The status and future of directional recoil detection

Ciaran O'Hare
University of Sydney

[2102.04596] - a review of directional detection

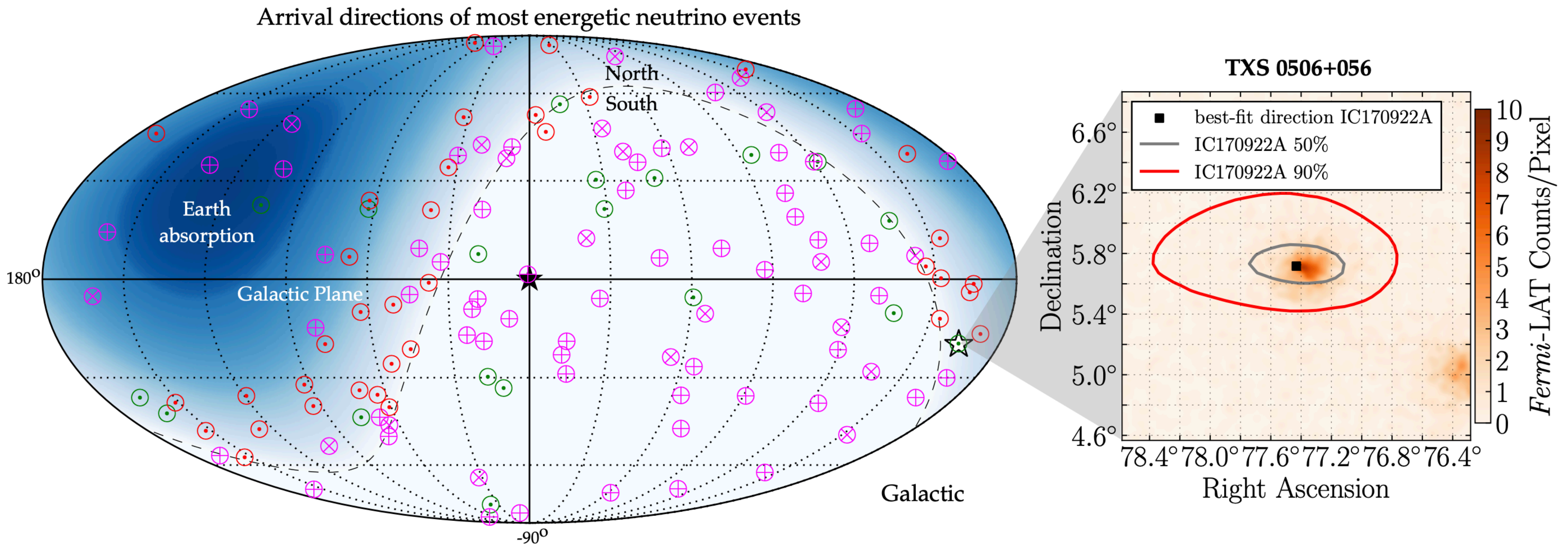
[2002.07499] - directional detection in Xe/Ar

[2008.12587] - directional detection with gas TPCs

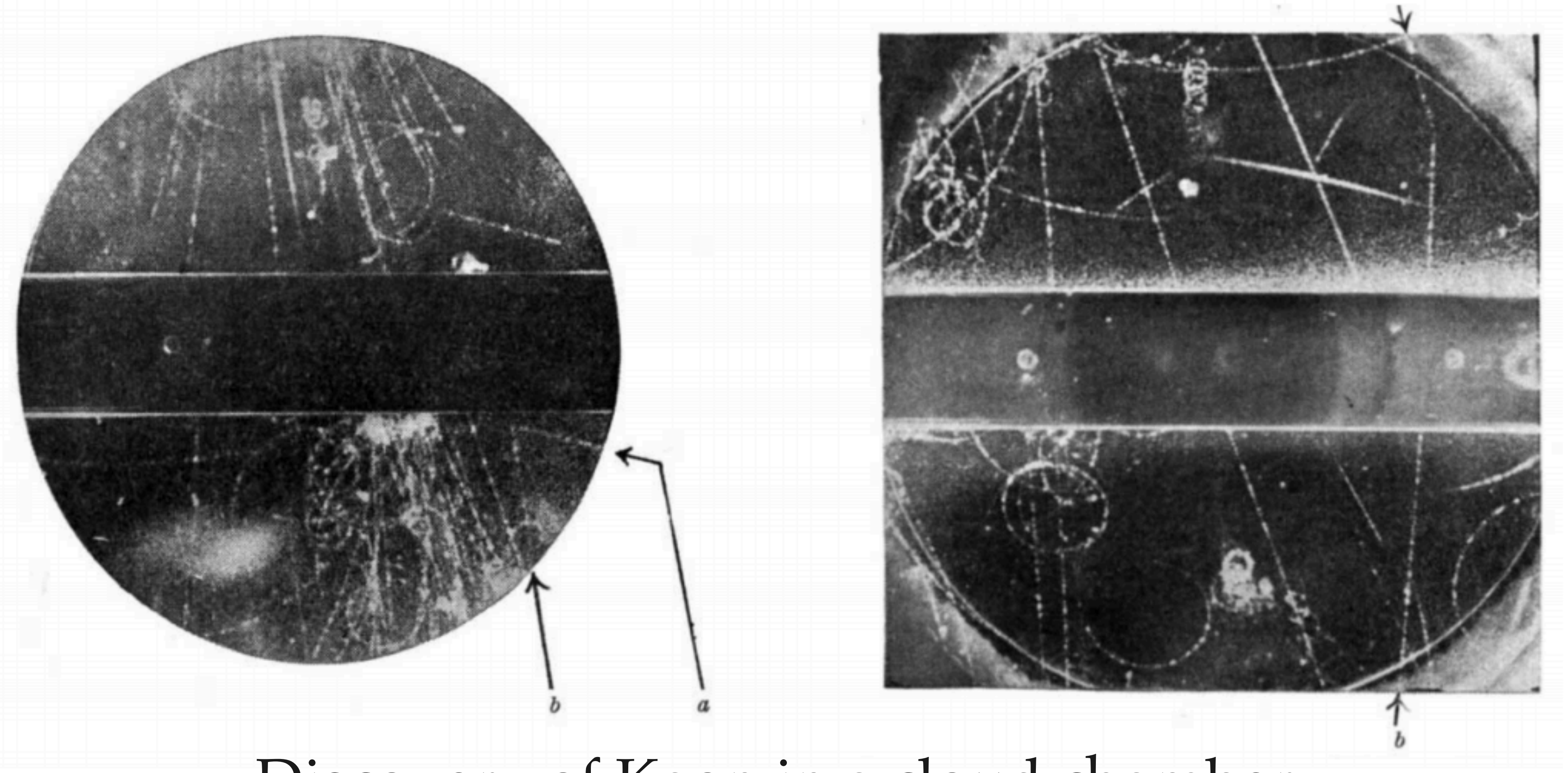
[2105.11949] - directional detection with DNA

Basic message: detecting particle directions is useful for astroparticle physics, but hard to do at low energies

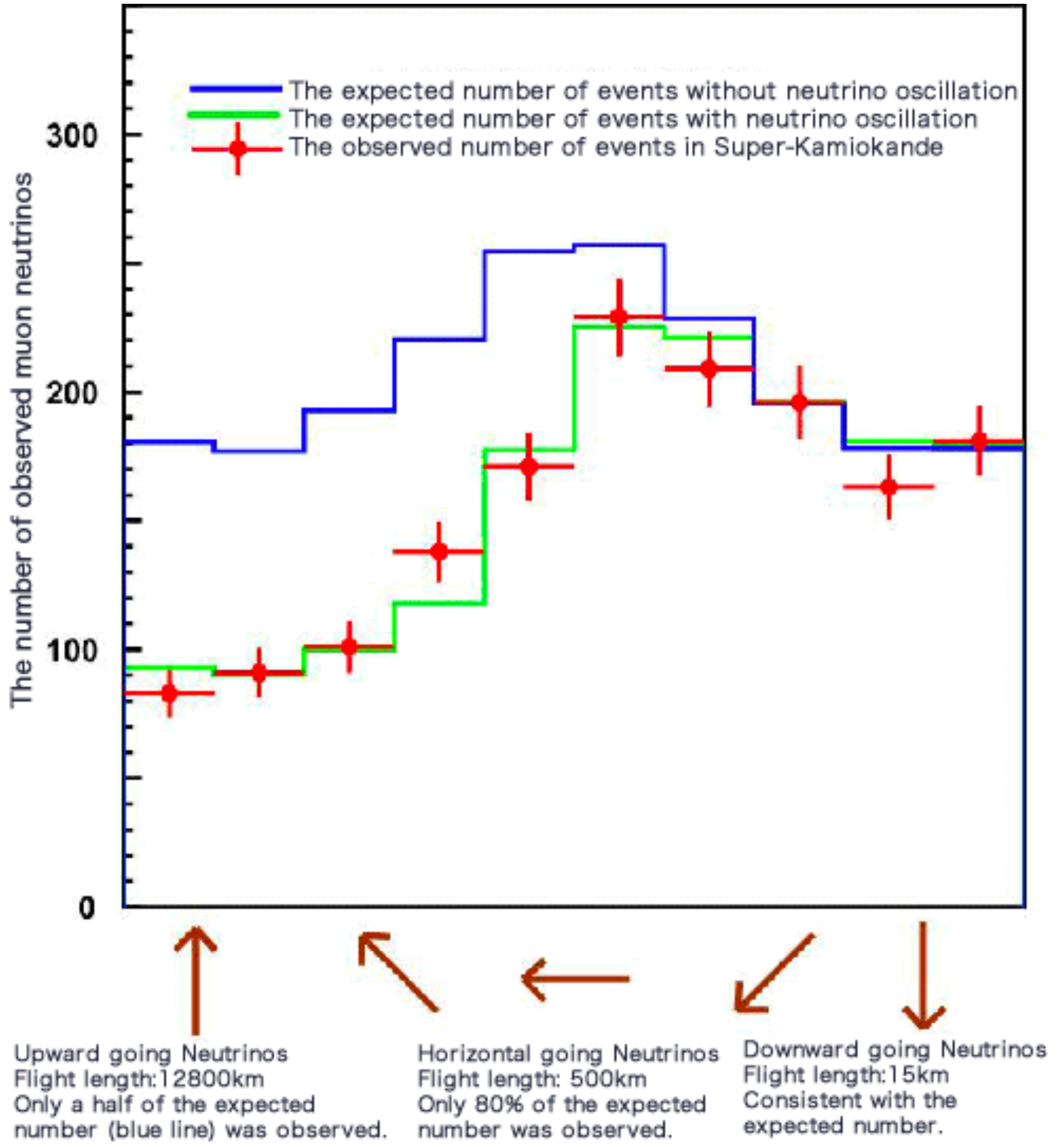
Detecting particle directions is useful



IceCube high energy ν sky
1911.02561

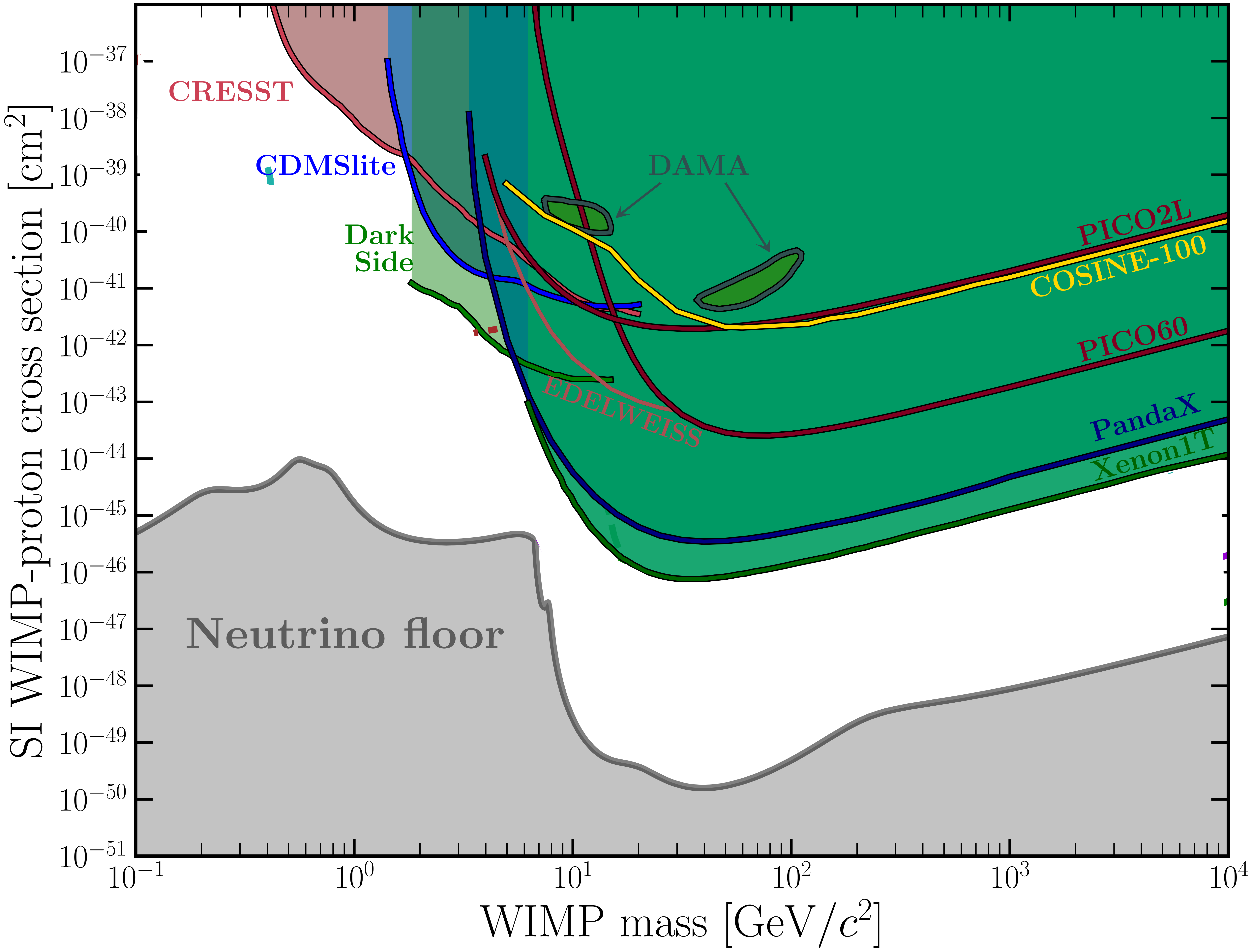


Discovery of Kaon in a cloud chamber
Rochester & Butler (1947)



Atmospheric ν_μ
(Super-K)

Outstanding problem of today: search for dark matter



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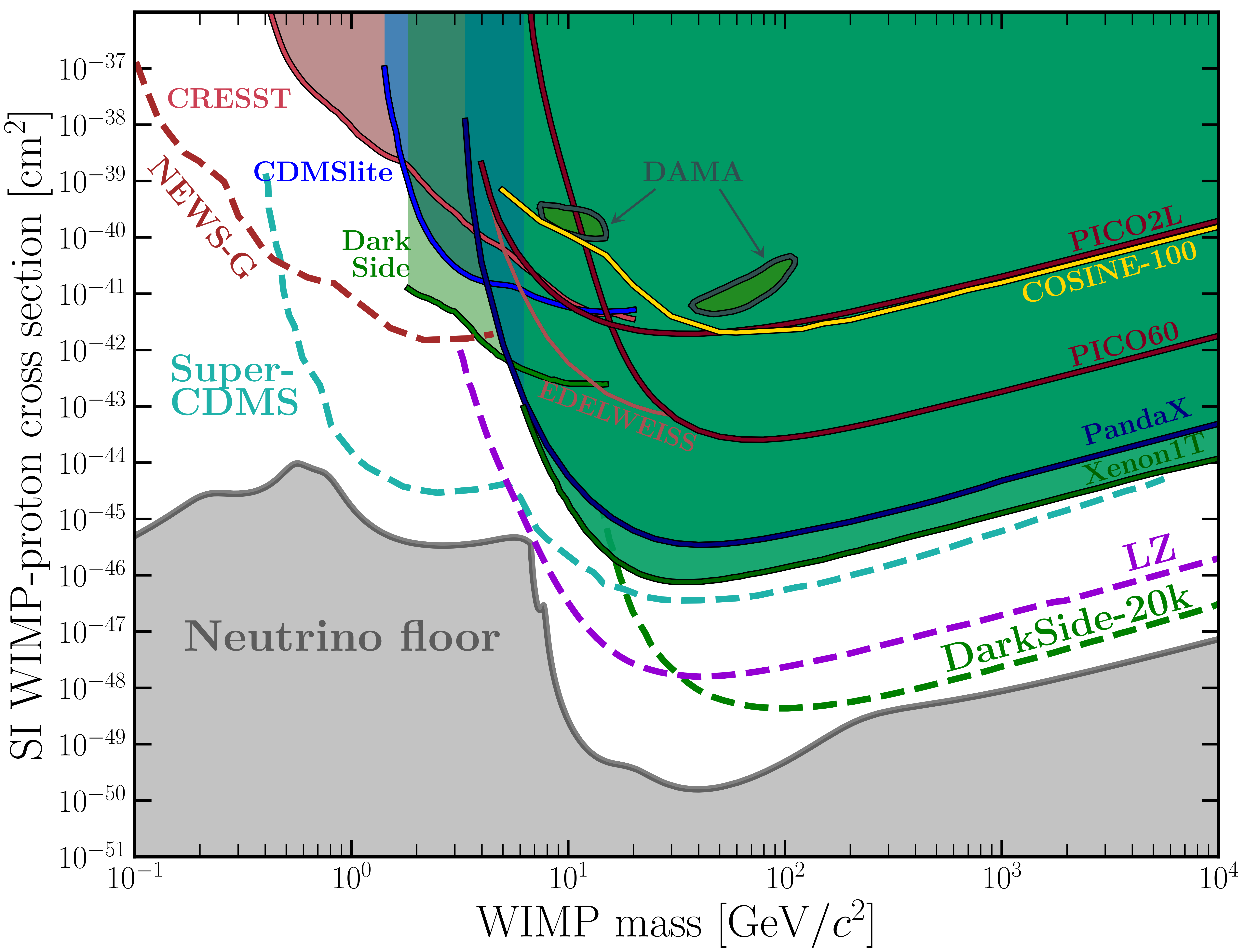
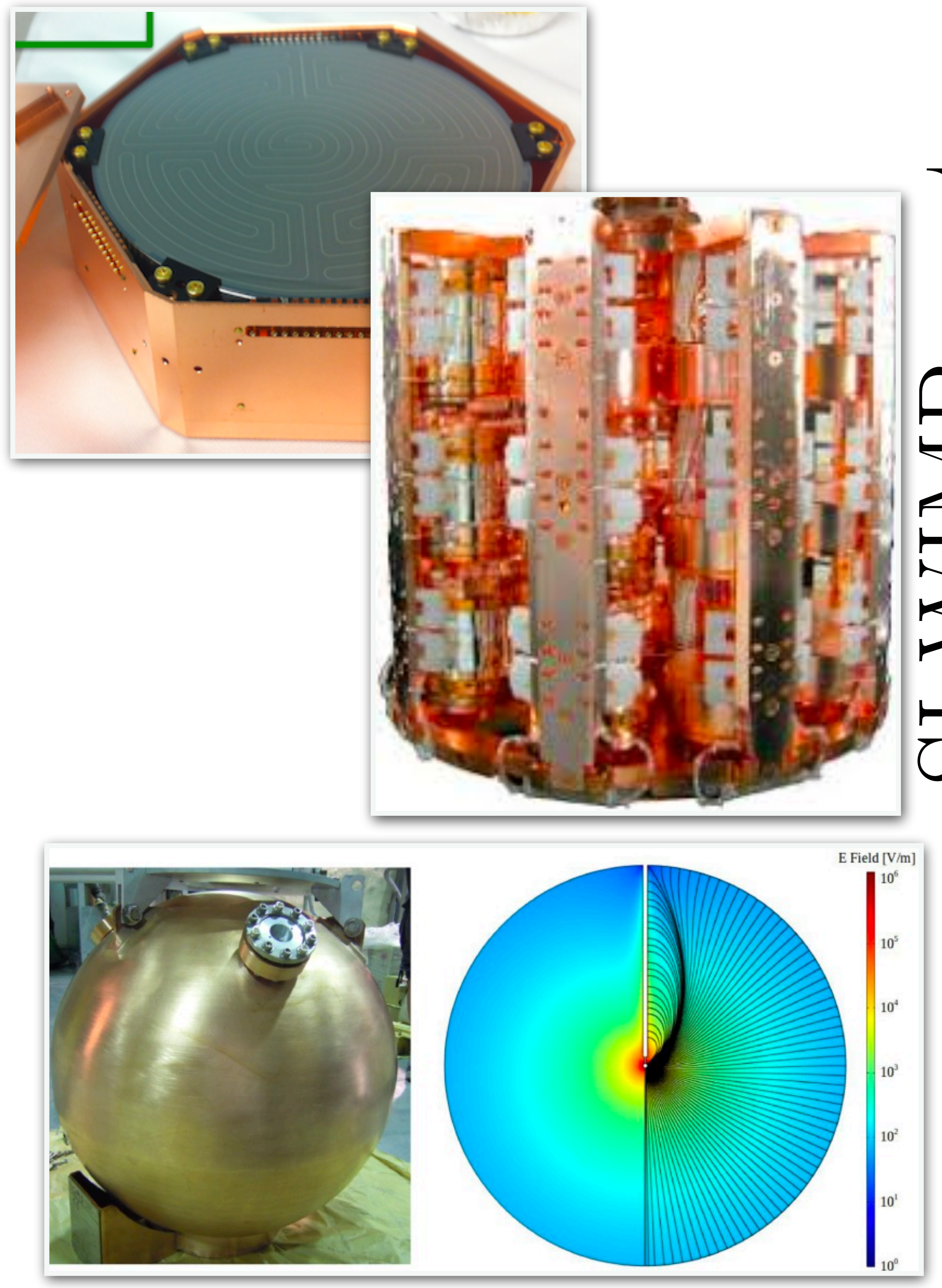
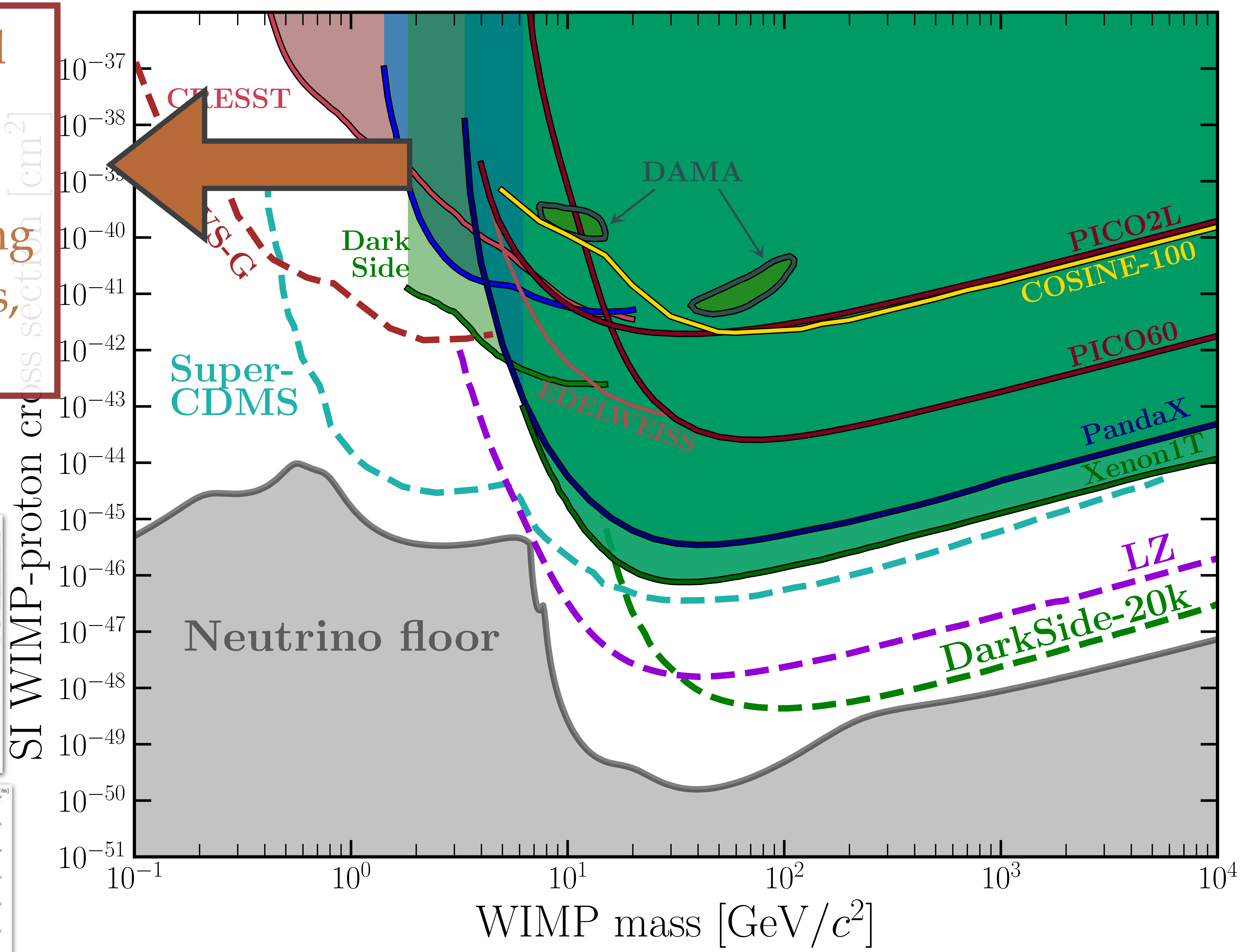


Outstanding problem of today: search for dark matter

Low threshold detectors

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





Outstanding problem of today: search for dark matter

Low threshold detectors

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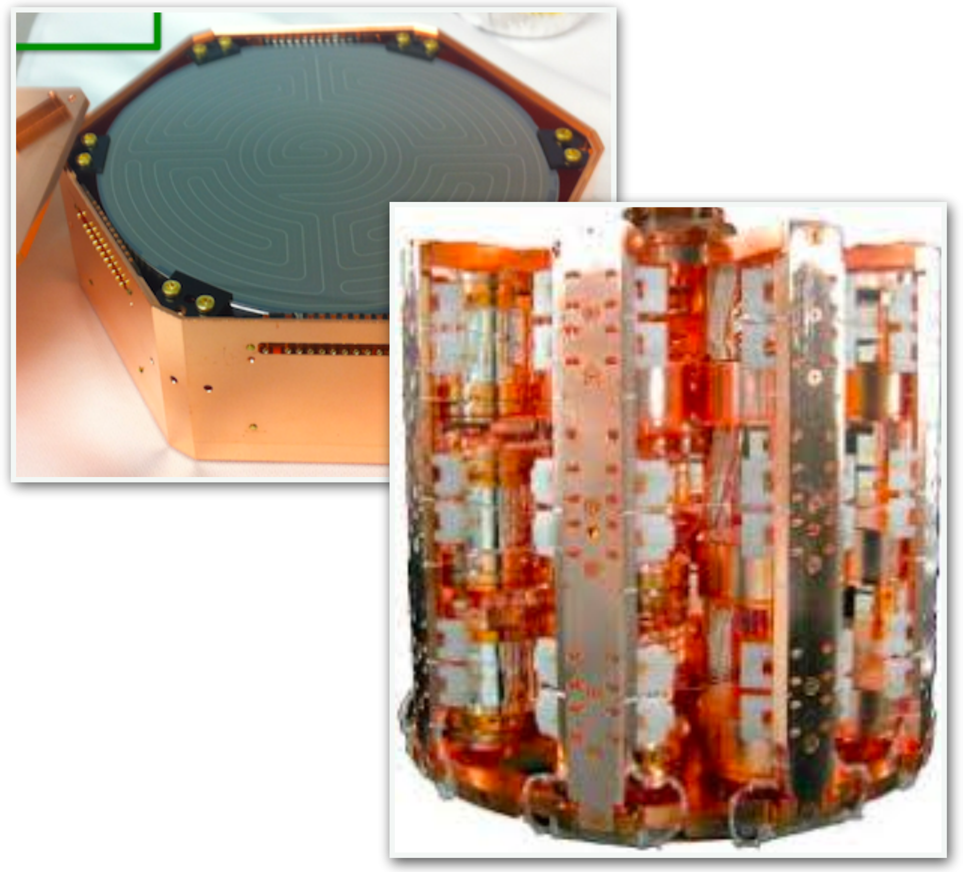
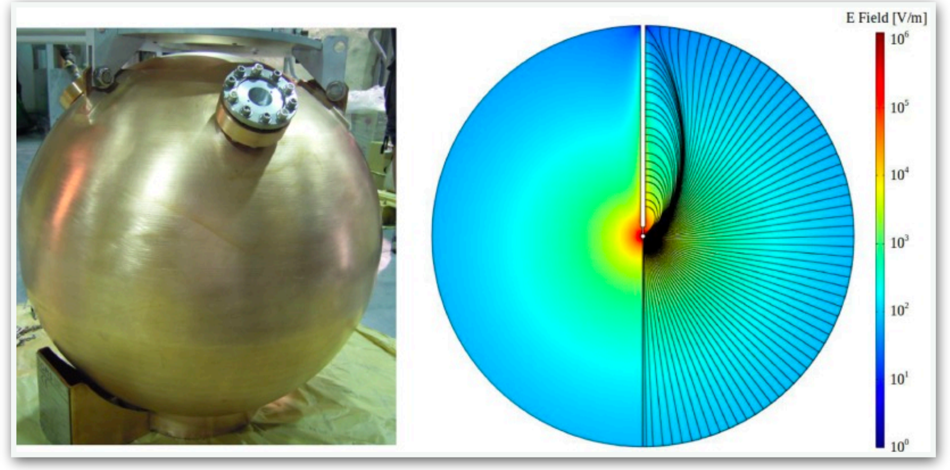
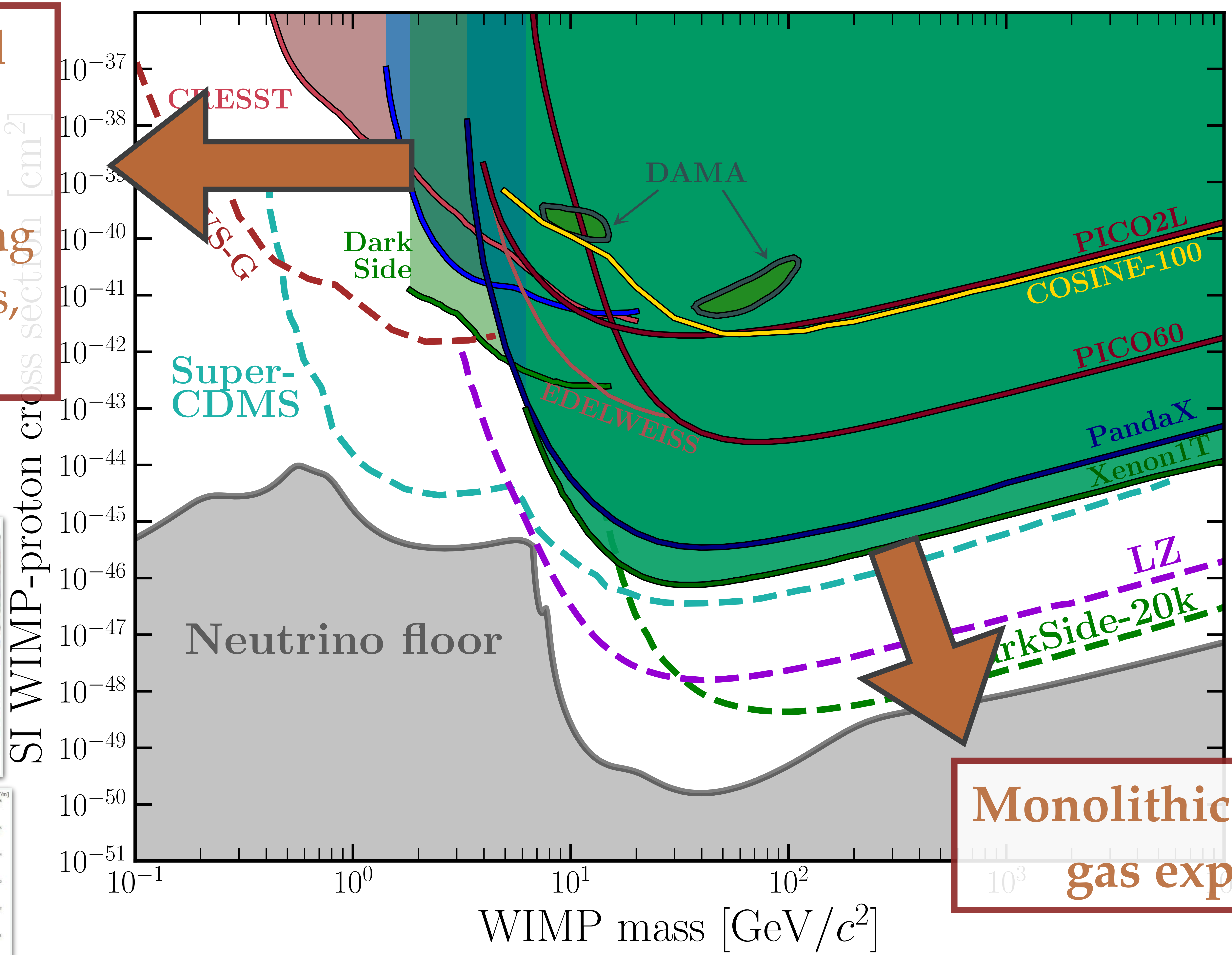
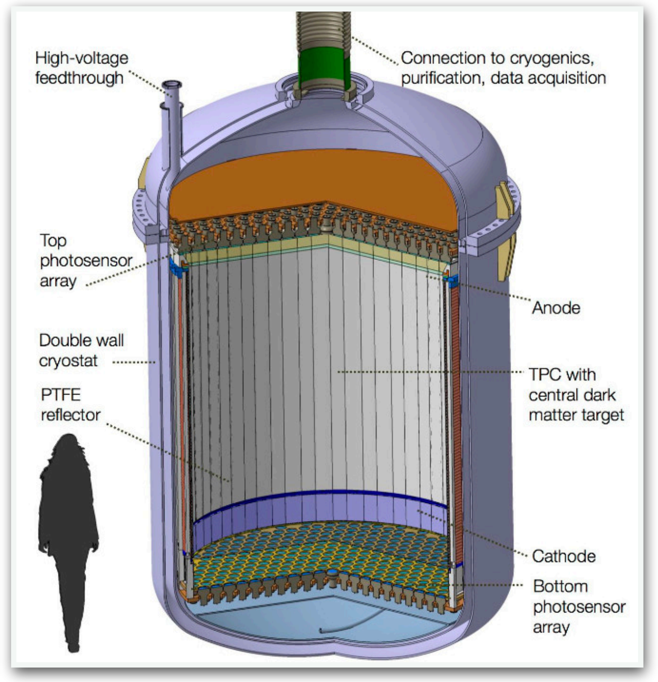






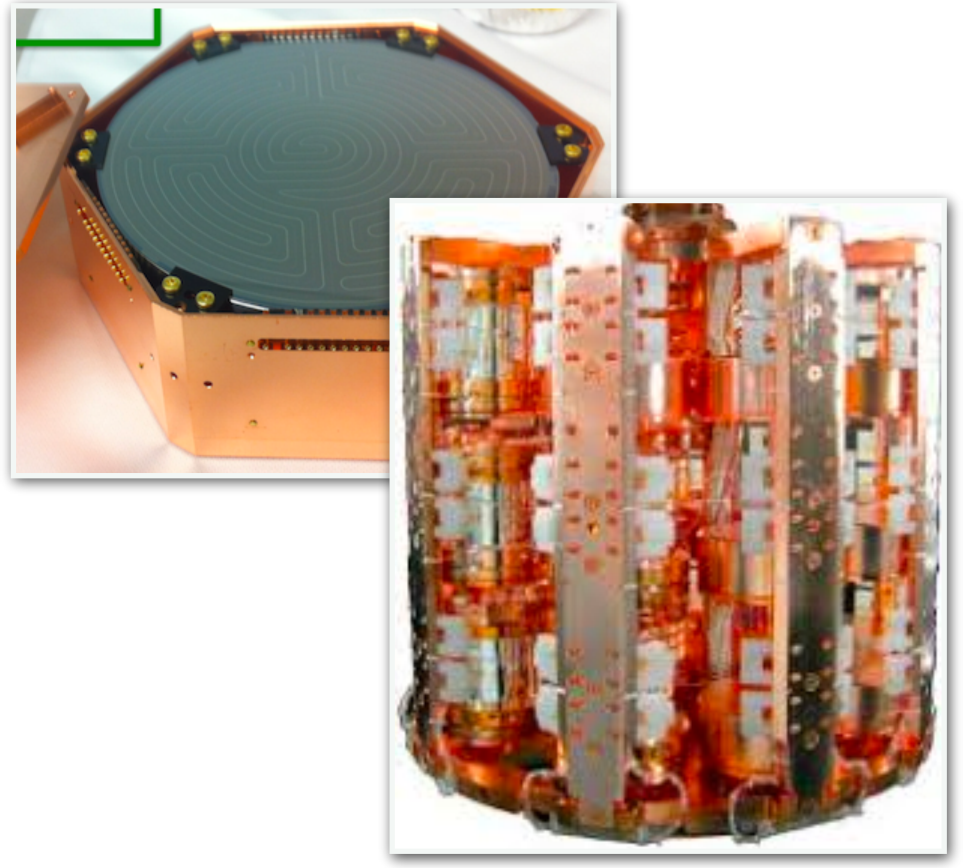


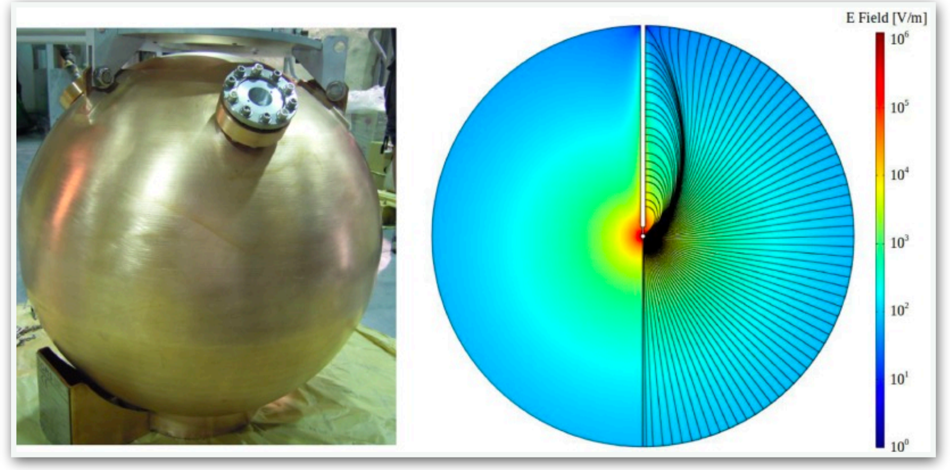
Monolithic liquid noble gas experiments

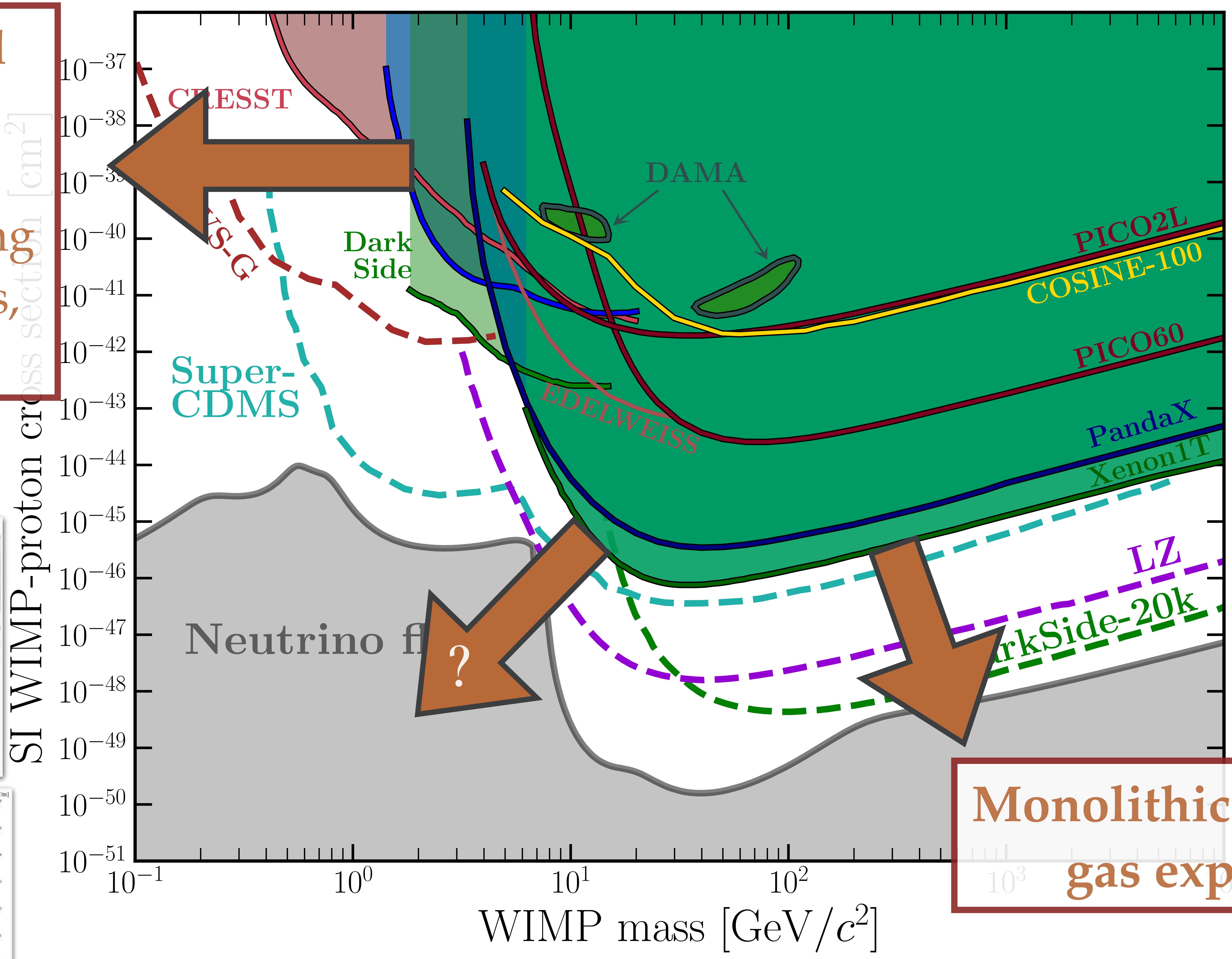
Outstanding problem of today: search for dark matter

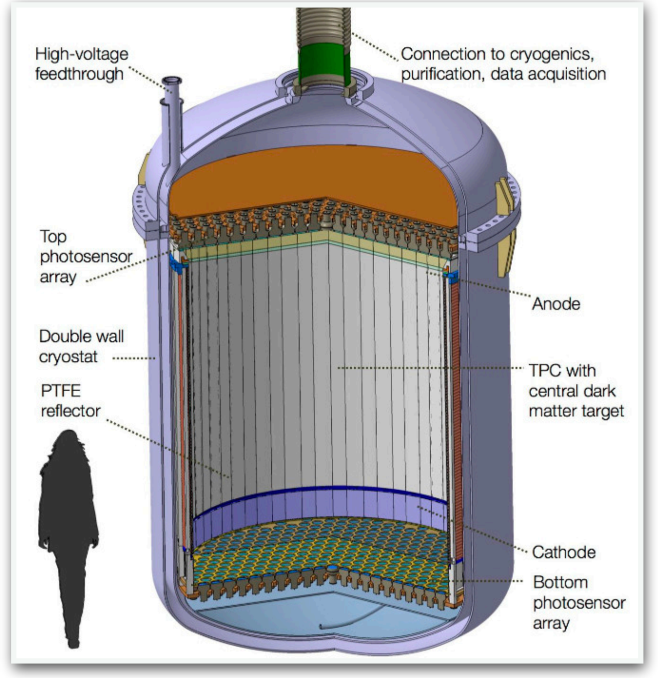
Low threshold detectors

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





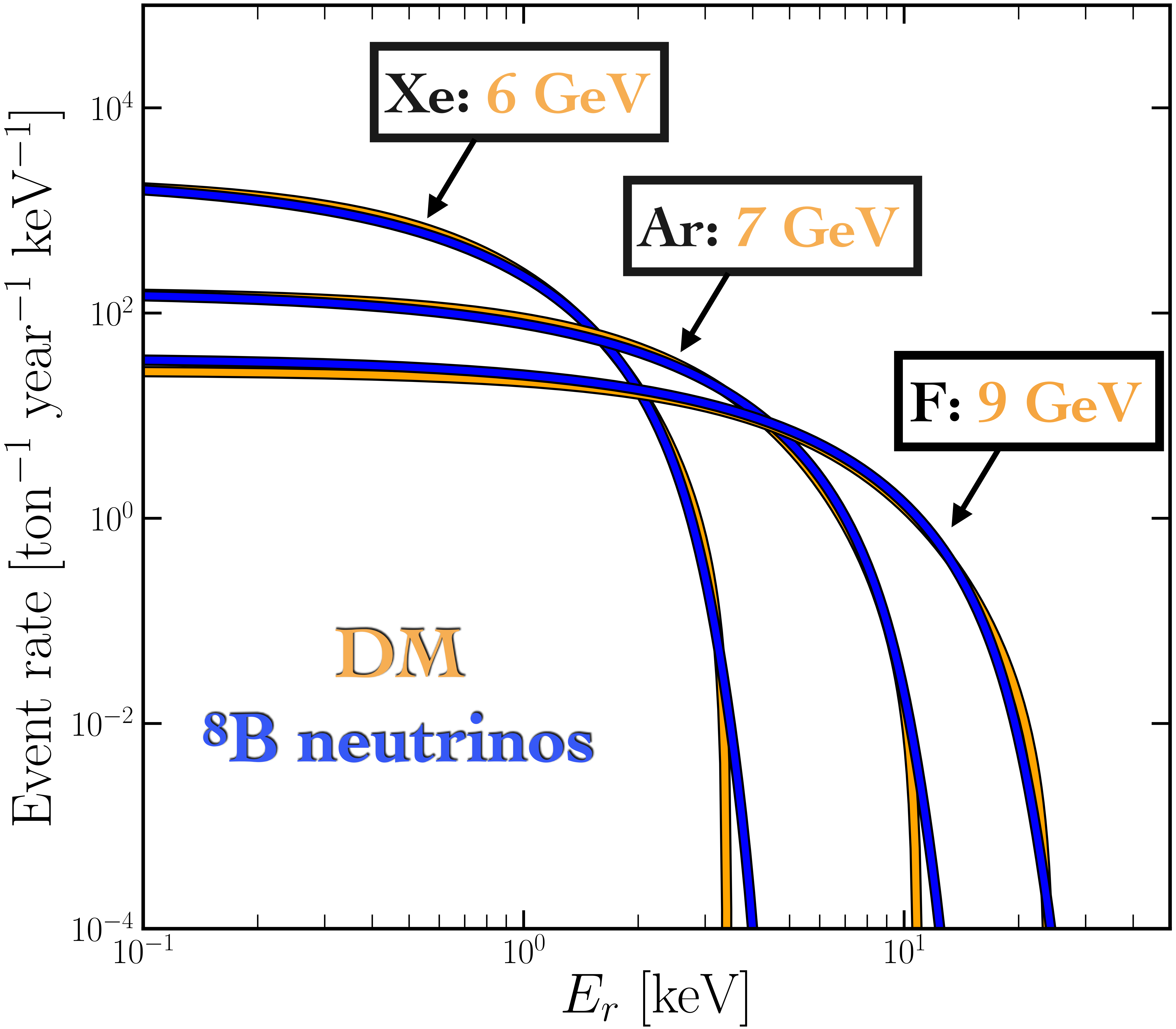




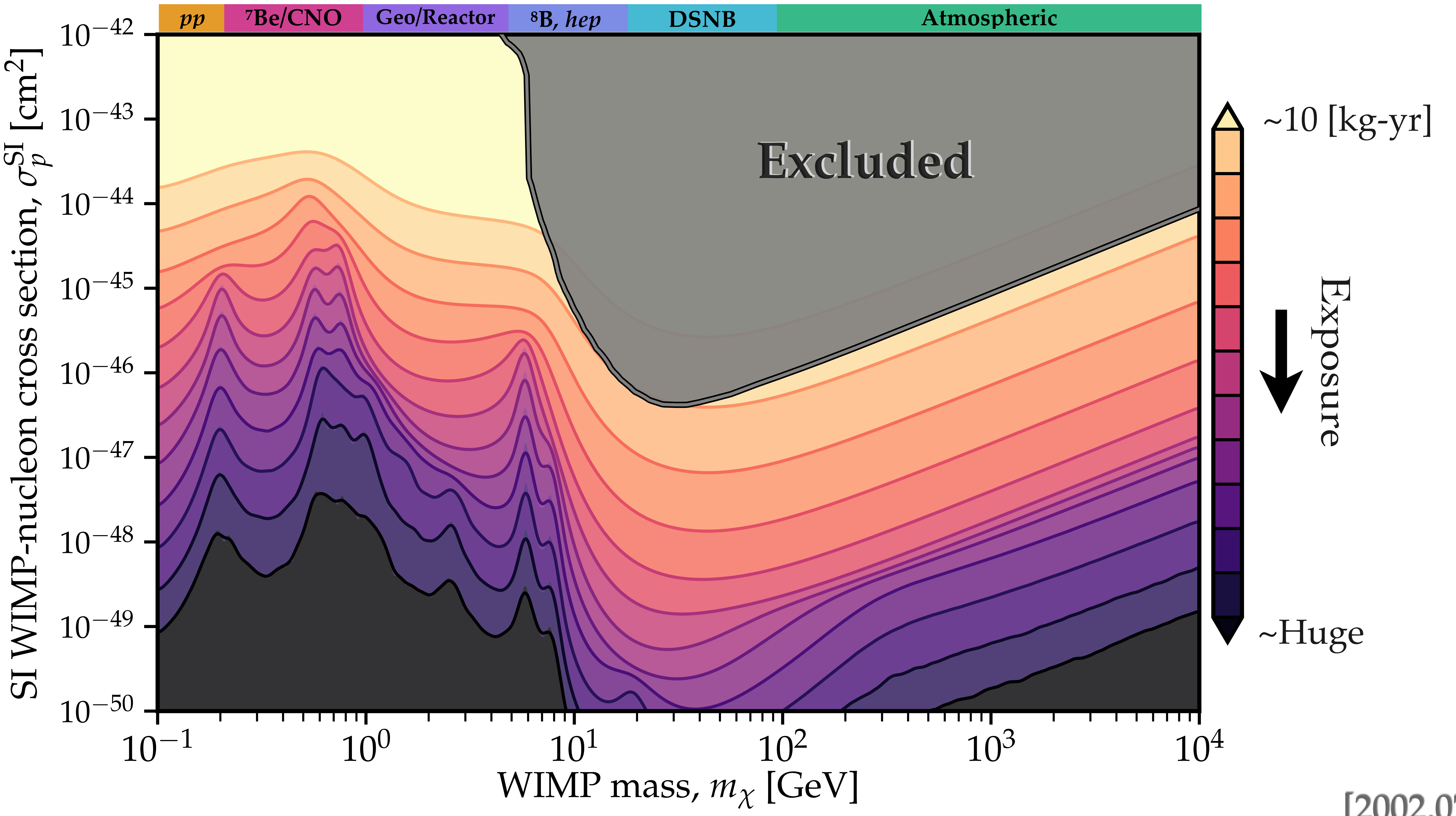
Monolithic liquid noble gas experiments

Why is there a neutrino floor?

→ spectral match between DM and solar neutrinos recoil energy signal in direct searches



The “neutrino fog”



[2002.07499]

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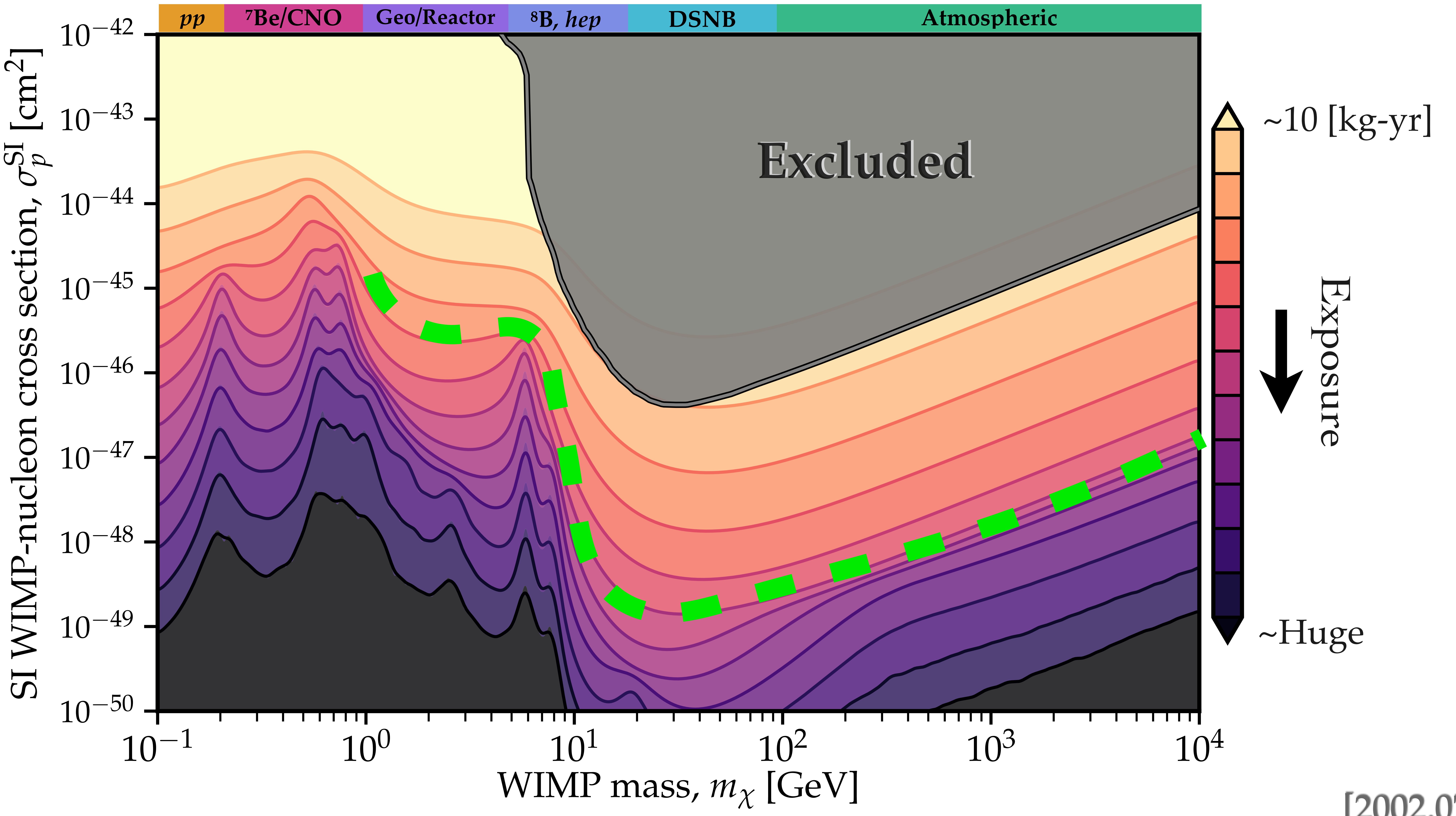
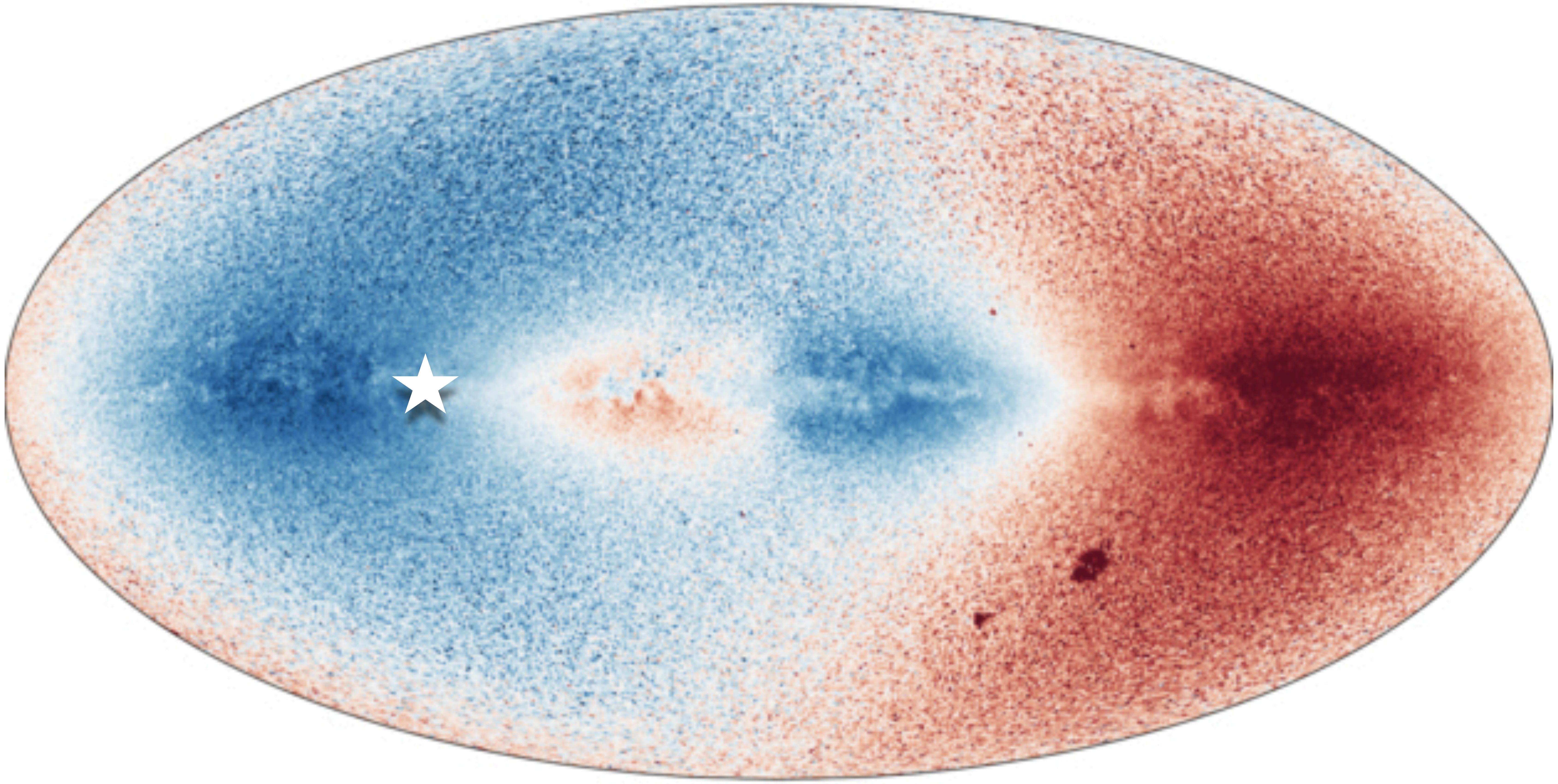
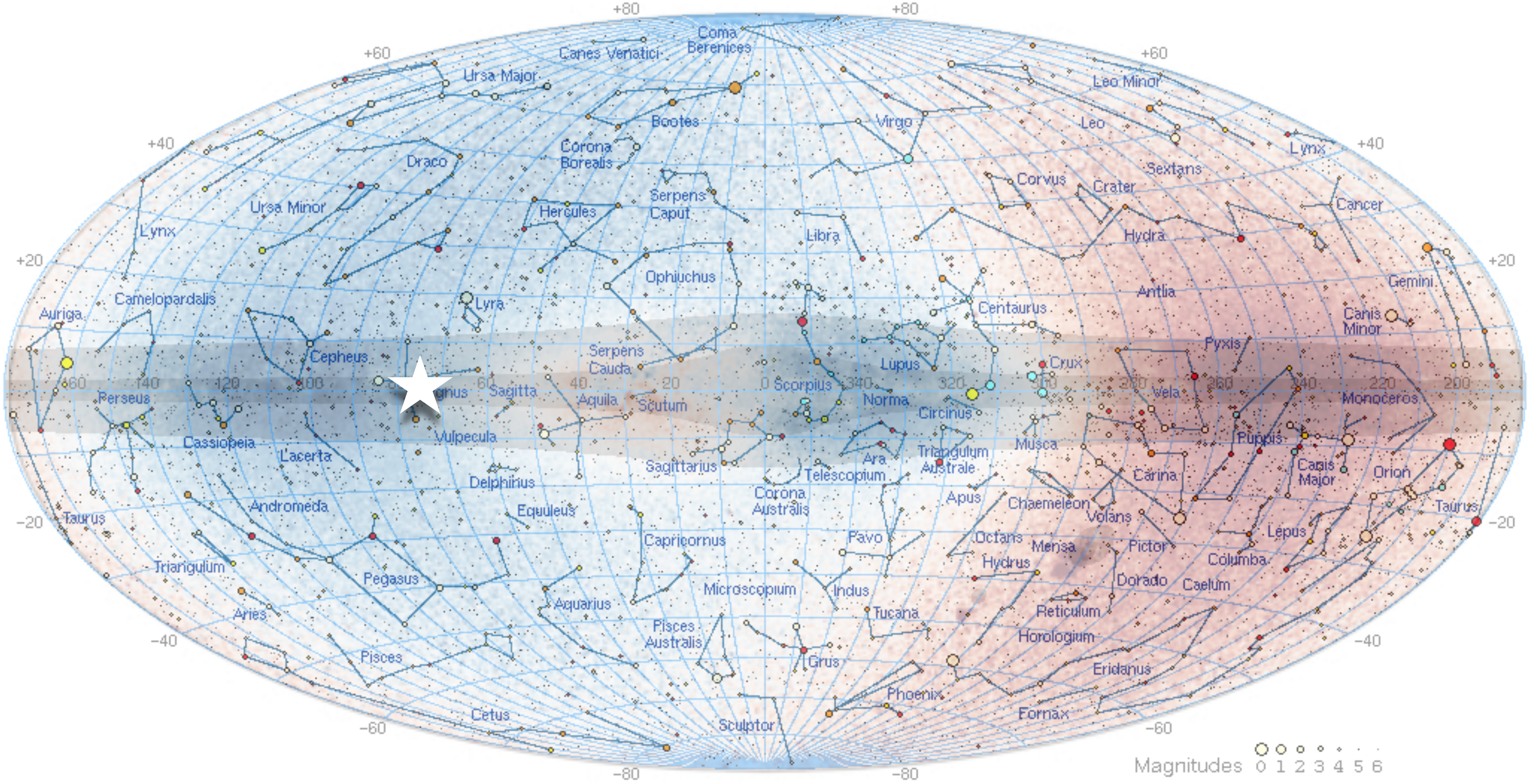


[2002.07499]


Cygnus
Jun
Dec



Gaia RVS skymap of line of sight velocities
Blue = moving towards us (relatively)
Red = moving away from us



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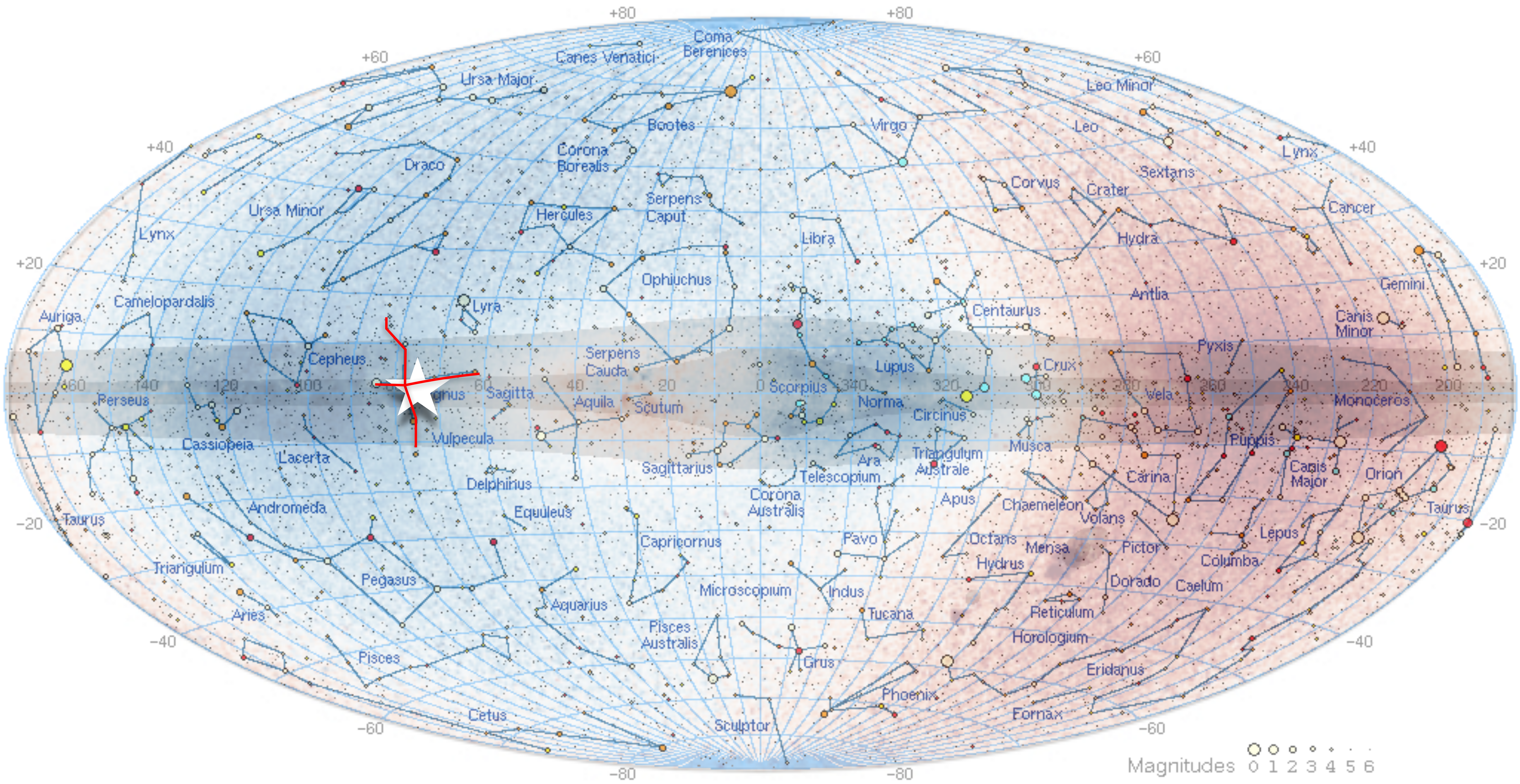

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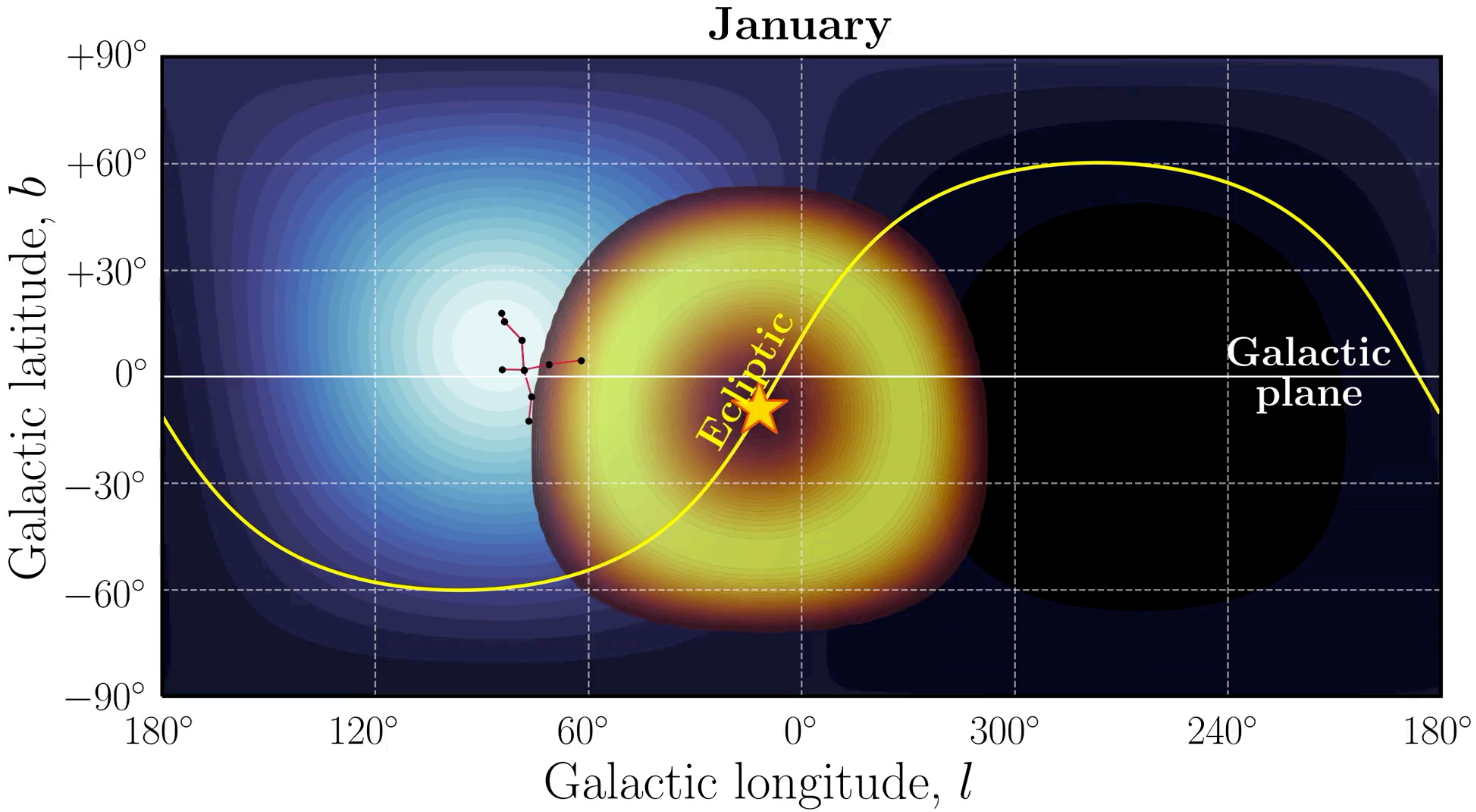
Nothing should mimic dark matter's directional signal, including solar neutrinos



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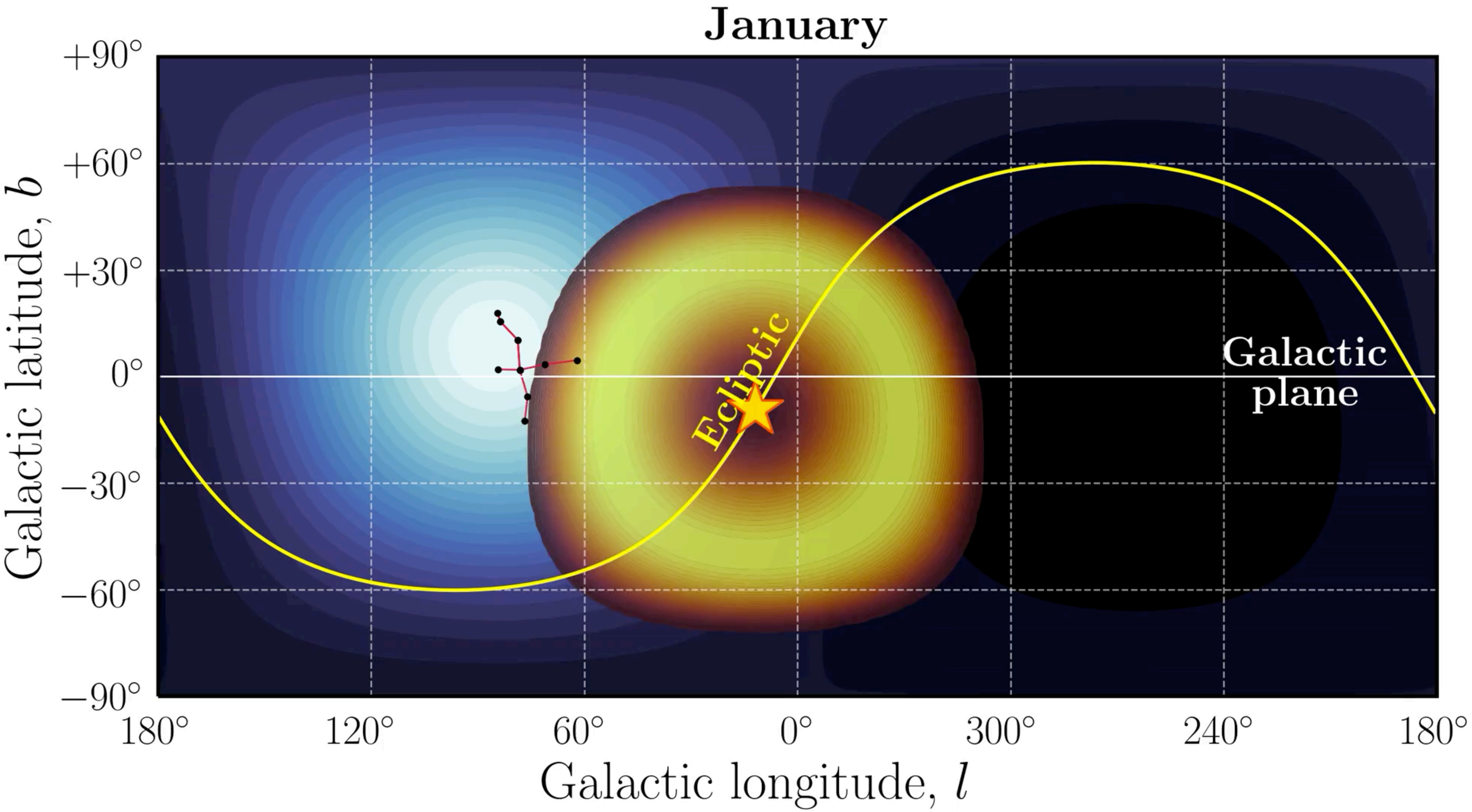
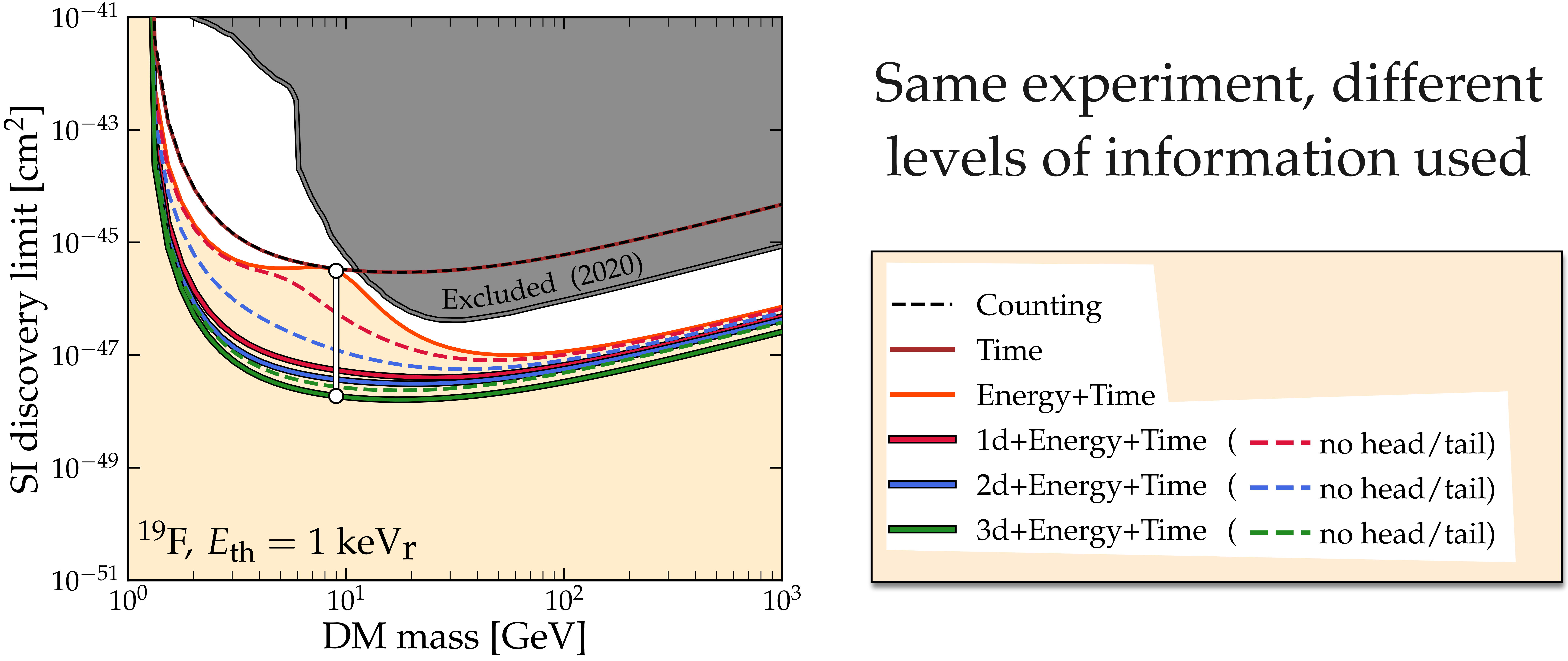
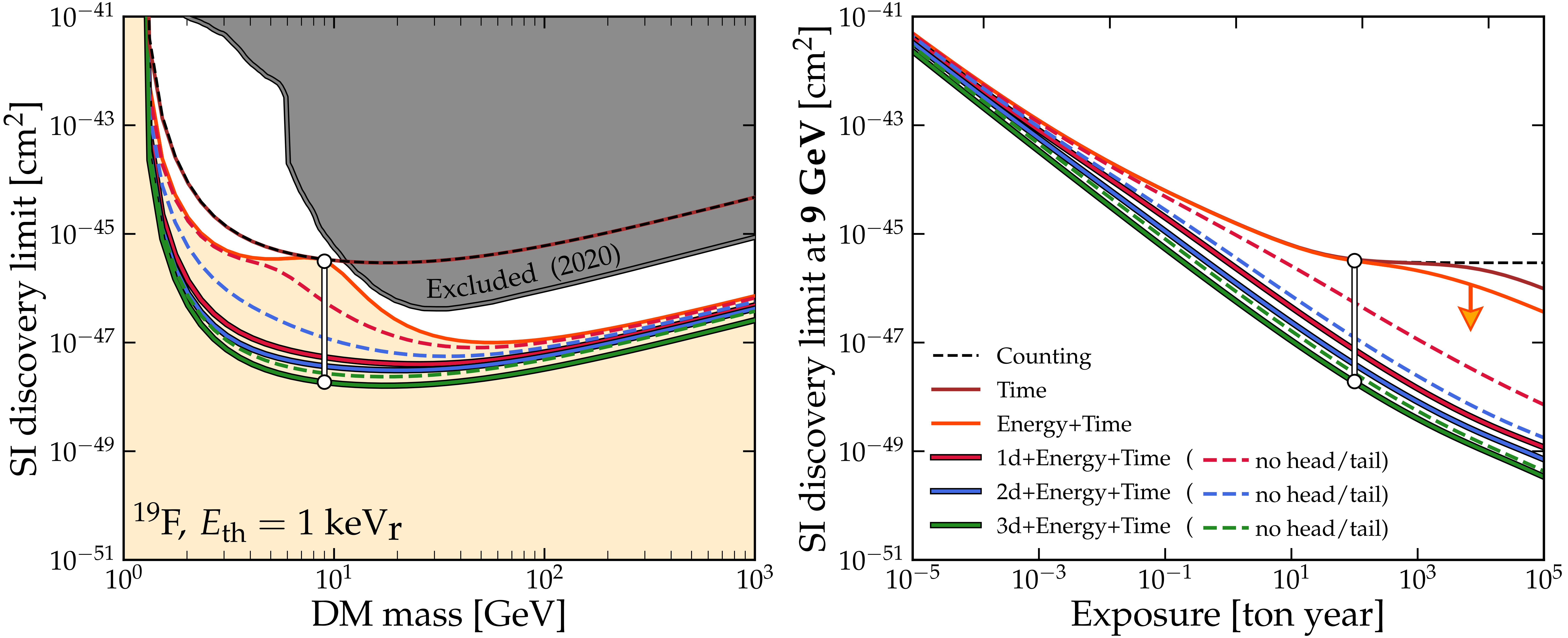


Subtracting the neutrino background

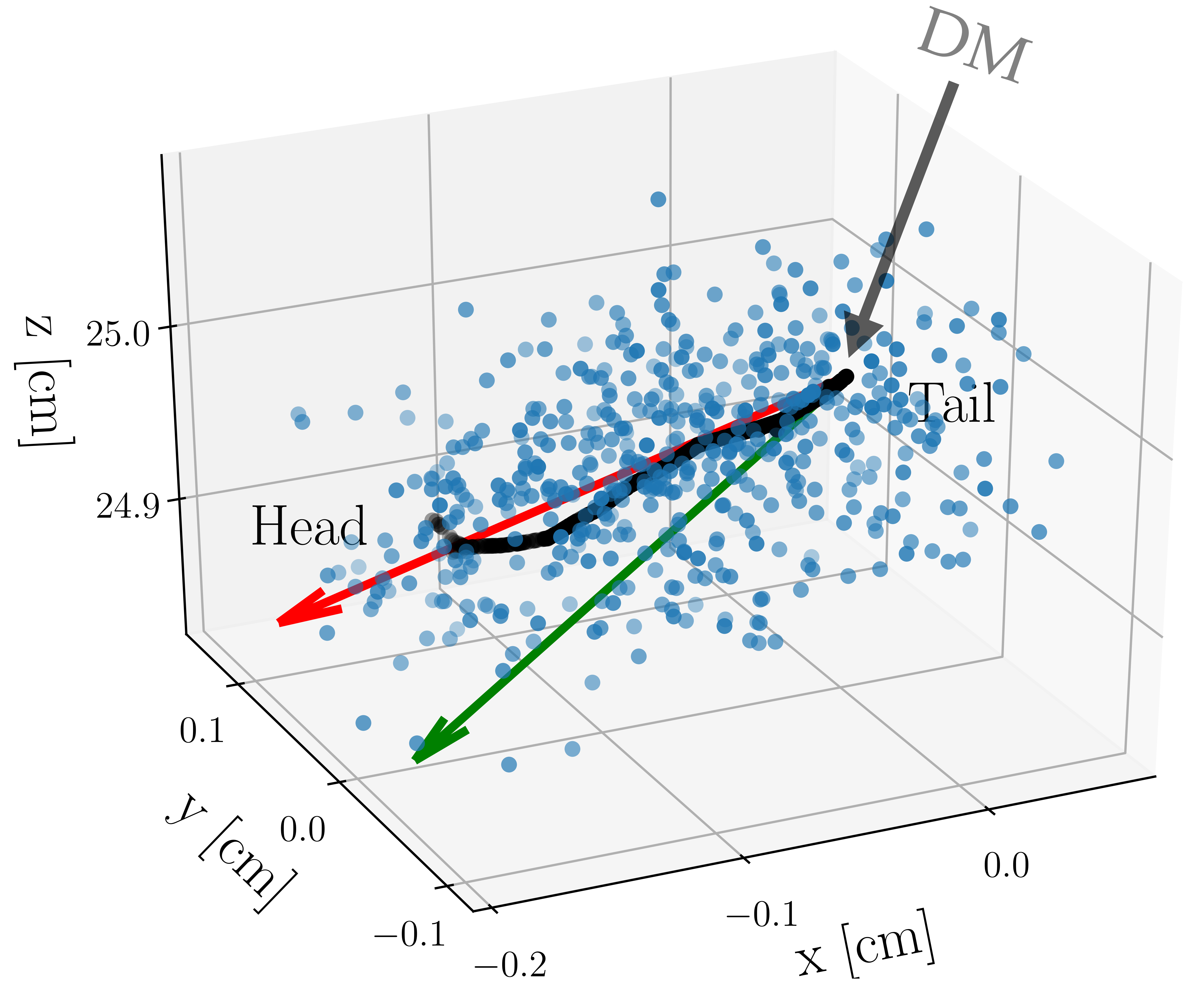


Same experiment, different levels of information used

Subtracting the neutrino background



Directional experiments are largely unaffected by the neutrino fog



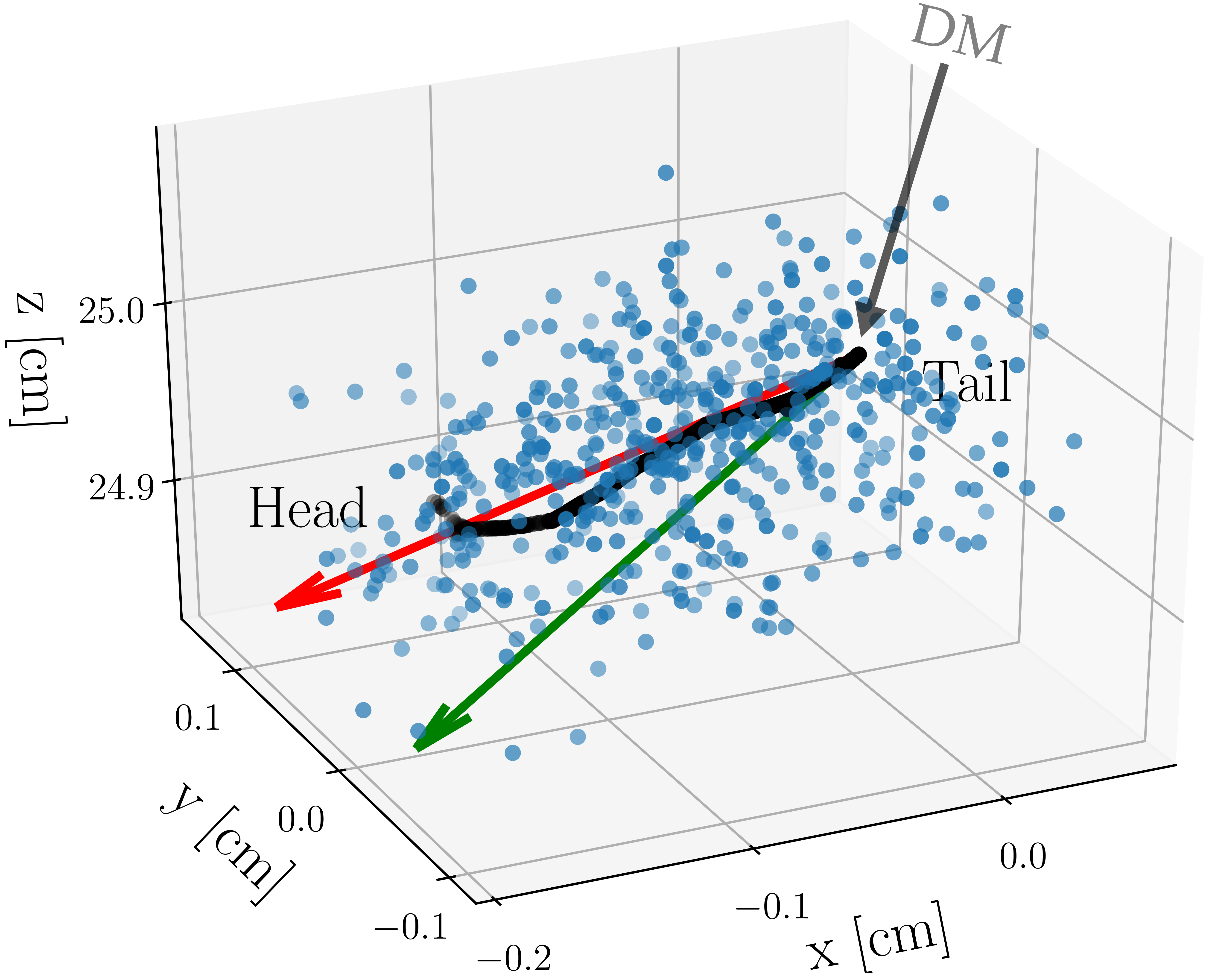
How to detect nuclear recoils at the keV-scale?

● **Initial track**

● **After diffusion**

↑ **True recoil dir.**

↑ **Straggled recoil dir.**



The ideal detector measures:

- **Initial** recoil direction (i.e. what the DM scattering predicts)
- 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)

CYGNUS

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

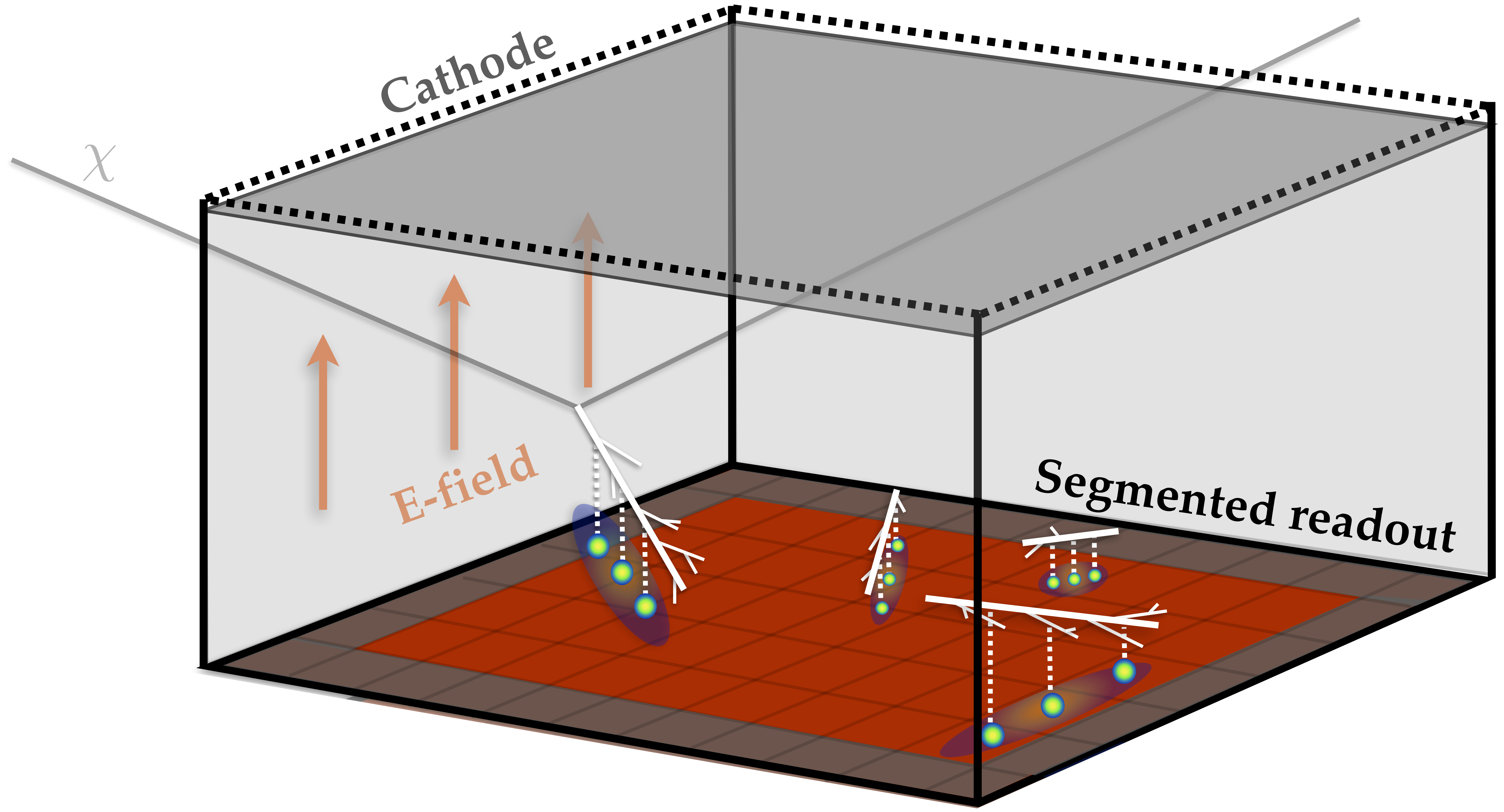
[2008.12587]

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:SF_6 at 755:5, negative ion drift



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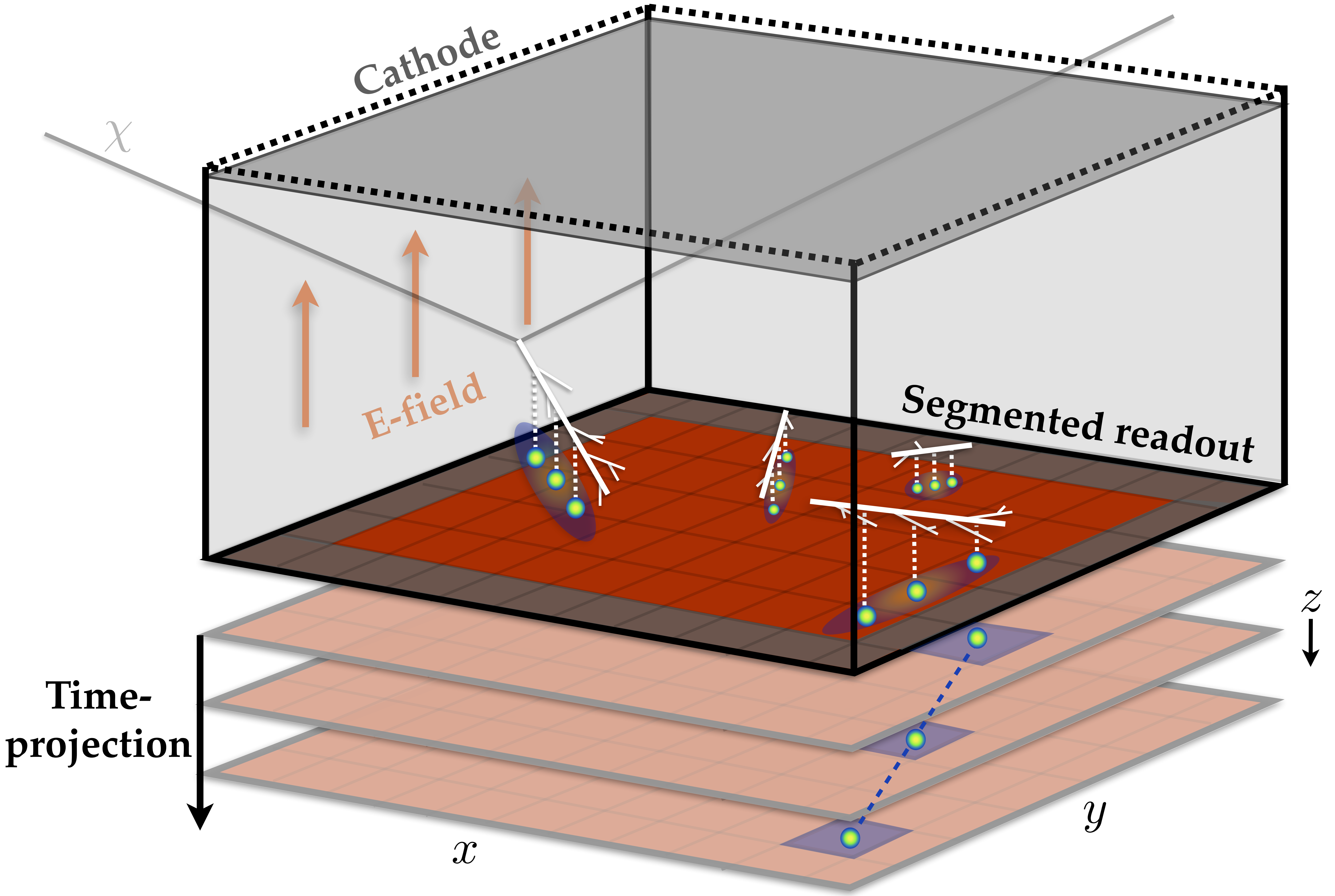

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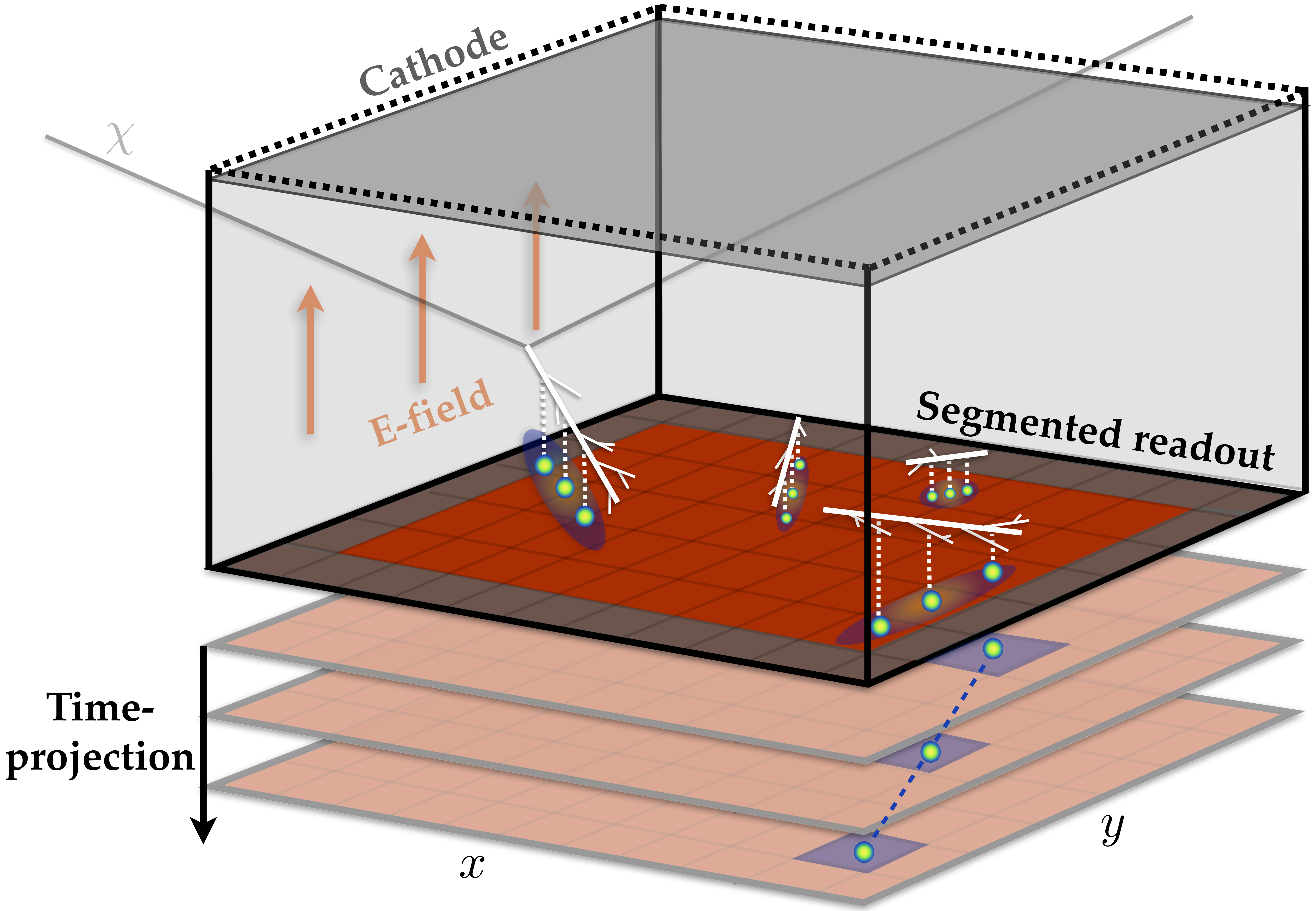
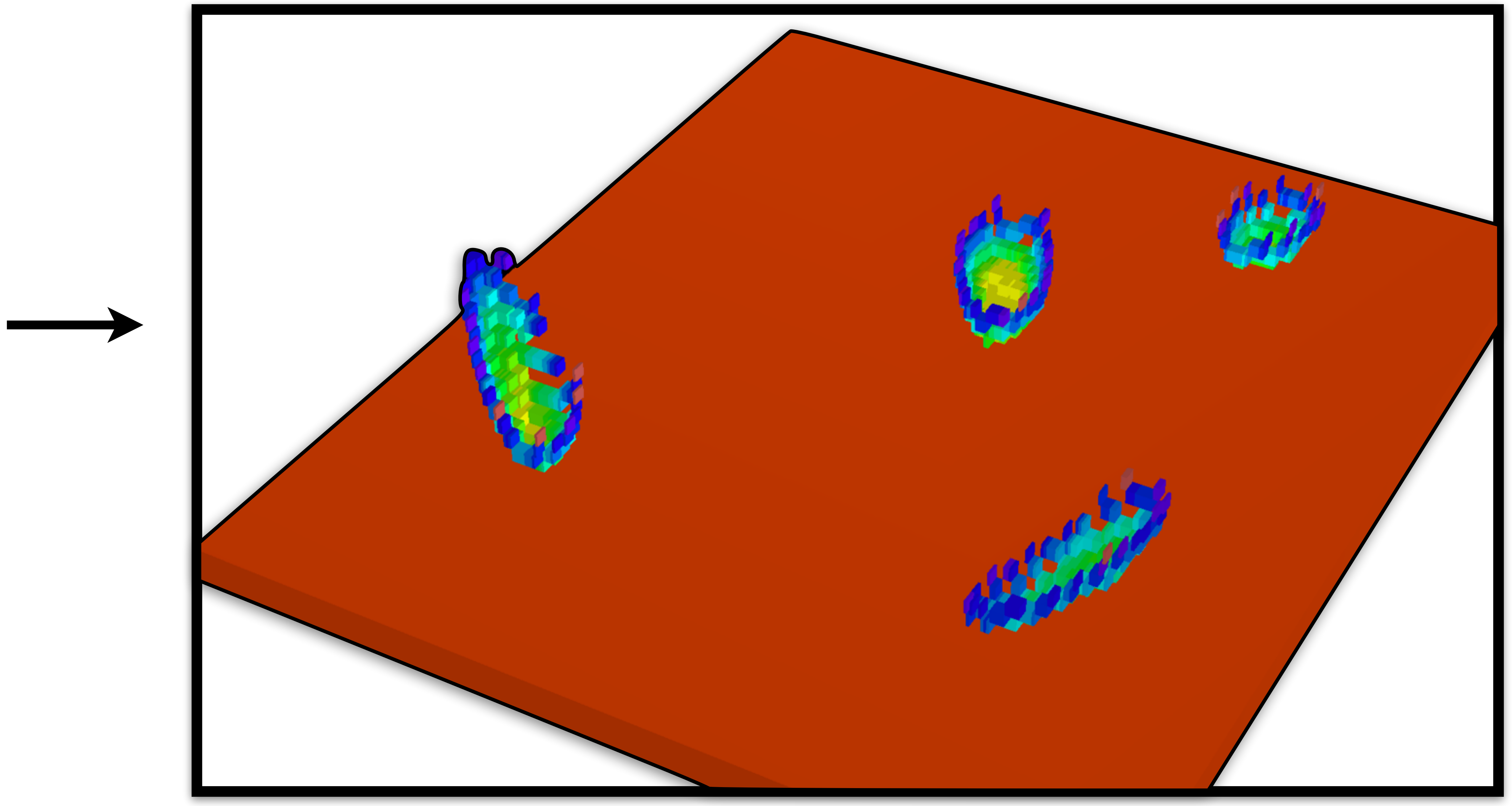


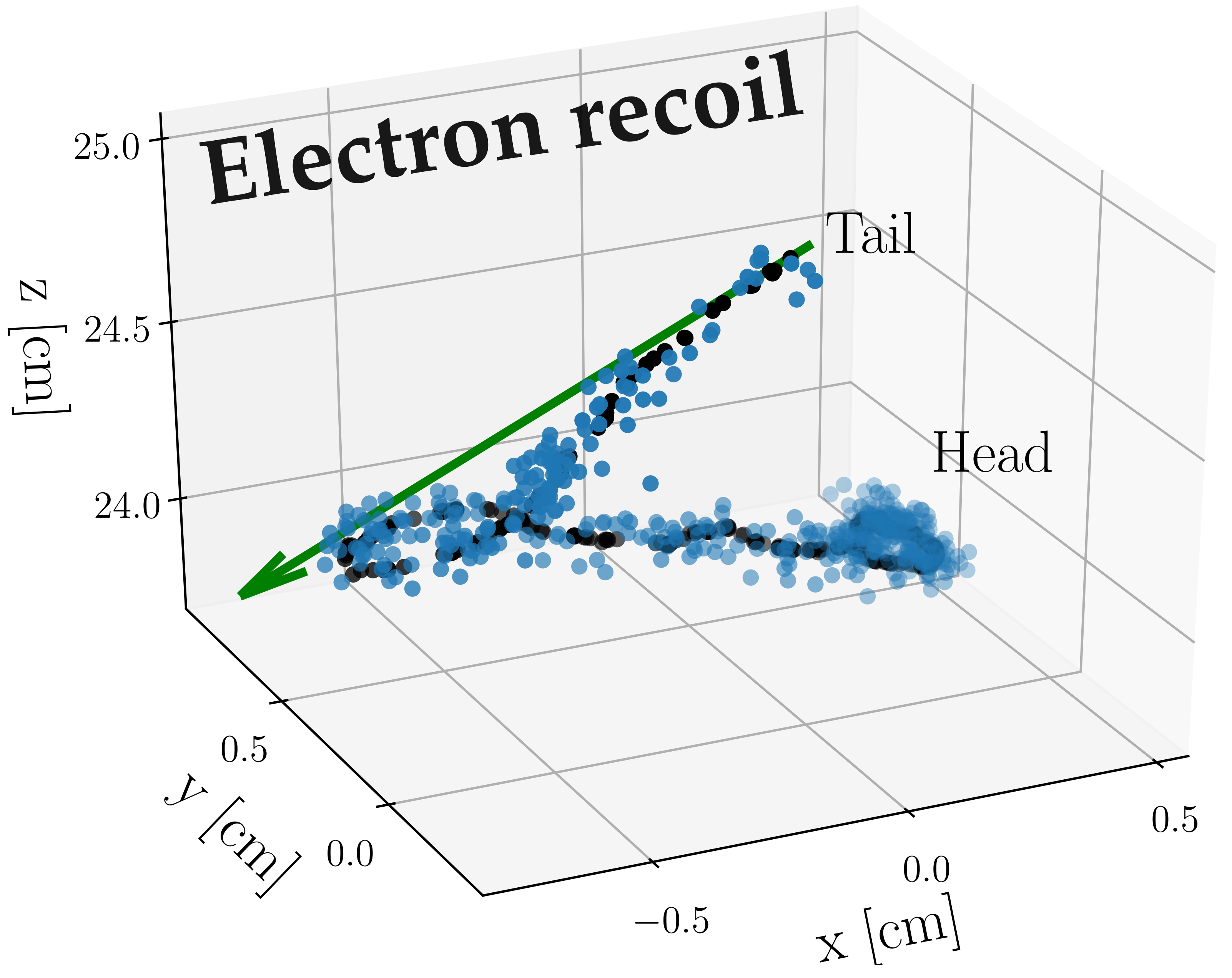


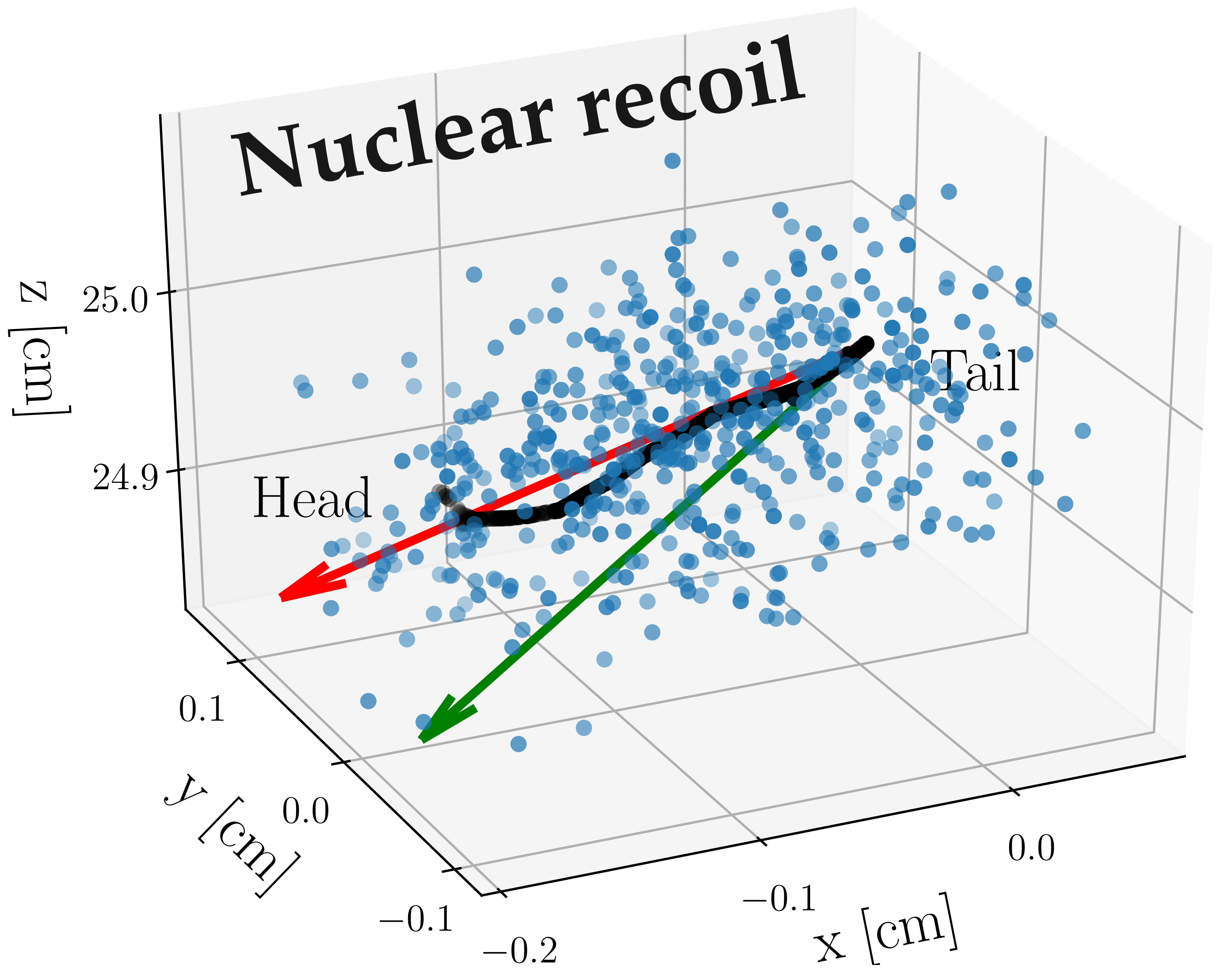
Angular performance

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 lower, harder to measure head-tail
- All this makes it harder to distinguish ER/NRs, so worse background rejection

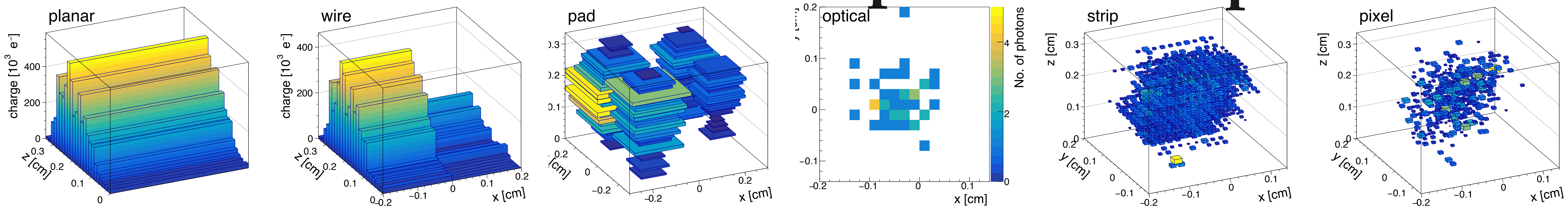
→ Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals





Readout technologies

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



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

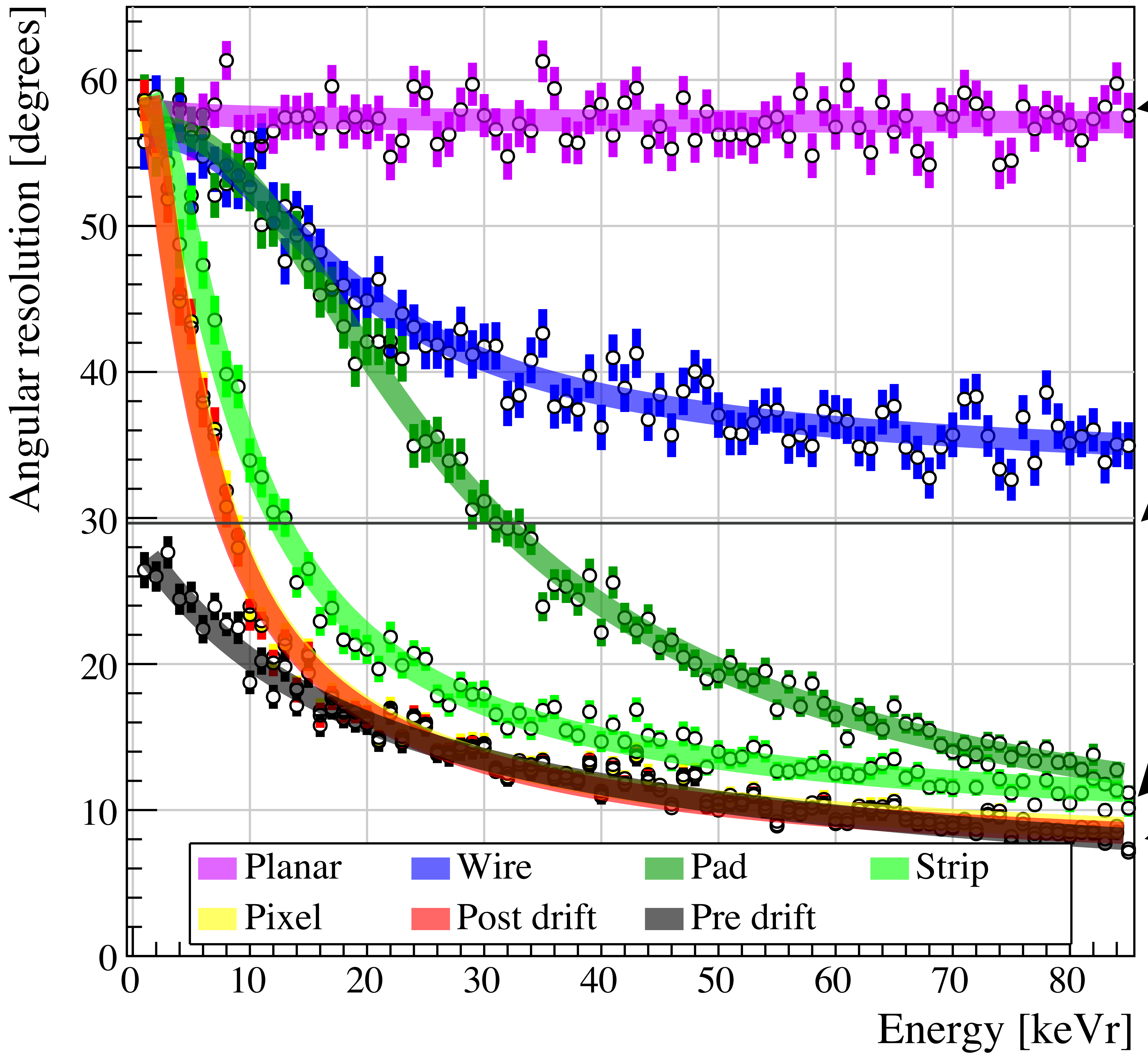
Simplest readouts
→ Worst directional sensitivity but lower cost

Most highly segmented readouts
→ Best directional sensitivity but Highest cost

Need a balance between directional performance and *cost*

Angular resolution, comparing different readouts

Dispersion in measured (axial) angles relative to initial recoil direction



Worst performance.

1 rad. = No directional sensitivity

Rough requirement for neutrino/DM discrimination

Strip: Best cost/performance trade-off

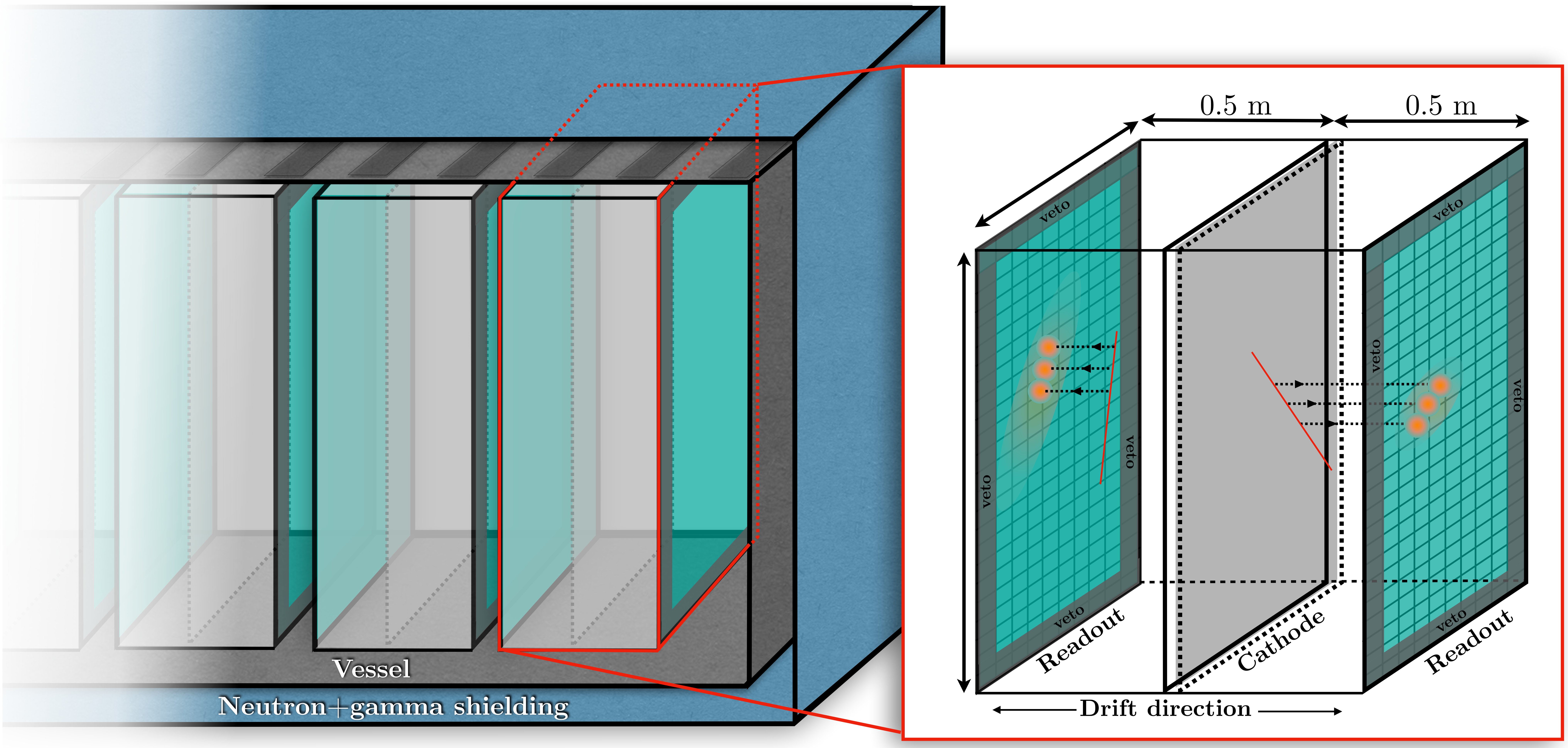
Optimal performance.

Main thing limiting readouts from optimal performance is diffusion

How to scale up?

Modularity is both necessary, and advantageous

CYGNUS-Nm^3 **CYGNUS**-10 m^3 module



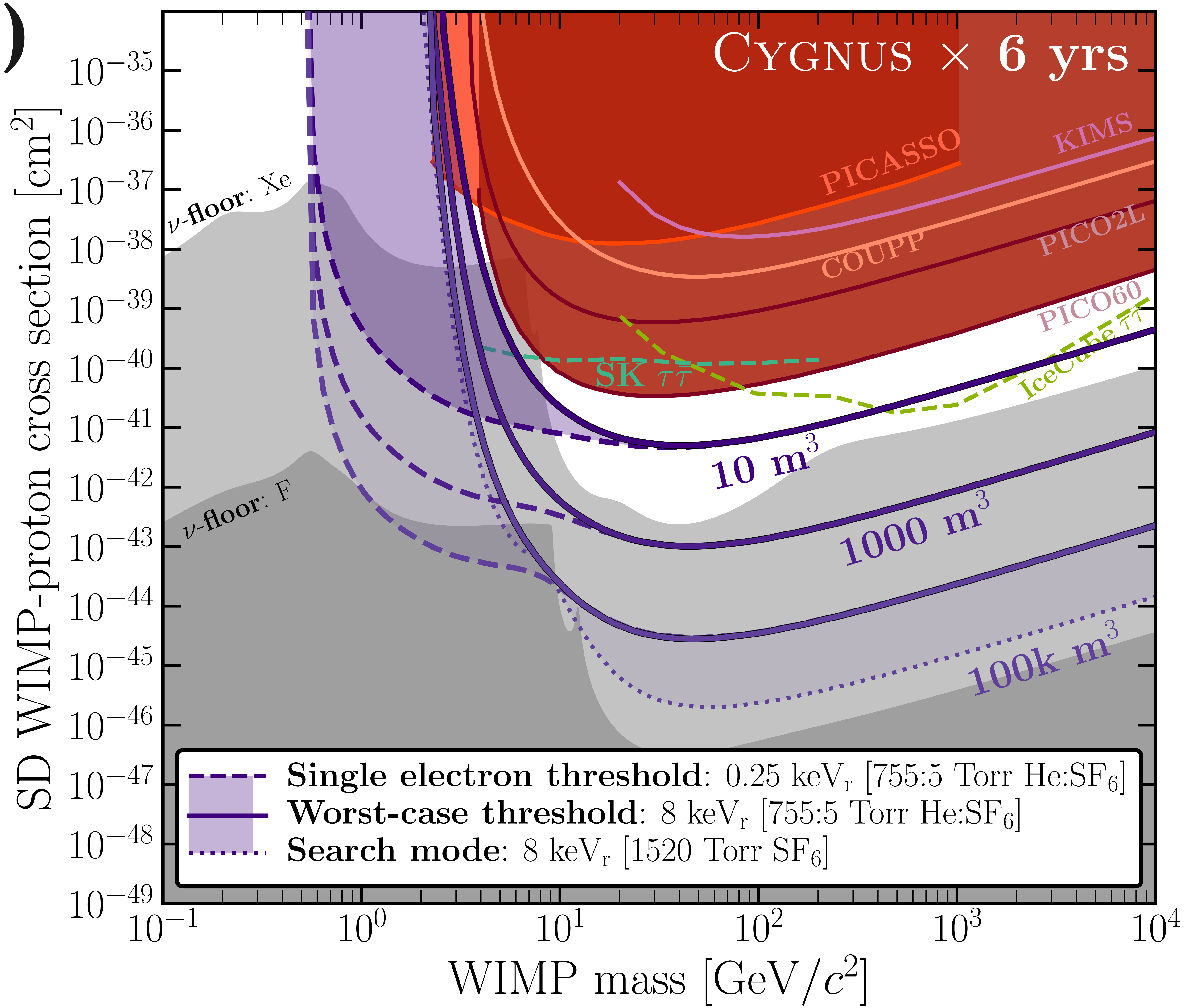

CYGNUS
CYGNUS-10
Boulby, UK
CYGNUS-KM
Kamioka, Japan
CYGNUS-HD10
Lead, South Dakota
CYGNO
Gran Sasso, Italy
CYGNUS-OZ
Stawell, Aus.
CYGNUS-Andes
Chile/Argentina

Sensitivity (SD-p)

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

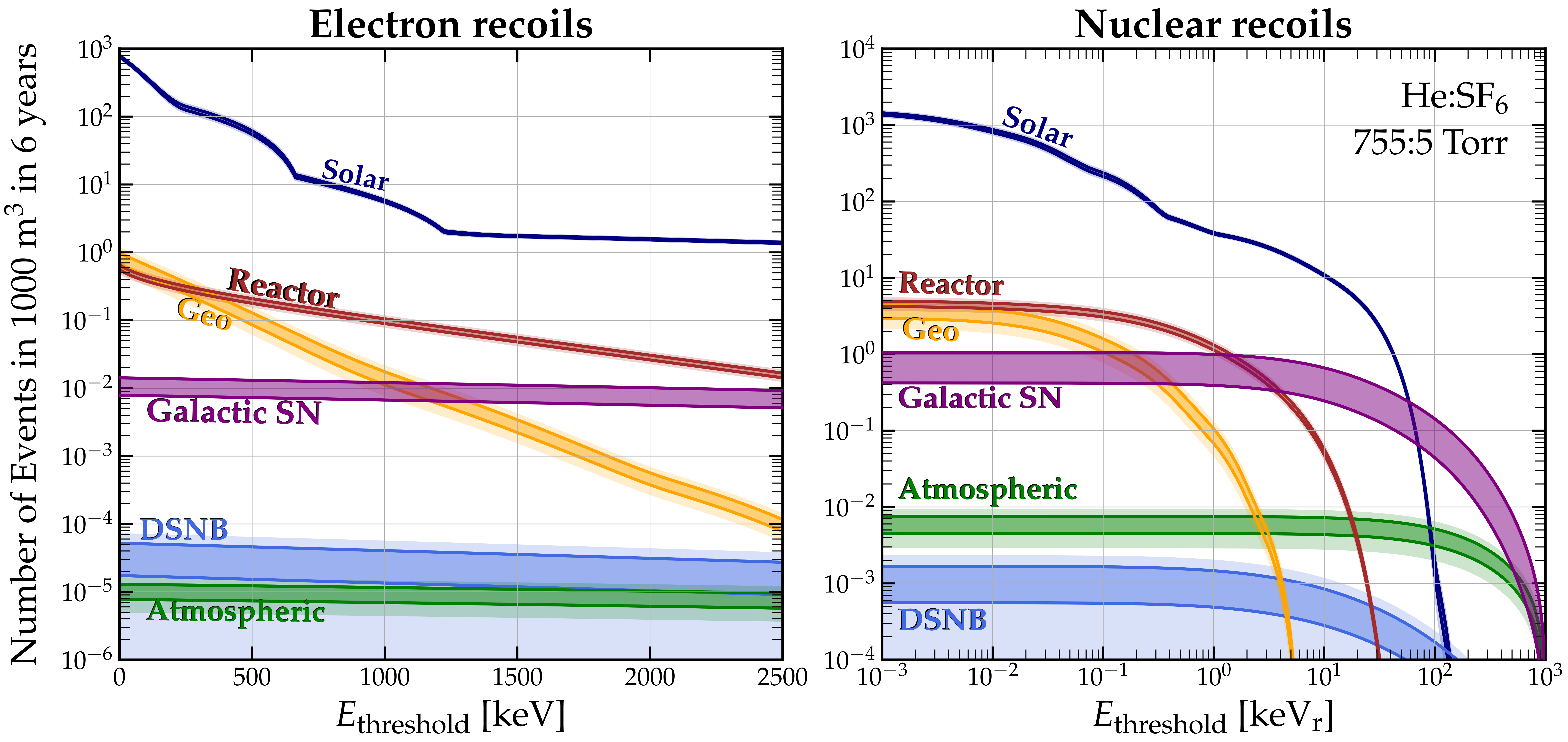
→ He does not set limits on this cross section

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



Directionality beyond dark matter

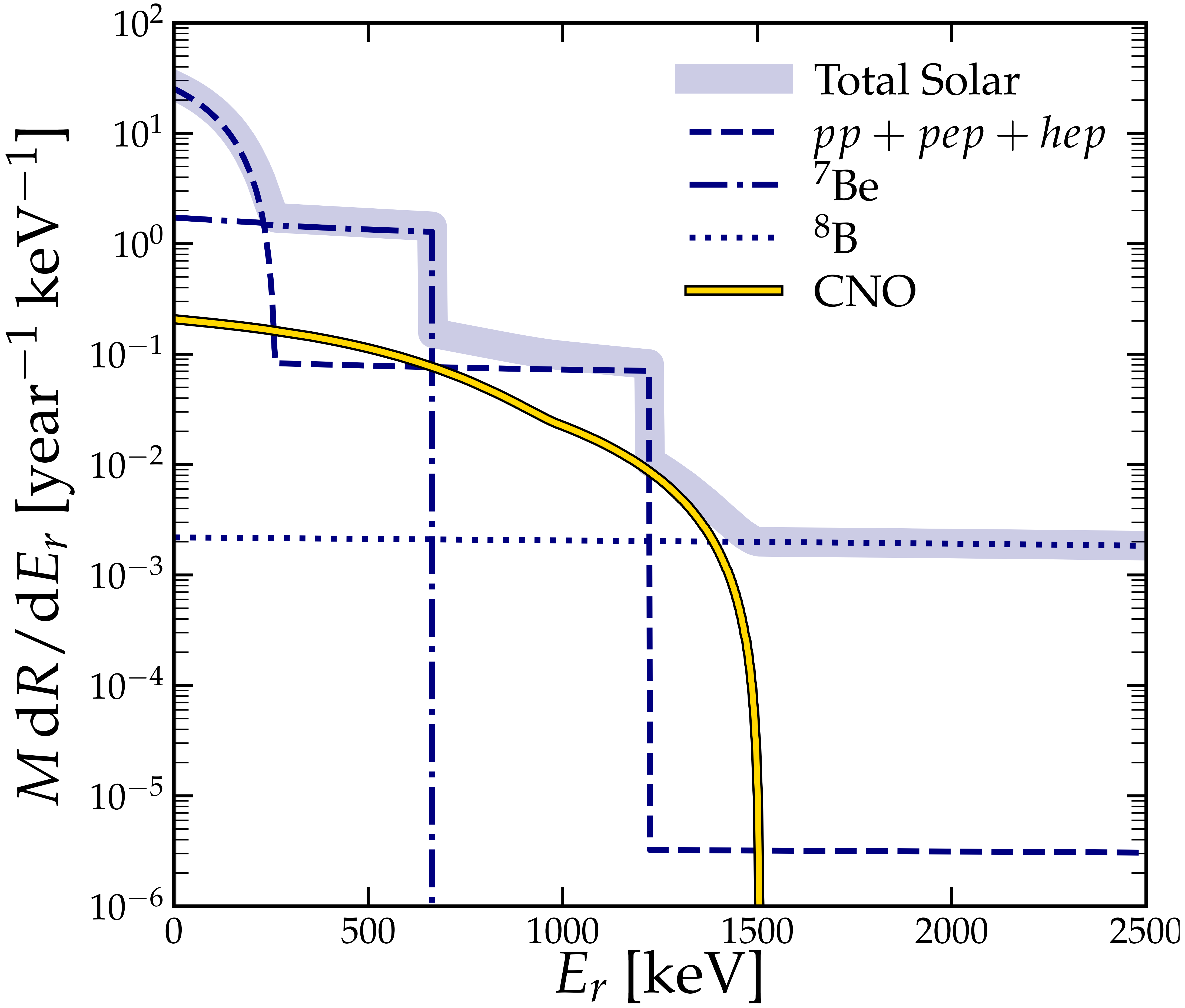
A directional detector has the potential for superior background rejection and NR/ER discrimination
→ this is true even if we're not interested about DM below the neutrino floor



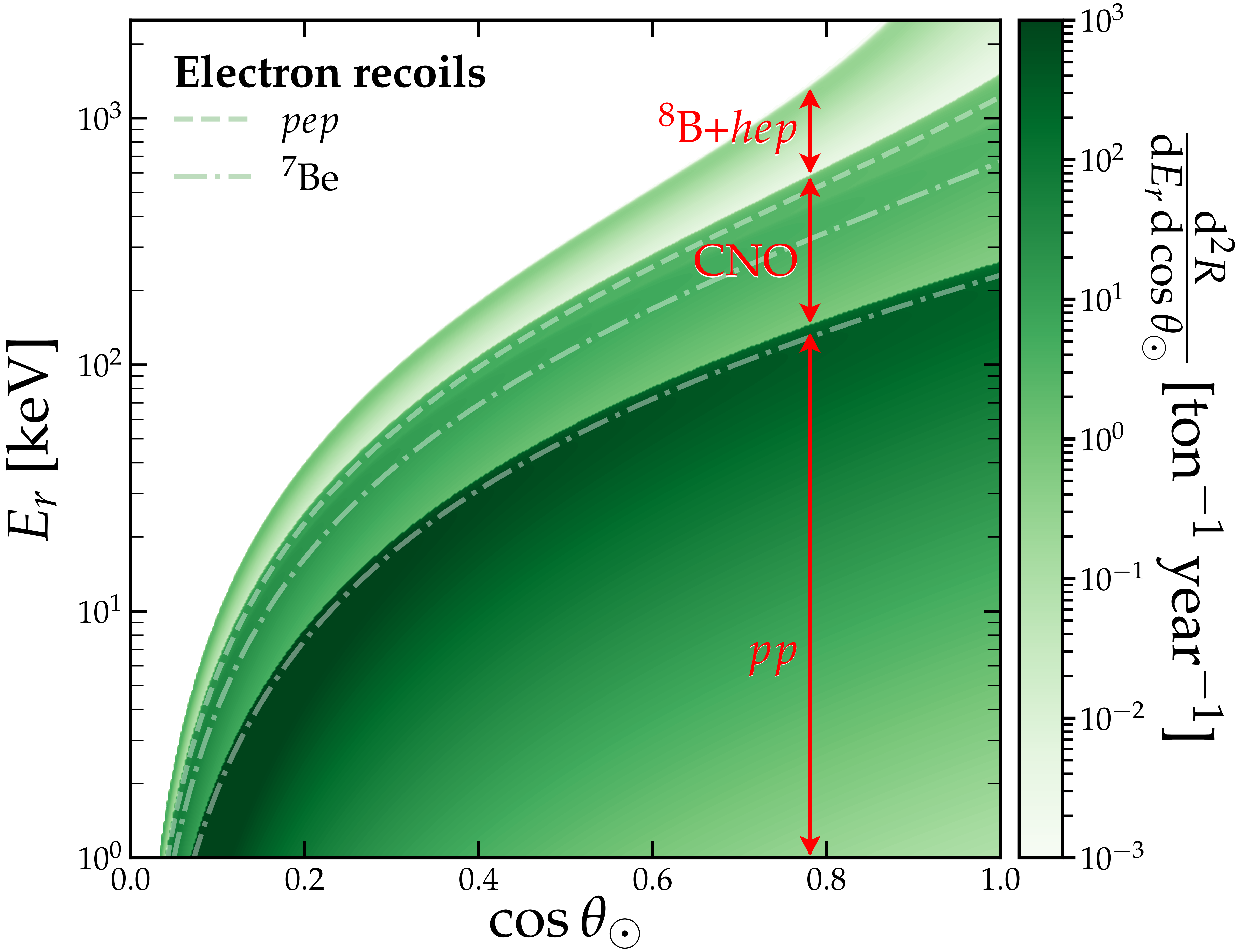
CYGνS?

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

Recoil energy spectrum (ERs)



Recoil energy-angle spectrum (ERs)



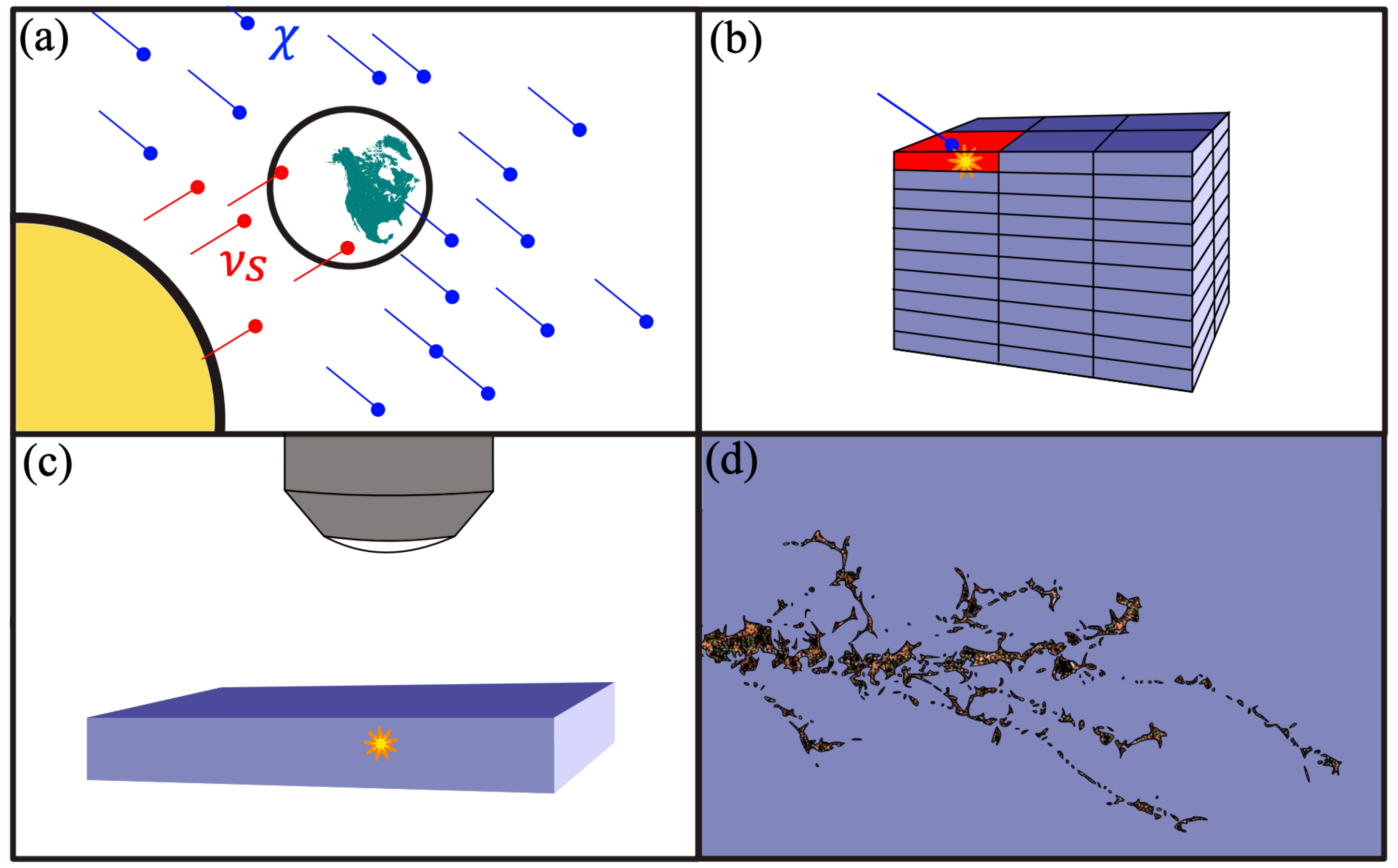
Beyond gas TPCs

What are the main limitations of the gas approach?

1. Target density
2. Diffusion

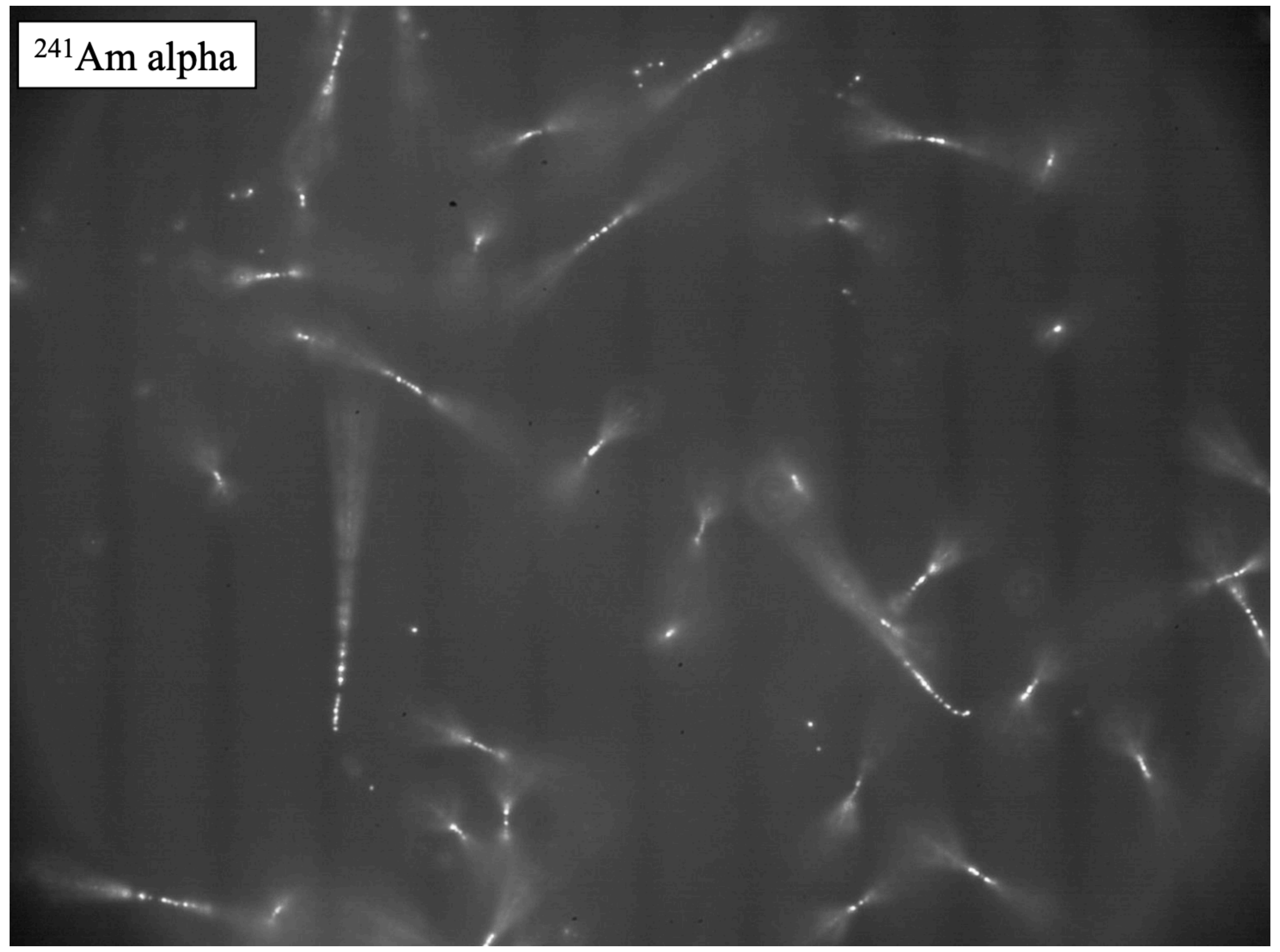
Directionality in solids

Nitrogen vacancy centres in diamond



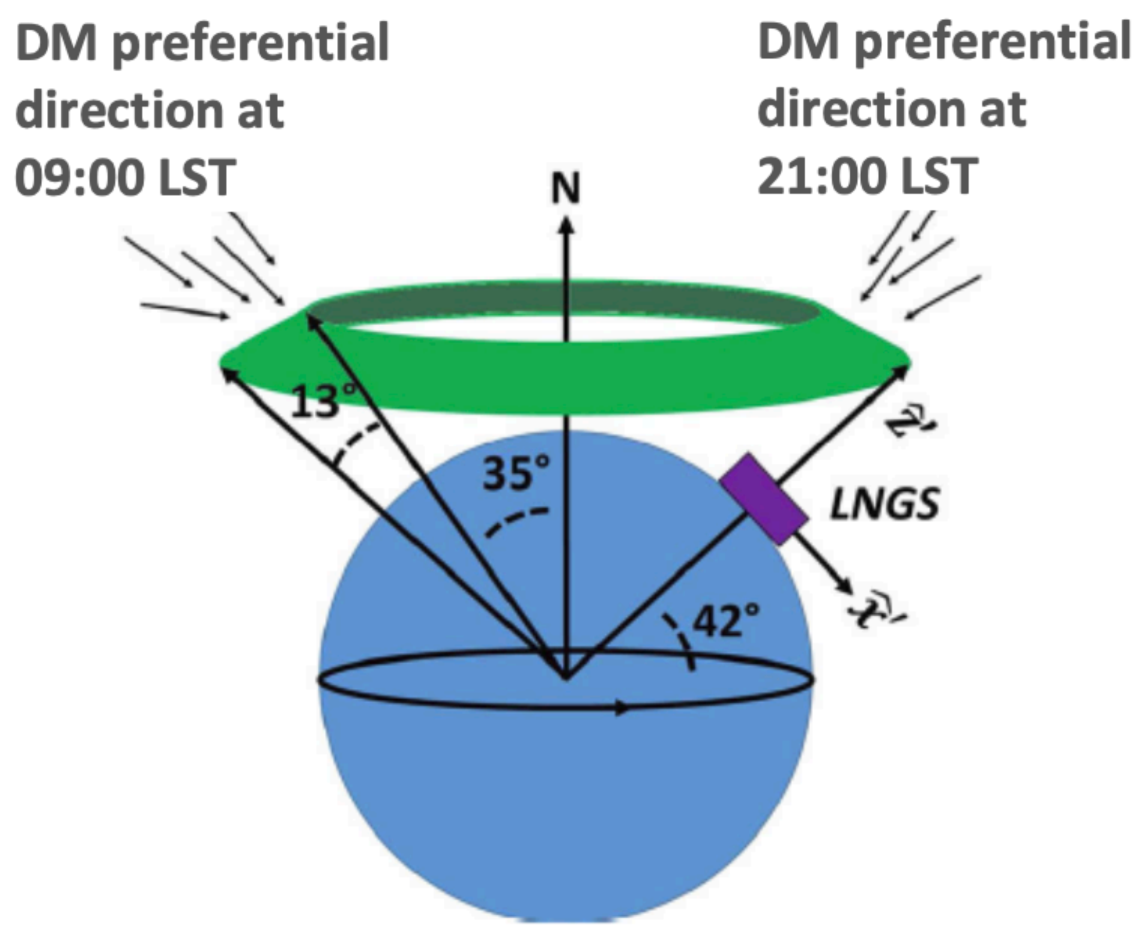
Marshall et al. [2009.01028]

Nuclear emulsions (NEWSdm)



T. Asada 1604.04199

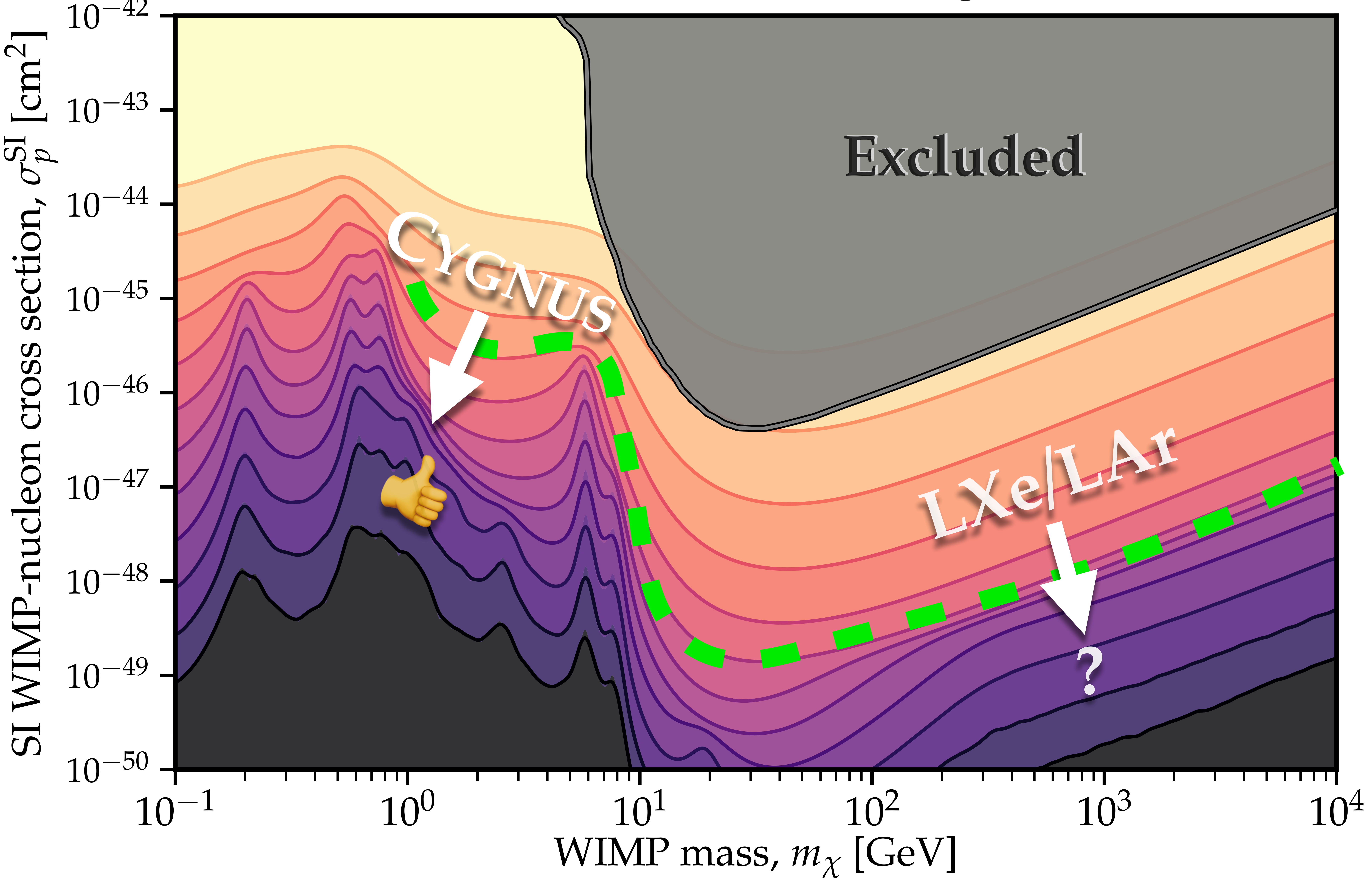
Anisotropic scintillators (ADAMO)



A. diMarco

Solid-state resolves both issues faced by gas (density/diffusion) but comes with additional challenges, e.g. scrambling of recoil directions or costly nano-scale imaging

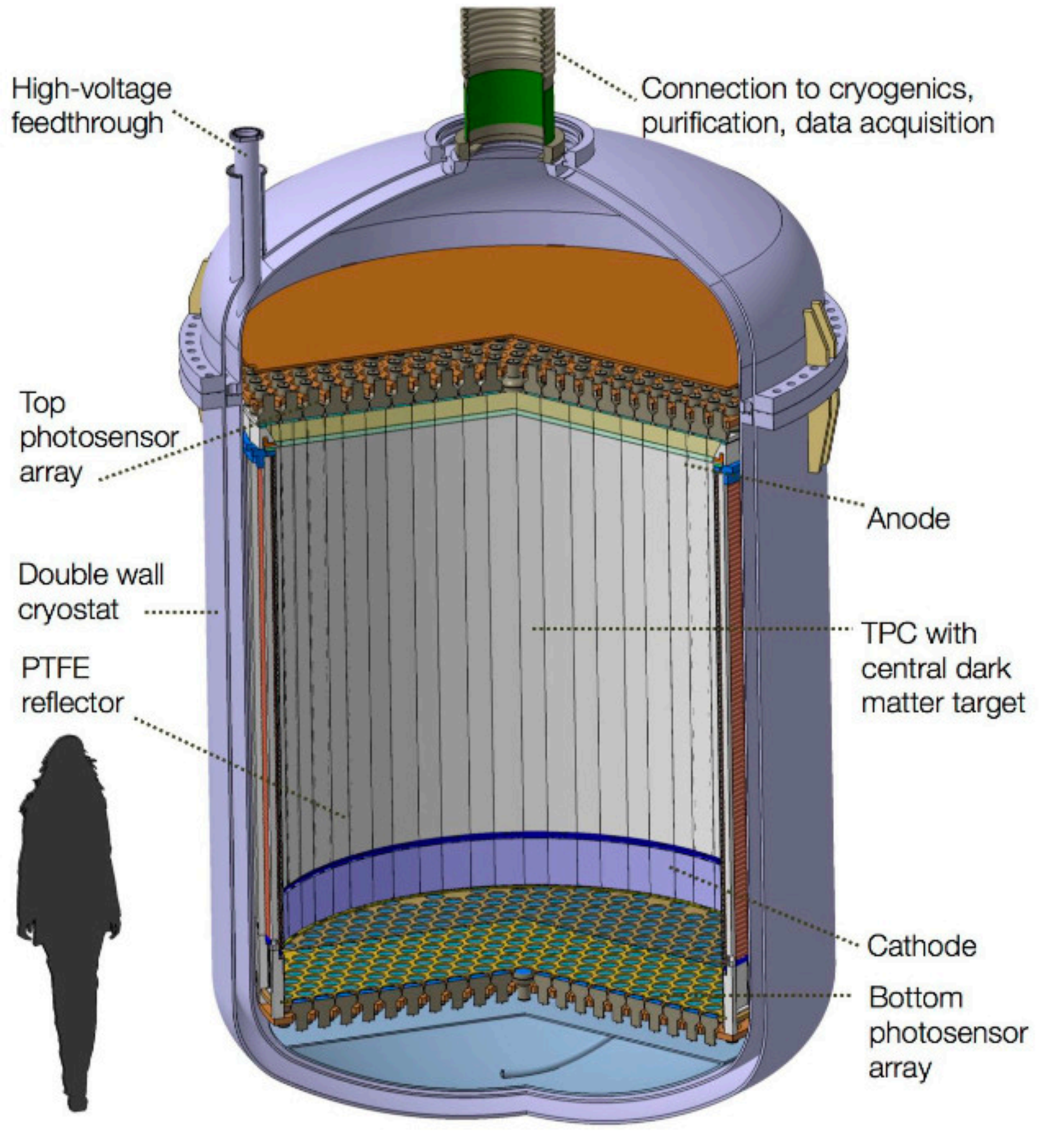
The neutrino fog

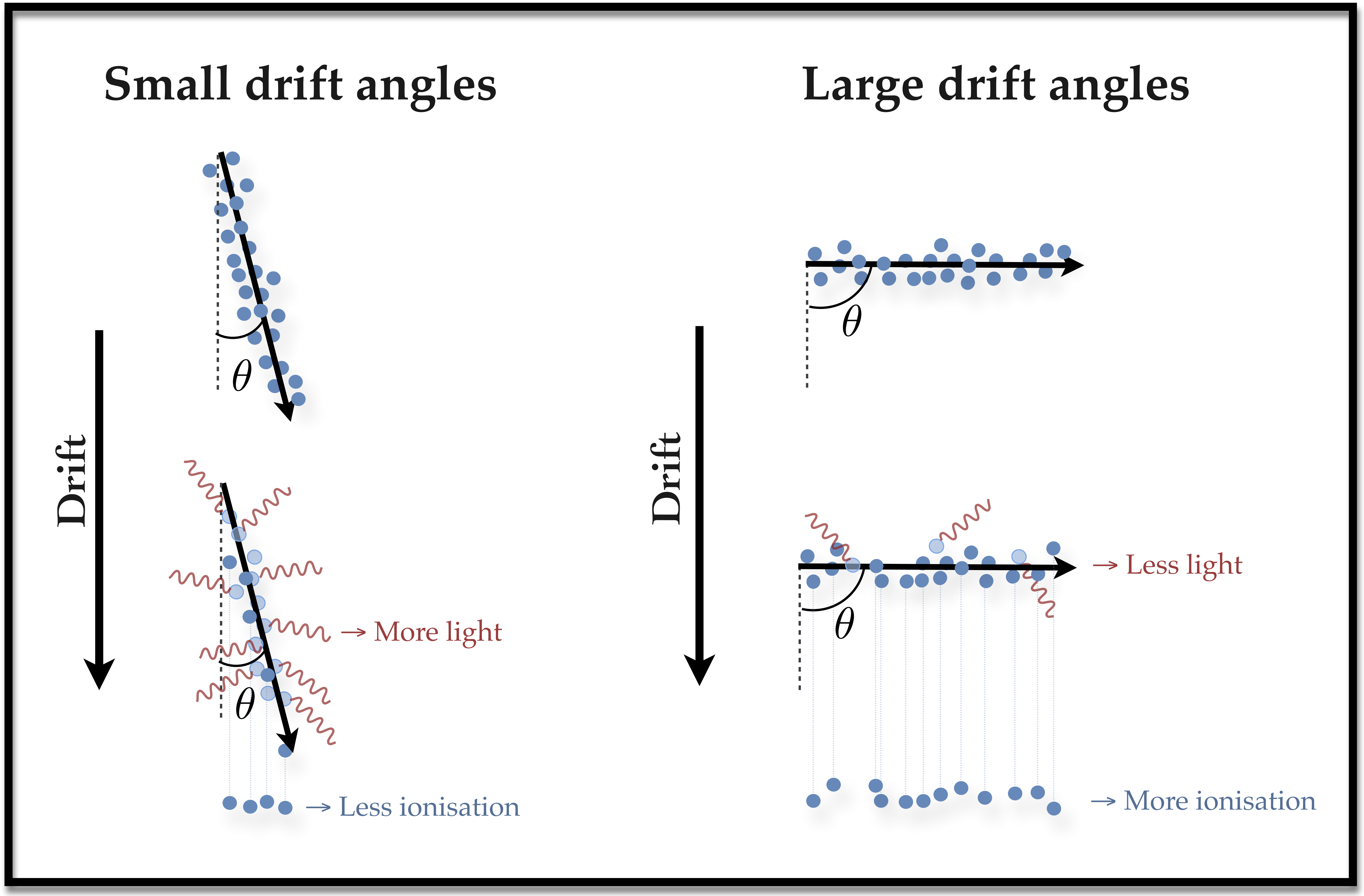


Directionality in liquids: columnar recombination

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





Directionality in liquids: columnar recombination

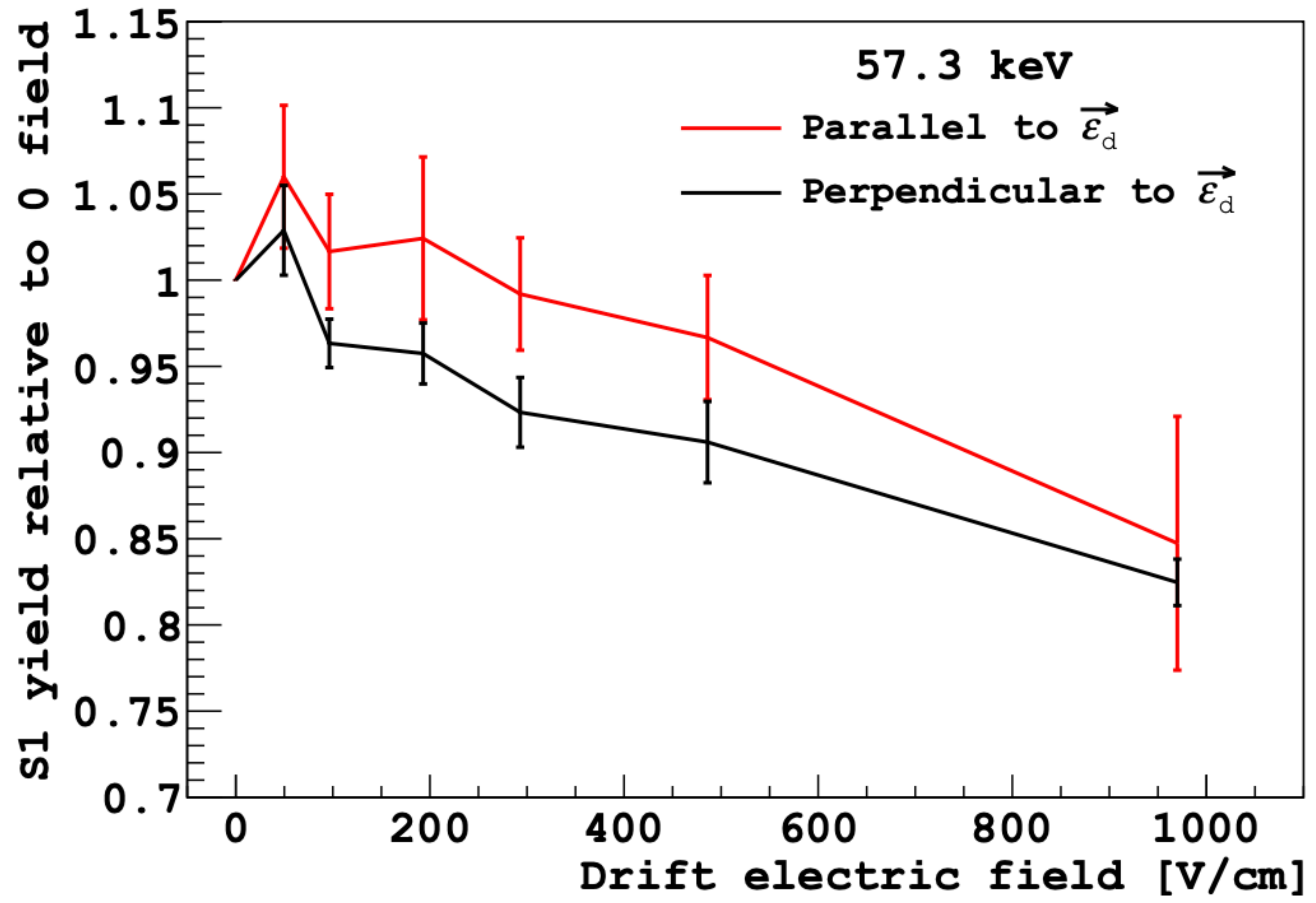
- Possible hint in LAr

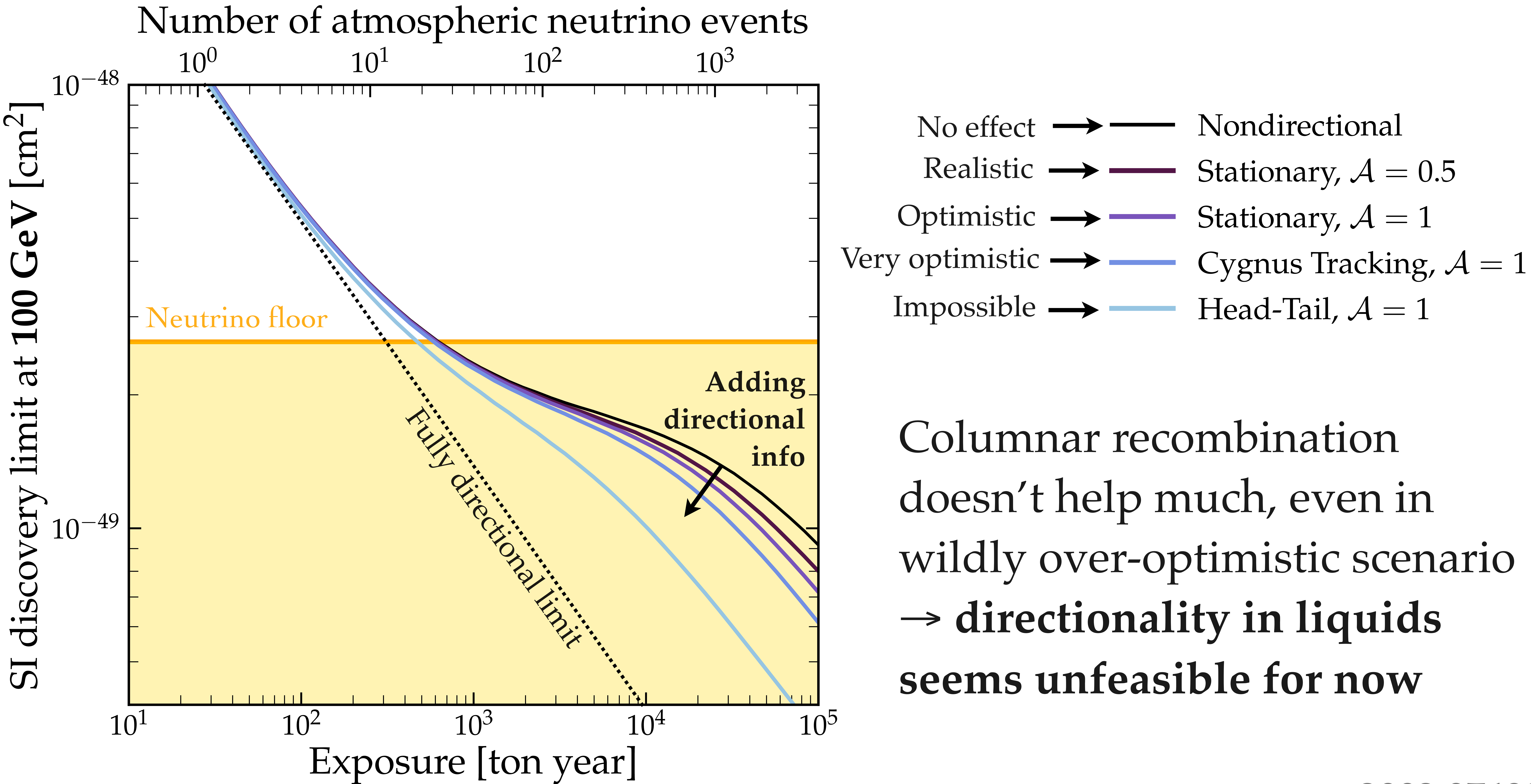
- Almost certainly unobservable in LXe (at interesting energies, though GXe is a possibility)

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

1406.4825

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 → **directionality in liquids seems unfeasible for now**

2002.07499

What about a radical re-thinking?

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*

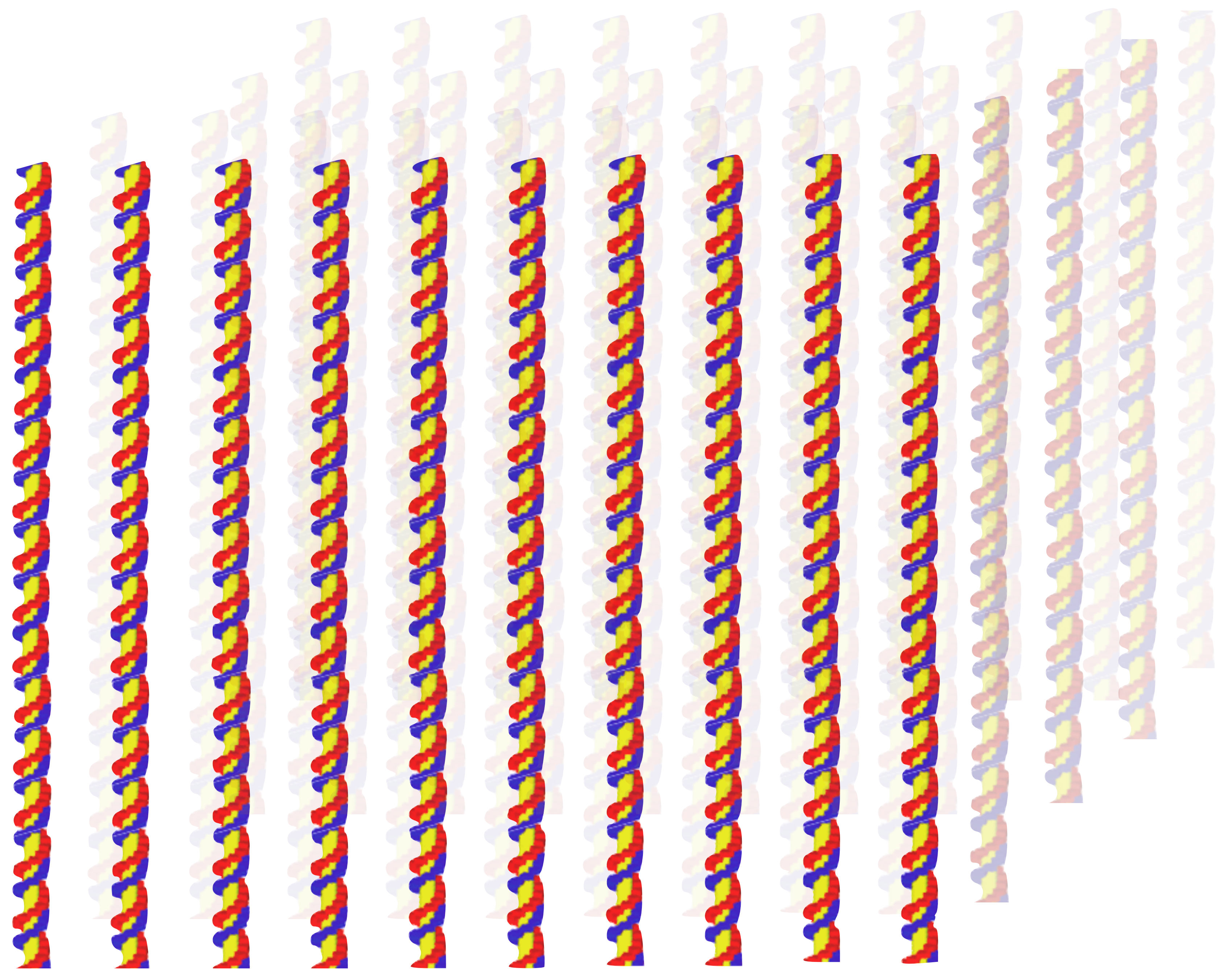
[2] *Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109*

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

1206.6809

DNA-based particle detector?

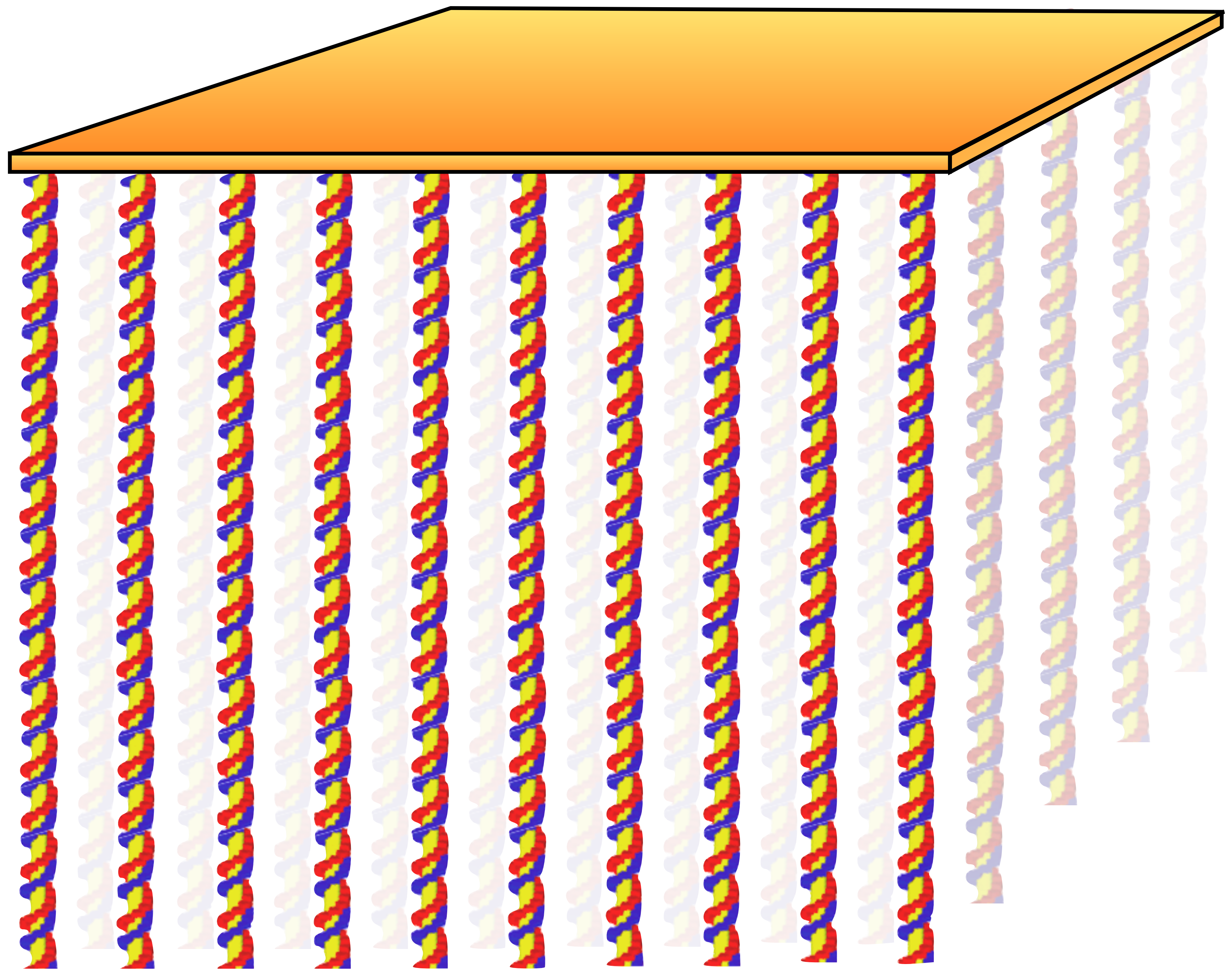
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases



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?

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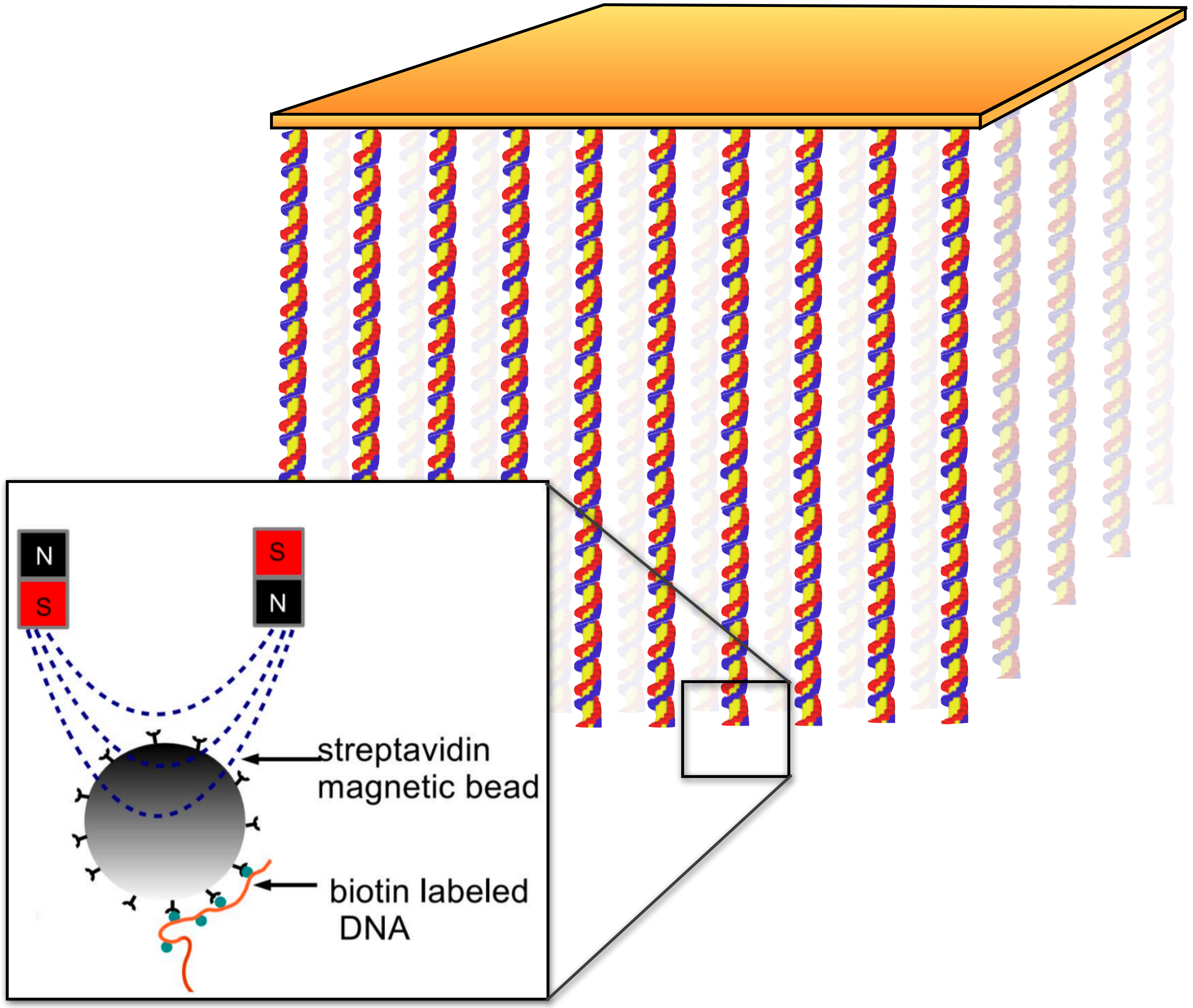
Step 3: Attach a paramagnetic bead to each strand



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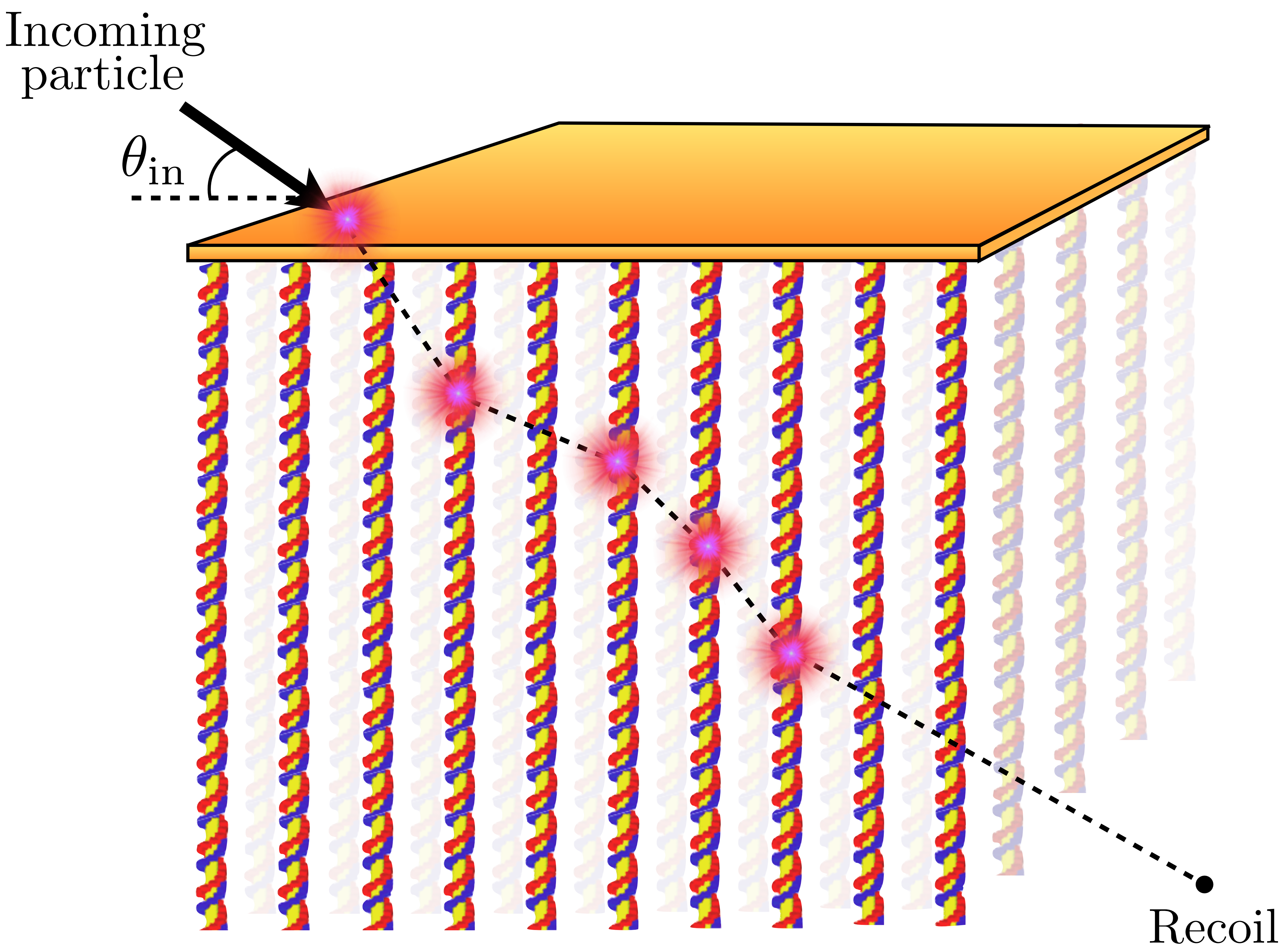
Step 4: Particles come in and break a sequence of bases



DNA-based particle detector?

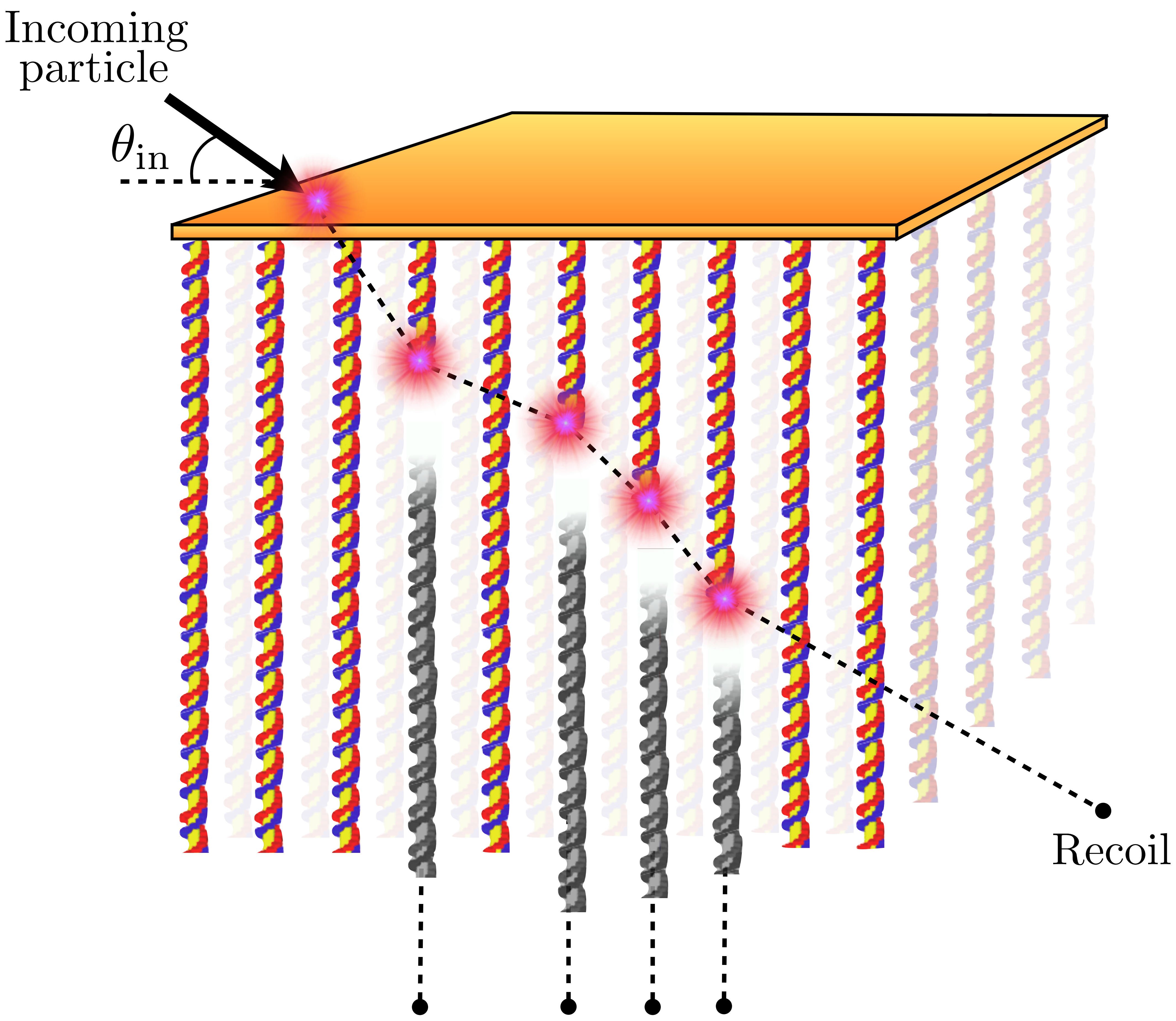
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases

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



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

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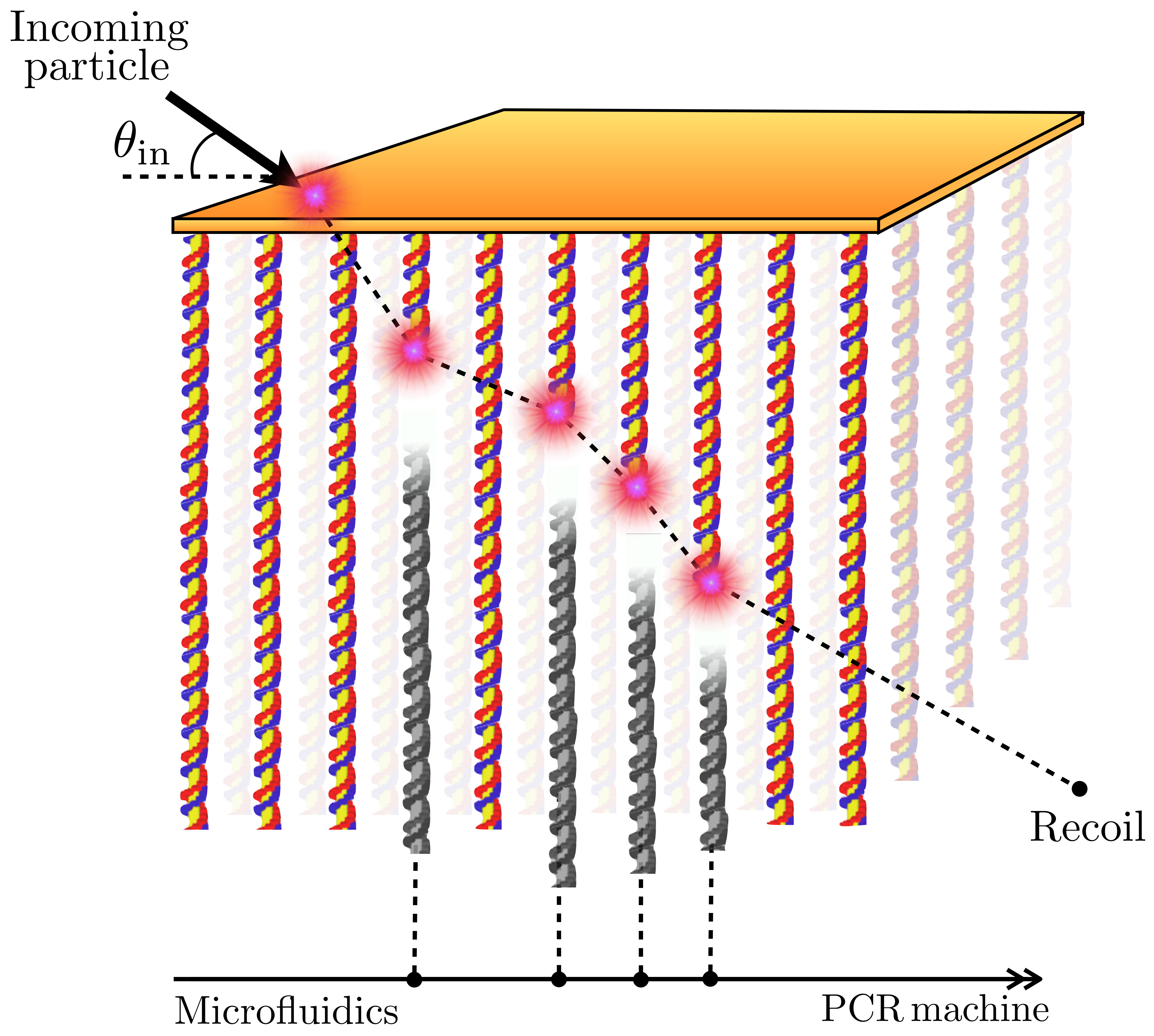
Step 6: System of microfluidics transports the strand segments to a PCR machine which amplifies them and the original (x,y,z) positions are reconstructed

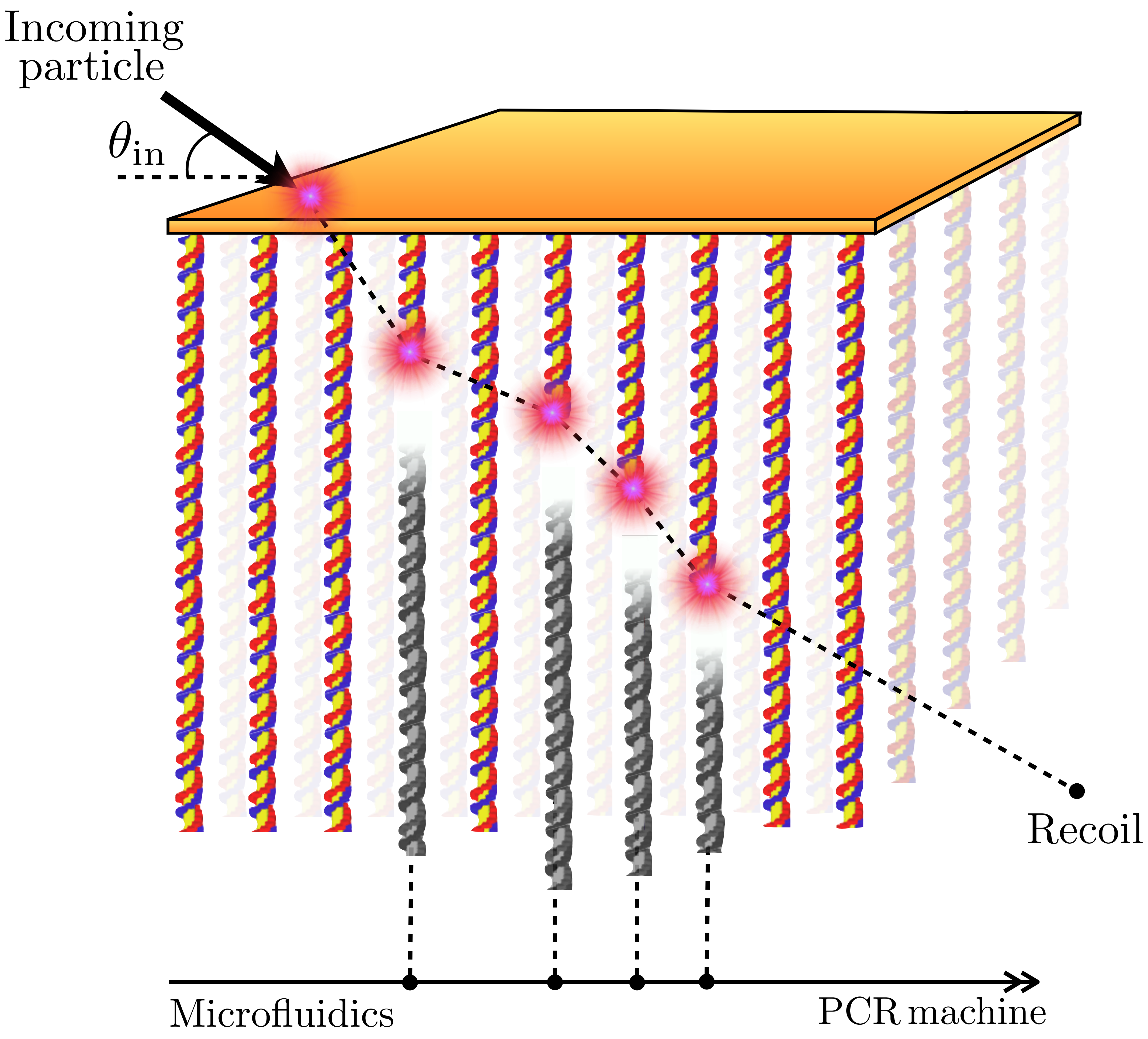


DNA-based particle detector?

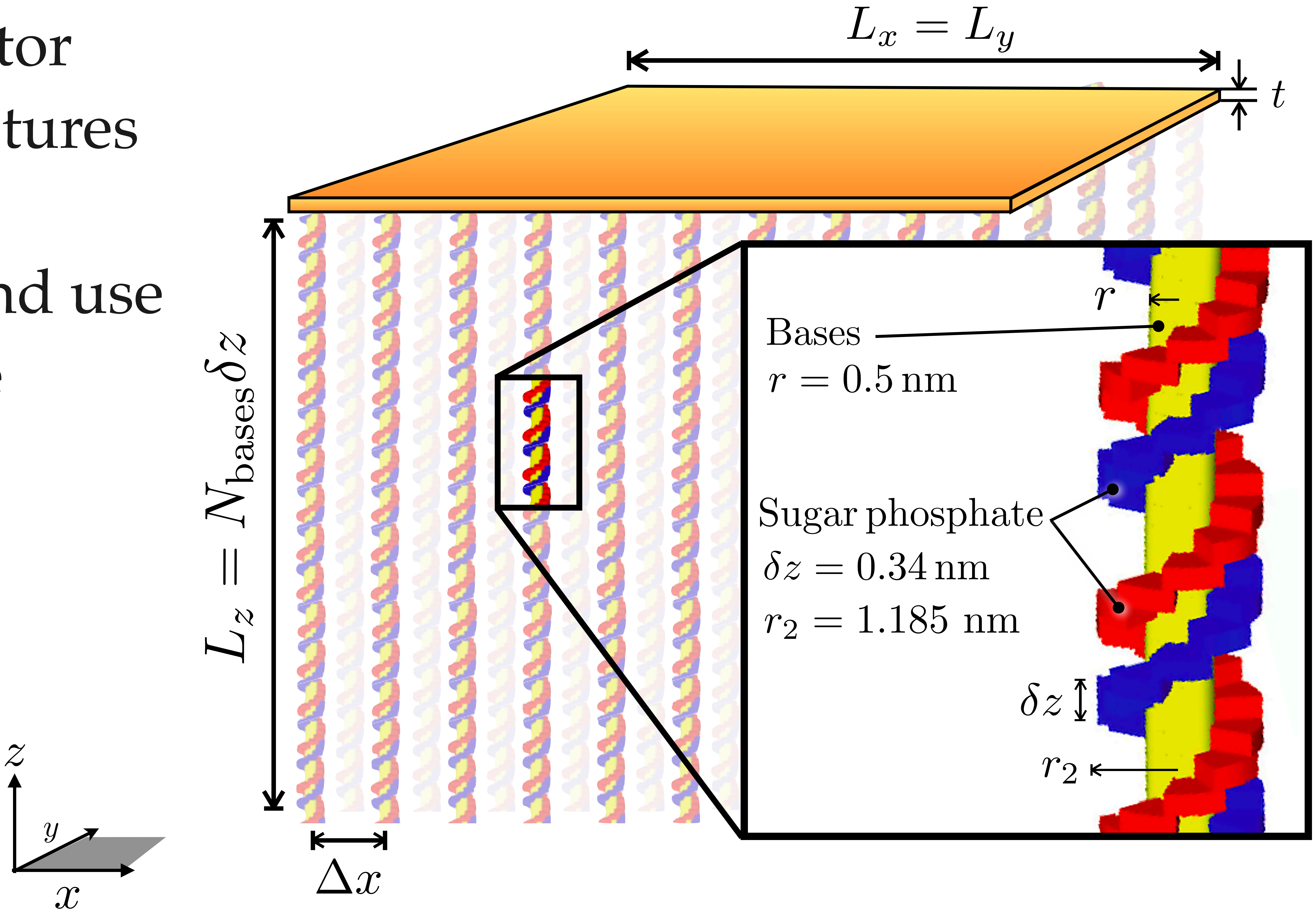
How crazy is it?

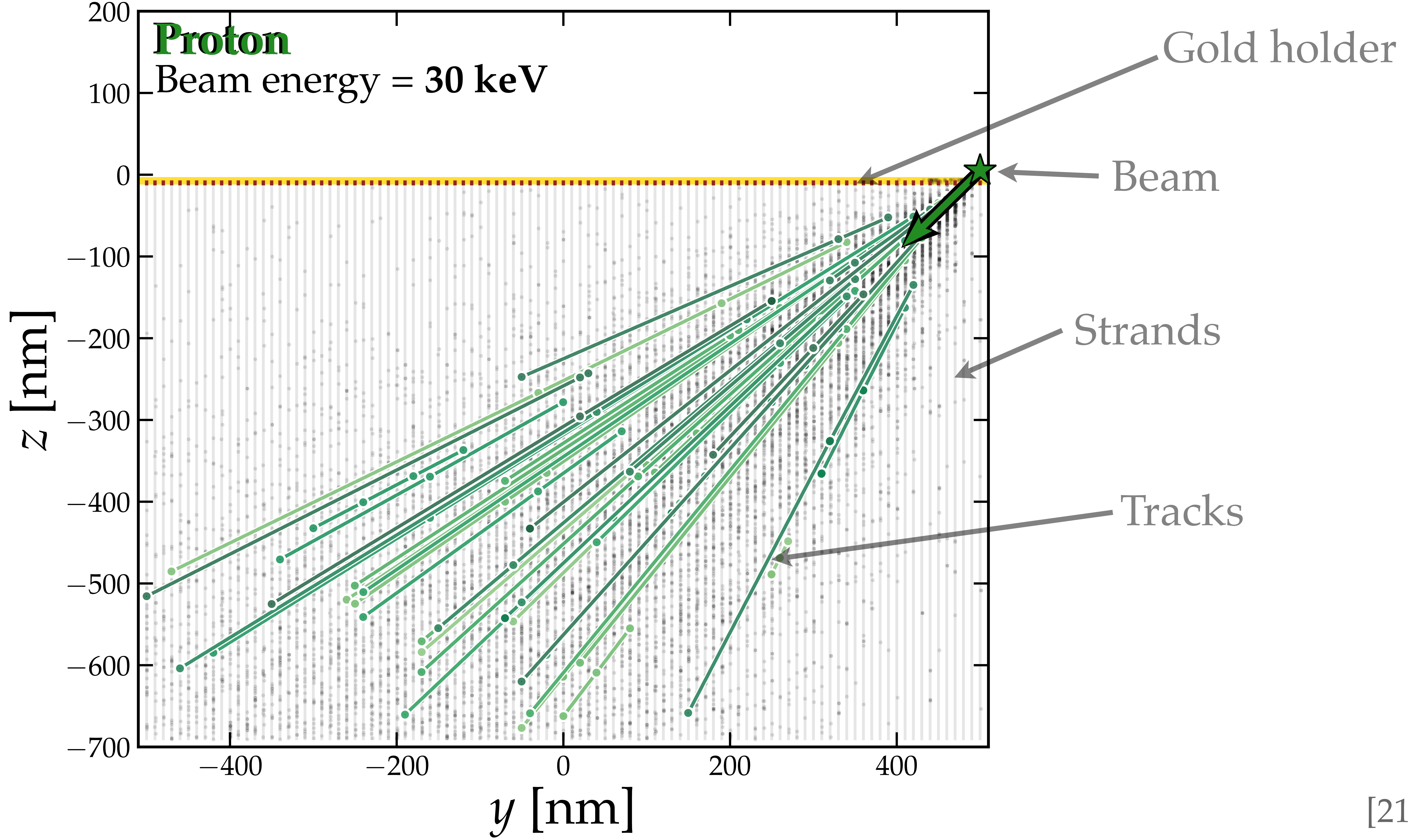
Putting aside the obvious experimental challenge, there is a clear advantage in the context of directional detection

→ No diffusion and no nanoscale interrogation required

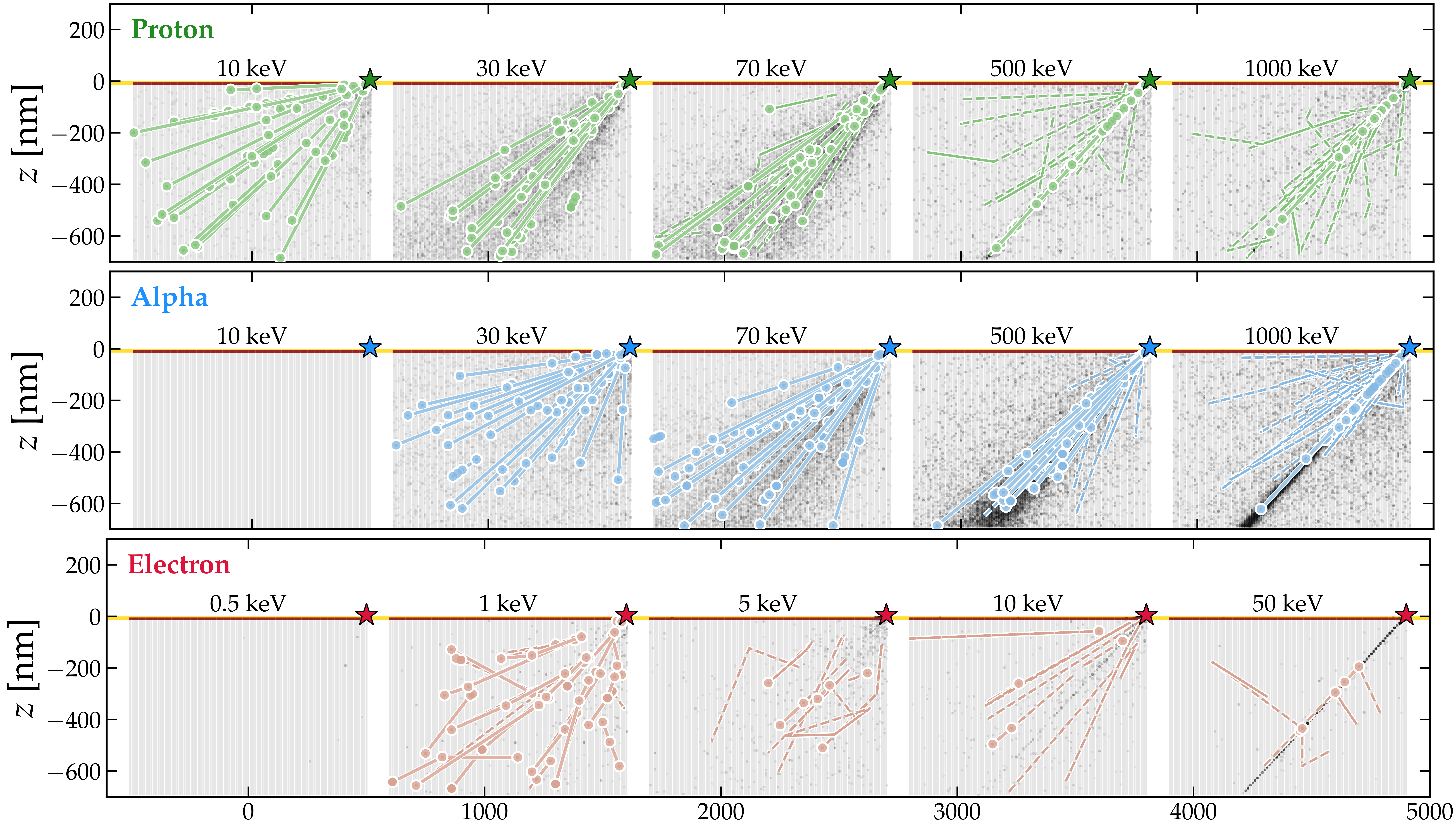


Idea: Lets make a crude model of the detector which roughly captures the geometry and material content and use Geant4 to simulate particle tracks

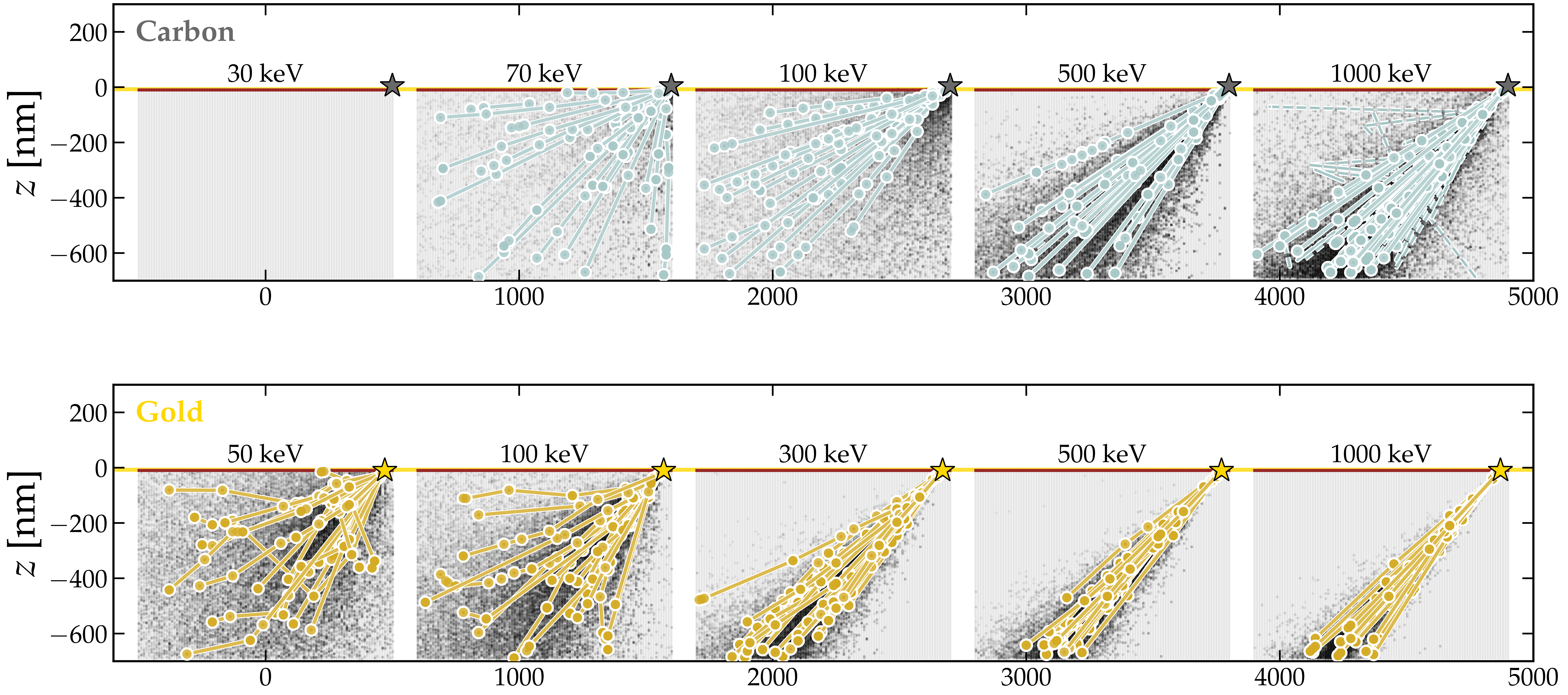



Proton
Beam energy = 30 keV
Gold holder
Beam
Strands
Tracks
z [nm]
y [nm]
200
100
0
−100
−200
−300
−400
−500
−600
−700
−400
−200
0
200
400

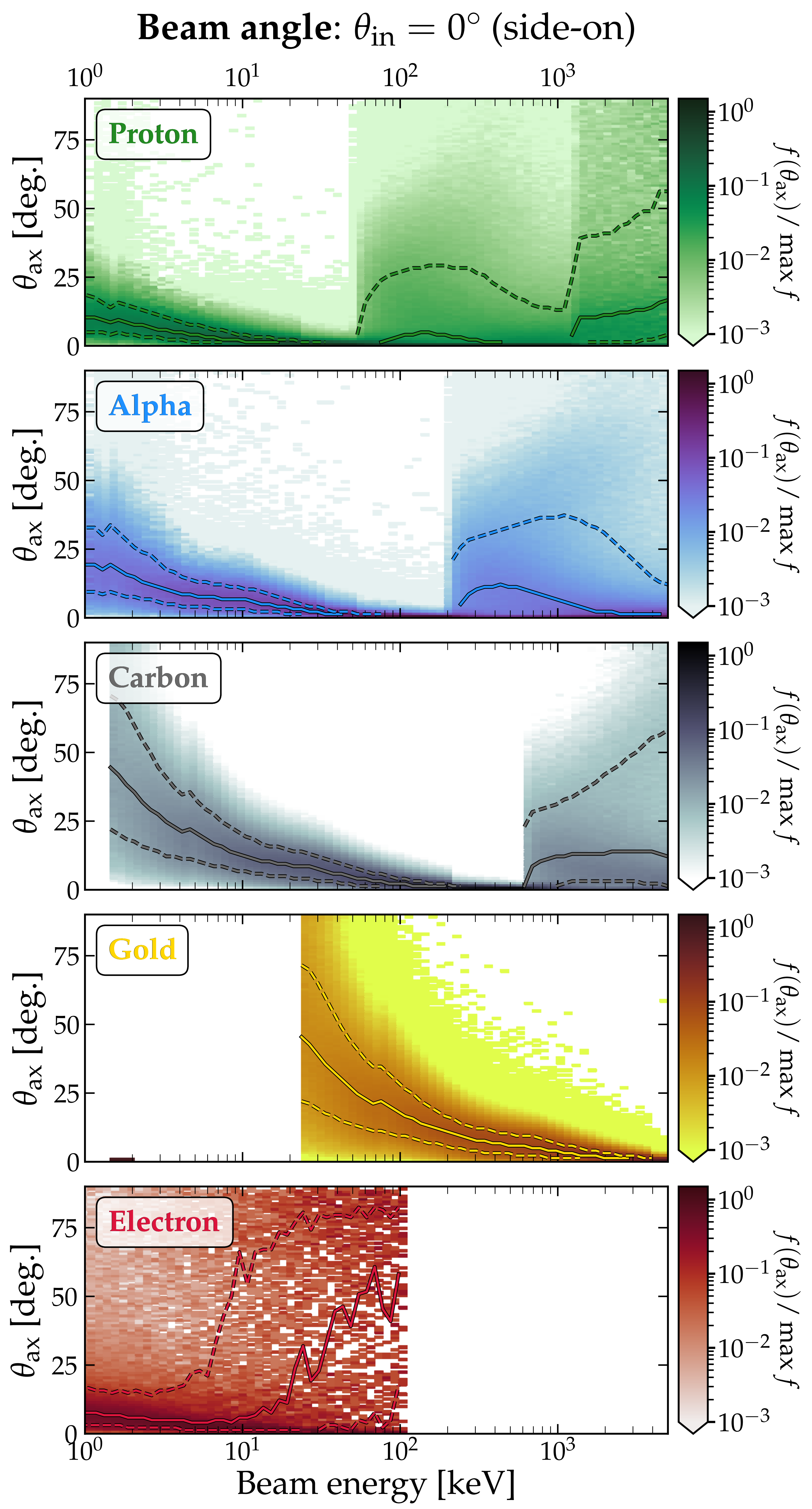
[2105.11949]


Proton
10 keV
30 keV
70 keV
500 keV
1000 keV
Alpha
10 keV
30 keV
70 keV
500 keV
1000 keV
Electron
0.5 keV
1 keV
5 keV
10 keV
50 keV
z [nm]
200
0
−200
−400
−600
0
1000
2000
3000
4000
5000

[2105.11949]


Carbon
30 keV
70 keV
100 keV
500 keV
1000 keV
Gold
50 keV
100 keV
300 keV
500 keV
1000 keV
z [nm]
200
0
−200
−400
−600
0
1000
2000
3000
4000
5000

[2105.11949]



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…

[2105.11949]

Experimental side

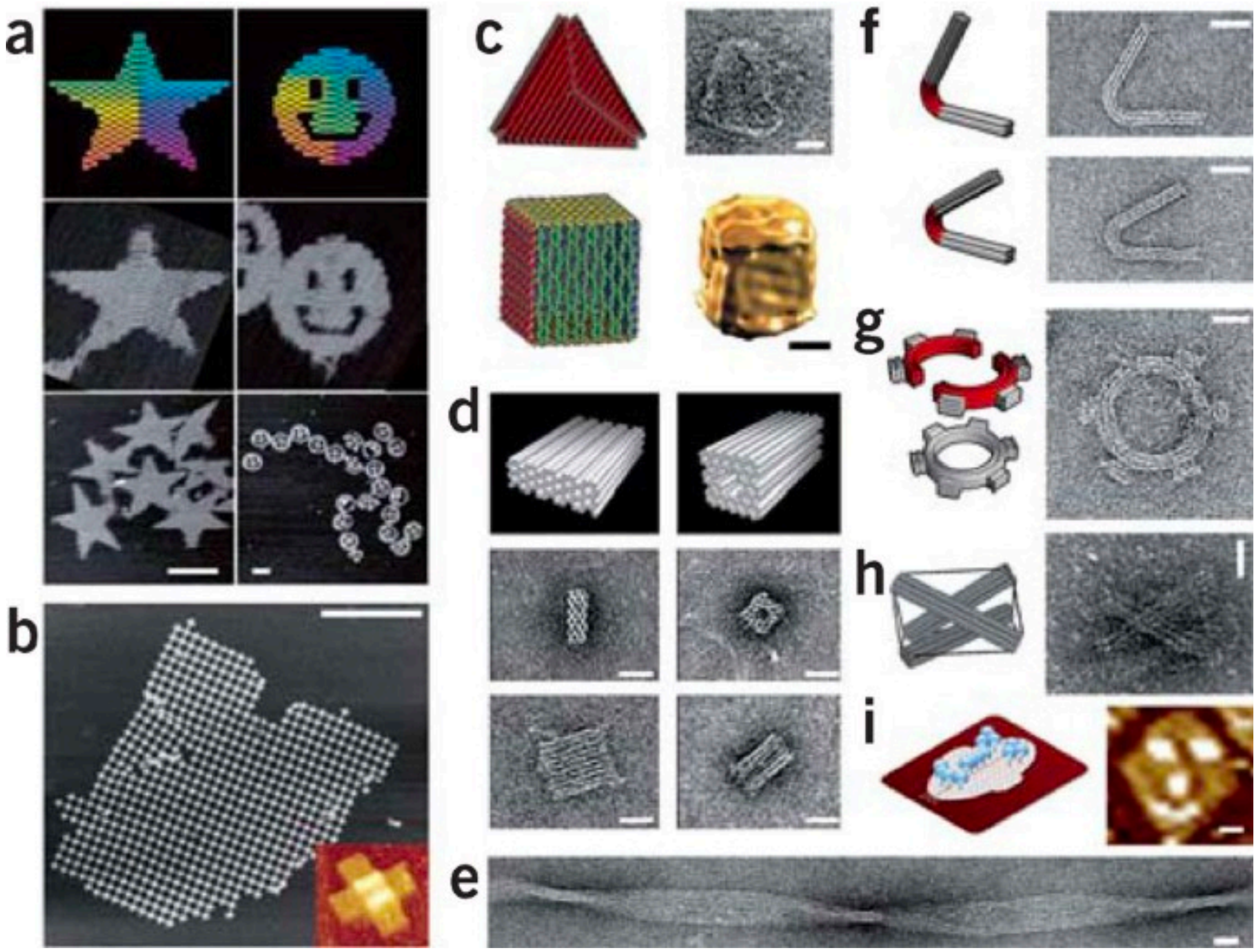
- **Detector construction →** DNA-origamists can make practically anything

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

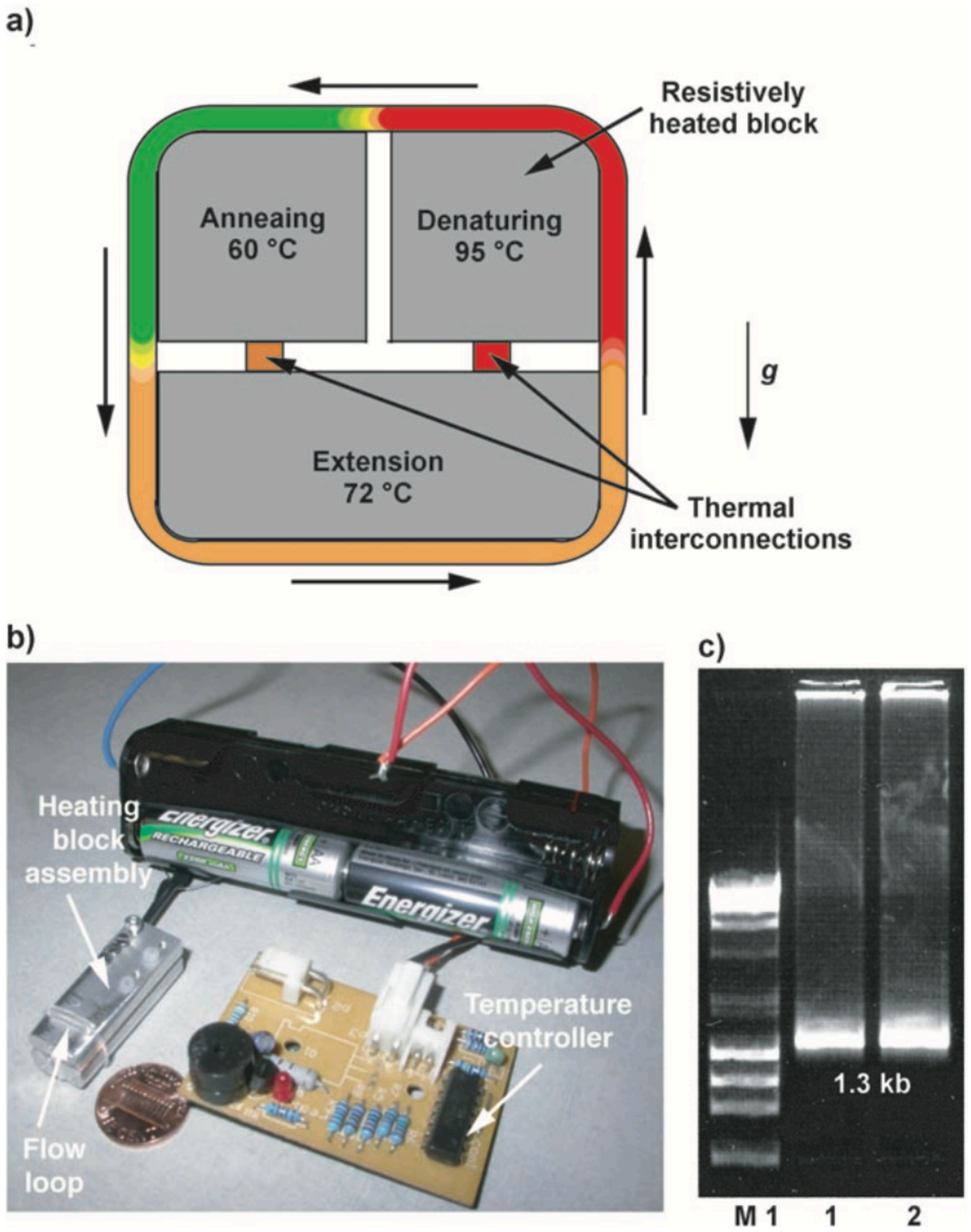


Experimental side

- **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**



https://pubmed.ncbi.nlm.nih.gov/17465434/

Experimental side

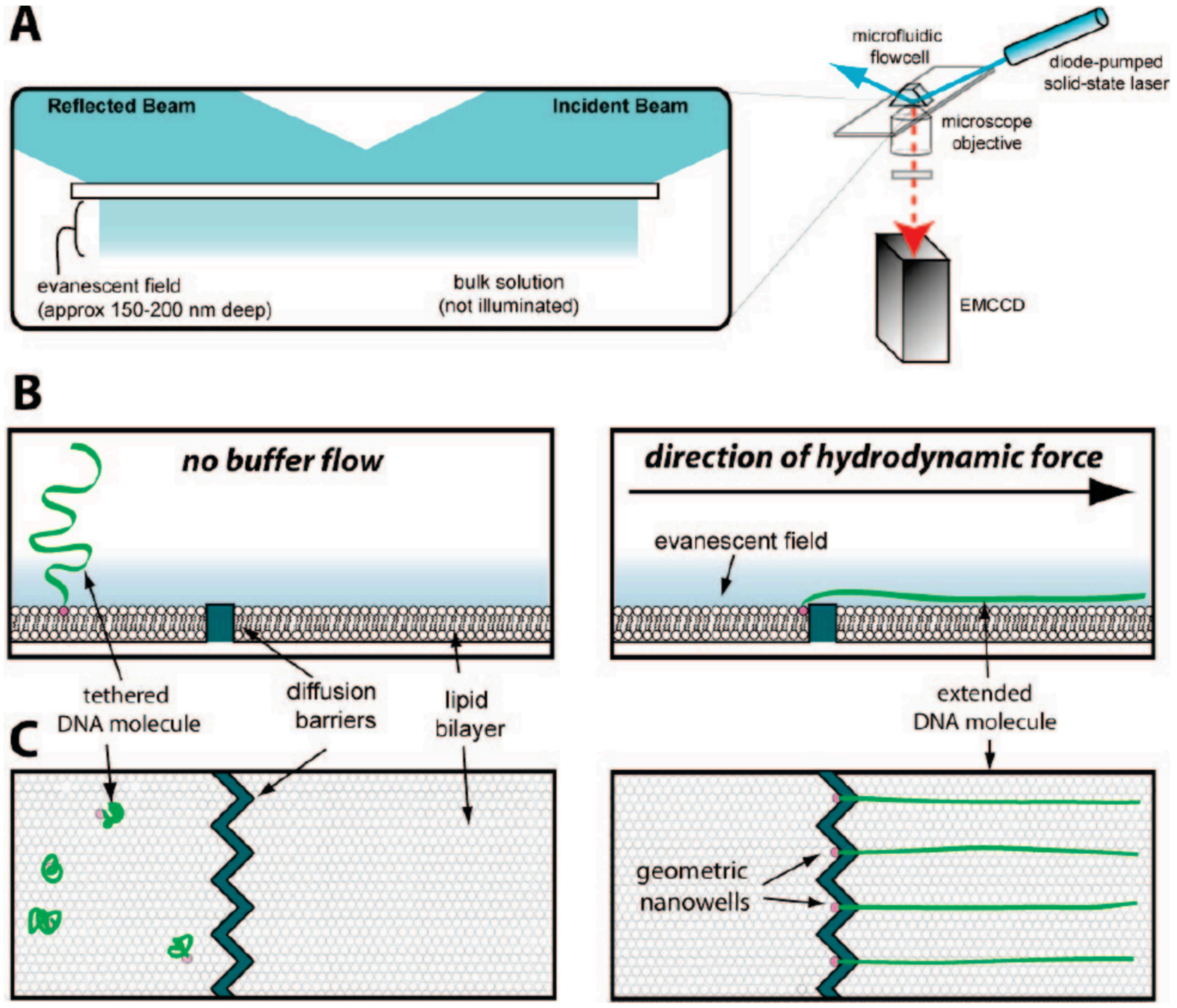
- **Detector construction →** DNA-origamists can make practically anything
- **PCR machines →** cheap, commercially available, portable, and fast.
- **DNA-substrate attachment →** standard protocols (looking at this in the lab right now!)

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



https://pubmed.ncbi.nlm.nih.gov/17465434/

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

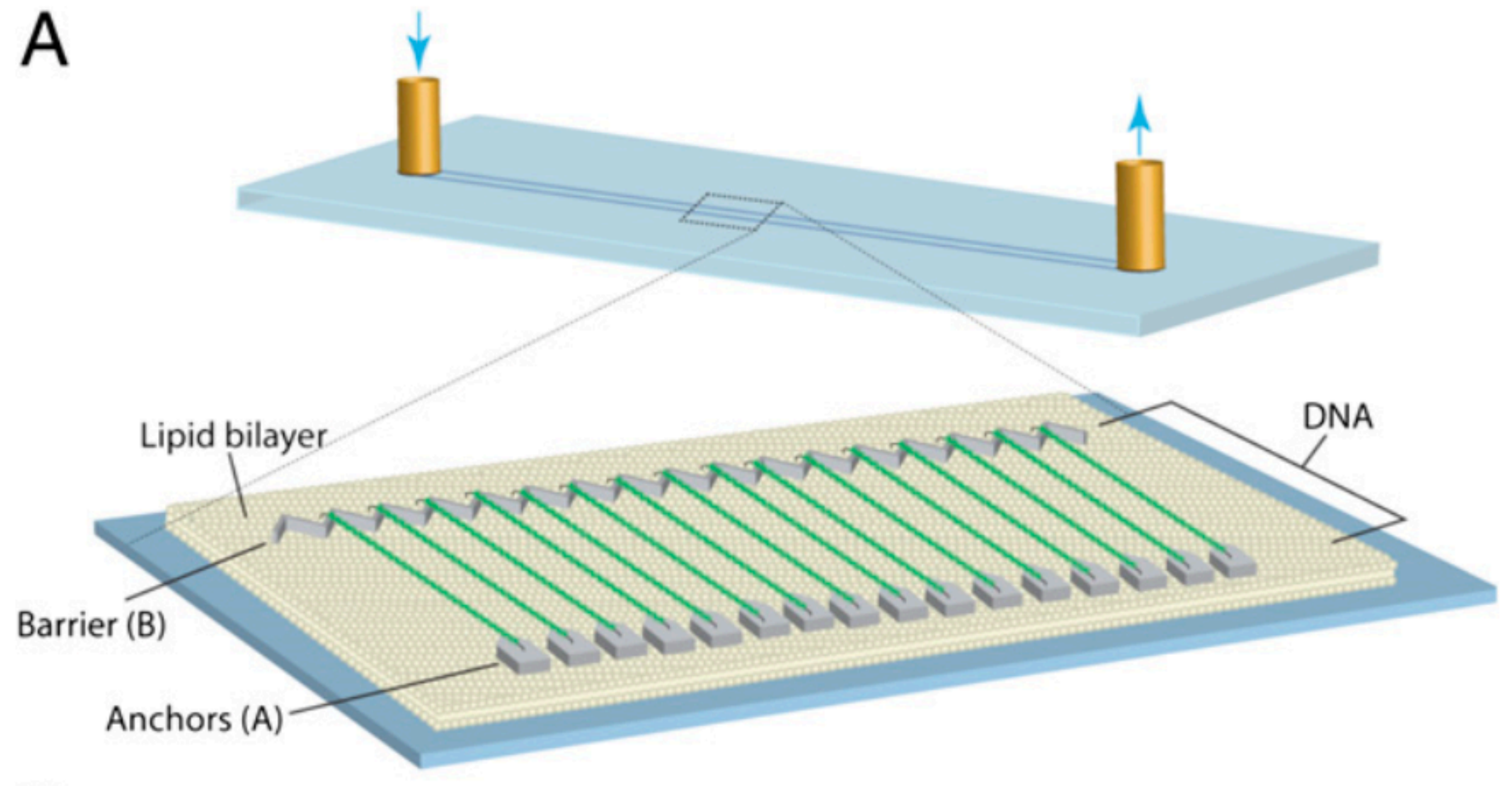
S. Kasra Tabatabaei[1], Boya Wang[2,8], Nagendra Bala Murali Athreya[3,8], Behnam Enghiad[4], Alvaro Gonzalo Hernandez[5], Christopher J. Fields[6], Jean-Pierre Leburton[3], David Soloveichik[2], Huimin Zhao[1,4,7]✉ & Olgica Milenkovic[3]✉

+

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]

[a]Department of Biochemistry and Molecular Biophysics and [c]Howard Hughes Medical Institute, Columbia University, New York, NY 10032; and [b]Department of Biochemistry, University of Oxford, Oxford OX1 3QU, United Kingdom



Status and future of directional recoil detection

- Directional TPC network "CYGNUS" is an exciting possibility that appears increasingly plausible. Primary physics goals are to set limits into the neutrino fog, and to study directional ν-e and ν-N scattering at low energies
- Many other experimental techniques under investigation. Some of them fill niches that are missed by gas experiments, although no proposal at the moment stands out in terms of performance and readiness like TPCs.
- DNA detector is a radical new idea with many interesting characteristics that build on extensive research in biotechnology, but is far away from being a real detector at the moment

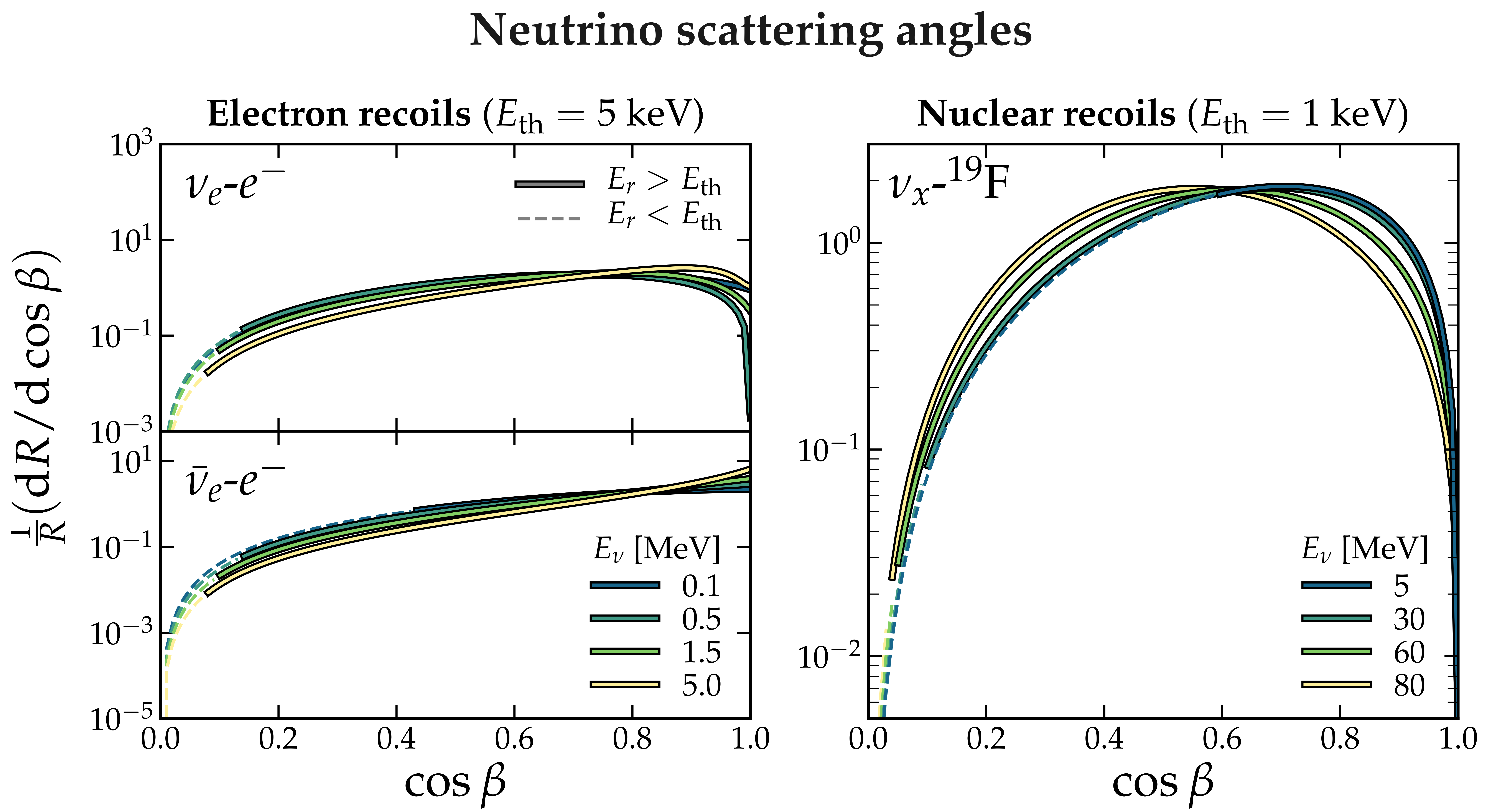
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

Extra slides

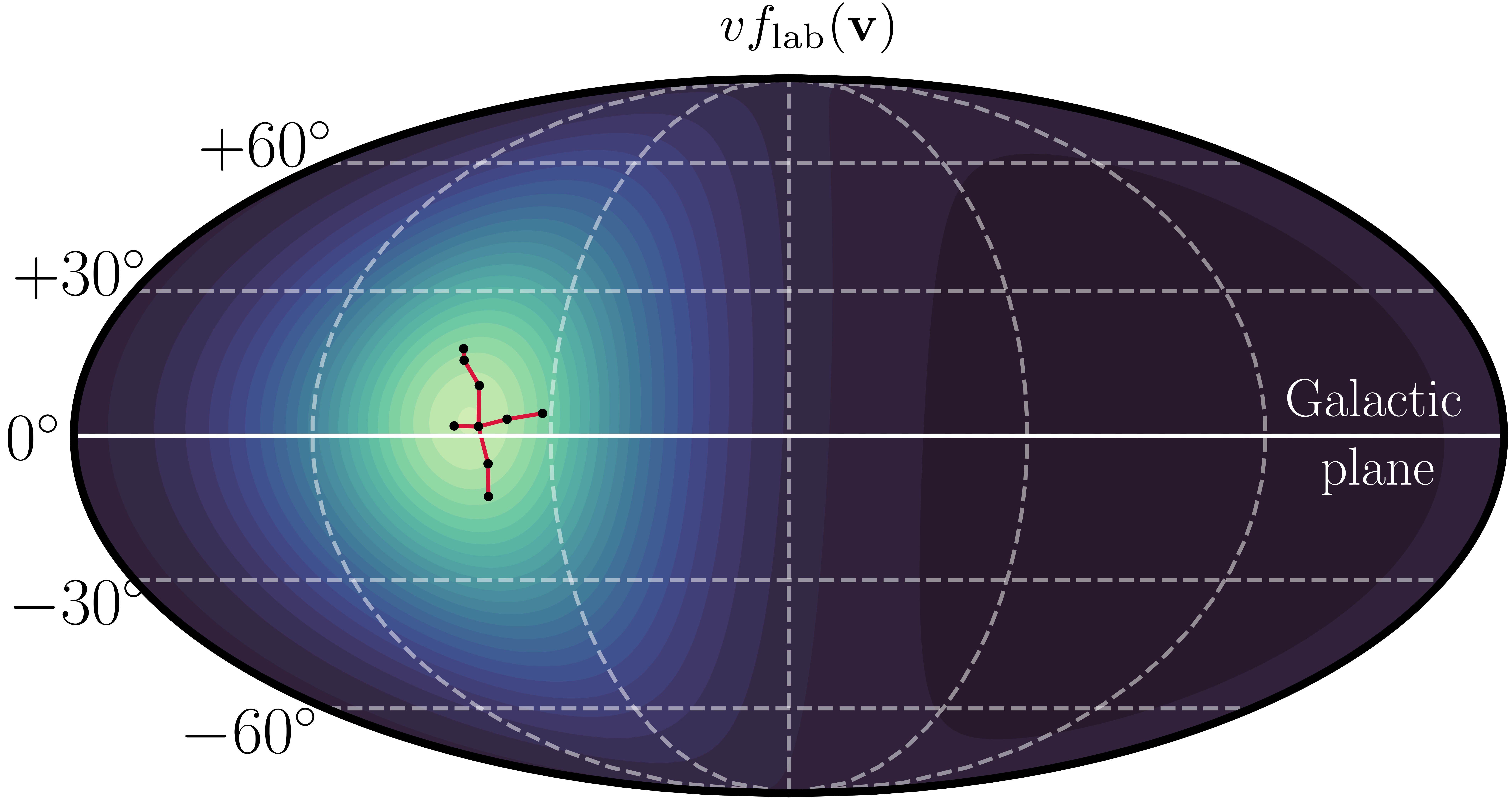
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

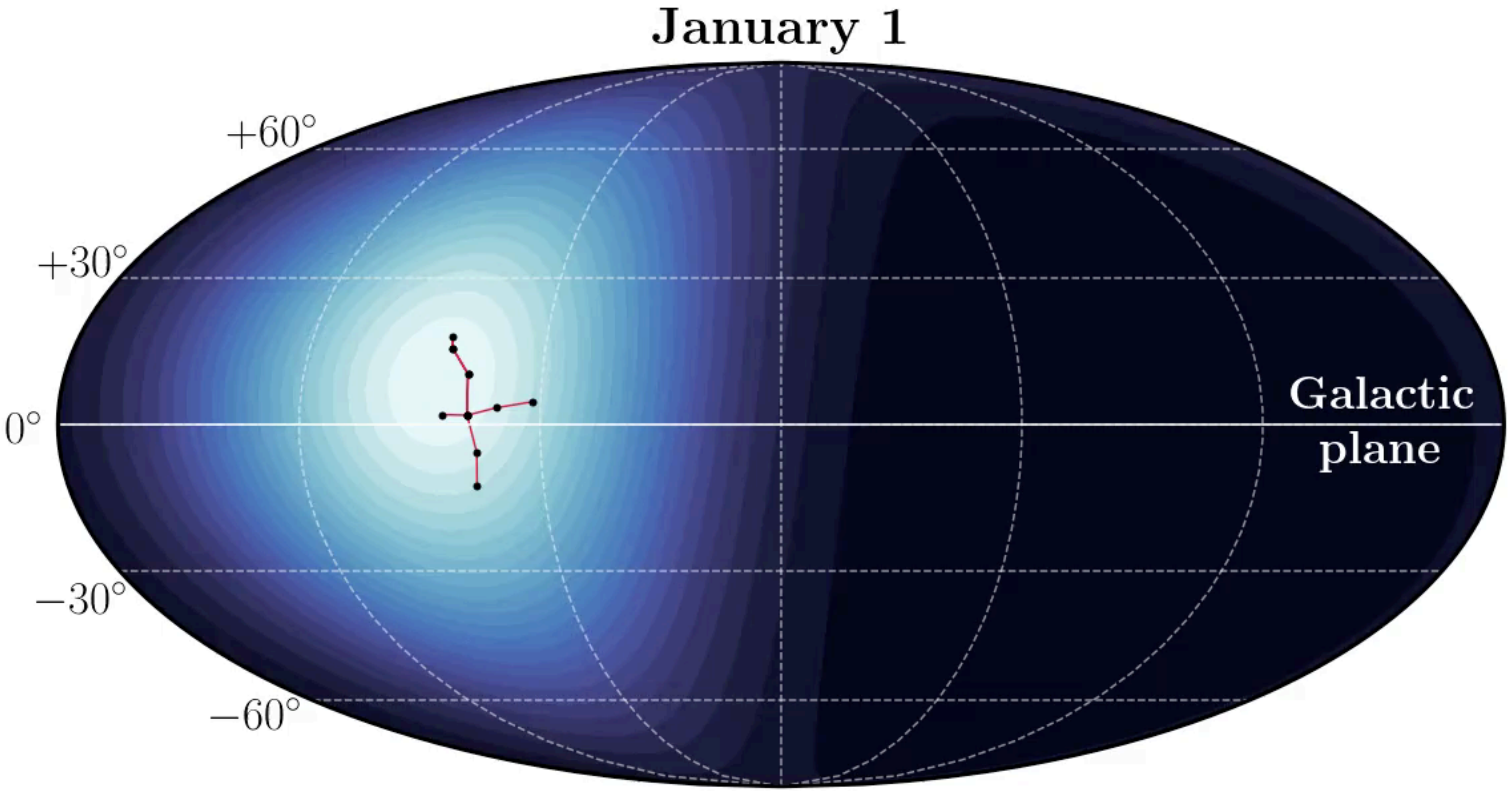


Neutrino scattering angles
Electron recoils ($E_{\rm th} = 5$ keV)
Nuclear recoils ($E_{\rm th} = 1$ keV)
ν_e-e^-
$\bar{\nu}_e$-e^-
ν_x-^{19}F
$E_r > E_{\rm th}$
$E_r < E_{\rm th}$
E_ν [MeV]
0.1
0.5
1.5
5.0
E_ν [MeV]
5
30
60
80
$\frac{1}{R}(\mathrm{d}R/\mathrm{d}\cos\beta)$
$\cos\beta$
$\cos\beta$

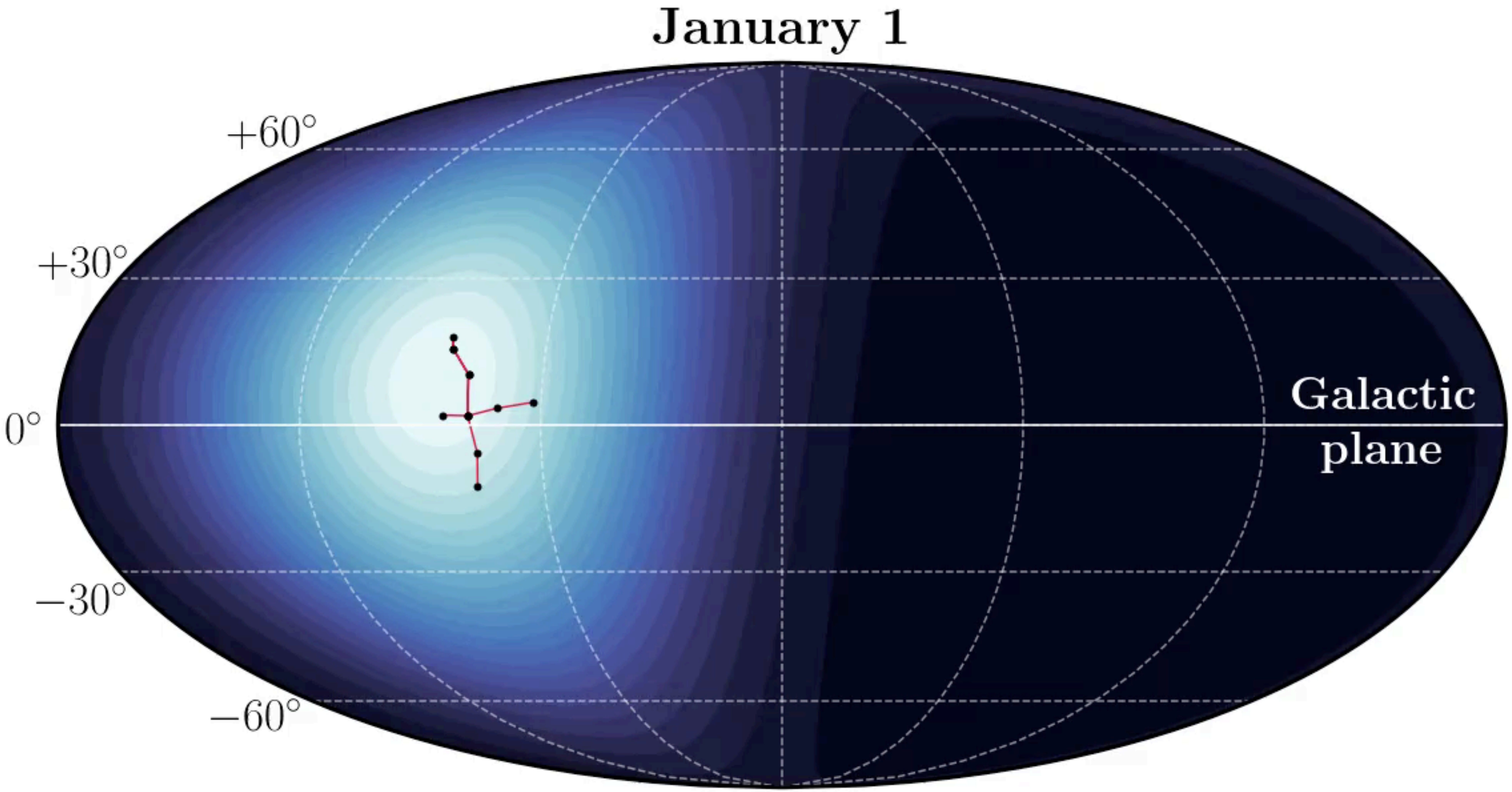
The dark matter flux is anisotropic → O(10) anisotropy in event rate



The dark matter flux is anisotropic → O(10) anisotropy in event rate



The dark matter flux is anisotropic → O(10) anisotropy in event rate



Target gas mixture: 755:5 He+SF_6 at 1 atm.

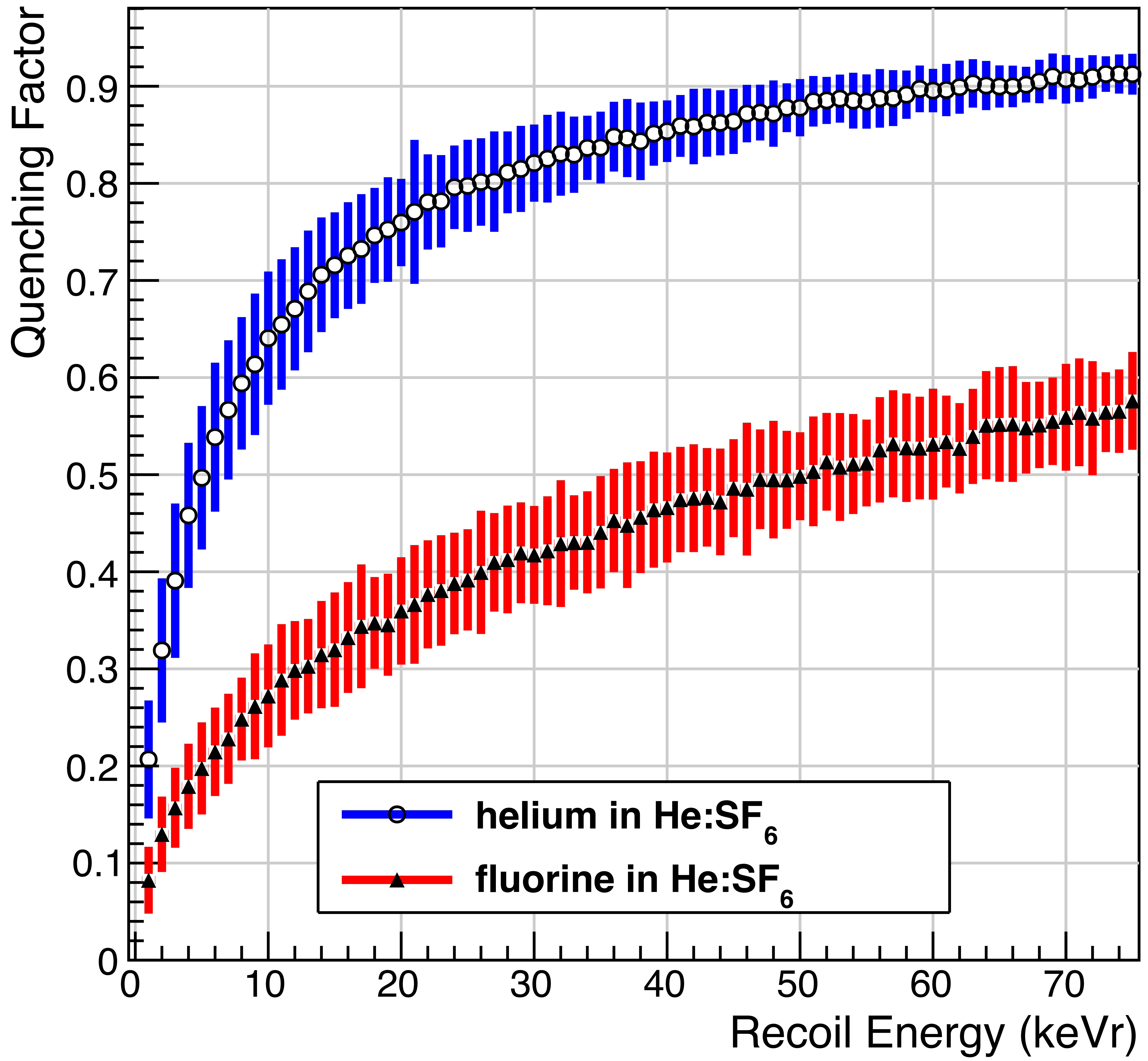
Why SF_6?

- ☑ **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)
- ☑ **^{19}F 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+SF_6

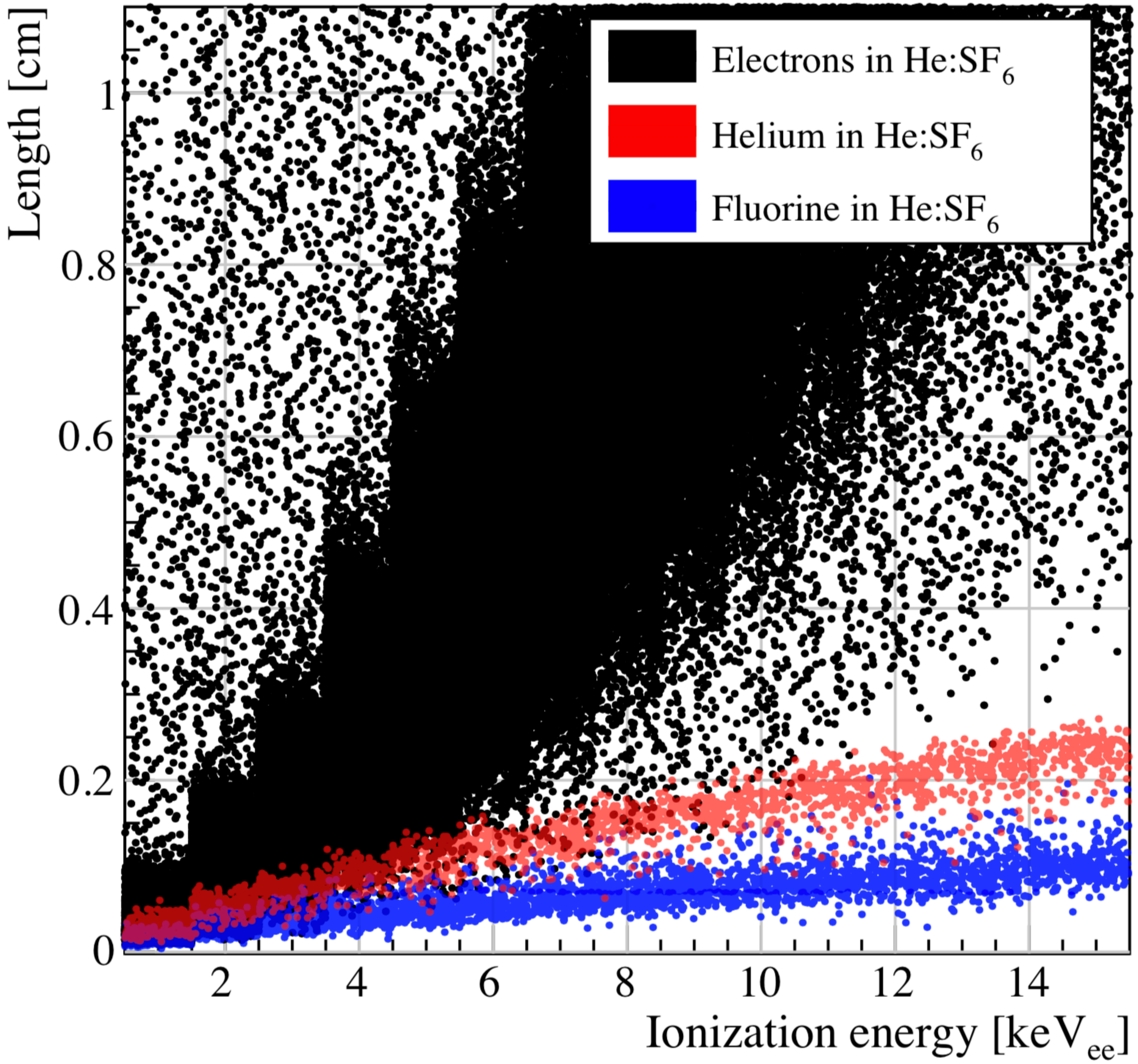


Electron discrimination

- Electrons have much longer tracks than nuclei so can discriminate based on this info.

- Track lengths for recoils in He+SF_6 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 [$\mu m/\sqrt{cm}$]	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

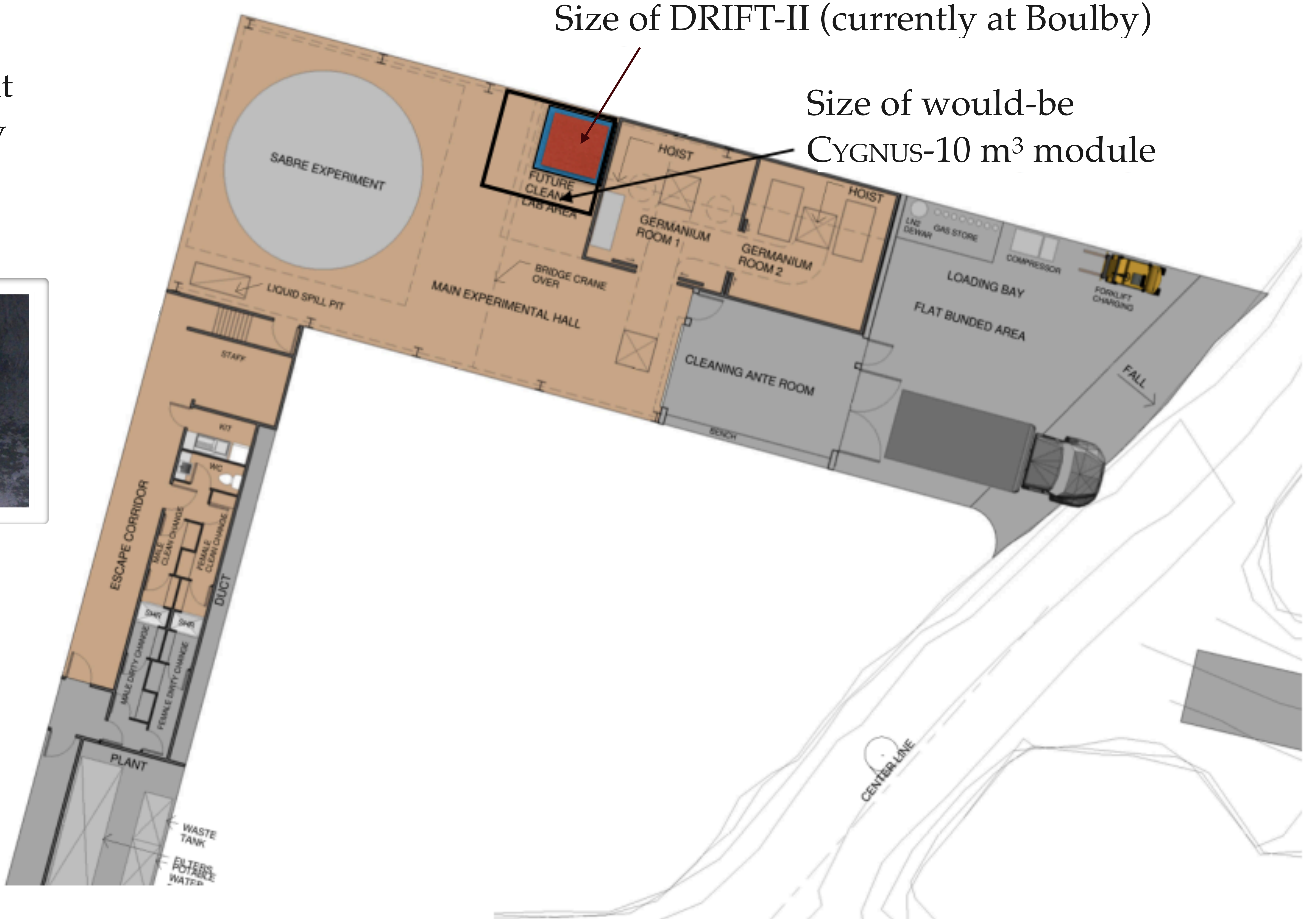
TABLE I. Various gas-dependent parameters assumed in the TPC detector simulation. The values are sourced as follows: the W factor for pure SF_6 is from a measurement with alpha particles [310], while the W factors for the $He:SF_6$ and $He:CF_4$ mixtures are calculated using Eq.(1) of Ref. [266]. The 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.

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

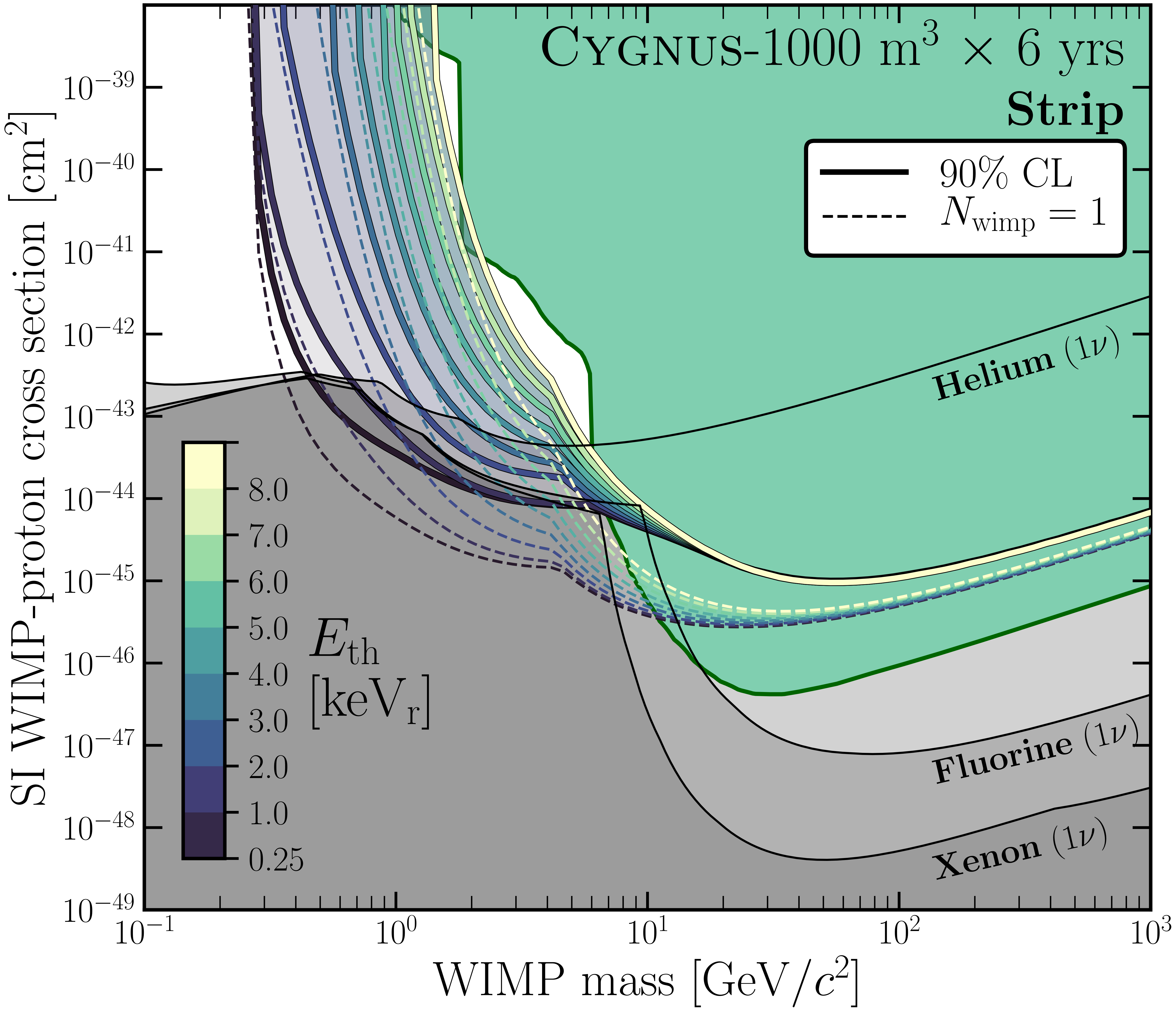
A closer look at dependence on threshold:

<u>Threshold:</u>

→ 8 keVr definitely feasible with simplest electron rejection strategy

→ 3 keVr is probably feasible with optimisation of gas, bespoke track fitting algorithms

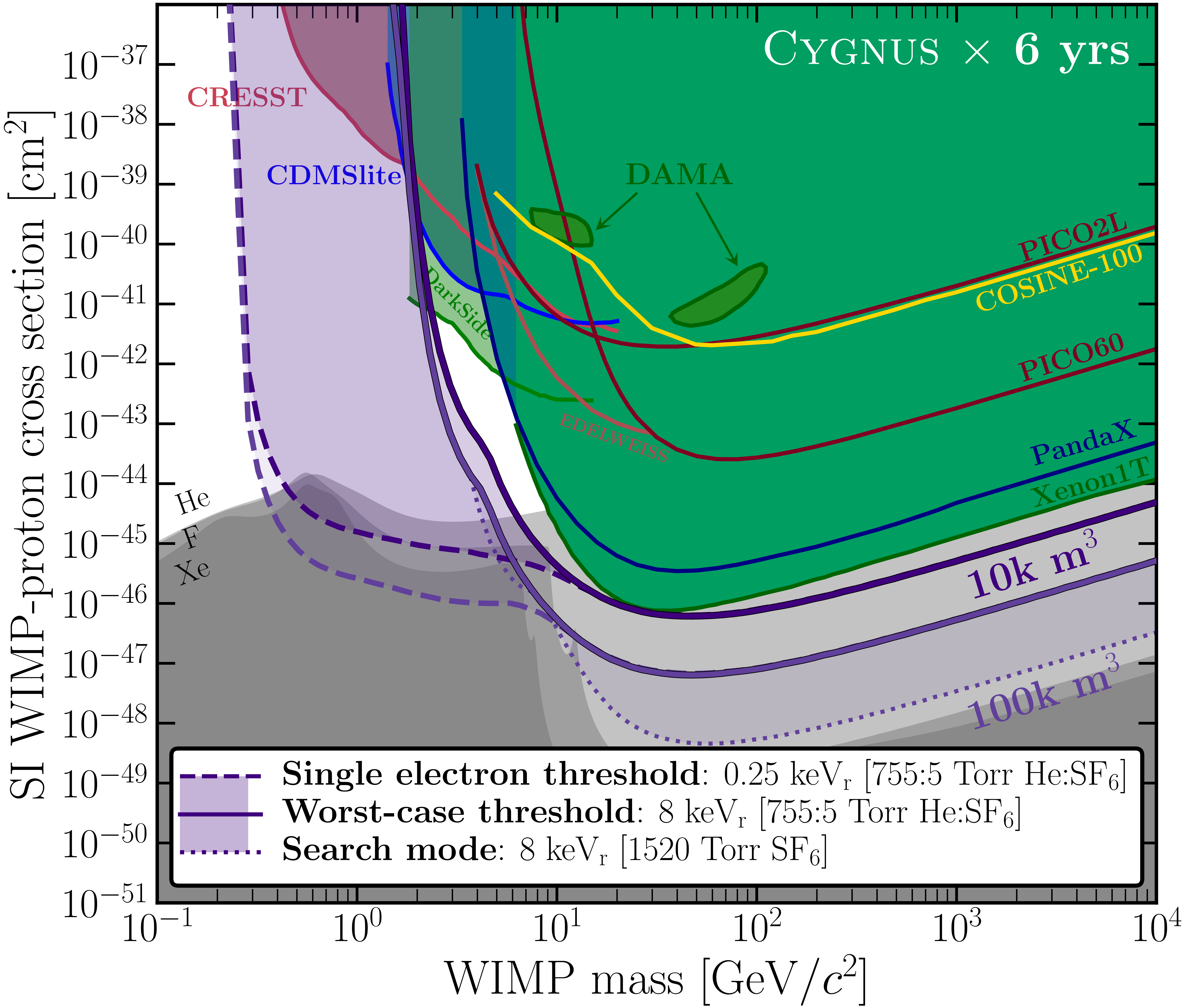
→ 0.25 keVr is theoretical minimum (single electron)



Sensitivity (SI)

→ Window worst/best case threshold
→ Search mode: 1 atm. of 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



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

Modulation-based directionality

Anisotropic scintillators (R&D)
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Indirect recoil event directionality

Columnar recombination (Proposed)
- Event-level 1d directions
- No head / tail
- Direction and energy are not independent

Time-integrated recoil imaging

Nuclear emulsions (Demonstrated)
- 2d recoil tracks, without head / tail
- No event times information recorded

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

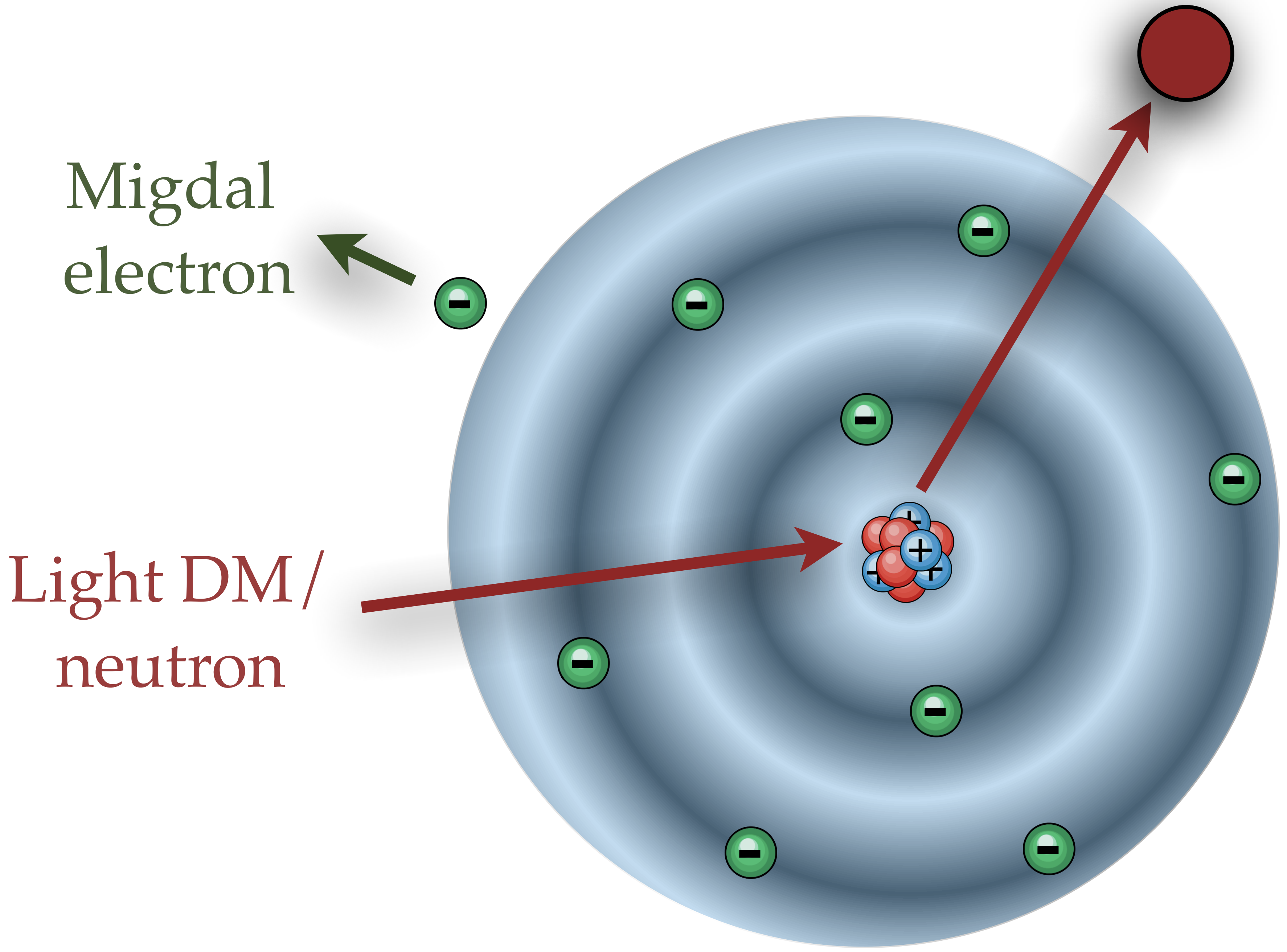
Time-resolved recoil imaging

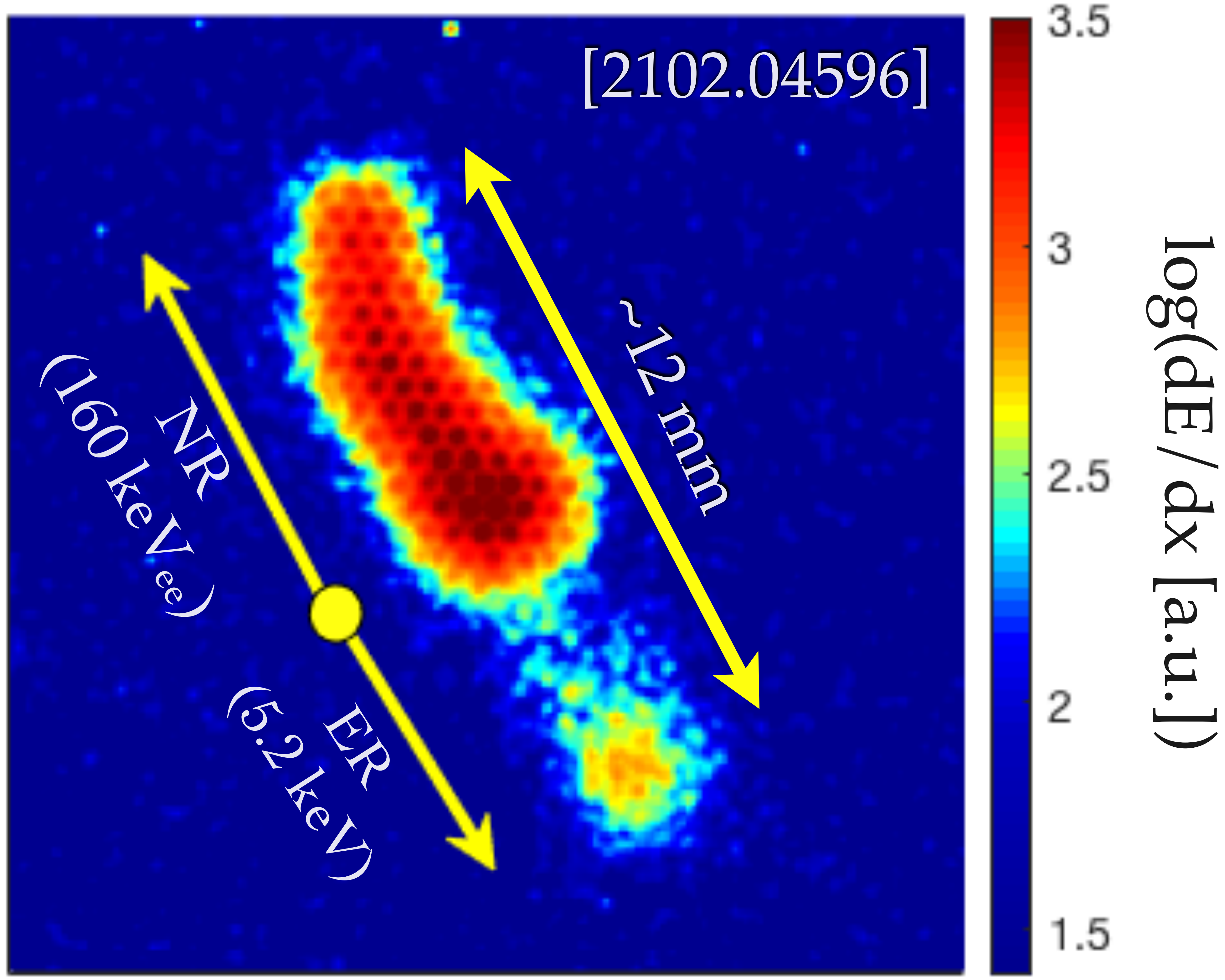
Gas TPC (Demonstrated)
- Head / tail measurable
- 1d, 2d or 3d
- Independent energy / direction measurement

Crystal defects (R&D)
- 3d track topology
- Head / tail measurable

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

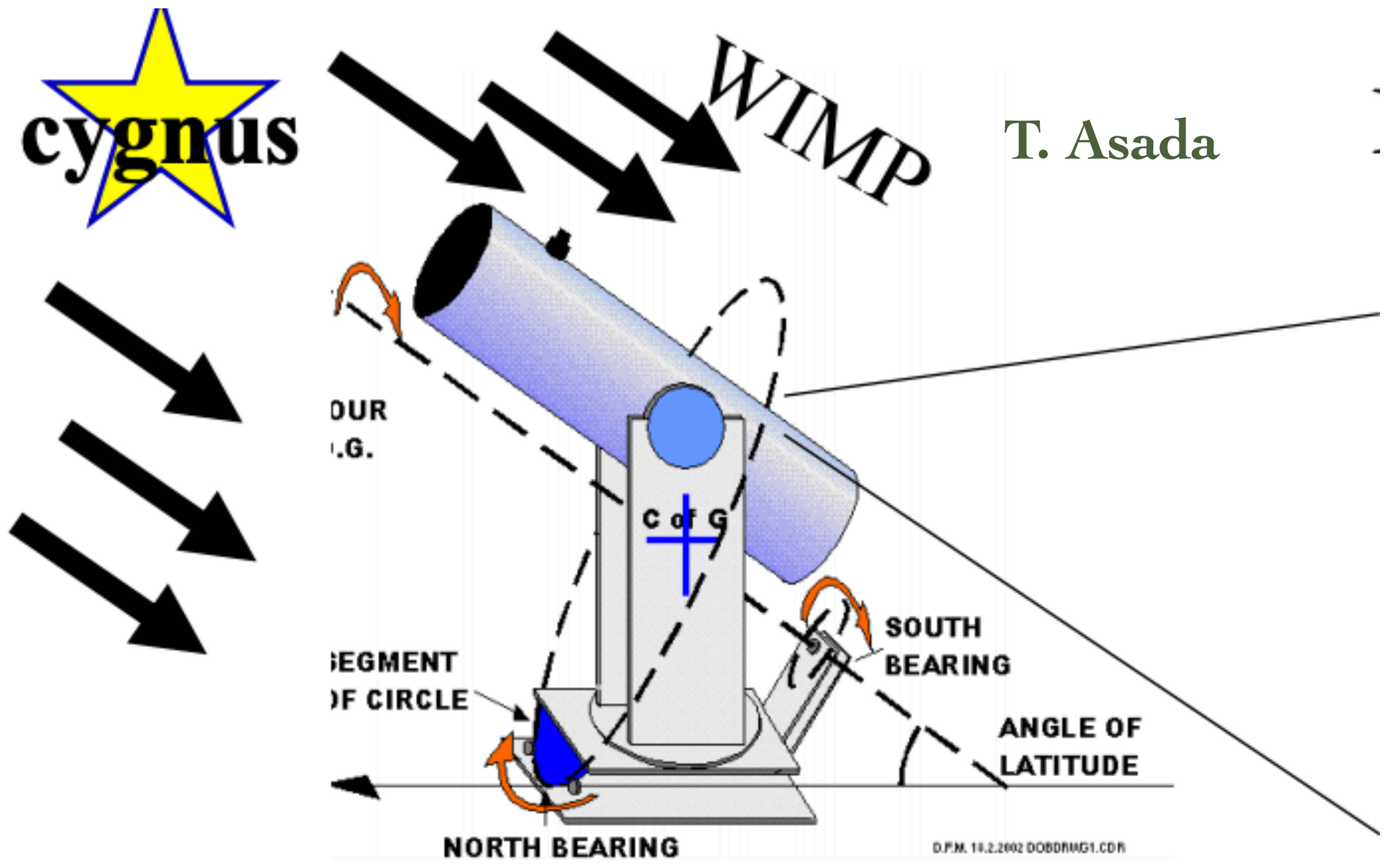


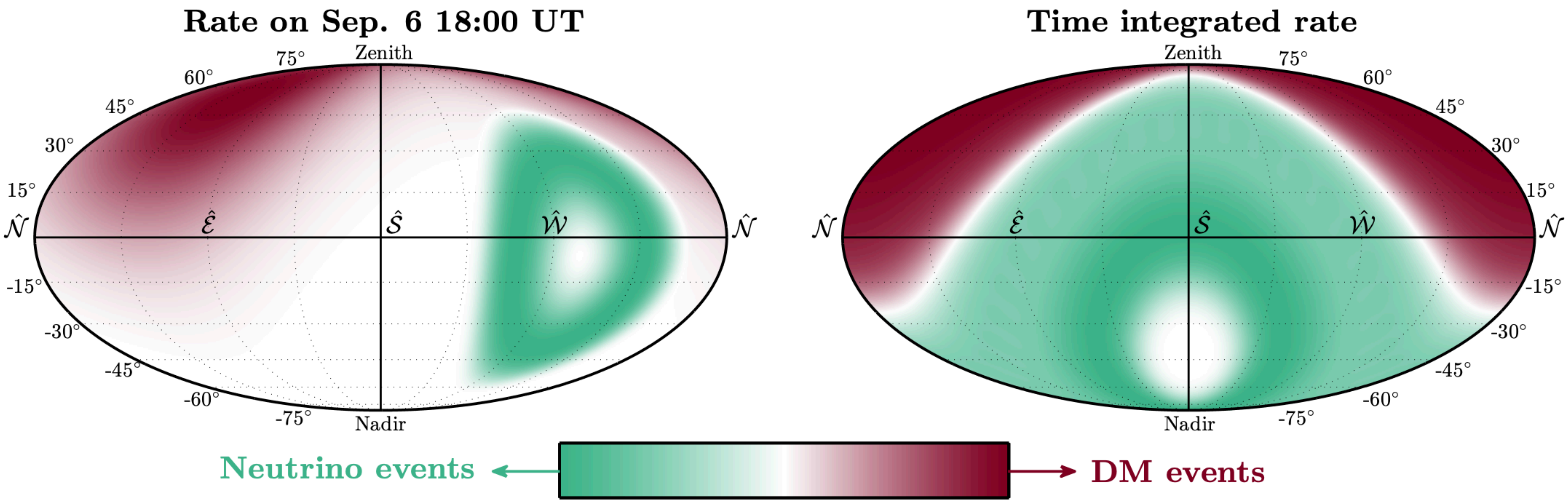


Could be confirmed directionally, using a small-scale TPC!

Time-integrated directional detection

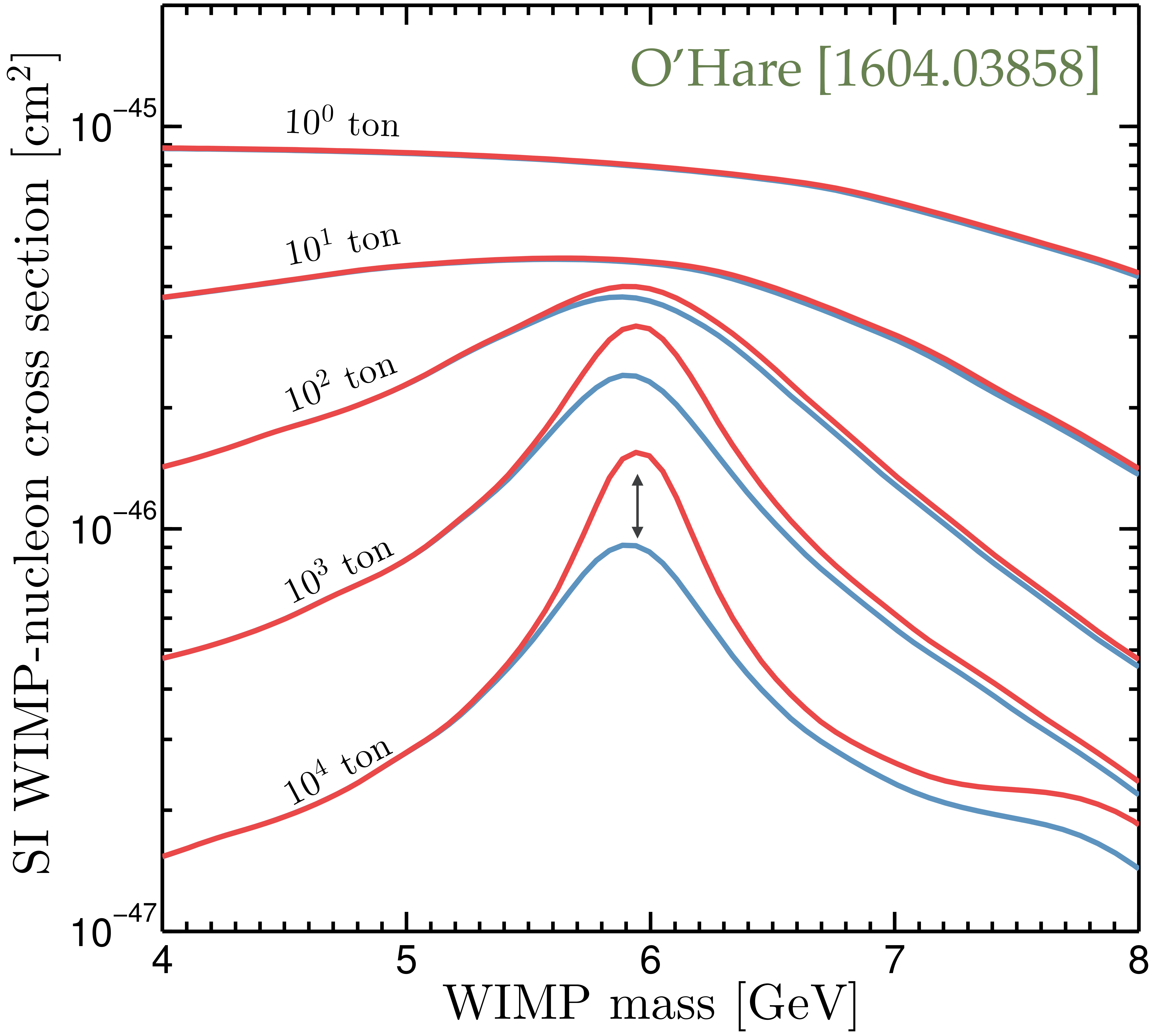
Experiments like NEWSdm need to develop tracks after exposure
→ rotation of Earth will wash out anisotropy unless some Cygnus-tracking is implemented





O'Hare et al. 1708.02959

Annual modulation: does it help?



Information used:

Energy only

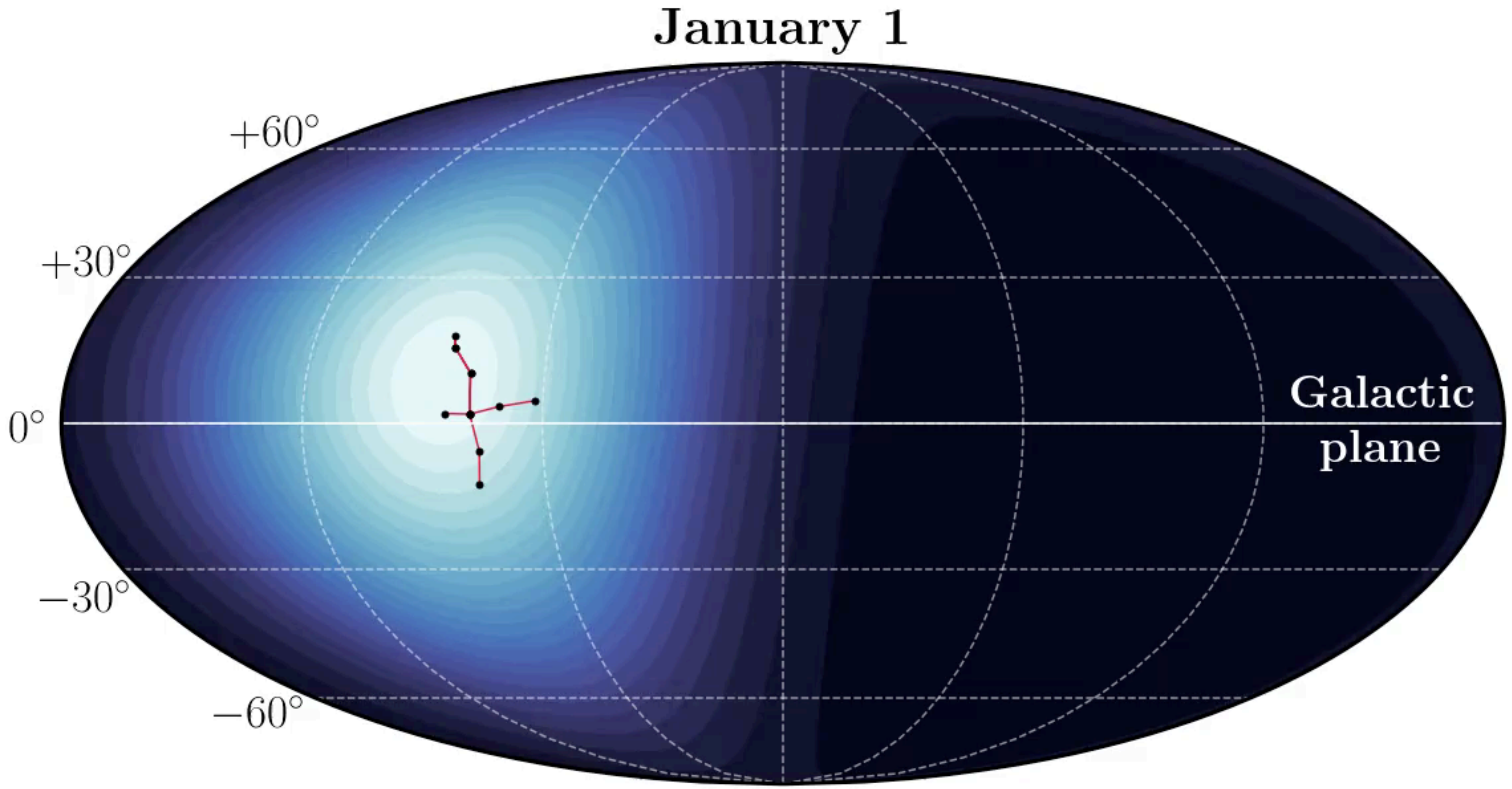
Energy+Time

Increasing exposure

Based on standard assumptions, what <u>should</u> the signal look like?

→ a Gaussian peaking towards Cygnus

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



Based on standard assumptions, what should the signal look like?
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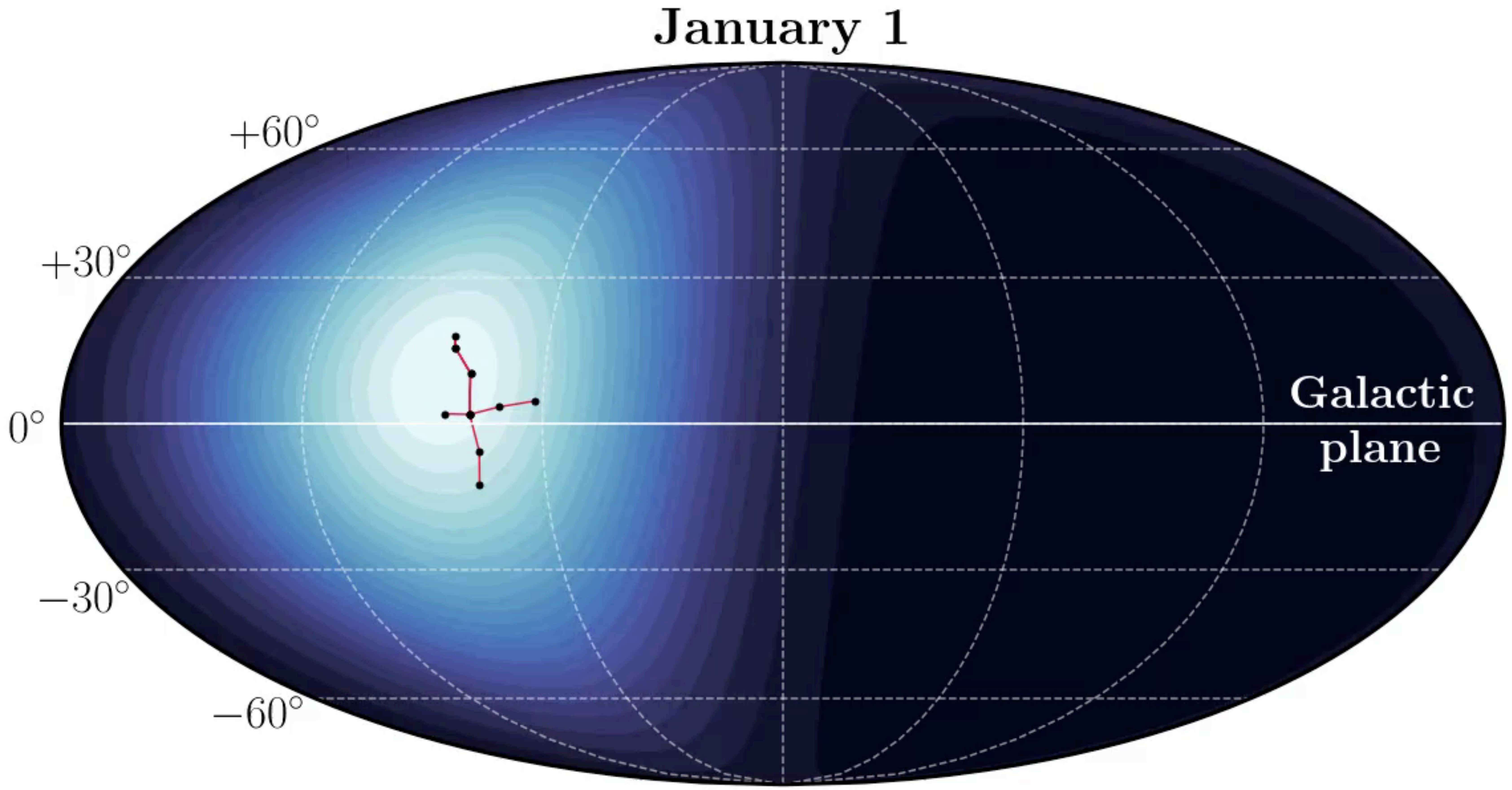
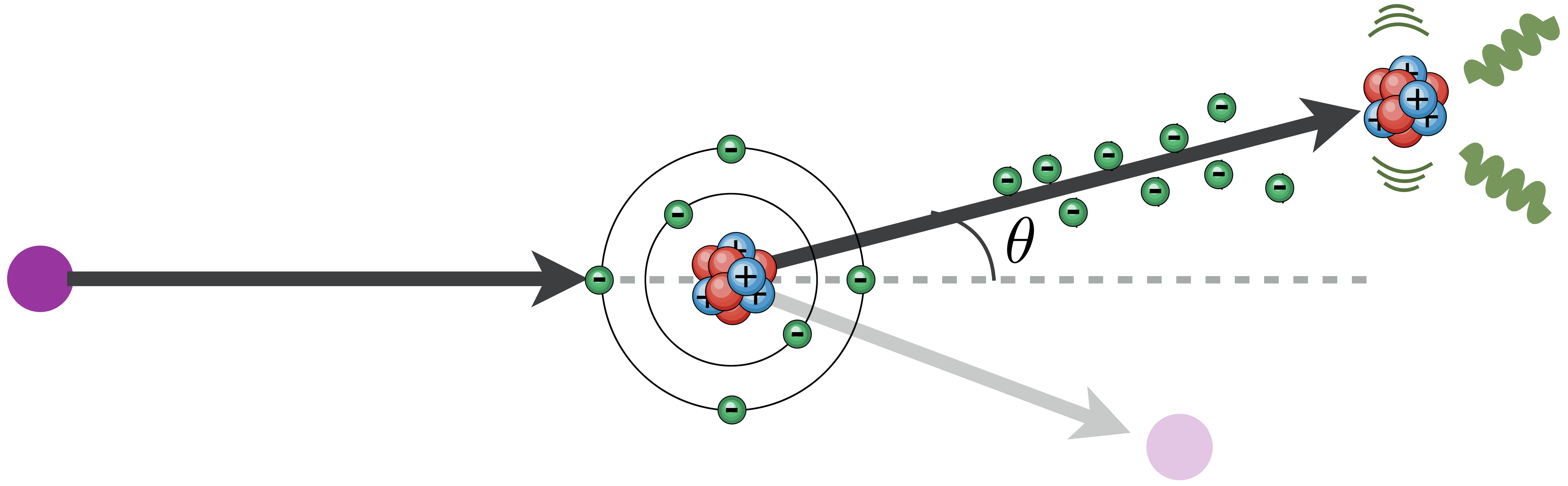
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\rm min} + v_{\rm lab}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$



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)

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

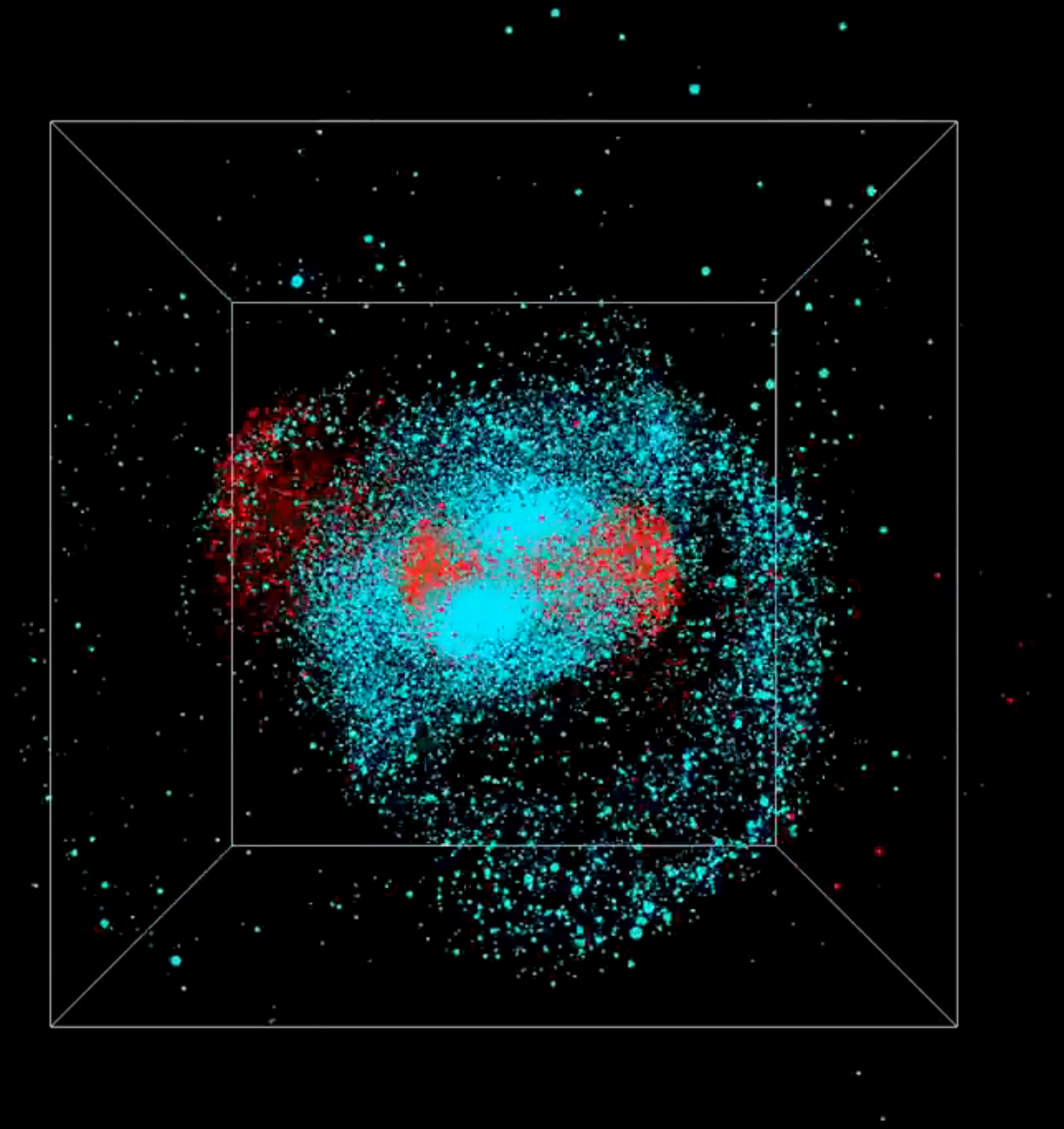
- DM-nucleus matrix element does not depend on velocity

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

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

Should the DM velocity distribution be a Gaussian?

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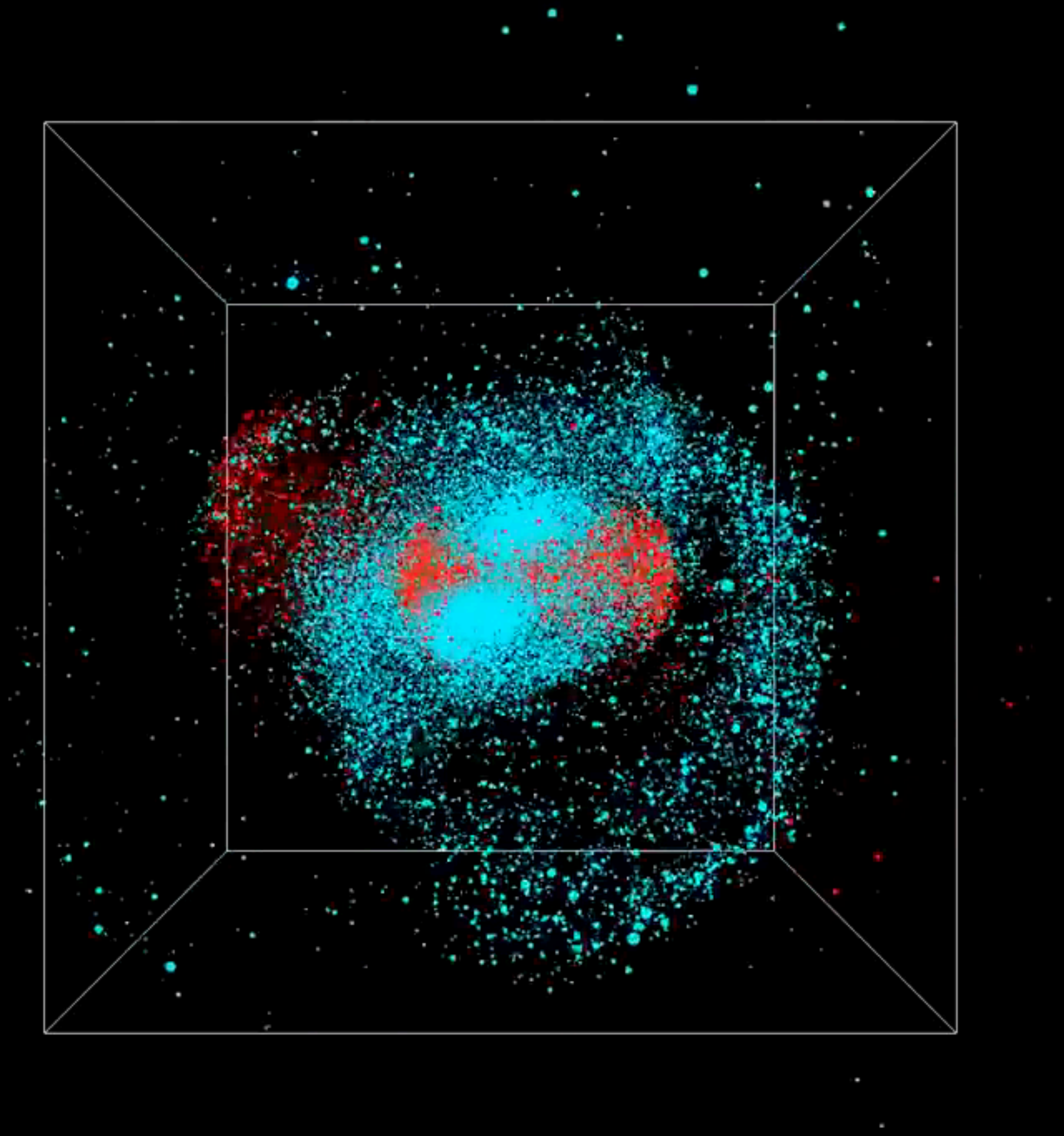
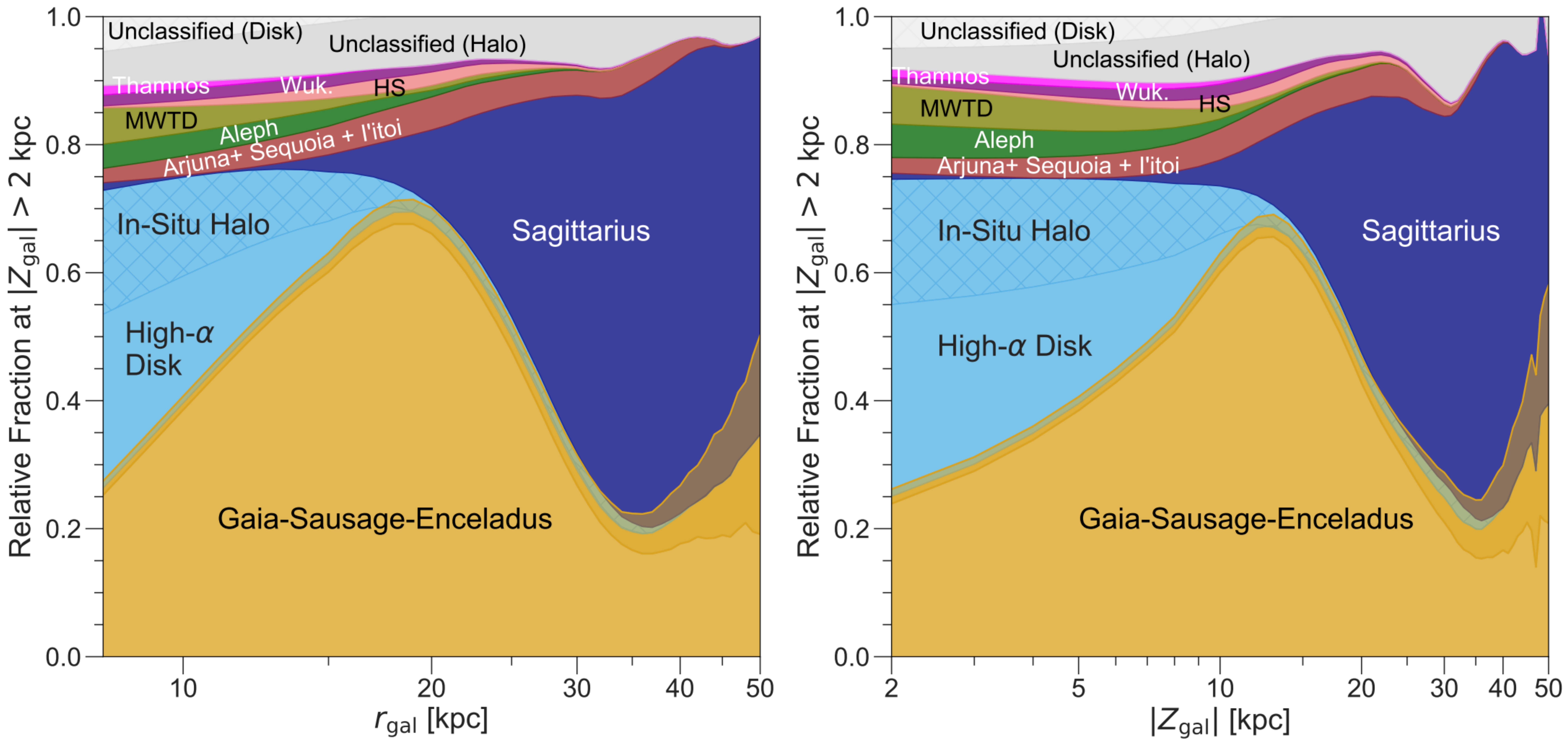


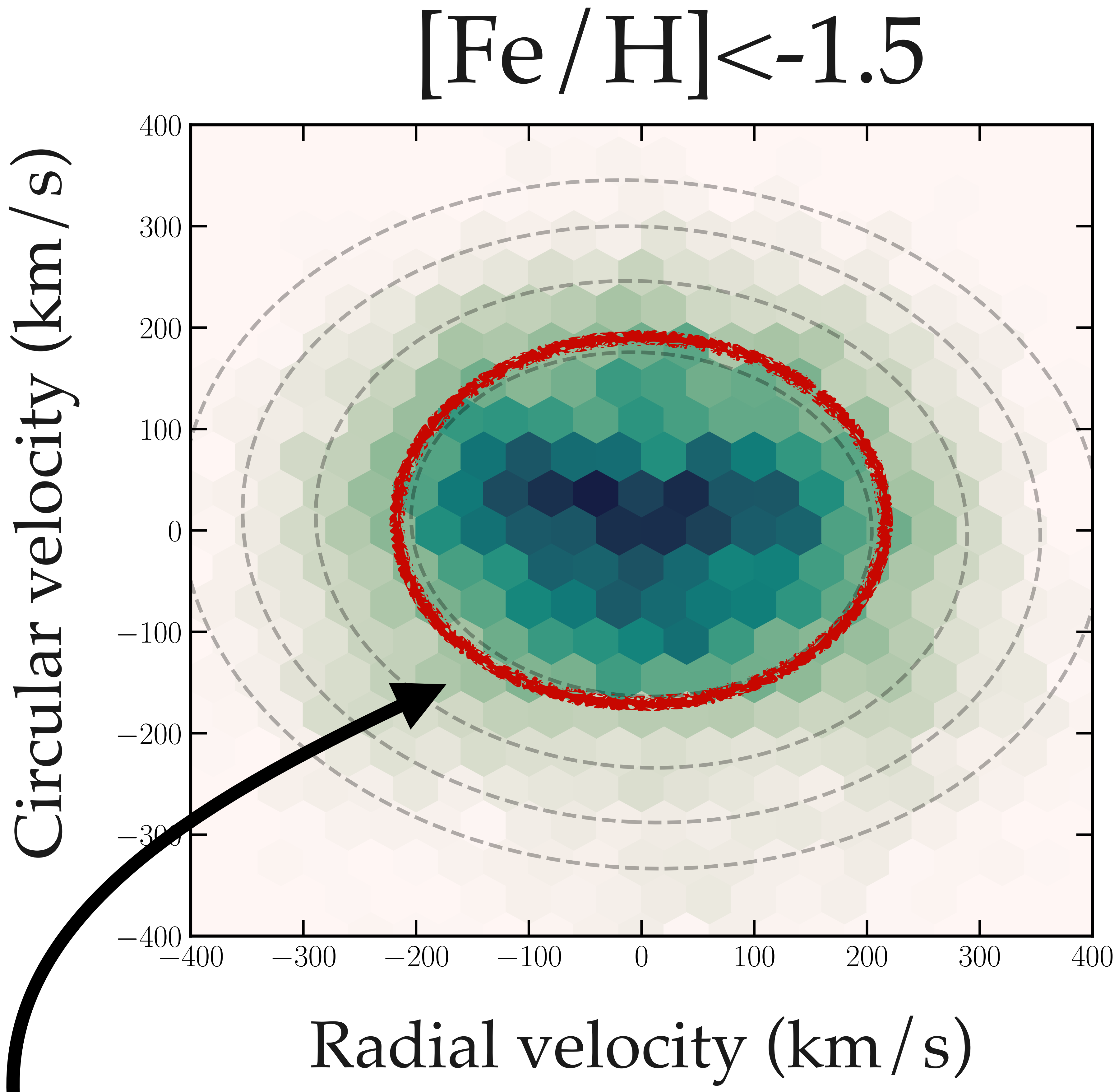
See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

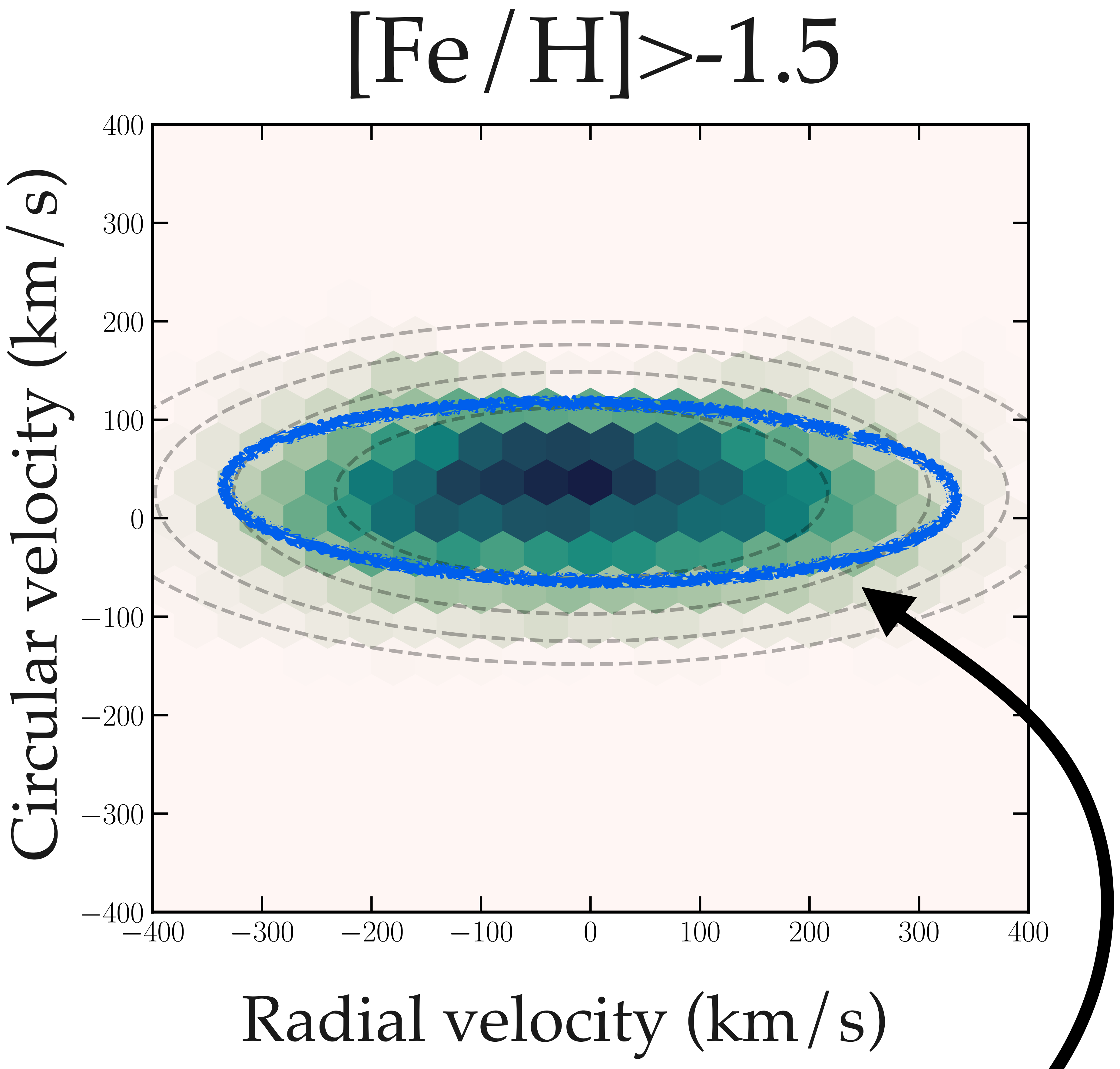
2006.08625

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

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. Cargile[1]







"Metal-poor" halo

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

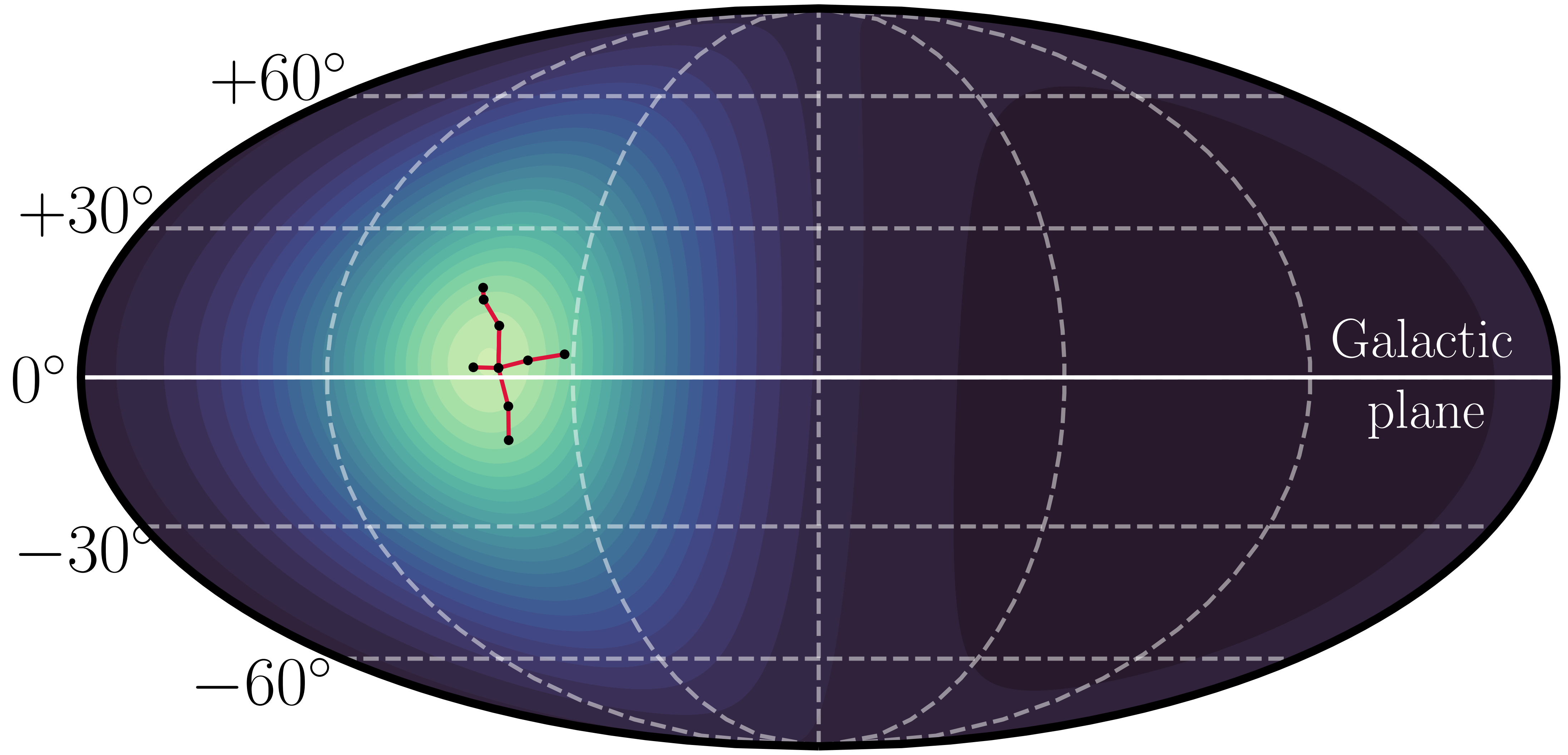
"Metal-rich" halo

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

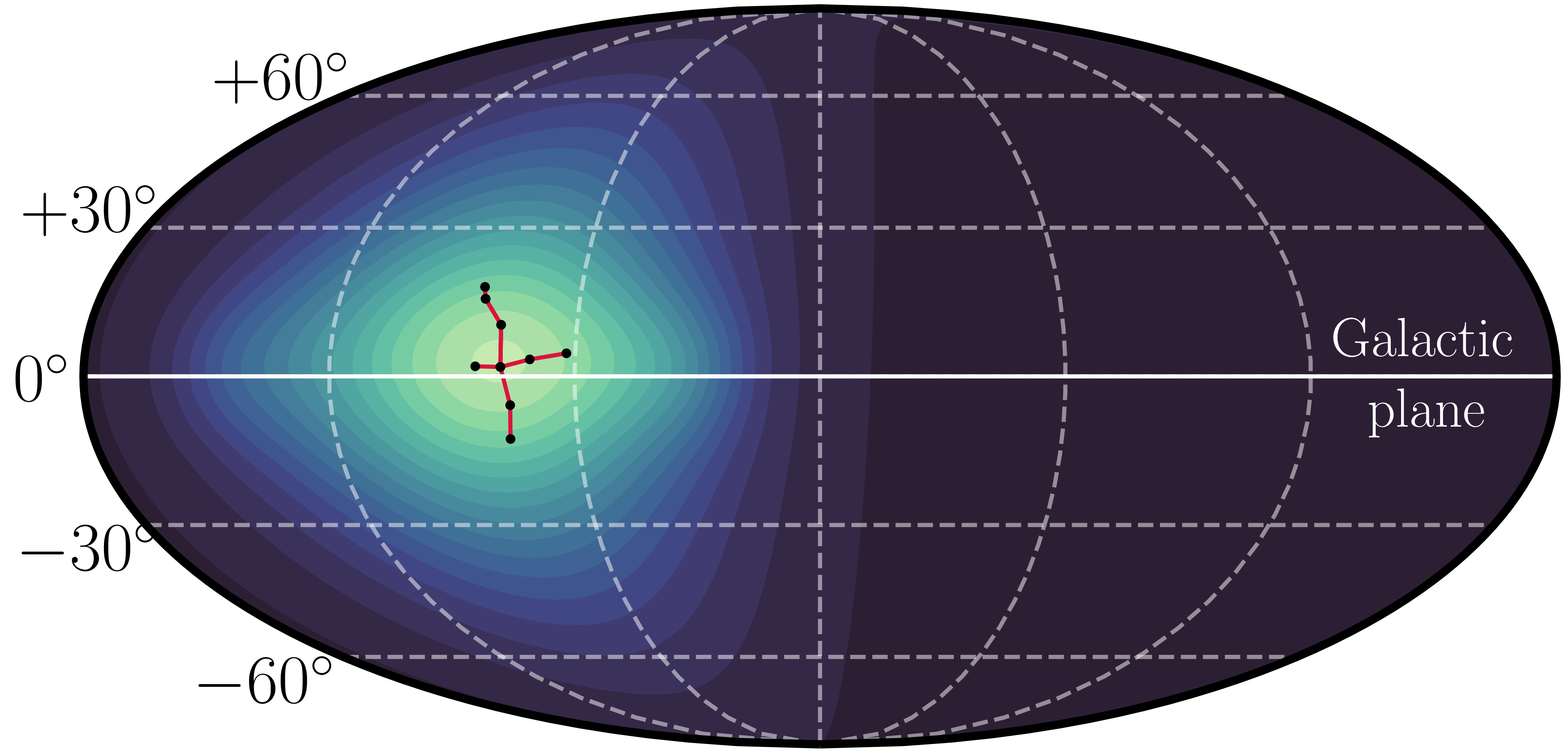
The Gaia Sausage

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

DM Flux for SHM
(Gaussian distribution)

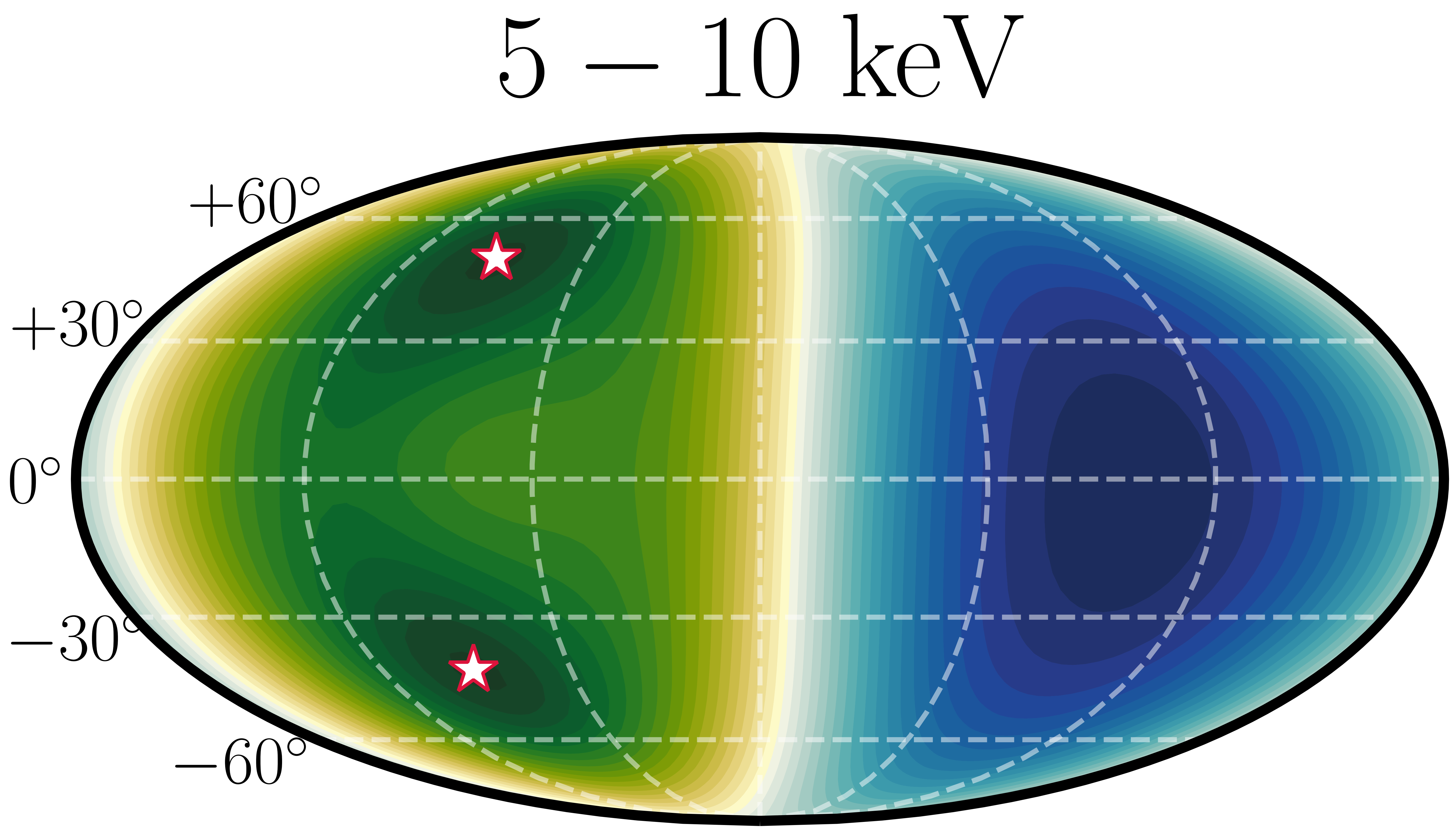


SHM + **Gaia Sausage**
(Isotropic and radially anistoropic components)



The Gaia Sausage gives rise to peaks off center from Cygnus

O'Hare+ [1909.04684]



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

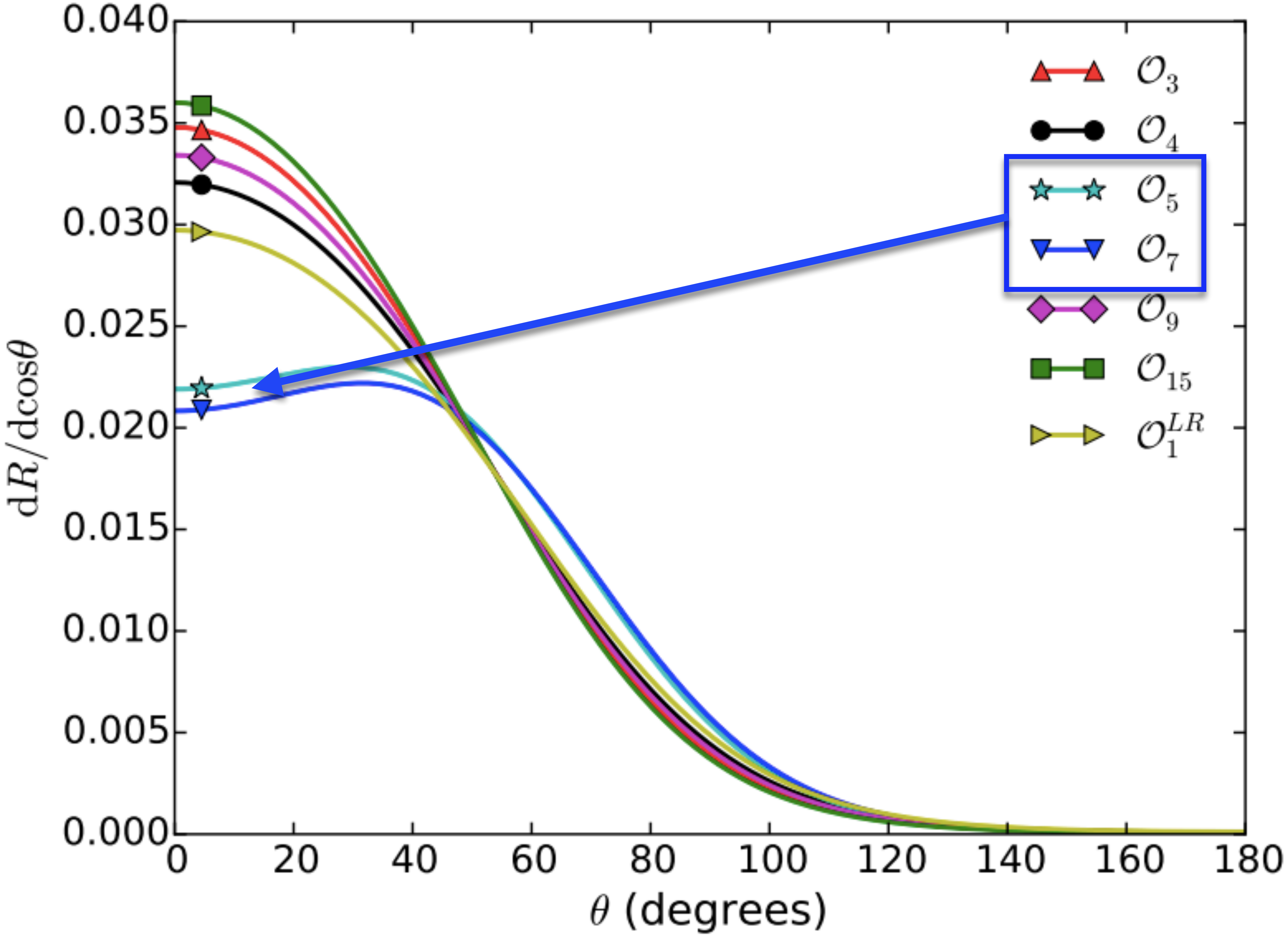
Halo model = SHM + Sausage

Non-relativistic EFT of DM-nucleus interaction

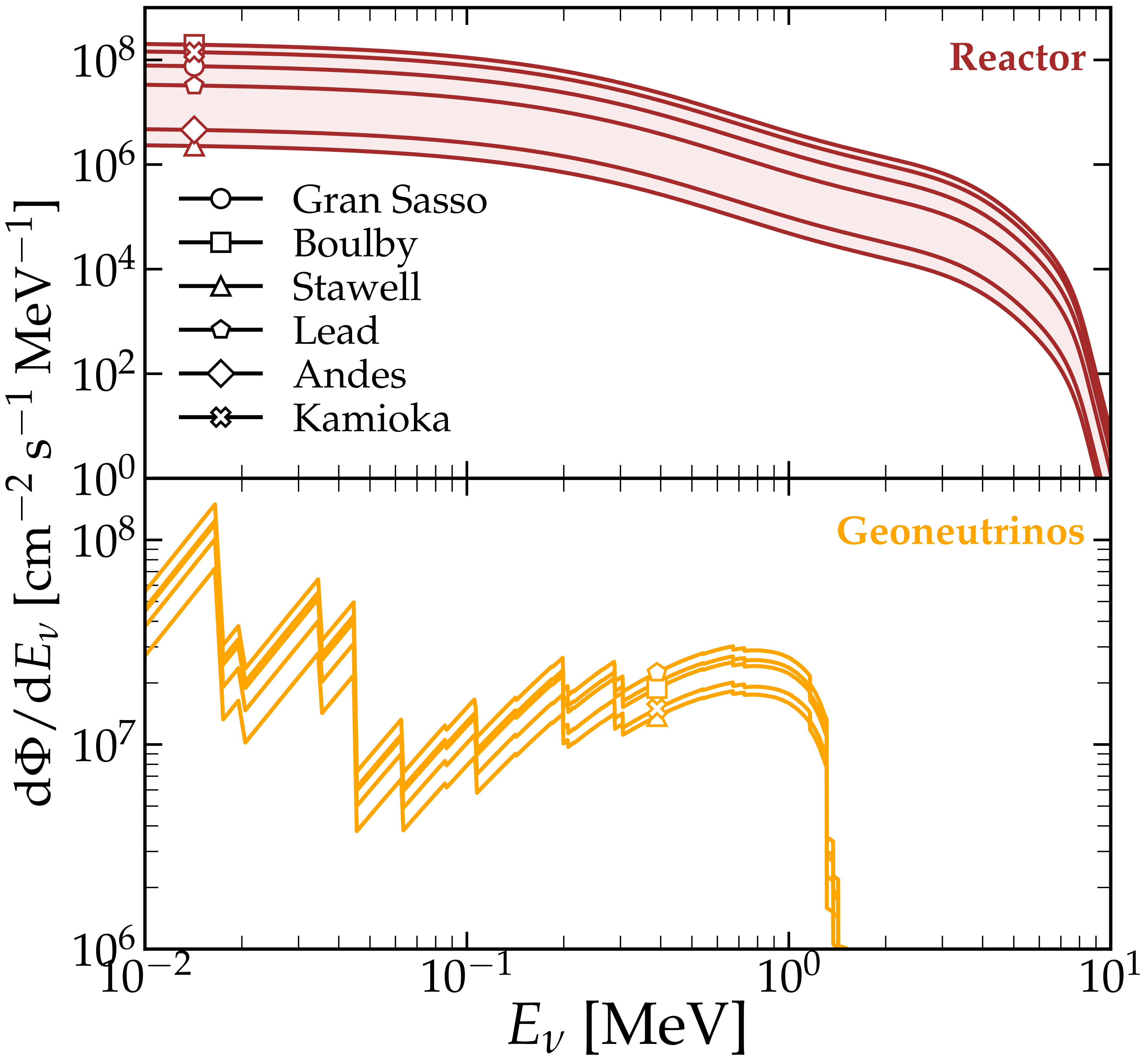
Allows for operators (e.g. O_5, O_7) dependent on transverse velocity:

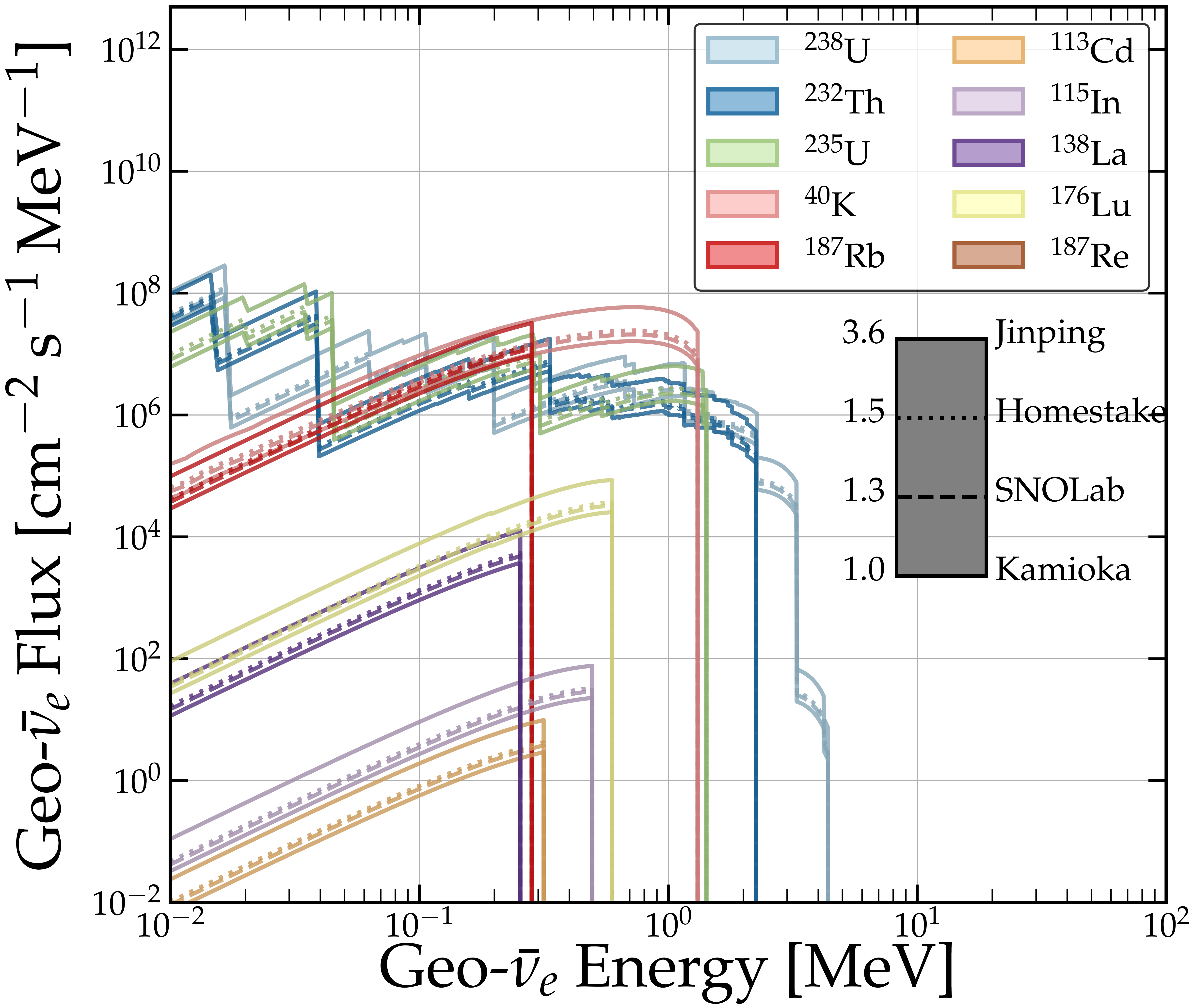
Kavanagh [1505.07406]

→ **Non-Gaussian angular distributions**

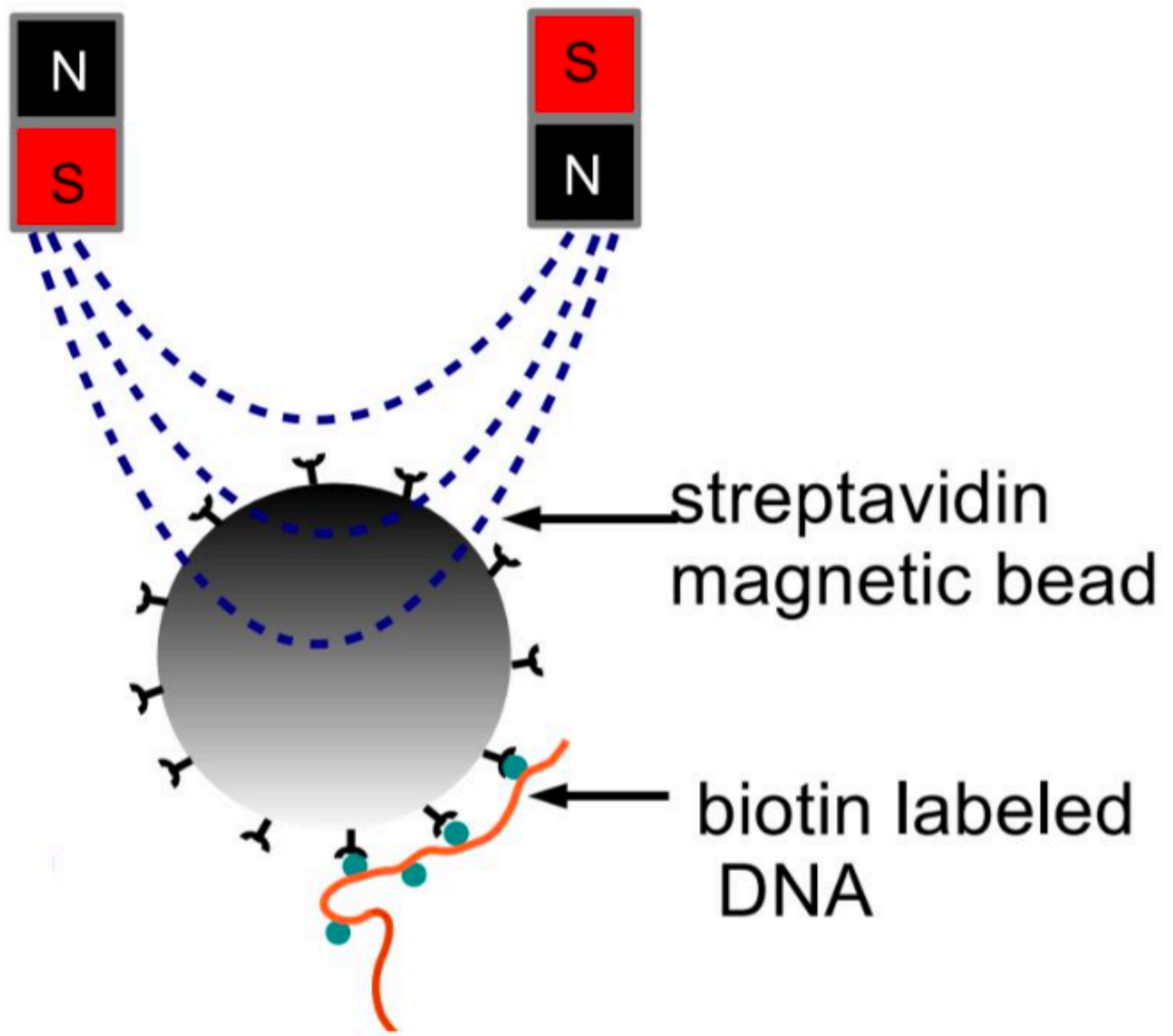


Geoneutrinos





Attachment of paramagnetic beads to the DNA strands



[t]

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.

https://iopscience.iop.org/article/10.1088/1478-3975/12/4/046011