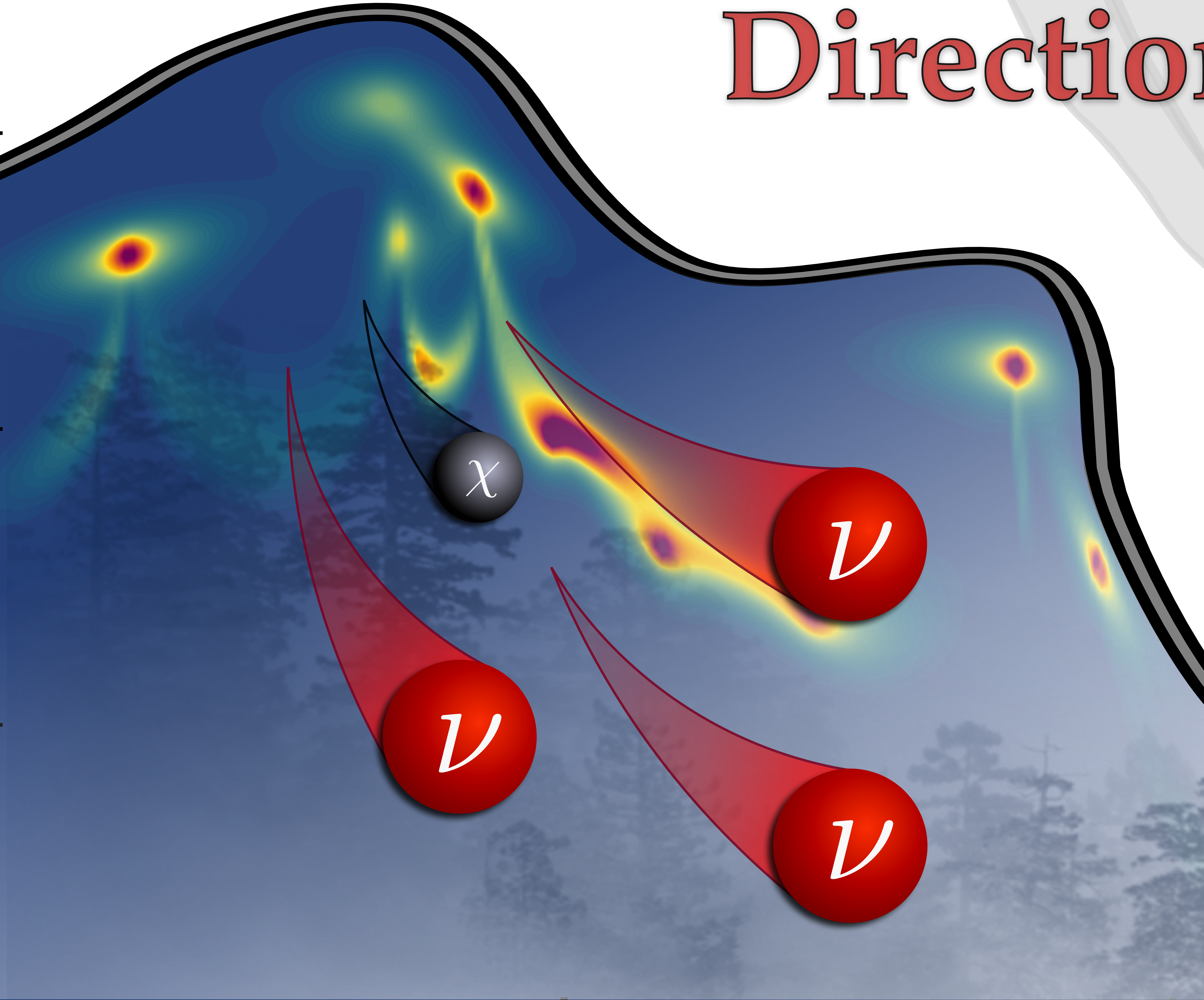
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

Directional recoil detection

(for DM, ν and BSM)



Ciaran O'Hare

University of Sydney

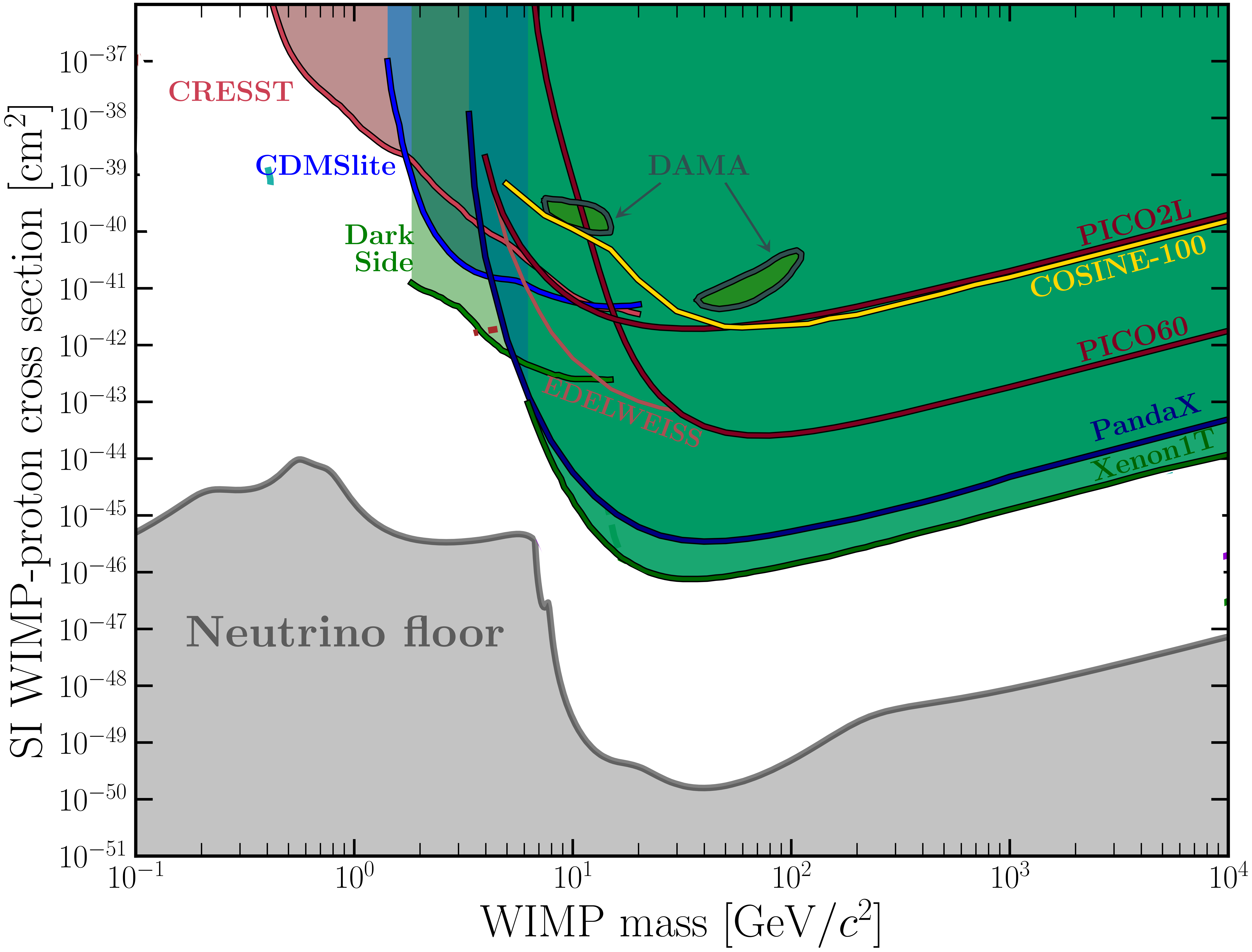
The neutrino fog

Directional dark matter detection

What else can we do?

Partially based on Snowmass white paper [2203.05914] and prior work

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



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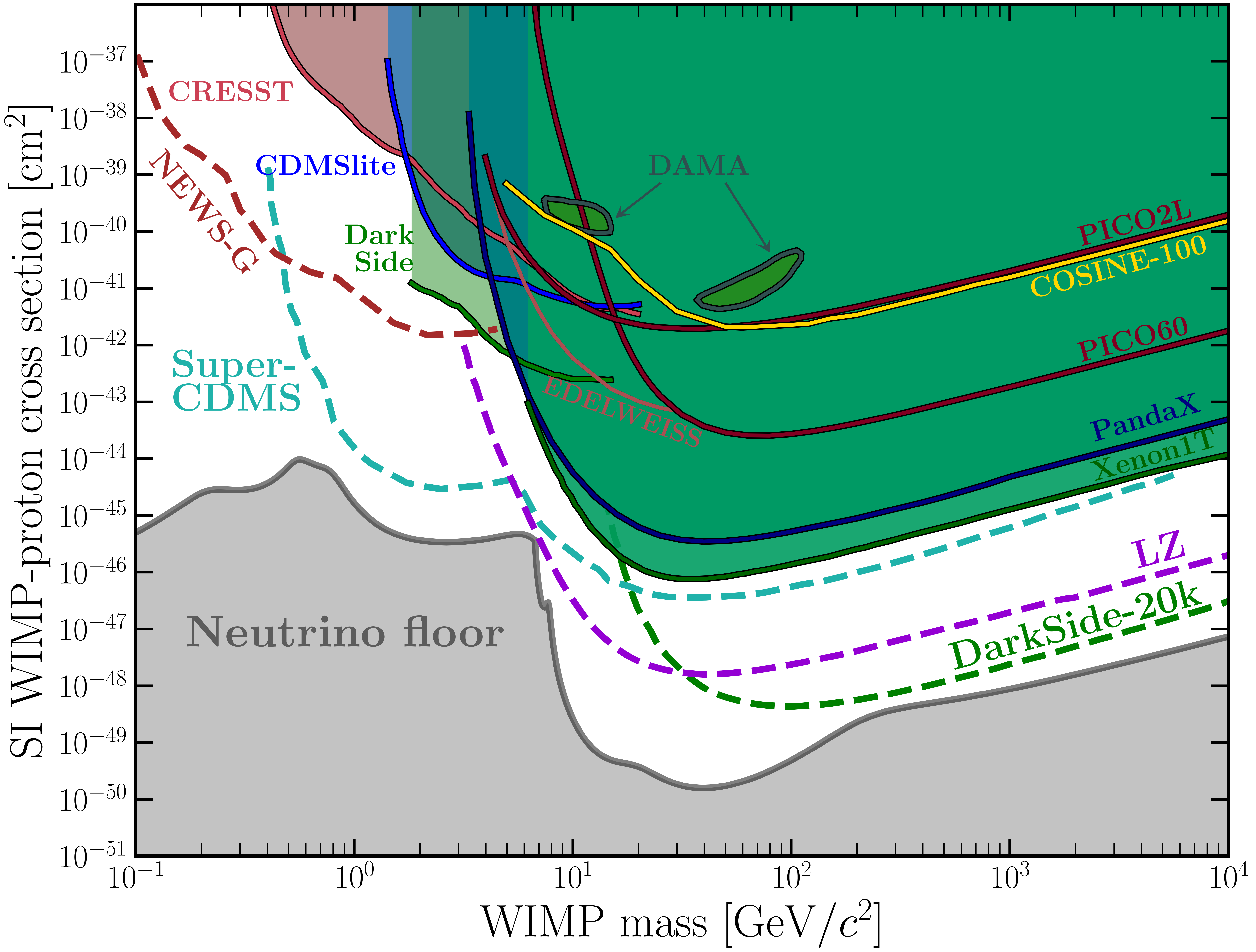
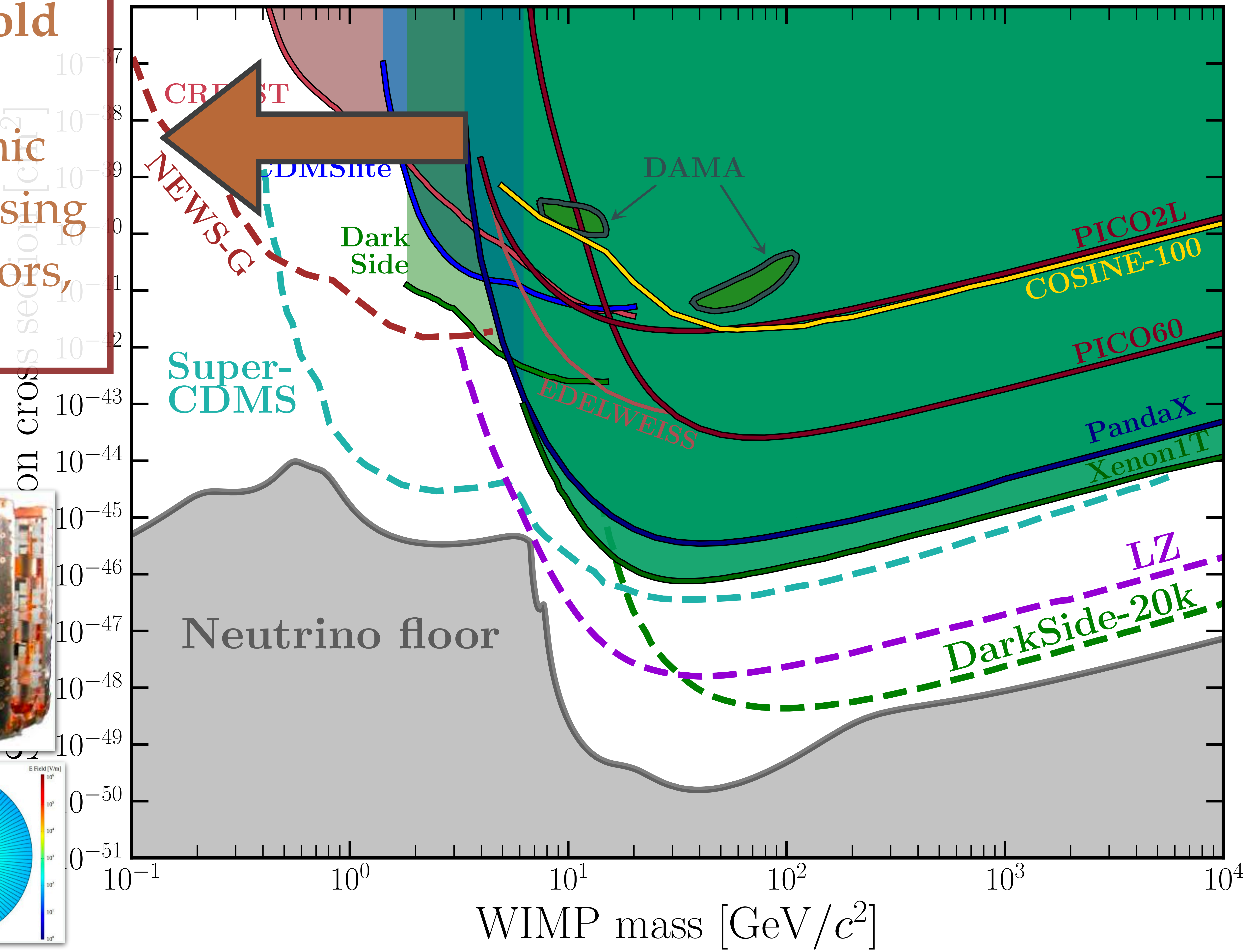
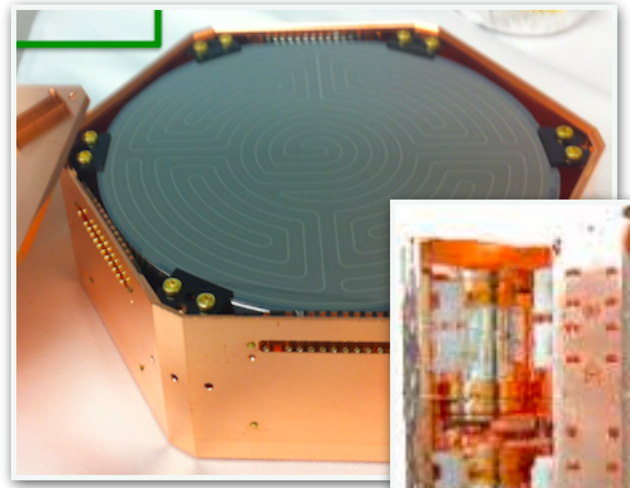


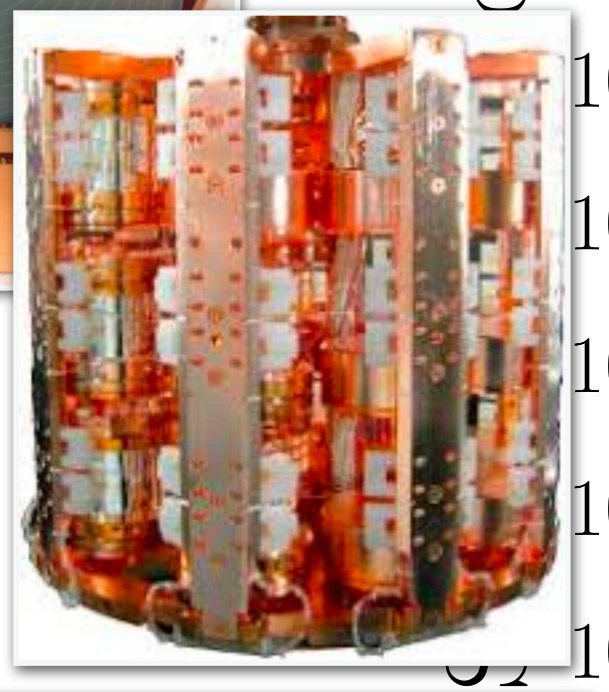
Status of searches for WIMP-like dark matter via <u>nuclear recoils</u>

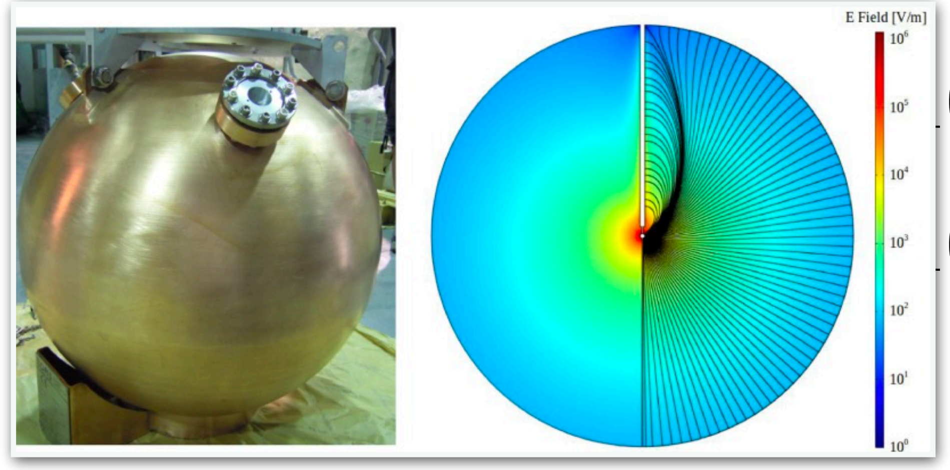
Low threshold detectors

e.g. cryogenic scintillators using semiconductors, gas SPCs









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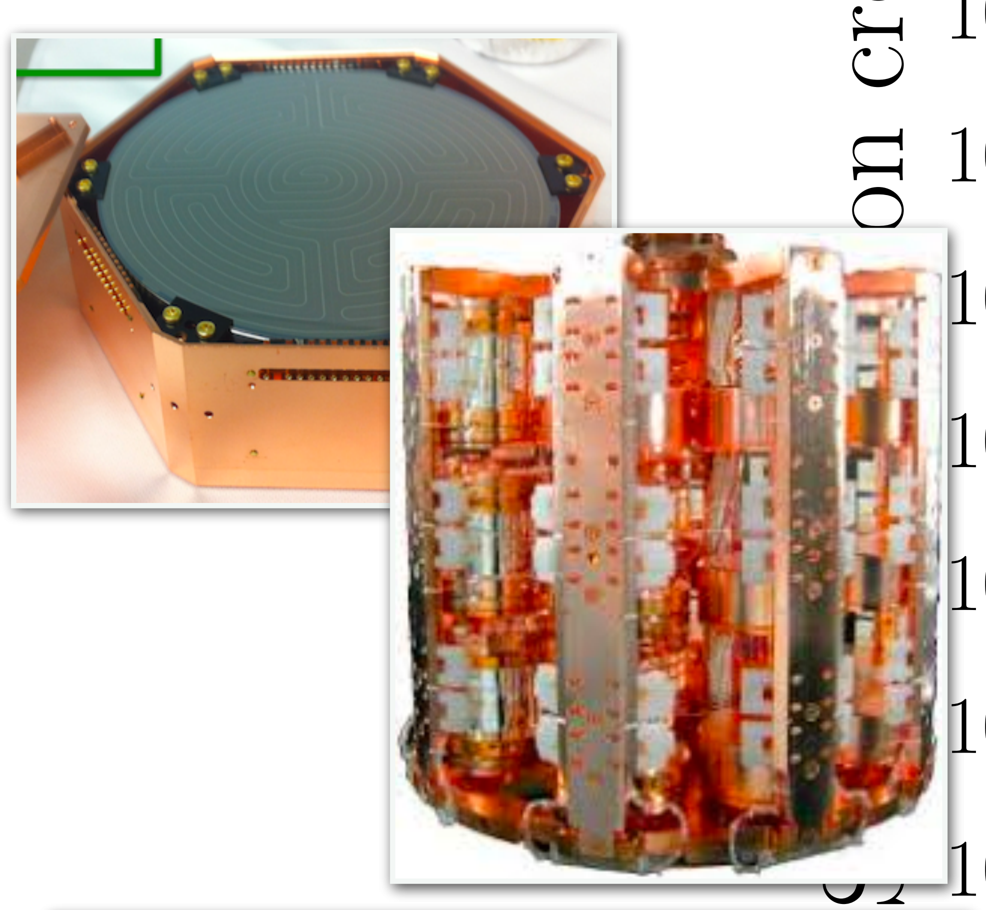

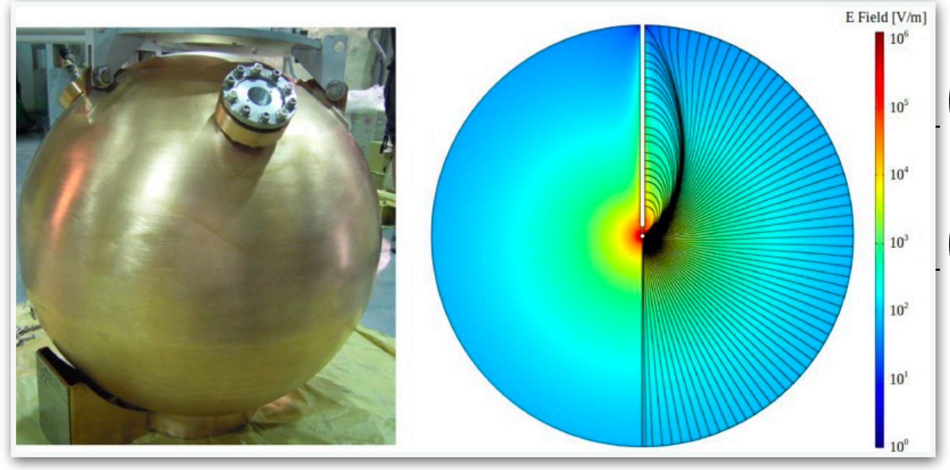

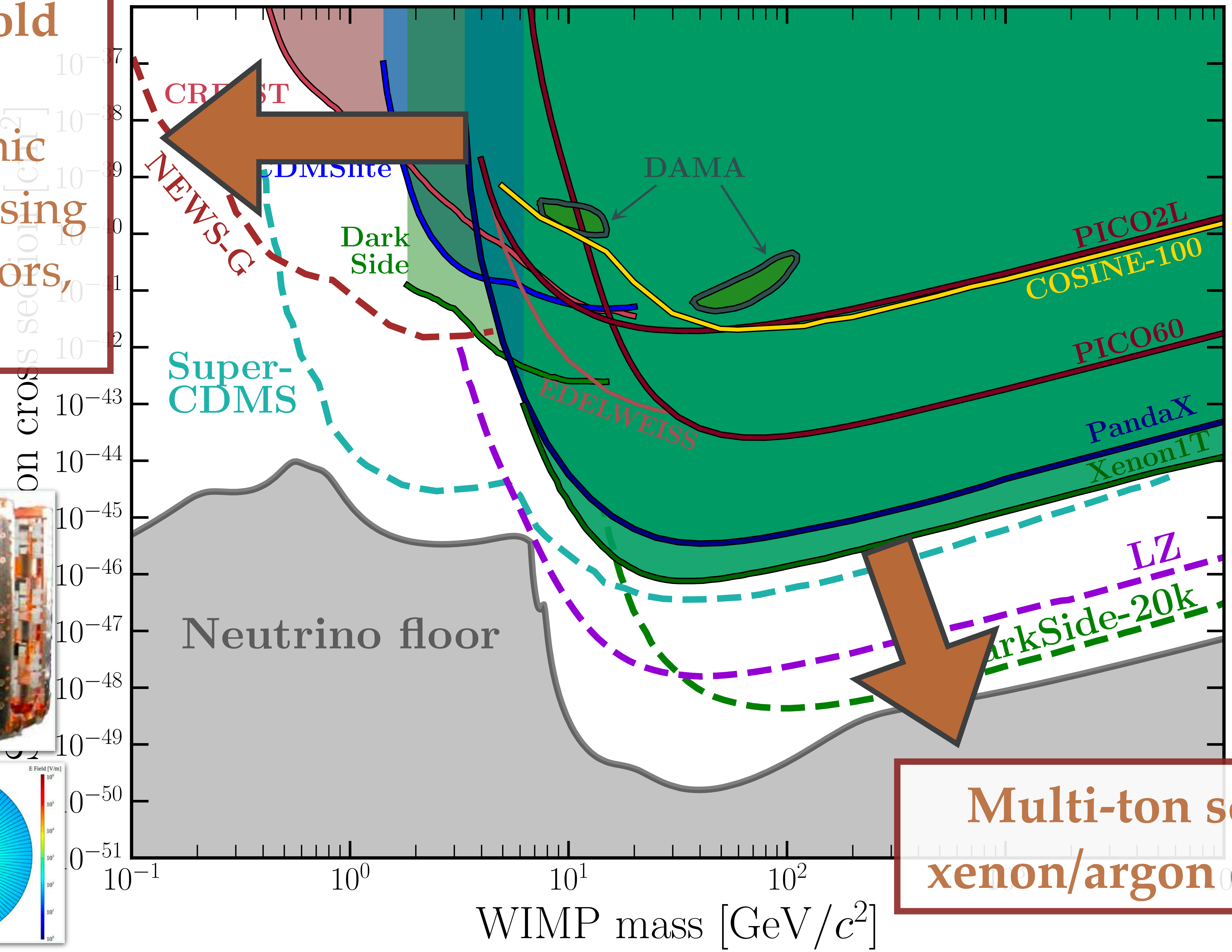

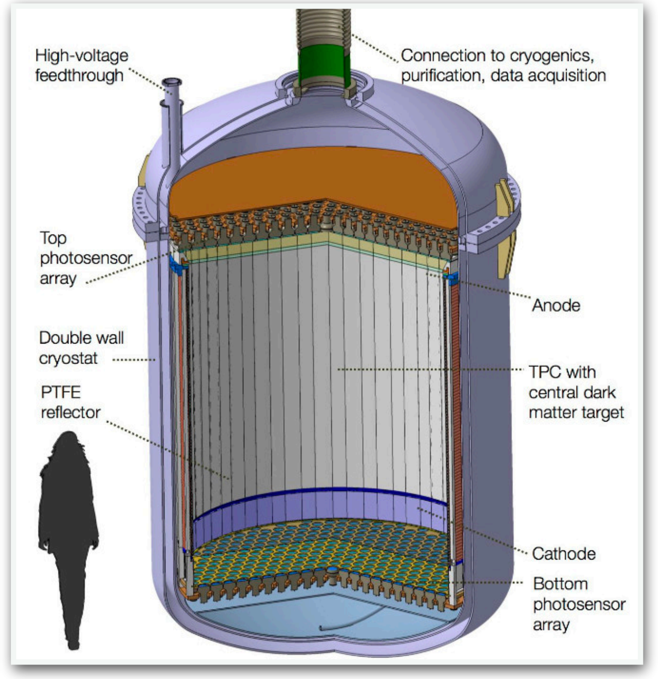

Multi-ton scale liquid xenon/argon experiments

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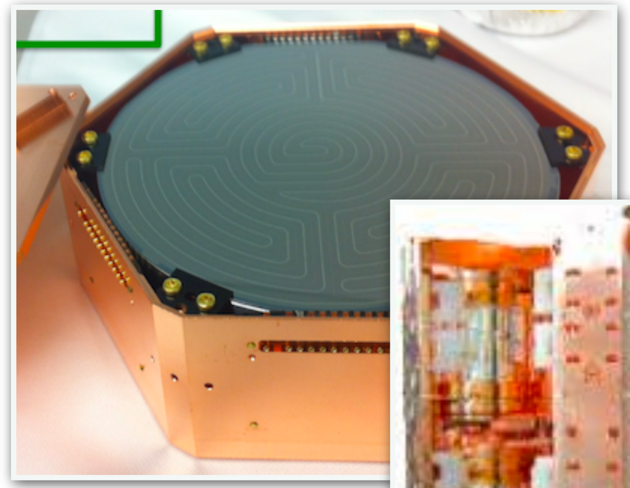
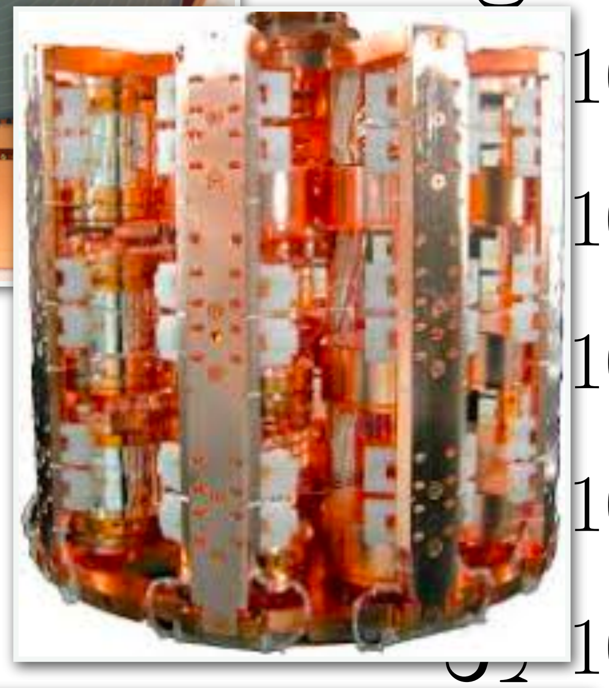
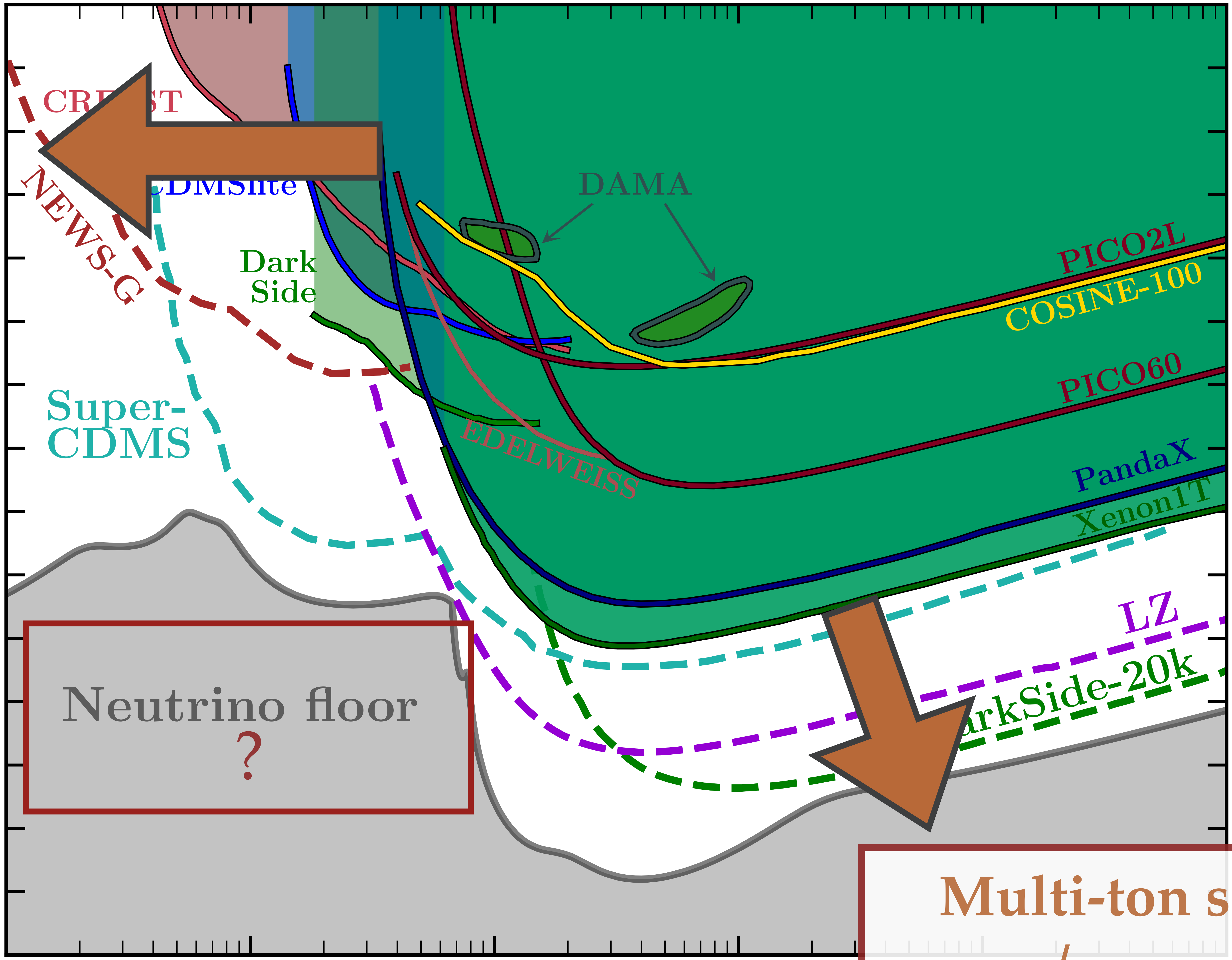
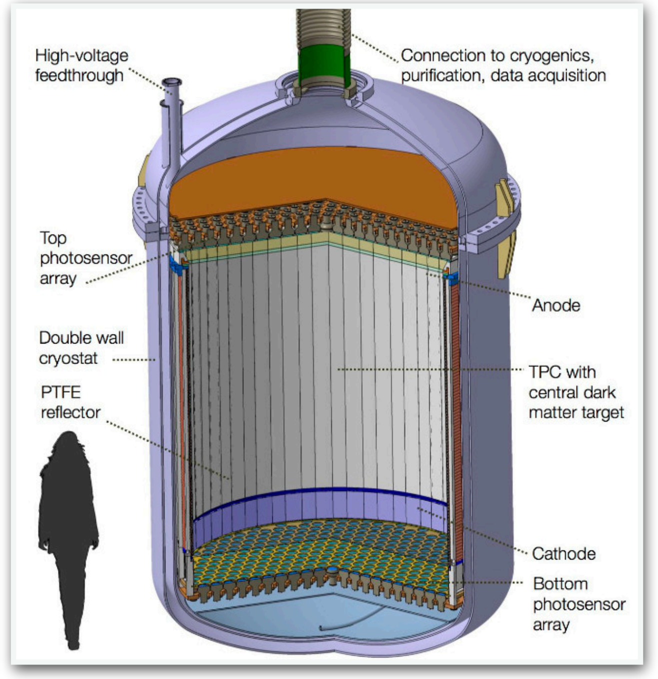




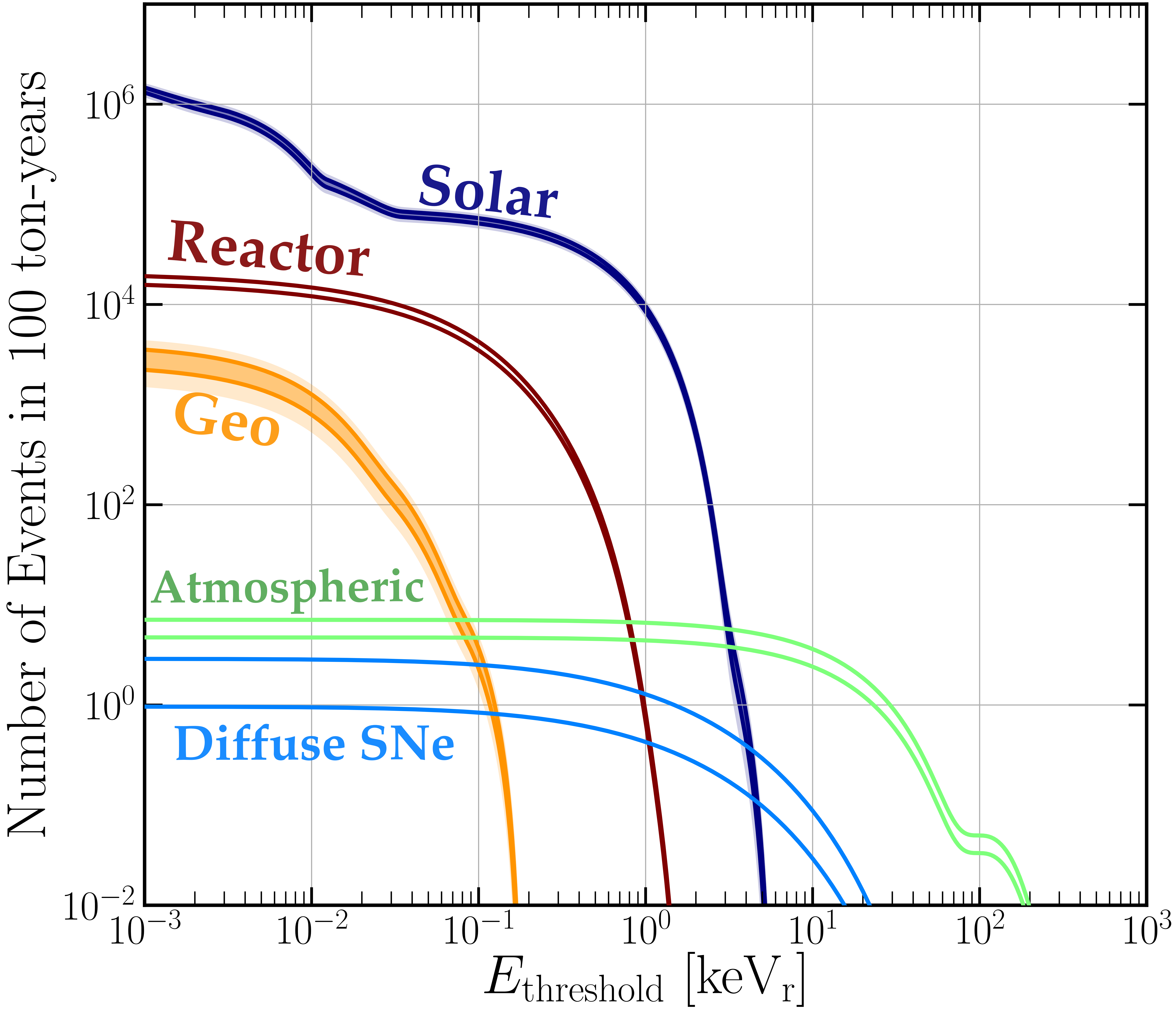




Multi-ton scale liquid xenon/argon experiments

The "neutrino floor" as it's usually presented

e.g. for LXe TPCs

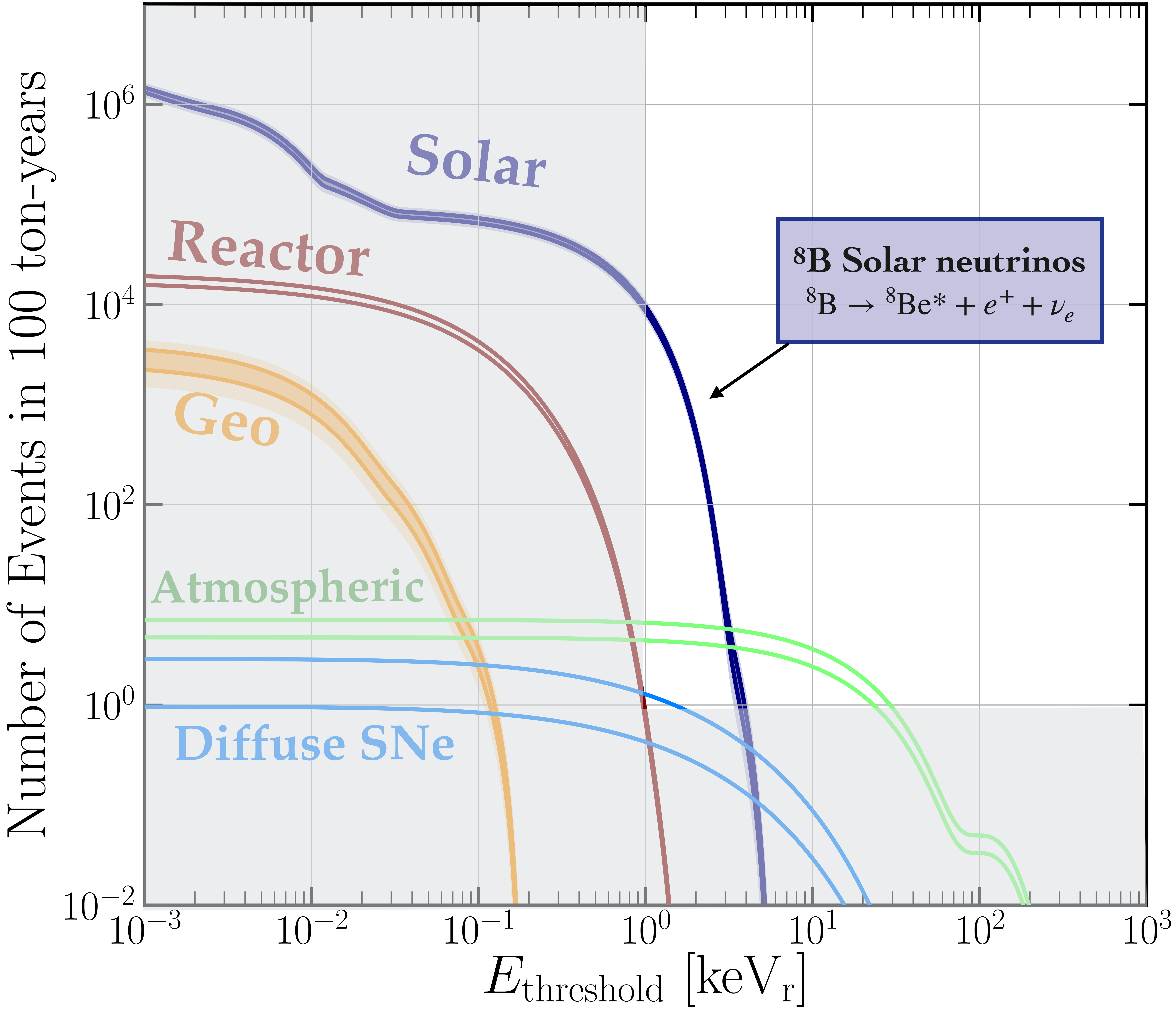


Neutrino fluxes relevant for dark matter searches

↓

CEvNS event rates for Xe target

$$\frac{\mathrm{d}R_\nu}{\mathrm{d}E_r} = \frac{1}{m_N}\int_{E_\nu^{\mathrm{min}}} \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu}\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\mathrm{d}E_\nu$$



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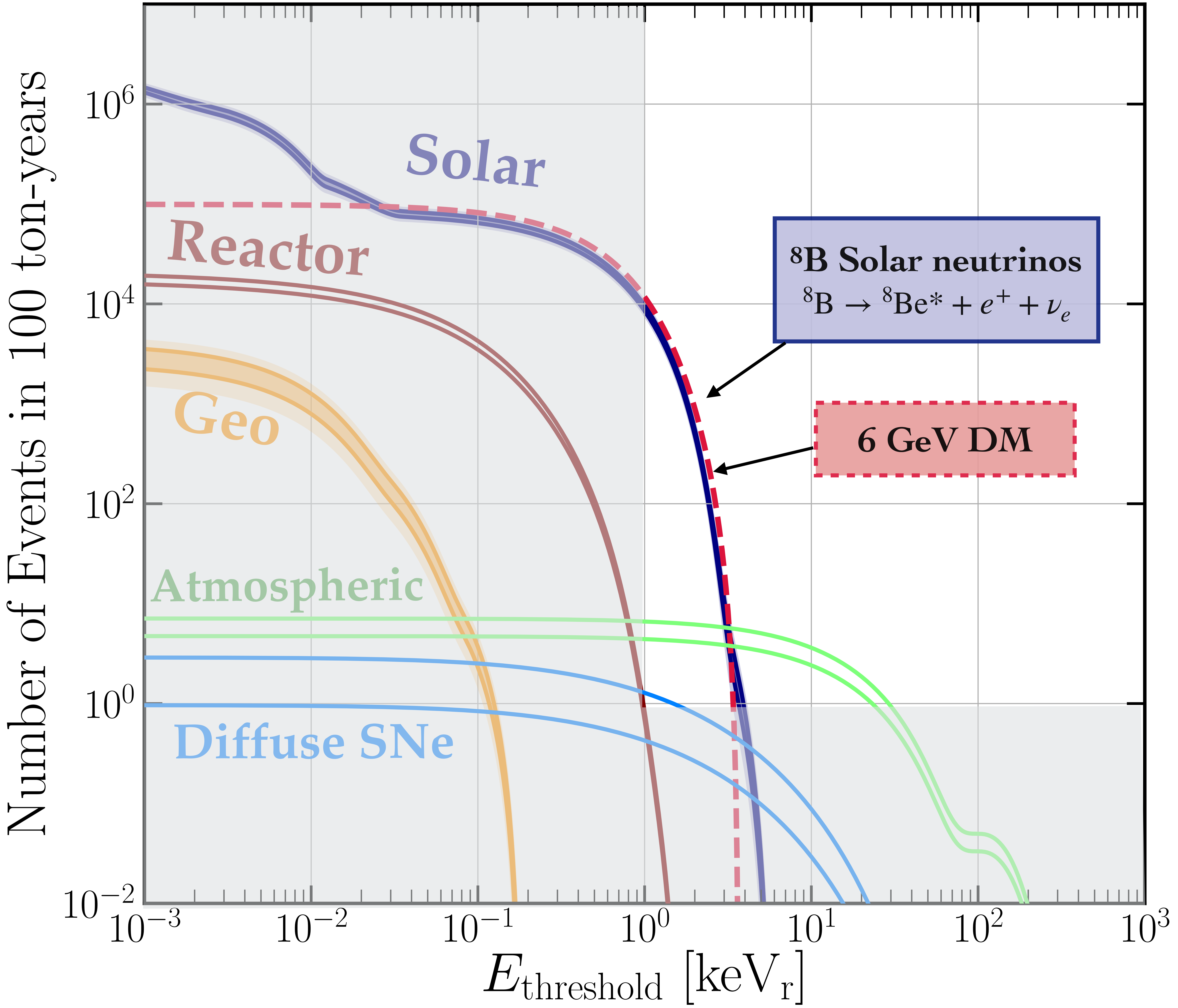

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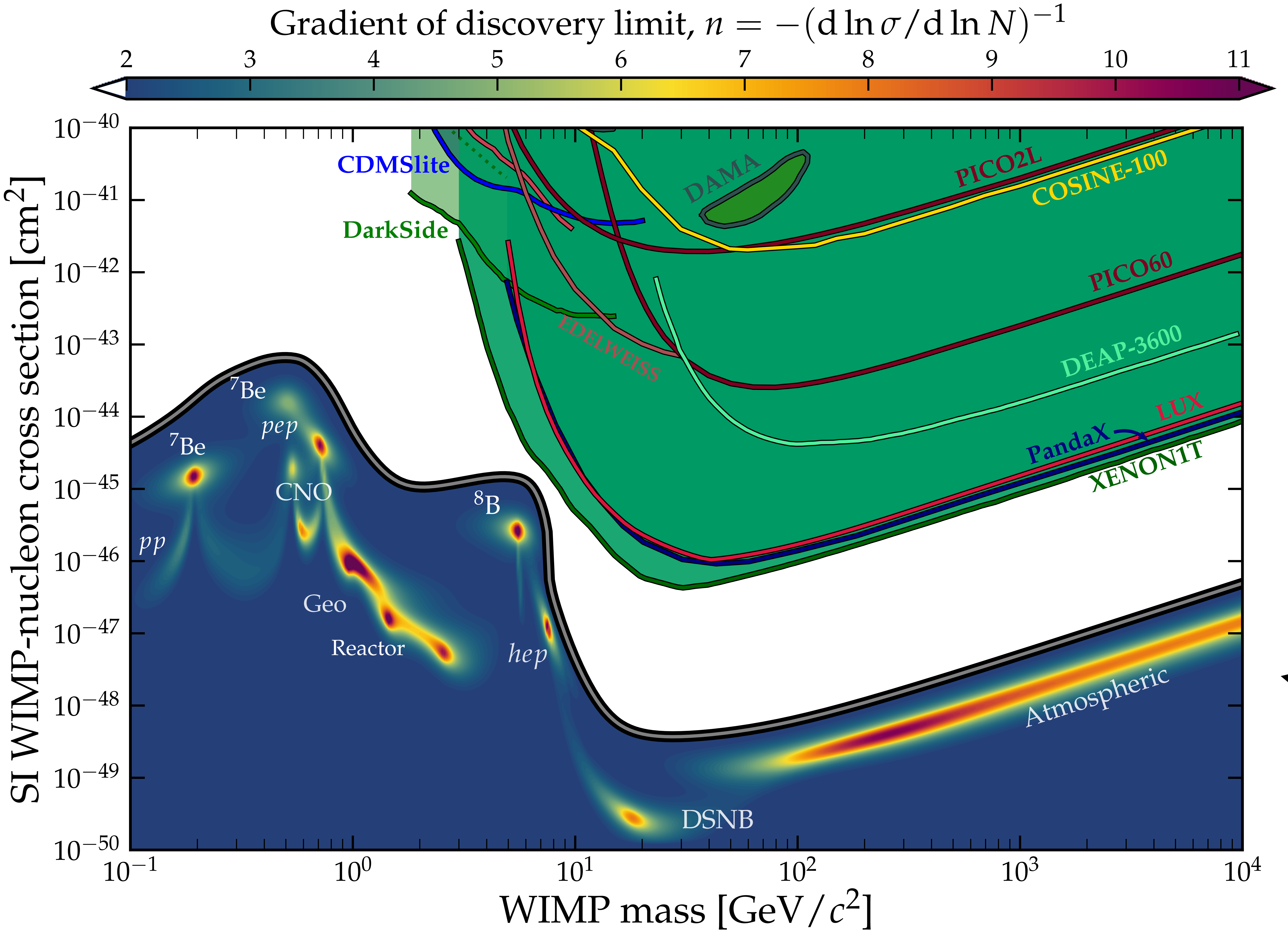
O’Hare [2109.03116]



The “neutrino fog”

colour encodes how badly the neutrino background inhibits DM discovery
→ the parameter space is not uniformly foggy

How to venture into the neutrino fog:

Several methods, ordered (sort of) in increasing effectiveness

1. Detect *a lot* of events

2. Use annual modulation

3. Have multiple target nuclei

4. Improve neutrino flux measurements

5. Use directional detectors

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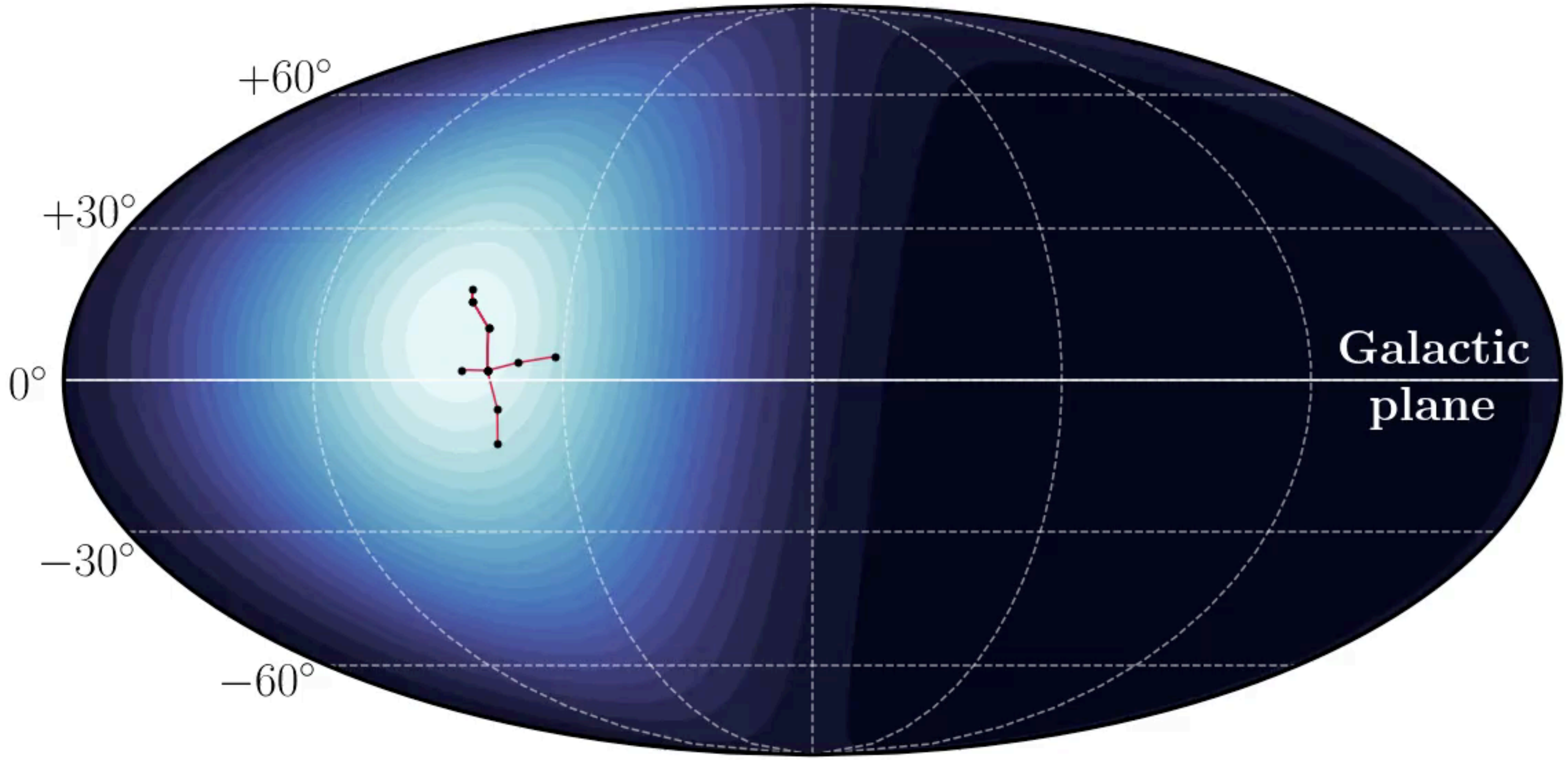
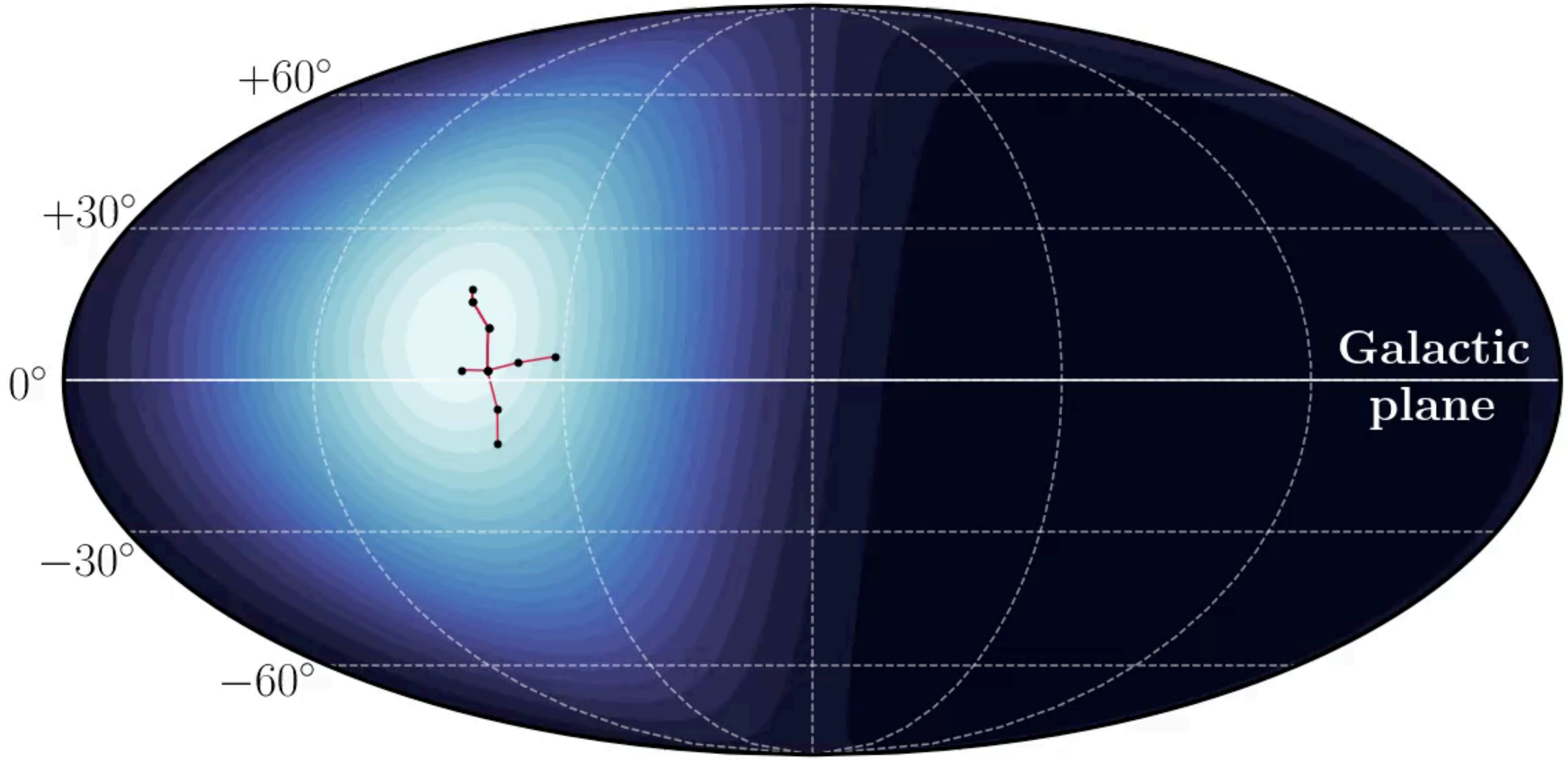
Cygnus
Jun
Dec



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



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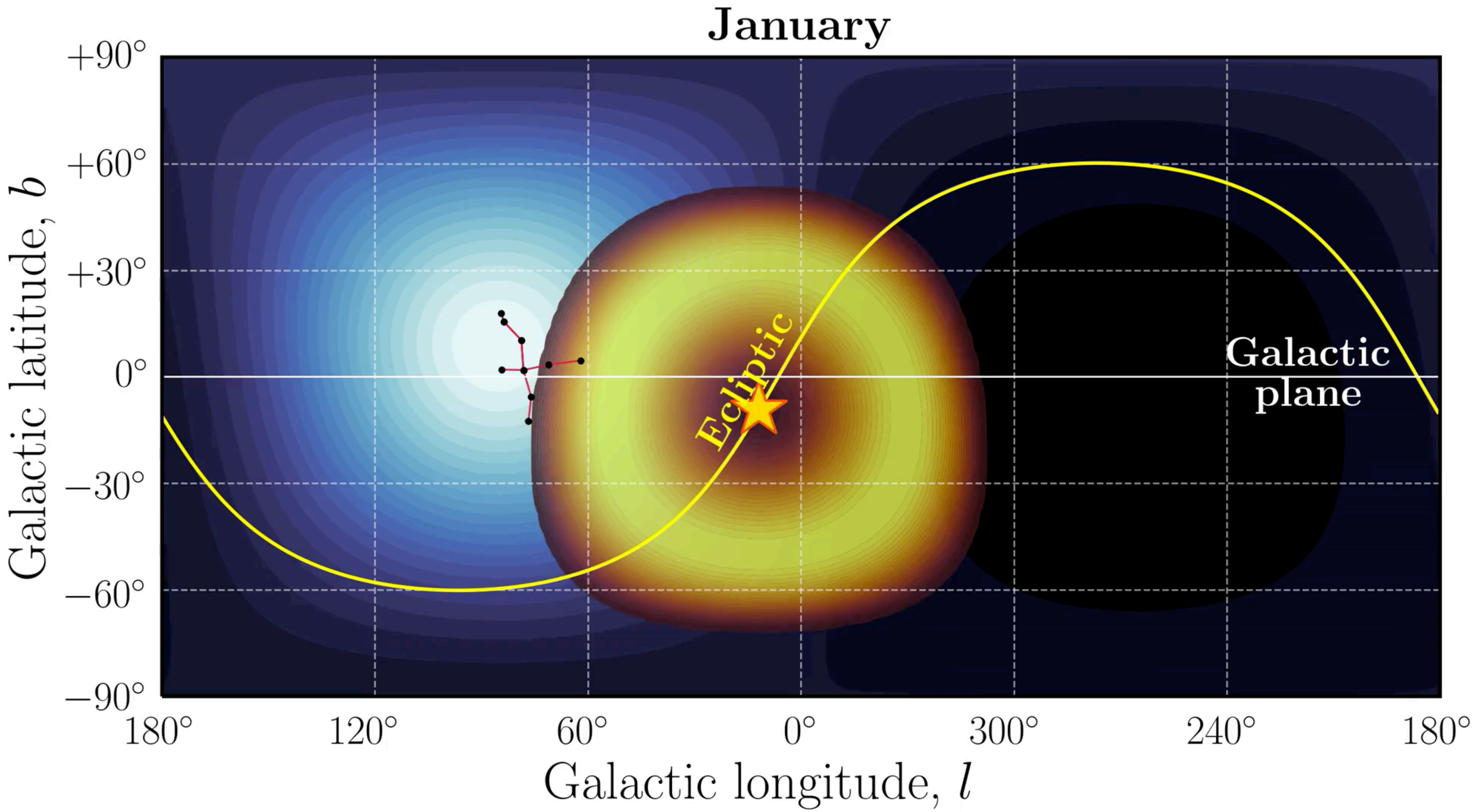

A directional detector should be able to “see through” the neutrino fog

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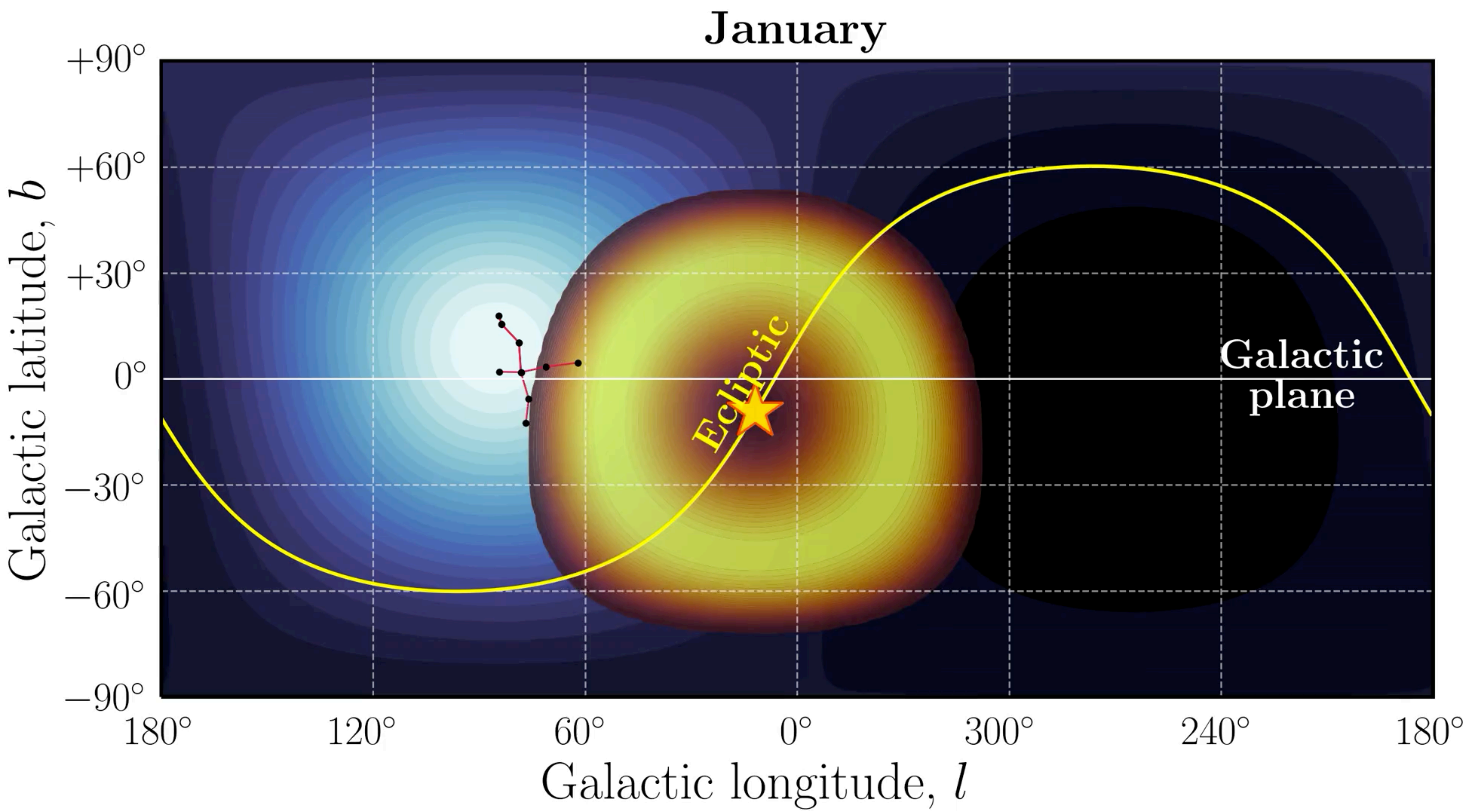
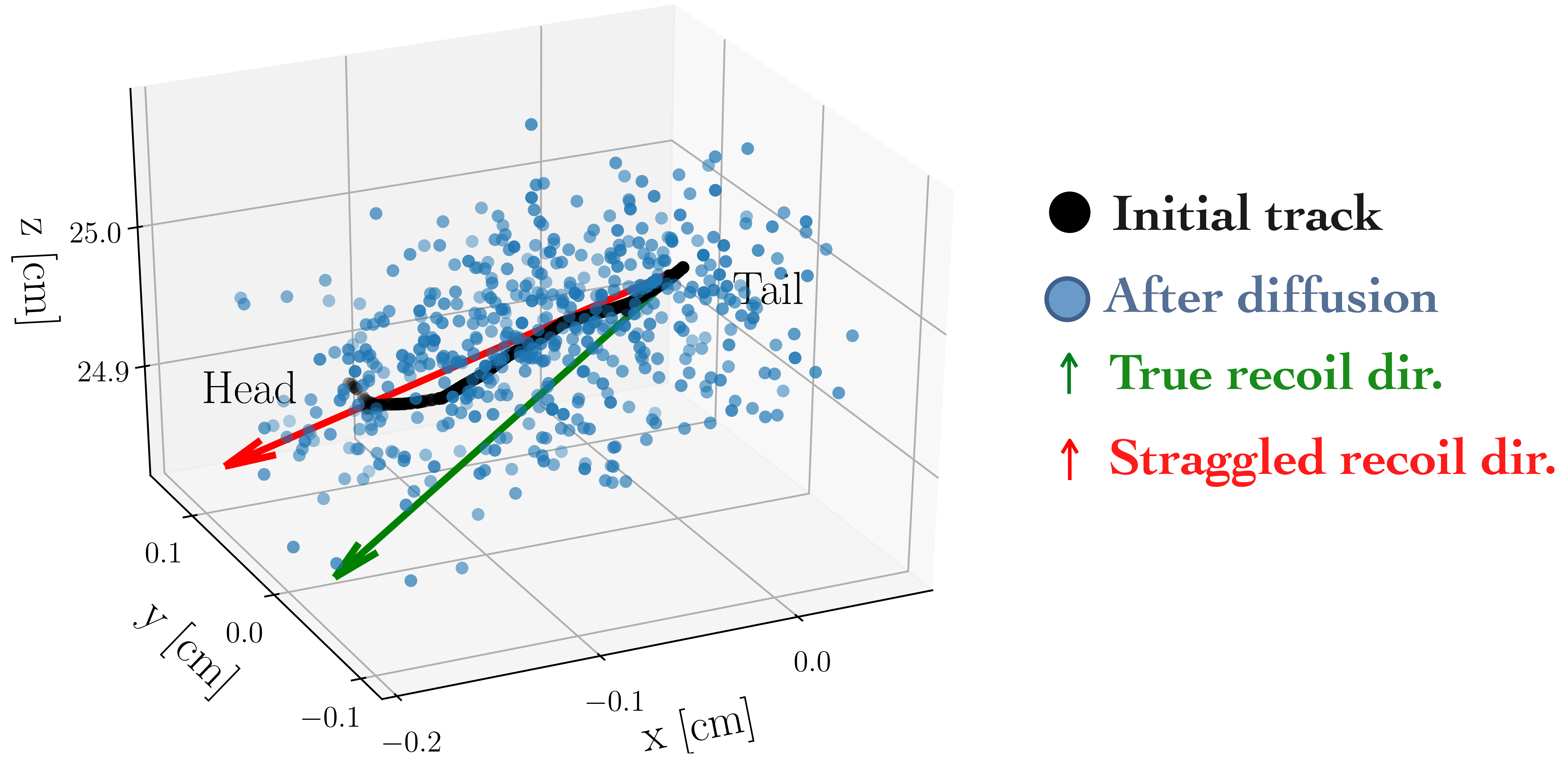


A directional detector should be able to "see through" the neutrino fog

How to detect nuclear recoil directions at the keV-scale?



How well do nuclear recoil directions need to be measured?

Some rough benchmarks for dark matter:

(see review [2102.04596] for reasoning)

- Angular resolution **<30°**
- Correct head / tail **>75%** of the time
- Fractional energy resolution $< 20\%$

If you don't achieve these then directionality adds nothing to the sensitivity (in the context of the ν background)

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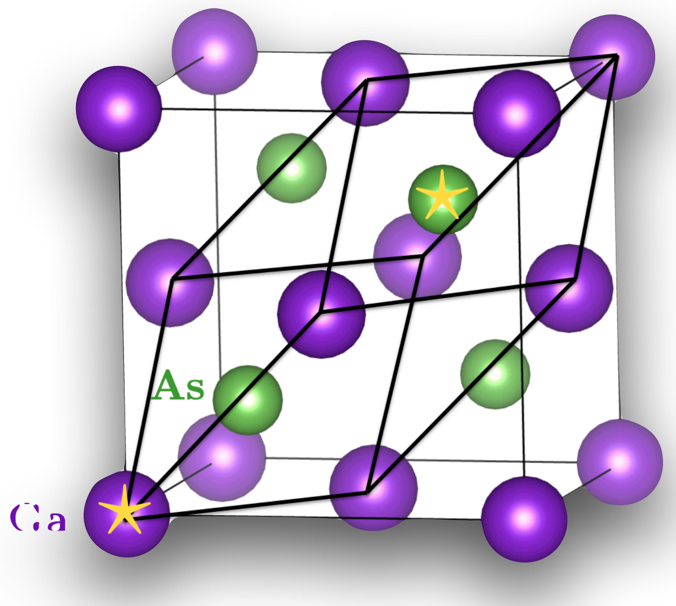
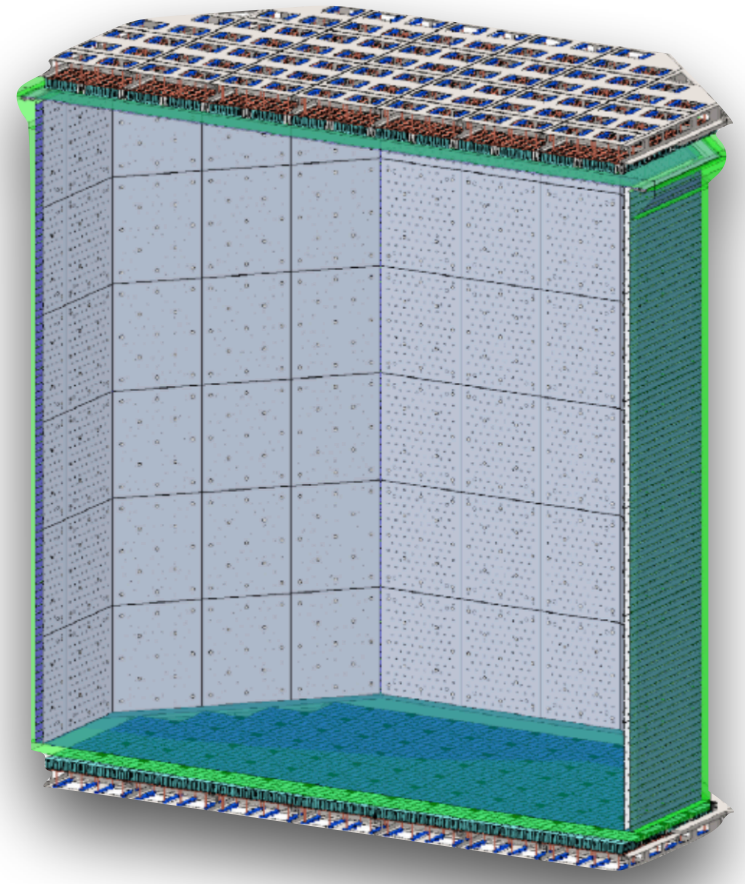
And achieved…

- At the level of individual events
- In as high a density target as possible (maximise target mass)
- Below <10 keVr (target dependent but usually CEvNS recoils are sub-10-keVr)
- With a timing resolution better than a few hours

What technique to use?

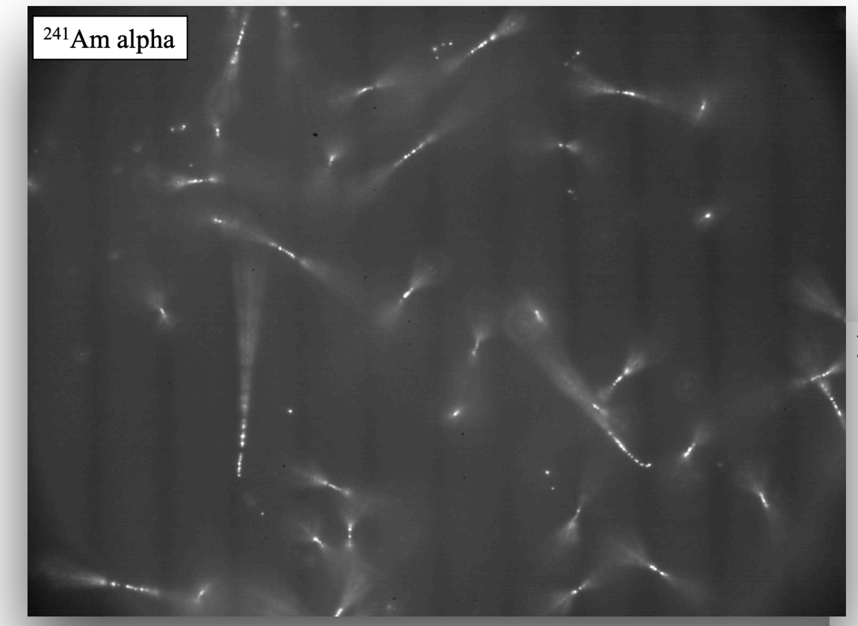
Anisotropic materials



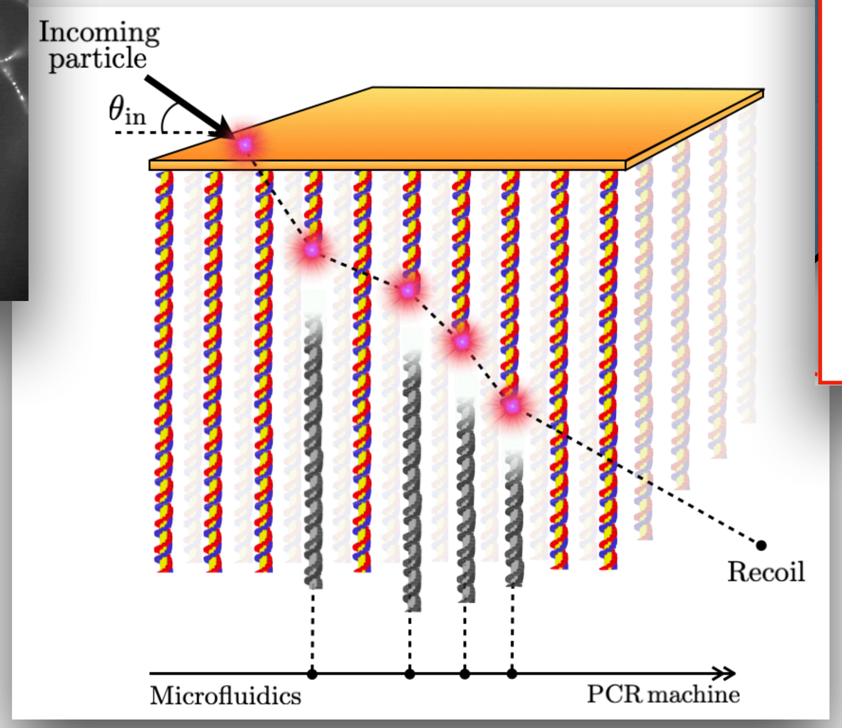


Columnar recombination

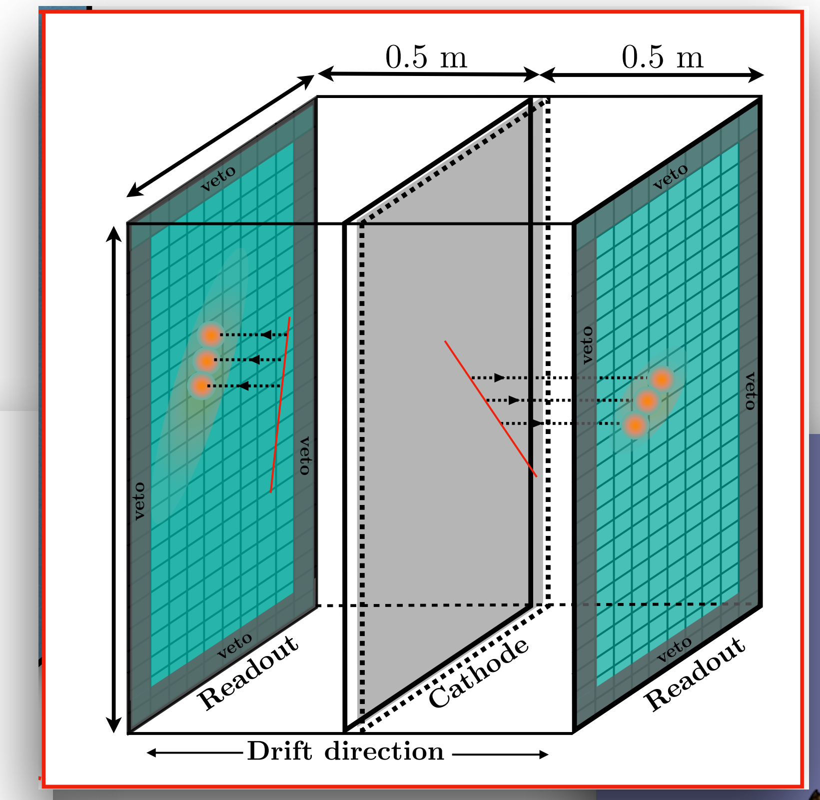
Nuclear emulsions



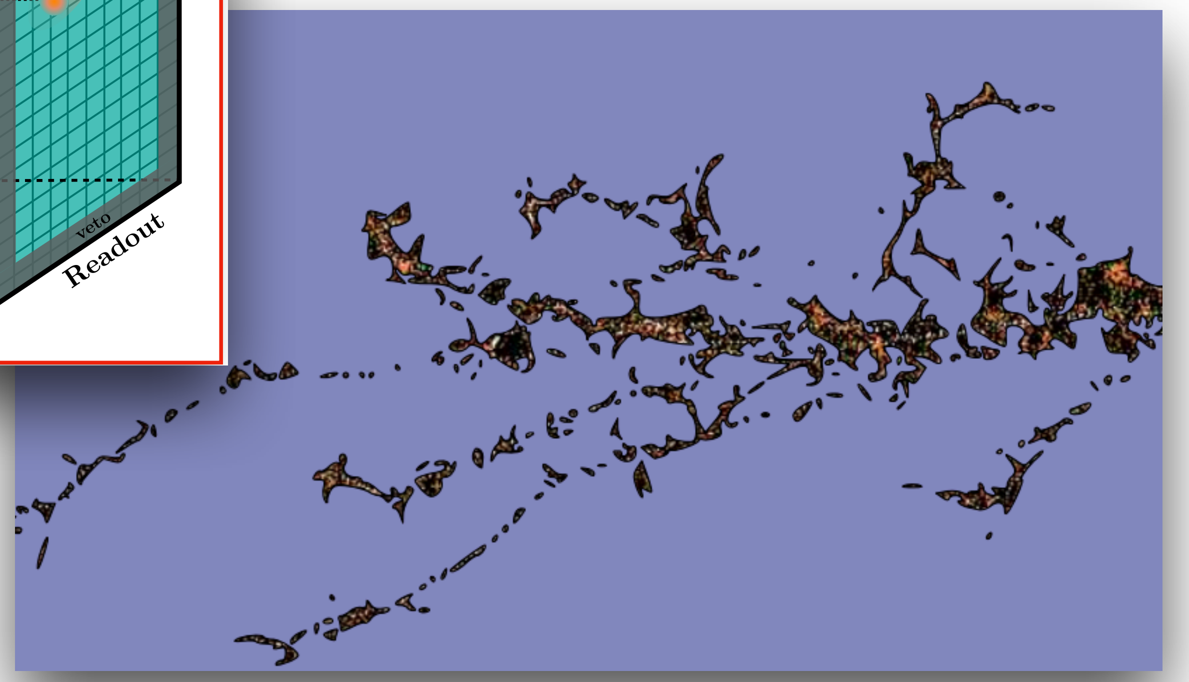
DNA



Micro-pattern gas detectors



Crystal defects



A lot of directional detector ideas proposed

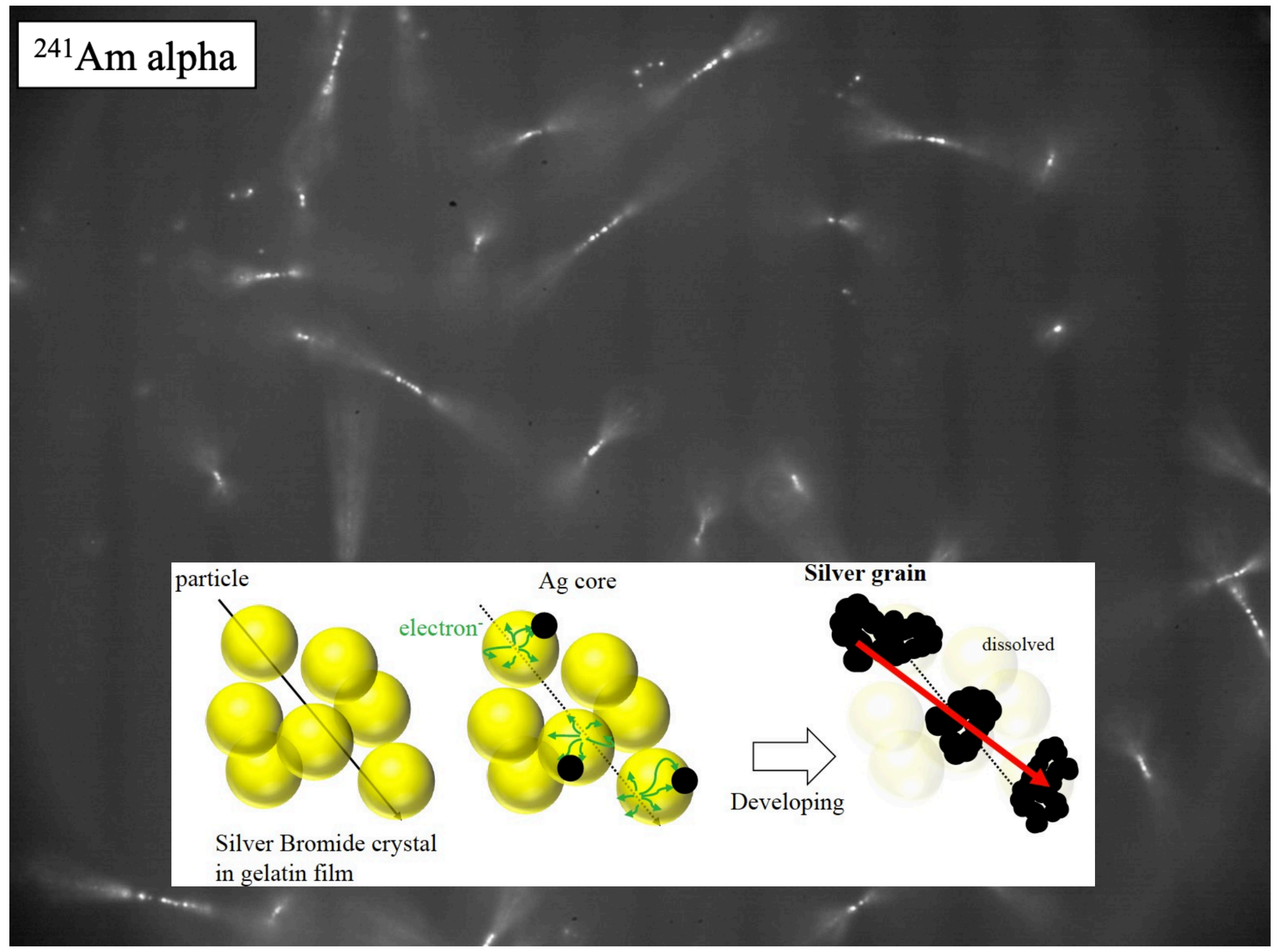
→ unfortunately many do not meet the performance goals even under the most optimistic scenarios imaginable

→ Need complete 3D time-resolved tracks with independent recoil energy measurements. Only a subset can do this, daily modulation is not enough.

Directionality in solids

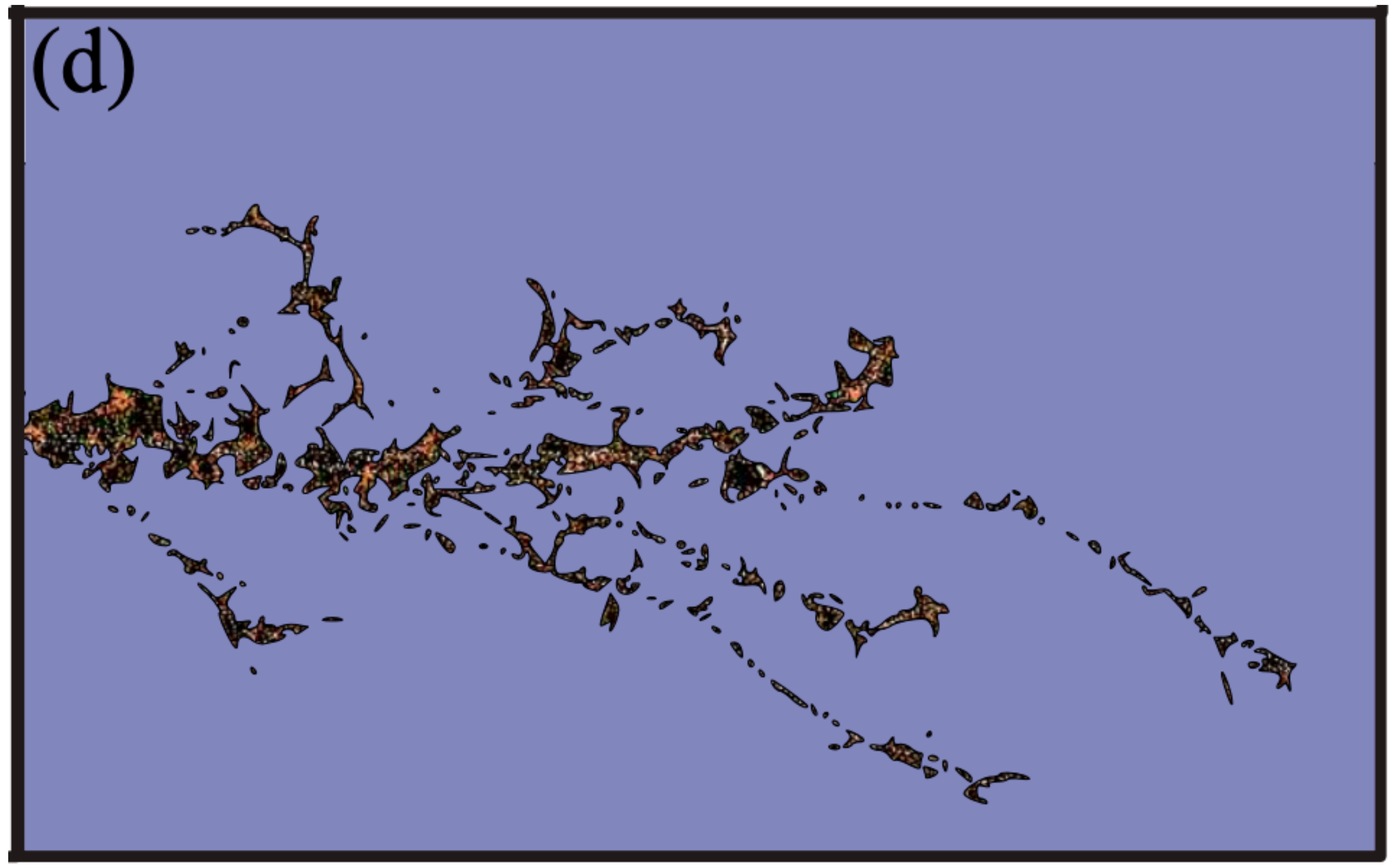
Clear advantage: high target density

Nuclear emulsions



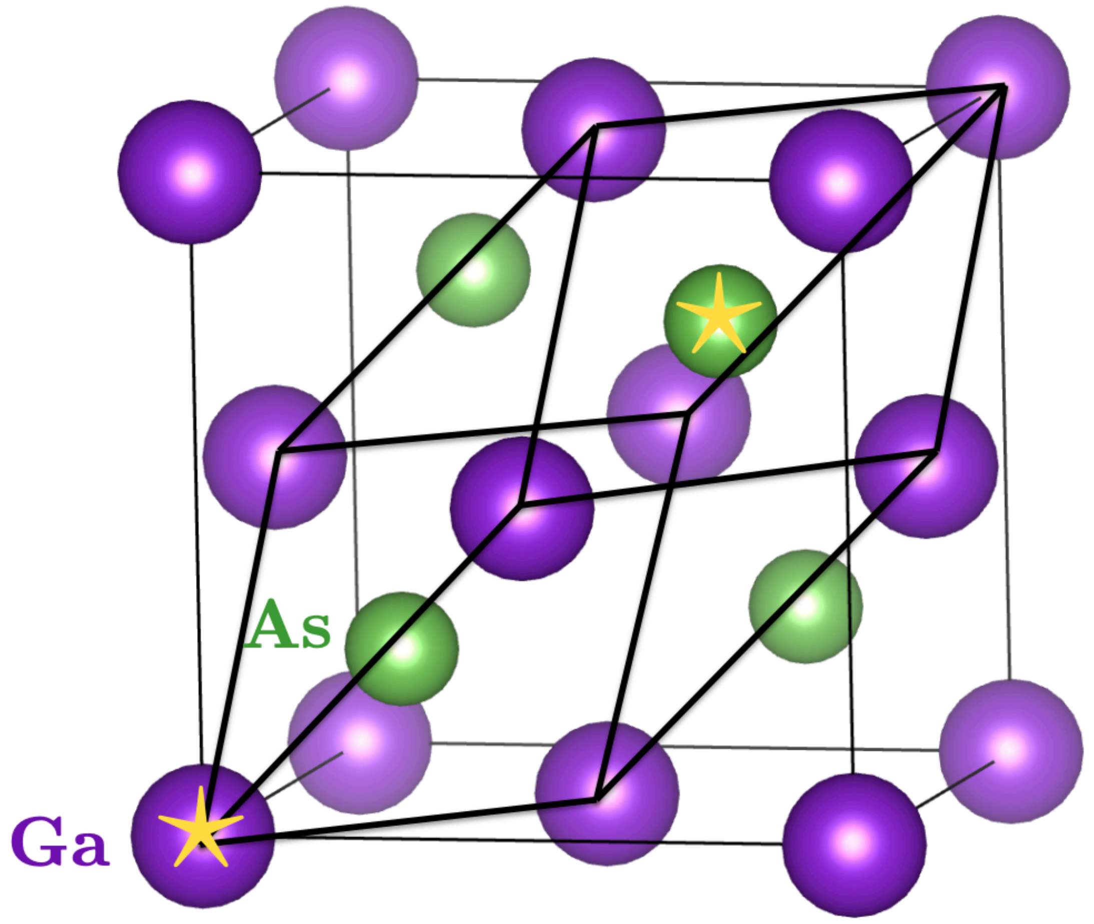
[1604.04199]

Crystal defects



[2009.01028],[2203.06037]

Anisotropic materials



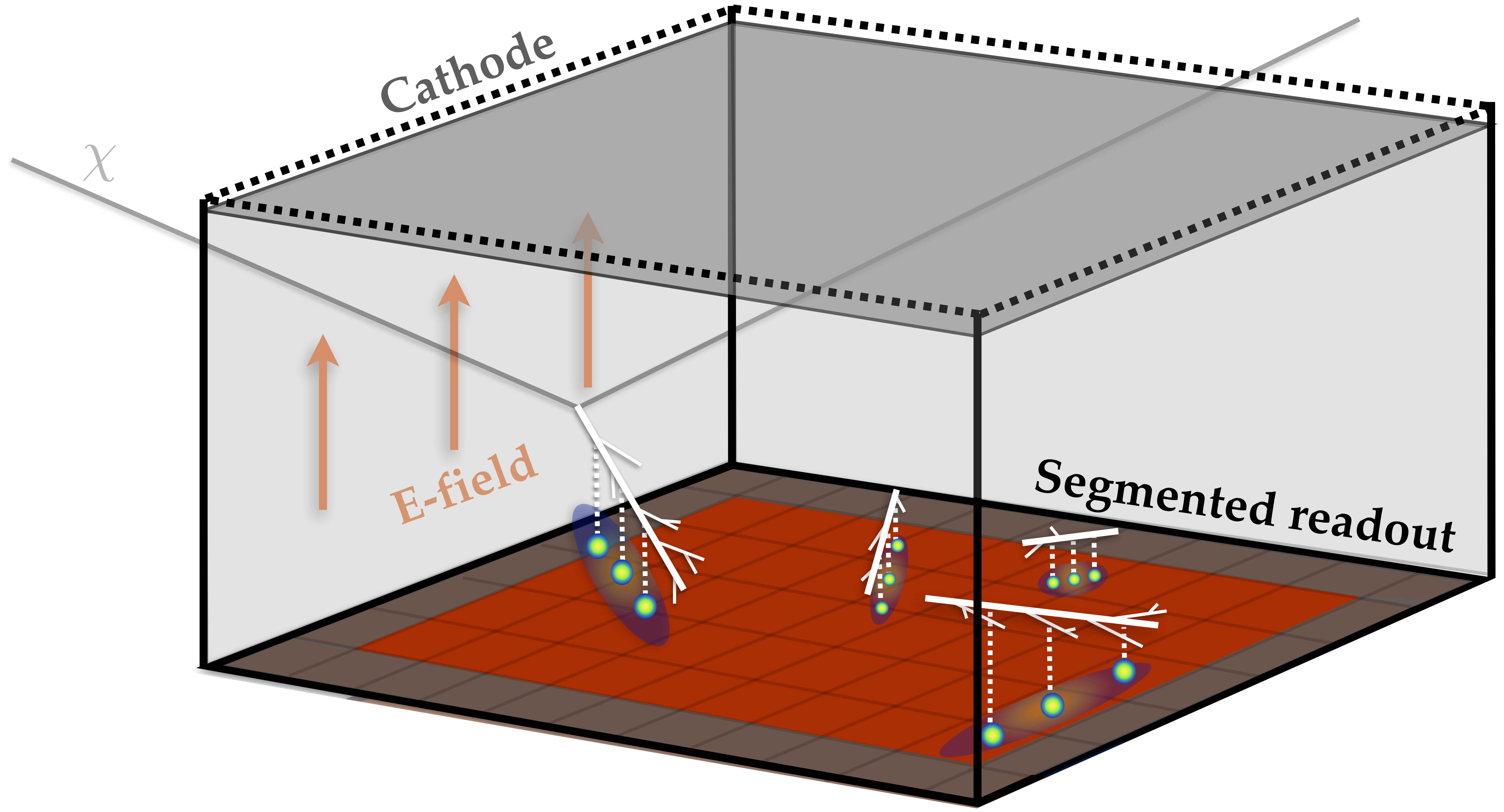
e.g. [1807.10291]

But: Need to image tracks *after* exposure, so have to figure out some method of reclaiming event time information or mitigating against Earth's rotation

No event-by-event recoil directions. Have to use daily modulation as a proxy for directionality

TPC + micro-pattern gas detector

In principle could provide high signal-to-noise detection of nuclear and electronic recoils with 100 μm^3-voxel size



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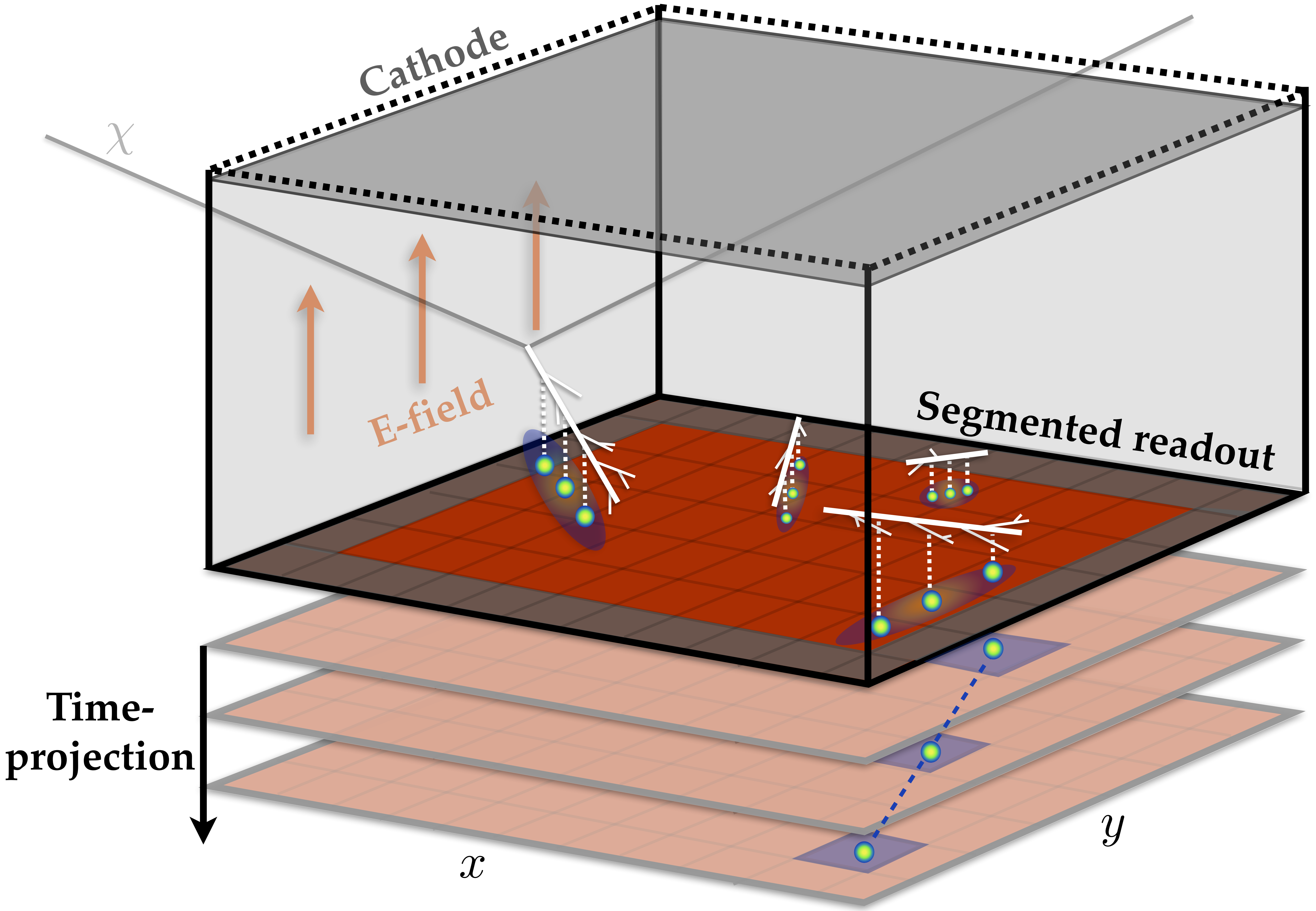

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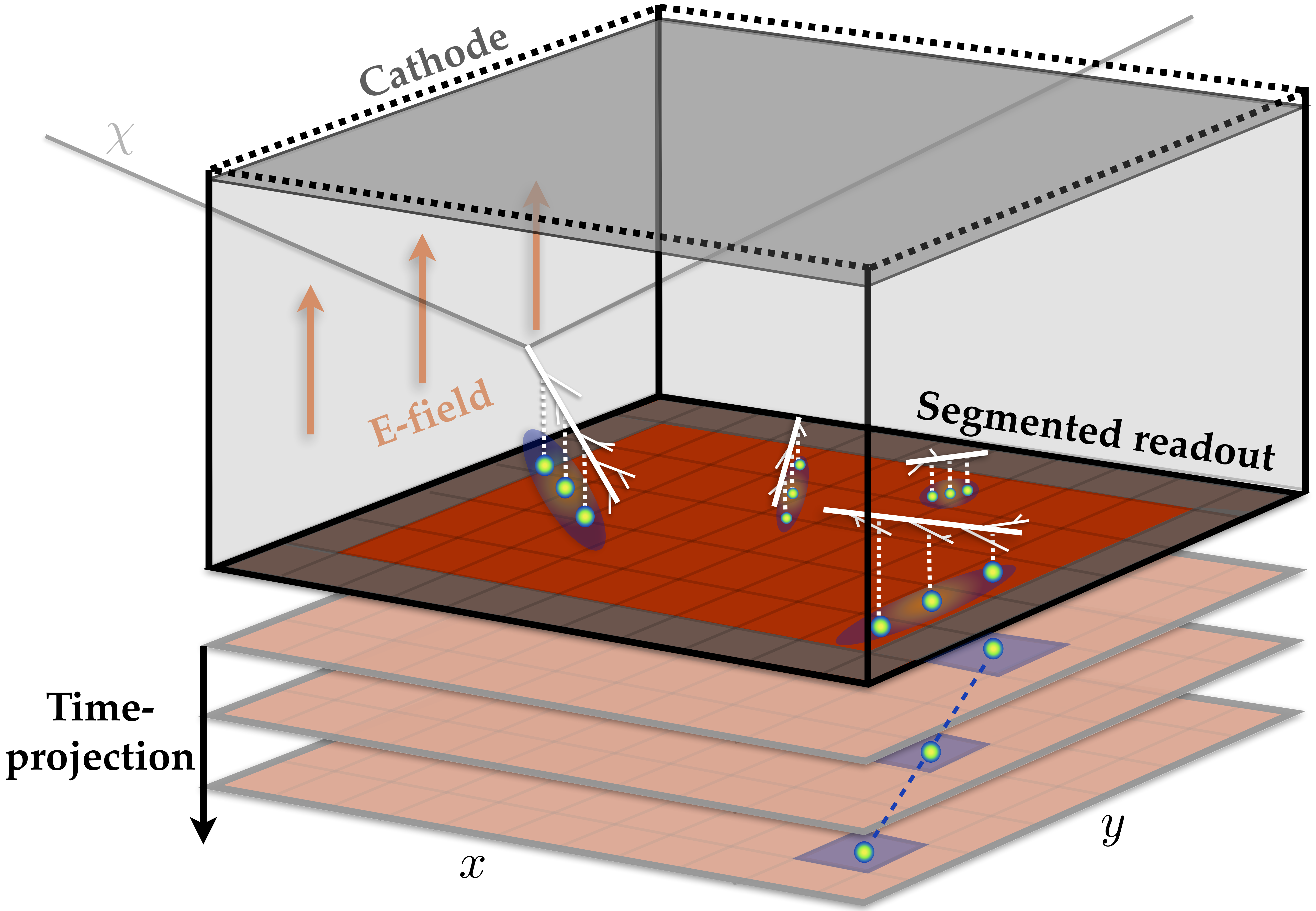
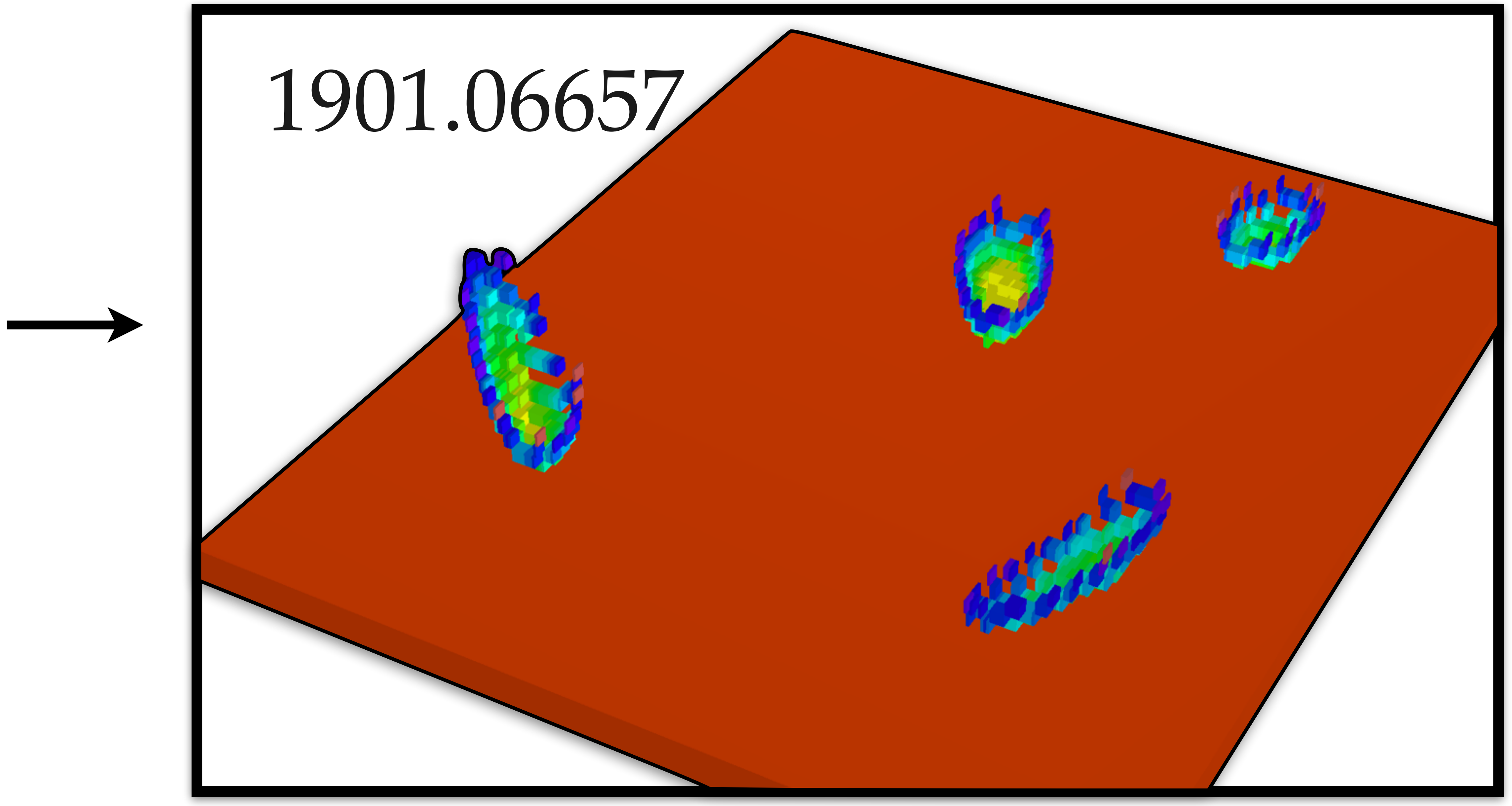


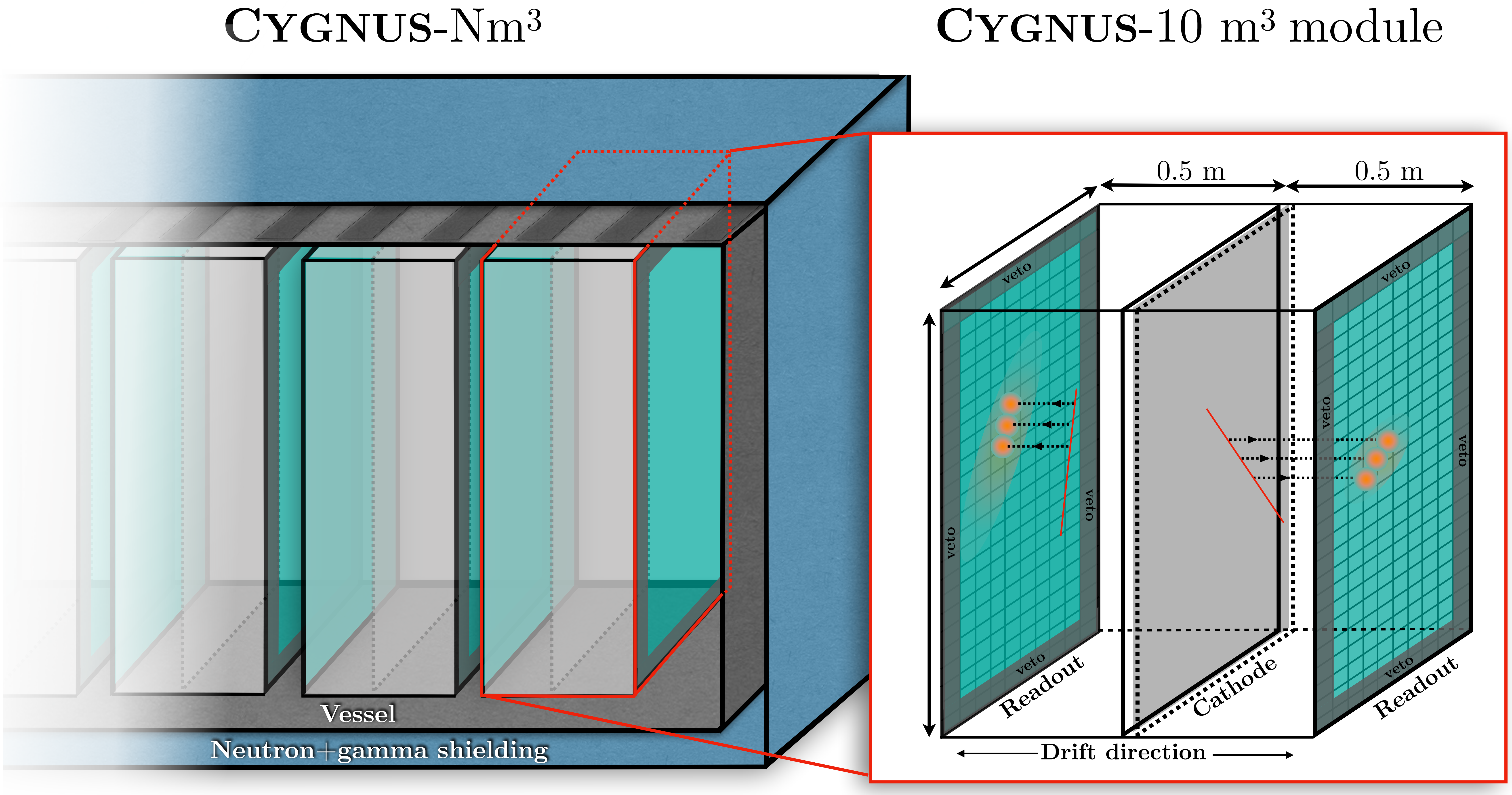


[2008.12587]

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]

He, SF_6, CF_4 at up to atm. pressure look most promising for reaching performance goals and competitive DM sensitivity

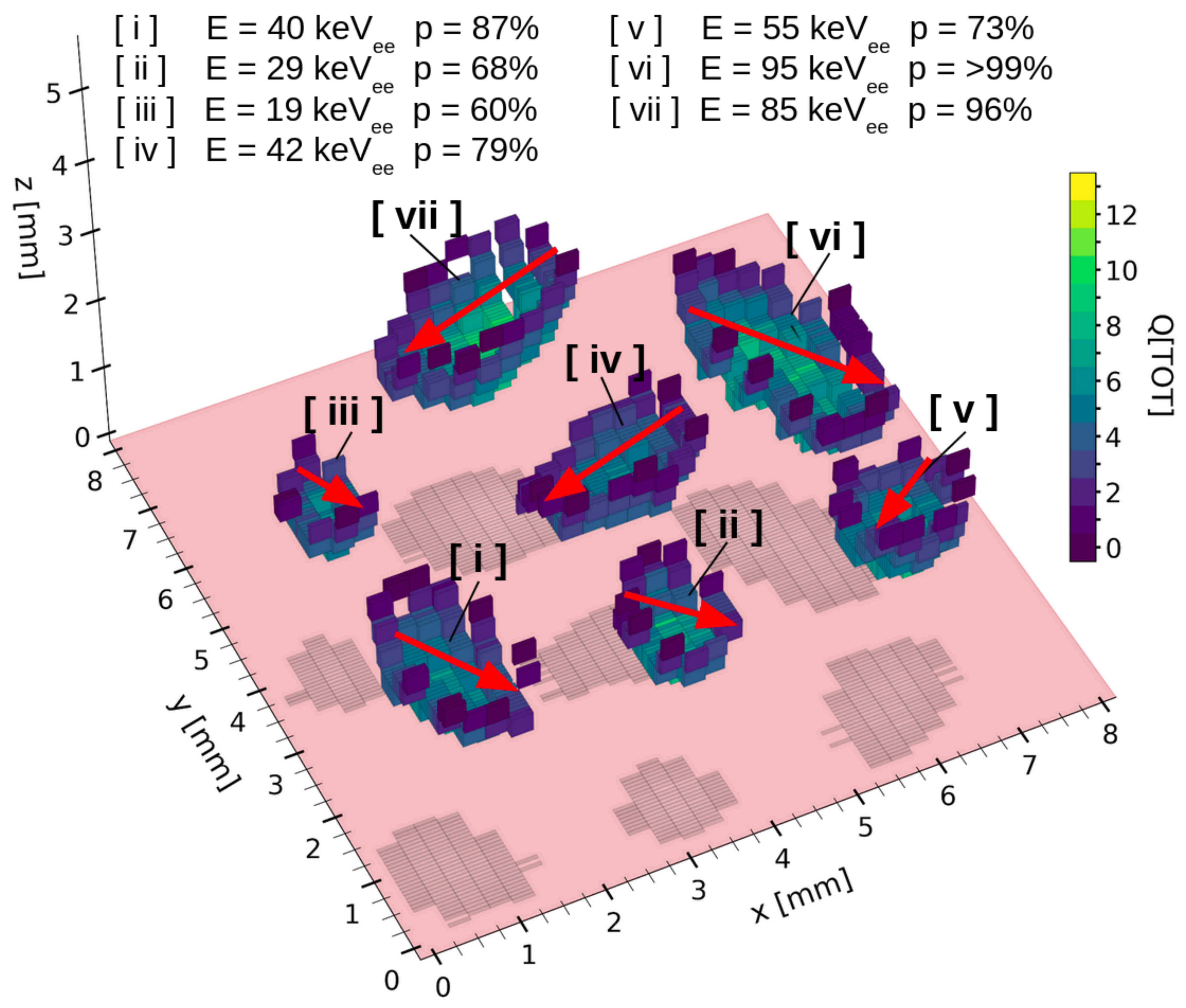


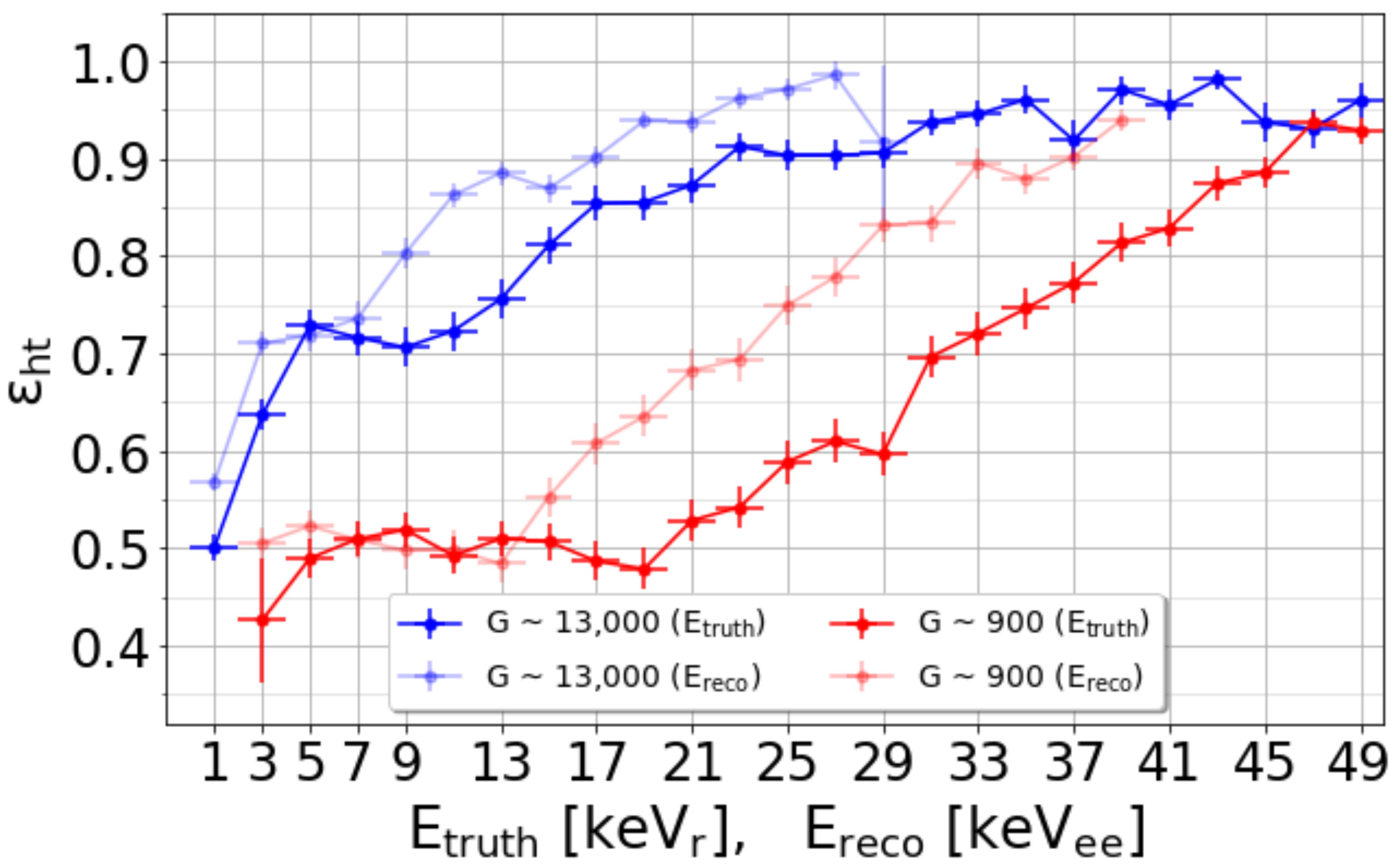
CYGNO (Italy) CYGNUS/DRIFT (UK) CYGNUS-Oz (Australia)

CYGNUS/UNM (USA) CYGNUS-HD 40 L (USA) CYGNUS/NEWAGE (Japan)

HD TPC performance studies

Final goal for high-definition imaging of recoils in 3D, meeting low-energy performance goals may not be so far away…



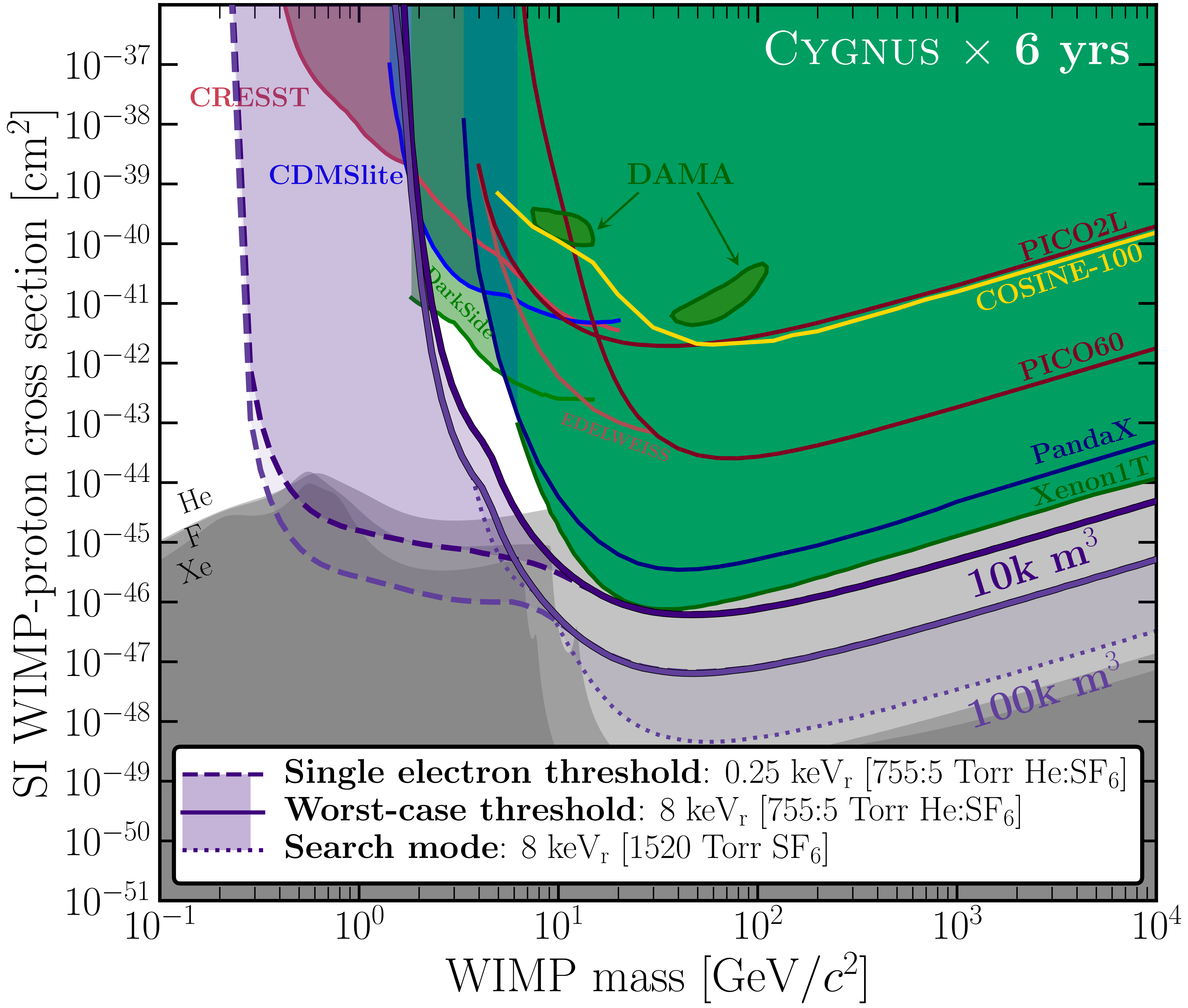


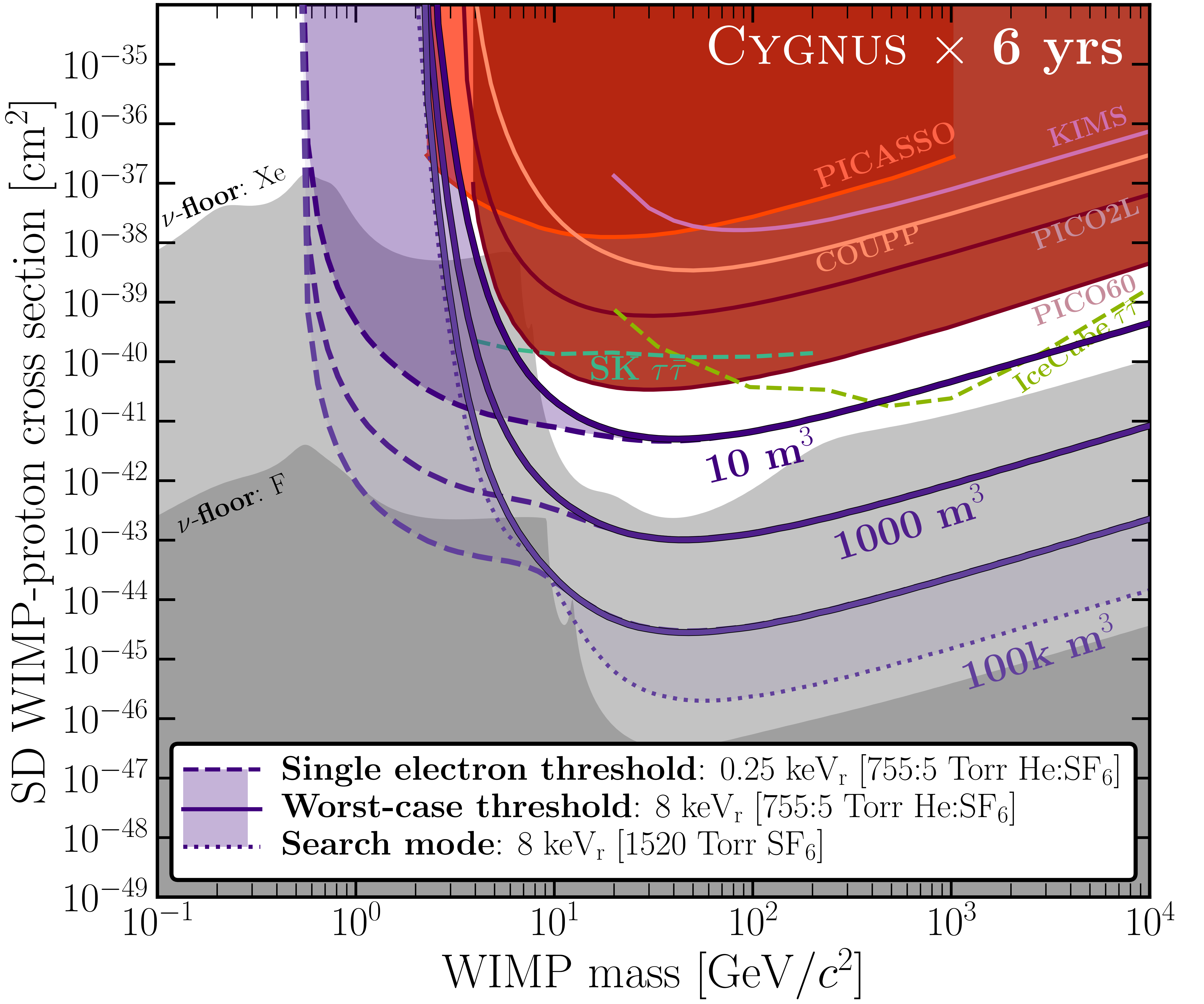
CNN reconstruction of neutron-induced He recoils in BEAST TPC
J. Schueler, S. Vahsen (U. Hawaii)

Vahsen, CAJO+ [2008.12587]

Cygnus: projected sensitivity

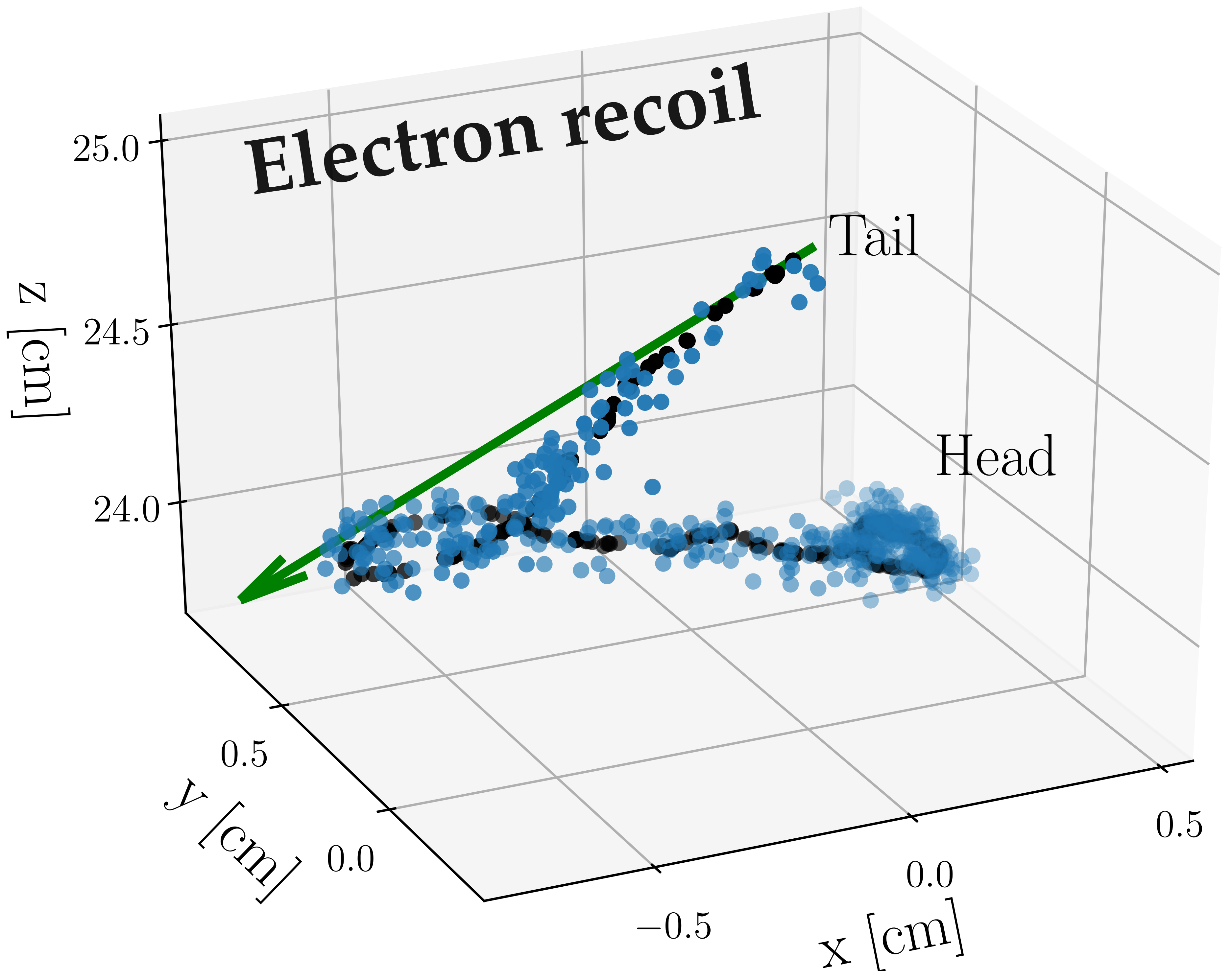
Target gas, volume, and threshold are still under investigation, but there is scope for world-leading limits even with a 10 m³ scale experiment (~2025–2030)

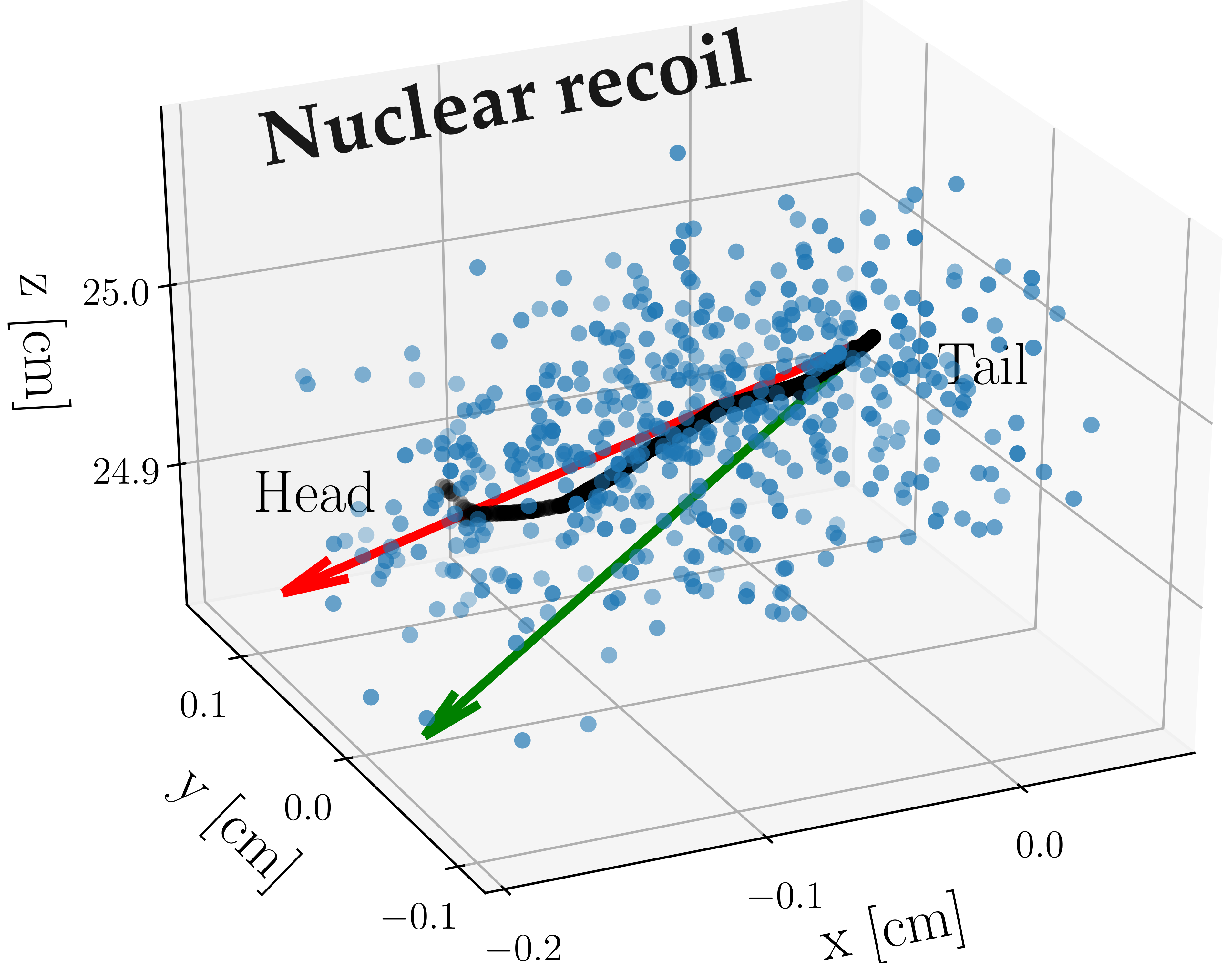




Directionality in MPGDs, beyond nuclear recoils

MPGDs can measure the directions of both electron recoils **and** nuclear recoils.
The directionality and track shapes also help distinguish between them
→ Is there other physics we can do?



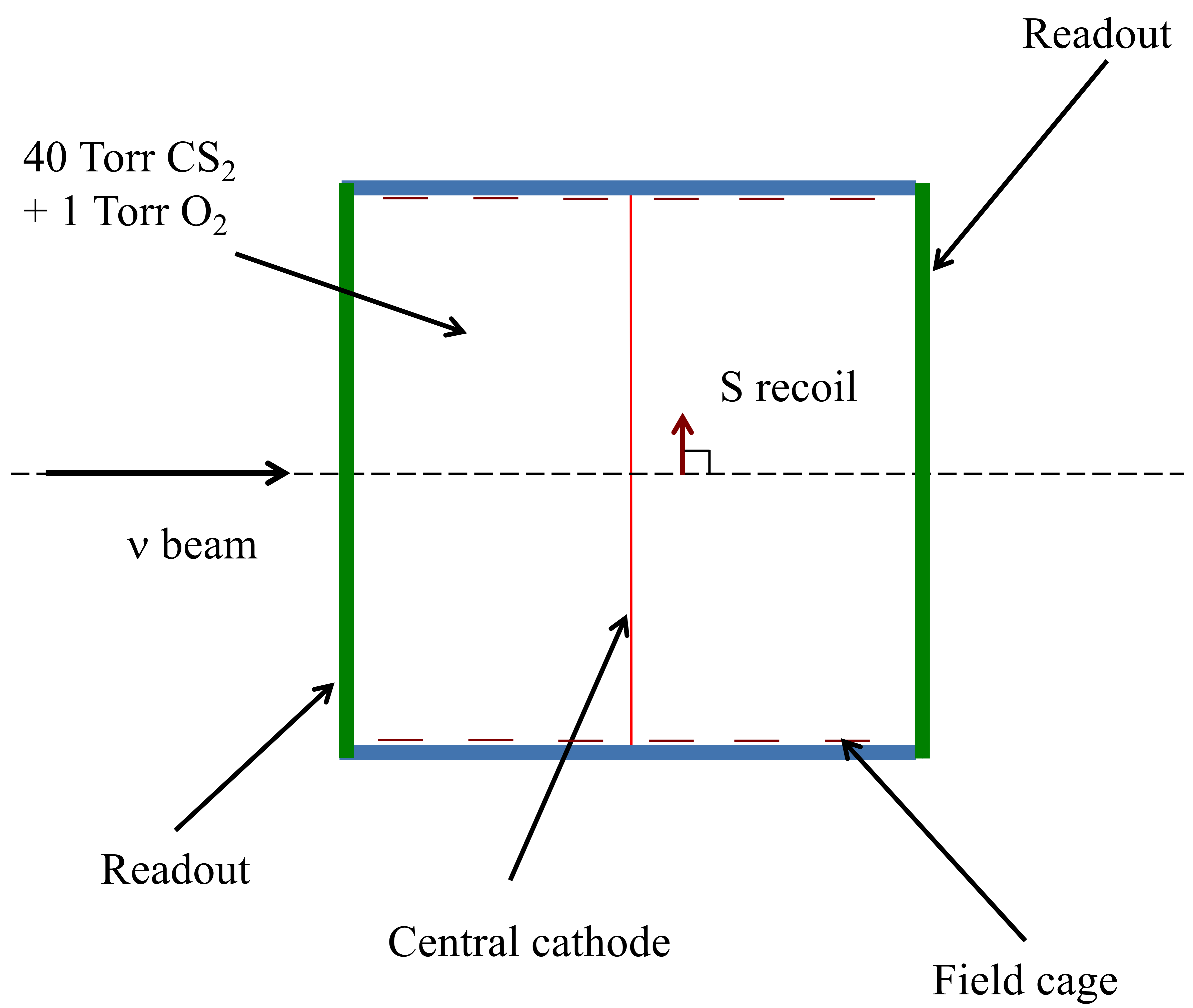


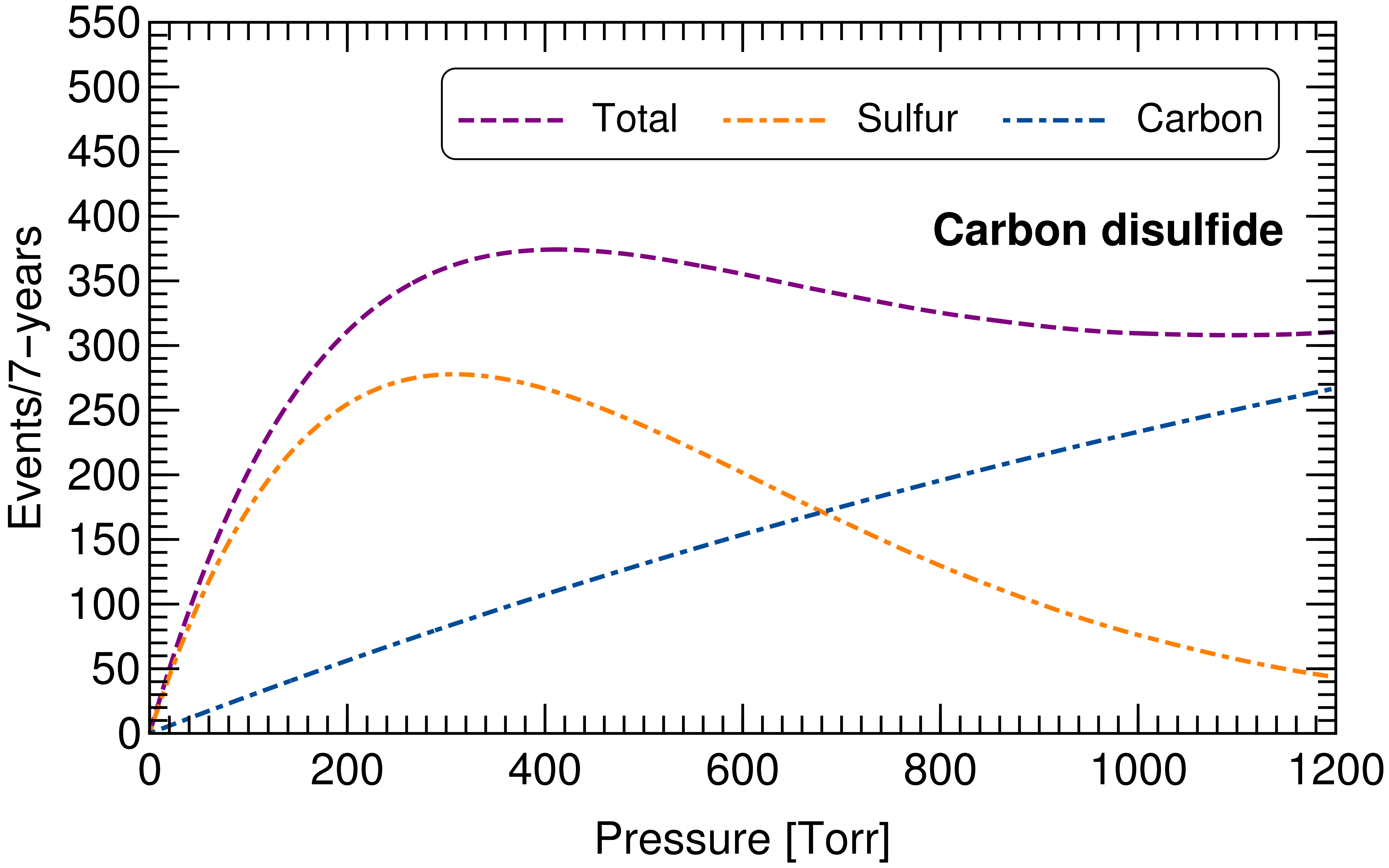
Vahsen, CAJO, Loomba [2008.12587]

CEνNS physics case

→ recoil imaging detector in conjunction with neutrino beam could be used to measure CEνNS.

→ Increased background rejection against non-neutrino sources, as well as for searches for BSM interactions

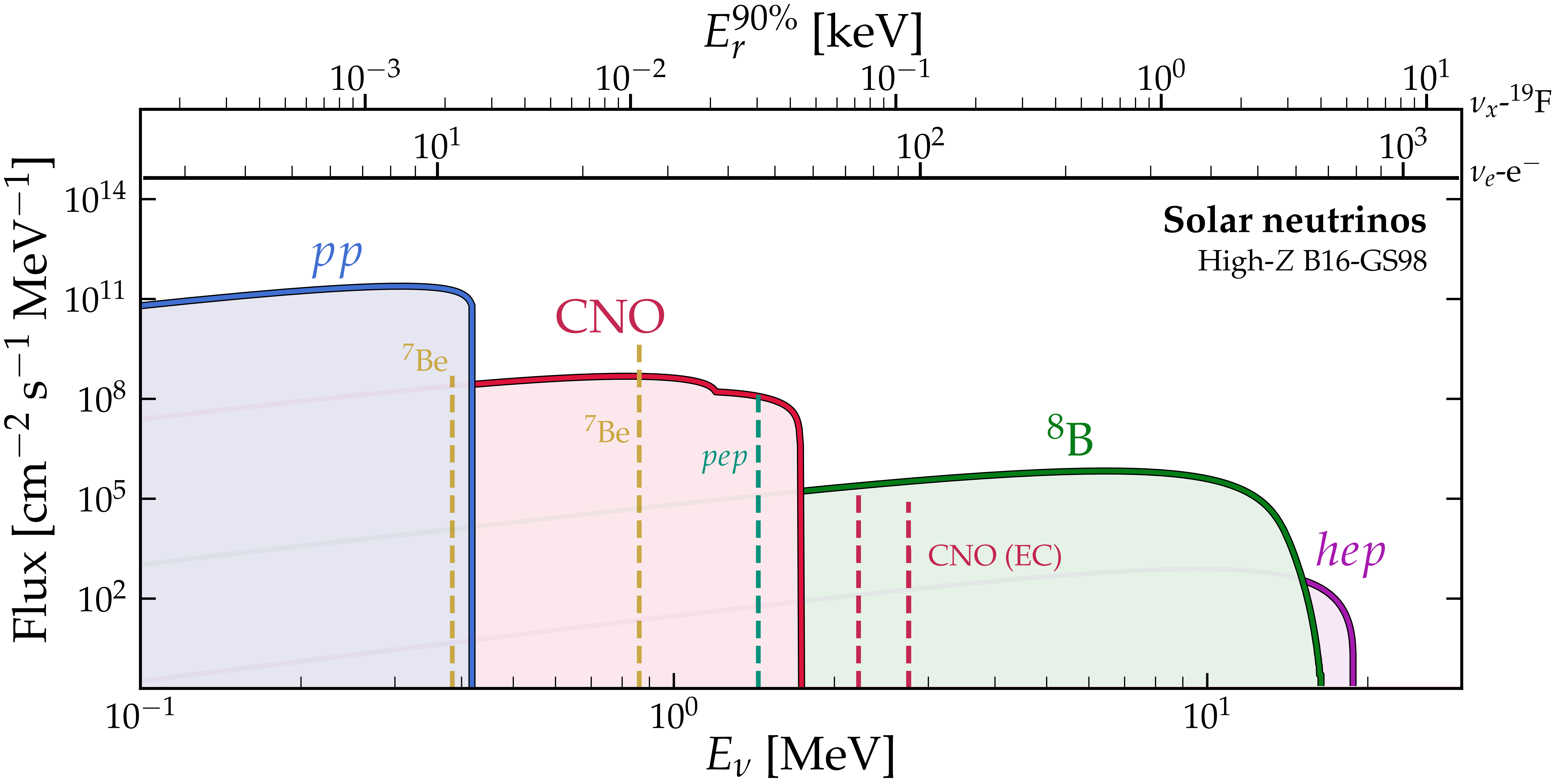




Being pursued by νBDX-DRIFT collaboration [2103.10857] and under discussion within CYGNUS collaboration

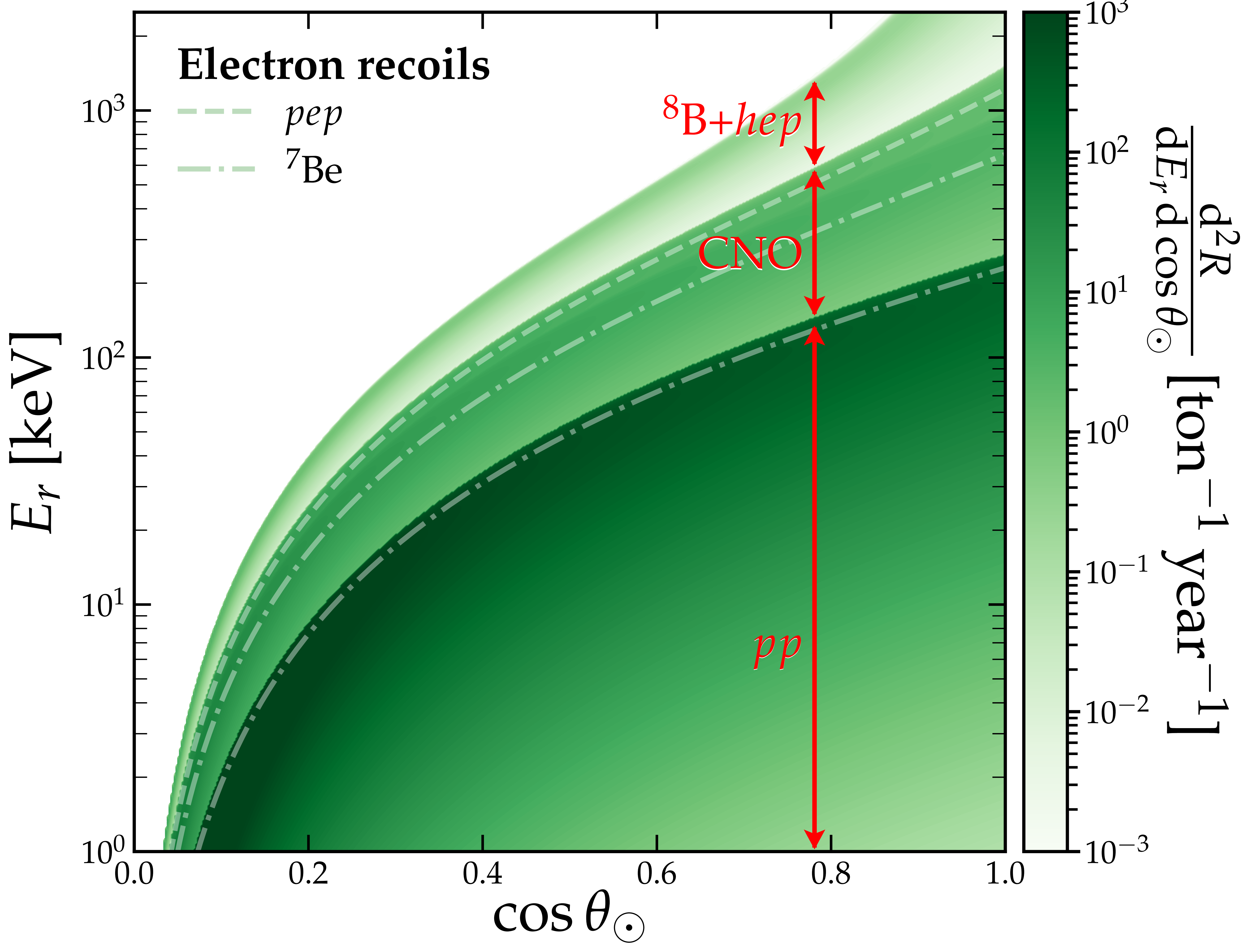
Electron *and* nuclear recoils

Solar neutrinos can scatter off electrons and nuclei → detectors have both!



Solar neutrinos

Recoil energy-angle spectrum: $(E_r, \cos\theta_\odot)$



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

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

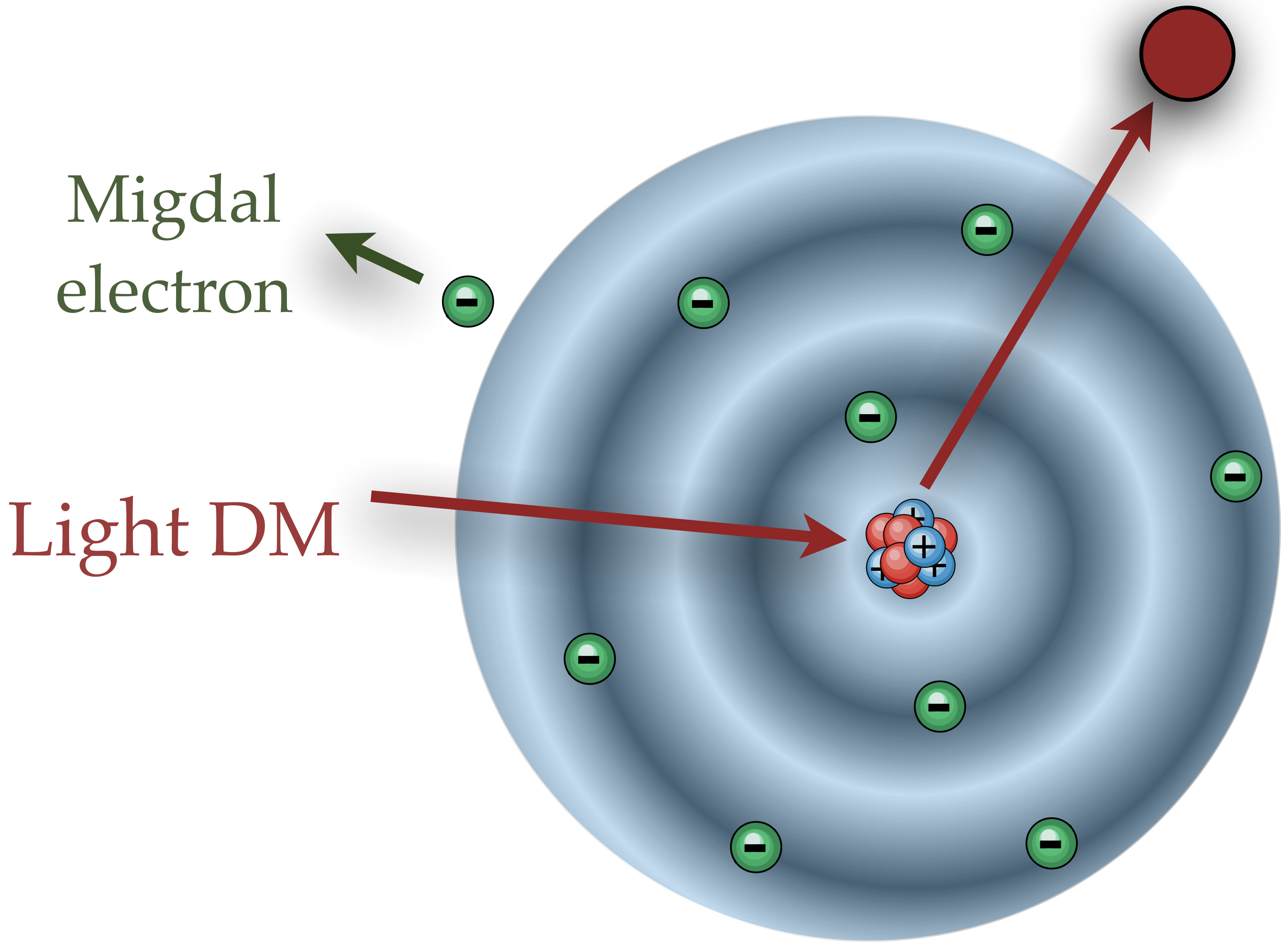
Measure recoil energies and angles

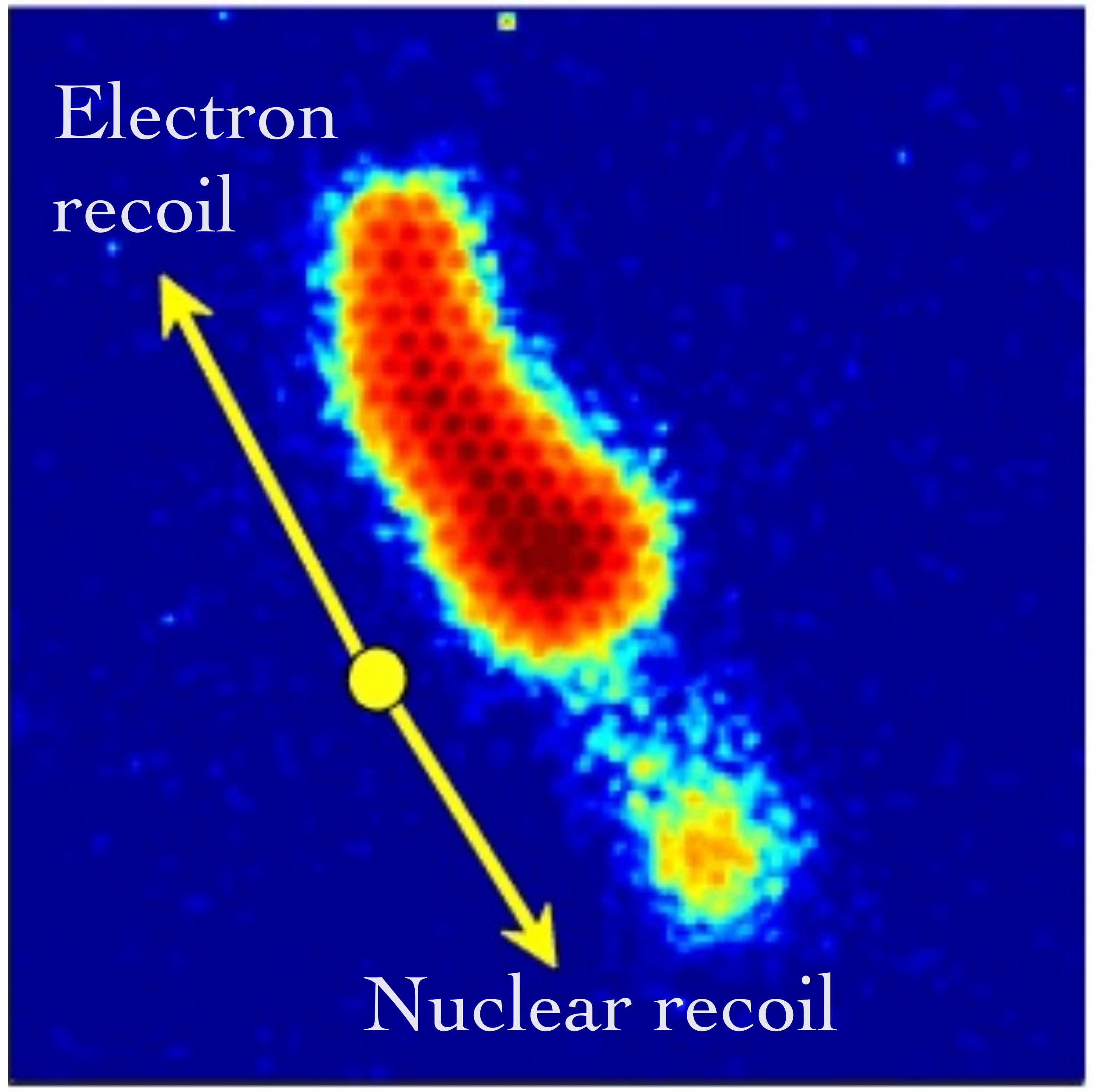
↓

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

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 optical TPC - MIGDAL collaboration exploring this in the UK

Summary

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

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Extra slides

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Further reading (of my own papers…)

[2203.05914] - Snowmass white paper on recoil imaging
[2102.04596] - a review of directional detection
[2002.07499] - directional detection in Xe/Ar
[2008.12587] - directional detection with gas TPCs
[2105.11949] - directional detection with DNA
[2109.03116] - the neutrino fog

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2102.04596

Directional Recoil Detection

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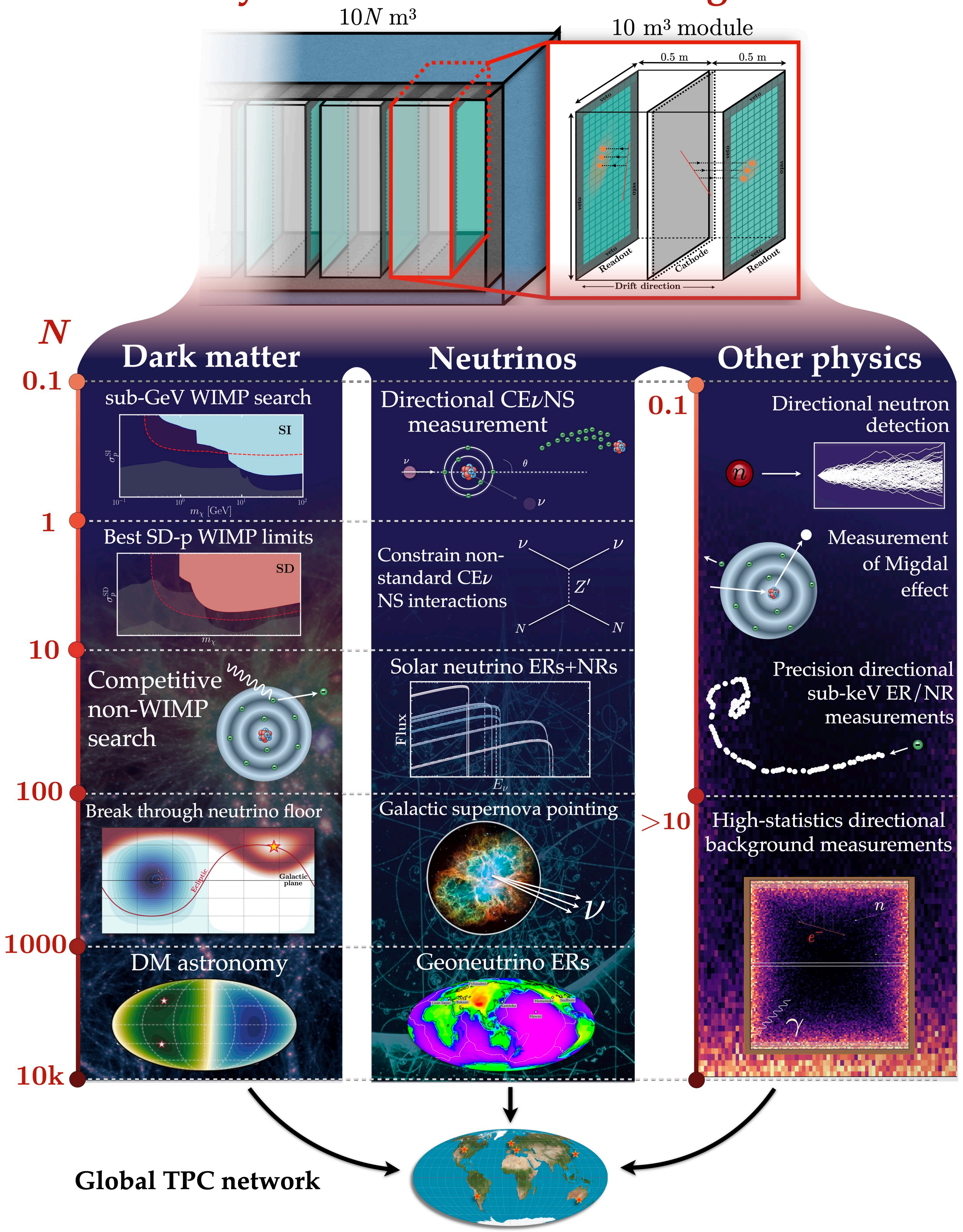
Keywords

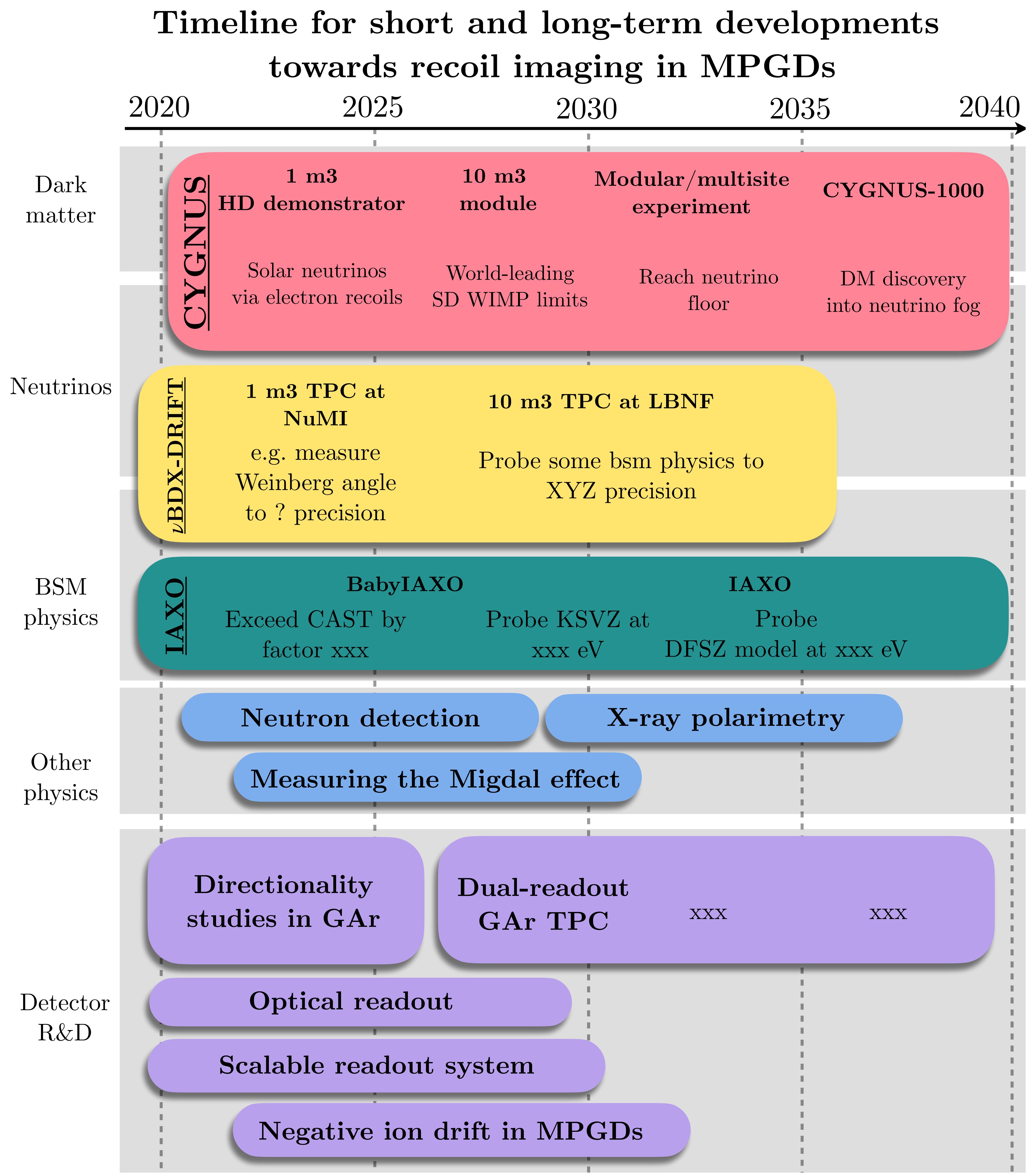
nuclear recoils, electron recoils, dark matter, neutrinos, gas time projection chambers, Migdal effect

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.

Physics case for a directional gas TPC




Timeline for short and long-term developments
towards recoil imaging in MPGDs
2020
2025
2030
2035
2040
Dark matter
CYGNUS
1 m3 HD demonstrator
Solar neutrinos via electron recoils
10 m3 module
World-leading SD WIMP limits
Modular/multisite experiment
Reach neutrino floor
CYGNUS-1000
DM discovery into neutrino fog
Neutrinos
νBDX-DRIFT
1 m3 TPC at NuMI
e.g. measure Weinberg angle to ? precision
10 m3 TPC at LBNF
Probe some bsm physics to XYZ precision
BSM physics
IAXO
BabyIAXO
Exceed CAST by factor xxx
Probe KSVZ at xxx eV
IAXO
Probe DFSZ model at xxx eV
Other physics
Neutron detection
X-ray polarimetry
Measuring the Migdal effect
Detector R&D
Directionality studies in GAr
Dual-readout GAr TPC
xxx
xxx
Optical readout
Scalable readout system
Negative ion drift in MPGDs

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

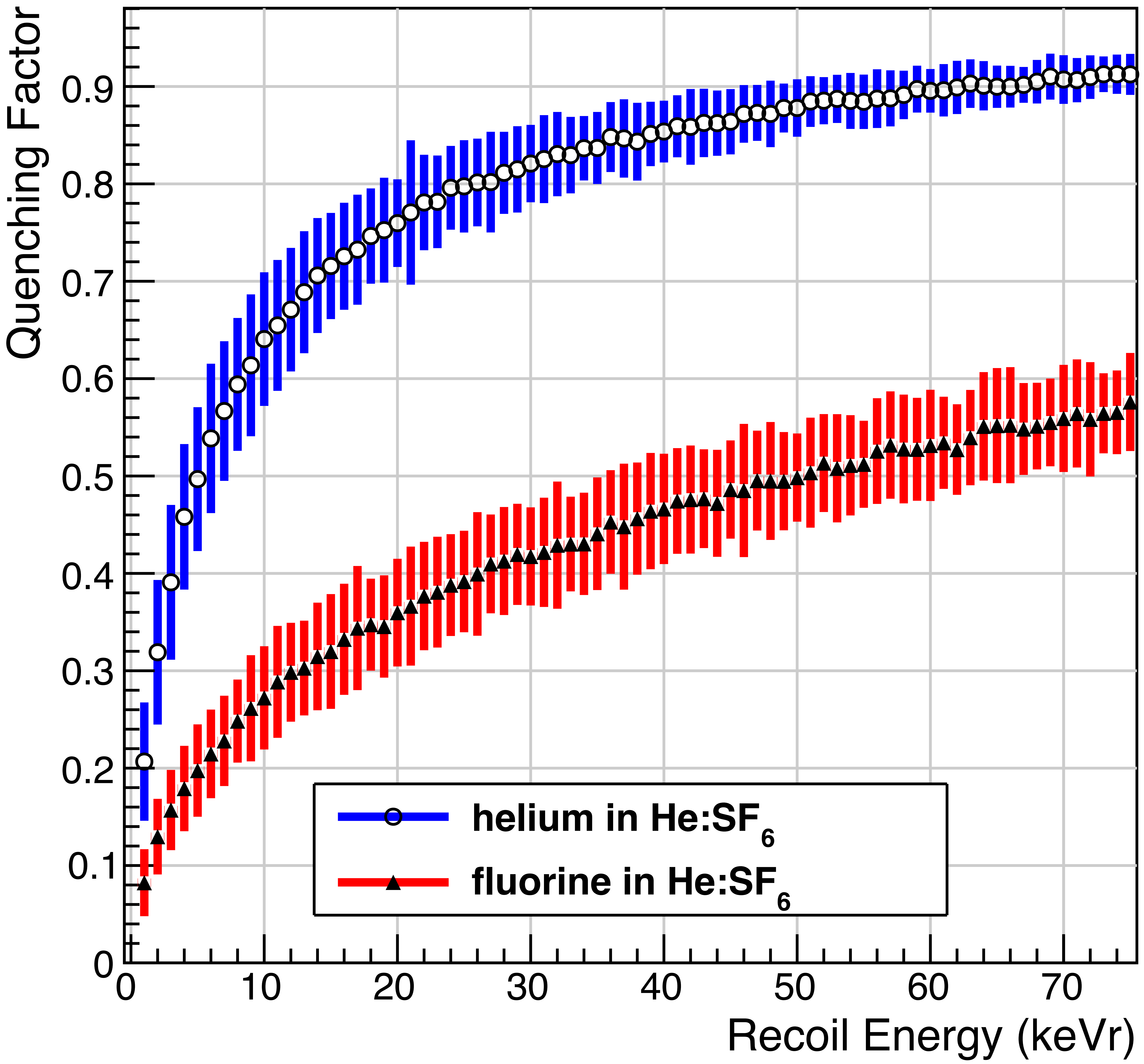
Why SF_6?

- ☑ **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 $He+SF_6$

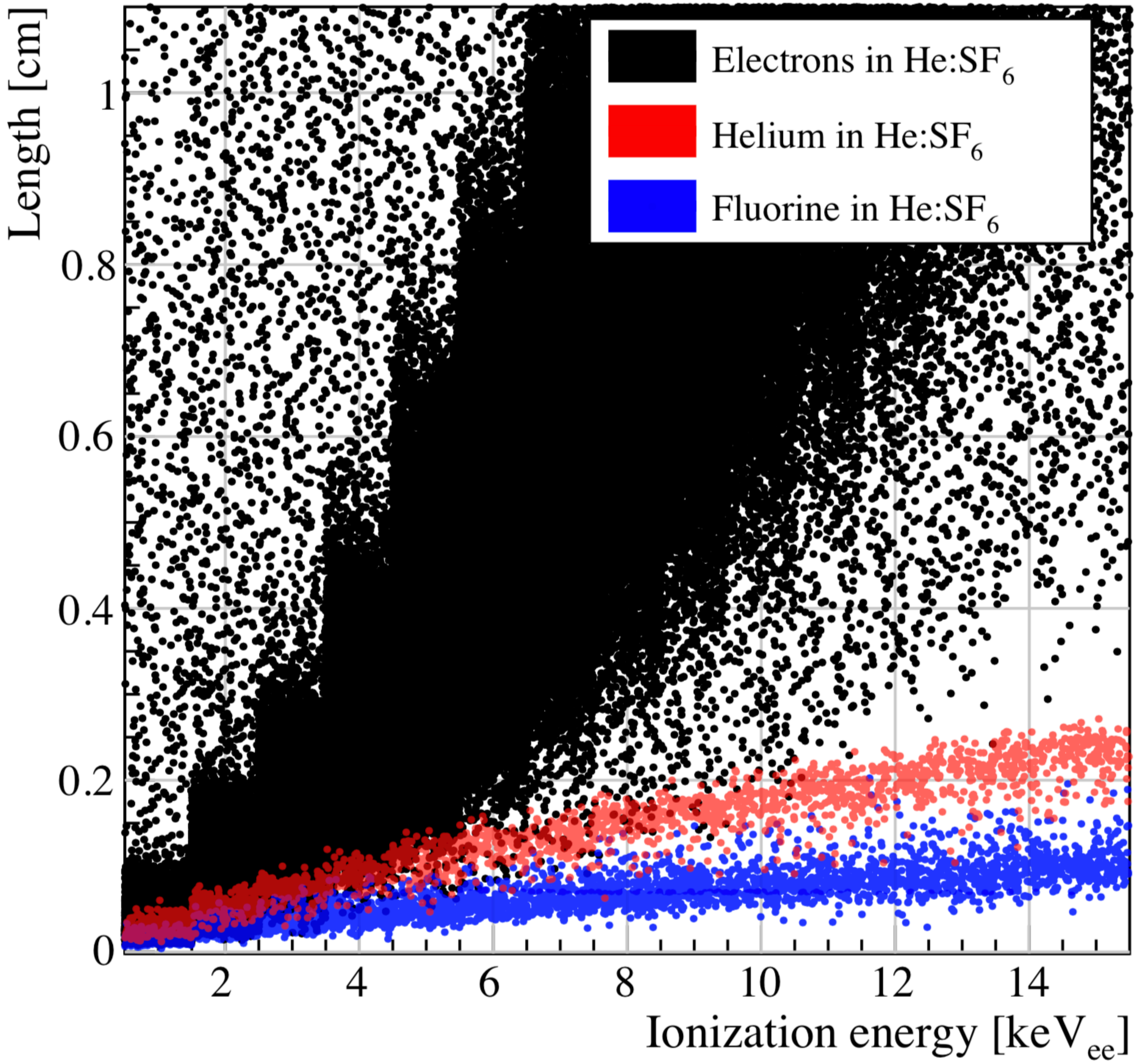


Electron discrimination

- 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

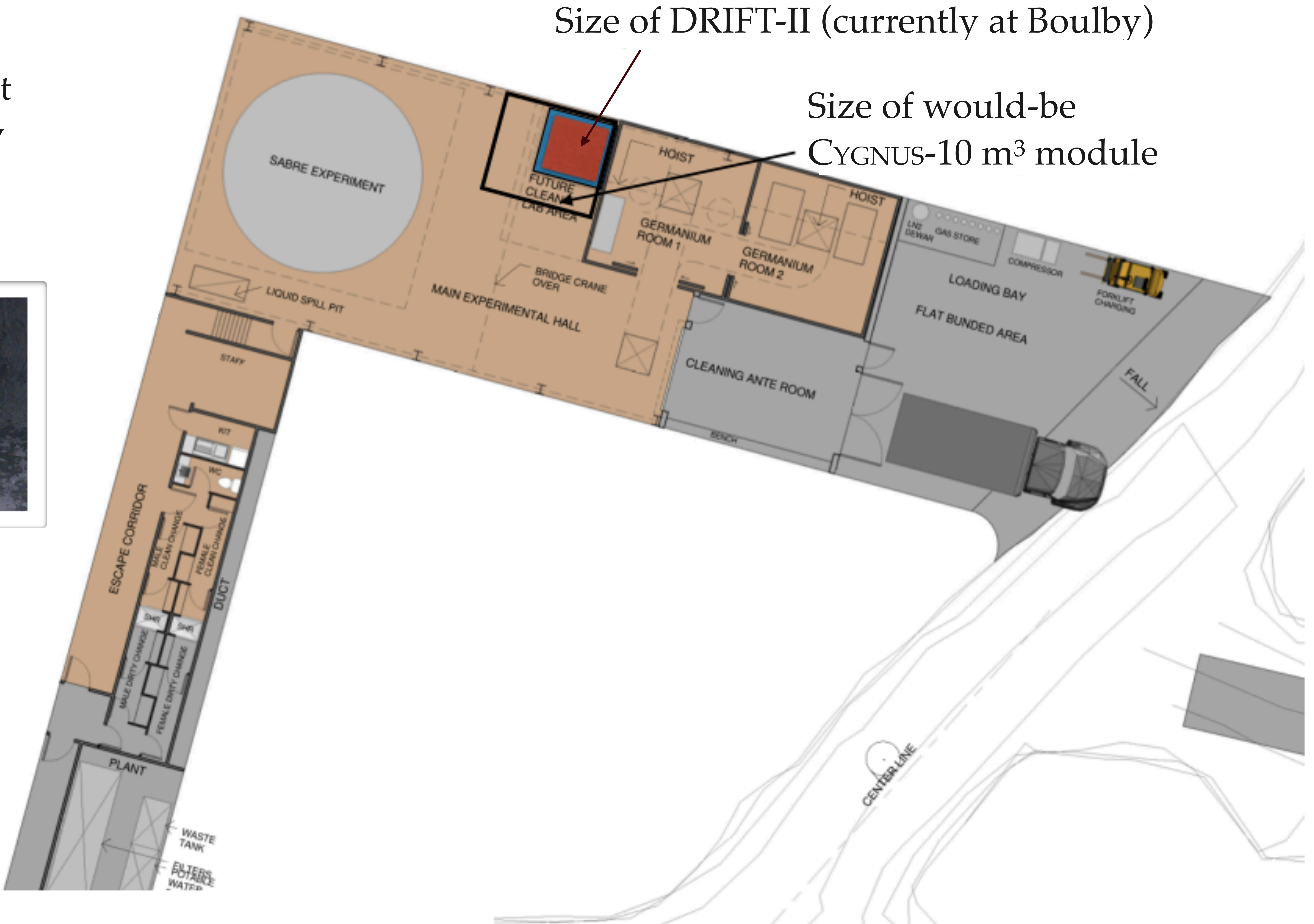
TABLE I. Various gas-dependent parameters assumed in the TPC detector simulation. The values are sourced as follows: the W factor for pure SF_6 is from a measurement with alpha particles [310], while the W factors for the $He:SF_6$ and $He:CF_4$ mixtures are calculated using Eq.(1) of Ref. [266]. The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

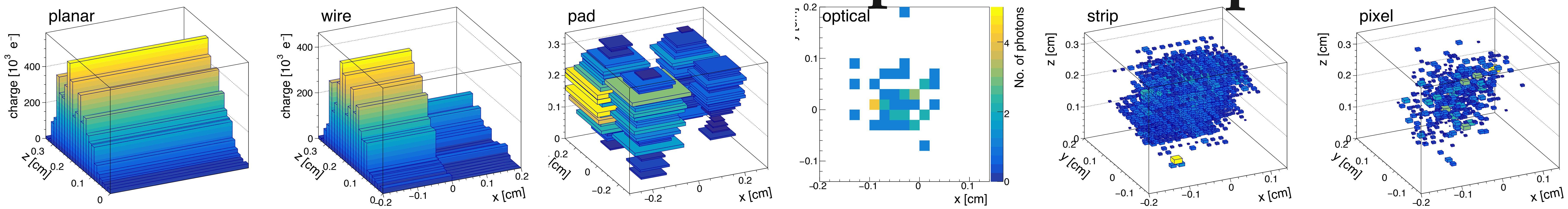
Stawell Underground Physics Laboratory (SUPL)

- 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



Readout technologies

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



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

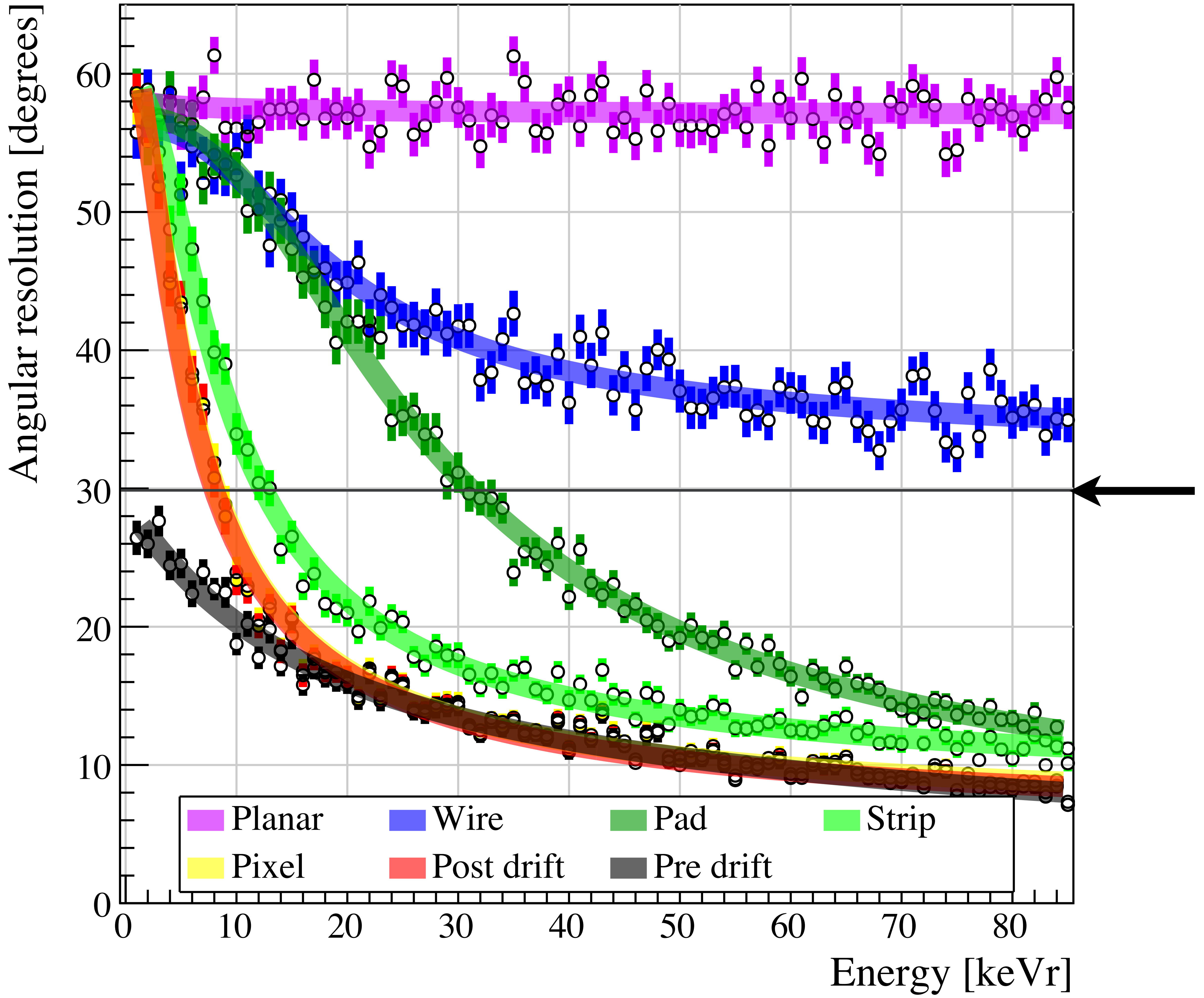
Simplest readouts
→ Worst directional sensitivity but lower cost

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)



Simulated charge readout comparison

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

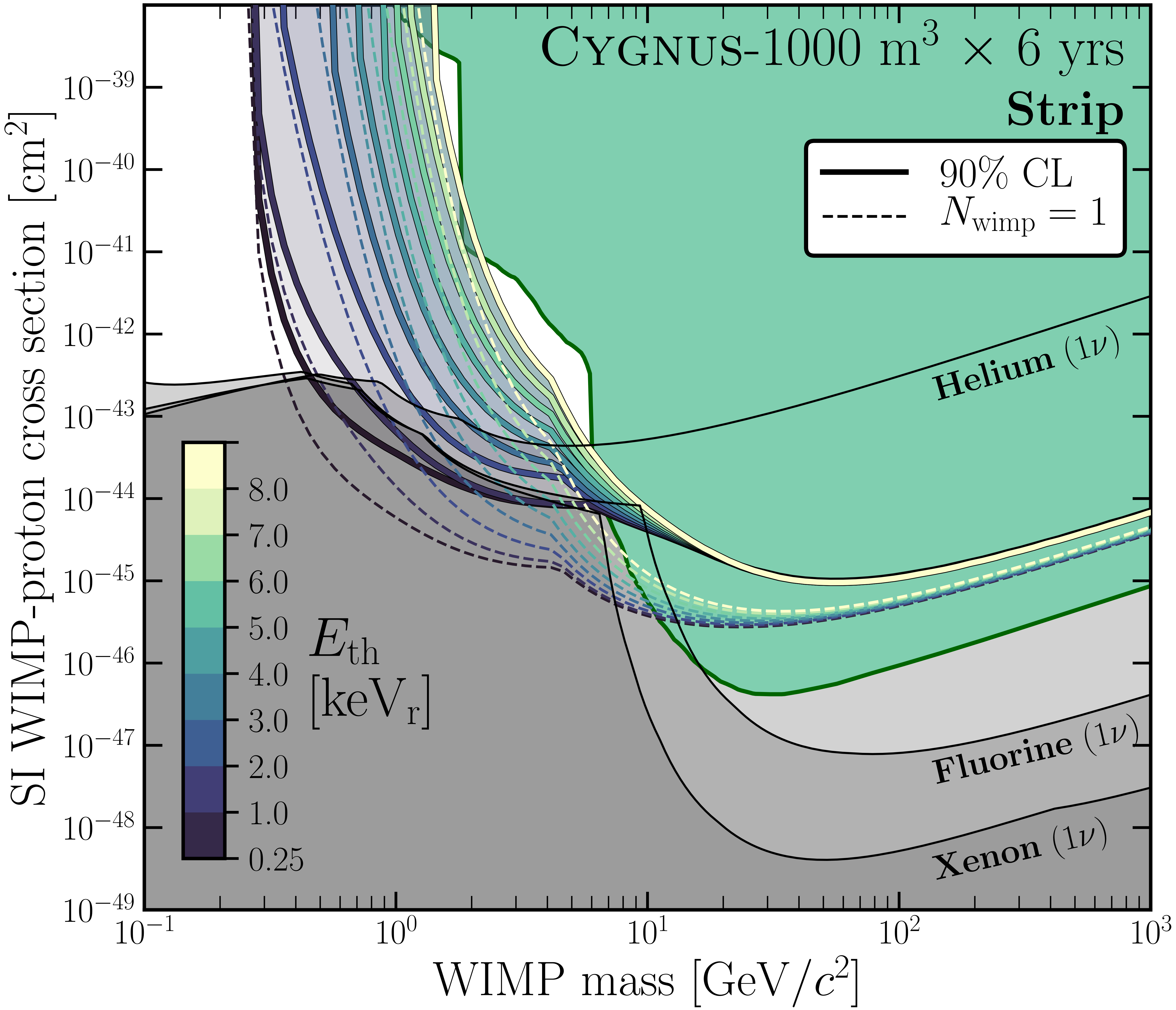
A closer look at dependence on threshold:

<u>Threshold:</u>

→ 8 keVr definitely feasible with simplest electron rejection strategy

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

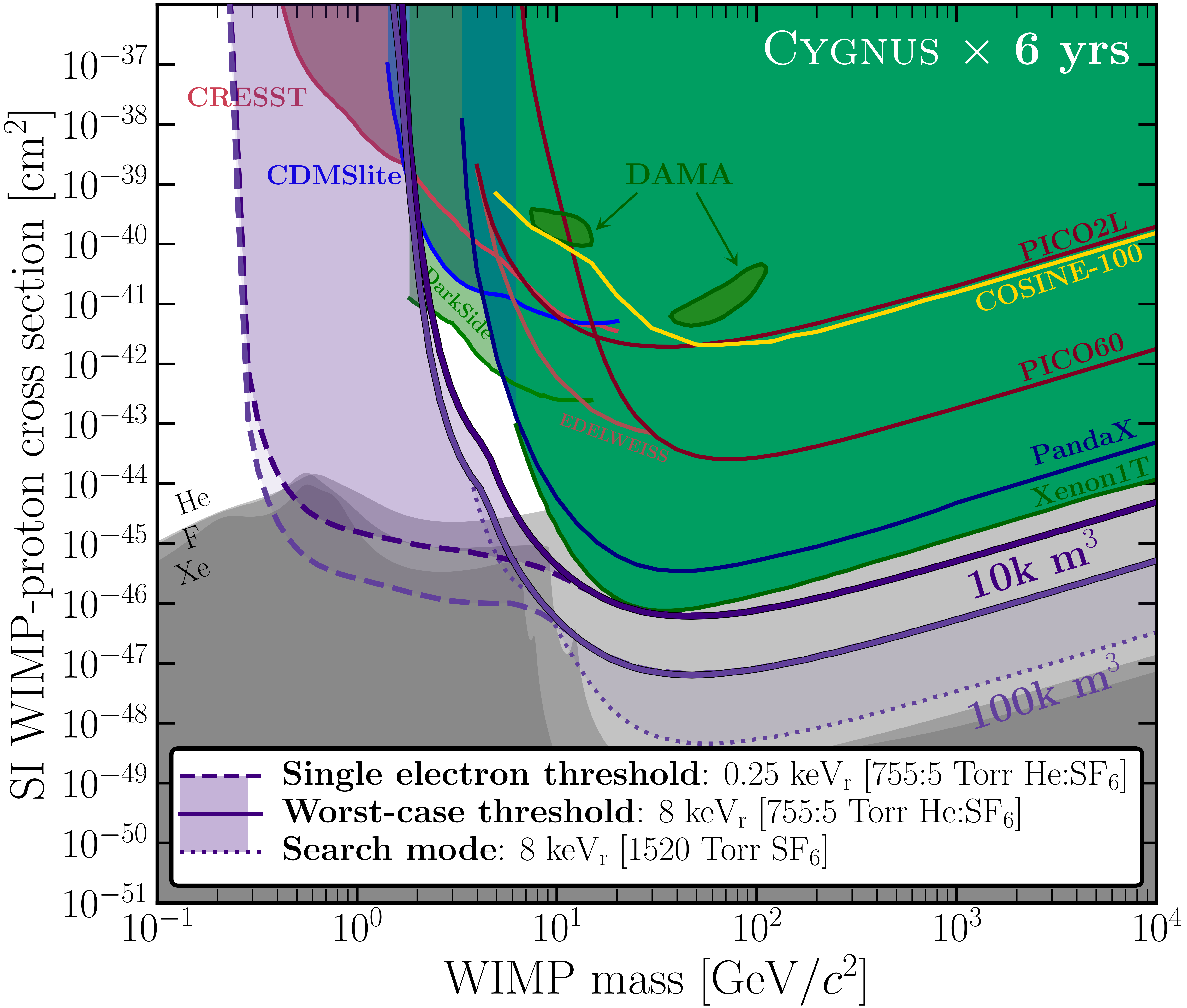
→ 0.25 keVr is theoretical minimum (single electron)



Sensitivity (SI)

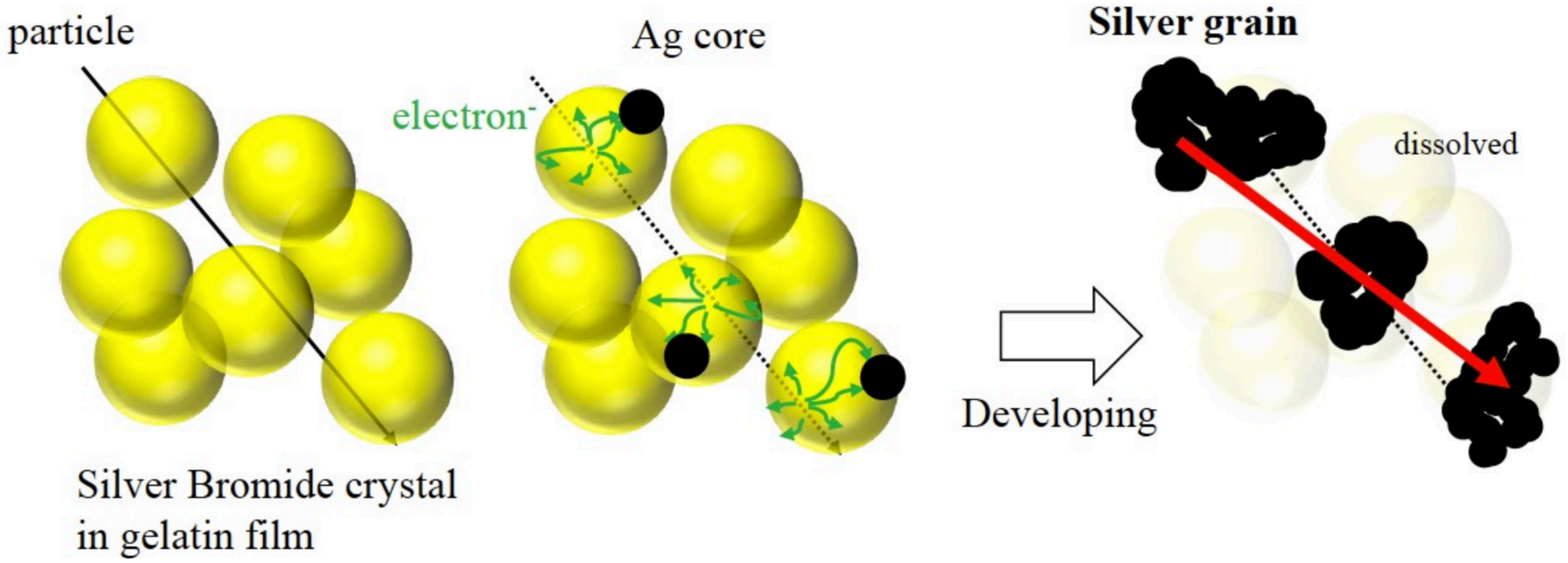
→ Window worst/best case threshold
→ Search mode: 1 atm. of SF_6 but <u>no</u> directionality (possible way to extend high mass sensitivity)

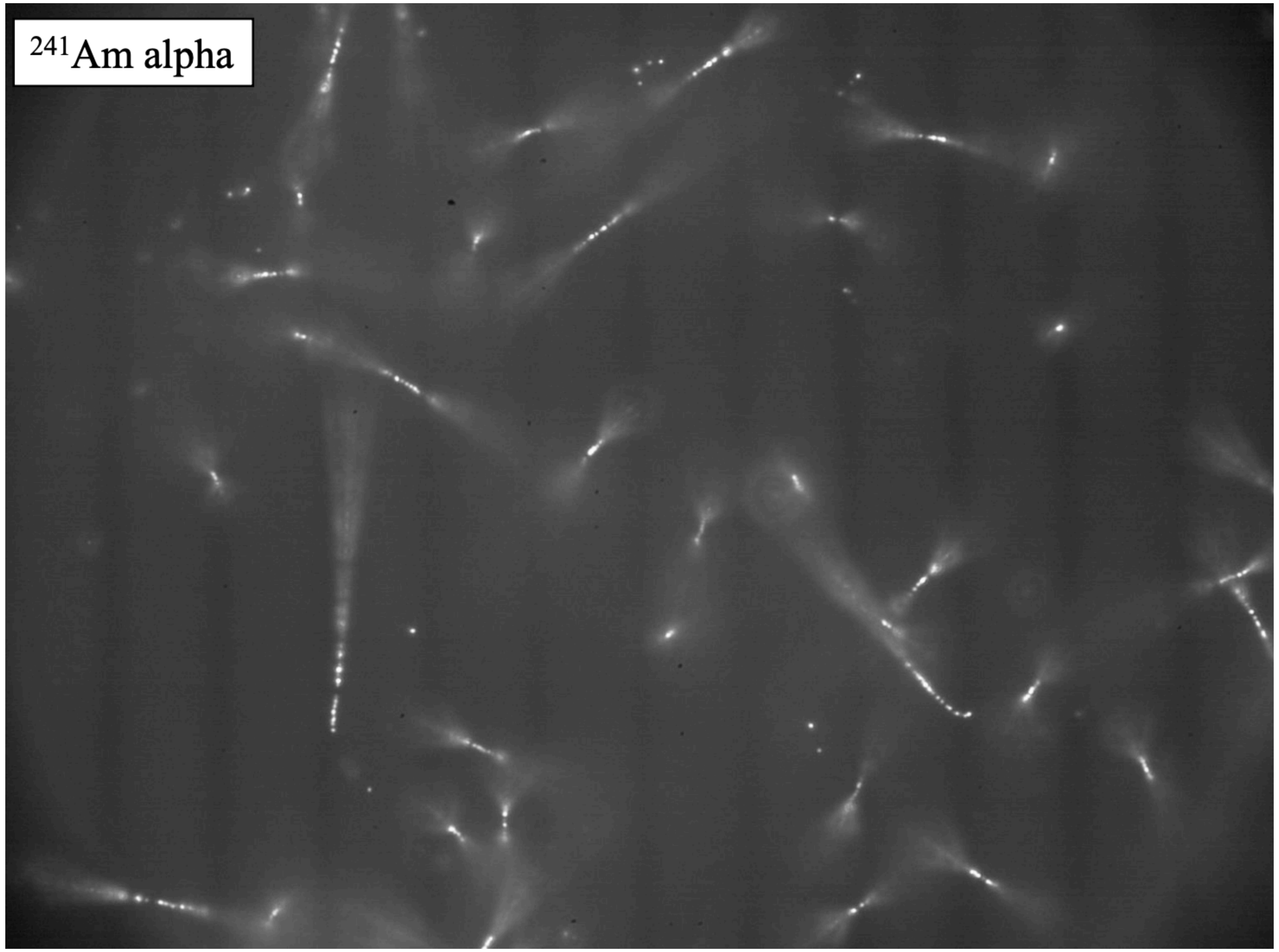
Important note: these limits are true discovery limits, i.e. a signal can be <u>confirmed</u> as DM, so comparison of Cygnus limits with other experiments undersells its potential



3D tracking in high density targets?

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



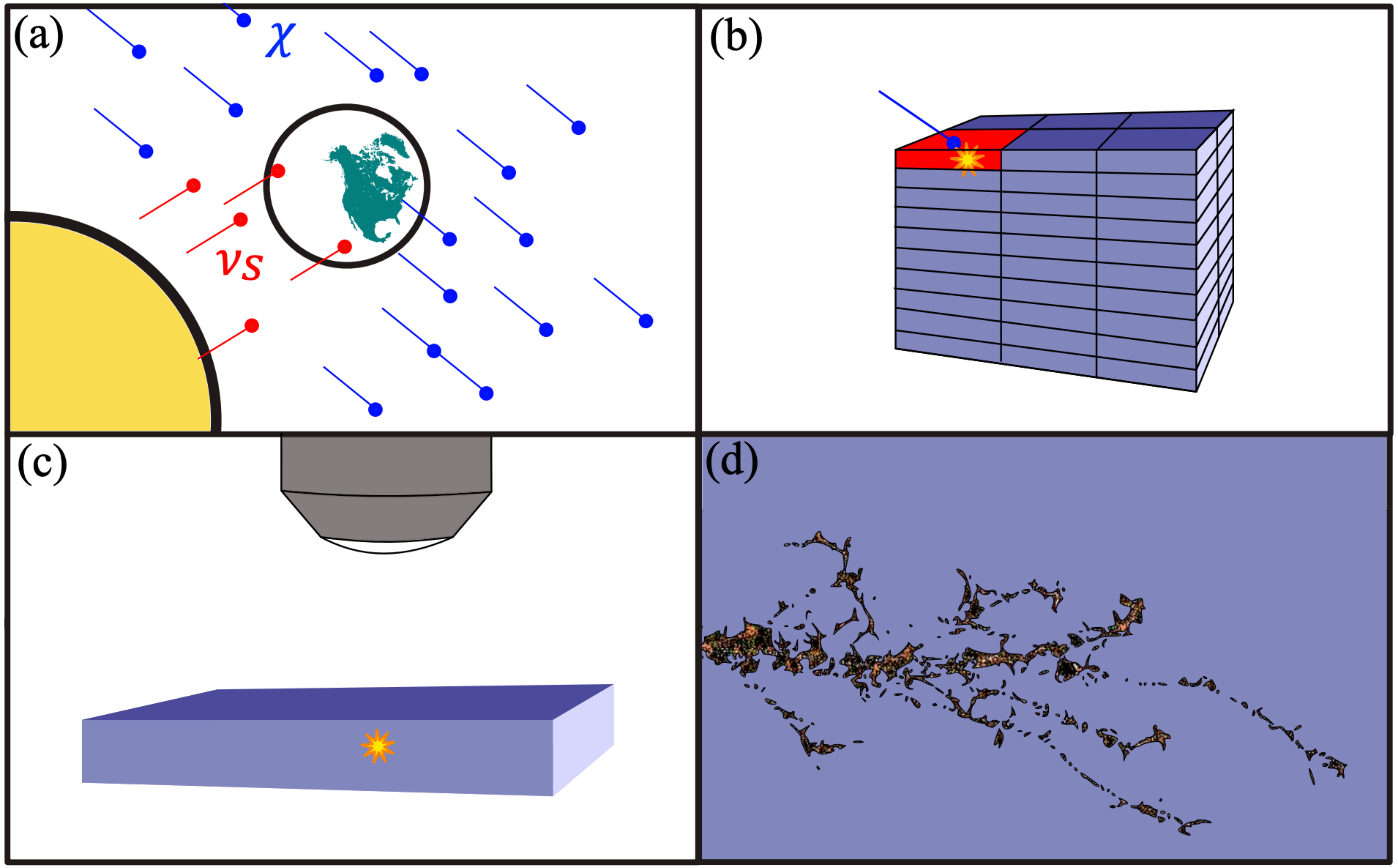


Another idea for a high-density directionality: Solid-State Quantum Sensing

Marshall+ [2009.01028]
Ebadi+ [2203.06037]

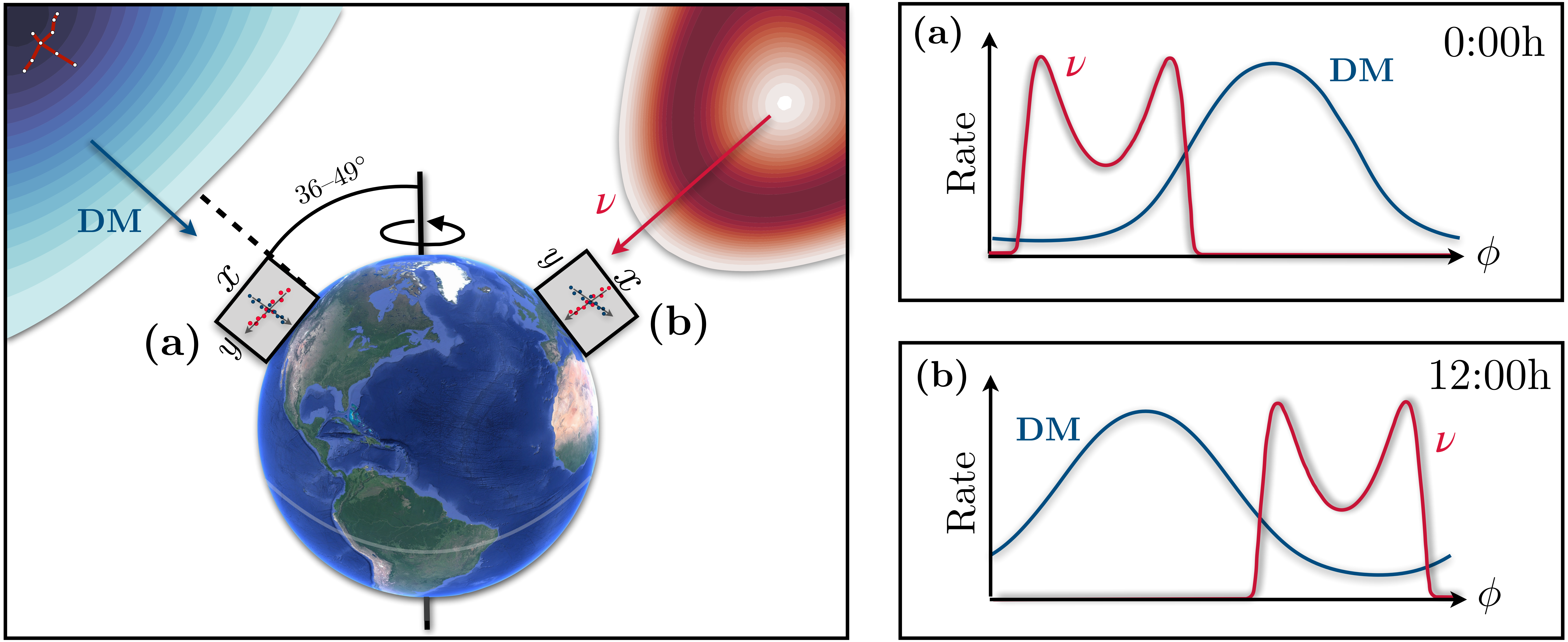
Nitrogen vacancy centres in diamond. Can spectroscopically interrogate crystal damage to detect tracks.

→ need slightly elaborate system to reclaim timing information



A different way of seeing directionality: Daily modulation

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

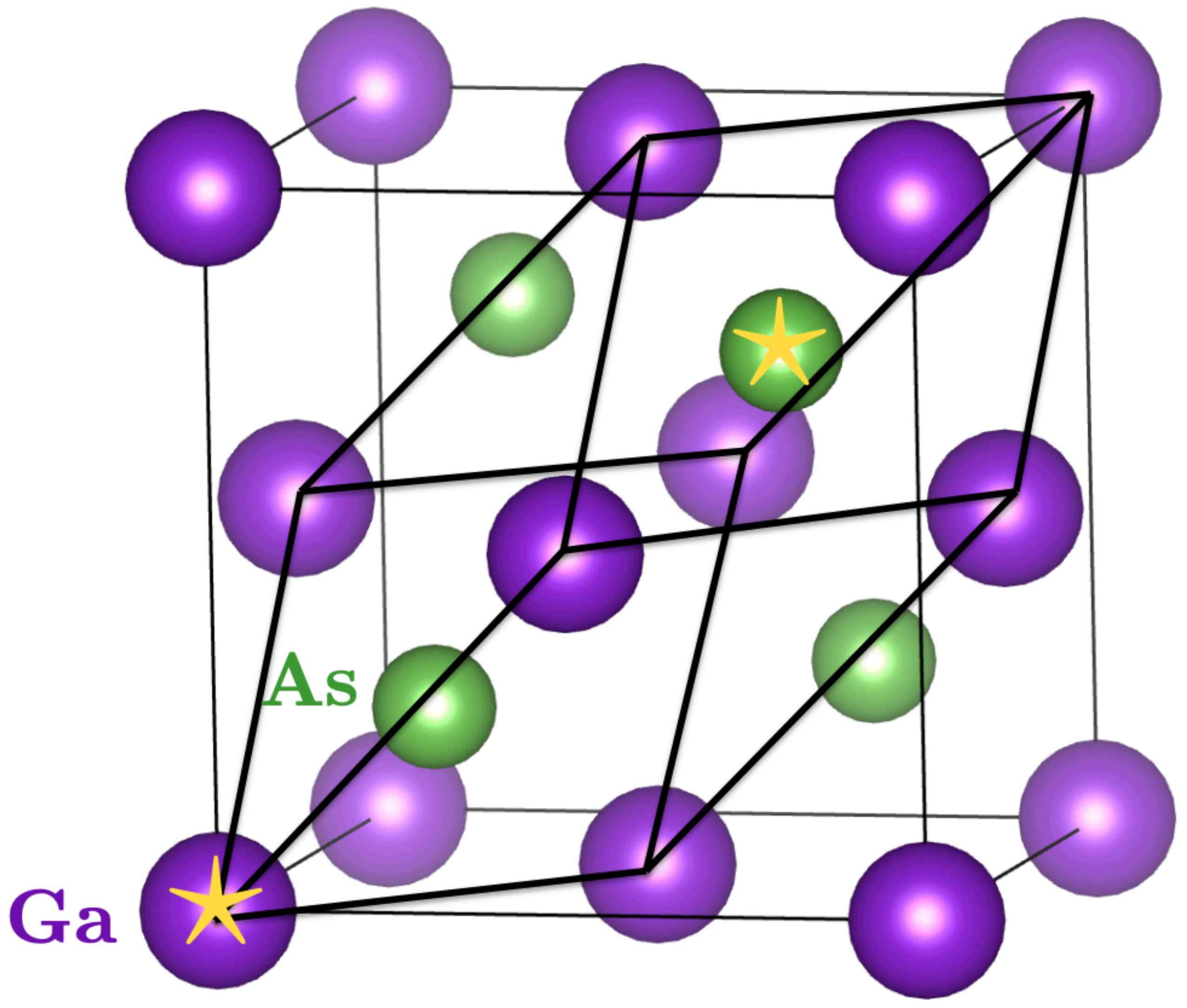


Vahsen, CAJO, Loomba [2102.04596]

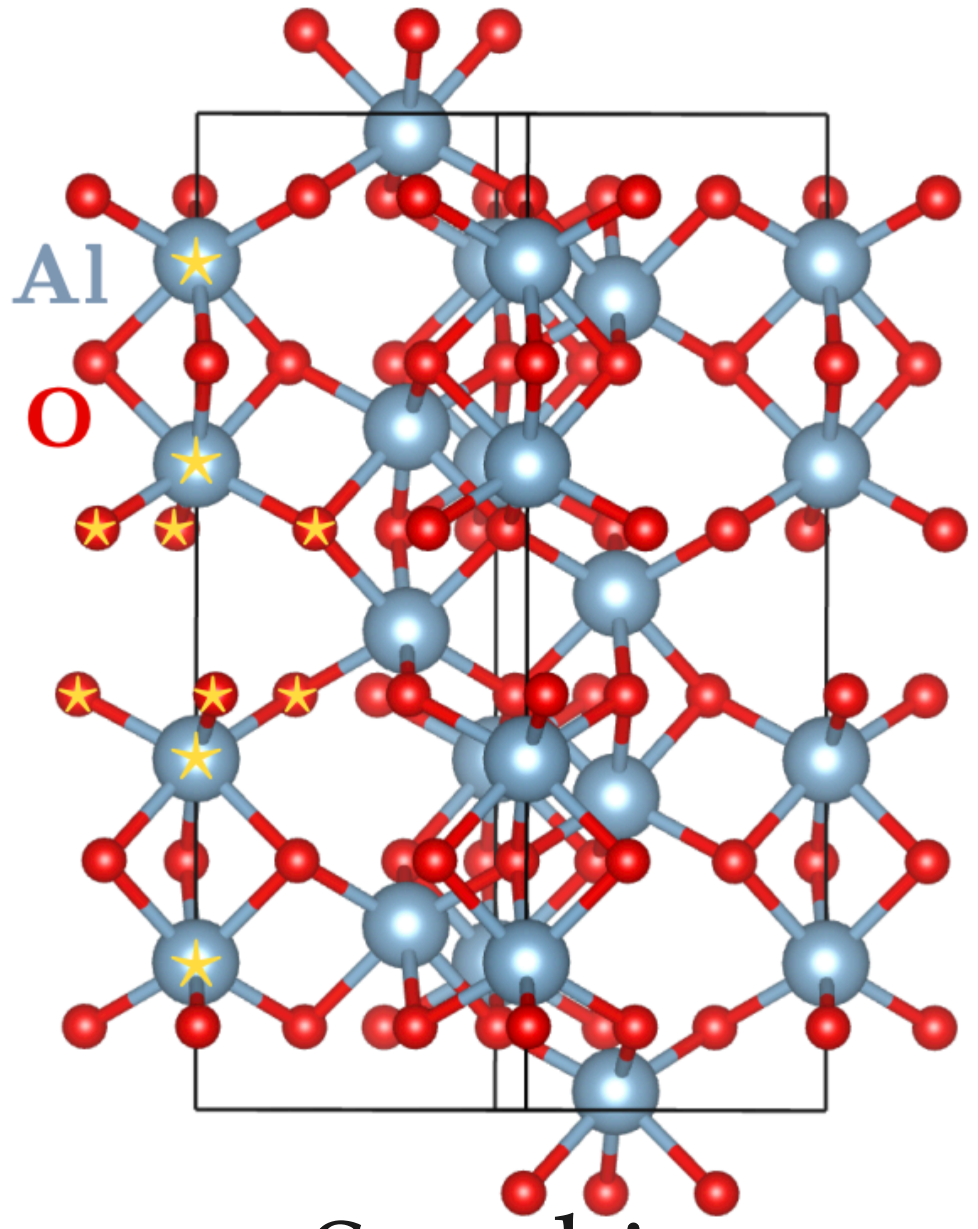
Indirect directionality: anisotropic materials

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

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



GaAs



Sapphire

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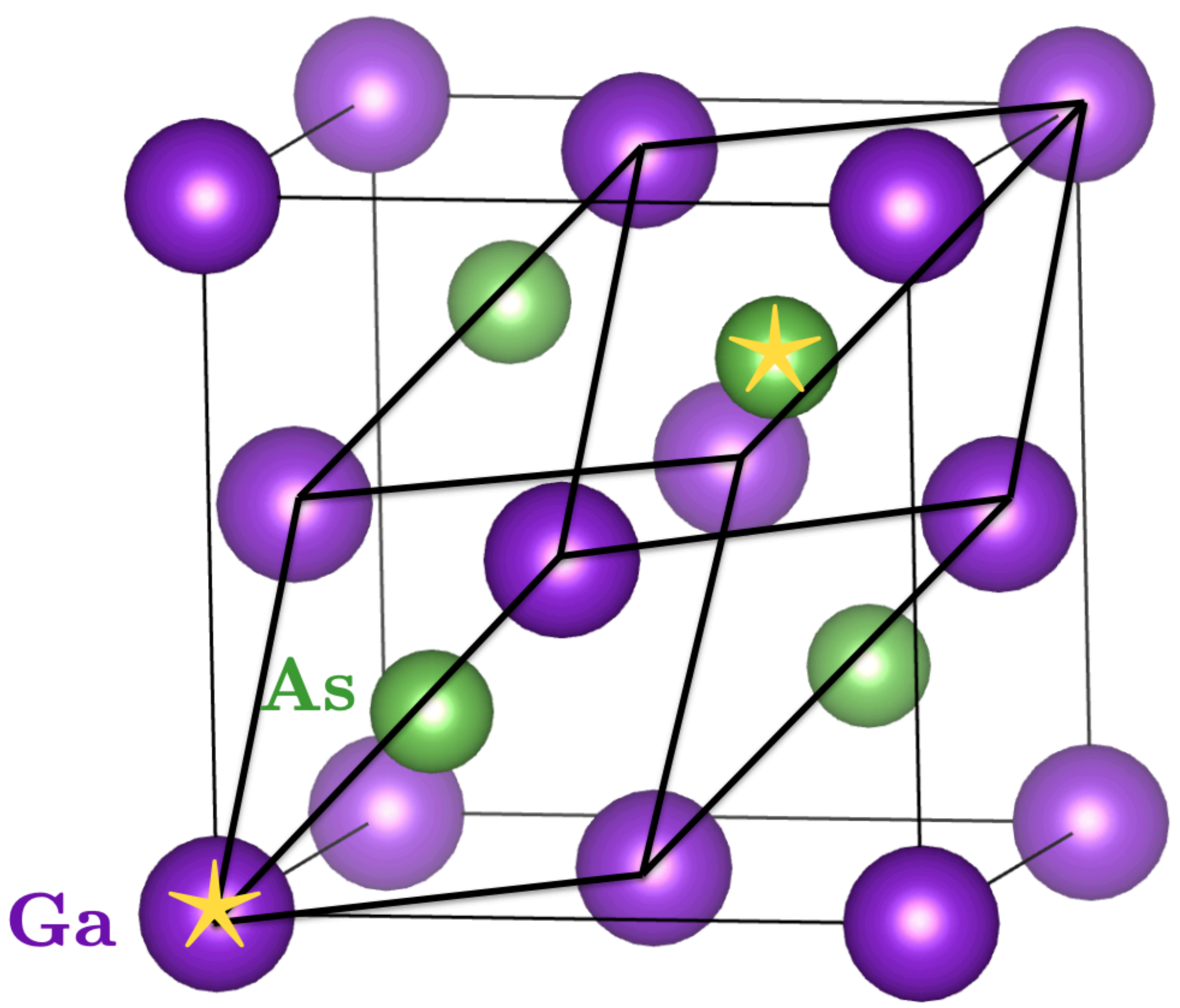
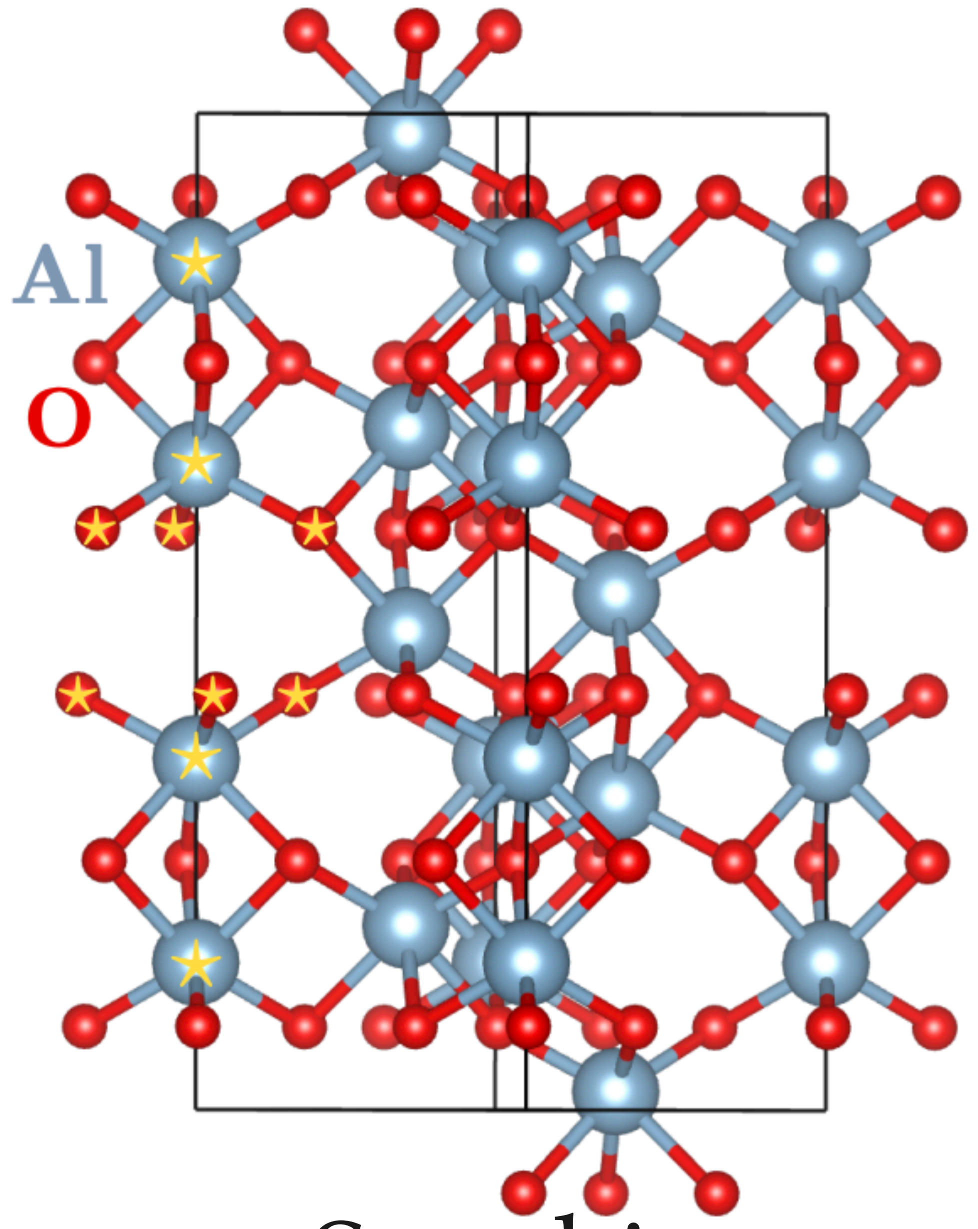
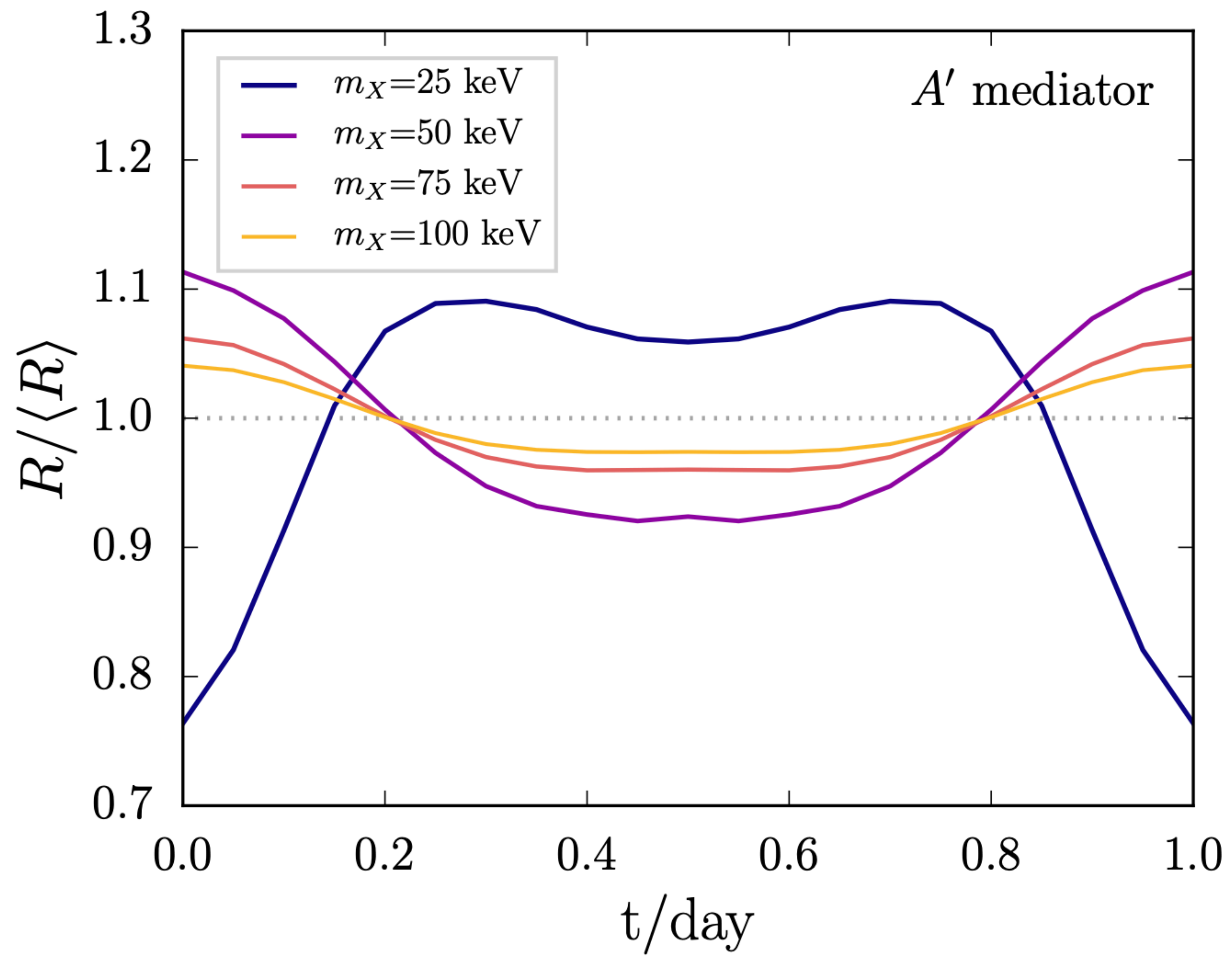


GaAs



Sapphire



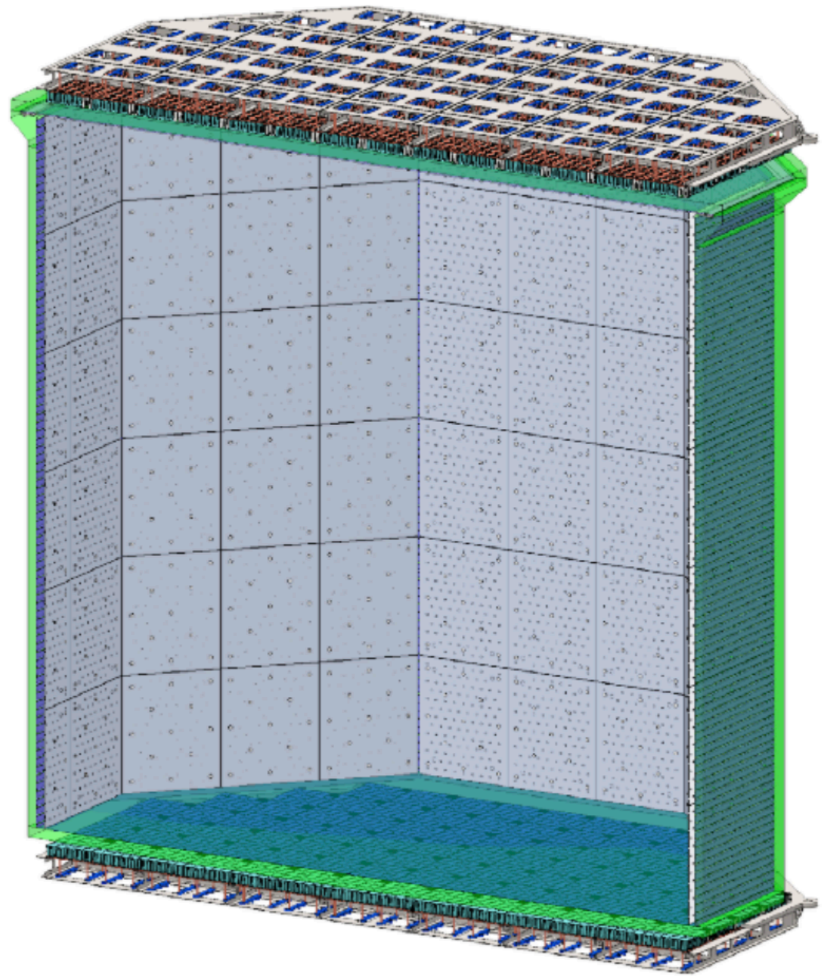
Important caveat: hard to do event-by-event directionality this way
→ Need to use daily modulation

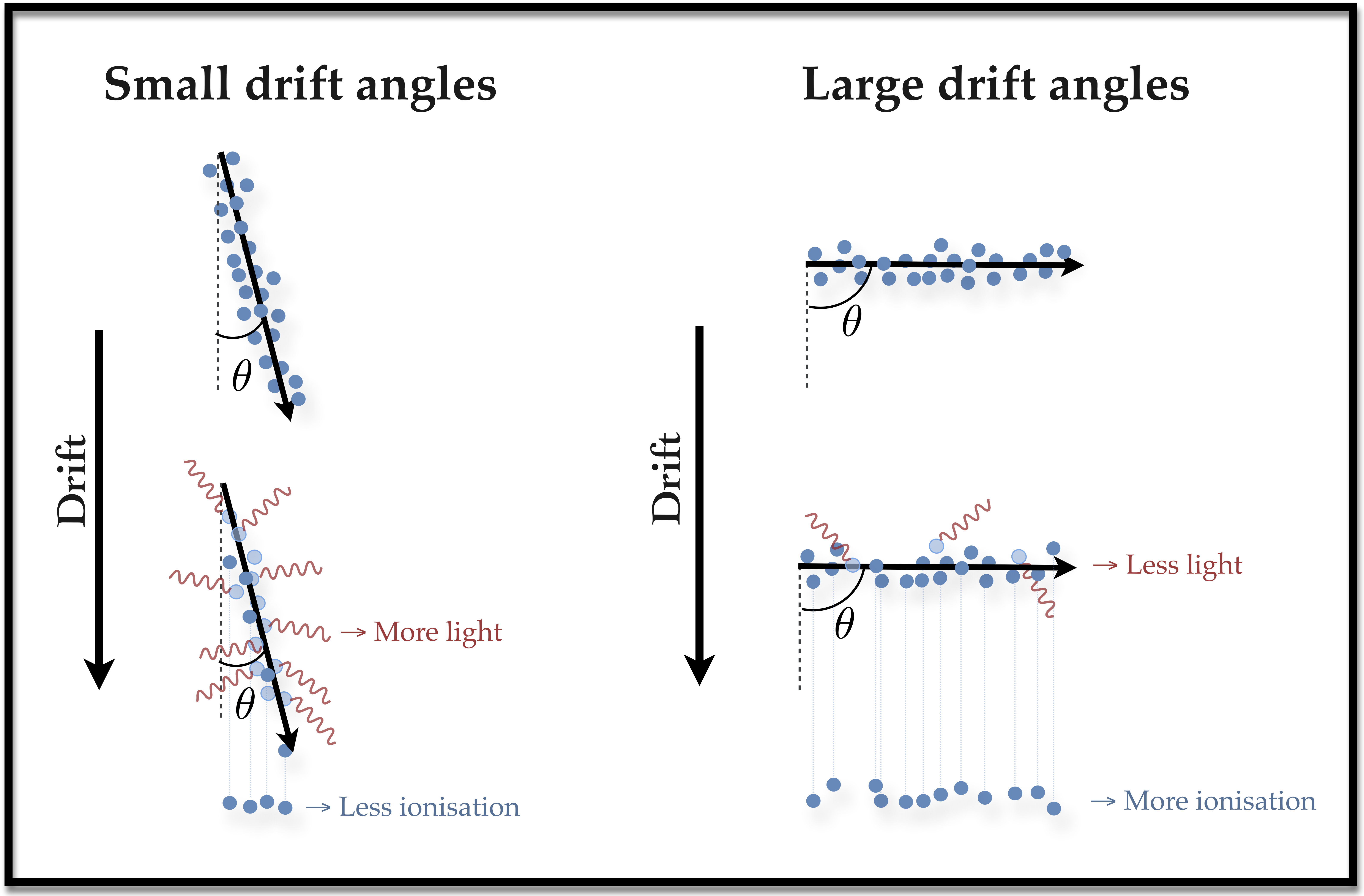
Liquids: columnar recombination

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

→ Directional effect where charge/light yield depends on angle of recoil w.r.t. electric field. Possible hint in LAr, but unobservable in LXe

DarkSide-20k. 2024-??

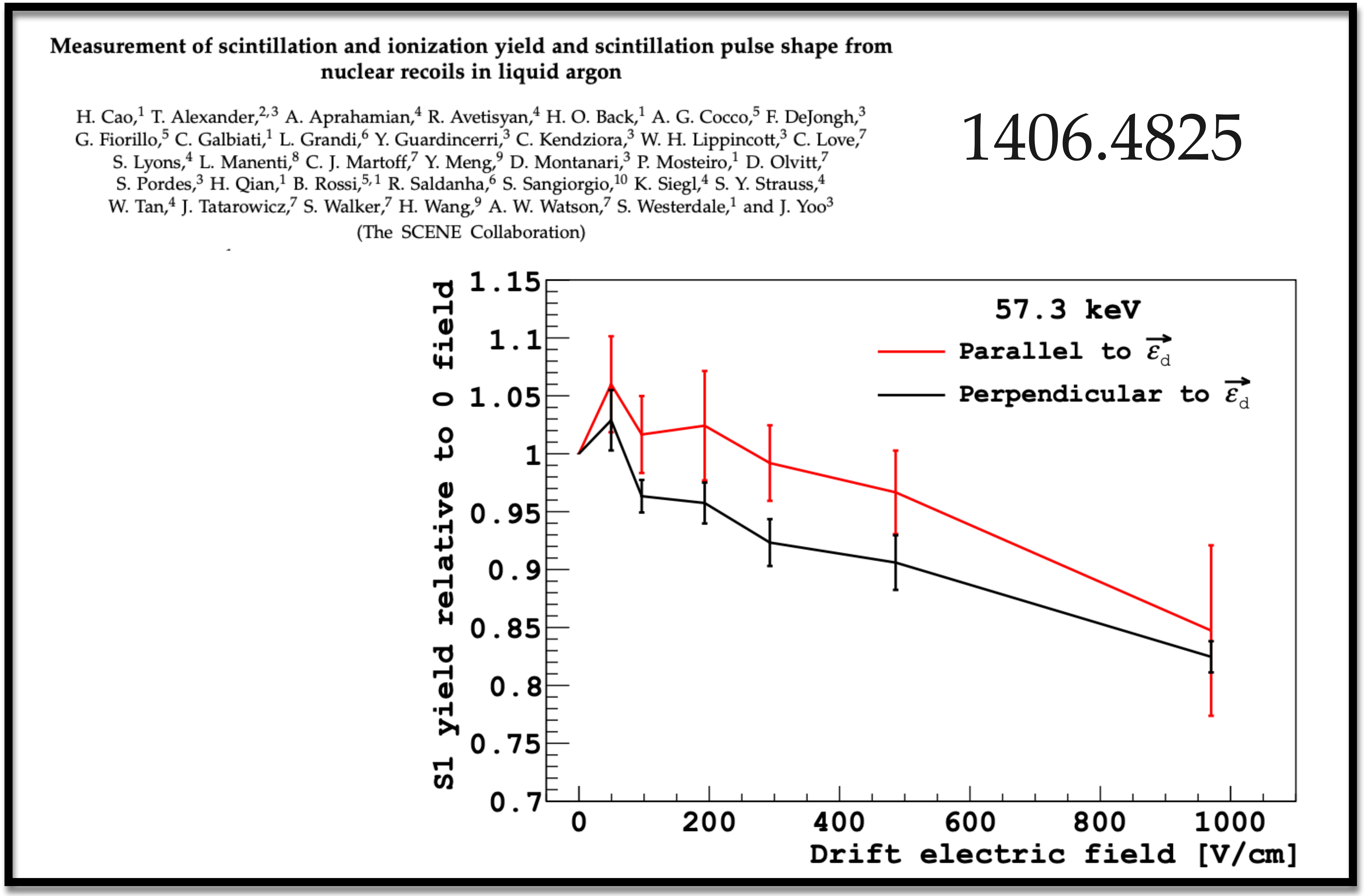




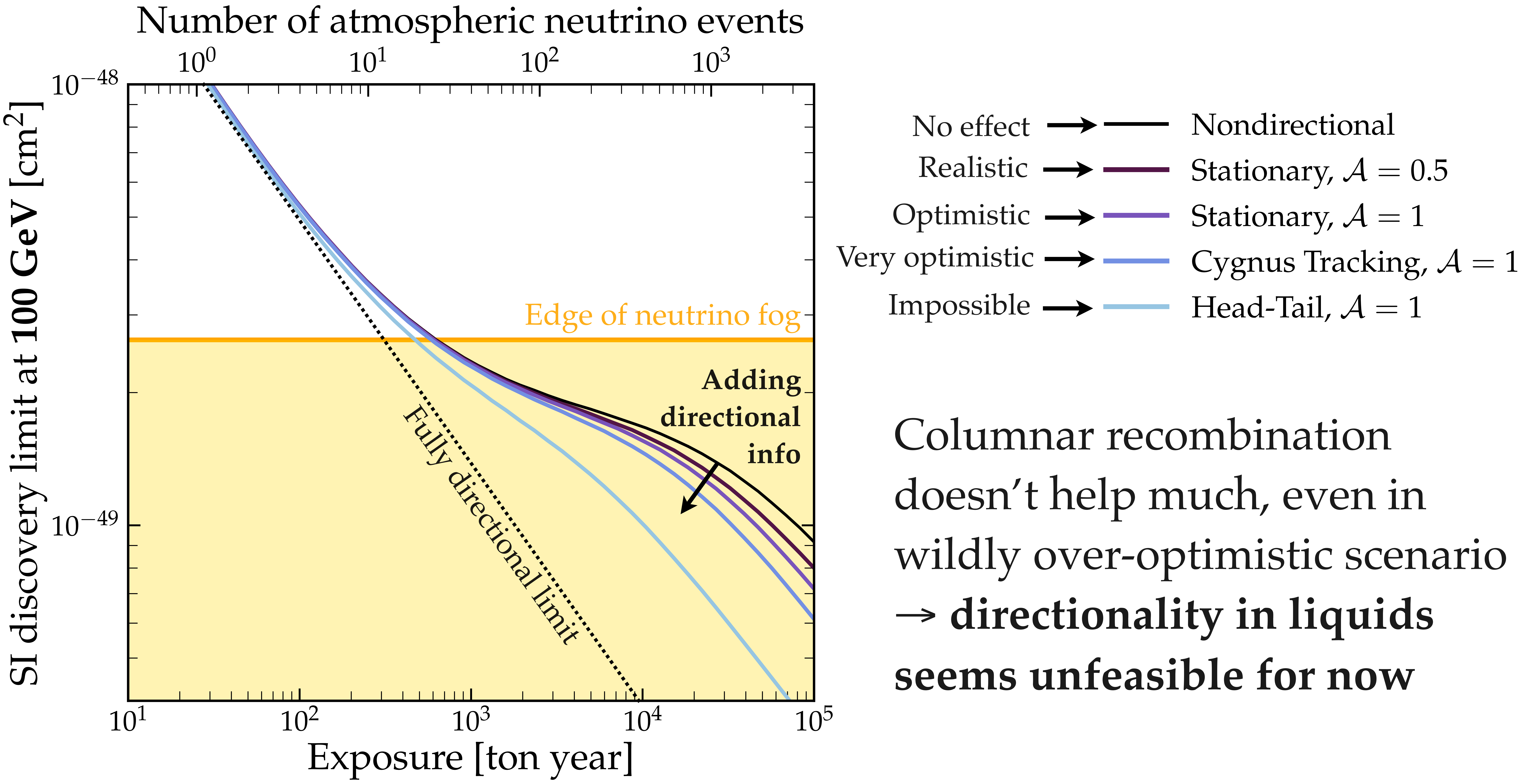
Liquids: columnar recombination

- Possible hint in LAr

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

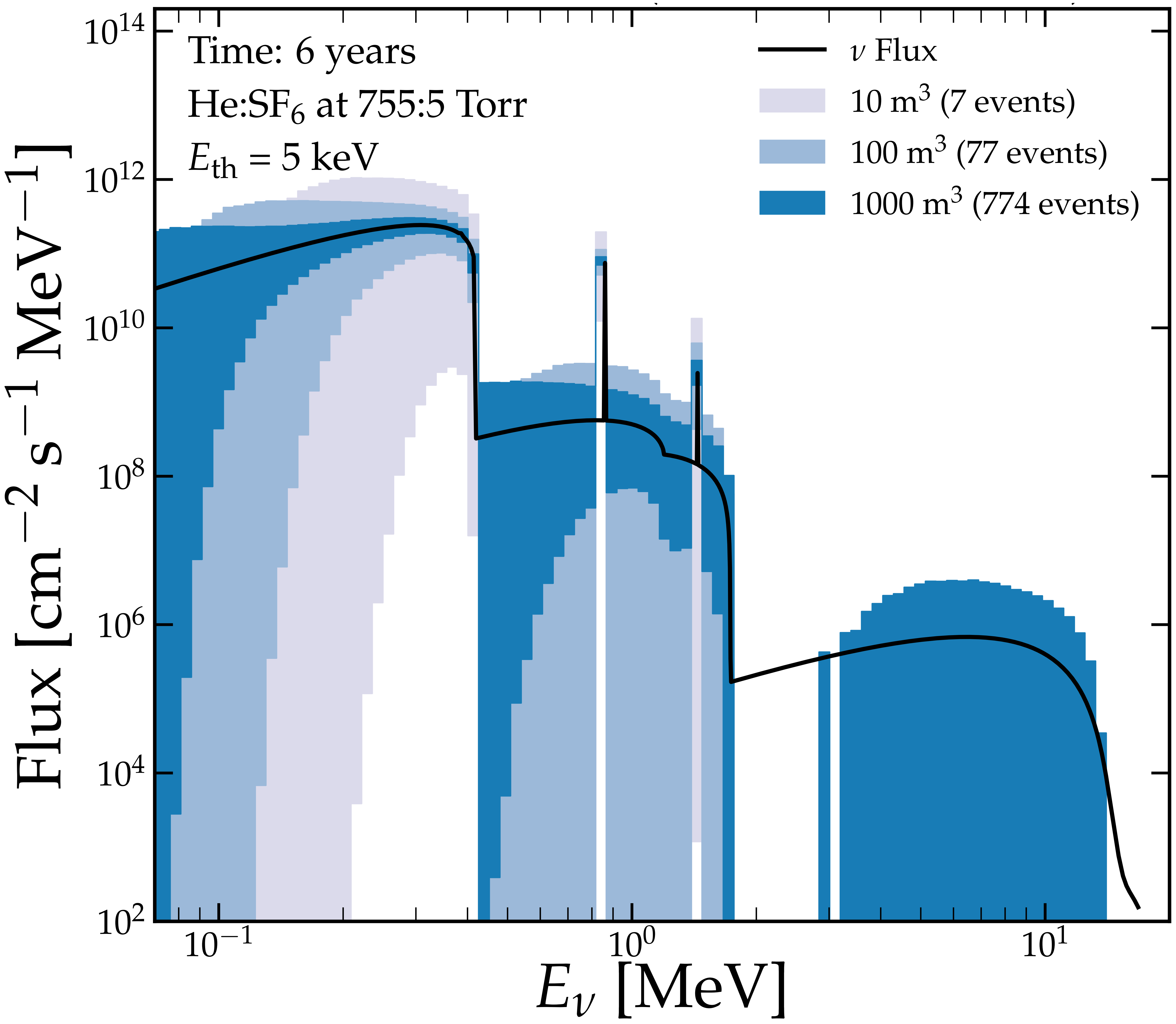


O’Hare [2002.07499]



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

The dream: Empirical flux reconstruction



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

↓

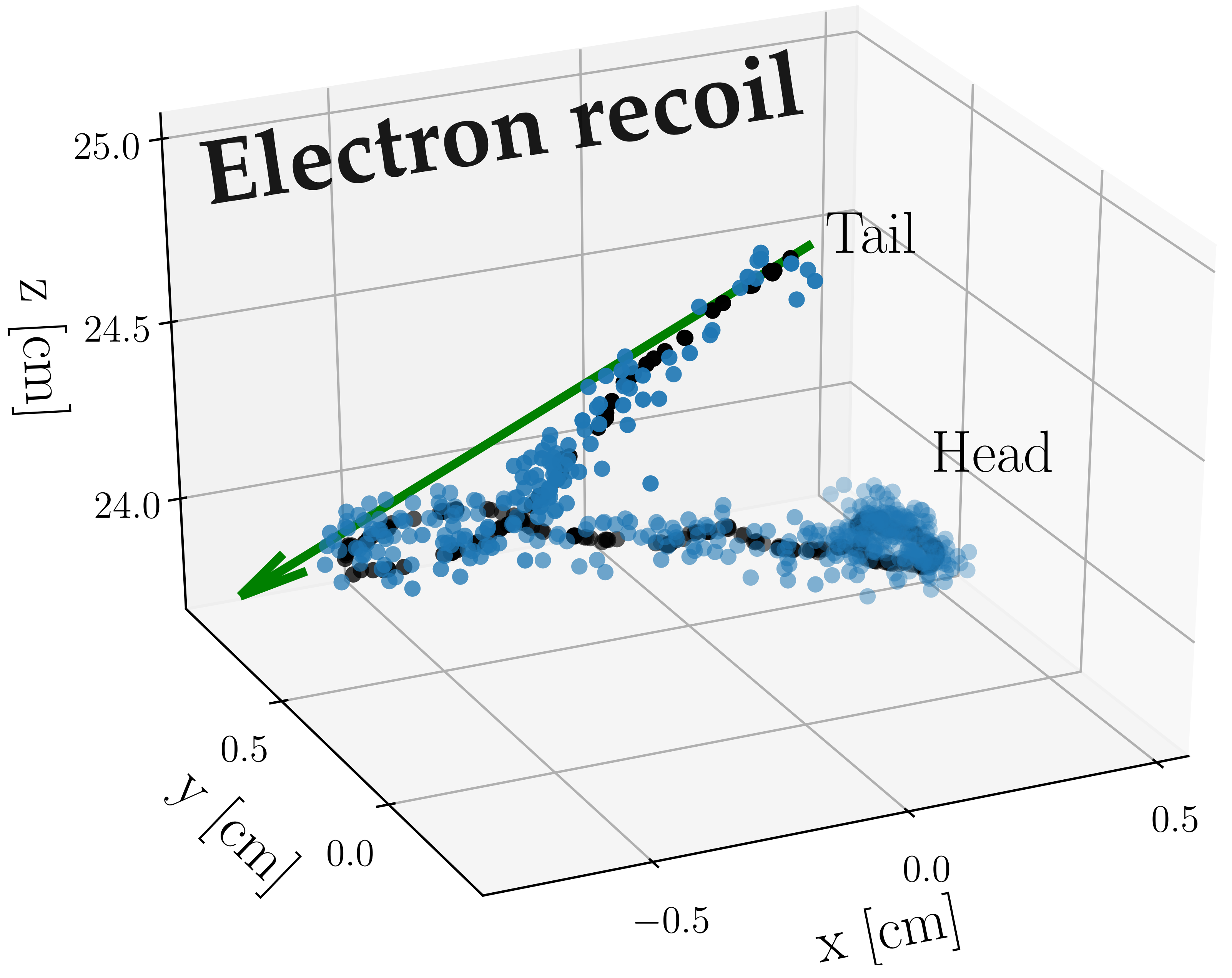
Potentially less in fact. This assumes 755:5 Torr He:SF6 which is good for ~10 keV NRs but >100 keV ERs may be more tolerant of higher pressures

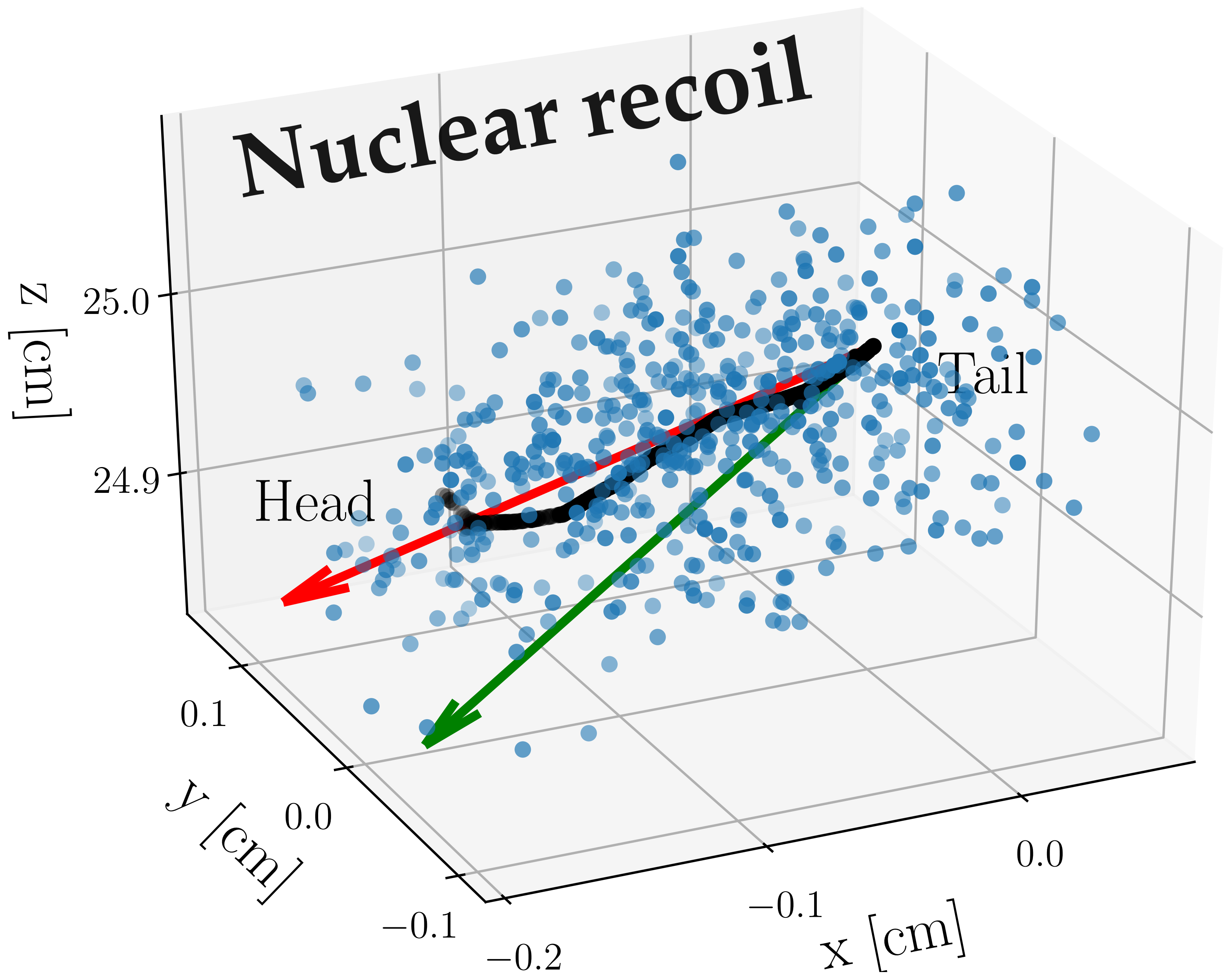
...Angular performance

Everything gets worse at lower energies:

- Decreasing quenching factor, means recoils are harder to detect
- Tracks get shorter → 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

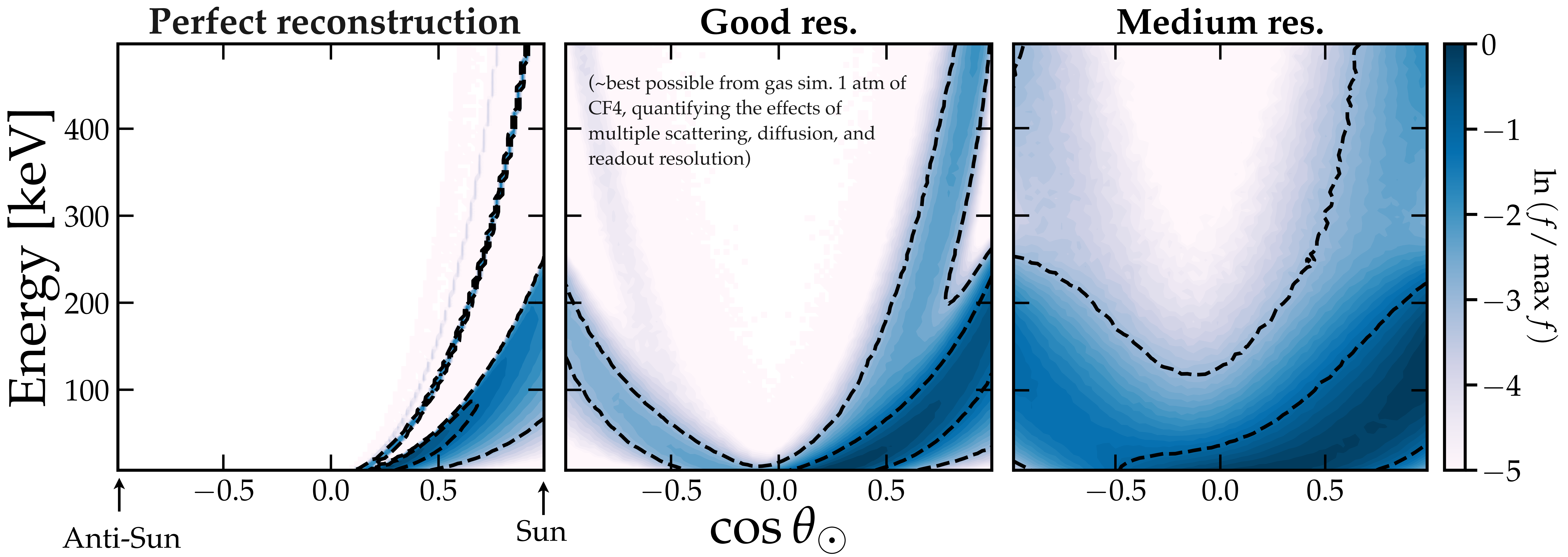
→ Energy dependence of directional performance is very important, and needs to be the focus of all directional detection proposals





Impact of energy/angular resolution on measuring solar neutrino energies

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

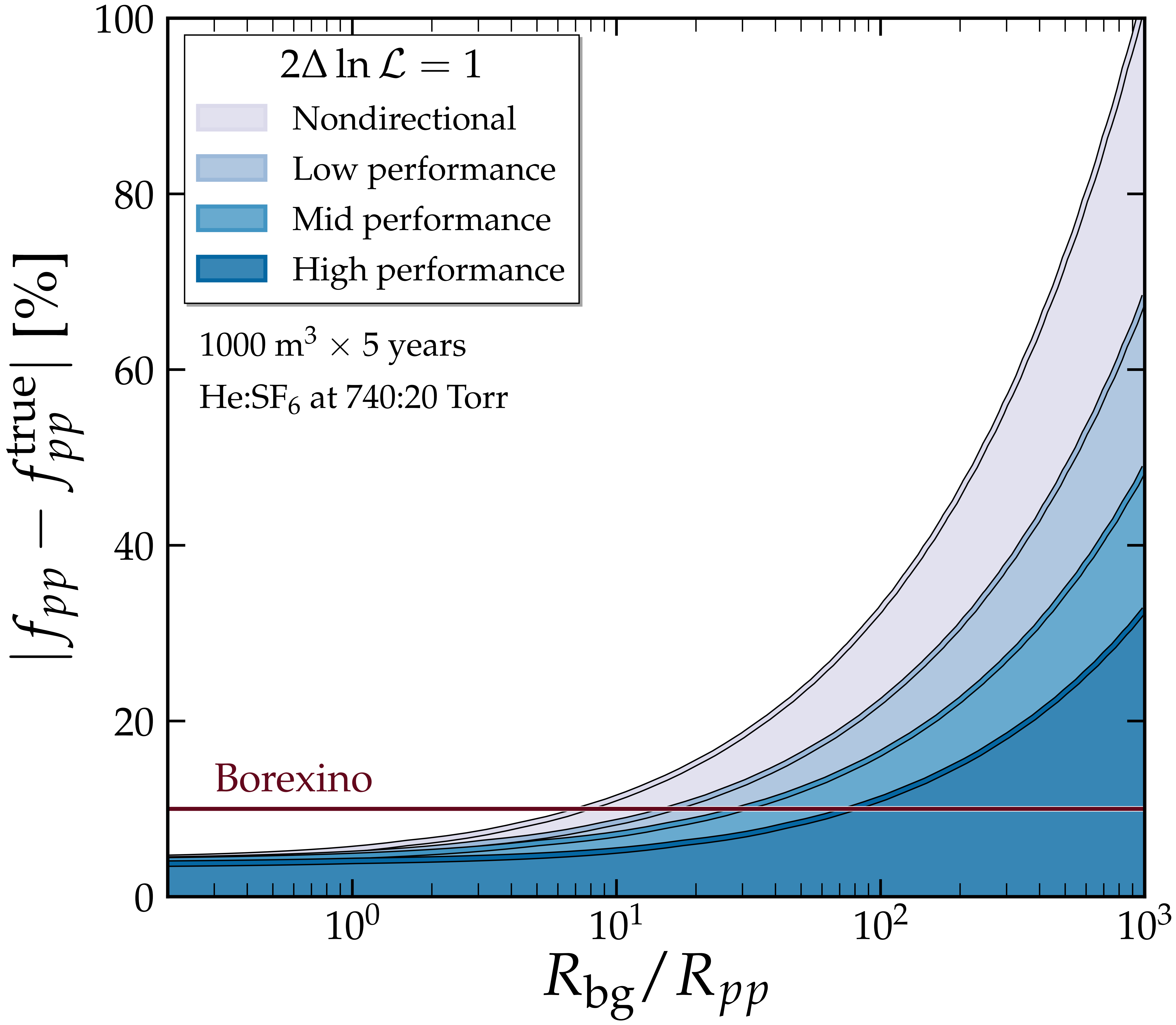


Another key issue → background rate

- A directional experiment can tolerate higher background, however Solar neutrino sensitivity (e.g. accuracy of pp flux reconstruction) crucially dependent on size of electron background (which is typically large)

- Using *pp* ER rate as a reference point, competitive sensitivity achievable even with background ~10–100 times higher than # neutrinos

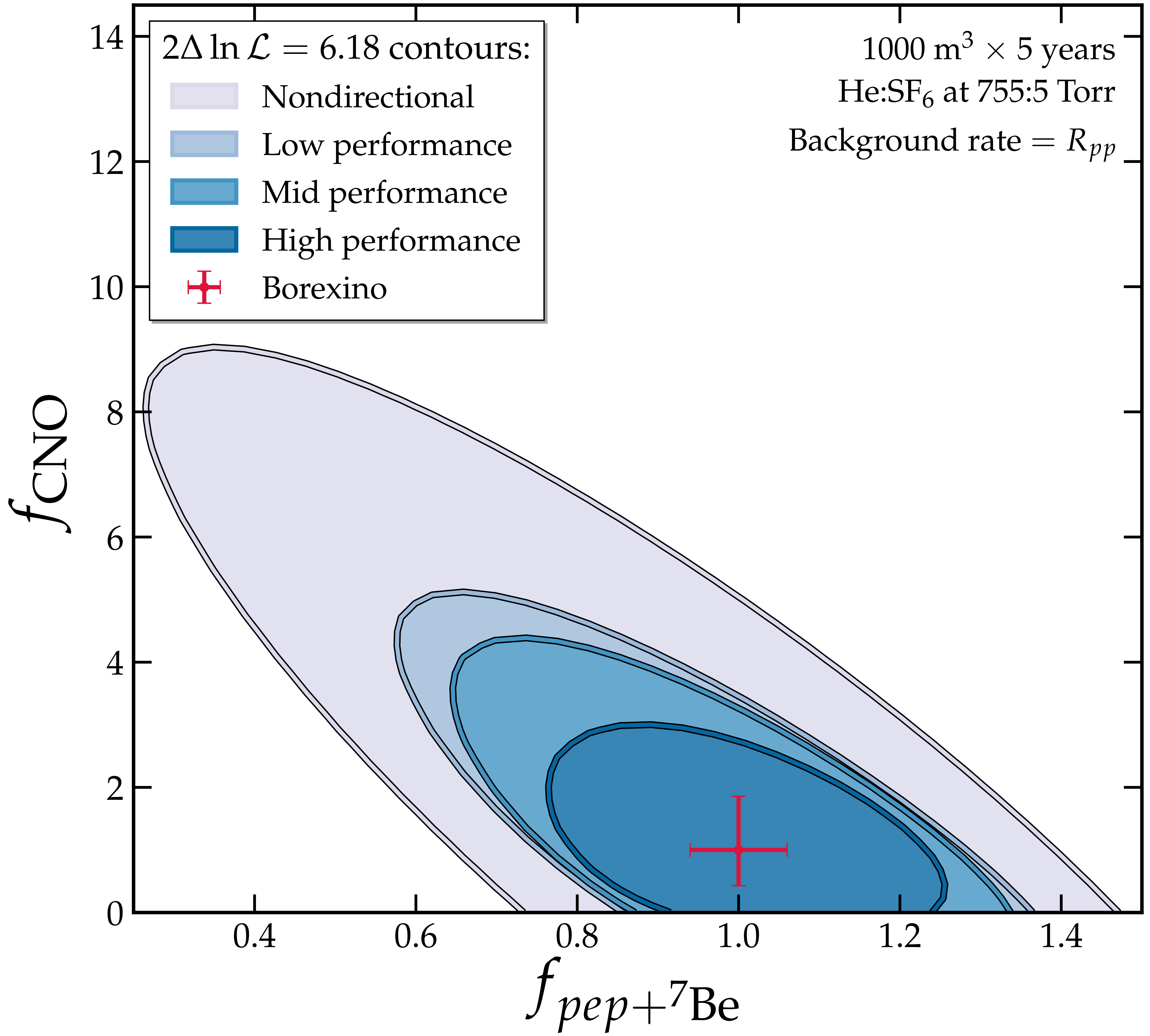
- Electron backgrounds at ~100 keV energies not well studied in gas TPCs as they are irrelevant for DM, however CYGNO study suggests this is still a little too high



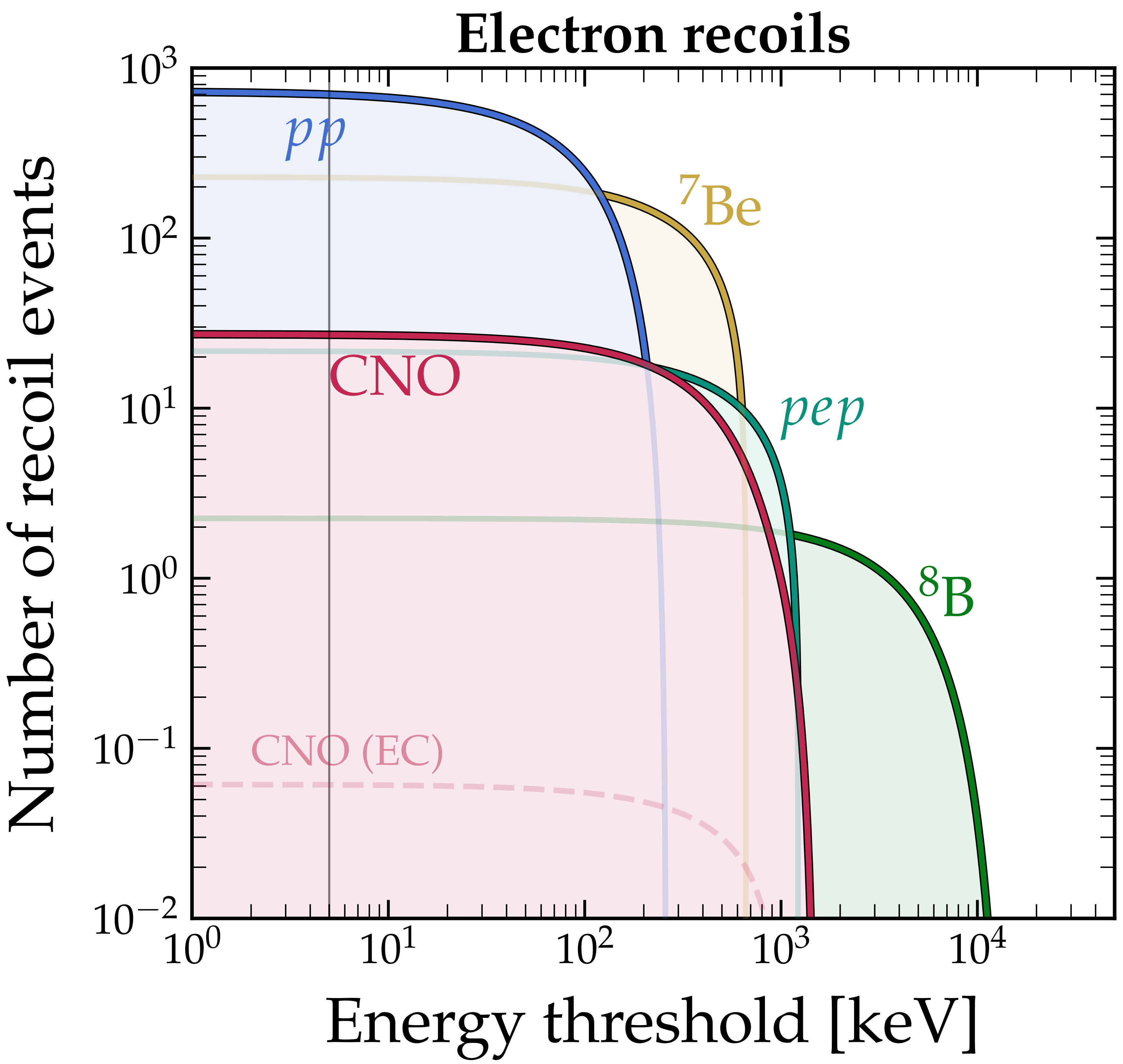
Solar neutrino spectroscopy

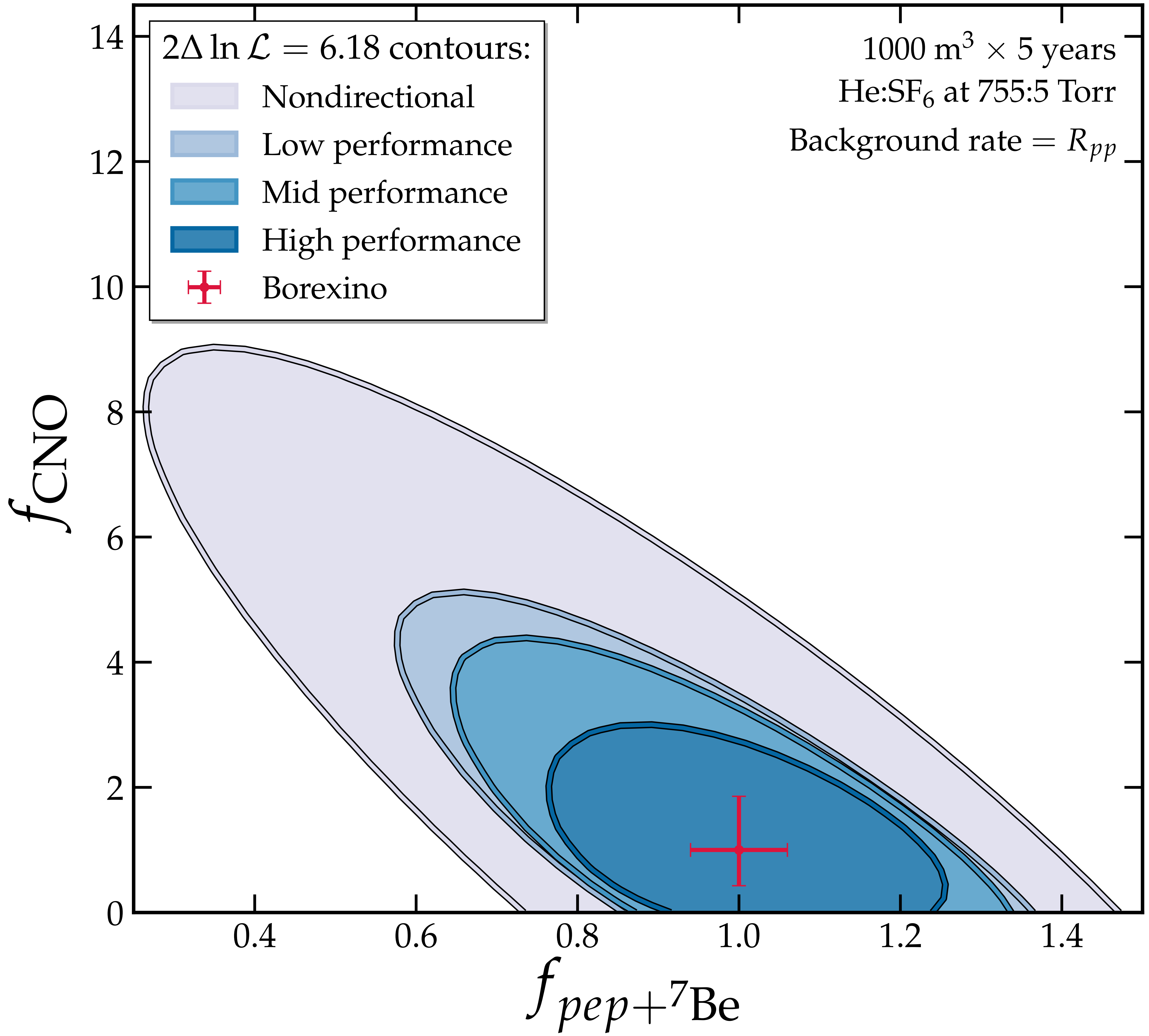
- Assuming optimistic configuration: CYGNUS-1000 with a good directional sensitivity on ~100 keV ERs, and isotropic backgrounds at a similar level to the neutrino rate

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



Solar neutrino spectroscopy

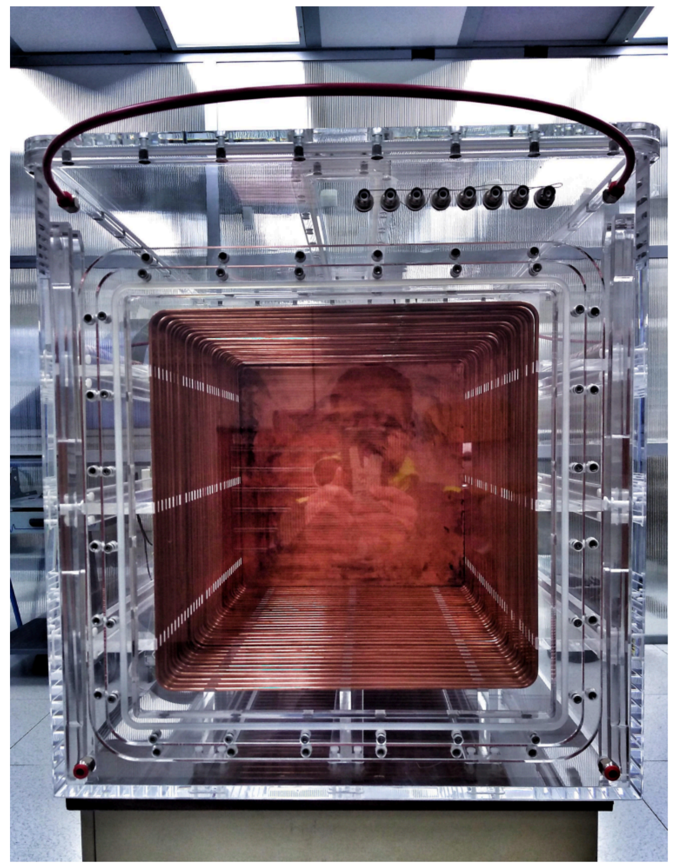


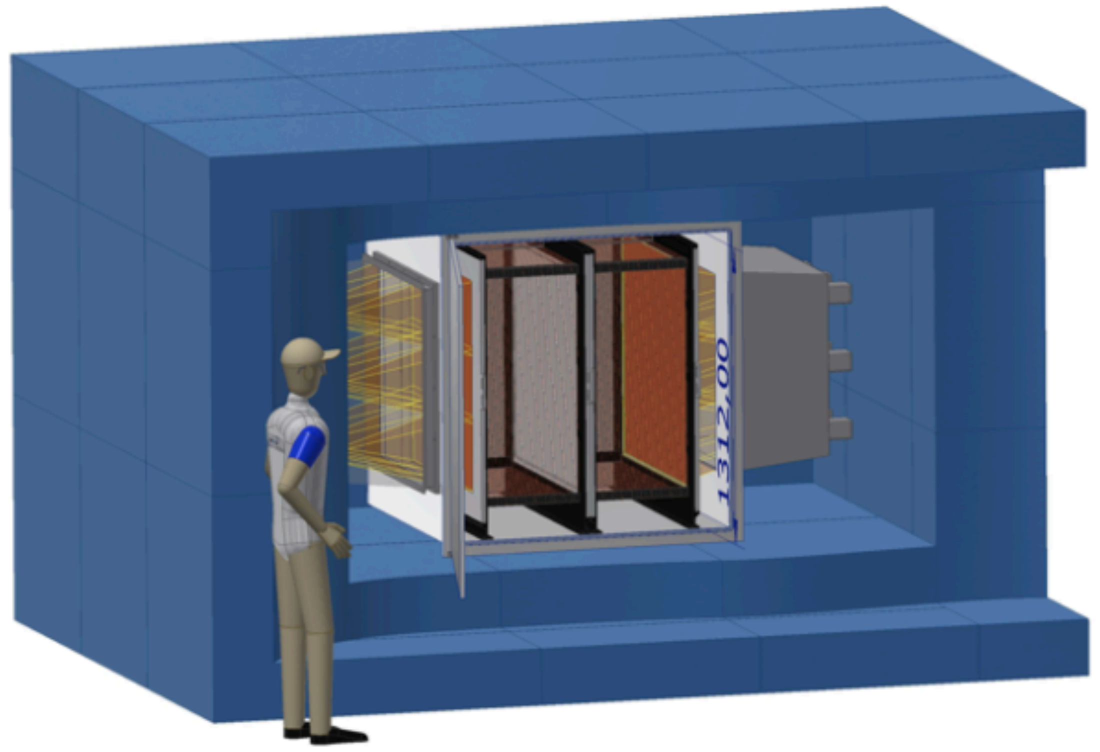


NB: not intending on beating Borexino! These measurements will be complementary, and (hopefully) *in addition* to DM detection

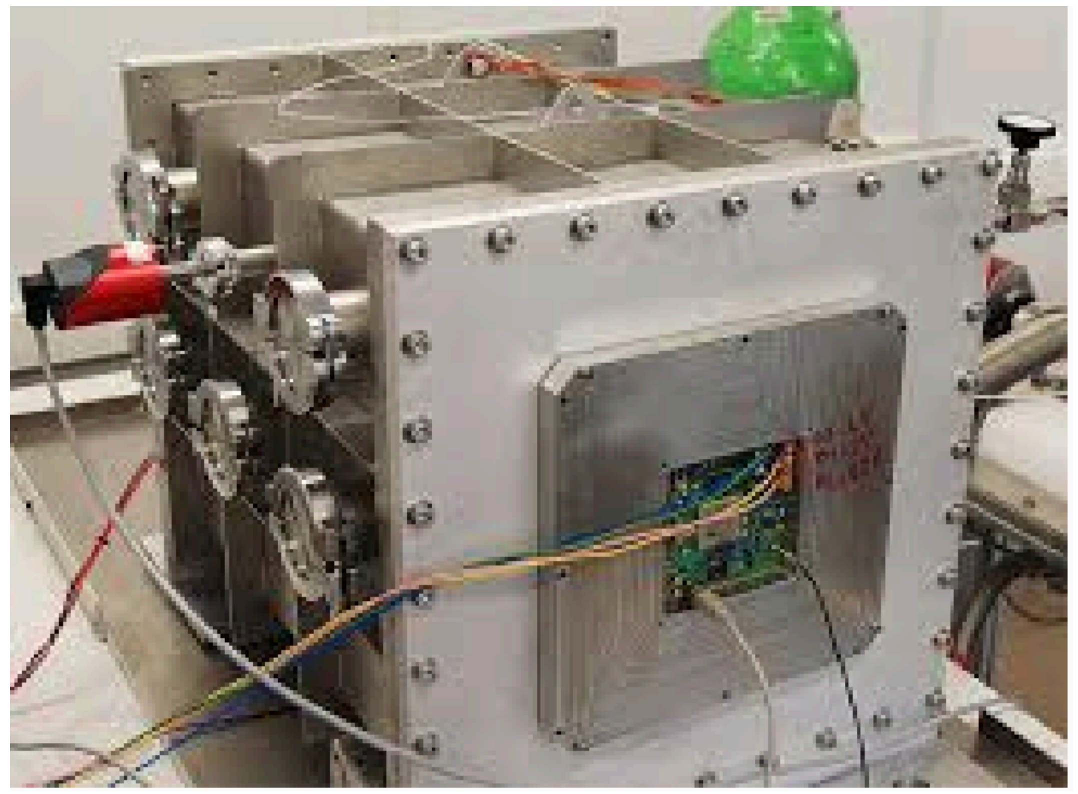
More experiments I didn’t have time to mention

CYGNO (various TPC projects)

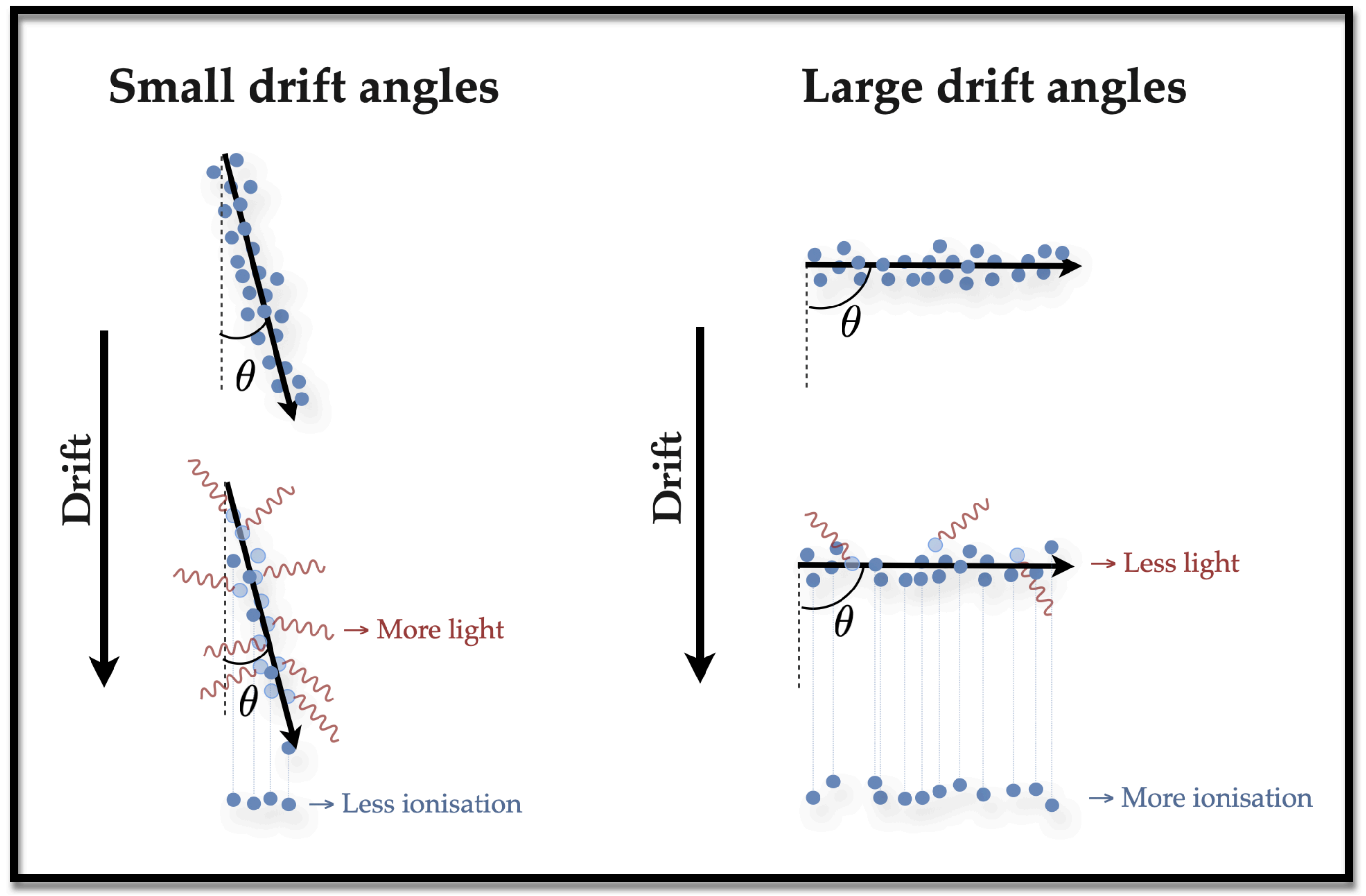




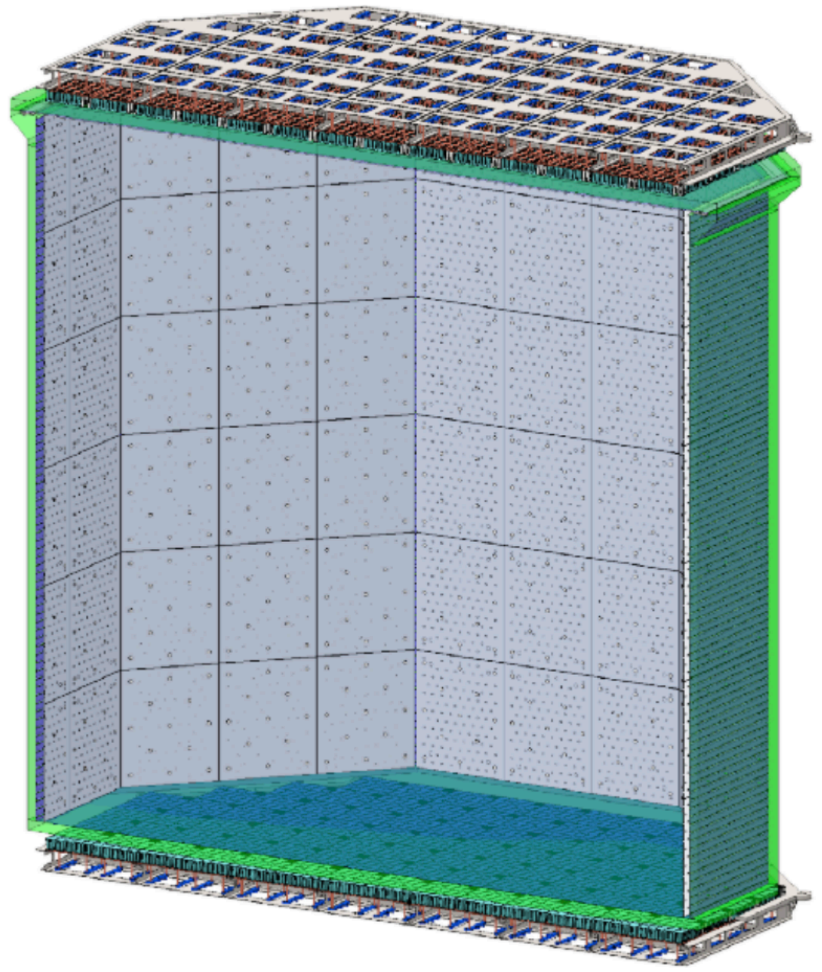
MIMAC (TPC)



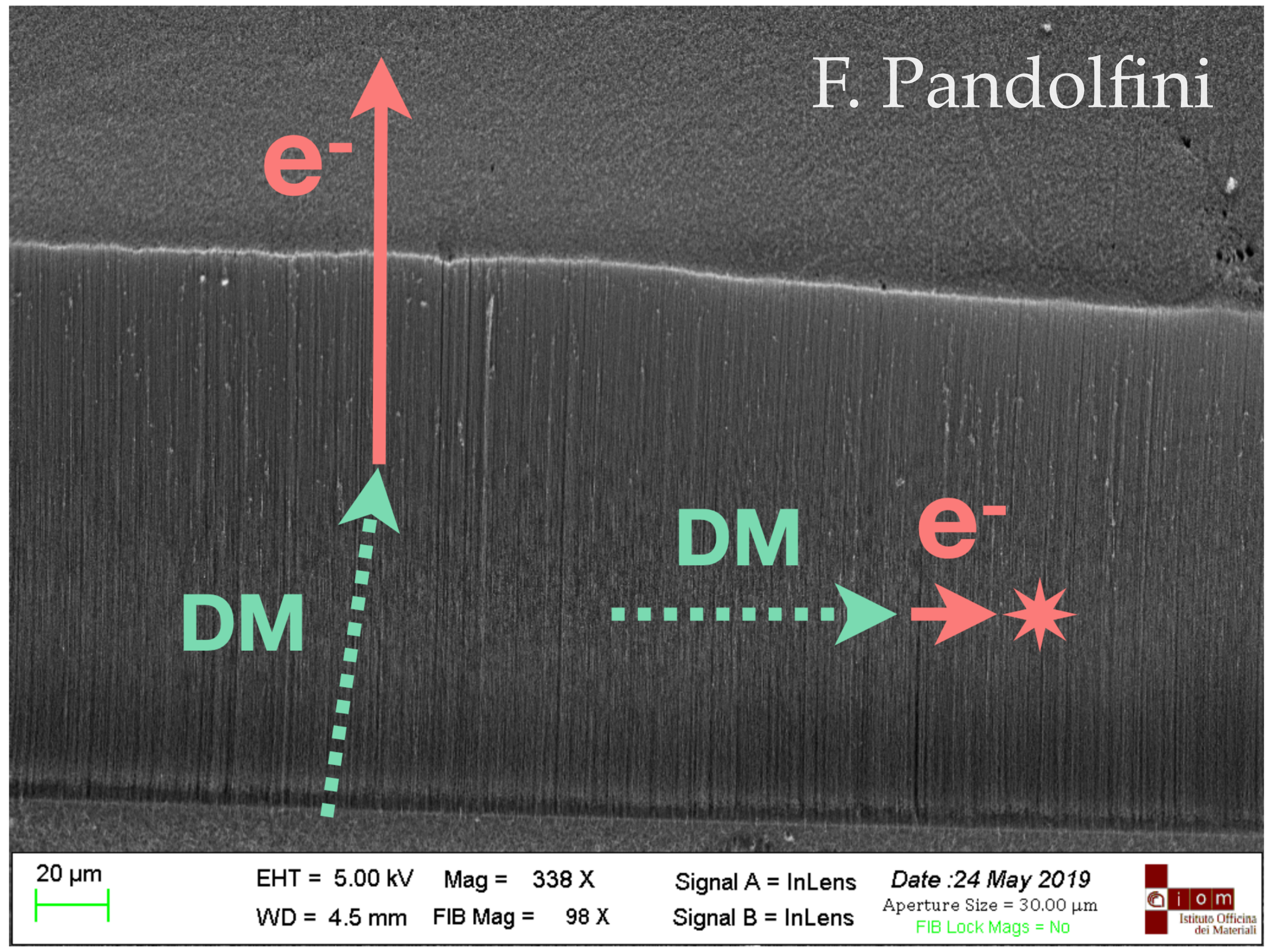
ReD/DarkSide
(columnar recombination in LAr)



DarkSide-20k. 2024-??



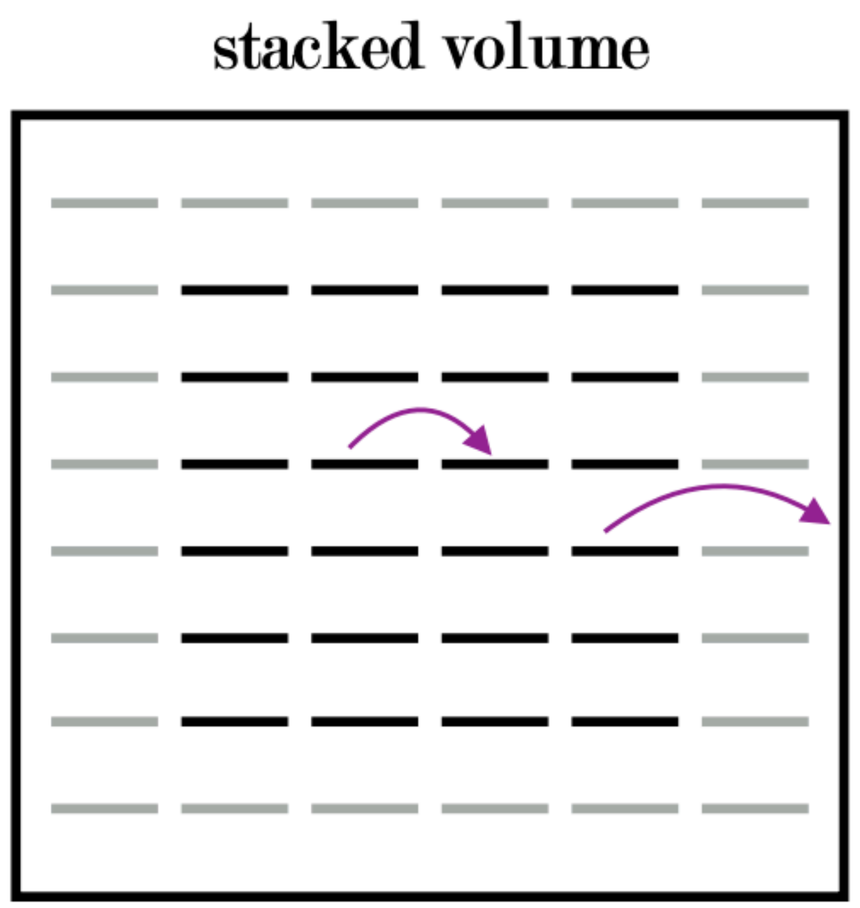
Dark-PMT (Carbon nanotubes)

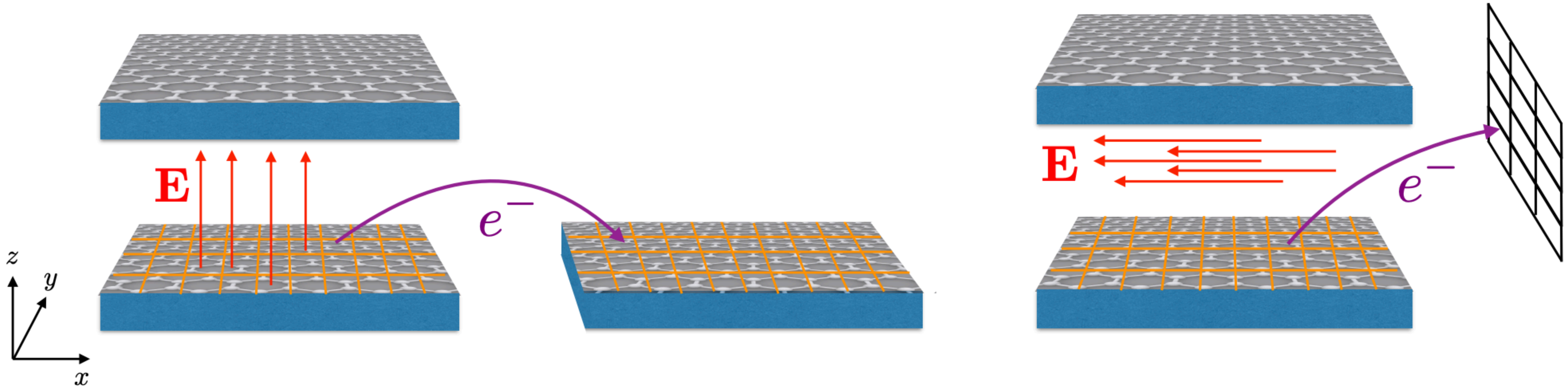


More concepts for light DM directionality

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

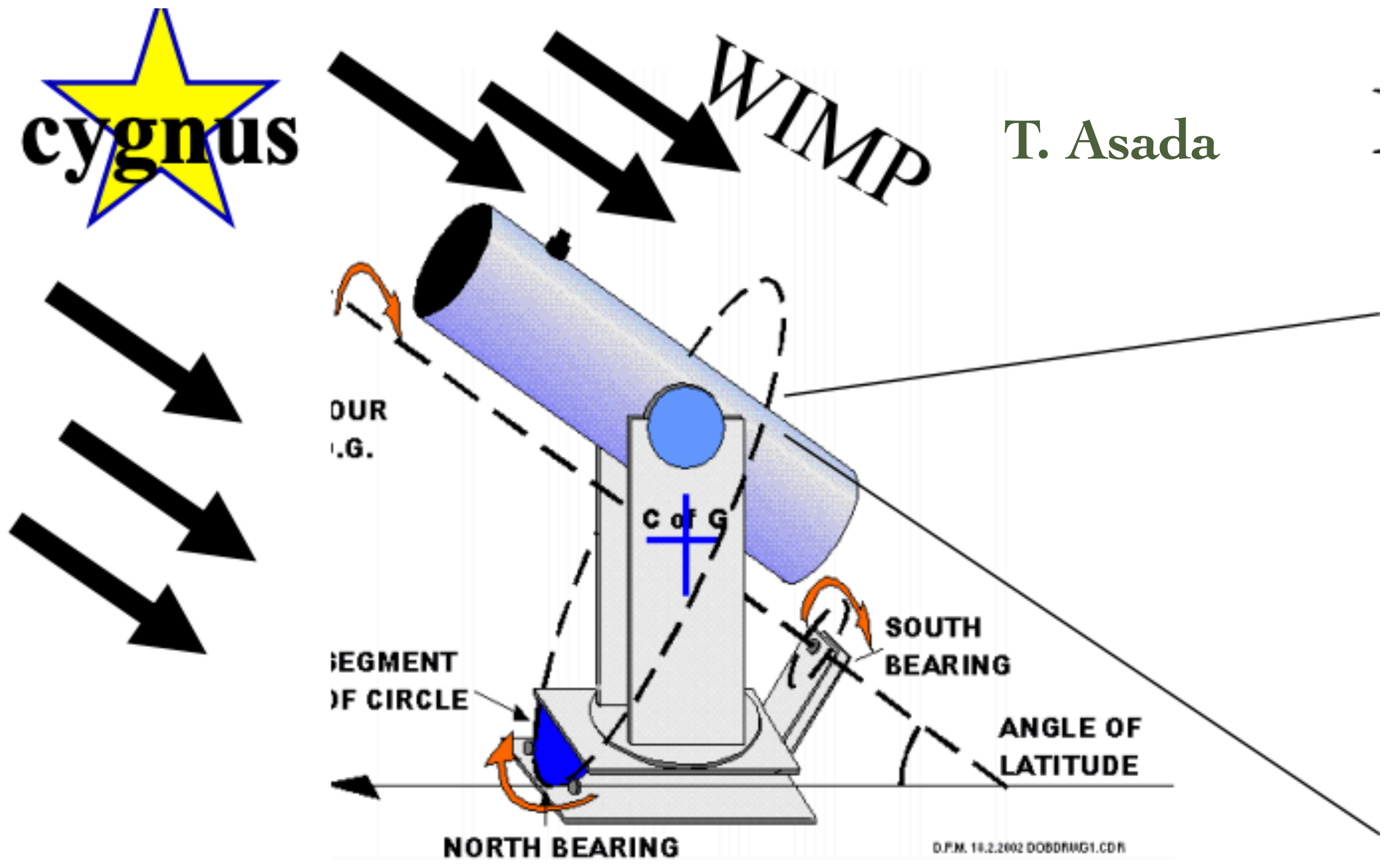
…

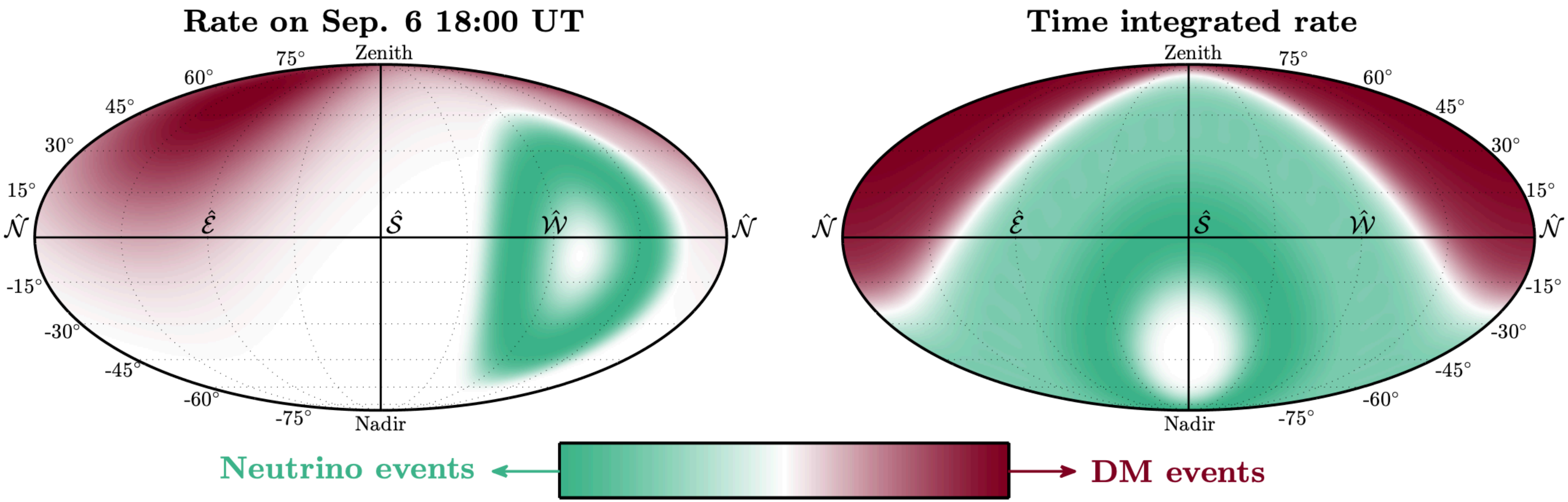




Time-integrated directional detection

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



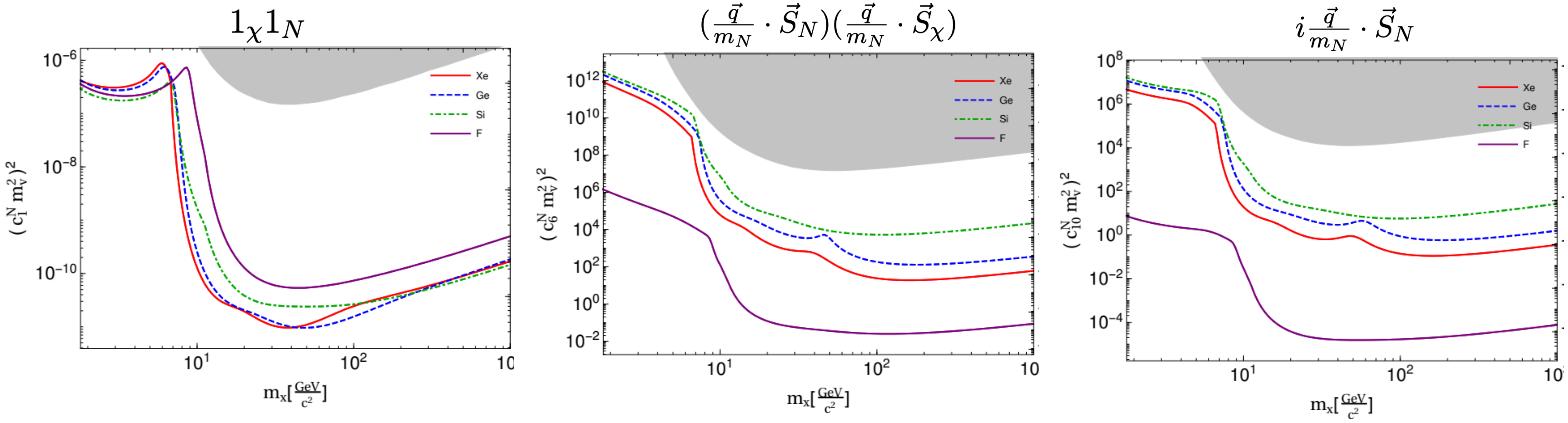


O'Hare et al. 1708.02959

Neutrino “floors” beyond SI

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

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



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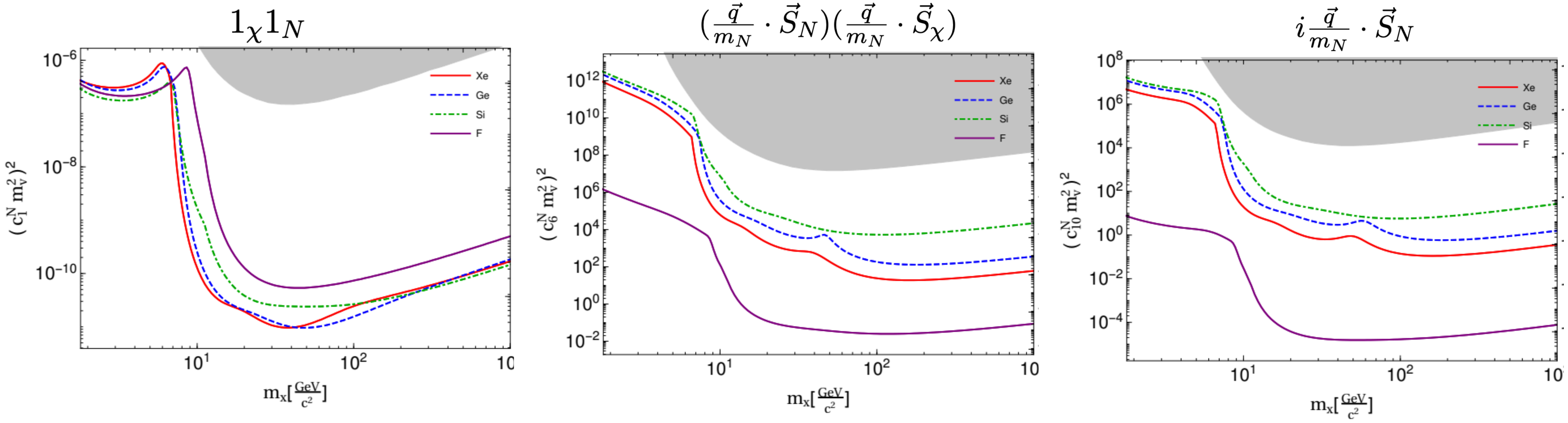
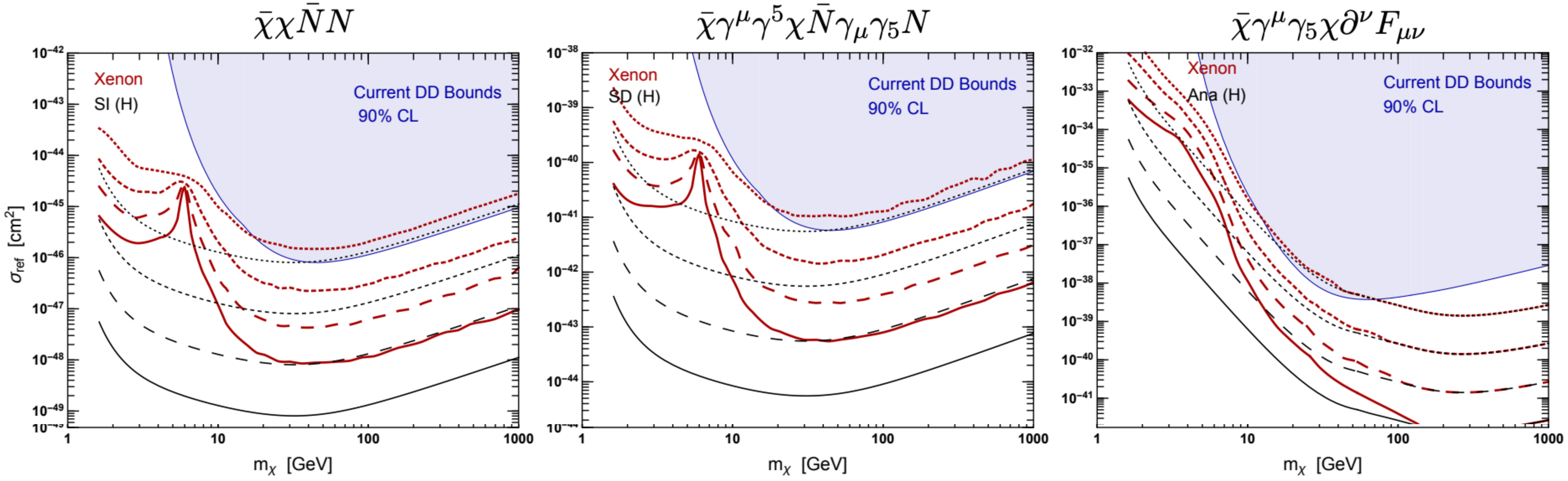
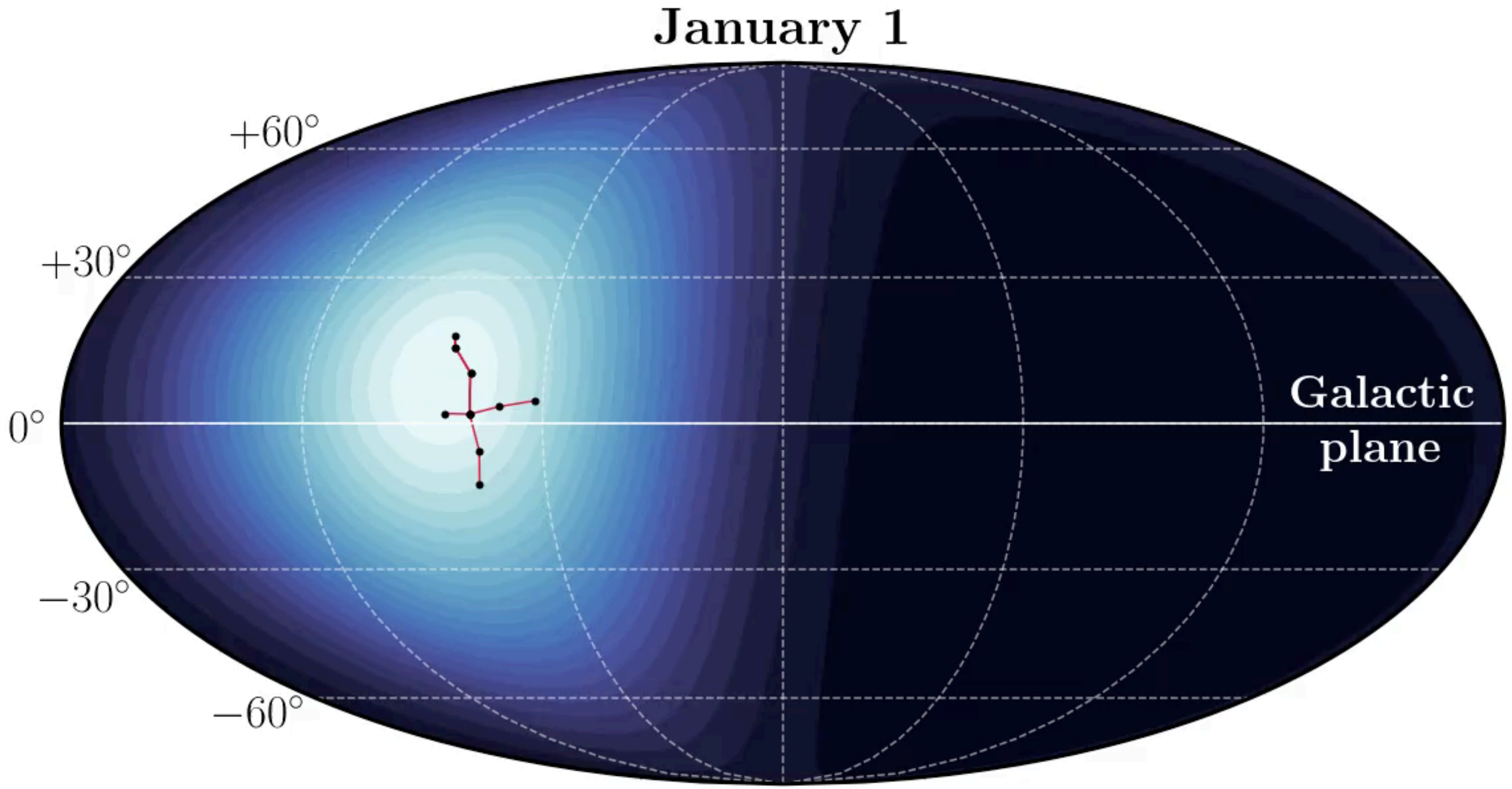


Gelmini et al. [1804.01638] → Various DM Interaction models



Based on standard assumptions, what **should** the signal look like?
→ a Gaussian peaking towards Cygnus

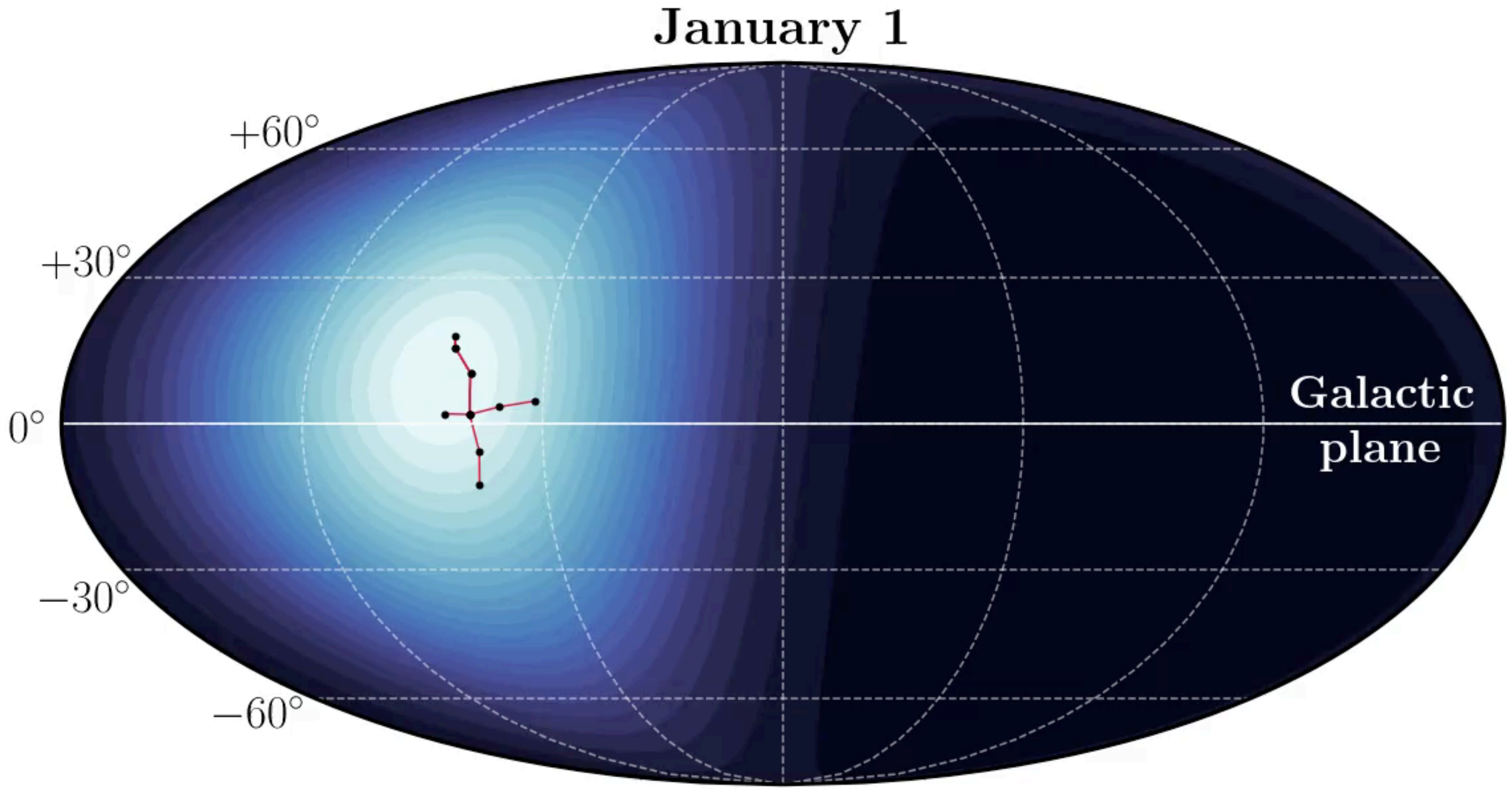
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\rm min} + v_{\rm lab}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$



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

→ a Gaussian peaking towards Cygnus

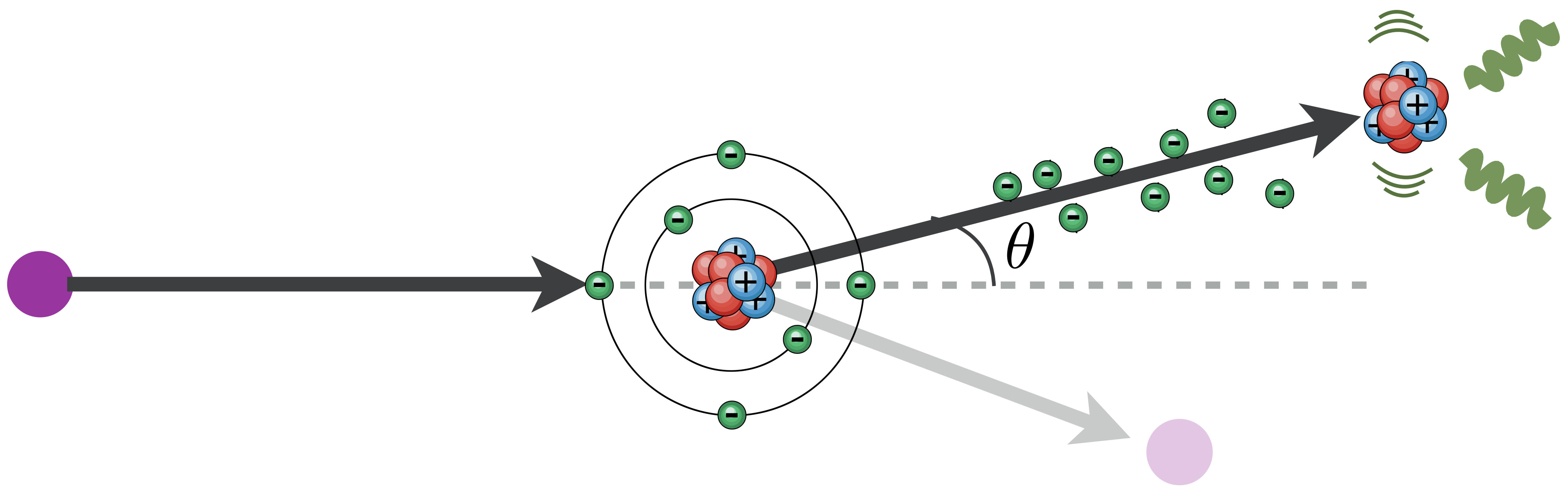
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\rm min} + v_{\rm lab}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$



Standard prediction based on a few assumptions

- The DM scatters elastically

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



- The DM velocity distribution is a Gaussian (SHM)

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

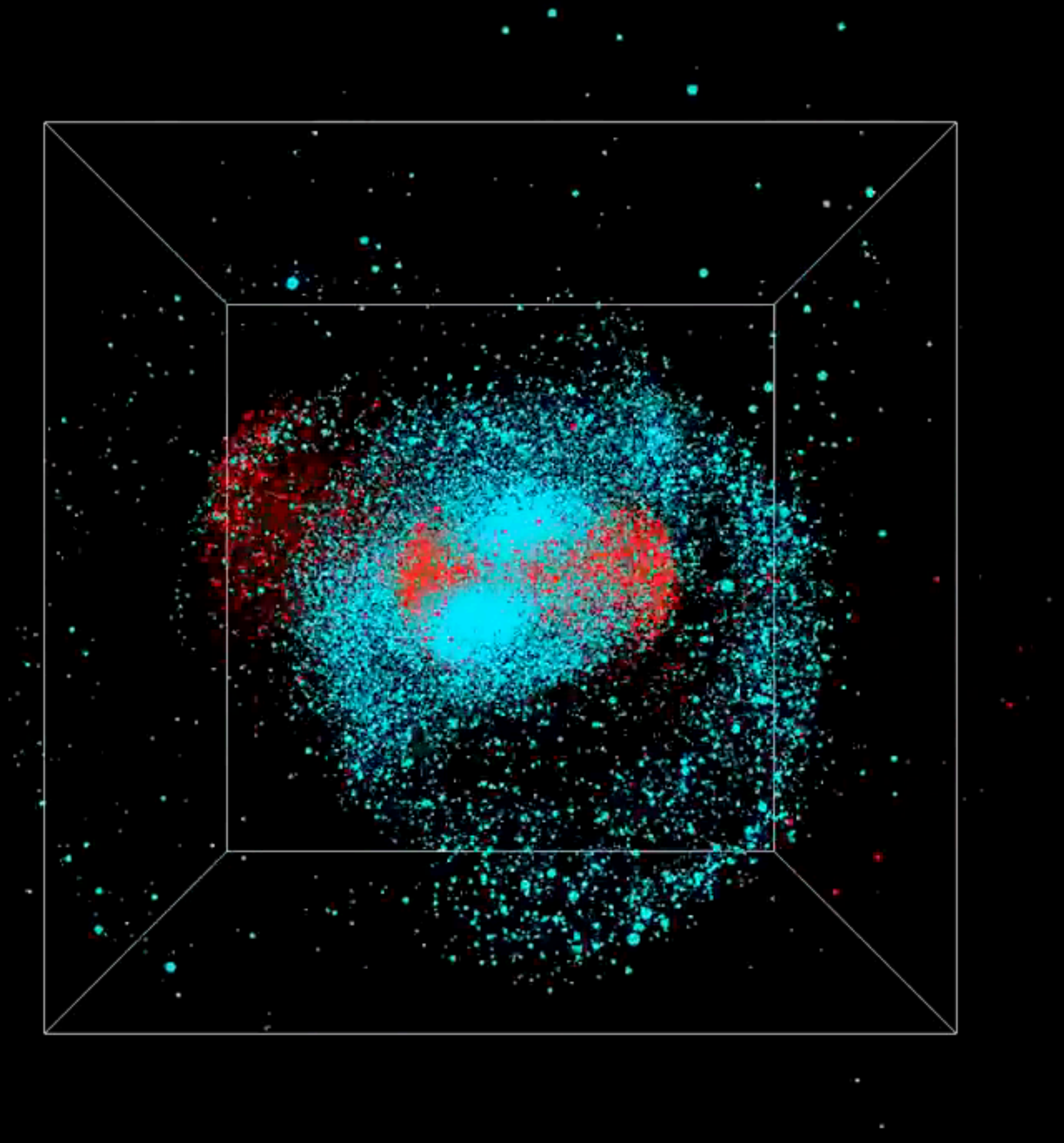
- DM-nucleus matrix element does not depend on velocity

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

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?

→ Evidence of significant merger in the MW's history

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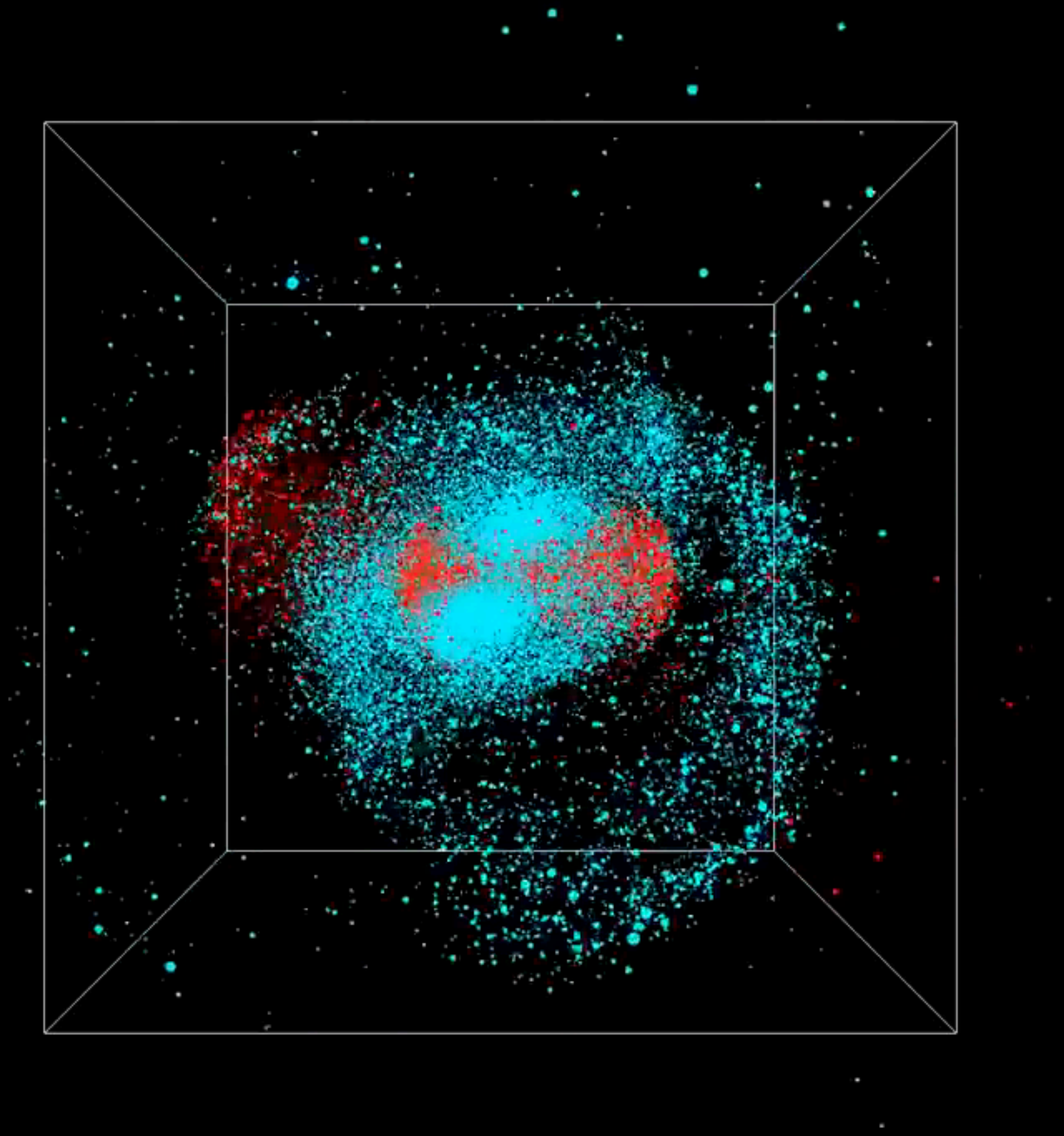
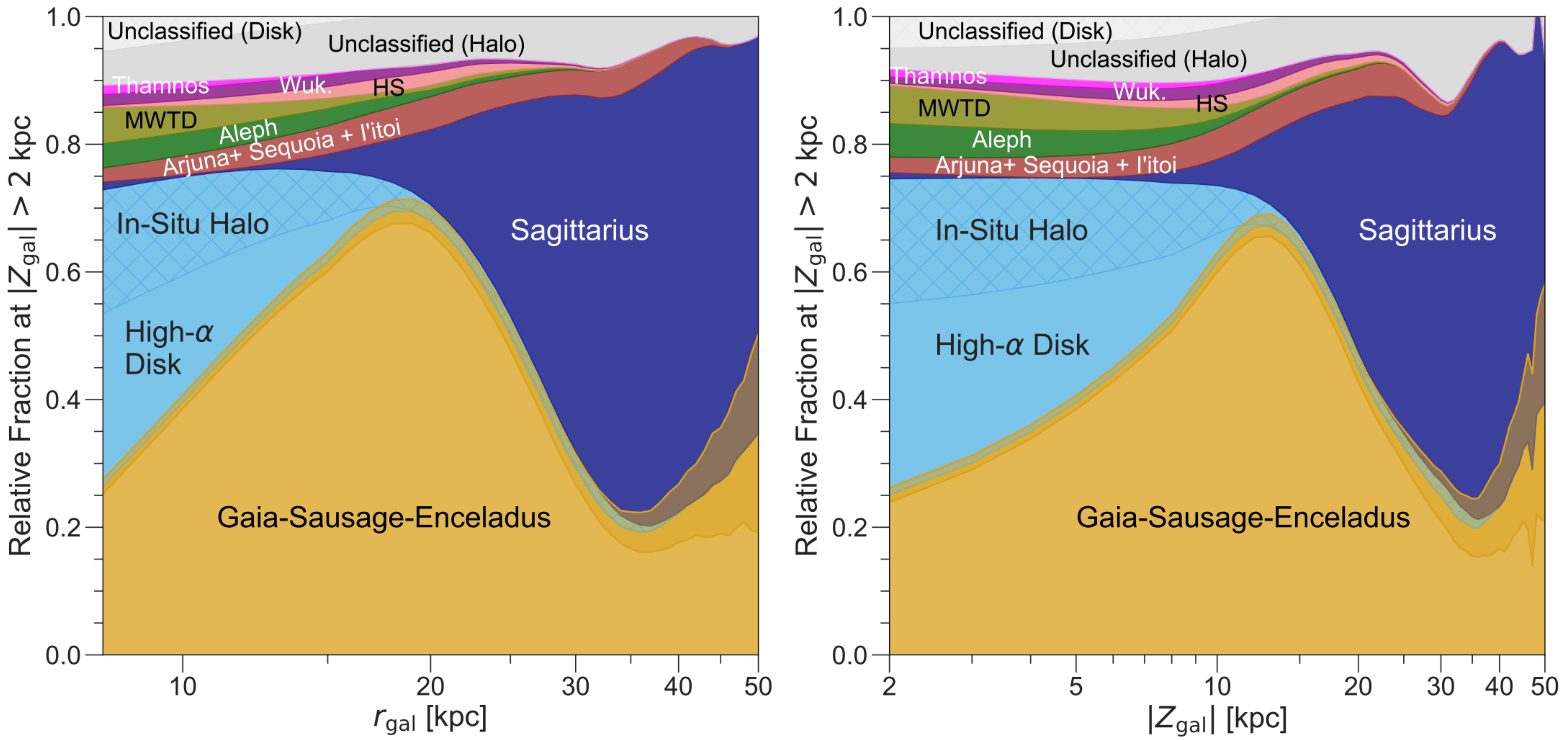


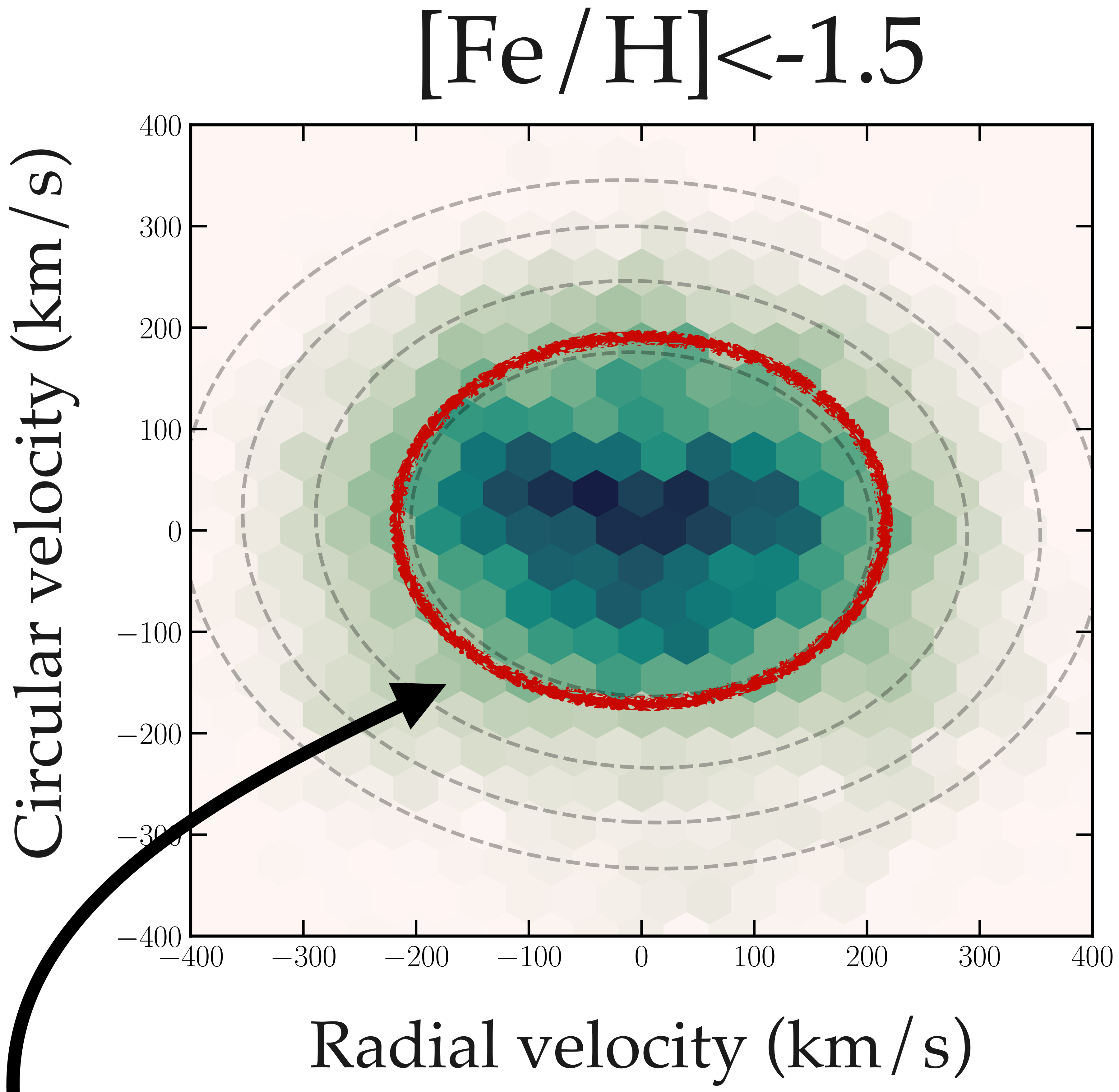
See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

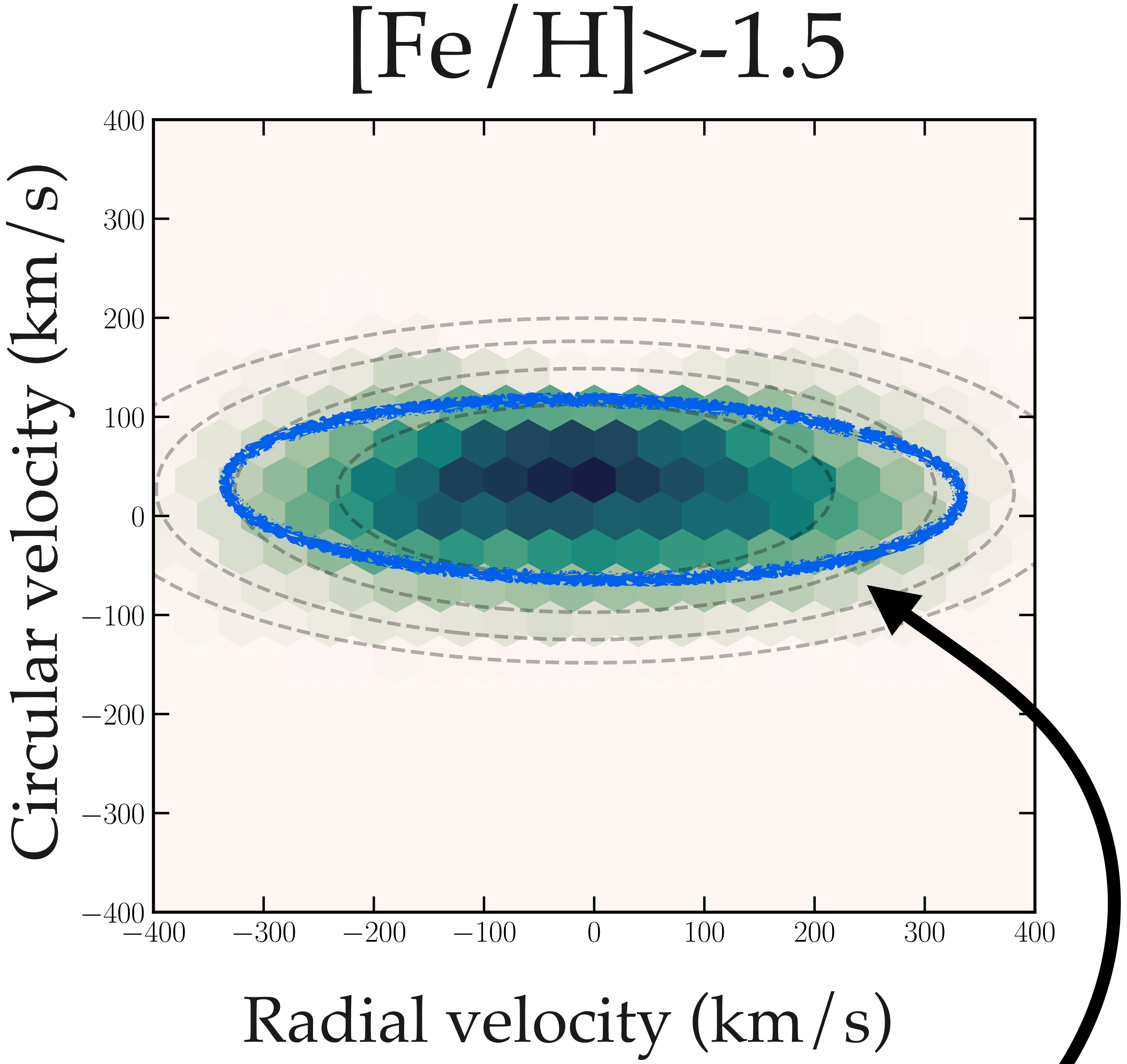
2006.08625

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]







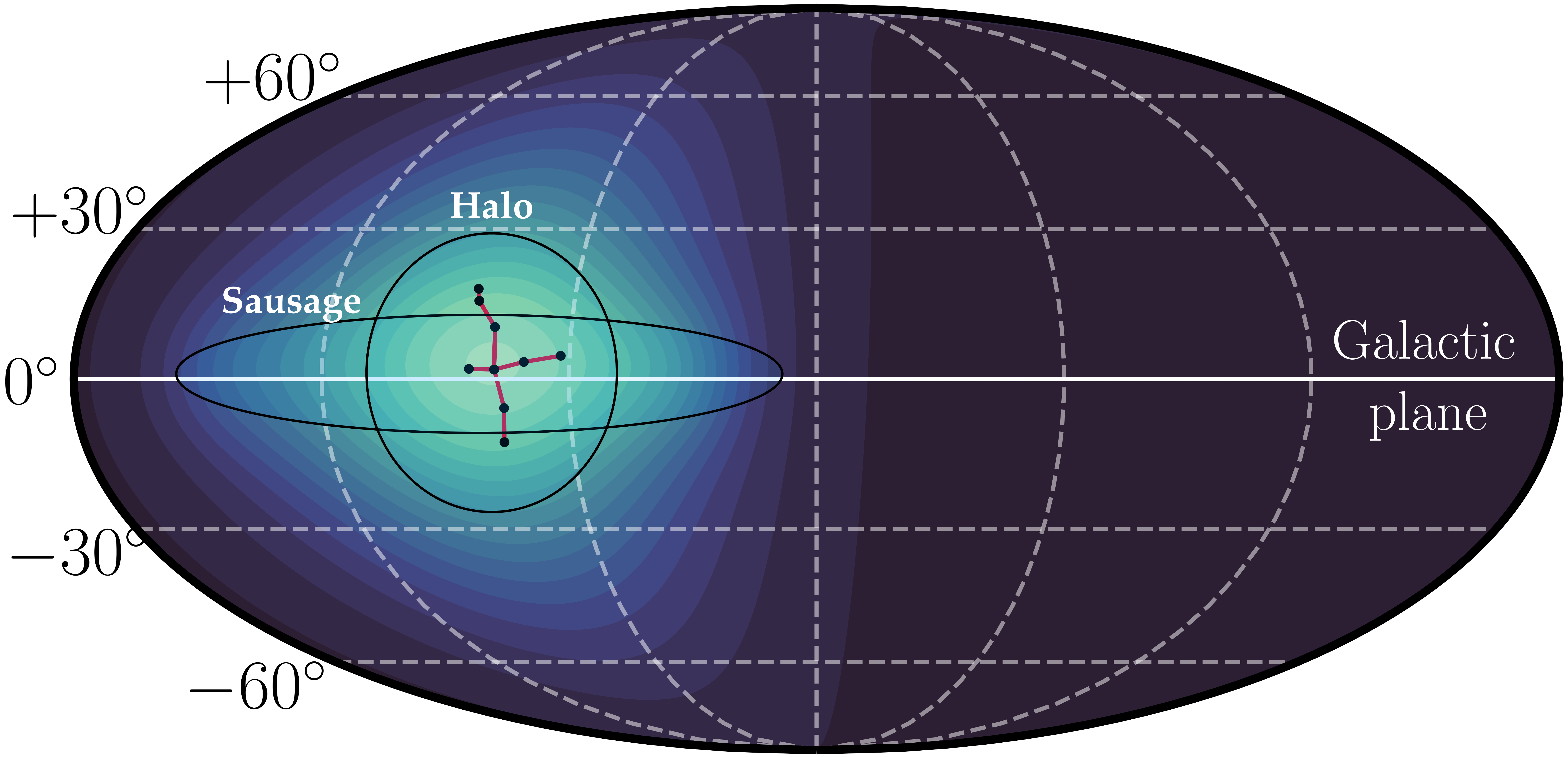
"Metal-poor" halo

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

"Metal-rich" halo

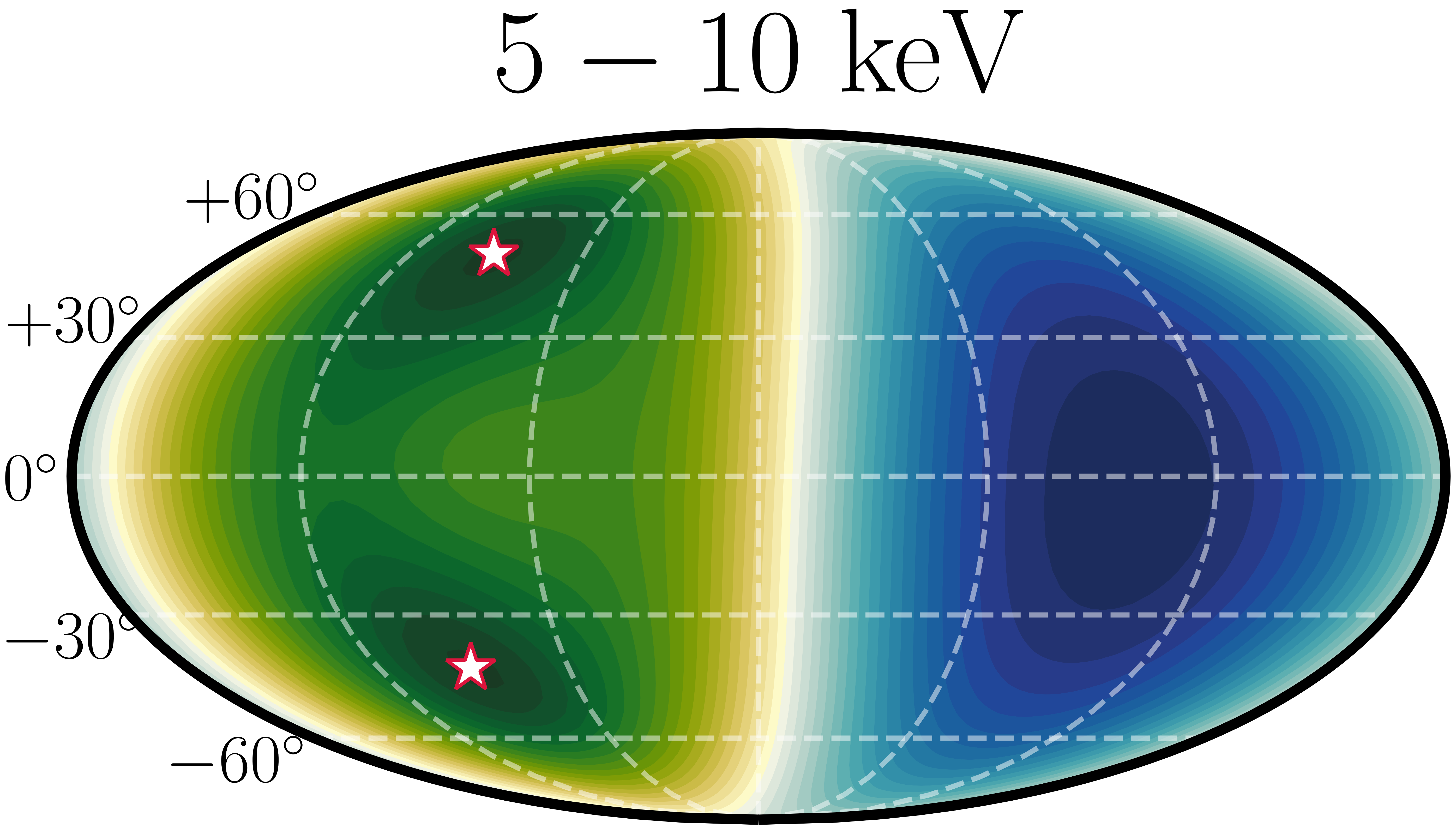
- Highly eccentric radial orbits
- Dominant contribution ~50%
- Characteristic metallicity [Fe/H] = -1.4

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



The Gaia Sausage gives rise to peaks off center from Cygnus

O'Hare+ [1909.04684]



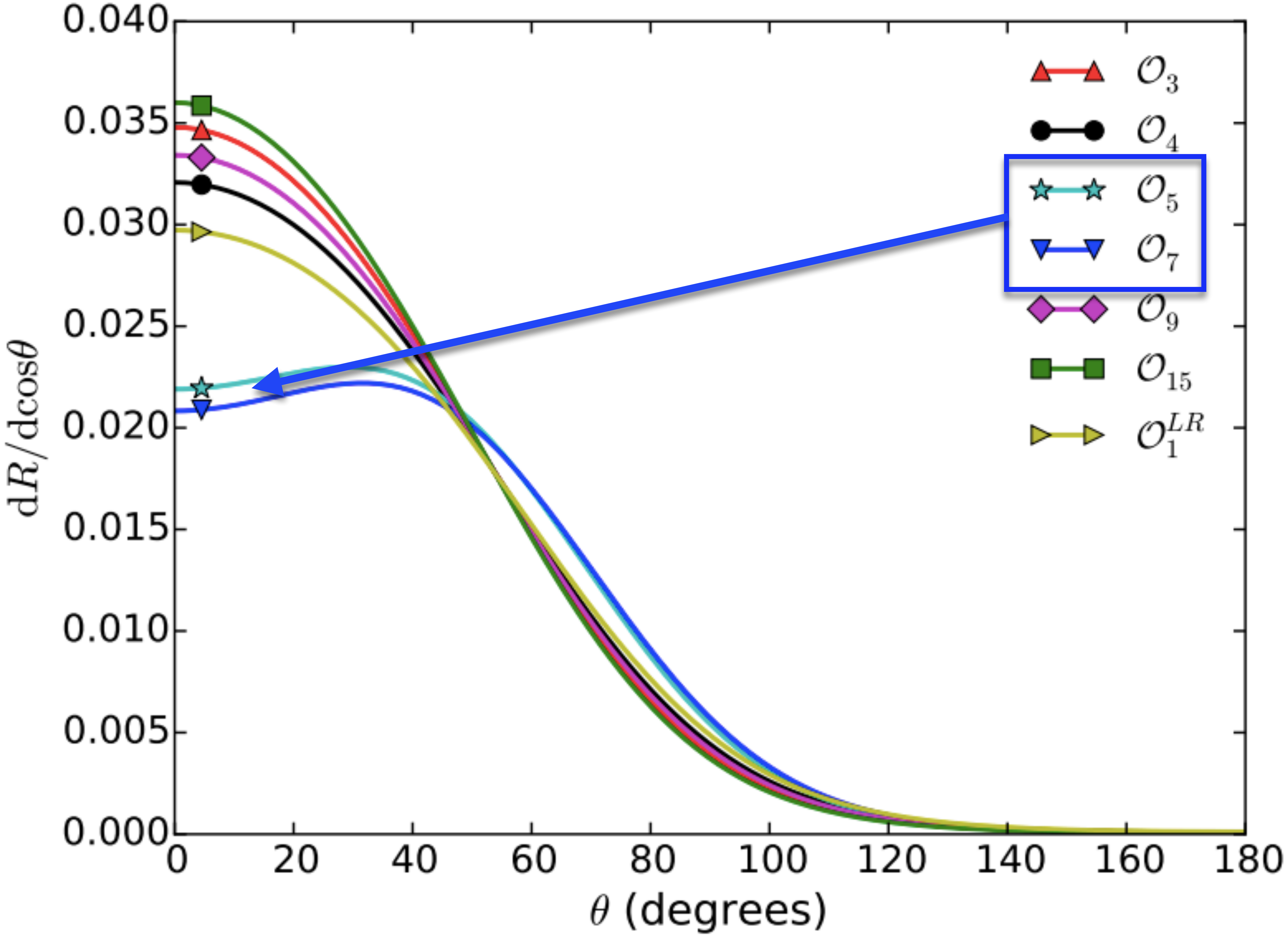
Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP

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**

DNA detector?

New Dark Matter Detectors using DNA or RNA for Nanometer Tracking

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

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

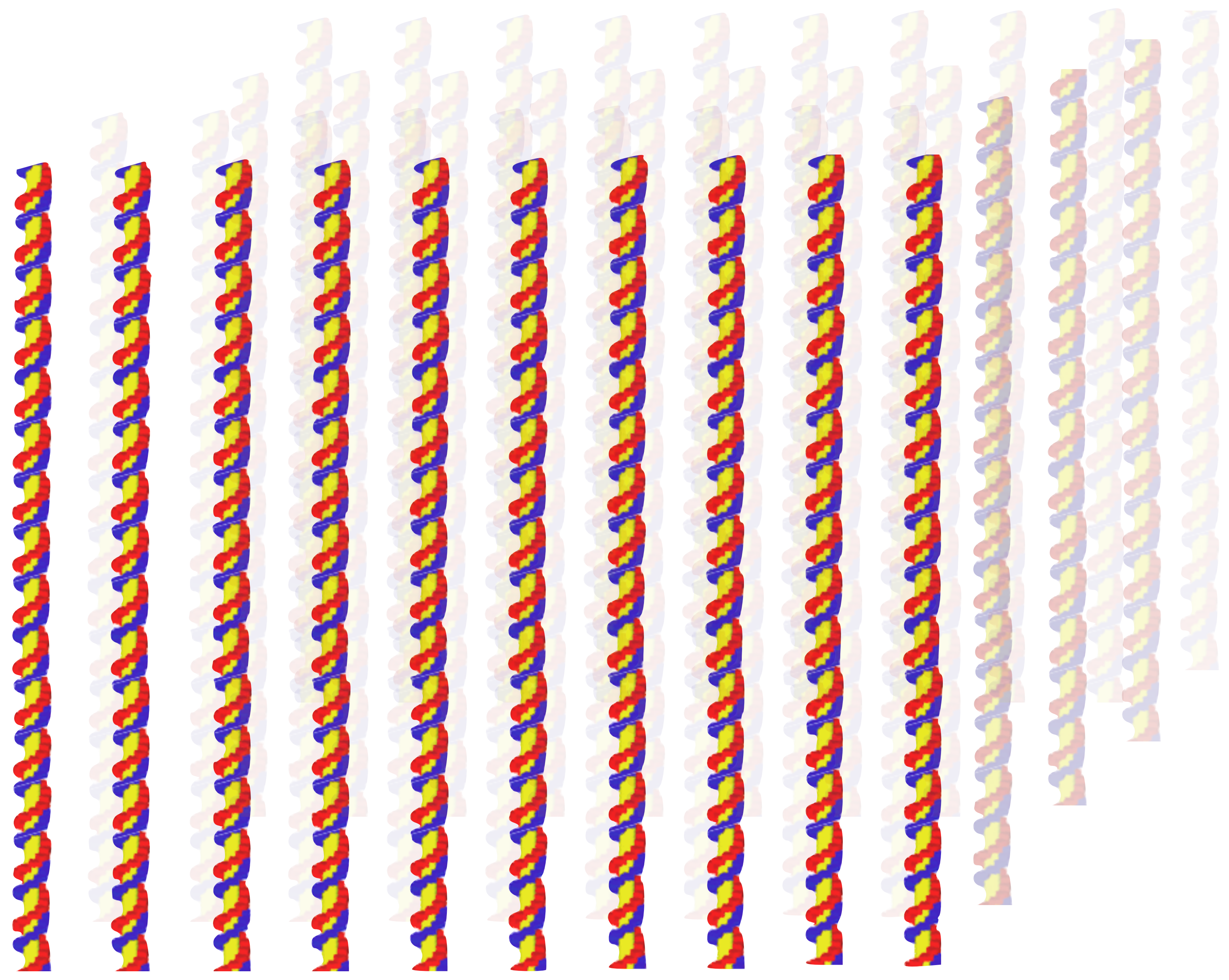
[2] *Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109*

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

1206.6809

DNA-based particle detector?

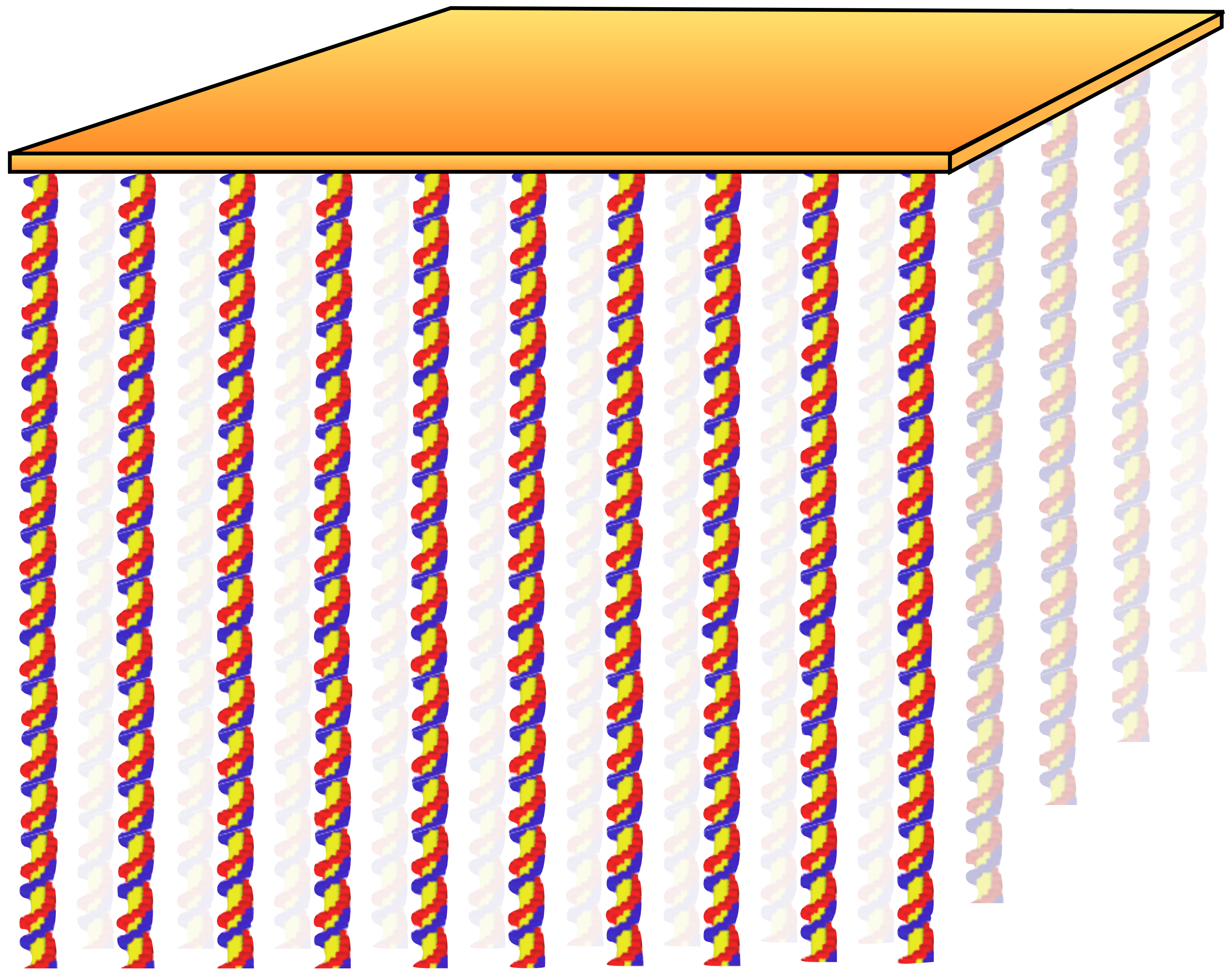
Step 1: acquire some double or single-stranded nucleic acids, each with a known sequences of bases



DNA-based particle detector?

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

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

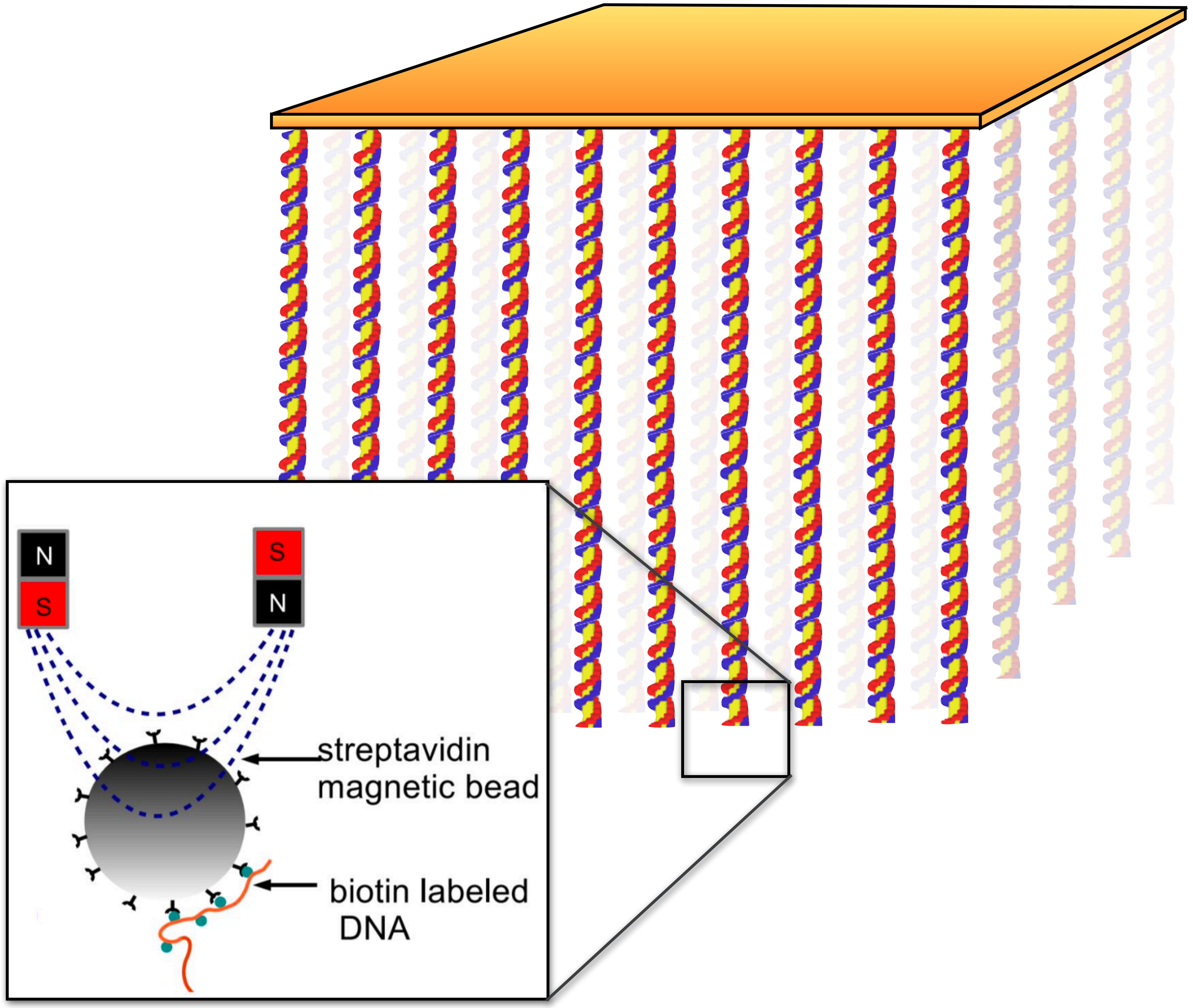


DNA-based particle detector?

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

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

Step 3: Attach a paramagnetic bead to each strand



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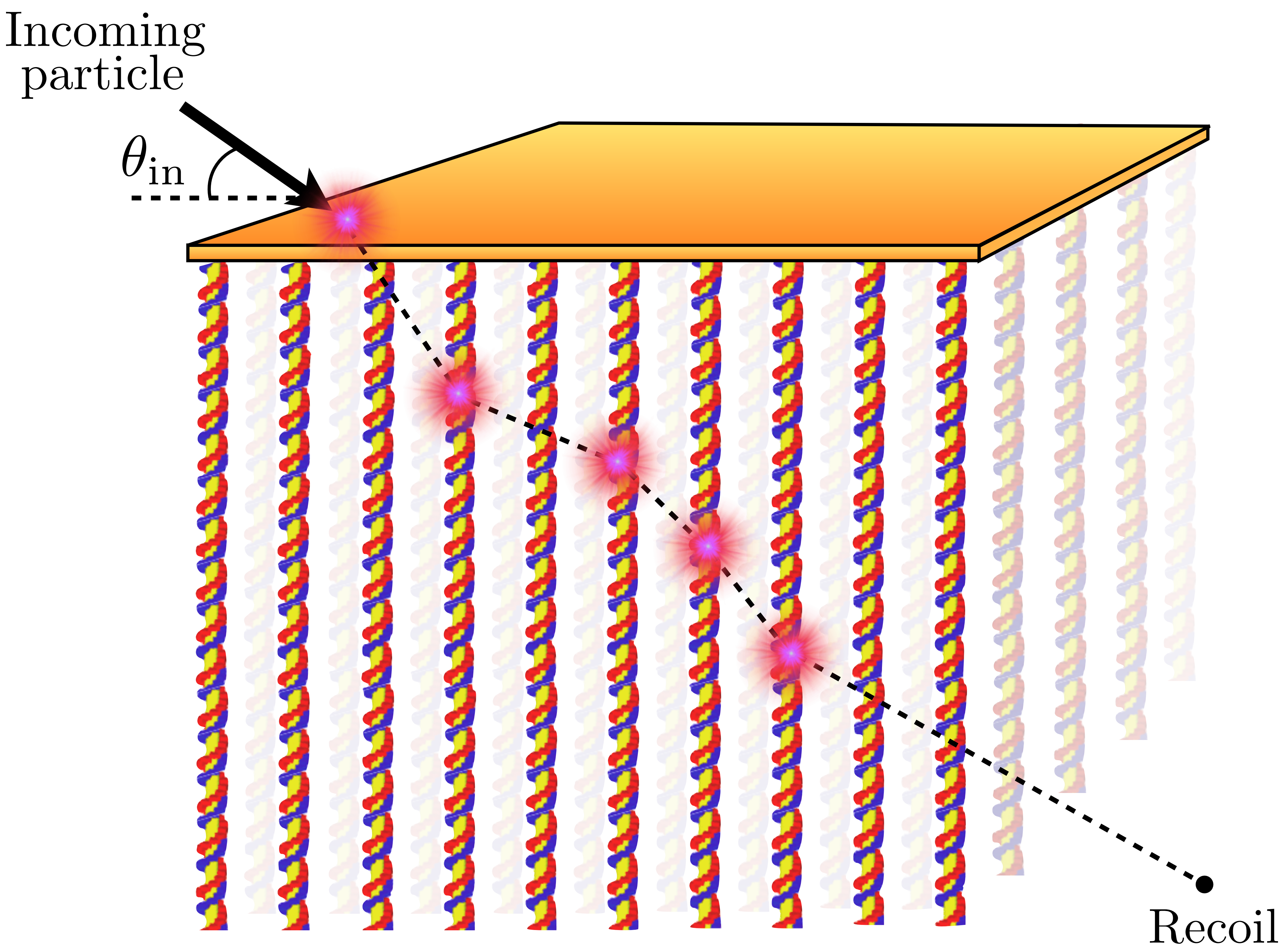
Step 4: Particles come in and break a sequence of bases



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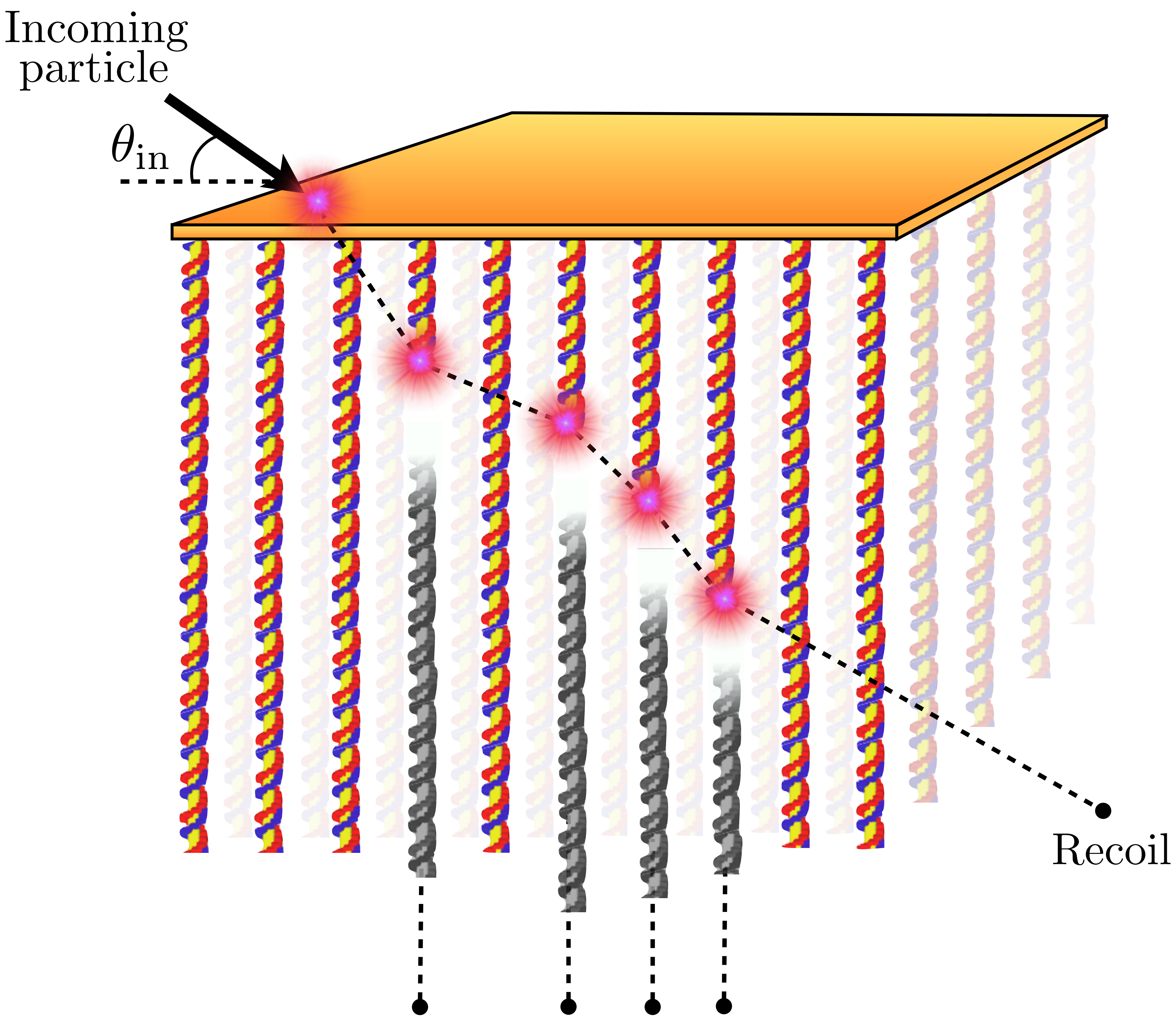
Step 5: Broken strand segments fall down



DNA-based particle detector?

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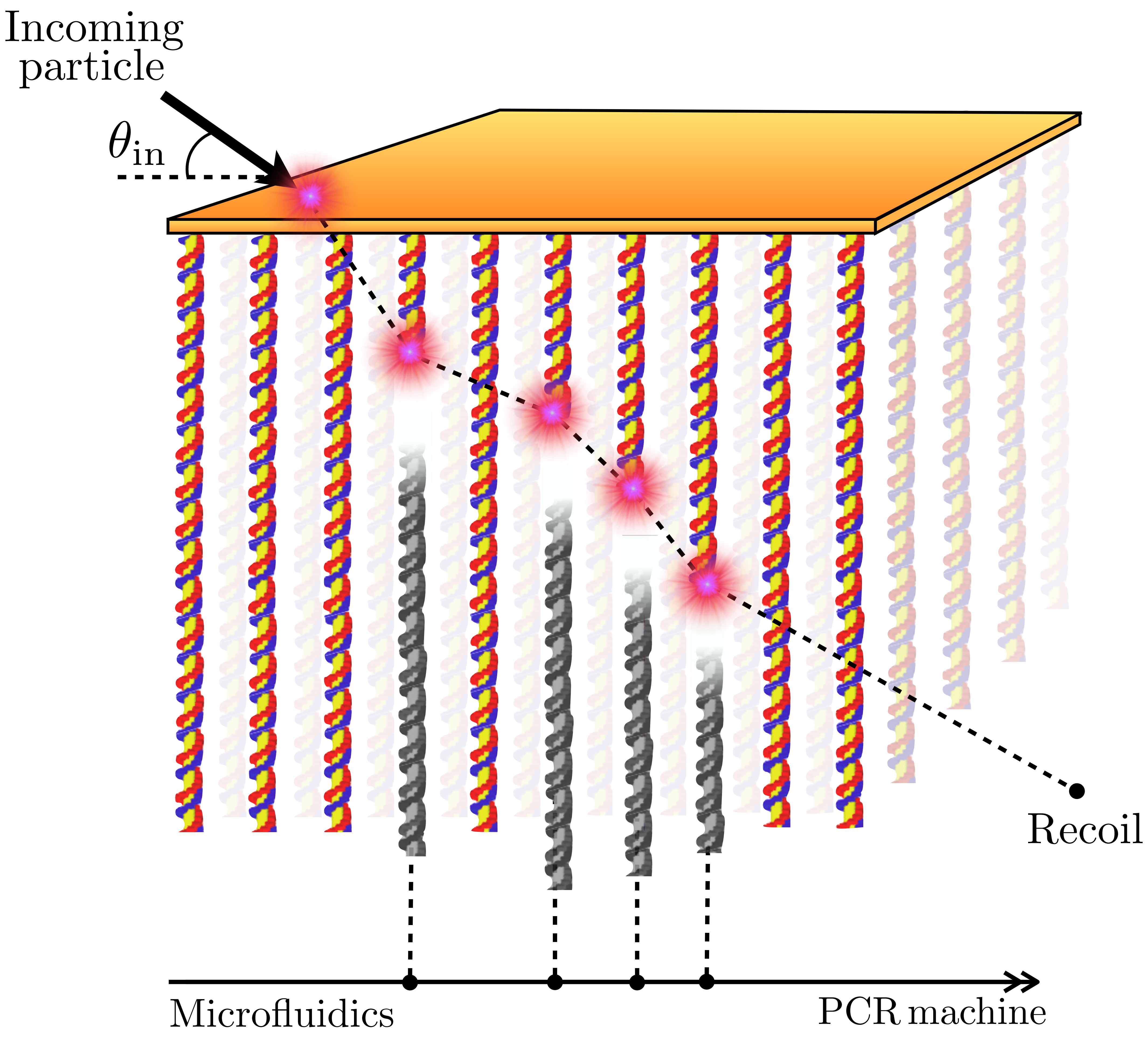
Step 3: Attach a paramagnetic bead to each strand

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

Step 5: Broken strand segments fall down

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

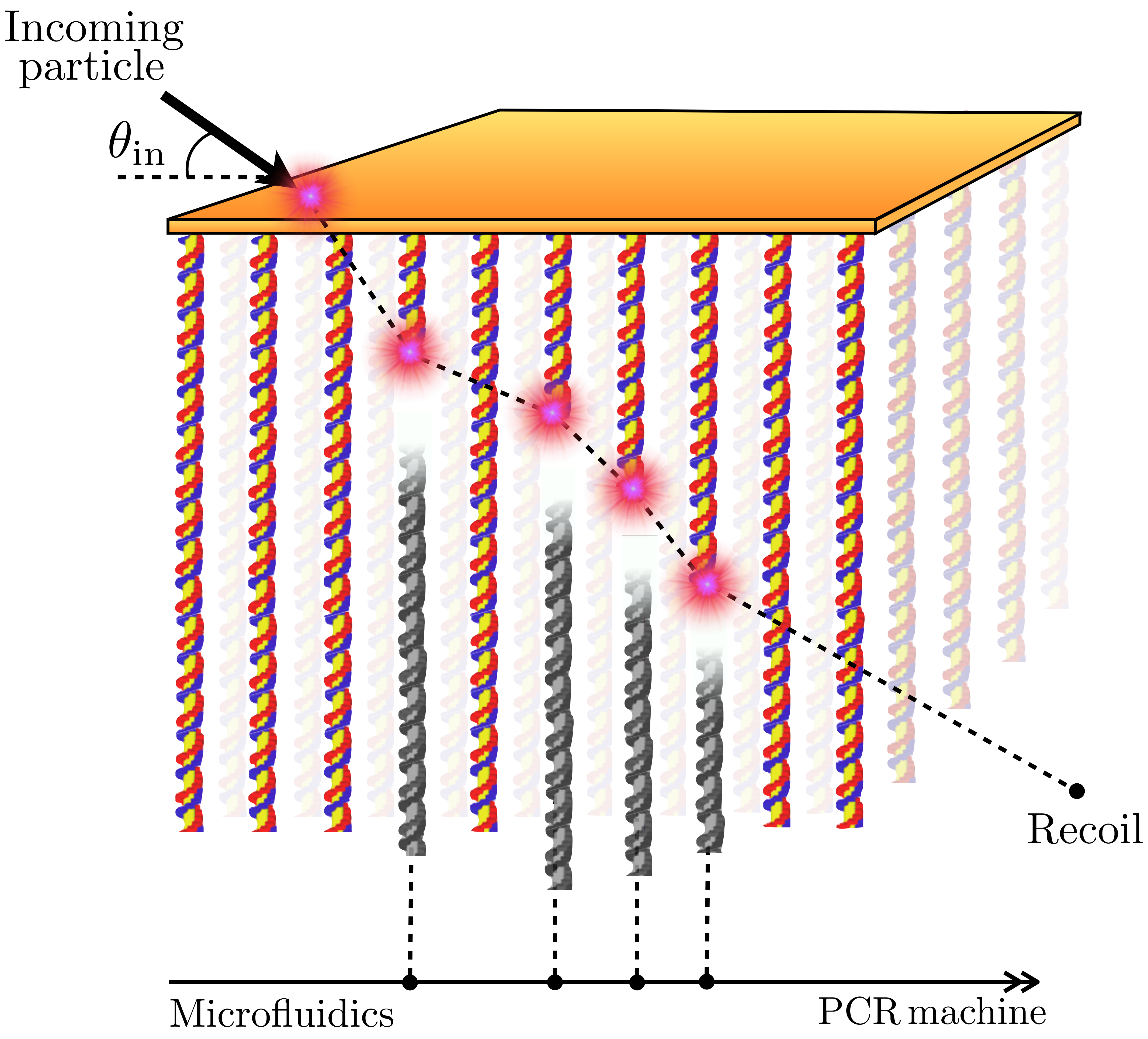


DNA-based particle detector?

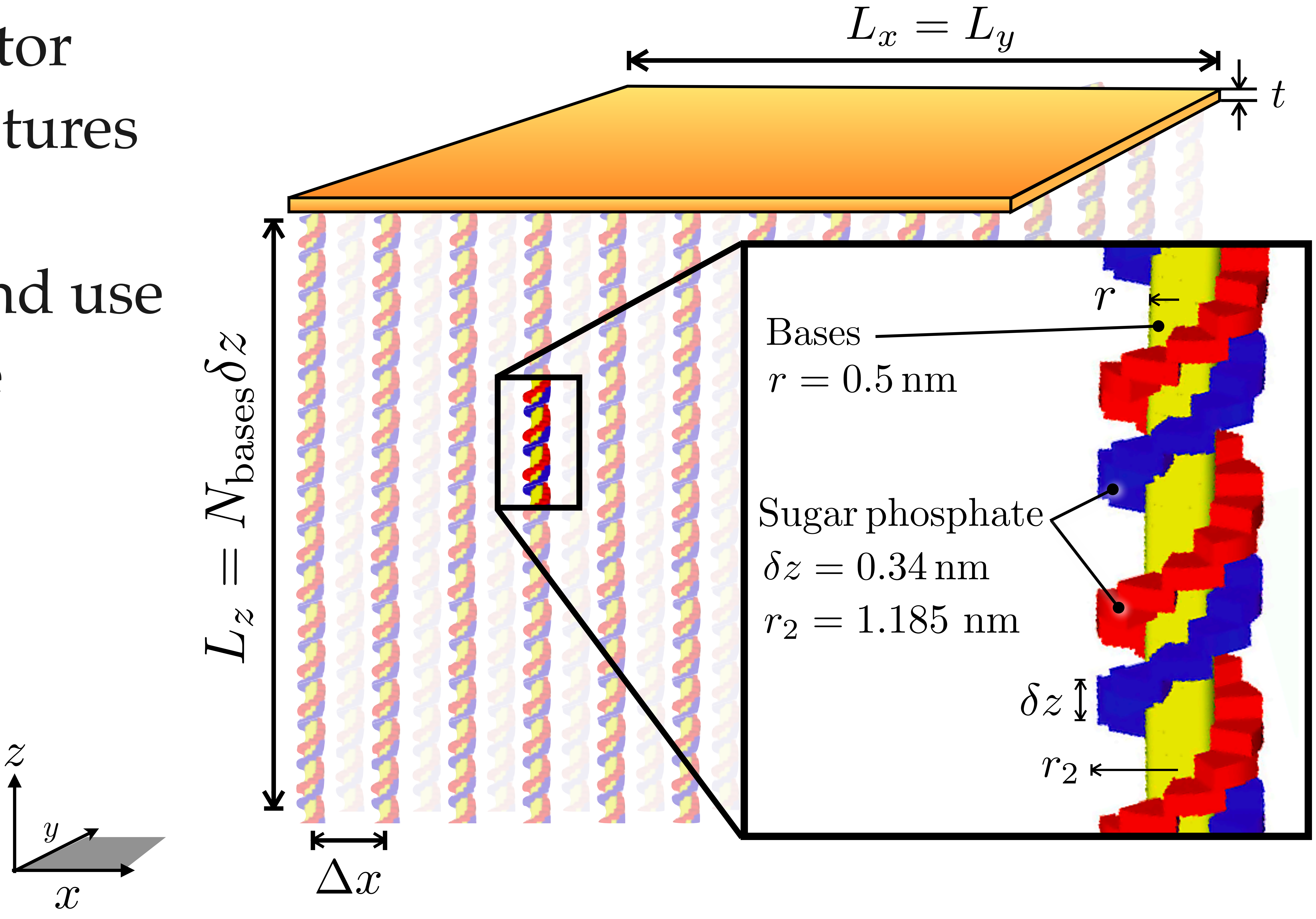
How crazy is it?

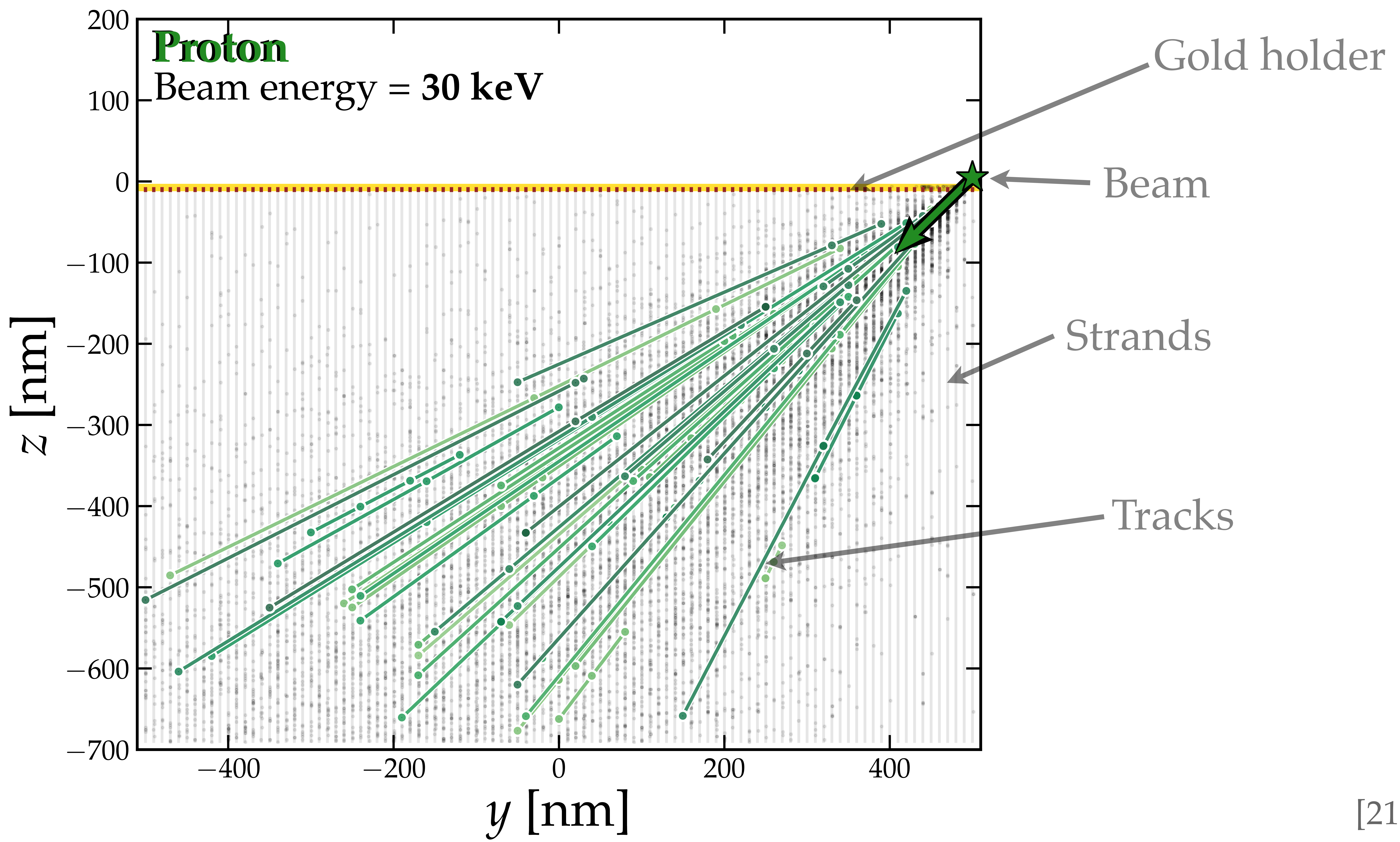
Putting aside the obvious experimental challenge, there is a clear advantage in the context of directional detection

→ No diffusion and no nanoscale interrogation required

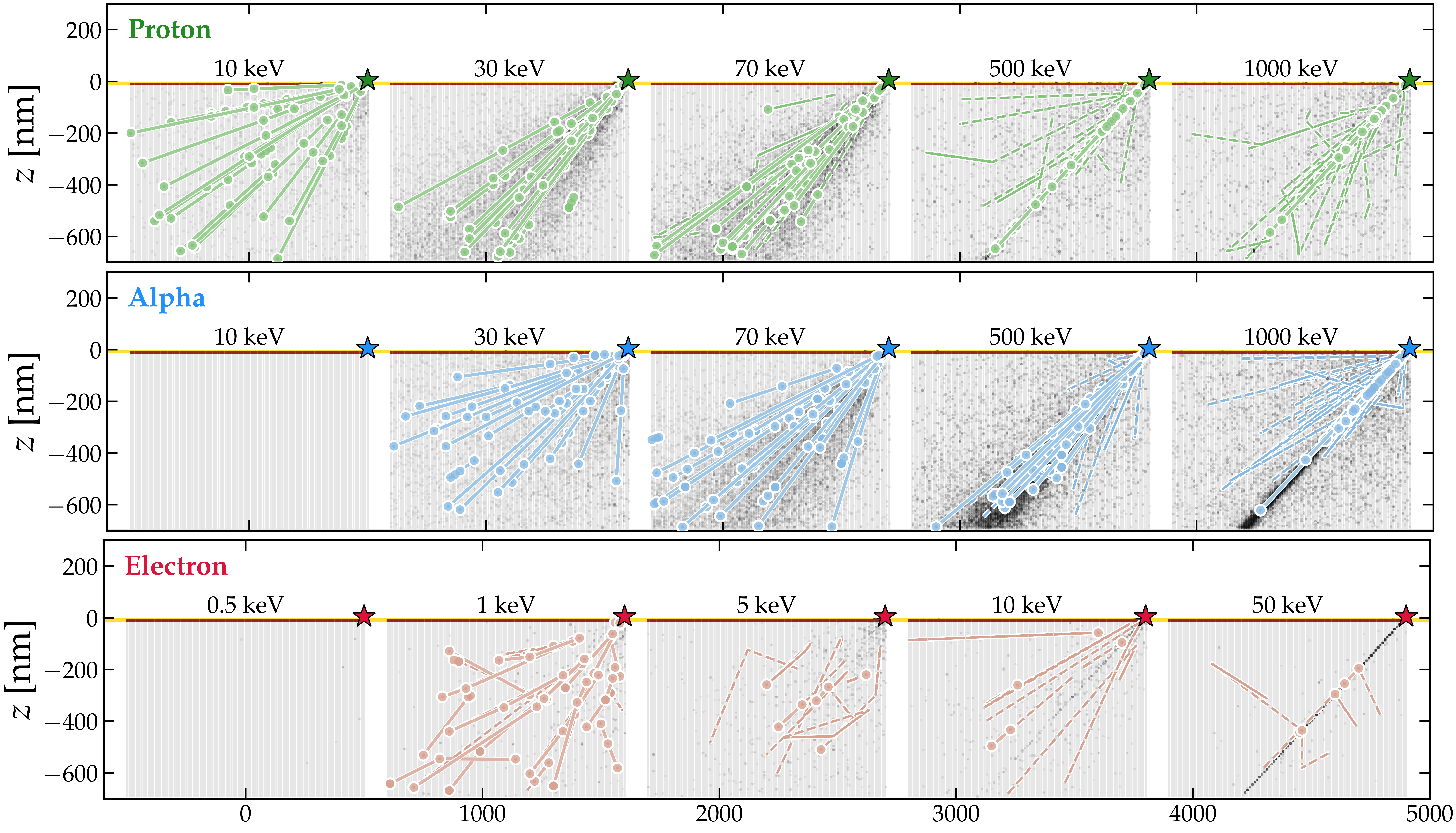


Idea: Lets make a crude model of the detector which roughly captures the geometry and material content and use Geant4 to simulate particle tracks

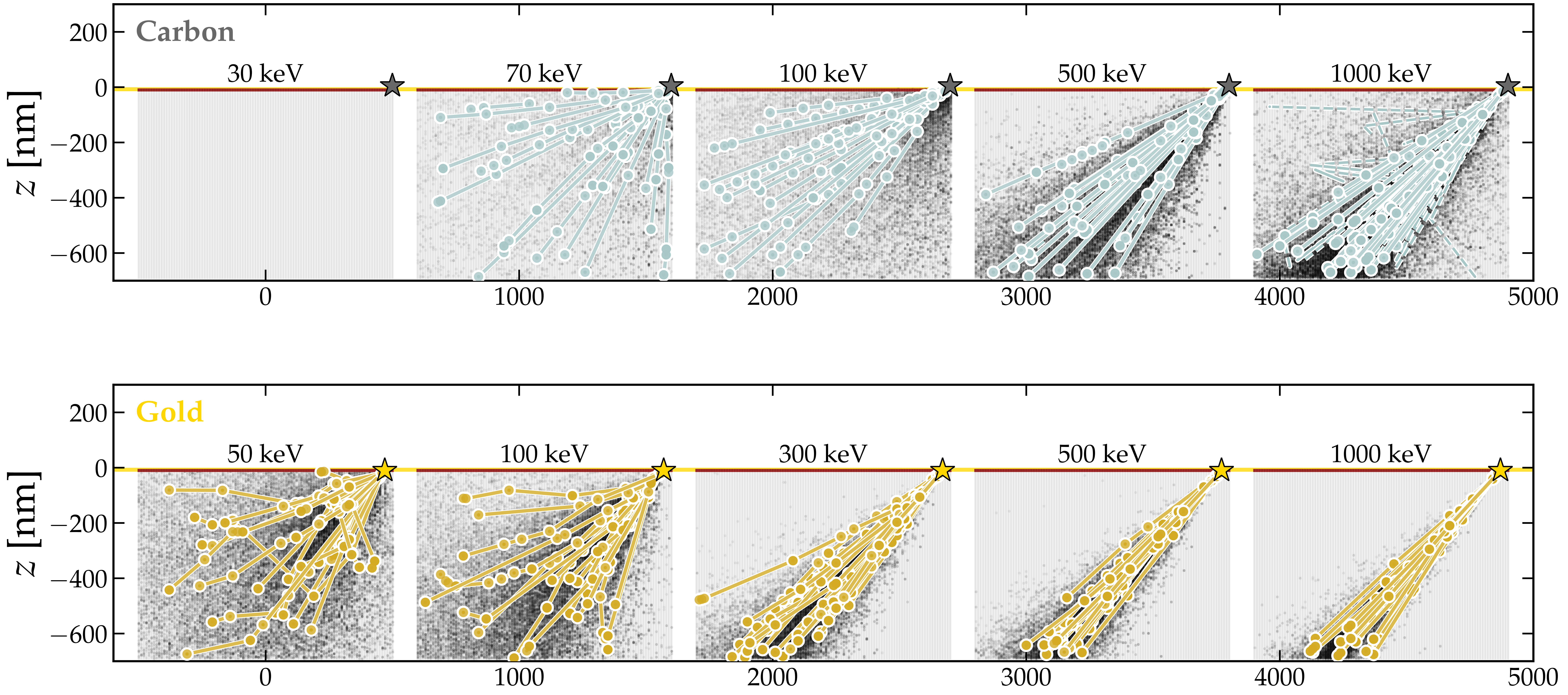



Proton
Beam energy = 30 keV
Gold holder
Beam
Strands
Tracks
z [nm]
y [nm]
200
100
0
−100
−200
−300
−400
−500
−600
−700
−400
−200
0
200
400

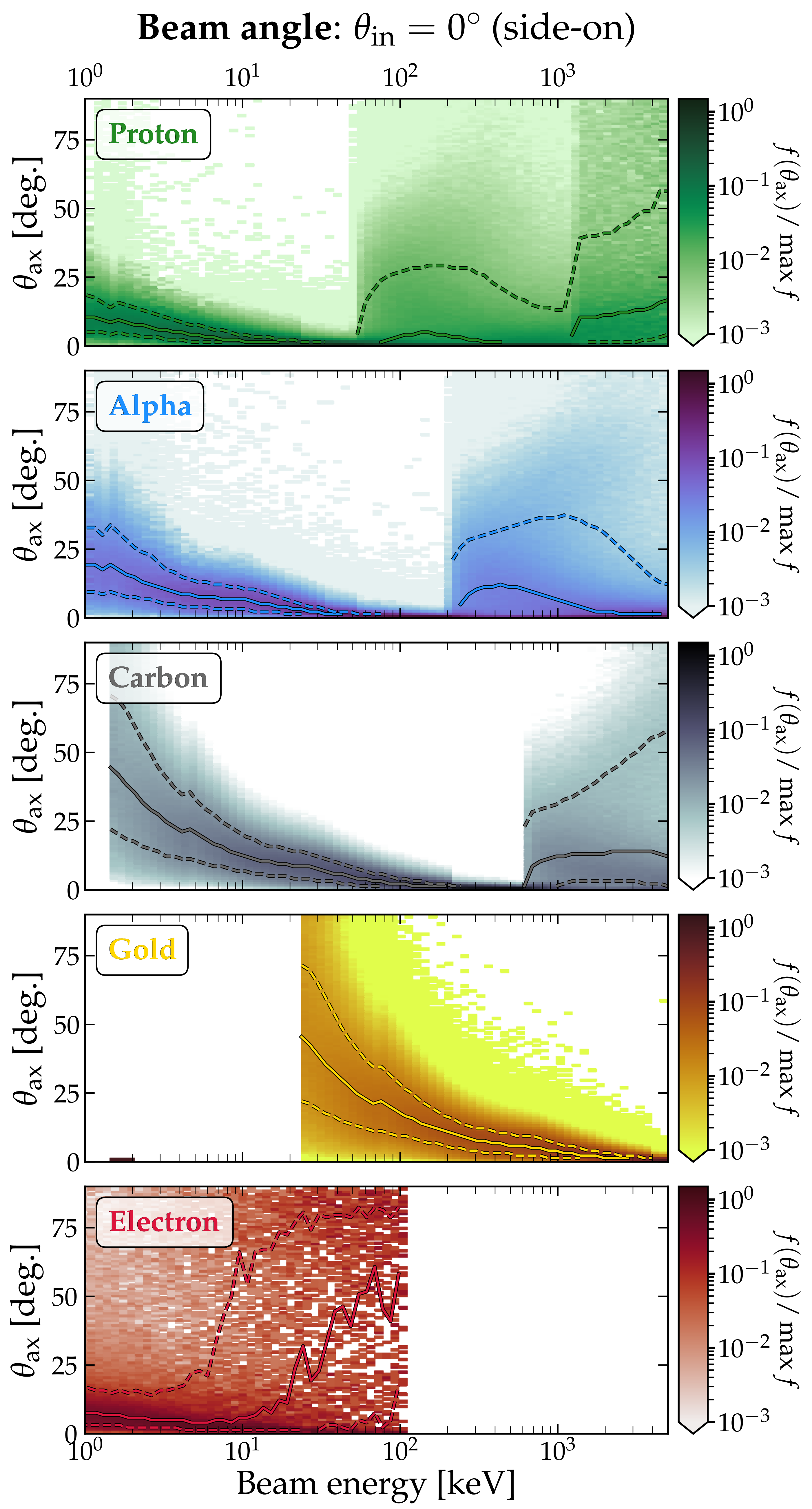
[2105.11949]


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

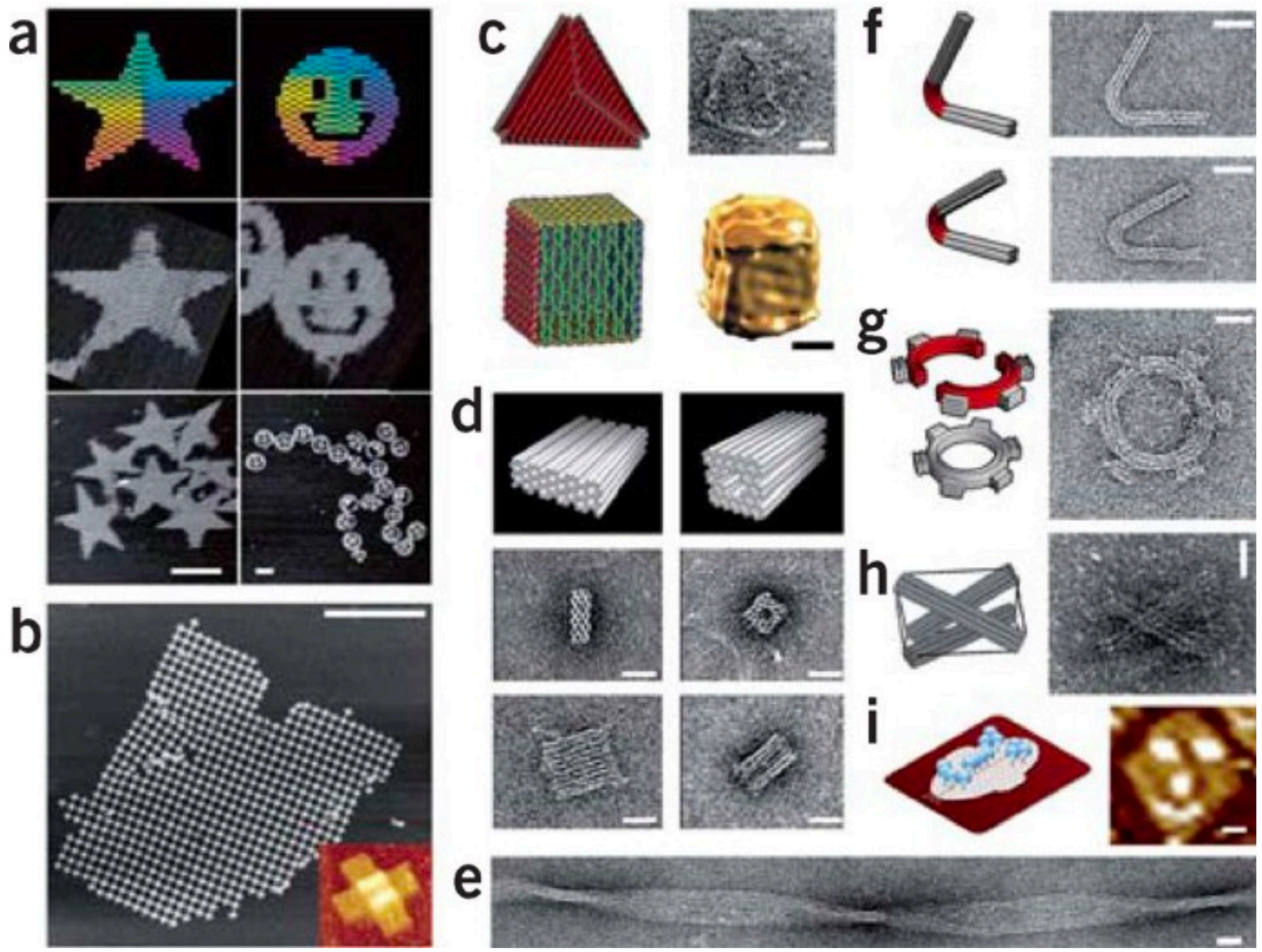
- **Detector construction →** DNA-origamists can make practically anything

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

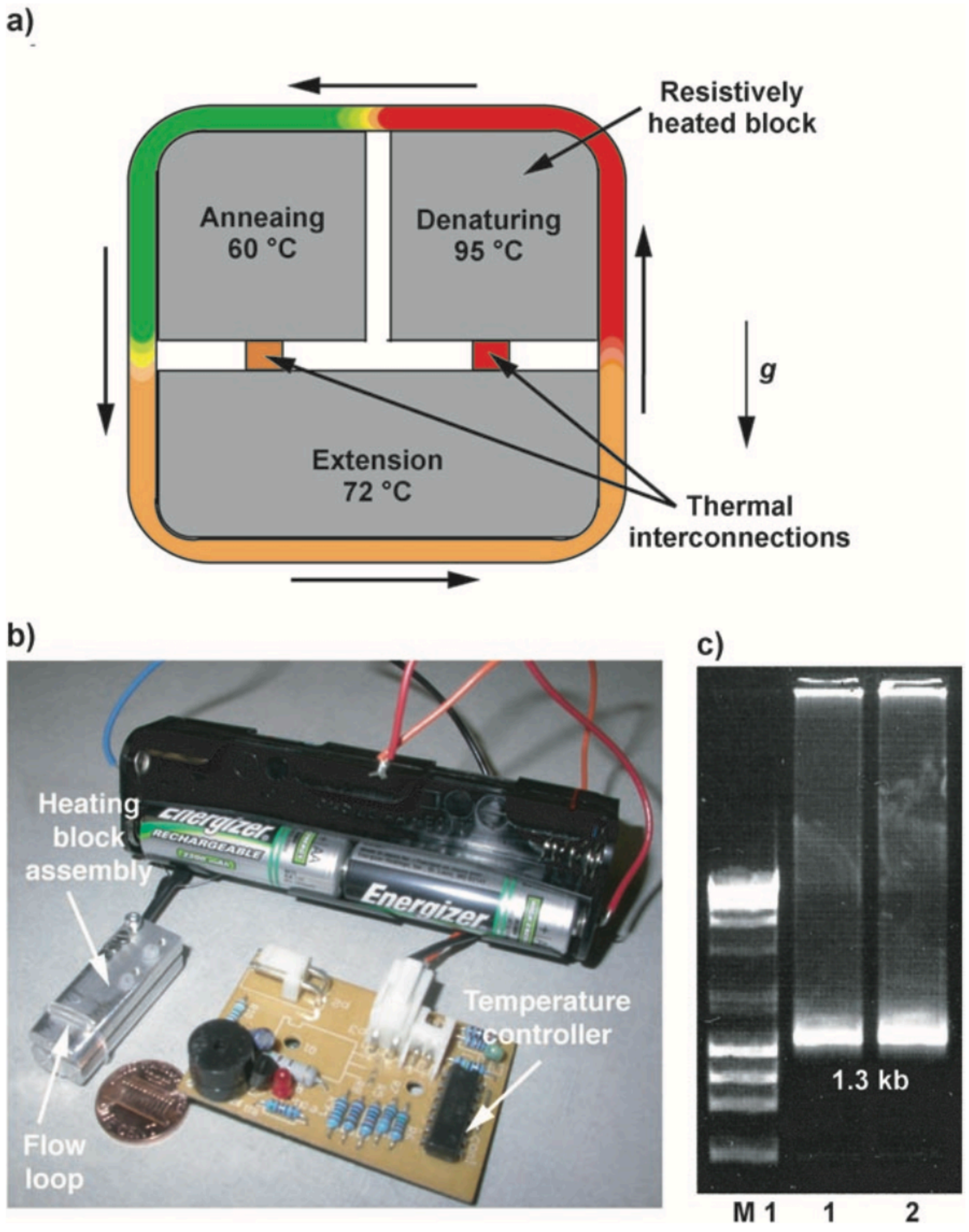


Experimental side

- **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

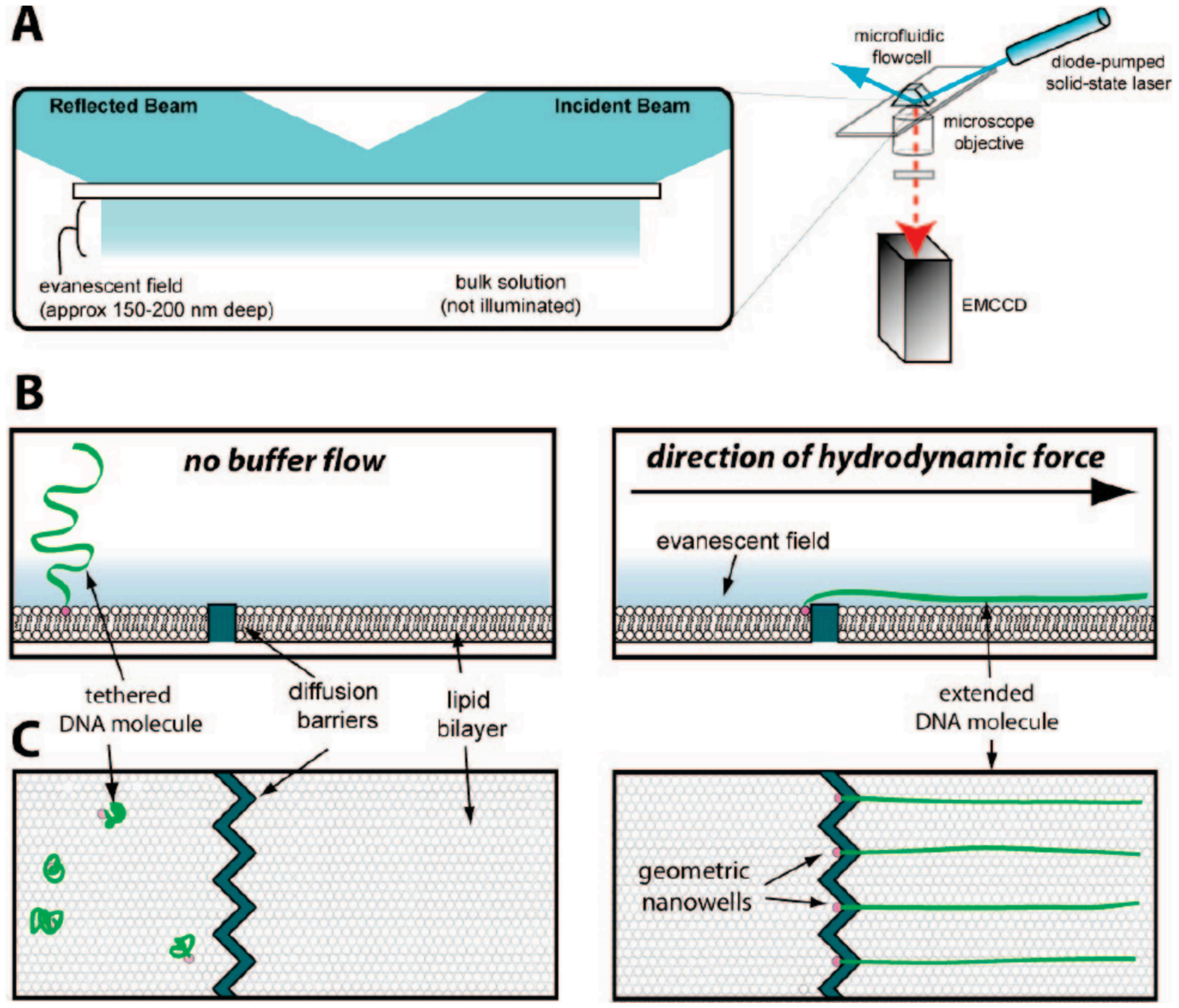
- **Detector construction →** DNA-origamists can make practically anything
- **PCR machines →** cheap, commercially available, portable, and fast.
- **DNA-substrate attachment →** standard protocols (looking at this in the lab right now!)

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

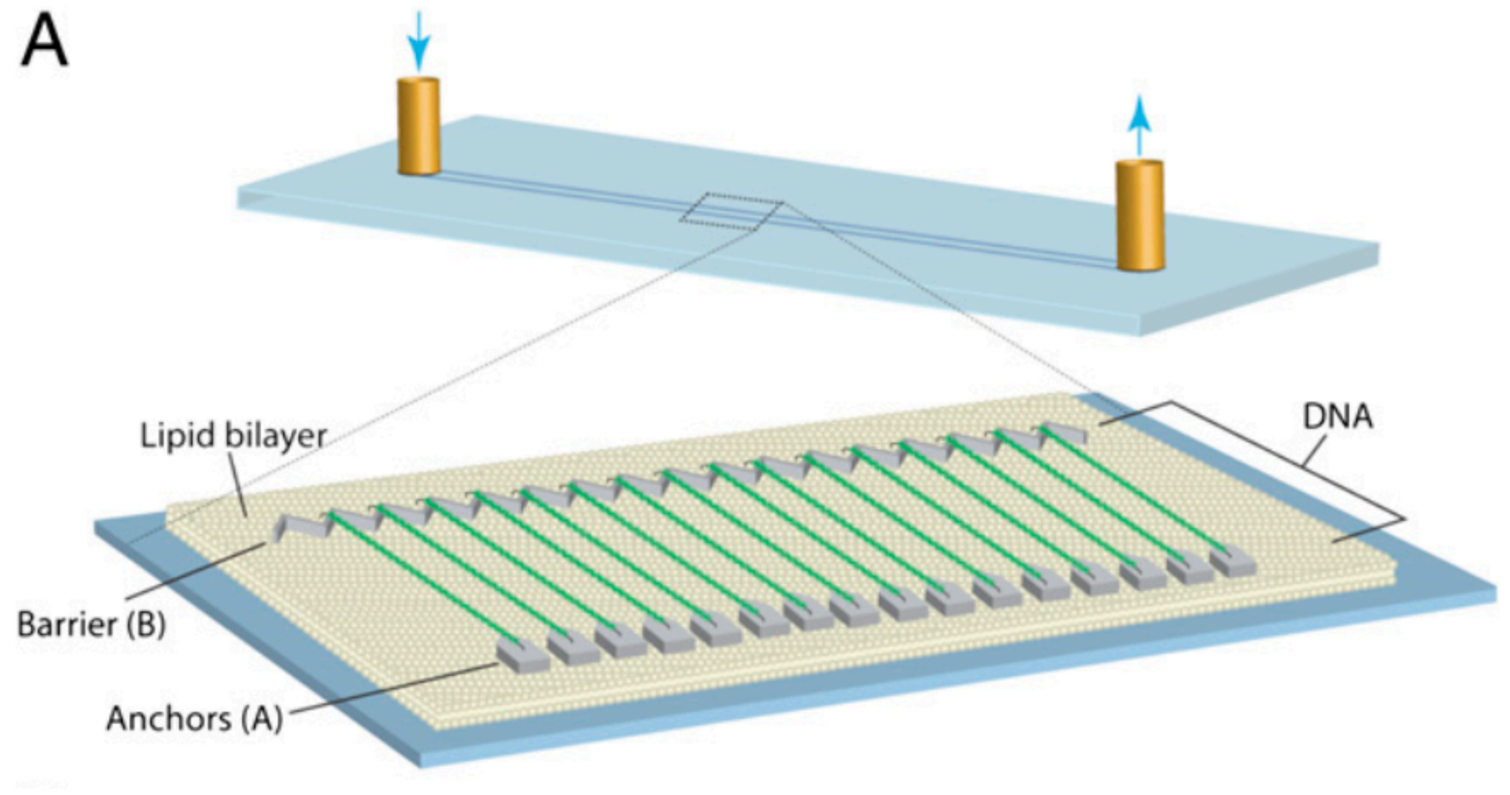
S. Kasra Tabatabaei[1], Boya Wang[2,8], Nagendra Bala Murali Athreya[3,8], Behnam Enghiad[4], Alvaro Gonzalo Hernandez[5], Christopher J. Fields[6], Jean-Pierre Leburton[3], David Soloveichik[2], Huimin Zhao[1,4,7] ✉ & Olgica Milenkovic[3] ✉

+

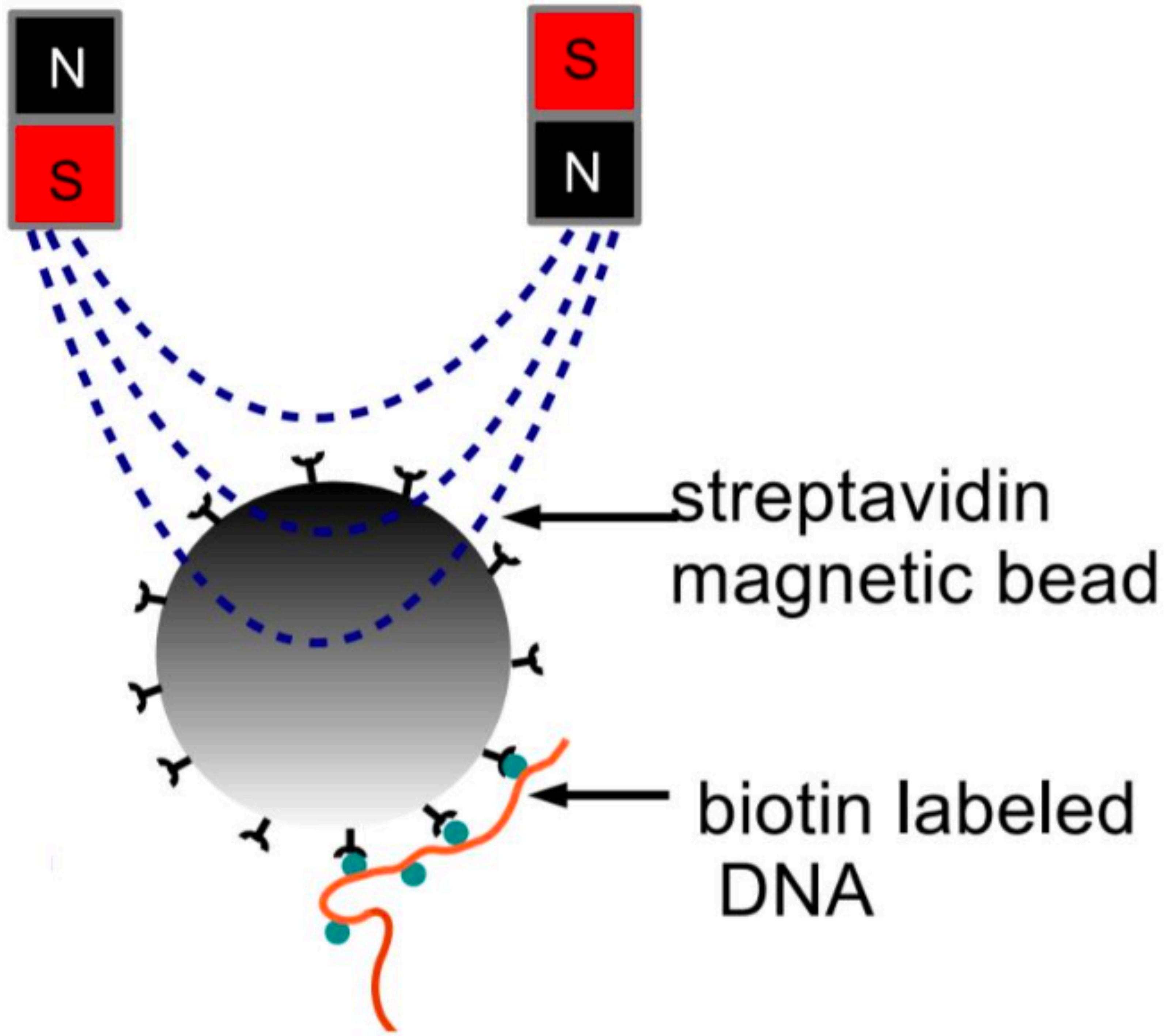
Single-molecule imaging of DNA curtains reveals mechanisms of KOPS sequence targeting by the DNA translocase FtsK

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



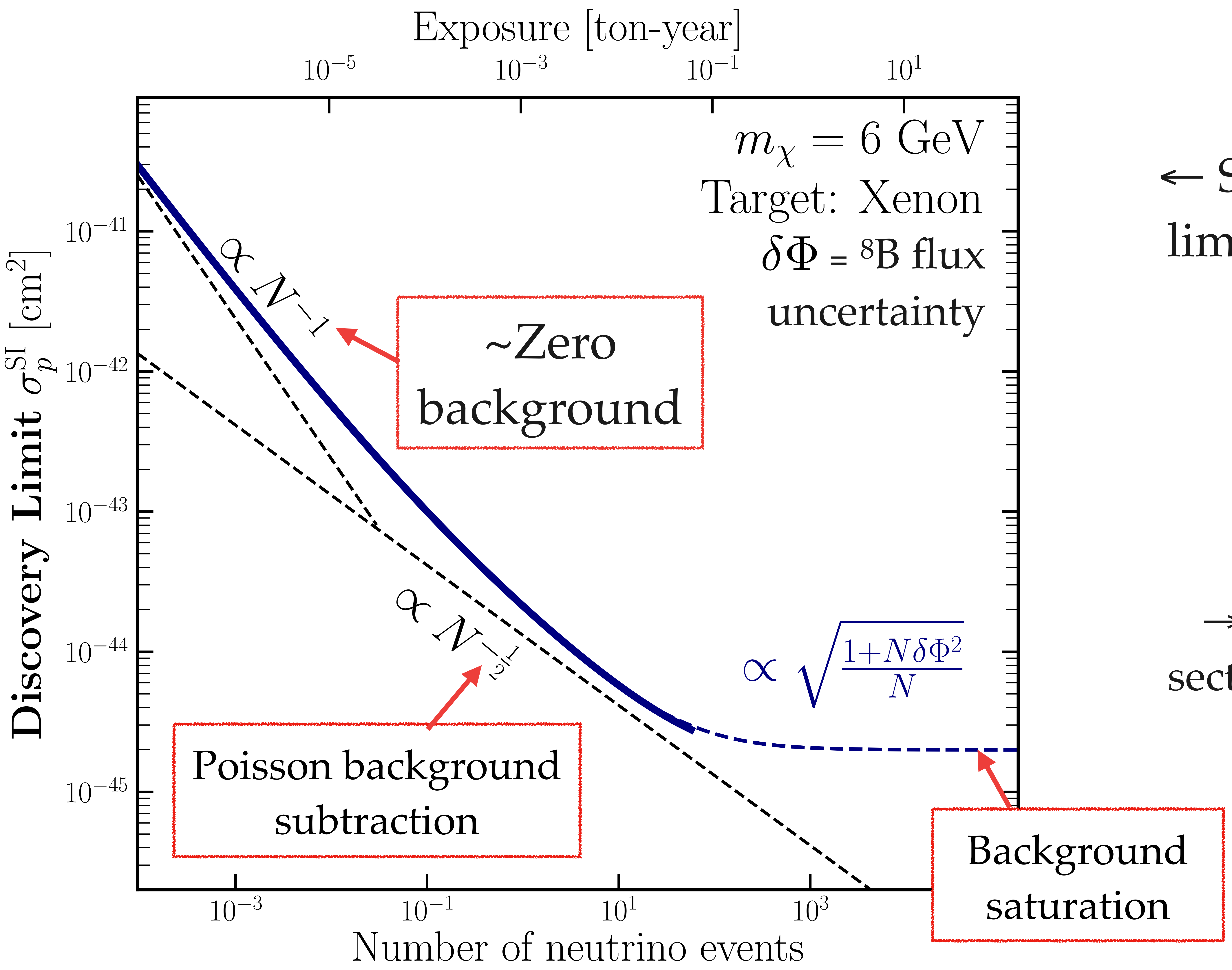
Attachment of paramagnetic beads to the DNA strands



[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



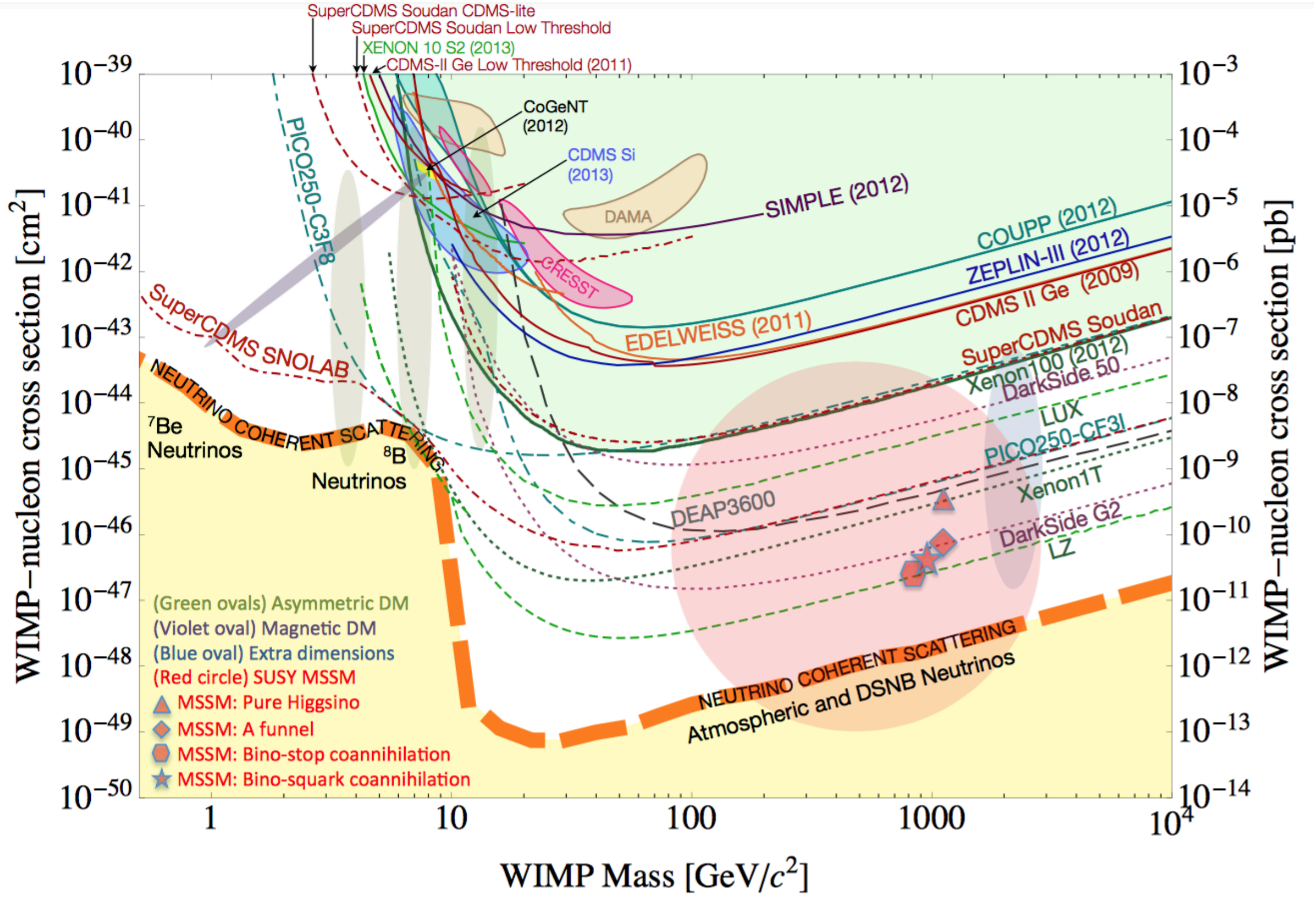
The neutrino "floor"

← Scaling of a DM discovery limit for increasing exposure

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

The neutrino "floor"

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



Interpolation of two discovery limits

(3σ discovery in 90% of expts)

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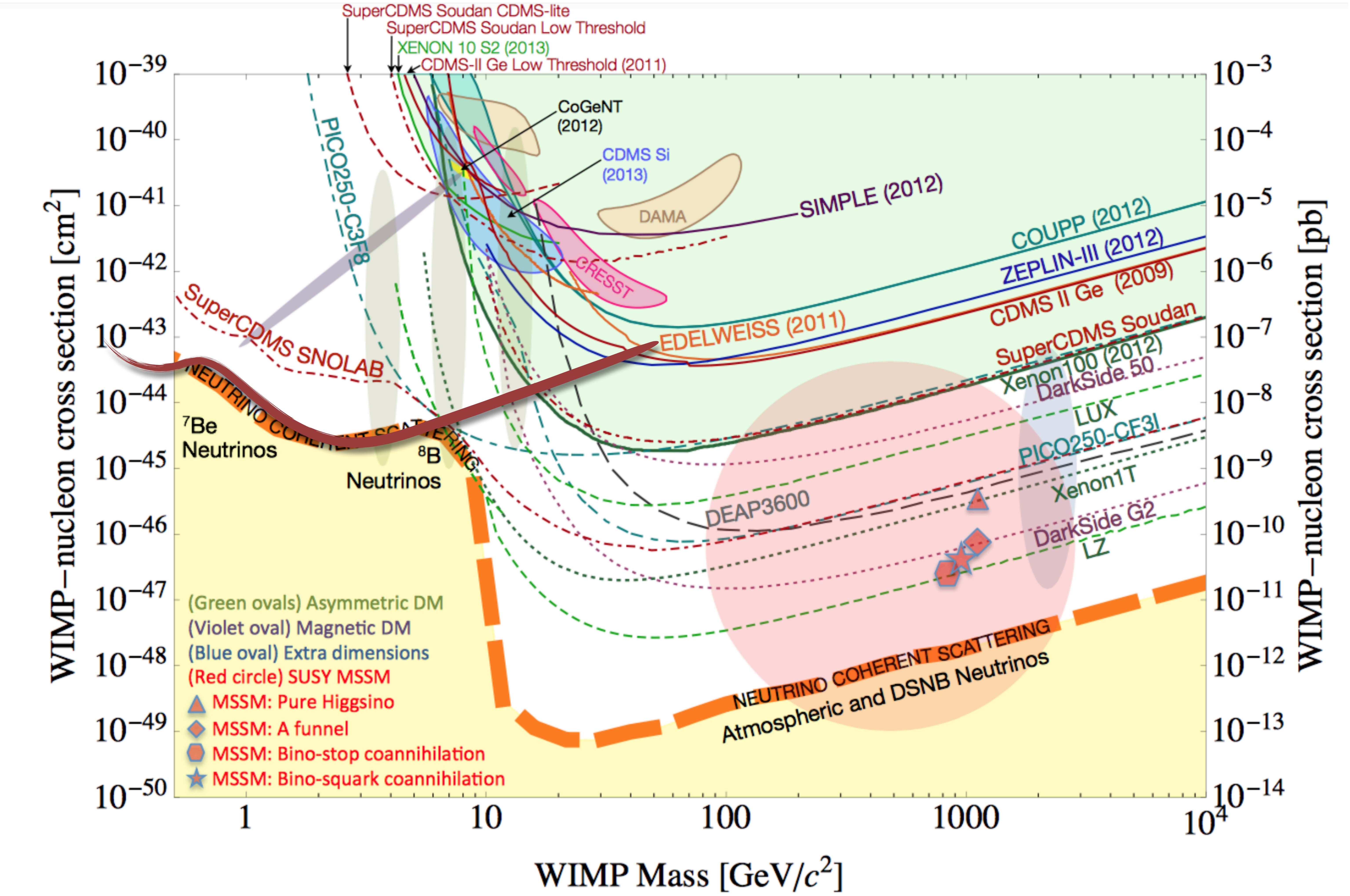


Interpolation of two discovery limits

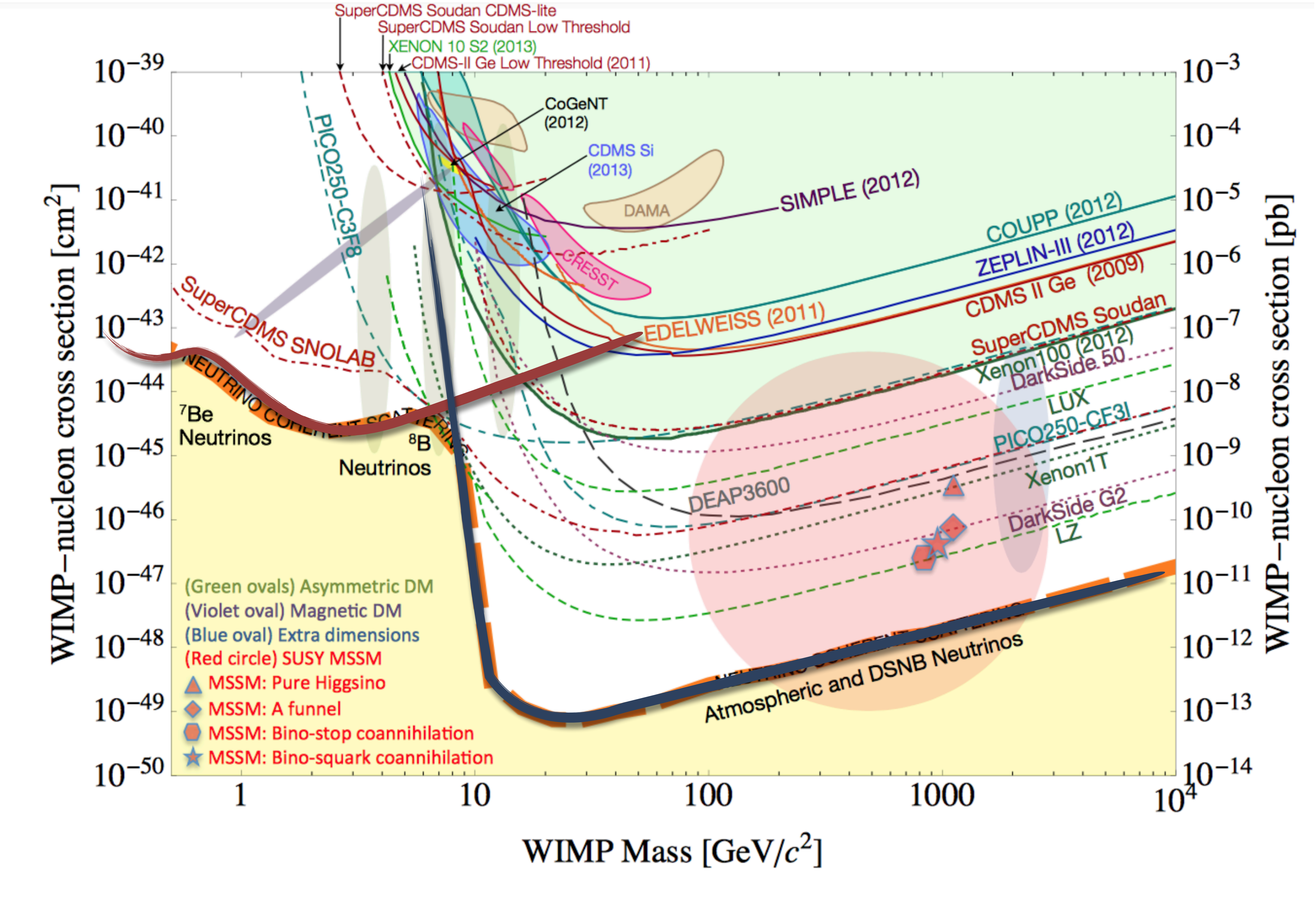
(3σ discovery in 90% of expts)

→ low mass / low threshold

(500 solar neutrino events)

The neutrino "floor"

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



Interpolation of two discovery limits

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→ low mass / low threshold (500 solar neutrino events)

→ high mass / high threshold (500 atmospheric events)

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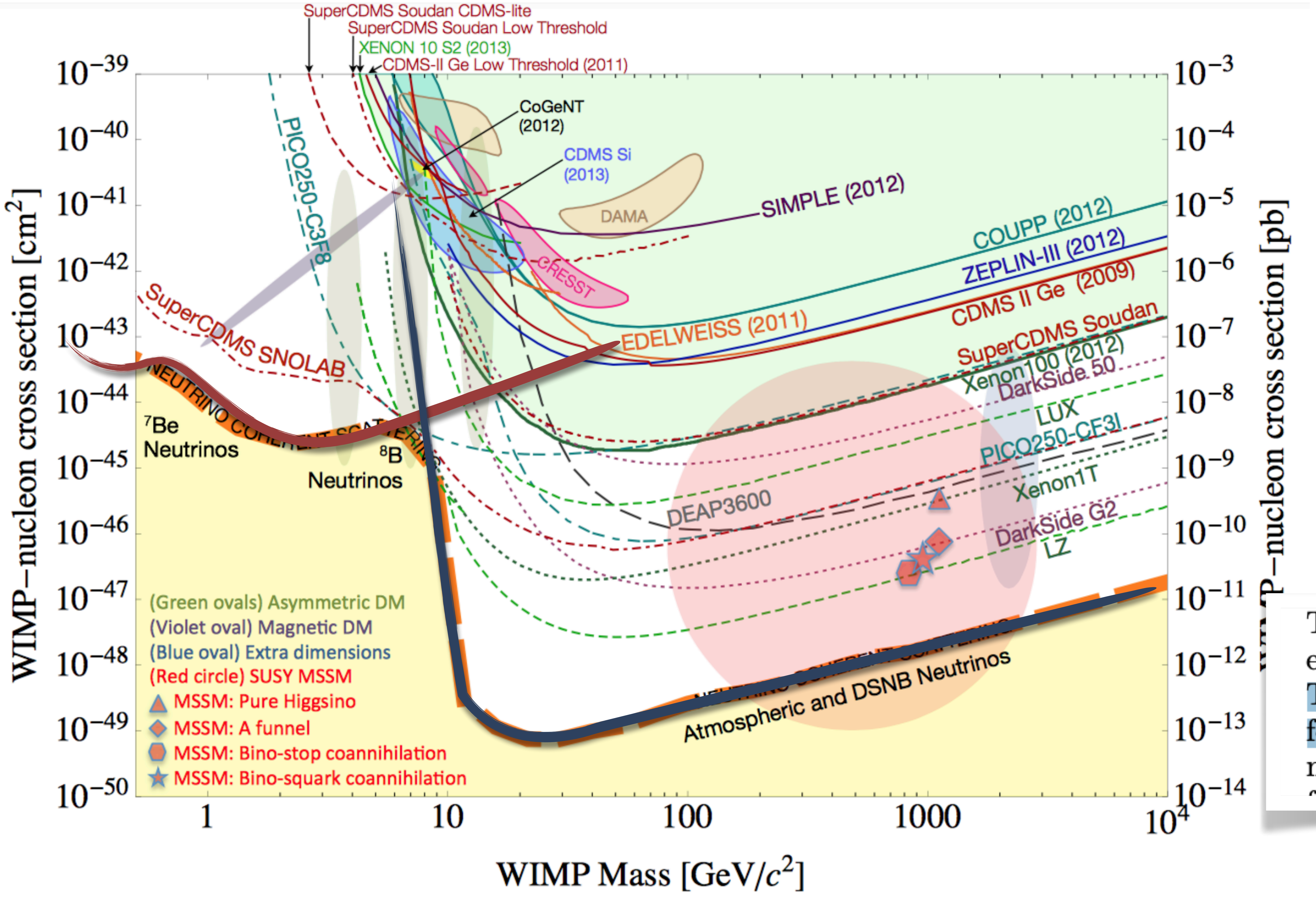


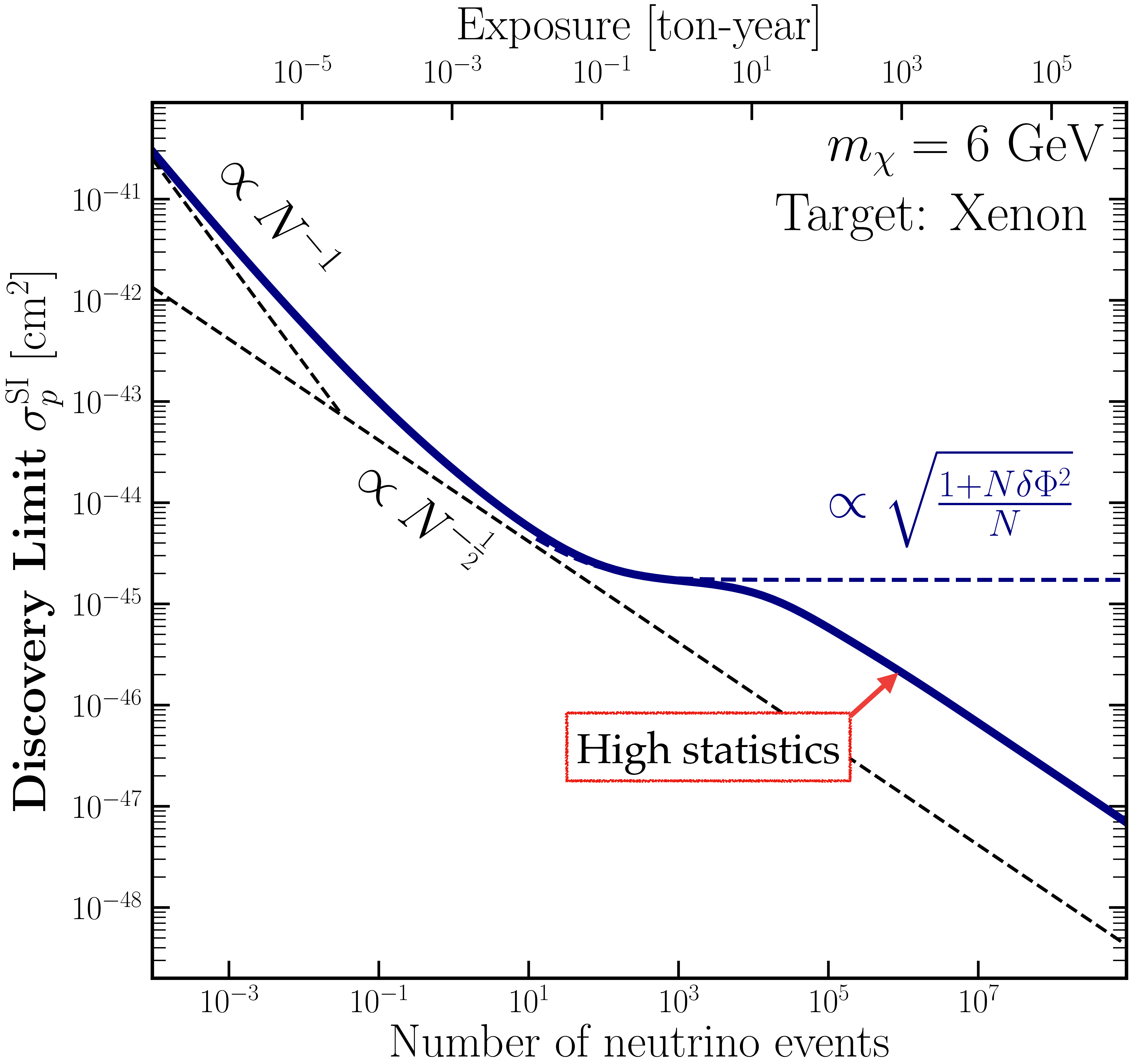
Interpolation of two discovery limits

(3σ discovery in 90% of expts)

→ low mass / low threshold (500 solar neutrino events)

→ high mass / high threshold (500 atmospheric events)

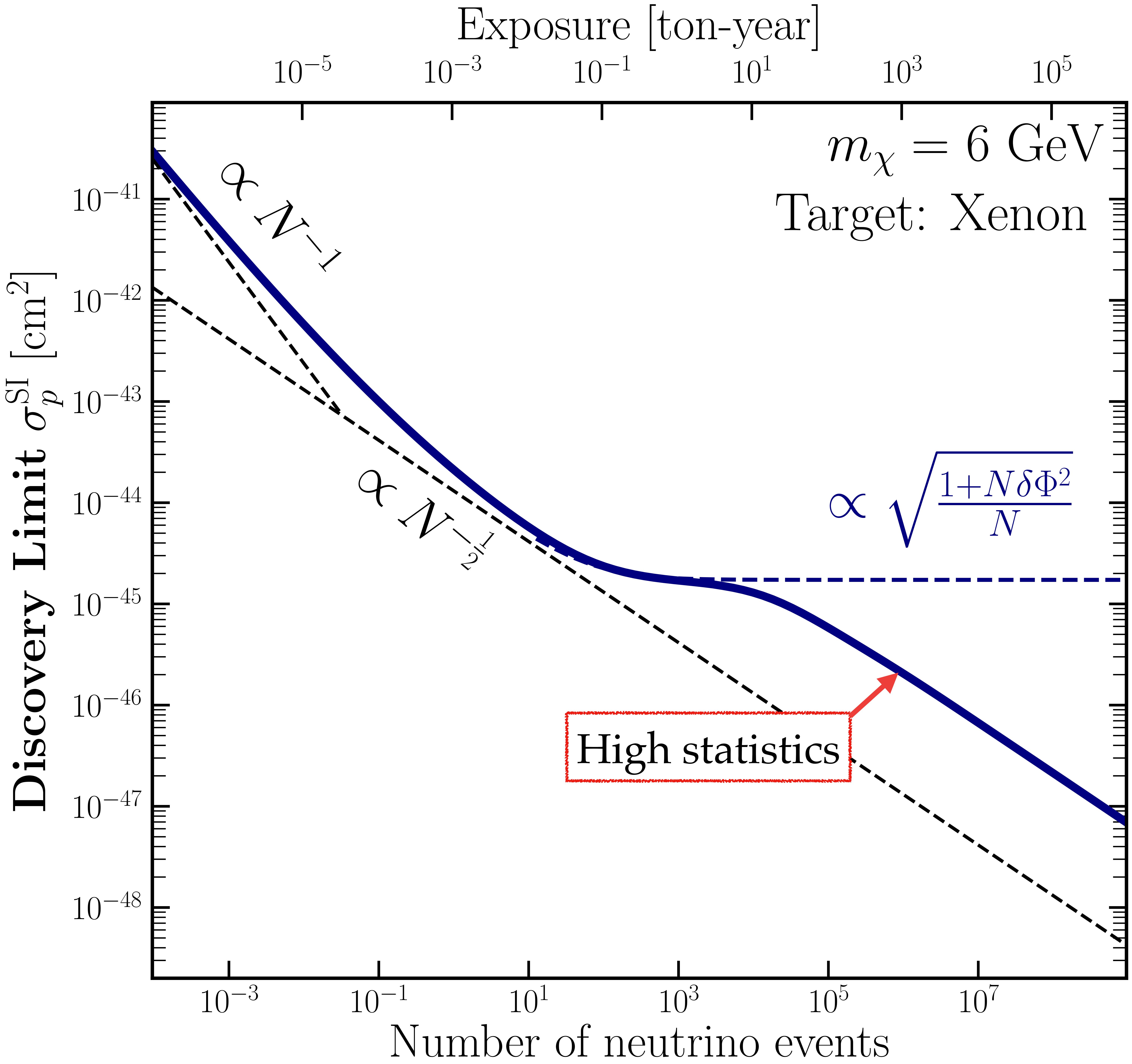
To ensure we are well into the systematics limited regime, exposures were increased to obtain 500 neutrino events. This line thus represents a hard lower discovery limit for dark matter experiments. Interestingly, we can denote three distinct features in the discovery limits coming



The neutrino "fog"

DM/CEvNS signals not **identical**

→ at high statistics, start to discriminate them with spectral information



The neutrino "fog"

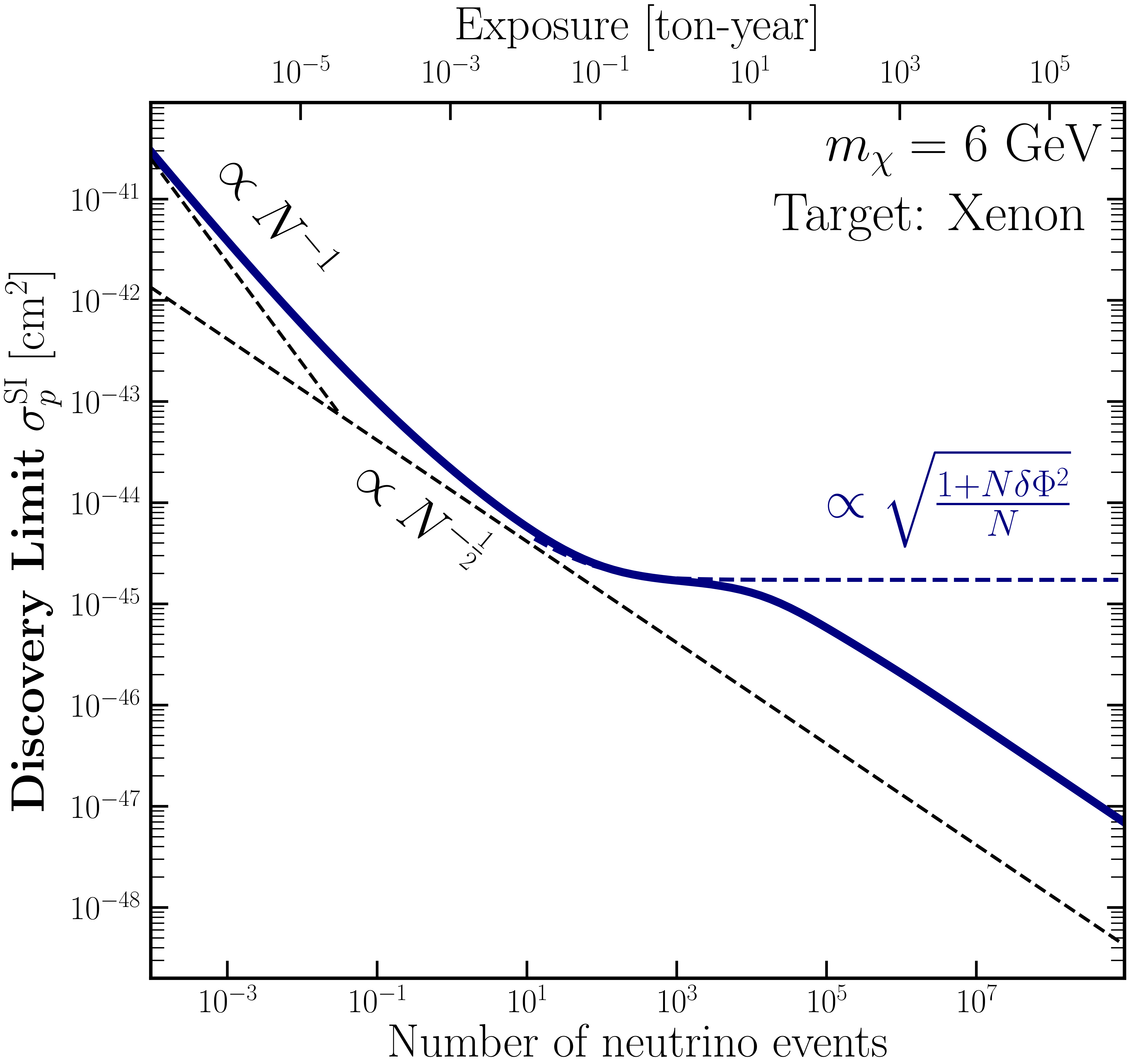
DM/CEvNS signals not **identical** → at high statistics, start to discriminate them with spectral information

→ Required exposures get very large, but there is no hard "floor"

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

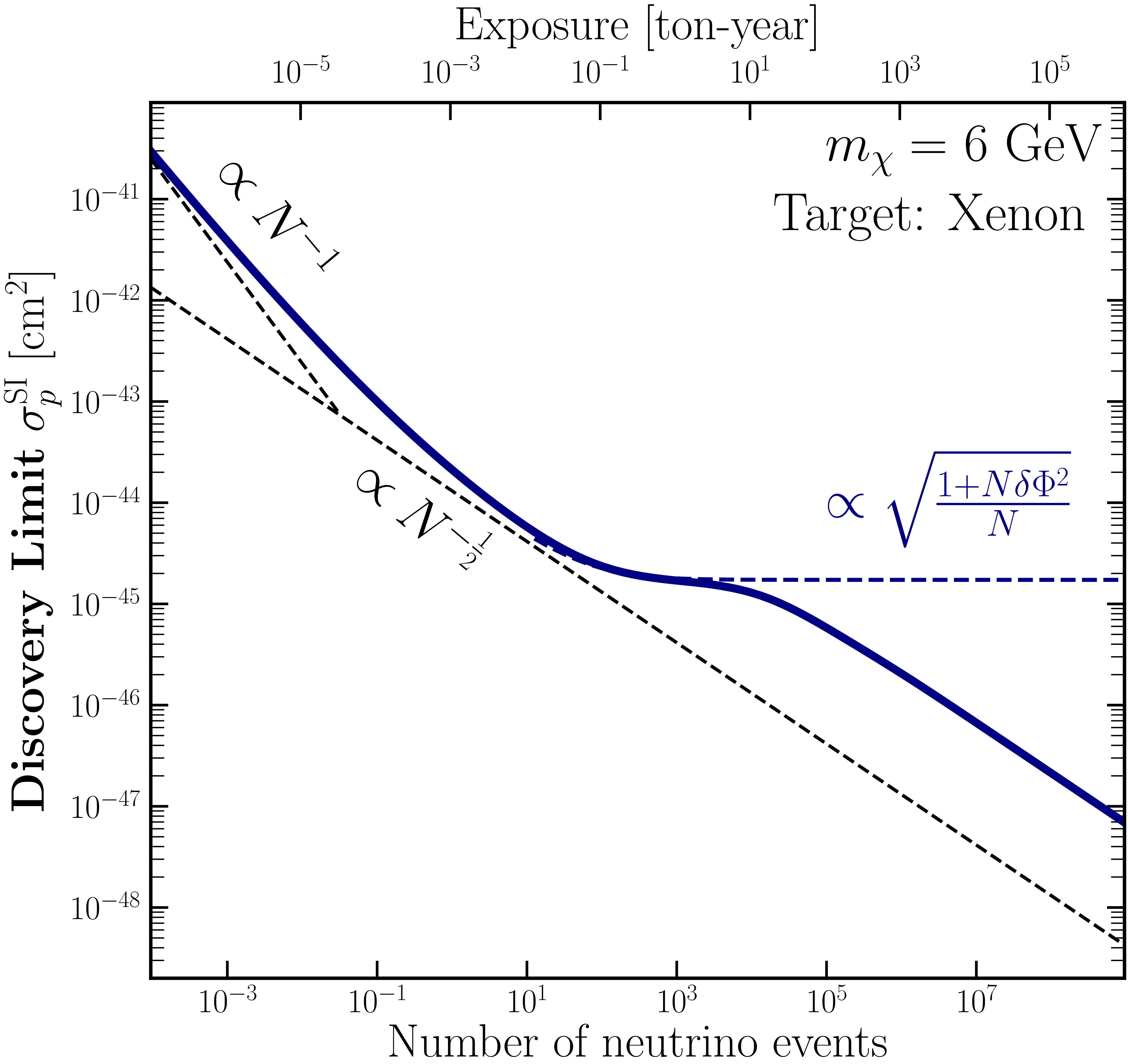
This should not be surprising, HEP experiments deal with backgrounds orders of magnitude larger than their signals all the time. We are in an era where DM experiments are no longer “background free”.

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



The neutrino fog

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



The neutrino fog

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

Define:

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

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

If we want to..

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

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

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

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

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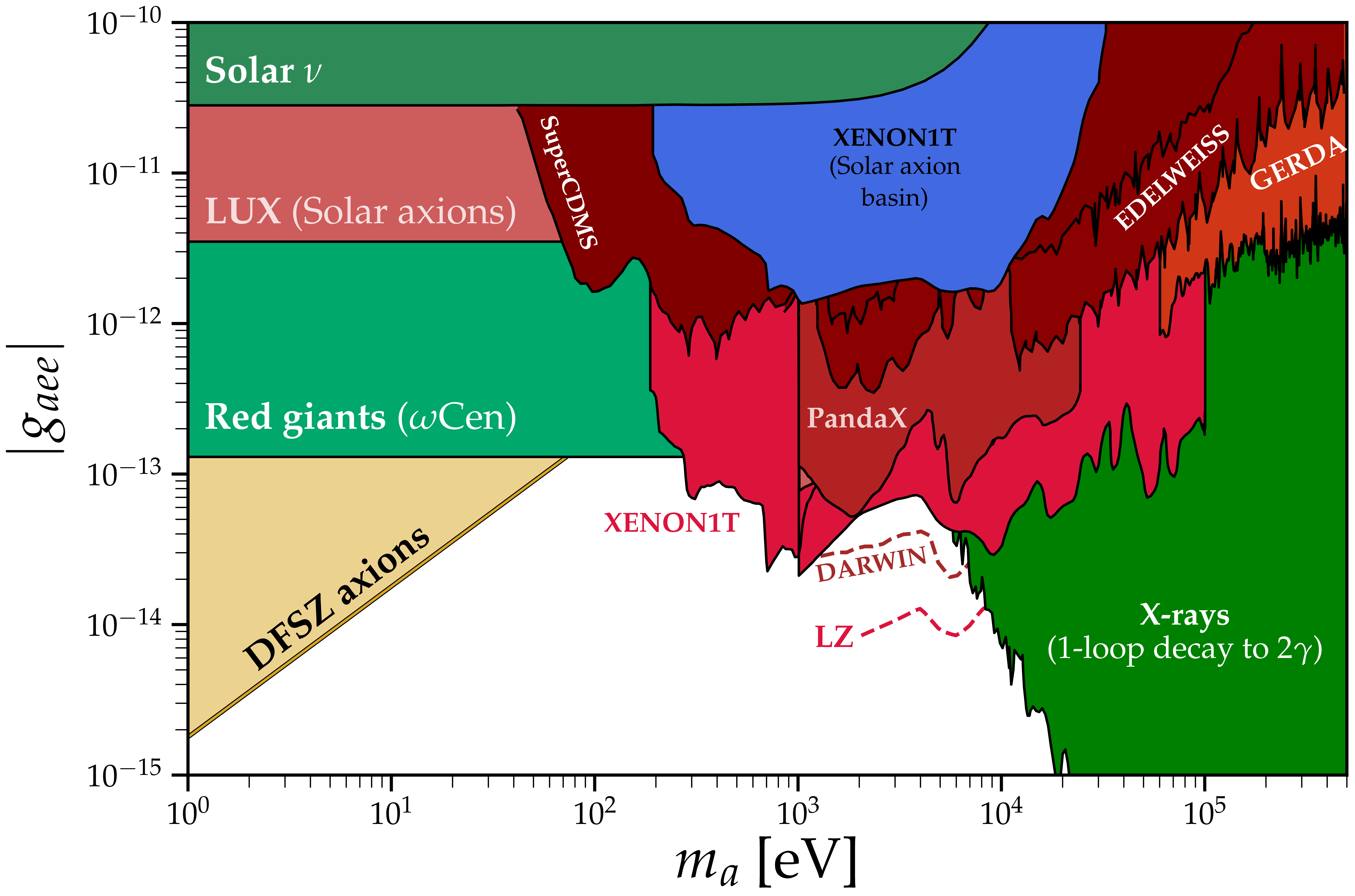
Then, we need strategies for dealing with the fog



Solar ν
LUX (Solar axions)
SuperCDMS
XENON1T
(Solar axion
basin)
EDELWEISS
GERDA
Red giants (ωCen)
PandaX
XENON1T
DARWIN
LZ
DFSZ axions
X-rays
(1-loop decay to 2γ)
|g_aee|
m_a [eV]
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^0
10^1
10^2
10^3
10^4
10^5