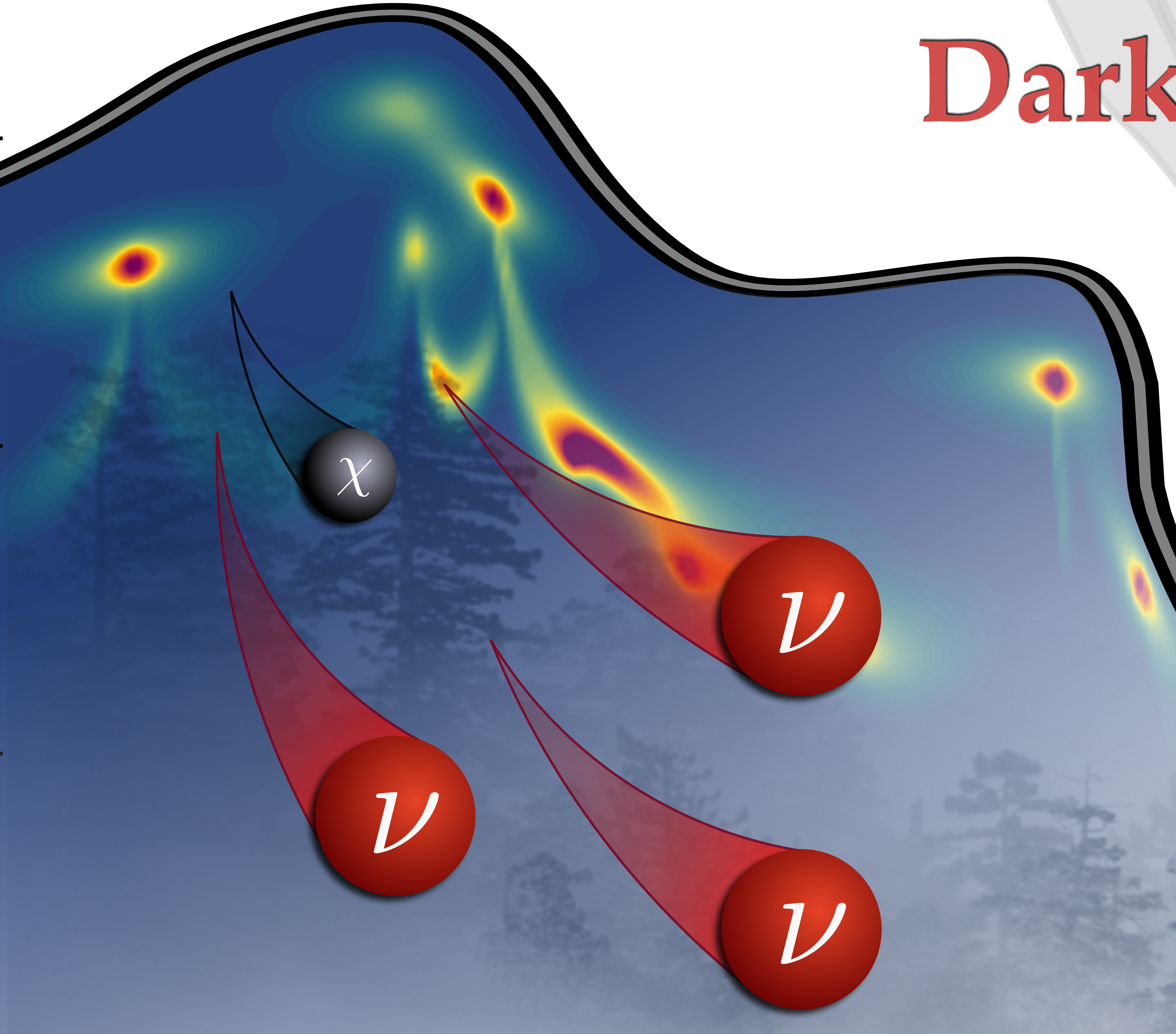
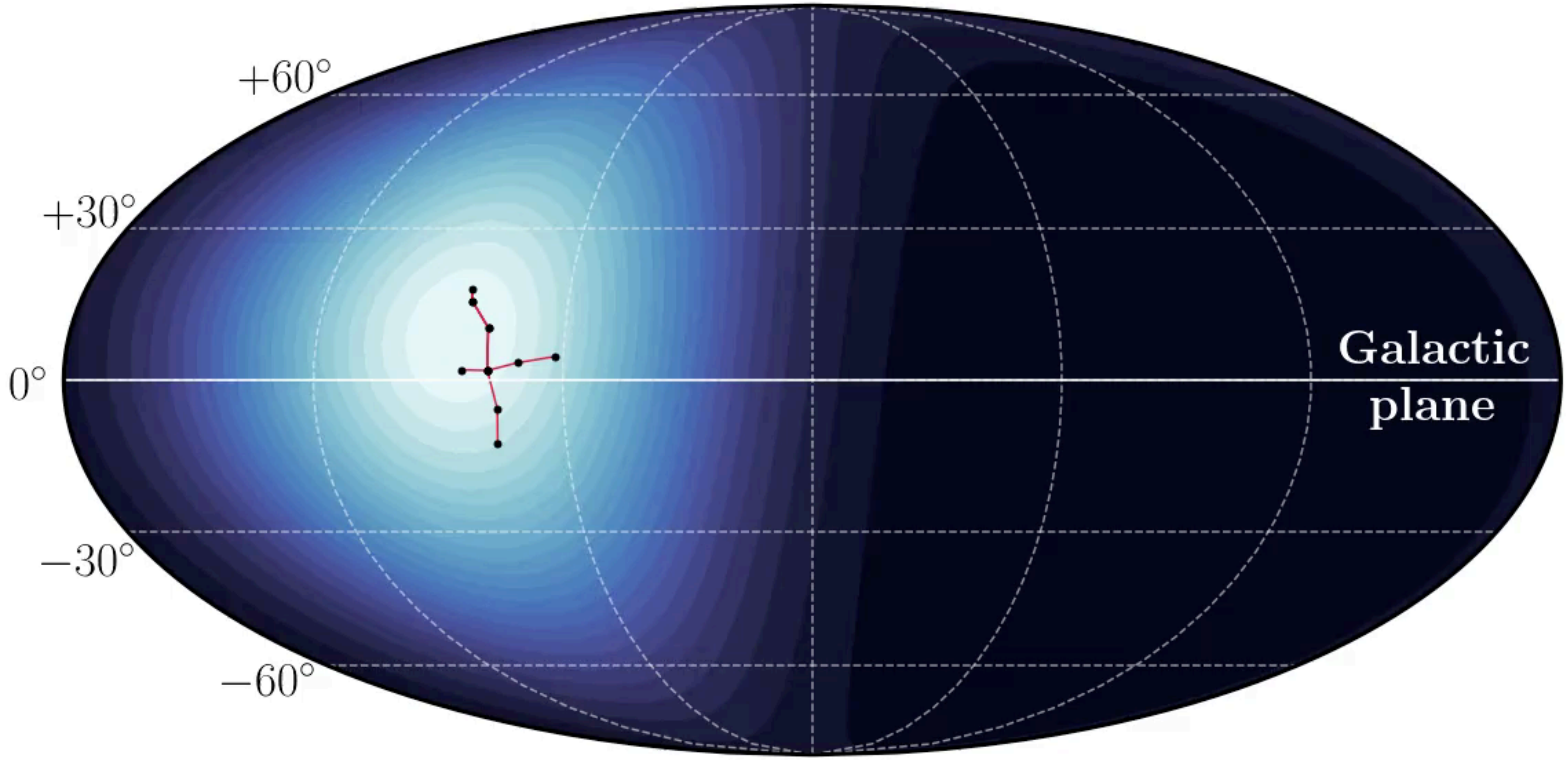
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF SYDNEY

Dark matter, neutrinos, and directional detection

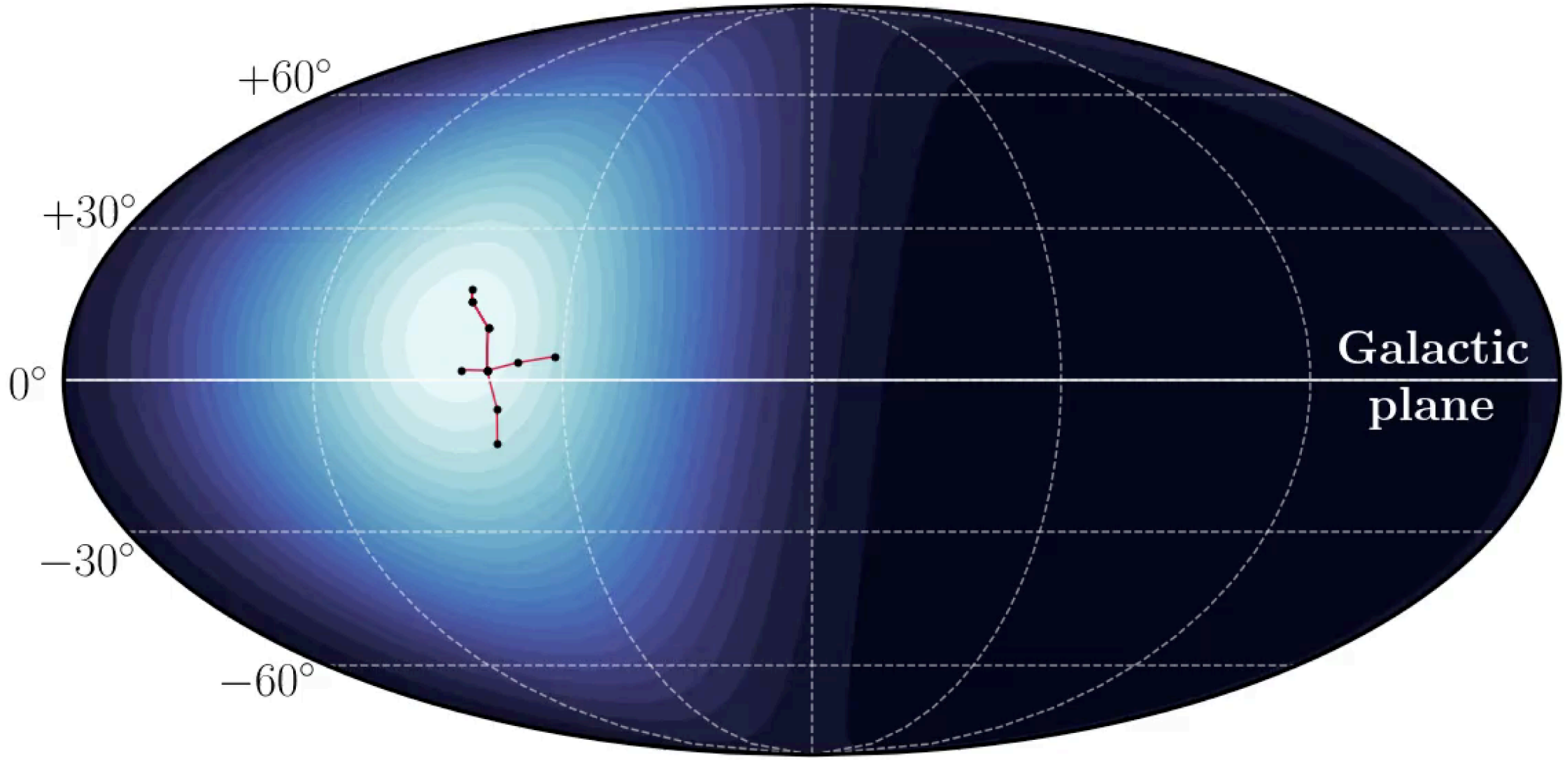


Ciaran O'Hare
University of Sydney



The dark matter flux on Earth is anisotropic and should align with the direction of galactic rotation

→ **This is taken almost as gospel now, how confident are we really?**



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The dark matter flux on Earth is anisotropic and aligns with the direction of galactic rotation

→ **What are the ways in which this statement could be false?**

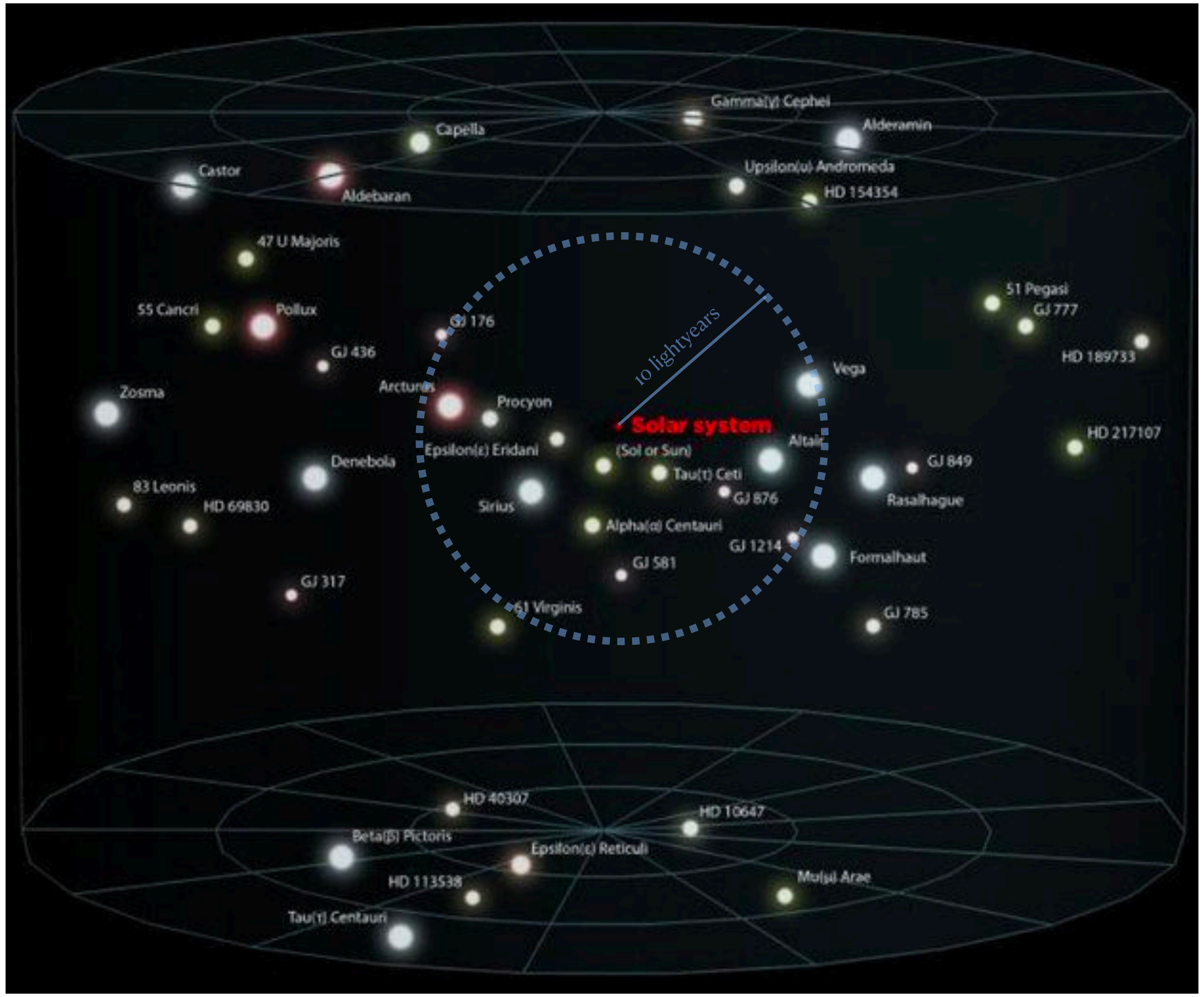
The dark matter flux on Earth is anisotropic and aligns with the direction of galactic rotation

→ **What are the ways in which this statement could be false?**

1. There is no dark matter around to detect
2. The dark matter halo is rotating (i.e. no DM wind)
3. There is a DM wind, but it doesn’t align with Cygnus

1. What if there is no dark matter around to detect?

Halos for ~GeV scale DM should imply a smooth density field around the Earth's position. We know this from measurements of our galaxy, and from simulations, but there is a question of scales:



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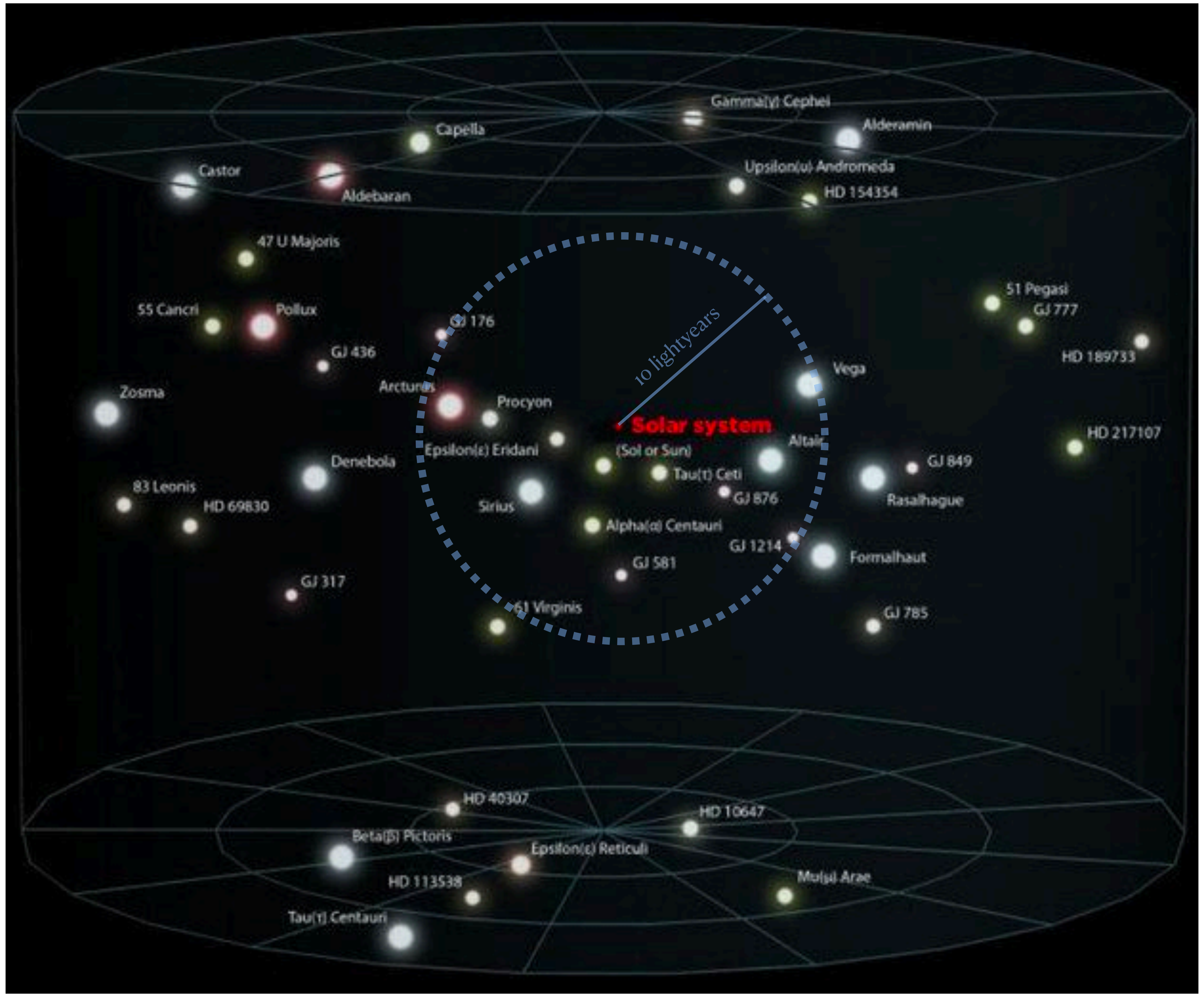
  → know this from nearby stars ~100 pc away



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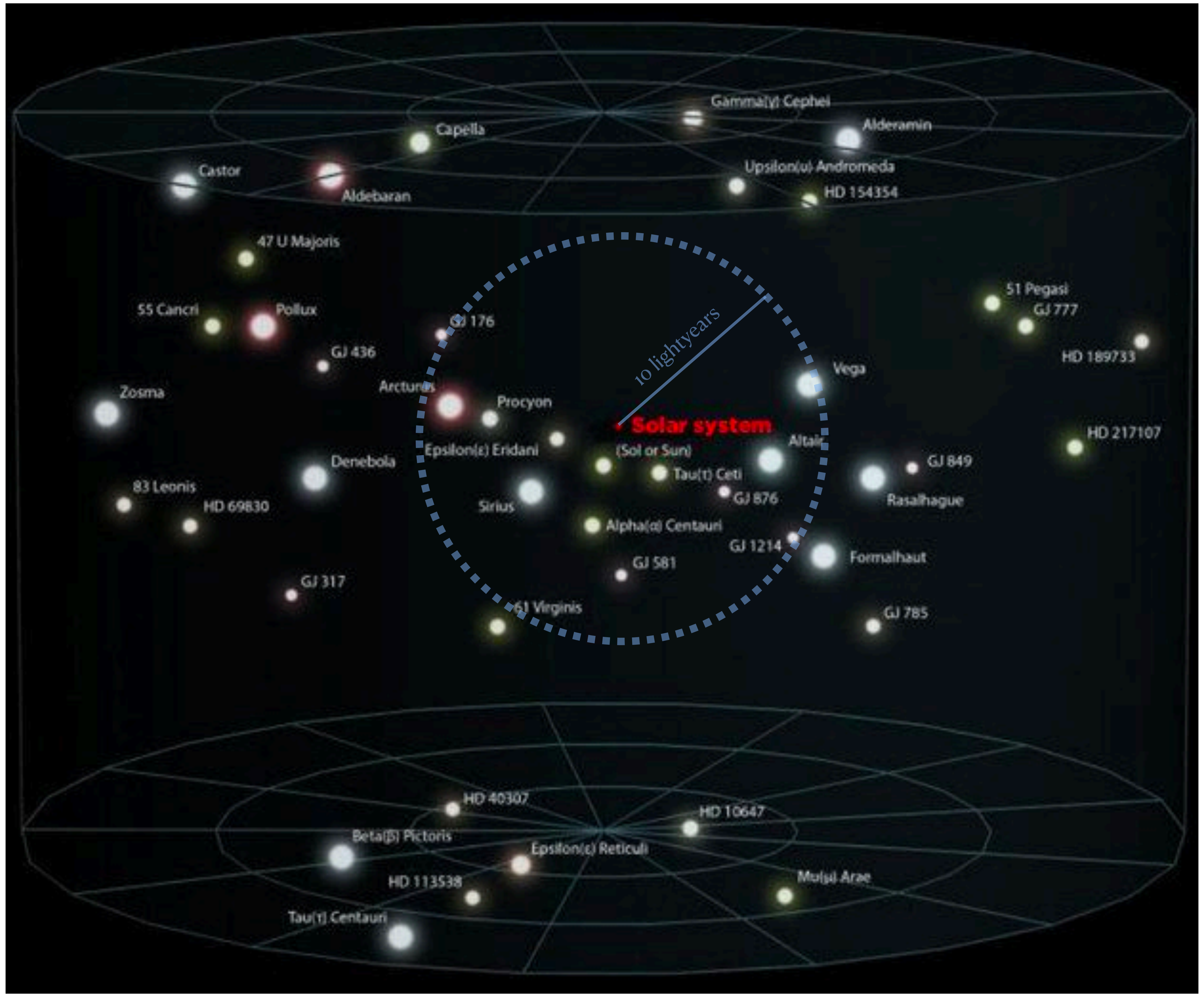

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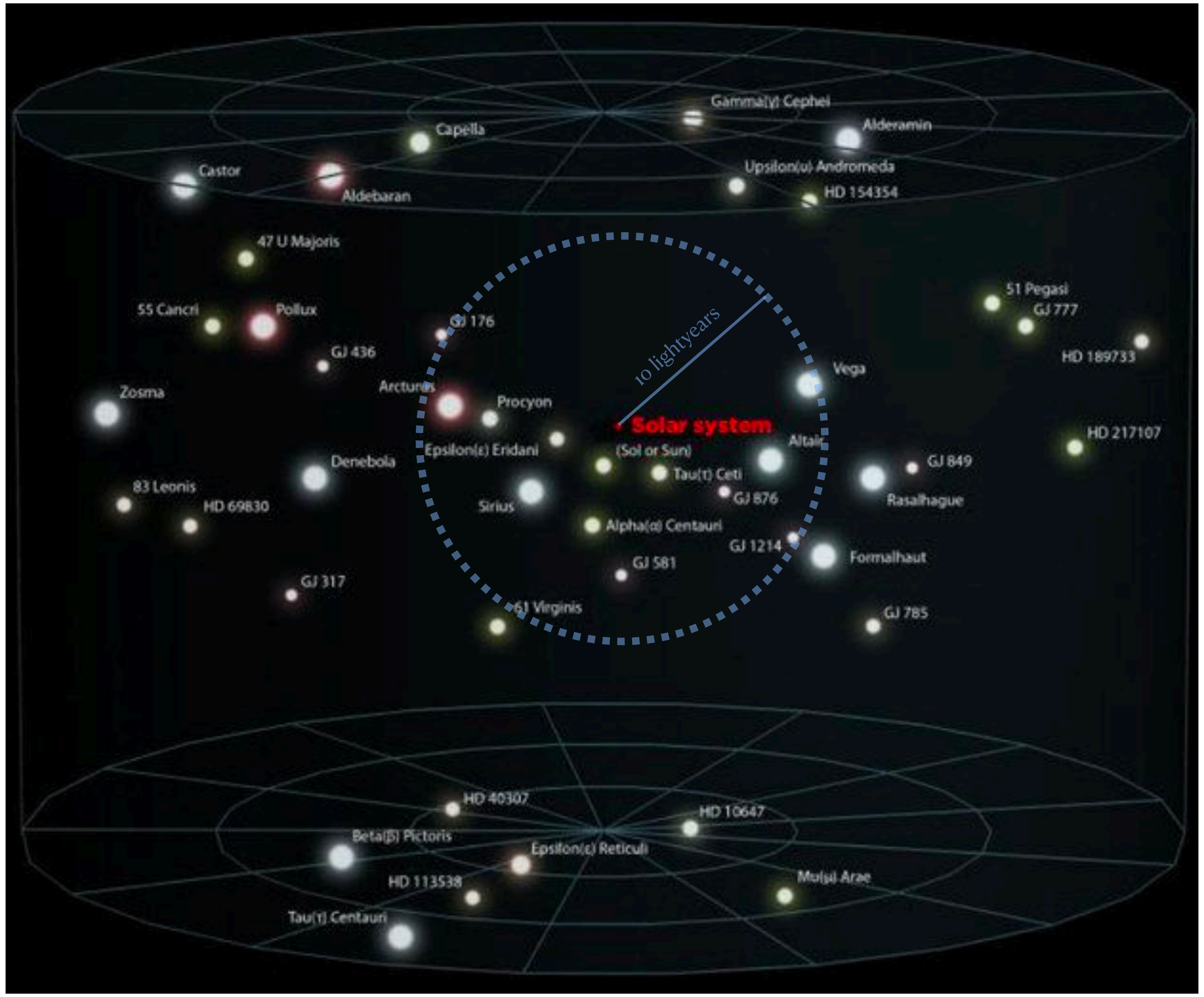
$\rightarrow$ The smallest scale we have evidence for a nonzero DM density is still ~5 orders of magnitude larger than the scale we are probing



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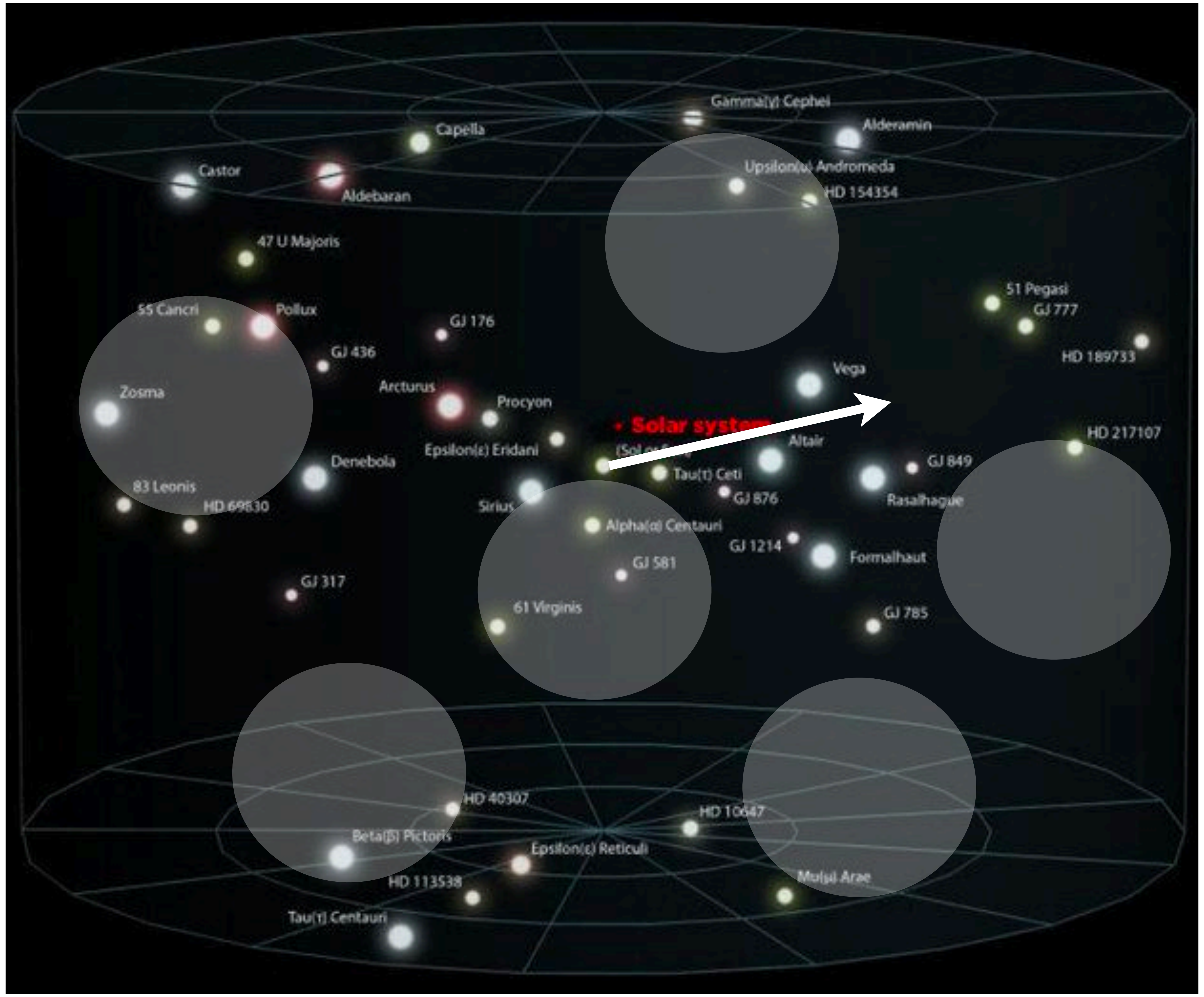
Knowledge about the DM density on sub-mpc scales is inaccessible to both observations and simulations. So the DM distribution could well be clumpy and we wouldn't have seen evidence for this.



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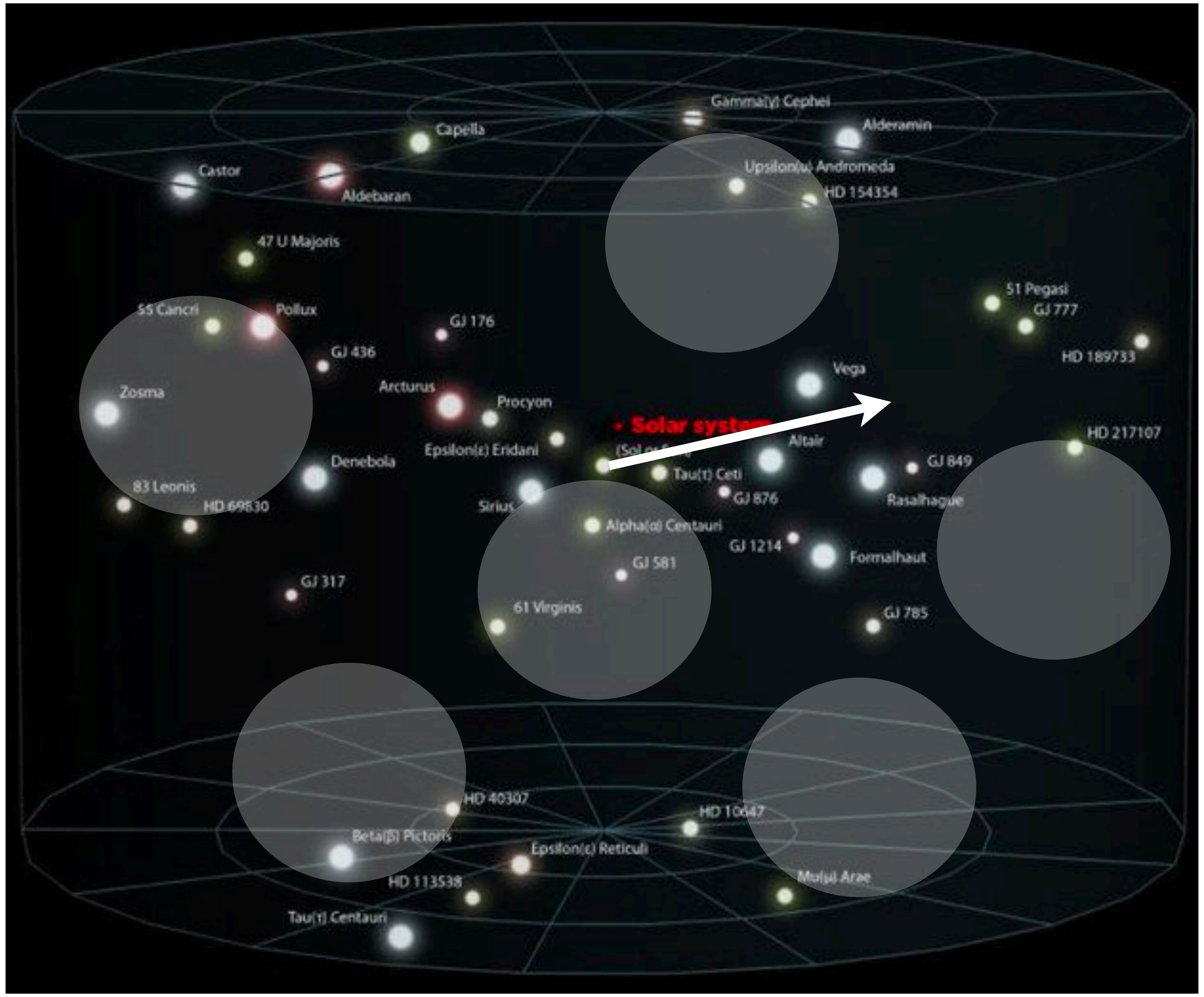
→ If we were in between clumps that were > mpc apart, a direct detection experiment would <u>never work</u>



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arXiv:[1002.3162]

- This problem is thought to have been resolved by this paper from 2010, but very few followups using more sophisticated simulations.

- This is an open problem that almost no one ever talks about. Needless to say it would doom all experiments, not just directional ones.

Streams and caustics: the fine-grained structure of ΛCDM haloes

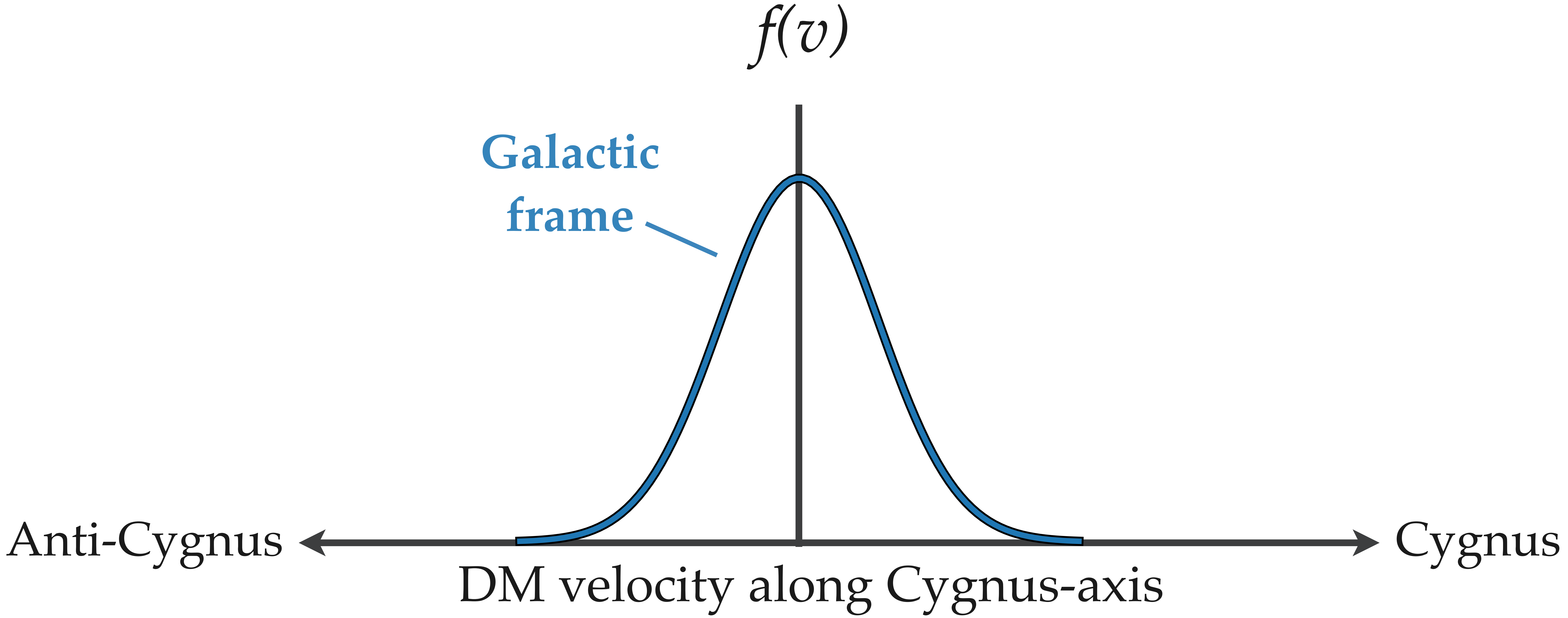
Mark Vogelsberger[1,2*], Simon D. M. White[1]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85740 Garching bei München, Germany*
[2] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

30 October 2018

ABSTRACT
We present the first and so far the only simulations to follow the fine-grained phase-space structure of galaxy haloes formed from generic ΛCDM initial conditions. We integrate the geodesic deviation equation in tandem with the N-body equations of motion, demonstrating that this can produce numerically converged results for the properties of fine-grained phase-space streams and their associated caustics, even in the inner regions of haloes. Our effective resolution for such structures is many orders of magnitude better than achieved by conventional techniques on even the largest simulations. We apply these methods to the six Milky Way-mass haloes of the Aquarius Project. At 8 kpc from halo centre a typical point intersects about 10^{14} streams with a very broad range of individual densities; the $\sim 10^6$ most massive streams contribute about half of the local dark matter density. As a result, the velocity distribution of dark matter particles should be very smooth with the most massive fine-grained stream contributing about 0.1% of the total signal. Dark matter particles at this radius have typically passed 200 caustics since the Big Bang, with a 5 to 95% range of 50 to 500. Such caustic counts are a measure of the total amount of dynamical mixing and are very robustly determined by our technique. The peak densities on present-day caustics in the inner halo almost all lie well below the mean local dark matter density. As a result caustics provide a negligible boost ($< 0.1\%$) to the predicted local dark matter annihilation rate. The effective boost is larger in the outer halo but never exceeds about 10%. Thus fine-grained streams and their associated caustics have no effect on the detectability of dark matter, either directly in Earth-bound laboratories, or indirectly through annihilation radiation, with the exception that resonant cavity experiments searching for axions may see the most massive local fine-grained streams because of their extreme localisation in energy/momentum space.

2. What if the DM halo is rotating?



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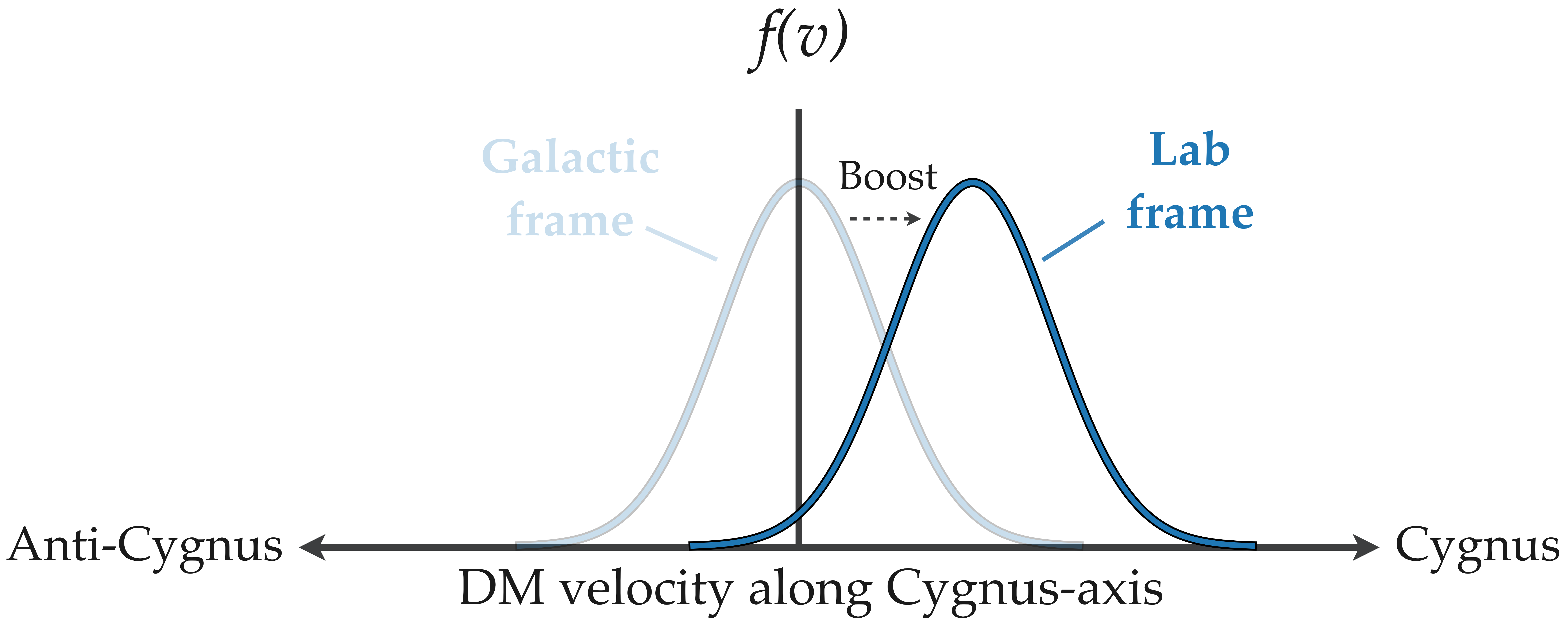

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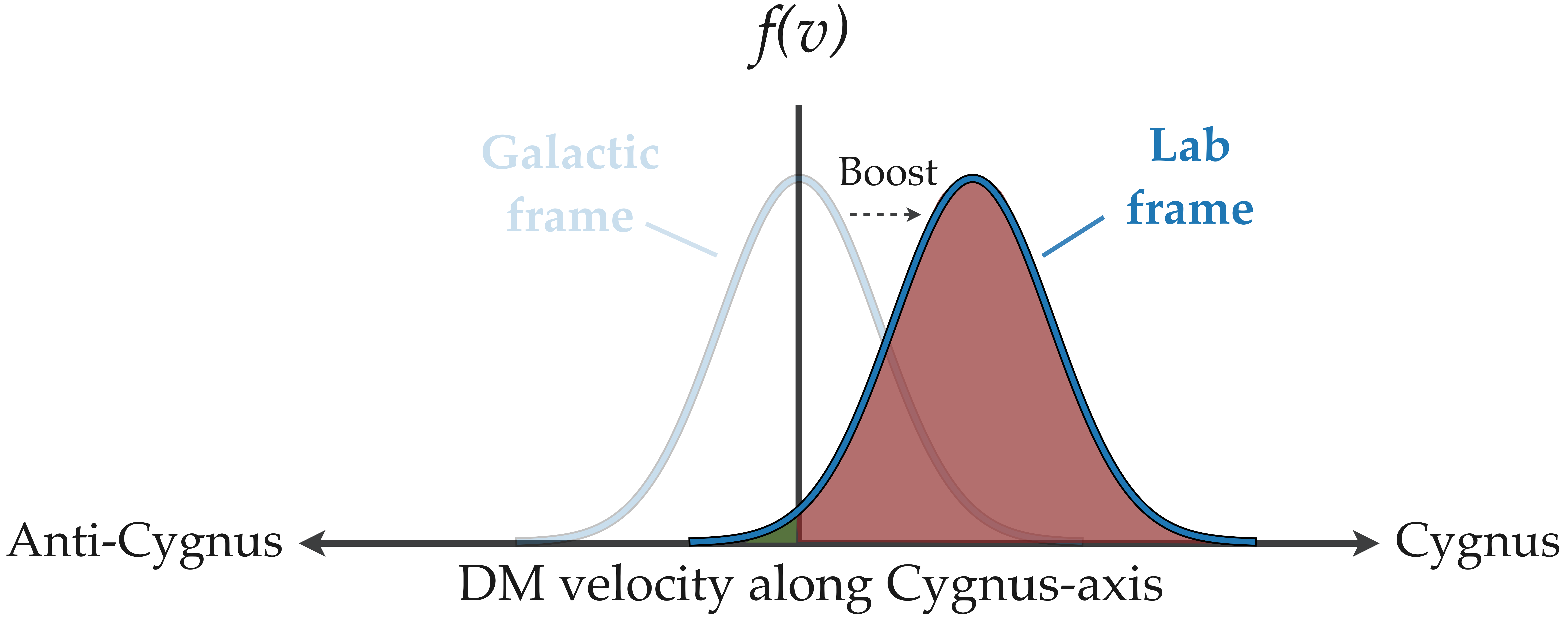
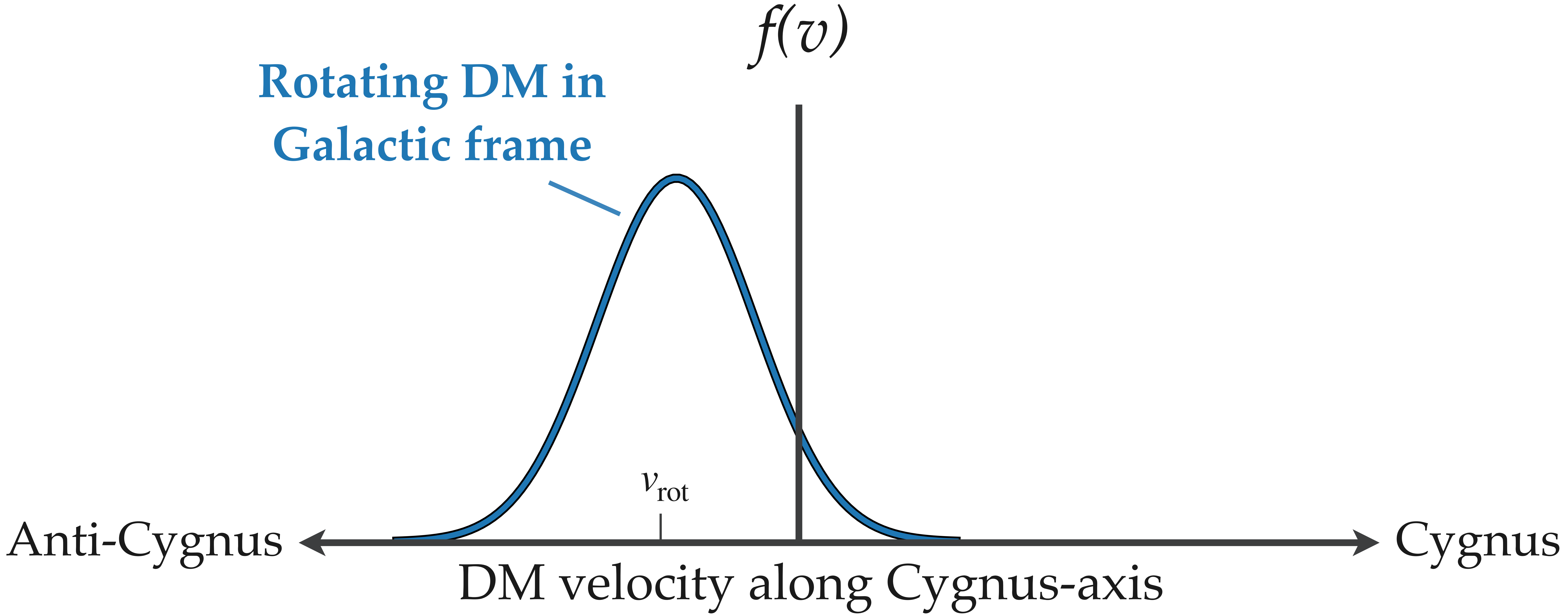


Anisotropy in DM flux is the ratio of **forward-going** particles to **backward-going** particles

What if the DM had some net rotation to begin with?



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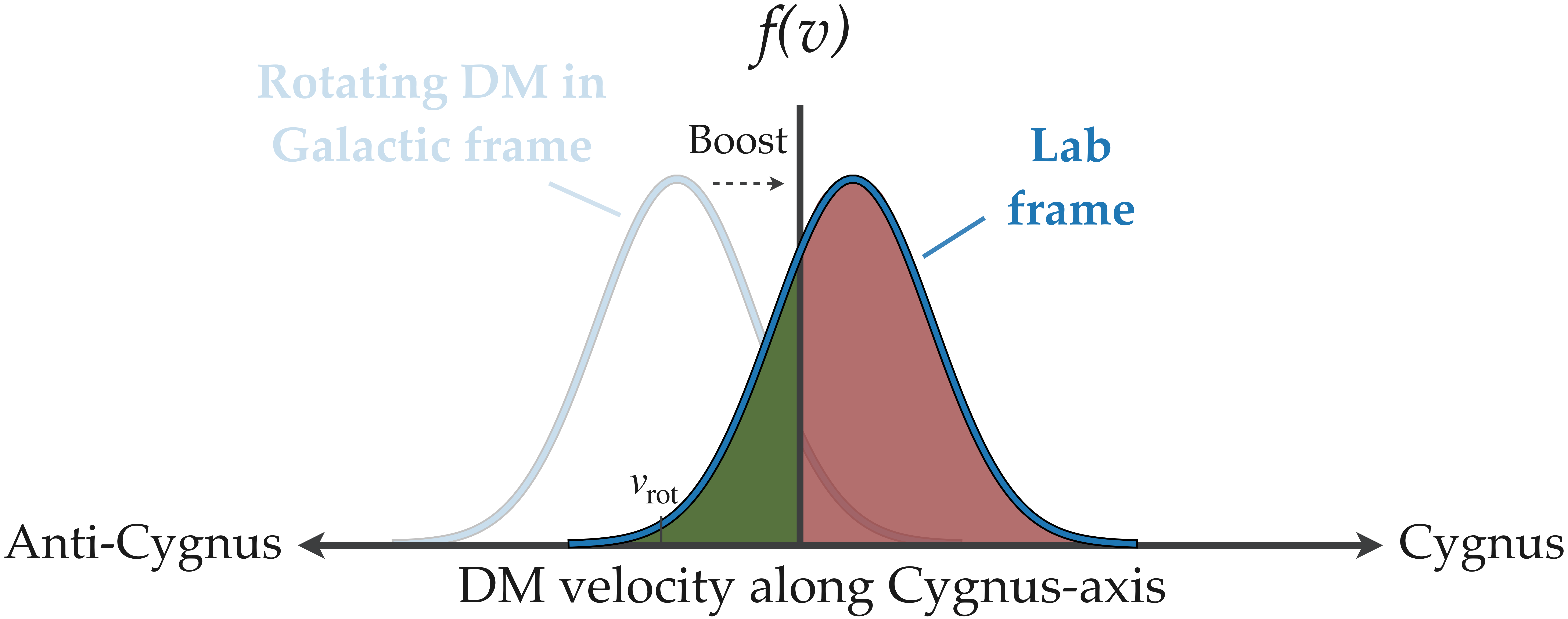


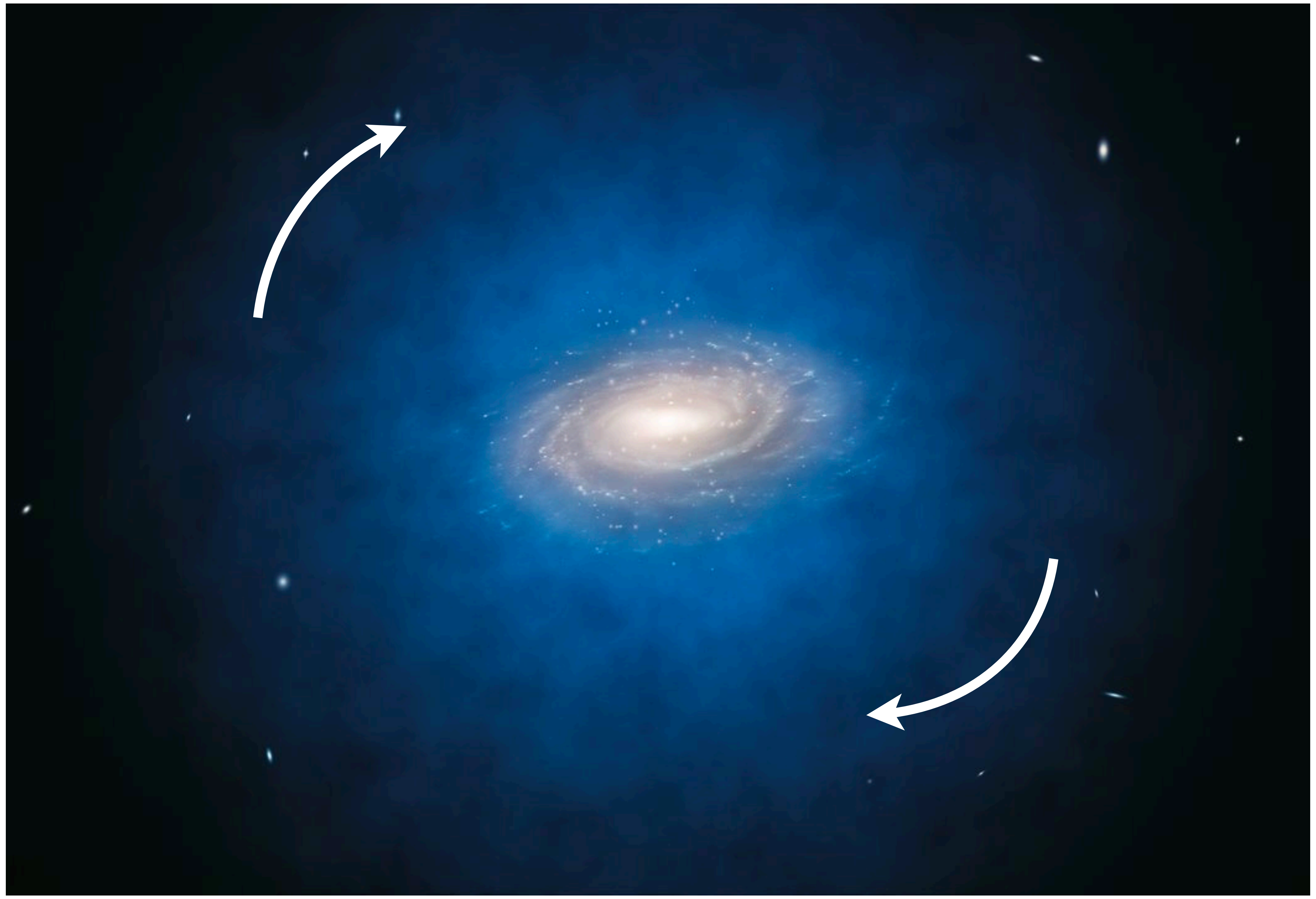
If rotation speed of DM is comparable to our galactic rotation speed then the anisotropy will be reduced

→ If $v_{rot} = 230$ km/s there is **no DM wind** at all

Can the DM halo be rotating?

→ Two possible scenarios

1. **Figure rotation aka "tumbling"**
   Triaxial halos like the MW's are expected to accumulate angular momentum via hierarchical formation. However, in simulations pattern speeds are typically very slow (~1 km/s in the inner halo). The figure rotation of the MW has not been well-measured yet (see e.g. 2110.11490, 2009.09004), so cannot be anomalously fast



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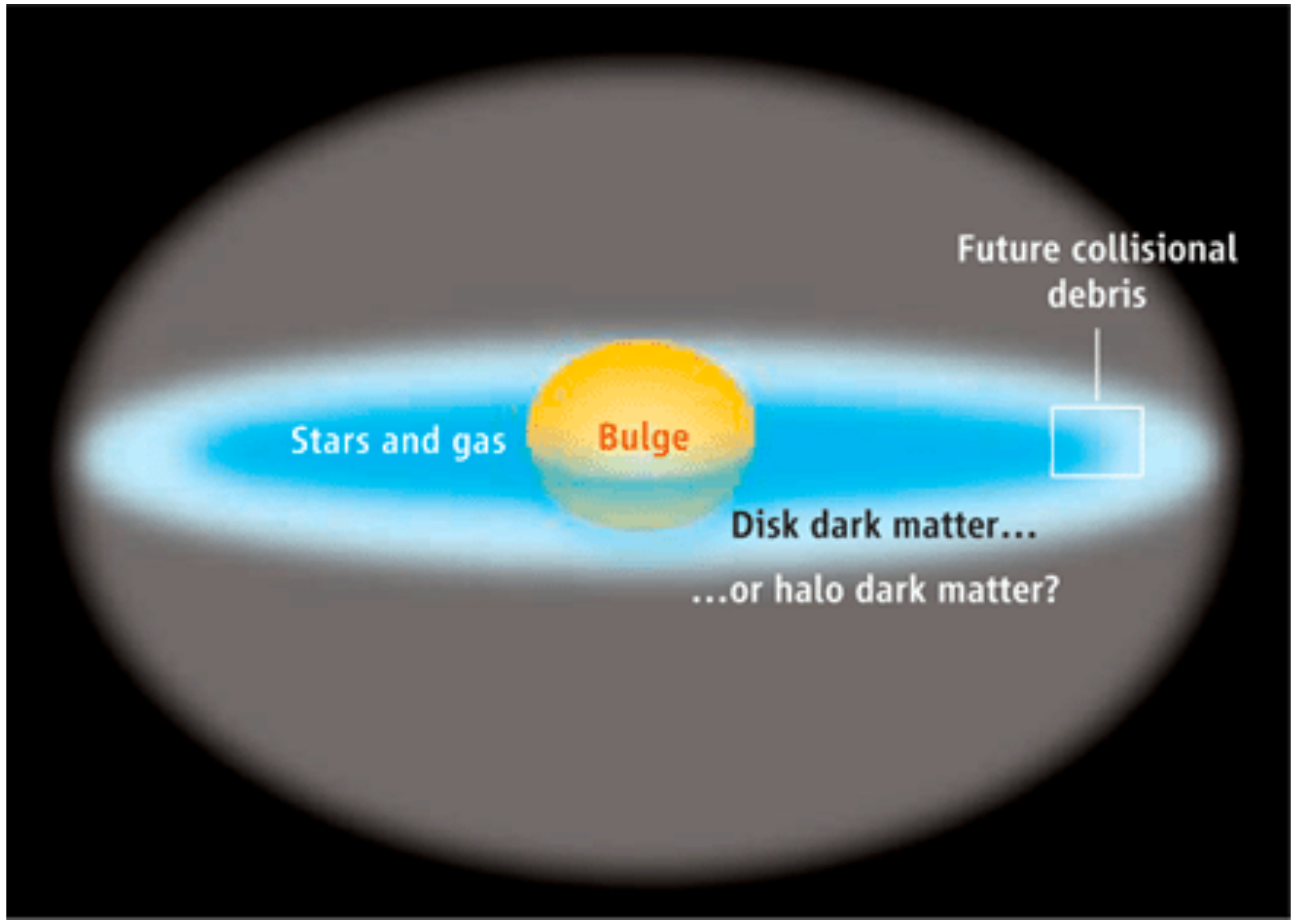
   It is possible that some of the dark matter halo collects in a disk-like configuration that co-rotates with the baryonic disk. However,



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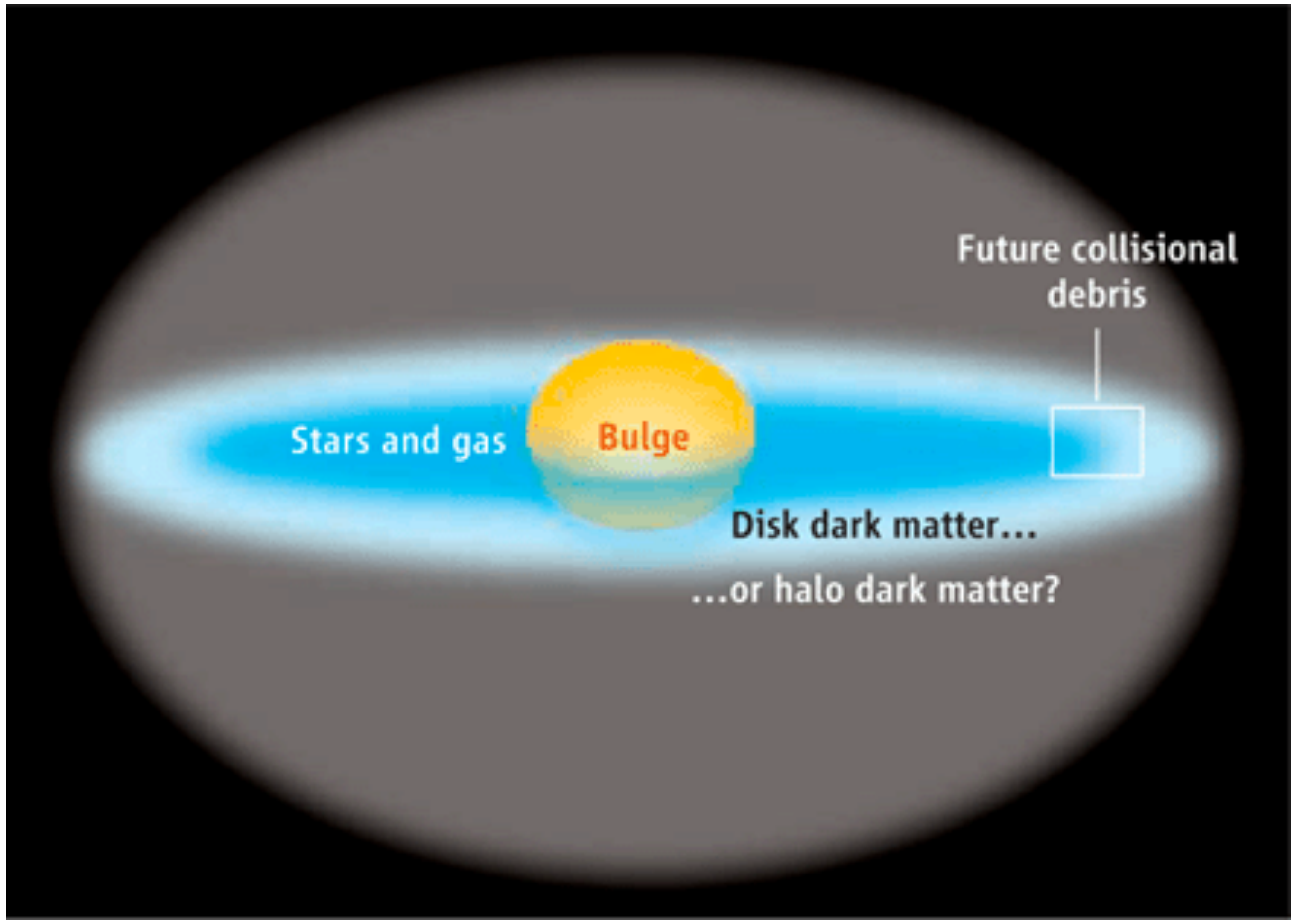
- Dark disks forming via merger require very specific conditions (see 1605.02770) that are not matched by the known MW mergers (e.g. Gaia-Enceladus, Sagittarius dwarf)



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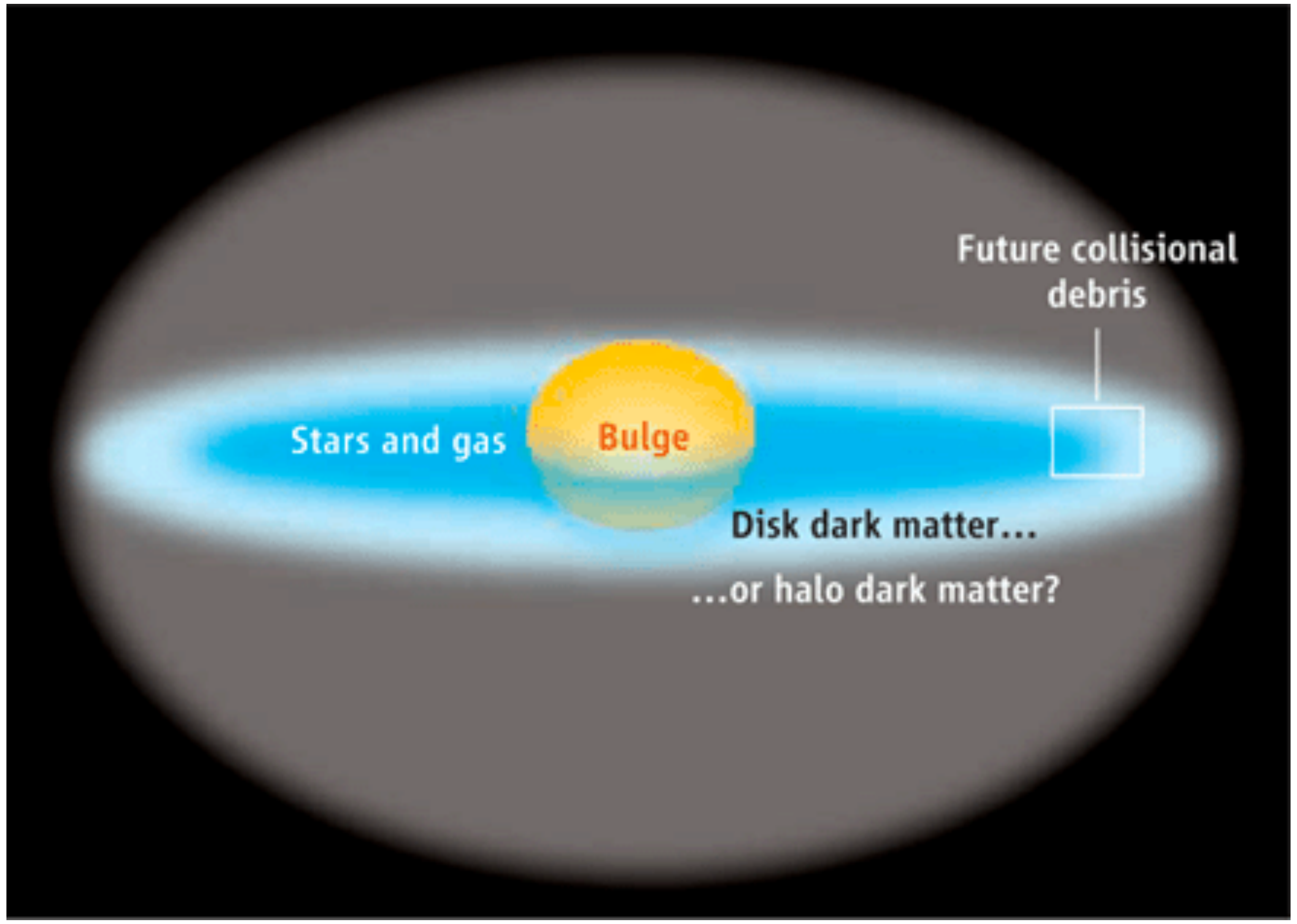

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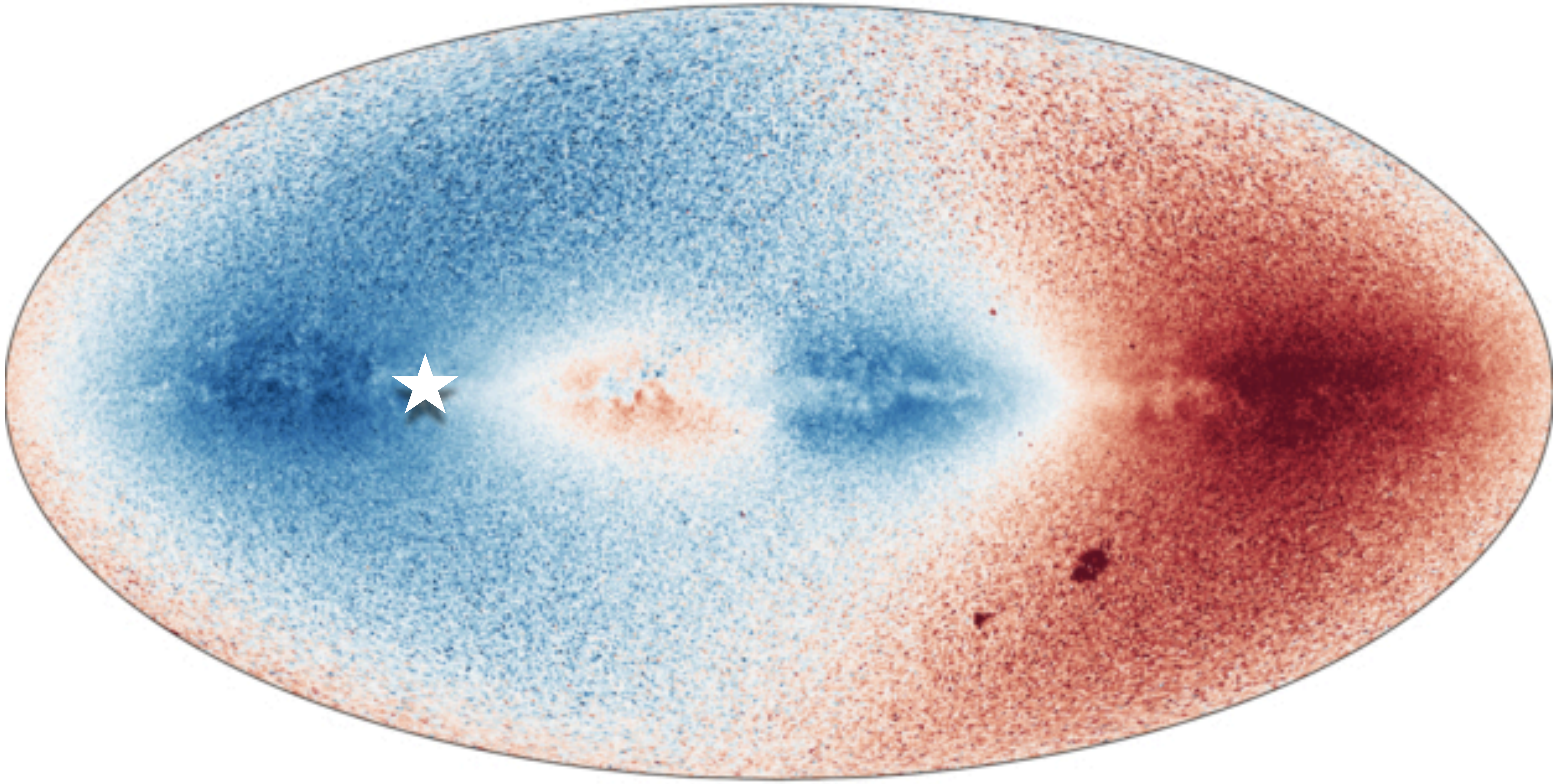
- A *thin* dark disk formed via dissipative DM self-interactions is constrained to be a sub-percent fraction of the DM (see e.g. 1808.05603)

What about a DM-wind away from Cygnus?



Gaia skymap of line of sight velocities of stars

Blue = moving towards us (relatively)

Red = moving away from us

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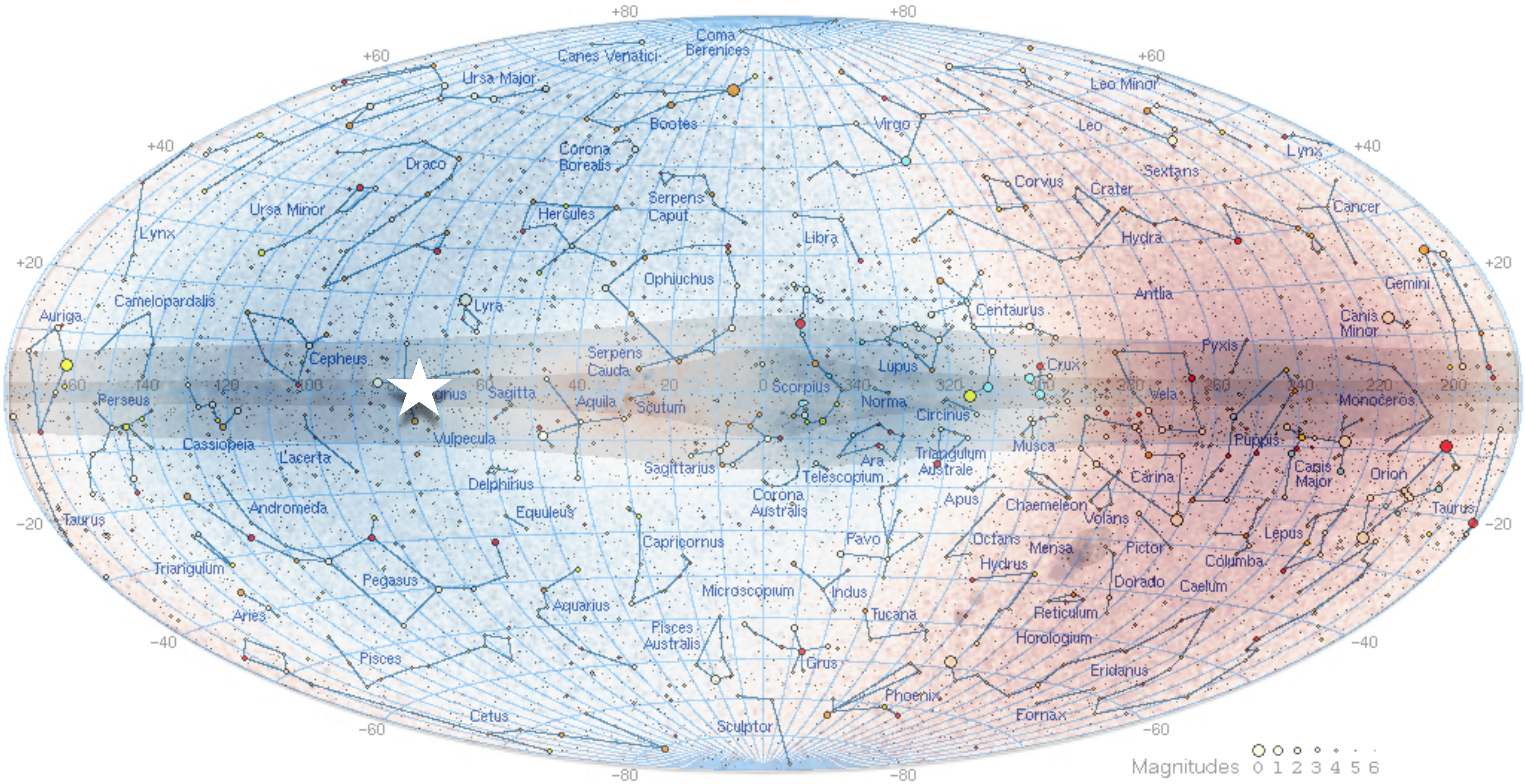

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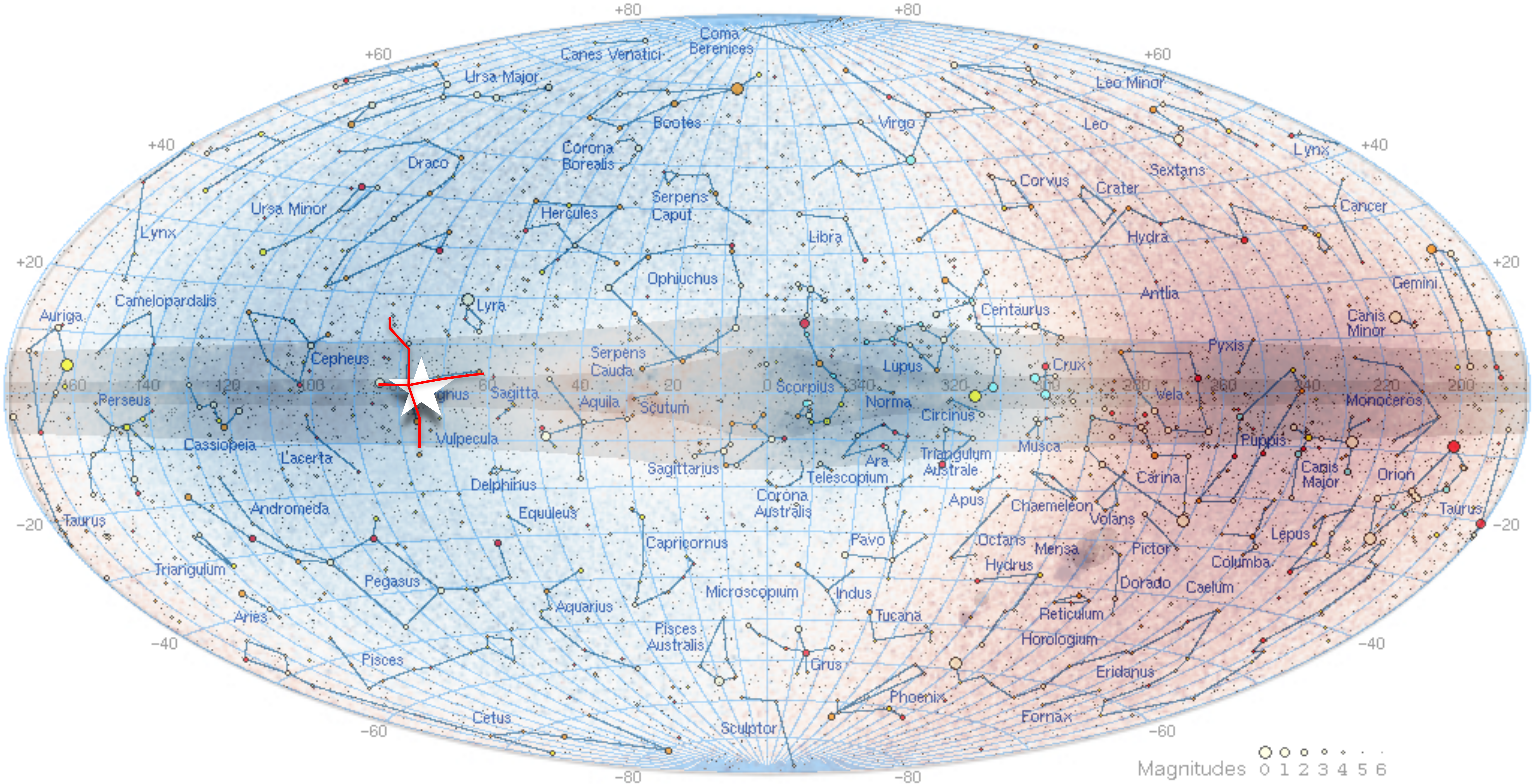

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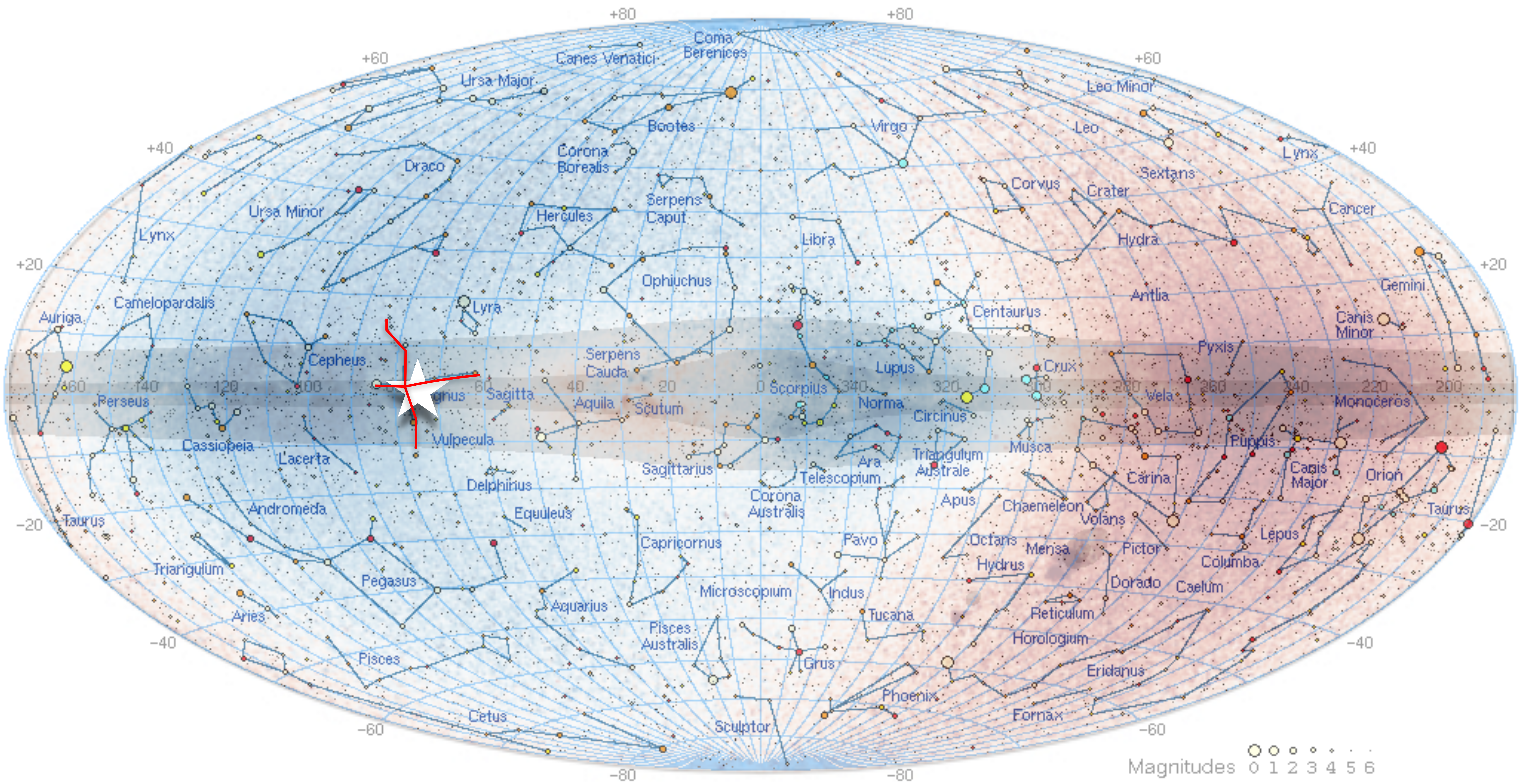
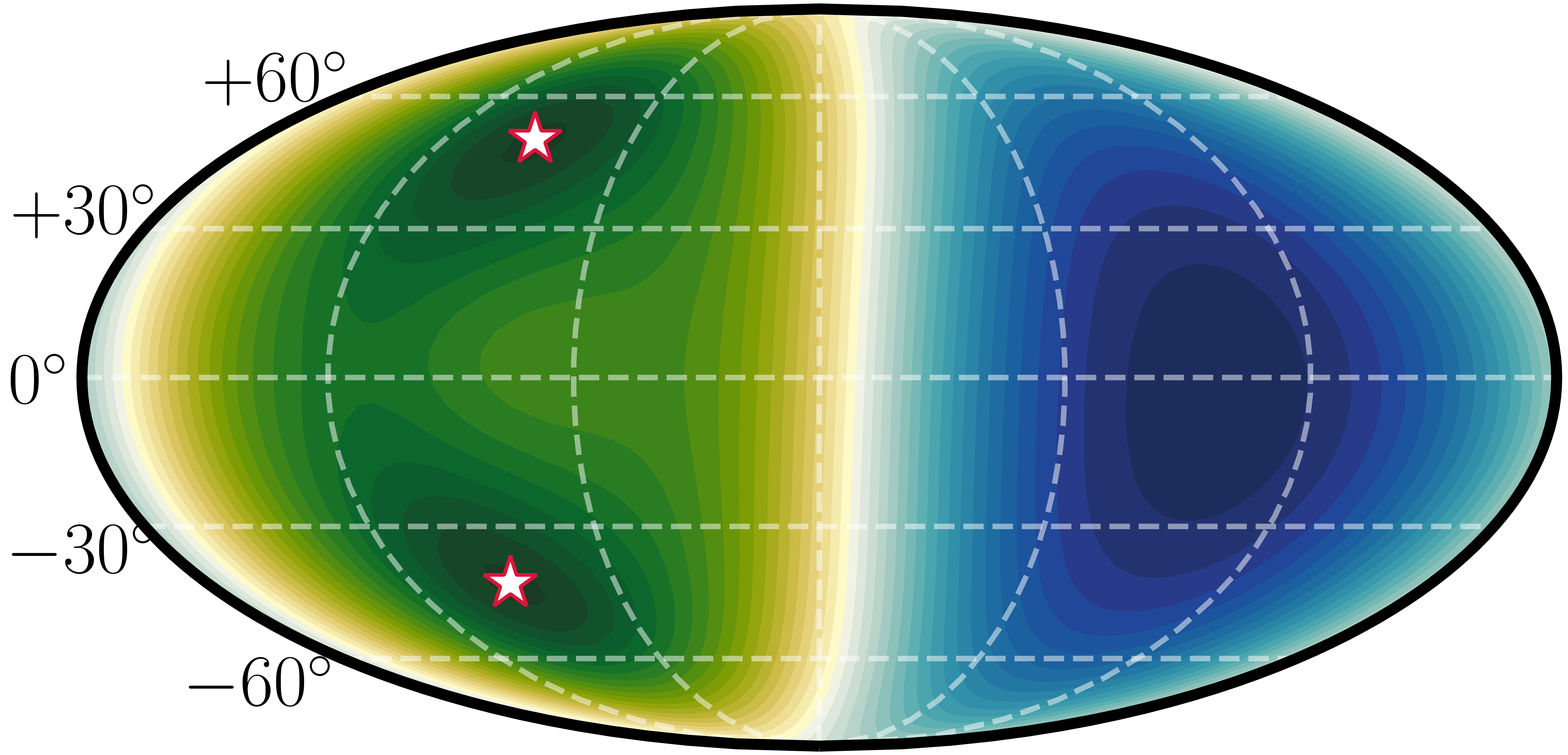


The fact that the DM wind aligns with Cygnus is a result of **our** motion, not the DM's. Our velocity vector through the galaxy is pinned down precisely by Gaia, so to get a DM wind pointing away from Cygnus, we need to mess with the halo model

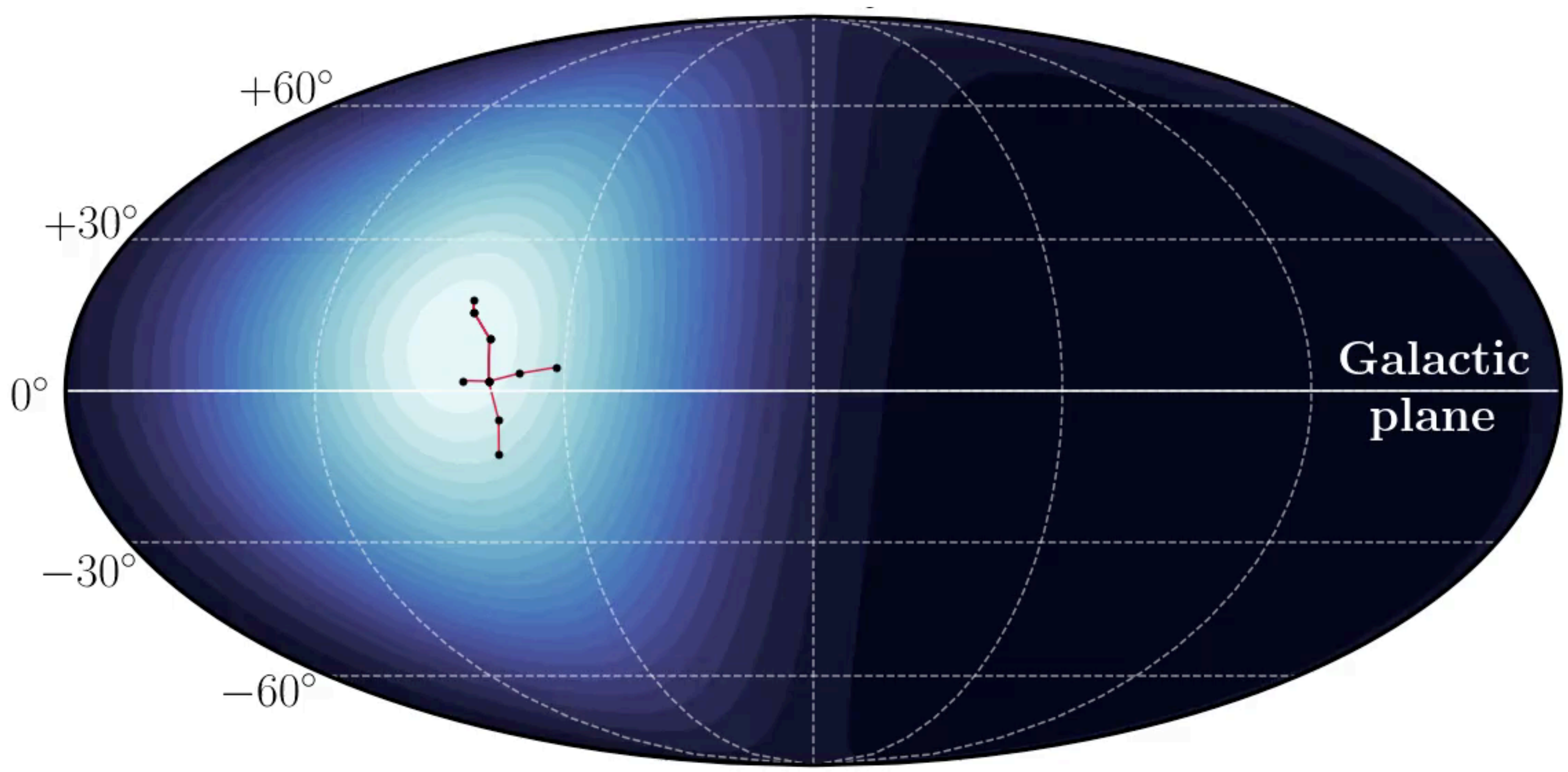
The last significant merger the MW underwent (called Gaia-Enceladus-Sausage) could give rise to peak directions of DM recoils off-centre from Cygnus

→ However, the forward-backward anisotropy persists, even in this model

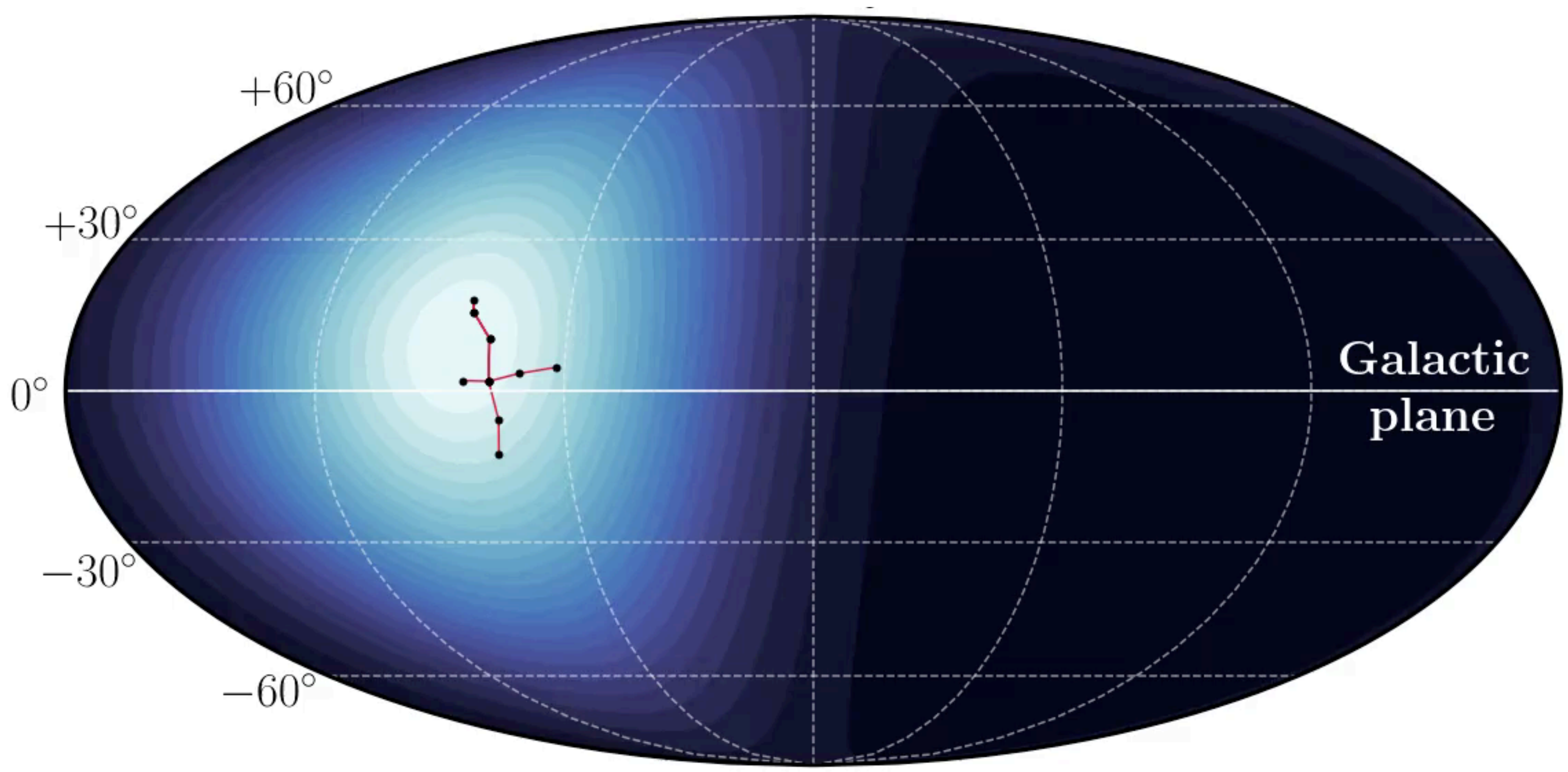
O'Hare+ [1909.04684]



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



The dark matter flux on Earth is anisotropic and should align with the direction of galactic rotation



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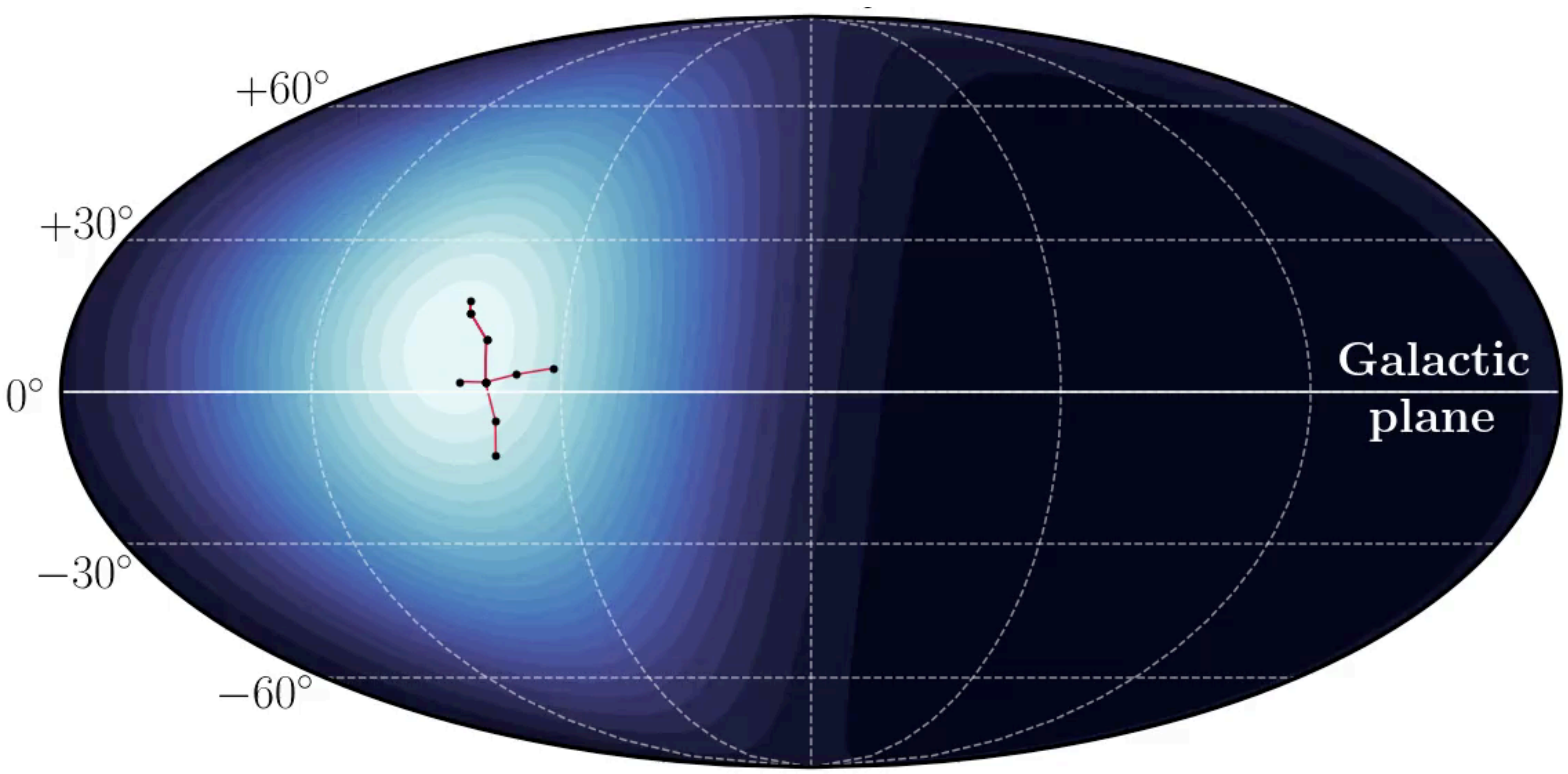

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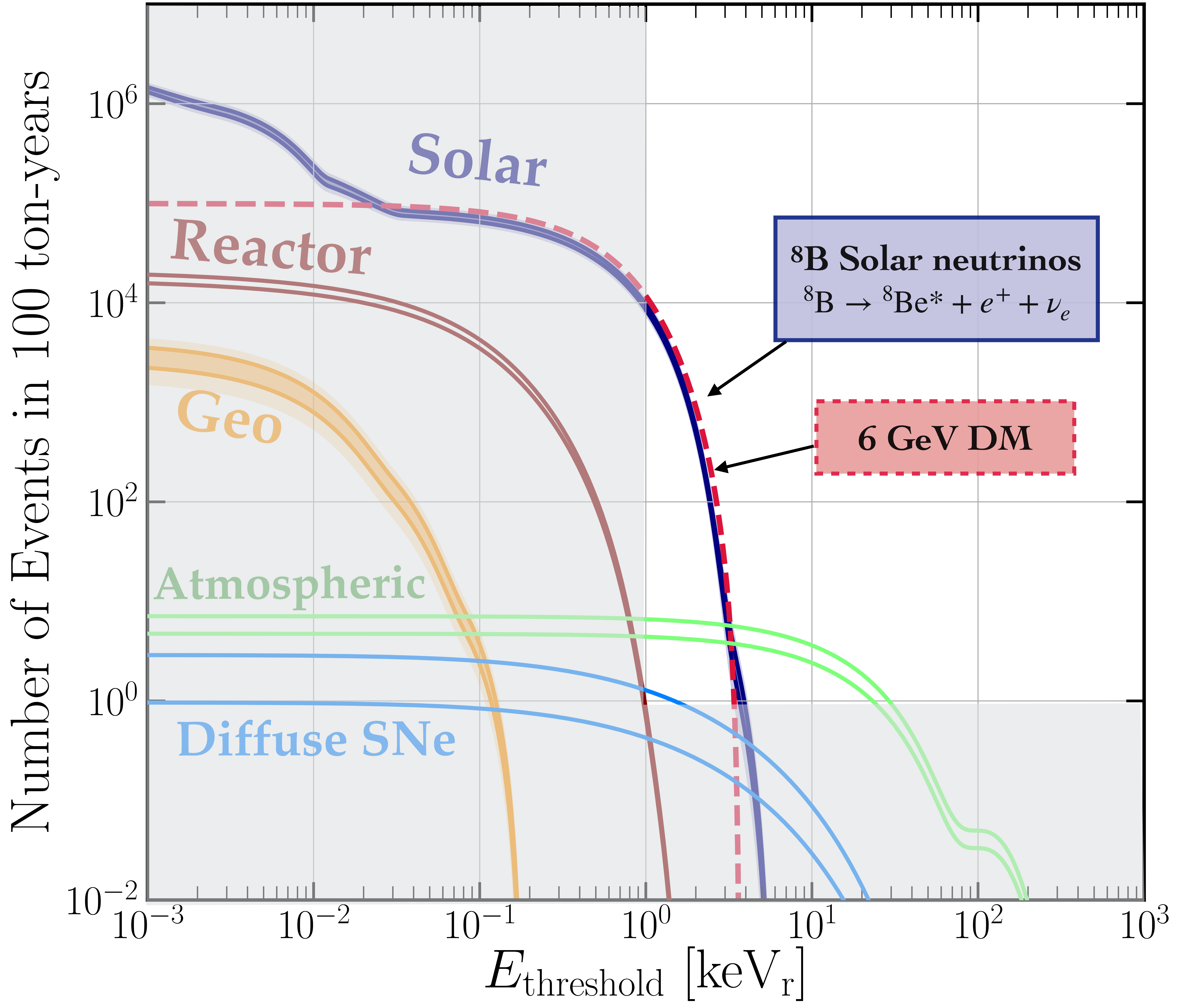
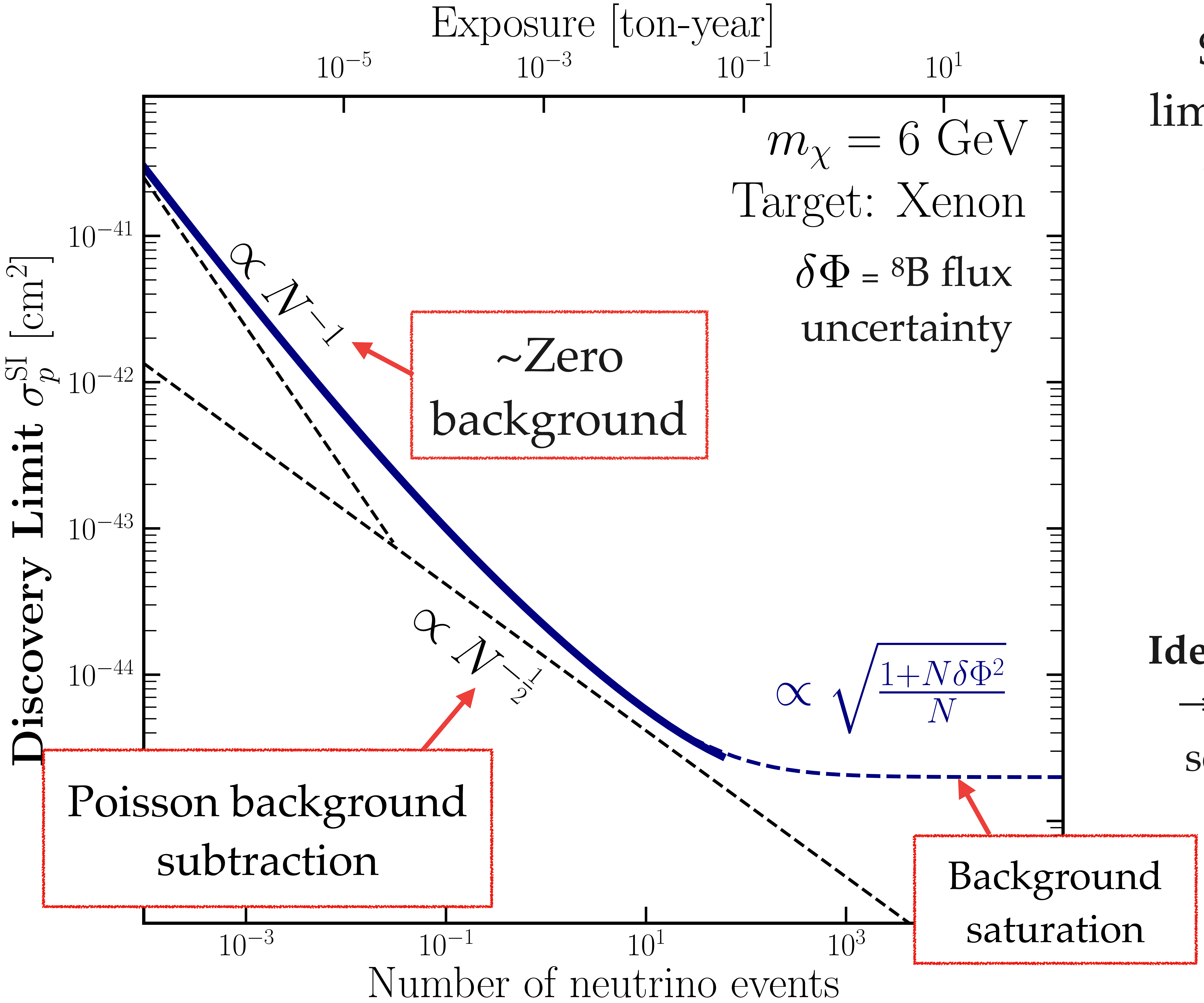
→ Conclusion: this seems to be true, and in fact is probably one of the only robust statements we can make about a generic signal of direct DM detection



CEvNS event rates versus energy threshold

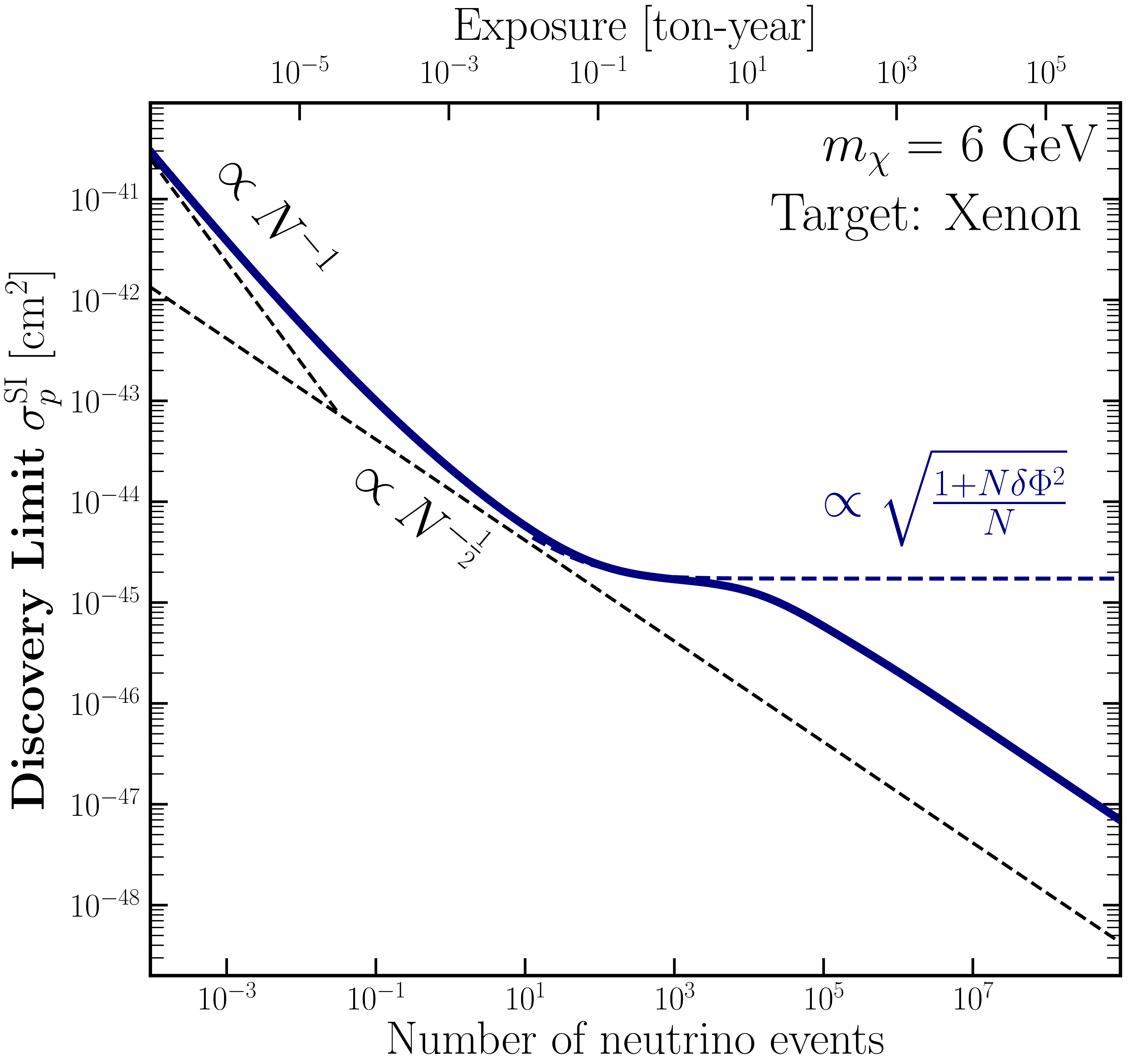
$$\frac{\mathrm{d}R_\nu}{\mathrm{d}E_r} = \frac{1}{m_N}\int_{E_\nu^\text{min}} \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu}\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\mathrm{d}E_\nu$$



Scaling of a DM discovery limit for increasing exposure
(or equivalently, # bg events)

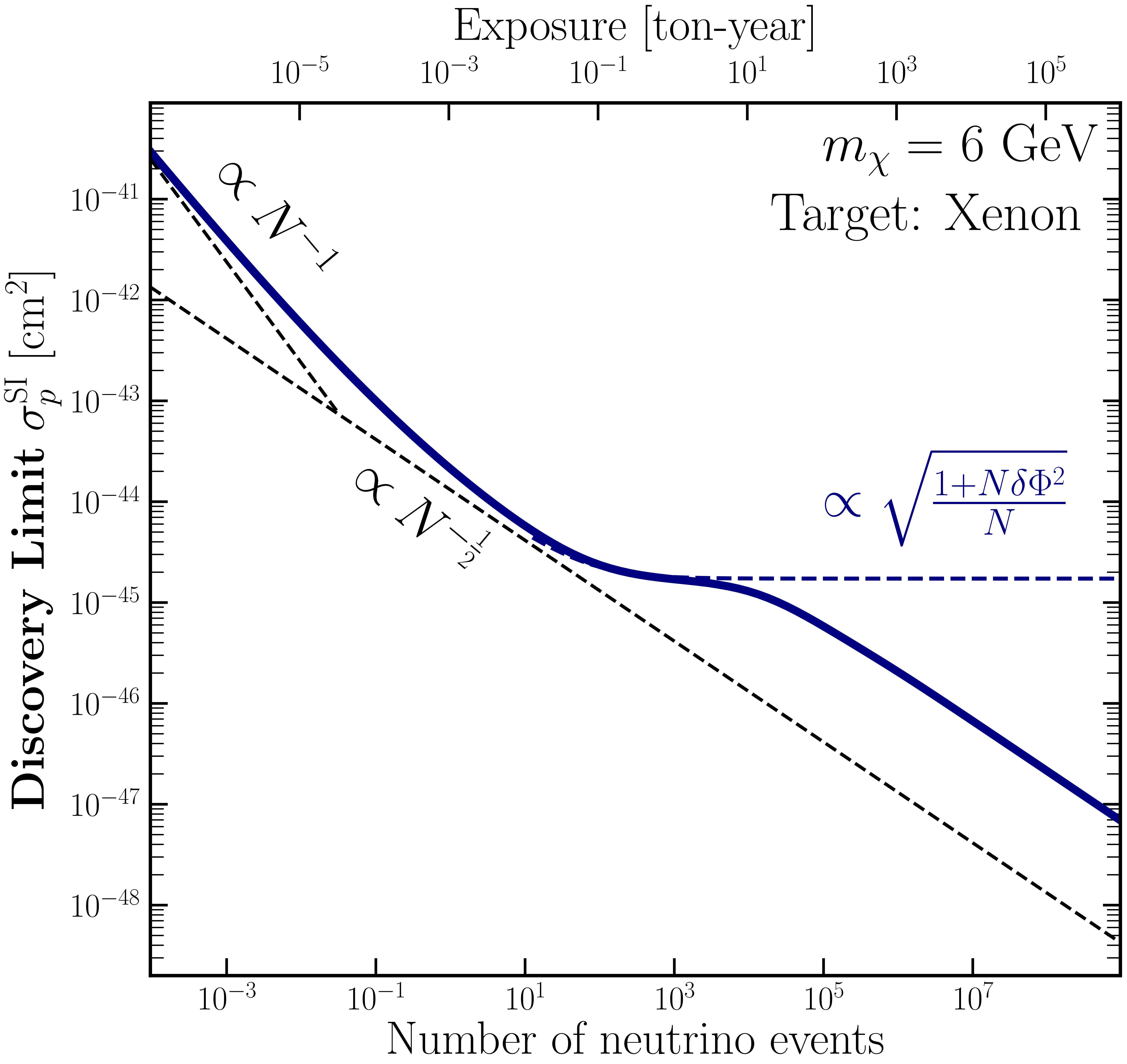
Idea behind the "neutrino floor"

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



The full story: neutrino "fog"

Strictly there is no hard floor, recoil energy information distinguishes DM/neutrinos with high-enough statistics



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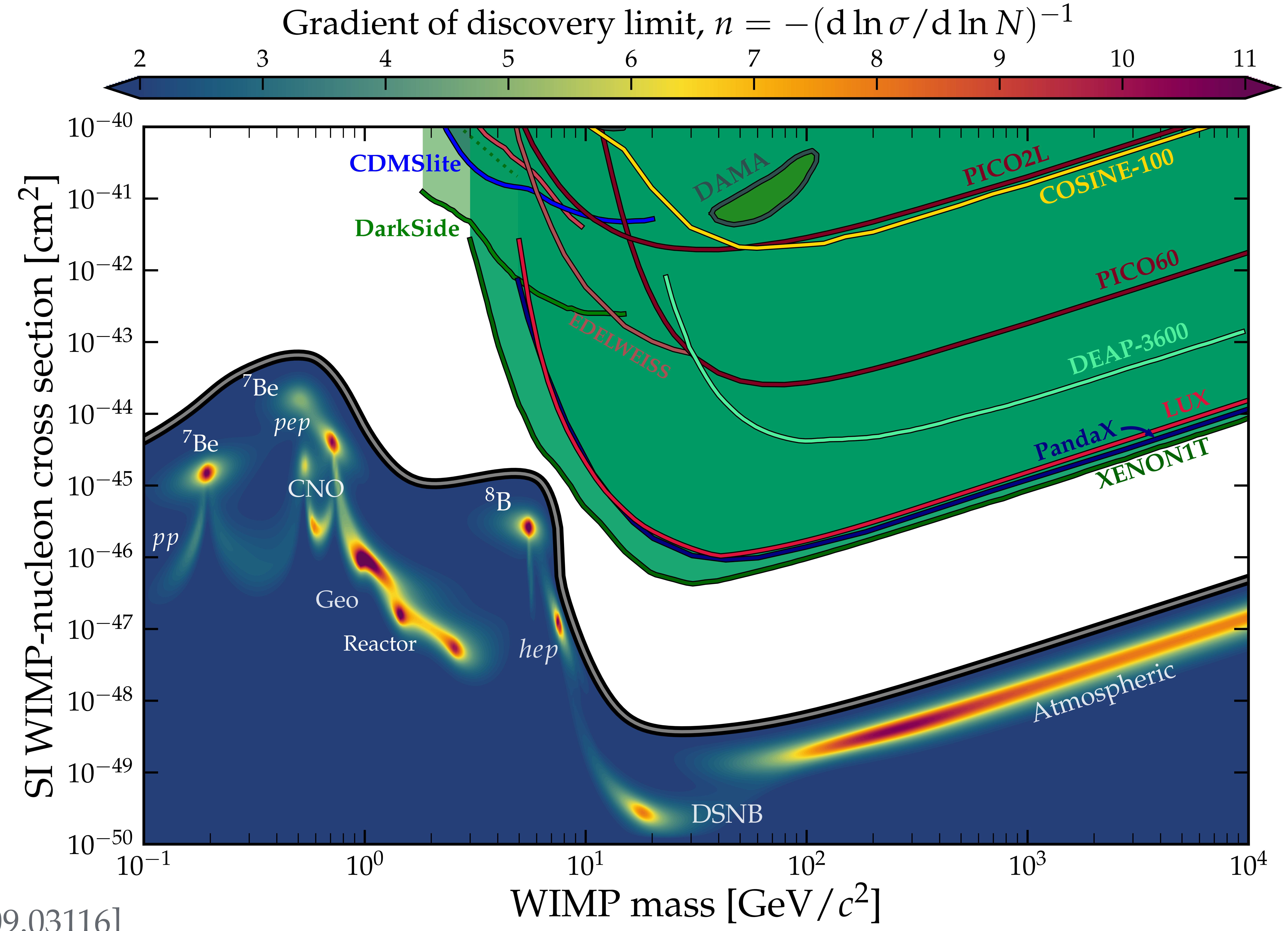
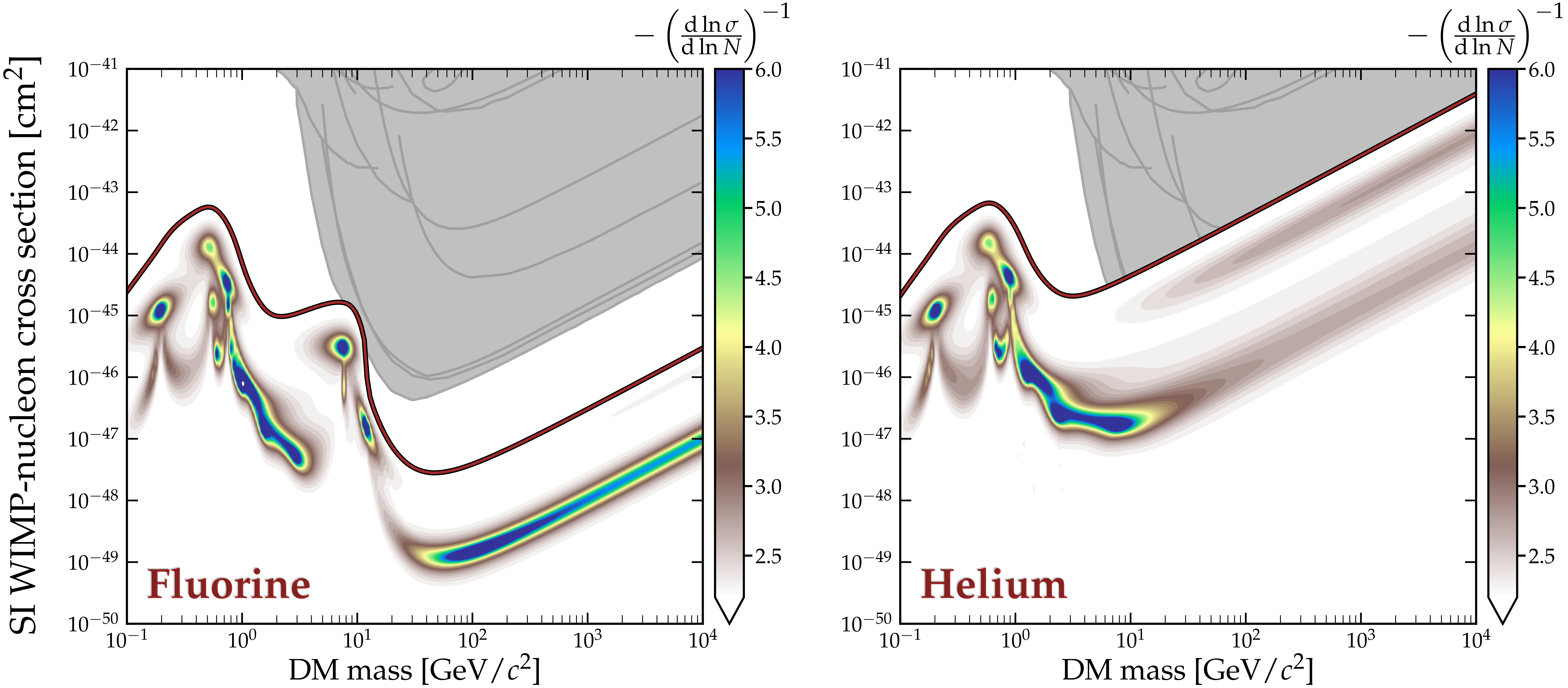
→ Quantify fogginess by looking how far the scaling departs from the Poissonian expectation:

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

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



O'Hare [2109.03116]



O'Hare [2109.03116]

If we want to..

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

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

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

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

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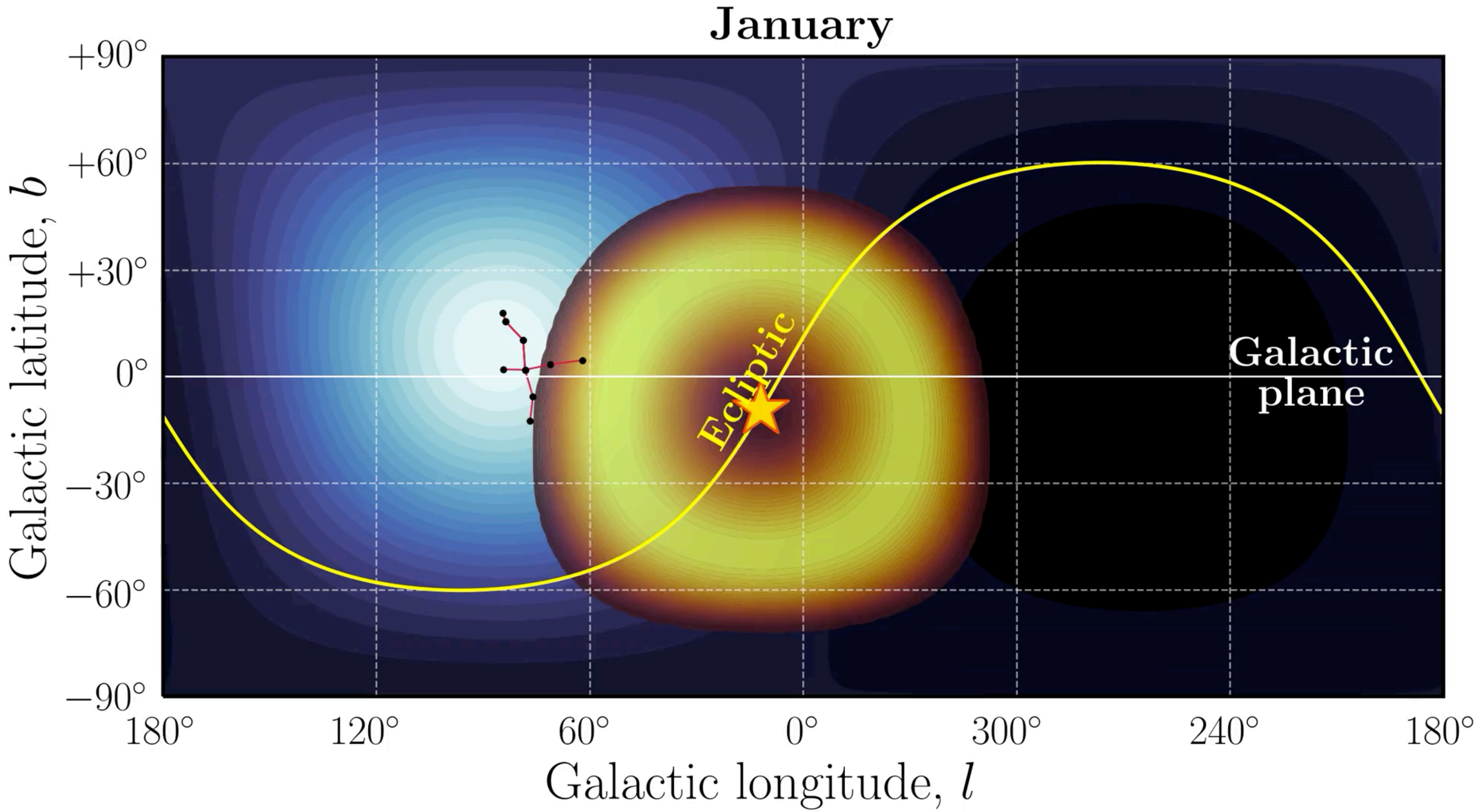
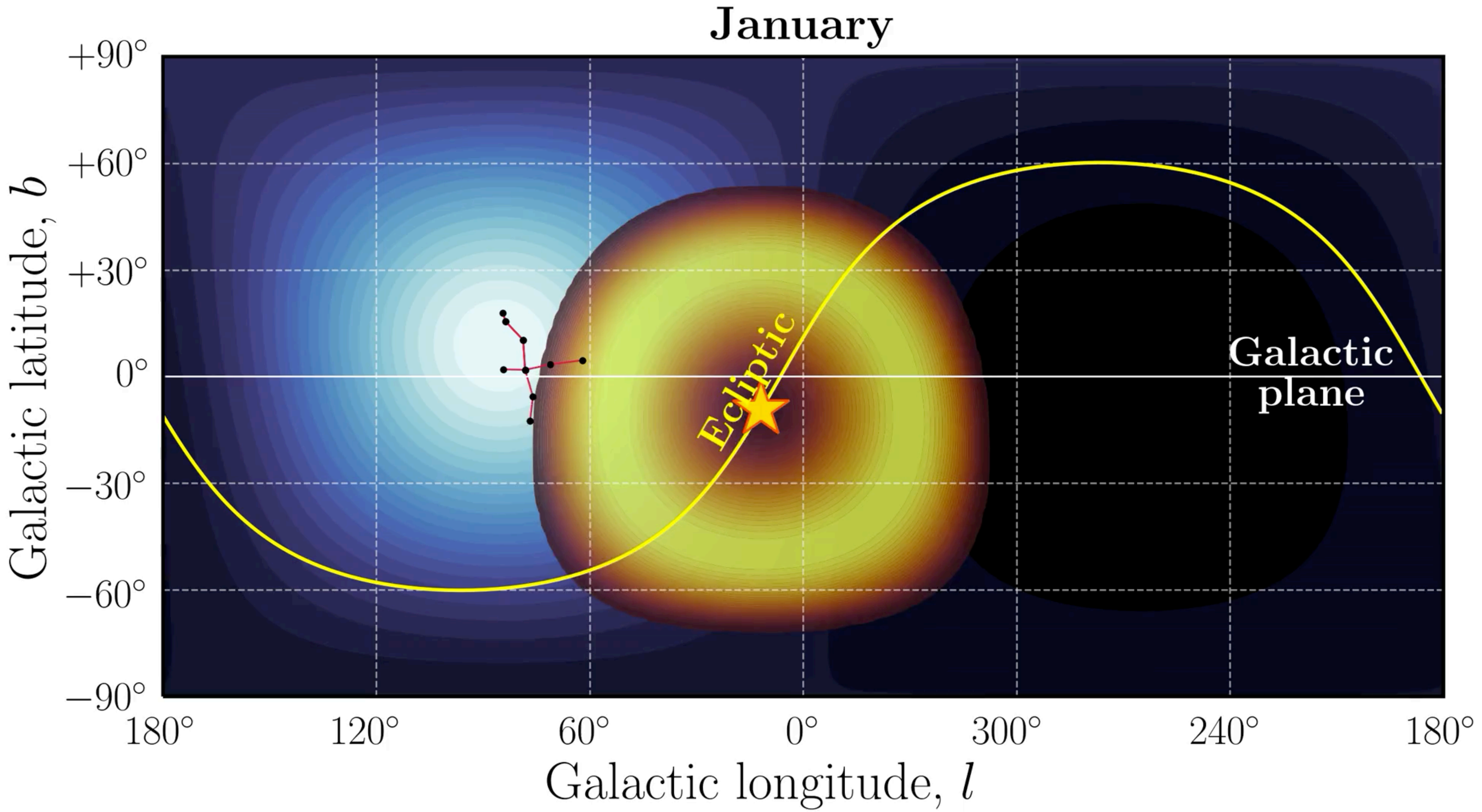
Then, we need a strategy for dealing with the fog
→ directional detection



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



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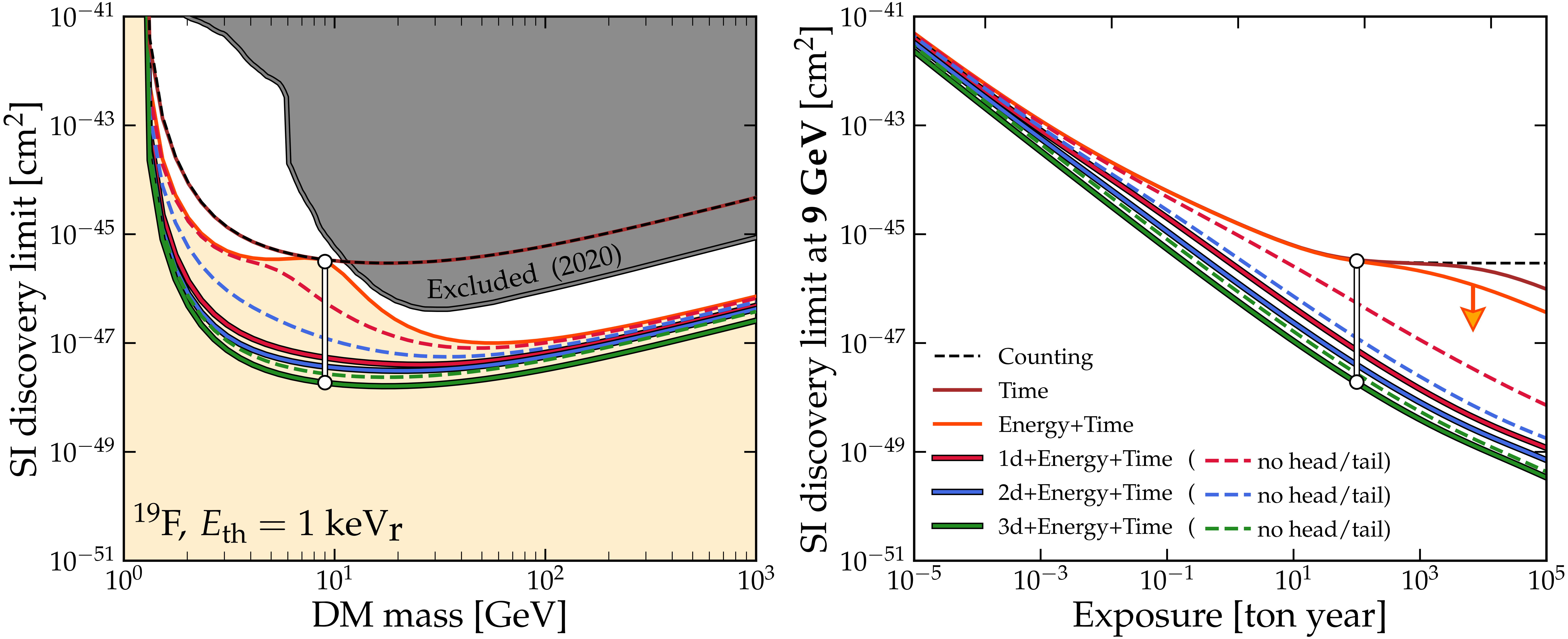
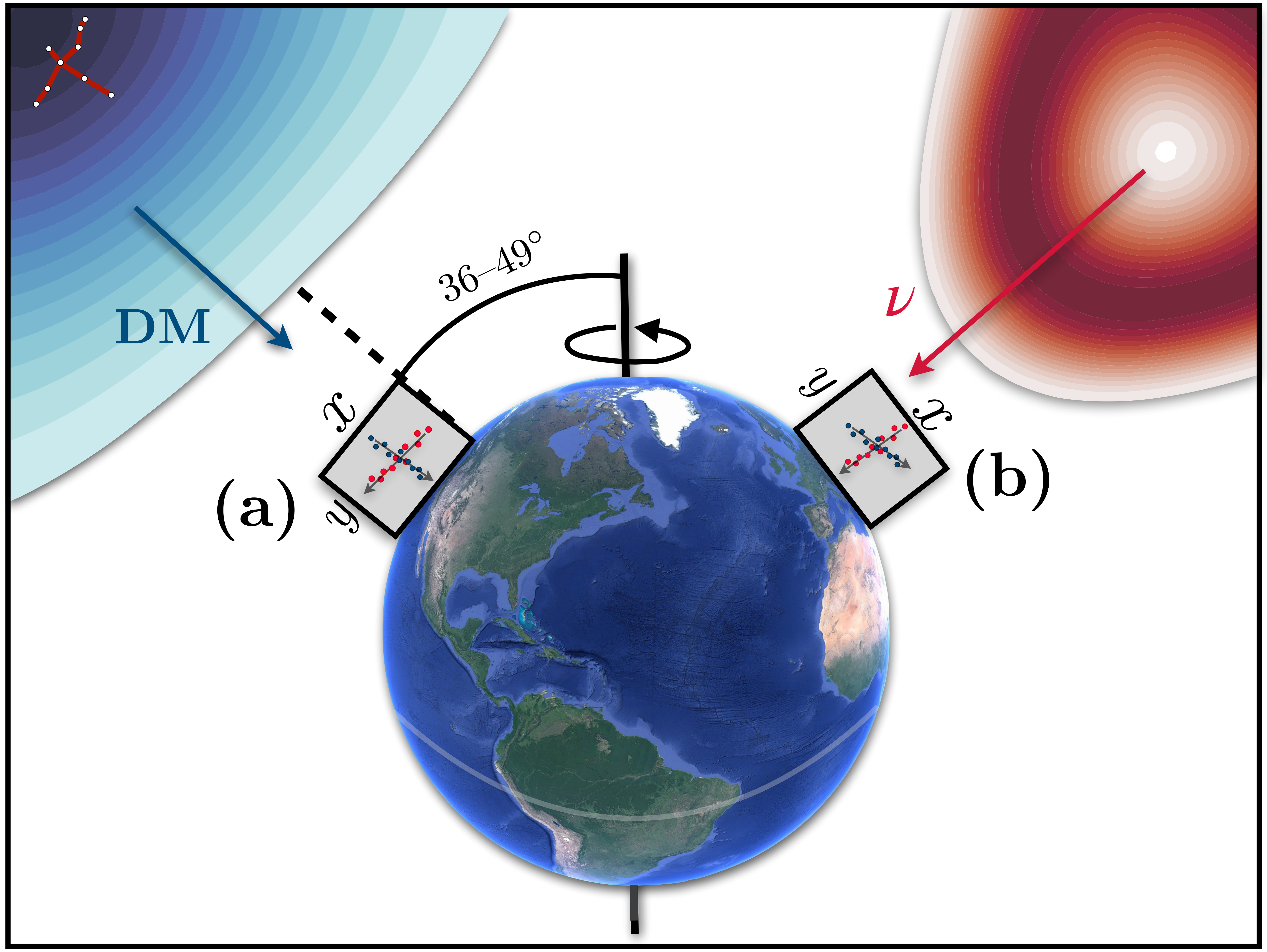
Subtracting the neutrino background

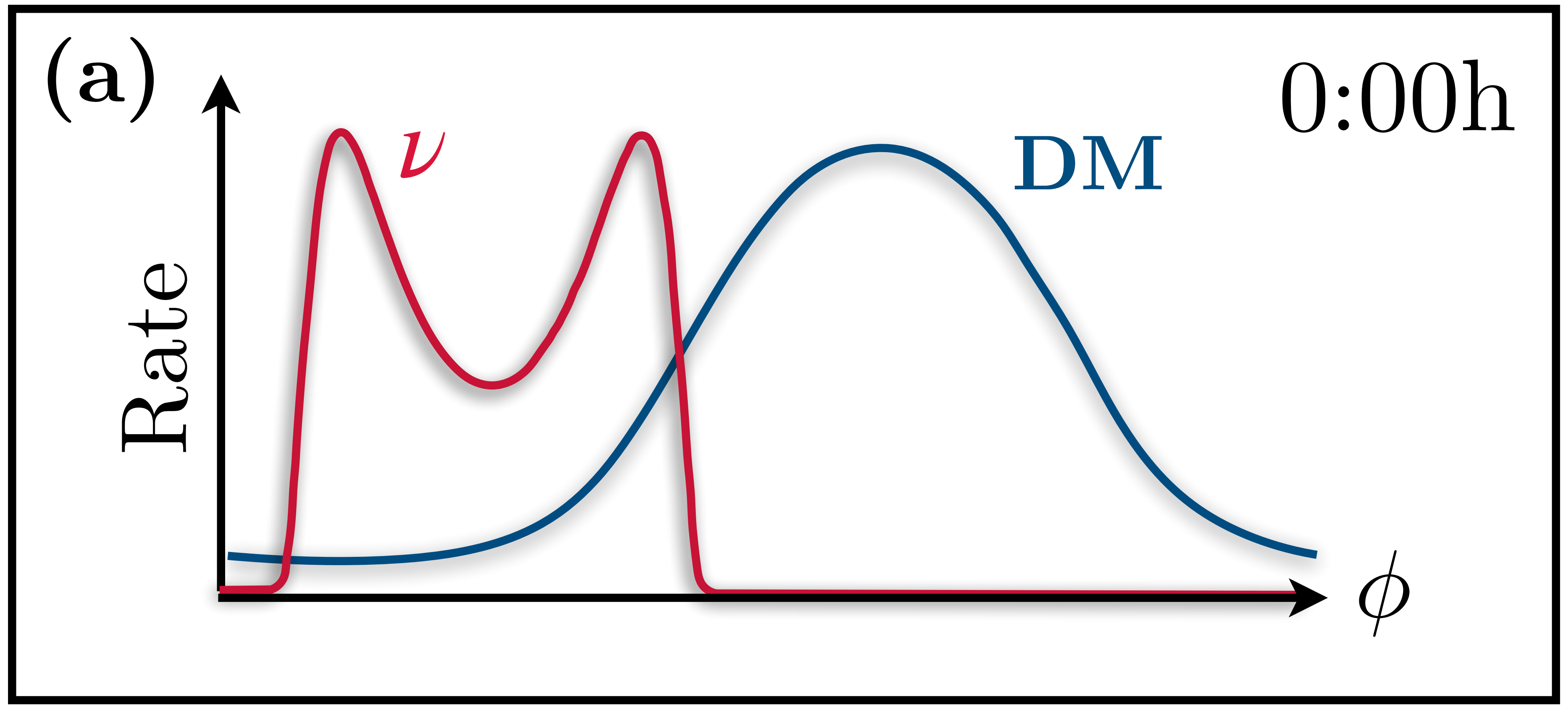


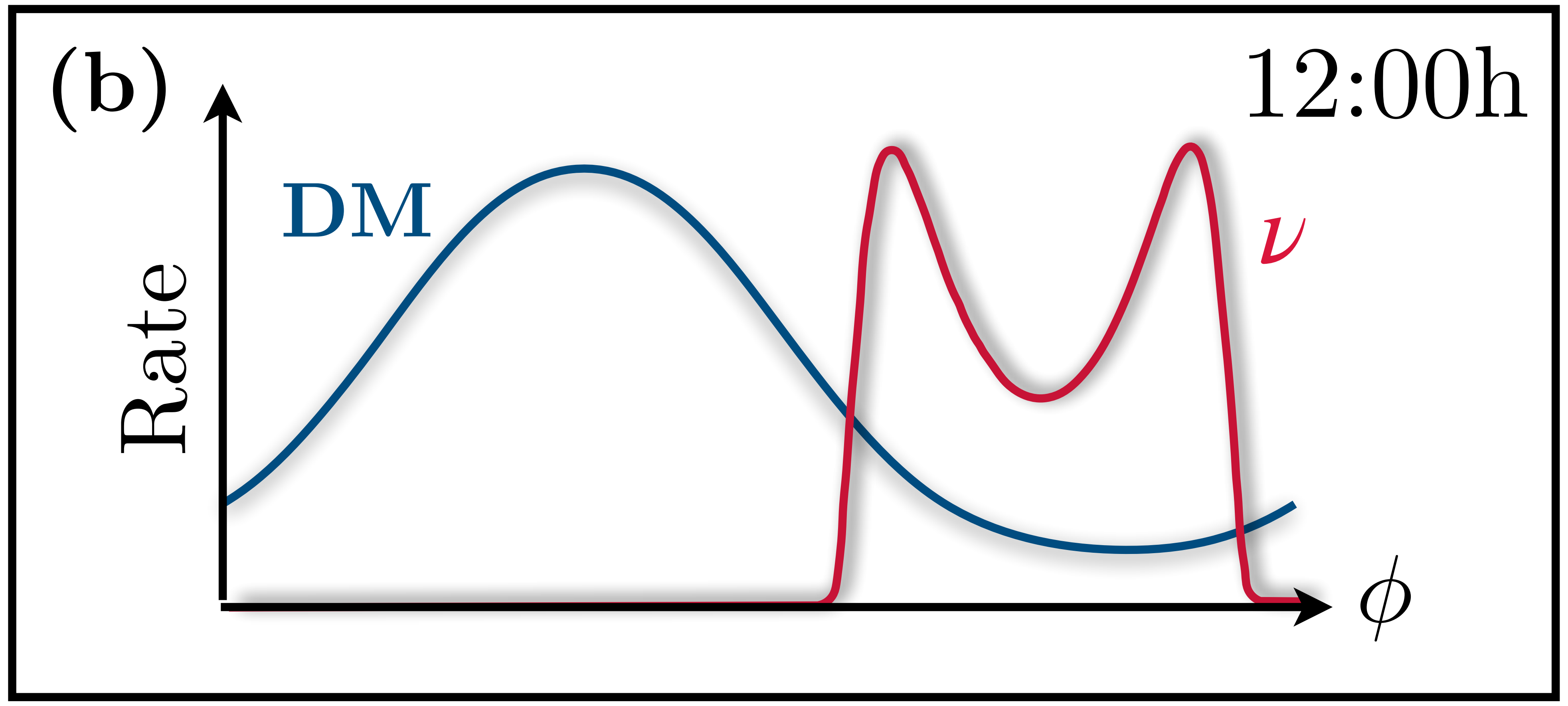
Vahsen, CAJO, Loomba [2102.04596]

A different way of seeing directionality: Daily modulation

From the detector's perspective, the galactic dipole signature translates to a sidereal daily modulation in angle → this is also a smoking gun that allows 1d, 2d directionality to work, however need to ensure $\lesssim$ hr timing resolution







Vahsen, CAJO, Loomba [2102.04596]

The ideal directional detector should have the following characteristics:

Event-by-event: directionality can be measured using a single event, and not just inferred from a distribution of events

Recoils resolved in time: sidereal event times are known so as to cancel off the effects of Earth rotation

Recoils imaged directly: recoil directions are fit using the recoils themselves, and not inferred via some other observable

Measure recoil energy: ability to reconstruct direction and energy information independently

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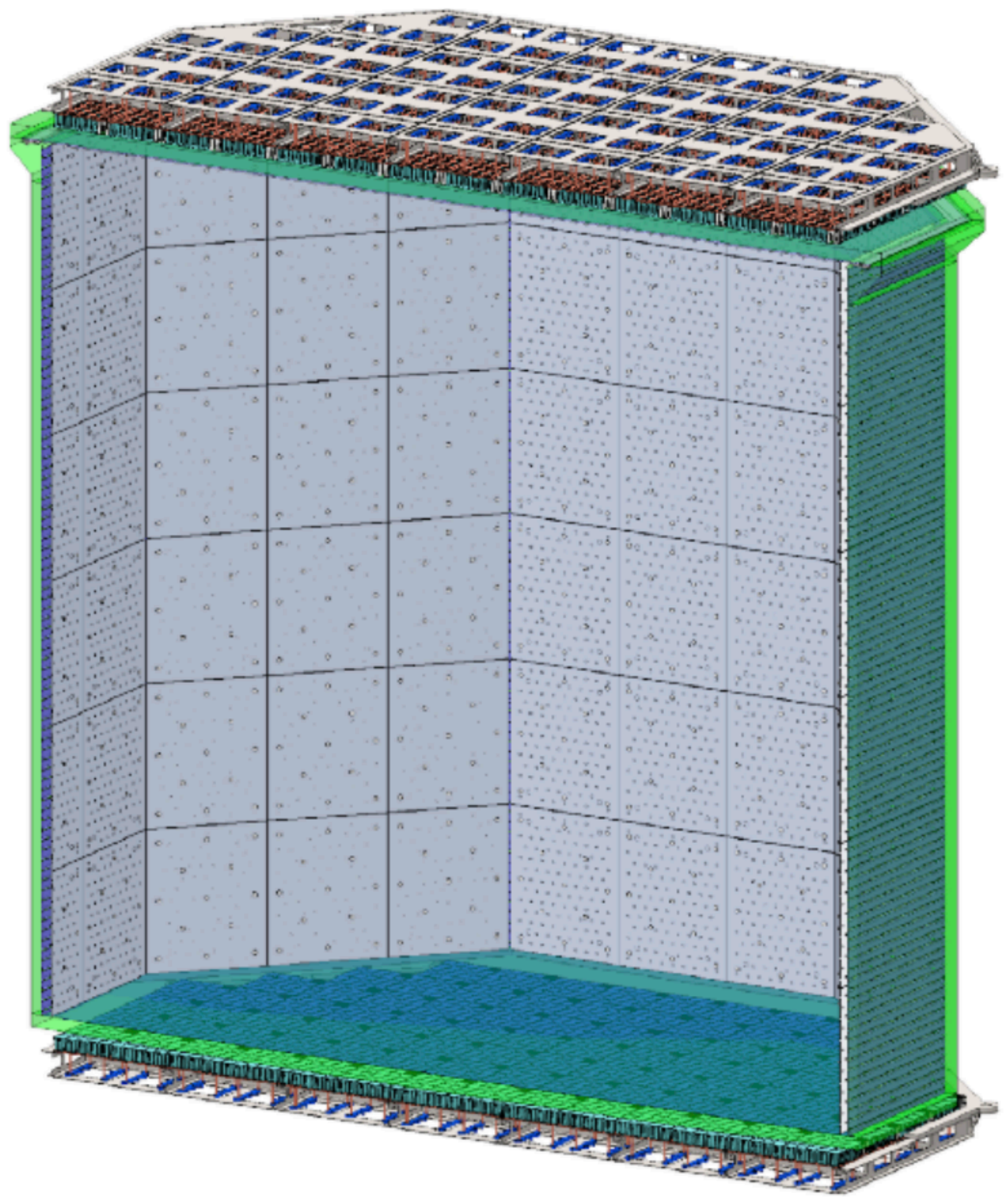
Imposing these requirements we see that real-time recoil imaging is the optimal strategy, of which the gas TPC is the only demonstrated example

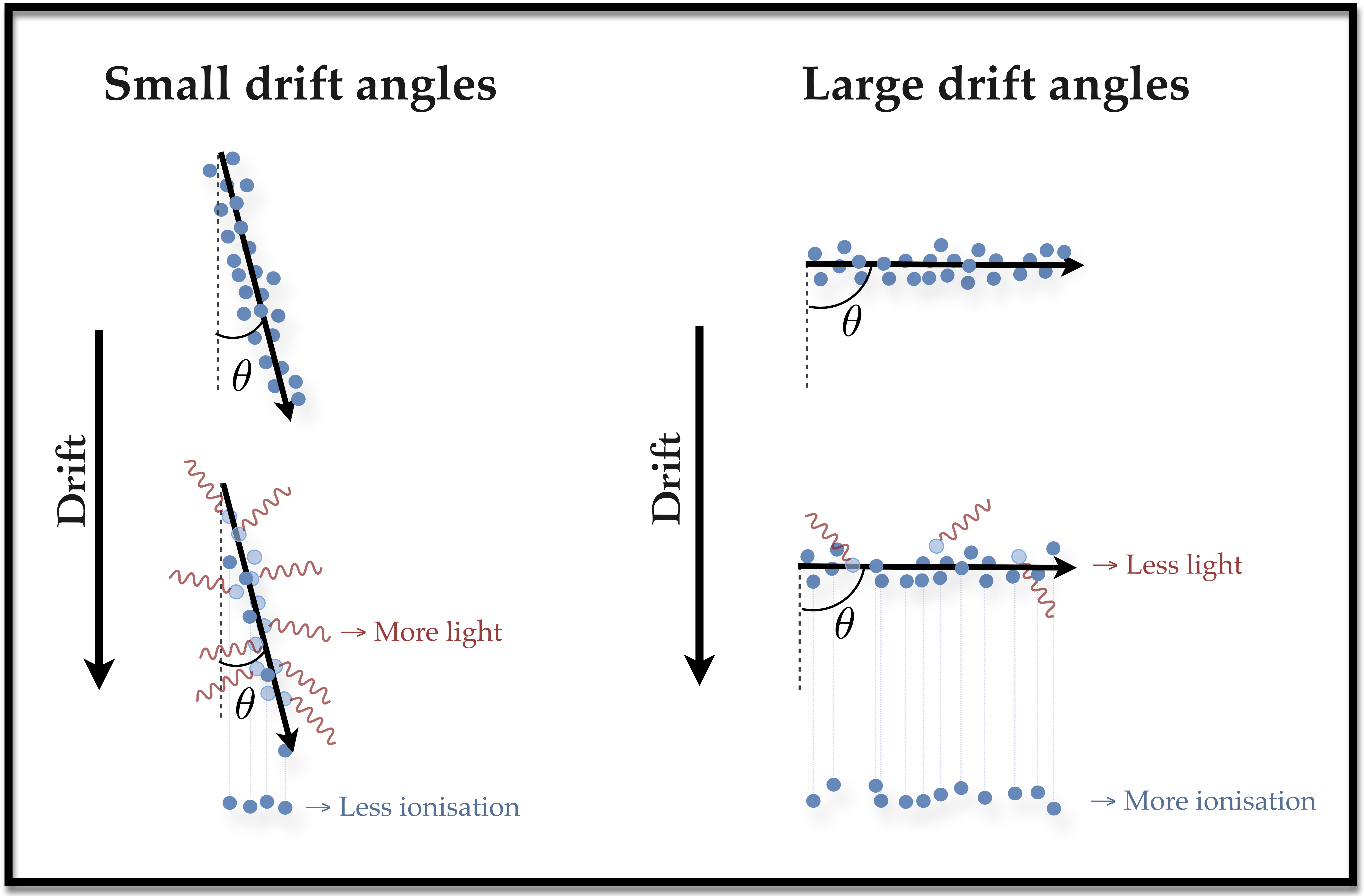
Counter example: Indirect directionality via columnar recombination

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

→ Possible directional effect where charge/light yield in LXe/LAr depends on angle of recoil w.r.t. electric field

DarkSide-20k. 2024-??

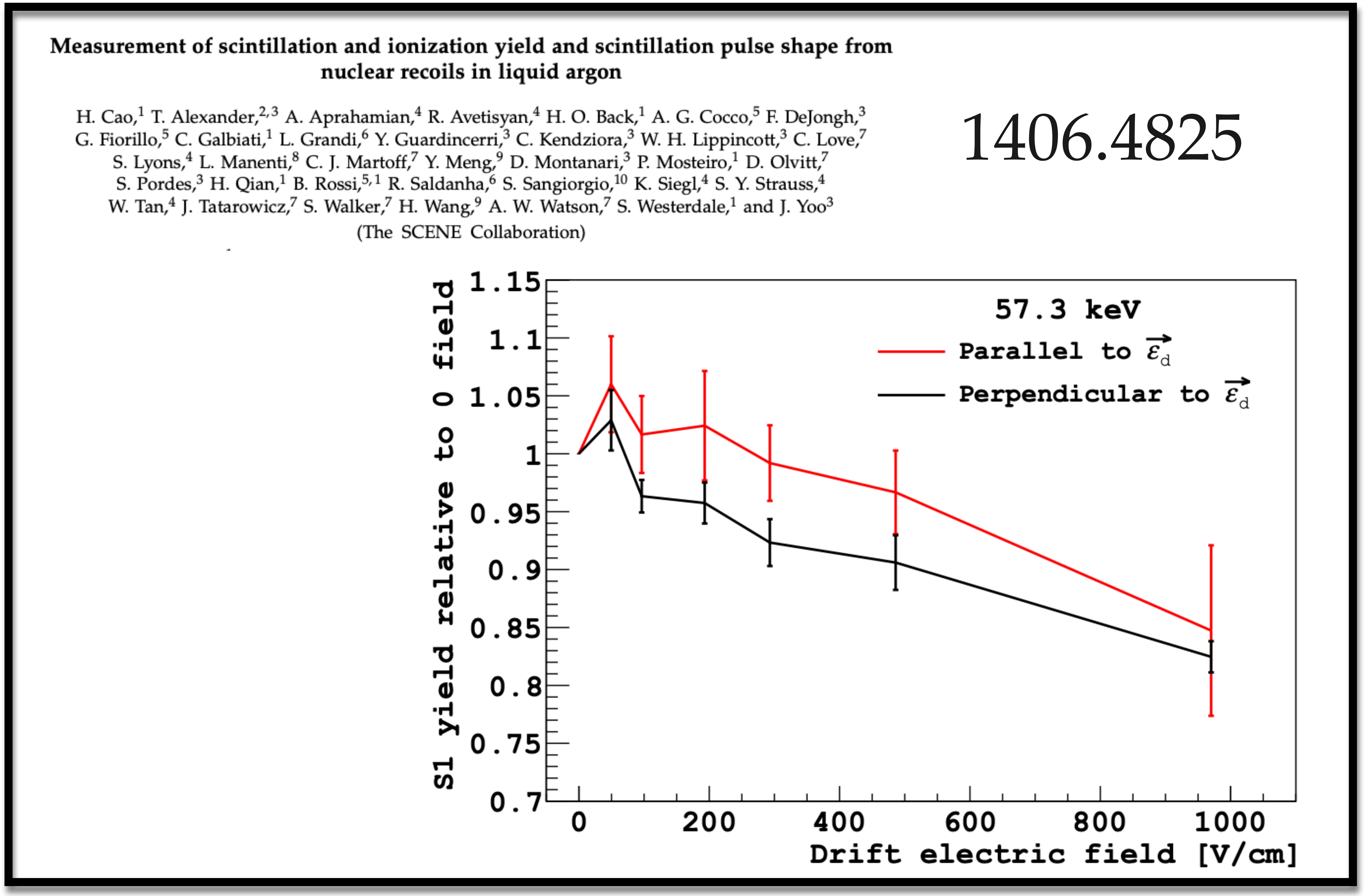




Counter example: Indirect directionality via columnar recombination

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

- Possible hint in LAr. ReD collaboration/ DarkSide are investigating this


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

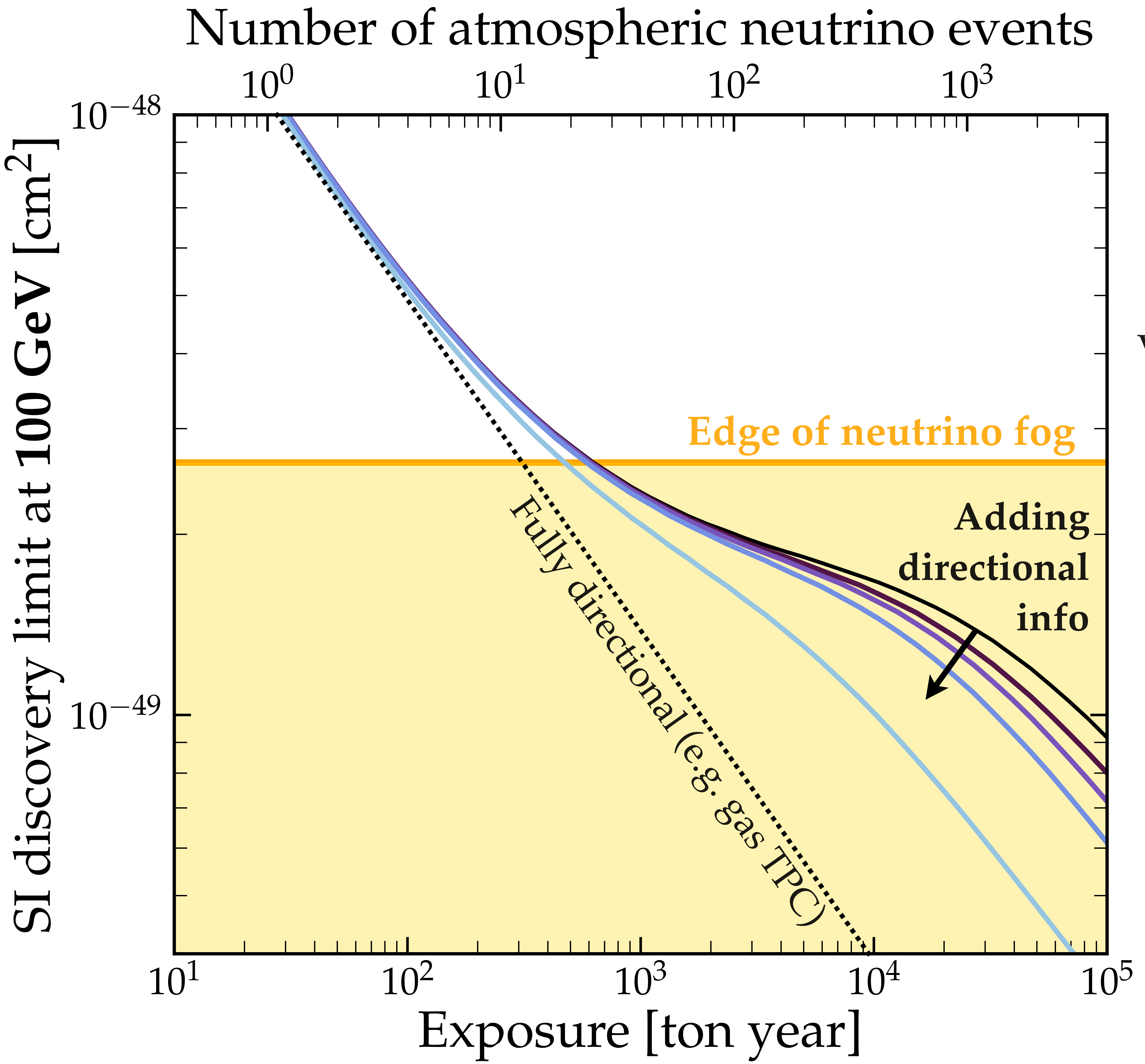
H. Cao,[1] T. Alexander,[2,3] A. Aprahamian,[4] R. Avetisyan,[4] H. O. Back,[1] A. G. Cocco,[5] F. DeJongh,[3] G. Fiorillo,[5] C. Galbiati,[1] L. Grandi,[6] Y. Guardincerri,[3] C. Kendziora,[3] W. H. Lippincott,[3] C. Love,[7] S. Lyons,[4] L. Manenti,[8] C. J. Martoff,[7] Y. Meng,[9] D. Montanari,[3] 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)

1406.4825

Even if the effect *were* observed in LAr, columnar recombination doesn't seem too promising:

1. One-dimensional signal (only depends on drift angle)
2. No head-tail signature at all
3. Effect is measured via scintillation/ionisation, so direction and recoil energy measurements will be correlated

O'Hare [2002.07499]



Columnar recombination doesn't help much, even in wildly over-optimistic scenario → **directionality in LAr seems impractical to me.**

Vahsen, CAJO, Loomba [2102.04596]

Detector classes by directional information

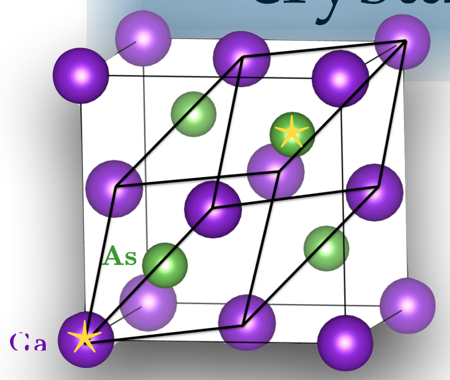
Demonstrated
R&D
Proposed

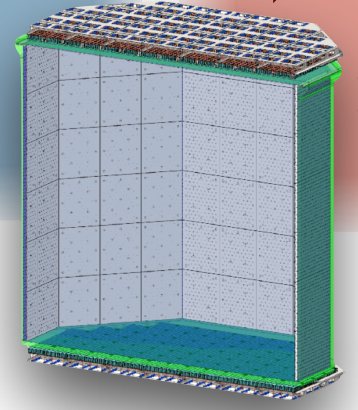
Indirect | **Recoil imaging**

Statistical | **Event-level**

Modulation-based directionality — Indirect recoil event directionality — Time-integrated recoil imaging — Time-resolved recoil imaging

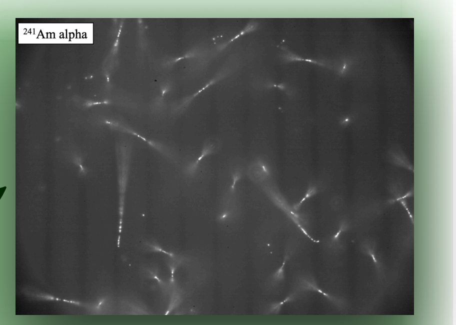
Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes



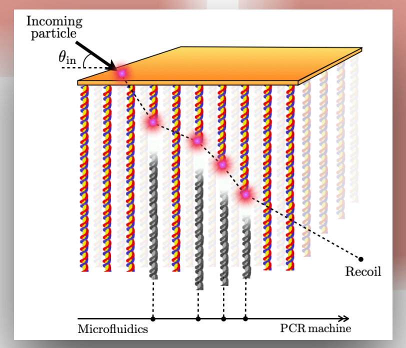


Columnar recombination
- Event-level 1d directions
- No head/tail
- Direction and energy are not independent

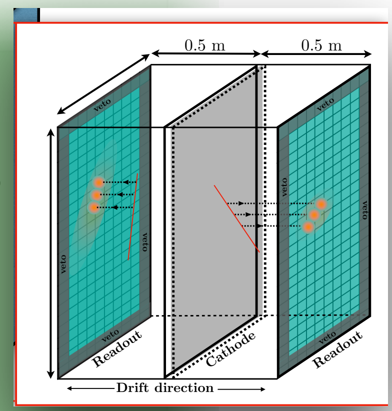
Nuclear emulsions
- 2d recoil tracks, head/tail
- No event times information recorded



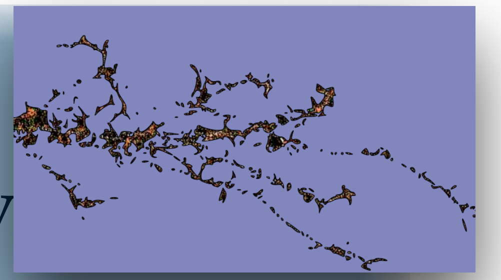
DNA detector
- 3d recoils without head/tail
- No event times recorded



Gas TPC
- Head/tail measurable
- 1d, 2d or 3d
- Independent energy/direction measurement



Crystal defects
- 3d track topology
- Head/tail measurable



Least directionality — Distance through the neutrino fog → Most directionality

Summary