ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF SYDNEY

CYGNUS

Directional dark matter detection

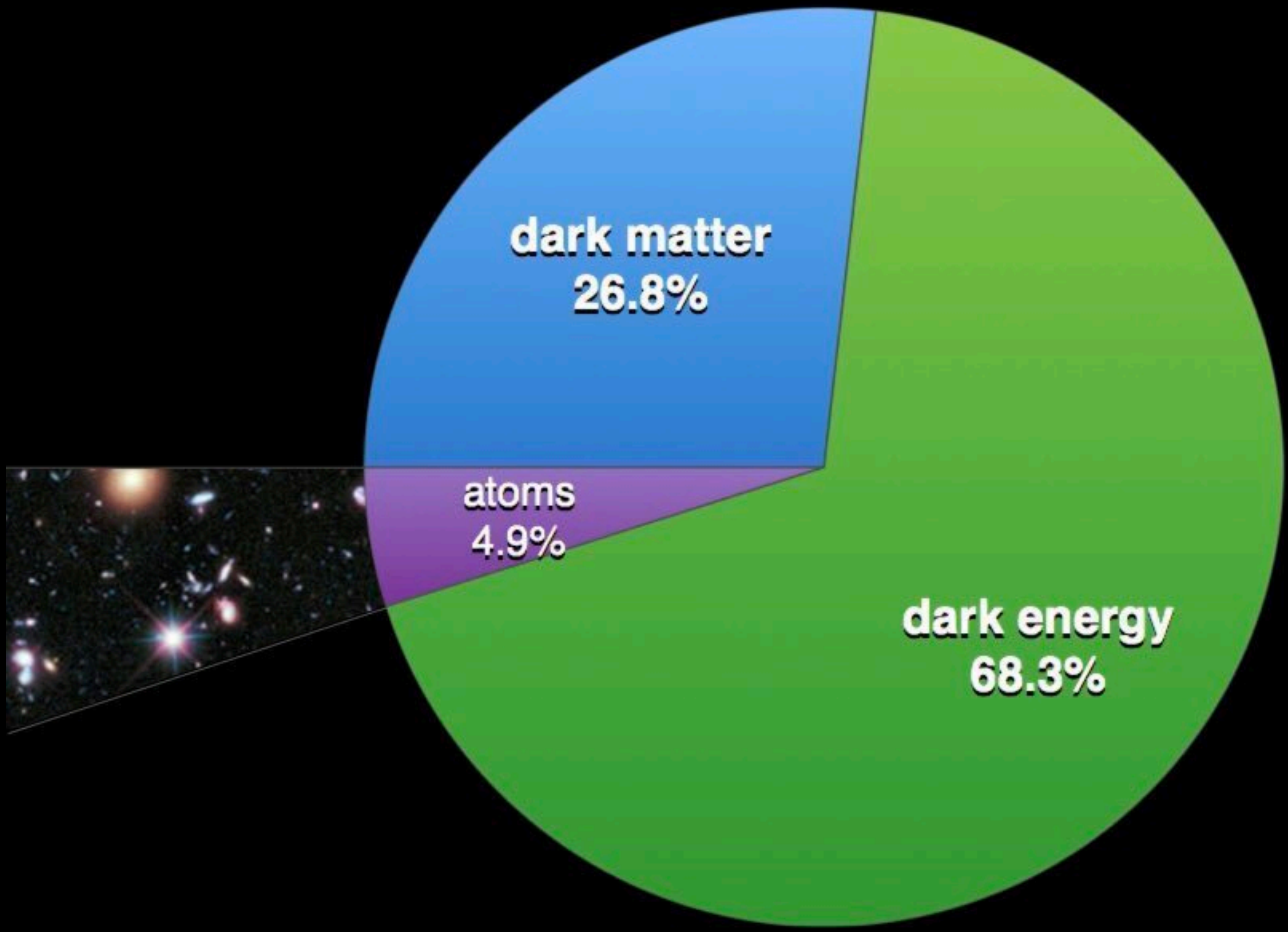
Ciaran O'Hare

University of Sydney

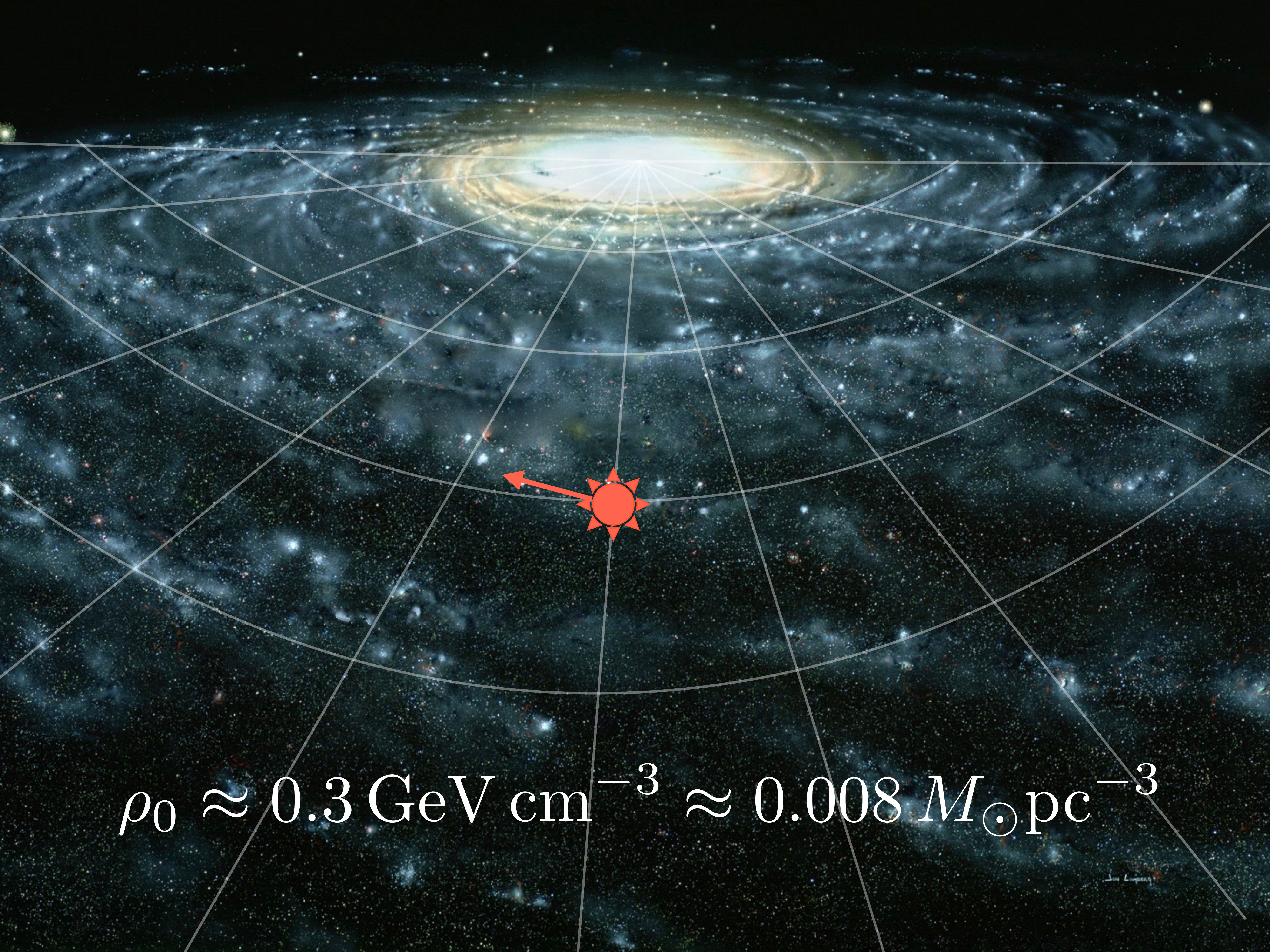
1. Why try and detect dark matter directionally?

2. How to do it

3. CYGNUS



@AstroKatie/Planck13



$$\rho_0 \approx 0.3\,\mathrm{GeV\,cm^{-3}} \approx 0.008\,M_\odot\,\mathrm{pc}^{-3}$$

How do we know $\rho_0 \approx 0.3\,\mathrm{GeV\,cm^{-3}}$?

$$\frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0 \longrightarrow$$

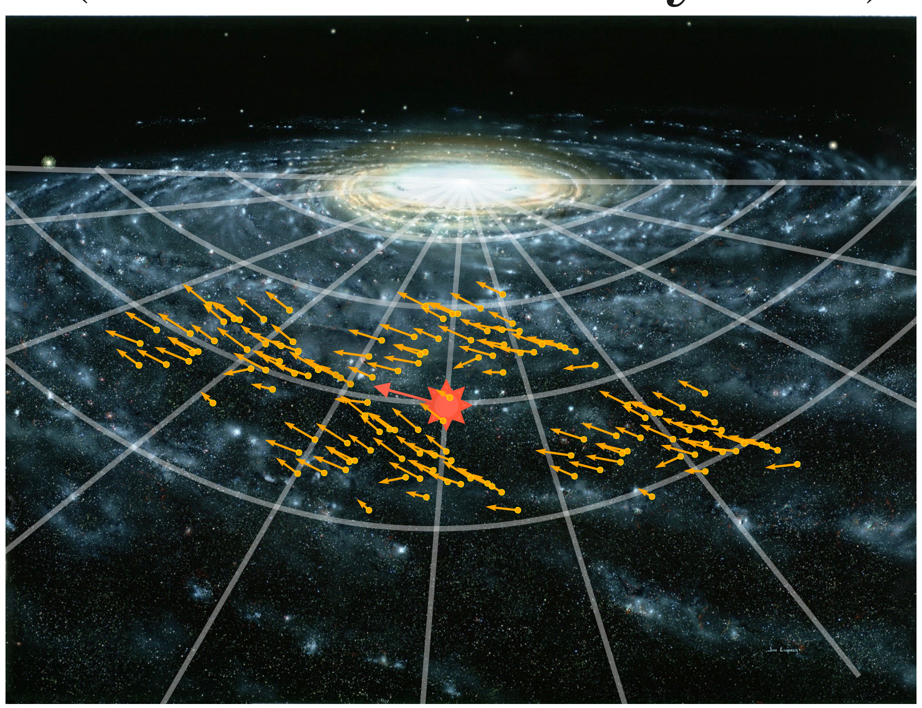
<u>(collisionless) Boltzmann eq.</u>
Distribution function → Grav. potential

$$\nabla_x^2 \Phi = 4\pi G \rho \longrightarrow$$

<u>Poission eq.</u>
Grav. potential → matter density

Local measure

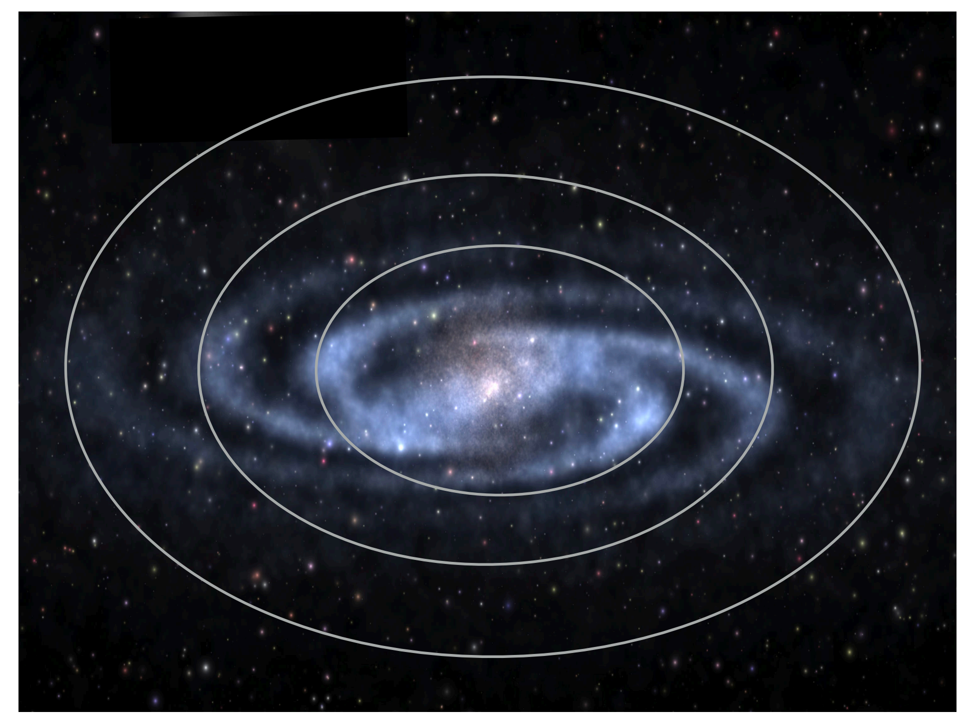
(kinematics of nearby stars)



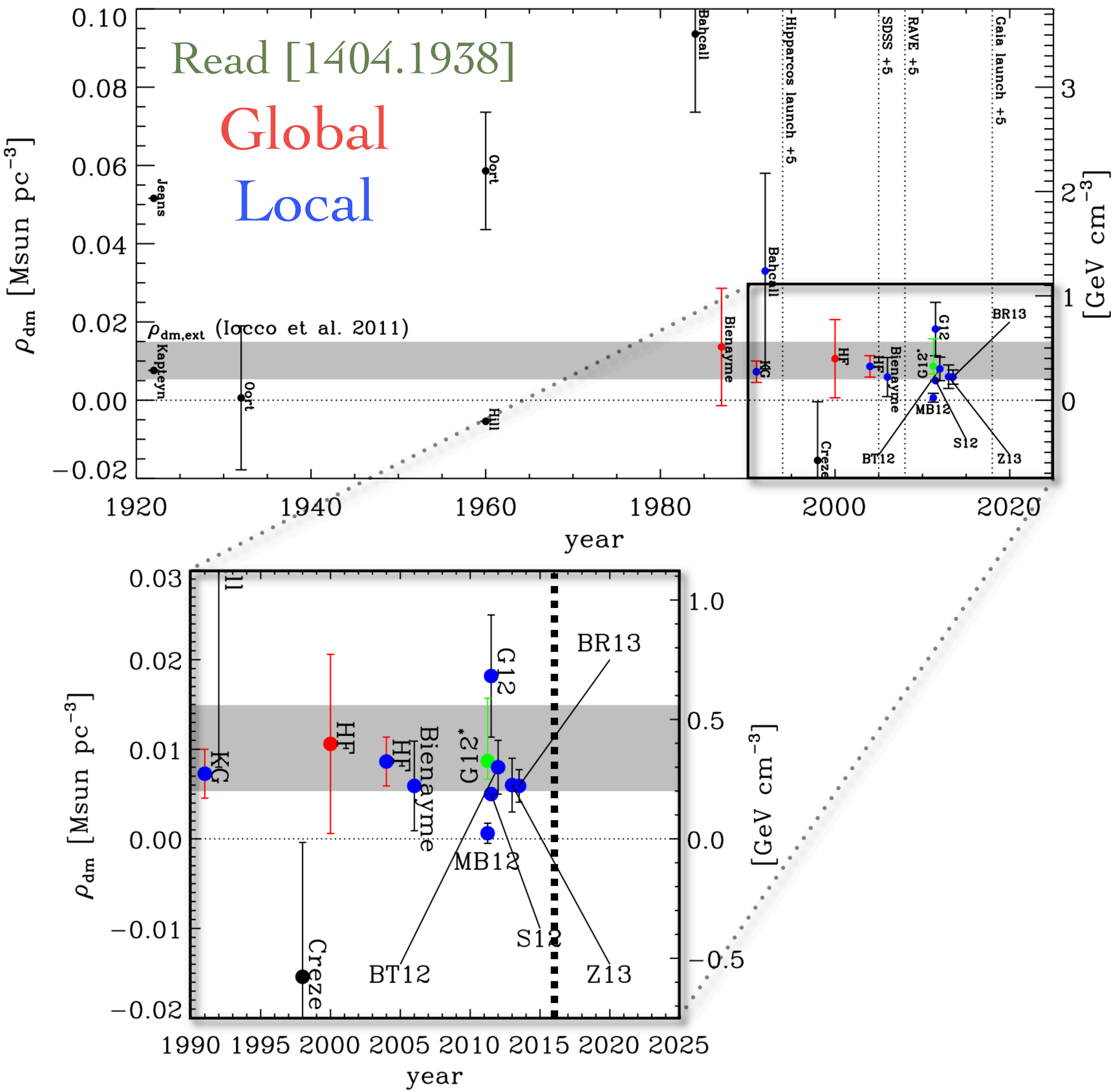
Pro: density that we want
Con: sensitive to baryonic model

Global measure

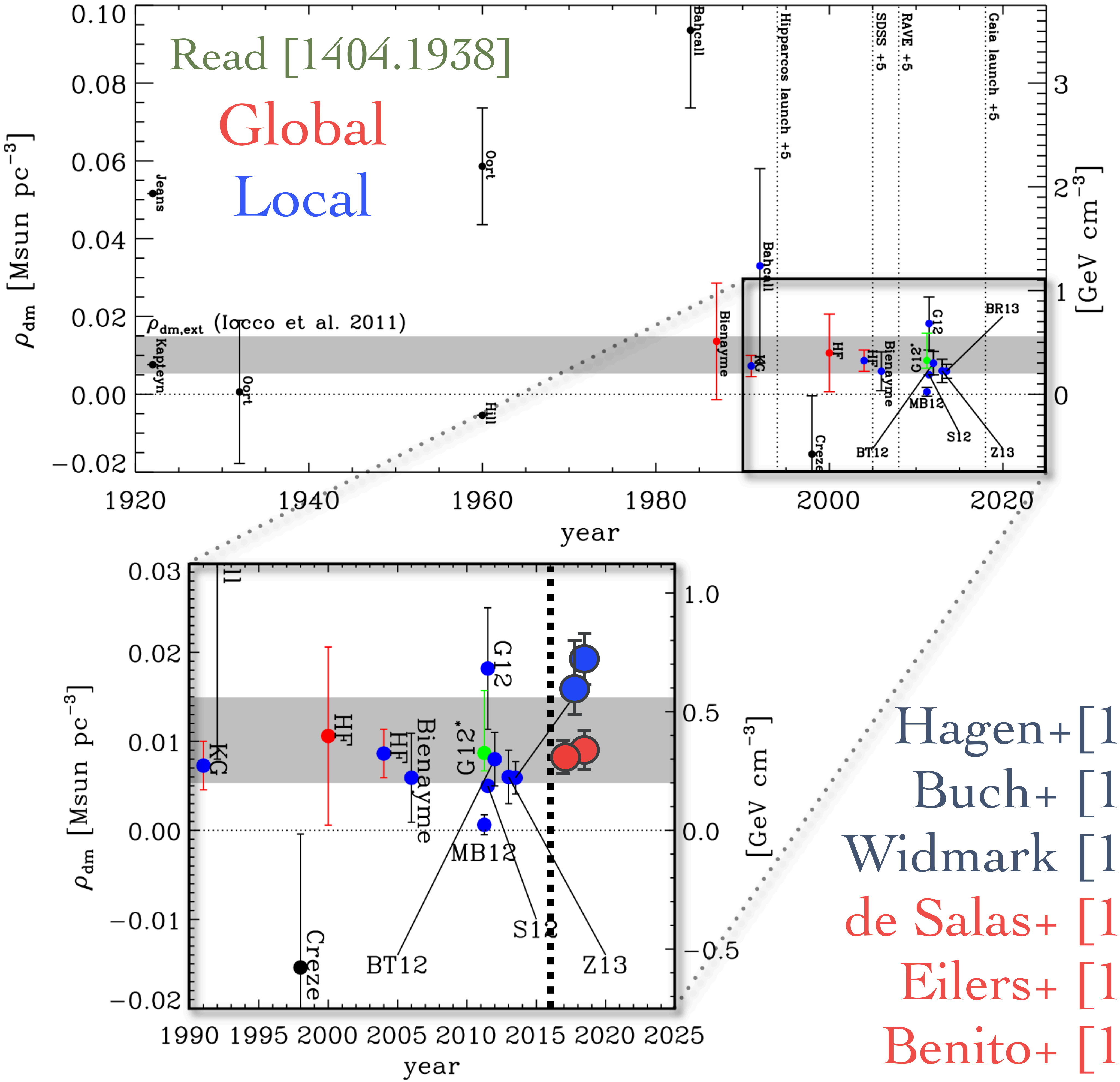
(build mass model for MW)



Pro: Average over a lot of halo/disk
Con: less direct measure of local density



Read [1404.1938]
Global
Local
ρ_{dm} [Msun pc^{-3}]
[GeV cm^{-3}]
year
$\rho_{dm,ext}$ (Iocco et al. 2011)
Jeans
Kapteyn
Oort
Hill
Bahcall
Bienayme
KG
Creze
HF
G12
G12*
BR13
MB12
BT12
S12
Z13
Hipparcos launch +5
SDSS +5
RAVE +5
Gaia launch +5



post-*Gaia*

Hagen+[1802.09291]

Buch+ [1808.05603]

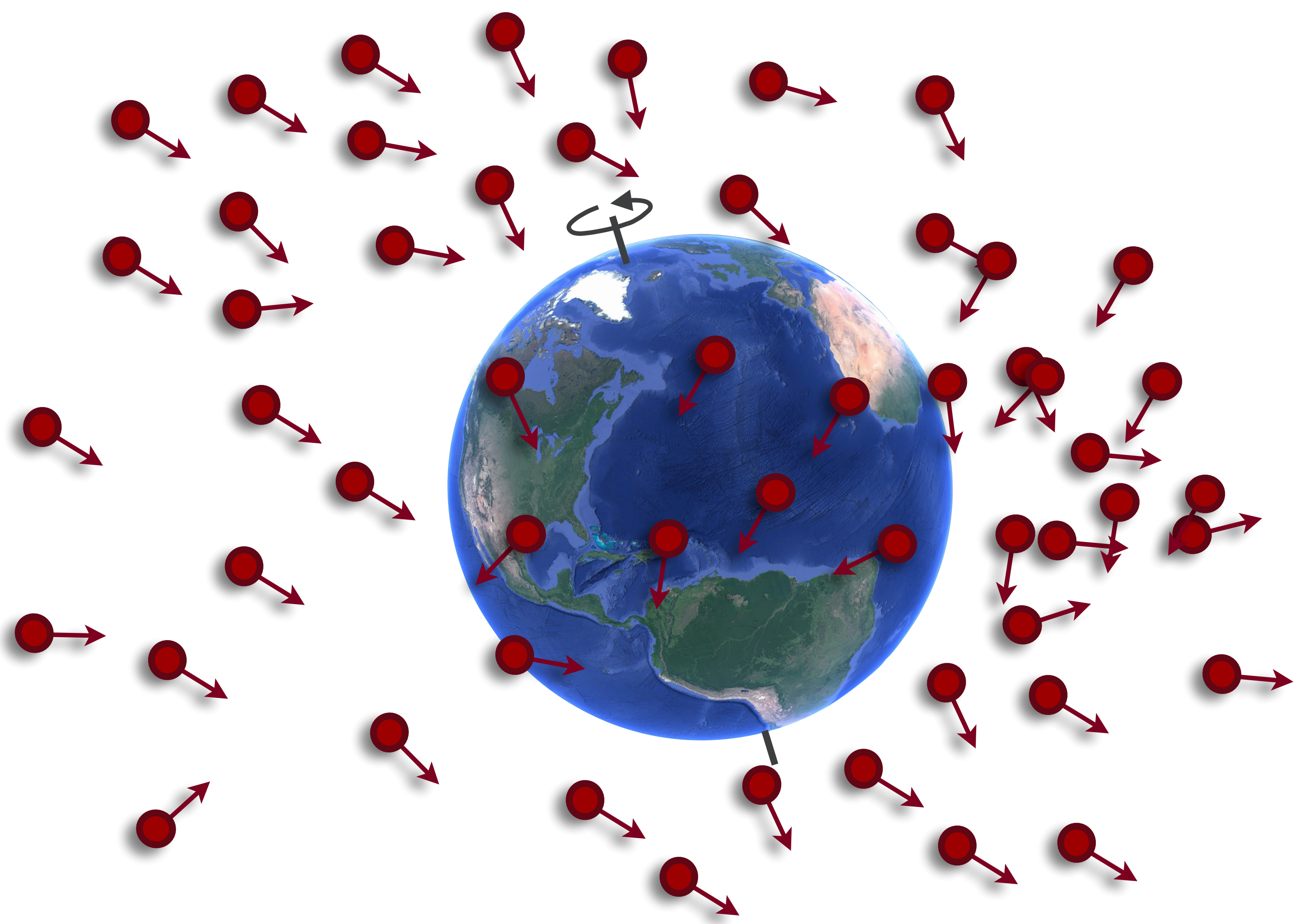
Widmark [1811.07911]

de Salas+ [1906.06133]

Eilers+ [1810.09466]

Benito+ [1901.02460]

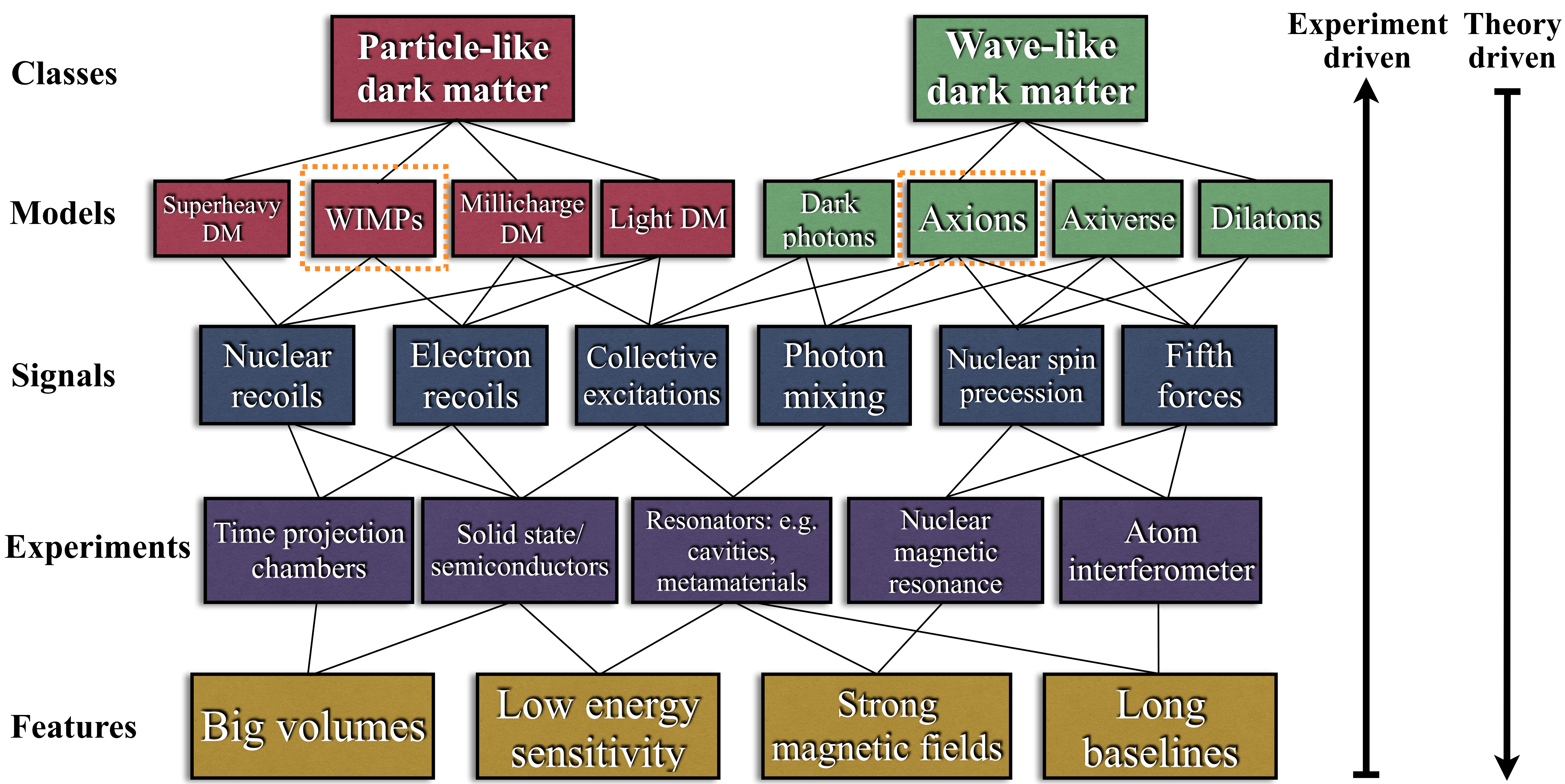
Direct dark matter detection on Earth



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

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

Approaches to direct detection



WIMPs

Weakly Interacting Massive Particles

What does that actually mean?

Dan Hooper
@DanHooperAstro

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

Has electroweak charge

Is a thermal relic

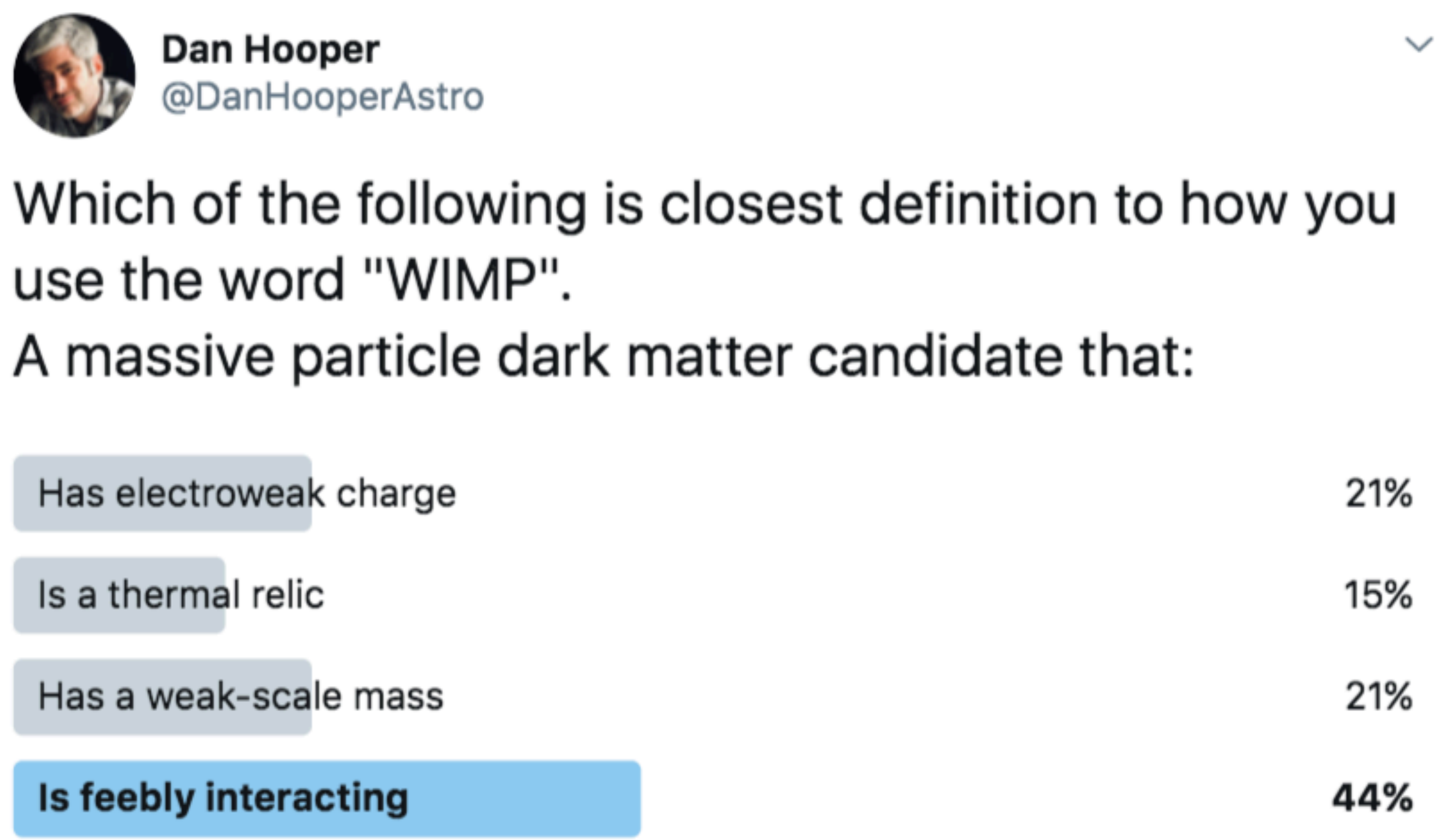
Has a weak-scale mass

Is feebly interacting

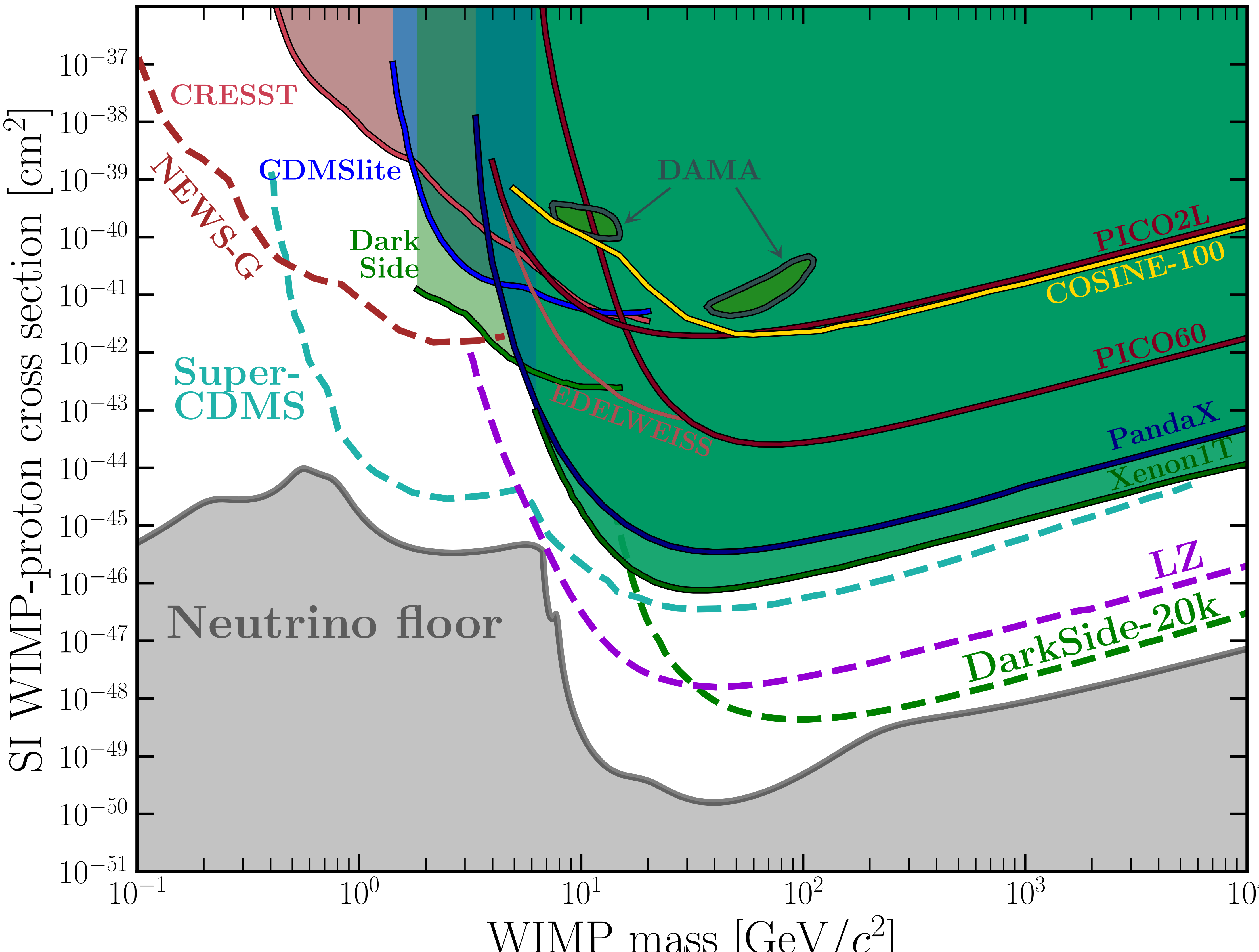
WIMPs

Weakly Interacting Massive Particles

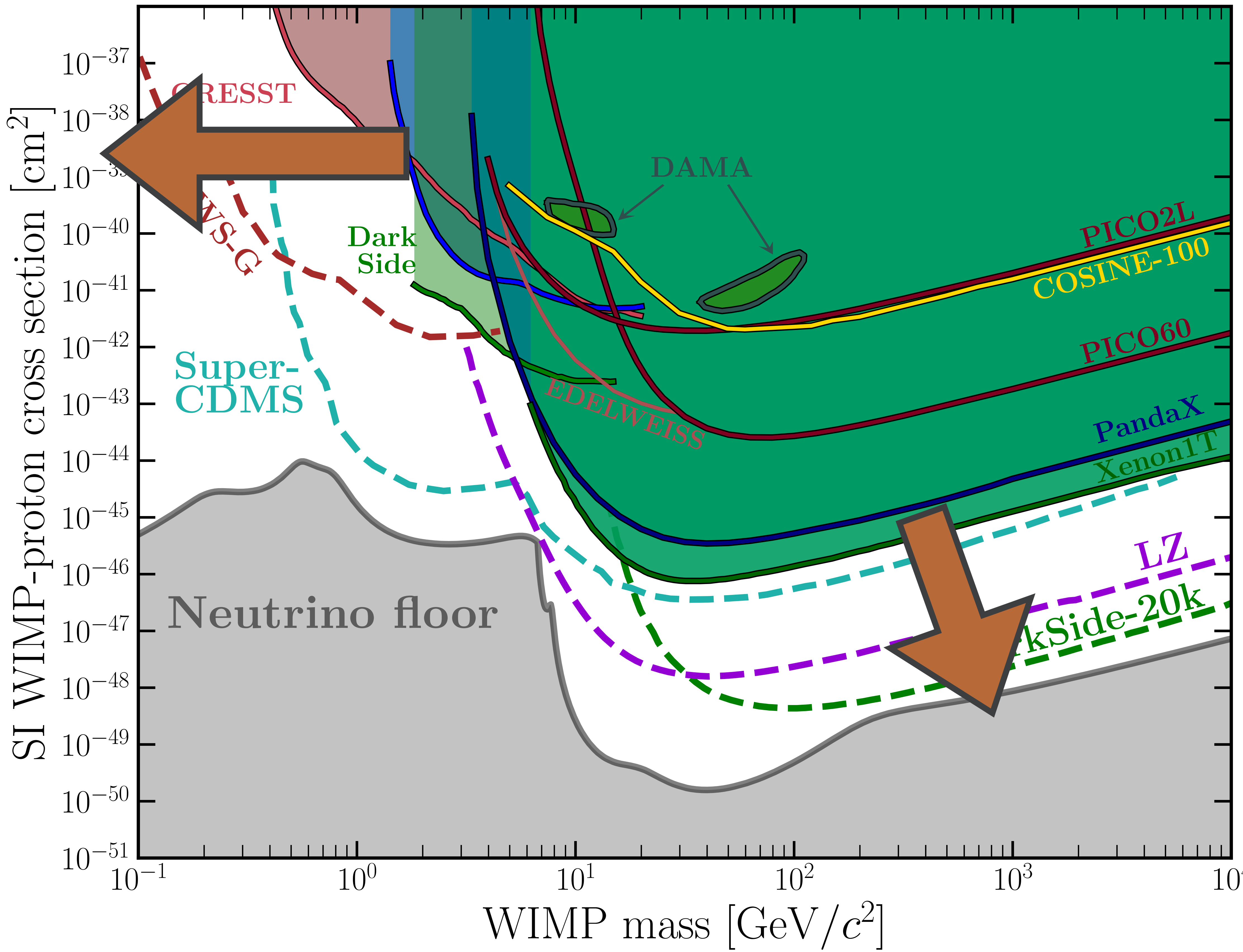
What does that actually mean?



Simple, demonstrative example: Spin-independent WIMP-nucleon cross section



Simple, demonstrative example: Spin-independent WIMP-nucleon cross section



What are the problems with direct WIMP searches?

What are the problems with direct WIMP searches?

1. How do you know what is recoiling?

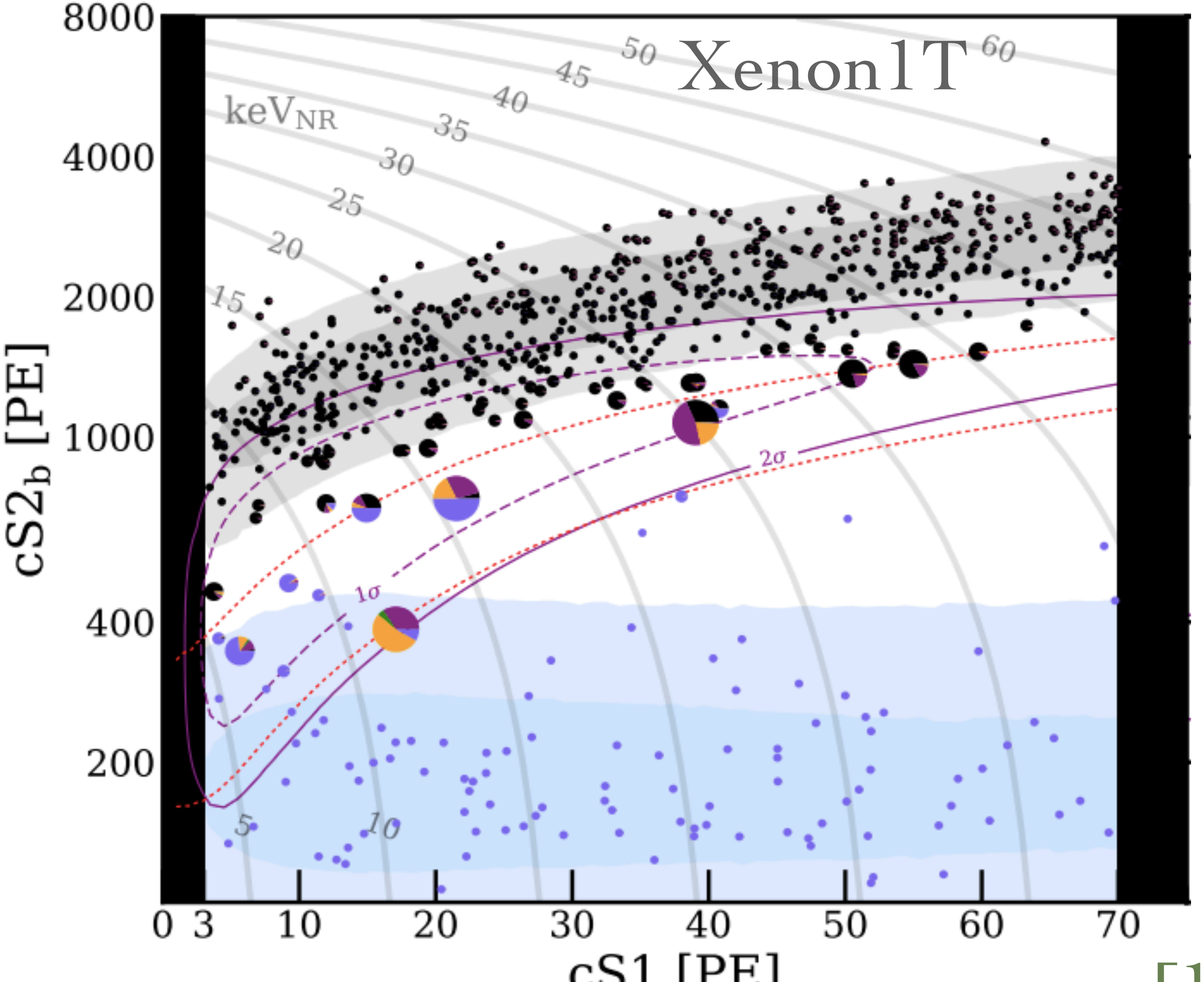
What are the problems with direct WIMP searches?

1. How do you know what is recoiling?

2. If you have **nuclear** recoil: how do you know what caused it?

This is more or less under control…

Thanks to multiple types of signal, fiducialisation, careful background study etc.



[1805.12562]

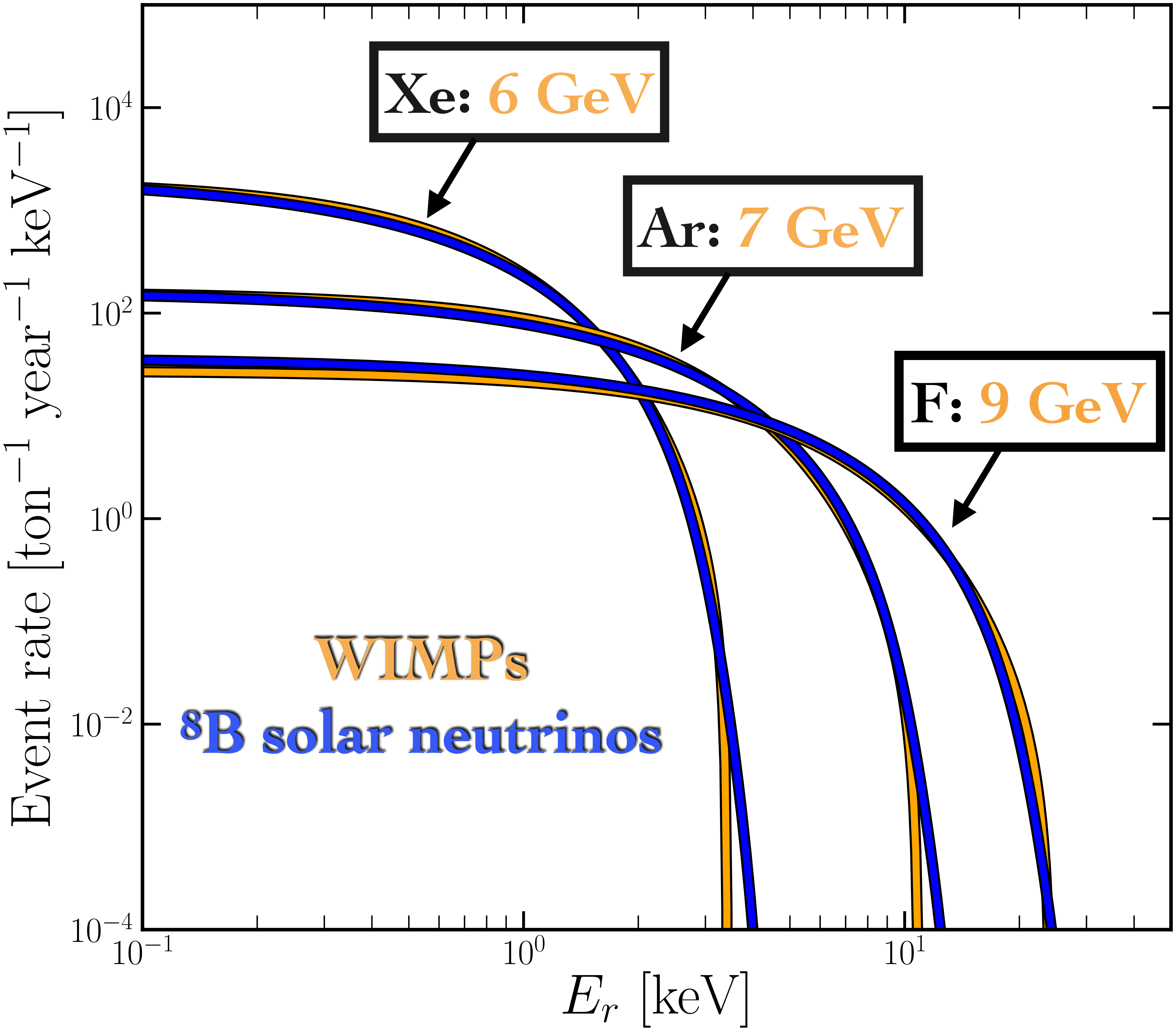
WIMP direct detection still has issues:

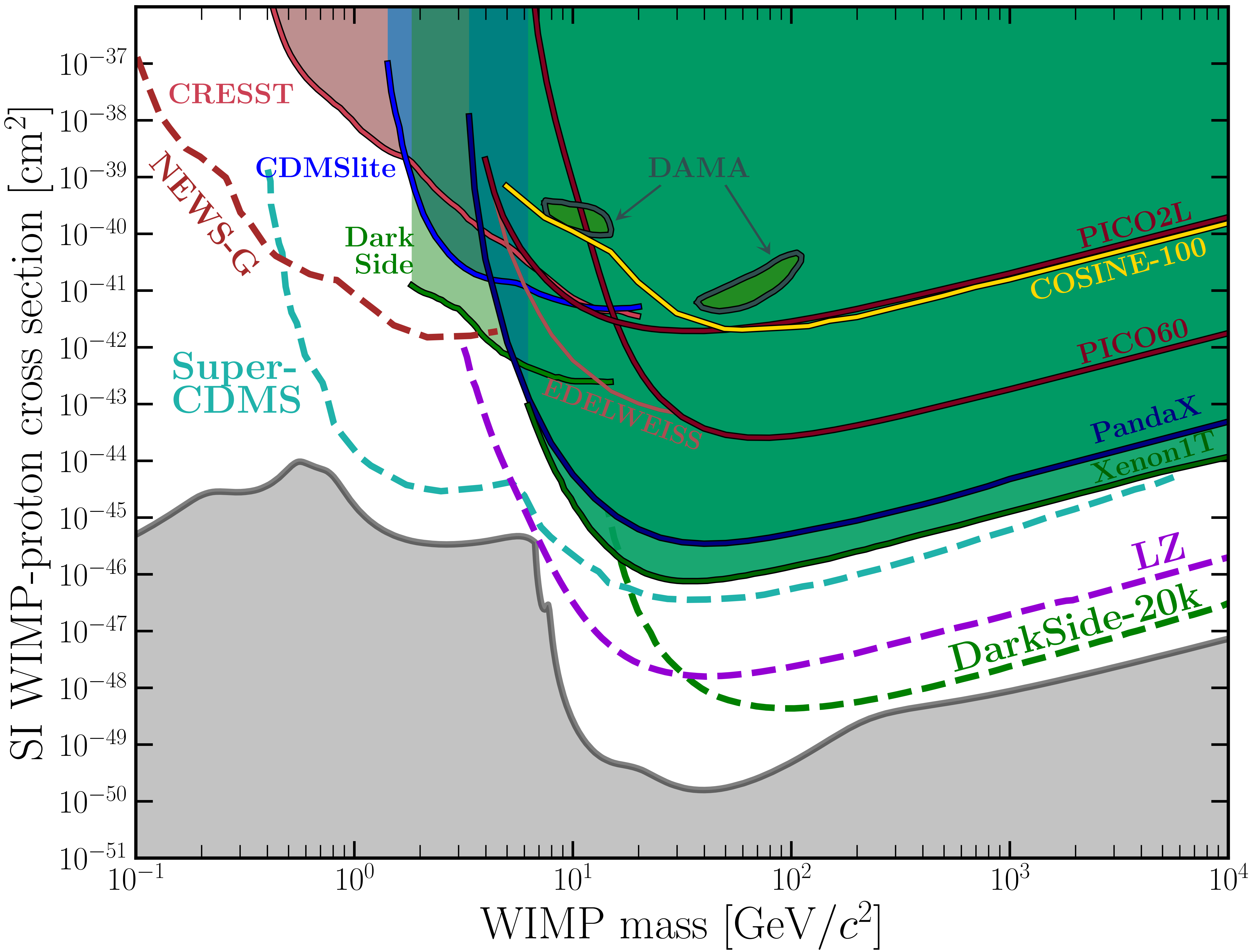
~~1. How do you know what is recoiling?~~

~~2. If you have **nuclear recoil**: how do you know what caused it?~~

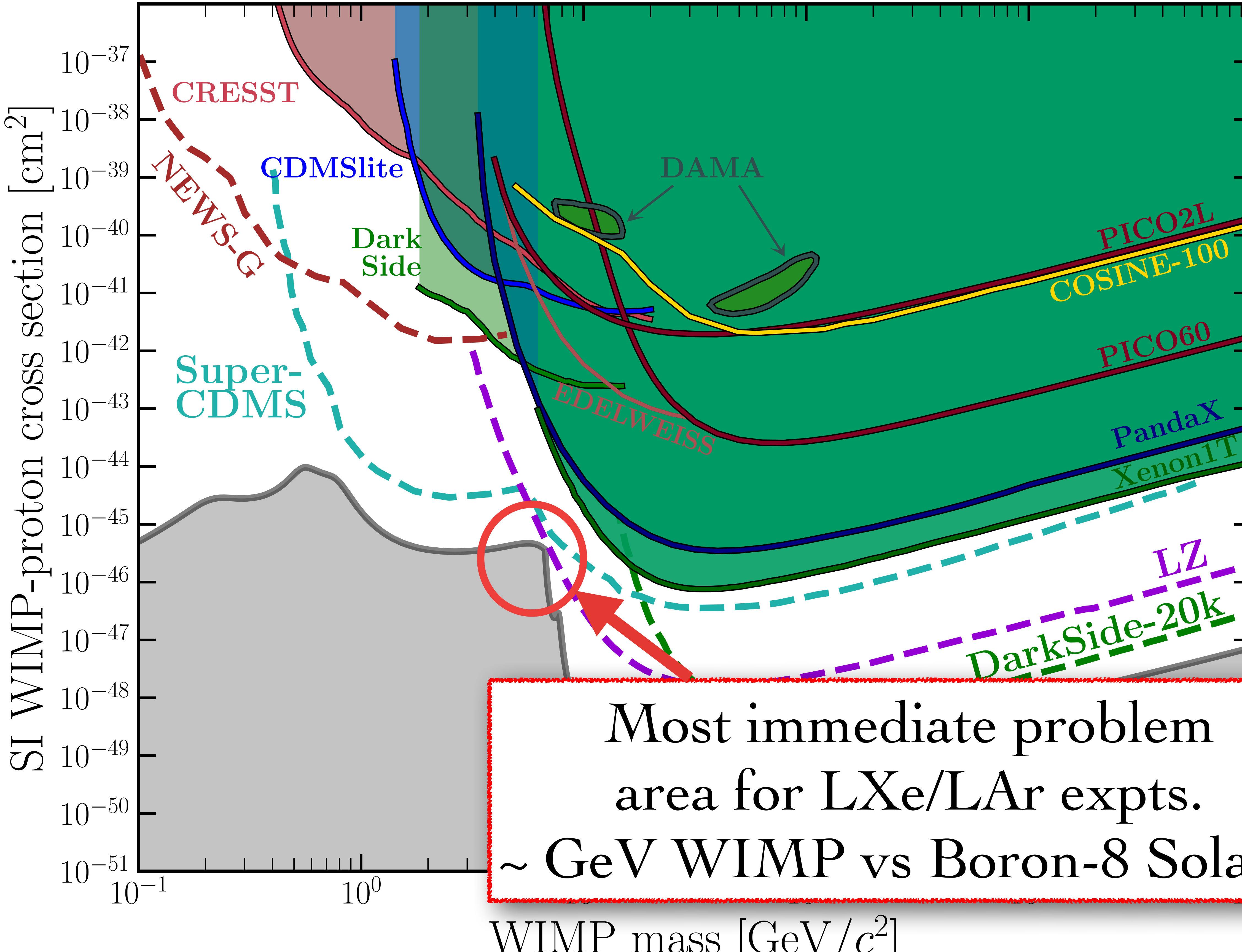
3. If you have a **non-background nuclear recoil**: was it a neutrino or a WIMP?

The problem:


Xe: 6 GeV
Ar: 7 GeV
F: 9 GeV
WIMPs
^{8}B solar neutrinos
Event rate [ton^{-1} year^{-1} keV^{-1}]
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-1}
10^{0}
10^{1}
E_r [keV]



CRESST
NEWS-G
CDMSlite
Dark Side
Super-CDMS
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
PandaX
Xenon1T
LZ
DarkSide-20k
SI WIMP-proton cross section [cm^2]
WIMP mass [GeV/c^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



Most immediate problem area for LXe/LAr expts.

~ GeV WIMP vs Boron-8 Solar-ν

WIMP direct detection still has issues:

1. ~~How do you know what is recoiling?~~

2. ~~If you have **nuclear recoil**: how do you know what caused it?~~

3. If you have a **non-background nuclear recoil**: was it a neutrino or a WIMP?

WIMP direct detection still has issues:

~~1. How do you know what is recoiling?~~

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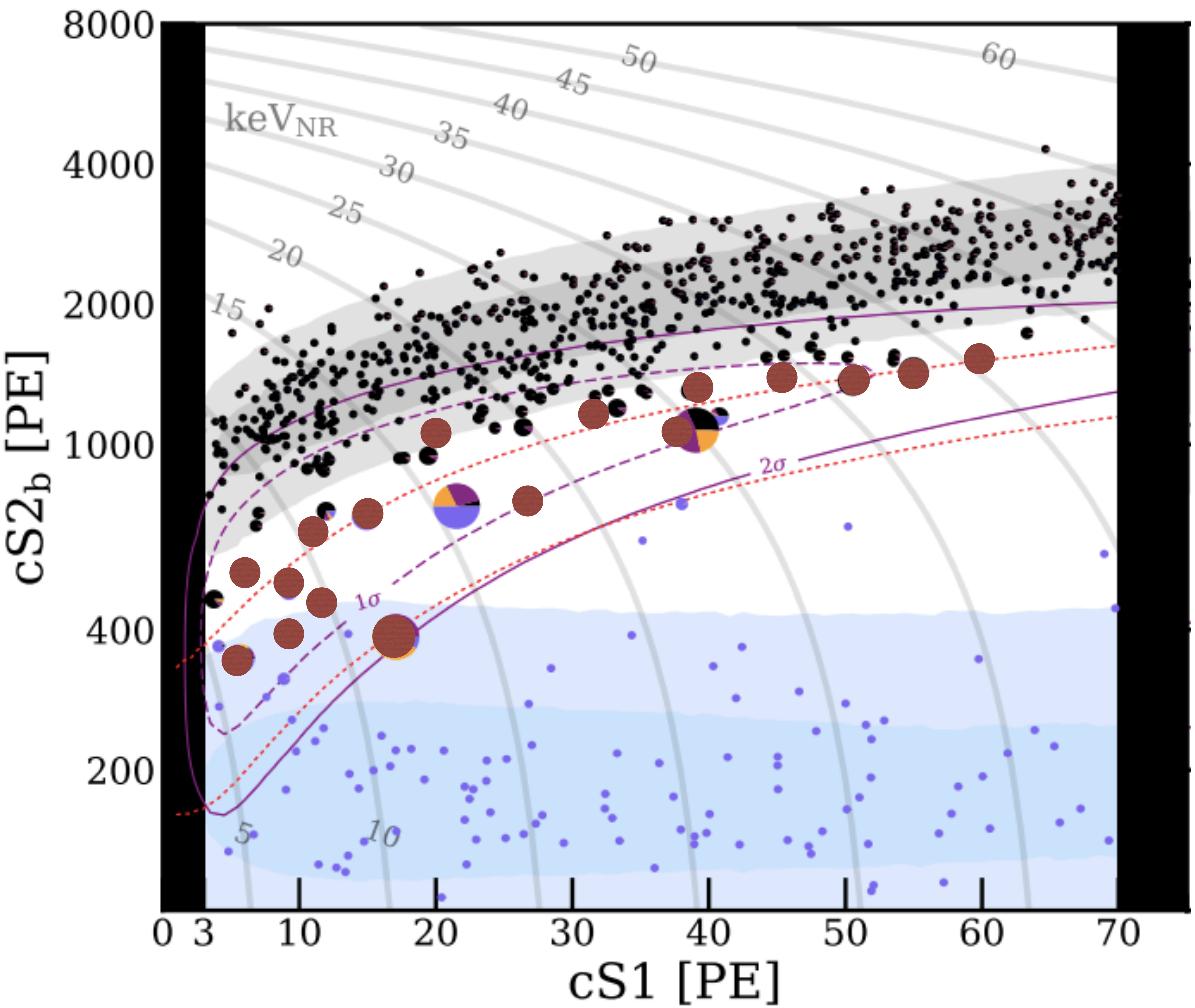
3. If you have a **non-background nuclear recoil**: was it a neutrino or a WIMP?

4. You have a **non-background, nuclear recoil, that's definitely not a neutrino**… is it *the* dark matter?

Say we see this plot in 10 years time…

Are we happy for a discovery of dark matter to look like this?



Conventional WIMP direct detection has issues:

~~1. How do you know what is recoiling?~~

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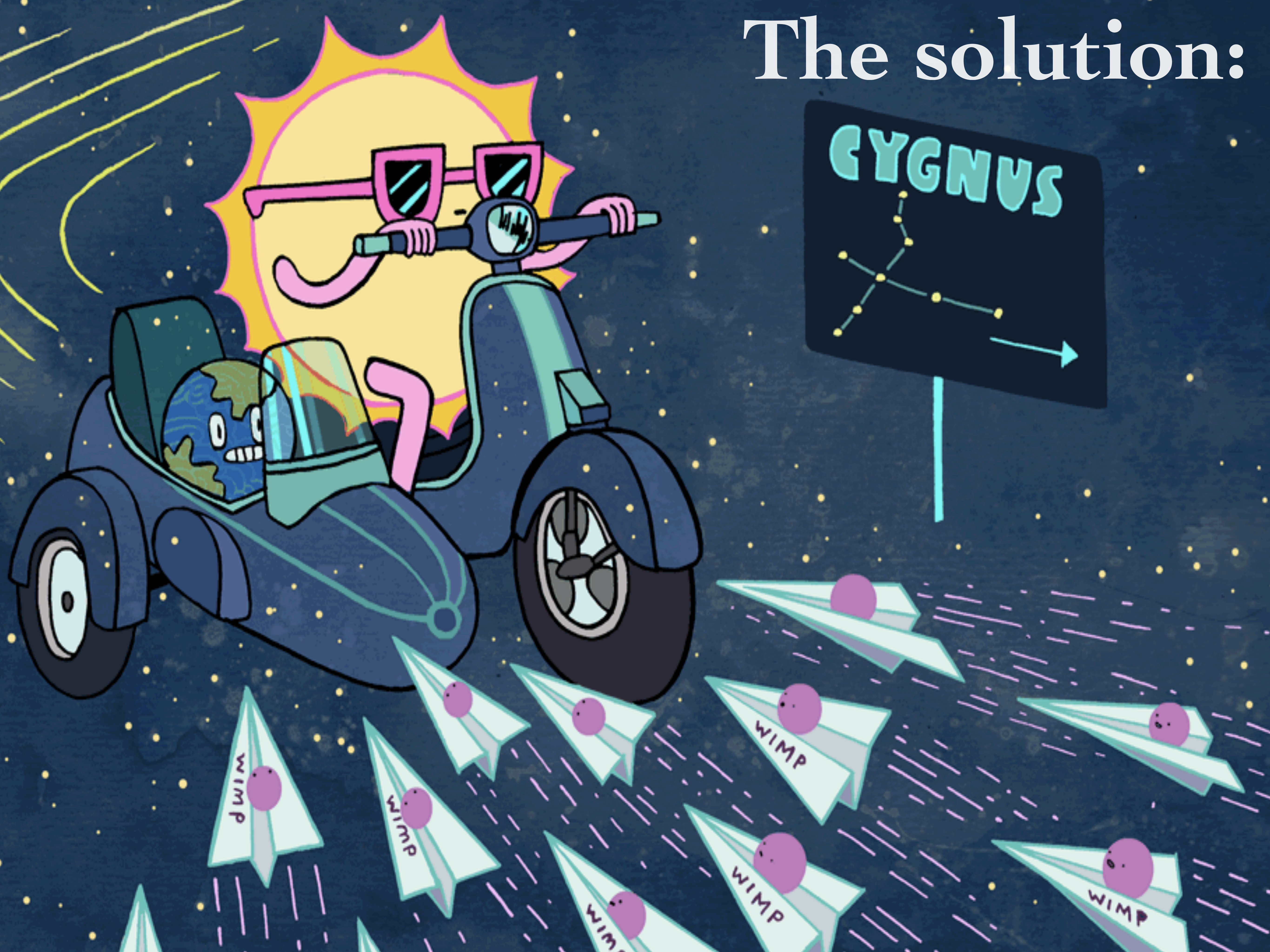
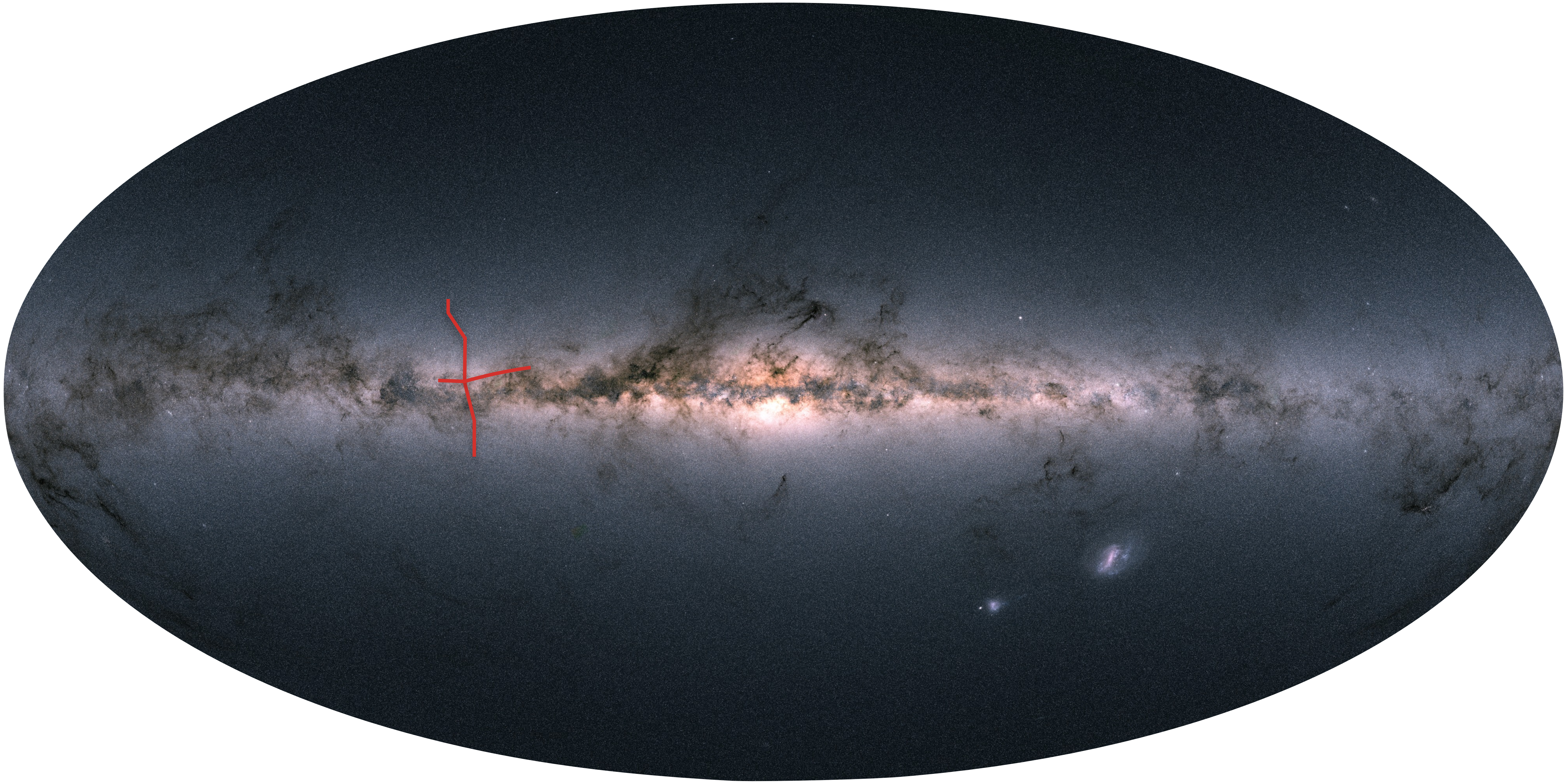
4. You have a **non-background, nuclear recoil, that's definitely not a neutrino**… is it *the* dark matter?

The solution:

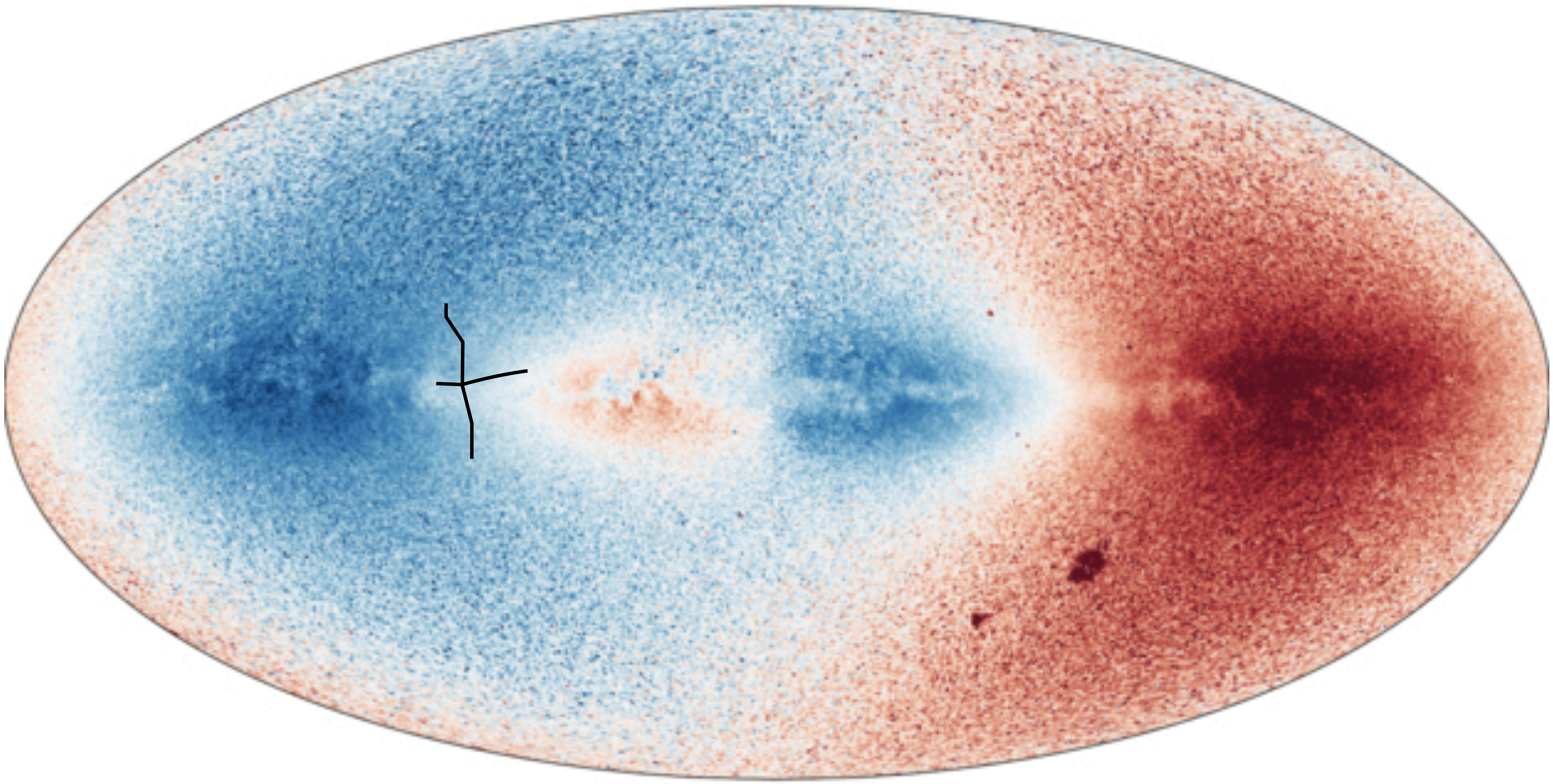


Why use directional information?



Gaia all-sky star map

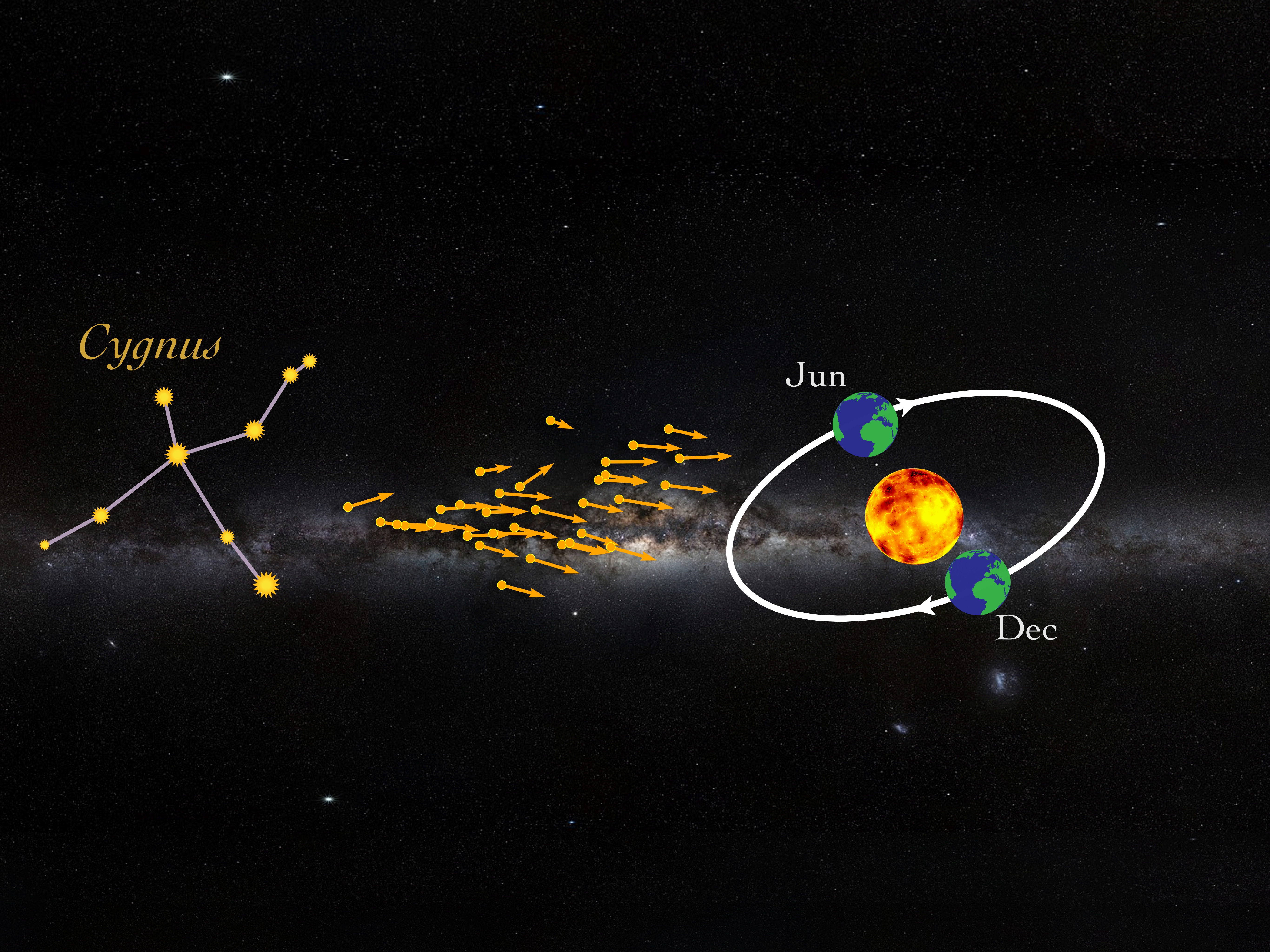
Why use directional information?



Gaia radial velocities

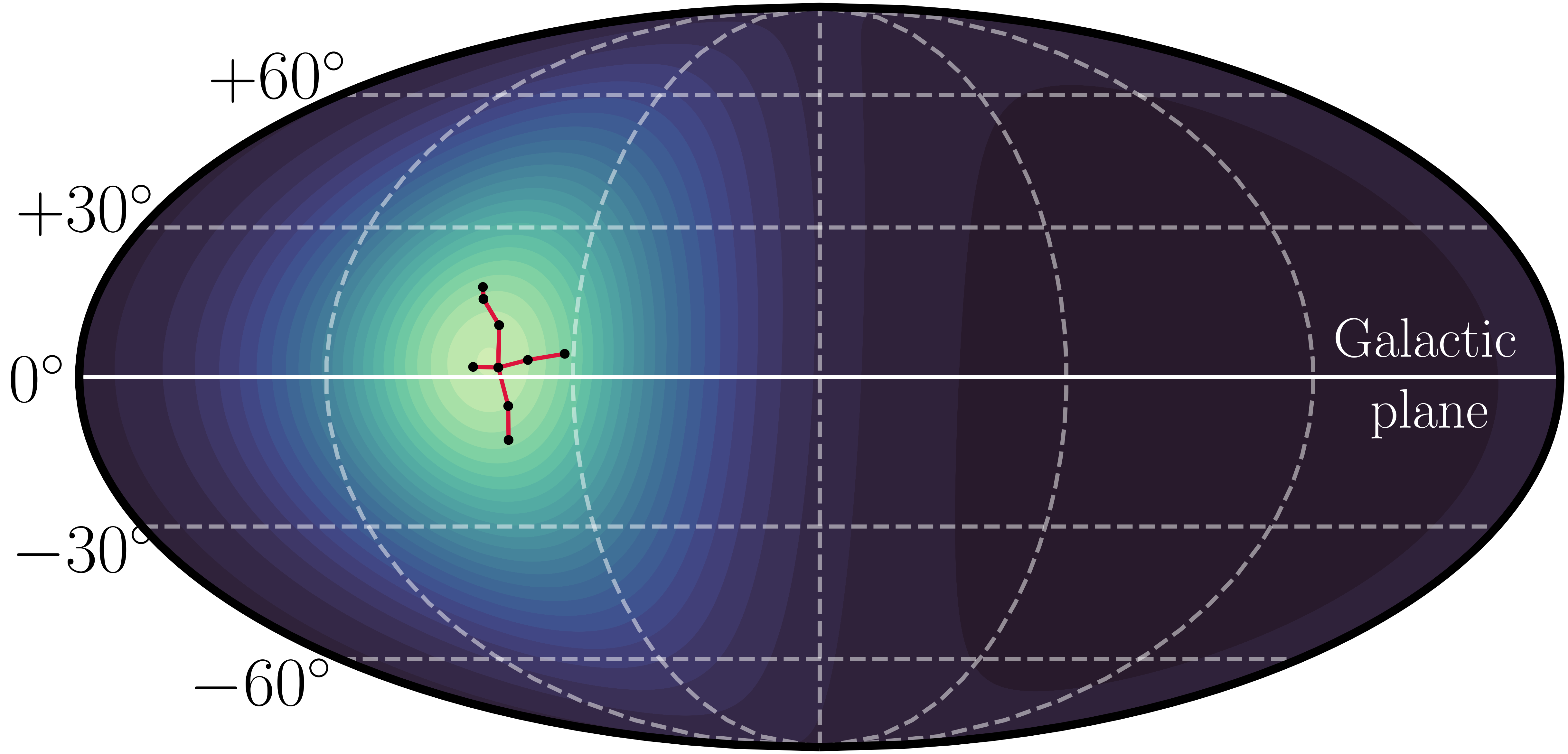
Blue = moving towards us (relatively)

Red = moving away from us

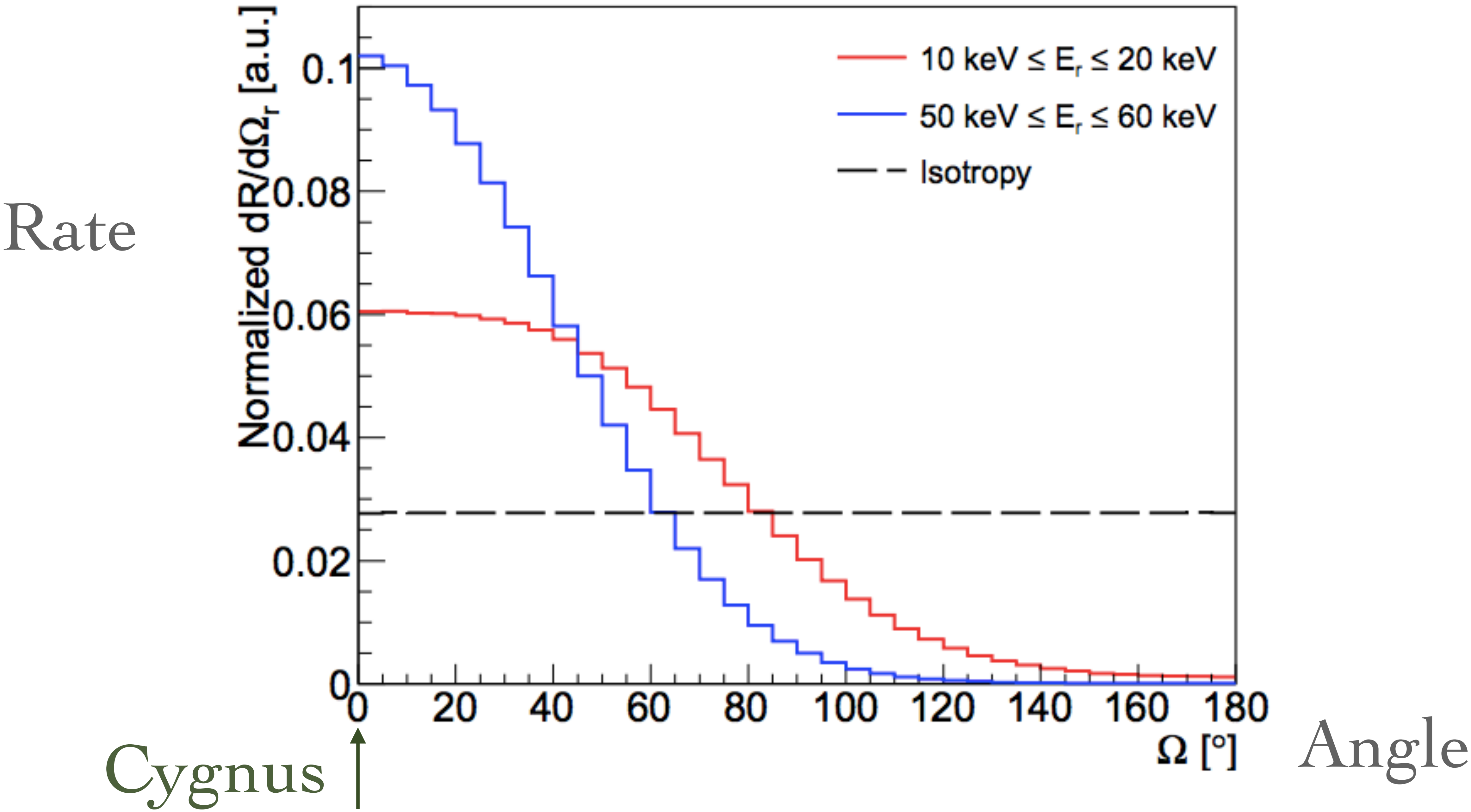

Cygnus
Jun
Dec

→ **The dark matter flux is anisotropic**

$v f_{\rm lab}(\mathbf{v})$



Mayet+ [1602.03781]



Signal pointing towards Cygnus is robust against particle and astrophysical uncertainties

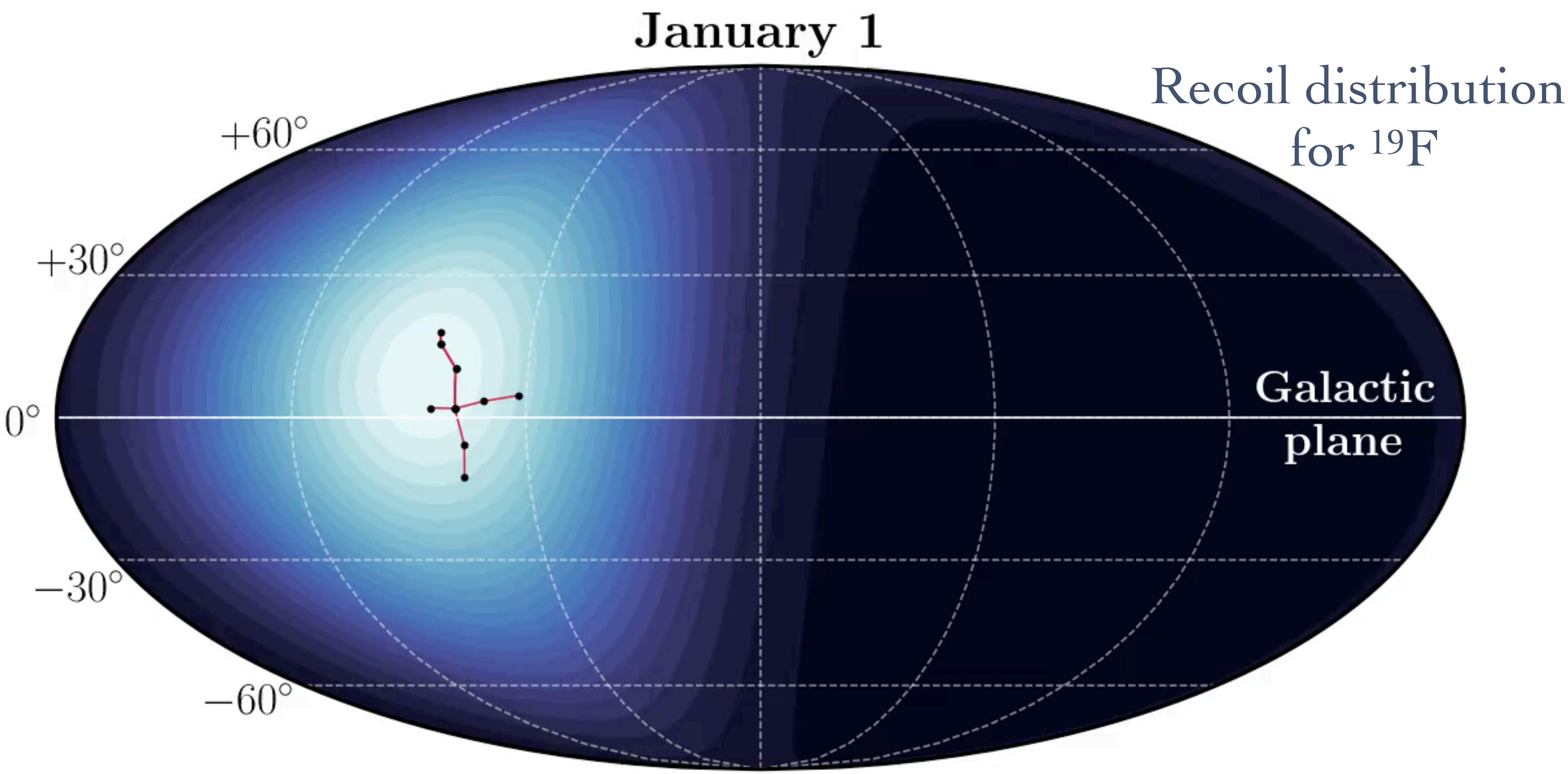
→ Can do a <u>non-parametric test</u> for isotropy on a set of recoil directions

→ O(10) events to exclude isotropy at 95% CL Morgan+[astro-ph/0408047]

But the case is stronger than that. **Nothing other than DM will give a signal that points back to Cygnus,**

→ A directional detector discovers DM

→ ~30 events needed to confirm signal aligned with Cygnus



(slight aberration due to motion of Earth around the Sun)

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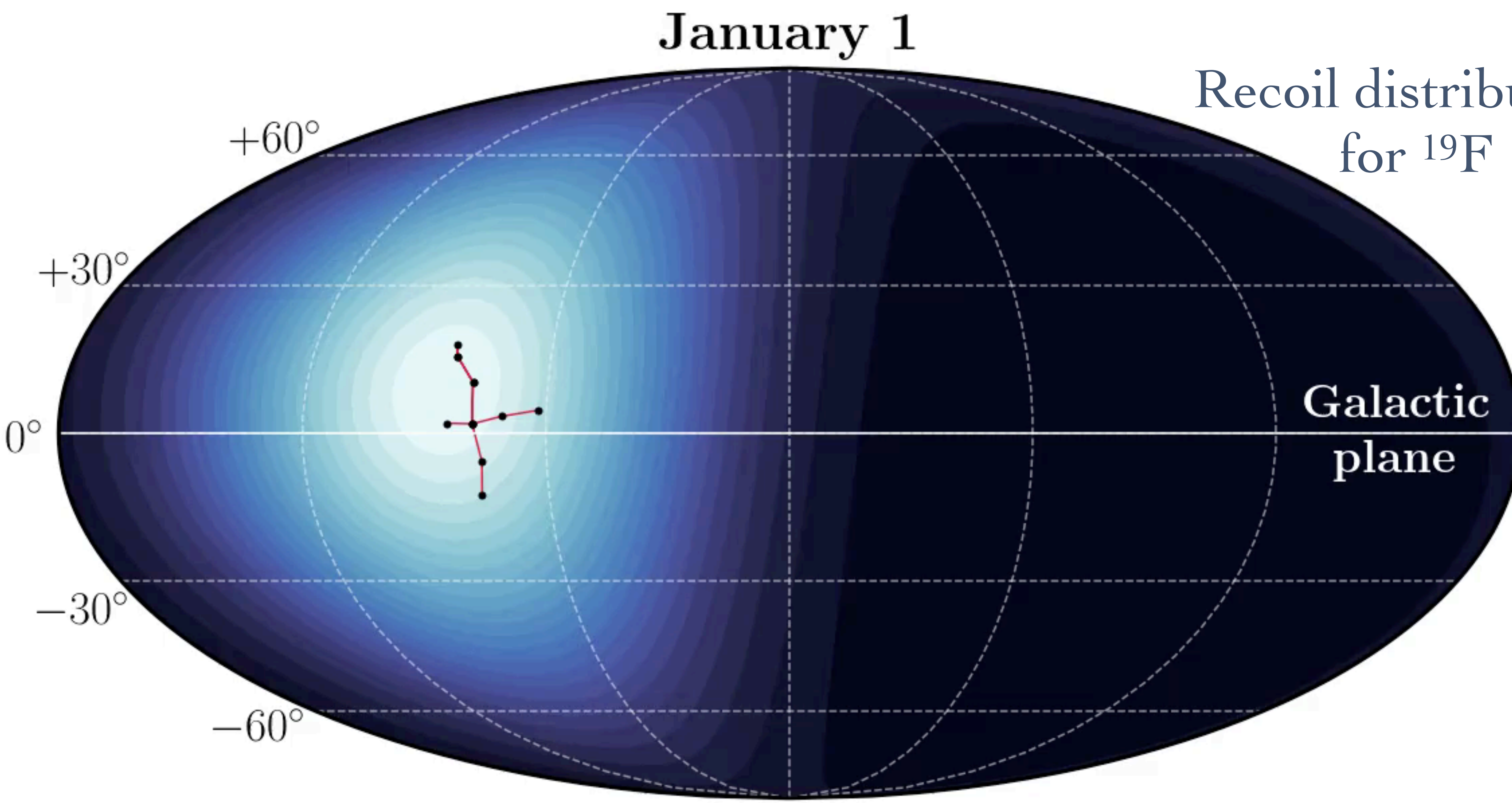
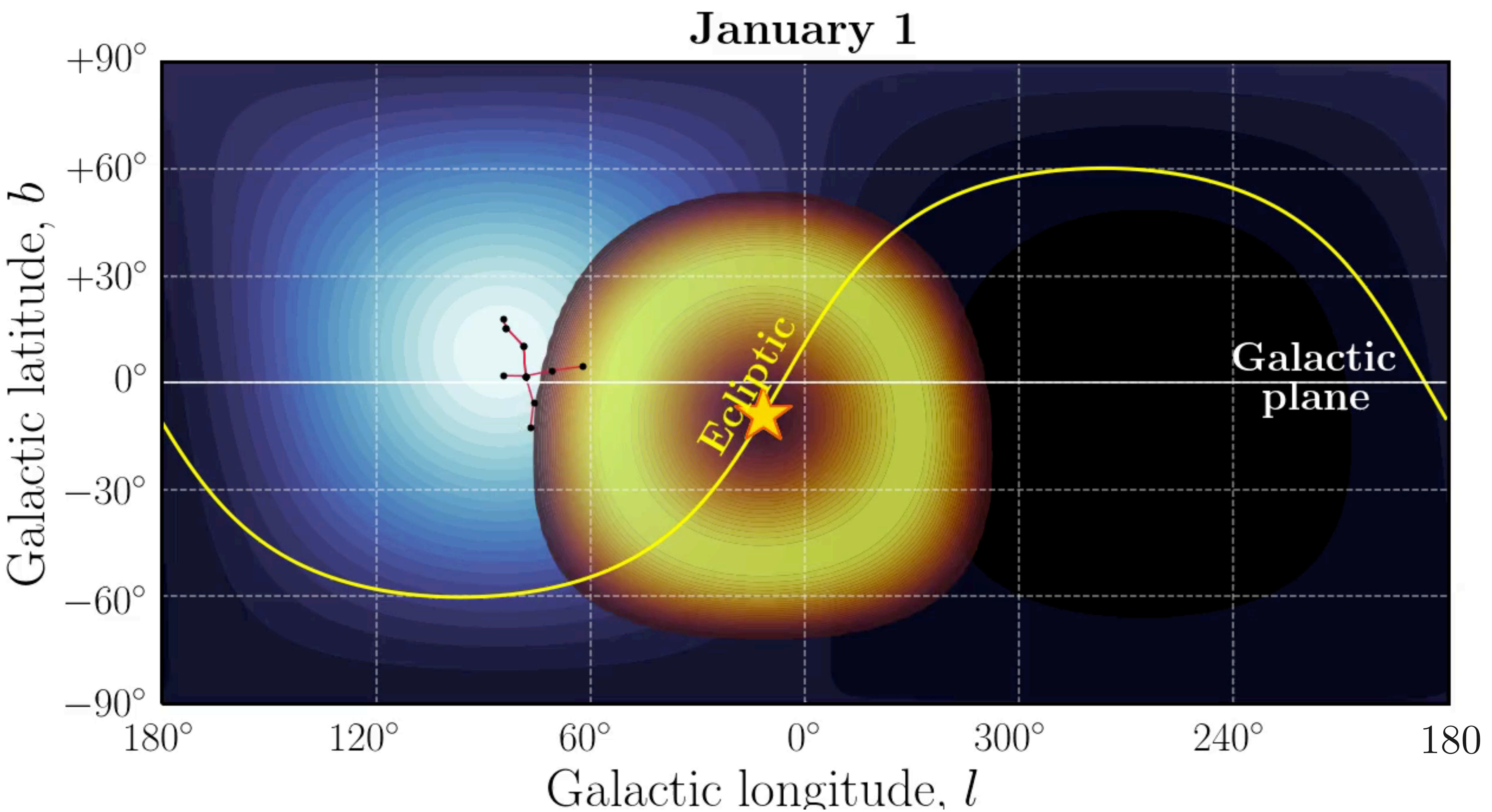


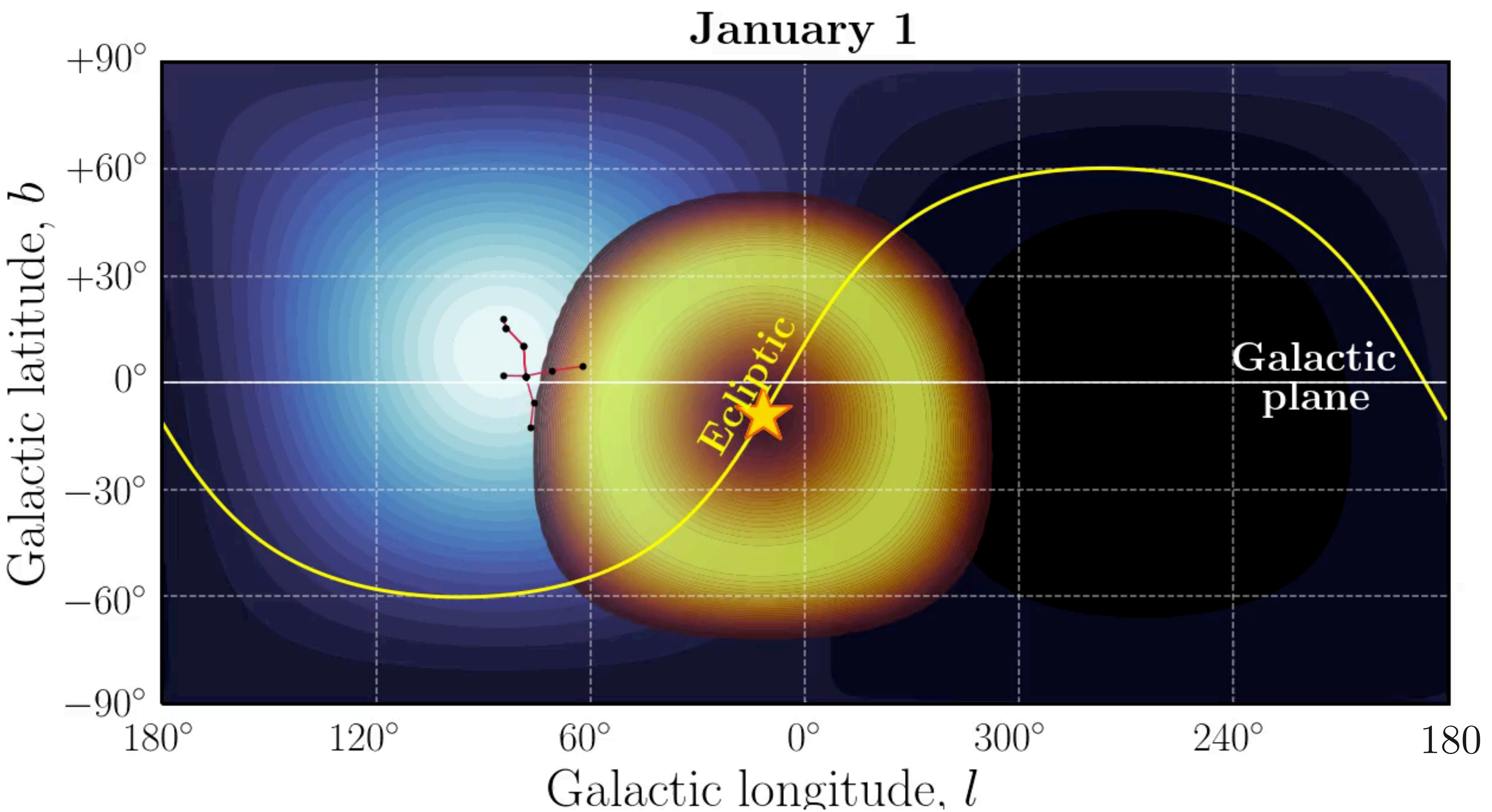
Recoil distribution for ^{19}F

(slight aberration due to motion of Earth around the Sun)

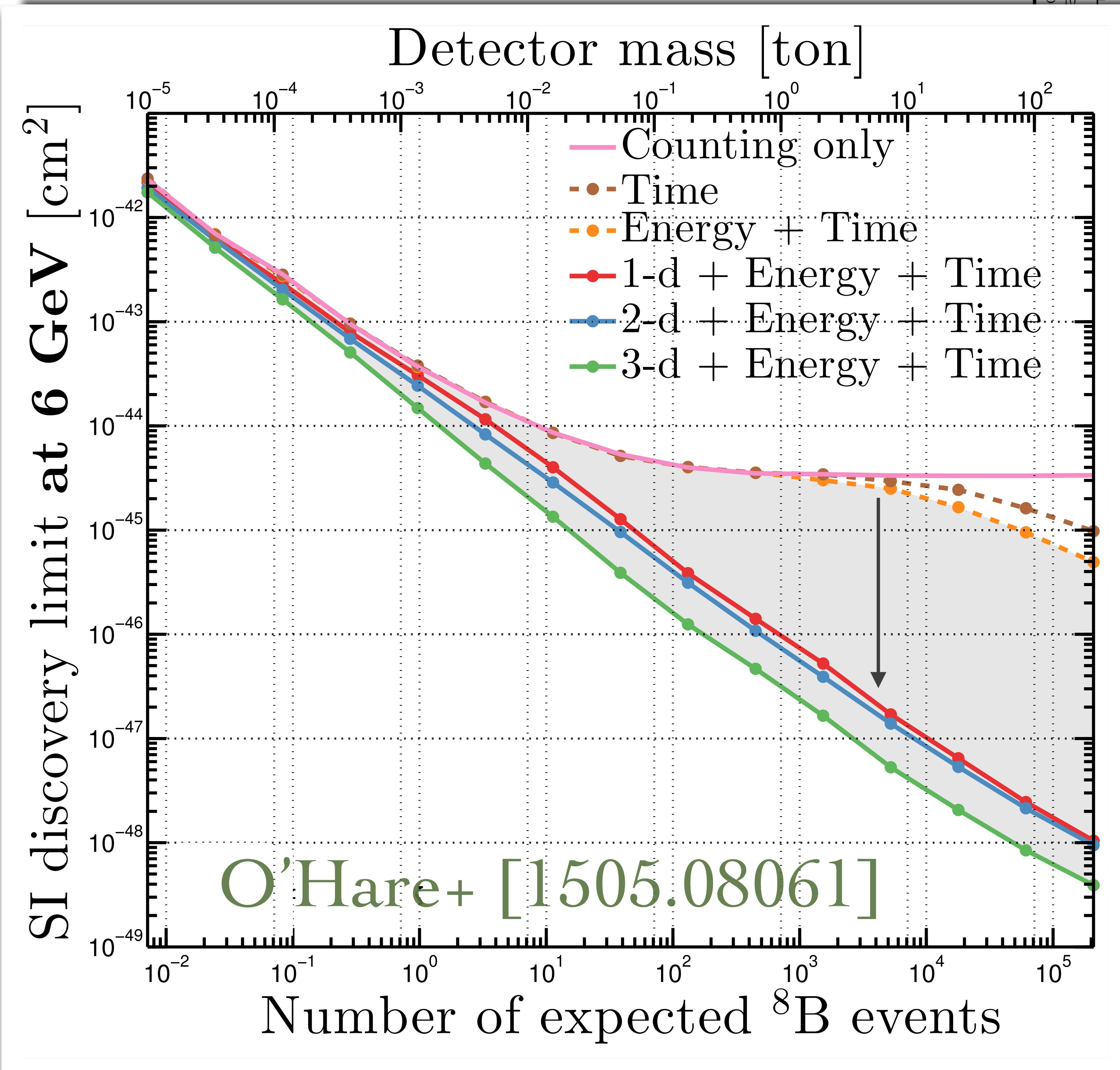
Nothing mimics dark matter, including solar neutrinos

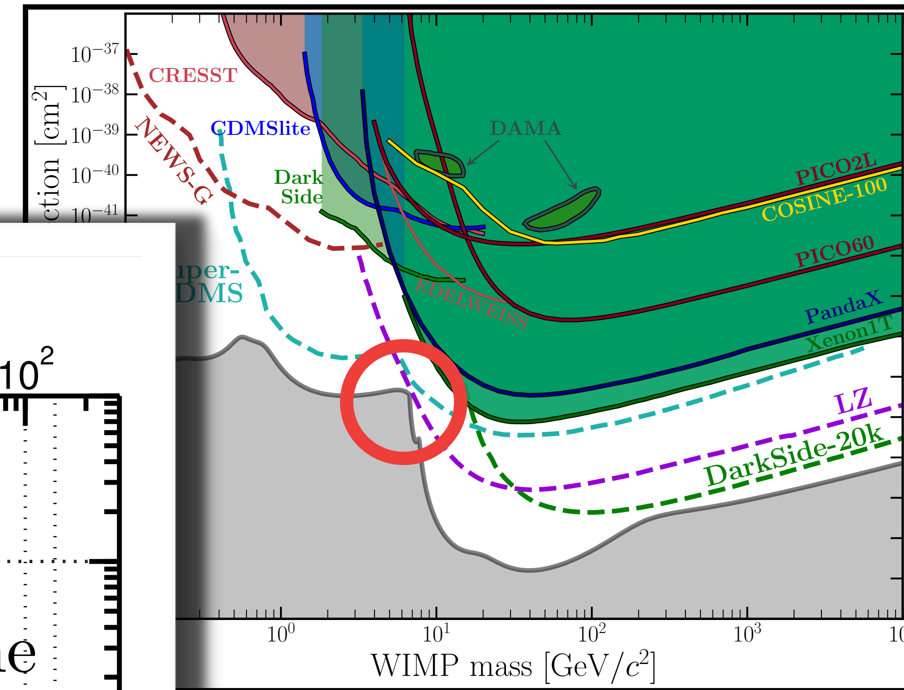


Nothing mimics dark matter, including solar neutrinos



Subtracting the neutrino background





Directional info <u>should be</u> powerful for subtracting Solar neutrinos

Physics case for a directional detector (numbers for idealised detector)

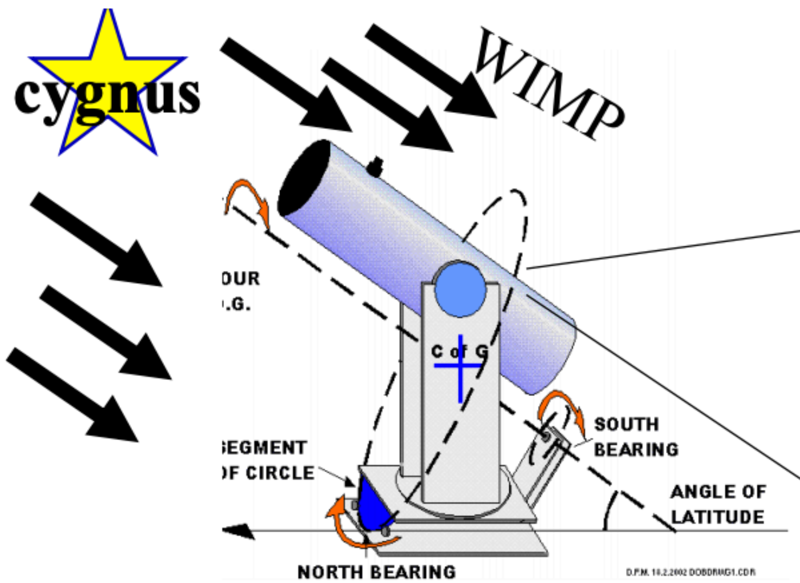
	Events in a non-directional detector	Events in a directional detector
Exclude background	O(10)	~10
Confirmation of **Galactic** signal	O(>100)/Impossible	~30
Discovery below neutrino floor	O(1000)/Impossible	O(10)
Measure DM velocity distribution	O(1000)/Impossible	O(100)

Methods of directional detection

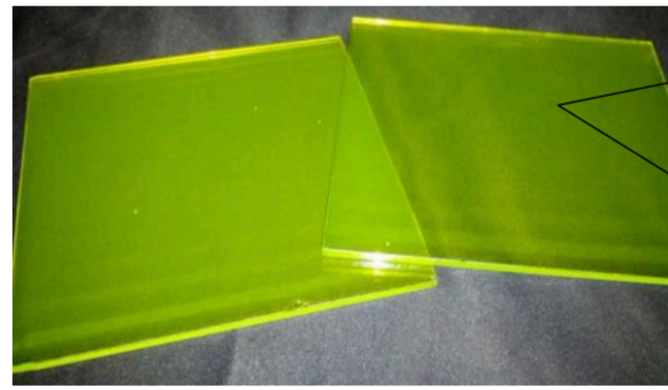
- Nuclear emulsions
- Anisotropic scintillators
- Nitrogen vacancy centres in diamond
- Carbon nanotubes
- Columnar recombination in LAr
- DNA
- Gas TPCs

T. Asada 1604.04199

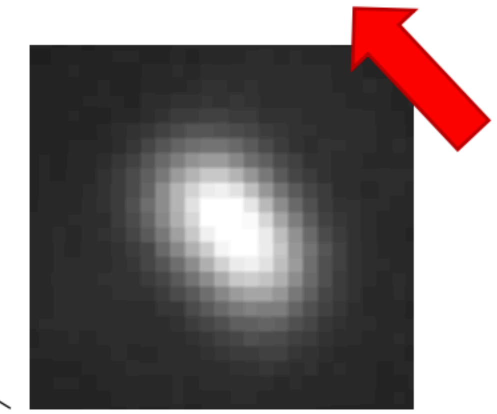
NEWSdm

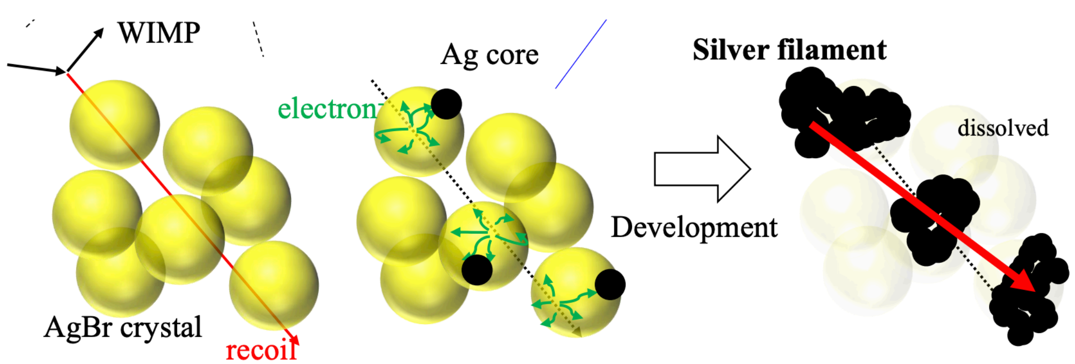


Fine crystal nuclear emulsion
NIT

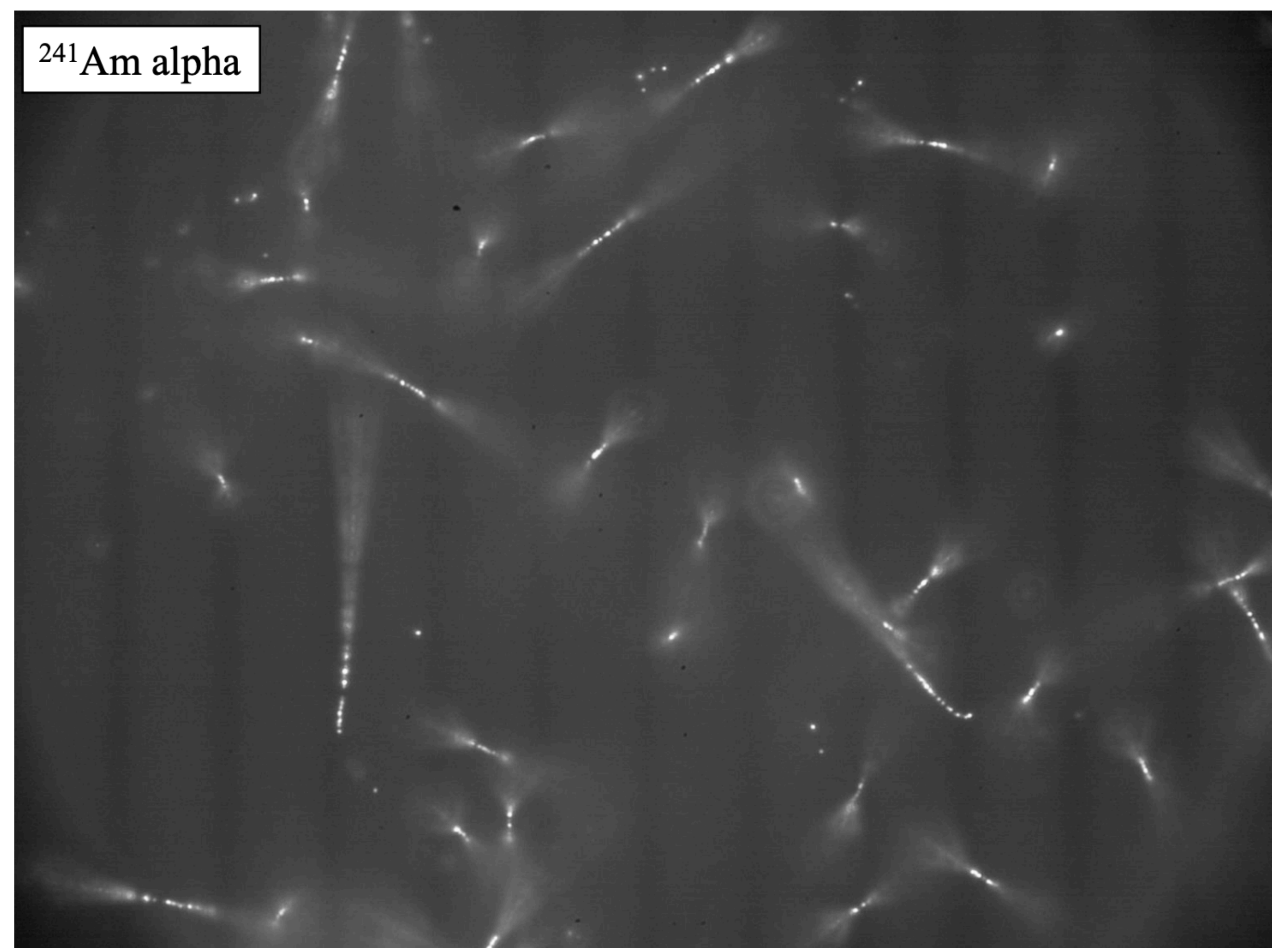


Direction recognizing

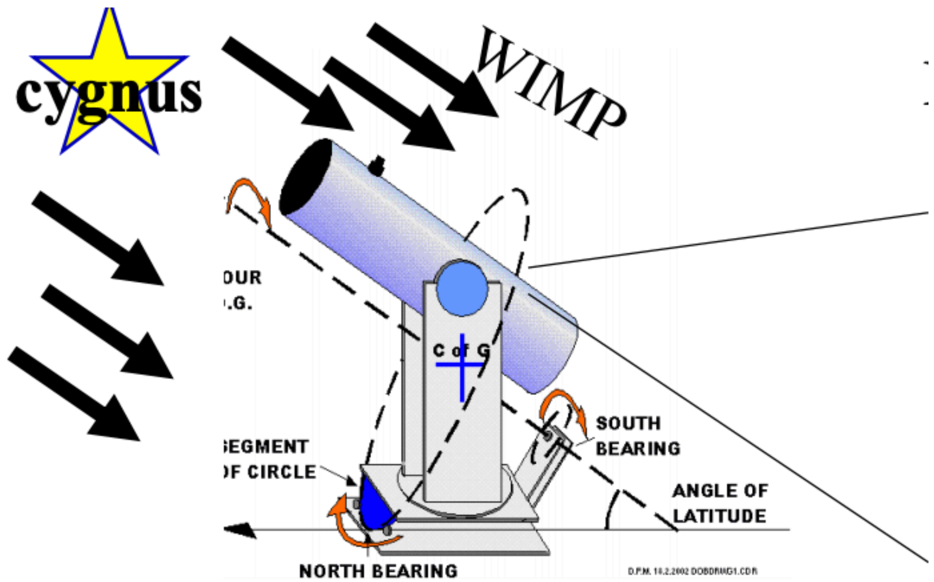




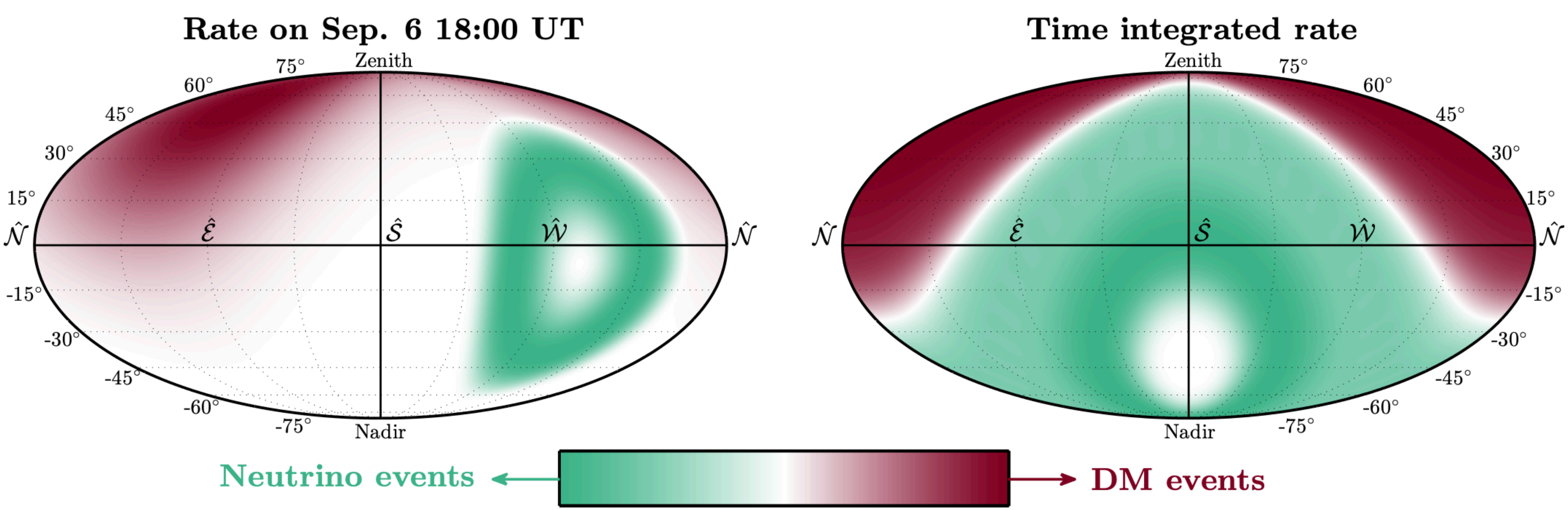
Nuclear emulsions-based directional WIMP search prototyping in LNGS
→ limited directionality: 2d without head/tail?
+ time-integrated



Time-integrated directional detection



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



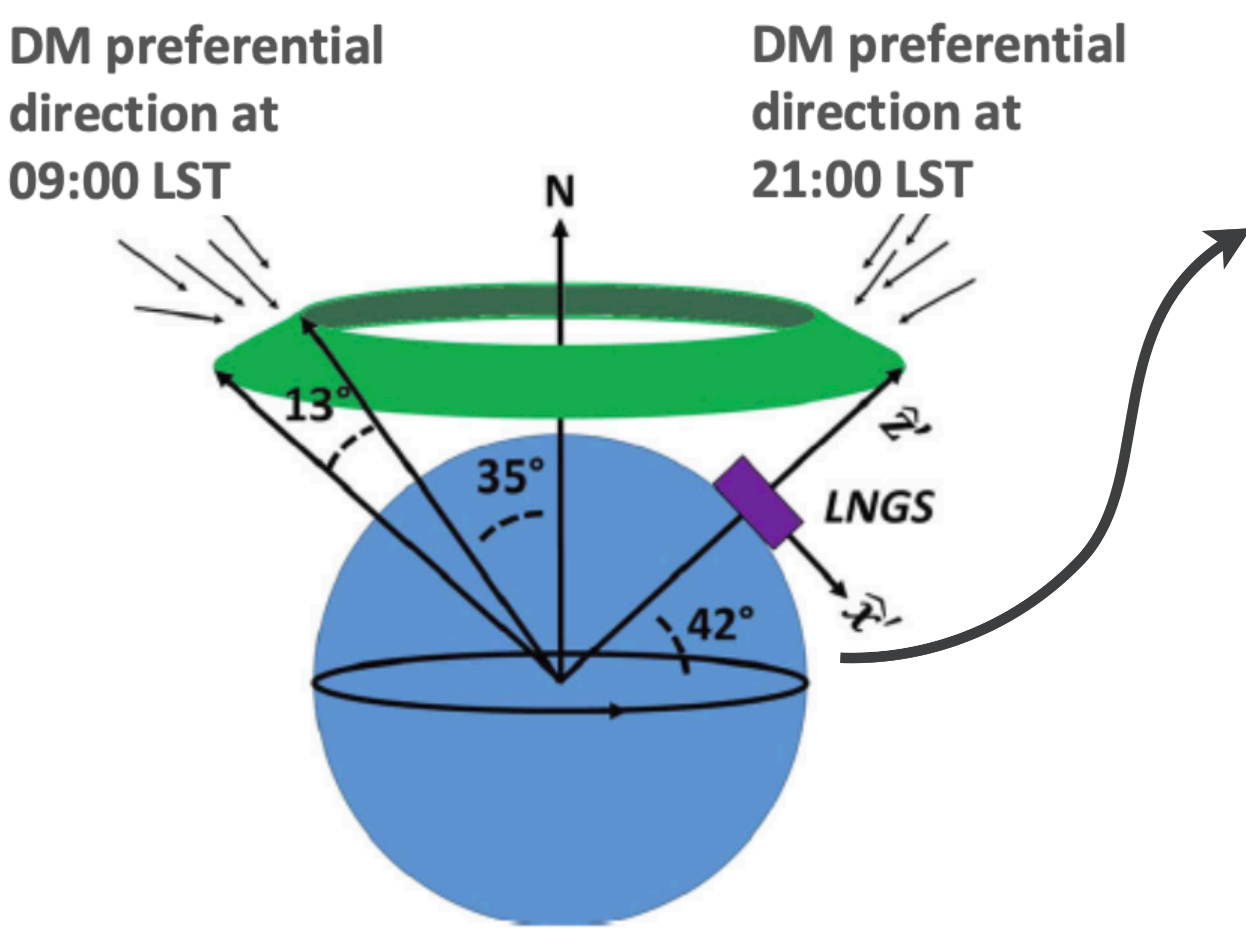
O'Hare et al. 1708.02959

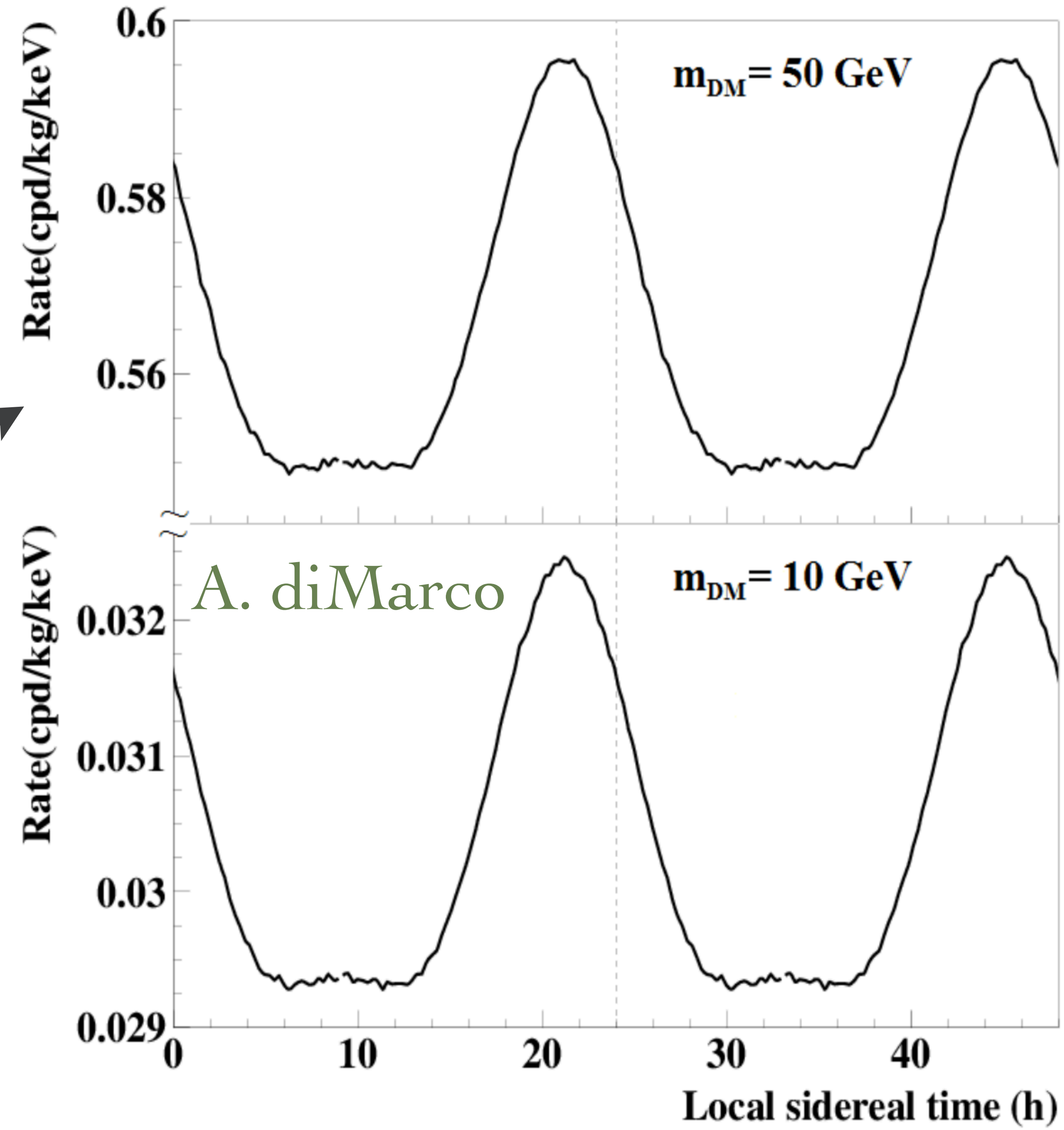
Anisotropic scintillators

- Materials where scintillation yield + pulse shape depends on direction of heavy impinging particle w.r.t crystal axes

e.g. anthracene, stilbene, $CdWO_4$, $ZnWO_4$, $MgWO_4$ are all proposed

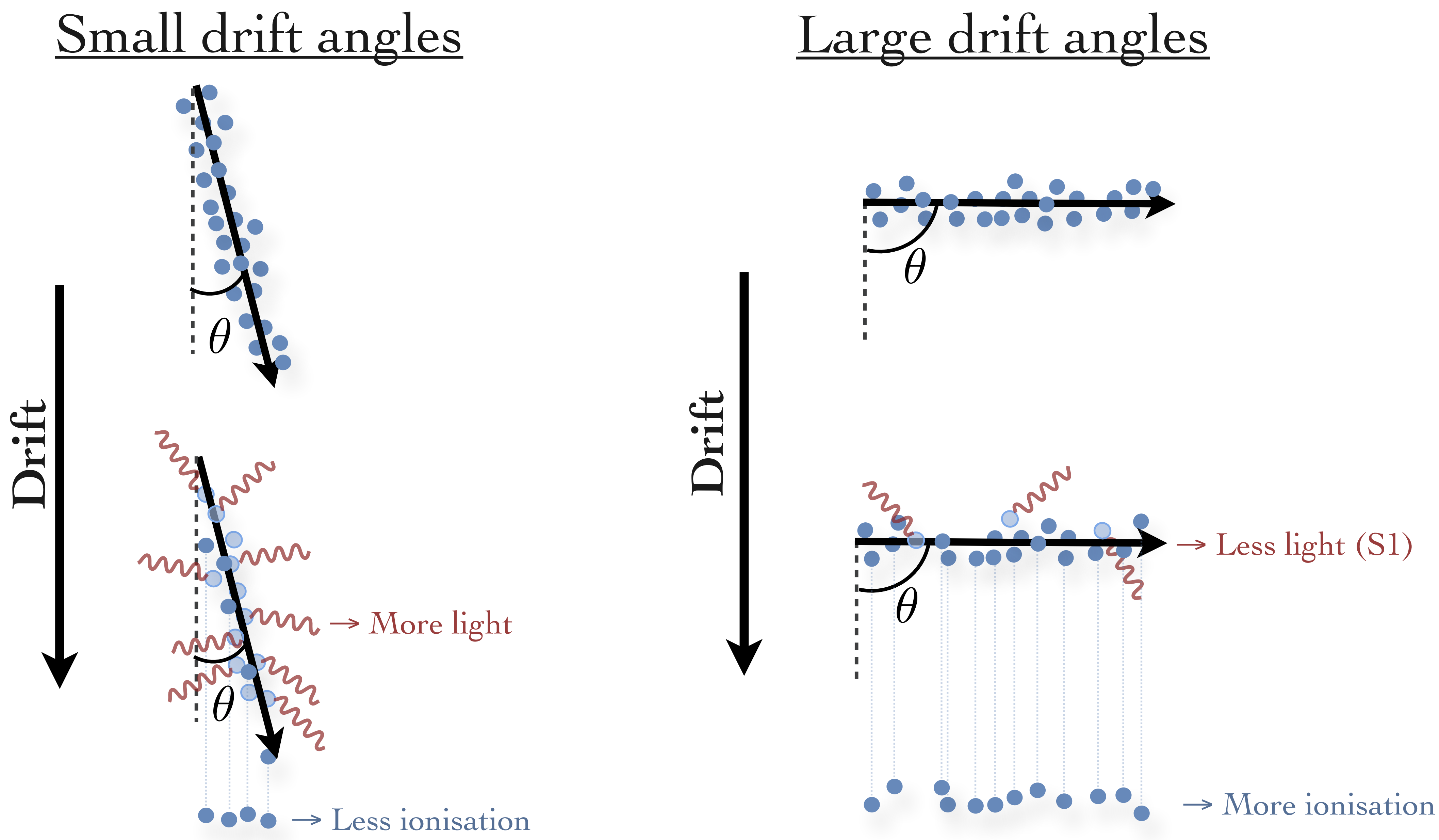
- Rely on diurnal modulation of rate for directionality



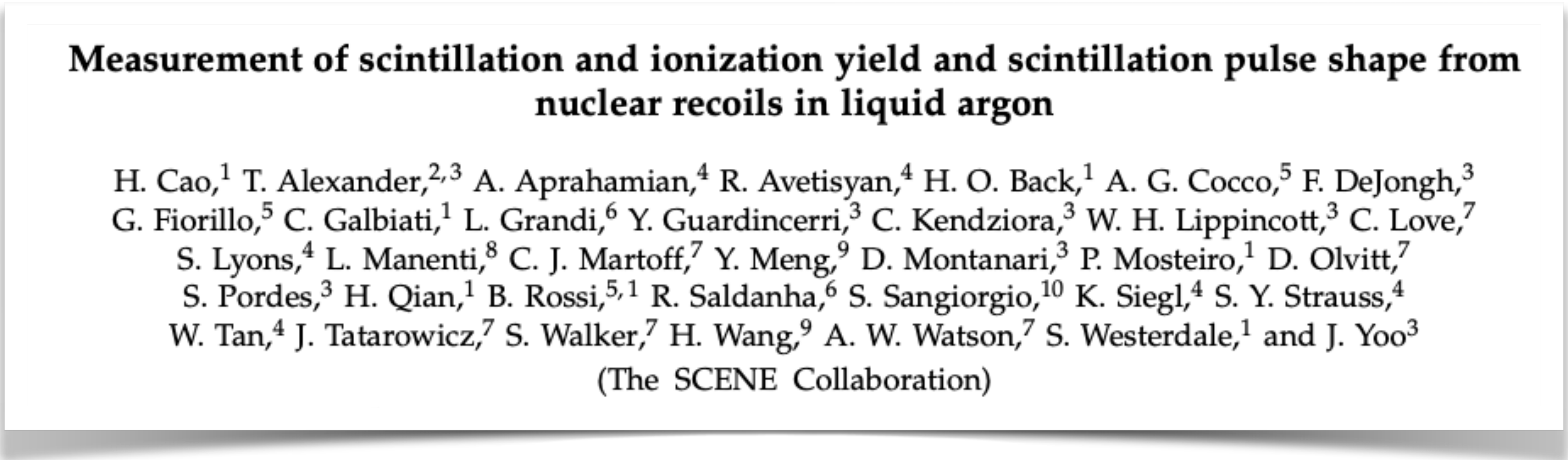


Columnar recombination in LXe/LAr?

→ Possible directional effect where charge/light yield depends on angle of recoil w.r.t. electric field D R Nygren 2013 J. Phys.: Conf. Ser. 460 012006



→ Interesting if achievable in existing ton-scale TPCs but it is 1-dimensional directionality, again with no head-tail signature

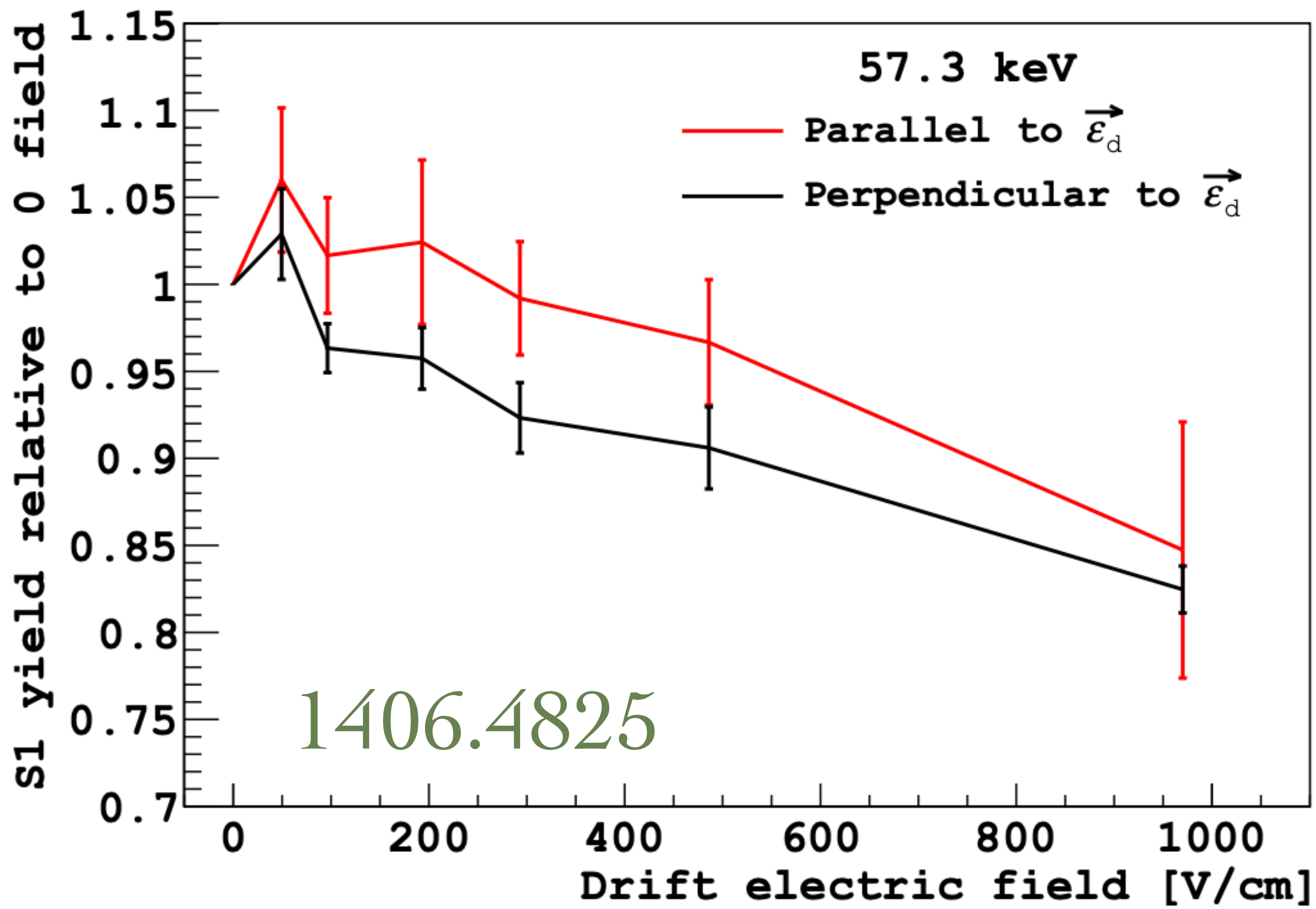


Measurement of scintillation and ionization yield and scintillation pulse shape from nuclear recoils in liquid argon

H. Cao,[1] T. Alexander,[2,3] A. Aprahamian,[4] R. Avetisyan,[4] H. O. Back,[1] A. G. Cocco,[5] F. DeJongh,[3] G. Fiorillo,[5] C. Galbiati,[1] L. Grandi,[6] Y. Guardincerri,[3] C. Kendziora,[3] W. H. Lippincott,[3] C. Love,[7] S. Lyons,[4] L. Manenti,[8] C. J. Martoff,[7] Y. Meng,[9] D. Montanari,[3] P. Mosteiro,[1] D. Olvitt,[7] S. Pordes,[3] H. Qian,[1] B. Rossi,[5,1] R. Saldanha,[6] S. Sangiorgio,[10] K. Siegl,[4] S. Y. Strauss,[4] W. Tan,[4] J. Tatarowicz,[7] S. Walker,[7] H. Wang,[9] A. W. Watson,[7] S. Westerdale,[1] and J. Yoo[3]
(The SCENE Collaboration)

- Possible hint in LAr

- Almost certainly unobservable in LXe
  (at interesting energies)



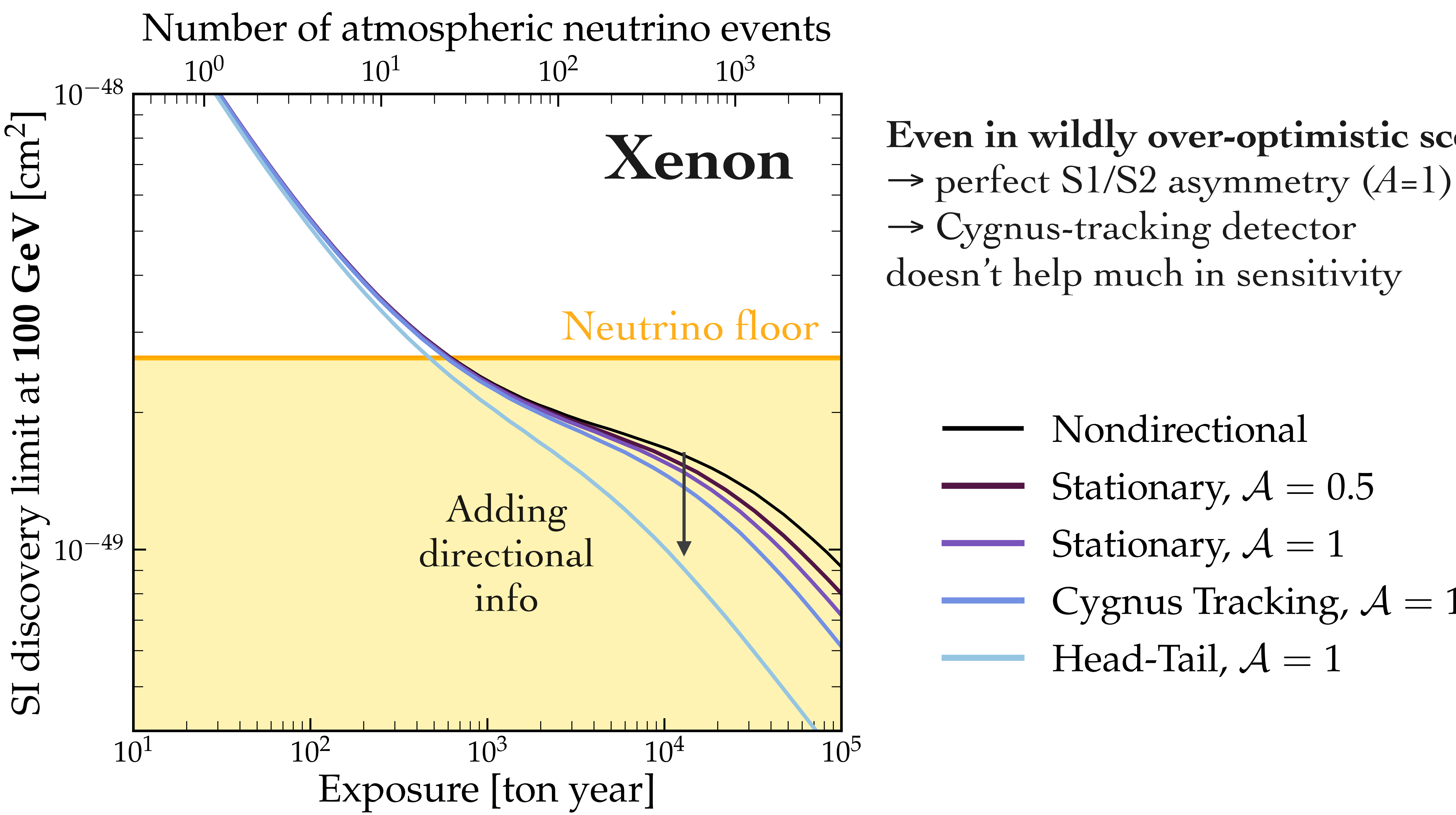
Can we overcome the neutrino floor at high masses?

2002.07499

Ciaran A. J. O'Hare[1,a]

[1]*Sydney Consortium for Particle Physics and Cosmology, University of Sydney, School of Physics, NSW 2006, Australia*

(Dated: September 28, 2020)



Even in wildly over-optimistic scenario
→ perfect S1/S2 asymmetry ($\mathcal{A}$=1)
→ Cygnus-tracking detector
doesn't help much in sensitivity

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*

DNA?

1206.6809

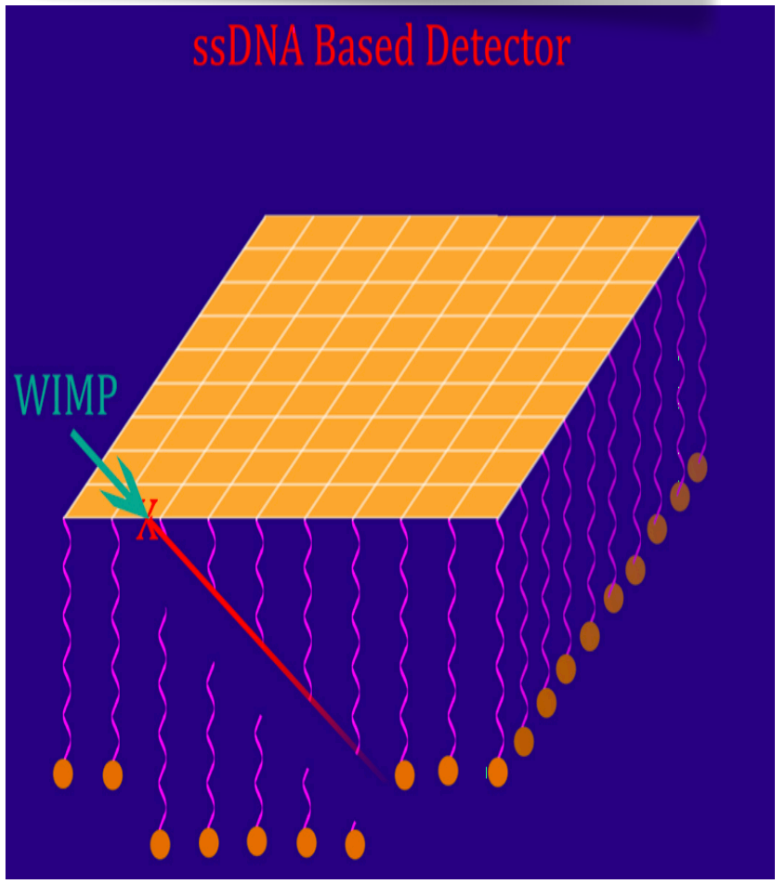
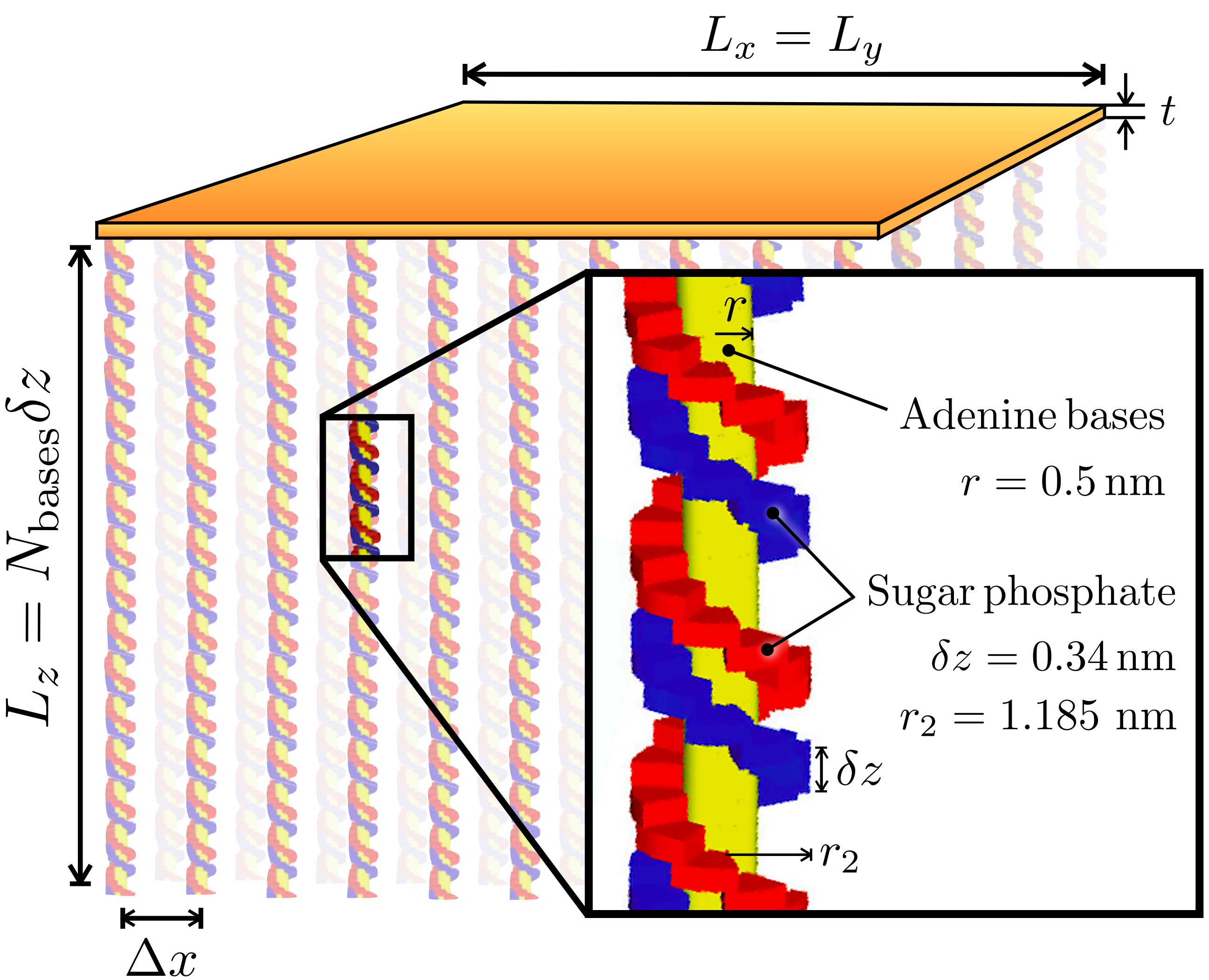
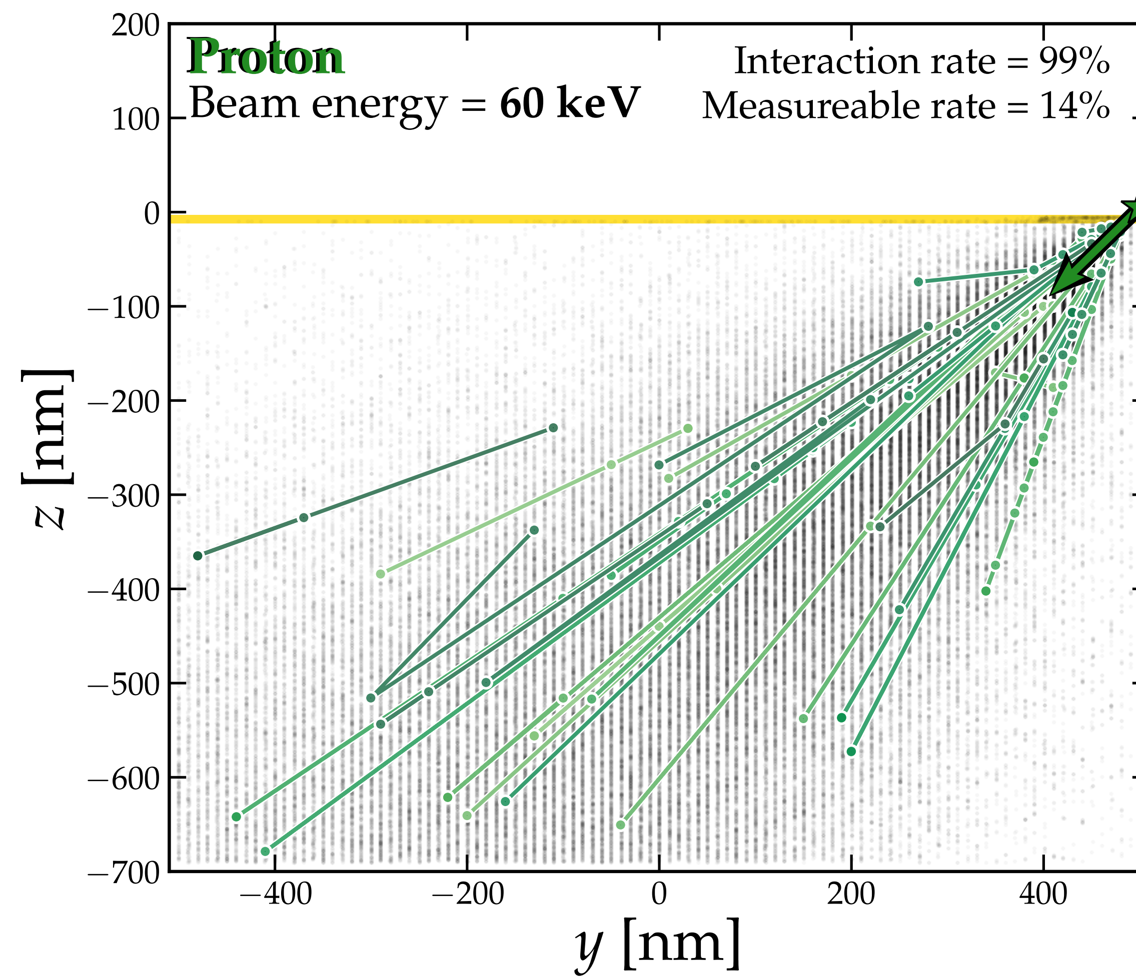


FIG. 2: ssNA/Au Tracking Chamber: A WIMP from the Galaxy scatters elastically with a gold nucleus situated in a thin gold foil. The recoiling Au nucleus traverses hanging strings of single stranded NA, and severs any ssNA it hits. The location of the breaks can be found by amplifying and sequencing the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

DNA as a particle detector?





Work in progress with students at Sydney

→ Probably not a good DM detector (low mass), but still interesting

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

Which technology?

	Pros	Cons	Readiness
Nuclear emulsions	• high target density • nm tracking	• Time integrated readout • 2-dimensional • No obvious head-tail	In prep.
Columnar recombination	• high target density • Uses existing ton-scale detectors (LAr/LXe)	• High energy threshold • 1-dimensional • No head-tail	Unclear
Anisotropic scintillators	• high target density • Benefits from good BG discrimination in scintillators	• Unverified directionality • Reliant on daily modulation	Low
DNA	• Potentially very cheap • Cool idea?	• Totally unverified on all fronts • May not even be possible in principle	Very low
Gas time projection chambers	• Full 3-D tracking • Excellent NR/ER disc. • No cryogenics	• Need big volumes to reach competitive target mass	Good!

CYGNUS

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

[2008.12587]

CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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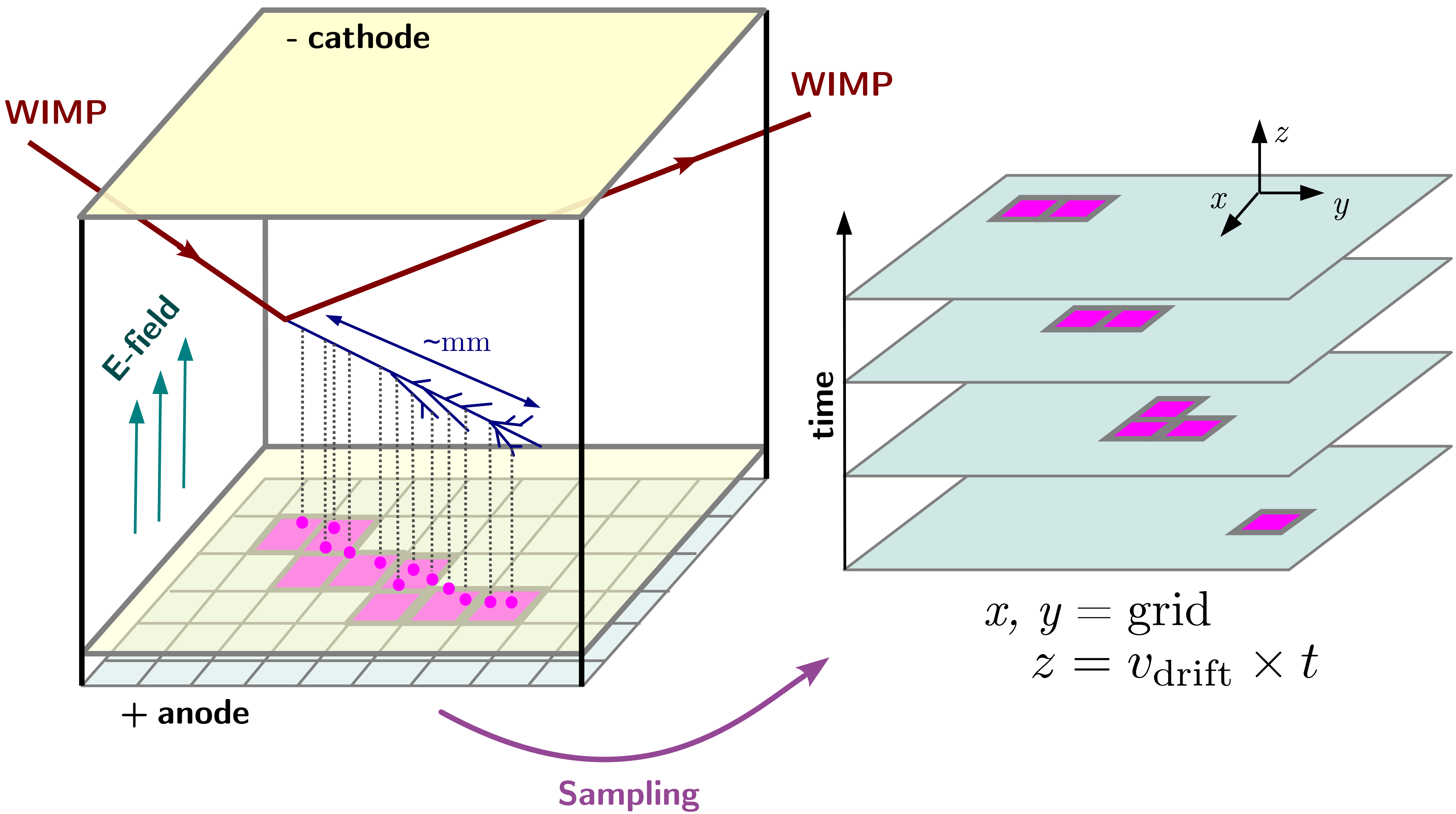
Gas time projection chamber (TPC)



CYGNUS TPC: Basic Parameters

1000 m^3 of He:SF$_6$ at atmospheric pressure and temperature

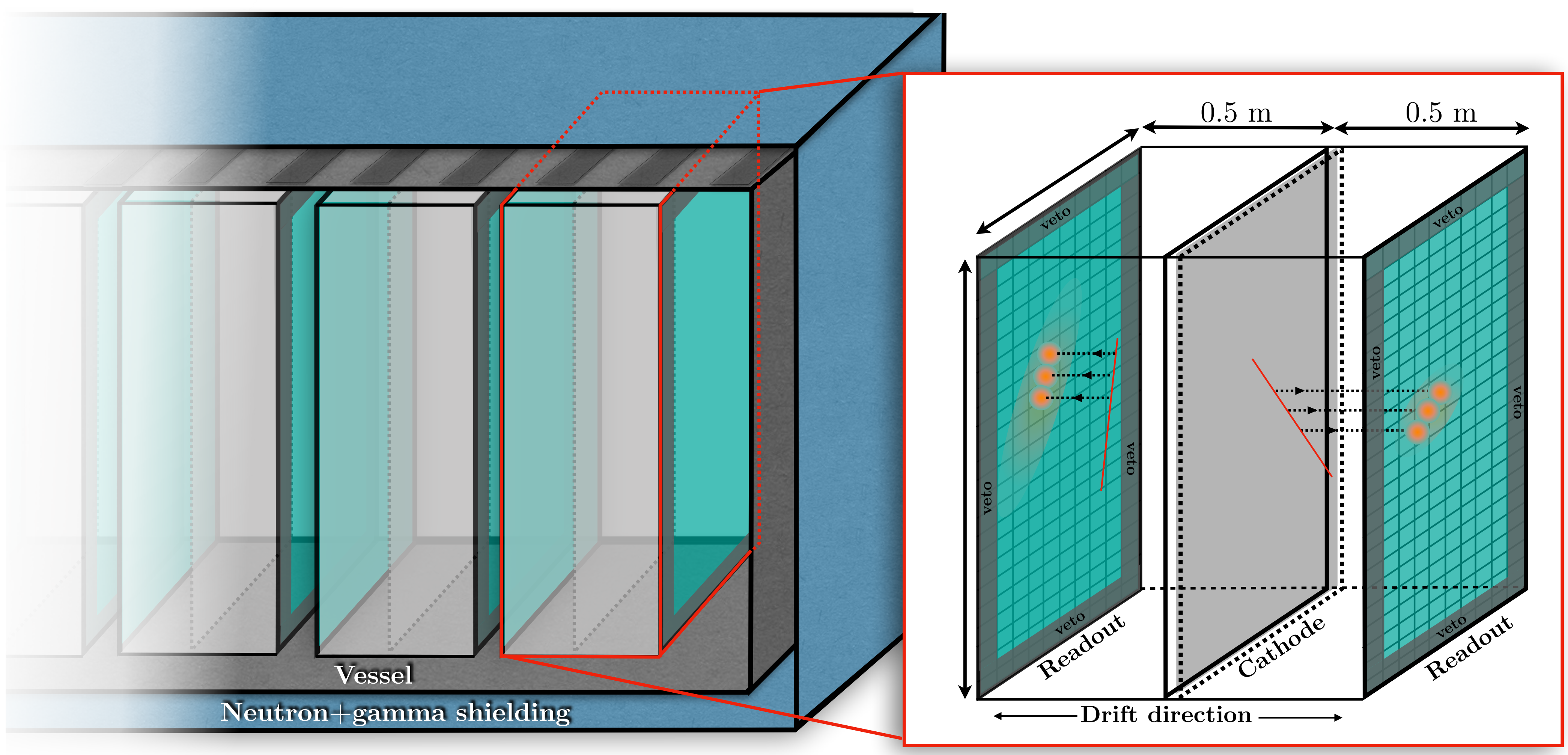
Big volume, but there are certain advantages

→ Can be modular and/or multi-site.

→ No cryogenics, no restrictions on the shape of the expt.

→ Atmospheric pressure so thinner vessel walls possible

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



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

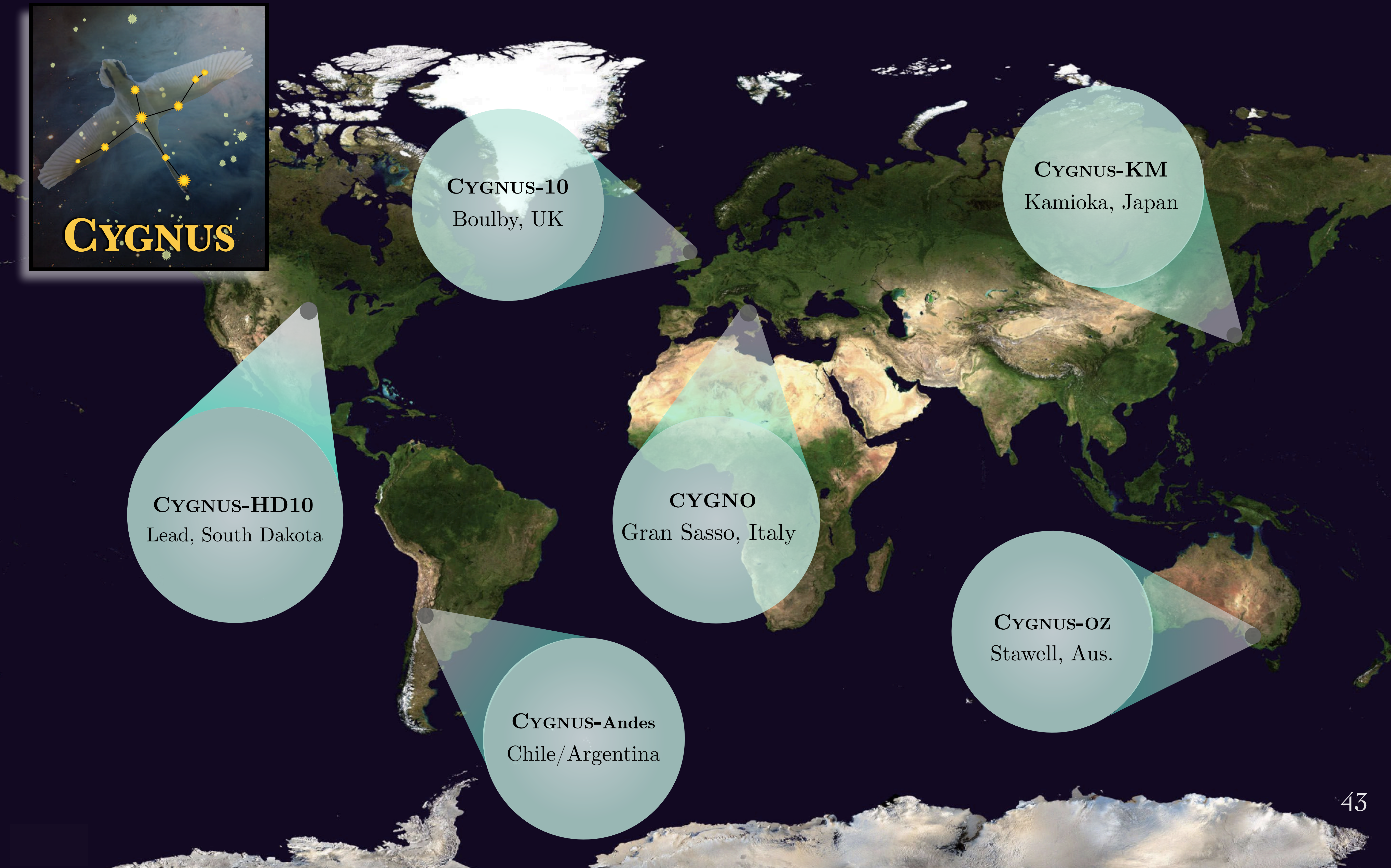
Why SF_6?

- ☑ **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** $\langle S_{\text{proton}} \rangle$ 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

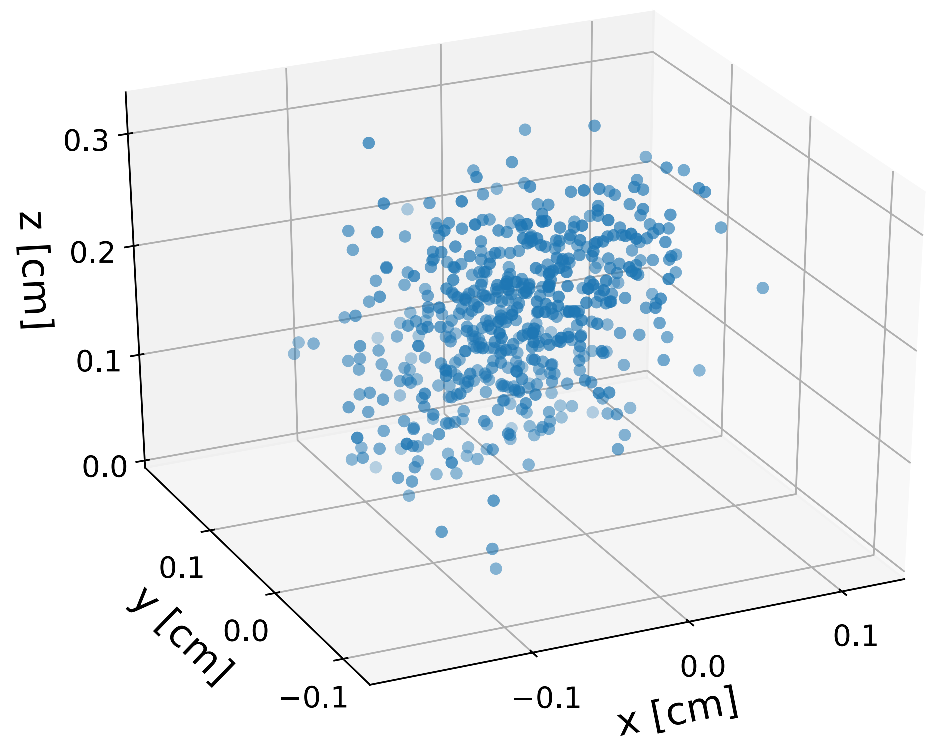
Possible underground sites



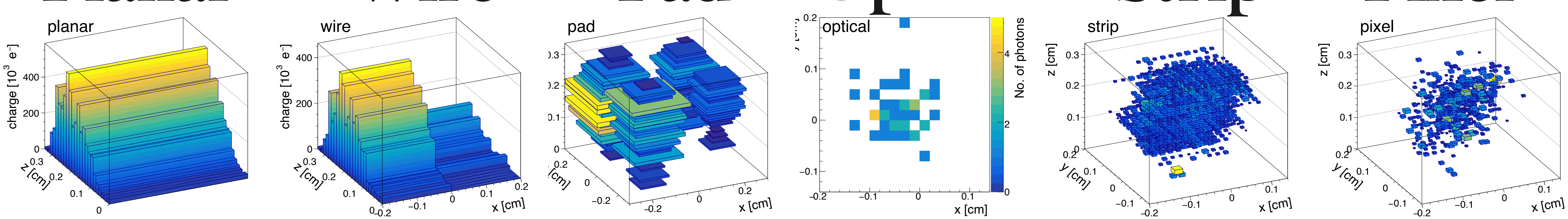
Readout technologies

Important advancement in this study
→ ground-up simulation of six readout technologies for reconstructing low energy electron/nuclear recoils

Recoil track

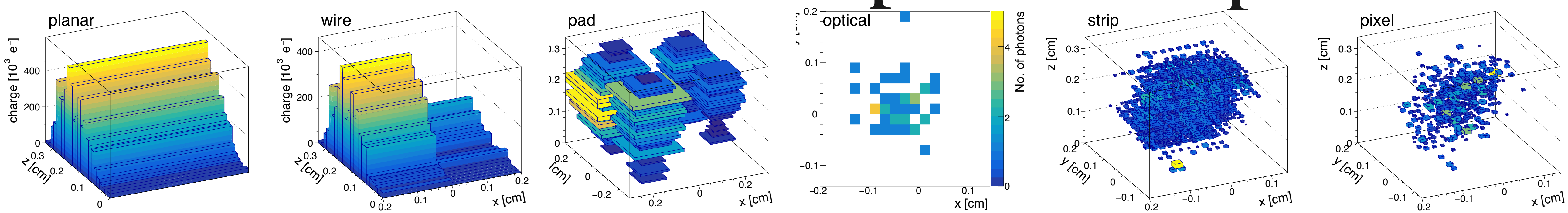


Planar **Wire** **Pad** **Optical** **Strip** **Pixel**



Readout technologies

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



1D | 1D | 2D | 3D (when combined with PMTs) | 3D | 3D

Simplest readouts → Worst directional sensitivity but lower cost

Most complex readouts → Best directional sensitivity but higher cost

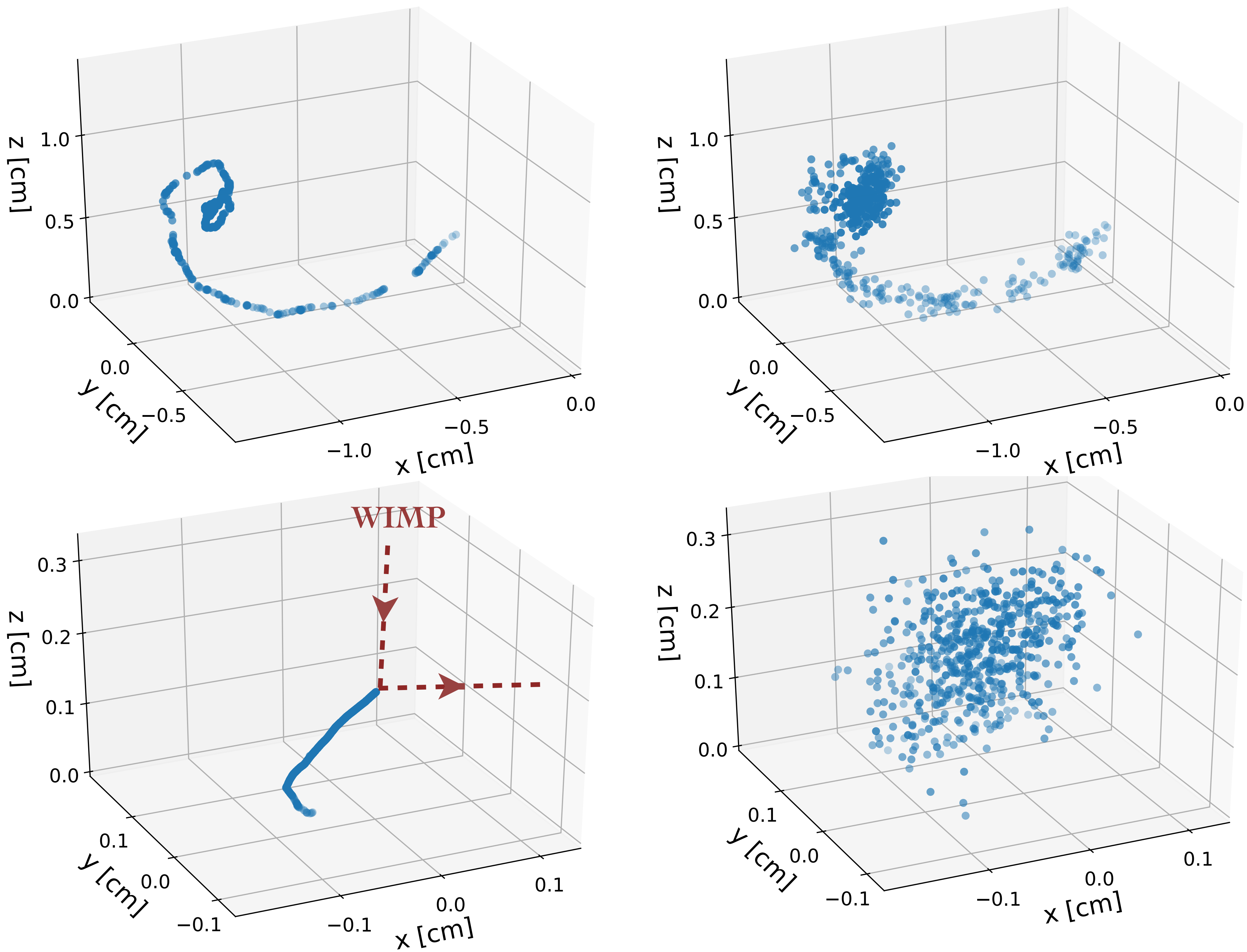
Balancing cost *vs* directional performance is the goal of this study

Recoil tracks (in He+SF_6 at 1 atm)

Before drift | After 25 cm drift

Electron: 20 keV

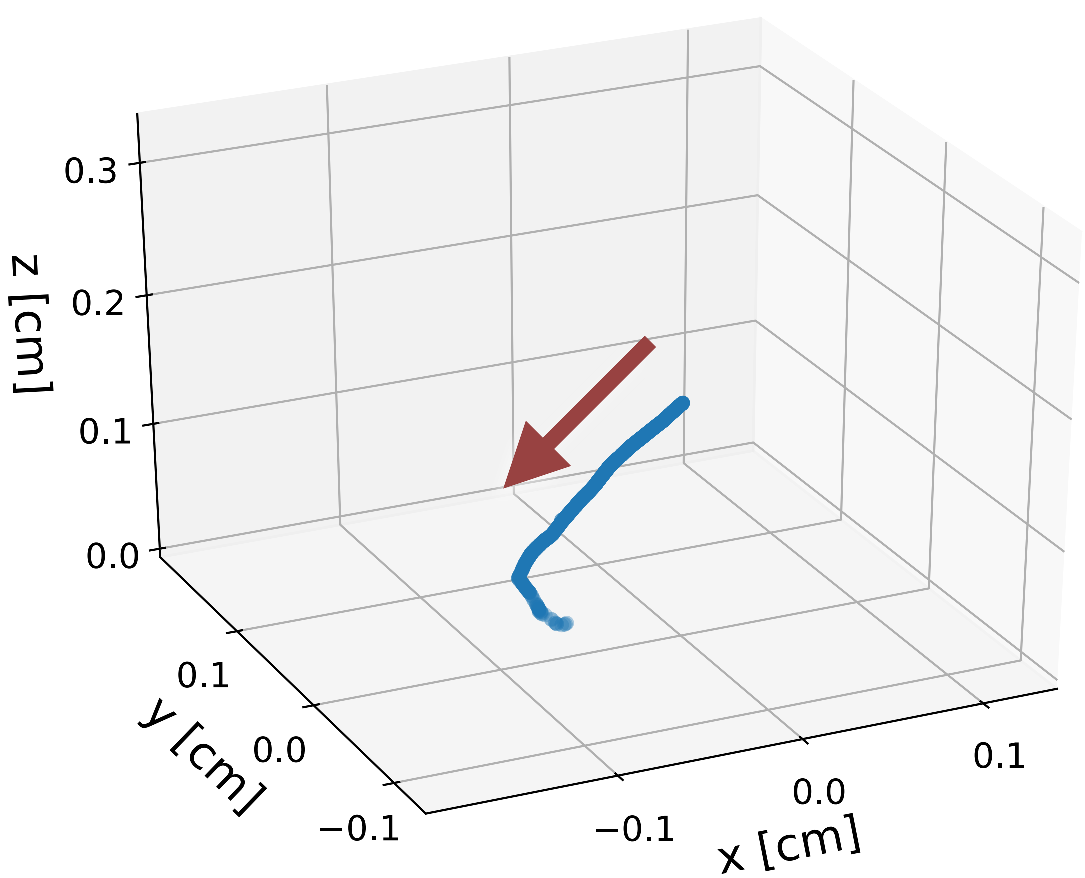
He nucleus: (25 keVr)



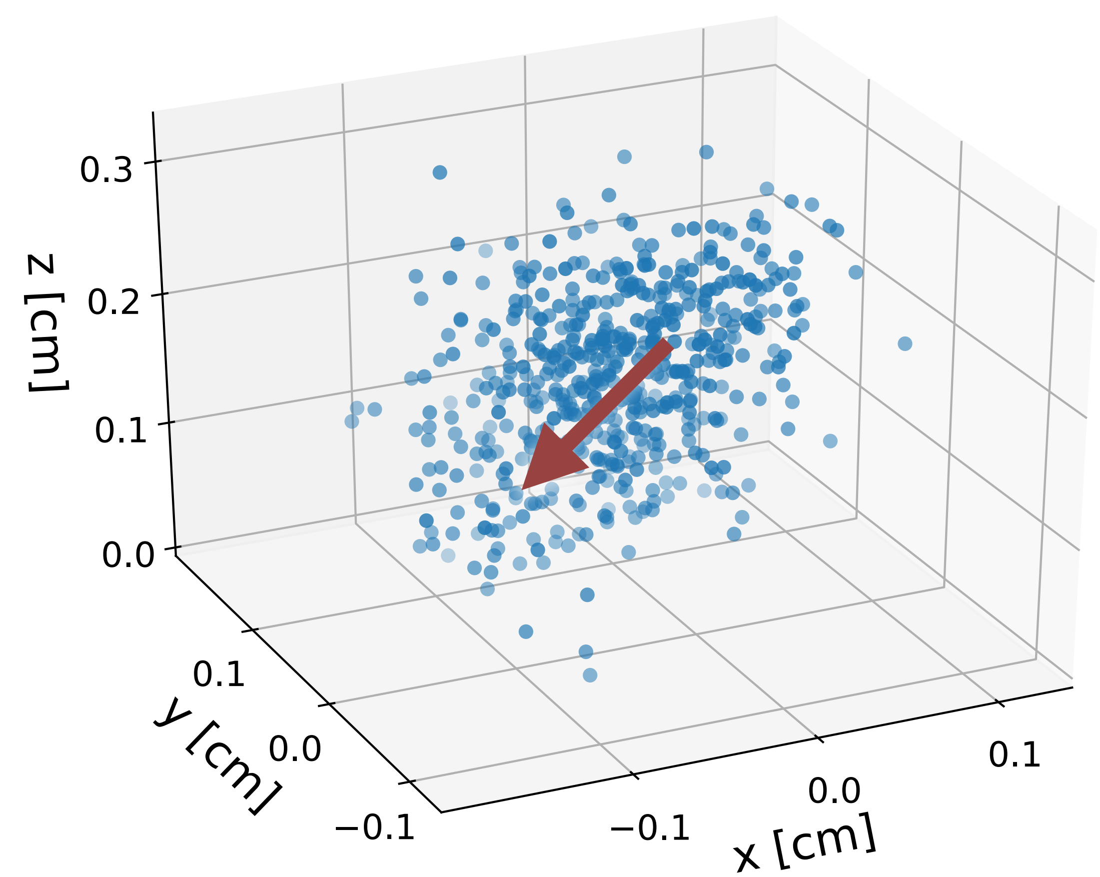
Angular resolution

Limited by two main effects: straggling & diffusion

Original track



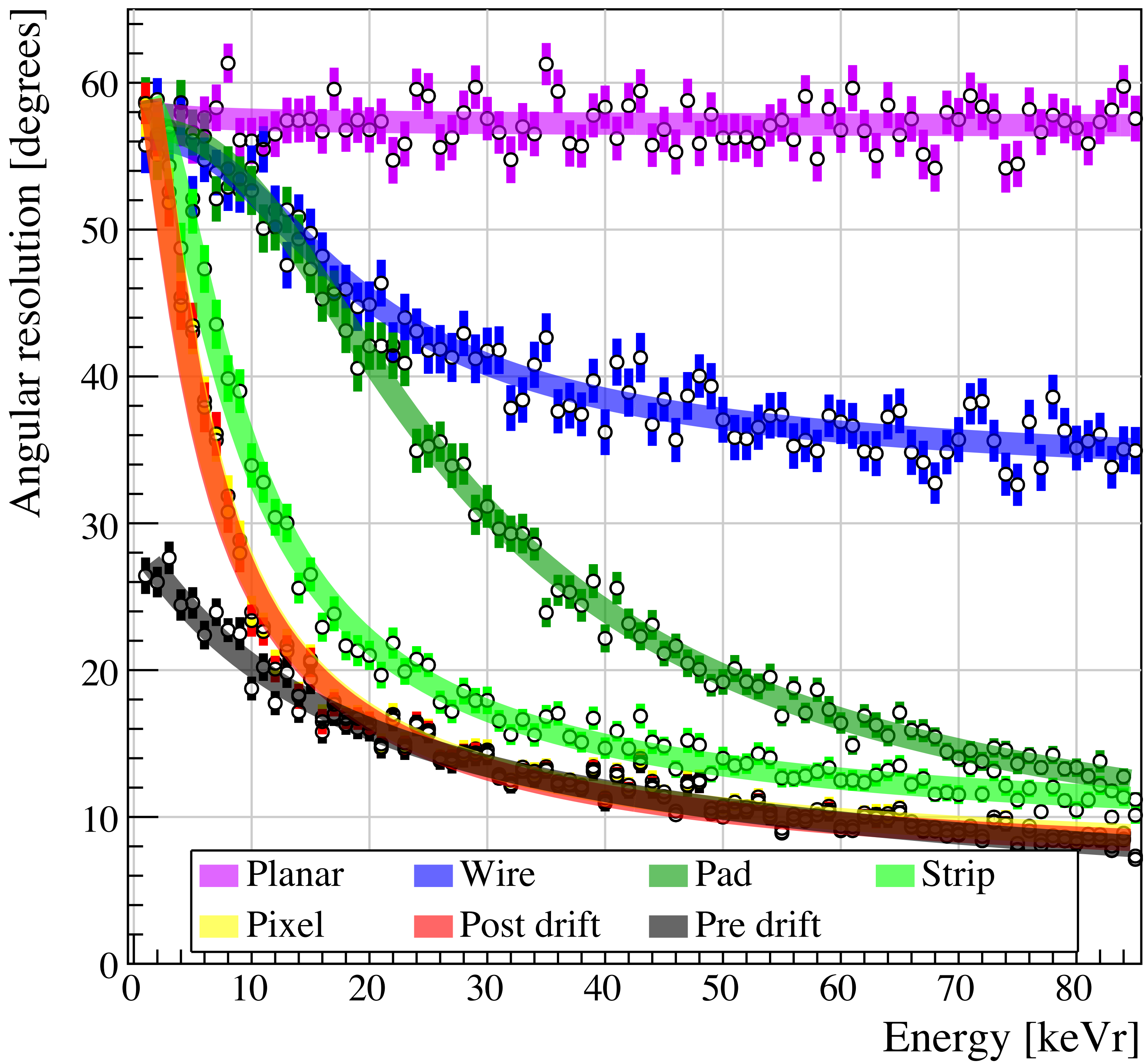
Track after 25 cm drift



25 keVr Helium recoil in *755:5* Torr of He:SF_6

Angular resolution

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



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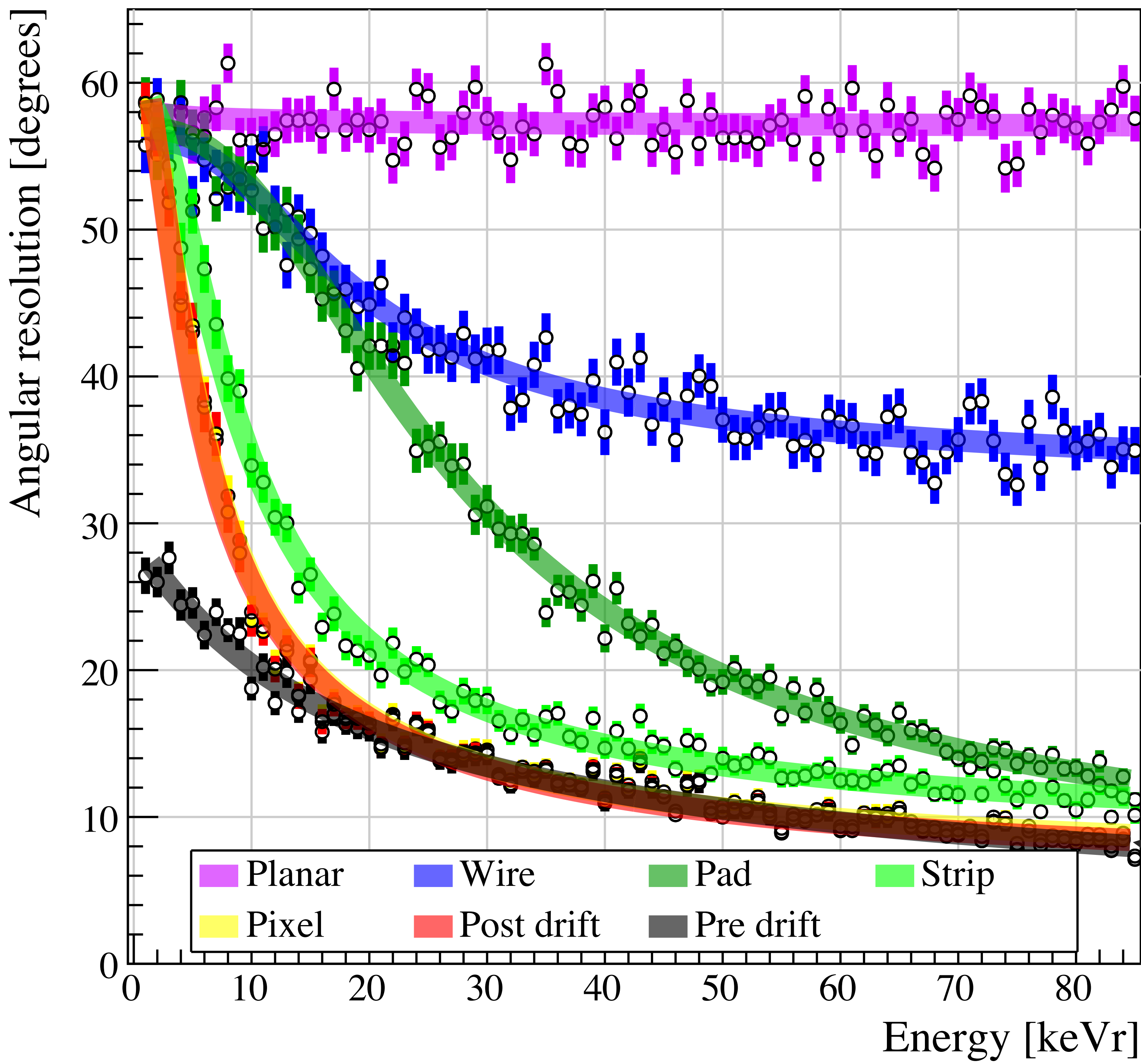

Pre-drift: the track is well preserved, loss in directionality at low energies just due to straggling

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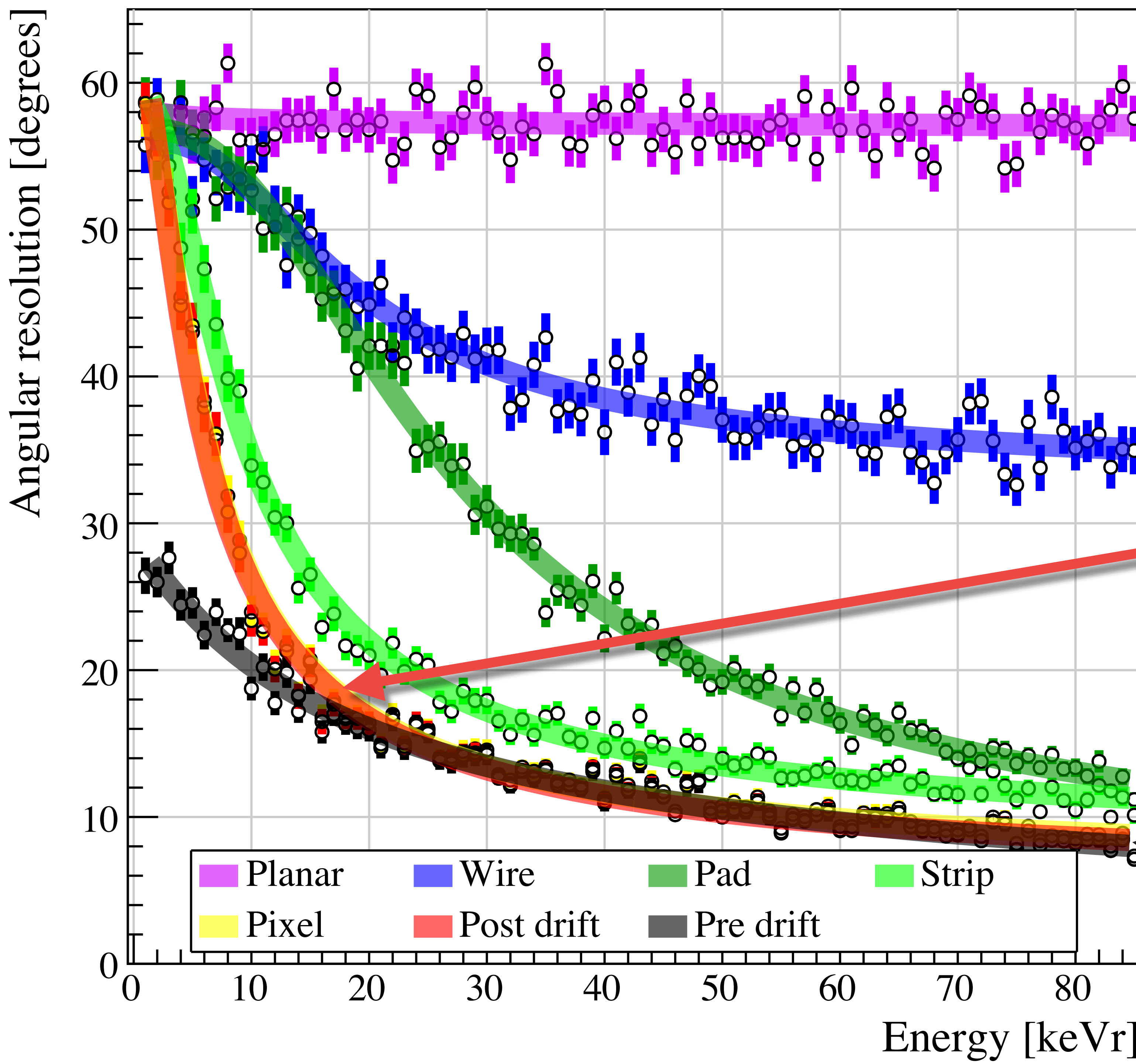

Post-drift: directionality washed out by diffusion especially for low energy tracks

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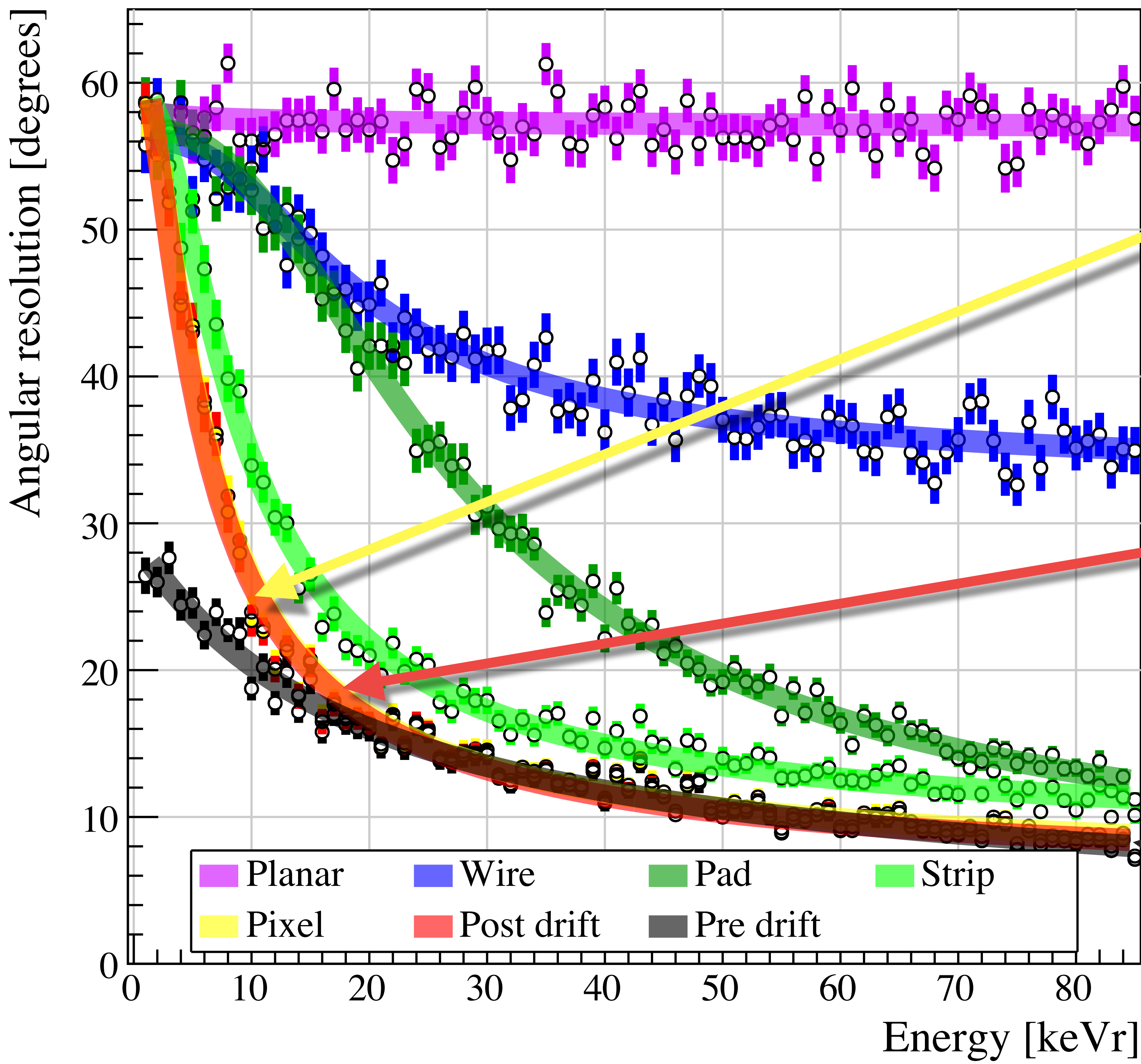

Pixel readout performs as good as post-drift → almost no loss in directionality after charge readout (promising!)

Post-drift: directionality washed out by diffusion especially for low energy tracks

Pre-drift: the track is well preserved, loss in directionality at low energies just due to straggling

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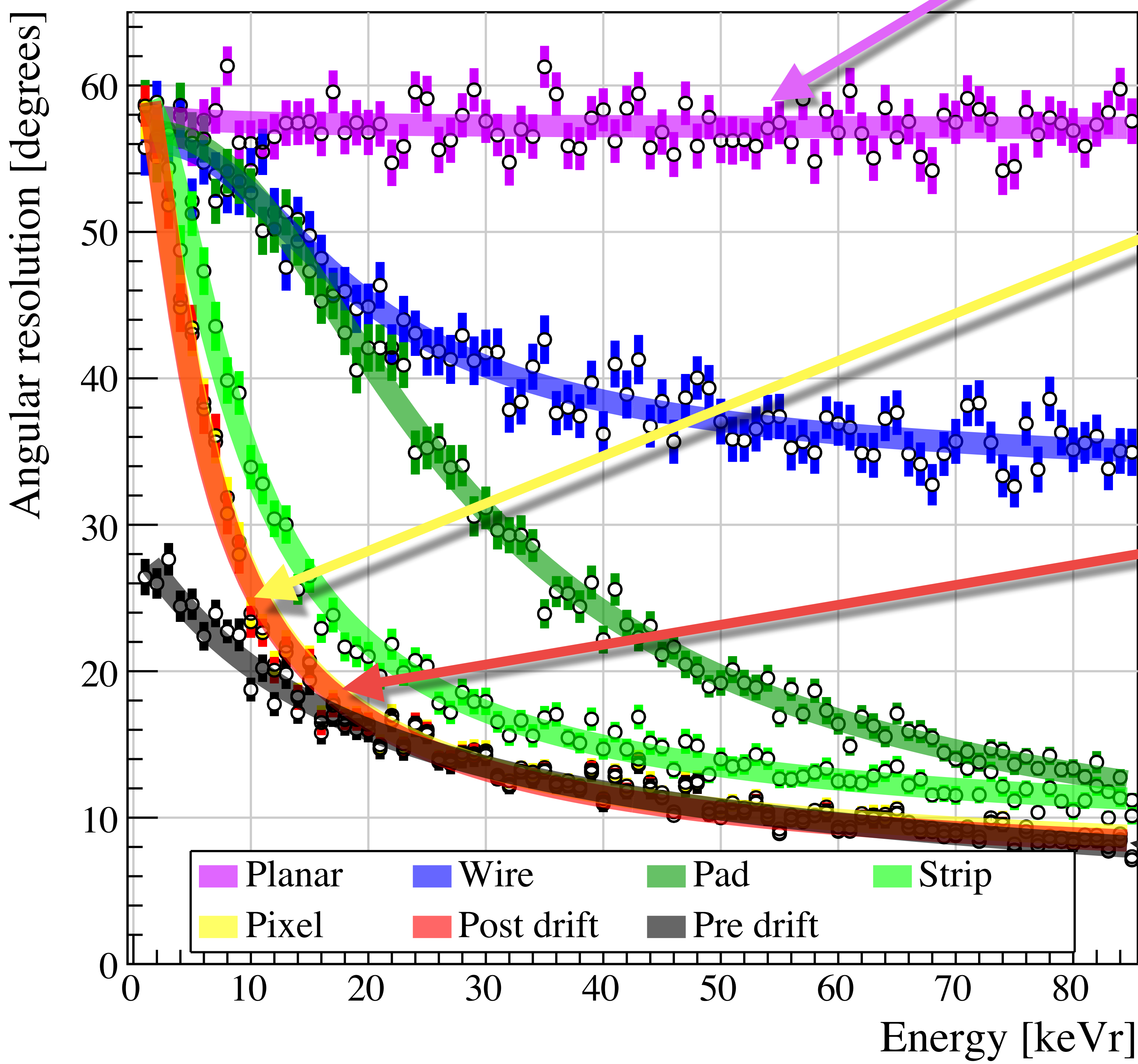


Planar readout performs the worst here, readout so simple that no angular information is measurable

Pixel readout performs as good as post-drift → almost no loss in directionality after charge readout (promising!)

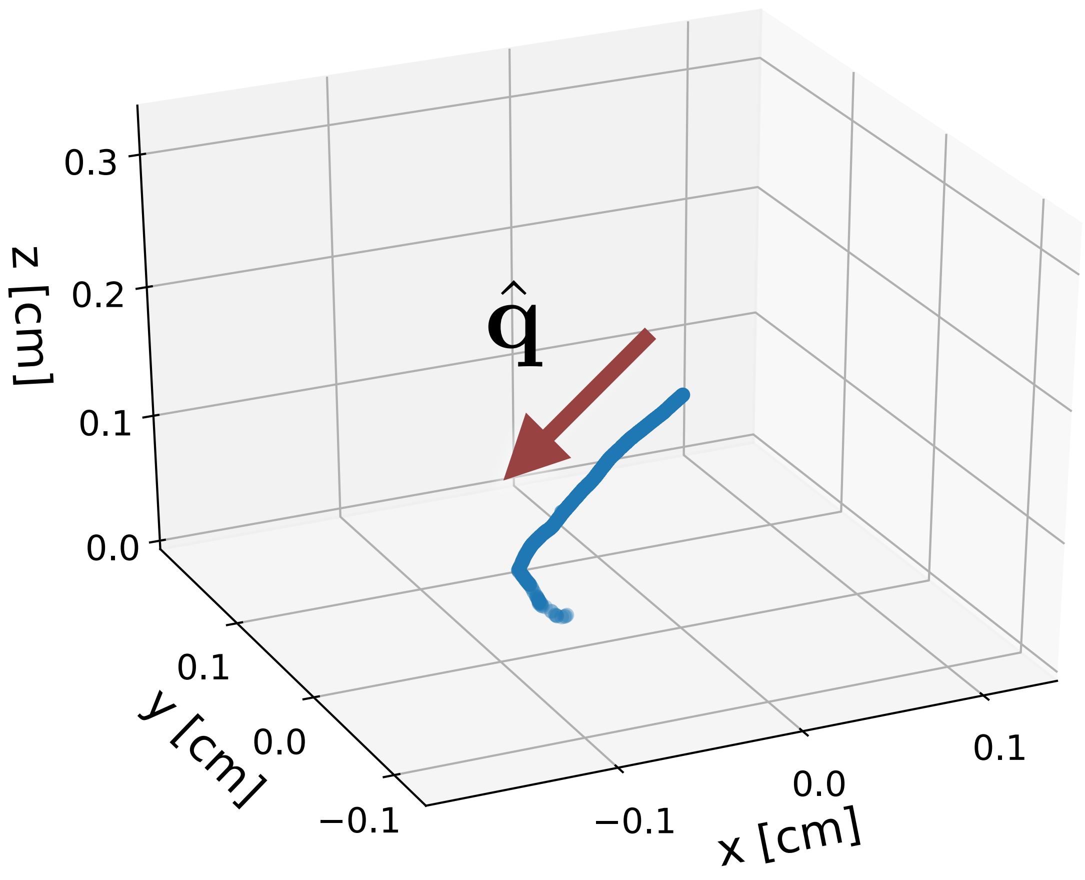
Post-drift: directionality washed out by diffusion especially for low energy tracks

Pre-drift: the track is well preserved, loss in directionality at low energies just due to straggling

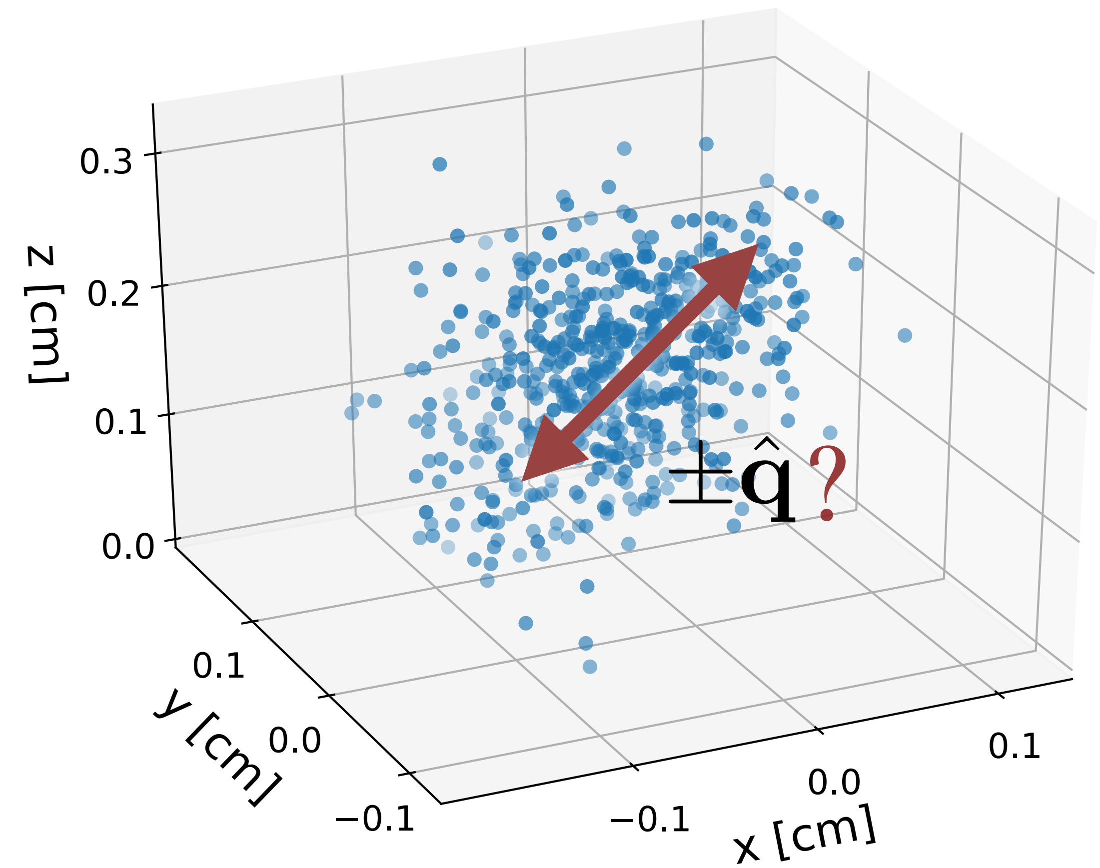
Head-tail recognition

Ability to recognise the forward-backward sense of a recoil

Original track

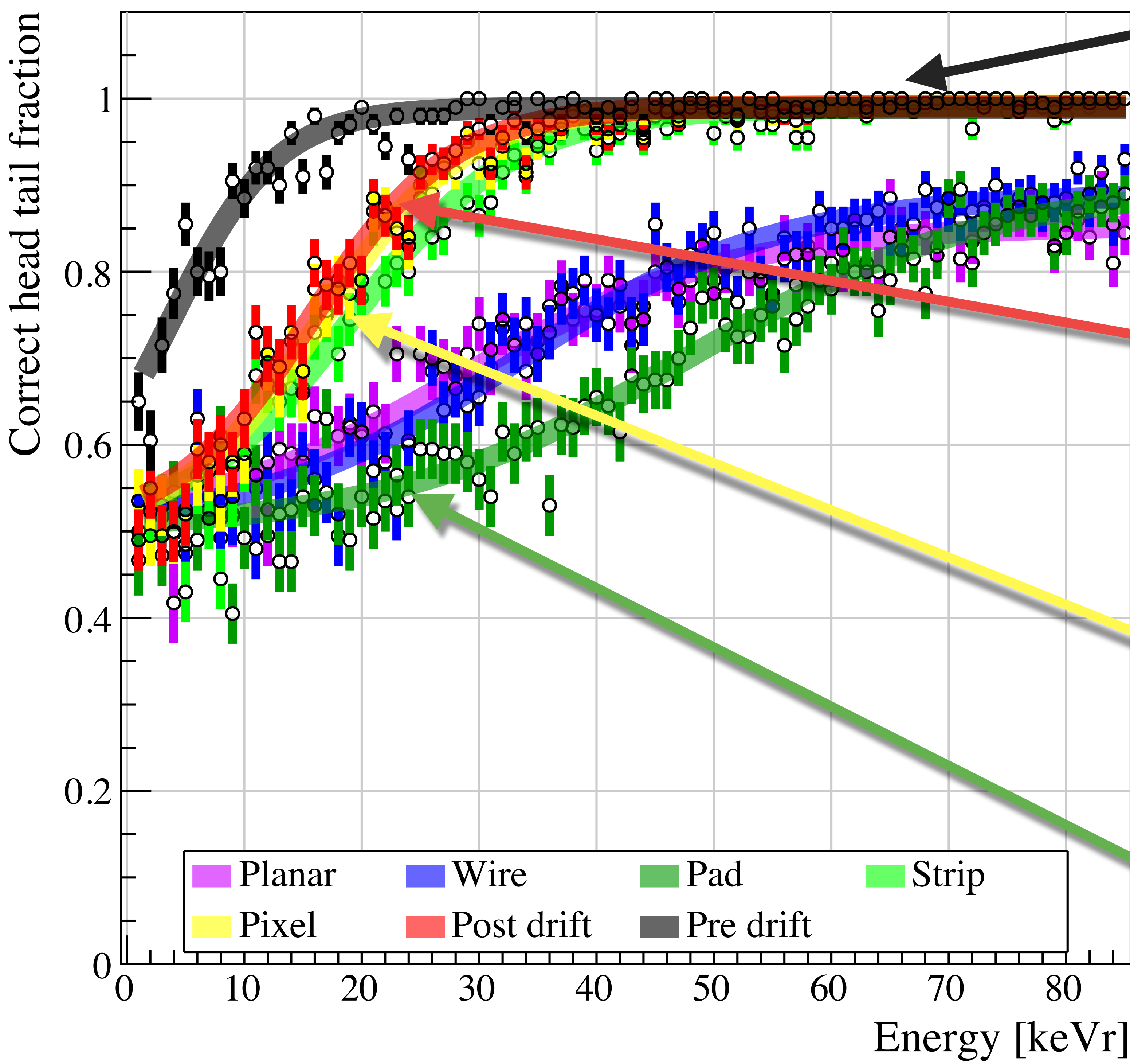


Track after 25 cm drift



Head-tail recognition

How often you can measure head/tail correctly (50% is random chance)



Pre-drift: the track is well preserved, loss in directionality at low energies just due to straggling

Post-drift: some directionality lost due to diffusion

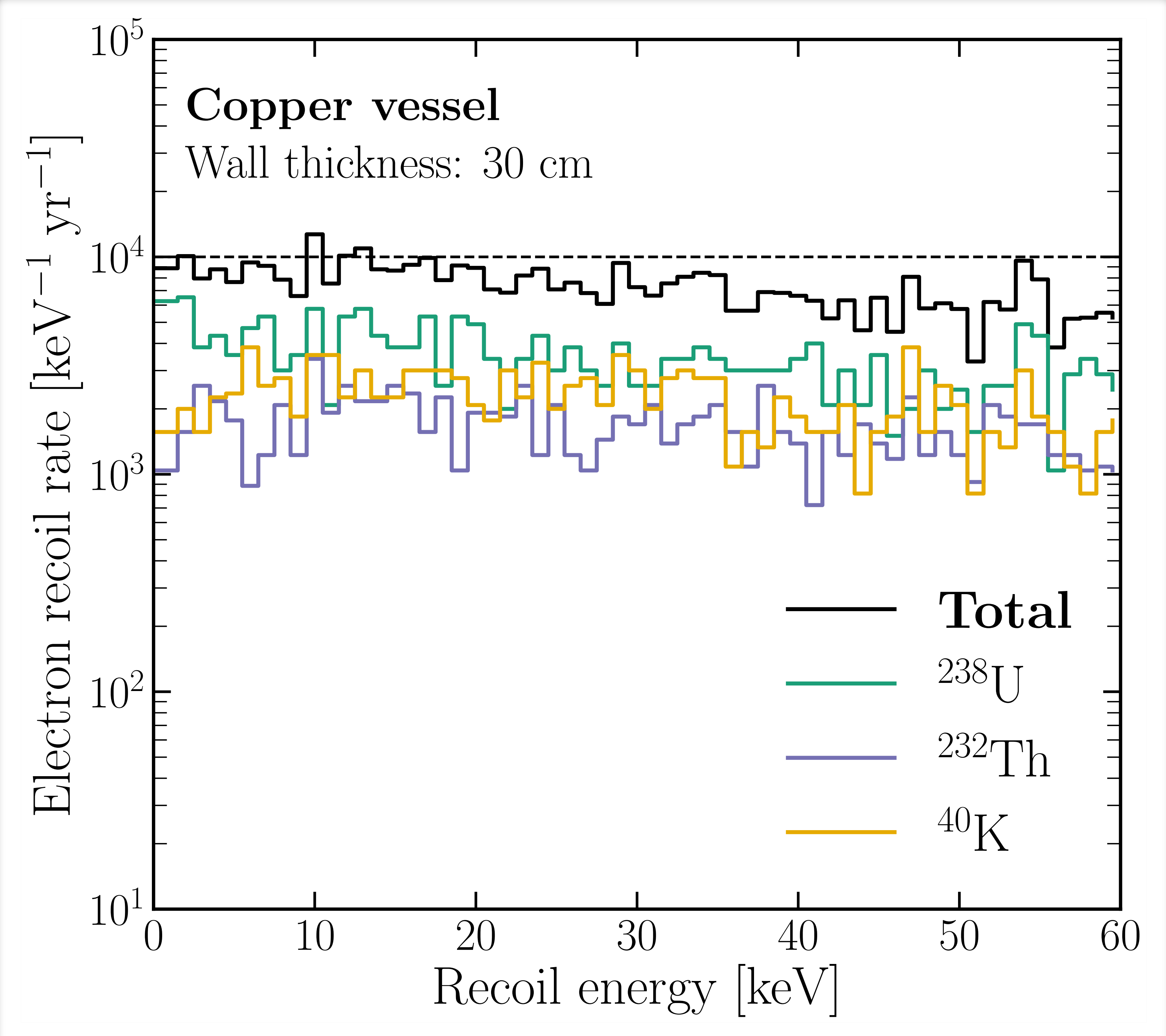
Pixel readout performs best again → almost no loss in directionality after readout

Pad readout performs the worst here, very weak HT signature along readout dimension

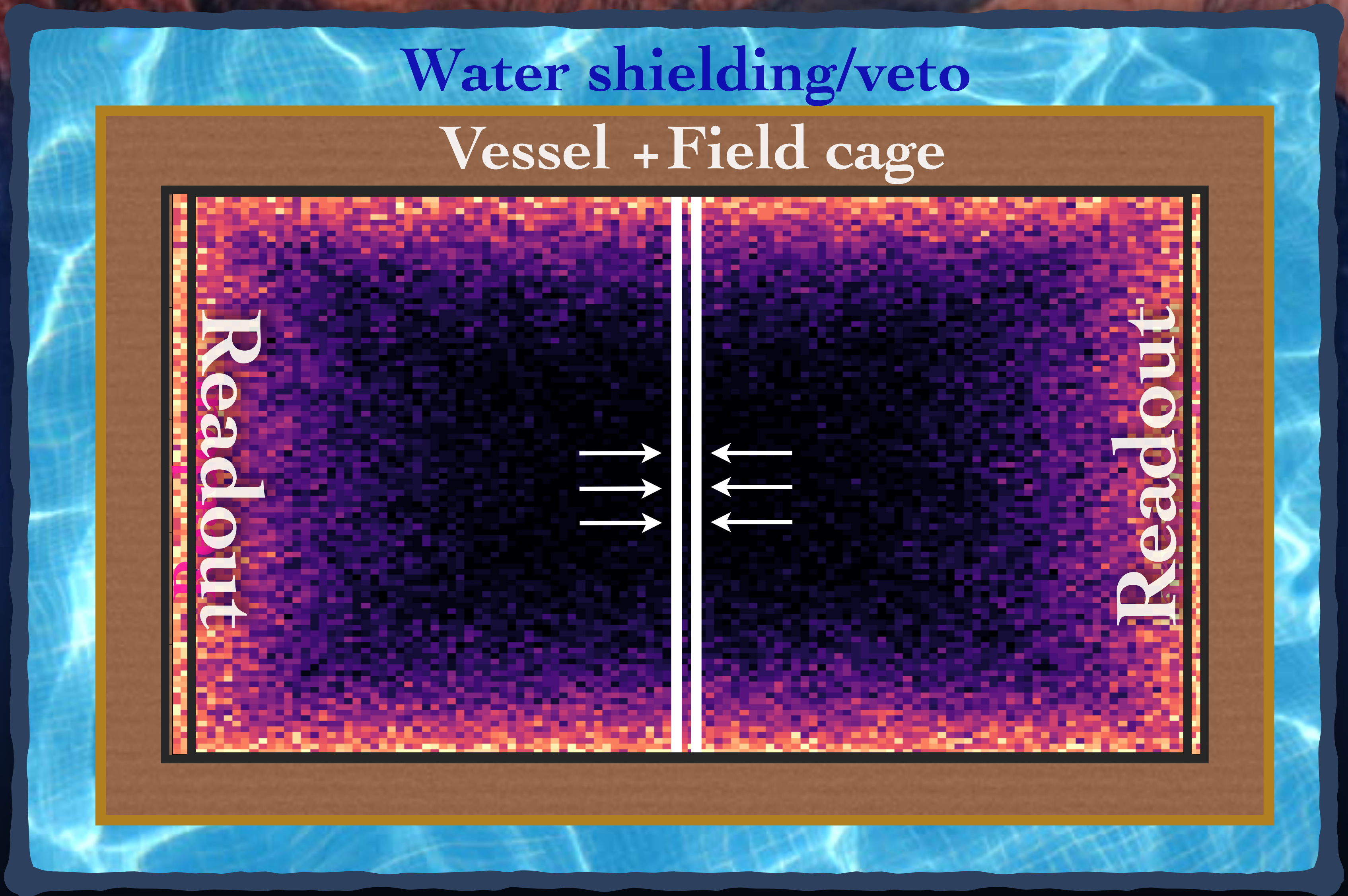
Backgrounds

We want: <1 NRs yr^{-1} and $<10^4$ ERs keV^{-1} yr^{-1} in 1000 m^3

Full Monte Carlo background study done by Neil Spooner's group

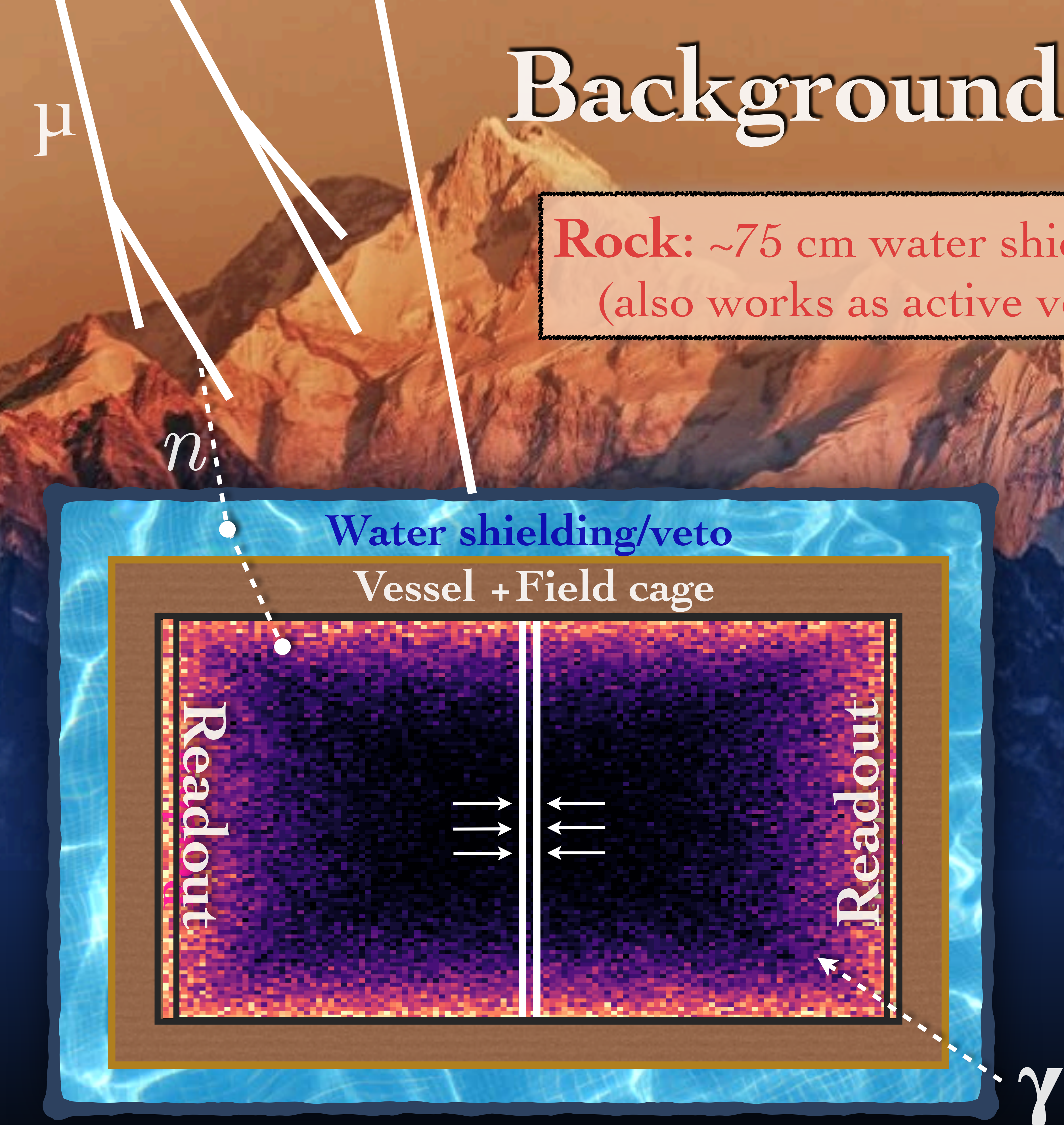


Background summary



Background summary

Rock: ~75 cm water shielding
(also works as active veto)



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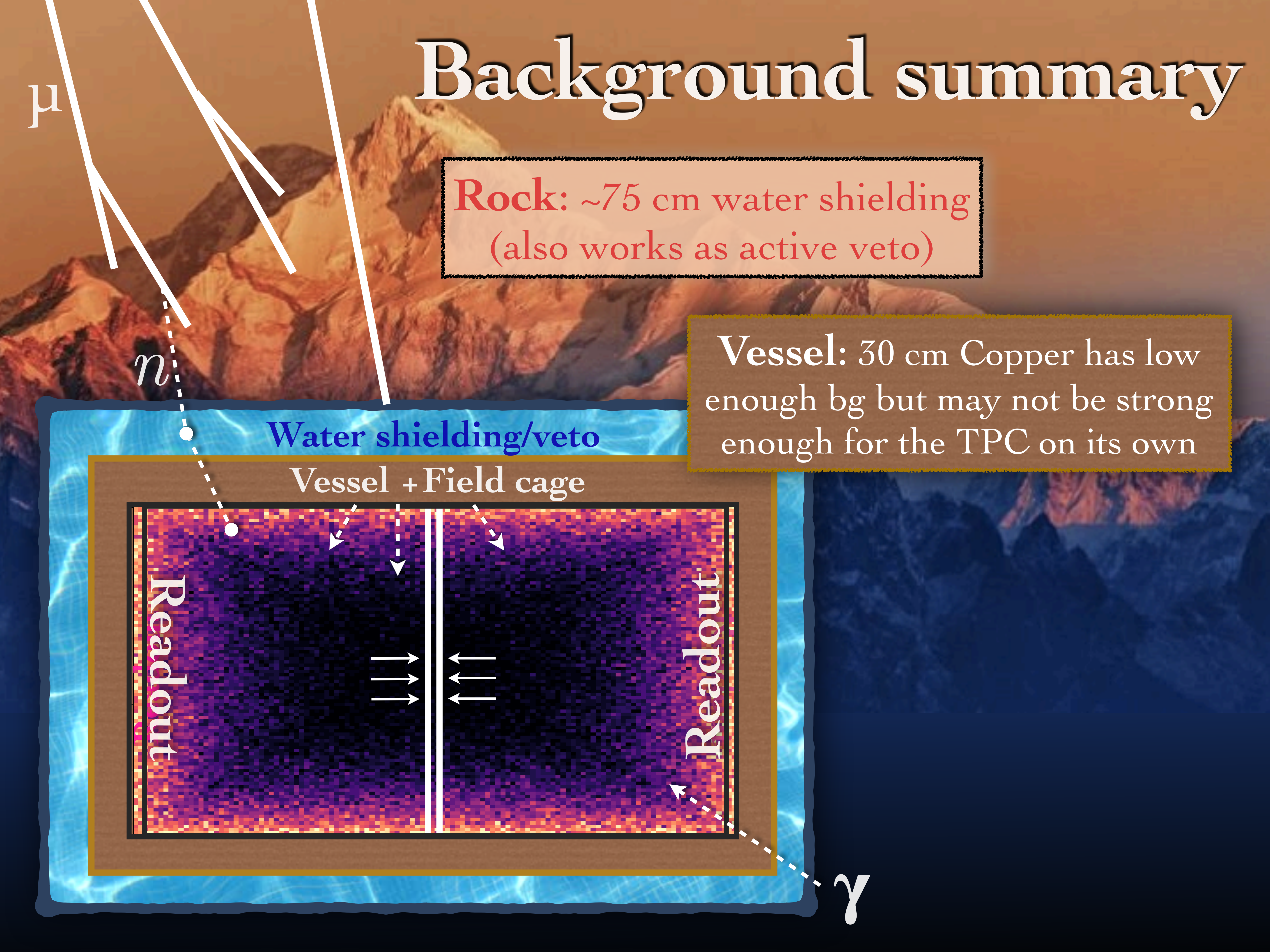

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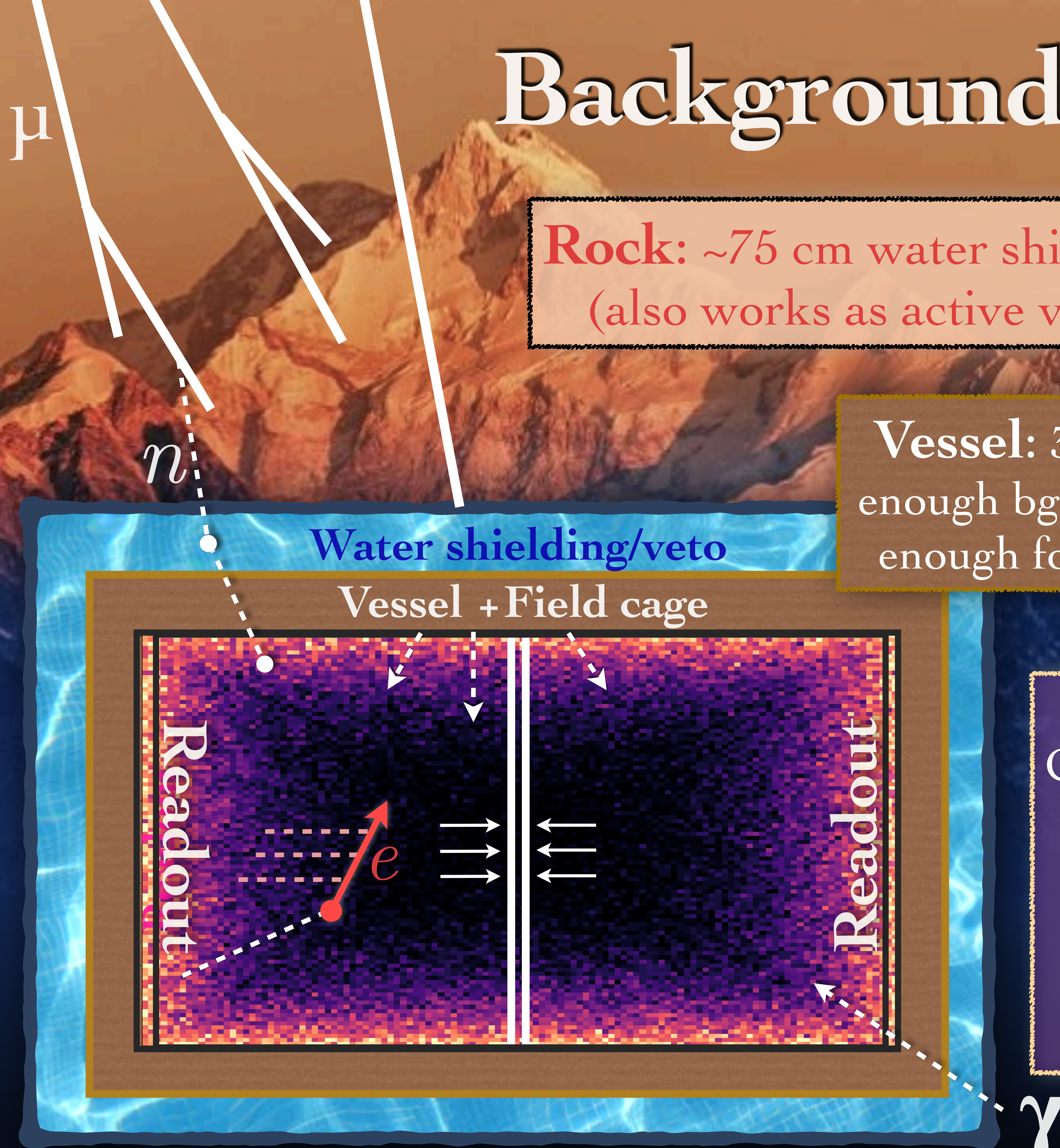


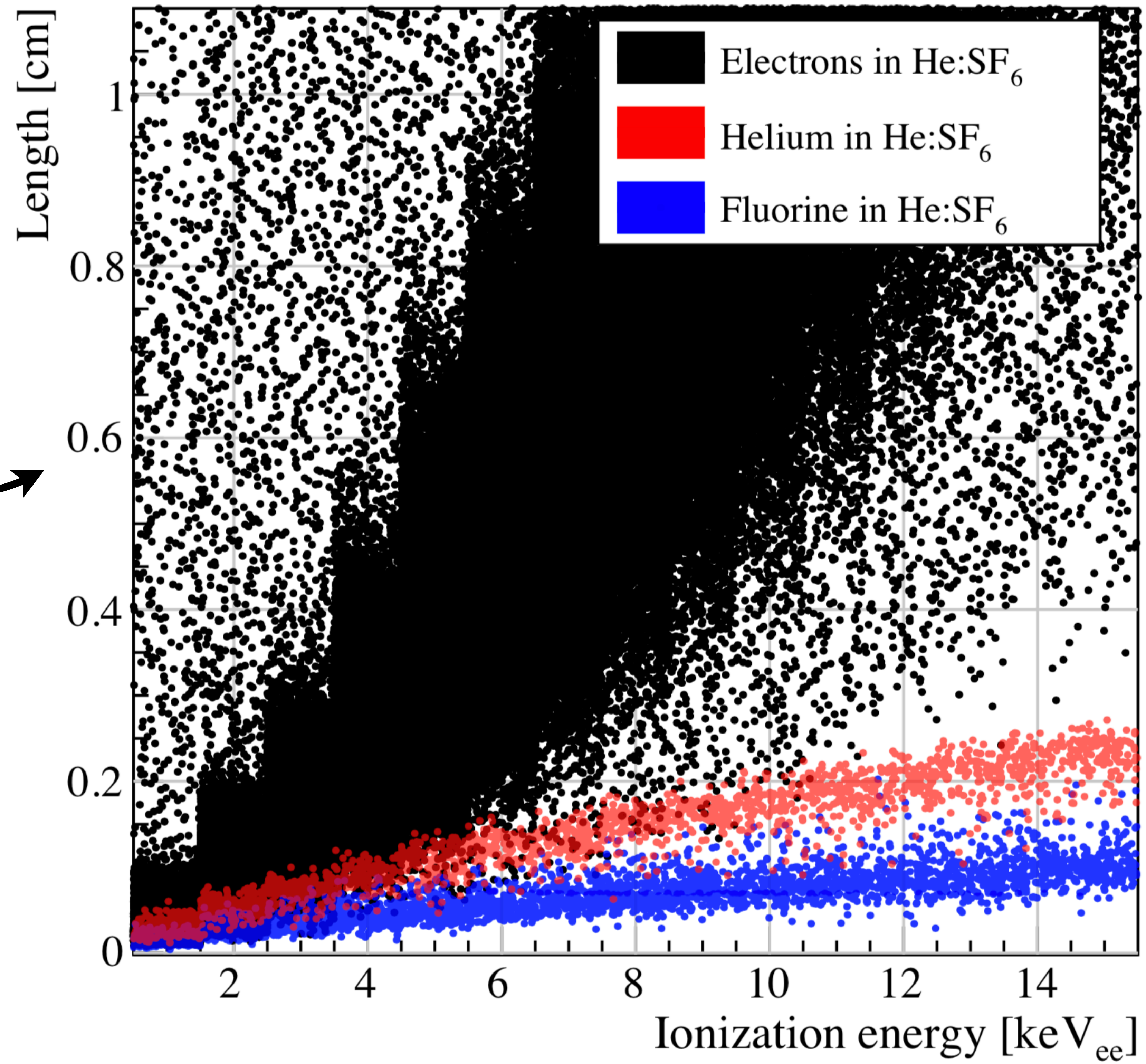
Rock: ~75 cm water shielding (also works as active veto)

Vessel: 30 cm Copper has low enough bg but may not be strong enough for the TPC on its own

Readout/Internal bg: Close, but not there yet, need more radiopurity screening of certain component materials e.g. polyimide, silicon, kapton, ceramic

Electron discrimination

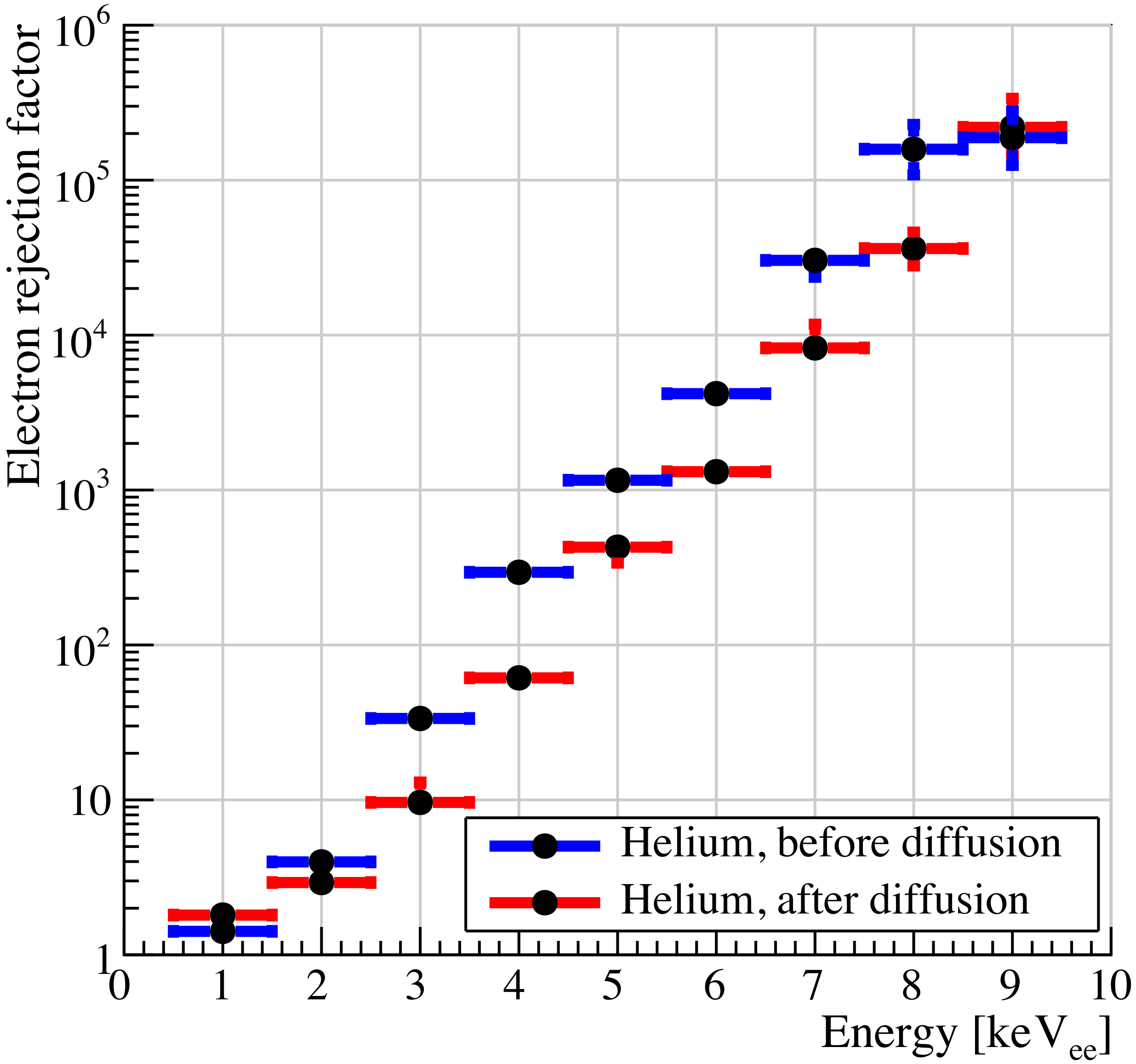
- Electrons have much longer tracks than nuclei so can discriminate based on this info.
- Track lengths for recoils in He+SF_6 at 1 atm:

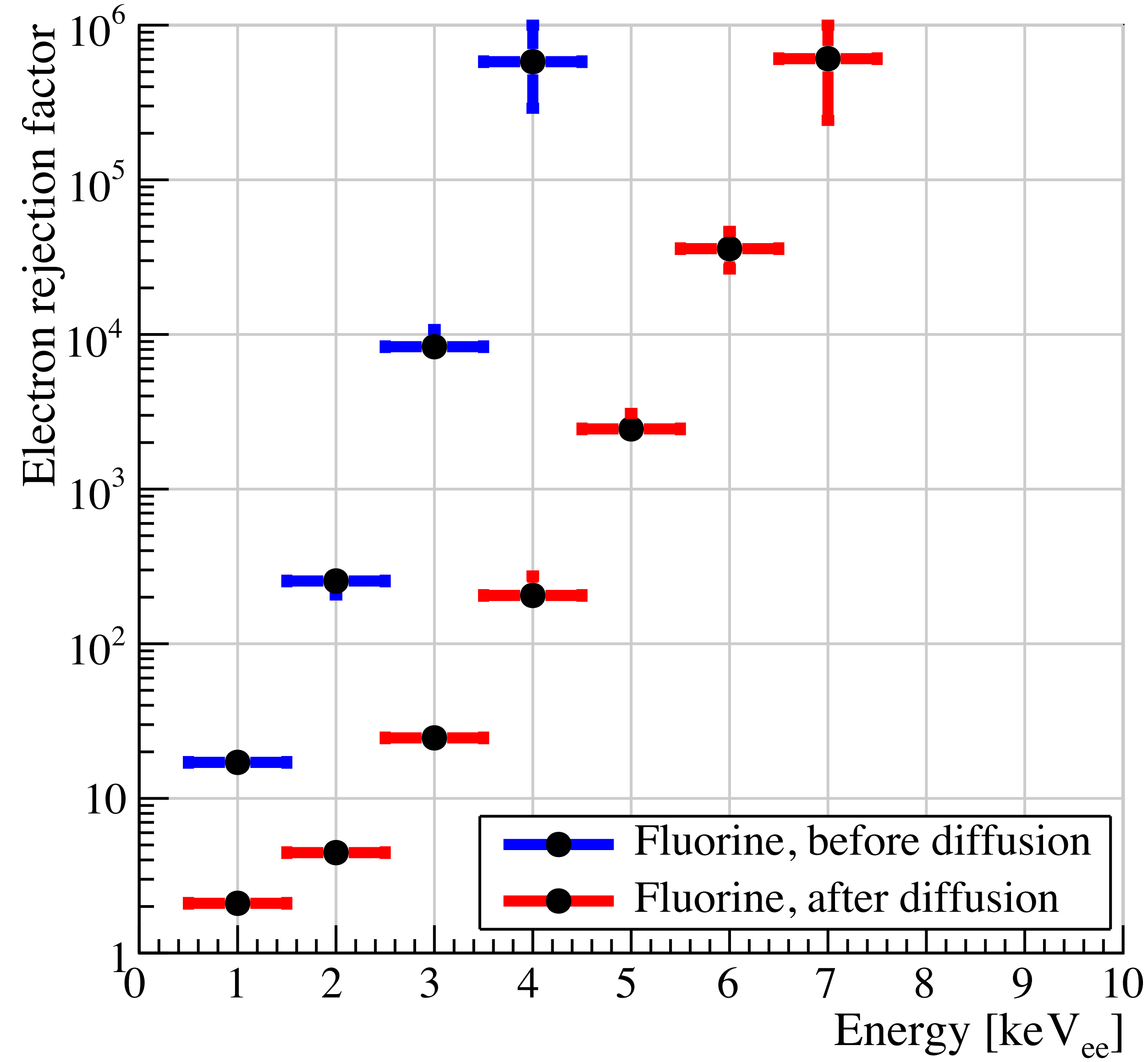


Energy threshold will be based on how low this can be achieved

Energy threshold → electron rejection>90%

- 8 keVr is feasible already with just track length vs energy
- But this is at the very tail of the ^{8}B neutrino recoil spectrum.
- Improve with: more sophisticated track fitting, discrimination algorithms (e.g. w/ Machine learning), and gas parameters can still be optimised further. 8 keVr is a very conservative estimate for threshold.

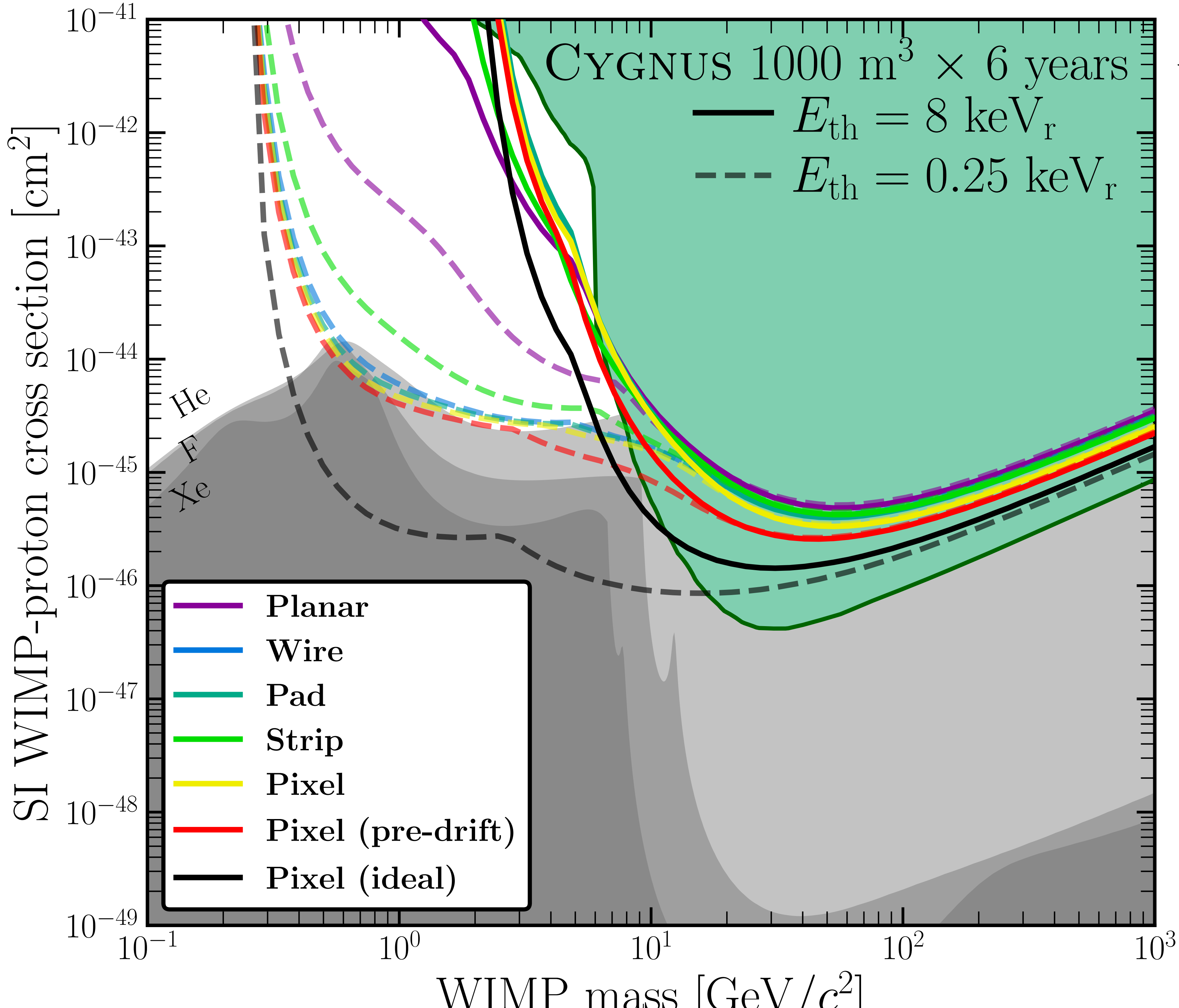




WIMP reach: spin independent (SI-nucleon)

(90% CL exclusion of WIMP hypothesis under neutrino background)

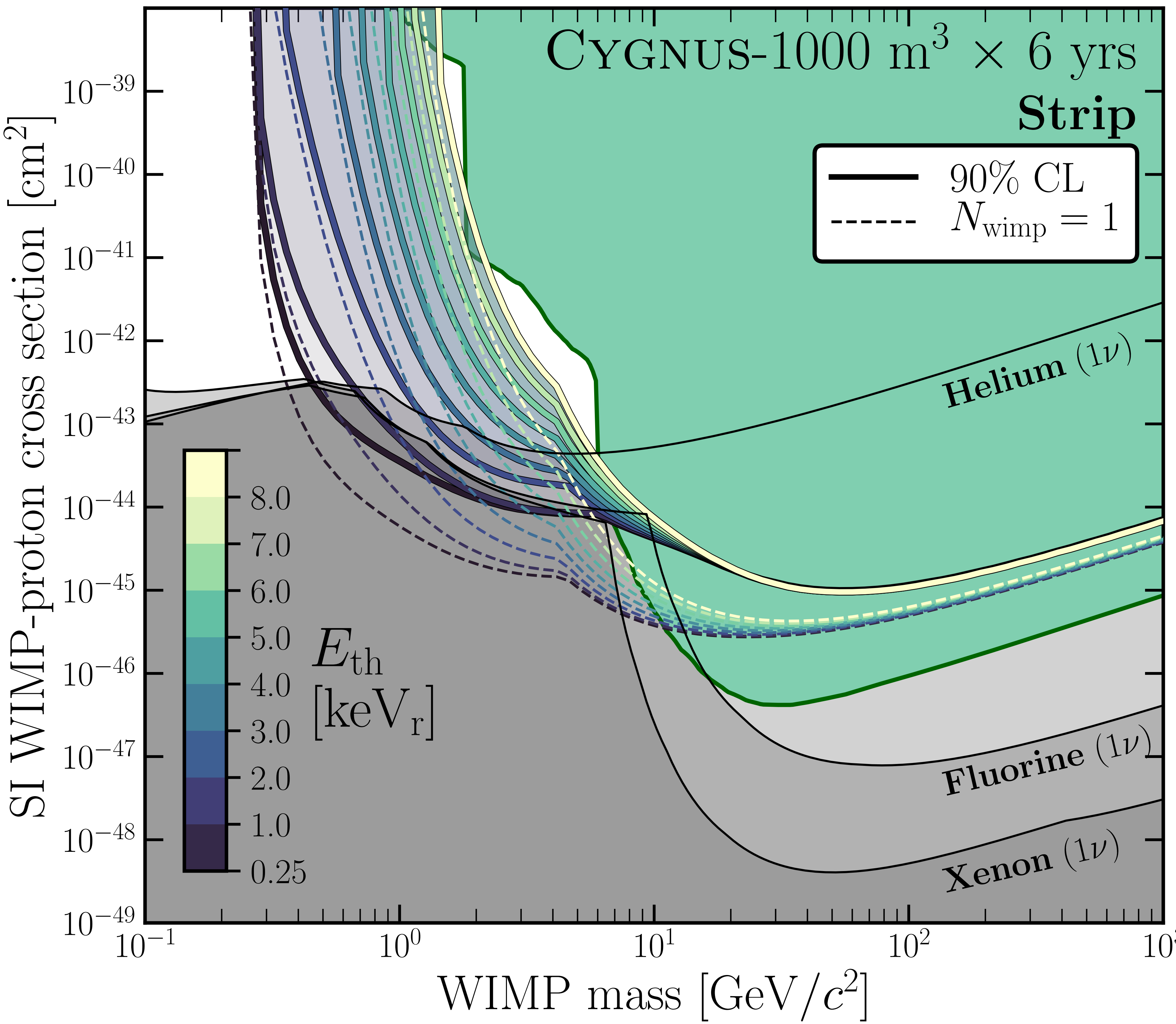
Threshold: 8 keVr currently feasible → 0.25 keVr is theoretical minimum



1000 m³ × 6 years
≈ 1 ton-year

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

A closer look at dependence on threshold:

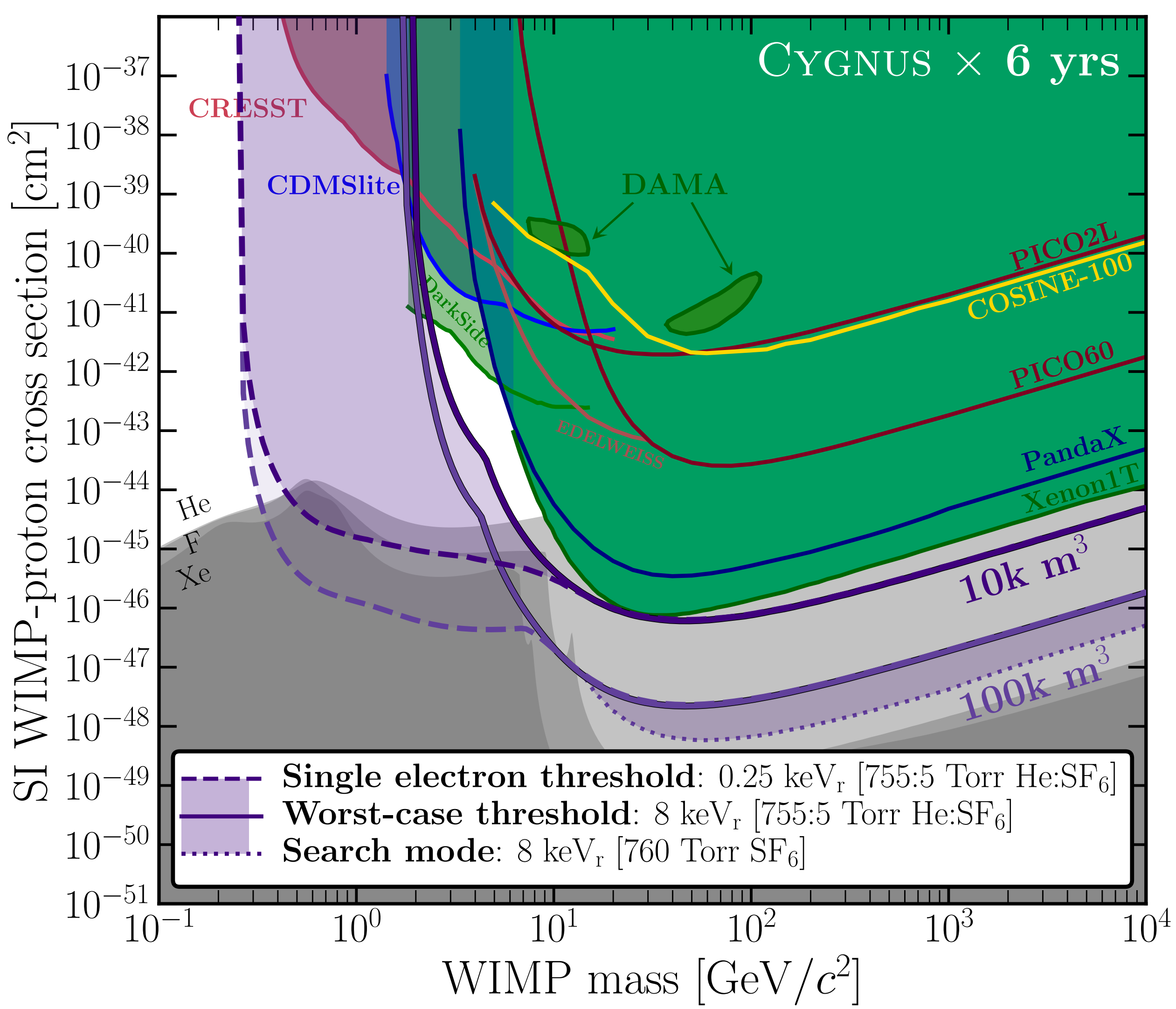


Headline discovery reach

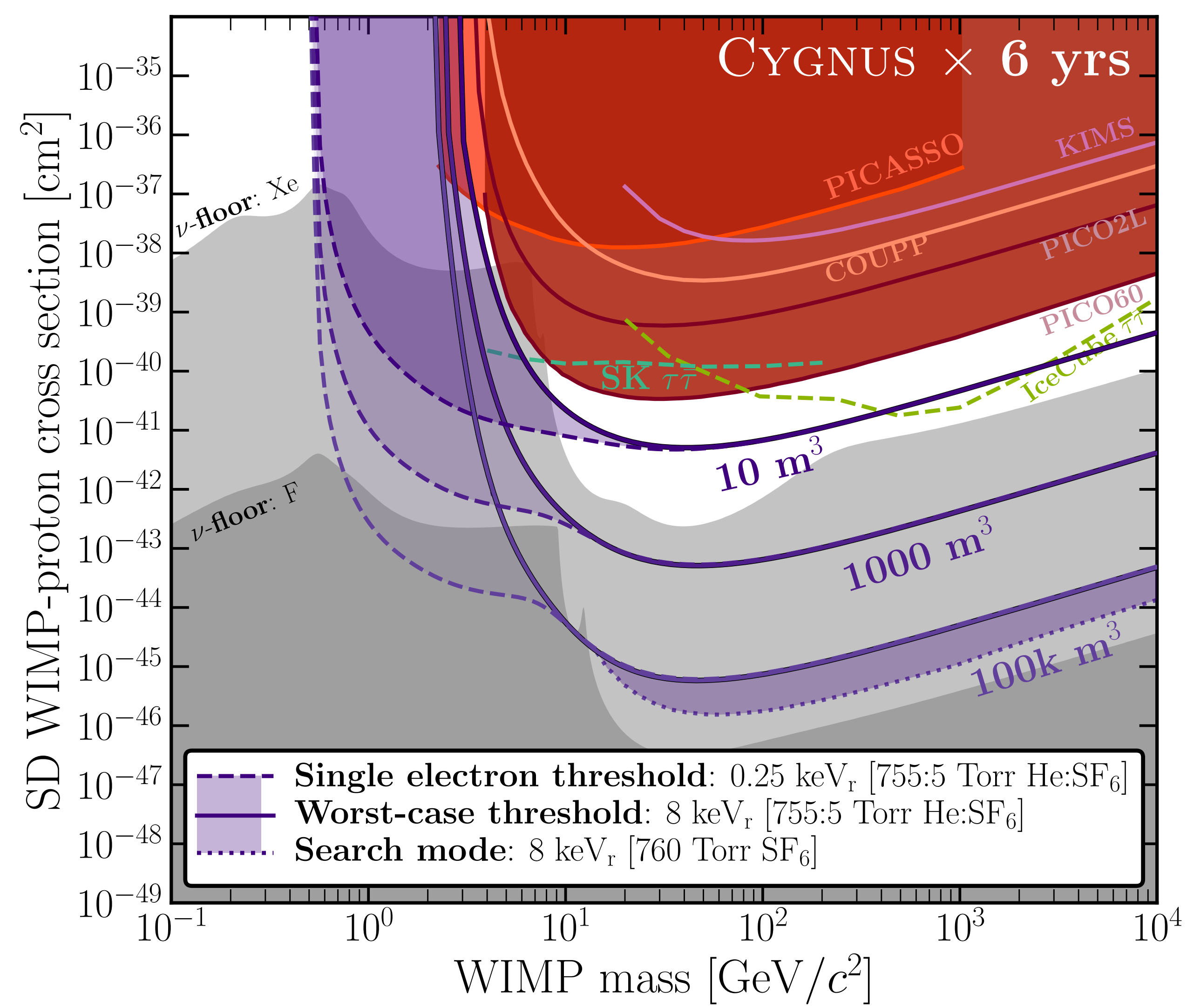
Three possible projections

→ Directional sensitivity down to a single-electron 0.25 keVr (very optimistic)
→ Very rudimentary electron rejection threshold, 8 keVr (very pessimistic)
→ Search mode: 1 atm. of SF6 but <u>no</u> directionality (possible way to extend high mass sensitivity)

Spin independent



Spin dependent (proton)



Say we build Cygnus and find that…

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1. We have a signal

Say we build Cygnus and find that…

1. We have a signal

2. We don't

Say we build Cygnus and find that…

1. **We have a signal**

2. **We don't**

Then what?

Say we build Cygnus and find that…

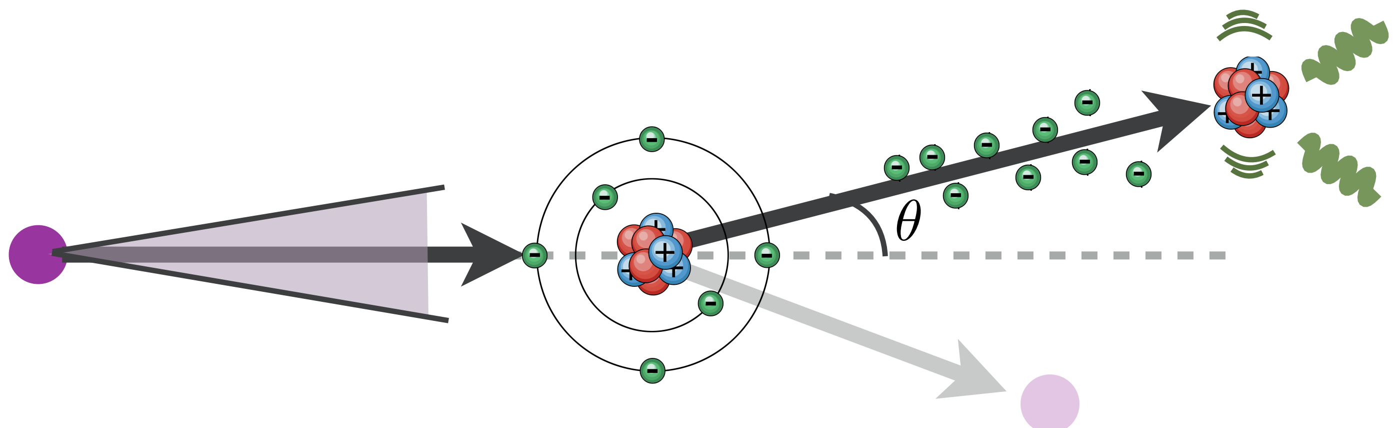
1. **We have a signal**

   ↳ We study it

2. **We don't**

Then what?

What should the signal look like?



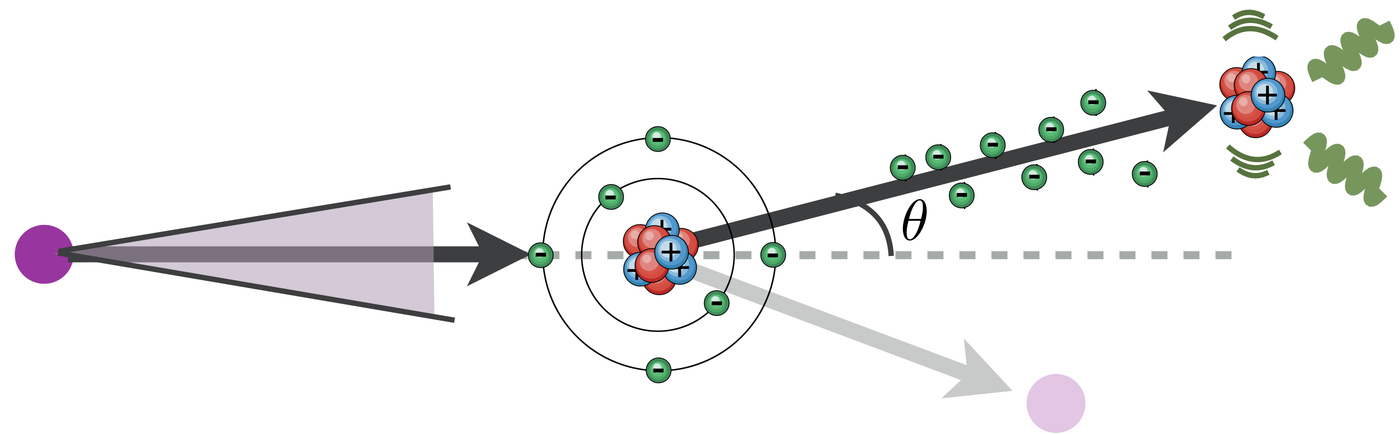
The standard prediction involves a few main assumptions:

- The DM scatters elastically

- The DM velocity distribution is a Gaussian (SHM)

- DM-nucleus matrix element does not depend on velocity

What should the signal look like?



The standard prediction involves a few main assumptions:

- The DM scatters elastically

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

m_N = Nucleus mass
m_χ = DM mass

- The DM velocity distribution is a Gaussian (SHM)

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

$\mathbf{v}_{\rm lab}$ = Our velocity
σ_v = Velocity dispersion

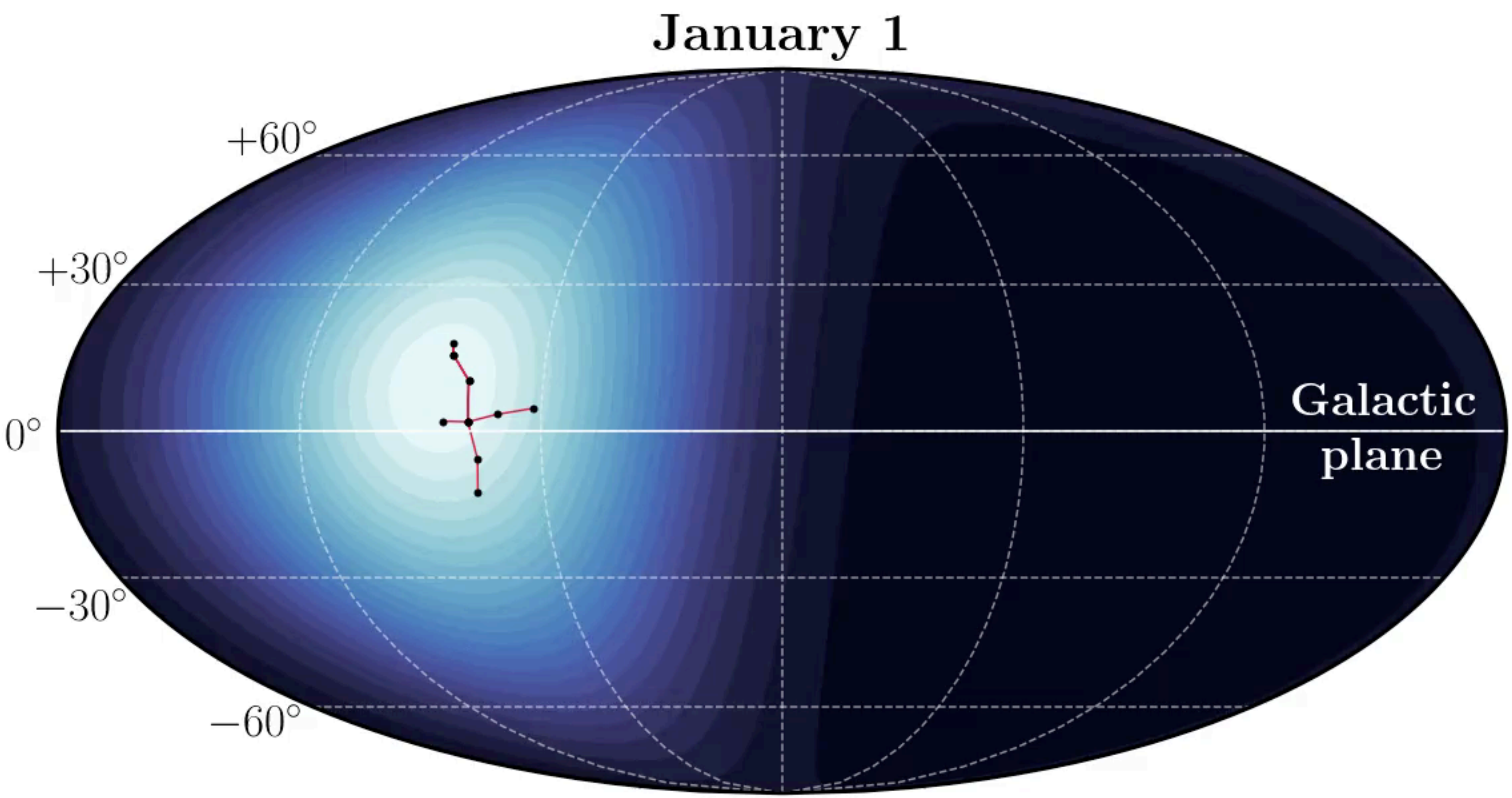
- DM-nucleus matrix element does not depend on velocity

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

Angular rate is the Radon transform of $f(\mathbf{v})$

Under these assumptions the angular signal is a Gaussian peaking towards Cygnus

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



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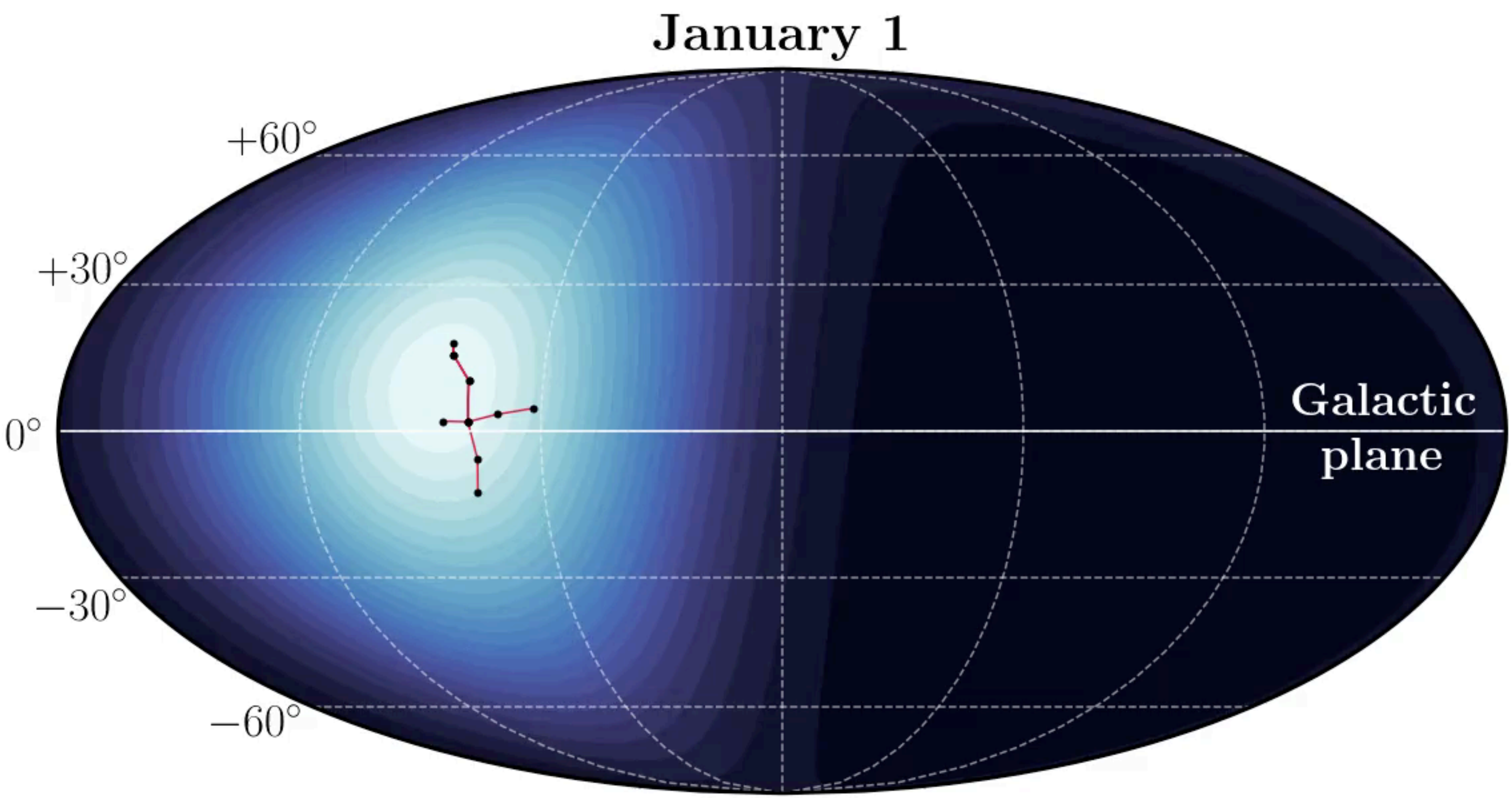

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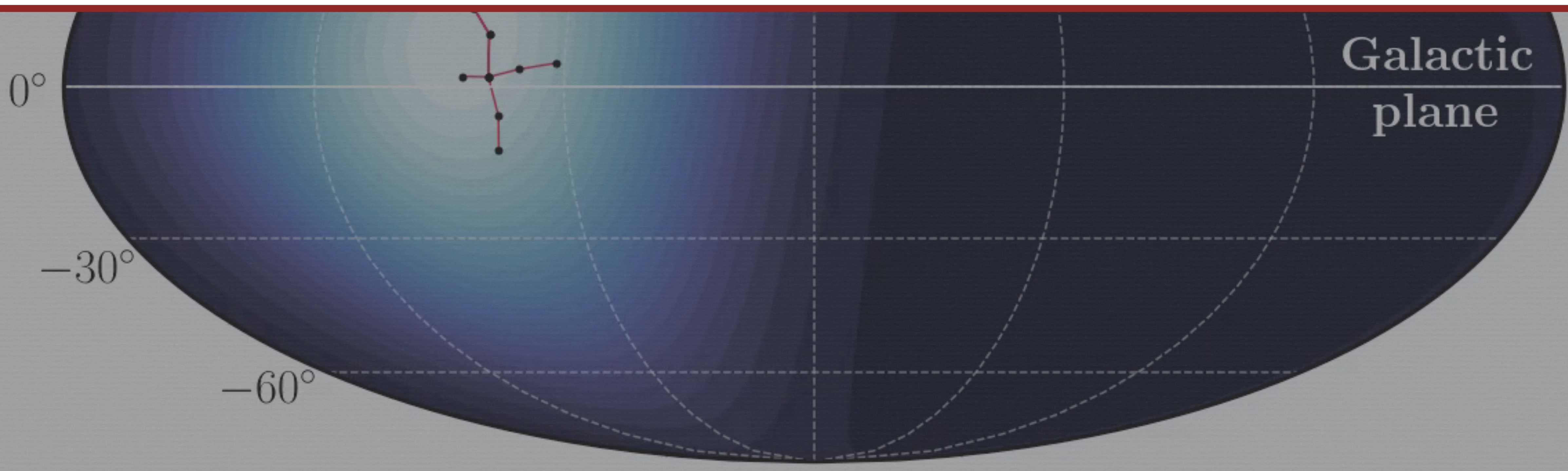
But this is **wrong** if we break those assumptions,
and we have reason to…

→ The DM velocity distribution is <u>not</u> a Gaussian

→ WIMPs may not scatter elastically

→ The WIMP-nucleus interaction may involve velocity-dependent operators



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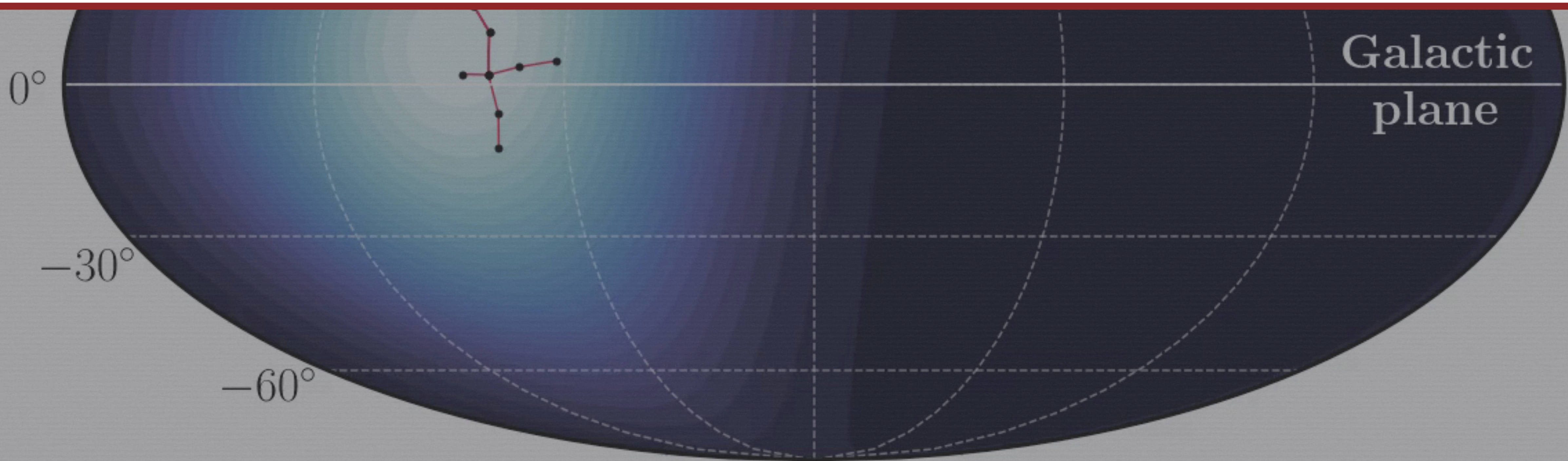
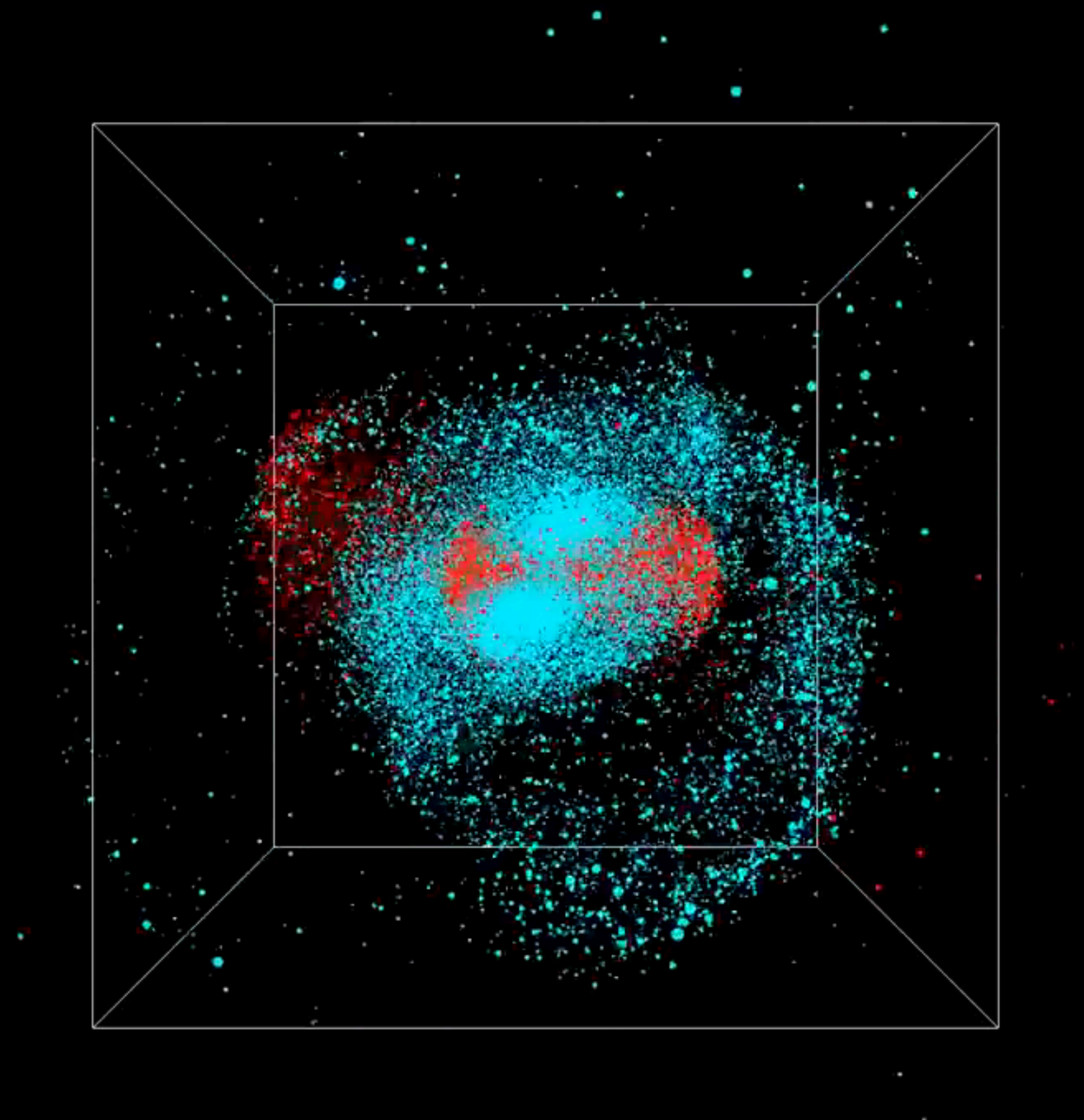


Should the DM velocity distribution be a Gaussian?

→ 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

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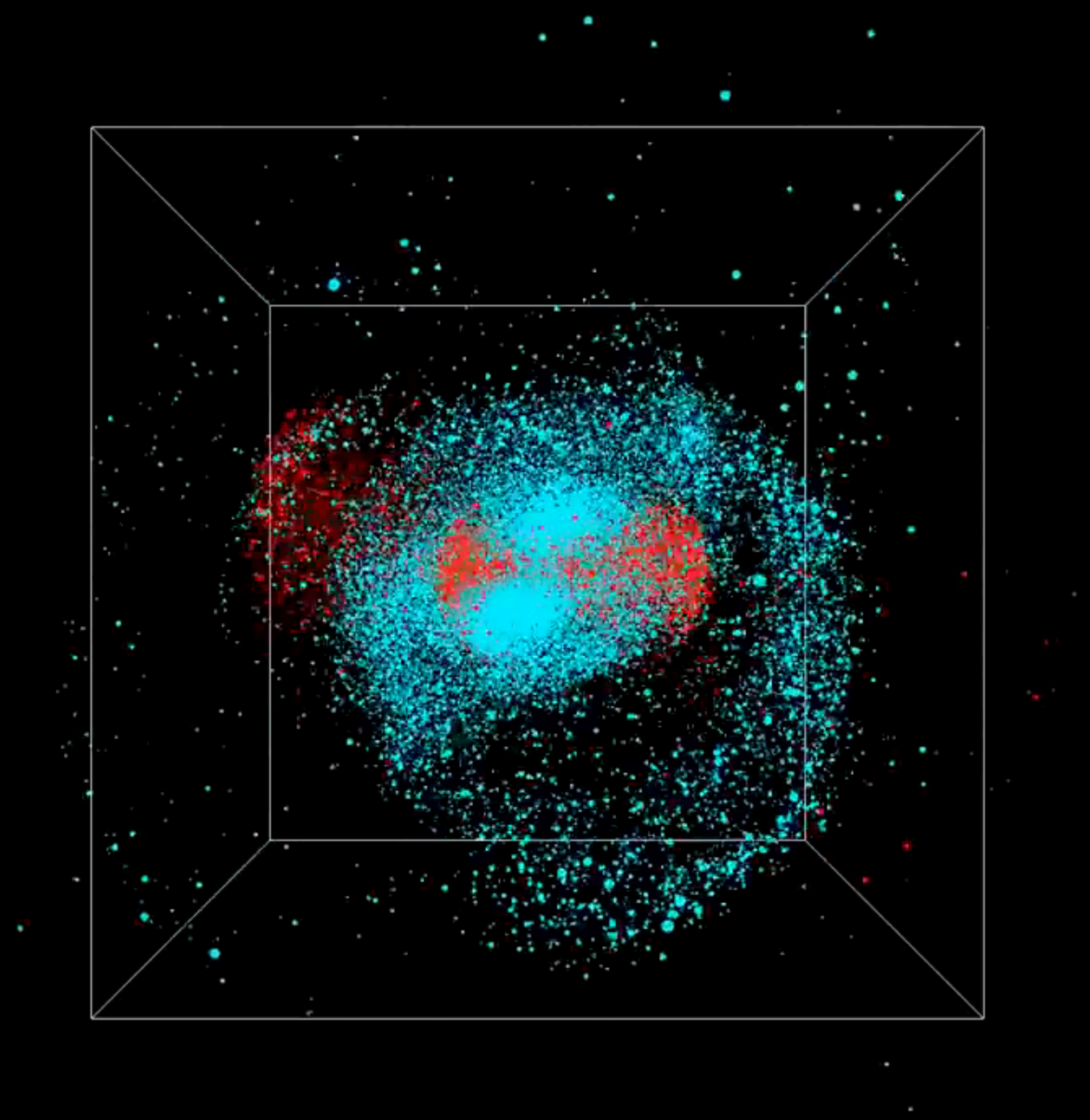

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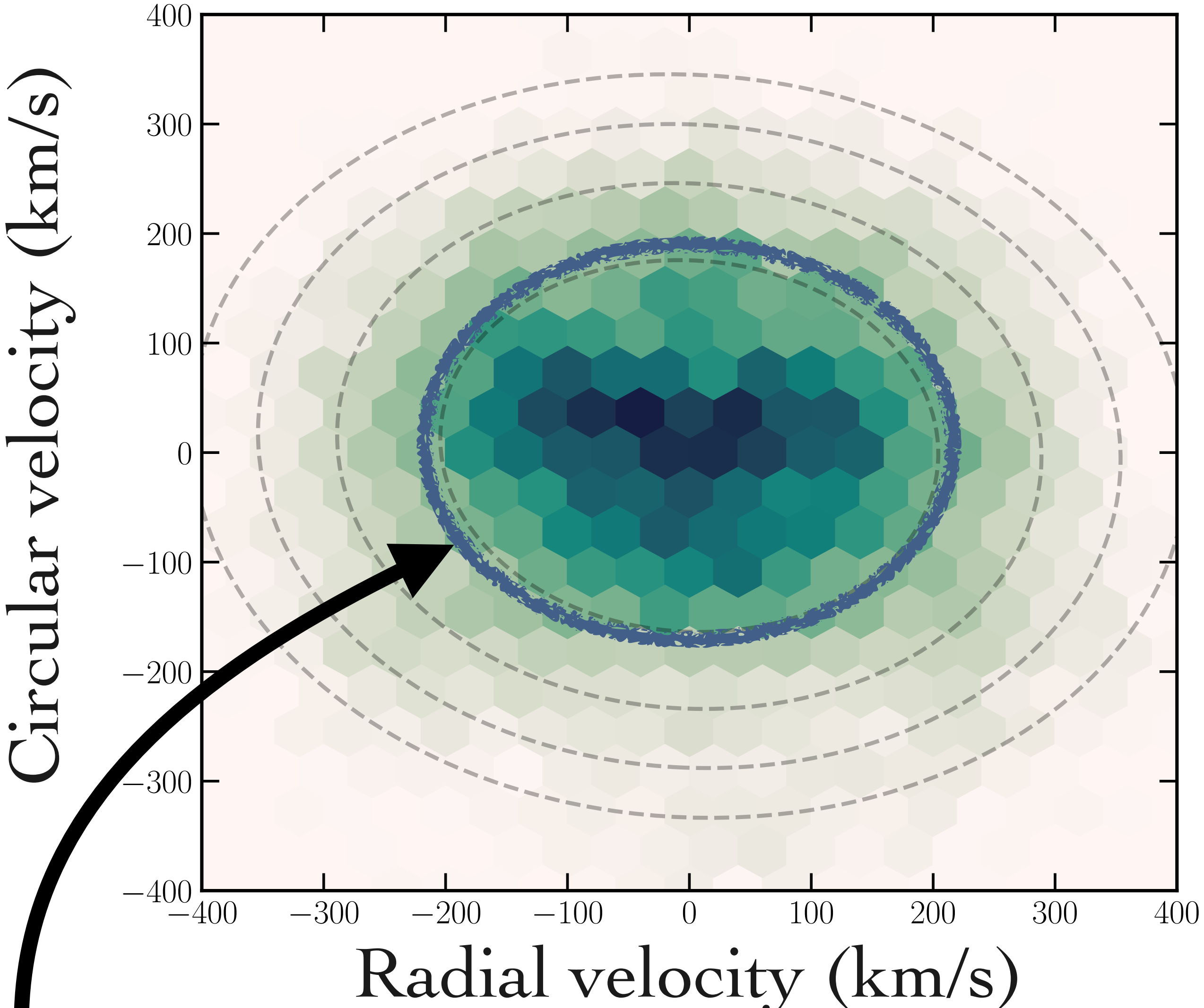
Metal-poor halo
[Fe/H]<-1.5



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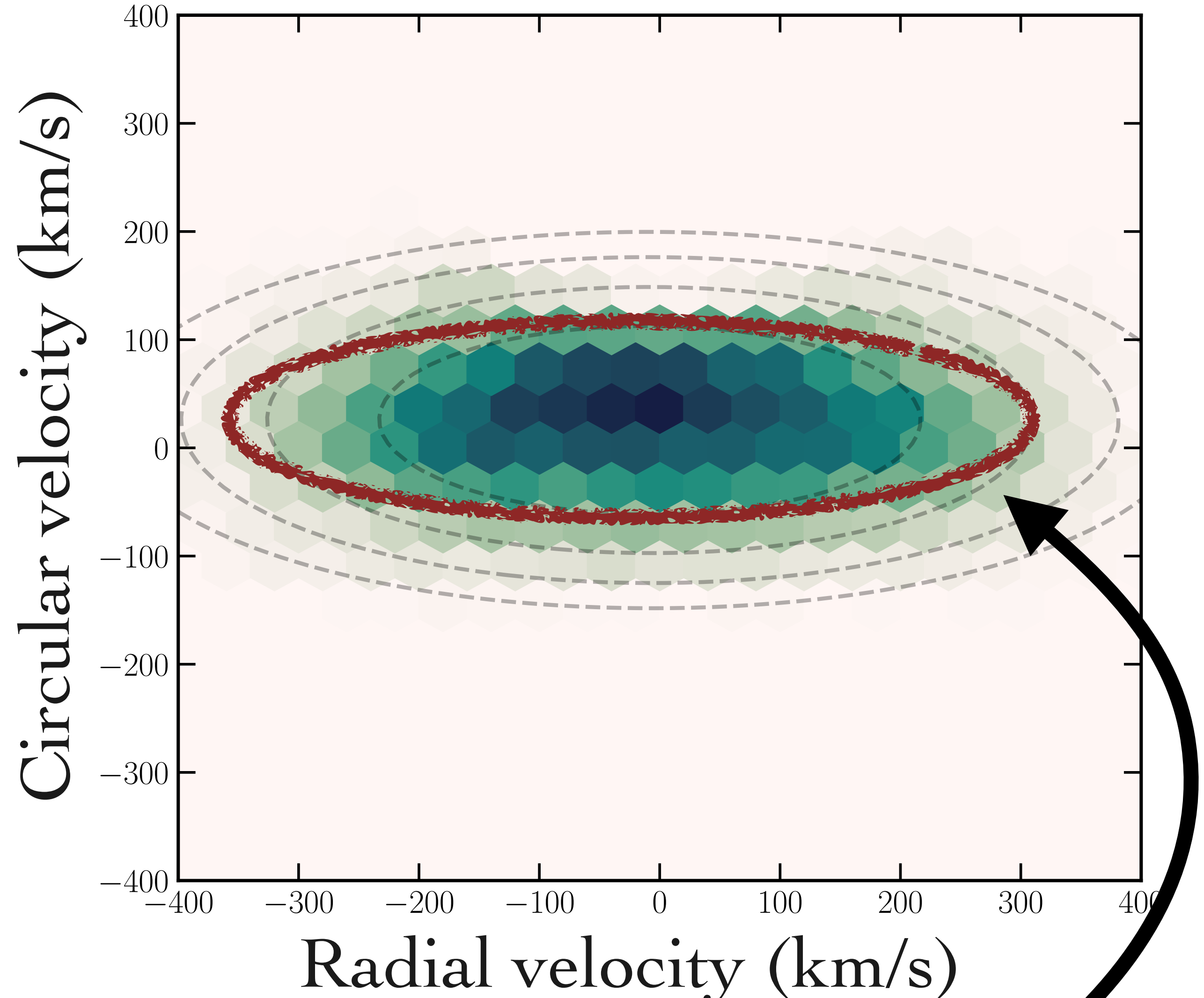


The "Halo"

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

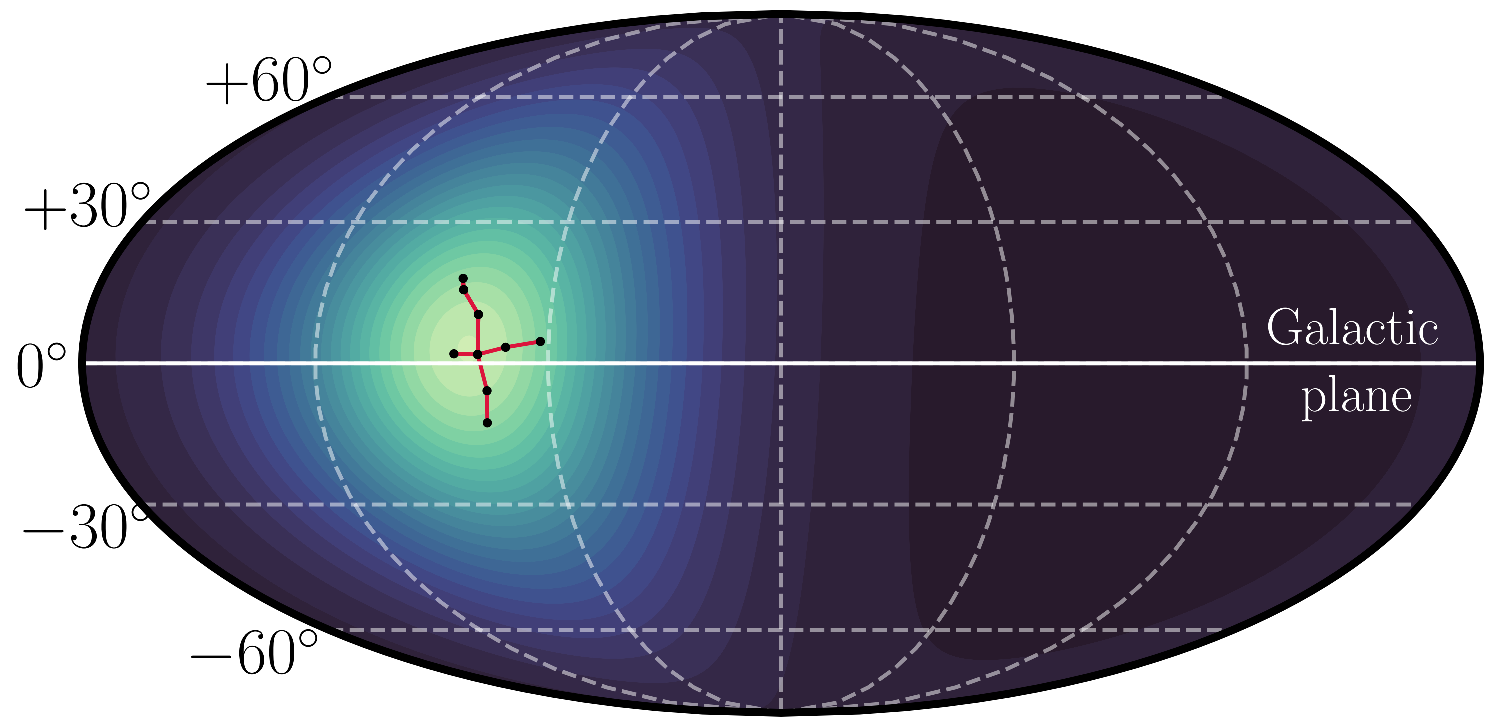
The "Sausage"

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

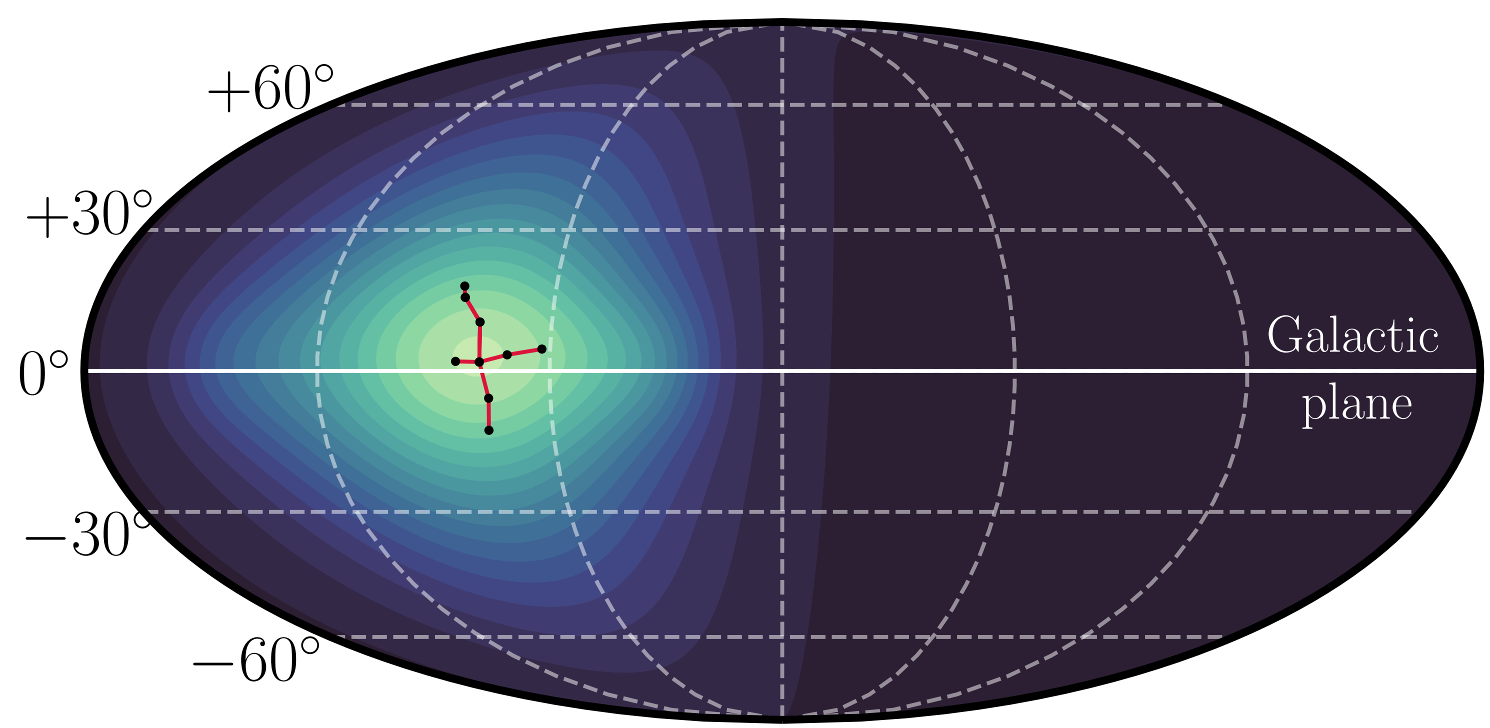
The Gaia Sausage

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

DM Flux for SHM
(Gaussian distribution)

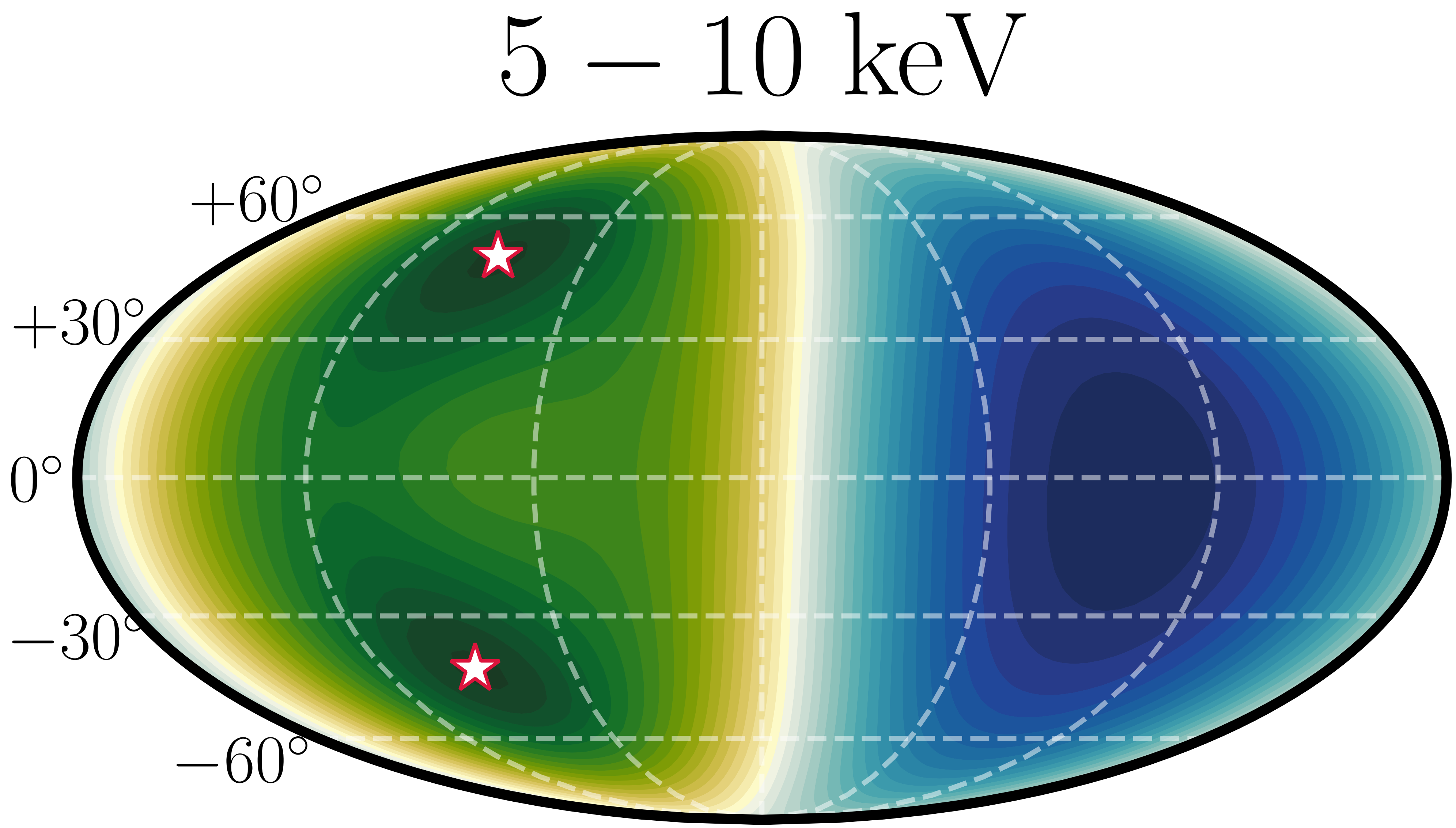


SHM + **Gaia Sausage**
(Anisotropic component due to merger with a dwarf galaxy)



O'Hare+ [1909.04684]

The Gaia Sausage gives rise to peaks off center from Cygnus



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

Halo model = SHM + Sausage

O'Hare+ [1909.04684]

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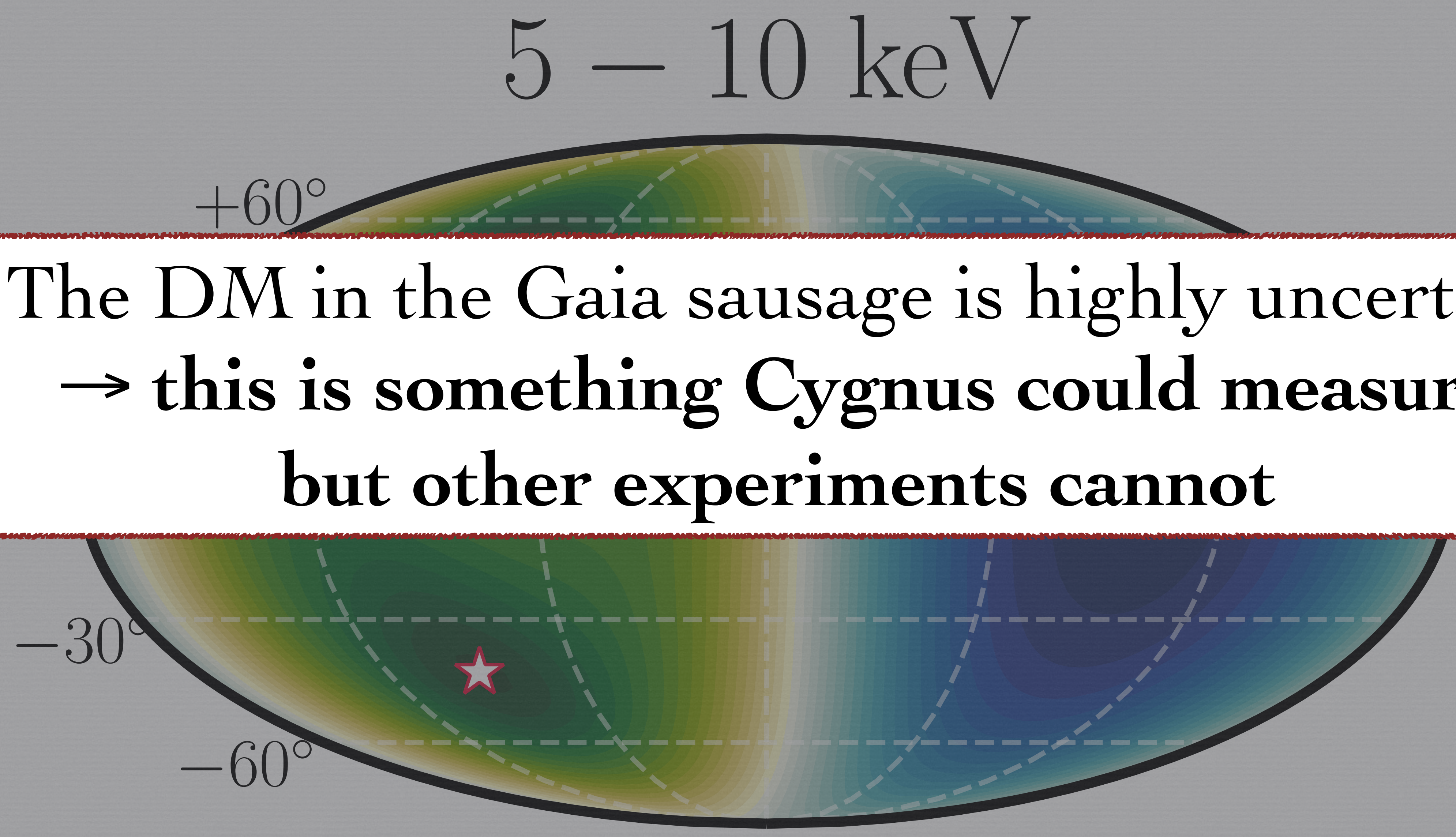
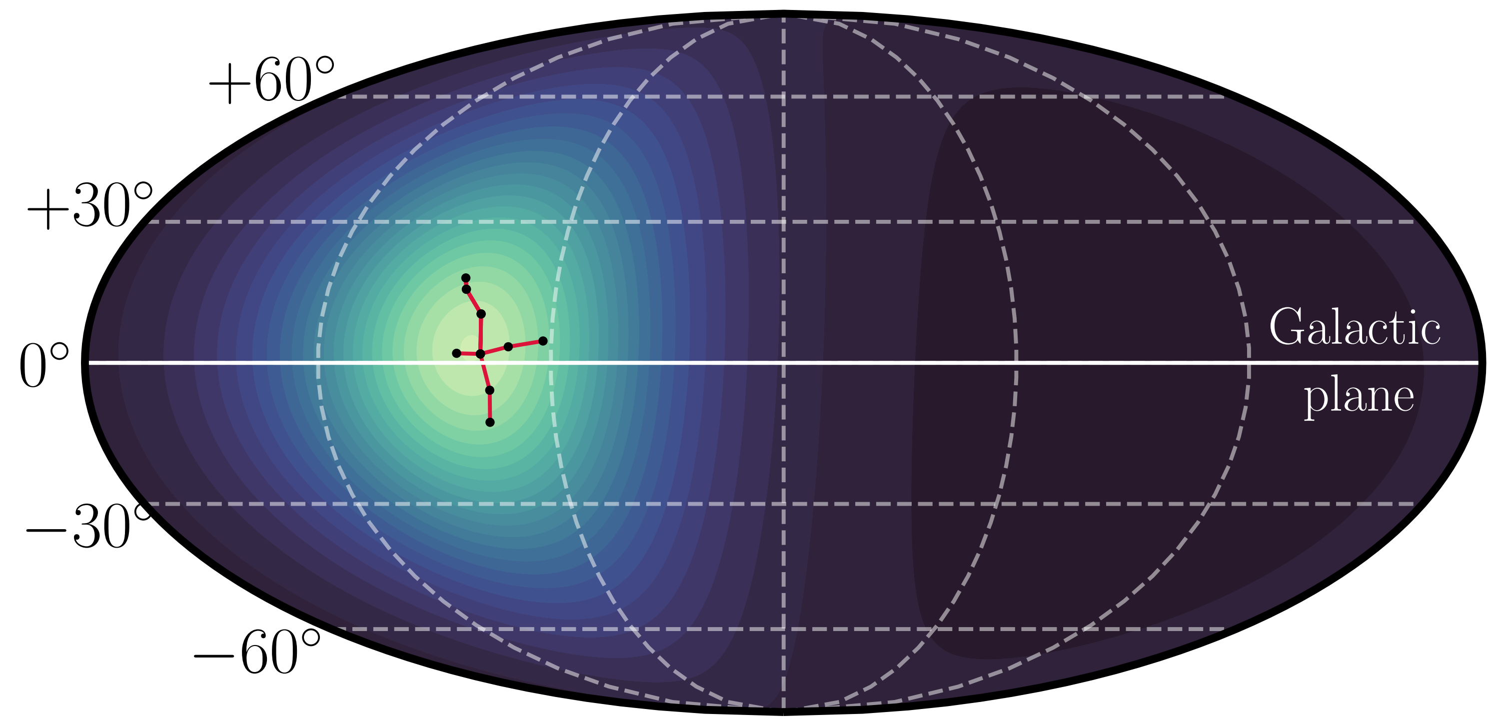


The DM in the Gaia sausage is highly uncertain
→ **this is something Cygnus could measure but other experiments cannot**

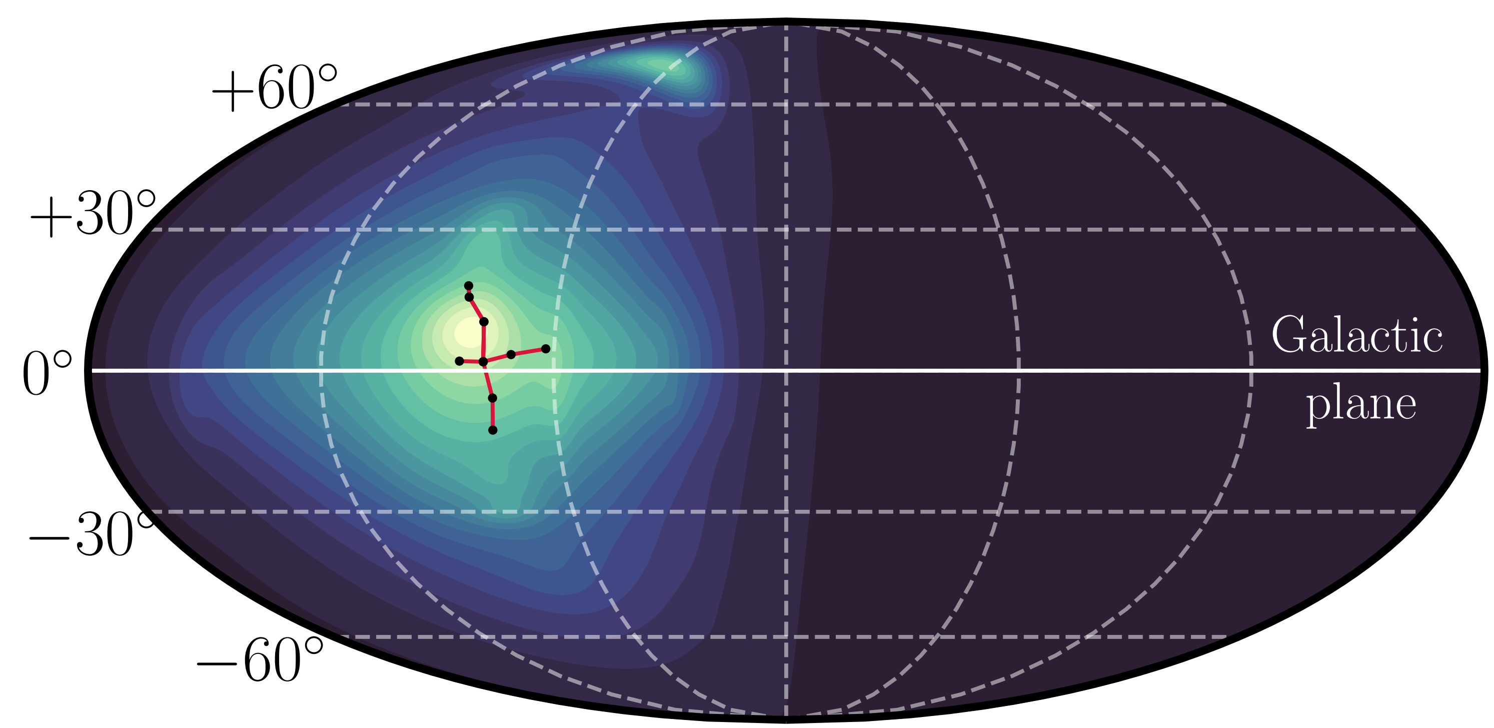
Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP
Halo model = SHM + Sausage

Gaia also shows evidence of substructure passing through Solar position → e.g. S1 (hurricane), S2 streams

SHM DM flux
(Gaussian distribution)



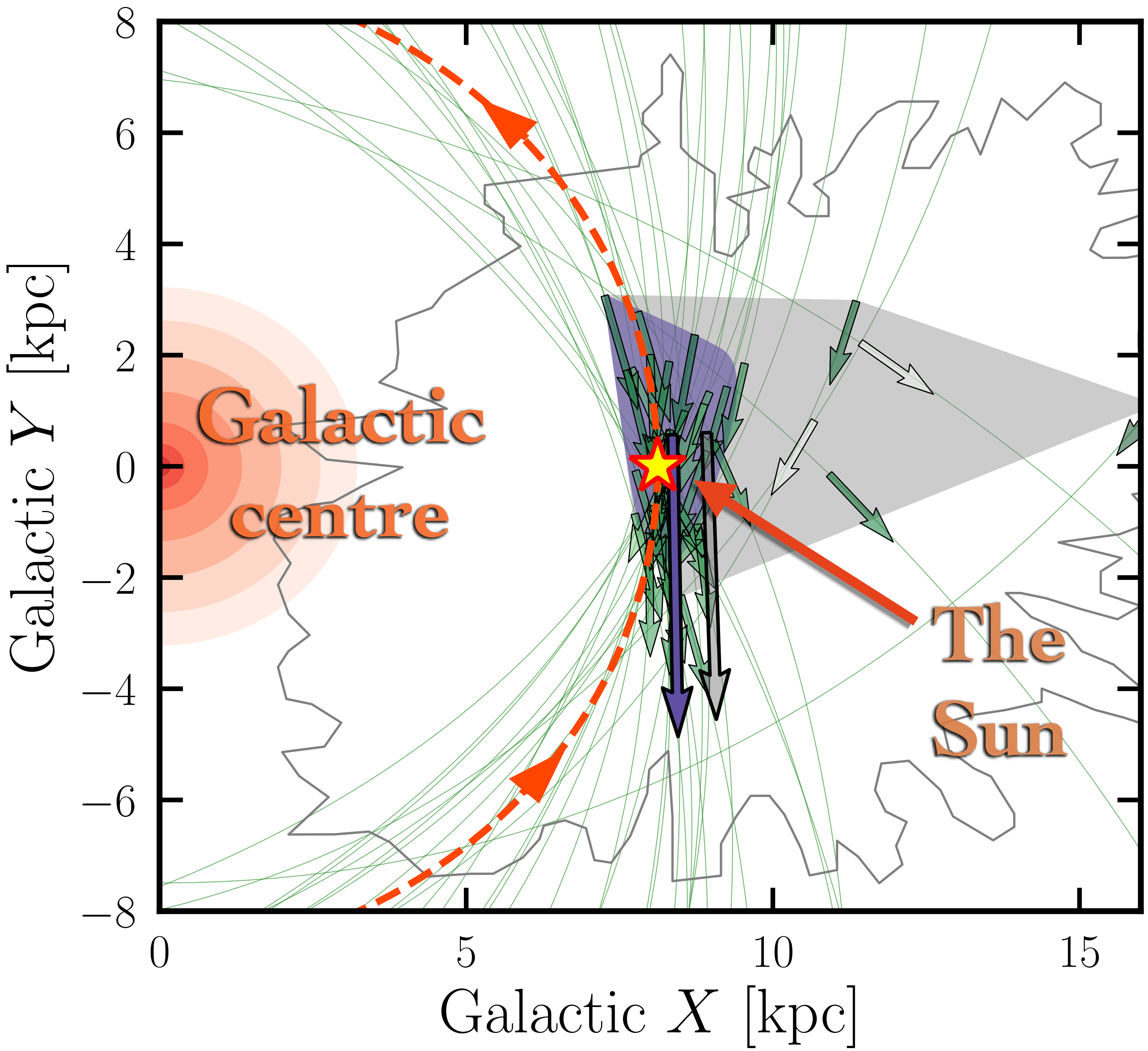
SHM + **Gaia Sausage + Local substructures**
(Peaks in other directions due to streams)



O'Hare+ [1909.04684]

O'Hare+ [1909.04684]
O'Hare+ [1807.09004]

The S1 stream

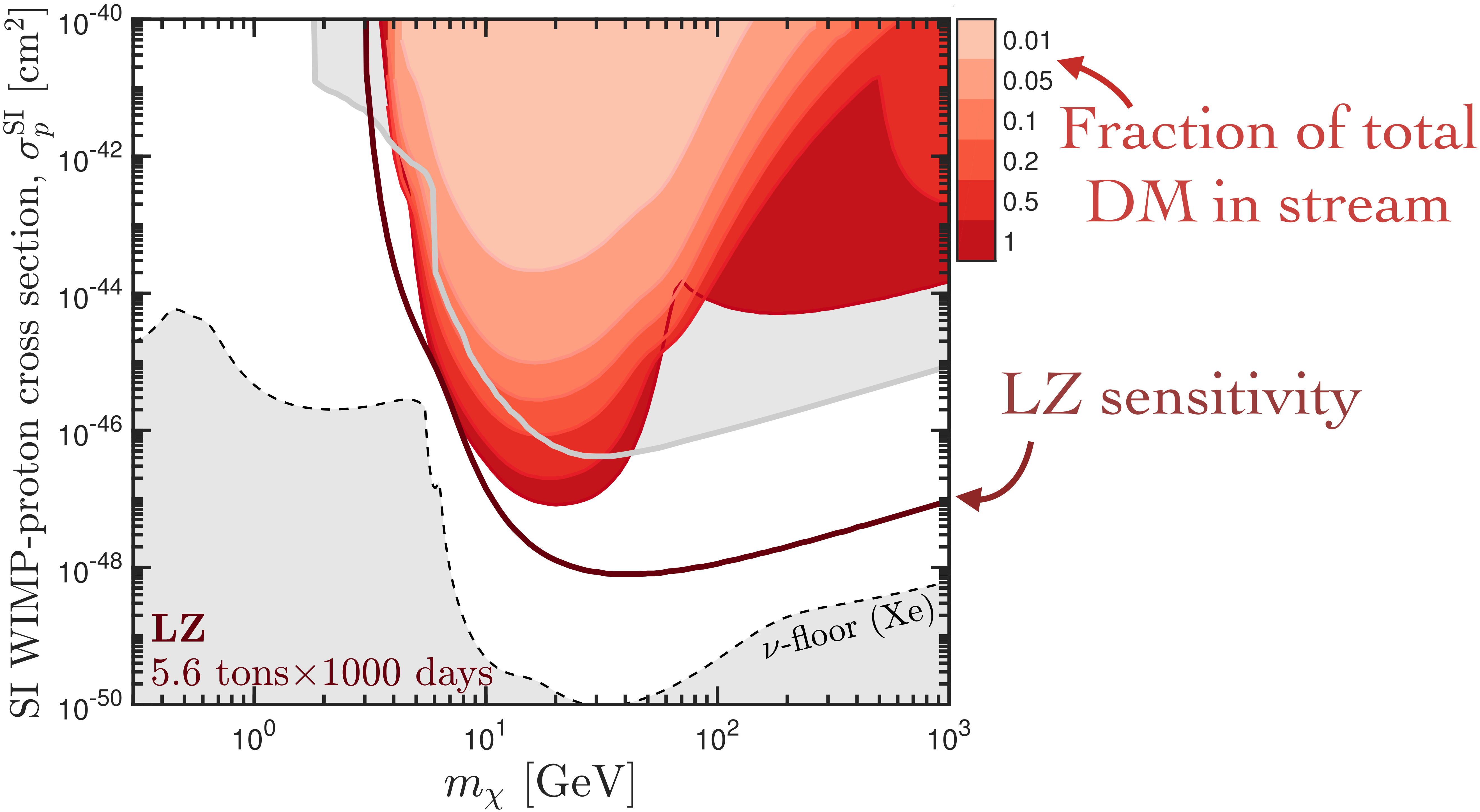


- Most prominent substructure encompassing the Solar System
- Likely the remnant of a large (Fornax-sized) dwarf spheroidal accreted around the same time as the Sausage event
- S1 and other retrograde stars possibly linked to a larger "Sequoia" event. Also responsible for several anomalous retrograde GCs (see 1904.03185)

O’Hare+ [1807.09004]

S1 in LZ

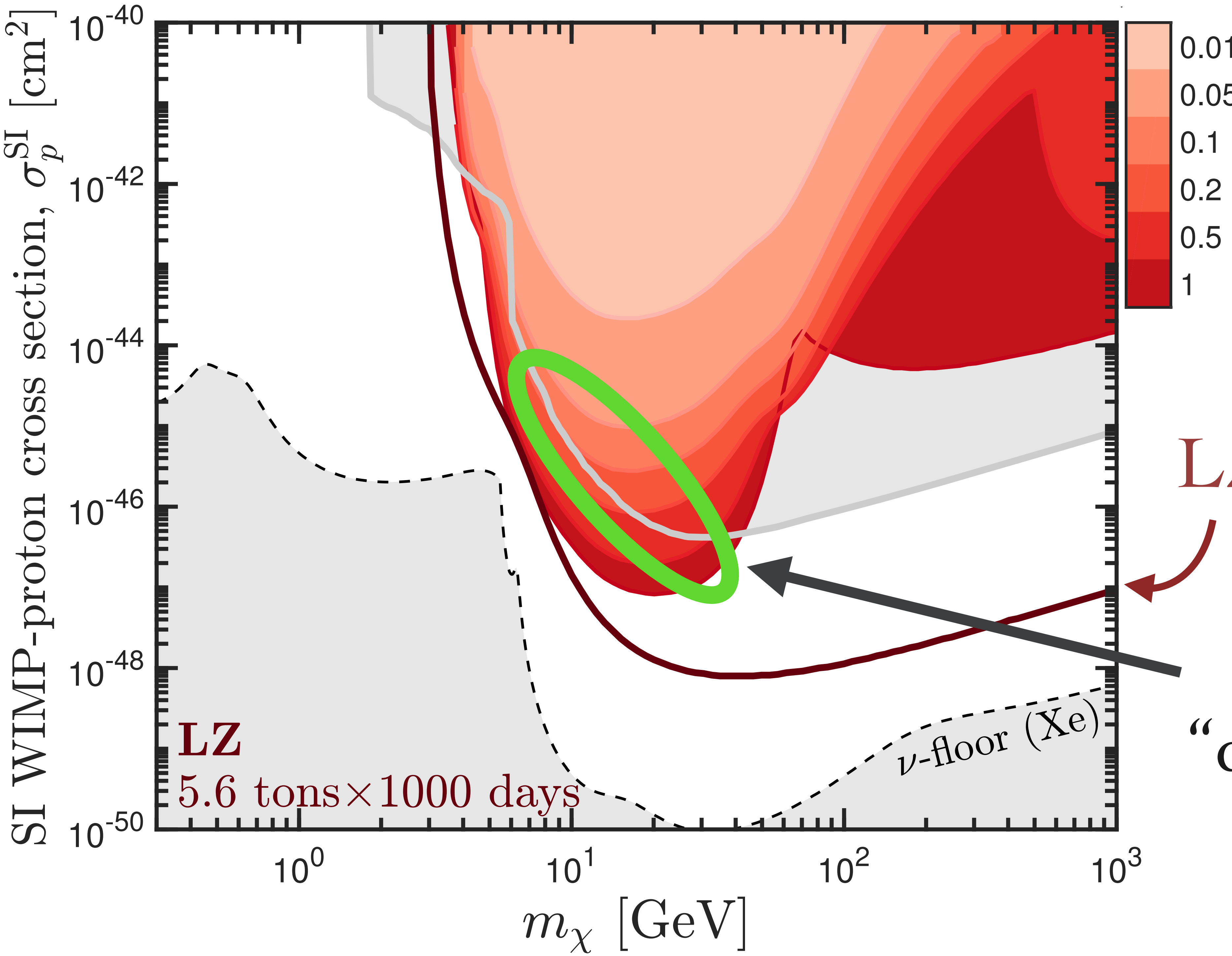
Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma



O'Hare+ [1807.09004]

S1 in LZ

Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma



Fraction of total DM in stream

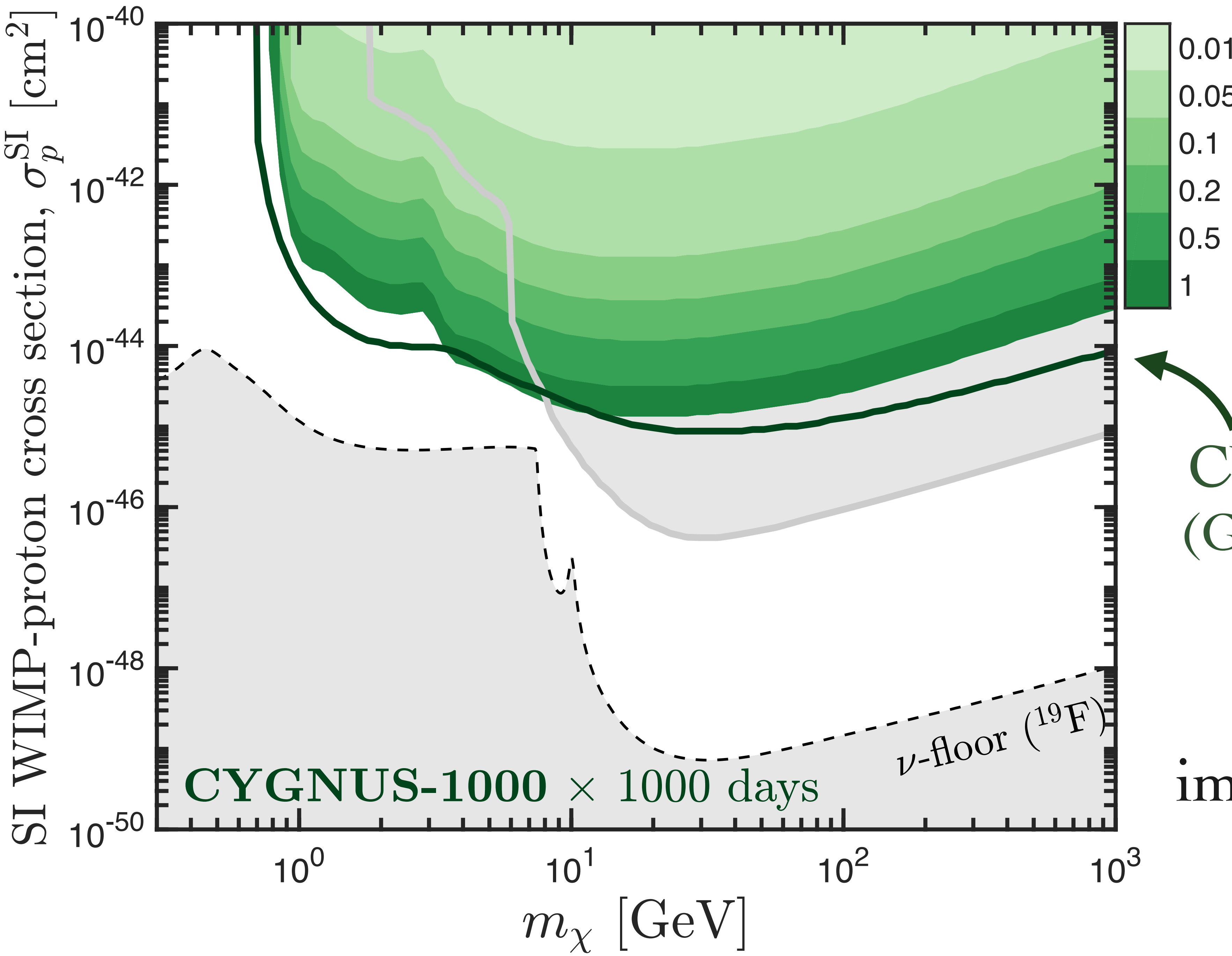
LZ sensitivity

Stream only "detectable" here

O'Hare+ [1807.09004]

S1 in a directional detector

Green regions: range of WIMP models for which the stream can be distinguished from the halo in CYGNUS at 3 sigma



Fraction of DM in stream

CYGNUS sensitivity (Gas TPC with He+SF_6)

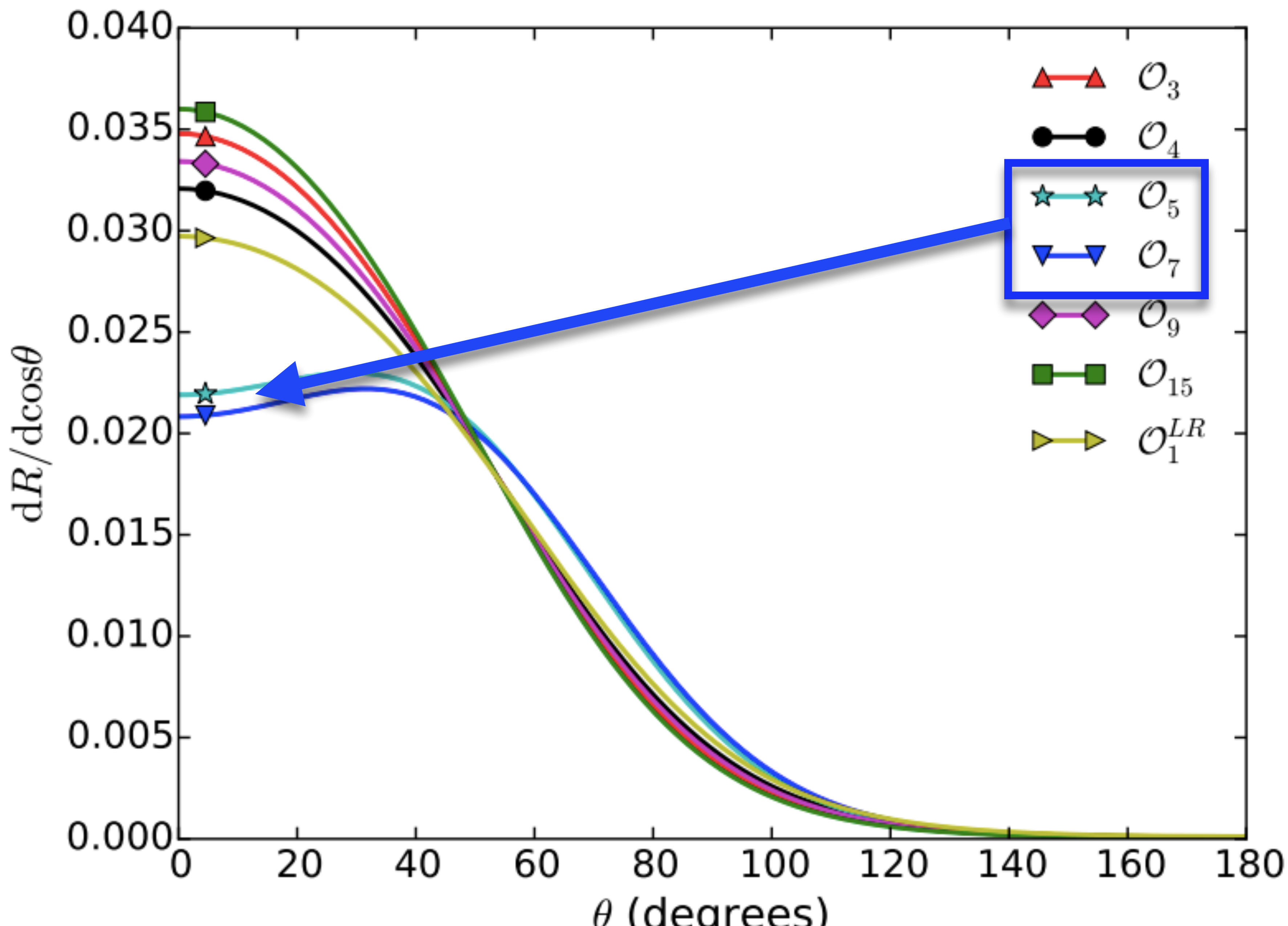
Directionality improves sensitivity to stream

Non-relativistic EFT of DM-nucleus interaction

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

$$\mathbf{v}^{\perp} = \mathbf{v} + \mathbf{q}/2\mu_{\chi A}$$

→ Non-Gaussian angular distributions



How wrong are these assumptions?

→ Gaussian velocity distribution

→ No WIMP elastic scattering

→ No velocity dependent operators

How wrong are these assumptions?

→ Gaussian velocity distribution

→ No WIMP elastic scattering

→ No velocity dependent operators

We don't know, but that's the point…

Non-directional detectors are (realistically) unable to probe these assumptions **even with a DM signal** → they rely on directional information to test

*+more ideas that I haven't discussed, like measuring the DM spin, detecting axion-like particles, superheavy WIMPs, sub-GeV DM…

Say we build Cygnus and find that…

1. **We have a signal**

   ↳ We study it

2. **We don't**

Say we build Cygnus and find that…

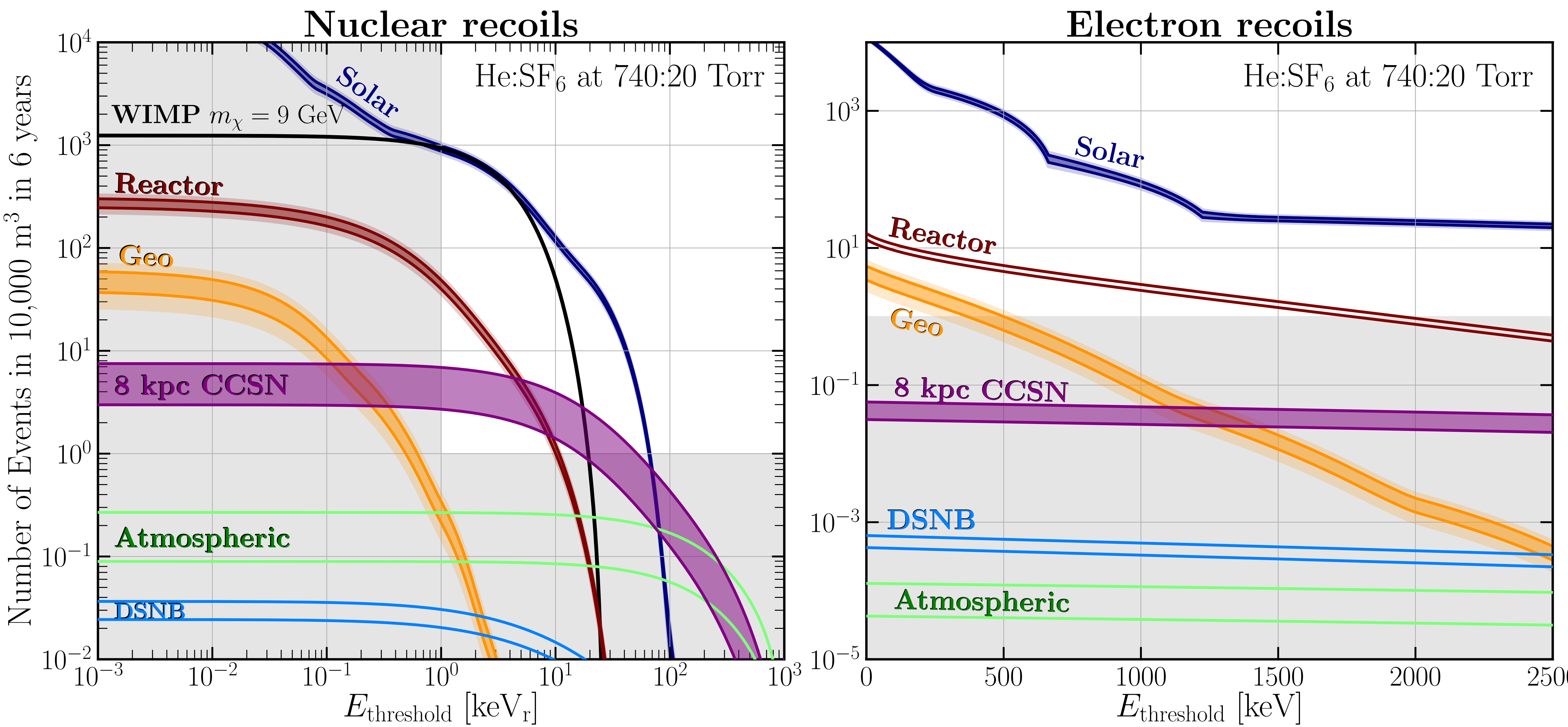
1. We have a signal

→ We study it

2. We don't

→ Our background is our signal

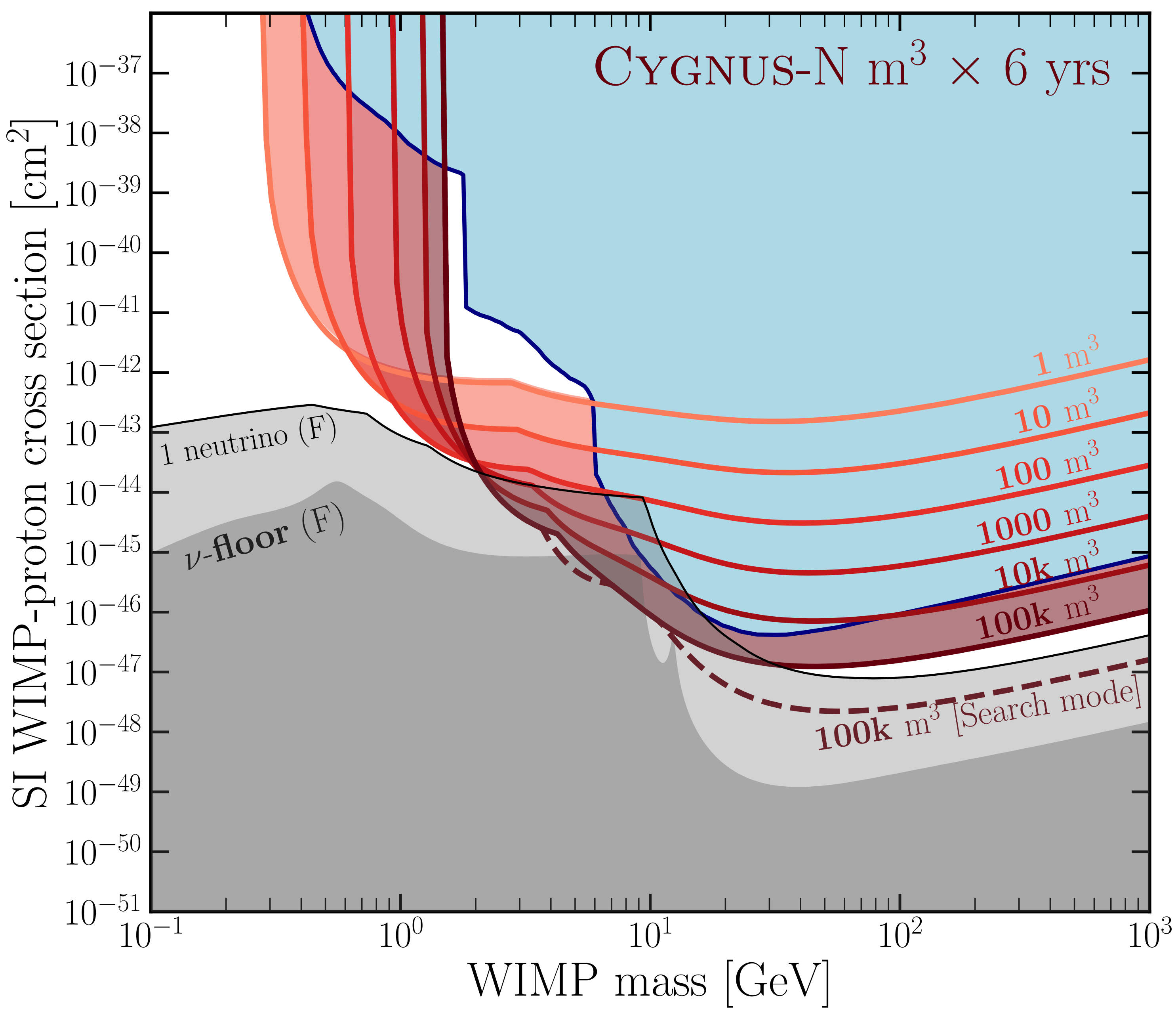
The neutrino background



A directional detector has the potential for superior background rejection and NR/ER discrimination

→ this is true even if you're not talking about DM

A potential CYGNUS timeline



CYGNUS-1 m³

Background-free operation down to 0.25 keV$_r$

Improve upon WIMP limits for <2 GeV

CYGNUS-10 m³

Background-free operation down to 0.5 keV$_r$

Best SD-proton limits across all masses

CYGNUS-100 m³

~1 Solar neutrino per year

CYGNUS-1000 m³

Sensitive to reactor neutrinos

$\mathcal{O}(10)$ Solar neutrinos per year

CYGNUS-10k m³

Best SI limits across all masses

Detect core-collapse supernova at 8 kpc

CYGNUS-100k m³

1 order of magnitude below neutrino floor at 9 GeV

Measure geoneutrinos

Conclusions

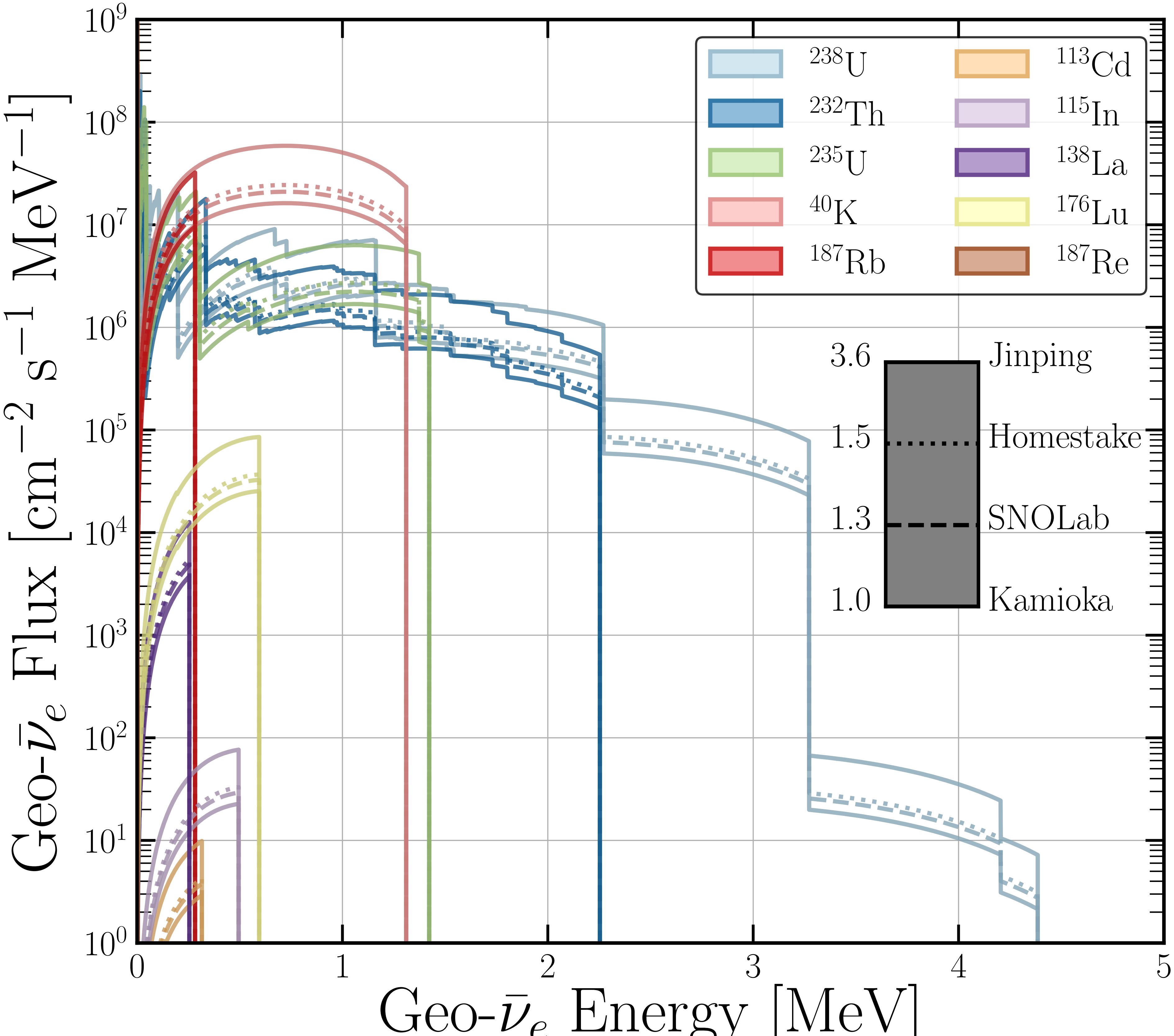
- Cygnus aims to be the first experiment with DM discovery reach below the neutrino floor
- Extremely strong motivation as well as post-discovery potential
- End goal: >1000 m^3 gas-TPC
- With currently available readout techs. it seems reasonable with further optimisation to get down to <8 keV_r with:
    - Angular resolution <30°
    - HT recognition >75%
    - $>10^4$ electron rejection

Extra slides

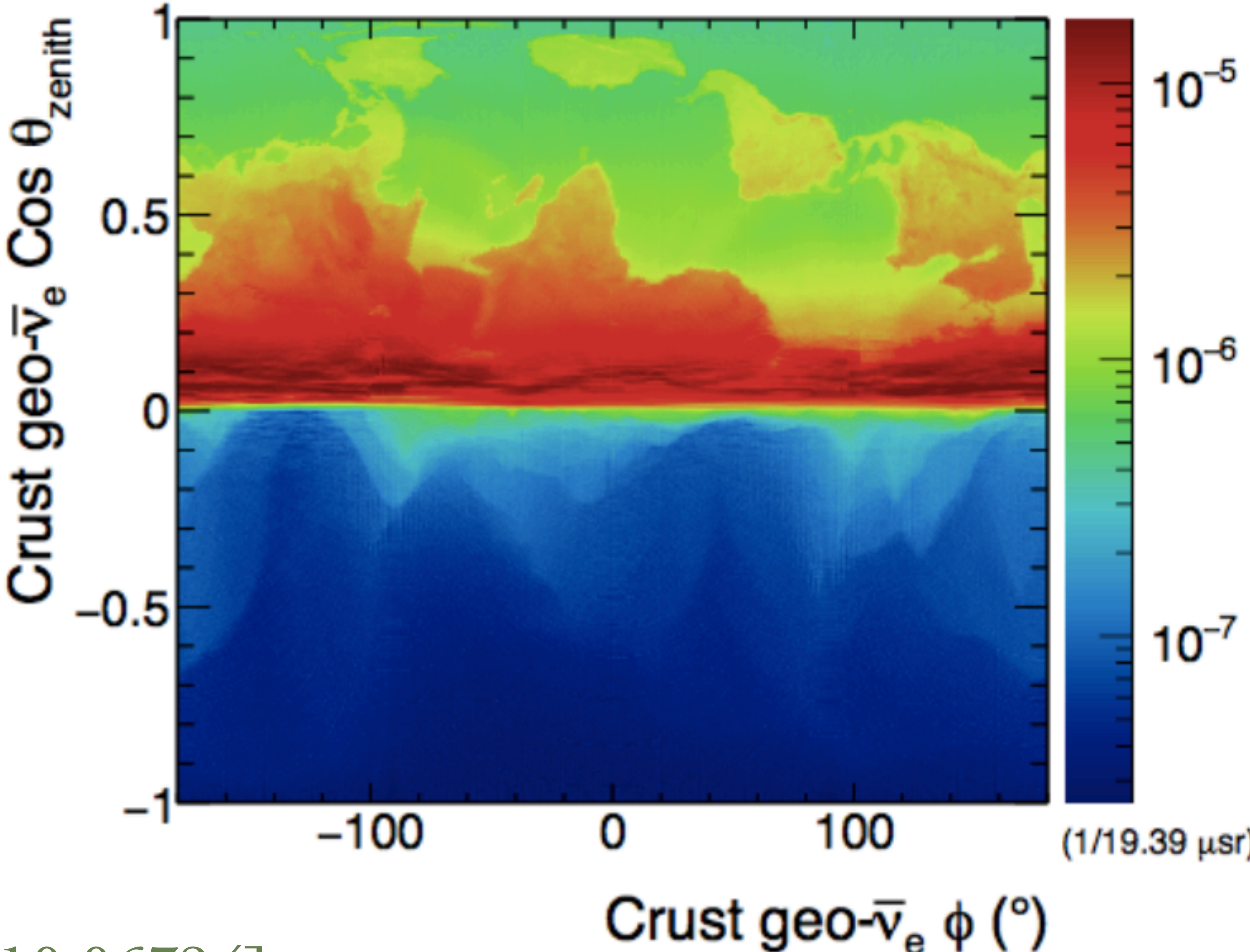
Why 8 keV is likely an upper limit of a feasible threshold:

- Rejection via track length alone is a simple metric, electrons and nuclei have very different track topologies and this information is currently unused.
- Currently assuming a fixed 25 cm drift length, but diffusion ~ sqrt(drift length), so closer recoils than 25 cm will diffuse a lot less than further ones will diffuse more.
- Preliminary studies with machine learning-based techniques for electron discrimination suggest possible sub-1 keV_{ee} electron rejection

Geoneutrino flux



Geoneutrino flux



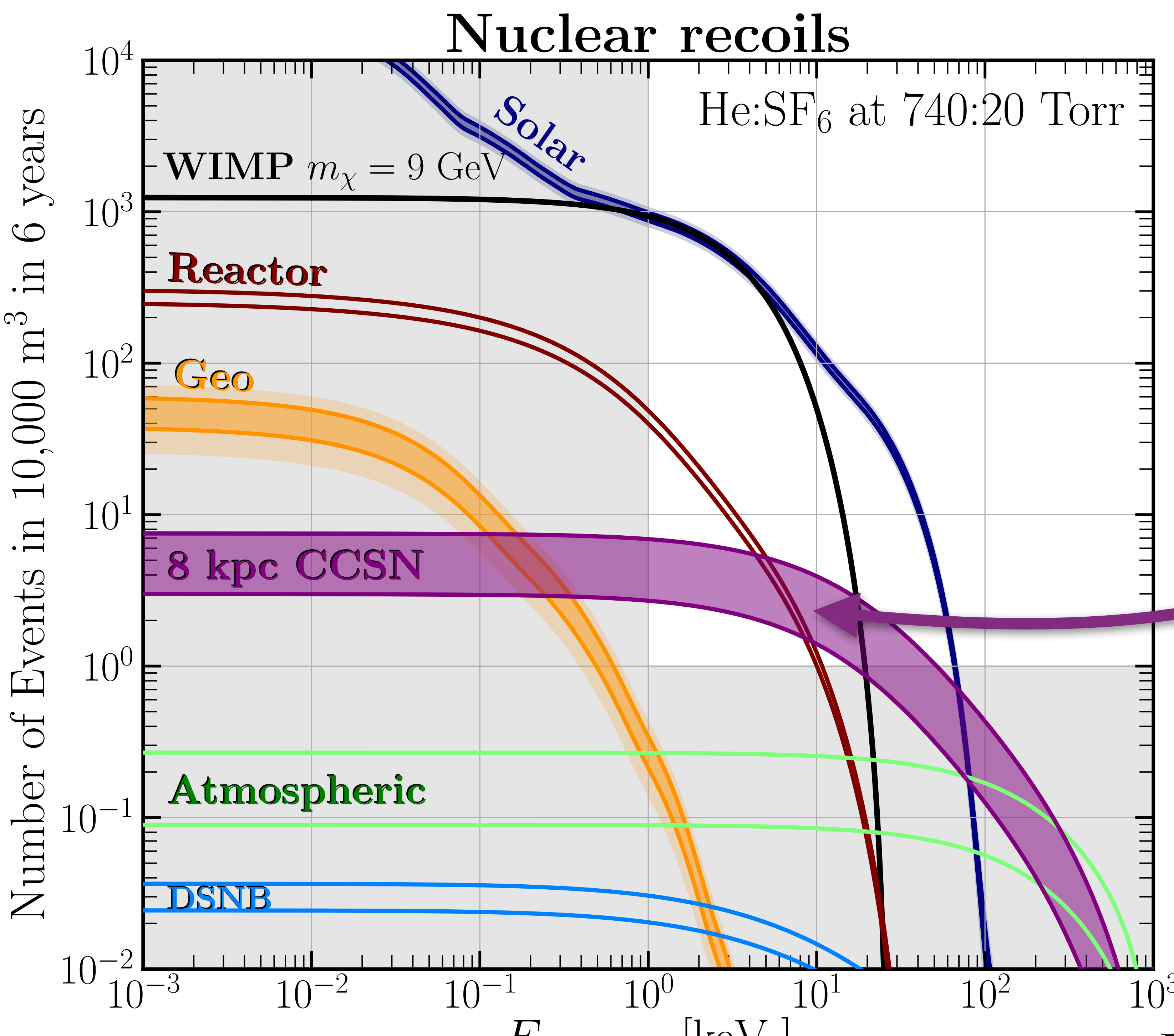
Leyton+ [1710.06724]

Physics case includes:

- Measure radioactive contribution to Earth's heat generation (10 ton-years)
- Measuring Earth's ^{40}K content (100 ton-years)
- Probing the source of Earth's magnetic field (>100 ton-years)

Pointing to a supernovae

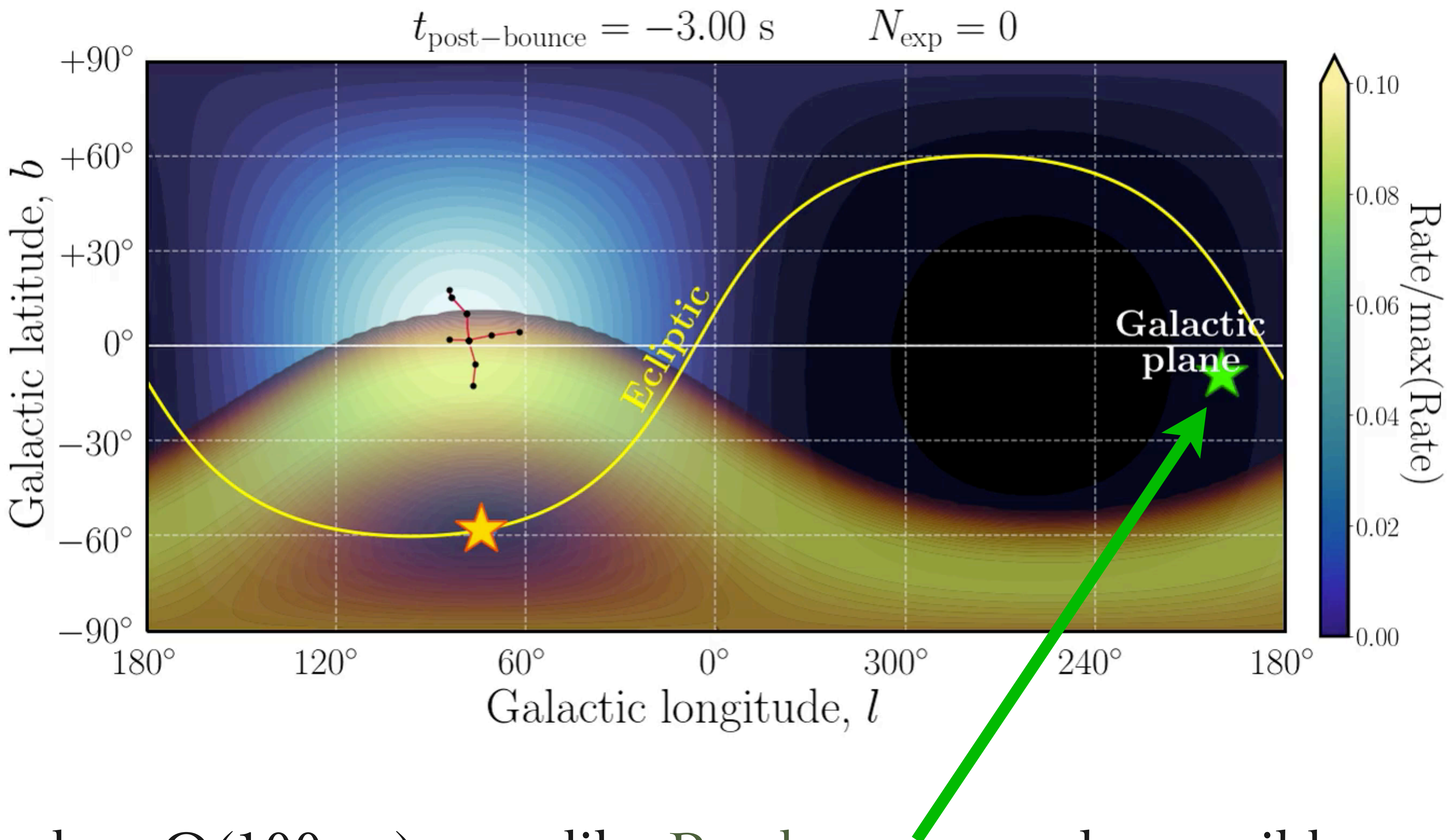
Expect >3 events in CYGNUS-10k for 10-30 $M_\odot$ core-collapse Supernova closer than >8 kpc



→ But flux goes as d^{-2}

Pointing to a supernovae

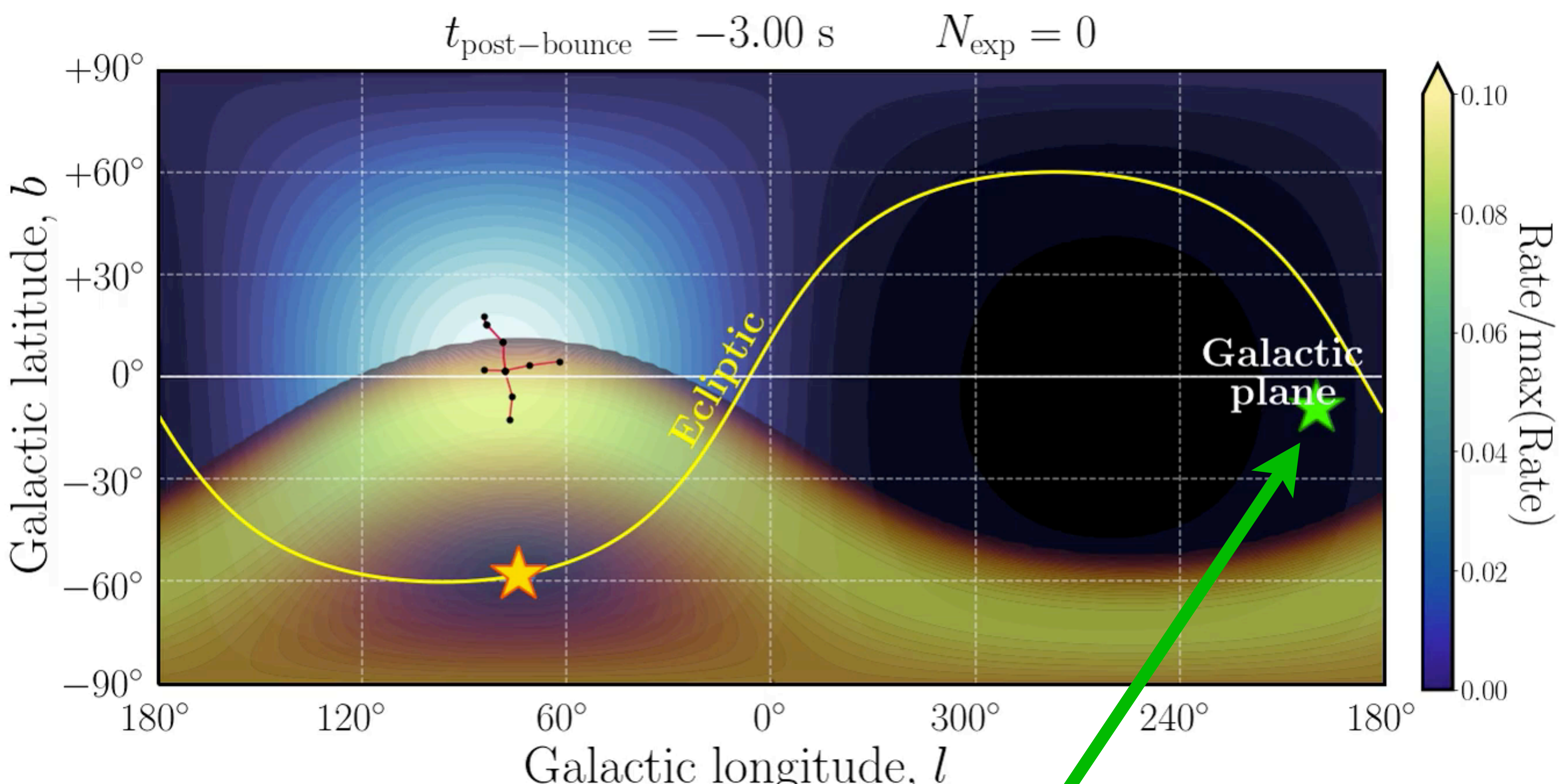
(movie)



Very close O(100 pc) stars like Betelgeuse, may be possible to point to pre-supernova neutrinos days in advance, see e.g. [1905.09283]

Pointing to a supernovae

(movie)

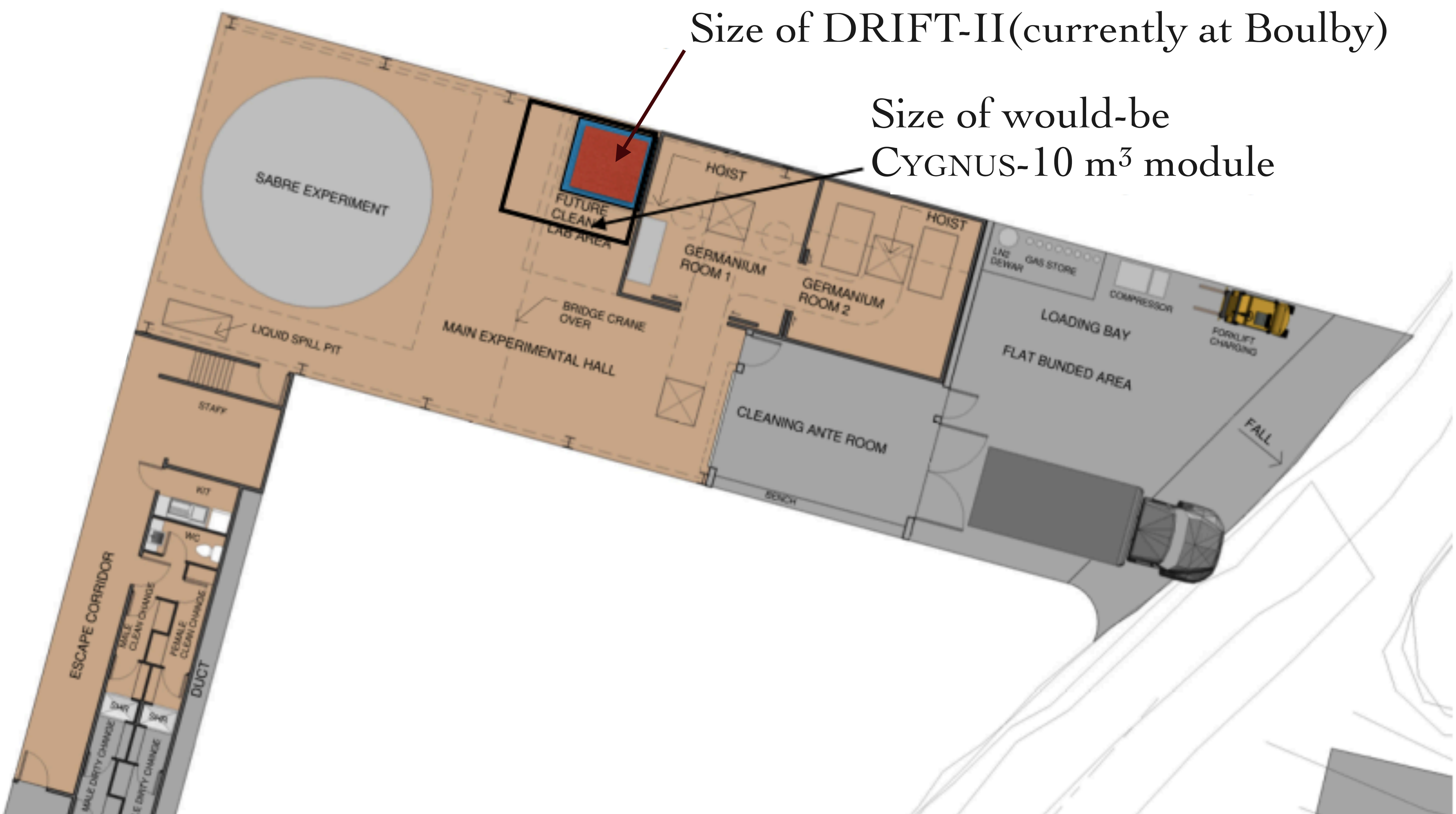


Very close O(100 pc) stars like Betelgeuse, may be possible to point to pre-supernova neutrinos days in advance, see e.g. [1905.09283]

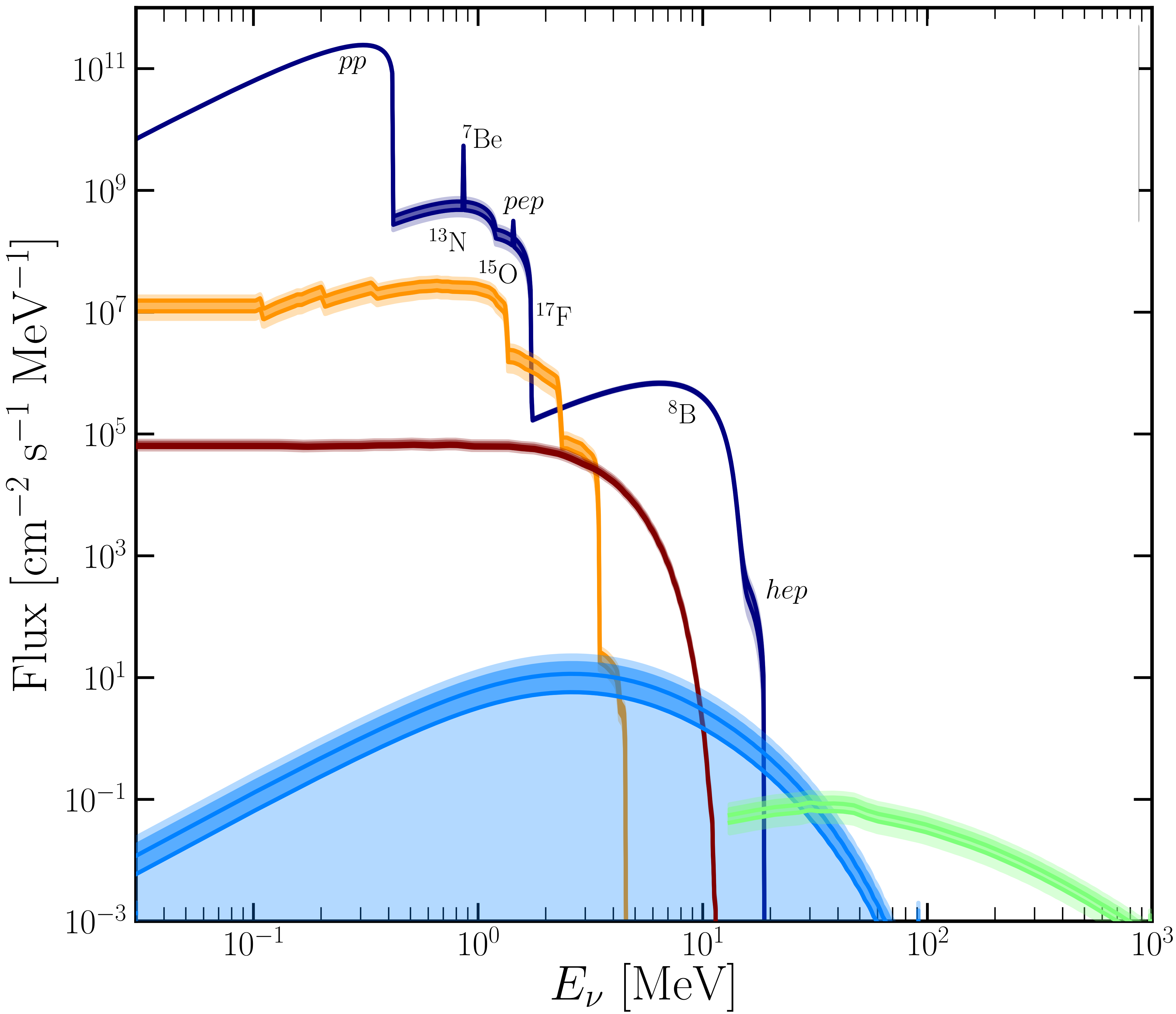
New site under construction in Victoria

Stawell Underground Physics Laboratory (SUPL)

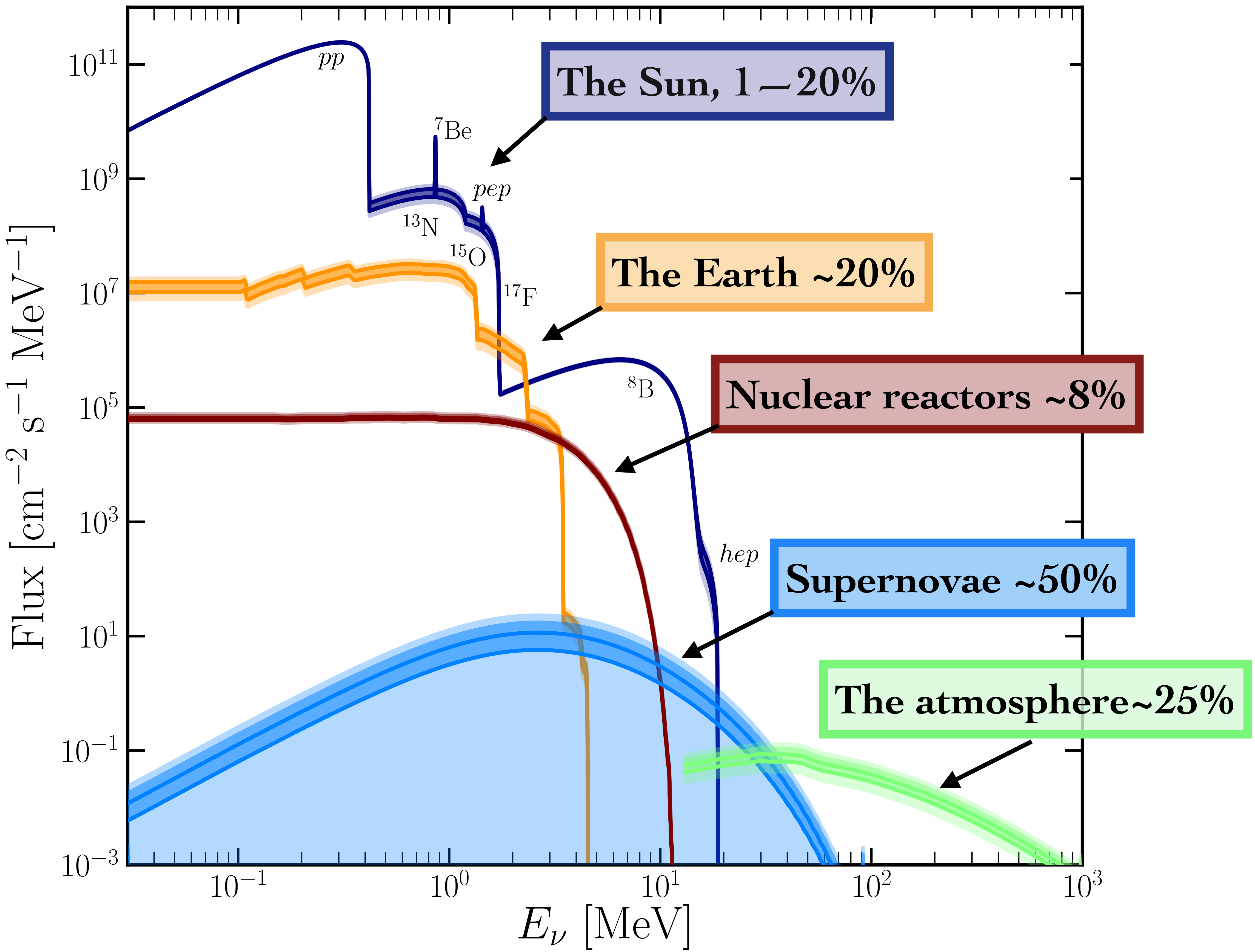
- 1.6 km depth
- First underground site in Southern Hemisphere



Neutrino fluxes

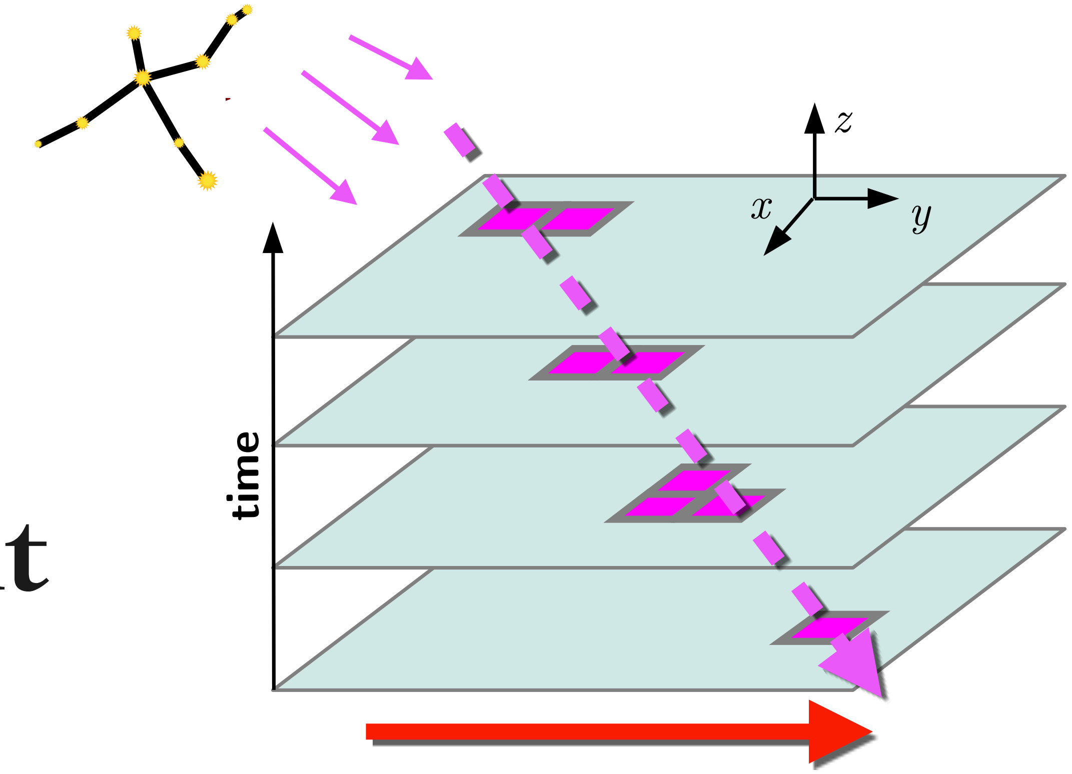


Neutrino fluxes



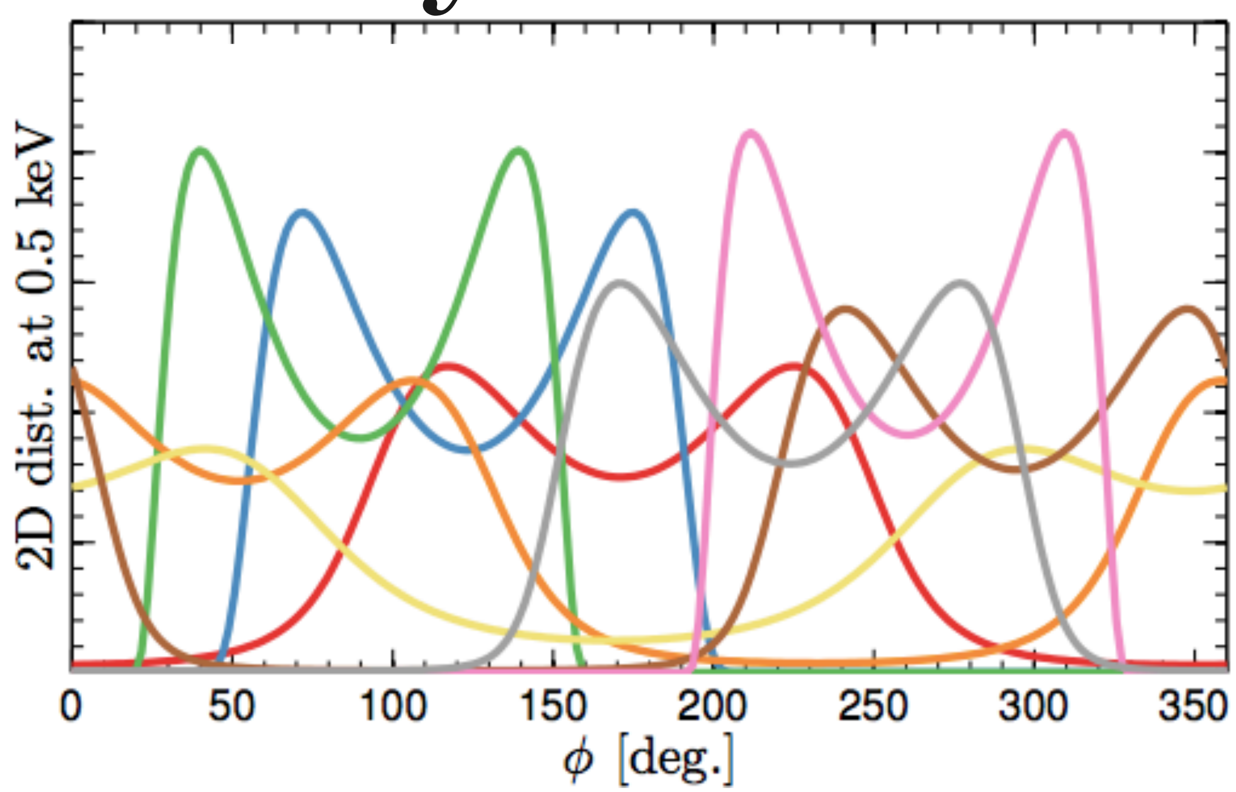
O'Hare+ [1505.08061]

2D Readout

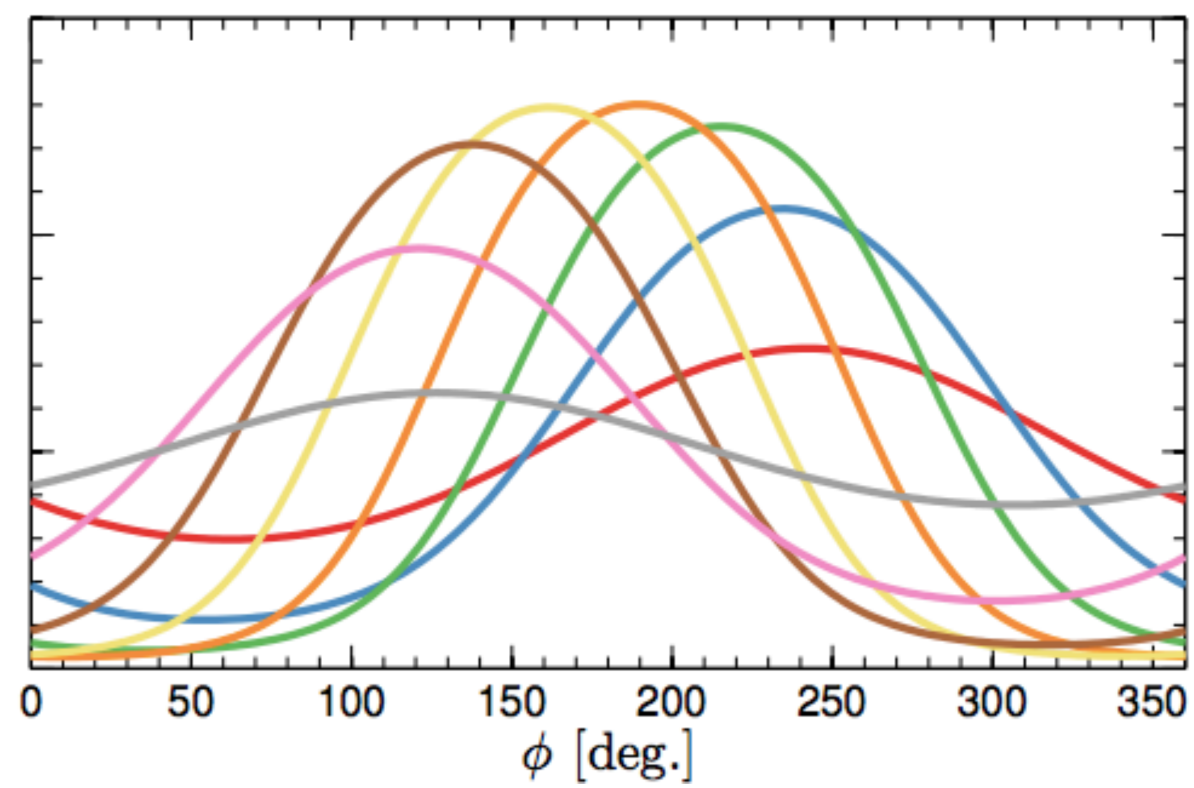


$$\hat{\mathbf{q}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$$

Neutrino Daily modulation

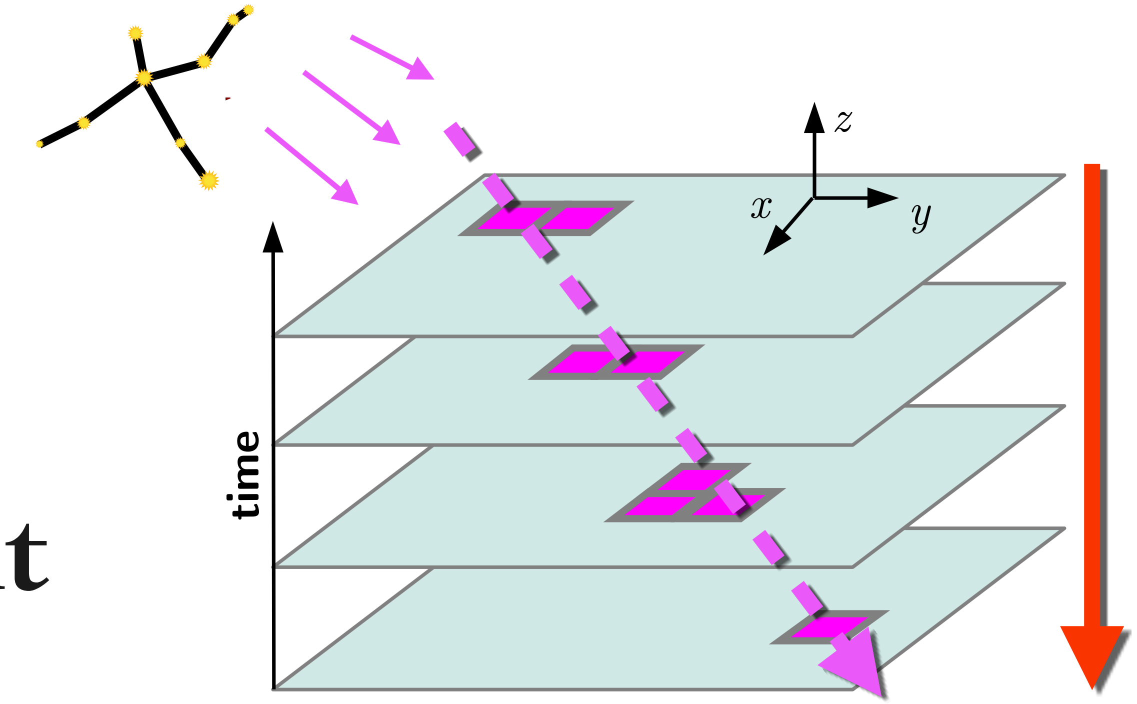


WIMP Daily modulation



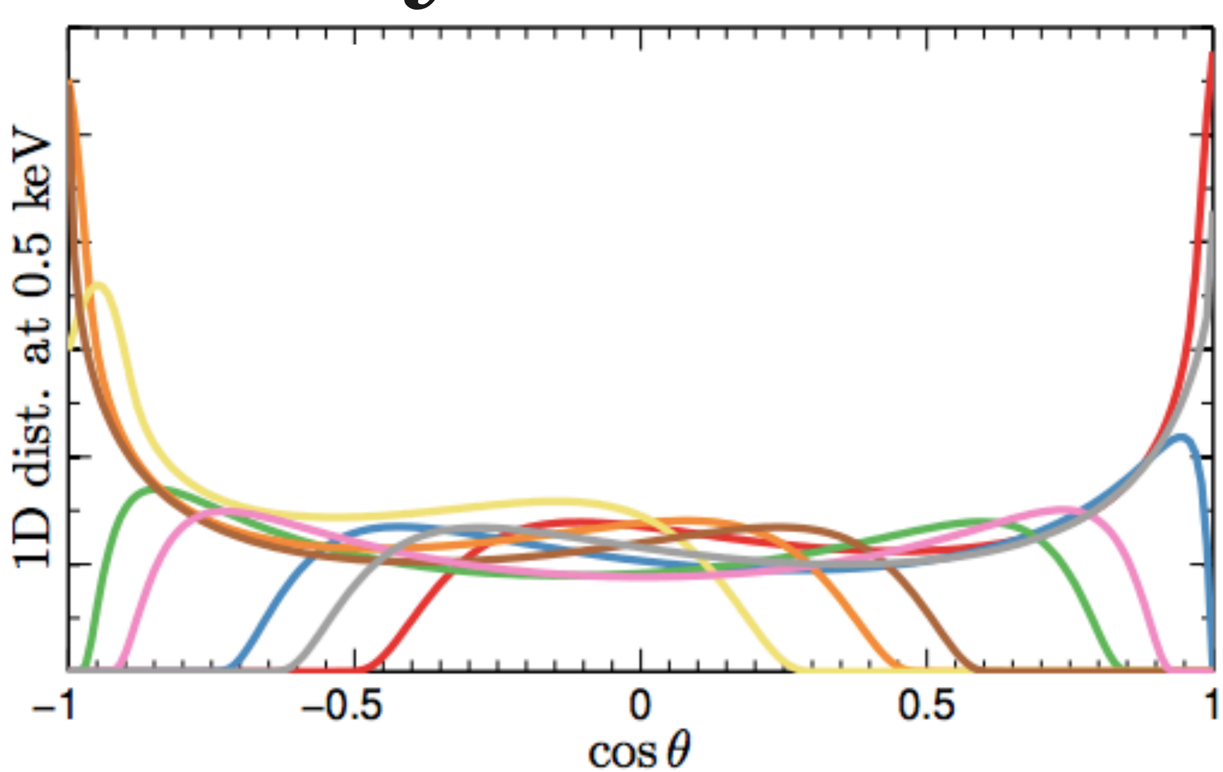
O’Hare+ [1505.08061]

1D Readout

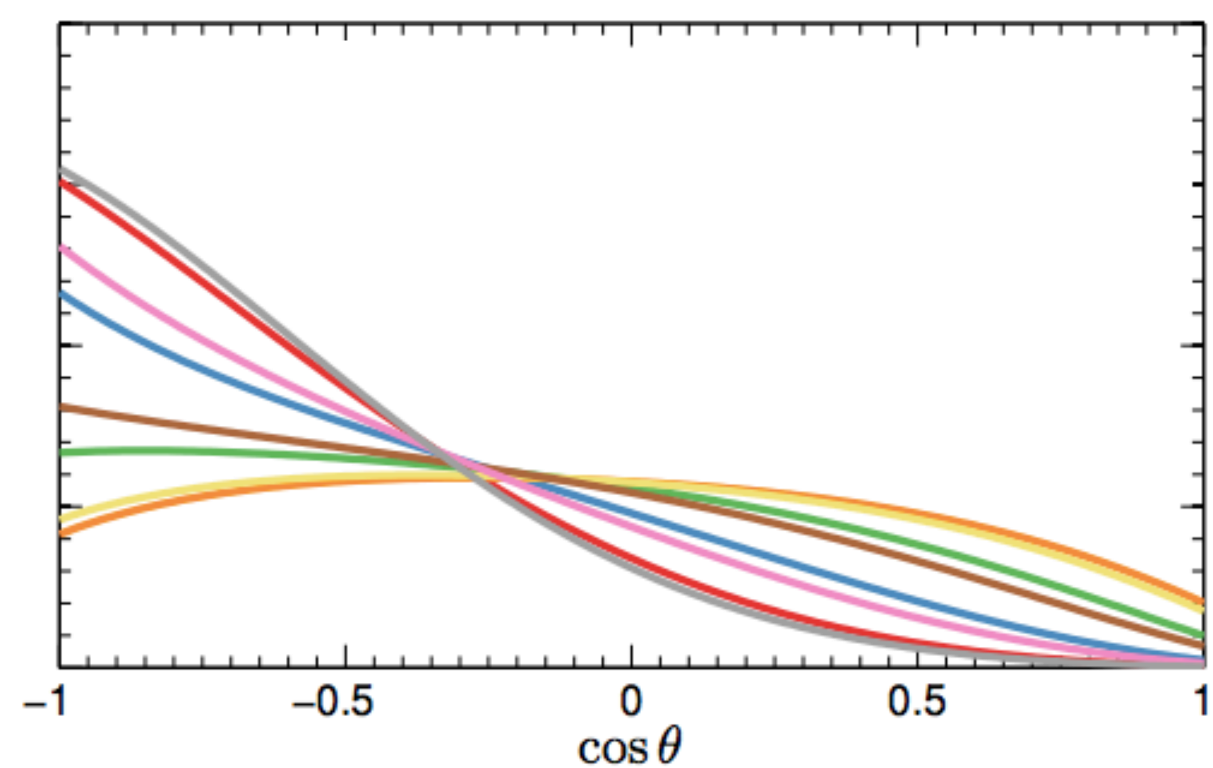


$$\hat{\mathbf{q}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$$

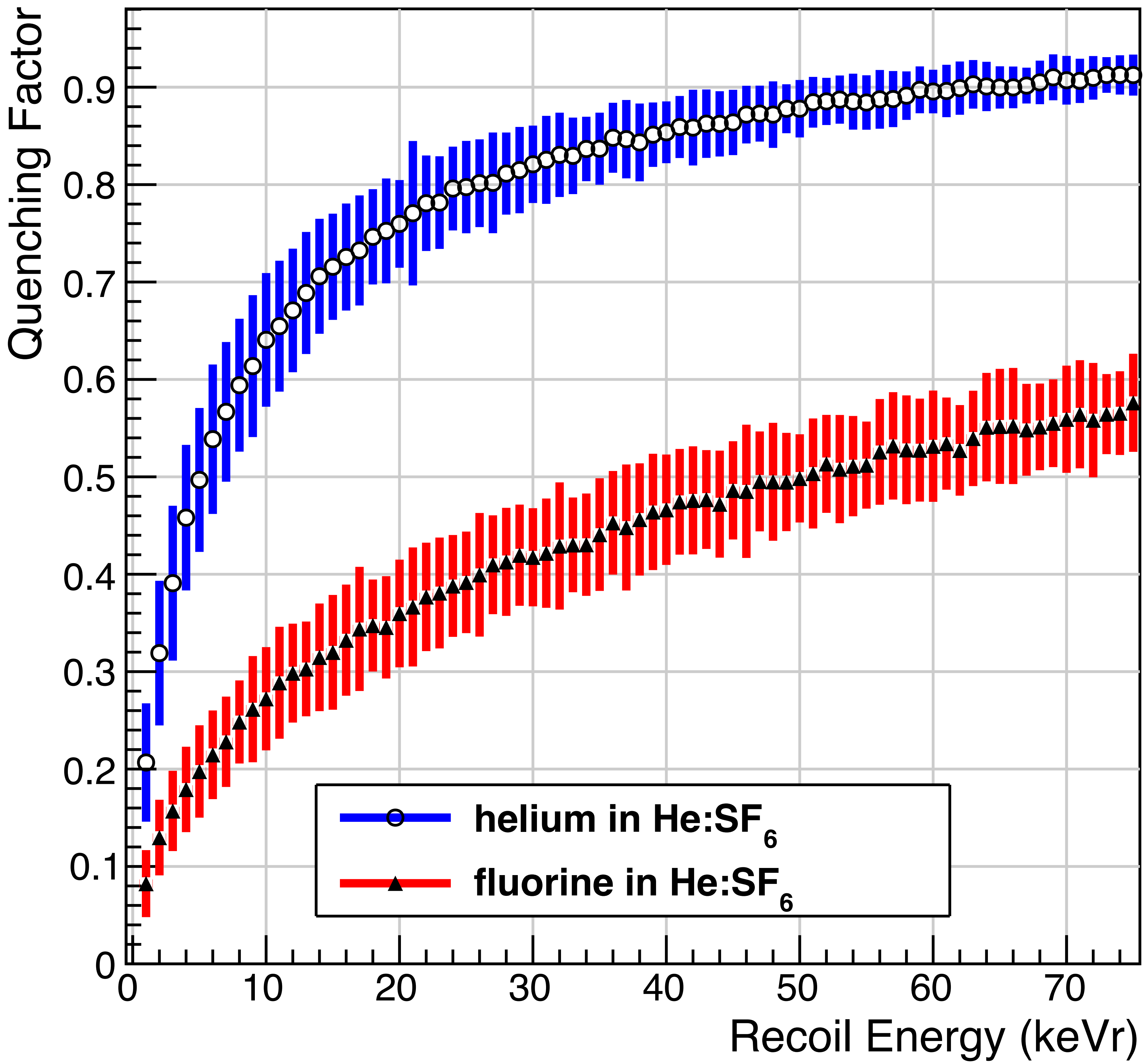
Neutrino Daily modulation



WIMP Daily modulation



Quenching factors for recoils in 1 atm of $He+SF_6$



Gas mixture	SF_6	He:SF_6	He:SF_6
Pressure [Torr]	20	740:20	755:5
Density [kg/m^3]	0.16	0.32	0.20
W [eV/ion pair]	35.5	38.0	40.0
Trans. diffusion [μm/$\sqrt{\text{cm}}$]	116.2	78.6	78.6
Long. diffusion [μm/$\sqrt{\text{cm}}$]	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.