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# Dark matter in the Milky Way & implications for axion experiments

Ciaran O'Hare

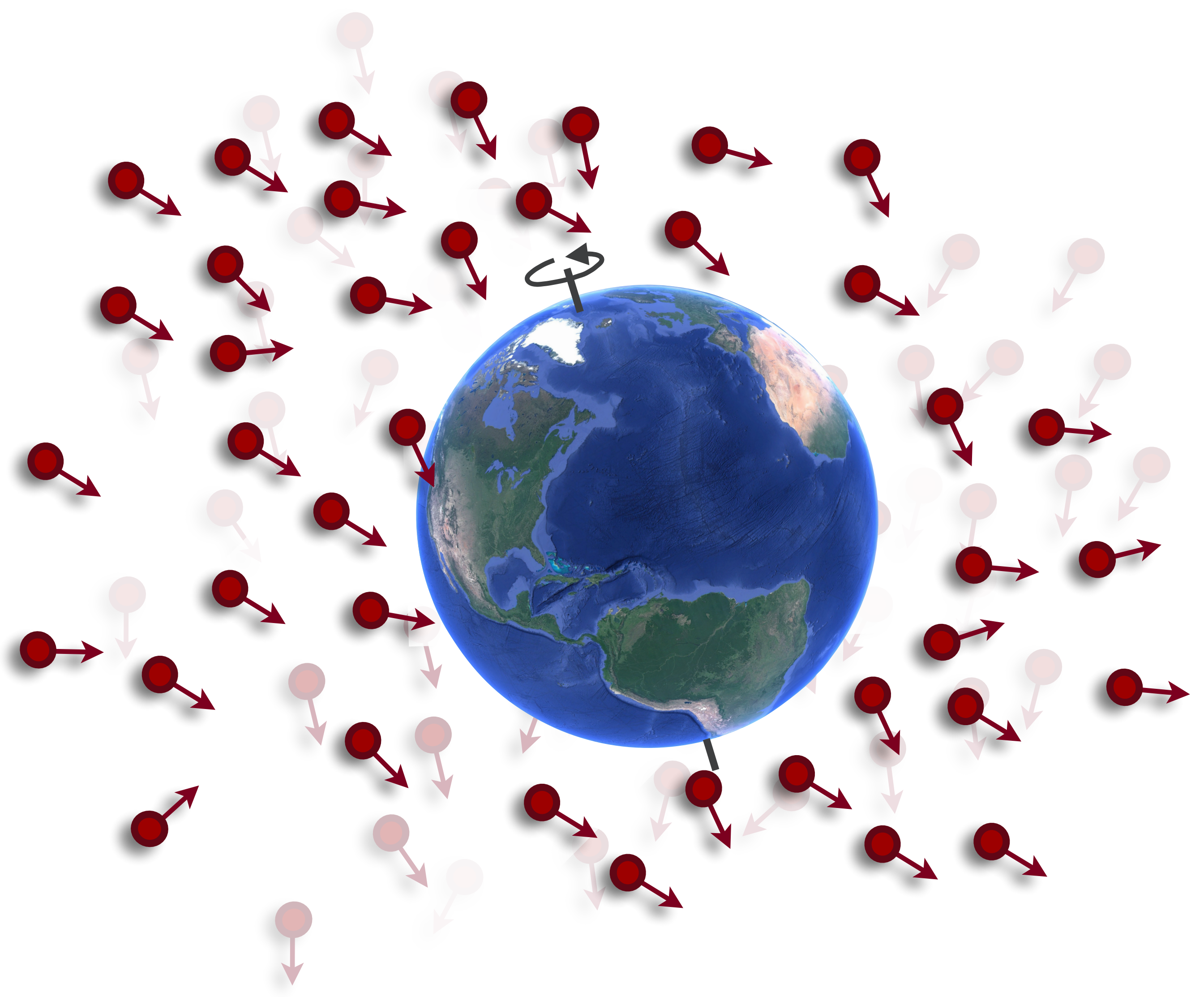
# Axion experiments & the local dark matter distribution

1. Astrophysical assumptions and uncertainties in direct axion searches
2. Recent discoveries about the Milky Way's halo
3. Axion experiments as astronomical instruments

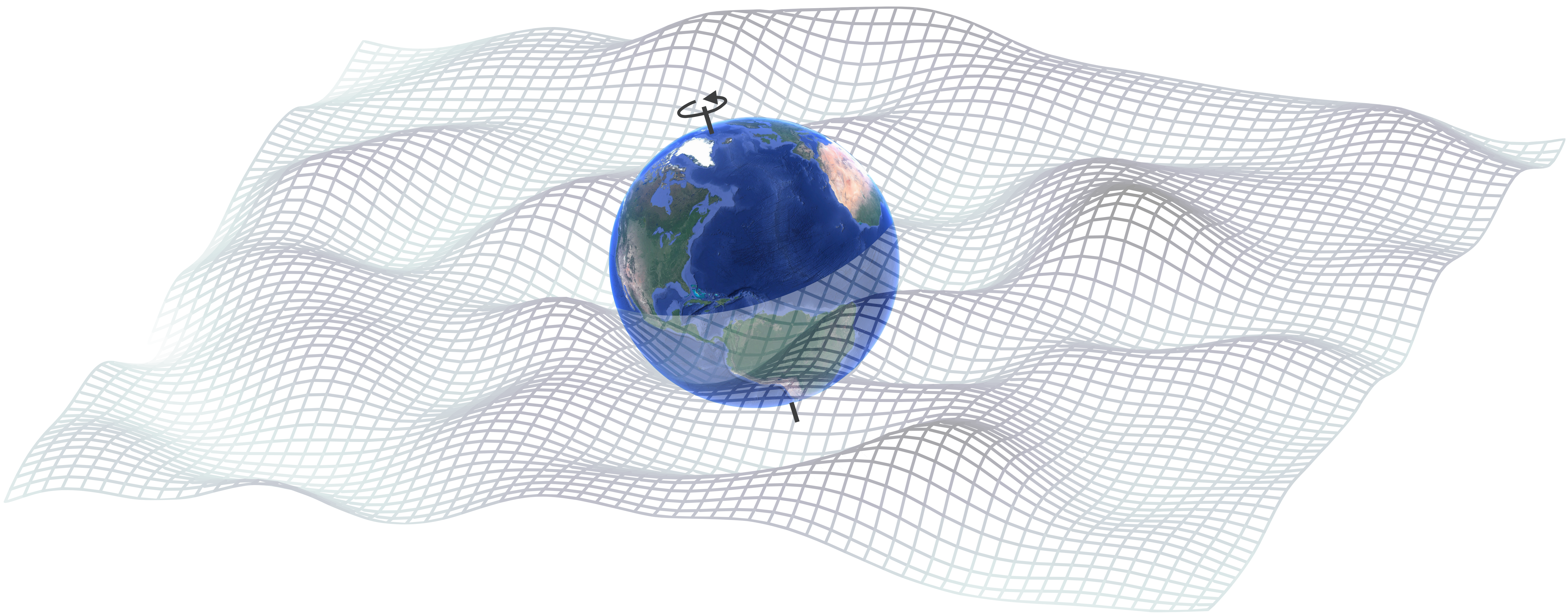
## To calculate an experimental signal of dark matter we need to know

1. How much dark matter there is around the Earth, $\rho$
2. How fast it's moving, $v$

**Particle-like**



**Wave-like**



**Number density** $n_\chi = \rho/m_\chi$

**Flux** $\Phi = v n_\chi$

**Amplitude** $A = \dfrac{\sqrt{2\rho}}{m_\chi}$

**Frequency** $\omega = m_\chi + \dfrac{1}{2} m_\chi v^2$

# In more detail, what we need is the Galactic dark matter phase space distribution observed in the laboratory's rest frame

$$\mathrm{d}N = f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}^3x\, \mathrm{d}^3v$$

$$\frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0$$ ← *Collisionless Boltzmann eq.*

**Liouville's theorem:** $f(\mathbf{x}(t), \mathbf{v}(t)) =$ const. along particle trajectories $\mathbf{x}(t), \mathbf{v}(t)$, as long as $f$ is not evolving, $\partial f/\partial t = 0$

Can get the distribution at Earth, by finding the velocities of particles falling in to the experiment from infinity. → $f(\mathbf{x}_\oplus, \mathbf{v}_\oplus) = f(\mathbf{x}_\infty, \mathbf{v}_\infty)$

**Most of the time** → results in a measured $f(\mathbf{v})$ given by a Galilean boost into rest frame of laboratory, $f(\mathbf{v} + \mathbf{v}_{\rm lab})$ …. (Ignores spatial variation of $f$, and gravitational fields of Sun/Earth, though these are potentially important)

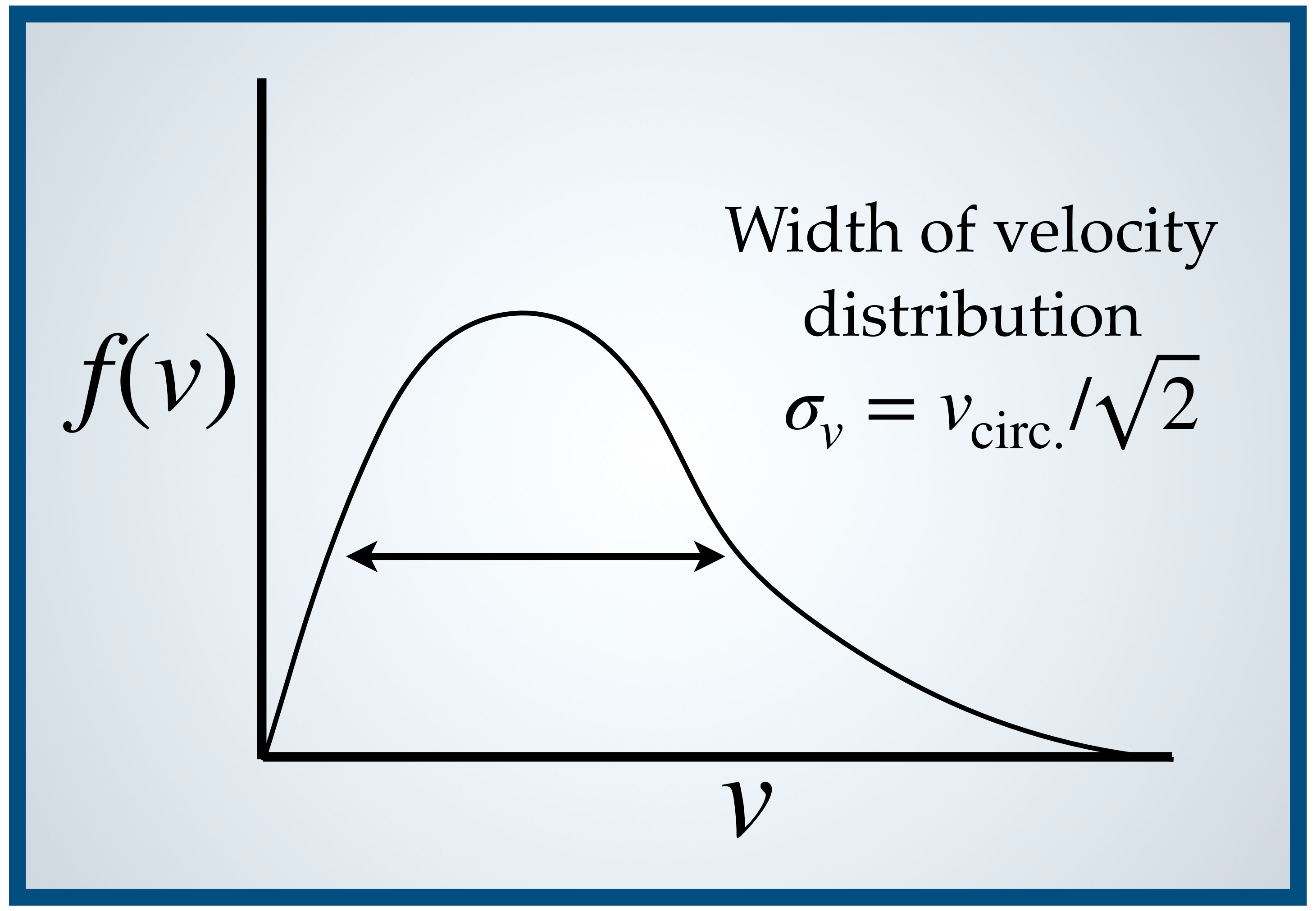
# The usual assumption for $f(\mathbf{x}, \mathbf{v})$: the Standard Halo Model

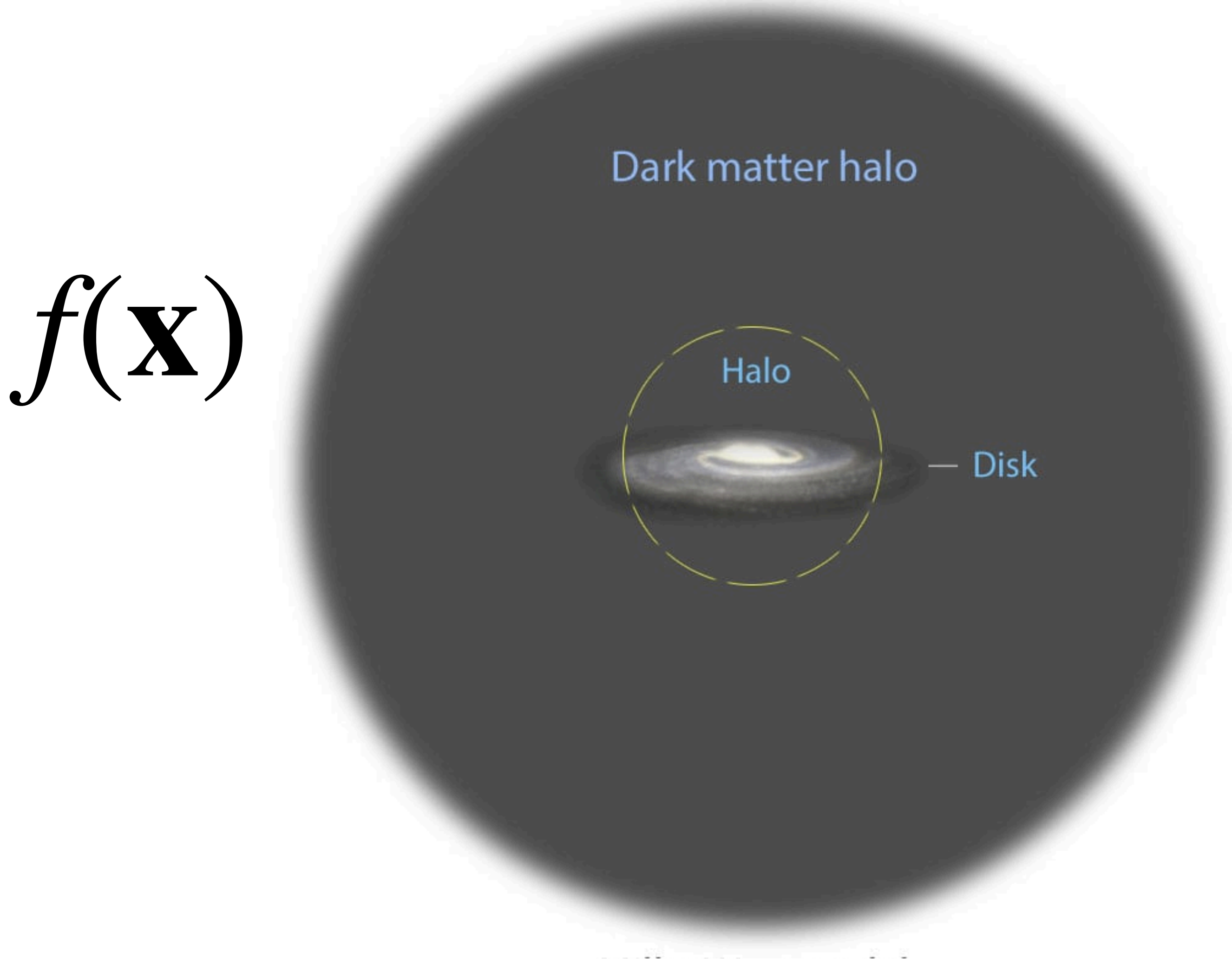
## → very reasonable, if all you are going for is a simple model that is broadly correct, if not in detail

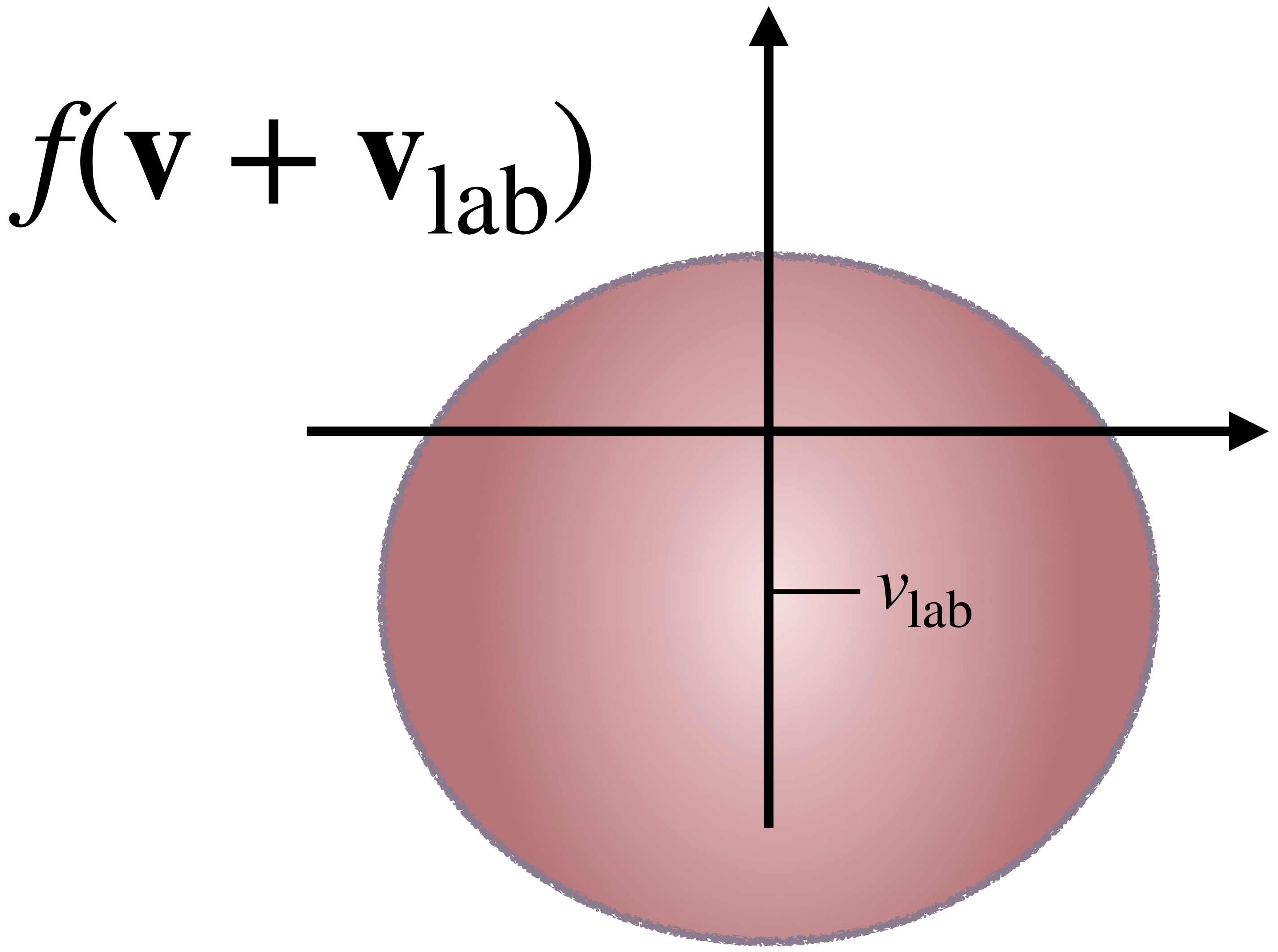
- Infinite isothermal sphere → Simplest halo model that gives a flat asymptotic rotation curve

$$\rho \sim 1/r^2$$

$$f(\mathbf{v}) \sim \exp(-|\mathbf{v}^2|/v_{\rm circ}^2)$$







- Most implementations also correct for the finite extent of the real MW halo, by truncating at $v_{\rm esc}$ . Important when you are most sensitive to high speed tail (e.g. light DM), but trivial otherwise

# Accounting for distribution of velocities in the description of the oscillating axion field

$$a(\mathbf{x}, t) = \frac{\sqrt{2\rho_a}}{m_a} \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} |\mathcal{A}(\mathbf{p})| \cos\left(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha_{\mathbf{p}}\right)$$

amplitude distribution ~ related to $f(\mathbf{v})$

Coherence time: time scale for oscillation to dephase

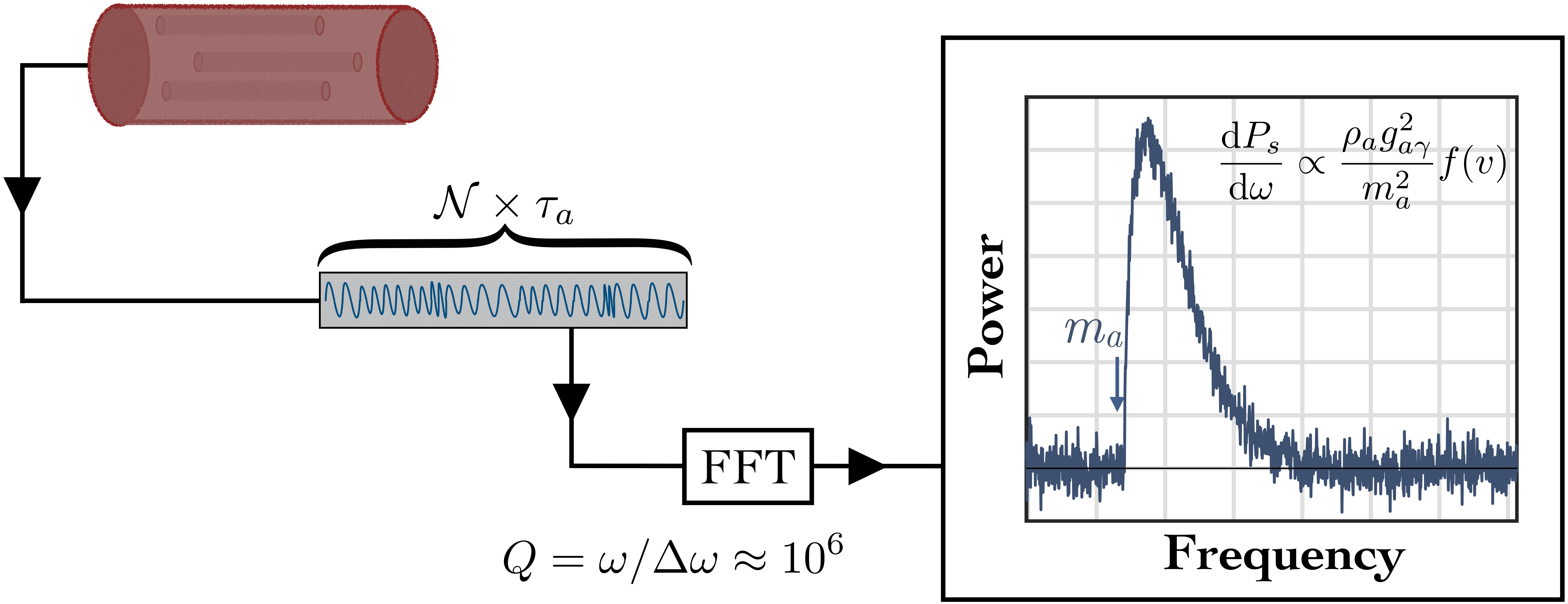
$$\tau_a = \frac{2\pi}{m_a \sigma_v^2} \simeq 40\,\mu\mathrm{s}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

Coherence length: length scale for oscillation to dephase

$$\lambda_a = \frac{2\pi}{m_a \sigma_v} \simeq 12.4\,\mathrm{m}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

# Desirably, we run an experiment for $T \gg \tau_a$ , and $L \lesssim \lambda_a$

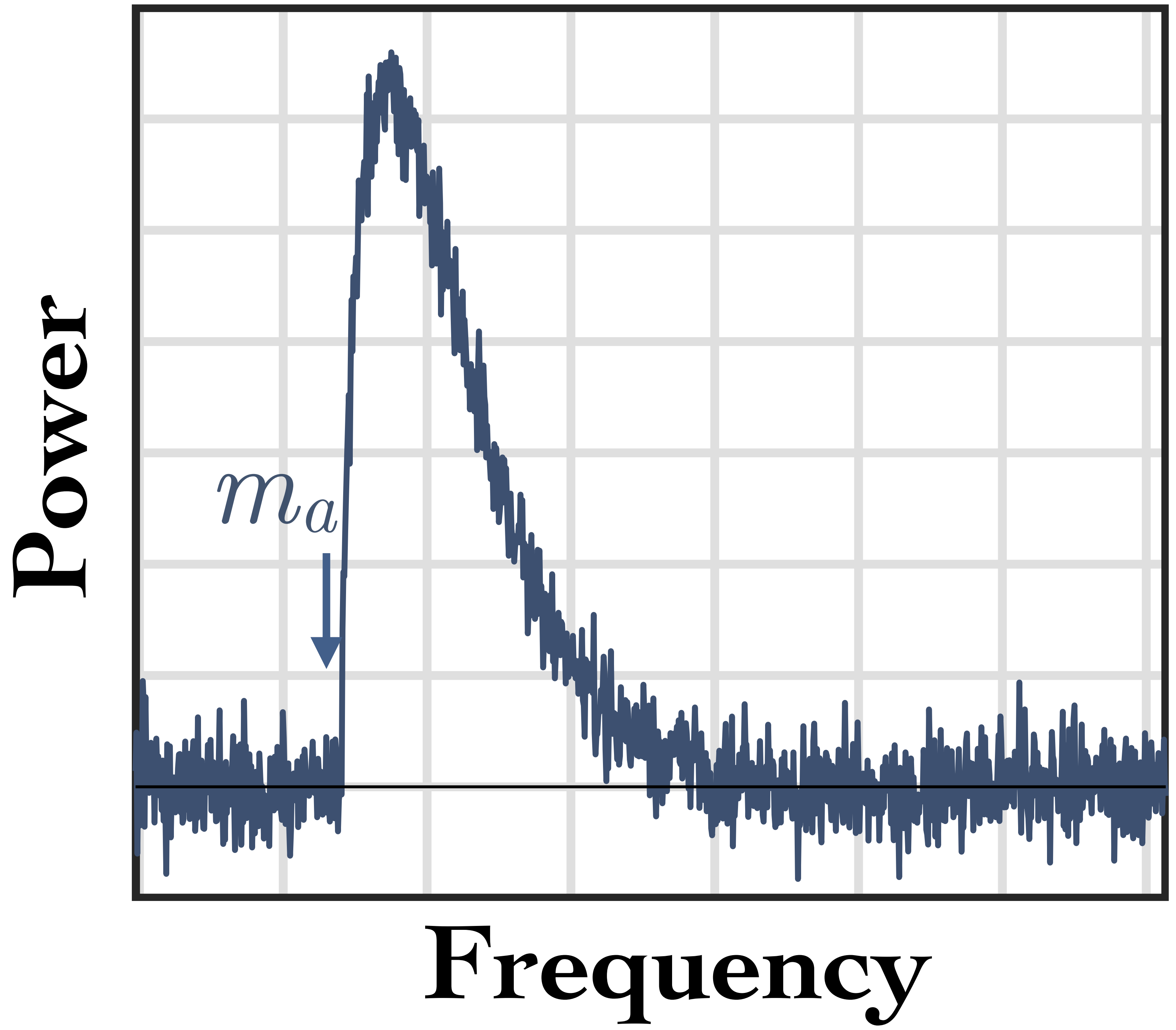
Signal is coherent over experimental volume, and oscillates many times per observation duration → FT of signal timeseries approaches *f(v)*



$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} f(v)$$

$$Q = \omega/\Delta\omega \approx 10^6$$

# Axion signal is stronger for higher densities and narrower distributions



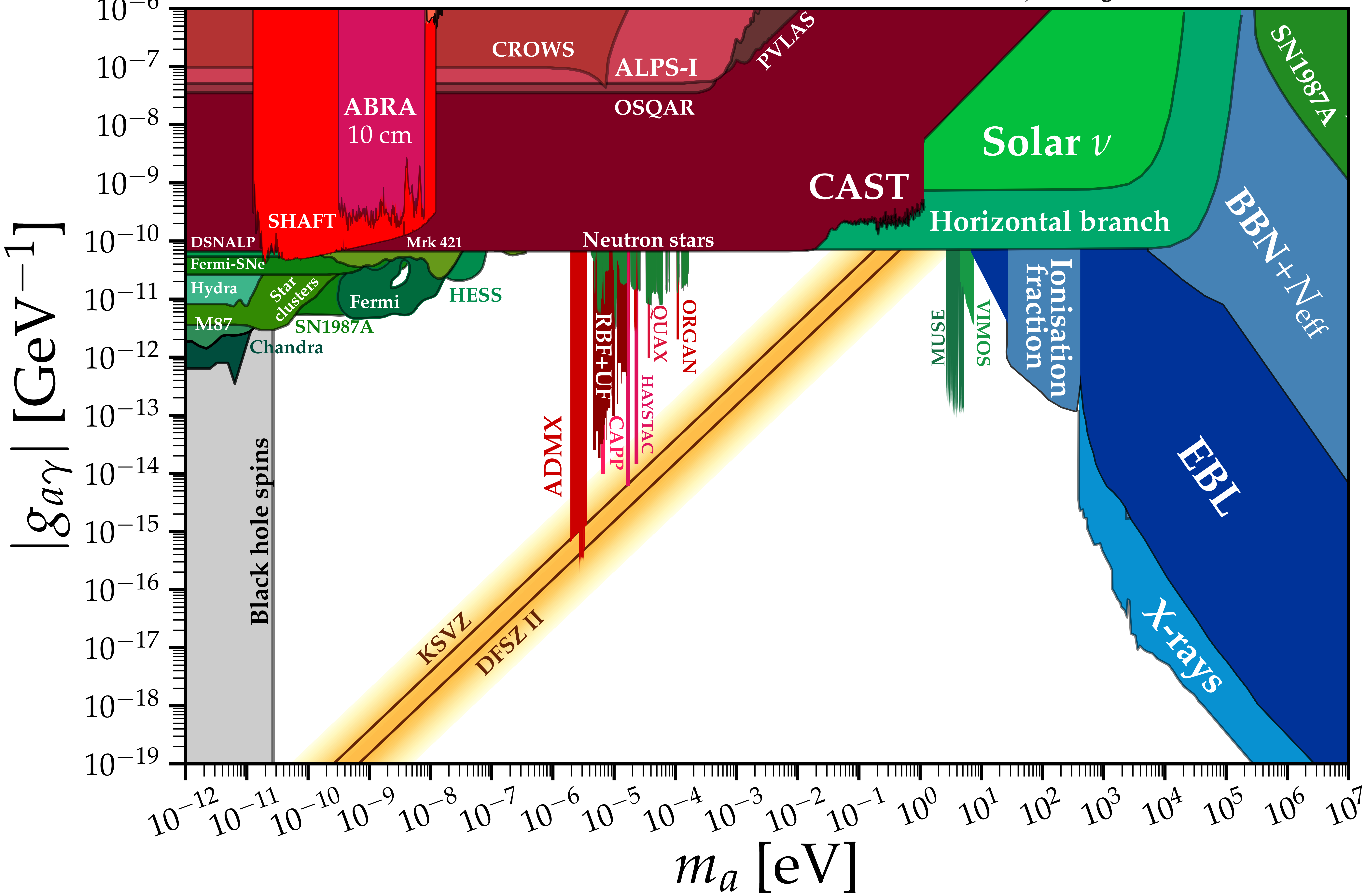
$$\longrightarrow \quad \frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} f(v)$$

+ Experimental noise

+ Fundamental noise from random distribution of phases of the axion field*

*See: Derevianko [1605.09717]
Foster+ [1711.10489]
Centers+ [1905.13650]

# As long as we agree on some benchmark parameters that are roughly correct, e.g. $\rho \sim 0.3\,\mathrm{GeV\,cm^{-3}}$ and $v_0 \sim 220\,\mathrm{km\,s^{-1}}$, do the precise values matter?



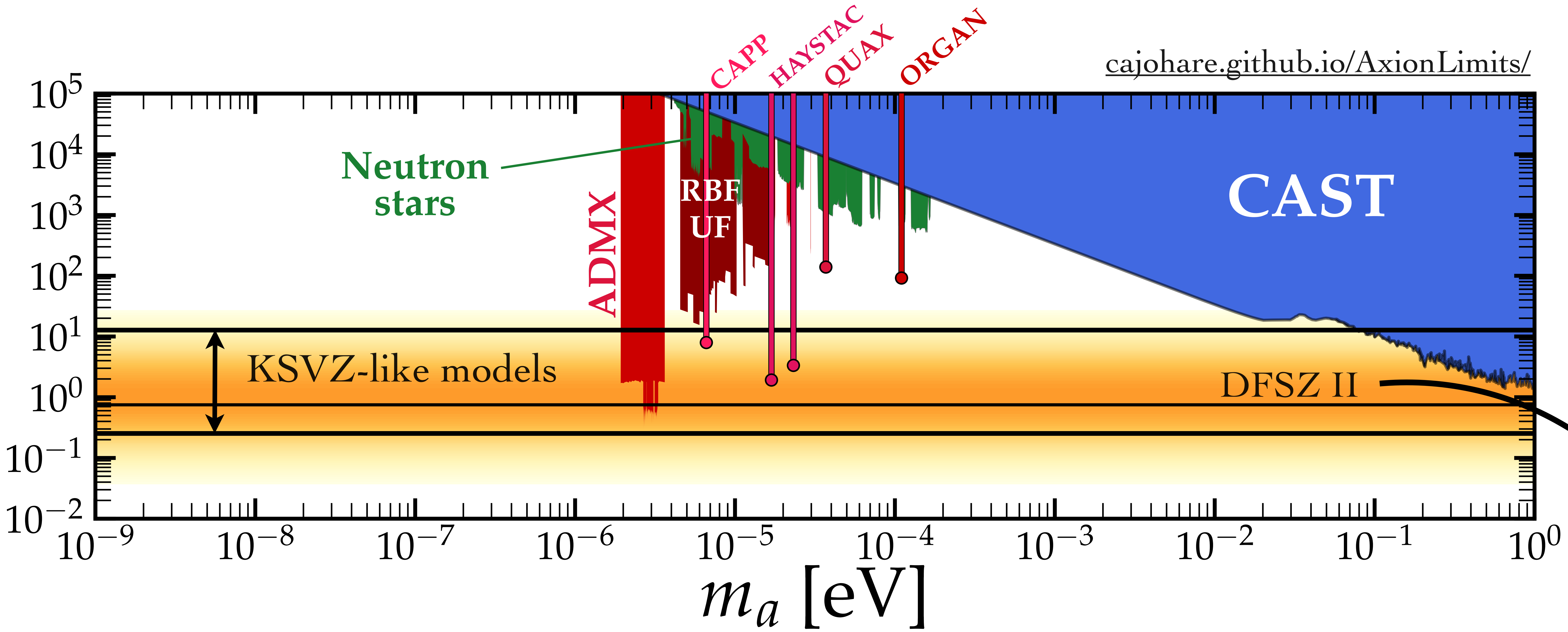
cajohare.github.io/AxionLimits/

$$\sqrt{\rho_{\rm dm}}\left(\int \frac{1}{v} f_{\rm lab}(v)^2 \, {\rm d}v\right)^{1/4}$$

If we were just comparing haloscopes, could we just absorb the constants into the coupling?

?

$$\frac{2\pi f_a g_{a\gamma}}{\alpha}$$



$$\frac{E}{N} - 1.92$$

Yes… but this must be reckoned with when targeting a precise model prediction

# Issue becomes very relevant when we think about, for example, the scanning rate required for a cavity to reach a specific axion model with some fixed $(E/N - 1.92)$

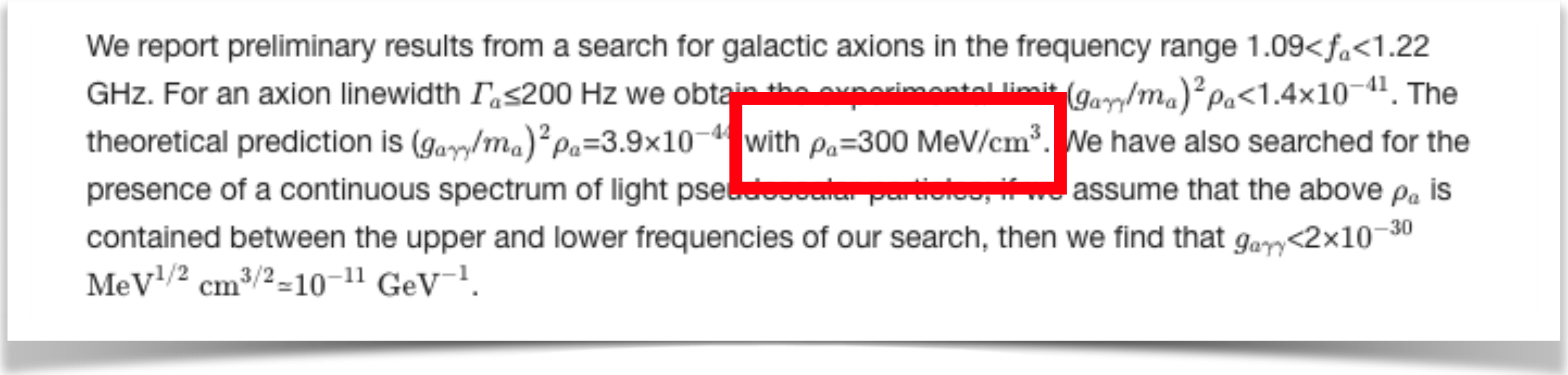
$$\frac{dm_a}{dt} = \frac{Q_a}{Q}\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2\left(\frac{T_{\mathrm{sys}}}{P_{\mathrm{axion}}}\right)^2$$

$$P_{\mathrm{axion}} \propto \rho_{\mathrm{dm}} m_a^2 Q V B^2 \left(\frac{E}{N} - 1.92\right)^2$$

If our assumed value of $\rho_{\mathrm{dm}}$ was too large by, say, 0.15 GeV / cm$^3$ this means DFSZ would take more than twice as long to exclude

# History of the local DM density used in haloscope publications

**1987** RBF
0.3 GeV/cm$^3$



We report preliminary results from a search for galactic axions in the frequency range $1.09<f_a<1.22$ GHz. For an axion linewidth $\Gamma_a \leq 200$ Hz we obtain the experimental limit $(g_{a\gamma\gamma}/m_a)^2\rho_a<1.4\times10^{-41}$. The theoretical prediction is $(g_{a\gamma\gamma}/m_a)^2\rho_a=3.9\times10^{-44}$ with $\rho_a$=300 MeV/cm$^3$. We have also searched for the presence of a continuous spectrum of light pseudoscalar particles; if we assume that the above $\rho_a$ is contained between the upper and lower frequencies of our search, then we find that $g_{a\gamma\gamma}<2\times10^{-30}$ MeV$^{1/2}$ cm$^{3/2}$≈$10^{-11}$ GeV$^{-1}$.

**2009** ADMX
0.45 GeV/cm$^3$

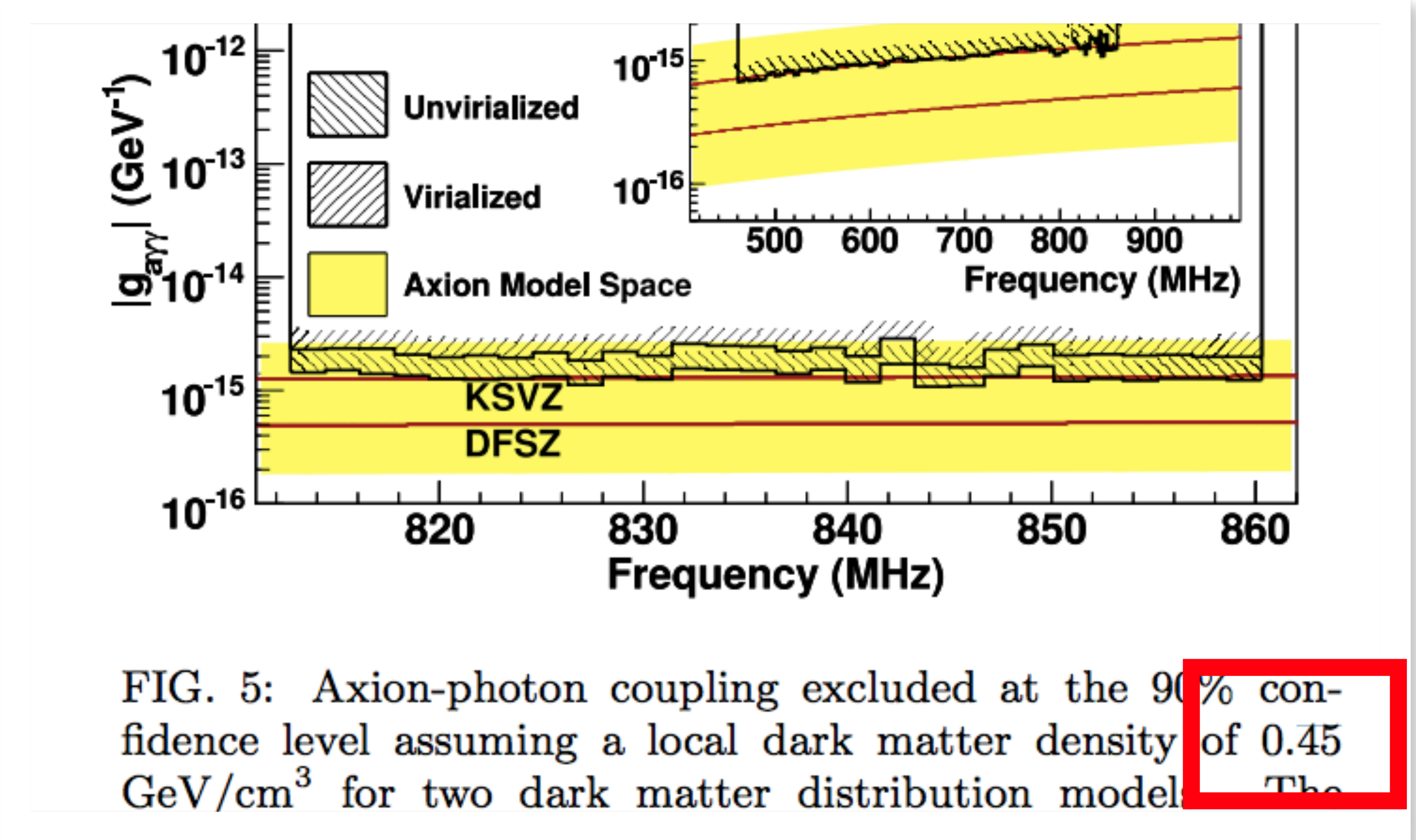
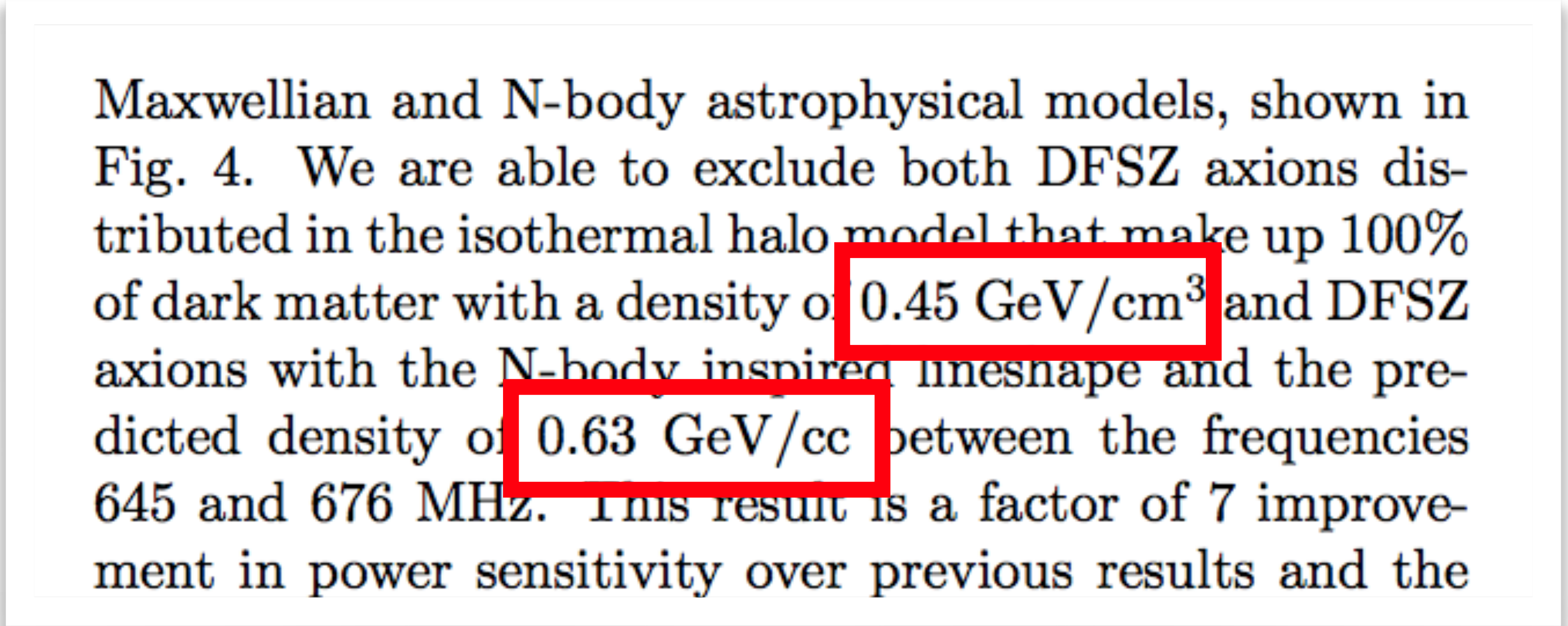


FIG. 5: Axion-photon coupling excluded at the 90% confidence level assuming a local dark matter density of 0.45 GeV/cm$^3$ for two dark matter distribution models. The

**2018** ADMX
0.63 GeV/cm$^3$



Maxwellian and N-body astrophysical models, shown in Fig. 4. We are able to exclude both DFSZ axions distributed in the isothermal halo model that make up 100% of dark matter with a density of 0.45 GeV/cm$^3$ and DFSZ axions with the N-body inspired lineshape and the predicted density of 0.63 GeV/cc between the frequencies 645 and 676 MHz. This result is a factor of 7 improvement in power sensitivity over previous results and the

# Can we infer $\rho_{\mathrm{dm}}$ from astronomy?

$$\frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0 \longrightarrow$$

(collisionless) Boltzmann eq.
Distribution function → Grav. potential

$$\nabla_x^2 \Phi = 4\pi G \rho \longrightarrow$$

Poission eq.
Grav. potential → matter density

## Local measure

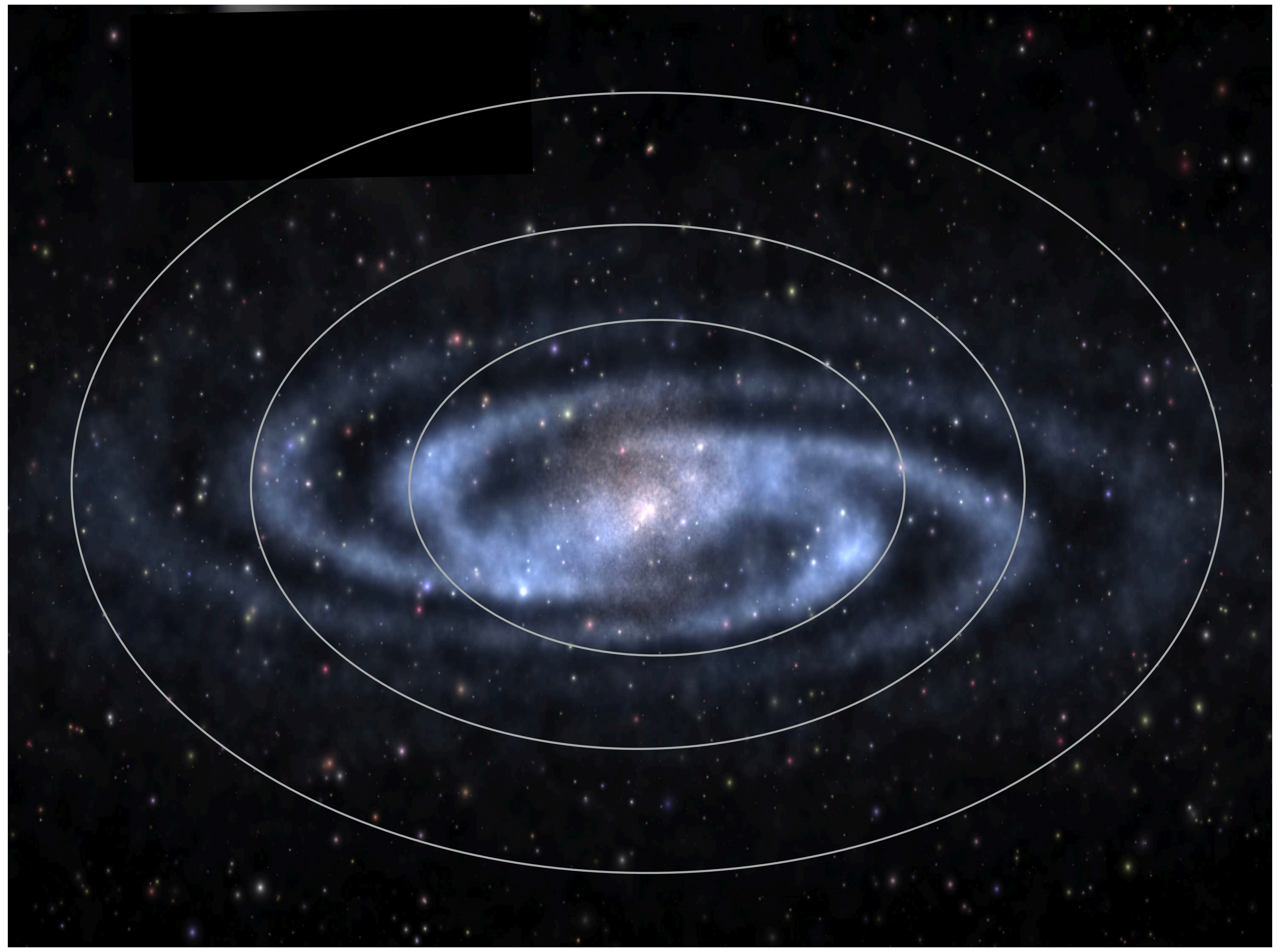
(kinematics of nearby stars)

Pro: density that we are interested in

Con: sensitive to baryonic density model

## Global measure

(build mass model for MW)



Pro: Average over a lot of halo/disk

Con: less direct measure of local density

## Local measures

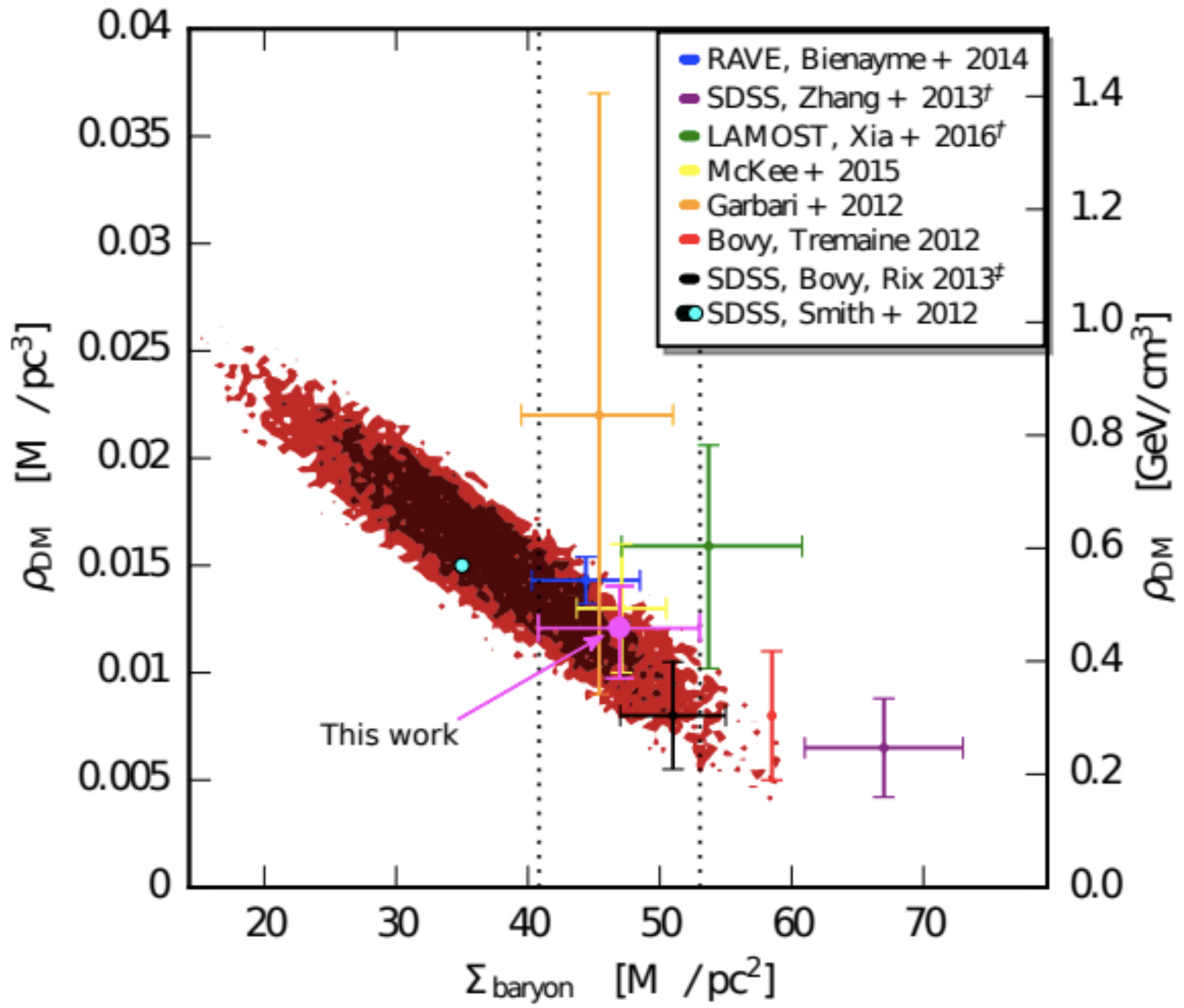
e.g. Sivertsson+ [1708.07836]

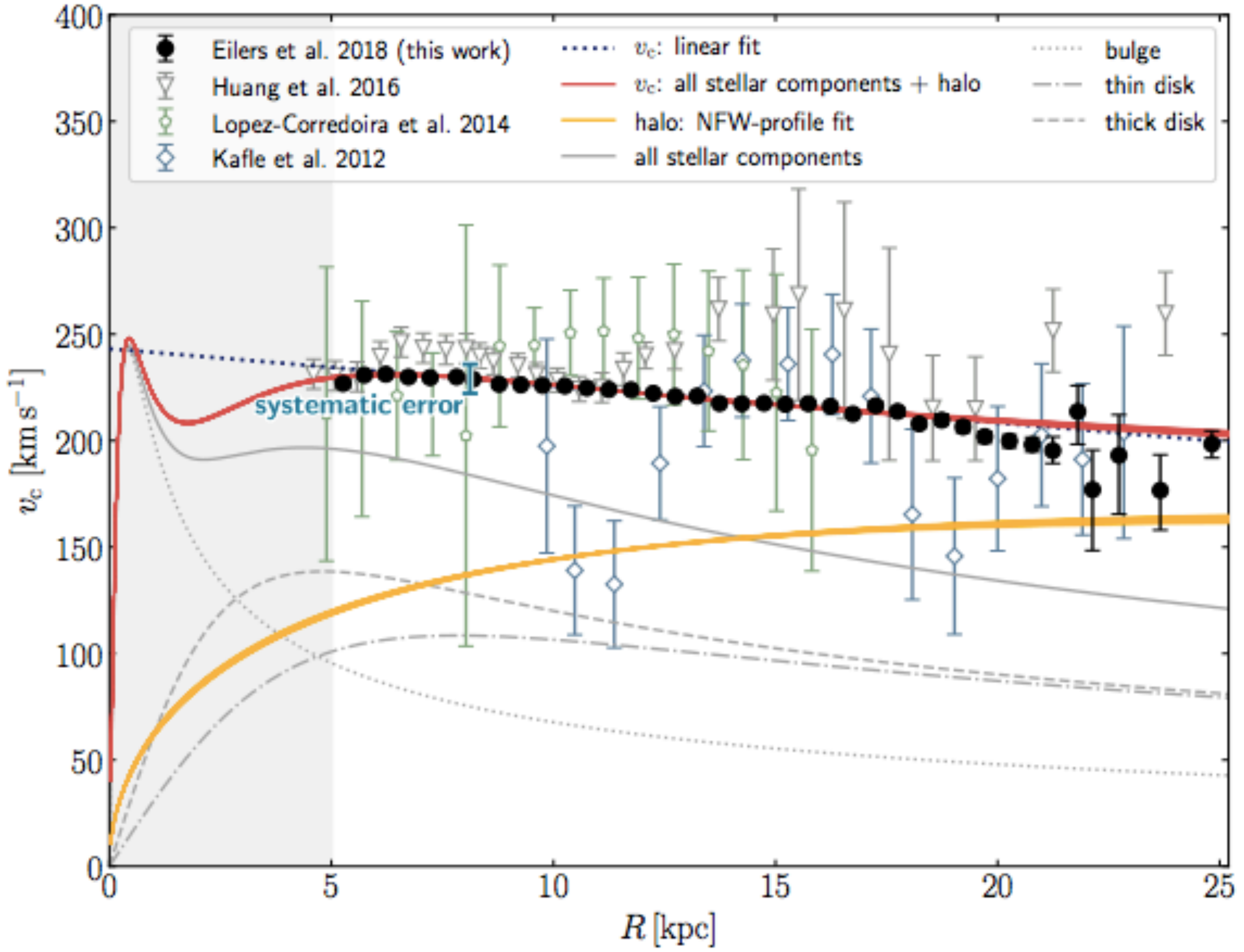
0.46 ± ~0.1 GeV / cm³

## Global measures

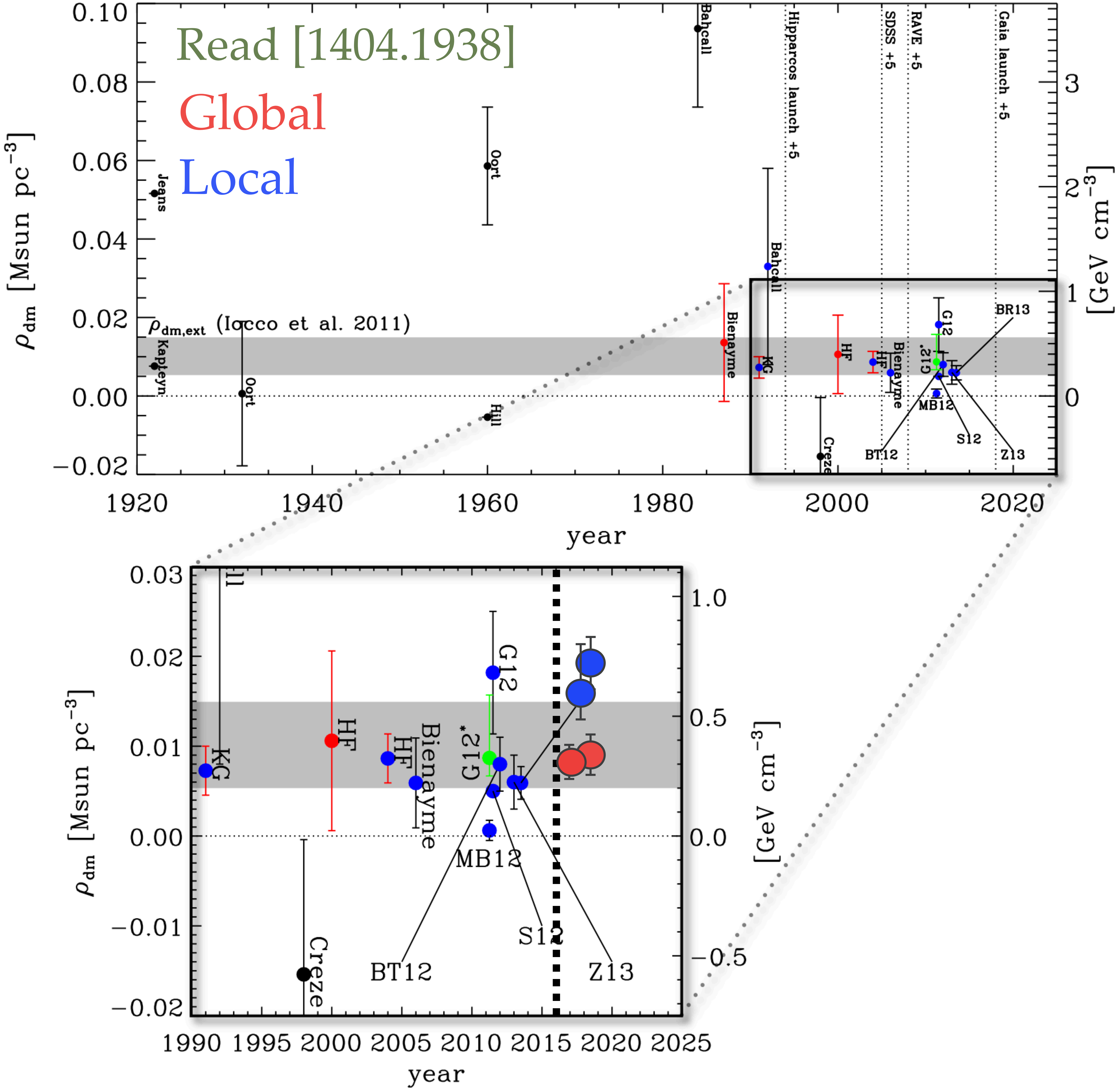
e.g. Eilers+ [1810.09466]

0.3 ± 0.03 GeV / cm³





- Global measure has tiny statistical errors, but inferred over large scales
- Local measures give the more relevant density but are still systematics dominated



**Recent estimates**

Hagen+[1802.09291]

Buch+ [1808.05603]

Widmark [1811.07911]

de Salas+ [1906.06133]

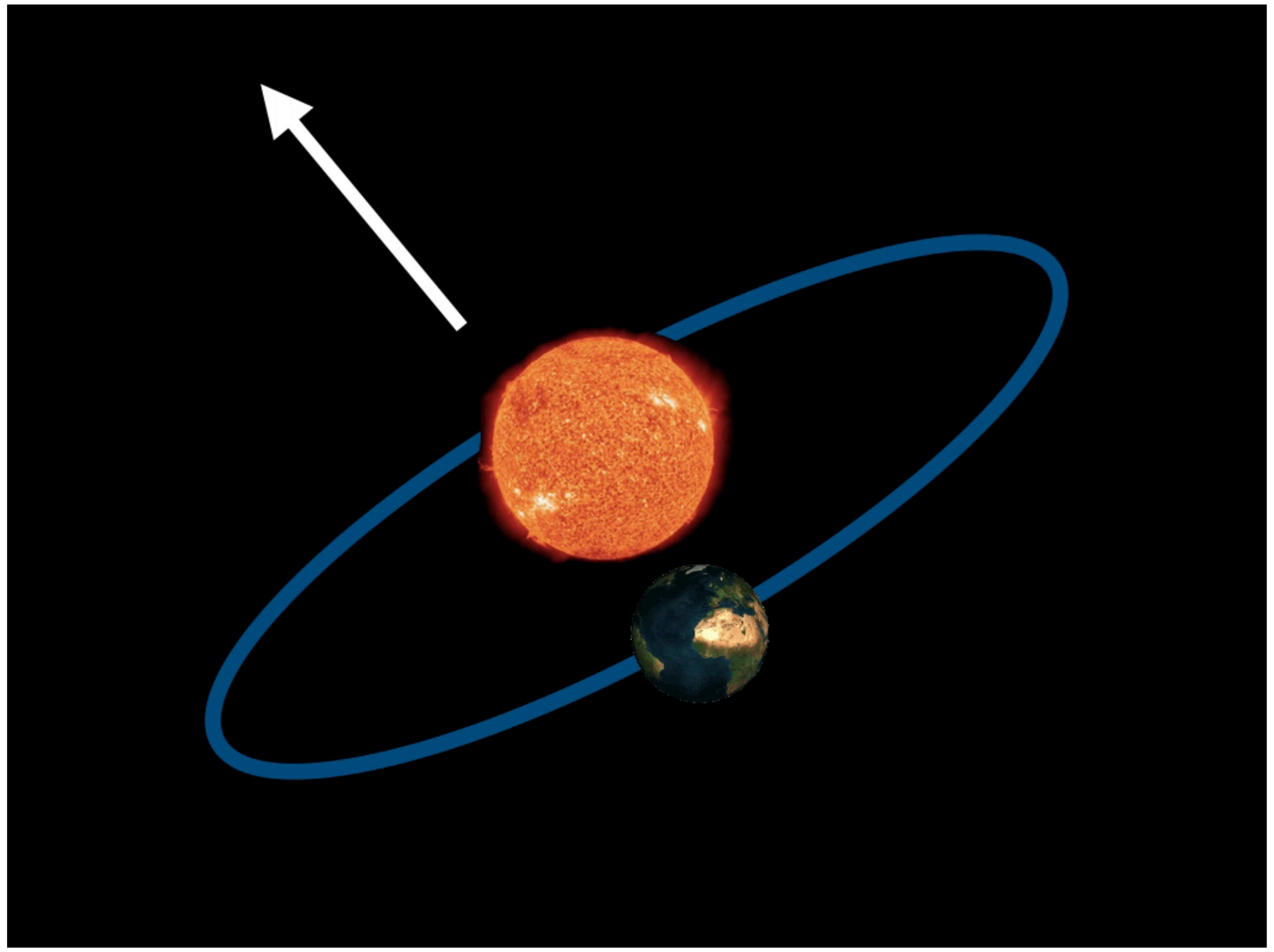
Eilers+ [1810.09466]

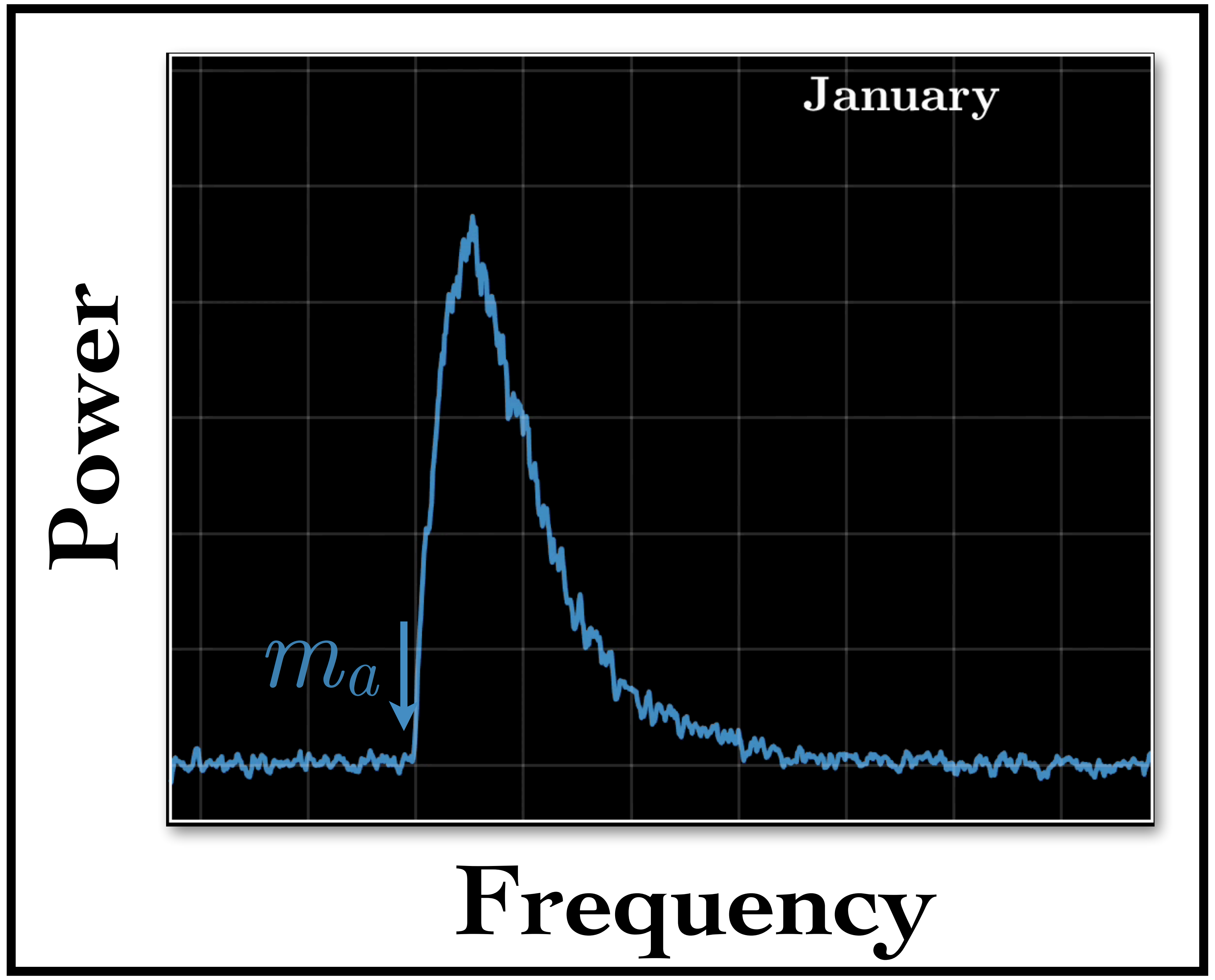
Benito+ [1901.02460]

# What do we expect a more accurate axion signal to look like?

→ For sure, it will modulate annually due to the orbit of the Earth: an essential signal to confirm a detection of DM, but are we confident about the structure of *f(v)*?

$$f(v) \sim v^2 \exp\left(-\frac{(\mathbf{v} + \mathbf{v}_{\rm lab}(t))^2}{2\sigma_v^2}\right) \textbf{ ?}$$

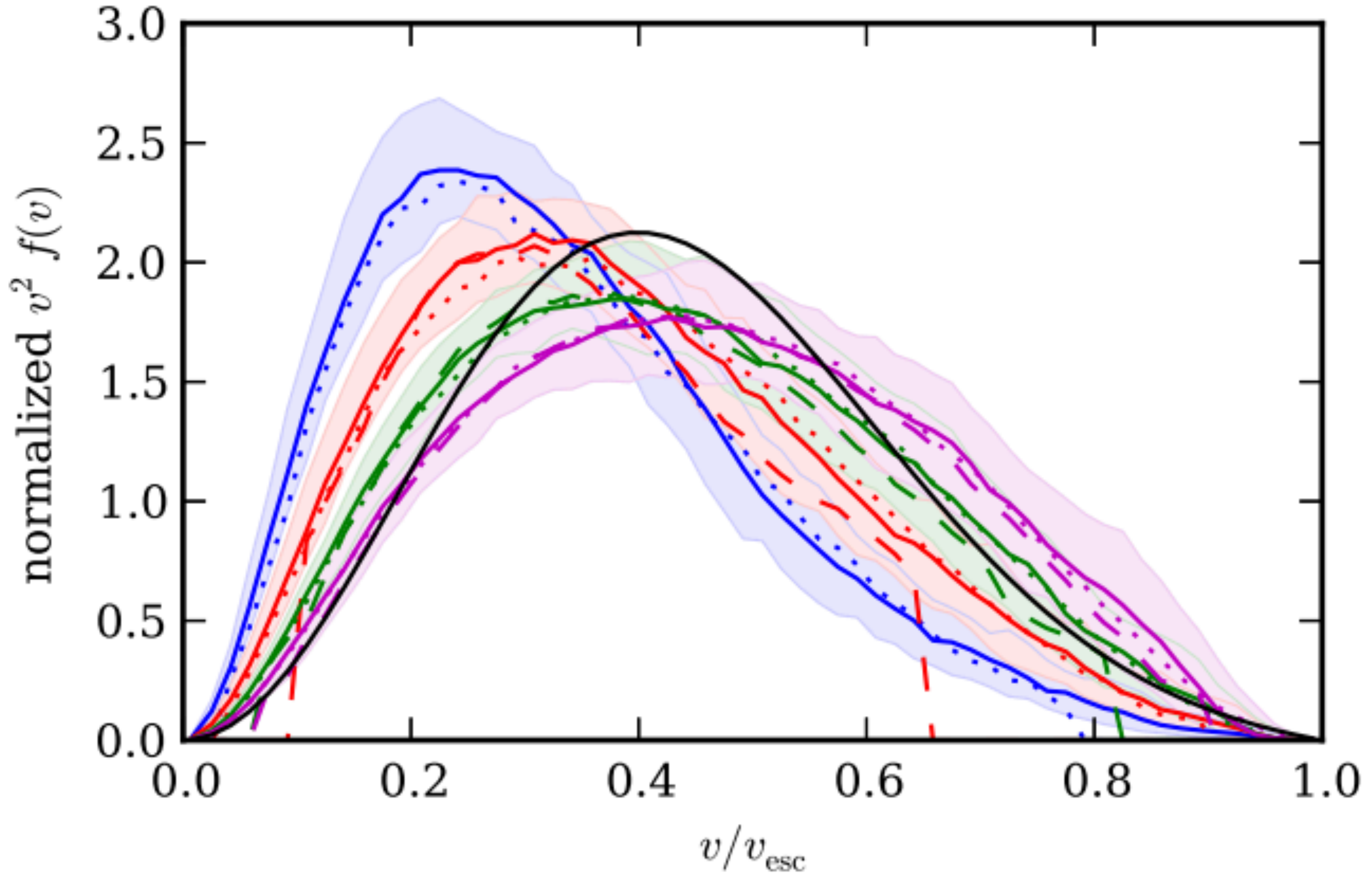




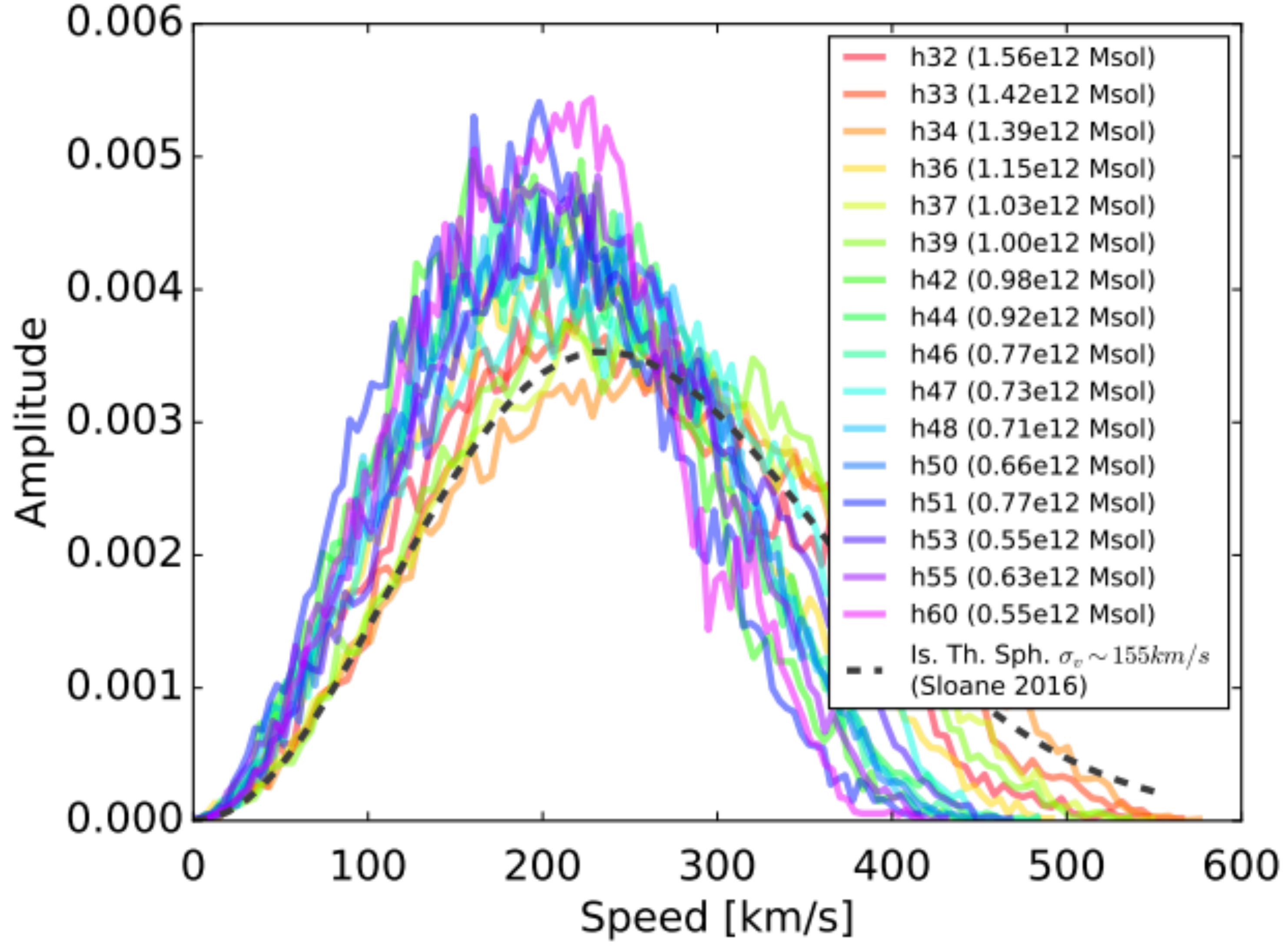
# What do we expect a more accurate *f(v)* to look like?

Numerous studies comparing SHM's Maxwellian *f(v)* with simulated MW analogues

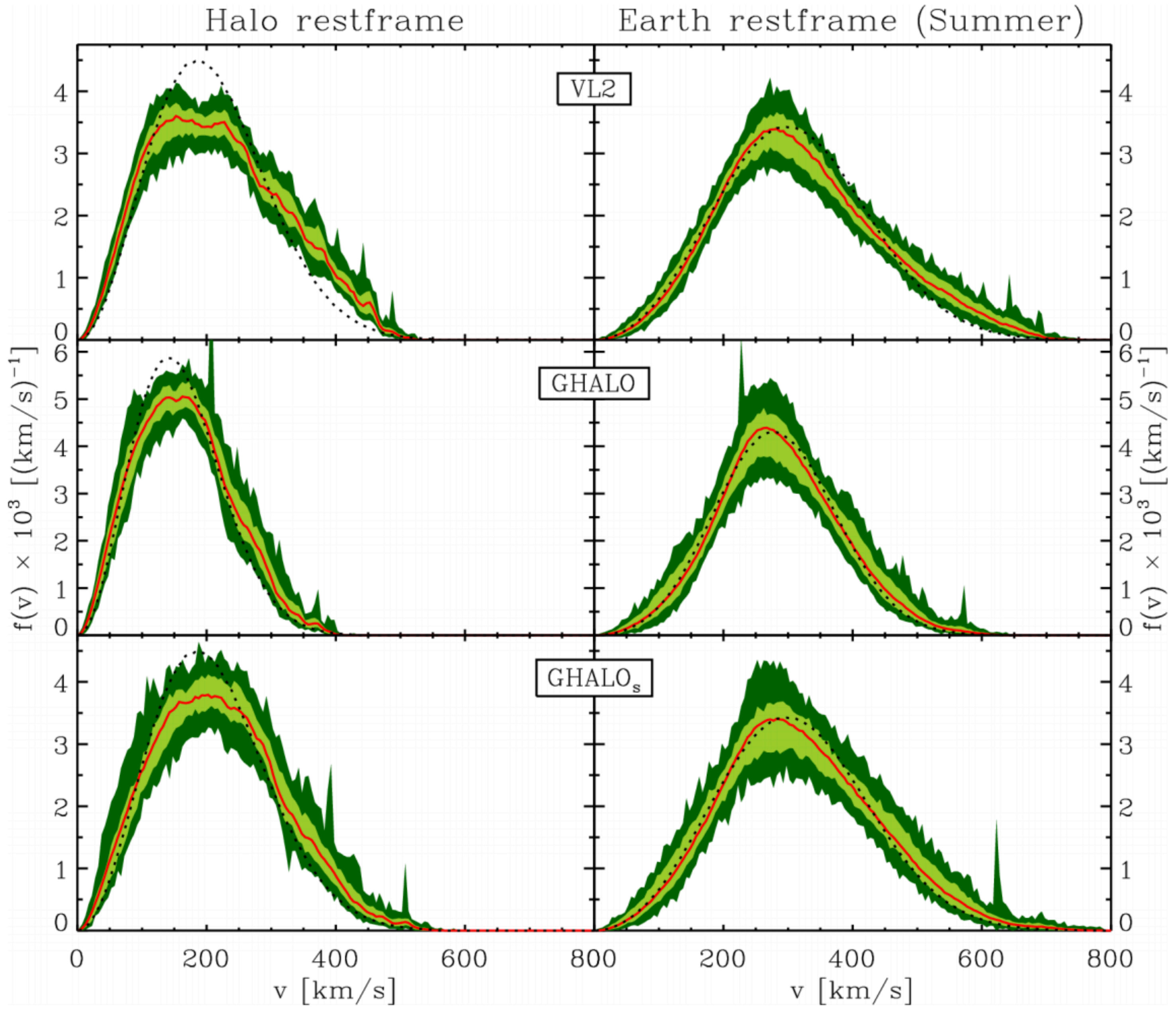
**Mao+ [1210.2721]**



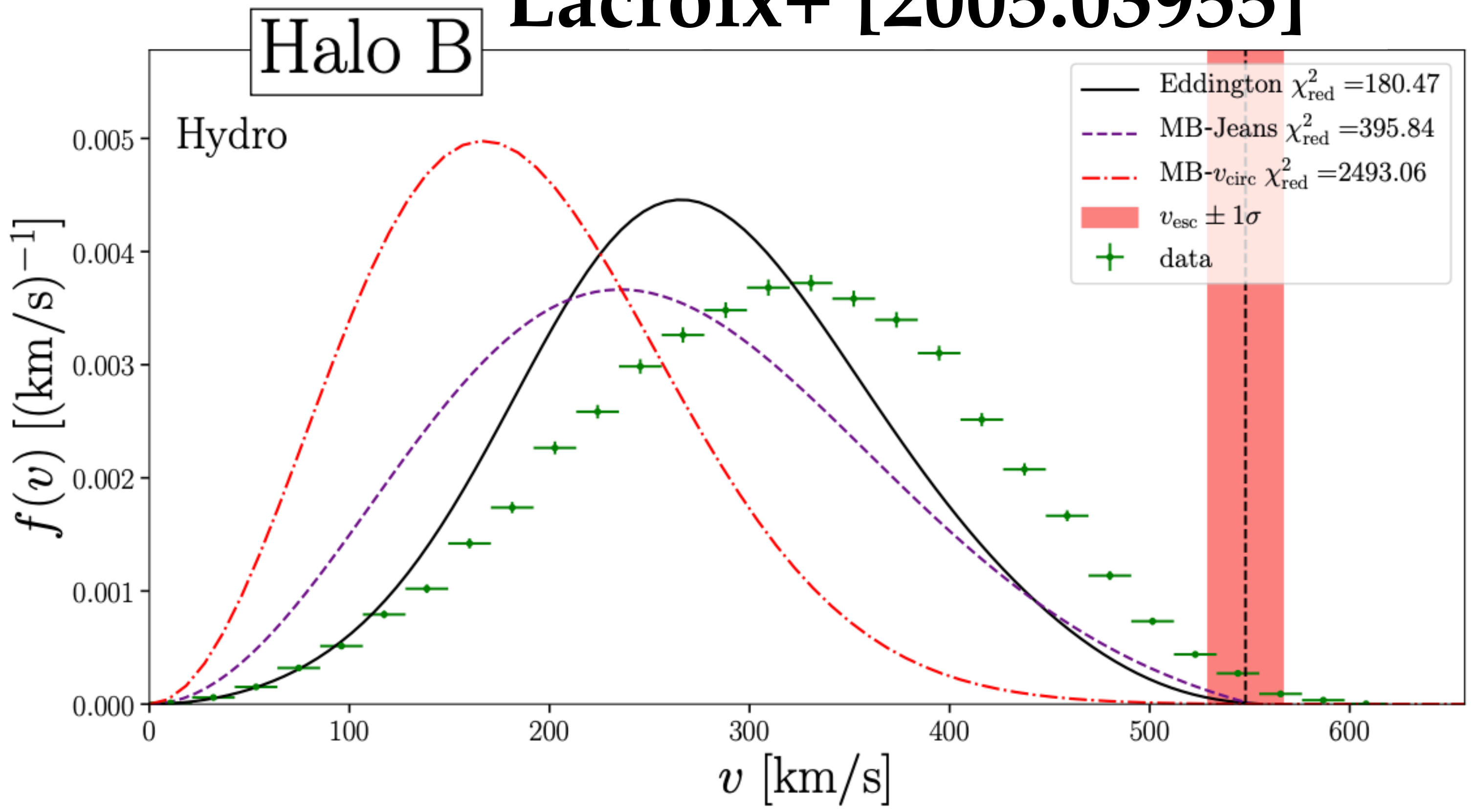
**Lentz+ [1703.06937]**



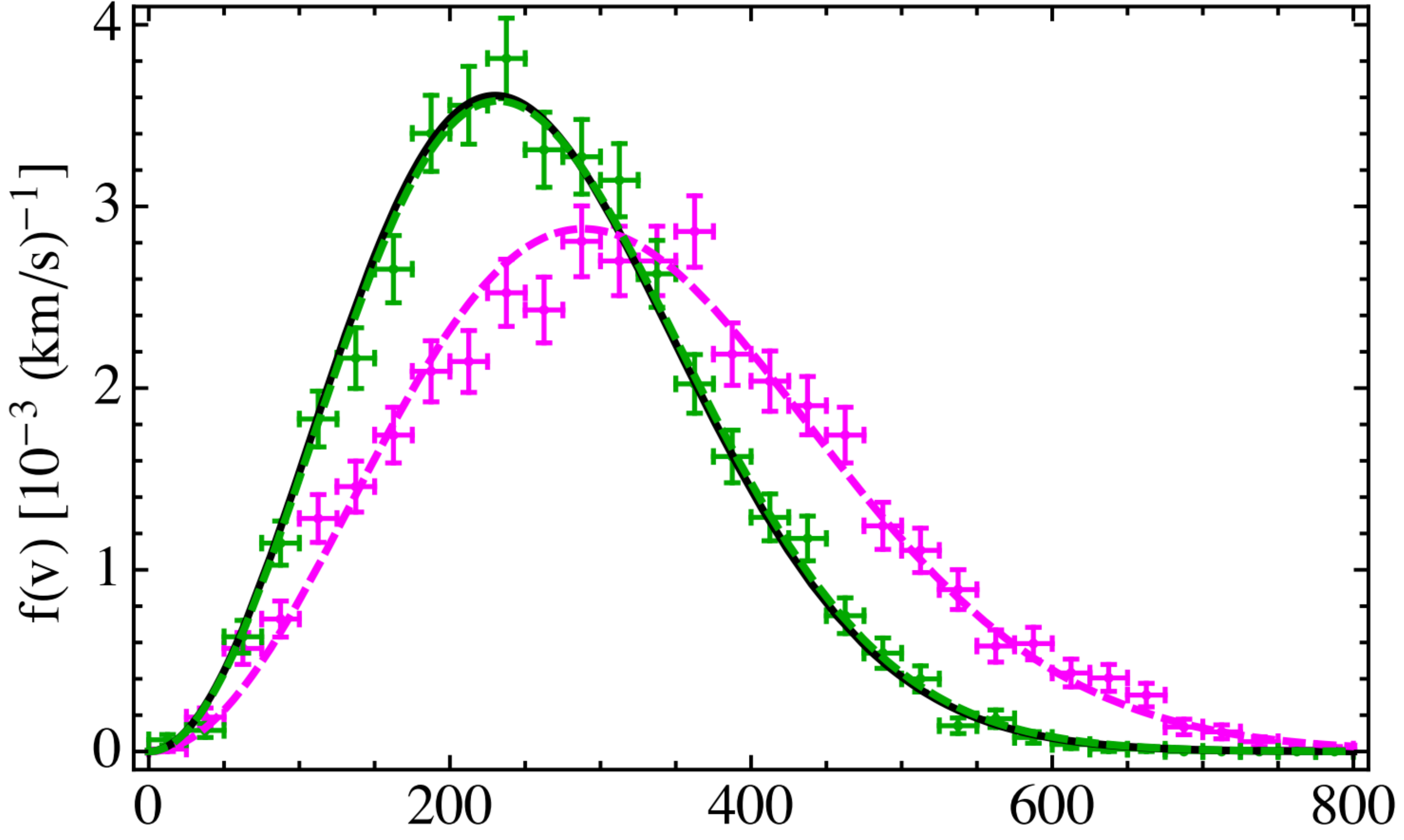
**Kuhlen+ [0912.2358]**



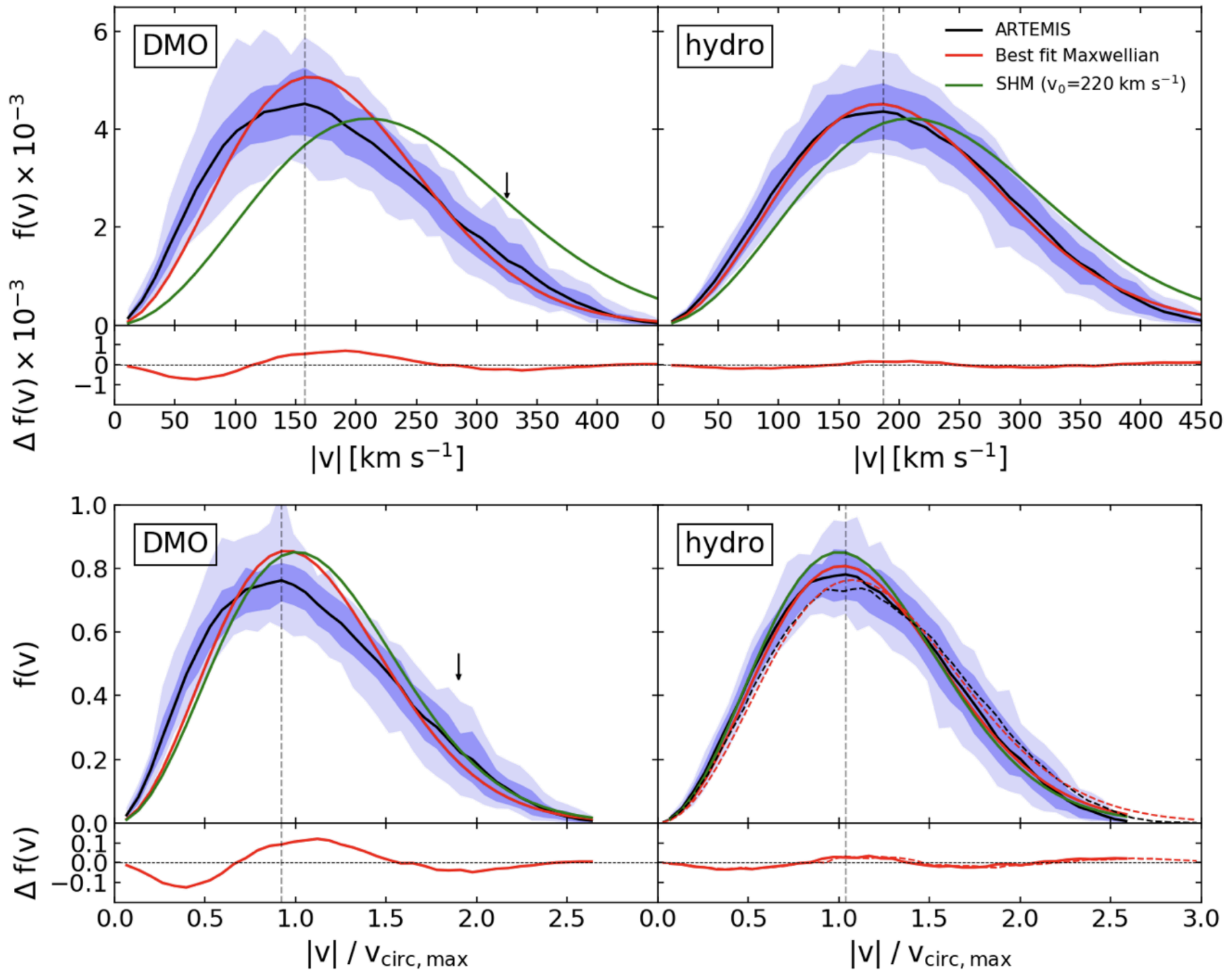
**Lacroix+ [2005.03955]**



**Bozorgnia+ [1601.04707]**



**Poole-Mackenzie+ [2006.15159]**



# *Gaia*

- 1.7 billion stars (1% of MW)
- 1.3 billion in 5D $(\alpha,\delta,\varpi,\mu_{\alpha^*},\mu_\delta)$
- 7 million in 6D $(x,y,z,v_x,v_y,v_z)$

# Structure of the Milky Way

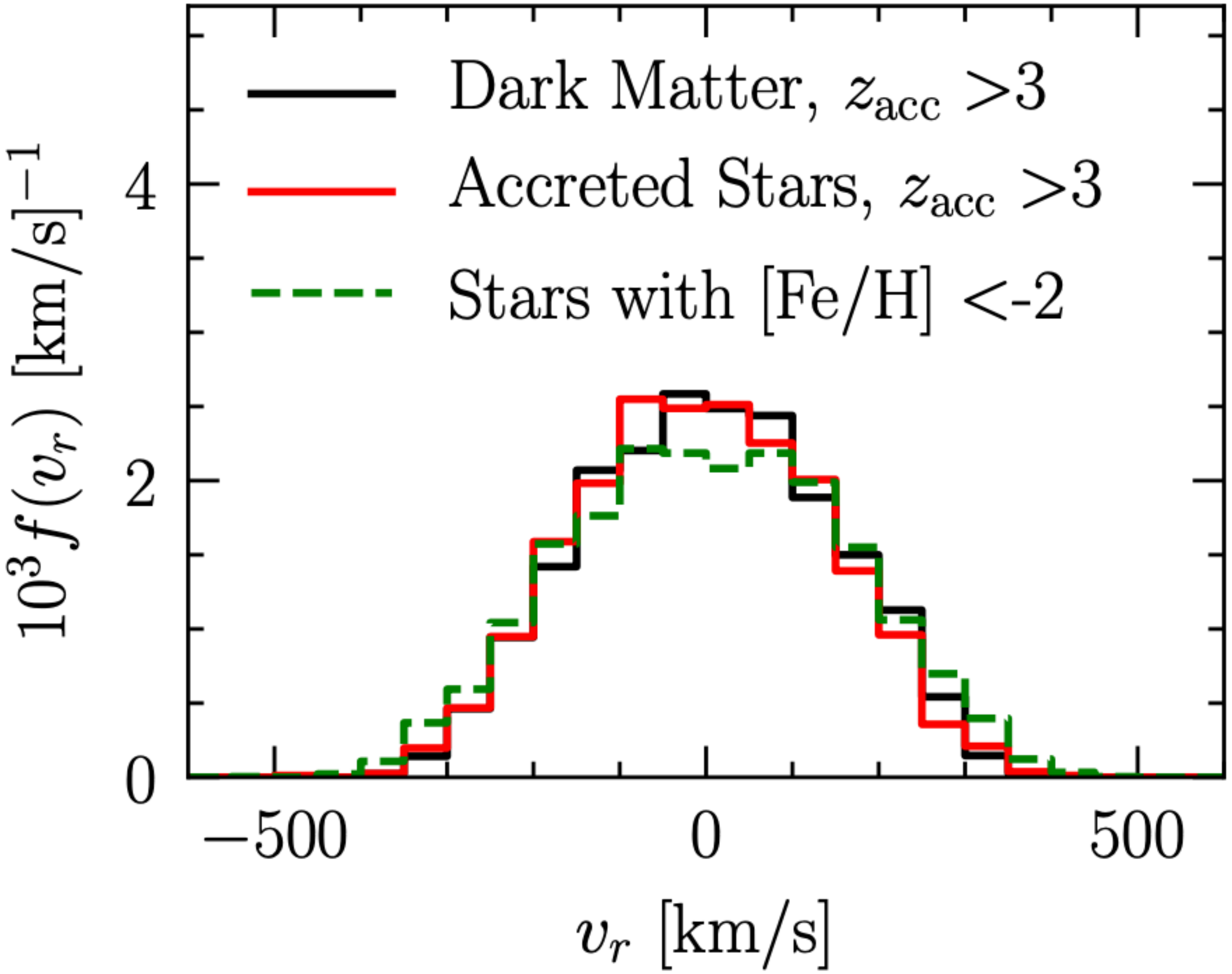
universetoday.com

# Dark/stellar halo connection

Suggestions from simulations that if you can find nearby accreted stars in the stellar halo, you can use them to trace the kinematics of nearby accreted DM

Necib+ [1810.12301]

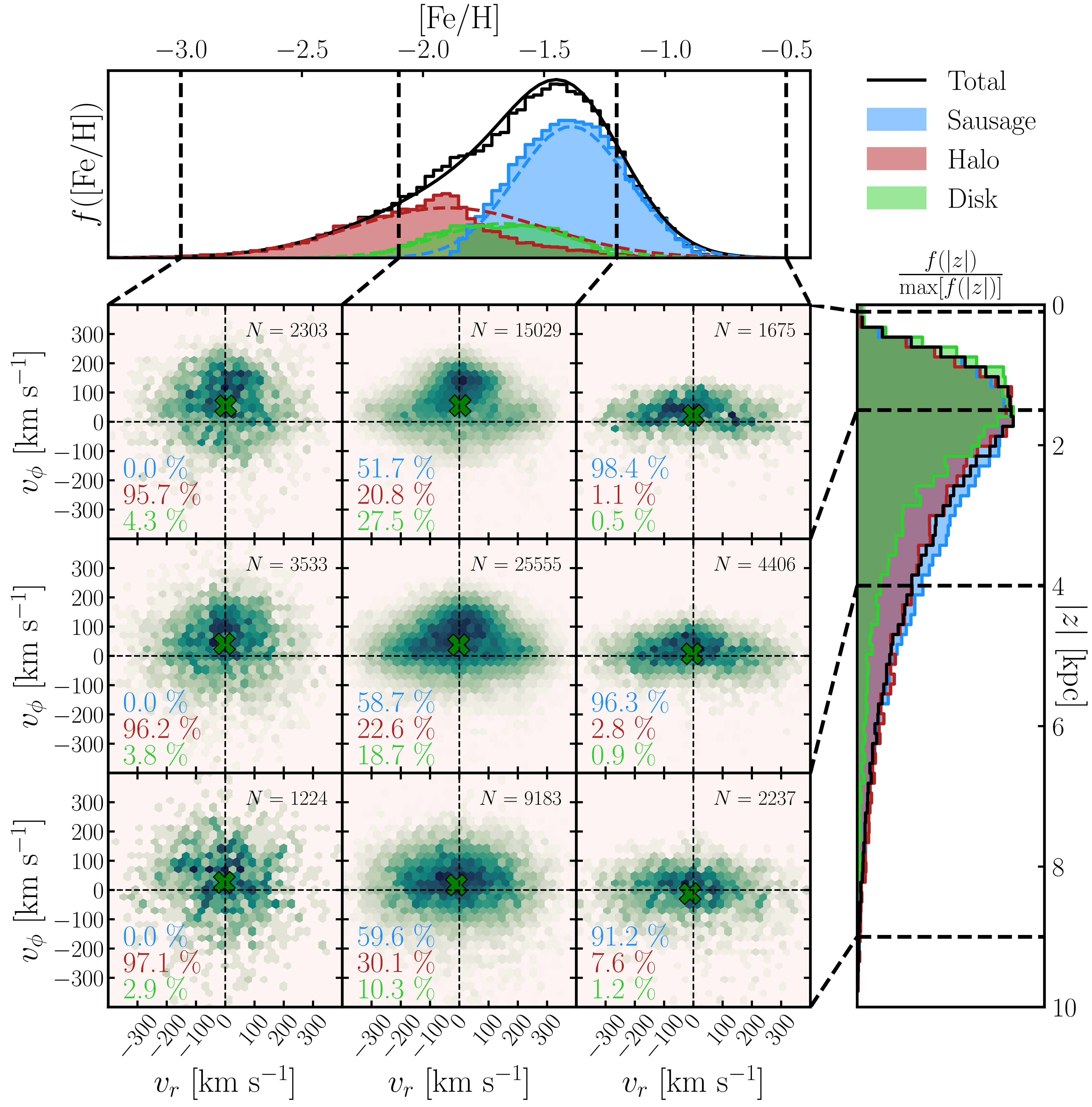
**Speed dist. (radial dir.) in MW-like galaxy in high res. FIRE simulation**



# What does the stellar halo look like?

Sample of Gaia-SDSS main sequence stars from stellar halo within 10 kpc

Metallicity →

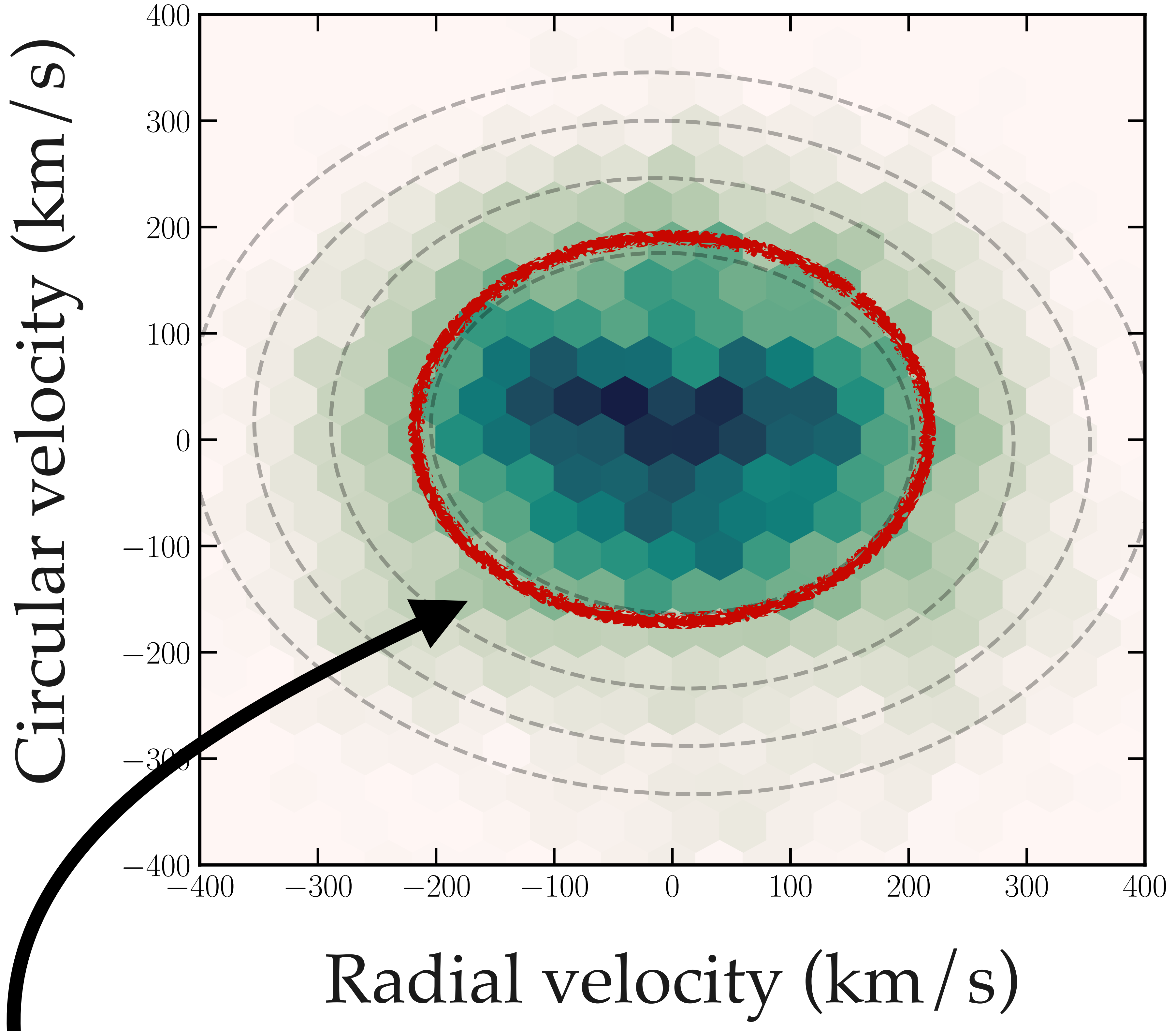


Circular velocity (km/s)

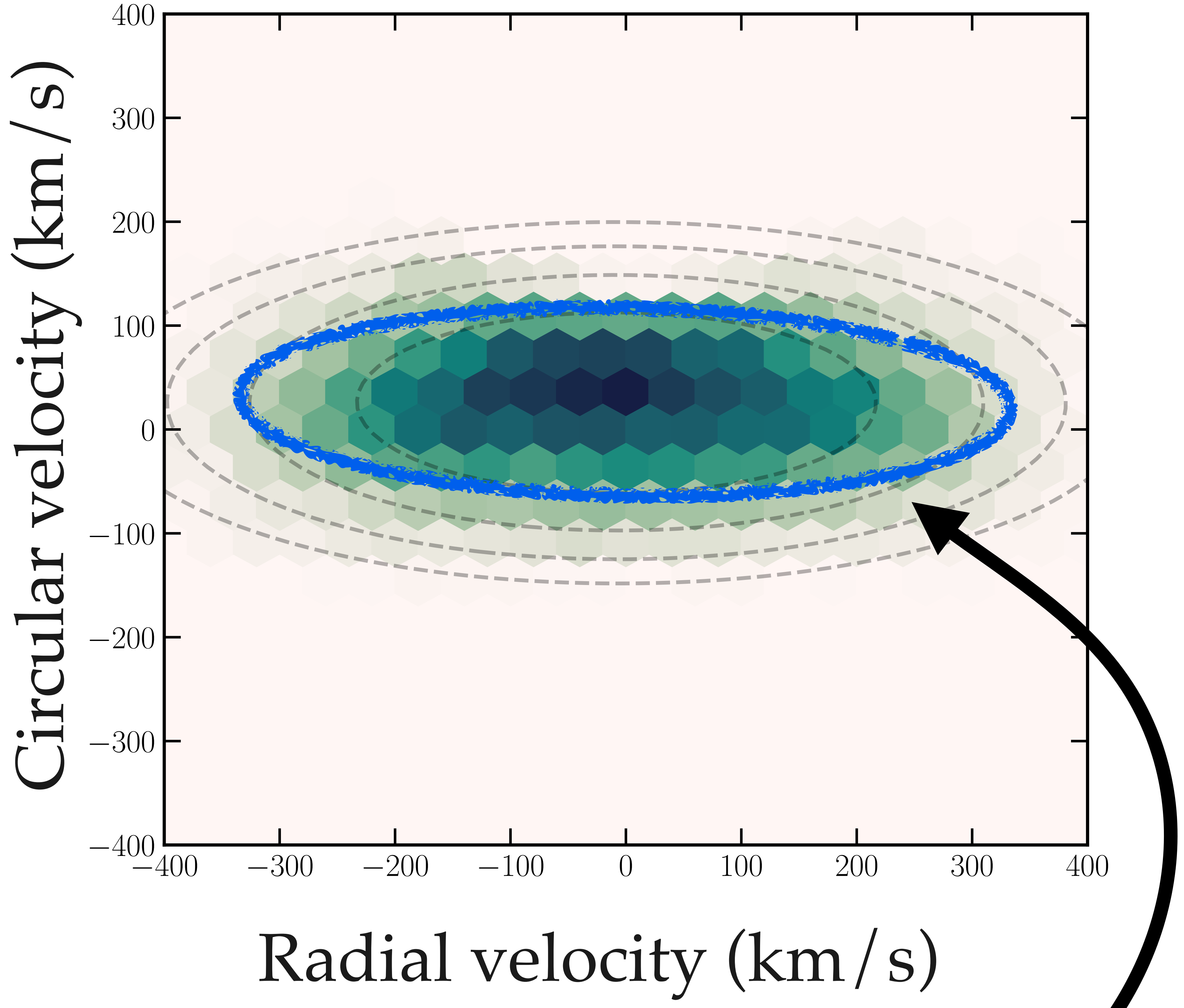
Radial velocity (km/s)

Height above disk ↓

[Fe/H]<-1.5



[Fe/H]>-1.5



## “Metal-poor” halo

- Round velocity ellipsoid
- ~30% of main sequence halo sample
- More metal-poor on average

## “Metal-rich” halo

- Highly eccentric radial orbits
- Dominant contribution ~50%
- Characteristic metallicity [Fe/H] = -1.4

# “Gaia Enceladus”

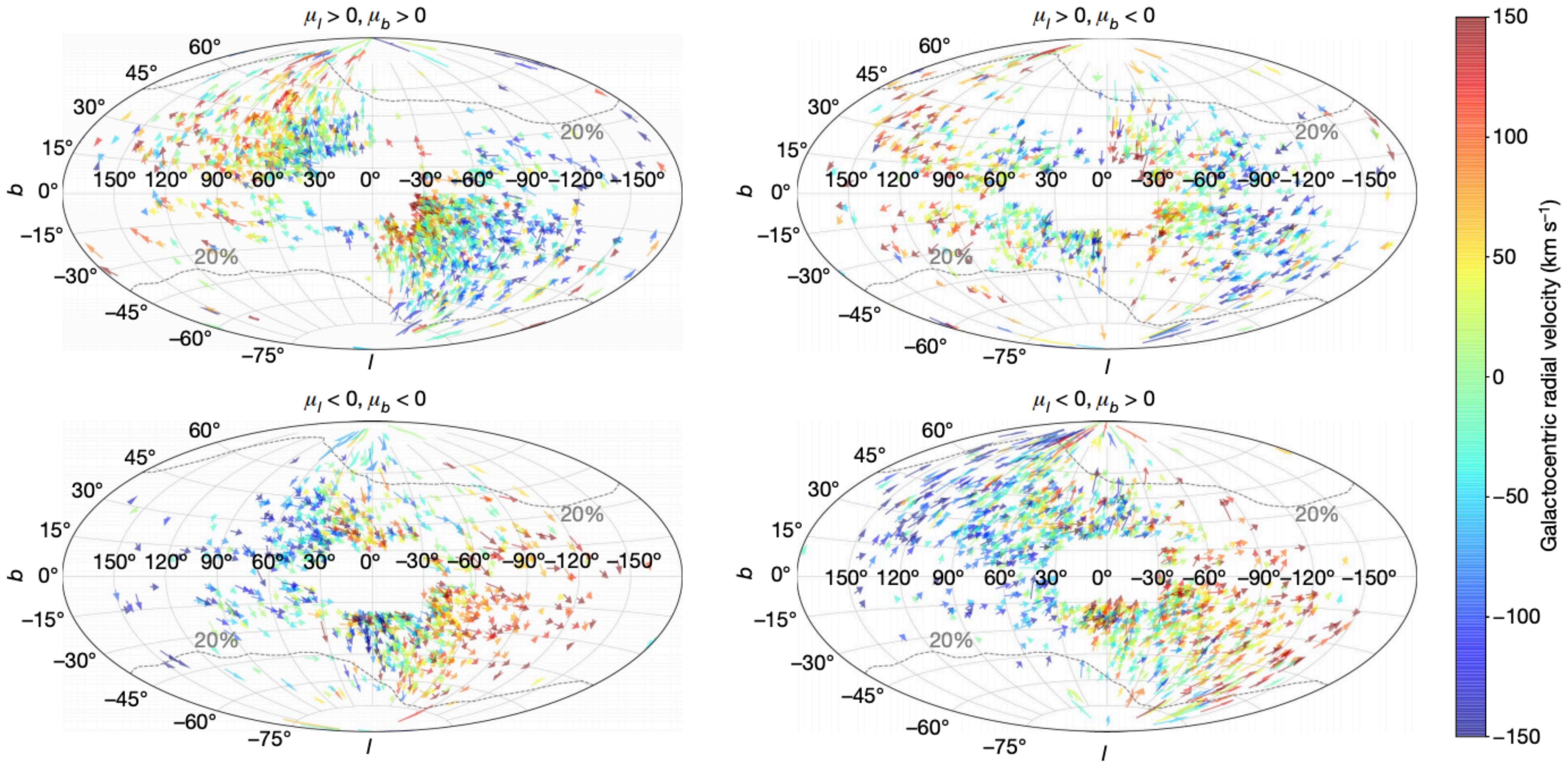
1806.06038

# “Gaia Sausage”

1802.03414

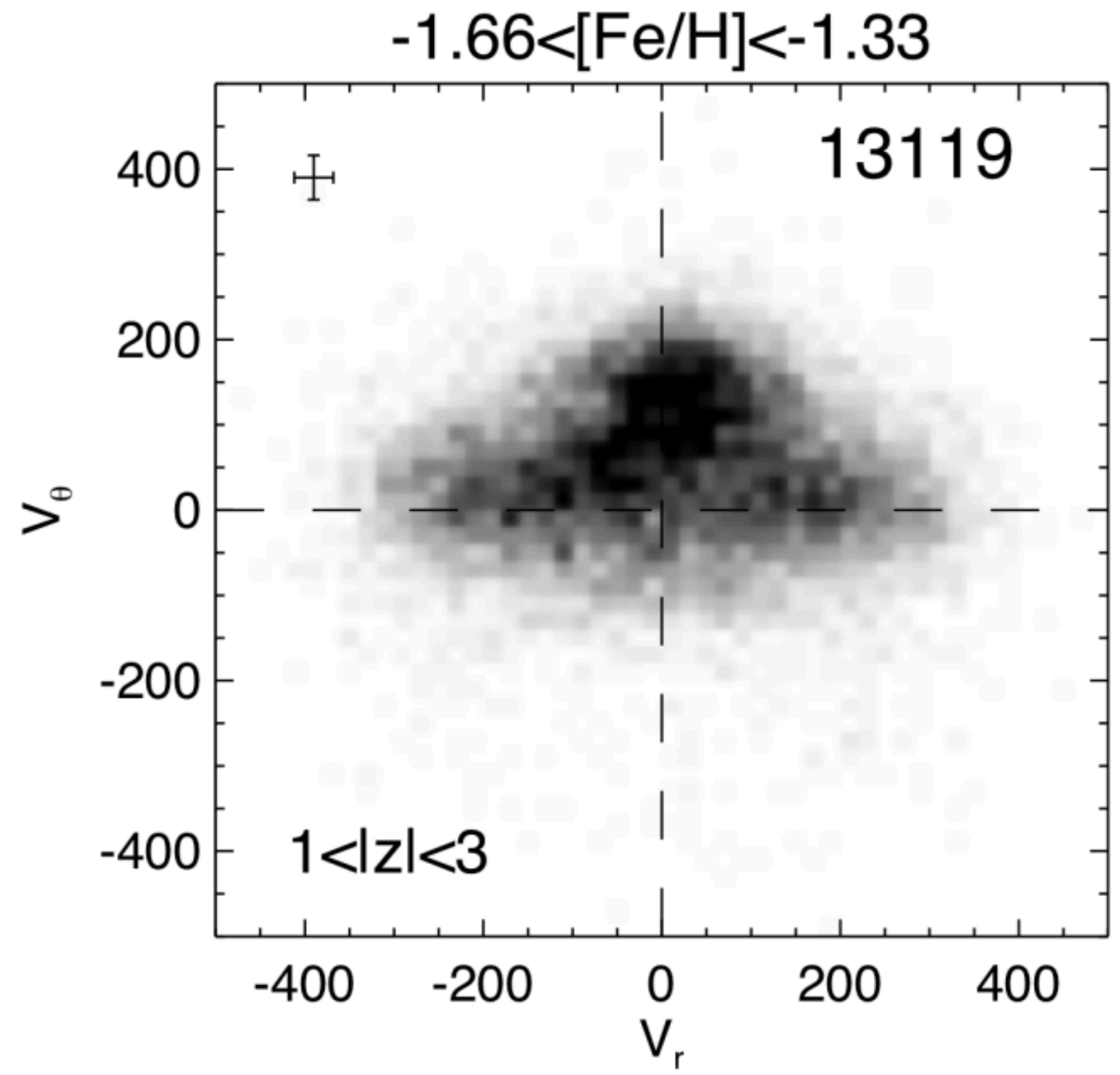
## The merger that led to the formation of the Milky Way’s inner stellar halo and thick disk

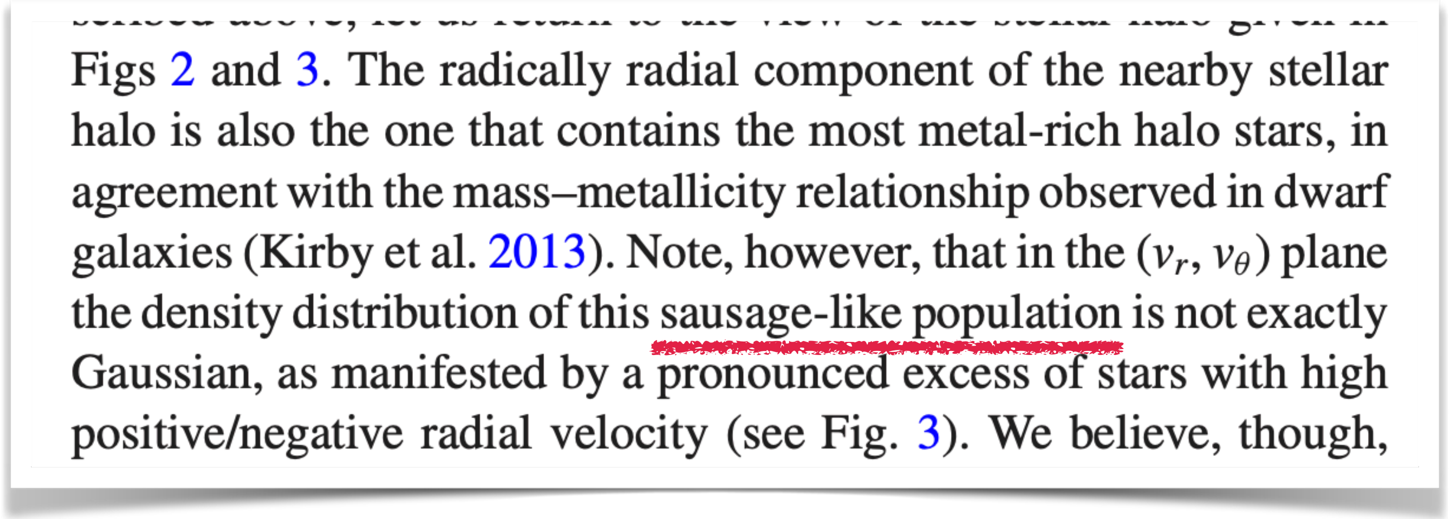
Amina Helmi[1]*, Carine Babusiaux[2,3], Helmer H. Koppelman[1], Davide Massari[1], Jovan Veljanoski[1] & Anthony G. A. Brown[4]



## Co-formation of the disc and the stellar halo★

V. Belokurov,[1,2]† D. Erkal,[1,3] N. W. Evans,[1] S. E. Koposov[1,4] and A. J. Deason[5]




Figs 2 and 3. The radically radial component of the nearby stellar halo is also the one that contains the most metal-rich halo stars, in agreement with the mass–metallicity relationship observed in dwarf galaxies (Kirby et al. 2013). Note, however, that in the $(v_r, v_\theta)$ plane the density distribution of this sausage-like population is not exactly Gaussian, as manifested by a pronounced excess of stars with high positive/negative radial velocity (see Fig. 3). We believe, though,

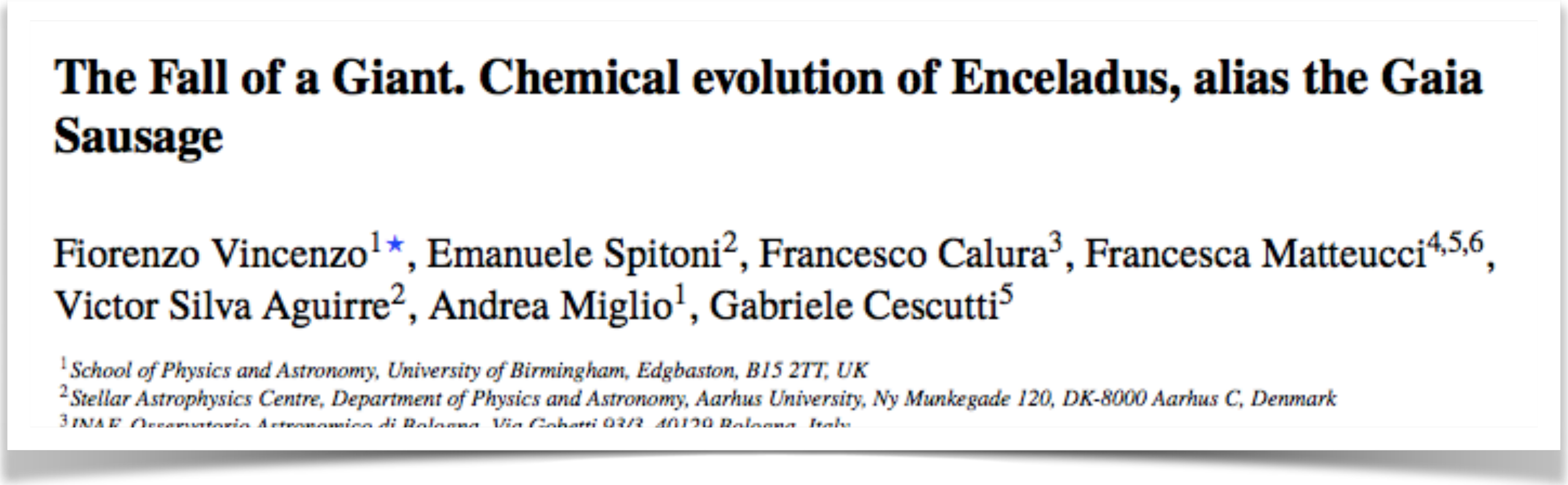
# **The great debate:** which of the equally terrible names should we use for this discovery?

**Gaia-Enceladus?**

**Gaia-Enceladus/Sausage?**

**Gaia-Sausage?**

**Gaia radially anisotropic substructure?**



### The Fall of a Giant. Chemical evolution of Enceladus, alias the Gaia Sausage

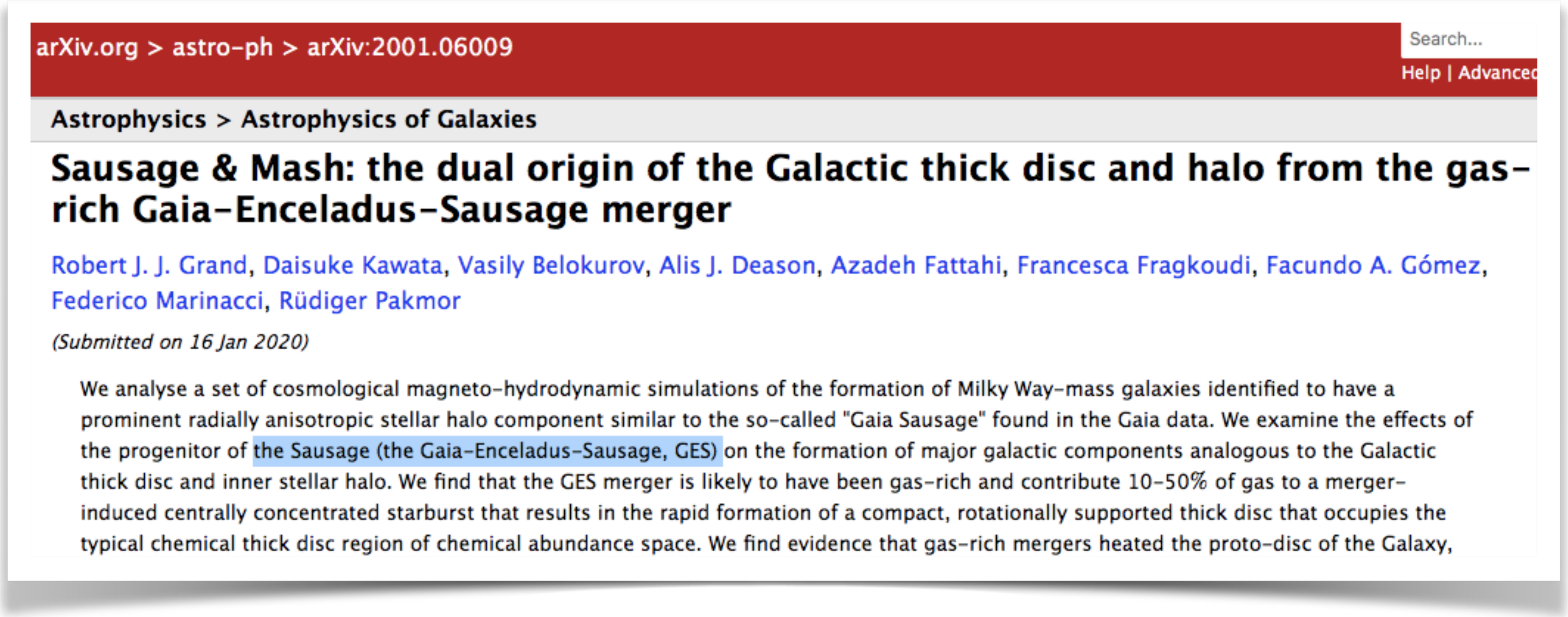
Fiorenzo Vincenzo[1★], Emanuele Spitoni[2], Francesco Calura[3], Francesca Matteucci[4,5,6], Victor Silva Aguirre[2], Andrea Miglio[1], Gabriele Cescutti[5]

[1] *School of Physics and Astronomy, University of Birmingham, Edgbaston, B15 2TT, UK*
[2] *Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*
[3] *INAF, Osservatorio Astronomico di Bologna, Via Gobetti 93/3, 40129 Bologna, Italy*

### The dark matter component of the Gaia radially anisotropic substructure

**Nassim Bozorgnia,[a] Azadeh Fattahi,[b] Carlos S. Frenk,[b] Andrew Cheek,[a,c] David G. Cerdeño,[a] Facundo A. Gómez,[d,e] Robert J. J. Grand,[f] and Federico Marinacci[g]**

[a] Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, UK
[b] Institute for Computational Cosmology, Durham University,



arXiv.org > astro-ph > arXiv:2001.06009

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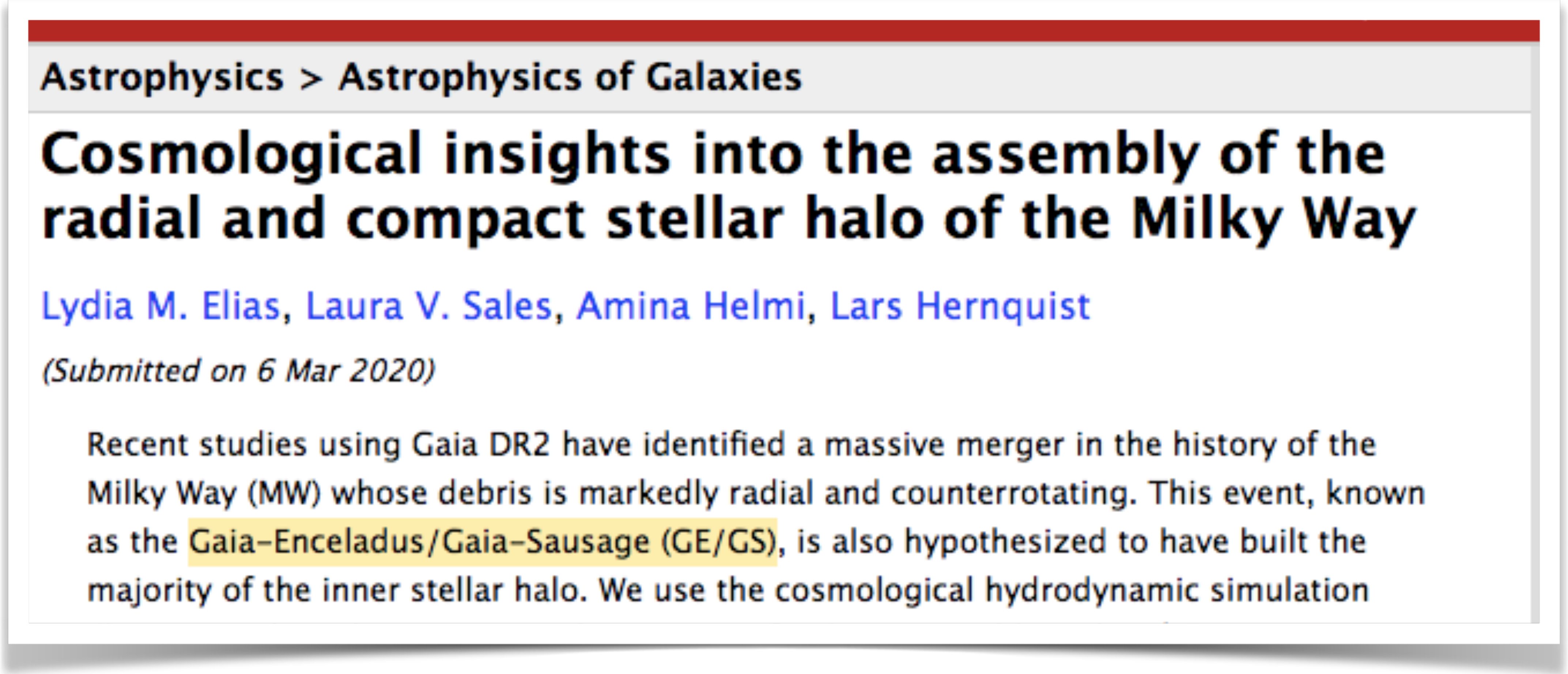
Astrophysics > Astrophysics of Galaxies

### Sausage & Mash: the dual origin of the Galactic thick disc and halo from the gas-rich Gaia-Enceladus-Sausage merger

Robert J. J. Grand, Daisuke Kawata, Vasily Belokurov, Alis J. Deason, Azadeh Fattahi, Francesca Fragkoudi, Facundo A. Gómez, Federico Marinacci, Rüdiger Pakmor

*(Submitted on 16 Jan 2020)*

We analyse a set of cosmological magneto-hydrodynamic simulations of the formation of Milky Way-mass galaxies identified to have a prominent radially anisotropic stellar halo component similar to the so-called "Gaia Sausage" found in the Gaia data. We examine the effects of the progenitor of the Sausage (the Gaia-Enceladus-Sausage, GES) on the formation of major galactic components analogous to the Galactic thick disc and inner stellar halo. We find that the GES merger is likely to have been gas-rich and contribute 10-50% of gas to a merger-induced centrally concentrated starburst that results in the rapid formation of a compact, rotationally supported thick disc that occupies the typical chemical thick disc region of chemical abundance space. We find evidence that gas-rich mergers heated the proto-disc of the Galaxy,



Astrophysics > Astrophysics of Galaxies

### Cosmological insights into the assembly of the radial and compact stellar halo of the Milky Way

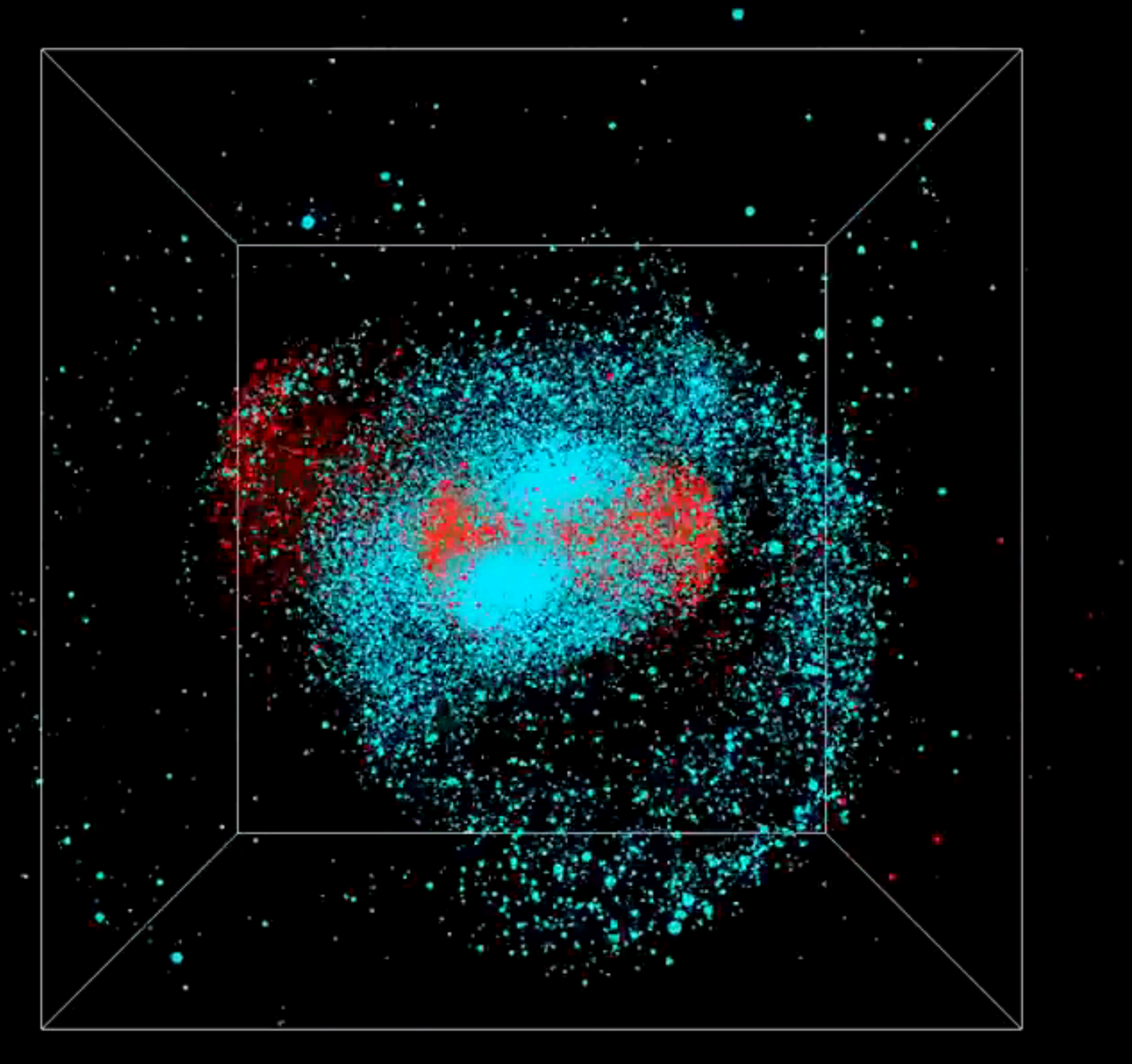
Lydia M. Elias, Laura V. Sales, Amina Helmi, Lars Hernquist

*(Submitted on 6 Mar 2020)*

Recent studies using Gaia DR2 have identified a massive merger in the history of the Milky Way (MW) whose debris is markedly radial and counterrotating. This event, known as the Gaia-Enceladus/Gaia-Sausage (GE/GS), is also hypothesized to have built the majority of the inner stellar halo. We use the cosmological hydrodynamic simulation

# Distinct chemodynamical signature implies that the **highly radial stars** were brought in by a 4:1 merger with a $10^{9\text{-}10}\,M_\odot$ stellar mass galaxy, 8-10 billion years ago

→ Highly radial orbits suggest low-inclination head-on collision

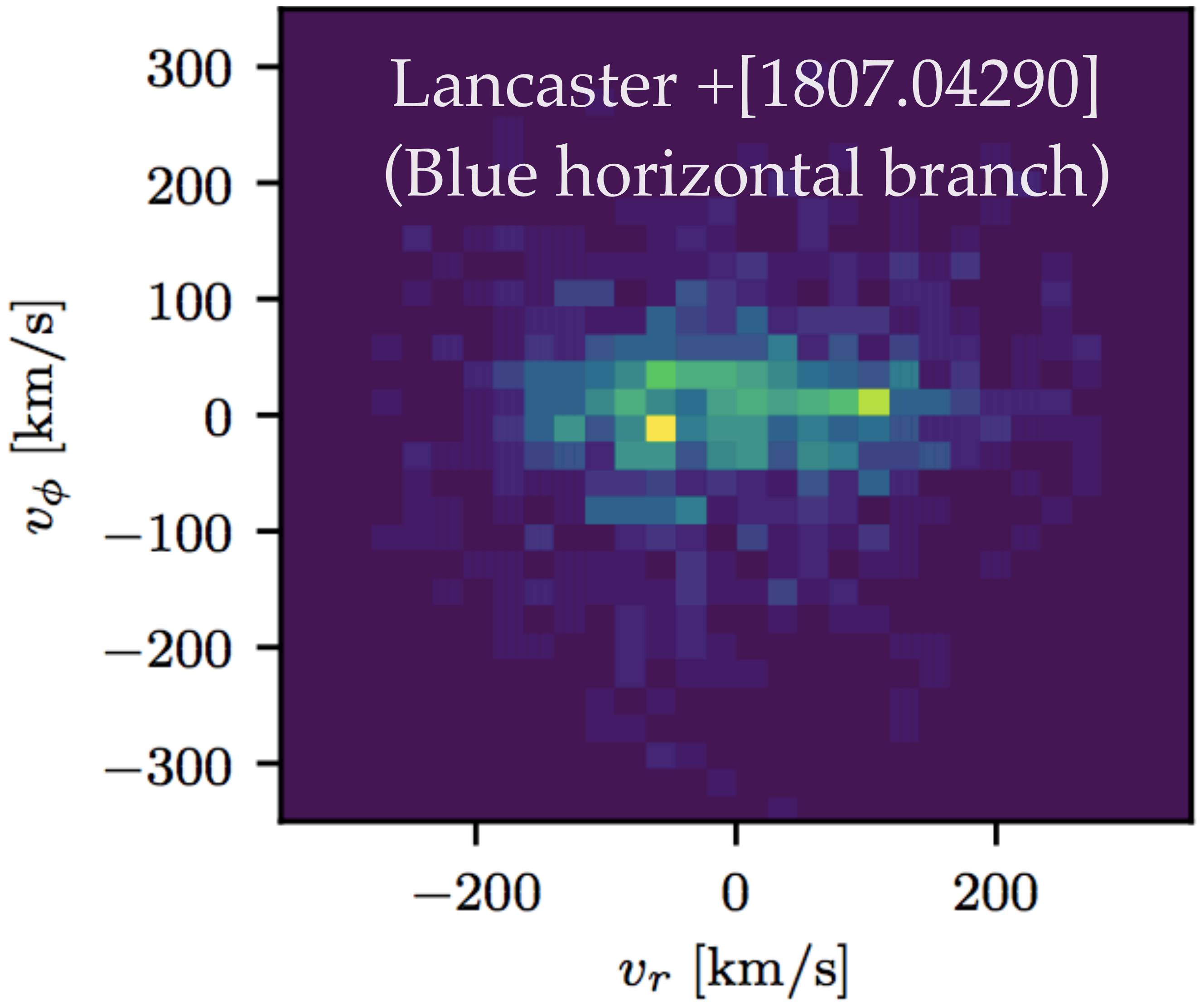


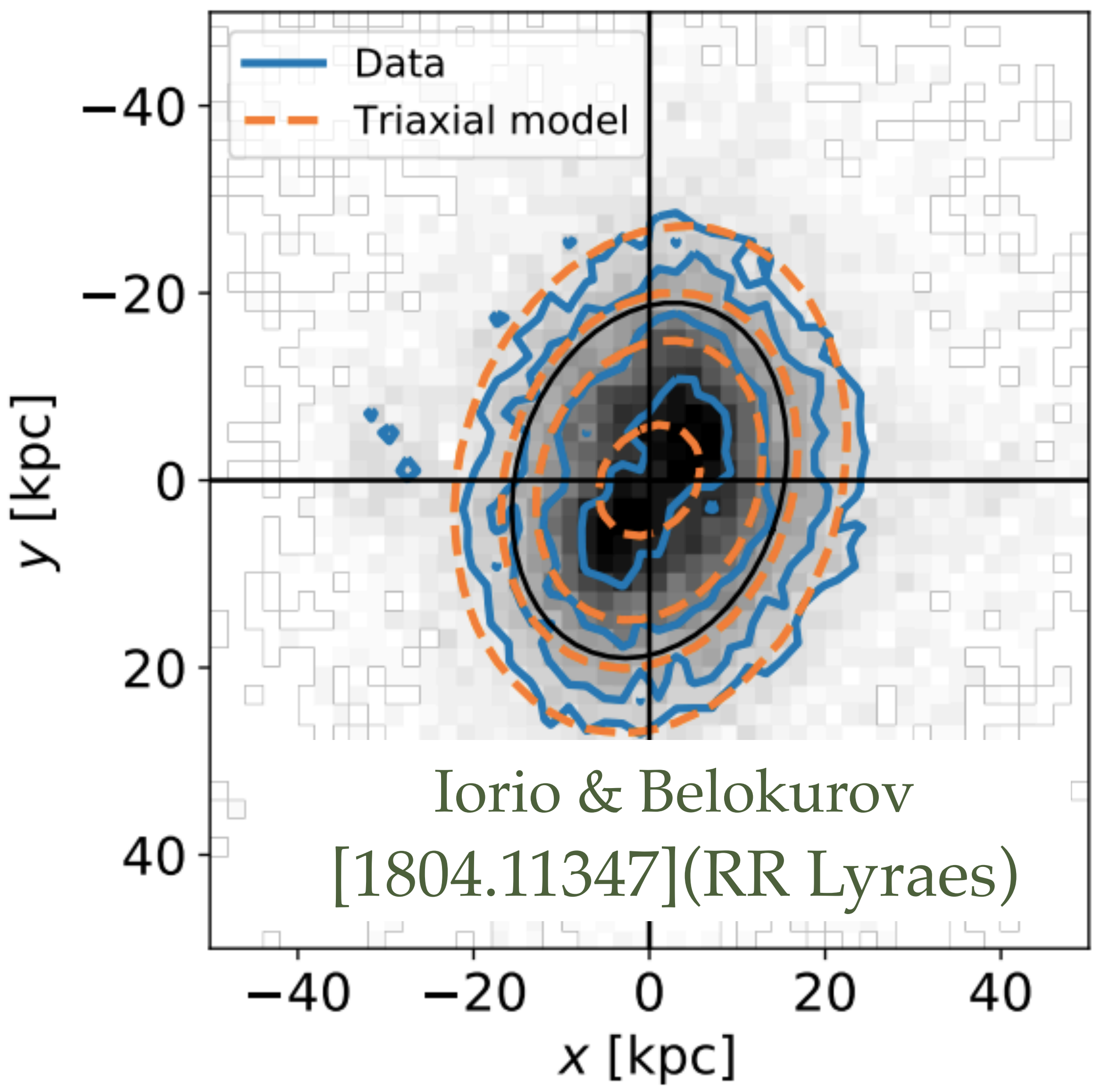
Helmi et al. [1806.06038]

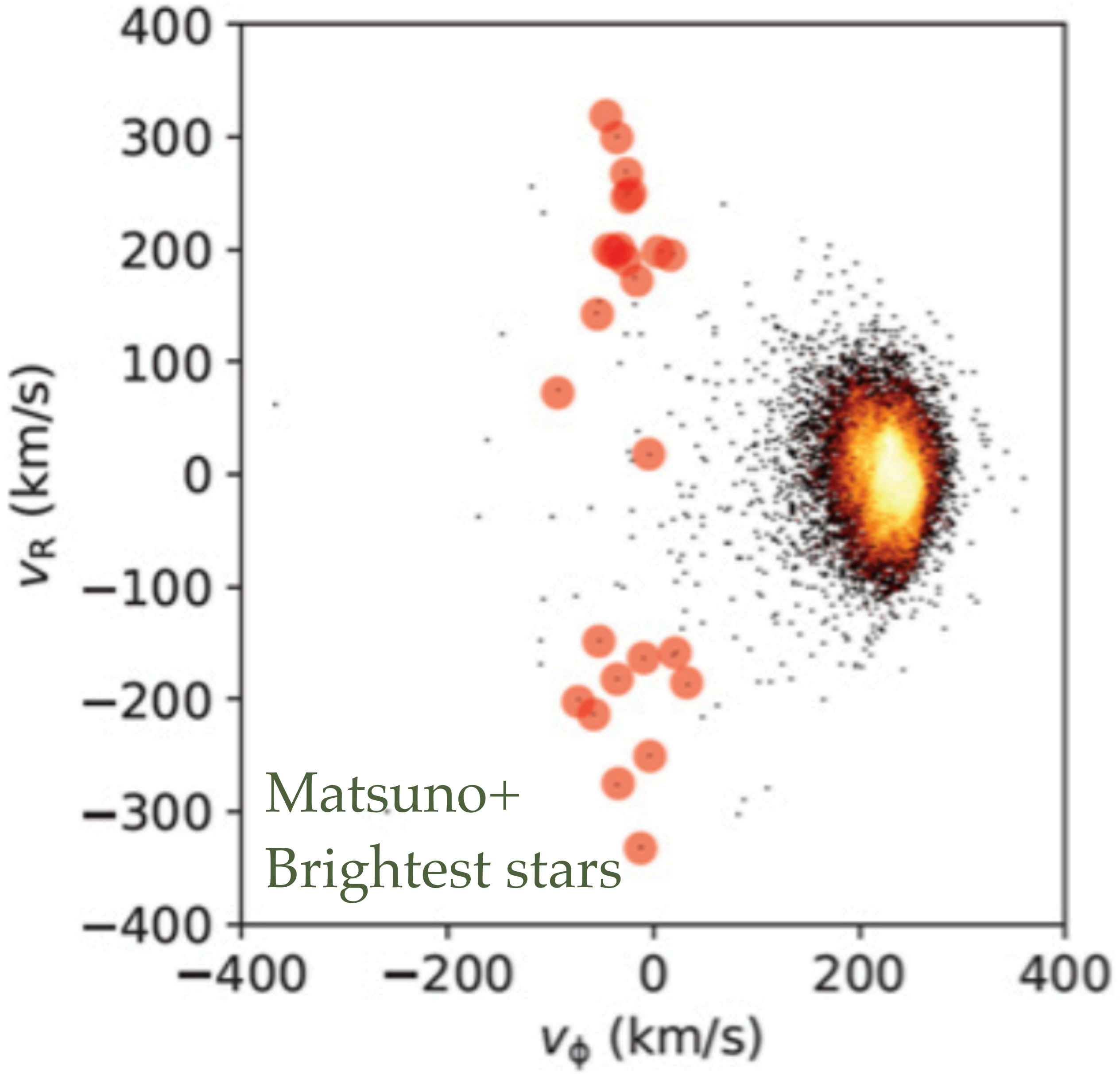
**Further evidence:**

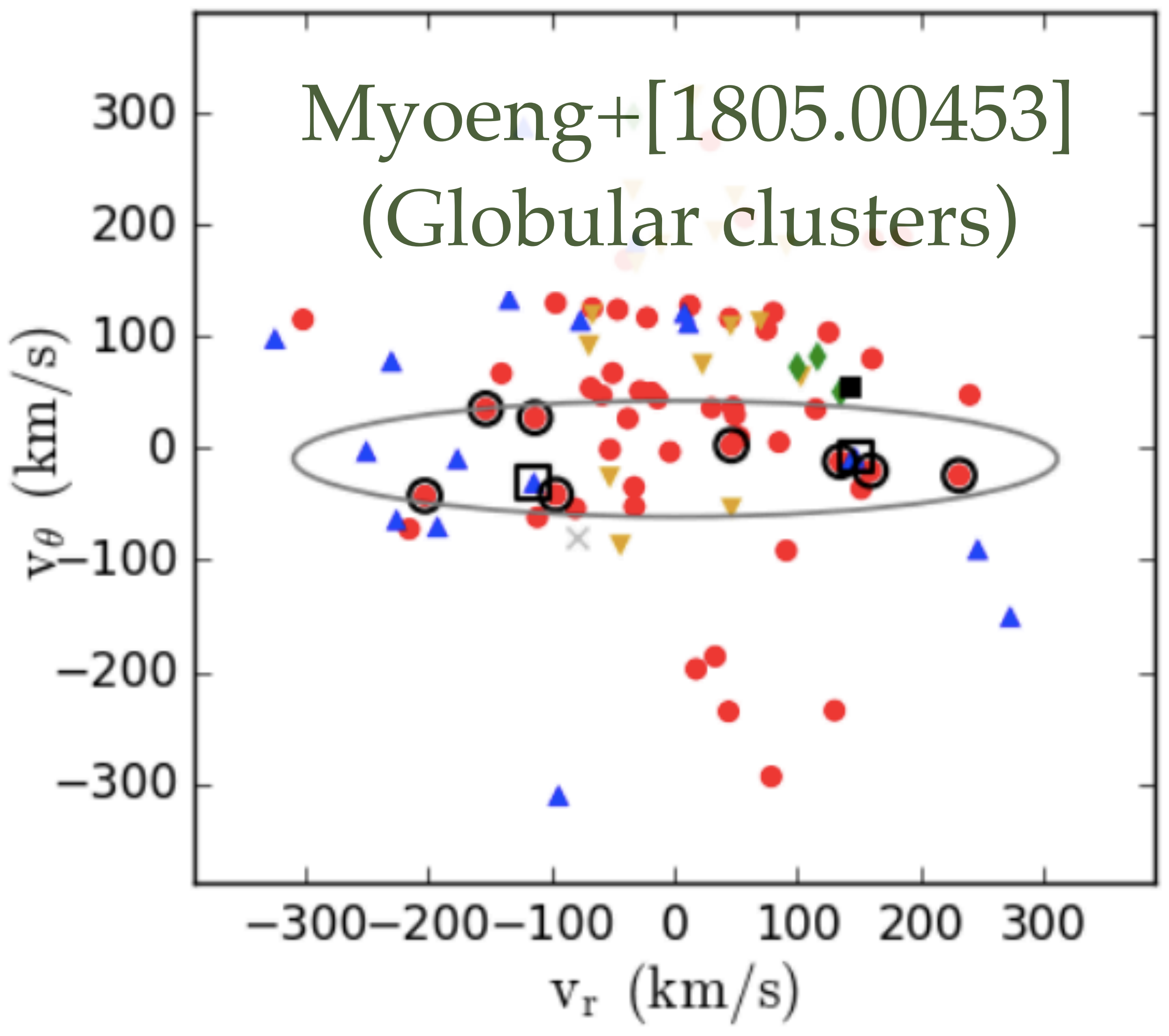
- Stellar density break at 20 kpc from pileup of stars at apocentre
  Deason+[1805.10288]
- Dynamical heating of thick disk stars into halo-like orbits (the "Spash")
  Belokurov+ [1909.04679, 2008.02280]
- Connected to at least 8 known GCs
  Myeong+ [1805.00453]

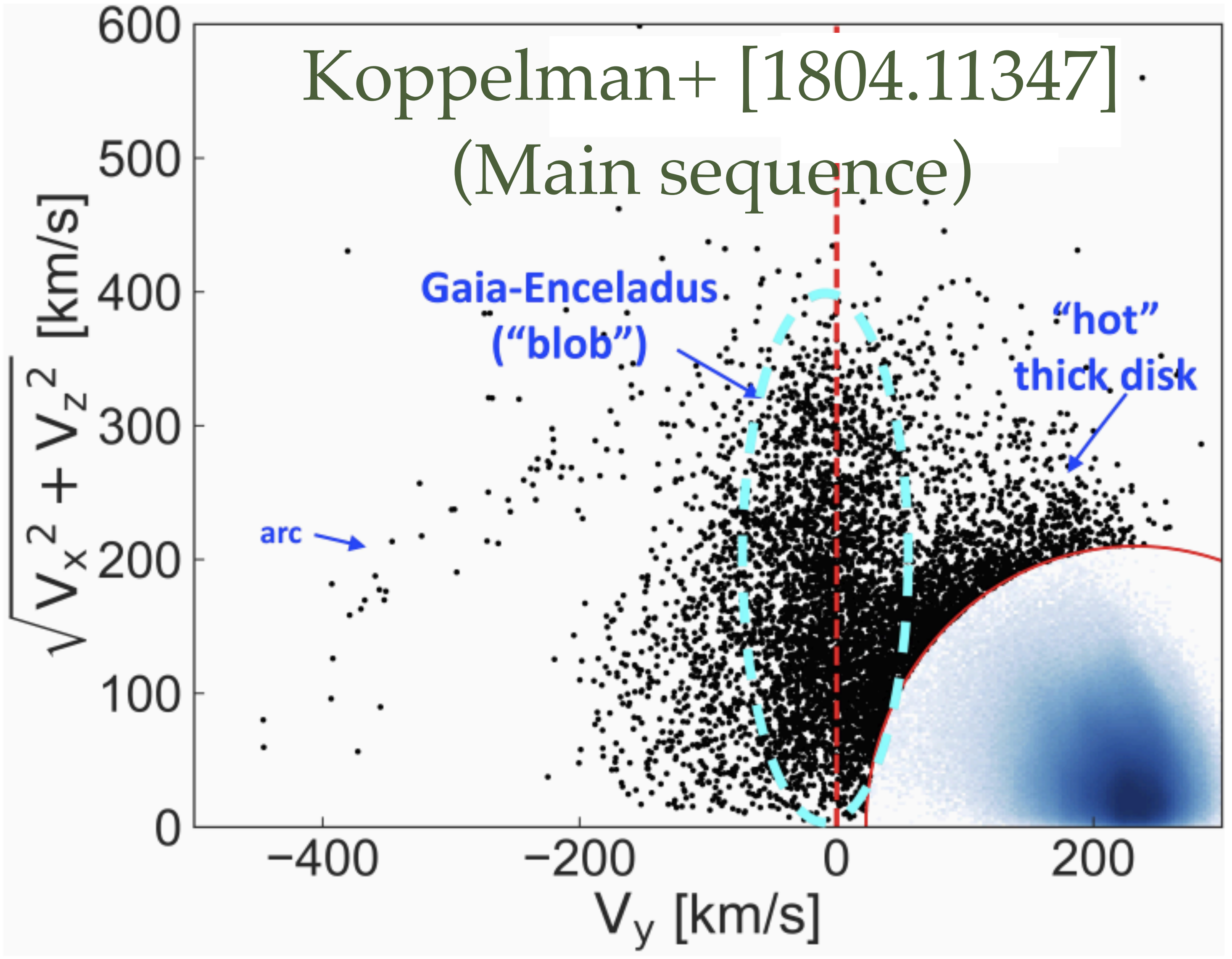
# More on the sausage…

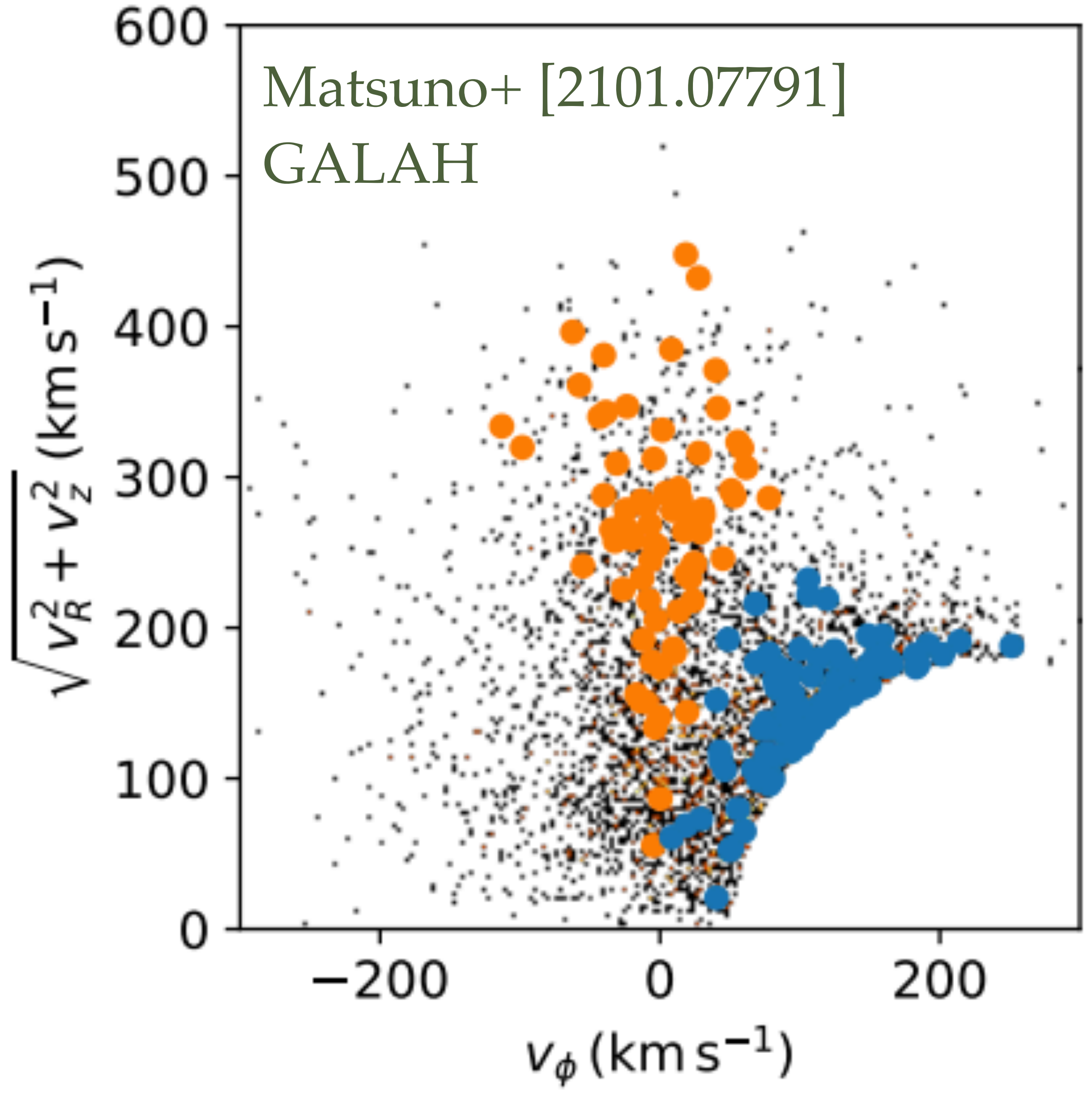

Lancaster +[1807.04290]
(Blue horizontal branch)


Iorio & Belokurov
[1804.11347](RR Lyraes)


Matsuno+
Brightest stars


Myoeng+[1805.00453]
(Globular clusters)


Koppelman+ [1804.11347]
(Main sequence)


Matsuno+ [2101.07791]
GALAH

# Q: What % of the local dark halo is made of sausage?

>0% ?

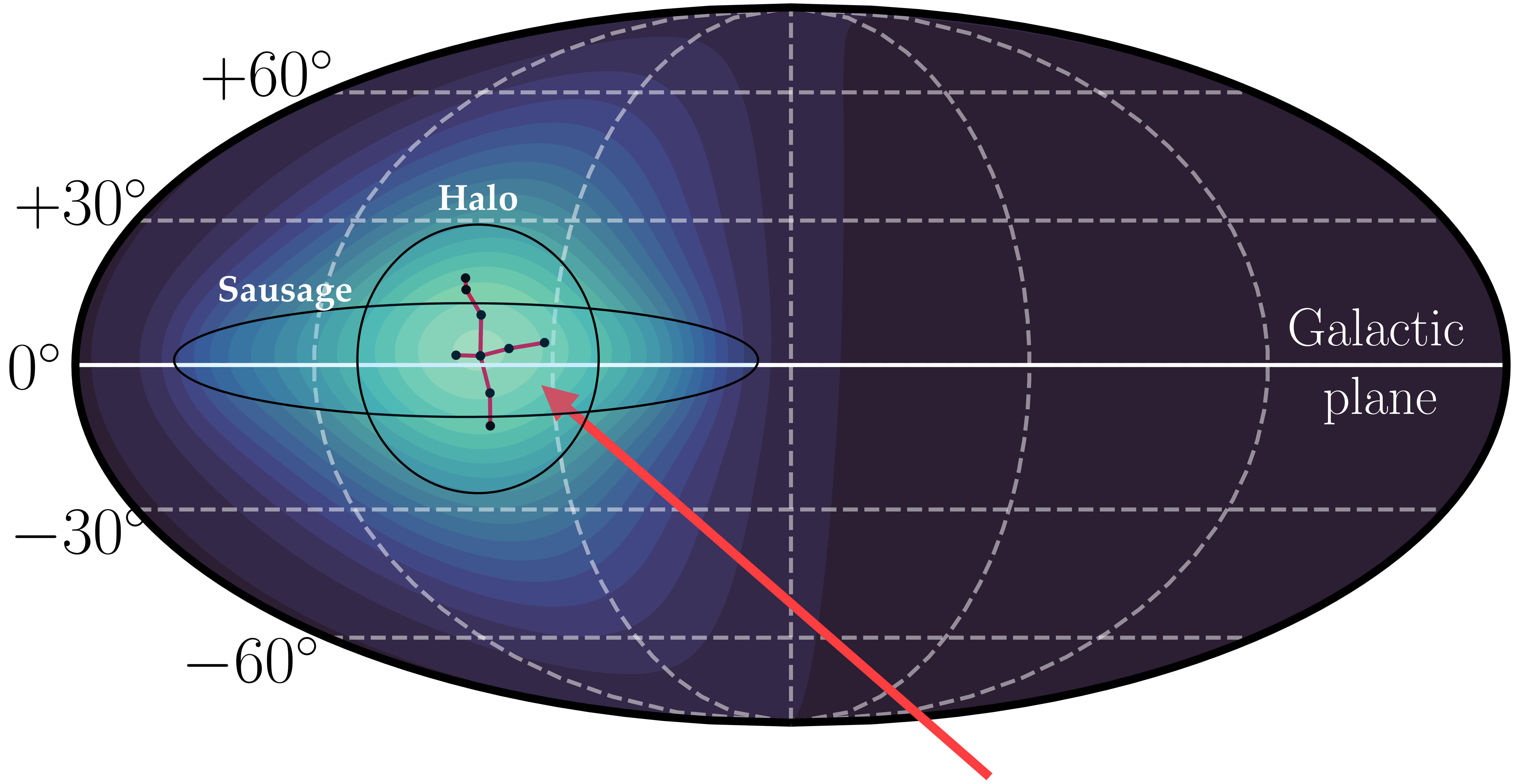
- **Well represented in stellar halo***: e.g. ~50% of all MS stars within 10 kpc in *Gaia*-SDSS halo sample + and plentiful in other pops.
- **Necib+ [1810.12301]:** ~40±25% of local DM accreted from luminous mergers is in Sausage-like form (FIRE sim)

**However:**

- **Fattahi+ [1810.07779]:** $\lesssim$ 10% of local DM within 20 kpc brought in by Sausage-like events (Auriga sim)
- **Evans+ [1810.11468]:** sphericity of equipotentials means that fraction of halo mass in a triaxial figure should be $\lesssim$ 20%

*[see '17-'20 papers by Helmi+, Naidu+, Myeong+, Koppelman+, Belokurov+, Matsuno+… and many others cited later in this talk]

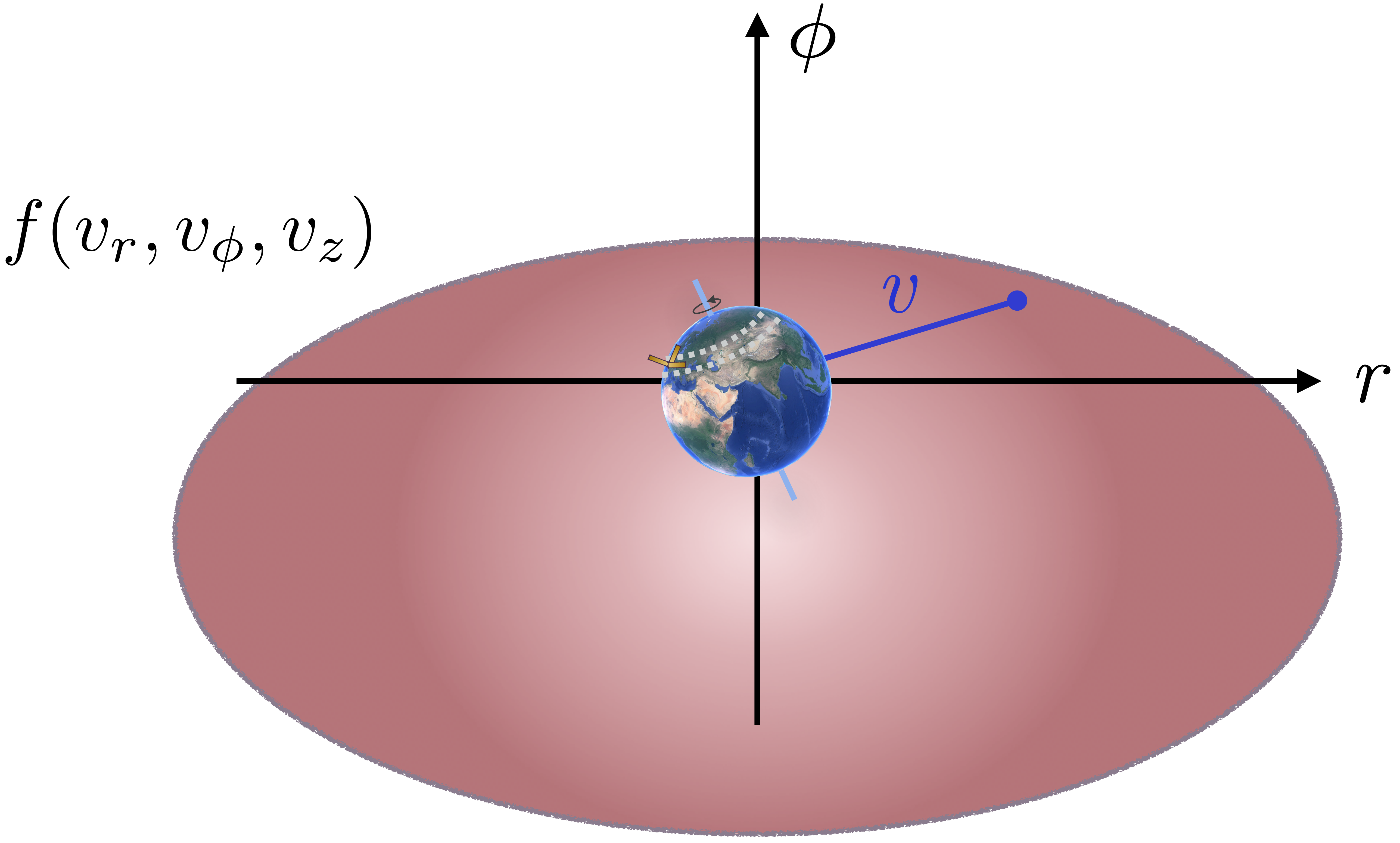
# Flux of DM from the Sausage versus the rest of the halo



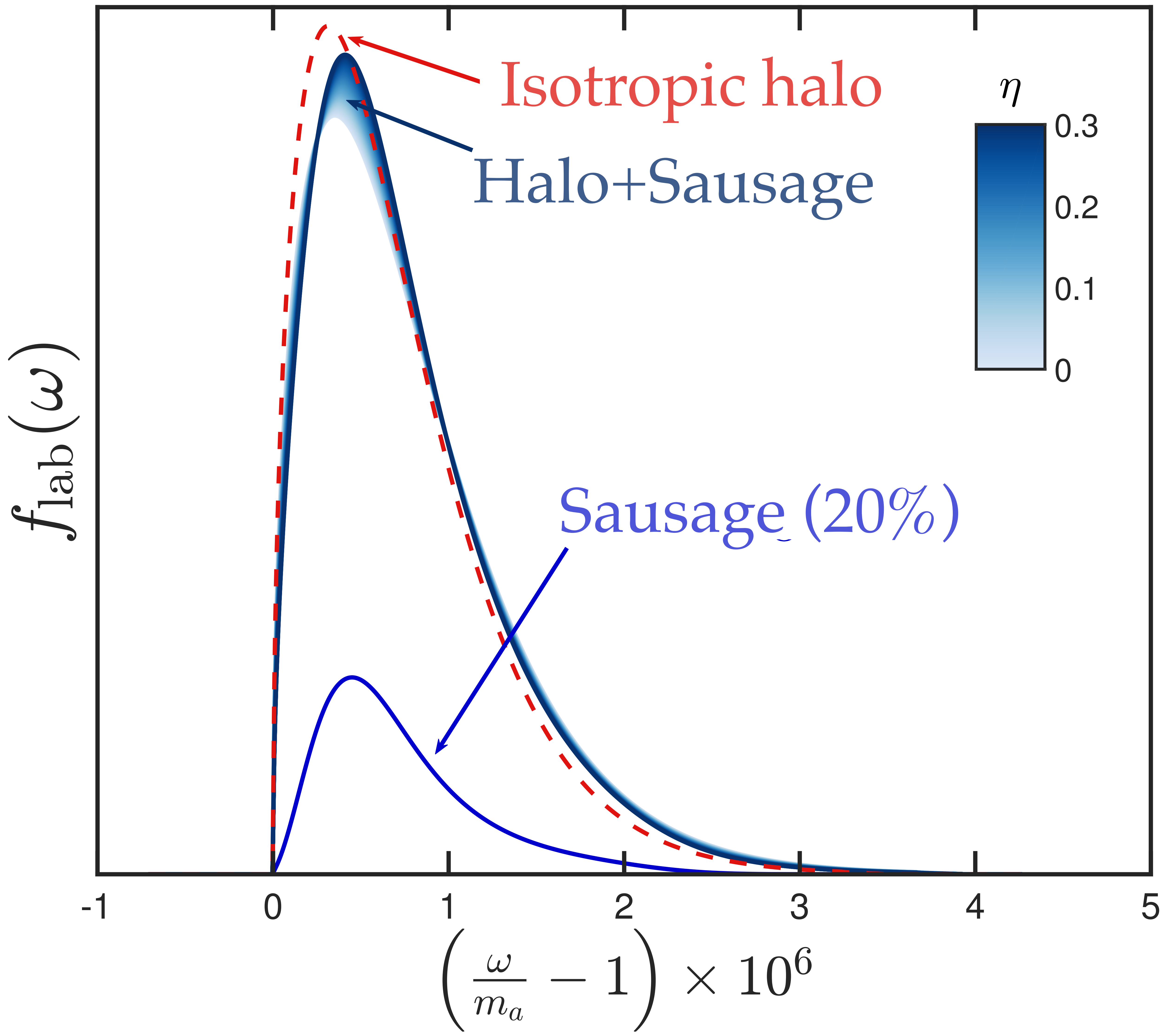
Cygnus constellation

# Anisotropy of velocity ellipsoid

- Influence of the Sausage makes axion linewidth slightly wider in the galactic radial direction than the other two directions… but this information is integrated over

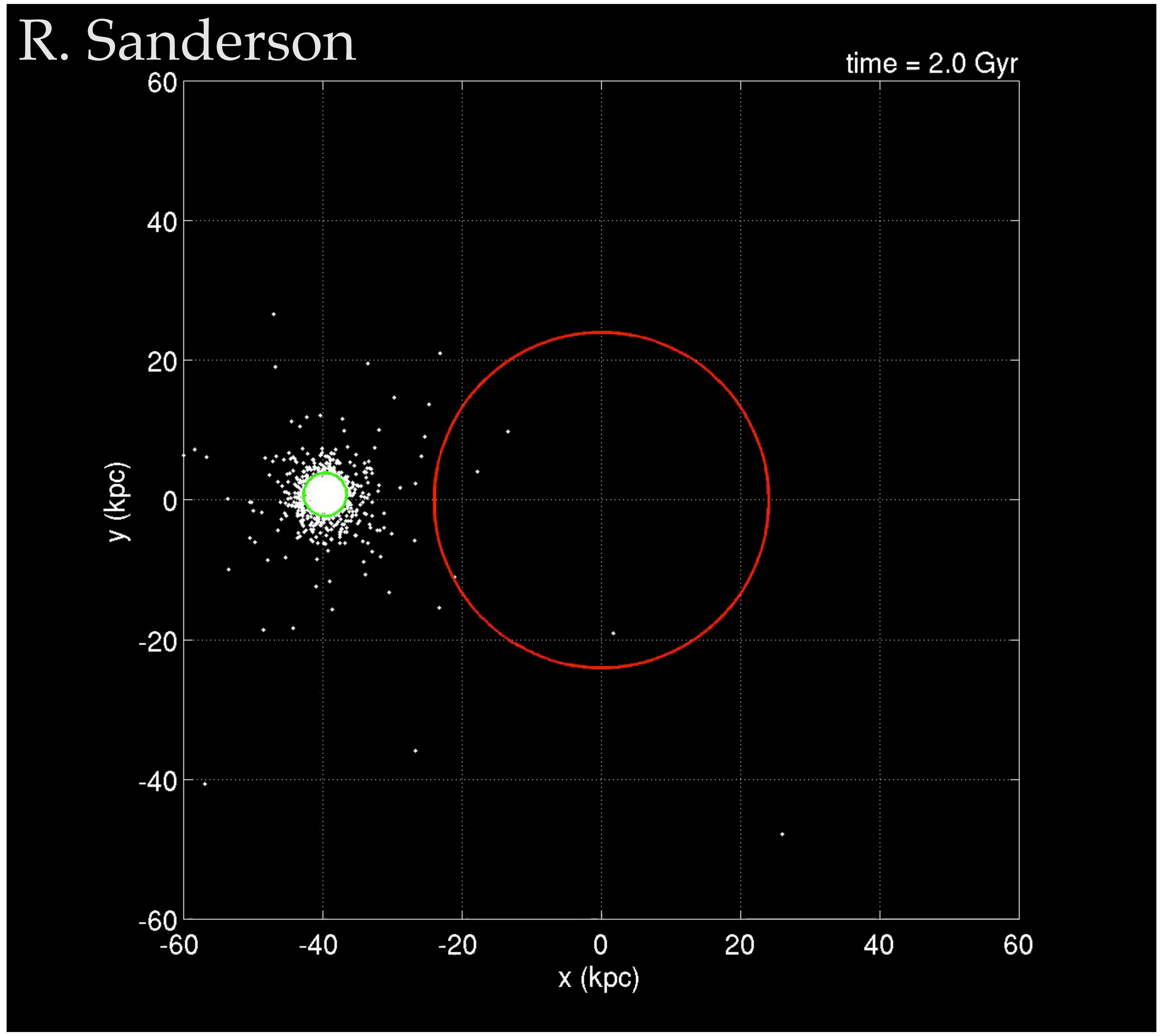


# Is this important for an axion signal model?

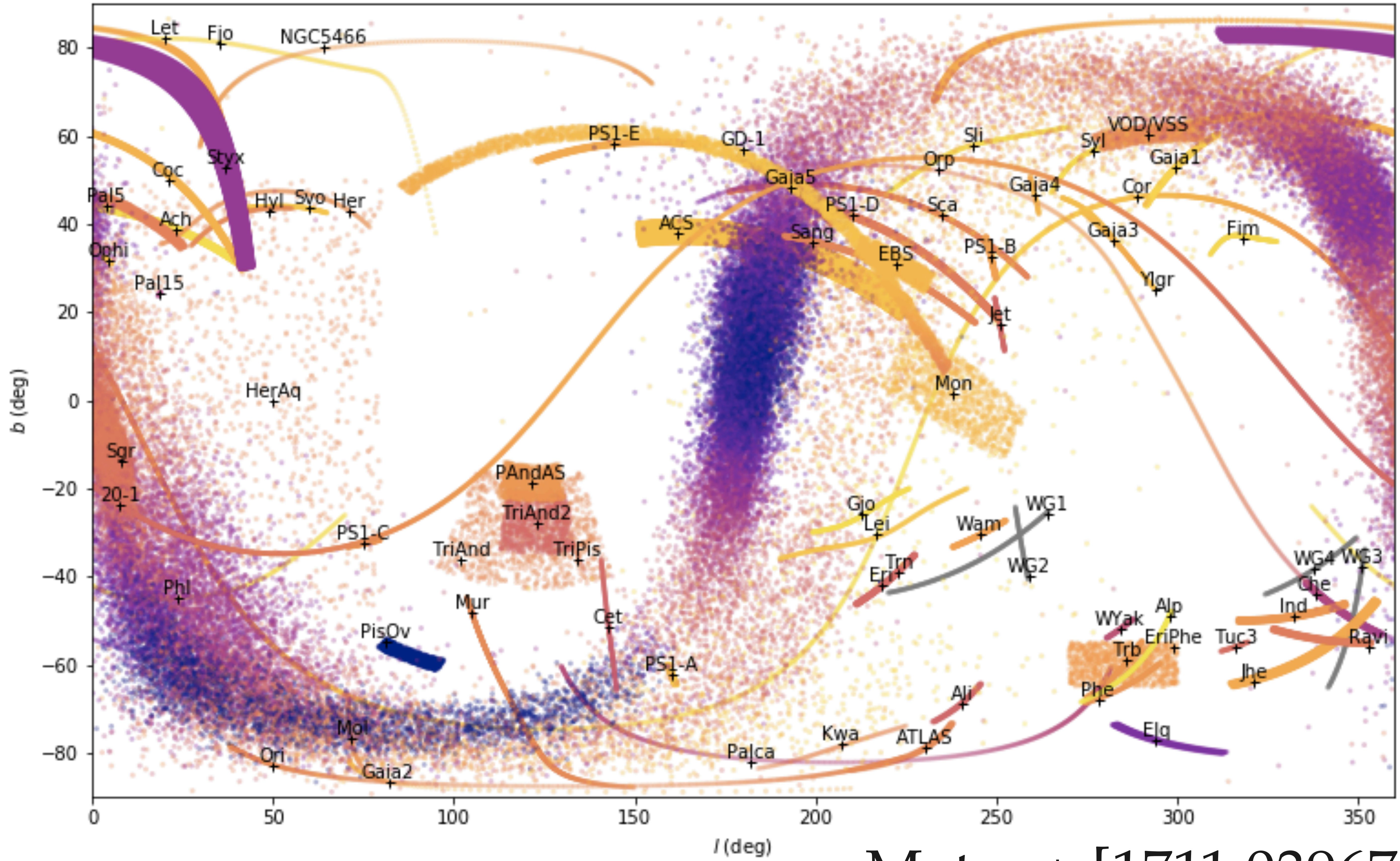


Surprisingly, not very important
→ More important for directional and annual modulation searches, see later…

# **Generic result of hierarchical structure formation:**
## Streams of stars/DM from tidally stripped GCs, dwarfs, subhalos …



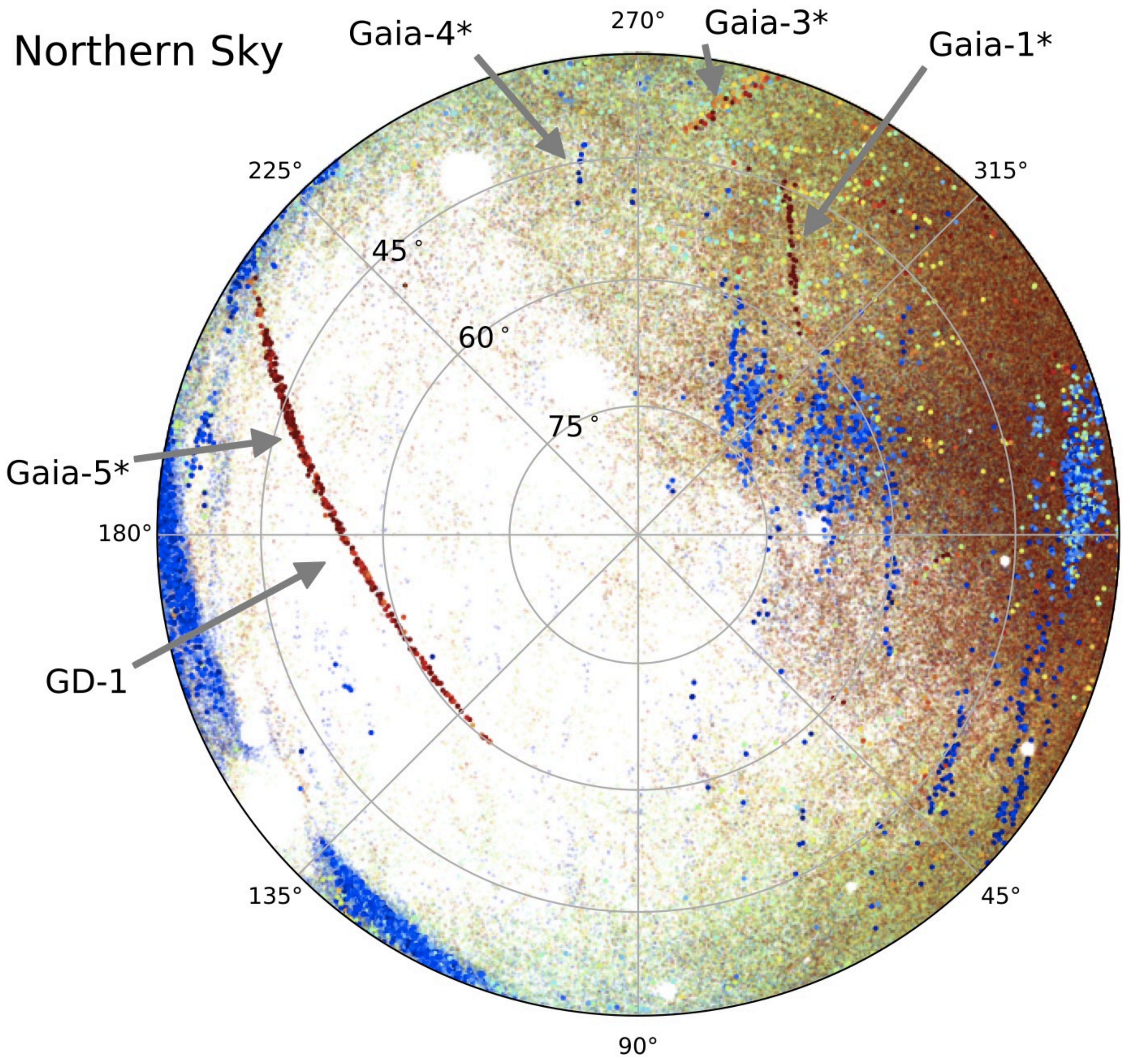
R. Sanderson



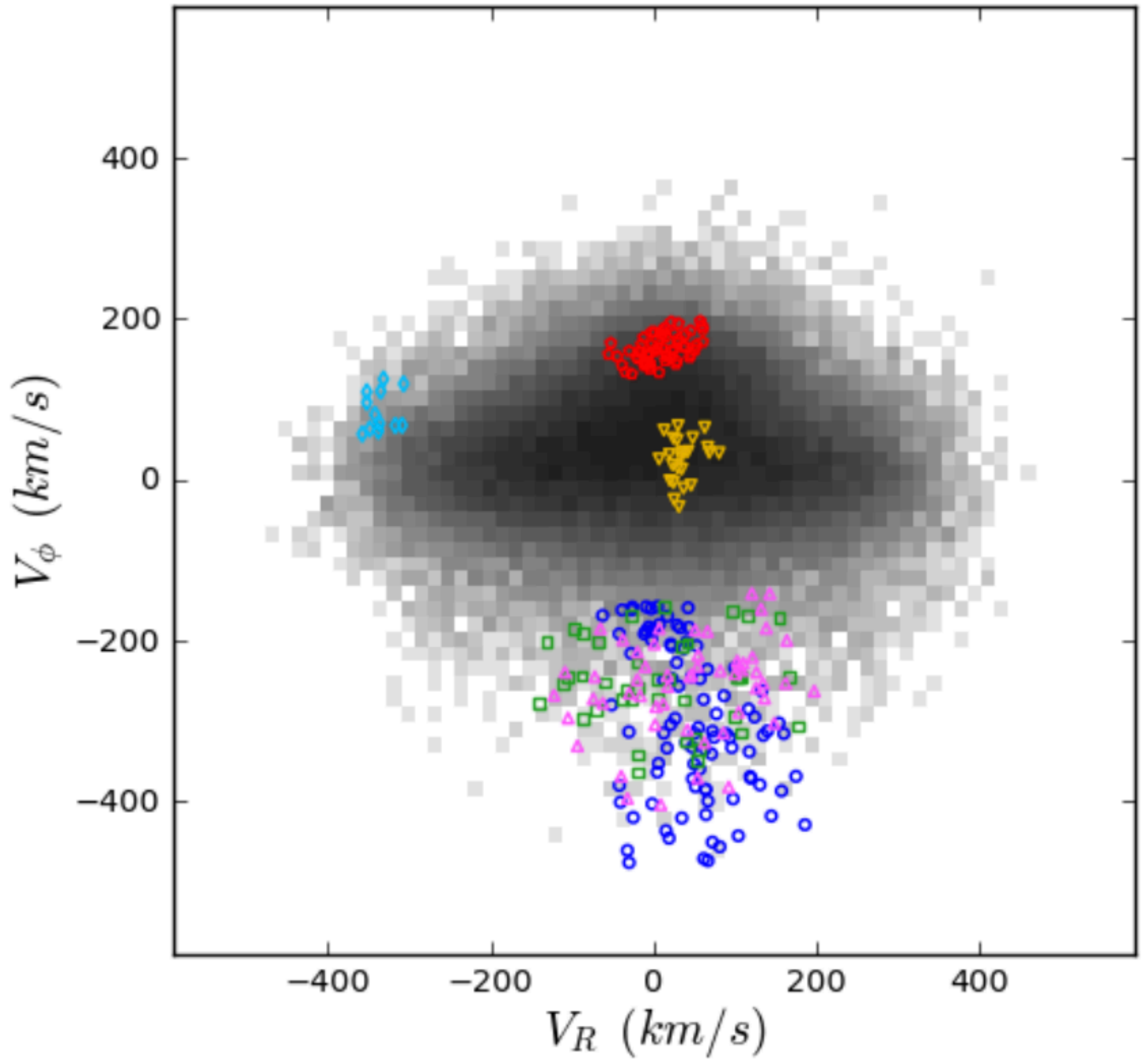
Mateu+ [1711.03967]

# Finding streams

- Far away streams can be seen projected on the sky:



- Nearby streams (including ones we are inside of) must be searched for in phase space:



# A galaxy is built from orbits

### Phase space

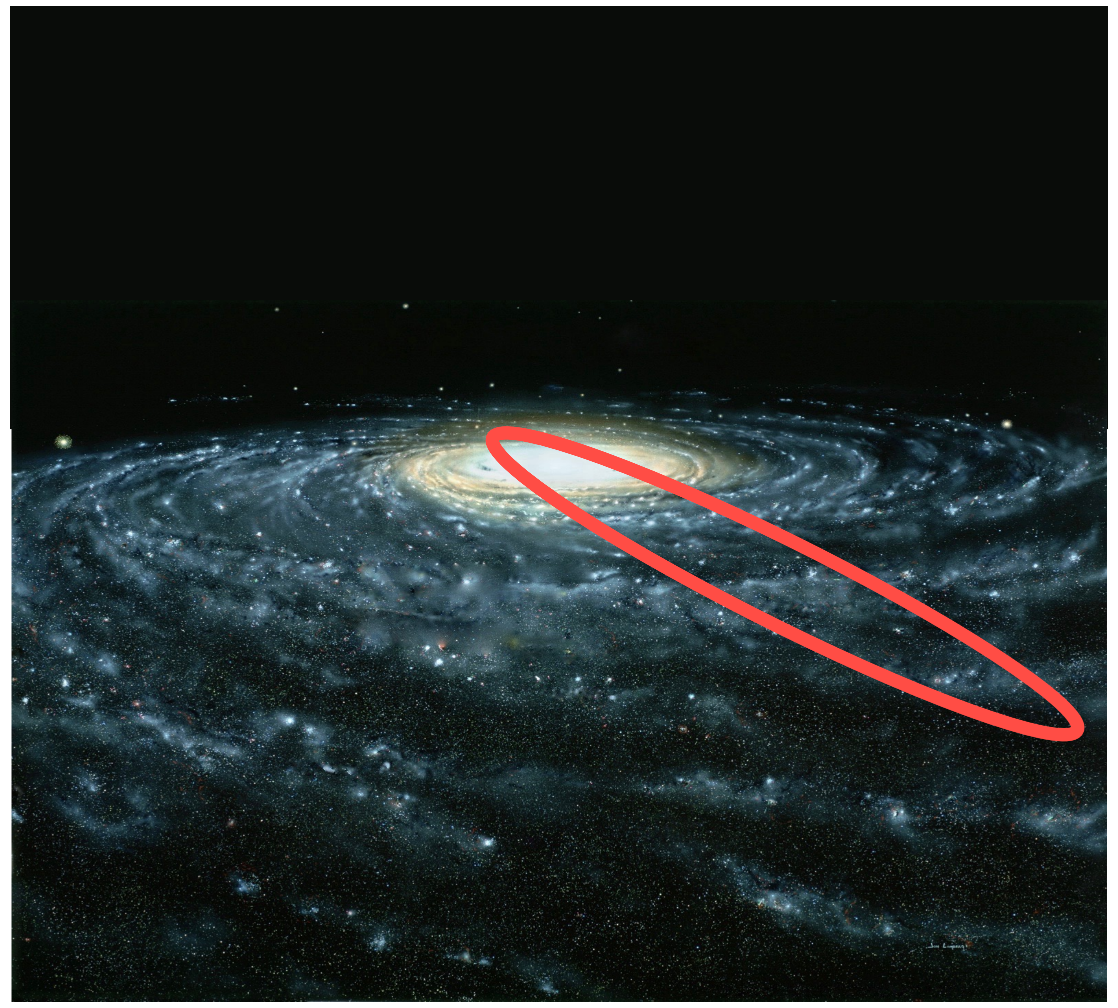
Each star sits at a location in 6D $(x, y, z, v_x, v_y, v_z)$

(integrate orbit assuming grav. potential)

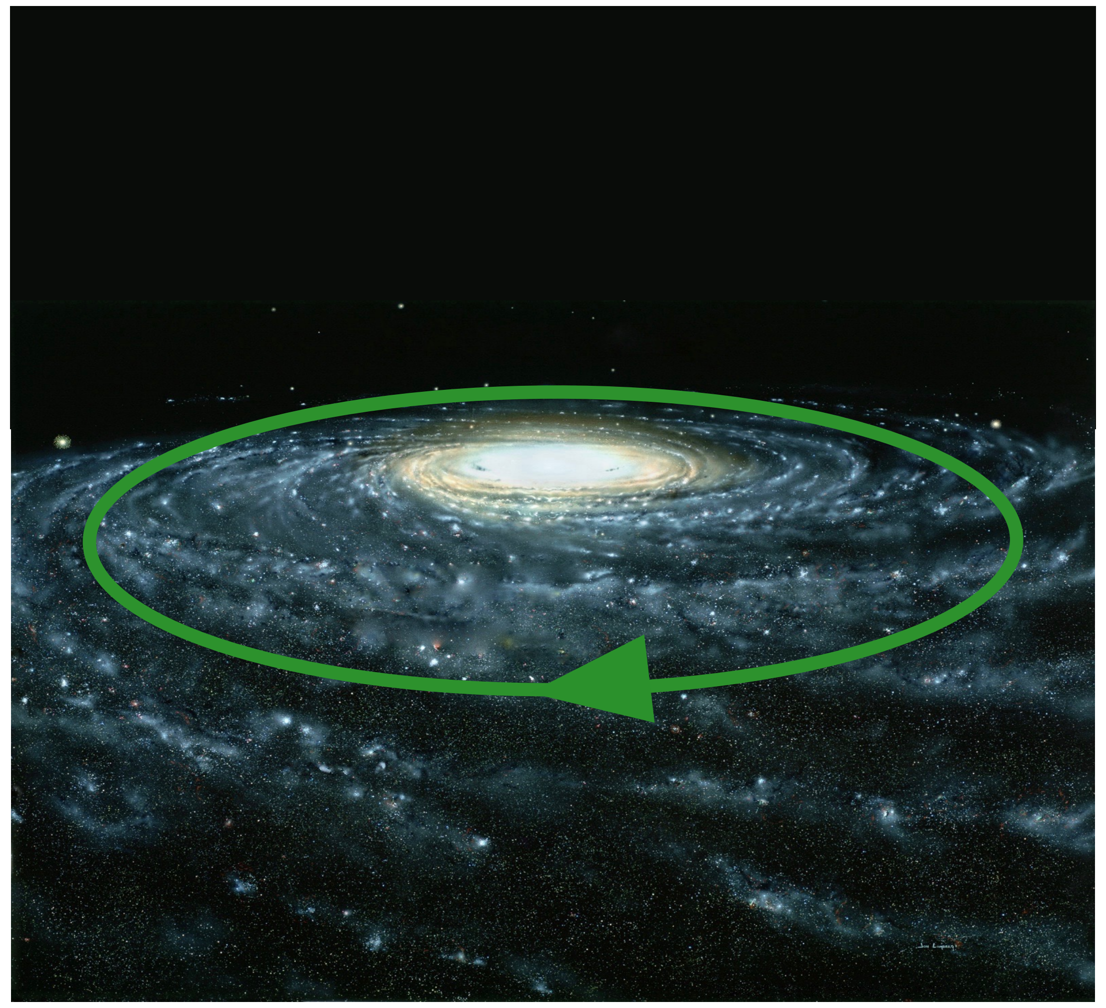
### Action space

Stars are locations in 3D space of orbits

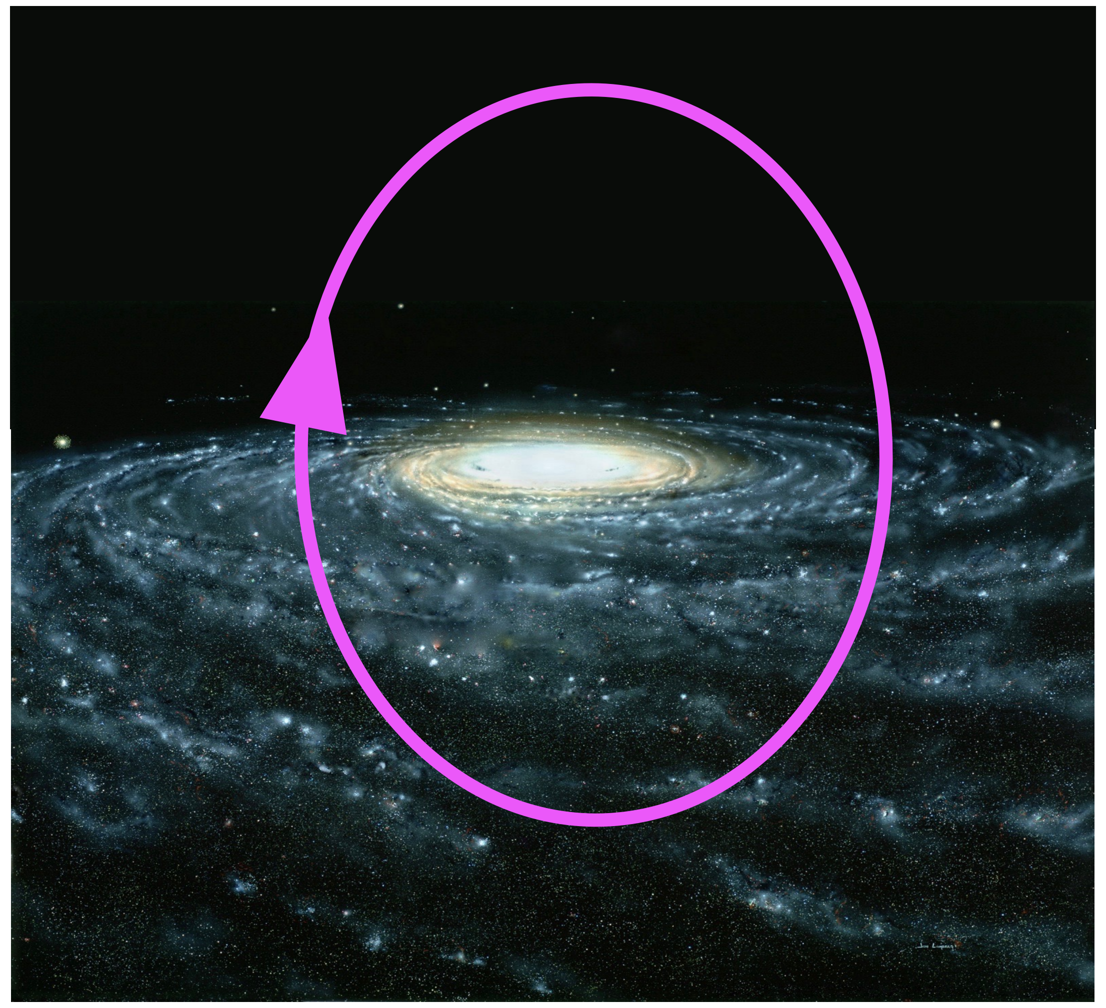
Radial action $(J_R)$



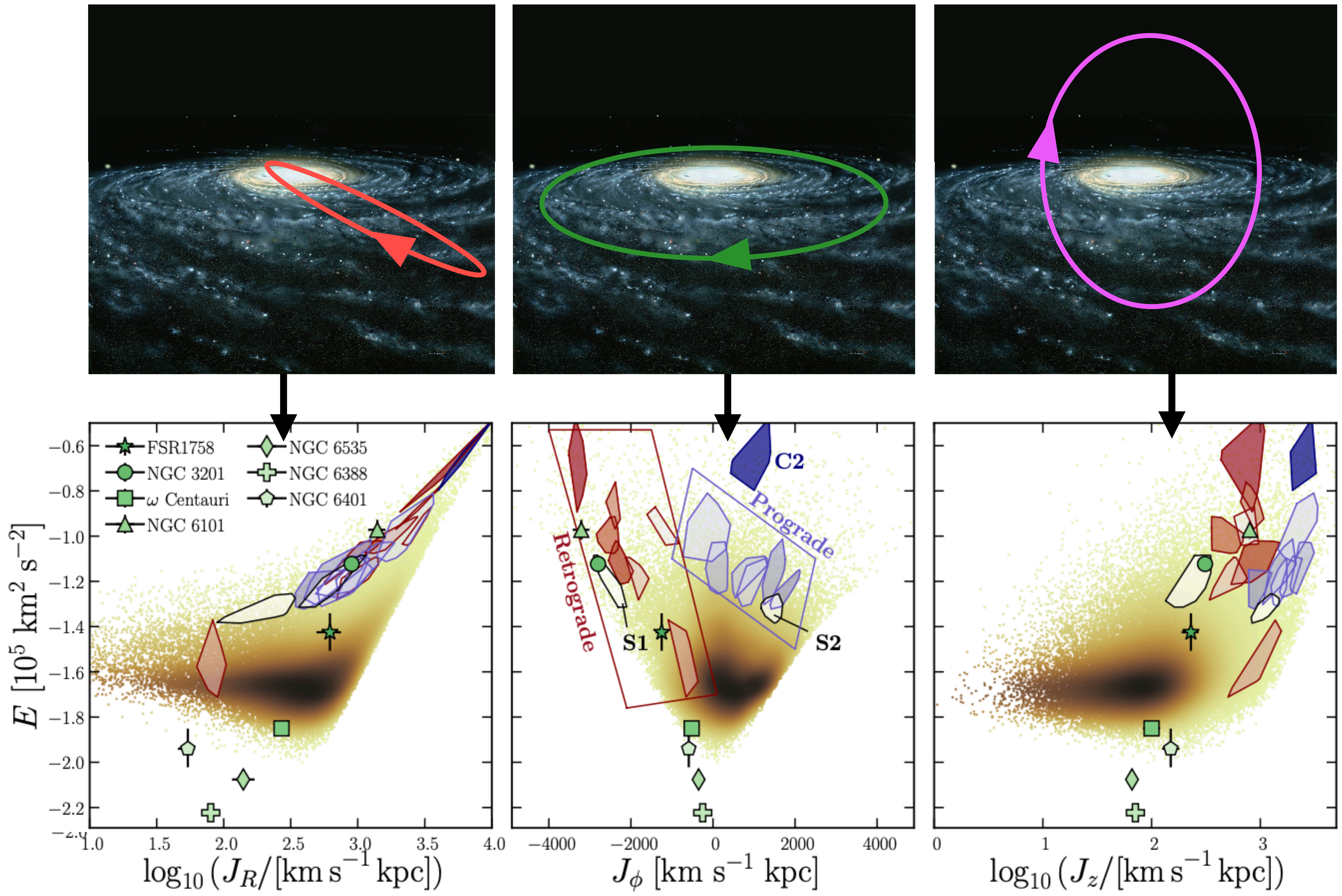
Azimuthal action $(J_\phi)$

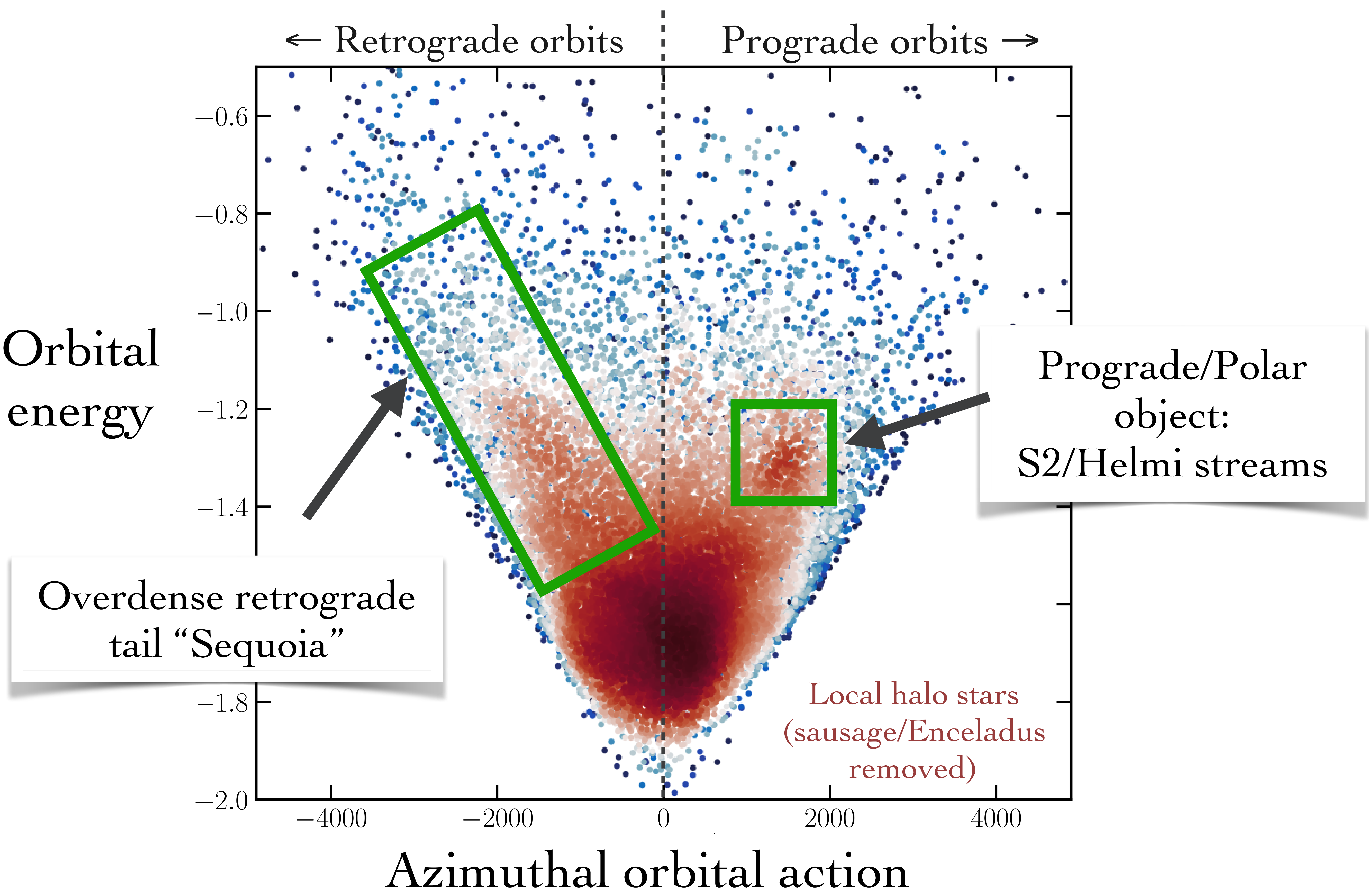


Vertical action $(J_z)$



Radial action ($J_R$) Azimuthal action ($J_\phi$) Vertical action ($J_z$)





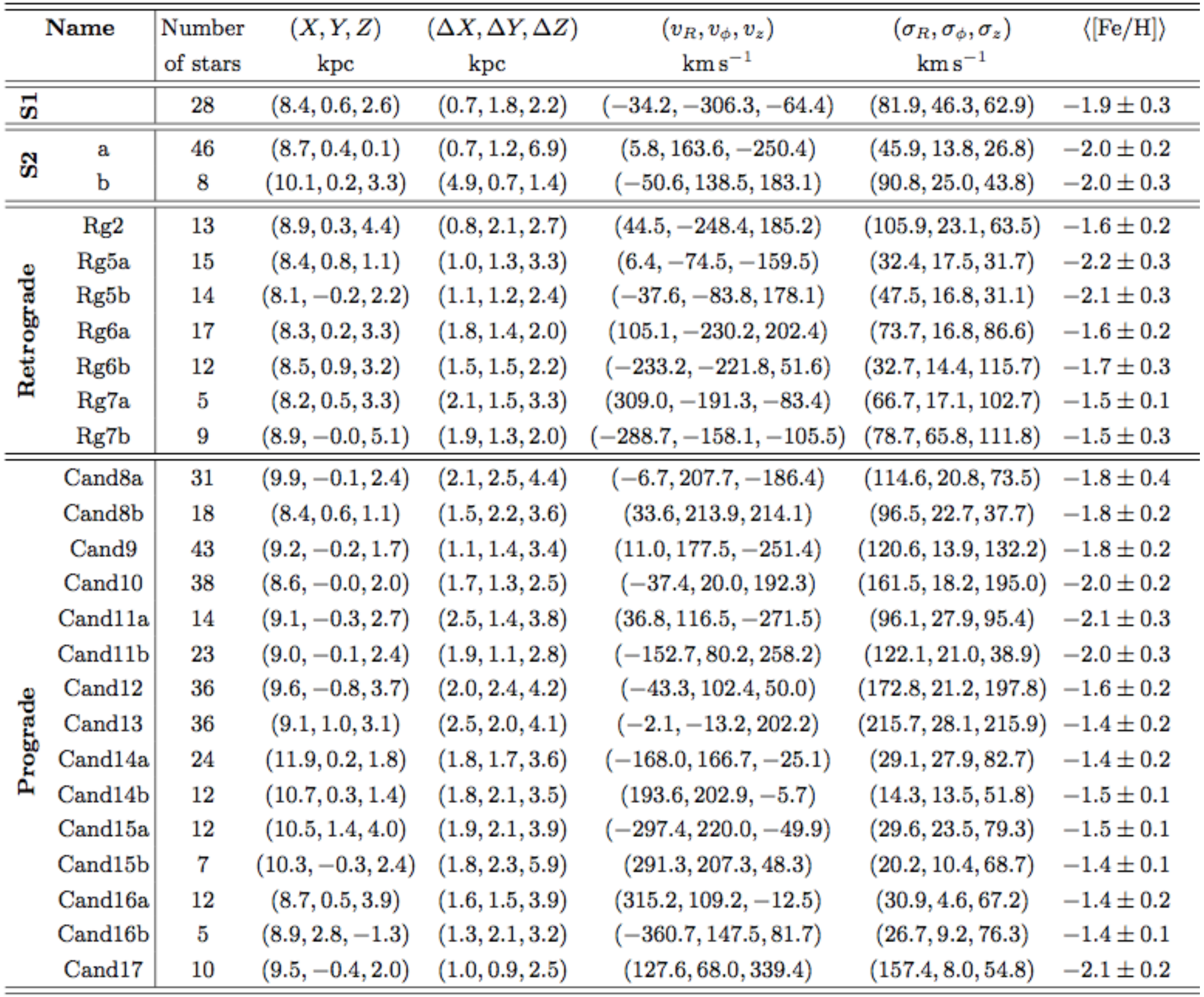
Overdense retrograde tail "Sequoia"

Prograde/Polar object: S2/Helmi streams

Local halo stars (sausage/Enceladus removed)

# Local action-space substructures in *Gaia* DR2+SDSS

Many high significance structures with orbits intersecting solar position e.g."S1 / Sequoia" and "S2 / Helmi streams"

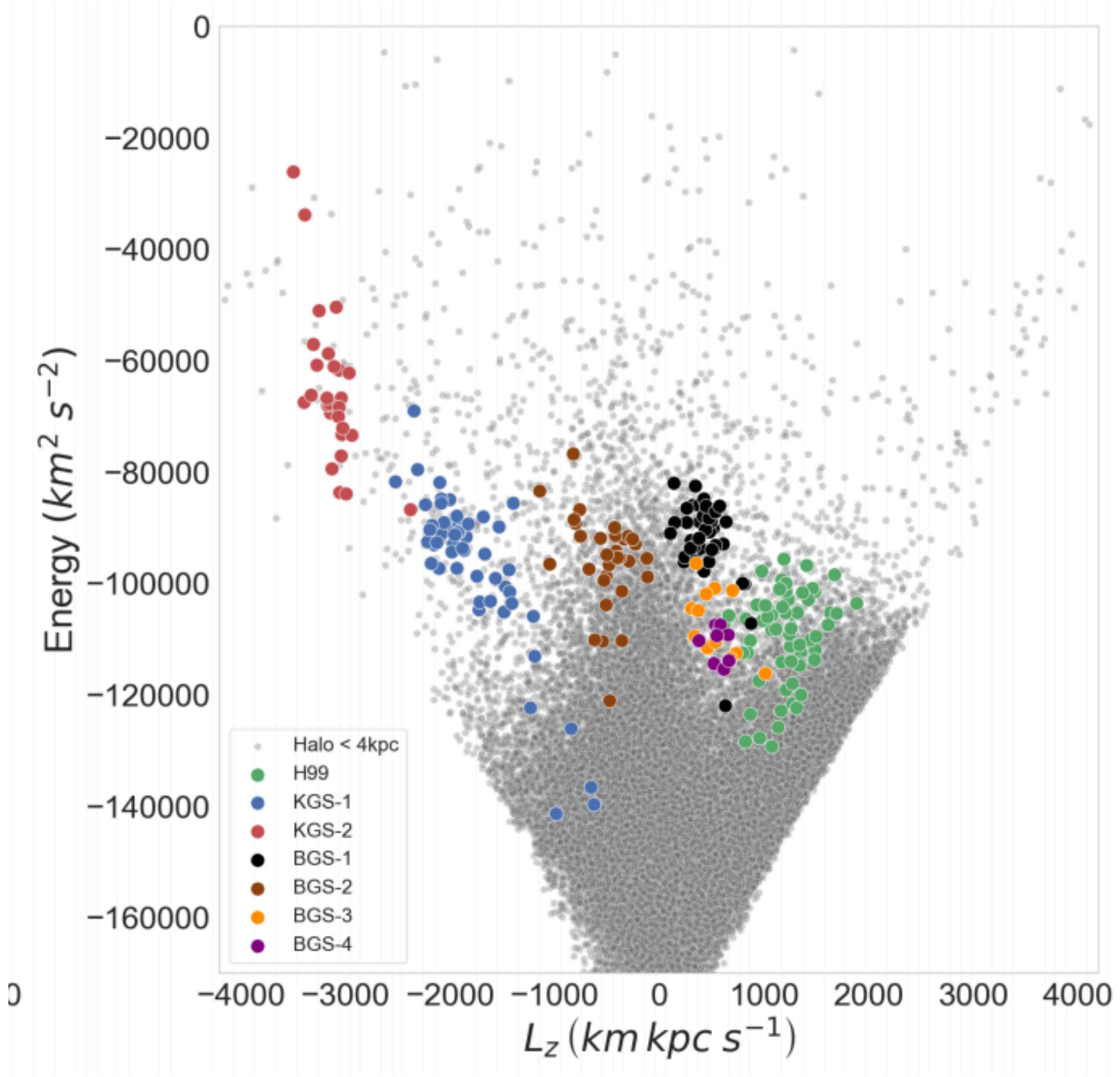


| Name | | Number of stars | $(X, Y, Z)$ kpc | $(\Delta X, \Delta Y, \Delta Z)$ kpc | $(v_R, v_\phi, v_z)$ $\mathrm{km\,s^{-1}}$ | $(\sigma_R, \sigma_\phi, \sigma_z)$ $\mathrm{km\,s^{-1}}$ | $\langle[\mathrm{Fe/H}]\rangle$ |
|---|---|---|---|---|---|---|---|
| **S1** | | 28 | (8.4, 0.6, 2.6) | (0.7, 1.8, 2.2) | (−34.2, −306.3, −64.4) | (81.9, 46.3, 62.9) | $-1.9 \pm 0.3$ |
| **S2** | a | 46 | (8.7, 0.4, 0.1) | (0.7, 1.2, 6.9) | (5.8, 163.6, −250.4) | (45.9, 13.8, 26.8) | $-2.0 \pm 0.2$ |
| | b | 8 | (10.1, 0.2, 3.3) | (4.9, 0.7, 1.4) | (−50.6, 138.5, 183.1) | (90.8, 25.0, 43.8) | $-2.0 \pm 0.3$ |
| **Retrograde** | Rg2 | 13 | (8.9, 0.3, 4.4) | (0.8, 2.1, 2.7) | (44.5, −248.4, 185.2) | (105.9, 23.1, 63.5) | $-1.6 \pm 0.2$ |
| | Rg5a | 15 | (8.4, 0.8, 1.1) | (1.0, 1.3, 3.3) | (6.4, −74.5, −159.5) | (32.4, 17.5, 31.7) | $-2.2 \pm 0.3$ |
| | Rg5b | 14 | (8.1, −0.2, 2.2) | (1.1, 1.2, 2.4) | (−37.6, −83.8, 178.1) | (47.5, 16.8, 31.1) | $-2.1 \pm 0.3$ |
| | Rg6a | 17 | (8.3, 0.2, 3.3) | (1.8, 1.4, 2.0) | (105.1, −230.2, 202.4) | (73.7, 16.8, 86.6) | $-1.6 \pm 0.2$ |
| | Rg6b | 12 | (8.5, 0.9, 3.2) | (1.5, 1.5, 2.2) | (−233.2, −221.8, 51.6) | (32.7, 14.4, 115.7) | $-1.7 \pm 0.3$ |
| | Rg7a | 5 | (8.2, 0.5, 3.3) | (2.1, 1.5, 3.3) | (309.0, −191.3, −83.4) | (66.7, 17.1, 102.7) | $-1.5 \pm 0.1$ |
| | Rg7b | 9 | (8.9, −0.0, 5.1) | (1.9, 1.3, 2.0) | (−288.7, −158.1, −105.5) | (78.7, 65.8, 111.8) | $-1.5 \pm 0.3$ |
| **Prograde** | Cand8a | 31 | (9.9, −0.1, 2.4) | (2.1, 2.5, 4.4) | (−6.7, 207.7, −186.4) | (114.6, 20.8, 73.5) | $-1.8 \pm 0.4$ |
| | Cand8b | 18 | (8.4, 0.6, 1.1) | (1.5, 2.2, 3.6) | (33.6, 213.9, 214.1) | (96.5, 22.7, 37.7) | $-1.8 \pm 0.2$ |
| | Cand9 | 43 | (9.2, −0.2, 1.7) | (1.1, 1.4, 3.4) | (11.0, 177.5, −251.4) | (120.6, 13.9, 132.2) | $-1.8 \pm 0.2$ |
| | Cand10 | 38 | (8.6, −0.0, 2.0) | (1.7, 1.3, 2.5) | (−37.4, 20.0, 192.3) | (161.5, 18.2, 195.0) | $-2.0 \pm 0.2$ |
| | Cand11a | 14 | (9.1, −0.3, 2.7) | (2.5, 1.4, 3.8) | (36.8, 116.5, −271.5) | (96.1, 27.9, 95.4) | $-2.1 \pm 0.3$ |
| | Cand11b | 23 | (9.0, −0.1, 2.4) | (1.9, 1.1, 2.8) | (−152.7, 80.2, 258.2) | (122.1, 21.0, 38.9) | $-2.0 \pm 0.3$ |
| | Cand12 | 36 | (9.6, −0.8, 3.7) | (2.0, 2.4, 4.2) | (−43.3, 102.4, 50.0) | (172.8, 21.2, 197.8) | $-1.6 \pm 0.2$ |
| | Cand13 | 36 | (9.1, 1.0, 3.1) | (2.5, 2.0, 4.1) | (−2.1, −13.2, 202.2) | (215.7, 28.1, 215.9) | $-1.4 \pm 0.2$ |
| | Cand14a | 24 | (11.9, 0.2, 1.8) | (1.8, 1.7, 3.6) | (−168.0, 166.7, −25.1) | (29.1, 27.9, 82.7) | $-1.4 \pm 0.2$ |
| | Cand14b | 12 | (10.7, 0.3, 1.4) | (1.8, 2.1, 3.5) | (193.6, 202.9, −5.7) | (14.3, 13.5, 51.8) | $-1.5 \pm 0.1$ |
| | Cand15a | 12 | (10.5, 1.4, 4.0) | (1.9, 2.1, 3.9) | (−297.4, 220.0, −49.9) | (29.6, 23.5, 79.3) | $-1.5 \pm 0.1$ |
| | Cand15b | 7 | (10.3, −0.3, 2.4) | (1.8, 2.3, 5.9) | (291.3, 207.3, 48.3) | (20.2, 10.4, 68.7) | $-1.4 \pm 0.1$ |
| | Cand16a | 12 | (8.7, 0.5, 3.9) | (1.6, 1.5, 3.9) | (315.2, 109.2, −12.5) | (30.9, 4.6, 67.2) | $-1.4 \pm 0.2$ |
| | Cand16b | 5 | (8.9, 2.8, −1.3) | (1.3, 2.1, 3.2) | (−360.7, 147.5, 81.7) | (26.7, 9.2, 76.3) | $-1.4 \pm 0.1$ |
| | Cand17 | 10 | (9.5, −0.4, 2.0) | (1.0, 0.9, 2.5) | (127.6, 68.0, 339.4) | (157.4, 8.0, 54.8) | $-2.1 \pm 0.2$ |

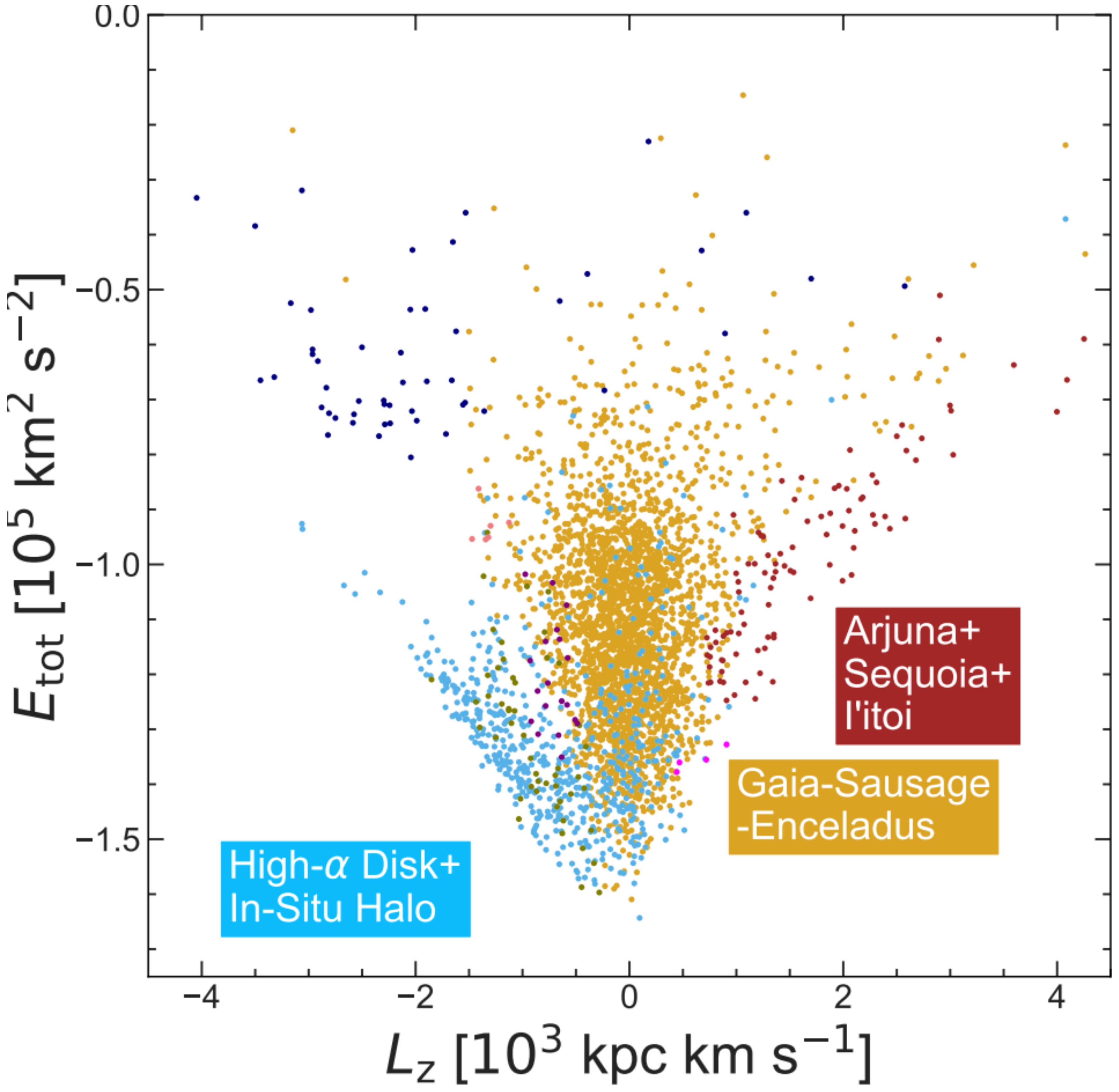
Myeong+ [1804.07050]
O'Hare+[1909.04684]

## A lot of substructures discovered and re-discovered with different datasets, stellar samples, search methods, → a few prominent cases are emerging

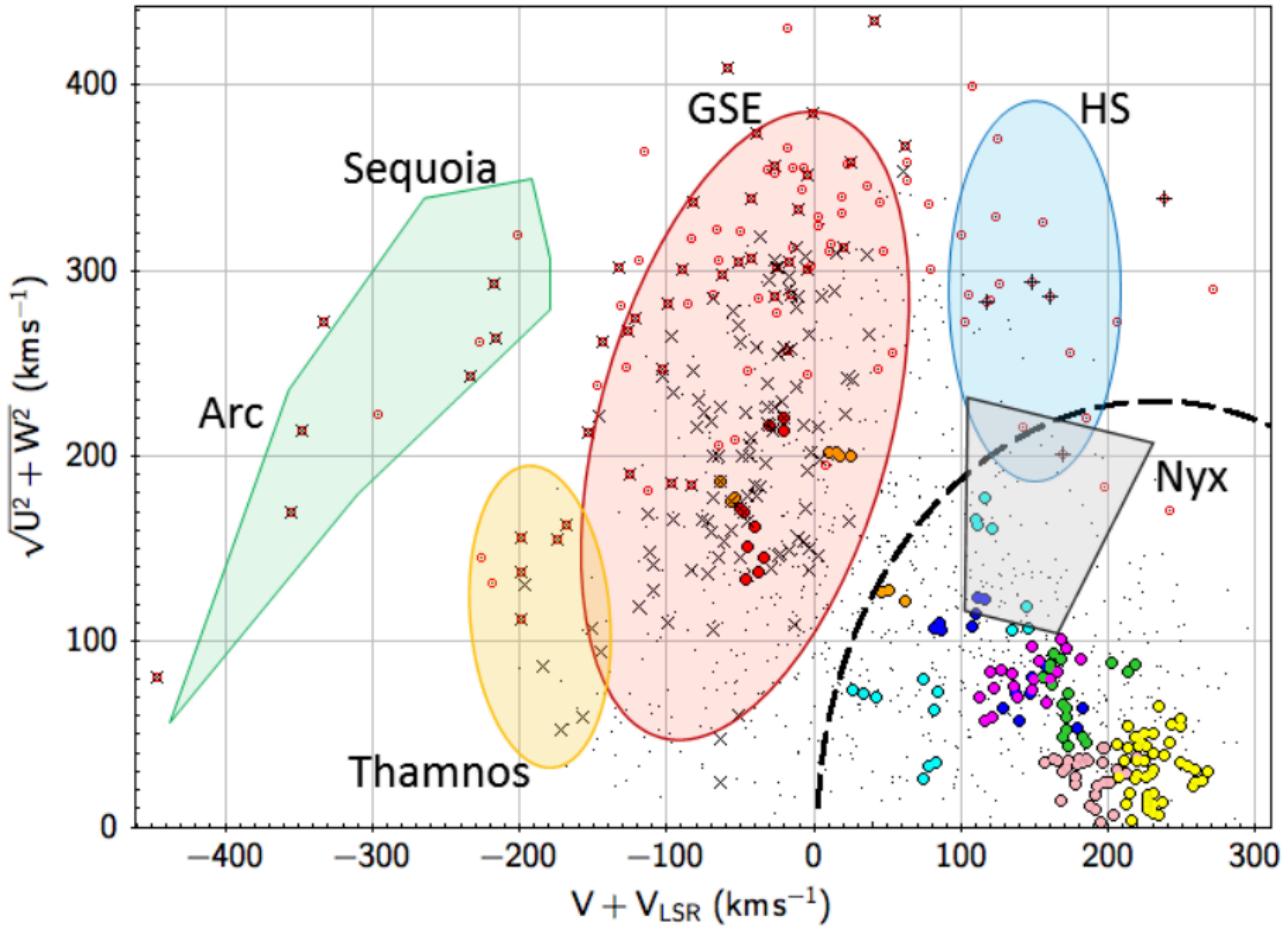
Borsato+ [1907.02527]



Naidu+ [2006.08625]

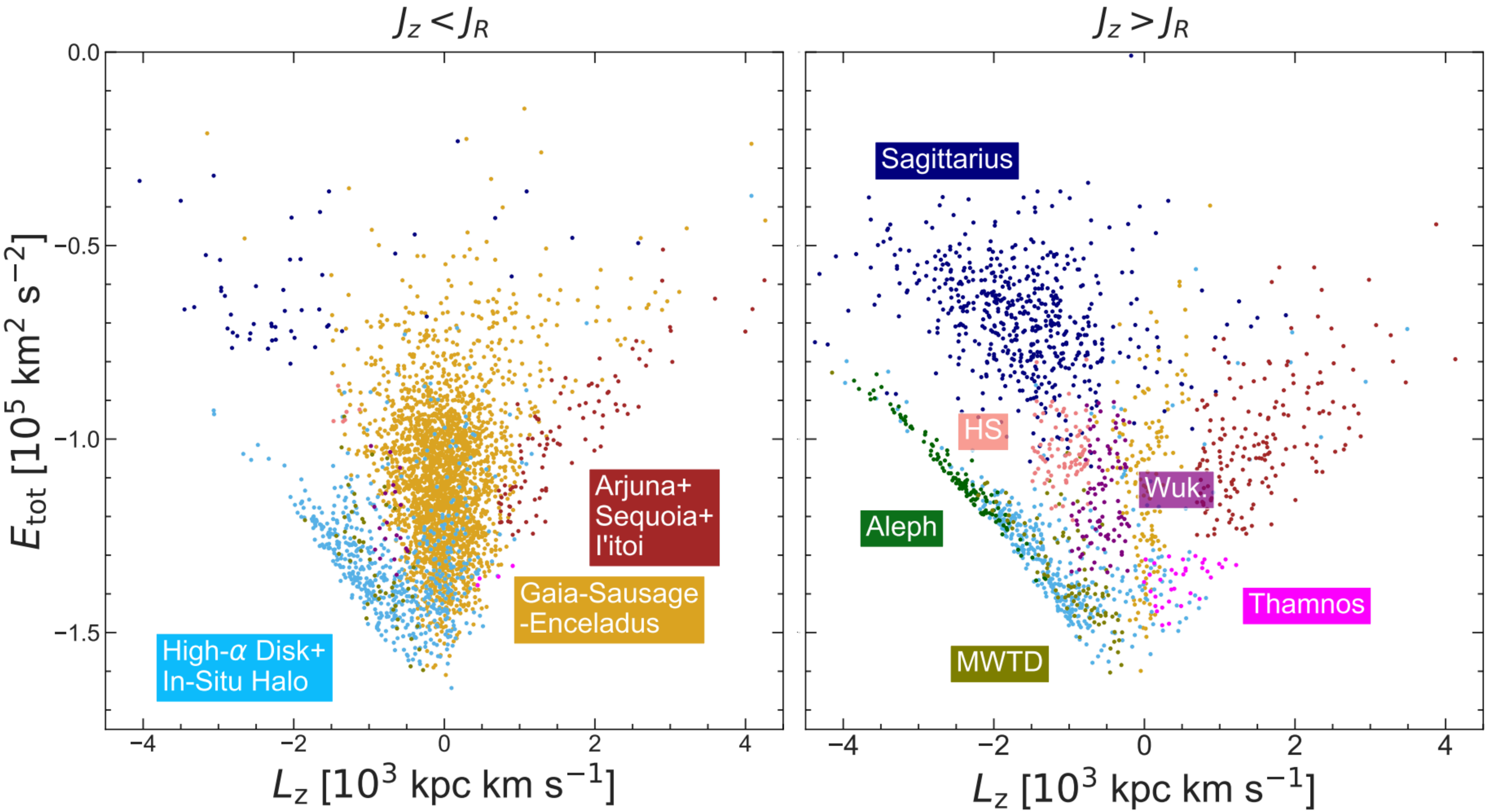


Fiorentin+ [2012.10957]



# More thorough taxonomy of stellar halo with H3 survey

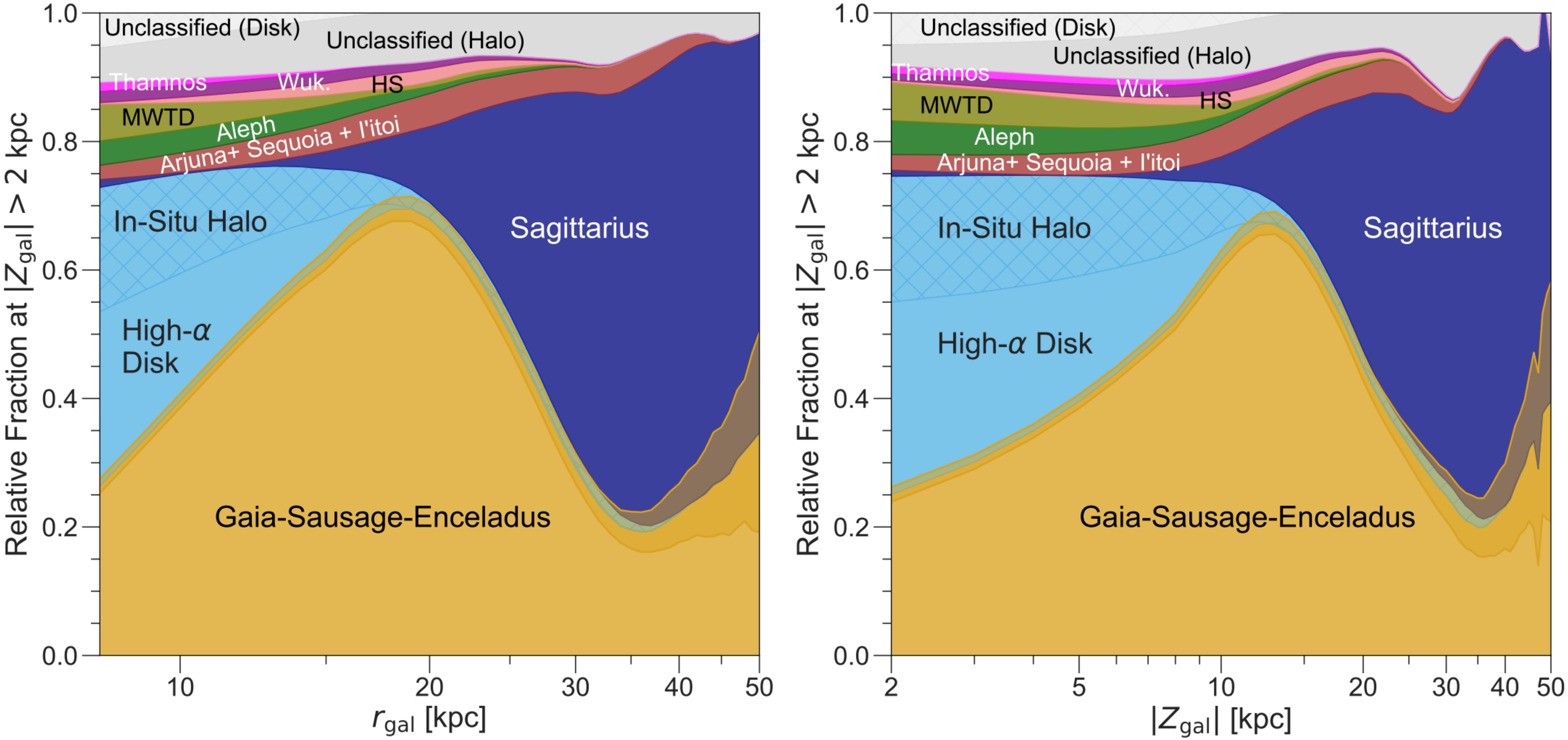
Naidu et al. 2006.08625



2006.08625

# Evidence from the H3 Survey that the Stellar Halo is Entirely Comprised of Substructure

Rohan P. Naidu,[1] Charlie Conroy,[1] Ana Bonaca,[1] Benjamin D. Johnson,[1] Yuan-Sen Ting (丁源森),[2,3,4,5,*]
Nelson Caldwell,[1] Dennis Zaritsky,[6] and Phillip A. Cargile[1]



# Helmi streams

One of the first inner halo substructures discovered (Helmi et al. 1999)

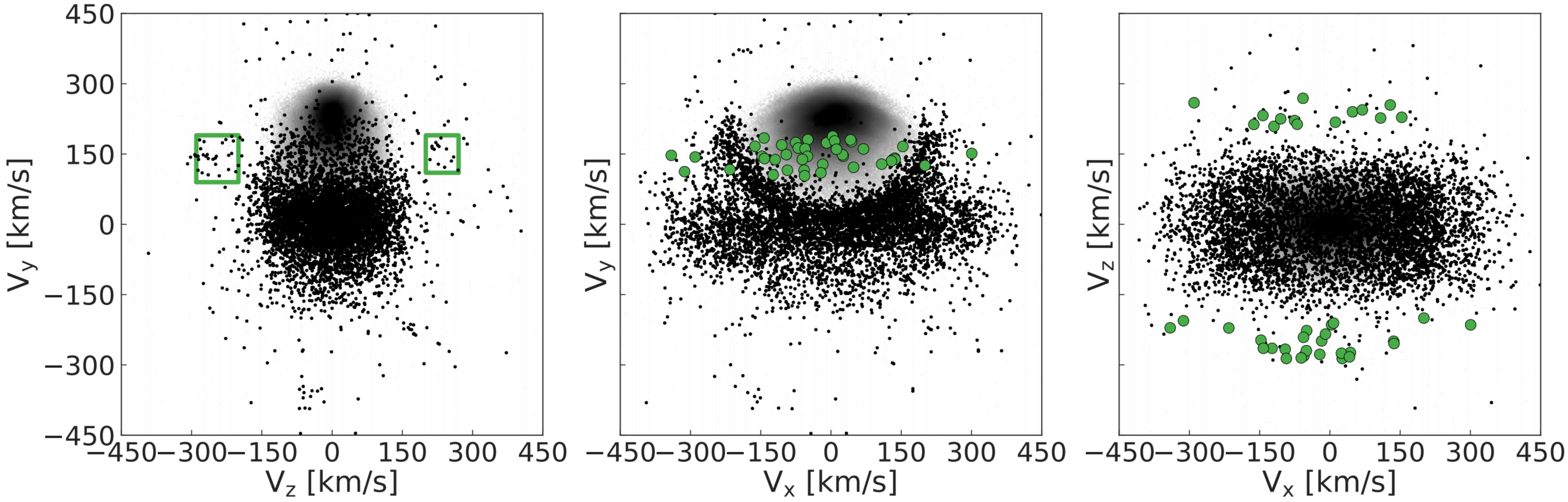
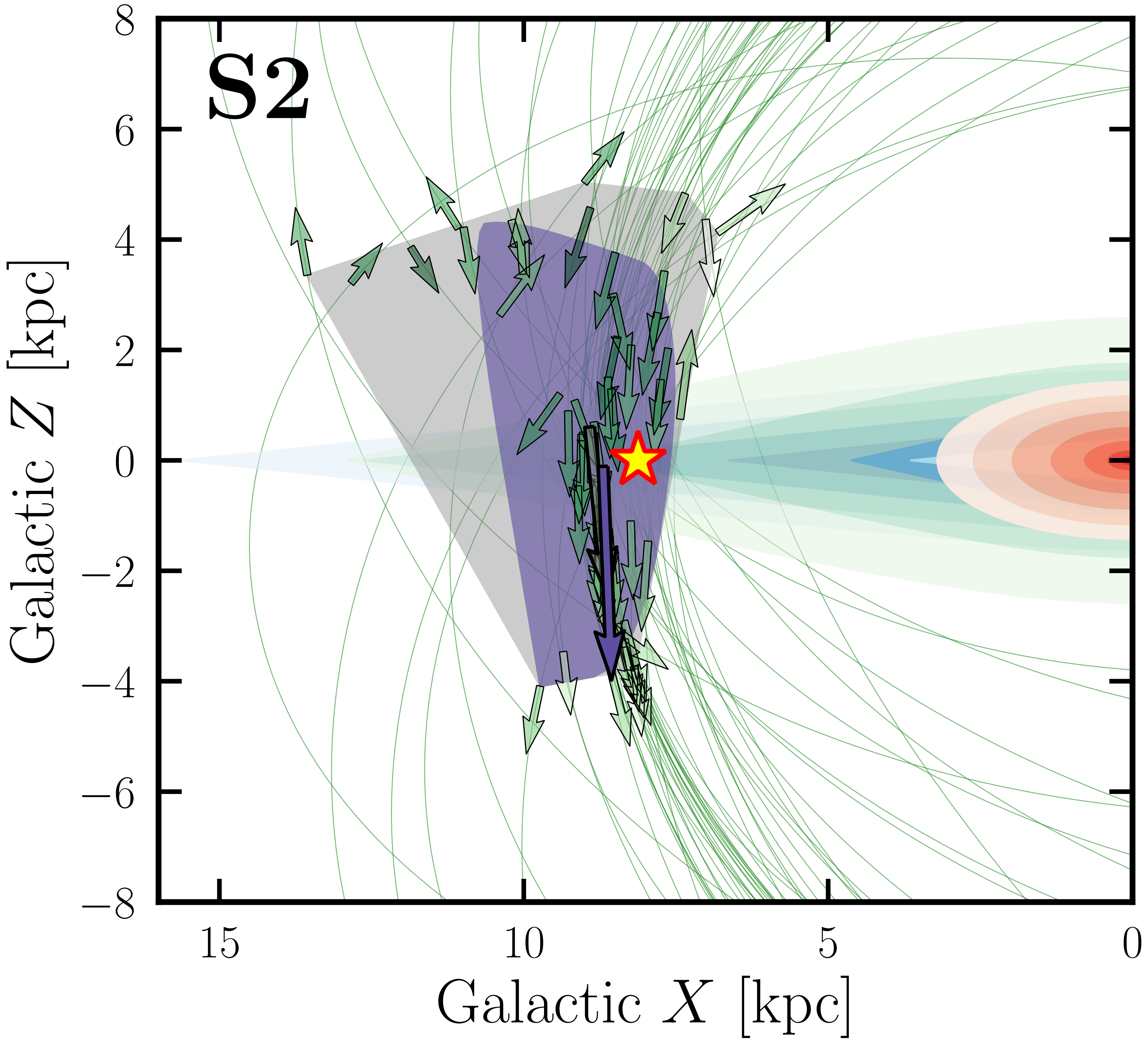


**Fig. 1.** Velocity distribution of kinematically selected halo stars (black dots) within 1 kpc from the Sun from the *Gaia*-only 6D sample. The grey density in the background shows the location and extent of the disk in this diagram. The velocities have been corrected for the motion of the Sun and LSR. The green boxes in the left panel indicate the location of the Helmi streams, and are drawn based on the velocities of the original stream members. The stars inside these boxes are highlighted with green symbols in the other two panels.

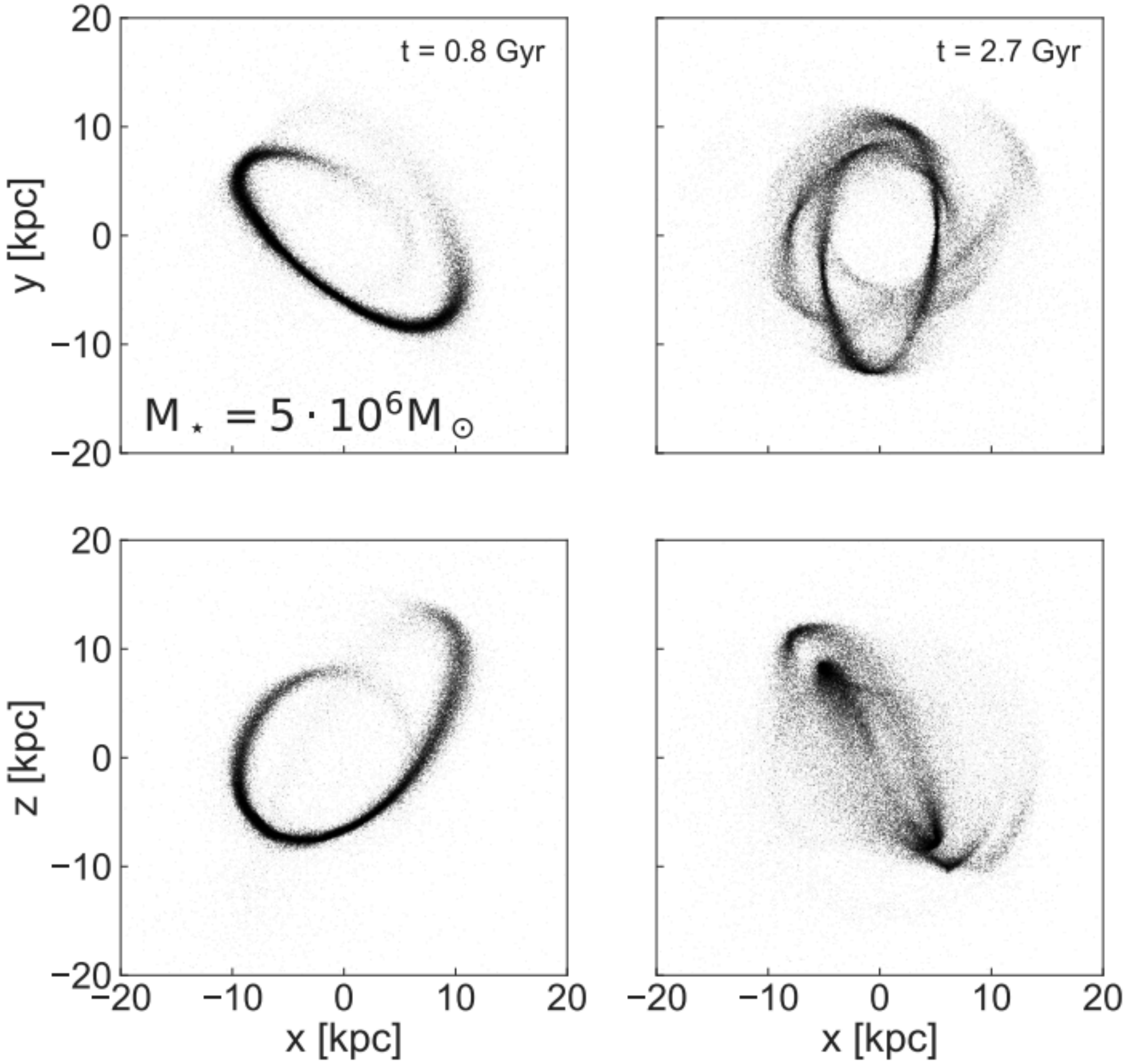
1812.00846

# S2/Helmi streams

O'Hare+
[1909.04684]



Koppelmann+ 1812.00846

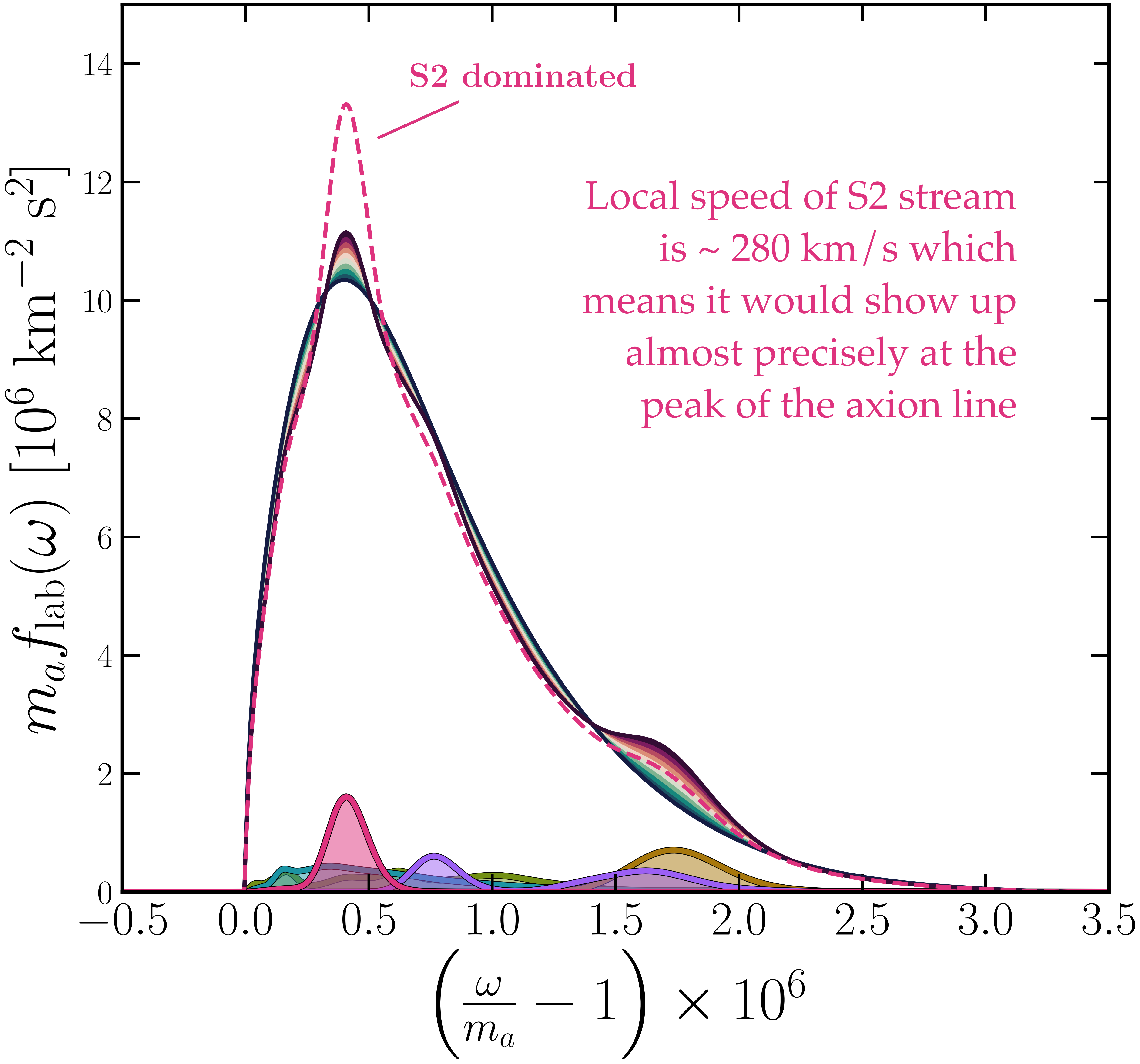


→ Helmi and S2 both have two components with $\pm v_z$

→ Interpreted as multiple wraps of a larger stream

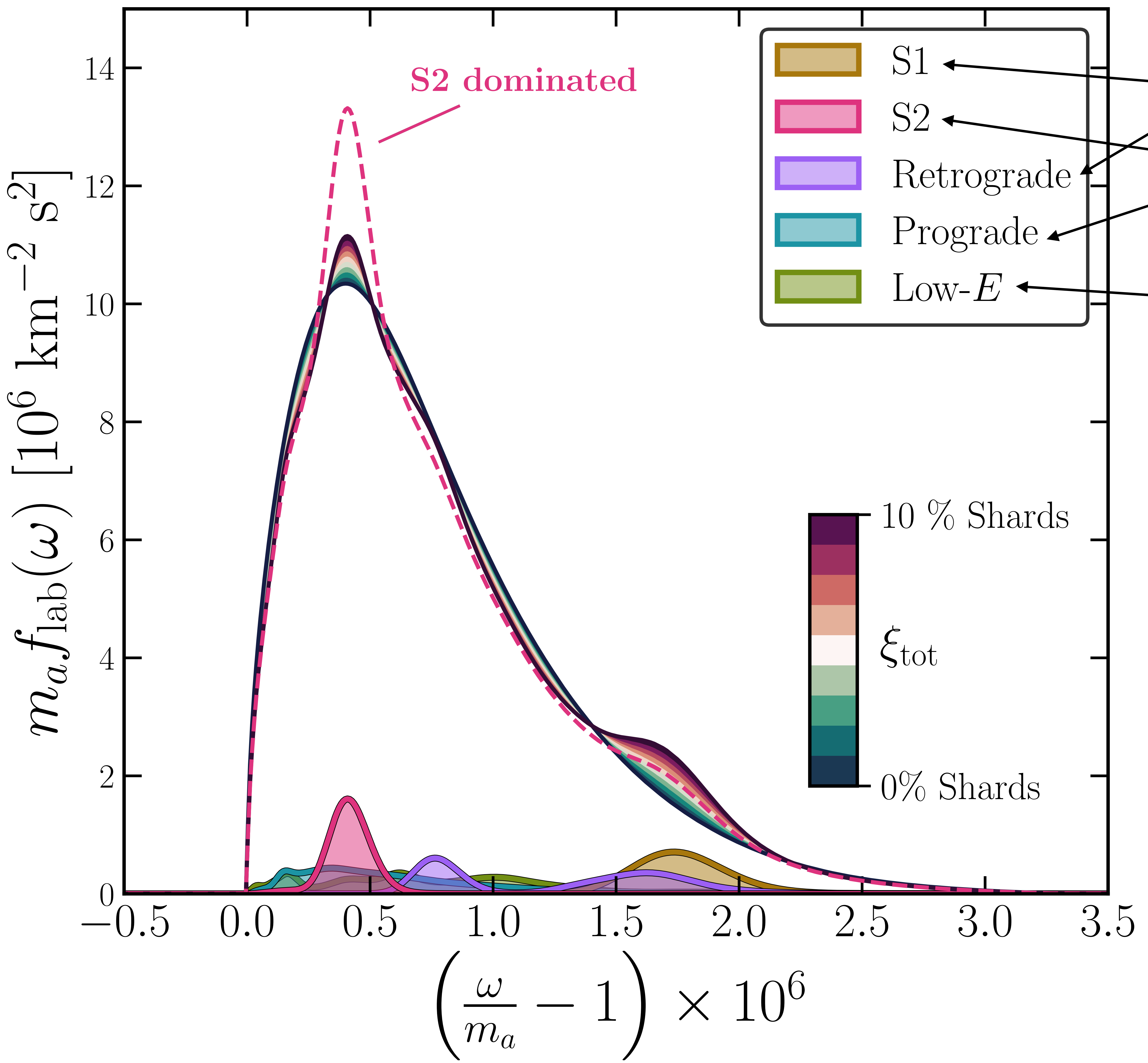
→ Spectroscopic study confirms primordial dwarf galaxy origin Aguado+ [2007.11003]

# Streams in the axion line



Local speed of S2 stream
is ~ 280 km/s which
means it would show up
almost precisely at the
peak of the axion line

# Streams in the axion line



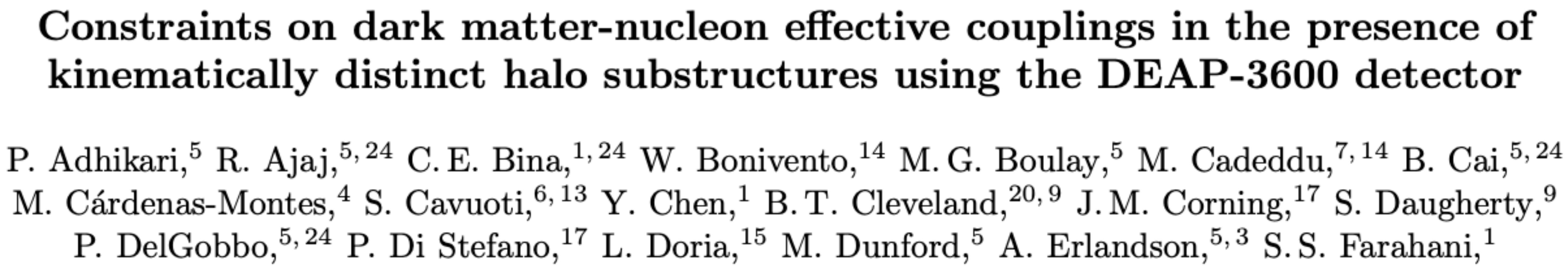
**Sequoia**

**Probably related to Helmi streams**

**Possibly related to Sausage/Enceladus**

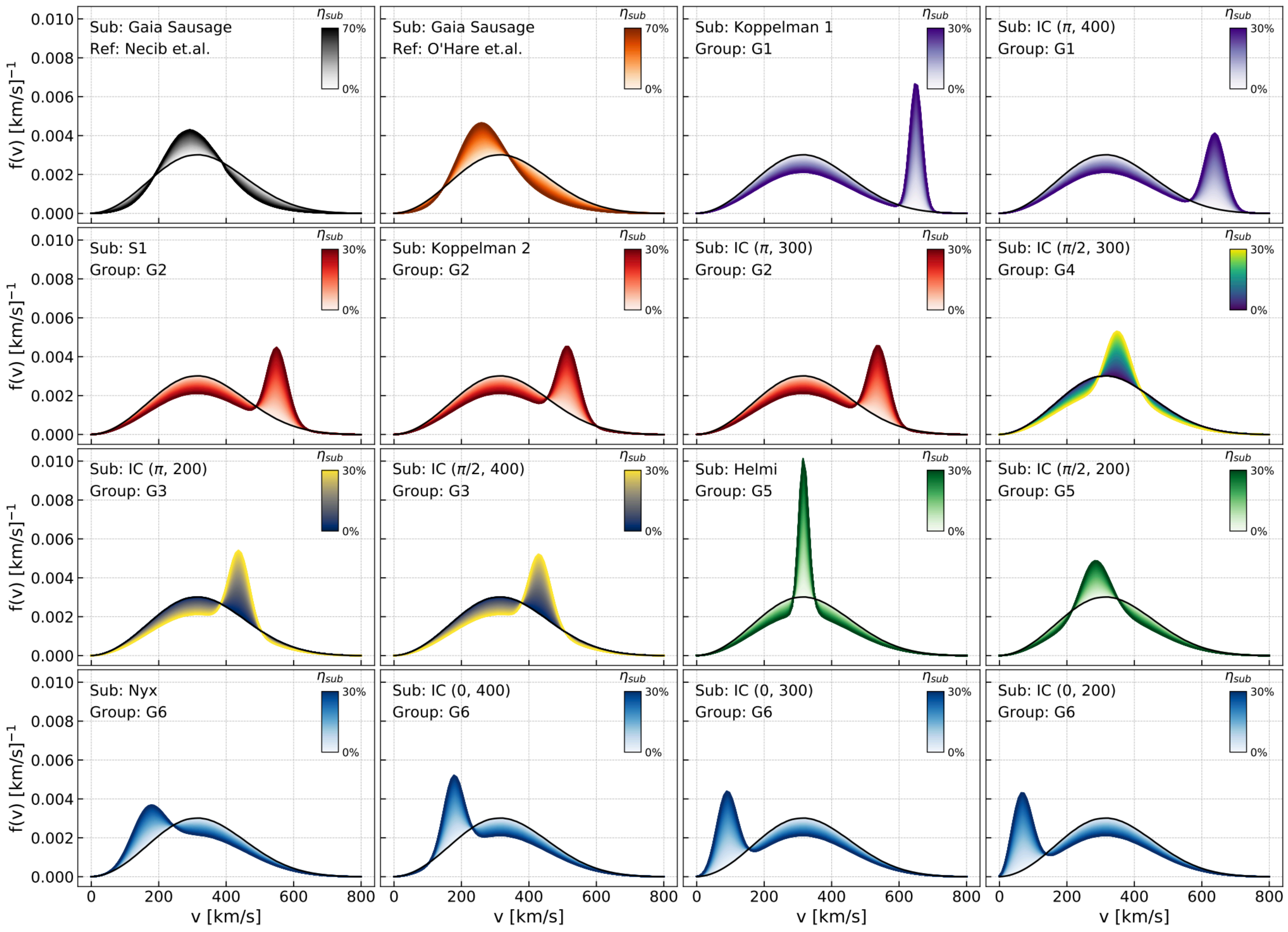
**Important NB:**
We don't know how much dark matter to ascribe to substructures, if any. We also cannot necessarily predict with 100% accuracy the velocity structure of the DM stream from the stellar stream, but it provides a starting point

[2005.14667]



# Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector

P. Adhikari,[5] R. Ajaj,[5,24] C. E. Bina,[1,24] W. Bonivento,[14] M. G. Boulay,[5] M. Cadeddu,[7,14] B. Cai,[5,24]
M. Cárdenas-Montes,[4] S. Cavuoti,[6,13] Y. Chen,[1] B. T. Cleveland,[20,9] J. M. Corning,[17] S. Daugherty,[9]
P. DelGobbo,[5,24] P. Di Stefano,[17] L. Doria,[15] M. Dunford,[5] A. Erlandson,[5,3] S. S. Farahani,[1]



←

**Axion lineshape:** $f(\omega) = \dfrac{\mathrm{d}v}{\mathrm{d}\omega} f(v)$

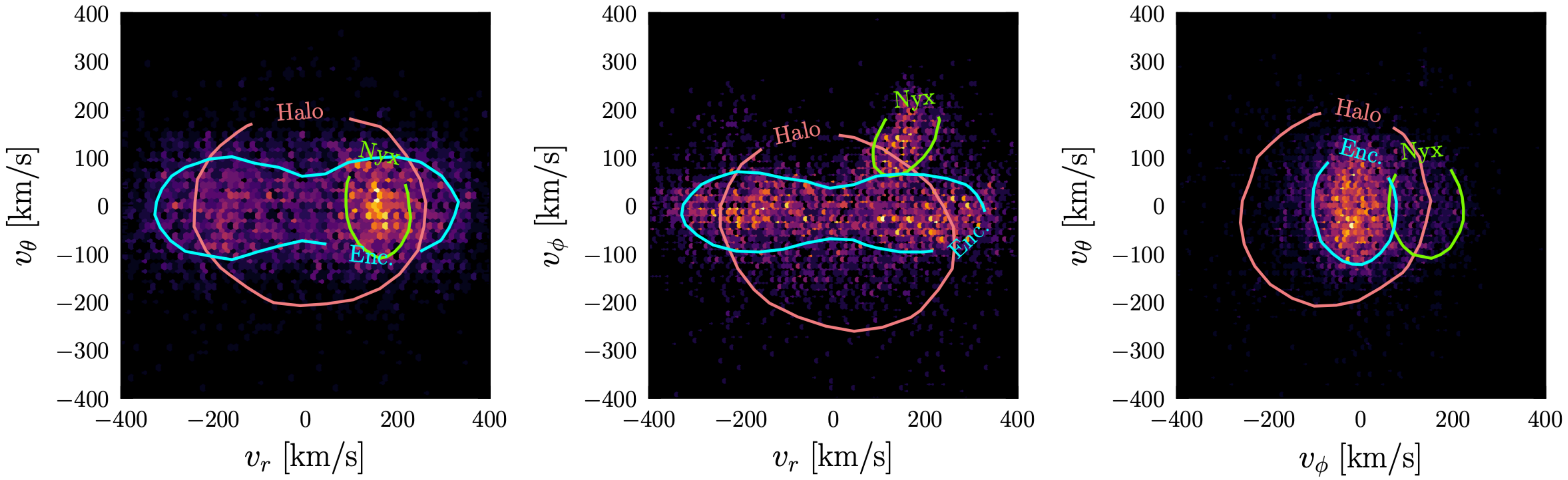
**is more concentrated around low speeds, so most interesting substructures for axion line are the slow ones**

(which tend to be prograde streams)

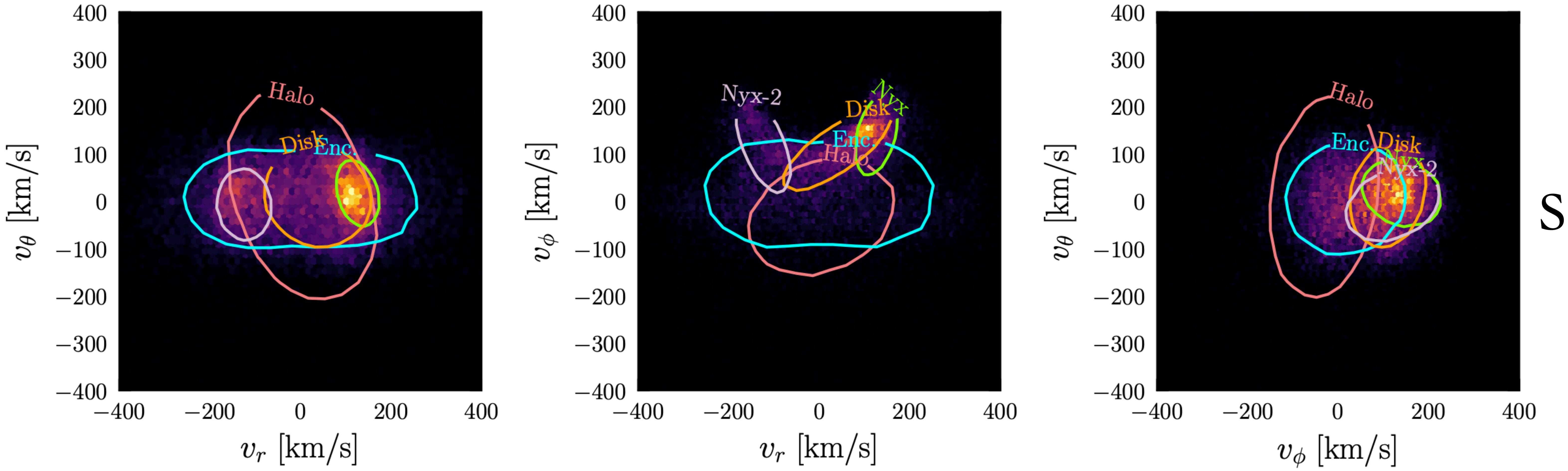
**Deep-learning based method of extracting accreted stars in stellar halo samples**

→ identified large prograde stream “Nyx”. Seems to be unrelated to any previously known streams, though some have suggested a potential connection to thick disk, or “splash”

Ostdiek, Necib+ [1907.07681, 1907.07190]



High purity sample

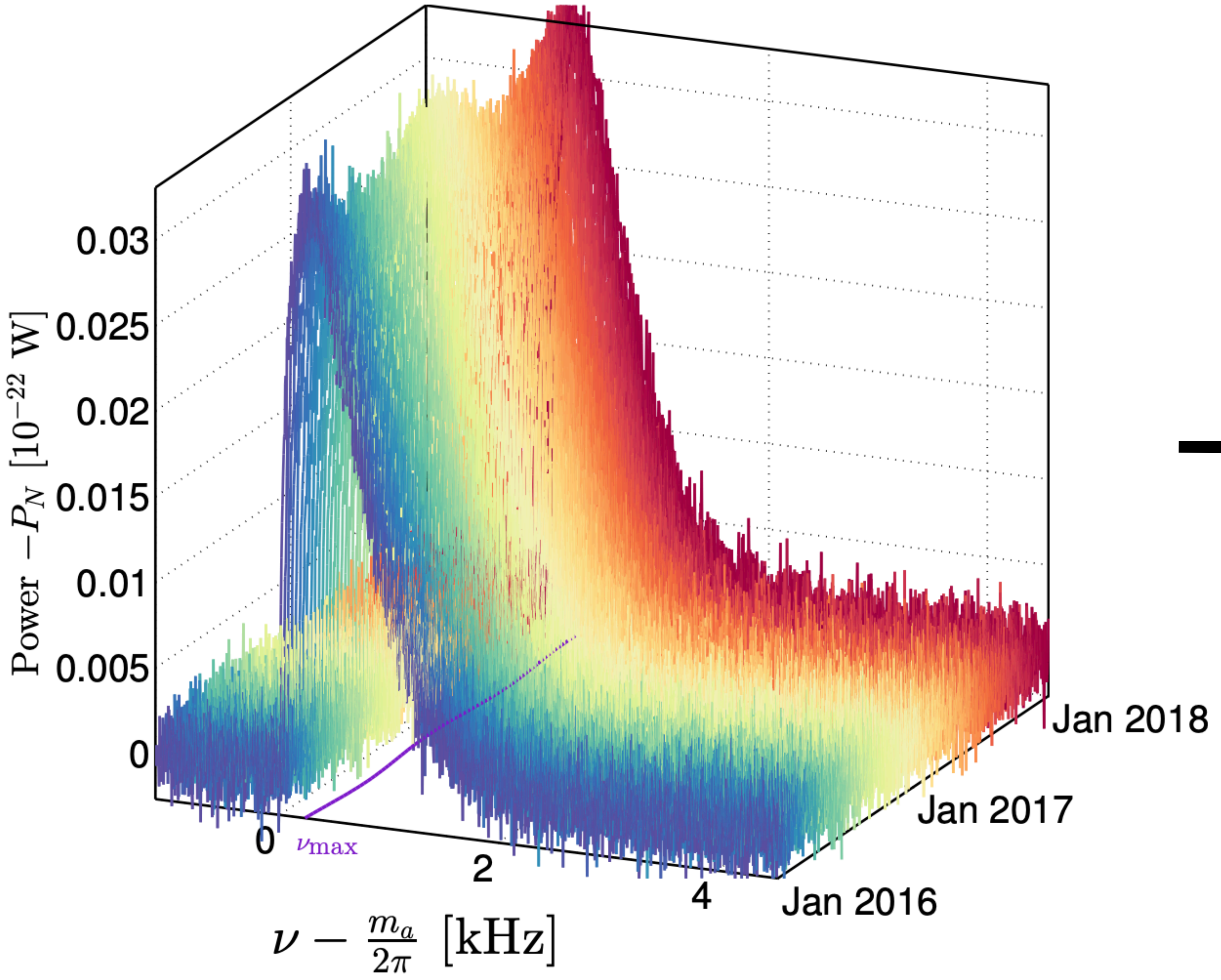


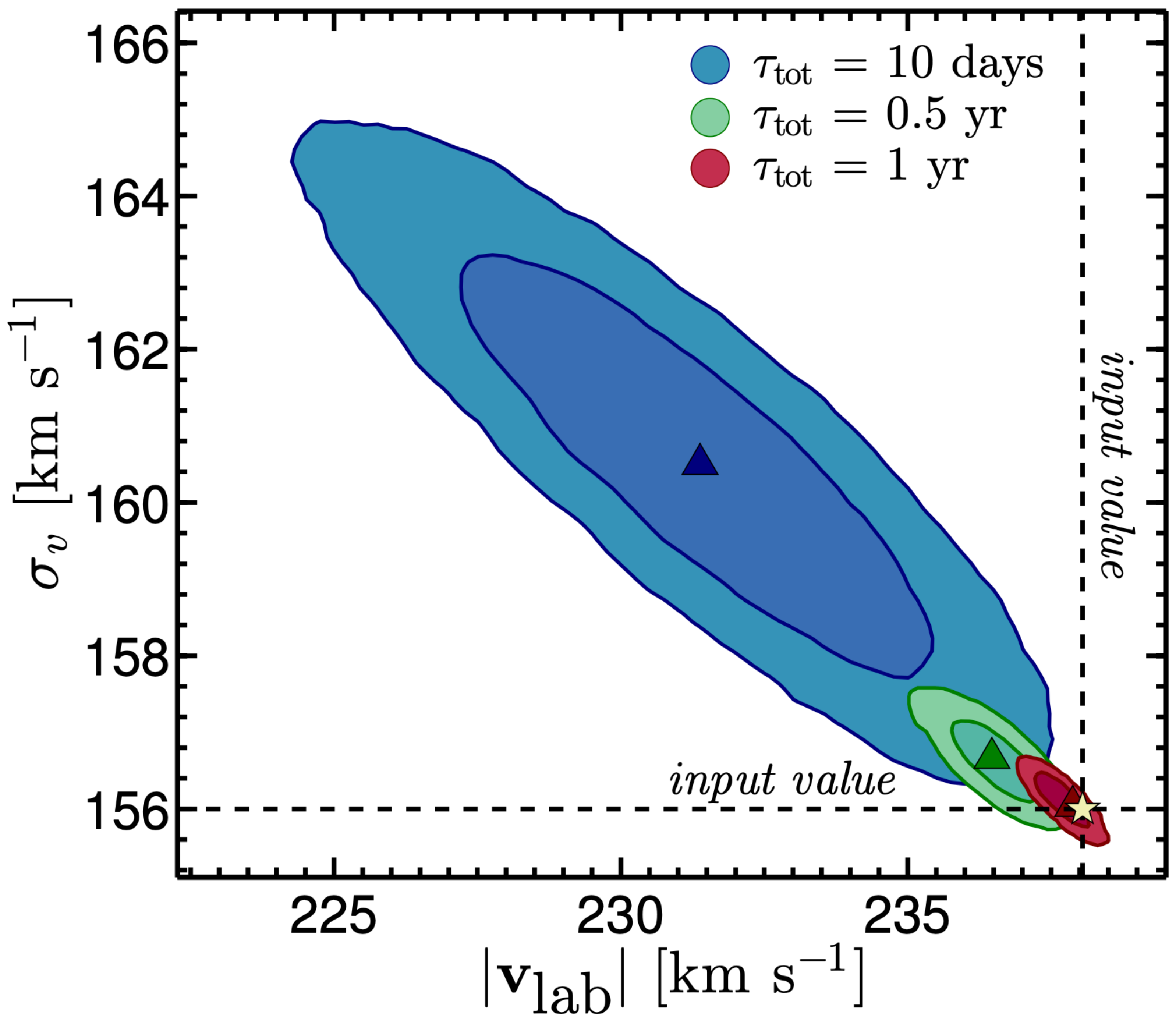
Semi-pure sample

# Axion “astronomy”

# Axion "astronomy"

With a positive axion detection, high S/N studies of axion lineshape become possible very quickly





***Direct*** measurement of purely astrophysical quantities such as the width of the DM distribution, galactic velocity of the Sun, possible within ~1 year of detection.

# Axion “astronomy”

Annual modulation signal also carries information about the **velocity** structure of the local DM distribution

- Haloscopes measure *speed* distribution: $f(v,t) = \int v^2 f(\mathbf{v} + \mathbf{v}_{\rm lab}(t))\, {\rm d}\Omega_v$

  so for an <u>isotropic</u> $f(\mathbf{v})$, the phase of the annual modulation is governed solely by $\mathbf{v}_{\rm lab}(t)$

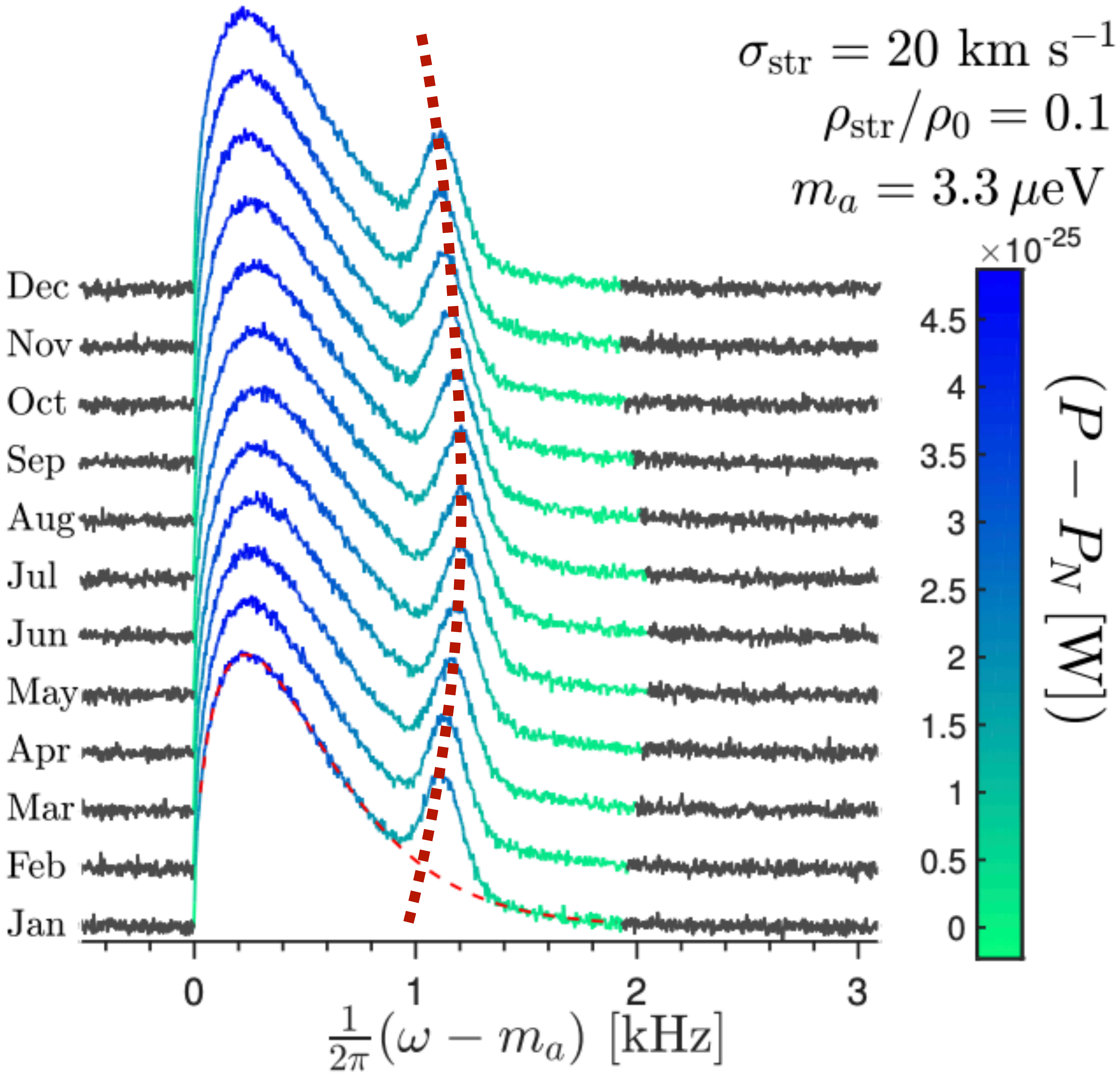
- But for an <u>anisotropic</u> $f(\mathbf{v})$, e.g. $f(\mathbf{v}) \propto \exp\left(-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{v_\phi^2}{2\sigma_\phi^2}\right)$ defined in galactic coords,

  the observed speed distribution at a given day depends upon the projection of the $\mathbf{v}_{\rm lab}(t)$ along each galactic axis, and the width of the distribution along that axis

**Can change the phase, frequency dependence, and make the distribution non-sinusoidal**

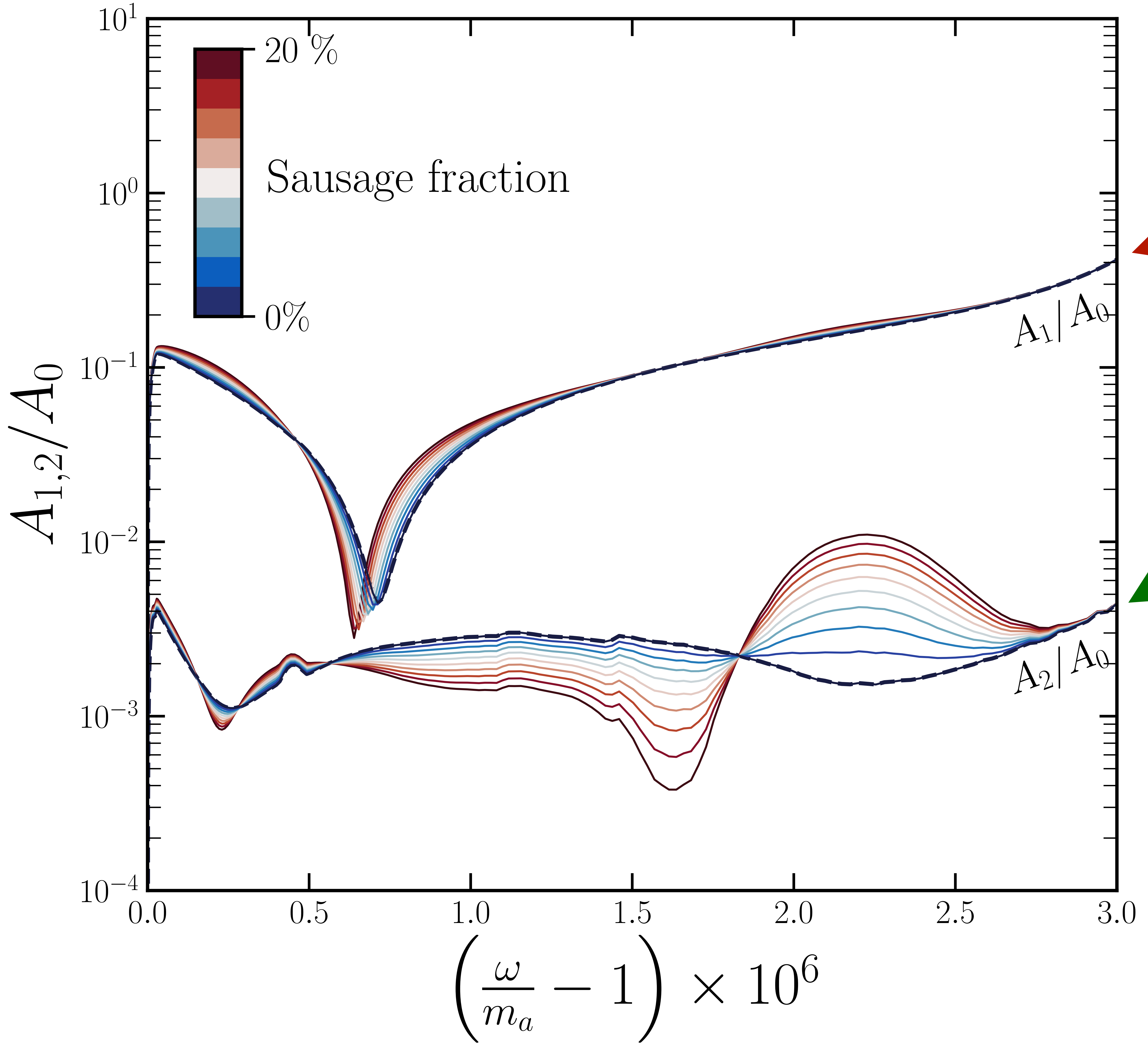
# Axion "astronomy": identifying streams

e.g. a stream will undergo its own annual modulation with a different phase depending on the alignment of the streaming velocity with respect to the orbit of the Earth



# Approach sometimes taken in annual modulation searches:

→ Fourier series expansion of modulating signal



$$f(\omega) = A_0 + \sum_{n=1}^{\infty}\left[A_n \cos\left(\frac{2\pi n\,(t-t_n)}{1\text{ year}}\right)\right]$$

Unlike streams, the Sausage does not show up prominently in the **first mode**, but does in **higher order modes**

→ Statistics needed to access these modes are very high, but not necessarily out of the question for an axion experiment

# Directional axion detection

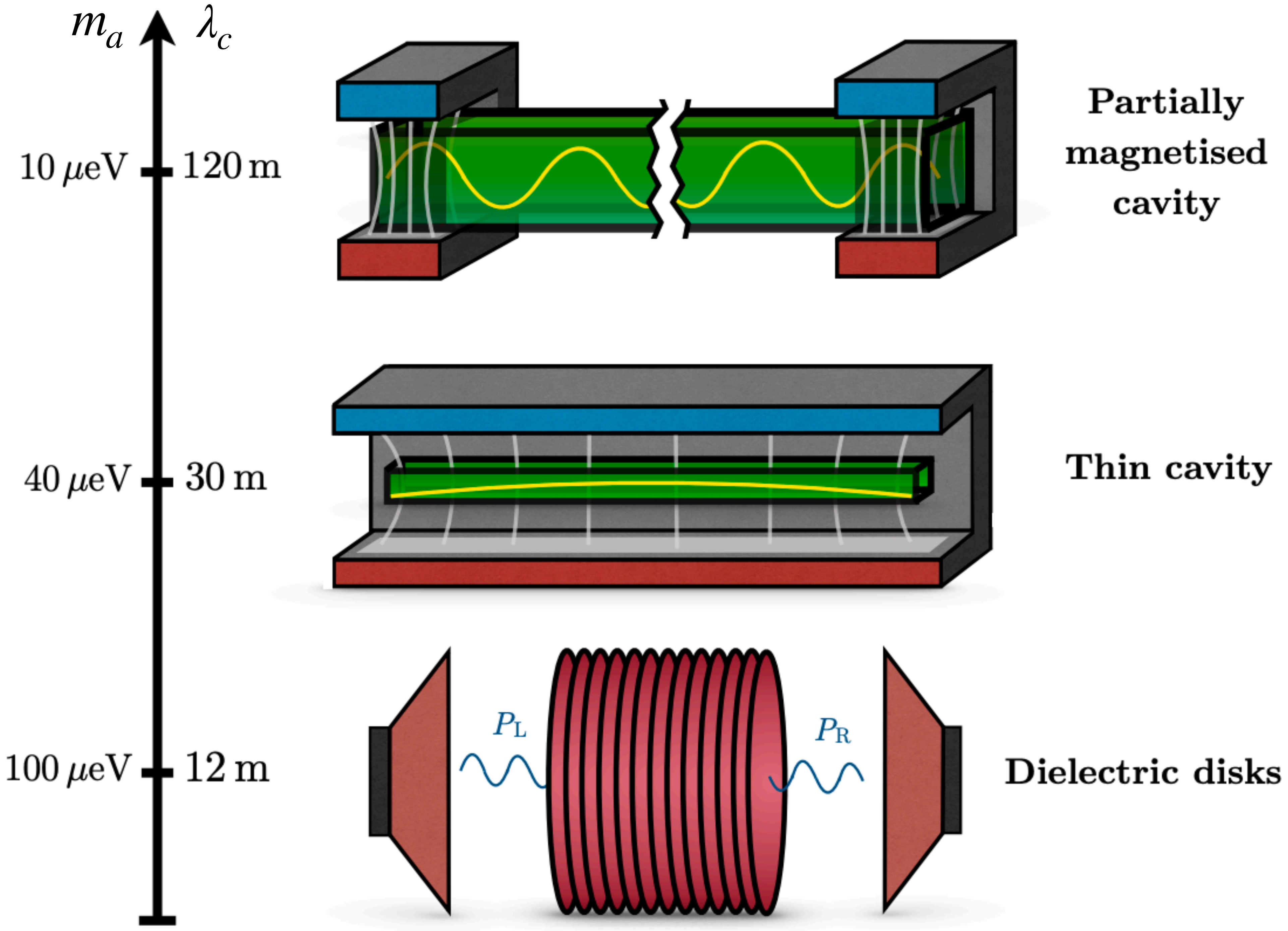
May also be possible to do some kind of directional measurement to extract even more information

$$a(\mathbf{x}, t) = \frac{\sqrt{2\rho_a}}{m_a} \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} |\mathcal{A}(\mathbf{p})| \cos\left(\omega t - \boxed{\mathbf{p}\cdot\mathbf{x}} + \alpha_{\mathbf{p}}\right)$$

**Single experiment directionality**

→ Exploit time dependent loss of coherence for experiments on a similar scale to the axion field's coherence length

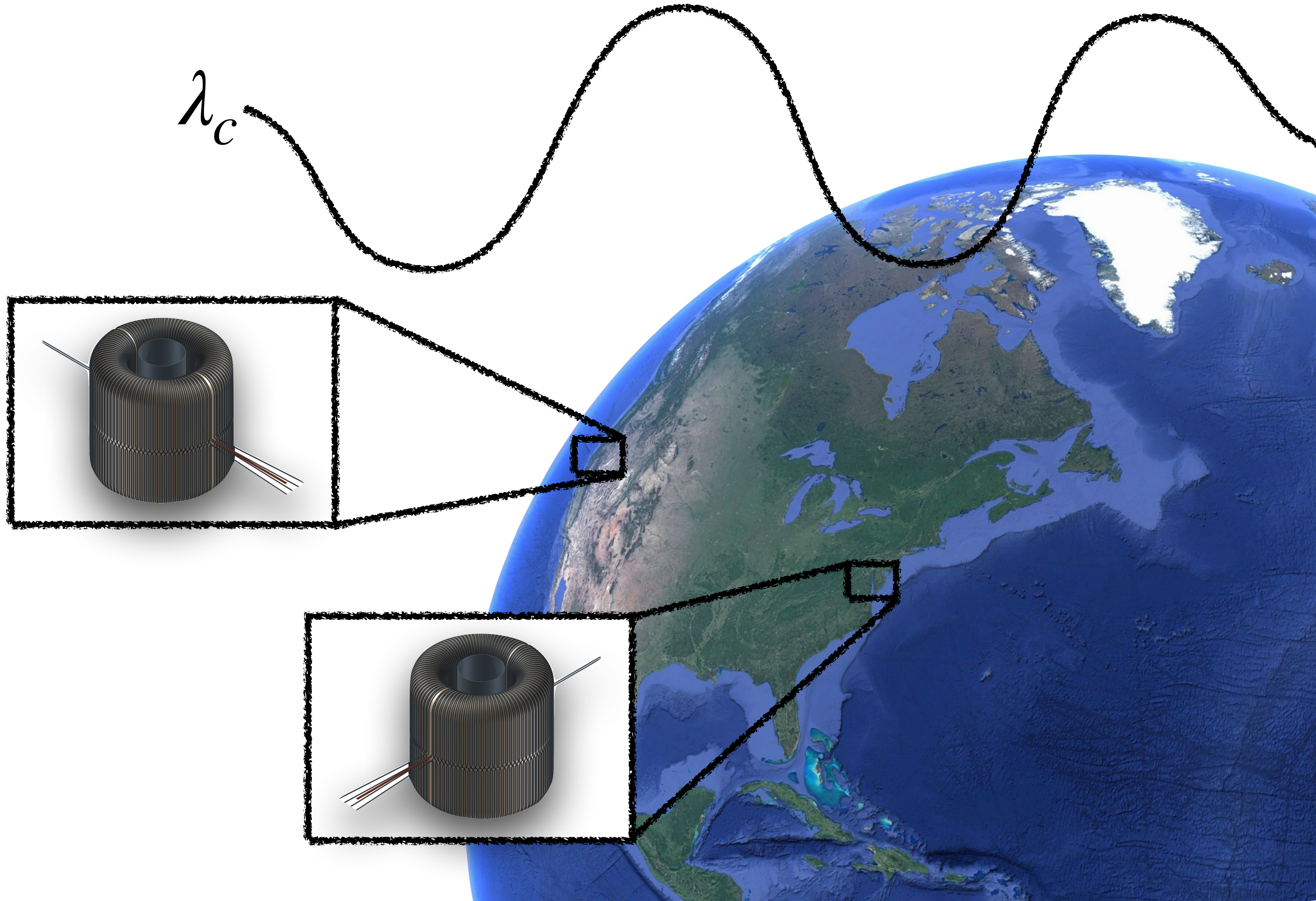
Knirck+ [1806.05927]



**Multi-experiment directionality**

→ combine precise axion phase information at detectors separated by a few coherence lengths

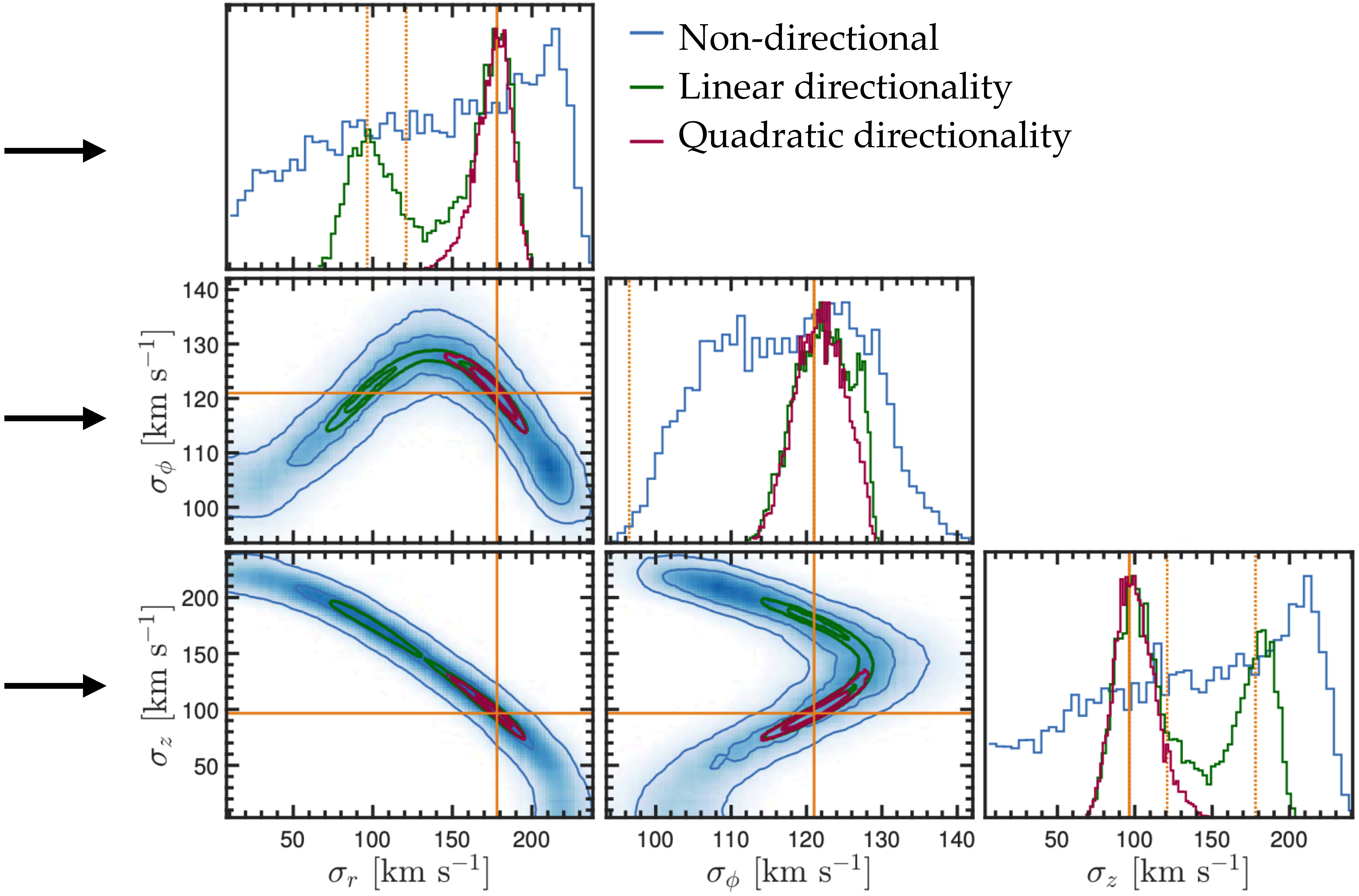
Foster+ [2009.14201]



# Directional axion detection: Sausage

Anisotropy (e.g. sausage) somewhat difficult to measure, as it is a subtle axis-dependent shift in the linewidth

**Dispersion along 3 galactic axes**

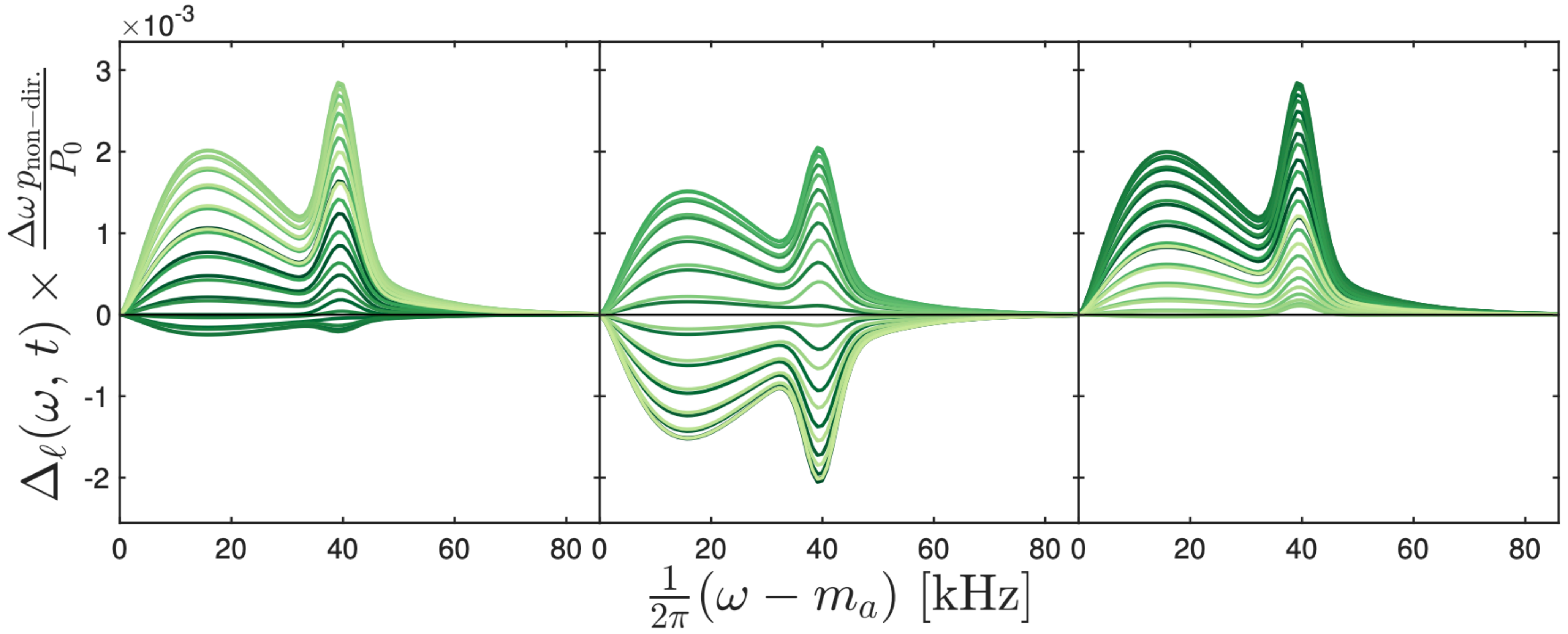


# Directional axion detection: streams

Streams are kinematically localised features and can have large angles away from the primary DM wind
Earth's daily rotation causes feature to sweep over the sky - well suited for detection via direction dependence

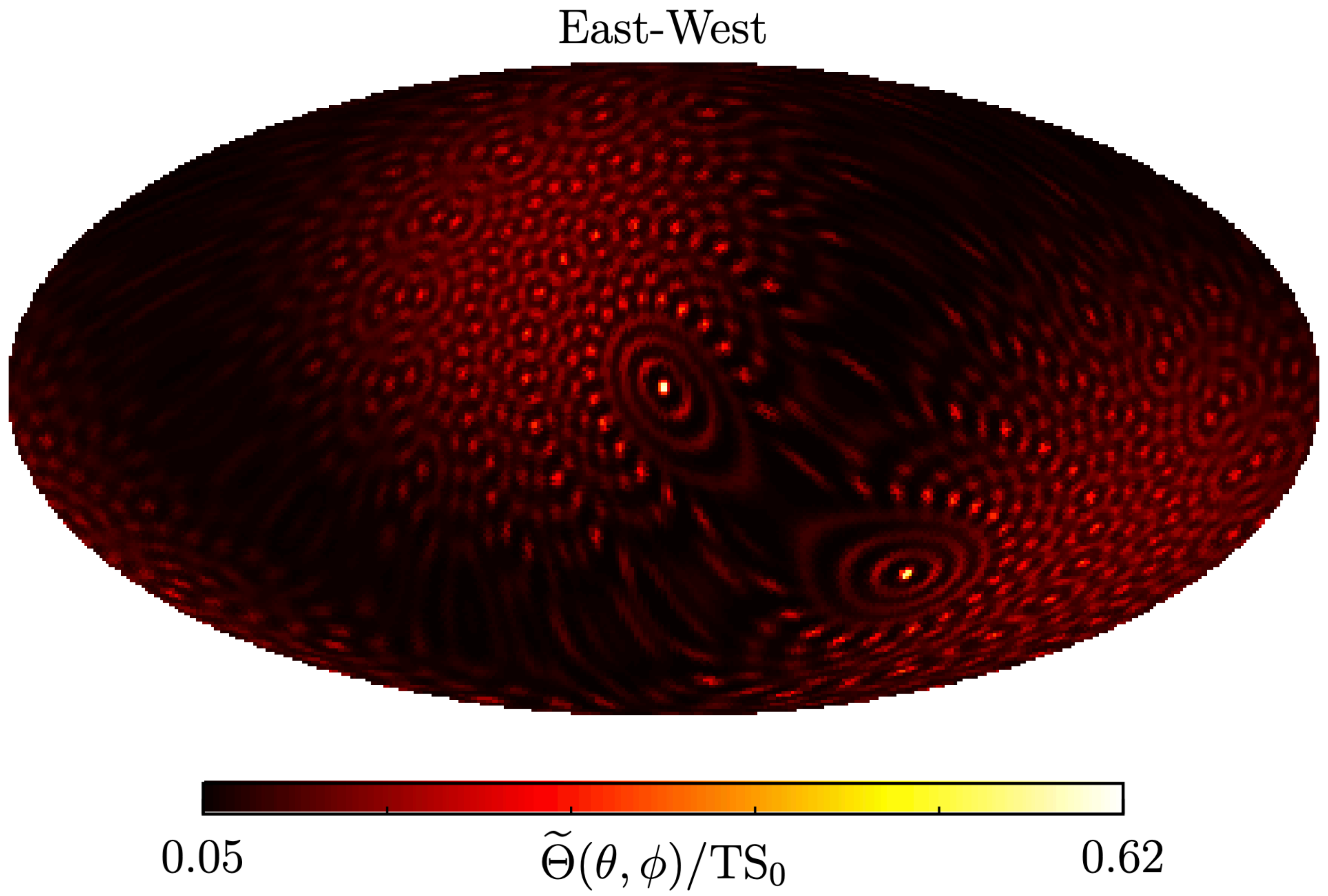
## Single-experiment directionality

Knirck+ [1806.05927]

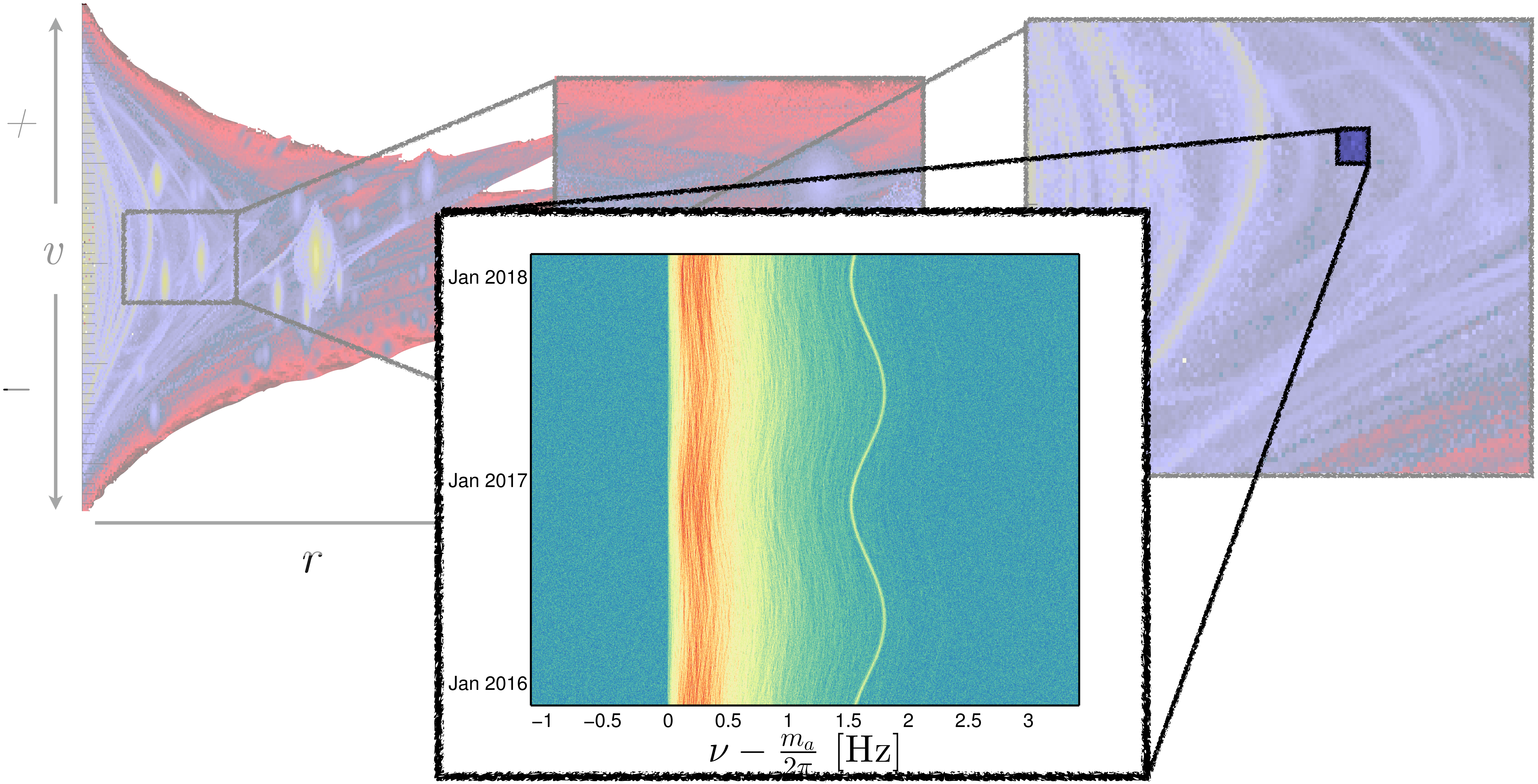


## Multi-experiment directionality

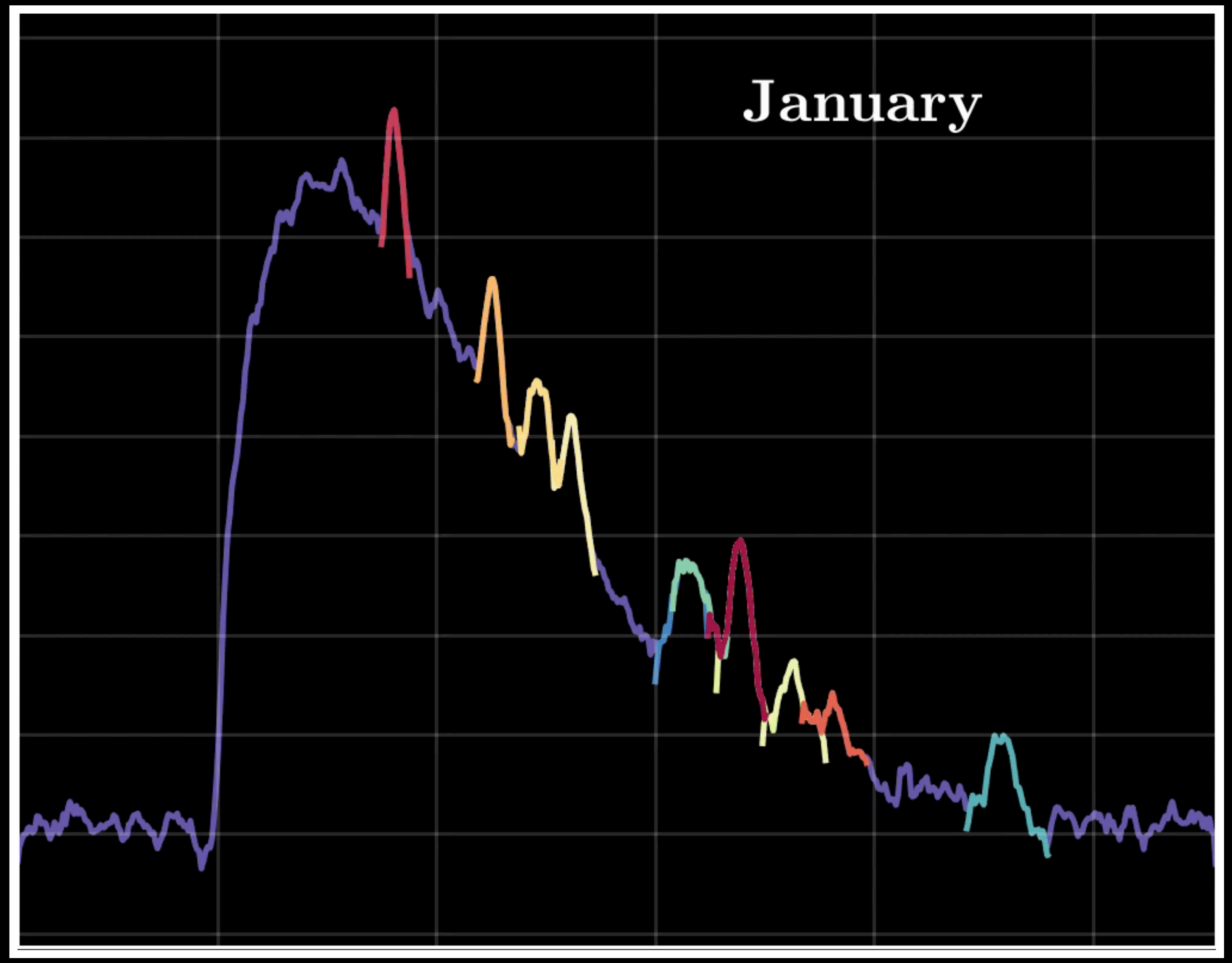
Foster+ [2009.14201]

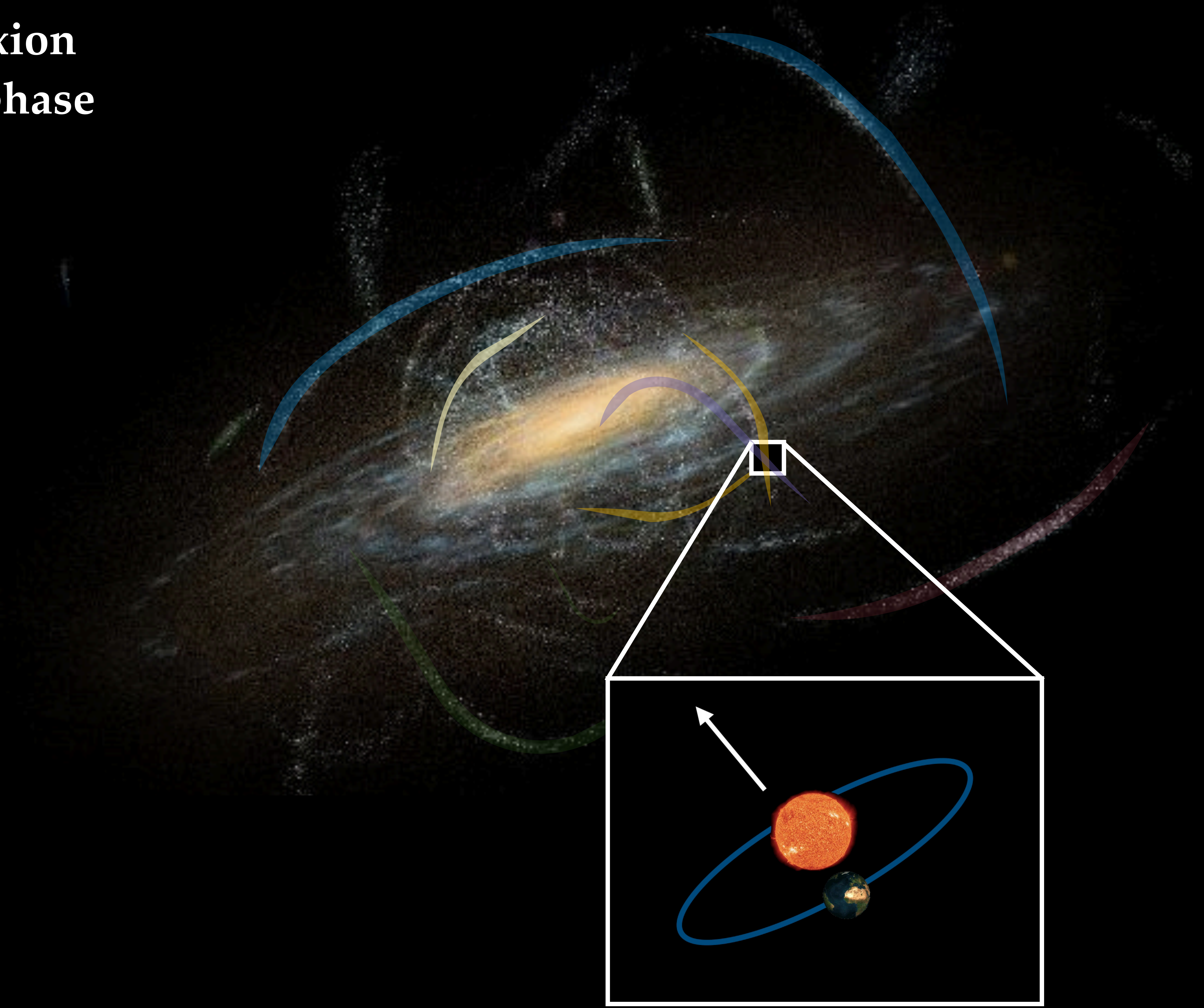


# Assuming perfectly cold DM, at some level the halo will have ultra-fine grained substructure, even if it consists of millions of overlapping streams Vogelsberger+ [1002.3162]



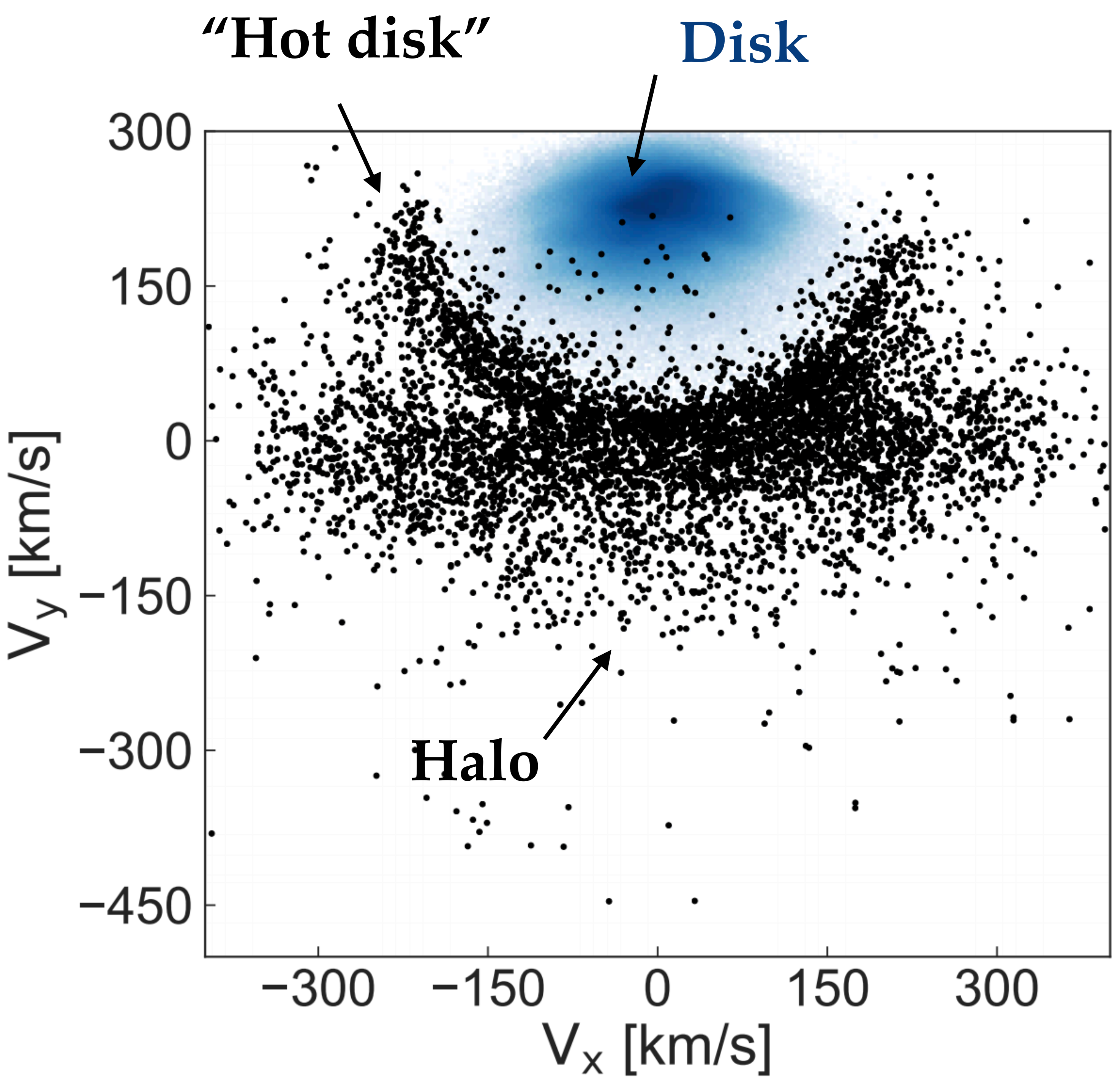
# Eventual ultra long-term goal is for axion experiments to unravel the complex phase space distribution of the DM halo



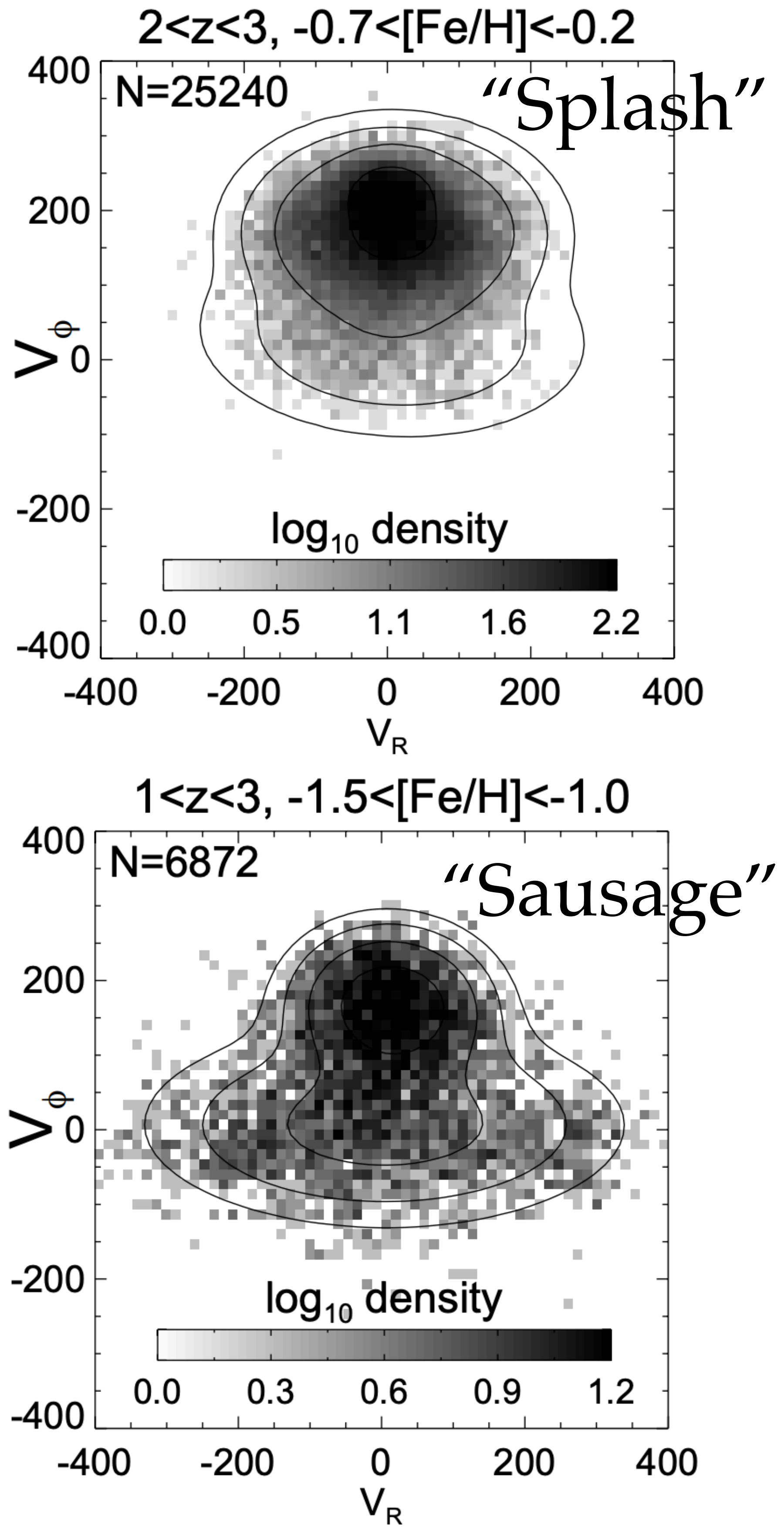


# Extra slides

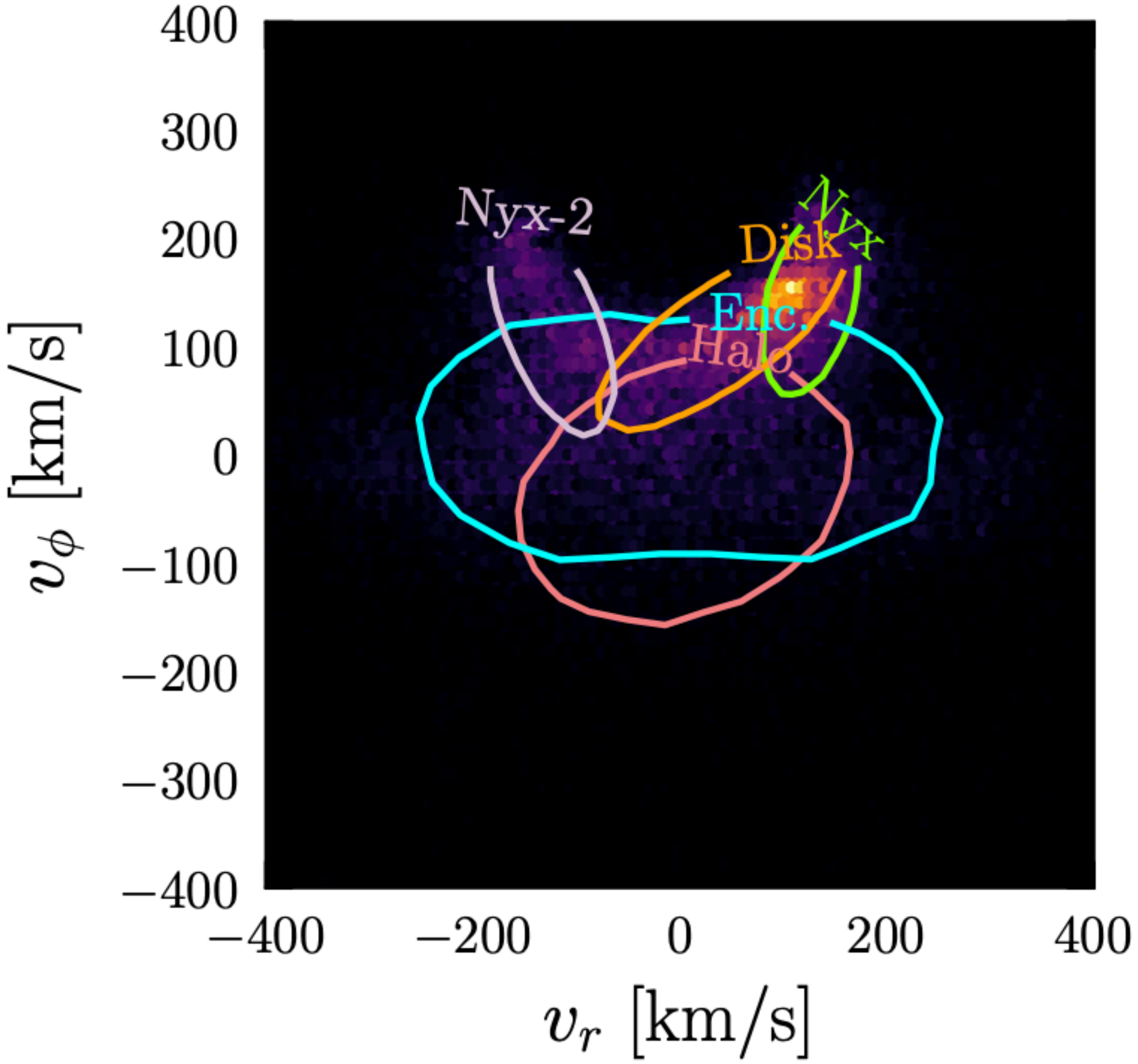
From Helmi's review of substructure in the MW [2002.04340]



Belokurov et al. [1909.04679]



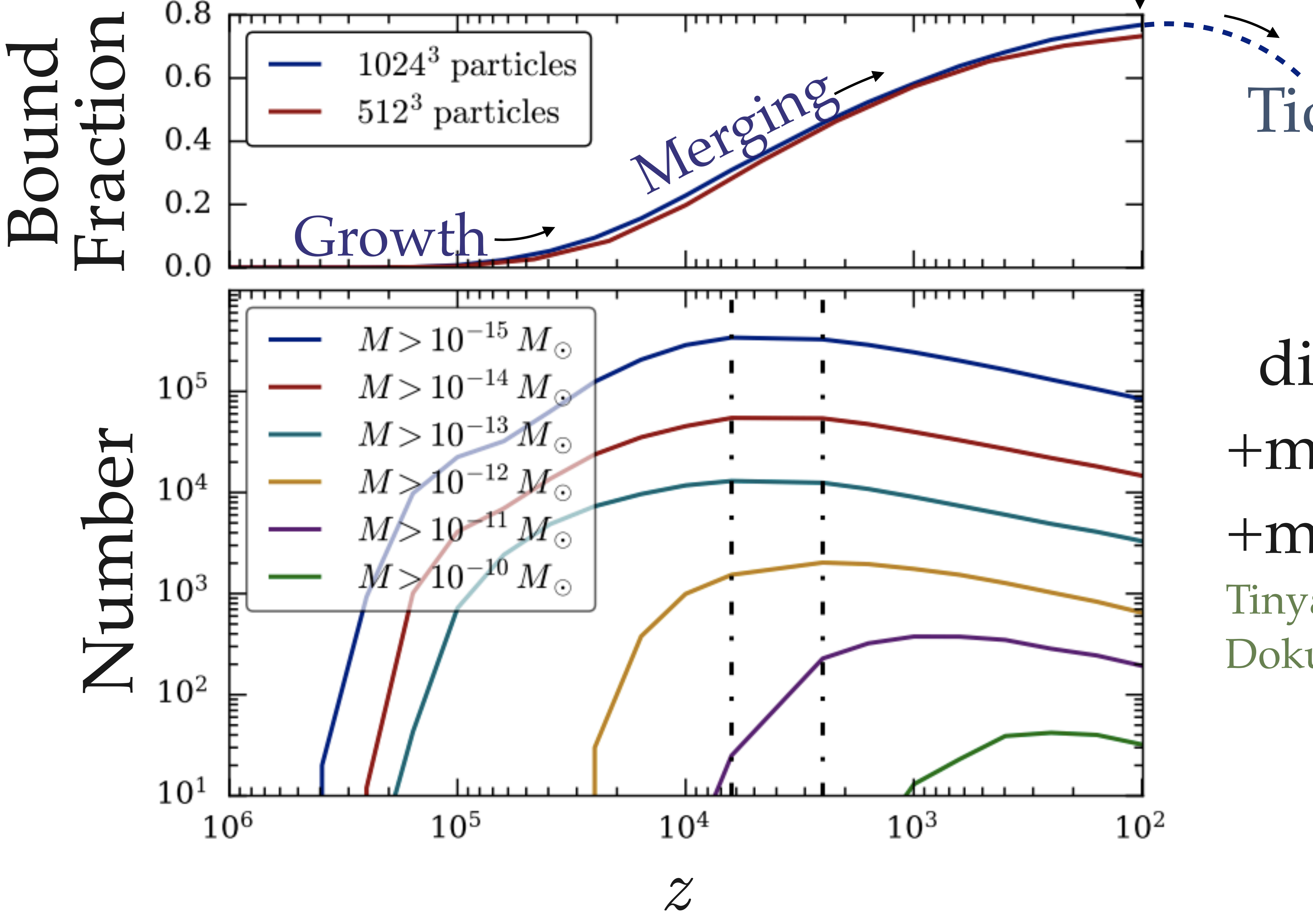
Nyx stream



# Galaxies made of axion miniclusters+diffuse axions

Eggemeier+ [1911.09417]

$f_{\mathrm{clump}}(z = 100) = 0.75$



Tidal disruption?

diffuse axions

+miniclusters

+ministreams ~ 1%?

Tinyakov+ [1512.02884]

Dokuchaev+ [1710.09586]

# Fate of miniclusters in the galaxy

**Problems** for direct detection → encounter rate ~ 1 per 10,000—1,000,000 years

Kavanagh et al. [2011.05377]

**Opportunities** for indirect detection → collision of miniclusters with neutron stars

Edwards et al. [2011.05378]

→ Miniclusters passing line of sight

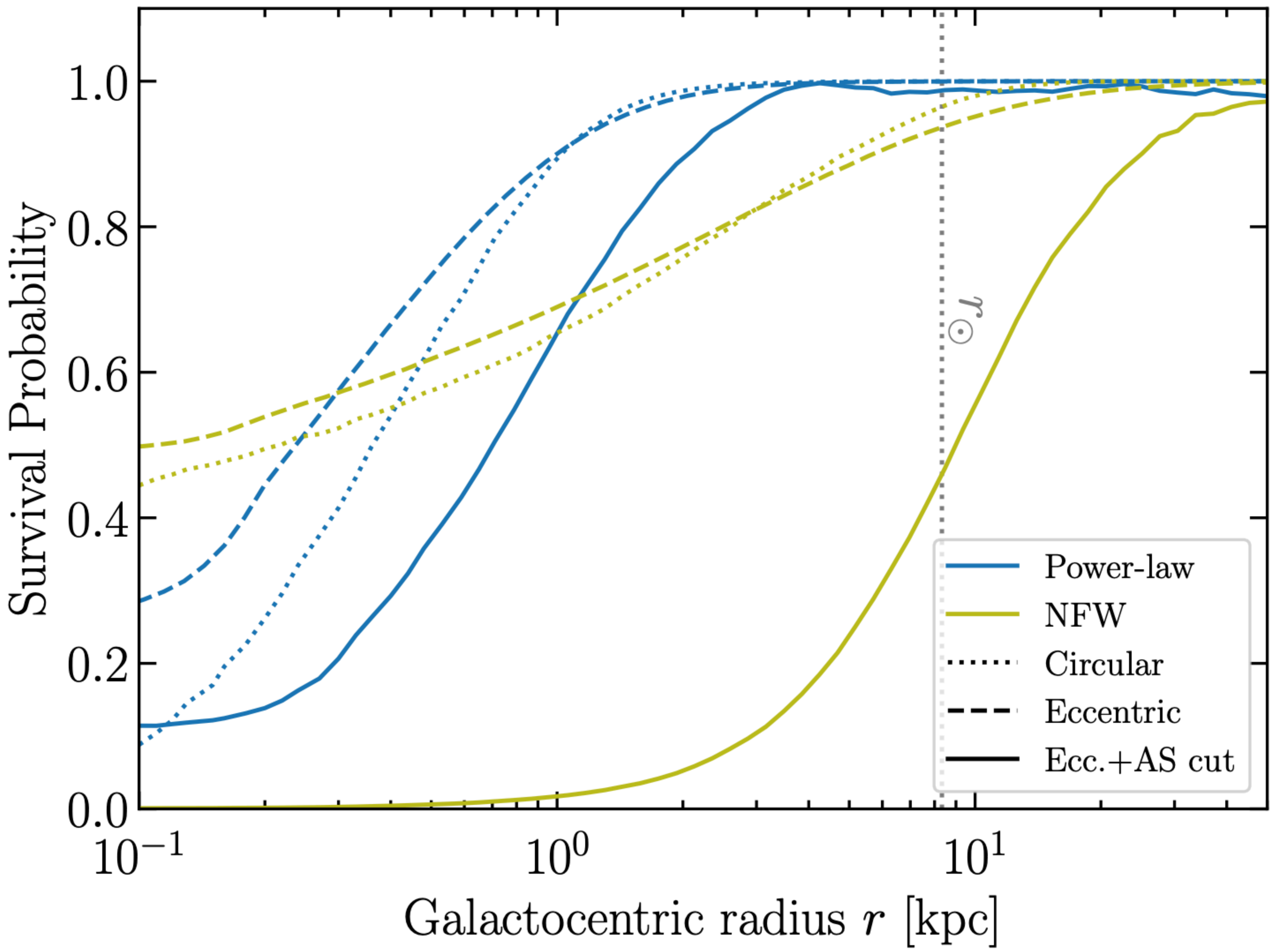
Dai & Miralda Escudé [1908.01773]

Fairbairn et al. [1701.04787]

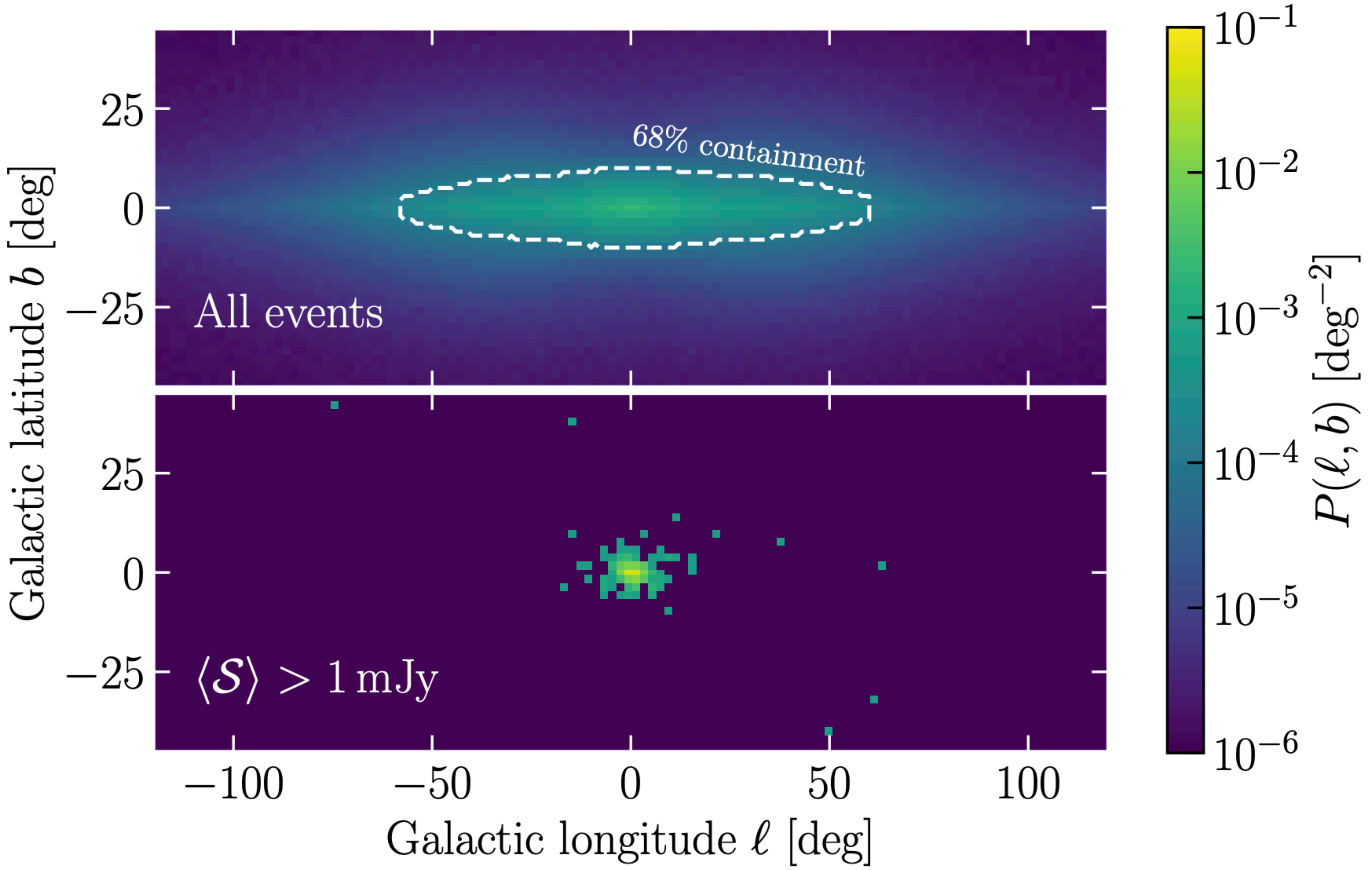
# Fate of miniclusters in the galaxy - 2 recent papers

Kavanagh, Edwards, Visinelli, Weniger

**[2011.05377]** Survival probability of miniclusters versus minicluster density profile and position in galaxy

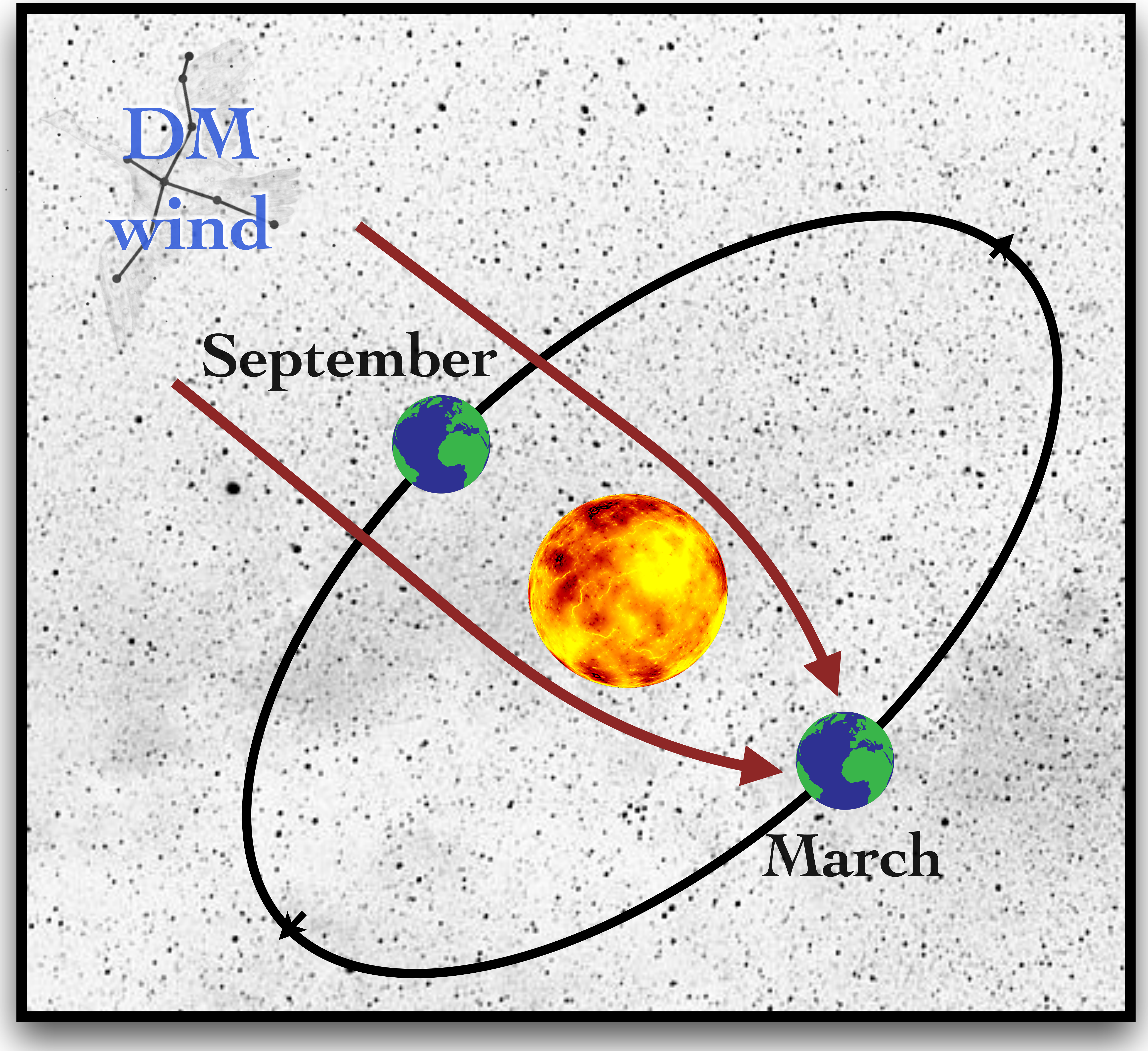


**[2011.05378]** Encounter rate between miniclusters and neutron stars → radio transients every 1—100 days towards GC

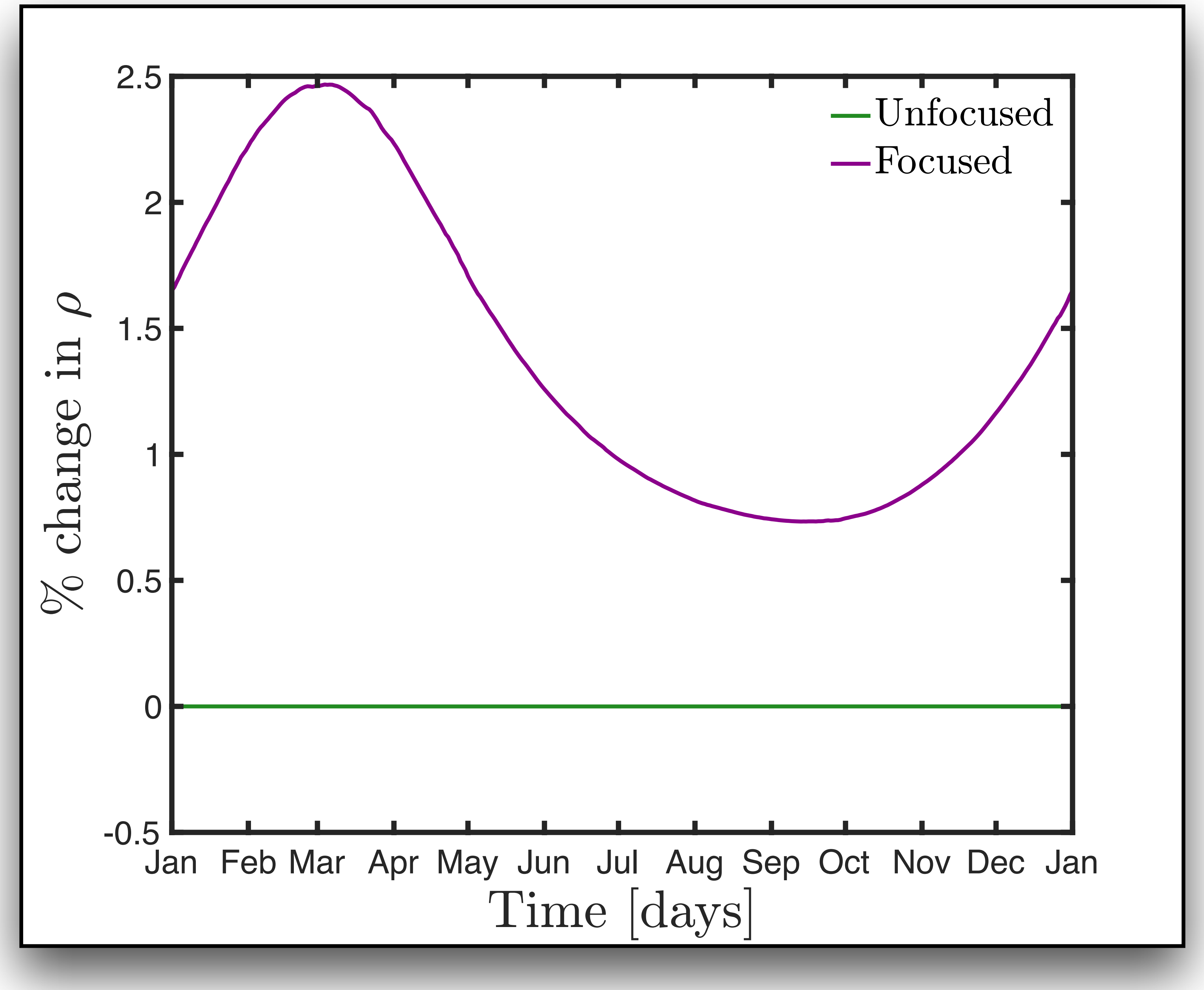


Still many uncertainties remaining → but results suggest that NS radio transients are a promising indirect signal and miniclusters at Earth's position could be disrupted

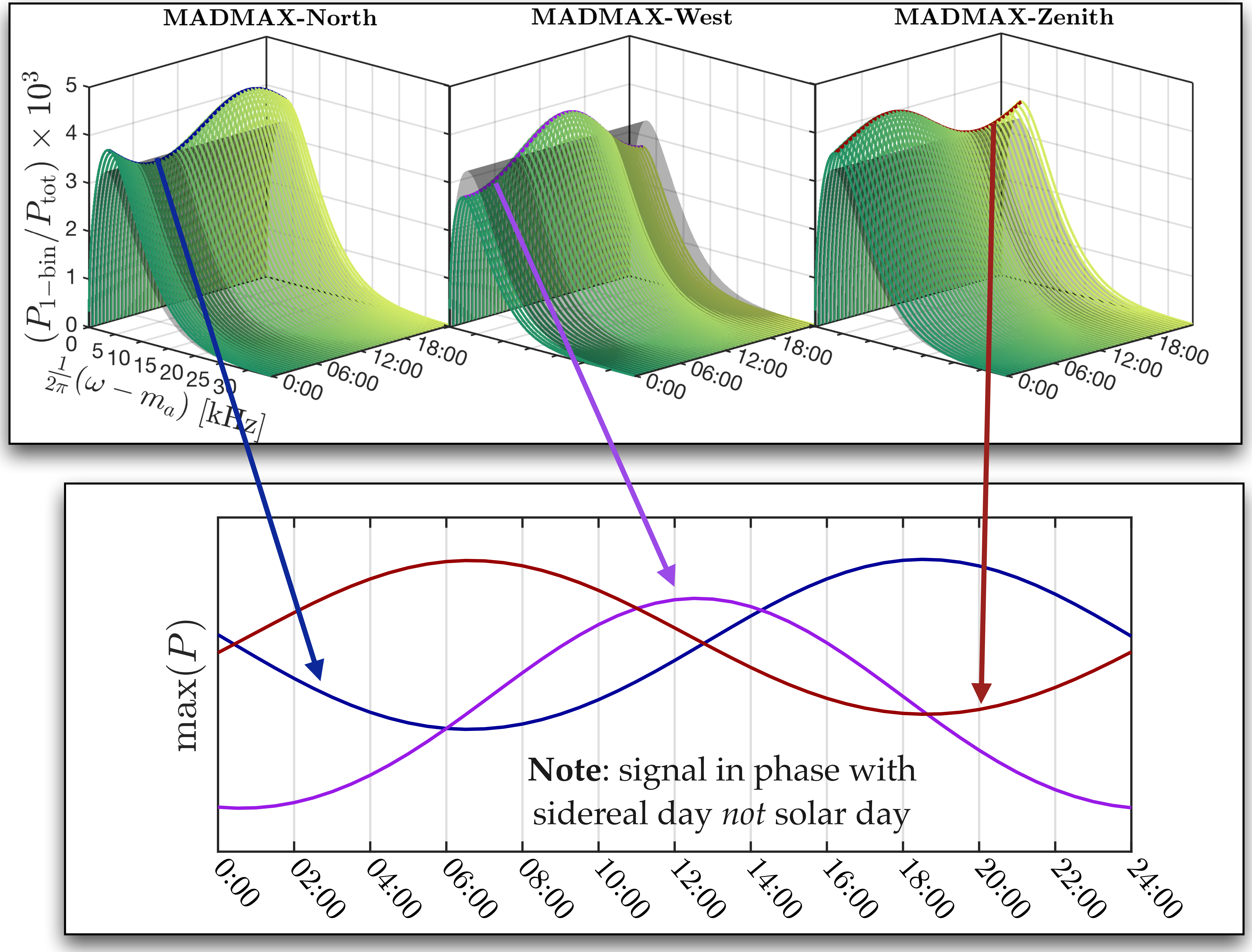
# Gravitational focusing



Additional ~2% modulation in DM density (+shift of *f*($v$) at small $v$)



# Daily modulation for a directional experiment



**Note**: signal in phase with sidereal day *not* solar day