Cygnus and directional DM detection

[2102.04596], [2008.12587]

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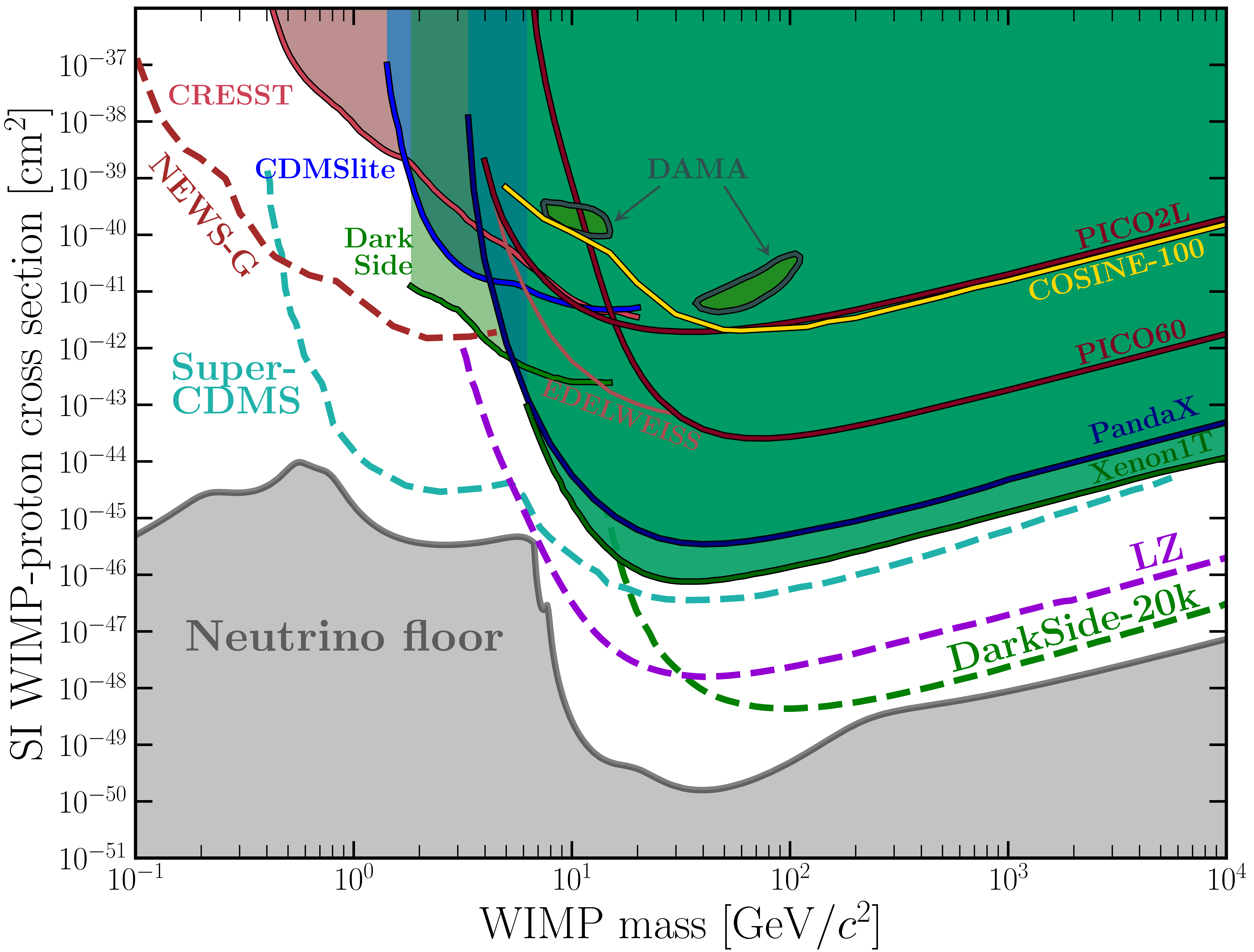
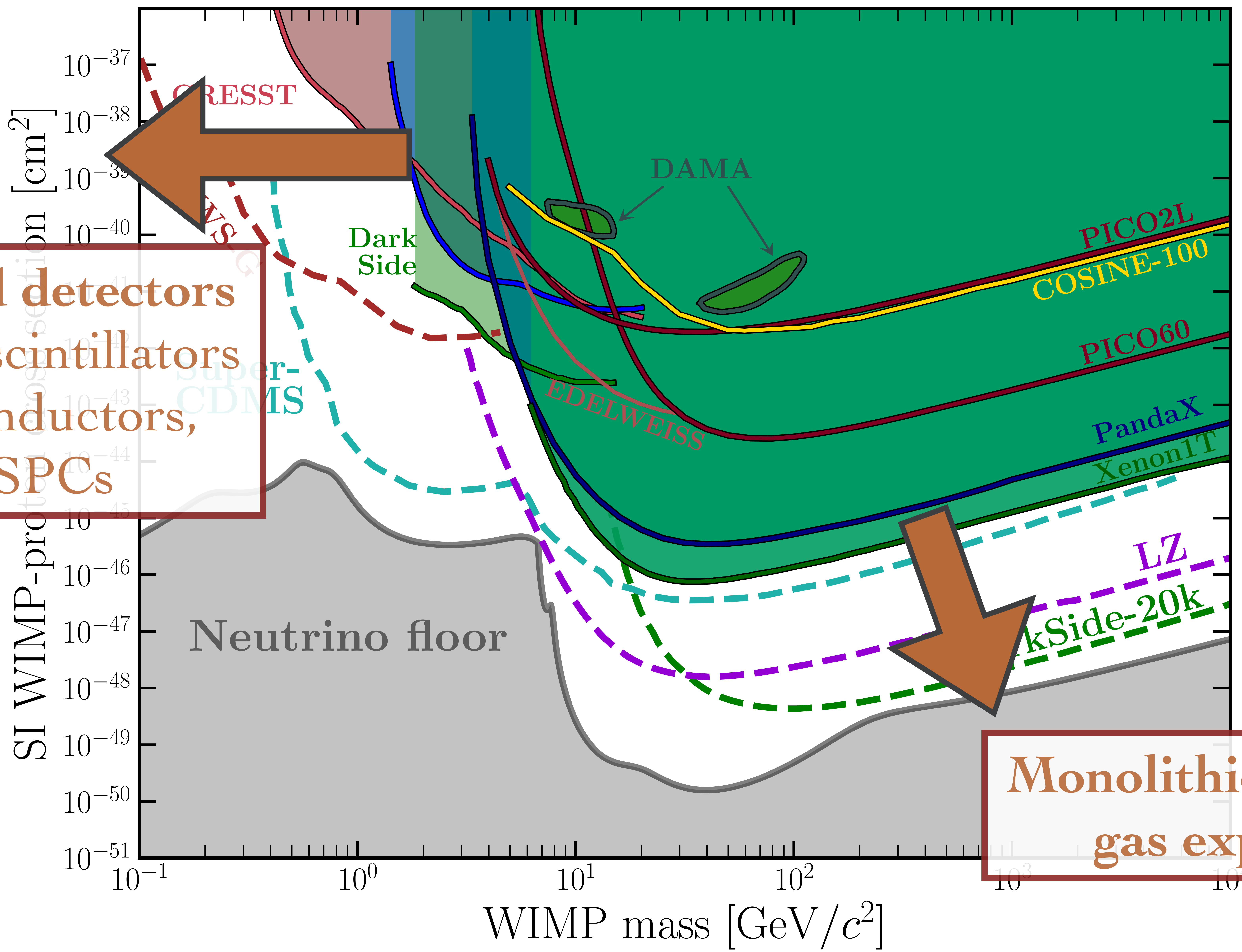
Current status of direct detection: SI WIMP-nucleon cross section



Current status of direct detection: SI WIMP-nucleon cross section



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

Monolithic liquid noble gas experiments

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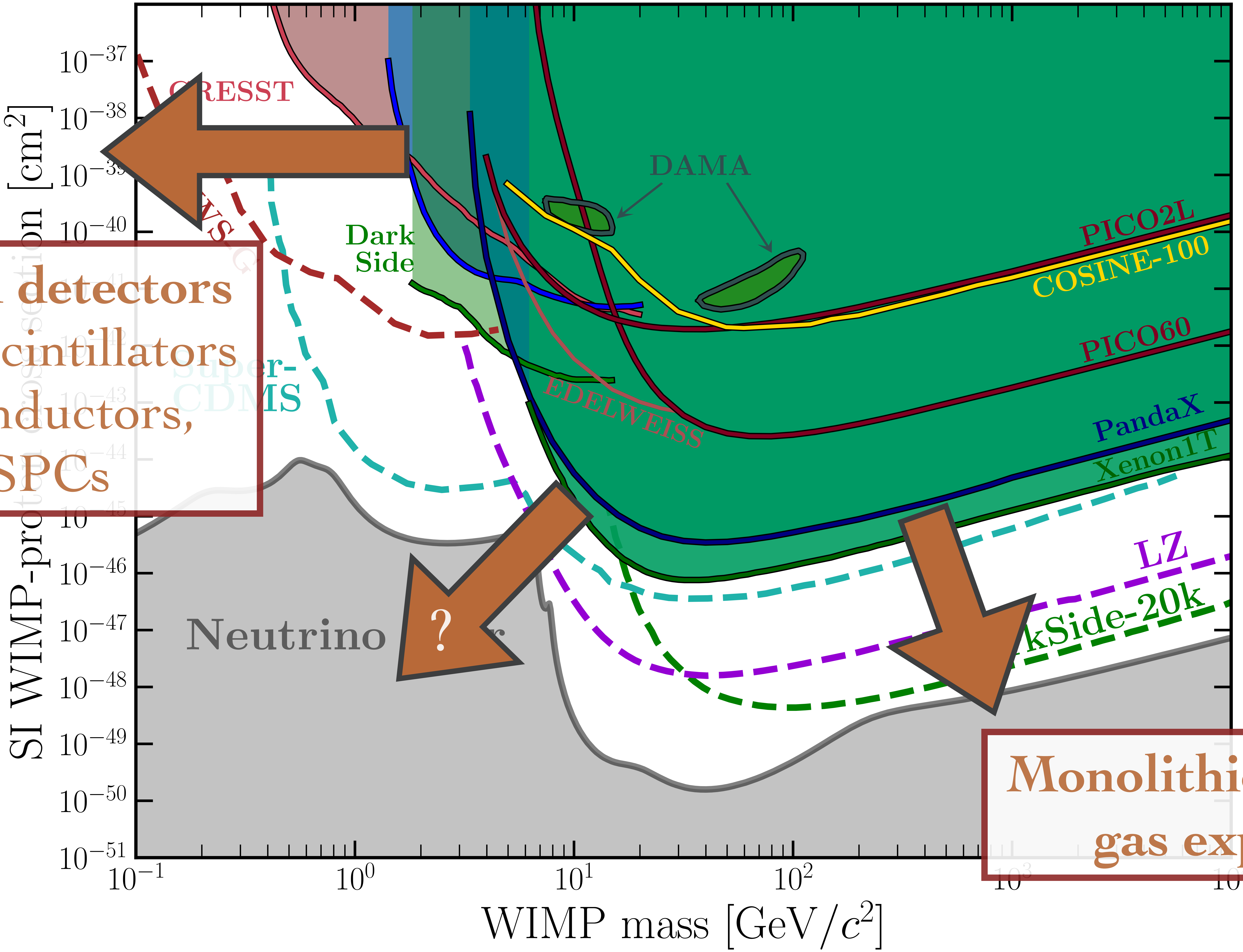

Low threshold detectors
e.g. cryogenic scintillators
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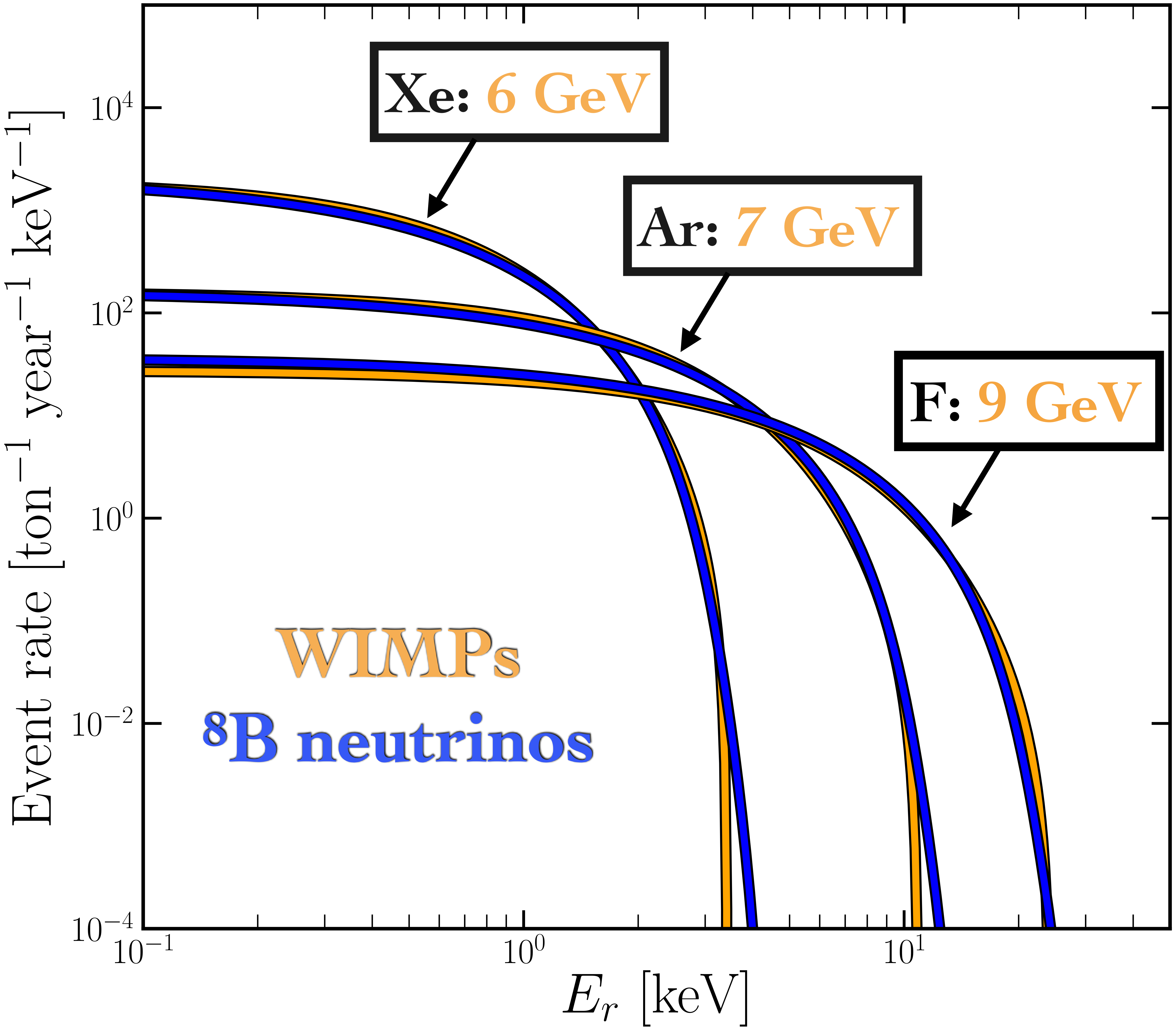
Monolithic liquid noble gas experiments

Why is there a neutrino floor?

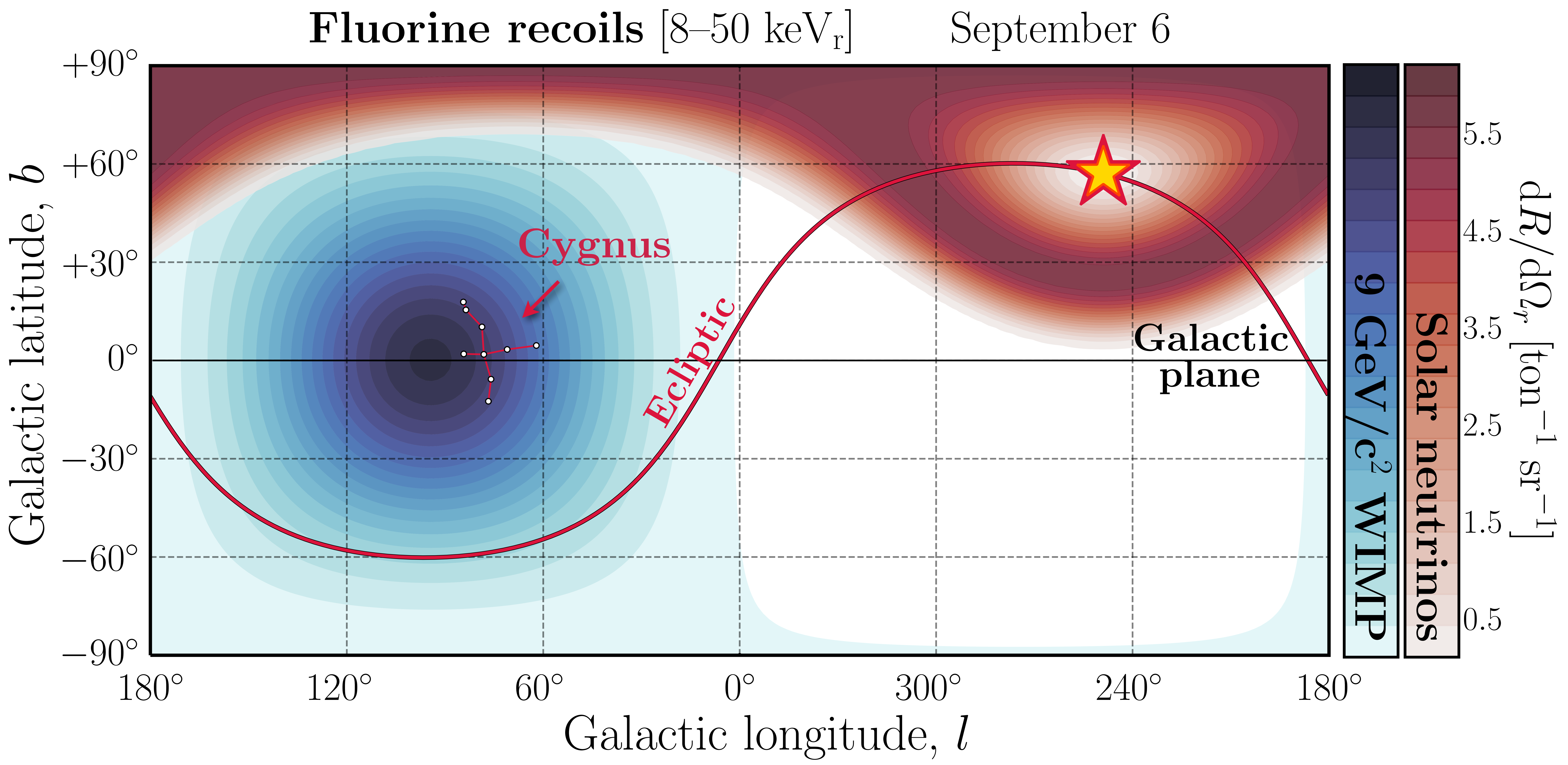
→ spectral match between DM and solar neutrinos



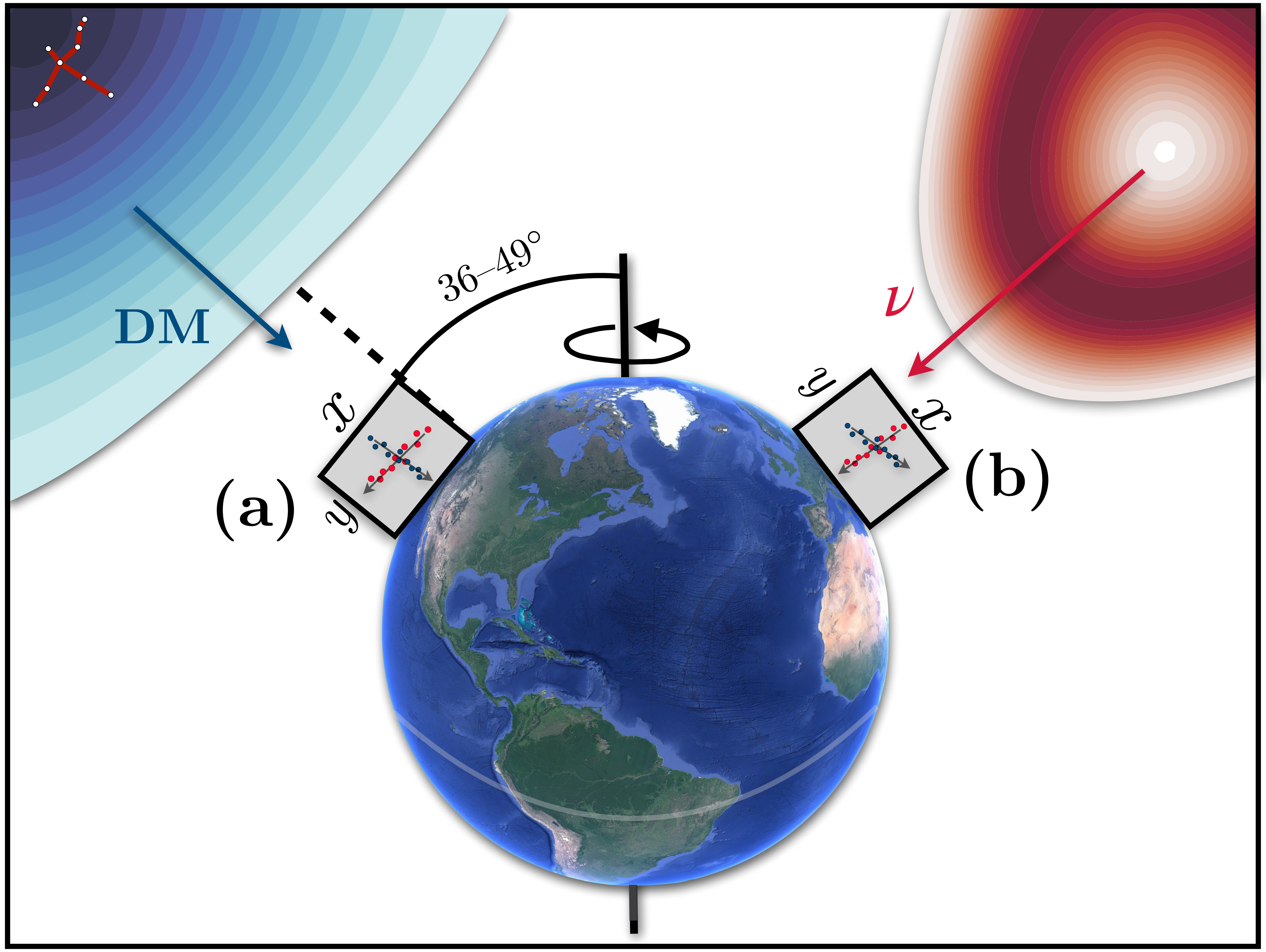

CYGNUS
WIMP
WIMP
WIMP
WIMP
WIMP
WIMP

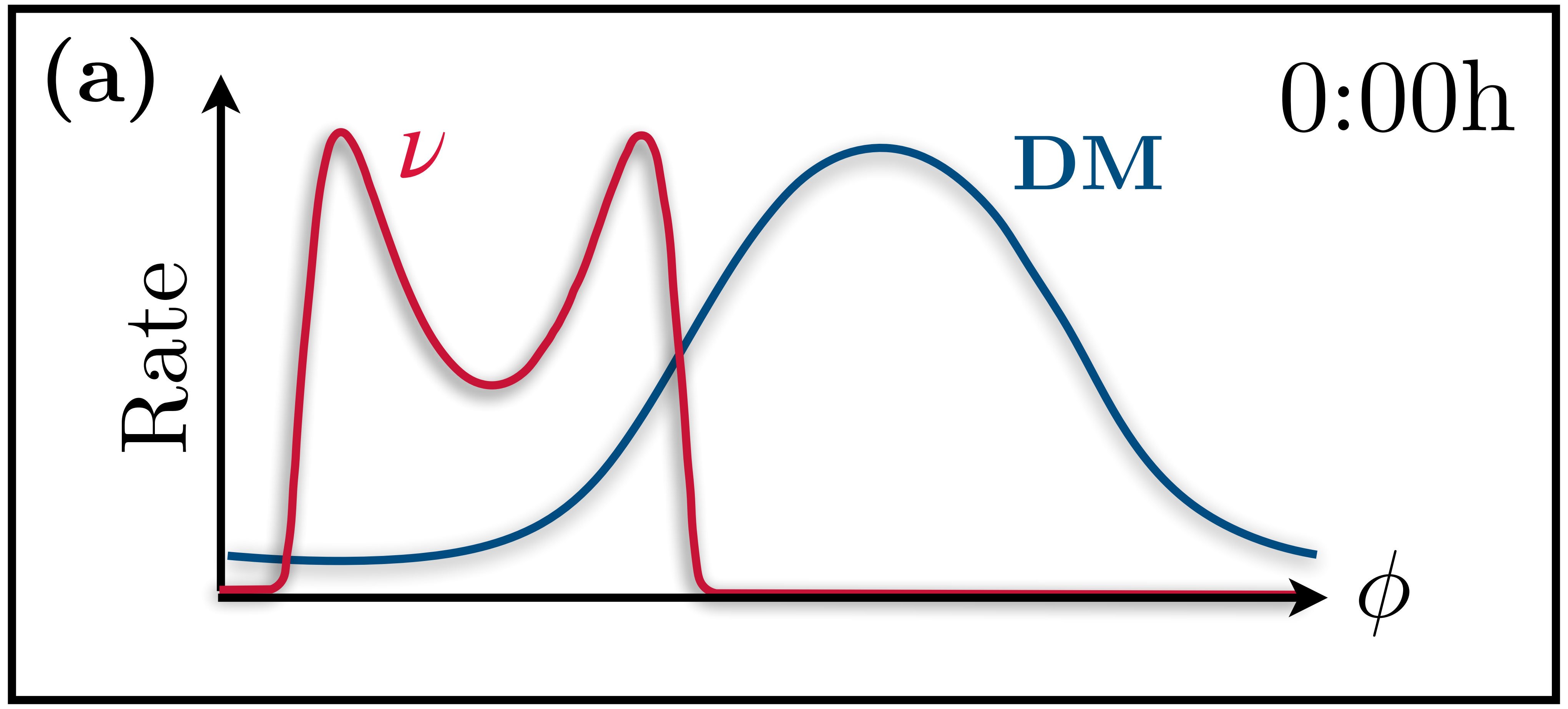

Cygnus
Jun
Dec

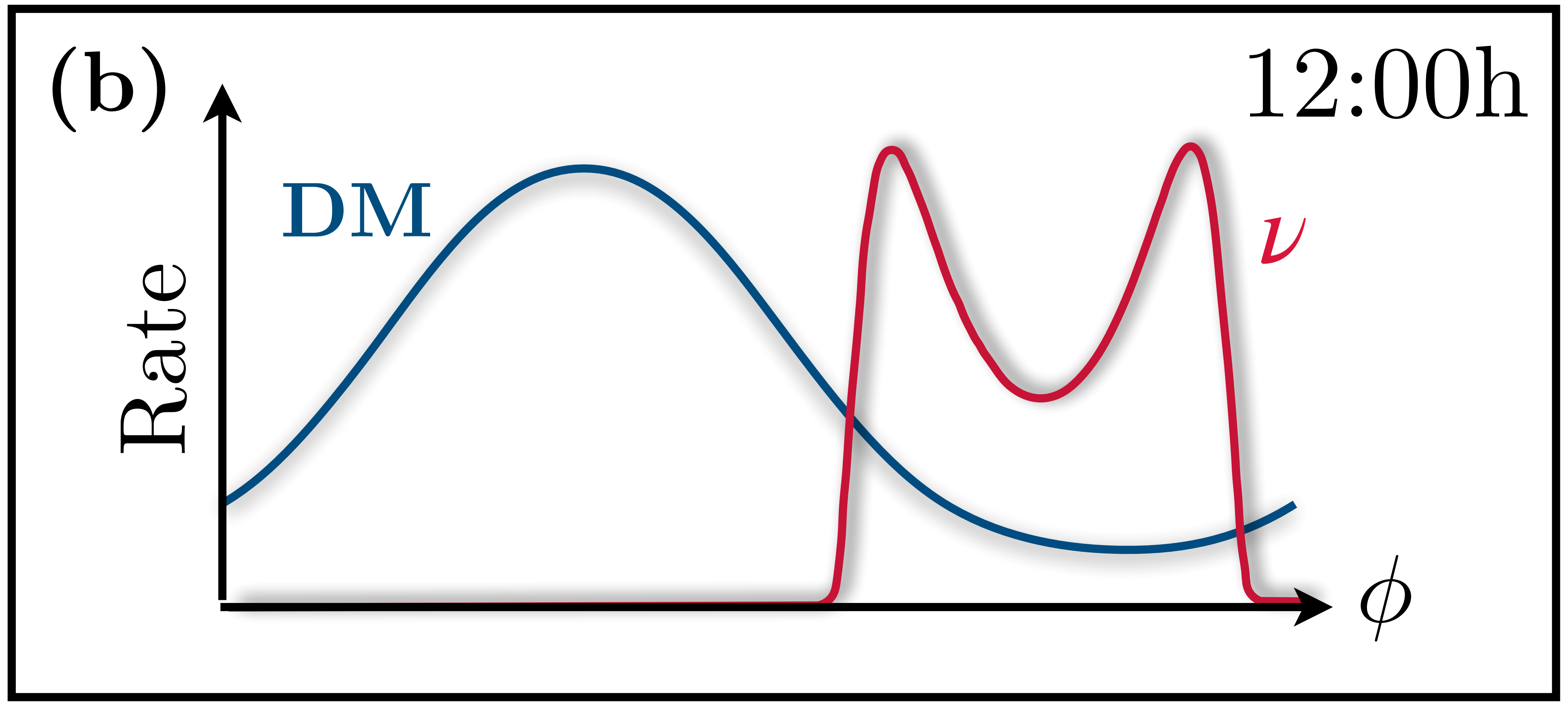
Nothing mimics dark matter, including solar neutrinos



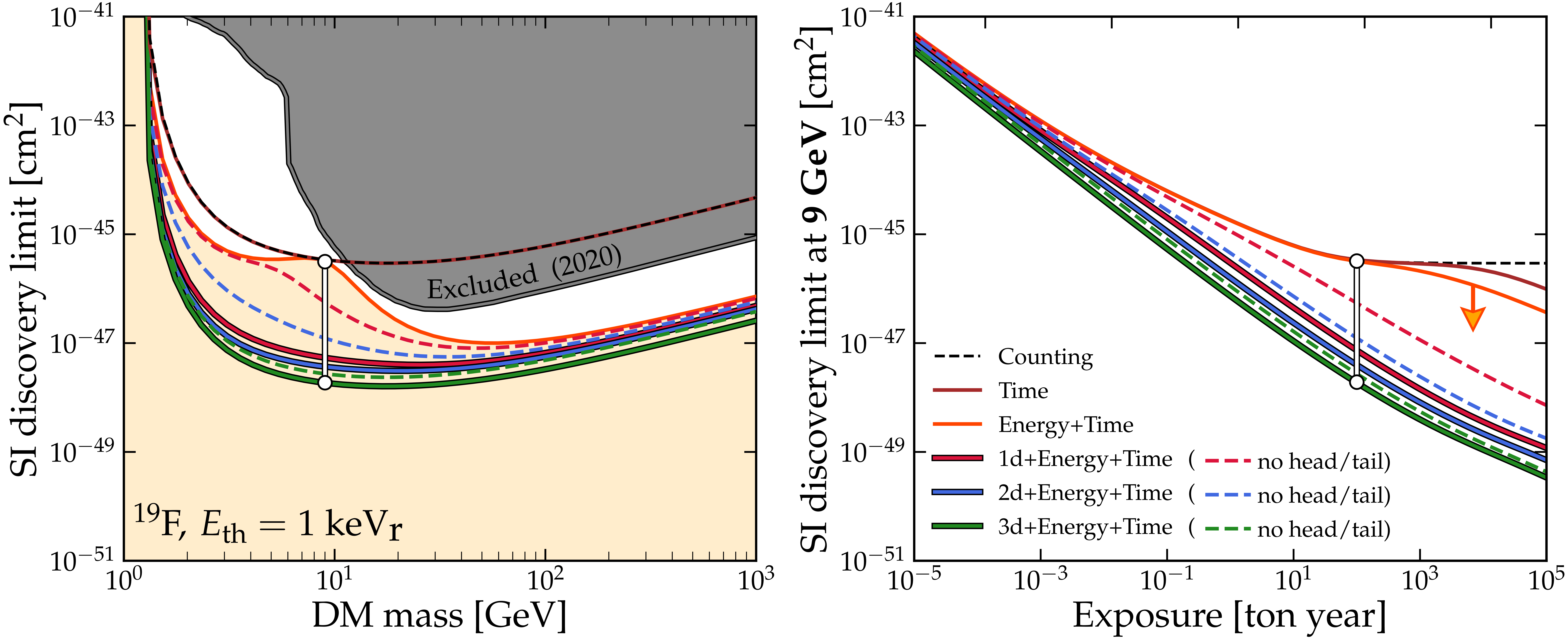
From the detector's perspective, the galactic dipole signature translates to a sidereal daily modulation in angle



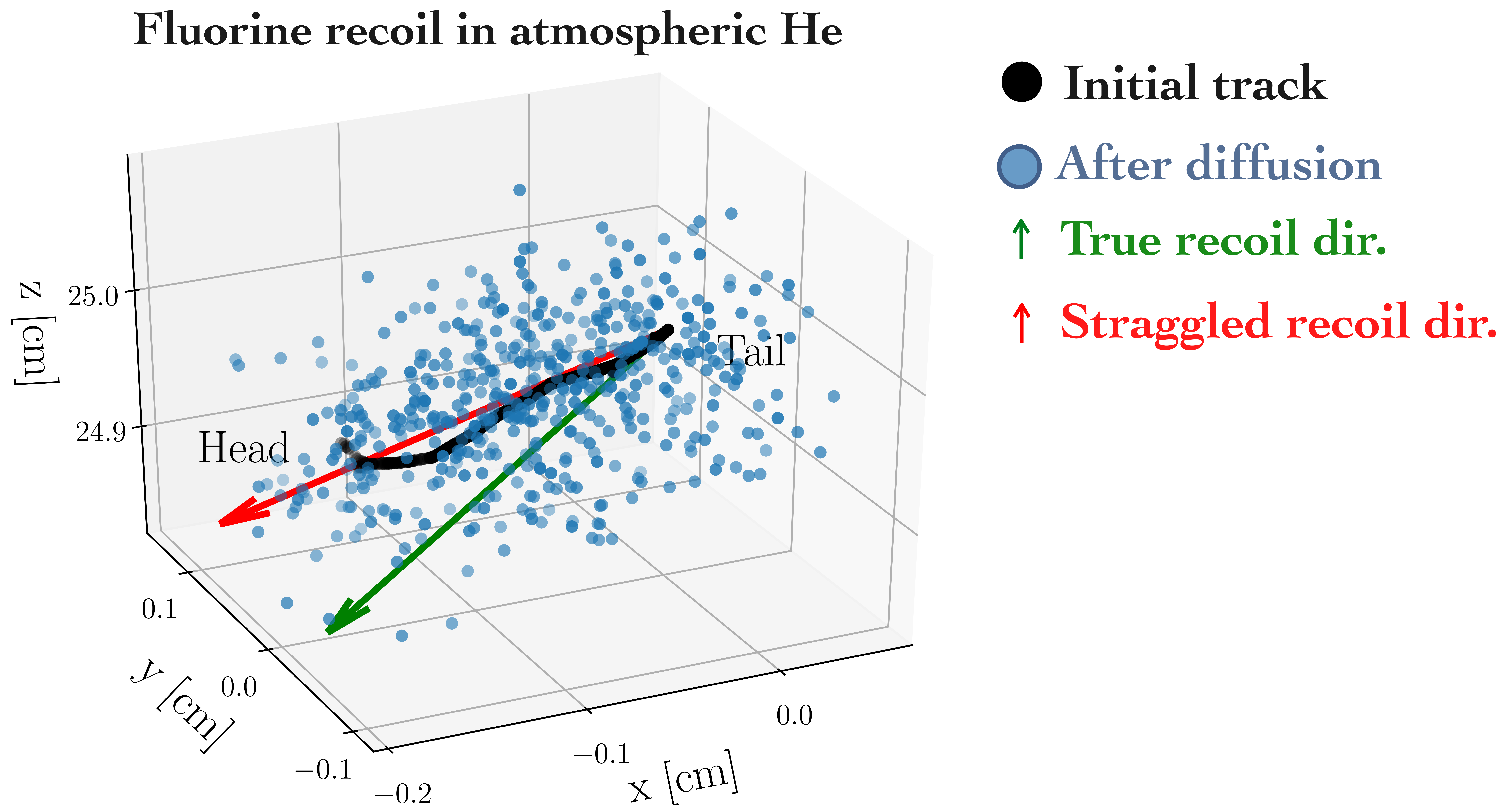




Subtracting the neutrino background



Orange region is inaccessible without directional information


Fluorine recoil in atmospheric He
● Initial track
● After diffusion
↑ True recoil dir.
↑ Straggled recoil dir.
Head
Tail
z [cm]
25.0
24.9
y [cm]
0.1
0.0
−0.1
x [cm]
−0.2
−0.1
0.0

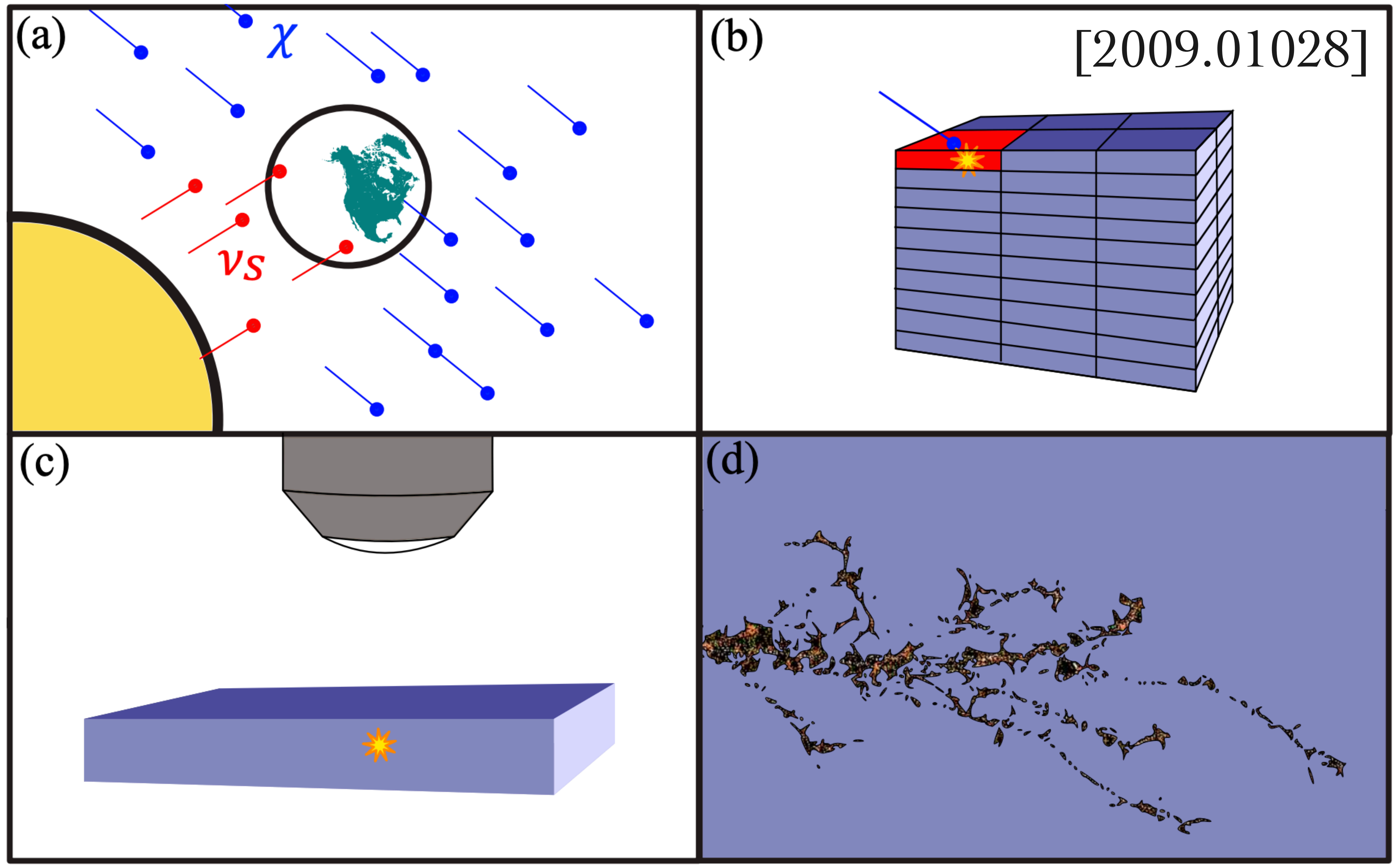
What would you use to detect keV-scale nuclear recoils?

	Pros	**Cons**
Solid	• High target mass • Well-established technologies, e.g. scintillators	• Need nm—μm resolution to image tracks • No way to transport track topology to a readout • Highly scrambled by straggling
Liquid	• High target mass • Readily scalable to large volumes	• Tracks much shorter than diffusion scale
Gas	• Tracks are at resolvable mm-scale • Nuclear/Electronic tracks are easily distinguishable • Recoil track imaging in gas TPC has been demonstrated since 1990s	• Low target mass

Many alternative approaches to directional detection not taken by Cygnus, but being investigated by others, e.g.

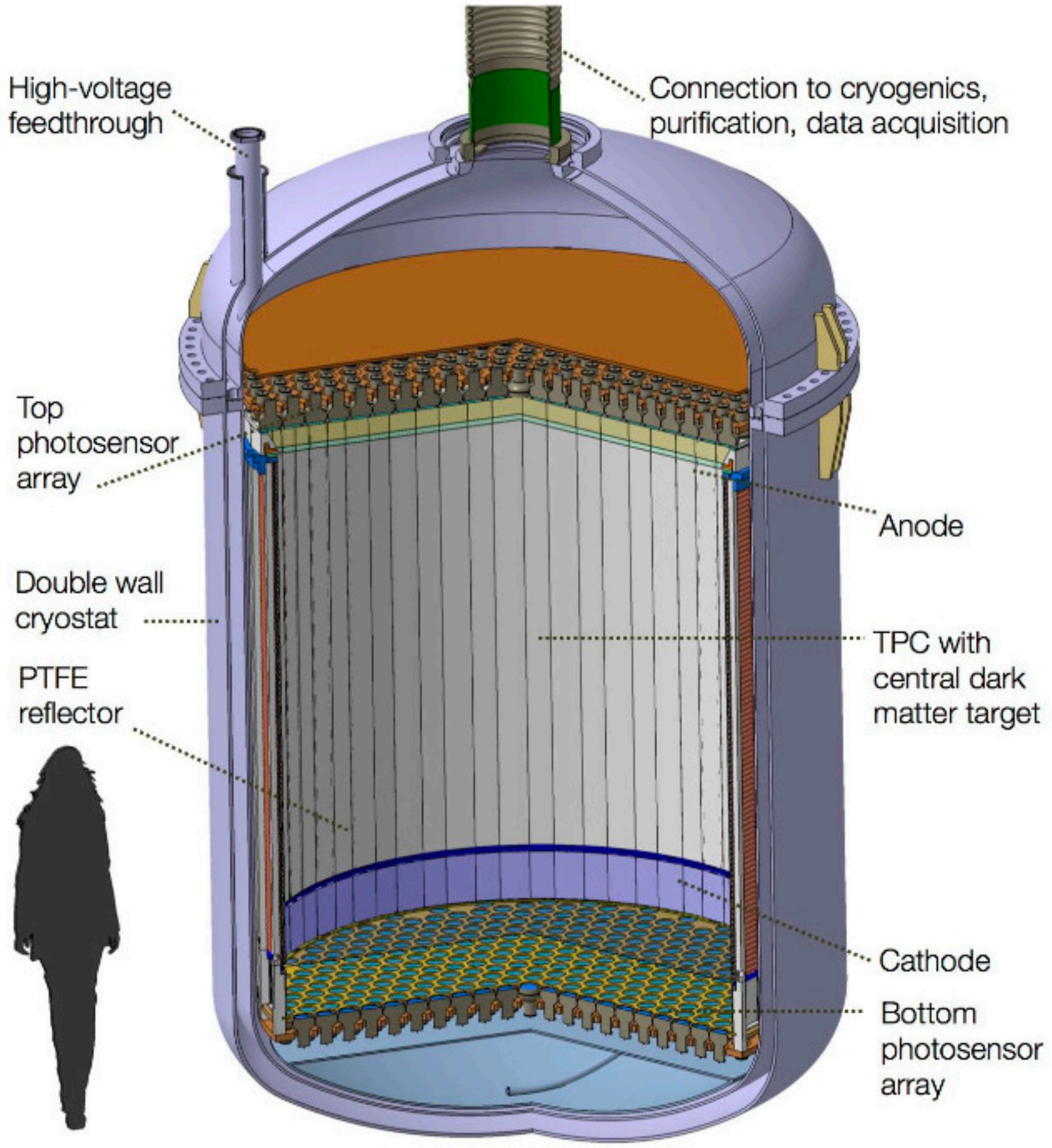
Solid

Crystal defect spectroscopy



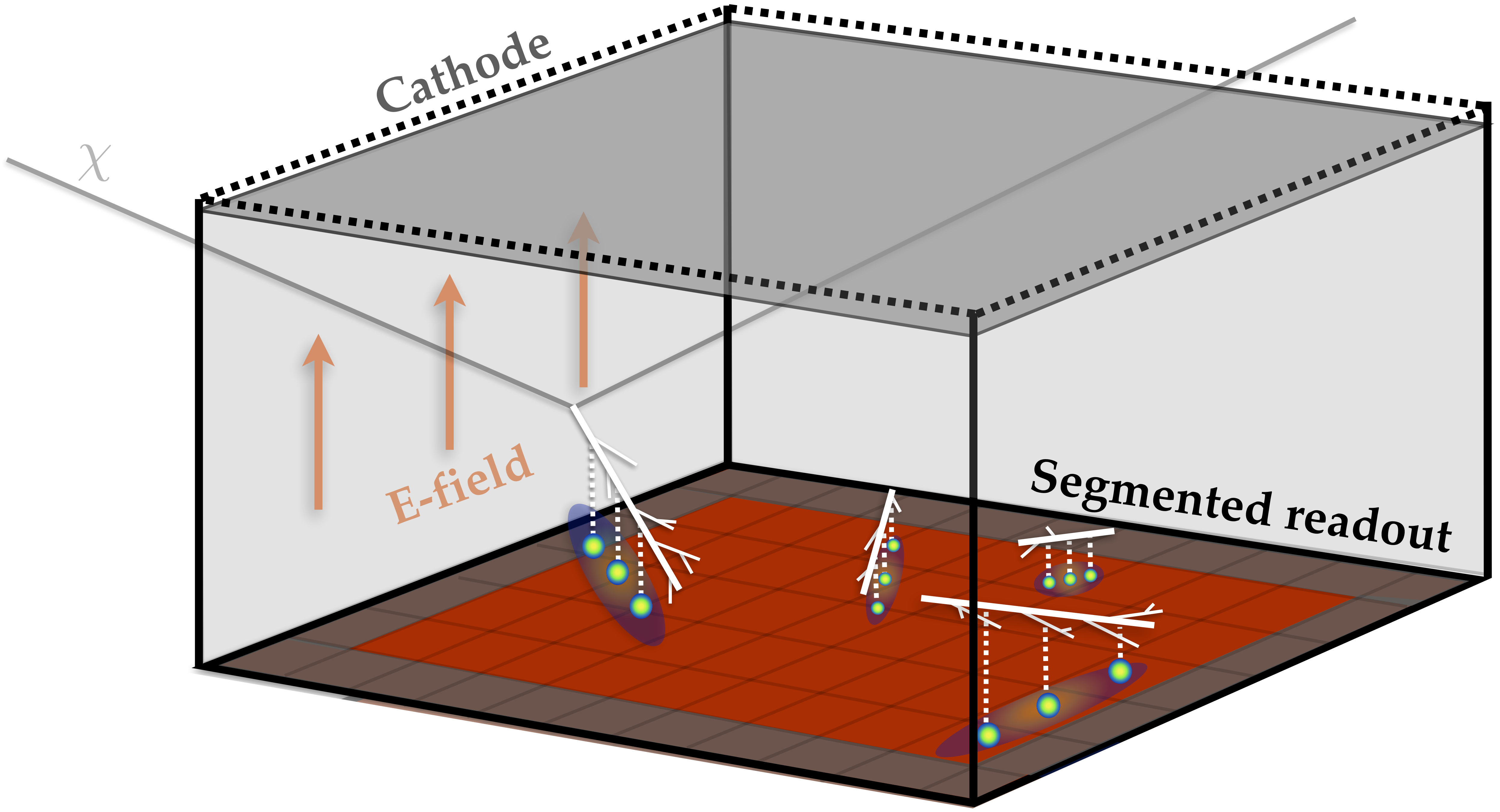
Liquid (Ar/Xe)

Columnar recombination

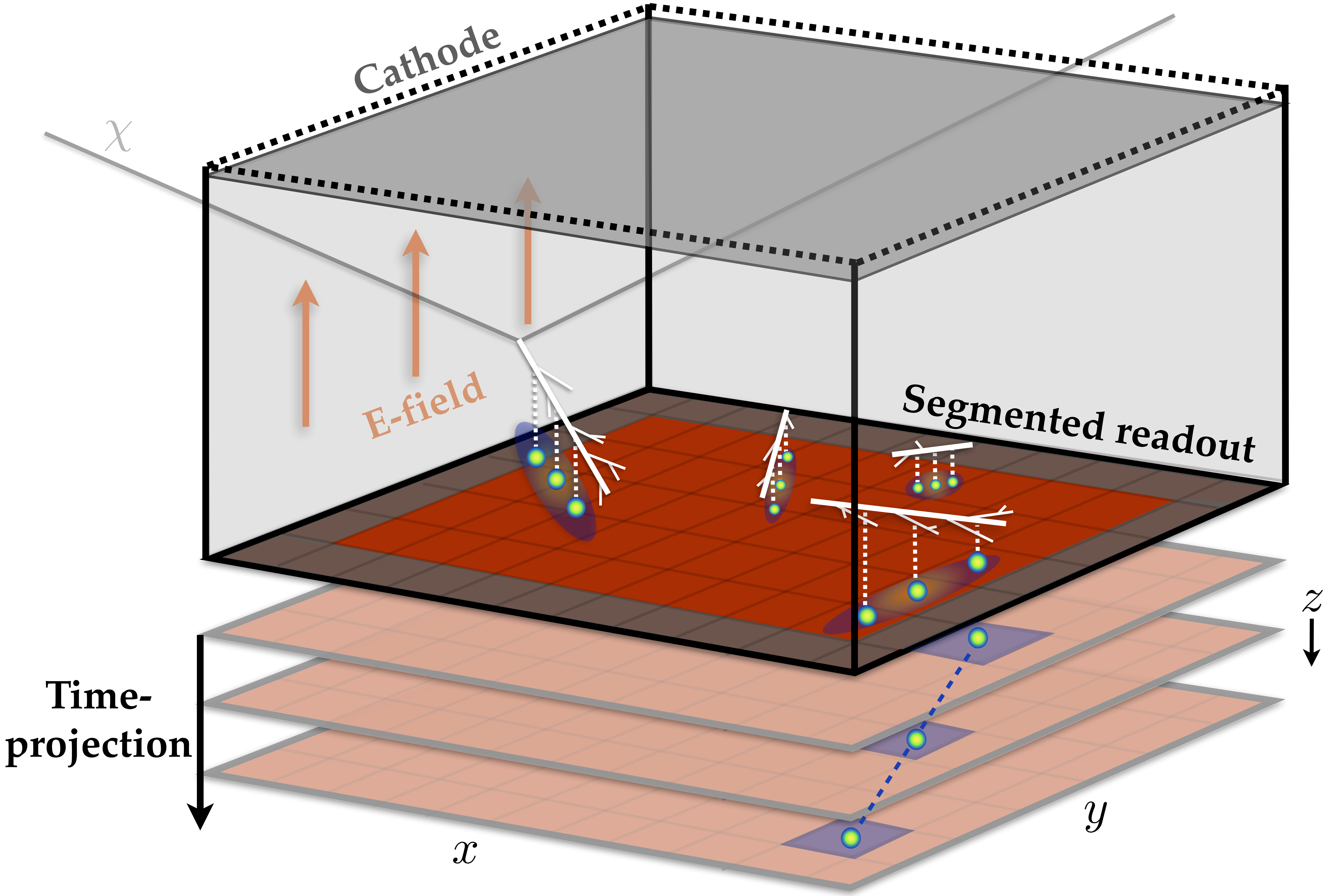


+ other techniques in nano-engineered detectors, e.g. graphene, nanotubes, DNA/biomaterial

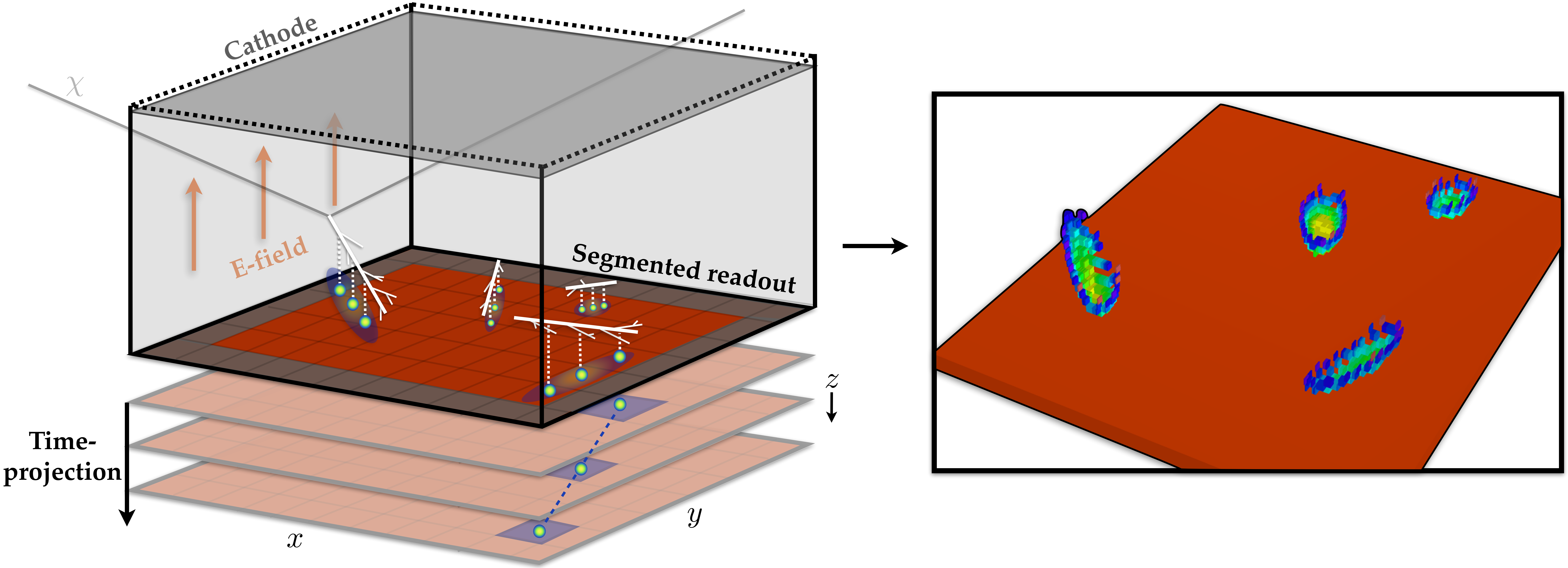
Focus of Cygnus: gas time projection chamber



Focus of Cygnus: gas time projection chamber



Focus of Cygnus: gas time projection chamber

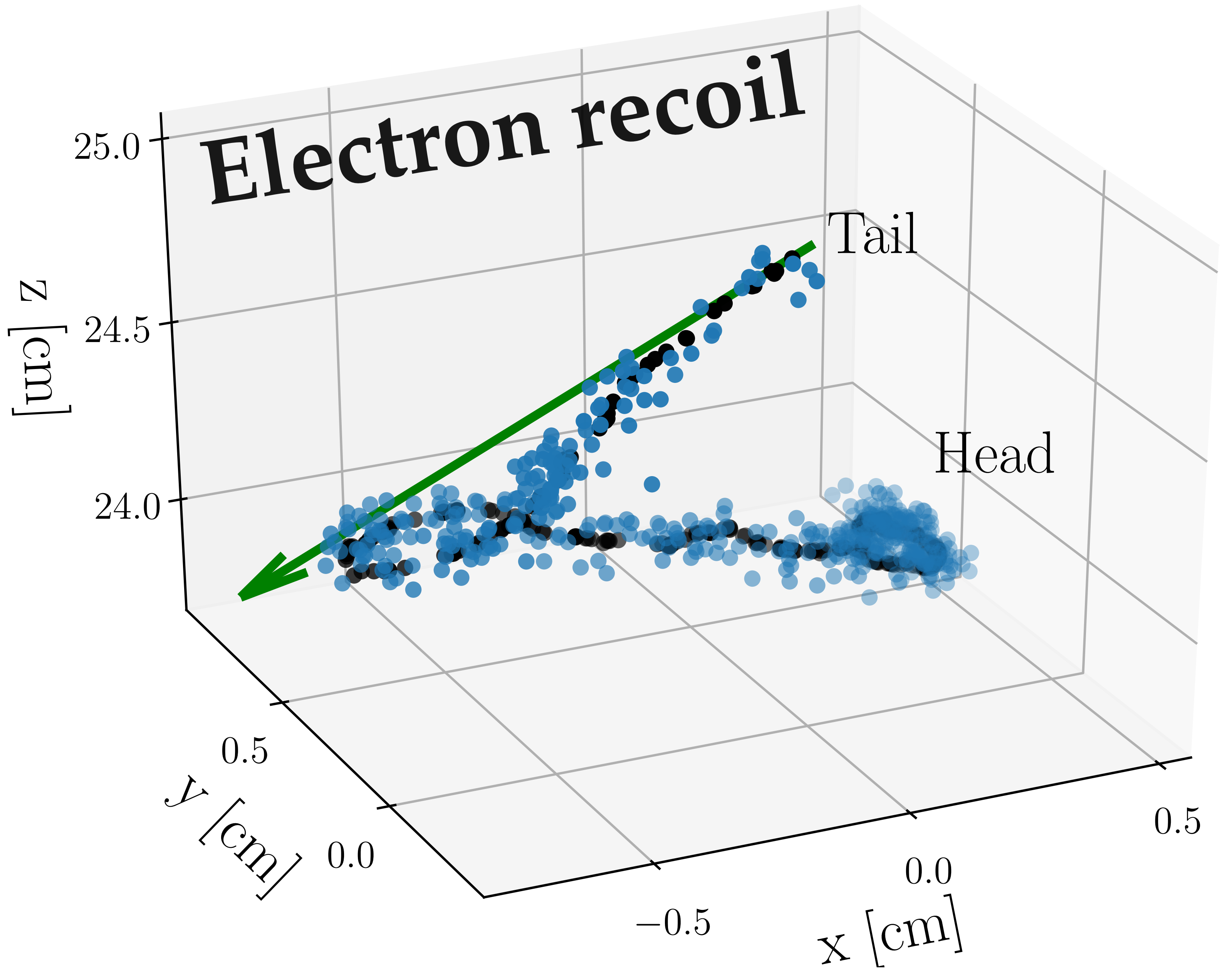


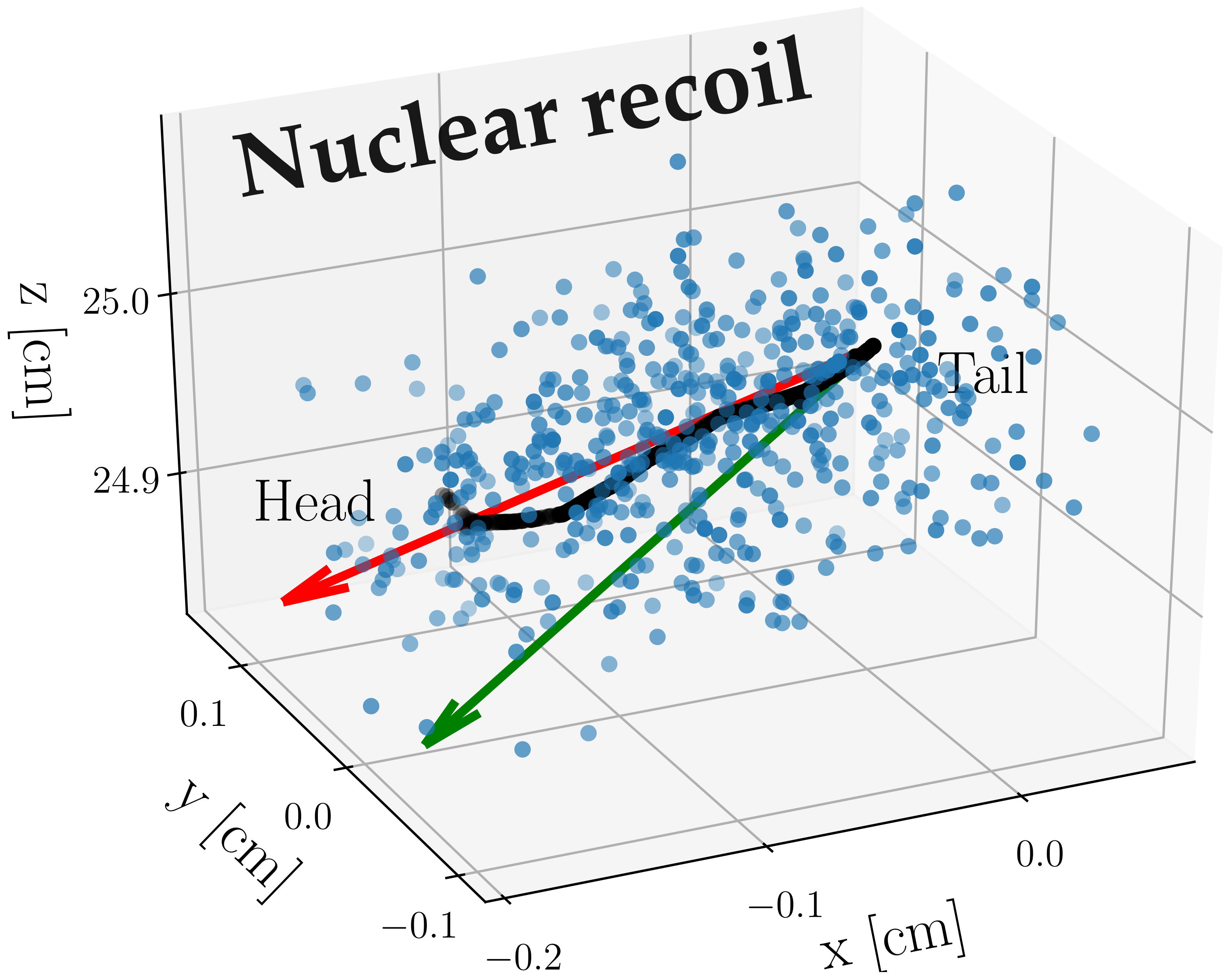
Angular performance

Everything gets worse at lower energies:

- Decreasing quenching factor, means recoils are harder to detect
- Tracks get shorter → harder to measure directions
- Harder to distinguish ER/NRs since tracks are short

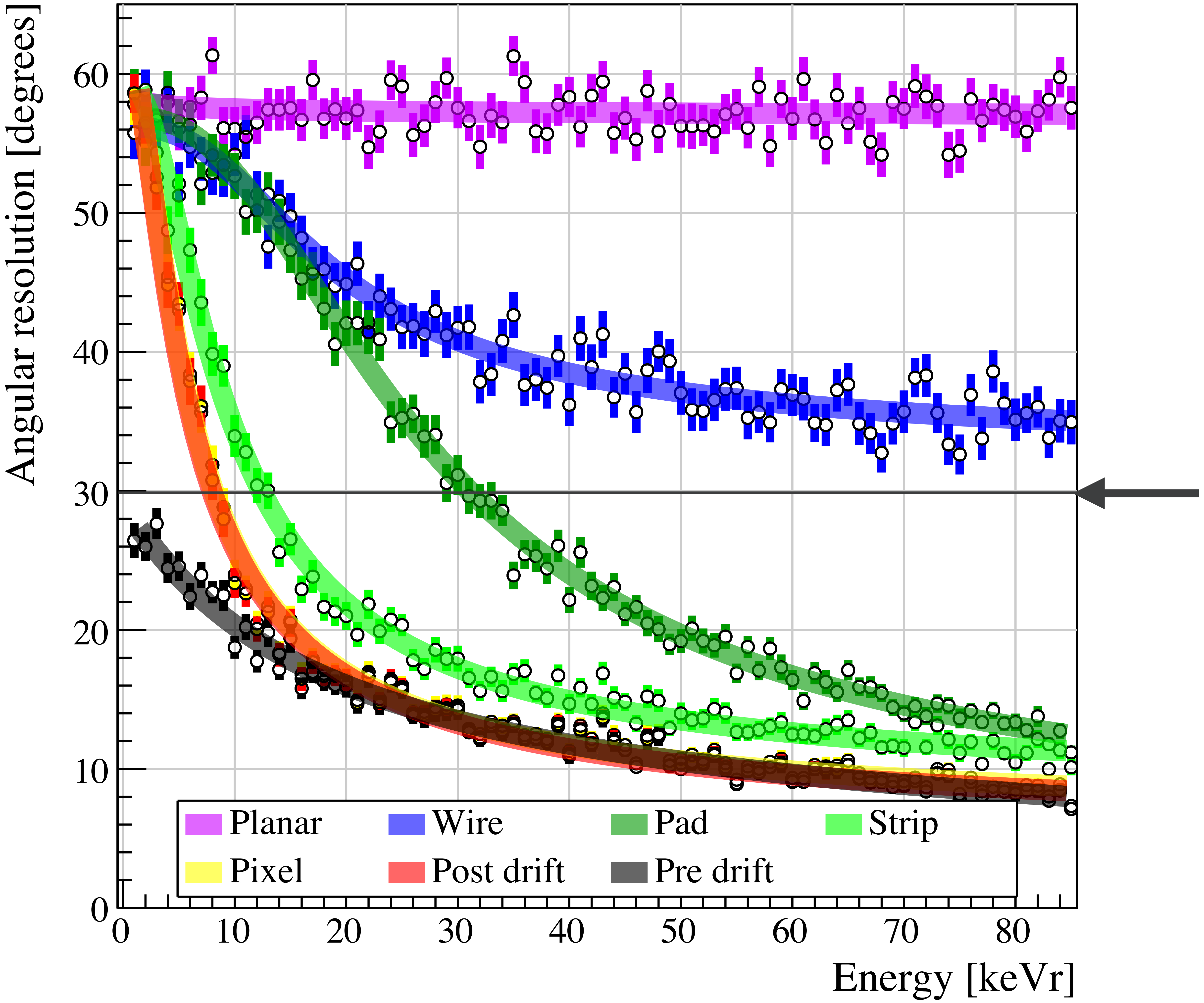
→ Energy dependence of directional performance is very important, and needs to be the focus now





Example: angular resolution

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

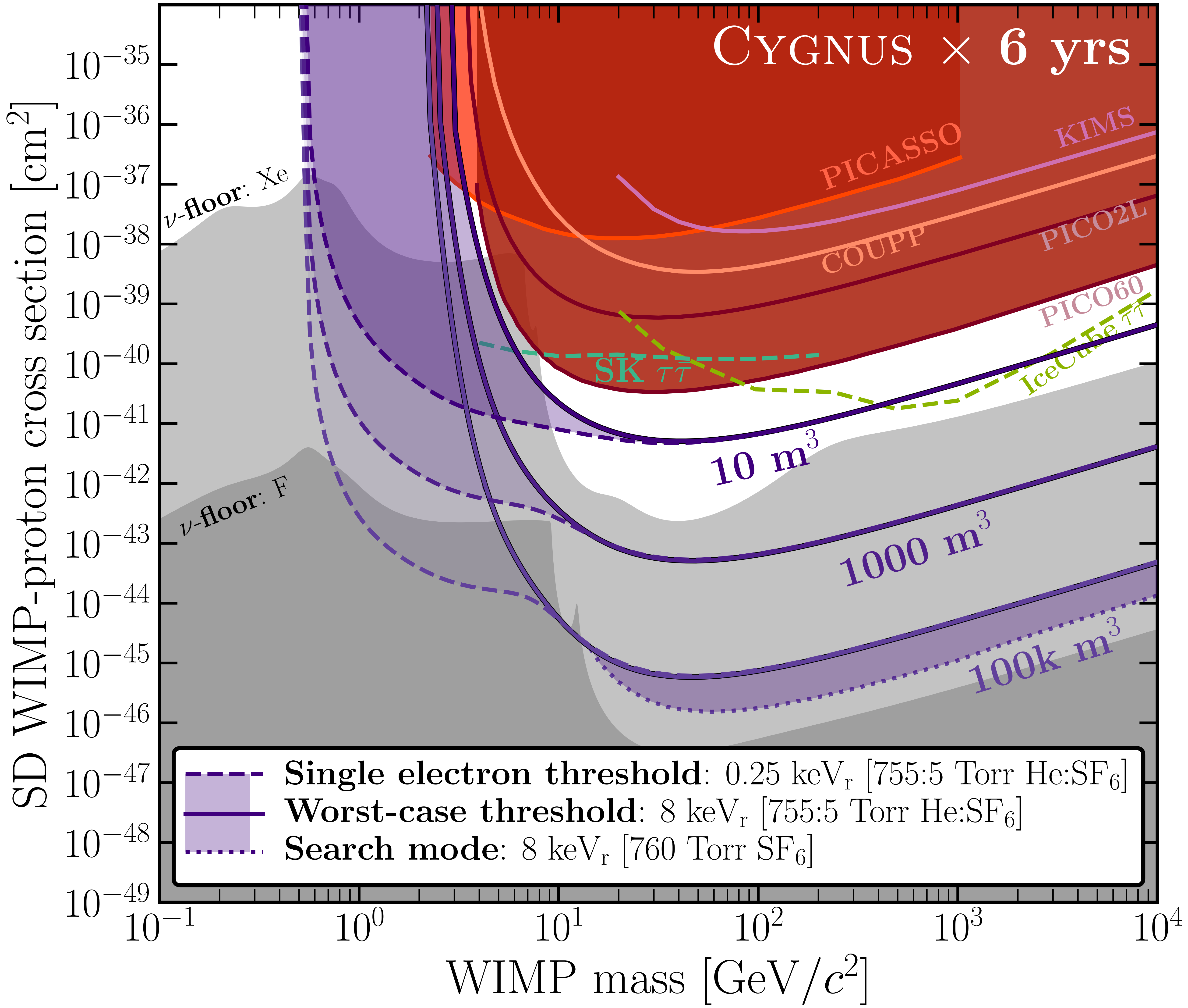


<u>Simulated charge readout comparison</u>

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

Sensitivity

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



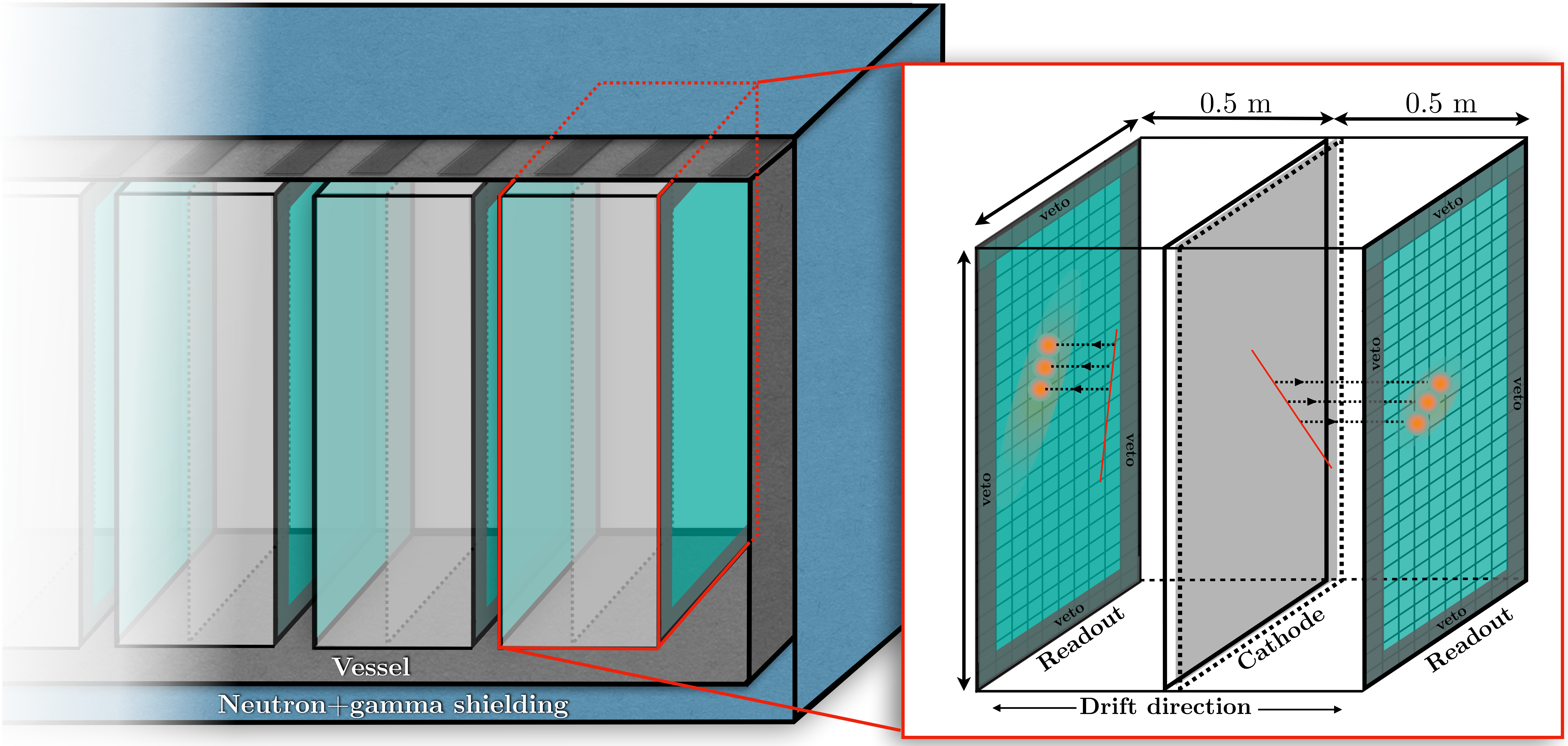
To get below neutrino floor we need:

- Good directional sensitivity
- Low threshold O(1) keVr
- ~1000 m^3 volume

Important note: these limits are true discovery limits, i.e. a signal can be confirmed as DM

→ comparison of Cygnus limits with other experiments undersells its potential

Modularity is both necessary, and advantageous



CYGNUS-Nm^3

CYGNUS-10 m^3 module

CYGNUS

CYGNUS-10
Boulby, UK

CYGNUS-KM
Kamioka, Japan

CYGNUS-HD10
Lead, South Dakota

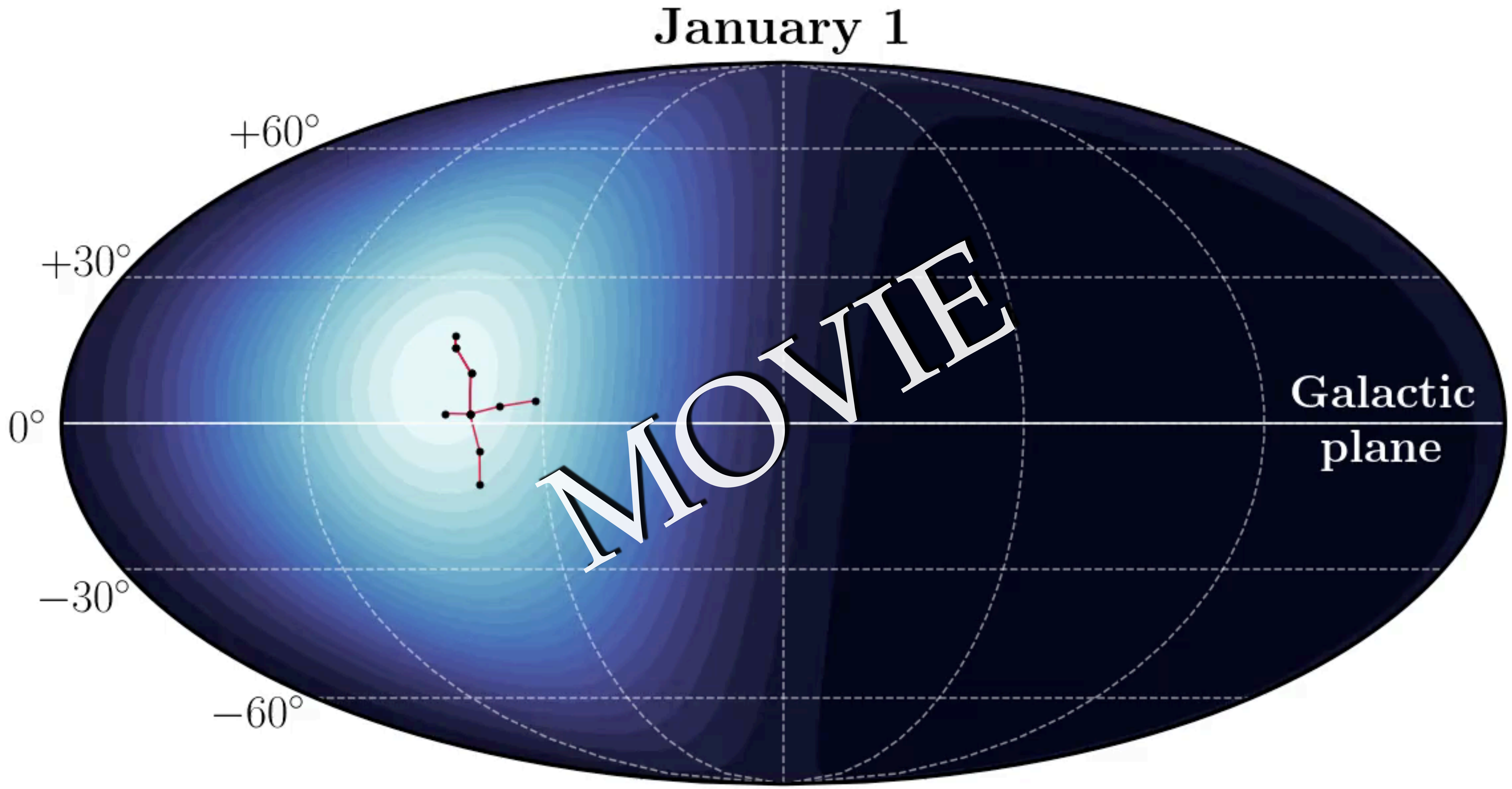
CYGNO
Gran Sasso, Italy

CYGNUS-OZ
Stawell, Aus.

CYGNUS-Andes
Chile/Argentina

What should the signal look like?
→ a Gaussian peaking towards Cygnus

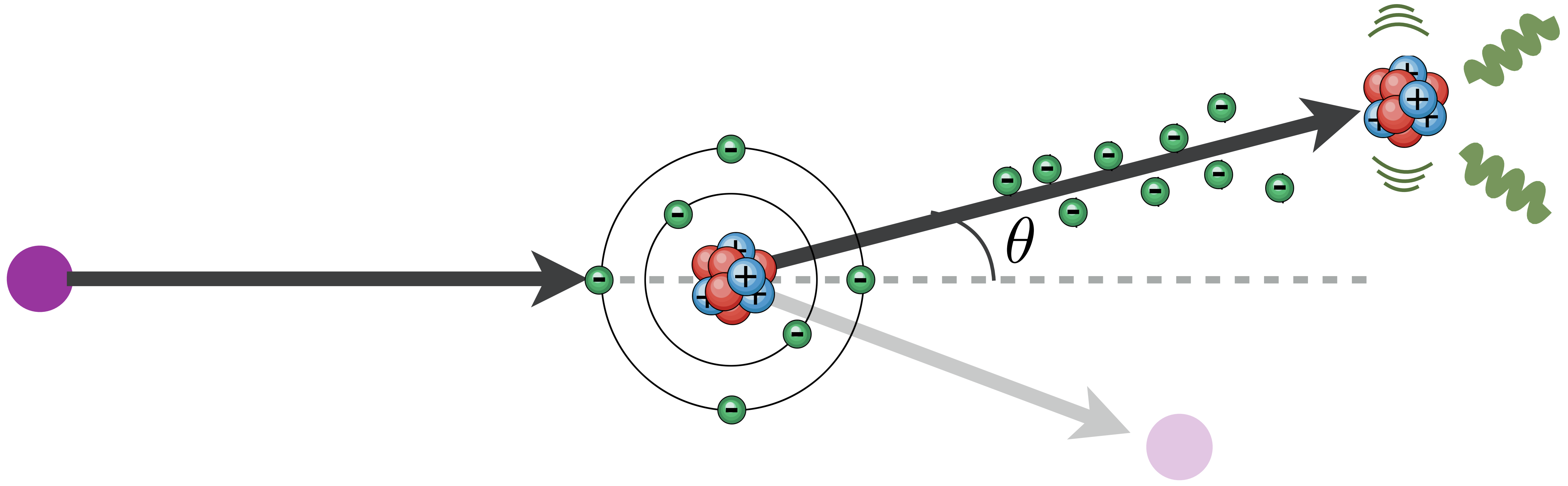
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{\left(2\pi\sigma_v^2\right)^{1/2}} \exp\left(-\frac{\left(v_{\mathrm{min}} + v_{\mathrm{lab}}(t)\cos\theta\right)^2}{2\sigma_v^2}\right)$$



Standard prediction based on a few assumptions

- The DM scatters elastically

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



- The DM velocity distribution is a Gaussian (SHM)

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

- DM-nucleus matrix element does not depend on velocity

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

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

Non-standard 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

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

Non-standard DM-nucleus kinematics/interactions,
- → inelastic DM
- → EFT operators with transverse velocity dependence
- → Lum
- → Mult

Non-Gau
- → The
- → Stre

DM flux
- → Sup
- → Cosmic ray-upscattered DM
- → Boosted DM

Exciting prospects:

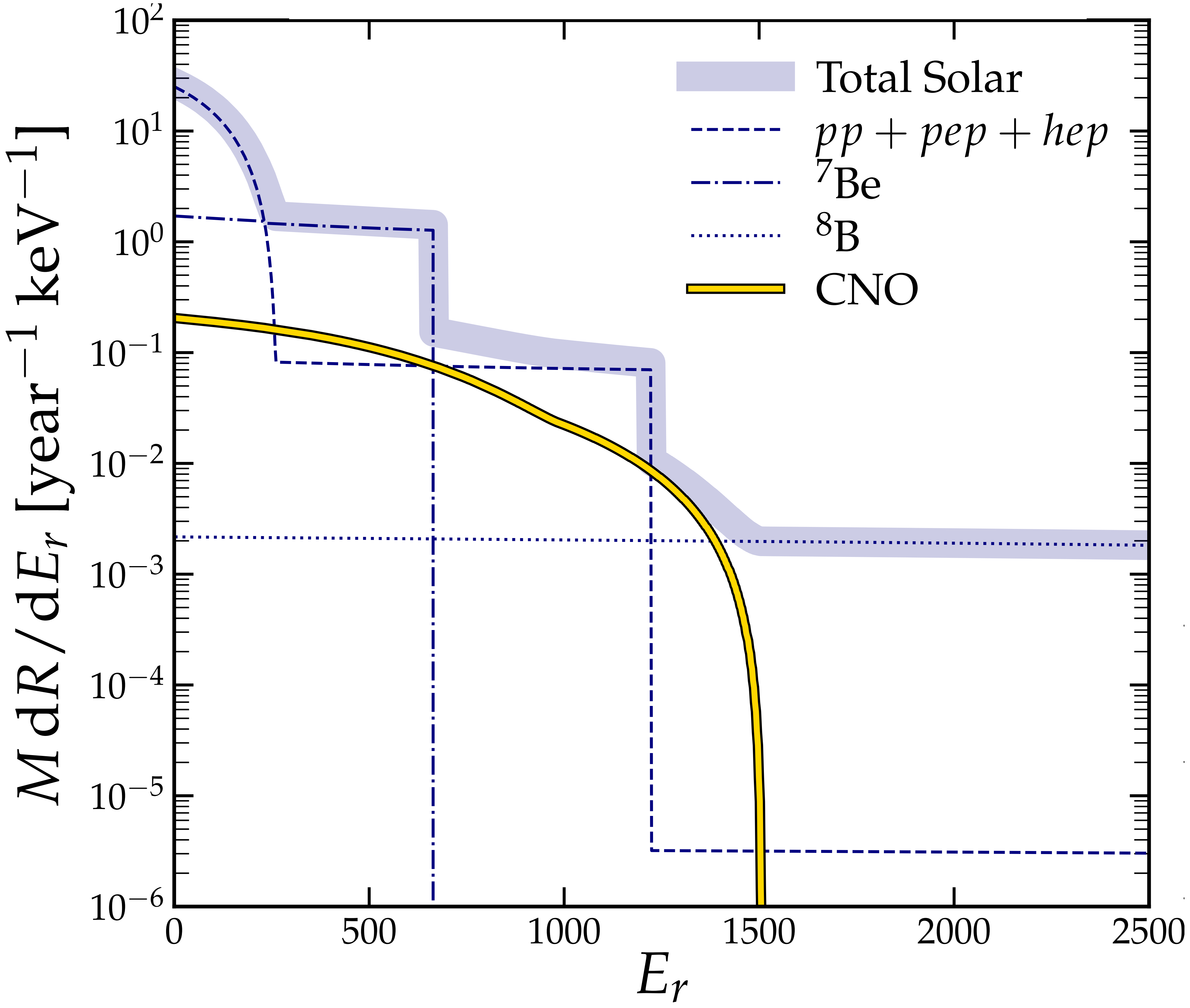
These are all challenging for non-directional experiments to probe

→ Many opportunities for theoretical studies to determine the full physics potential of a directional TPC network

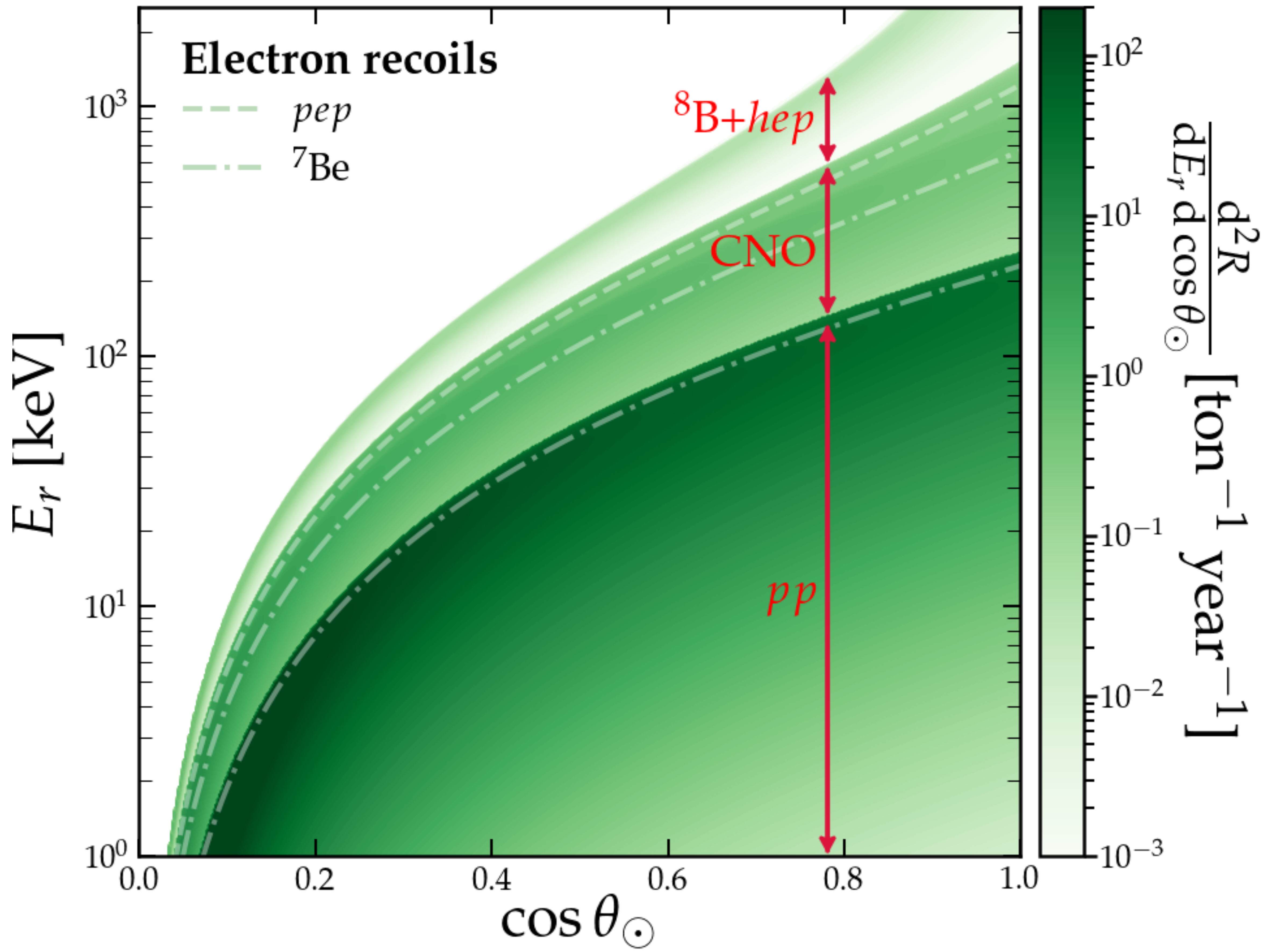
Directional neutrino measurements

Beyond 10 m³ scale, start to get sizeable rate of solar neutrinos via **electron recoils**

Recoil energy spectrum

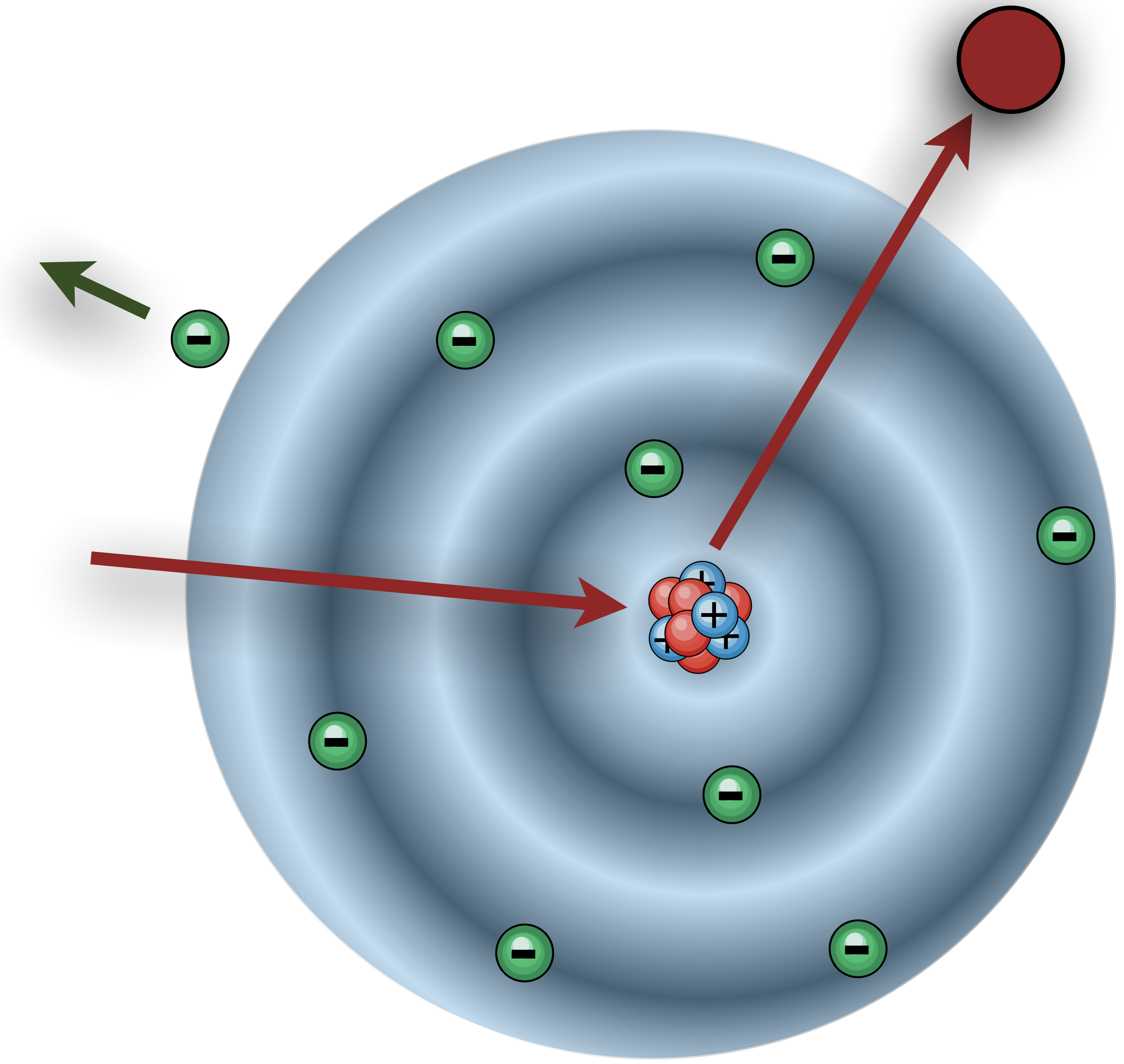


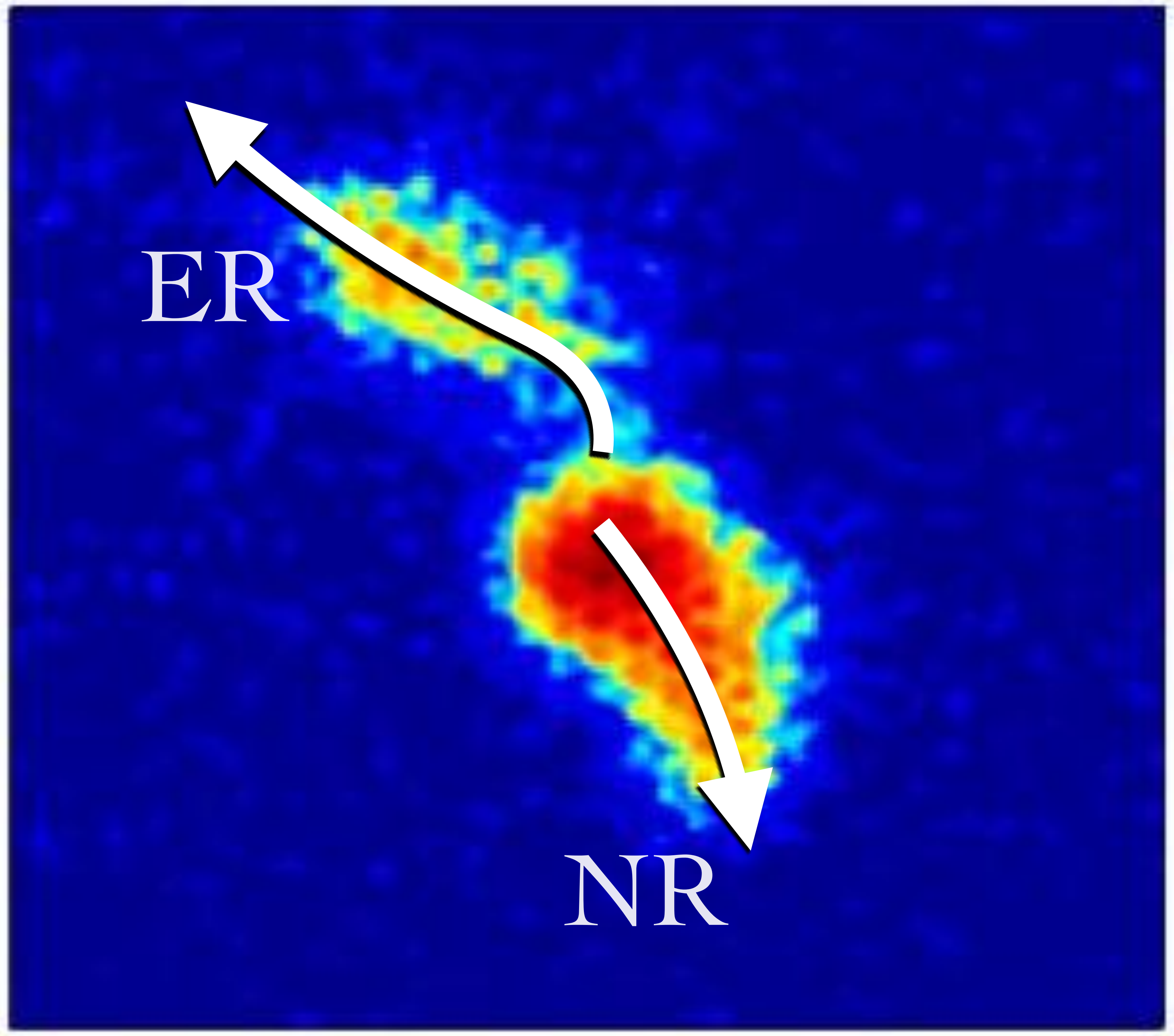
Recoil energy+angle spectrum



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
- 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 case 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

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF SYDNEY

CYGNUS

2102.04596

Directional Recoil Detection

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Annual Review of Nuclear and Particle Science
2021. XX:1–45

This article's doi:
10.1146/annurev-nucl-020821-035016

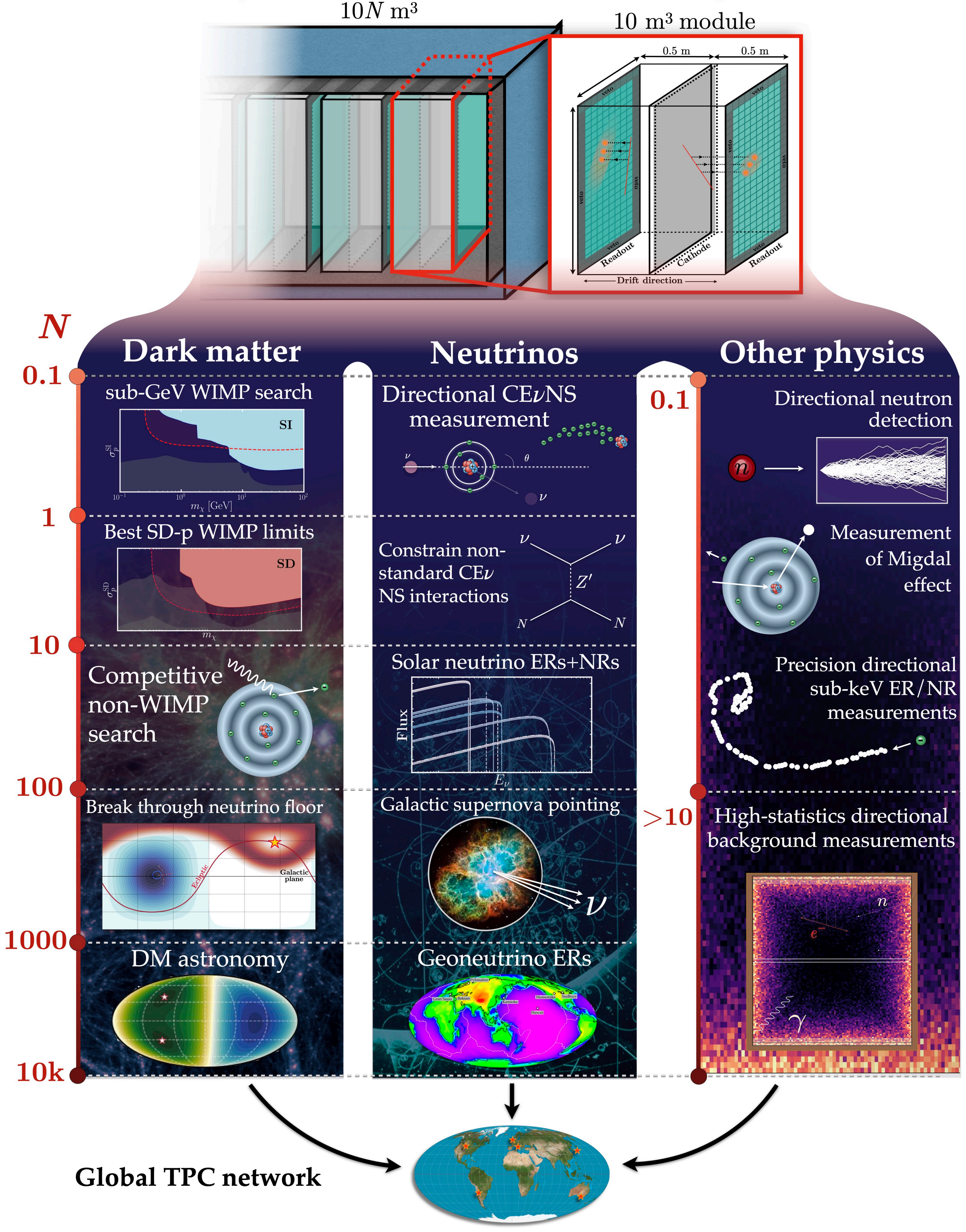
Keywords

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



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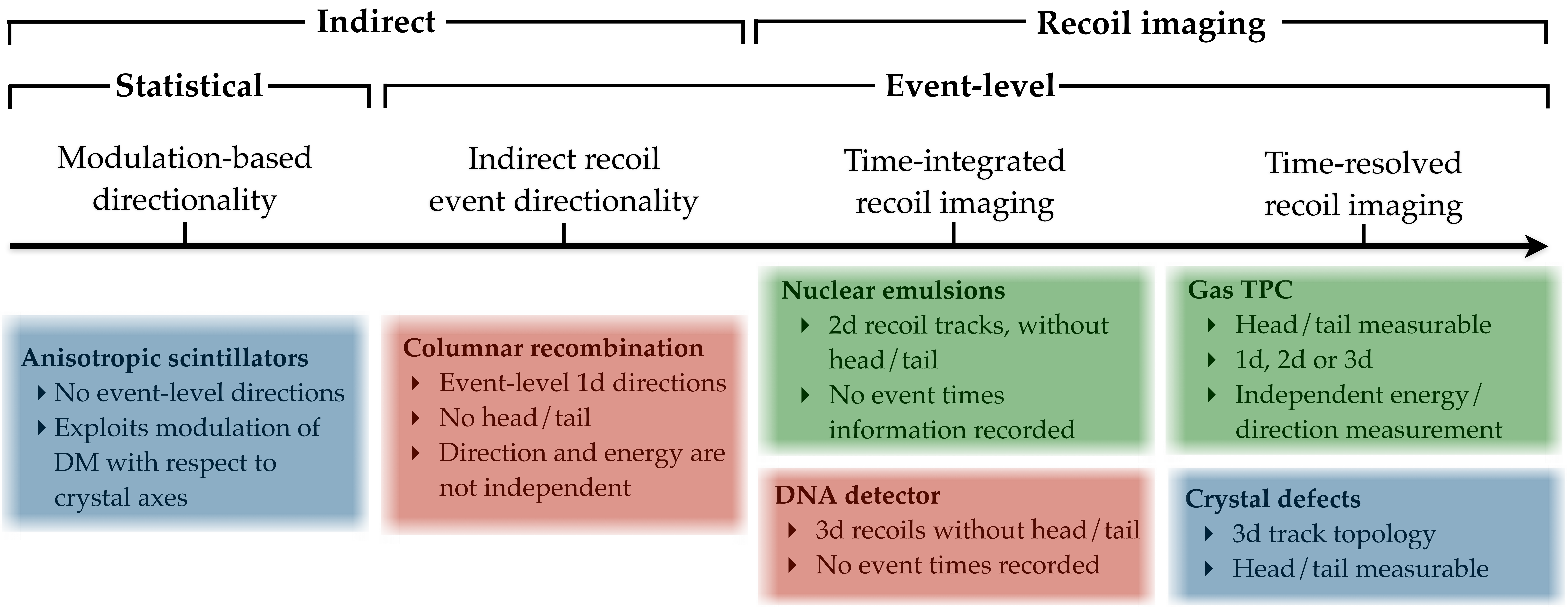
Detector classes by directional information

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

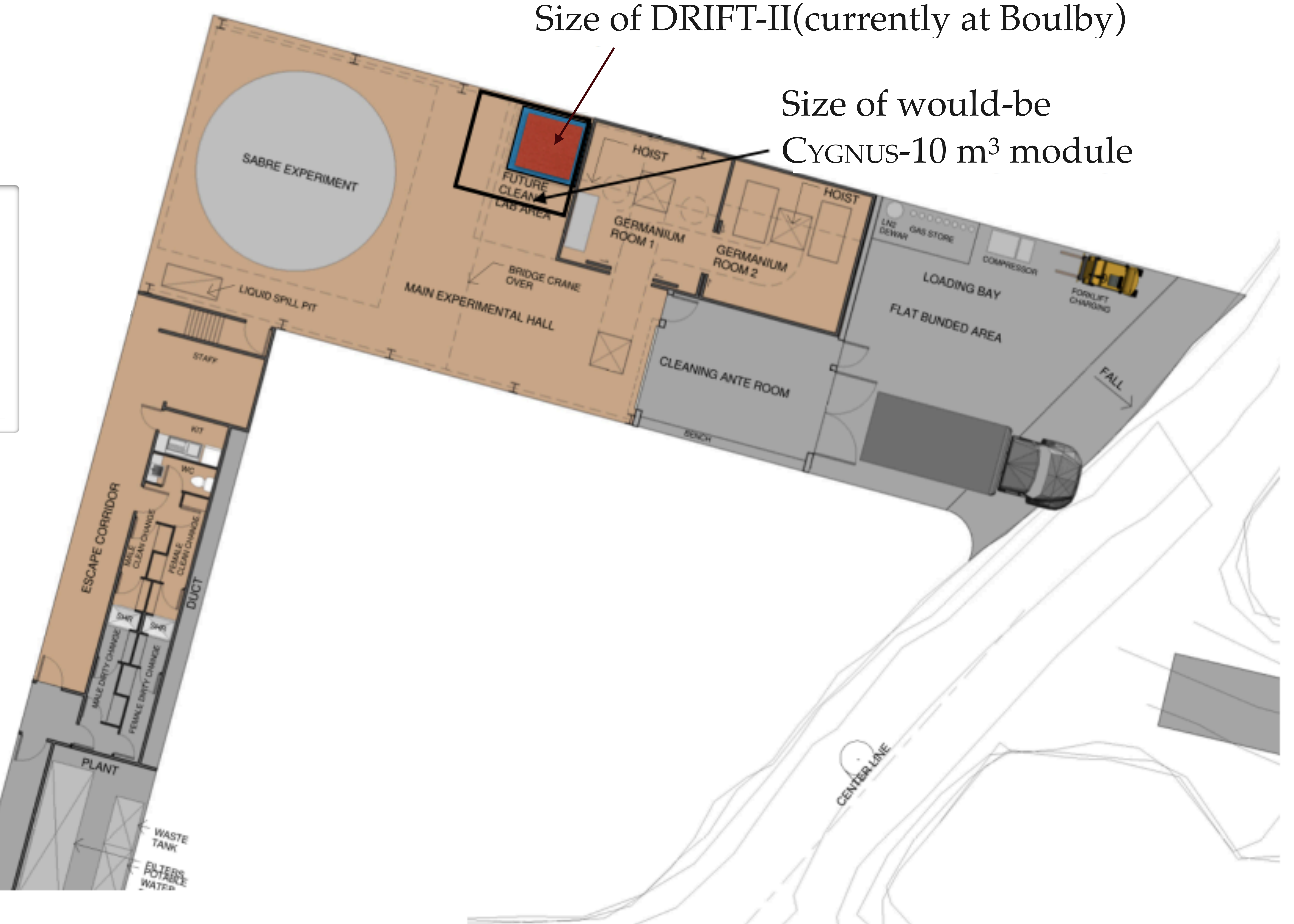
DNA detector
- 3d recoils without head/tail
- No event times recorded

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

Crystal defects
- 3d track topology
- Head/tail measurable

Stawell Underground Physics Laboratory (SUPL)

- 1.6 km depth
- First underground site in Southern Hemisphere



Size of DRIFT-II(currently at Boulby)

Size of would-be CYGNUS-10 m^3 module

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.