The Local Velocity Distribution

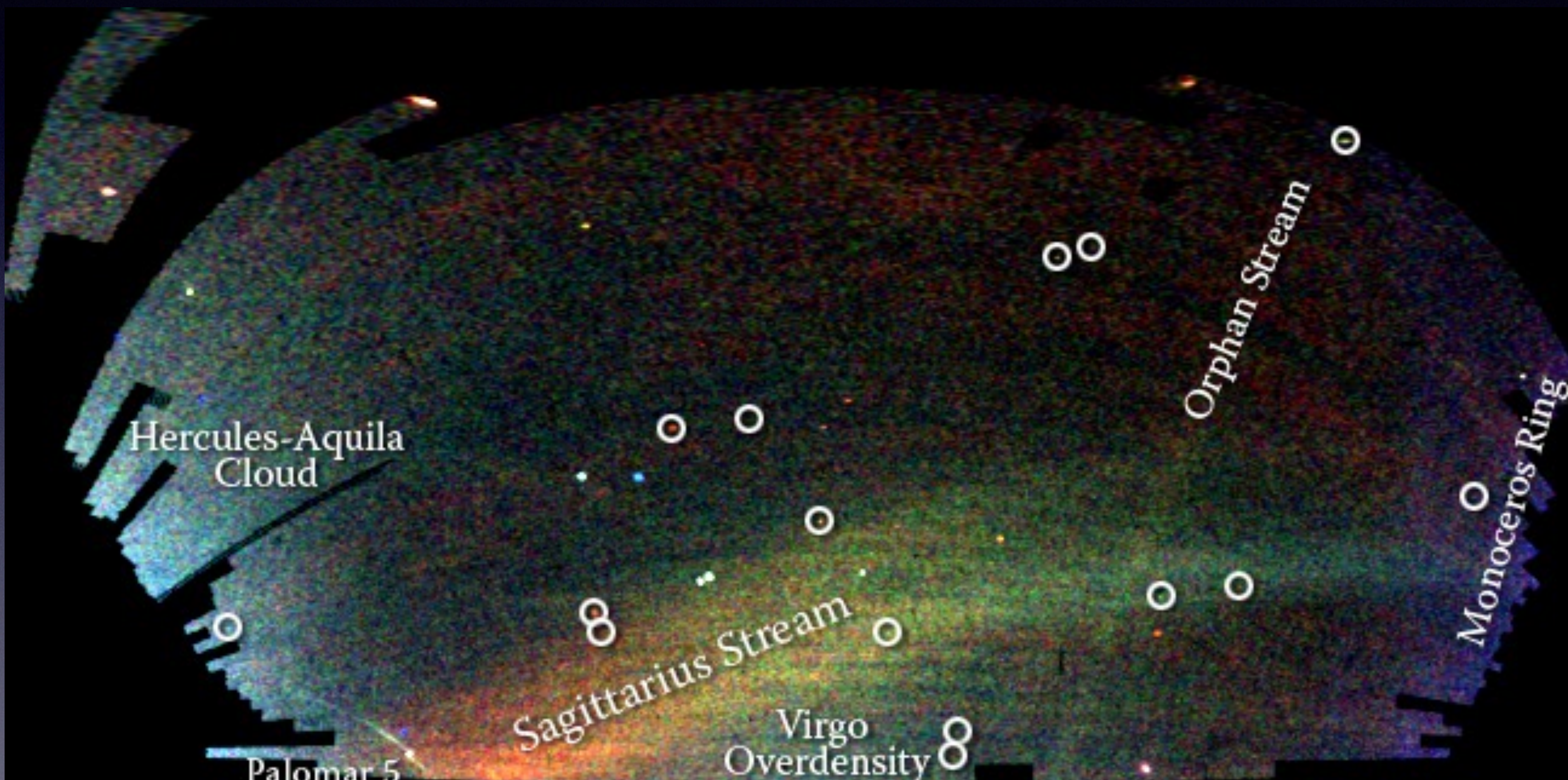
N W Evans (Cambridge)

with GyuChul Myeong, Vasily Belokurov,
Christopher McCabe and Ciaran O'Hare

Durham, 3 Dec 2019

Or,
The Sausage, the Sequoia
and the Splash

Milky Way Substructure



'The Field of Streams', Belokurov, Zucker, Evans et al 2006

Local Stellar halo in 7-D

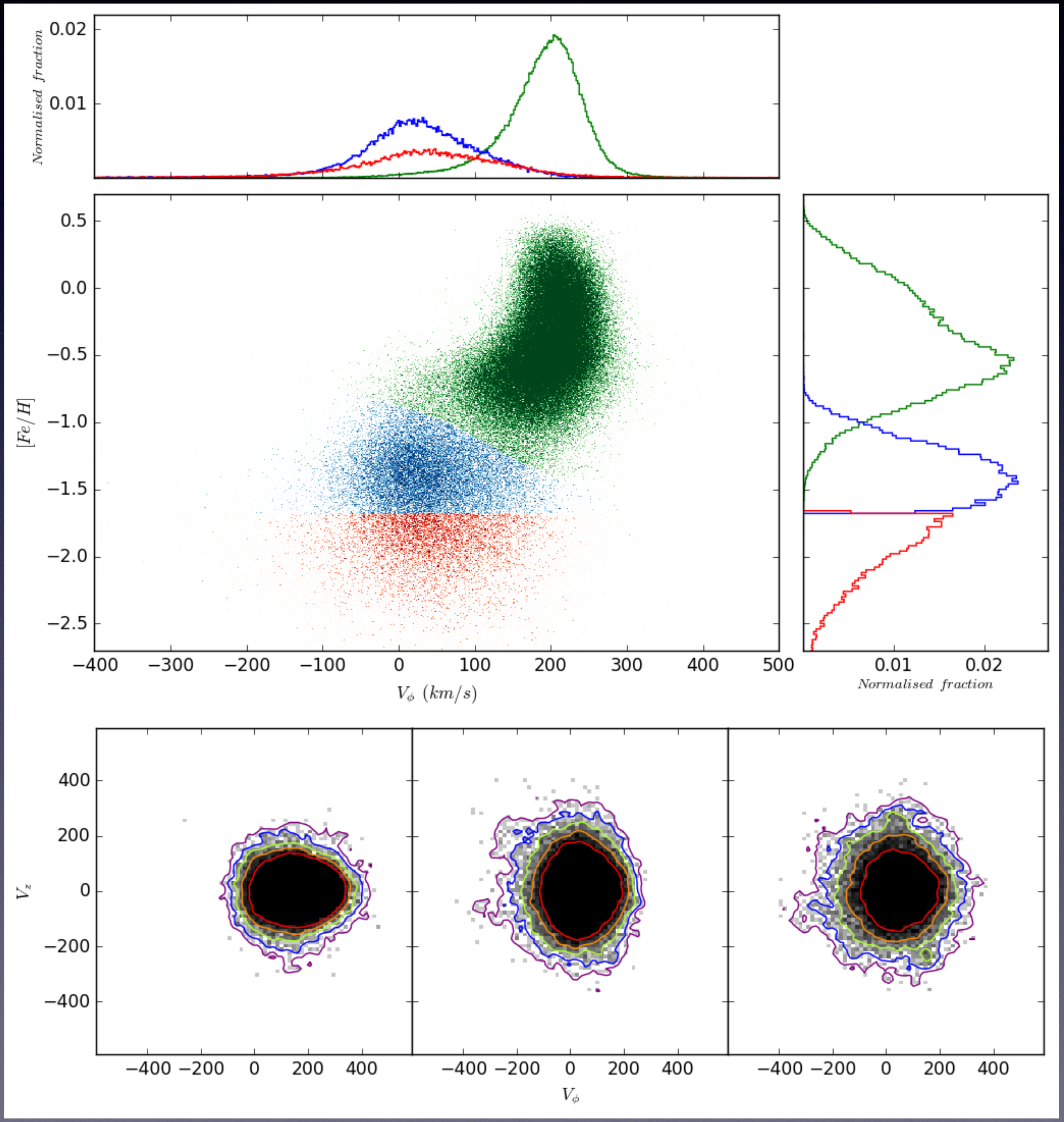
1. Position on the sky
2. Position on the sky
3. Color+magnitude
4. Proper motion RA
5. Proper motion Dec
6. Line-of-sight velocity
7. Metallicity

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

SDSS+Gaia DR1: ~250,000 Main Sequence stars in 10x10x10 kpc box entered on the Sun

The S1 and S2 streams

Myeong et al 2018a

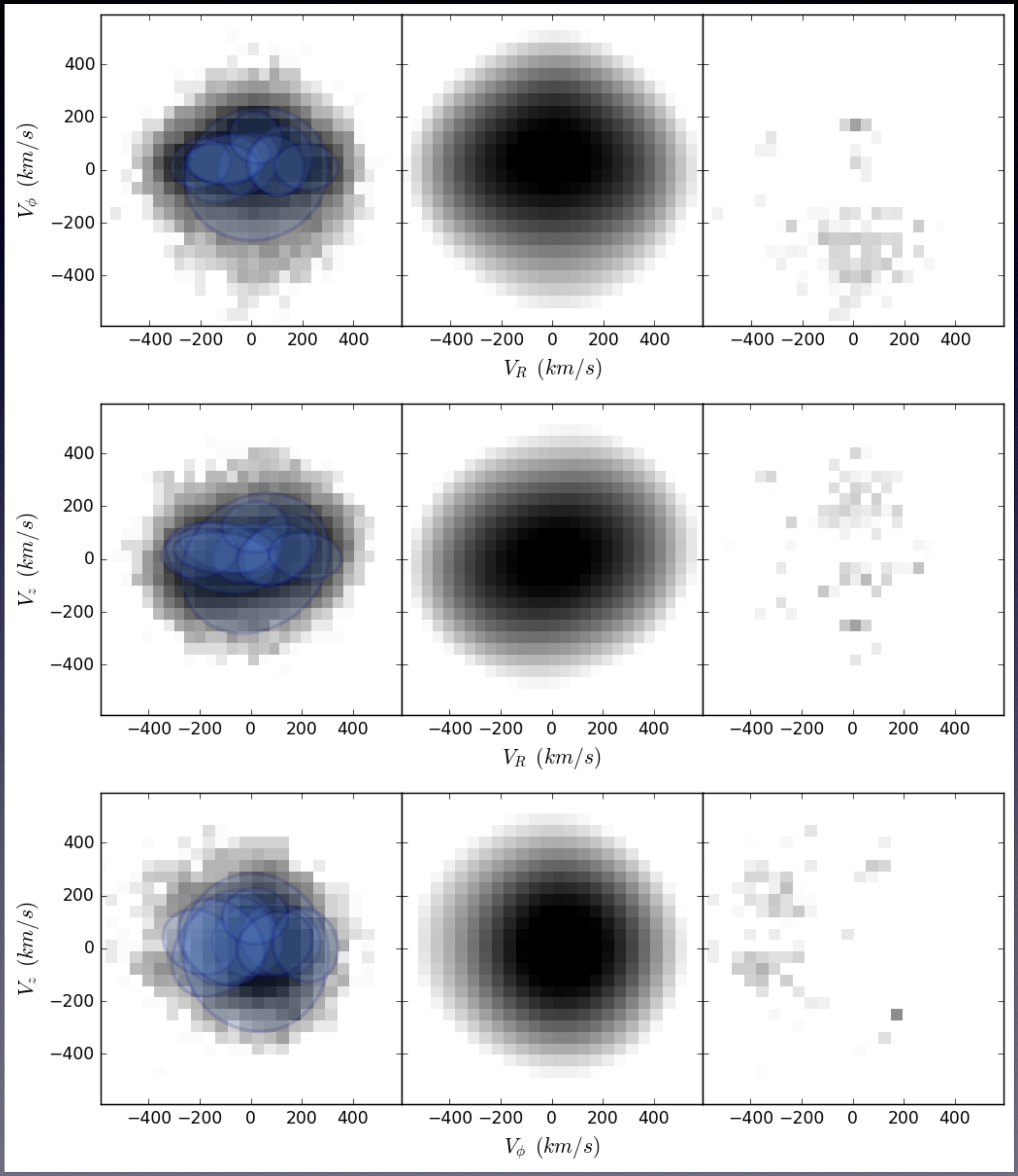


Sample of ~250,000 with D < 5 kpc

The S1 and S2 streams

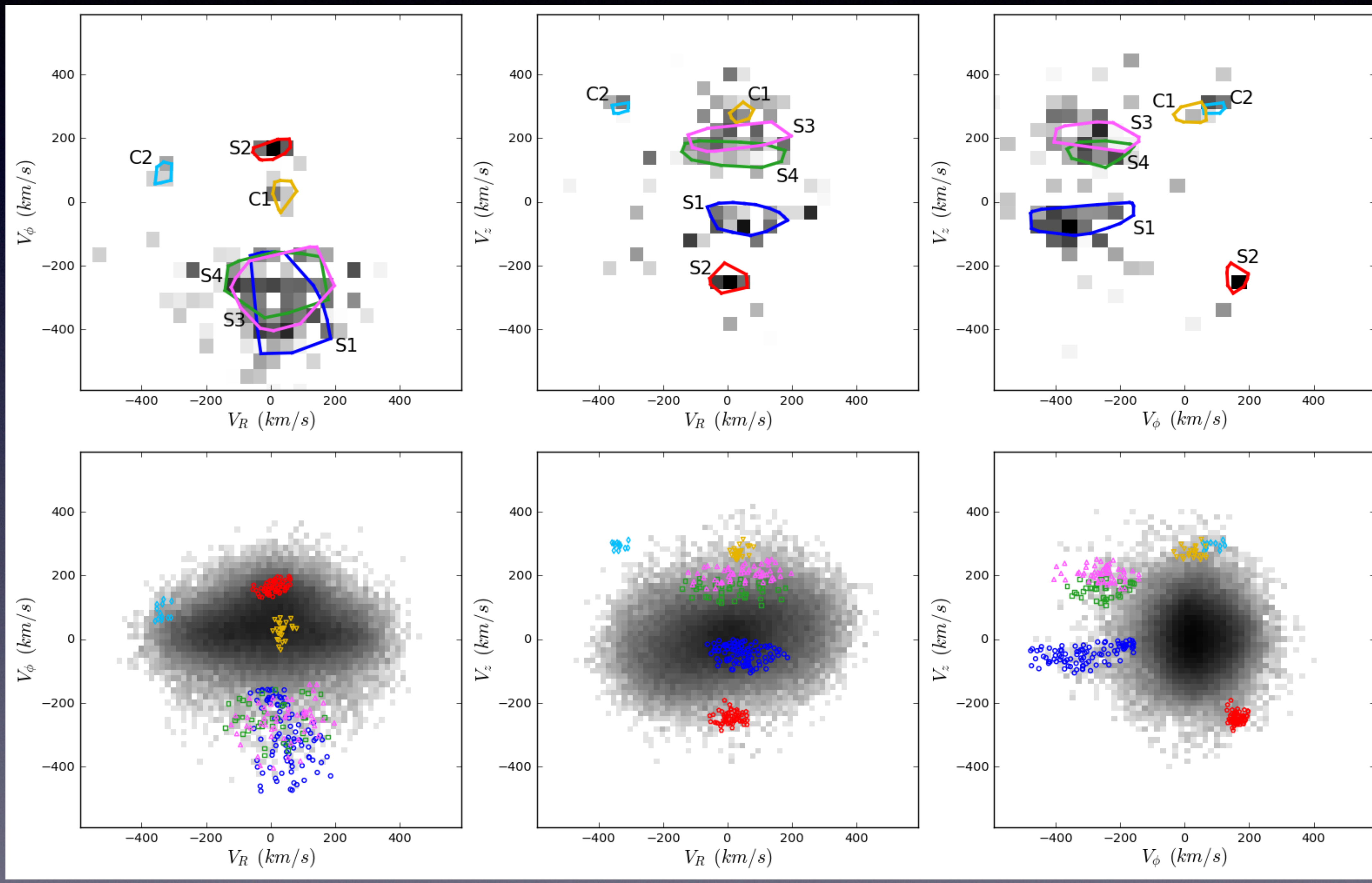
- We use the entire halo sample to develop a smooth background model (Gaussian Mixture Model) against which substructure is identified.
- We measure the local density of any star by using a *k* nearest neighbour search (*k*=6).
- The significance of any over density can be assesses via (measured number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

The S1 and S2 streams



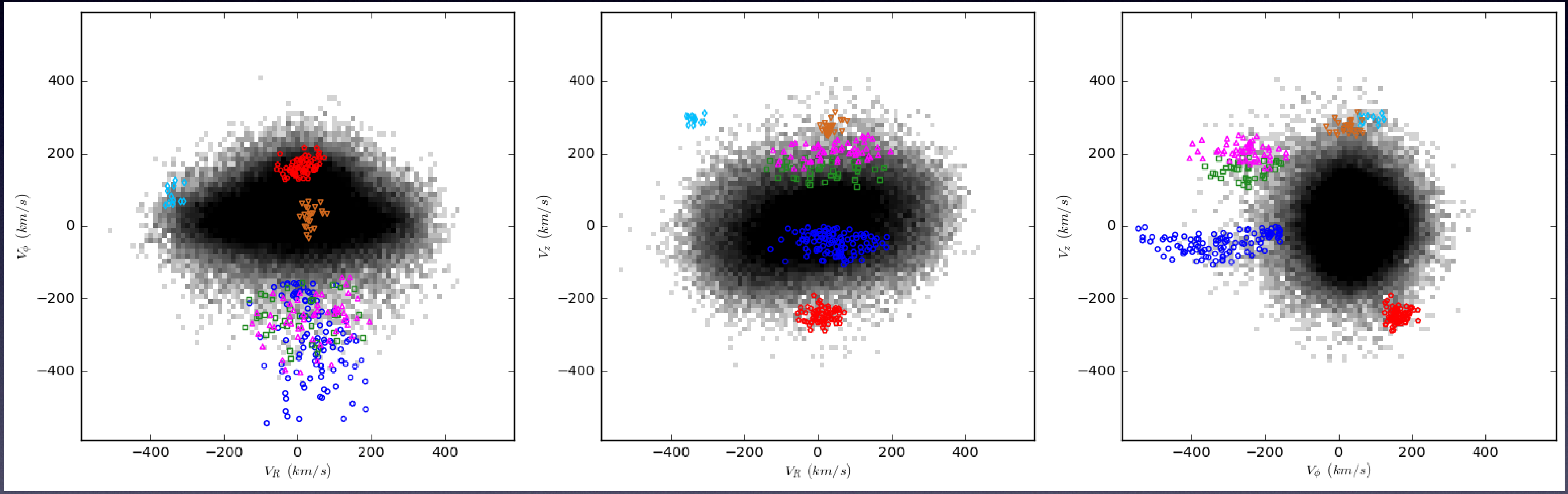
Myeong et al 2018a

The S1 and S2 streams



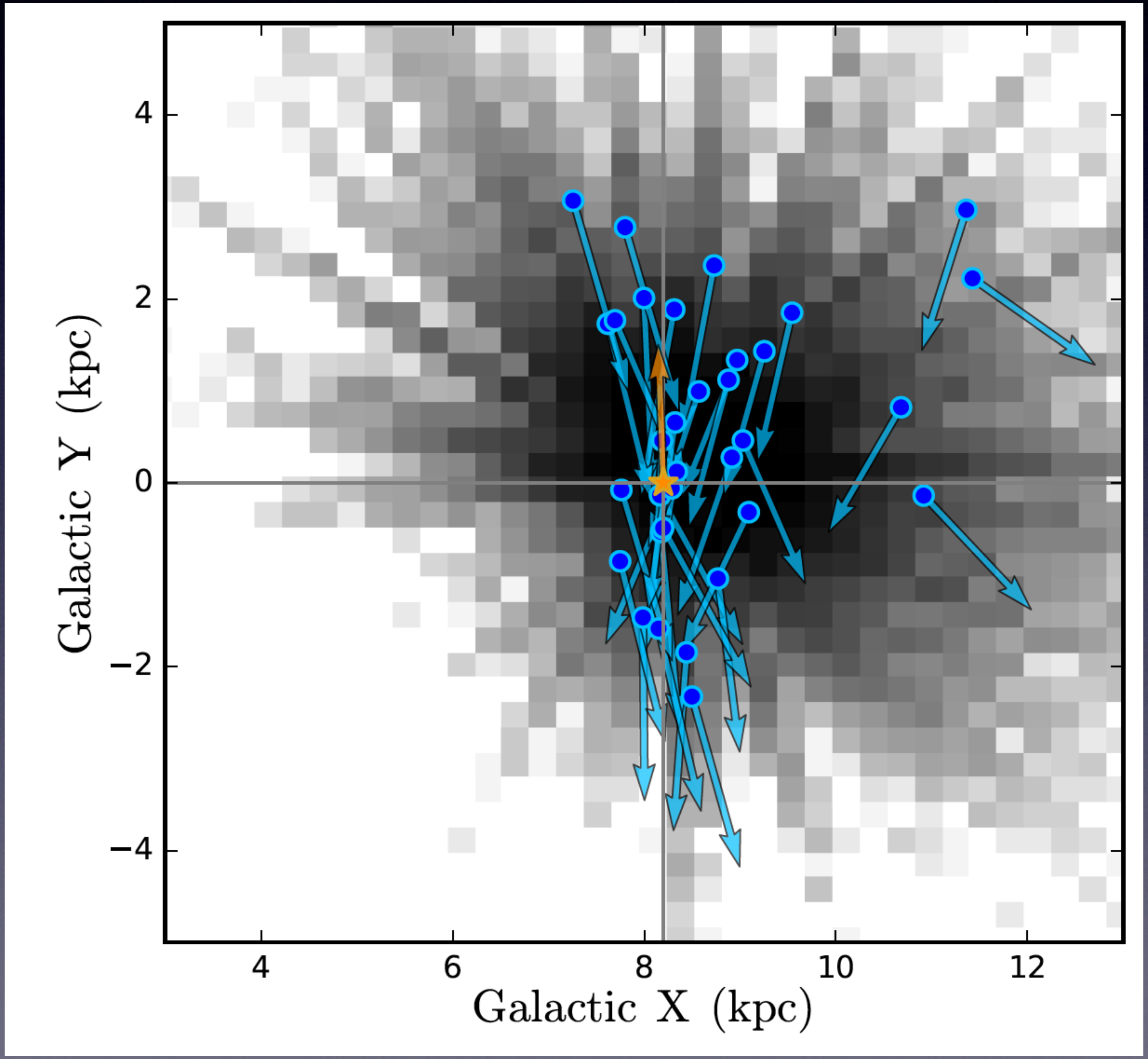
Myeong et al 2018a

The S1 and S2 streams



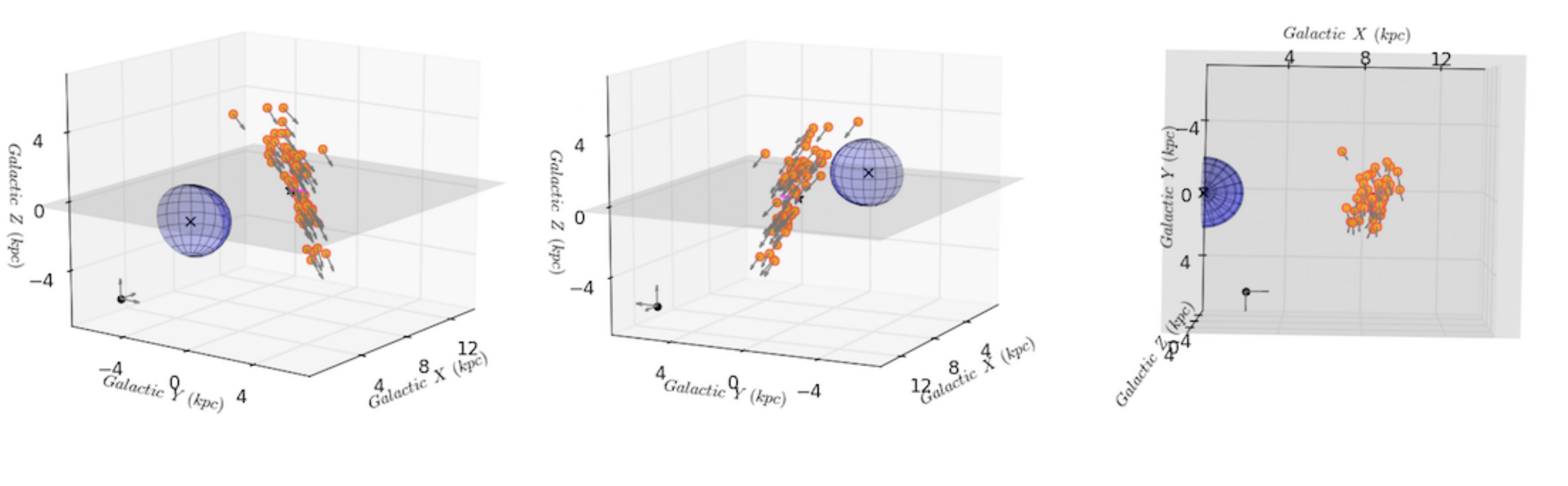
Velocity histograms of the sample of halo stars, together with substructure identified against the smooth component. Let's look at the blue splodge.

The Retrograde S1 stream



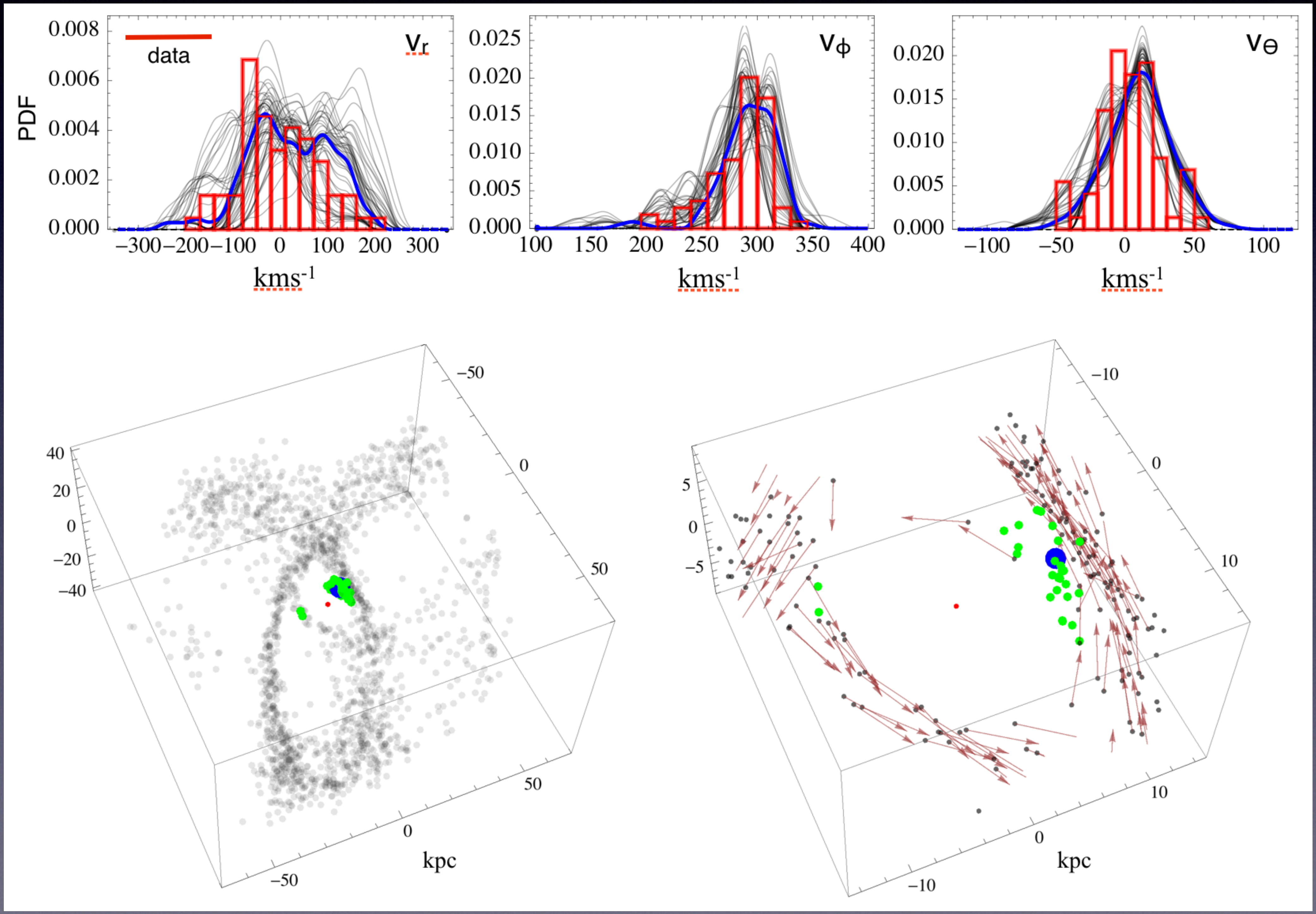
O'Hare et al 2018

The Prograde S2 stream



Location of stream relative to a schematic Galactic bulge (sphere of radius 2 kpc) and Galactic disk

The prograde S2 stream



Work with Nicola Amorisco

The Retrograde S2 Stream

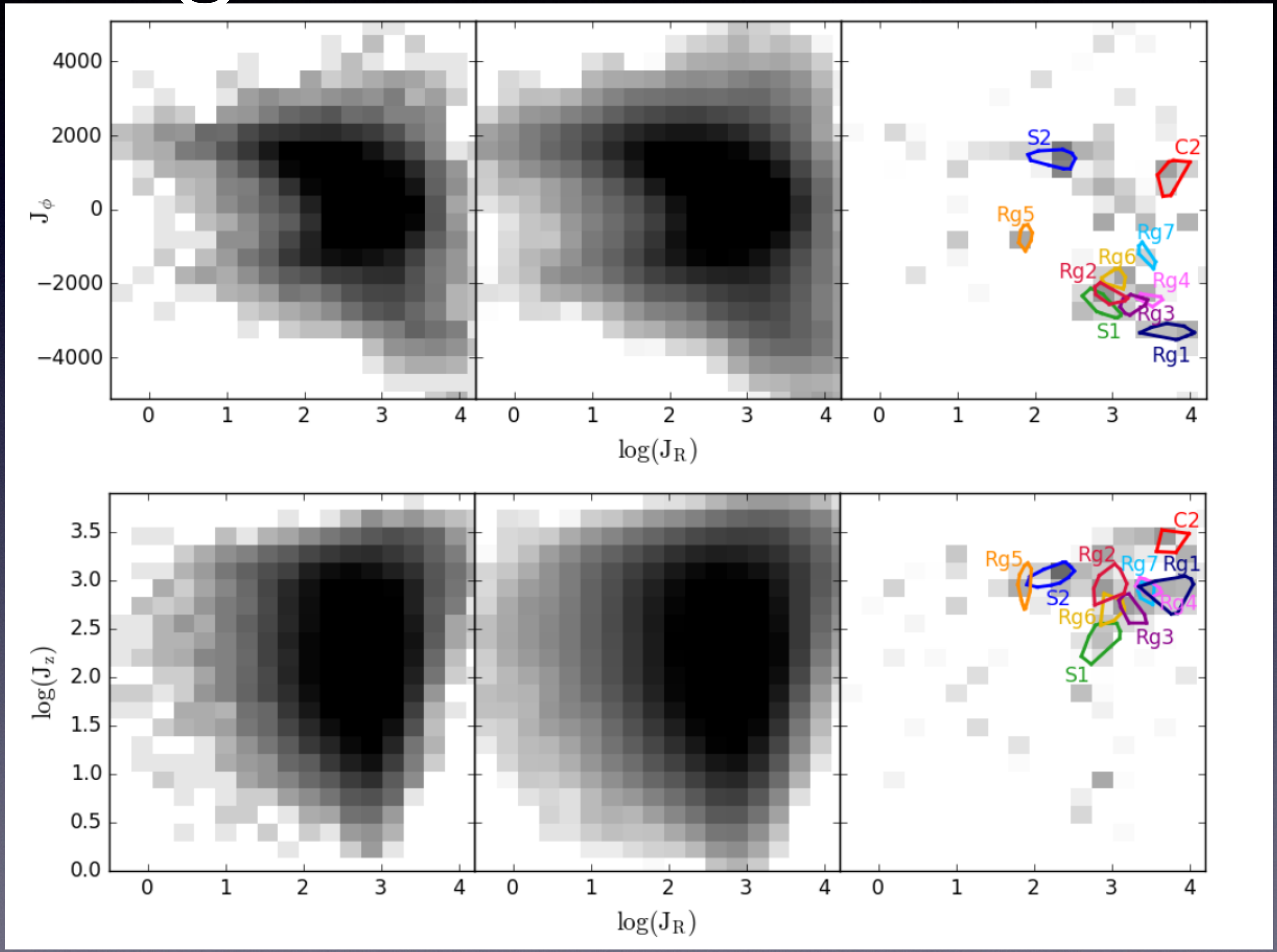
- Satellite has a virial mass ratio of 1:100 at infall, implying a starting mass of $5 \times 10^9 M_\odot$ at infall time ~ 11 Gyr ago, and an initial eccentricity of 0.5.

- There are a number of models close in parameter space, so one can trade a higher initial mass (1:50) with a later infall time (~ 8 Gyr).

The S1 and S2 streams

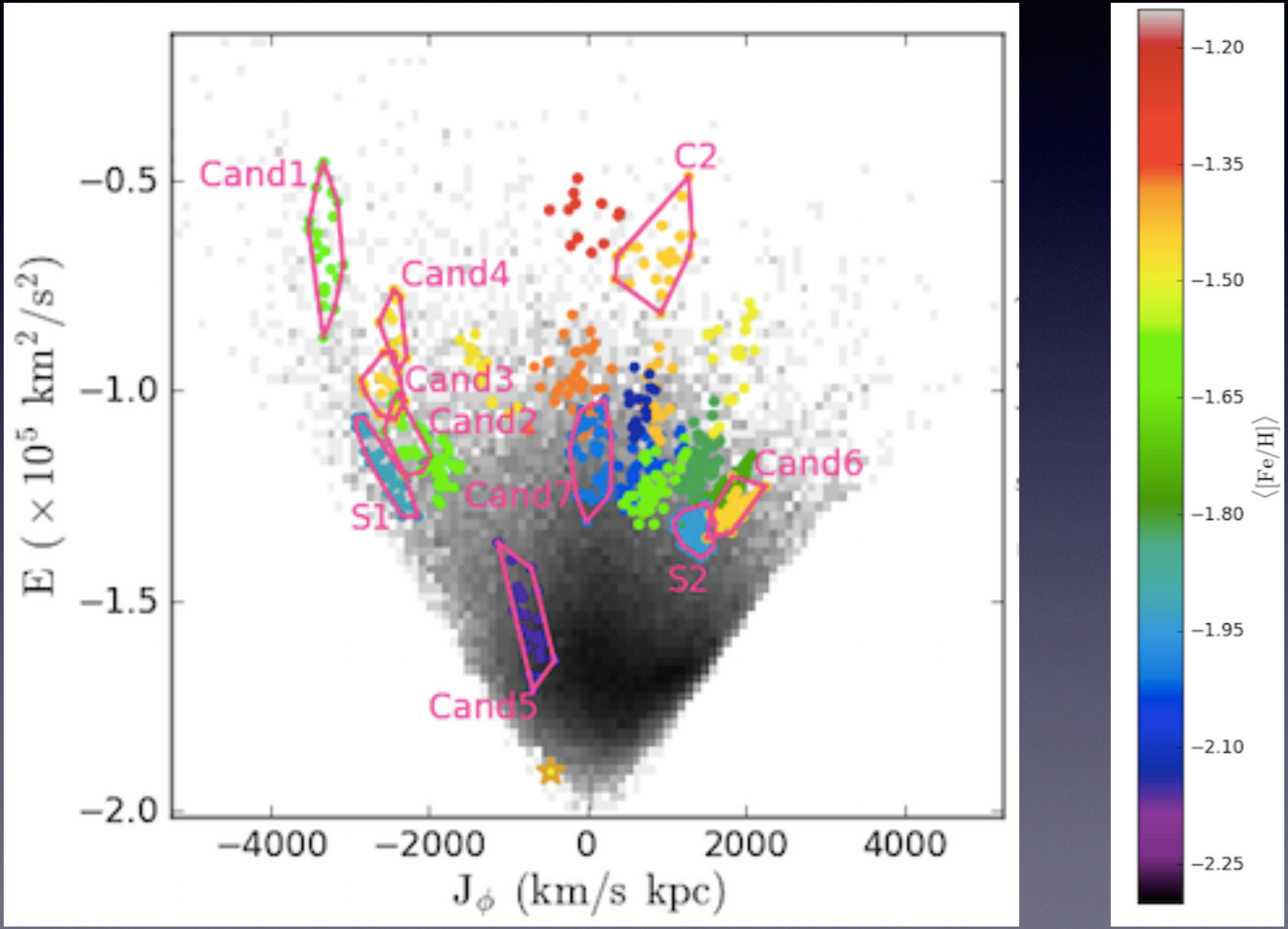
- The S1 and S2 streams were discovered by Myeong et al. (2018a) by a substructure search in velocity space.
- Myeong et al (2018b) complemented this with a search through the same Gaia-SDSS data in action space.

Retrograde Substructures

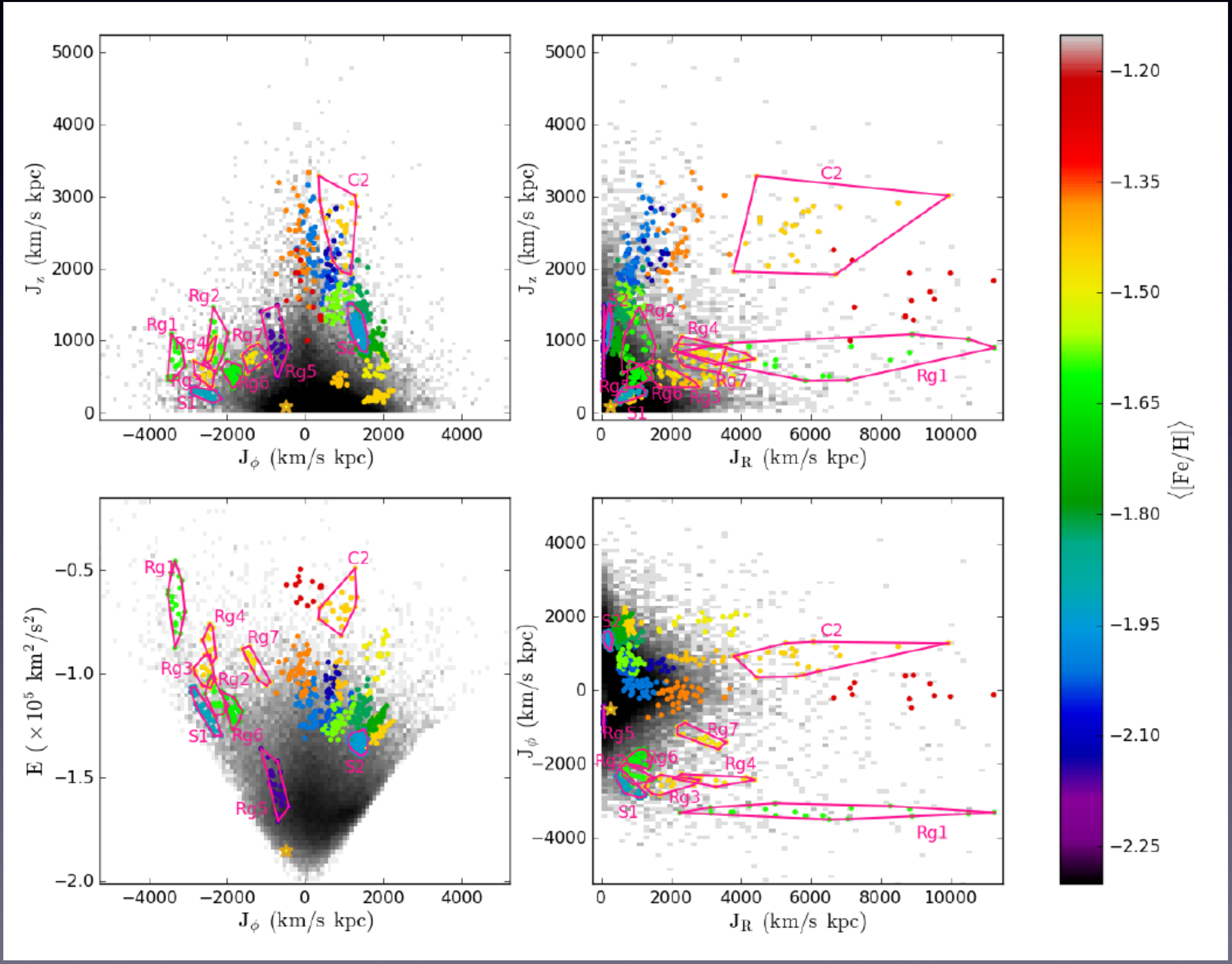


Myeong et al 2018b

Retrograde Substructures



Retrograde Substructures



Myeong et al 2018b

Retrograde Substructures

- Myeong et al. (2018b) recovered the retrograde S1 stream (as well as the other substructures found in velocity space).

- Myeong et al. (2018b) also found seven new retrograde substructures (Rg1, … Rg7).

- What is the cause of the abundant retrograde high energy substructure ?

Retrograde Substructures

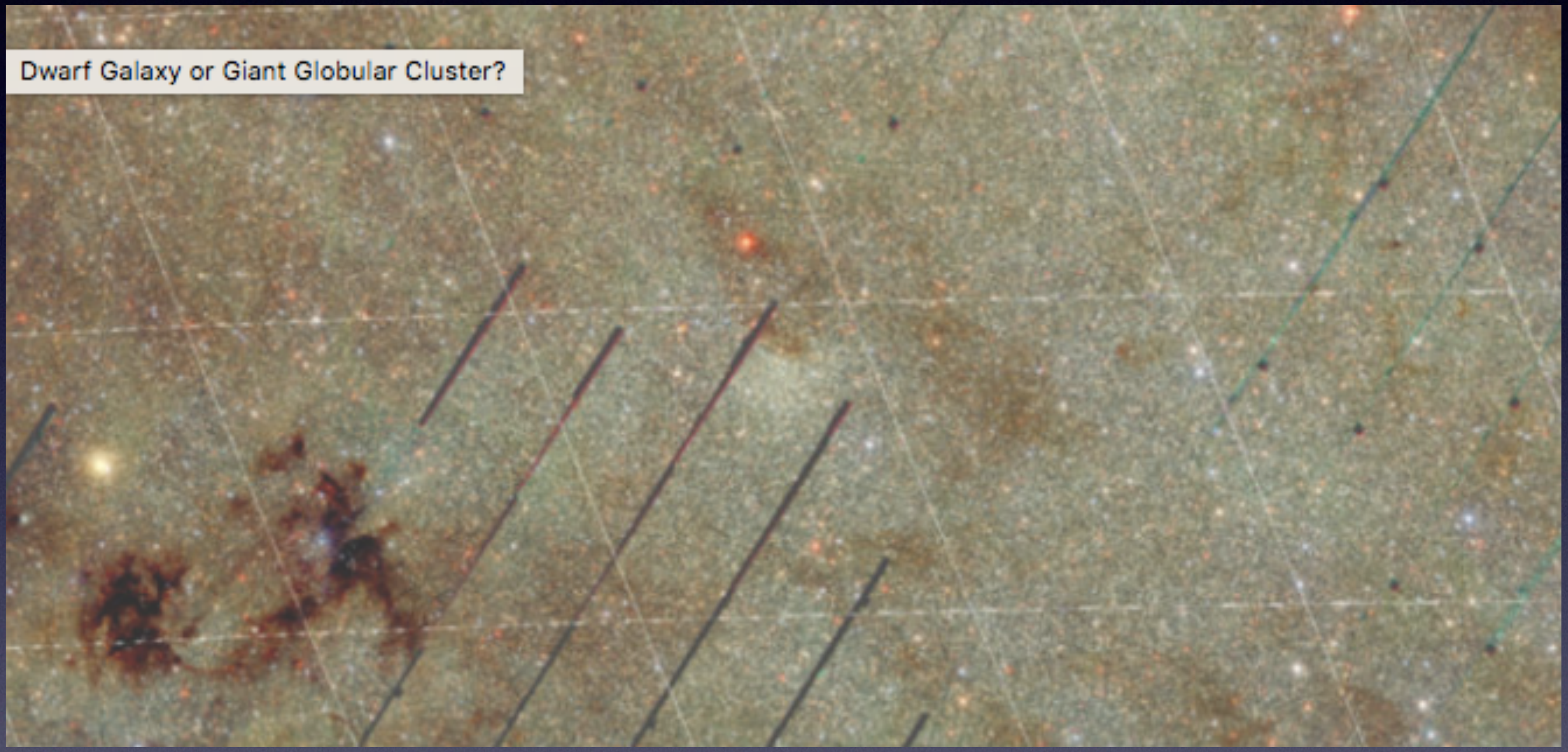
Credit:Paul Sandelle, CloudyNights

Known to Ptolemy !

Retrograde Substructures

- Retrograde substructures may be related to the globular cluster ω Centauri. This has a present-day mass of 5 x 10^6 $M_\odot$ and may be the stripped nucleus of a dwarf (Bekki & Freeman 2003).
- ω Centauri has multiple stellar populations. The stars in ω Centauri exhibit a large metallicity spread & there are extreme star-to-star variations in many light elements.
- If ω Centauri was a dwarf, then its virial mass may have been ~ 10^{10} $M_\odot$ based on models of the chemical evolution of multi-population clusters.

Retrograde Substructures



FSR 1758, discovered by Barba et al (2019)

The Retrograde FSR 1758

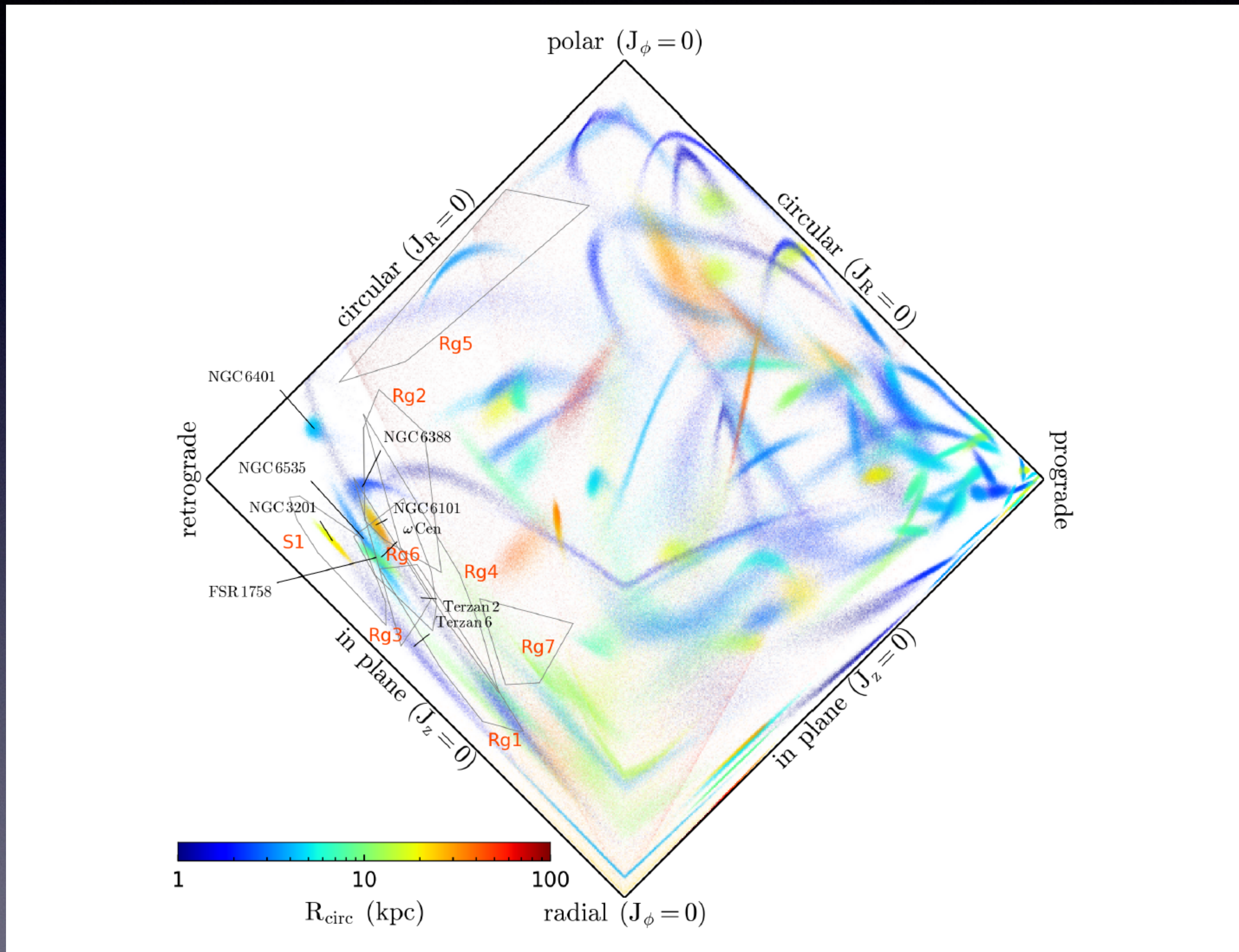
- FSR 1758 was found by Barba et al. (2019) using DECaPS & VVV data, complemented with Gaia DR2. It is an extended agglomeration of stars, located at ($l = 349^o$, $b = 3^o$) and with a distance of ~10 kpc.

- Barba et al. (2019) equivocated as to whether FSR 1758 is the remnant of a dwarf galaxy or an unusually large globular cluster.

- Simpson (2019) showed it is very retrograde & the PM dispersion profile of Vasiliev confirms that it is a cluster.

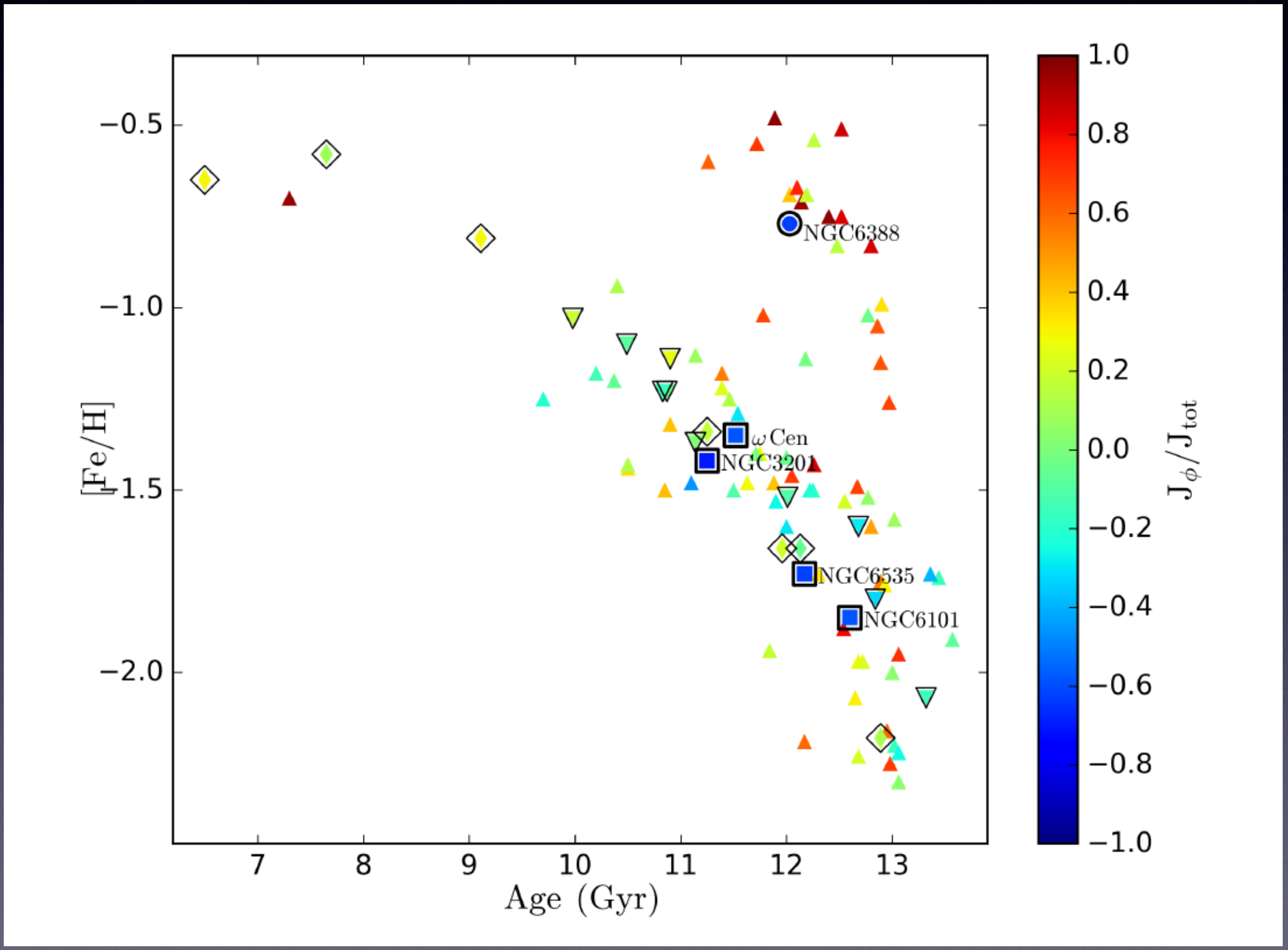
FSR 1758

Myeong et al 2019



Horizontal axis is J_ϕ , vertical axis is J_Z-J_R

The Sequoia Clusters



This is the same pattern as seen for the Sagittarius & the Sausage.

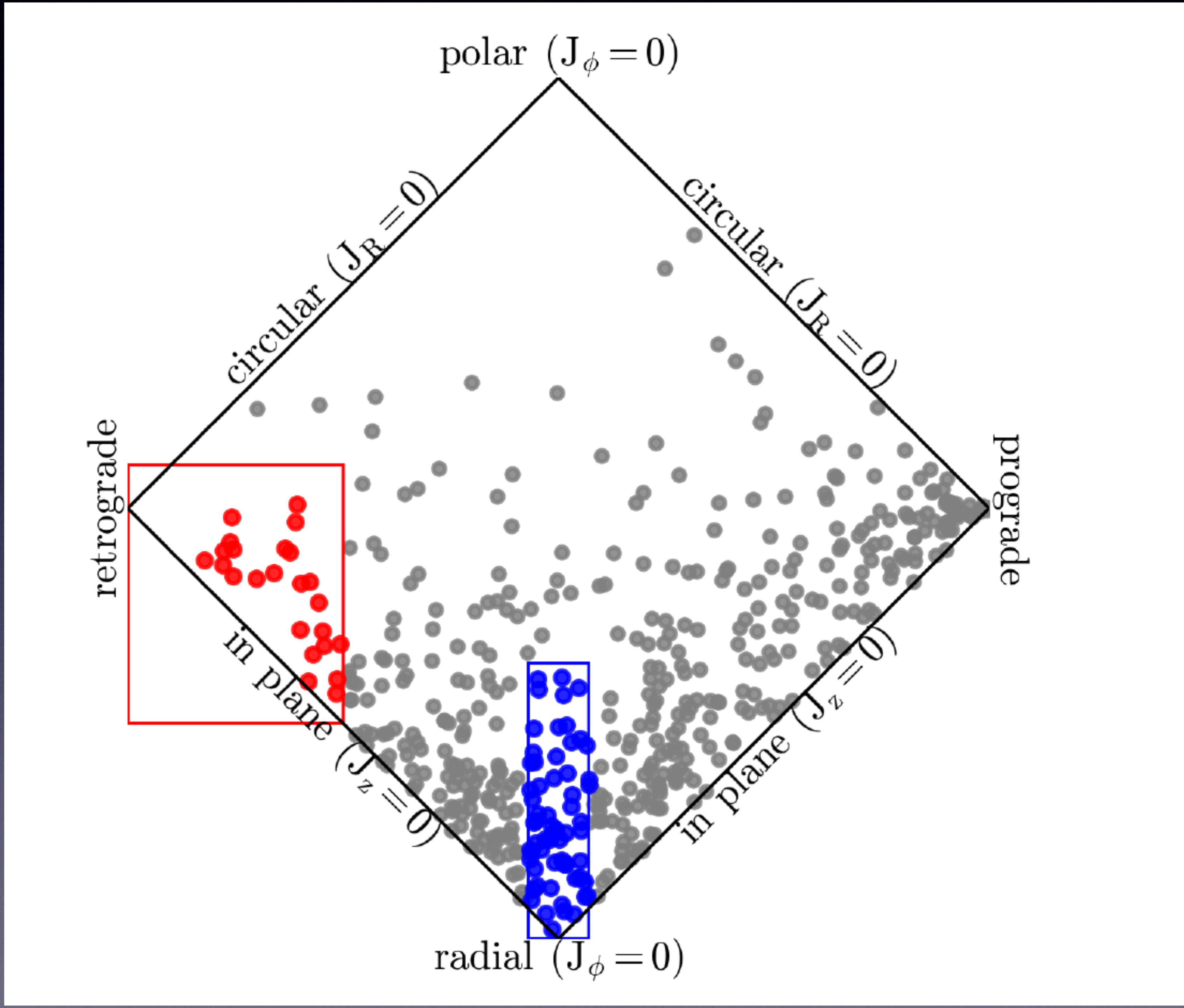
The Sequoia Clusters

- There are 5 globular clusters probably associated with the Sequoia Event. They are FSR 1758, NGC 3201, ω Centauri, NGC 6101 and NGC 6535. All have $e \simeq 0.6$, $i \simeq 160^{o}$.

- Two other possibles are NGC 6388 and NGC 6401.

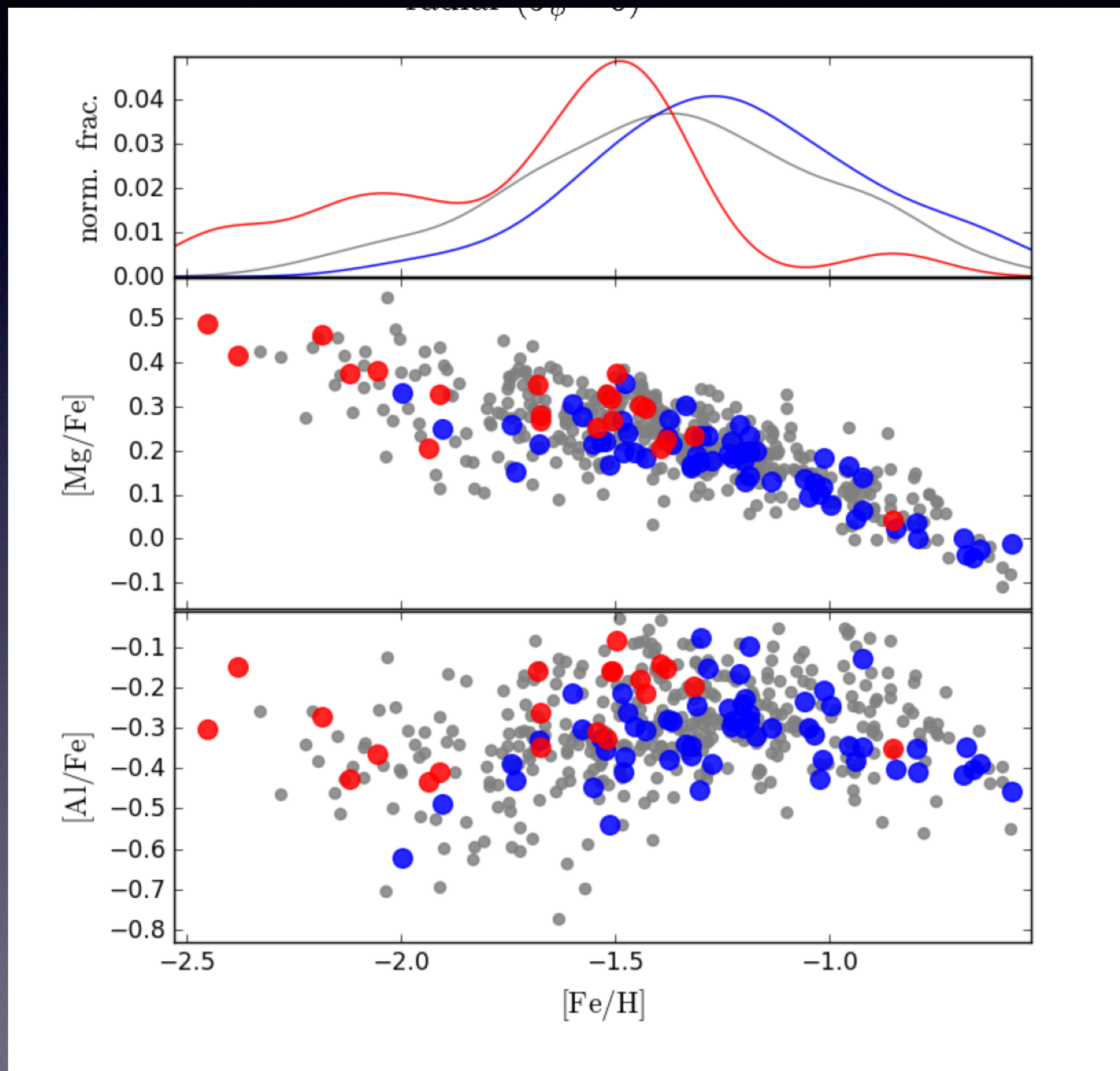
- NGC 3201 is known to be associated with the retrograde S1 stream (O' Hare et al. 2018).

The Sequoia Event



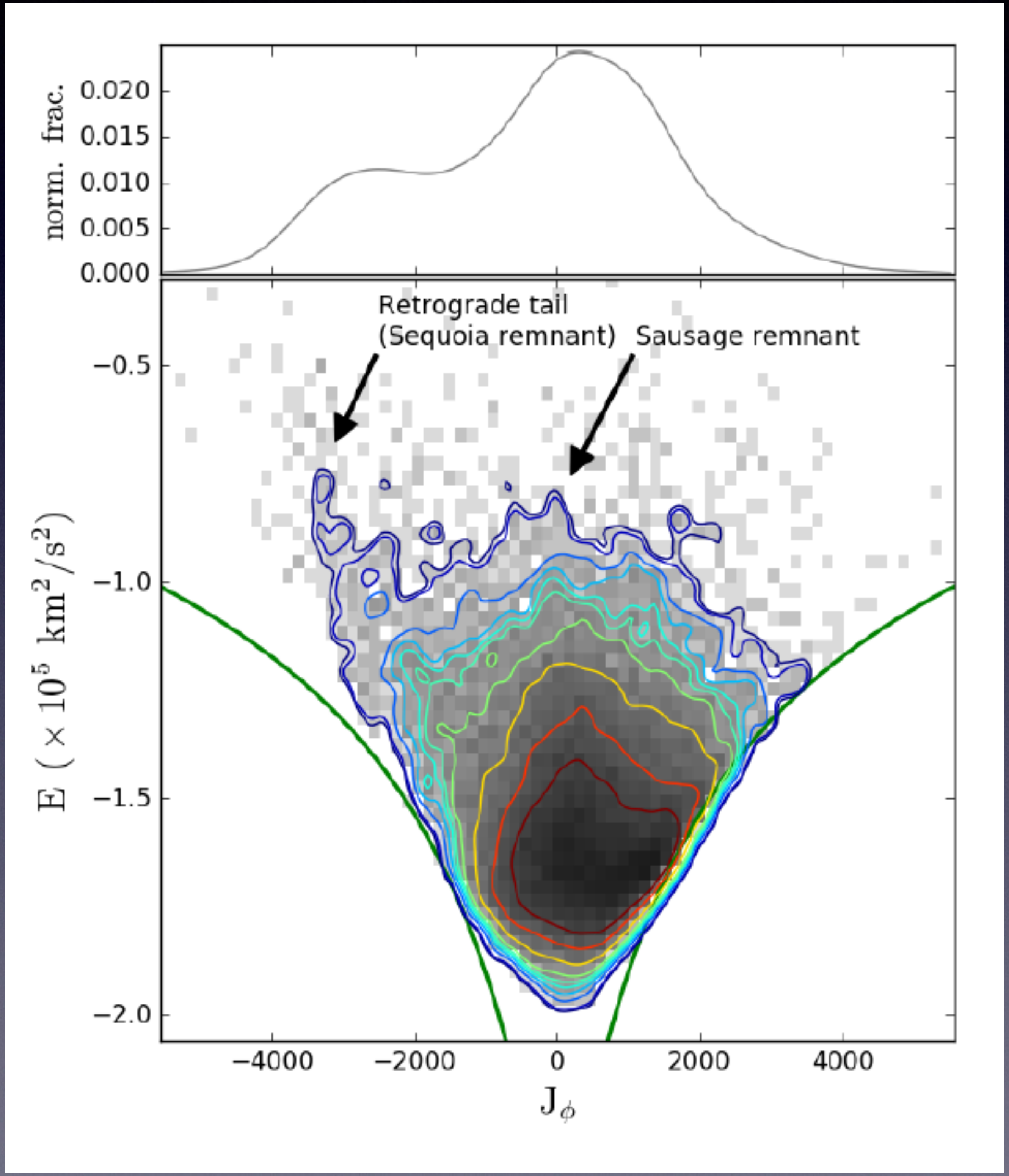
Myeong et al 2019

The Sequoia Event



Myeong et al 2019

The Sausage and the Sequoia



The Sausage and the Sequoia …

- The Gaia Sausage is the biggest structure in the stellar halo, with a stellar mass of ~ 5 - 50 x 10^8 $M_\odot$. This is the stellar mass of the Small or Large Magellanic Cloud. The DM mass is ~ 1-5 x 10^{11} $M_\odot$.

- The Sequoia has a stellar mass of ~ 5-70 x 10^6 $M_\odot$. This is the stellar mass of Fornax. The DM mass is ~ 1-5 x 10^{10} $M_\odot$.

Retrograde Substructures

Evidence for Two Early Accretion Events That Built the Milky Way Stellar Halo

G. C. Myeong[1], E. Vasiliev[1,2], G. Iorio[1], N. W. Evans[1], V. Belokurov[1]
[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2] *Lebedev Physical Institute, Leninsky Prospekt 53, Moscow 119991, Russia*

3 April 2019

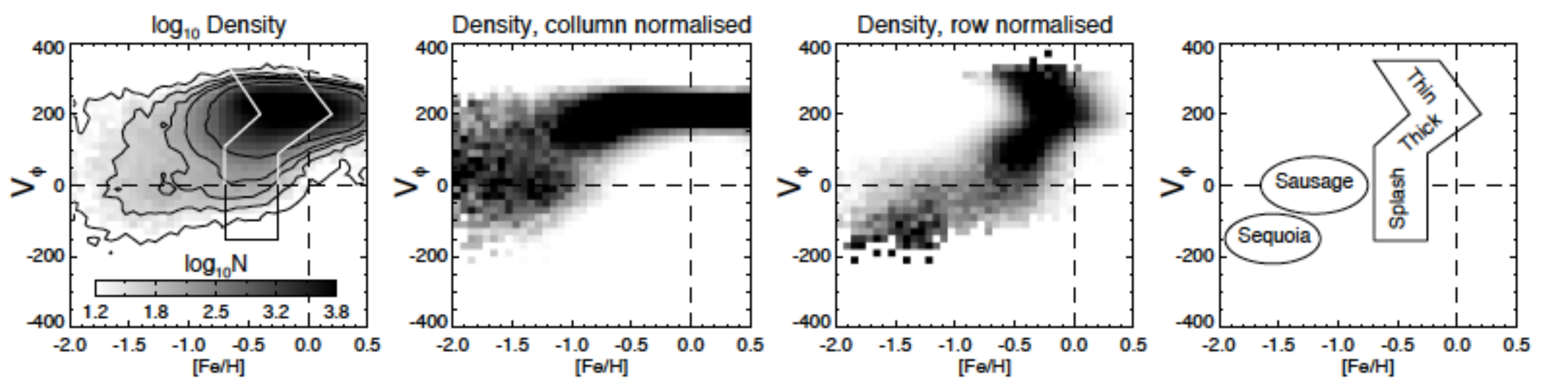
ABSTRACT
The Gaia Sausage is the major accretion event that built the stellar halo of the Milky Way galaxy. Here, we provide dynamical and chemical evidence for a second substantial accretion episode, distinct from the Gaia Sausage. The Sequoia Event provided the bulk of the high energy retrograde stars in the stellar halo, as well as the recently discovered globular cluster FSR 1758. There are up to 6 further globular clusters, including ω Centauri, as well as many of the retrograde substructures in Myeong et al. (2018), associated with the progenitor dwarf galaxy, named the Sequoia. The stellar mass in the Sequoia galaxy is $\sim 5 \times 10^7 \ M_\odot$, whilst the total mass is $\sim 10^{10} \ M_\odot$, as judged from abundance matching or from the total sum of the globular cluster mass. Although clearly less massive than the Sausage, the Sequoia has a distinct chemodynamical signature. The strongly retrograde Sequoia stars have a typical eccentricity of ~ 0.6, whereas the Sausage stars have no clear net rotation and move on predominantly radial orbits. The Sequoia stars have lower metallicity and higher abundance ratios as compared to the Sausage.

Key words: Galaxy: stellar content – Galaxy: halo – Galaxy: formation – Galaxy: kinematics and dynamics

… and Gaia-Enceladus

- Helmi et al. (2019) proposed that a similar ancient major merger - ‘Gaia-Enceladus' - could have given rise to the bulk of the retrograde stars in the halo as well as the low-angular momentum debris.
- Selection criteria of $L_z < 150$ kpc km/s.
- Gaia-Enceladus is a melange, a mish-mash of the Sausage and the Sequoia.

… and The Splash

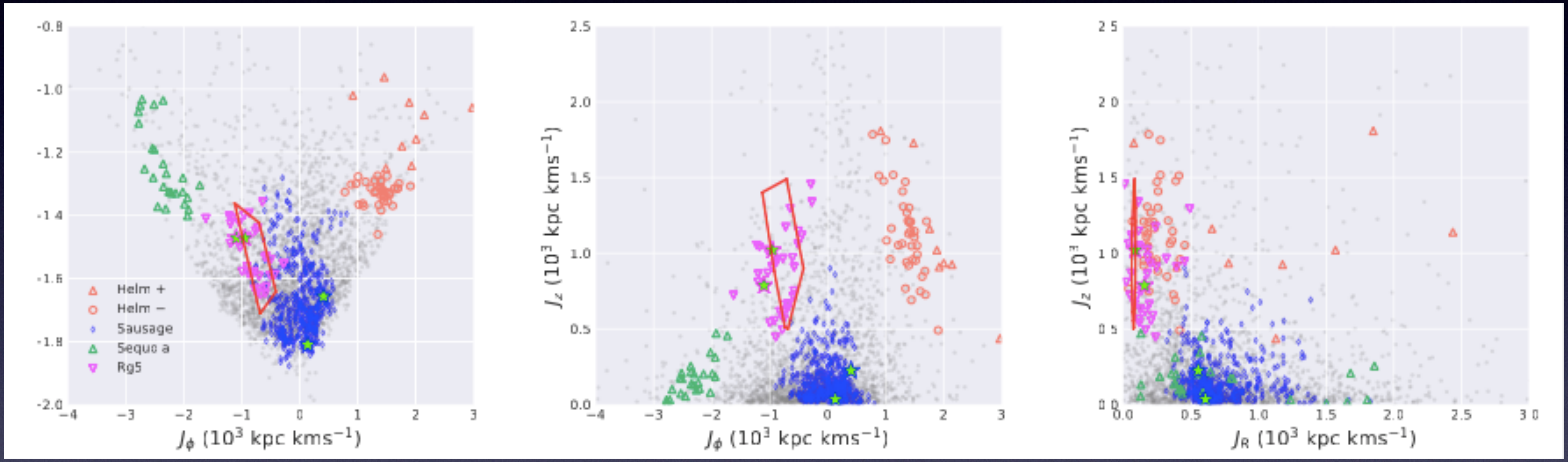


Belokurov et al 2019

Splash stars have little or no angular momentum, but are as metal-rich as the Thick Disk.The Splash stars may have been born in the Milky Way's proto-disc prior to the Sausage which drastically altered their orbits.

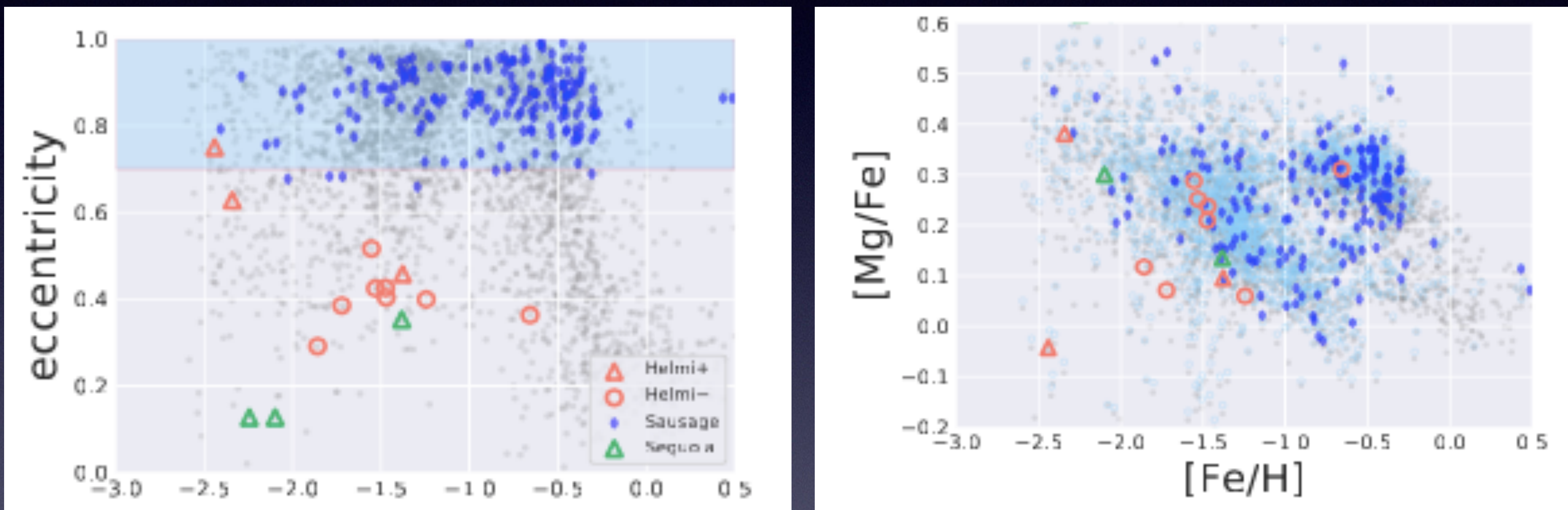
The VMP stars

Yuan et al 2019



Many of the substructures are also seen in an independent analysis with Self Organising Maps applied to the LAMOST Very Metal-Poor Catalogue ([Fe/H] <-2)

The VMP stars



Yuan et al 2019

Notice the eccentric stars are split into two sequences in the alpha/metallicity plane

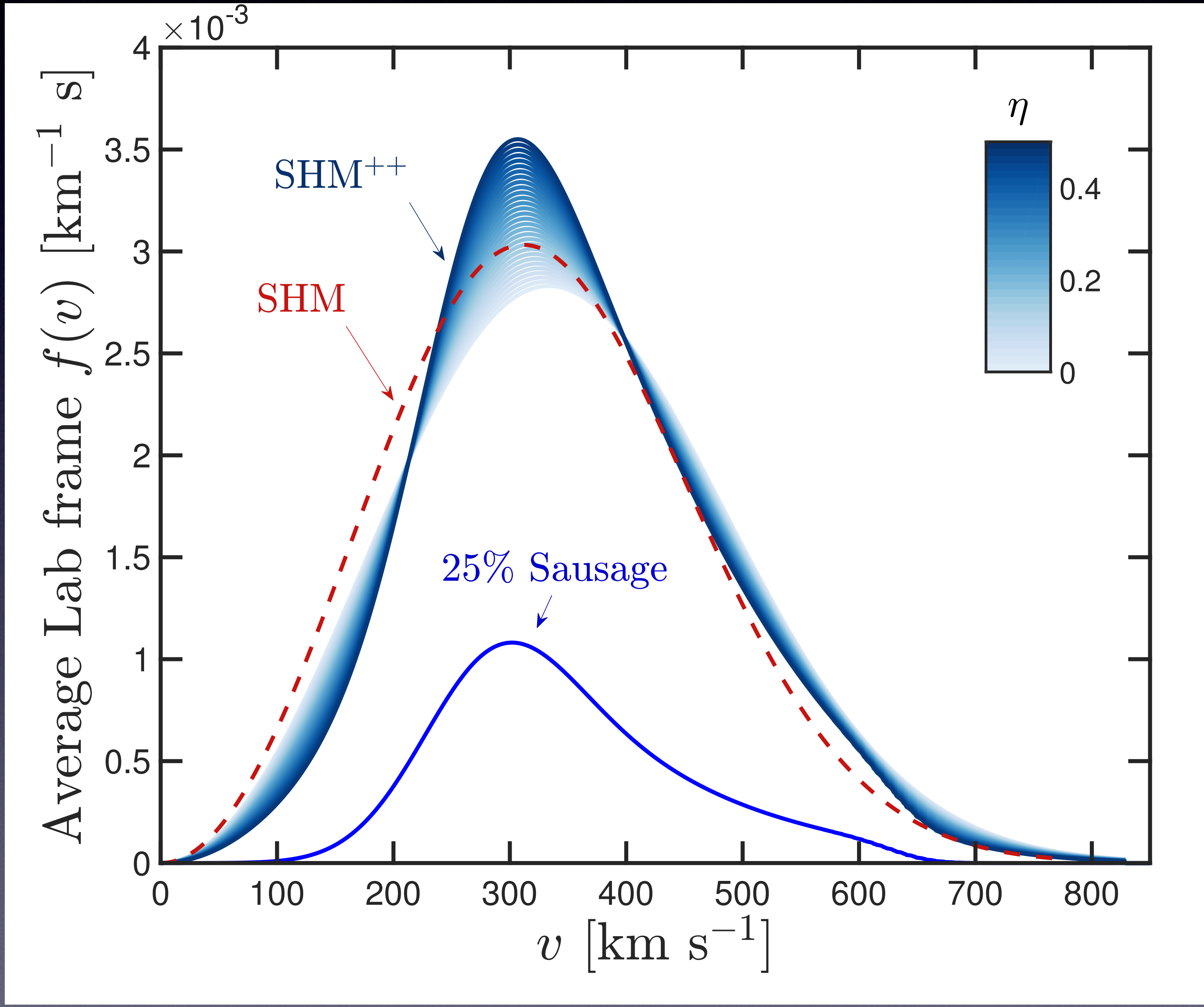
The Dark Sausage

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

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

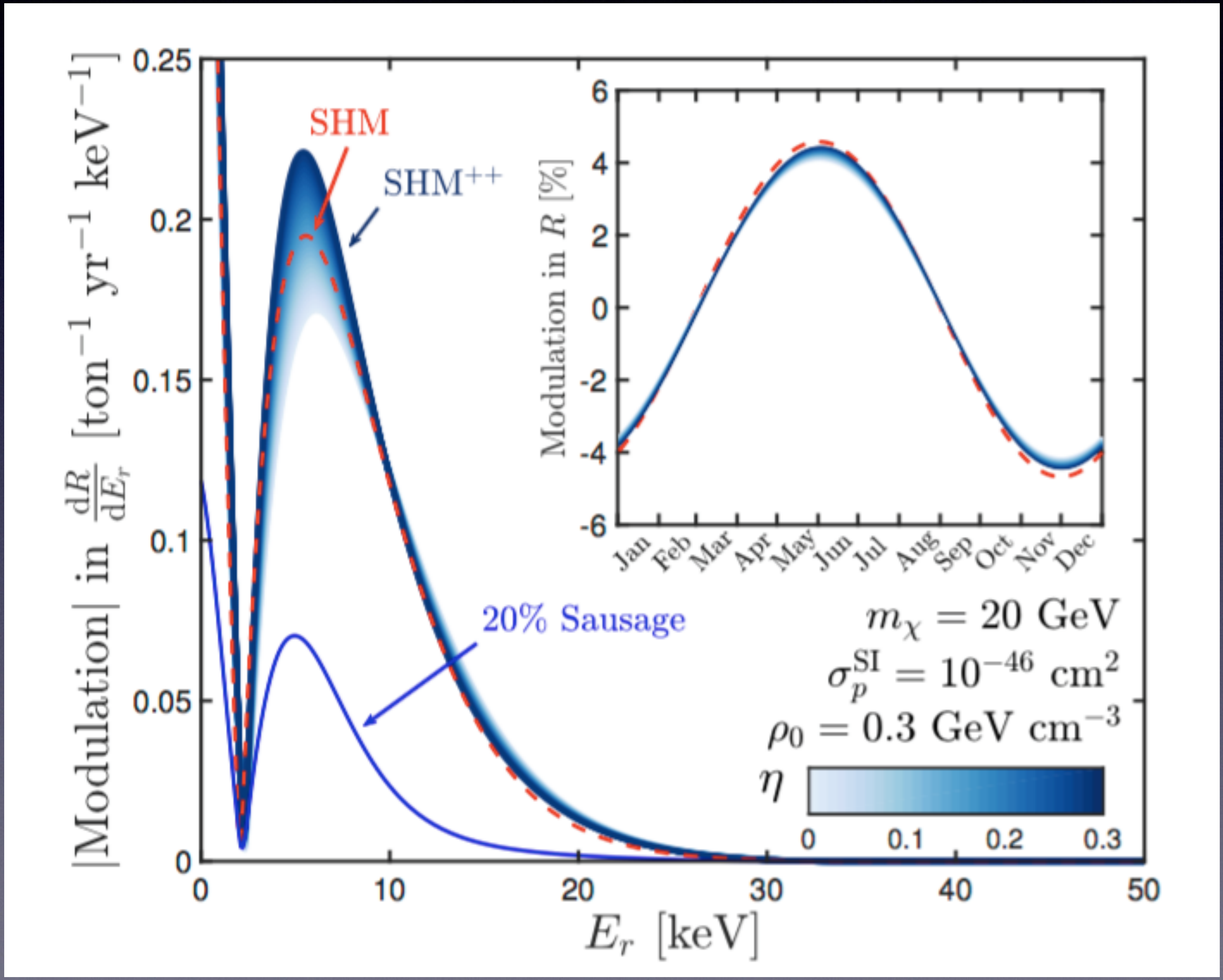
Here, η is the fraction of dark matter in the Sausage (~ 20±10%). Gaia has also provided new measurements of the local circular speed (=233±2 kms^{-1}) and the escape speed (~528±24 kms^{-1}).

The Dark Sausage

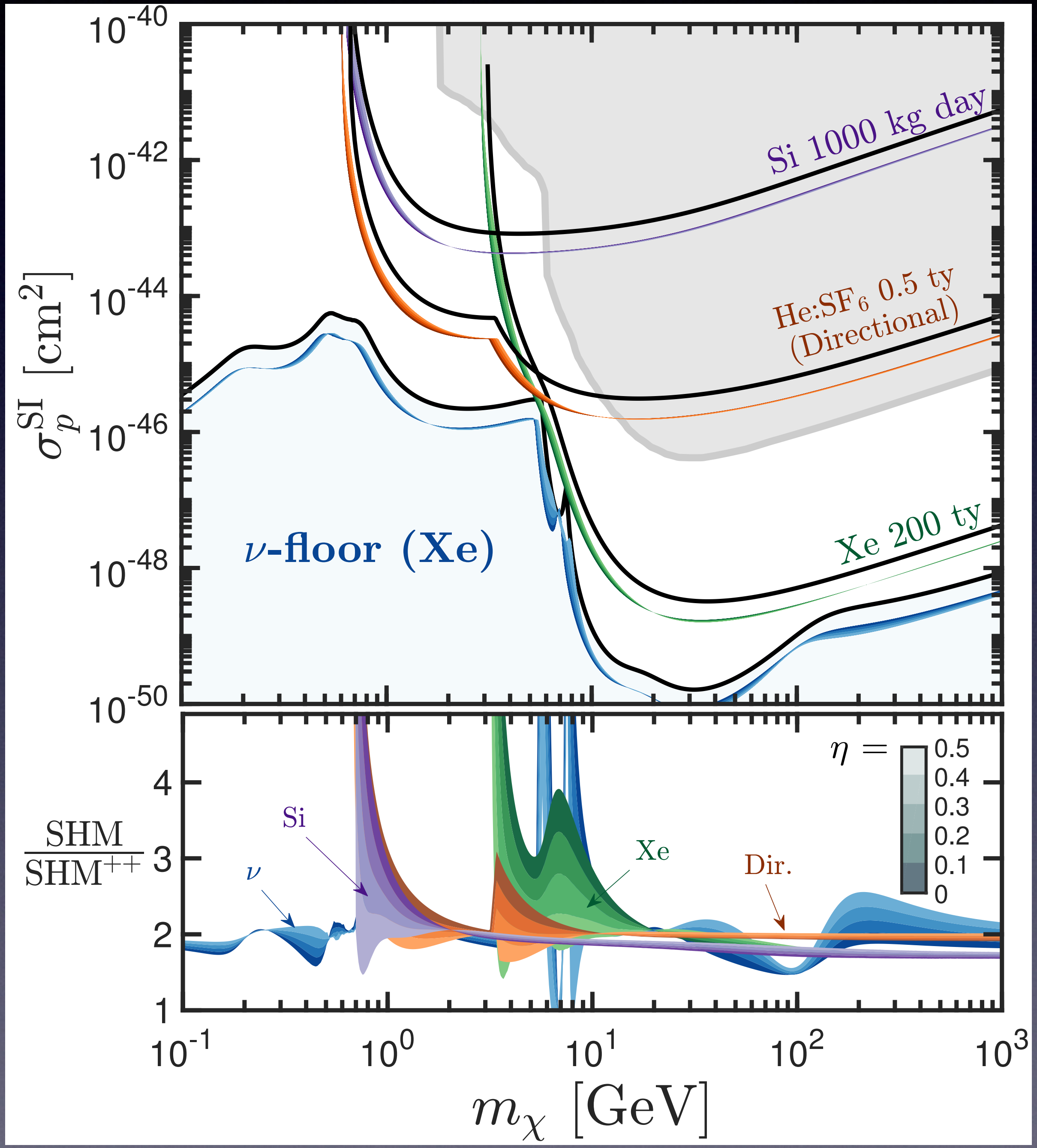


Average lab frame for velocity distribution depending on Sausage fraction

THE DARK SAUSAGE



The Dark Sausage

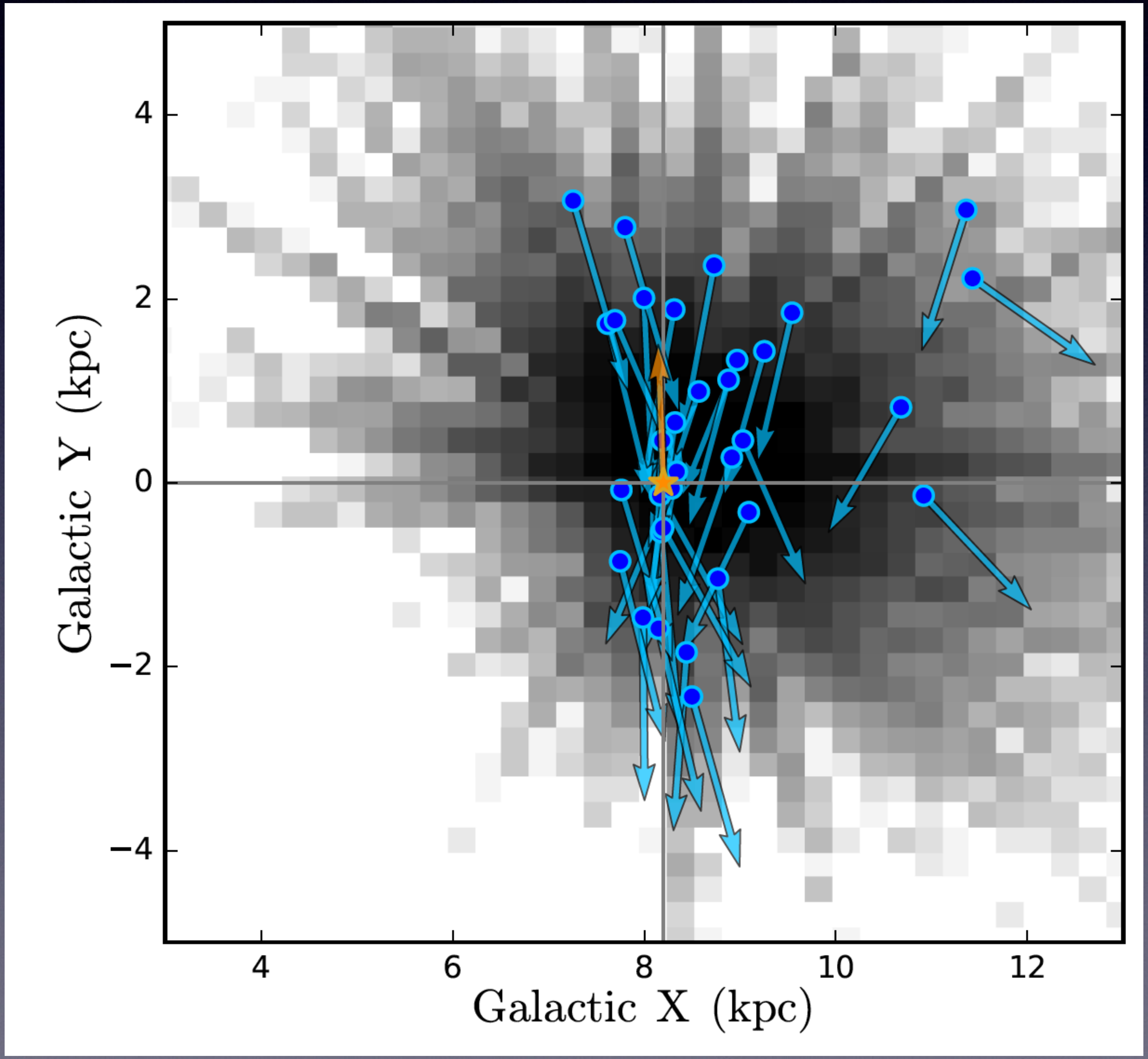


Orange: directional detection (using He and SF_6 gas mixture)

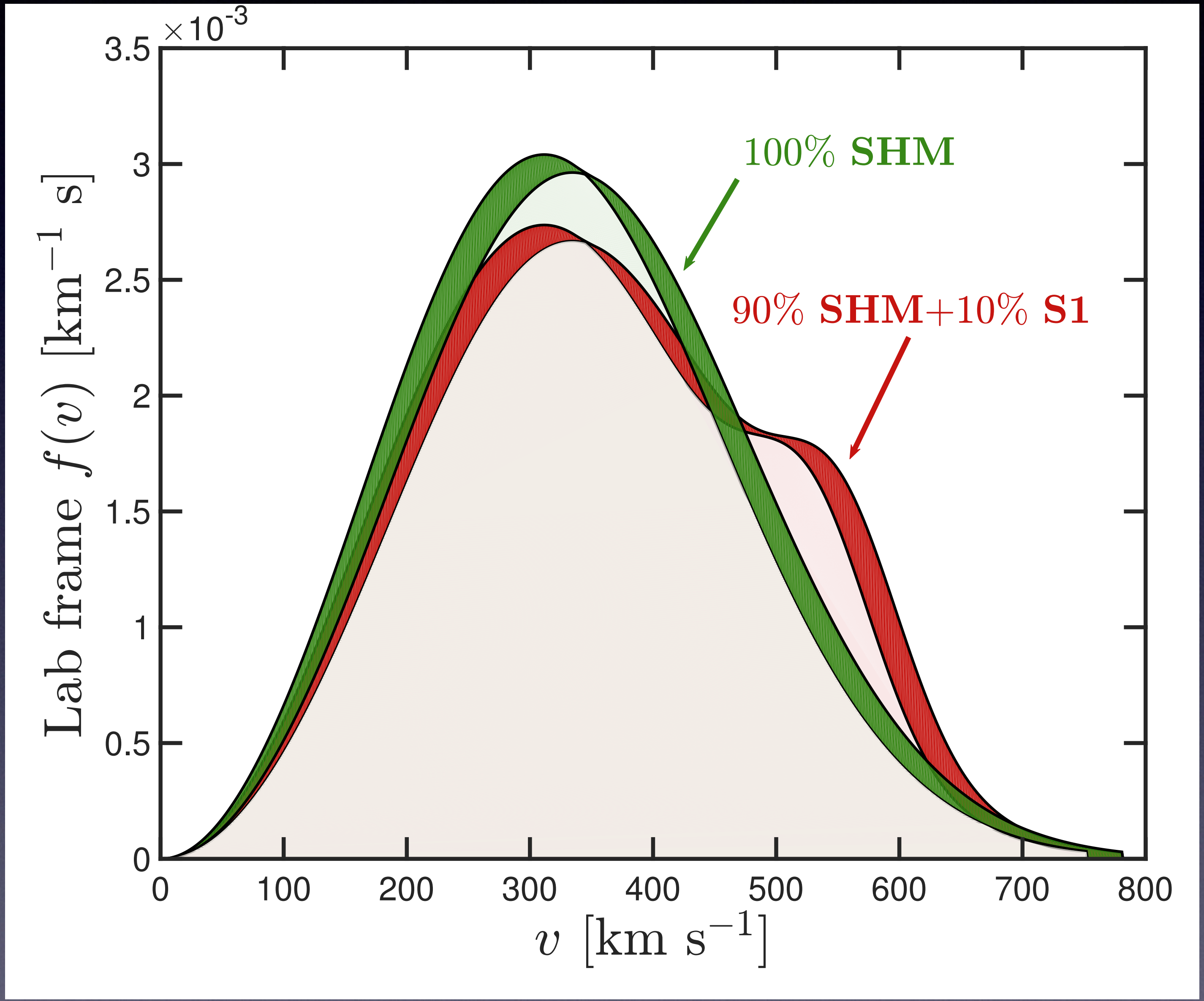
Green: a 200 ton-year exposure liquid Xe experiment (like DARWIN)

Exclusion limits, black lines are old SHM, coloured lines SHM^{++}

The Dark Matter Hurricane



S1: The DM Hurricane



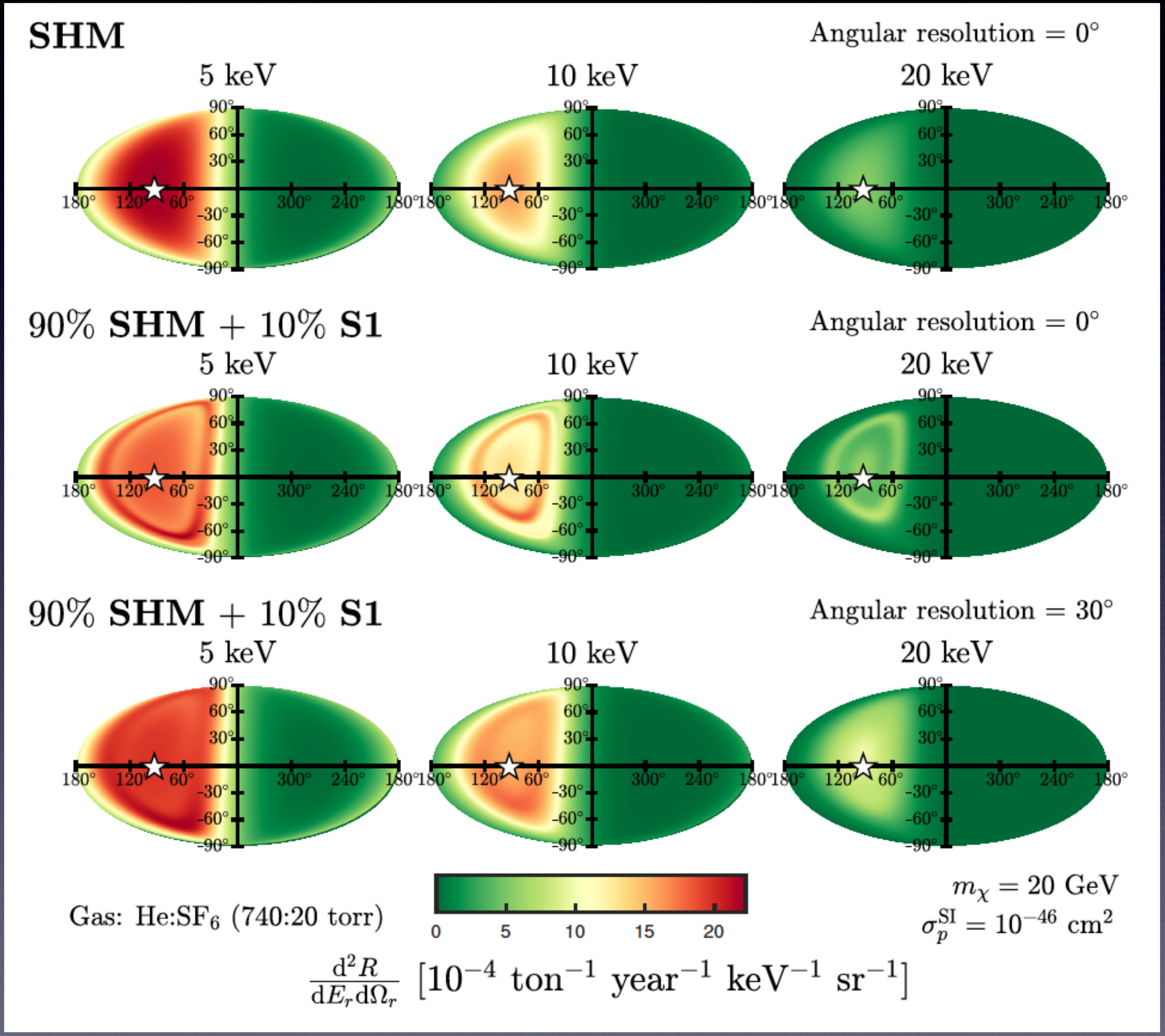
O'Hare et al 2018

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

S1: The DM Hurricane

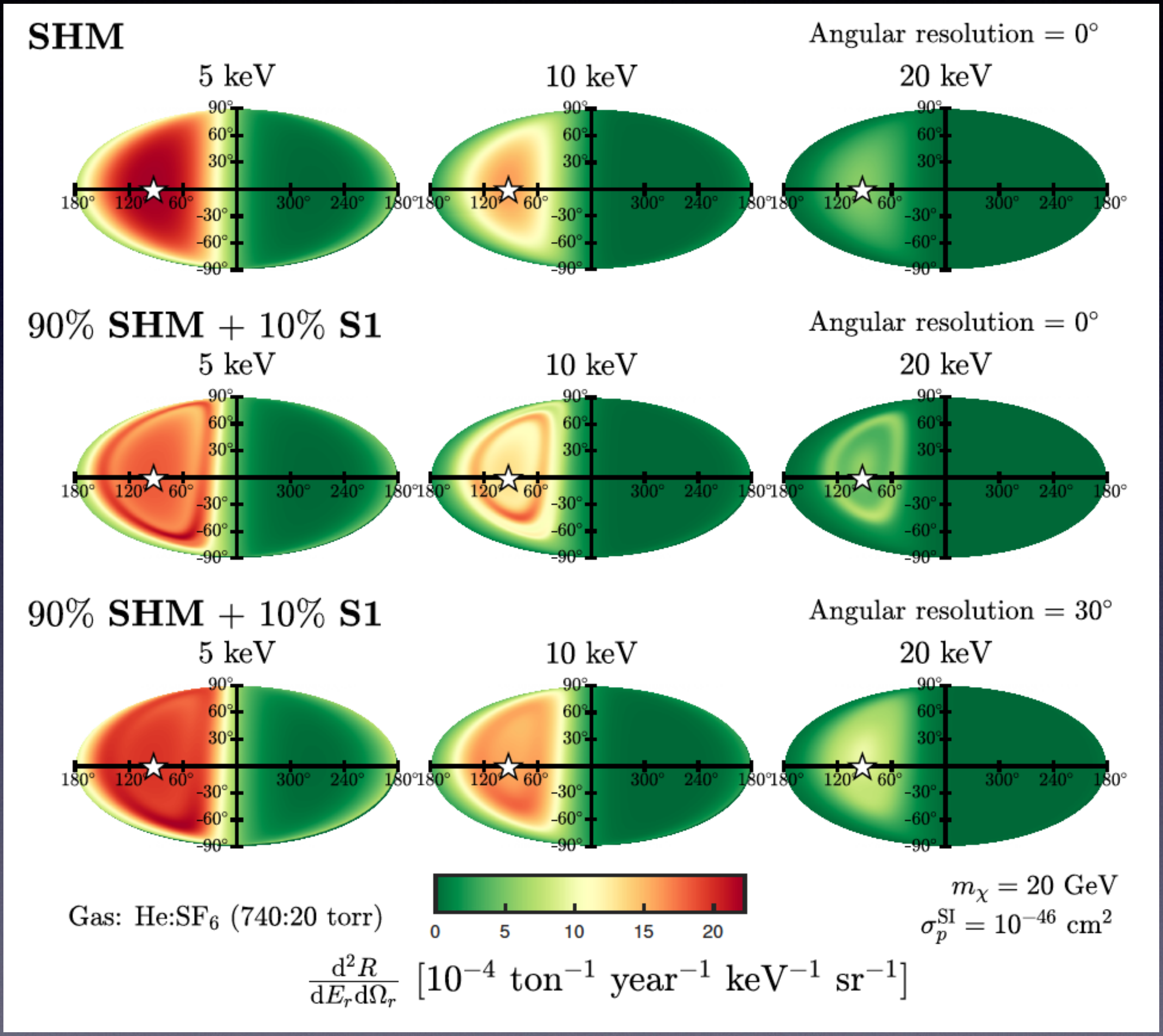
- In directional DM detection, the incoming velocity of the weakly interacting massive particle (WIMP) in a Stream is at a characteristic velocity.
- There is an exact relationship between recoil energy and scattering angle. At a given recoil energy, streams appear as rings in directional detection experiments.

S1: The DM Hurricane



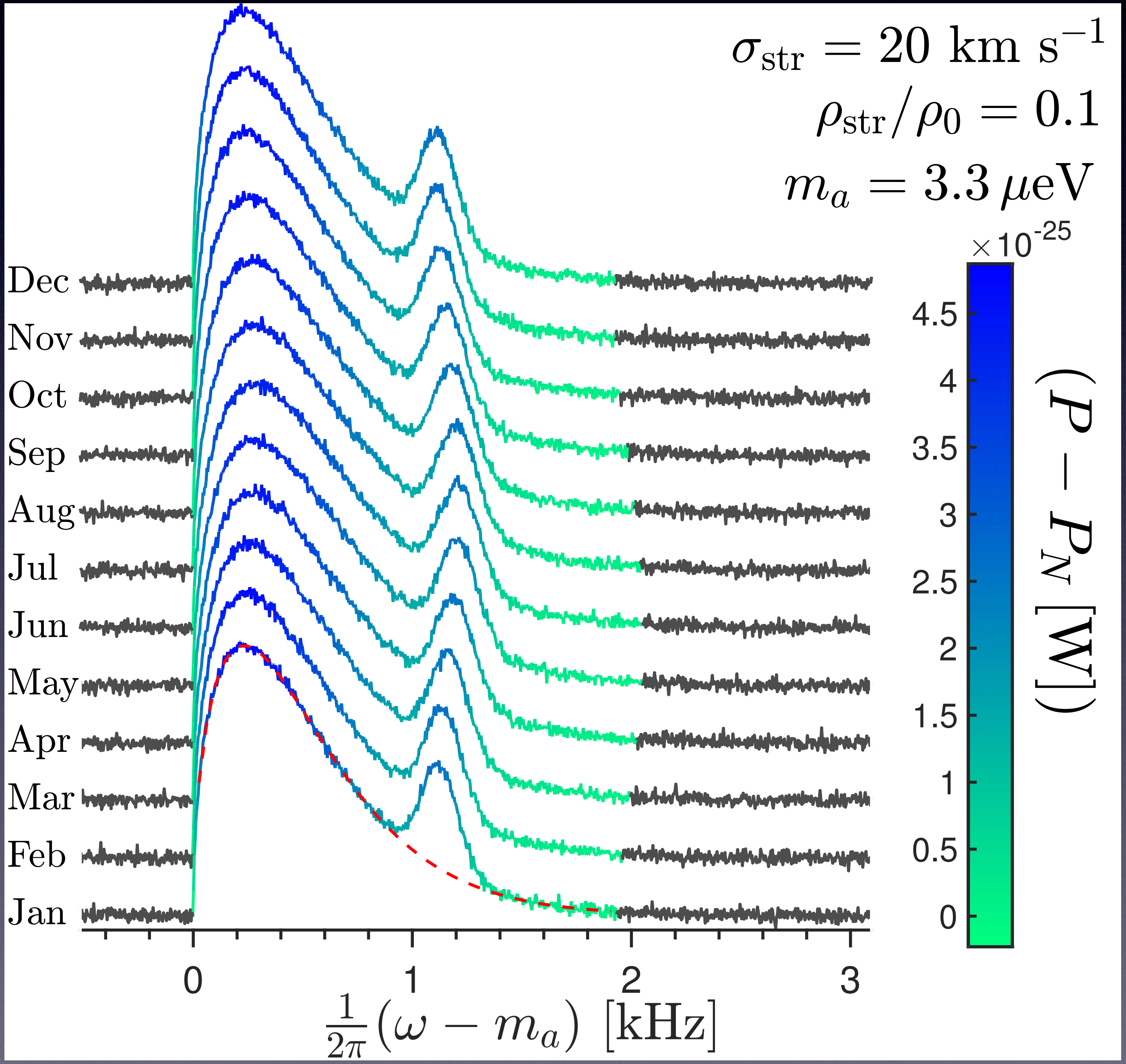
Double differential angular recoil rate as a function of inverse of recoil direction in Galactic coordinates

S1: The DM Hurricane



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

S1: The DM Hurricane

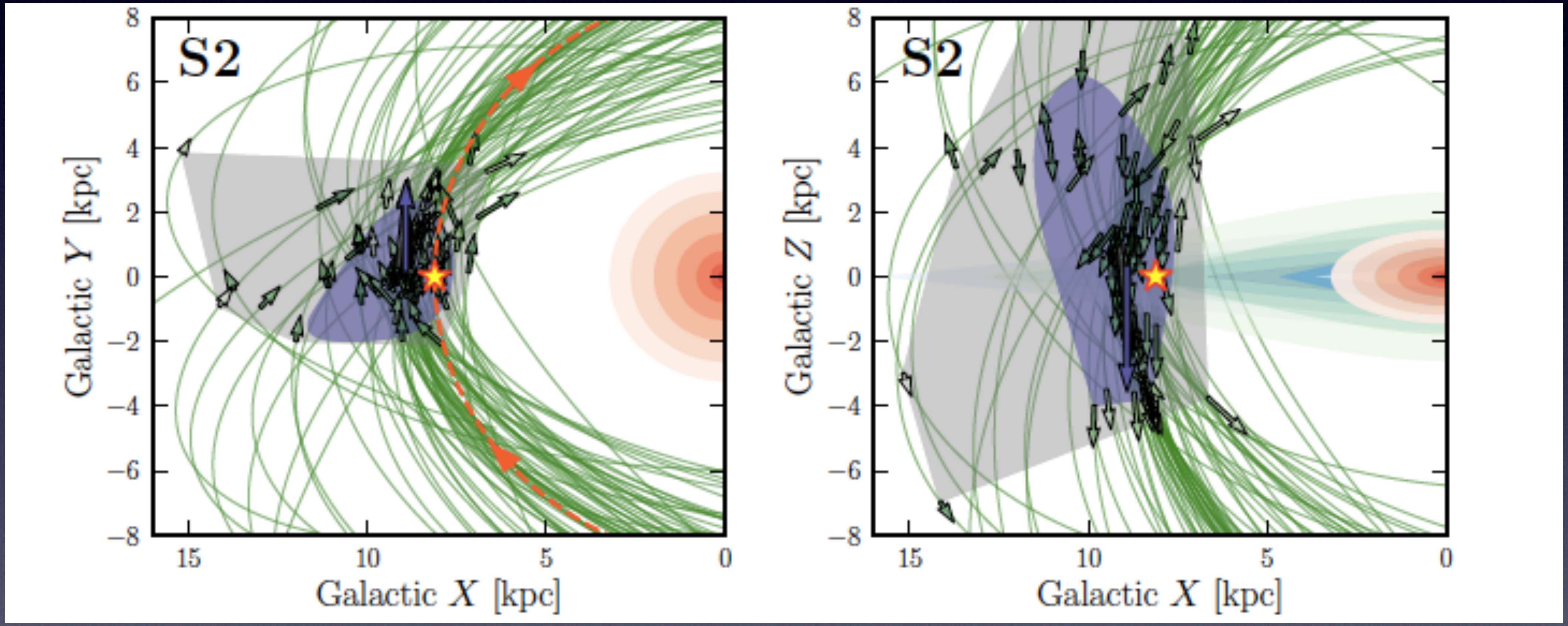


In a strong magnetic field, the axion converts its kinetic energy to a photon (ADMX). The axion power spectrum as a function of frequency enables us to read of the DM speed distribution.

S1: The DM Hurricane

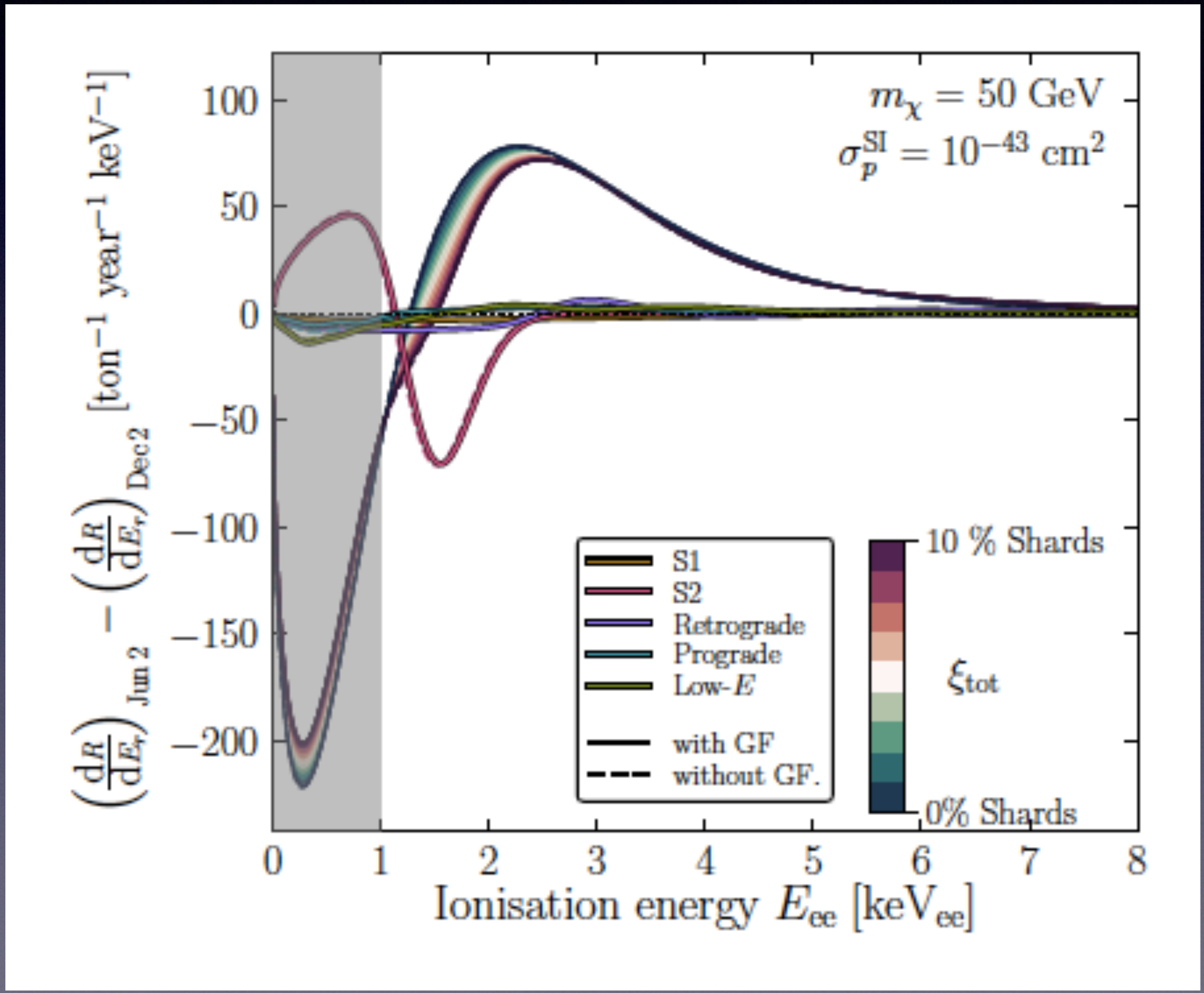
- Excellent prospects for detecting S1 in directional detectors (such as the proposed CYGNUS experiment) and axion haloscopes.
- Non-directional detectors are more limited,as much directional information is lost in the process of nuclear scattering.
- If detected, this is a convincing signal of DM.

S2: Annual Modulation

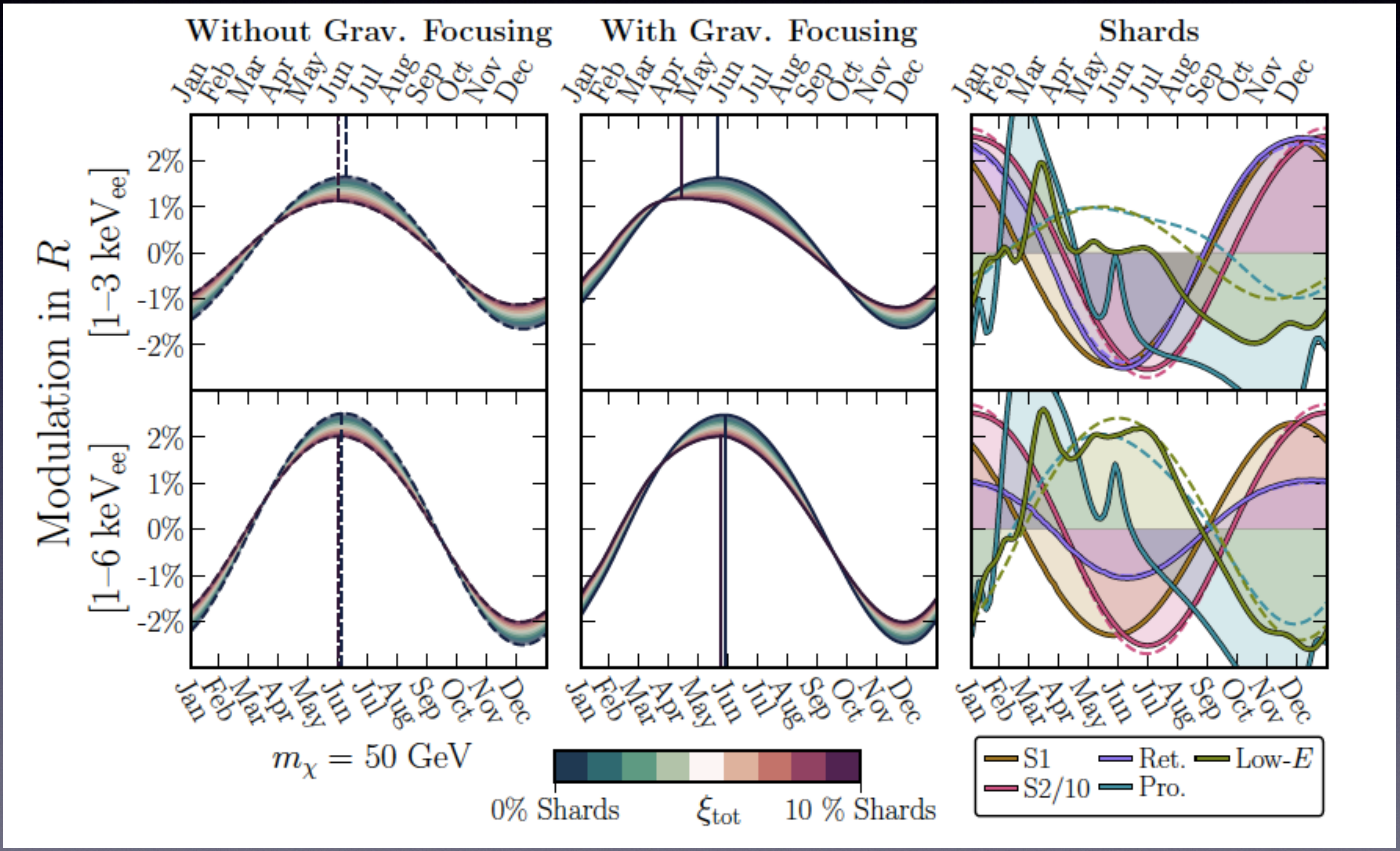


Most of the S2 stream has $v_z<0$, but there is a component with $v_z > 0$

S2: Annual Modulation



S2:Annual Modulation



Open Questions

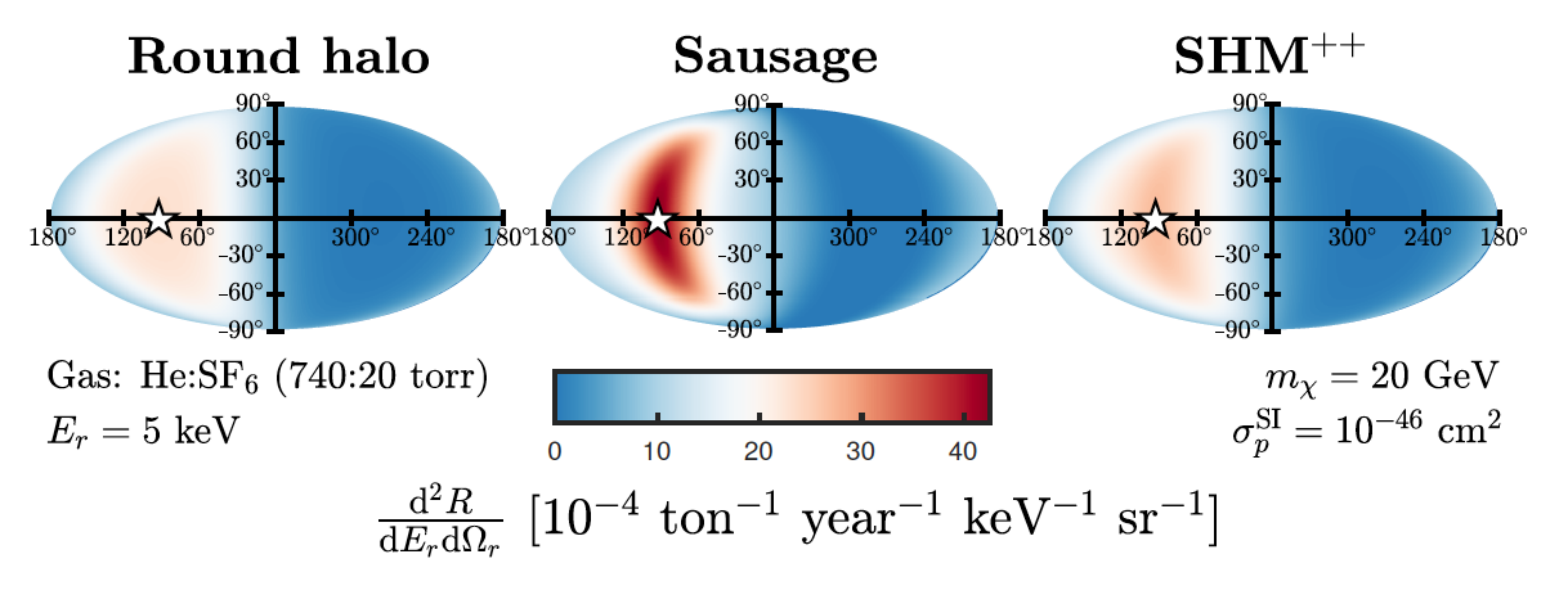
- How robust are the substructure searches? Zhen et al (2019) found some, but not all, of the substructures identified in Myeong et al (2018a,b)

- Substructure searches provide the stellar velocity distribution. What is the best way to relate the stellar velocity distribution to the DM velocity distribution?

Open questions

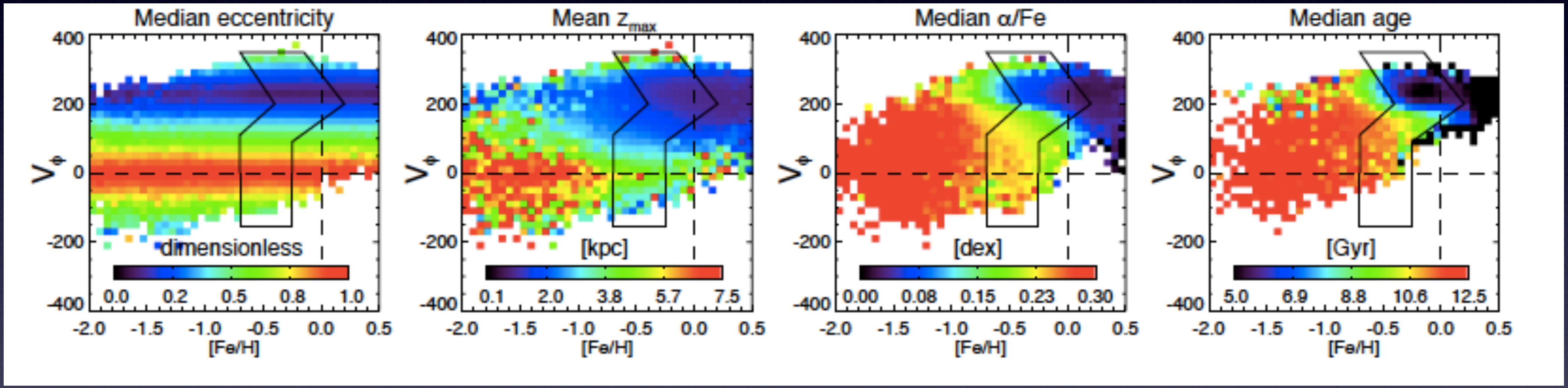
- Why do the DM velocity distributions inferred from simulations not correspond to analytic DFs ?
- What are the principal sources of error when a DM velocity distribution is inferred from the simulation?

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

… and the Splash



They are old, but not as old as stars deposited in the Sausage merger.

The Sequoia Event

Mackereth et al (2019) showed that halo stars with high eccentricity orbits tend to have lower [Mg/Fe] on average compared to the rest of the halo stars.

Matsuno et al. (2019) claim the knee in the abundance and metallicity plane differs by about 0.5 dex for the retrograde component and the Sausage (SAGA x APOGEE)