THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Directional dark matter detection

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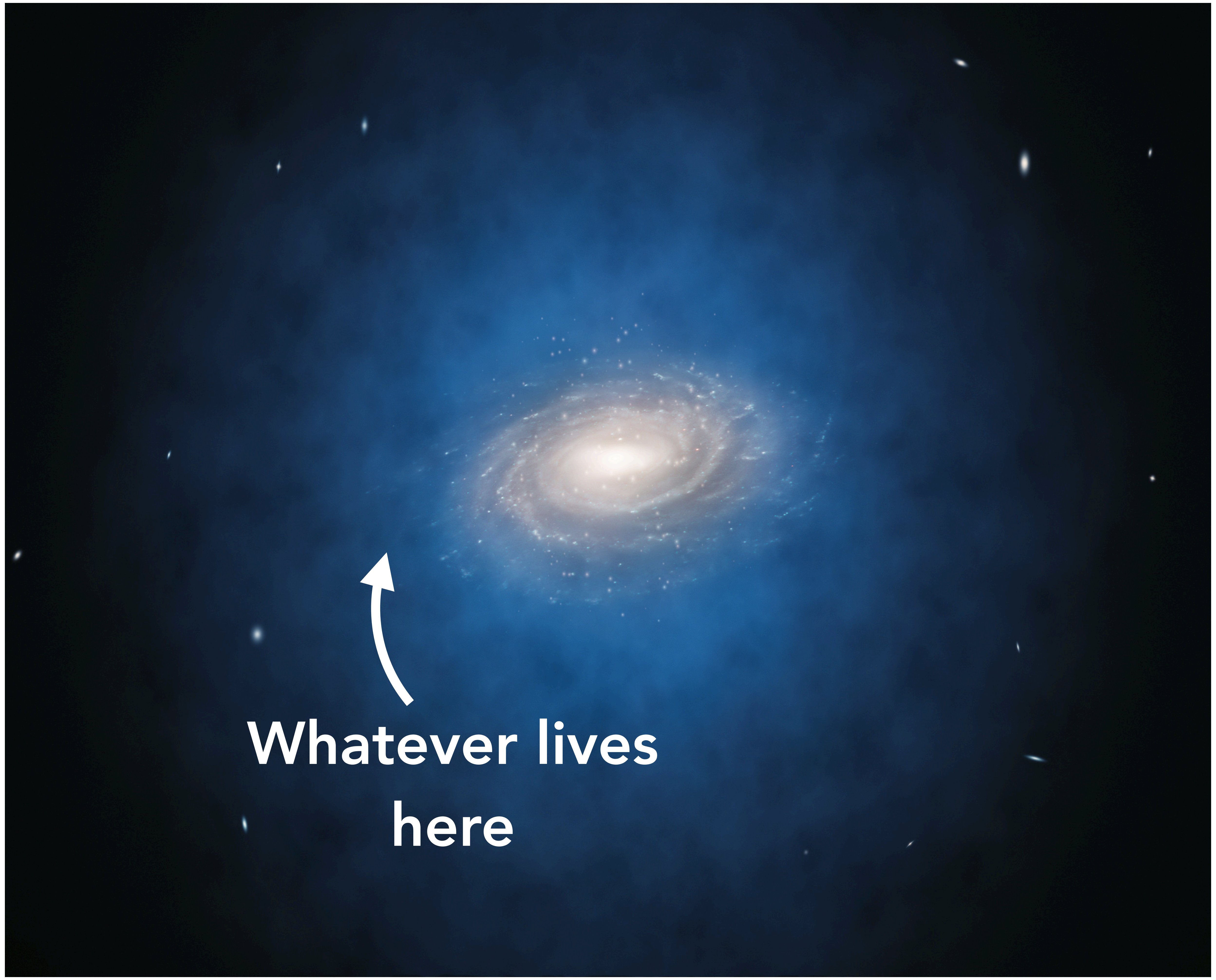
University of Sydney

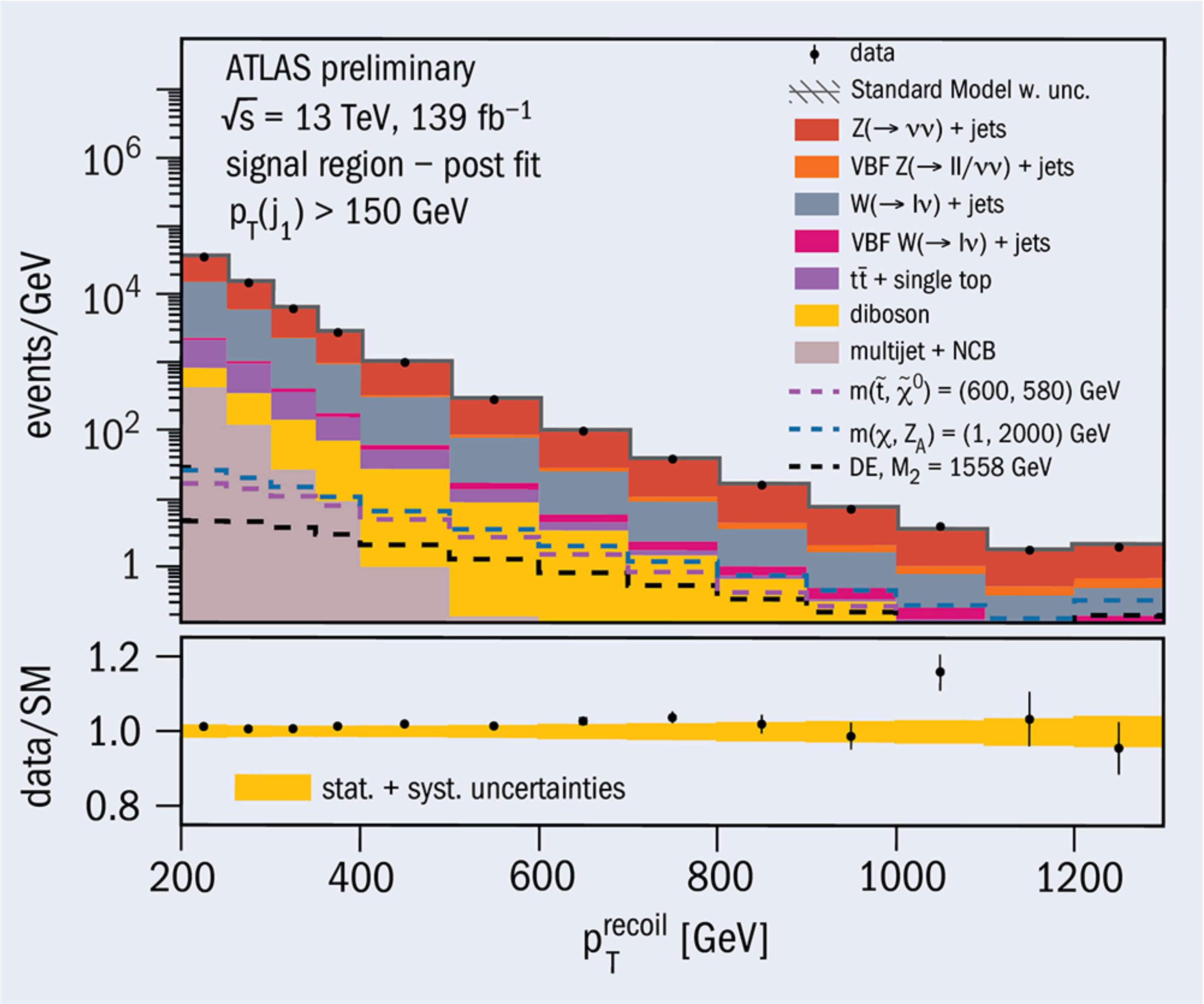
What is dark matter? A minimal definition for terrestrial searches

→ Any massive and non-relativistic cosmological relic that constitutes some or all of the halos of galaxies.

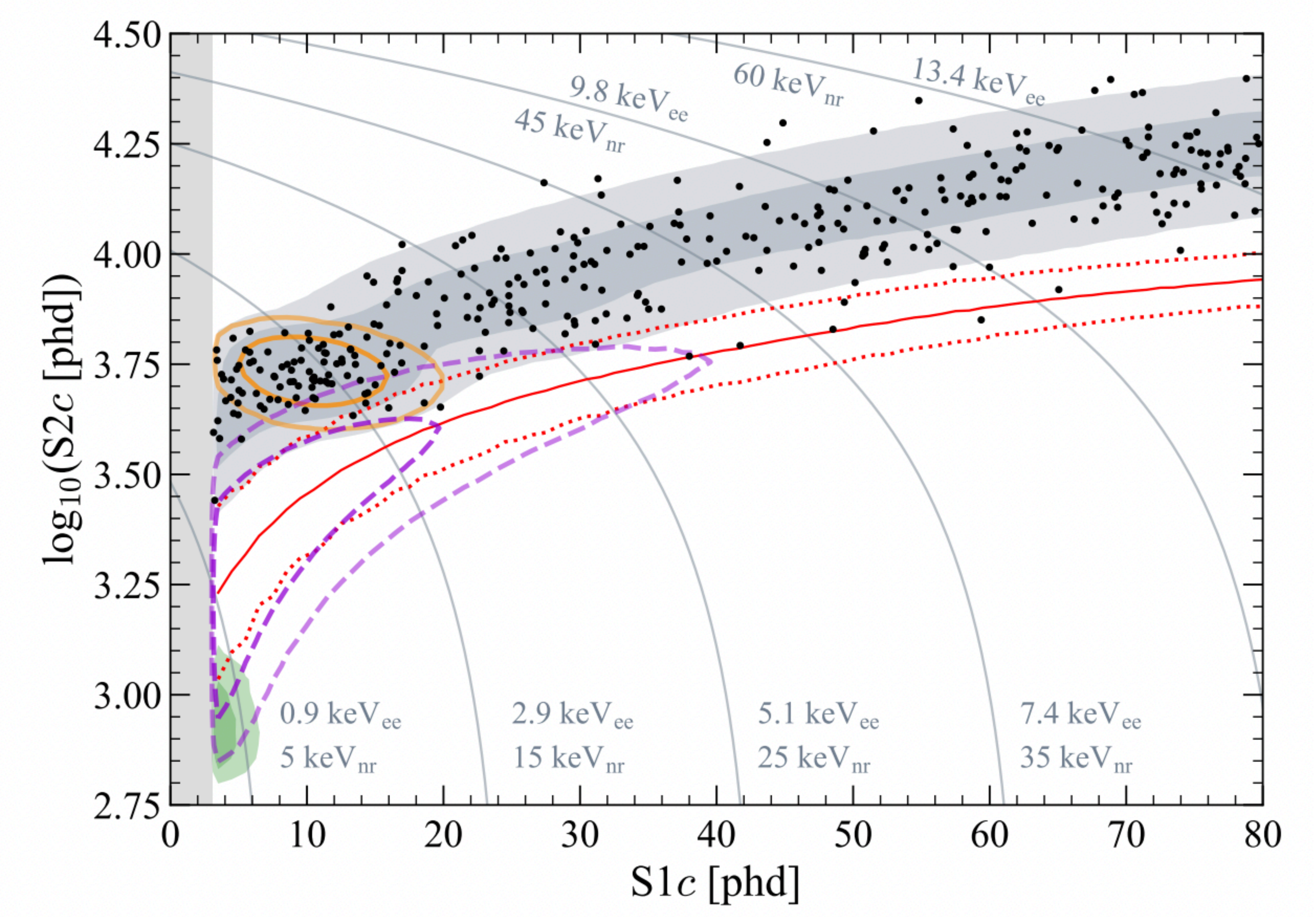


Some possible signatures of new physics that we could see in the future:

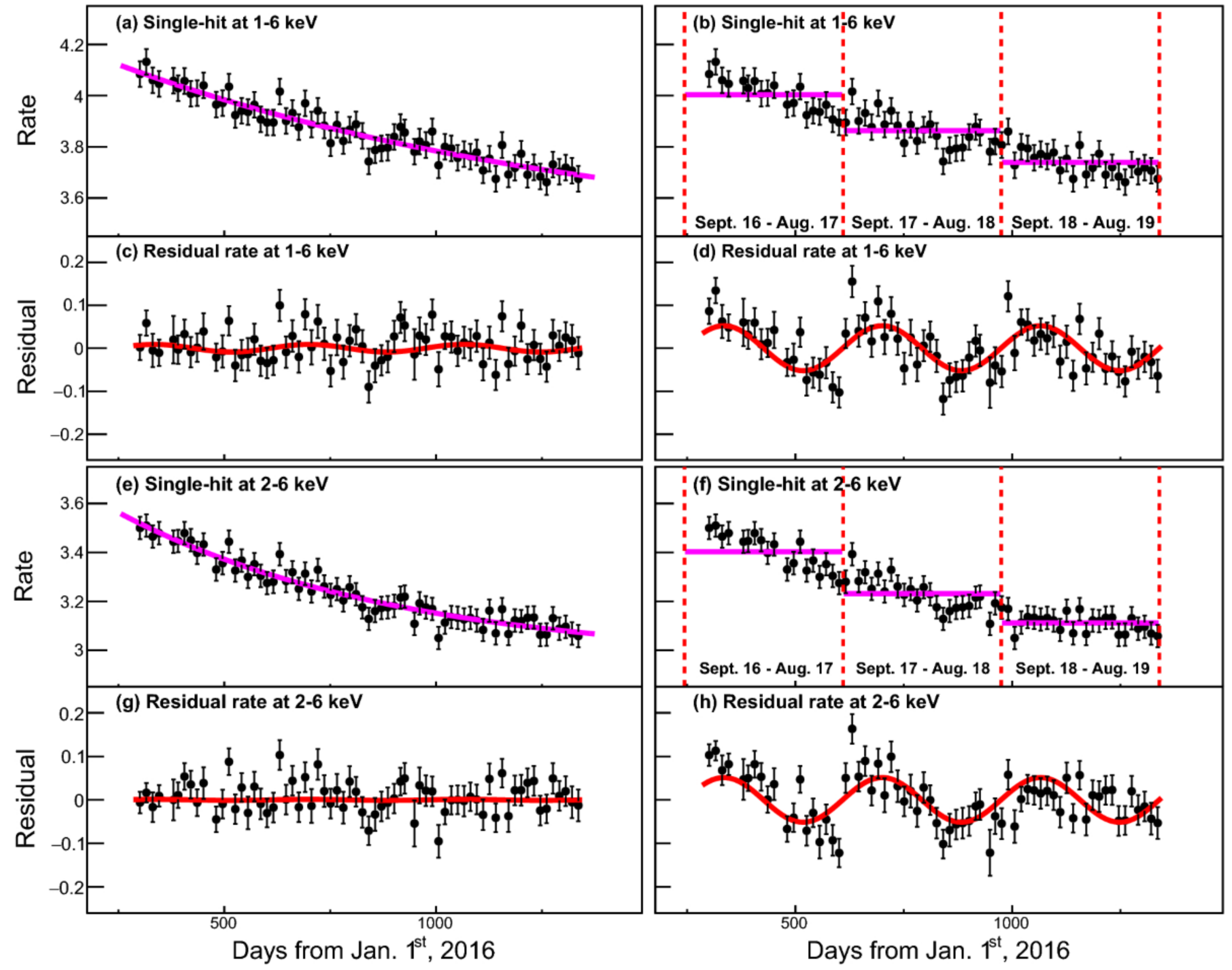
→ Do any of these constitute a discovery of dark matter under this definition?



5σ detection of missing transverse momentum in *pp* collisions



5σ detection of excess nuclear recoil events above background model



5σ detection of an annually modulating event rate

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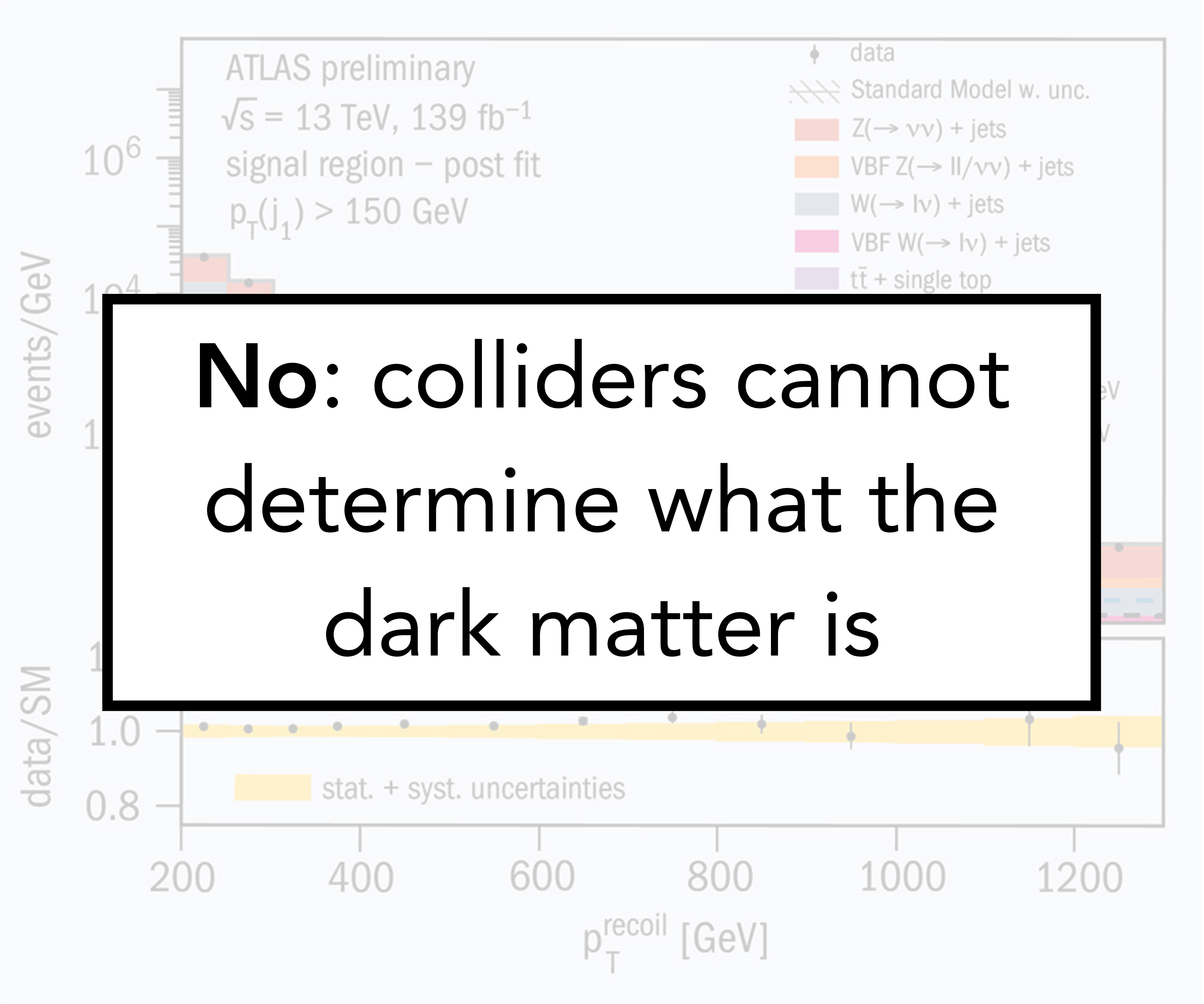
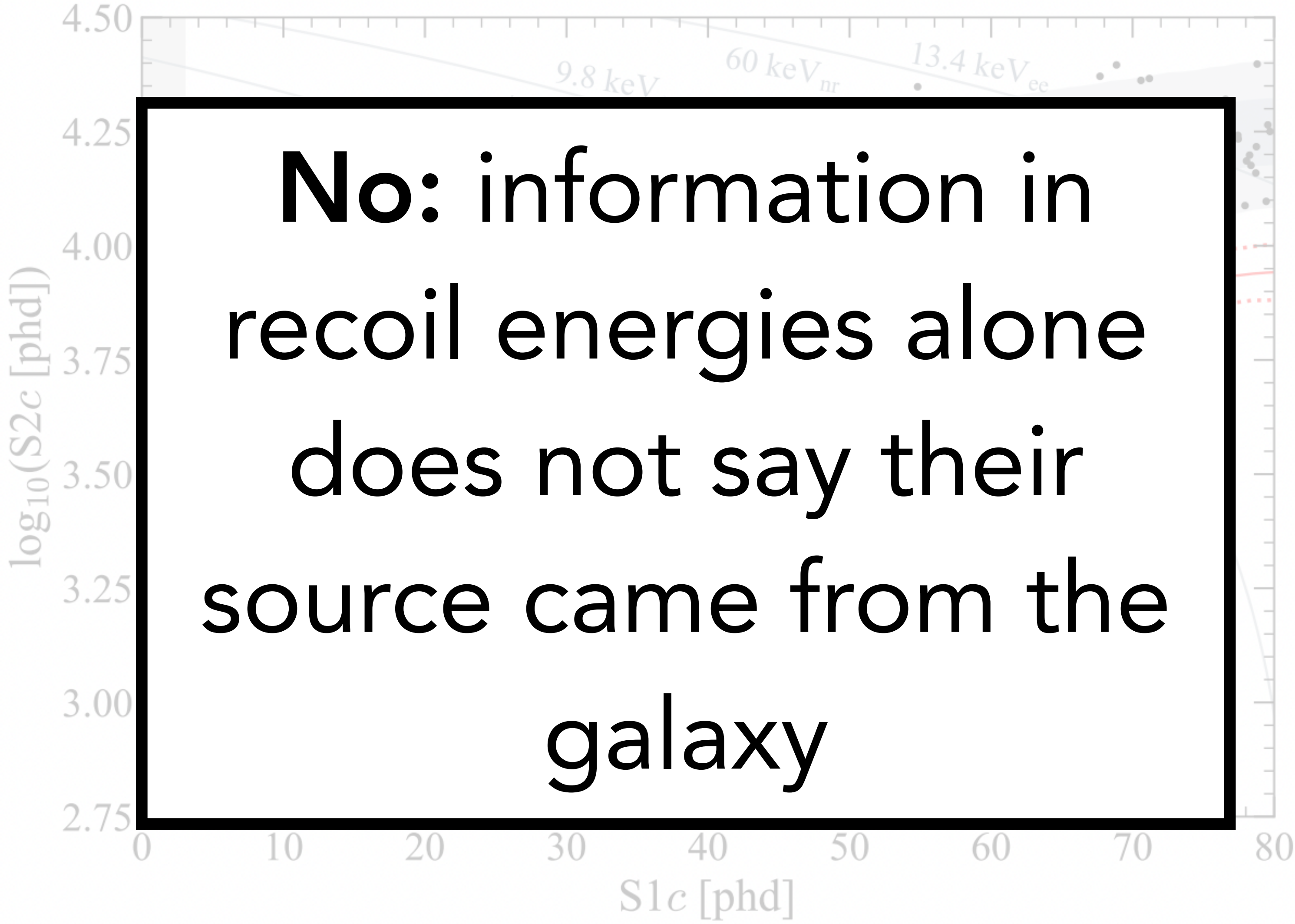


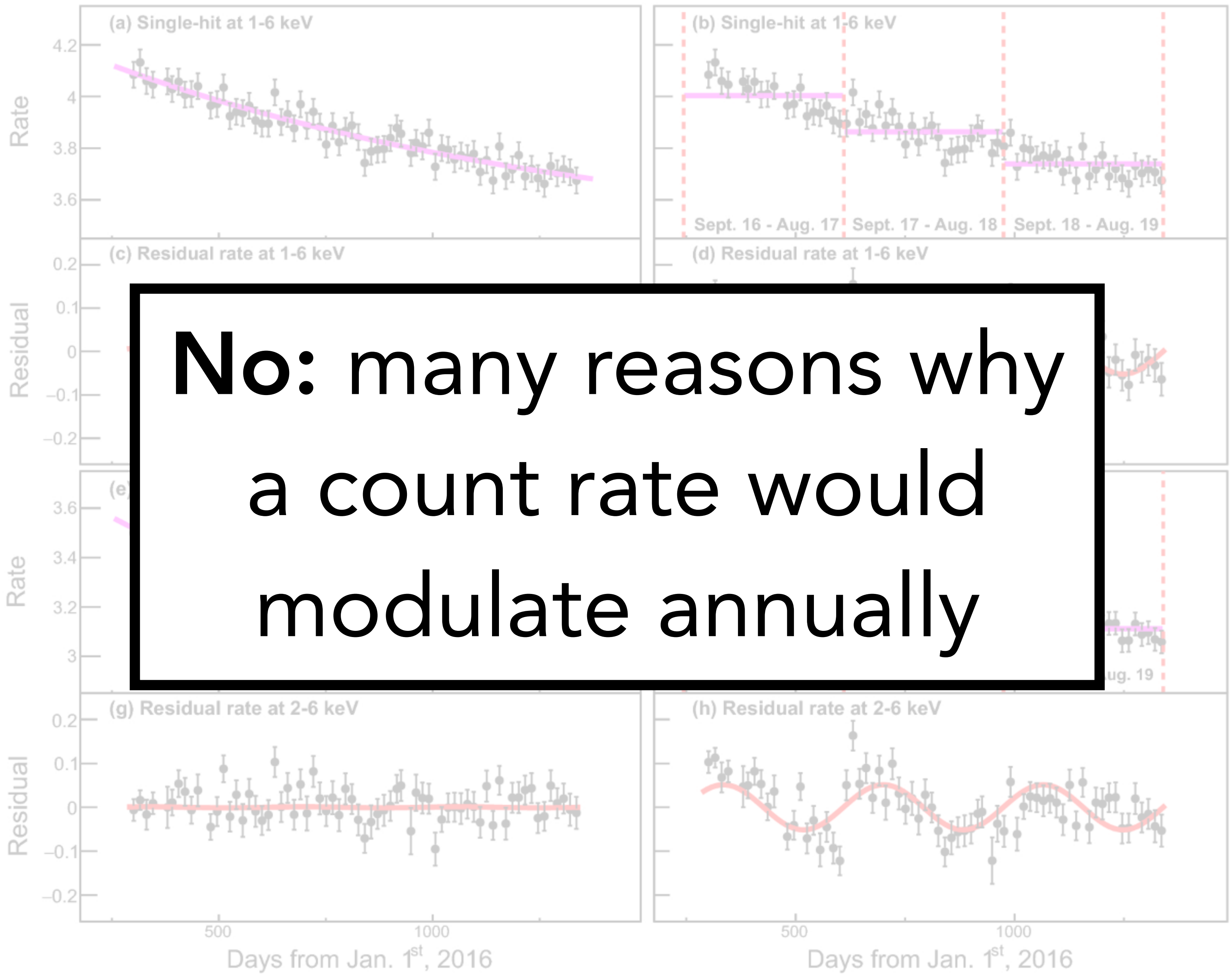
No: colliders cannot determine what the dark matter is

5σ detection of missing transverse momentum in *pp* collisions



No: information in recoil energies alone does not say their source came from the galaxy

5σ detection of excess nuclear recoil events above background model



No: many reasons why a count rate would modulate annually

5σ detection of an annually modulating event rate

Directionality of the DM flux

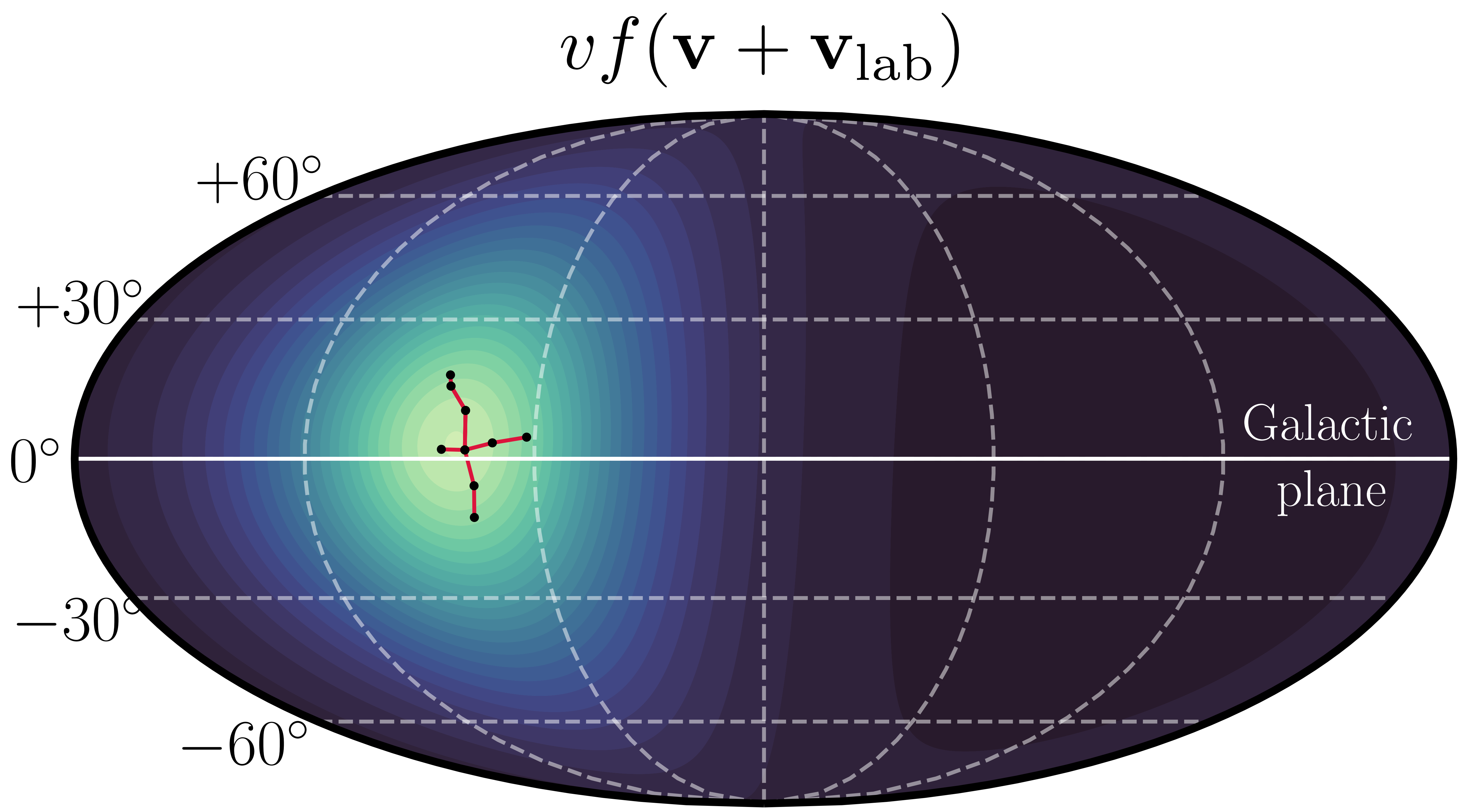
This is the only generic and unambiguous terrestrial signature of DM that results solely from the assumption that we live inside a DM halo.

Directionality of the DM flux

Expectation is for the flux to peak towards the constellation Cygnus with dipole asymmetry of $\mathscr{D} = N_{\rm fw}/N_{\rm bw} \sim 25$

Depends on two assumptions

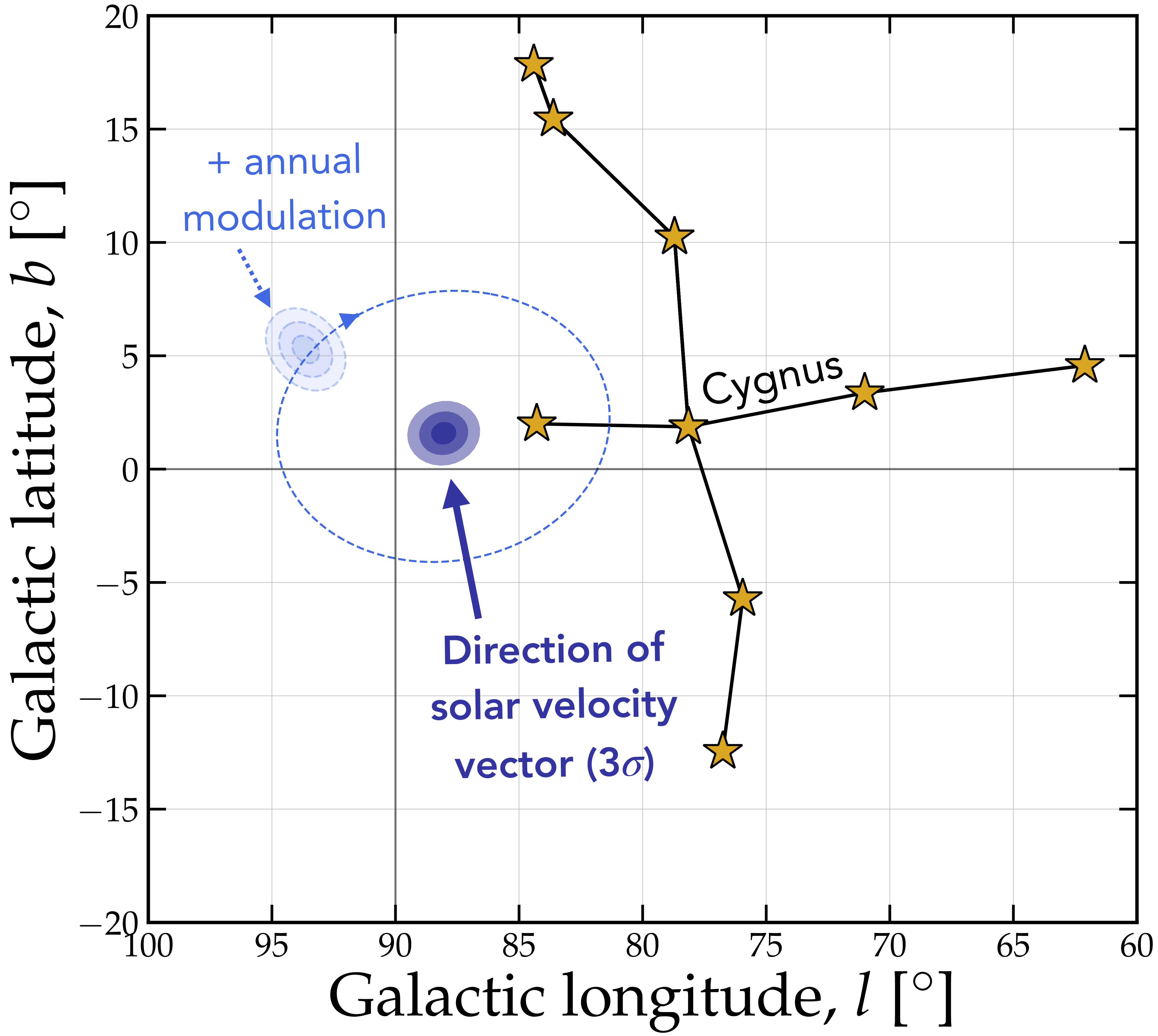
1. Sun's galactic velocity points towards constellation of Cygnus.
2. Milky Way DM halo does not have any substantial net motion in galactocentric frame



Assumption 1: Our velocity vector points towards Cygnus

Not controversial: velocity of Sun relative to galactic centre $v = (U, V, W)$ known precisely

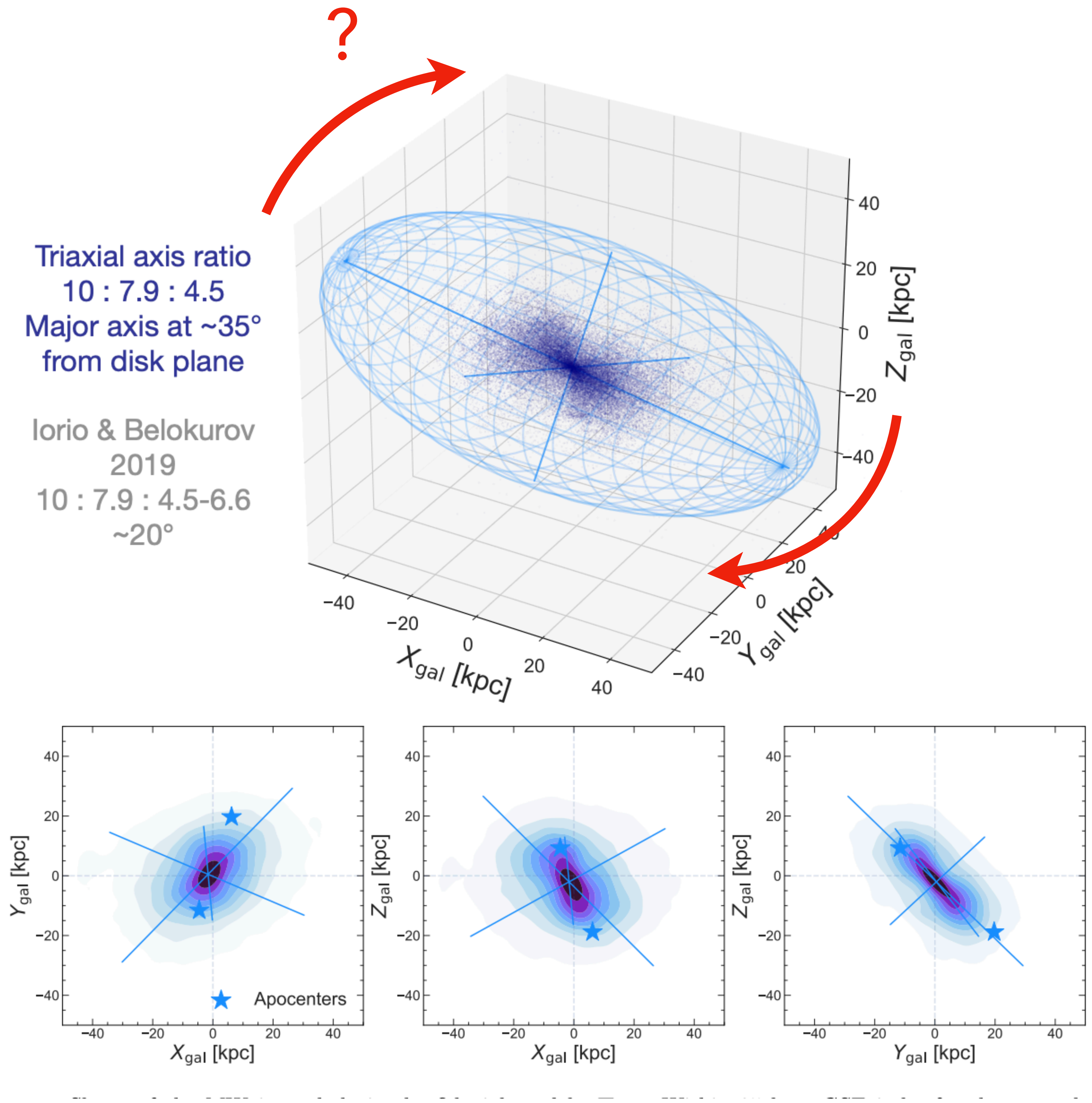
- Thanks to GRAVITY [2101.12098] and PM of Sgr A* [astro-ph/0408107], we know our tangential motion with respect to central SMBH precisely: $v_T = \sqrt{V^2 + W^2} = 250 \pm 3\,\mathrm{km/s}$
- Radial peculiar motion of Sun is $U = 8.3 \pm 1\,\mathrm{km/s}$ e.g. [1608.00971]
- This means we know the direction of our motion with respect to the galactic centre to a precision of <1 degree on the sky.



Assumption 2: DM halo is stationary in galactocentric frame

Rotation of the Milky Way DM halo not measured, but there are a few things we can say.

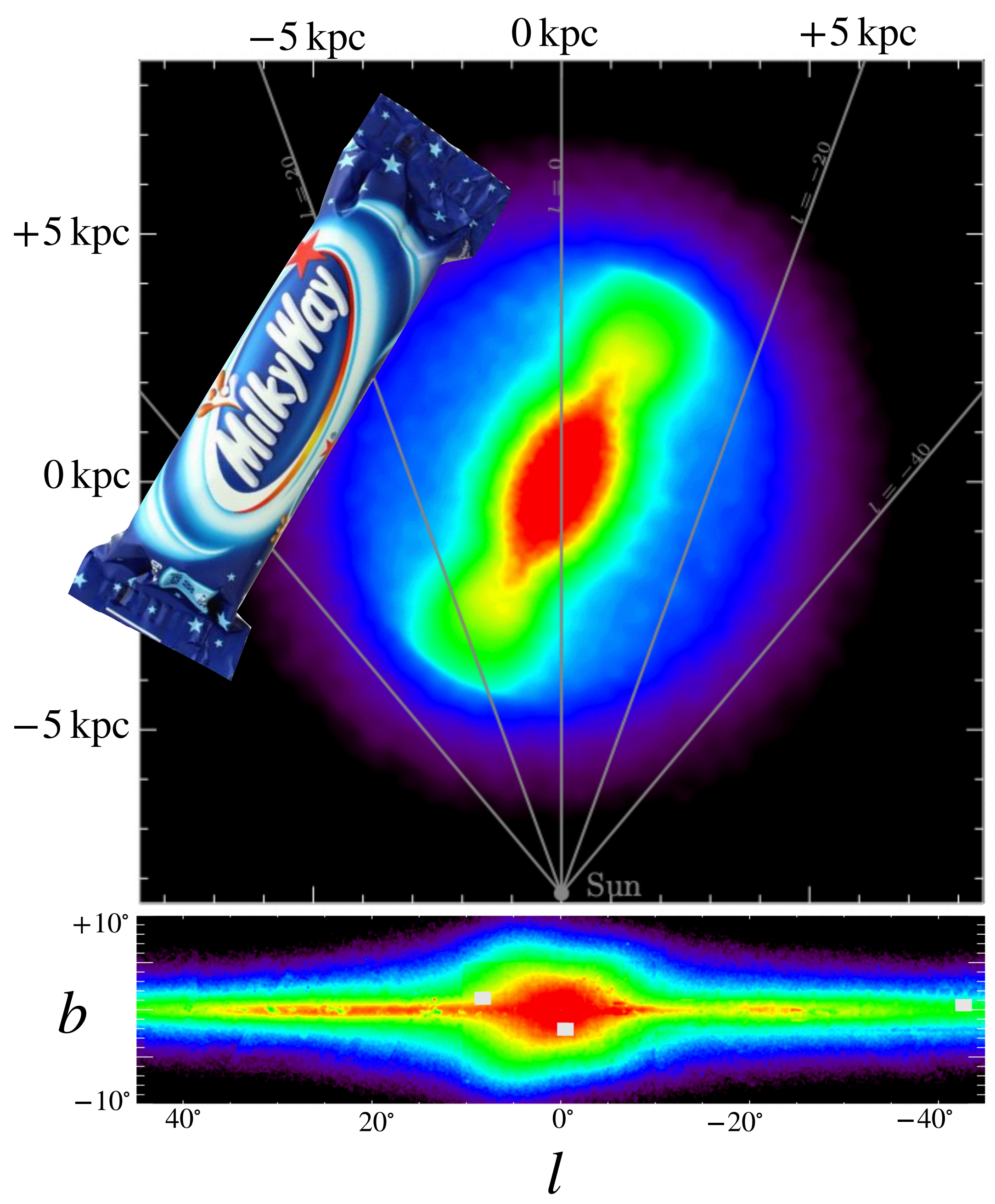
1. In simulations, triaxial DM halos undergo net figure rotation with pattern speeds at the level of:
   $\Omega_p \sim 0.15 - 0.6 \text{ km s}^{-1}\,\text{kpc}^{-1} \sim 9^\circ - 35^\circ\,\text{Gyr}^{-1}$
2. MW halo is triaxial and tilted relative to the disk [2208.04327], but anomalously fast rotation would already be seen to affect stellar streams, e.g. [2009.09004]
3. The MW *stellar* halo has a slow prograde rotation <20 km/s [1703.09230], but there are also substantial retrograde subpopulations due to recent mergers like Gaia Sausage-Enceladus, Sequoia.



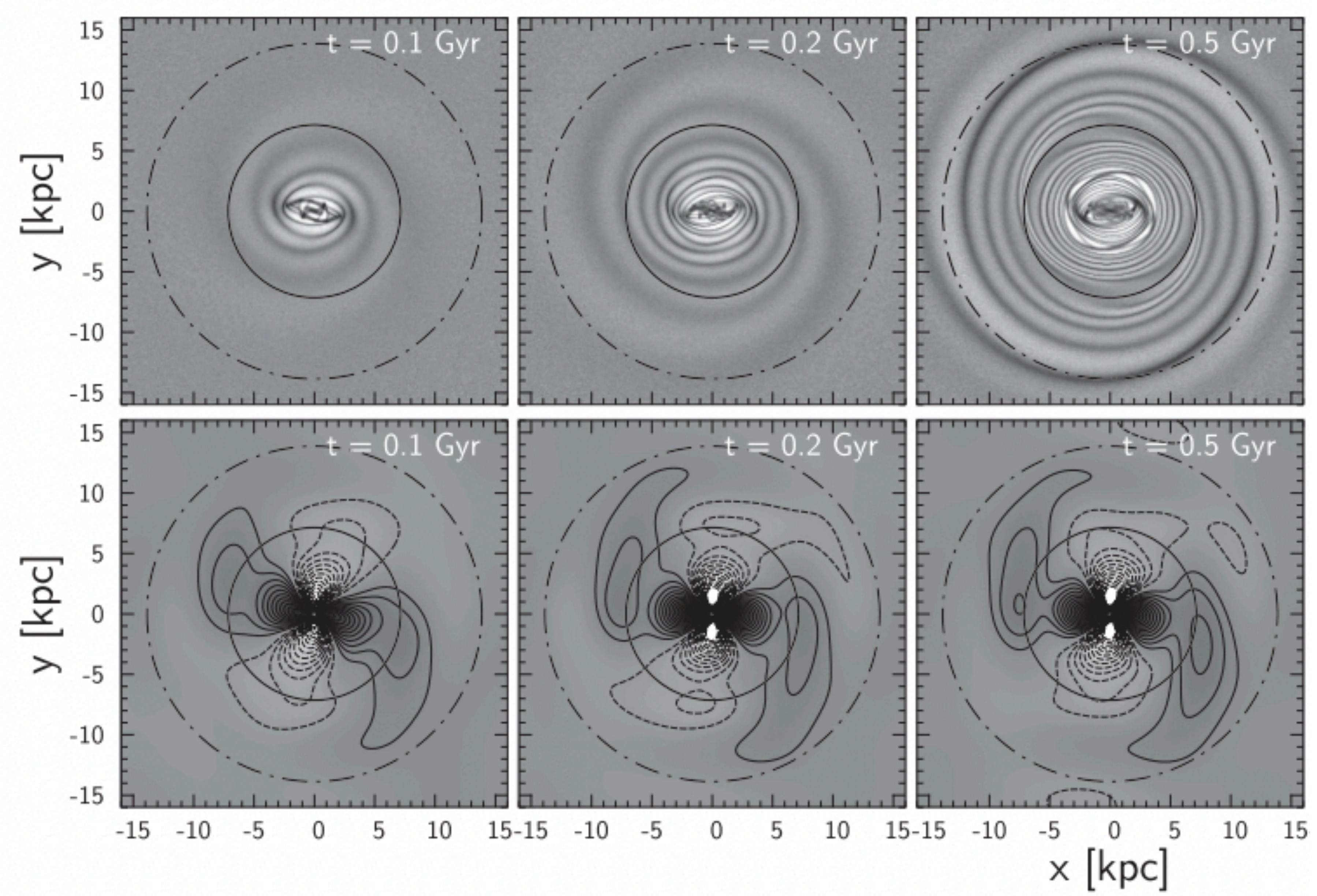
Potential caveats to Assumption 2

- MW has a central stellar bar. Stellar bars are expected to slow down through dynamical friction on the DM halo leading to exchange of angular momentum.
- MW halo is being dragged towards LMC as it falls into our galaxy
- Both interesting, but unlikely to substantially affect broad expectation for directionality of DM flux

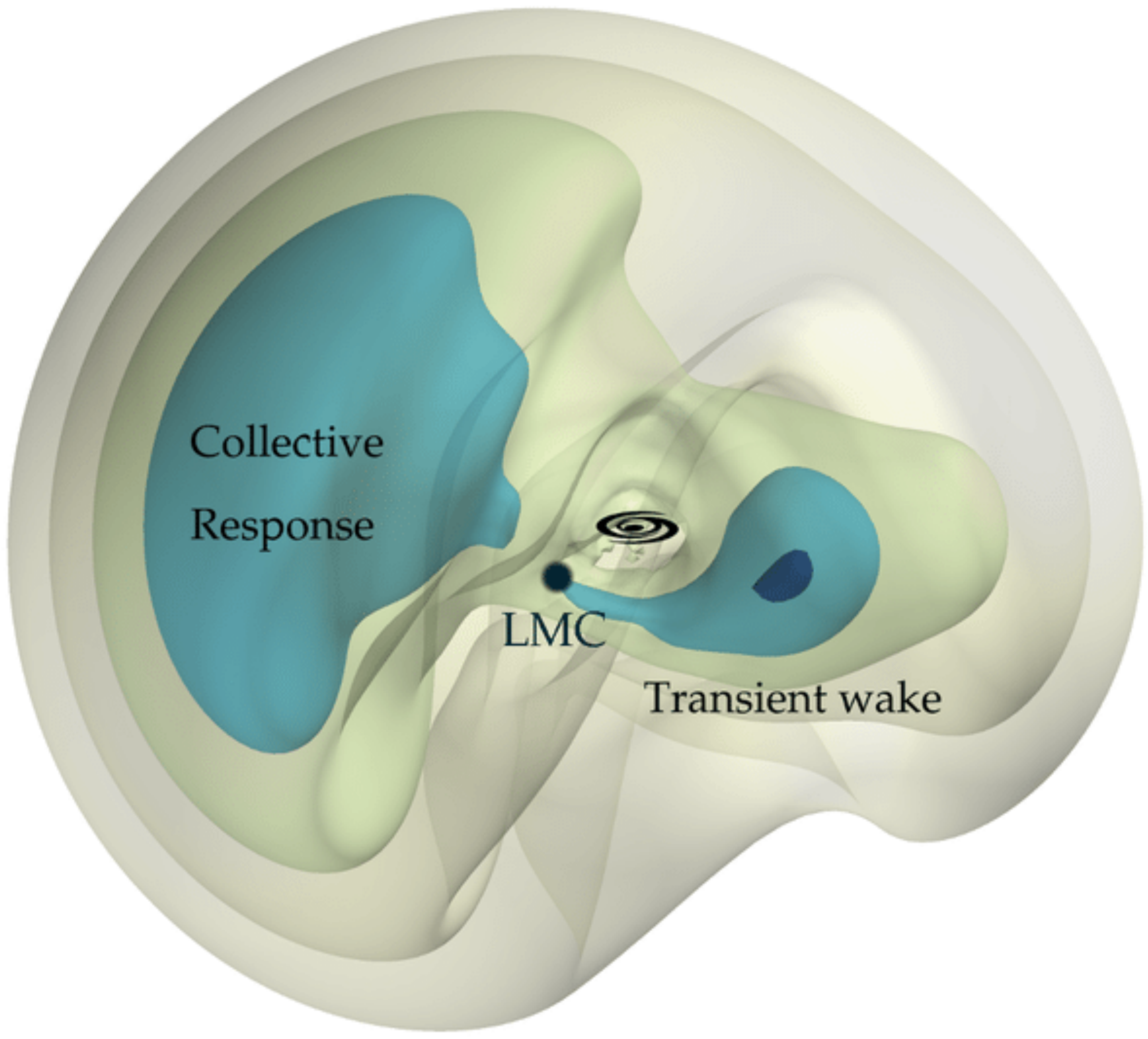
Reconstructed map of MW bar using red clump stars [1504.01401]



Simulated dark matter wake from rotating stellar bar [2109.10910]



Reflex motion MW halo due to LMC [2010.00816]

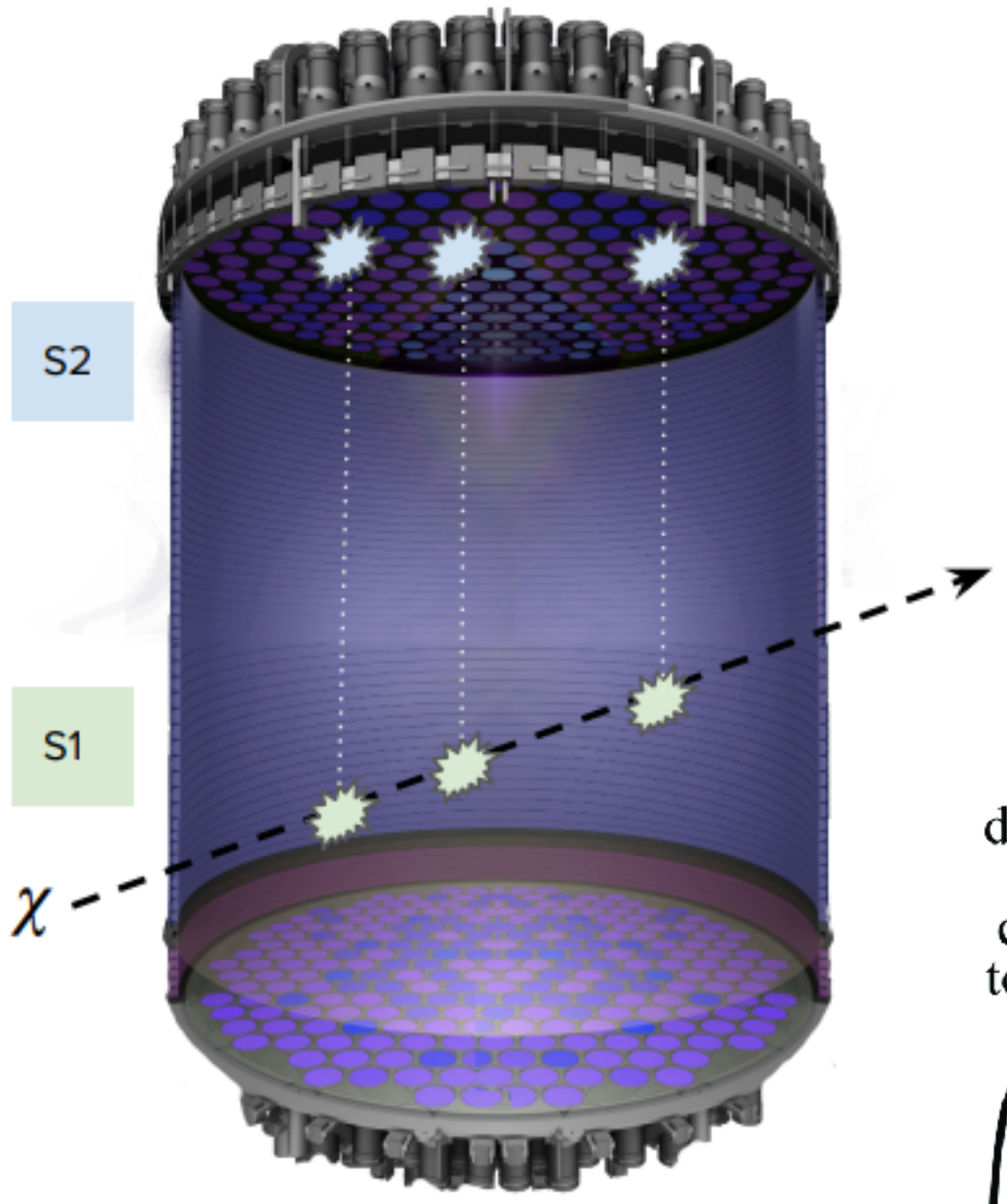


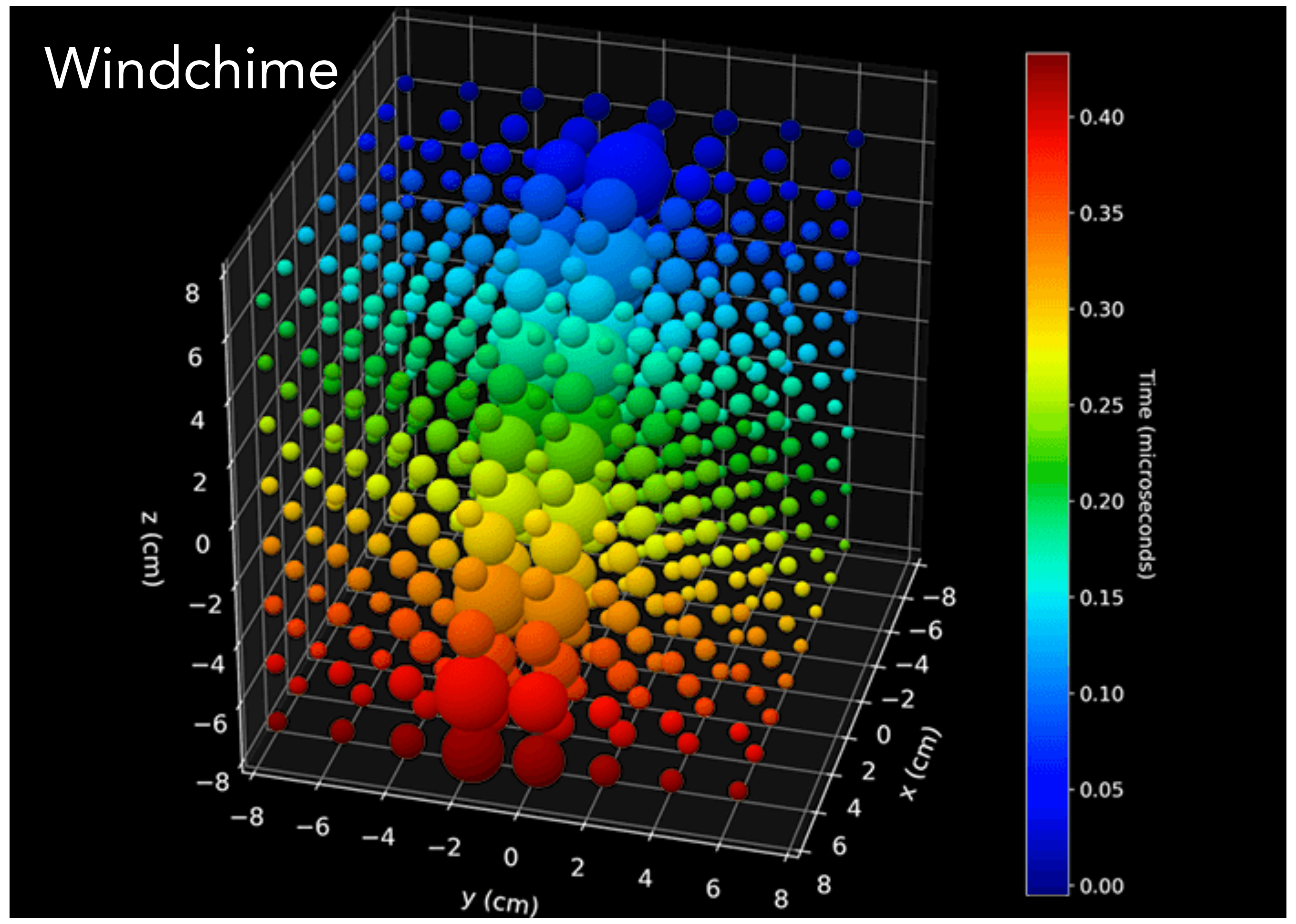
In an ideal world, directionality would be built into the primary search strategy for a direct detection experiment

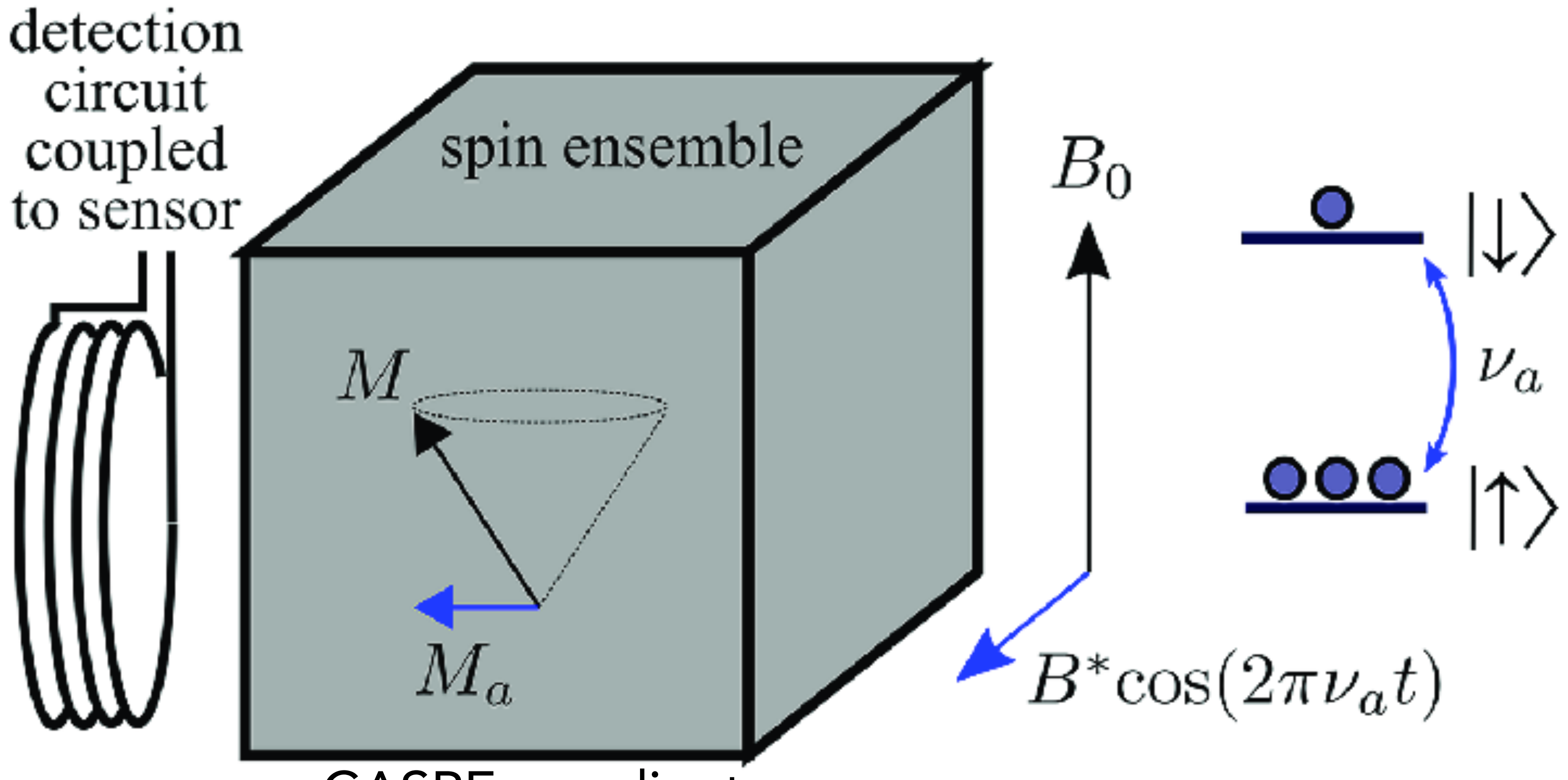
There are a few examples where directionality is intrinsic to the primary DM signal, e.g.

- CASPEr-gradient [2101.01241]
- Sensor arrays (e.g. Windchime) [1903.00492]
- "MIMPs" in LXe/LAr [2304.10931, 2402.08865]

Most of the time it is not.







Why aren't all direct detection experiments direction-sensitive?

The reason is fairly obvious: it is hard enough as it is just to find DM. Trying to tease out a directional signal at the same time is impossible or impractical in most cases.

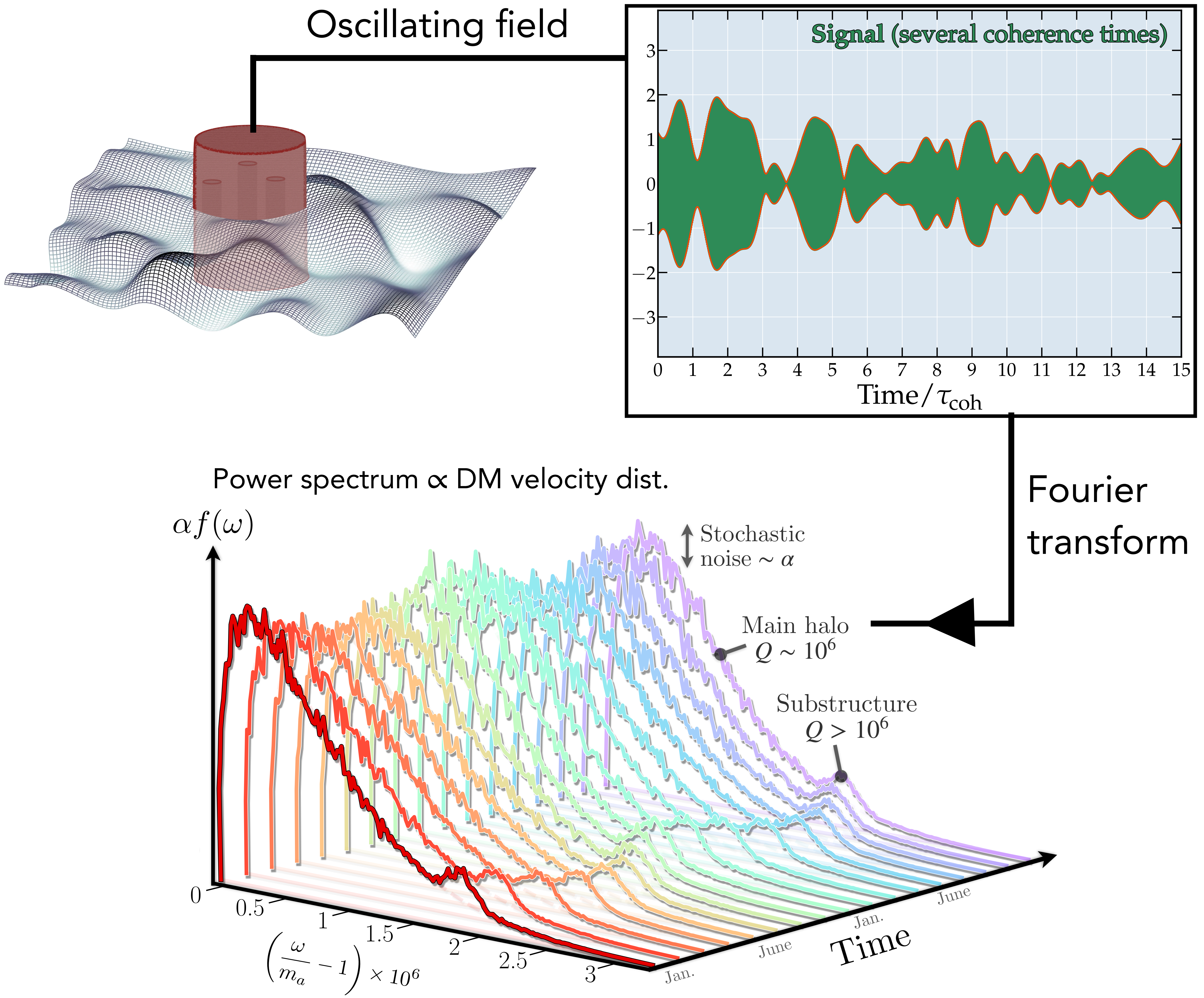
→ But is this a good enough reason to dismiss the idea of directional detection?

I am arguing the answer is no, for 3 main reasons:

1. Majority of existing and proposed detection strategies are unable to claim that a positive signal is *the* dark matter.
2. There are irreducible backgrounds in some experiments that could prevent even the initial *identification* of that signal in the first place.
3. Directionality provides additional information that will allow us to learn about the particle/astrophysical nature of a signal (i.e. do science with DM rather than just identify it)

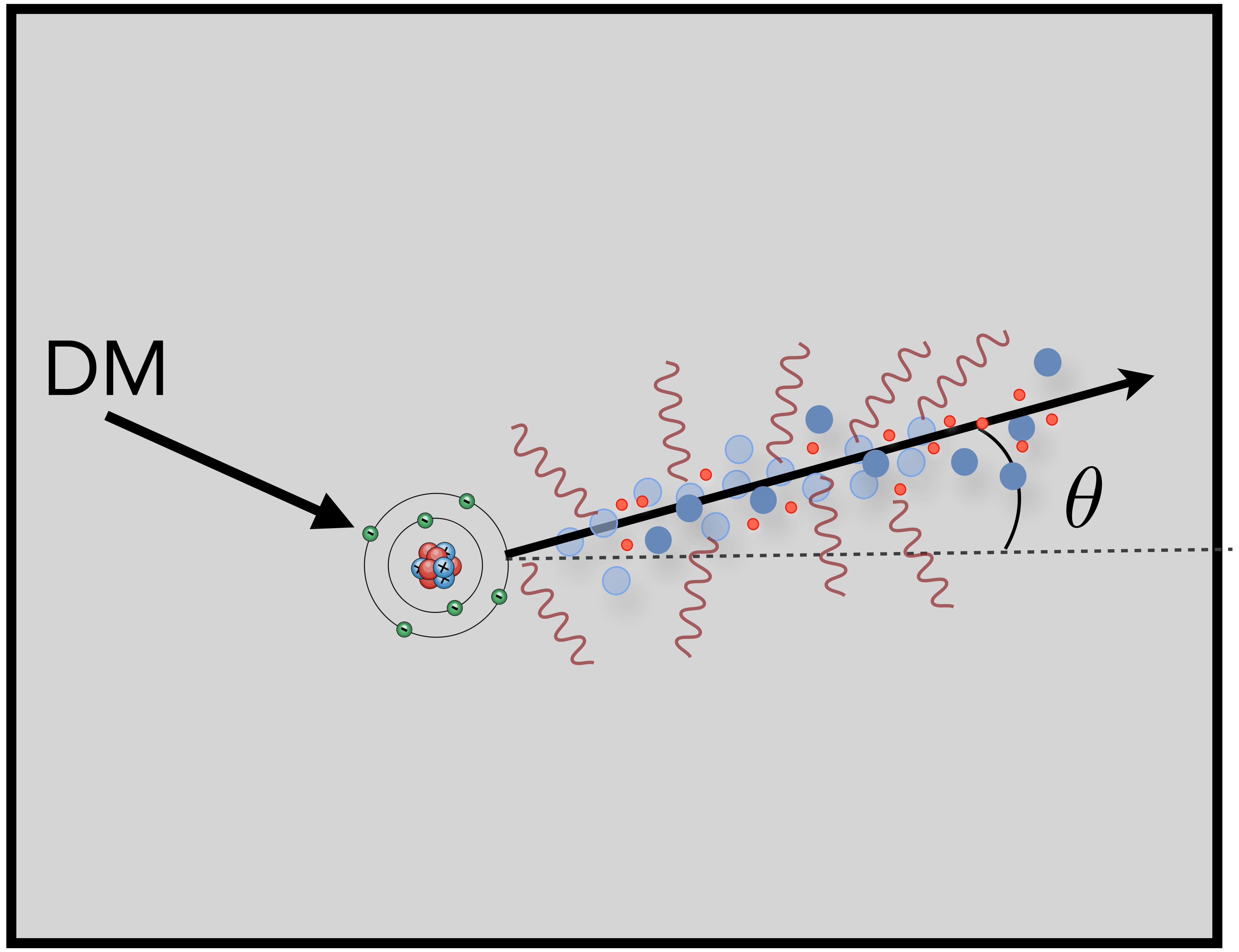
Making a discovery claim for wave-like DM (e.g. axions)

- Axion experiments are called 'haloscopes' for good reason. They can measure the DM mass and kinetic energy distribution independently, so can check if a putative signal is coming from some non-relativistic particle with a velocity dispersion consistent with our halo.
- Several haloscopes already build this cross-check into their discovery pipeline.
- Directionality manifests as a *sidereal* modulation in the lineshape which would require high S/N to see, but no fundamental obstacle preventing this from being done.



Directional detection of particle-like DM

Take m_χ~MeV—TeV dark matter interacting with atoms in some way, main signal will usually be recoils with energies O(eV - 100 keV) with directions aligning with incoming DM velocity to some extent. The question then becomes finding a medium where those directions are preserved and a resulting signature which traces that direction.



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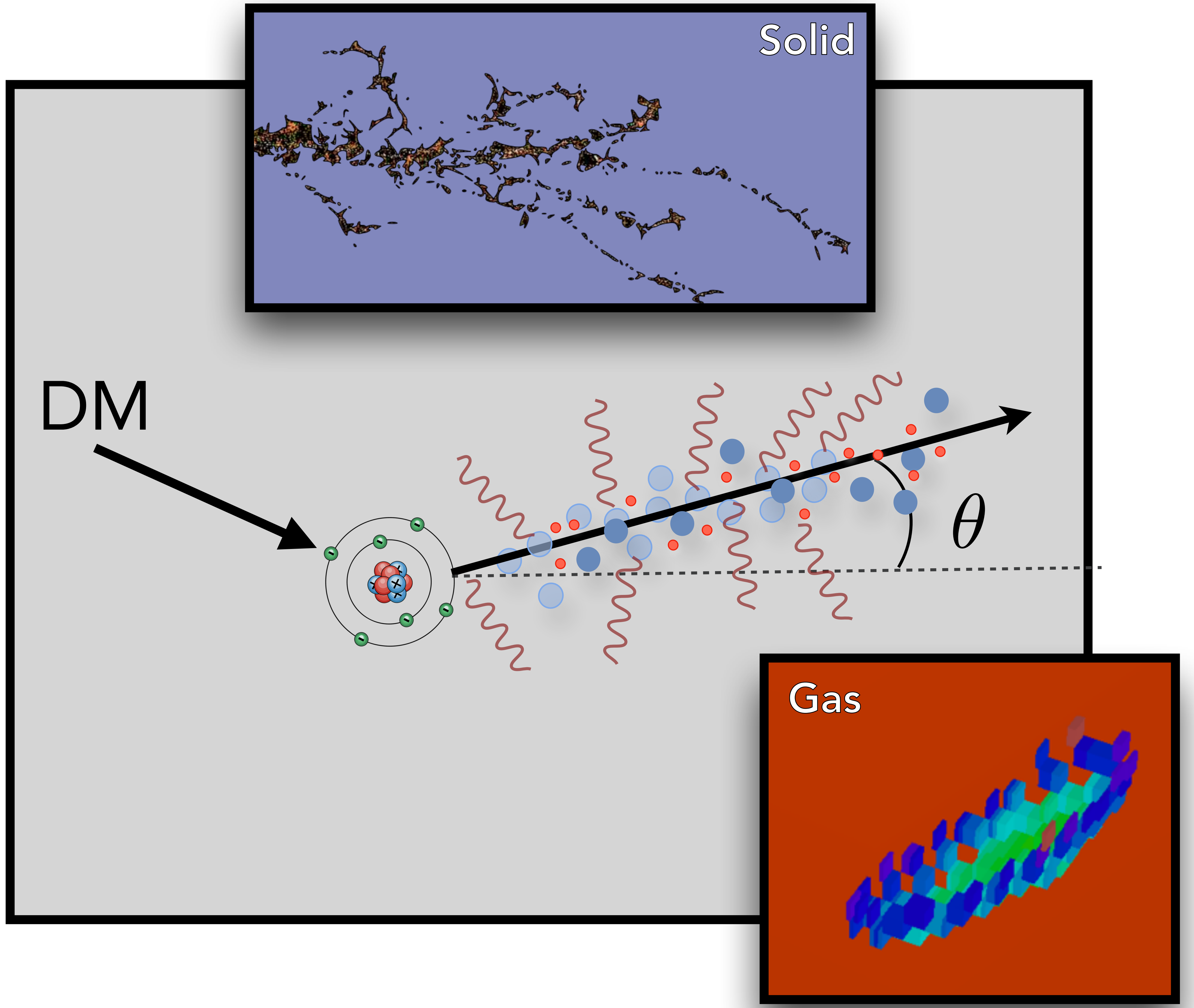
- ➔ **Solids:** Recoils are physically small (nanoscale), but in some materials information can be preserved
- ✗ **Liquids:** Recoils are physically small and information about them (e.g. ionisation) is washed away by recombination and diffusion
- ➔ **Gases:** Recoils are not microscopic, diffusion much lower and controllable through gas pressure

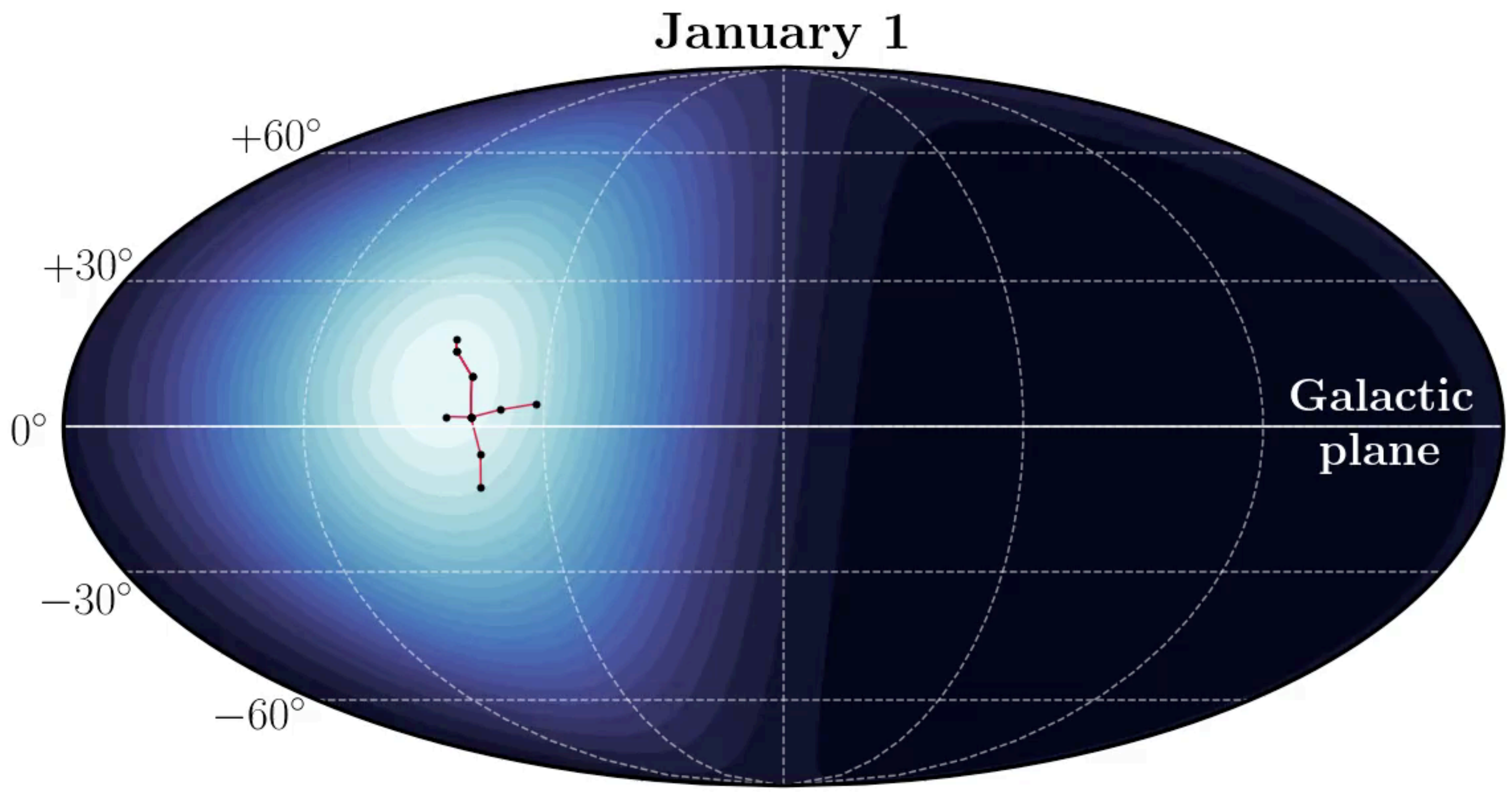


Discovering DM through recoil directions

- Assuming backgrounds are isotropic, a background-only hypothesis can be excluded at 3σ with O(10) recoil directions and a discovery claim made with factor ~few more.

- The true power is that this can be done *non-parametrically*, e.g. test for whether the recoil directions are isotropic to exclude the background, and test if they align with Cygnus to claim discovery

Nuclear recoil angular distribution

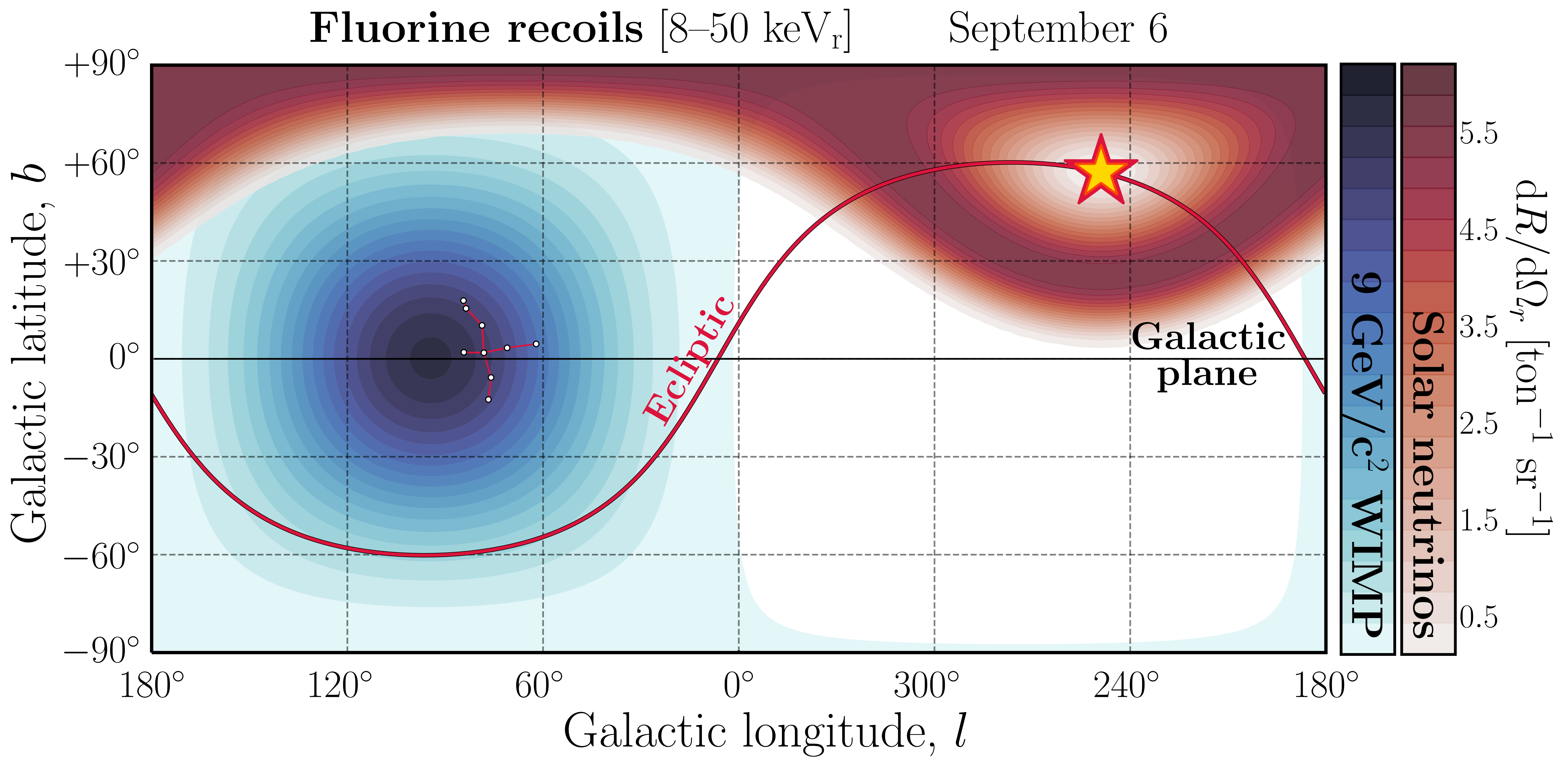


- However, doing this requires that directionality is fully 3-dimensional. If only 2d/1d projections of vectors available, or if not measurable at the event level, then this directionality becomes a precision effect and requires more detailed modelling of signal.

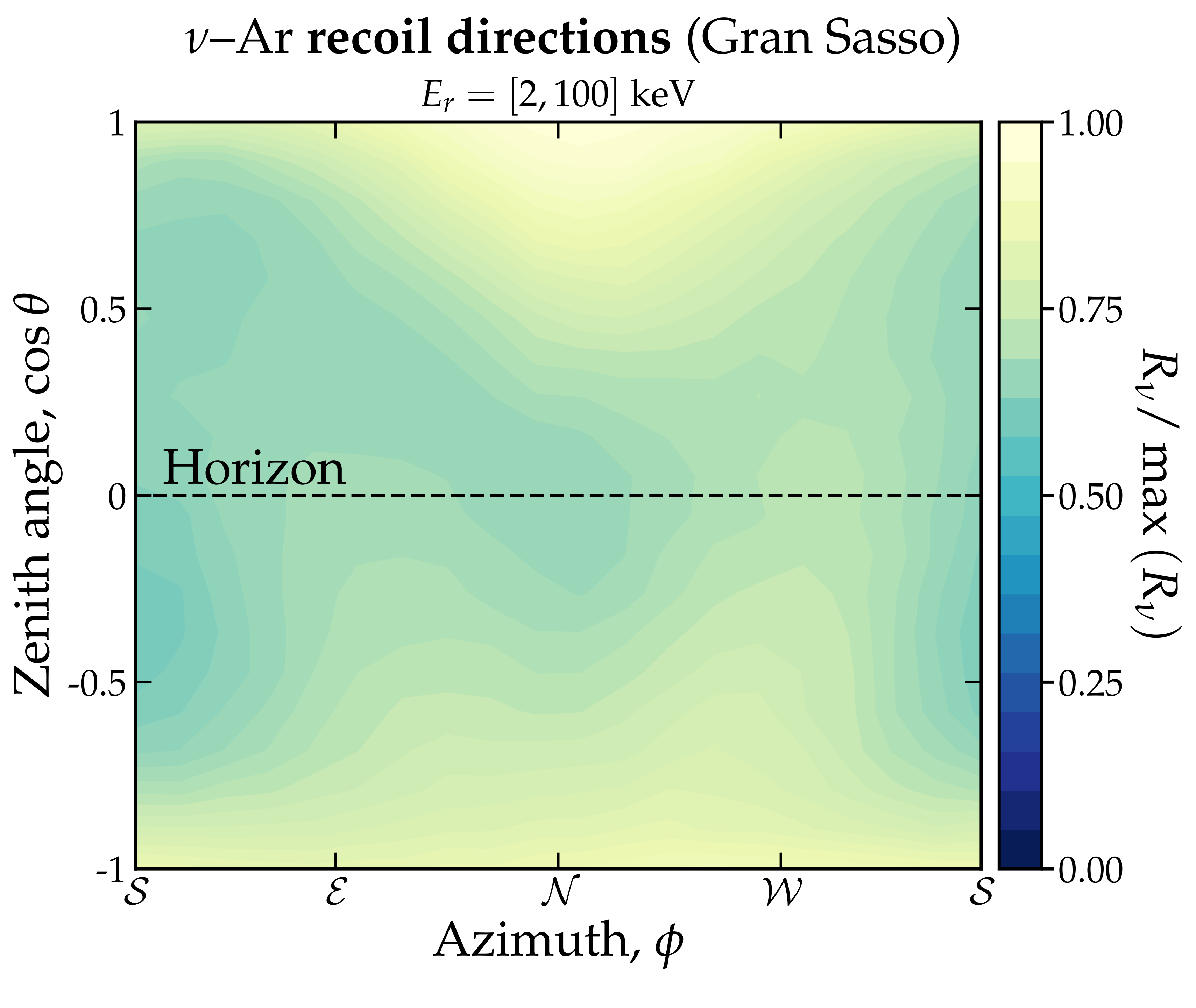
Discriminating against neutrinos

One of the most obvious motivations for pursuing directionality for particle DM is to confront the neutrino fog. CEvNS angular distribution due to solar neutrinos is highly anisotropic, and ~isotropic for atmospheric neutrinos. Directionality provides the only realistic way to subtract this otherwise irreducible background. **As of yesterday, neutrinos are no longer "on the horizon", they are in the room.**

Solar neutrinos (CEvNS)

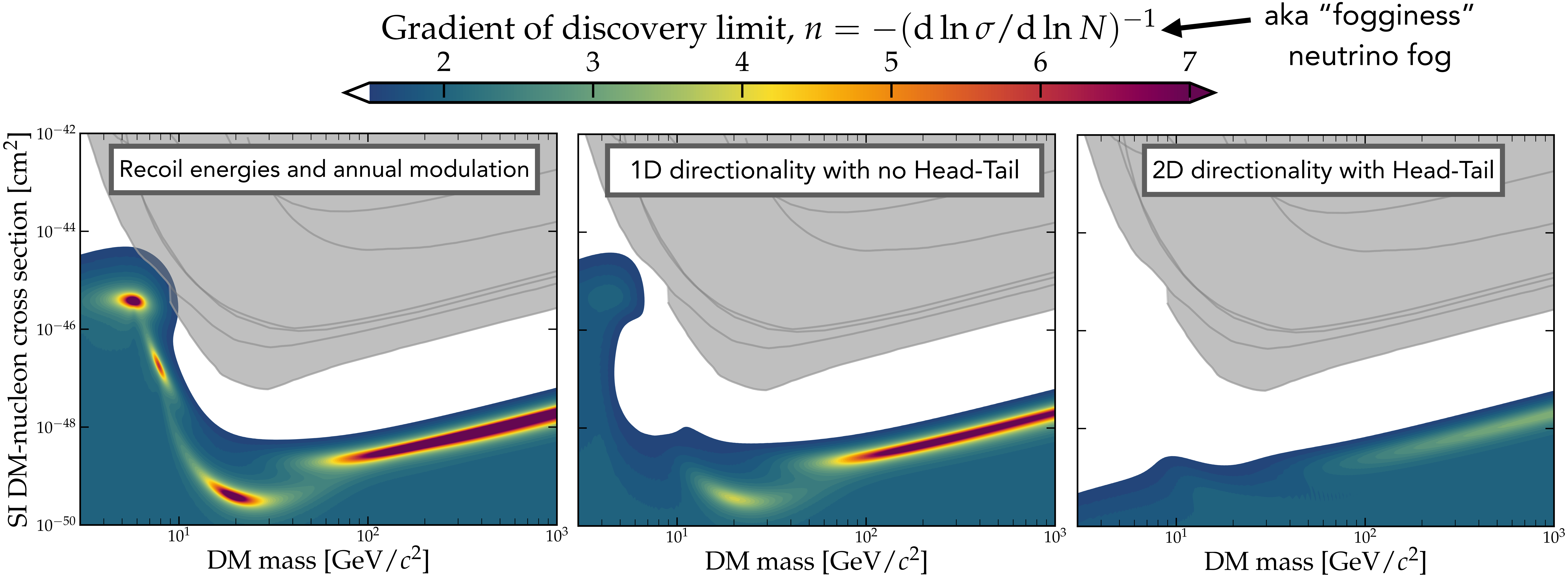


Atmospheric neutrinos (CEvNS)



Neutrino fog for directional experiments

There is essentially no neutrino fog for direction-sensitive experiments. Even low levels of directionality (e.g. 2D) can fully subtract the solar neutrino background.



Recoil imaging

The DM signal is a dipole, so does not demand extremely fine angular resolution. However *because* the signal is a dipole, distinguishing it from isotropic backgrounds requires (ideally) 3D recoil vectors with ±sense information (referred to as "head-tail").

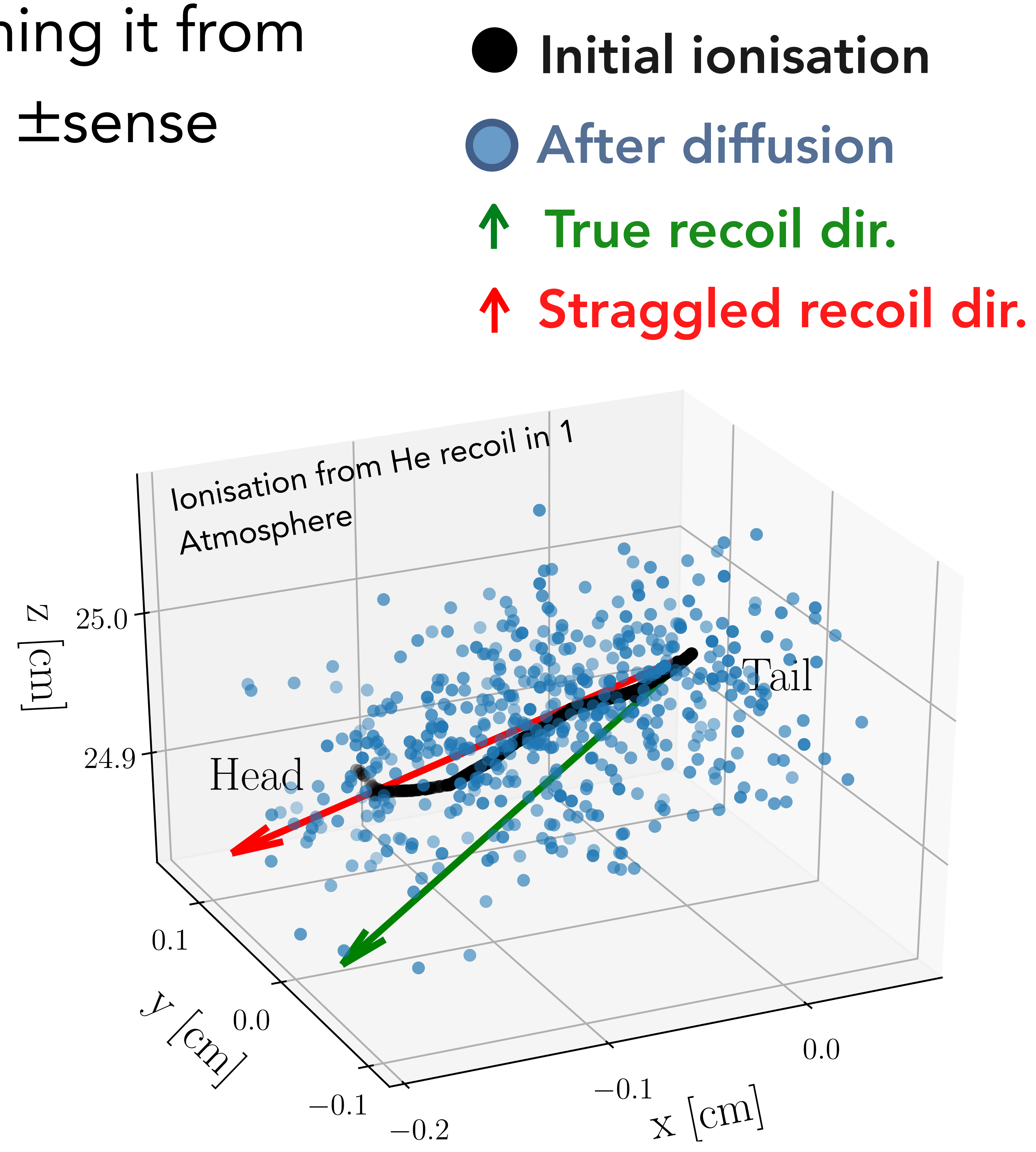
Challenges:

→ 3D ionisation distribution often cannot be obtained all at once, instead a 2D projection is imaged and 3rd projection inferred through timing

→ Head/tail information stored in dE/dx profile, so need to resolve ionisation density as well as just the track shape

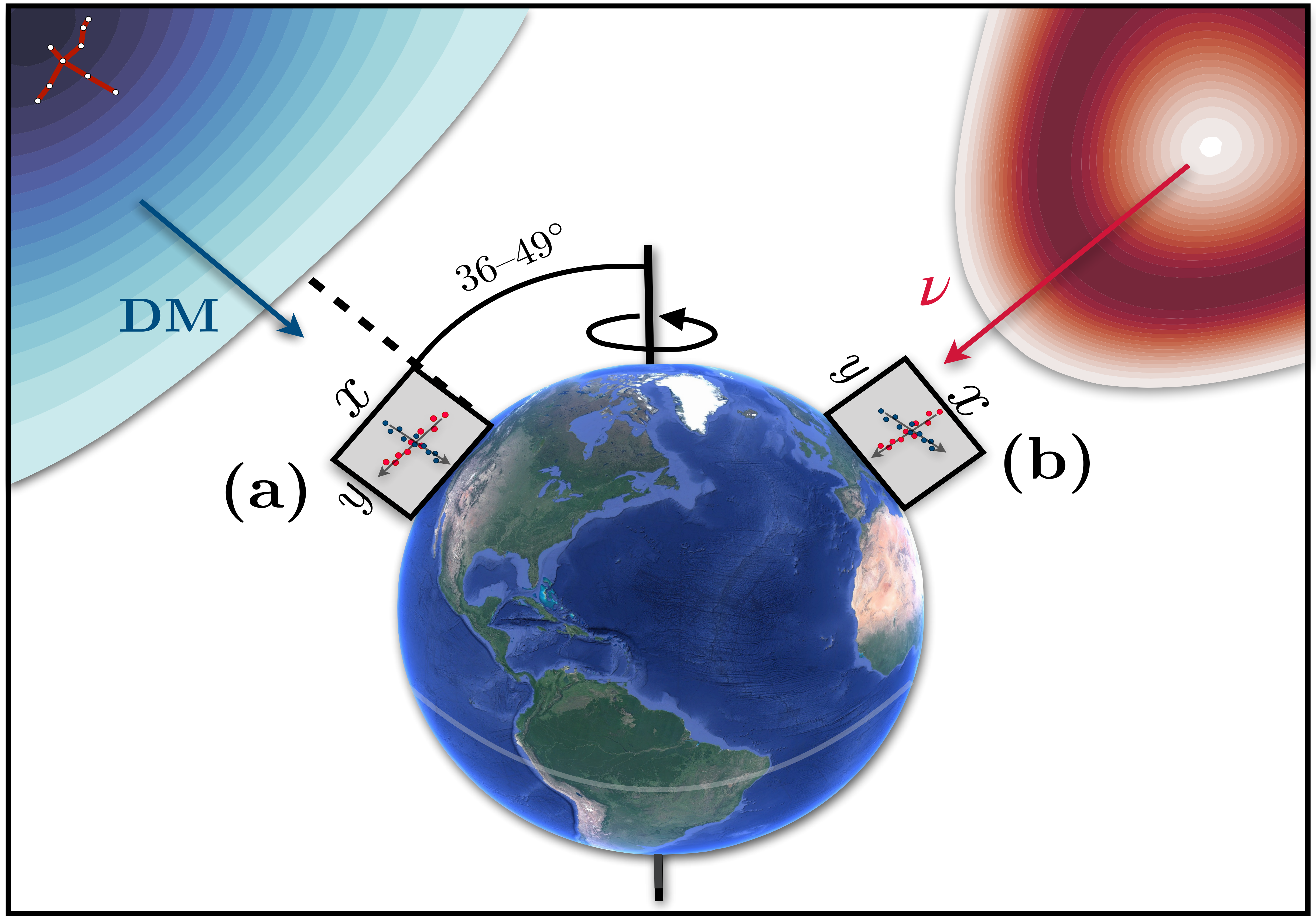
→ Straggling, diffusion, and charge amplification all limit how much of the initial directionality is preserved.

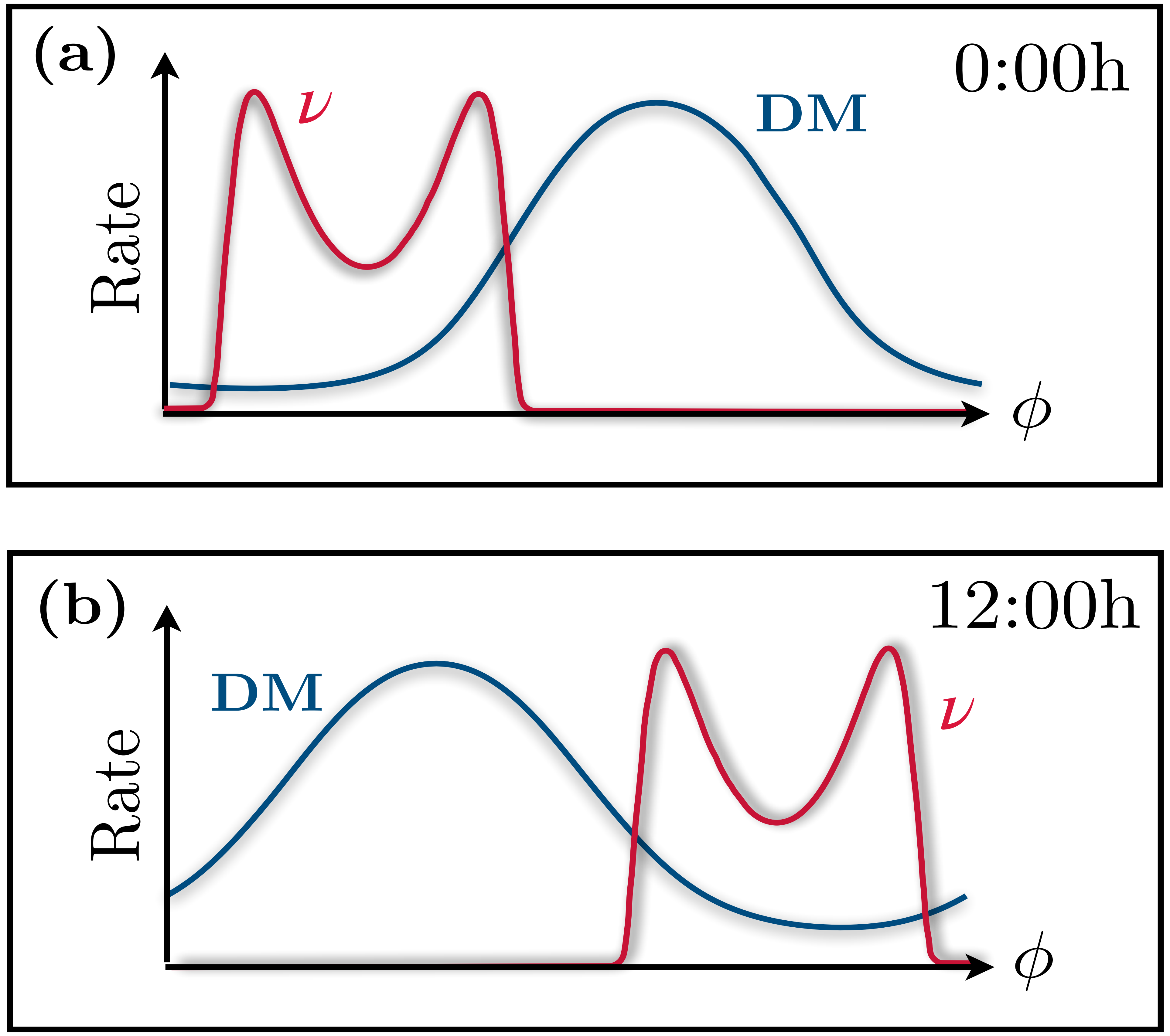
→ Nuclear recoils are *small*. In atmospheric pressure gas, spatial resolution of O(100 μm^3) required for keV-scale recoils from DM and neutrinos



The importance of time-resolved event-by-event directionality

In the detector, directionality manifests as a sidereal daily modulation of the rate across its angular coordinates. Events must be **time-resolved**, otherwise Earth rotation washes out this signal.





Vahsen, CAJO, Loomba [2102.04596]

Demonstrated
R&D
Proposed

Detector classes by directional information

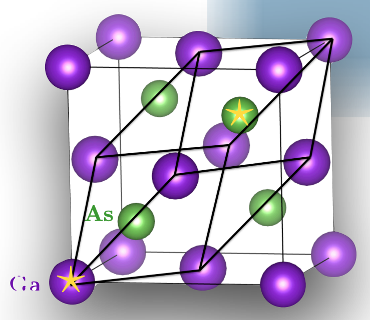
Least information → *Most information*

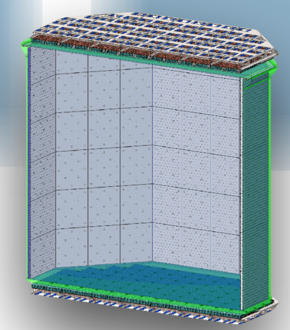
Indirect | **Recoil imaging**

Statistical | **Event-level**

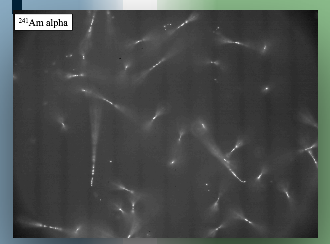
Modulation-based directionality | Indirect recoil event directionality | Time-integrated recoil imaging | Time-resolved recoil imaging

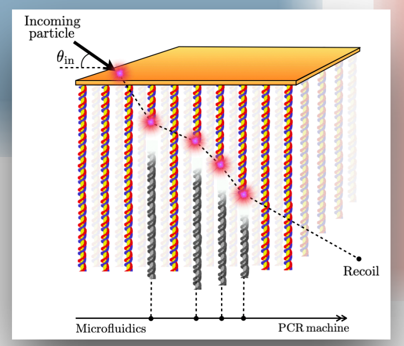
Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes





Columnar recombination
- Event-level 1d directionality
- No head/tail information

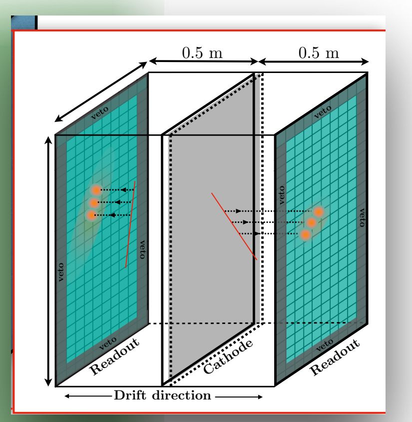




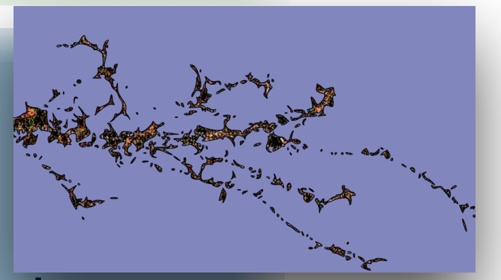
Nuclear emulsions
- 2d recoil tracks, without head/tail
  No event times recorded

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



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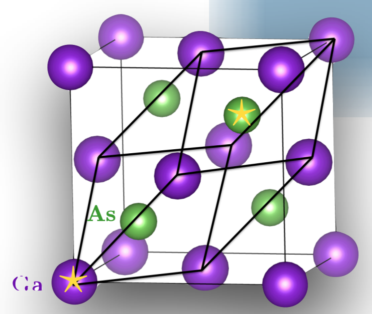

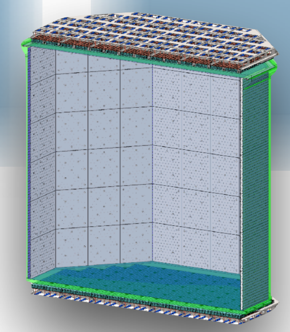

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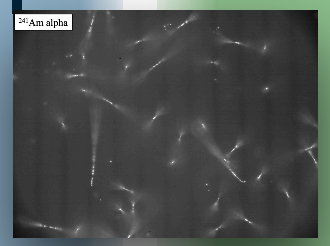

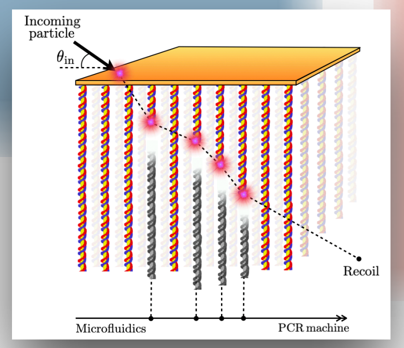

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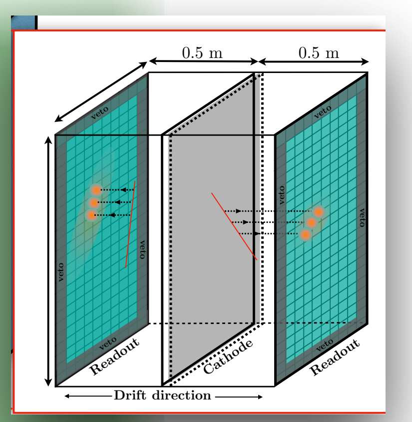

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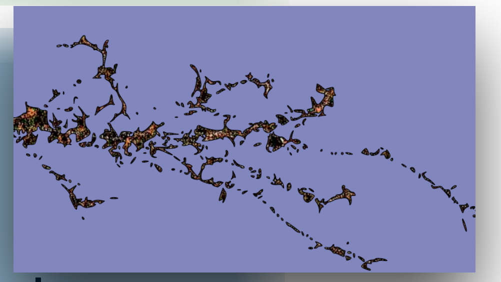
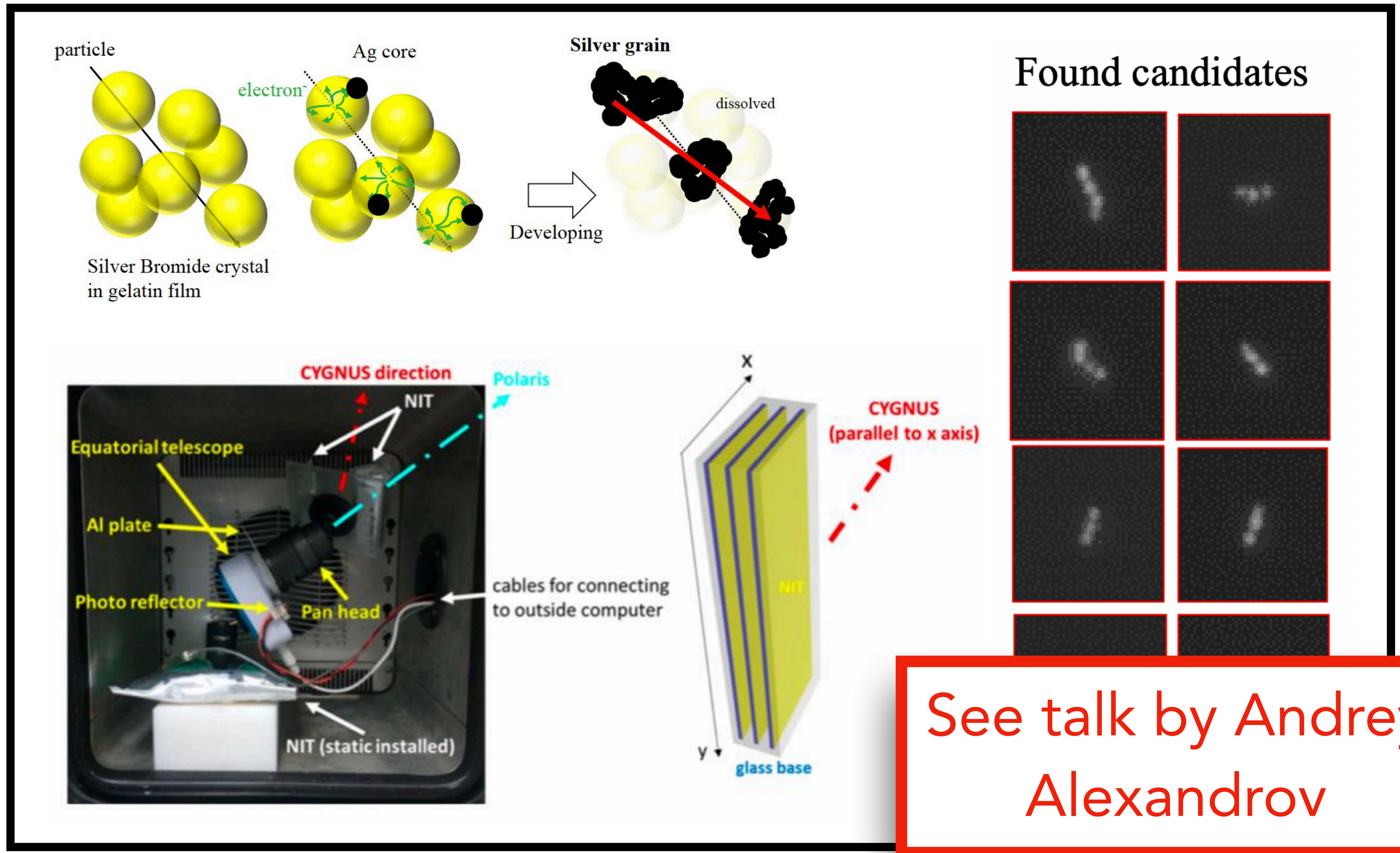


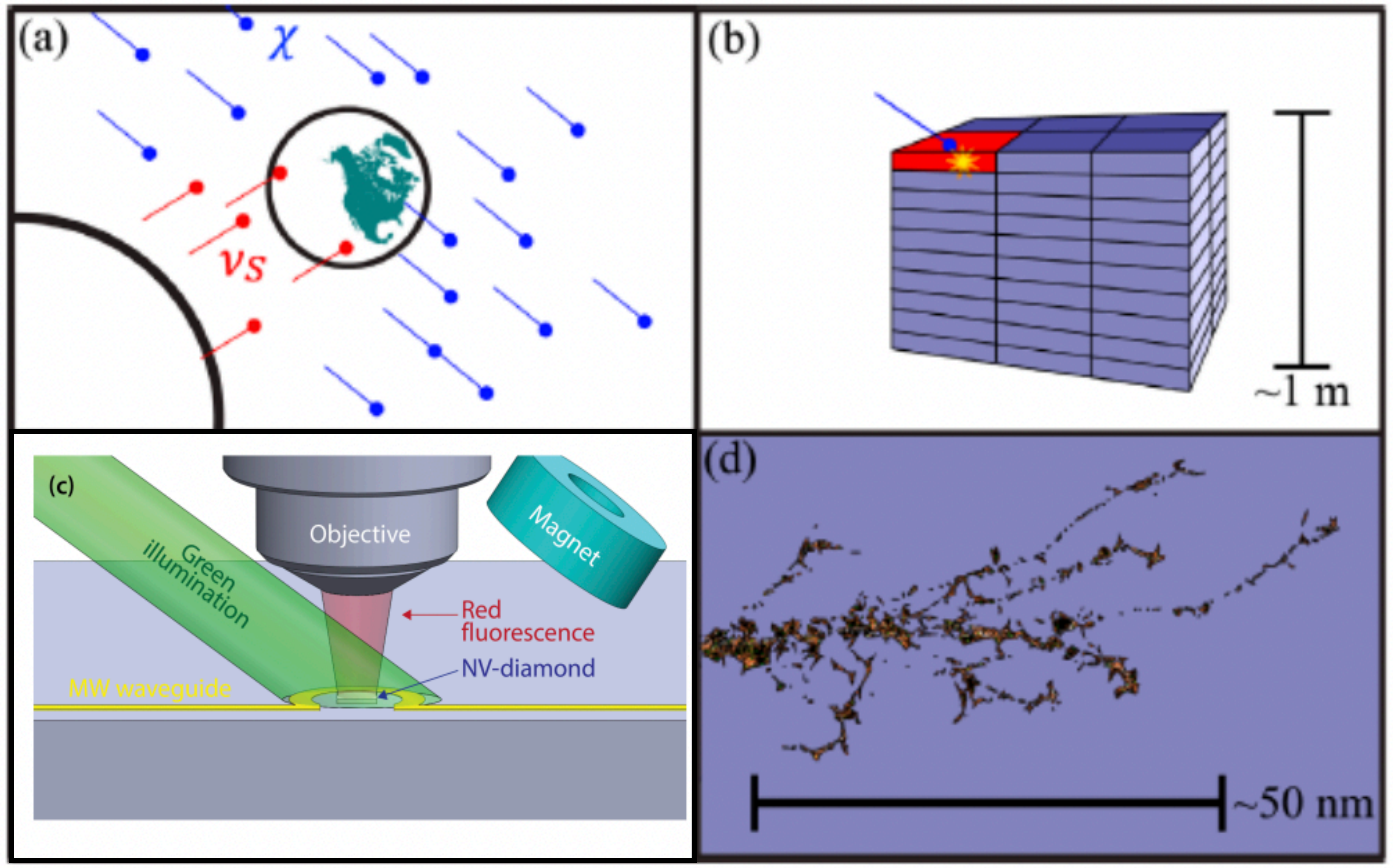
Recoil imaging in solids

- Nuclear emulsions, e.g. NEWSdm [2310.06265]



See talk by Andrey Alexandrov

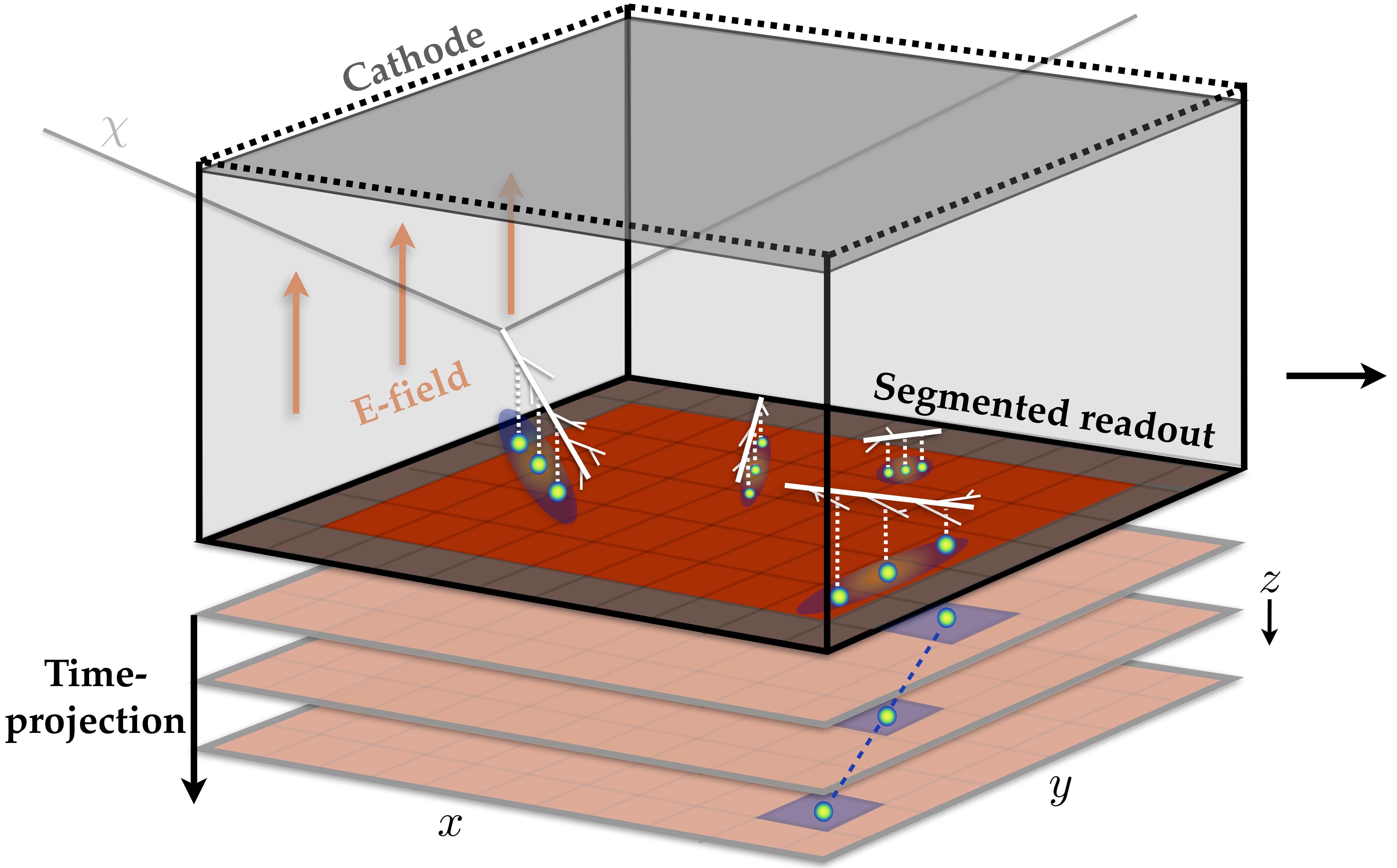
- Image damage tracks in diamond using NV centres [2203.06037]

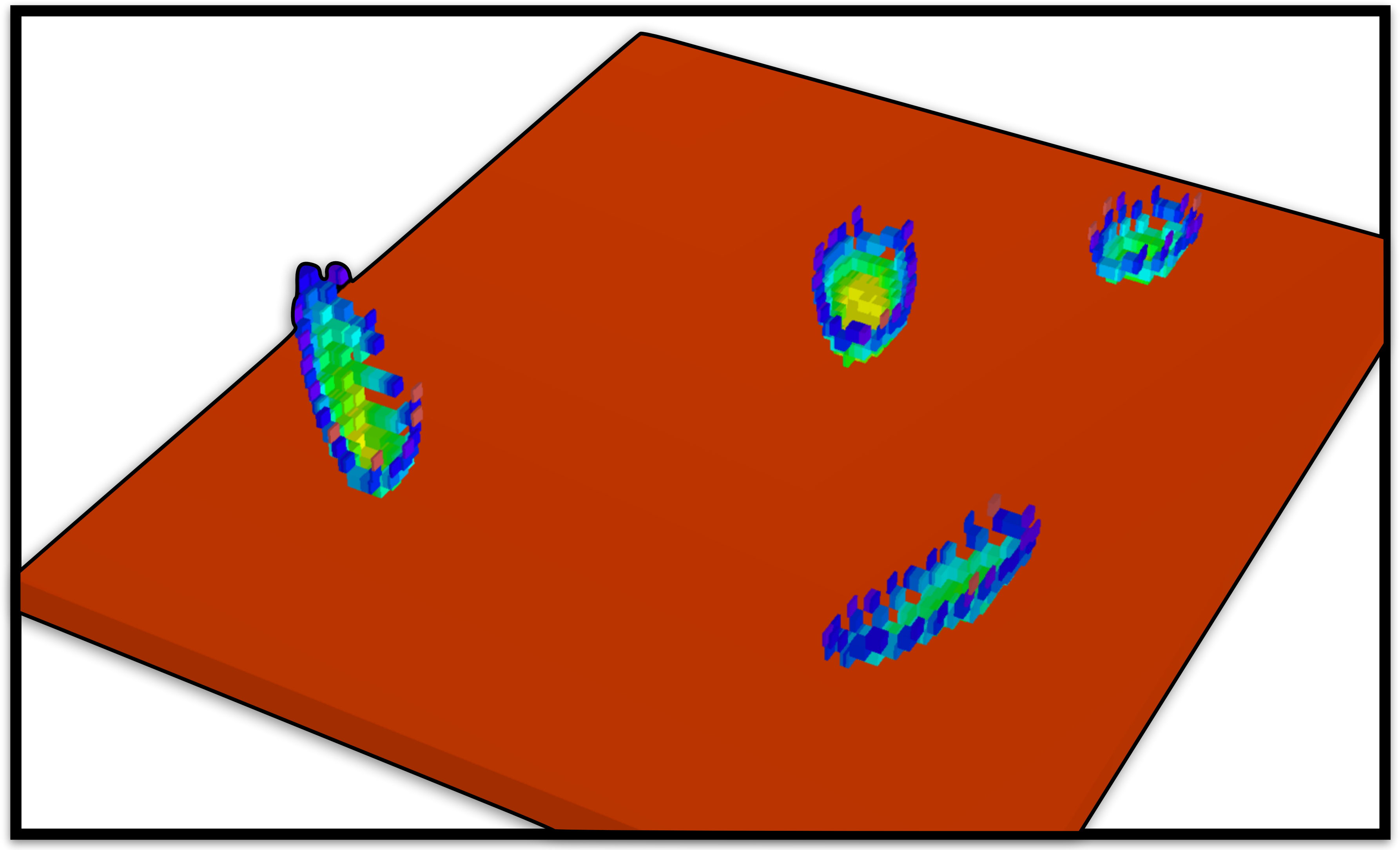


Note: In both cases tracks are lodged in the solid bulk and need to be imaged through some time-intensive microscopy. Earth rotation would therefore wash out the directionality if tracks were only collected after the exposure time. Different ways to tackle this include rotating the detector on an equatorial mount so tracks are always aligned in galactocentric coordinates, or by time-tagging events using some additional trigger.

Directionality in gas (Micro-pattern gaseous detectors, MPGDs)

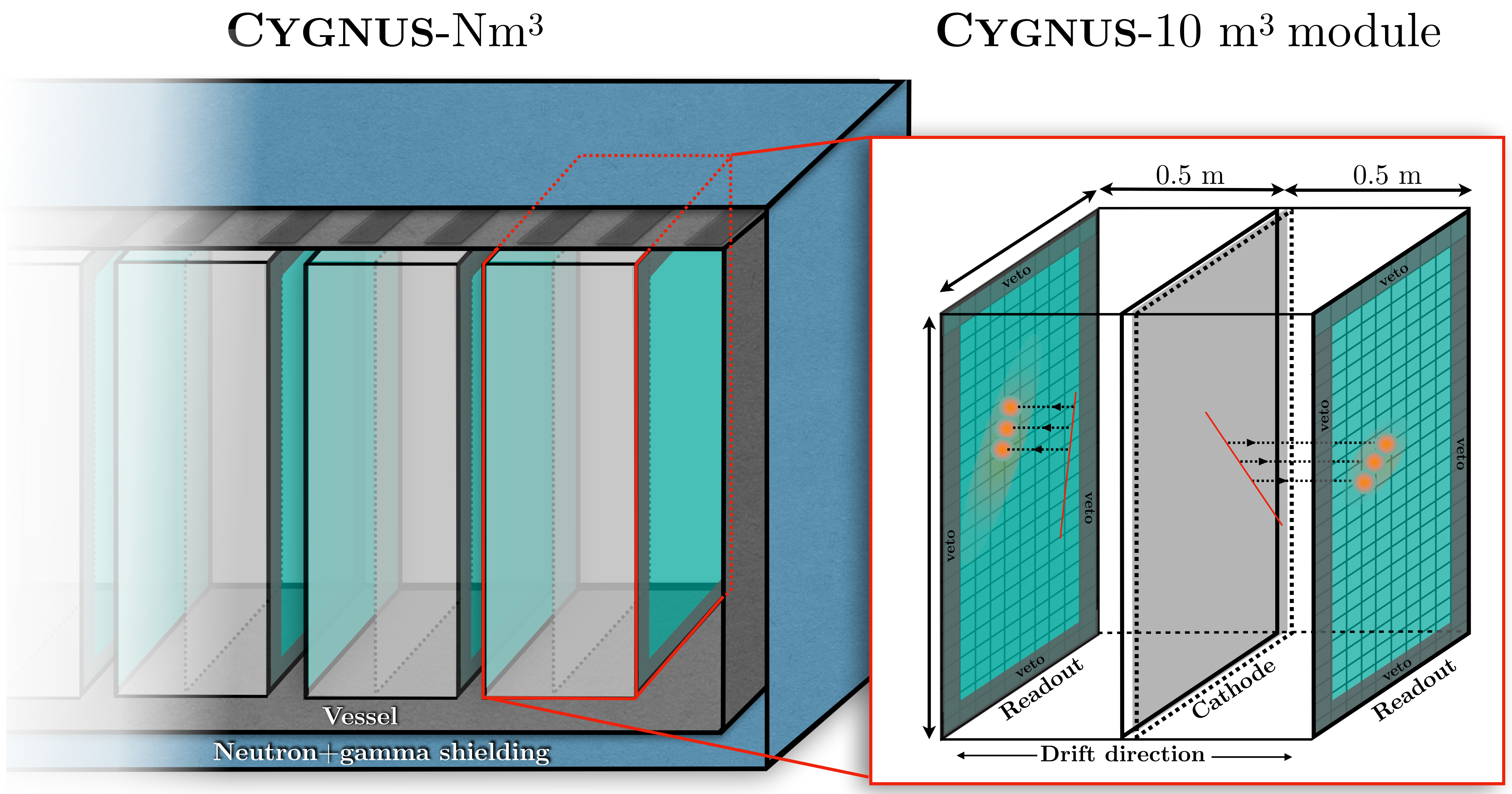
To fully image 3D ionisation tracks in gas, want to use a time-projection chamber with a finely-segmented gas avalanche amplification stage and segmented charge/light readouts. High signal-to-noise reconstruction of tracks with O(100) μm^3-voxel size would be sufficient for DM and neutrino detection, but also needs to be implemented at scale, in as high-density gas as possible, and come with low-enough backgrounds.

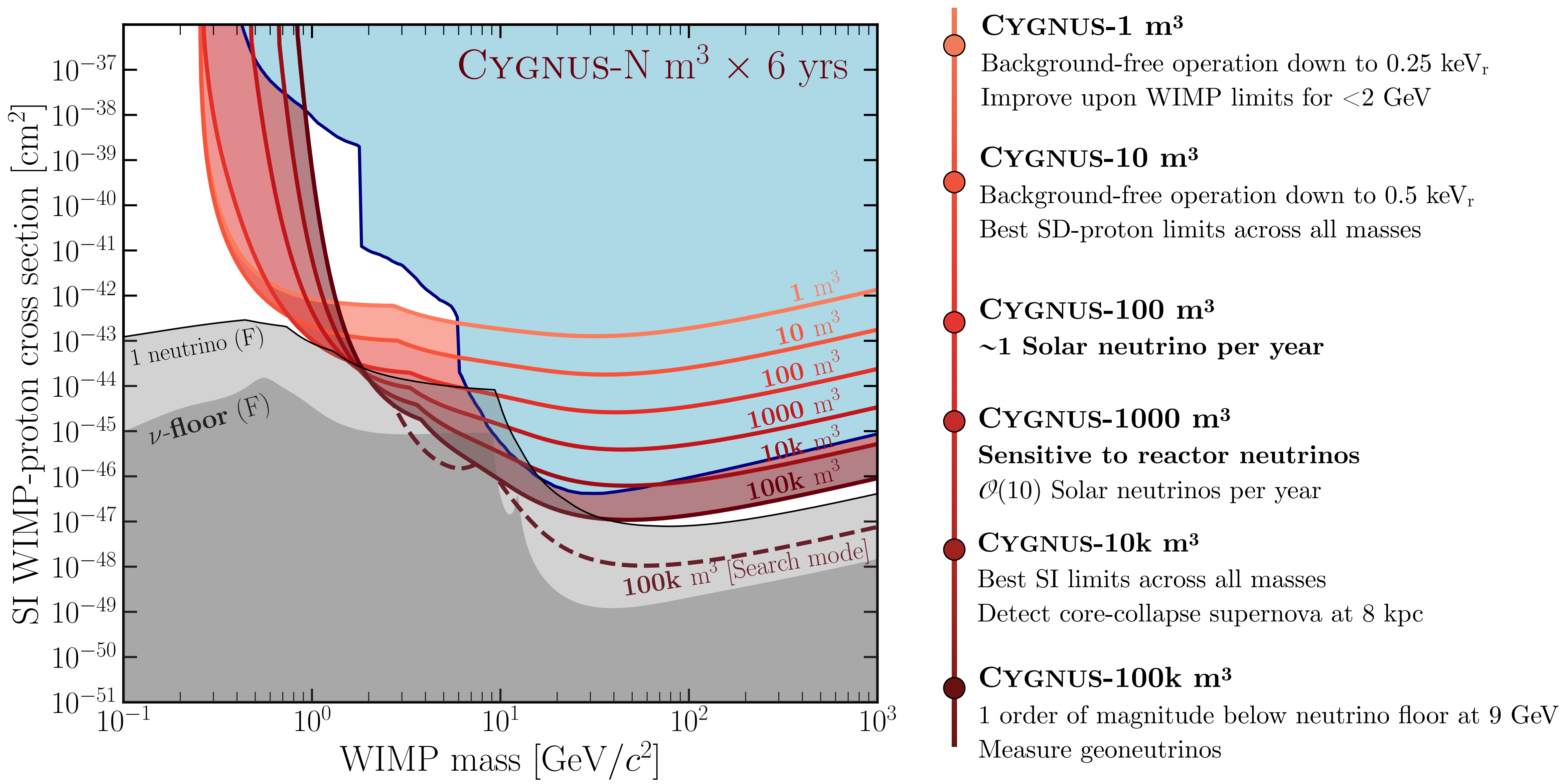




3d low-energy neutron-induced Helium recoils
Jaegle+ [1901.06657]

Ultimate goal: CYGNUS "recoil observatory"





Challenges:

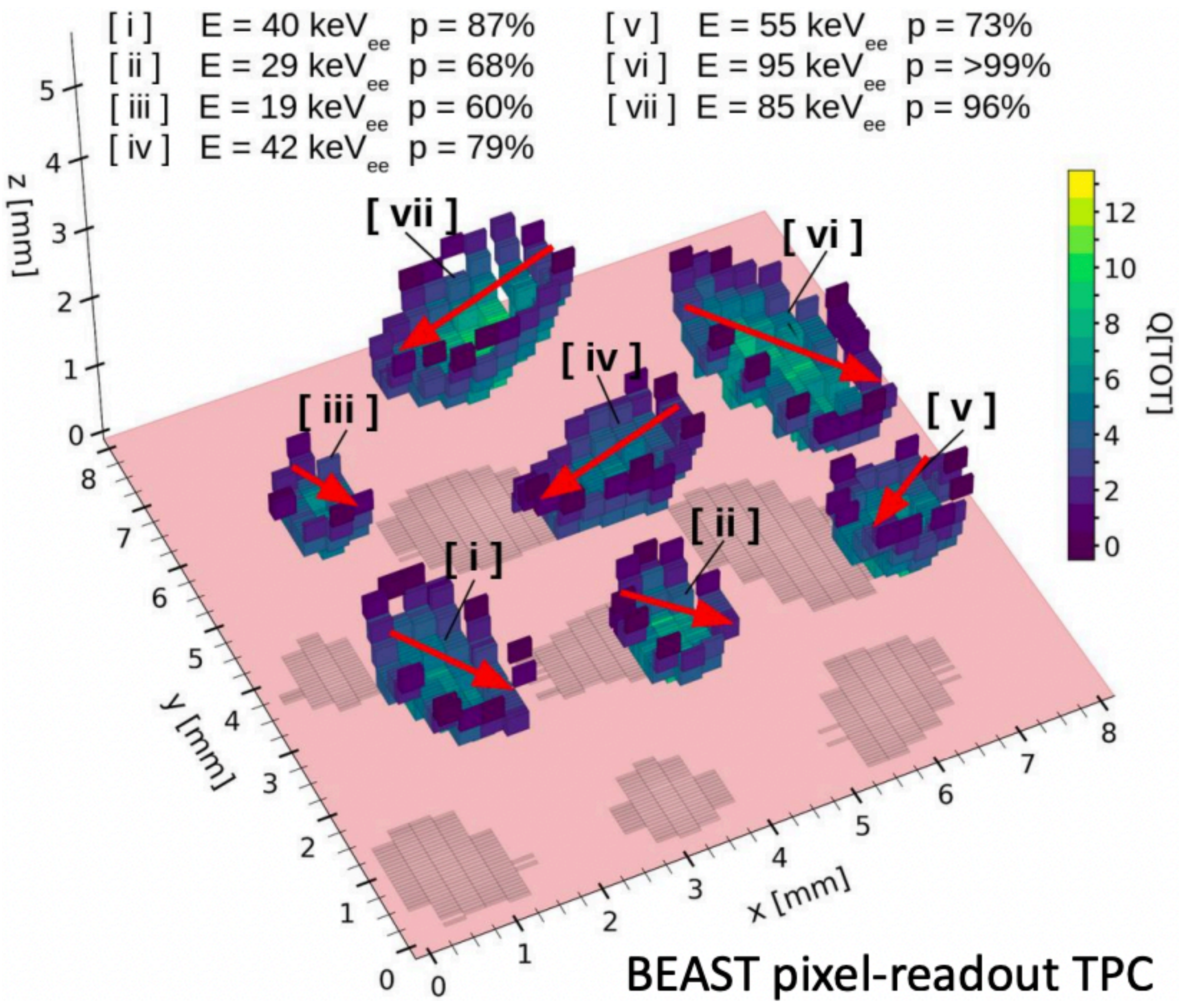
→ Design must be chosen to limit the drift distance as much as possible (>25 cm of diffusion washes out ~keV-scale tracks), but this raises cost per volume due to expensive readout planes.

→ Gas choice: e.g. SF6 for negative ion drift or CF4 for electron drift. Adding helium enables atmospheric pressure operation without substantially impacting directional performance.

→ Readout combination: e.g. fully 3D with fast pixel charge readout, or 2D + 1D with optical readout and use PMTs to reclaim third direction along drift axis (e.g. CYGNO).

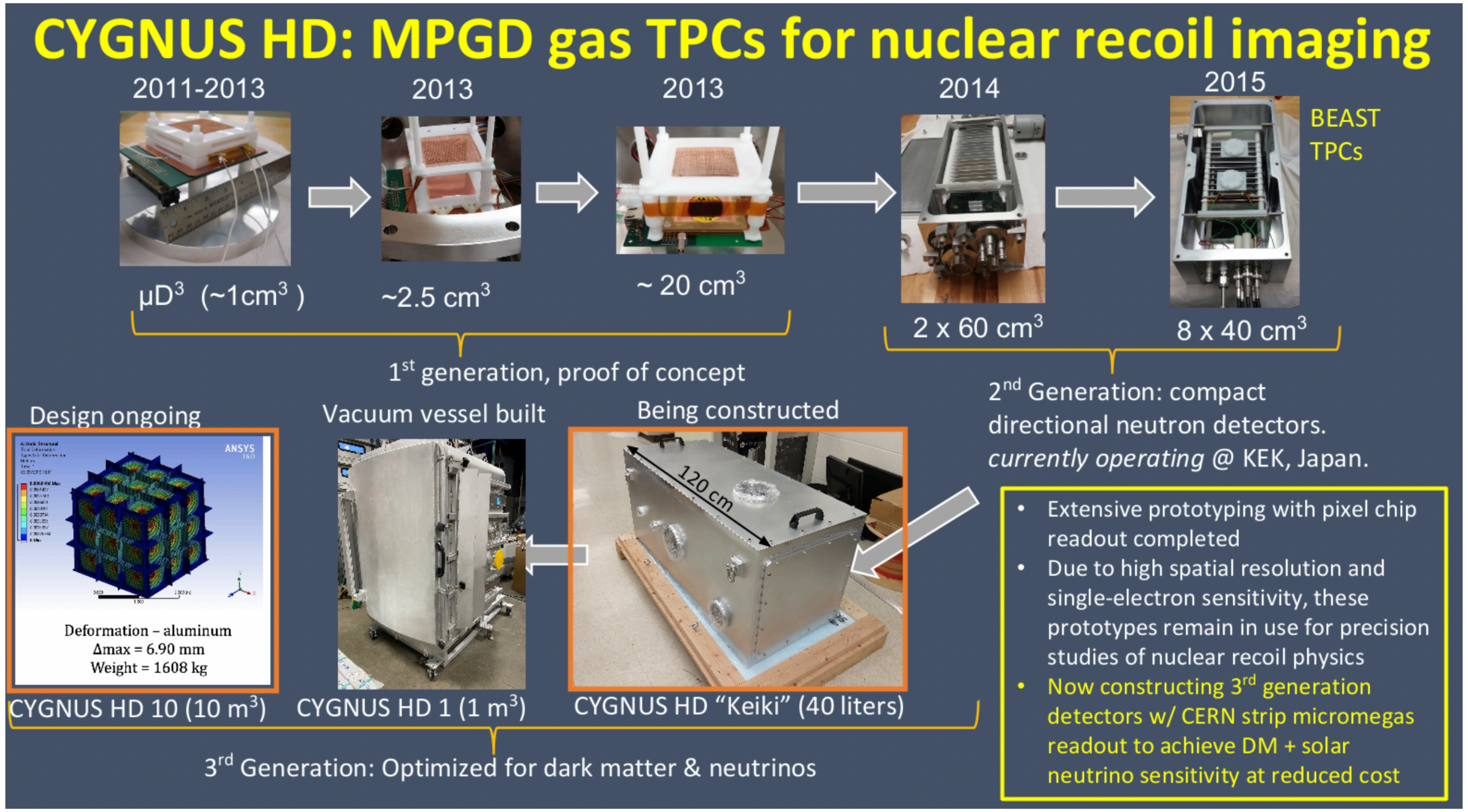
→ Background reduction for several materials such as kapton, acrylic, camera lenses

Experimental activity: Charge readout



3D Pixel readout: event-level Head-Tail recognition on He recoils enabled through CNN (Schueler, Vahsen)

U. Hawaii: 40l detector "Keiki" being built based on optimised readout choice of strip micromegas (Ghrear, Vahsen+ 2024). Dedicated machine learning-powered approaches for direction-finding and head-tail recognition for low-energy nuclear and electron recoil tracks being developed.

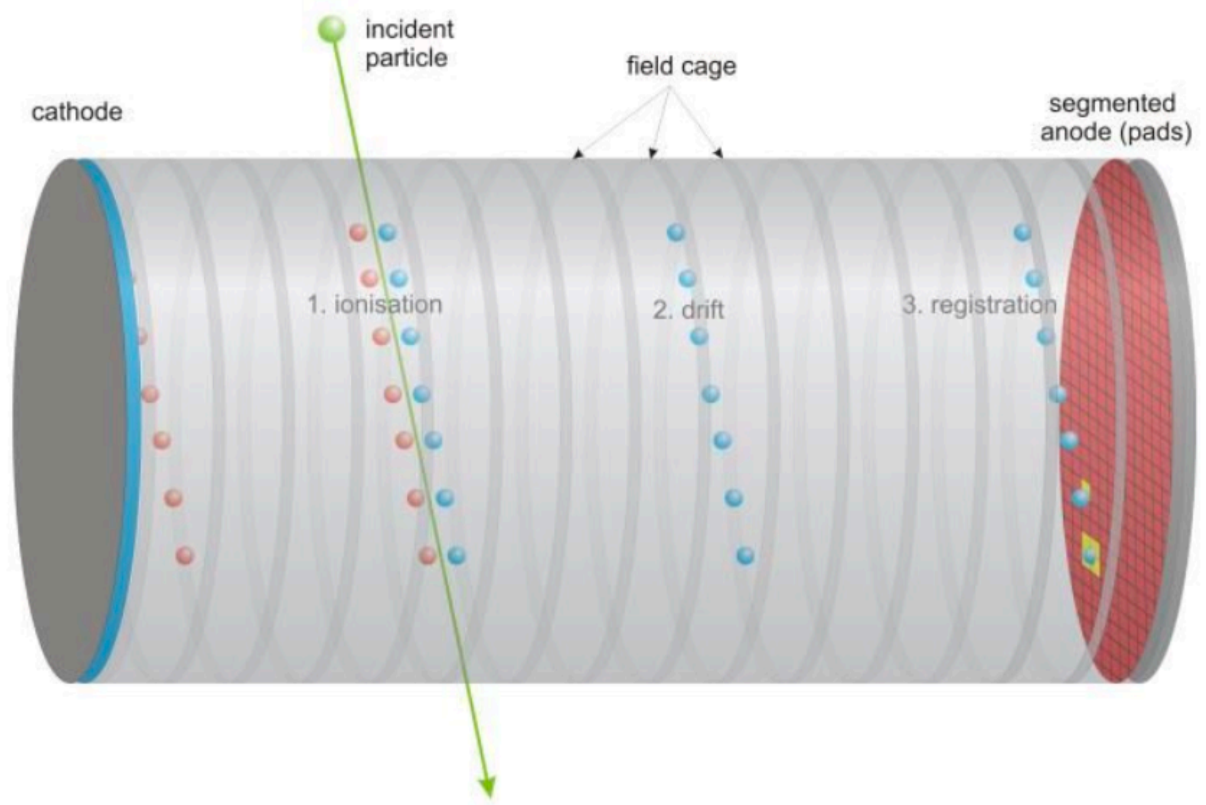


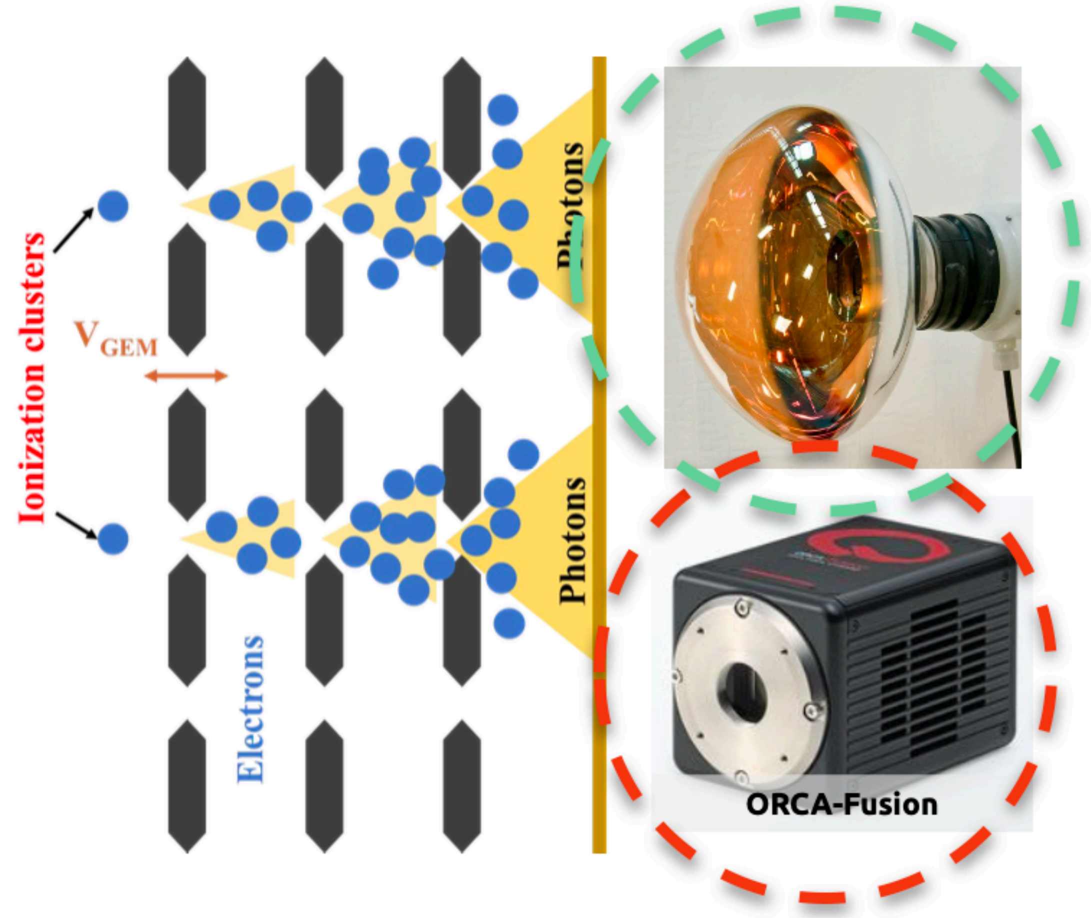
Experimental activity: Optical readout

CYGNO - What's the setup?

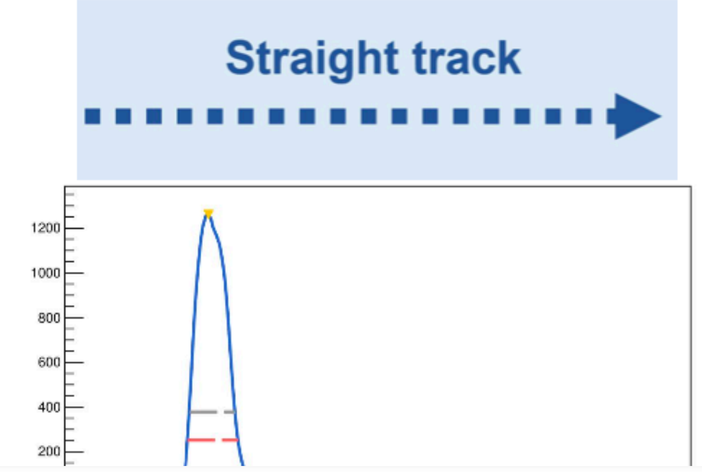
(He+CF4)

TPC → **Triple GEM** Charge multiplication → **Camera + PMT** **Light** from **gas scintillation** during electron avalanche



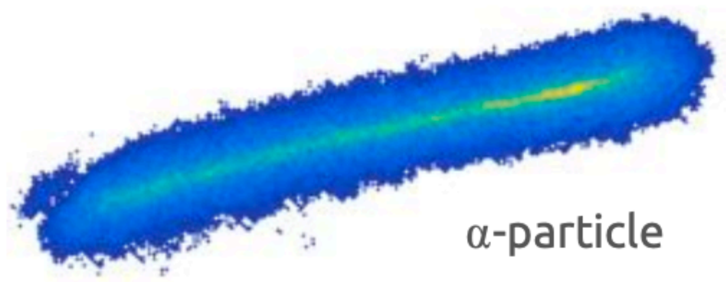


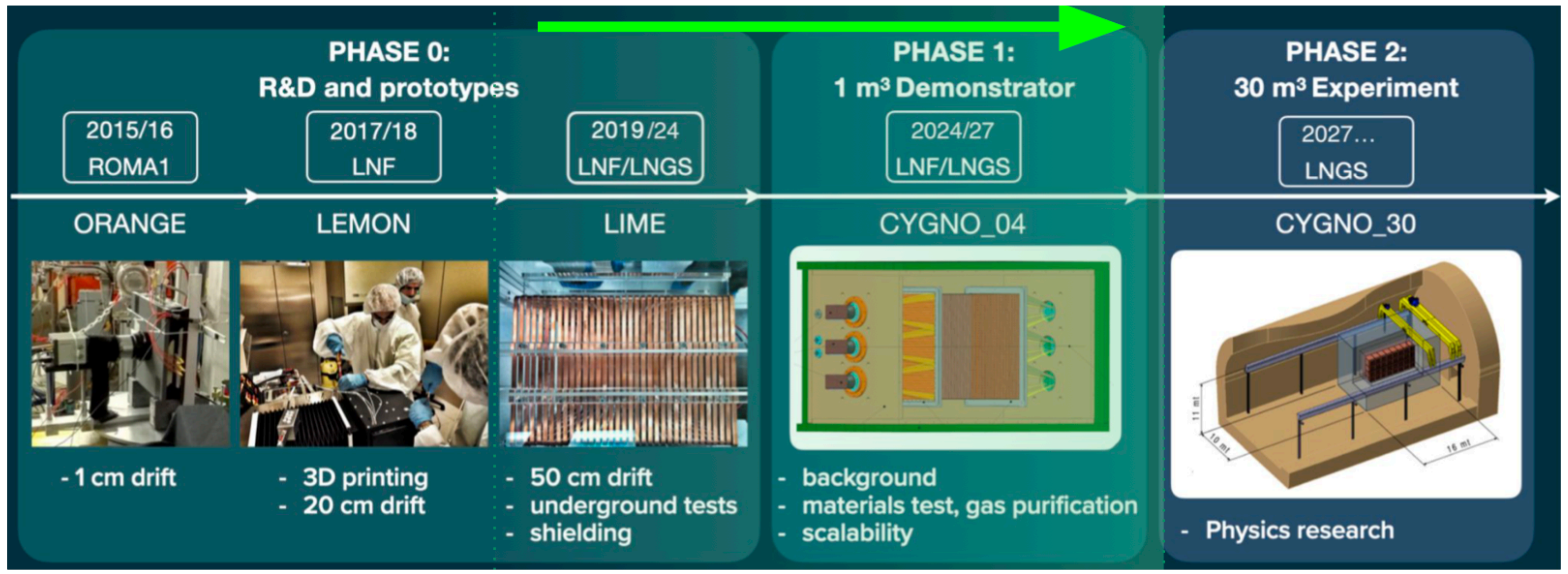
1. Independent **energy** measurement.
2. Electrons **times of arrival** ⇒ **dZ coordinate** (track's tilt)



- Talk by David Marques
- Poster by Giorgio Dho

With the high granularity of the camera, we measure **energy** + **X & Y coordinates**

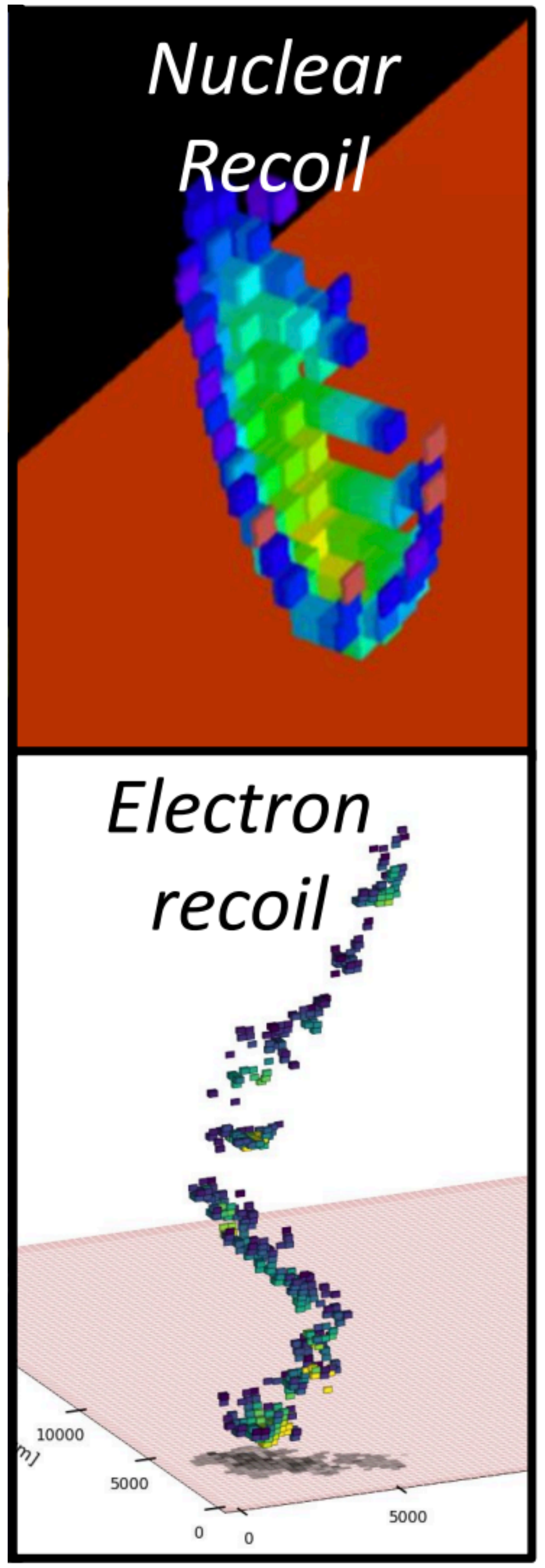


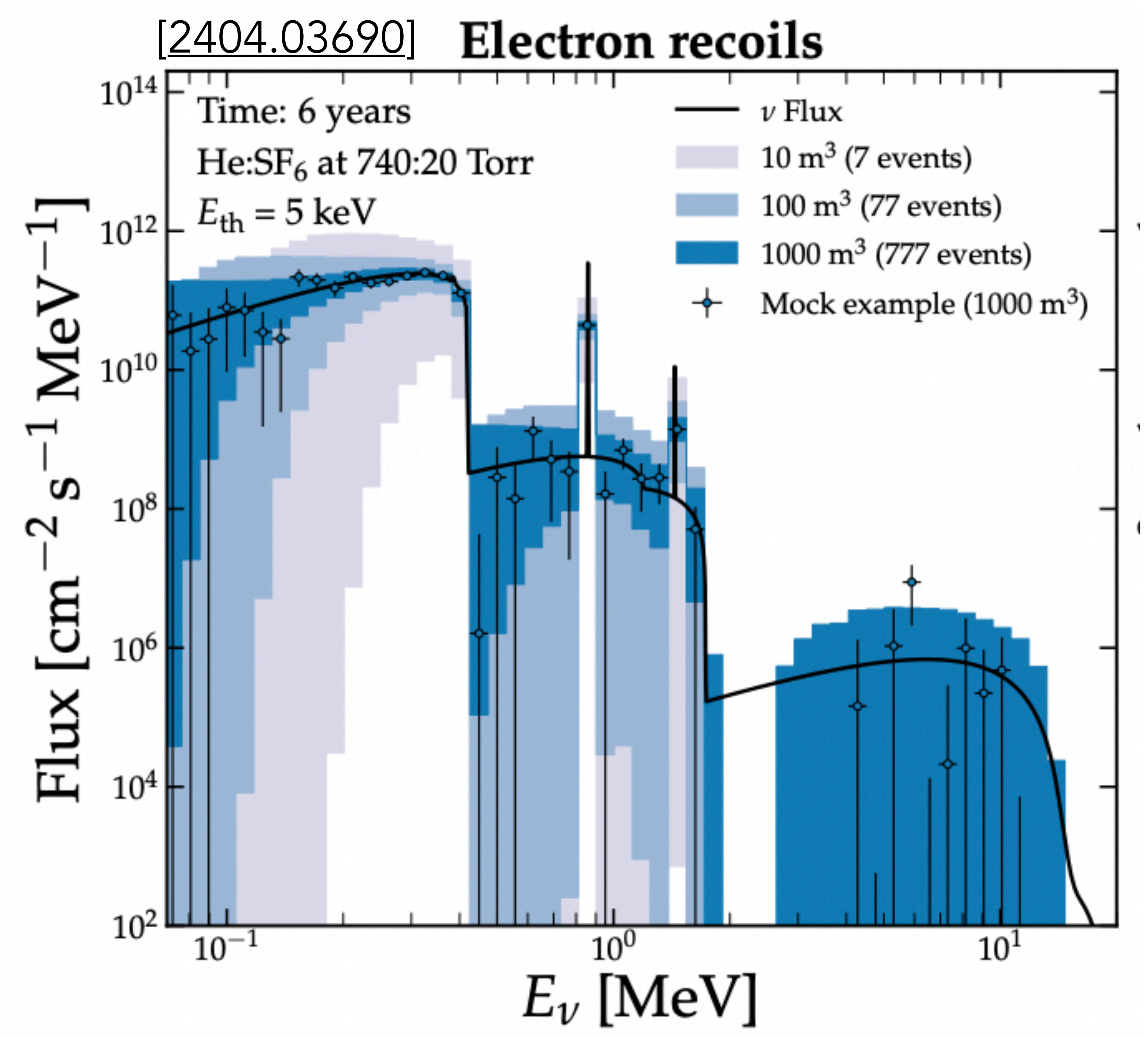


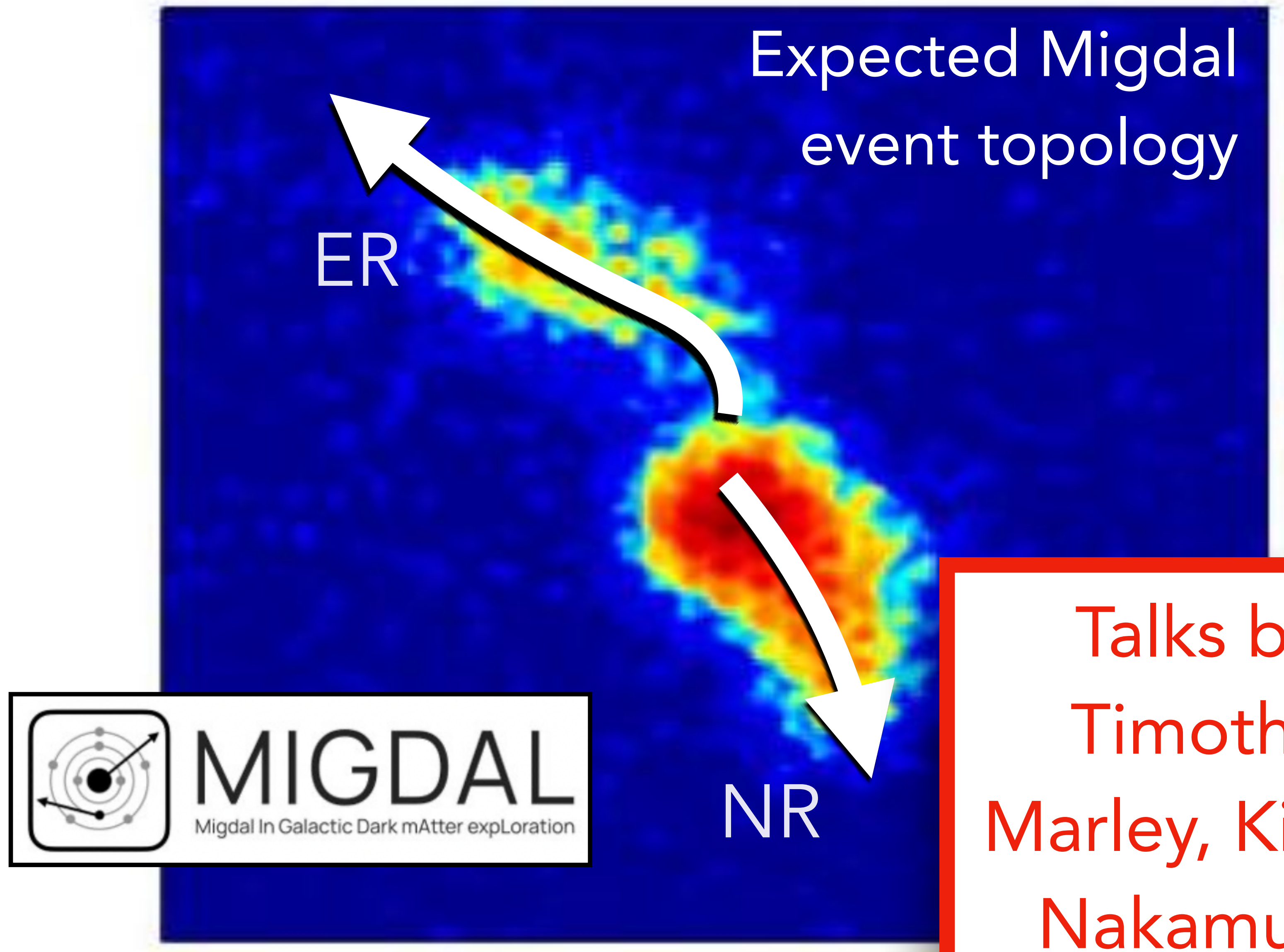
Beyond dark matter

Similar technology can be used for…

- Measurement of the Migdal effect (ER and NR tracks connected by common vertex)
- Solar neutrino spectroscopy enabled through electron/nuclear recoil directions (Lisotti, O'Hare+ [2404.03690])
- Directional measurement of CEvNS cross-section (e.g. at neutrino source, preliminary investigations ongoing)



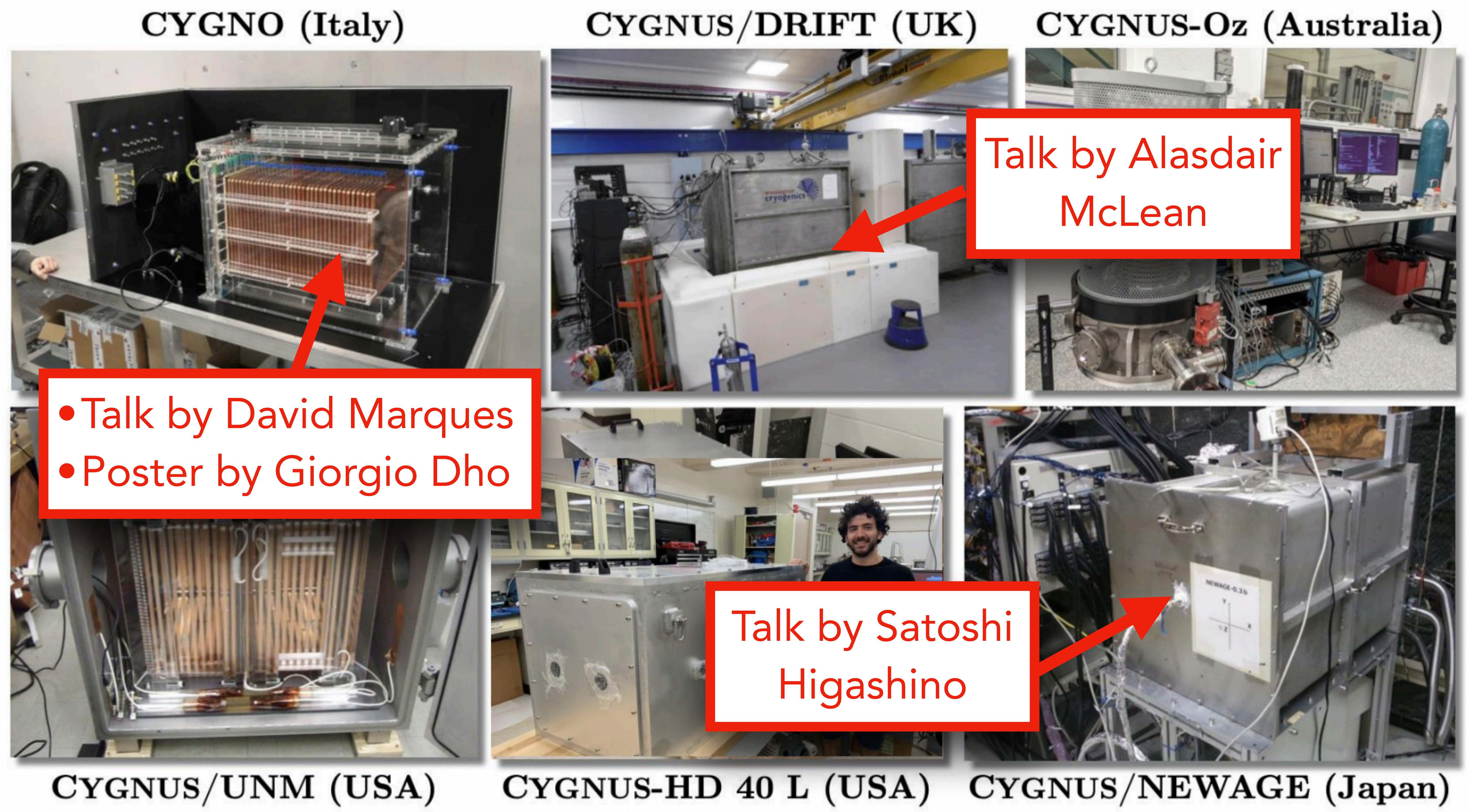




Talks by Timothy Marley, Kiseki Nakamura

CYGNUS Consortium

Workshop in Sydney December 2023, decision was made to unite groups working on gas-detector development for DM + neutrinos + BSM physics under the "**CYGNUS Consortium**". Slides from the meeting available here: https://indico.cern.ch/event/1258644/



Takeaways

- The anisotropy of the DM flux is the only generic signature of DM that is present for essentially all models and is robust against our limited knowledge of the Milky Way halo.
- Directionality remains one of the only realistic ways a discovery claim on a dark matter signal can be made. Very few proposals exploit this fact.
- For wave-like DM, directional detection can be achieved through phase correlation of spatially separated detectors or by measuring the field gradient.
- For particle-like DM, directionality is best measured by spatially resolving ionisation distributions from their recoils through a medium.
- To be useful for DM they need to be 3D, time-resolved, and measure energy+direction independently at the event level.
- Gas TPCs with highly-segmented MPGDs can achieve this. R&D currently being pursued by several groups within the international *CYGNUS consortium*

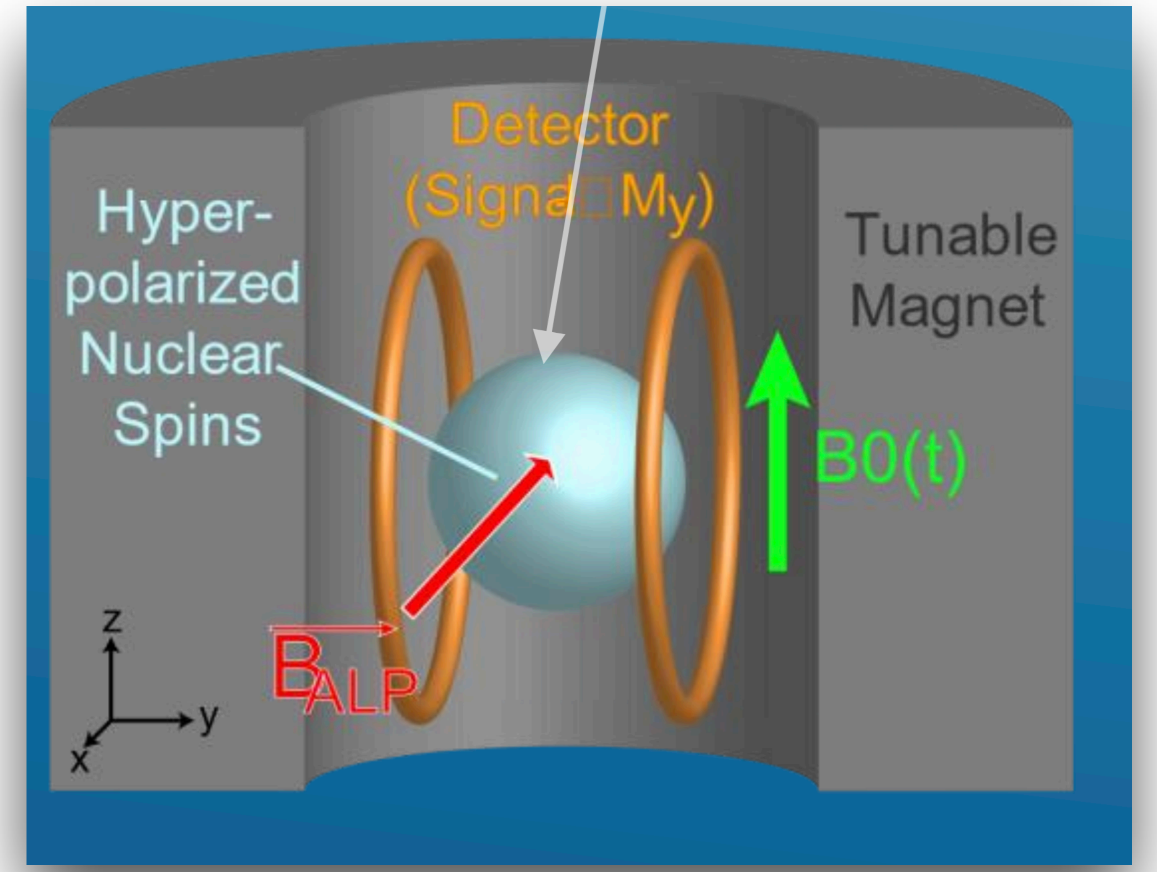
Directional detection of wave-like dark matter

Directionality stored in spatial oscillations, how to extract it?

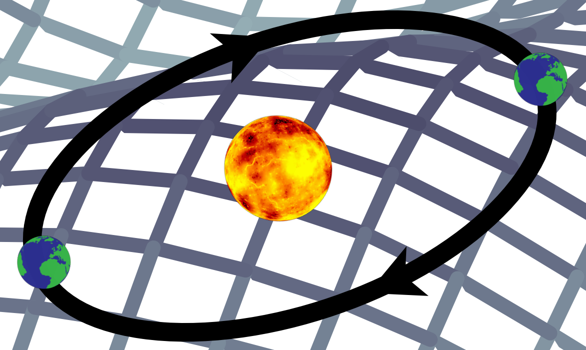
$$a(\mathbf{x},t) \approx \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos\left(m_a t - m_a \mathbf{v}\cdot\mathbf{x} + \phi\right)$$

1. Measure field at two spatial points where $|\mathbf{x}_1 - \mathbf{x}_2| \gtrsim 1/m_a v$
2. Measure gradient of the field $\nabla a \sim \mathbf{v}\sin(m_a t - m_a \mathbf{v}\cdot\mathbf{x} + \phi)$

2. e.g.

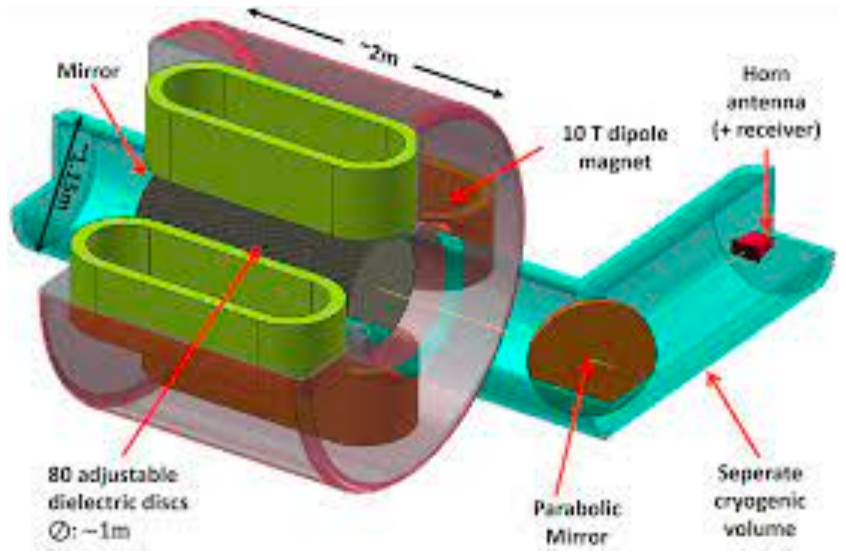


e.g. CASPEr-Gradient

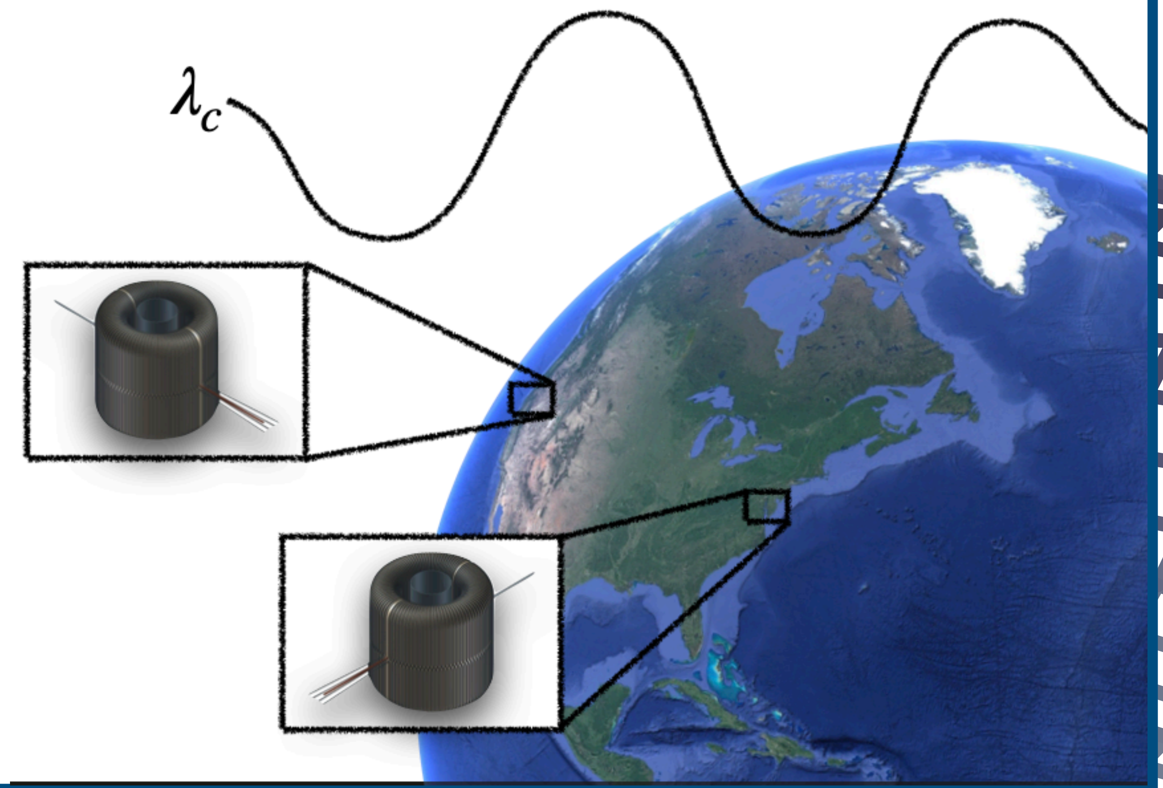


1.

MADMAX (final stage), mildly directionally sensitive, see e.g. [1806.05927]



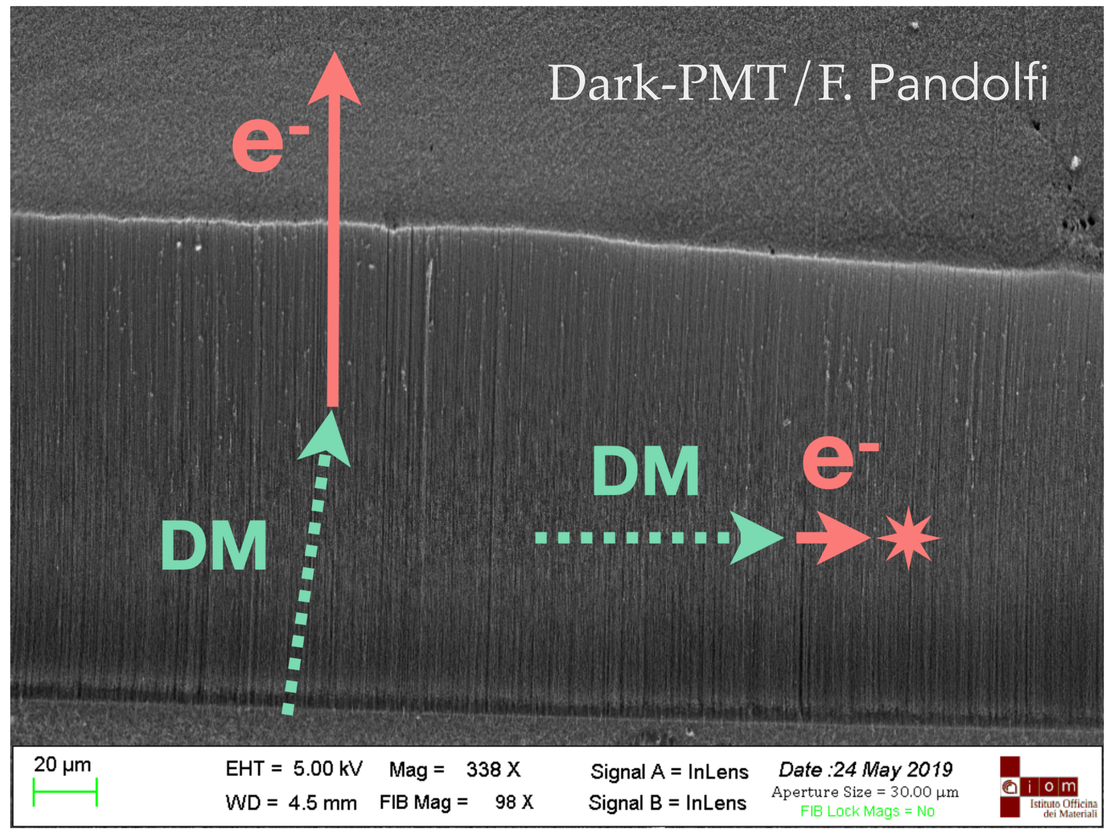
Correlate measurements in two spatially separated experiments, e.g. [2009.14201]



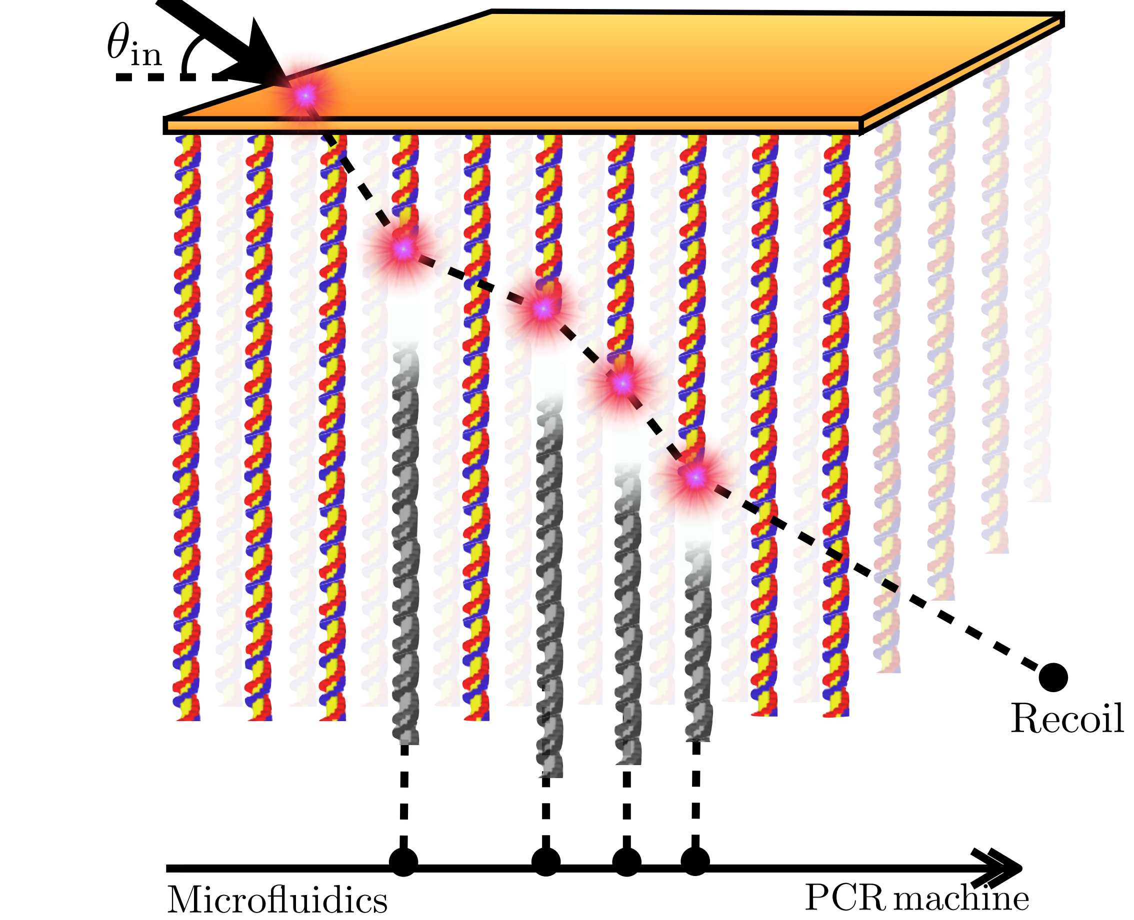
Other materials are available…

- Anisotropic scintillators, e.g. ZnWO4 [2002.09482]
- Polar materials, e.g. GaAs [1807.10291]
- Graphene [1606.08849]
- Carbon nanotubes [1706.02487]
- Superfluid helium [2012.01432, 2306.09726]
- Biological nanostructures [1206.6809, 2105.11949]

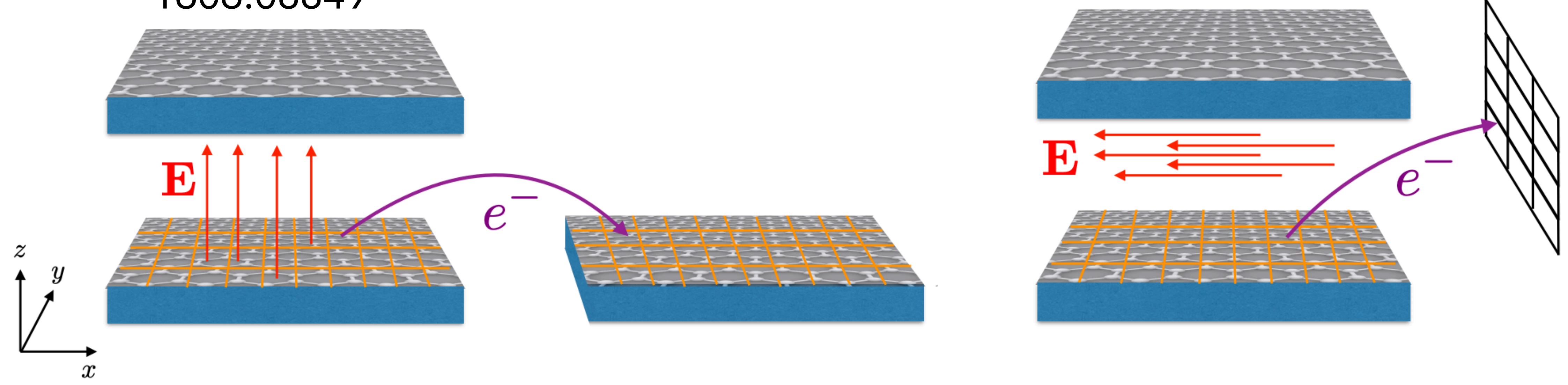
Some of these are particularly interesting for models where DM generates extremely low-energy/single electron events

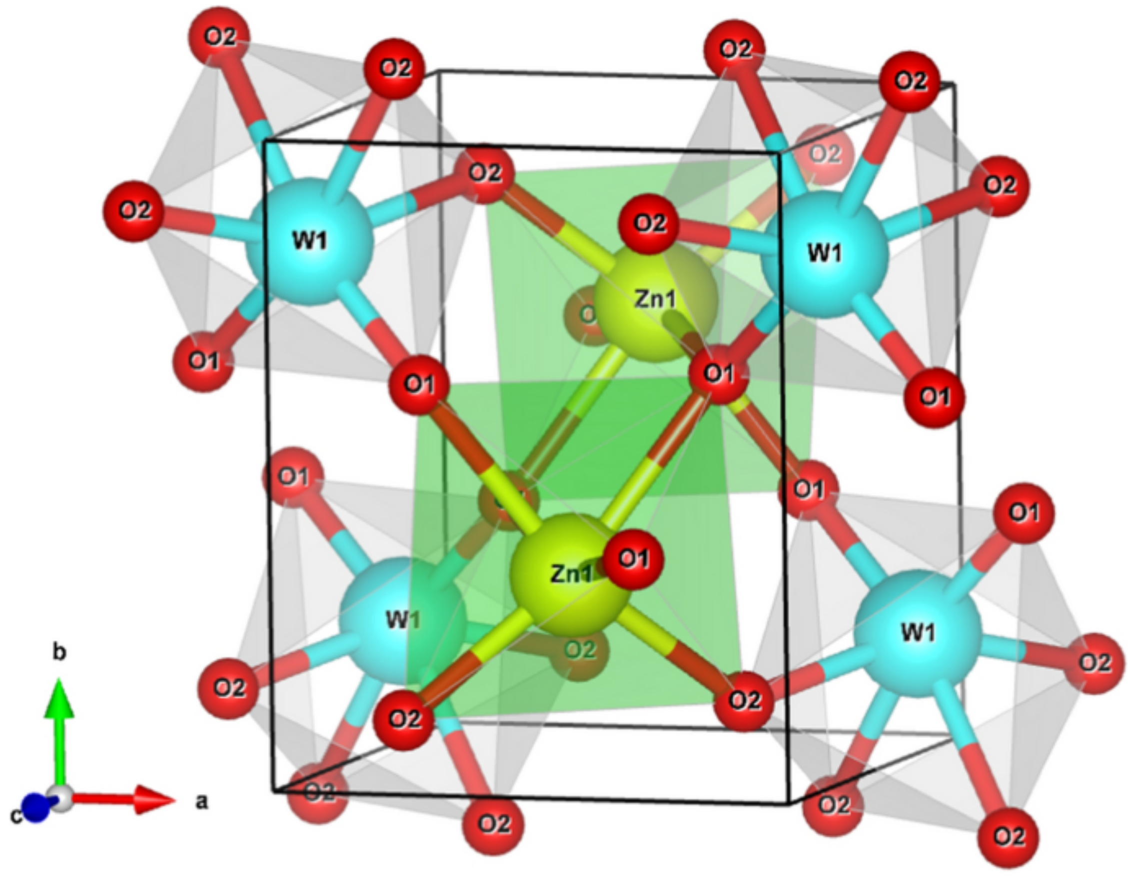


2105.11949

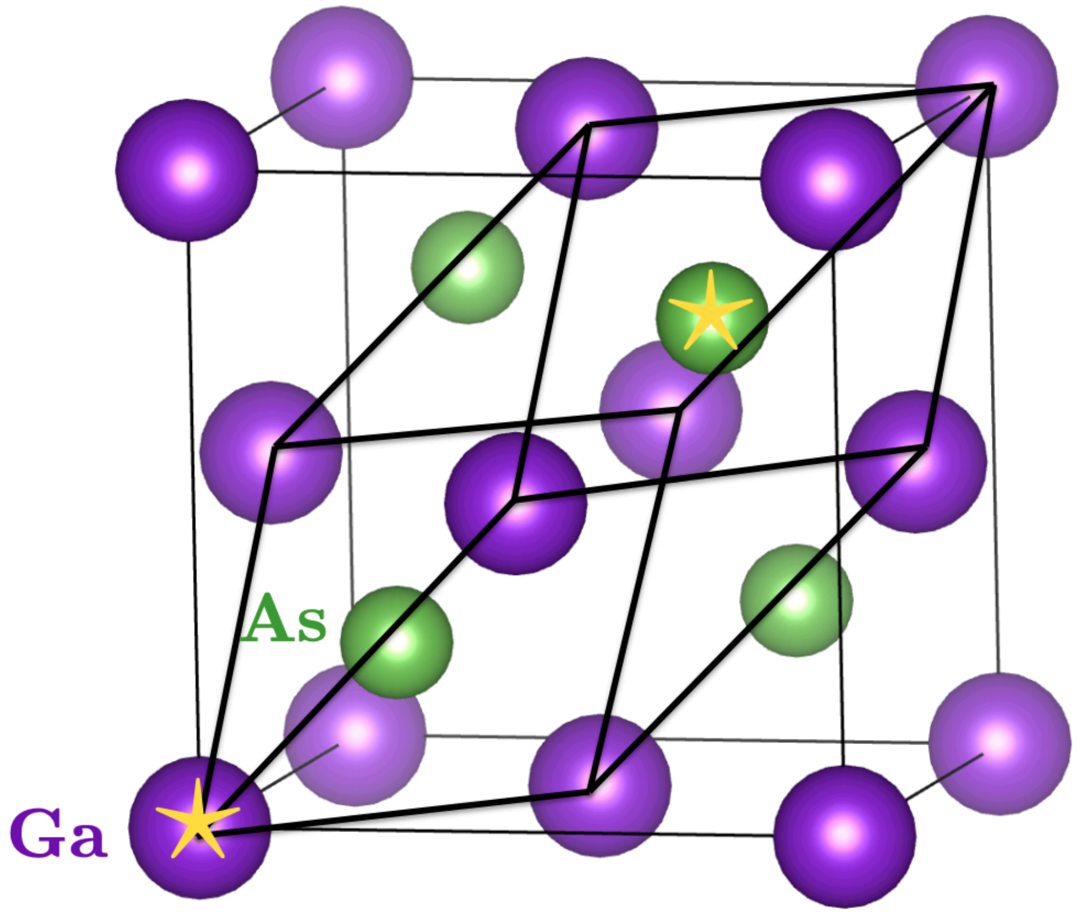


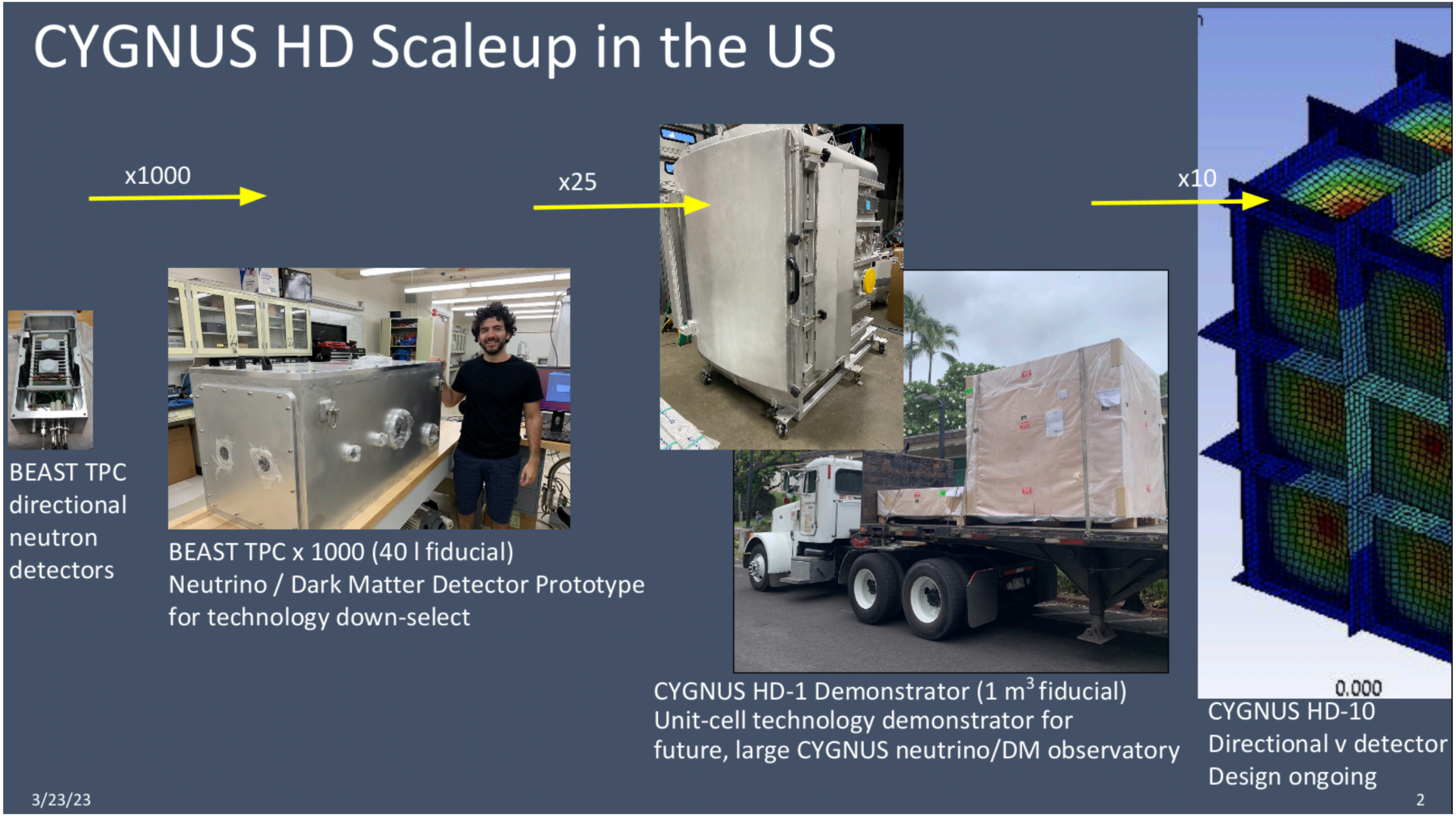
1606.08849





1807.10291





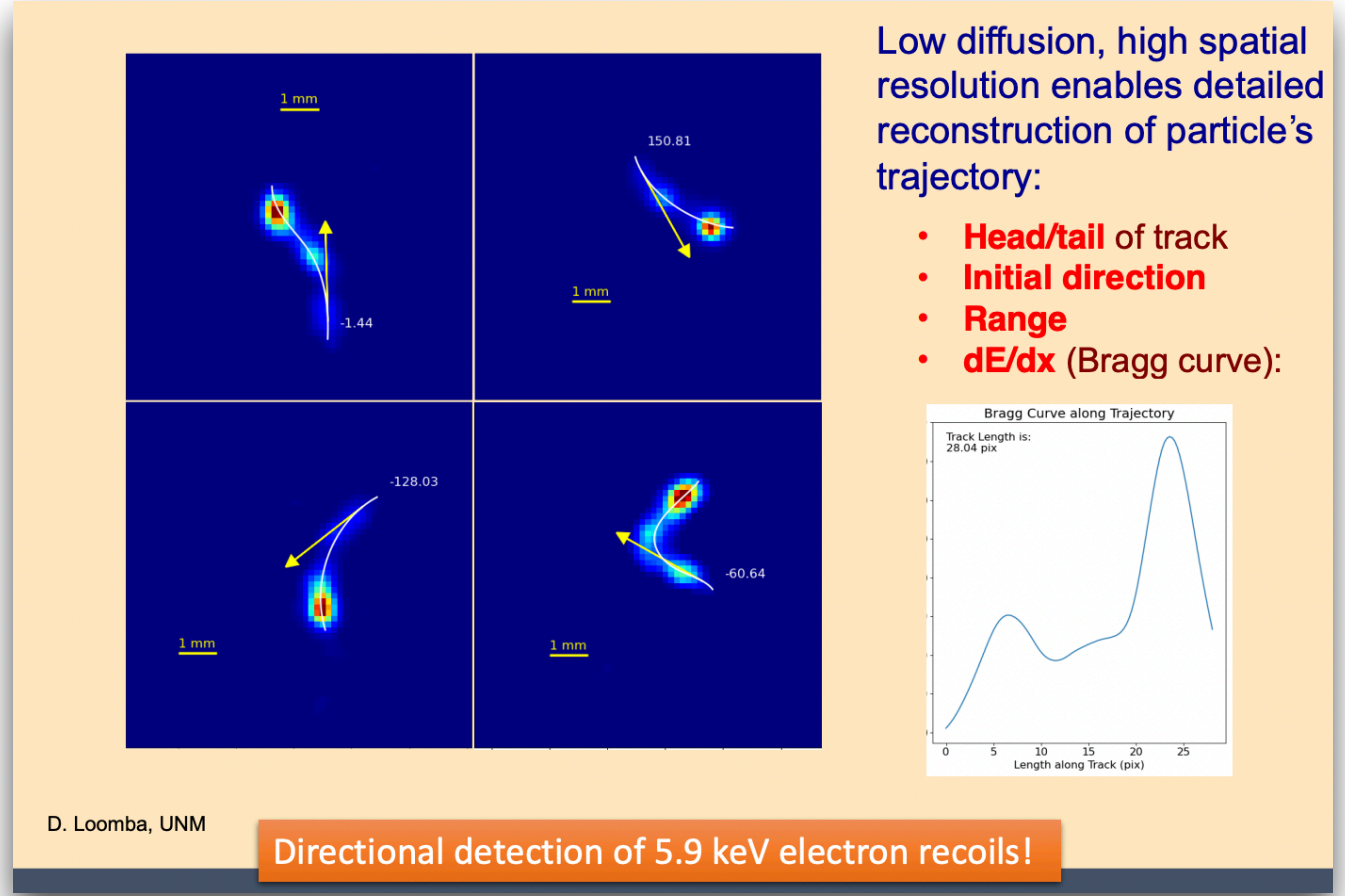
Slide: Sven Vahsen

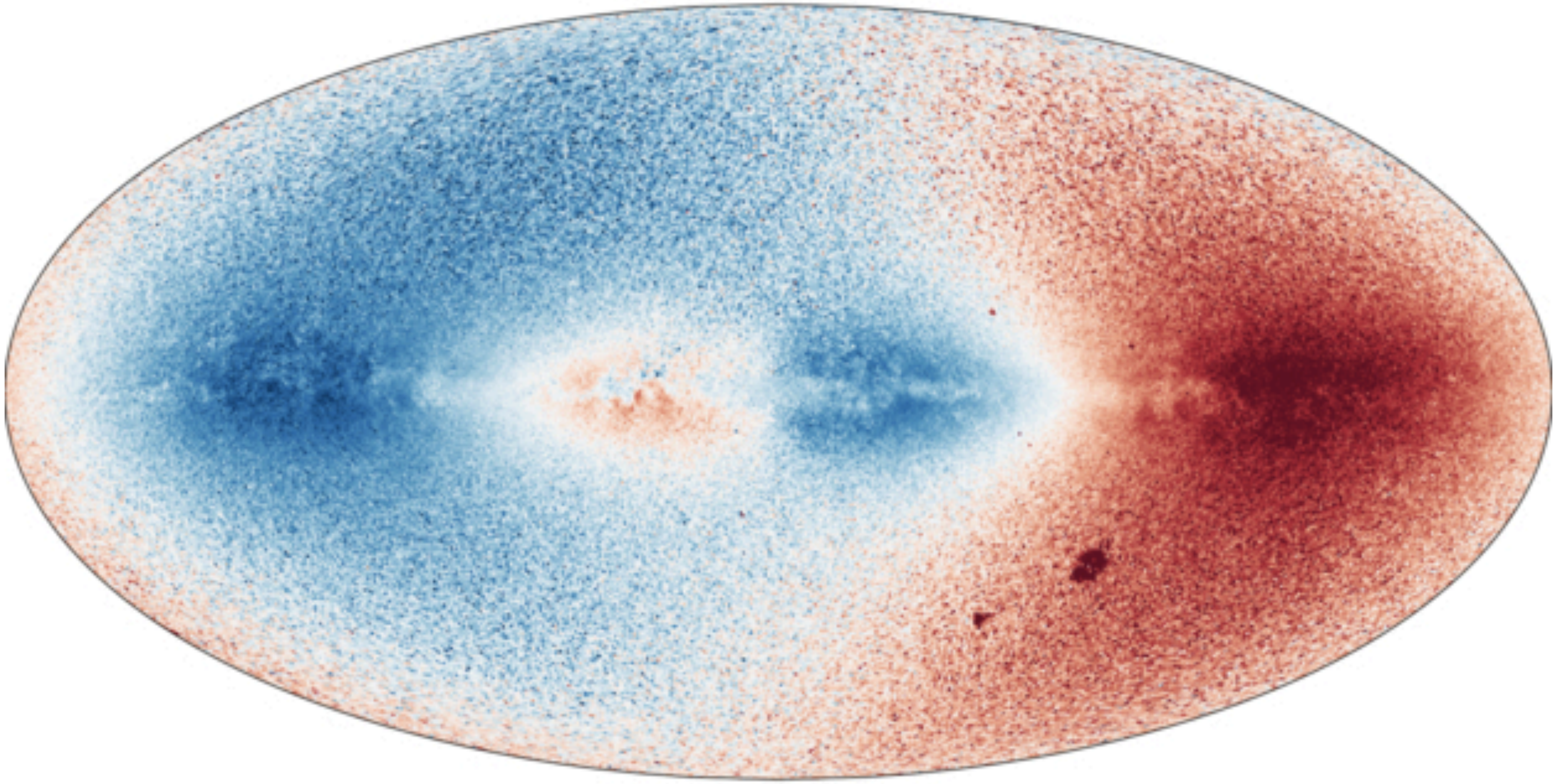
Negative ion drift

D. Loomba (UNM)

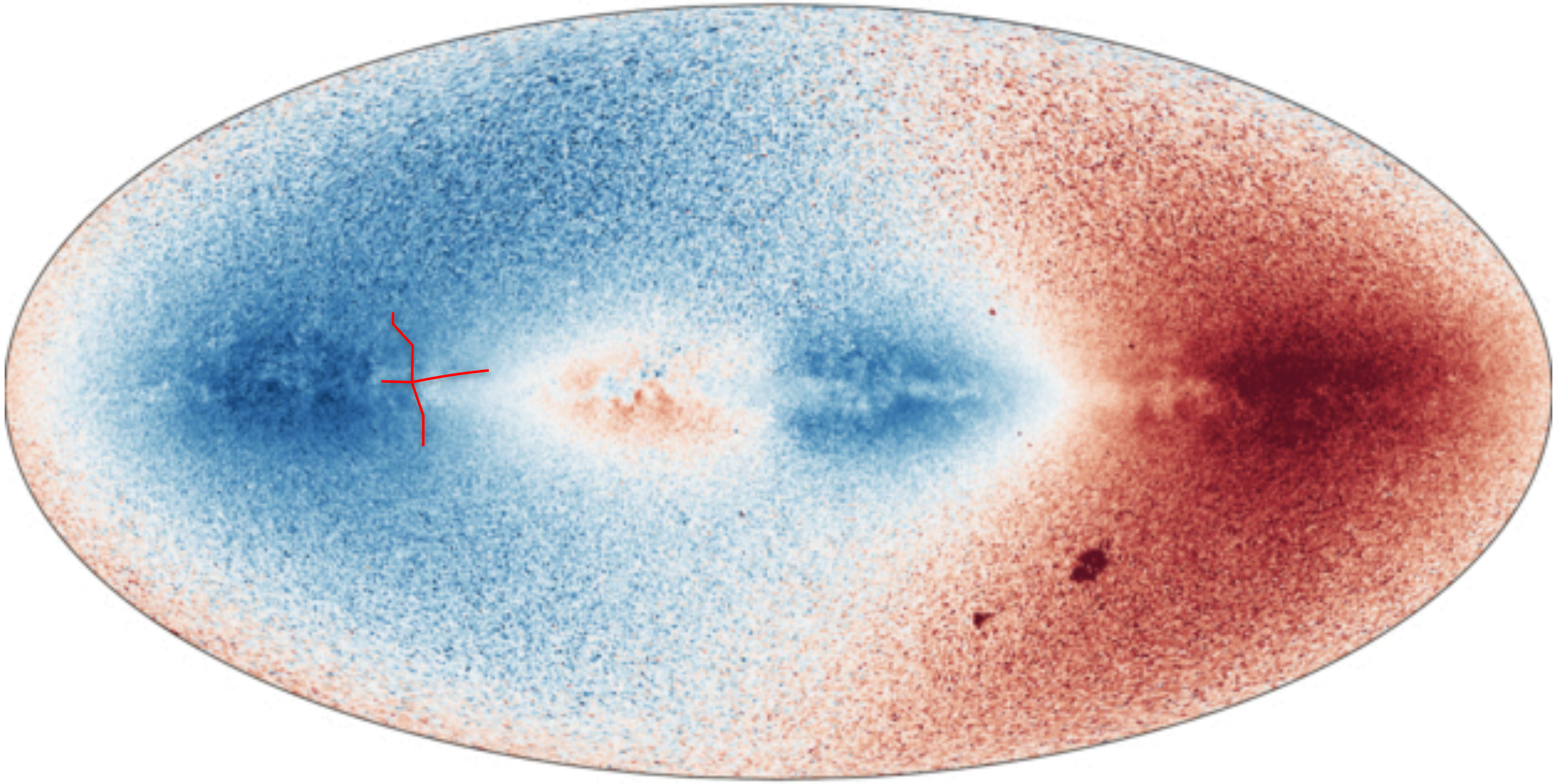
SF6 gas mixture for negative-ion drift comes with lower diffusion and enables high resolution reconstruction of tracks.

SF6 has minority carriers with different drift speeds enabling fiducialisation along the drift direction via their arrival times.





Gaia skymap of line of sight velocities of stars
Blue = moving towards us (relatively)
Red = moving away from us



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