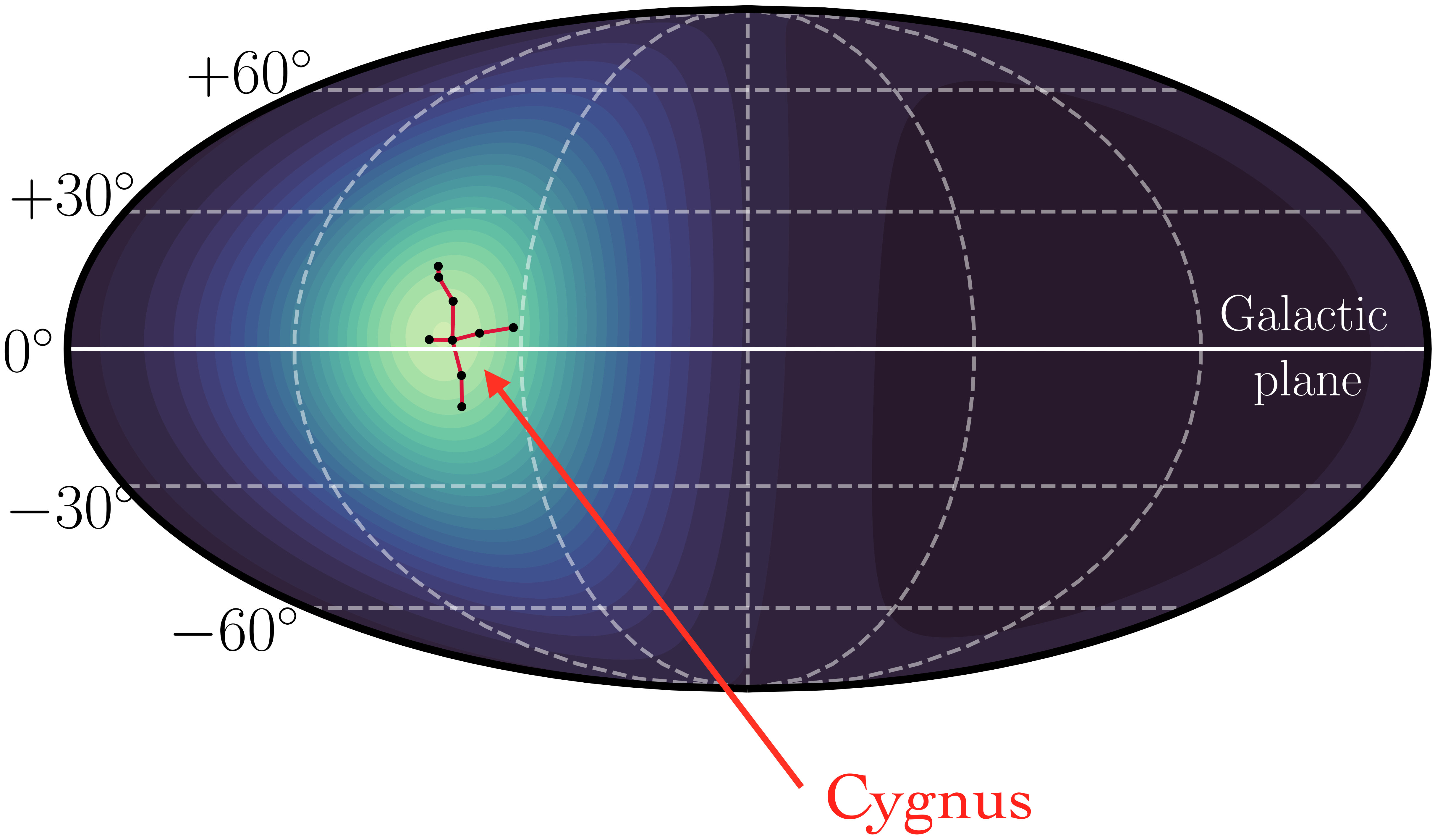
Universidad
Zaragoza
1542

CYGNUS

Motivation and physics reach for CYGNUS

Ciaran O'Hare

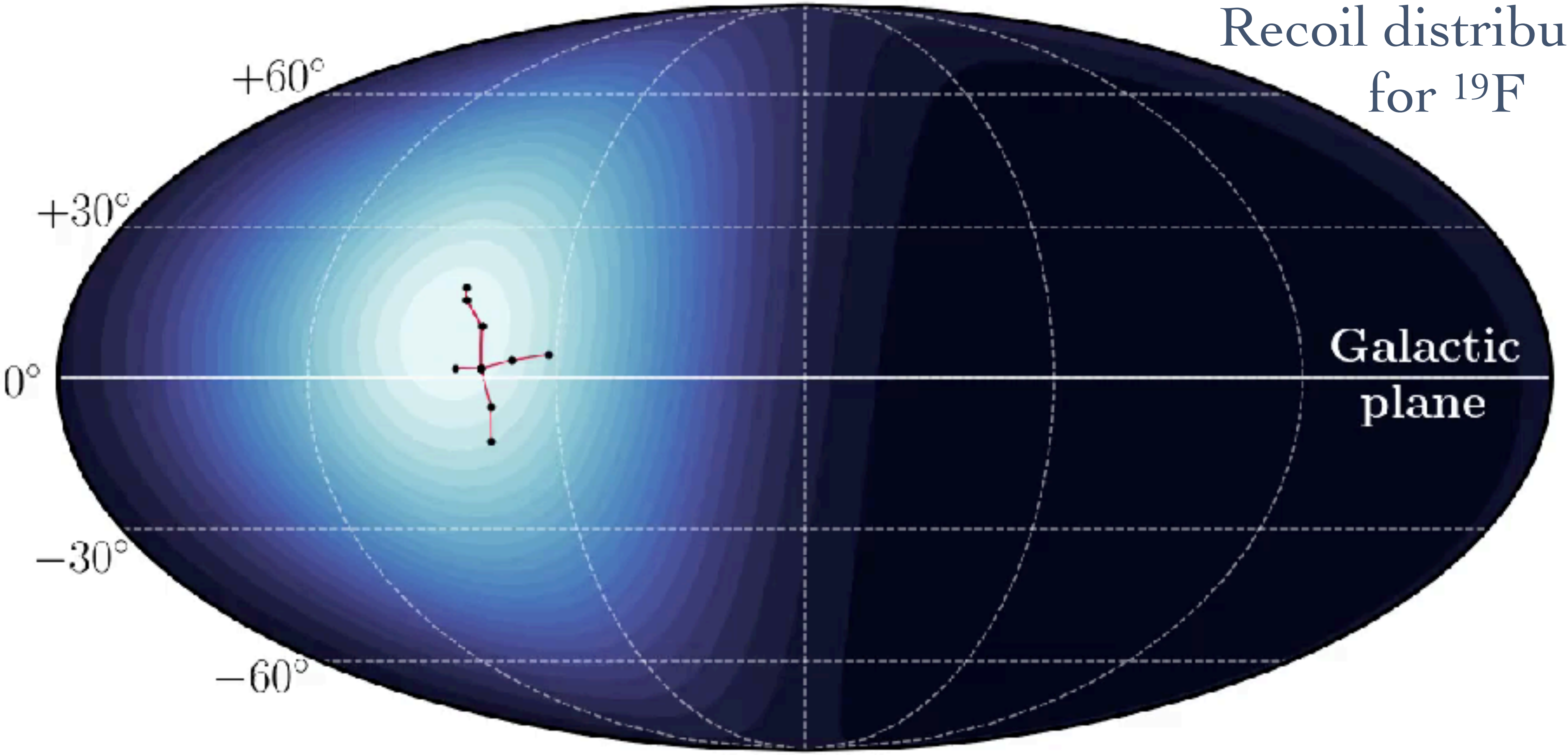
Why are we here?
→ The dark matter flux is anisotropic



To confirm a galactic signal we need it to be fixed* in galactic coordinates

Nothing other than dark matter will do this…

January 1

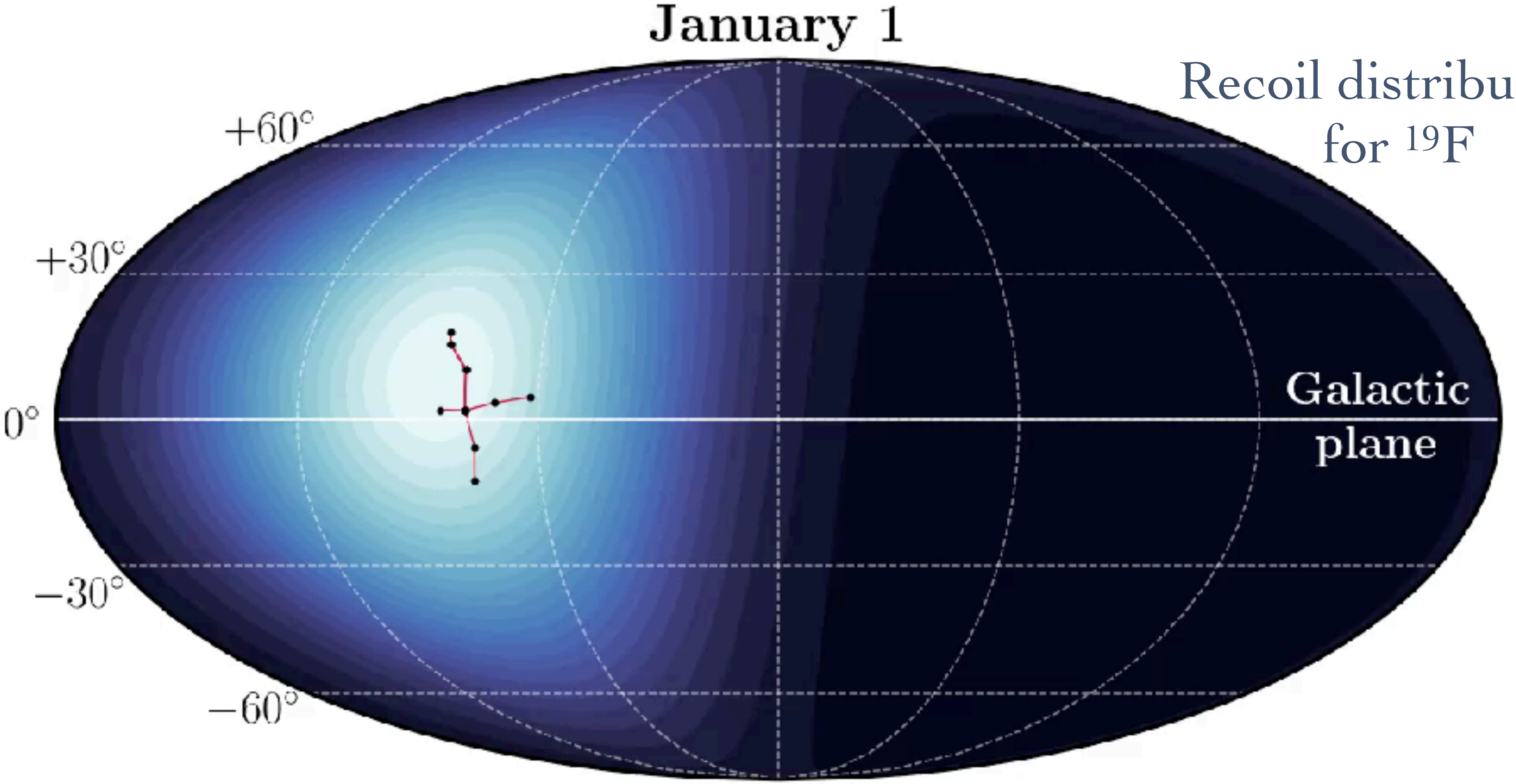


Recoil distribution for ^{19}F

*slight aberration due to motion of Earth around the Sun

To confirm a galactic signal we need it to be fixed* in galactic coordinates

Nothing other than dark matter will do this…



January 1

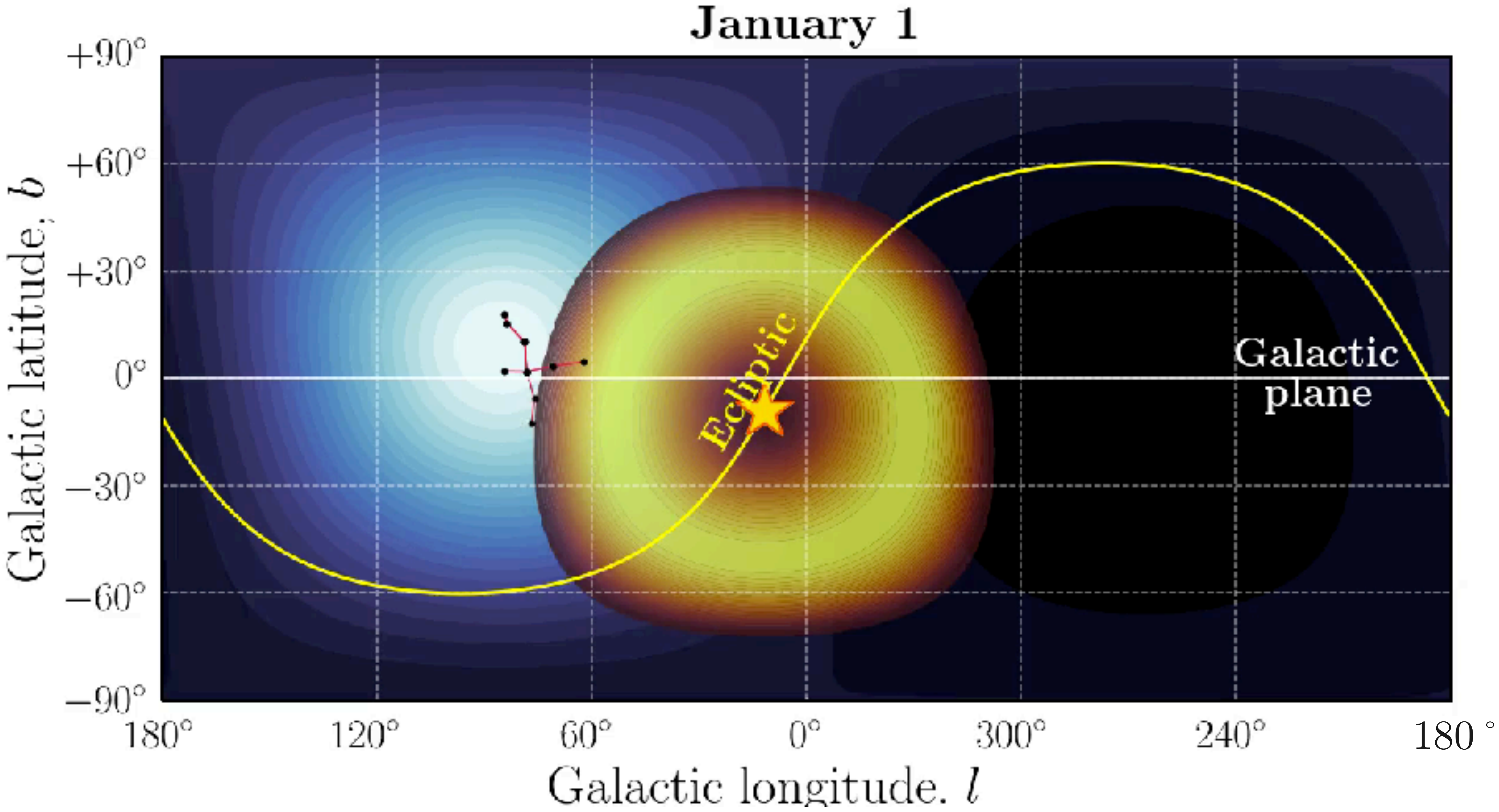
Recoil distribution for ^{19}F

Galactic plane

*slight aberration due to motion of Earth around the Sun

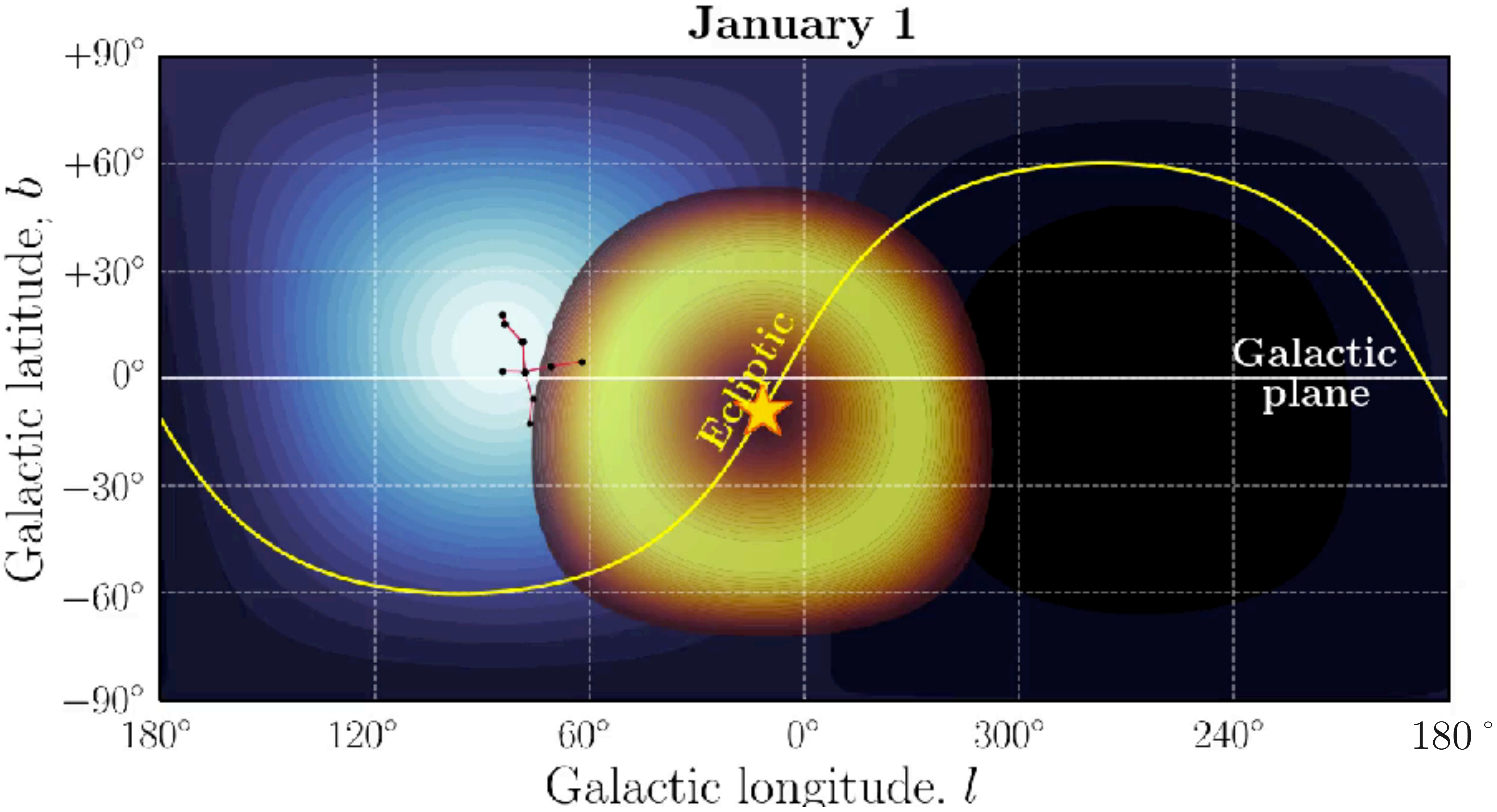
To confirm a galactic signal we need it to be fixed* in Galactic coordinates

Nothing other than dark matter will do this…
…including solar neutrinos



To confirm a galactic signal we need it to be fixed* in Galactic coordinates

Nothing other than dark matter will do this…
…including solar neutrinos



Dimensionality of readout

Still the case even if only one angle is available

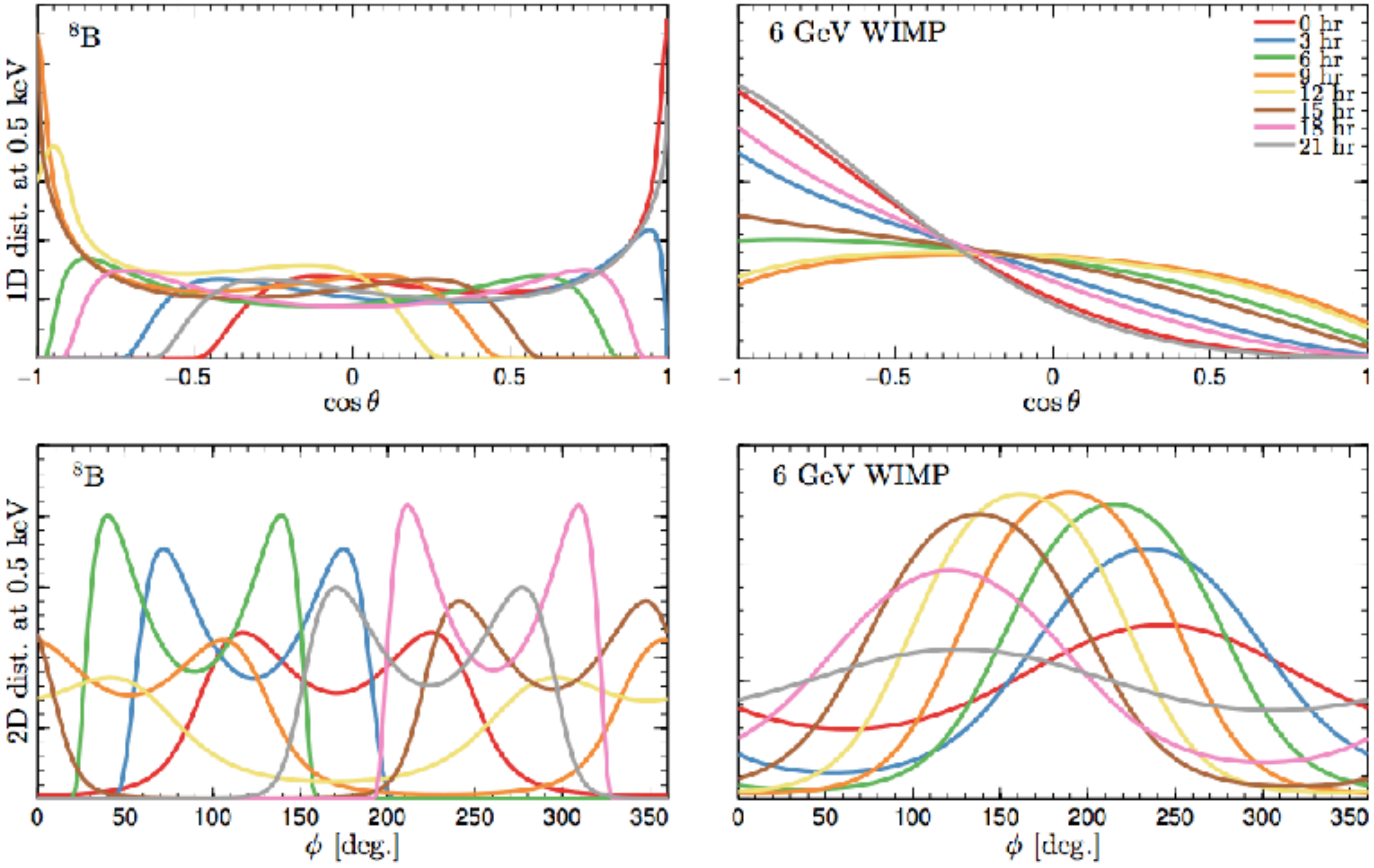
Neutrinos **WIMP**

1D

(e.g. angle w.r.t. drift direction)

2D

(e.g. angle across readout plane)



Physics case for a directional detector is pretty clear in the idealised case:

	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)

Physics case for a directional detector is pretty clear in the idealised case:

	Events in a non-directional detector	Events in a directional detector
[illegible]	O(10)	~10
[illegible]	[illegible]sible	~30
[illegible]	[illegible]sible	O(10)
Measure DM velocity distribution	O(1000)/Impossible	O(100)

That's for an ideal directional detector with perfect track reconstruction, what could a real detector do?

The CYGNUS paper aims to answer this
→ realistic detector model based on full gas and readout simulation

Targets: Helium and Fluorine

- He at 755 torr (1000 m^3 = 0.163 tons)
- F (as in SF_6) at 5 torr (1000 m^3 = 0.04 tons)

Backgrounds: just neutrinos

- Solar, Atmospheric, Reactor, Geo, Diffuse SN
- Perfect ER/NR discrimination (no electron recoils)

Detectors: (from Sven's simulations)

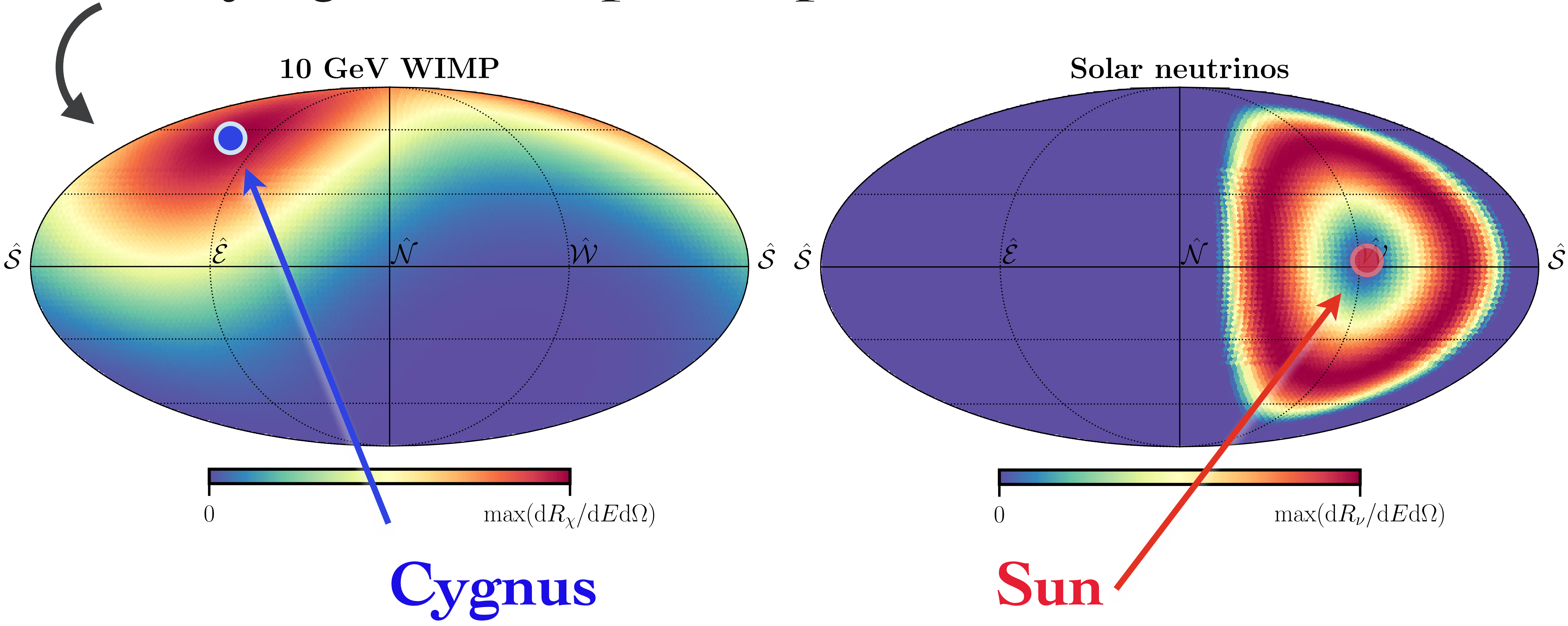
- Threshold: 8 keVr (*e* discrimination) down to maybe 0.25 (single electron)
- Pre diffusion: angular resolution <30 deg
- Pre diffusion: head-tail recognition >80%

$\}$ These are **very** important

Signal in laboratory coordinates:

Expt: Fluorine recoils above 3 keV_r
Location: Boulby, UK
Time: 12 Sep. 18:00 GMT

Underlying recoil maps (i.e. perfect track reconstruction)

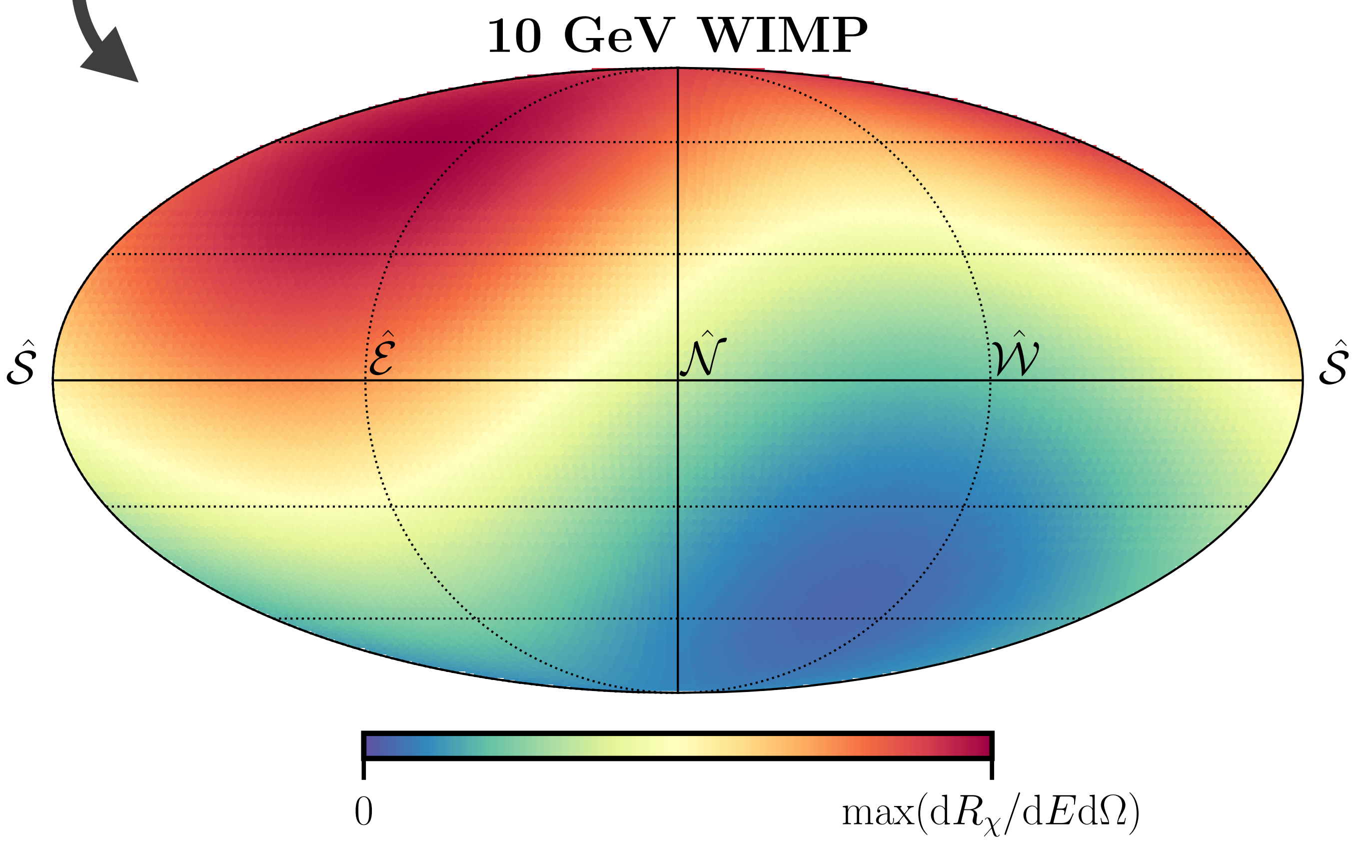


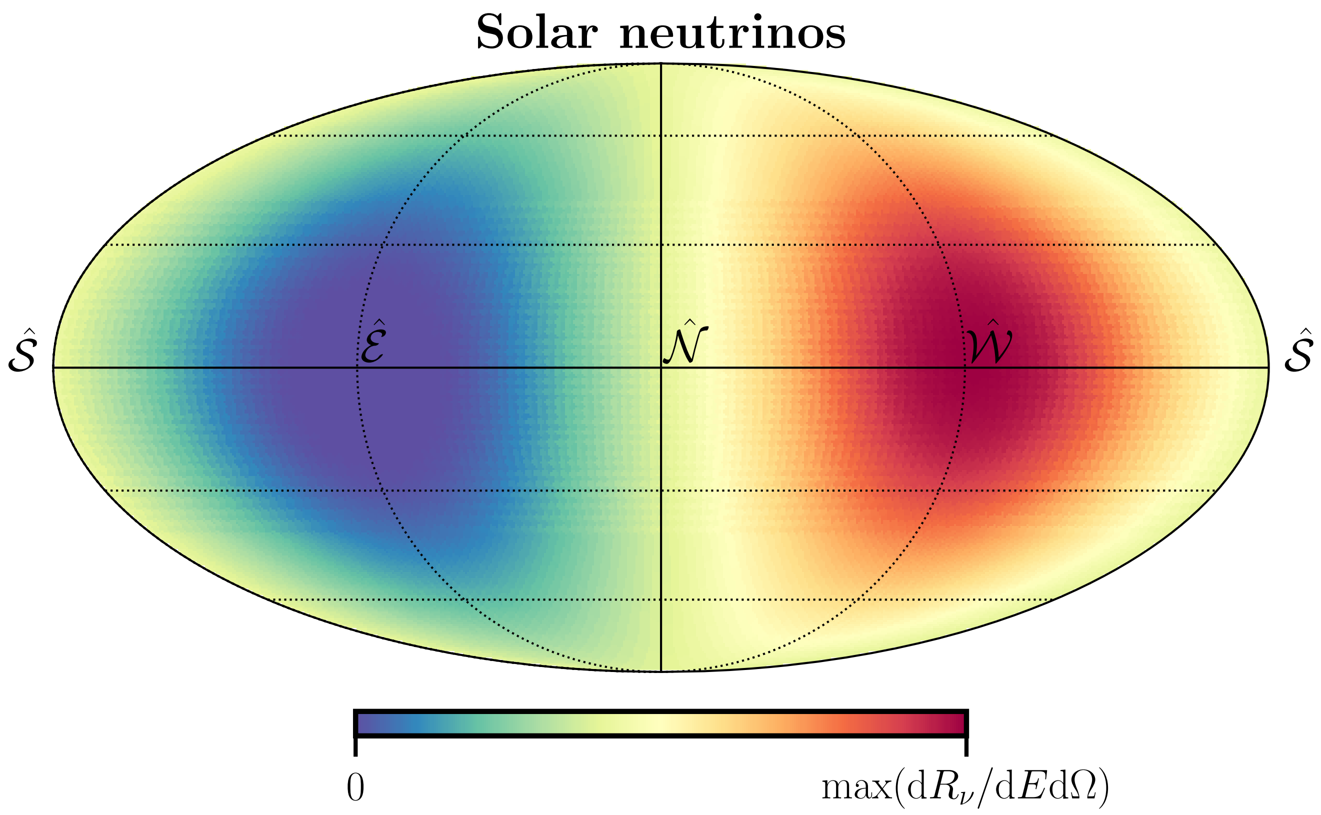
What about a real detector?

Angular resolution → smears distributions in angle

No head-tail → folds one half of sky on to the other

The same maps after 30° **angular resolution** applied

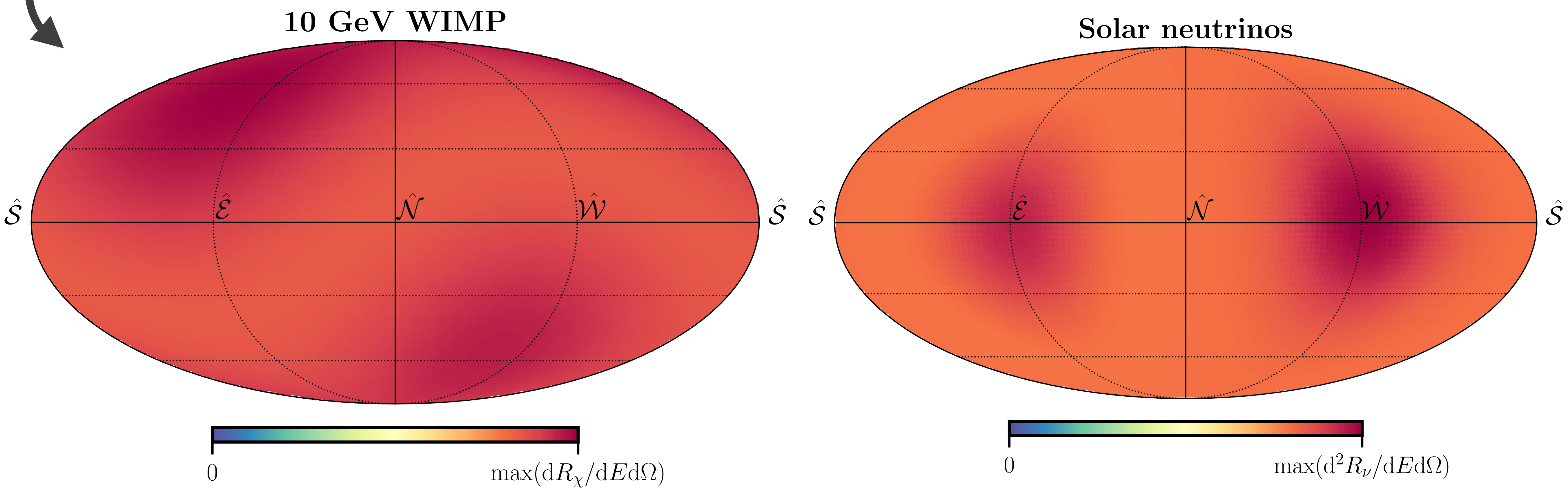




What about a real detector?

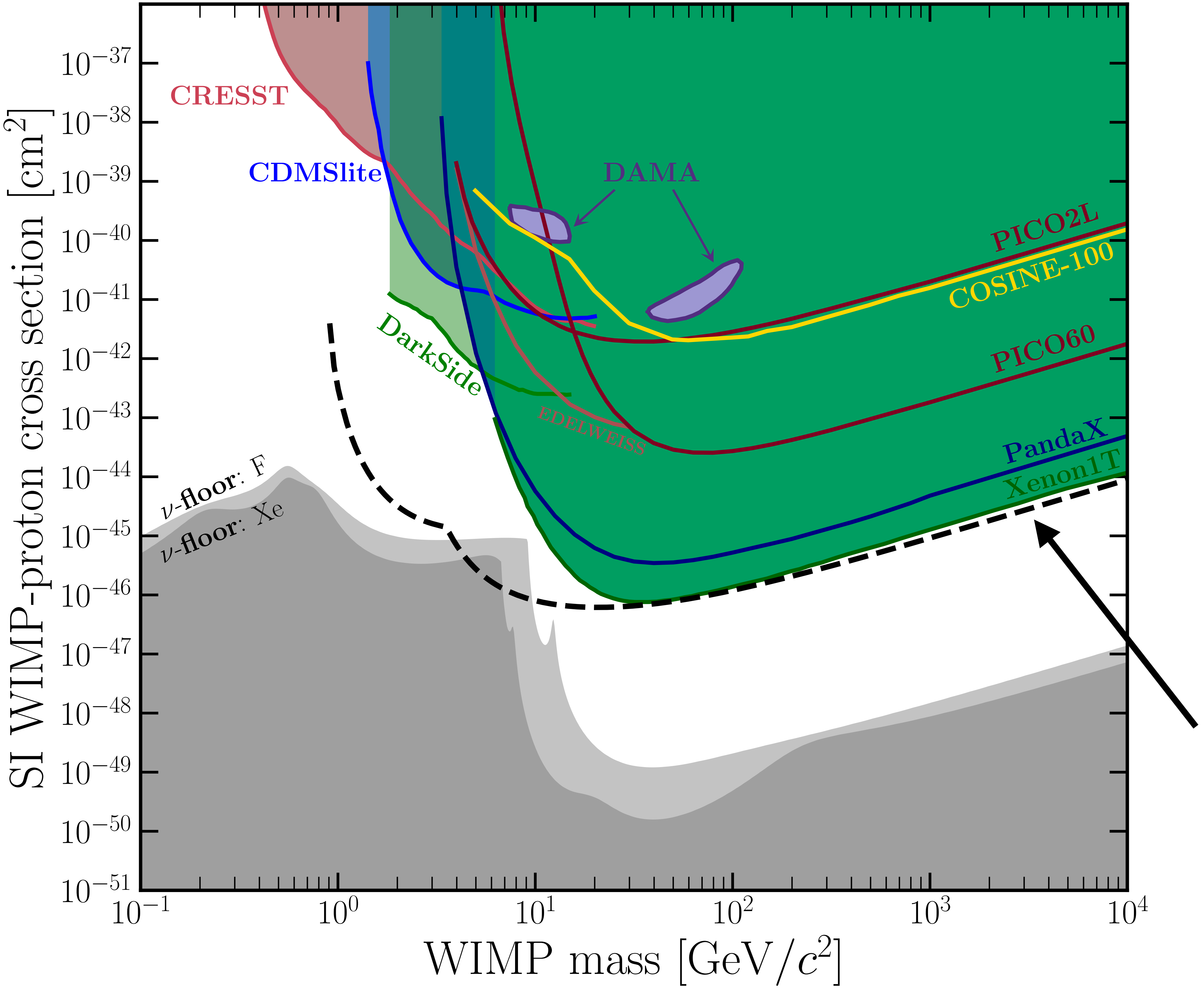
Angular resolution → smears distributions in angle
No head-tail → folds one half of sky on to the other

30° **angular resolution** and *75%* correct **head-tail recognition**



How much does detector performance matter?

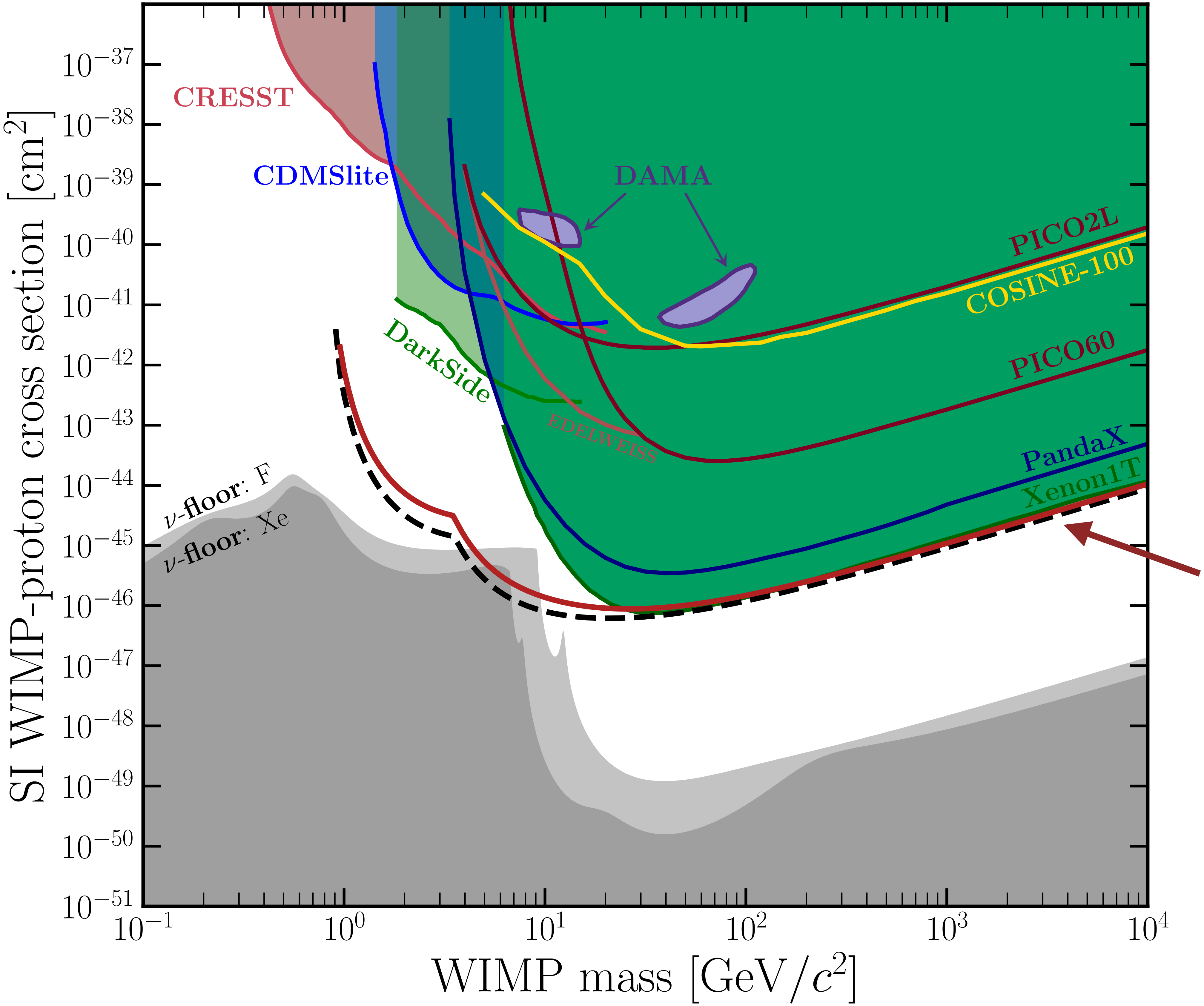
(CYGNUS 1000 m^3 x 6 years)



Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(Cygnus 1000 m^3 x 6 years)

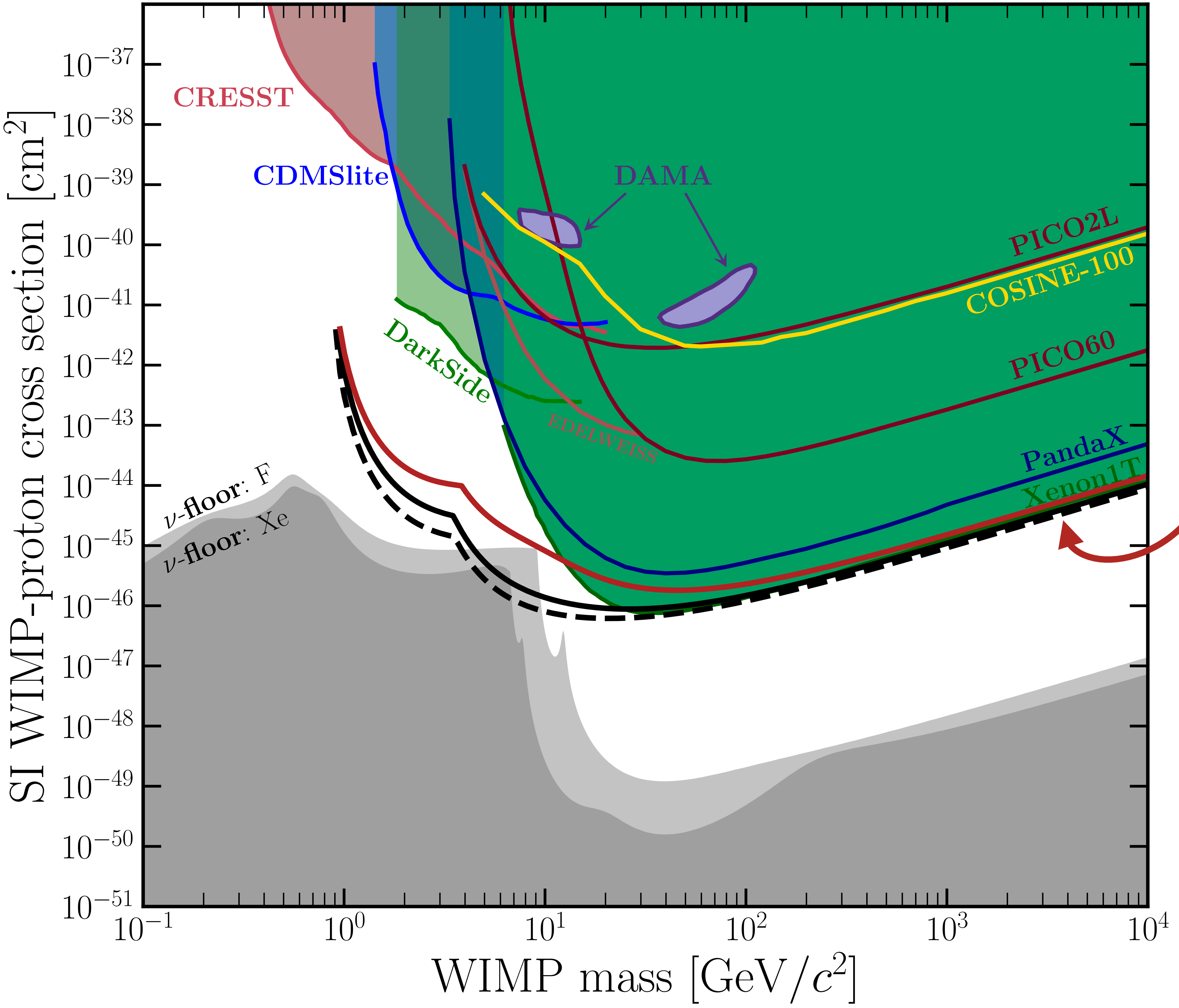


Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(Cygnus 1000 m^3 x 6 years)



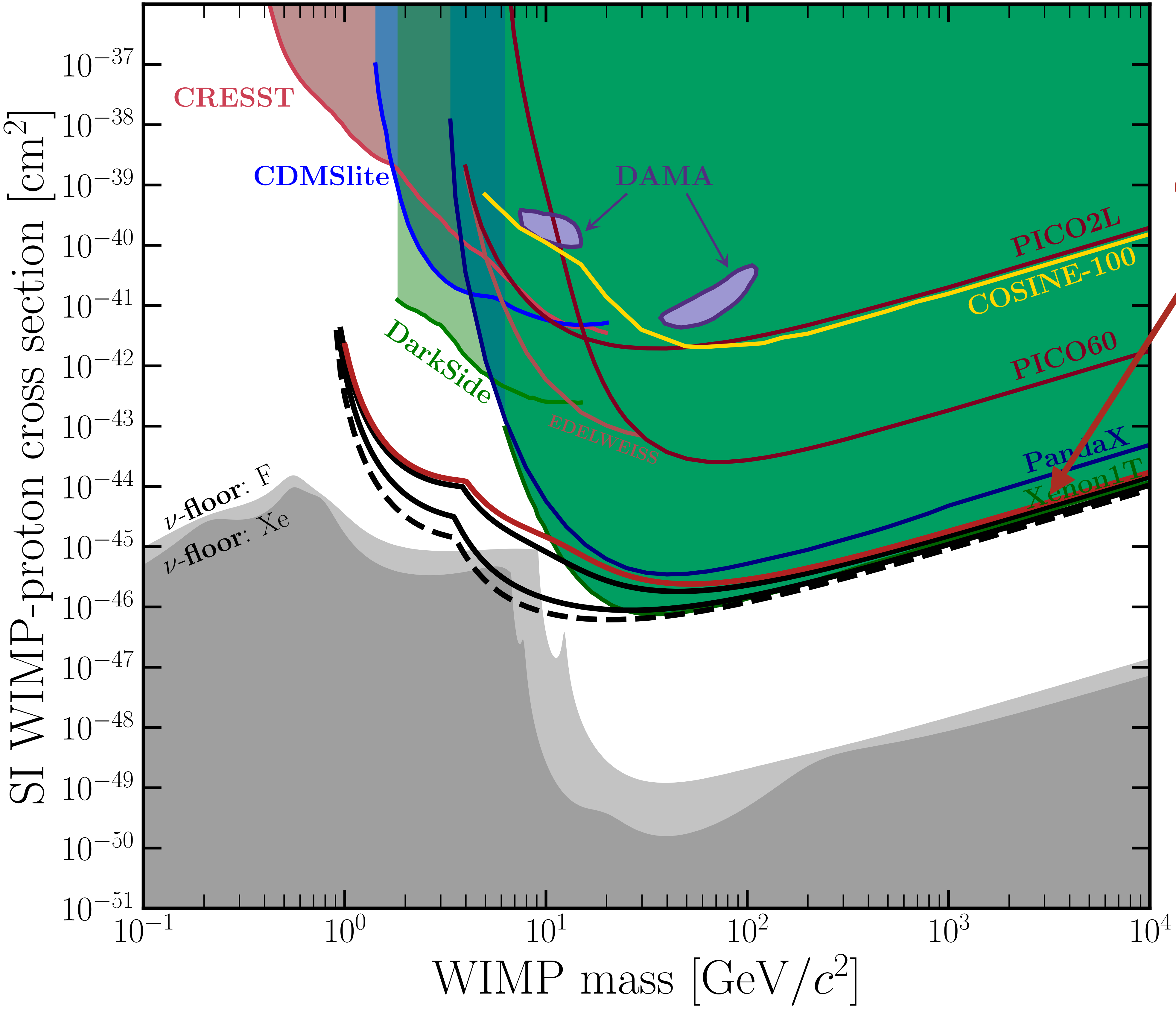
Case 3: Realistic
30° angular res.
75% head-tail

Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

How much does detector performance matter?

(Cygnus 1000 m^3 x 6 years)



Case 4: No directionality
1 rad angular res.
50% head-tail

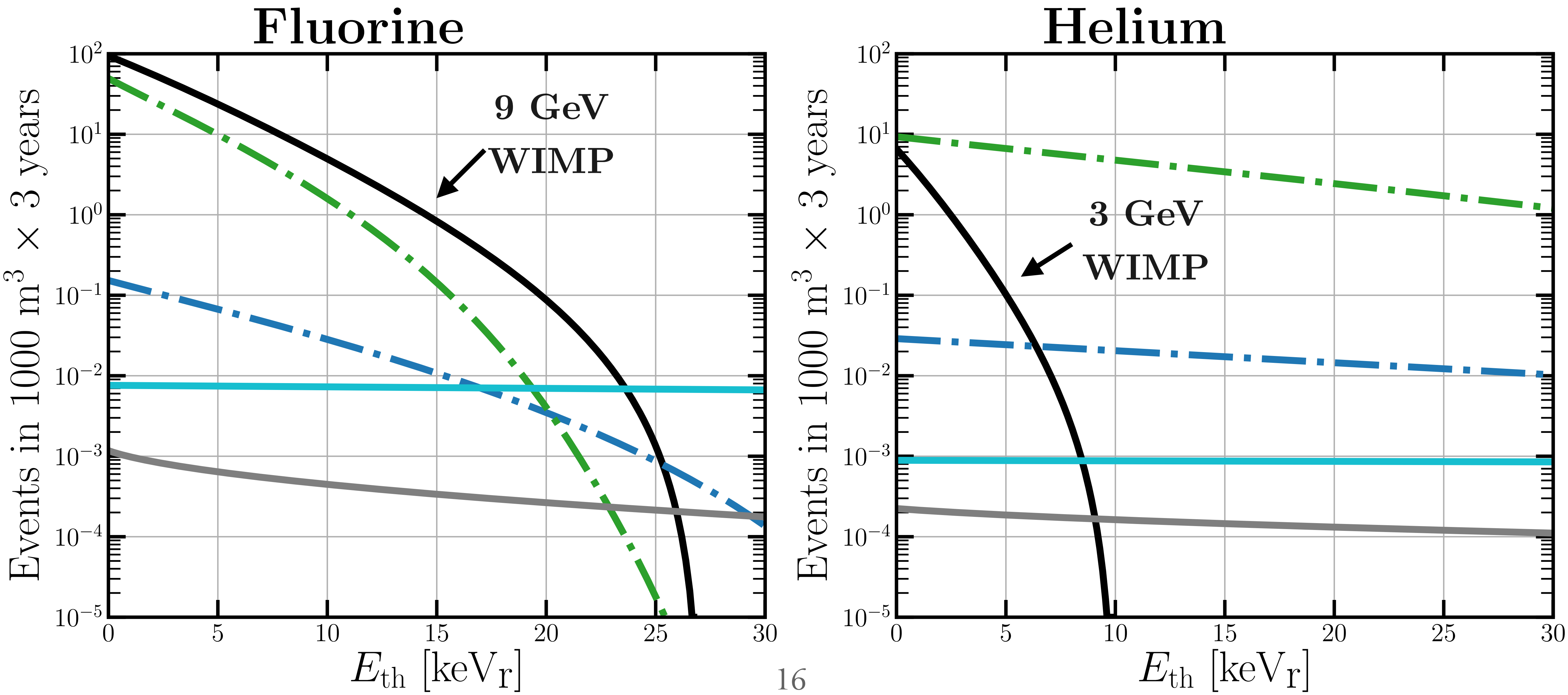
Case 3: Realistic
30° angular res.
75% head-tail

Case 2: Perfect HT
30° angular res.
100% head-tail

Case 1: Idealised
0° angular res.
100% head-tail

It gets worse…
Threshold energies

Number of events above a NR threshold
(1 atm, 1000 m^3 x 3 years)



Subtracting the neutrino background: the harsh reality

- For targets like C and F, must focus on validating readout performance for recoil energies <10 keVr
- **There are ~no Fluorine-neutrino recoils above 15 keVr**
- If low energy performance is not better than ~50° angular res. and ~75% HT recognition then directionality **adds nothing** over an equivalent non-directional detector
- If Vol<1000 m^3 then can't get below nu-floor with He (~1 atm)

We've built Cygnus and we find that…

We’ve built Cygnus and we find that…

1. We have a signal

We’ve built Cygnus and we find that…

1. We have a signal

2. We don’t

We’ve built Cygnus and we find that…

1. **We have a signal**

2. **We don’t**

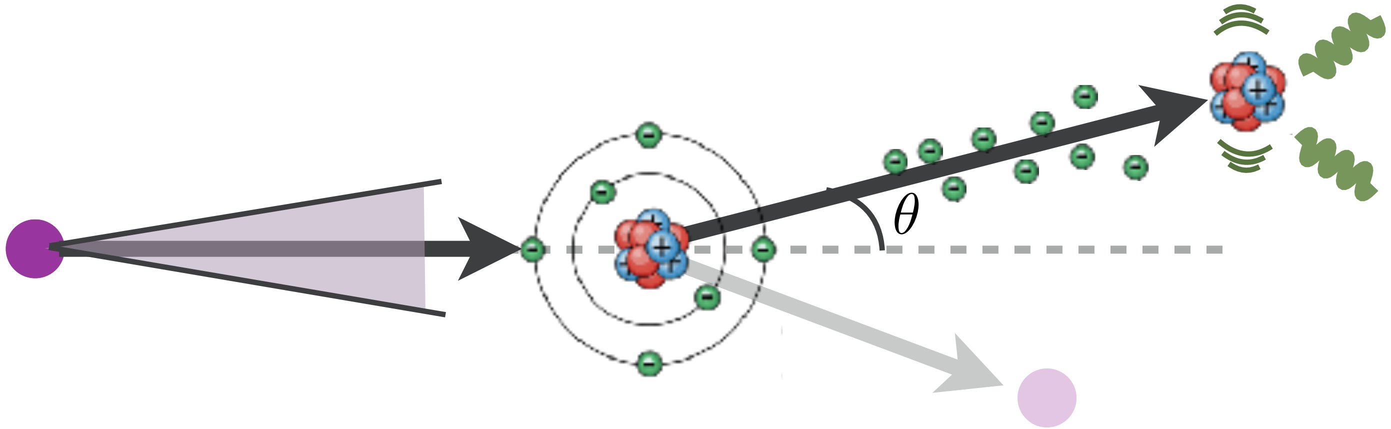
Then what?

We've built Cygnus and we find that…

1. **We have a signal**
    - We study it
2. **We don't**

Then what?

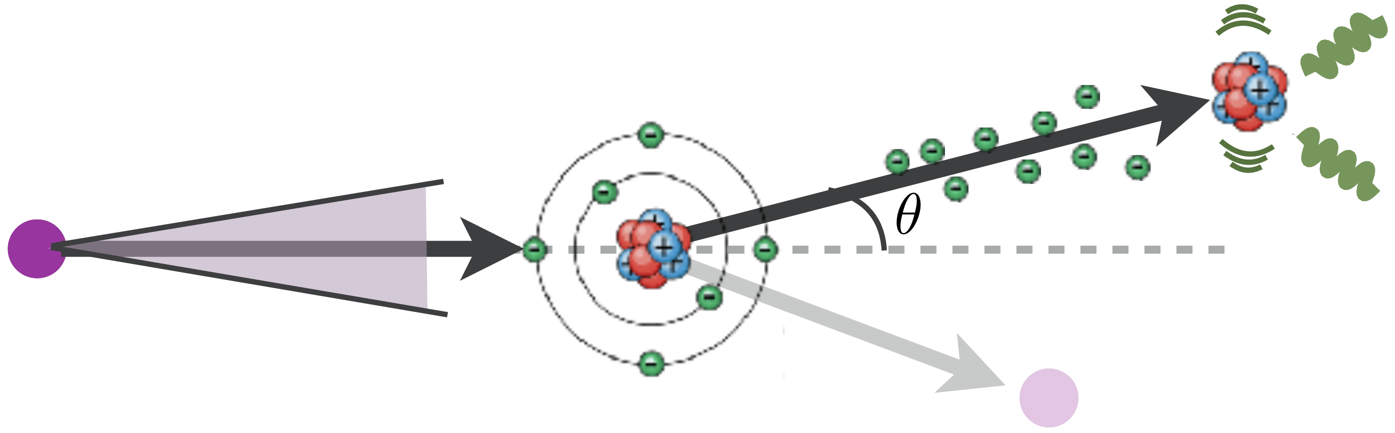
What <u>should</u> the signal look like?



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

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

$m_N =$ Nucleus mass
$m_\chi =$ DM mass

- The DM velocity distribution is a Gaussian (SHM)

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

$\mathbf{v}_{\text{lab}} =$ Our velocity
$\sigma_v =$ Velocity dispersion

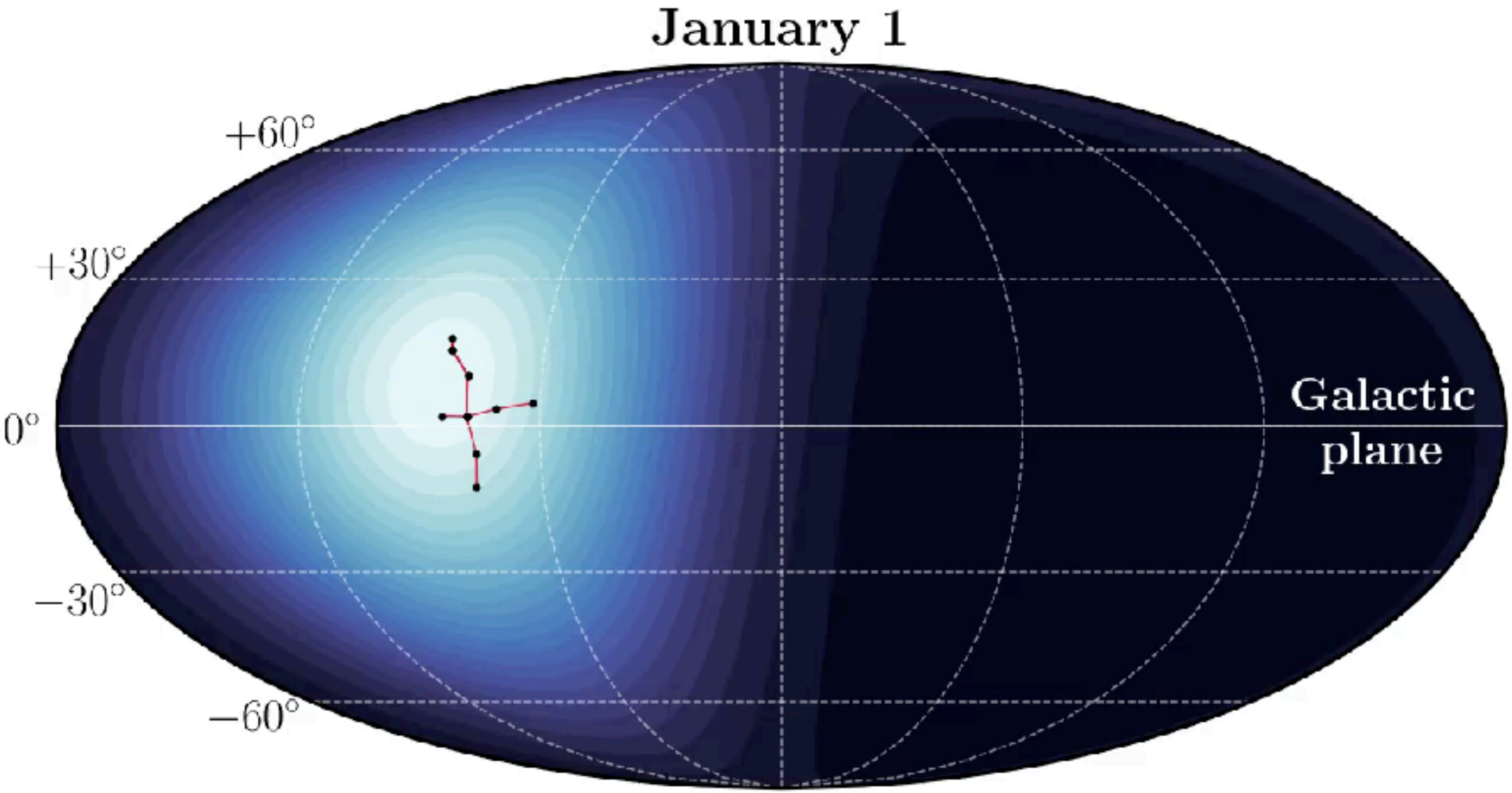
- DM-nucleus matrix element does not depend on velocity

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

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

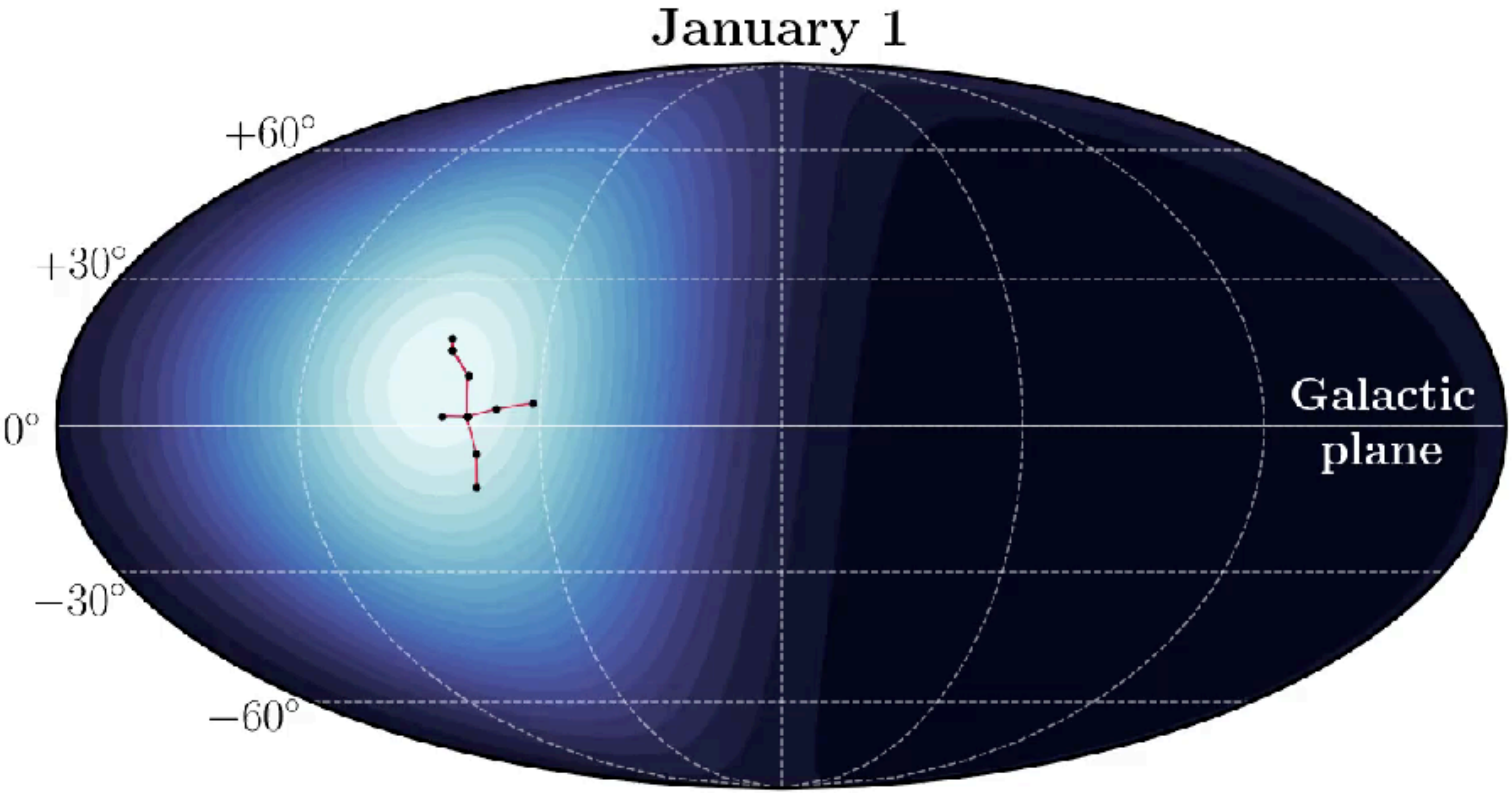
Under these assumptions the angular signal is a Gaussian peaking towards Cygnus

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



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

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



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

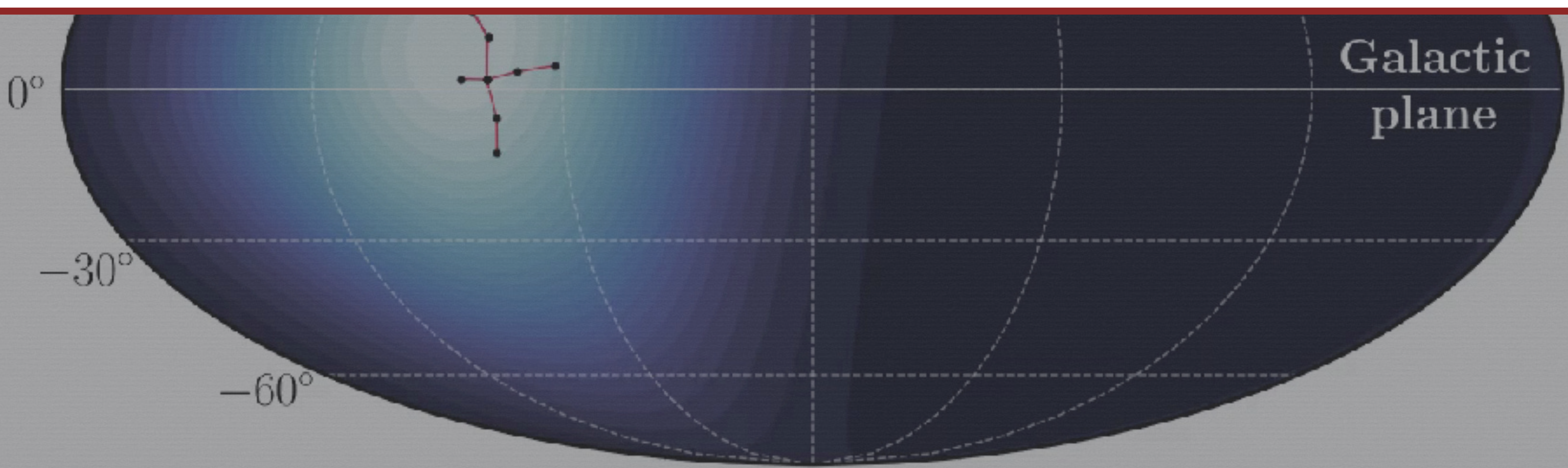
↳ $$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp\left(-\frac{(v_{\mathrm{min}}+v_{\mathrm{lab}}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$

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



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

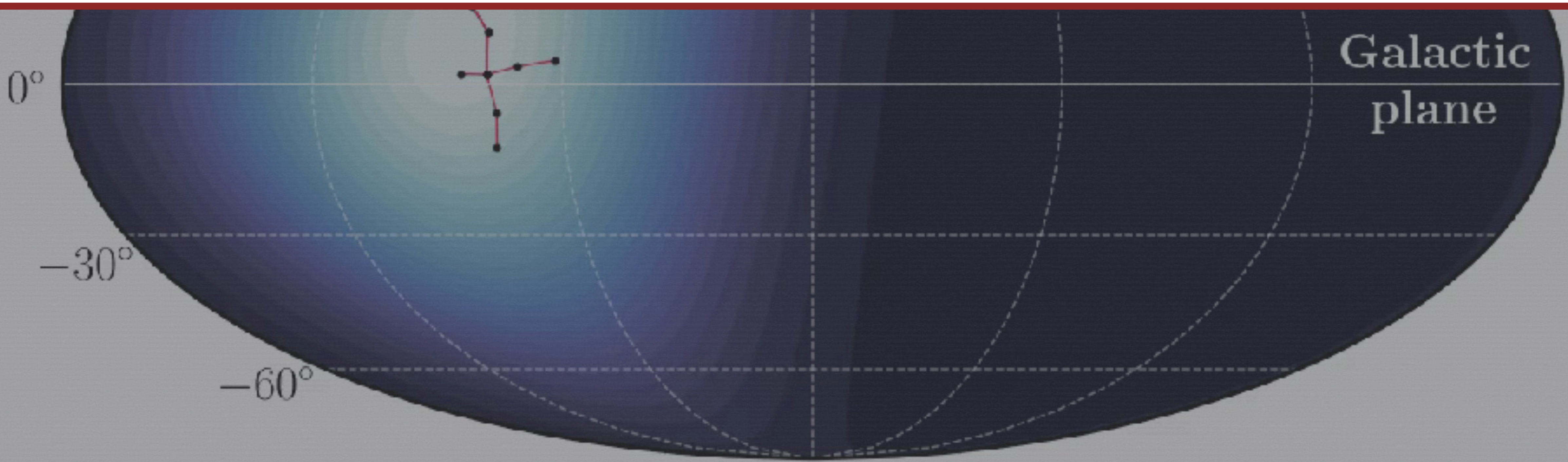
↳
$$\left.\frac{\mathrm{d}R(t)}{\mathrm{d}\cos\theta}\right|_{E_r} \propto \frac{1}{(2\pi\sigma_v^2)^{1/2}}\exp\left(-\frac{(v_{\mathrm{min}}+v_{\mathrm{lab}}(t)\cos\theta)^2}{2\sigma_v^2}\right)$$

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

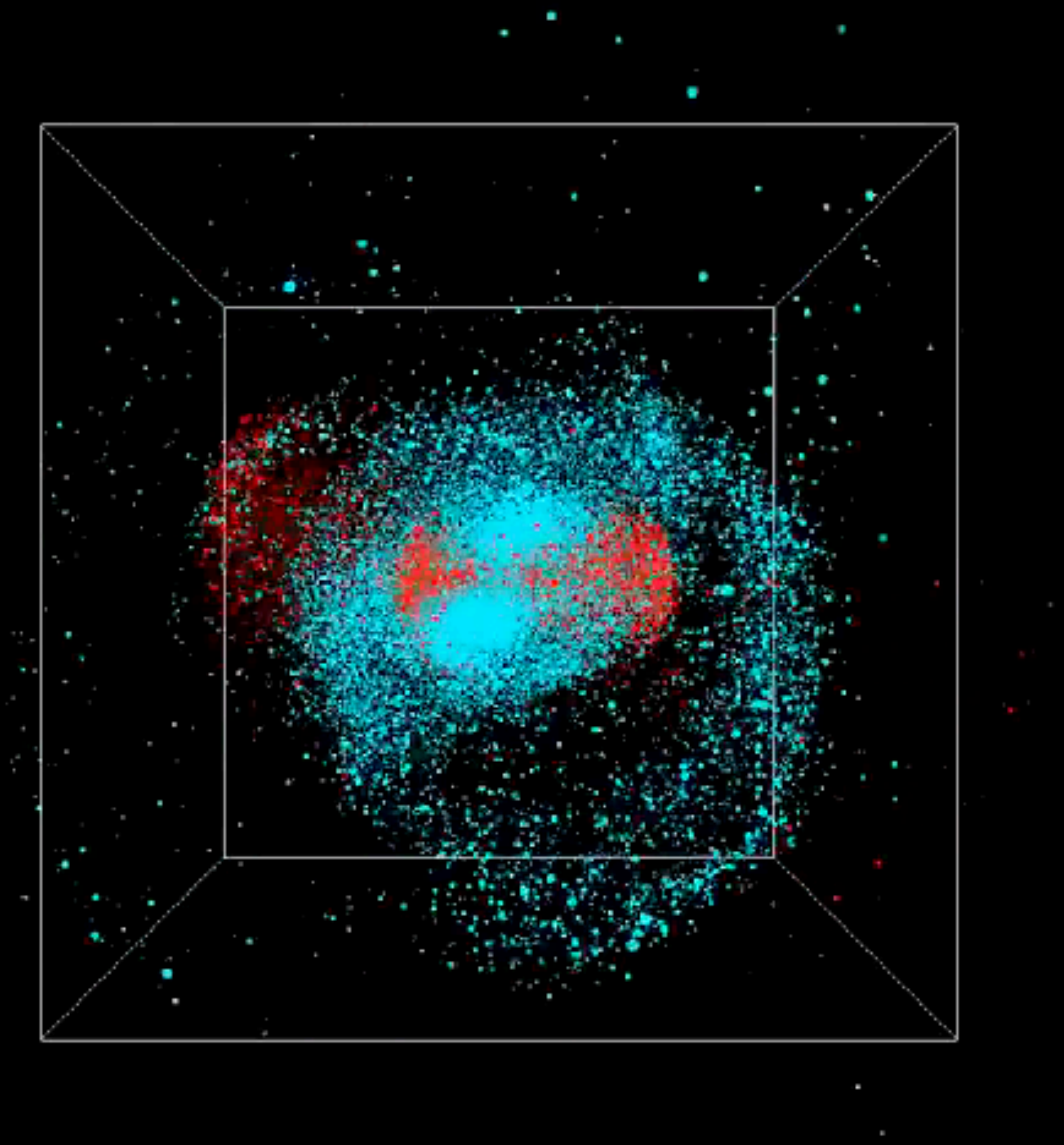
→ The WIMP-nucleus interaction may involve velocity-dependent operators



Should the DM velocity distribution be a Gaussian?

→ Evidence of significant merger in the MW's history

The Gaia Sausage

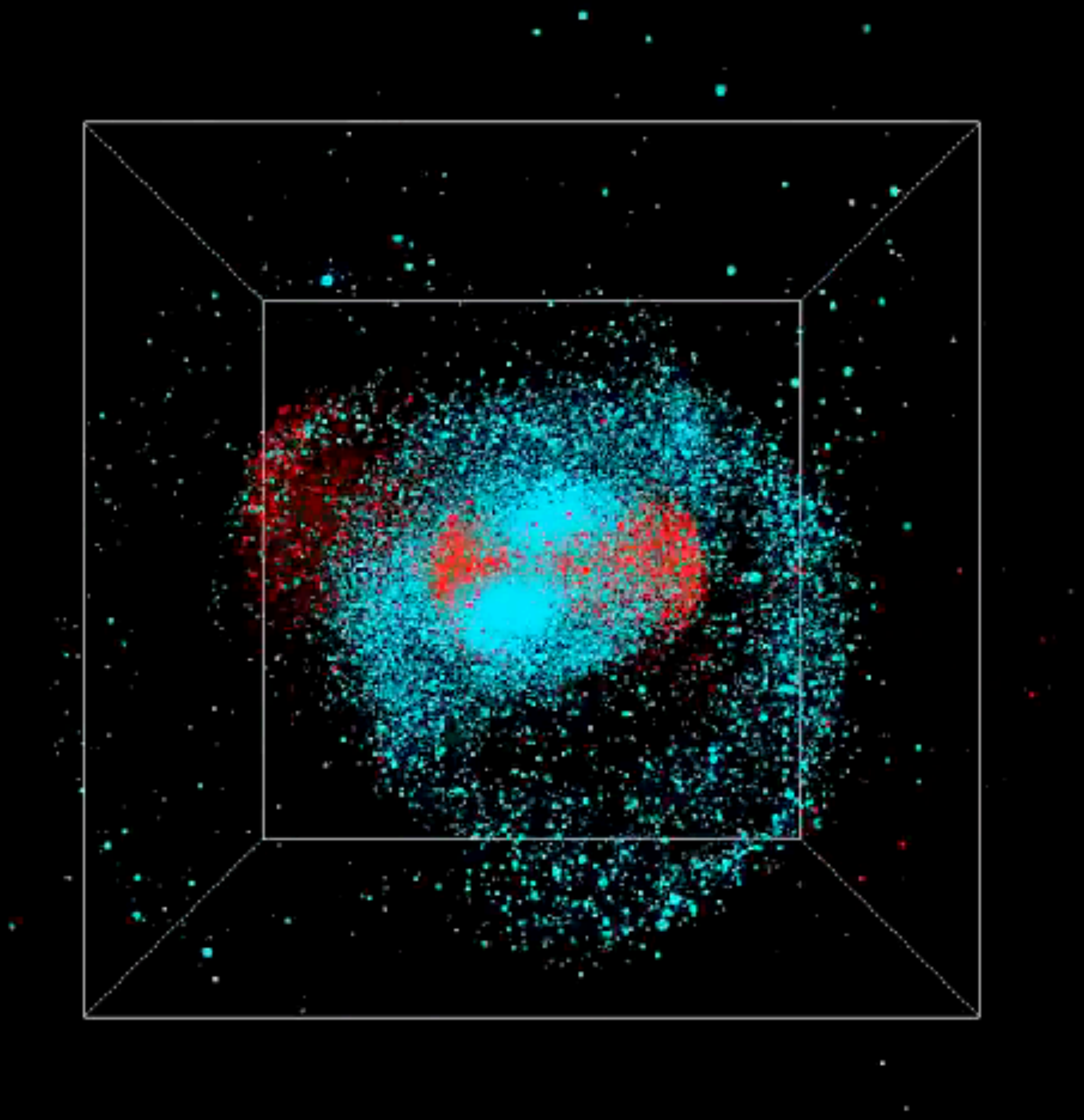


See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

Should the DM velocity distribution be a Gaussian?

→ Evidence of significant merger in the MW's history

The Gaia Sausage

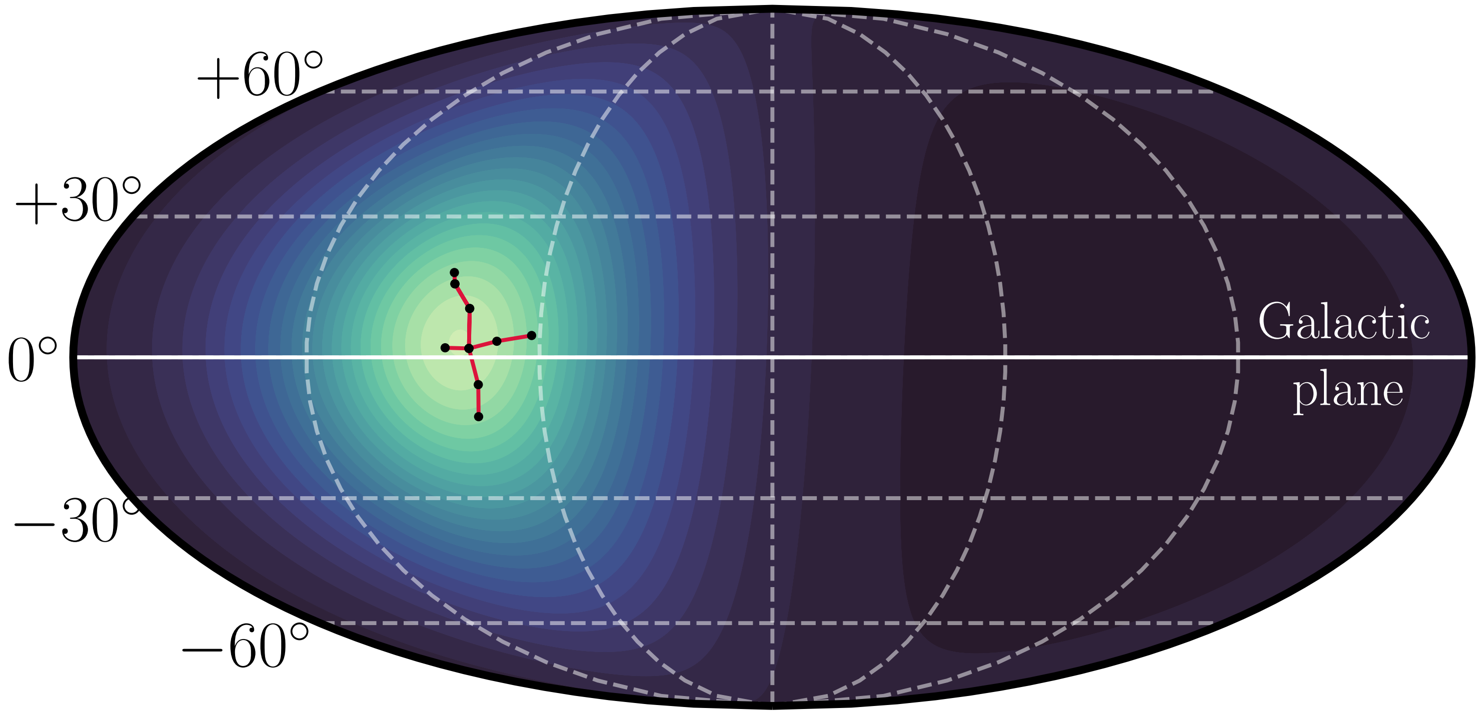


See e.g. Helmi et al. 1806.06038, O'Hare et al., 1810.11468, Necib et al. 1810.12301

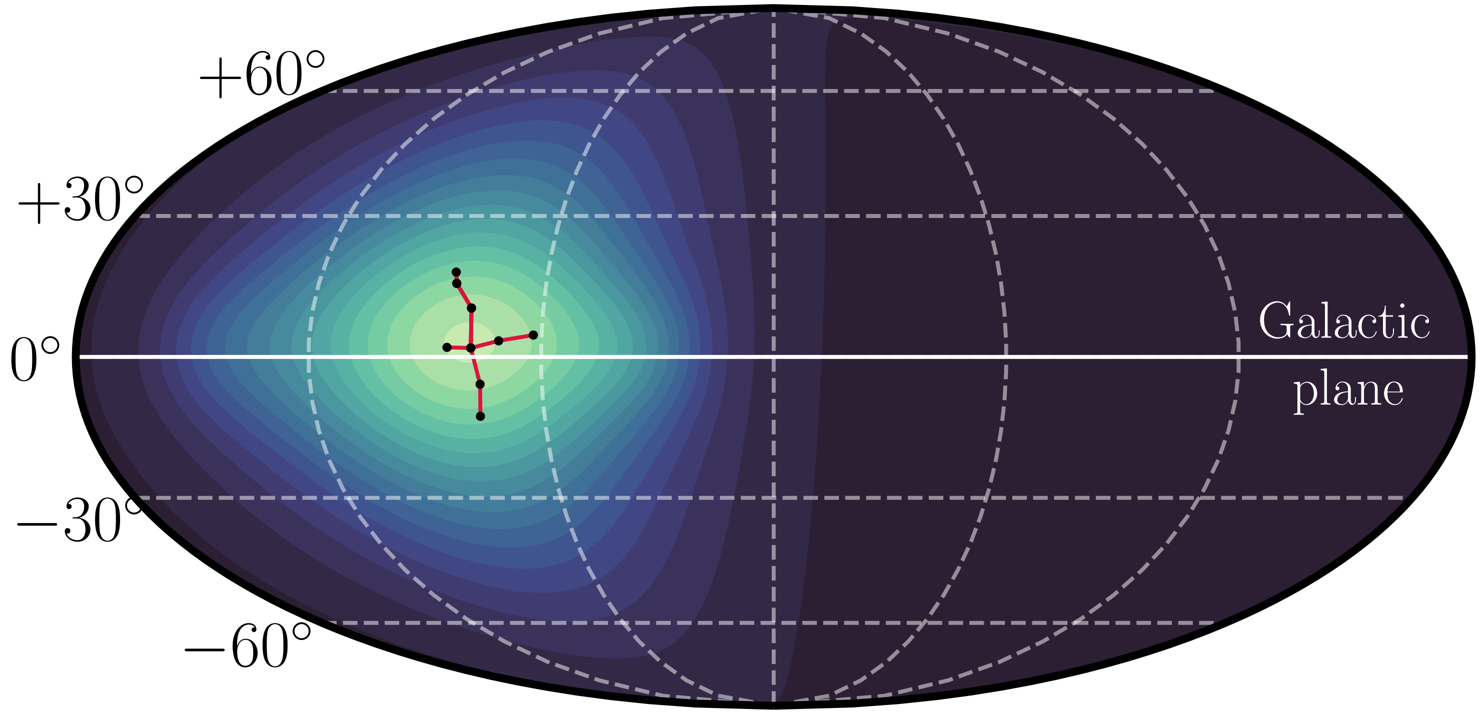
The Gaia Sausage

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

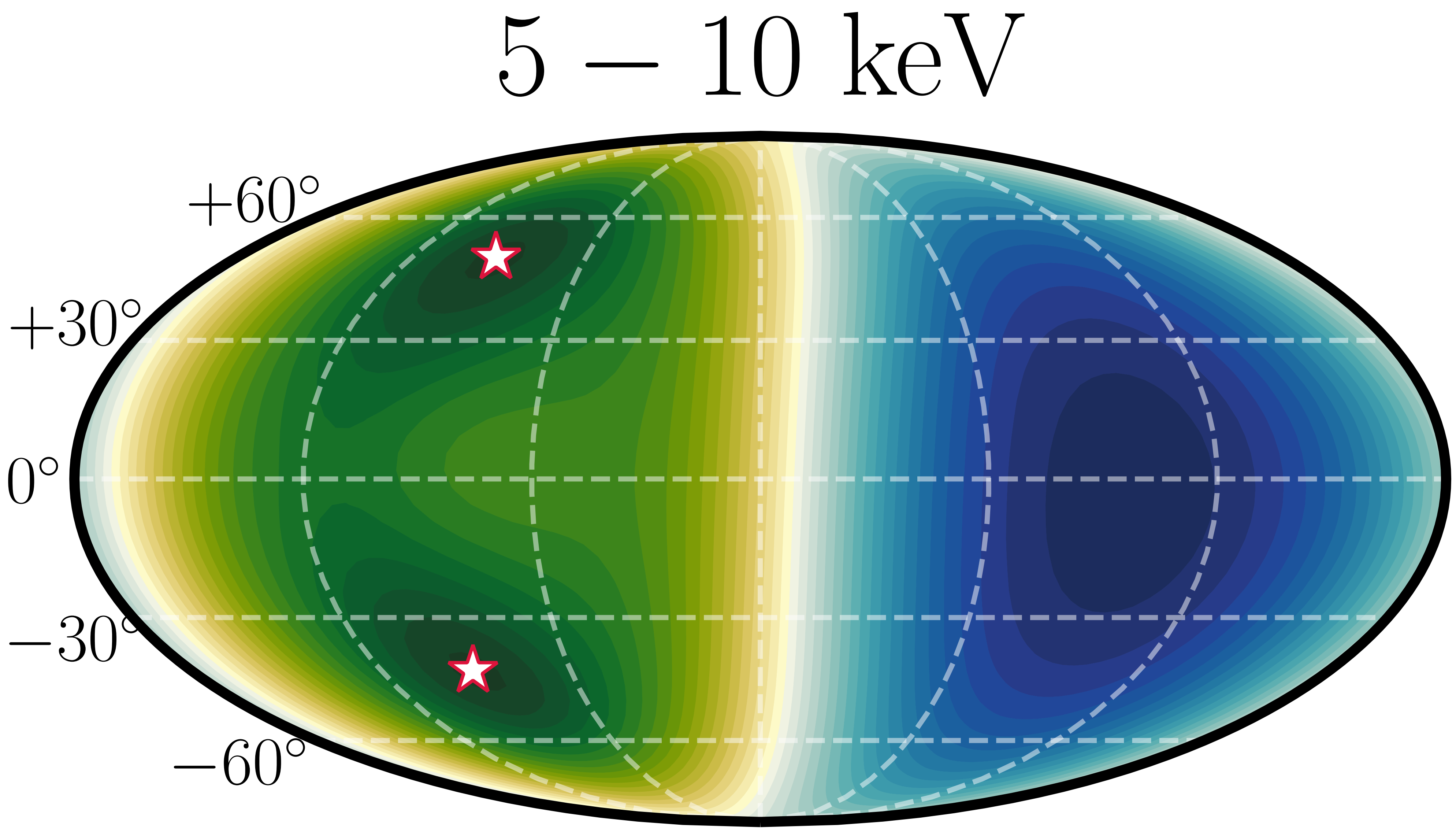
DM Flux for SHM
(Gaussian distribution)



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



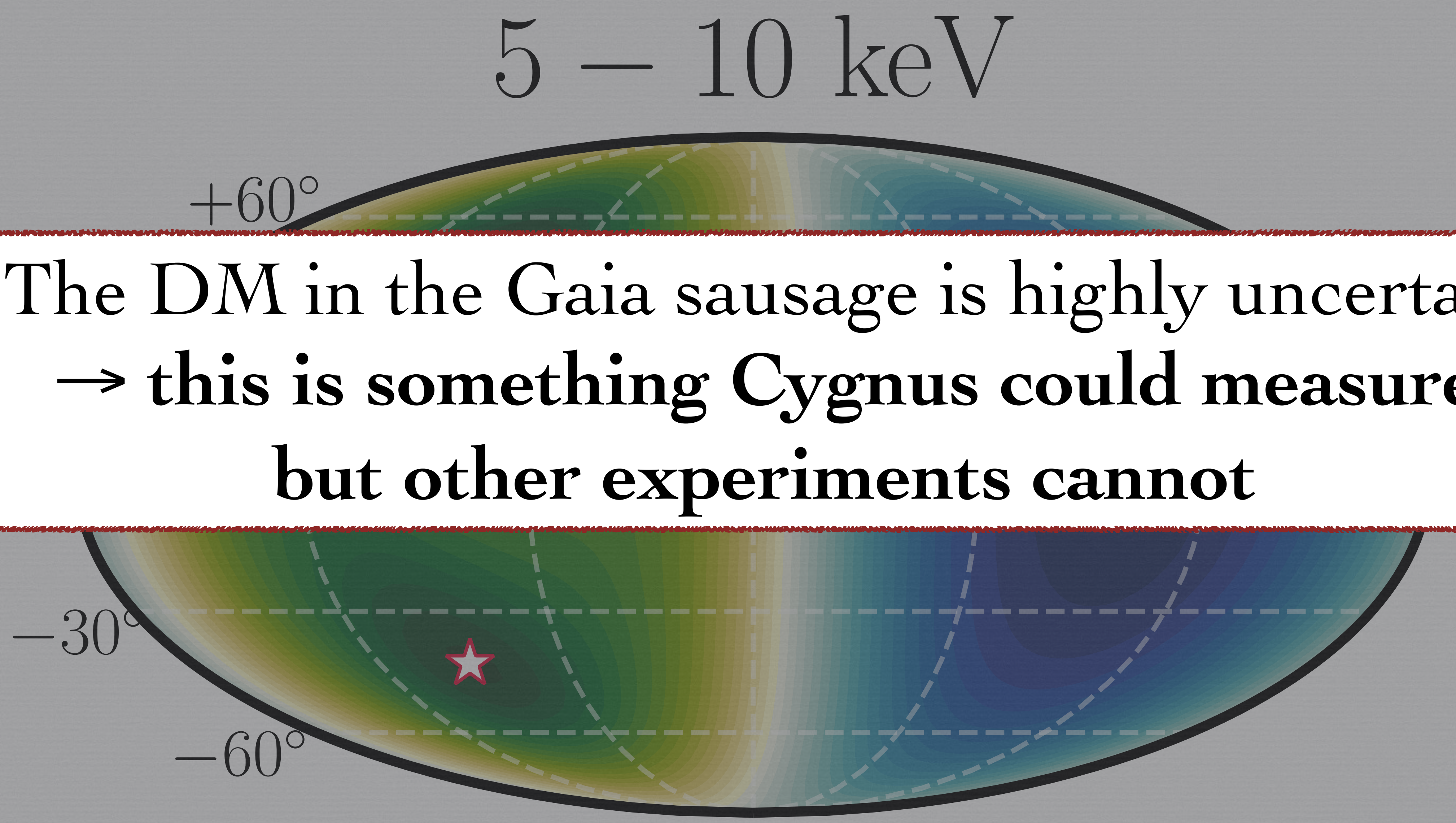
The Gaia Sausage gives rise to peaks off center from Cygnus



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

Halo model = SHM + Sausage

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

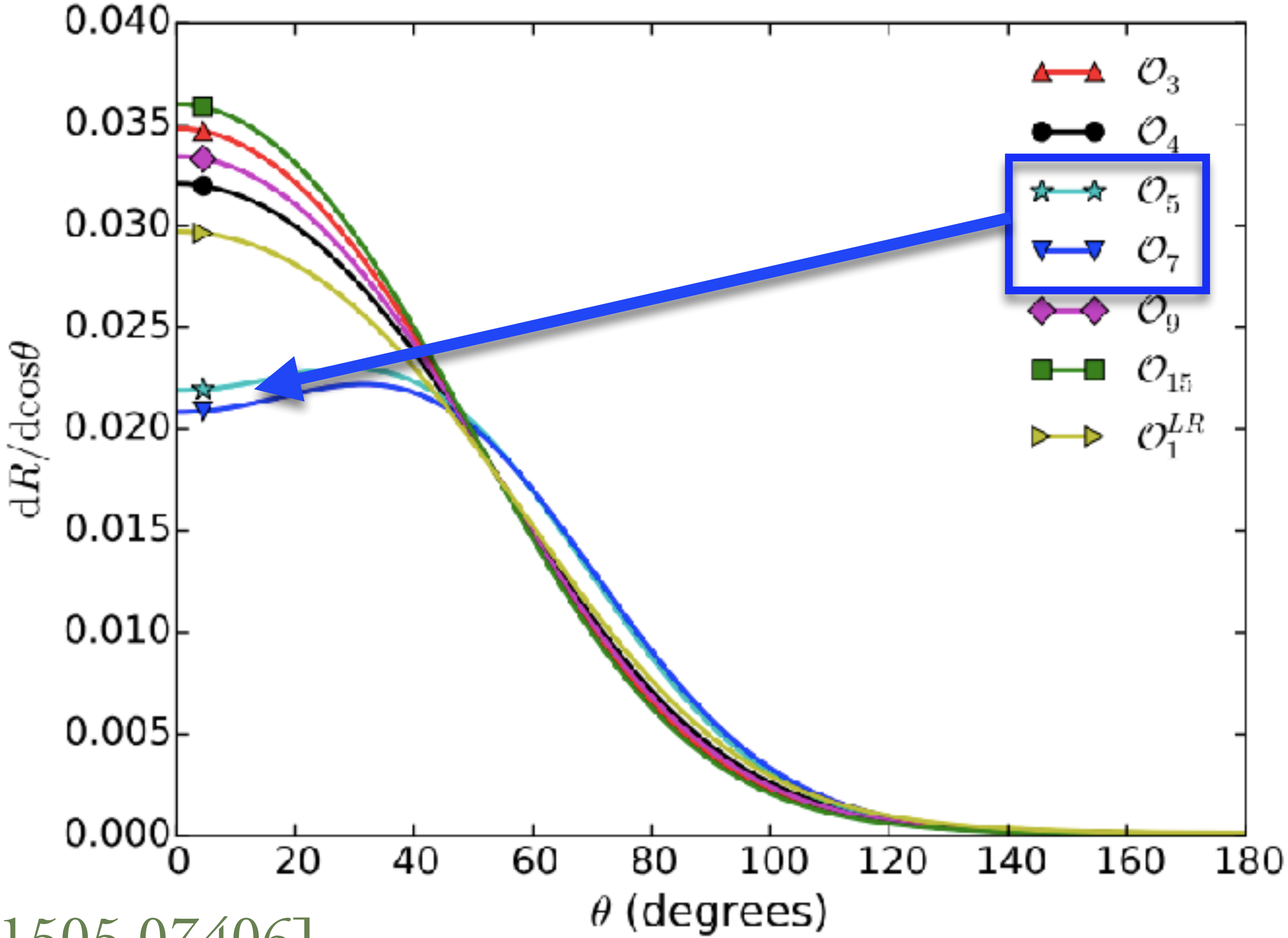
Halo model = SHM + Sausage

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

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…

We've built Cygnus and we find that…

1. **We have a signal**

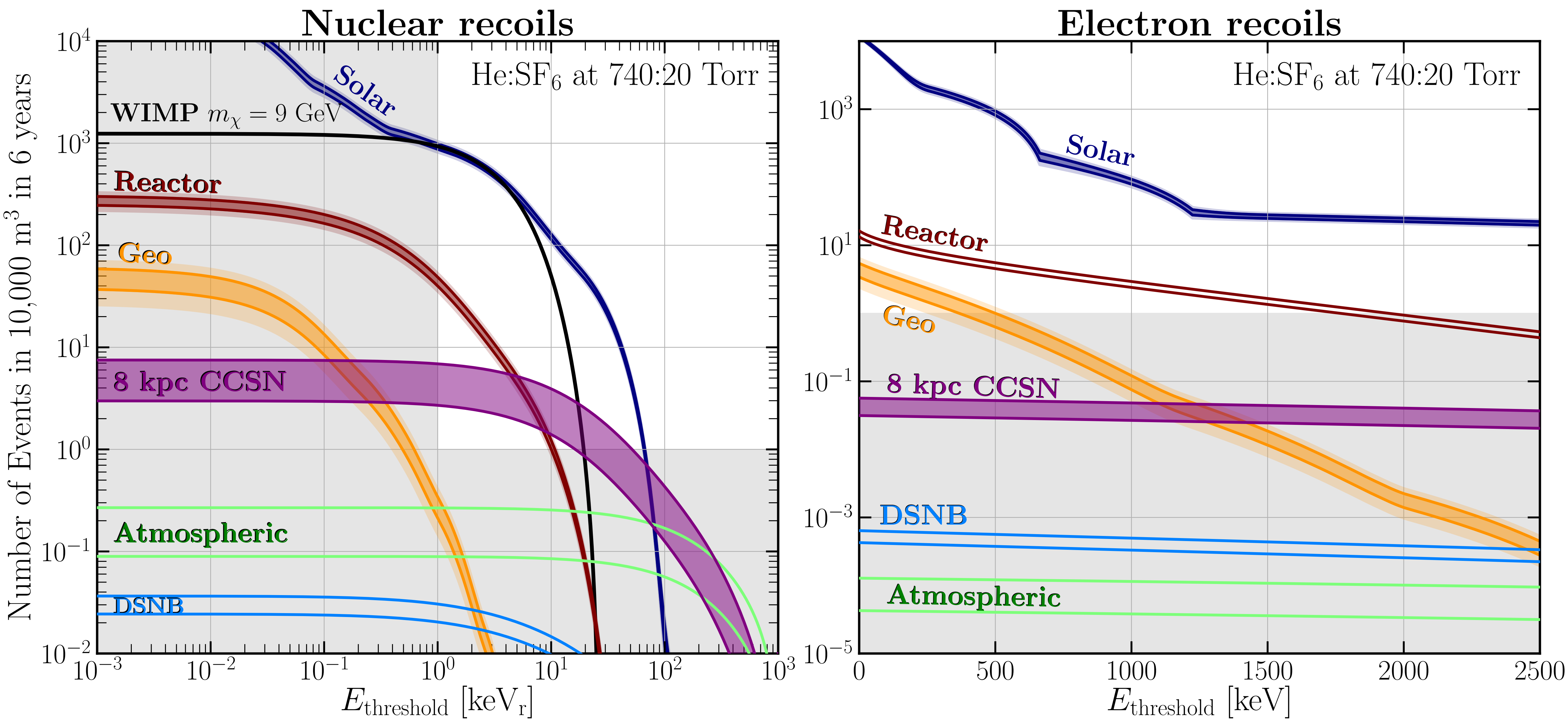
    ↳ We study it

2. **We don't**

We’ve built Cygnus and we find that…

1. **We have a signal**
   - We study it
2. **We don’t**
   - Our background is our signal

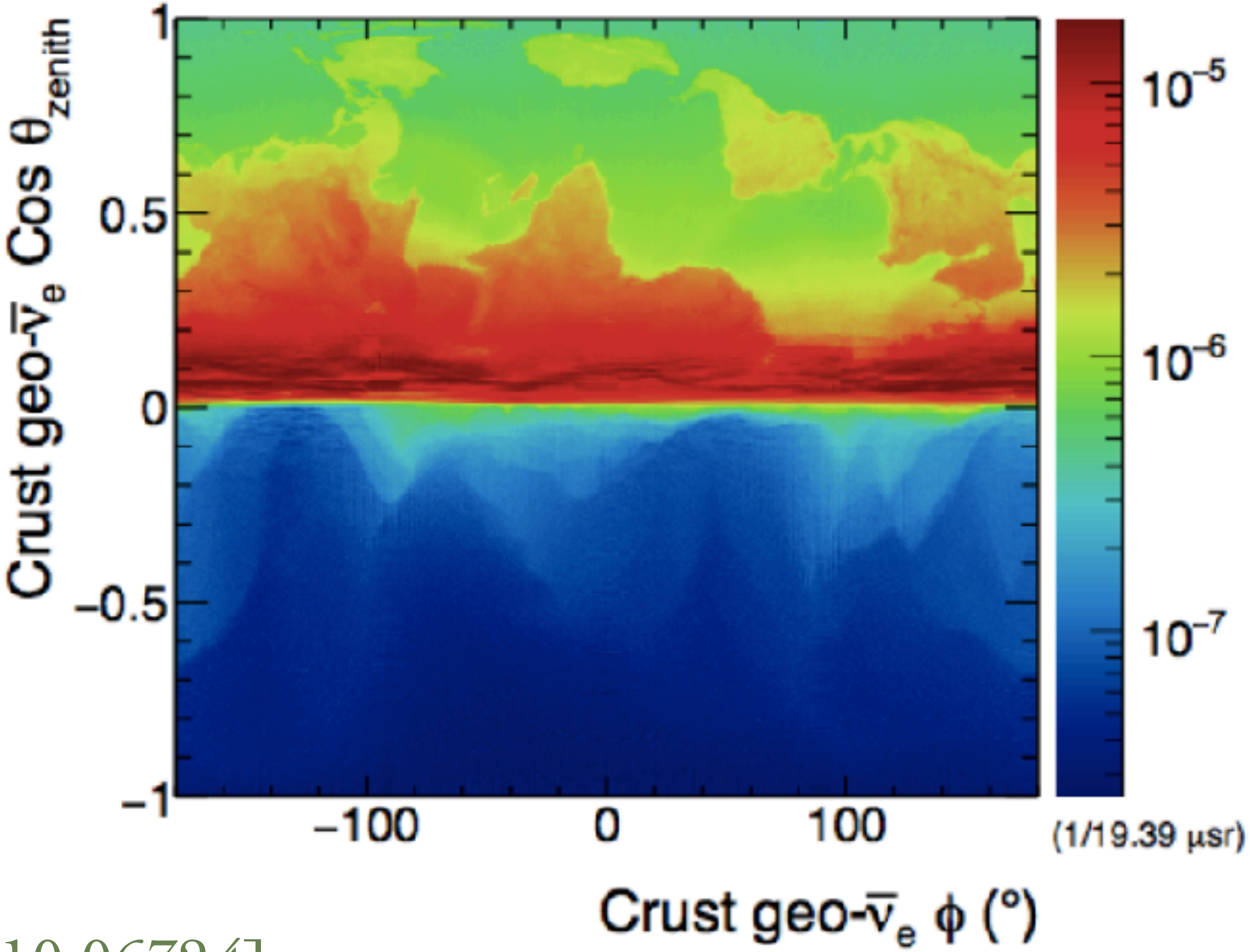
The neutrino background



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

Geoneutrino flux



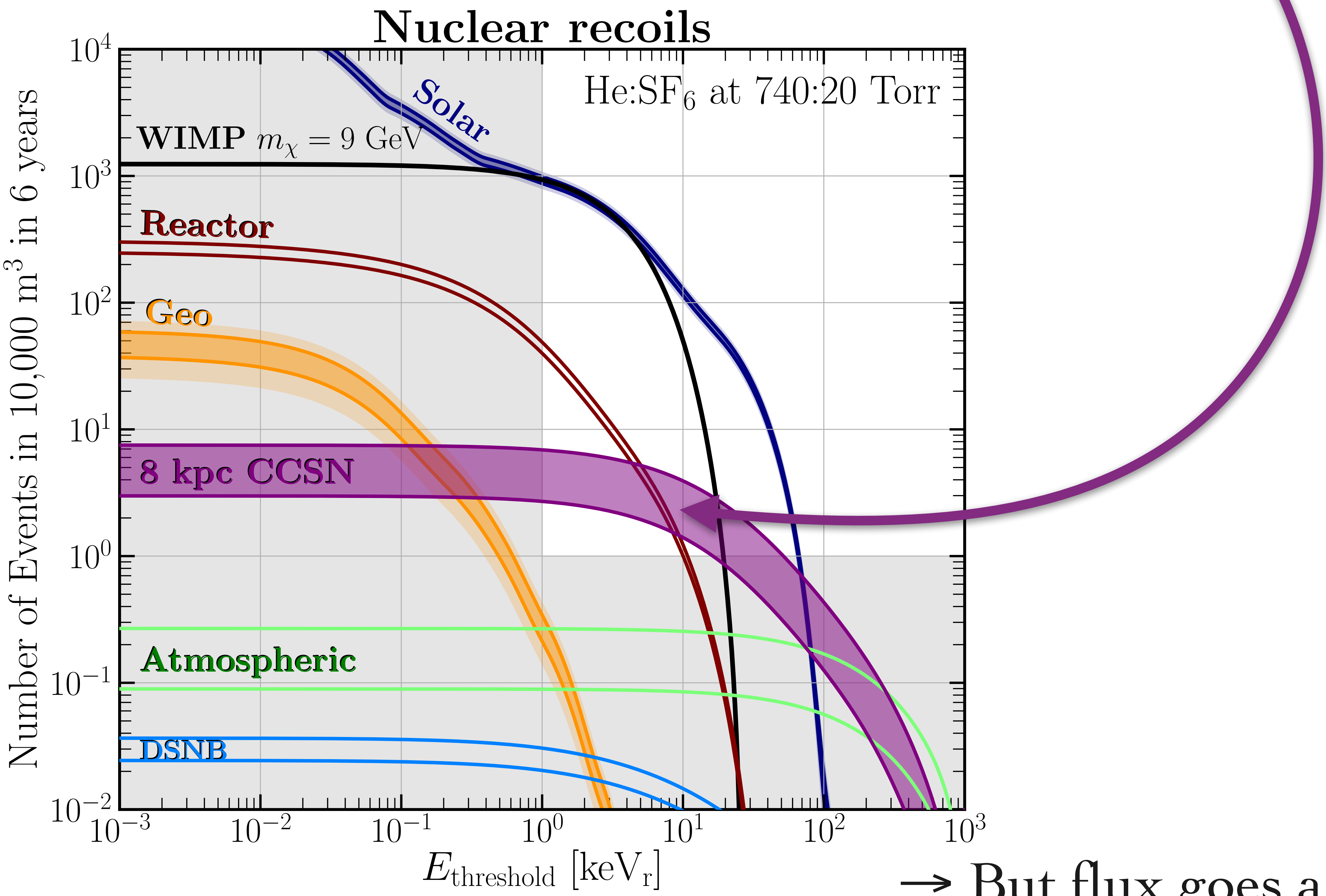
Leyton+ [1710.06724]

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)

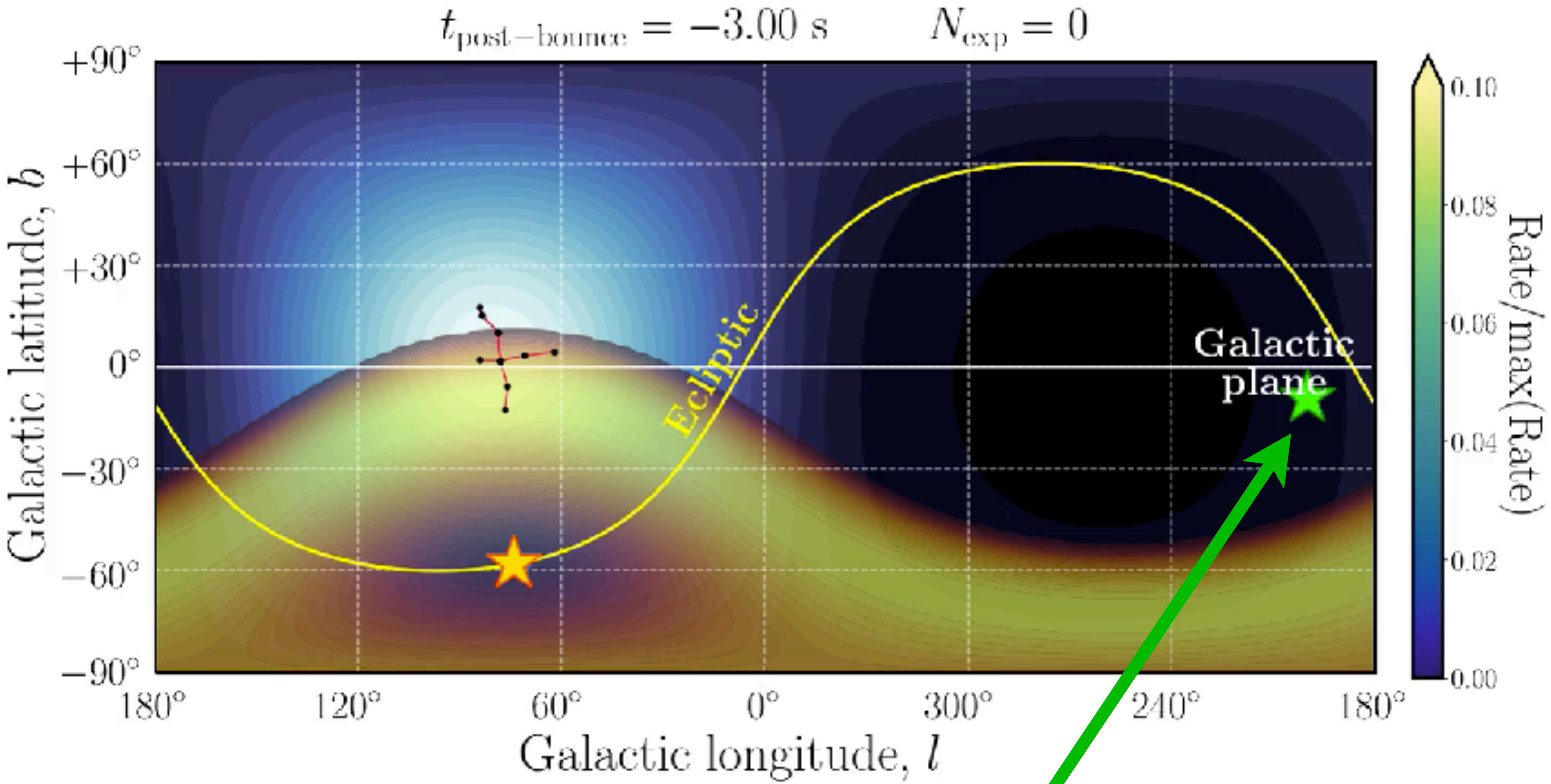
Pointing to a supernovae

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



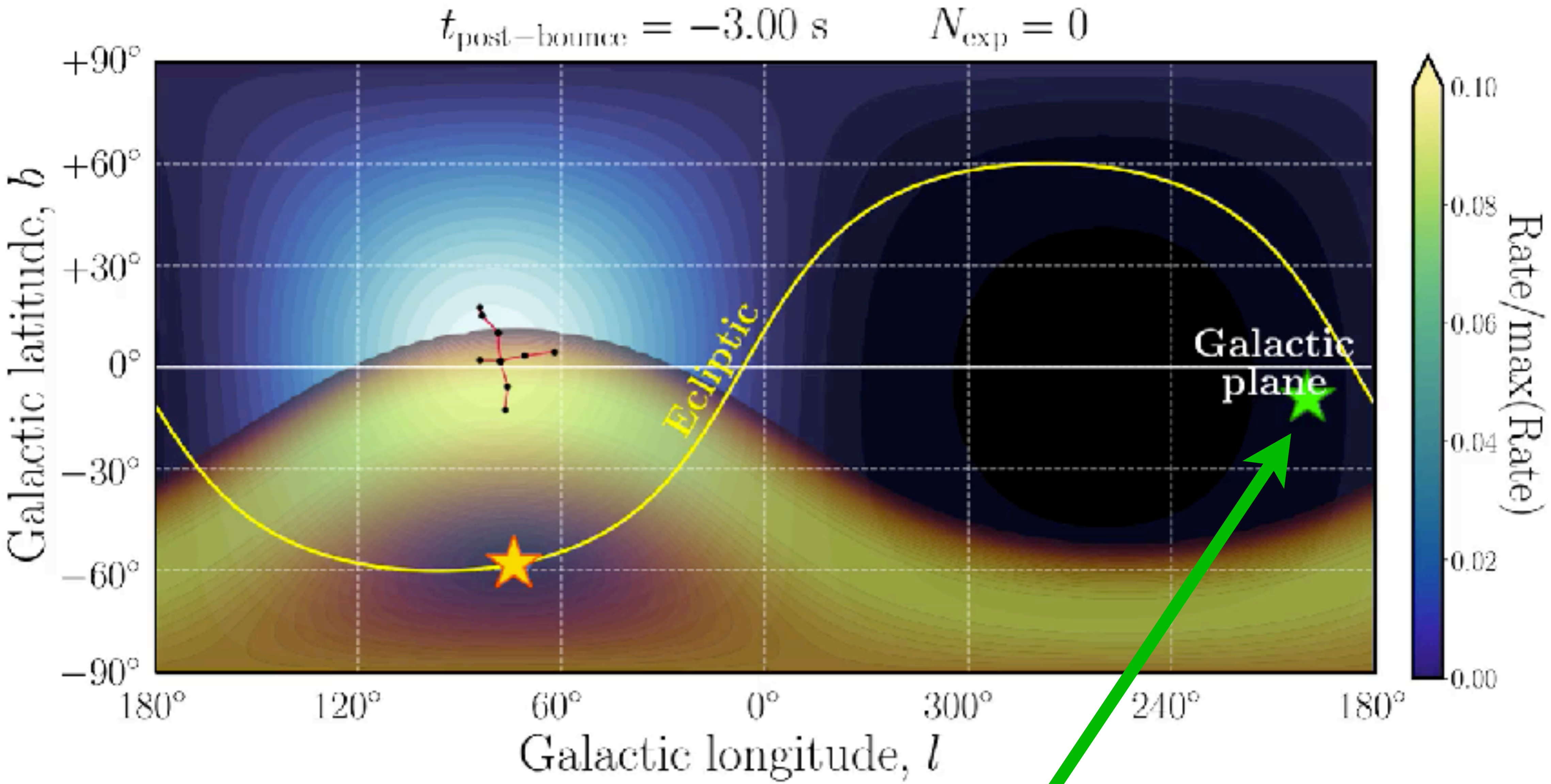
→ But flux goes as d^{-2}

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]

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]

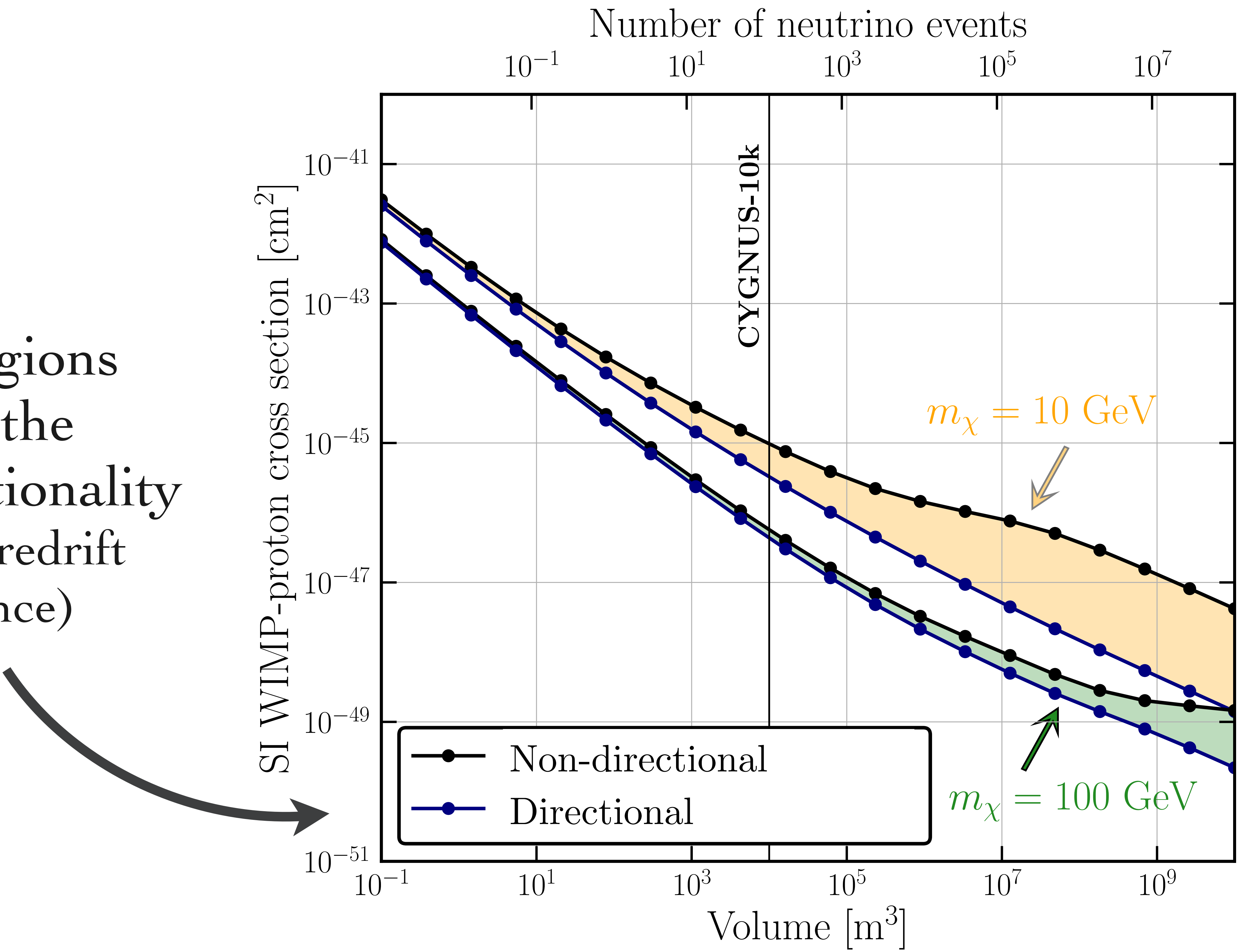
Conclusions

- A directional expt. can get you below the neutrino floor, but requires a lot from the detector
- A directional detector allows you to test models of the MW and measure aspects of the DM that are invisible in other experiments
- CYGNUS is also a neutrino observatory with pointing ability

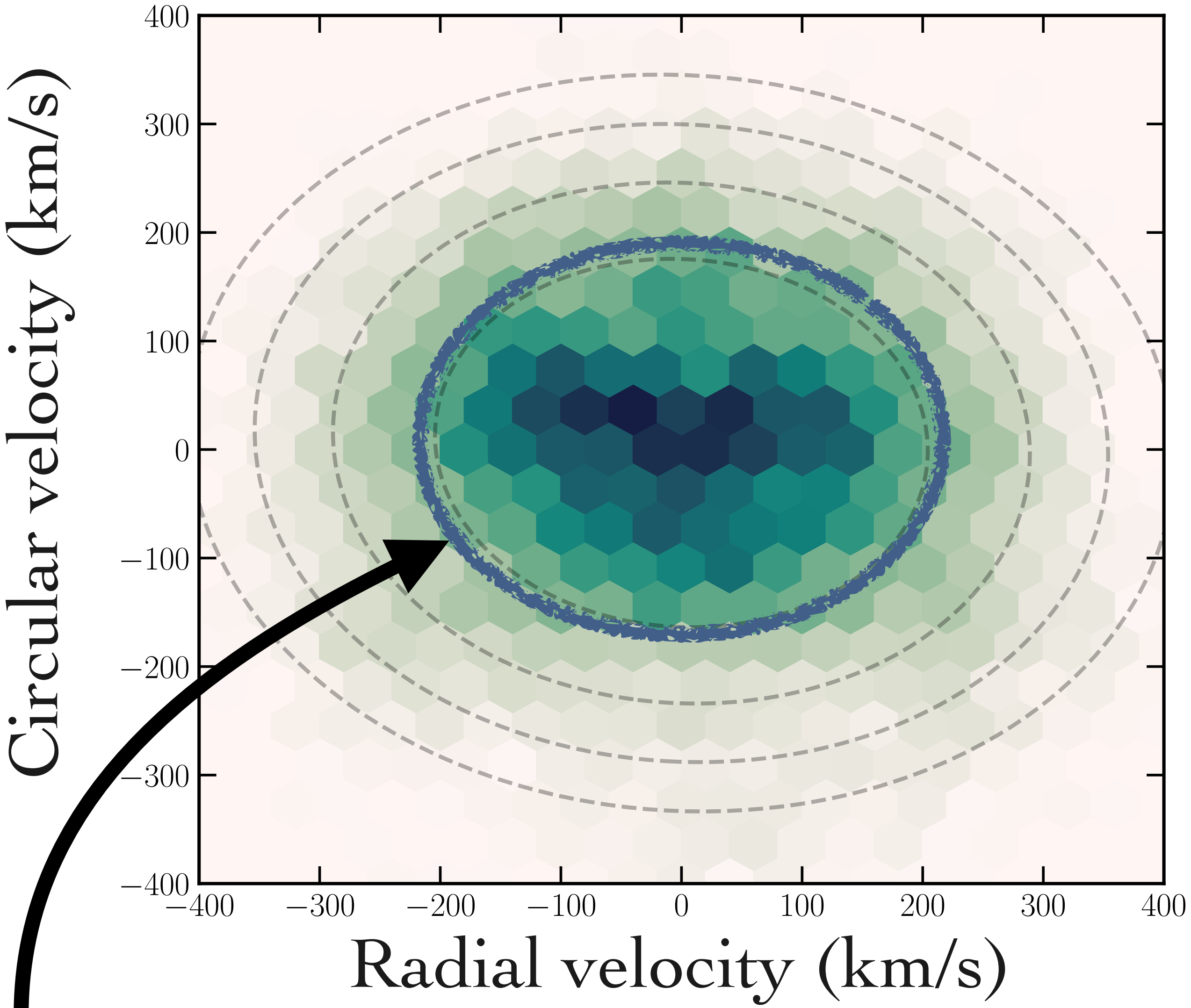
Bonus + technical things

Discoverable WIMP cross section
vs number of neutrino events

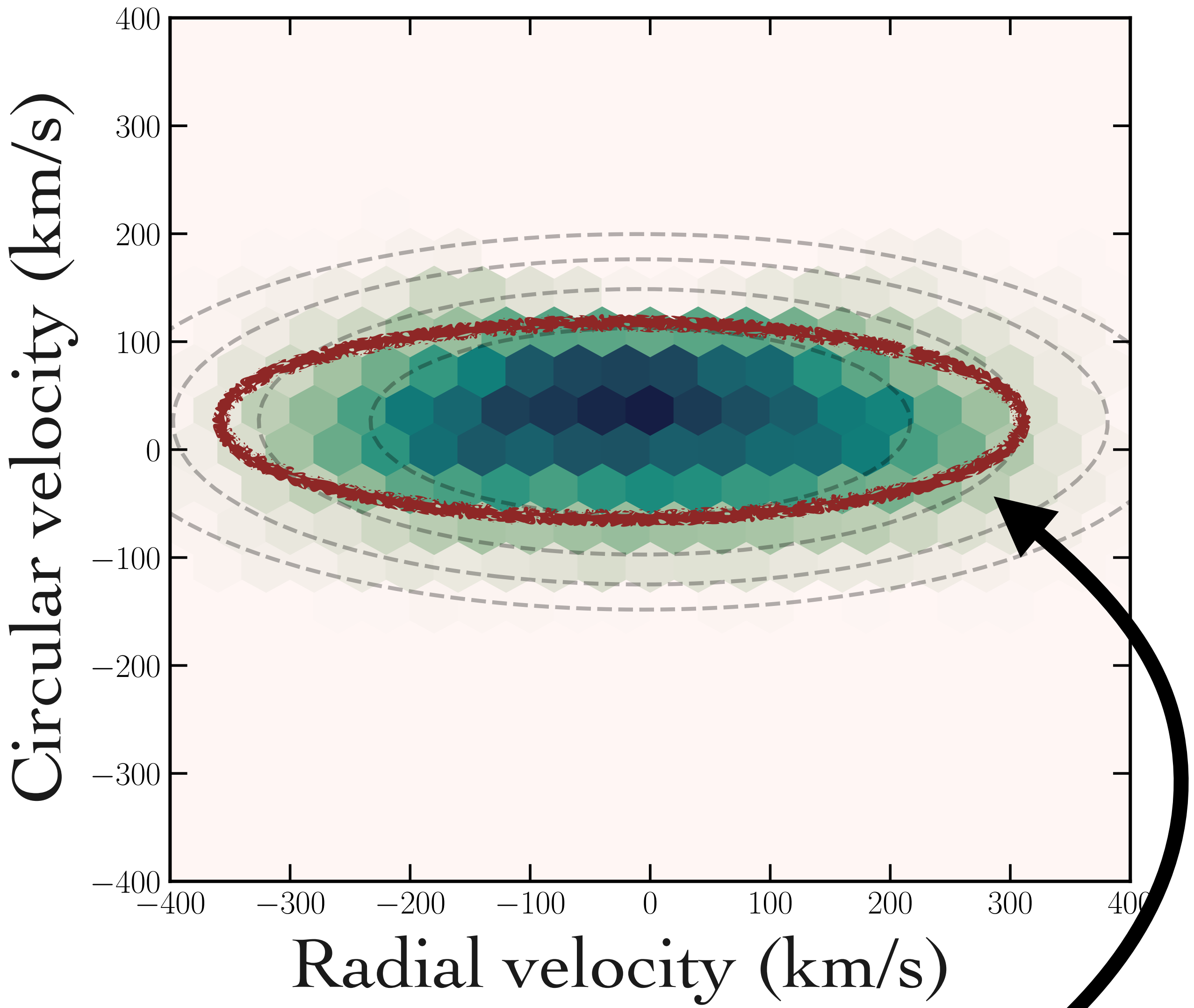
Shaded regions
indicate the
gain of directionality
(assuming predrift
performance)



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



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

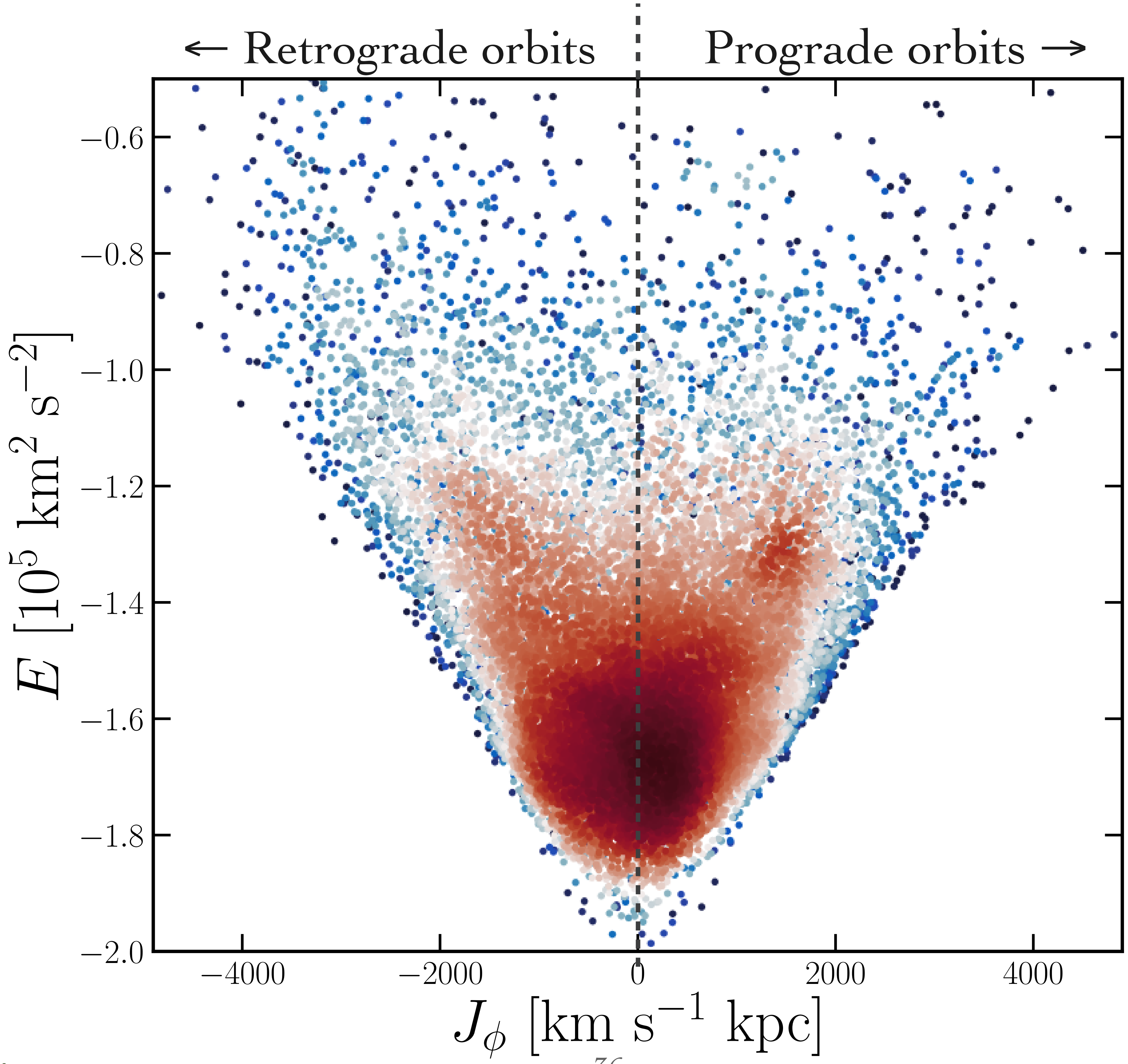


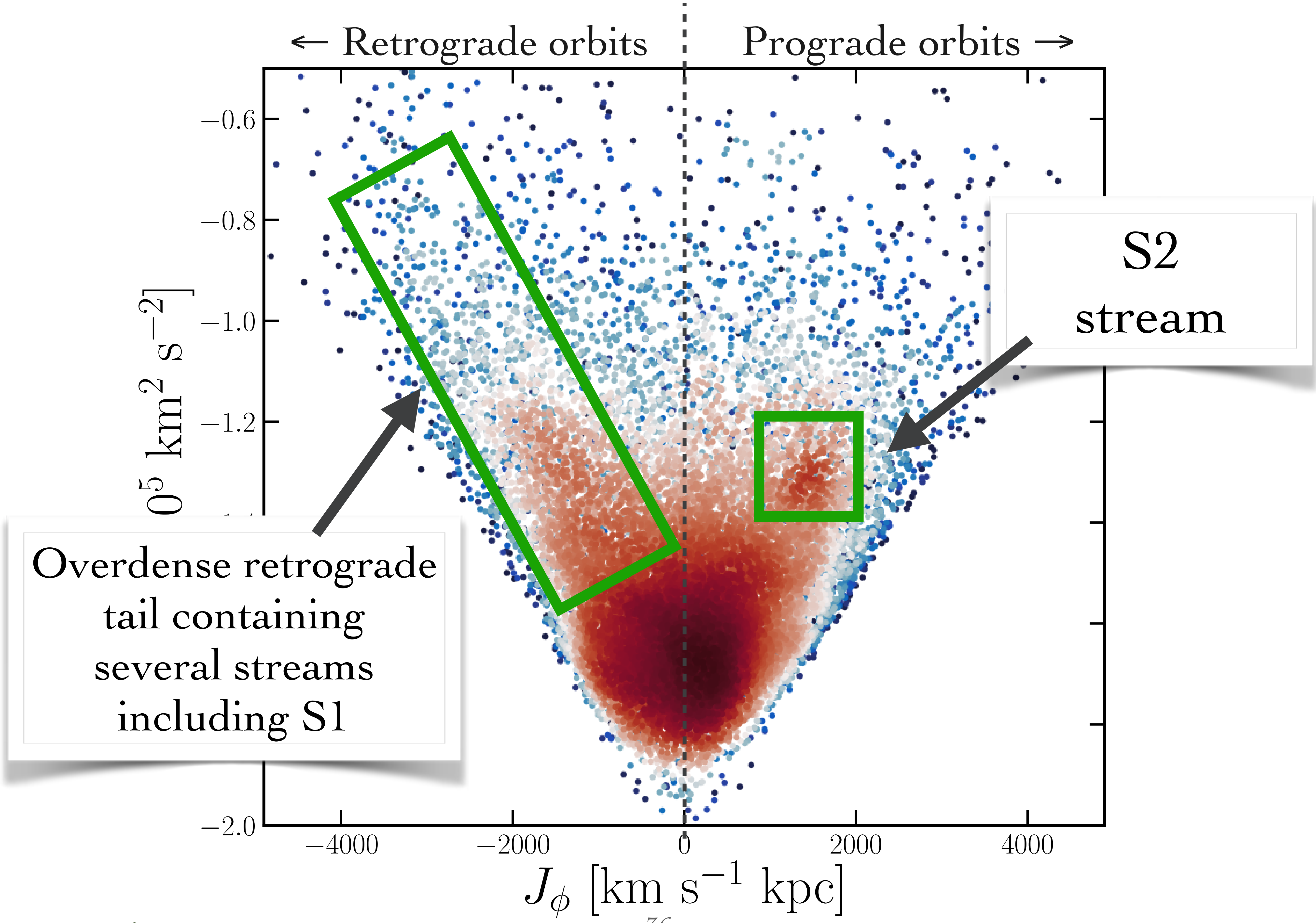
The "Halo"

- 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


← Retrograde orbits
Prograde orbits →
E [10^5 km^2 s^{-2}]
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
−4000
−2000
0
2000
4000
J_ϕ [km s^{-1} kpc]

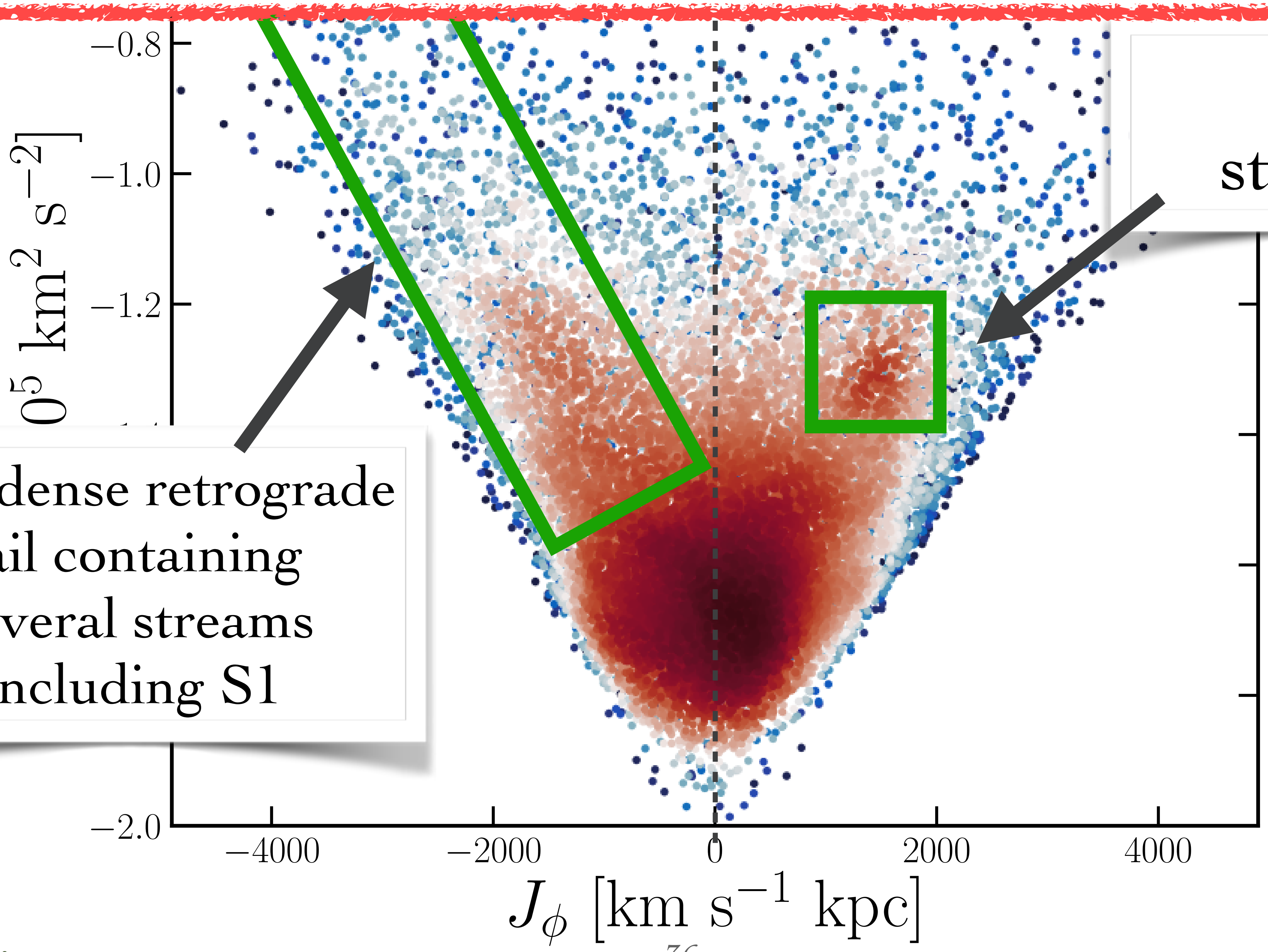


Overdense retrograde tail containing several streams including S1

S2 stream

Substructures cluster in action space even when they are not clustered in phase space or visible on the sky

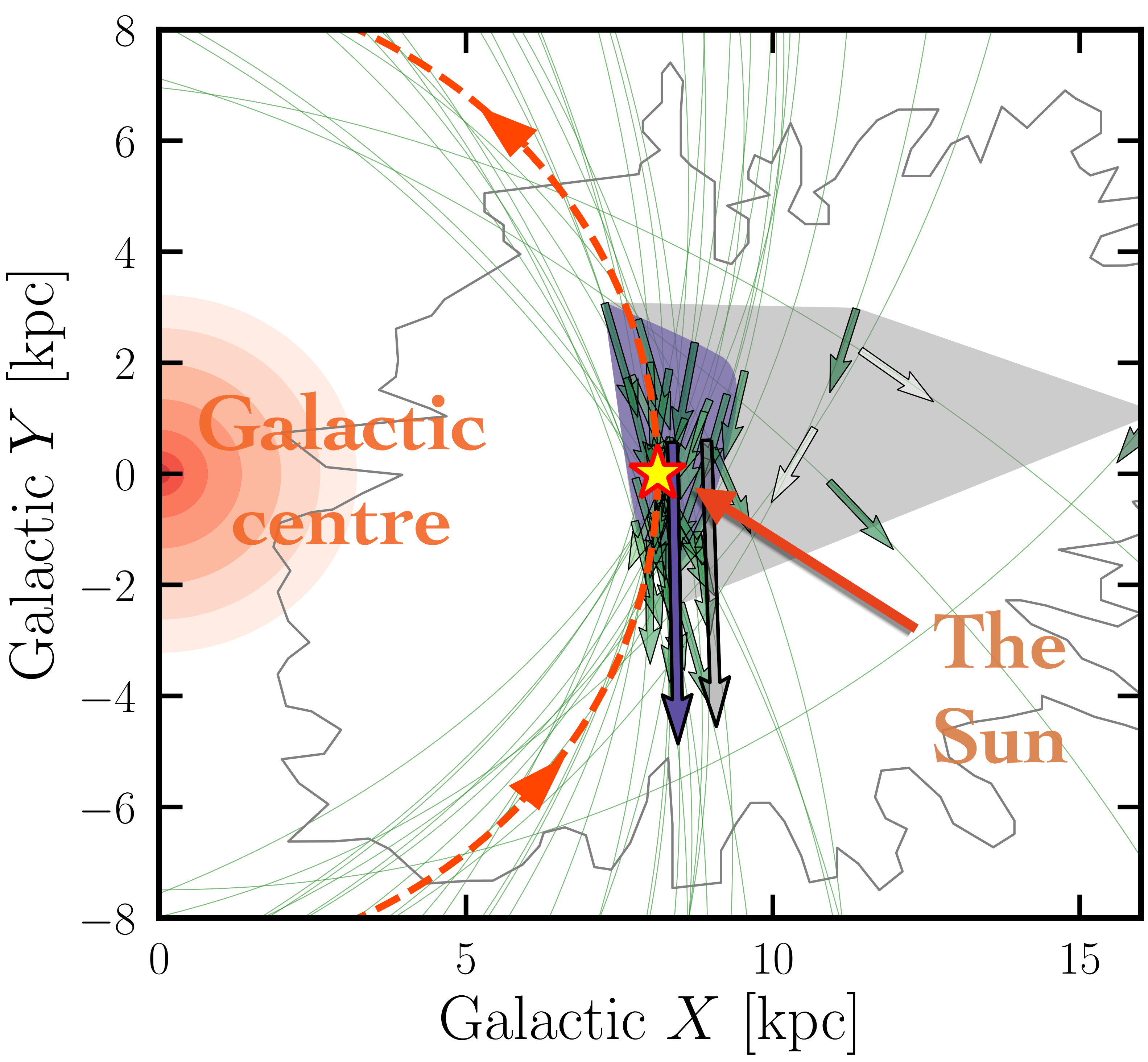
→ **we can see streams that we are inside of**



S2
stream

Overdense retrograde tail containing several streams including S1

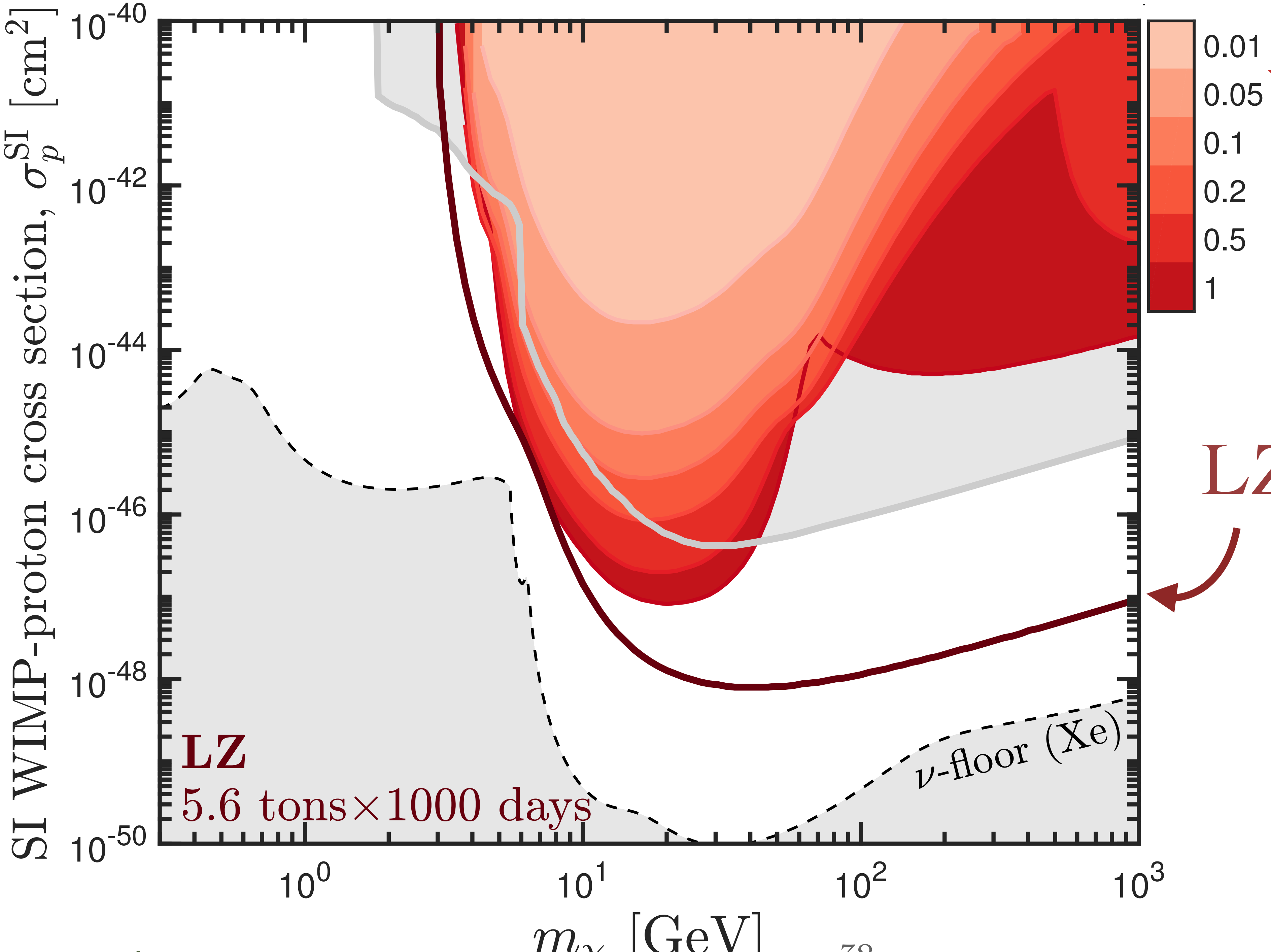
The S1 stream



- 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

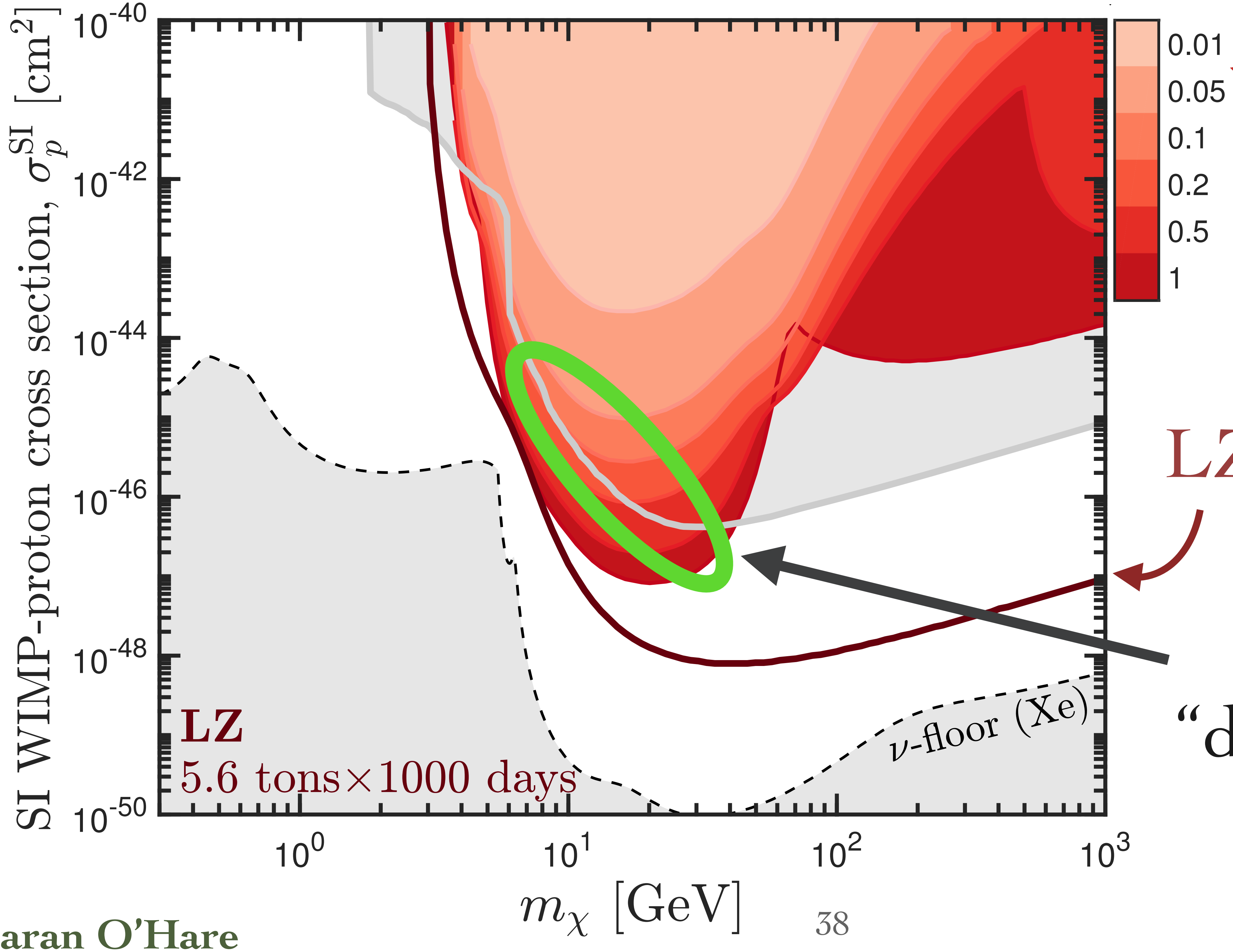


Fraction of total DM in stream

LZ sensitivity

S1 in LZ

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



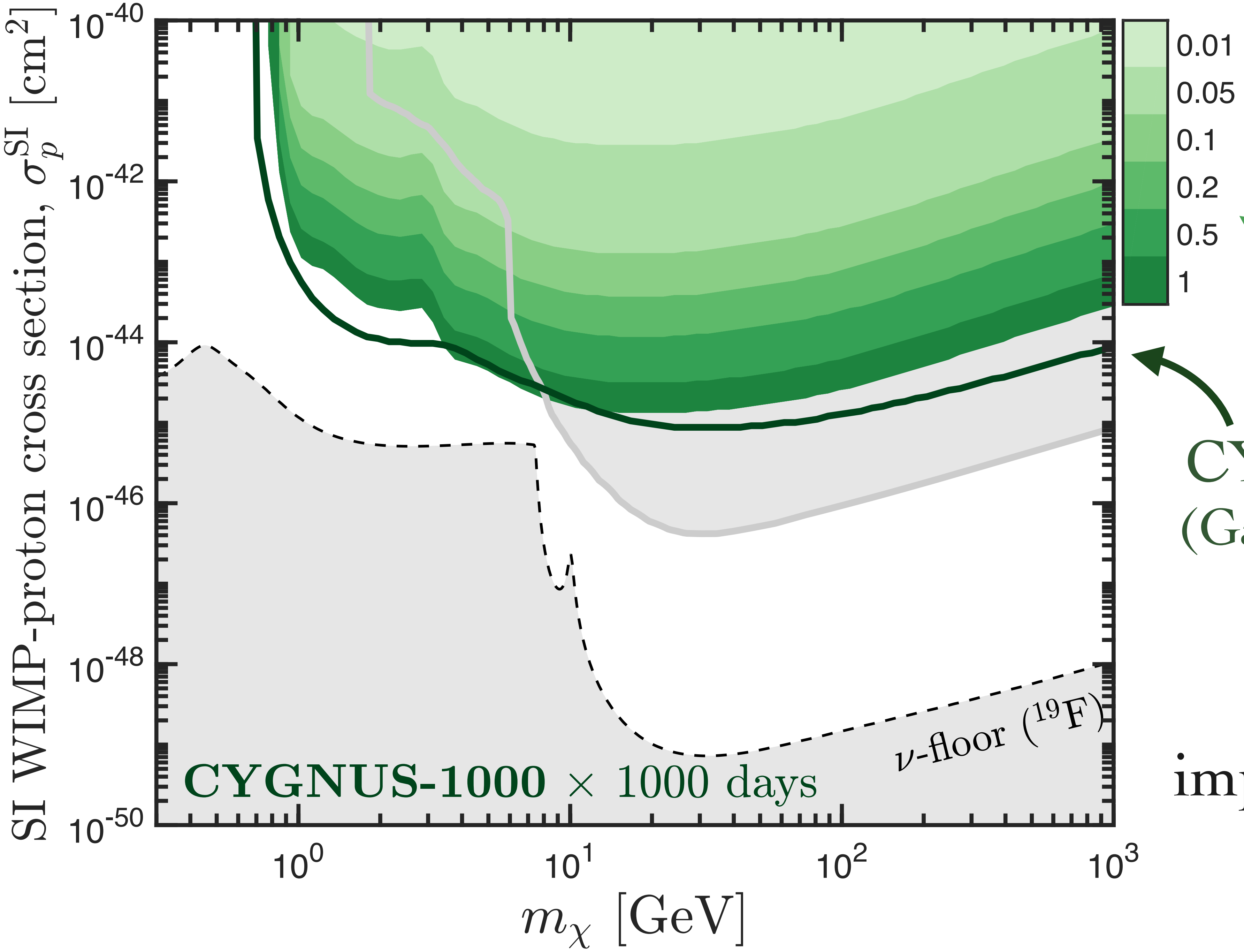
Fraction of total DM in stream

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



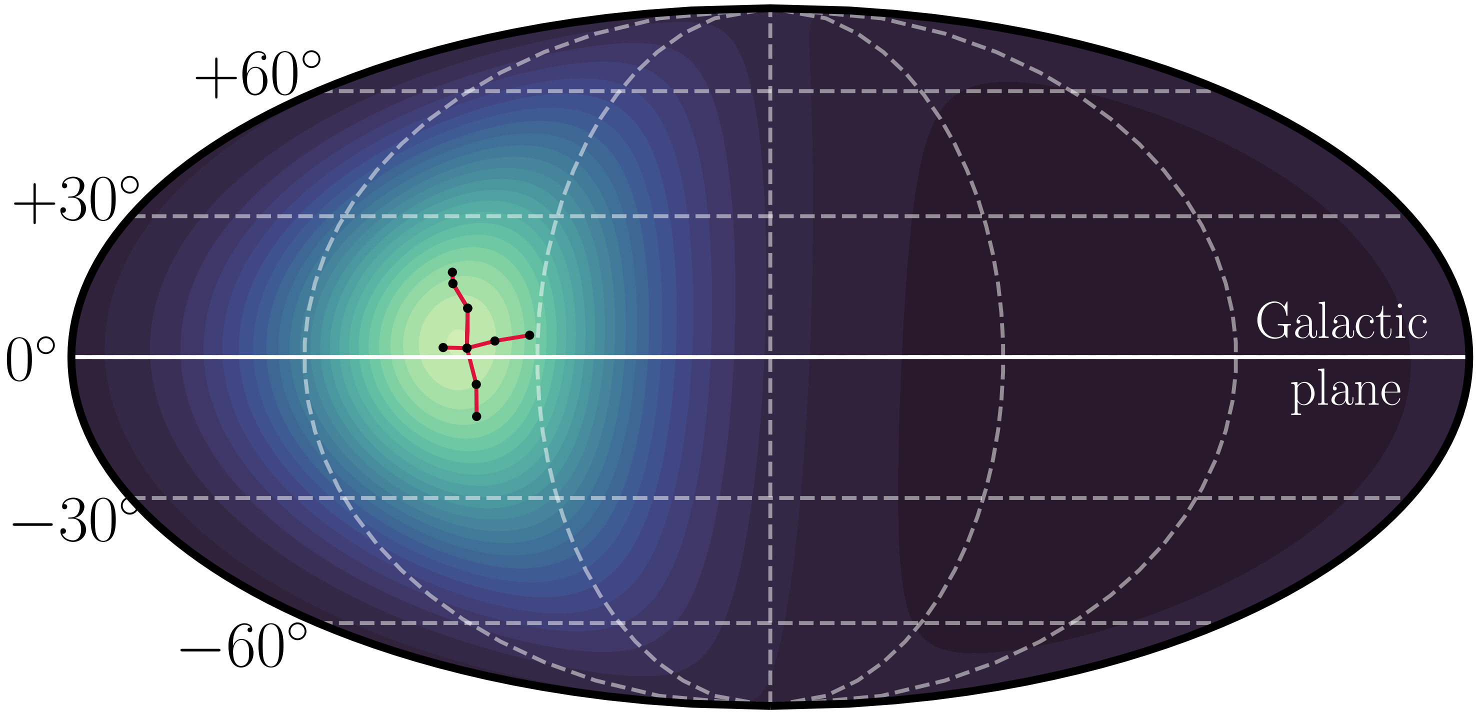
Fraction of DM in stream

CYGNUS sensitivity (Gas TPC with He+SF$_6$)

Directionality improves sensitivity to stream

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)