ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF SYDNEY

CYGNUS

Cygnus, and directional DM detection

[2102.04596], [2008.12587]

Ciaran O'Hare
University of Sydney

What is directional detection?

Detecting the directions of low energy nuclear or electron recoils, as well as just their energies

Why?

→ Extend searches for WIMPs below the neutrino floor

→ Provide a means of discovering—or confirming the discovery of—dark matter

→ Directionally detect neutrinos via CEνNS or electron scattering

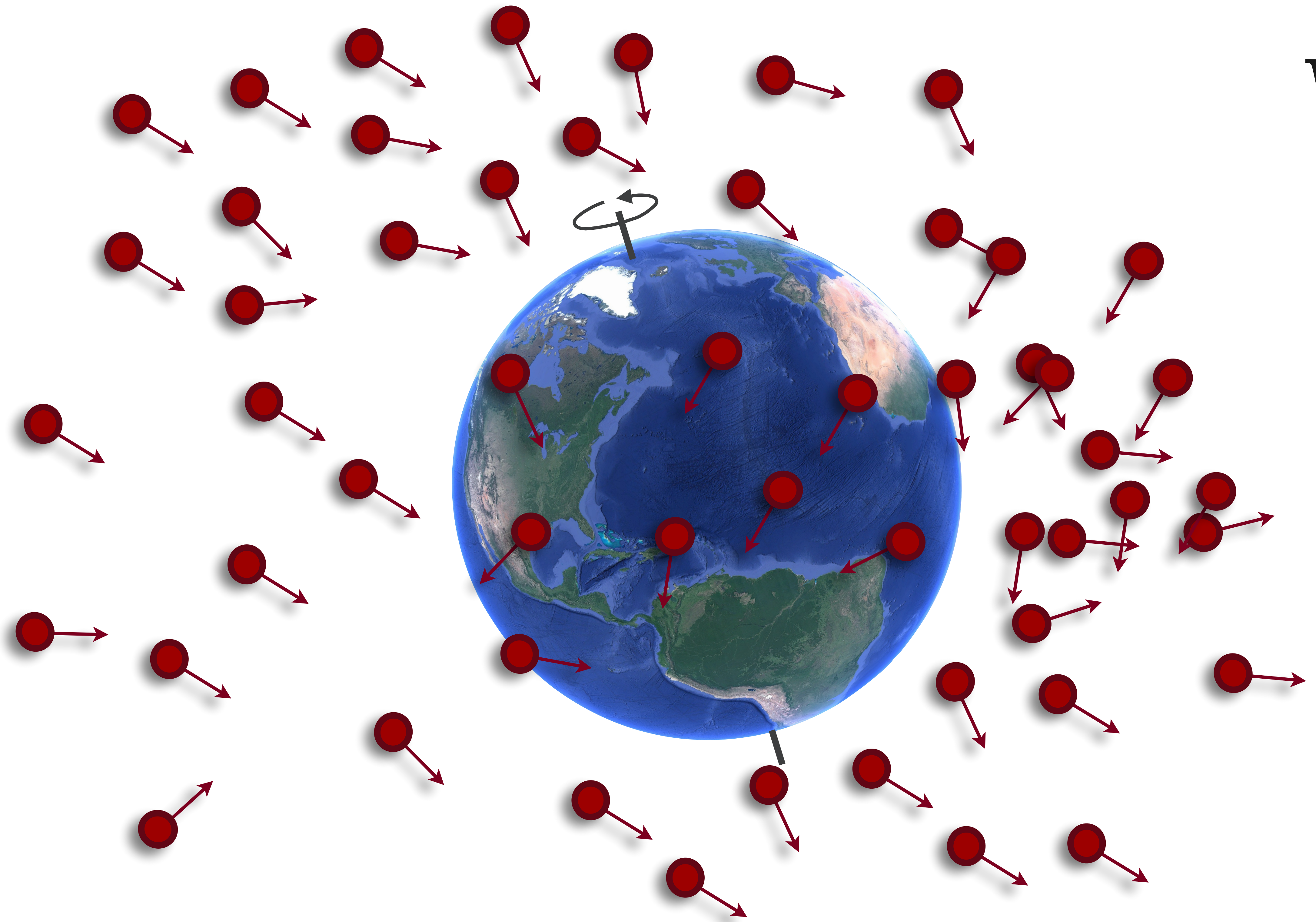
How?

→ Many experimental proposals at varying stages of technological readiness

→ Cygnus collaboration built around finding a workable gas TPC with high definition charge readout at a competitive scale

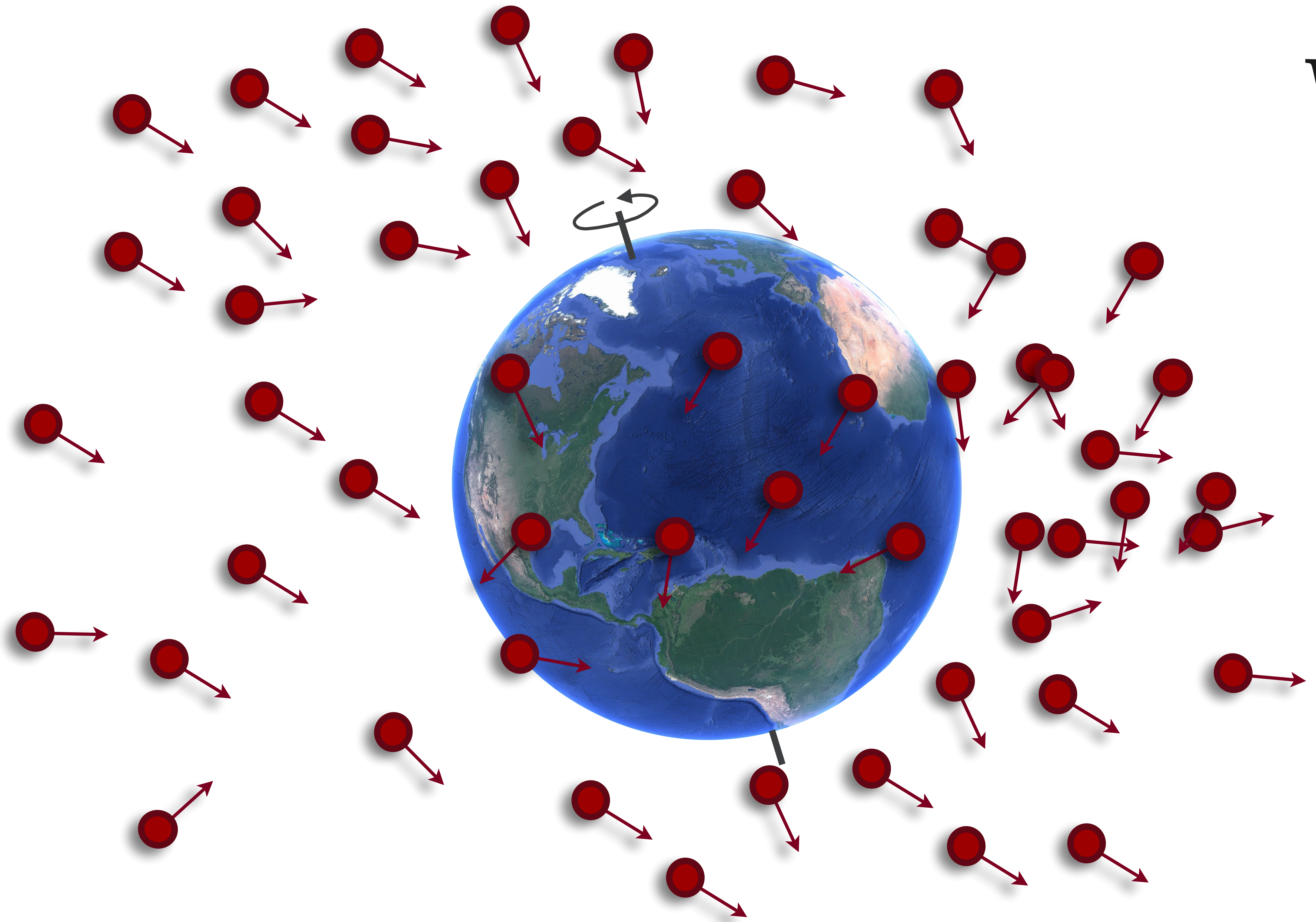
WIMPs

Weakly Interacting Massive Particles



$$\rho \sim 0.3\,\mathrm{GeV cm^{-3}}$$

$$v \sim 300\,\mathrm{km\,s^{-1}}$$



$$\rho \sim 0.3\,\mathrm{GeV cm^{-3}}$$

$$v \sim 300\,\mathrm{km\,s^{-1}}$$

WIMPs

Weakly **I**nteracting **M**assive **P**articles

What does that actually mean?

Dan Hooper
@DanHooperAstro

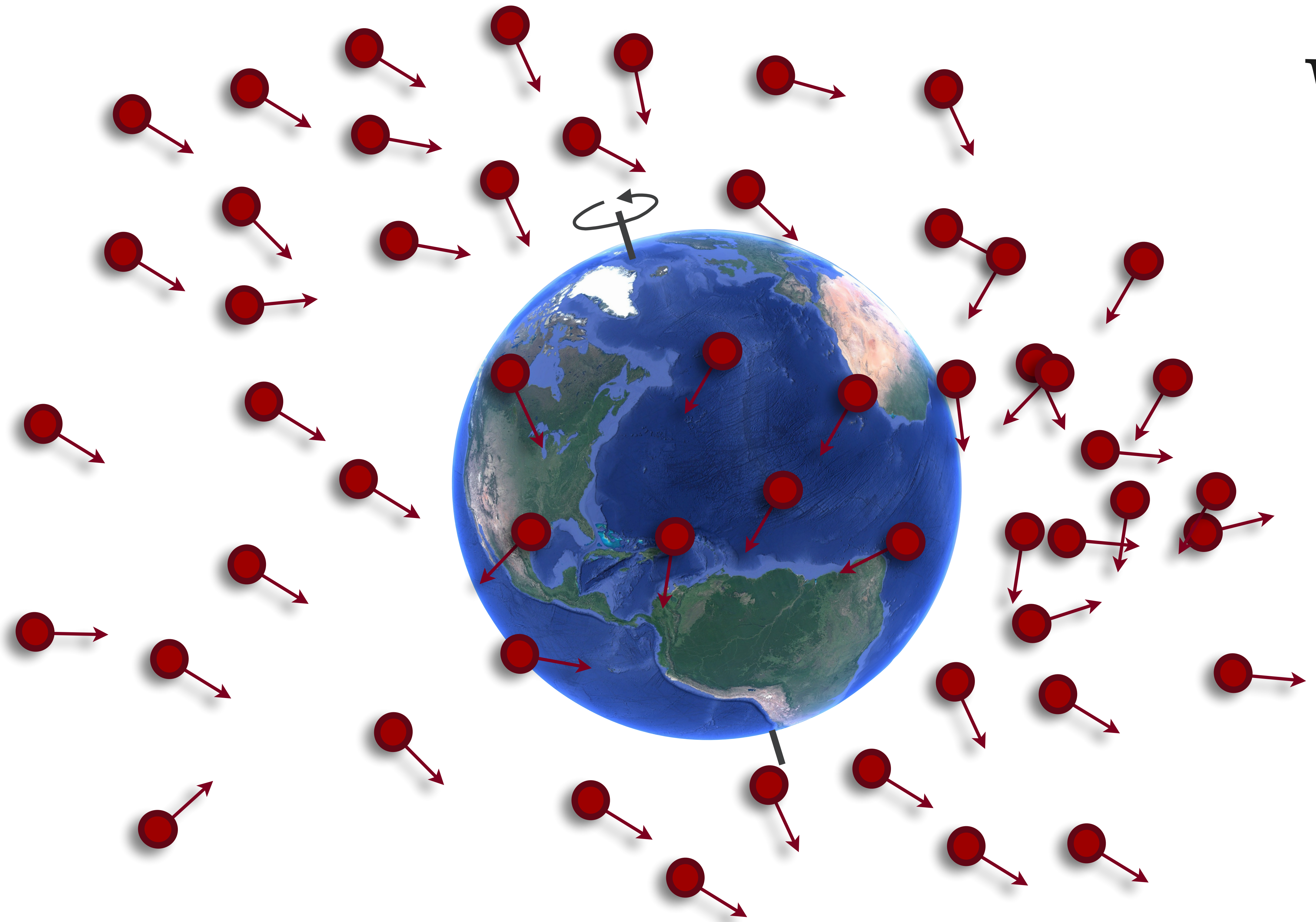
Which of the following is closest definition to how you use the word "WIMP".
A massive particle dark matter candidate that:

- Has electroweak charge
- Is a thermal relic
- Has a weak-scale mass
- Is feebly interacting

WIMPs

Weakly Interacting Massive Particles

What does that actually mean?



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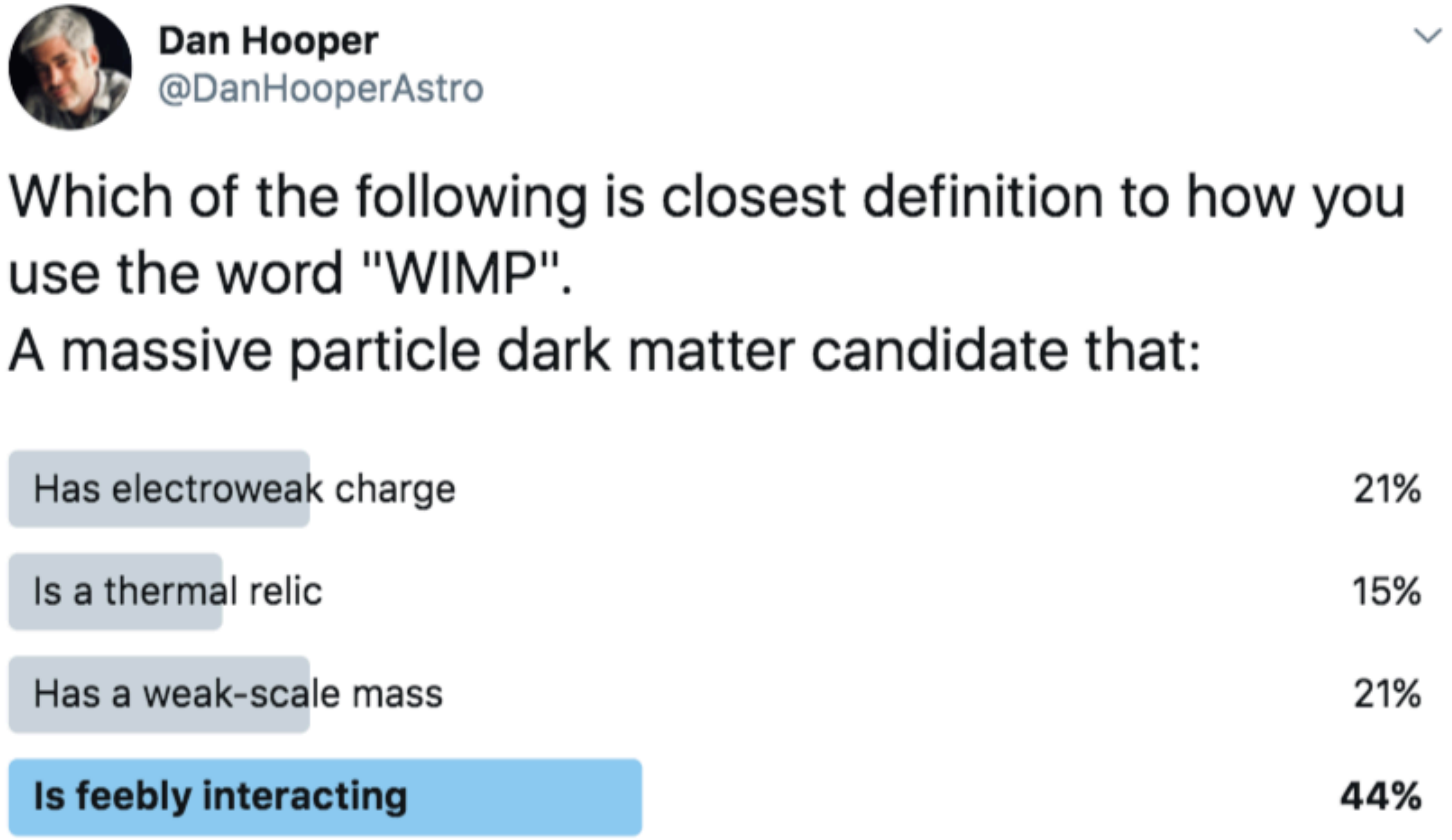
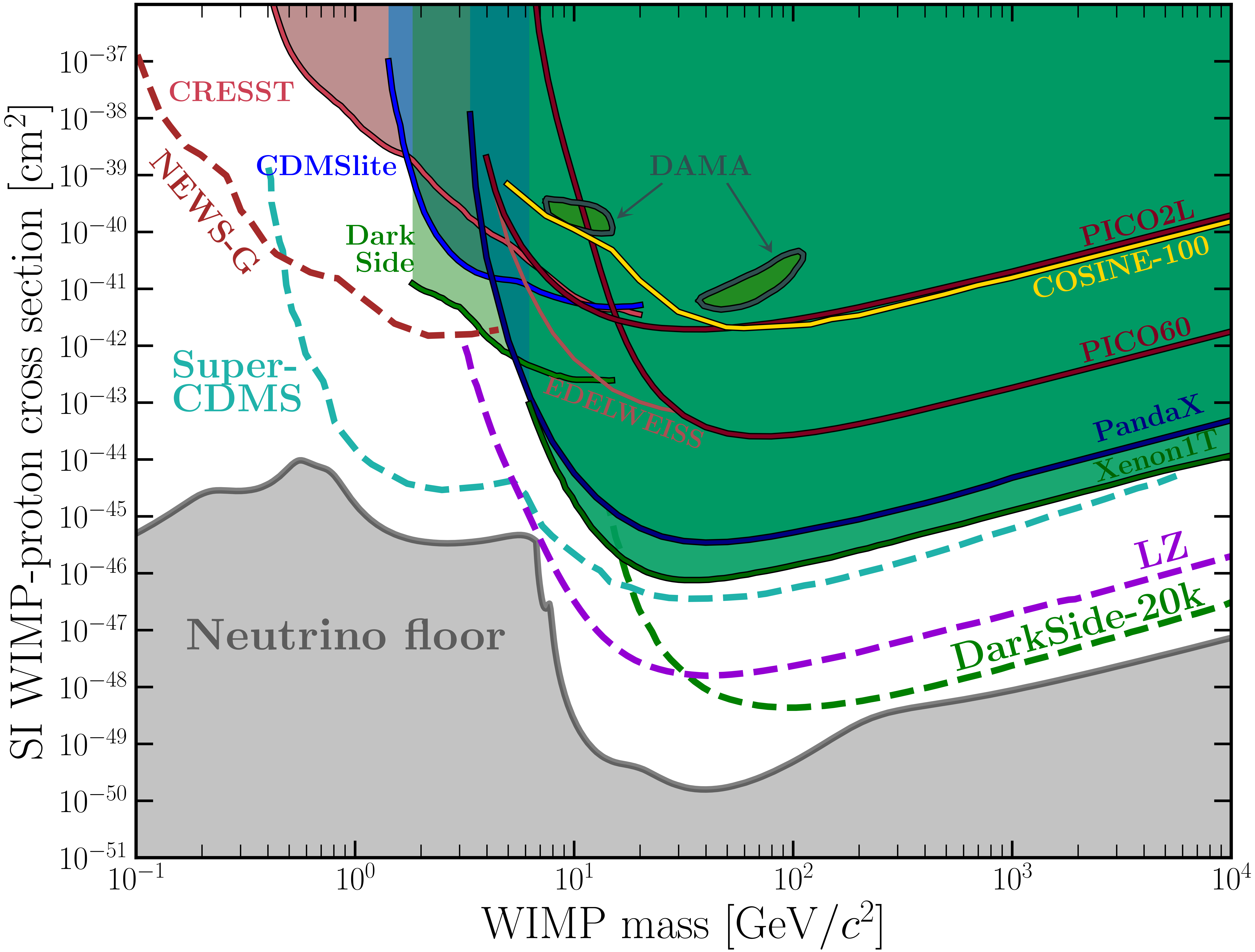


Current status of WIMP direct detection: SI cross section



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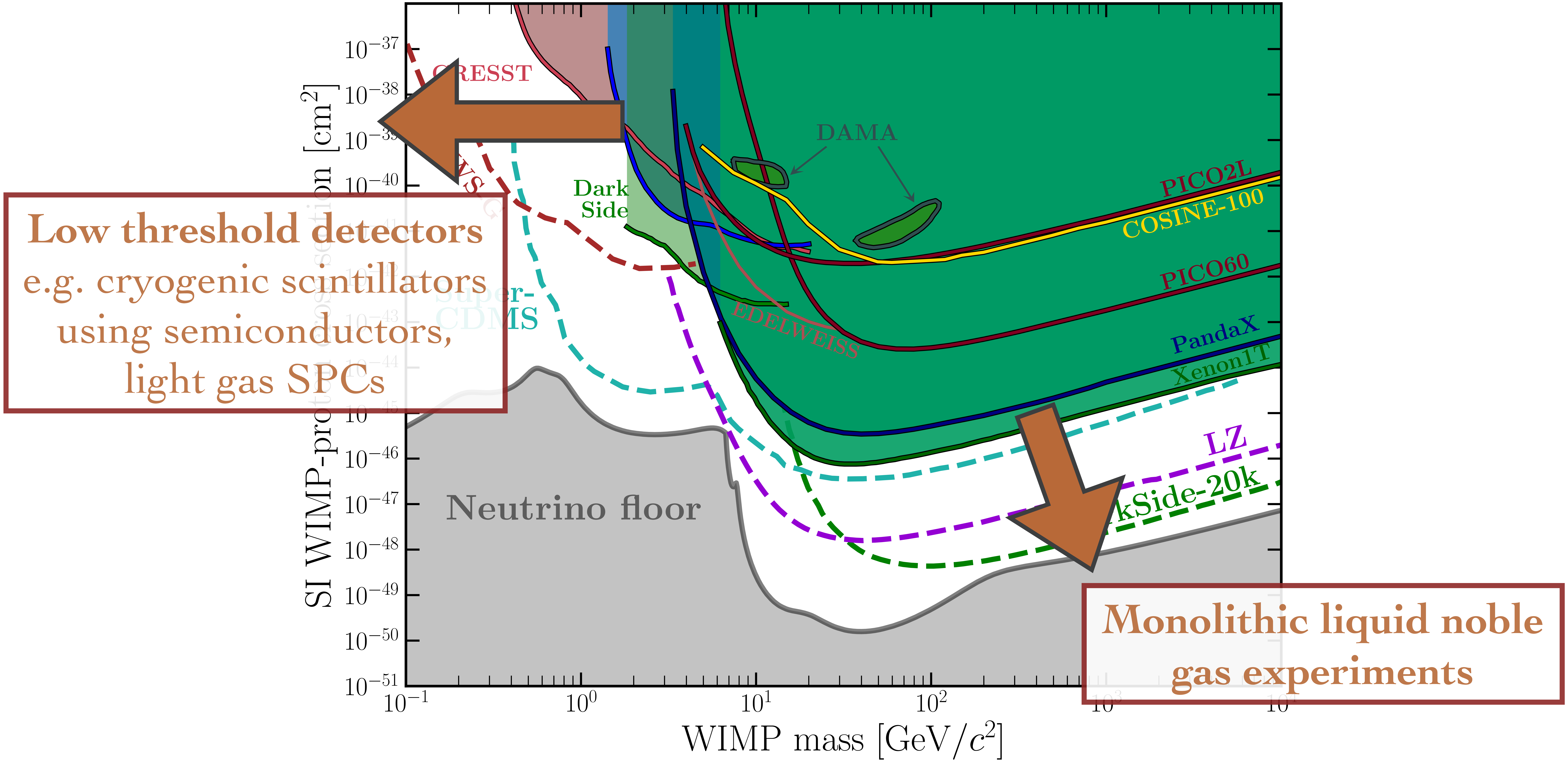

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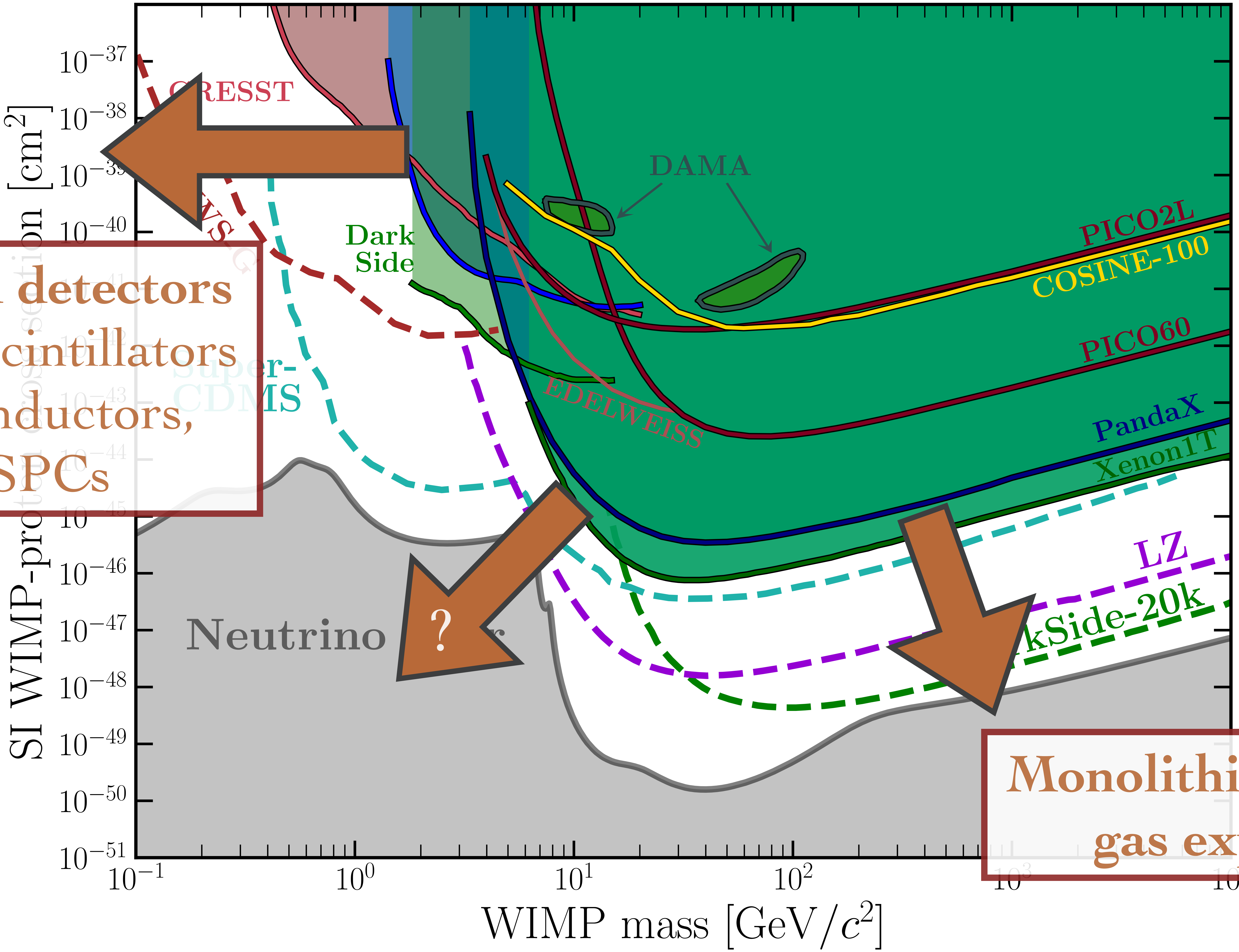
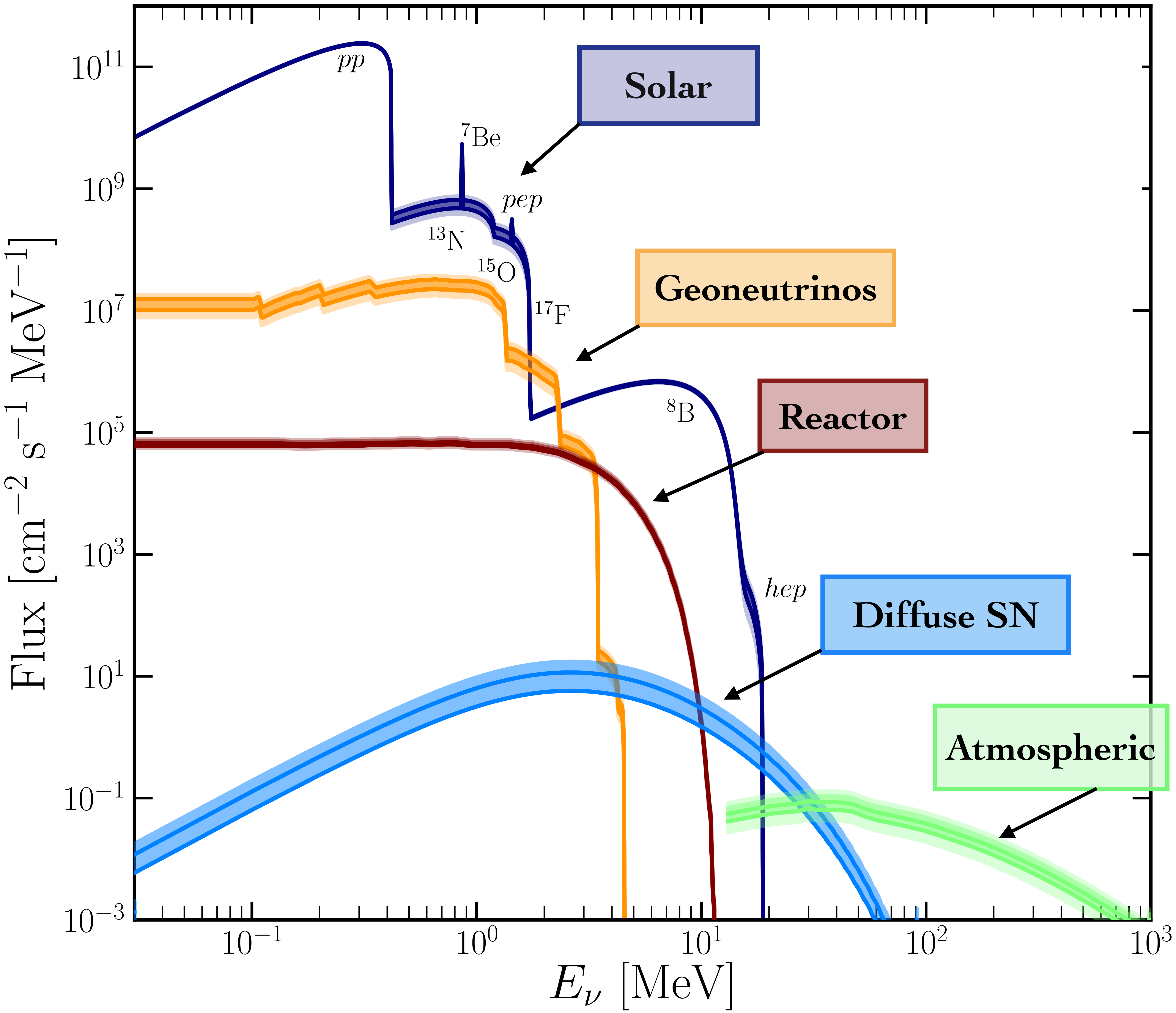
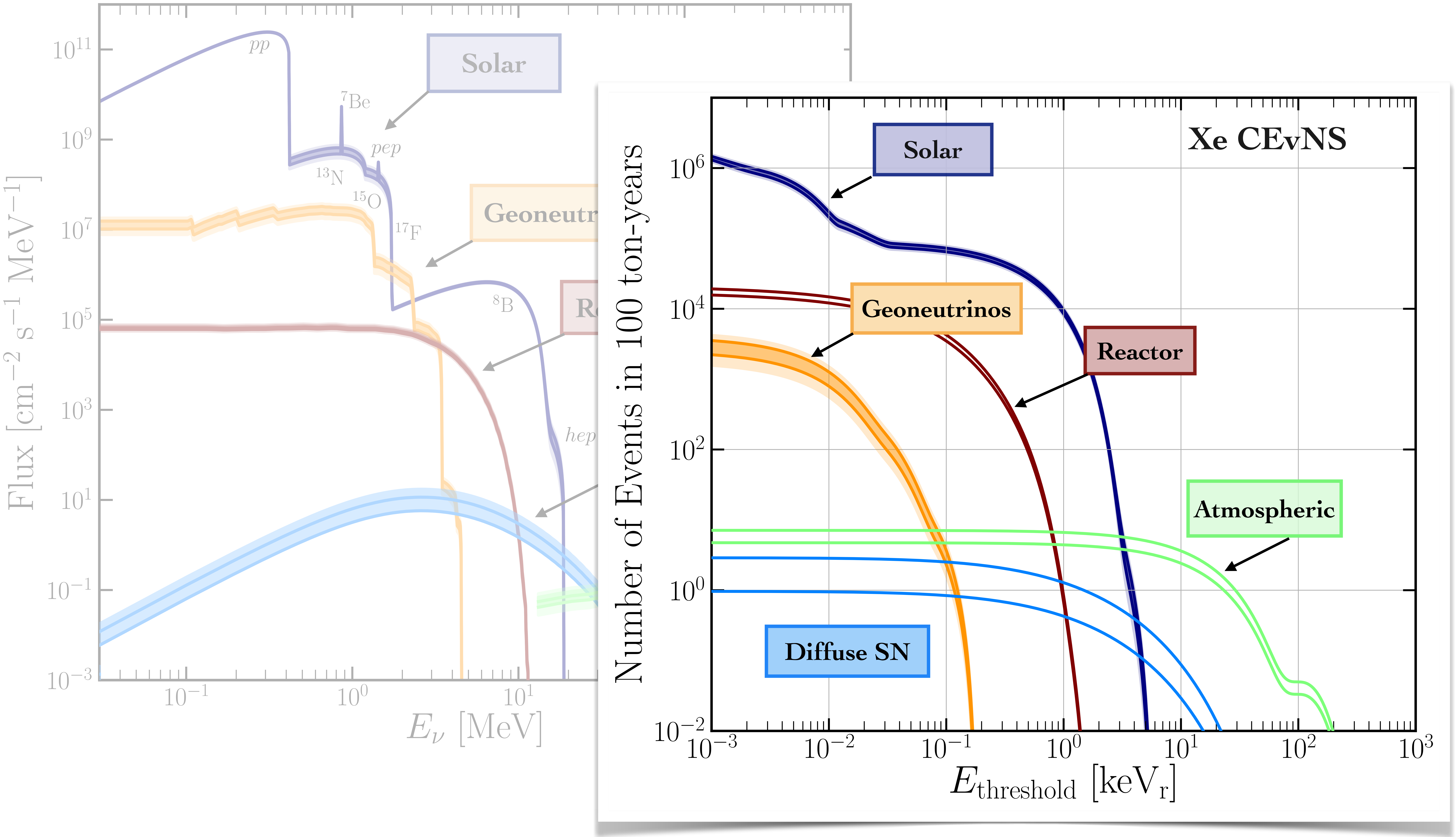


Low threshold detectors
e.g. cryogenic scintillators using semiconductors, light gas SPCs

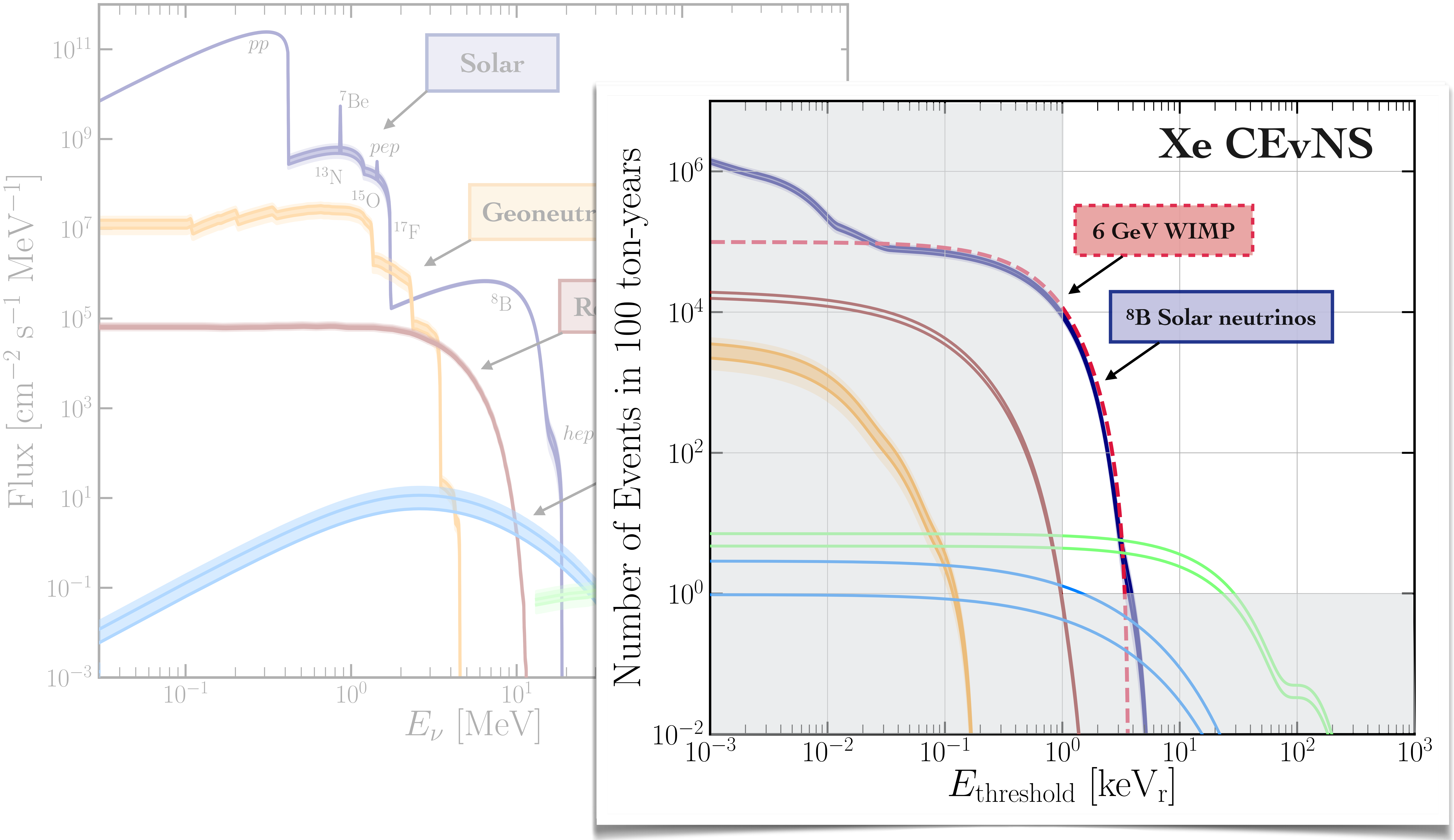
Monolithic liquid noble gas experiments



Solar
Geoneutrinos
Reactor
Diffuse SN
Atmospheric
pp
^{7}Be
pep
^{13}N
^{15}O
^{17}F
^{8}B
hep
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Flux [cm^{-2} s^{-1} MeV^{-1}]
E_ν [MeV]



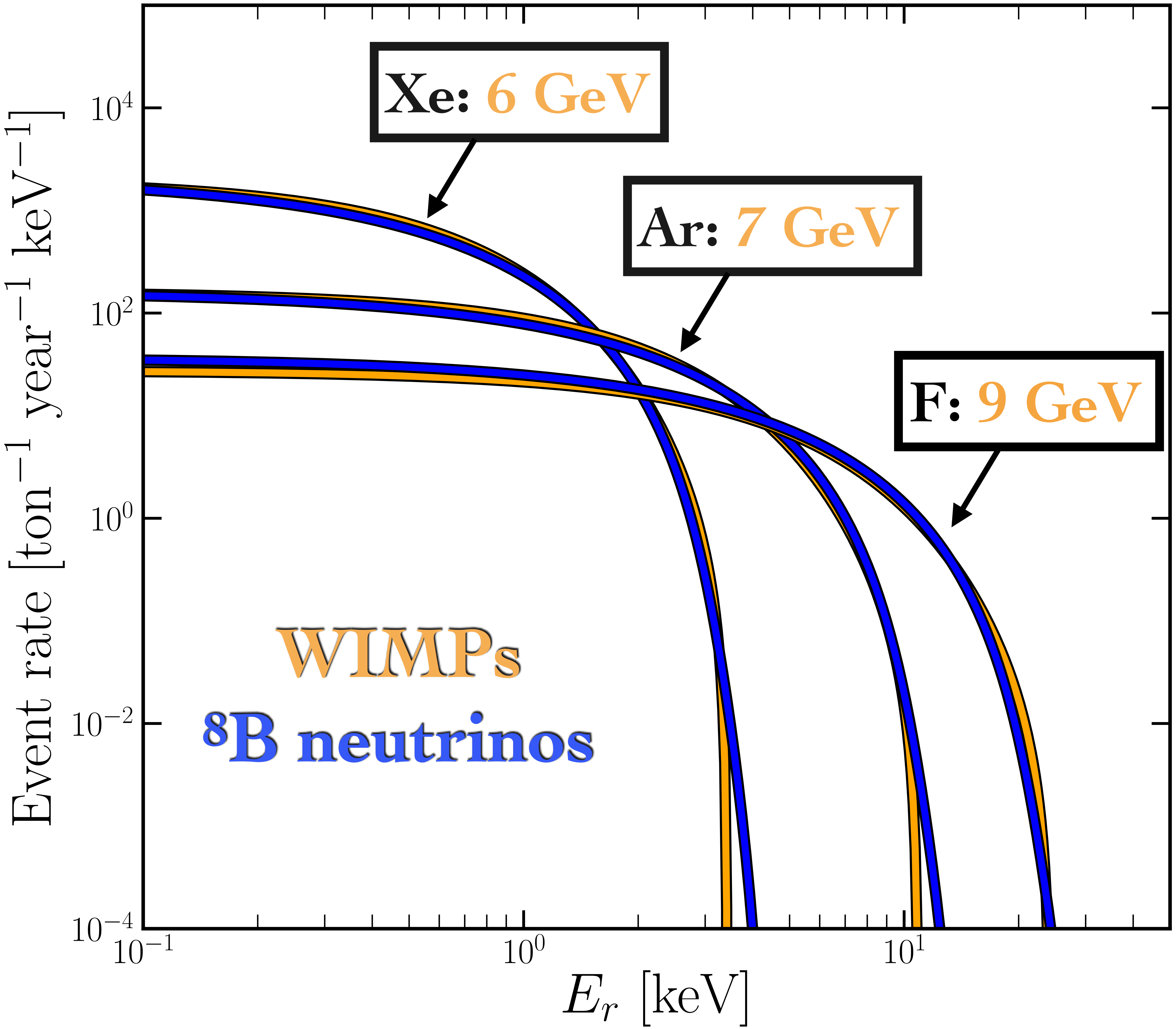
Solar
Geoneutr
Flux [cm^{-2} s^{-1} MeV^{-1}]
E_ν [MeV]
pp
^{7}Be
pep
^{13}N
^{15}O
^{17}F
^{8}B
hep
Xe CEvNS
Solar
Geoneutrinos
Reactor
Atmospheric
Diffuse SN
Number of Events in 100 ton-years
$E_{\rm threshold}$ [keV$_{\rm r}$]

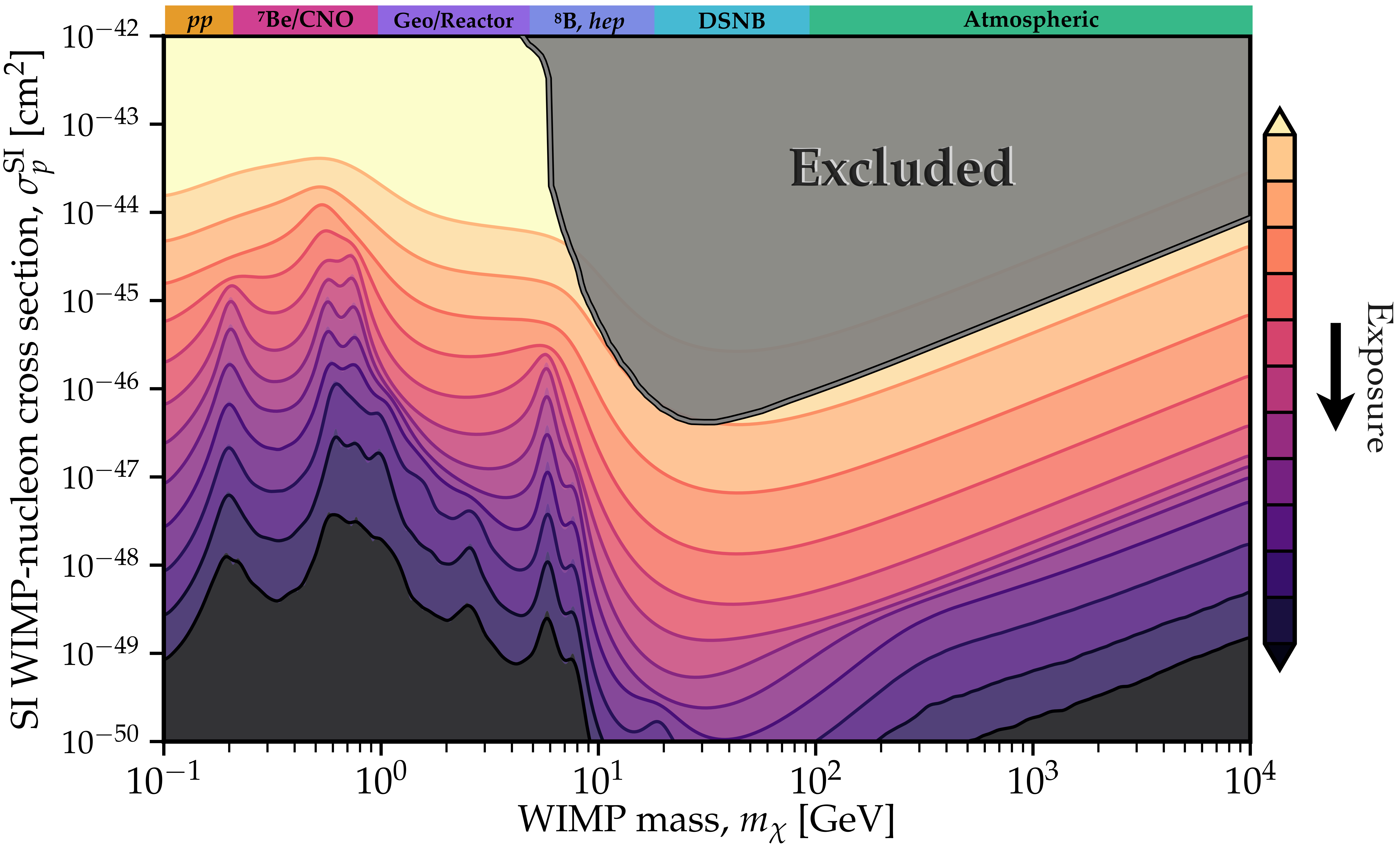


Solar
Geoneutr
pp
7Be
pep
13N
15O
17F
8B
hep
Flux [cm−2 s−1 MeV−1]
Eν [MeV]
Xe CEvNS
6 GeV WIMP
8B Solar neutrinos
Number of Events in 100 ton-years
Ethreshold [keVr]

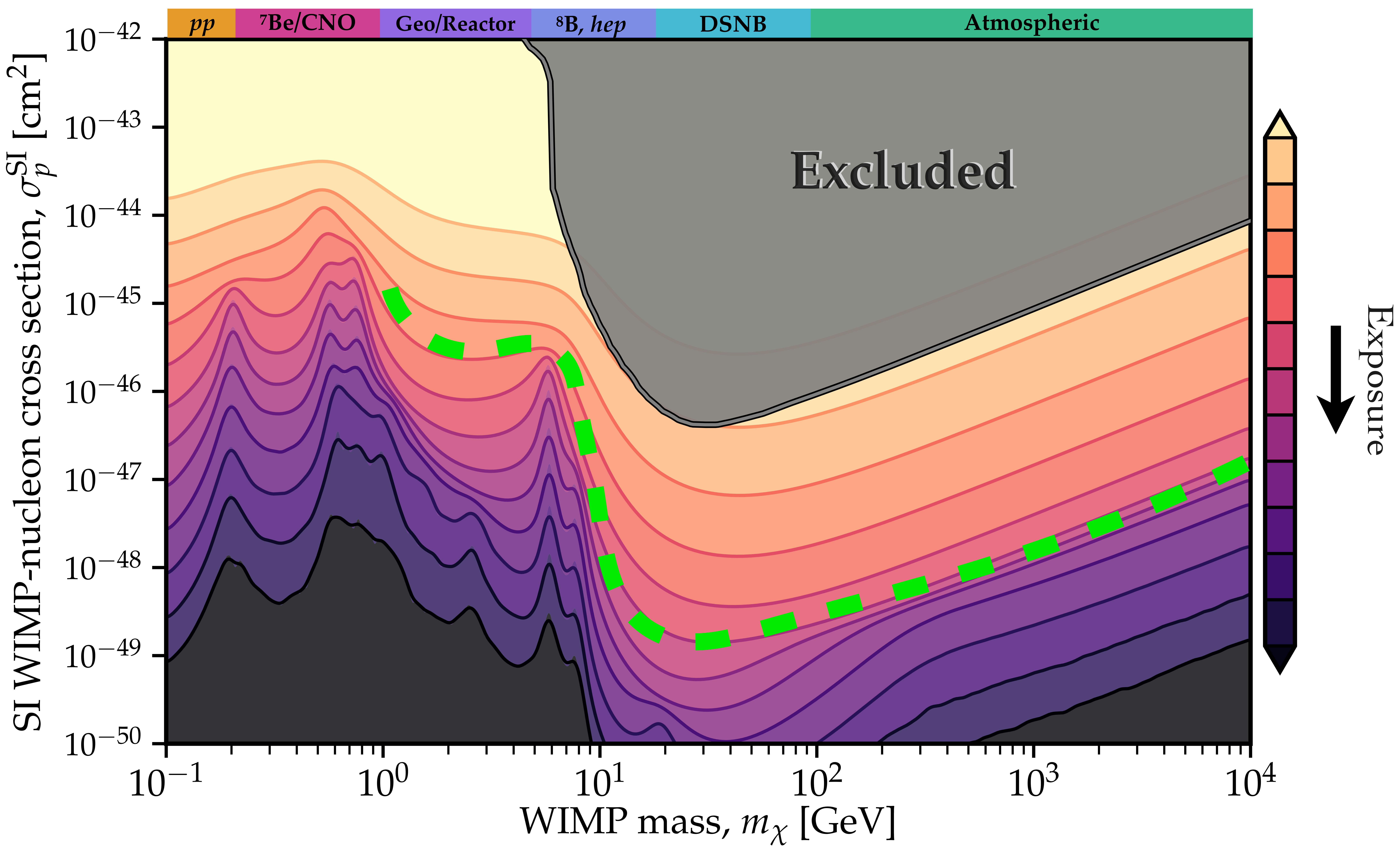
Why is there a neutrino floor?

→ spectral match between DM and solar neutrinos





pp
7Be/CNO
Geo/Reactor
8B, hep
DSNB
Atmospheric
Excluded
Exposure
SI WIMP-nucleon cross section, $\sigma_p^{\rm SI}$ [cm^2]
WIMP mass, m_χ [GeV]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



pp
⁷Be/CNO
Geo/Reactor
⁸B, hep
DSNB
Atmospheric
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Exposure
SI WIMP-nucleon cross section, σ_p^{SI} [cm^2]
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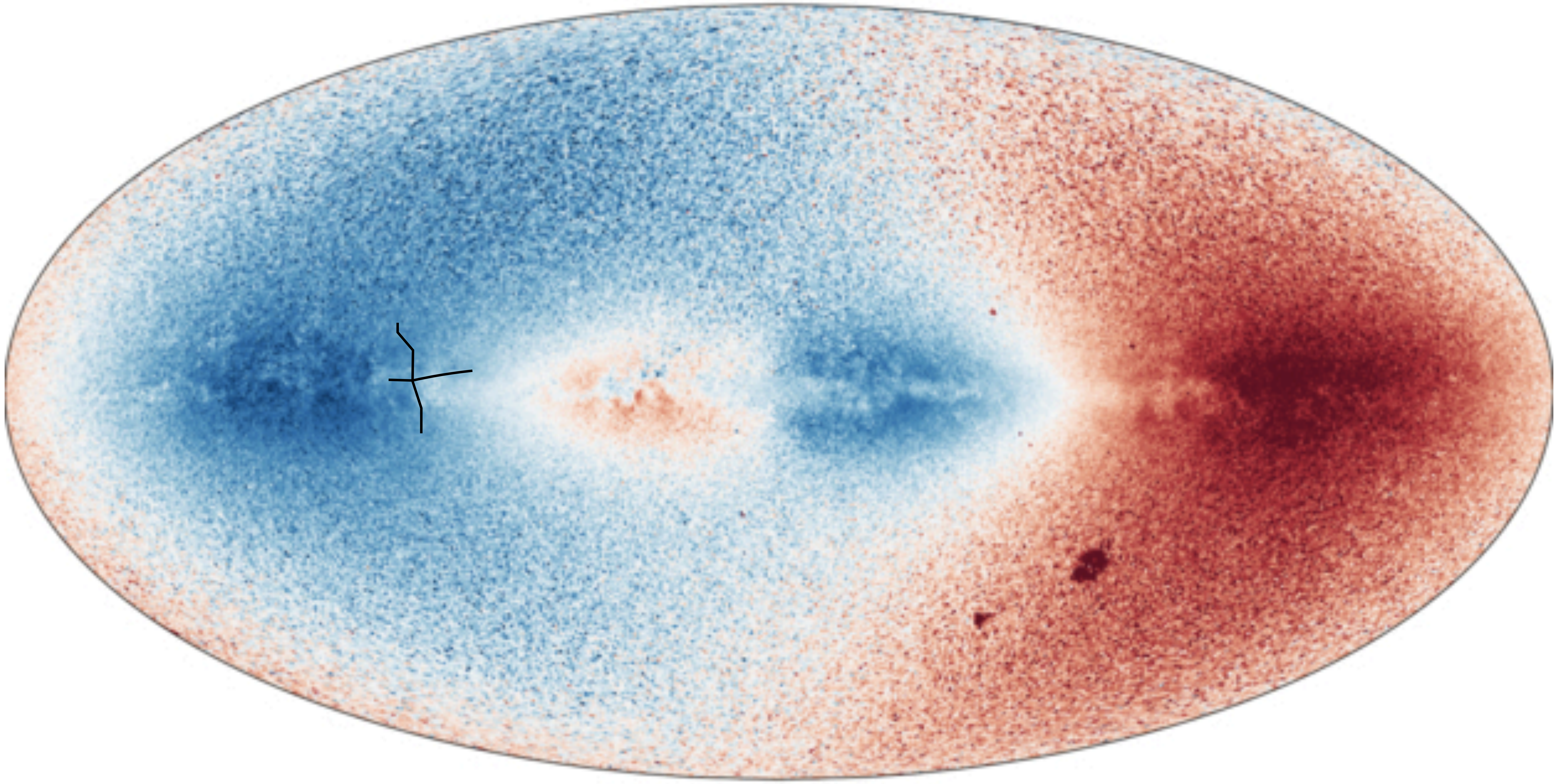
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}


CYGNUS
WIMP
WIMP
WIMP
WIMP
WIMP
WIMP


Cygnus
Jun
Dec

Why use directional information?

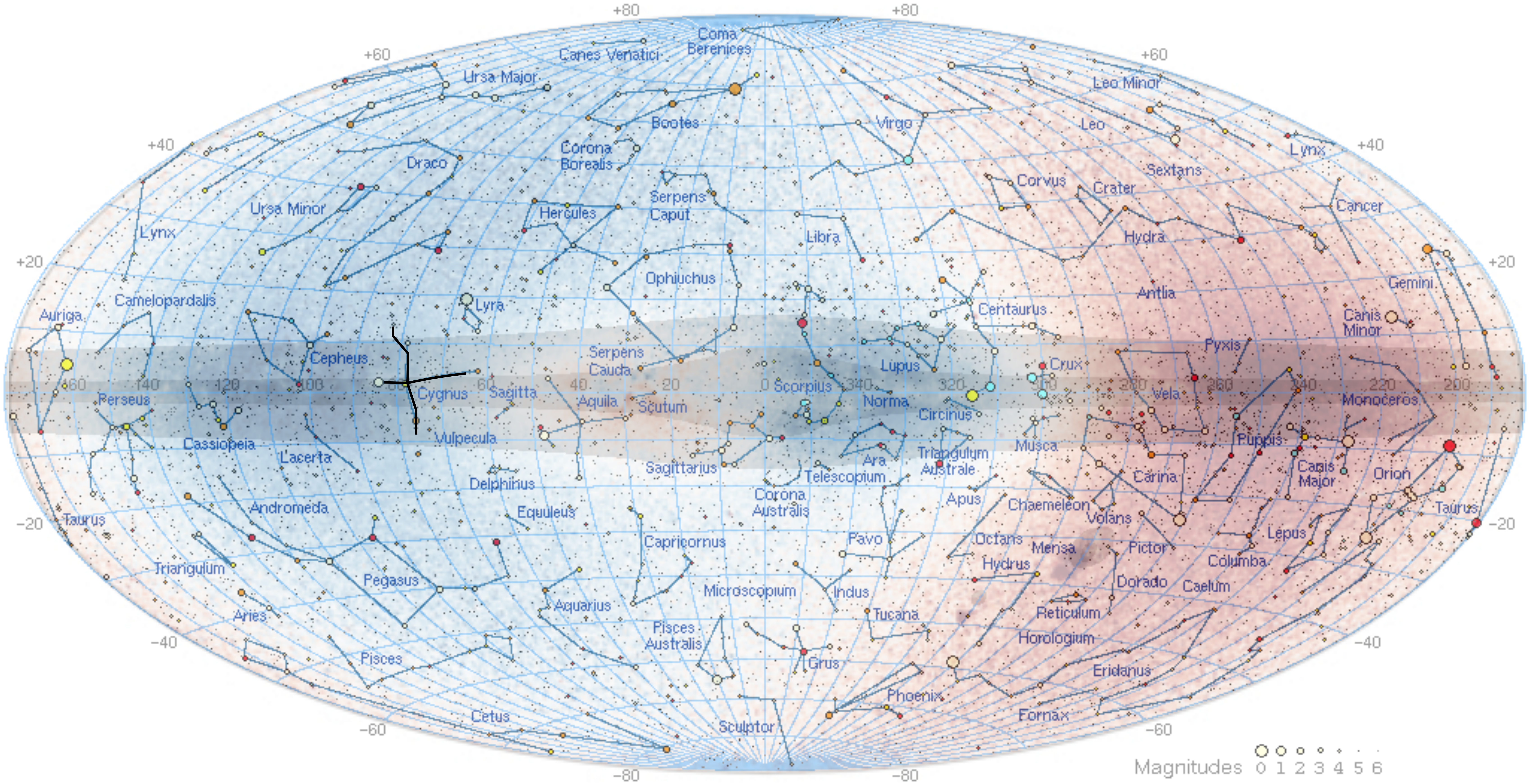


Gaia radial velocities

Blue = moving towards us (relatively)

Red = moving away from us

Why use directional information?

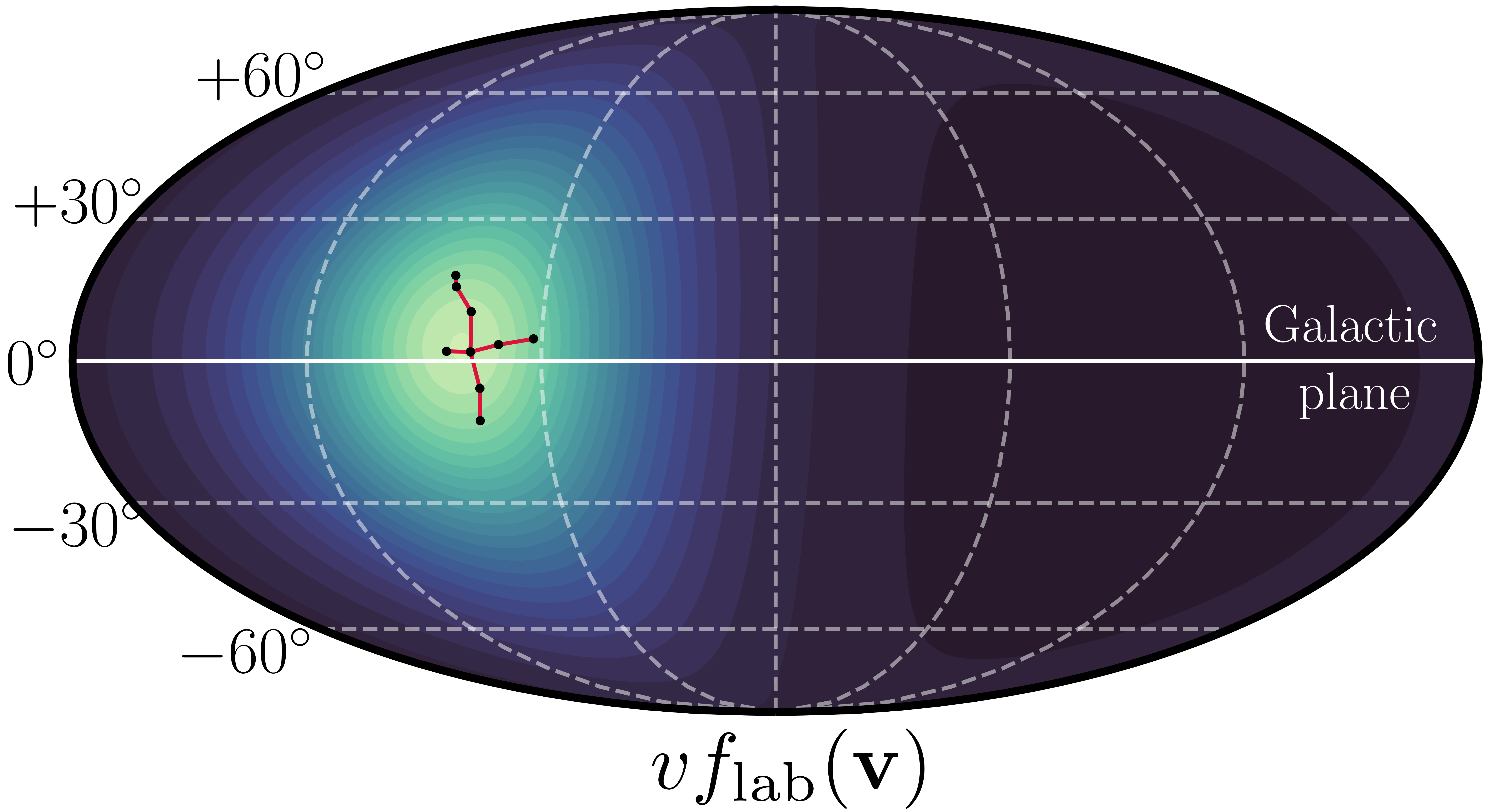


Gaia radial velocities

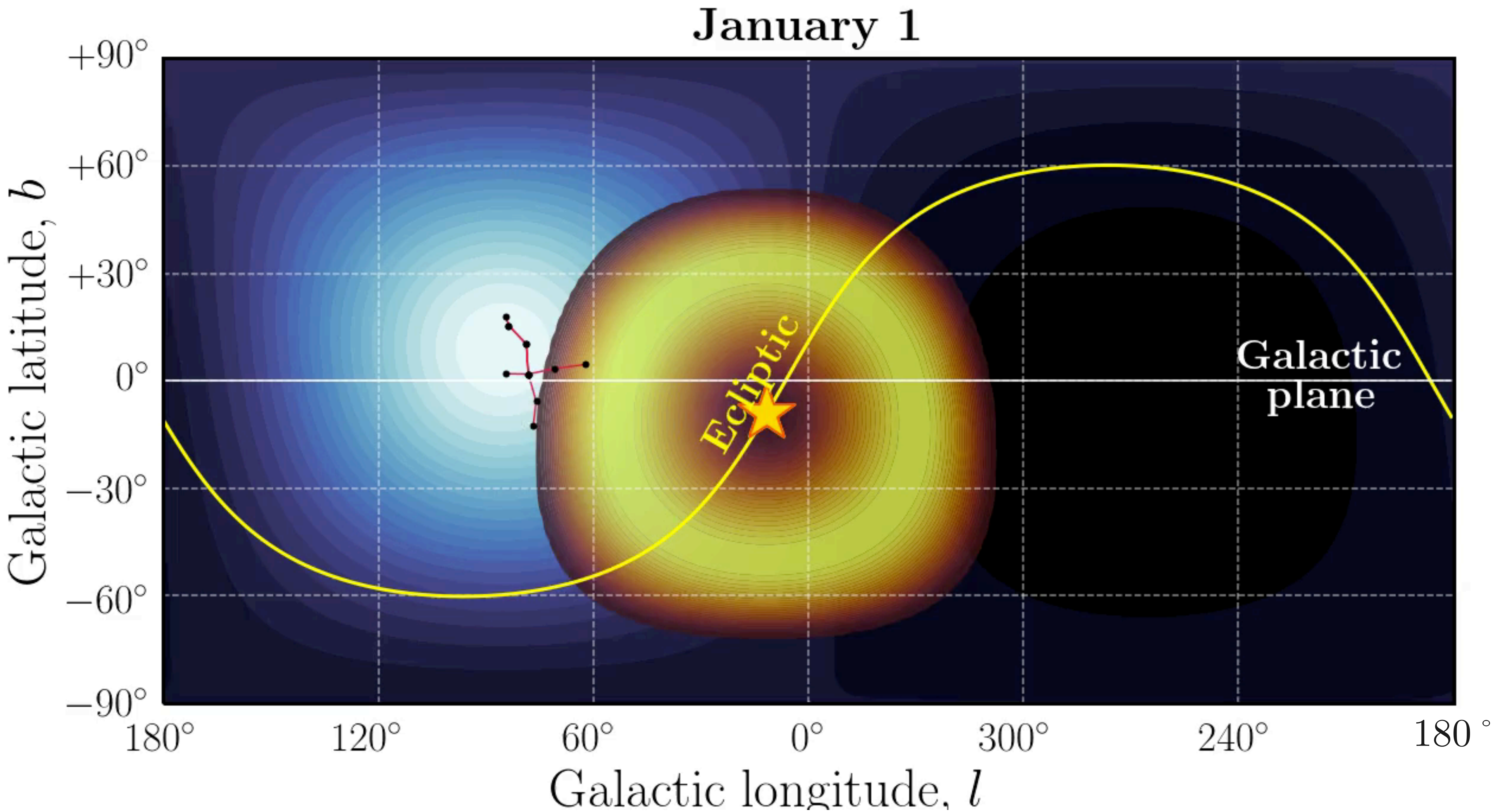
Blue = moving towards us (relatively)

Red = moving away from us

→ The dark matter flux is anisotropic in the half of the sky centred on Cygnus



Nothing should mimic dark matter, including solar neutrinos



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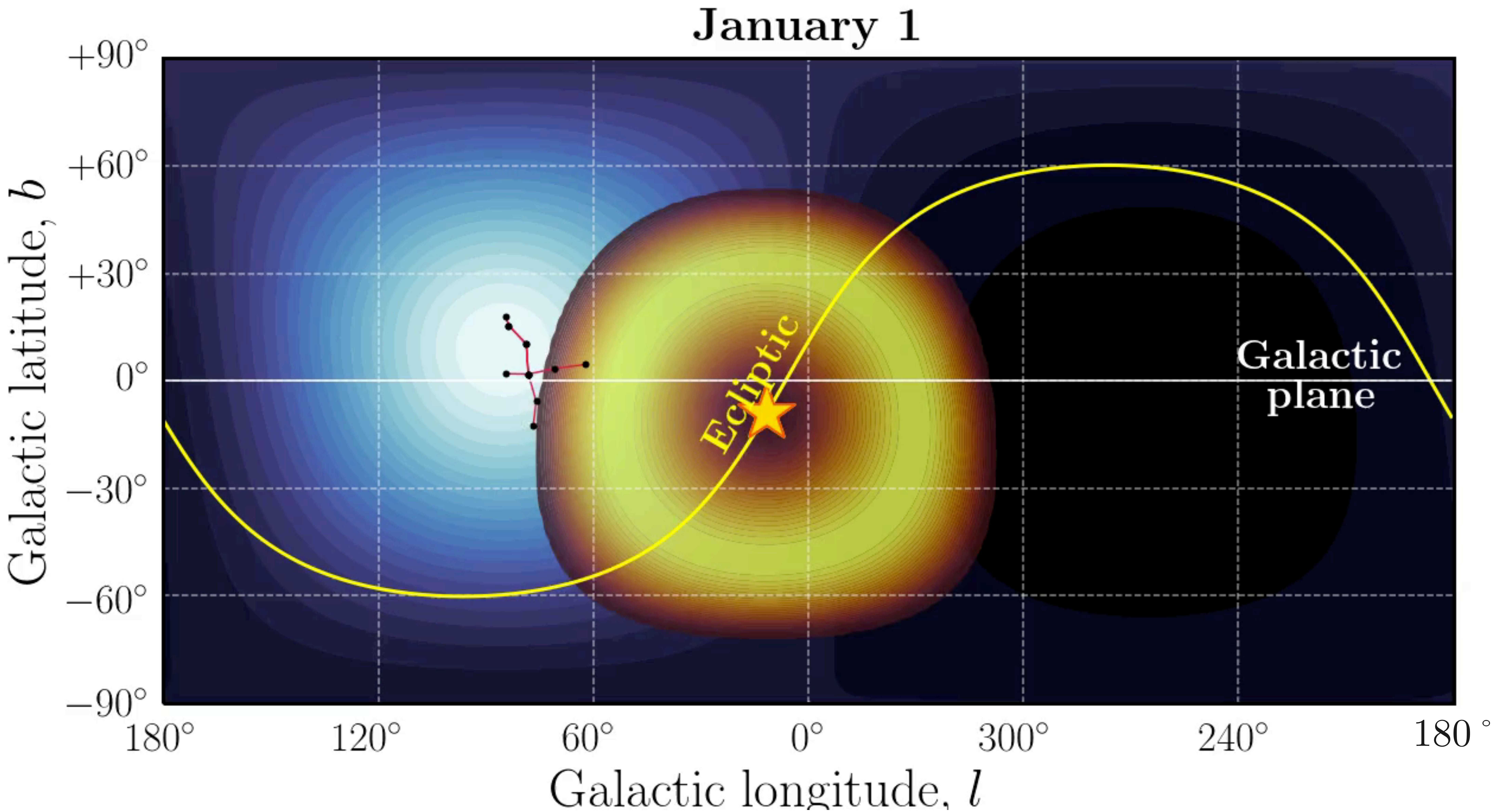
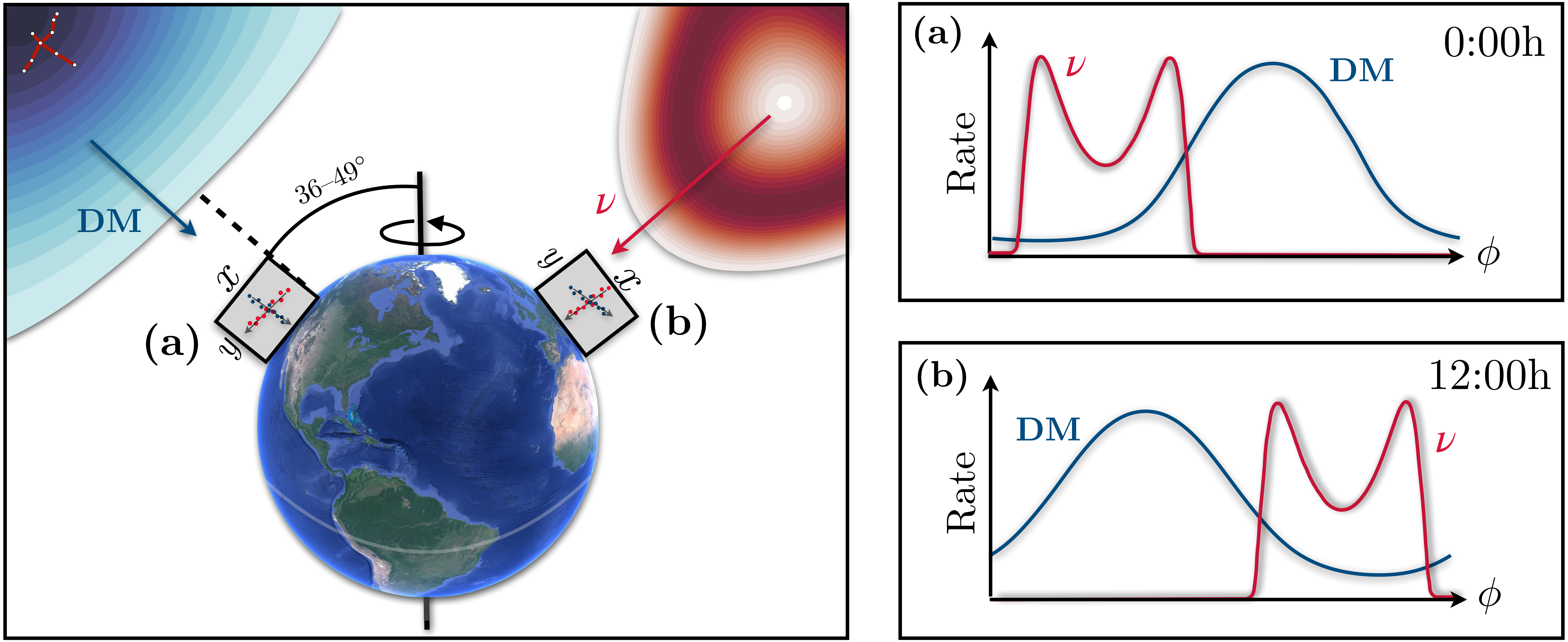
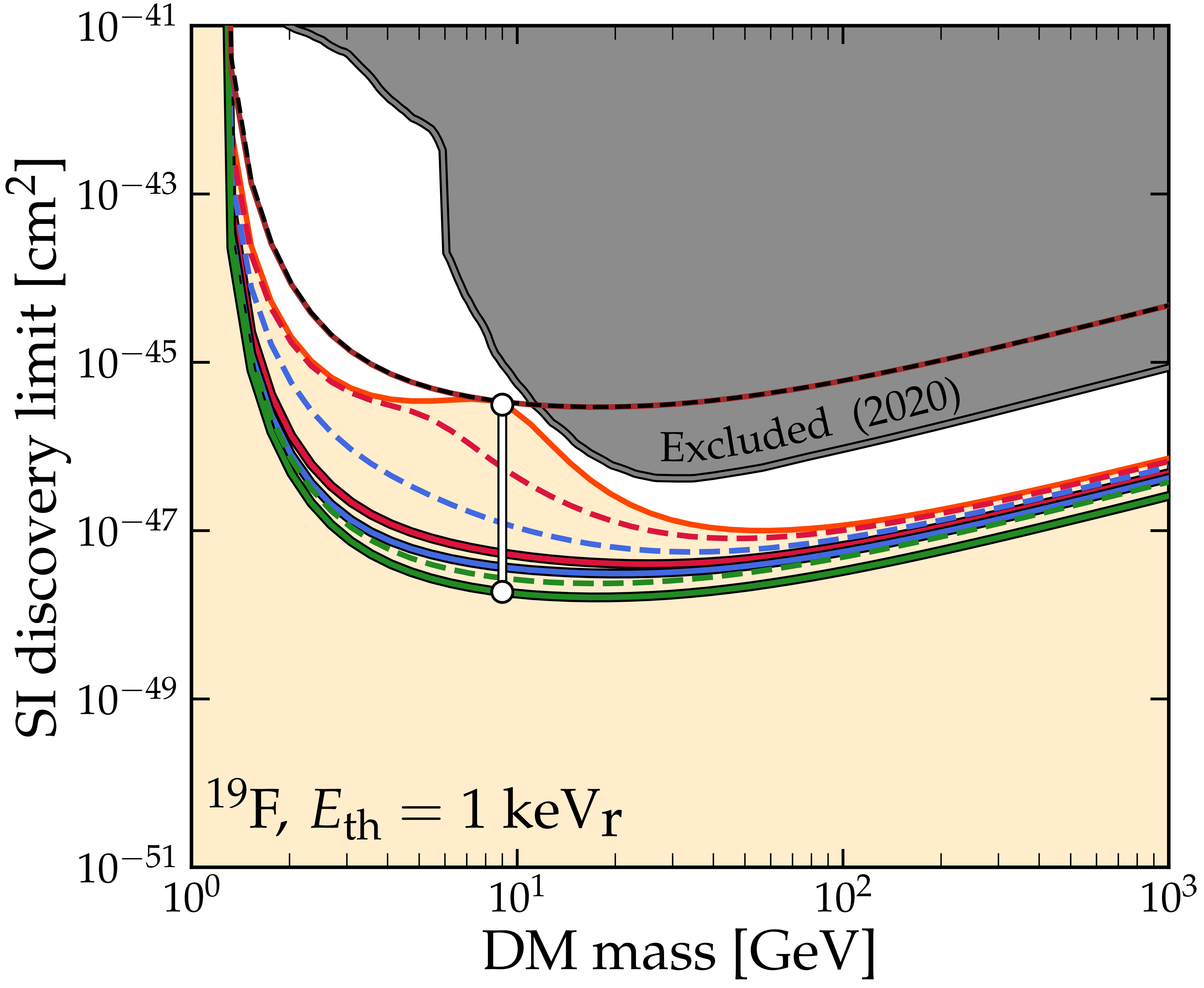


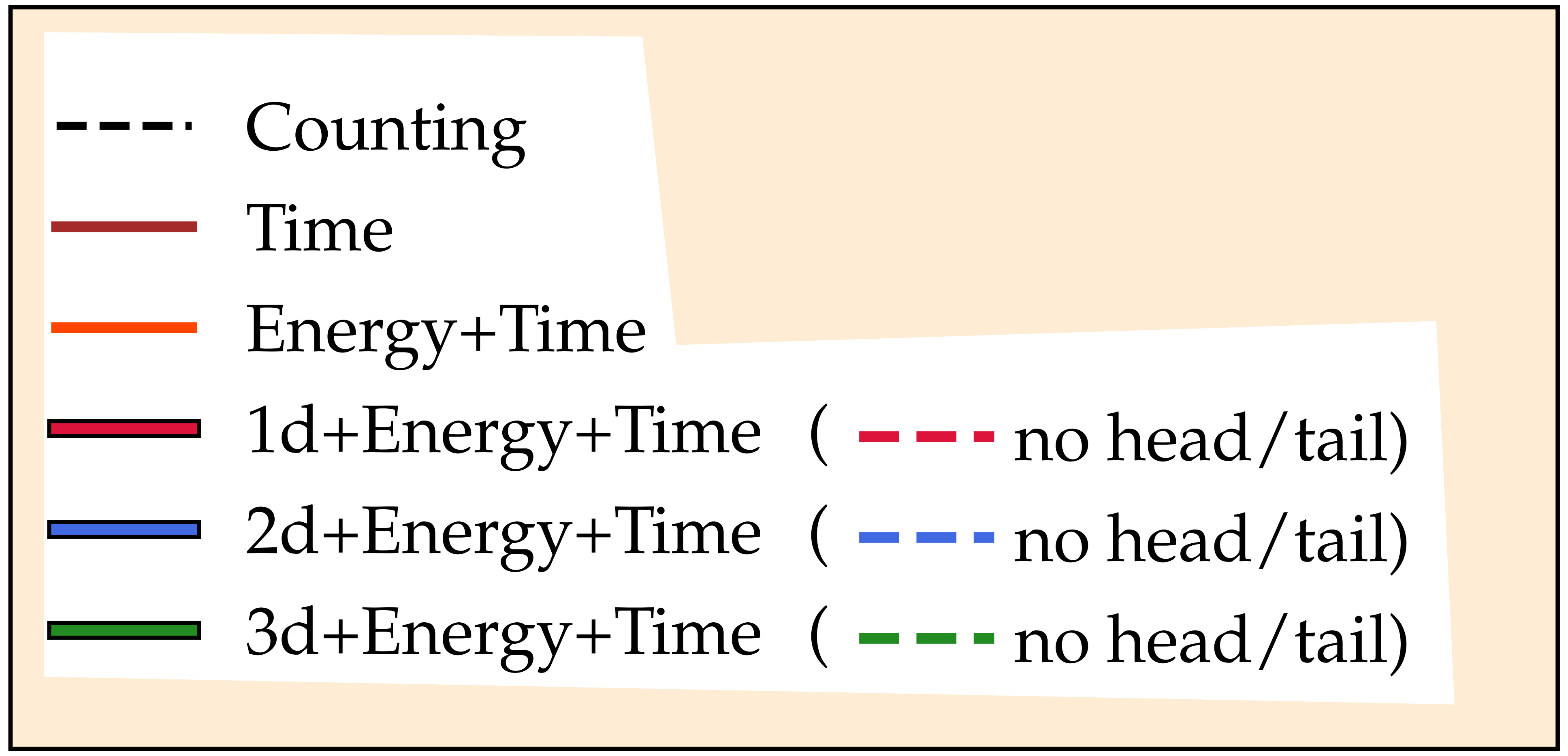
From the detector's perspective, the galactic dipole signature translates to a sidereal daily modulation in angle



Subtracting the neutrino background

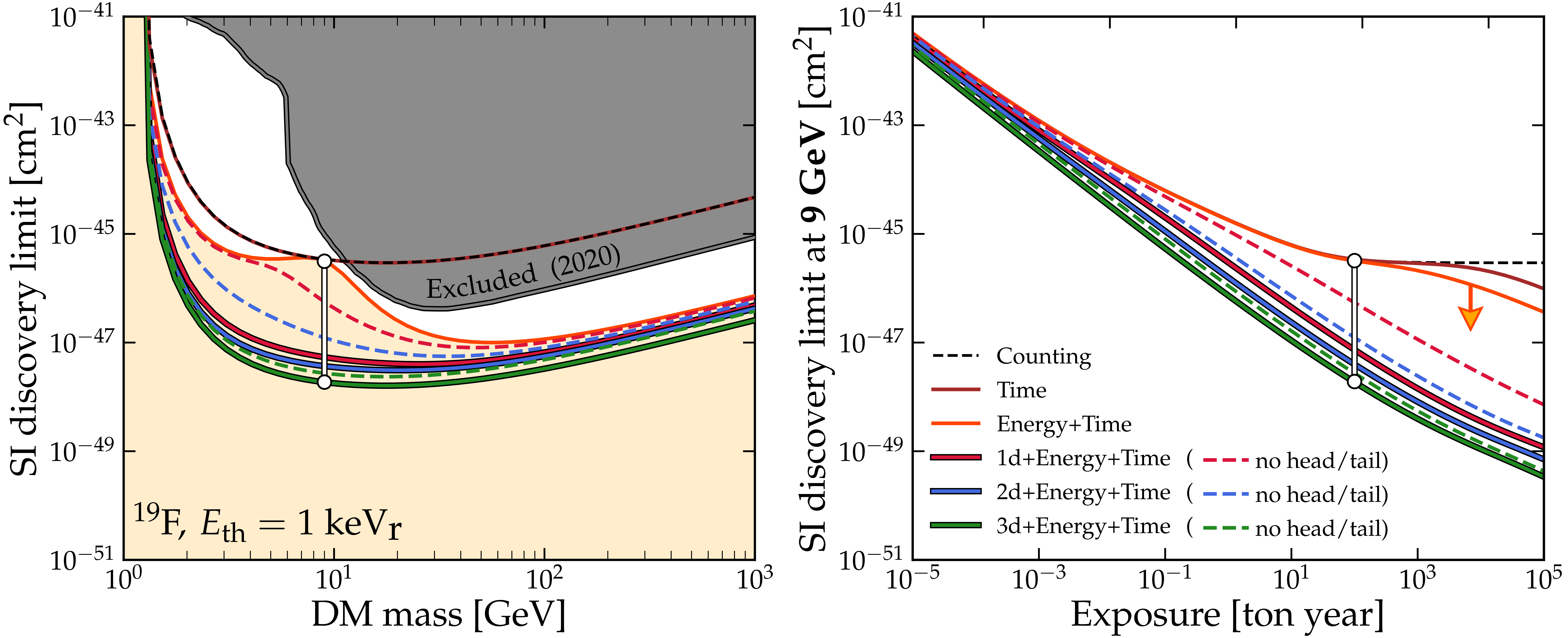


Same experiment, different levels of information used

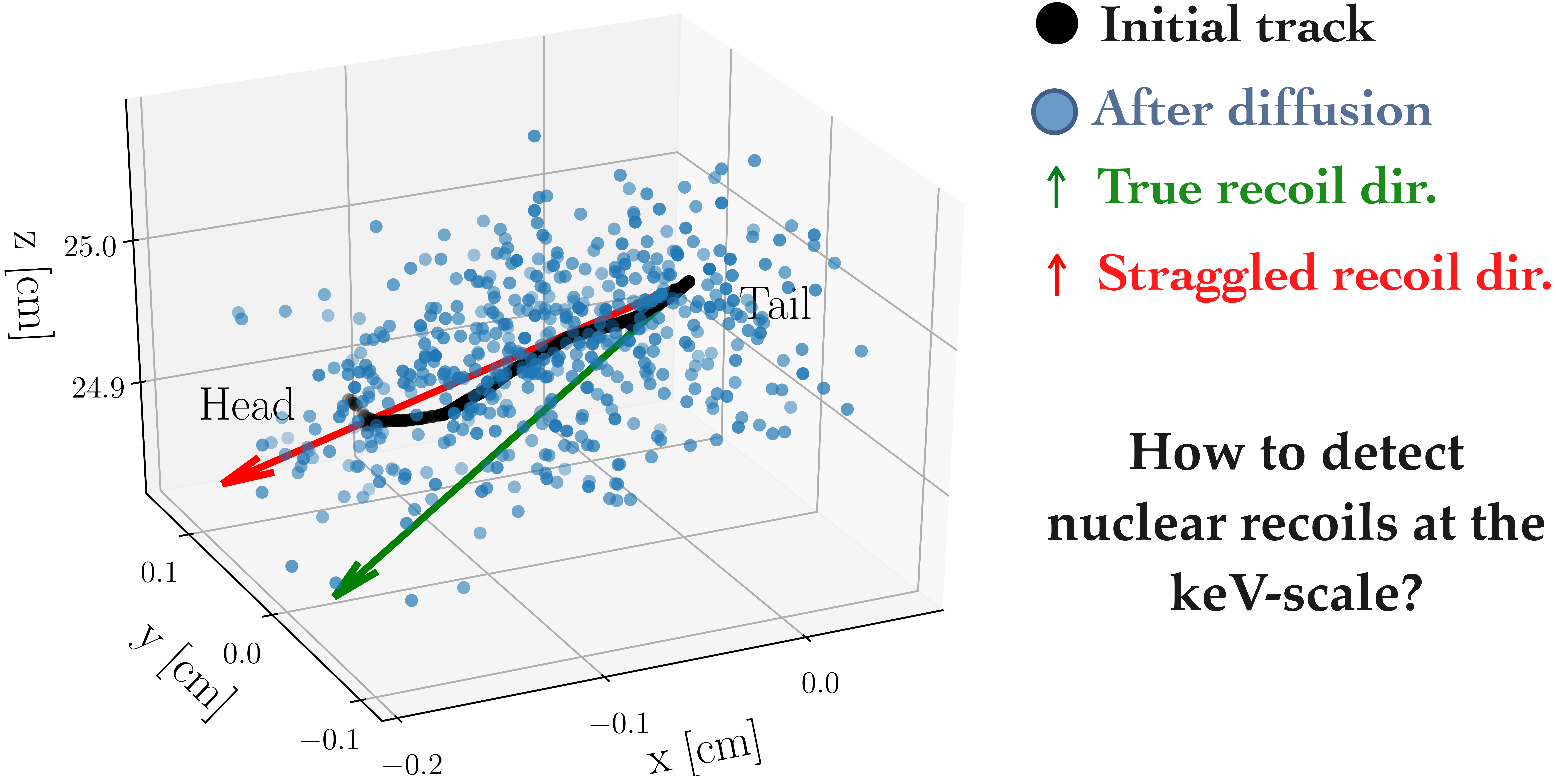


Orange region is inaccessible without directional information

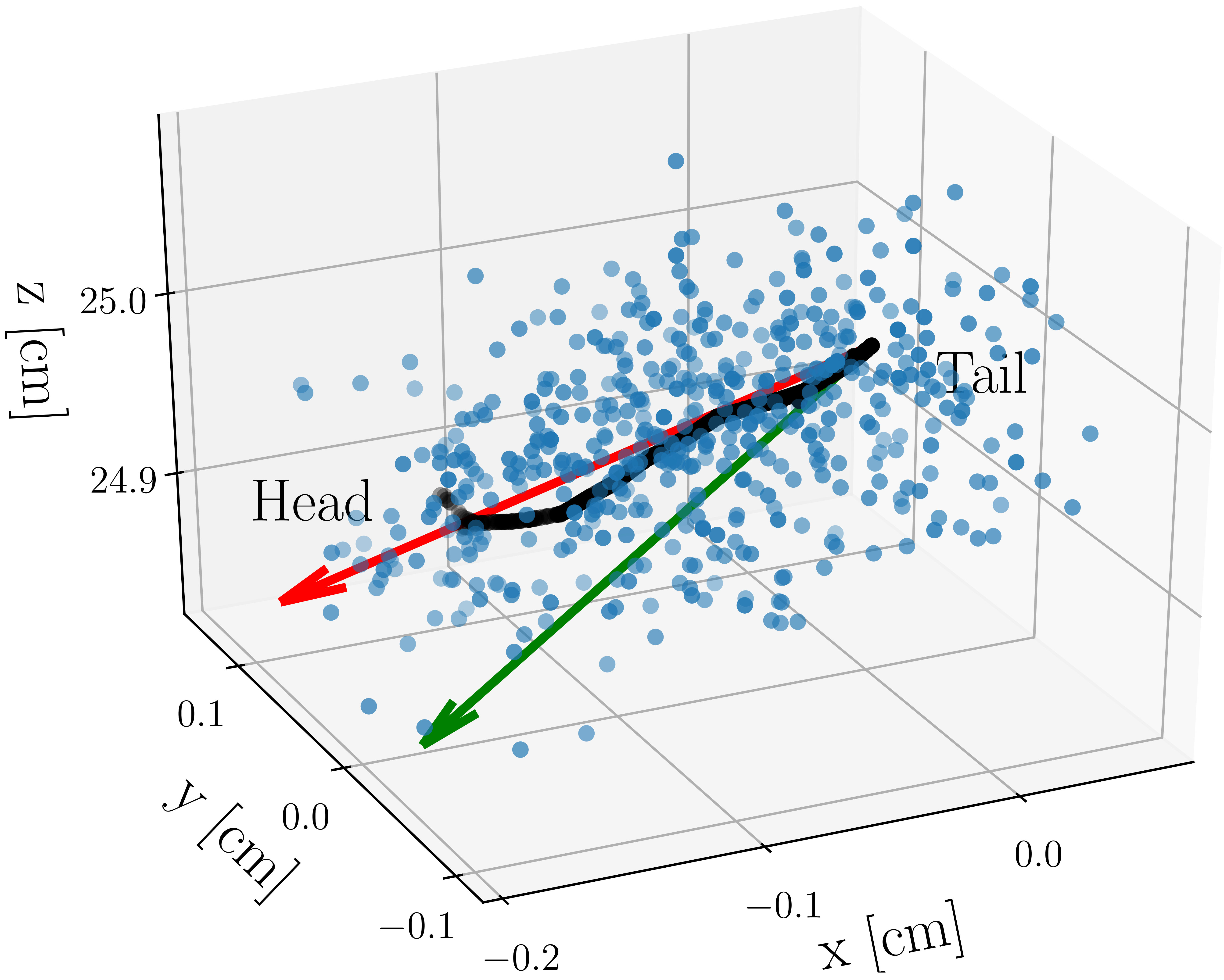
Subtracting the neutrino background



Orange region is inaccessible without directional information



How to detect nuclear recoils at the keV-scale?



The ideal detector measures:

- **Initial** recoil direction, or at least the initial ionisation
- The full 3-dimensions of the track
- The head / tail (i.e. sign of the track vector)
- The time of the event (to account for Earth rotation)

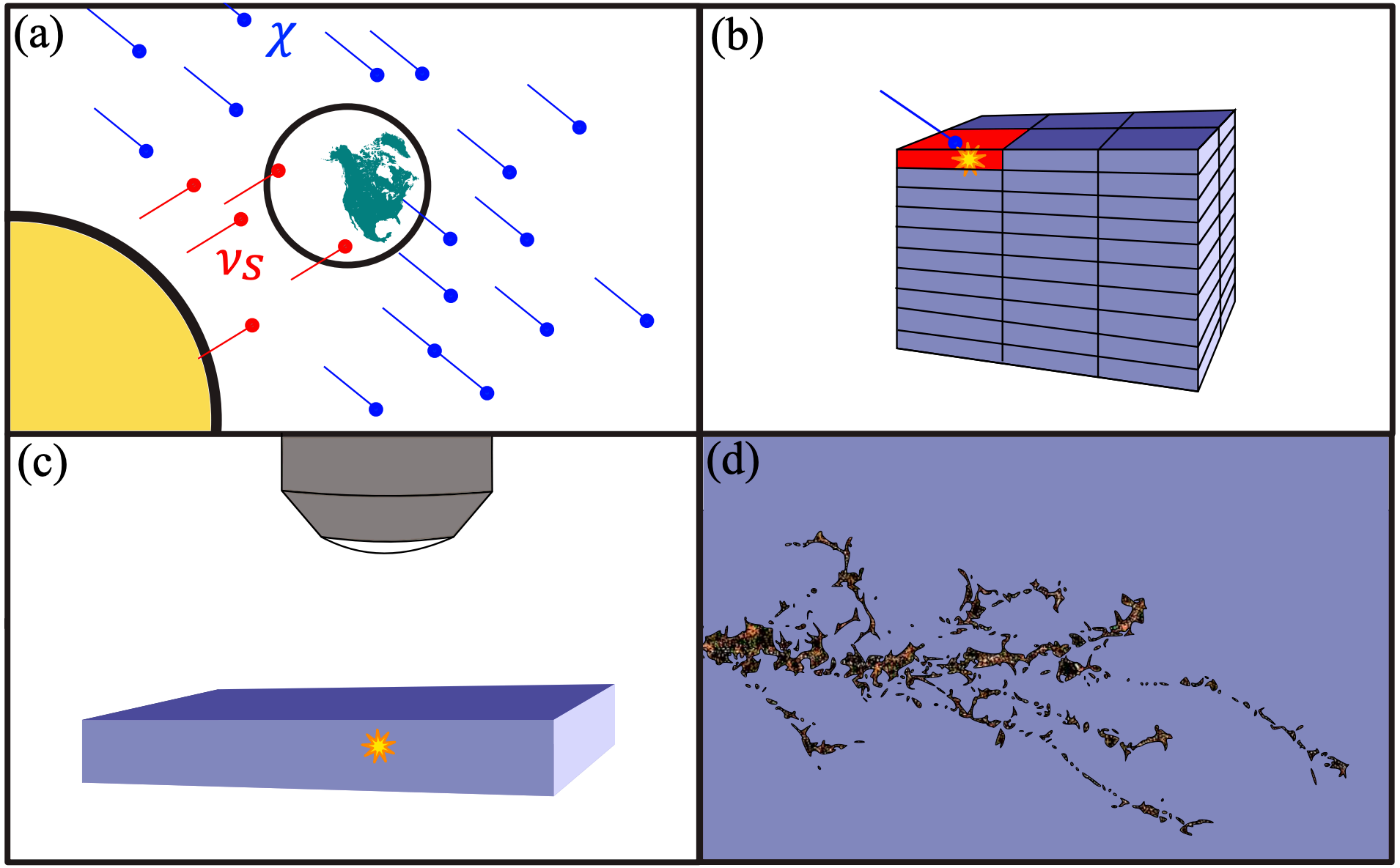
What would you use to detect keV-scale nuclear recoils?

	Pros	Cons
Solid	• High target mass • Well-established technologies, e.g. scintillators	• Need ultra high resolution imaging • Tracks highly scrambled
Liquid	• High target mass • Readily scalable to large volumes	• Tracks too short relative to diffusion
Gas	• Tracks at mm-scale • Nuclear/Electronic tracks are easily distinguishable • Imaging in gas TPCs demonstrated since 1990s	• Low target mass

Directionality in solids: crystal defect spectroscopy

Marshall et al. [2009.01028]

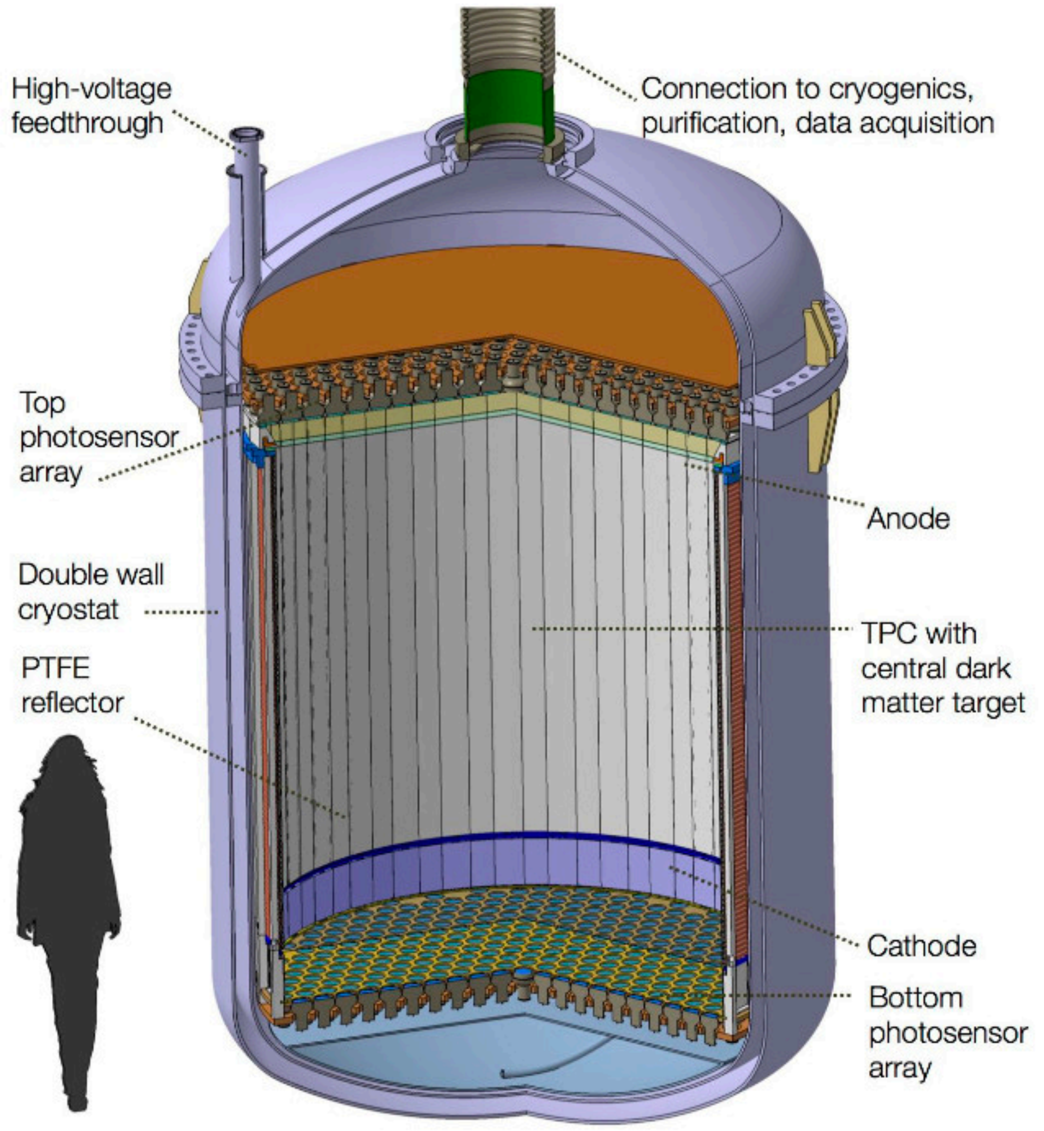
Nitrogen vacancy centres in diamond

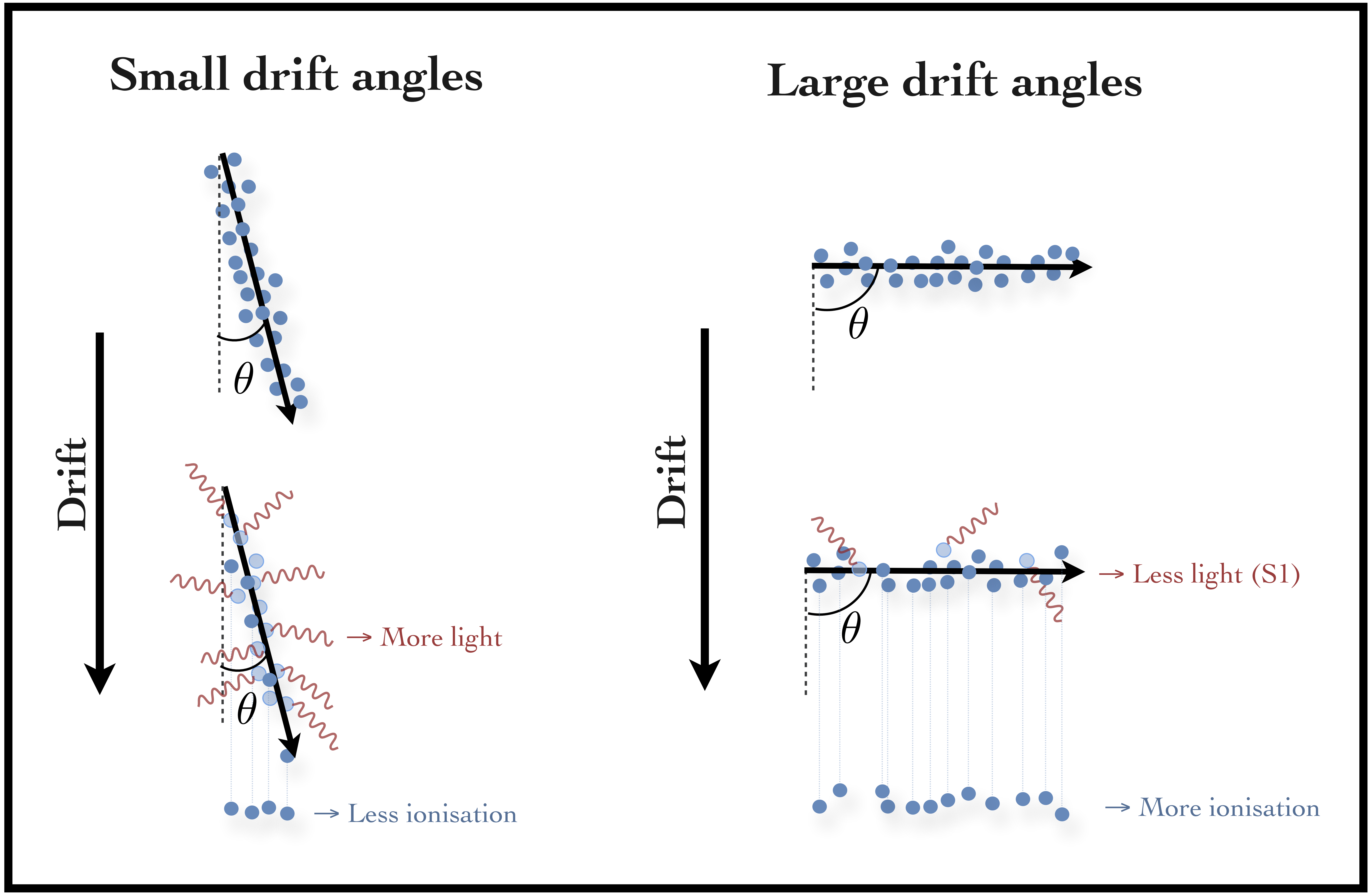


Directionality in liquids: columnar recombination

D R 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

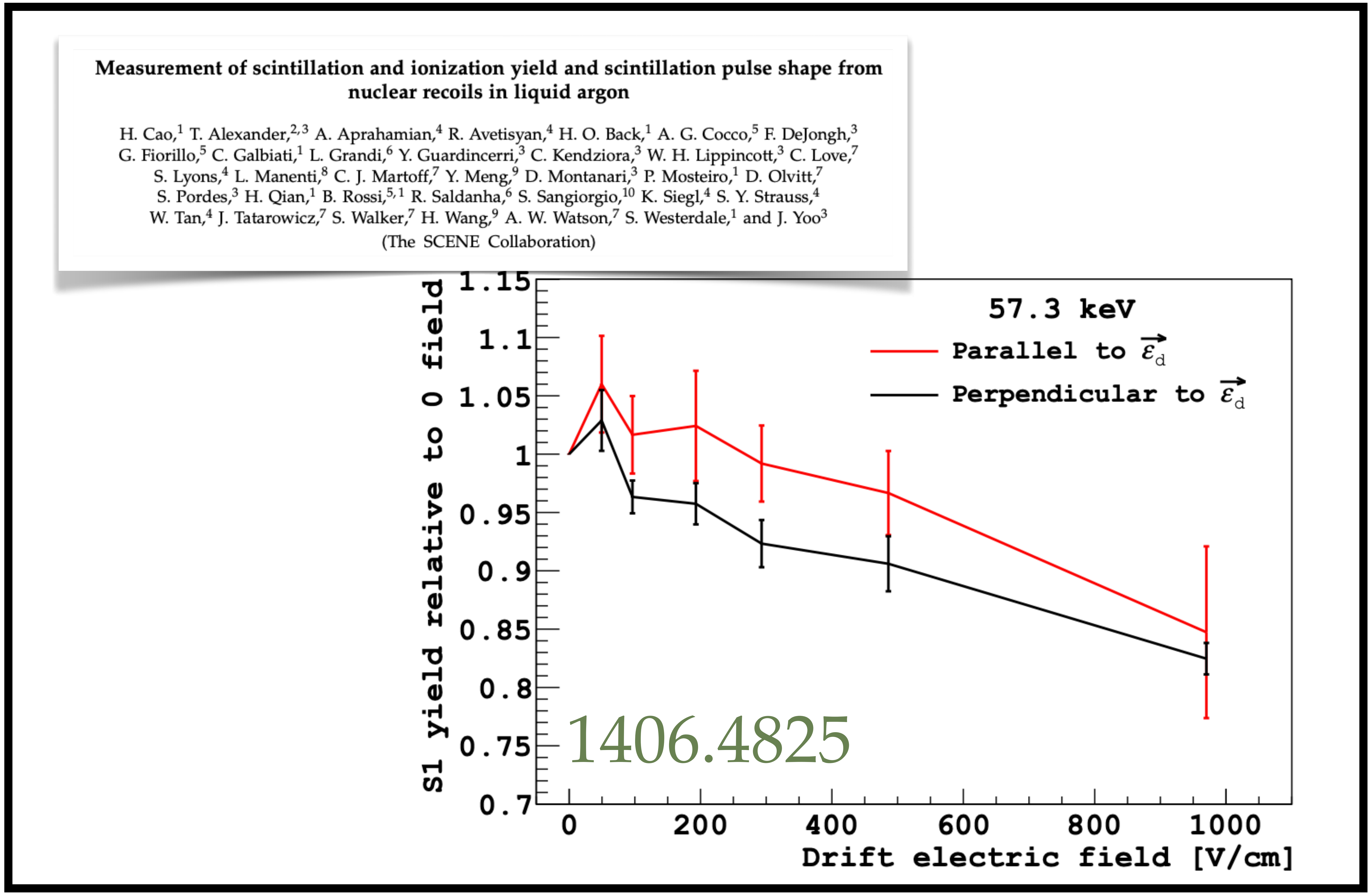




Directionality in liquids: columnar recombination

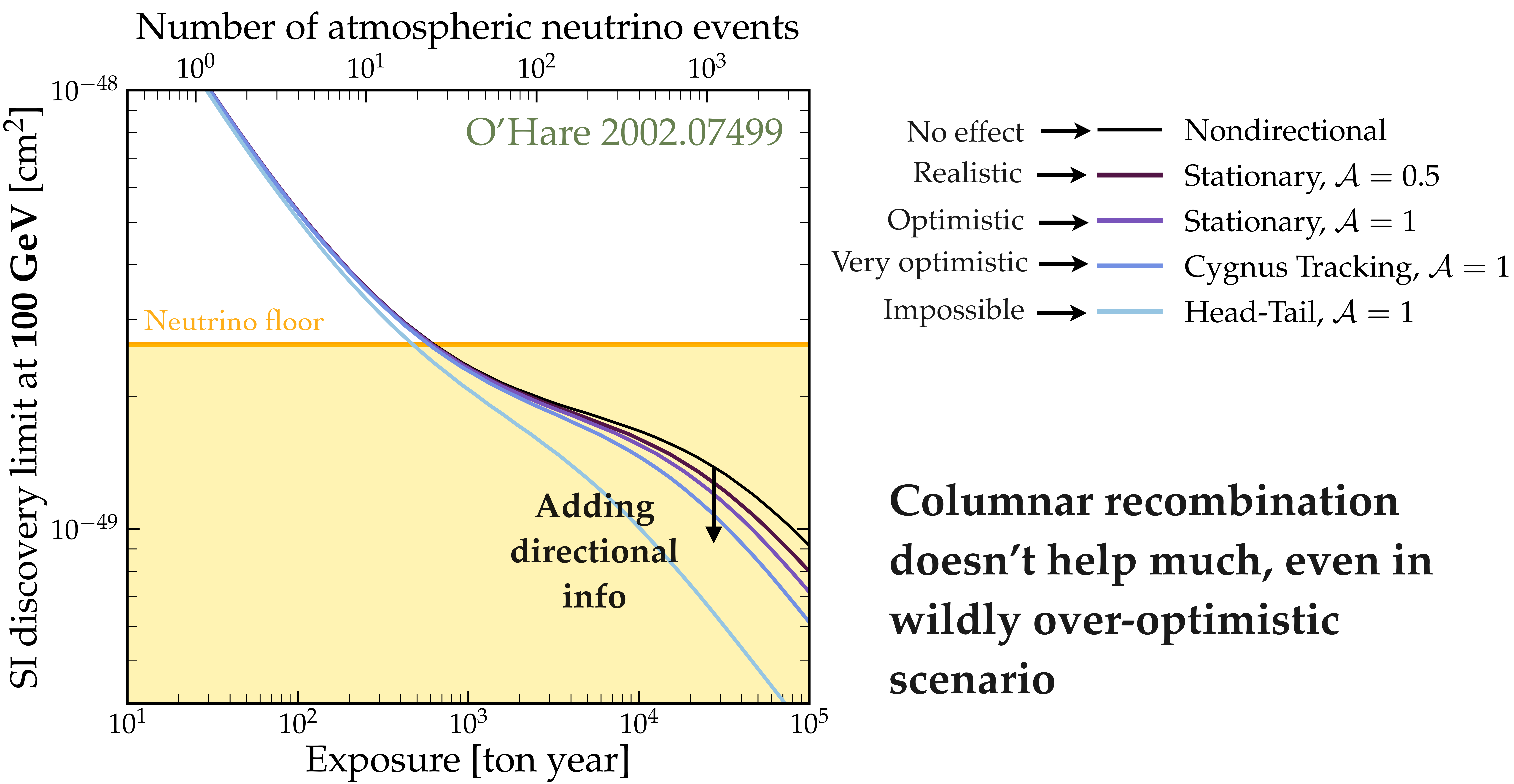
- Possible hint in LAr

- Almost certainly unobservable in LXe (at interesting energies)



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. Olvitt,[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. Yoo[3]
(The SCENE Collaboration)



Columnar recombination doesn't help much, even in wildly over-optimistic scenario

DNA detector?

1206.6809

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*

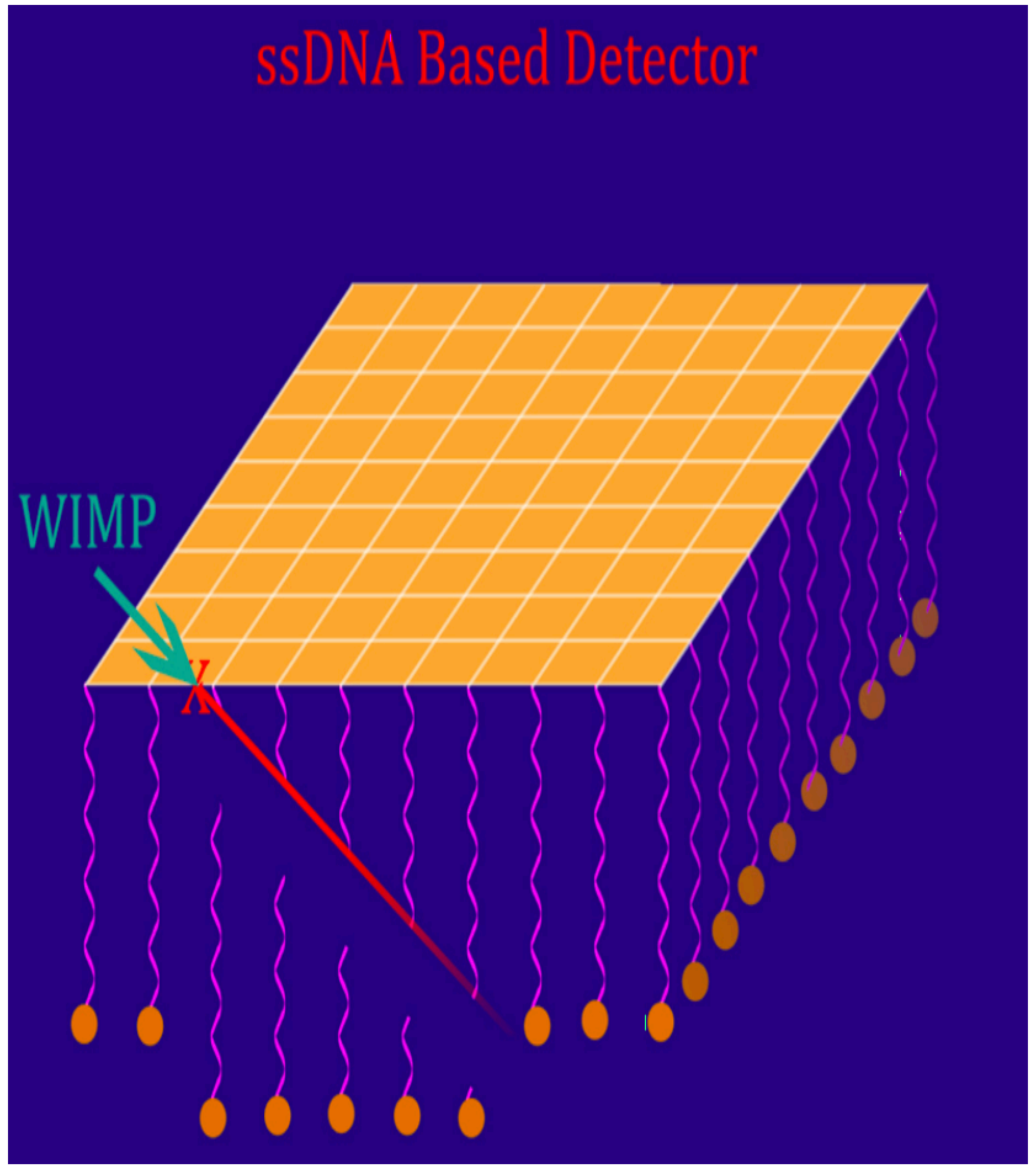
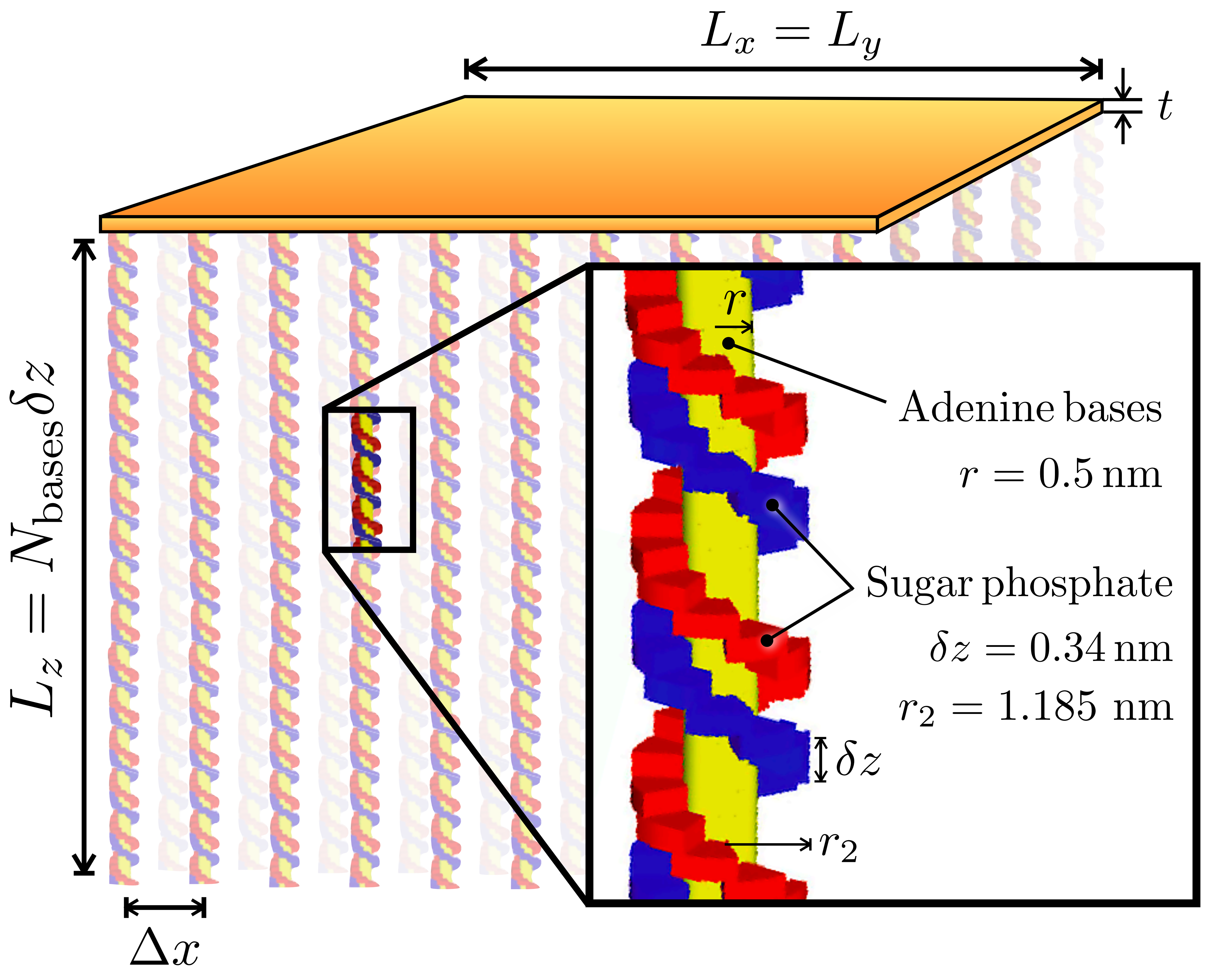
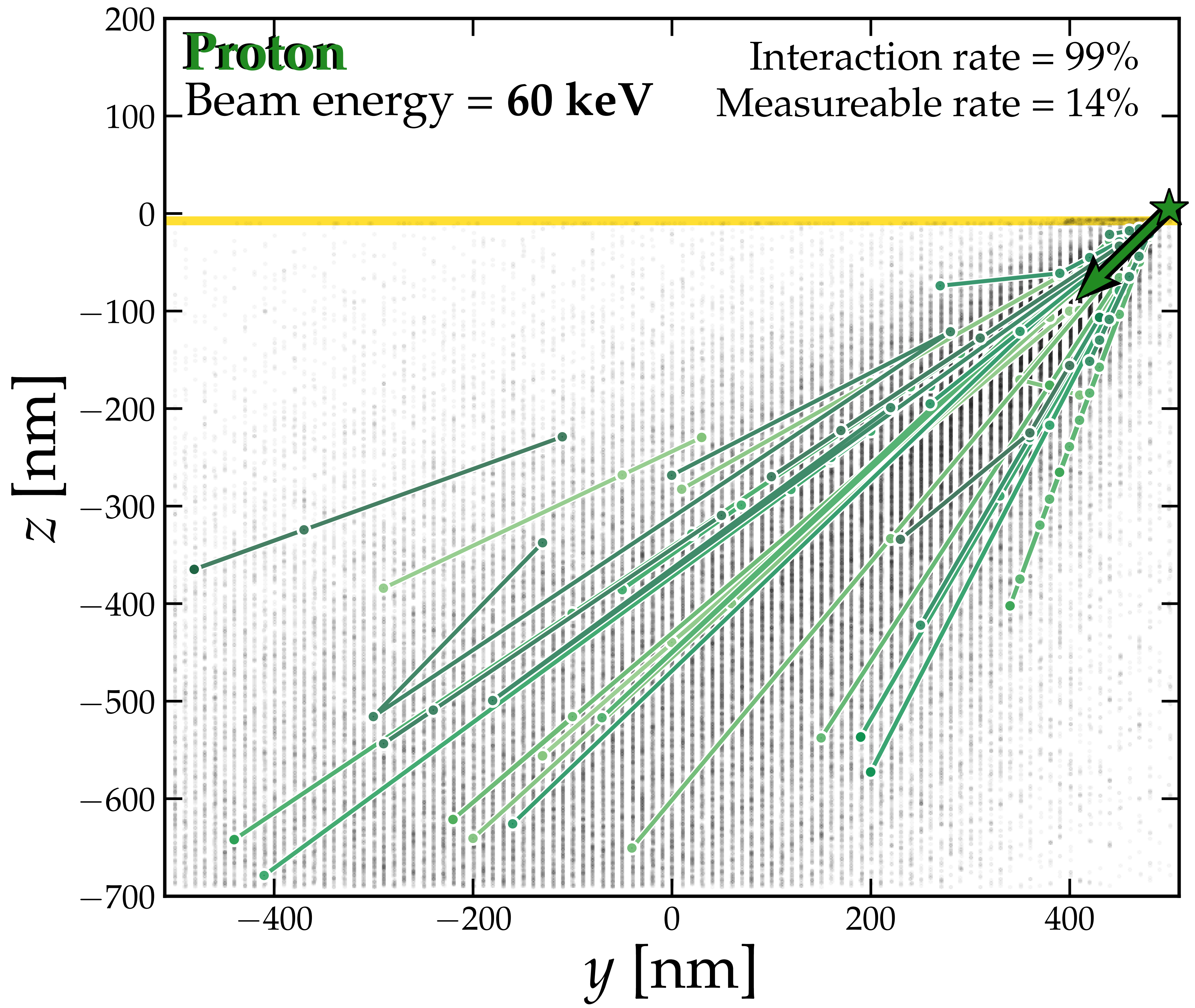


FIG. 2: ssNA/Au Tracking Chamber: A WIMP from the Galaxy scatters elastically with a gold nucleus situated in a thin gold foil. The recoiling Au nucleus traverses hanging strings of single stranded NA, and severs any ssNA it hits. The location of the breaks can be found by amplifying and sequencing the fallen ssNA segment, thereby allowing reconstruction of the track of the recoiling Au nucleus with nanometer accuracy.

DNA as a particle detector?





Work in progress with students at Sydney

→ Probably not a good DM detector (low target mass), but still interesting as it completely reimagines the idea of recoil imaging

→ Surprisingly this would not be very technologically demanding or expensive, just needs optimisation and verification that it can be useful.

2102.04596

Detector classes by directional information

Demonstrated
R&D
Proposed

Indirect | **Recoil imaging**

Statistical | **Event-level**

Modulation-based directionality

Indirect recoil event directionality

Time-integrated recoil imaging

Time-resolved recoil imaging

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, without 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

CYGNUS

- **Proto-Collaboration: >50** members from US, UK, Aus., Japan, Italy, Spain, China
- **Focus**: Ton-scale gas time projection chamber (TPC)
- **Primary goal:** WIMP discovery below the neutrino floor
- **Secondary goal:** Directional detection of solar neutrinos
- **Tertiary goals:** study DM velocity dist., non-WIMP DM, supernovae + more?

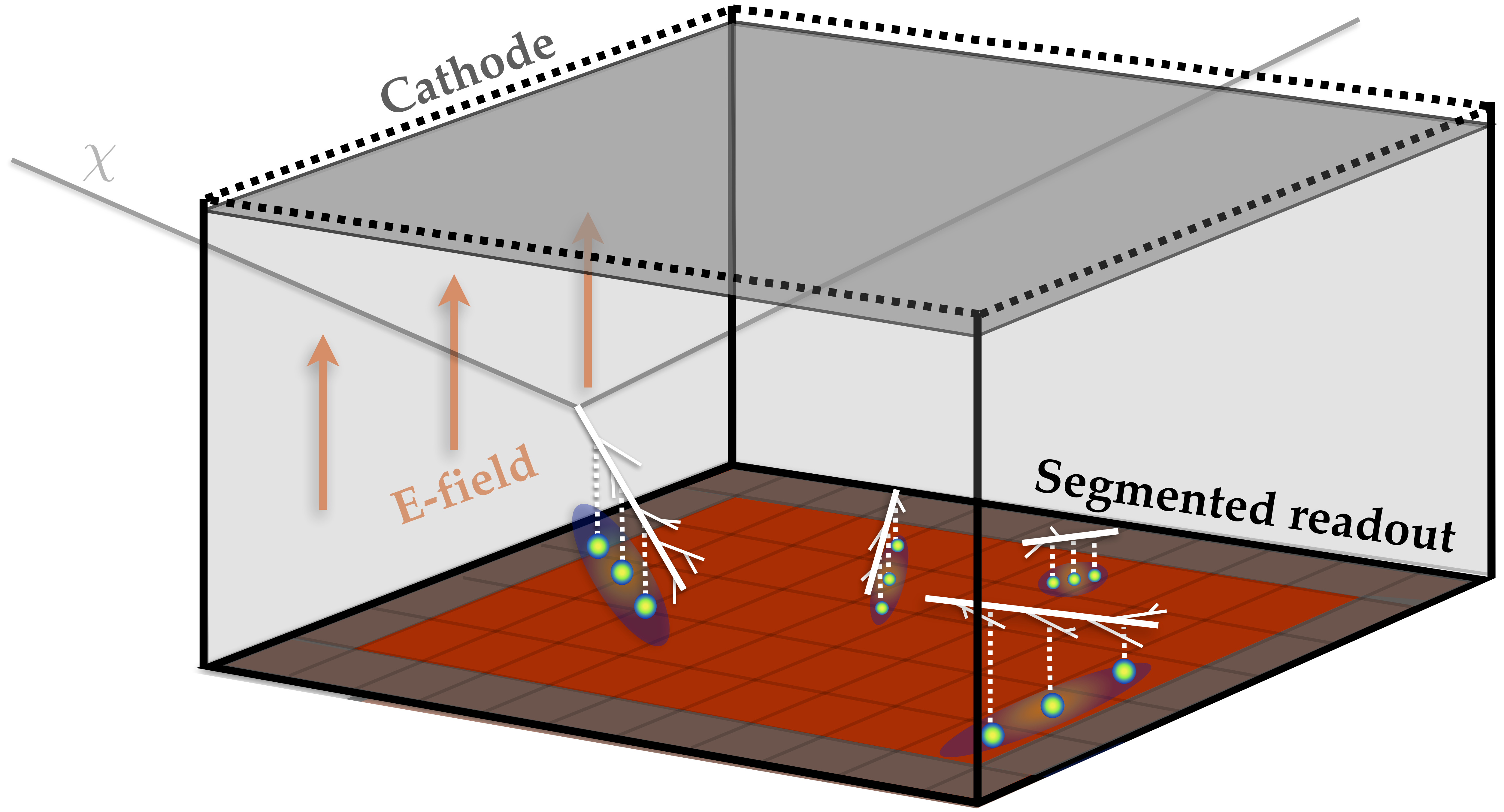
[2008.12587]

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]

Focus of Cygnus: gas time projection chamber

Current gas of interest: 1 atm. of He:SF6 at 755:5



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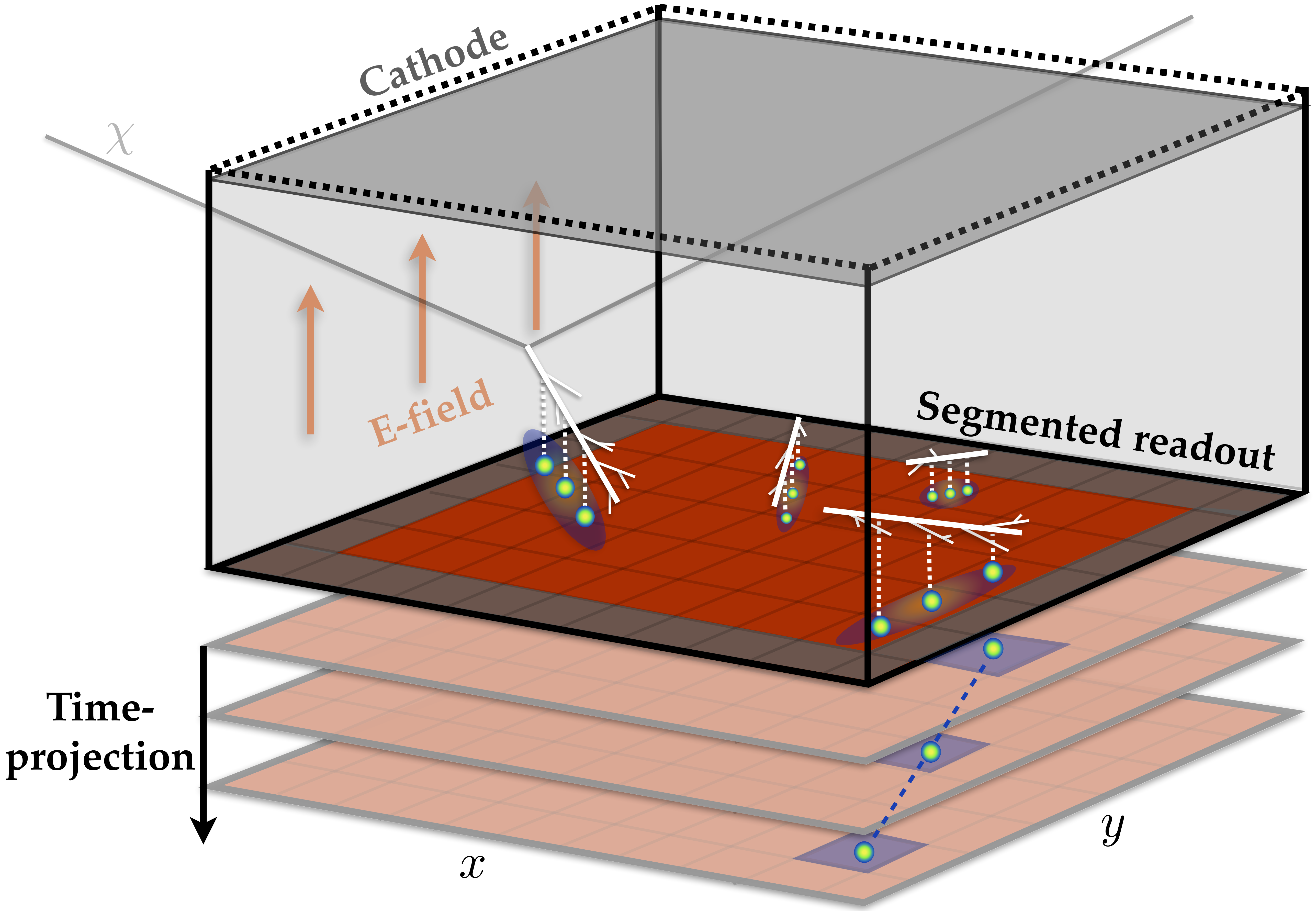

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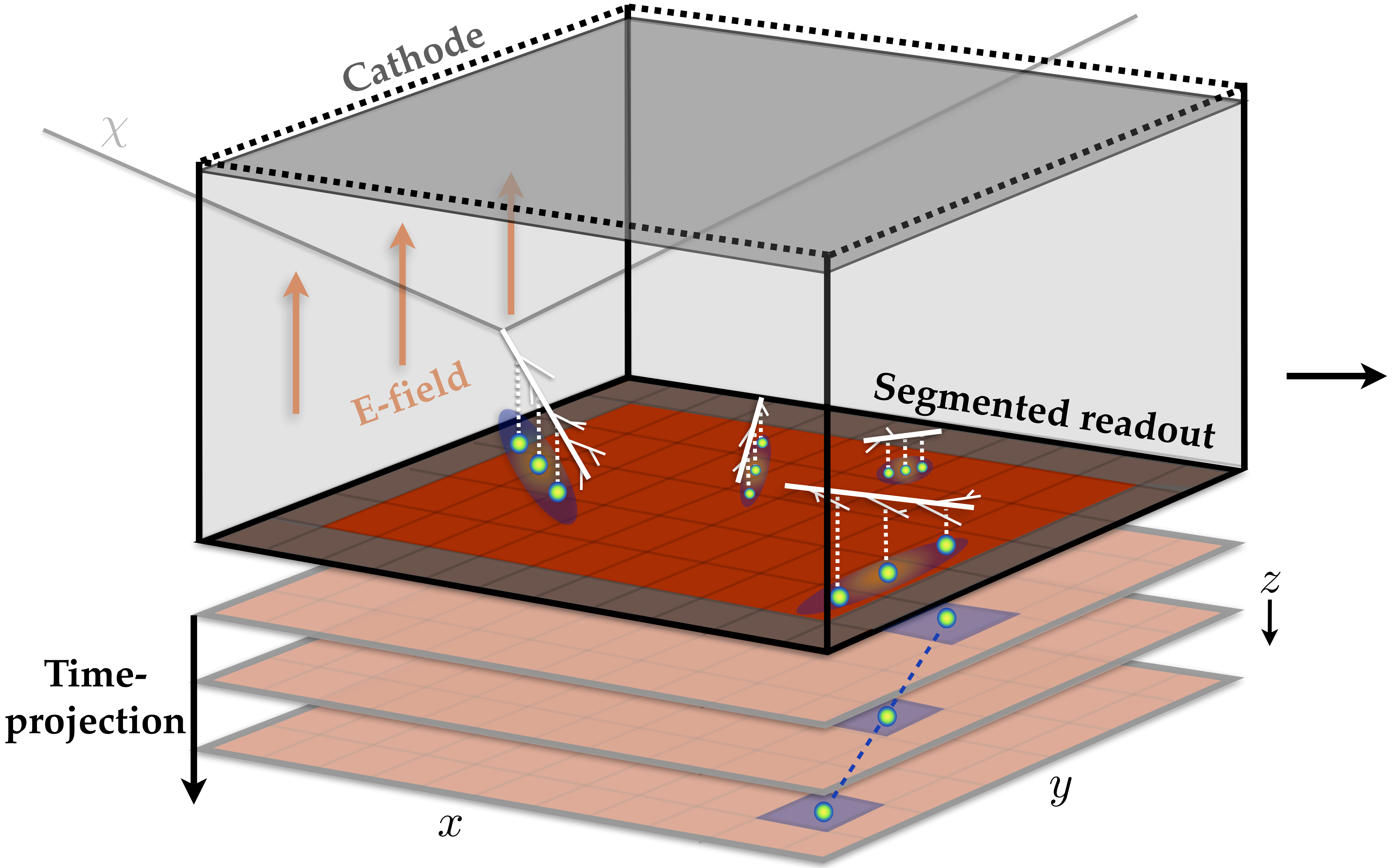
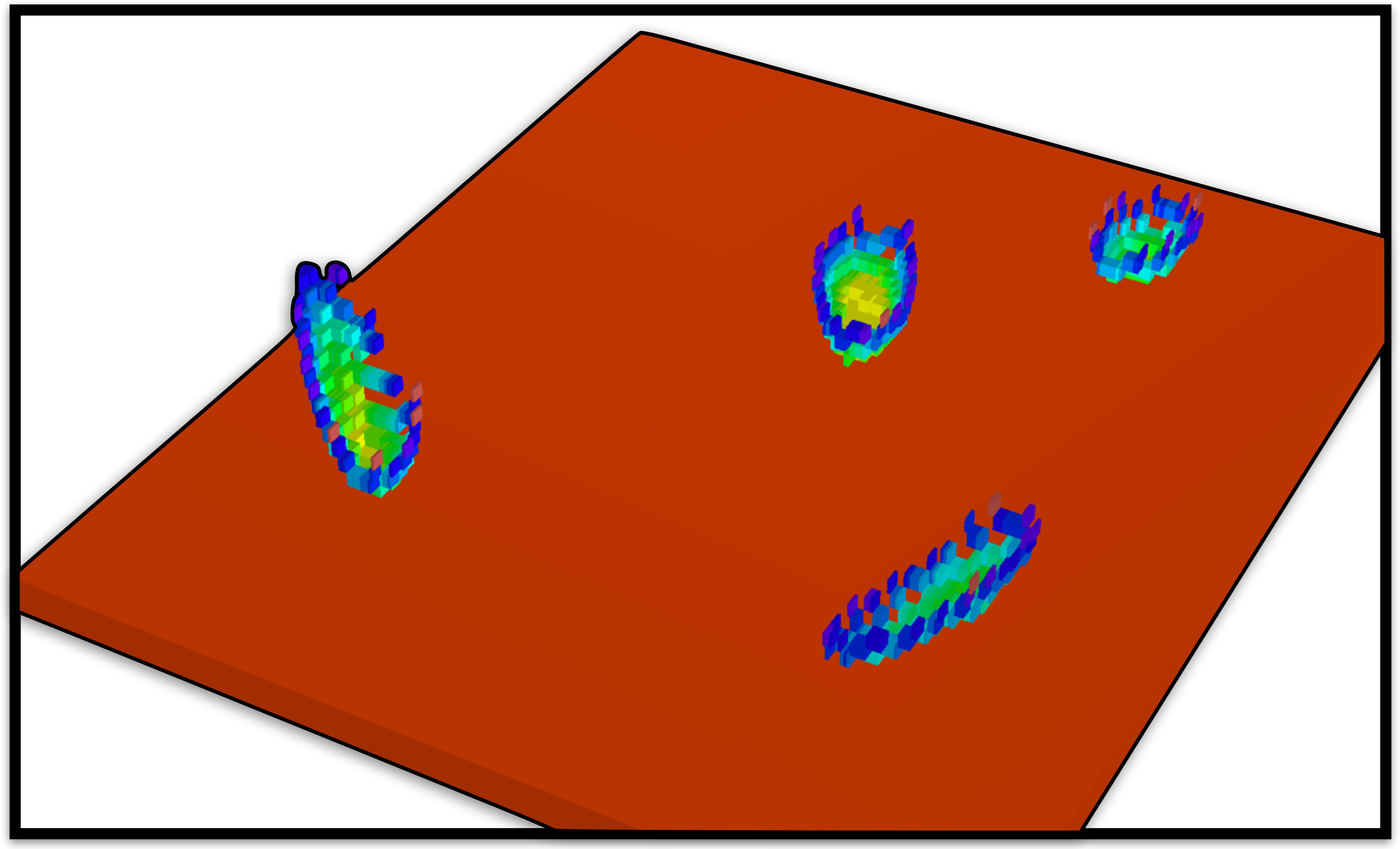


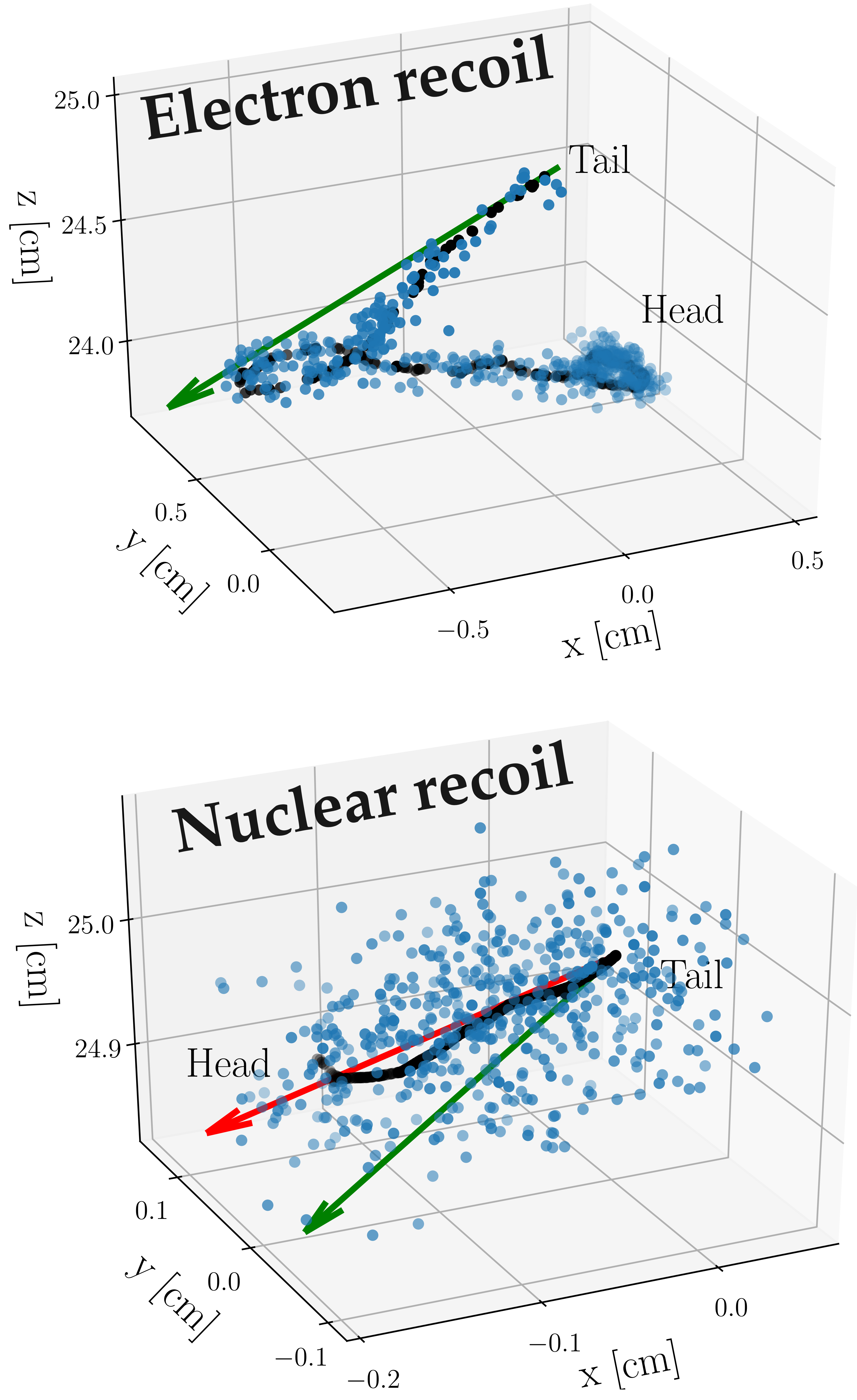


Angular performance

Everything gets worse at lower energies:

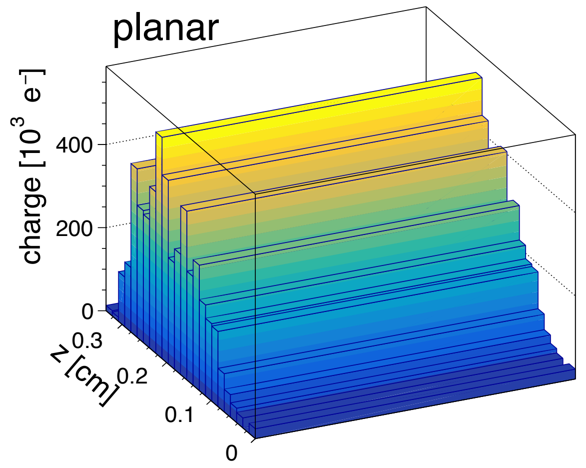
- Decreasing quenching factor, means recoils are harder to detect
- Tracks get shorter → harder to measure directions
- Contrast in dE/dx is slower, harder to measure head-tail
- Harder to distinguish ER/NRs since tracks are short

→ Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals



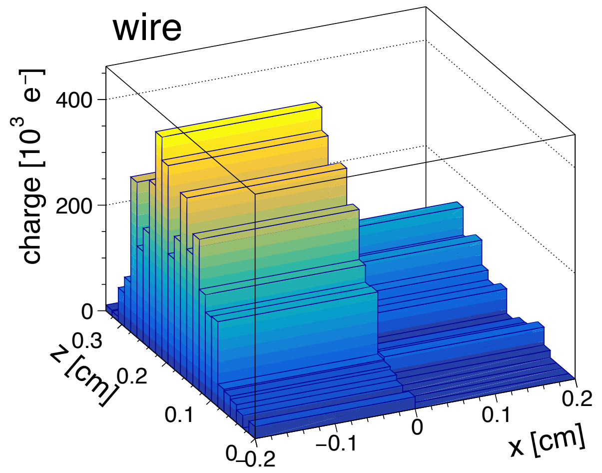
Readout technologies

Planar



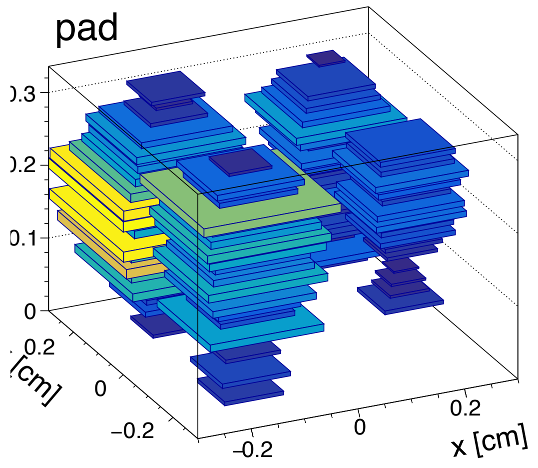
1D

Wire



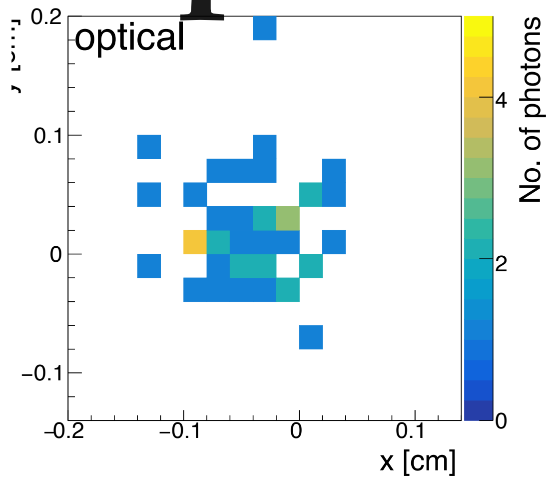
1D

Pad



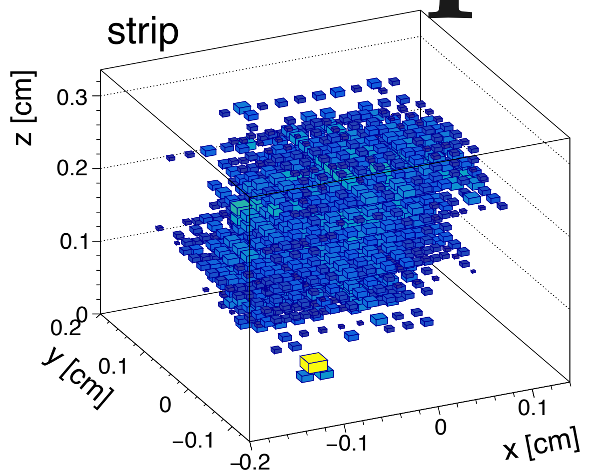
2D

Optical



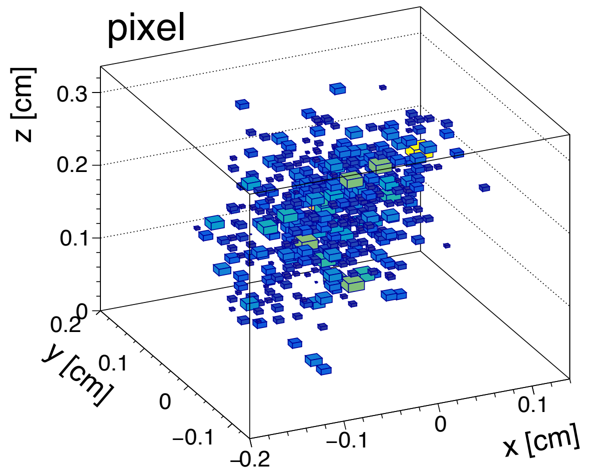
3D
(when combined with PMTs)

Strip



3D

Pixel



3D

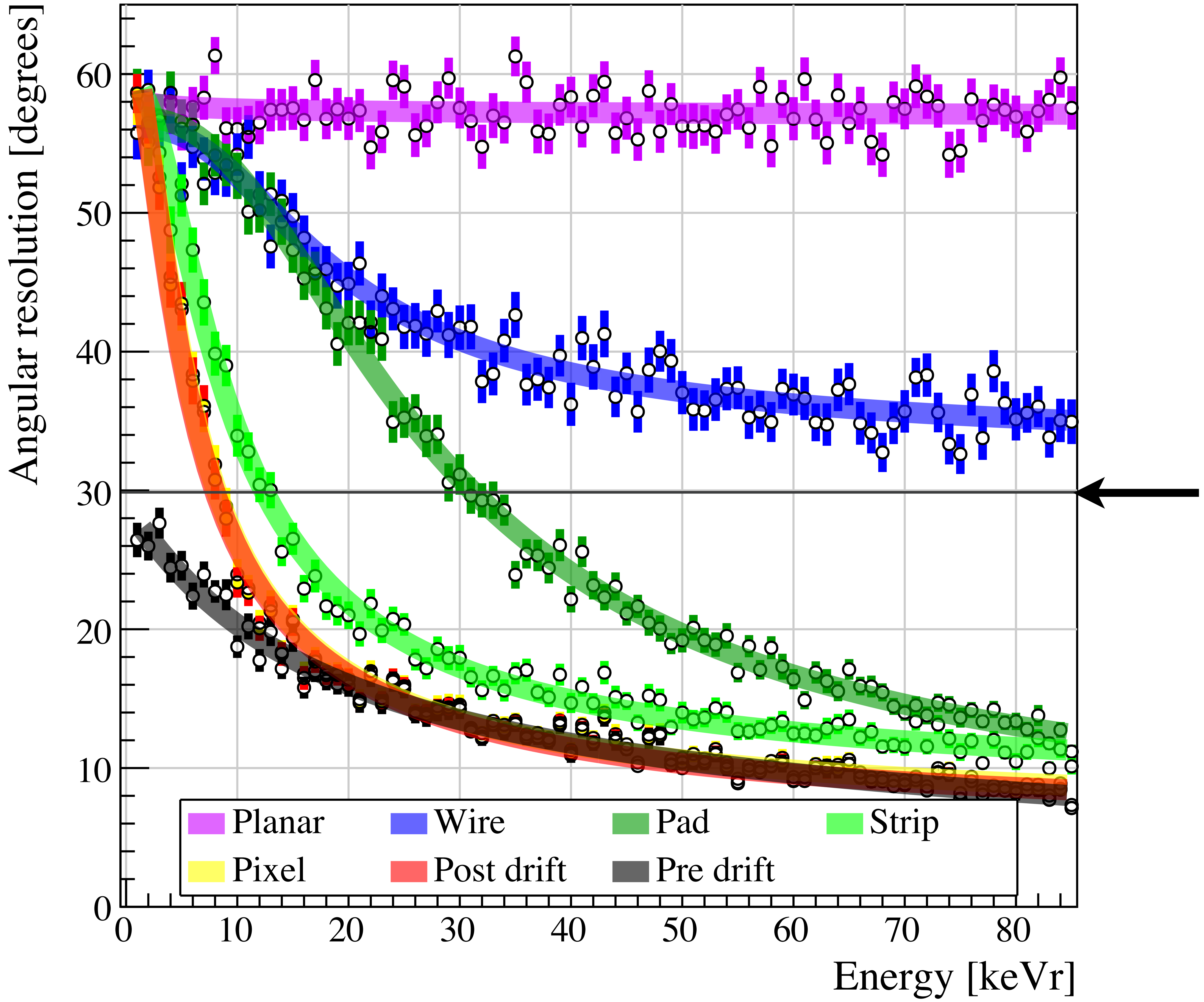
Simplest readouts
→ Worst directional sensitivity but
lower cost

Most highly segmented readouts
→ Best directional sensitivity but
Highest cost

Need a balance between cost *and* directional performance

Example: angular resolution

Dispersion in measured (axial) angles relative to initial recoil direction (=1 rad. if there is no correlation and angles are isotropically distributed)



<u>Simulated charge readout comparison</u>

To realistically discriminate DM and neutrinos, need angular resolution better than ~30°

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

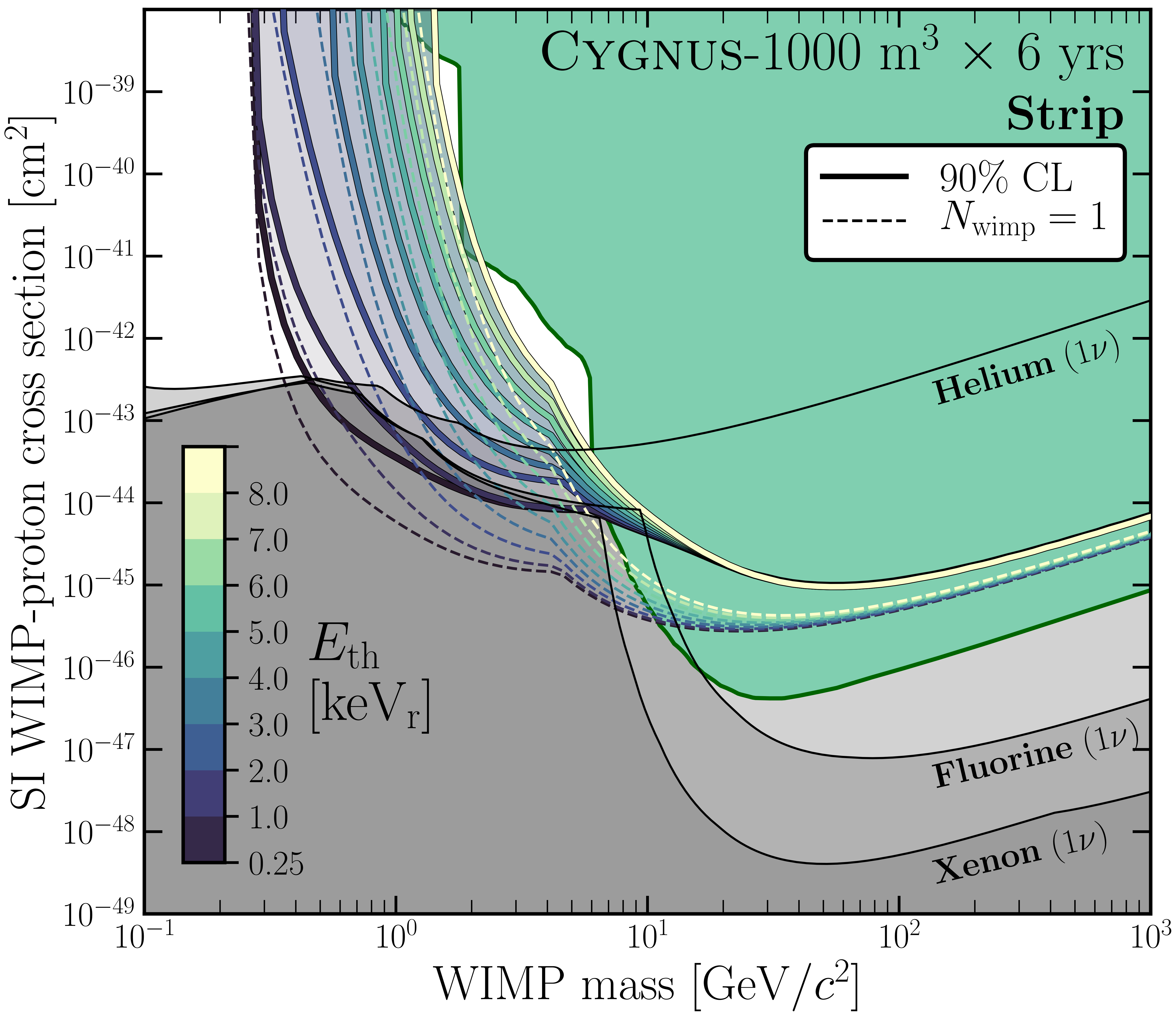
A closer look at dependence on threshold:

<u>Threshold:</u>

→ 8 keVr definitely feasible with simplest electron rejection strategy

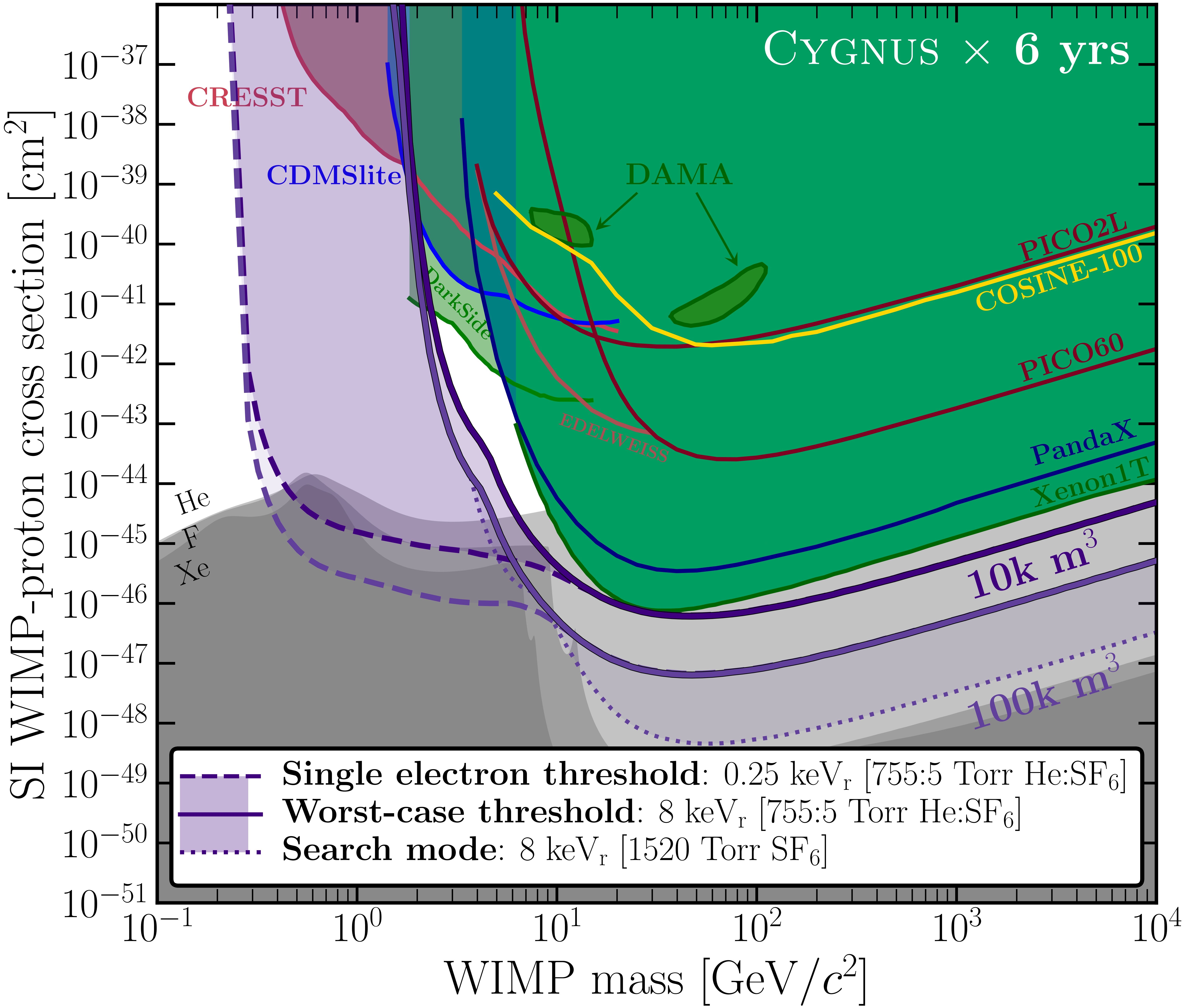
→ 3 keVr is probably feasible

→ 0.25 keVr is theoretical minimum (single electron)



Sensitivity (SI)

→ Window worst/best case threshold
→ Search mode: 1 atm. of SF_6 but <u>no</u> directionality (possible way to extend high mass sensitivity)



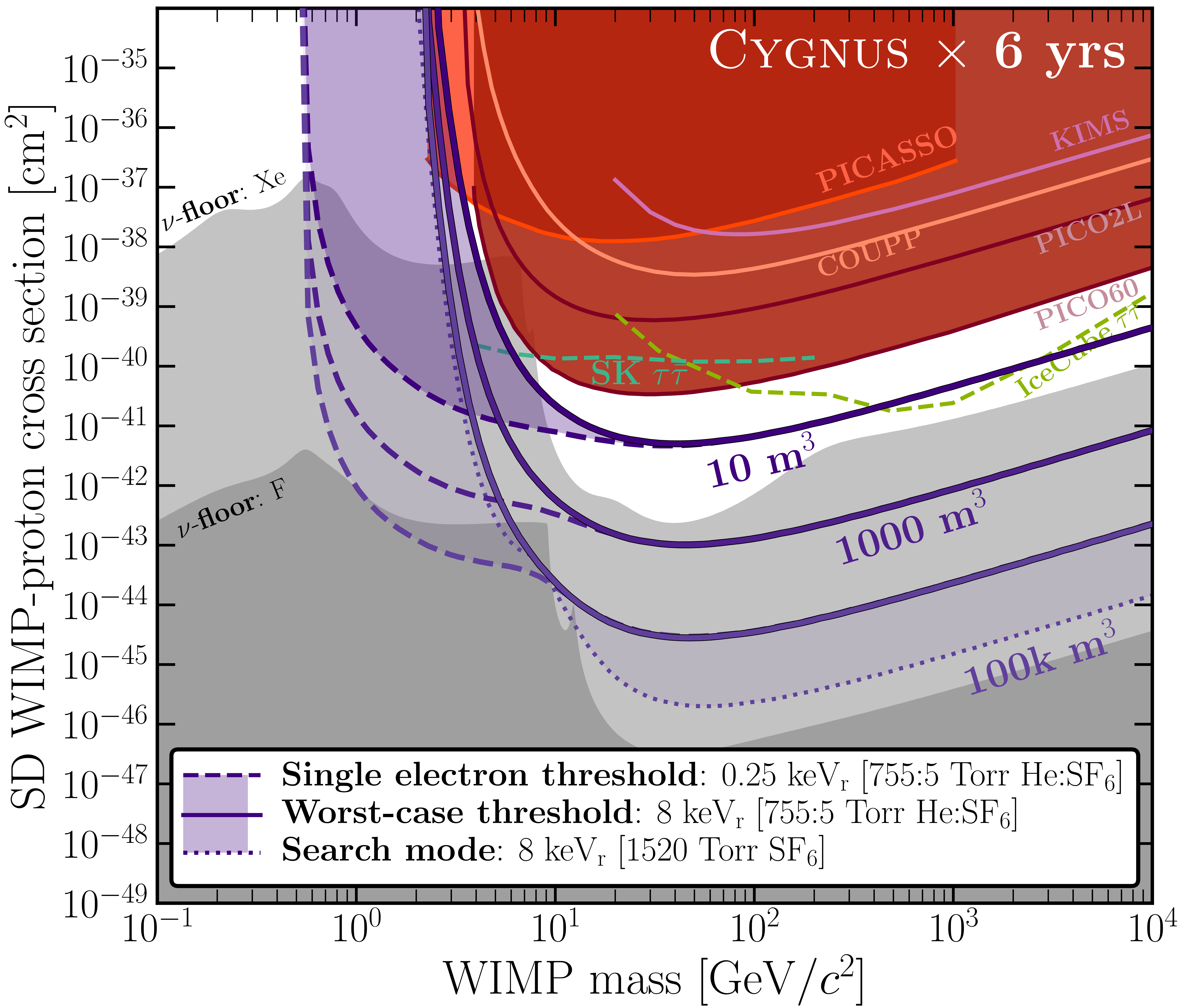
Important note: these limits are true discovery limits, i.e. a signal can be <u>confirmed</u> as DM, so comparison of Cygnus limits with other experiments undersells its potential

Sensitivity (SD-p)

→ Fluorine-based fill gases have high proton spin $\langle S_p \rangle$ → naturally good SD-proton limits

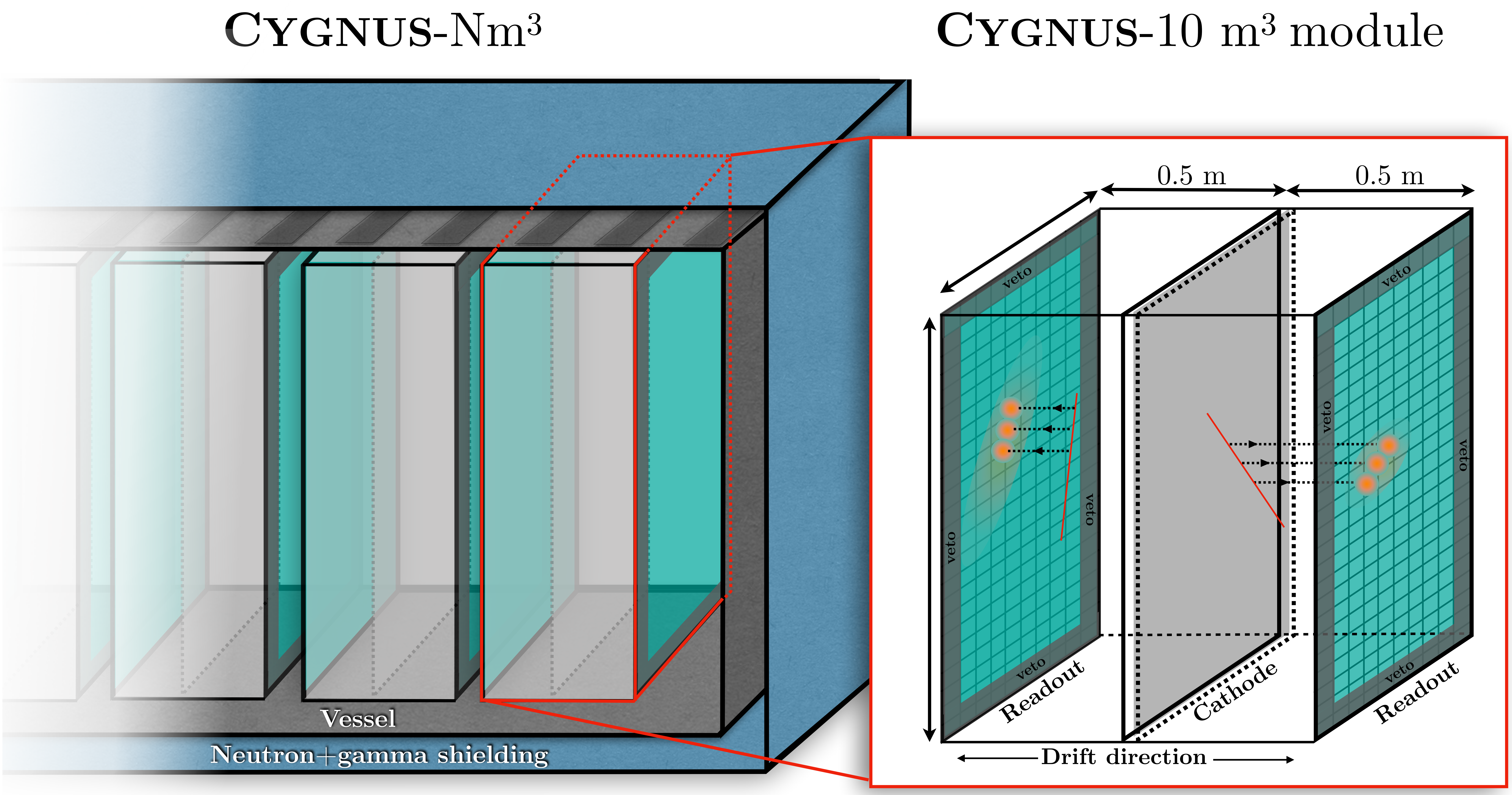
→ He does not set limits on this cross section

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



How to scale up?

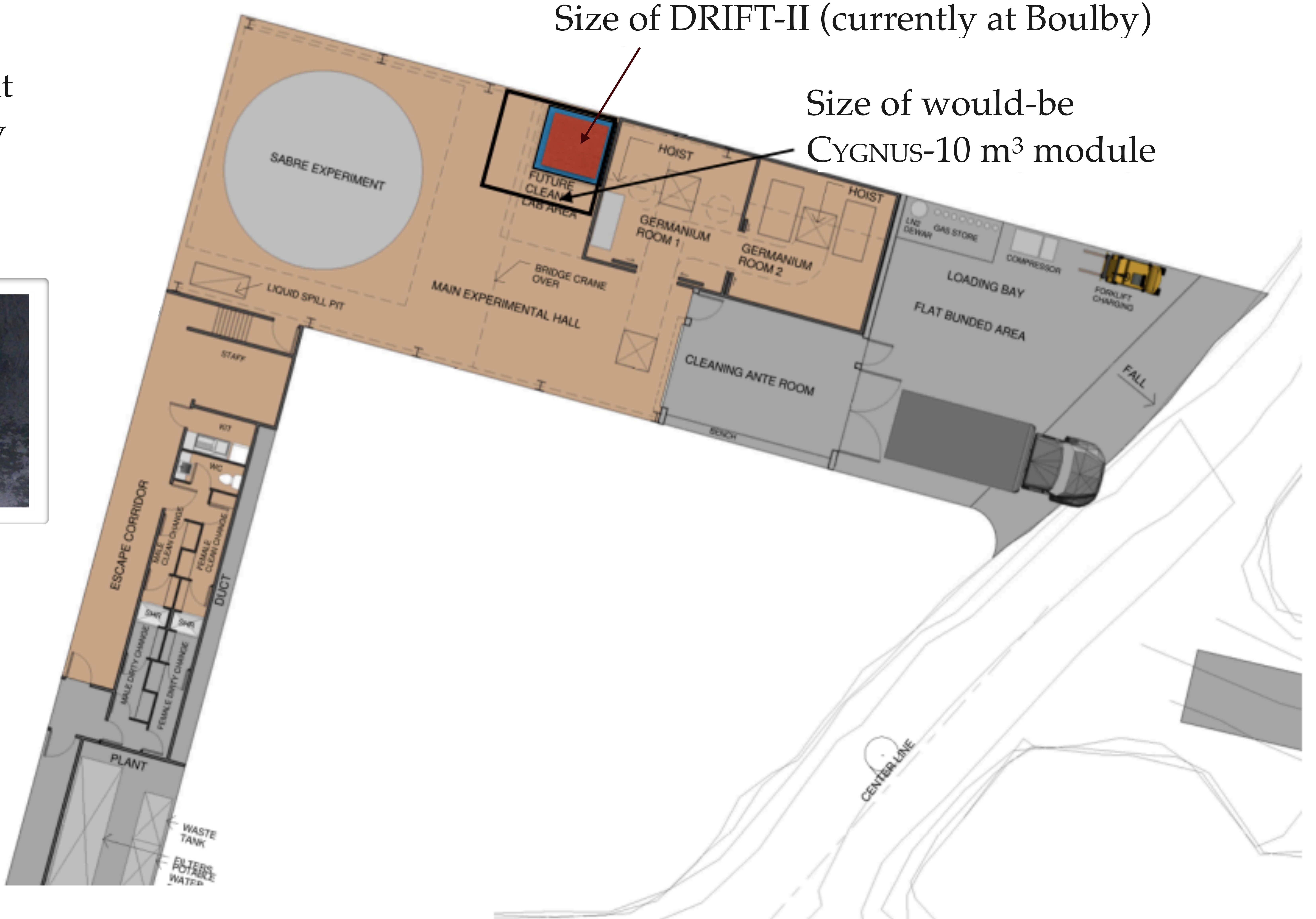
Modularity is both necessary, and advantageous




CYGNUS
CYGNUS-10
Boulby, UK
CYGNUS-KM
Kamioka, Japan
CYGNUS-HD10
Lead, South Dakota
CYGNO
Gran Sasso, Italy
CYGNUS-OZ
Stawell, Aus.
CYGNUS-Andes
Chile/Argentina

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



Say we build Cygnus and find that…

Say we build Cygnus and find that…

1. We have a signal

Say we build Cygnus and find that…

1. We have a signal

2. We don’t

Say we build Cygnus and find that…

1. **We have a signal**

2. **We don't**

Then what?

Say we build Cygnus and find that…

1. We have a signal

→ We study it

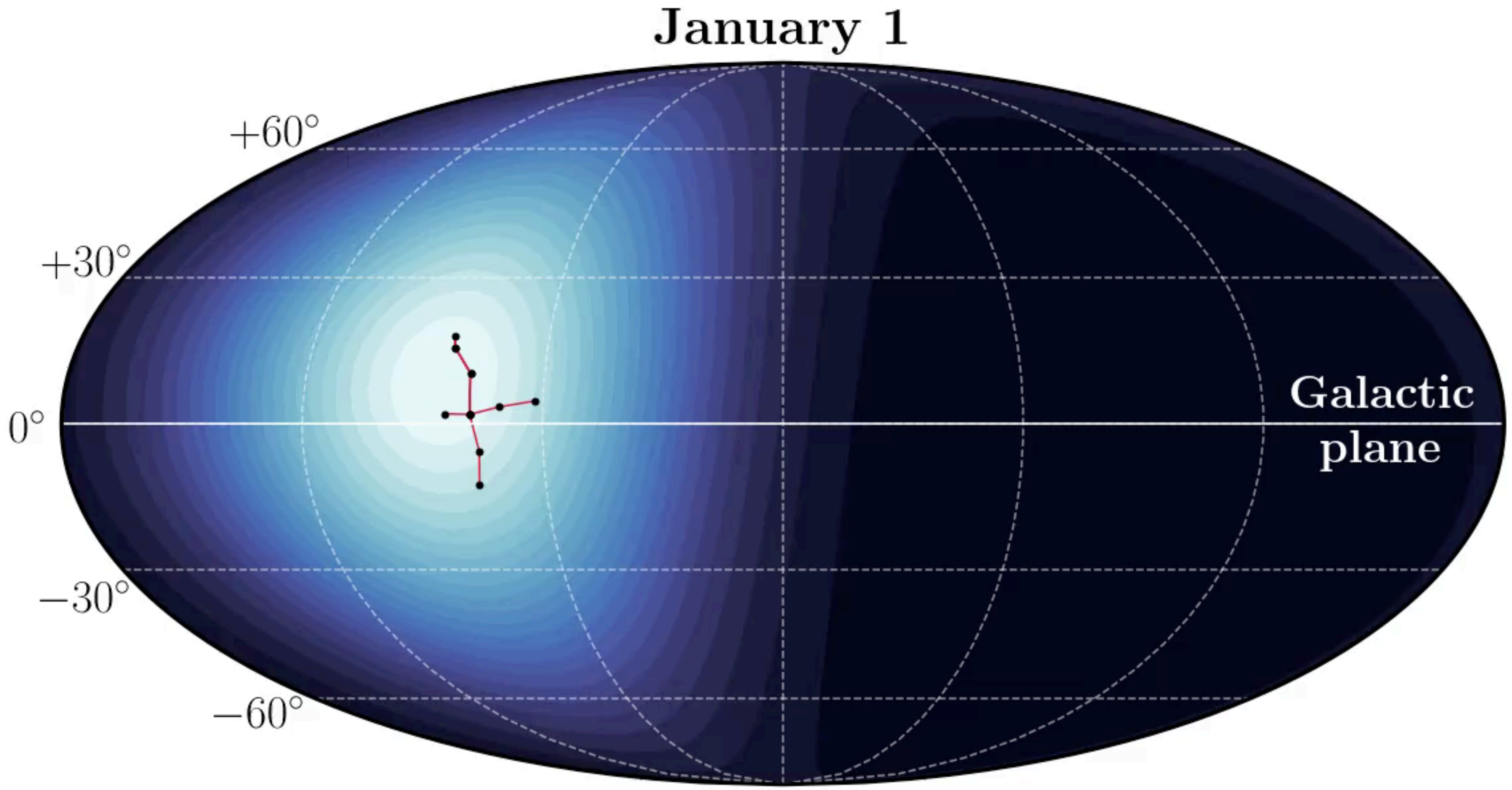
2. We don't

Then what?

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

→ a Gaussian peaking towards Cygnus

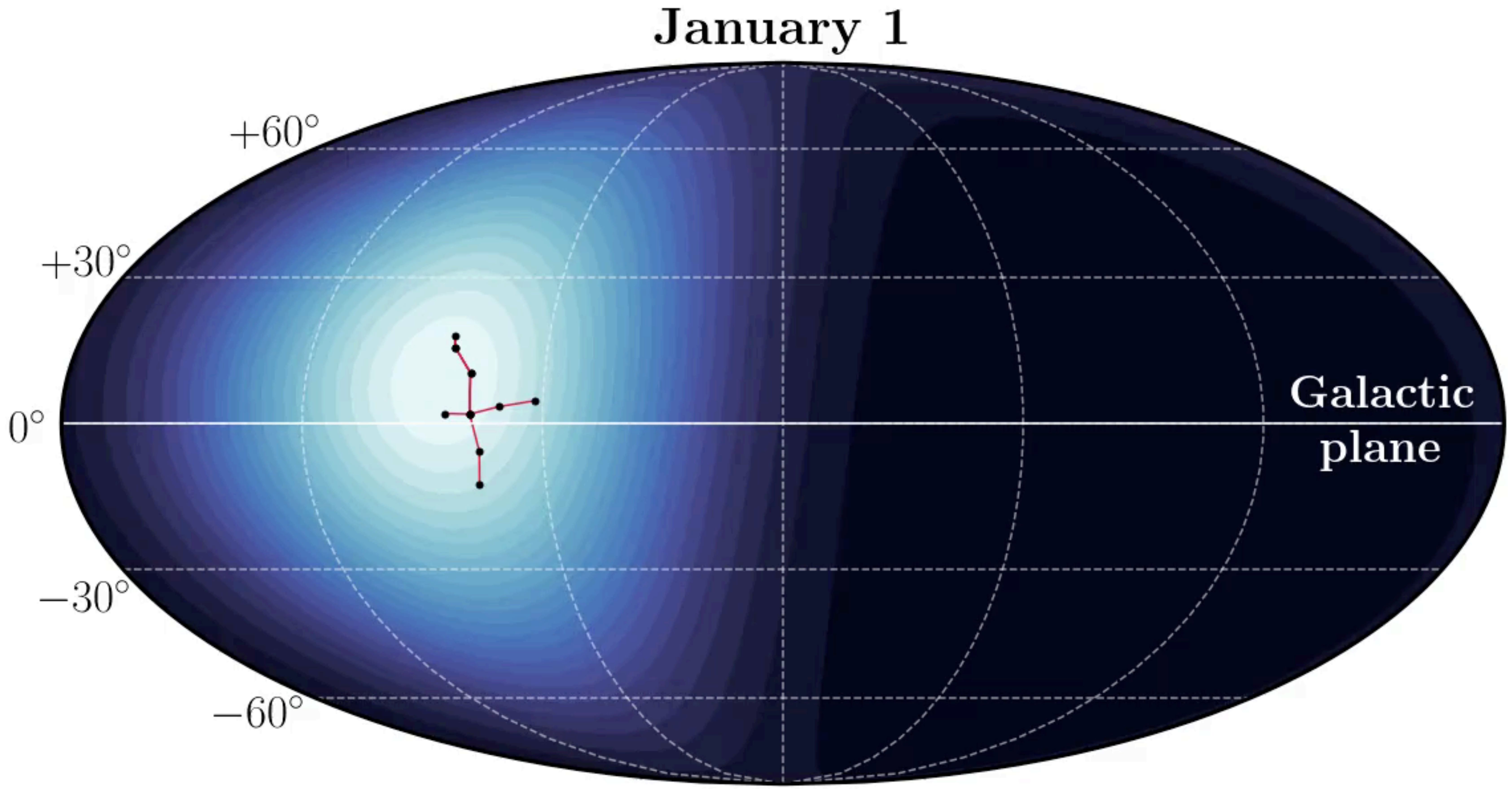
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\rm min}+v_{\rm lab}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$



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

→ a Gaussian peaking towards Cygnus

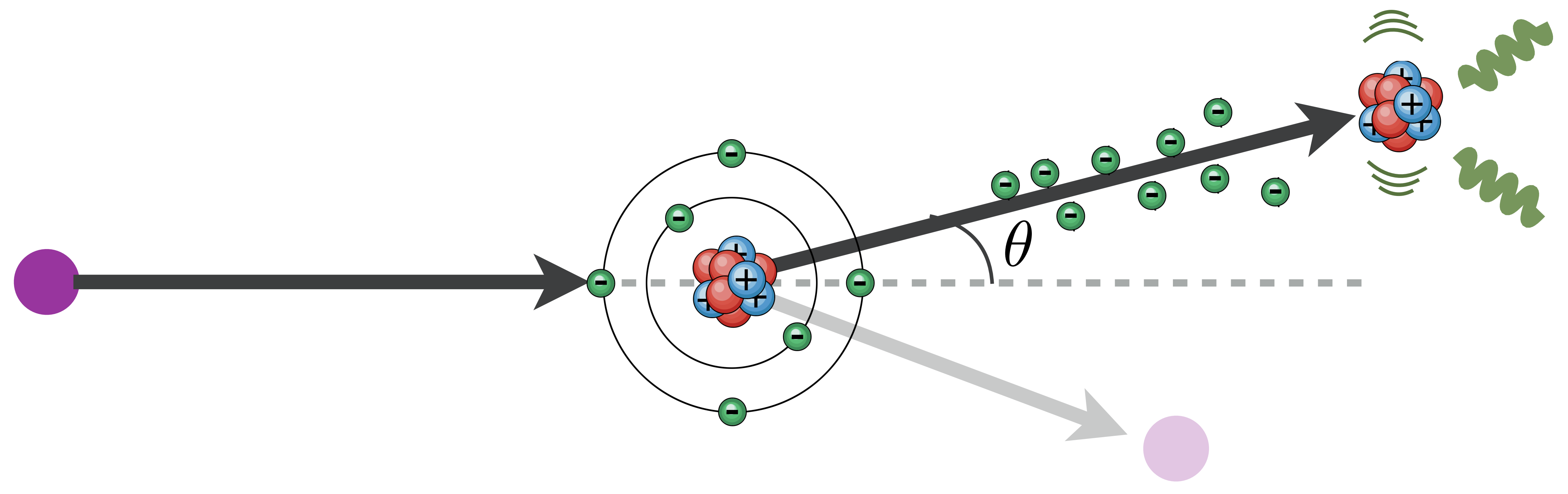
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\min} + v_{\mathrm{lab}}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$



Standard prediction based on a few assumptions

- The DM scatters elastically

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



- The DM velocity distribution is a Gaussian (SHM)

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

- DM-nucleus matrix element does not depend on velocity

$$\hookrightarrow \frac{\mathrm{d}R}{\mathrm{d}\Omega} \sim \int \delta\left(v\cos\theta - v_{\mathrm{min}}\right) f(\mathbf{v})\mathrm{d}^3\mathbf{v}$$

Interesting to consider cases where these aren't true, e.g.

Non-vanilla DM-nucleus kinematics/interactions,

→ inelastic DM
→ EFT operators with transverse velocity dependence
→ Luminous DM
→ Multi-scatter regime, e.g. superheavy/strongly interacting DM

Non-Gaussian velocity distributions

→ The Gaia Sausage/Enceladus
→ Streams and substructure

DM fluxes from directions other than Cygnus

→ Supernova-produced DM
→ Cosmic ray-upscattered DM
→ Boosted DM

Say we build Cygnus and find that…

1. **We have a signal**

   → We study it

2. **We don't**

Say we build Cygnus and find that…

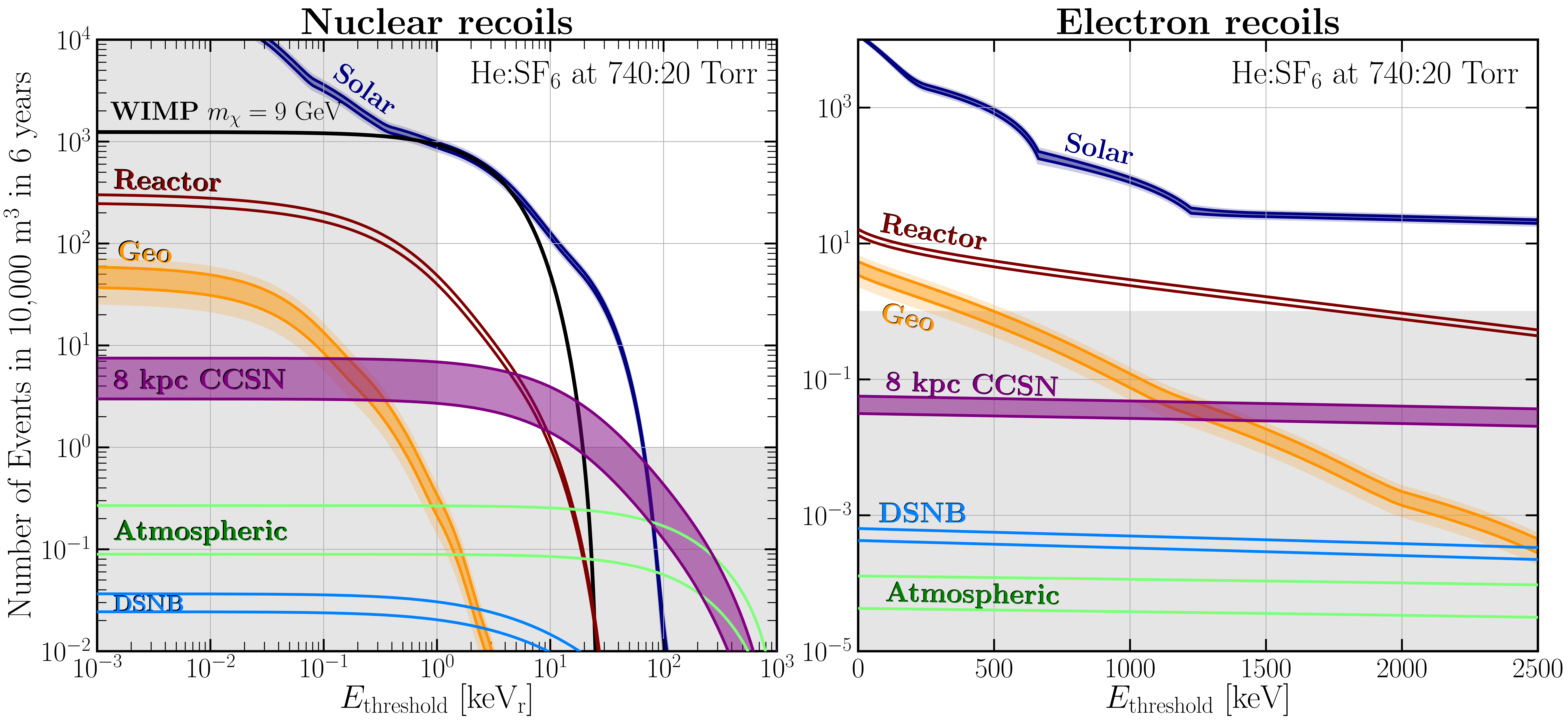
1. We have a signal

↳ We study it

2. We don’t

↳ Our background is our signal

The neutrino background

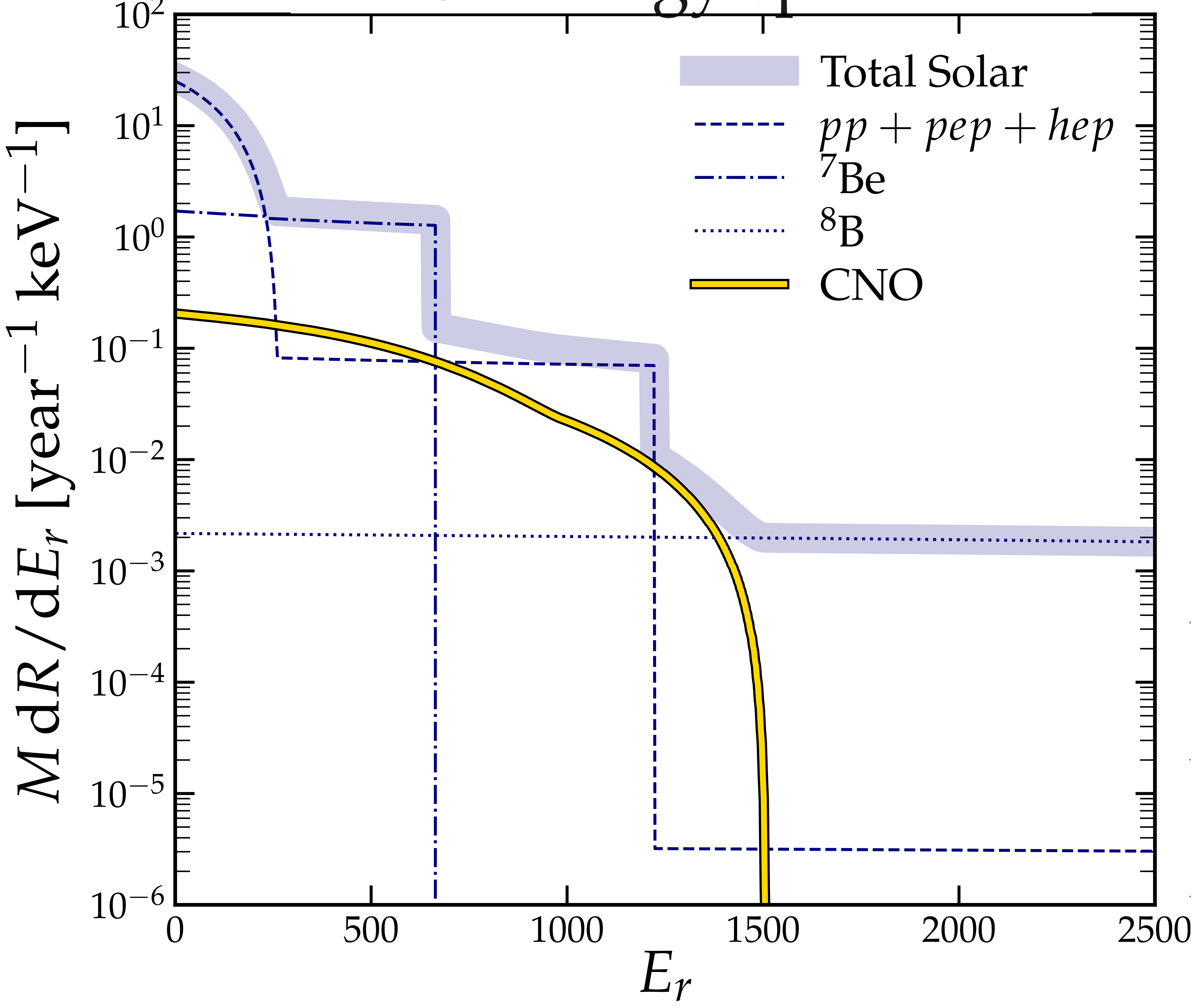


A directional detector has the potential for superior background rejection and NR/ER discrimination
→ this is true even if you're not talking about DM

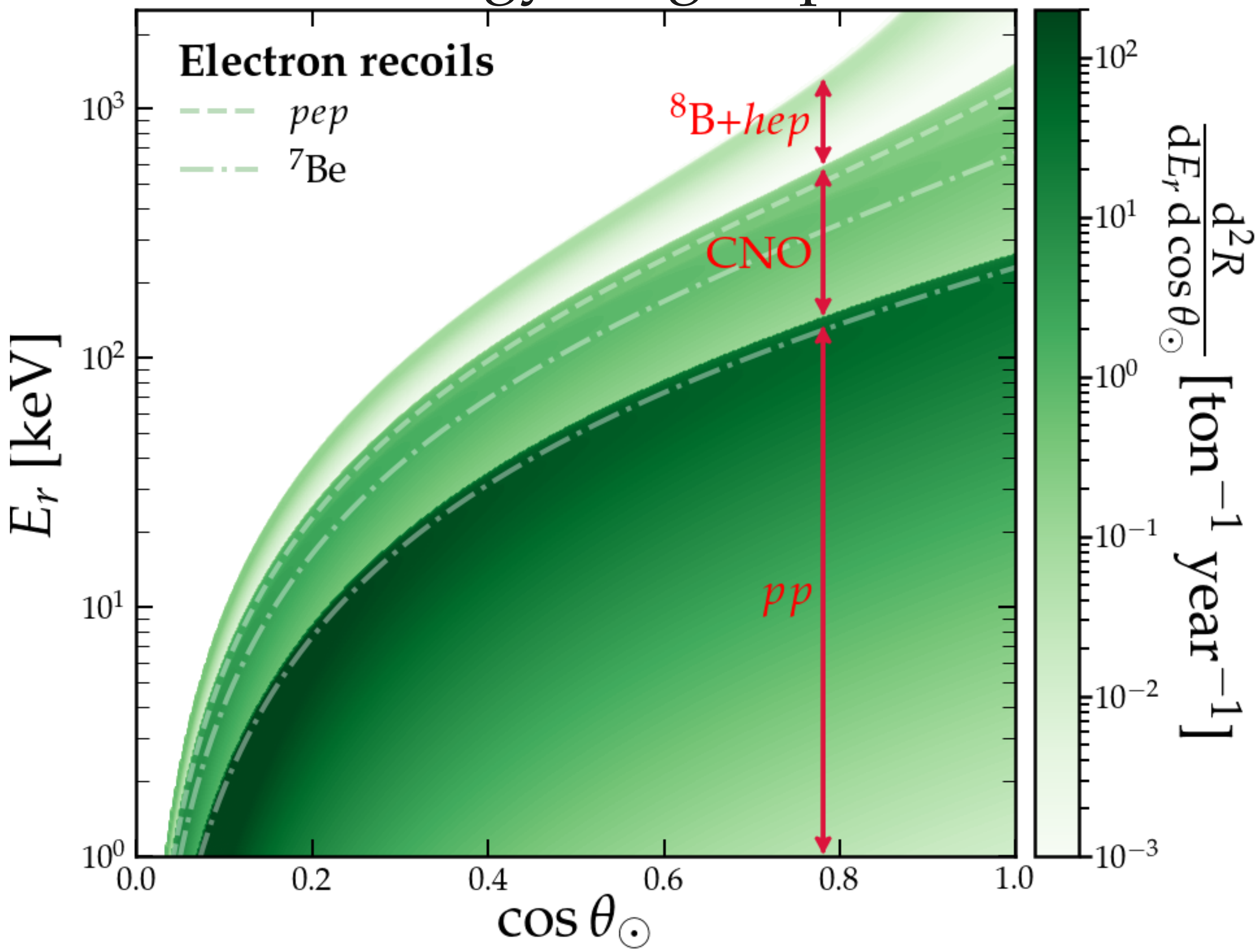
Directional neutrino measurements

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

Recoil energy spectrum



Recoil energy+angle spectrum



Say we build Cygnus and find that…

1. We have a signal

↳ We study it

2. We don't

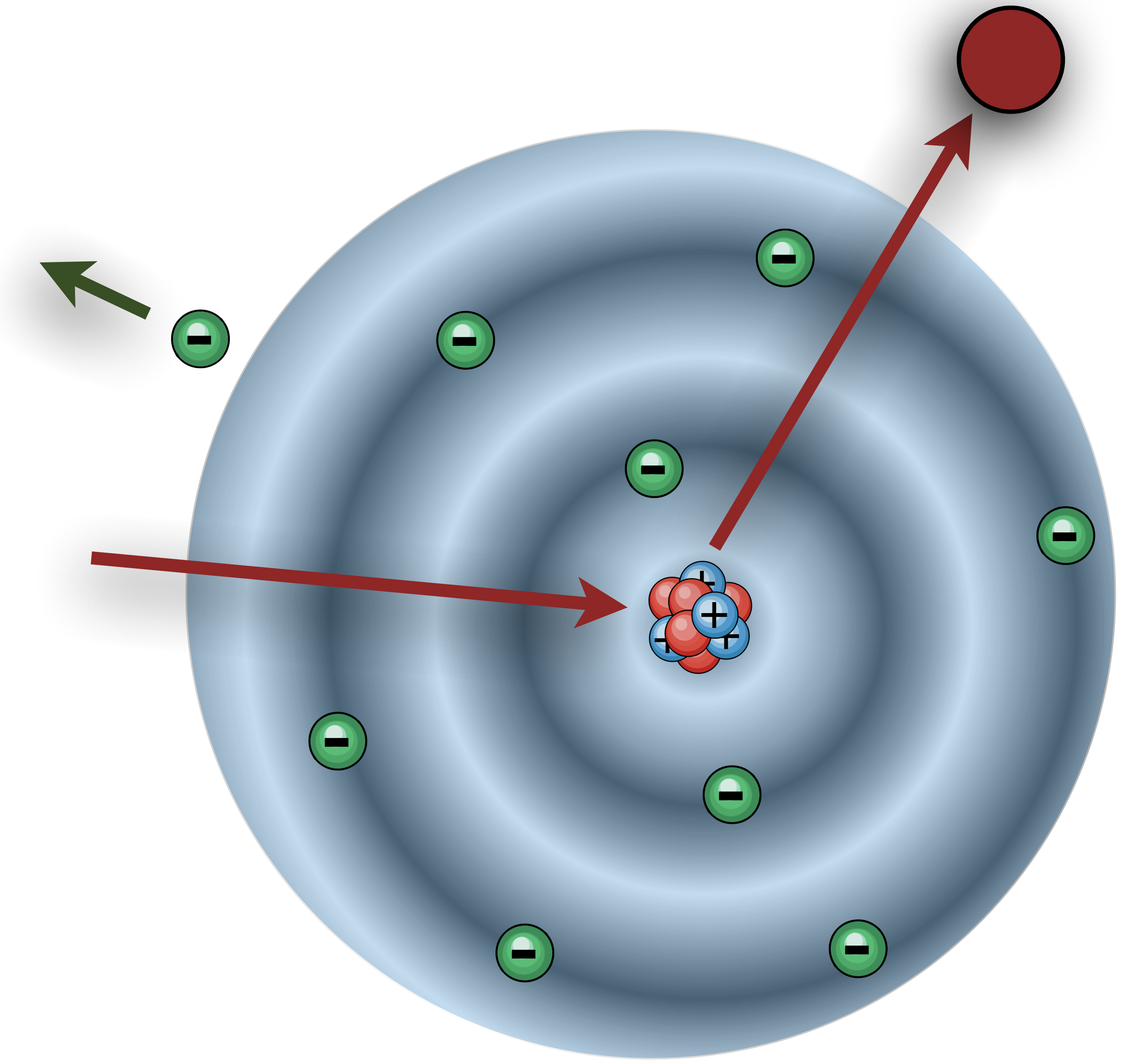
↳ Our background is our signal

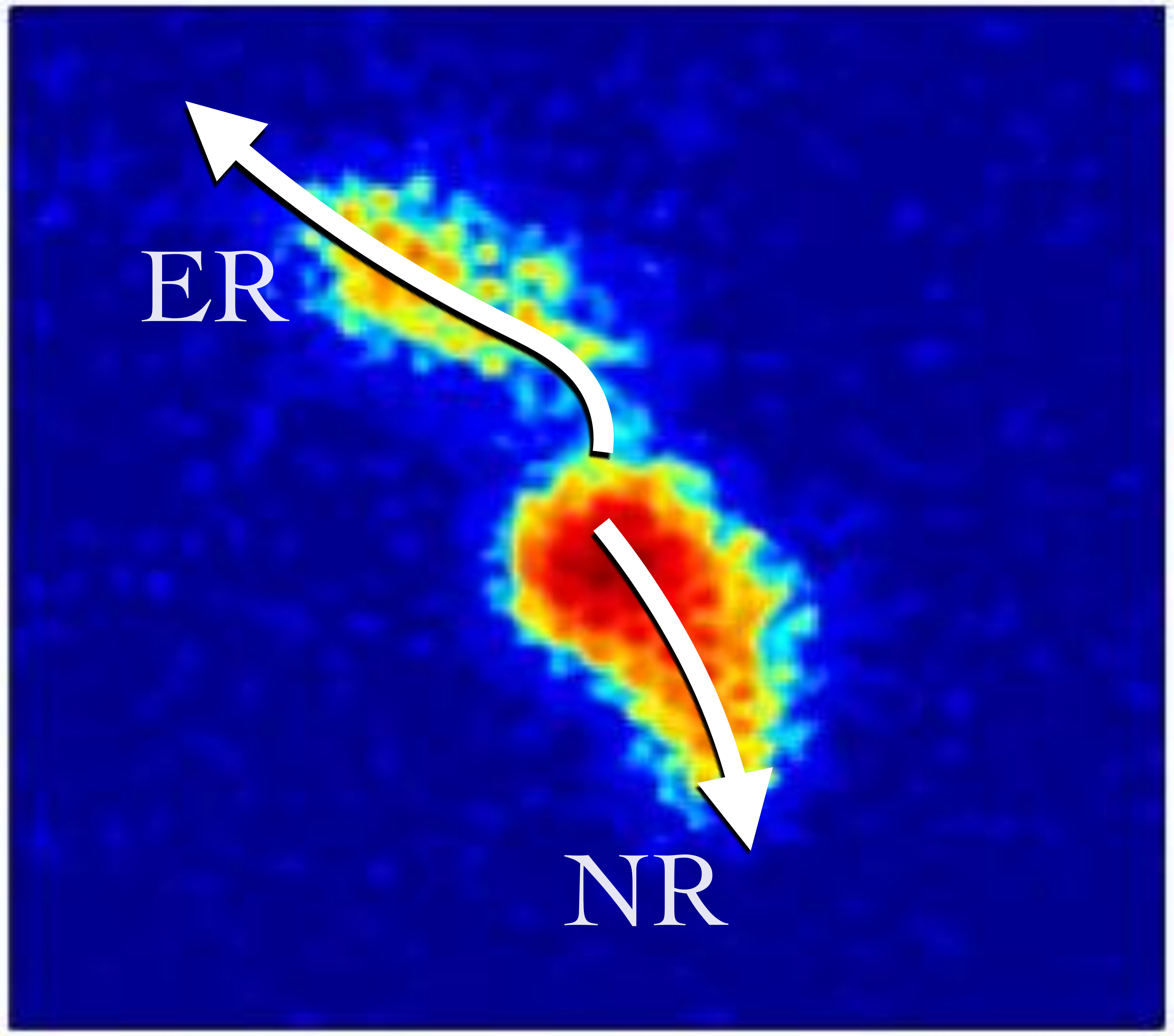
Both need large(ish) $\gtrsim$10 m^3 TPCs

Is there anything else that can be done in the meantime?

General physics: Measurement of the Migdal effect

→ Emission of ~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!

2102.04596

Directional Recoil Detection

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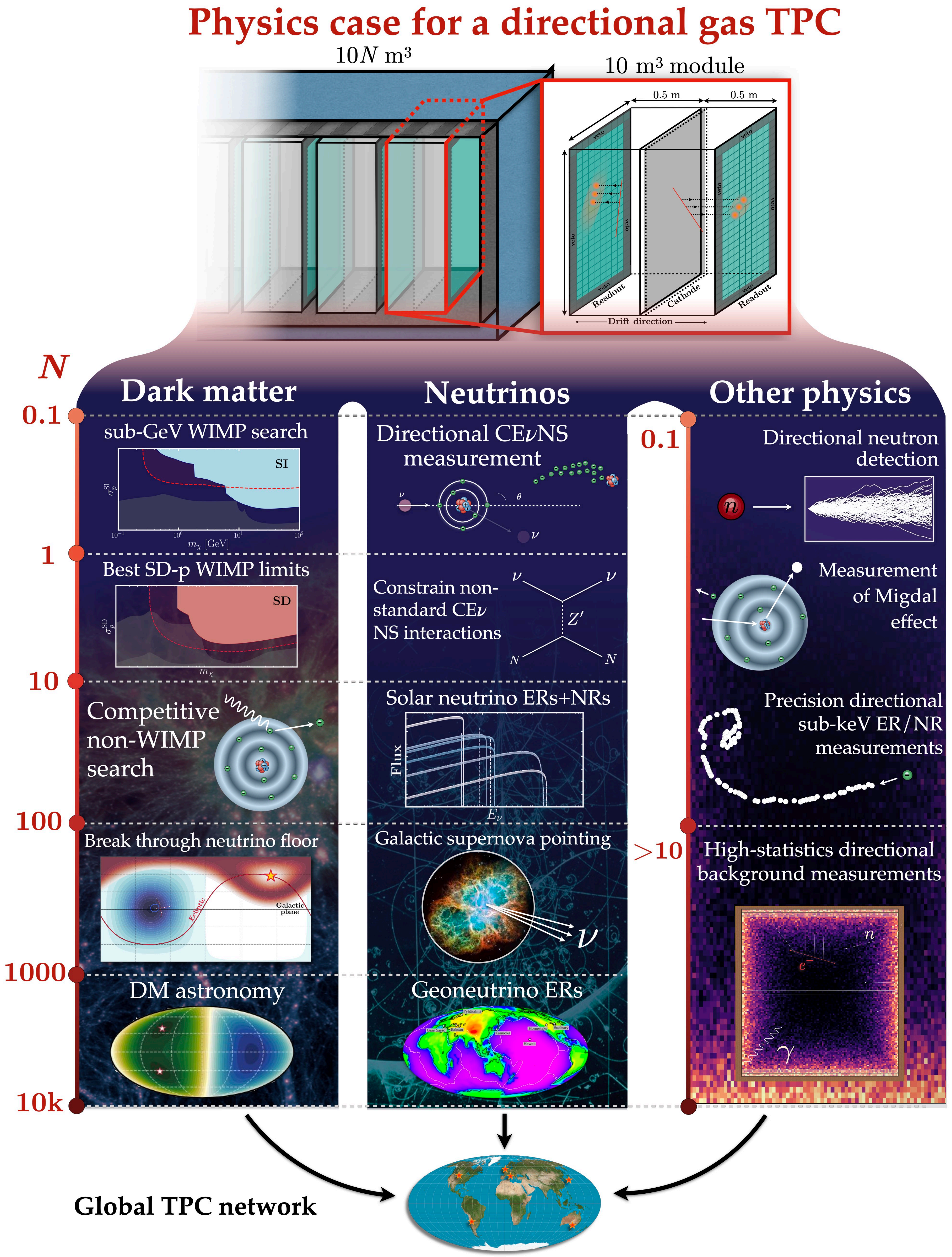
Keywords

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

Abstract

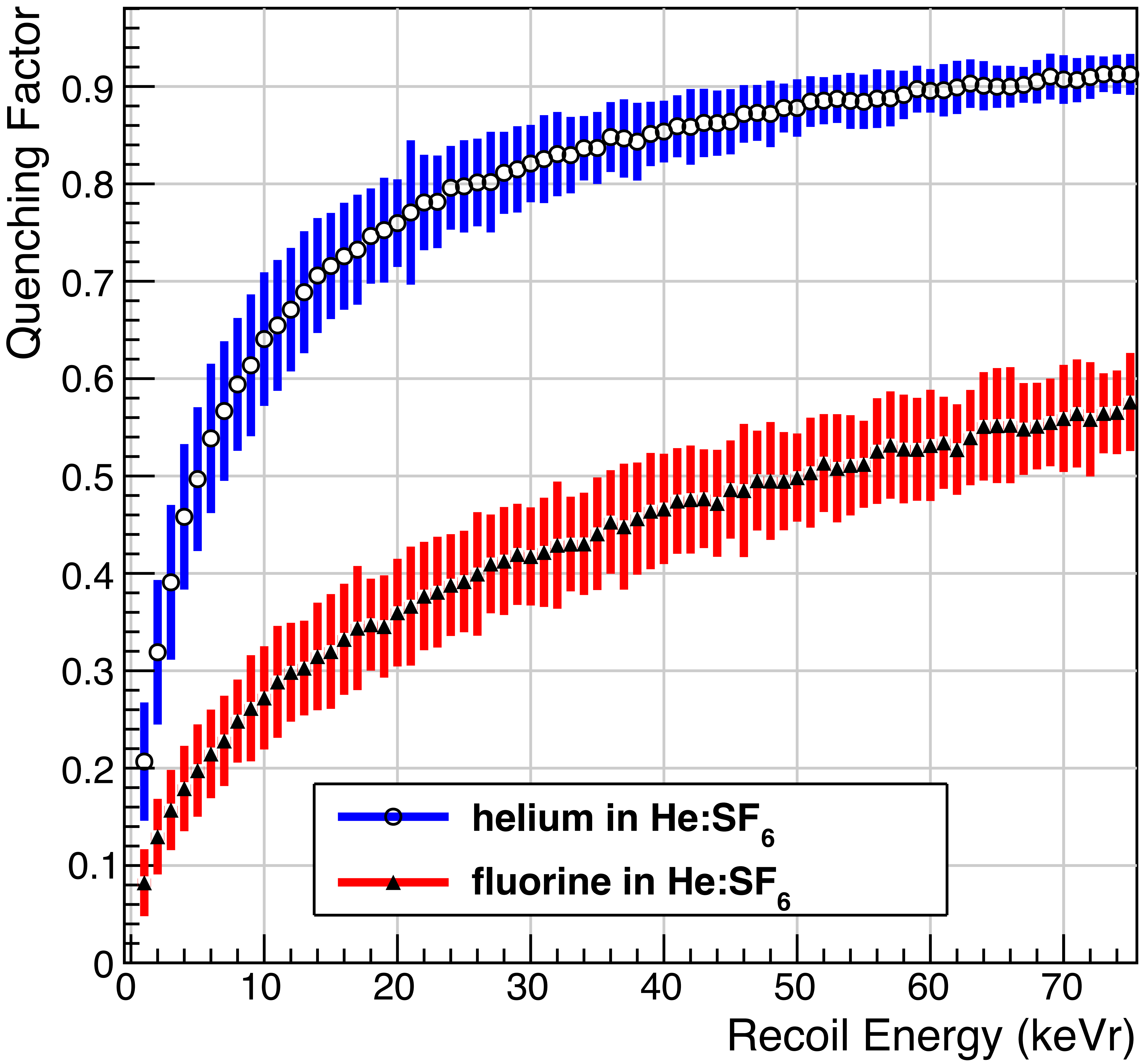
Searches for dark matter-induced recoils have made impressive advances in the last few years. Yet the field is confronted by several outstanding problems. First, the inevitable background of solar neutrinos will soon inhibit the conclusive identification of many dark matter models. Second, and more fundamentally, 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.



Summary

- Directional TPC network “Cygnus” is an exciting possibility that appears increasingly plausible
- Primary physics goals are to set limits beyond the neutrino floor, and to provide a convincing confirmation of DM in the event of detection
- Exciting physics cases for non-WIMP dark matter, neutrino physics, and general physics measurements, all deserving of further exploration now that the community is converging on a strategy

Quenching factors for recoils in 1 atm of He+SF_6



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 [$\mu m/\sqrt{cm}$]	116.2	78.6	78.6
Long. diffusion [$\mu m/\sqrt{cm}$]	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 SF_6 is from a measurement with alpha particles [310], while the W factors for the $He:SF_6$ and $He:CF_4$ mixtures are calculated using Eq.(1) of Ref. [266]. The diffusion values and drift velocity in 20 Torr of pure SF_6 were measured in Ref. [299]. For the $He:SF_6$ mixtures, no measurements or reliable simulations exist, so we use the 40 Torr pure SF_6 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 SF_6 has been achieved with THGEMs in Ref. [311] and triple thin GEMs in Ref. [312], and is also used for $He:SF_6$ mixtures.

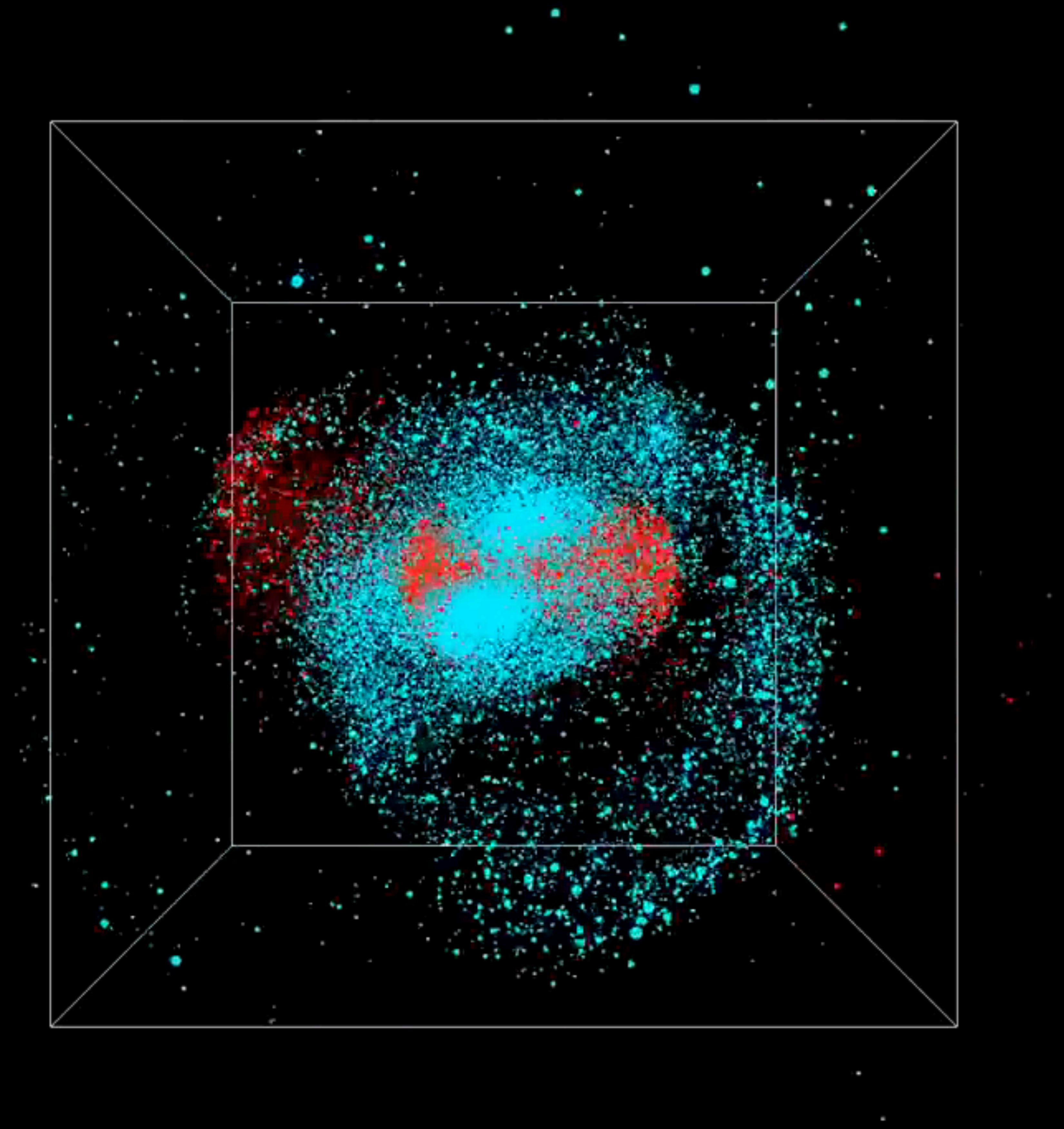
Readout type	Dimensionality	Segmentation ($x \times y$)	Capacitance [pF]	σ_{noise} in 1 µs	Threshold/σ_{noise}
planar	1d (z)	10 cm × 10 cm	3000	18000 e^-	3.09
wire	2d (yz)	1 m wires, 2 mm pitch	0.25	800 e^-	4.11
pad	3d (xyz)	3 mm × 3 mm	0.25	375 e^-	4.77
optical	2d (xyz)	200 µm × 200 µm	n/a	2 photons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

Should the DM velocity distribution be a Gaussian?

→ Evidence of significant merger in the MW's history

The Gaia Sausage

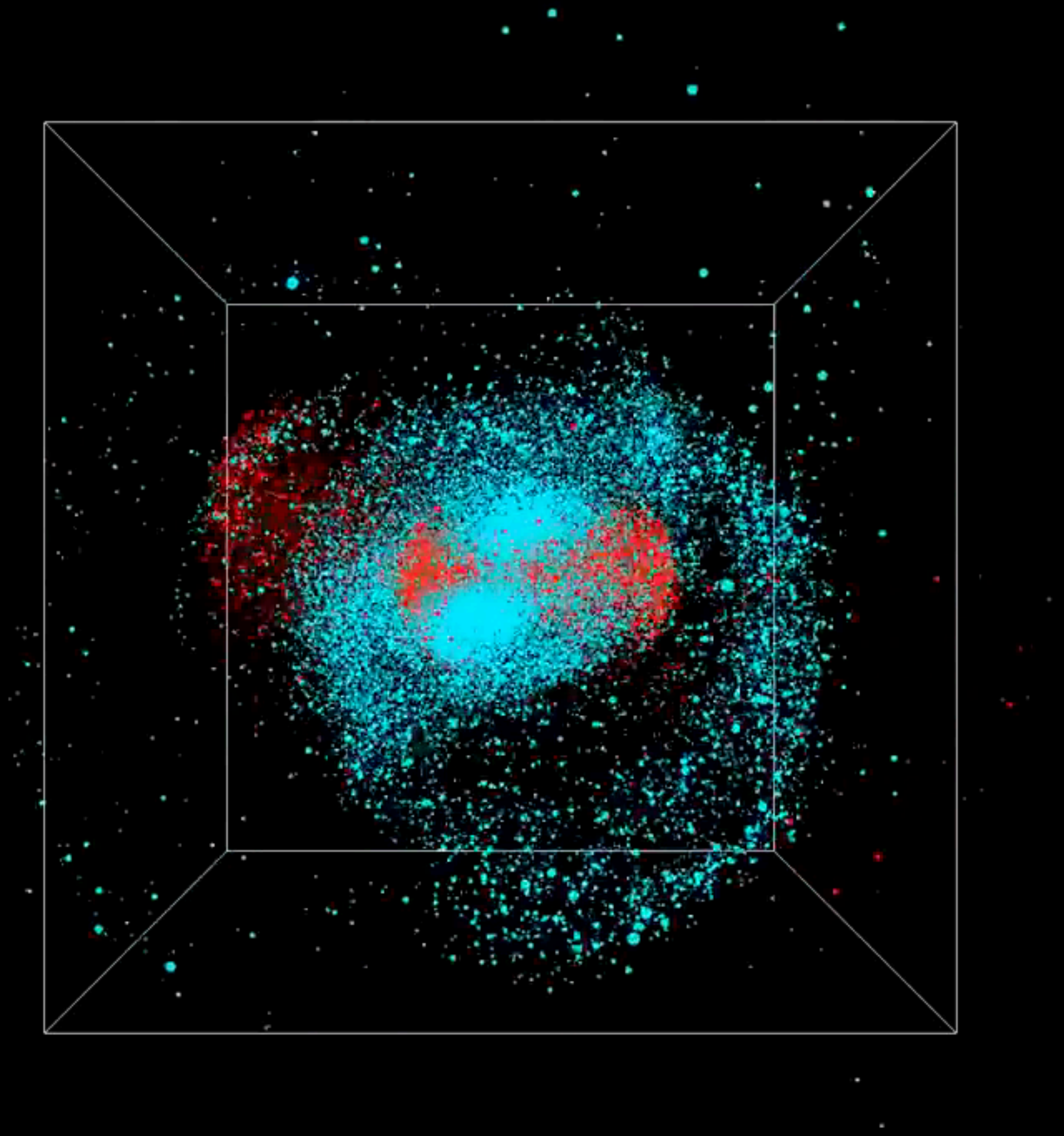


See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

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

2006.08625

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

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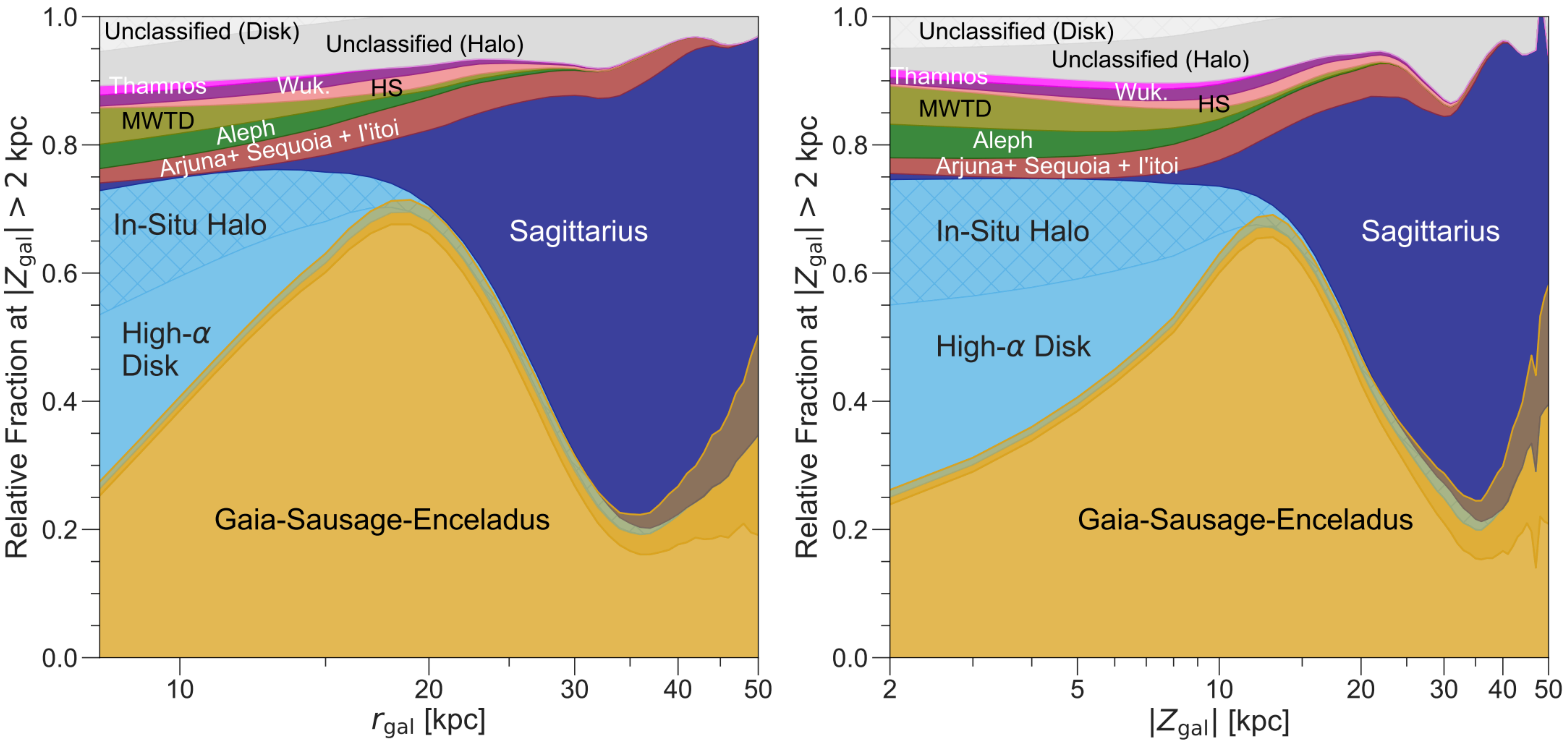
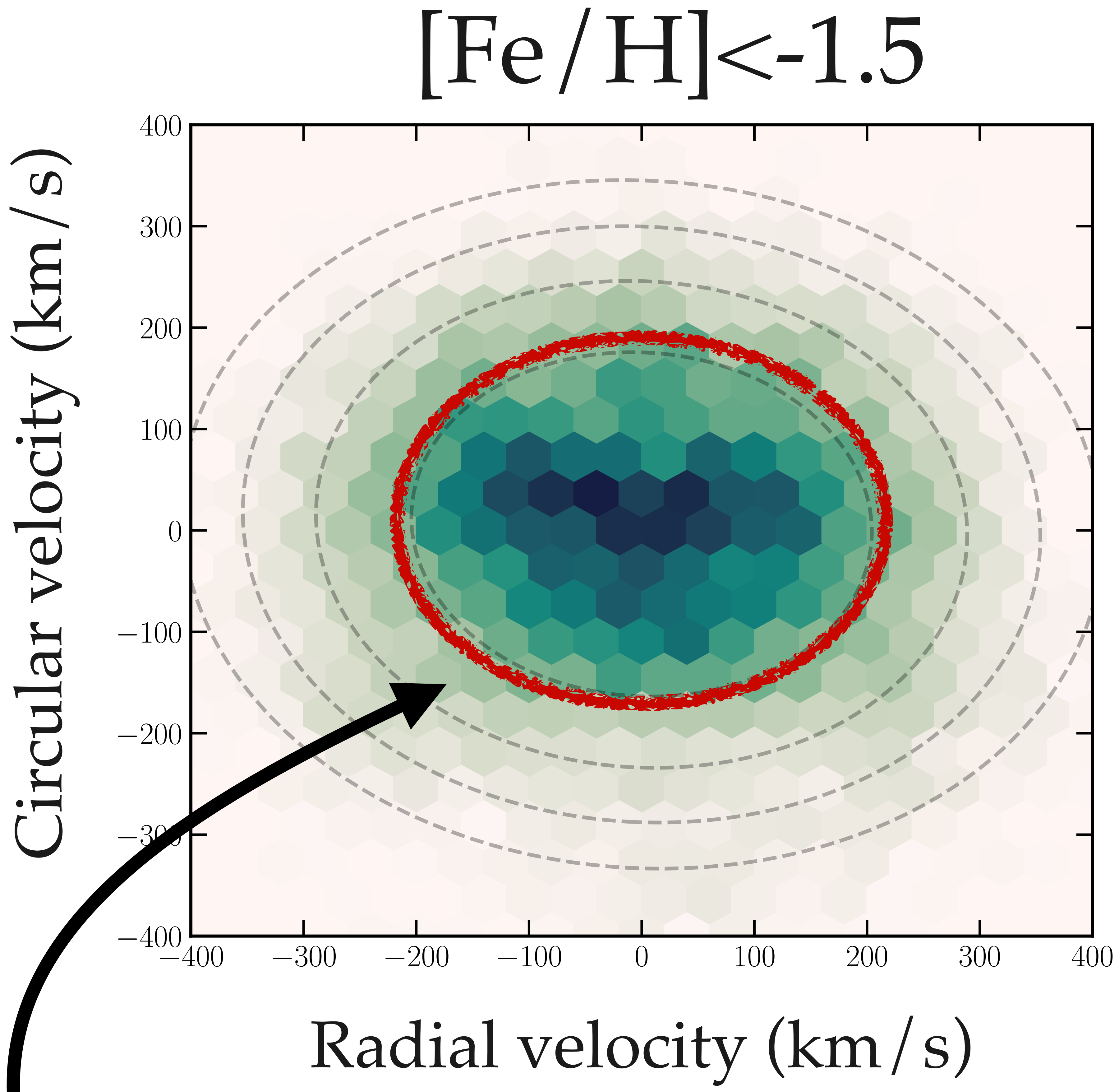
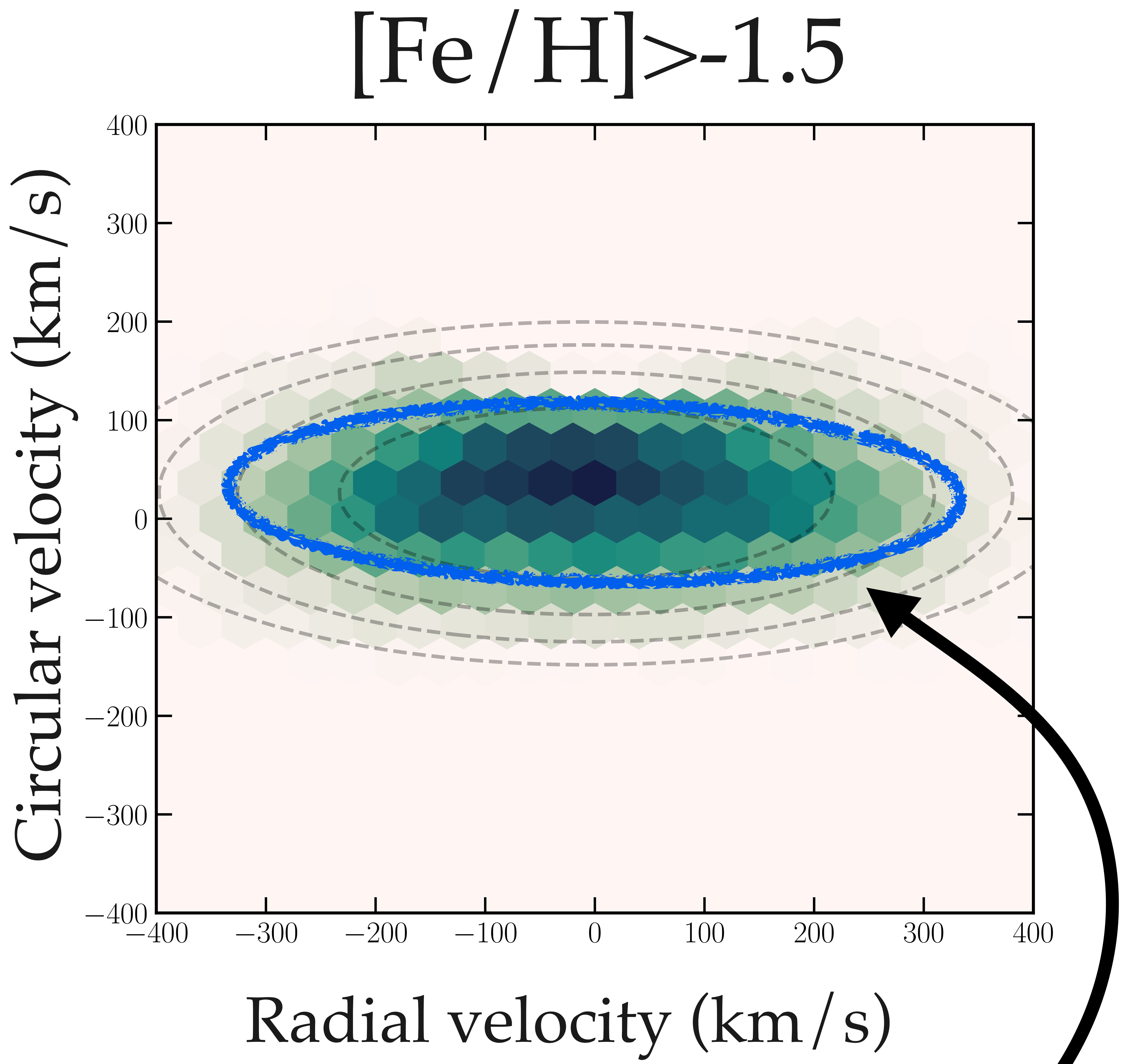
Nelson Caldwell,[1] Dennis Zaritsky,[6] and Phillip A. Cargile[1]







"Metal-poor" halo

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

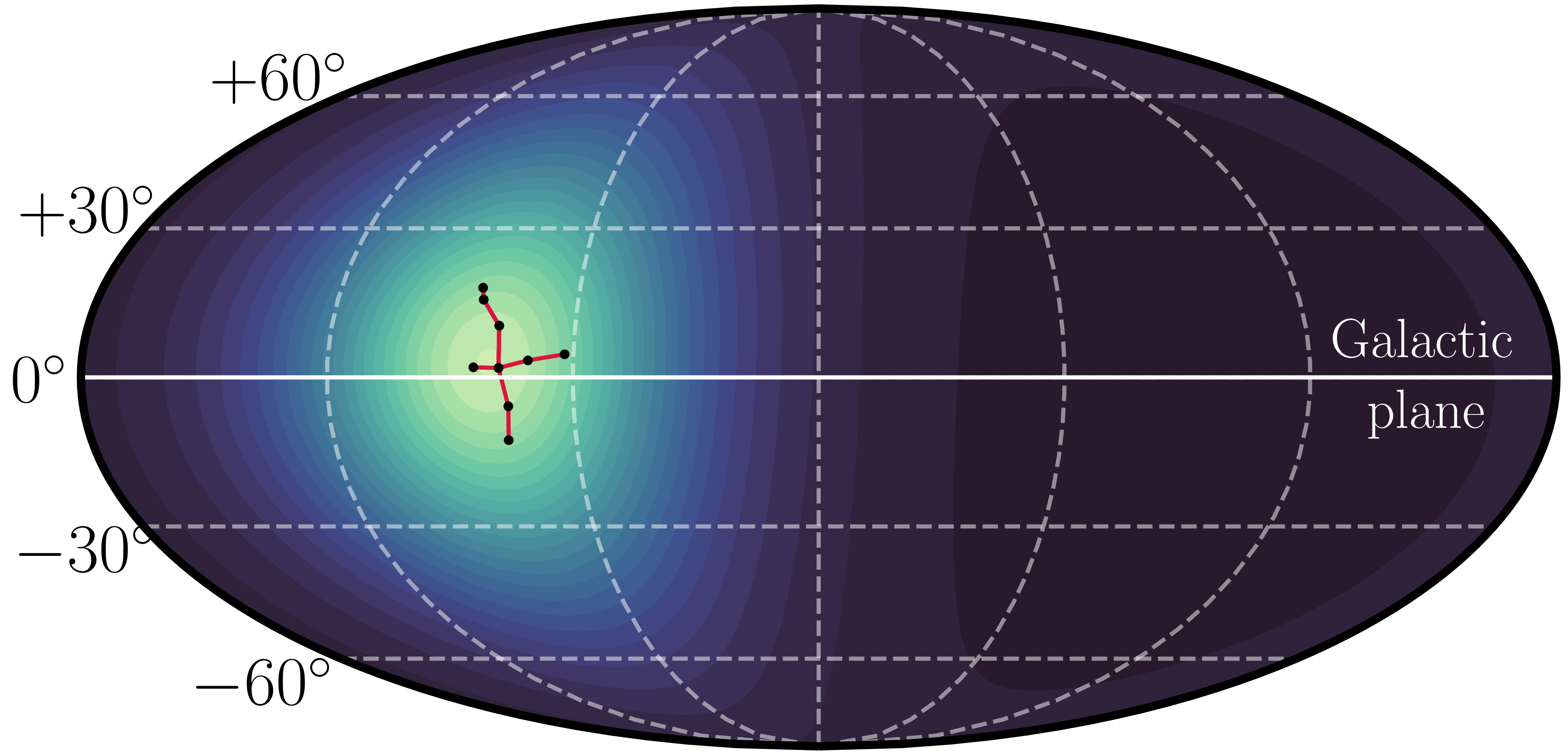
"Metal-rich" halo

- Highly eccentric radial orbits
- Dominant contribution ~50%
- Characteristic metallicity [Fe/H] = -1.4

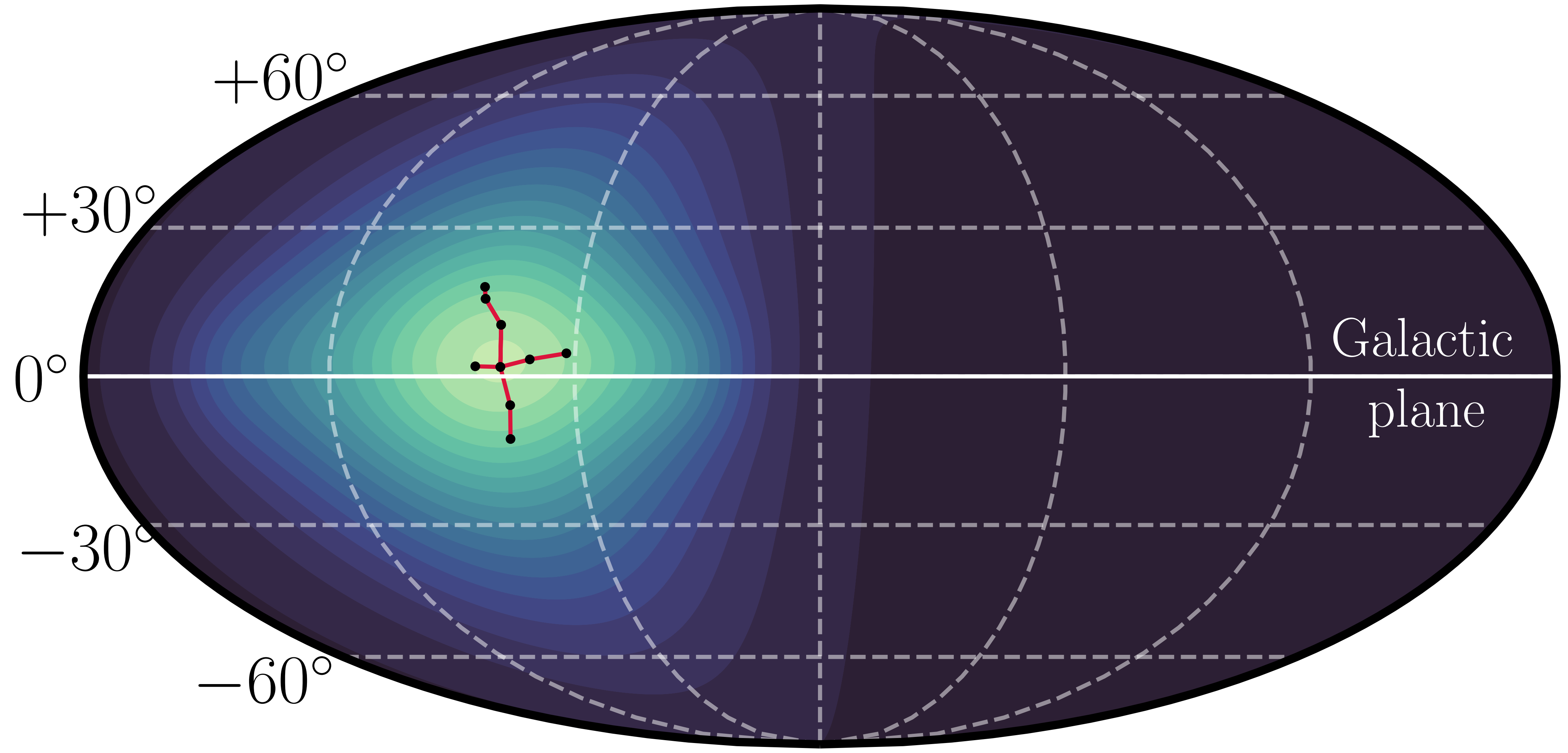
The Gaia Sausage

seen prominently in the Gaia data → Should also be present in DM distribution

DM Flux for SHM
(Gaussian distribution)

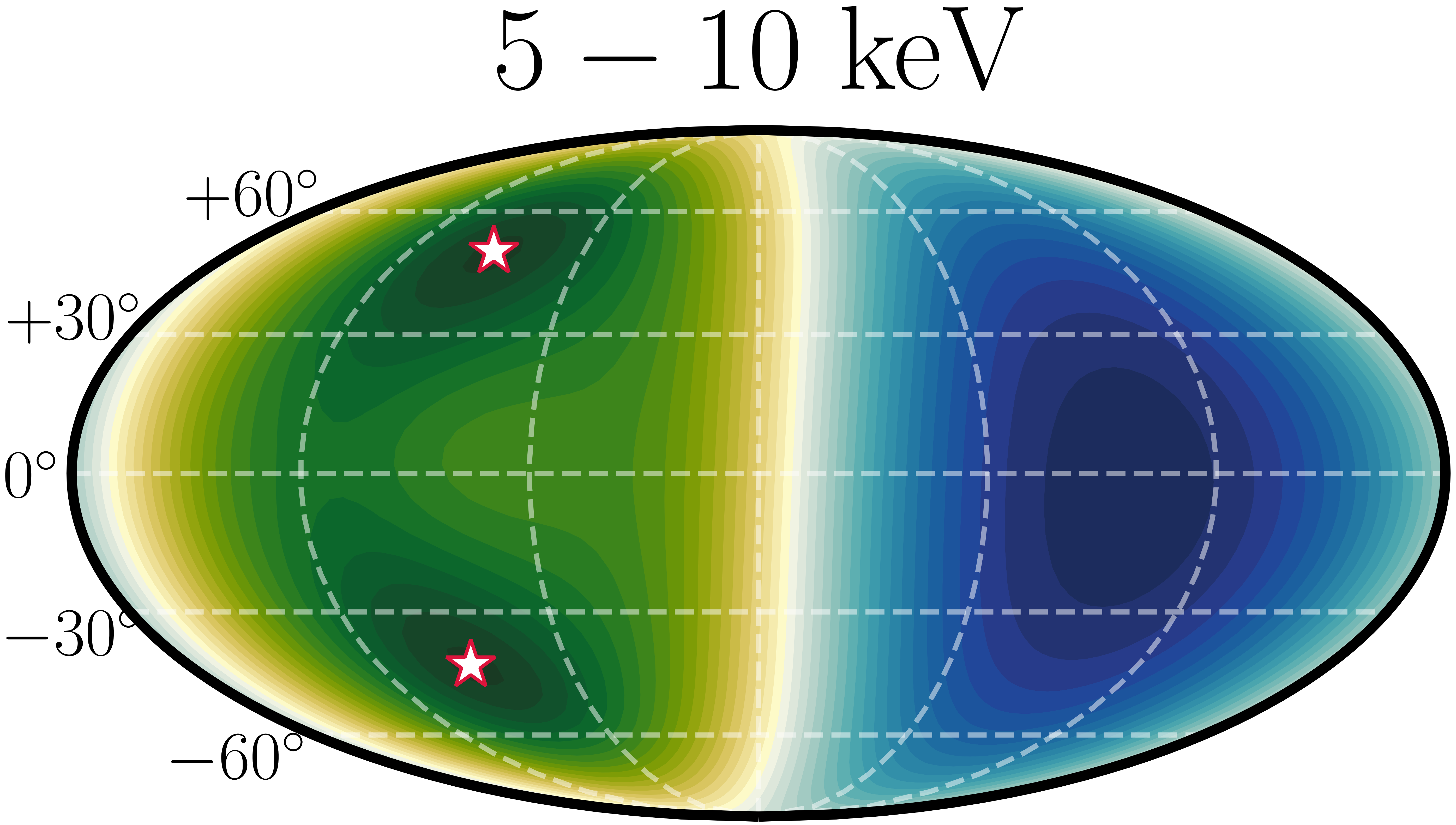


SHM + **Gaia Sausage**
(Isotropic and radially anistoropic components)



O'Hare+ [1909.04684]

The Gaia Sausage gives rise to peaks off center from Cygnus



Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP
Halo model = SHM + Sausage