Dark matter hurricanes, cyclones and downbursts

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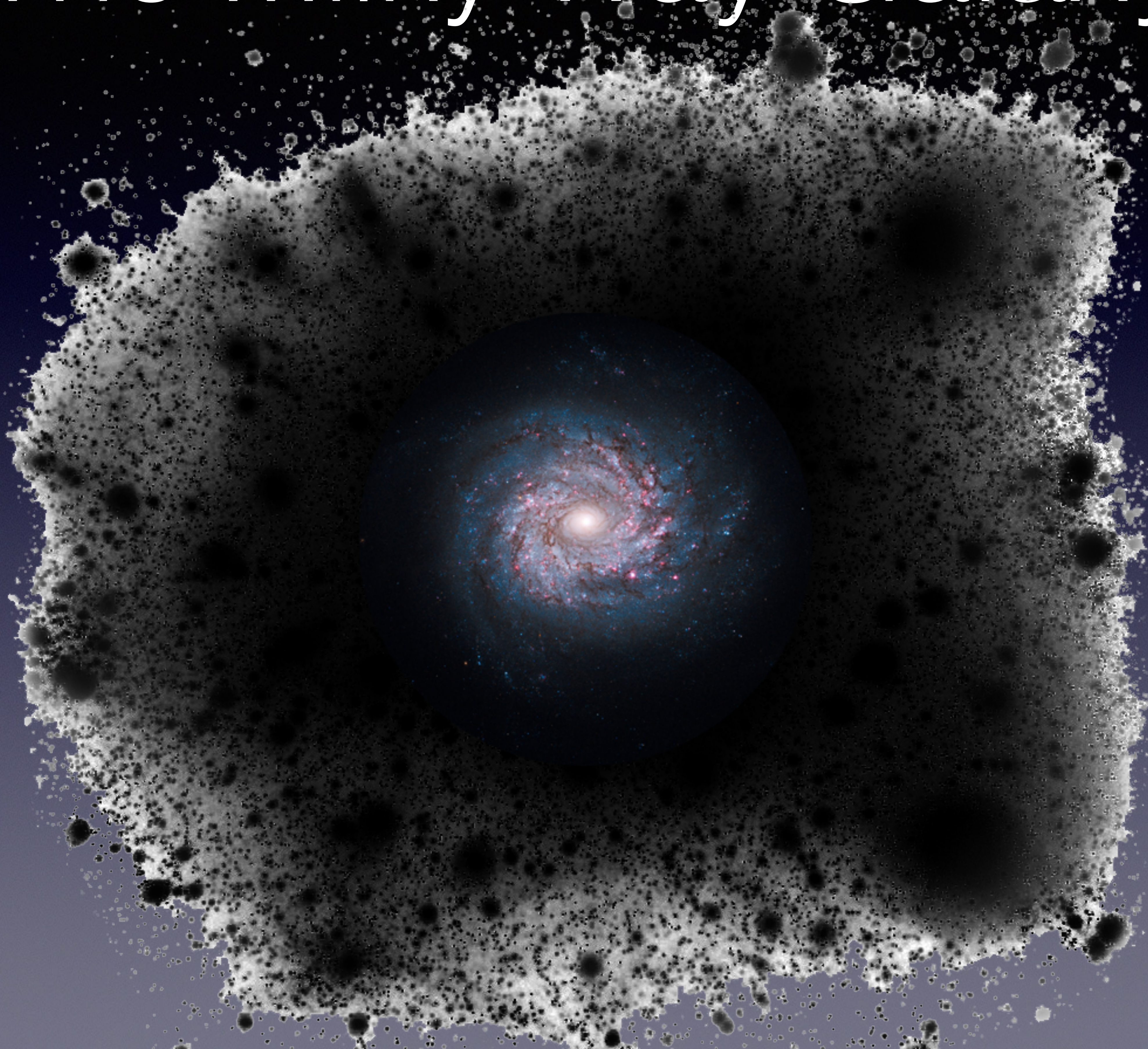
The Milky Way Galaxy



The Milky Way Galaxy

The stellar mass of the Milky Way Galaxy is ~ 5-6 x 10^{10} $M_\odot$, almost all in the Galactic disk & bulge/bar.

The total mass of the Galaxy is ~ 1-2 x 10^{12} $M_\odot$, mainly dark matter in the dark halo

The stellar halo contains just 1% of the stellar mass.This tenuous component has a very long relaxation time.

The Gaia Satellite

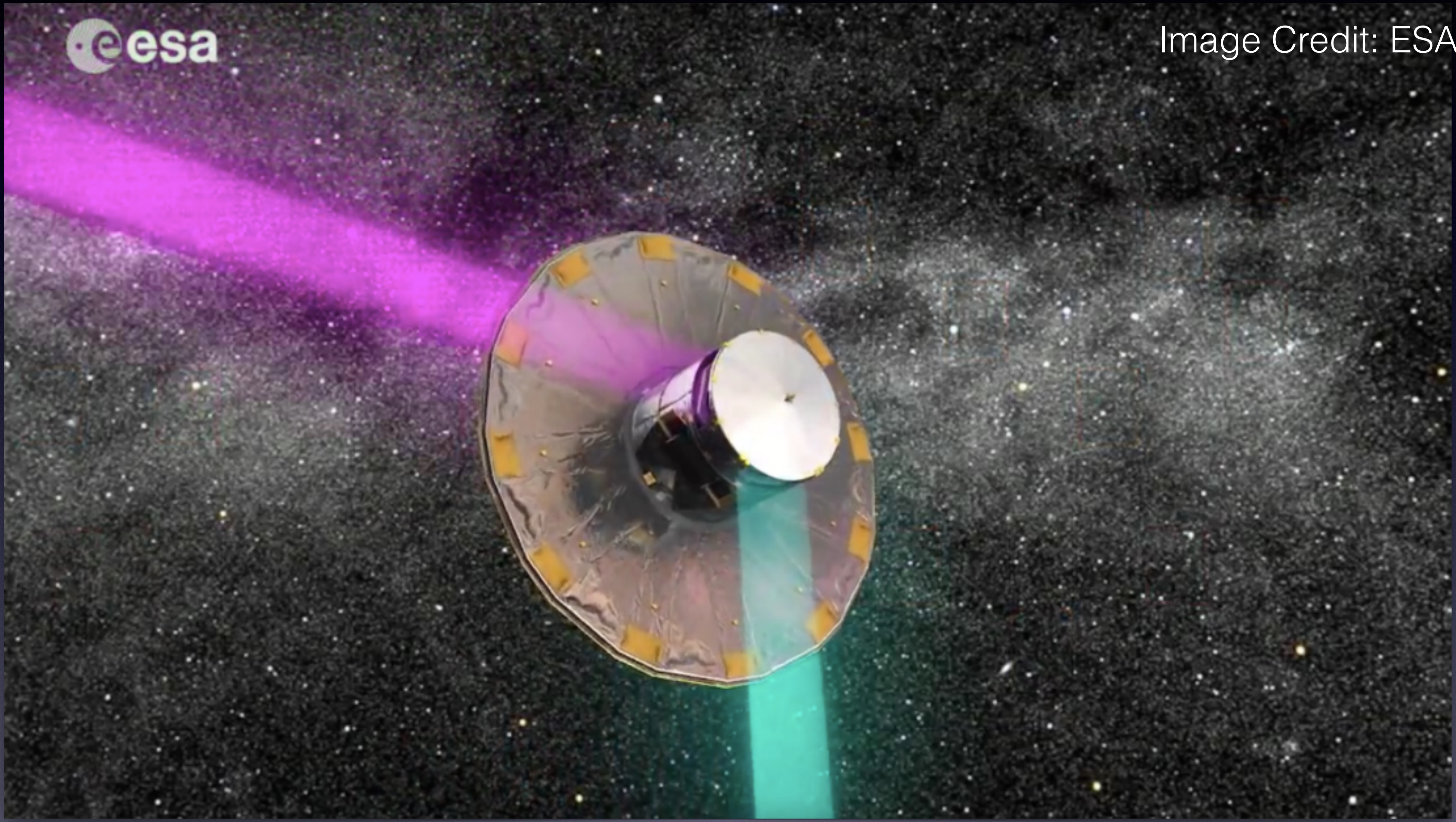


Image Credit: ESA

Satellite spins at 60 arcsec s^{-1}. The two astrometric fields of view are separated by 106.5^{o} & scan all objects on great circle perpendicular to spin axis in 6 hrs.

Local Stars in 7-D

1. Position on the sky
2. Position on the sky
3. Color+magnitude
4. Proper motion RA
5. Proper motion Dec
6. Line-of-sight velocity
7. Metallicity

1. Galactic X
2. Galactic Y
3. Galactic Z
4. Galactic Vx
5. Galactic Vy
6. Galactic Vz
7. Metallicity

We built a sample of ~250,000 Main Sequence stars in 10x10x10 kpc box entered on the Sun

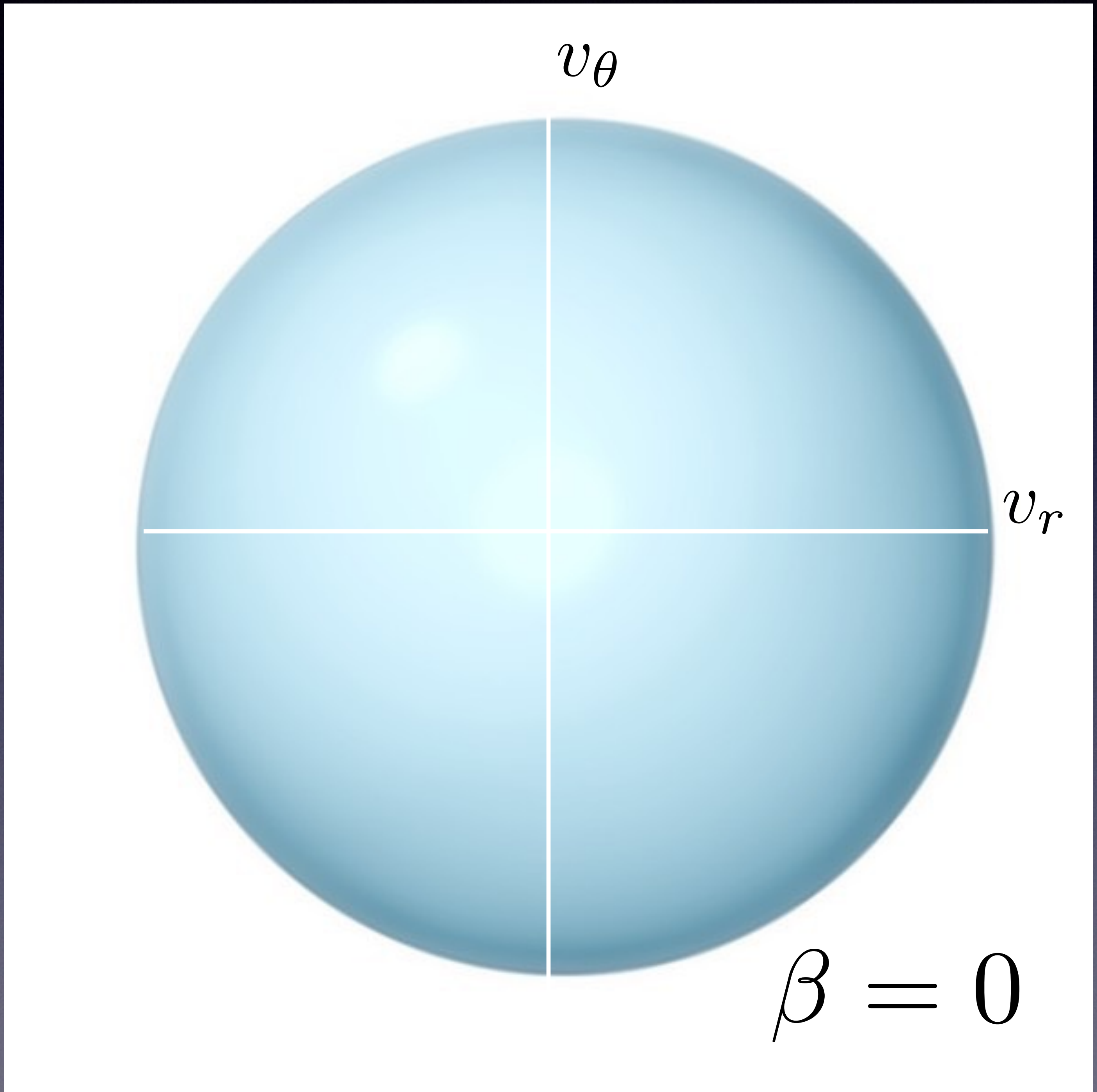
The Gaia Sausage

Introduce a velocity anisotropy parameter β

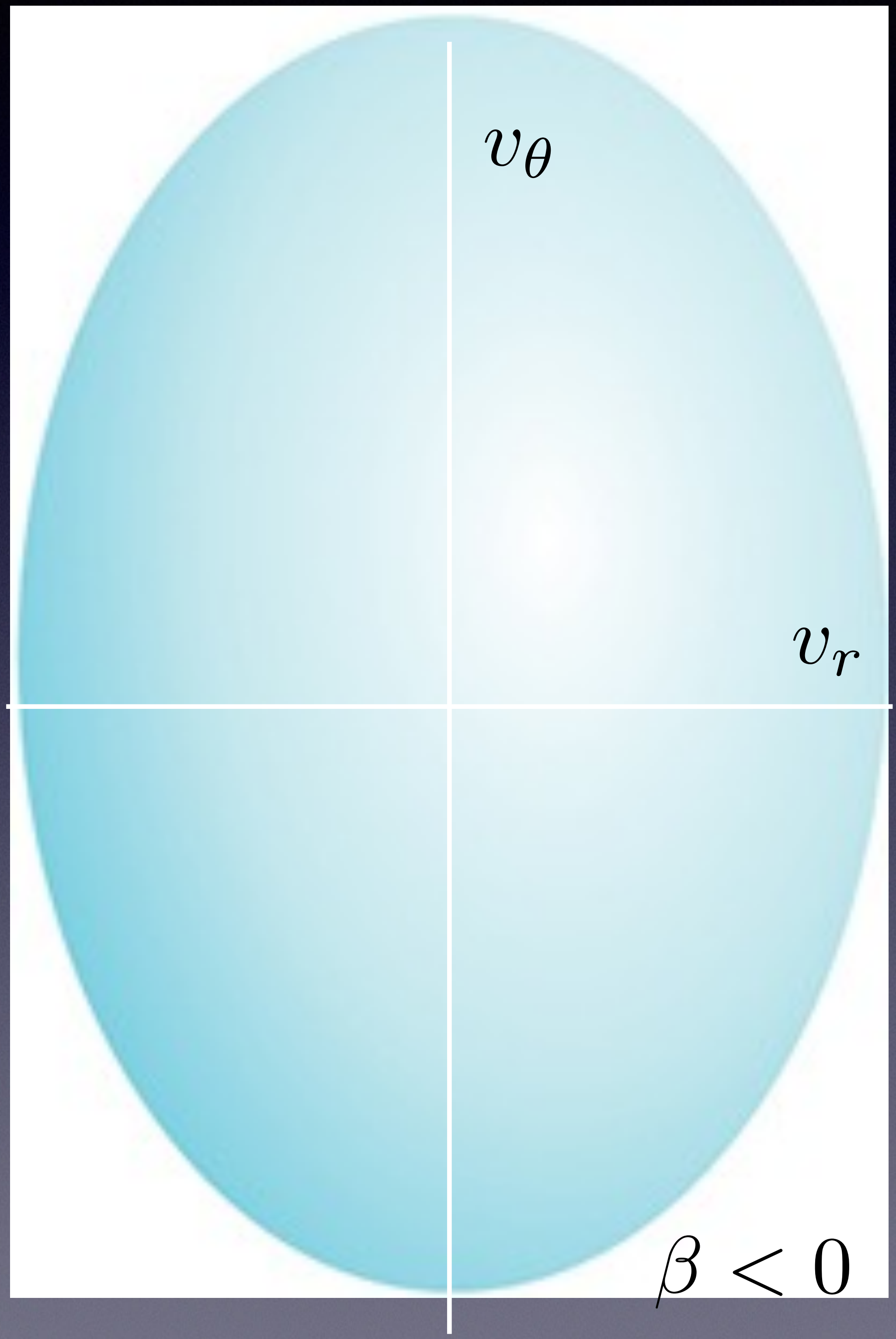
$$\beta = 1 - \frac{\langle v_T^2 \rangle}{2\langle v_r^2 \rangle}.$$

β =0, isotropic orbits; β =1, orbits are purely radial; β = -∞ orbits are all circular

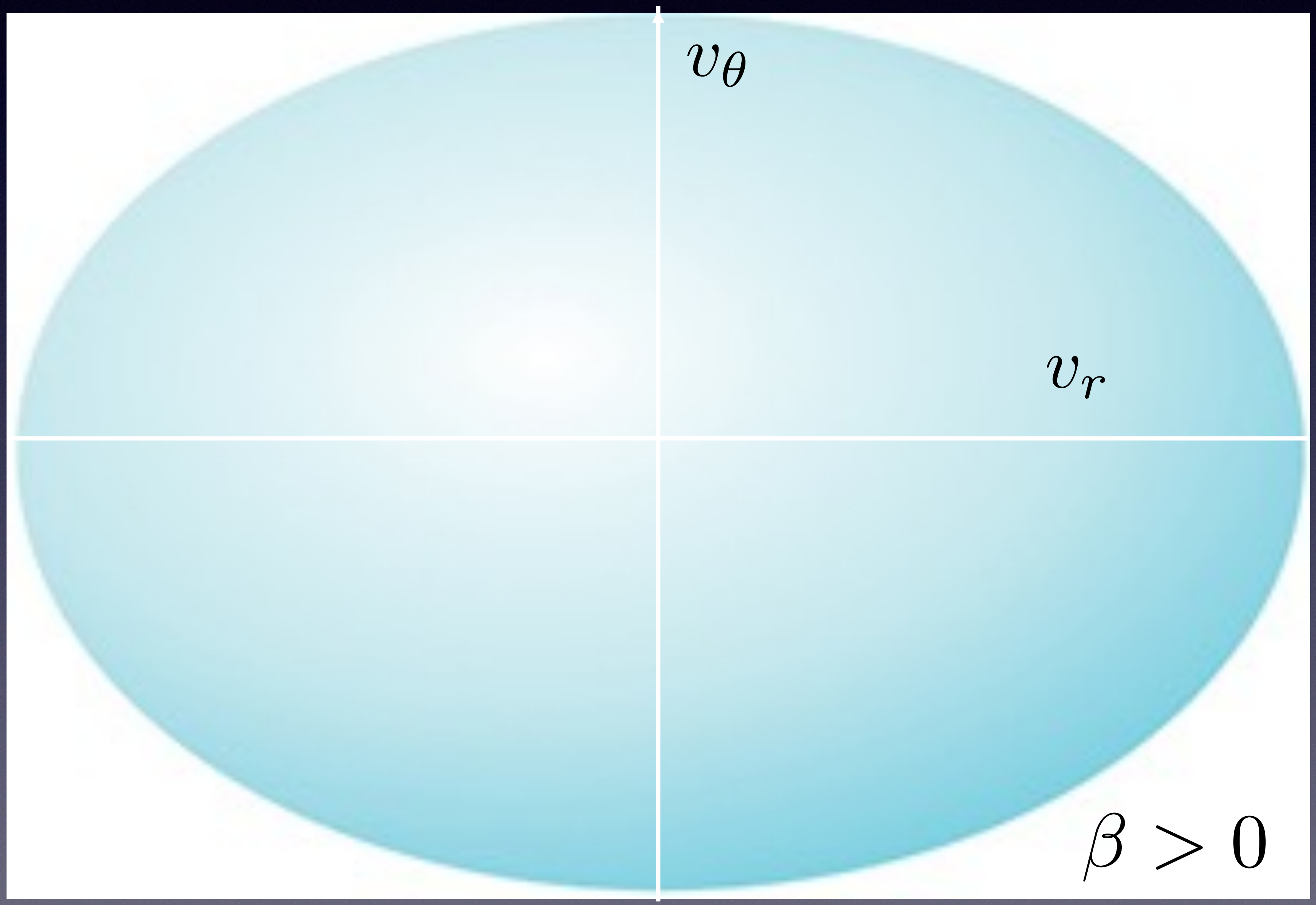
Meatball



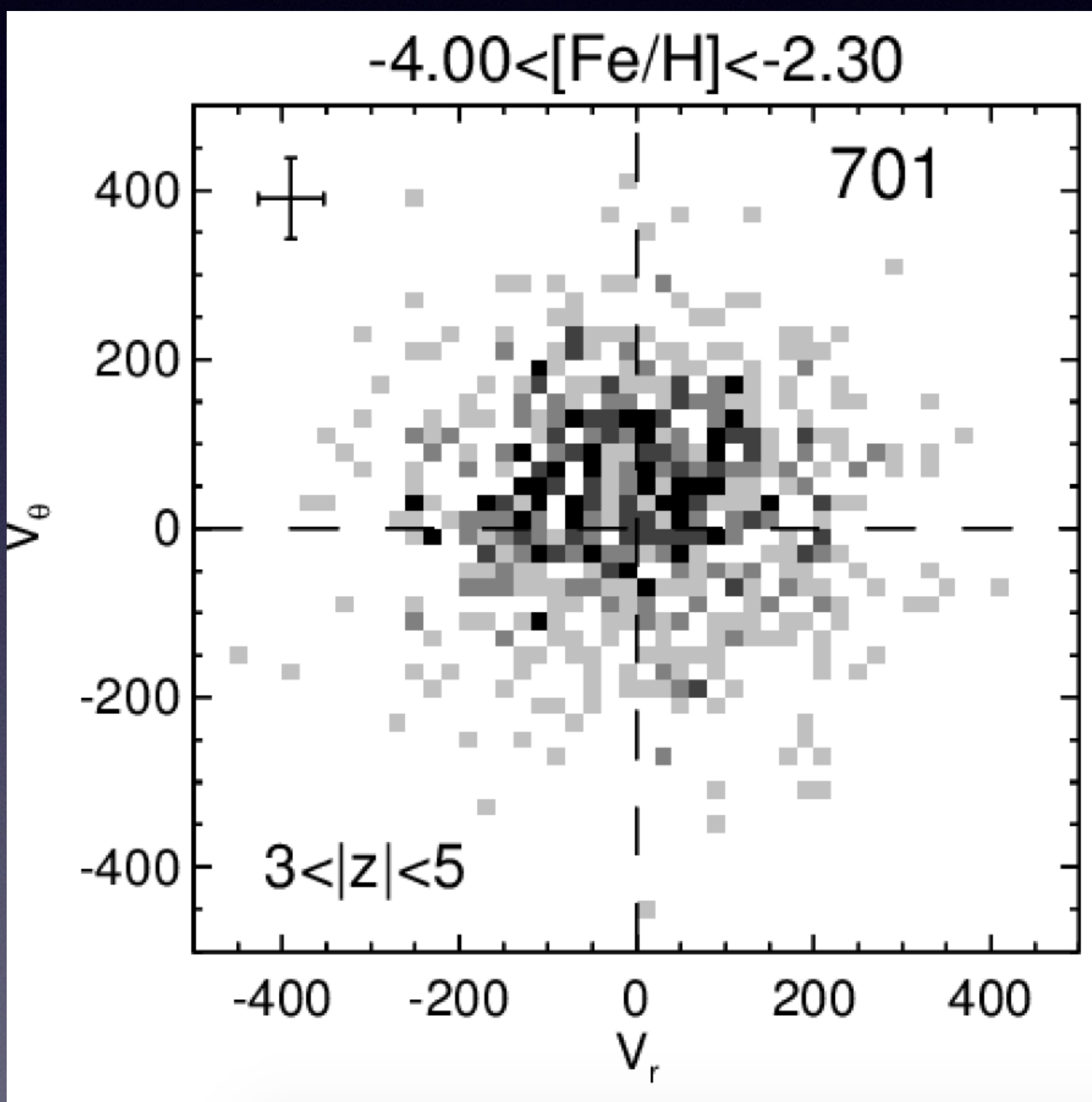
Burger

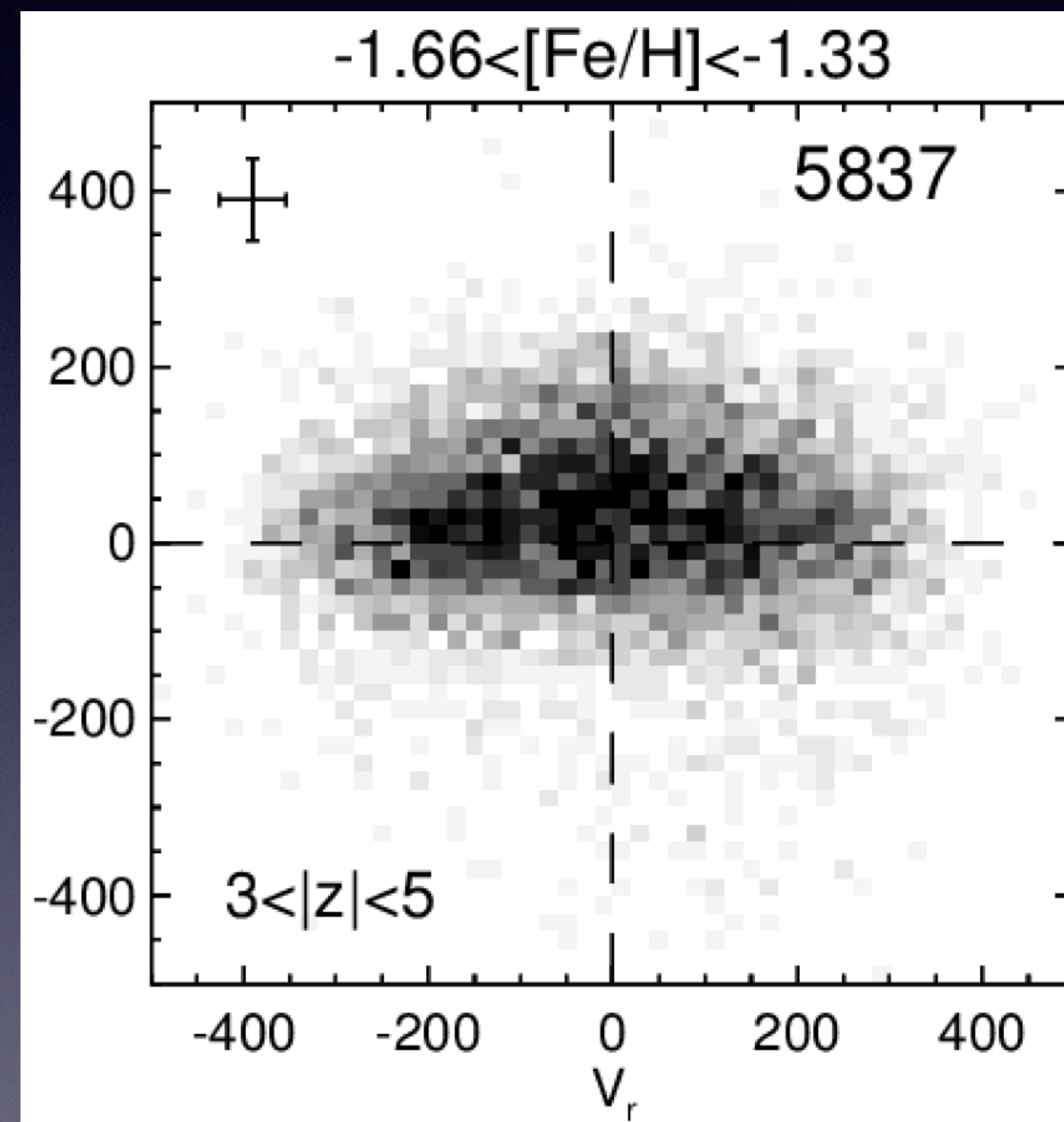


Sausage

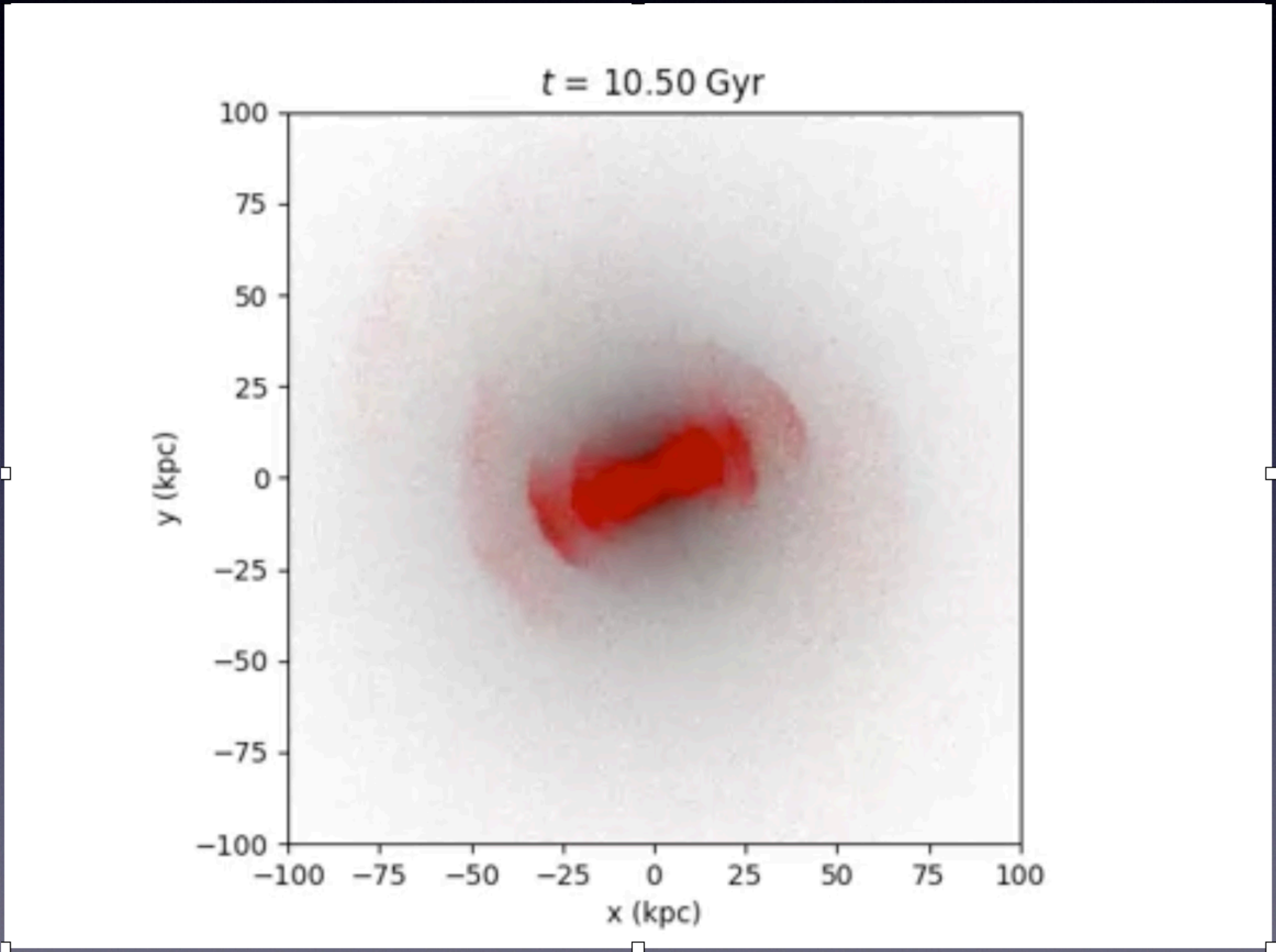


Meatballs & sausages





The Gaia Sausage



The Gaia Sausage

- The easiest way to build a metal-rich halo component with very radial orbits ($\beta \sim 0.9$) is to have one big clunker of a satellite (the Sausage Galaxy) coming in.

- The entirety of "the Gaia sausage" comes from one accreted object. Dynamical friction on a massive satellite (10^9 -10^{10} $M_\odot$) radialises the orbit and makes it eccentric.

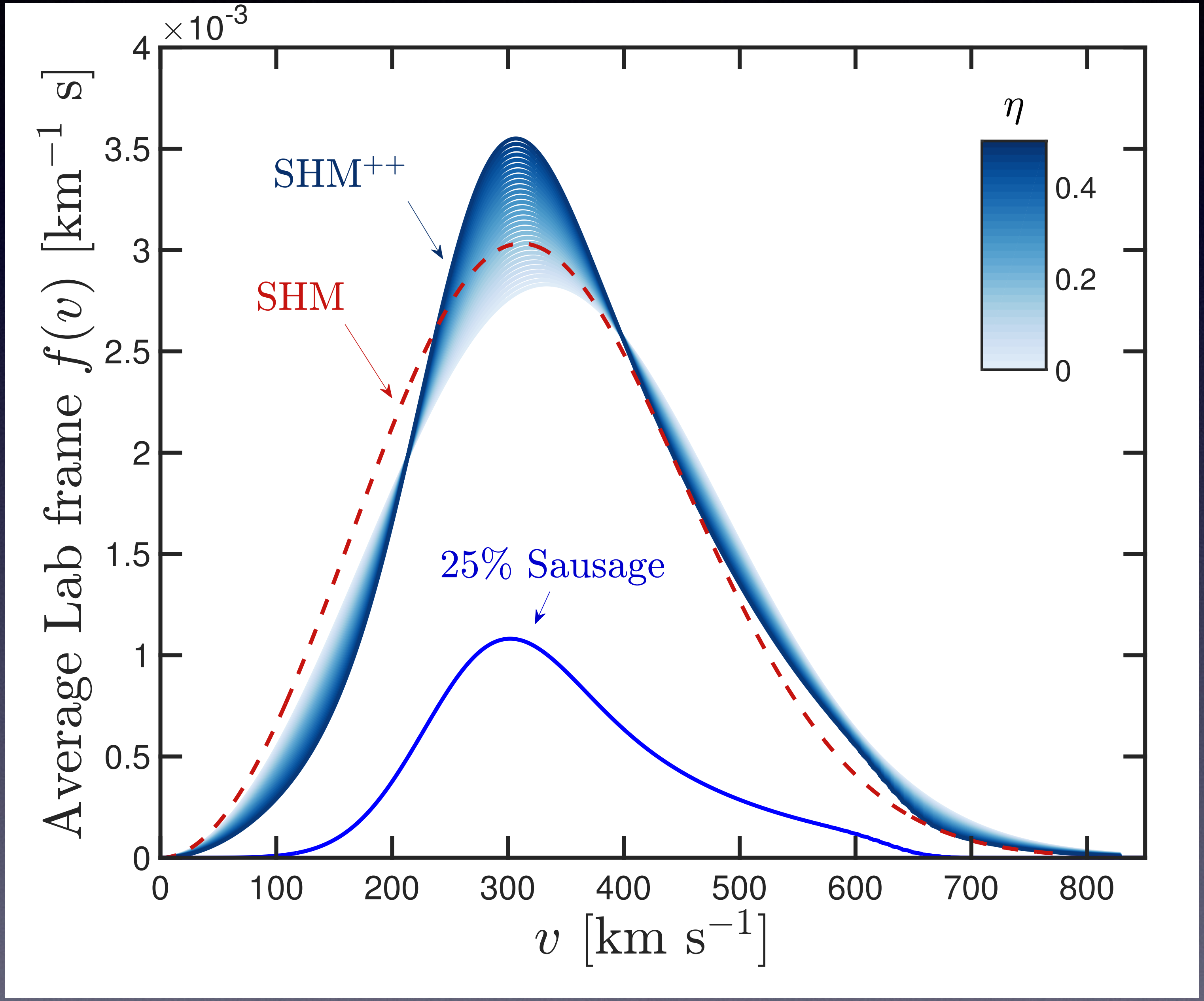
The Dark Sausage

We replace the standard halo model or SHM (truncated Maxwellian) with a new SHM^{++}

$$f(\mathbf{v}) = (1-\eta) f_{\mathrm{R}}(\mathbf{v}) + \eta f_{\mathrm{S}}(\mathbf{v})$$

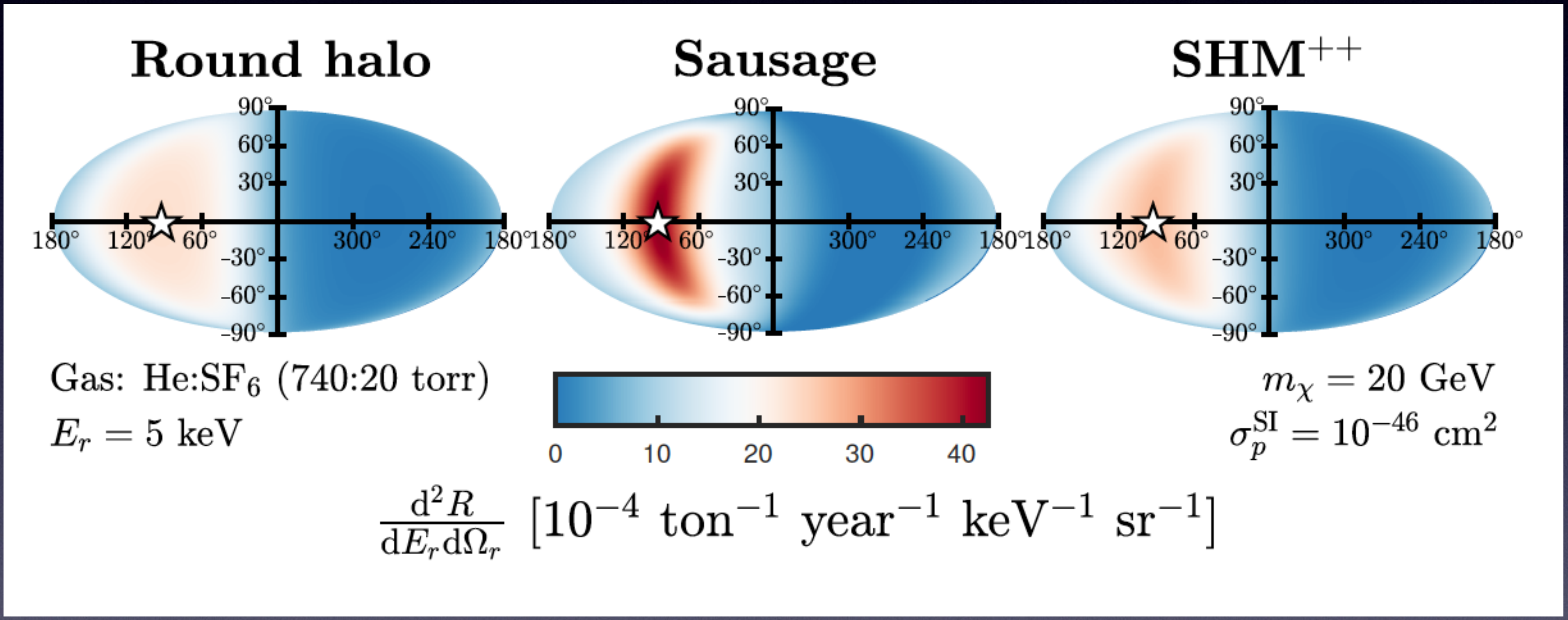
Here, η is the fraction of dark matter locally from the Sausage (~ 20±10%).

The Dark Sausage



Average lab frame for velocity distribution depending on Sausage fraction

The Dark Sausage

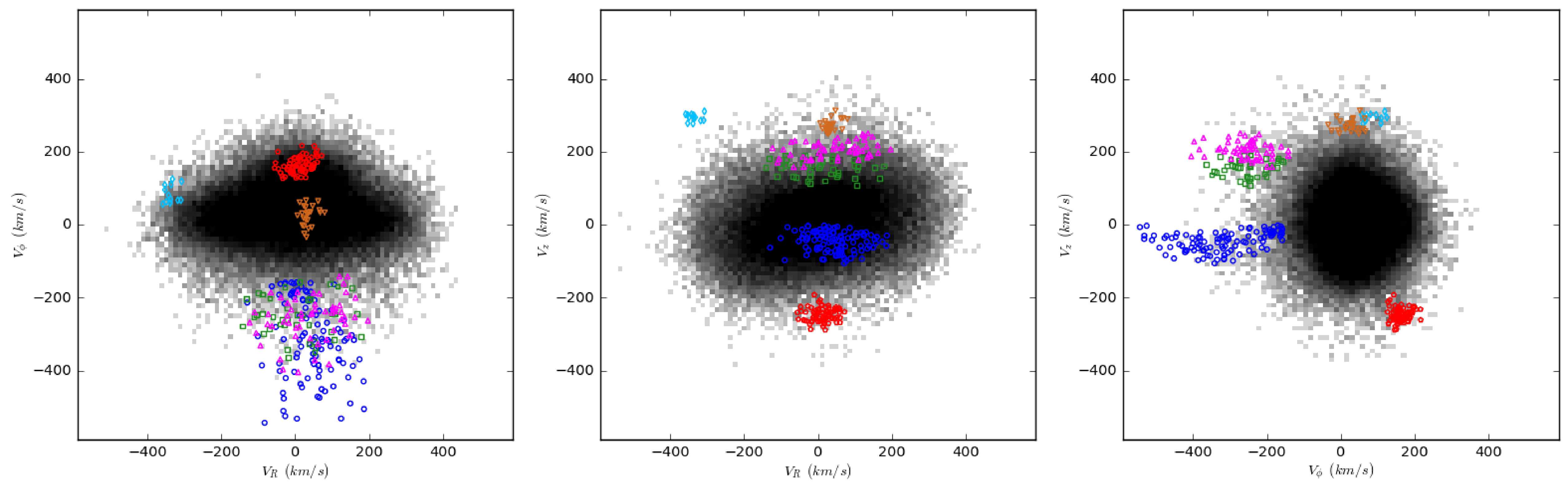


Mollweide projection in Galactic coordinates of the double differential angular recoil rate as a function of the inverse recoil energy at a fixed energy of 5 keV

The S1 stream

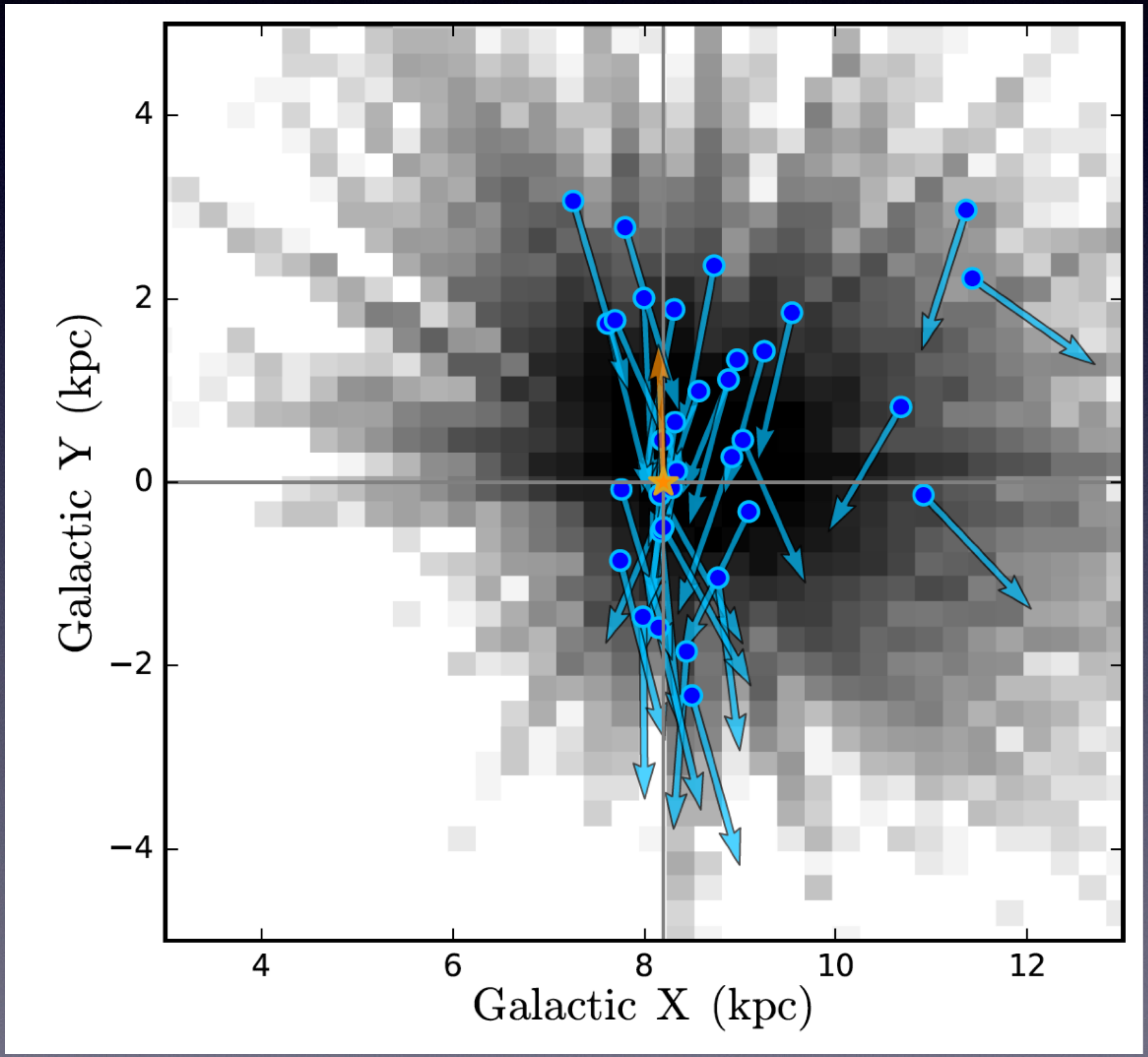
- We use the sample to develop a smooth background model (Gaussian Mixture Model) against which substructure is identified.
- We measure the local density of any star by using a *k* nearest neighbour search (*k*=6).
- The significance of any over-density can be assesses via (measured number - expected number) / Poisson uncertainty.

The S1 stream



Velocity histograms of the sample of halo stars, together with substructure identified against the smooth component. Let’s look at the blue splodge.

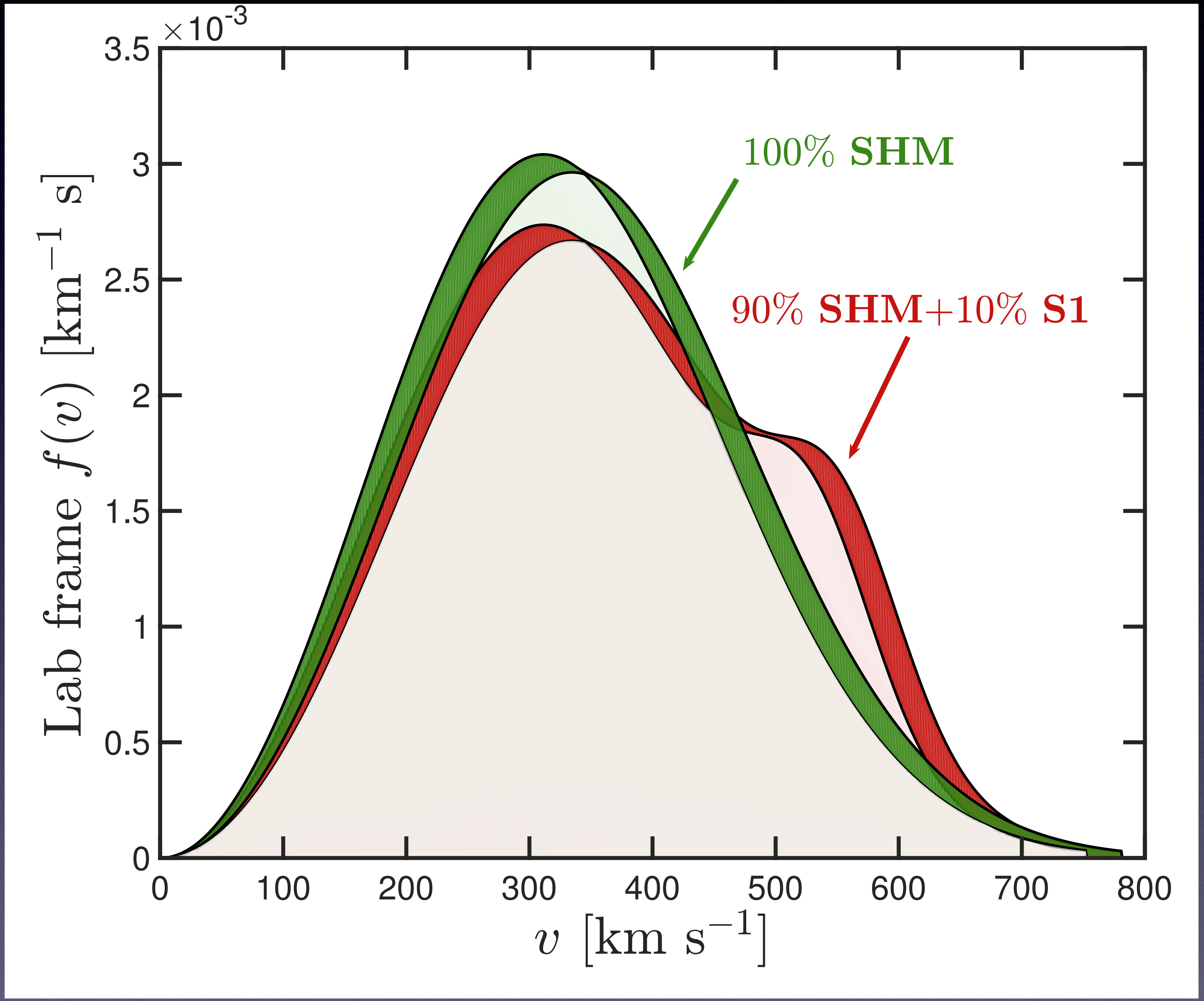
The Dark Matter Hurricane



The S1 Stream

- Myeong et al. (2018) found the S1 stream (as well as the other substructures in velocity space).
- S1 is the remnant of a dwarf galaxy comparable to the present-day Fornax with a stellar mass between 10^6 and 10^7 $M_{\odot}$. The DM mass will be a factor of ~ 10-100 greater.
- There is a DM hurricane blowing through the Martin Wood Lecture theatre

S1: The DM Hurricane



O'Hare et al 2018

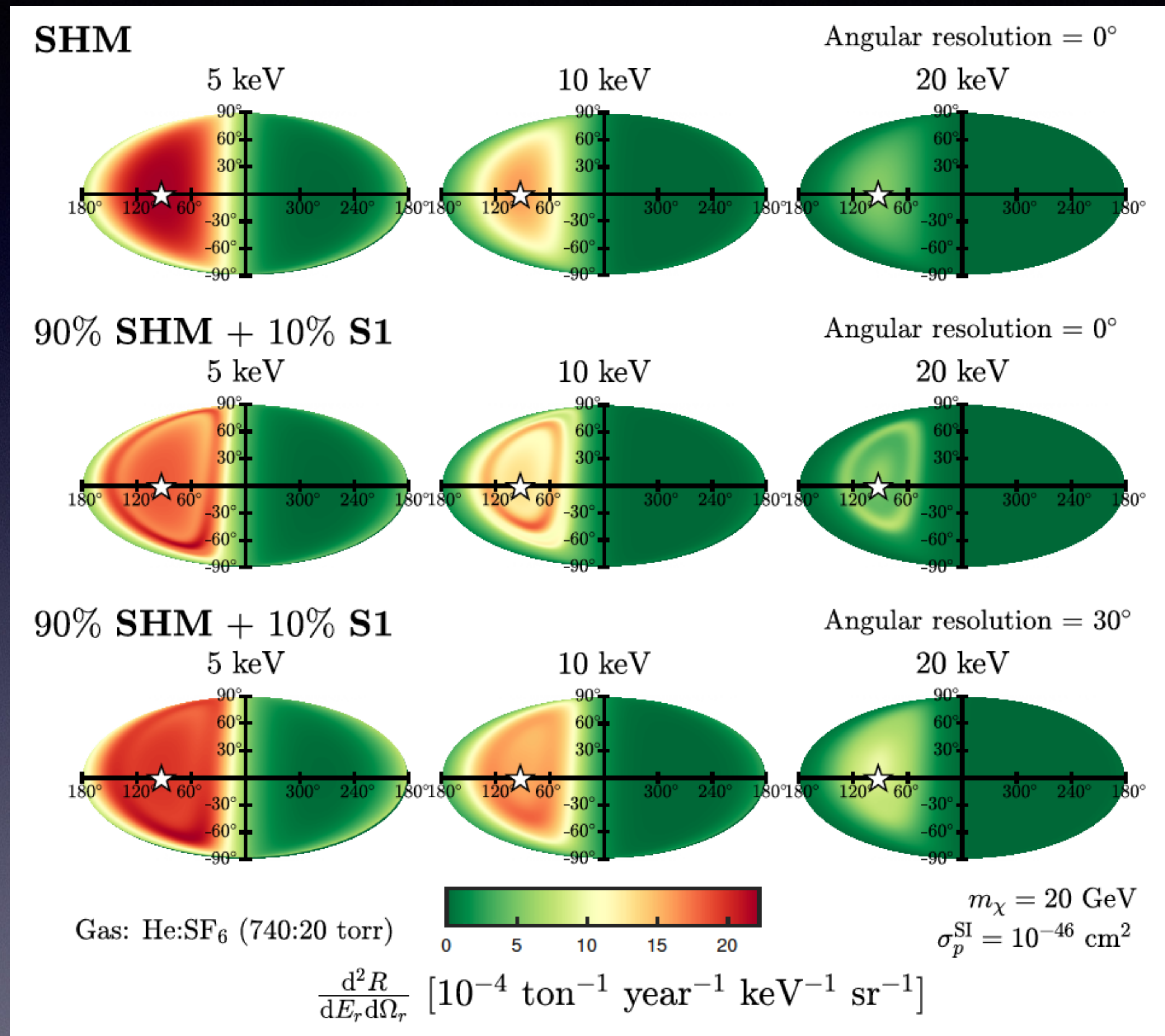
Distribution of WIMP velocities in laboratory frame over the course of a year

S1: The DM Hurricane

- In directional DM detection, the incoming velocity of the weakly interacting massive particle (WIMP) in a Stream is at a characteristic velocity.

- There is an exact relationship between recoil energy and scattering angle. At a given recoil energy, streams appear as rings in directional detection experiments.

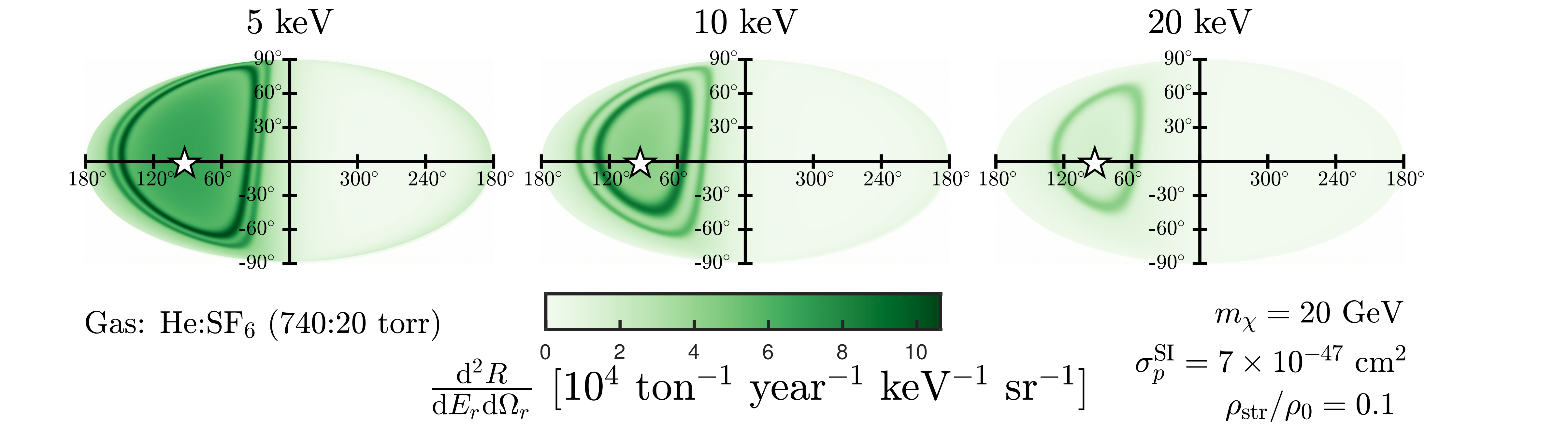
S1: The DM Hurricane



Double differential angular recoil rate as a function of inverse of recoil direction in Galactic coordinates

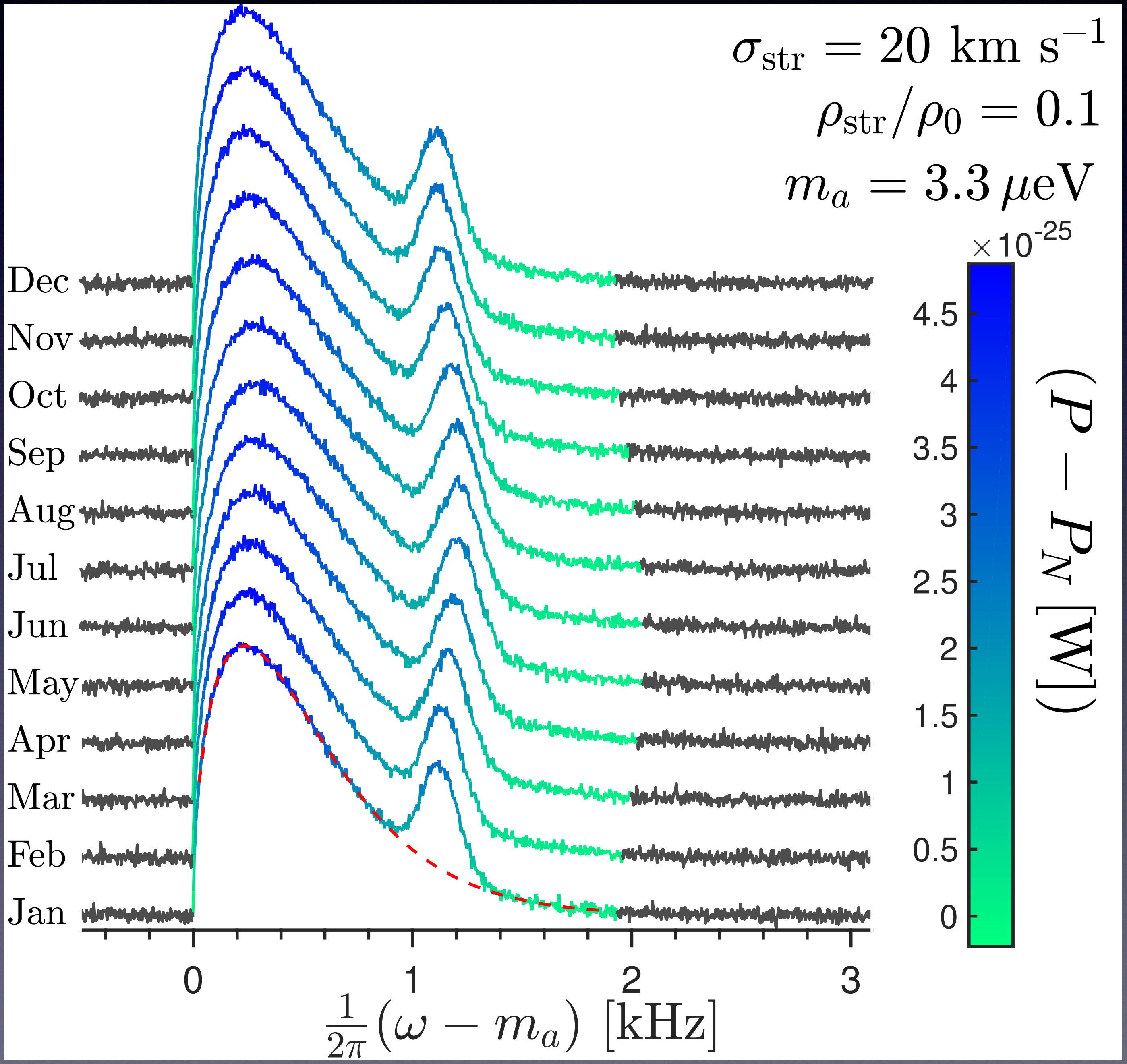
S1: The DM Hurricane

WIMPs scatter off He/SF_6 gas. The low pressure gas means that an interaction within the detector causes an ionisation track, which can be reconstructed to find the direction from which the particle came.



Double differential angular recoil rate as a function of inverse of recoil direction in Galactic coordinates

S1: The DM Hurricane



In a strong magnetic field, the axion converts its kinetic energy to a photon (ADMX). The axion power spectrum as a function of frequency enables us to read of the DM speed distribution.

S1: The DM Hurricane

- There are excellent prospects for detecting S1 in directional detectors (such as the proposed CYGNUS experiment) and axion haloscopes.
- Non-directional detectors are more limited, as much directional information is lost in the process of nuclear scattering.

Conclusions

- One of my vivid memories of Subir is him stating confidently at an Oxford seminar around 1995 that "*the dark matter particle will be identified in my lifetime.*" Perhaps he is more pessimistic now?

- How might any DM signal be convincing?

- *Gaia* is measuring the accretion history of the Milky Way. This enables the prediction of DM signals associated with specific accretion events (like the dark matter hurricane, S1). There are further examples in O'Hare et al (2021).

Conclusions

- The local dark halo is bimodal. The Sausage Galaxy brought in with it an avalanche of dark matter. The identification of the signal of the Dark Sausage is a goal for the next generation of direct detection experiments.
- The dark matter hurricane has a very unusual kinematic signature. It may be the easiest target of all to identify in direct detection experiments with directional sensitivity.