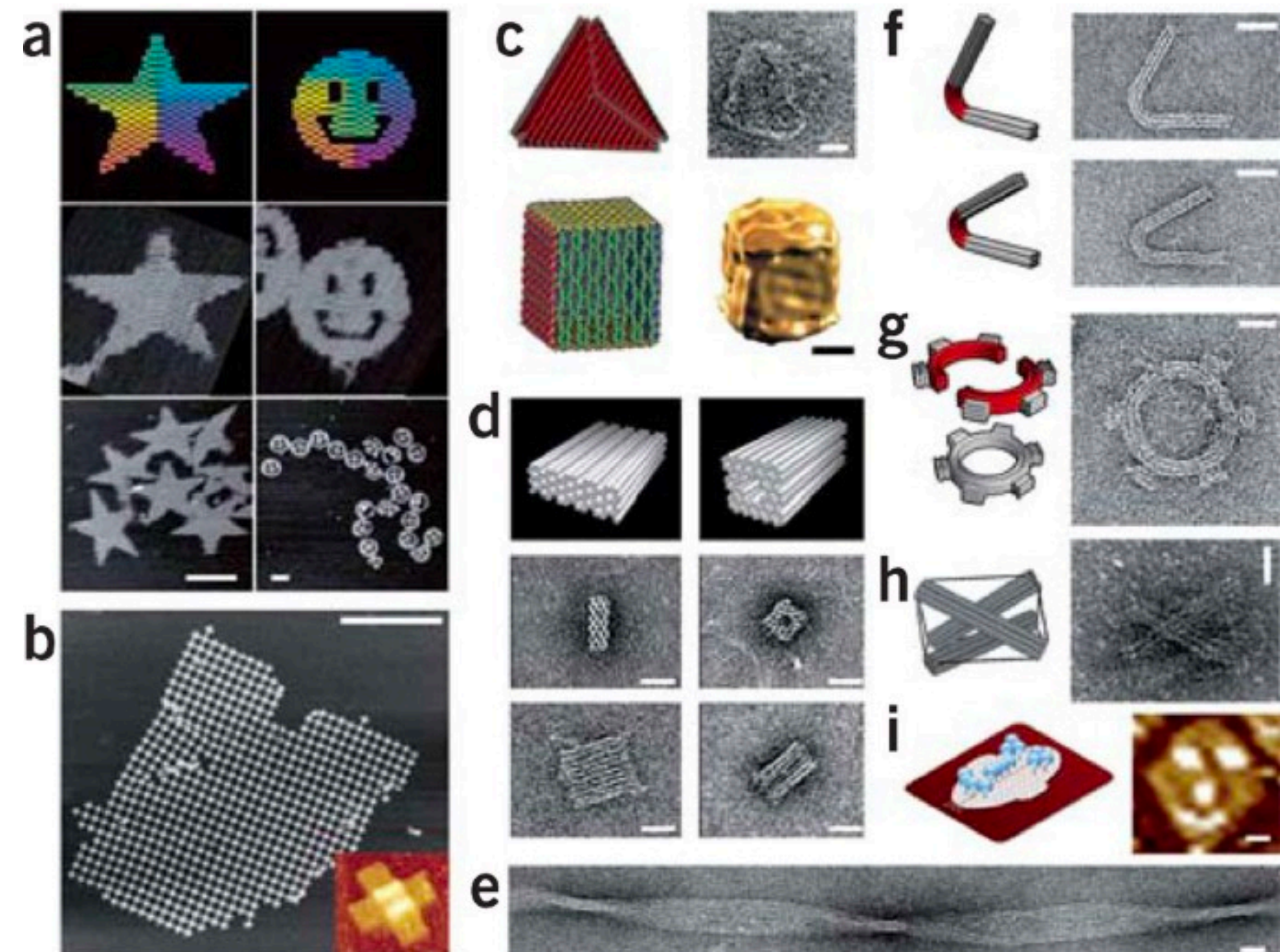
Primer | Published: 28 January 2021

DNA origami

Swarup Dey, Chunhai Fan , Kurt V. Gothelf , Jiang Li , Chenxiang Lin , Longfei Liu, Na Liu ,
Minke A. D. Nijenhuis, Barbara Saccà , Friedrich C. Simmel , Hao Yan  & Pengfei Zhan

Nature Reviews Methods Primers 1, Article number: 13 (2021) | [Cite this article](#)

11k Accesses | 7 Citations | 25 Altmetric | [Metrics](#)

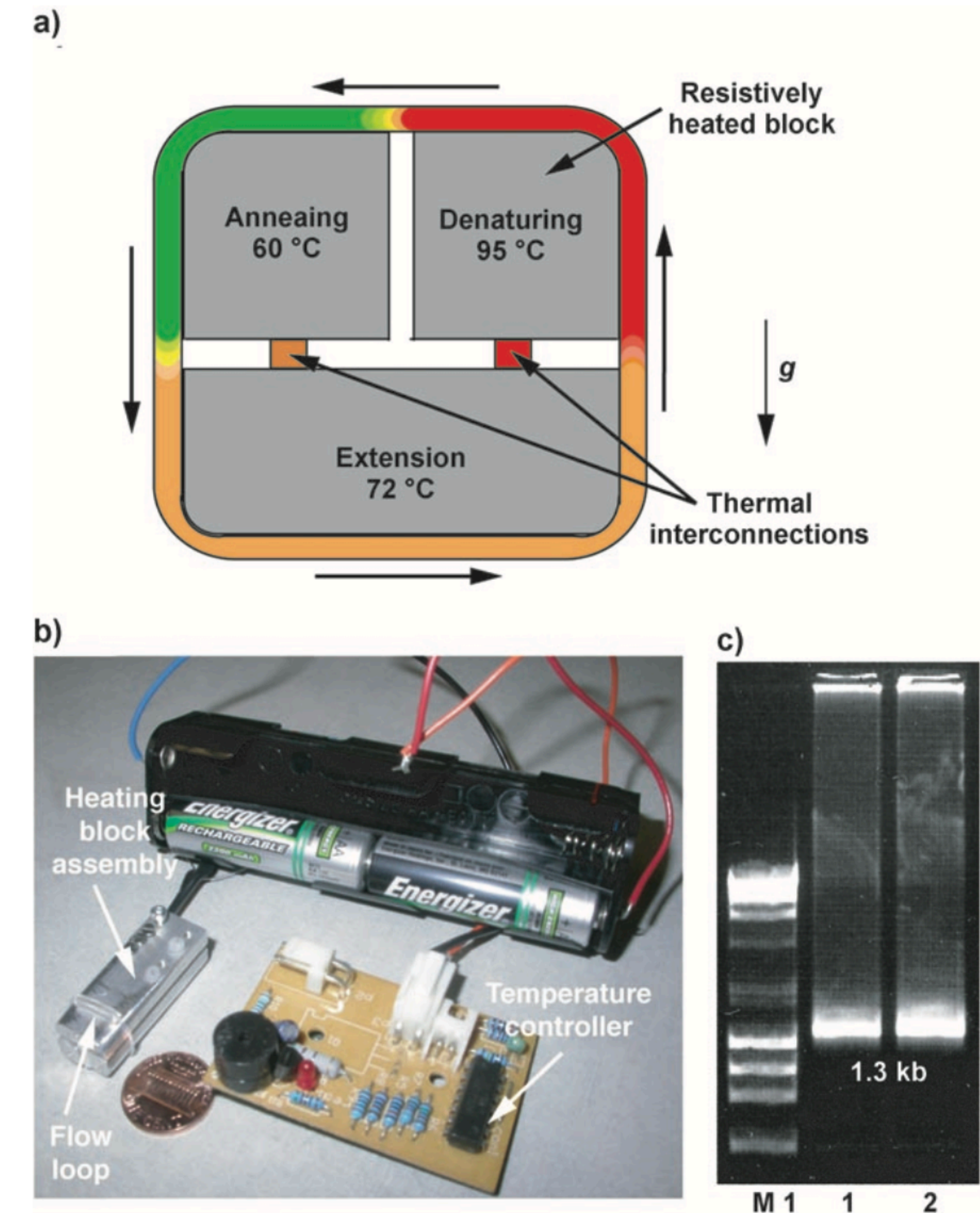


Experimental side

- **Detector construction** → DNA-origamists can make practically anything
- **PCR machines** → cheap, commercially available, portable, and fast.

A Pocket-Sized Convective PCR Thermocycler**

*Nitin Agrawal, Yassin A. Hassan, and Victor M. Ugaz**



Experimental side

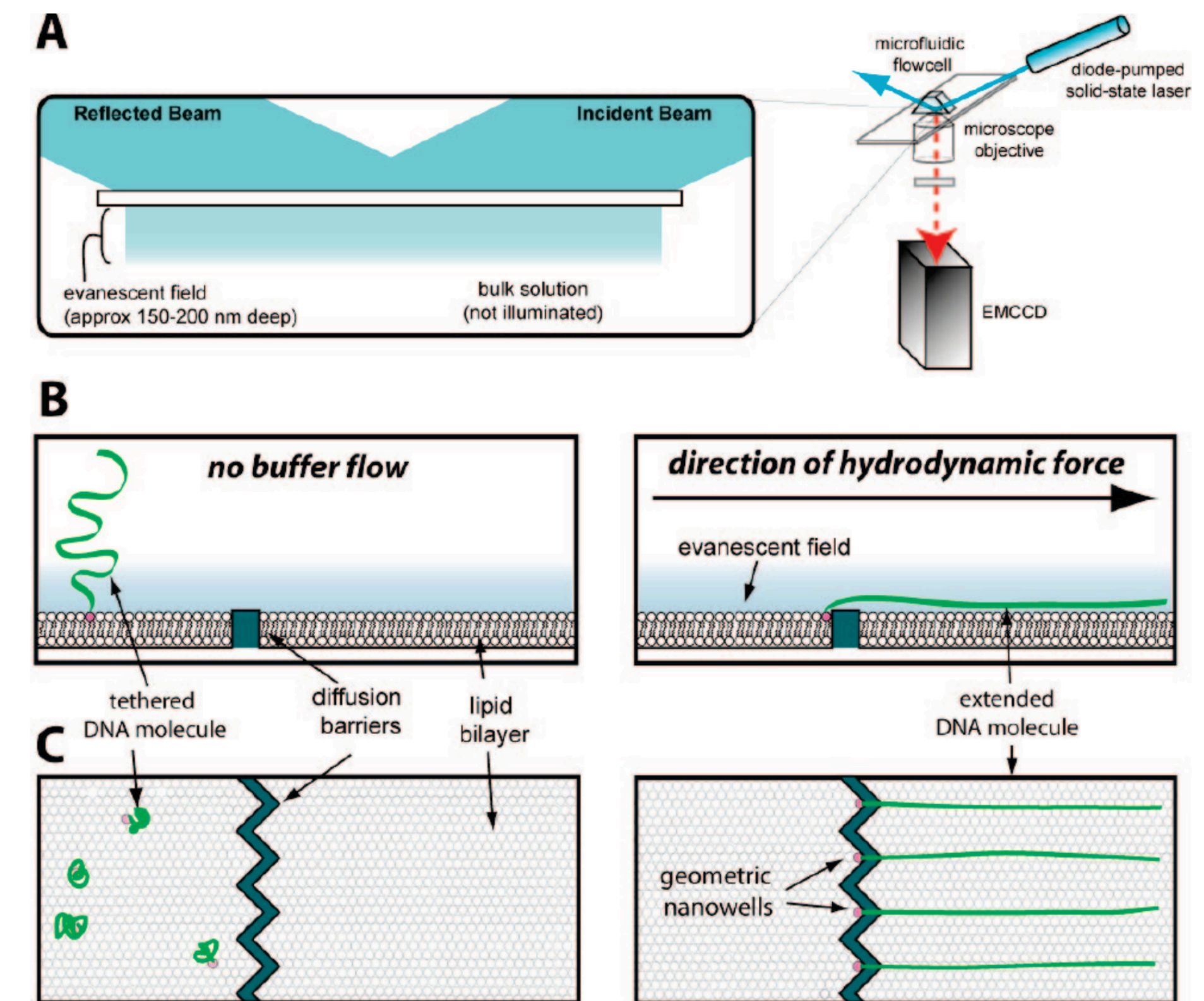
- **Detector construction** → DNA-origamists can make practically anything
- **PCR machines** → cheap, commercially available, portable, and fast.
- **DNA-substrate attachment** → standard protocols (looking at this in the lab right now!)

Parallel Arrays of Geometric Nanowells for Assembling Curtains of DNA with Controlled Lateral Dispersion

Mari-Liis Visnapuu,^{‡,§} Teresa Fazio,^{†,§} Shalom Wind,[†] and Eric C. Greene^{*,‡}

Department of Applied Physics and Applied Mathematics, Center for Electron Transport in Molecular Nanostructures, NanoMedicine Center for Mechanical Biology, Columbia University 1020 Schapiro CEPSR, 530 West 120th Street, New York, New York 10027, and Department of Biochemistry and Molecular Biophysics, Columbia University, 650 West 168th Street, Black Building Room 536, New York, New York 10032

Received June 6, 2008. Revised Manuscript Received August 18, 2008



Experimental side

- **Detector construction** → DNA-origamists can make practically anything
- **PCR machines** → cheap, commercially available, portable, and fast.
- **DNA-substrate attachment** → standard protocols (looking at this in the lab right now!)
- **Main challenge** → stability of detector and ensuring strands are collected, maybe a total rethink of design is in order (DNA-based harddrive?)

<https://doi.org/10.1038/s41467-020-15588-z>

DNA punch cards for storing data on native DNA sequences via enzymatic nicking

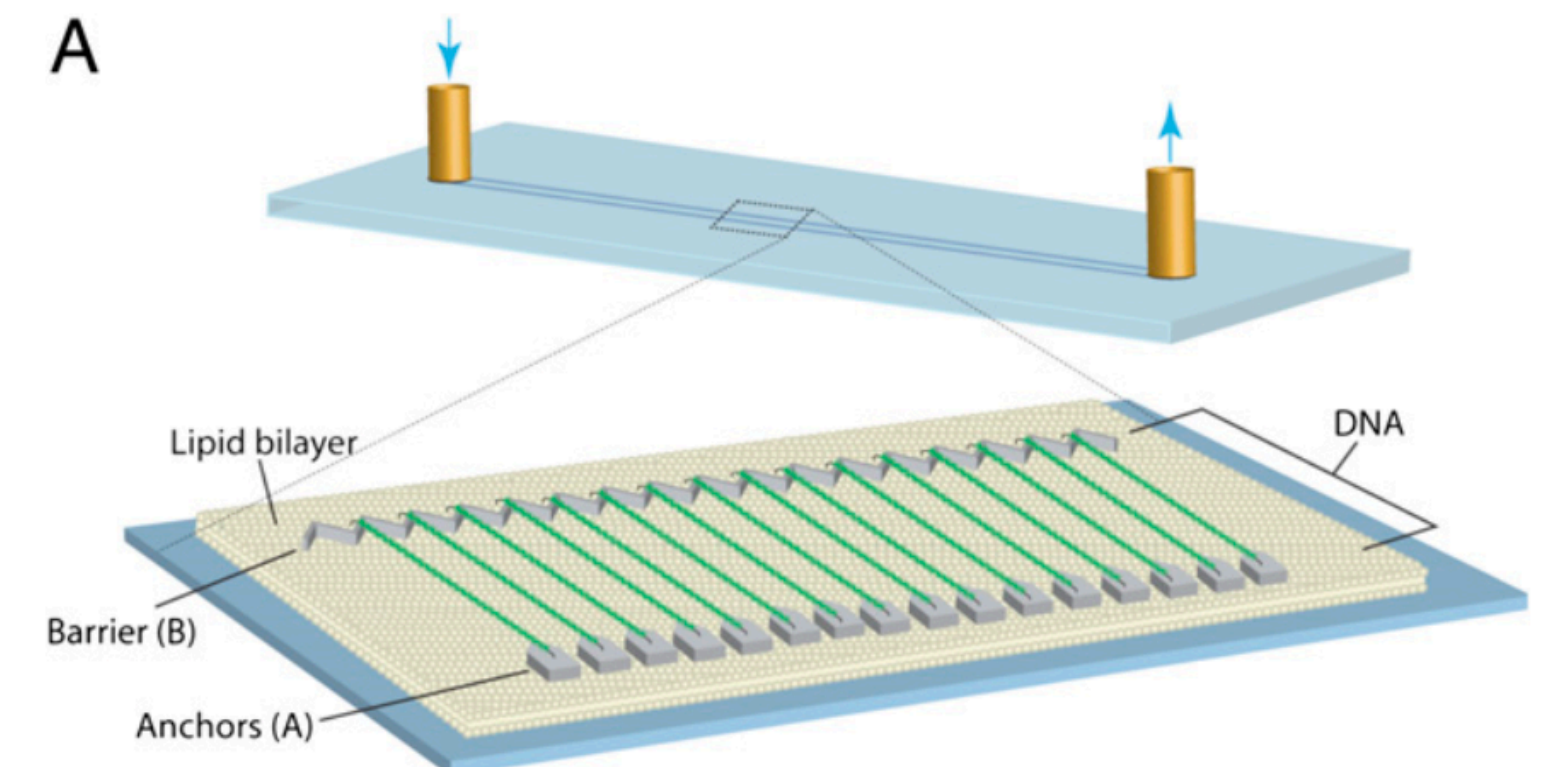
S. Kasra Tabatabaei¹, Boya Wang^{2,8}, Nagendra Bala Murali Athreya^{3,8}, Behnam Enghiad⁴, Alvaro Gonzalo Hernandez⁵, Christopher J. Fields⁶, Jean-Pierre Leburton³, David Soloveichik², Huimin Zhao^{1,4,7} & Olgica Milenkovic³

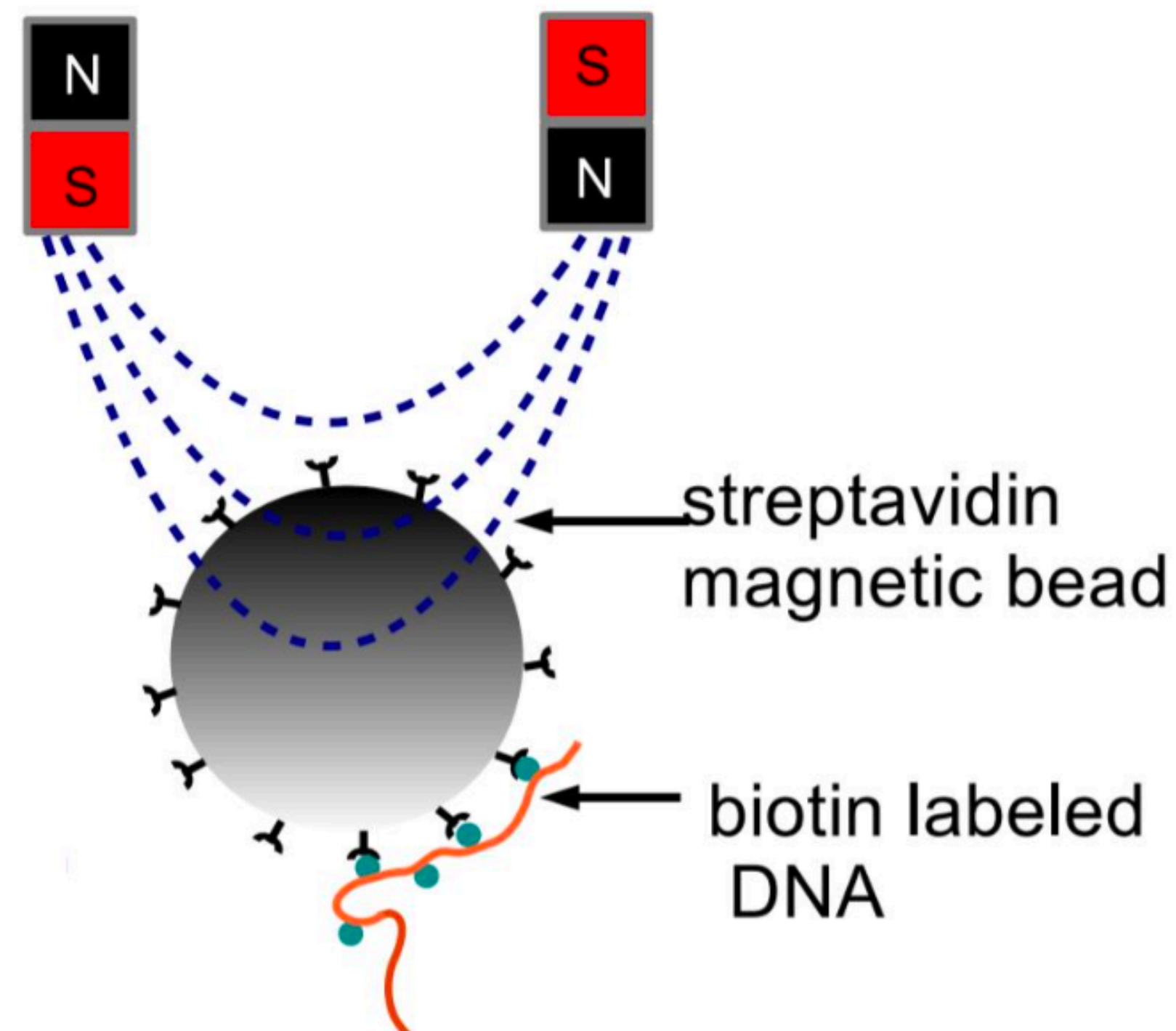
+

Single-molecule imaging of DNA curtains reveals mechanisms of KOPS sequence targeting by the DNA translocase FtsK

Ja Yil Lee^{a,1}, Ilya J. Finkelstein^{a,1}, Estelle Crozat^{b,2}, David J. Sherratt^b, and Eric C. Greene^{a,c,3}

^aDepartment of Biochemistry and Molecular Biophysics and ^cHoward Hughes Medical Institute, Columbia University, New York, NY 10032; and ^bDepartment of Biochemistry, University of Oxford, Oxford OX1 3QU, United Kingdom





[t]

Attachment of paramagnetic beads to the DNA strands

FIG. 3. Diagram from [16] illustrating the DNA to paramagnetic bead attachment and manipulation via an external magnetic field. The connection occurs due to the extreme affinity of Streptavidin (a type of protein) to biotin molecules (vitamin H). Streptavidin is known to form one of the strongest bonds known in nature with biotin.