Centre for Dark Matter Particle Physics

THE UNIVERSITY OF SYDNEY

CYGNUS

CYGNUS: A large scale directional detector for dark matter and neutrinos

TeVPA, 3 December 2019

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University of Sydney

The problems with detecting WIMPs via nuclear recoils

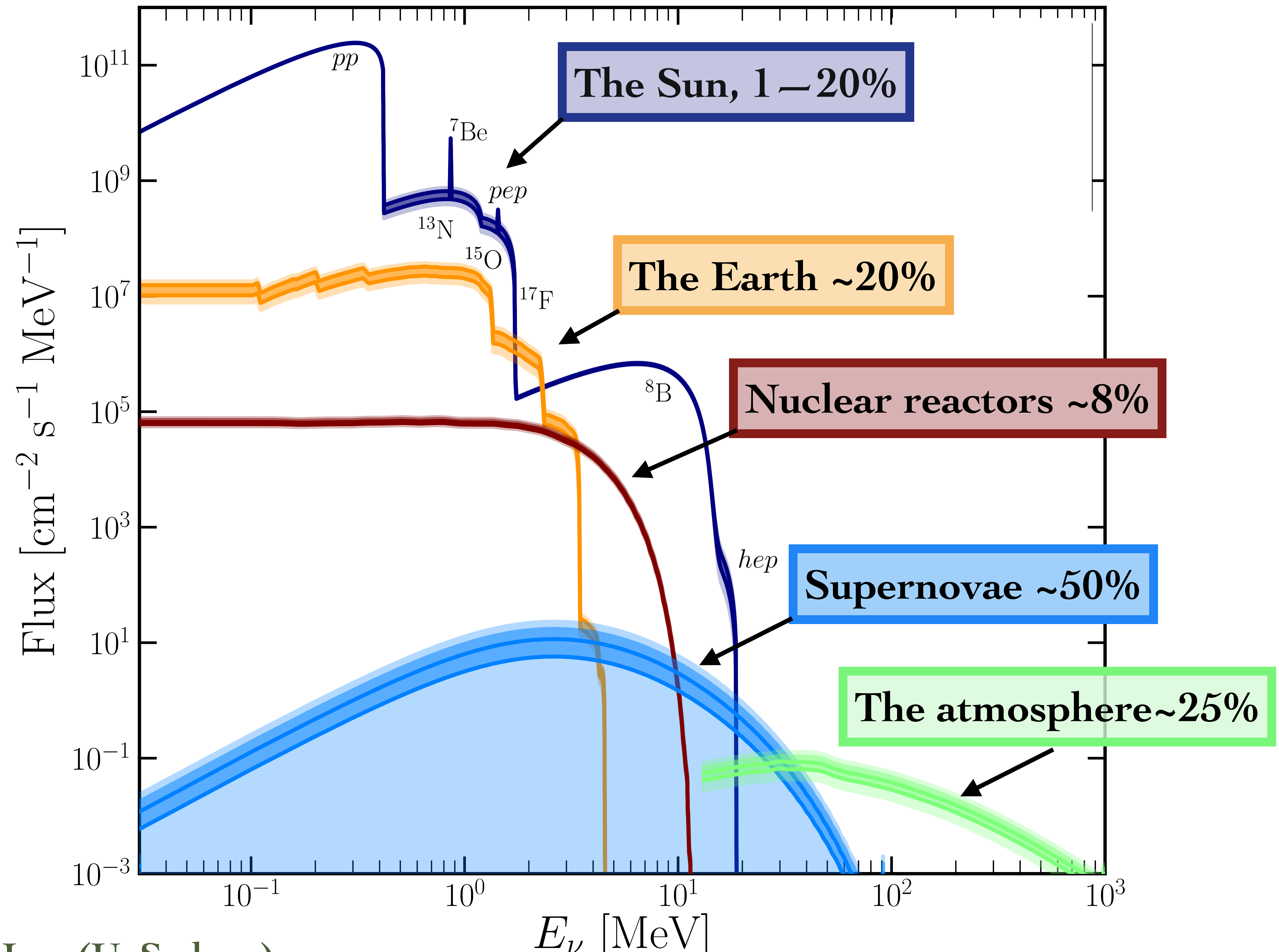
~~1. How do you know what is recoiling?~~

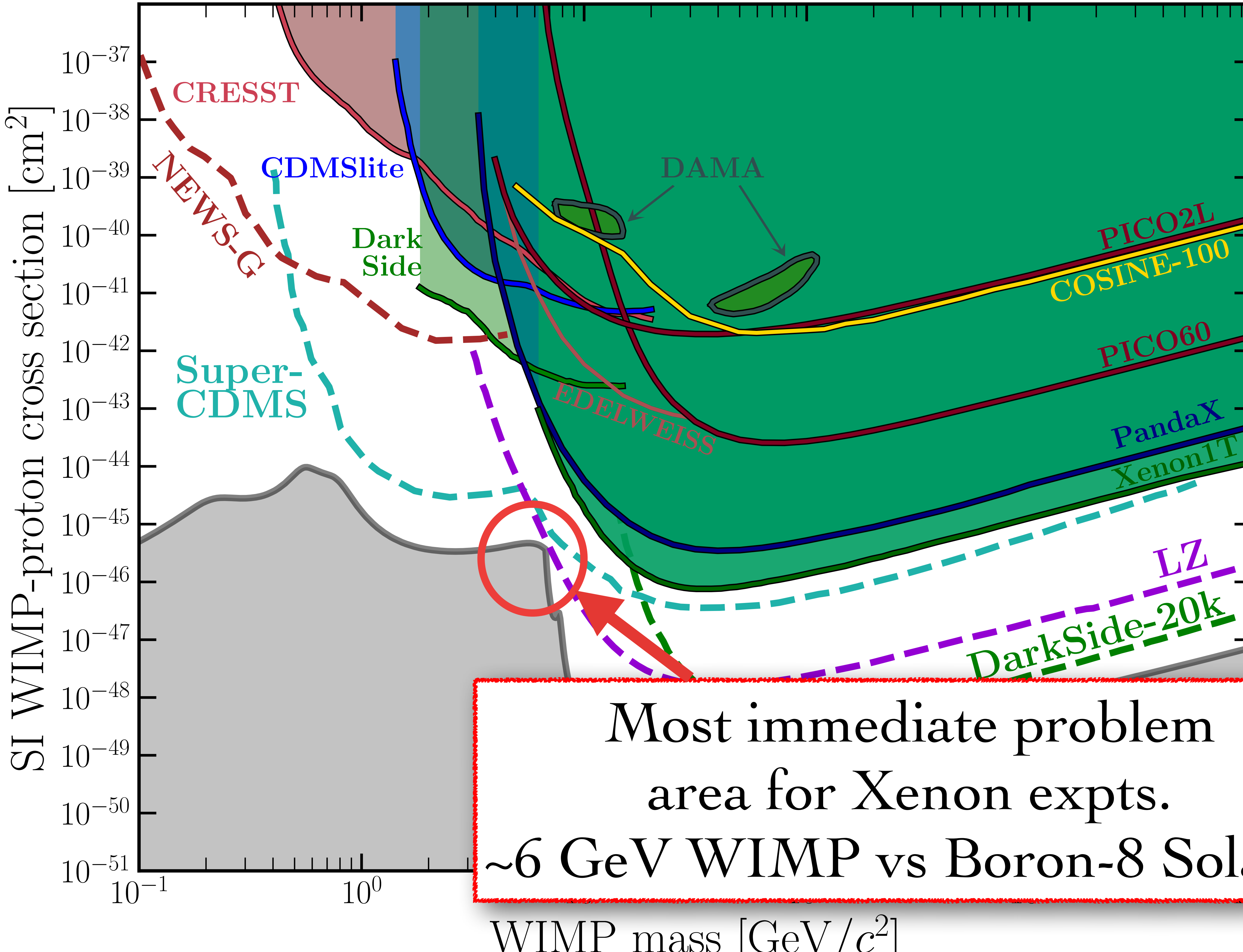
~~2. If you have **nuclear** recoil: how do you know what caused it?~~

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

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

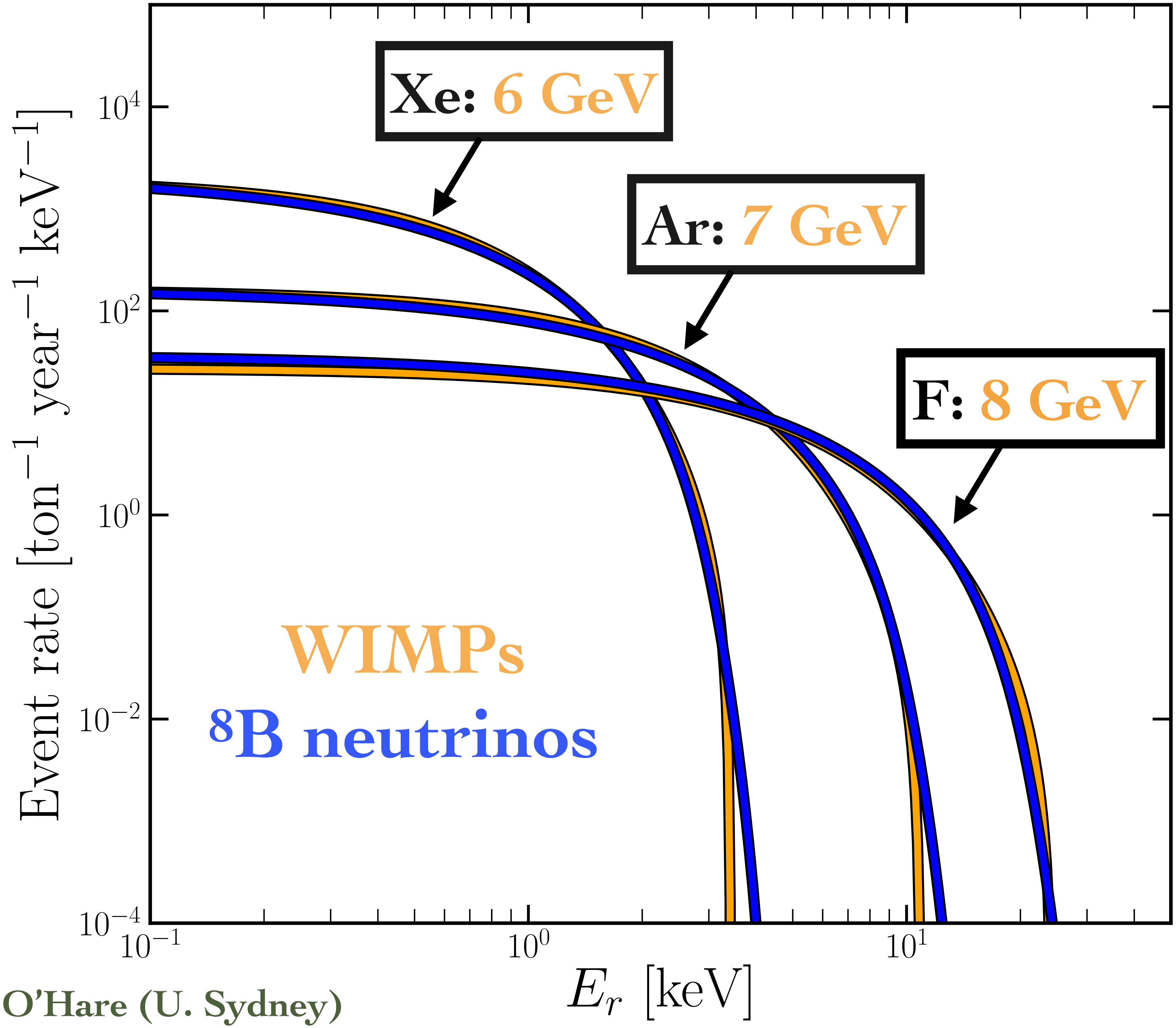
Neutrino fluxes





Most immediate problem area for Xenon expts.
~6 GeV WIMP vs Boron-8 Solar-ν

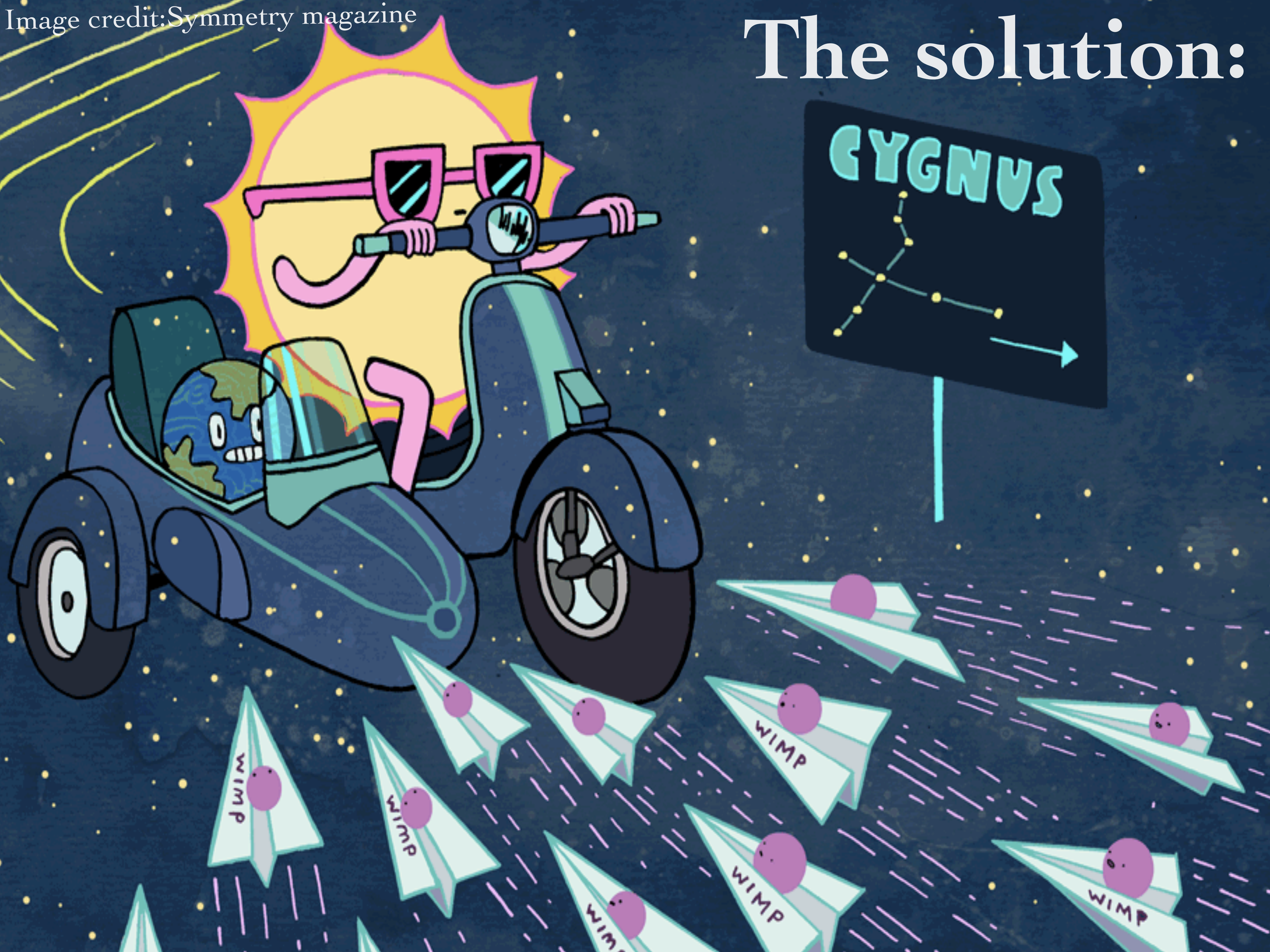
The problem:

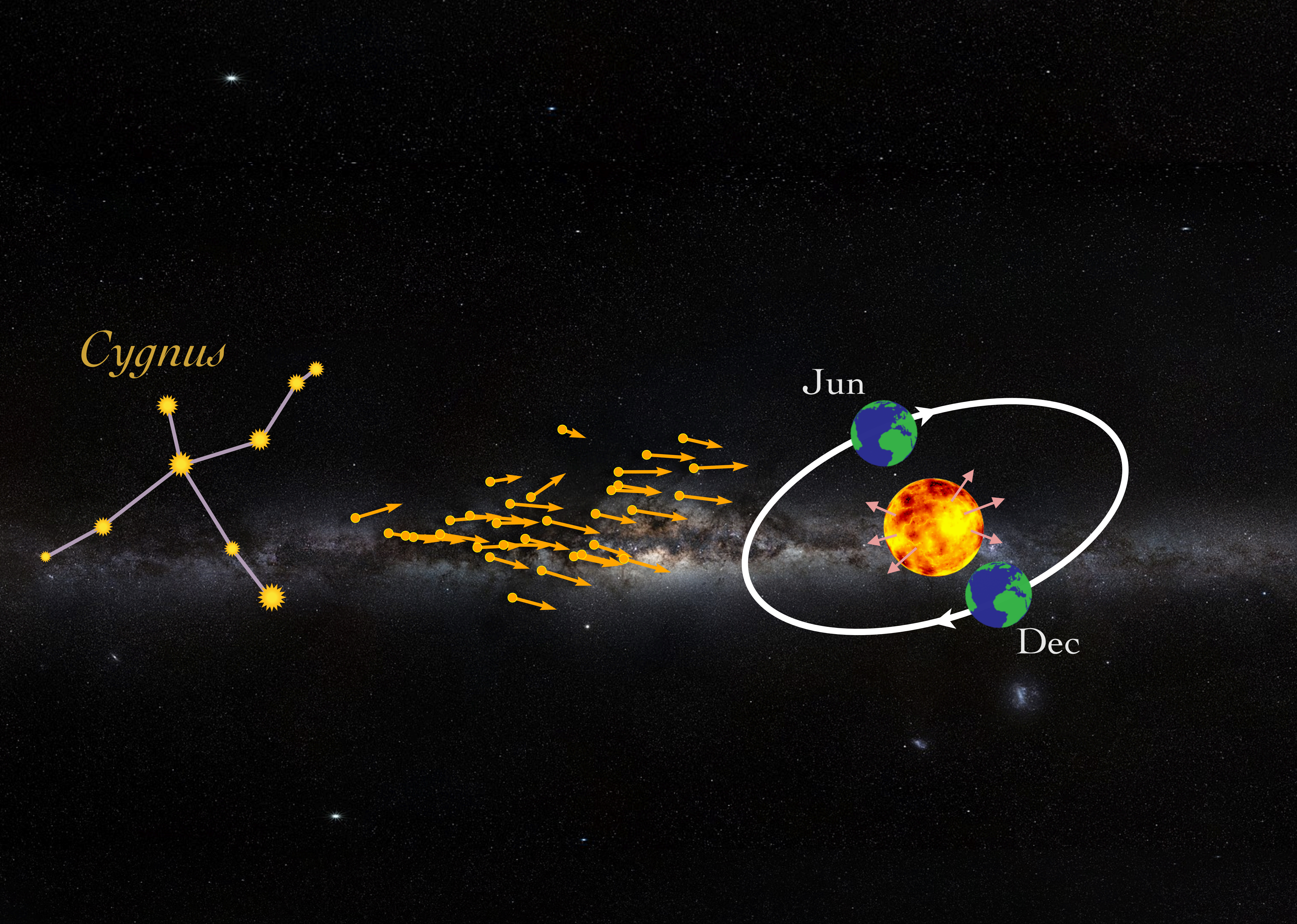


Xe: 6 GeV
Ar: 7 GeV
F: 8 GeV
WIMPs
^{8}B neutrinos
Event rate [ton^{-1} year^{-1} keV^{-1}]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-1}
10^0
10^1
E_r [keV]

Image credit:Symmetry magazine

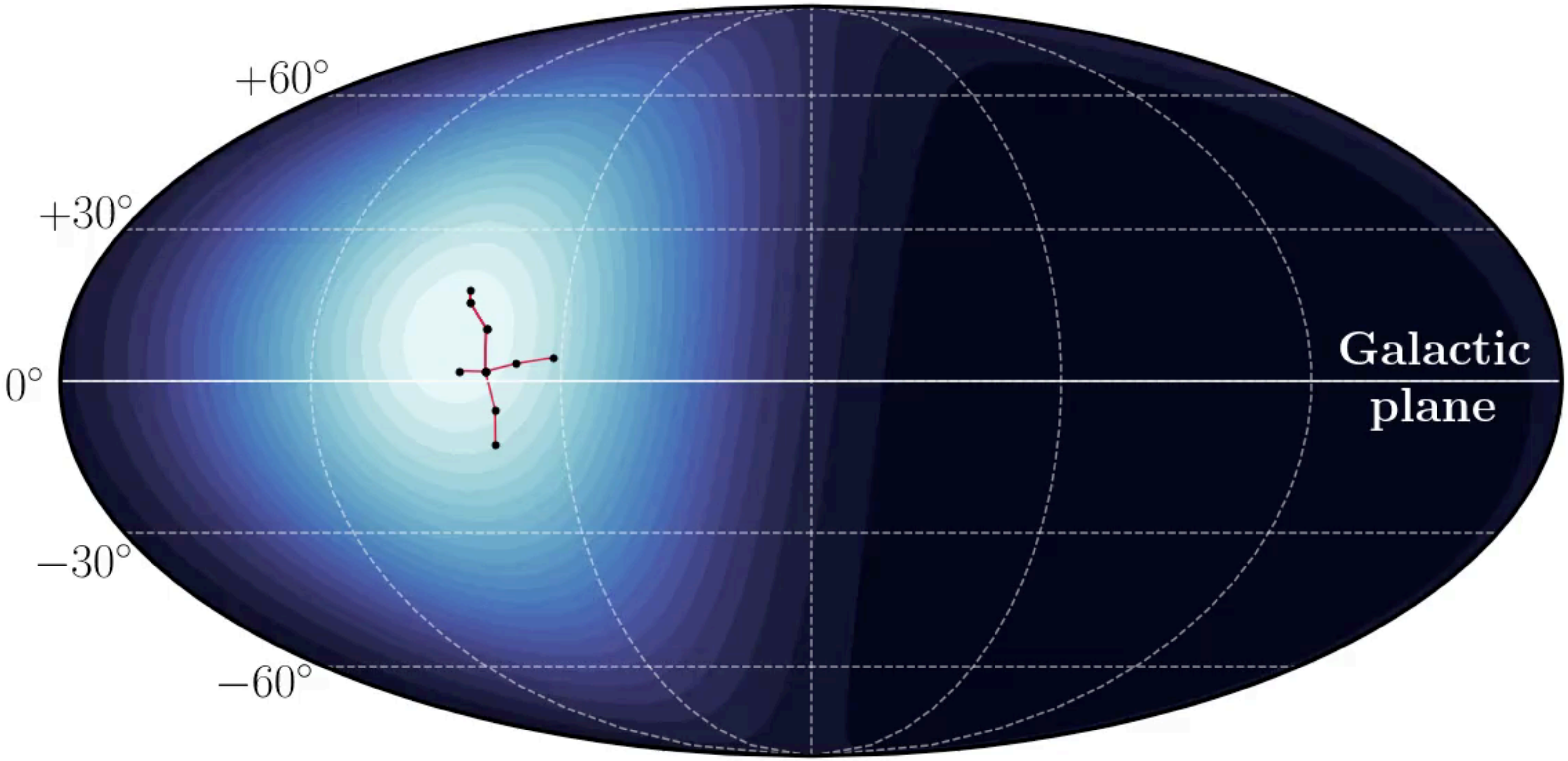
The solution:




Cygnus
Jun
Dec

A dark matter signal will align with our galactic motion
→ point back towards Cygnus

Nothing other than dark matter will do this…

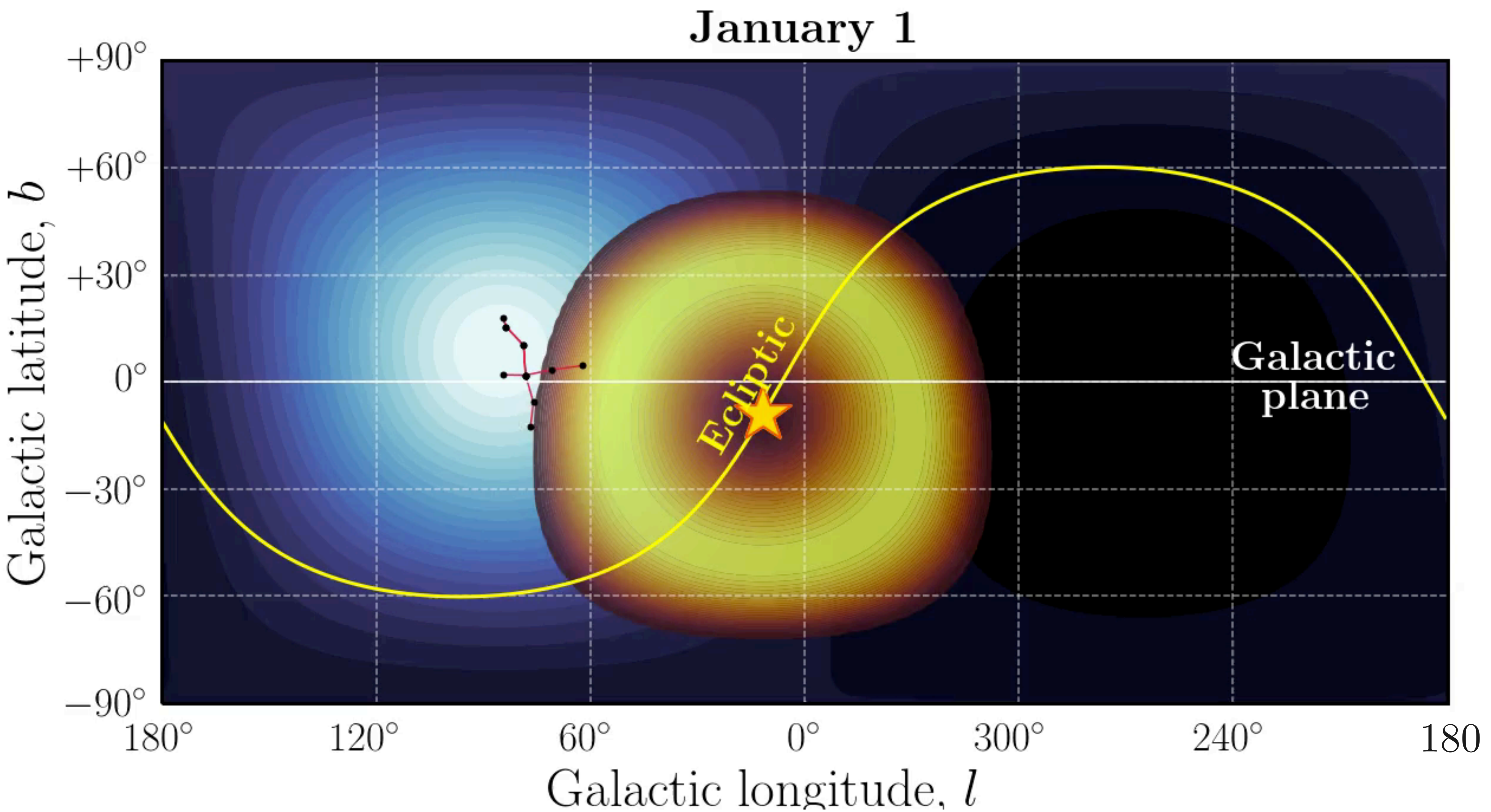


(Fluorine recoils above 3 keVr)

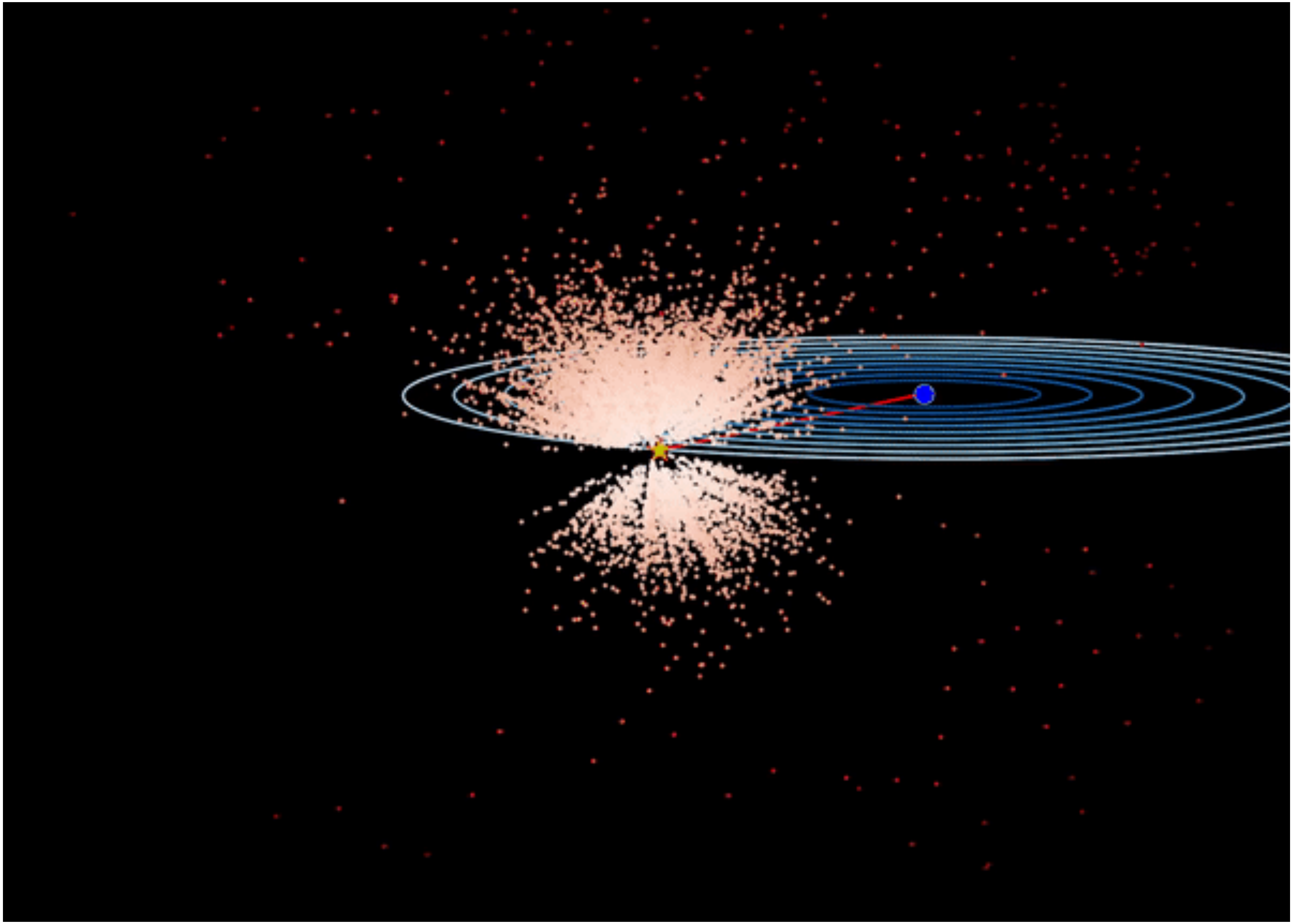
(movie)

Galactic coordinates

WIMP recoils **Solar neutrino recoils**

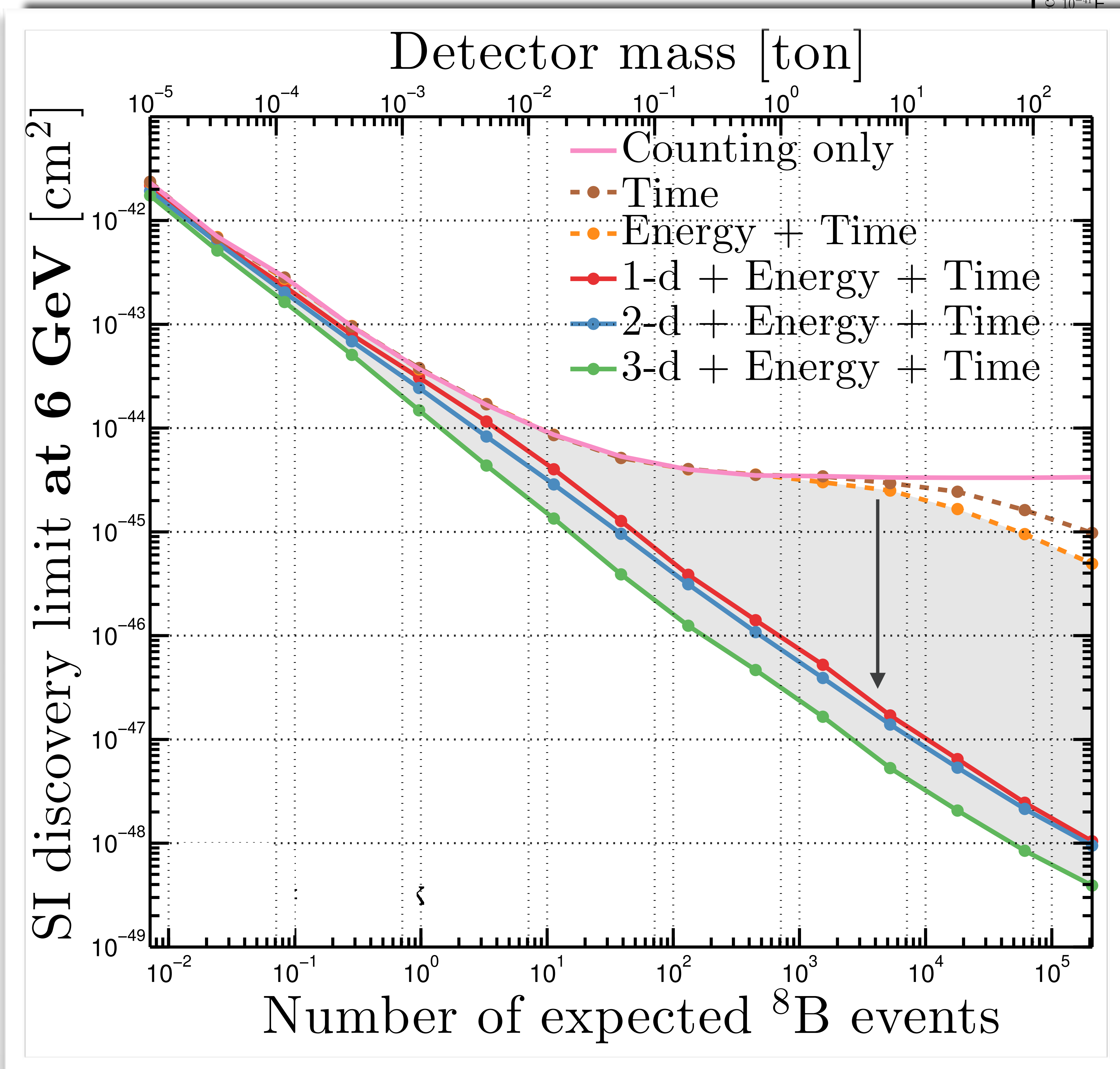


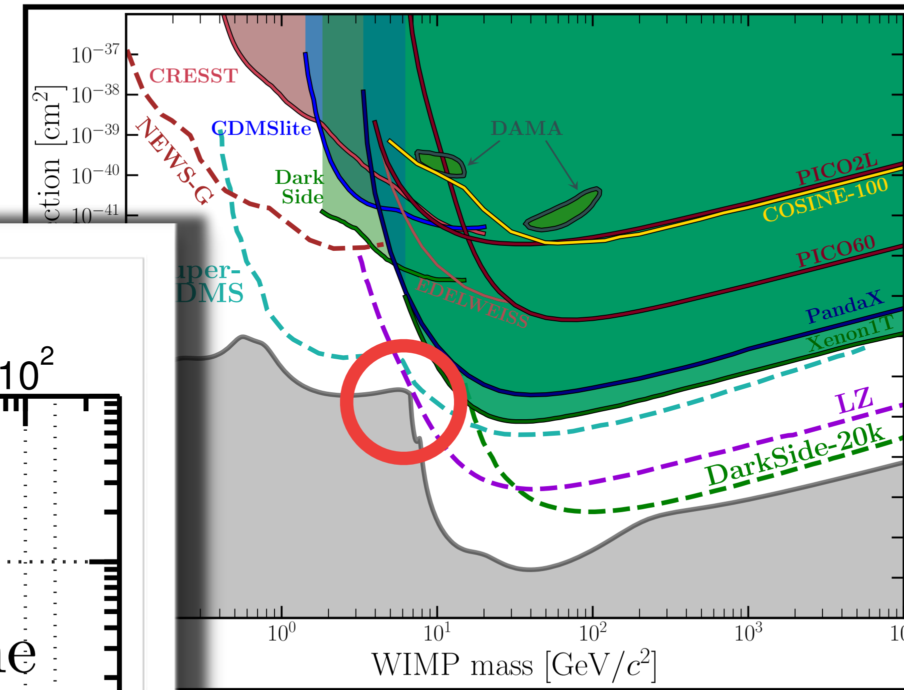
(movie)



(movie)

Subtracting the neutrino background





Directional info powerful for subtracting Solar neutrinos

But so far only studied under idealised conditions

A directional experiment can discover dark matter
No other experiment can unequivocally confirm a signal with galactic origin.

CYGNUS

- **Collaboration: >50** members from US, UK, Aus., Japan, Italy, Spain, China
- **Focus**: low pressure gas time projection chamber (TPC)
- **Primary goal:** WIMPs discovery below the neutrino floor
- **Secondary goal:** Directional detection of CEvNS with Solar ν's
- **Tertiary goals:** study DM velocity dist., directional ν-e$^-$ scattering…+more?

CYGNUS: Feasibility of a Nuclear Recoil Observatory with Directional Sensitivity to Dark Matter and Neutrinos

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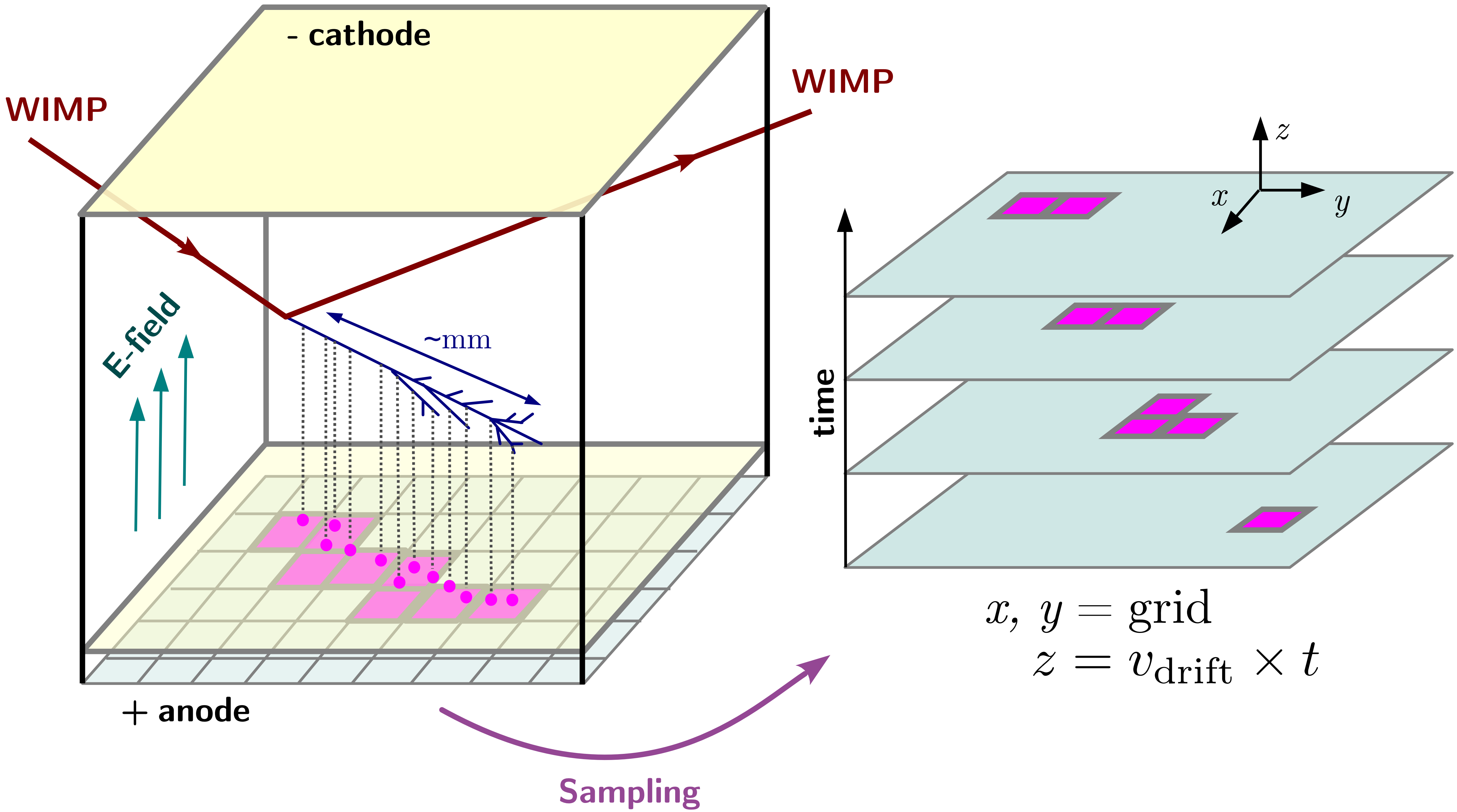
Low-pressure gas TPC



CYGNUS TPC: Basic Parameters

1000 m³ of He:SF_6 at atmospheric pressure and temperature

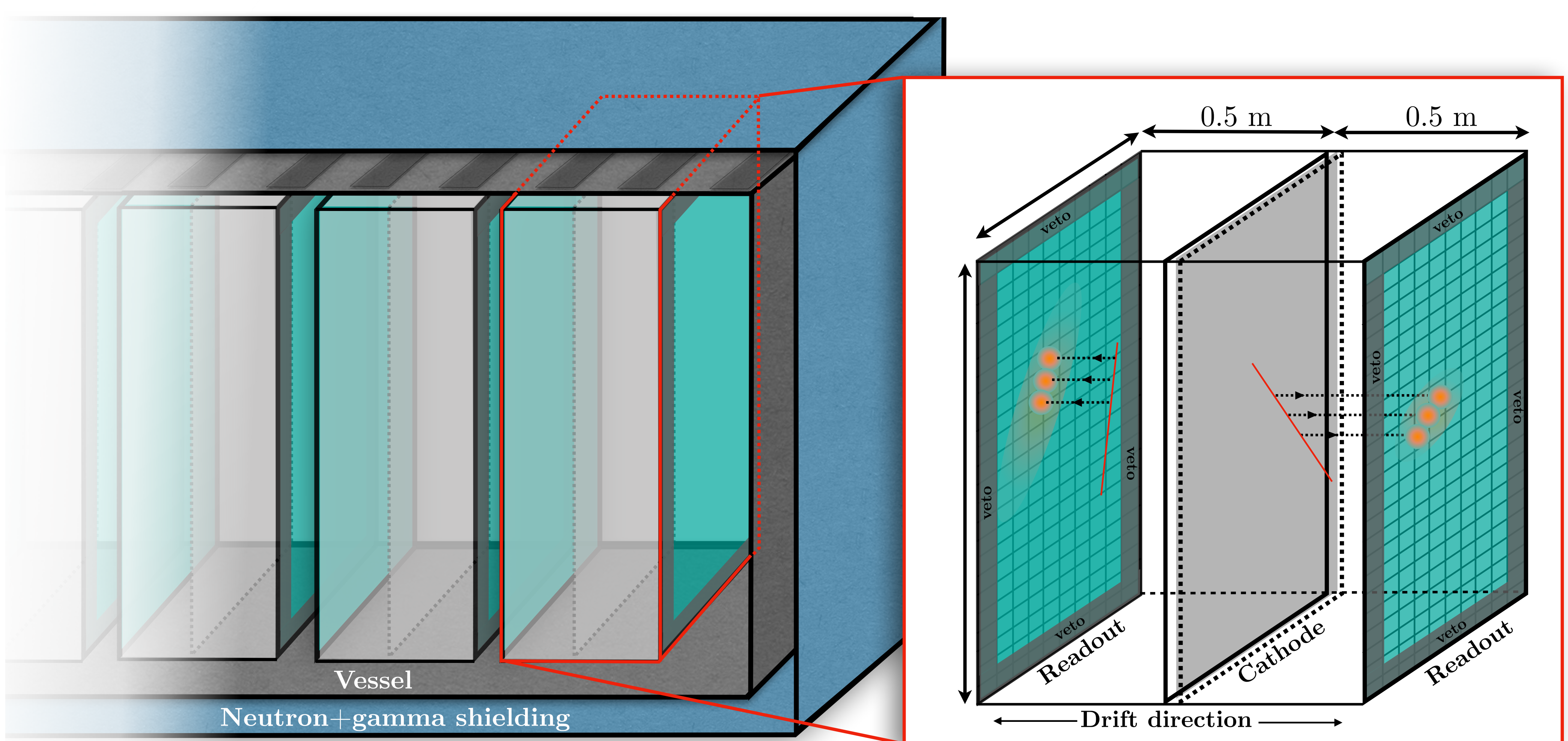
Big volume, but there are certain advantages to gas targets

→ 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-Nm³ **CYGNUS**-10 m³ module



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

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 ⟨S_{proton}⟩ so** sets powerful spin dependent WIMP limits (this is why PICO's SD-p limits are so good)

Why He?

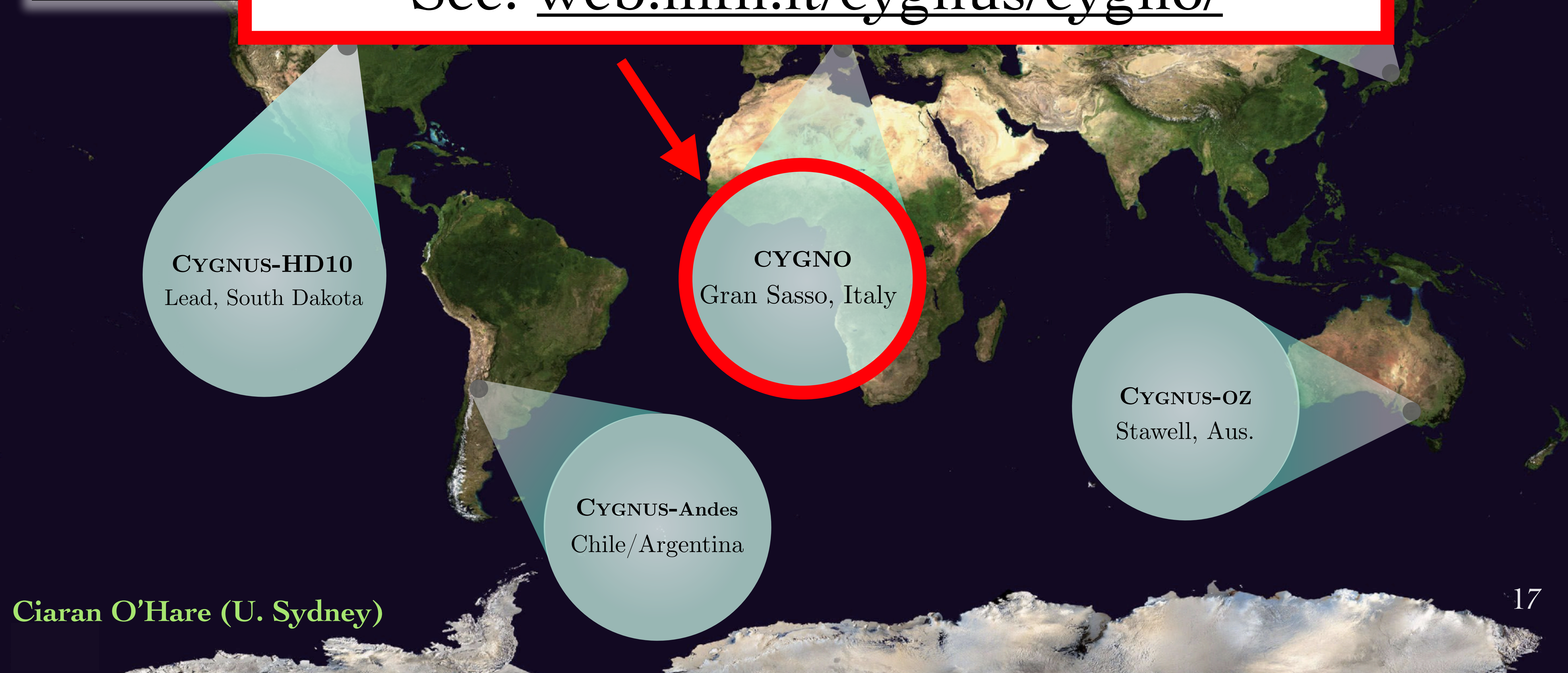
→ **Light WIMPs** still give large recoil energies with He: improves the low mass sensitivity

→ **High quenching factor** in gas mixture

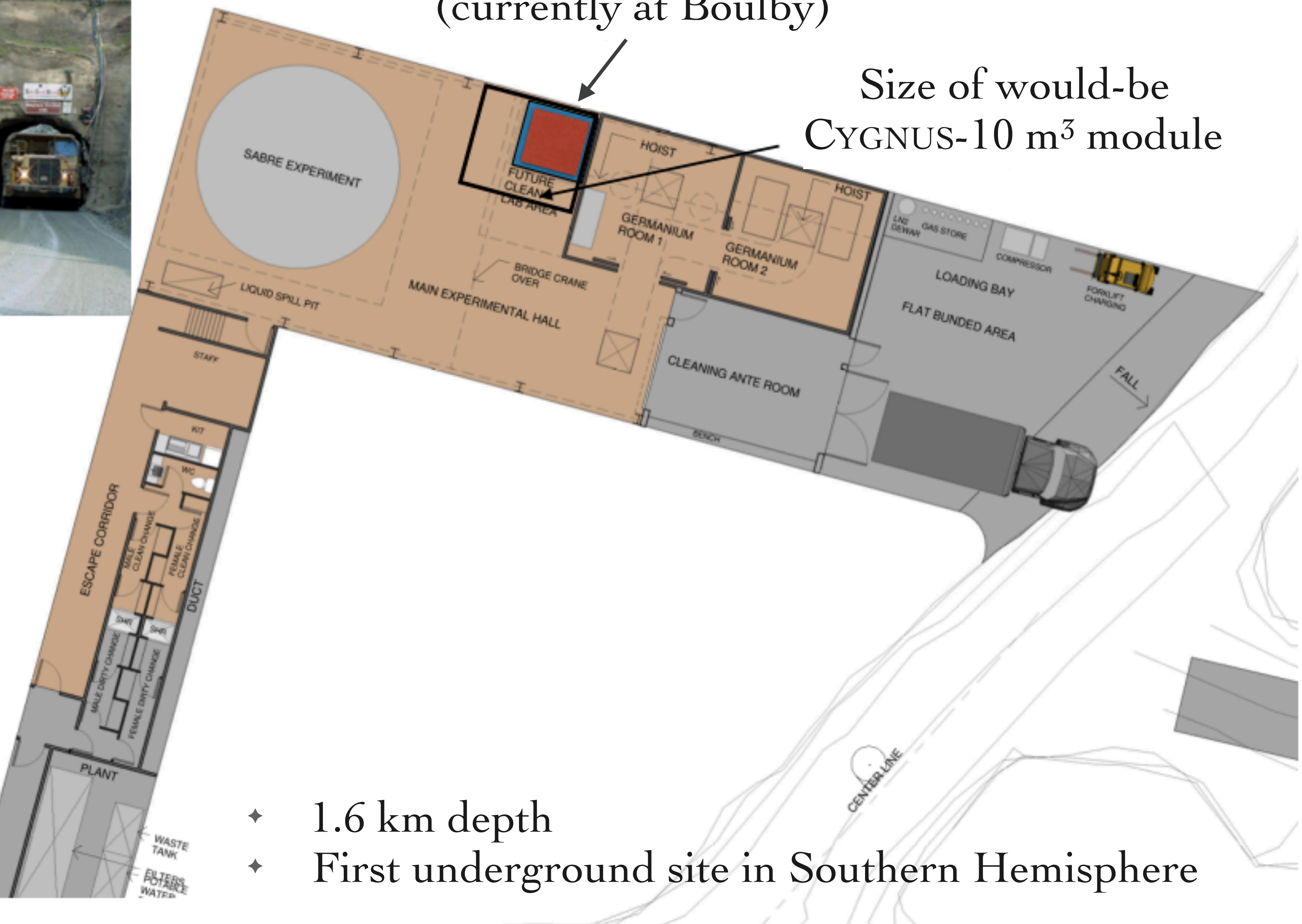
→ Does not significantly impact the Fluorine tracks, so can be used simultaneously

Possible underground sites

CYGNO project
He:CF_4 electron drift TPC
triple thin GEM+optical readout
Already in development by Italian group,
See: web.infn.it/cygnus/cygno/



New site under construction in Victoria
Stawell Underground Physics Laboratory (SUPL)



Size of DRIFT-II
(currently at Boulby)

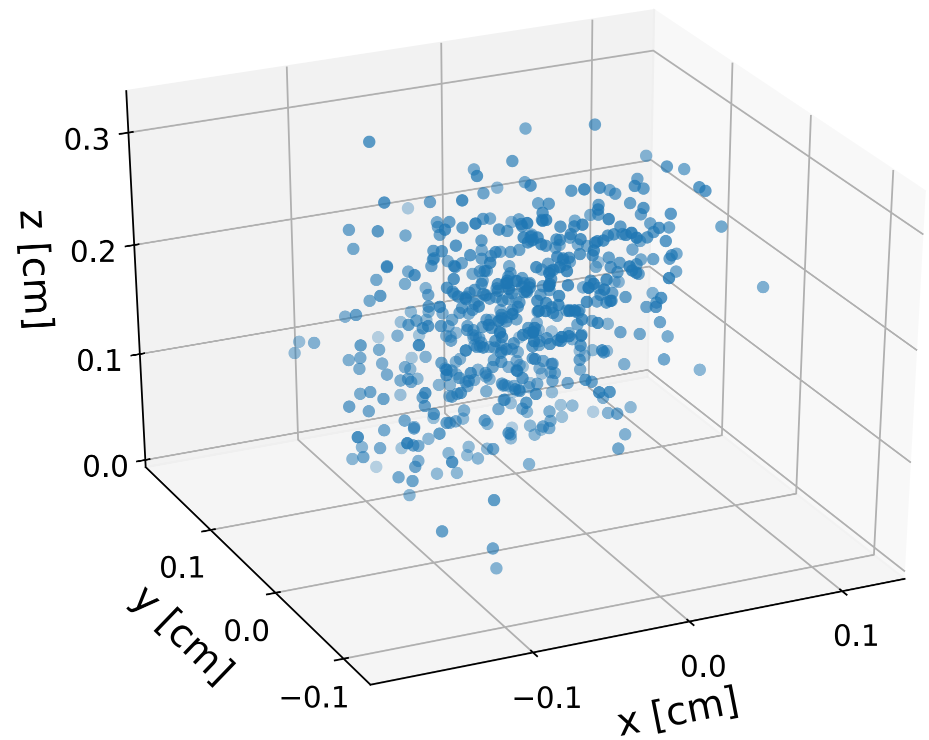
Size of would-be
CYGNUS-10 m^3 module

- 1.6 km depth
- First underground site in Southern Hemisphere

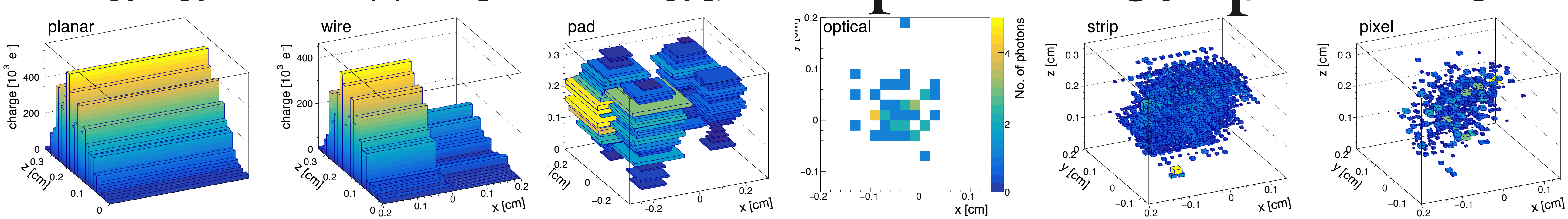
Readout technologies

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

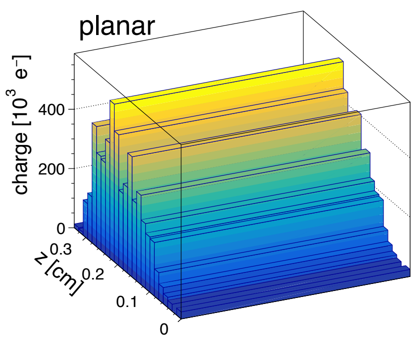
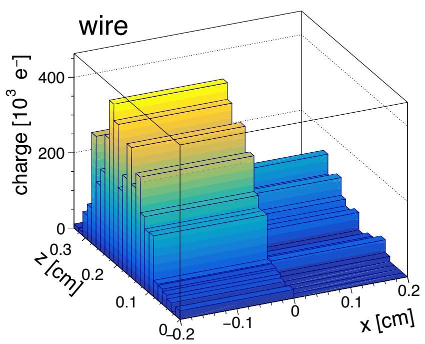
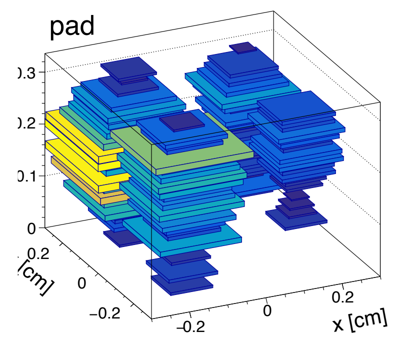
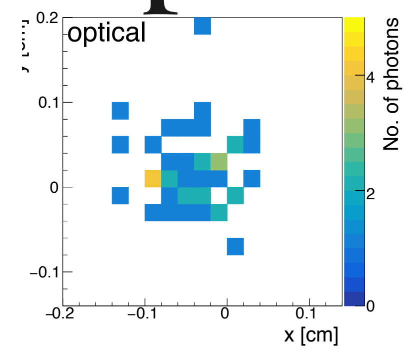
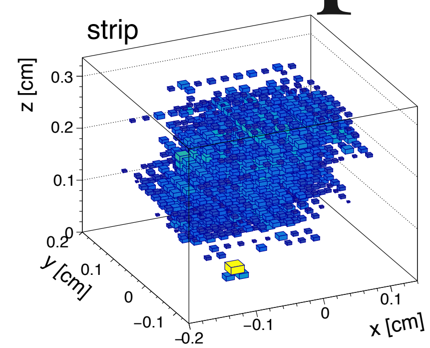
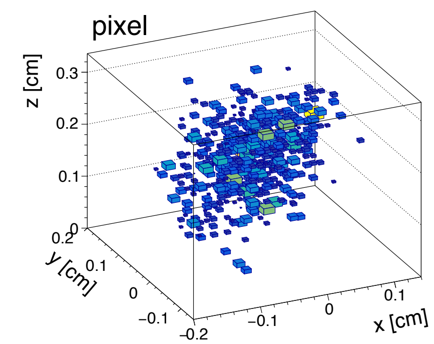
Recoil track



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



Readout technologies

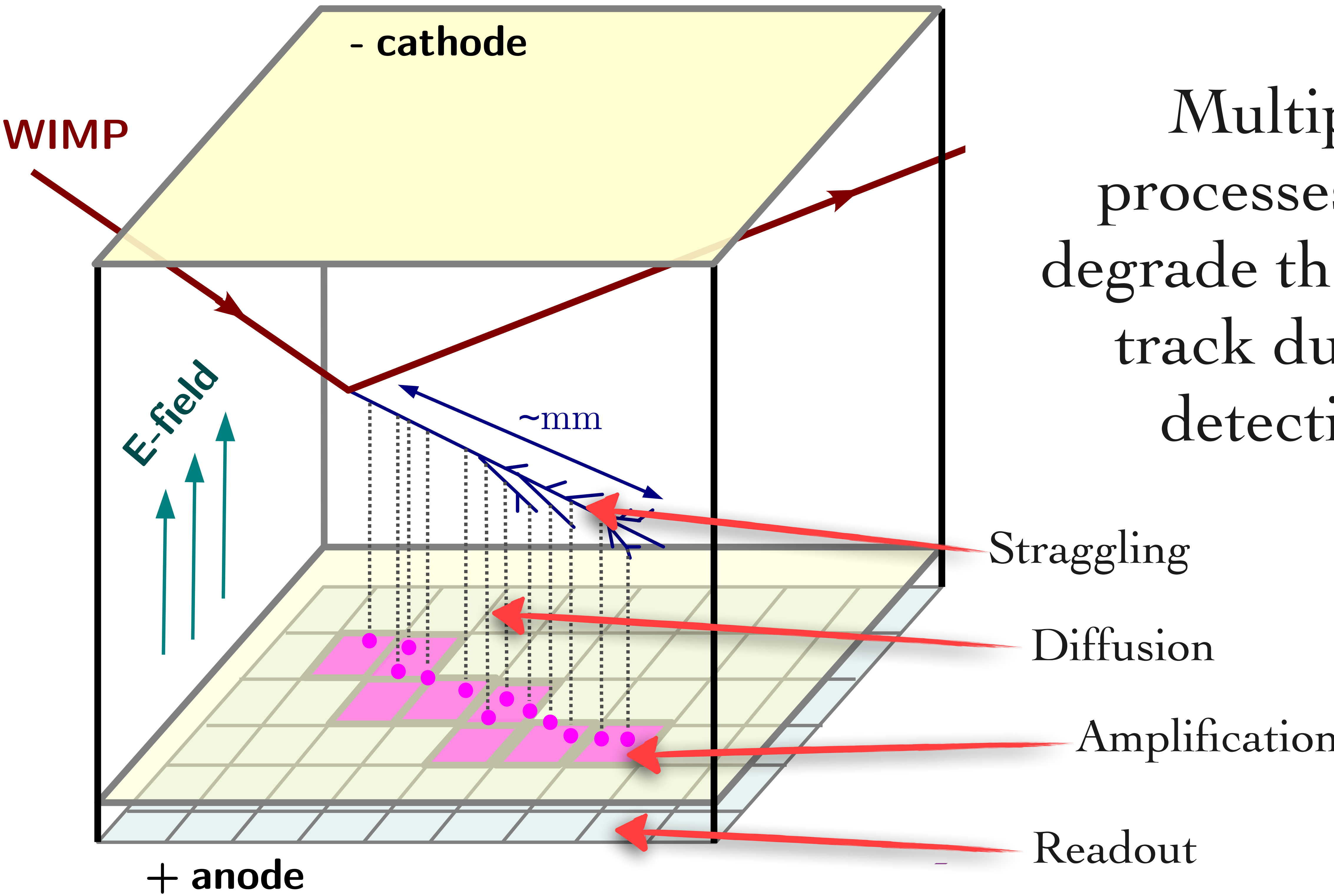
Planar	Wire	Pad	Optical	Strip	Pixel
					
1D	1D	2D	3D (when combined with PMTs)	3D	3D

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

Measuring tracks



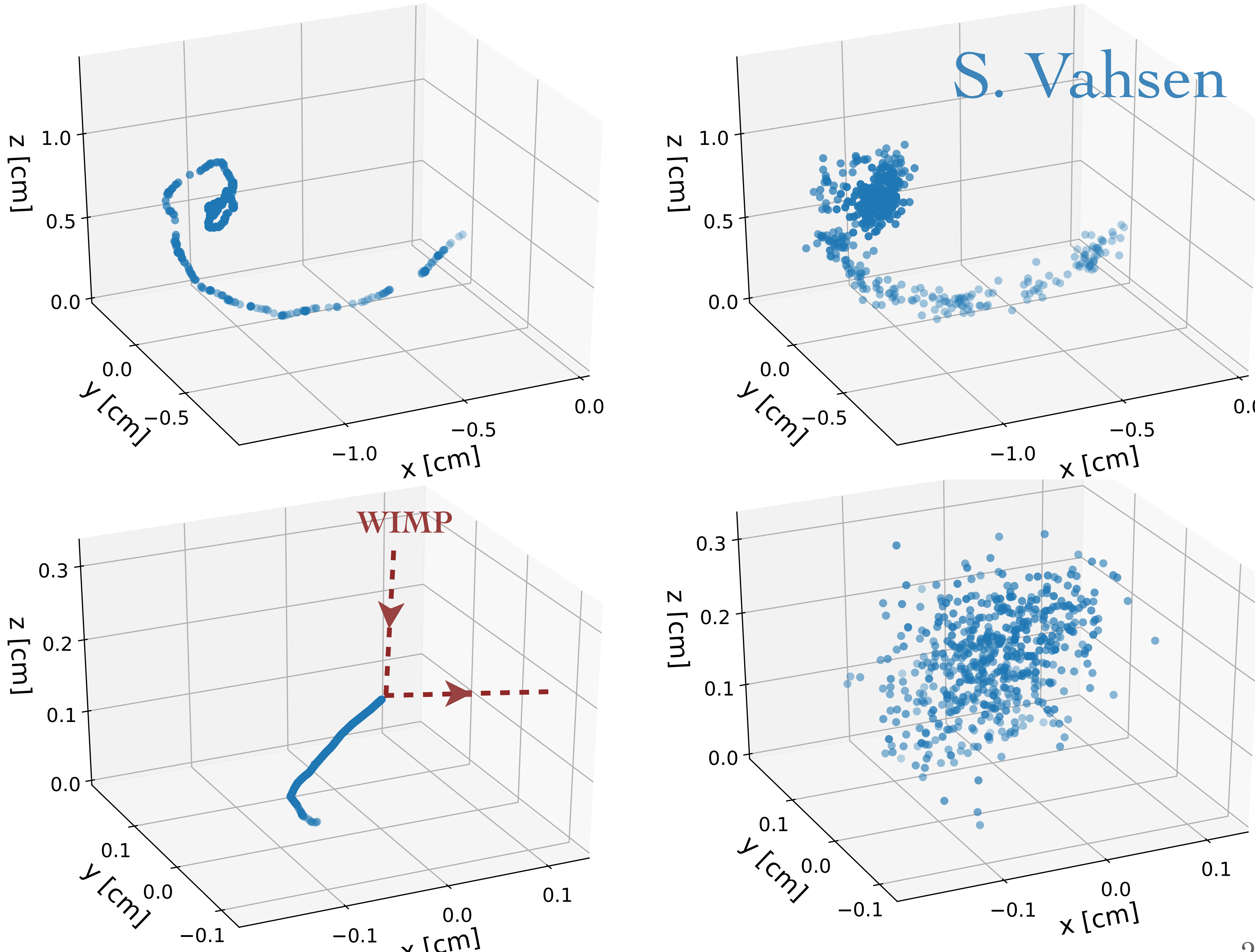
Multiple processes will degrade the recoil track during detection

Recoil tracks (in He+SF_6 at 1 atm)

Before drift | After 25 cm drift

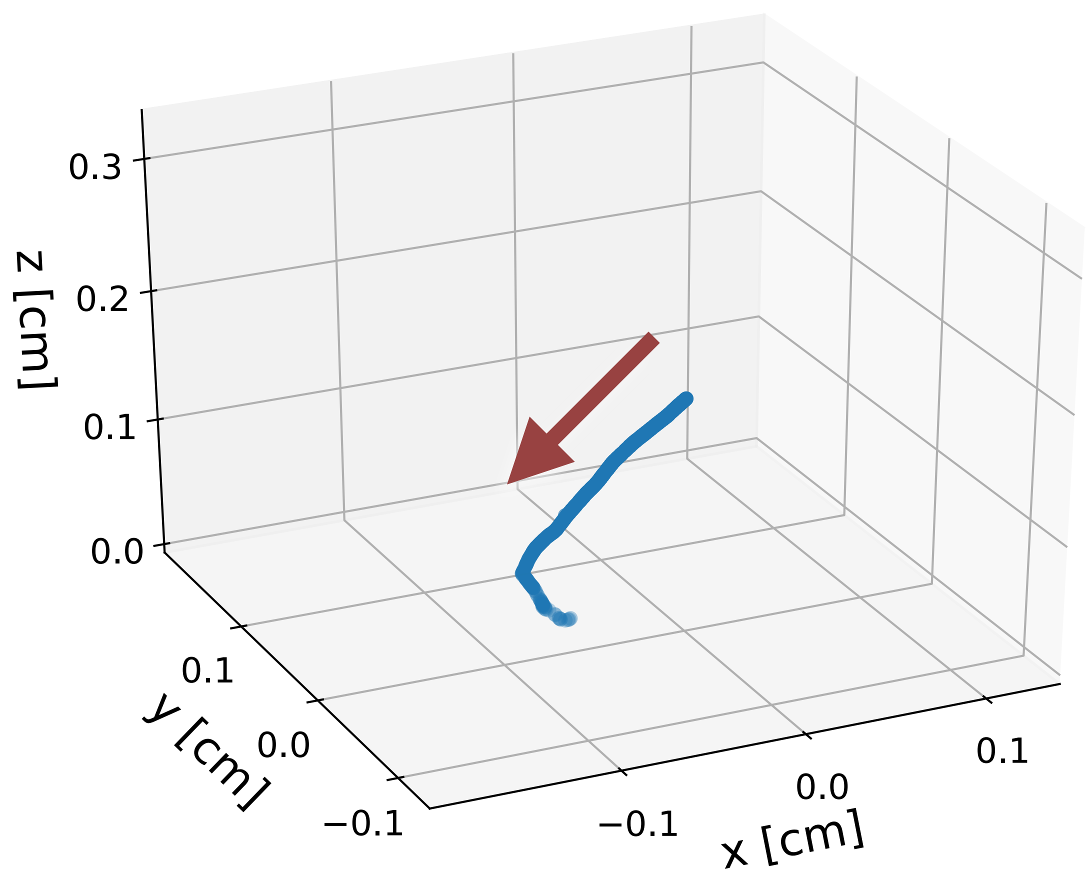
Electron: 20 keV

He Nucleus: (25 keVr)

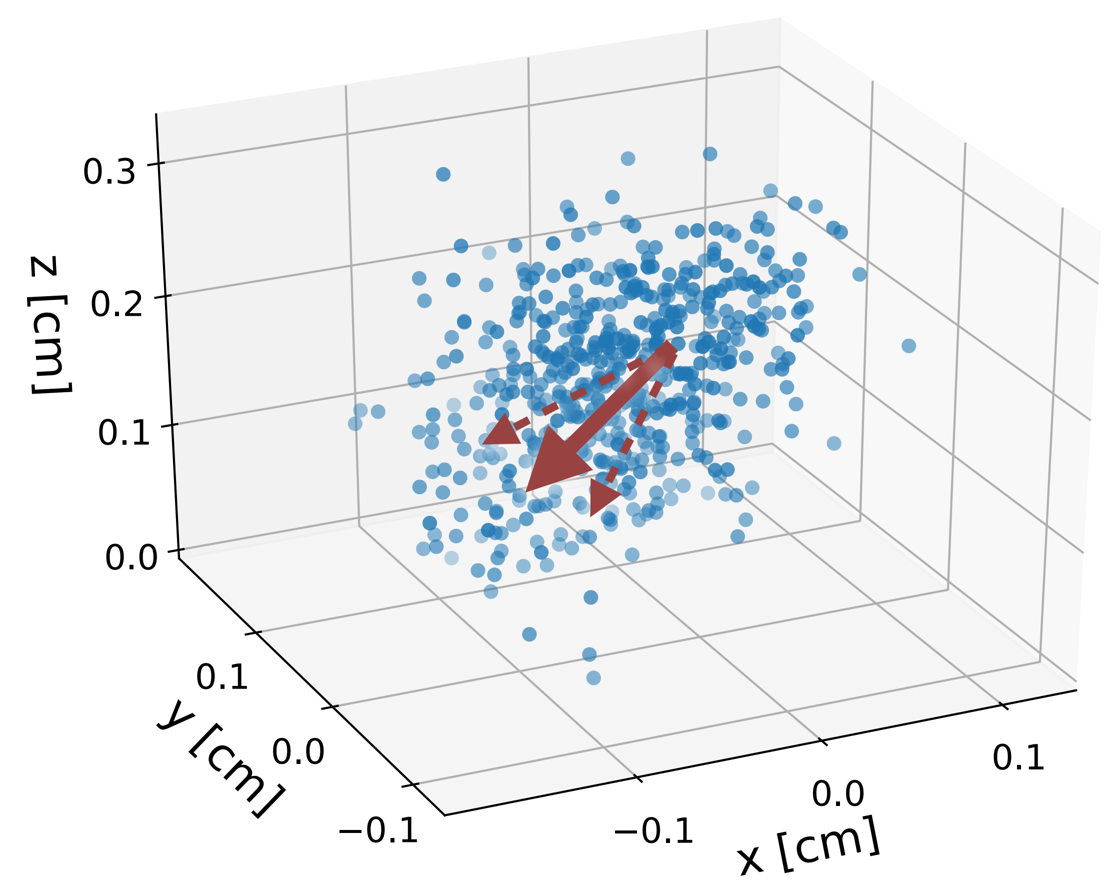


Angular resolution

Original track



Track after 25 cm drift

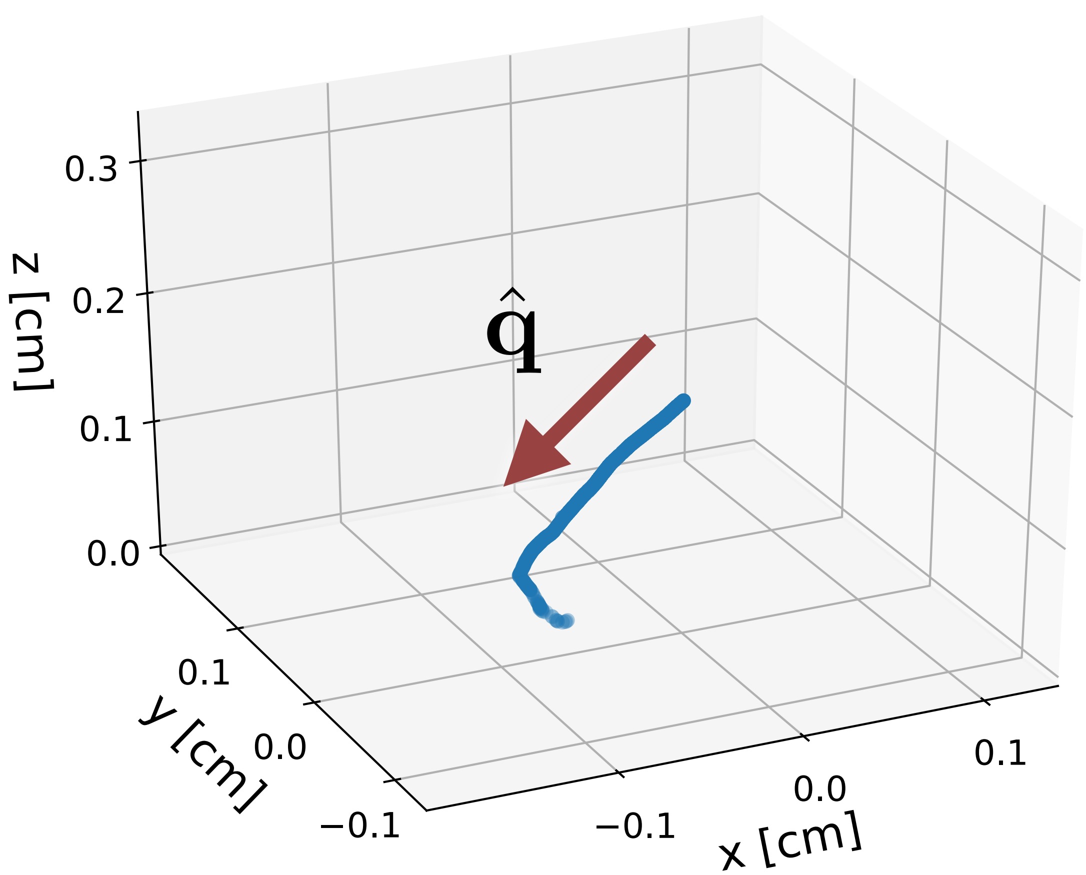


25 keV_r Helium recoil in 1 atm. of 755:5 $He:SF_6$

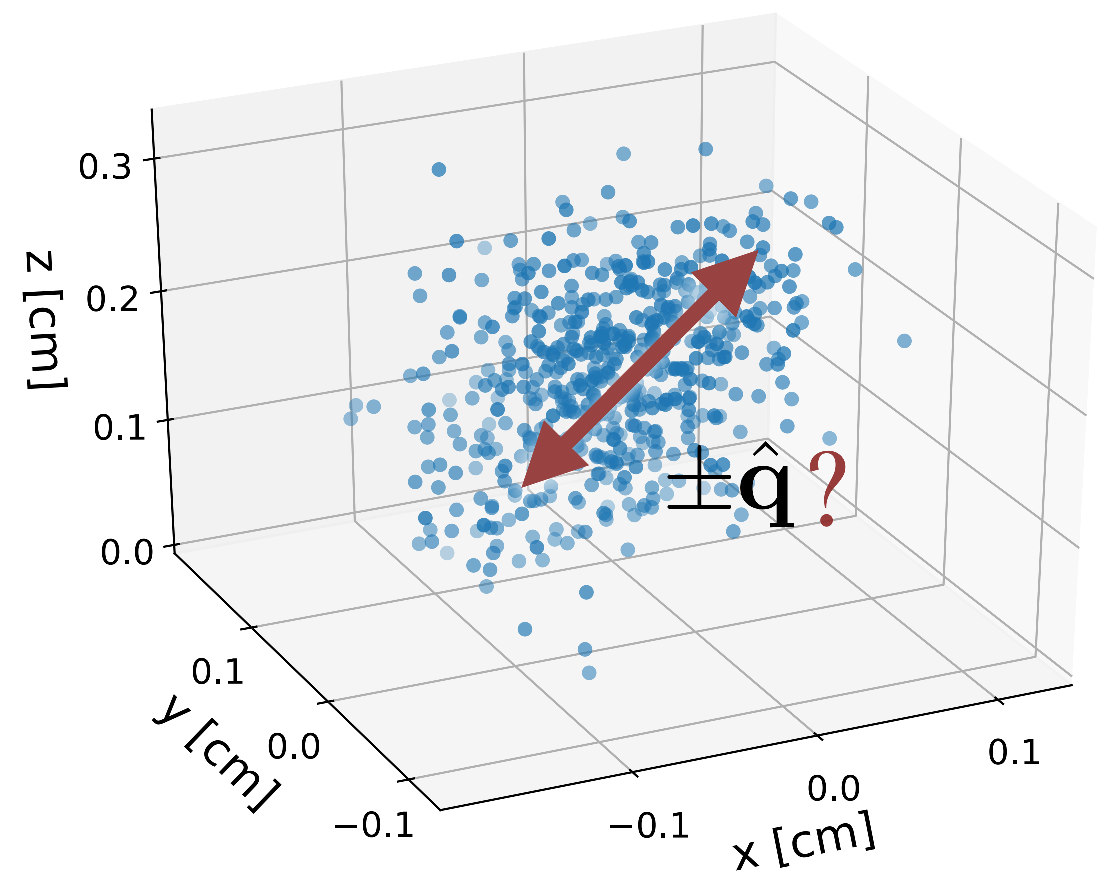
Head-tail recognition

Ability to recognise the forward-backward sense of a recoil

Original track

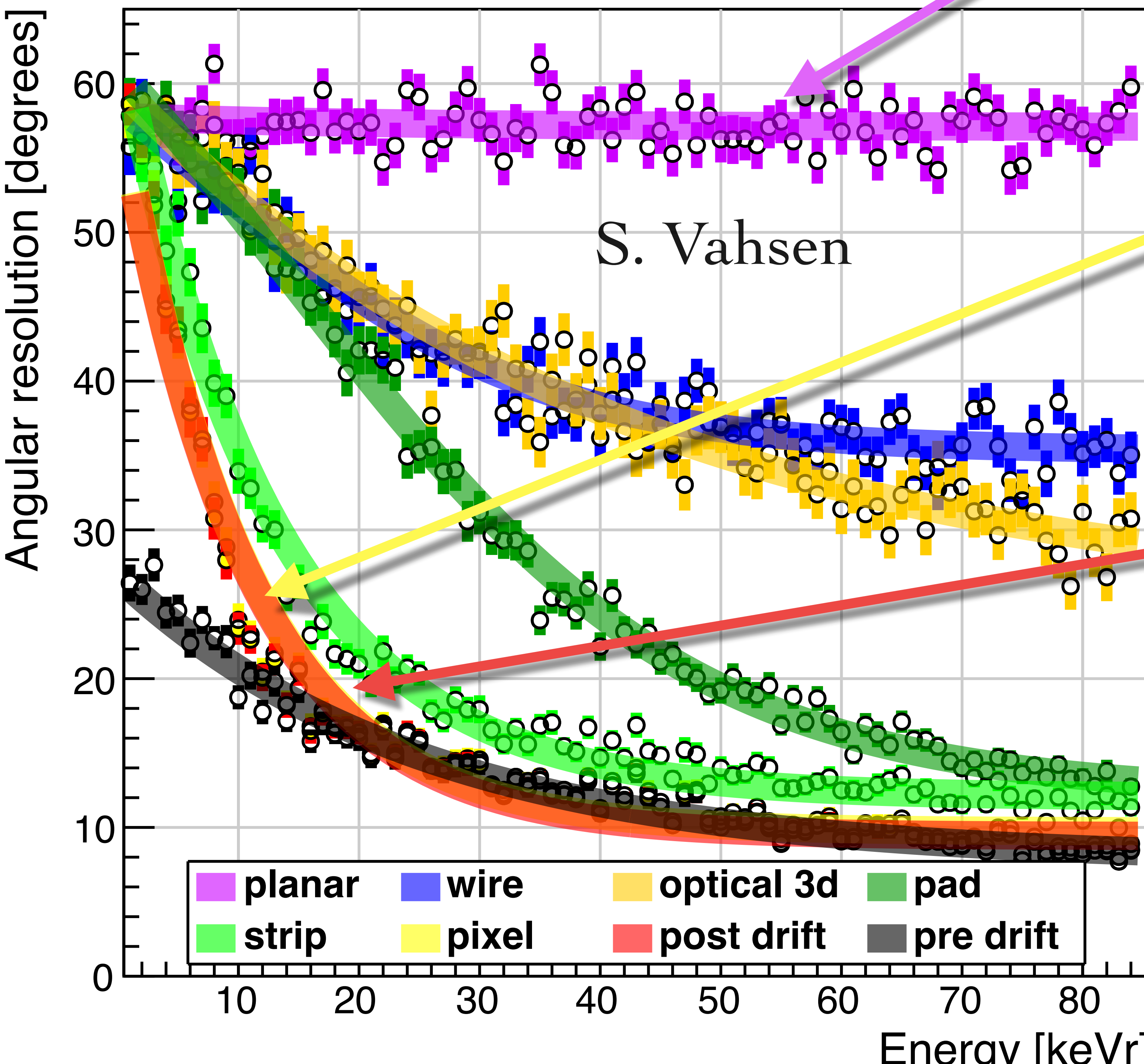


Track after 25 cm drift



Angular resolution

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



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

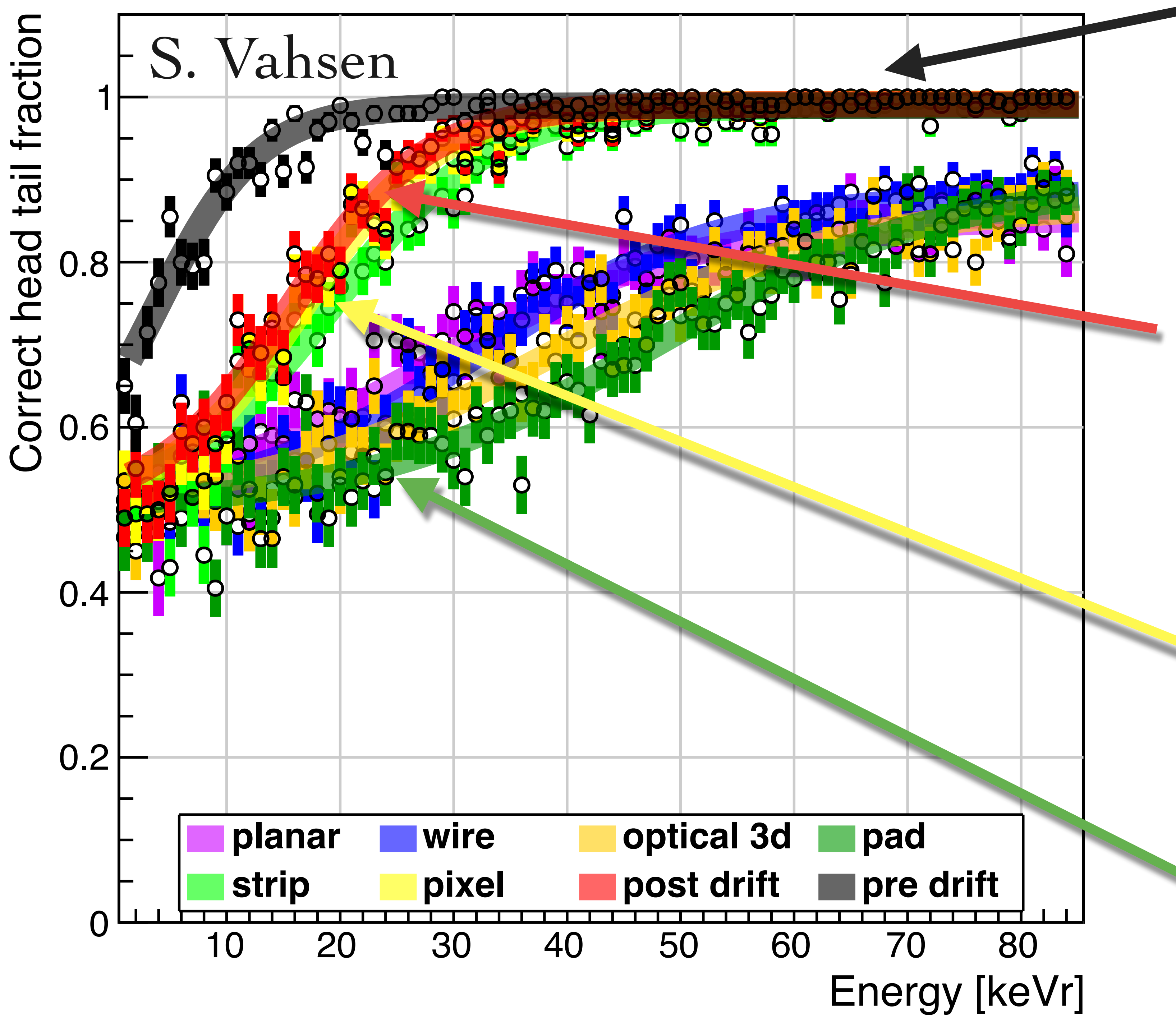
Pixel readout performs as good as post-drift → almost no loss in directionality after charge readout (promising!)

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

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

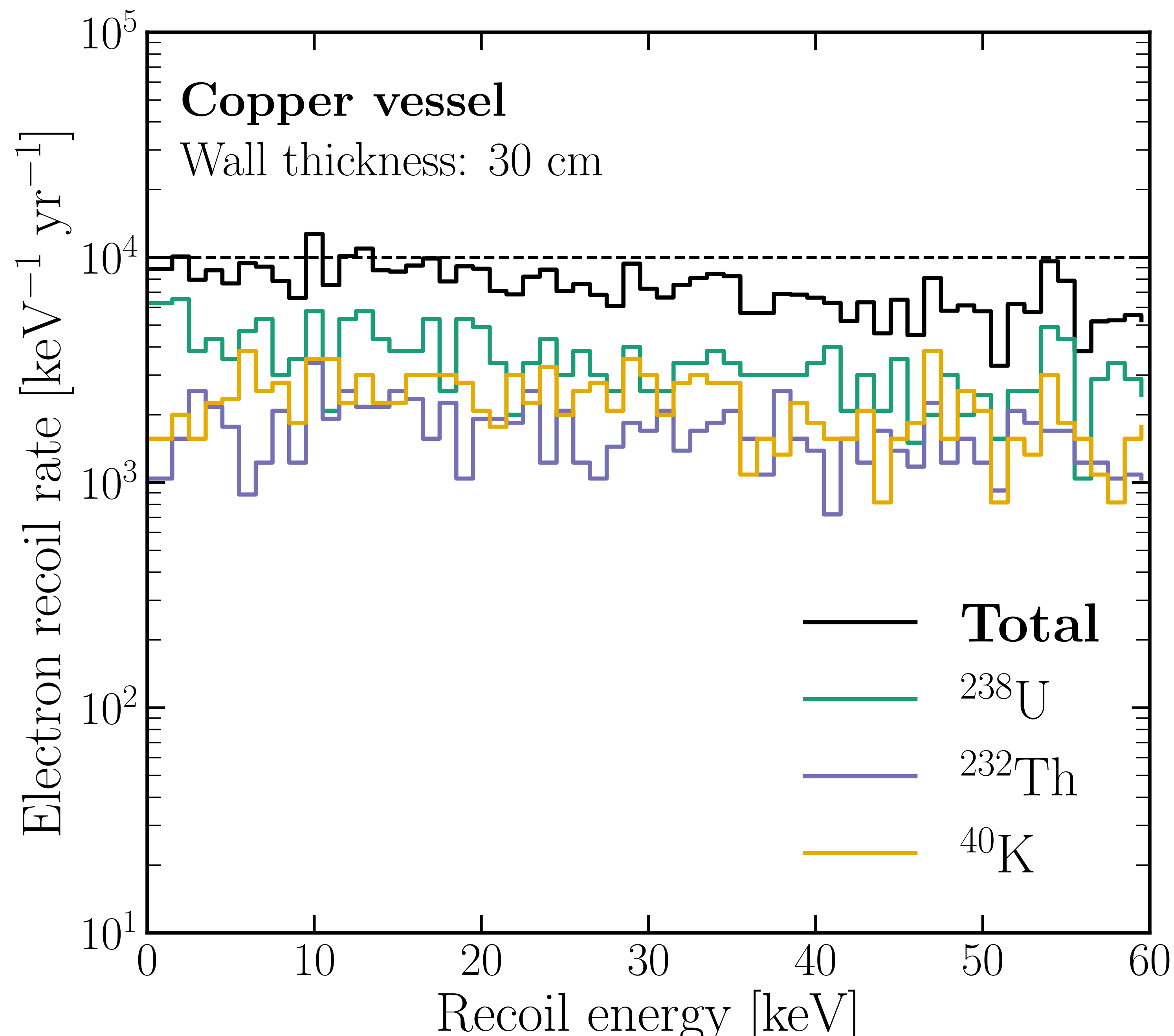
Pixel readout performs best again → almost no loss in directionality after readout

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 a 1000 m^3 TPC

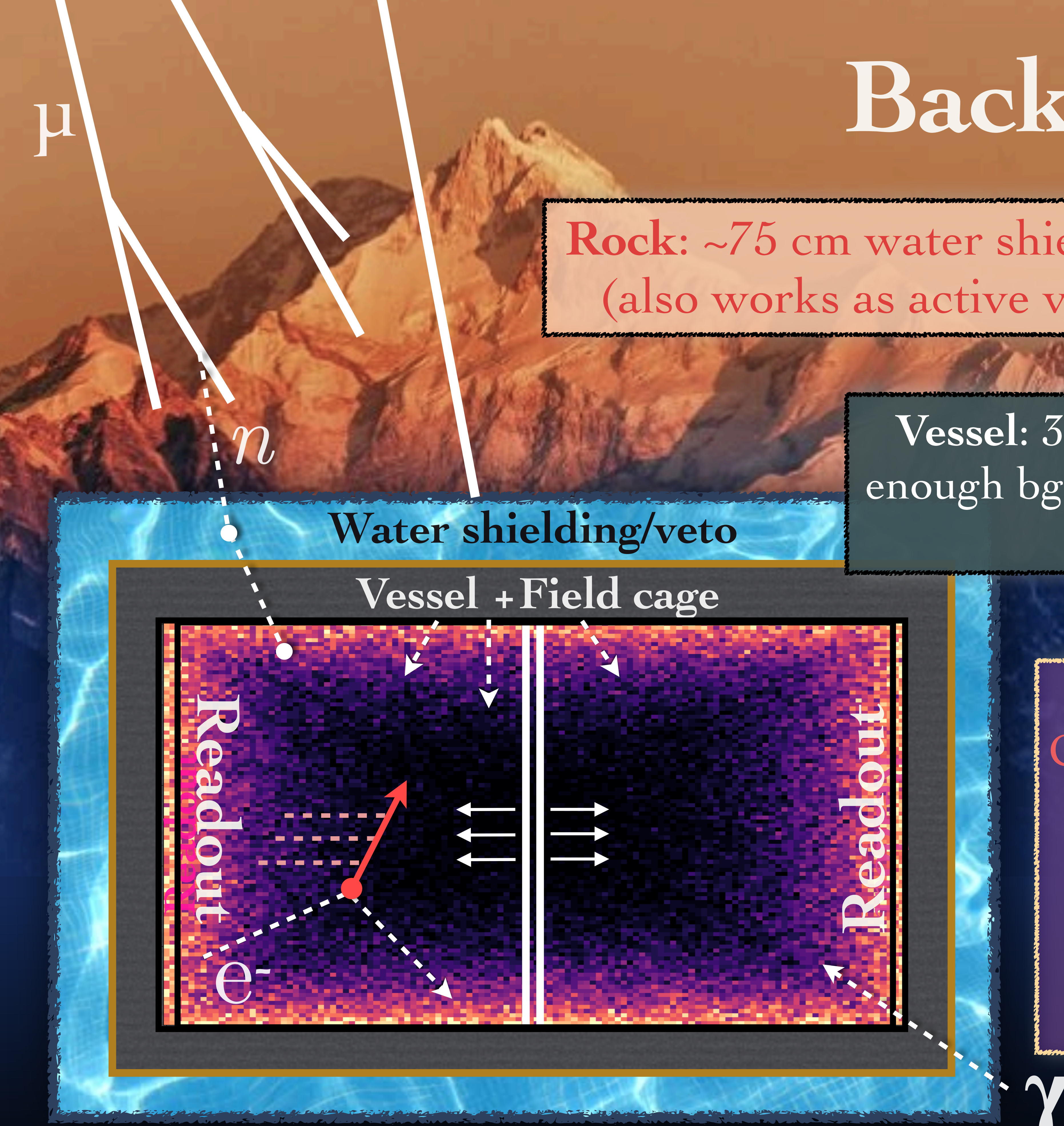
e.g. ERs from 30 cm copper TPC vessel



(Full MC background study will be in paper)

Backgrounds

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



Vessel: 30 cm Copper has low enough bg but may not be strong enough

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

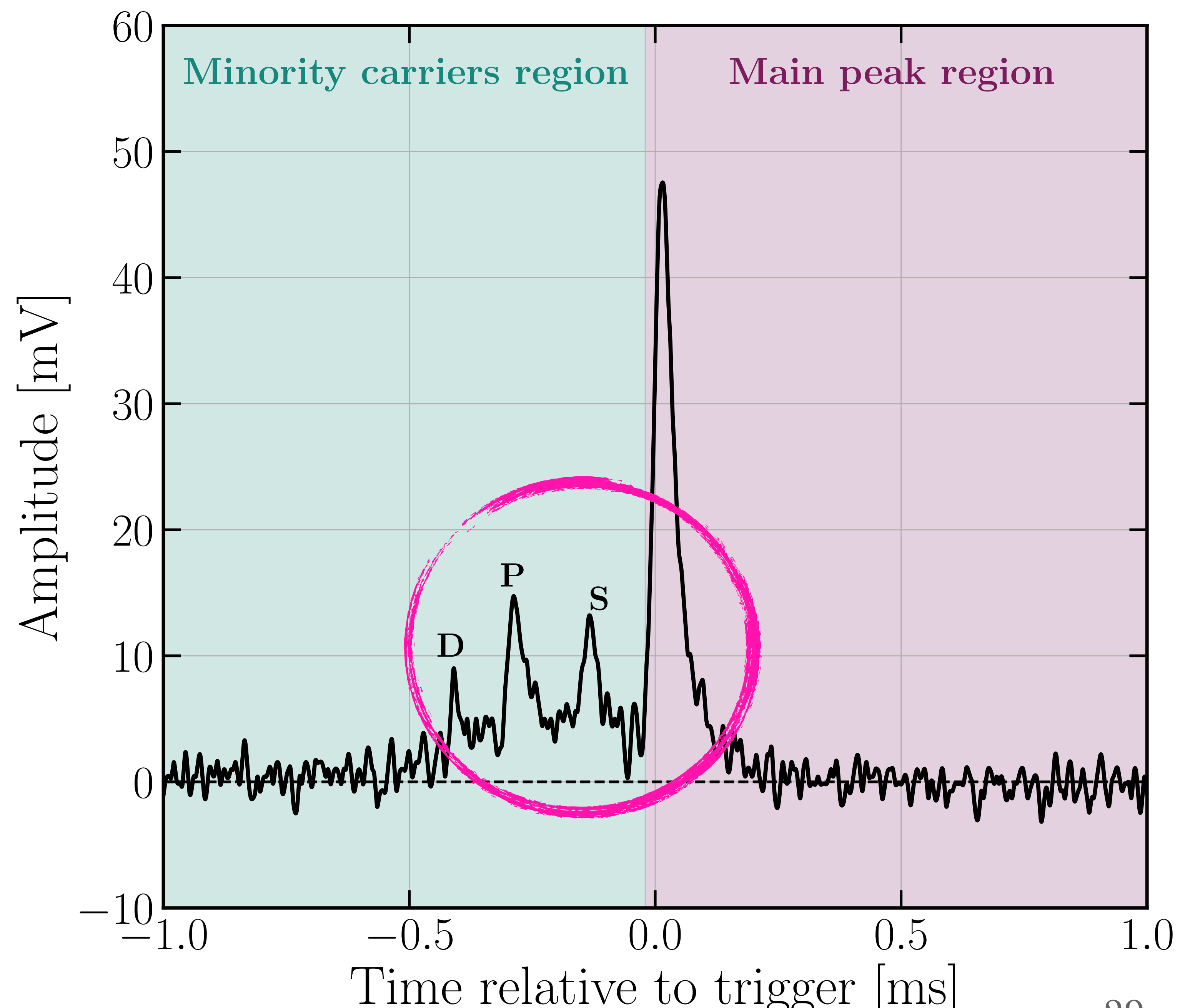
Backgrounds part 2: Fiducialisation

- We also need to be able to locate tracks in (x,y,z) to remove edge events, double scatters etc., especially from radon progeny recoils

- Readout does this in (x,y), but z is tricky

- but SF_6 gives us a way

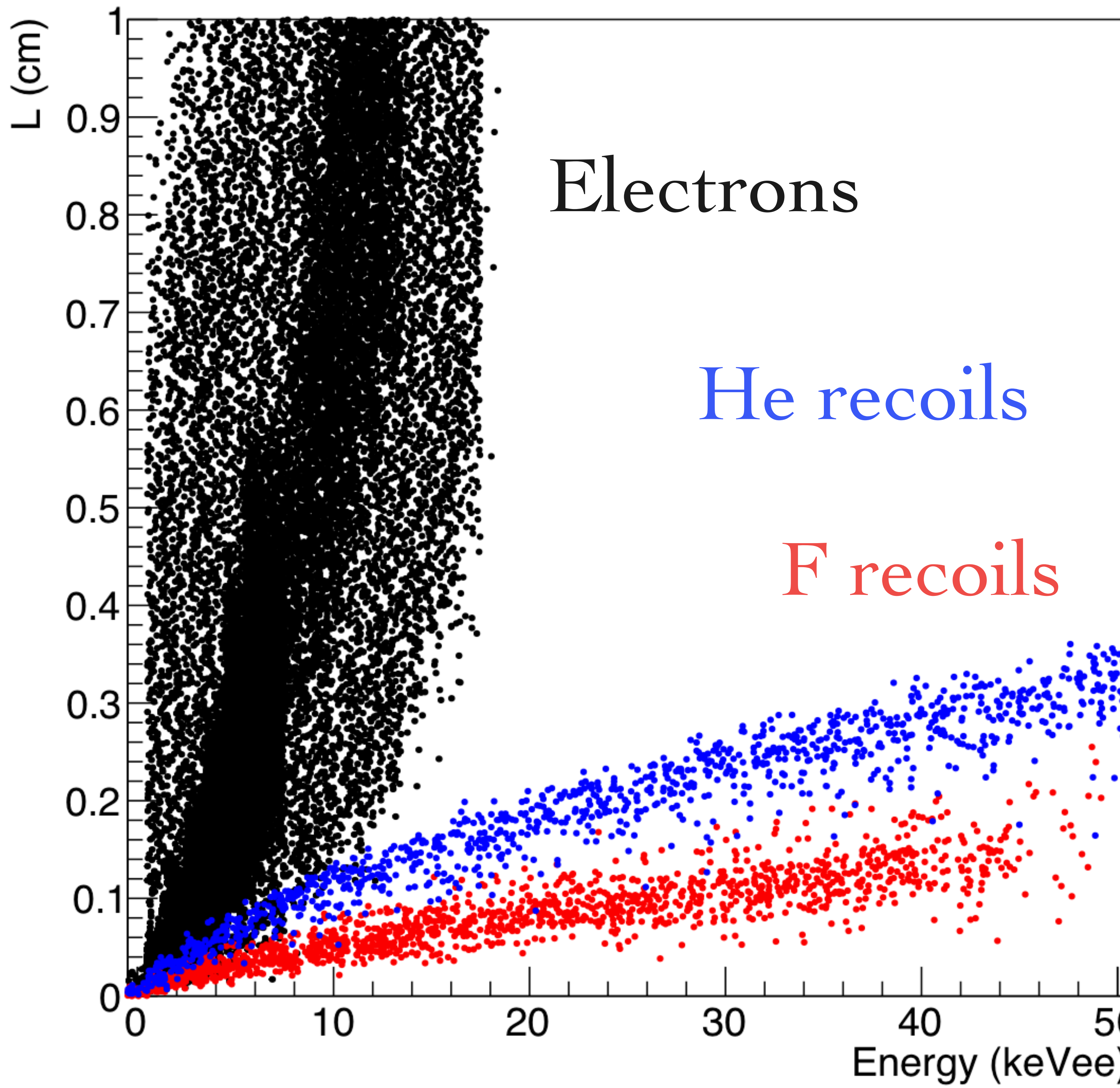
$\rightarrow$ Different ions of SF_6 called minority carriers drift at different speeds through the gas so delays in their arrival times at the readout tell us how far they drifted



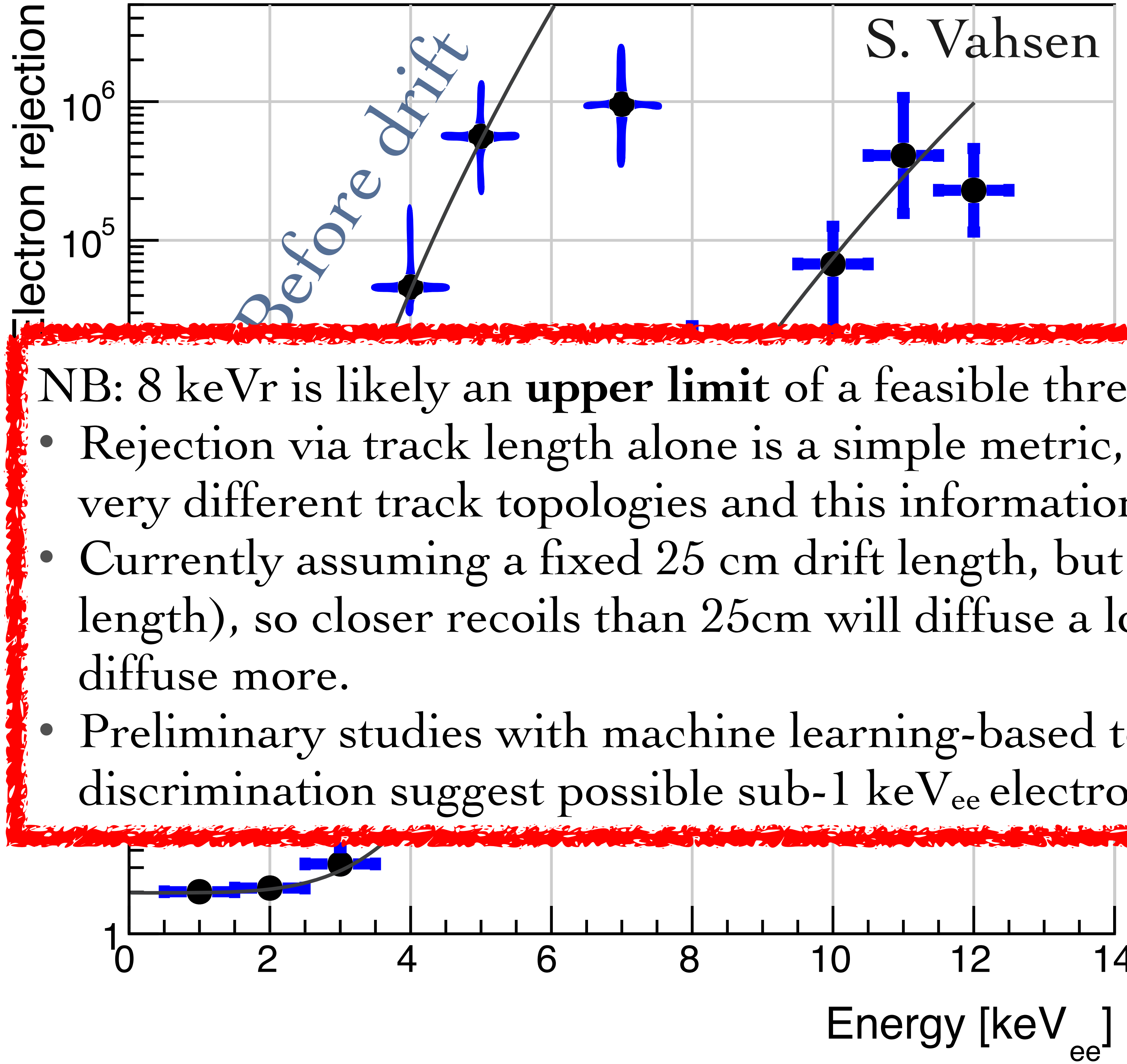
Threshold

We want an electron rejection factor of 10^4, in the range $1-10$ keV$_r$ our NR analysis threshold will be based on how low we can achieve this

Track lengths for recoils in He+SF_6 at 1 atm



Energy threshold → electron rejection >10^4



- ~8 keV is feasible already with just track length vs energy

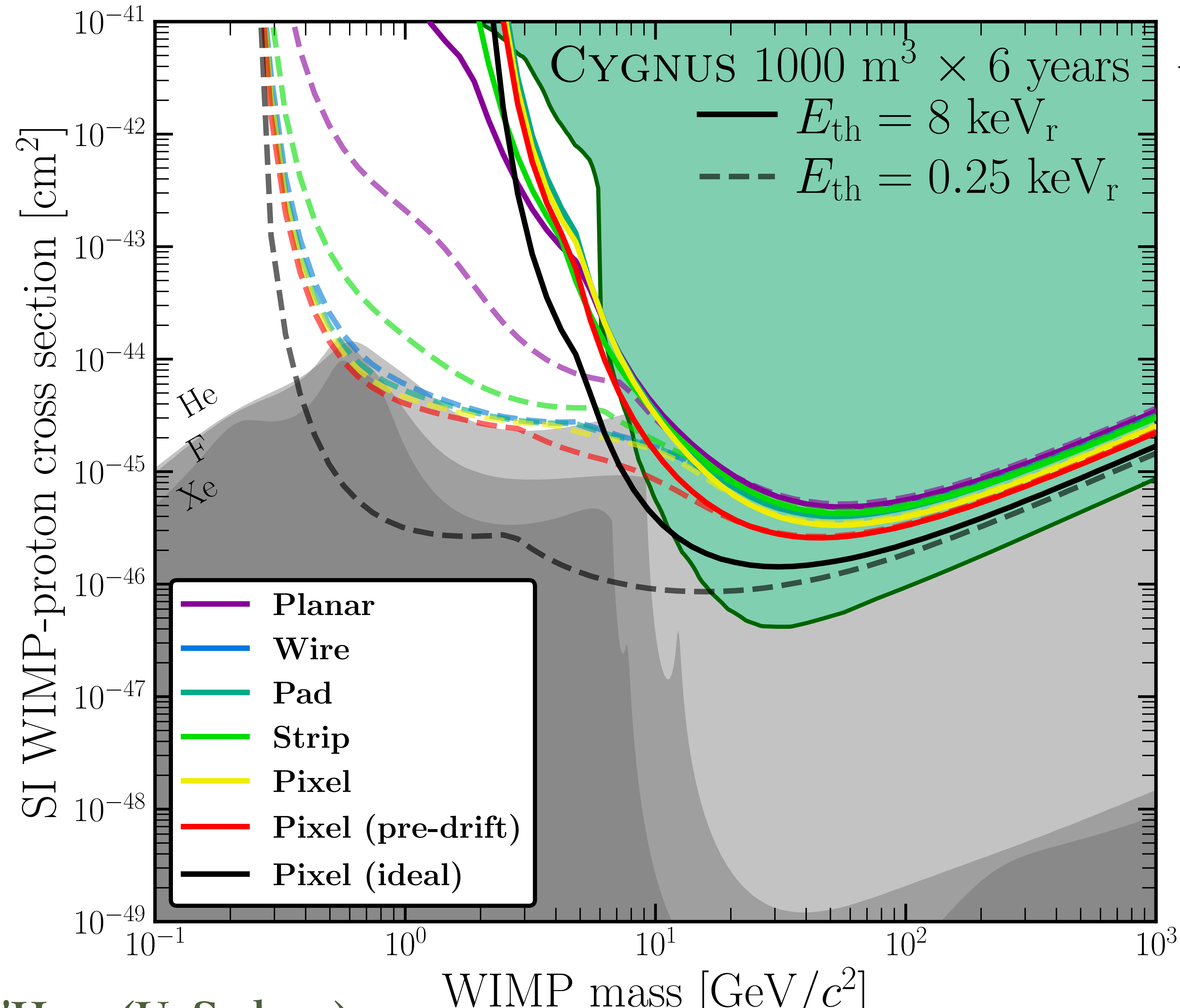
NB: 8 keVr is likely an **upper limit** of a feasible threshold:

- 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 25cm 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

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

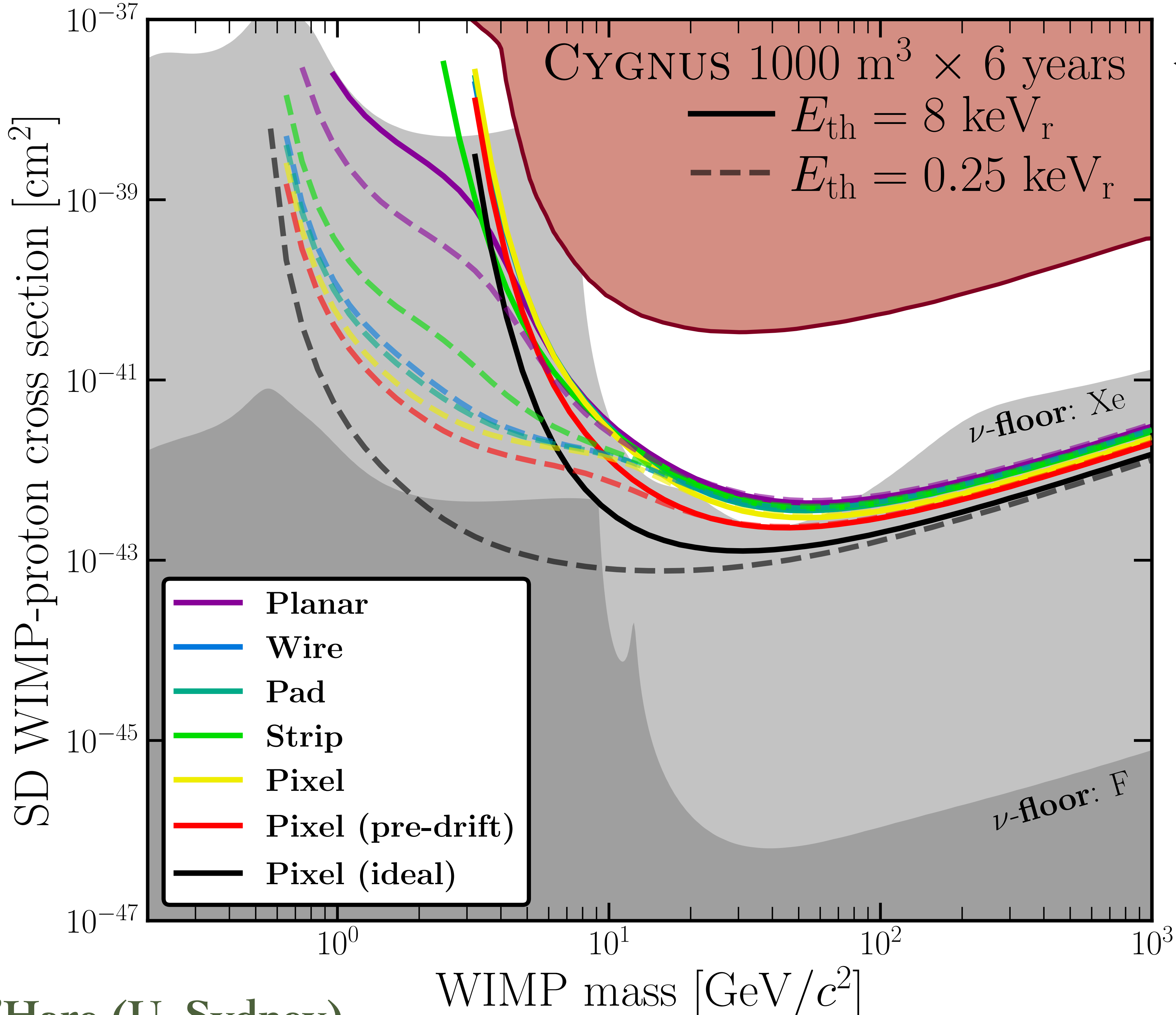


1000 m^3 × 6 years
≈ 1 ton-year

WIMP reach: spin independent (SD-proton)

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

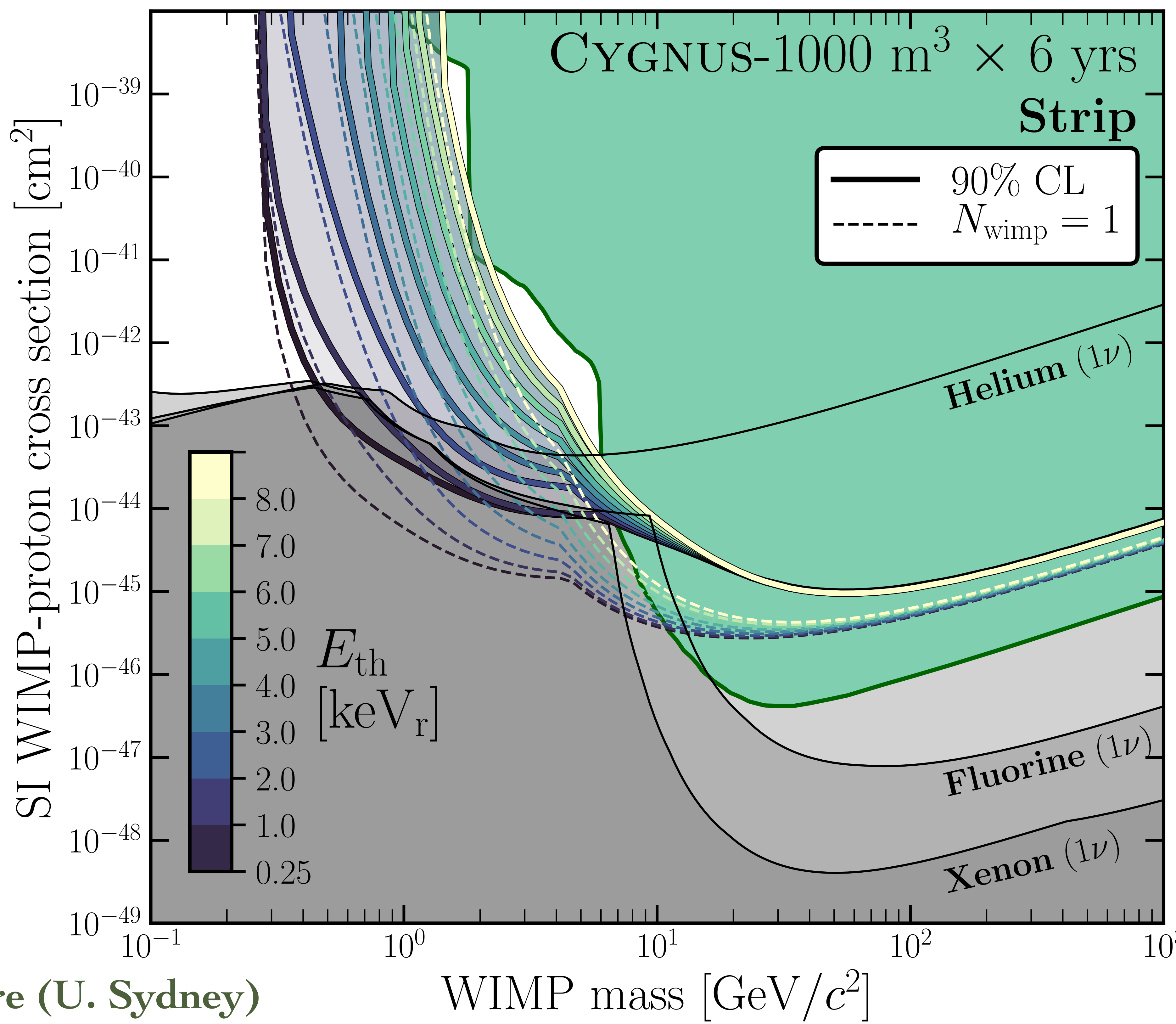
Threshold: 8 keVr currently feasible → 0.25 keVr is theoretical minimum



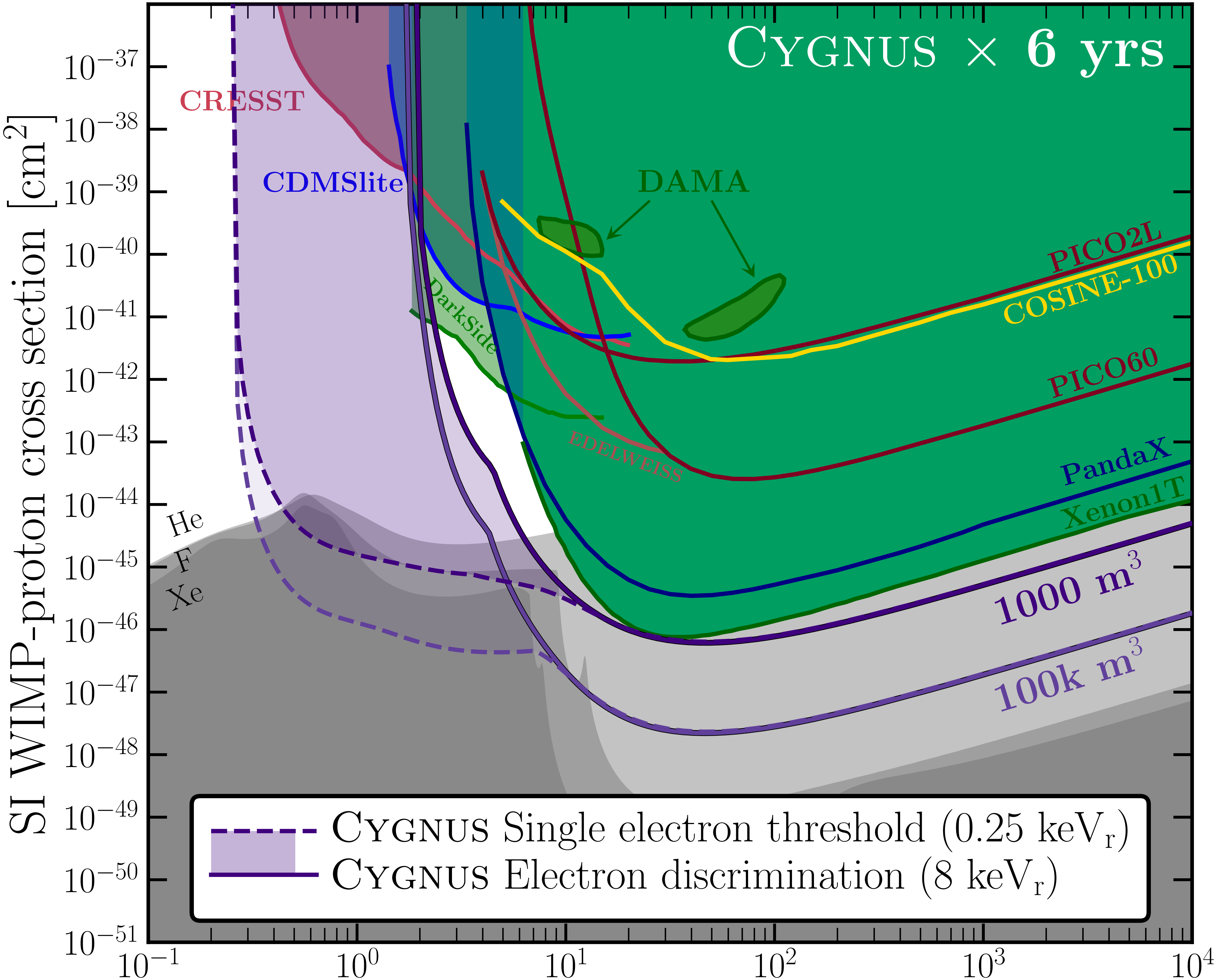
1000 m³ × 6 years
≈ 1 ton-year

μ-PIC (strip) based readout currently looks the best in terms of cost vs. WIMP reach

A closer look at dependence on threshold:



Headline plot



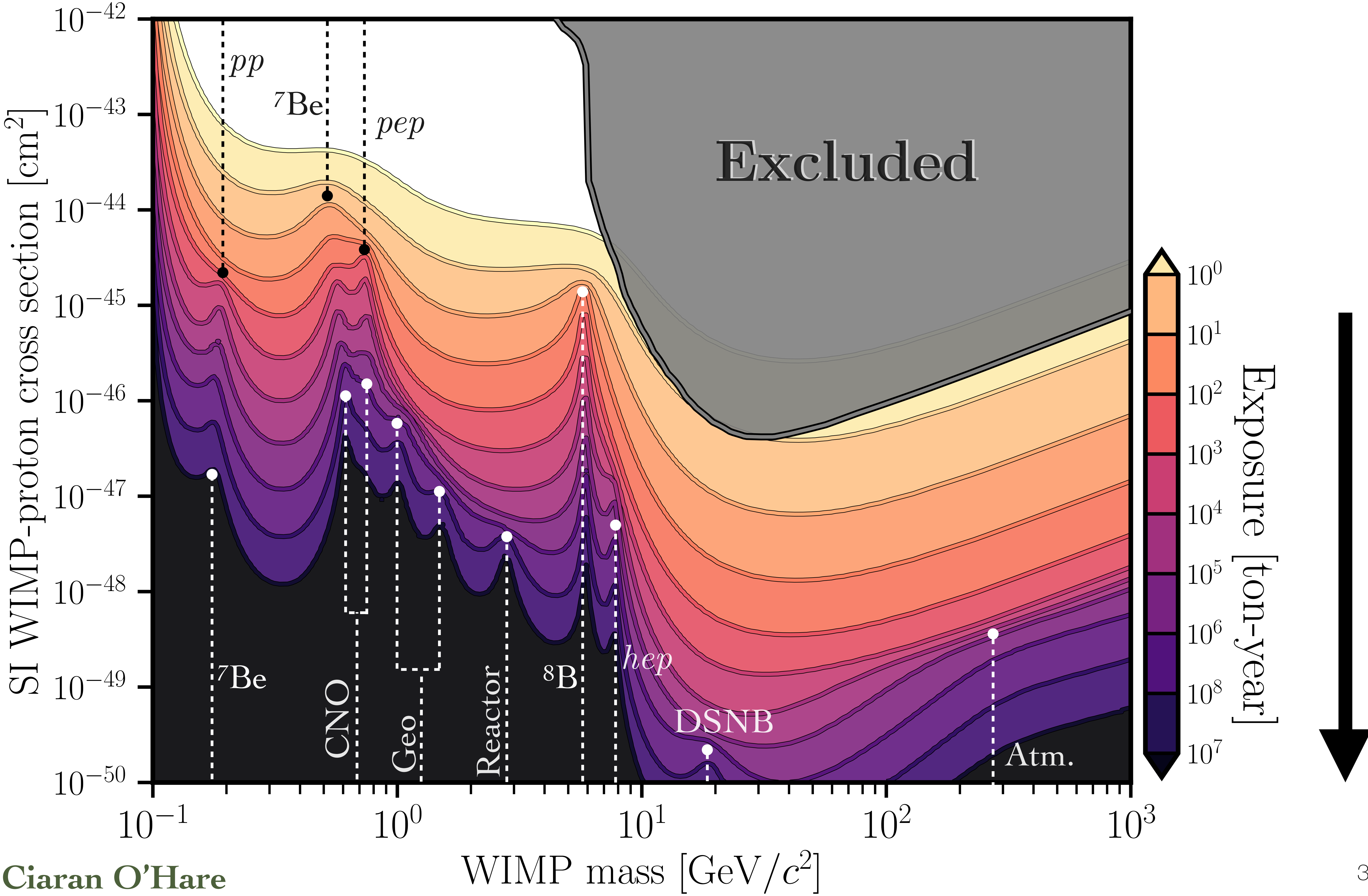
Conclusions

- Cygnus aims to be the first experiment with discovery capabilities for DM below the neutrino floor
- 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

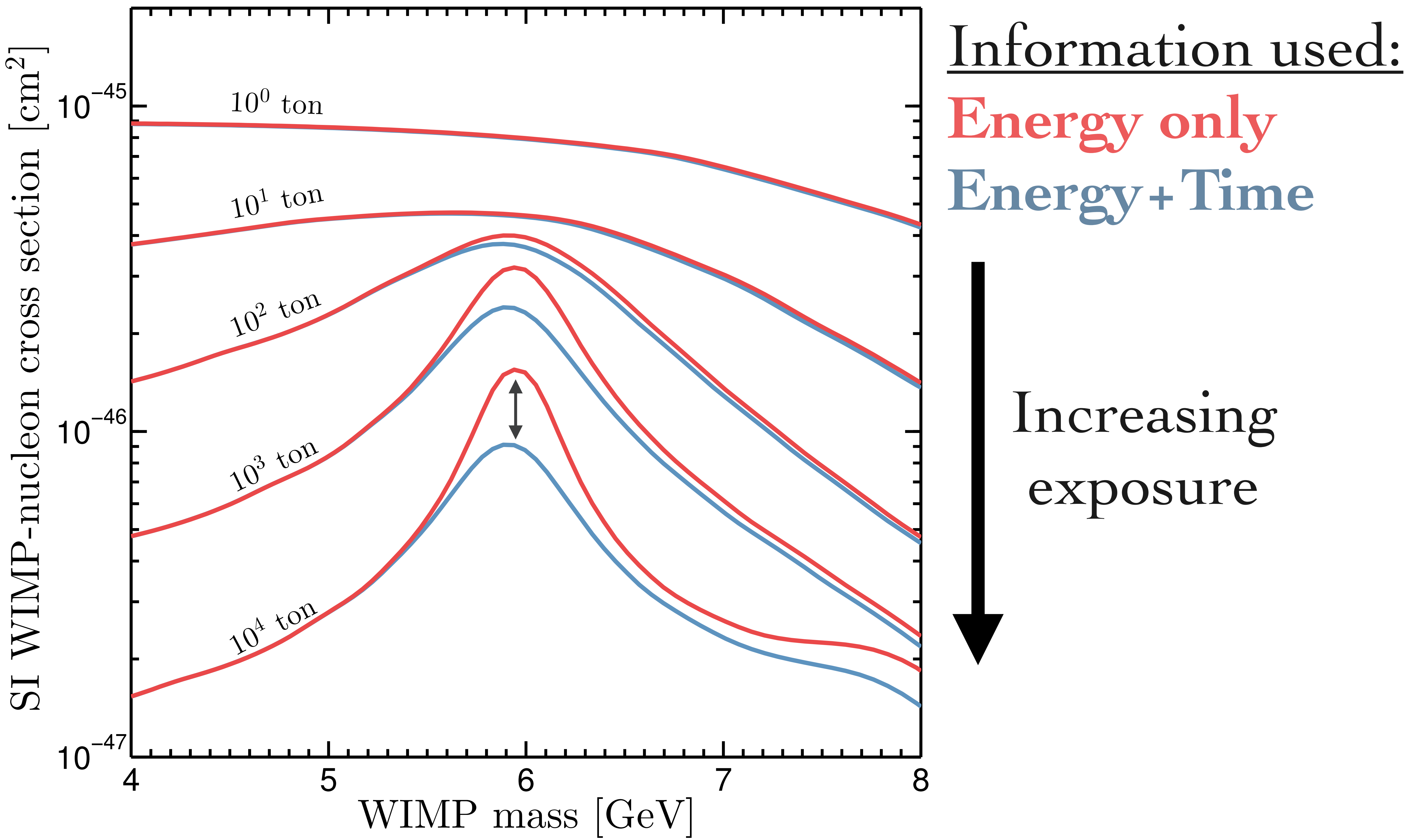
Work still ongoing and participation welcome

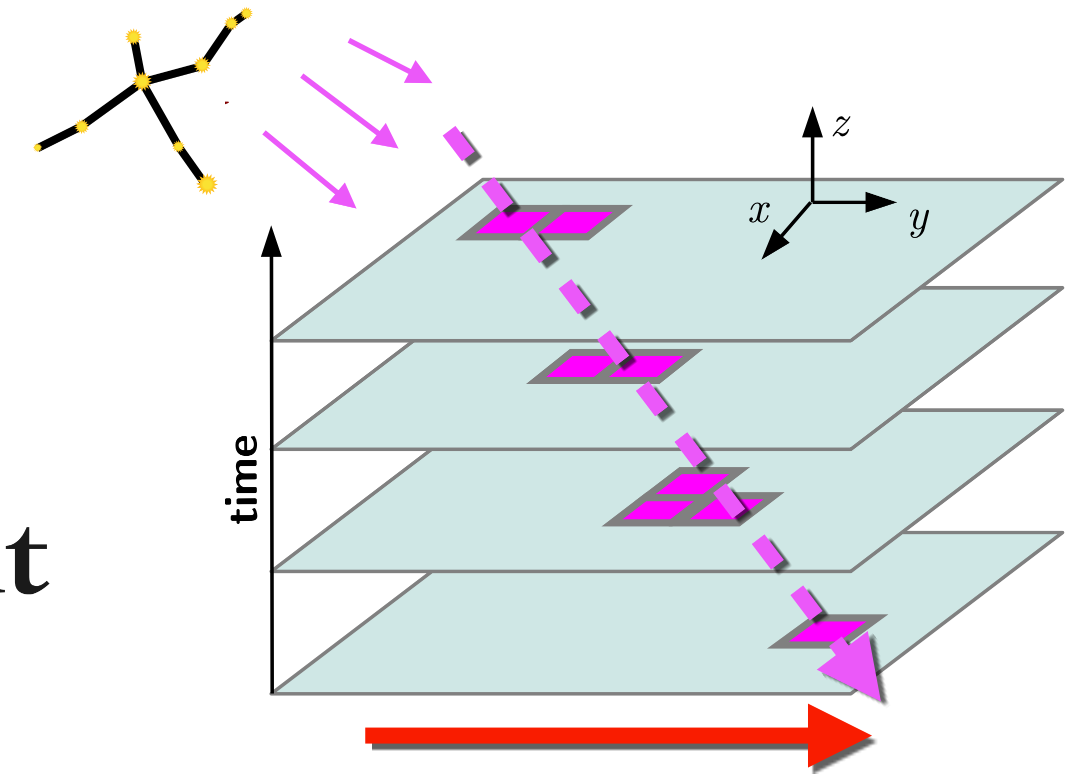
Extra slides

You can push through the background without directionality, but very slowly



Annual modulation: does it help?

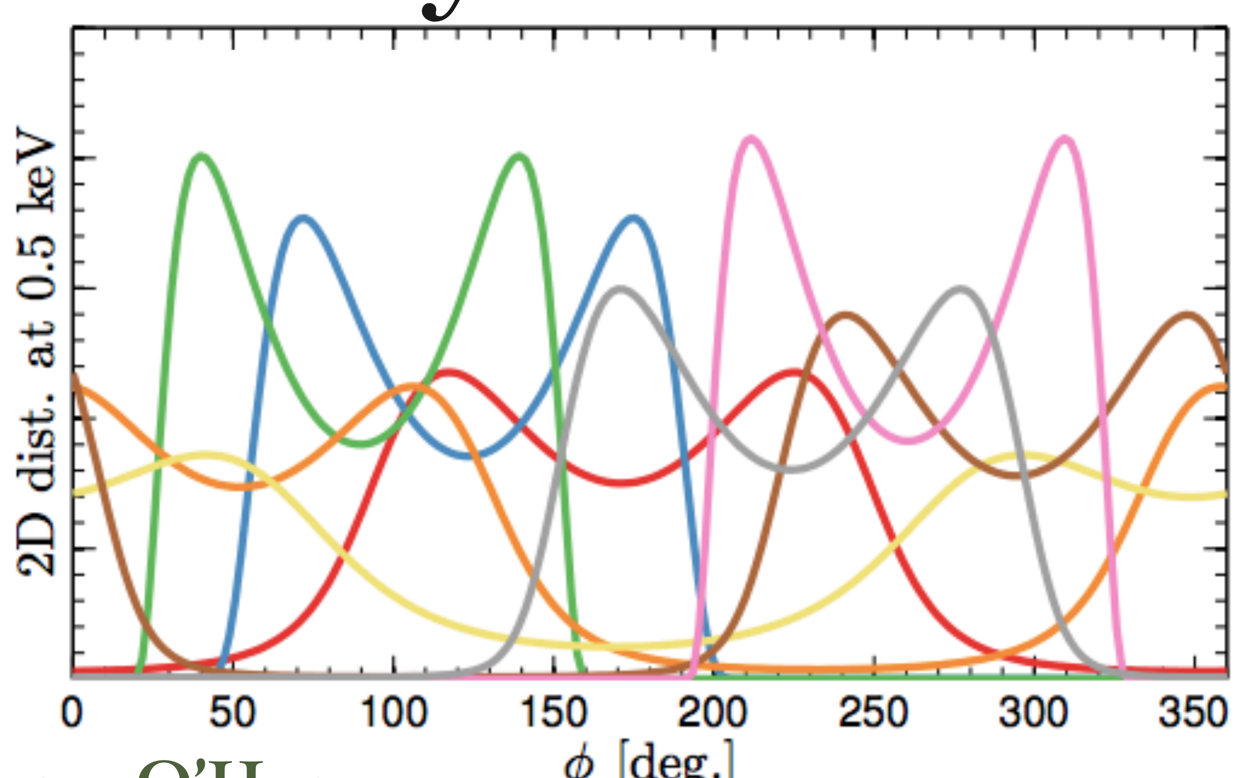




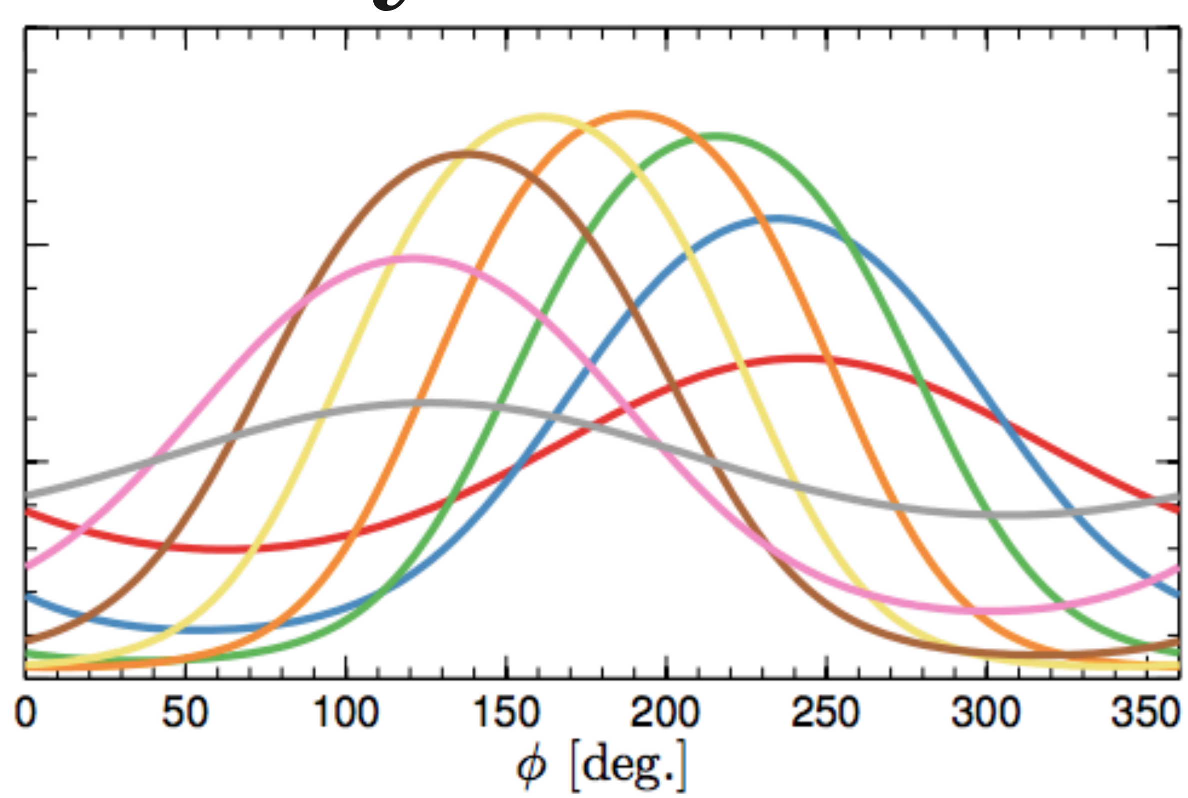
2D Readout

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

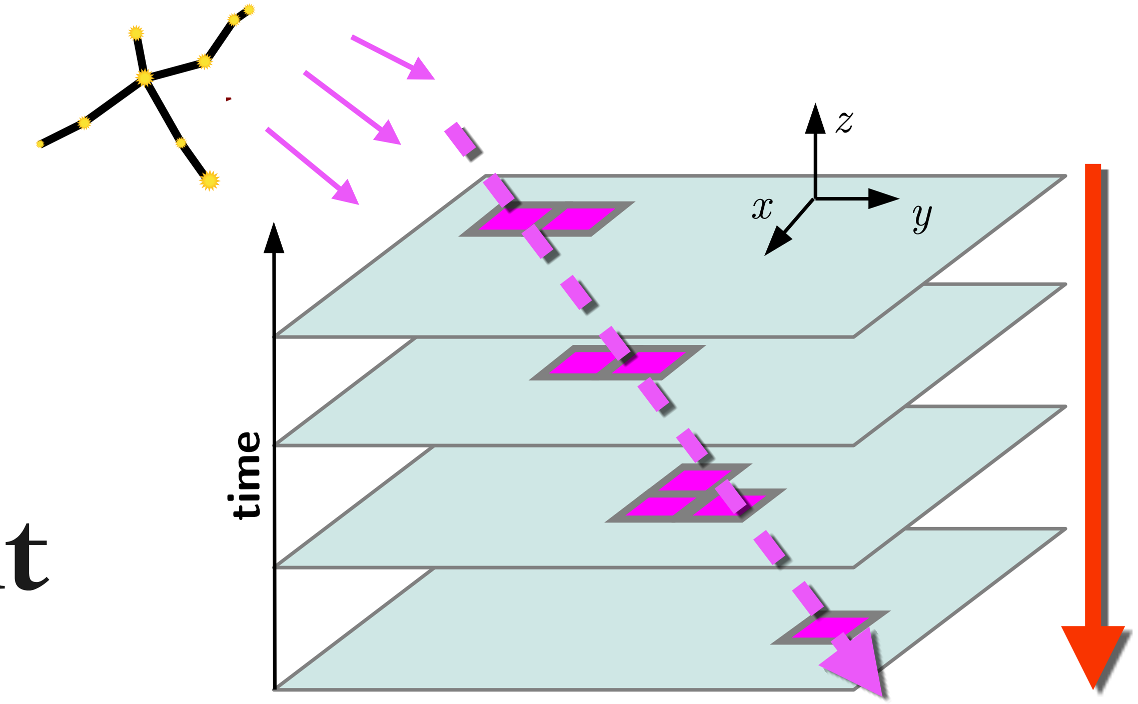
Neutrino Daily modulation



WIMP Daily modulation

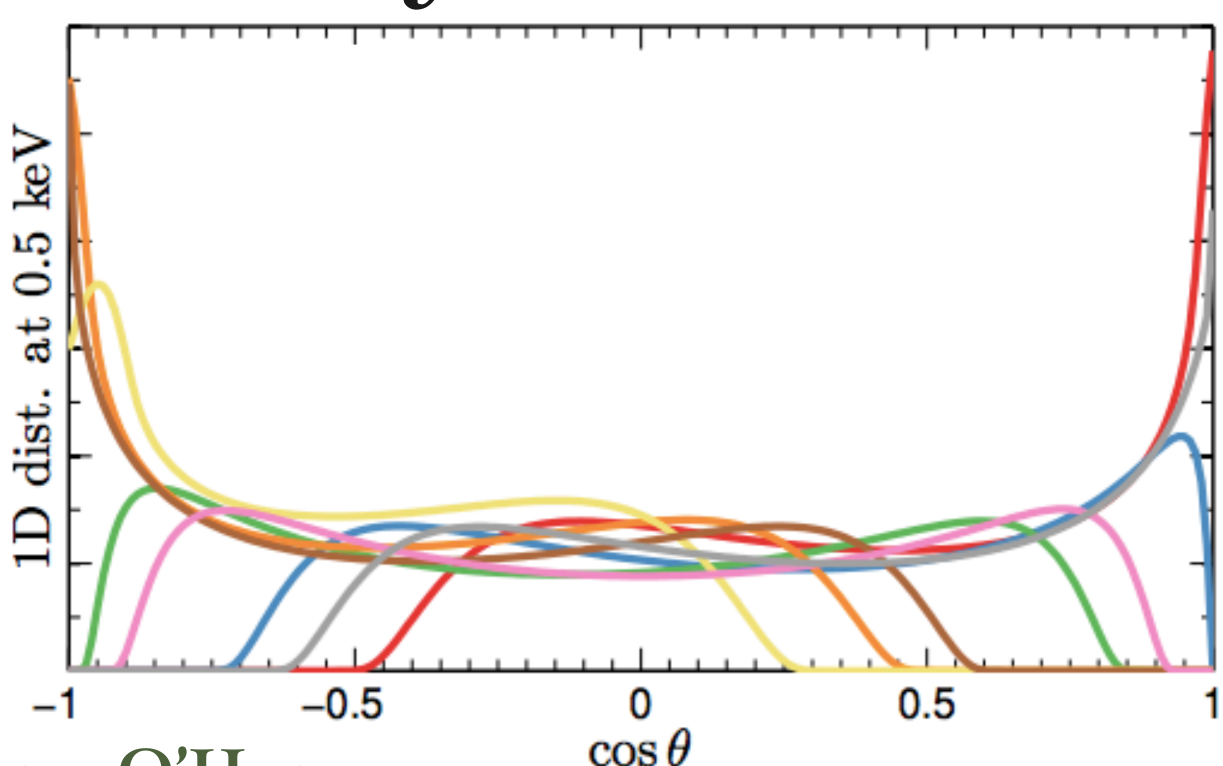


1D Readout

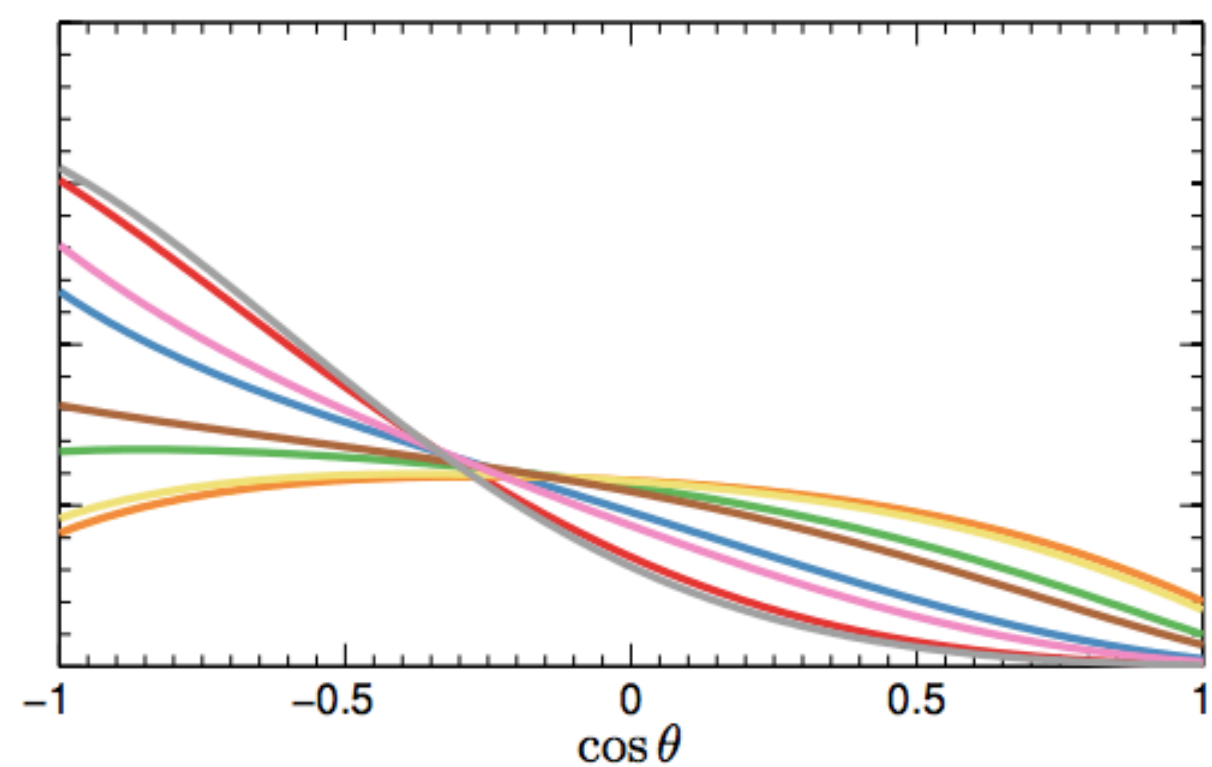


$$\hat{\mathbf{q}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$$

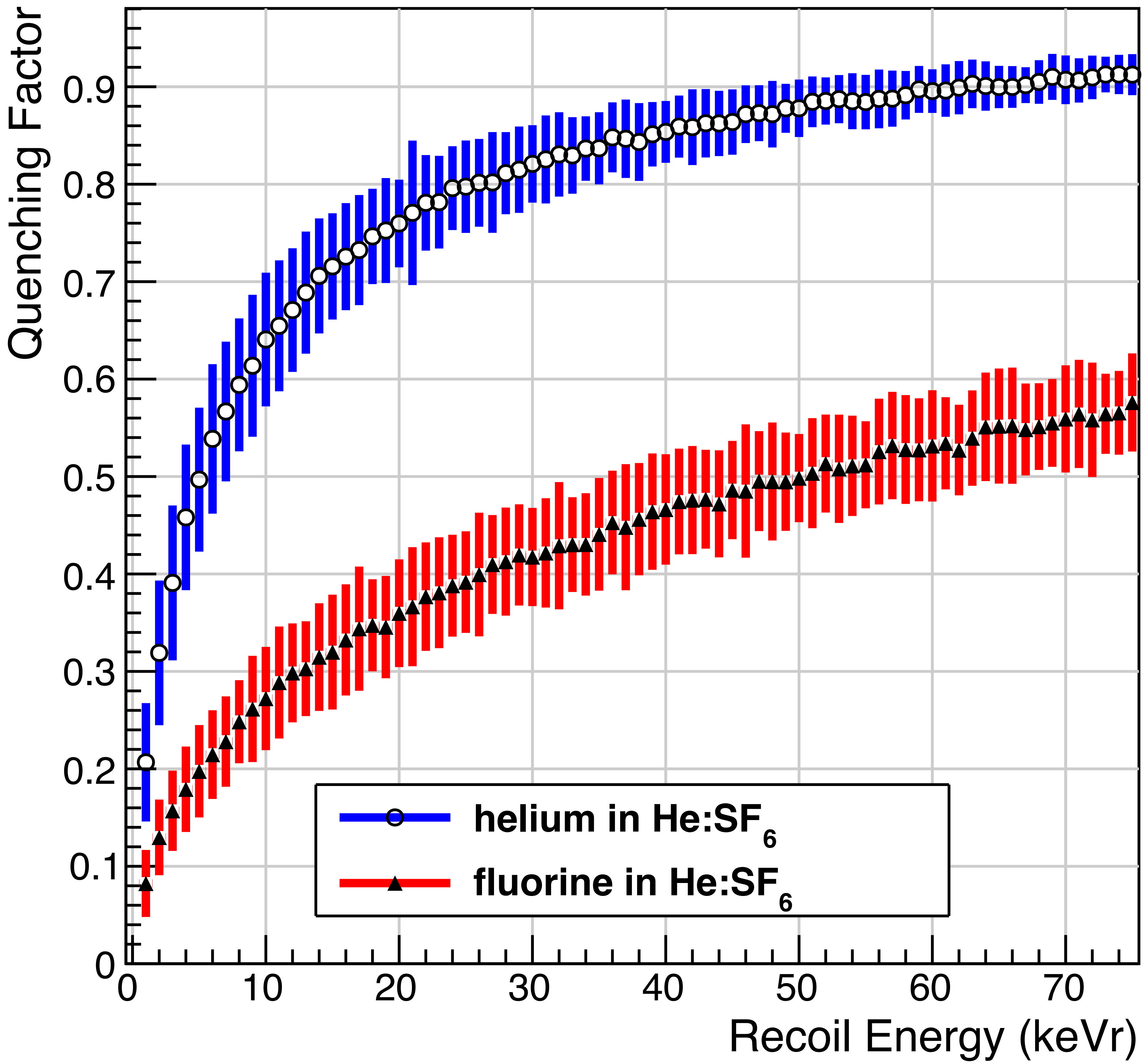
Neutrino Daily modulation



WIMP Daily modulation



Quenching factors for recoils in 1 atm of He+SF_6



Say we build Cygnus and find that…

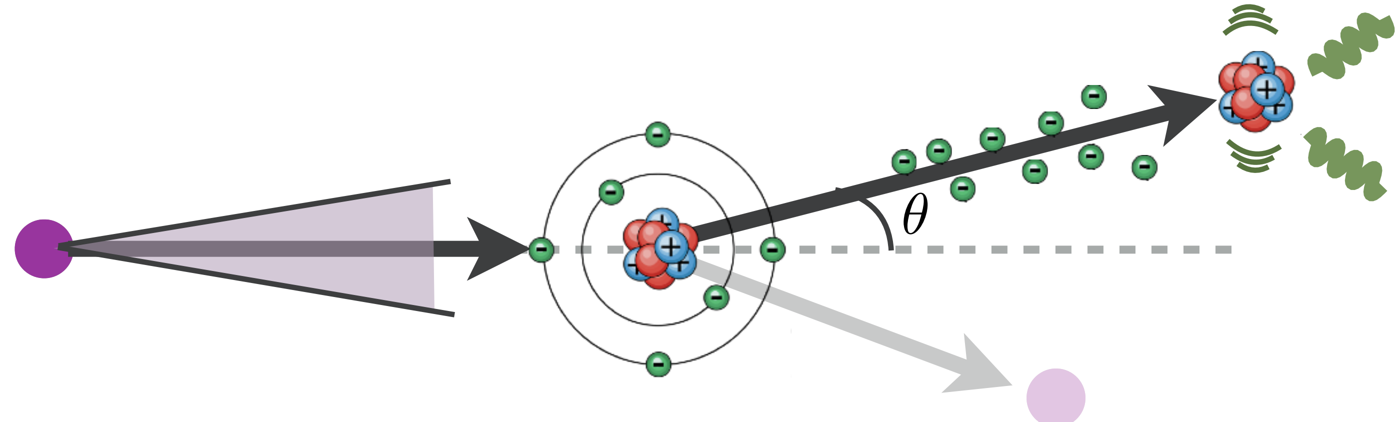
1. **We have a signal**

   ↳ 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

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

$m_N =$ Nucleus mass
$m_\chi =$ 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
$\sigma_v =$ Velocity dispersion

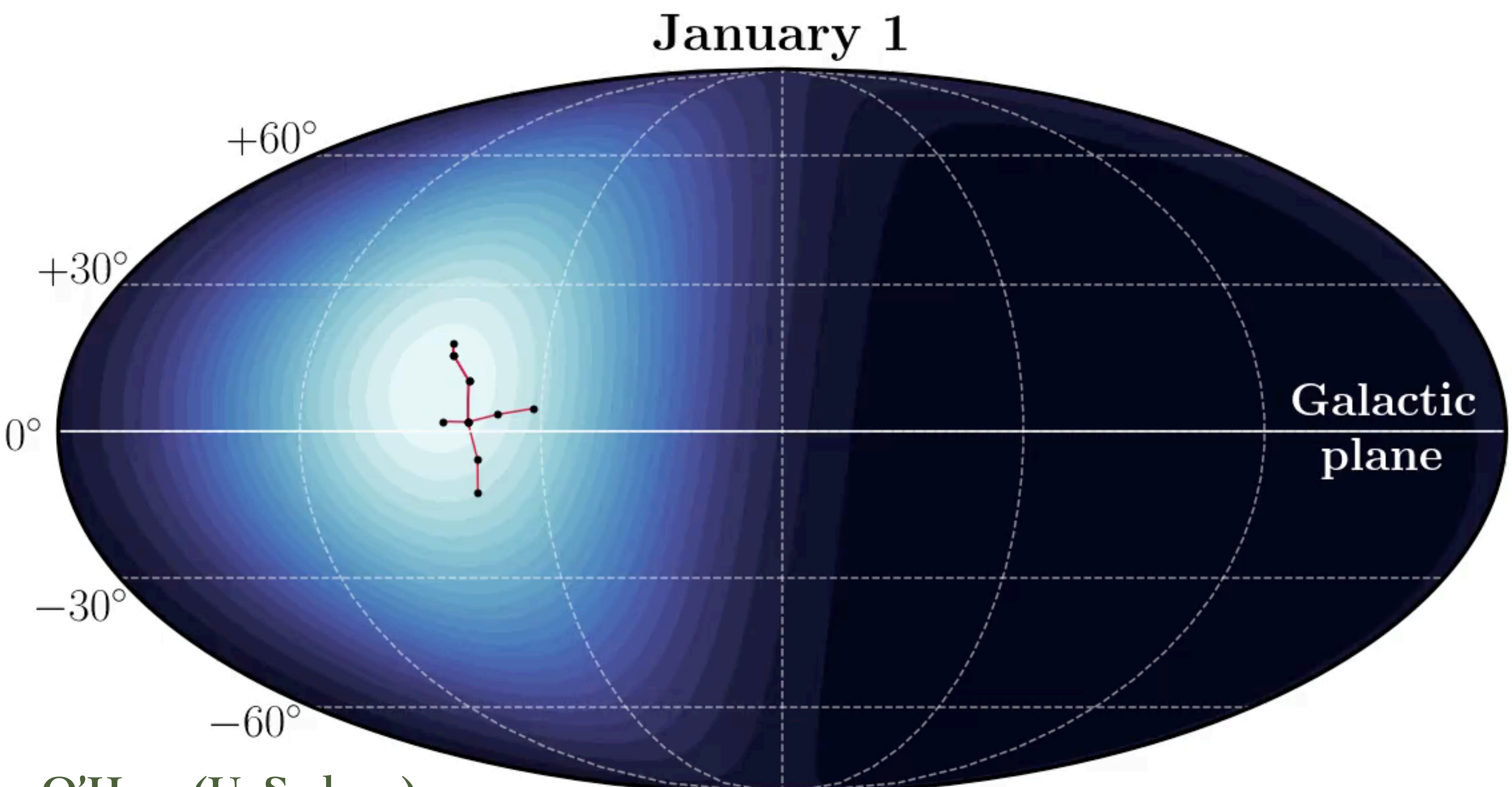
- DM-nucleus matrix element does not depend on velocity

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

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

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

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



Ciaran O'Hare (U. Sydney)

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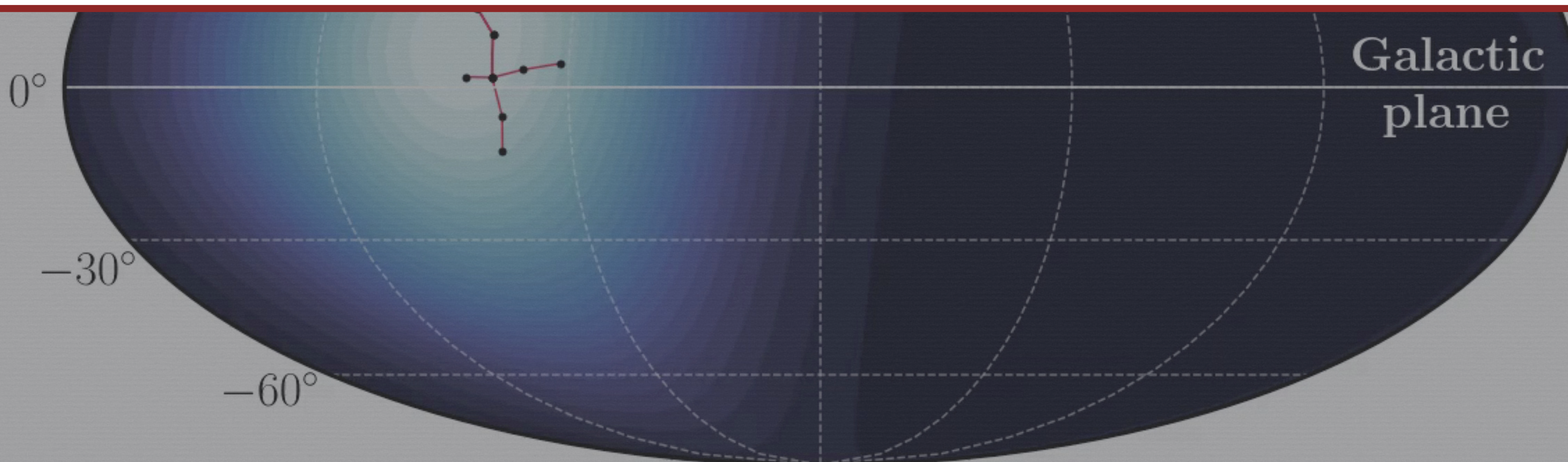
But this is **wrong** if we break those assumptions,
and we have reason to…

→ The DM velocity distribution is not a Gaussian

→ WIMPs may not scatter elastically

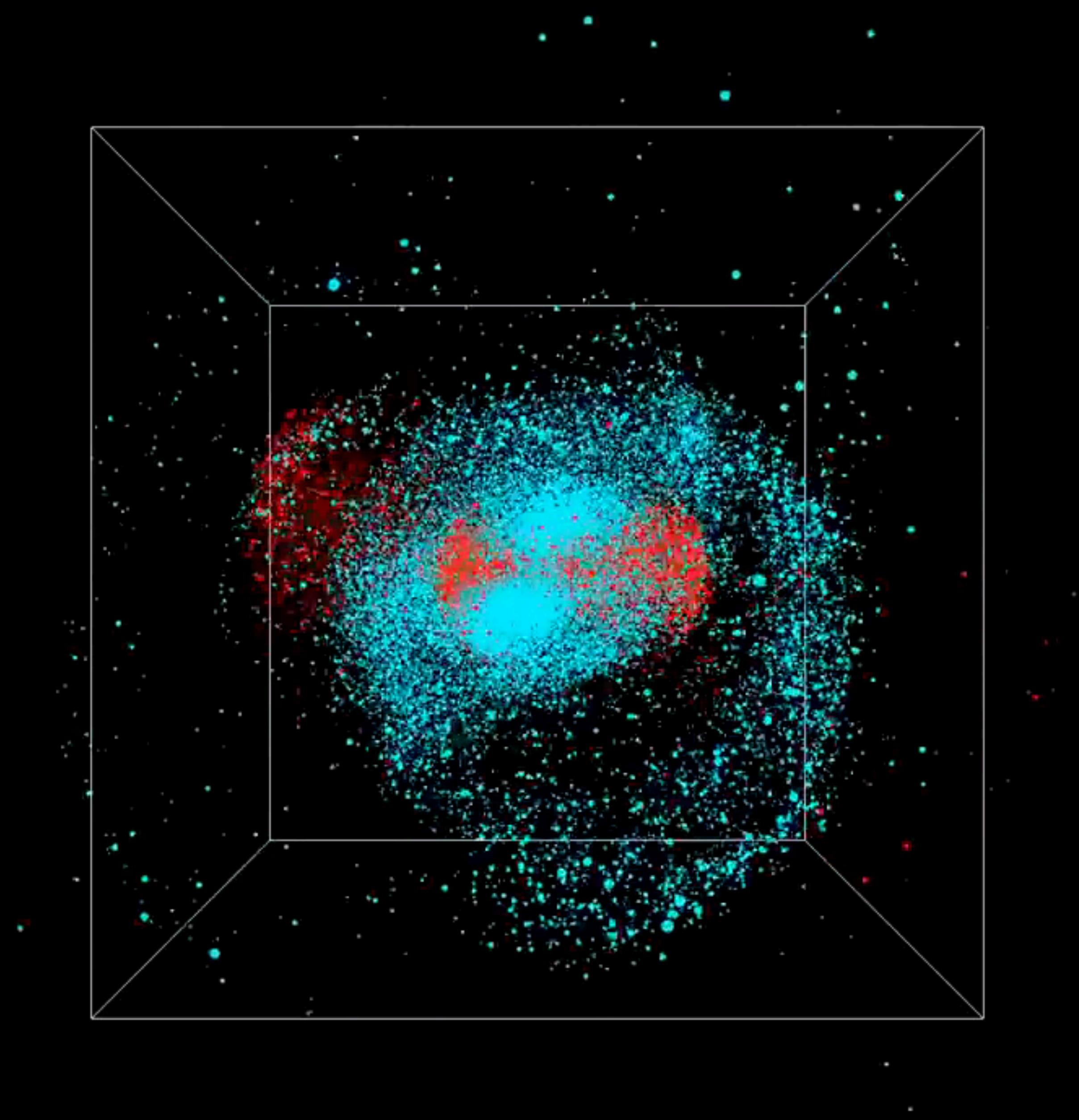
→ The WIMP-nucleus interaction may involve velocity-dependent operators



Should the DM velocity distribution be a Gaussian?

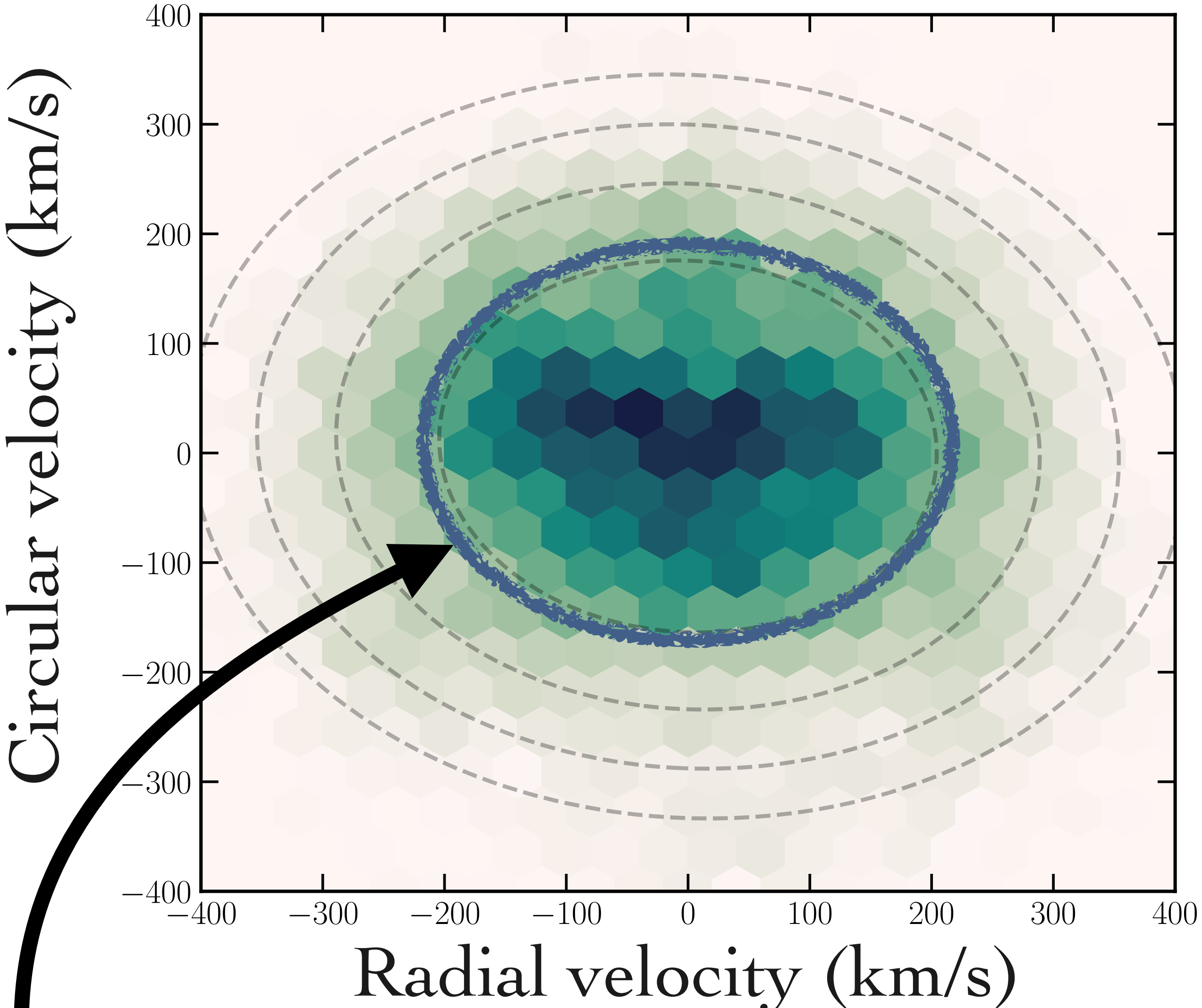
→ Evidence of significant merger in the MW's history

The Gaia Sausage

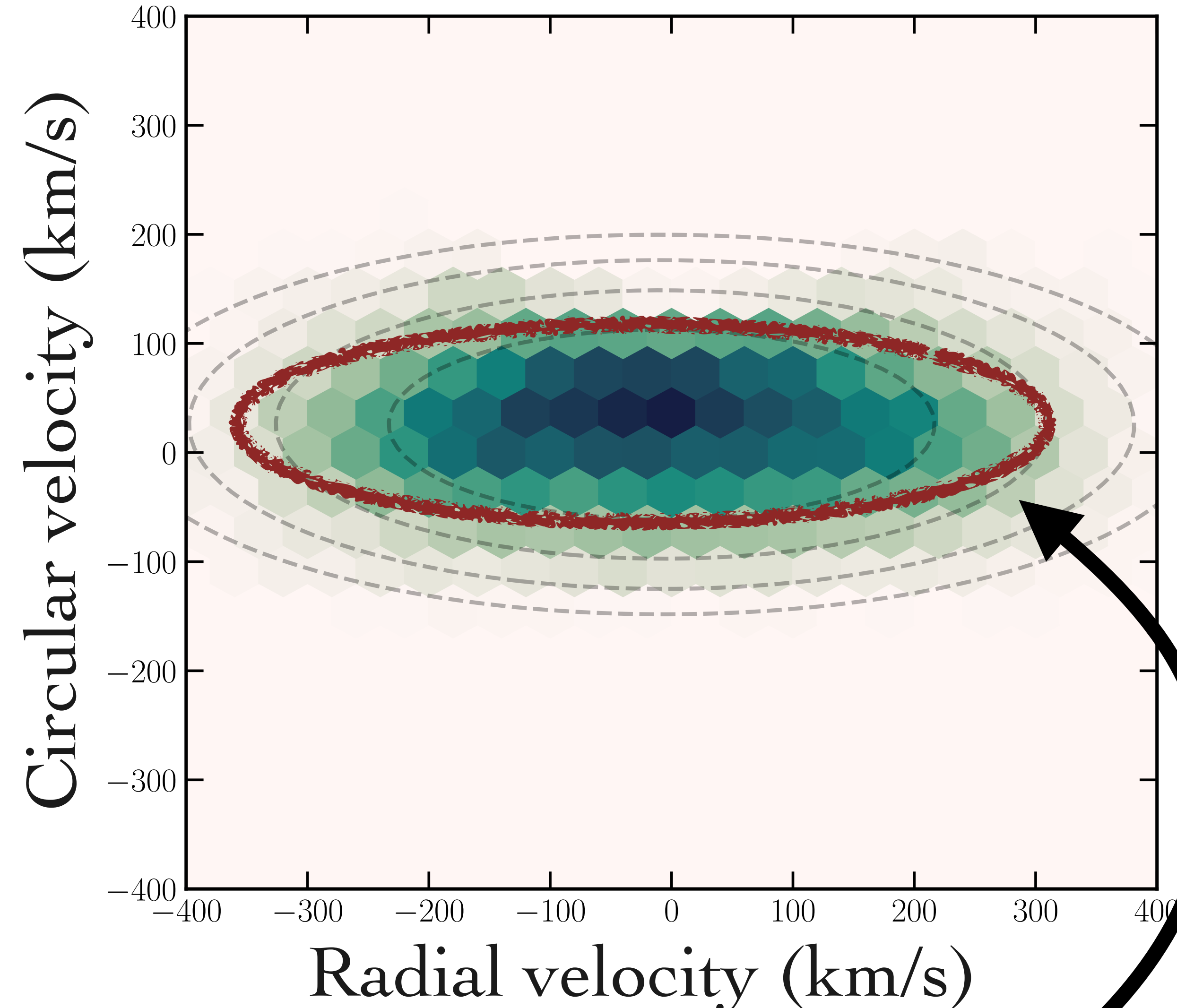


See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

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



Metal-rich halo [Fe/H]>-1.5



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

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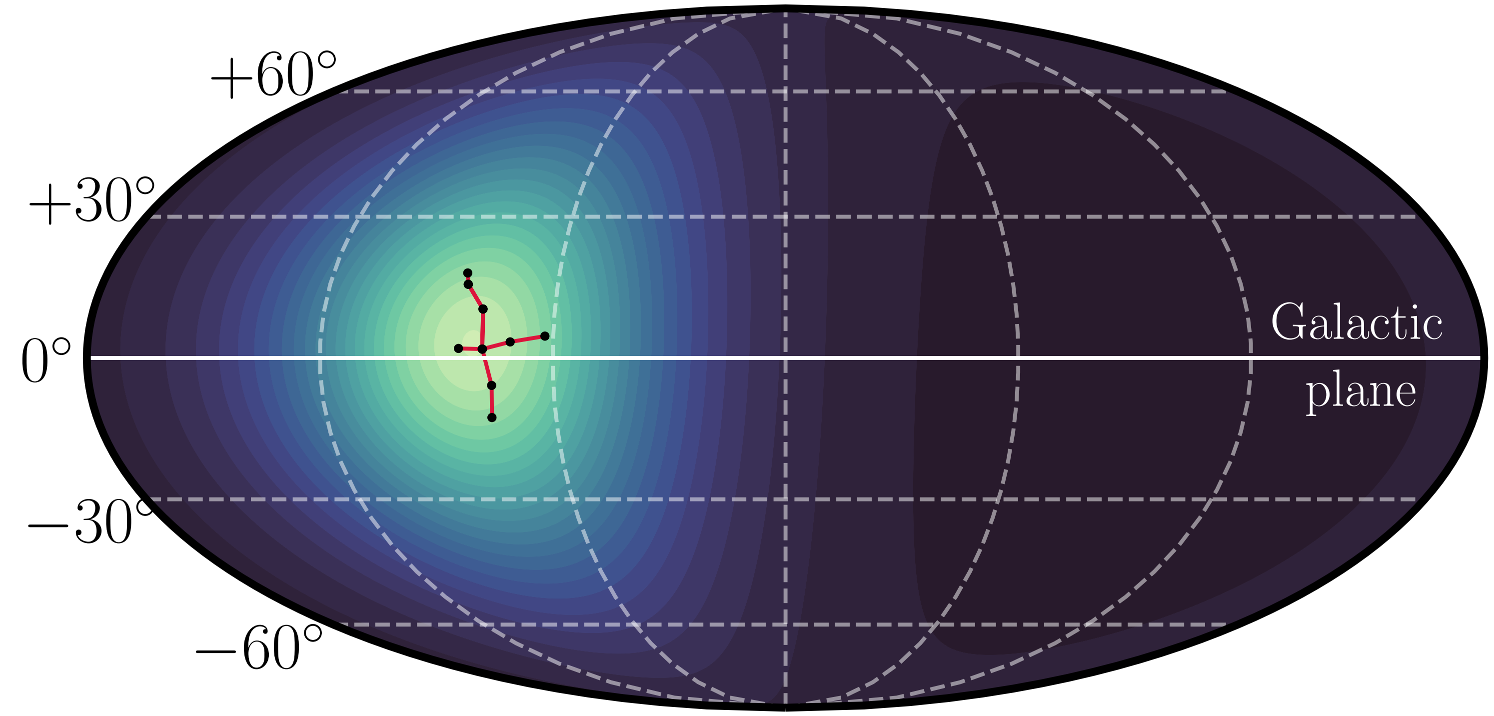
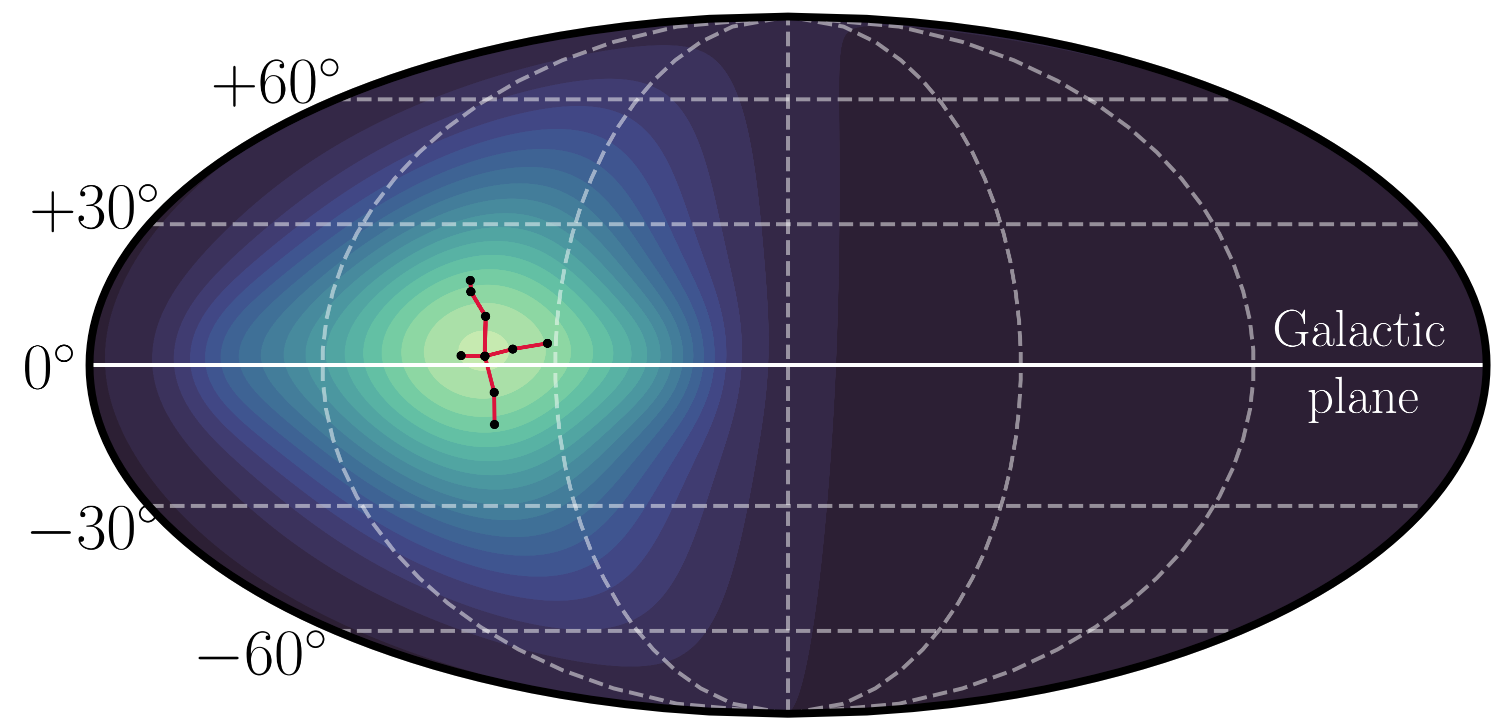
The Gaia Sausage

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)



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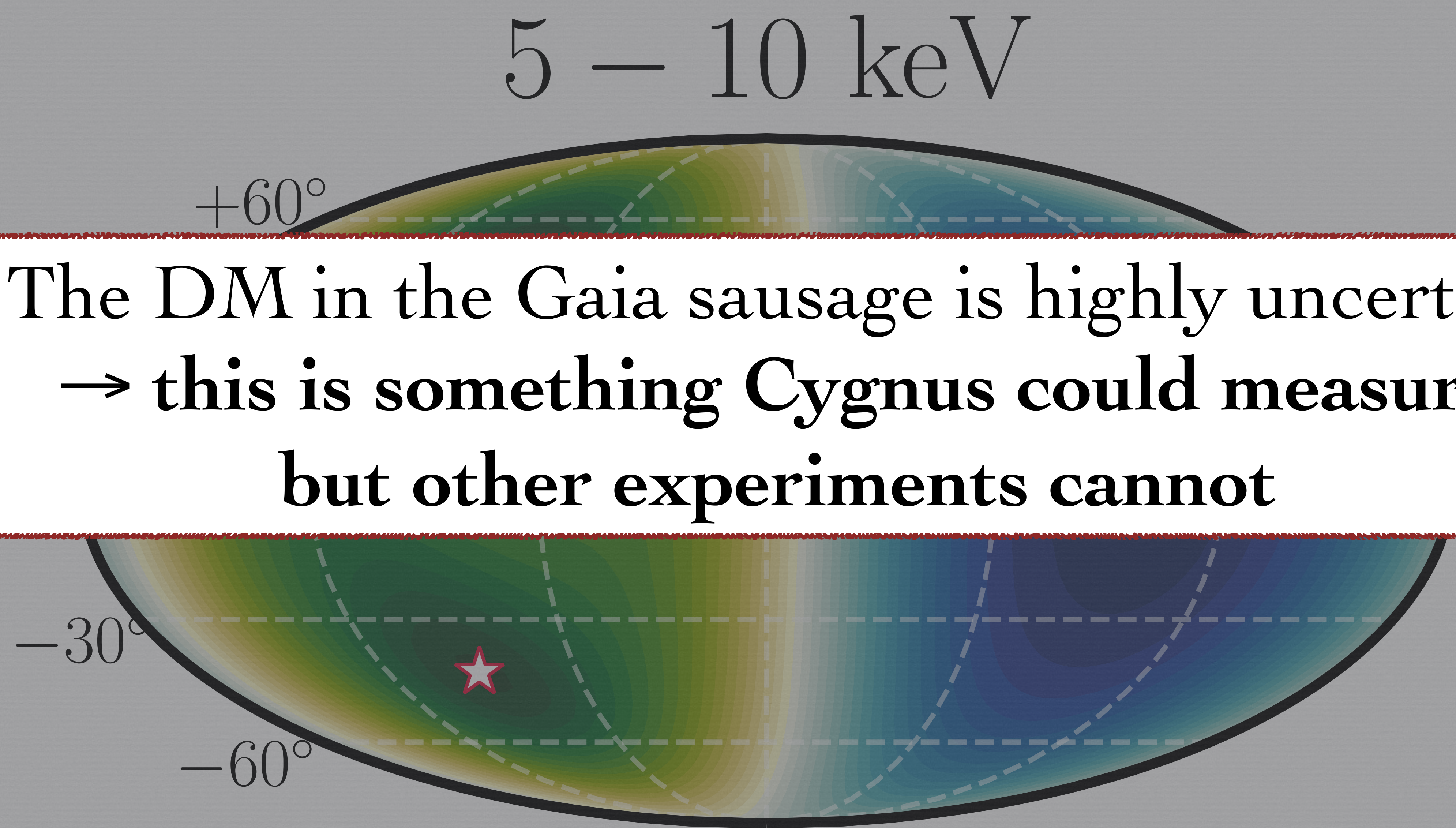
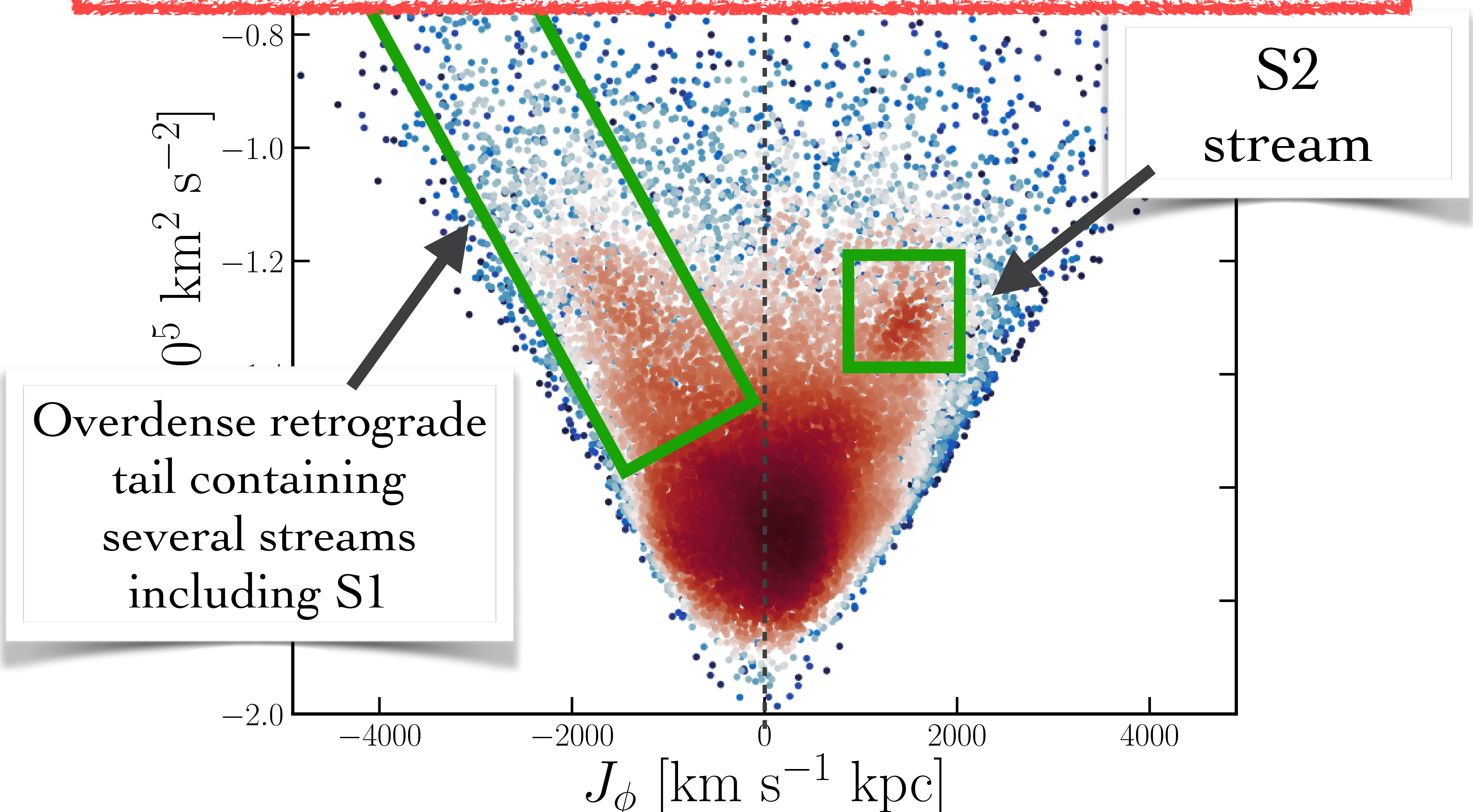
The Gaia Sausage gives rise to peaks off center from Cygnus



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

Substructures cluster in action space even when they are not clustered in phase space or visible on the sky
→ we can see streams that we are inside of



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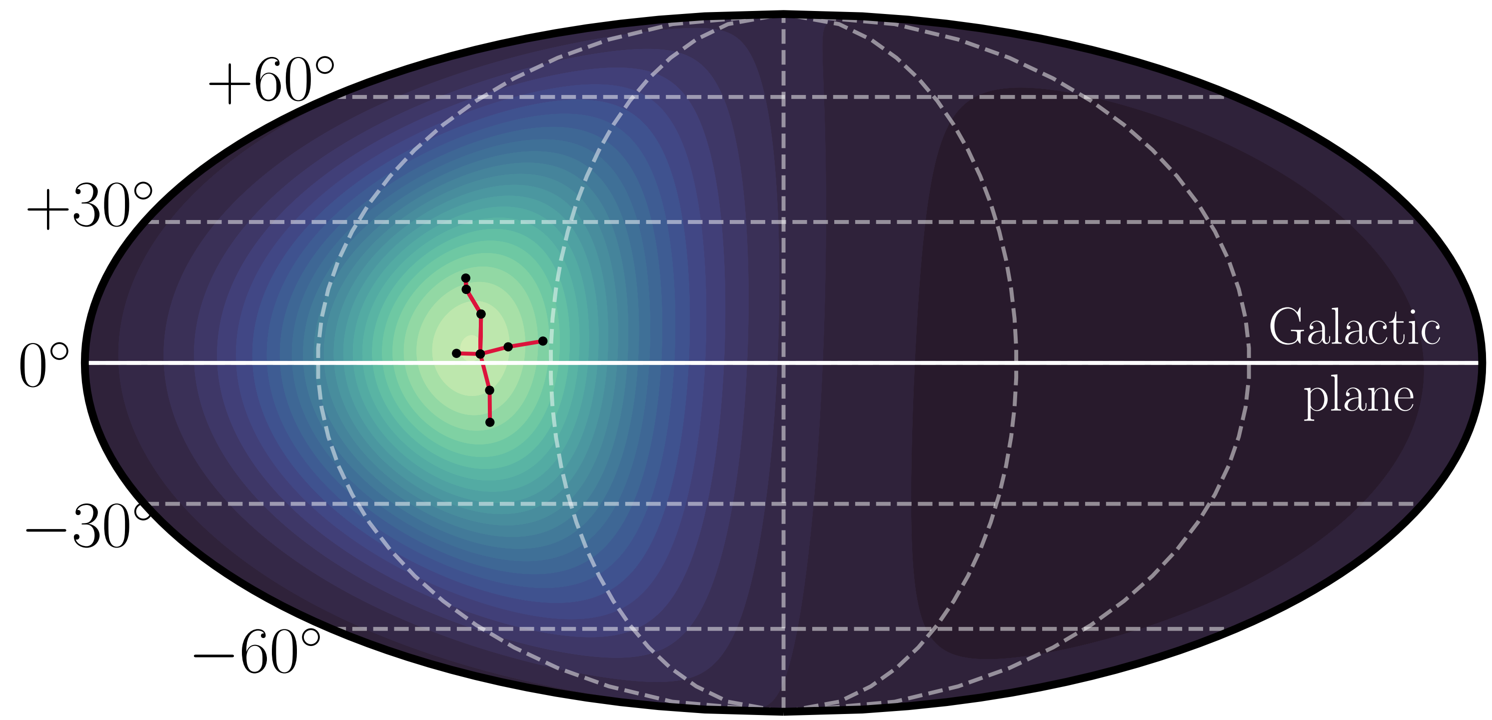
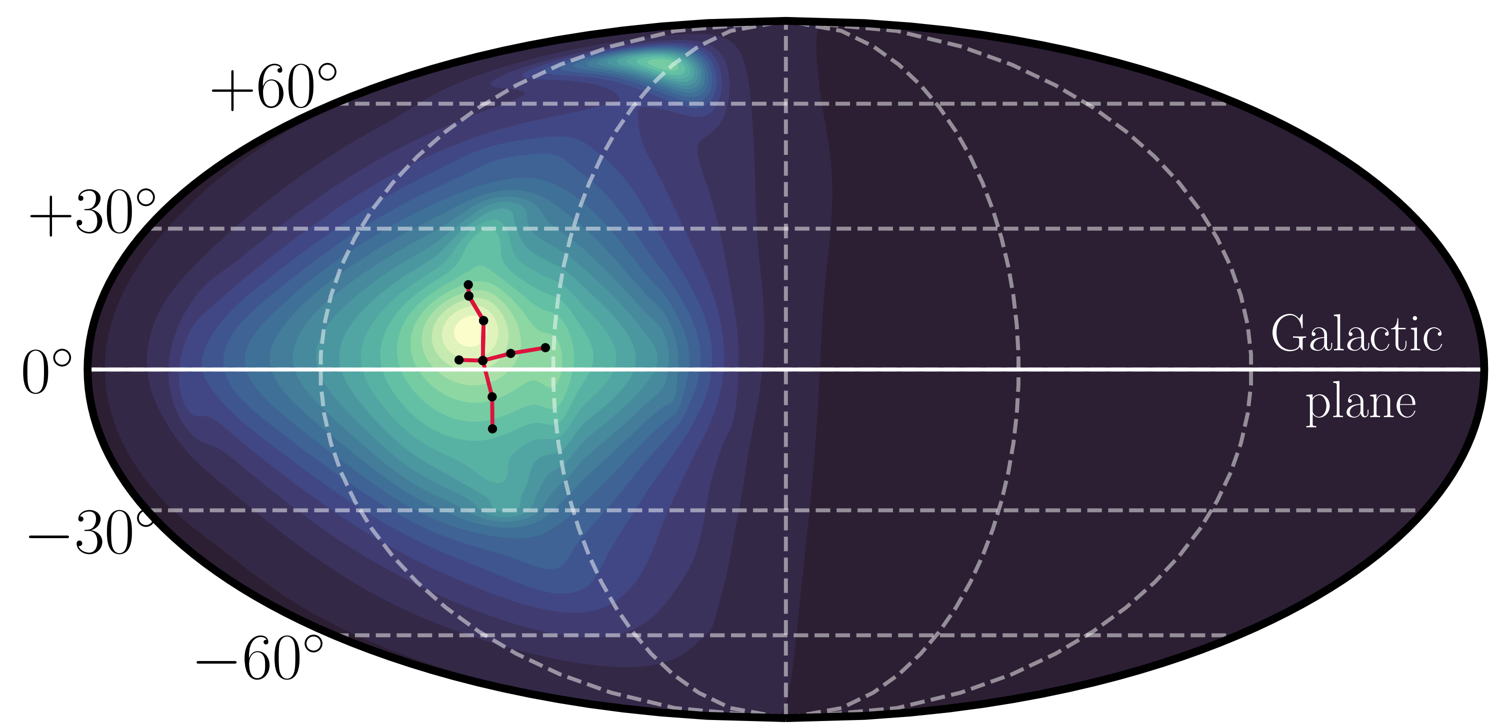
Gaia also shows evidence of substructure passing through Solar position → e.g. S1 (hurricane), S2 streams

SHM DM flux
(Gaussian distribution)



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



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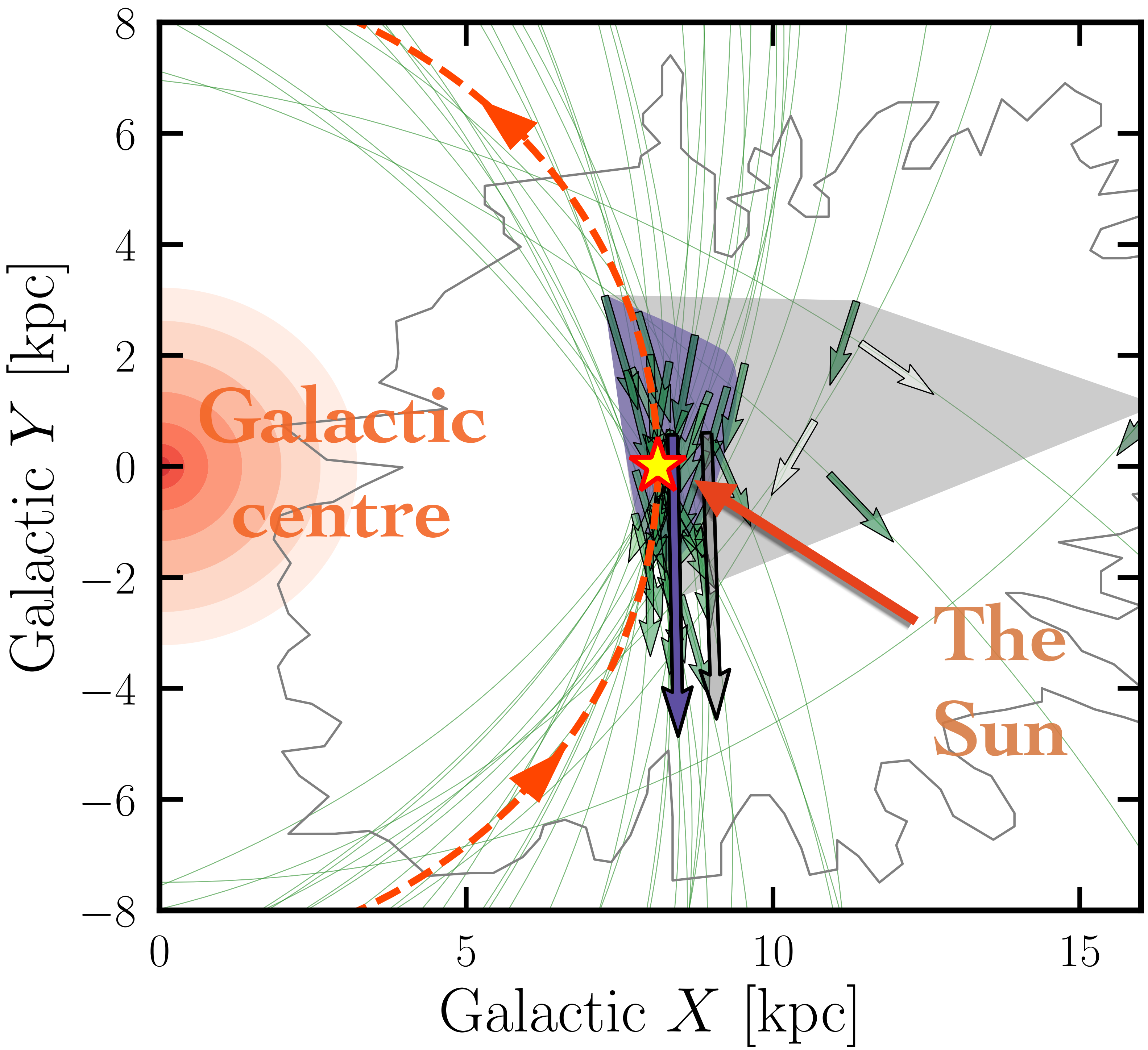
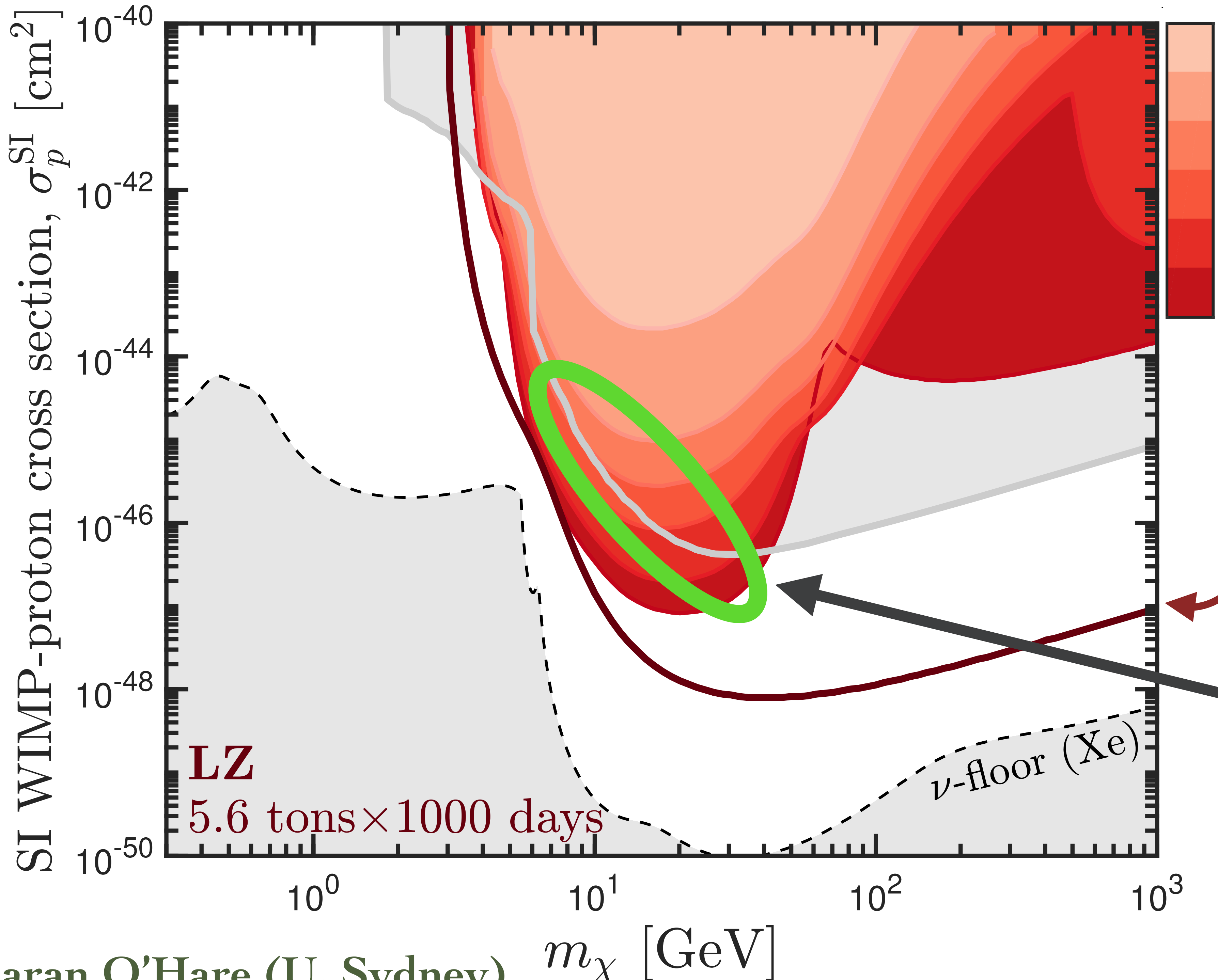
The S1 stream



- 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)

S1 in LZ

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



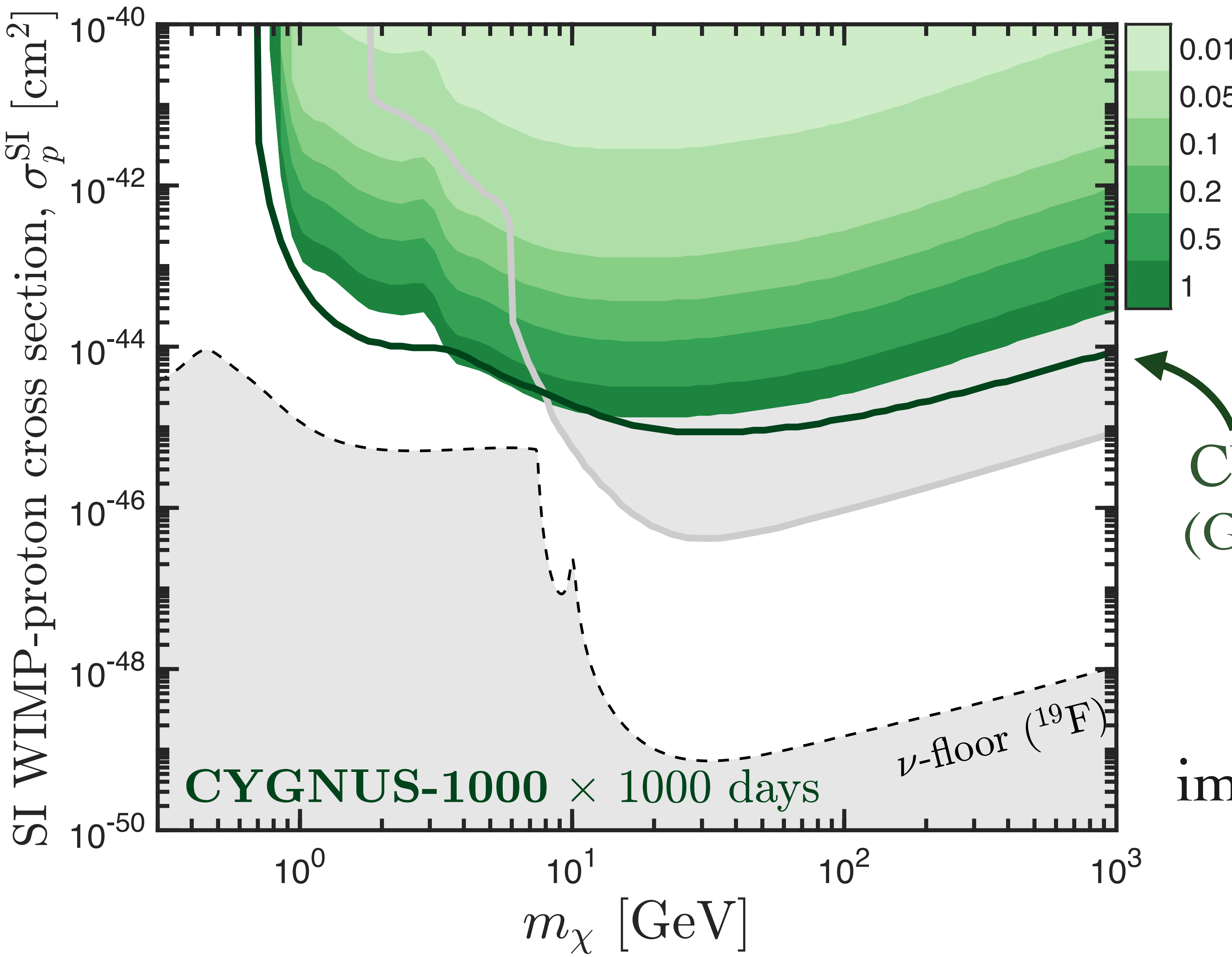
Fraction of total DM in stream

LZ sensitivity

Stream only "detectable" here

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)

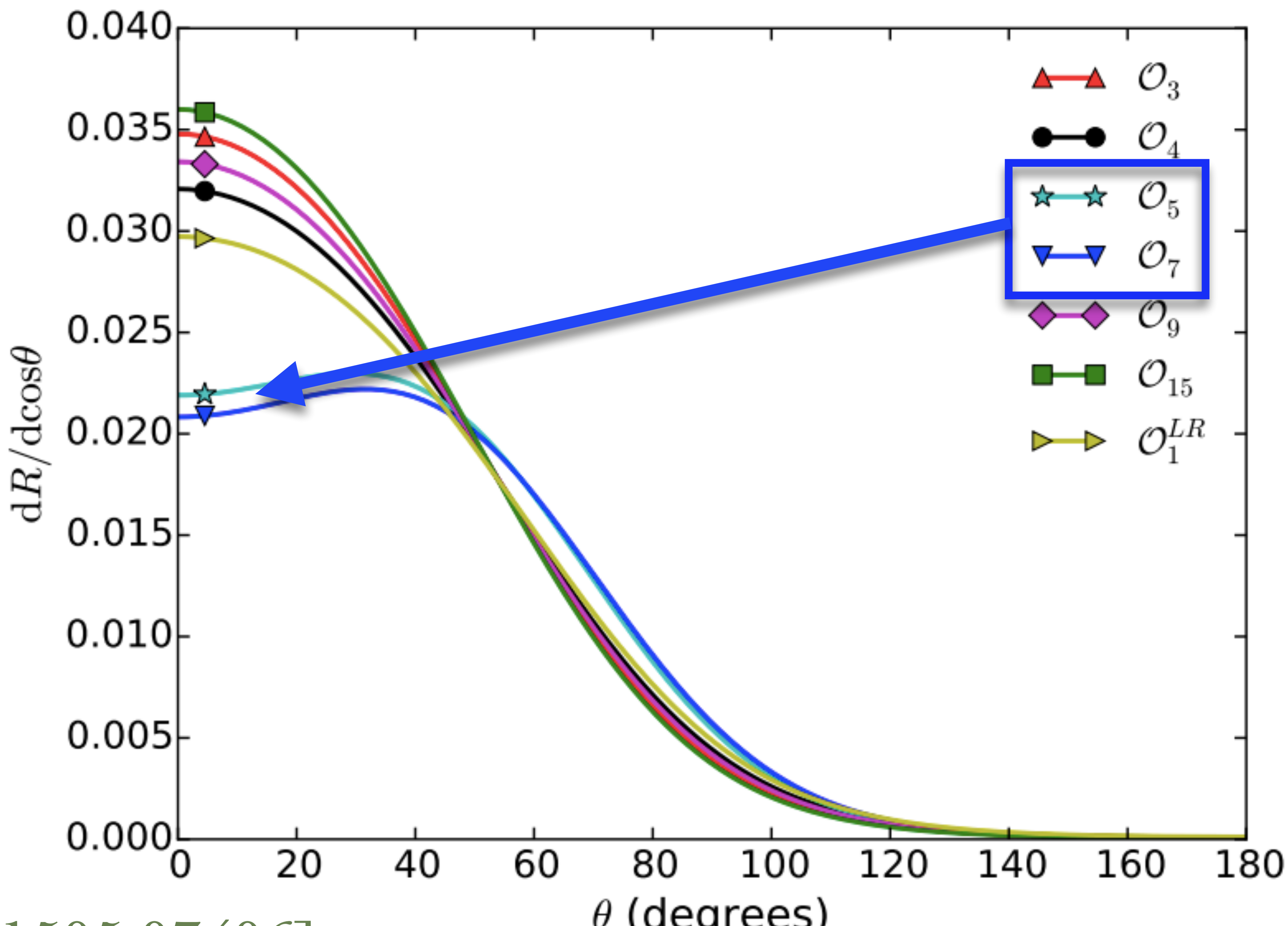
Directionality improves sensitivity to stream

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



Kavanagh [1505.07406]

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…

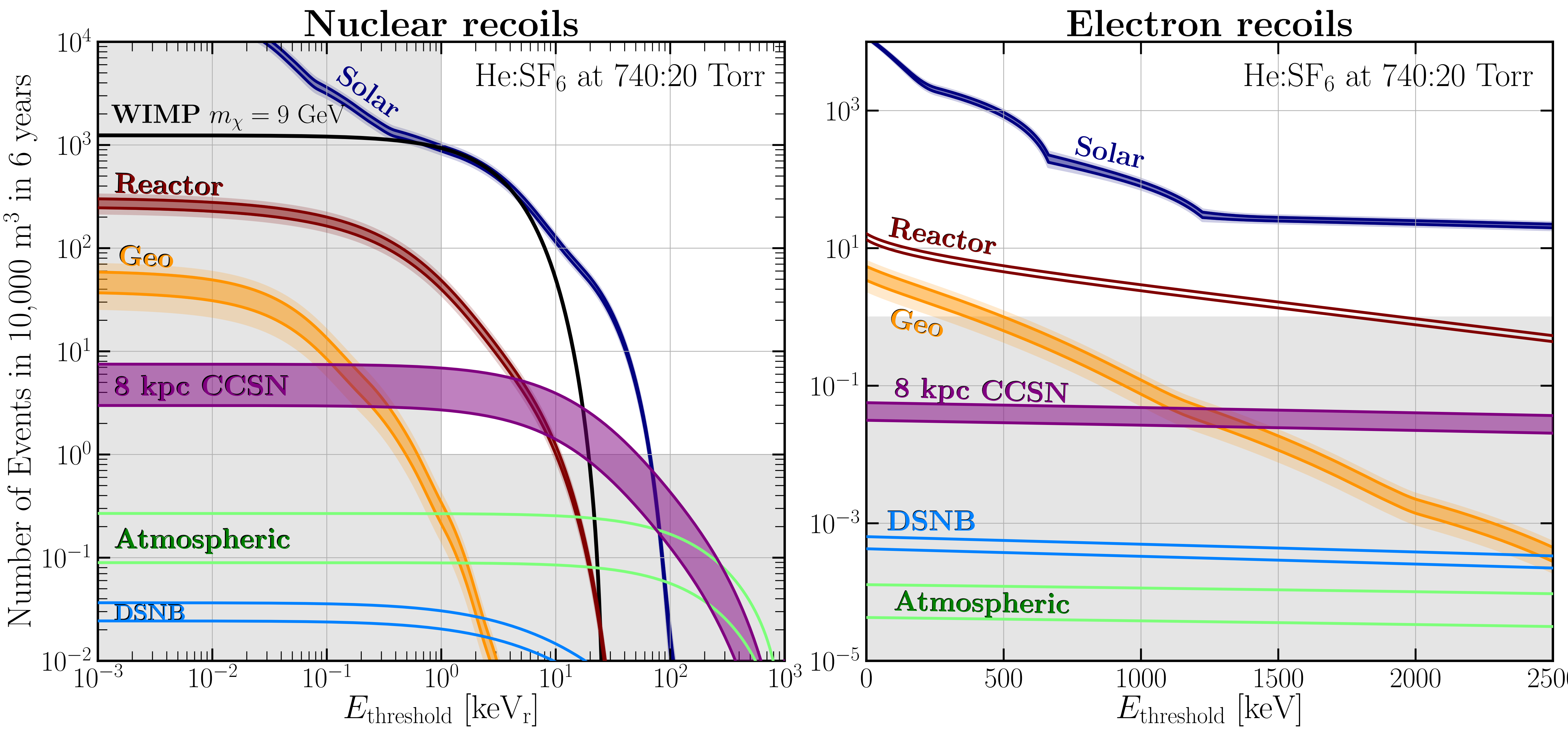
1. We have a signal

↳ We study it

2. We don't

↳ 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

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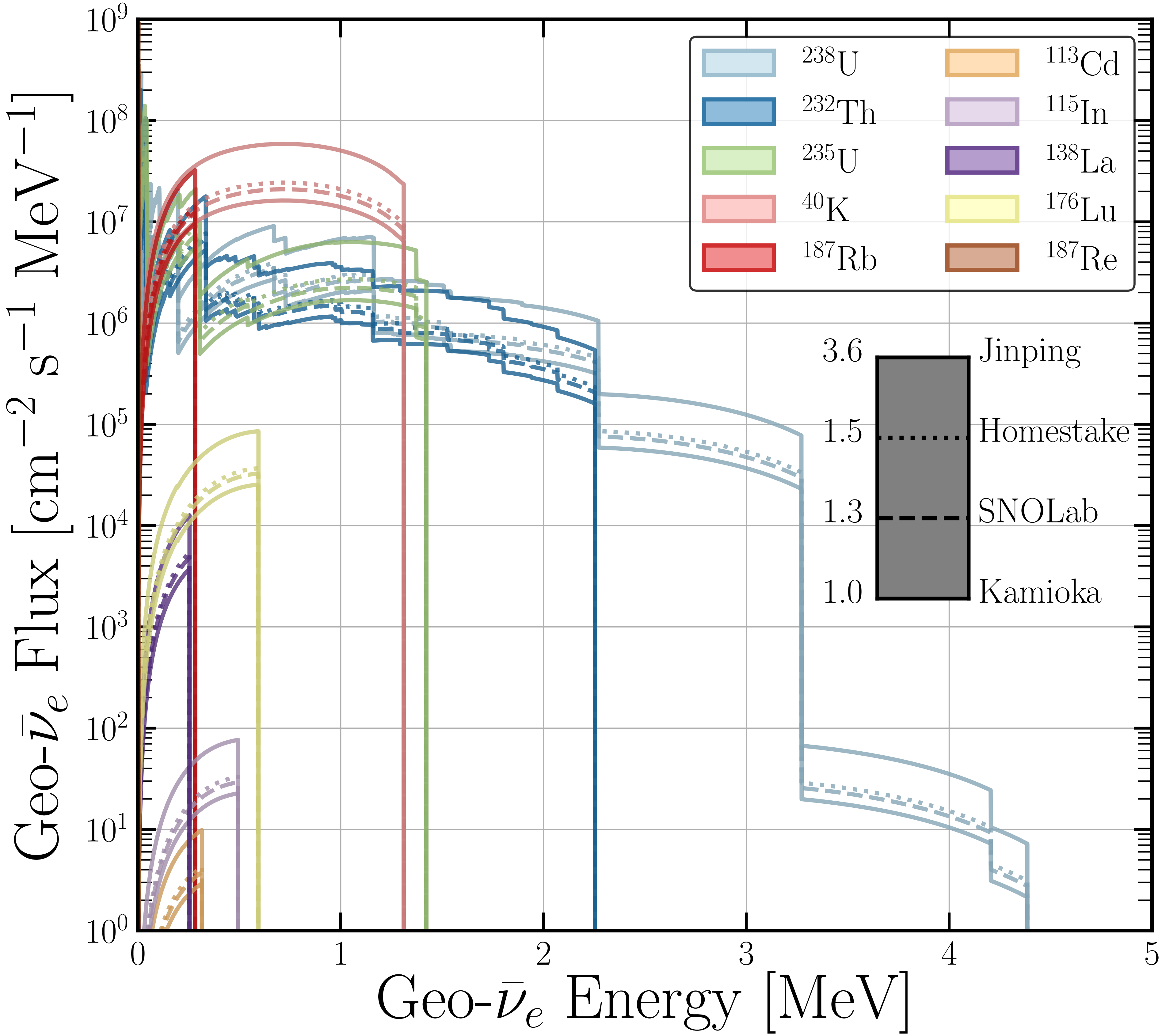
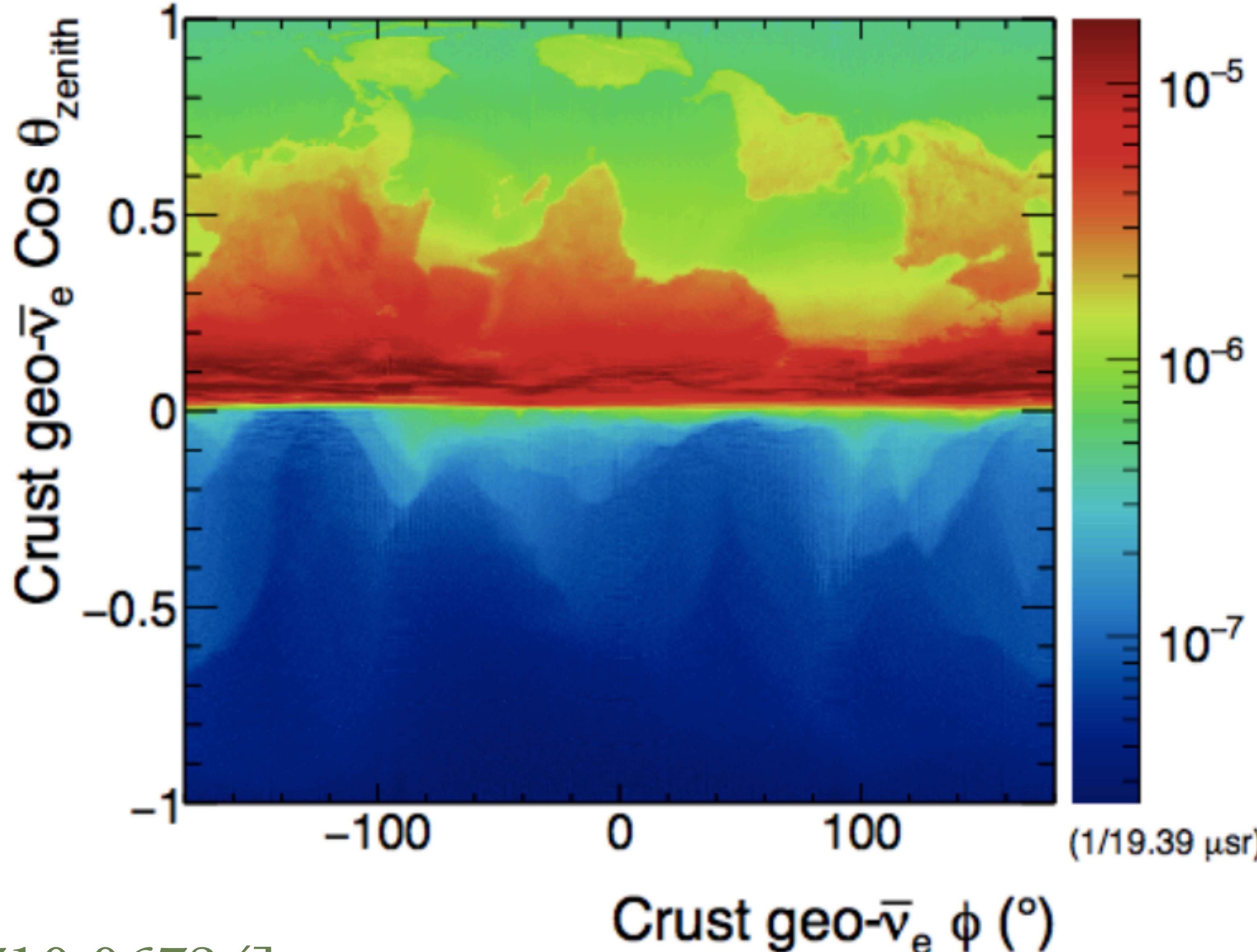
Geoneutrino flux



Geoneutrino flux



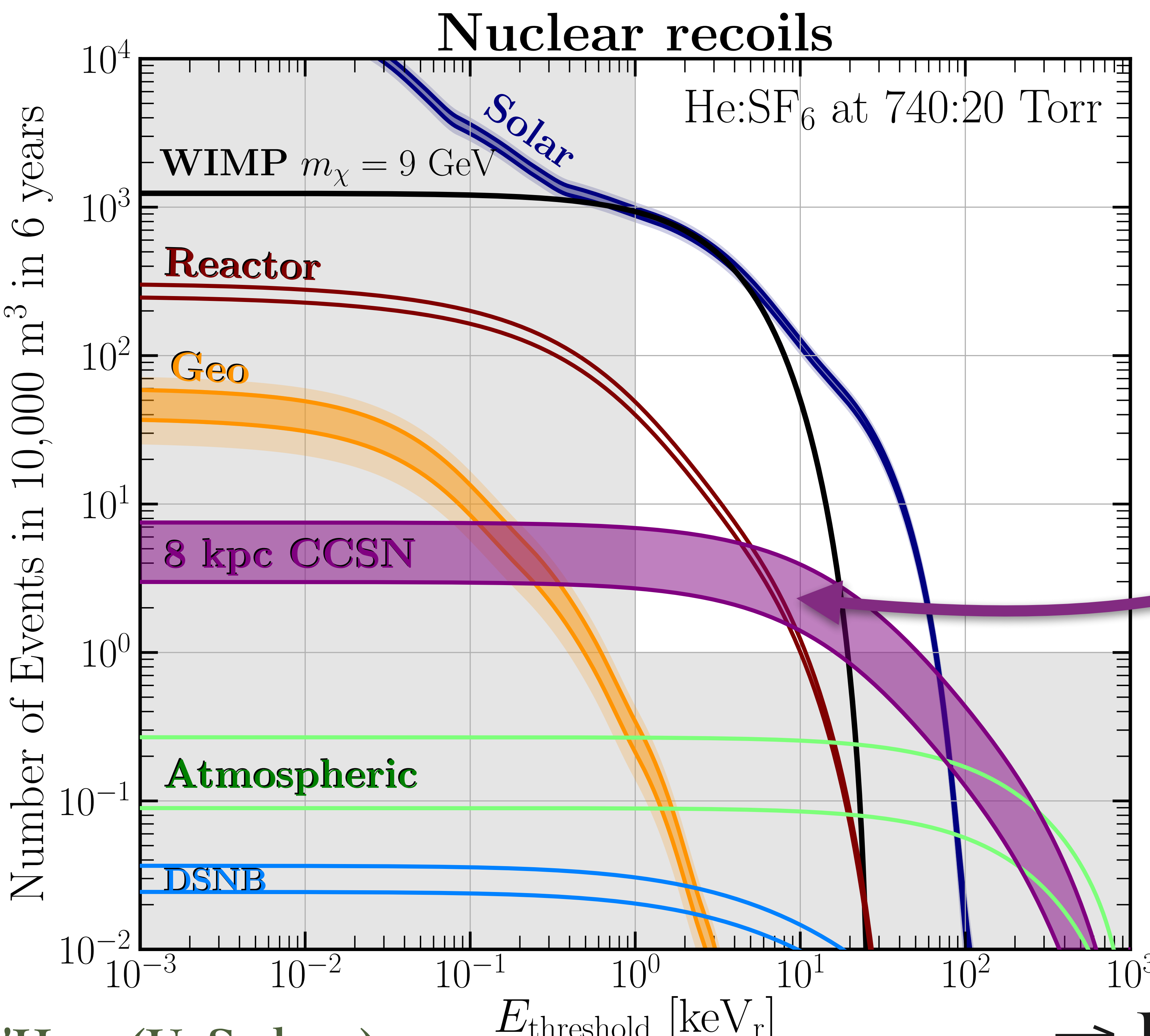
Leyton+ [1710.06724]

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)

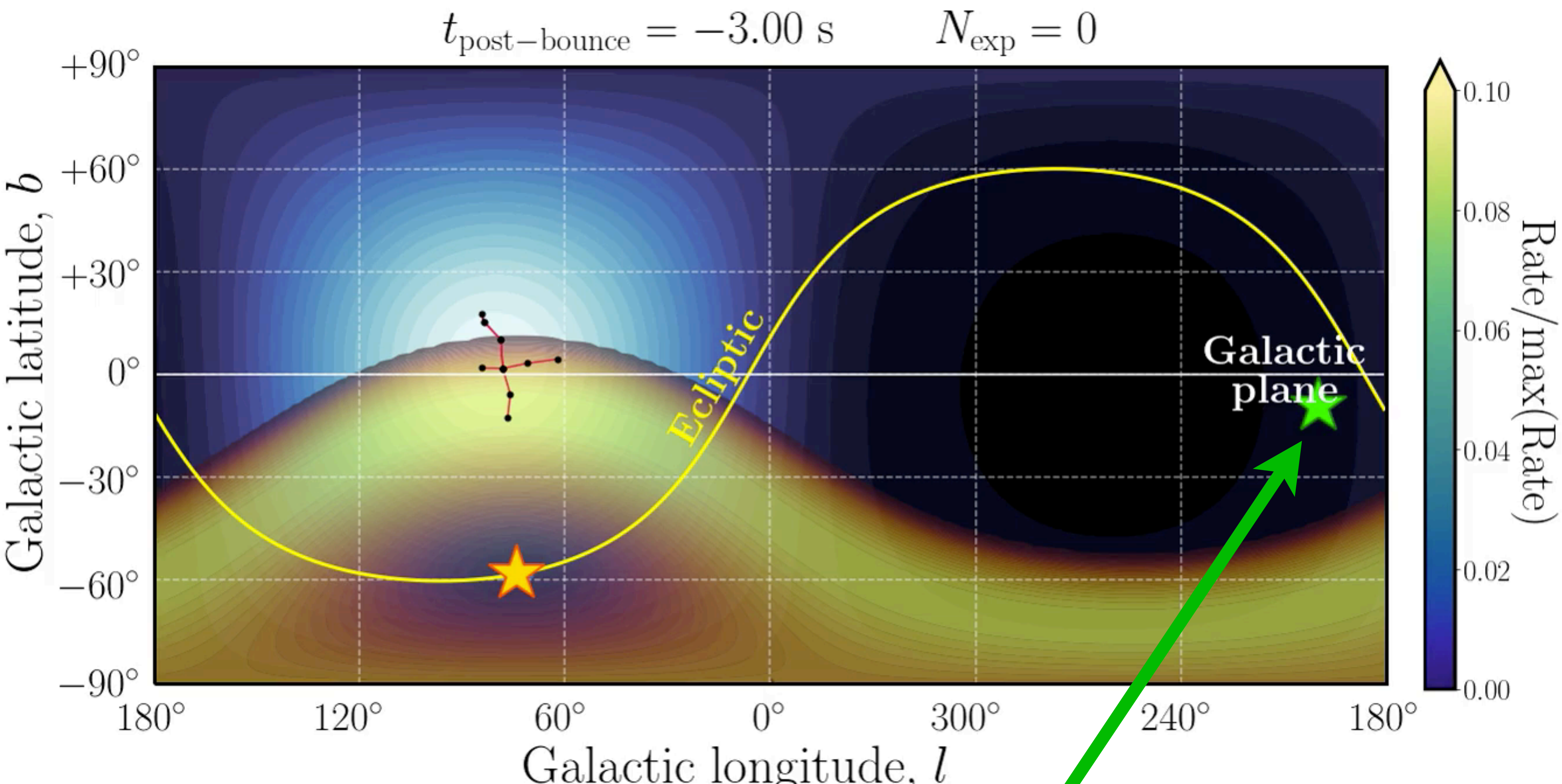
Pointing to a supernovae

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



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]