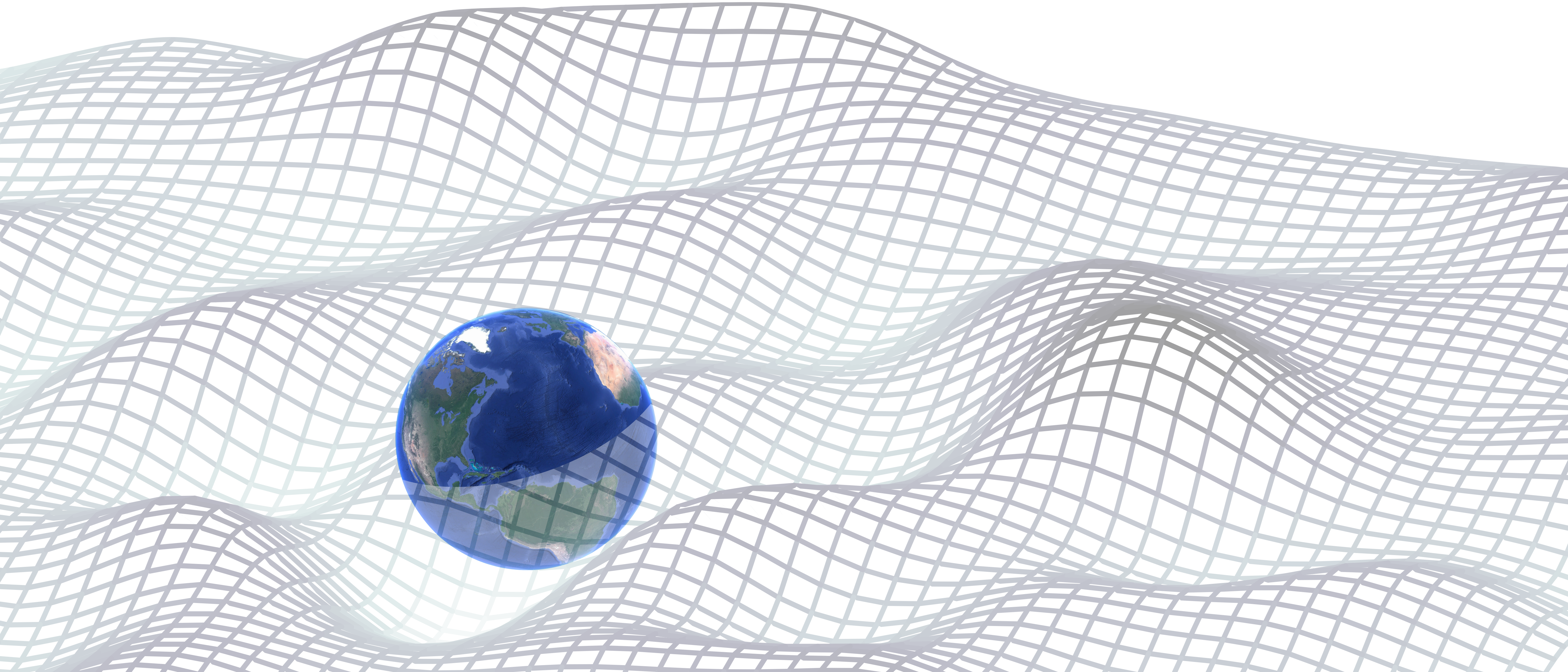
THE UNIVERSITY OF SYDNEY

Australian Government
Australian Research Council

Centre for Dark Matter Particle Physics

Axion haloscopes & the local dark matter distribution

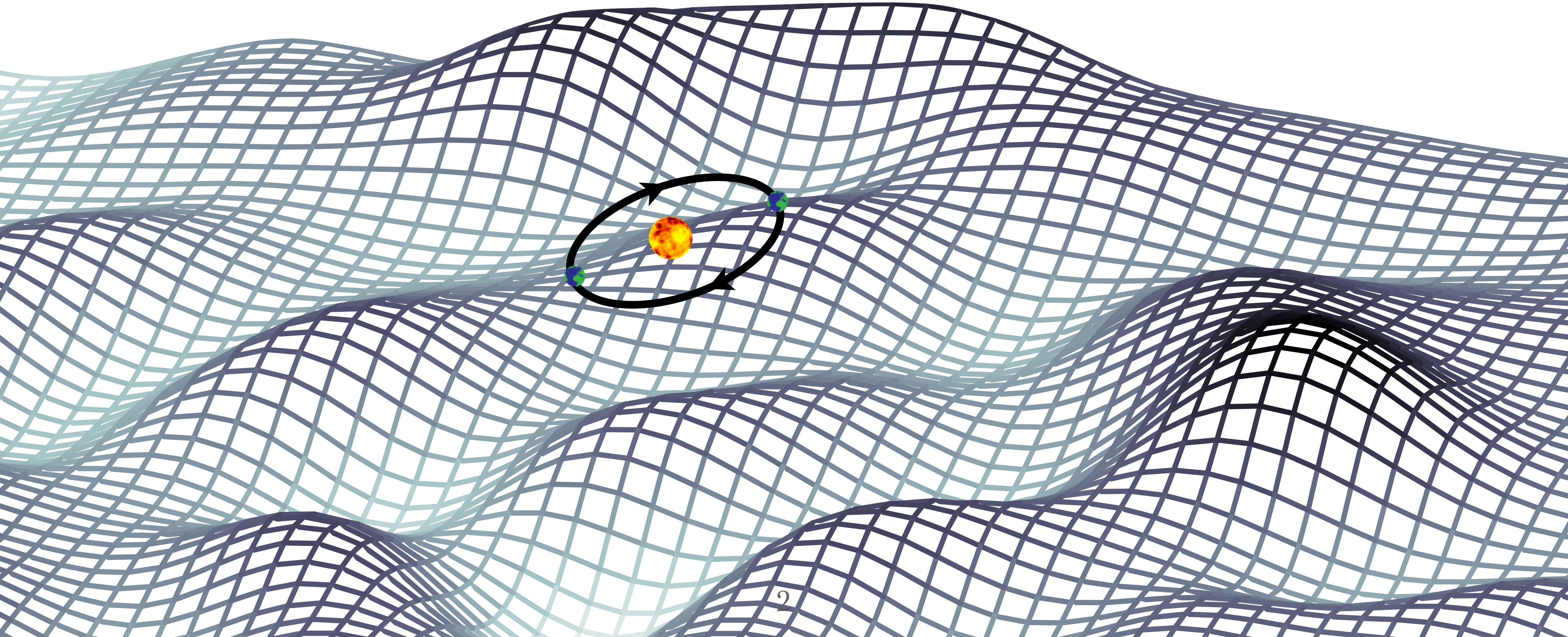
Ciaran O'Hare



DM axions: a classical field $a(\mathbf{x},t) \approx \frac{\sqrt{2\rho_a}}{m_a}\cos\left(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha\right)$

Oscillations in time: $\omega = m_a\left(1 + \frac{v^2}{2}\right)$

Oscillations in space: $\mathbf{p} = m_a\mathbf{v}$



Accounting for distribution of modes

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

velocity distribution $f(\mathbf{v})$, width: $\sigma_v \sim 156$ km/s

~Time scale for oscillation to dephase

~Length scale for oscillation to dephase

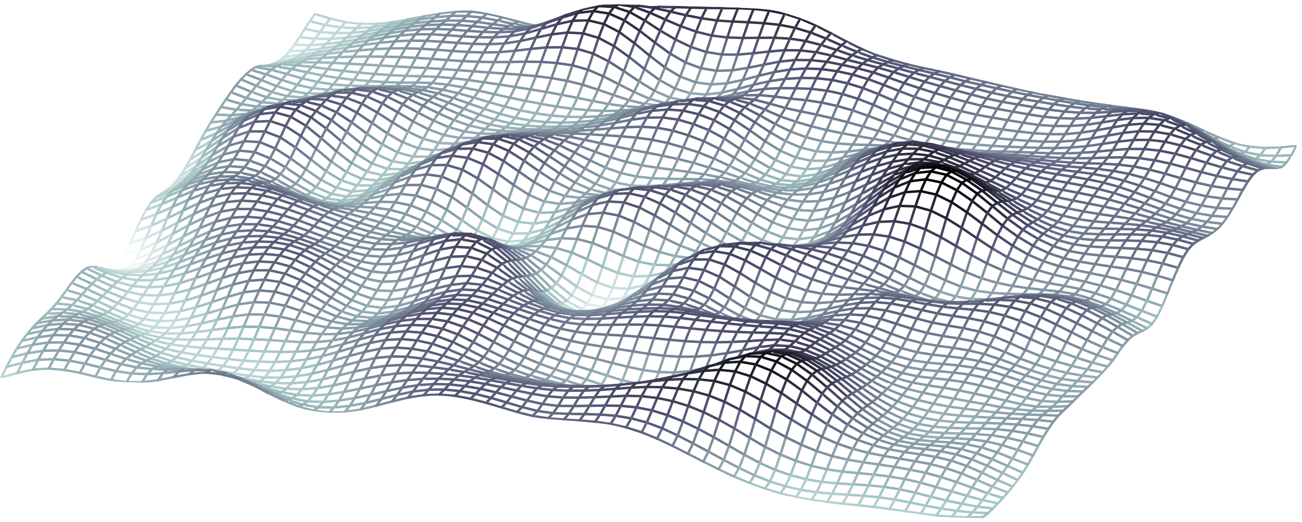
$$\tau_a = \frac{2\pi}{m_a\sigma_v^2} \simeq 40\,\mu\mathrm{s}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

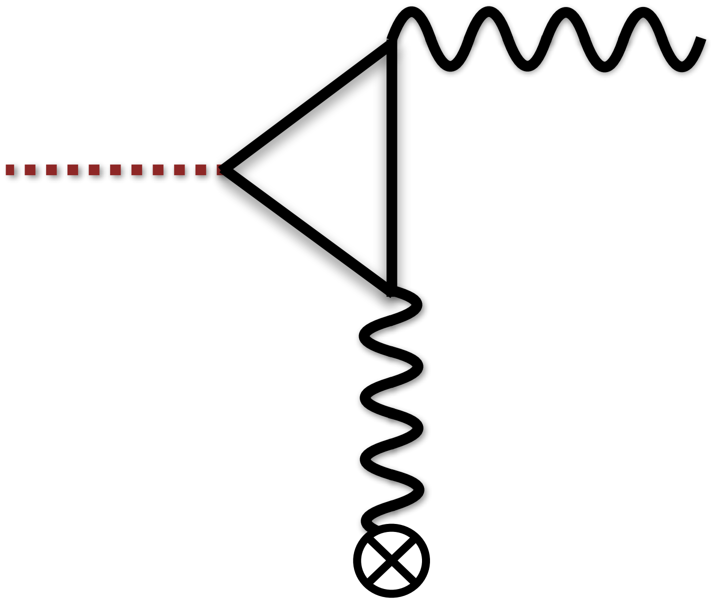
$$\lambda_a = \frac{2\pi}{m_a\sigma_v} \simeq 12.4\,\mathrm{m}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

dark matter
axions

+

axions converting
into photons





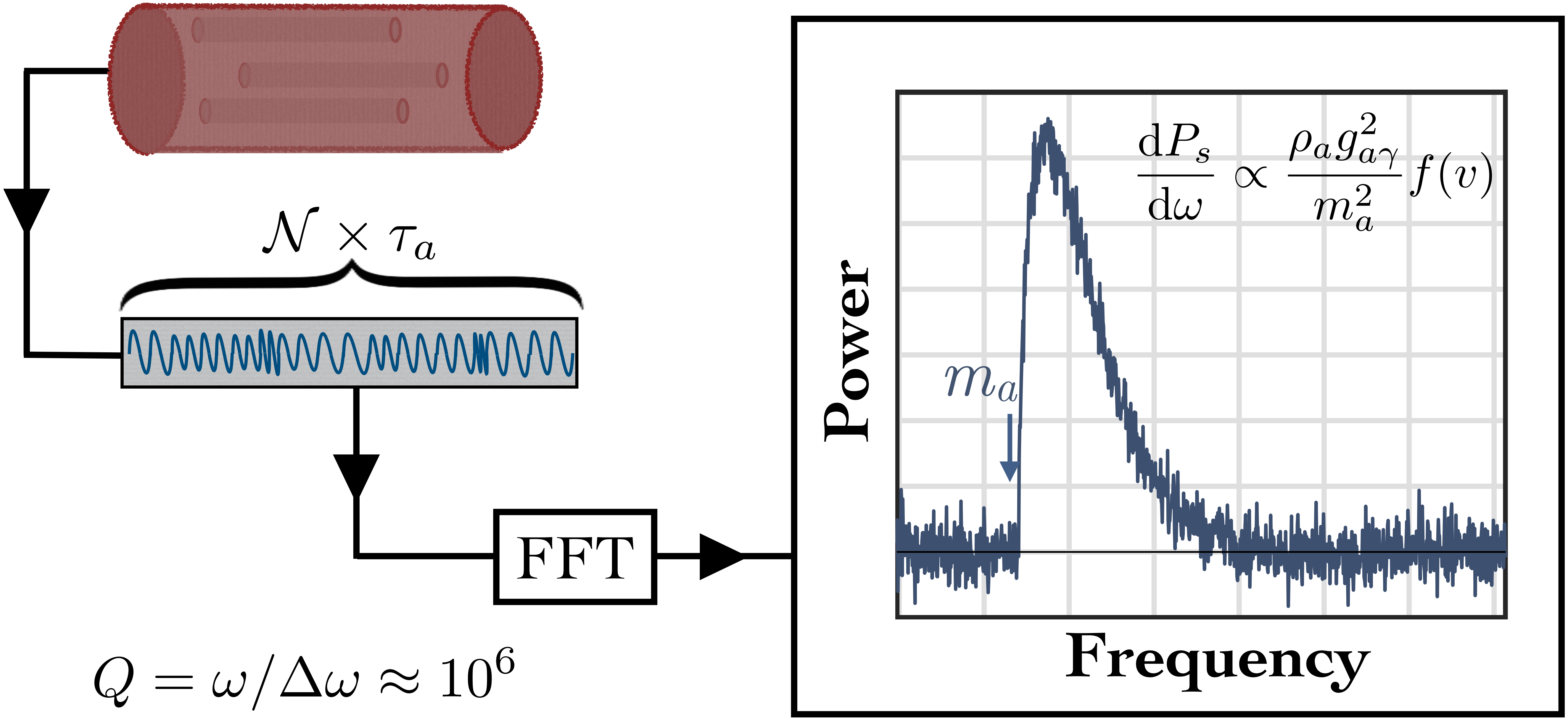
$$a(\mathbf{x},t) \approx \frac{\sqrt{2\rho_a}}{m_a}\cos\left(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha\right)$$

$$\omega = m_a\left(1 + \frac{v^2}{2}\right)$$

Ciaran O'Hare

Signal = a line at the axion mass

Power spectrum of EM time-series over many coherence times → $f(v)$



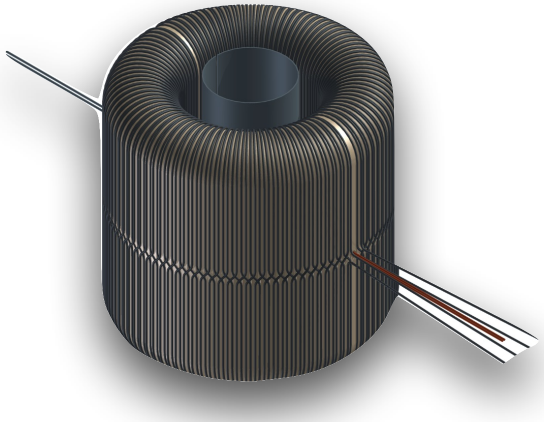
$$Q = \omega/\Delta\omega \approx 10^6$$

Haloscopes vs. axion Compton wavelength

$m_a < 0.1\ \mu\text{eV}$

Magnetic fields

→ ABRACADBRA



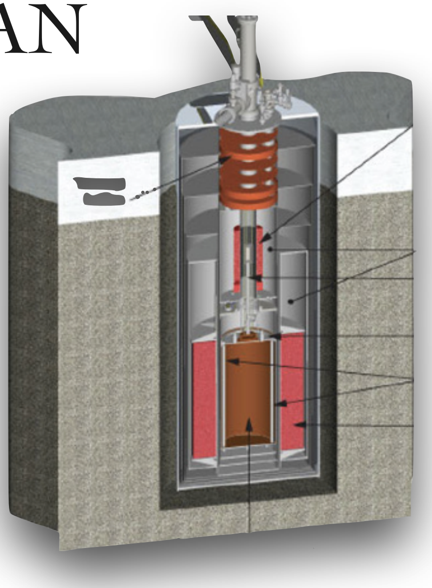
Toroidal magnet

→ axion acts as effective current, induces B-field in centre of toroidal magnet where there should be 0 field

$m_a \sim \mu\text{eV}$

Cavity modes

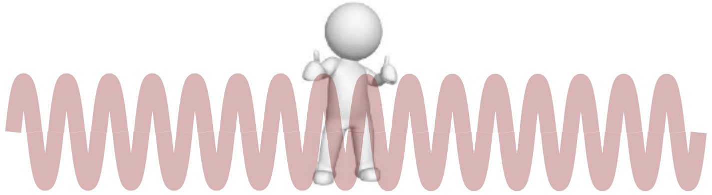
→ ADMX, CAPP, HAYSTAC, KLASH ORGAN



Tunable resonant cavity

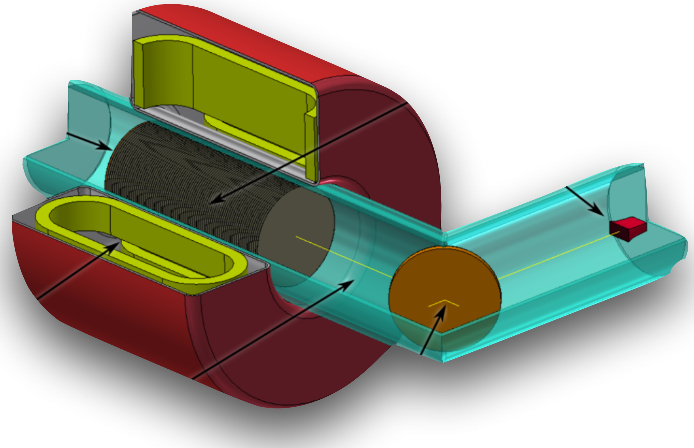
→ Detect enhanced EM-response when resonant mode is tuned precisely to axion mass

$m_a > 100\ \mu\text{eV}$



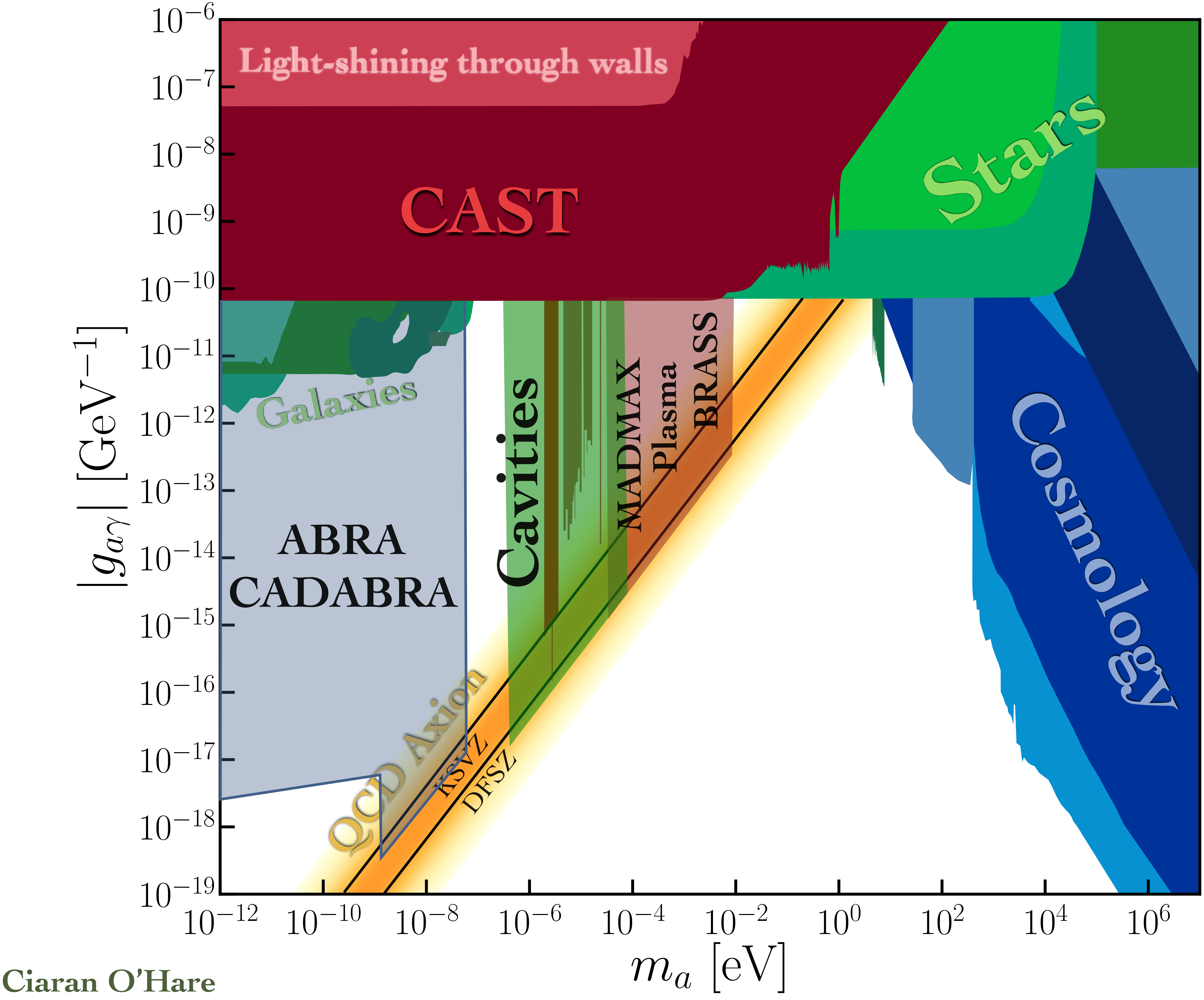
Electric fields

→ MADMAX, BRASS



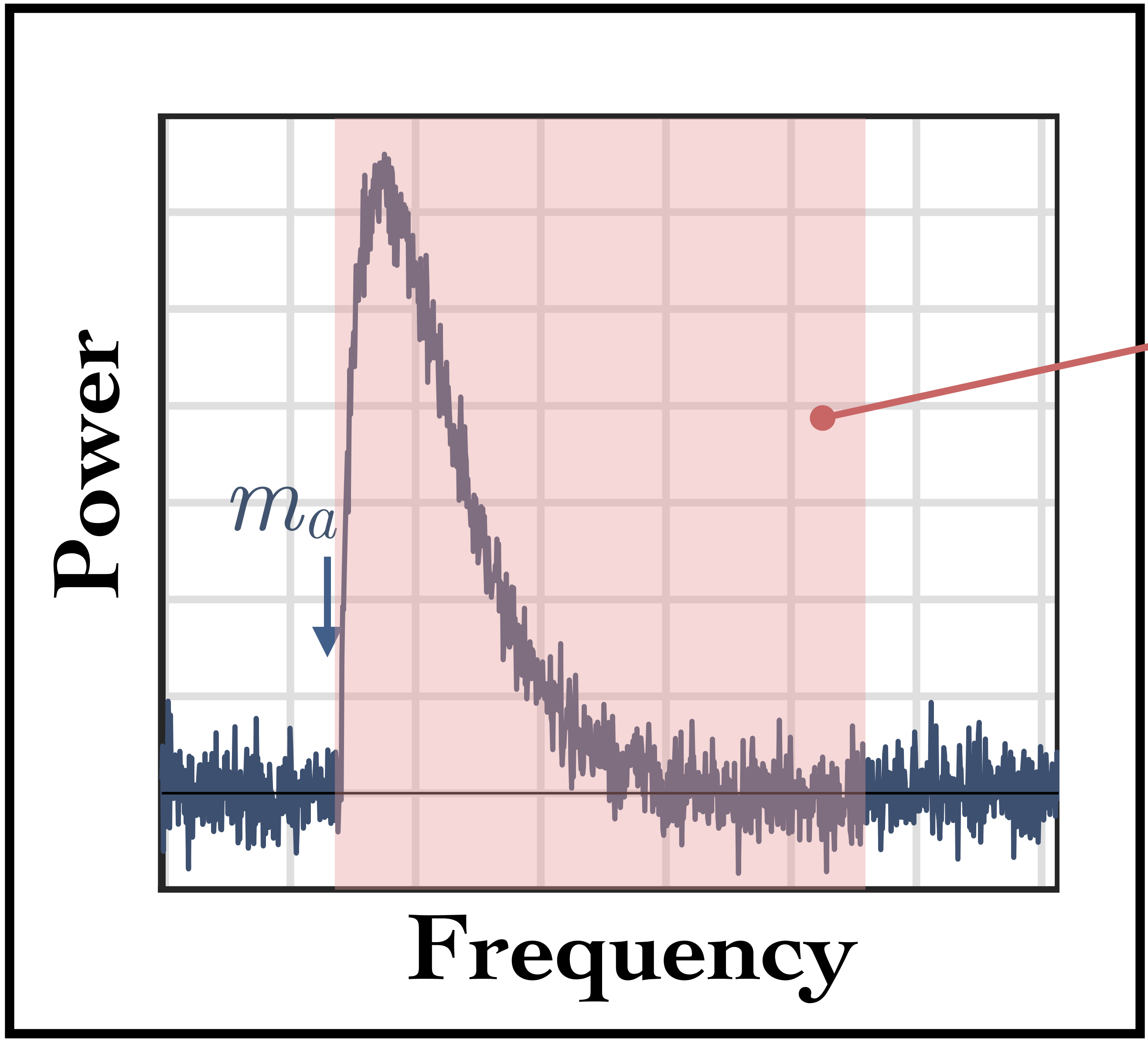
Dielectric disks

→ Radiation generated at magnetised dielectric interfaces, arrange layers of dielectrics to constructively interfere radiation


Light-shining through walls
CAST
Stars
Galaxies
Cavities
MADMAX
Plasma
BRASS
ABRA
CADABRA
Cosmology
QCD Axion
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Ciaran O'Hare

Haloscopes

Haloscopes try to measure some EM power from the axion signal, over some noise



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

We know roughly the linewidth, from *f(v)*

$$P_s \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2}$$ **x** experimental factors

→ Axion mass given by frequency, so total power lets us measure the coupling

Haloscopes

Except, we have this pesky degeneracy faced by almost all direct searches for DM

$$P_s \propto \rho \cdot g_{a\gamma}^2 \cdots$$

Degeneracy between local density of DM particle (astrophysics) & DM-SM coupling (particle physics)

For the QCD axion this degeneracy is important because we have benchmarks we wish to reach

$$P_s \propto \rho \cdot g_{a\gamma}^2$$

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

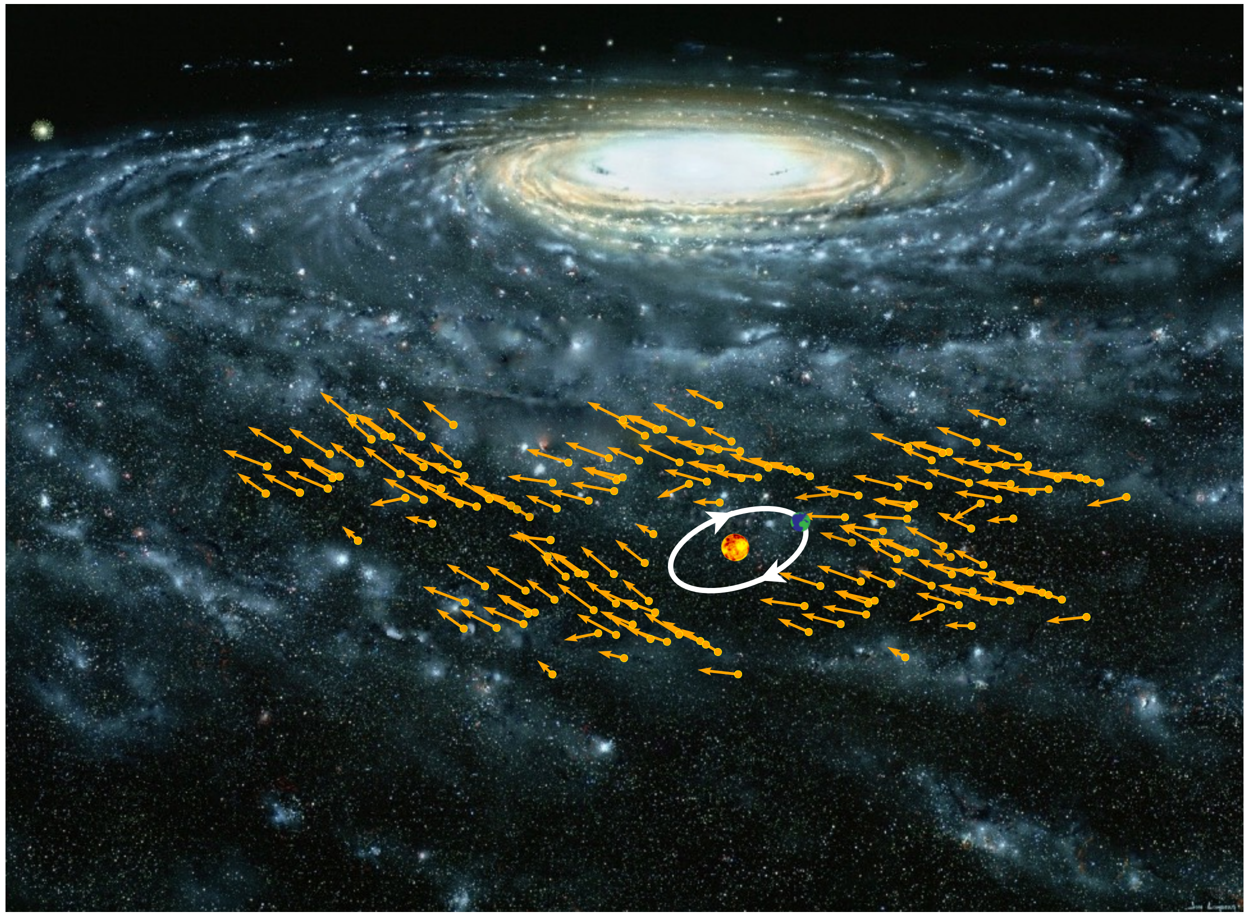
KSVZ: $C_{a\gamma} = -1.92$
DFSZ: $C_{a\gamma} = 0.75$

But we can infer the local **density** with astronomy

$$P_s \propto \boxed{\rho \cdot} \, g_{a\gamma}^2$$

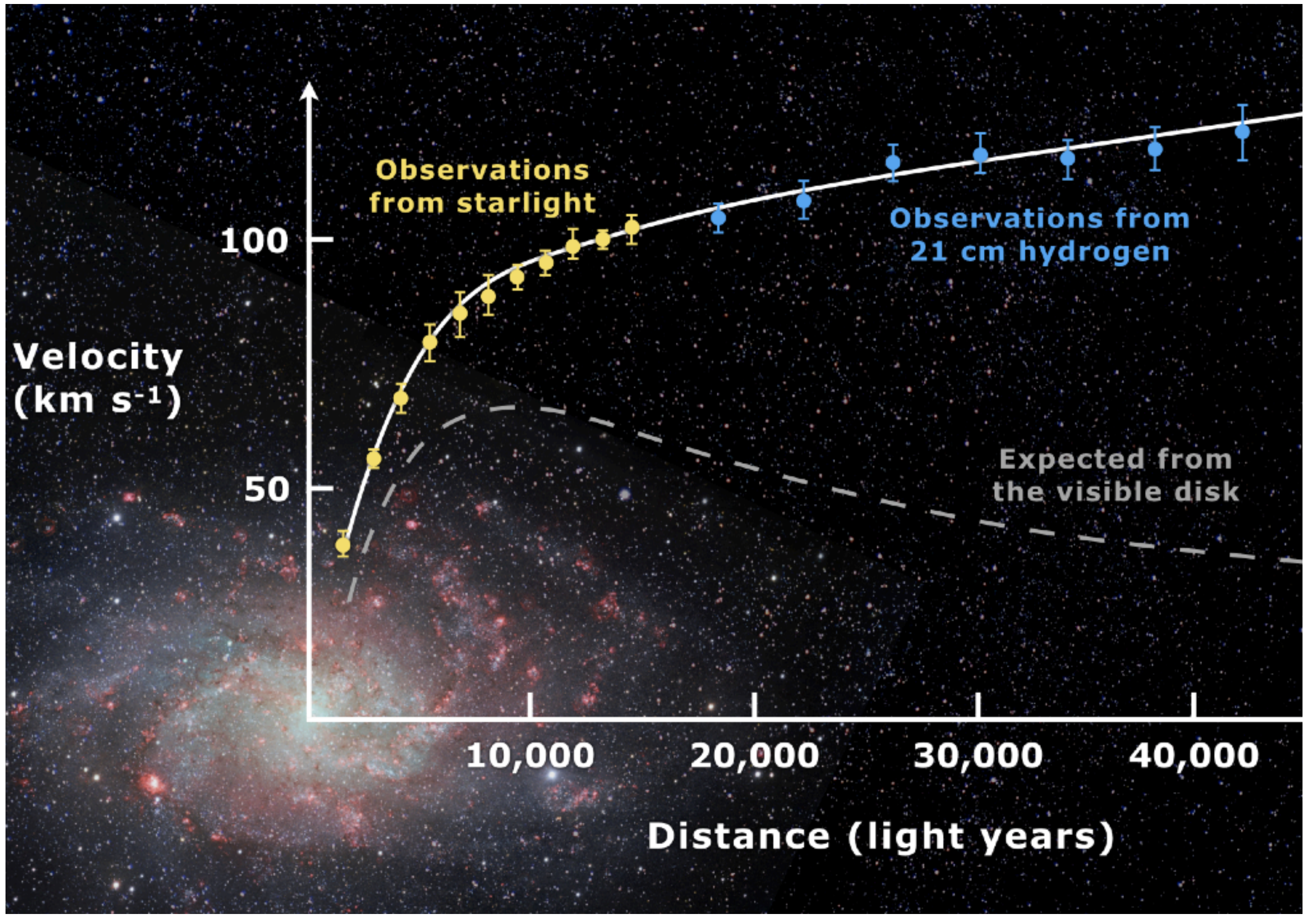
Local measure

(kinematics of nearby stars)



Global measure

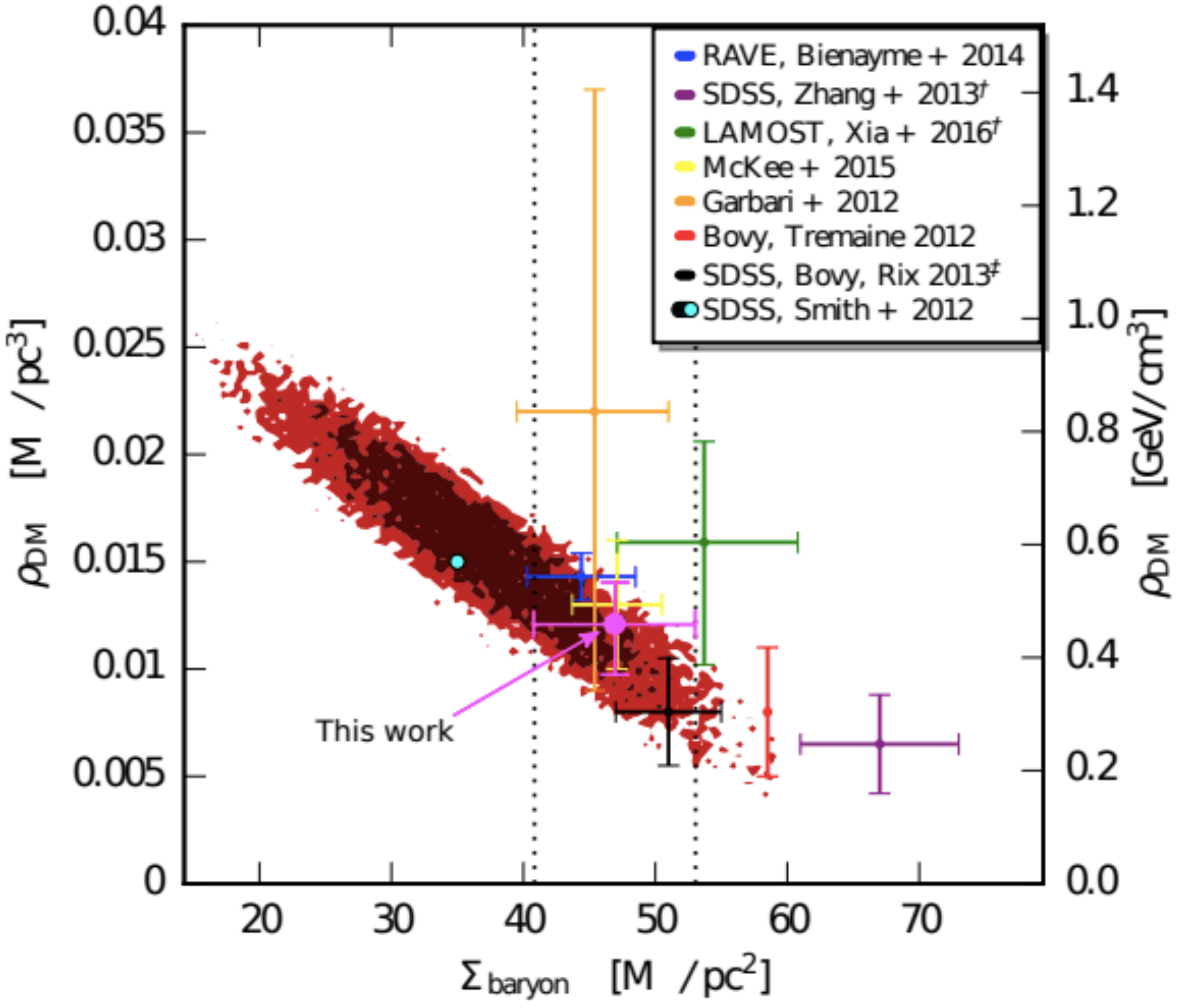
(build mass model for MW)



Local measures

e.g. Sivertsson+ [1708.07836]

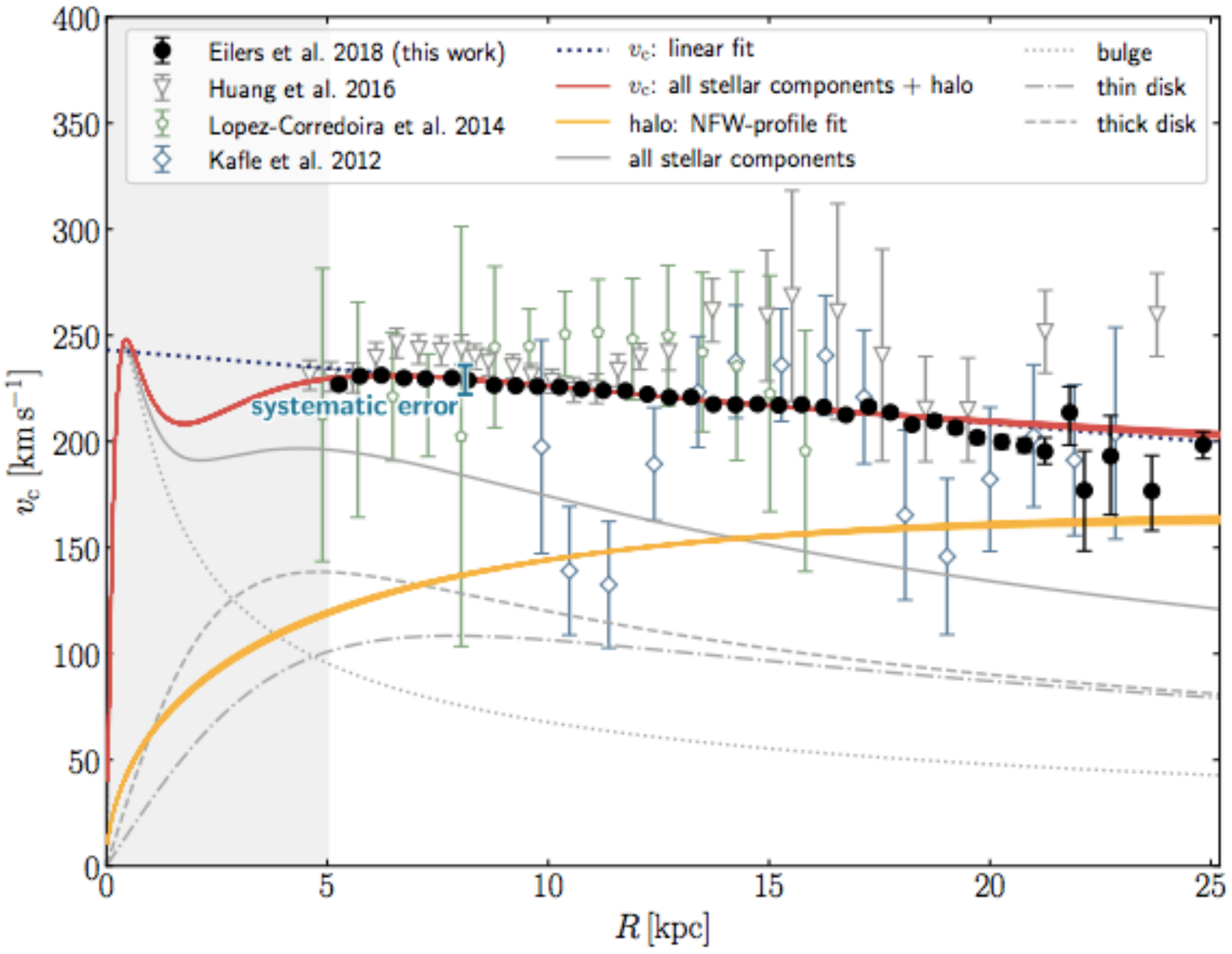
0.46 ± ~0.1 GeV/cm^3



Global measures

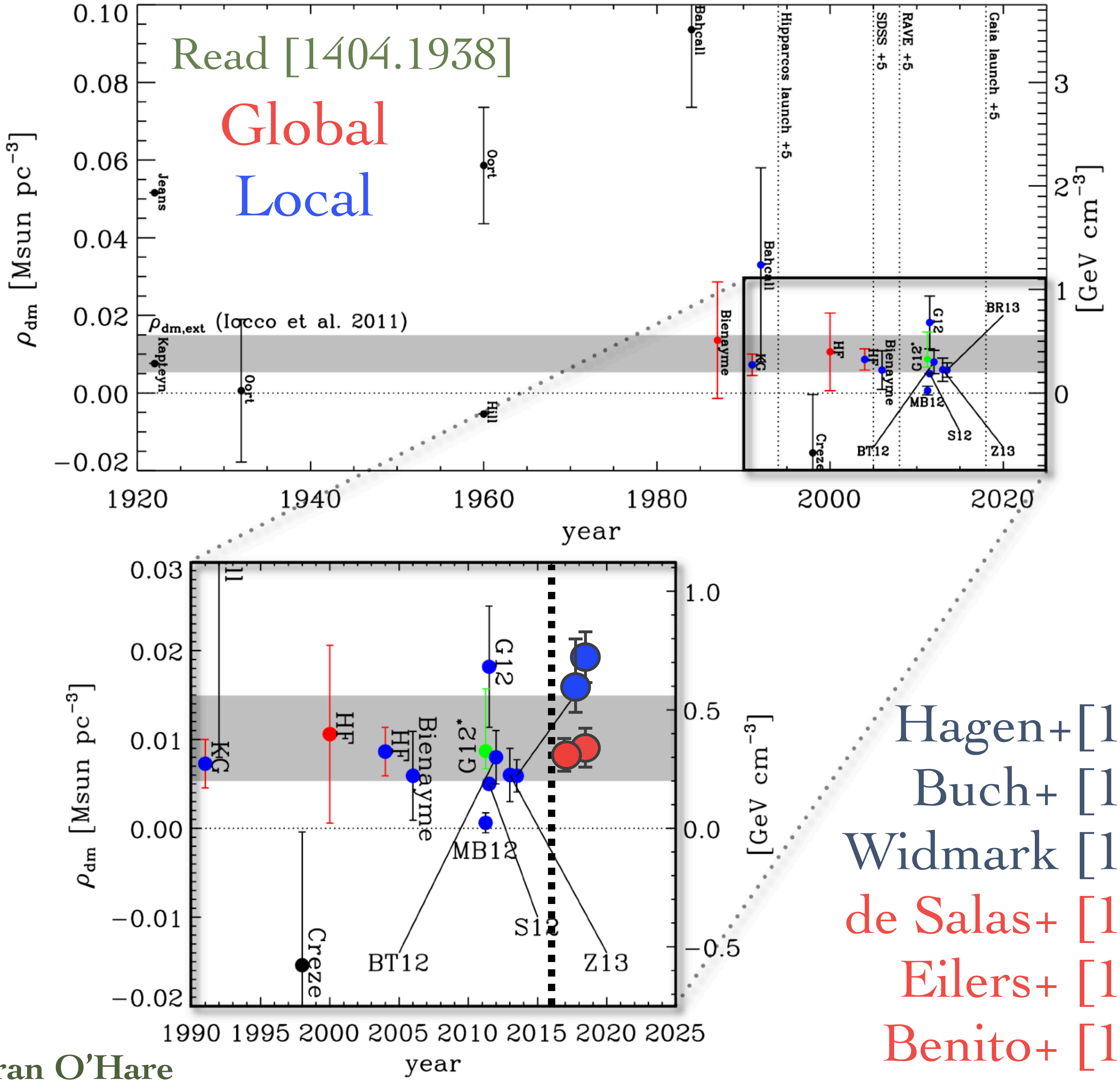
e.g. Eilers+ [1810.09466]

0.3 ± 0.03 GeV/cm^3



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

  → Gaia’s potential still not yet fully tapped



post-Gaia

Hagen+[1802.09291]

Buch+ [1808.05603]

Widmark [1811.07911]

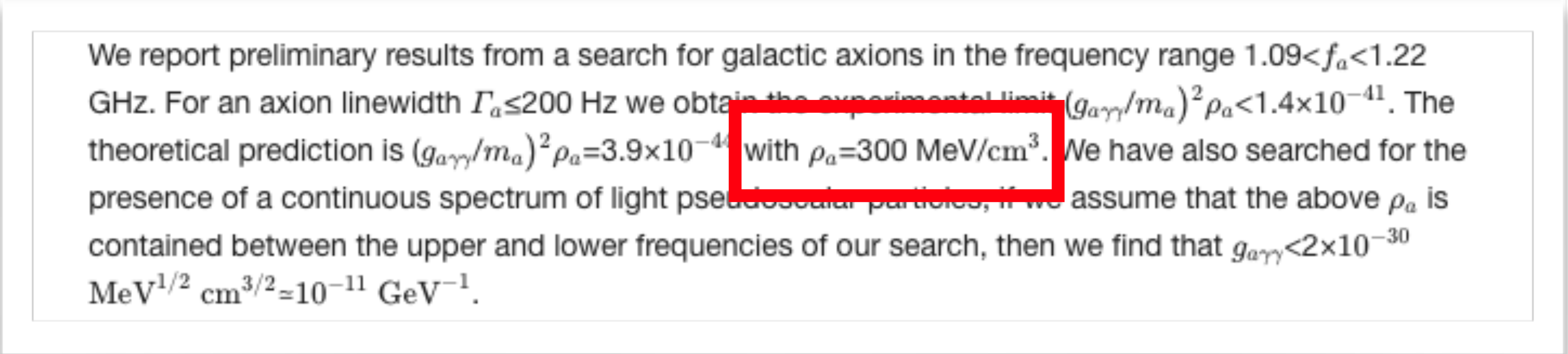
de Salas+ [1906.06133]

Eilers+ [1810.09466]

Benito+ [1901.02460]

History of “determinations” of the local DM density by haloscope experimental 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 ρ_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 ρ_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$^{3/2}\simeq10^{-11}$ GeV^{-1}.

2009
ADMX
0.45 GeV/cm^3

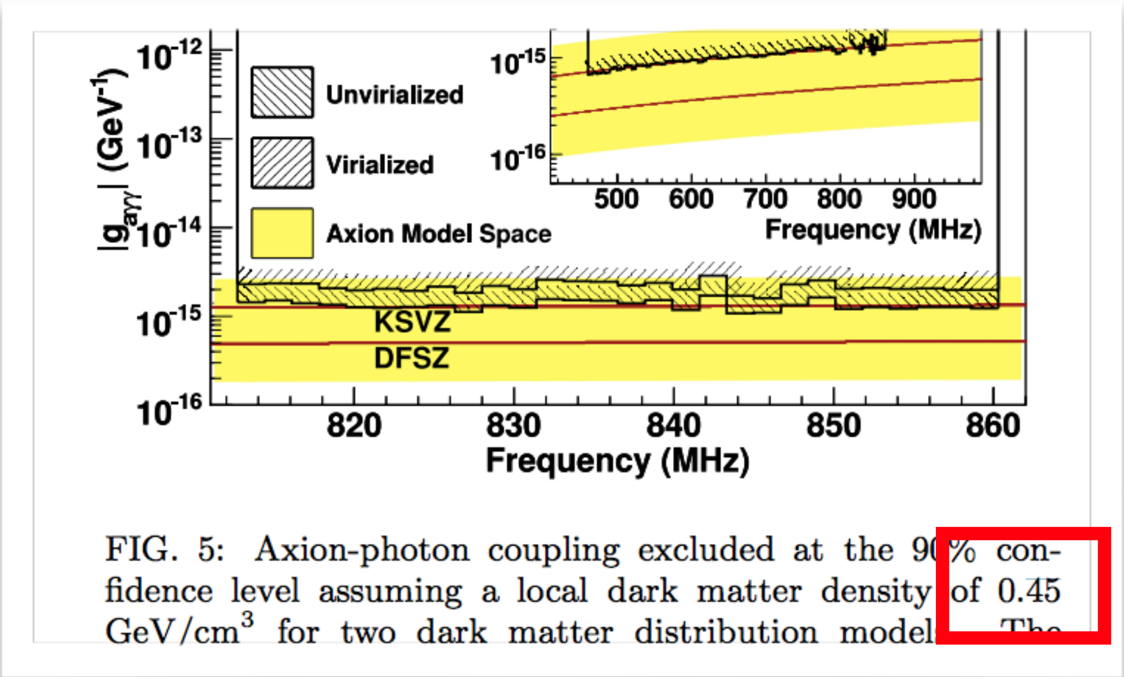
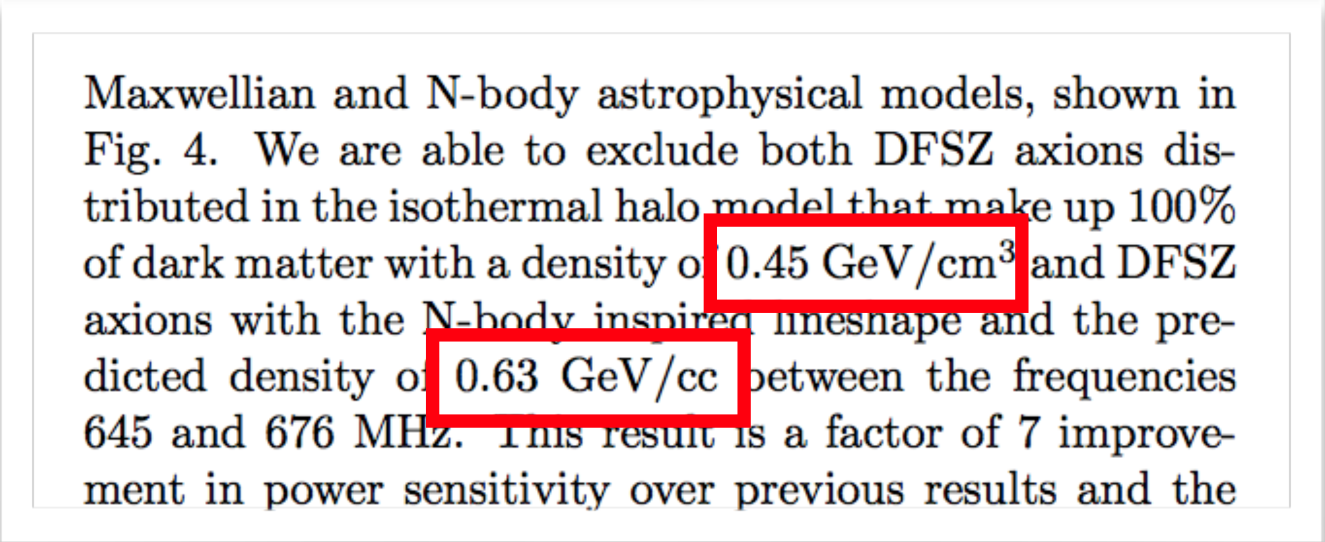


FIG. 5: Axion-photon coupling excluded at the 90% confidence level assuming a local dark matter density of 0.45 GeV/cm^3 for two dark matter distribution models. The

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

But for axions this density could also be more complicated than it seems

$$P_s \propto \rho_a \times g_{a\gamma}^2$$

$$\rho_a \propto f_{\text{axions}} \cdot \rho_{\text{dm}}\left(\mathbf{x}_\odot\right)$$

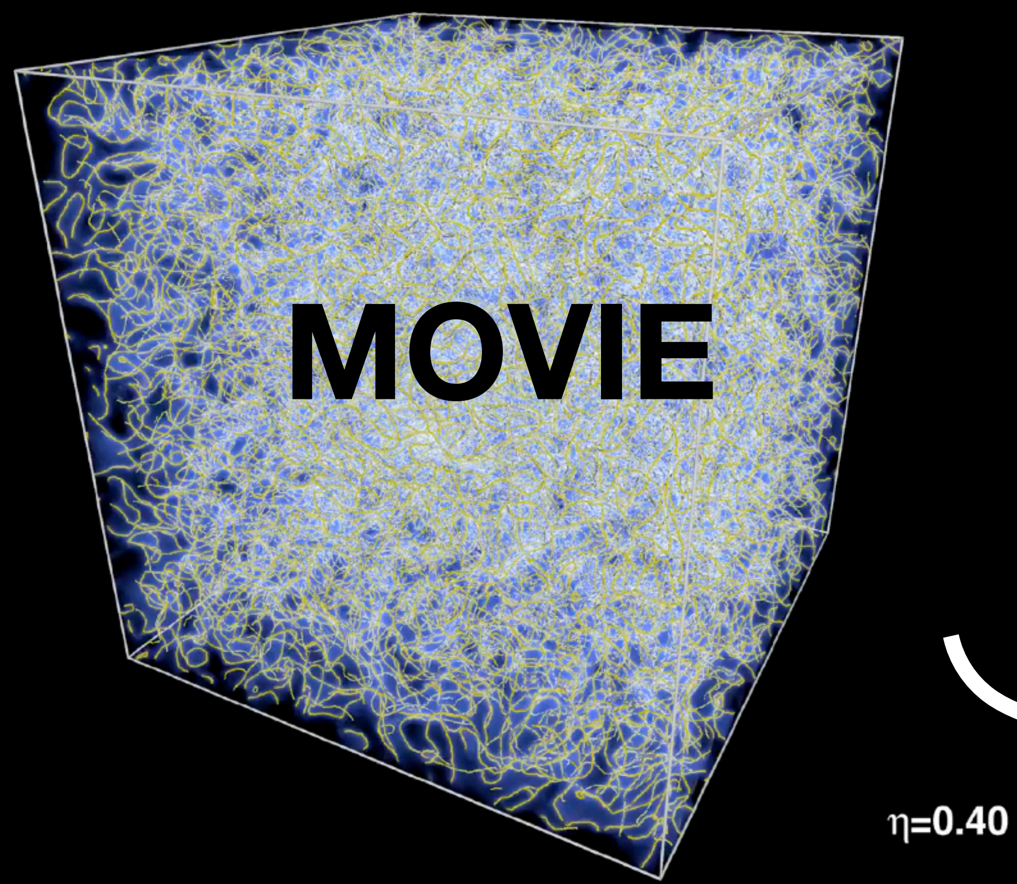
$$\rho_a \propto f_{\text{axions}} \cdot \left(1 - f_{\text{clump}}\right) \cdot \rho_{\text{dm}}\left(\mathbf{x}_\odot\right)$$

Fraction of axions
not in clumps

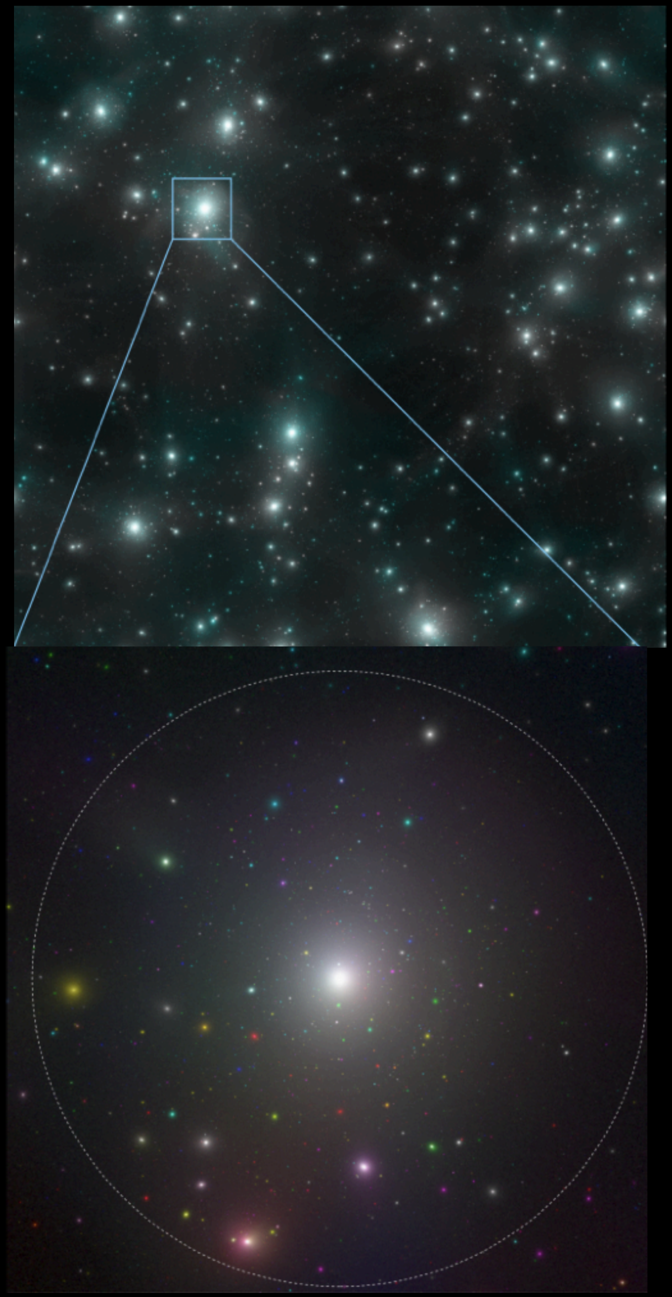
$f_{\rm clump} \neq 0$ is **expected** for post-inflationary axions

Gorghetto, Hardy, Villadoro [1806.04677]

Buschmann, Foster, Safdi [1906.00967]



→ bound clumps of axions with asteroid masses ~ 10^{-12} $M_\odot$

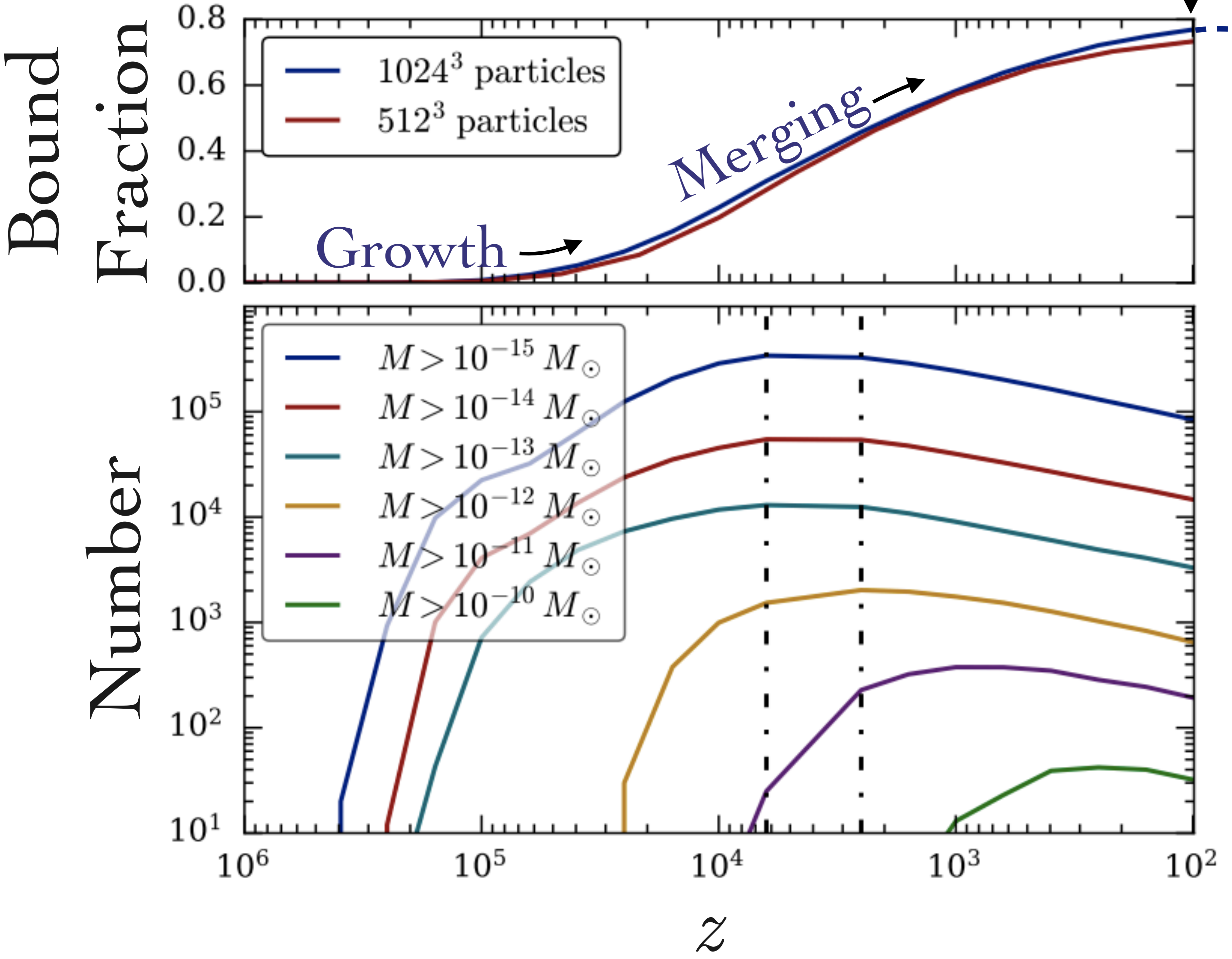


Eggemeier+ [1911.09417]

Galaxies made of axion miniclusters+diffuse axions

Eggemeier+ [1911.09417]

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

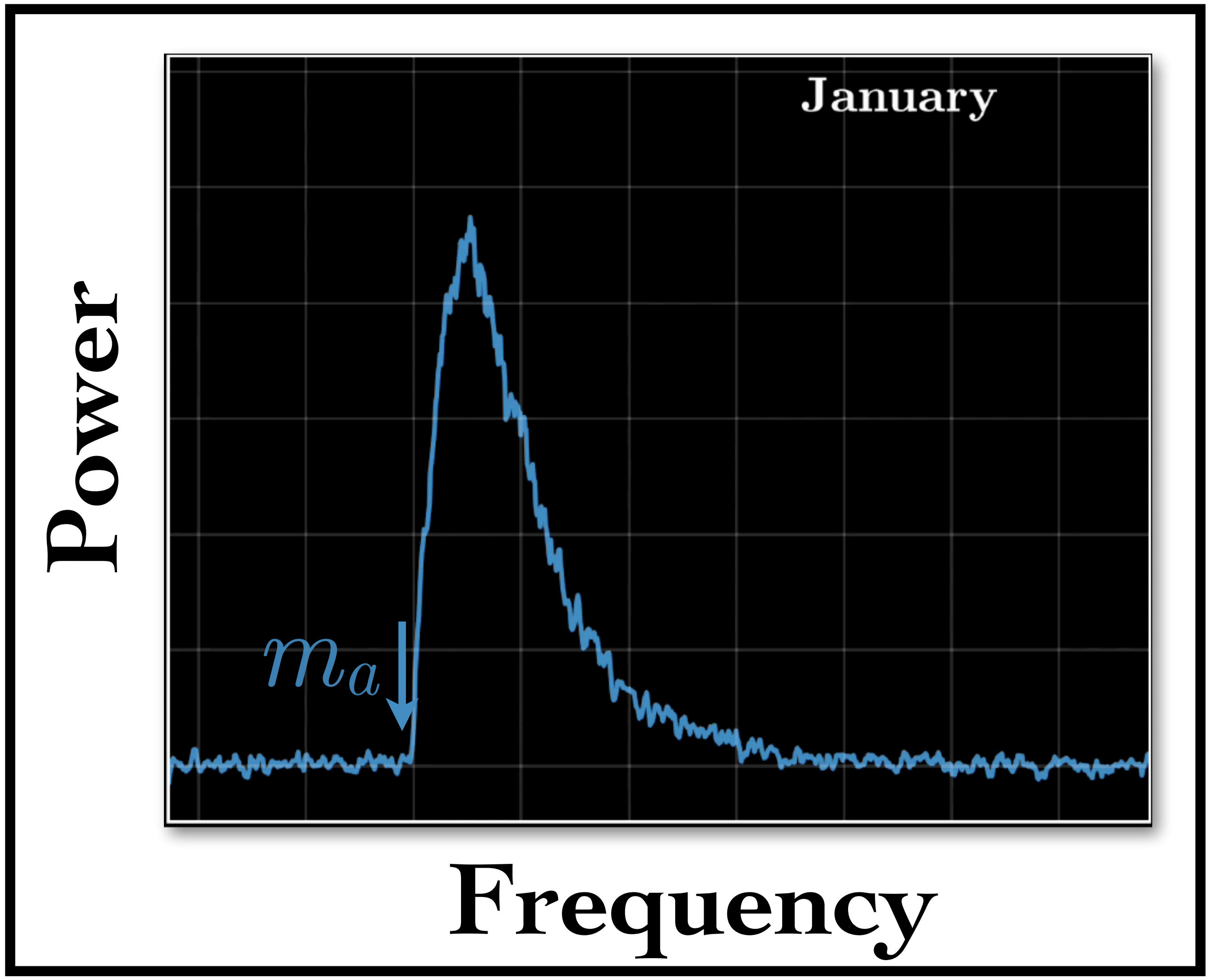


Tidal disruption?

diffuse axions
+miniclusters
+ministreams ~ 1%?

Tinyakov+ [1512.02884]
Dokuchaev+ [1710.09586]

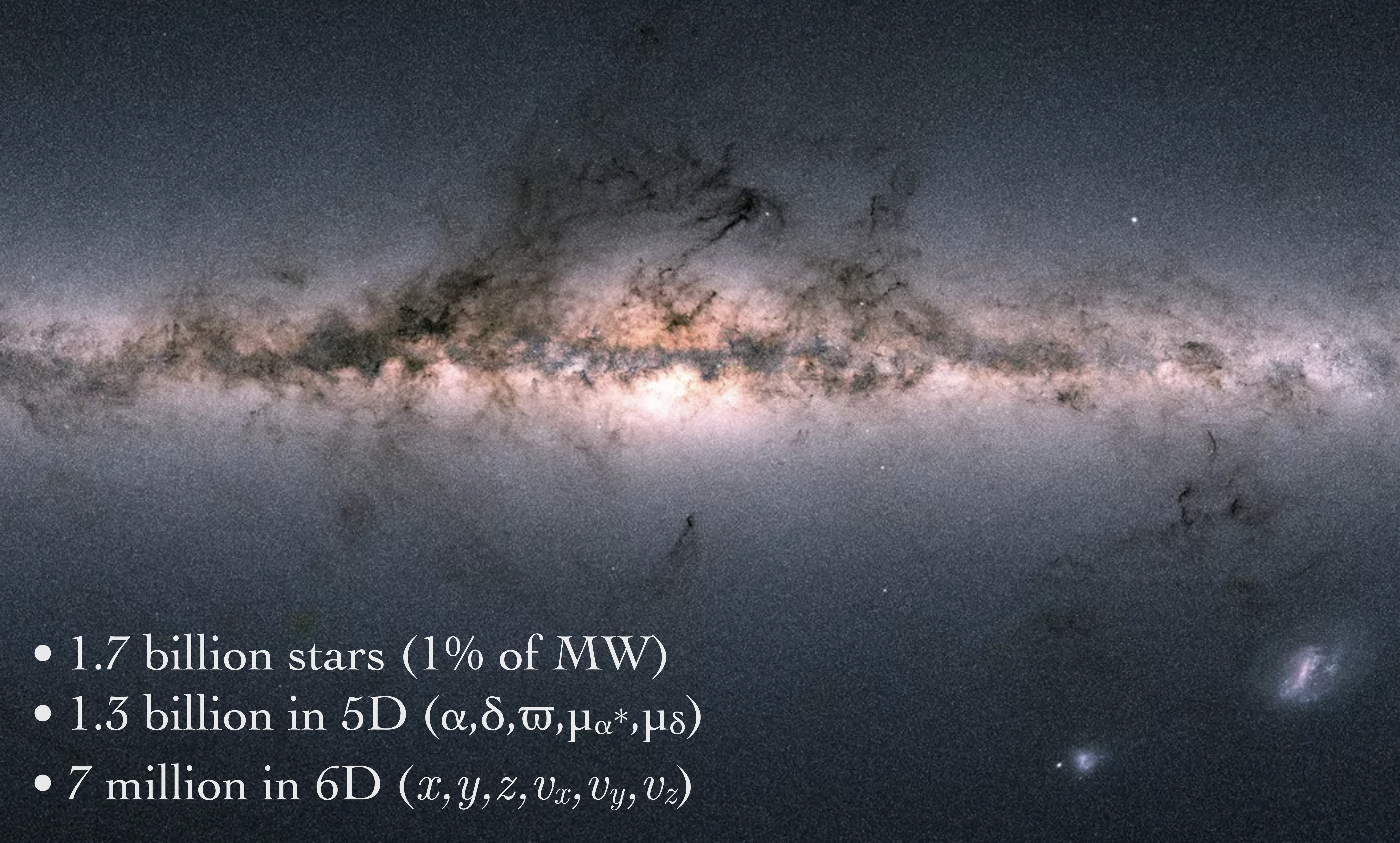
What do we expect $f(v)$ to look like?



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

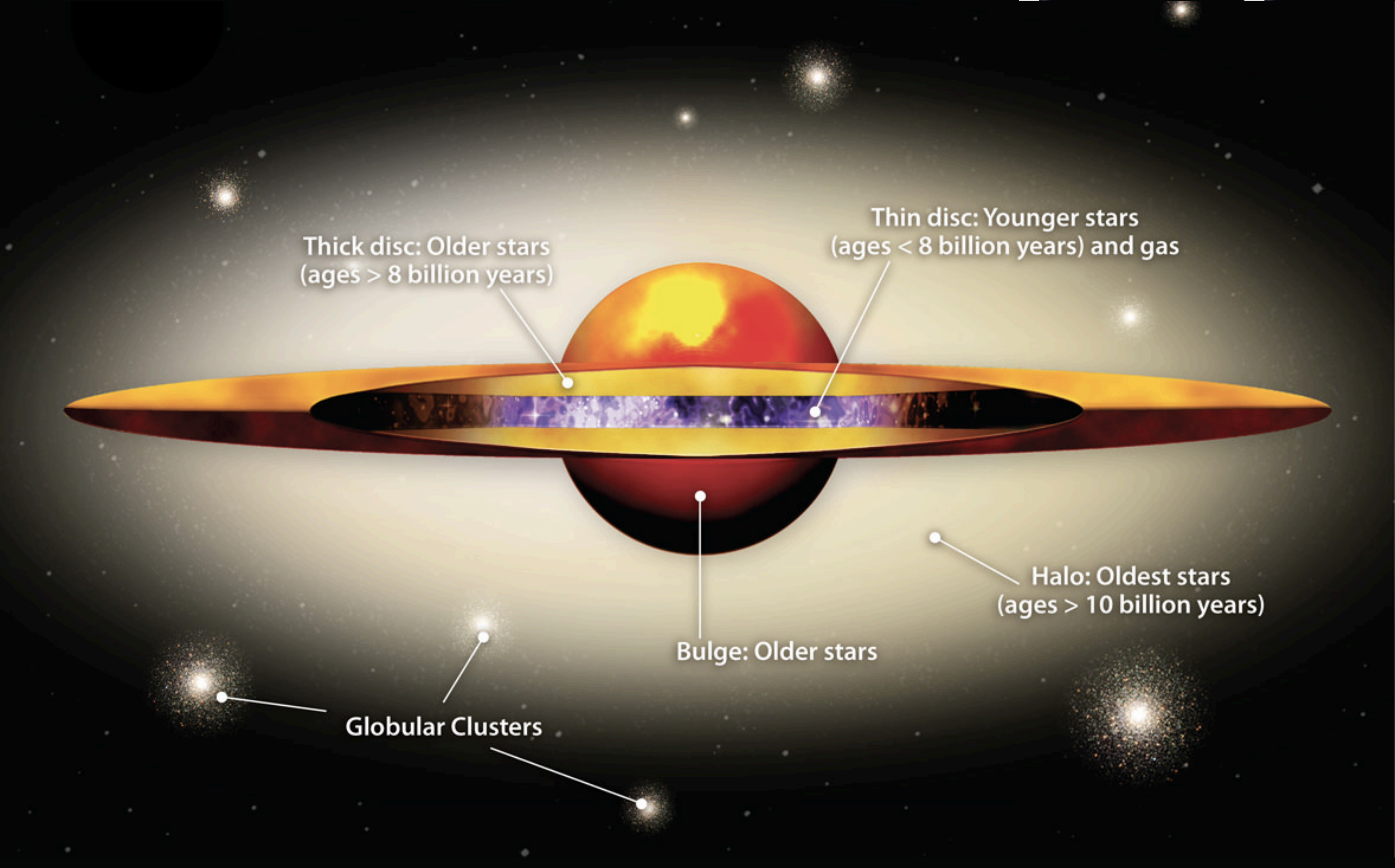
$$f(v) \sim v^2 \exp\left(-\frac{(\mathbf{v}+\mathbf{v}_{\rm lab}(t))^2}{2\sigma_v^2}\right)$$

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



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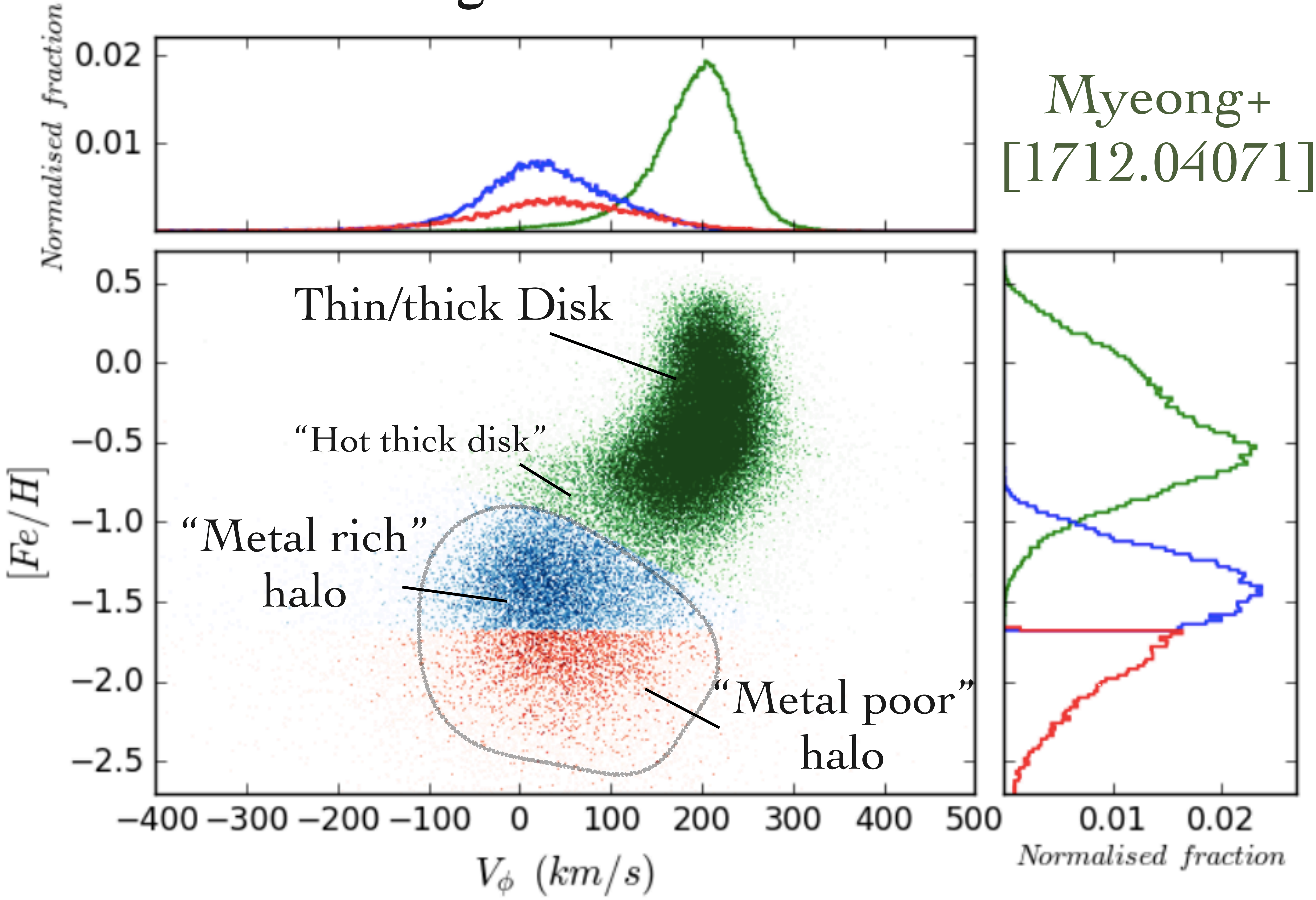
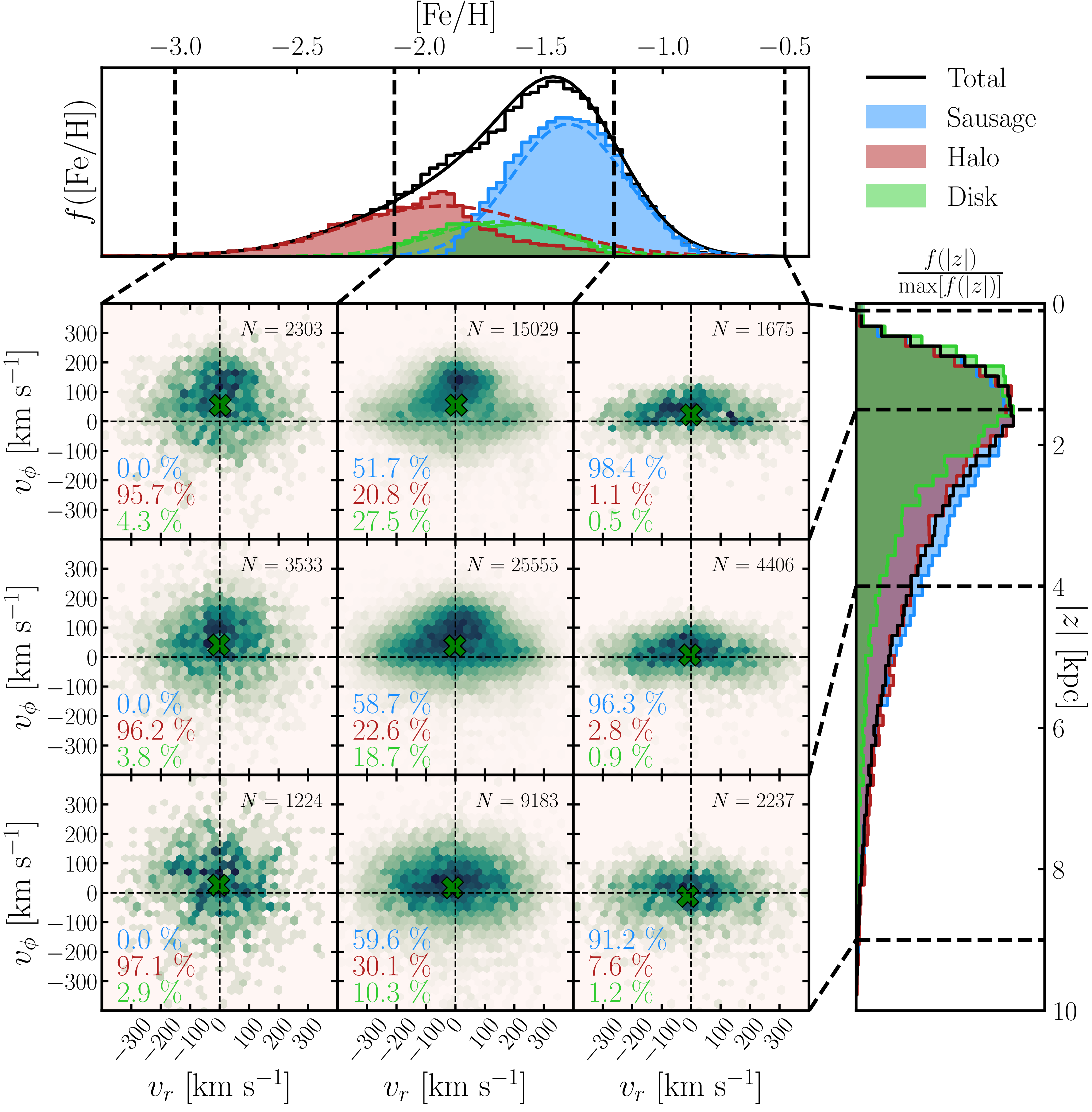
Extracting the stellar halo with Gaia



Myeong+ [1712.04071]

Metallicity →

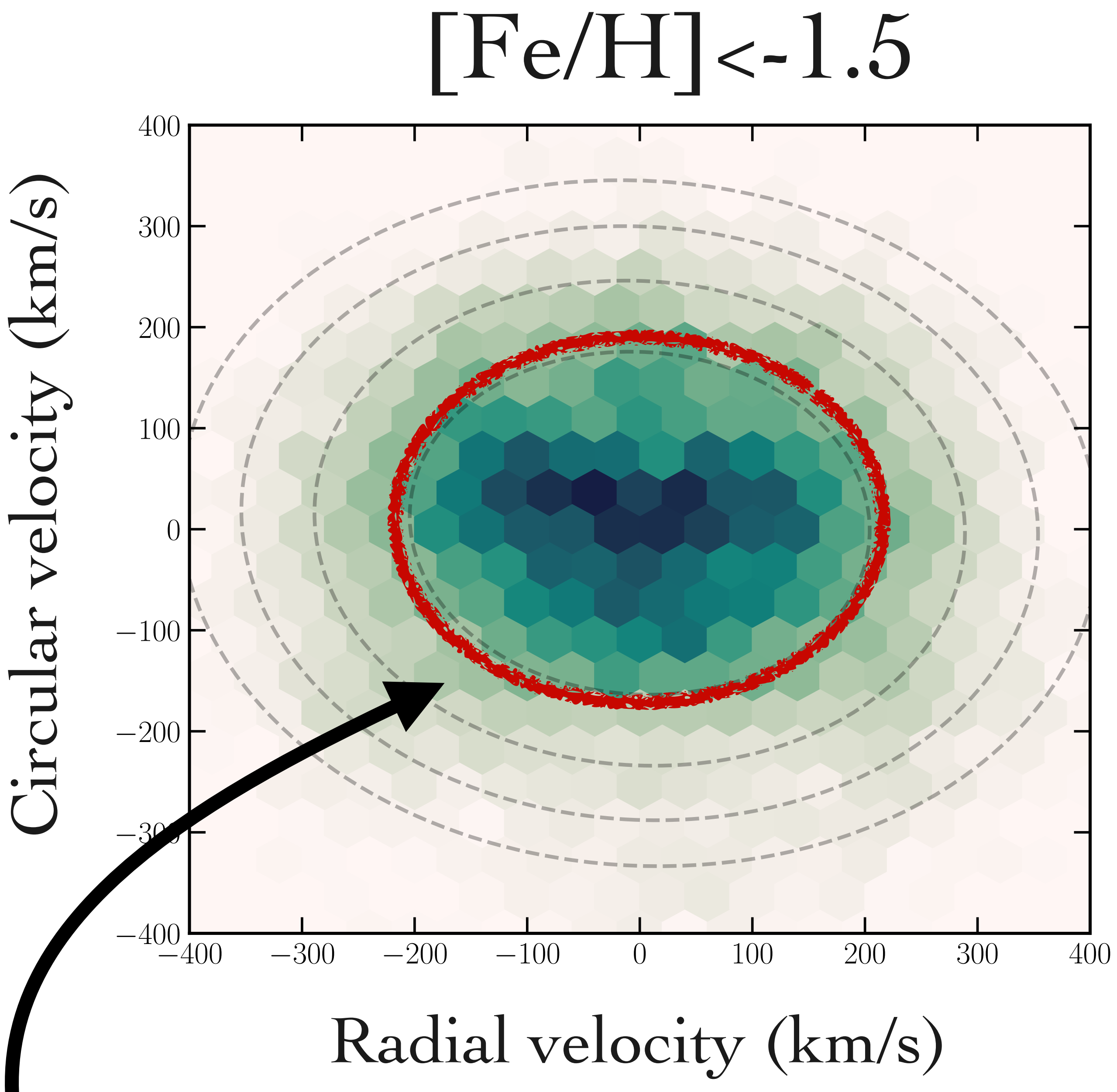
Sample of Gaia-SDSS main sequence stars < 10 kpc heliocentric distance

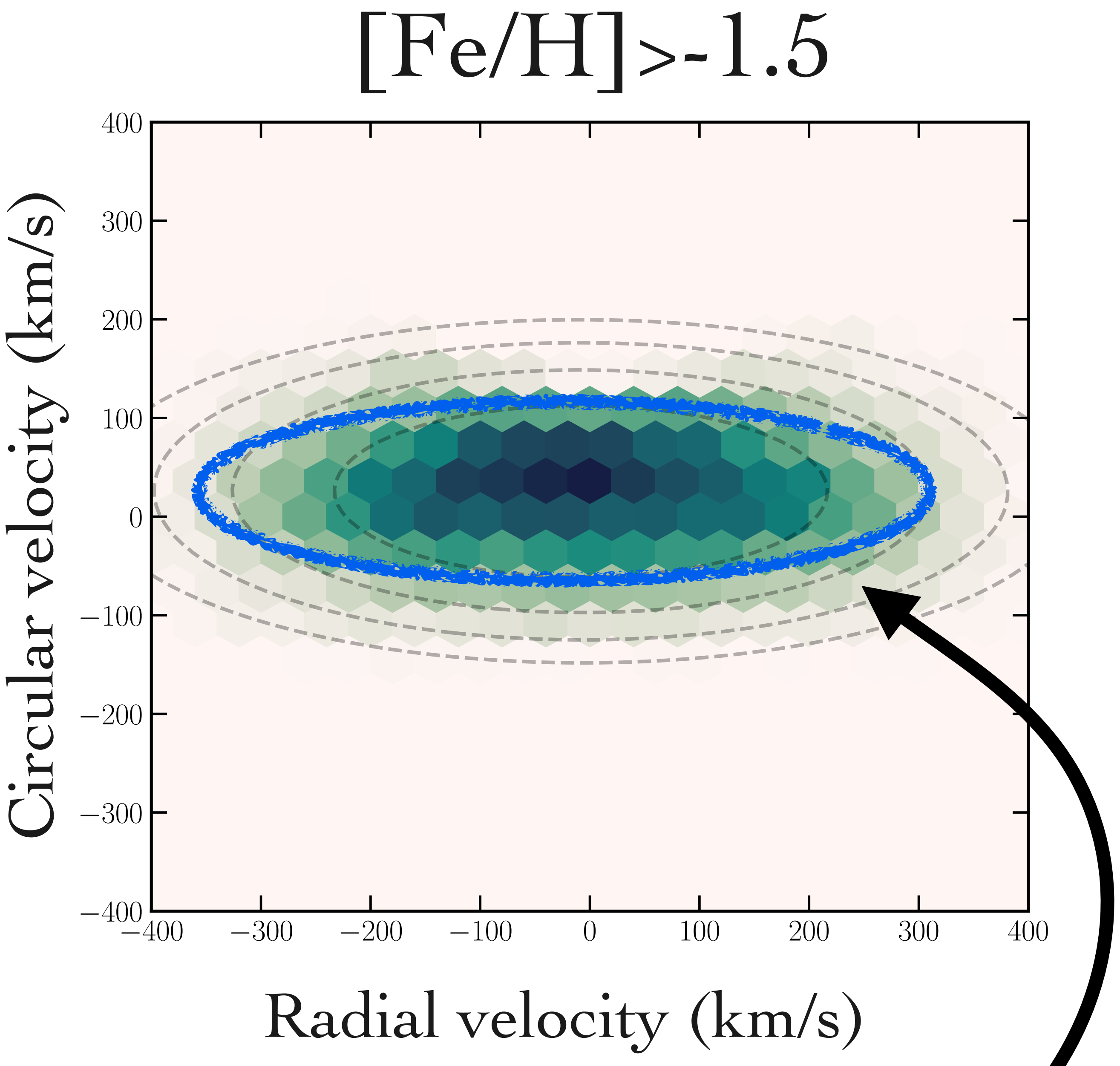


Height above disk ↓

Circular velocity (km/s)

Radial velocity (km/s)





“Metal-poor” halo

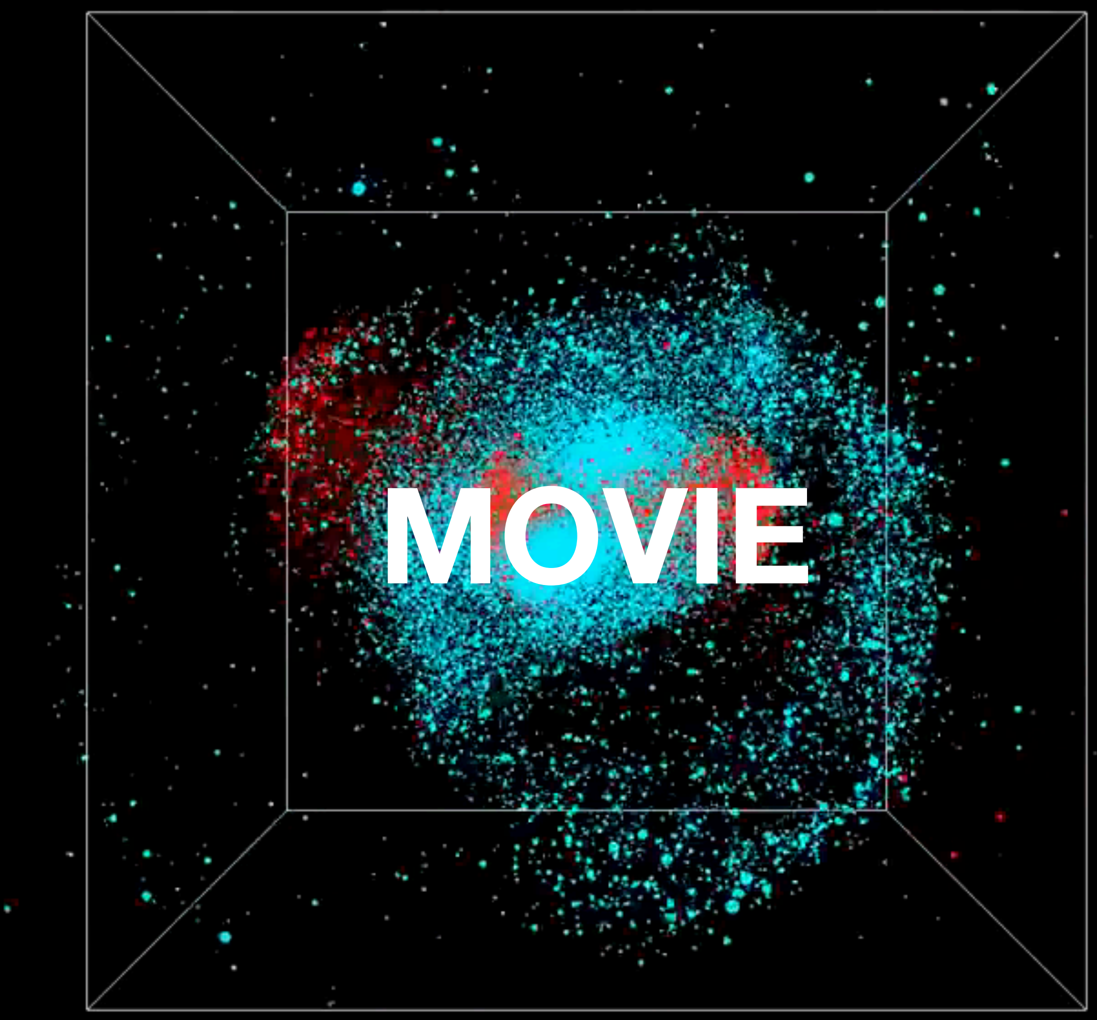
- Round velocity ellipsoid
- ~30% of main sequence halo sample
- More metal-poor on average

“Metal-rich” halo

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

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



Further evidence:

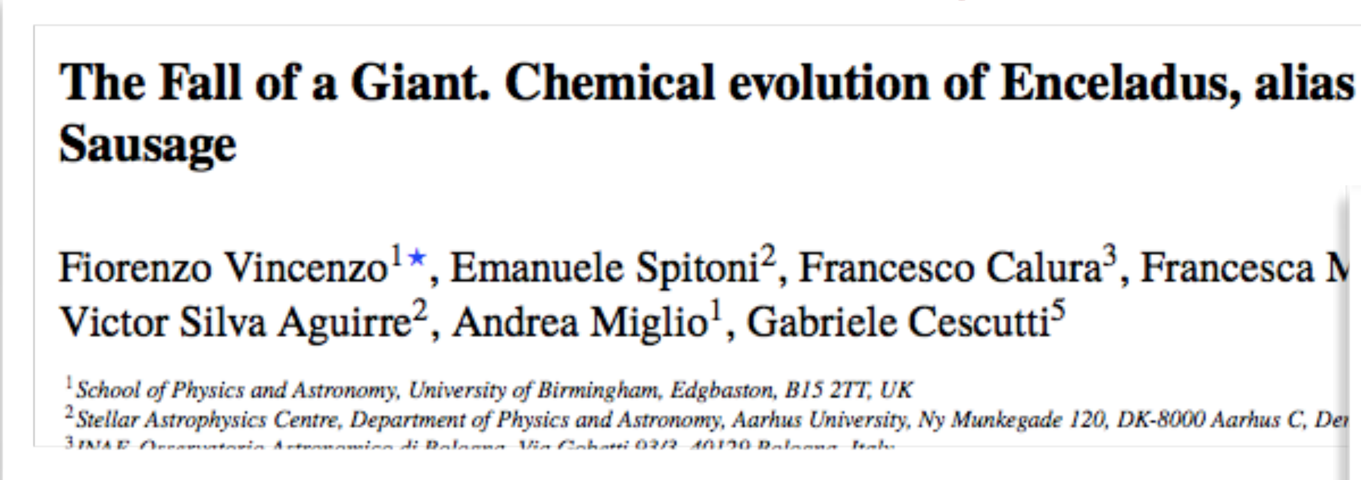
- Stellar density break at 20 kpc from pileup of stars at apocentre Deason+[1805.10288]
- Dynamical heating of thick disk stars into halo-like orbits Belokurov+ [1909.04679]

Helmi et al. 1806.06038

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

Gaia-Sausage?

Gaia-Enceladus?



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

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

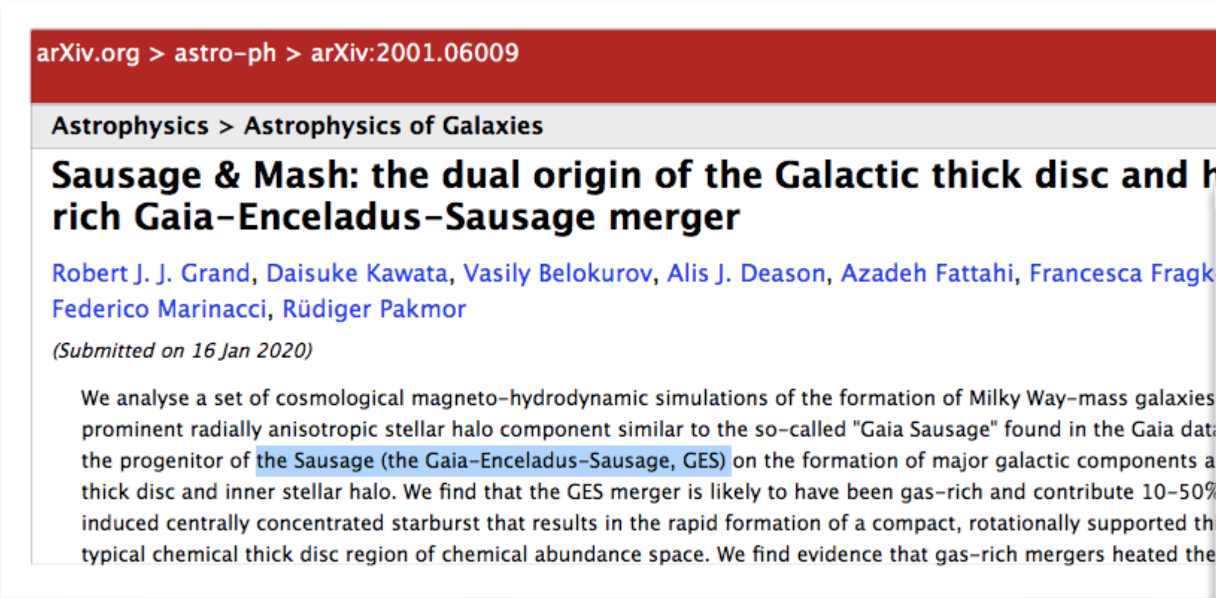
[1] *School of Physics and Astronomy, University of Birmingham, Edgbaston, B15 2TT, UK*
[2] *Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, De*

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,

Gaia radially anisotropic substructure?



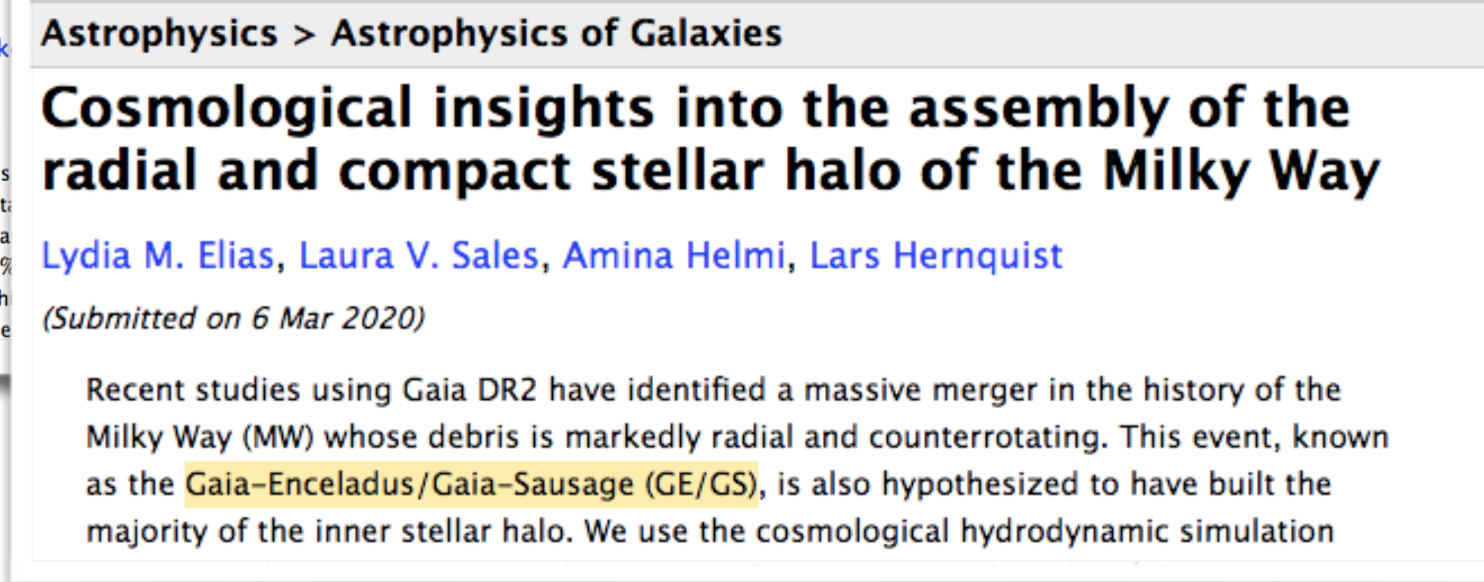
Astrophysics > Astrophysics of Galaxies

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 Fragk
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
prominent radially anisotropic stellar halo component similar to the so-called "Gaia Sausage" found in the Gaia dat
the progenitor of the Sausage (the Gaia-Enceladus-Sausage, GES) on the formation of major galactic components a
thick disc and inner stellar halo. We find that the GES merger is likely to have been gas-rich and contribute 10-50%
induced centrally concentrated starburst that results in the rapid formation of a compact, rotationally supported th
typical chemical thick disc region of chemical abundance space. We find evidence that gas-rich mergers heated the



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

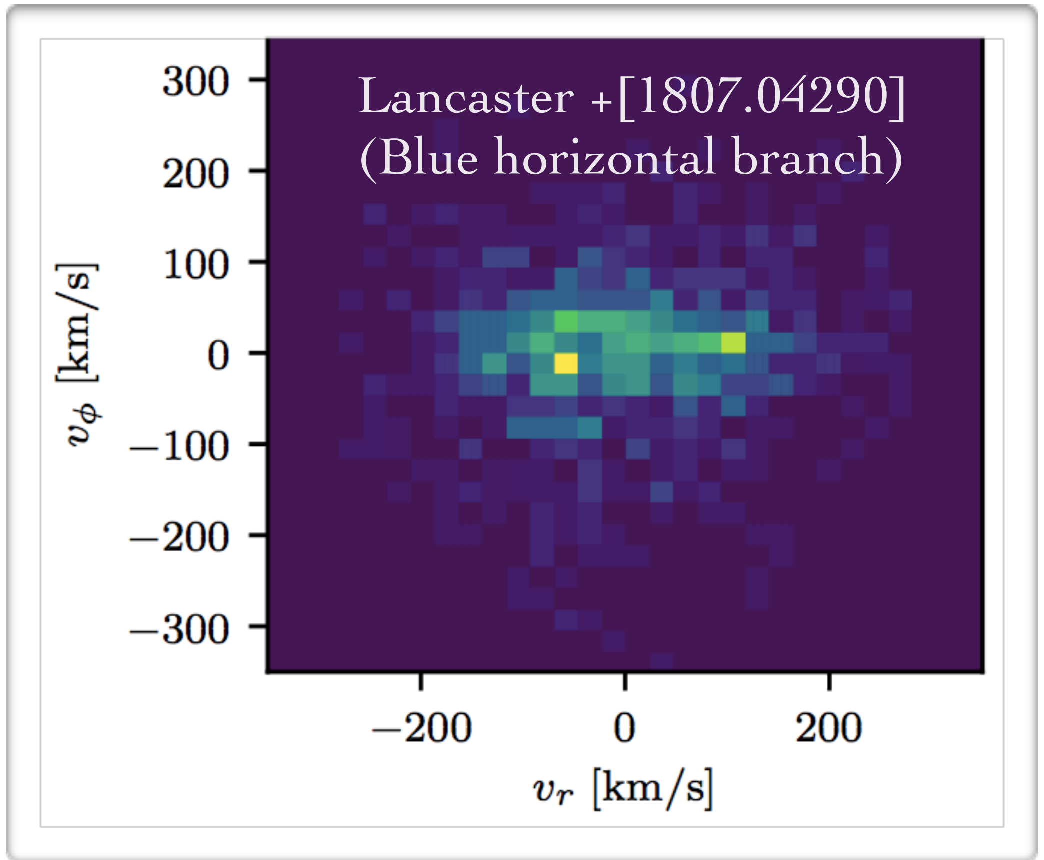
Gaia-Enceladus/Sausage!?

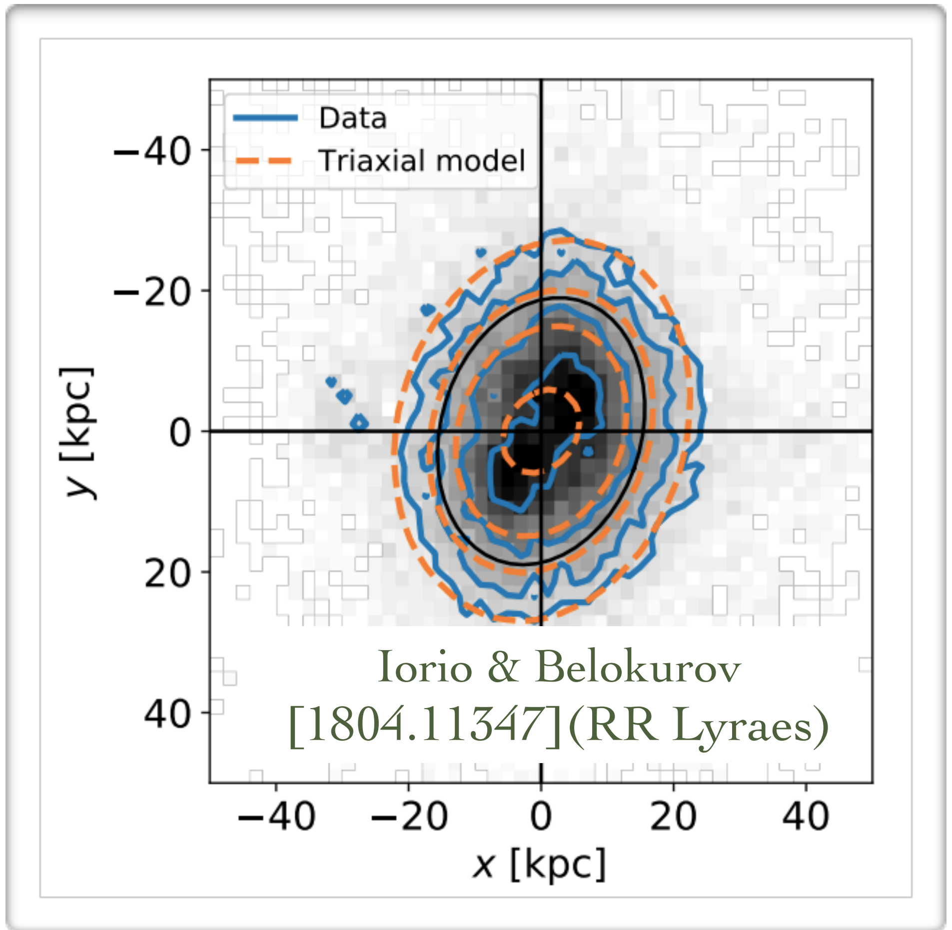
Gaia-Sausage + Gaia-Enceladus

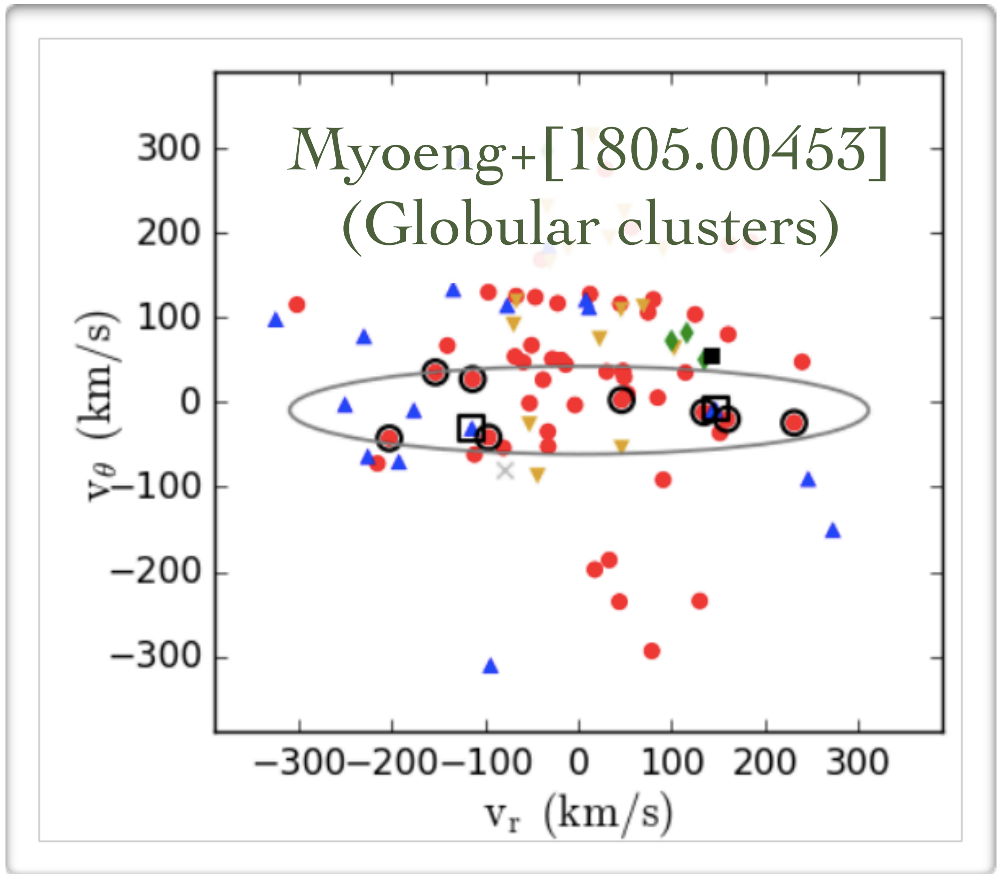
=

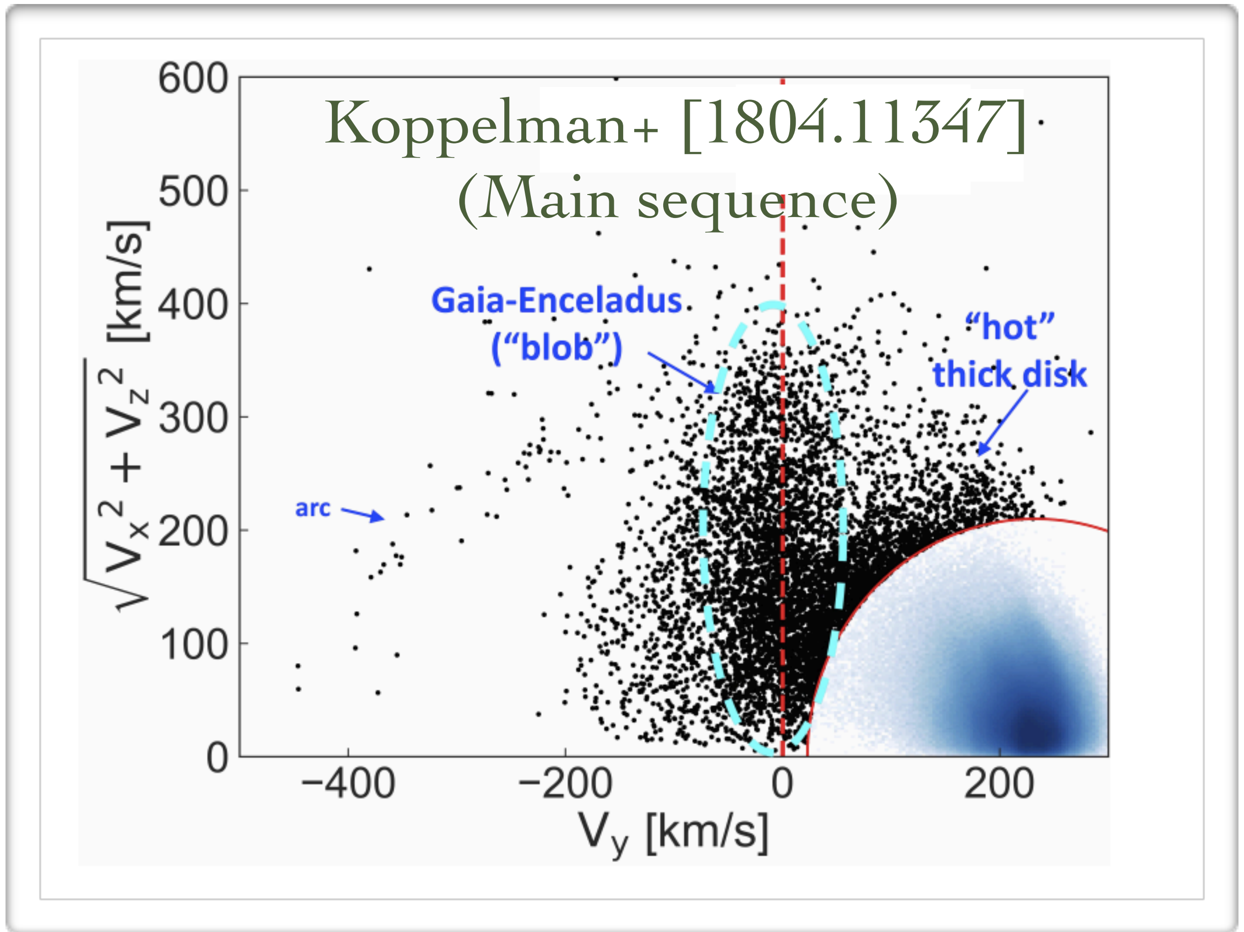
Gaia Enchilada

More on the sausage…


Lancaster +[1807.04290]
(Blue horizontal branch)


Iorio & Belokurov
[1804.11347](RR Lyraes)


Myoeng+[1805.00453]
(Globular clusters)


Koppelman+ [1804.11347]
(Main sequence)

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 in other pops
- **Necib+ [1810.12301]:** ~40±25% of local DM accreted from luminous mergers is in Sausage-like form (FIRE)

However:

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

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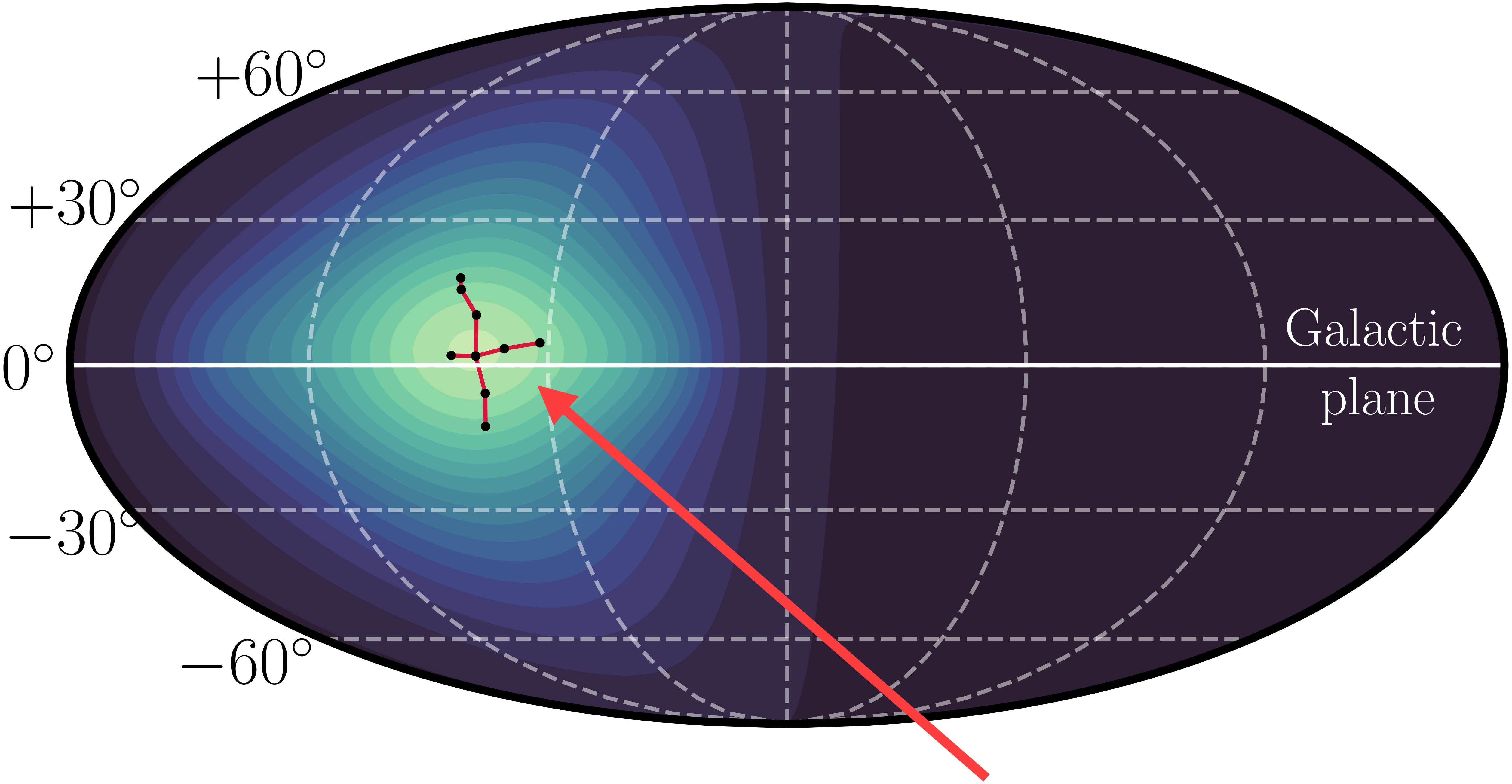
*[see '17-'20 papers by Helmi+, Myeong+, Koppelman+, Belokurov+, Matsuno+… and many others]

What kind of sausage is the Gaiawurst?

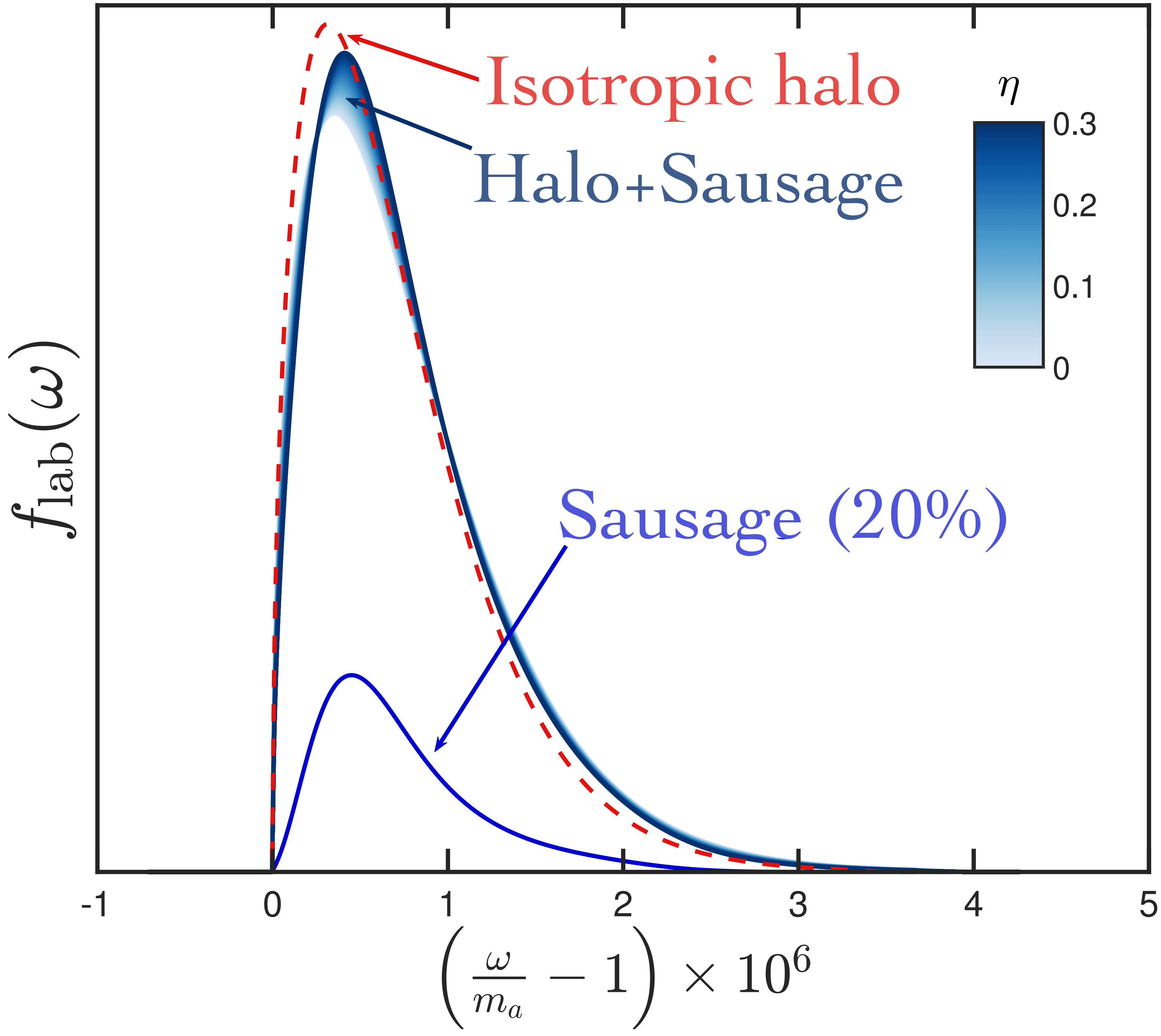
High iron abundance suggests Blutwurst is a good candidate? But too anisotropic → more (g)astronomy research needed

Flux of DM from the Halo and Sausage



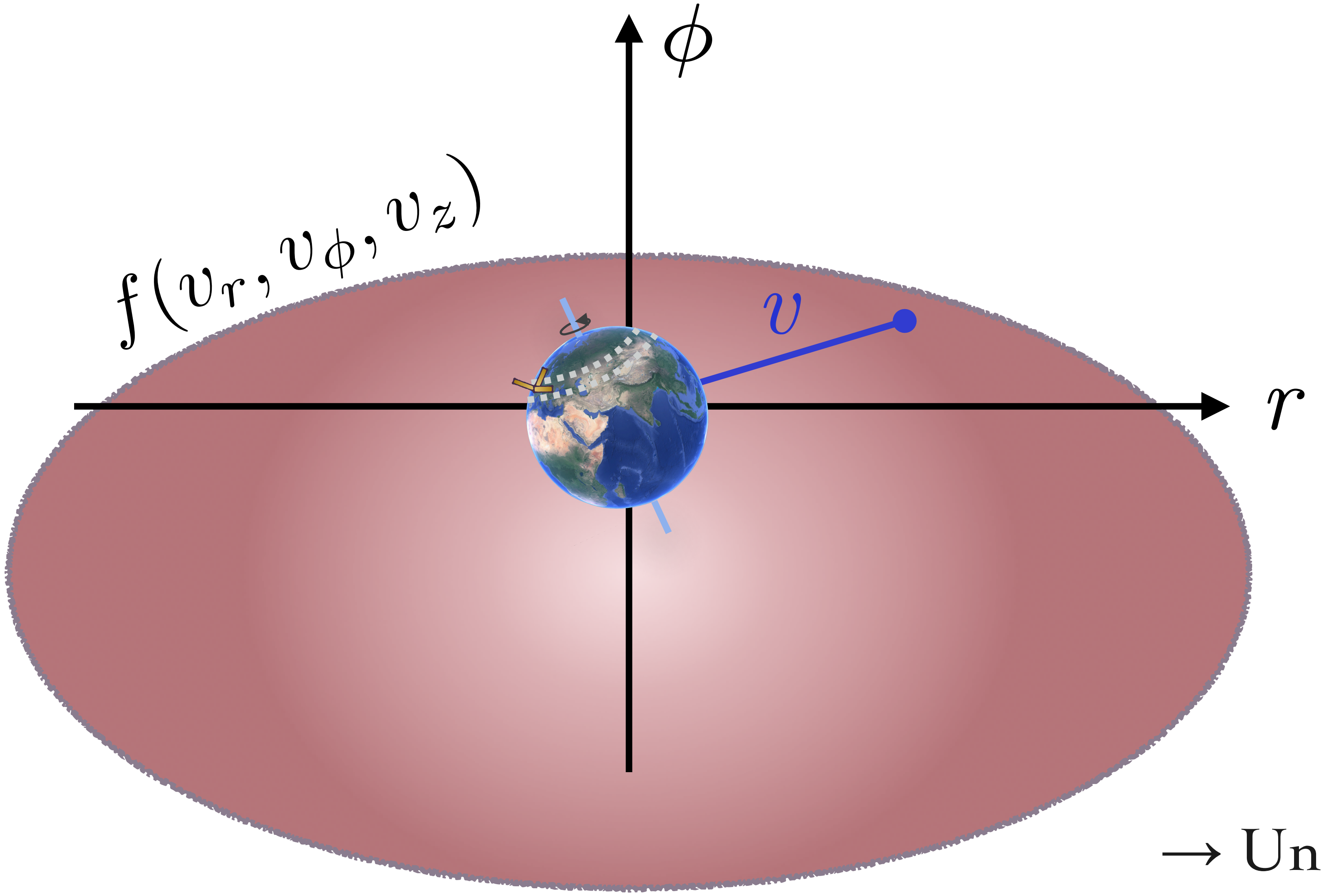
Cygnus constellation

Is this important for our axion signal model?



Anisotropy of velocity ellipsoid

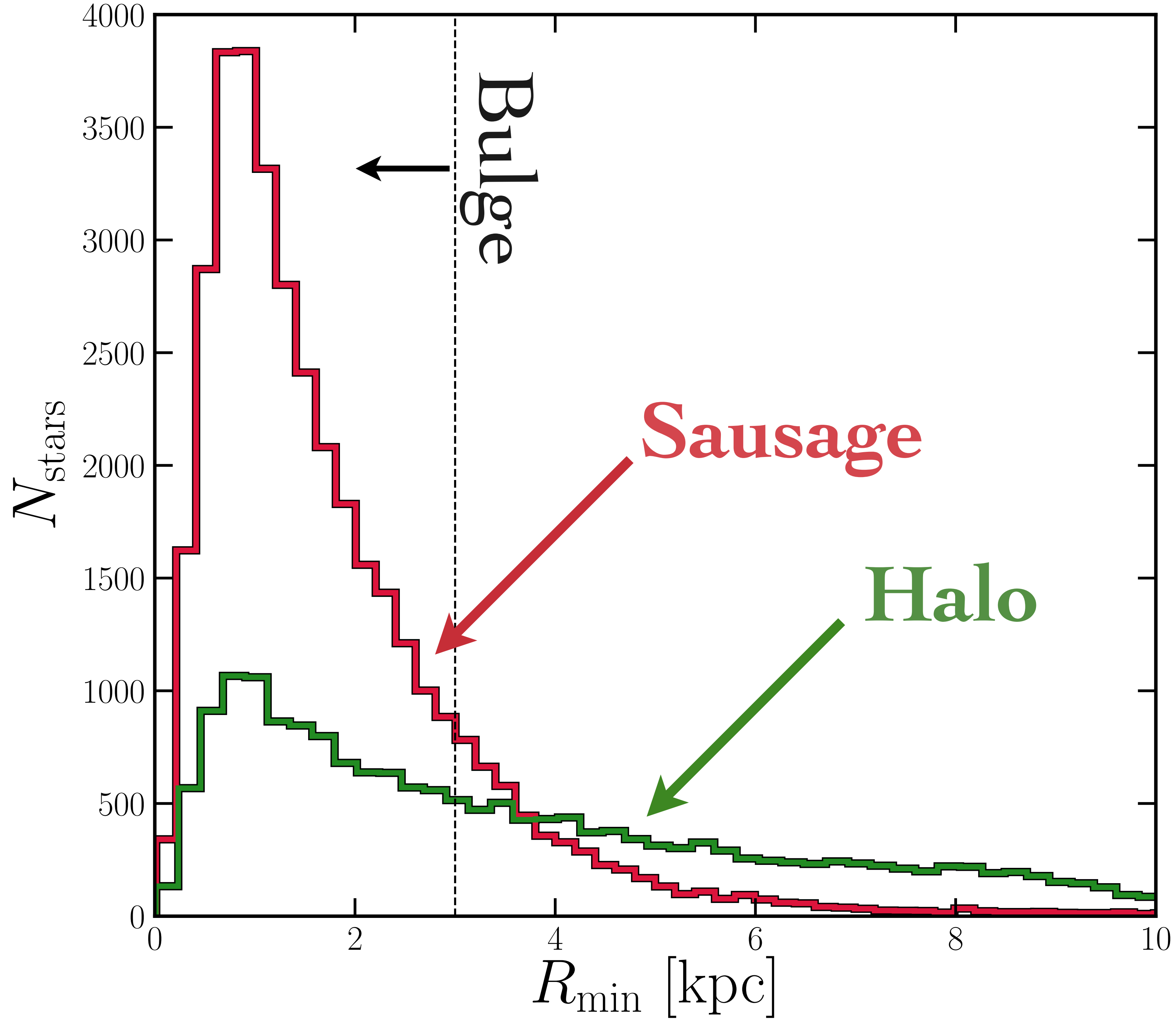
- Influence of the Sausage means that the halo will be hotter in the galactic radial direction $\sigma_r > \sigma_{z,\phi}$



→ Unique signature in axion-wind expts.

→ Annual modulation slightly non-sinusoidal

Sausage stars pass much closer to galactic centre than average stars in the rest of the halo…

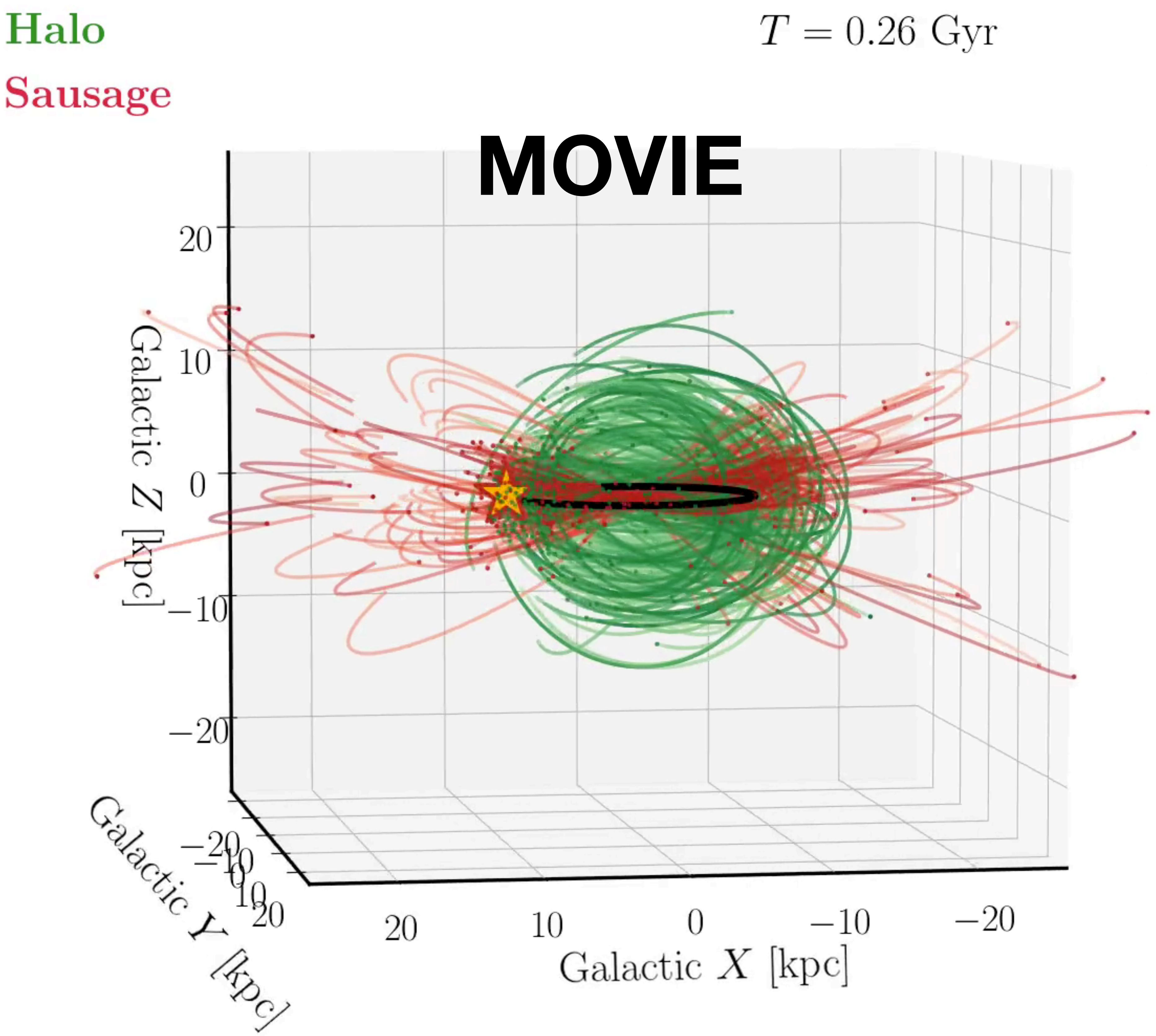


Gaia Sausage + post-inflationary axion:

→ more miniclusters on highly radial orbits

→ more disruption?

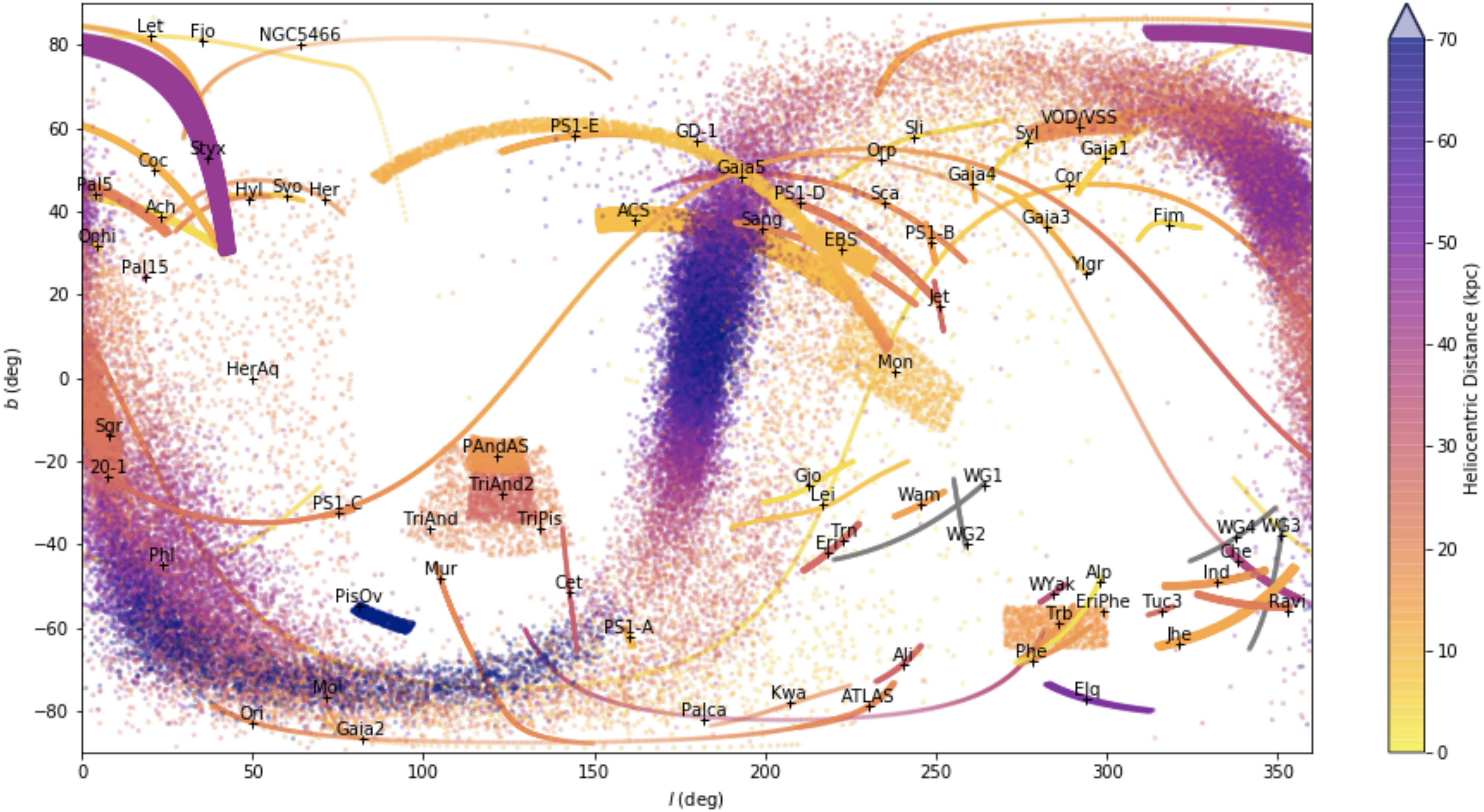
MOVIE


Halo
Sausage
$T = 0.26$ Gyr
20
10
0
−10
−20
Galactic Z [kpc]
−20
−10
10
20
Galactic Y [kpc]
20
10
0
−10
−20
Galactic X [kpc]

More substructure

Generic result of hierarchical structure formation:

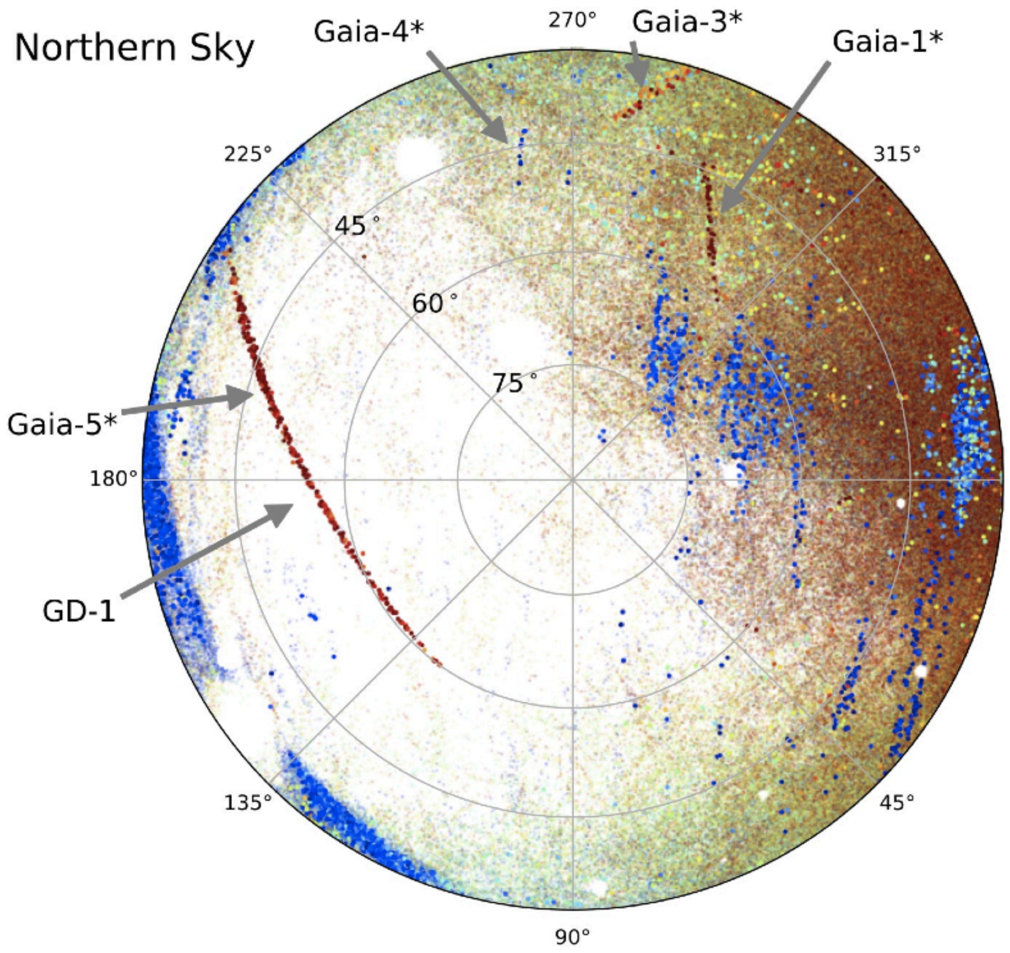
Streams of stars/DM from tidally stripped dwarfs, subhalos …



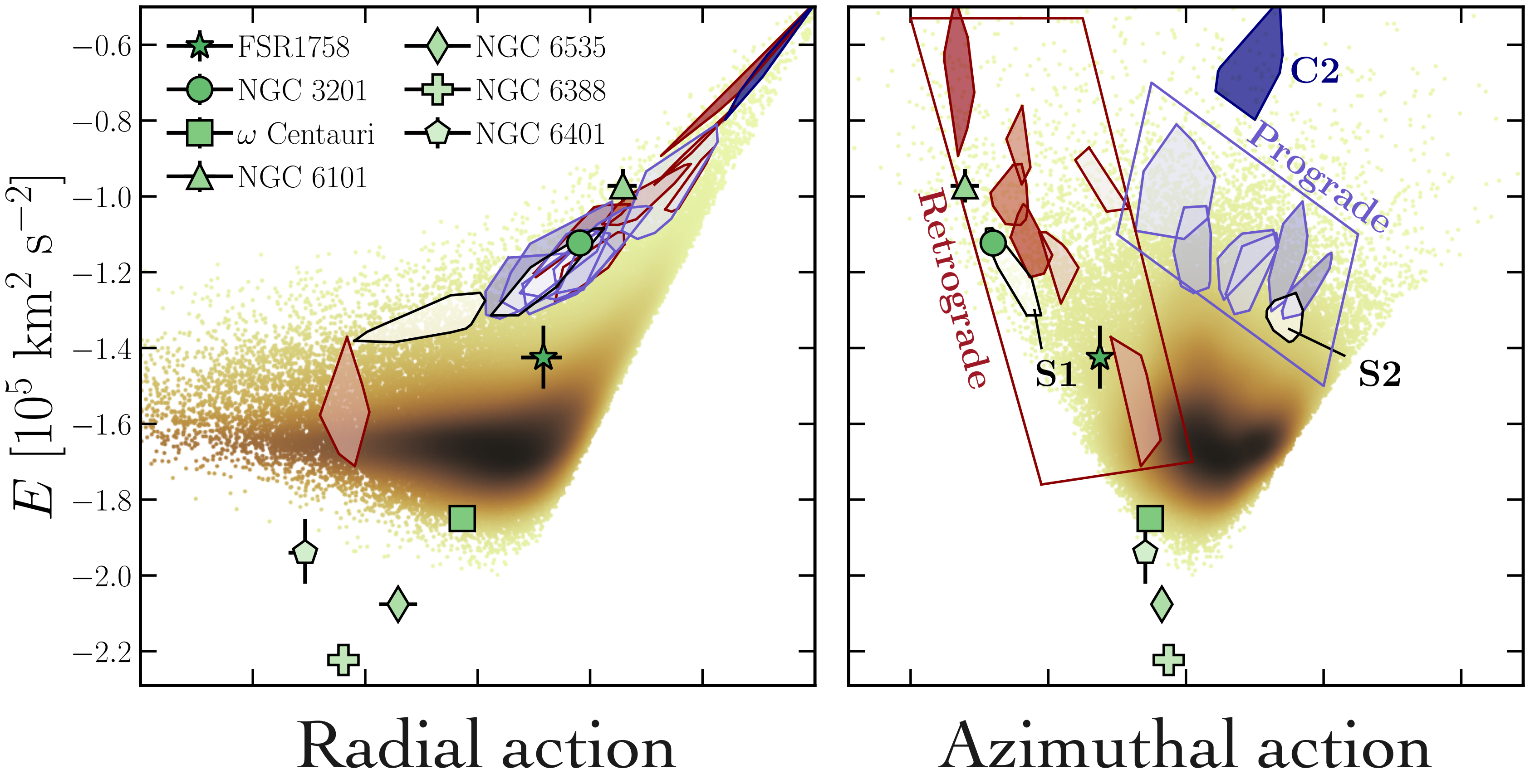
Mateu+ [1711.03967]

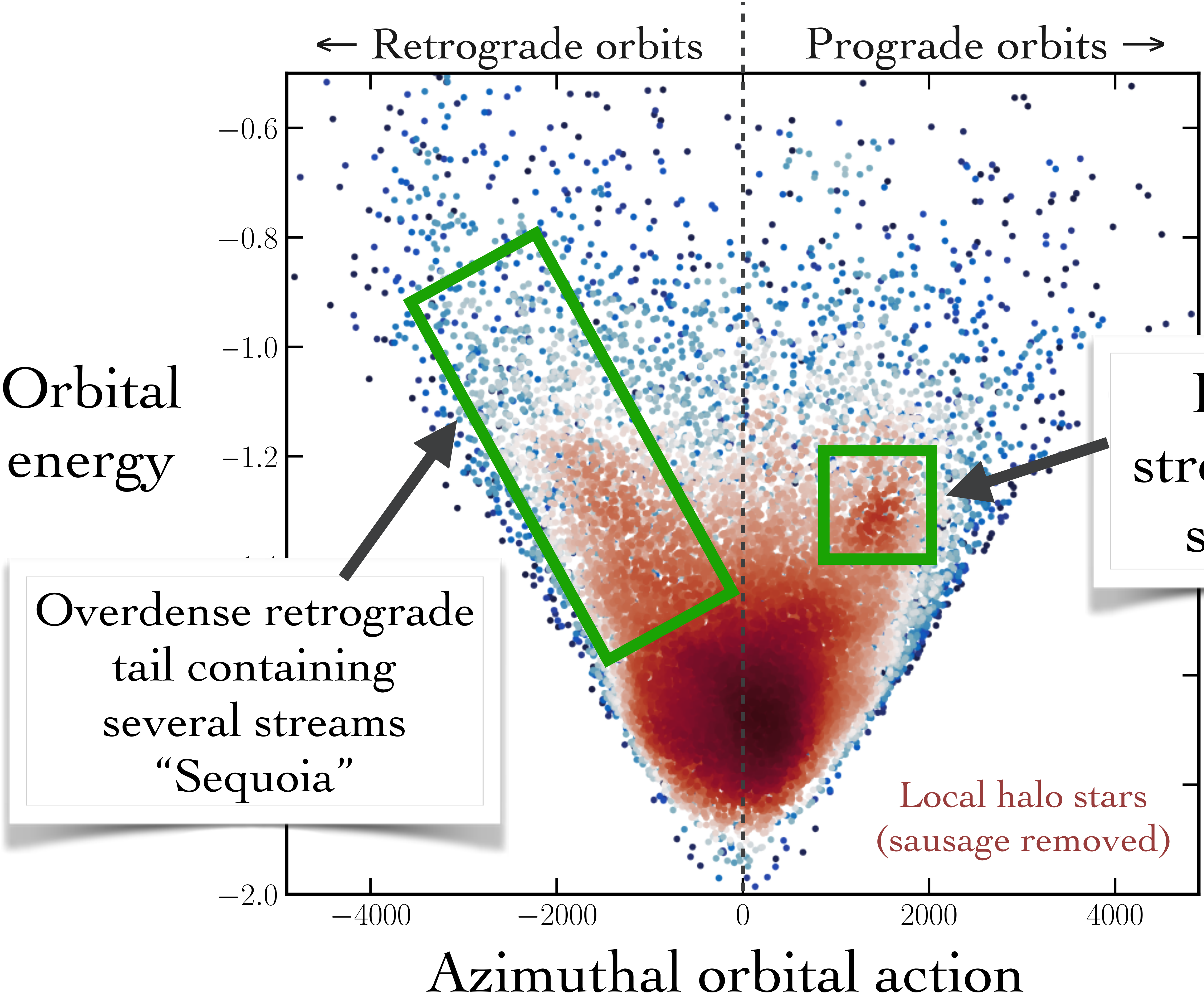
Ciaran O'Hare

- **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:**



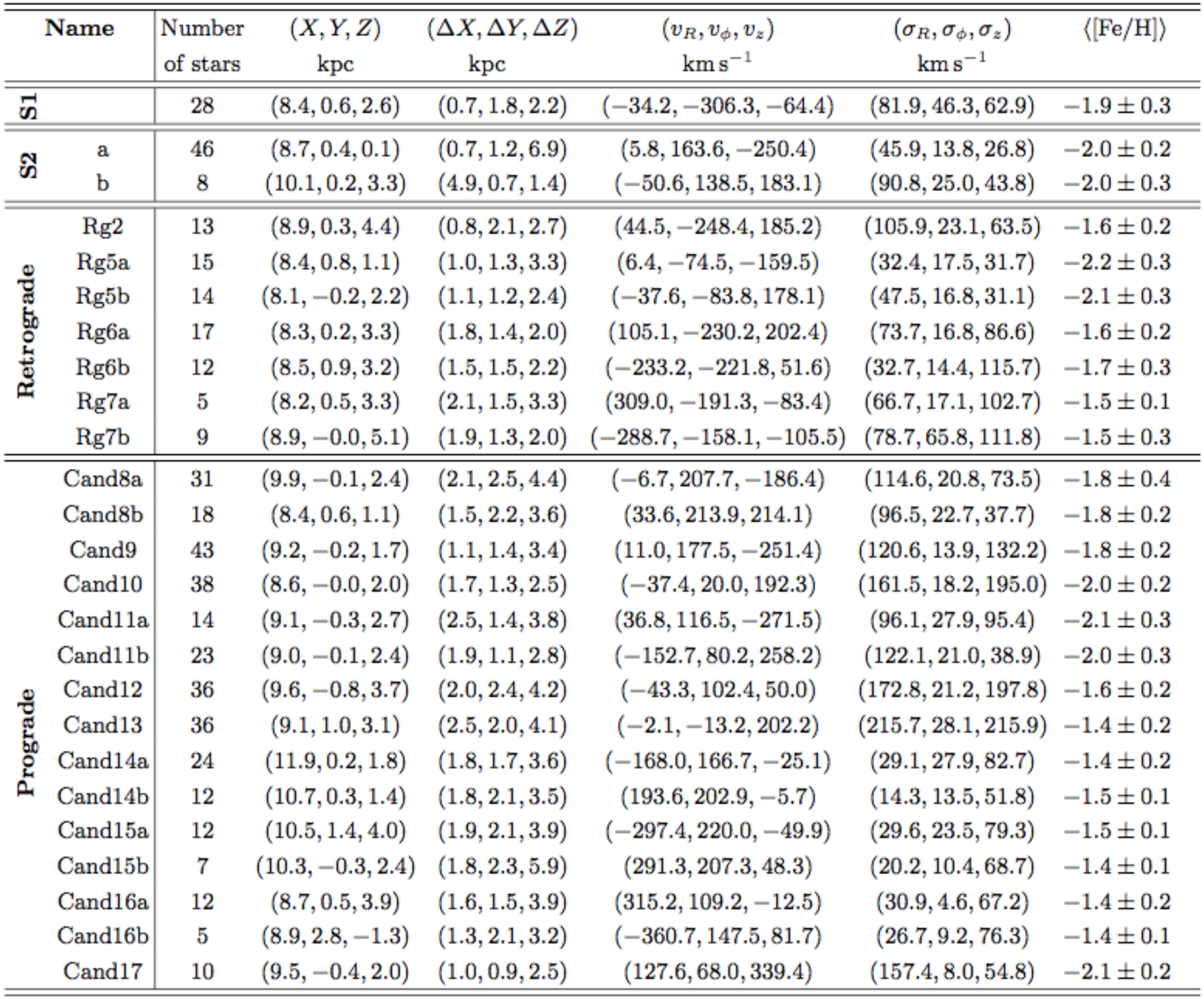


Overdense retrograde tail containing several streams “Sequoia”

Helmi streams/S2 stream

Local action-space substructures with orbits intersecting Solar position

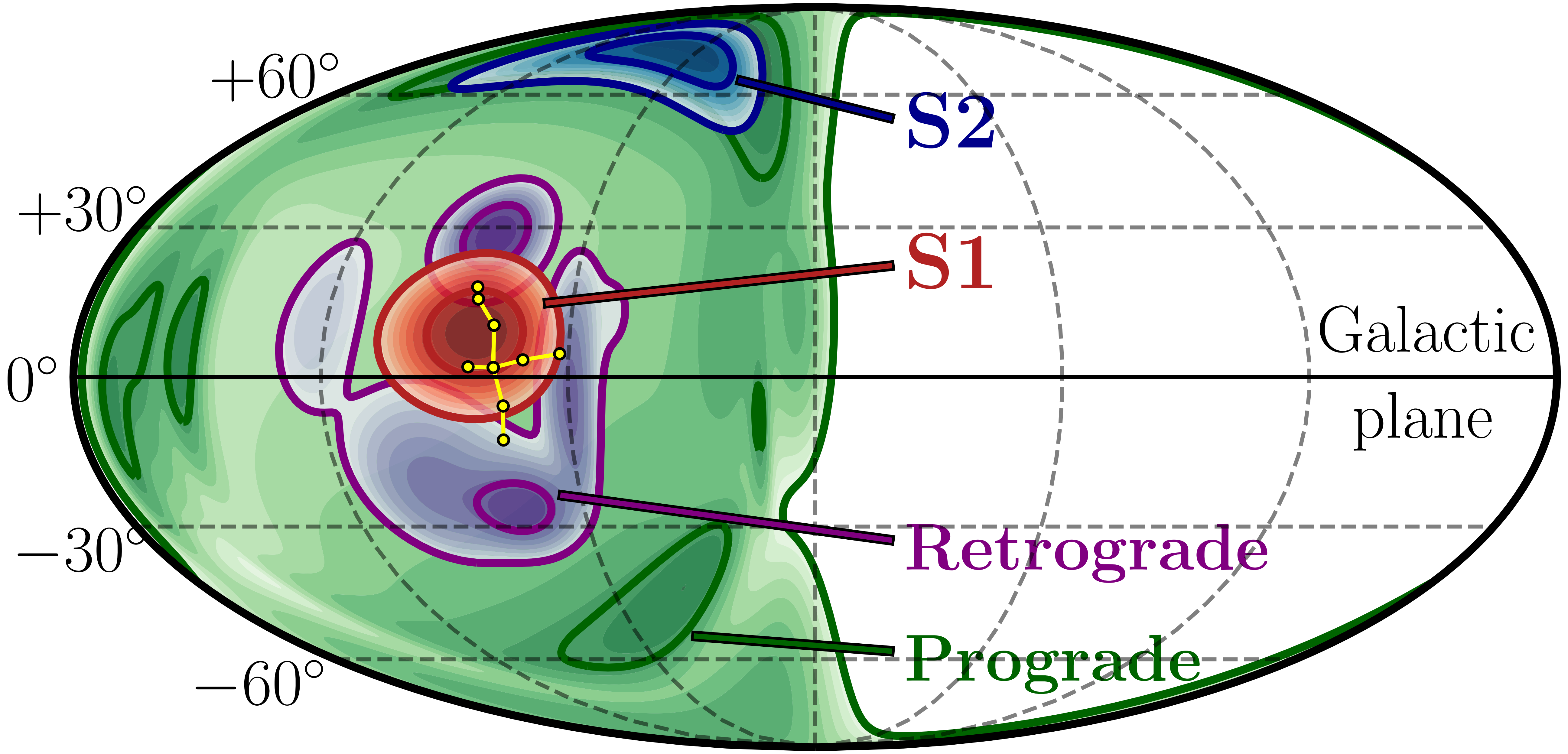
Two high significance streams “S1” and “S2”



	Name	Number of stars	(X, Y, Z) kpc	$(\Delta X, \Delta Y, \Delta Z)$ kpc	(v_R, v_ϕ, v_z) $\mathrm{km\,s^{-1}}$	$(\sigma_R, \sigma_\phi, \sigma_z)$ $\mathrm{km\,s^{-1}}$	⟨[Fe/H]⟩
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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 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 ± 0.2

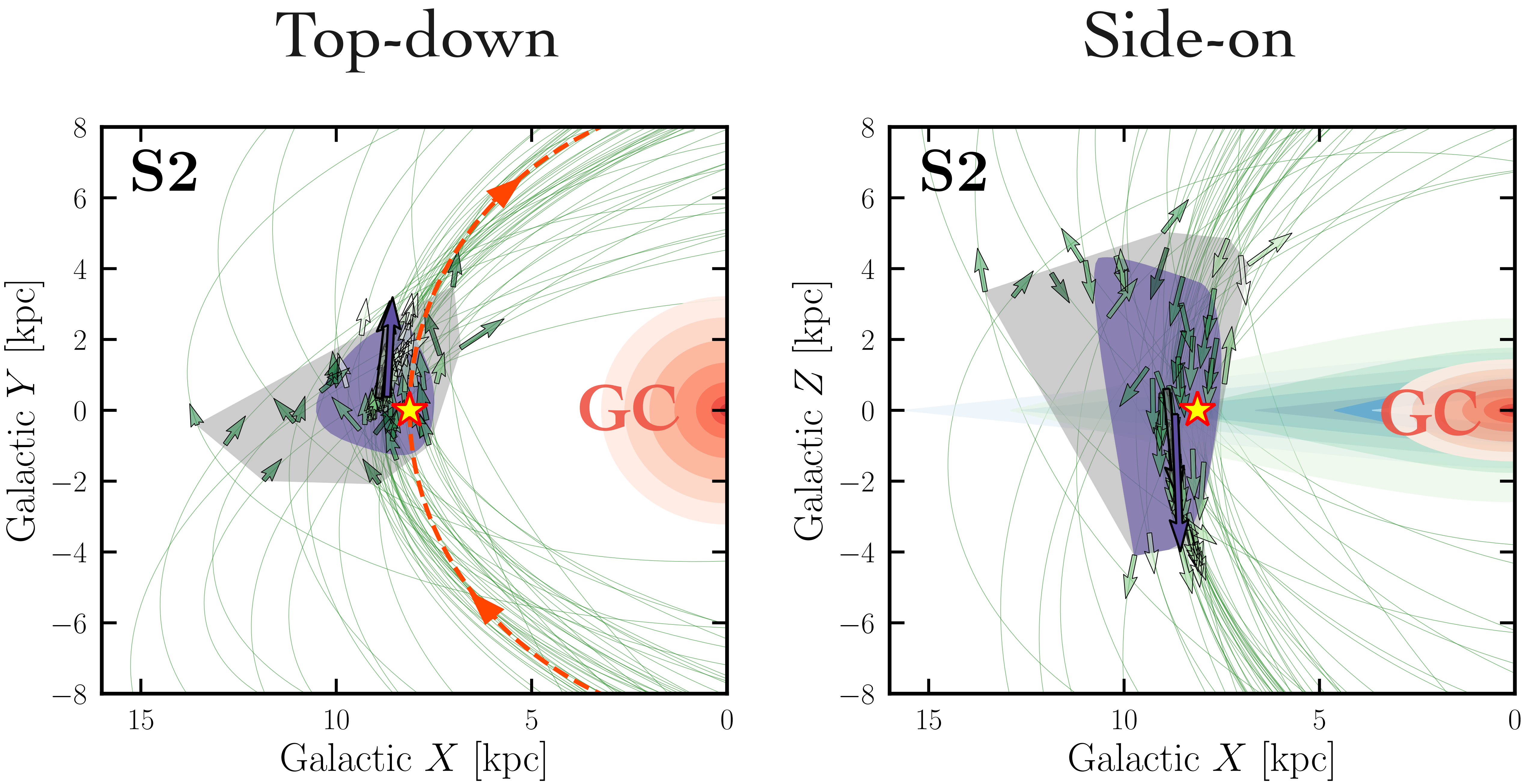
O’Hare+[1909.04684]

Distribution of known local substructure on the Sky in Earth rest frame



O'Hare+ [1909.04684]

S2 stream is on a prograde, polar orbit

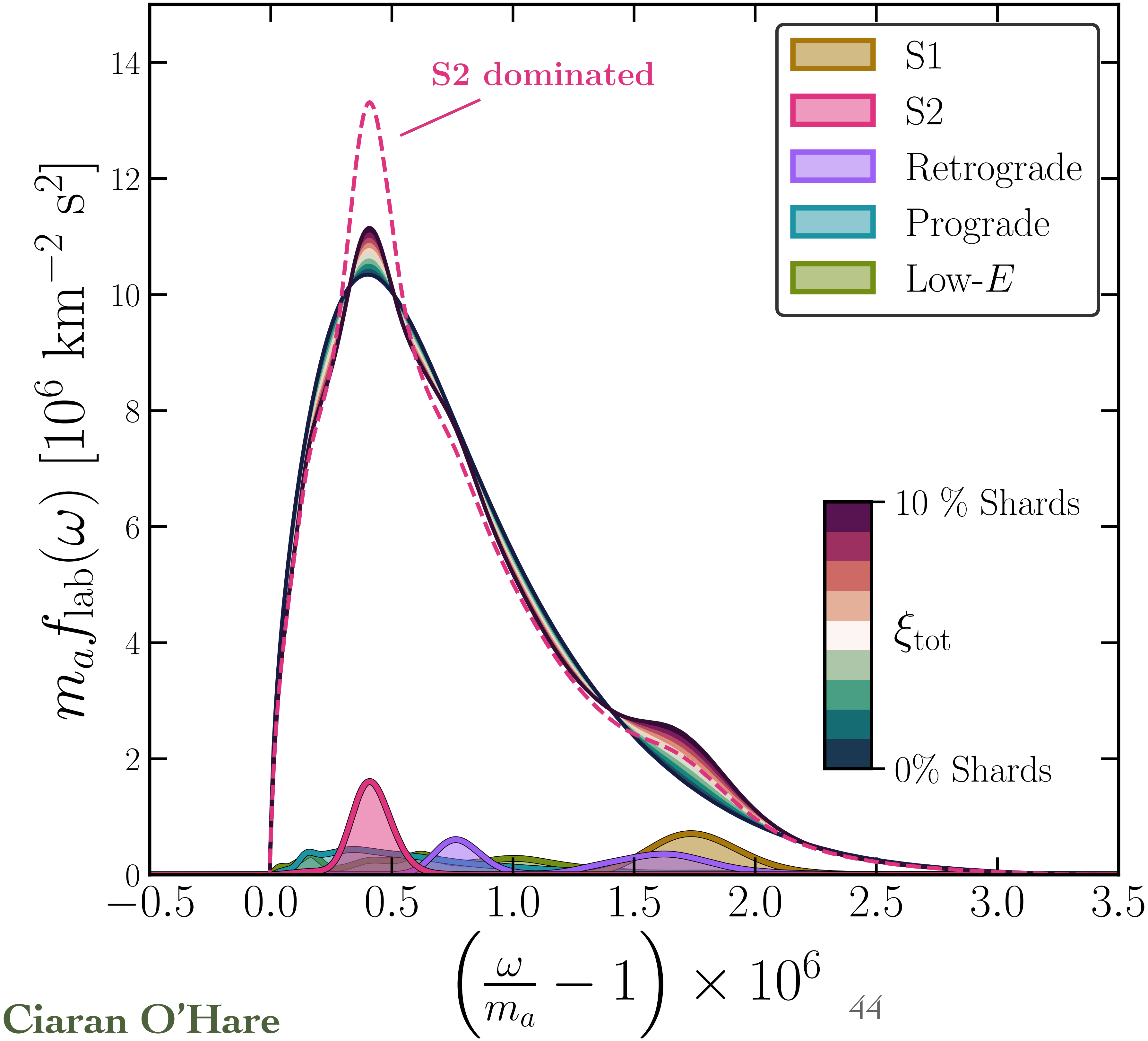


Contributes to the peak of $f(v)$

→ more important for axion searches

O'Hare+
[1909.04684]

If streams makeup a small chunk of the local DM density then they will show up and be measurable in axion signal



Important NB:
Dark matter density in substructure can still not be inferred with any great confidence from stars alone, further bespoke sims still required

Further questions

- Need refined estimates of local density fully exploiting Gaia data (ongoing)
  - → +agreement in community on benchmark, we may miss DFSZ if local density overestimated.
- Are direct searches for post-inflationary axions doomed to fail?
  - → How many miniclusters have survived locally?
  - → Does the major head-on merger with the sausage galaxy change this prediction?
  - → can indirect searches help?
- How are the kinematics of stars in the halo related to the kinematics of dark matter?

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