



Centre for Dark Matter
Particle Physics



THE UNIVERSITY OF
SYDNEY



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

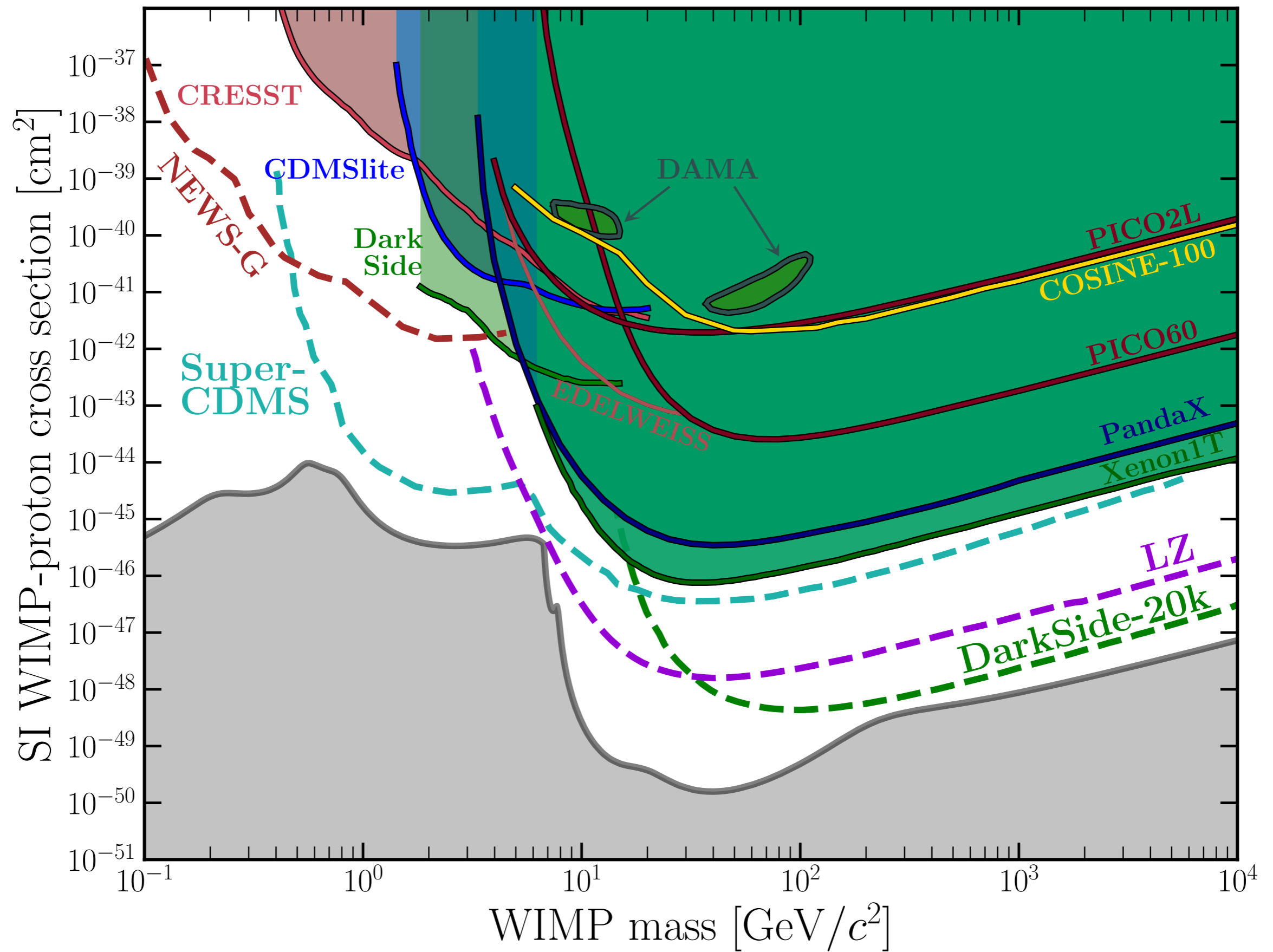
TeVPA, 3 December 2019

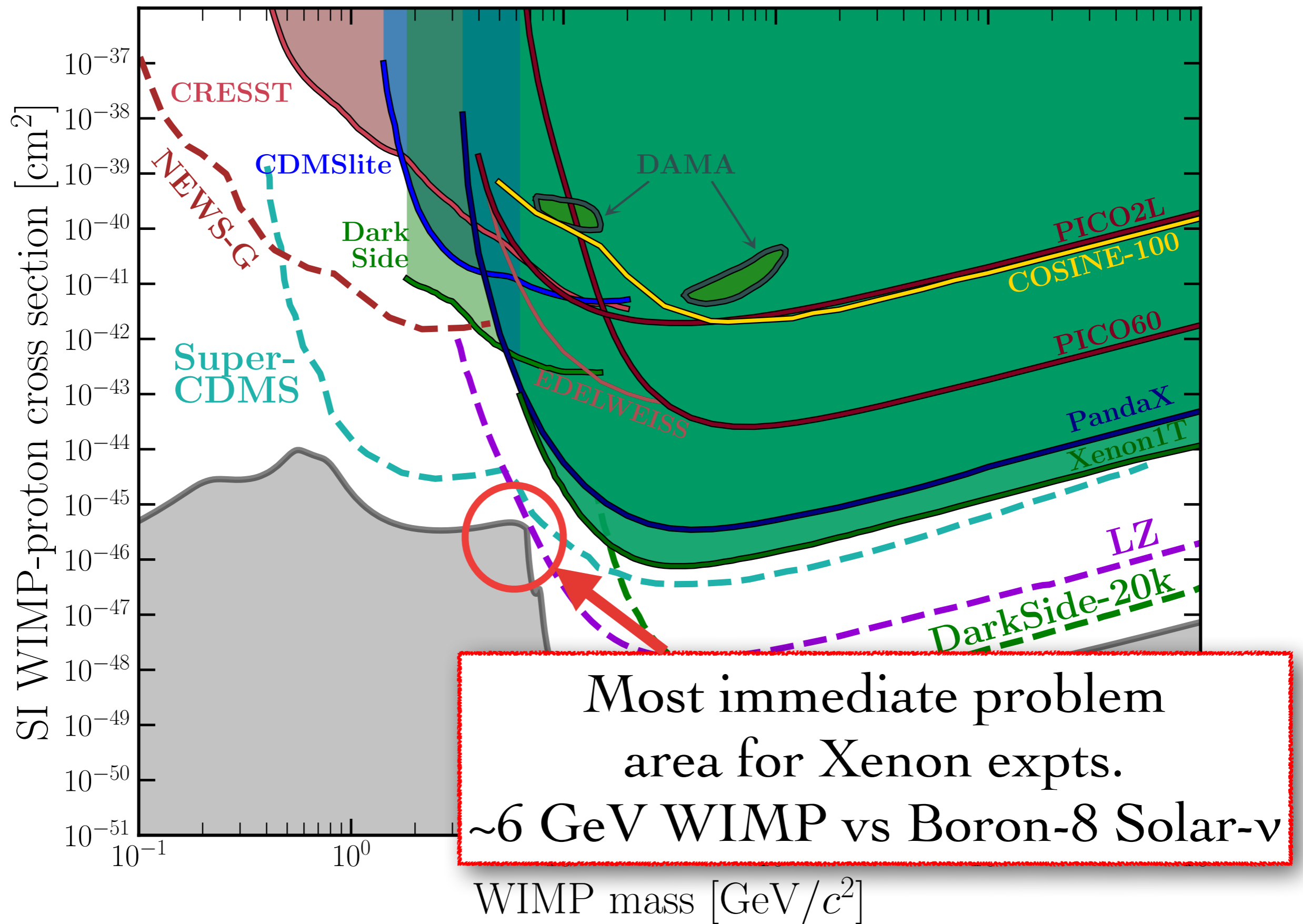
Ciaran O'Hare
University of Sydney



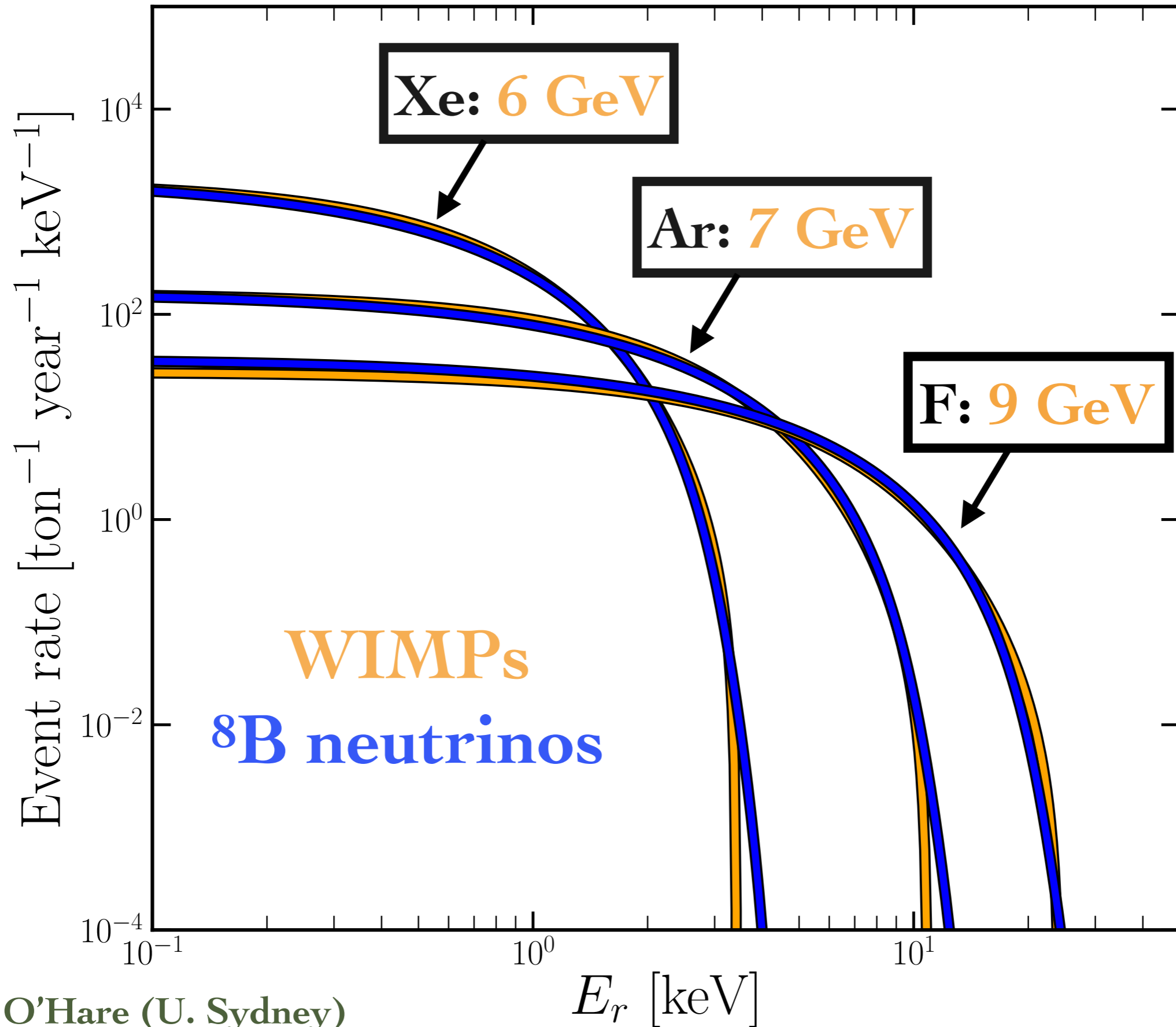
What: CYGNUS is a proto-collaboration aiming to determine the feasibility of building a dark matter experiment at the ton-scale that is able to measure the **directions** of recoiling nuclei

Why: A dark matter signal should point back to the constellation Cygnus. Directional information can be used to push the search for WIMP-dark matter **below** the neutrino floor

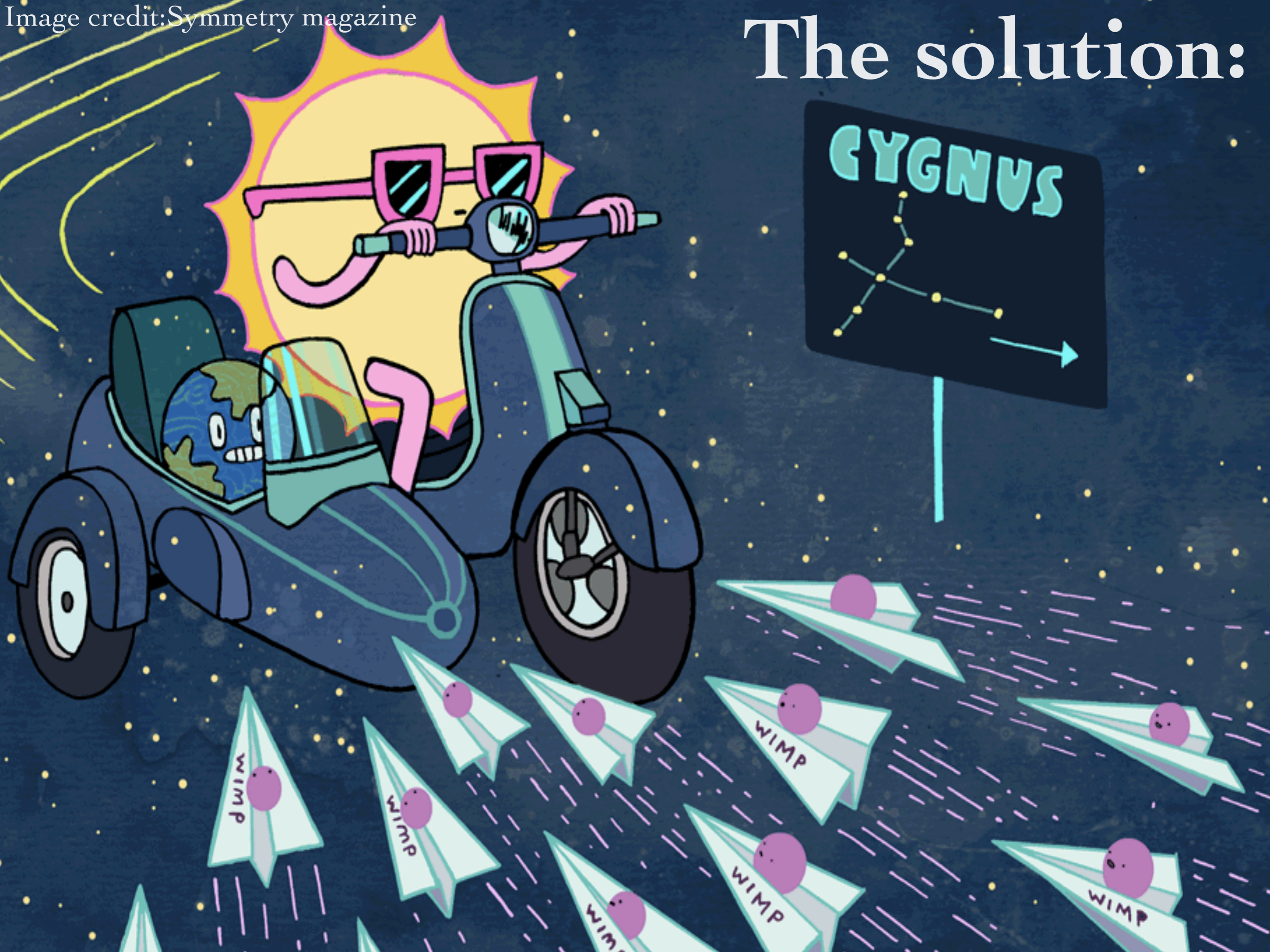




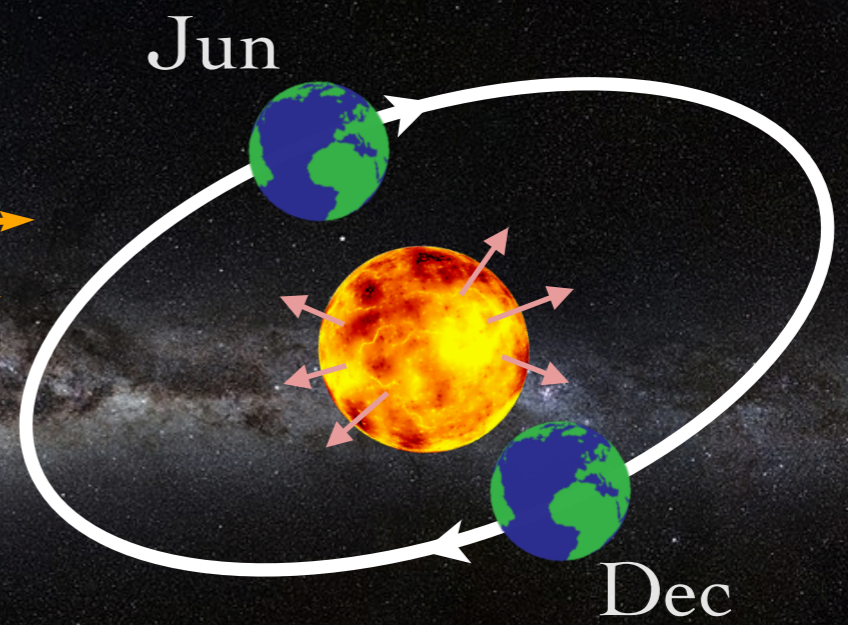
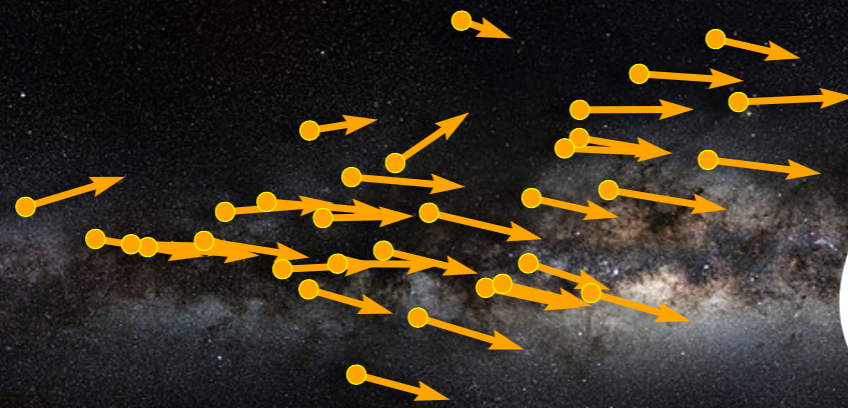
The problem:



The solution:

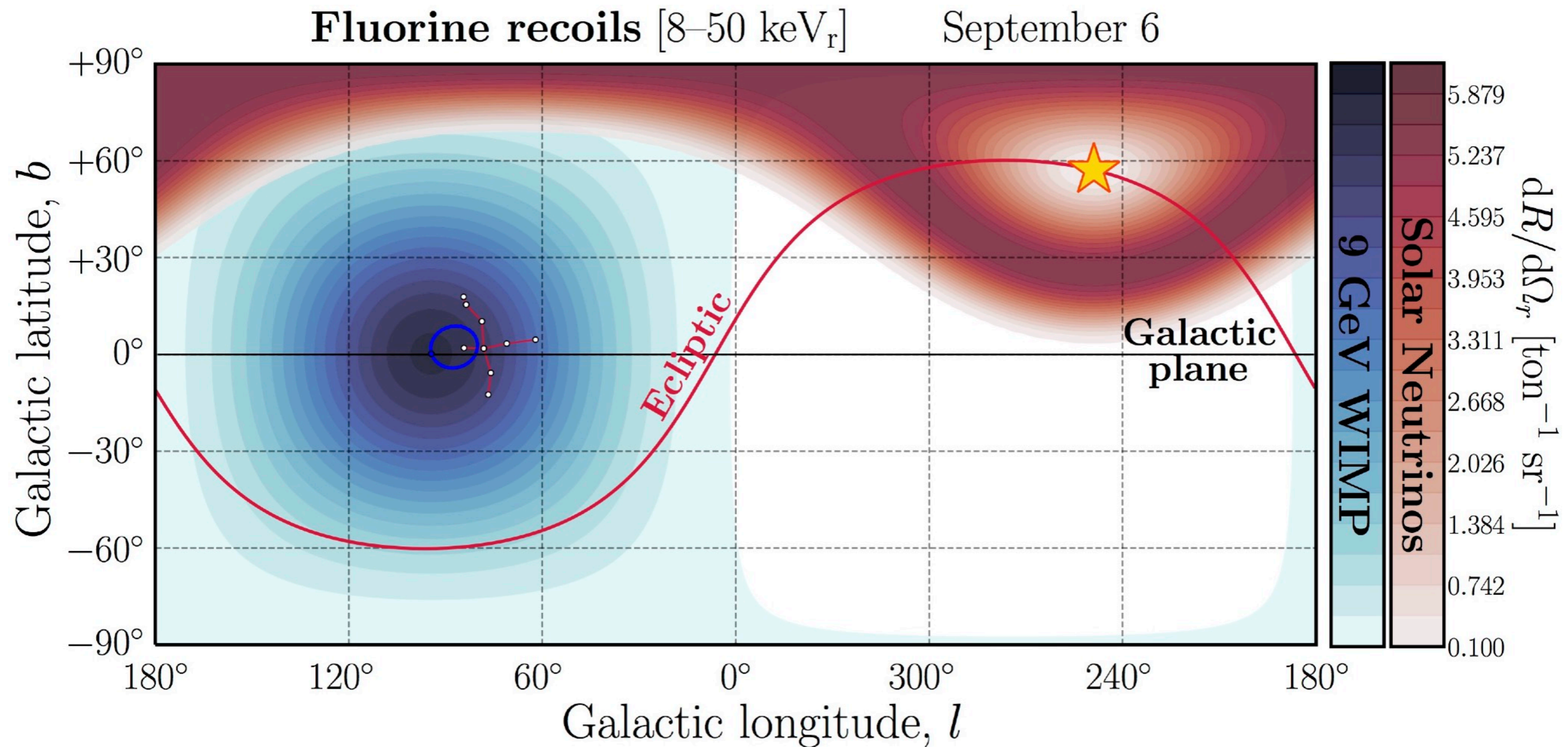


Cygnus

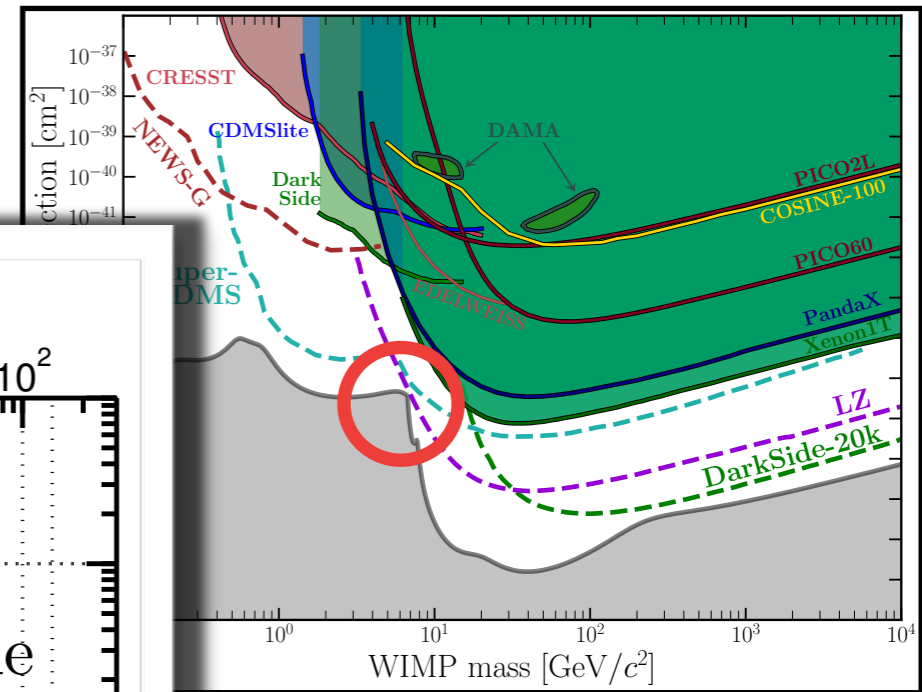
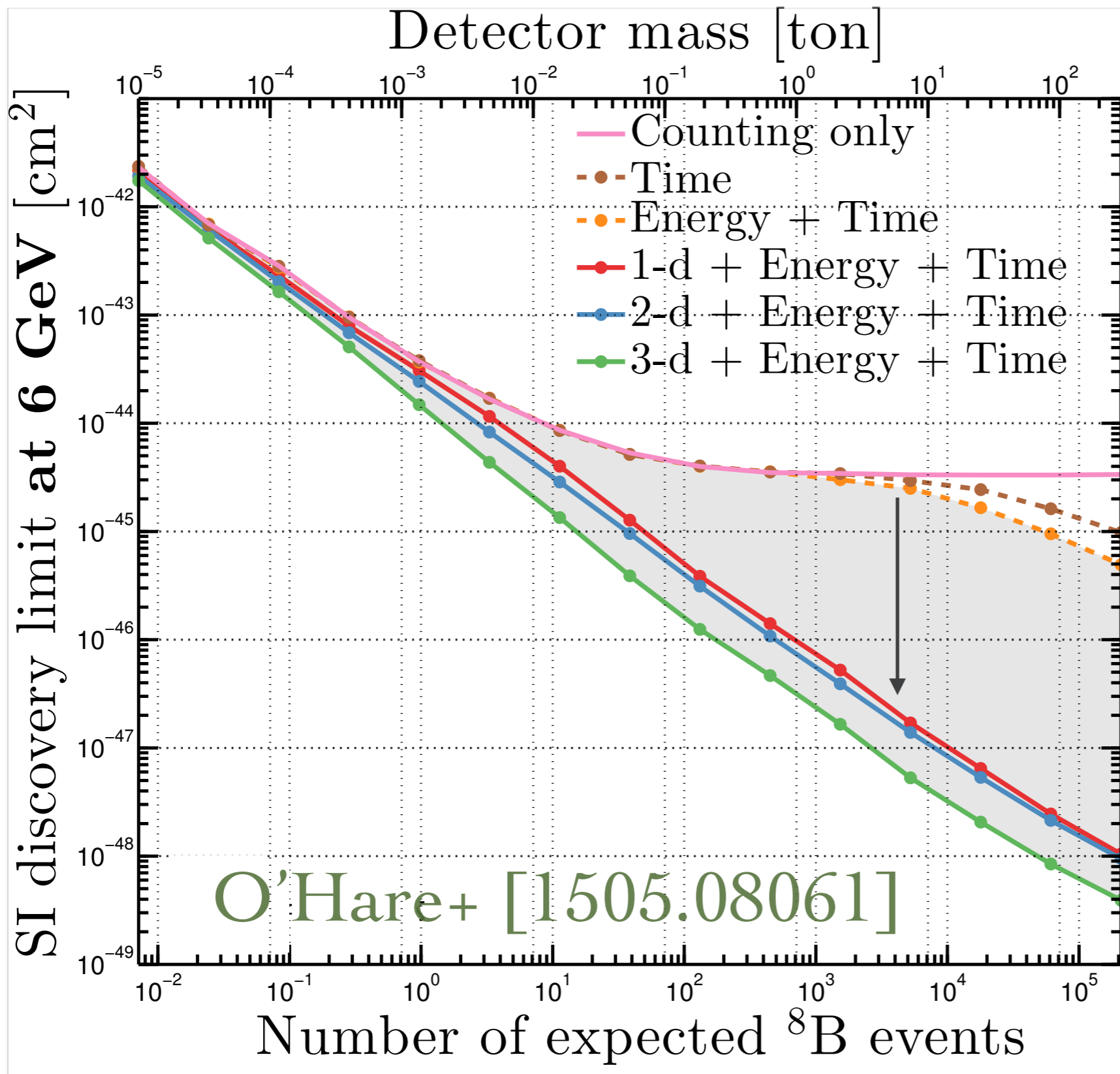


A dark matter signal will align with our galactic motion
→ point back towards Cygnus

Nothing other than dark matter will do this including **solar neutrinos...**



Subtracting the neutrino background



Directional info
powerful for
subtracting
Solar neutrinos

But so far only
studied under
idealised
conditions

CYGNUS

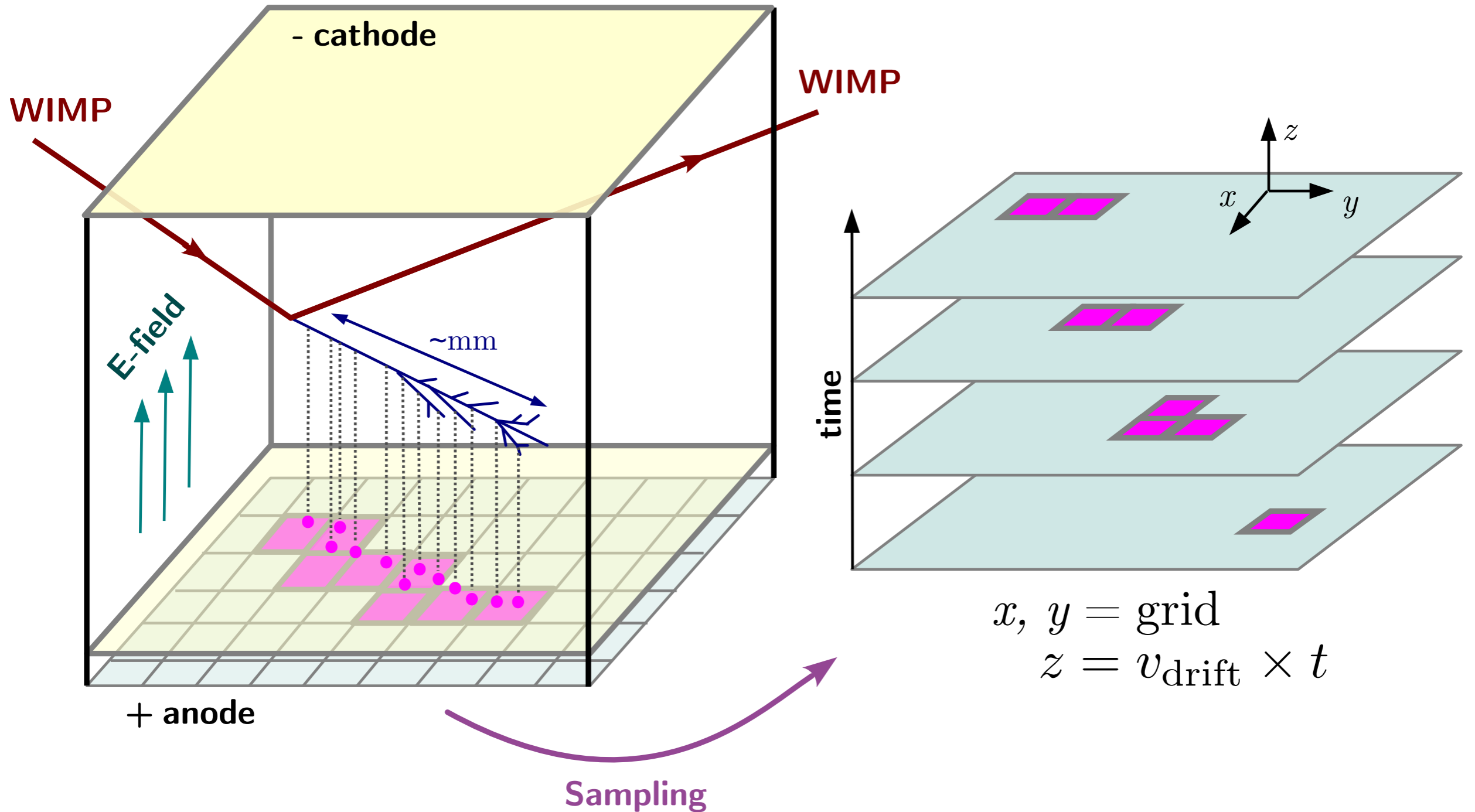
- **Proto-Collaboration:** >50 members from US, UK, Aus., Japan, Italy, Spain, China
- **Focus:** Ton-scale gas time projection chamber (TPC)
- **Primary goal:** WIMP discovery below the neutrino floor
- **Secondary goal:** Directional detection of CE ν NS with Solar neutrinos
- **Tertiary goals:** study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



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

E. Baracchini,^{1,2,3} P. Barbeau,⁴ J. B. R. Battat,⁵ B. Crow,⁶ C. Deaconu,⁷ C. Eldridge,⁸
A. C. Ezeribe,⁸ D. Loomba,⁹ W. A. Lynch,⁸ K. J. Mack,¹⁰ K. Miuchi,¹¹ N. S. Phan,¹²
C. A. J. O'Hare,^{13,14} K. Scholberg,⁴ N. J. C. Spooner,⁸ T. N. Thorpe,⁶ and S. E. Vahsen⁶

Gas time projection chamber (TPC)



CYGNUS TPC: Basic Parameters

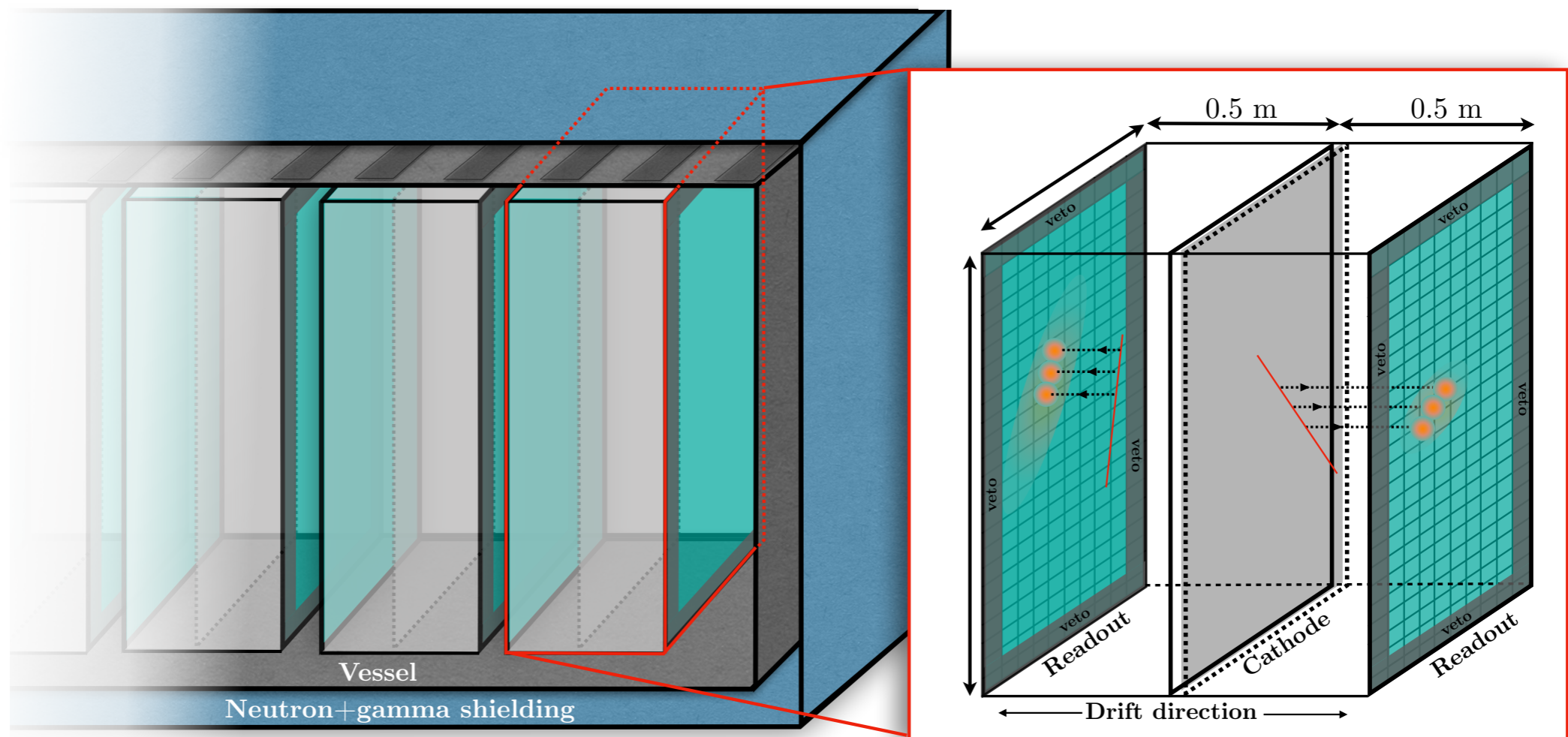
1000 m³ of He:SF₆ at atmospheric pressure and temperature

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-Nm³

CYGNUS-10 m³ module



Target gas mixture: 755:5 He+SF₆ at 1 atm.

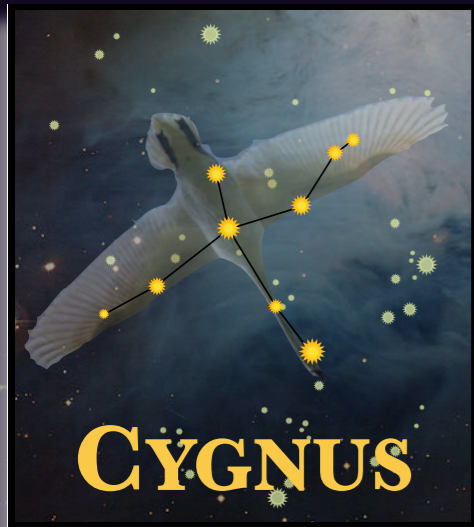
Why SF₆?

- ☑ **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)
- ☑ **¹⁹F 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



CYGNUS-10
Boulby, UK

CYGNUS-KM
Kamioka, Japan

CYGNUS-HD10
Lead, South Dakota

CYGNUS
Gran Sasso, Italy

CYGNUS-OZ
Stawell, Aus.

CYGNUS-Andes
Chile/Argentina

Possible underground sites

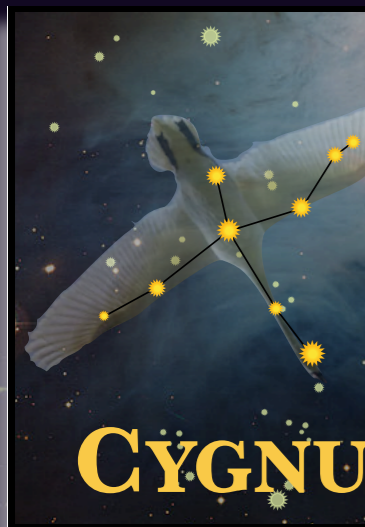
CYGNNO project

He:CF₄ electron drift TPC

triple thin GEM+optical readout

Already in development by Italian group,

See: web.infn.it/cygnus/cygnno/



CYGNUS-HD10
Lead, South Dakota

CYGNNO
Gran Sasso, Italy

CYGNUS-OZ
Stawell, Aus.

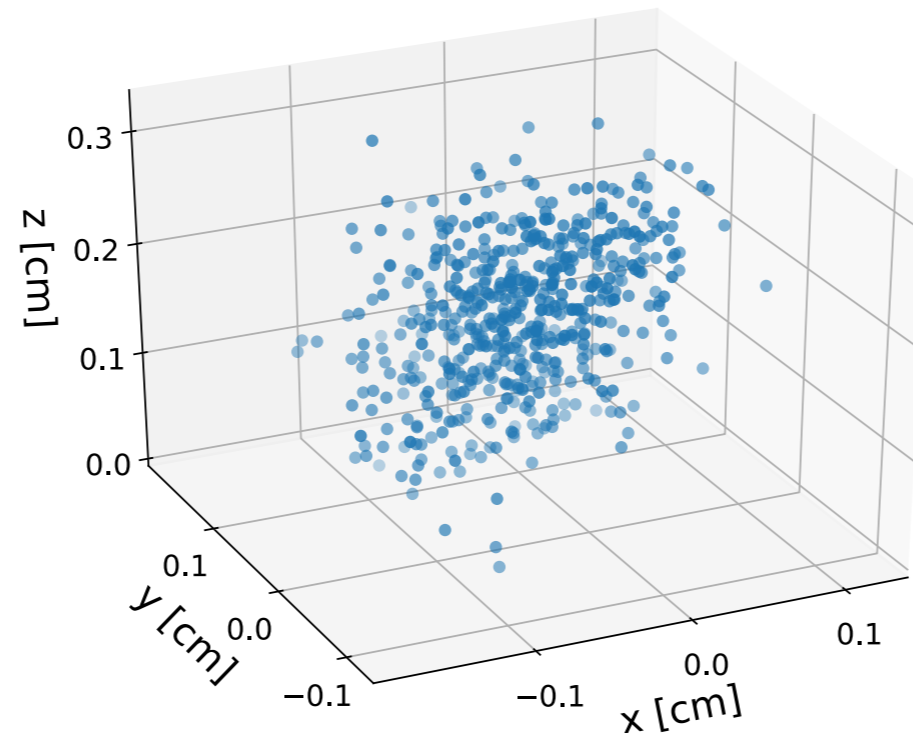
CYGNUS-Andes
Chile/Argentina

Readout technologies

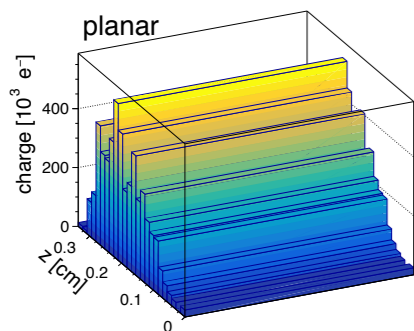
Important advancement in this study

→ ground-up simulation of six readout technologies for reconstructing low energy electron/nuclear recoils

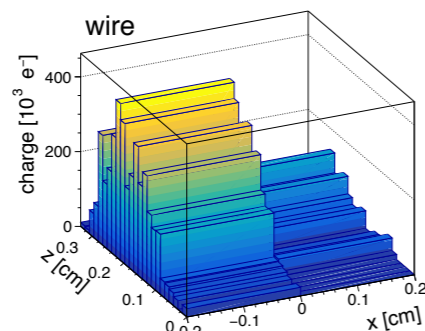
Recoil track



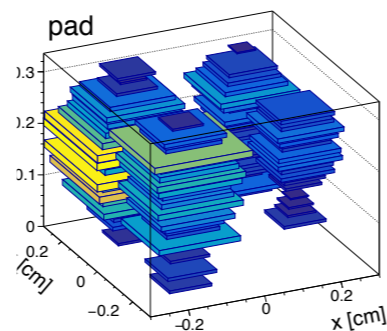
Planar



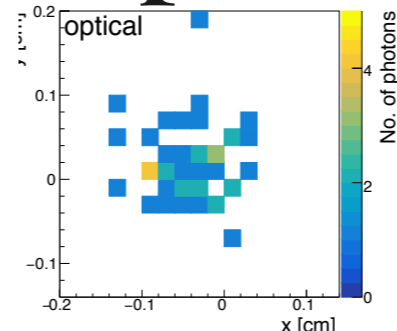
Wire



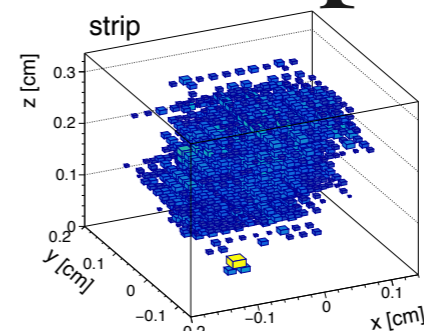
Pad



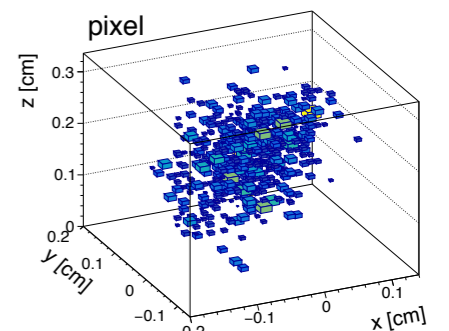
Optical



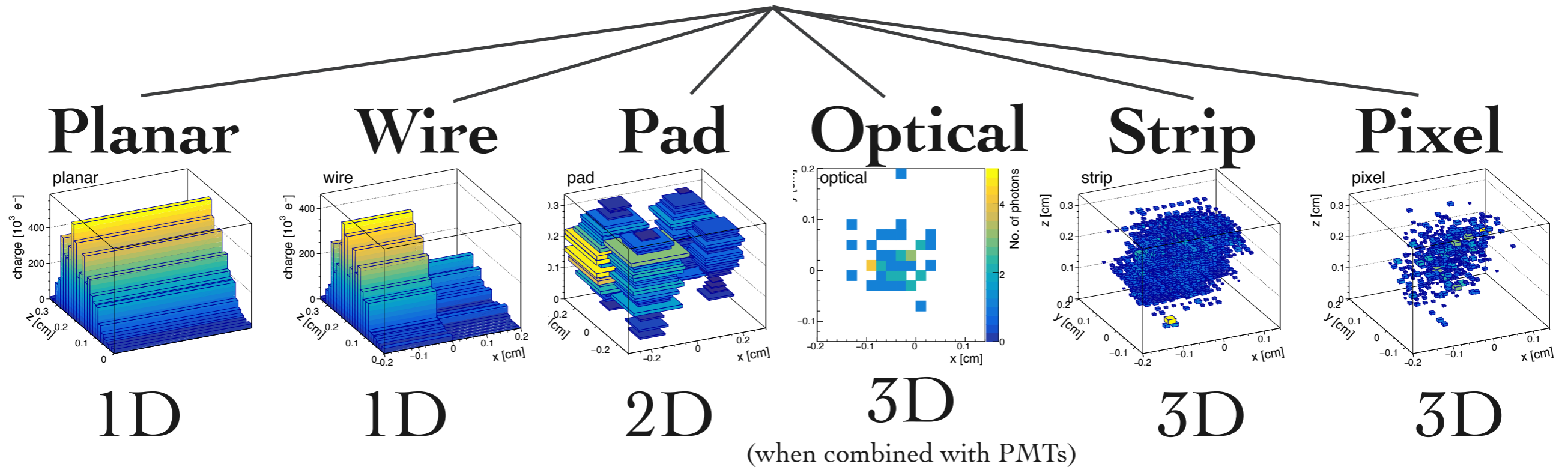
Strip



Pixel



Readout technologies

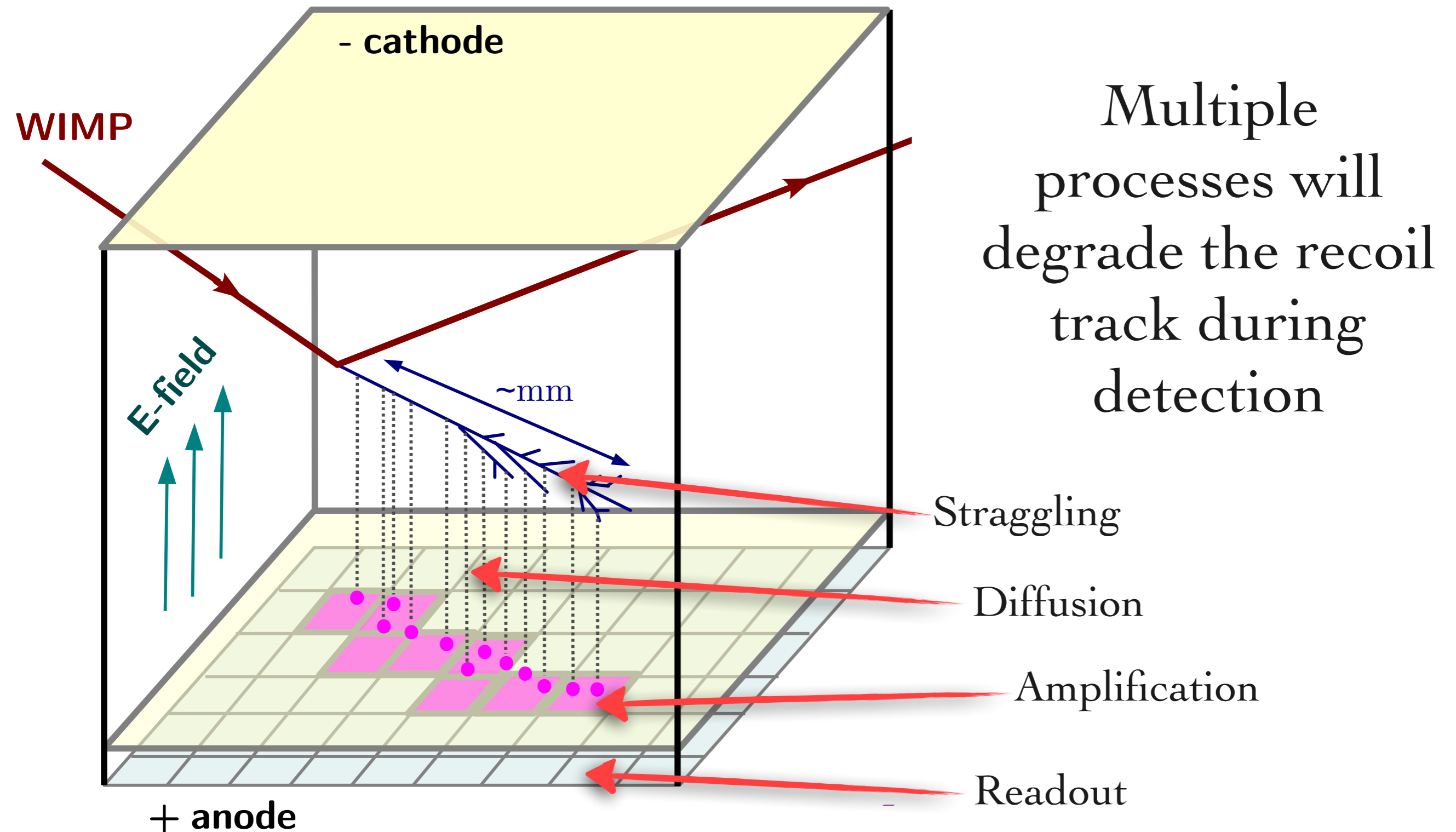


← Simplest readouts
→ Worst directional
sensitivity but
lower cost

Most complex readouts
→ Best directional
sensitivity but
higher cost

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

Measuring tracks

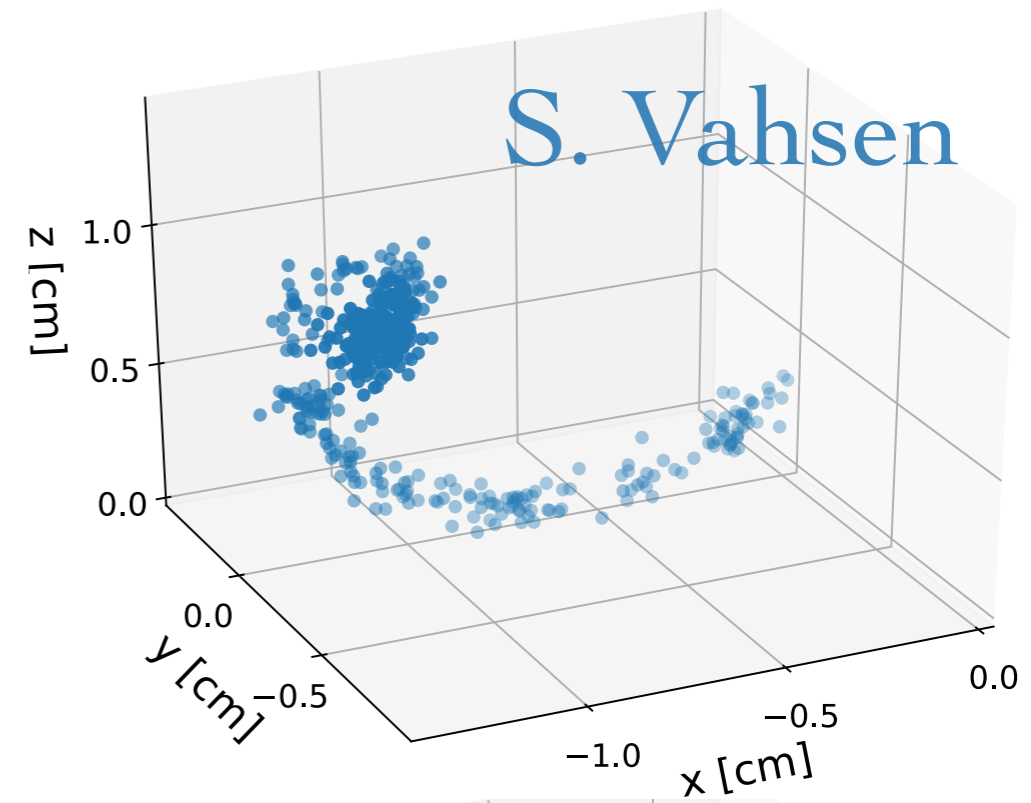
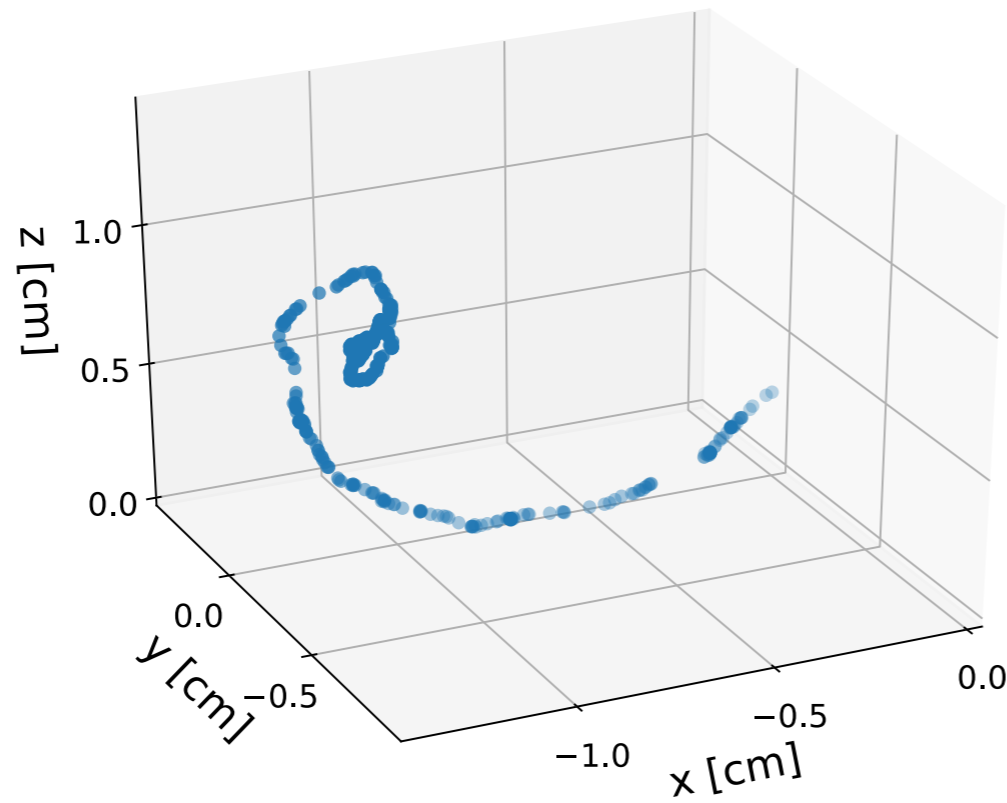


Recoil tracks (in He+SF₆ at 1 atm)

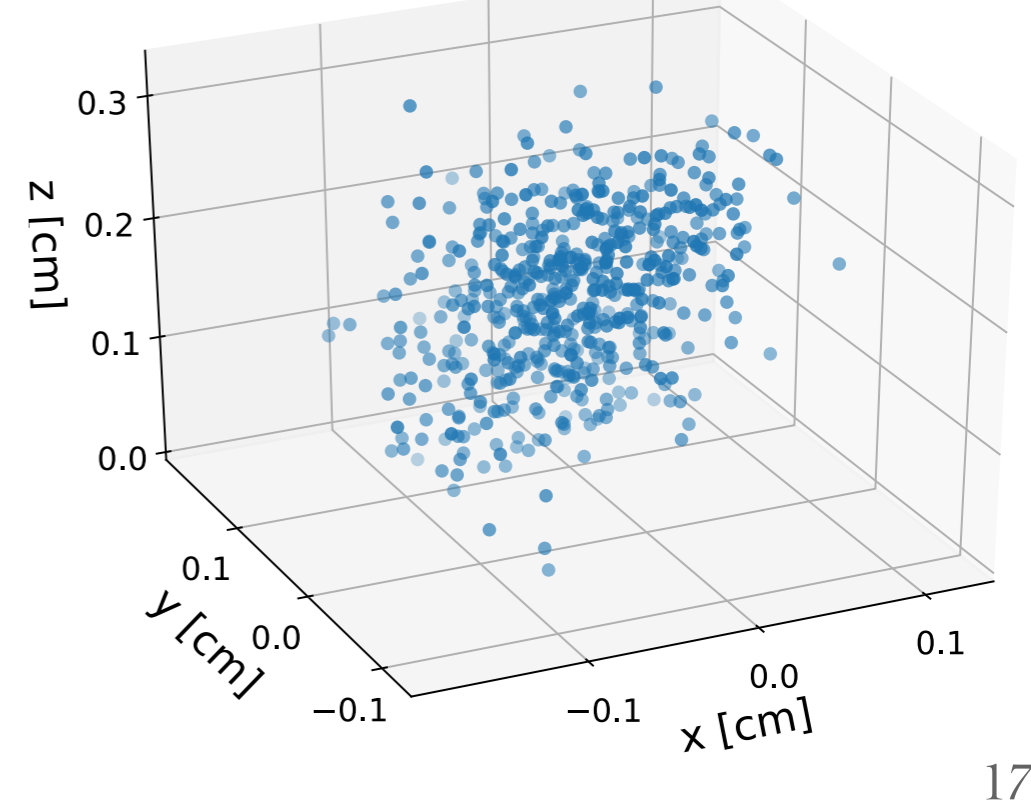
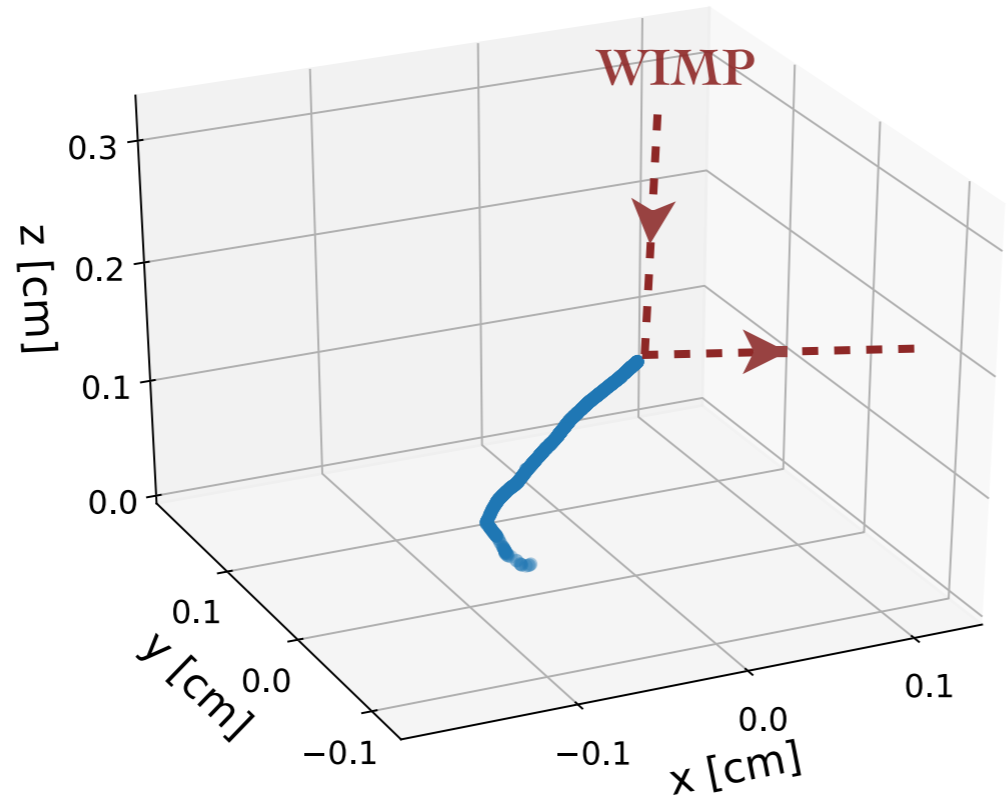
Before drift

After 25 cm drift

Electron:
20 keV

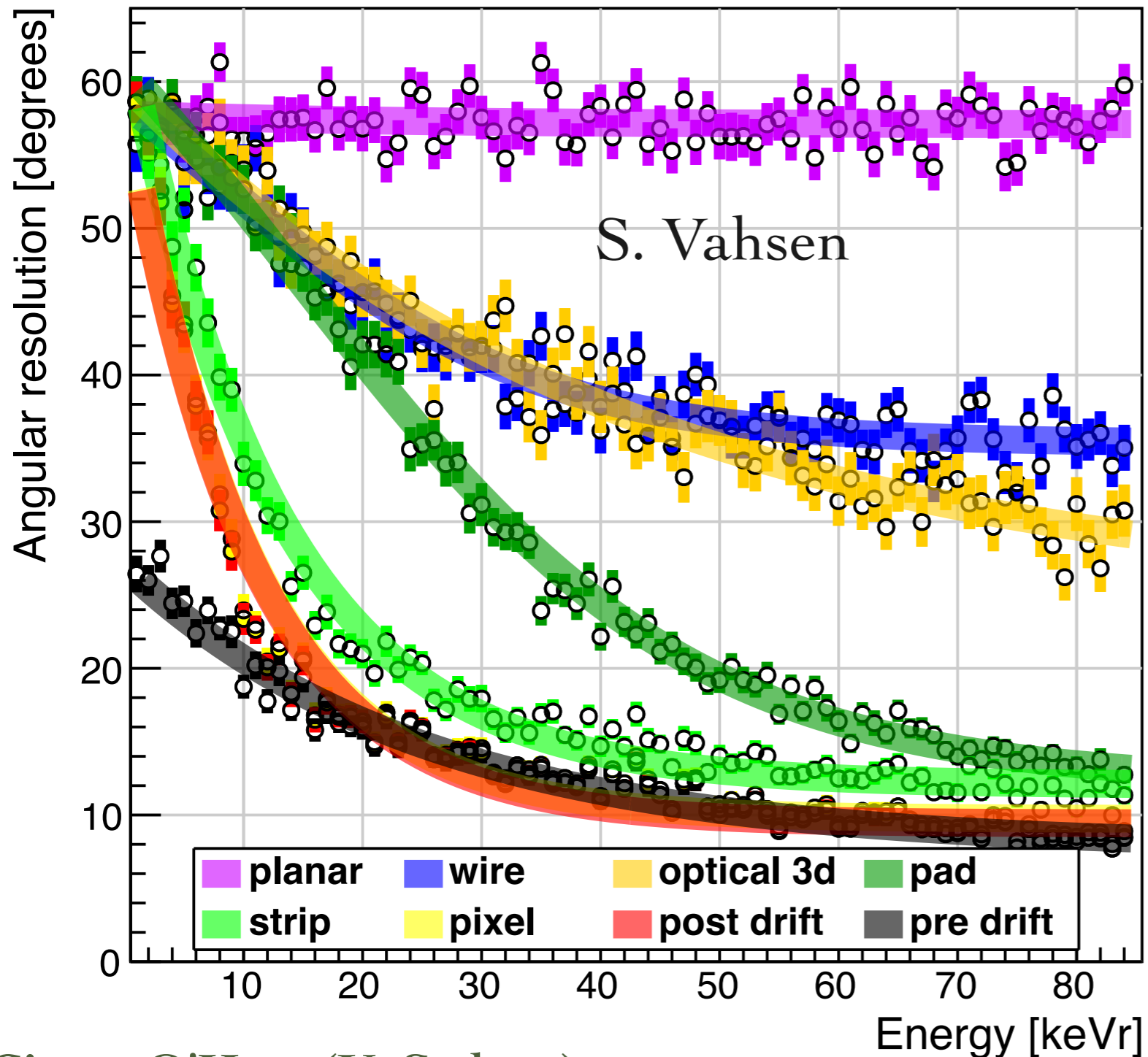


He nucleus:
(25 keVr)



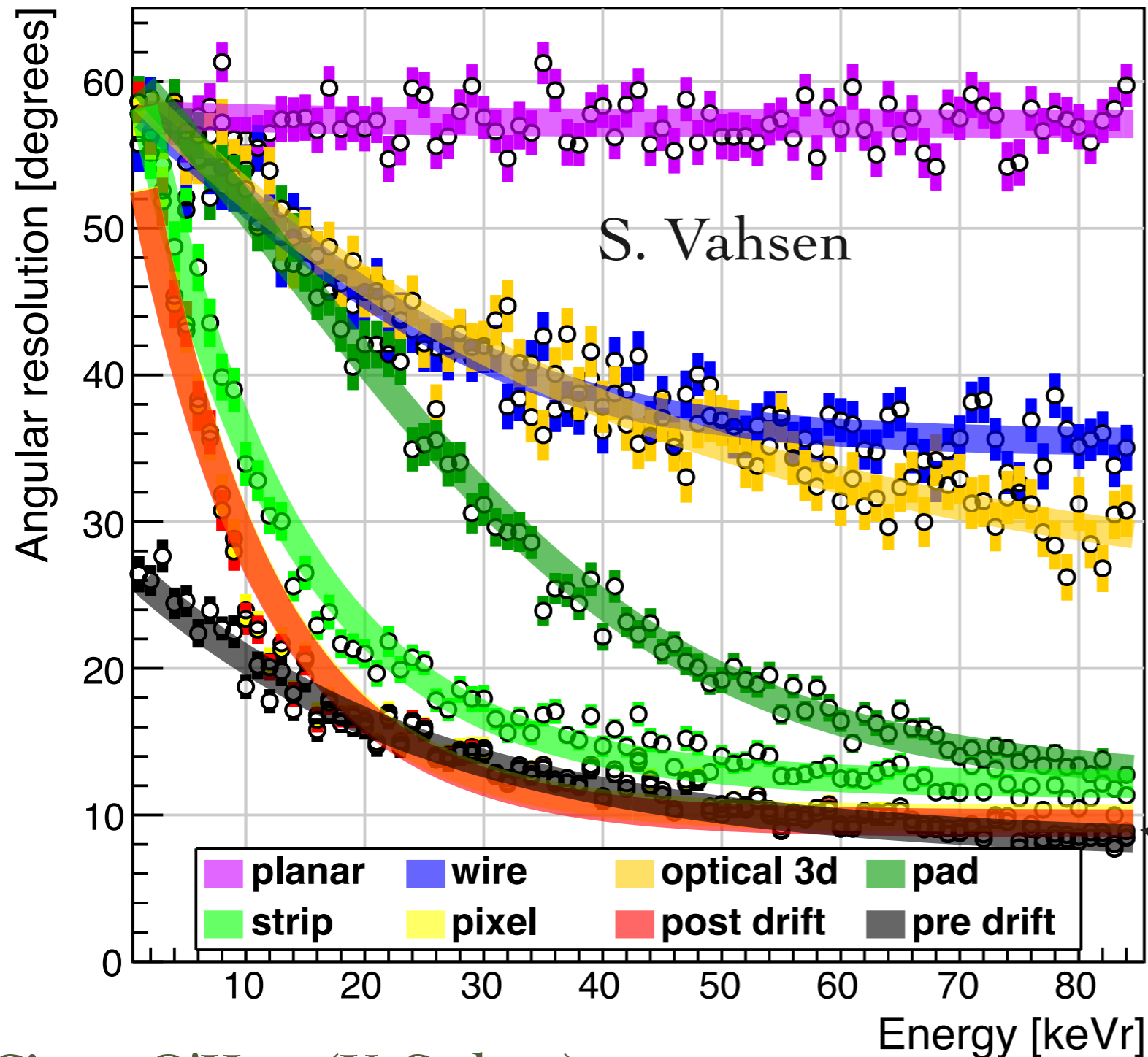
Angular resolution

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



Angular resolution

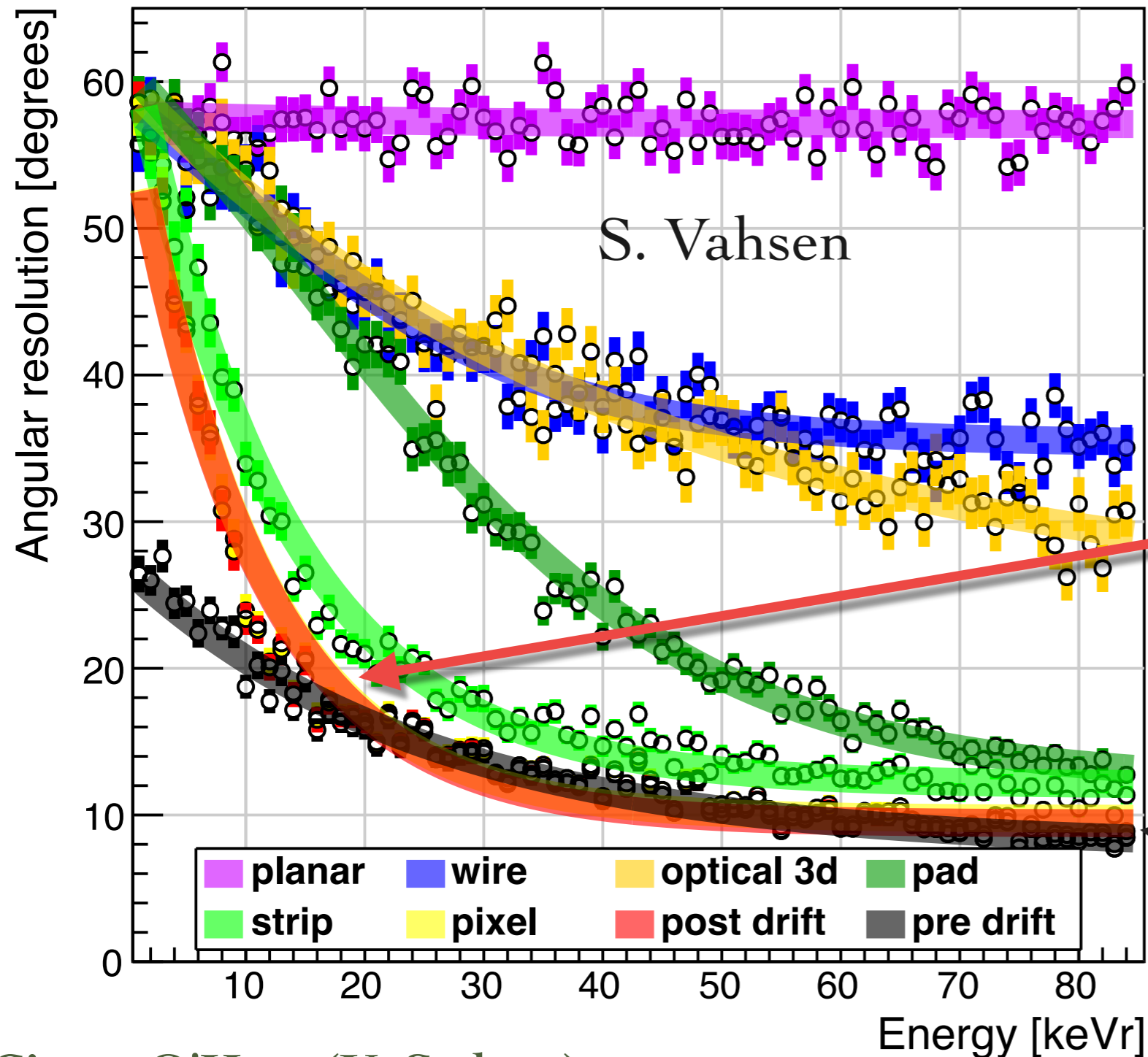
Dispersion in measured angles relative to initial recoil direction (=1 rad if there is no correlation and angles are isotropic)



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

Angular resolution

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

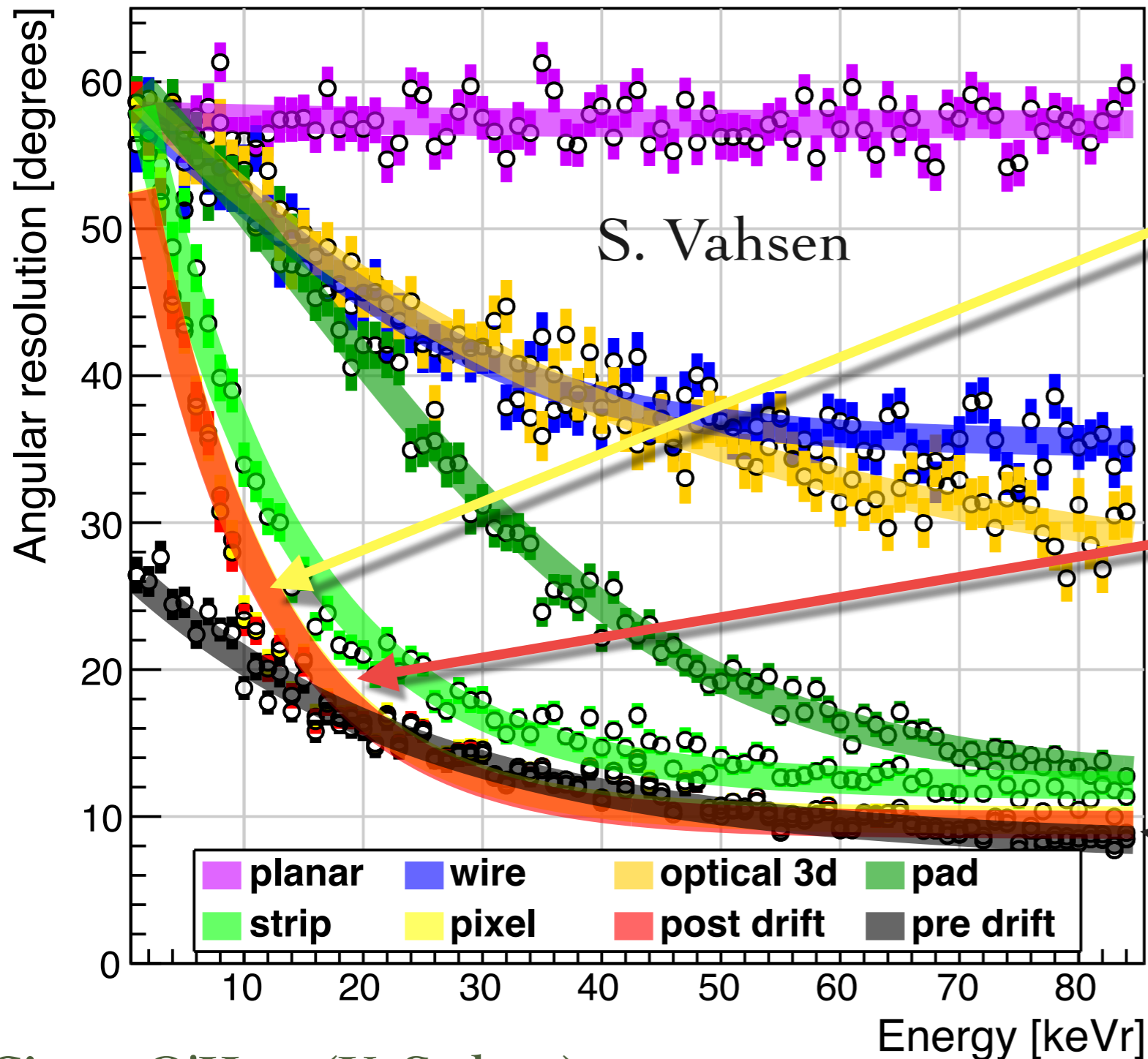


Post-drift: directionality washed out by diffusion especially for low energy tracks

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

Angular resolution

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



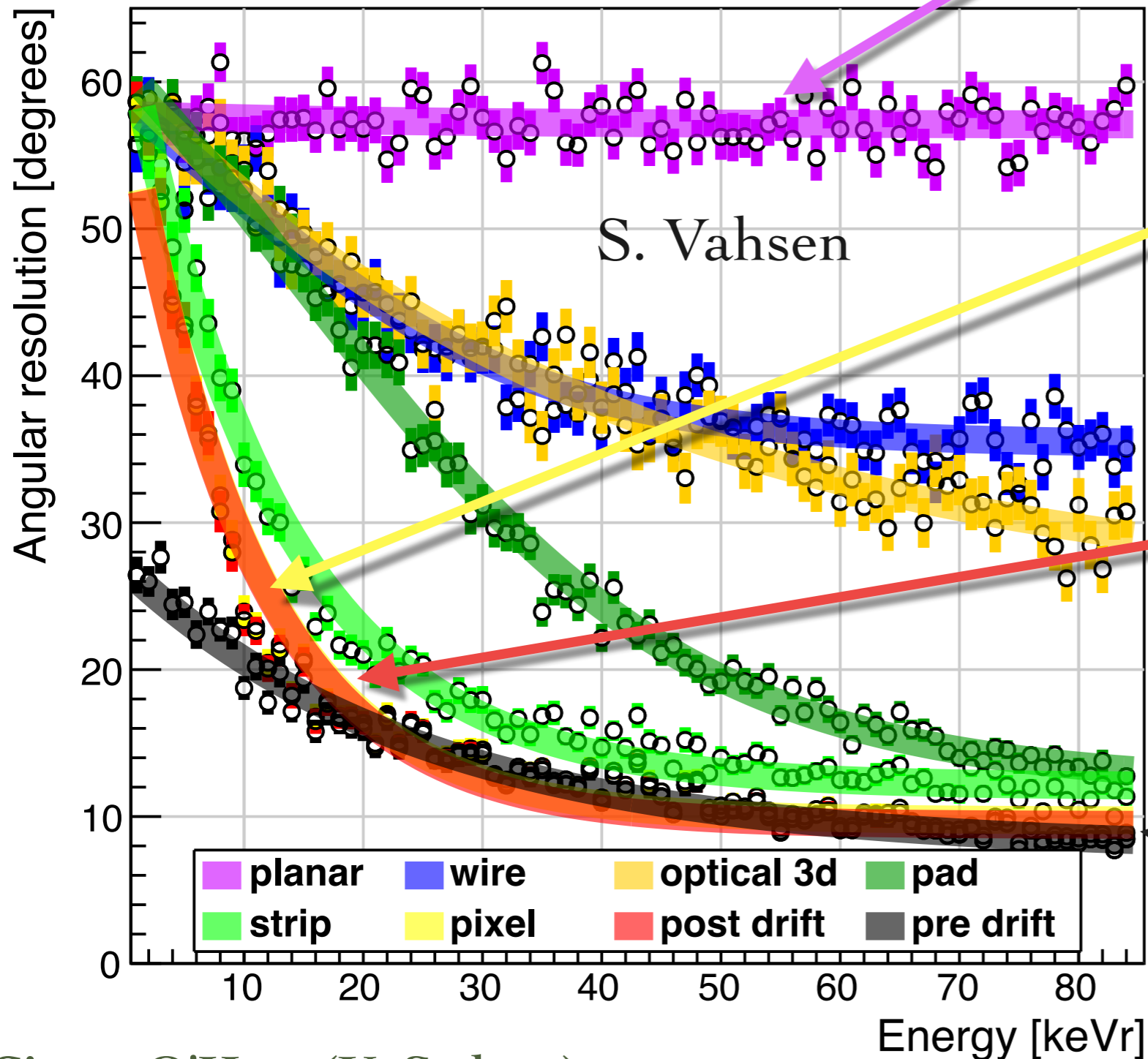
Pixel readout performs as good as post-drift → almost no loss in directionality after charge readout (promising!)

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

Angular resolution

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

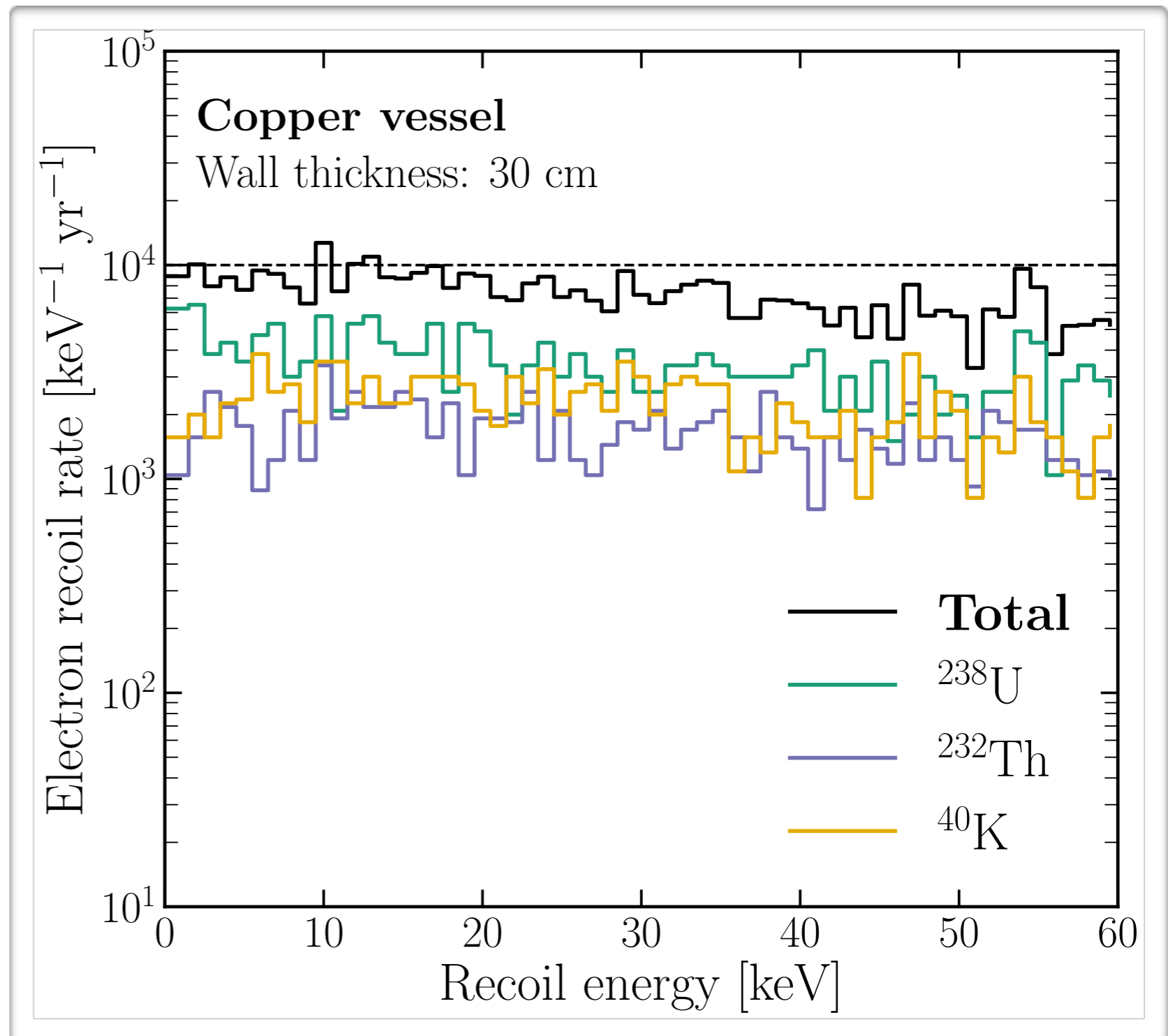
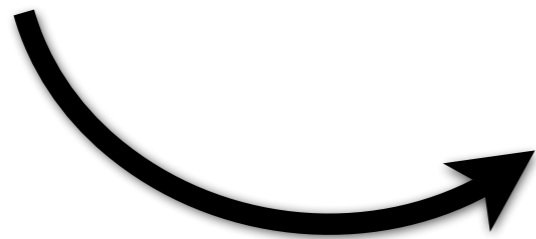
Post-drift: directionality washed out by diffusion especially for low energy tracks

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

Backgrounds

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

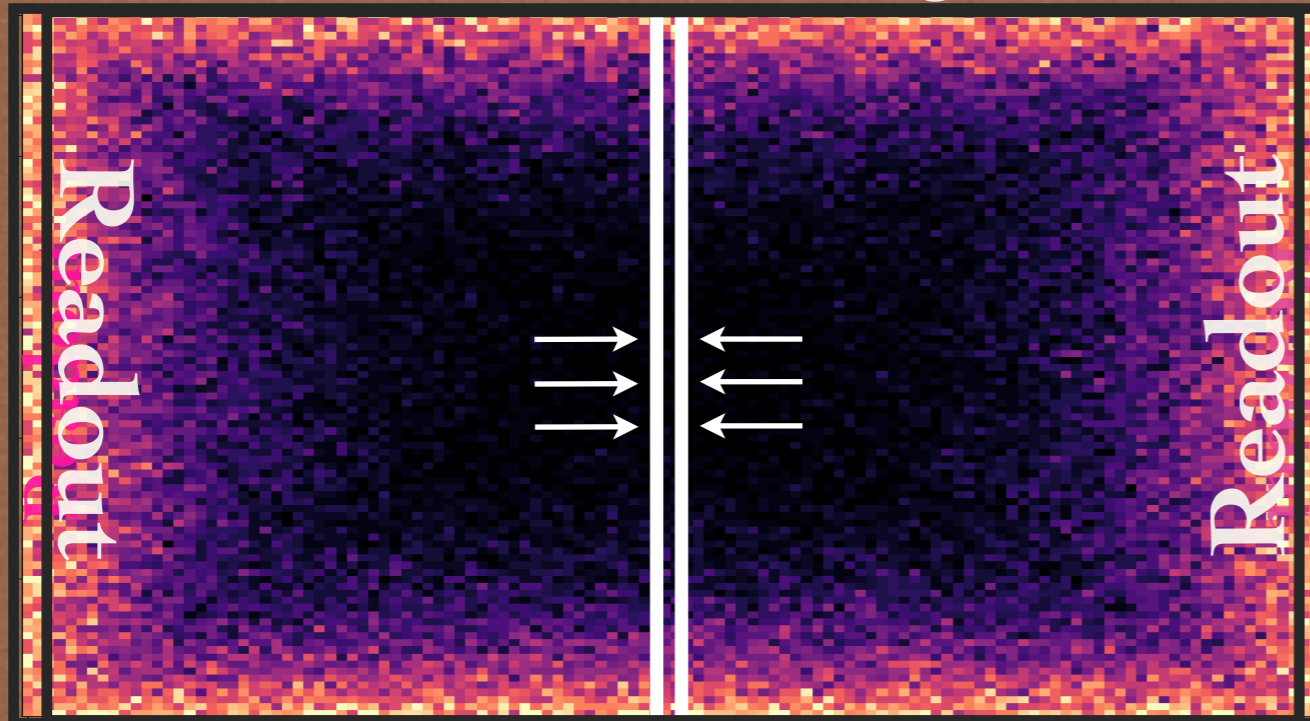
Full Monte Carlo
background study
will be in paper
e.g. Vessel ER
background



Backgrounds

Water shielding/veto

Vessel + Field cage



Backgrounds

μ

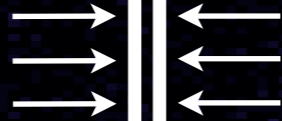
Rock: ~ 75 cm water shielding
(also works as active veto)

n

Water shielding/veto

Vessel + Field cage

Readout



Readout

γ

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 for the TPC on its own

Water shielding/veto

Vessel + Field cage

Readout

Readout

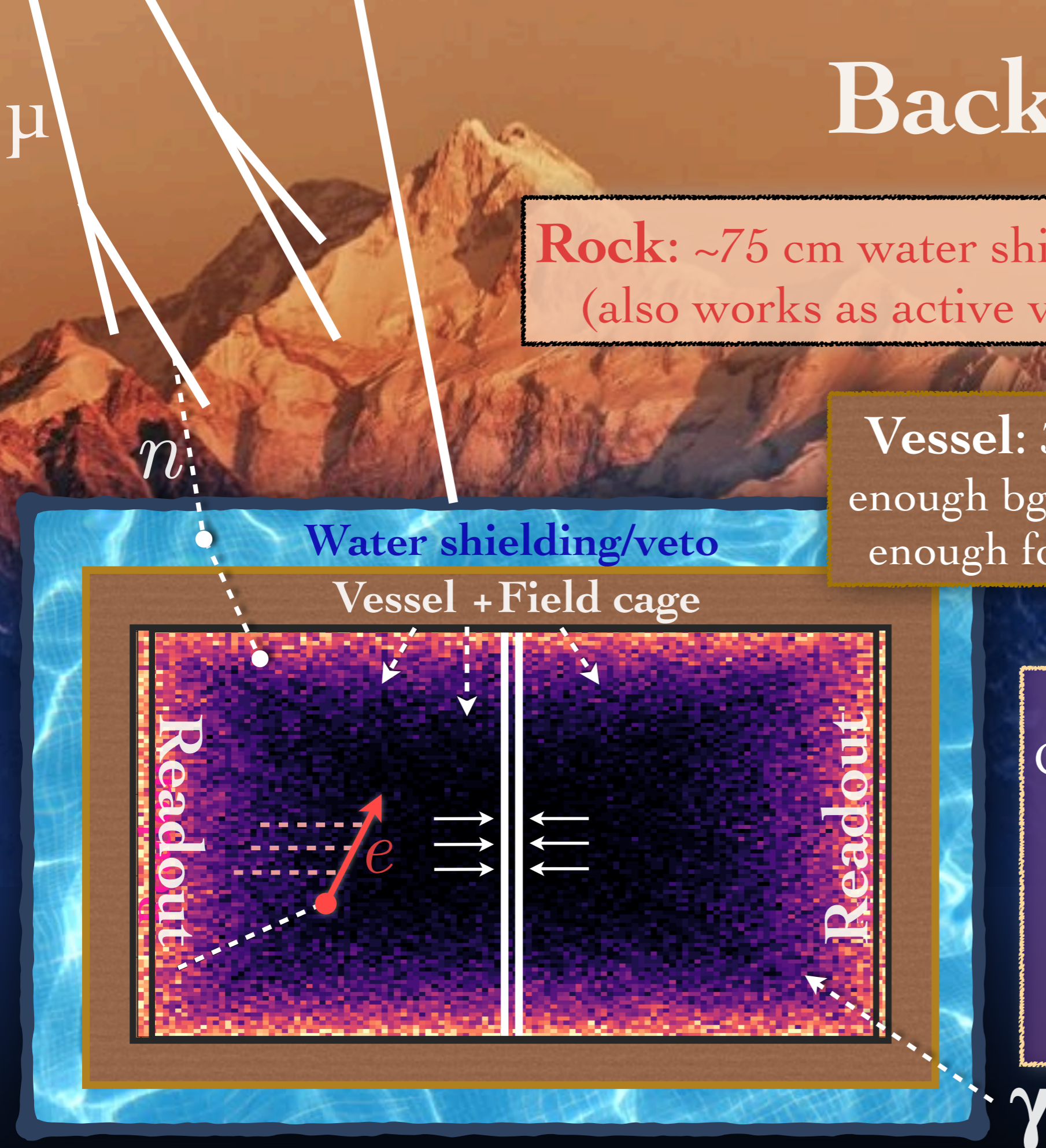
γ

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 for the TPC on its own

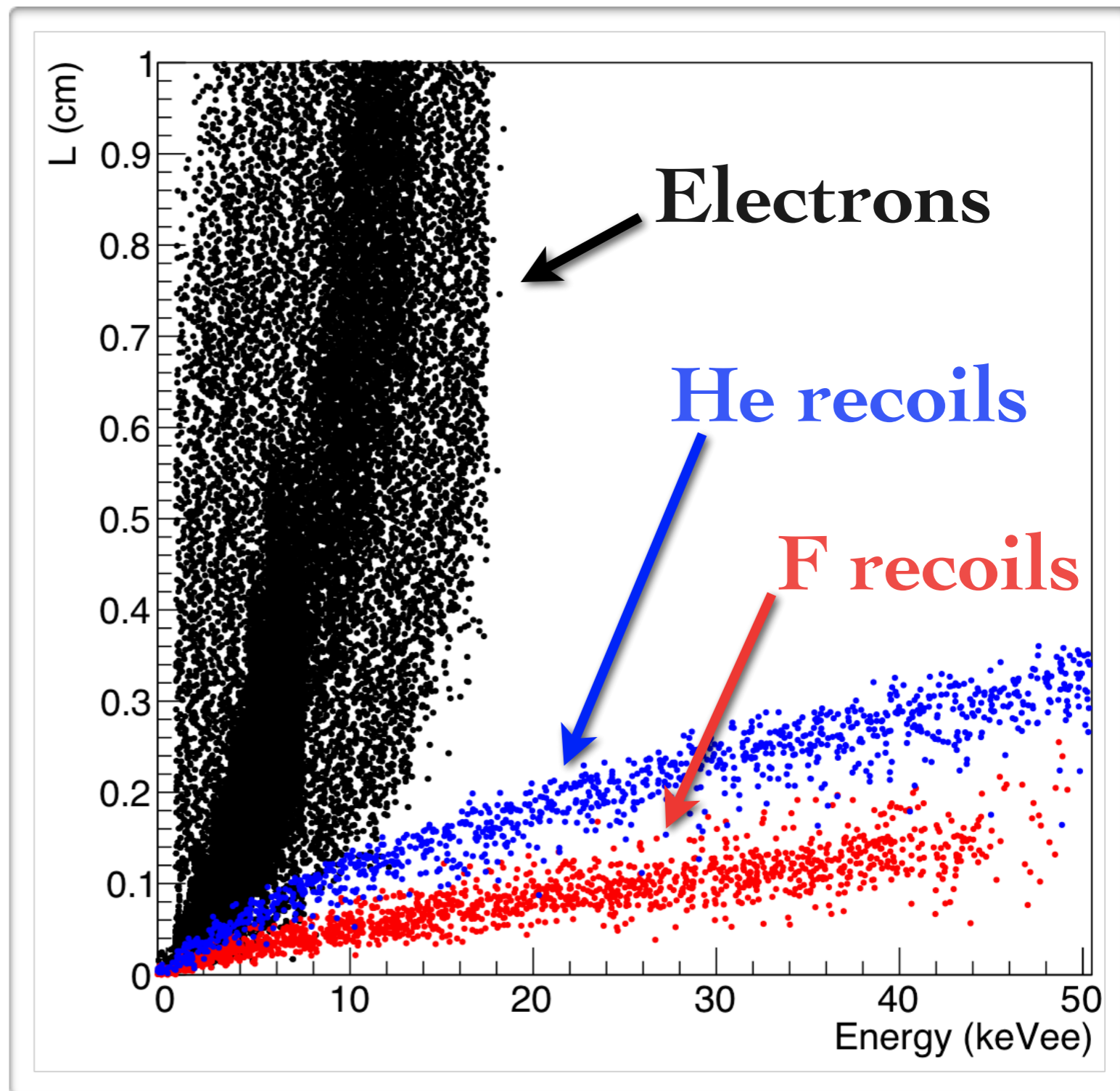
Readout/Internal bg:
Close, but not there yet, need more radiopurity screening of certain component materials e.g. polyimide, silicon, kapton, ceramic



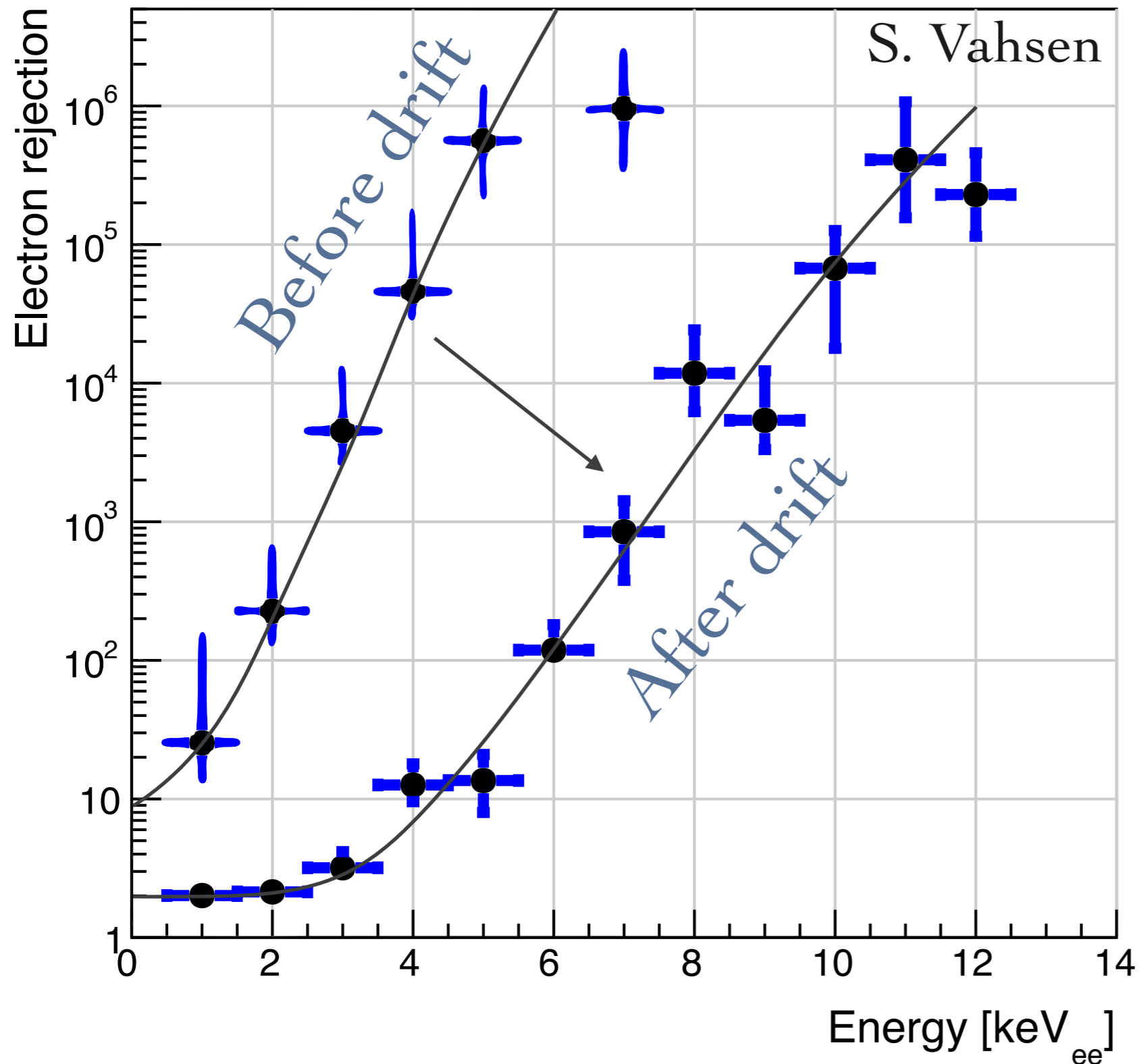
Electron discrimination

- Electrons have much longer tracks than nuclei so can discriminate based on this info.
- Track lengths for recoils in He+SF₆ at 1 atm:

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



Energy threshold \rightarrow electron rejection $> 90\%$

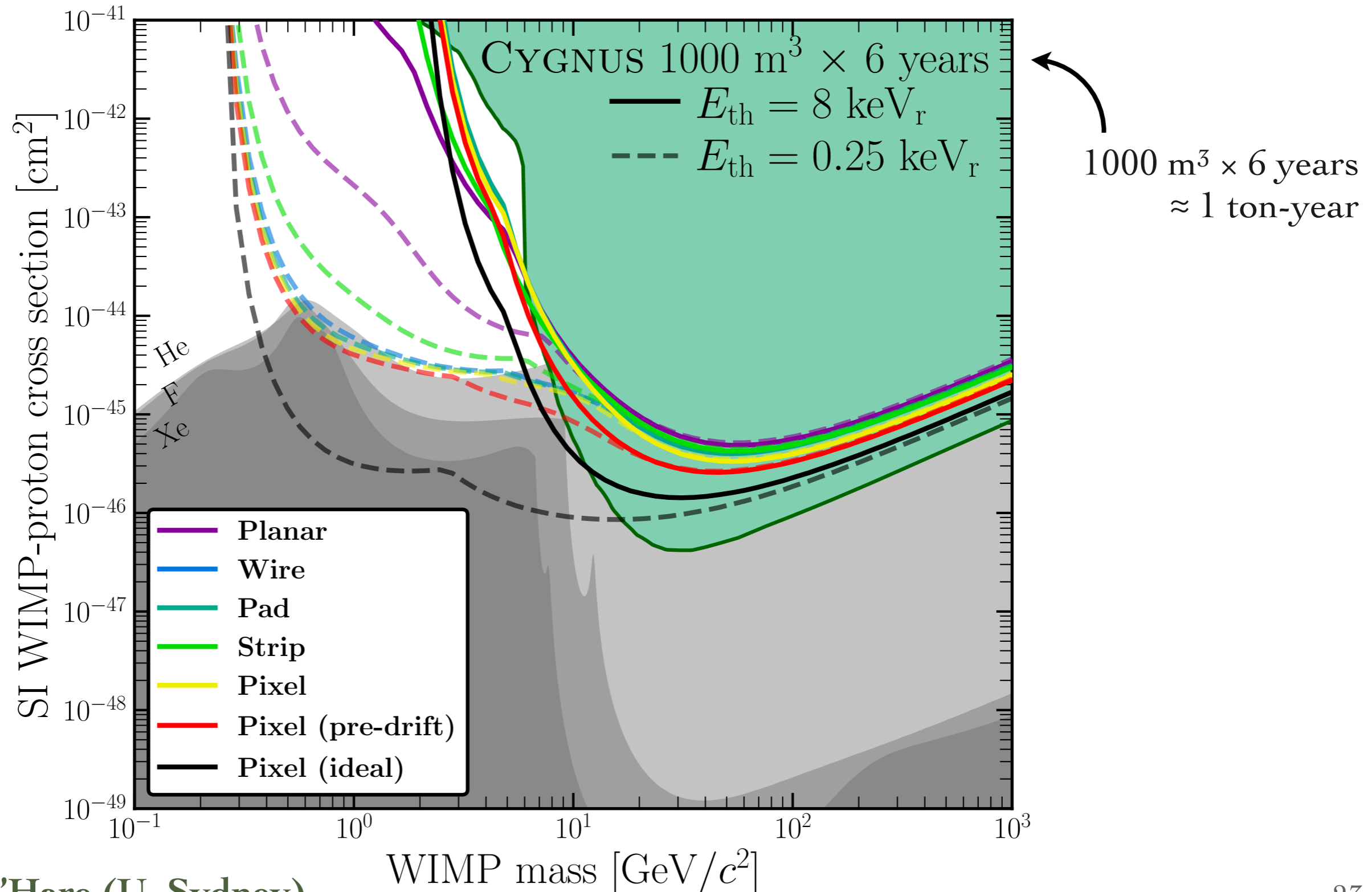


- **8 keVr** is feasible already with just track length vs energy (previous slide)
- But this is at the very tail of the ⁸B neutrino recoil spectrum. We should be able to improve this in the future.

WIMP reach: spin independent (SI-nucleon)

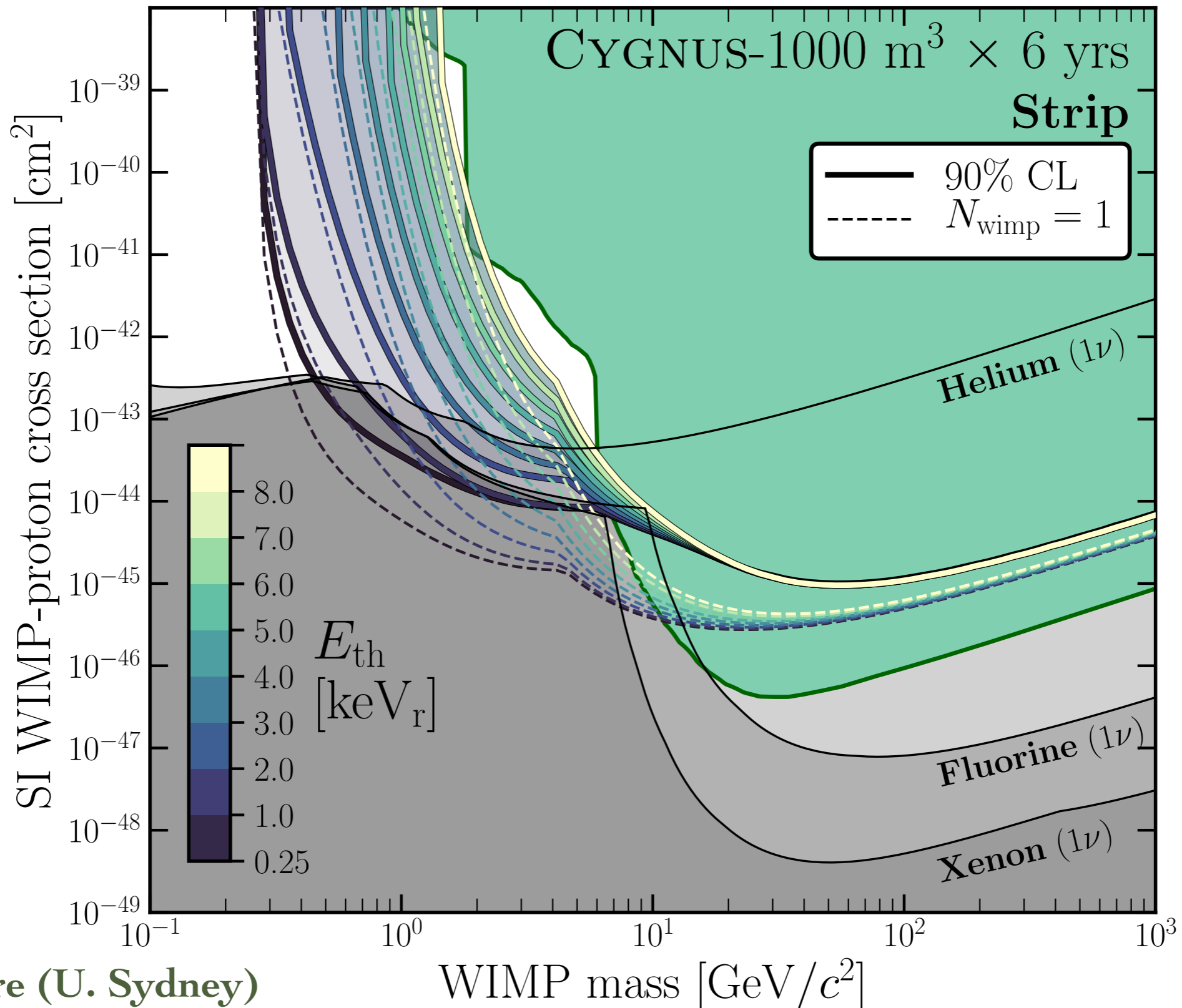
(90% CL exclusion of WIMP hypothesis under neutrino background)

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

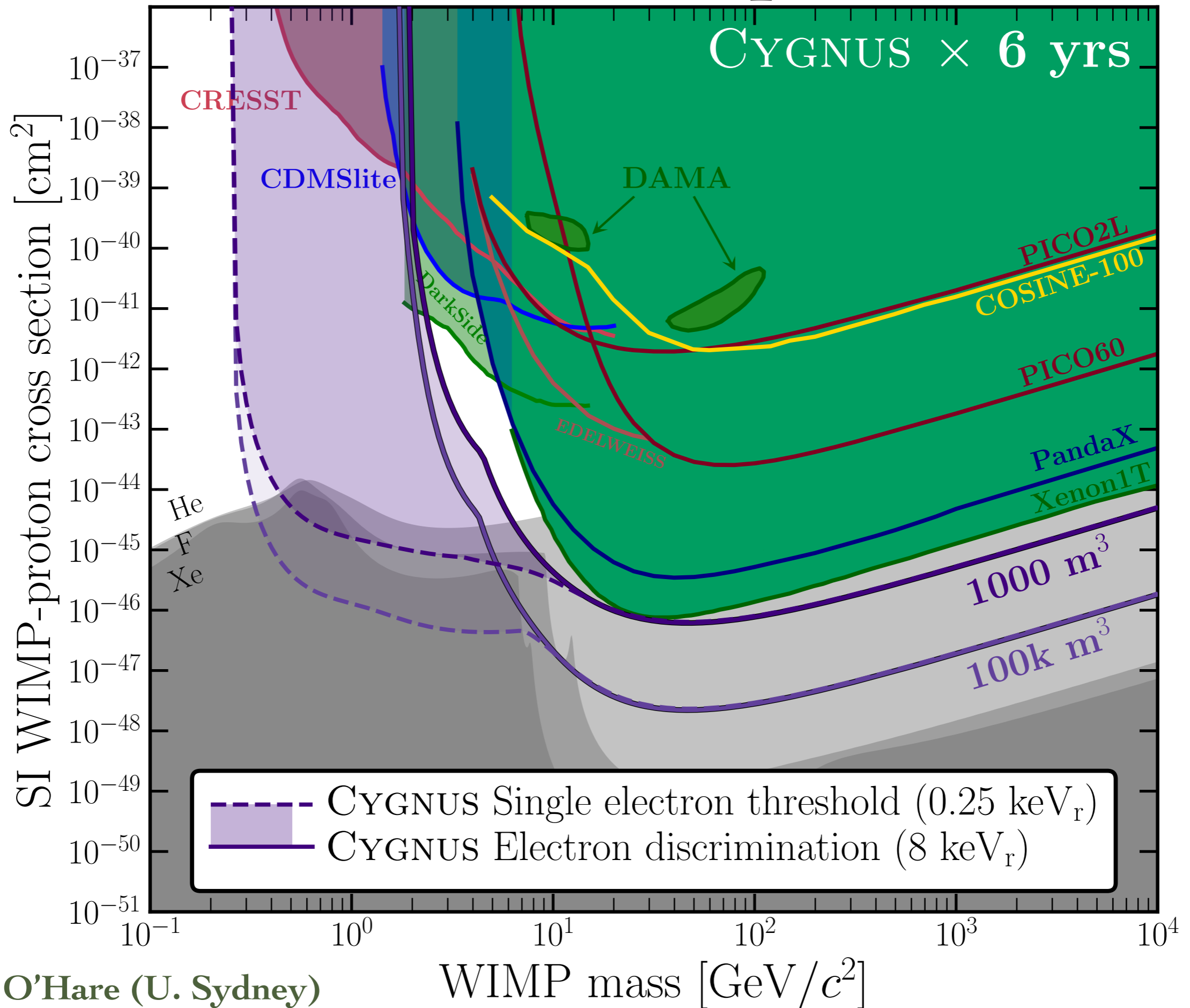


μ -PIC (strip) readout currently looks the best in terms of cost vs. WIMP reach

A closer look at dependence on threshold:



Headline plot



Conclusions

- Cygnus aims to be the first experiment with DM discovery reach below the neutrino floor
- End goal: $>1000 \text{ m}^3$ gas-TPC
- With currently available readout techs. it seems reasonable with further optimisation to get down to $<8 \text{ keV}_r$ with:
 - Angular resolution $<30^\circ$
 - HT recognition $>75\%$
 - $>10^4$ electron rejection

Work still ongoing and participation welcome

Extra slides

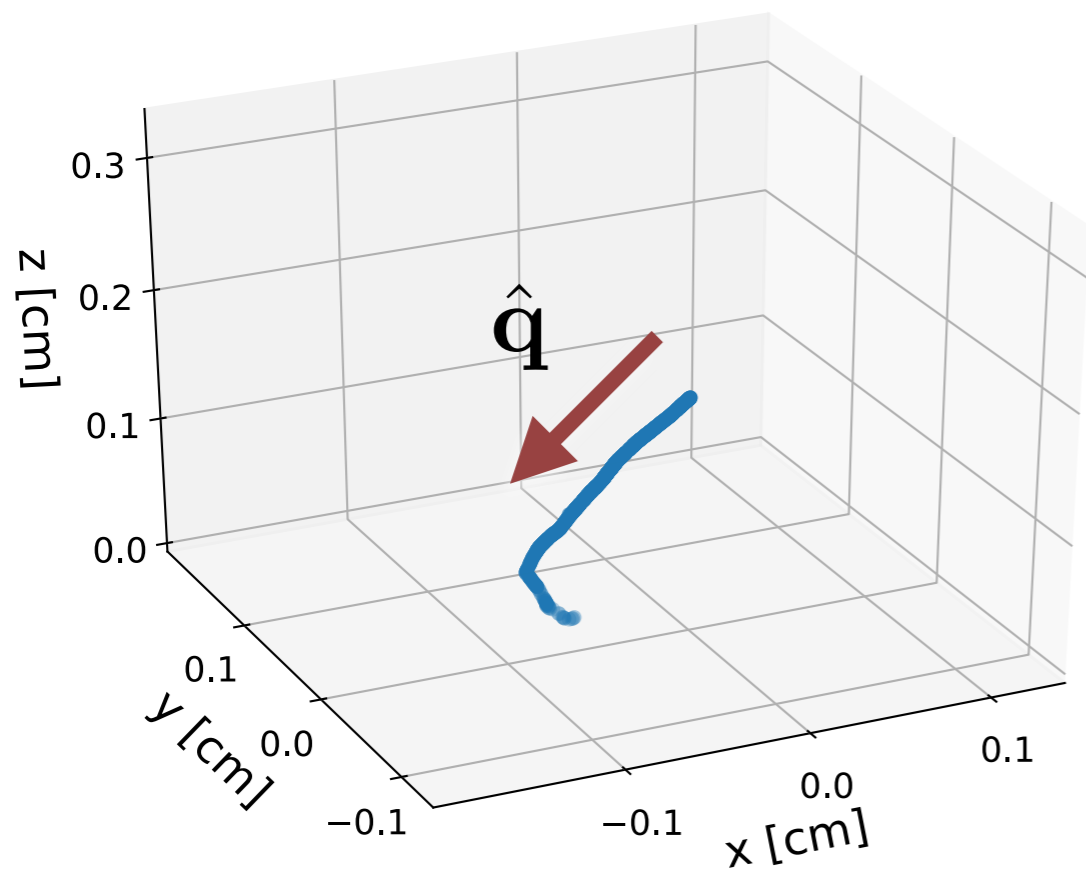
NB: 8 keV is likely an upper limit of a feasible threshold:

- 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 $\sim \sqrt{\text{drift length}}$, 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

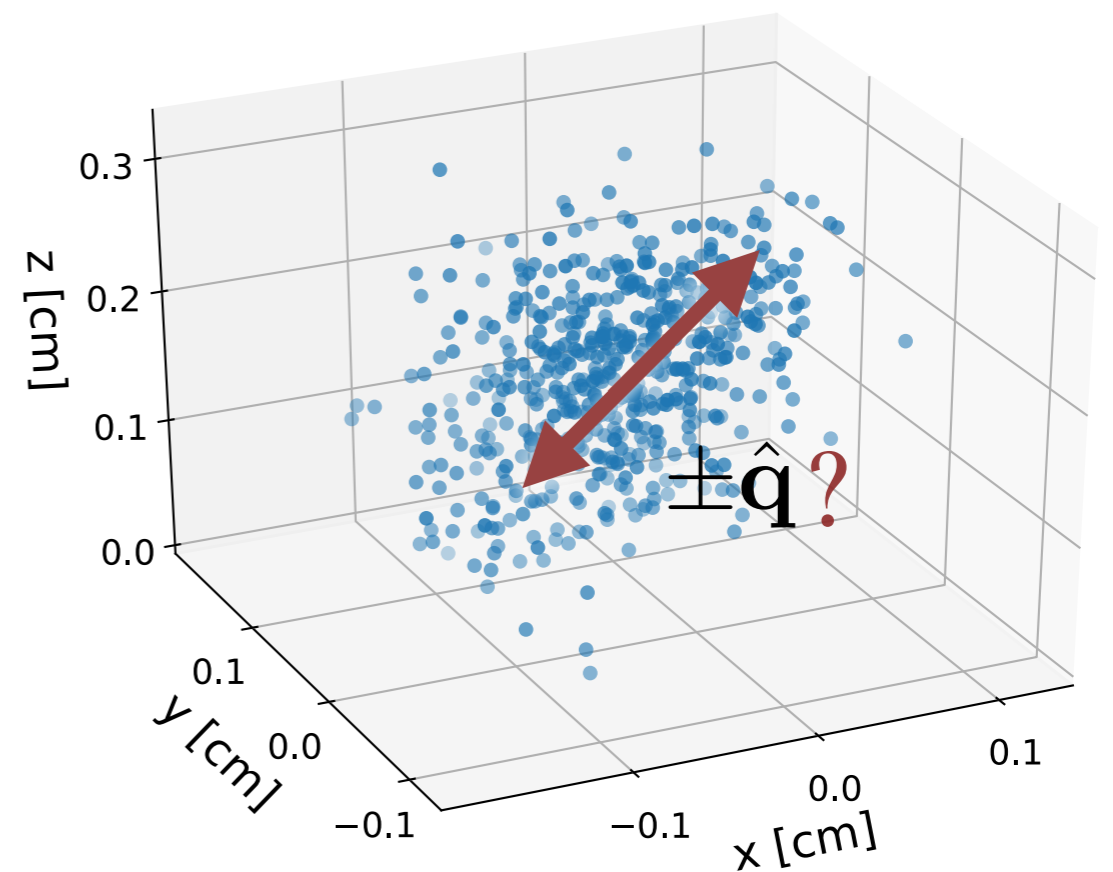
Head-tail recognition

Ability to recognise the forward-backward sense of a recoil

Original track

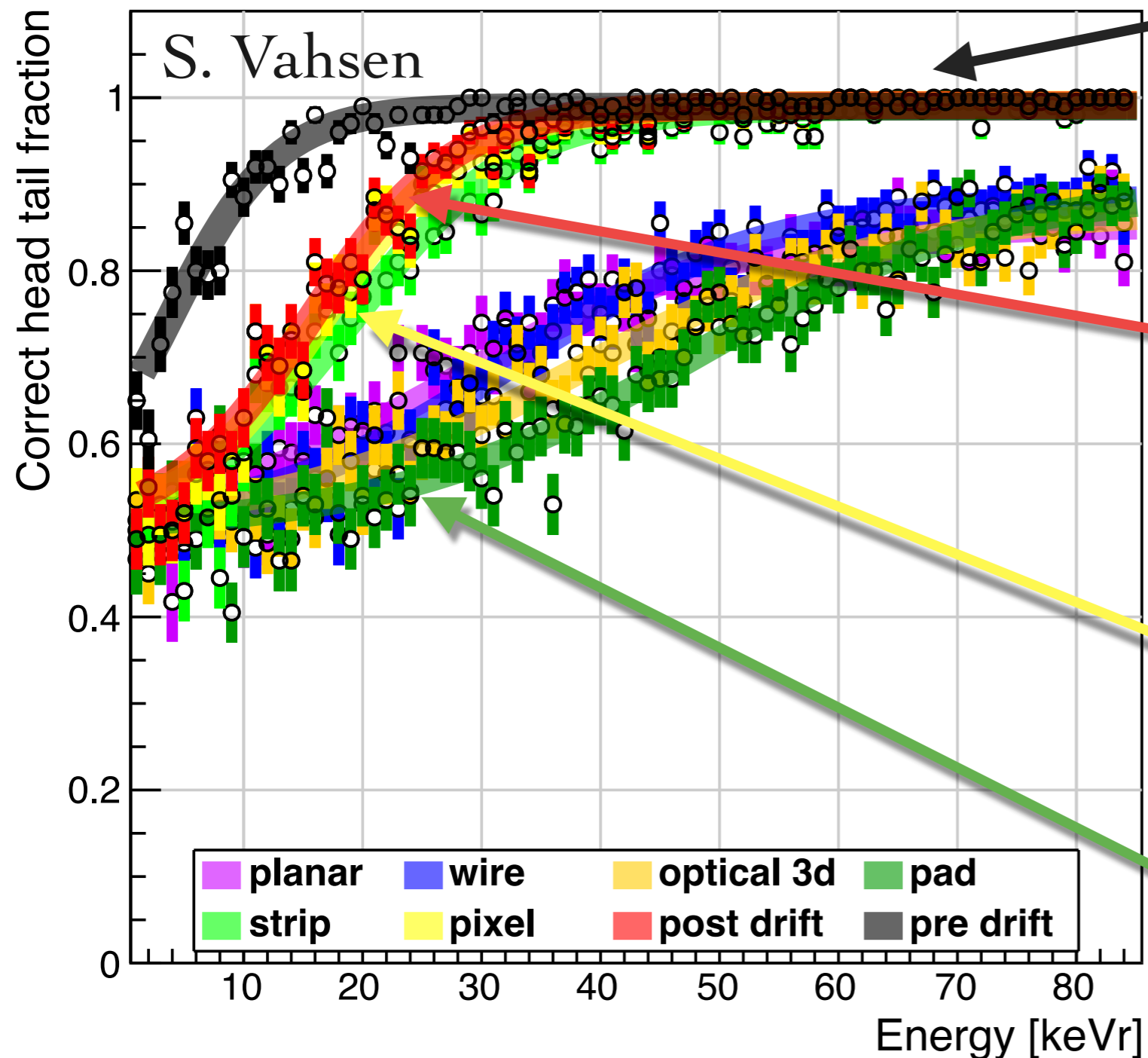


Track after 25 cm drift



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

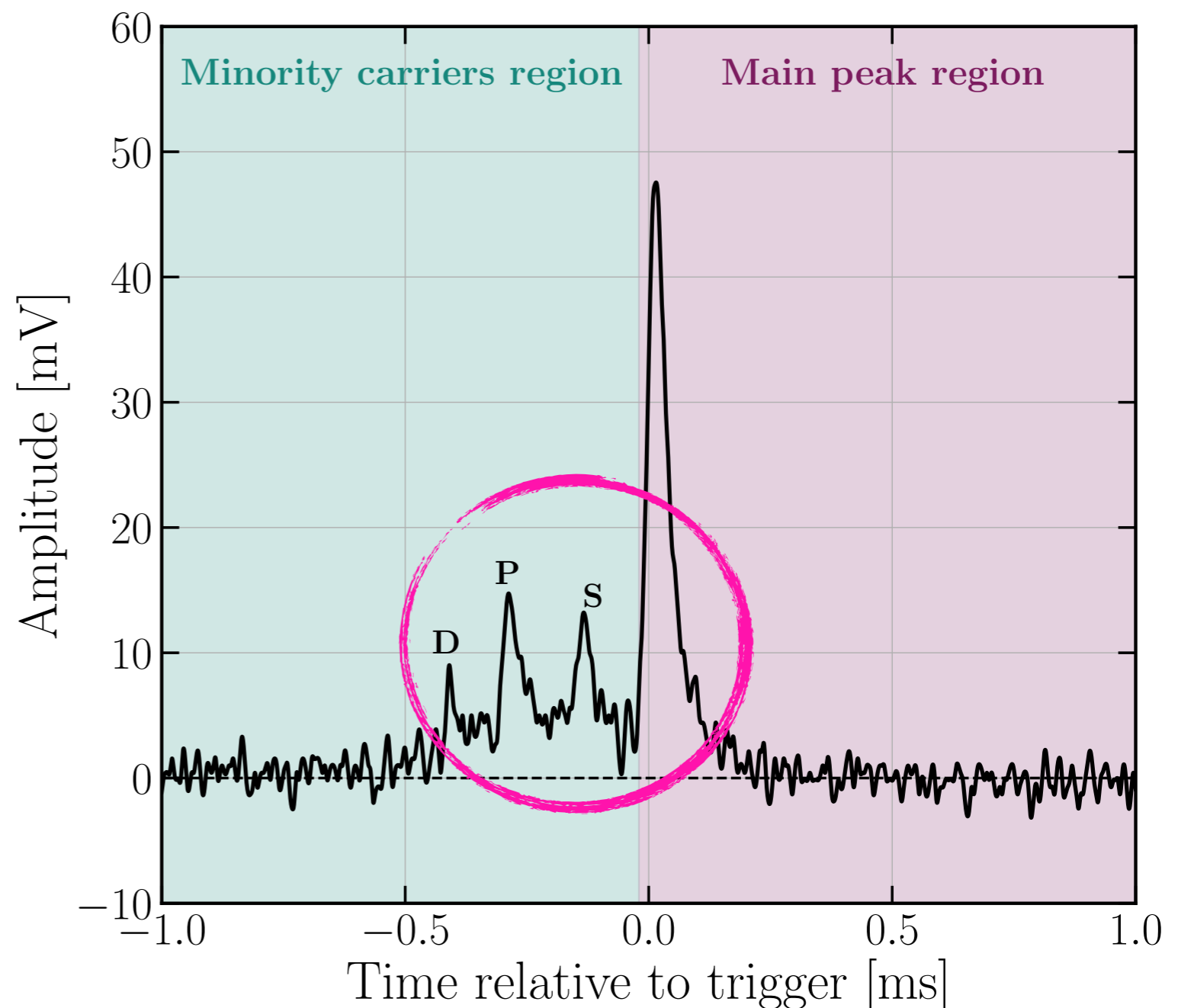
Post-drift: some directionality lost due to diffusion

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 part 2: Fiducialisation

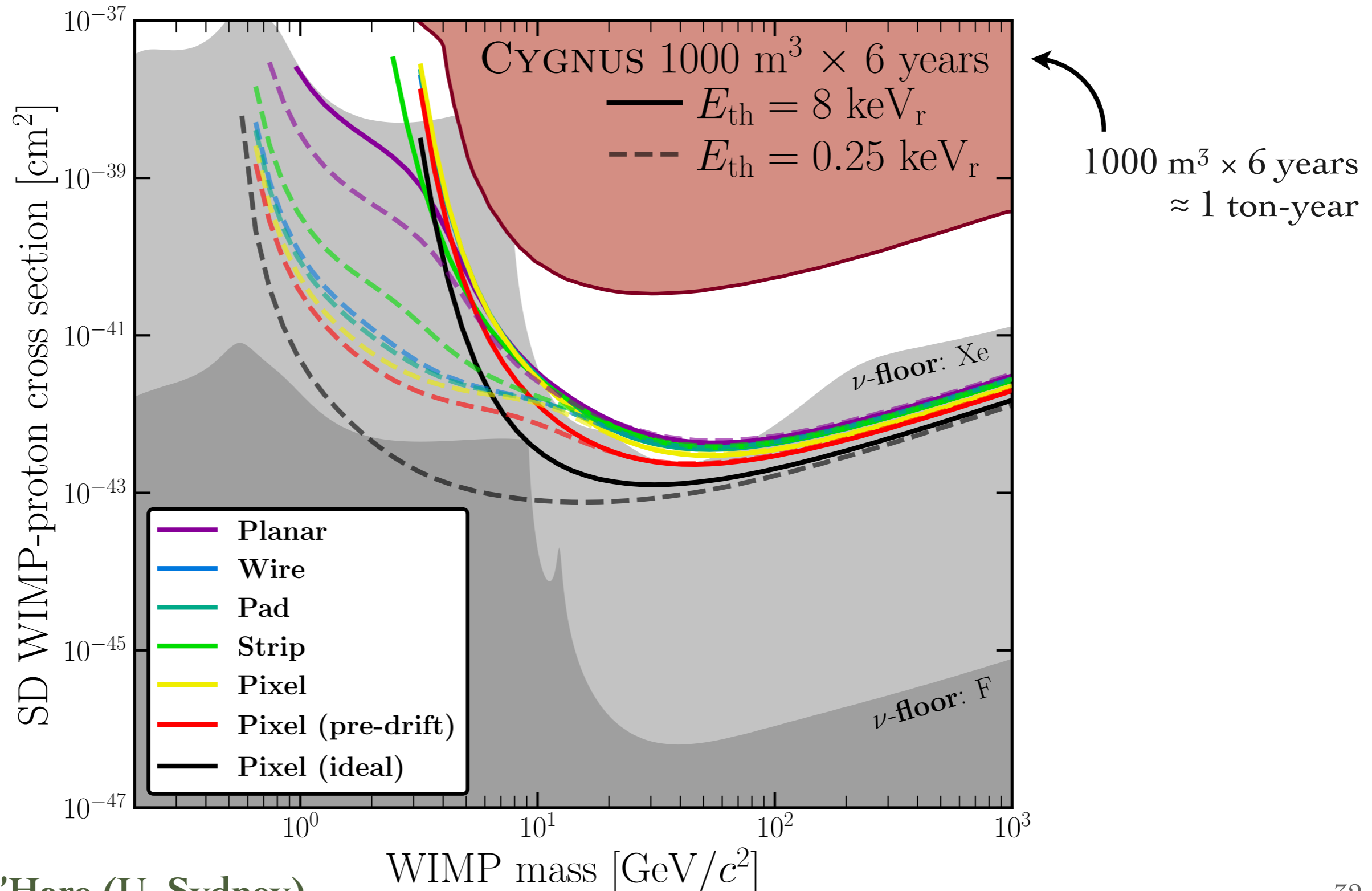
- We also need to be able to locate tracks in (x, y, z) to remove edge events, double scatters etc., especially from radon progeny recoils
- Readout does this in (x, y) , but z is tricky
- but SF_6 gives us a way:
→ Different ions of SF_6 called **minority carriers** drift at different speeds through the gas so delays in their arrival times at the readout tell us how far they drifted



WIMP reach: spin dependent (SD-proton)

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

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



New site under construction in Victoria

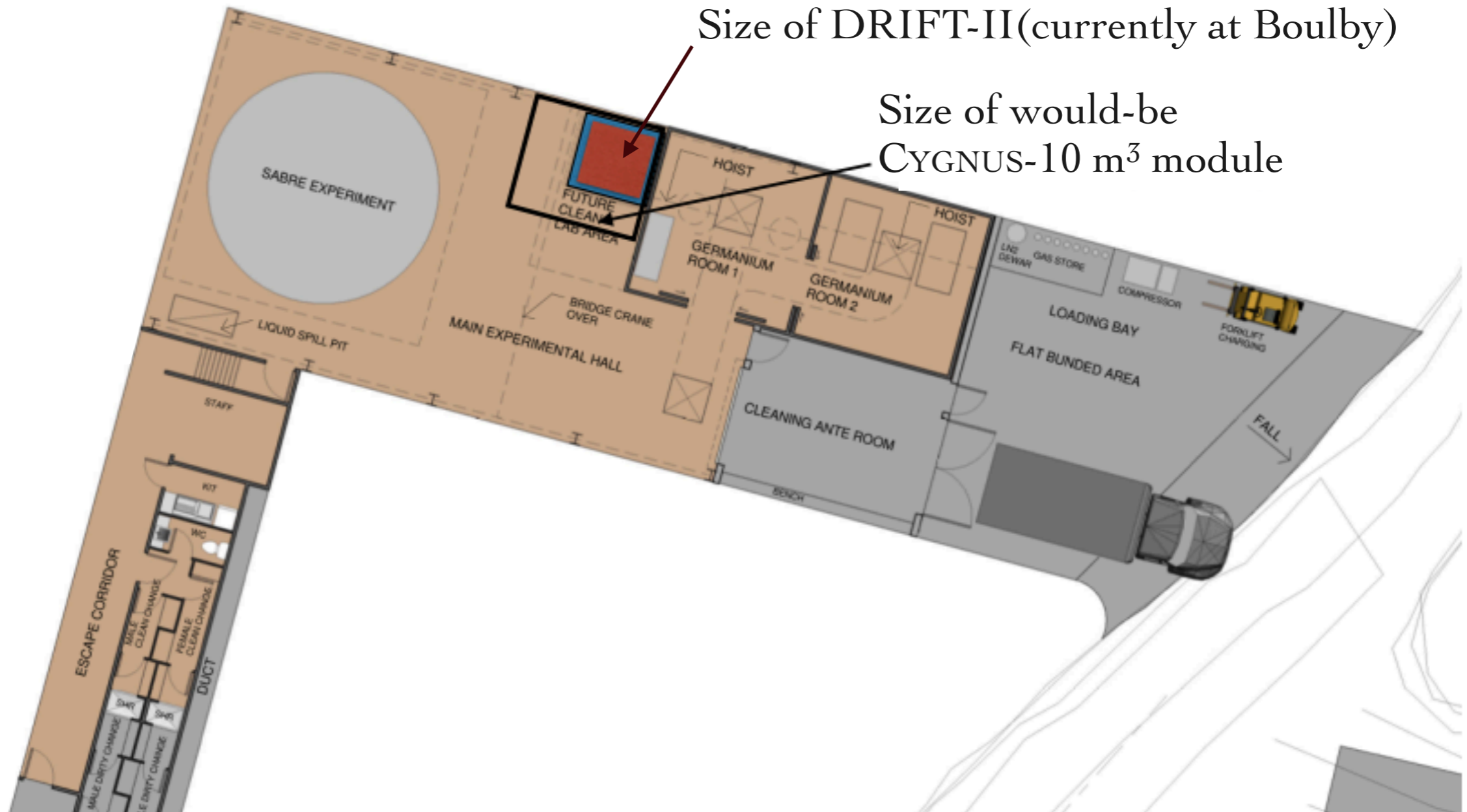
Stawell Underground Physics Laboratory (SUPL)

- ♦ 1.6 km depth
- ♦ First underground site in Southern Hemisphere

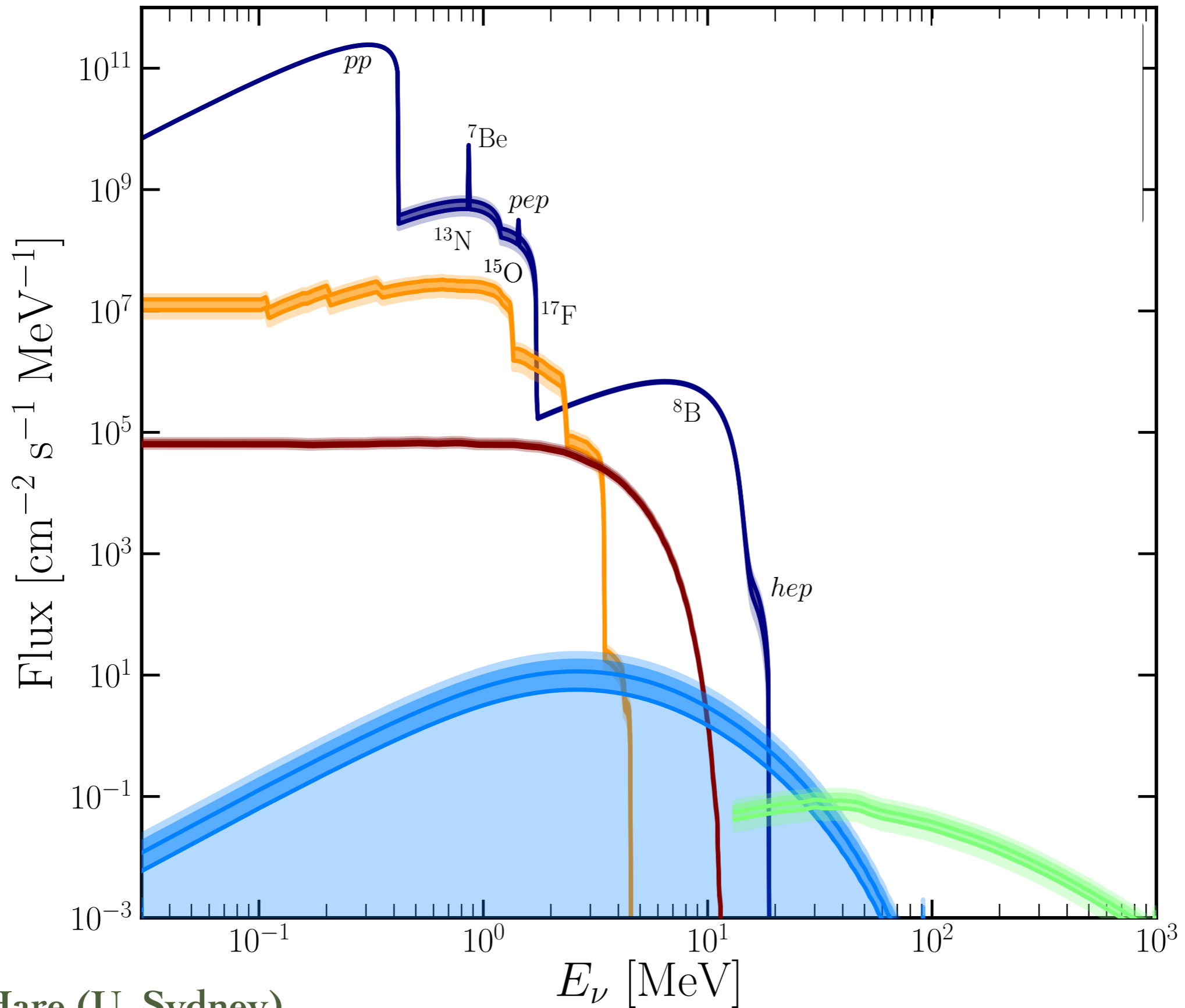


Size of DRIFT-II (currently at Boulby)

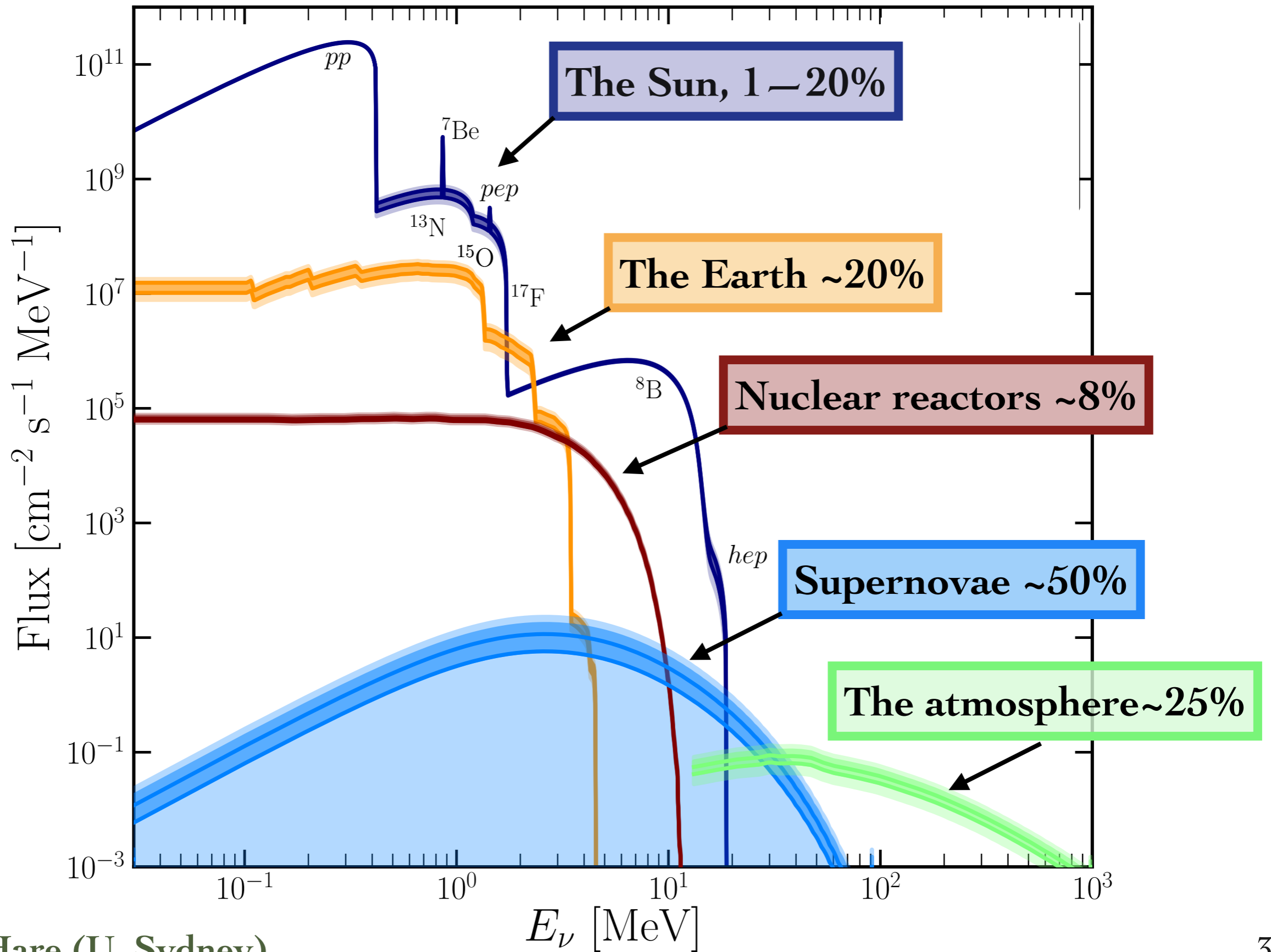
Size of would-be
CYGNUS-10 m³ module



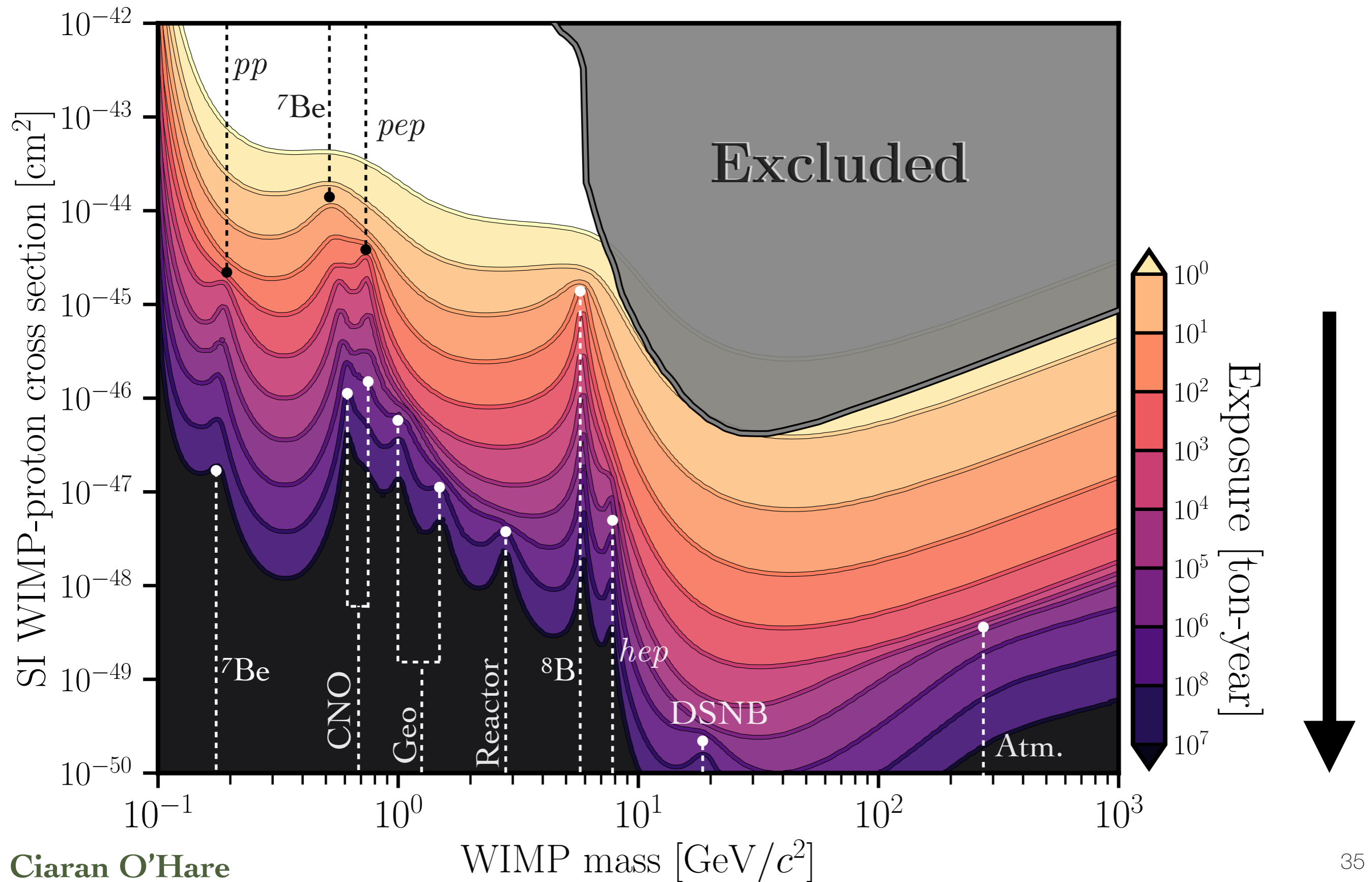
Neutrino fluxes



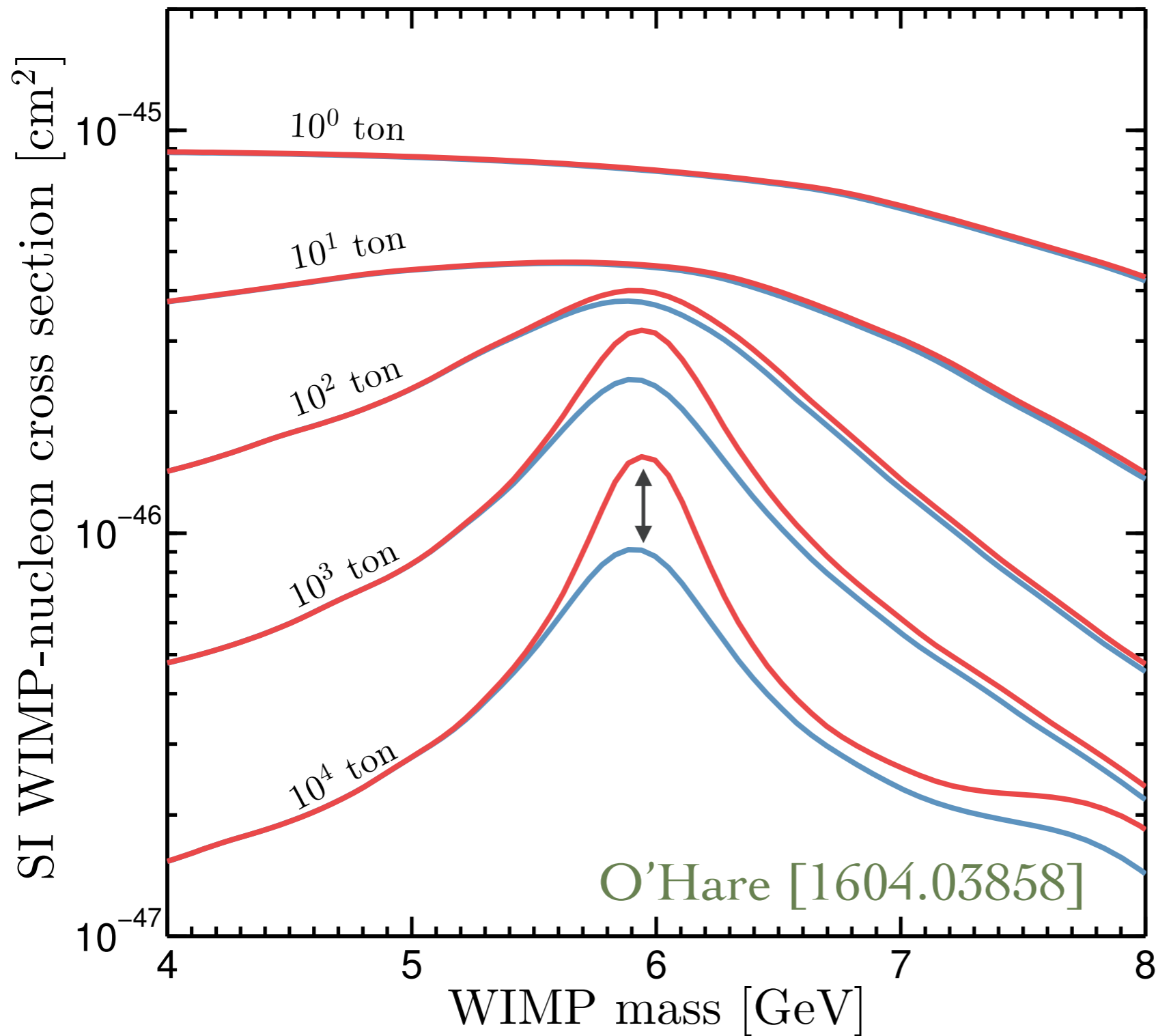
Neutrino fluxes



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



Annual modulation: does it help?



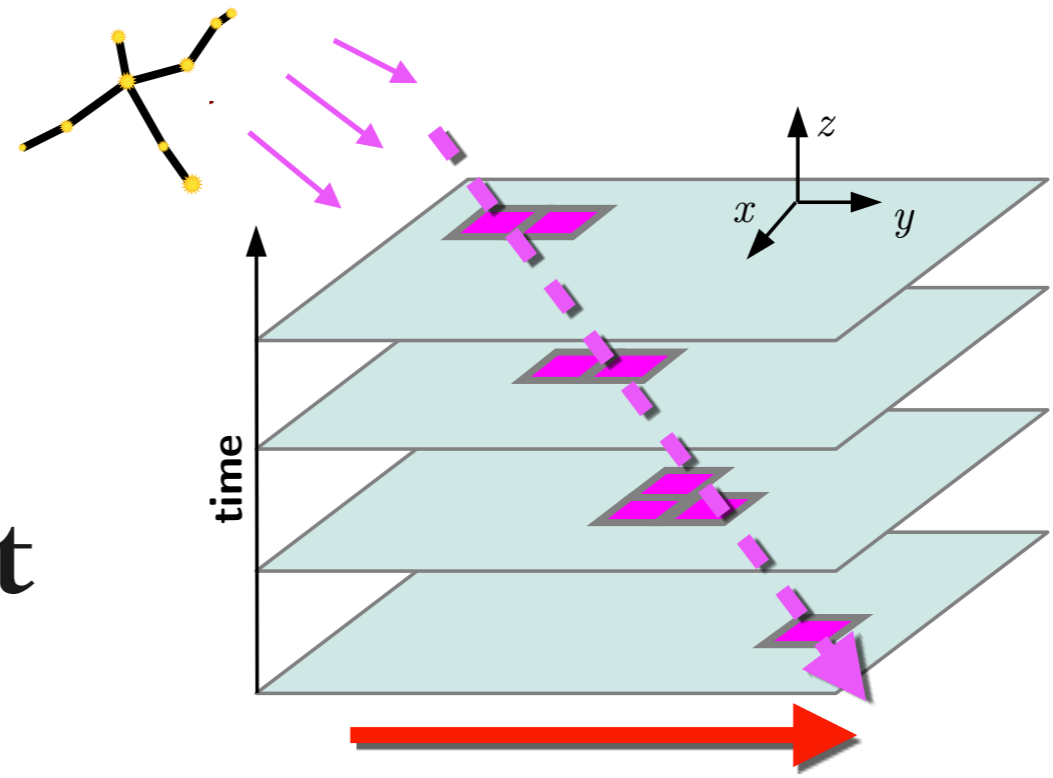
Information used:

Energy only

Energy + Time



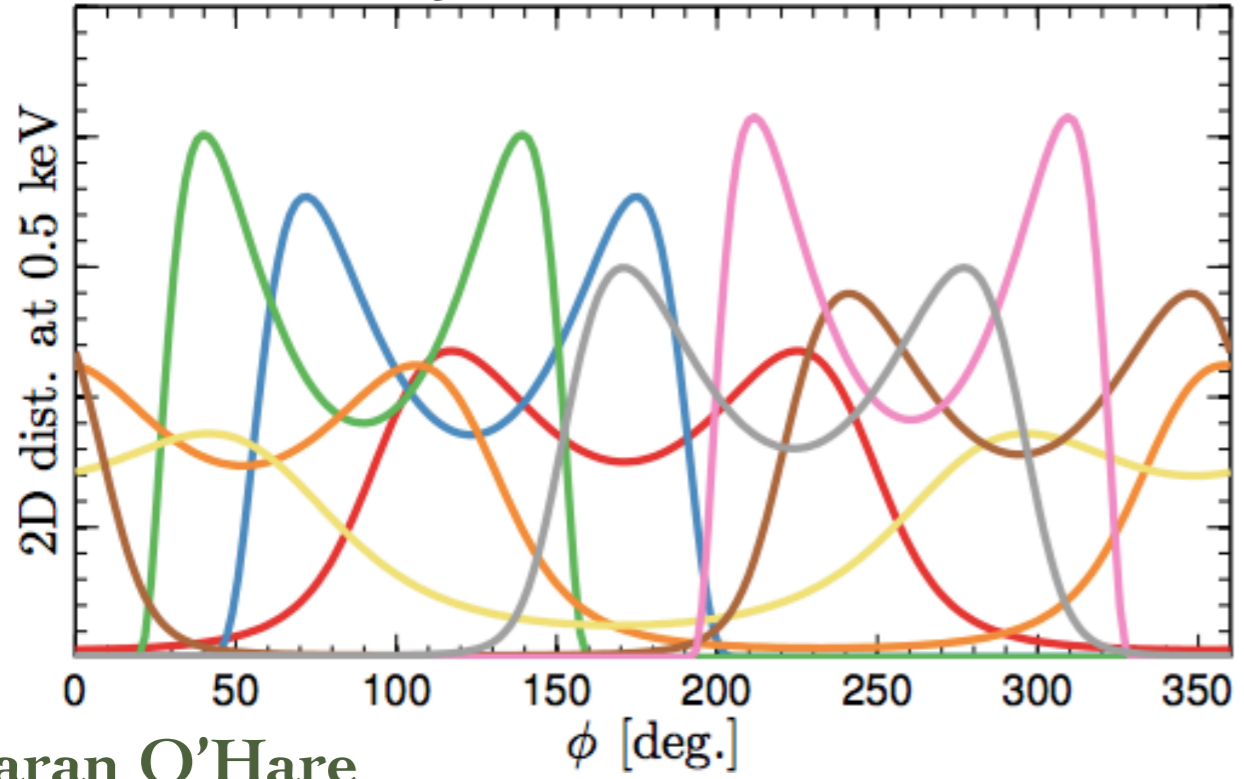
Increasing
exposure



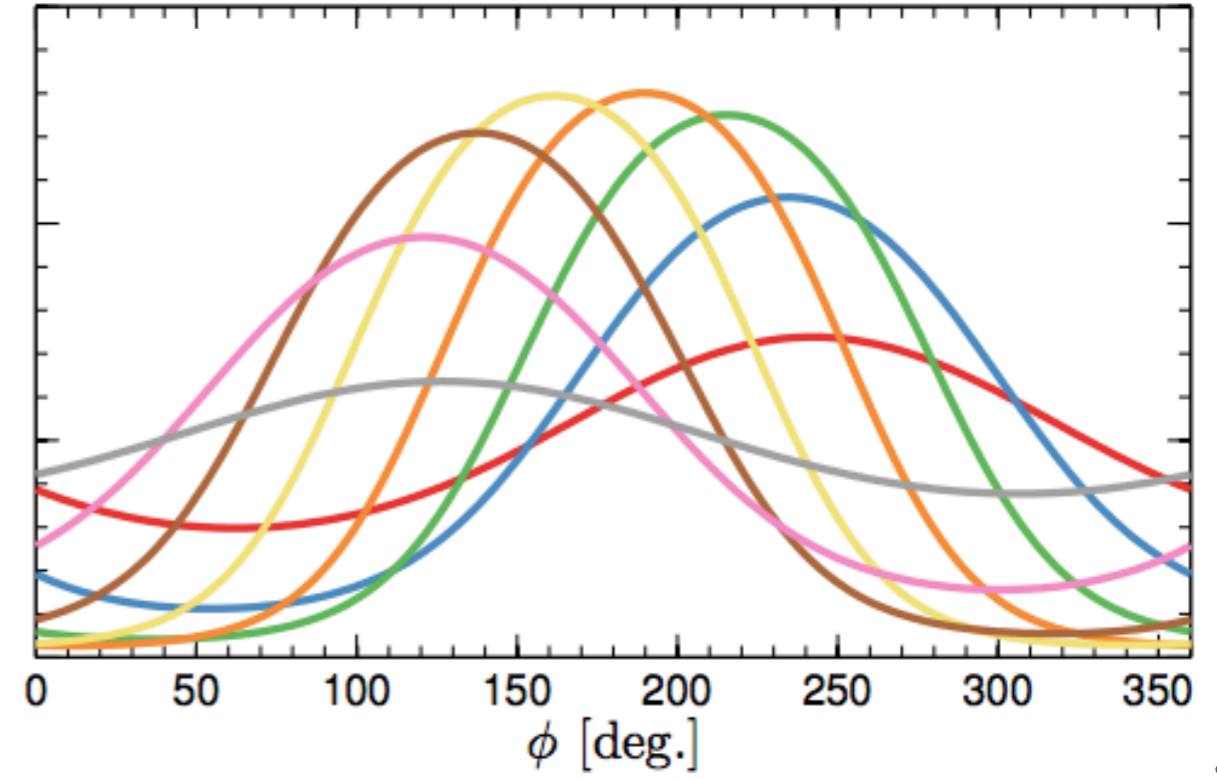
2D Readout

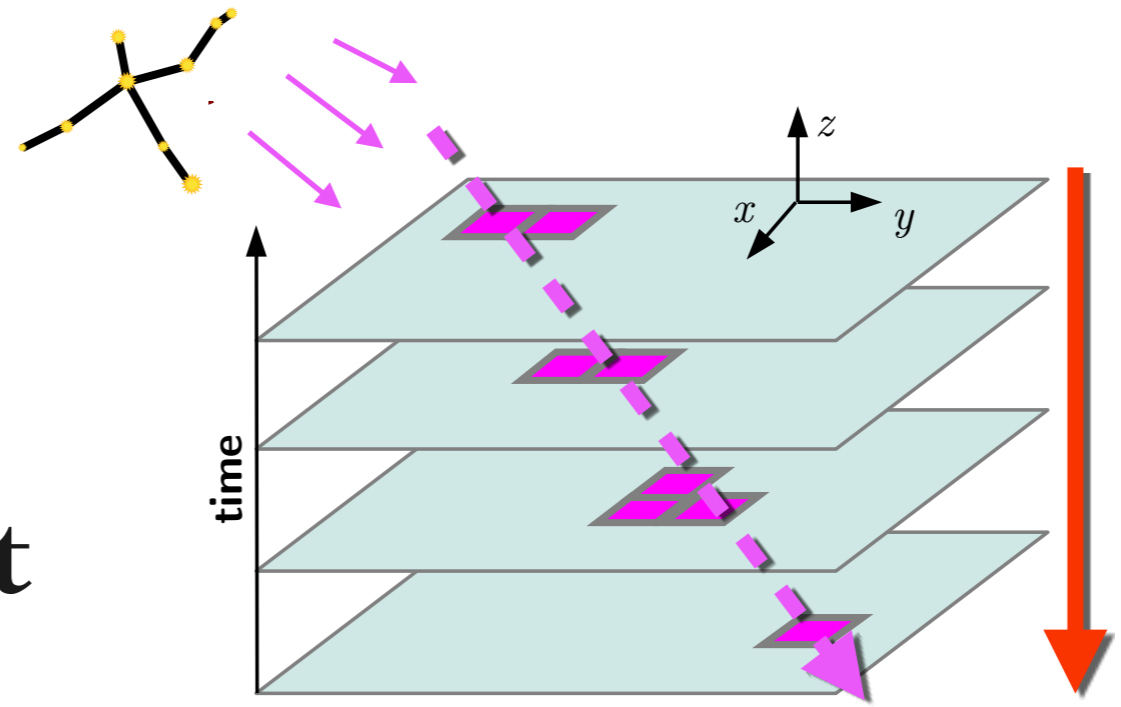
$$\hat{q} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}$$

Neutrino Daily modulation



WIMP Daily modulation





1D Readout

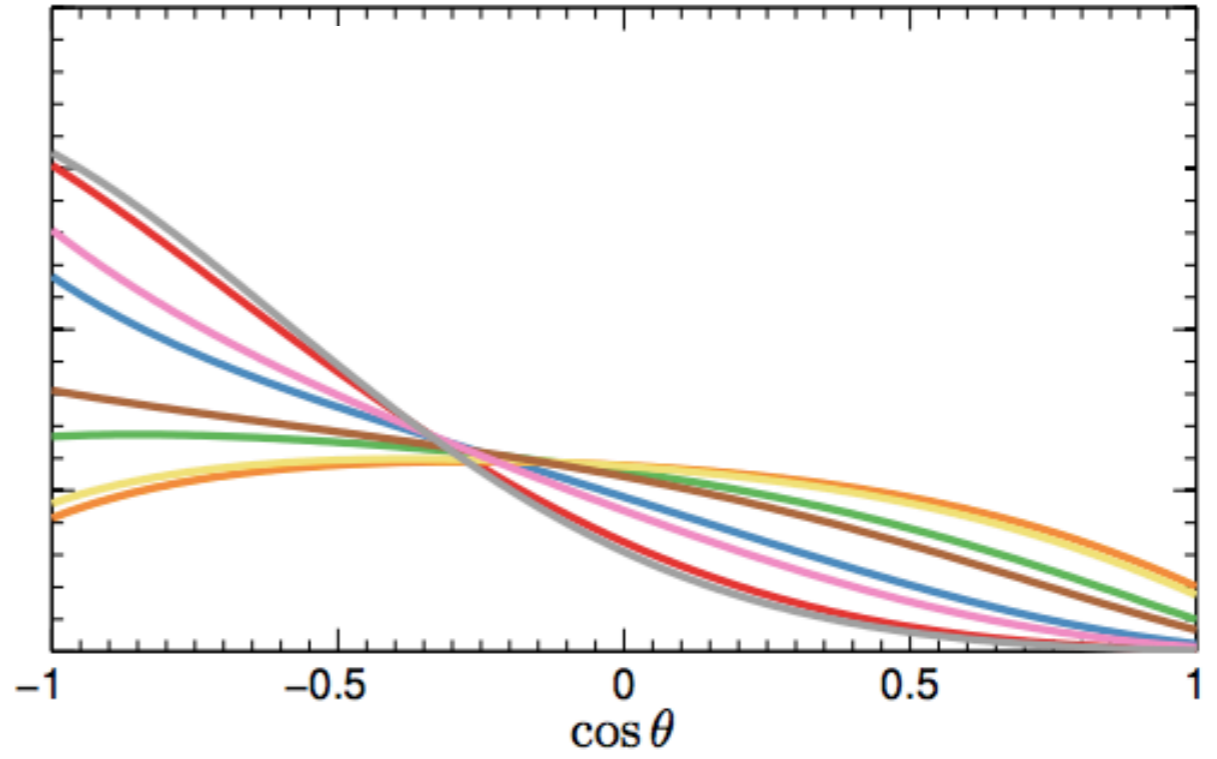
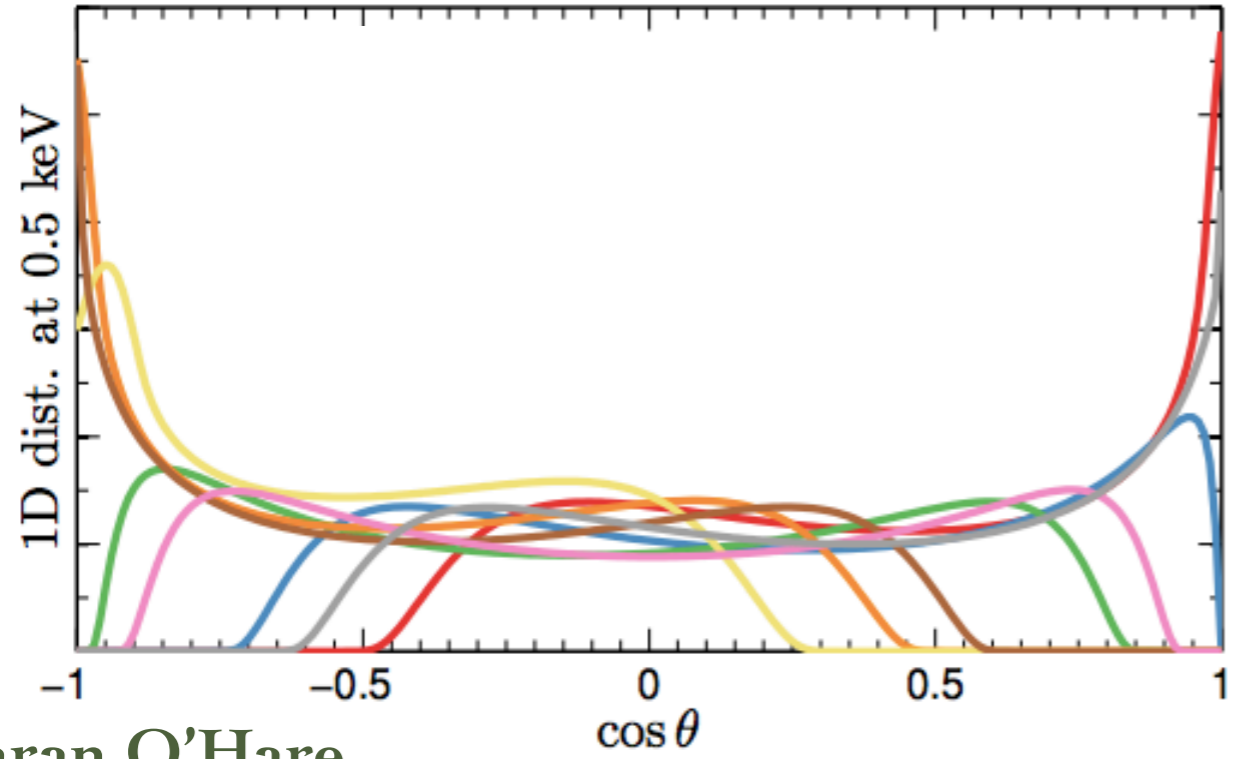
$$\hat{q} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}$$

Neutrino

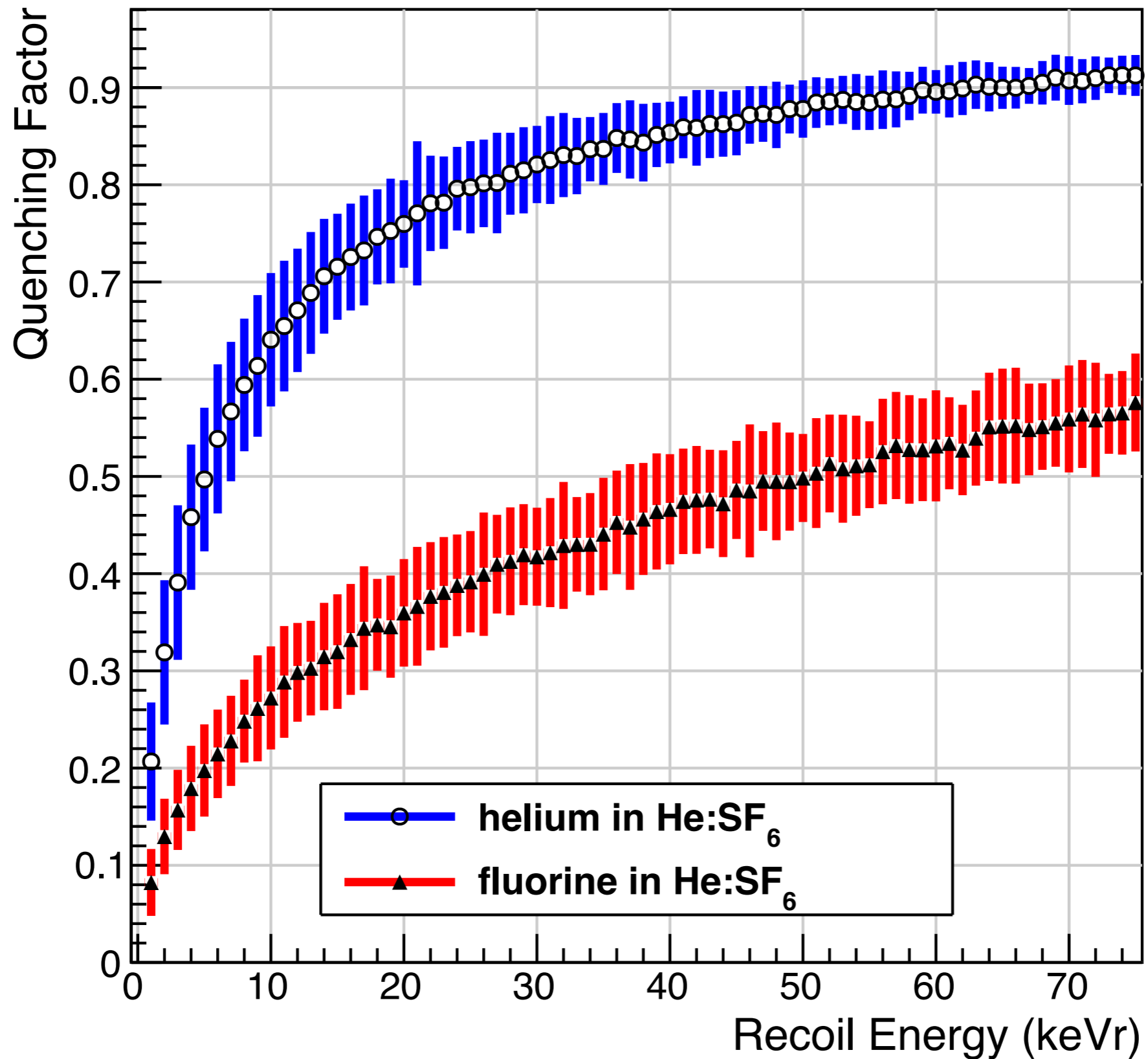
WIMP

Daily modulation

Daily modulation



Quenching factors for recoils in 1 atm of He+SF₆



Say we build Cygnus and find that...

Say we build Cygnus and find that...

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...

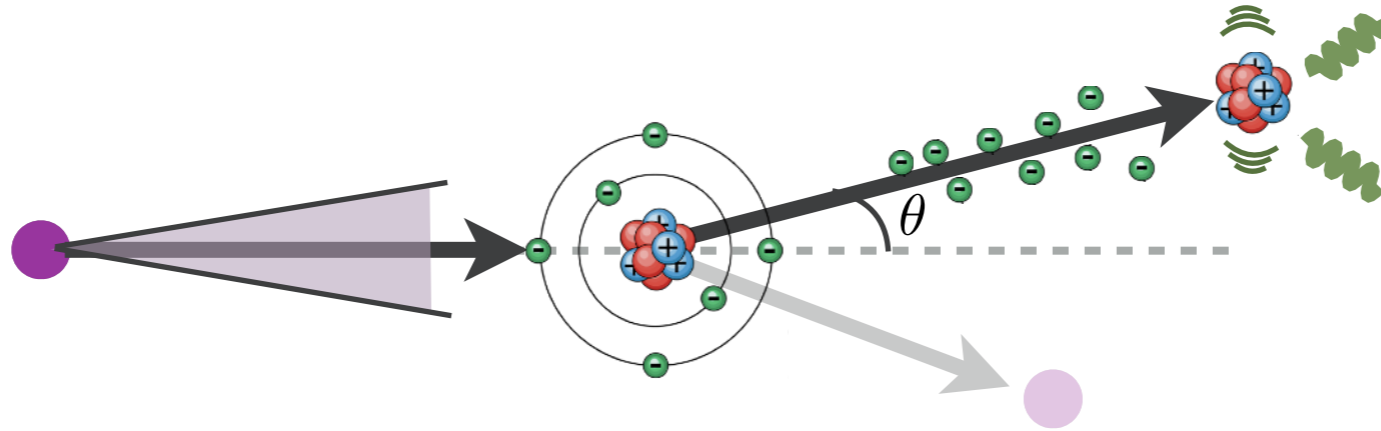
1. We have a signal

↳ We study it

2. We don't

Then what?

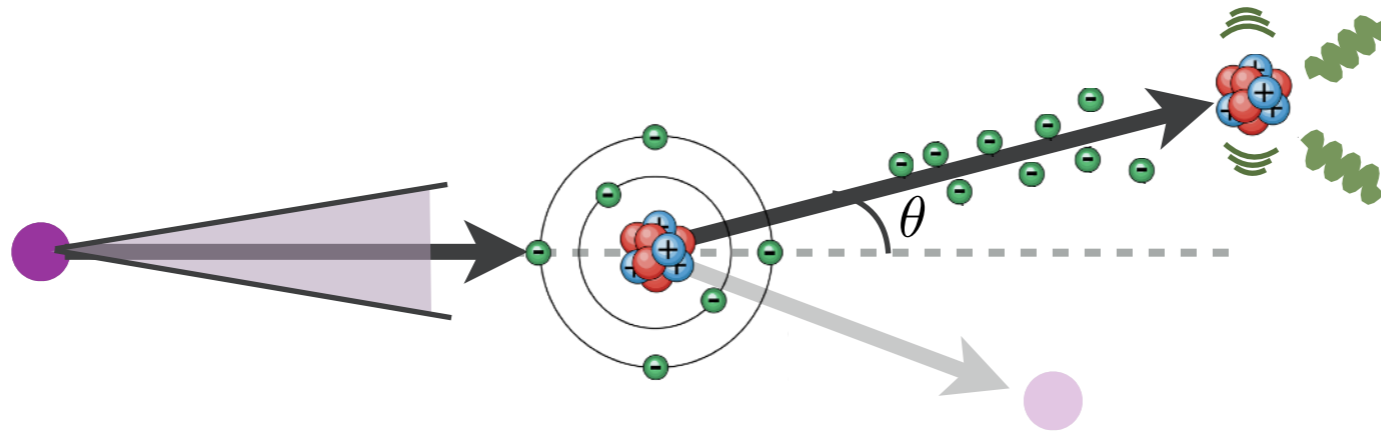
What should the signal look like?



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

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- The DM scatters elastically

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

m_N = Nucleus mass

m_χ = DM mass

- The DM velocity distribution is a Gaussian (SHM)

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

\mathbf{v}_{lab} = Our velocity

σ_v = Velocity dispersion

- DM-nucleus matrix element does not depend on velocity

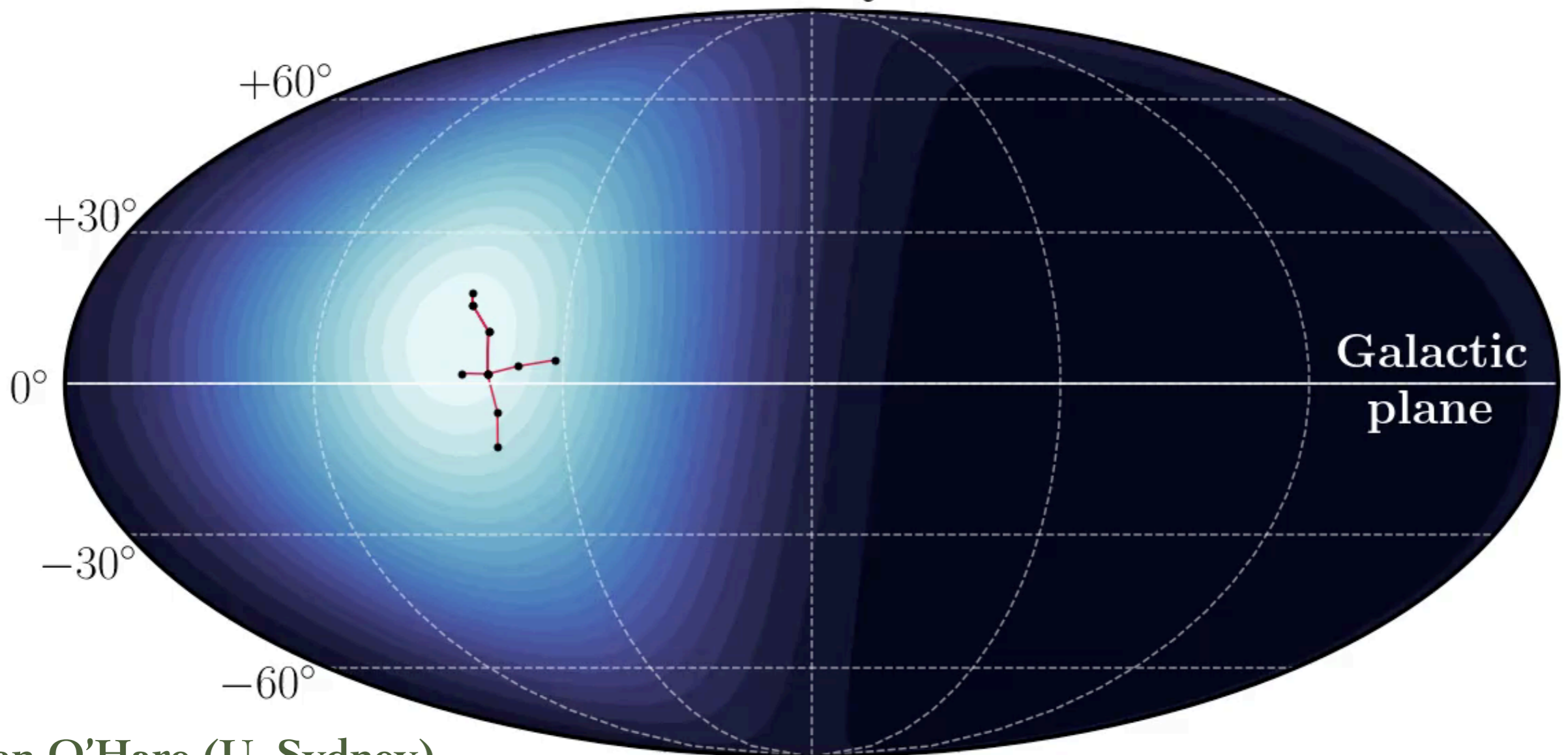
$$\hookrightarrow \frac{dR}{d\Omega} \sim \int \delta(v \cos \theta - v_{\text{min}}) f(\mathbf{v}) d^3\mathbf{v}$$

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

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

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

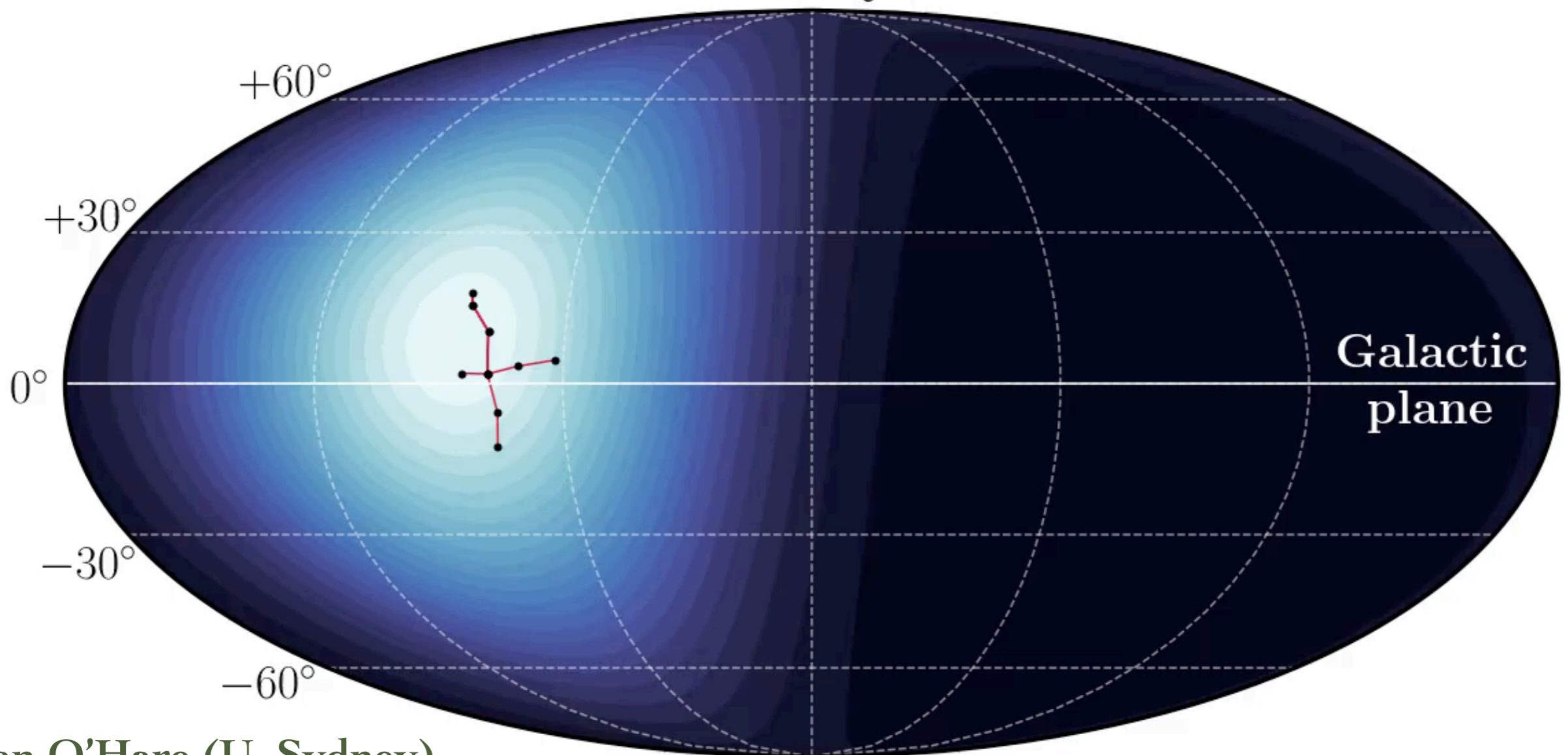
January 1



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January 1

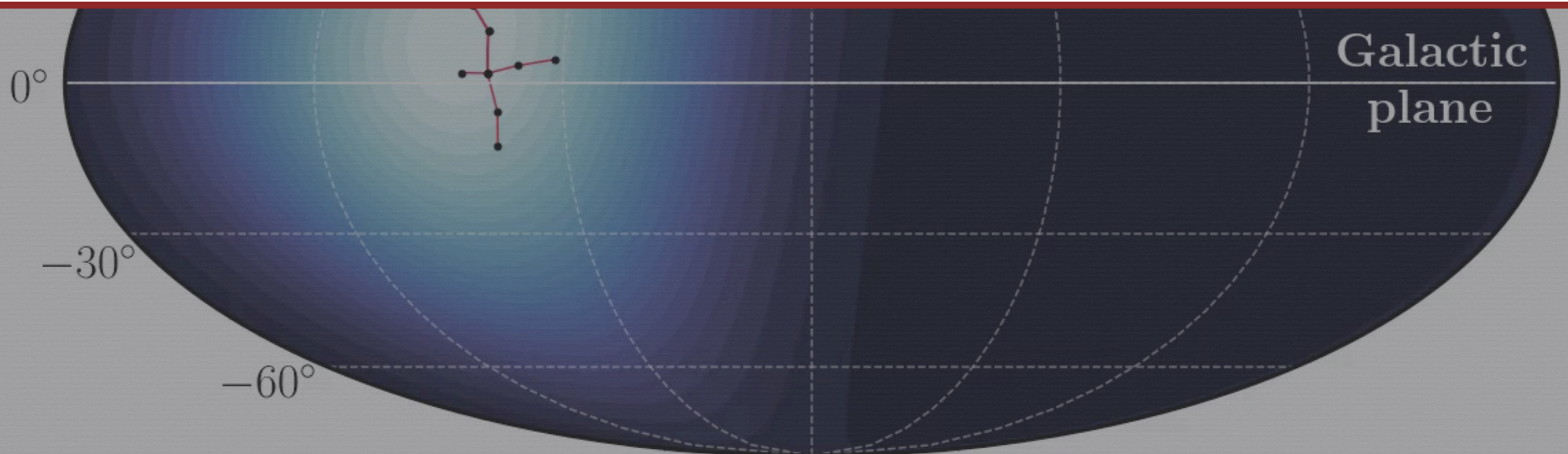


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But this is **wrong** if we break those assumptions, and we have reason to...

- The DM velocity distribution is not a Gaussian
- WIMPs may not scatter elastically
- The WIMP-nucleus interaction may involve velocity-dependent operators

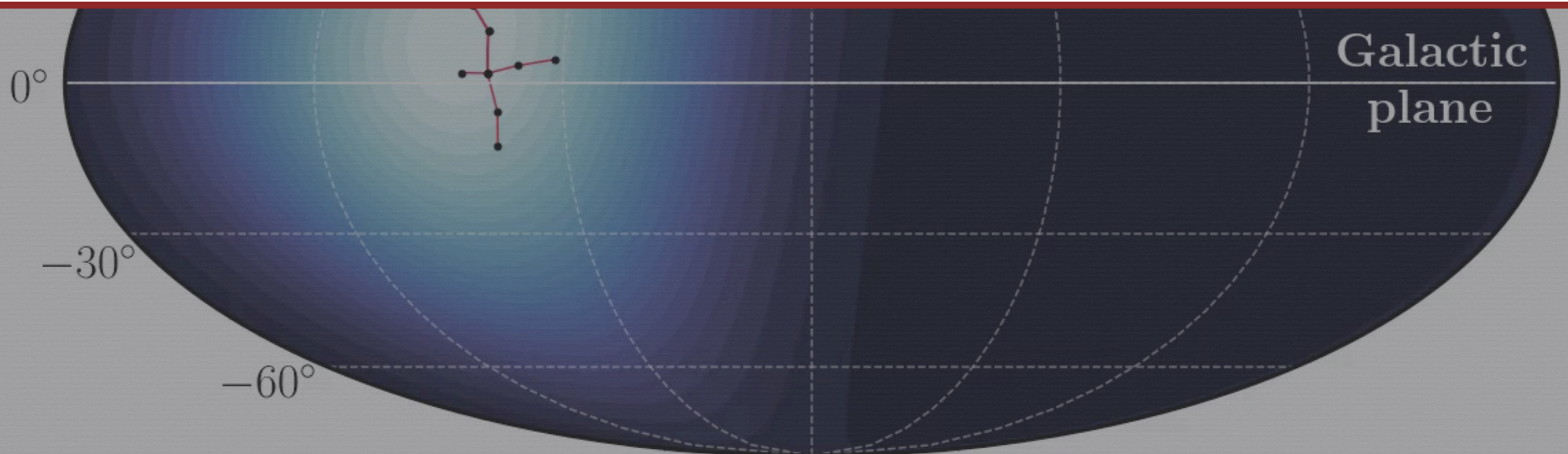


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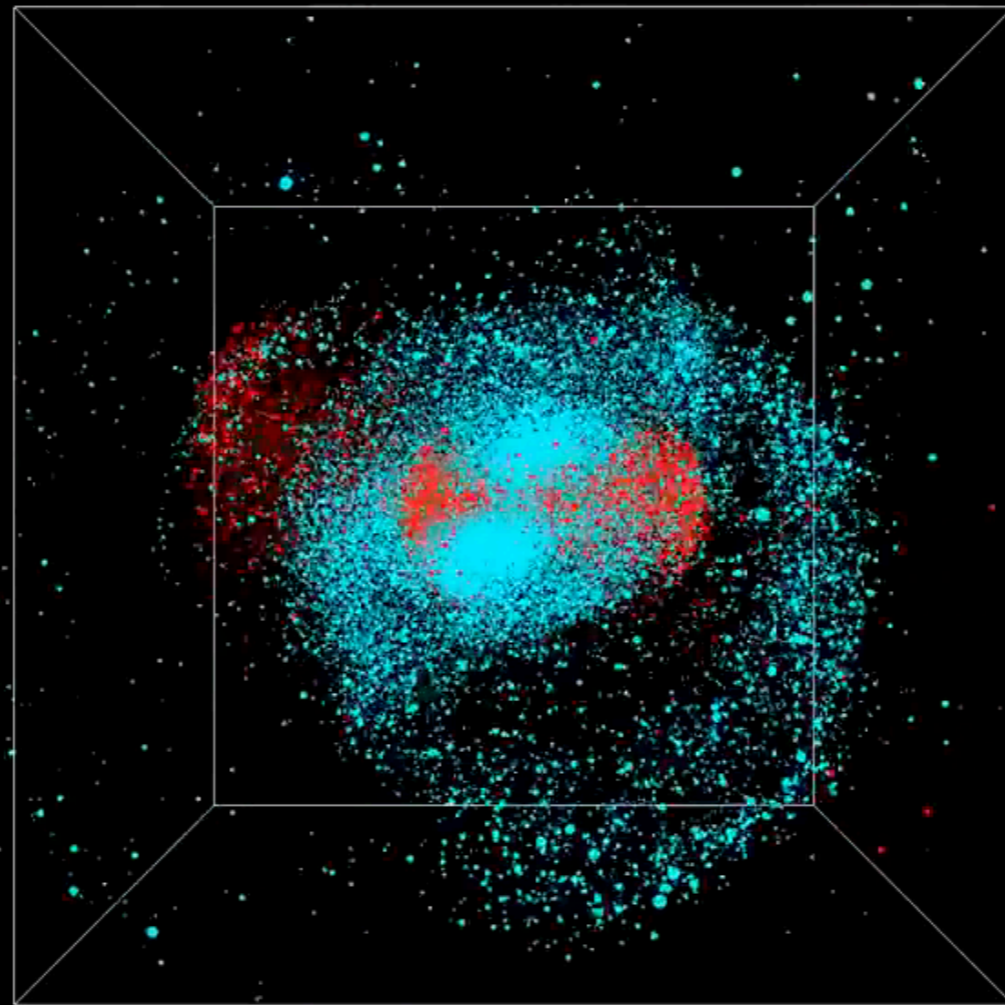
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Should the DM velocity distribution be a Gaussian?

→ Evidence of significant merger in the MW's history

The Gaia Sausage

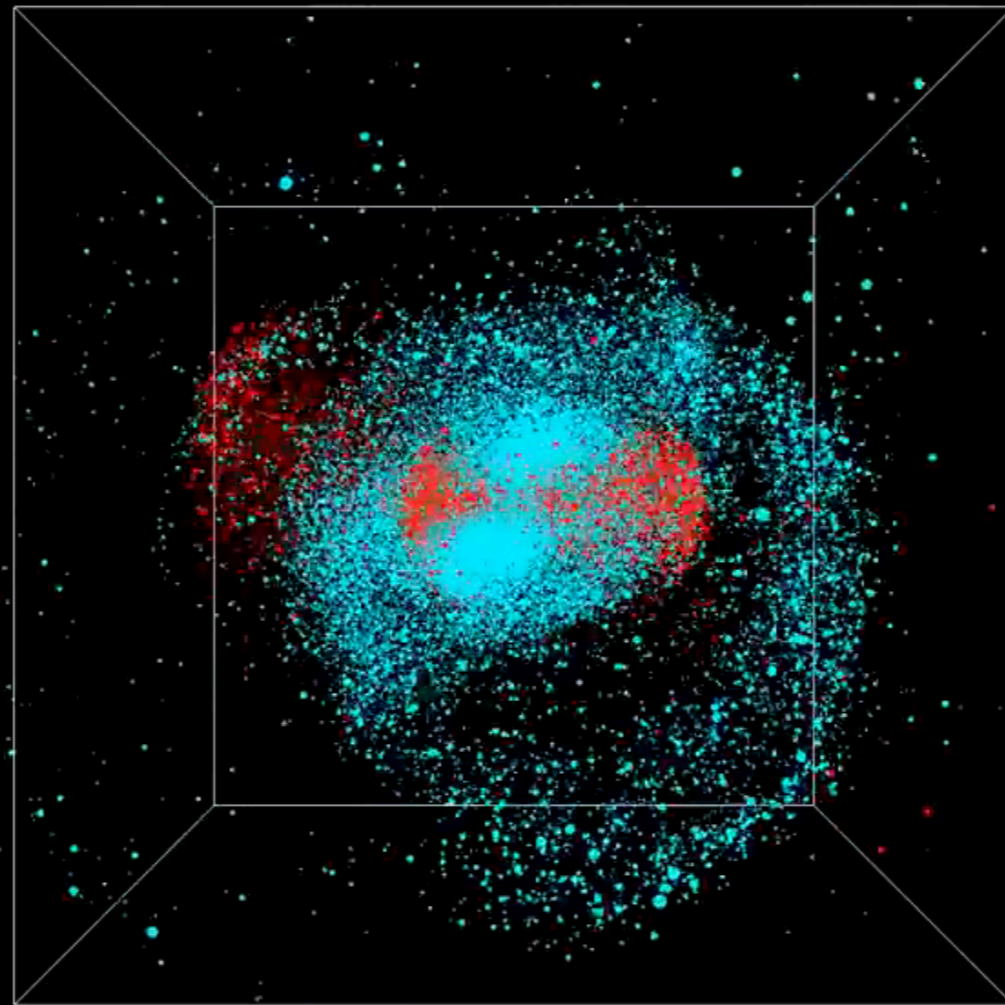


See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

Should the DM velocity distribution be a Gaussian?

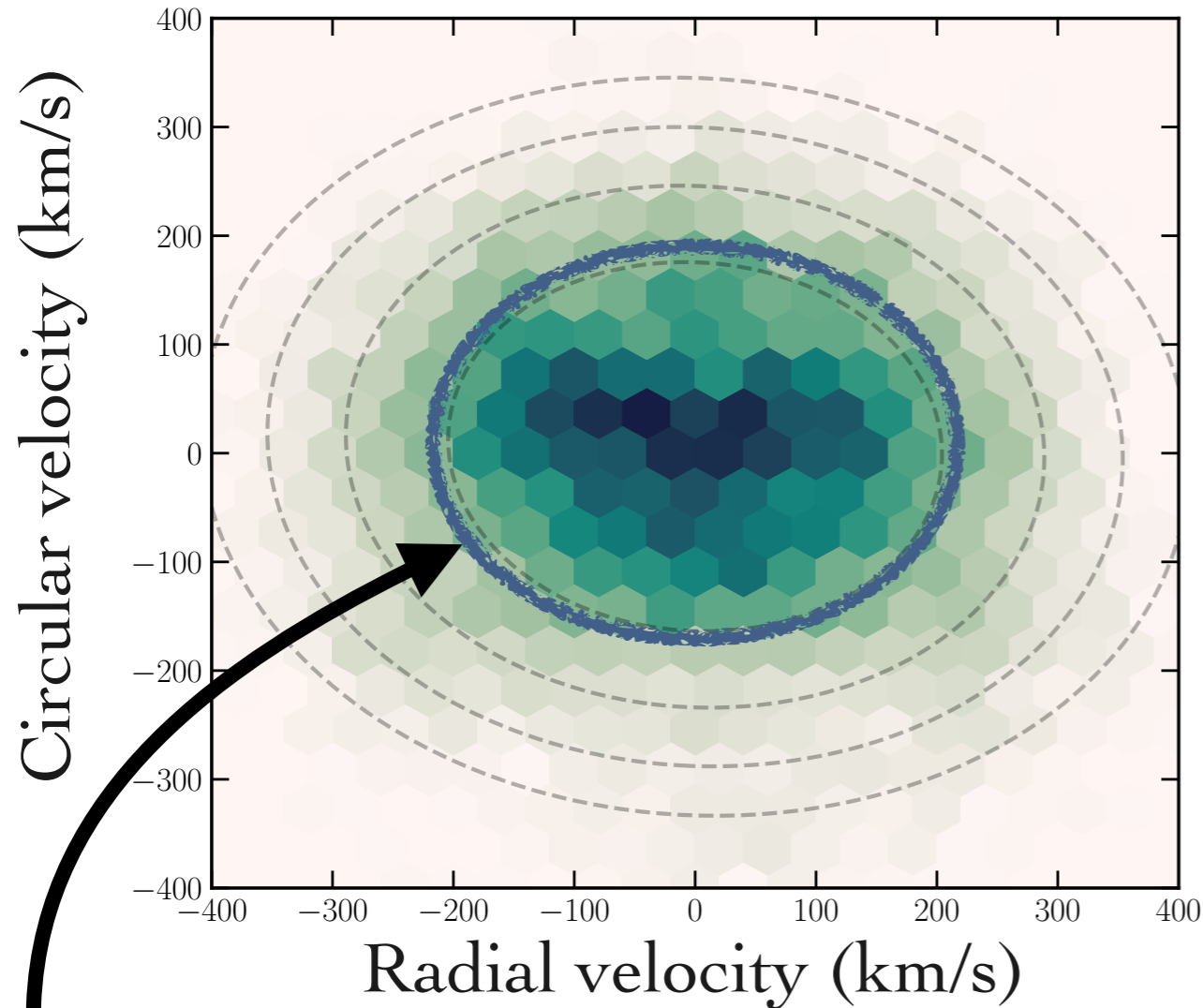
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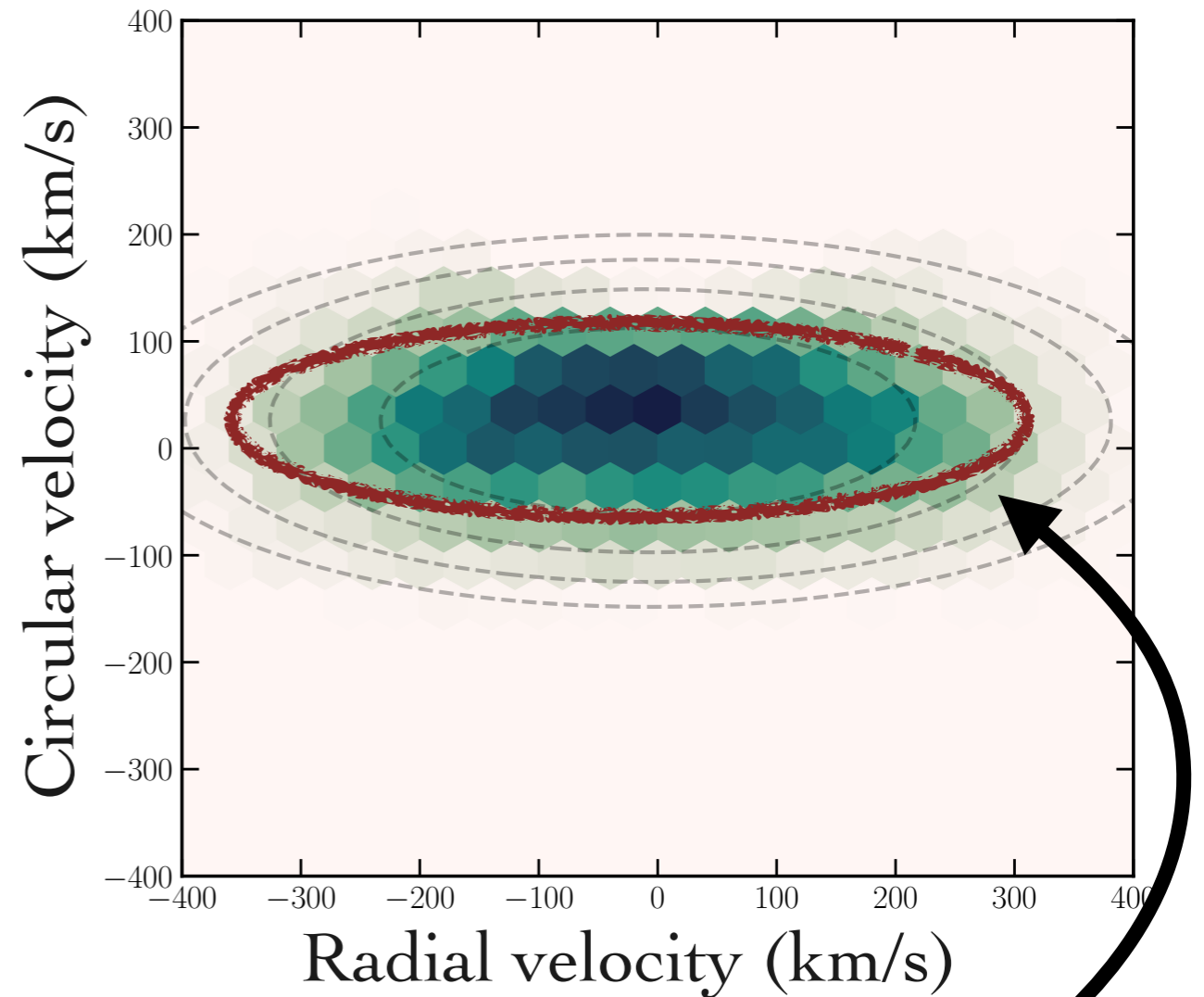
Metal-poor halo [Fe/H] < -1.5



The "Halo"

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

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



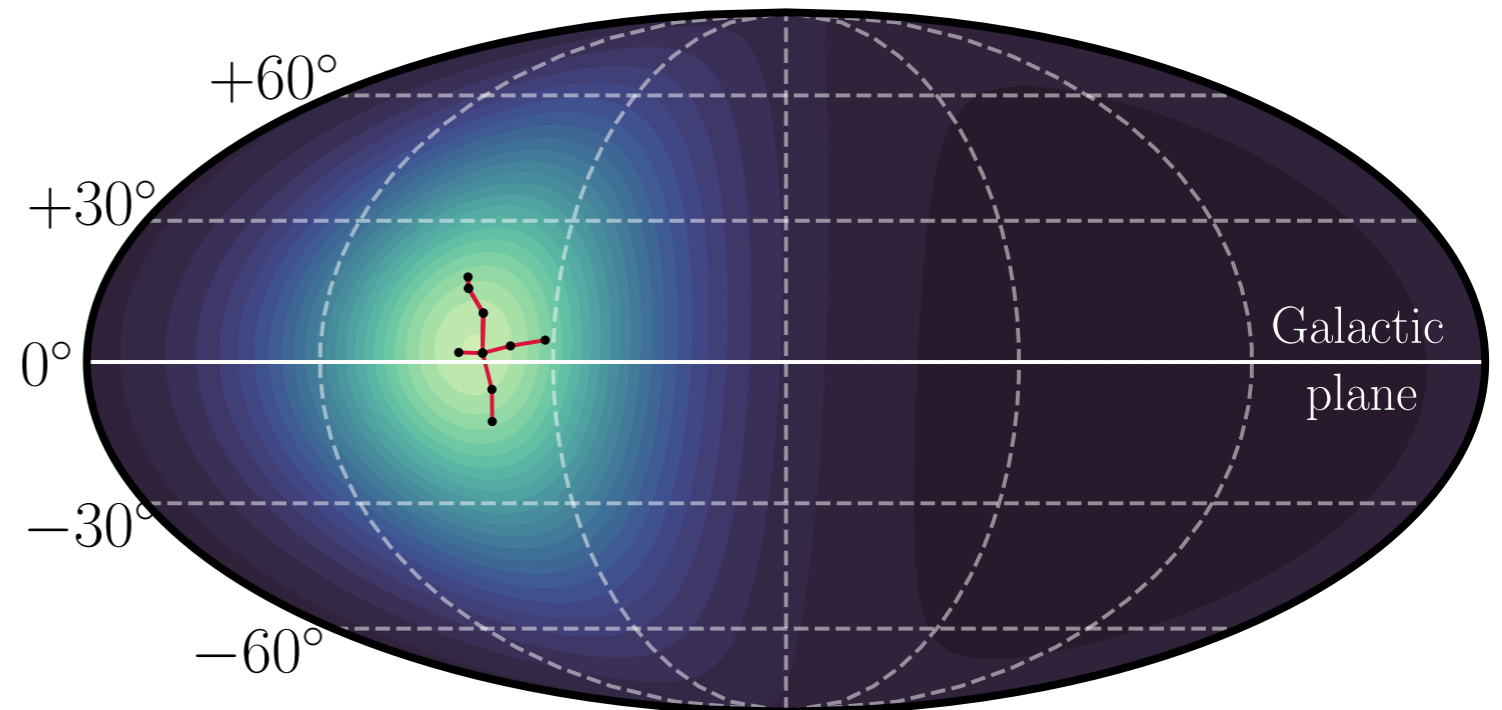
The "Sausage"

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

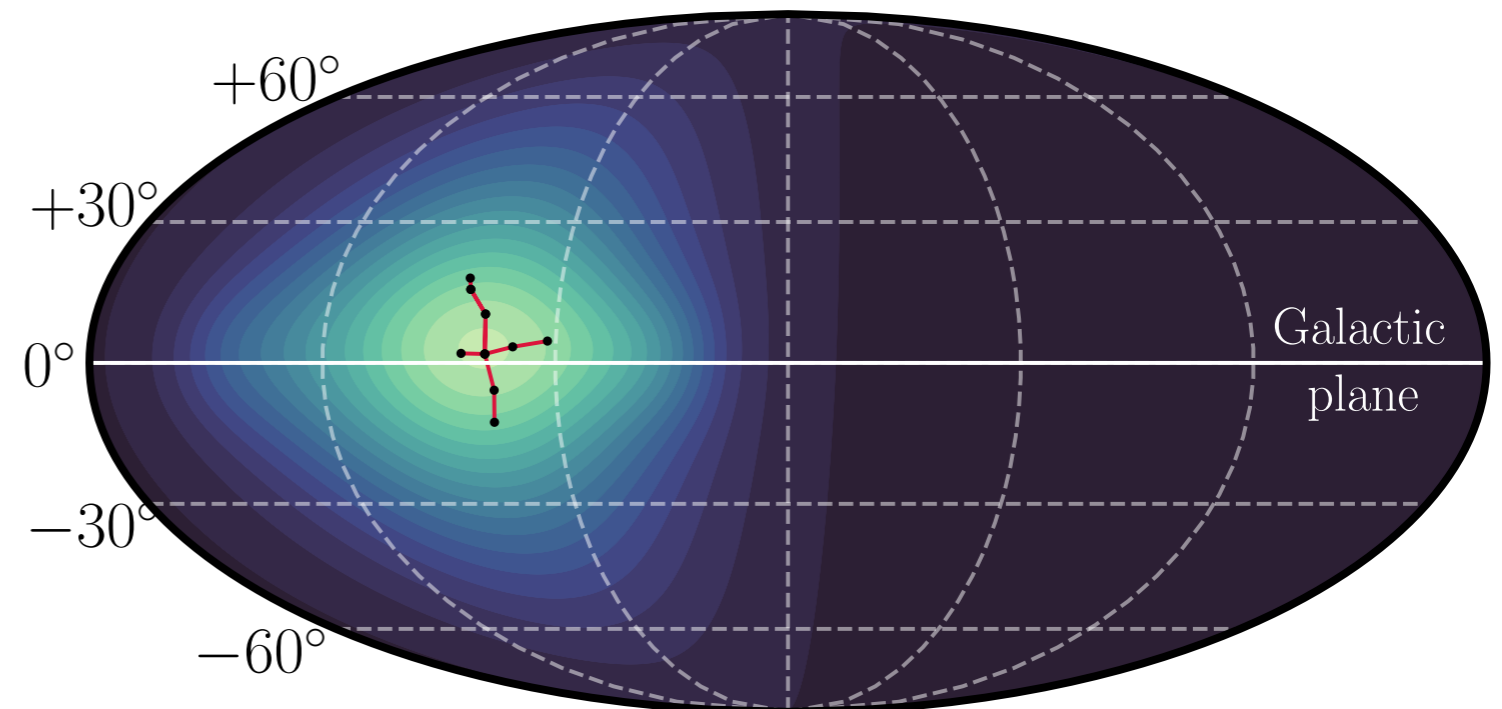
The Gaia Sausage

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

DM Flux for SHM
(Gaussian distribution)

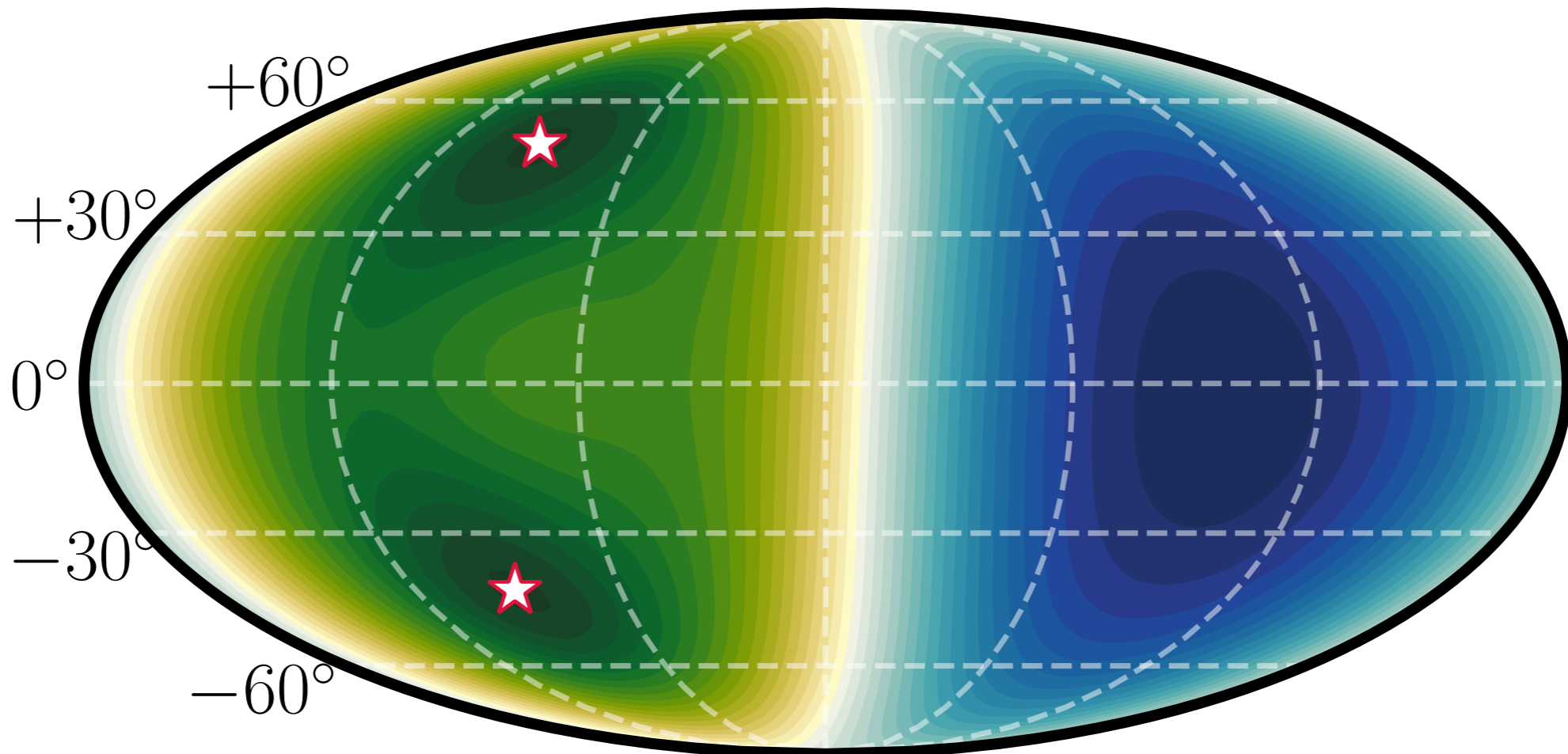


SHM + Gaia Sausage
(Anisotropic component due
to merger with a dwarf galaxy)



The Gaia Sausage gives rise to peaks off center from Cygnus

5 – 10 keV

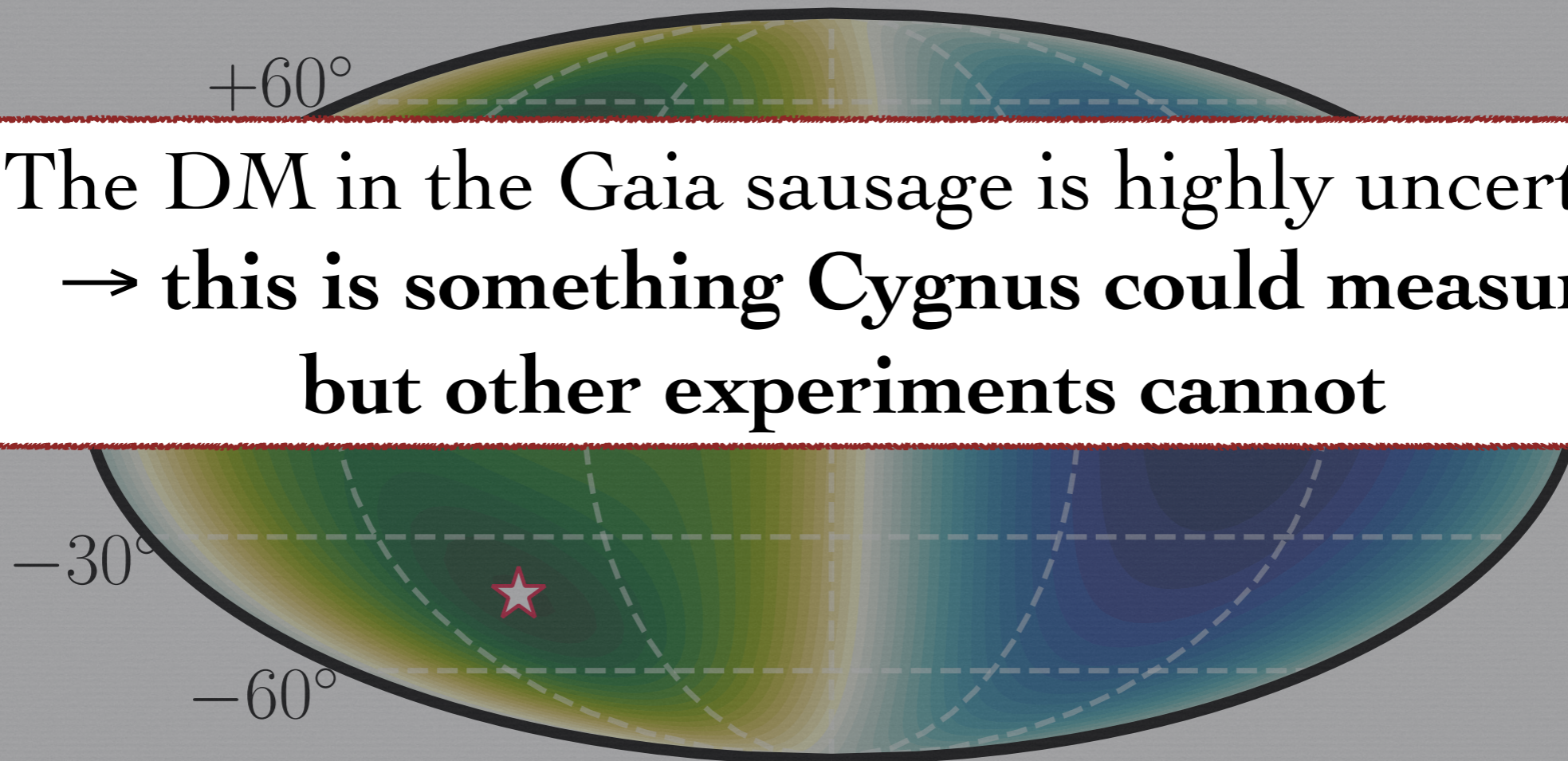


Distribution for 5-10 keVr Fluorine recoils with a 100 GeV WIMP
Halo model = SHM + Sausage

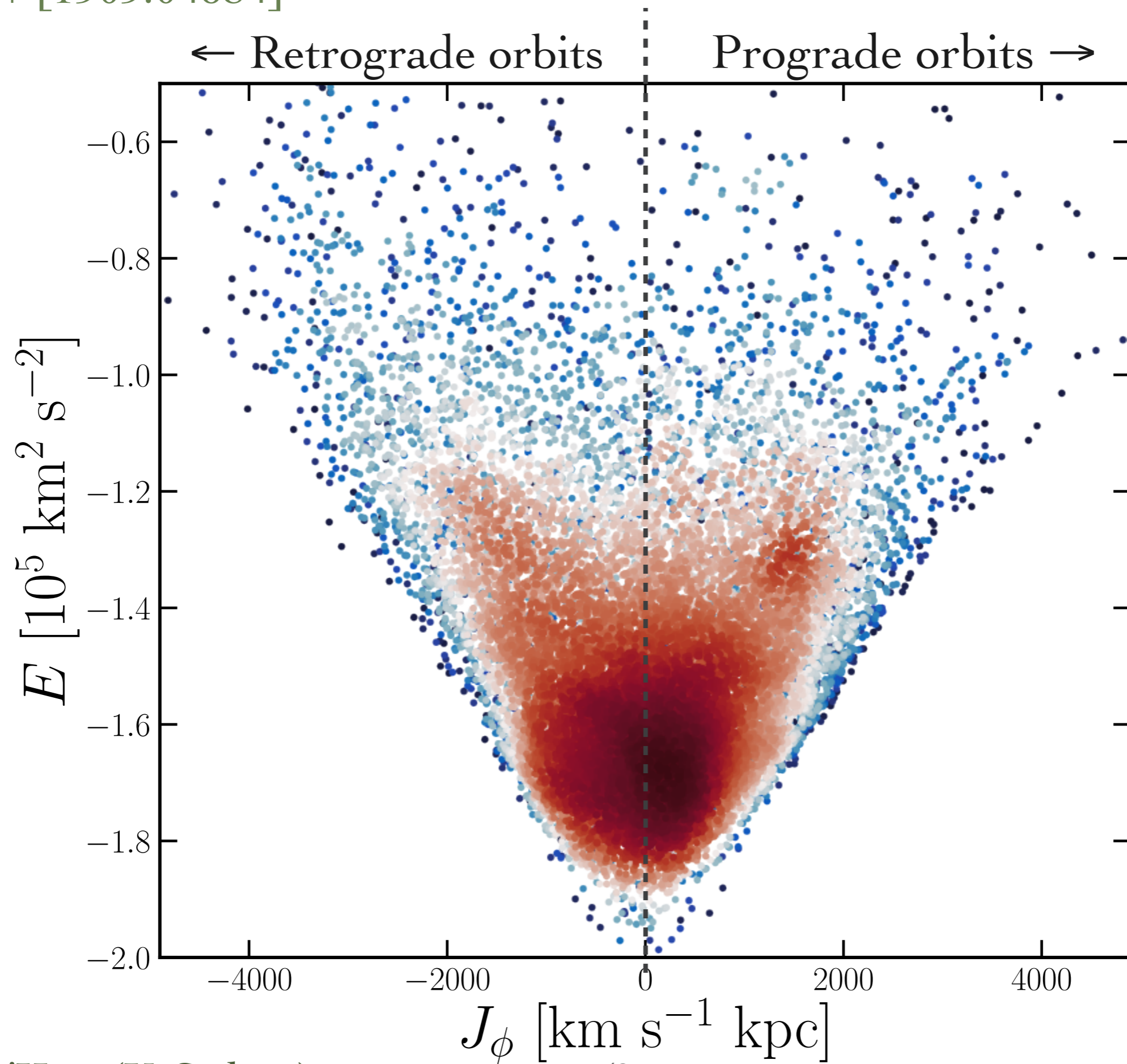
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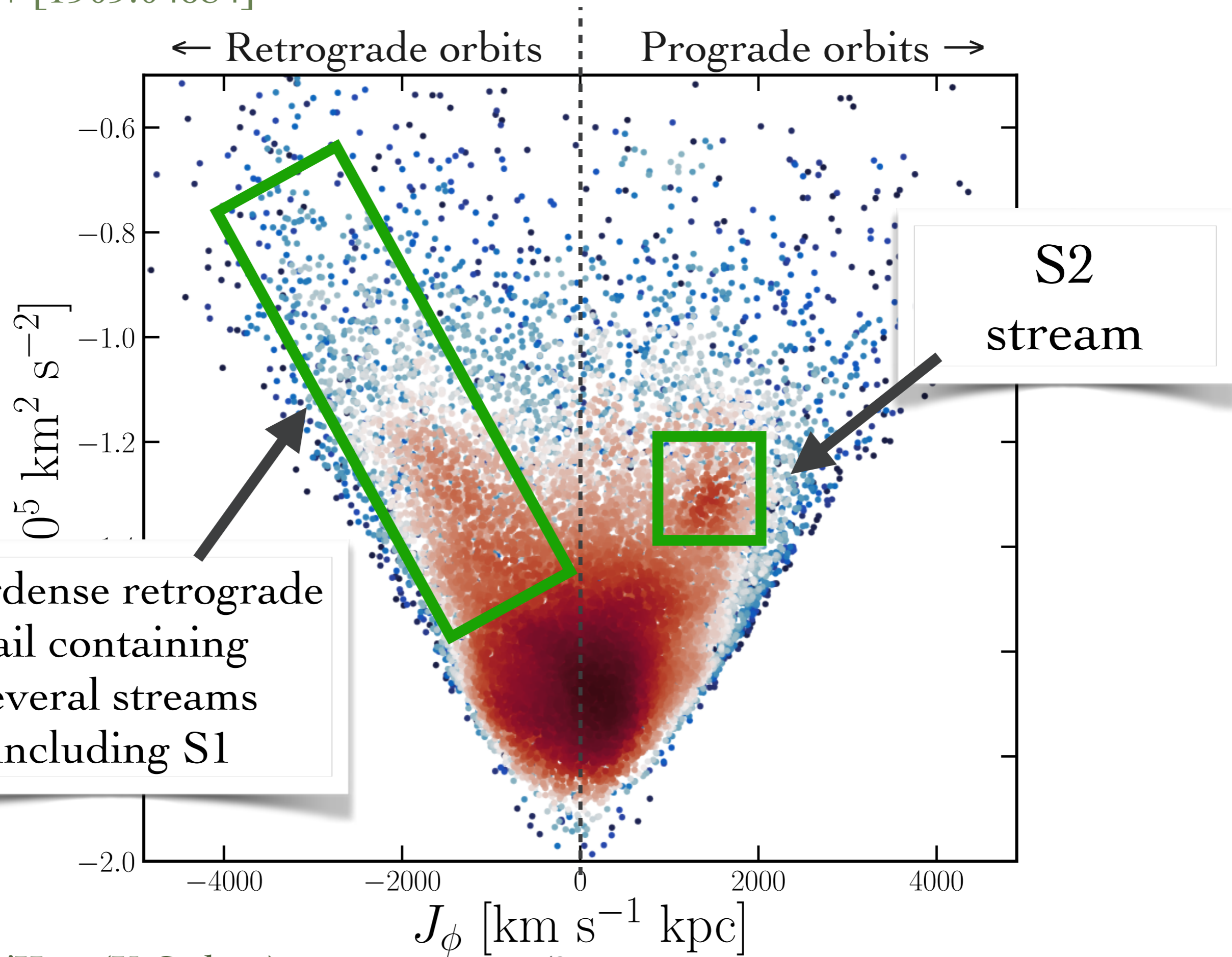
The DM in the Gaia sausage is highly uncertain
→ this is something Cygnus could measure
but other experiments cannot



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

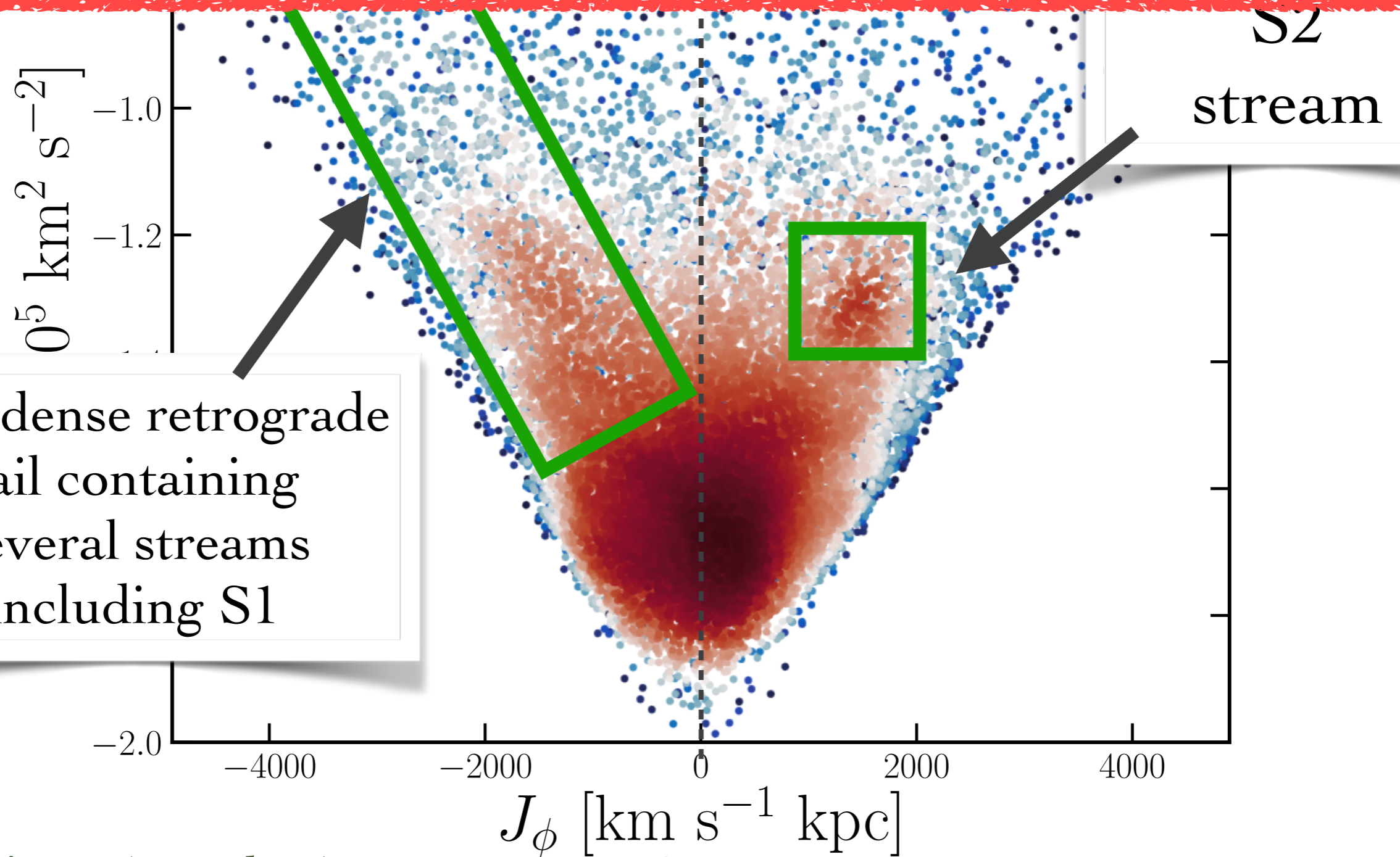


O'Hare+ [1909.04684]



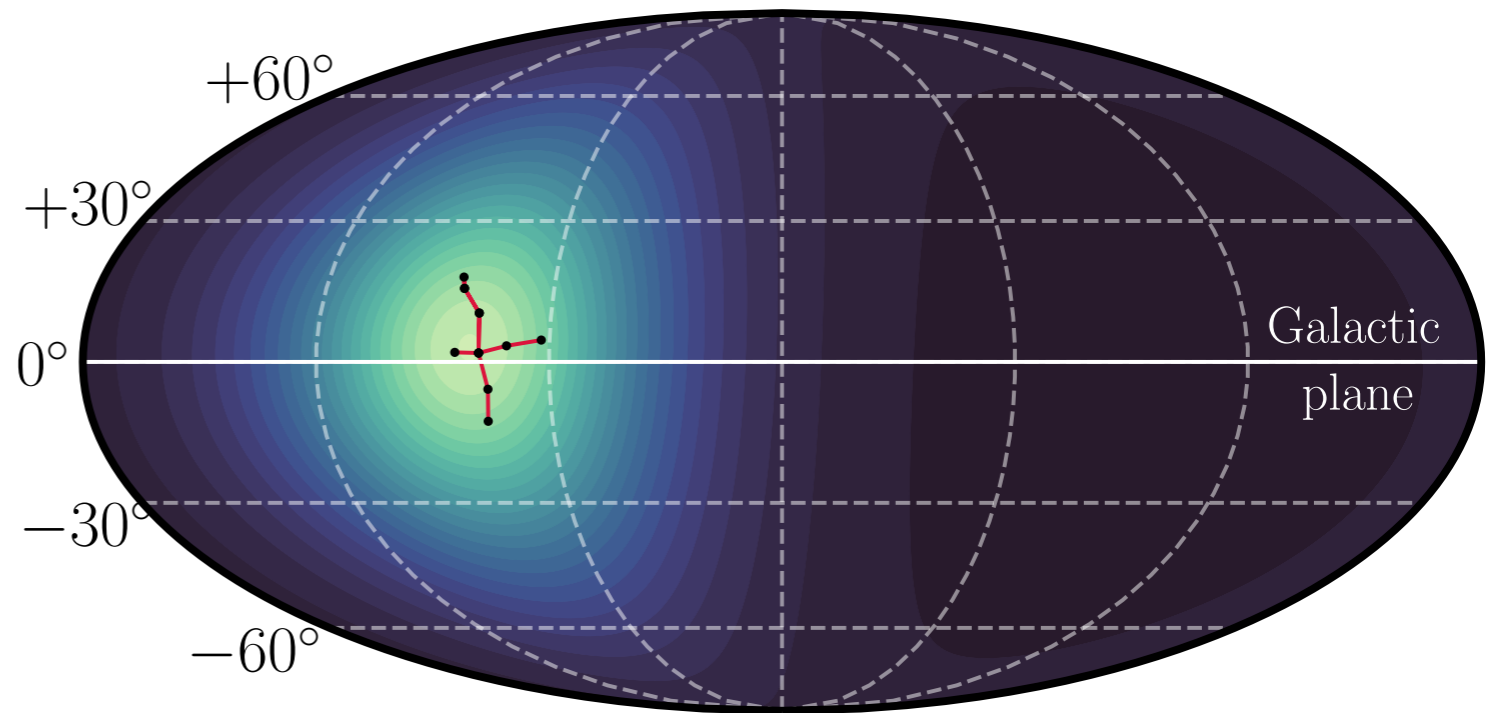
Ciaran O'Hare (U. Sydney)

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

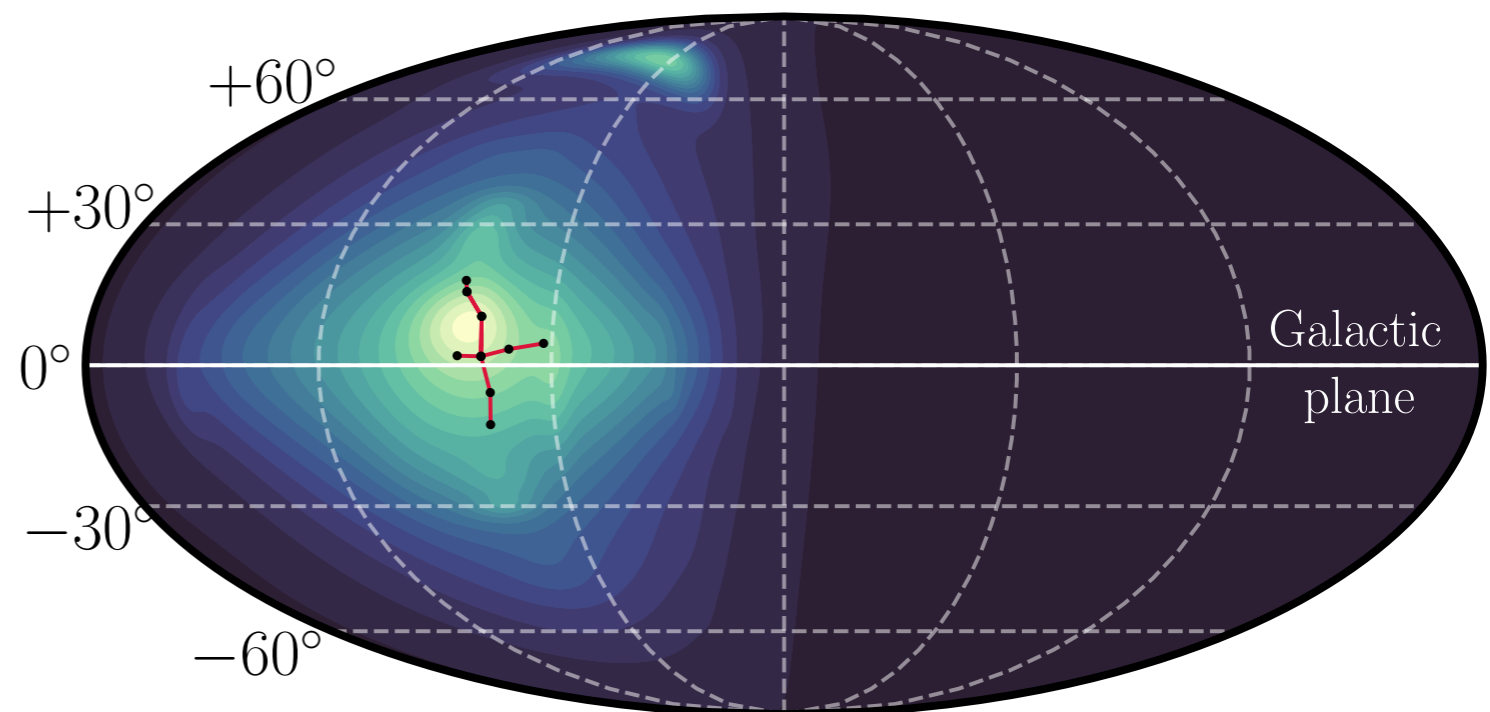


Gaia also shows evidence of substructure passing through Solar position
→ e.g. S1 (hurricane), S2 streams

SHM DM flux
(Gaussian distribution)

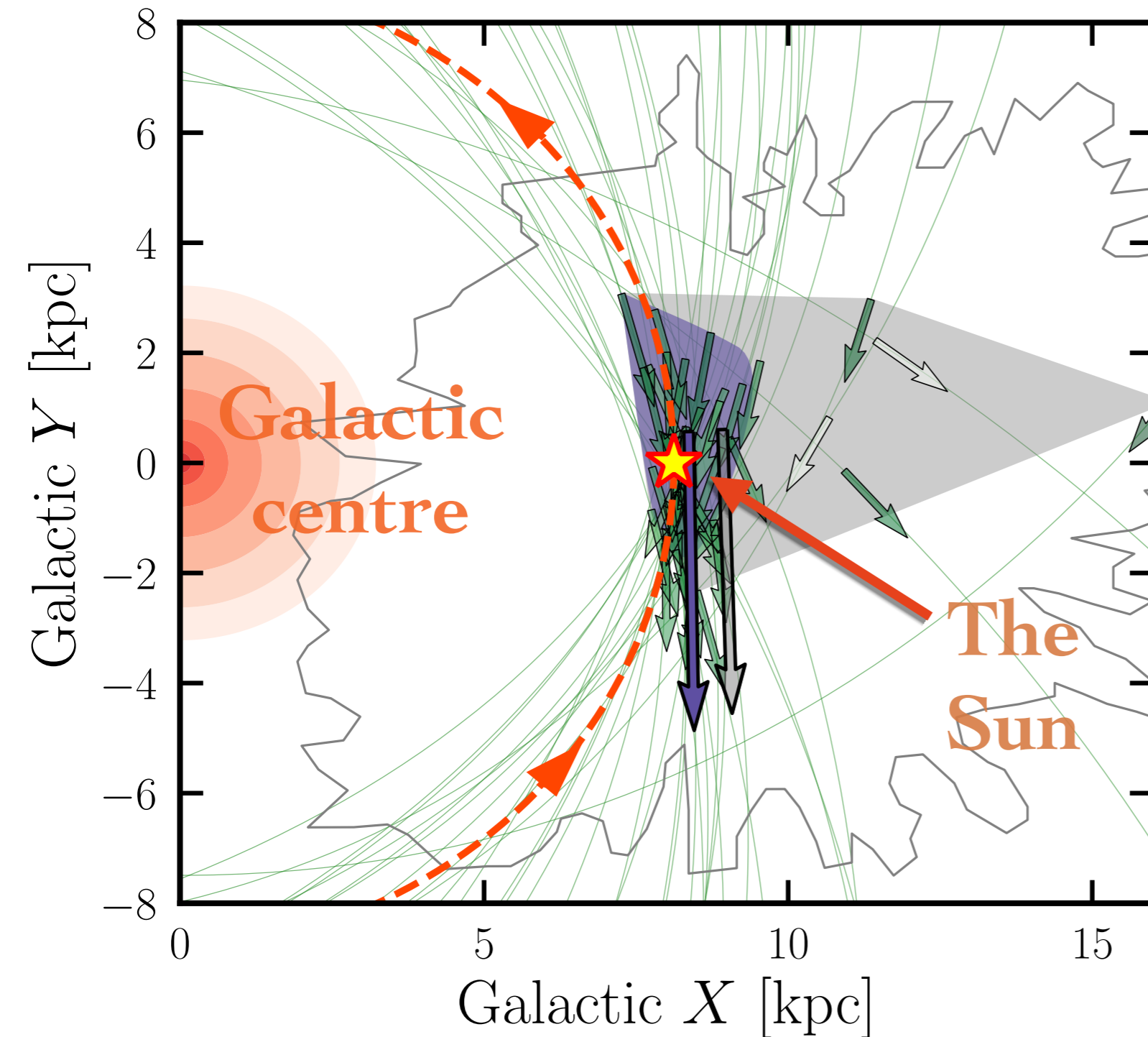


SHM + Gaia Sausage +
Local substructures
(Peaks in other directions due to
streams)



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

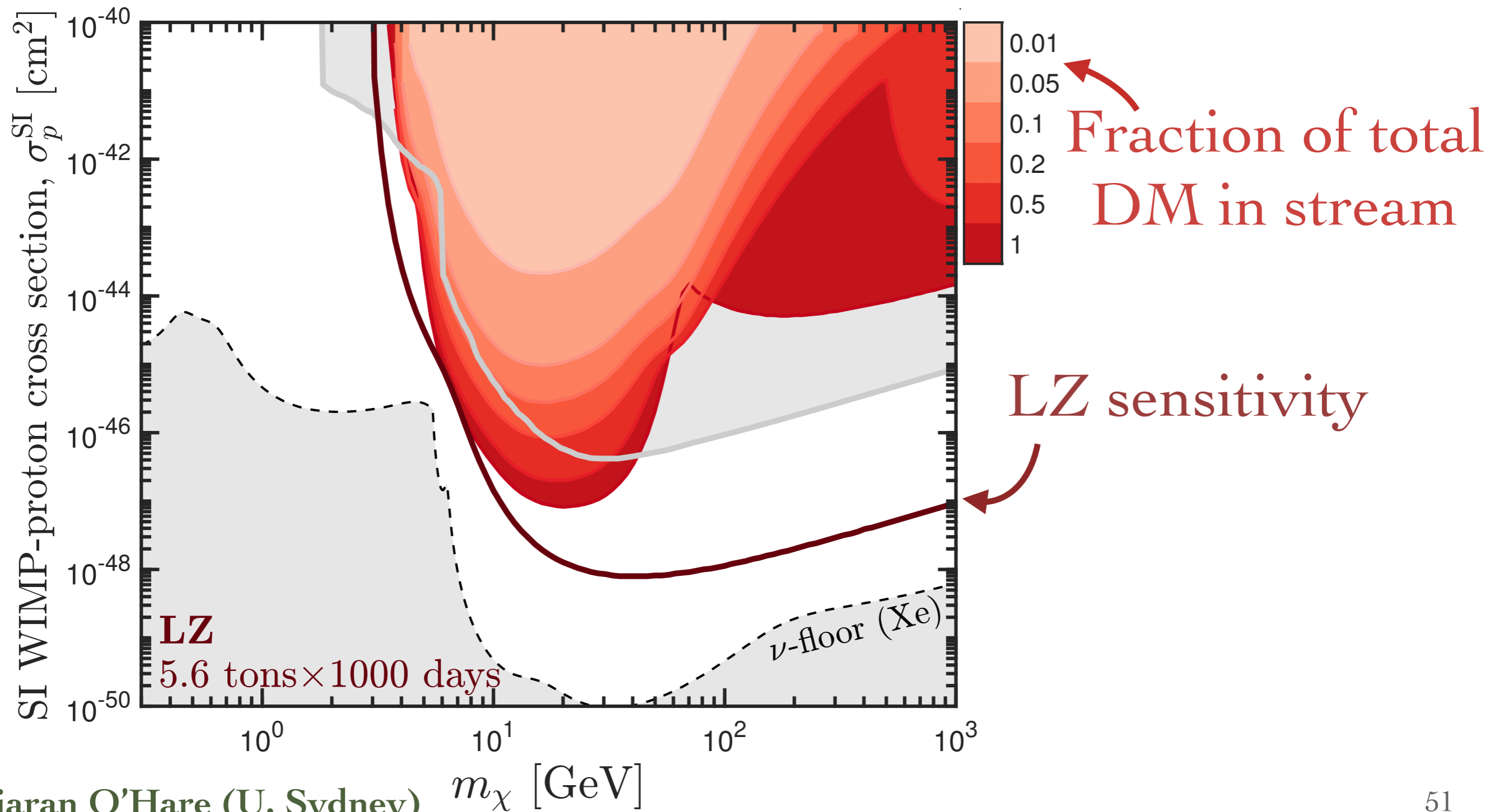
The S1 stream



- 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](#))

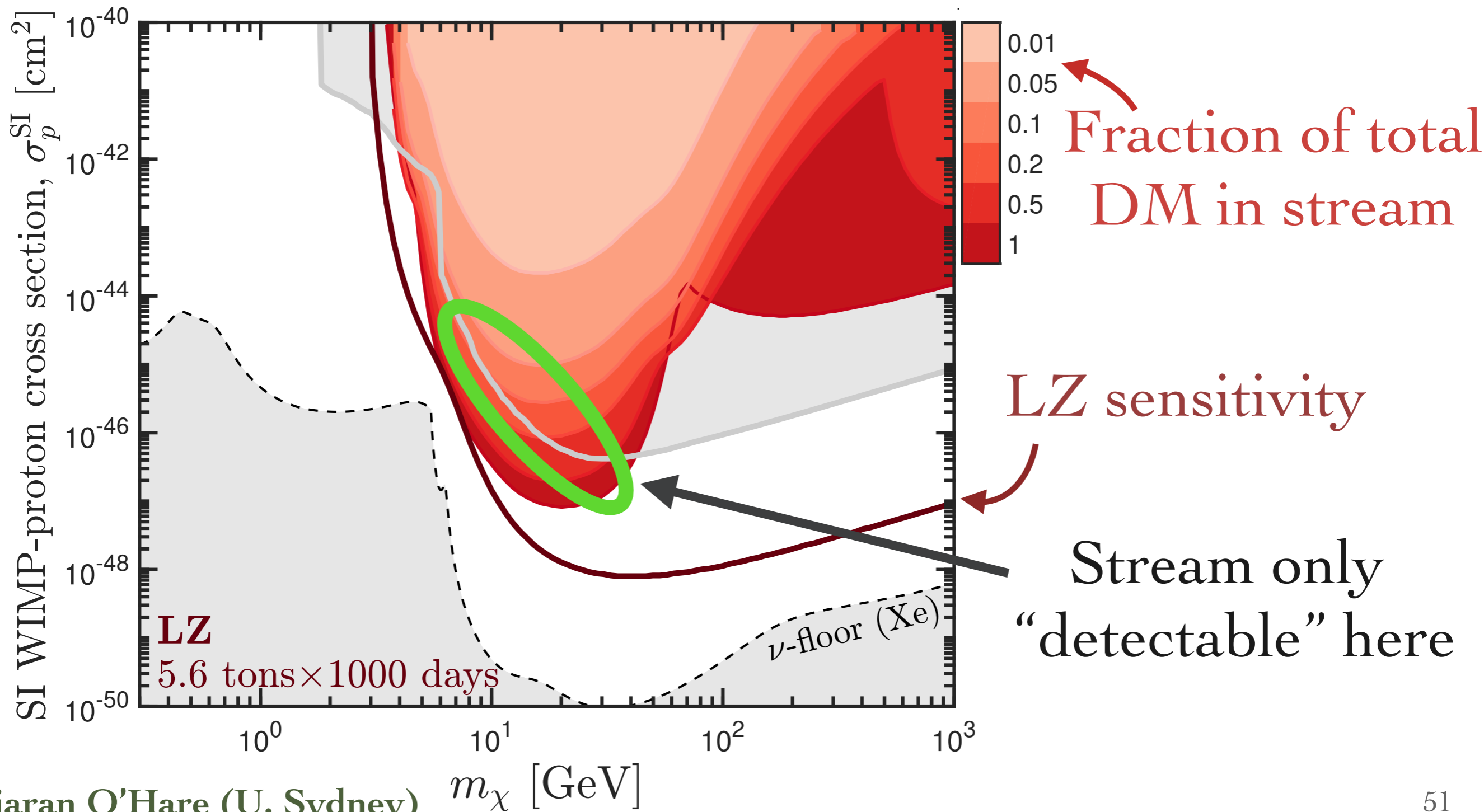
S1 in LZ

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



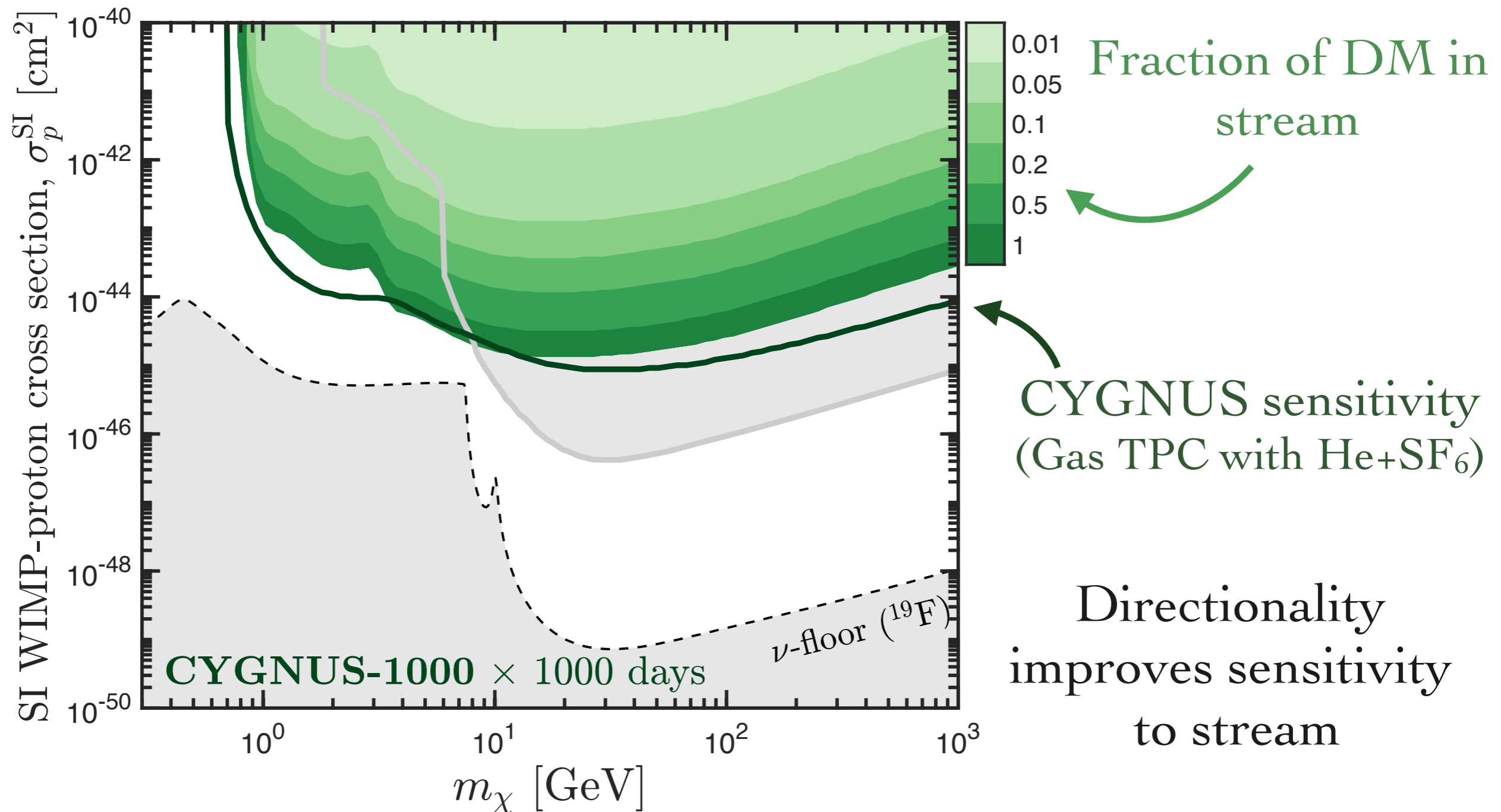
S1 in LZ

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



SI 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

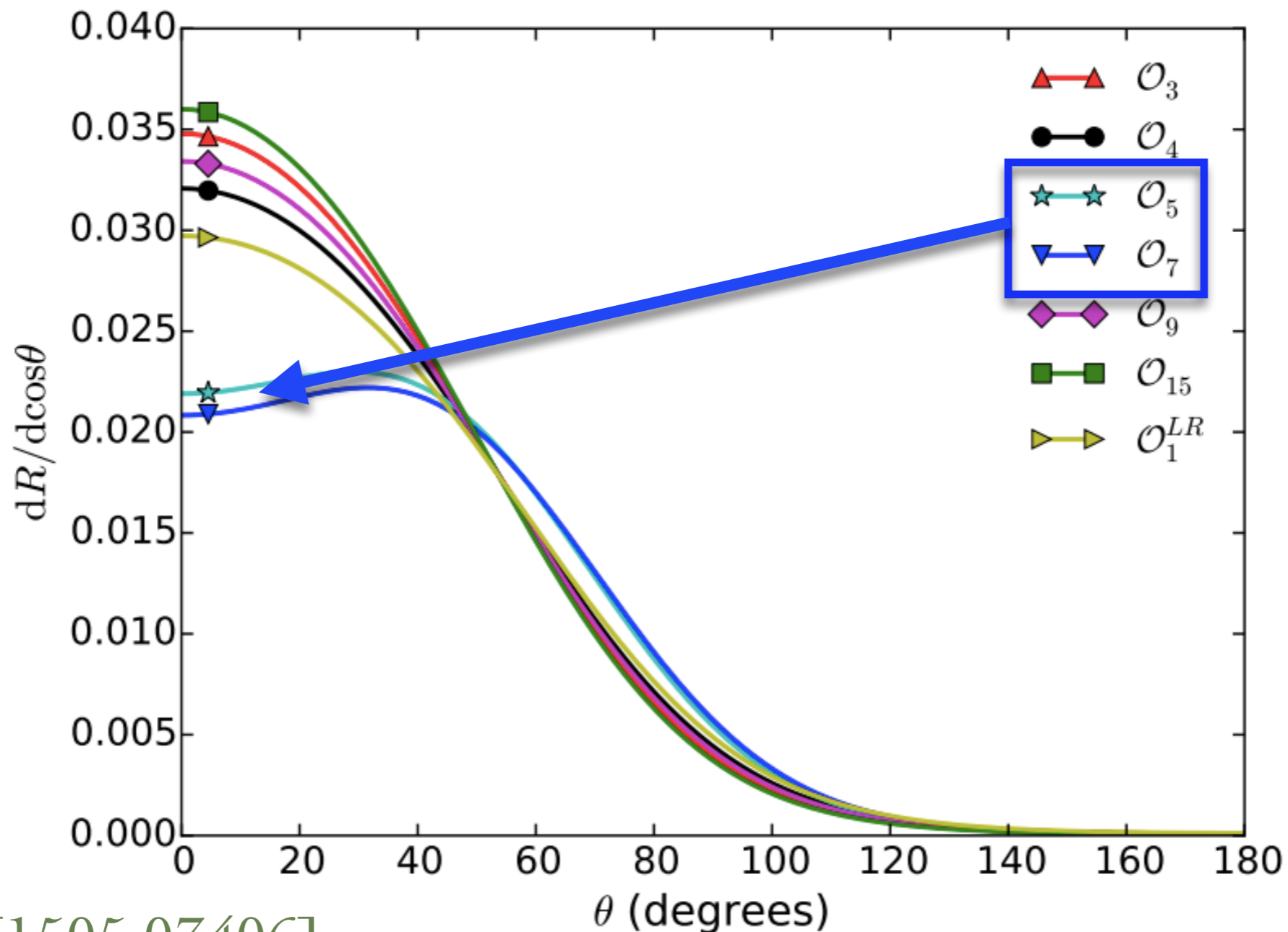


Non-relativistic EFT of DM-nucleus interaction

Allows for operators (e.g. \mathcal{O}_5 , \mathcal{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...

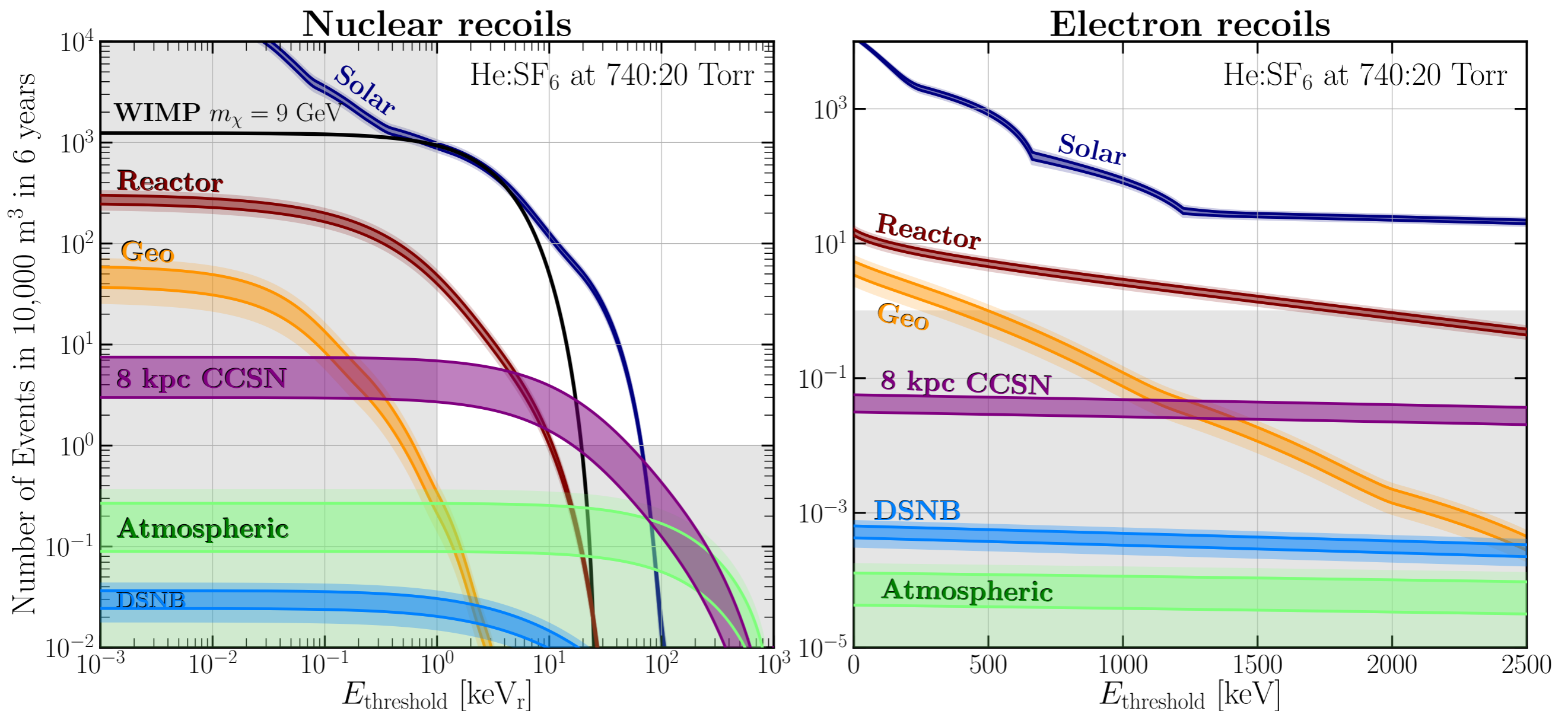
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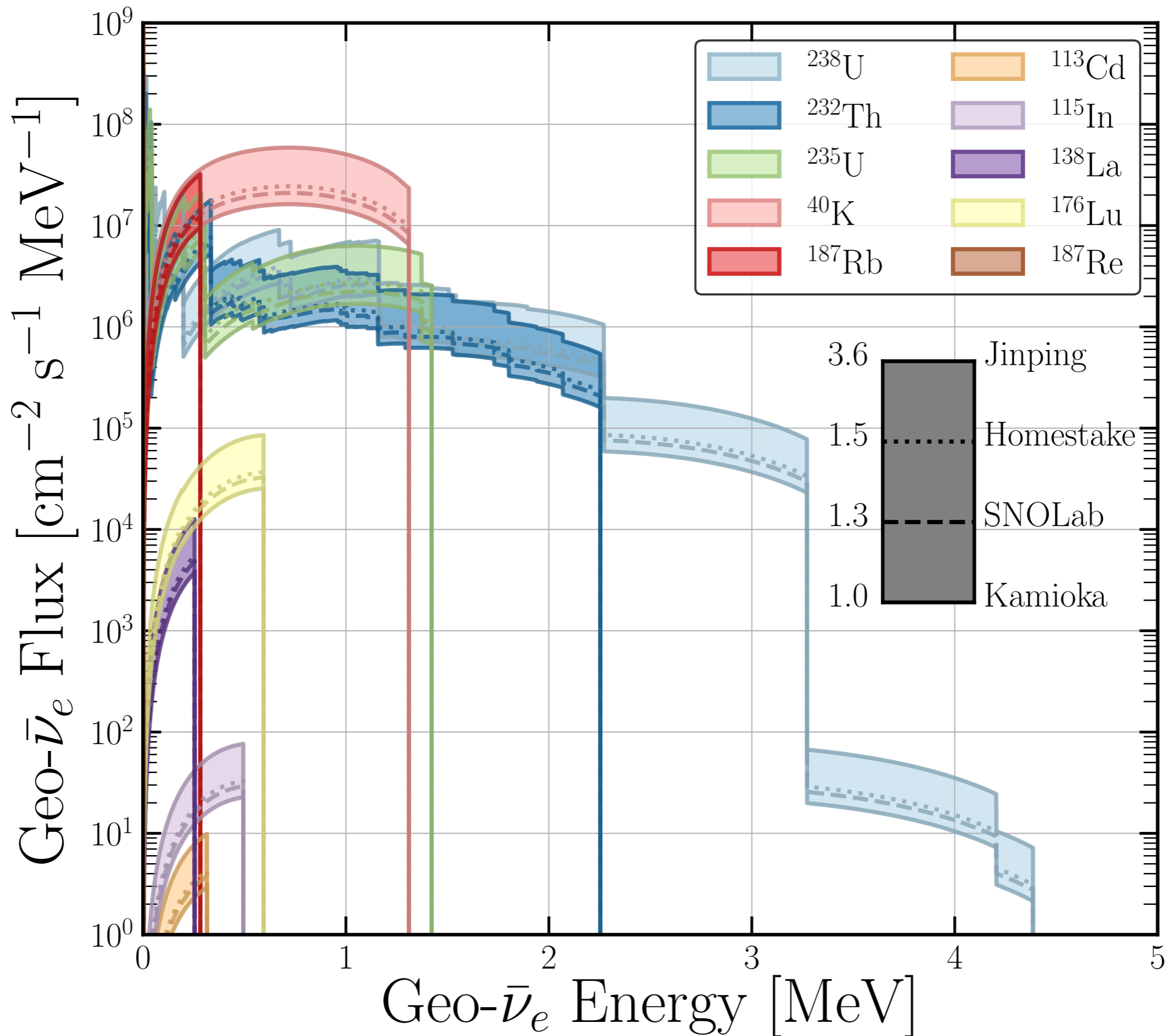
↳ Our background is our signal

The neutrino background

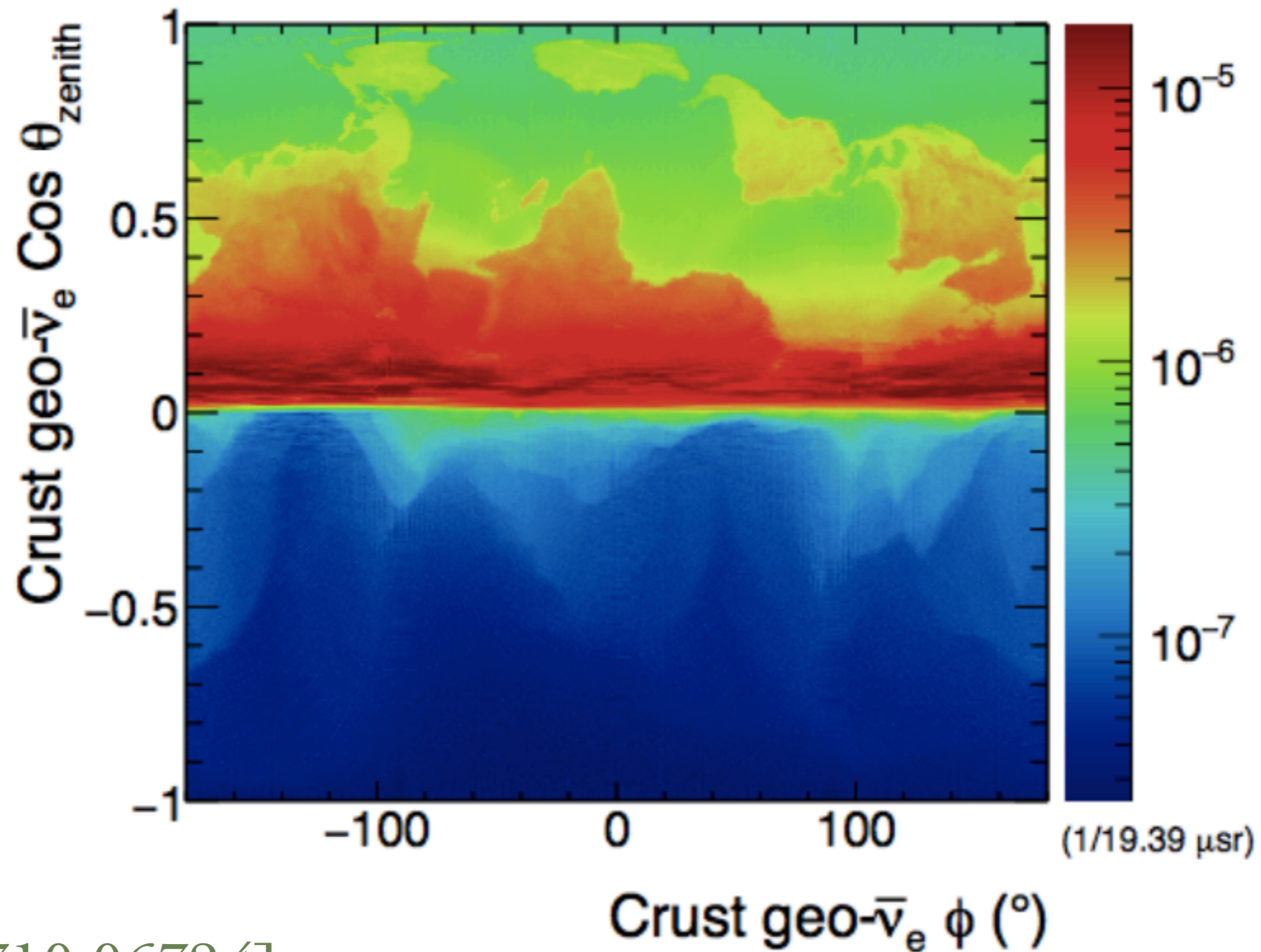


A directional detector has the potential for superior background rejection and NR/ER discrimination
→ this is true even if you're not talking about DM

Geoneutrino flux



Geoneutrino flux



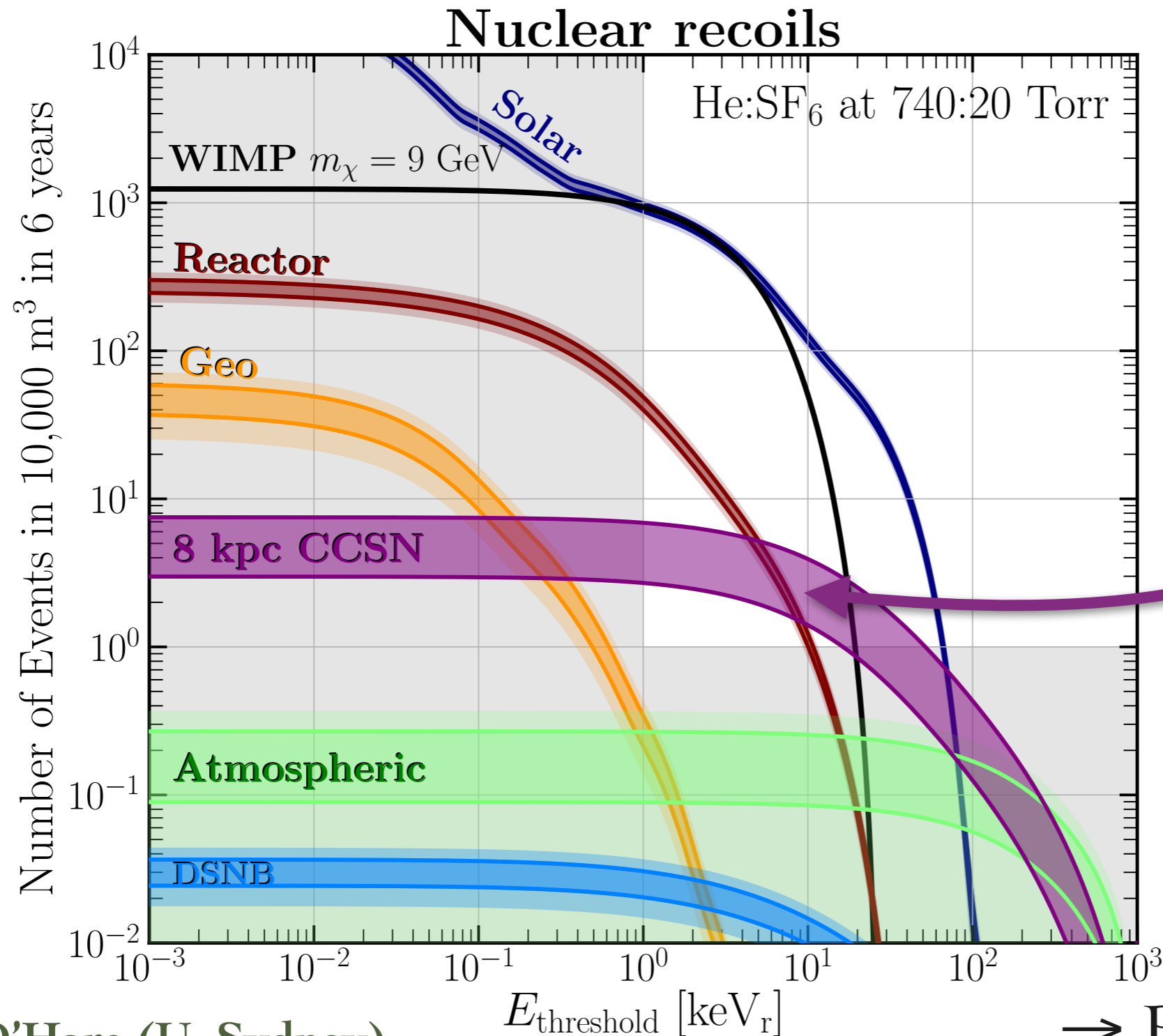
Leyton+ [1710.06724]

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

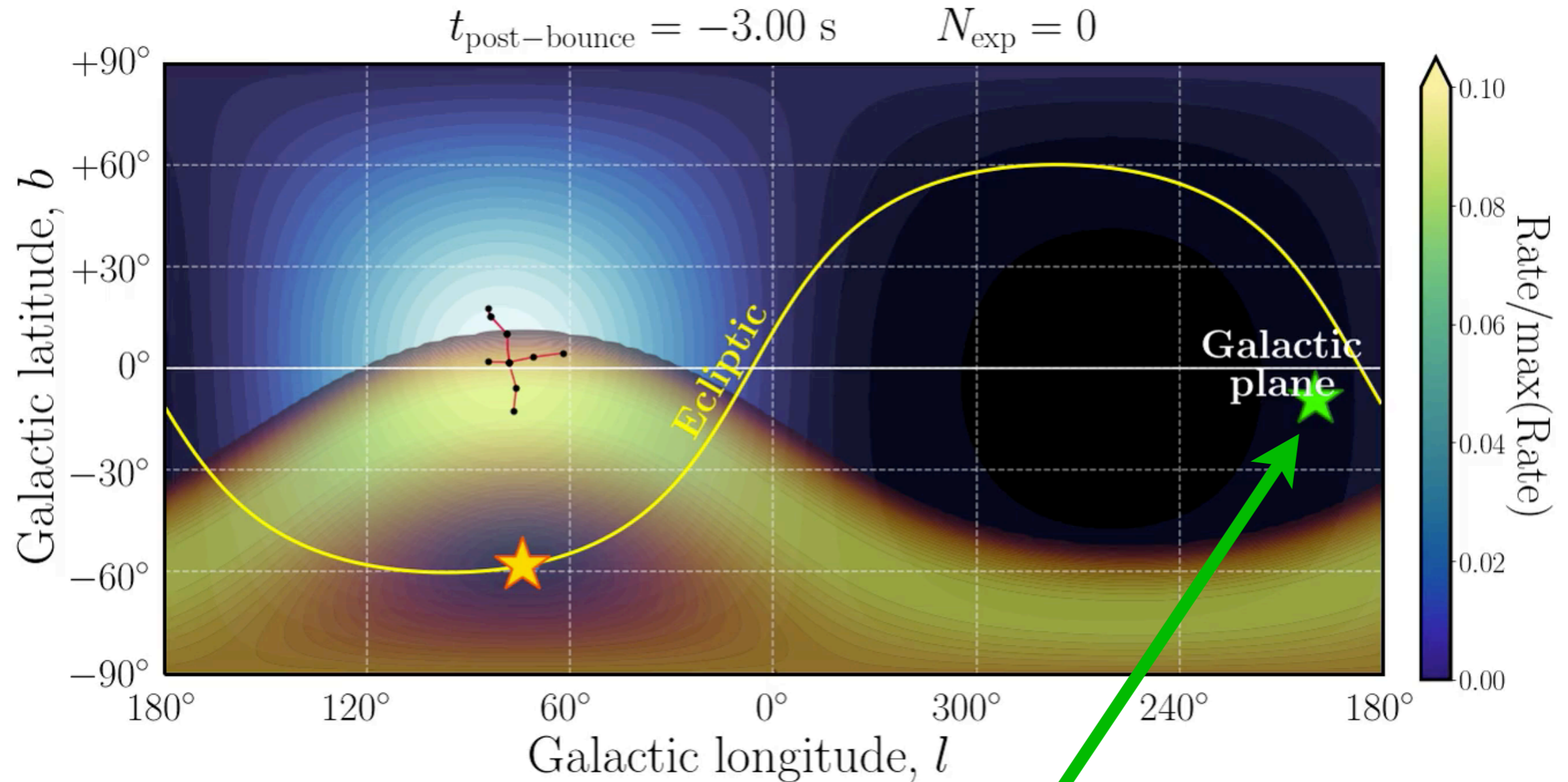
Expect >3 events in CYGNUS-10k for $10\text{-}30 M_{\odot}$ core-collapse Supernova closer than >8 kpc



→ But flux goes as d^{-2}

Pointing to a supernovae

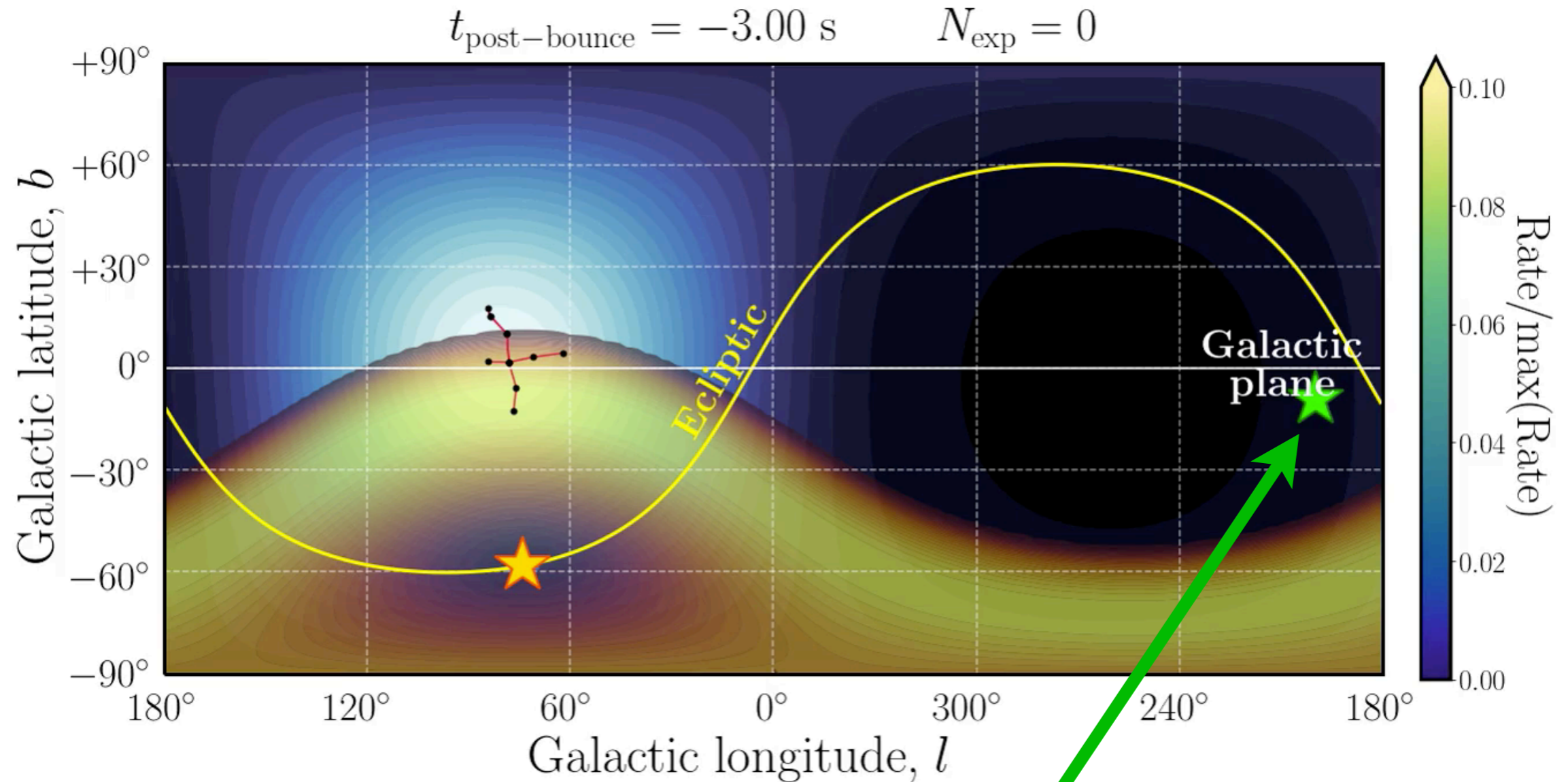
(movie)



Very close $O(100 \text{ pc})$ 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)



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