Cygnus, and directional DM detection

[2102.04596], [2008.12587]

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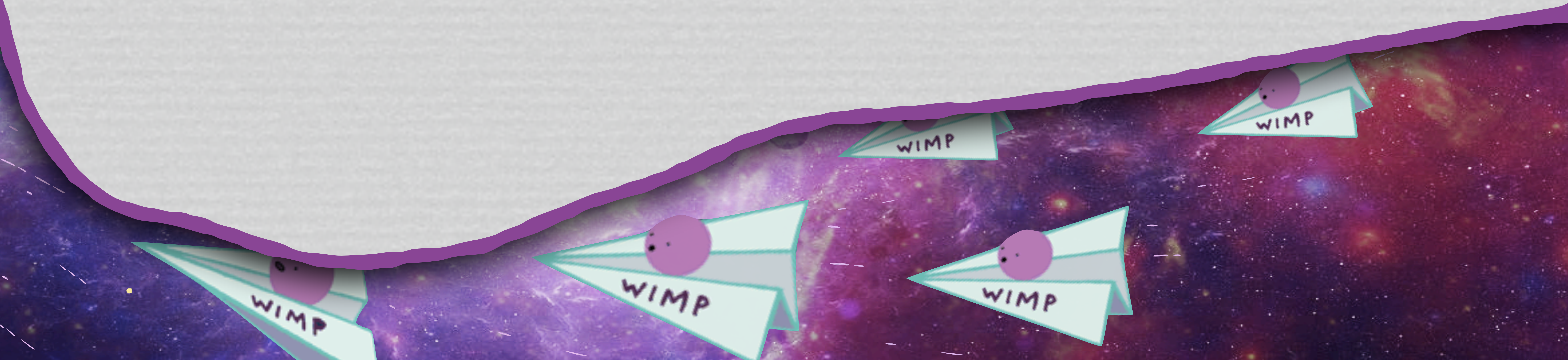


What is directional recoil detection?

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

Why?

→ Improve searches for Dark Matter

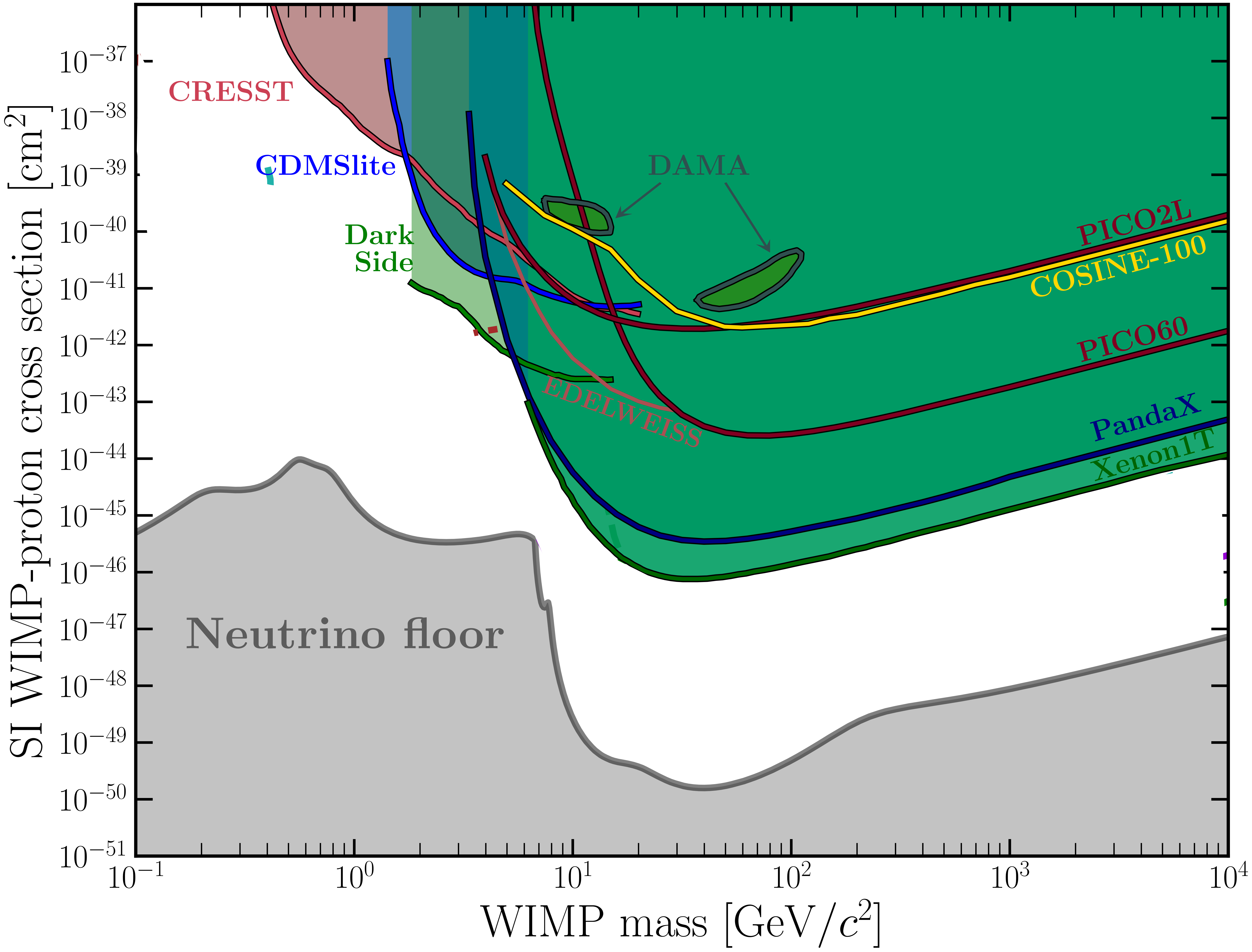
→ Directionally detect neutrinos via CEνNS or ν-e scattering

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

Current status of searches for Weakly Interacting Massive Particles



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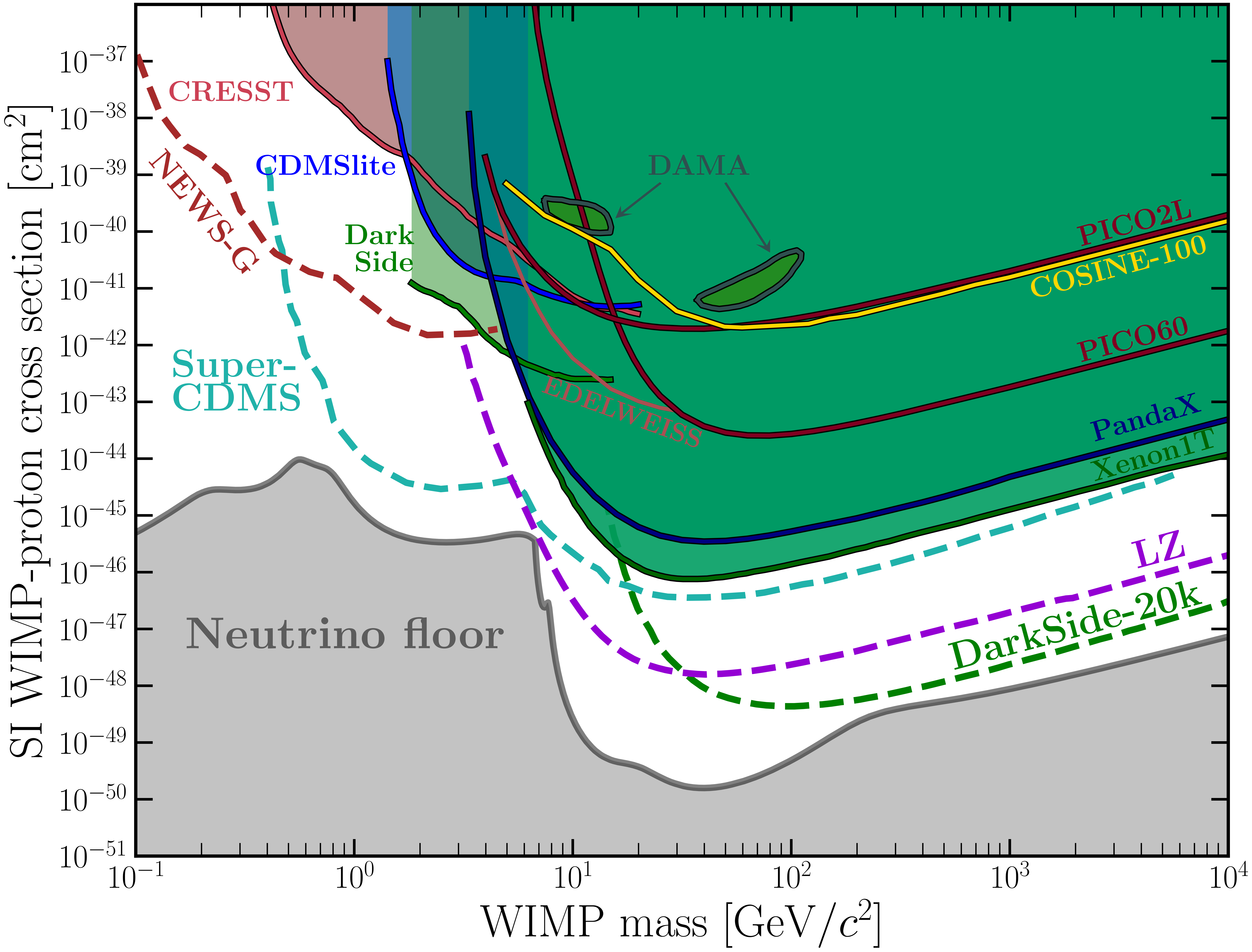
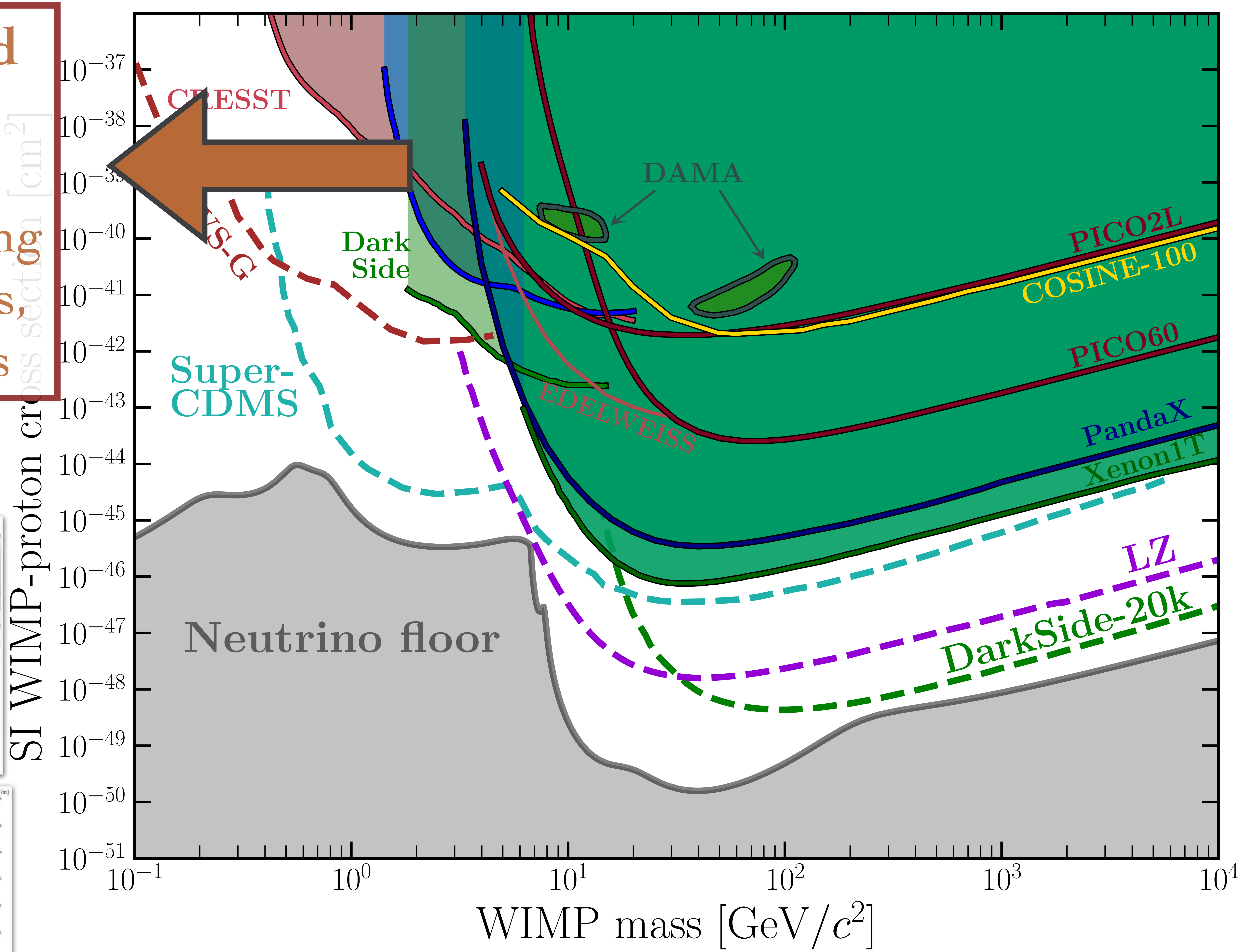
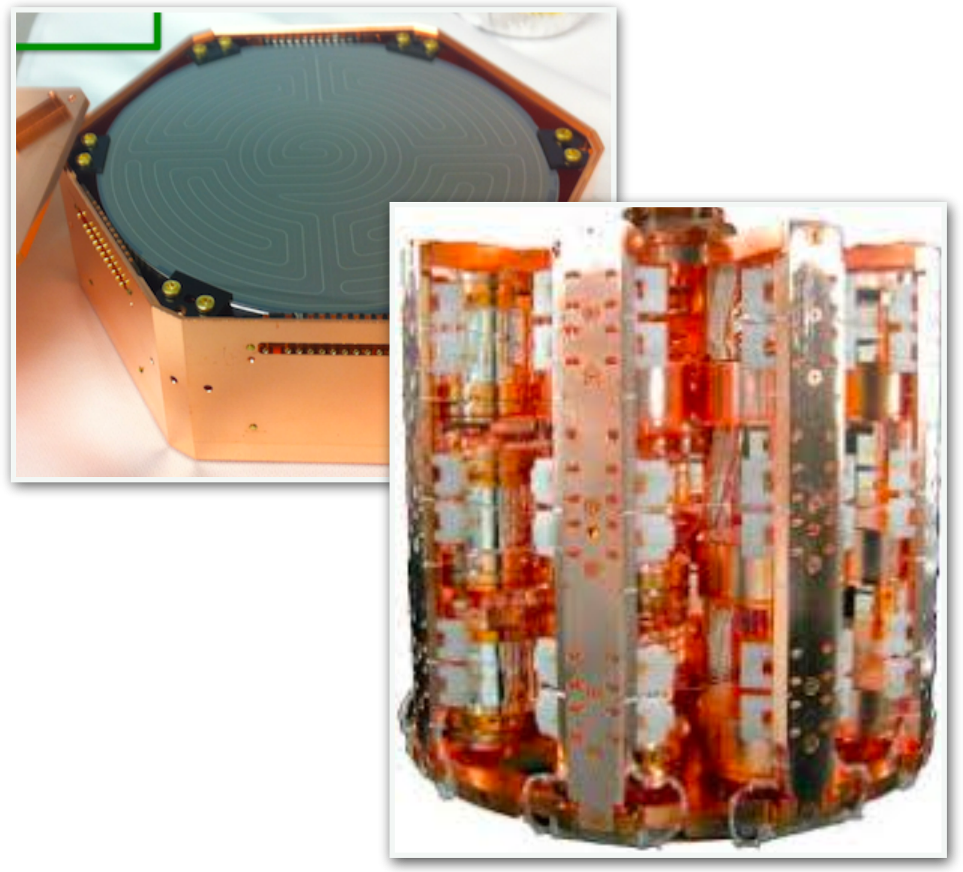


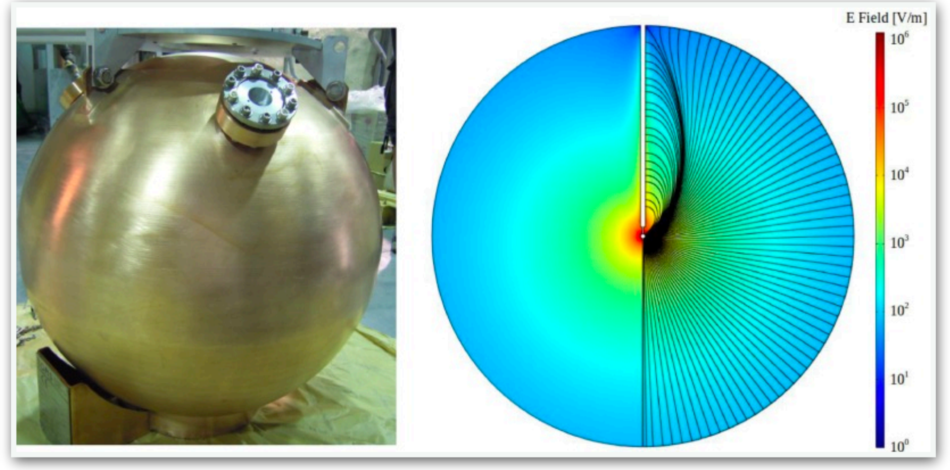
Current status of searches for Weakly Interacting Massive Particles

Low threshold detectors

e.g. cryogenic scintillators using semiconductors, light gas SPCs







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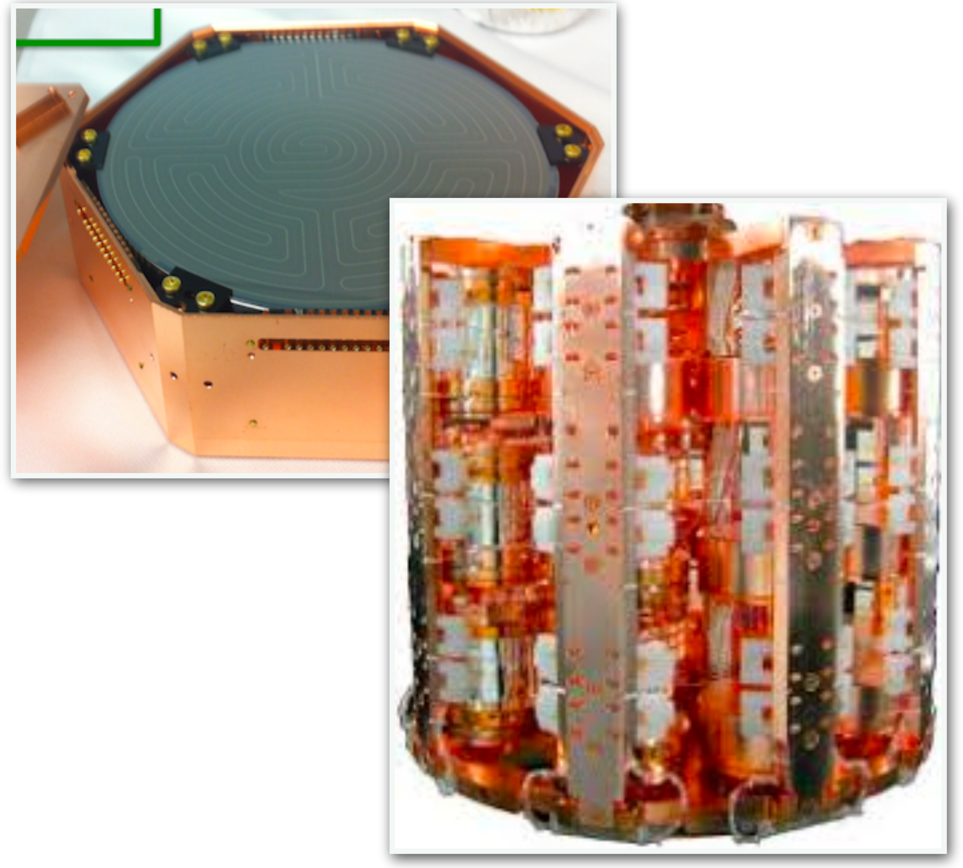
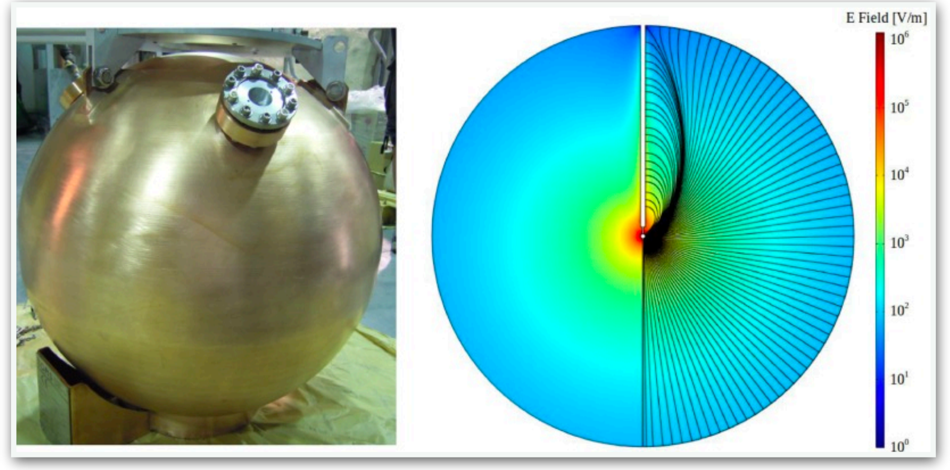
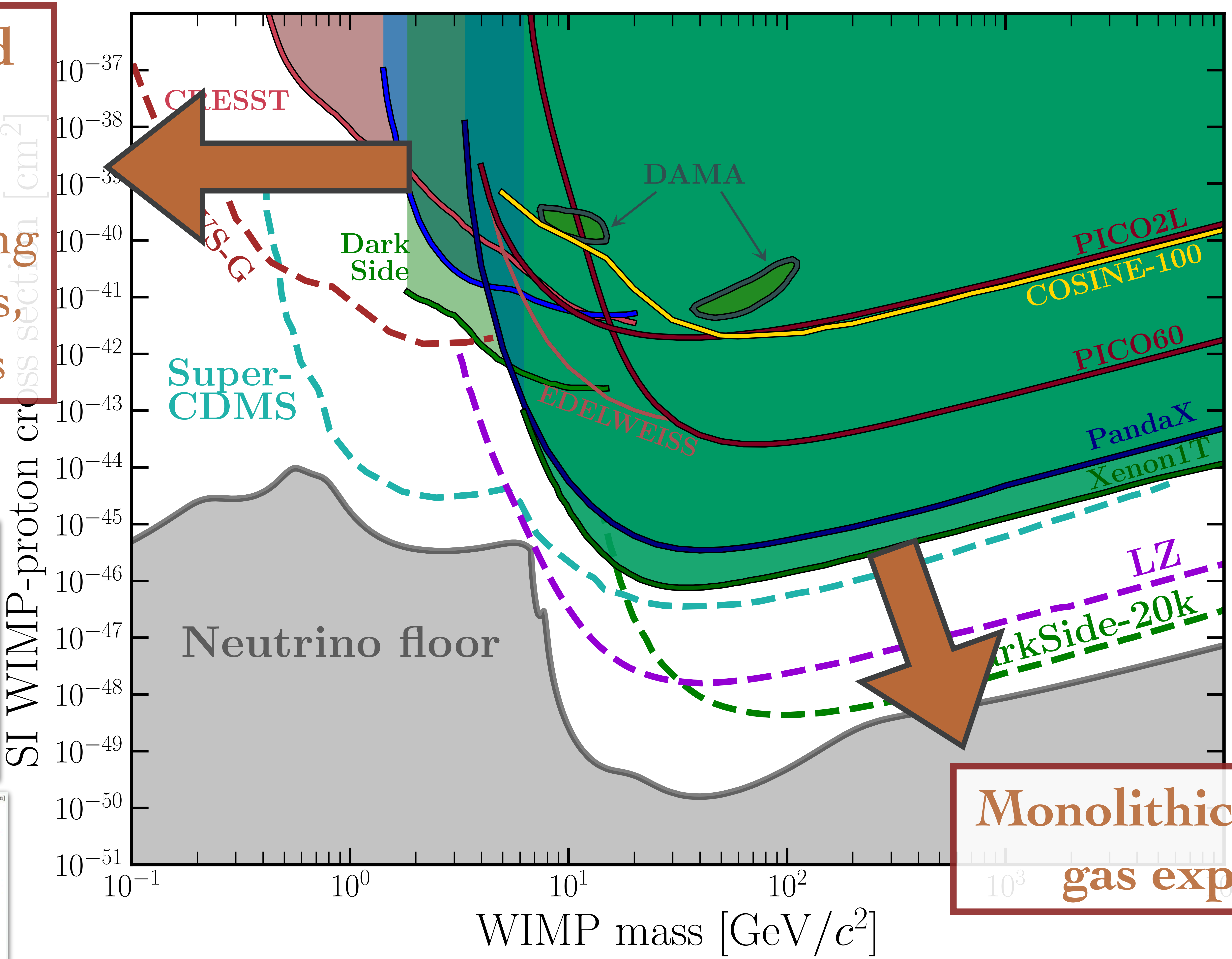
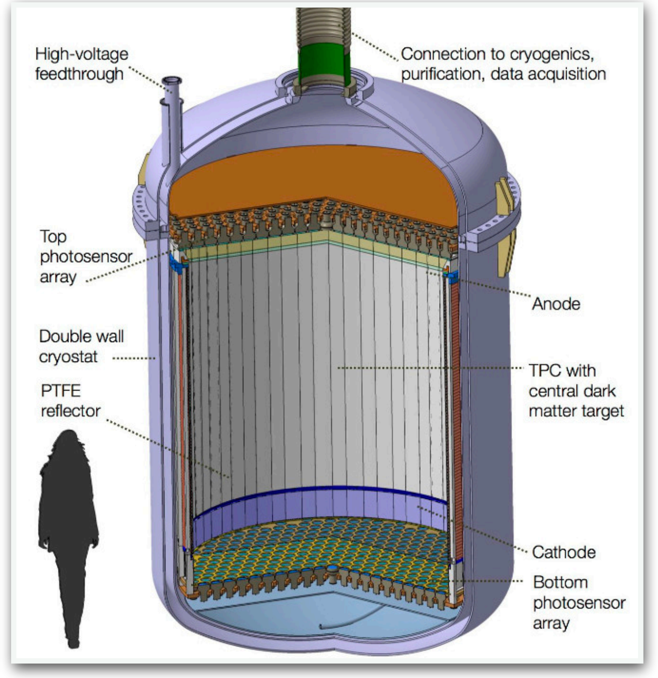






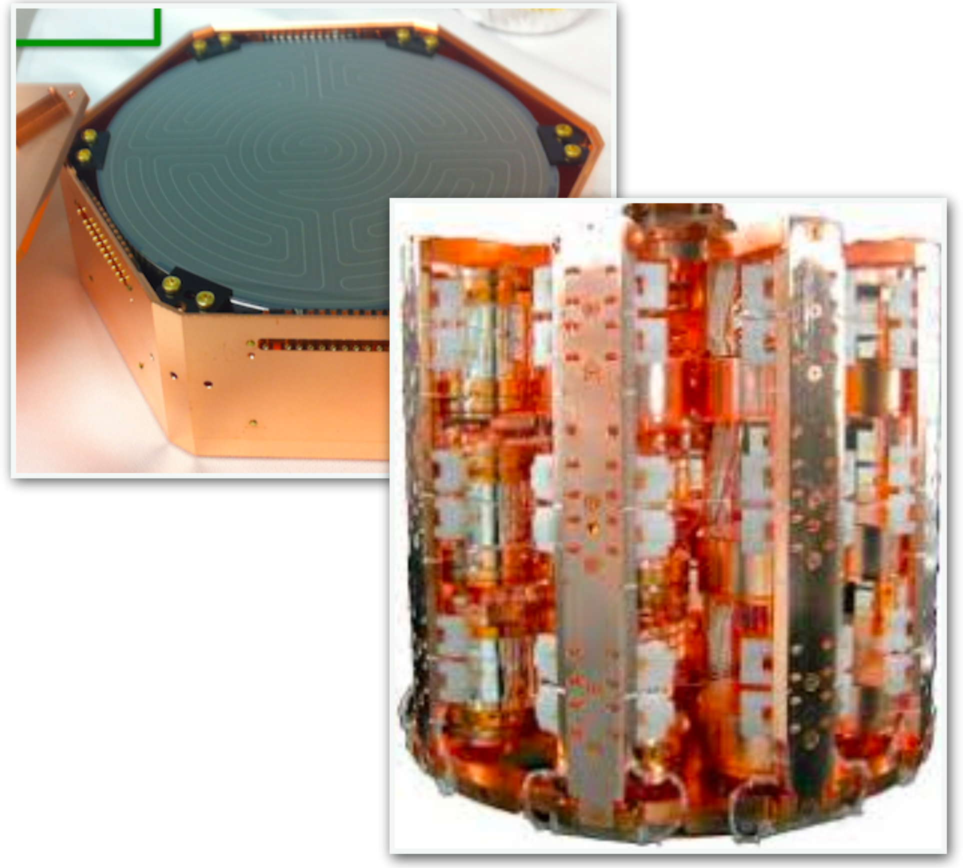


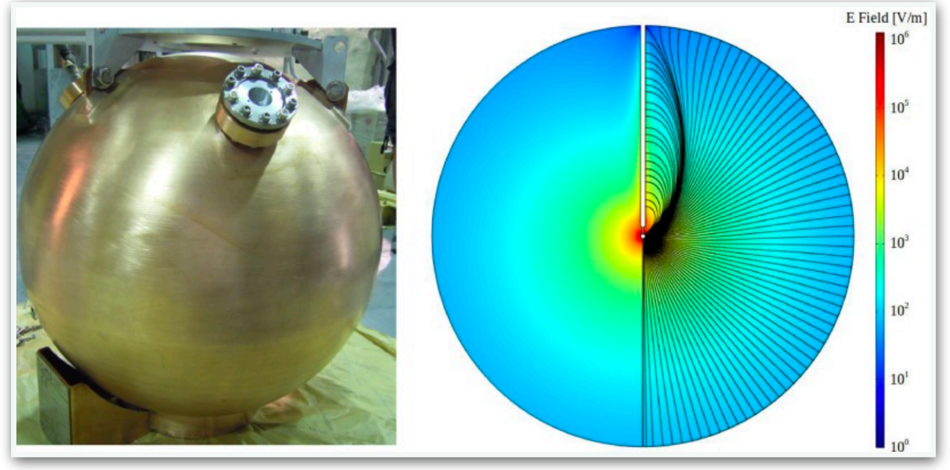
Monolithic liquid noble gas experiments

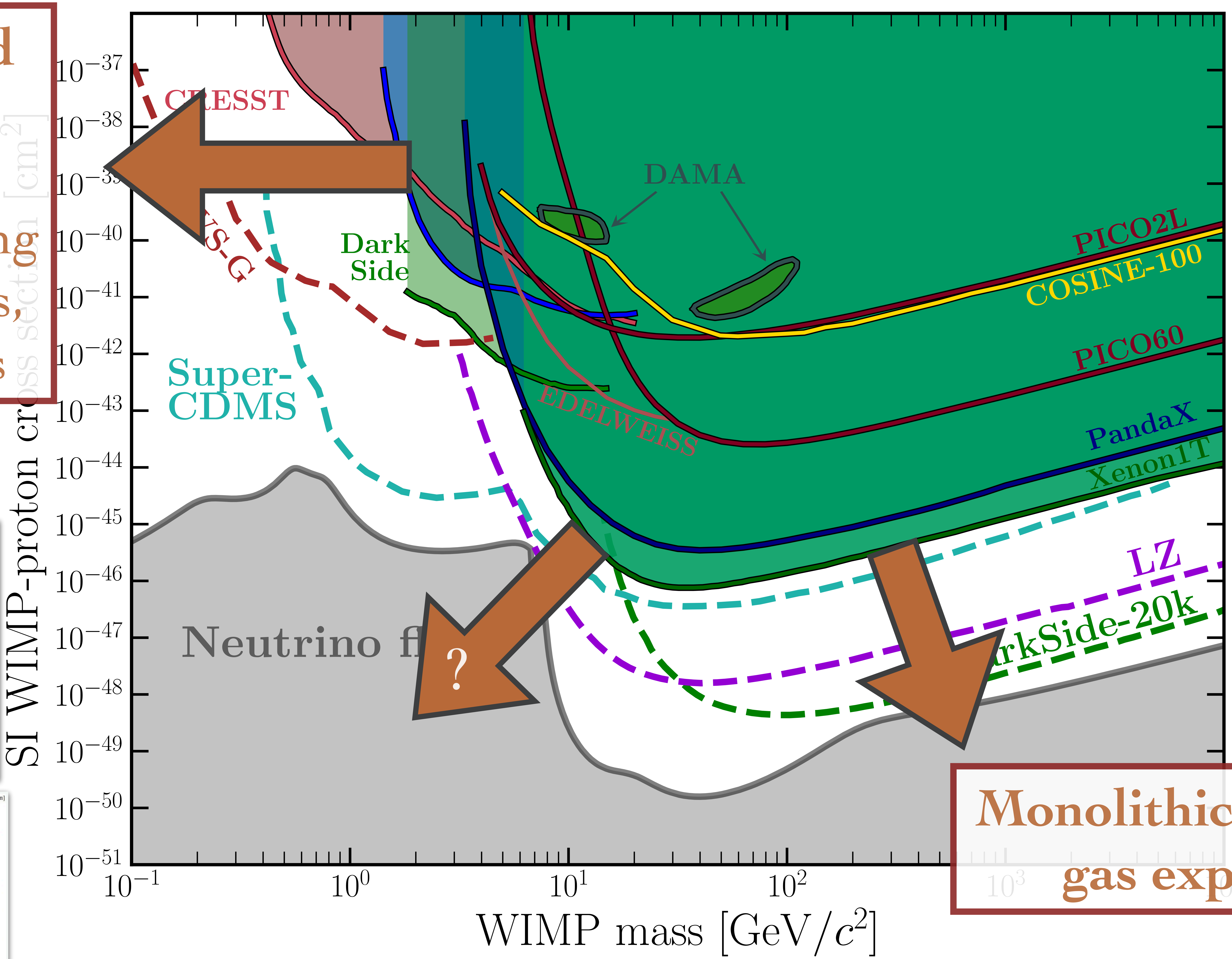
Current status of searches for Weakly Interacting Massive Particles

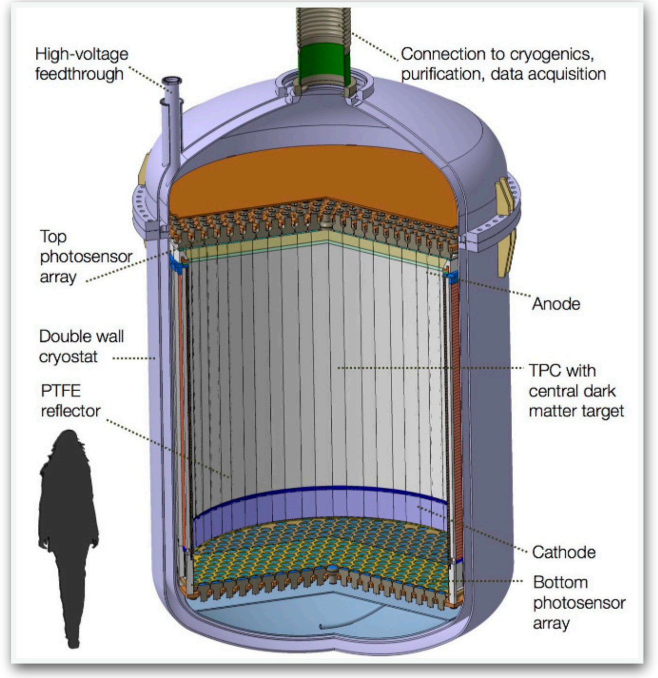
Low threshold detectors

e.g. cryogenic scintillators using semiconductors, light gas SPCs

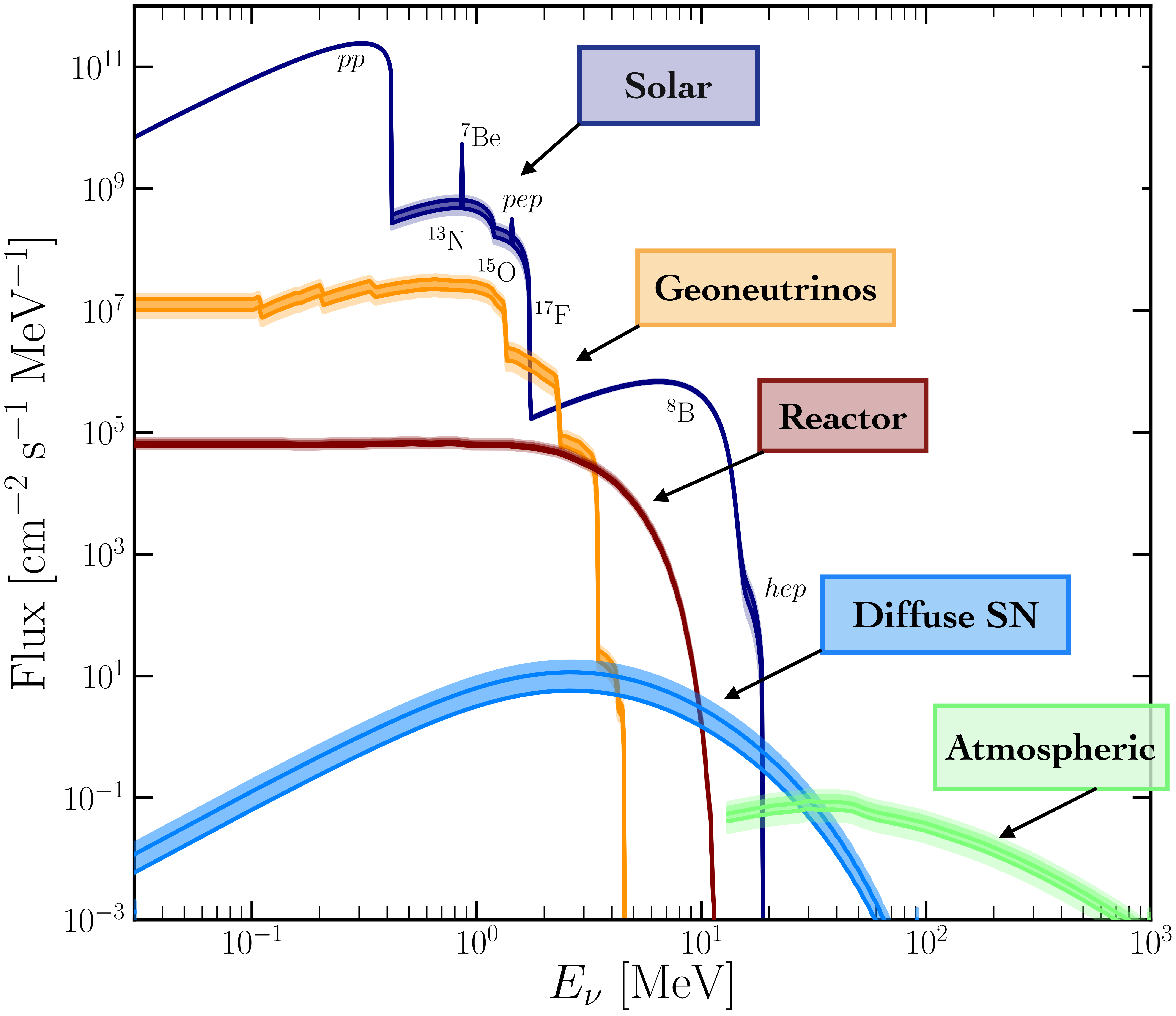




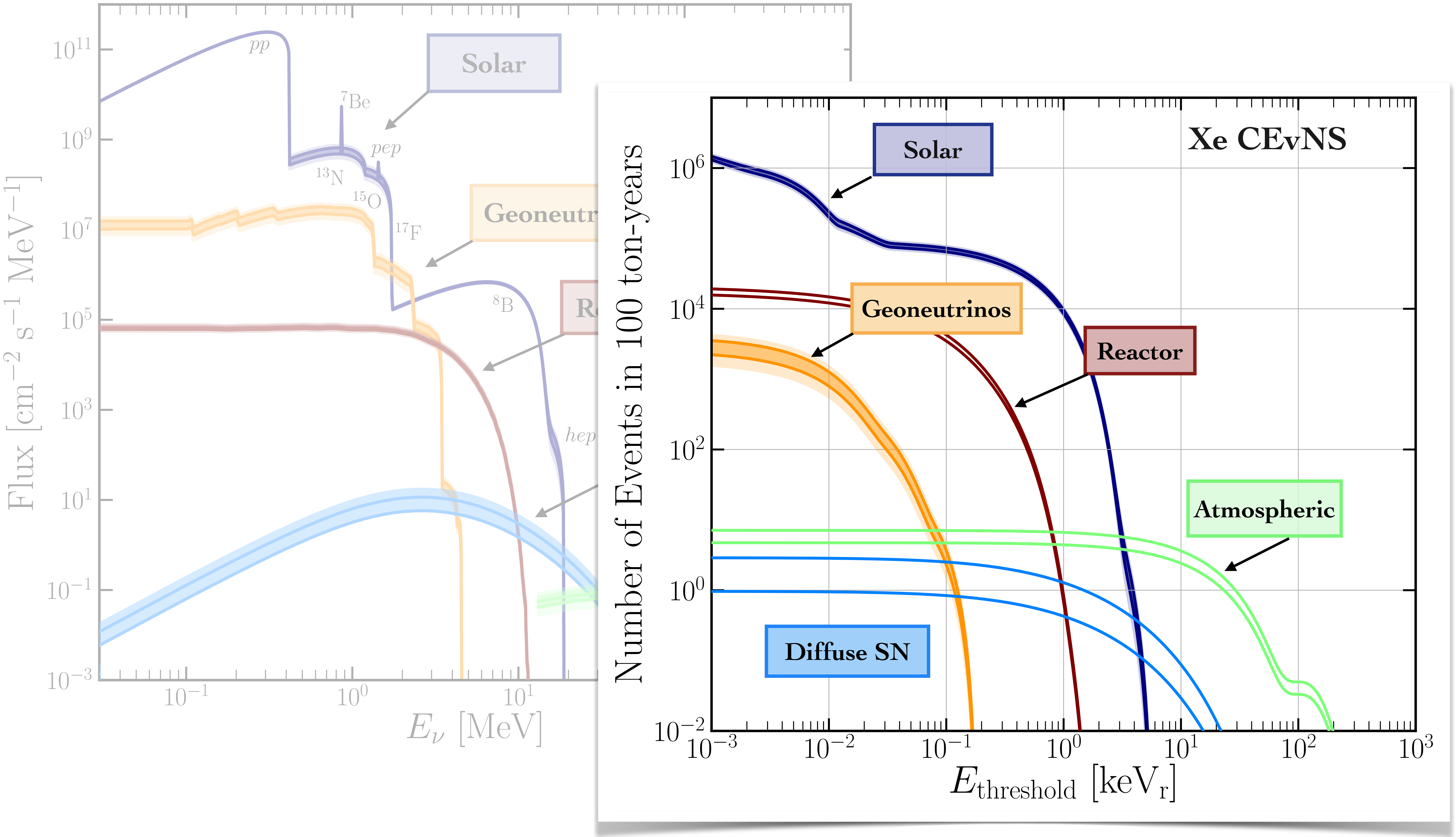




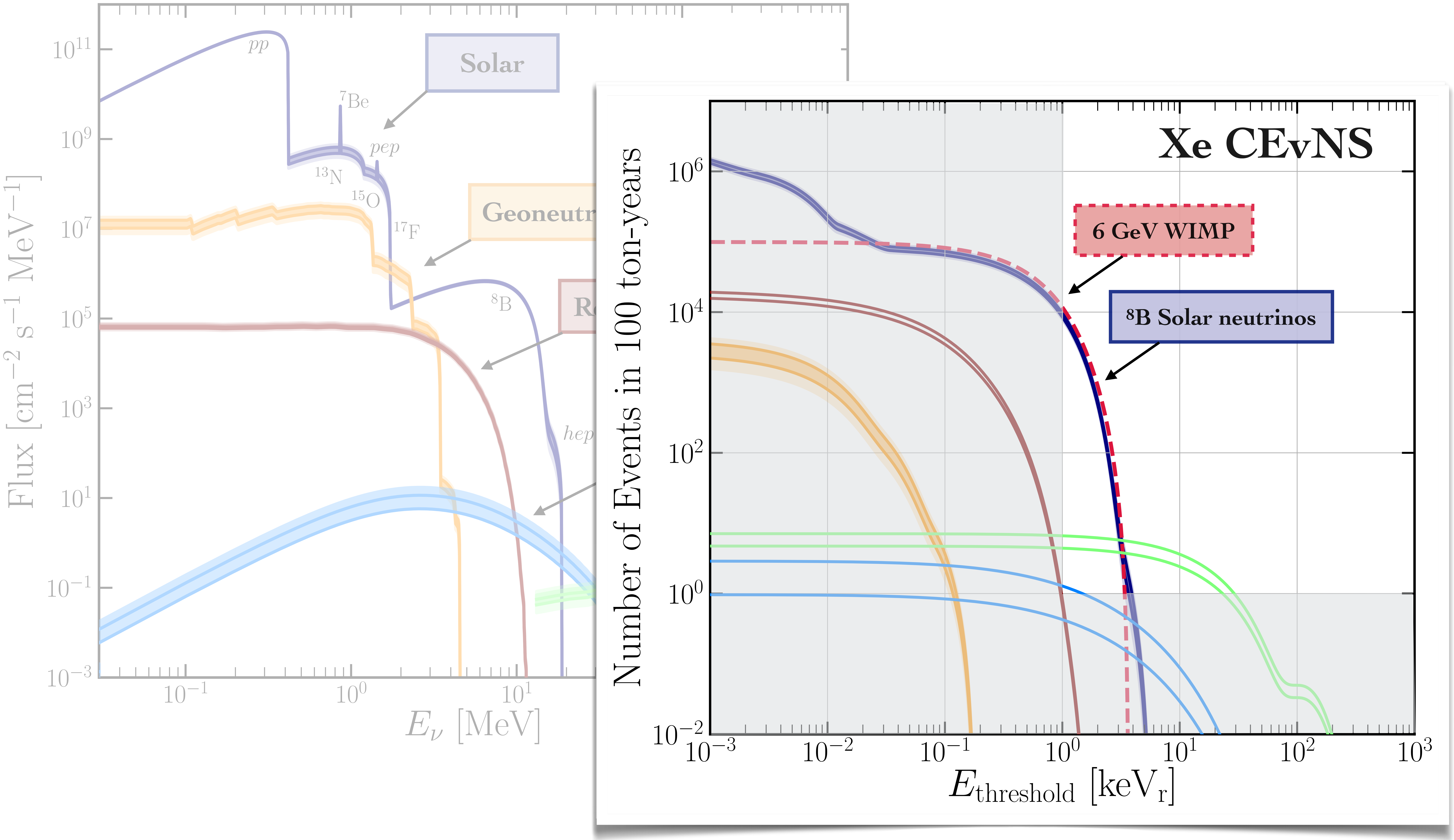
Monolithic liquid noble gas experiments



Solar
Geoneutrinos
Reactor
Diffuse SN
Atmospheric
pp
7Be
pep
13N
15O
17F
8B
hep
Flux [cm−2 s−1 MeV−1]
Eν [MeV]



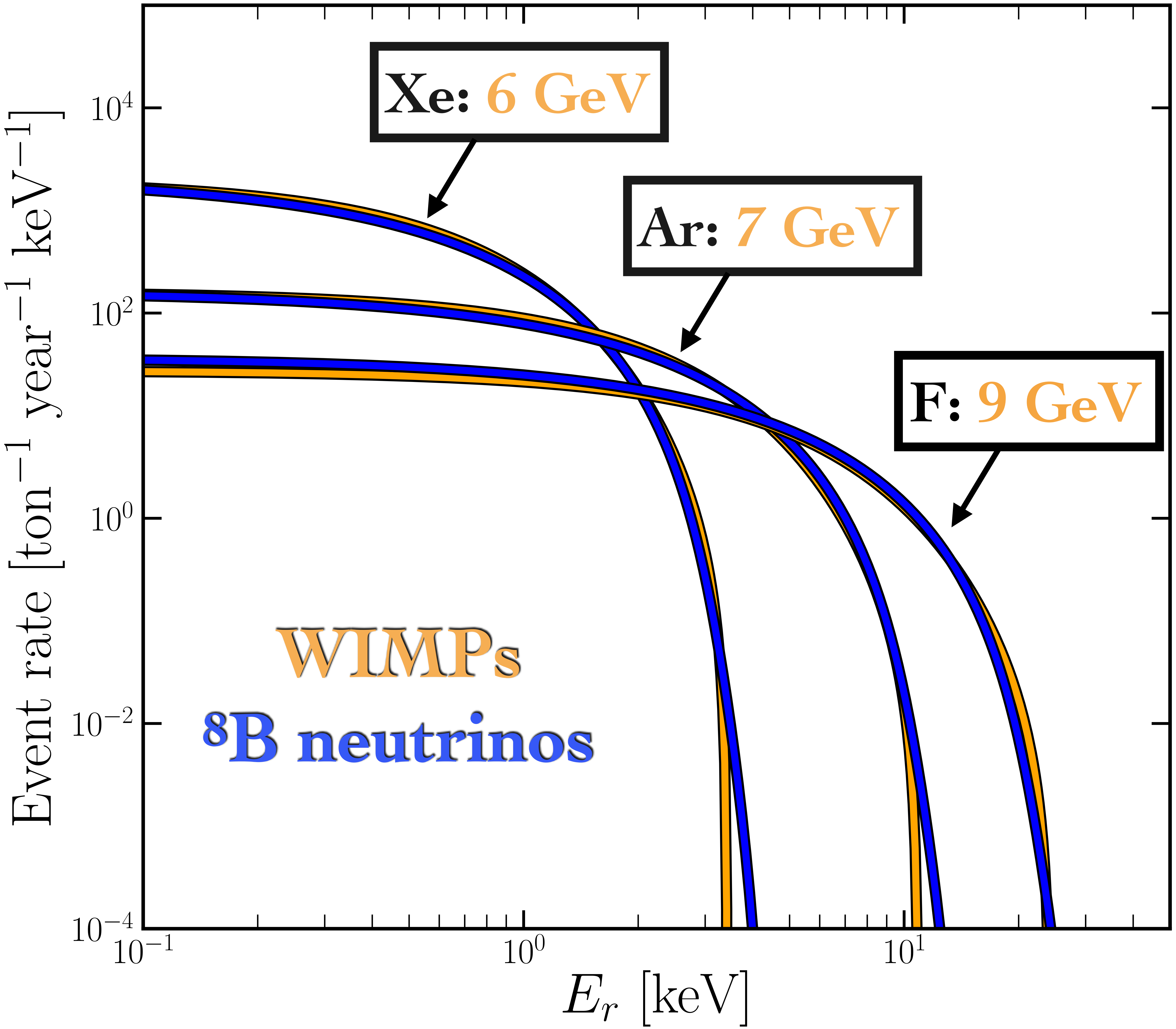
Flux [cm^{-2} s^{-1} MeV^{-1}]
E_ν [MeV]
Solar
Geoneutr
Re
pp
^{7}Be
pep
^{13}N
^{15}O
^{17}F
^{8}B
hep
Xe CEvNS
Number of Events in 100 ton-years
$E_{\rm threshold}$ [keV$_{\rm r}$]
Solar
Geoneutrinos
Reactor
Atmospheric
Diffuse SN



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?

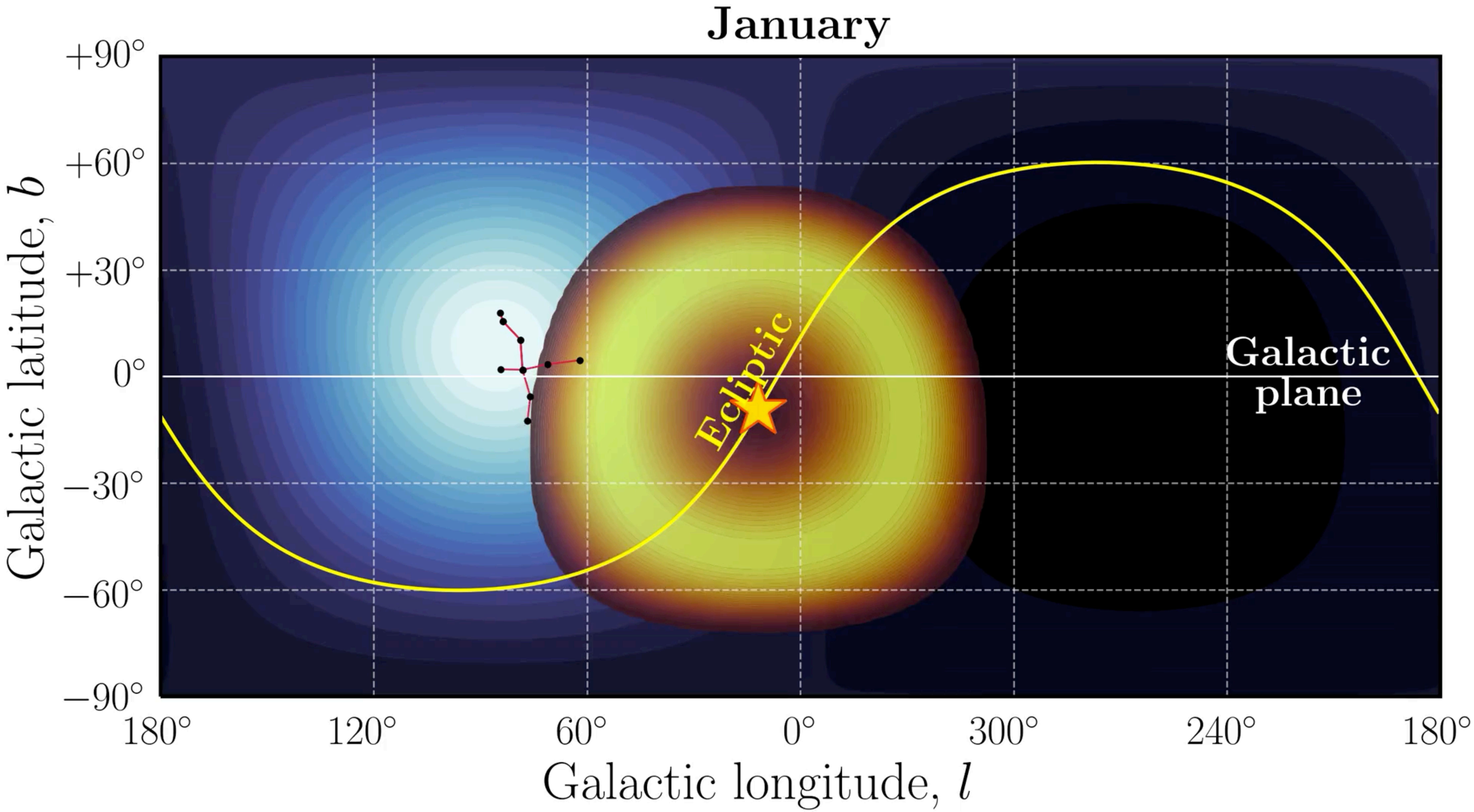
→ spectral match between DM and solar neutrinos



Impossible to tell the difference between WIMPs and neutrinos with just energy information

Dark matter should be a strongly directional signature

Nothing should mimic dark matter, including solar neutrinos



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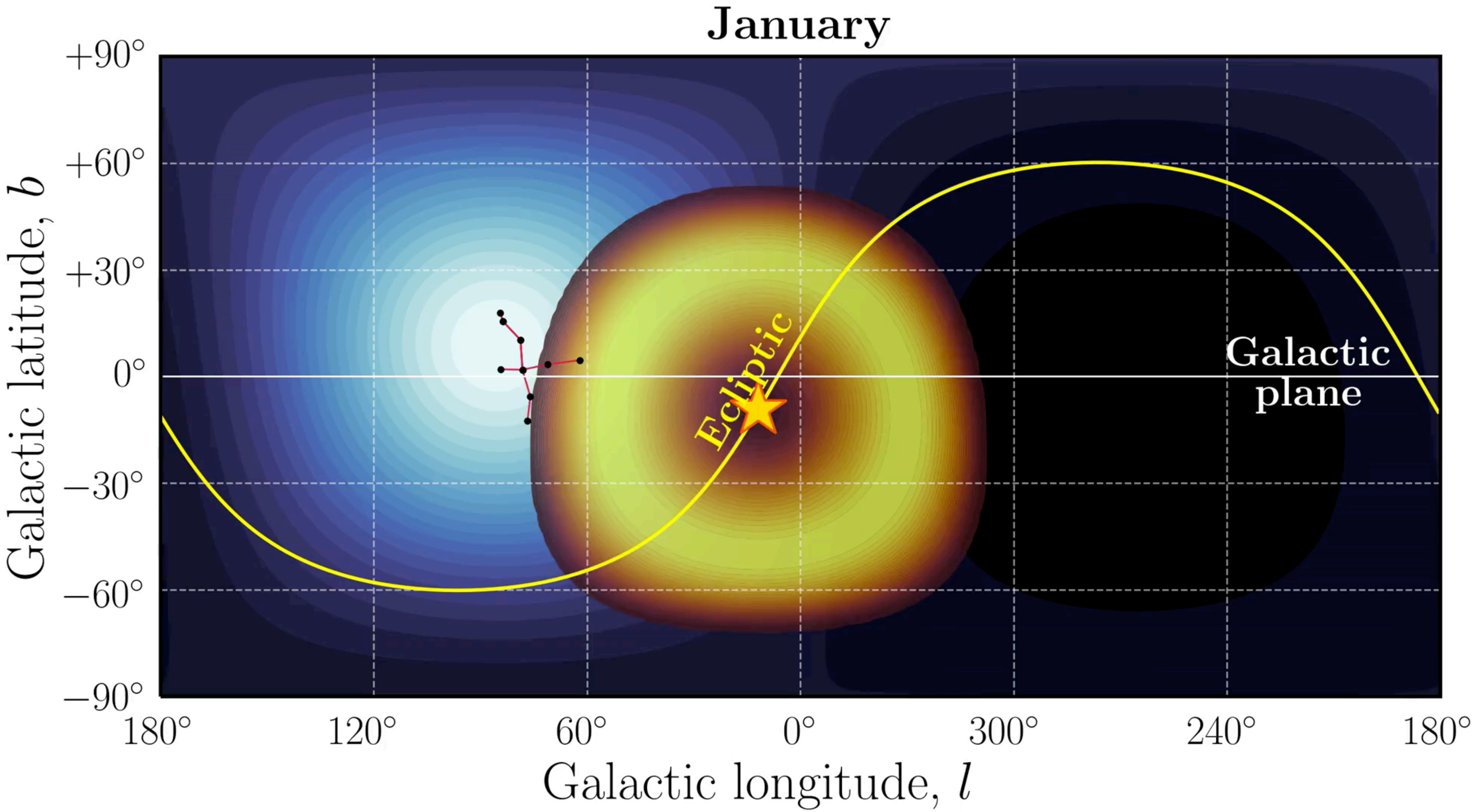
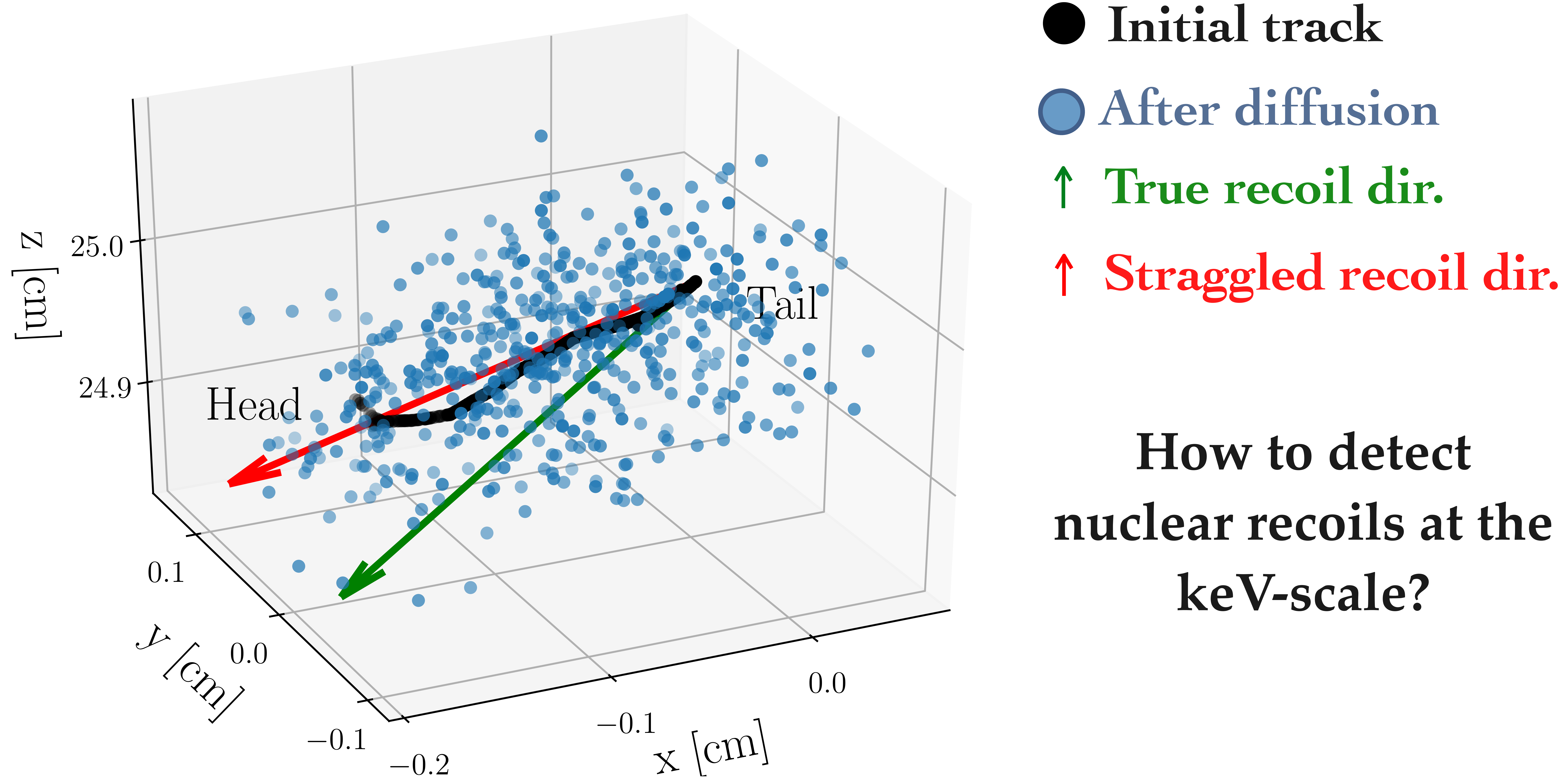
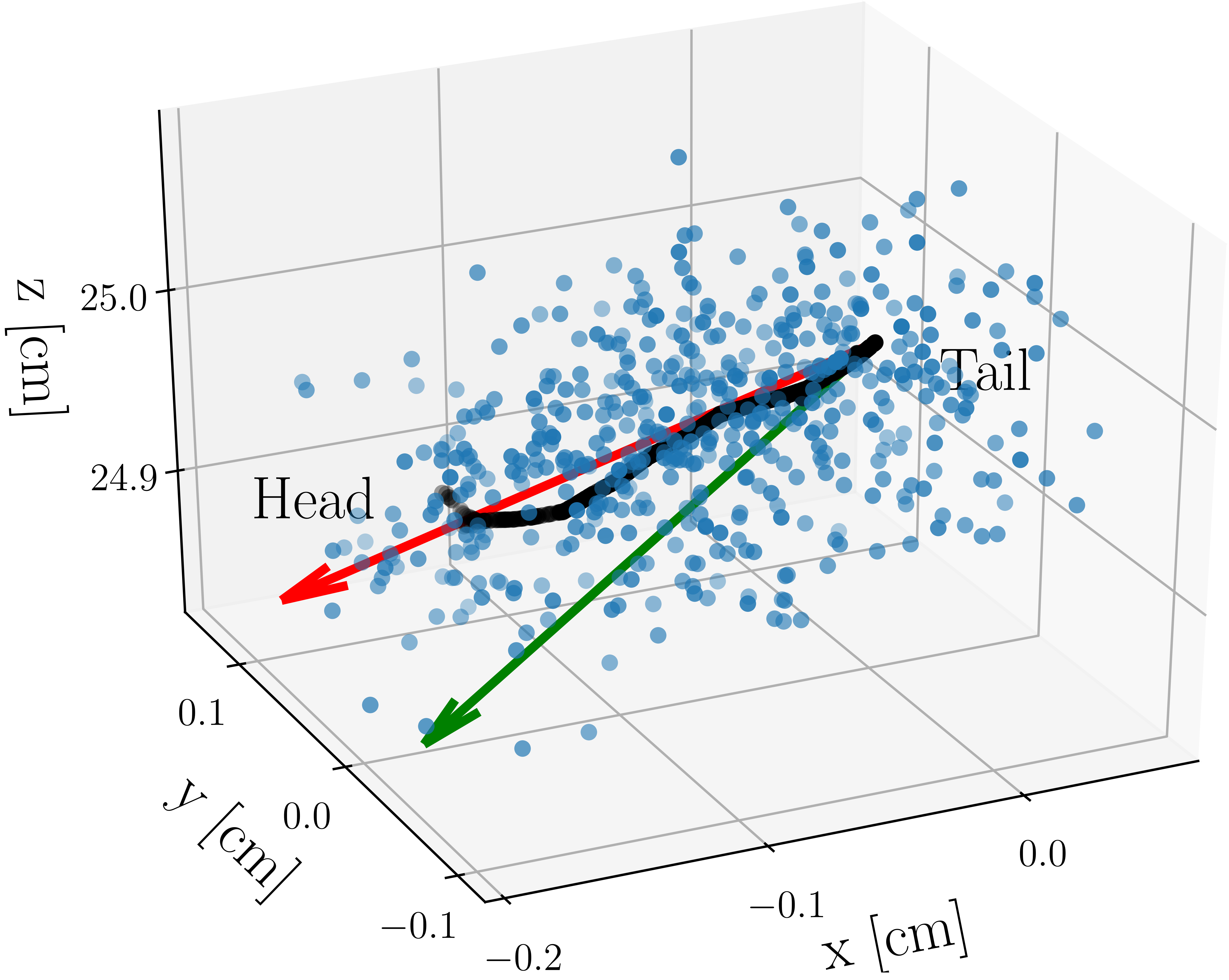




How to detect nuclear recoils at the keV-scale?



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)

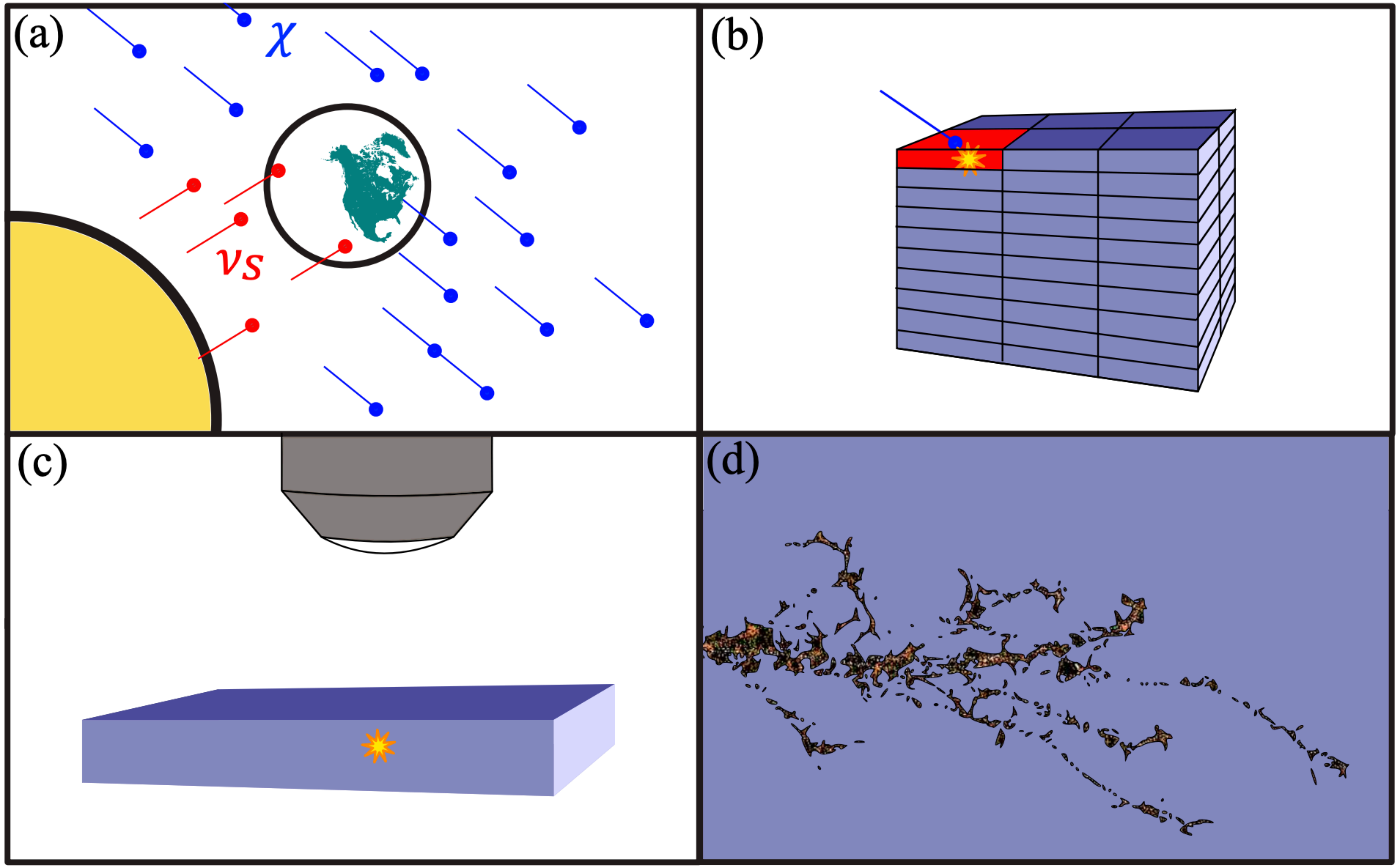
What would you use to detect keV-scale nuclear recoils?

	Pros	Cons
Solid	• High target mass • Well-established technologies, e.g. scintillators	• Need ultra high resolution imaging • Tracks directions 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]

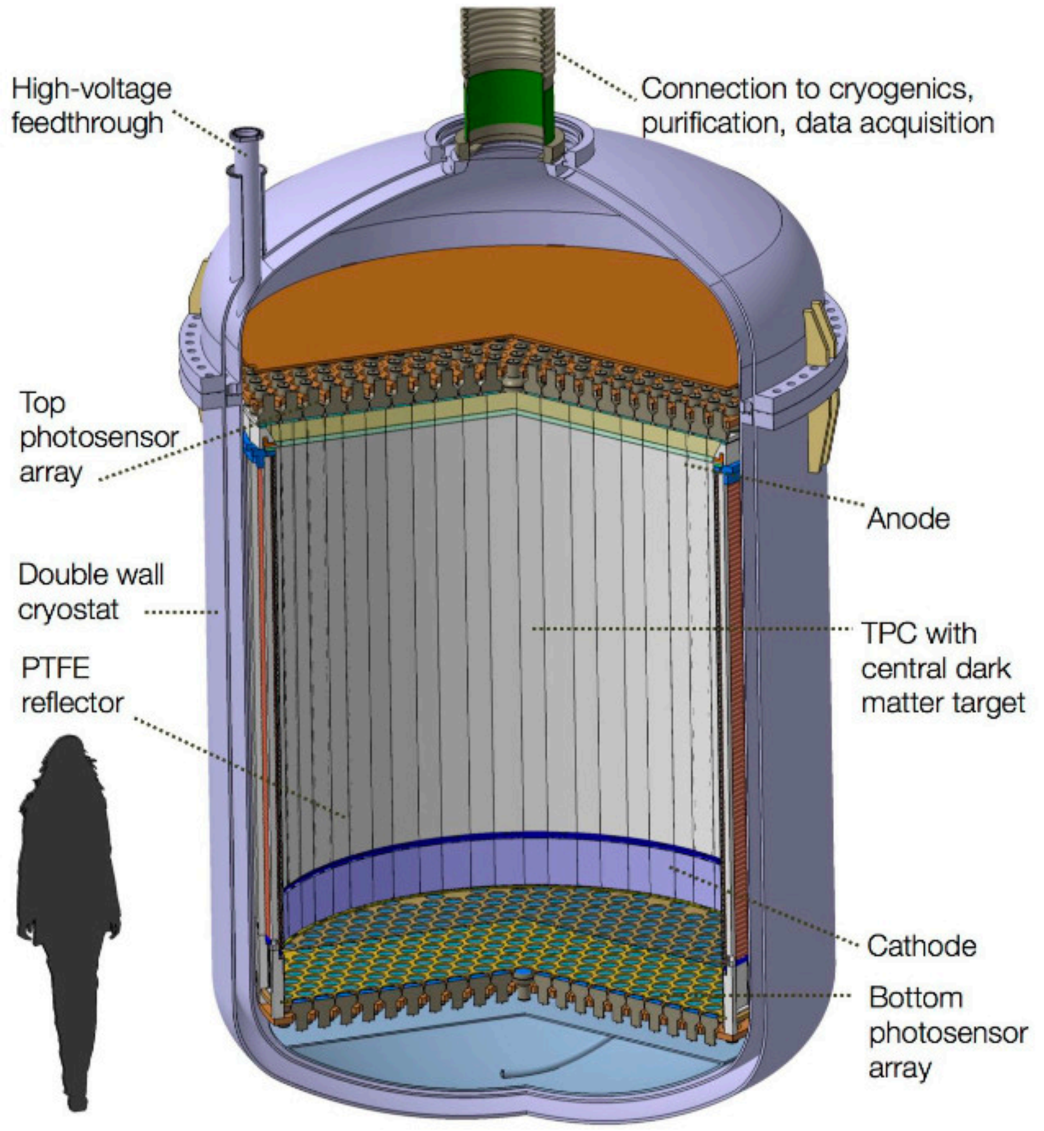
Nitrogen vacancy centres in diamond

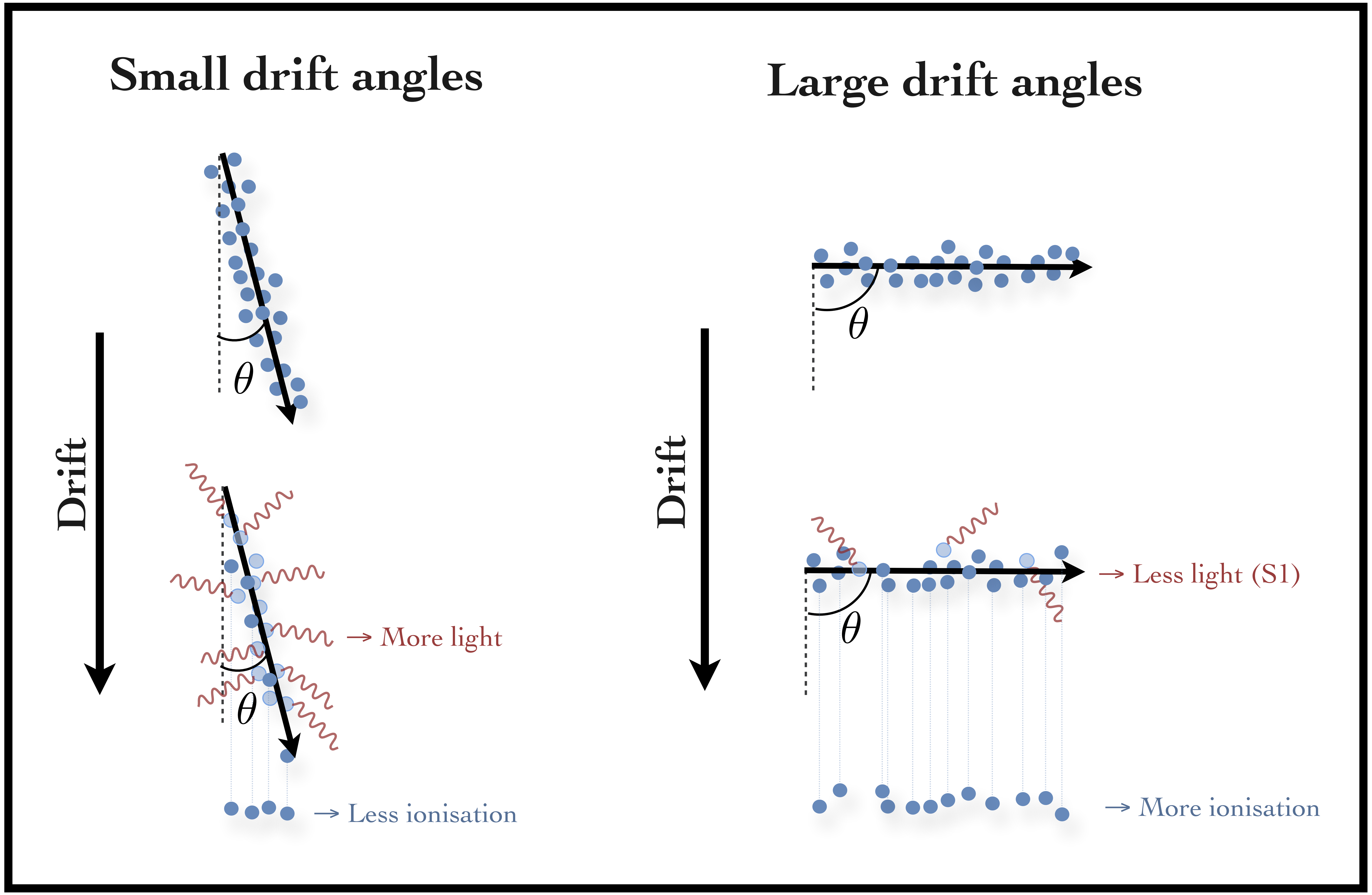


Directionality in liquids: columnar recombination

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





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

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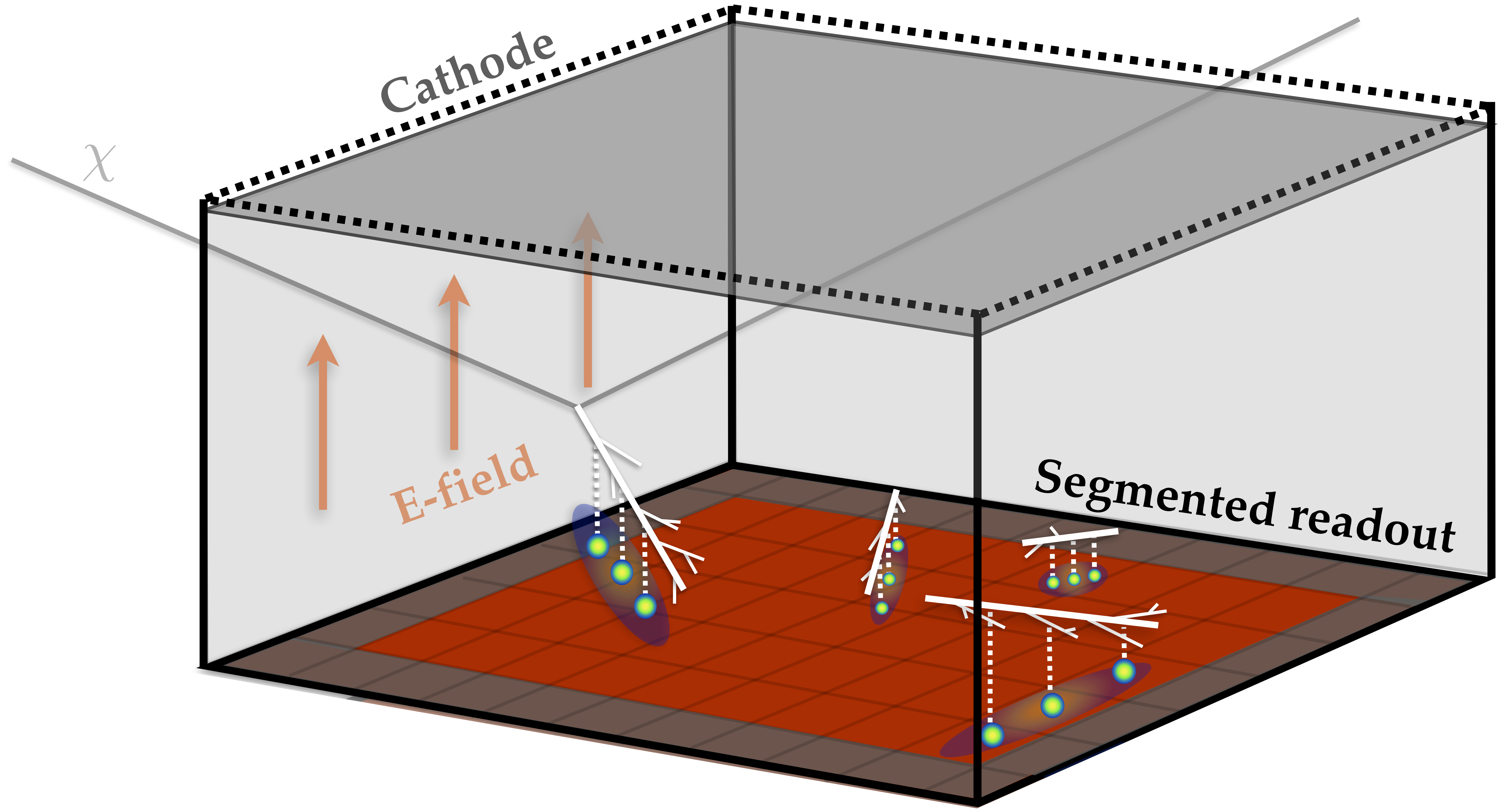
Focus of Cygnus: HD gas time projection chamber

Current gas of interest: 1 atm. of $He{:}SF_6$ at 755:5



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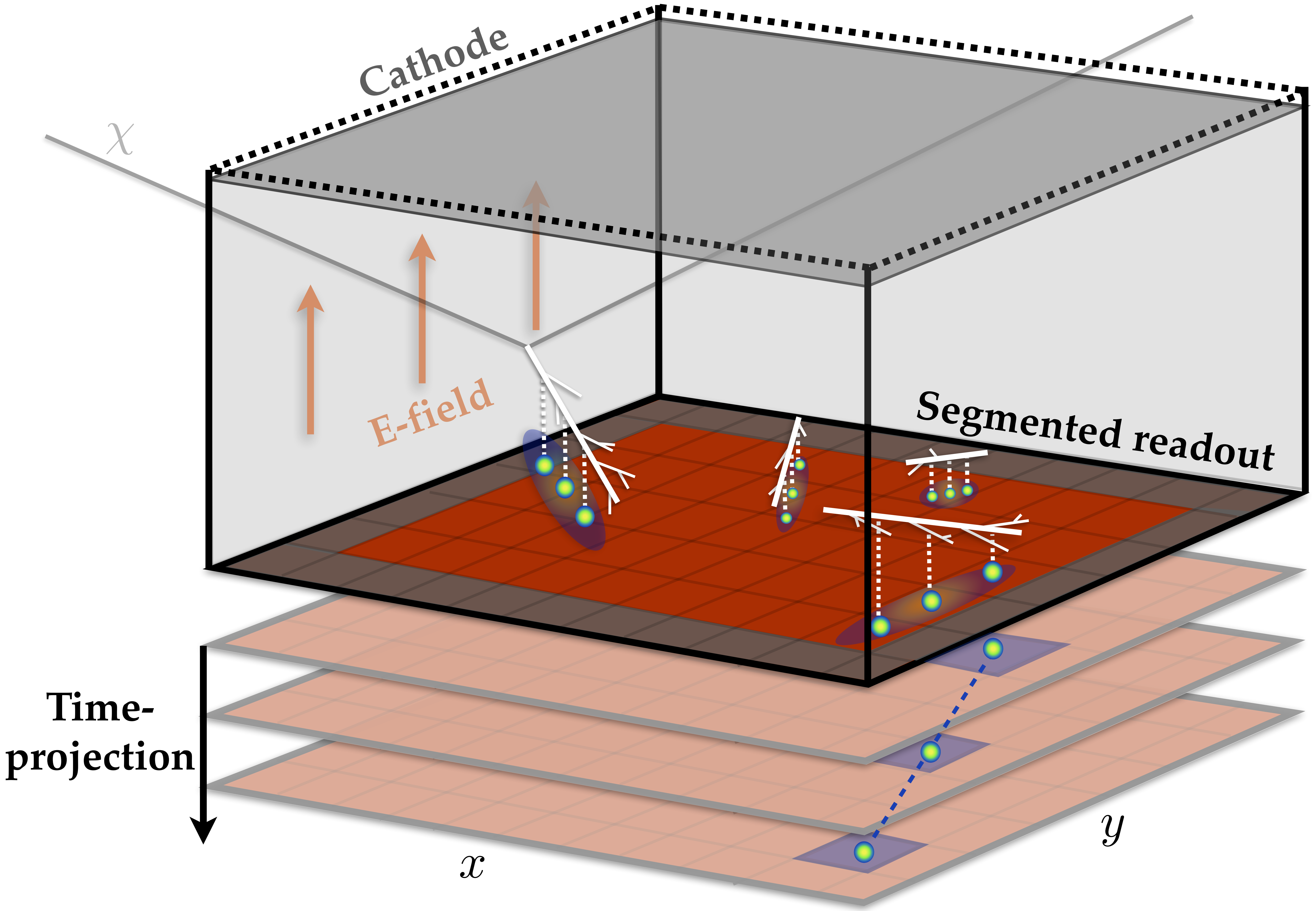

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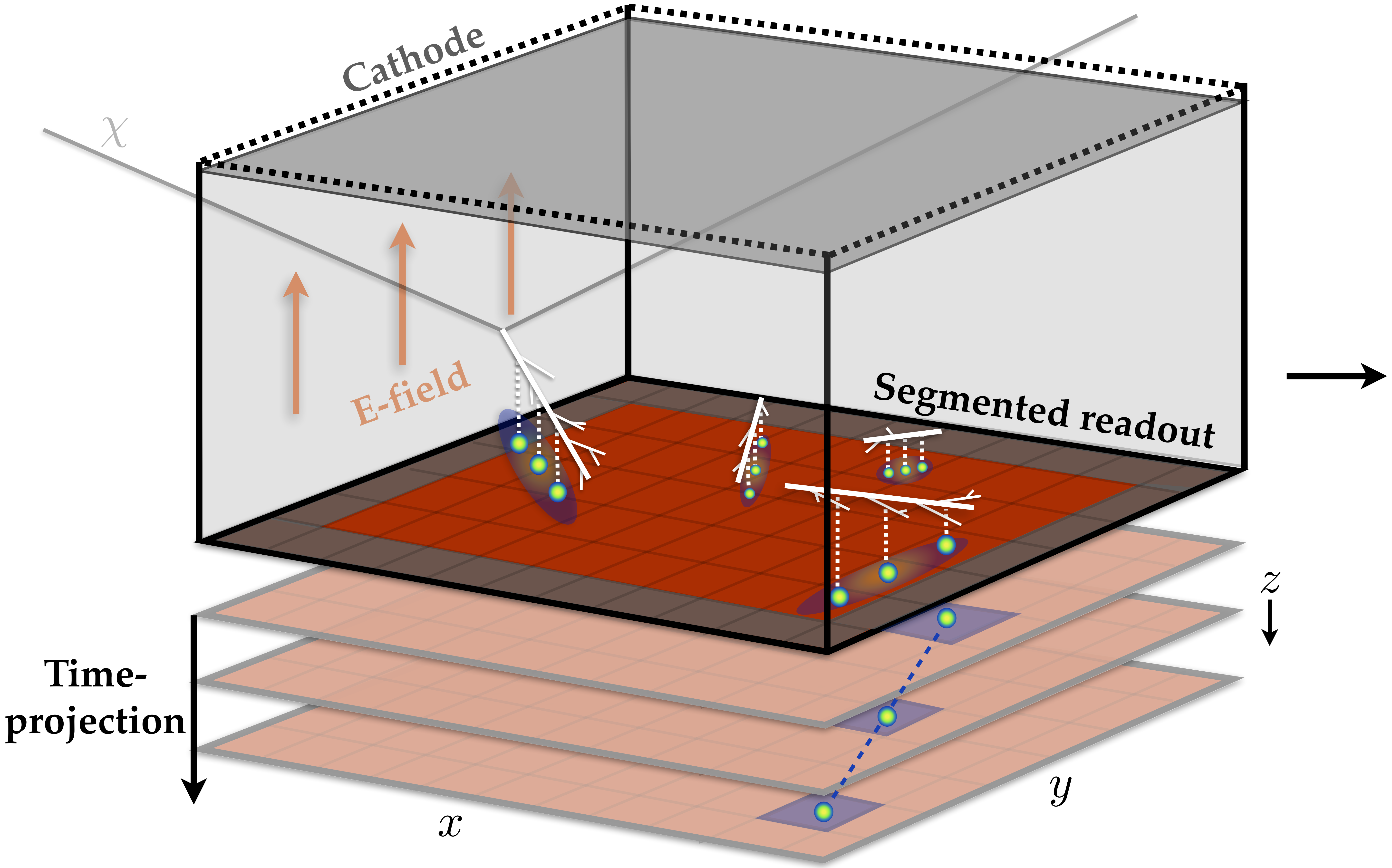
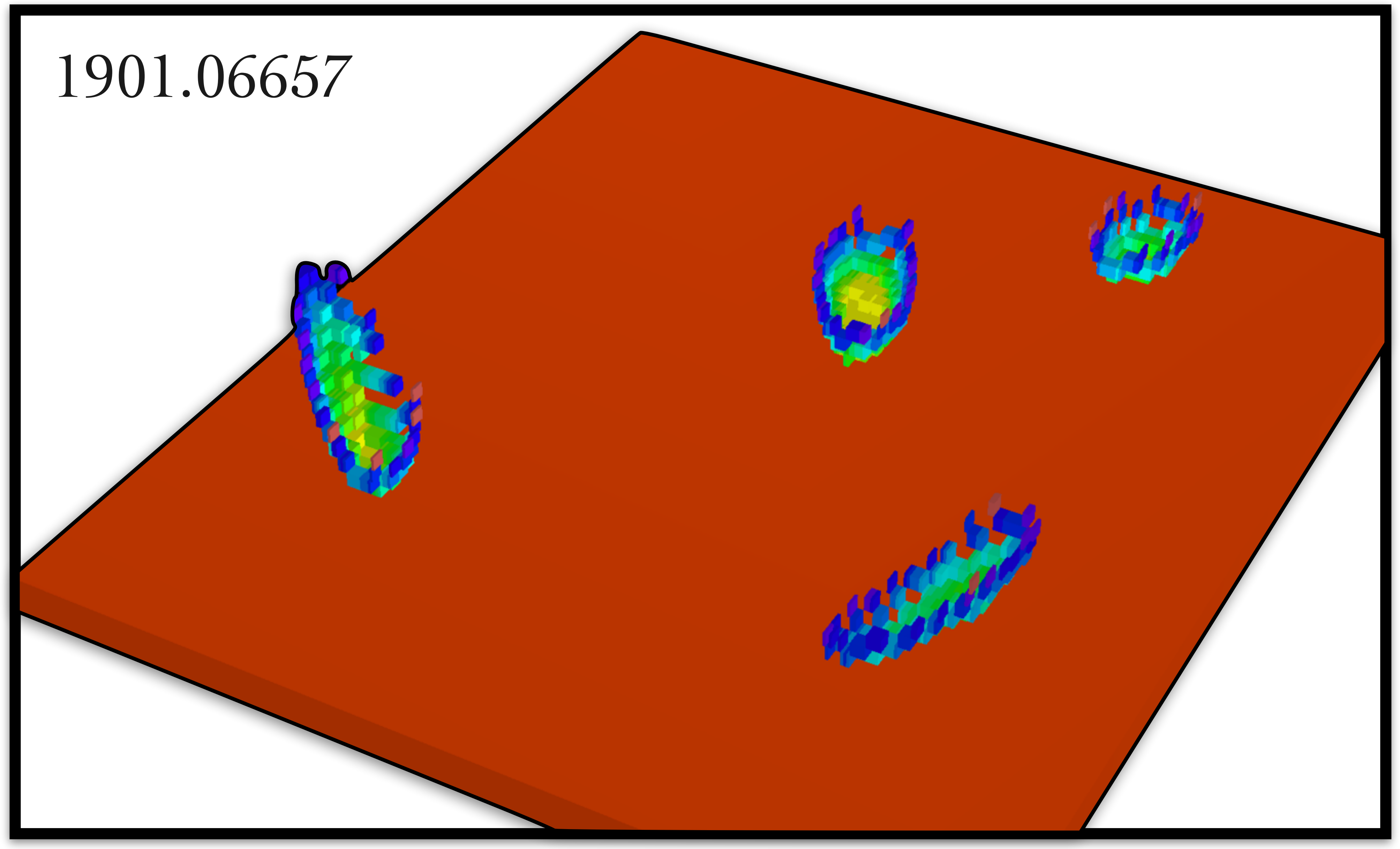


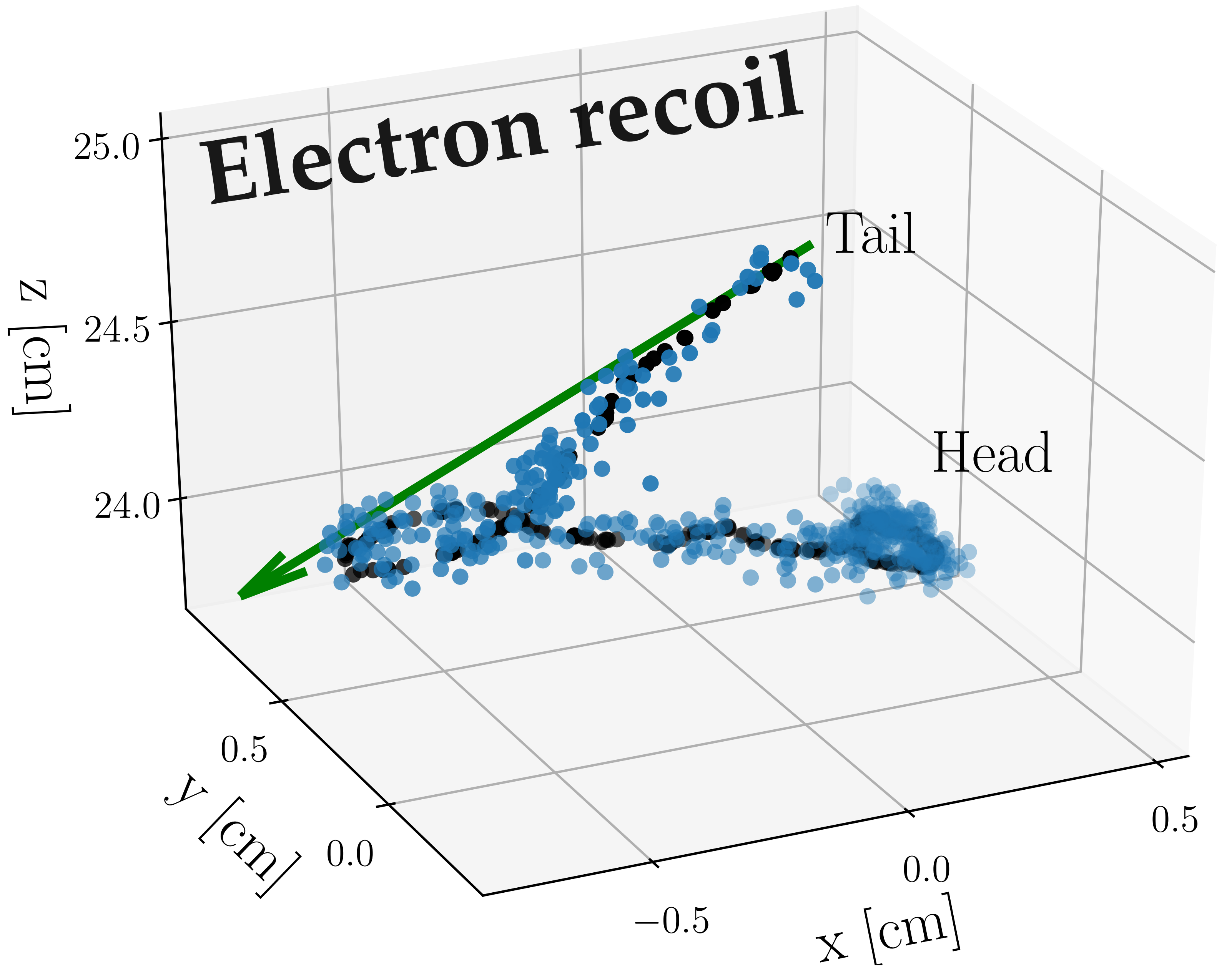


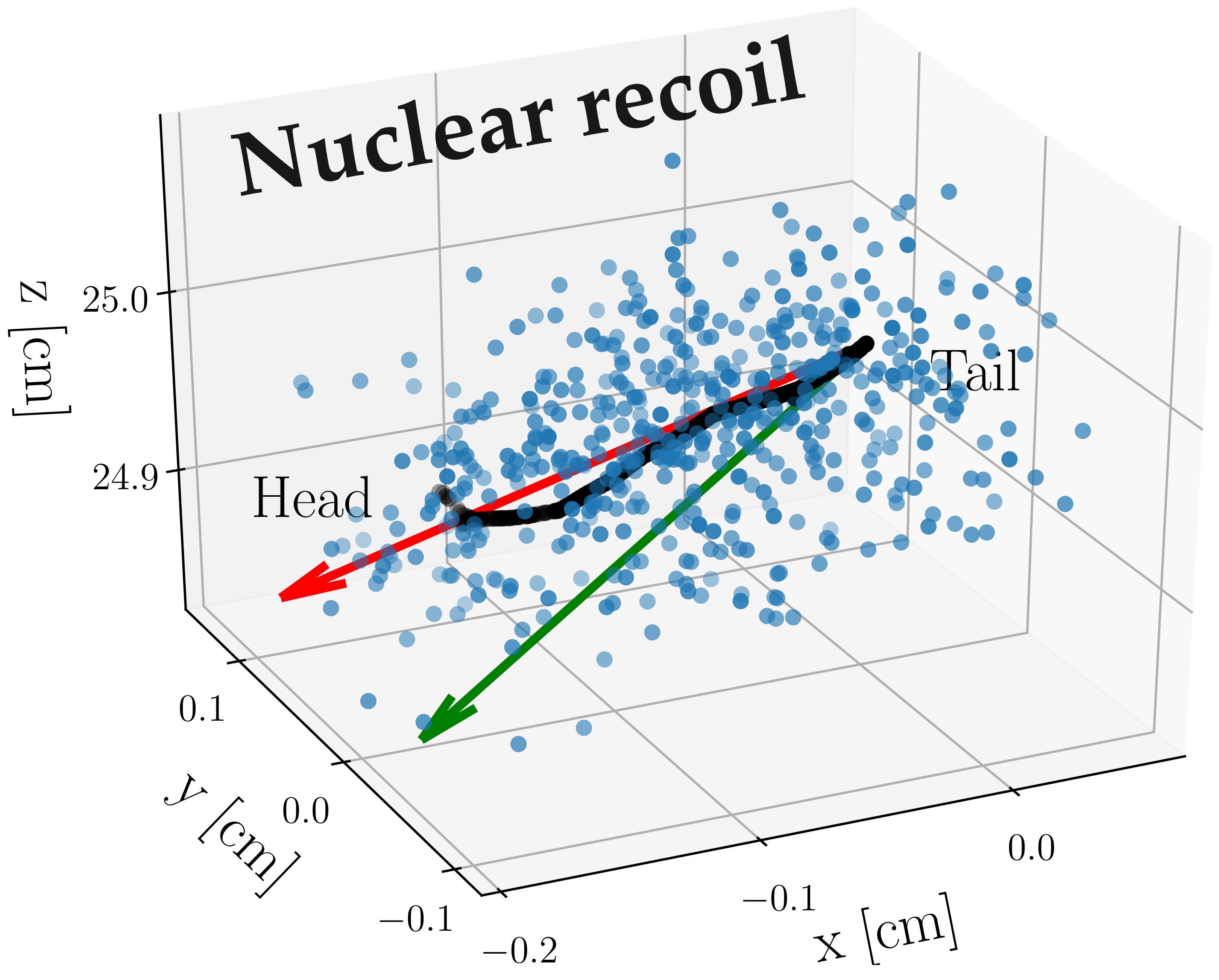
Angular performance

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

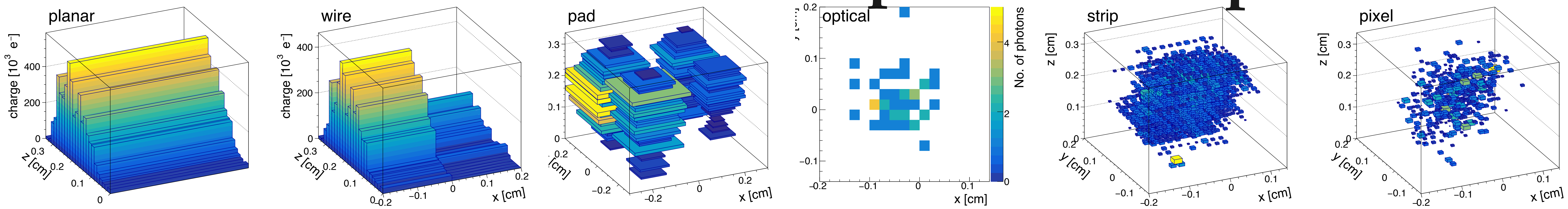
→ Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals





Readout technologies

Planar **Wire** **Pad** **Optical** **Strip** **Pixel**



1D 1D 2D 3D 3D 3D

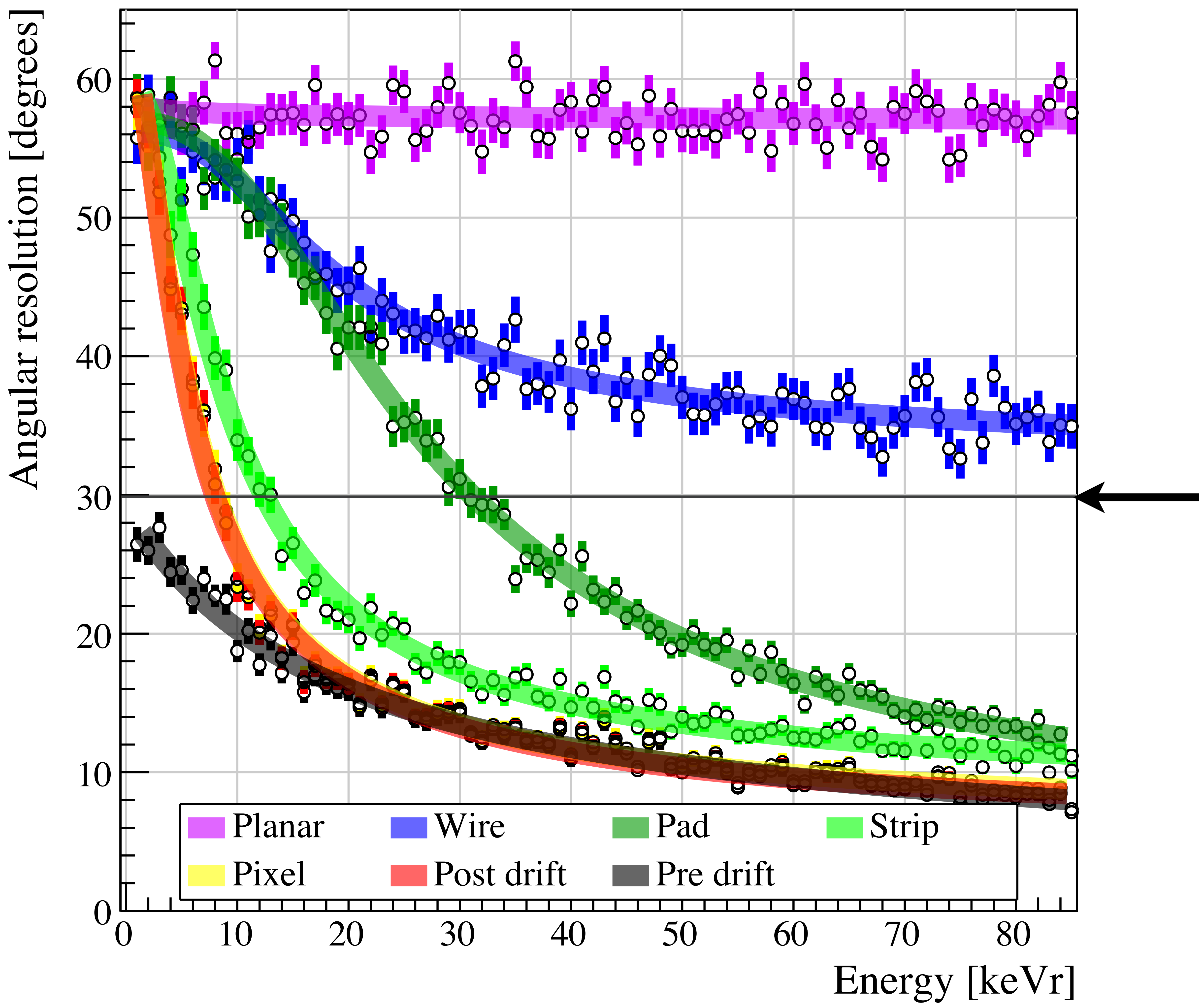
Simplest readouts
→ Worst directional sensitivity but lower cost

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)

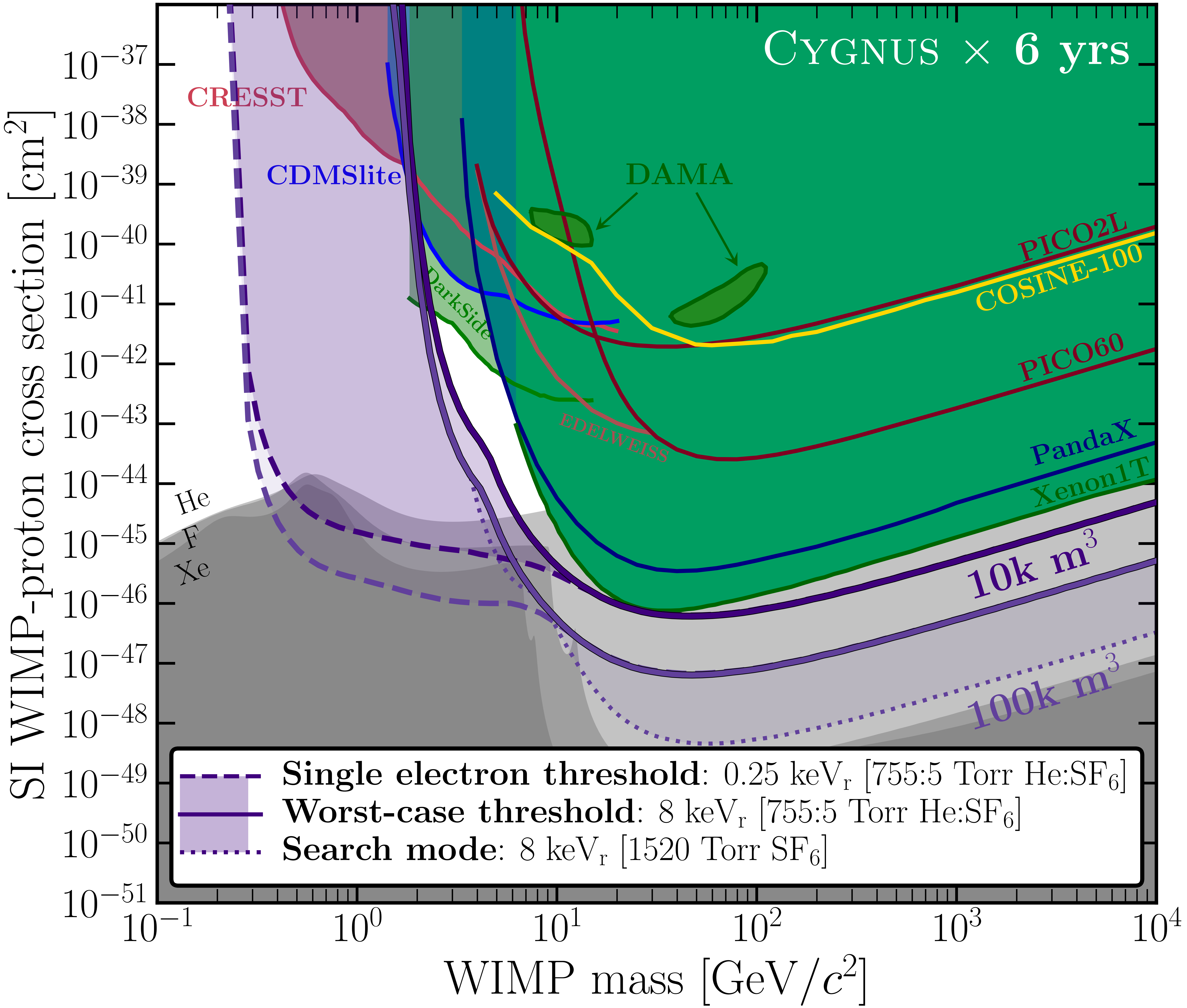


<u>Simulated charge readout comparison</u>

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

Sensitivity (SI)

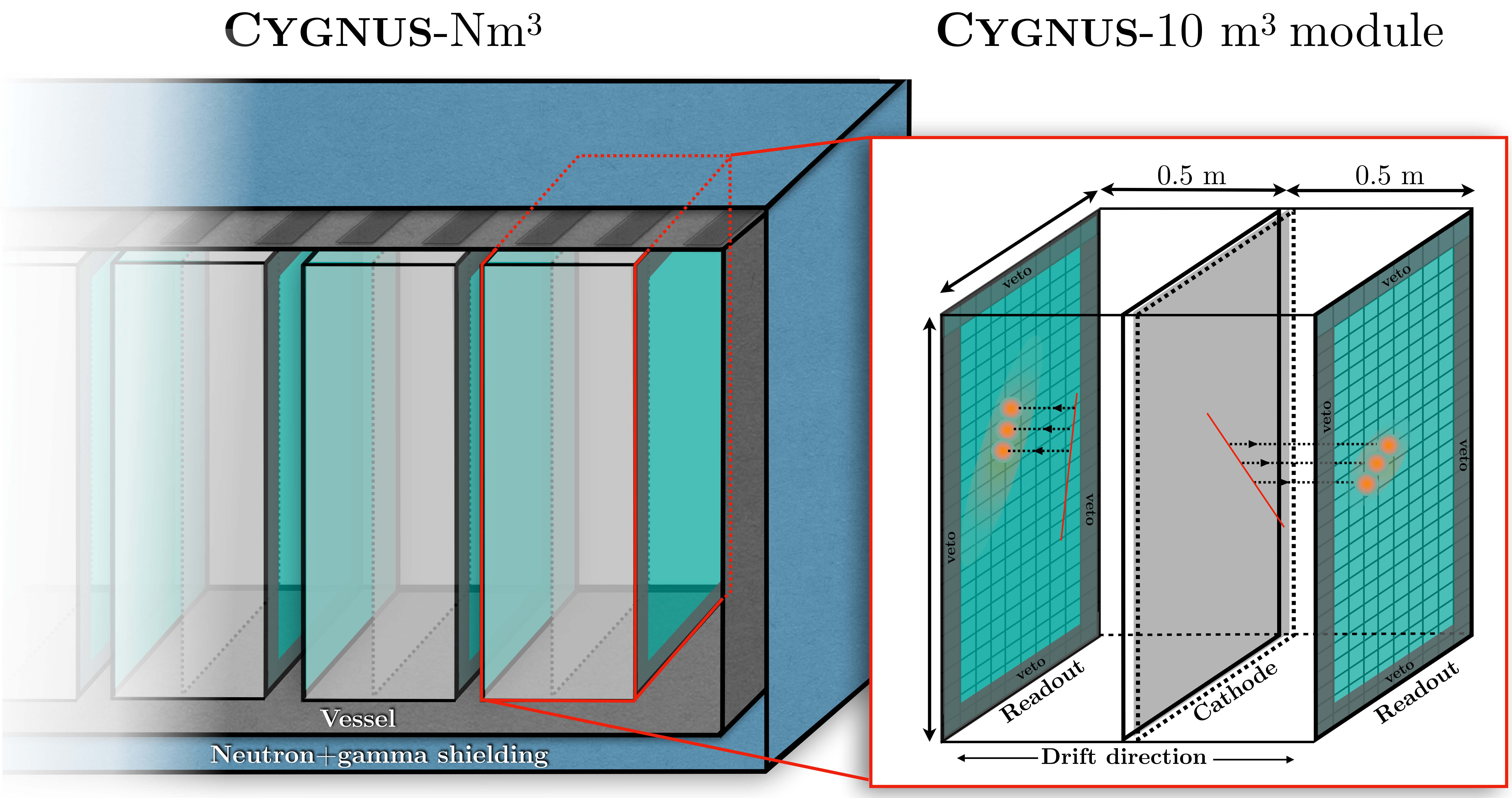
→ Window worst/best case threshold
→ Search mode: 1 atm. of SF_6 but <u>no</u> directionality (possible way to extend high mass sensitivity)



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

How to scale up?

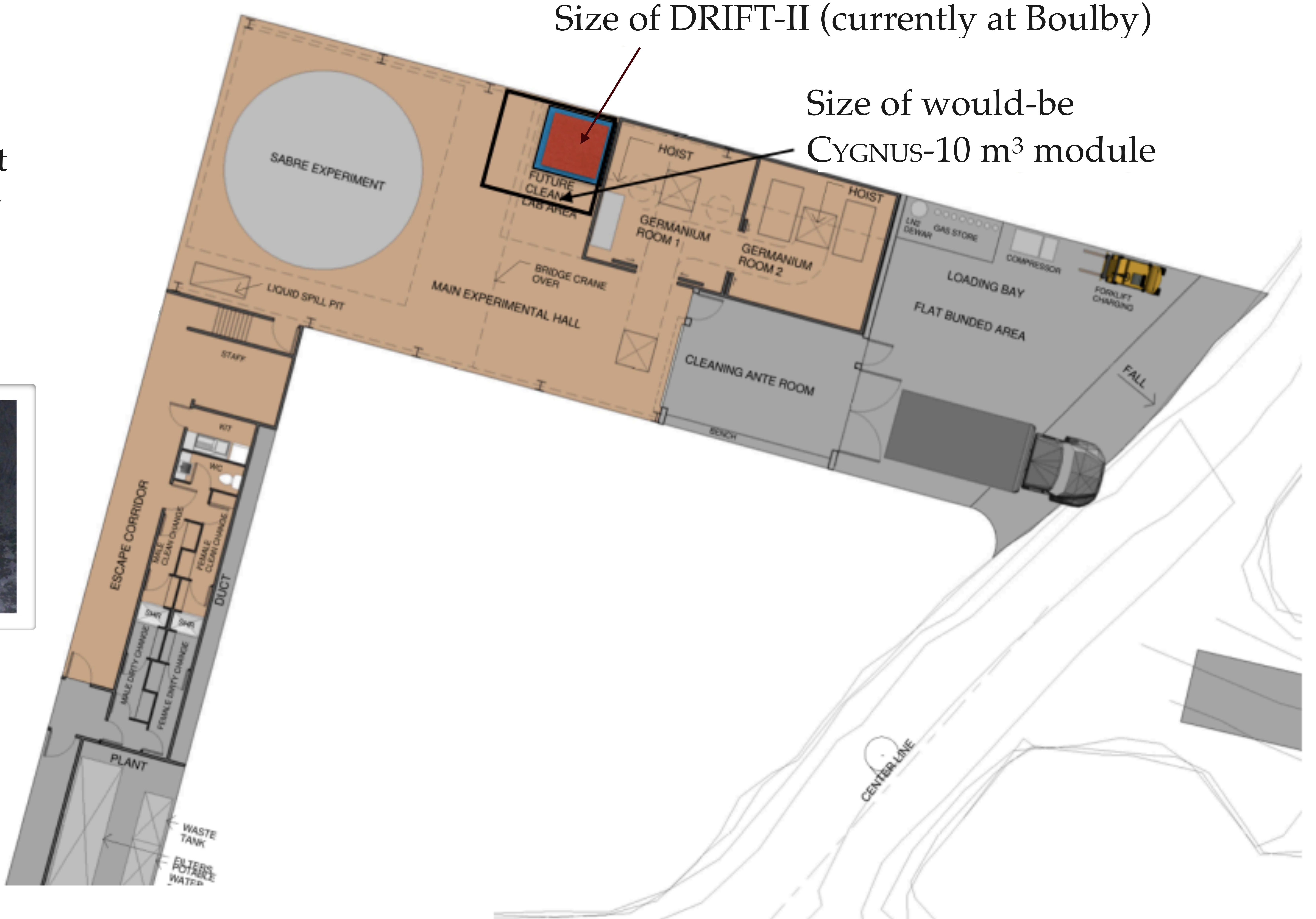
Modularity is both necessary, and advantageous



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

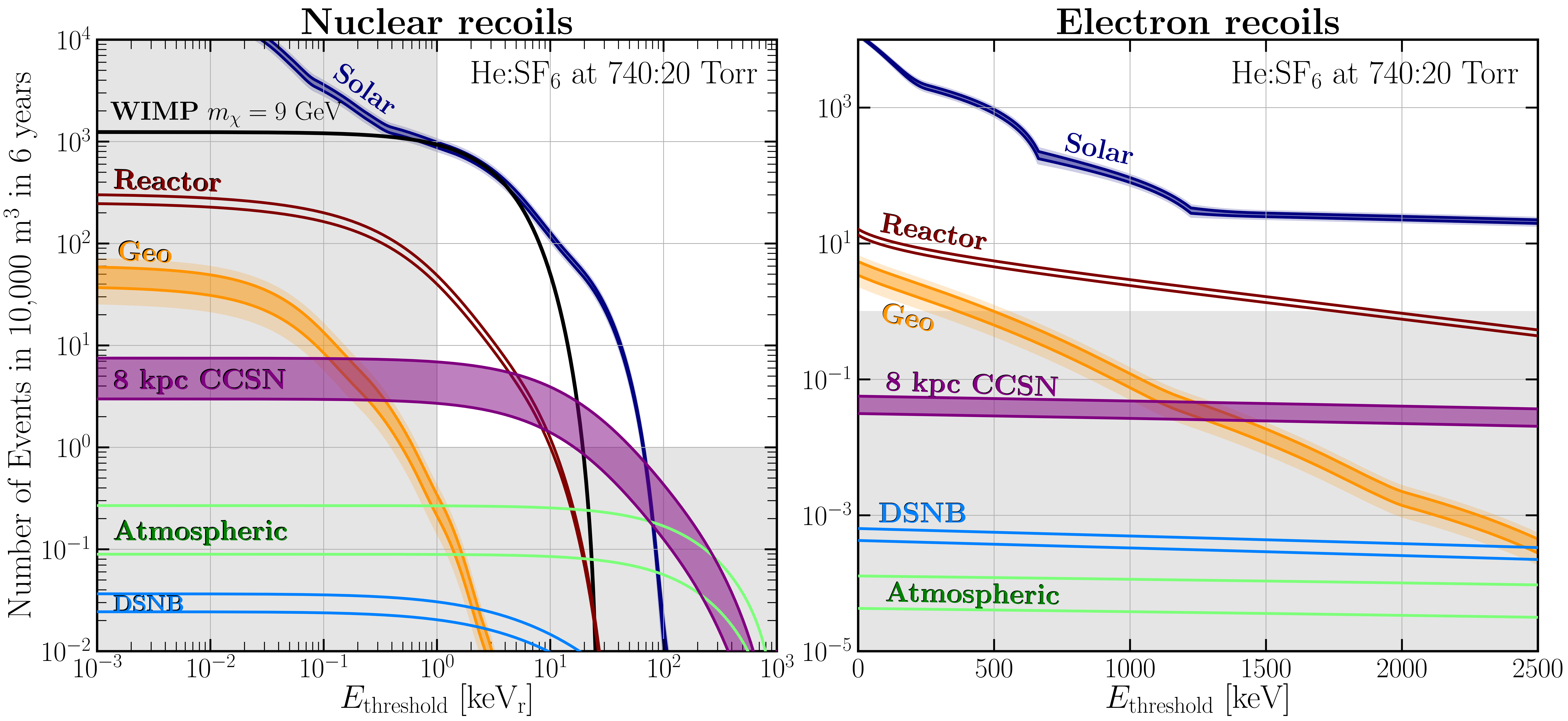
Stawell Underground Physics Laboratory (SUPL)

- 1.6 km depth, still operational gold mine in Australia
- 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



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

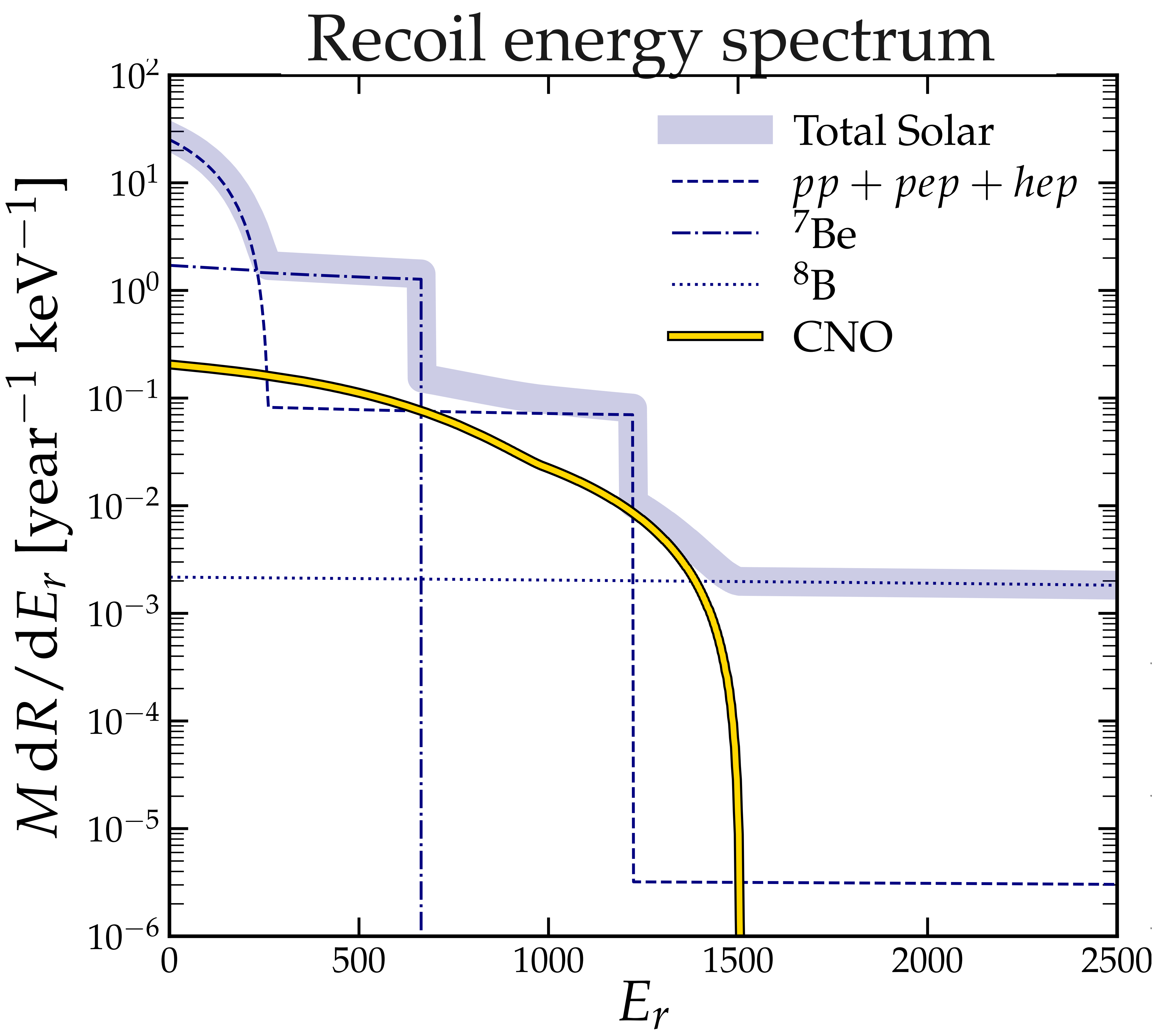
The neutrino background

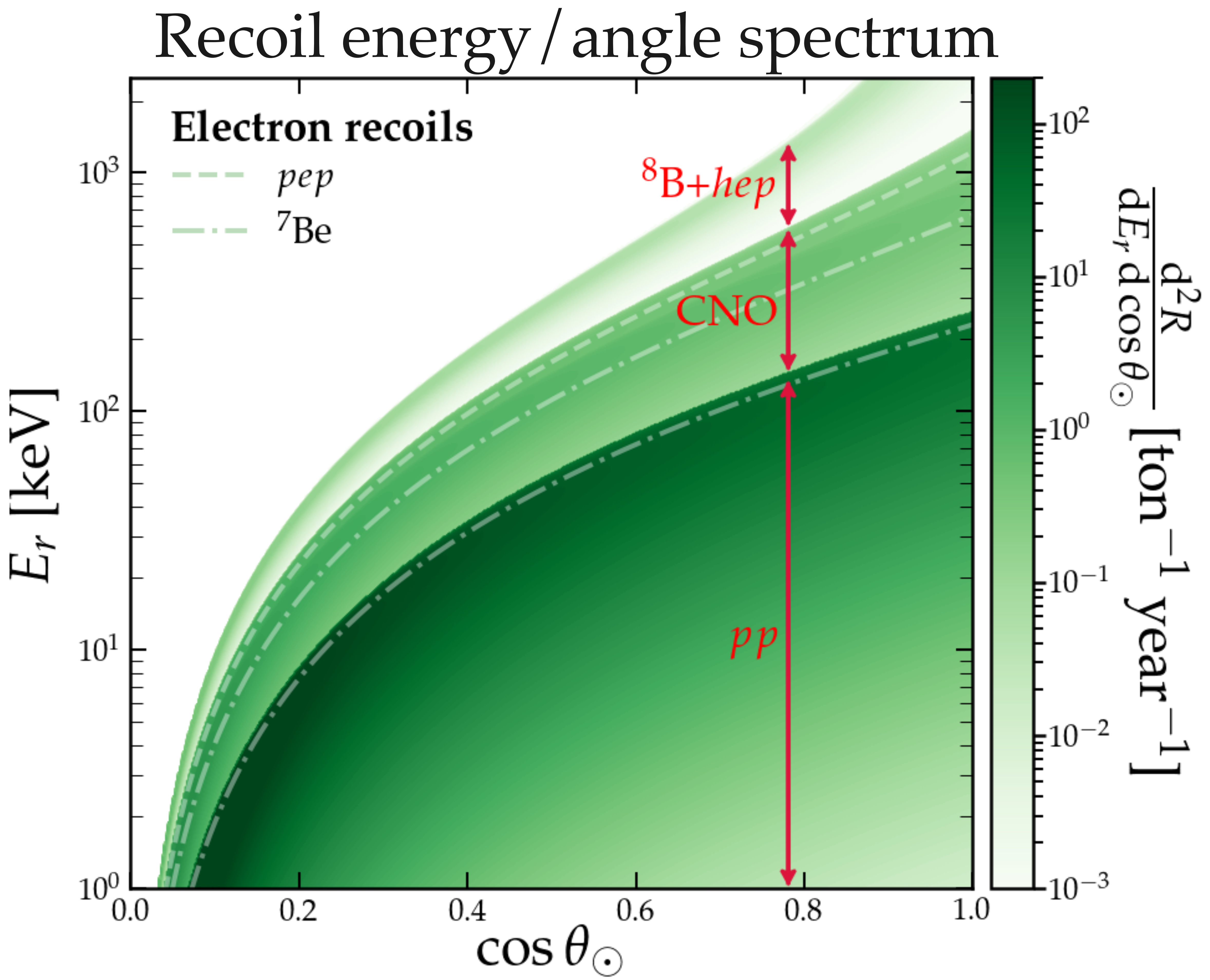


A directional detector has the potential for superior background rejection and NR/ER discrimination
→ this is true even if you're not talking about DM

Directional neutrino measurements

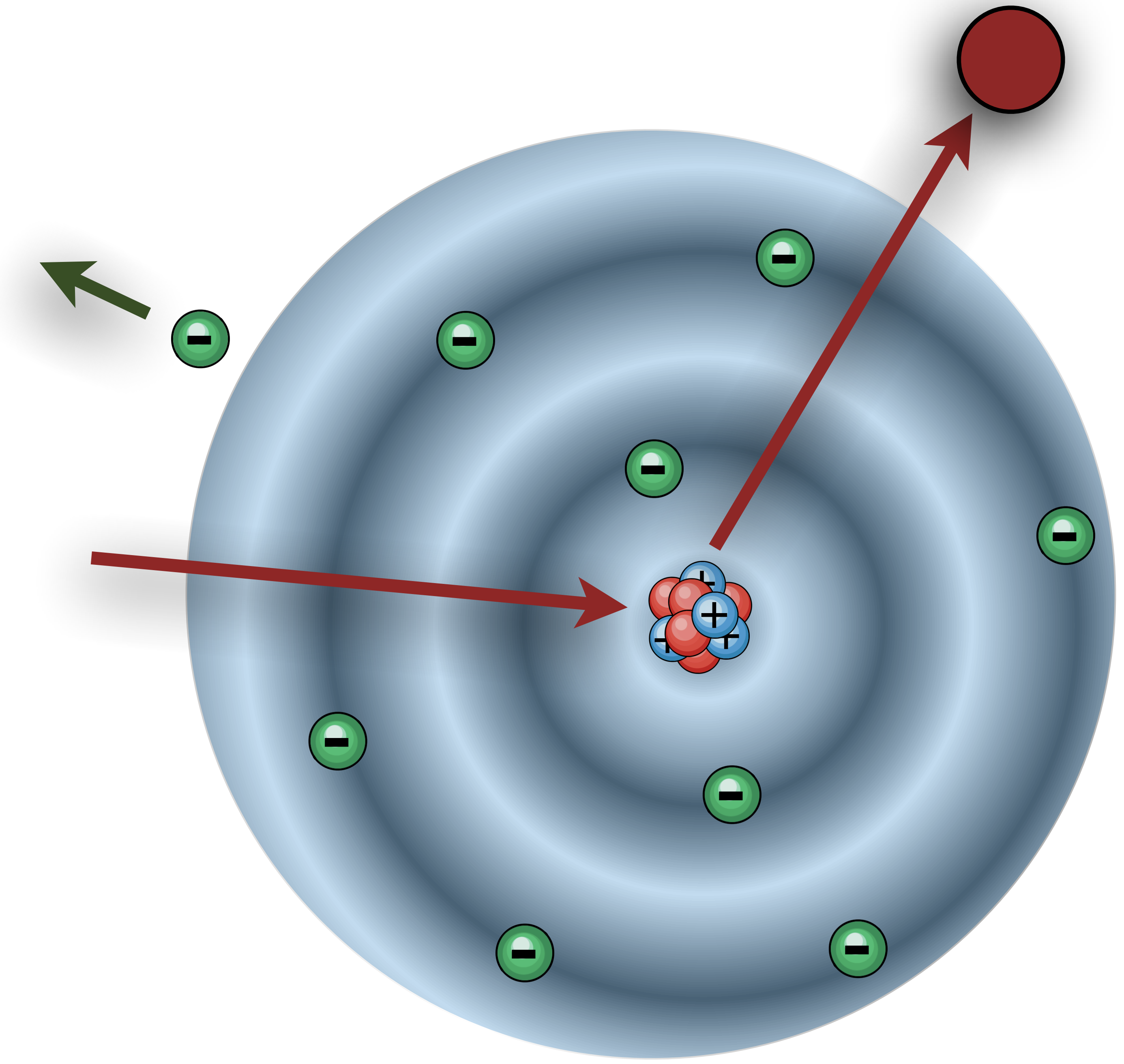
Given known direction to the Sun, directional information allows one to reconstruct the neutrino energy spectrum event-by-event (in principle)

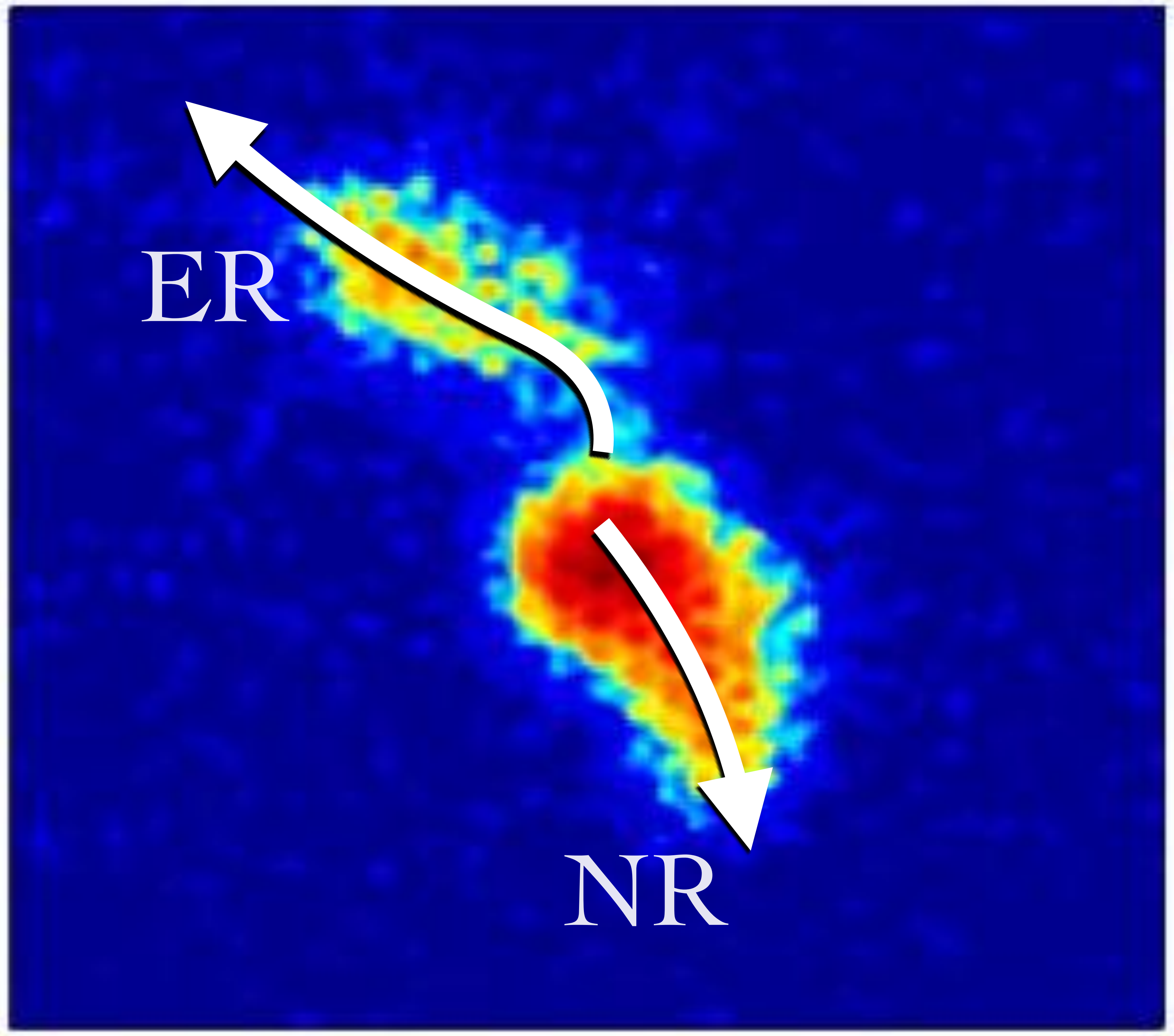




General physics: Measurement of the Migdal effect

→ 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!

Summary

- **Directional TPC network** "Cygnus" is an exciting possibility that appears increasingly plausible → actively seeking new collaborations

- 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 **neutrino physics** deserving of further exploration now that the community is converging on a strategy

2102.04596

Directional Recoil Detection

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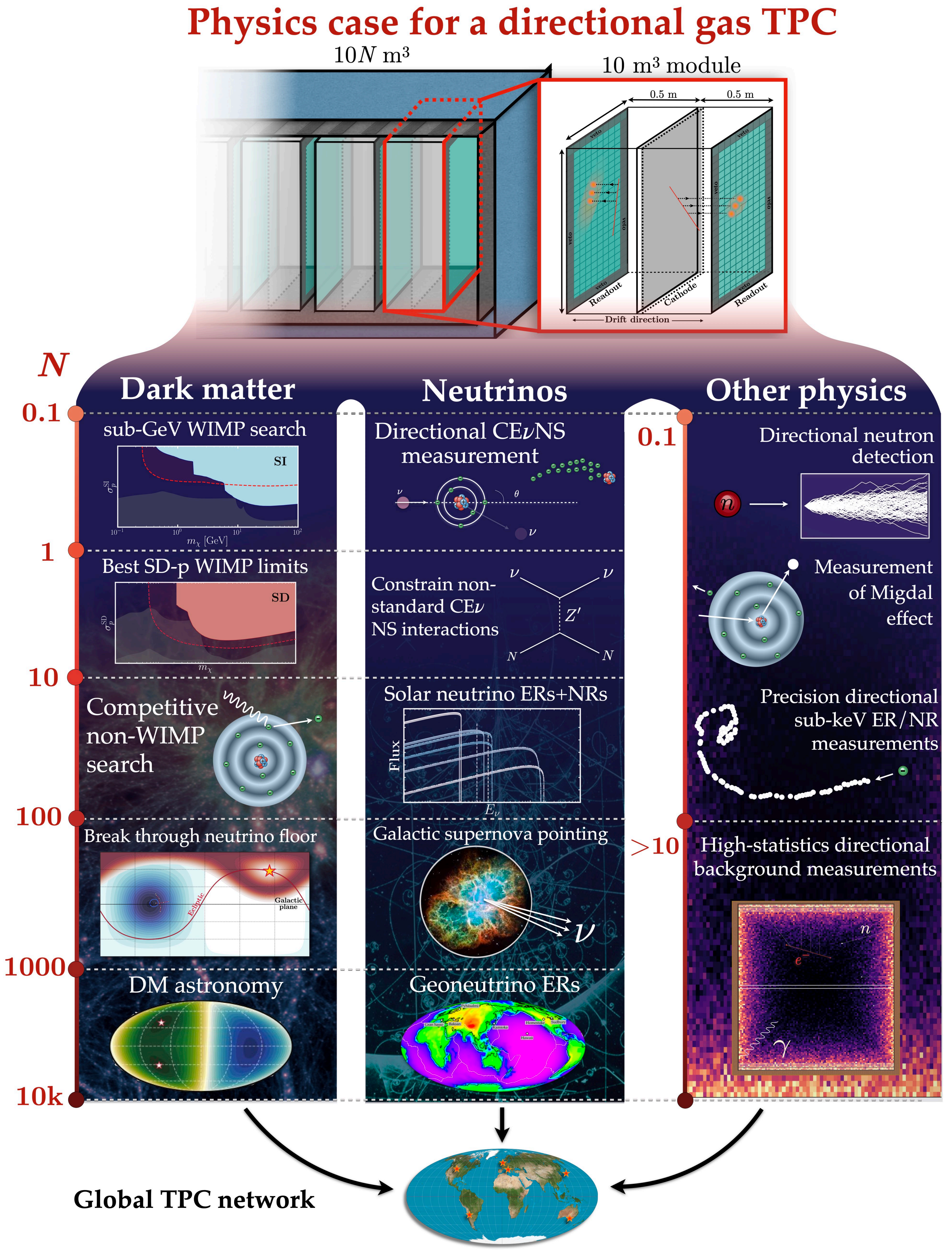
Keywords

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.



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.