the un-title

"… please send me a title for your talk ASAP. It is more important for me to get the title quickly than it is for it to be beautiful …"

(Heidi, 26.02.2019 22:08 GMT)

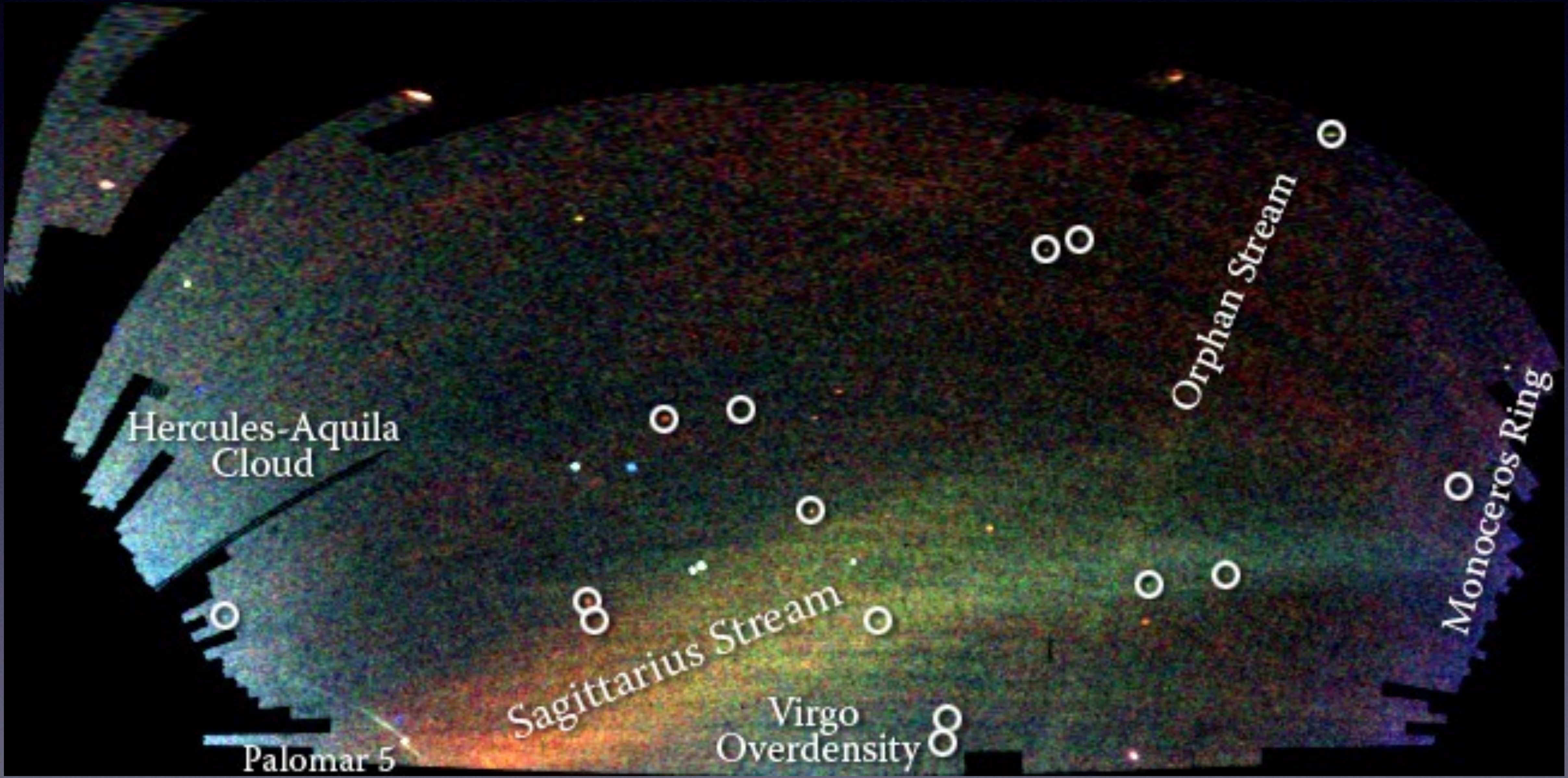
The Sausage and the Sequoia

N W Evans, Institute of Astronomy, Cambridge

Work with **GyuChul Myeong**, Vasily Belokurov, Sergey Koposov, Jason Sanders, Ciaran O'Hare, Christopher McCabe, Guilano Iorio, Eugene Vasiliev.

Santa Barbara, April 2019

Milky Way Substructure



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

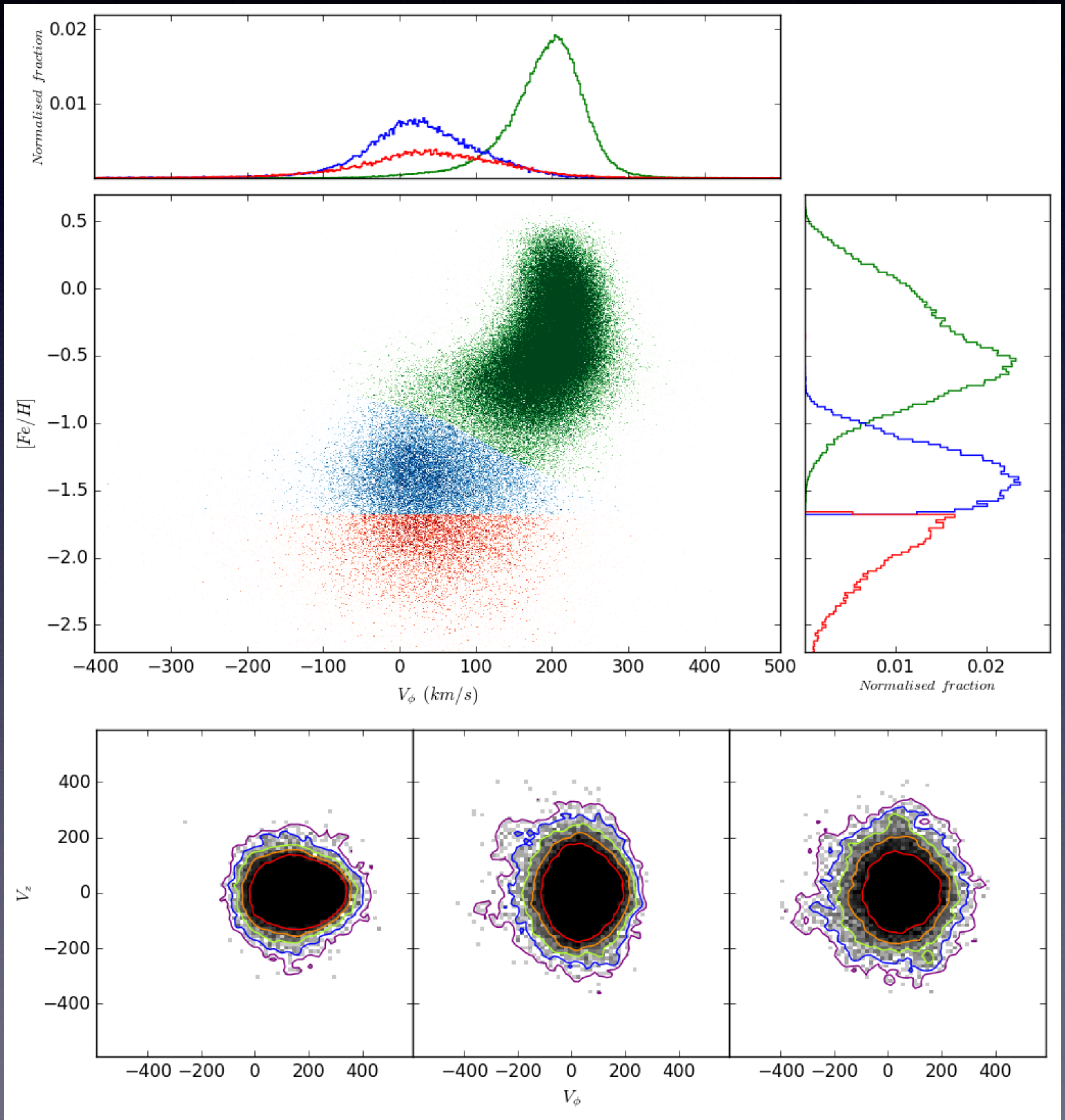
Local Stellar halo in 7-D

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

The Retrograde S1 stream



Sample of ~250,000 with D < 5 kpc

Myeong et al 2018a

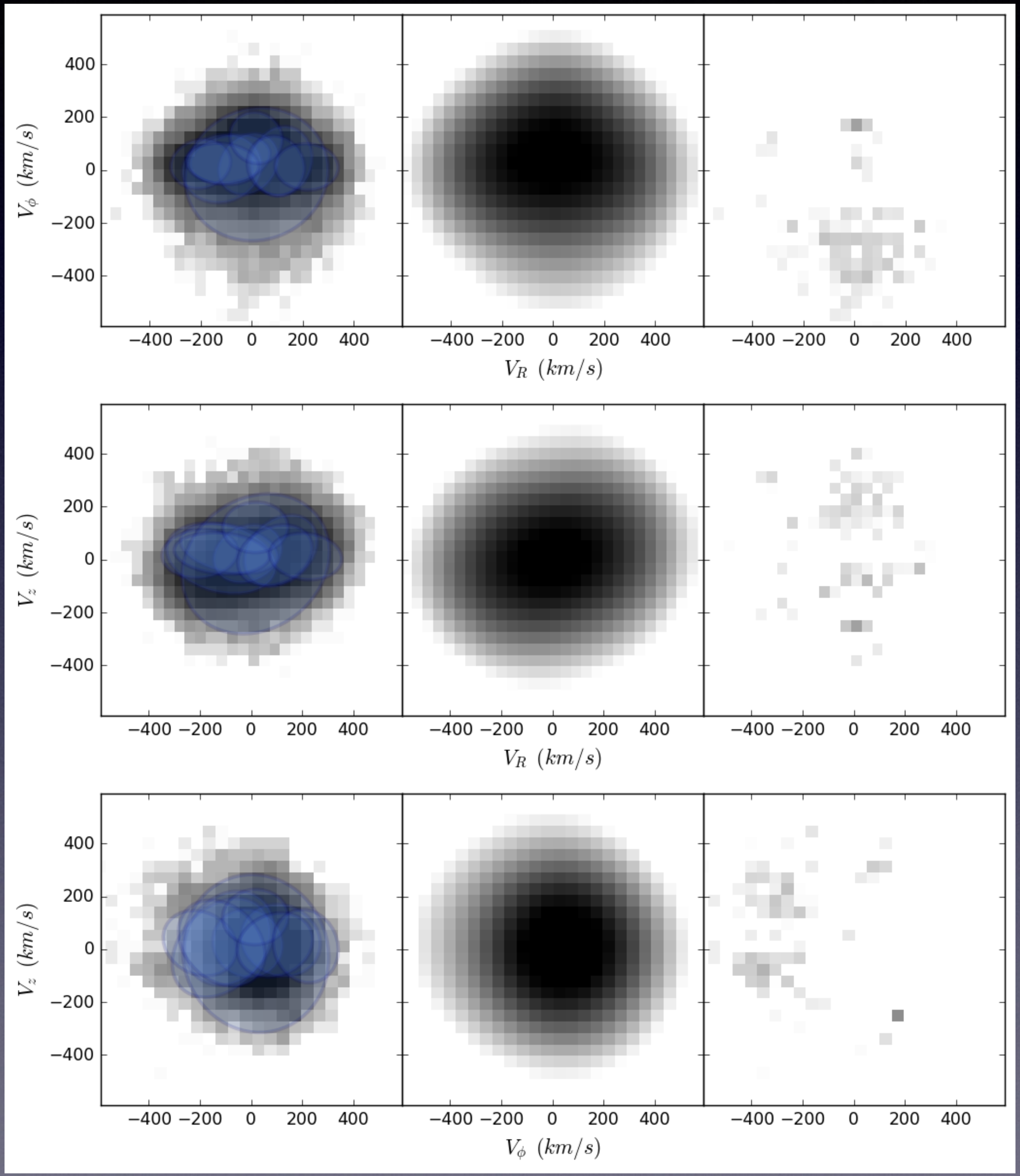
The Retrograde S1 stream

- 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).

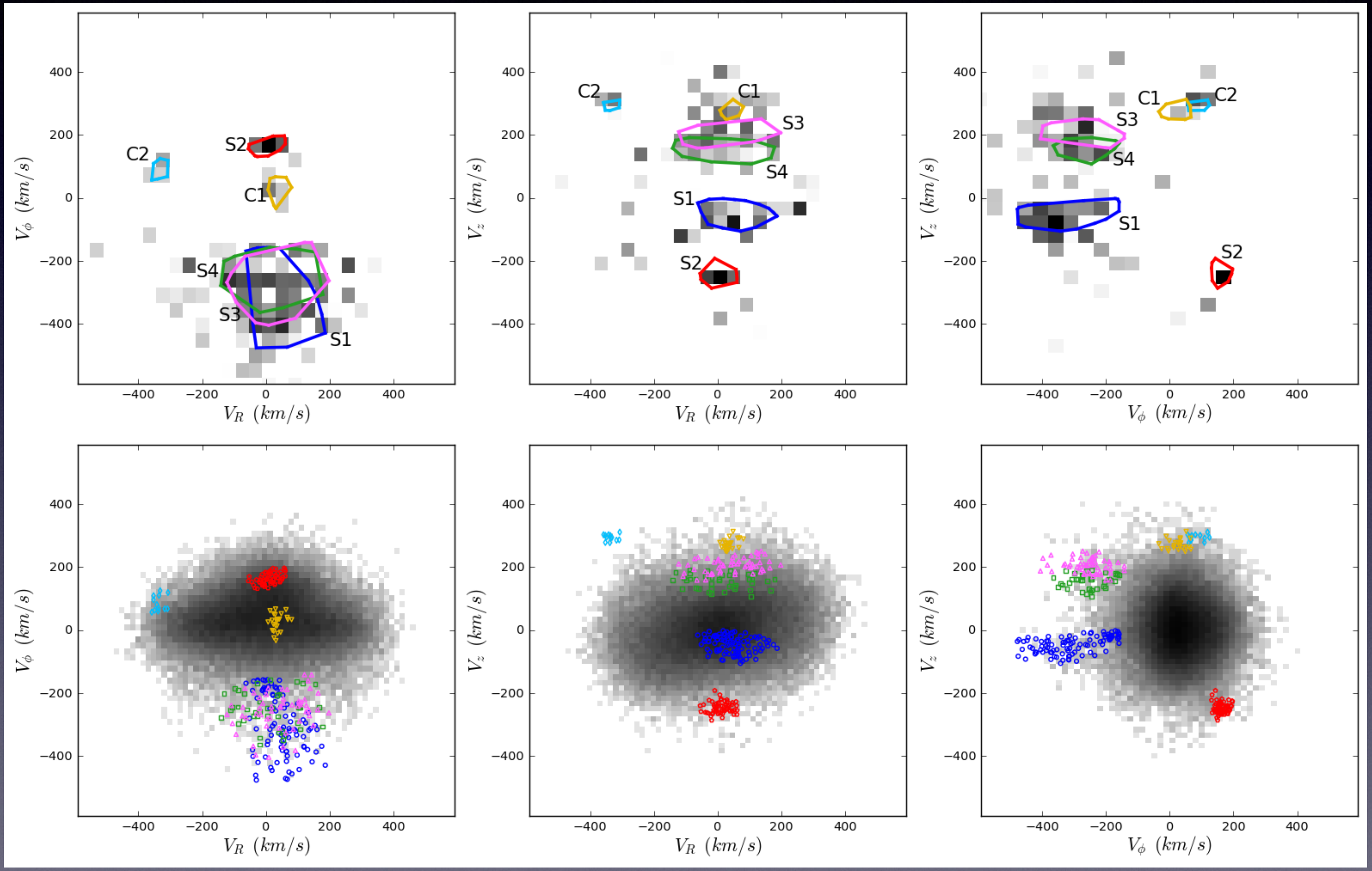
- The significance of any over density can be assesses via (measured number - expected number) / Poisson uncertainty.

The Retrograde S1 stream



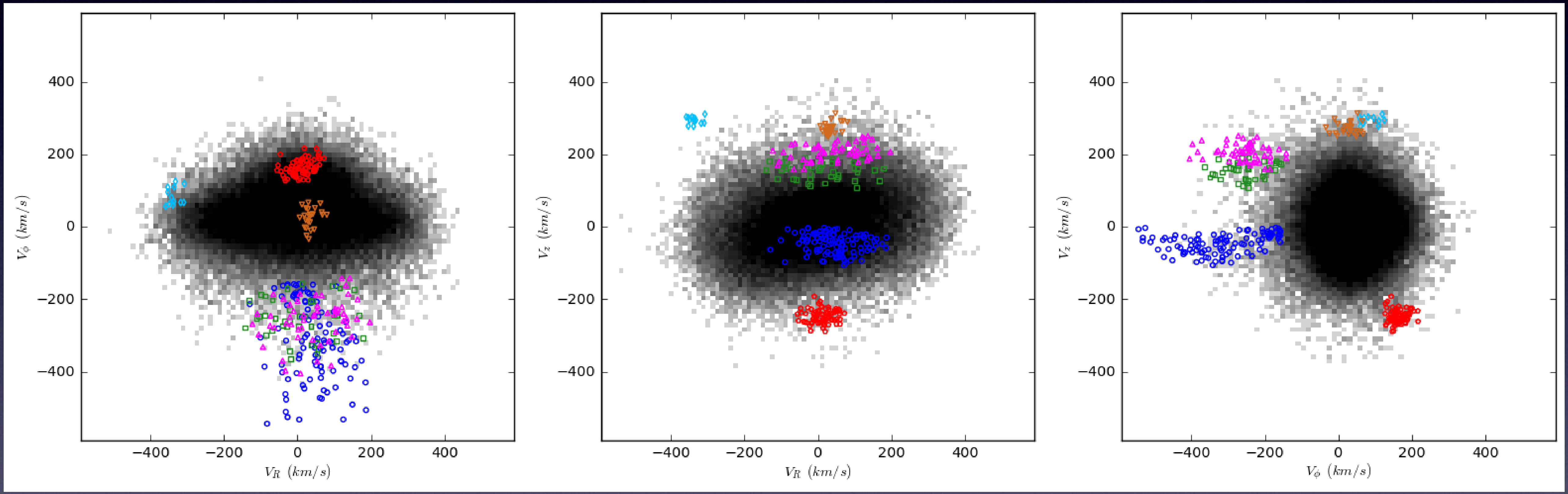
Myeong et al 2018

The Retrogarde S1 stream



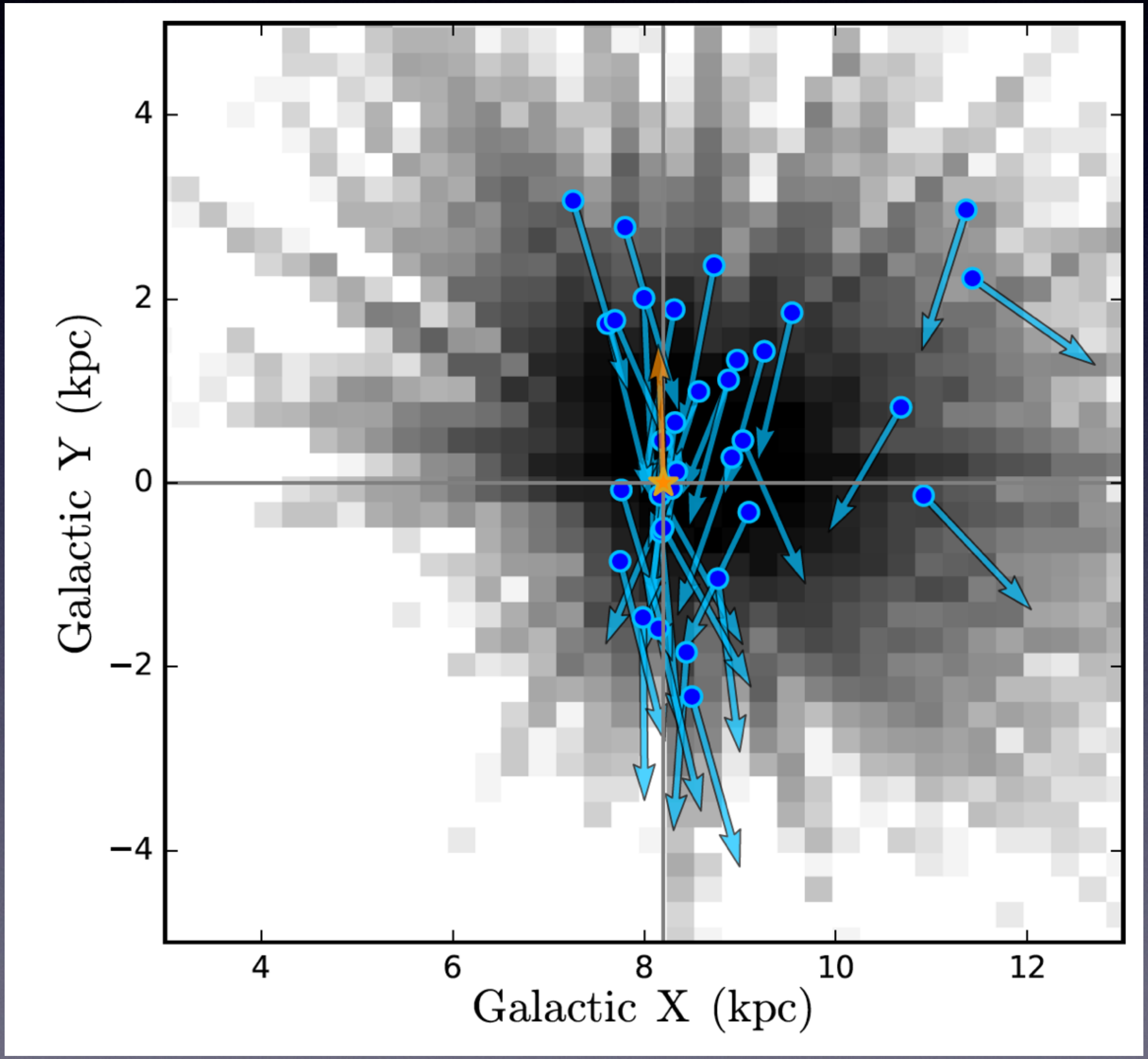
Myeong et al 2018a

The Retrograde 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 Retrograde S1 stream

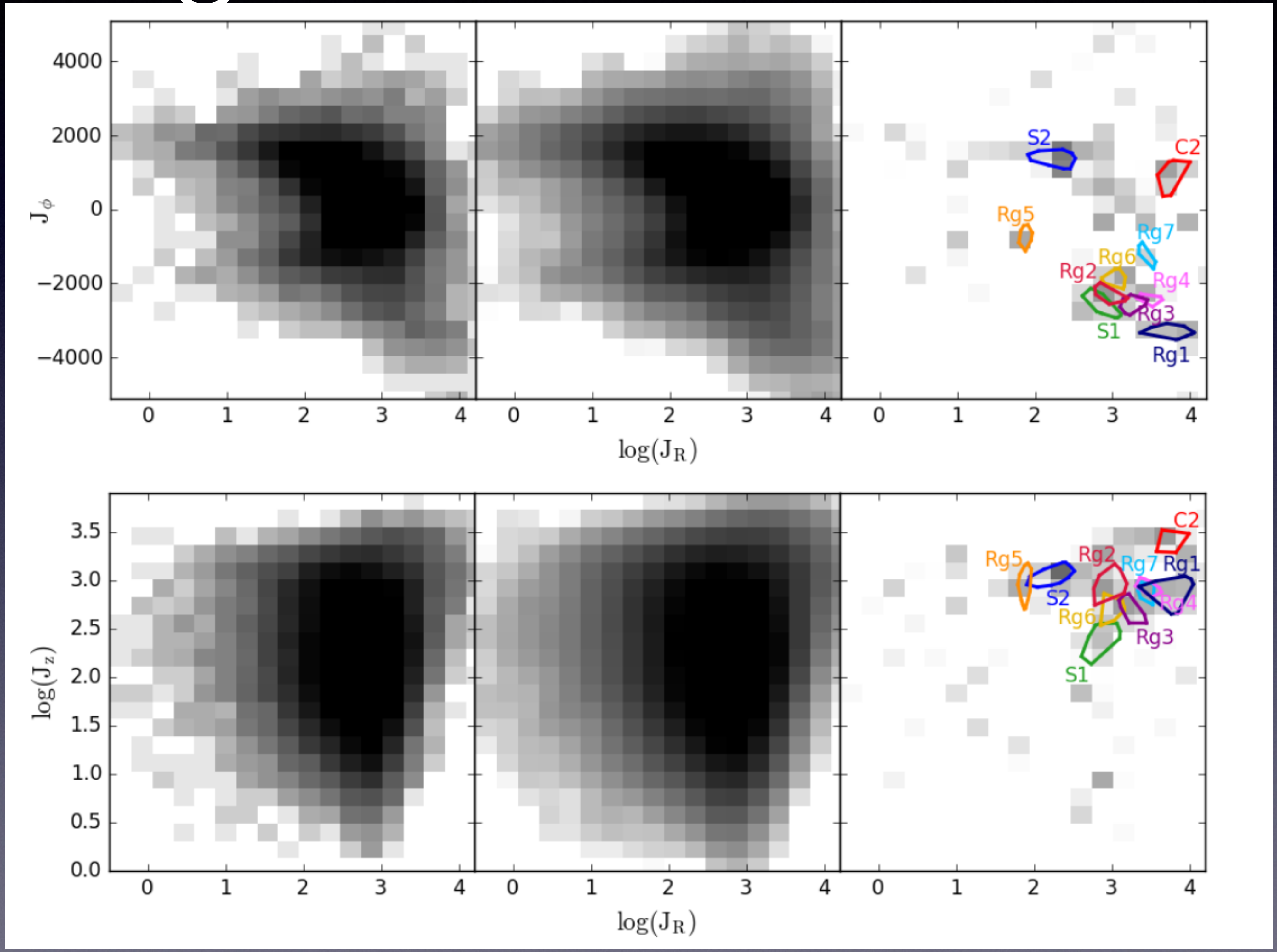


O'Hare et al 2018

Retrograde Substructures

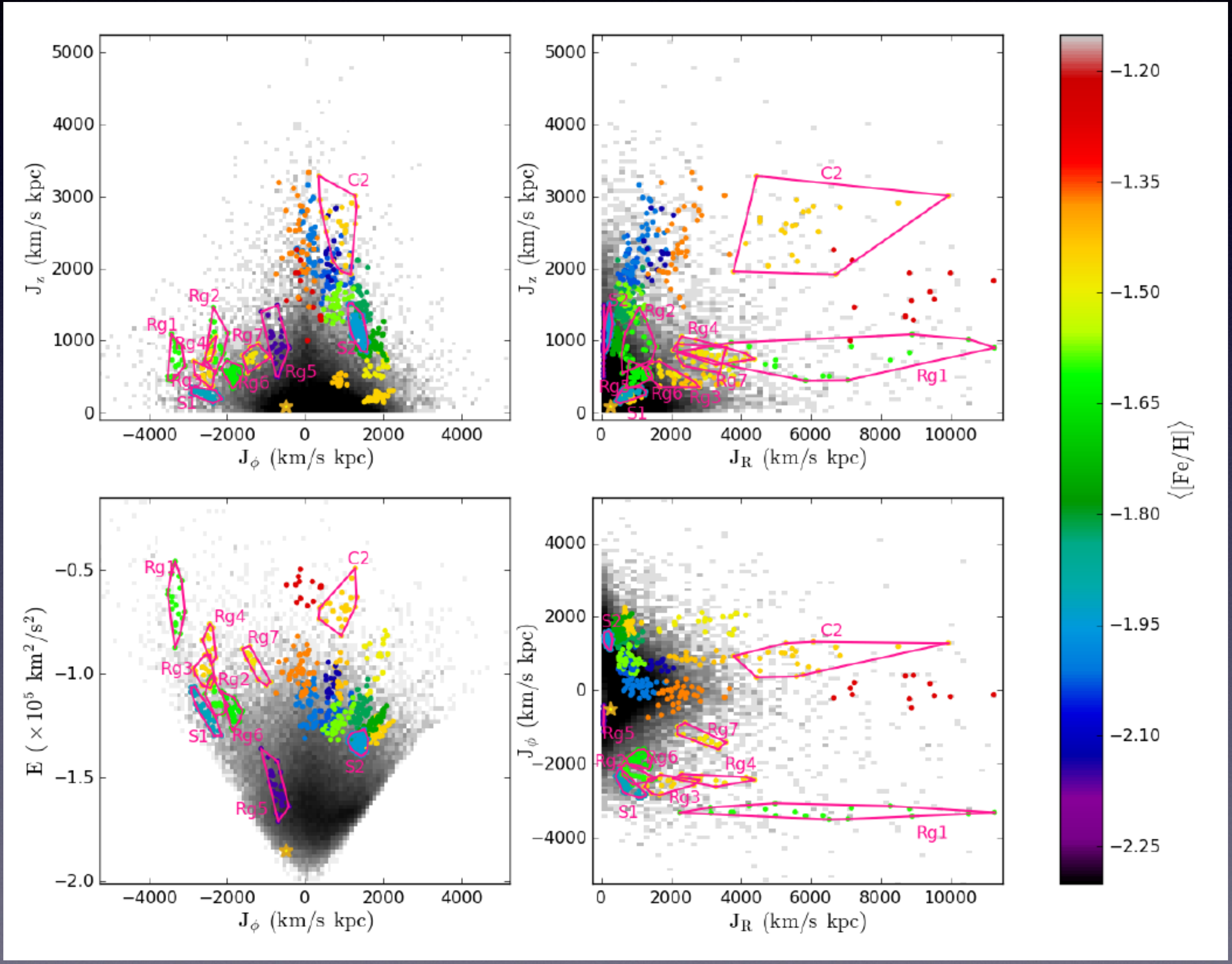
- The highly retrograde S1 stream was discovered by Myeong et al. (2018a) by a substructure search in velocity space.
- Myeong et al (2018b) complemented this with a search through the same Gaia-SDSS data in action space.

Retrograde Substructures



Myeong et al 2018b

Retrograde Substructures



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

- 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.

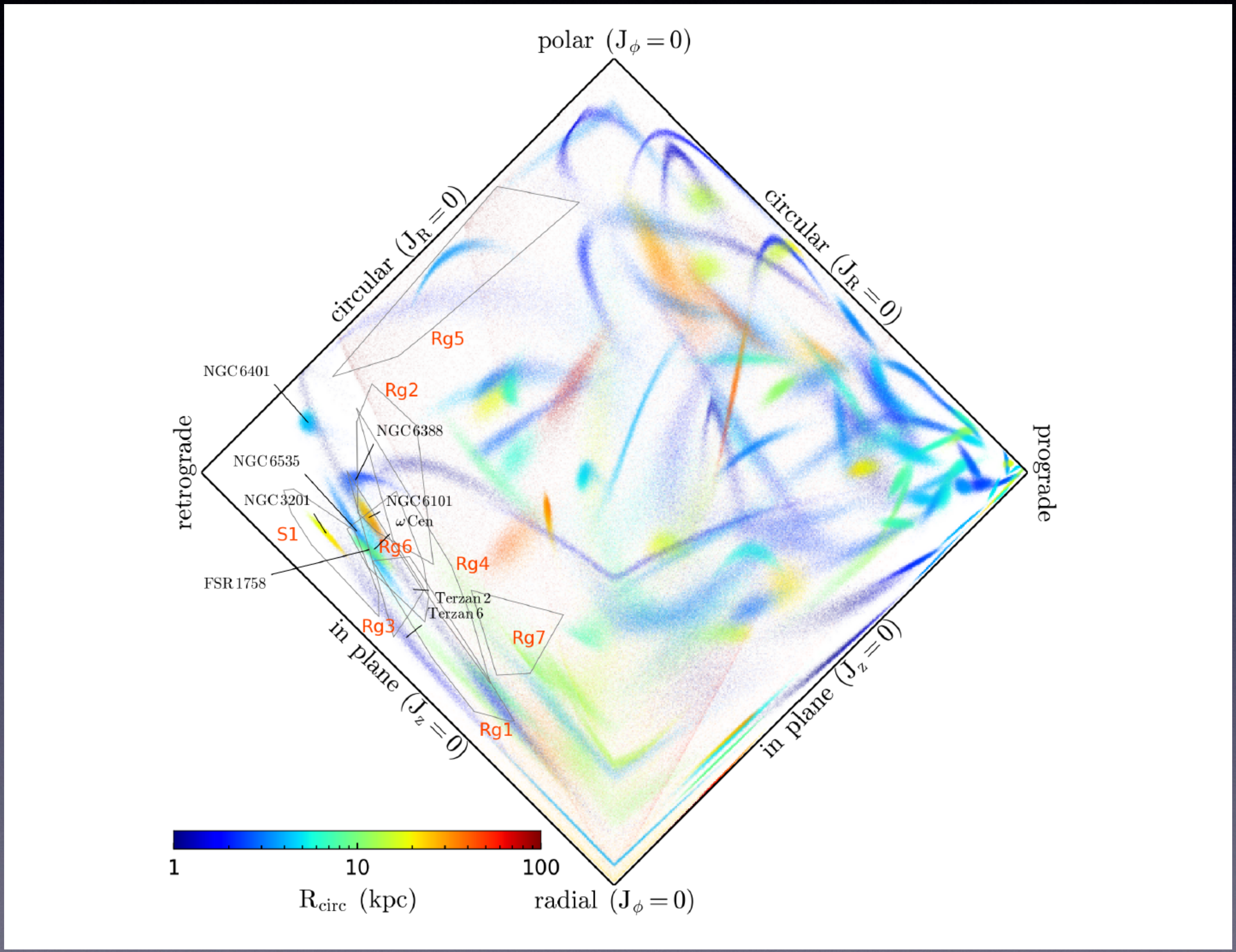
The Retrograde FSR 1758

- 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.

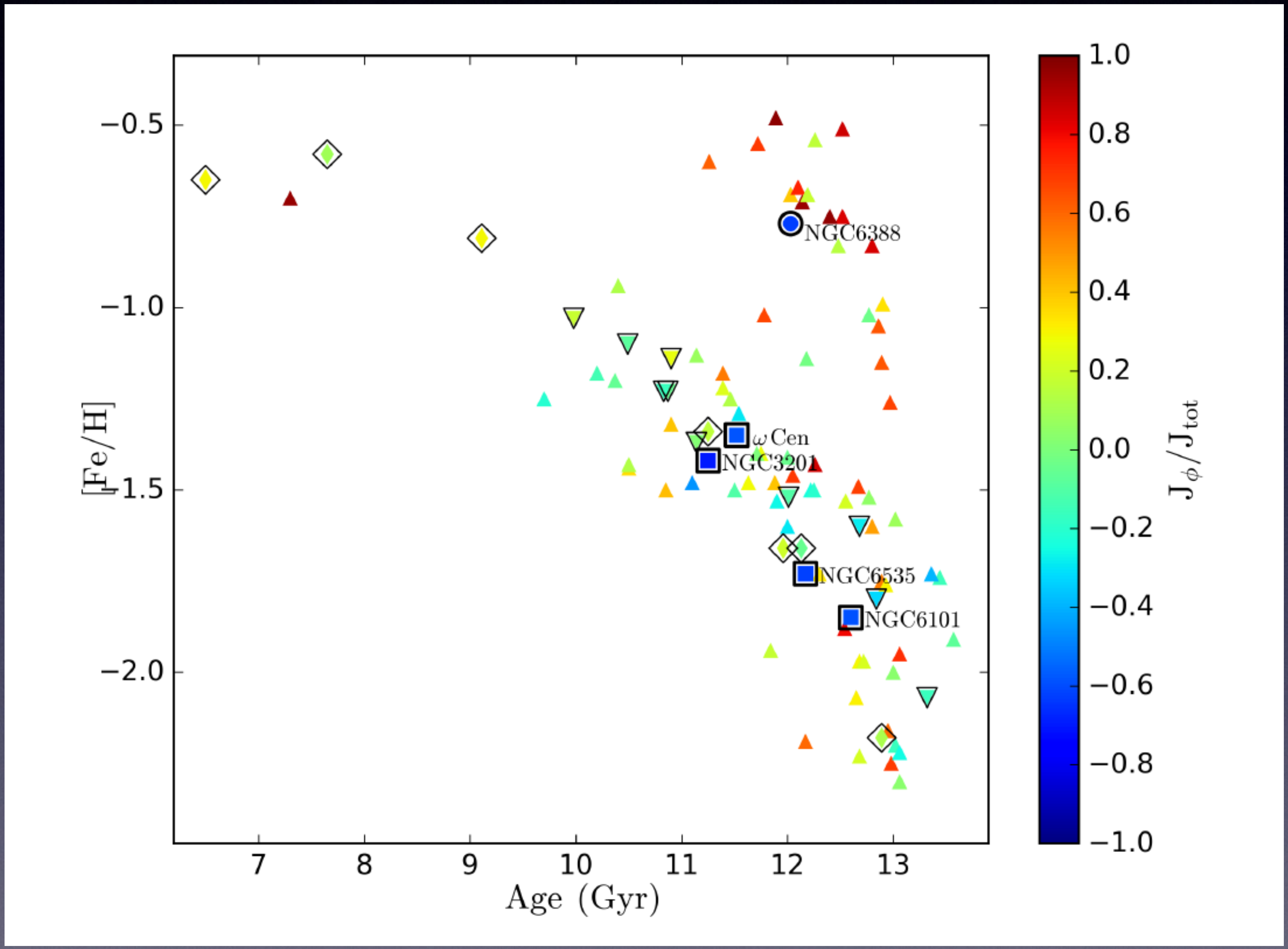
- Simpson (2019) showed it is very retrograde & the PM dispersion profile of Vasiliev confirms that it is a cluster.

FSR 1758



Myeong et al 2019, submitted to arXiv today

The Sequoia Clusters



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

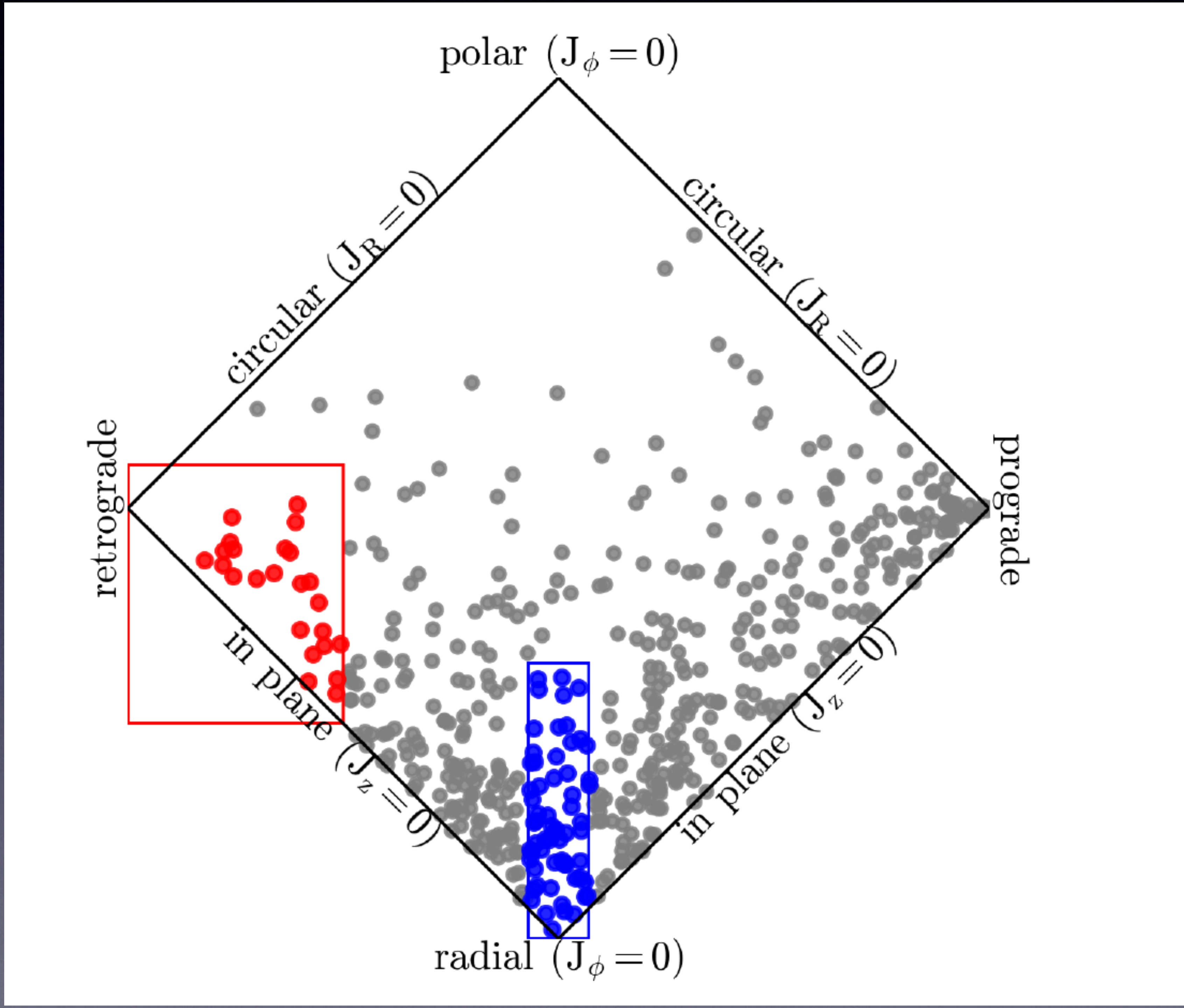
The Sequoia Clusters

- 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.

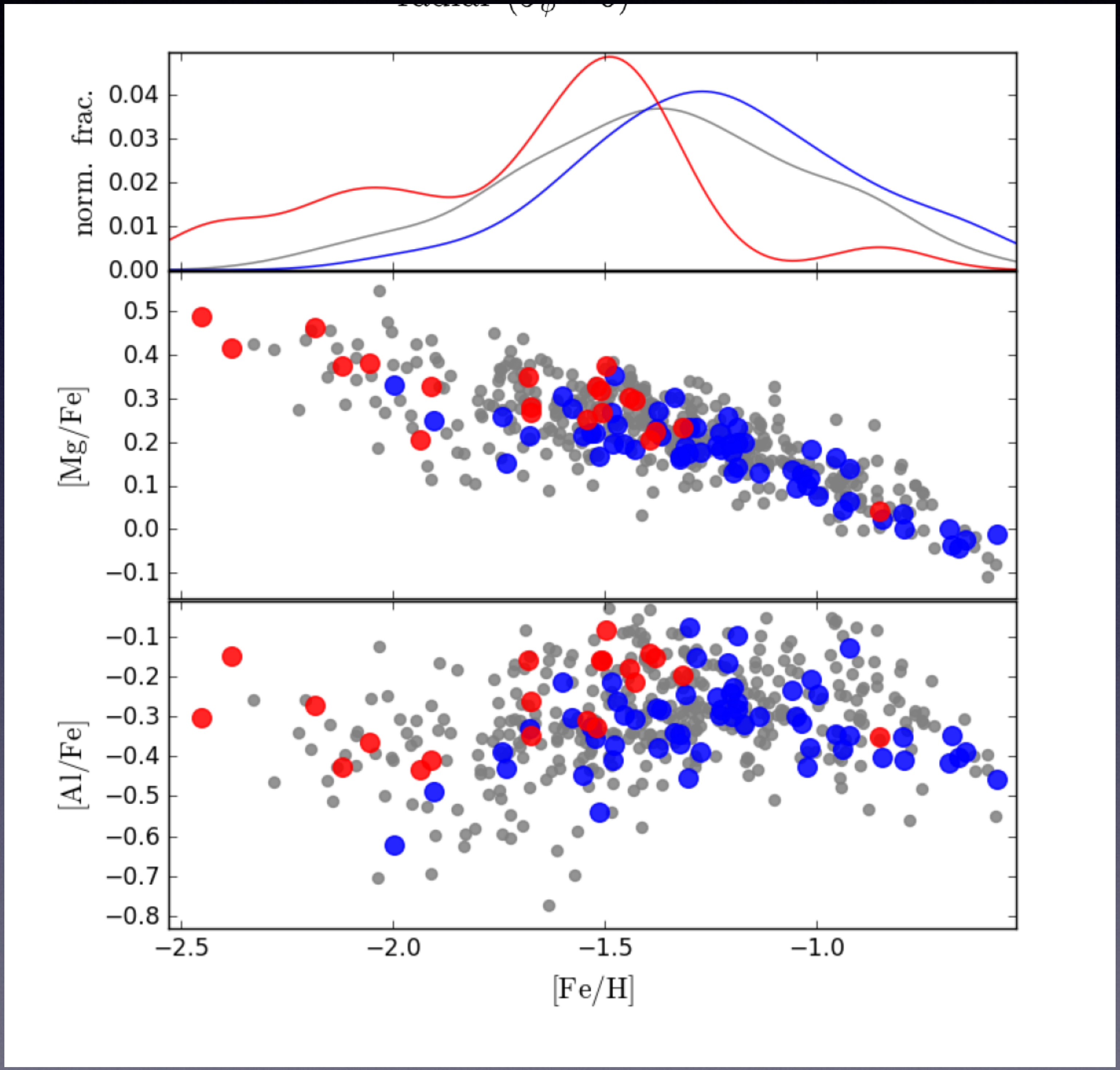
- NGC 3201 is known to be associated with the retrograde S1 stream (O' Hare et al. 2018).

The Sequoia Event



Myeong et al 2019, submitted to arXiv today

The Sequoia Event

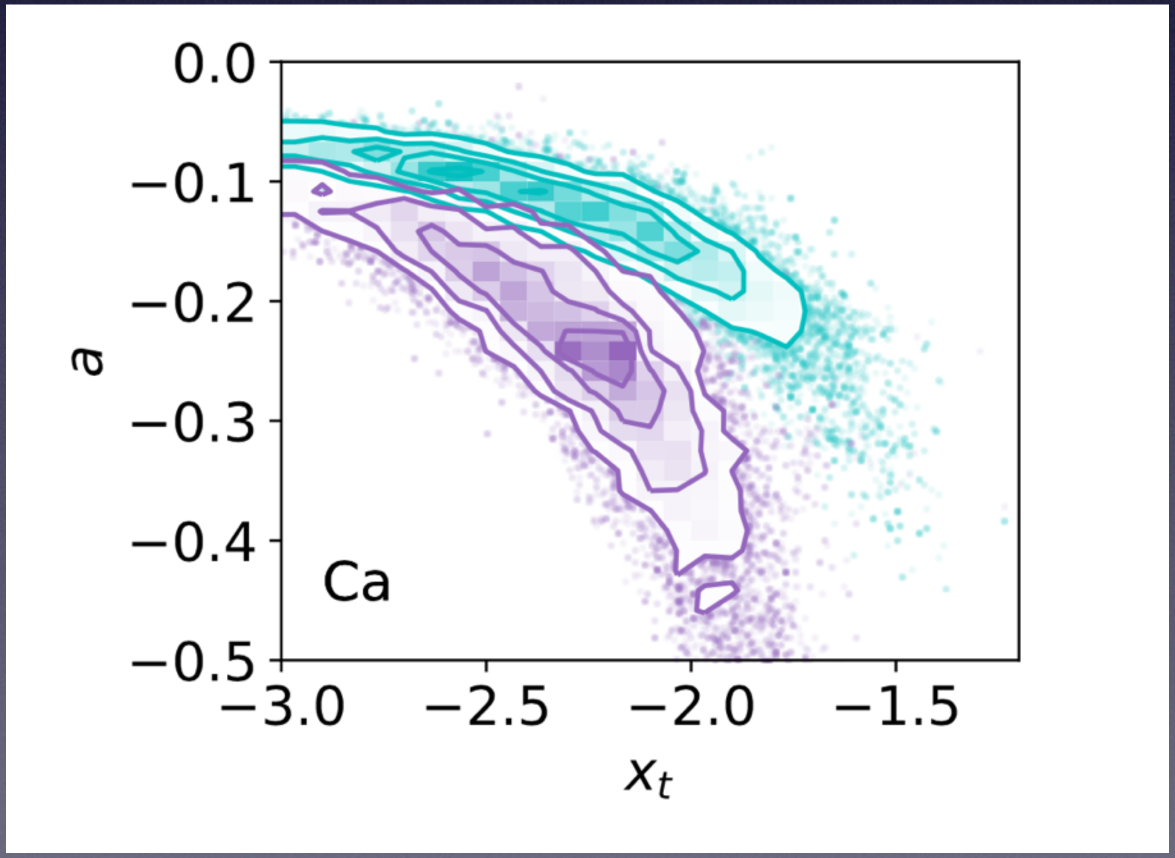


Myeong et al 2019, submitted to arXiv today

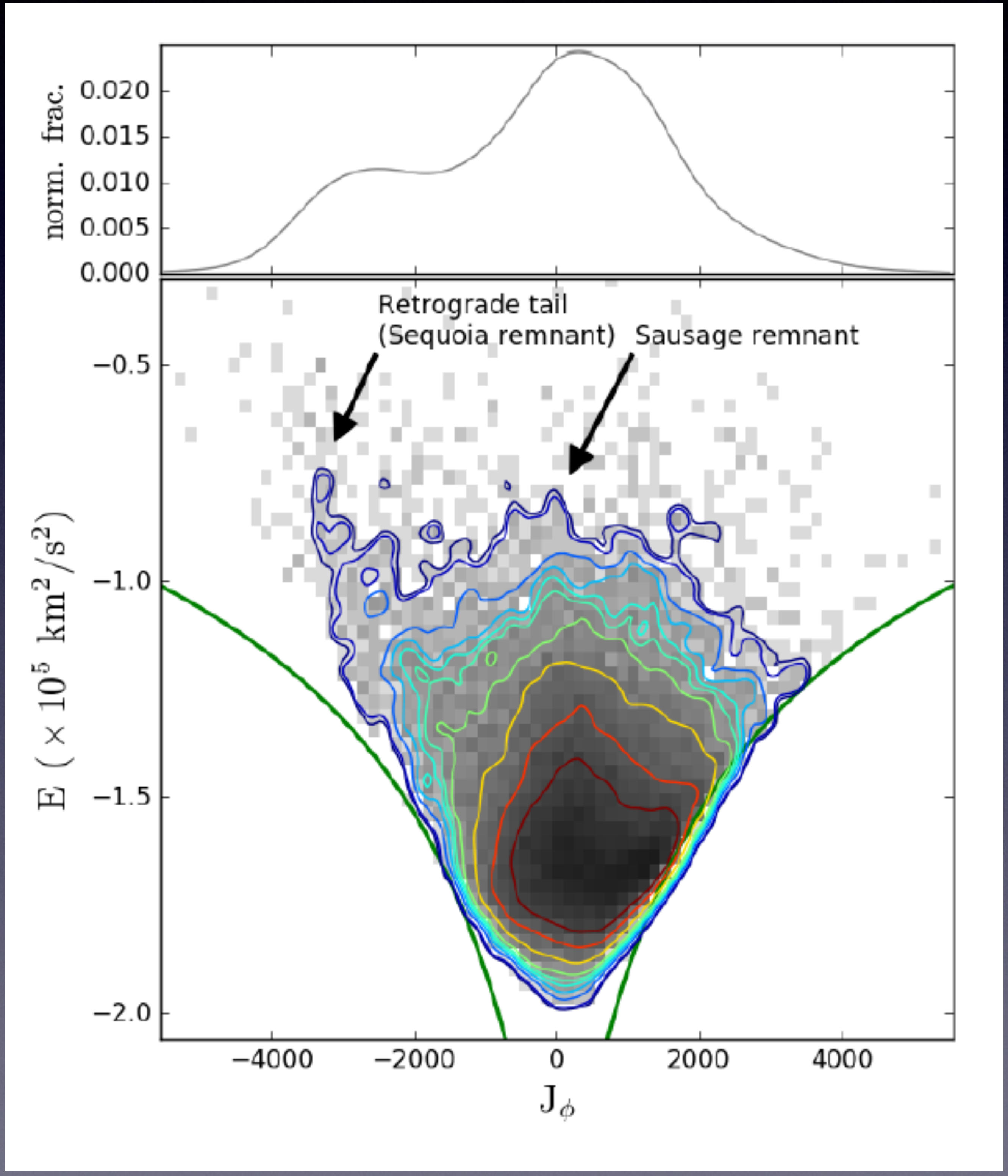
The Sequoia Event

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)



The Sausage and the Sequoia



The Sausage and the Sequoia …

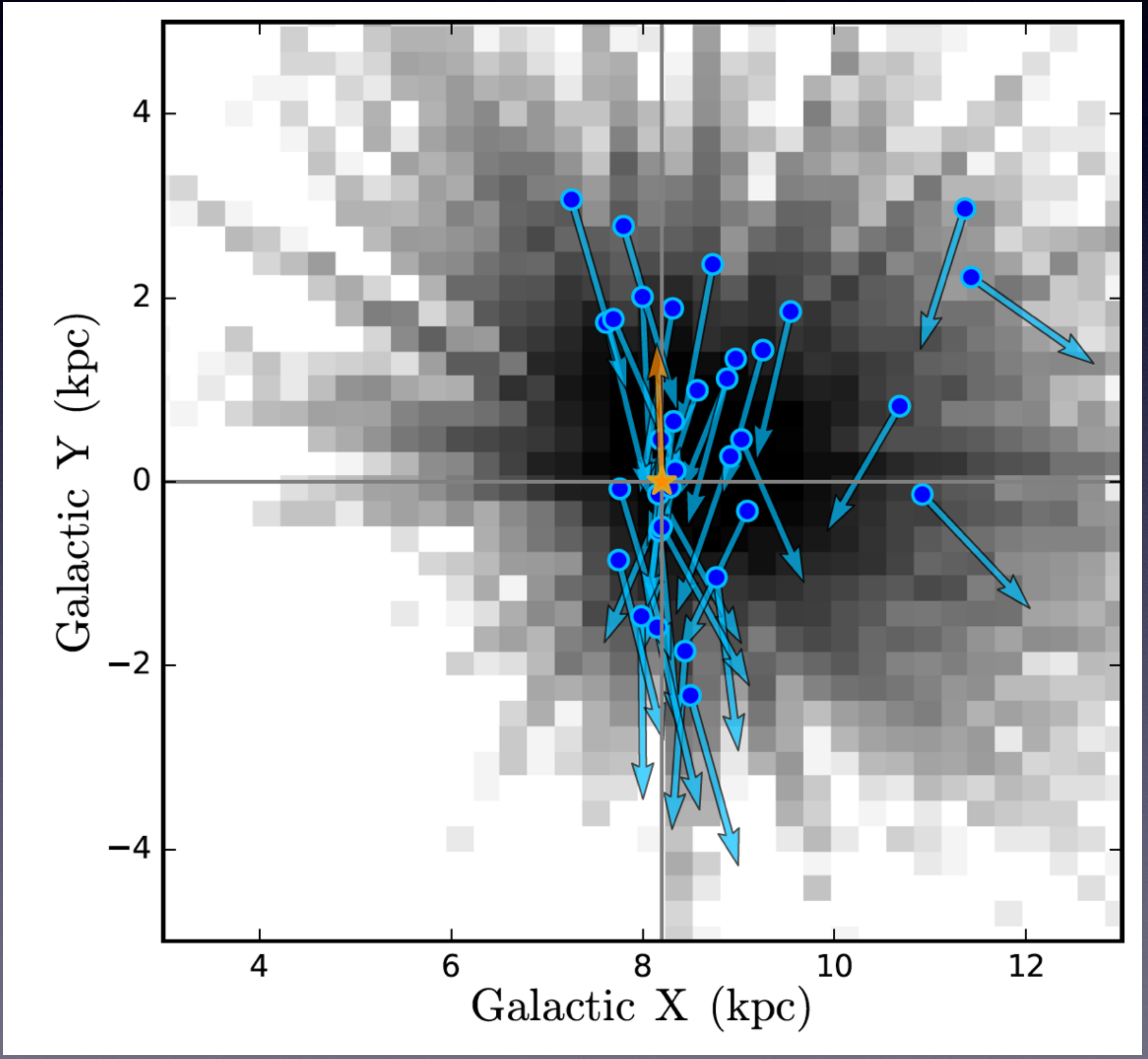
- The Gaia Sausage is the biggest structure in the stellar halo, with a stellar mass of ~ 5 - 50 x 10^8 $M_\odot$. This is the stellar mass of the Small or Large Magellanic Cloud. The DM mass is ~ 1-5 x 10^{11} $M_\odot$.

- 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} $M_\odot$.

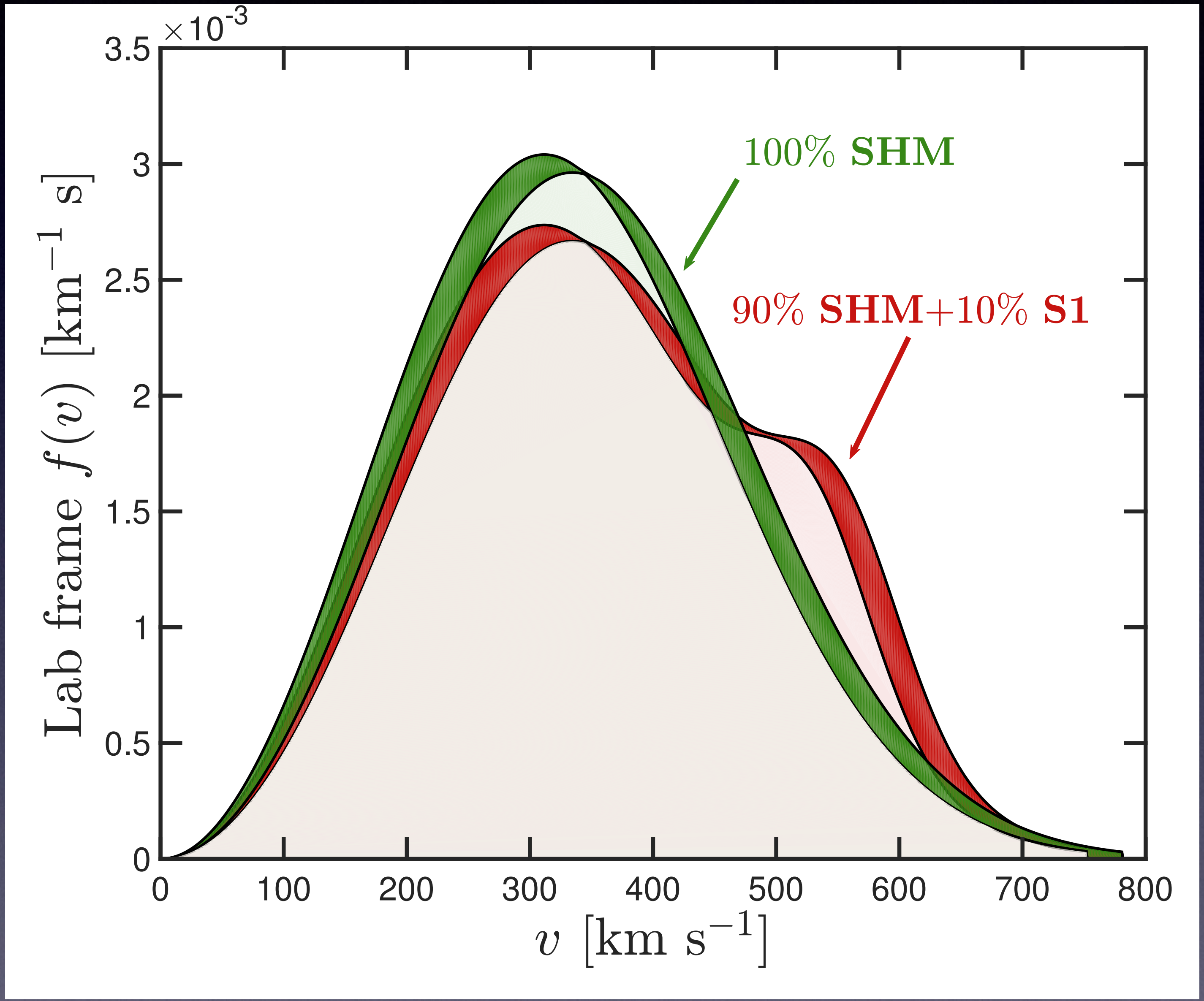
… and Gaia-Enceladus

- 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.

The Dark Matter Hurricane



S1: The DM Hurricane



O'Hare et al 2018

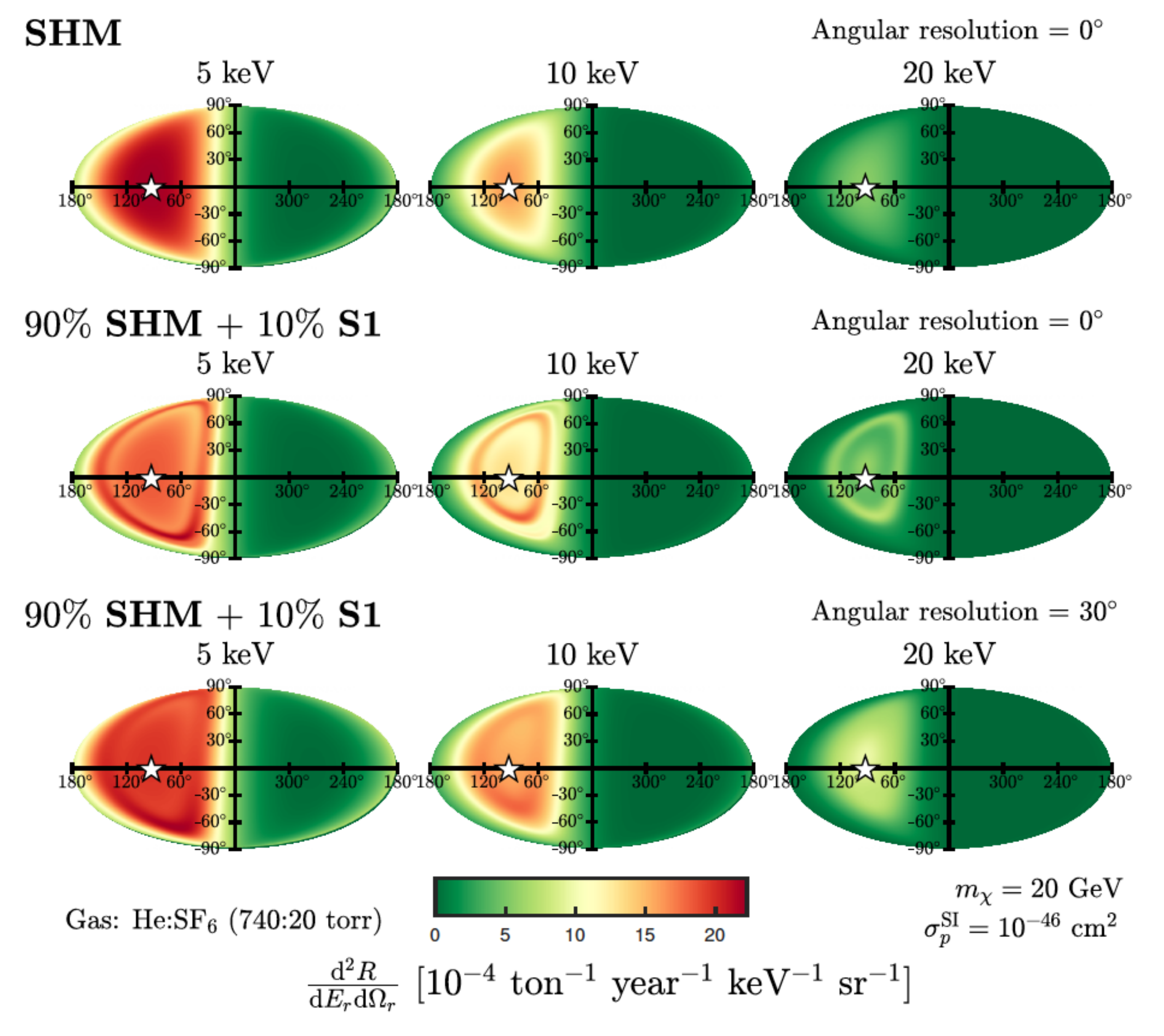
Distribution of WIMP velocities in laboratory frame over the course of a year

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.

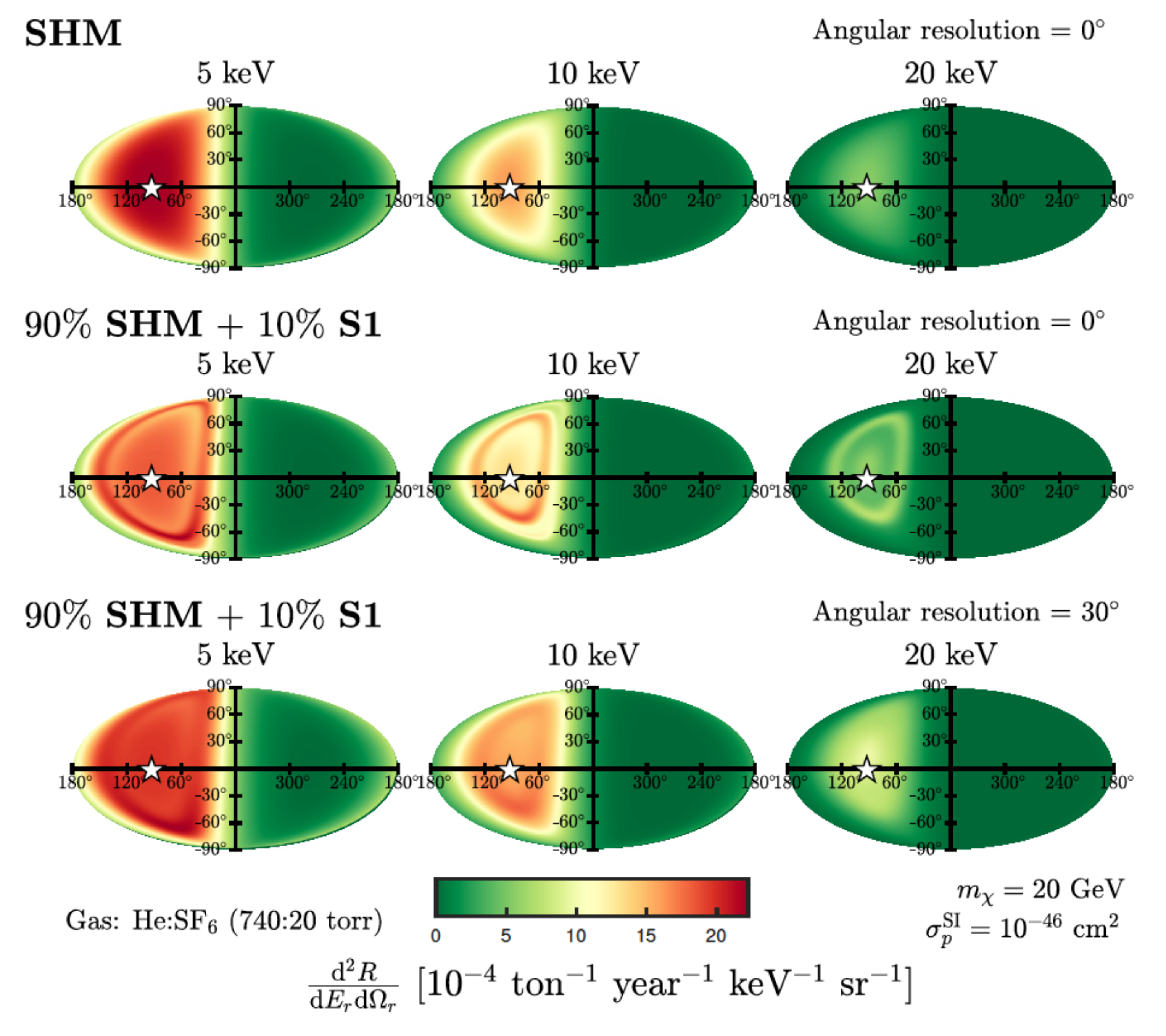
- There is an exact relationship between recoil energy and scattering angle. At a given coil energy, streams appear as rings in directional detection experiments.

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

- If detected, this is a really convincing signal of DM.

Conclusions

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

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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 chemo-dynamical 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

On Arxiv, Friday