New discoveries from the Gaia satellite, and direct searches for dark matter

Ciaran O'Hare

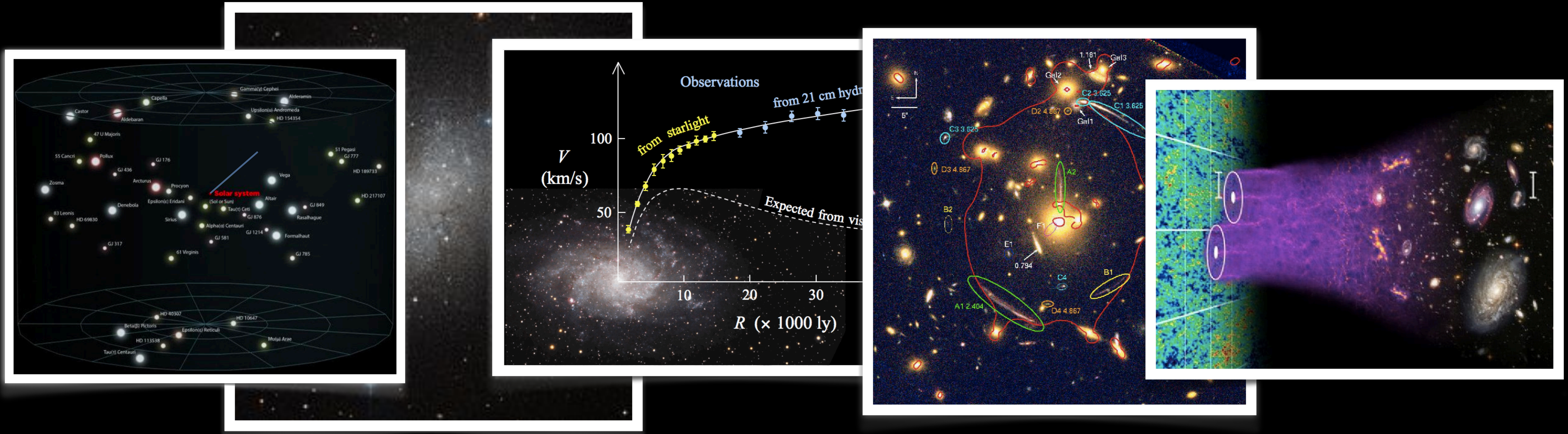
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF SYDNEY

Evidence for dark matter

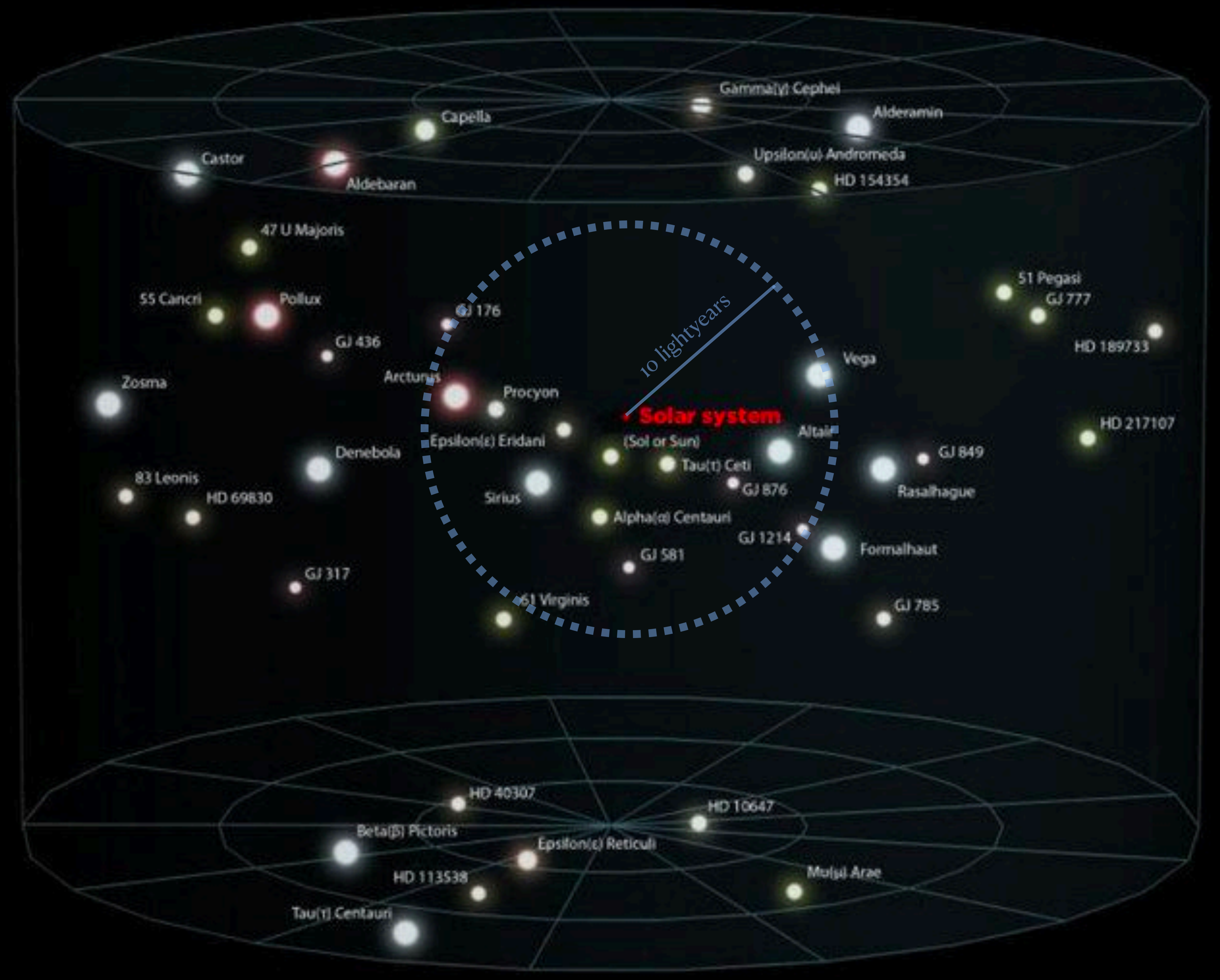
→ the universe is filled with a large quantity of some non-luminous matter

~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure



How much dark matter is around?

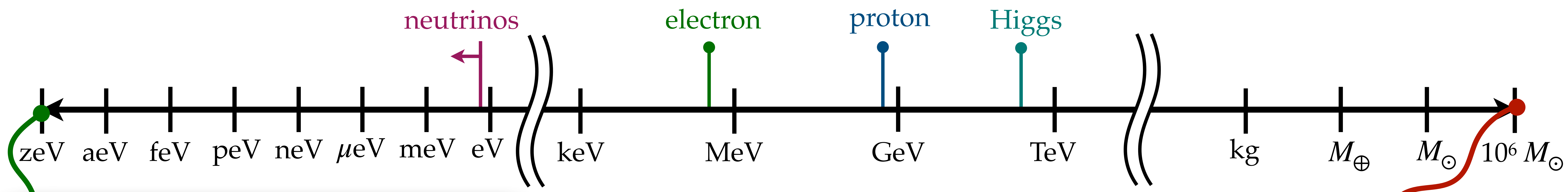
~100 pc ~kpc ~100 kpc ~Mpc >Gpc



<u>Local density of dark matter</u> (i.e. in this room!)

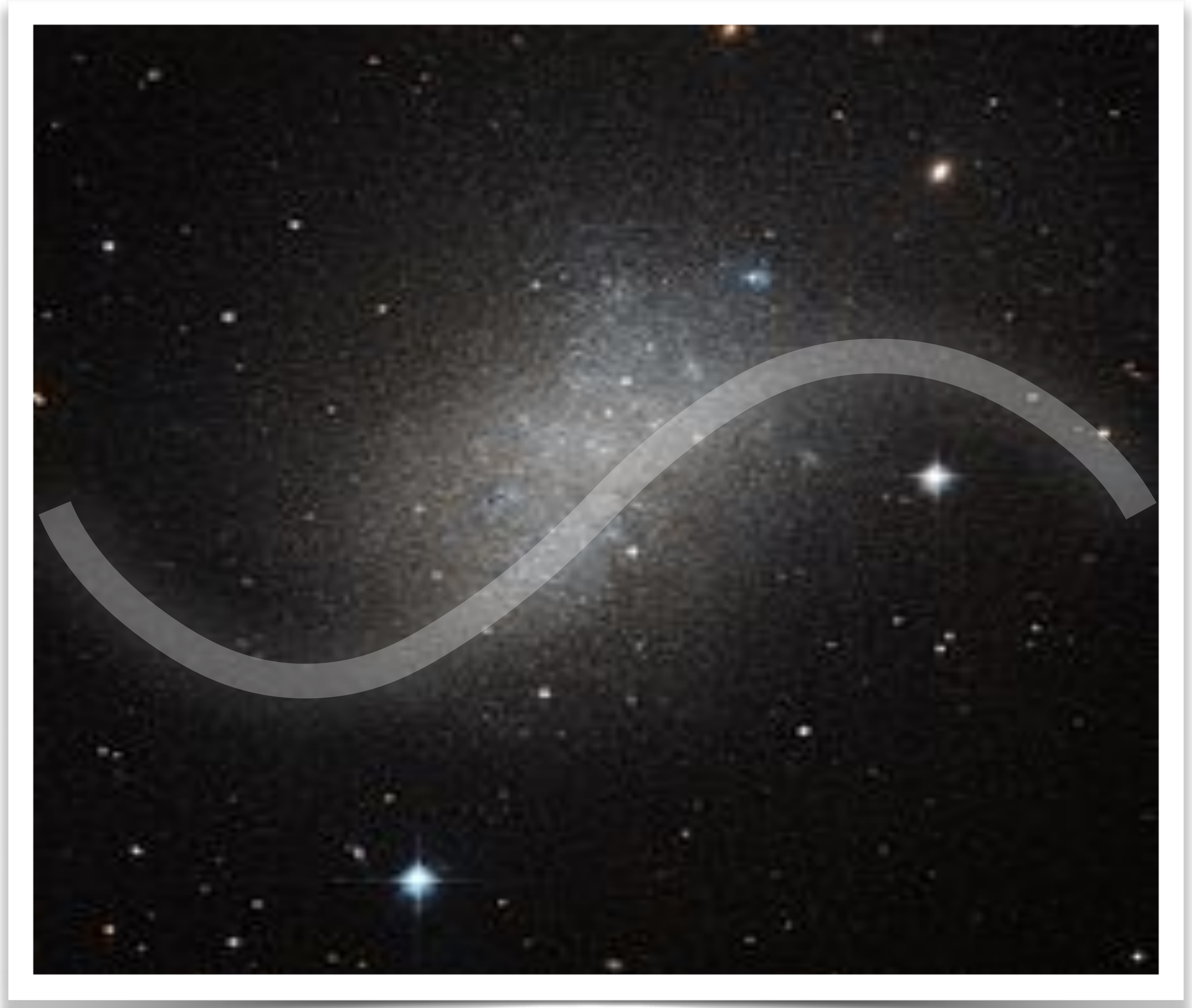
$$\rho_{\rm dm} \approx 0.4\,\mathrm{GeV/cm^3} \longleftarrow \textit{Particle physicist's unit}$$

$$\approx 0.01\,\mathrm{M_\odot/pc^3} \longleftarrow \textit{Astrophysicist's unit}$$

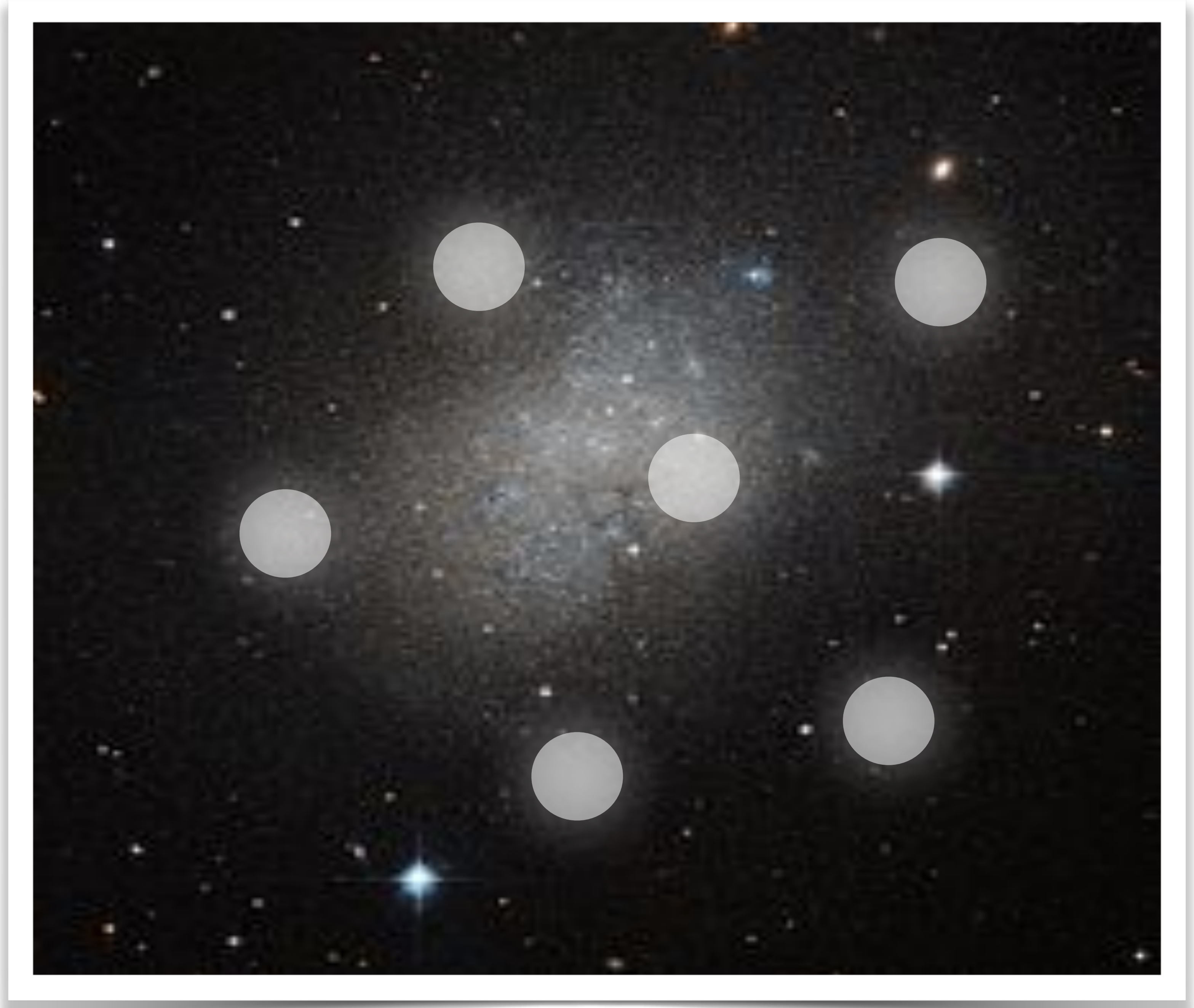


$m \gtrsim 10^{-21}$ eV
de Broglie wavelength must **fit inside** dwarf galaxies ~ 100 pc

$m \lesssim 10^6 M_\odot$
Must **fill** dwarf galaxies



Possible mass range only bounded by ~75 orders of magnitude, but it's a start

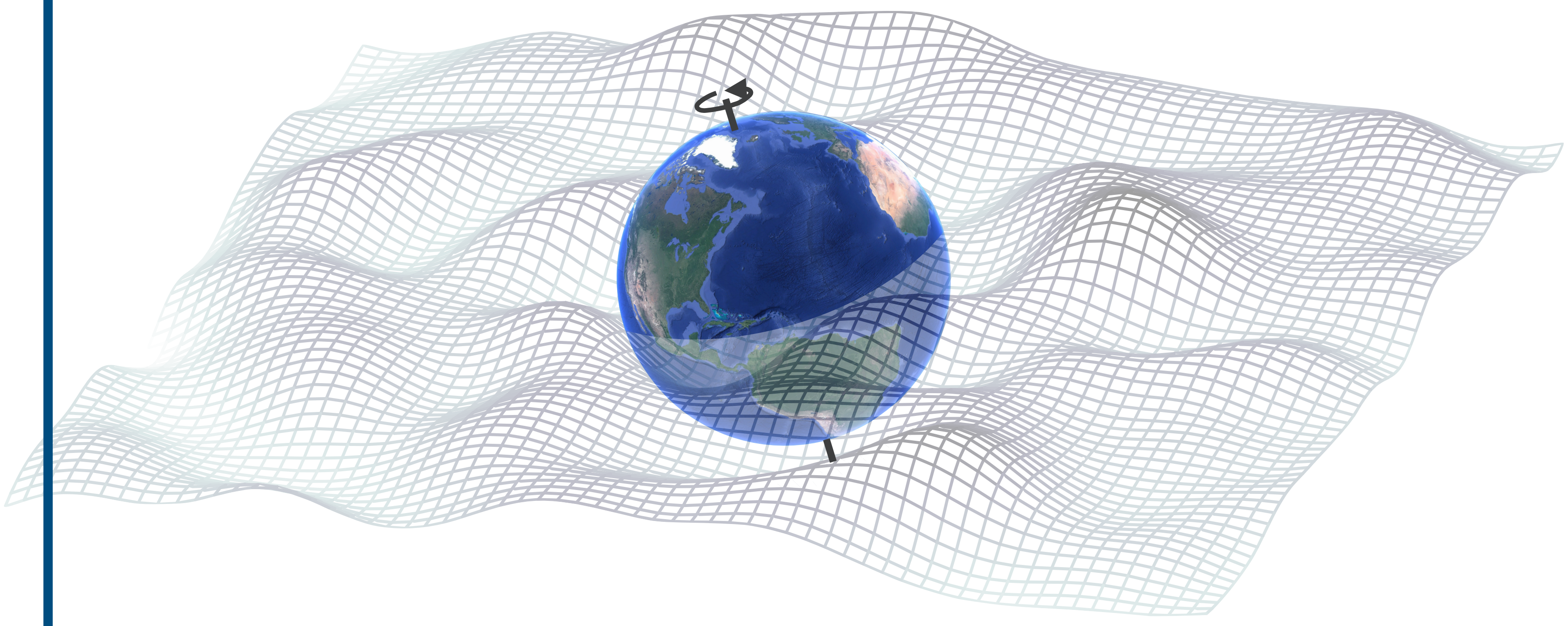


Types of dark matter

Mass → 10 eV … $M_{\rm pl}$

Wave-like

(Must be bosons due to Pauli exclusion principle)



Continuously oscillating and undulating field that can couple to other fields (e.g. the electromagnetic one)

Particle-like

(Can be fermions, bosons or even composite particles like dark nuclei)

Discrete particles occasionally colliding with each other or other stuff

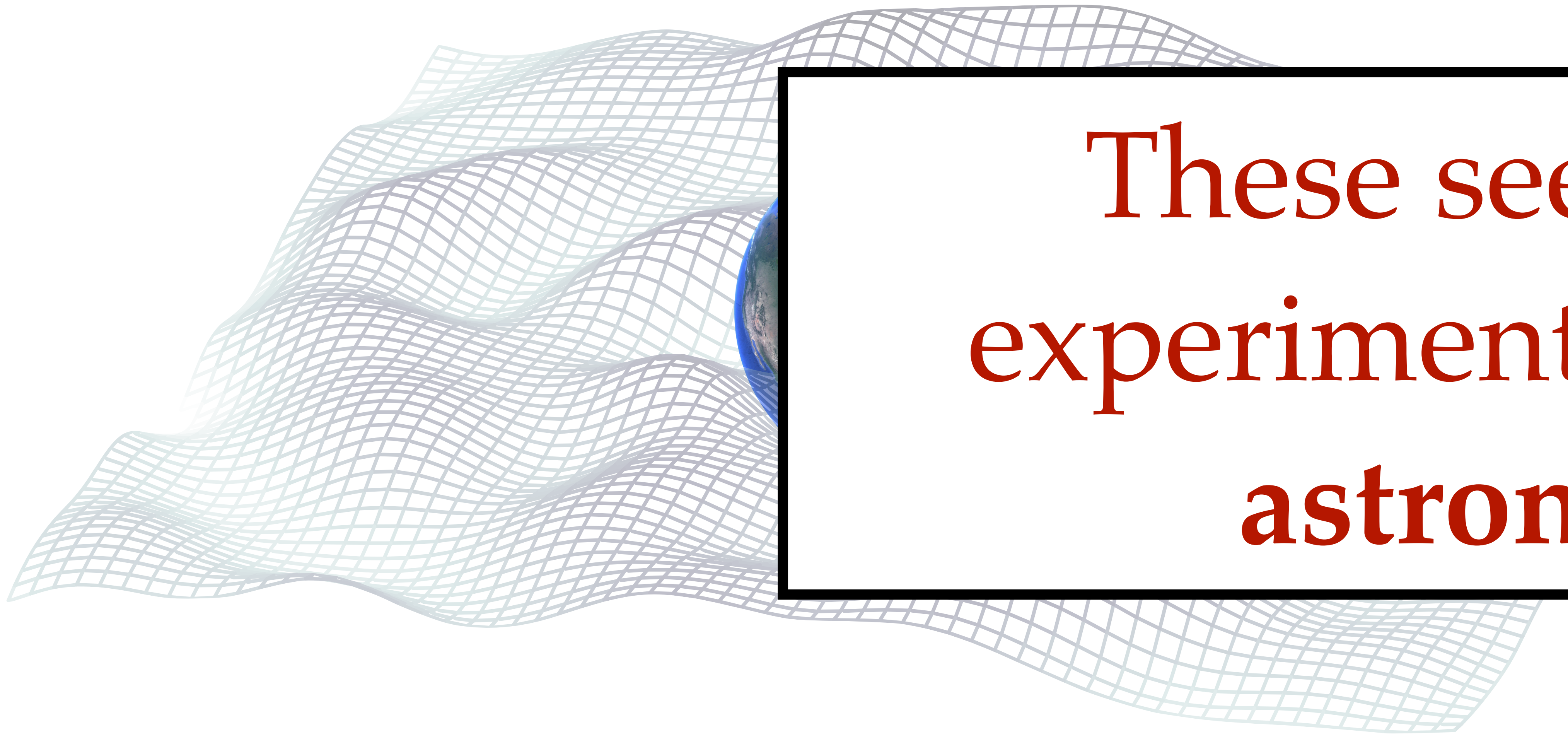
Object-like

(e.g. black holes)

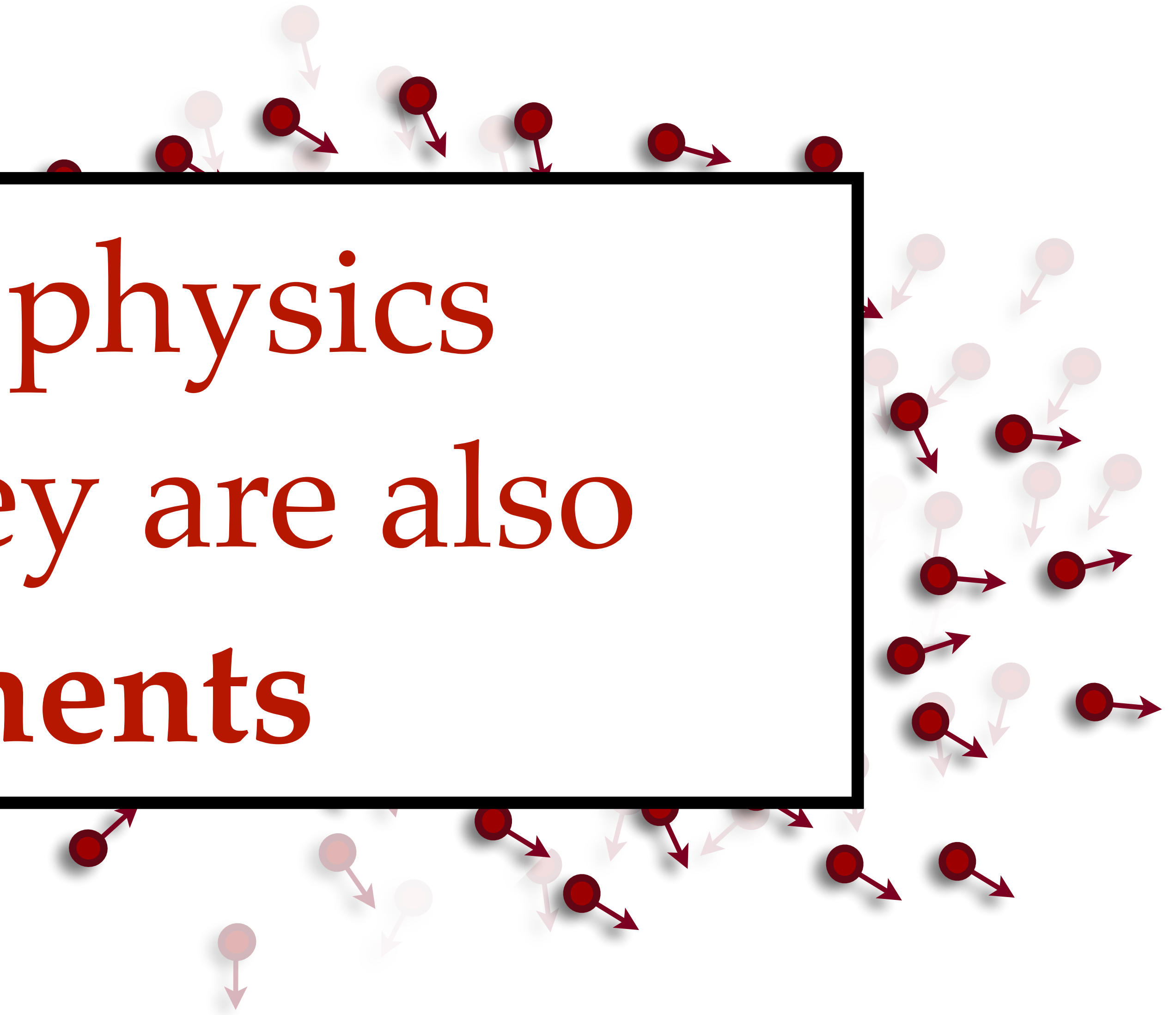
Very sparse population of heavy bodies exerting distant gravitational interactions

Experiments

Wave-like

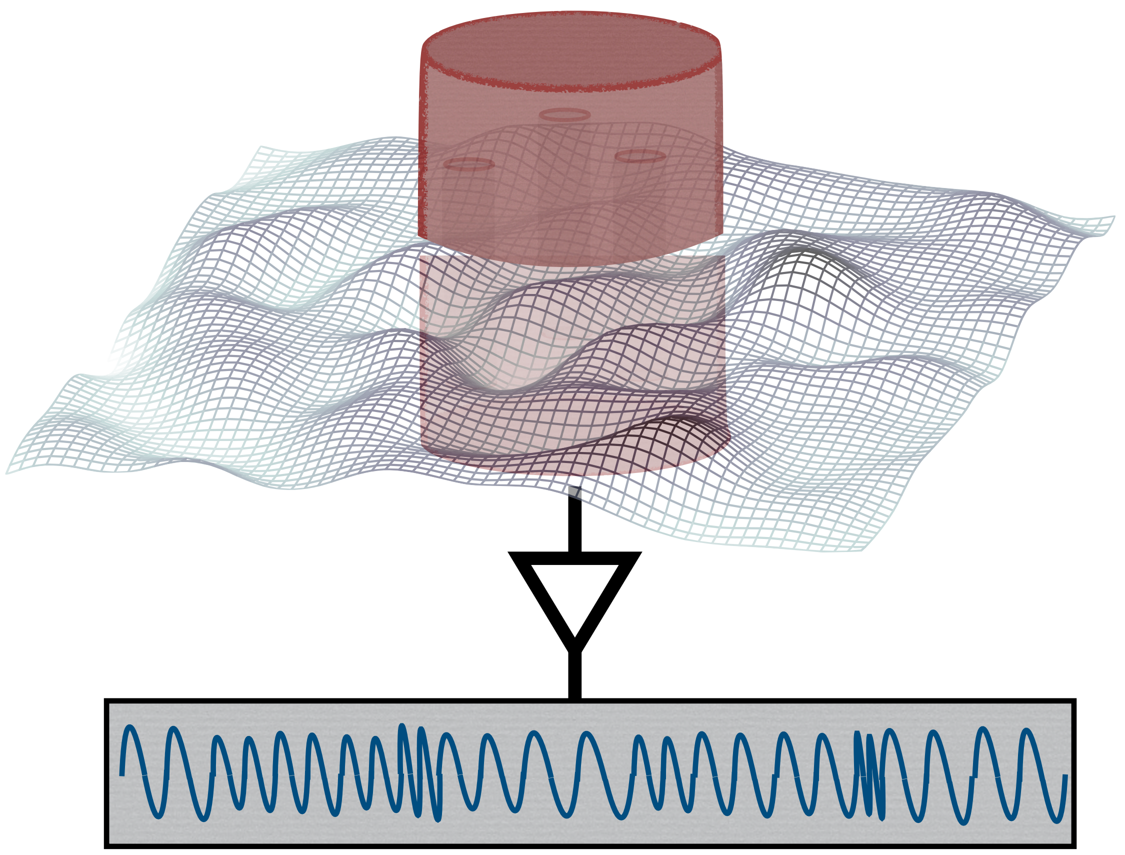


Particle-like

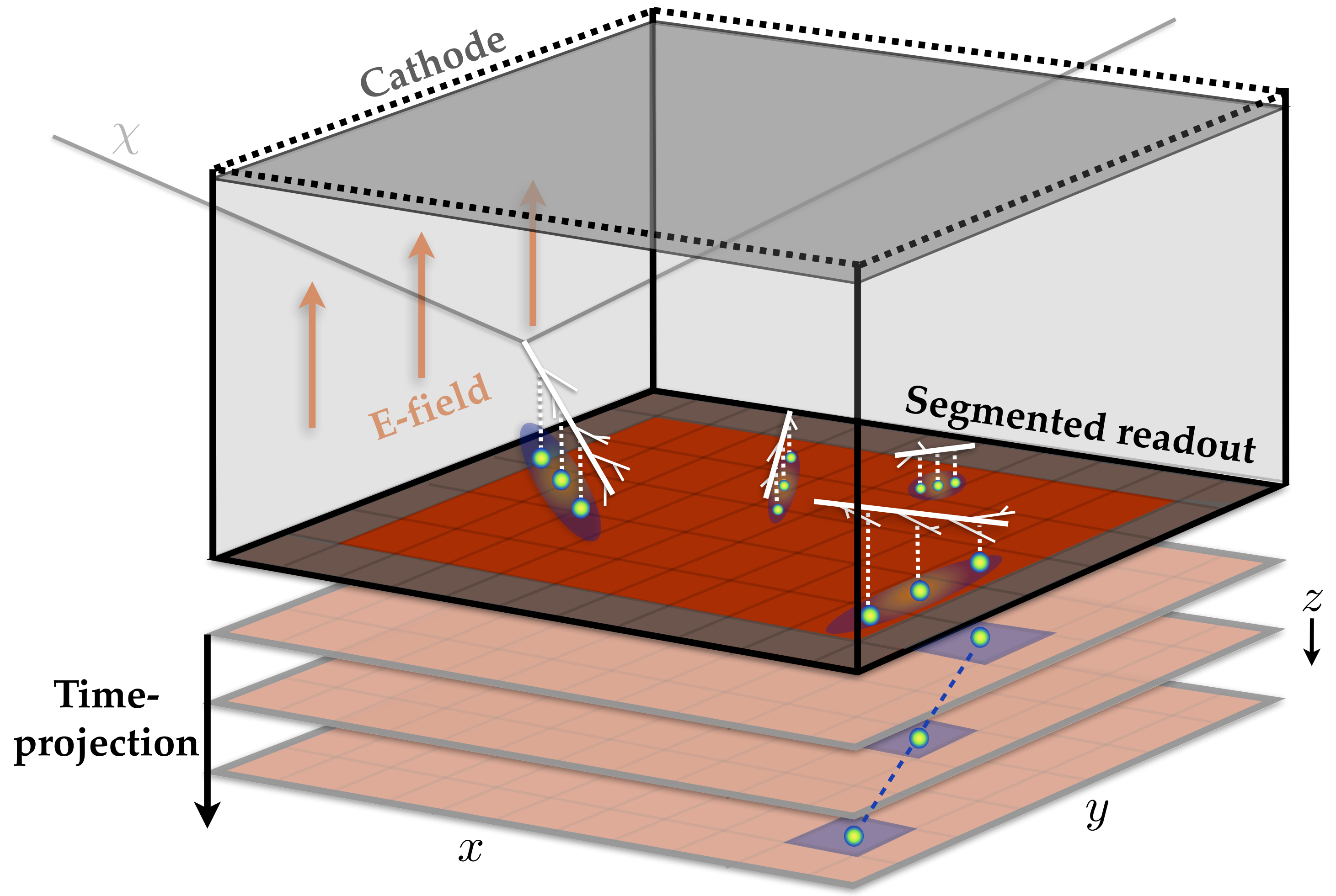


These seem like particle physics experiments, but really they are also **astronomical instruments**

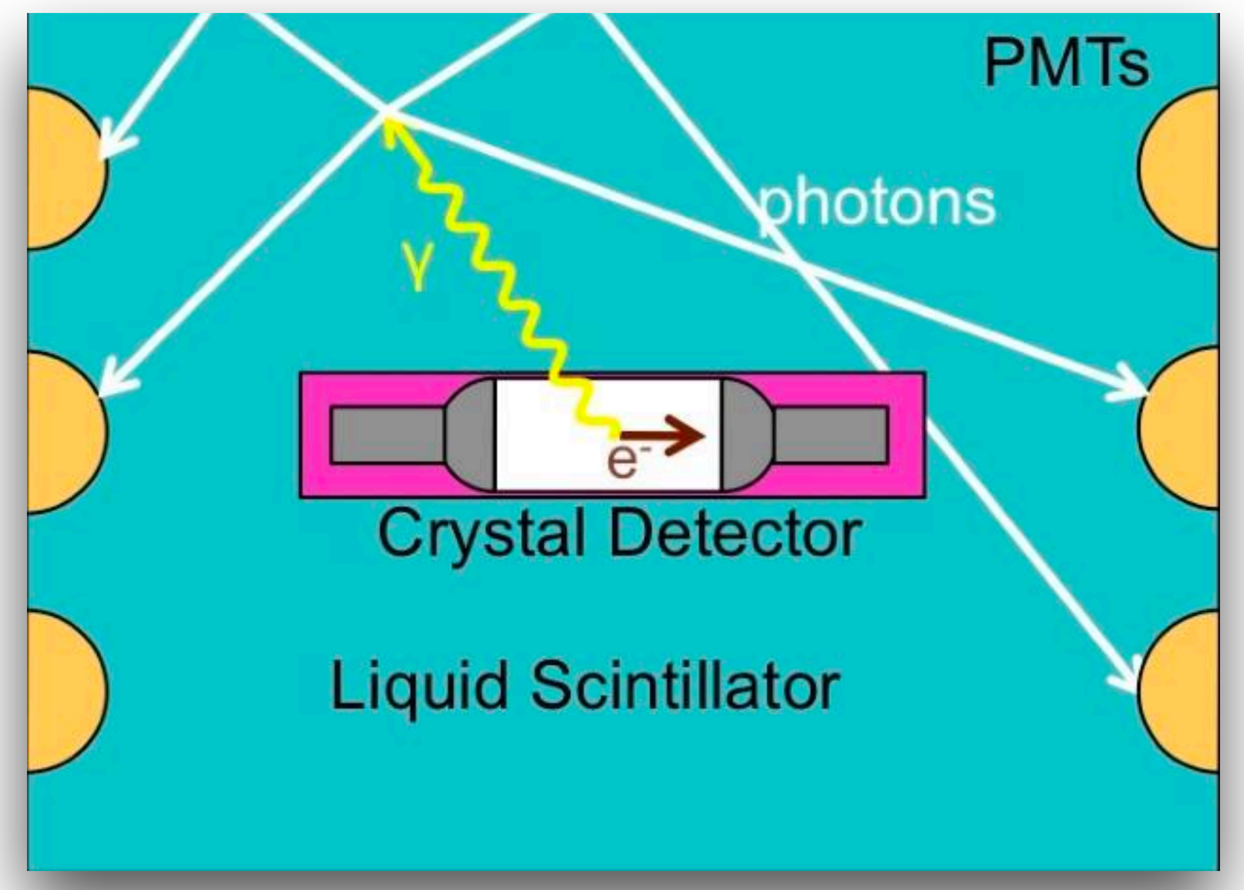
"Tunable microwaves" (e.g. ORGAN)



Gases (e.g. CYGNUS)



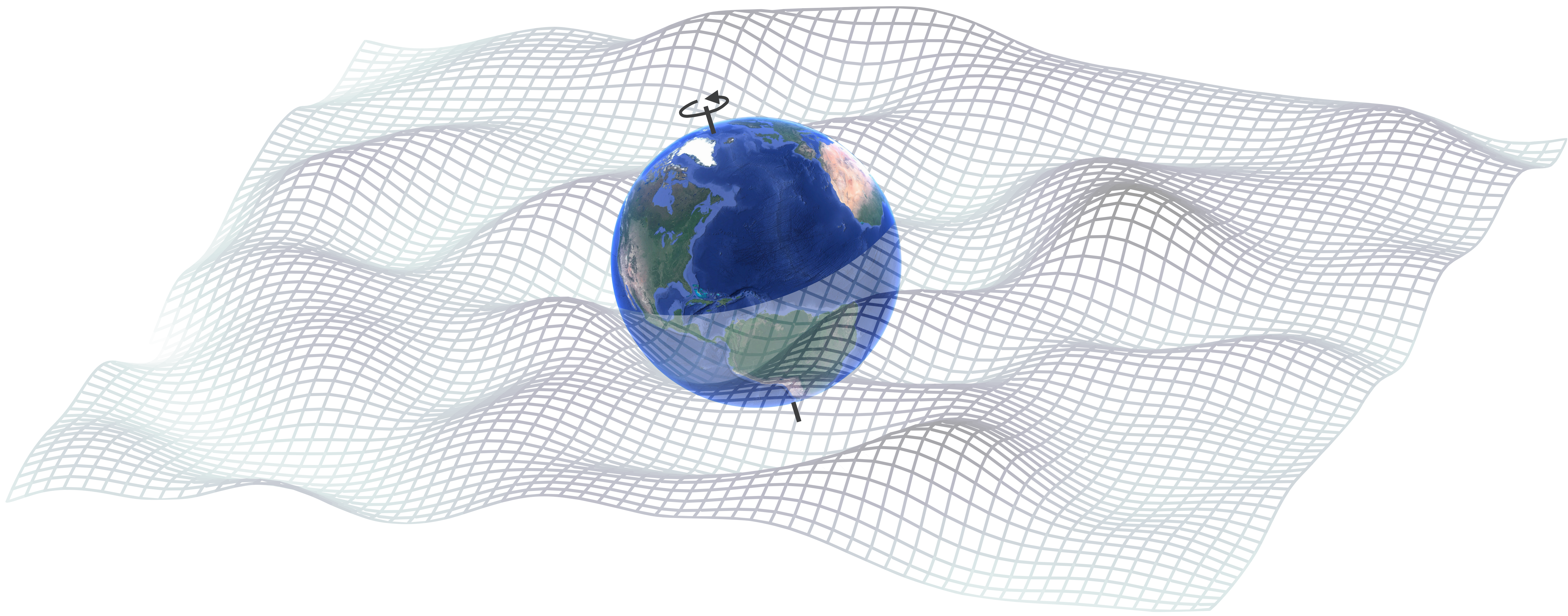
Crystals (e.g. SABRE)



To calculate *any* experimental signal of dark matter we need to know

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

Wave-like



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

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

Particle-like

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

Flux $\Phi = v n_\chi$

Can we infer $\rho(r = 8\,\mathrm{kpc}) \equiv \rho_0$ 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

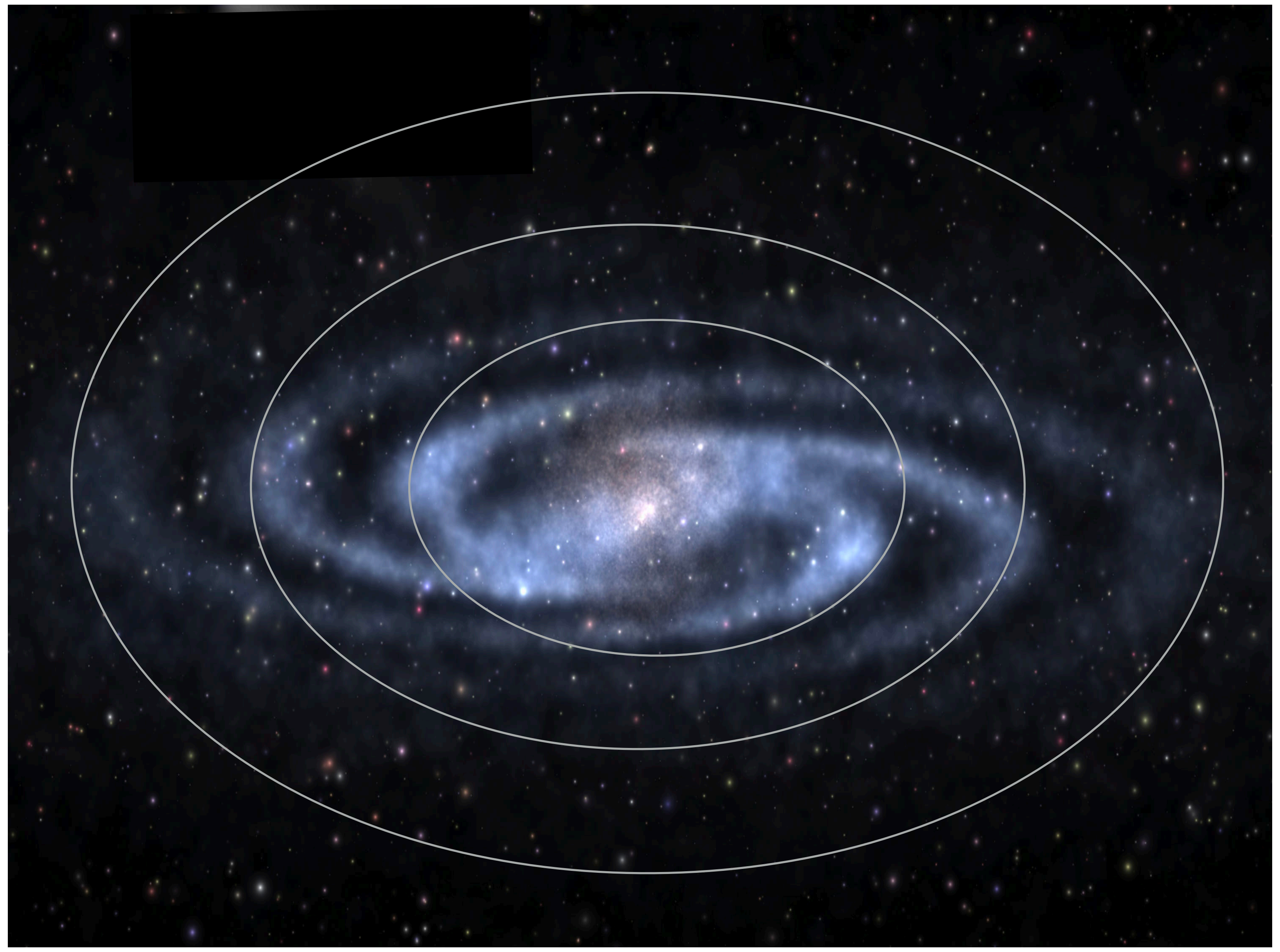
$$\nabla_x^2 \Phi = 4\pi G \rho \longrightarrow$$

Poission eq.
Grav. potential → matter density

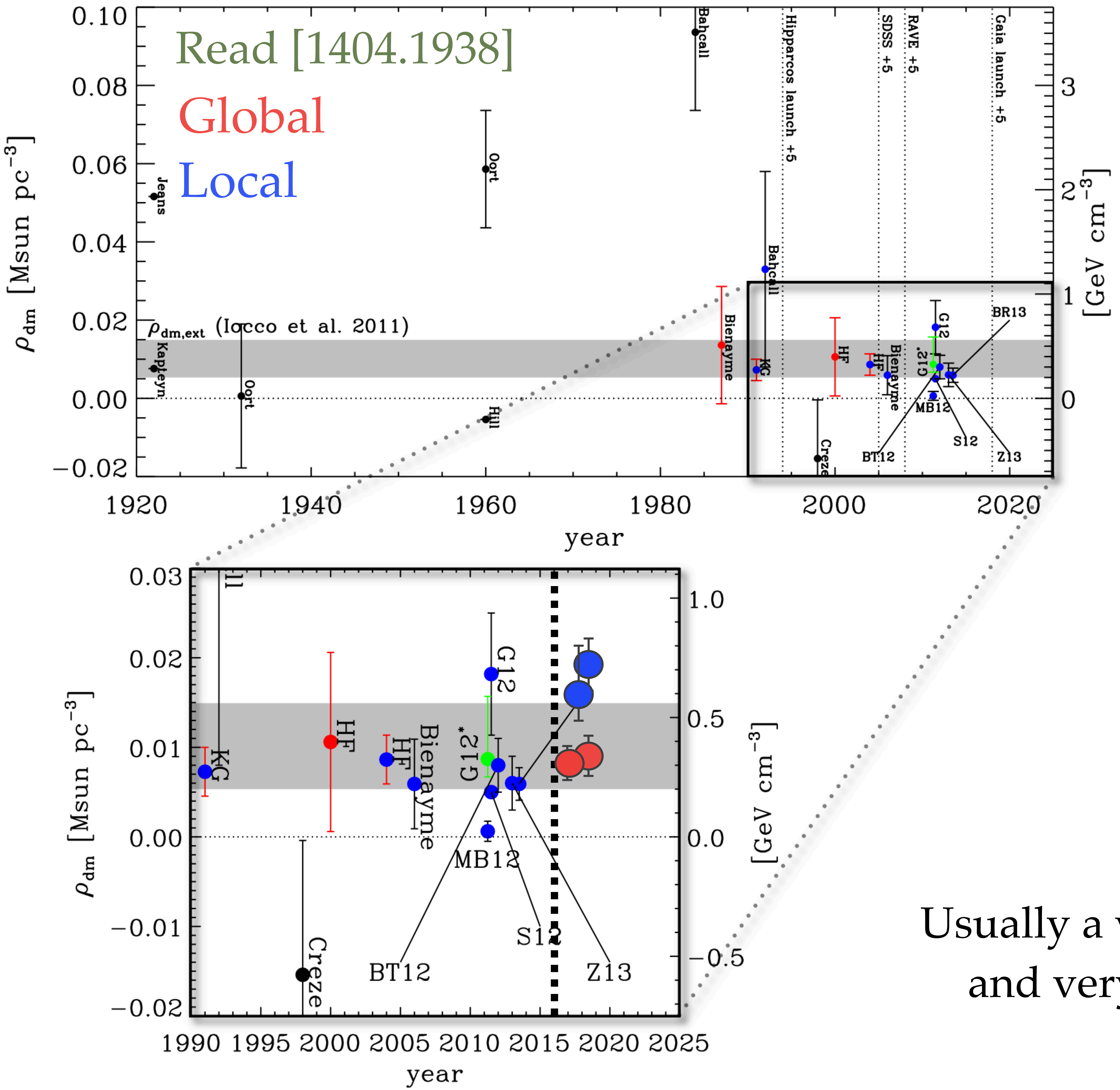
Local measure
(kinematics of nearby stars)

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



Recent estimates

Hagen+[1802.09291]

Buch+ [1808.05603]

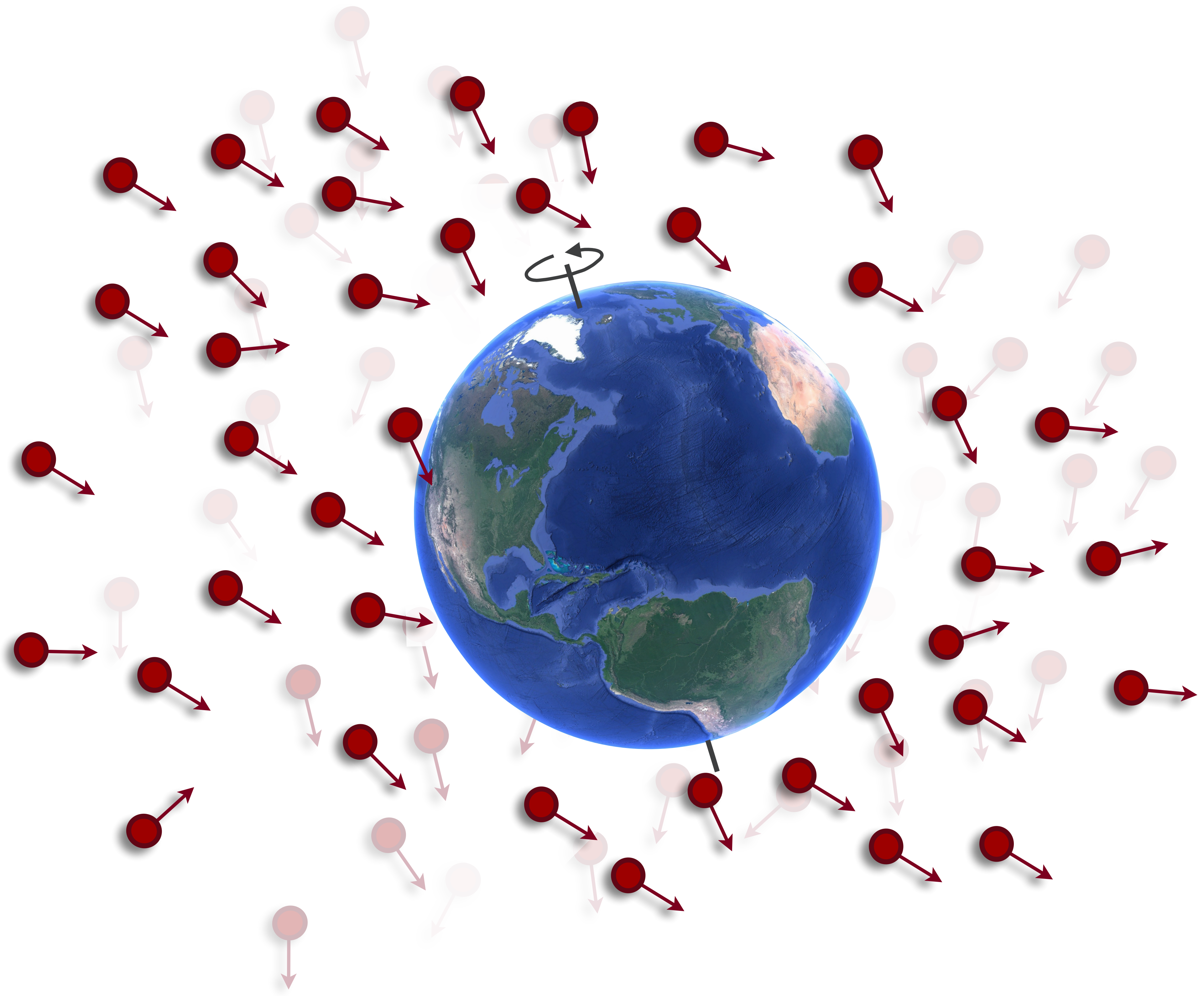
Widmark [1811.07911]

de Salas+ [1906.06133]

Eilers+ [1810.09466]

Benito+ [1901.02460]

Usually a value $\rho_0 = 0.3$ GeV cm^{-3} is assumed, and very reasonable based on measurements



Local density, ρ_0

→ Can be inferred from stars

→ Only ever sets the overall scale of signal so is almost always completely degenerate with the DM coupling strength

Velocity distribution, $f(\mathbf{v})$

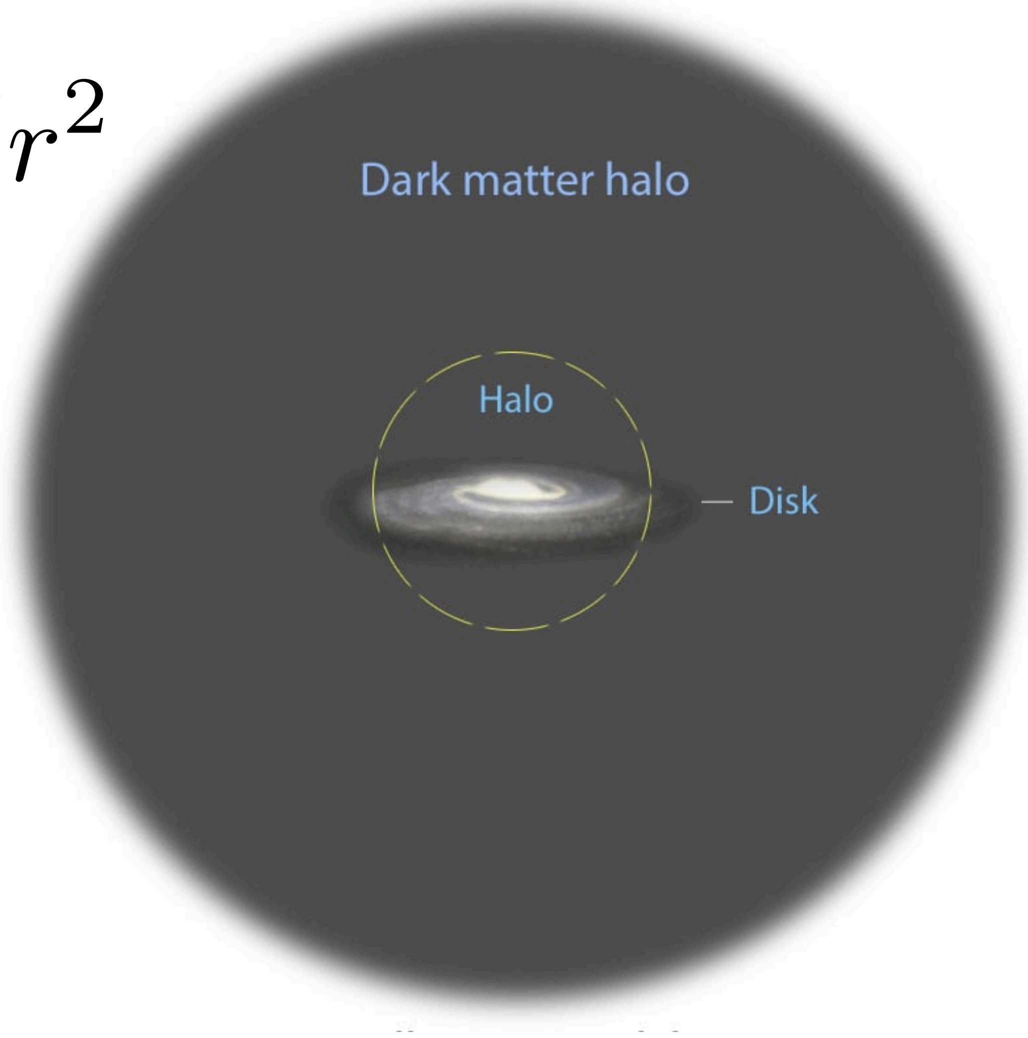
→ Cannot be measured directly

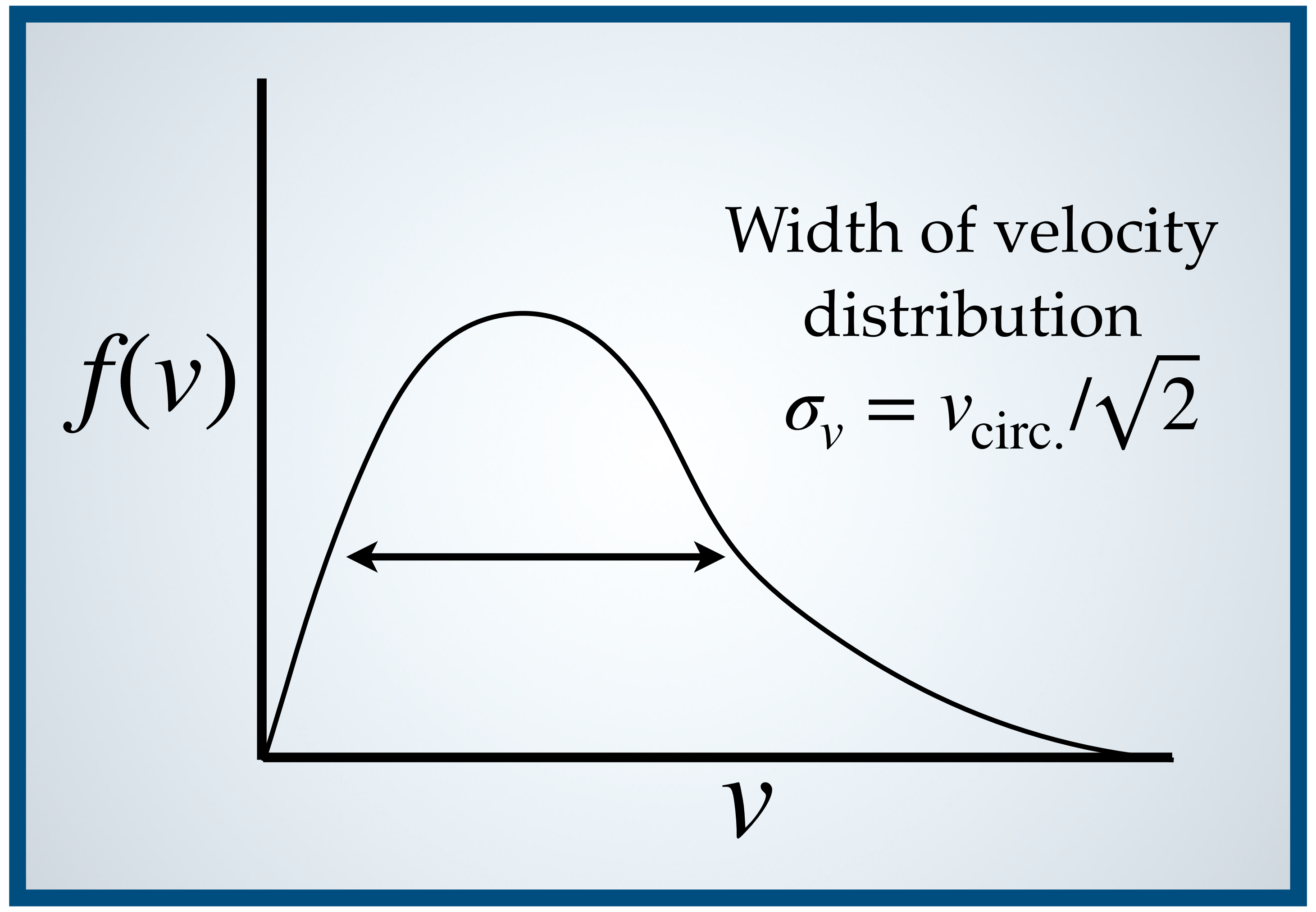
→ Enters non-trivially into direct dark matter detection signals, e.g. inside integrals over energy

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

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

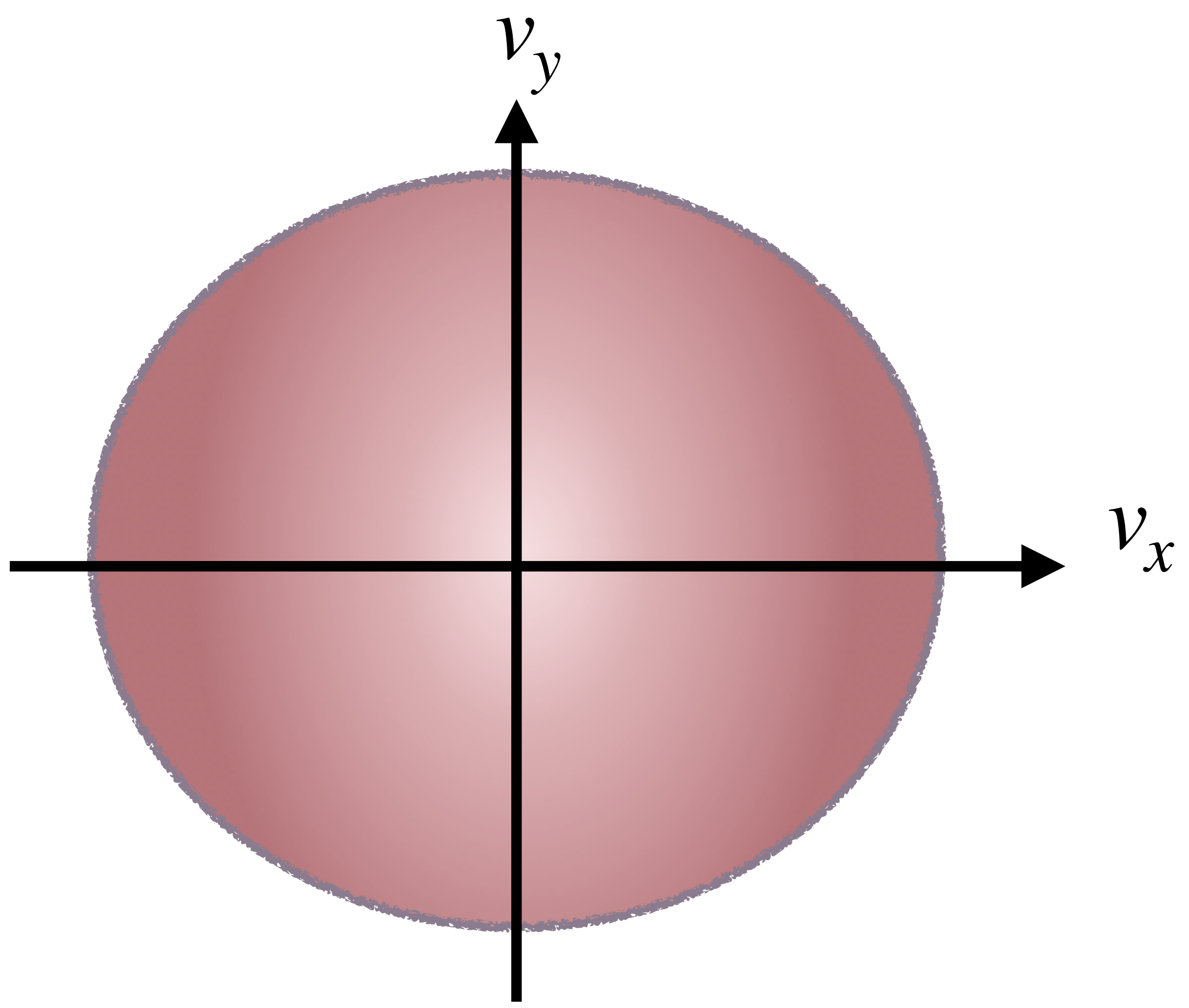
$\rho \sim 1/r^2$





$$\rho_{\rm dm} = 0.3\,{\rm GeV\,cm^{-3}}$$
$$v_{\rm circ} = 220\ {\rm km\ s^{-1}}$$
$$v_{\rm esc} = 544\,{\rm km\,s^{-1}}$$

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

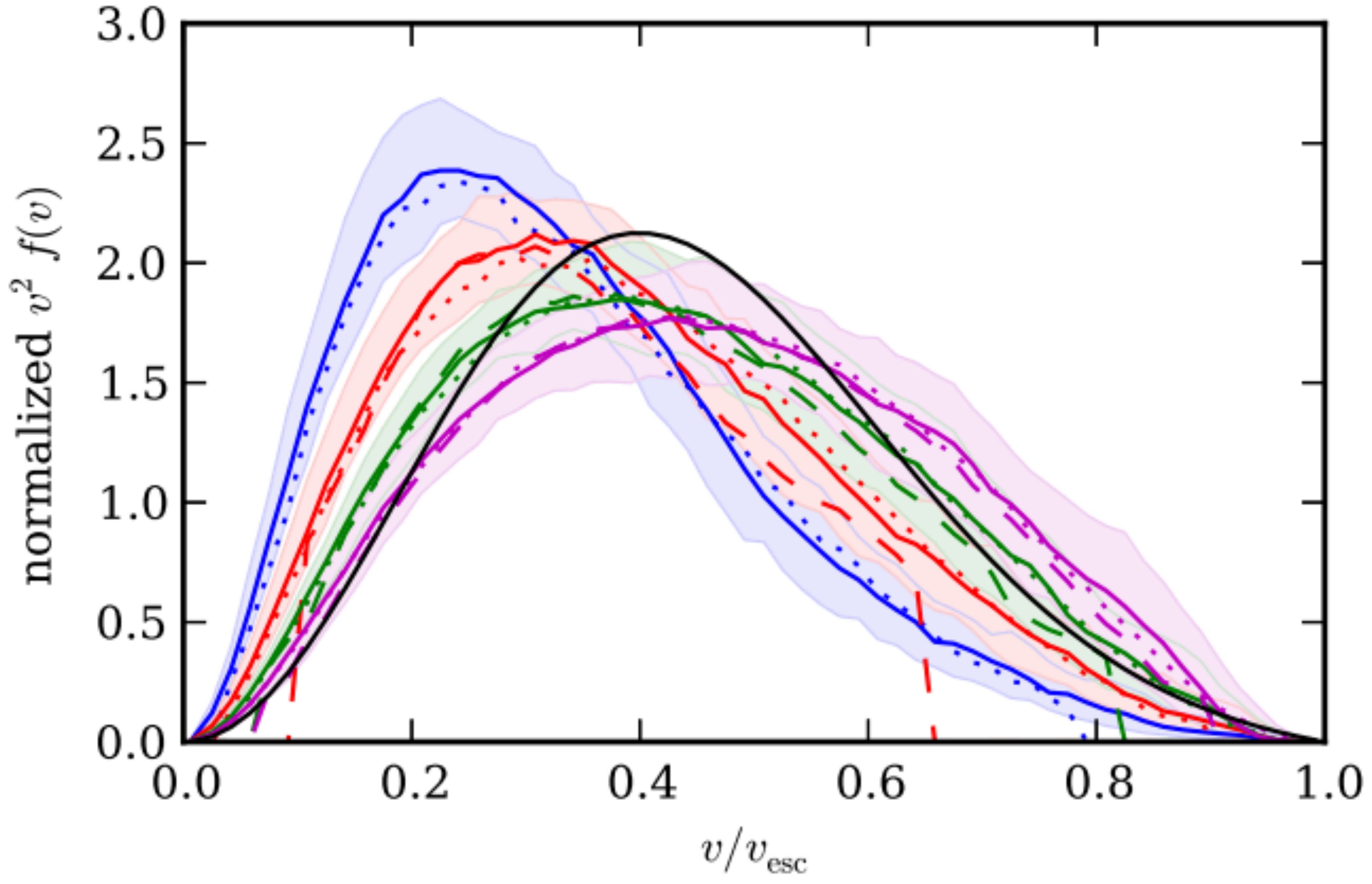


[Most implementations also correct for the finite extent of the real MW halo, by truncating at $v_{\rm esc}$. Important for experiments sensitive to high speed tail (e.g. light DM), but trivial otherwise]

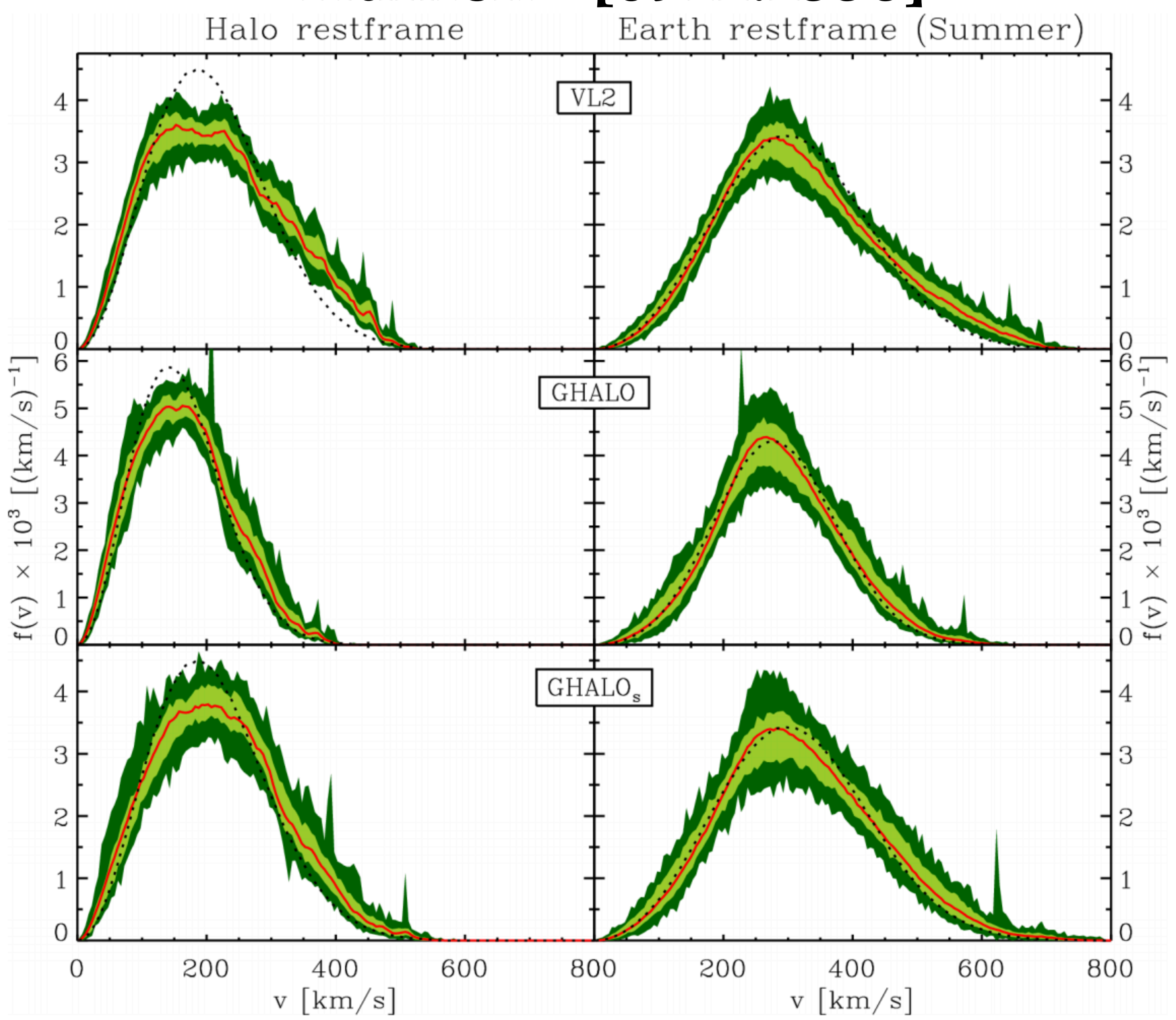
What do we expect a more accurate halo model to look like?

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

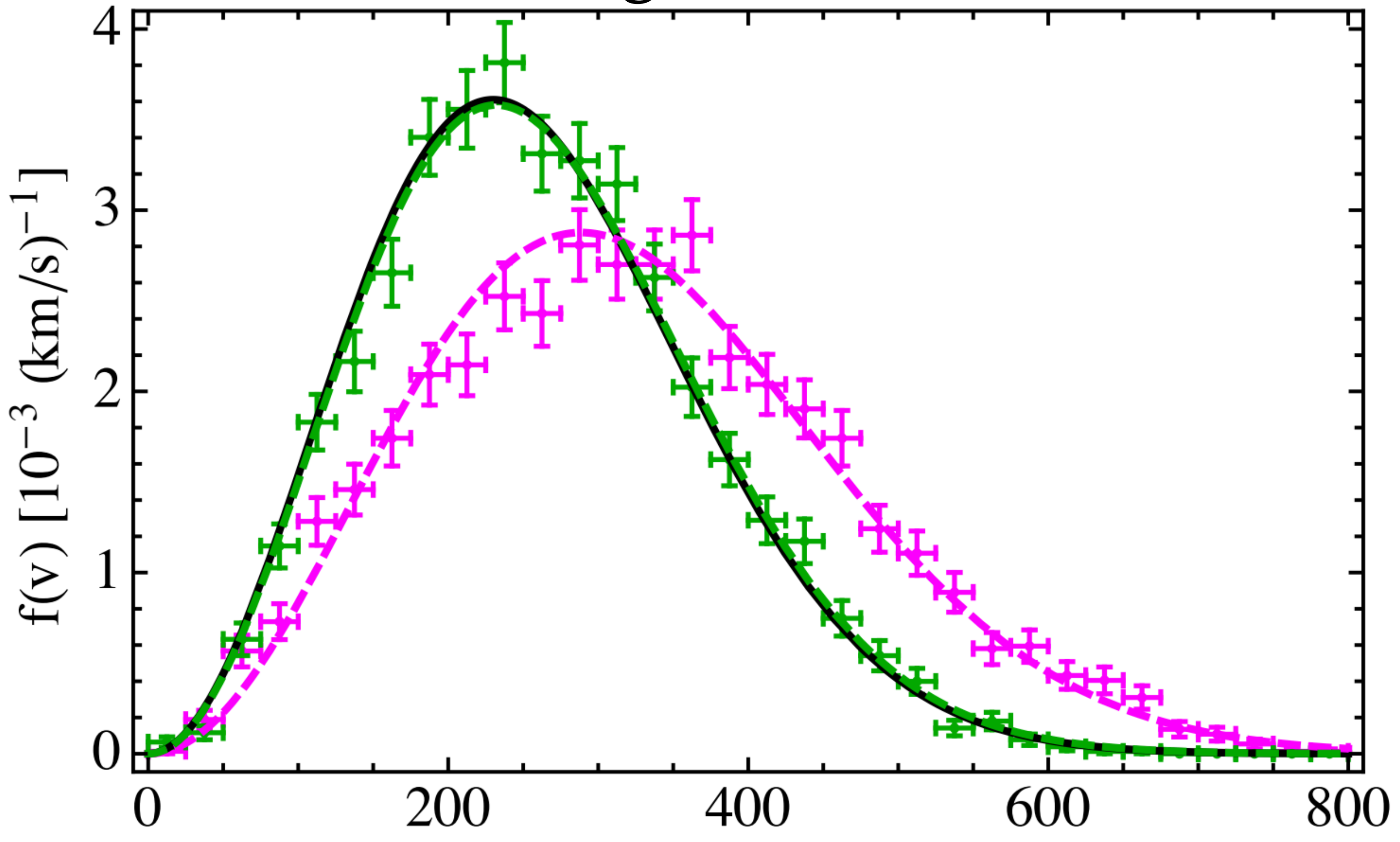
Mao+ [1210.2721]



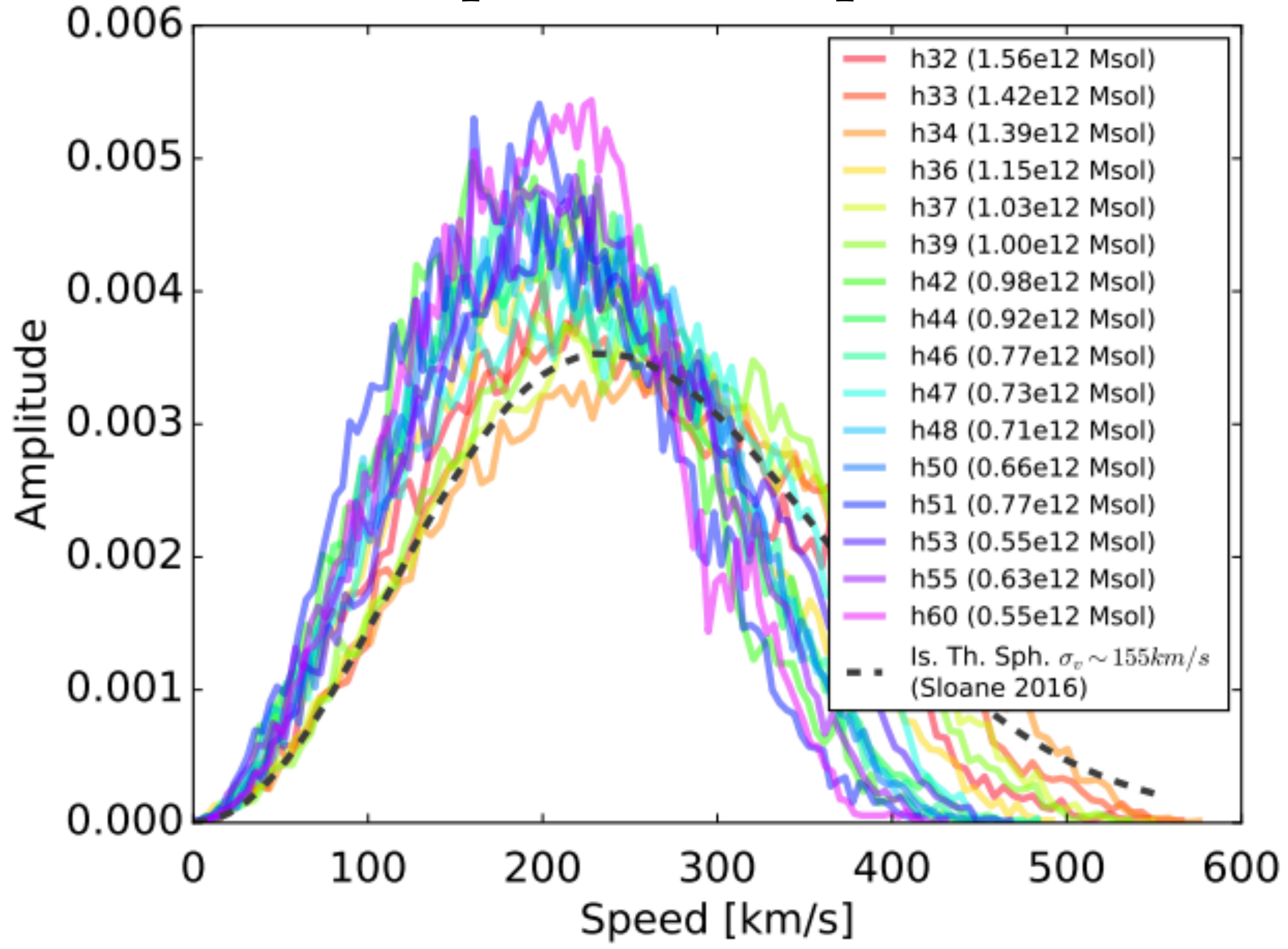
Kuhlen+ [0912.2358]



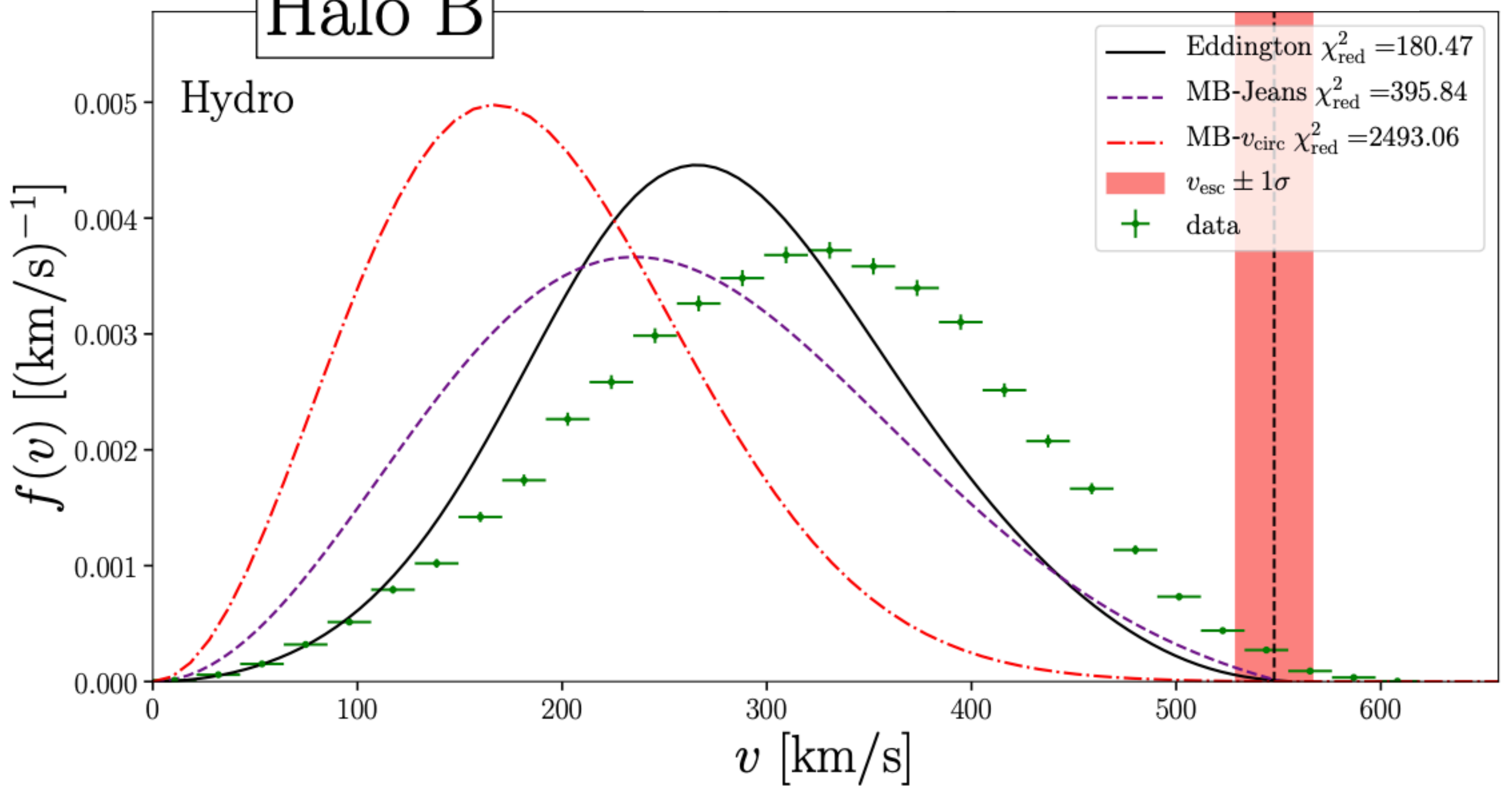
Bozorgnia+ [1601.04707]



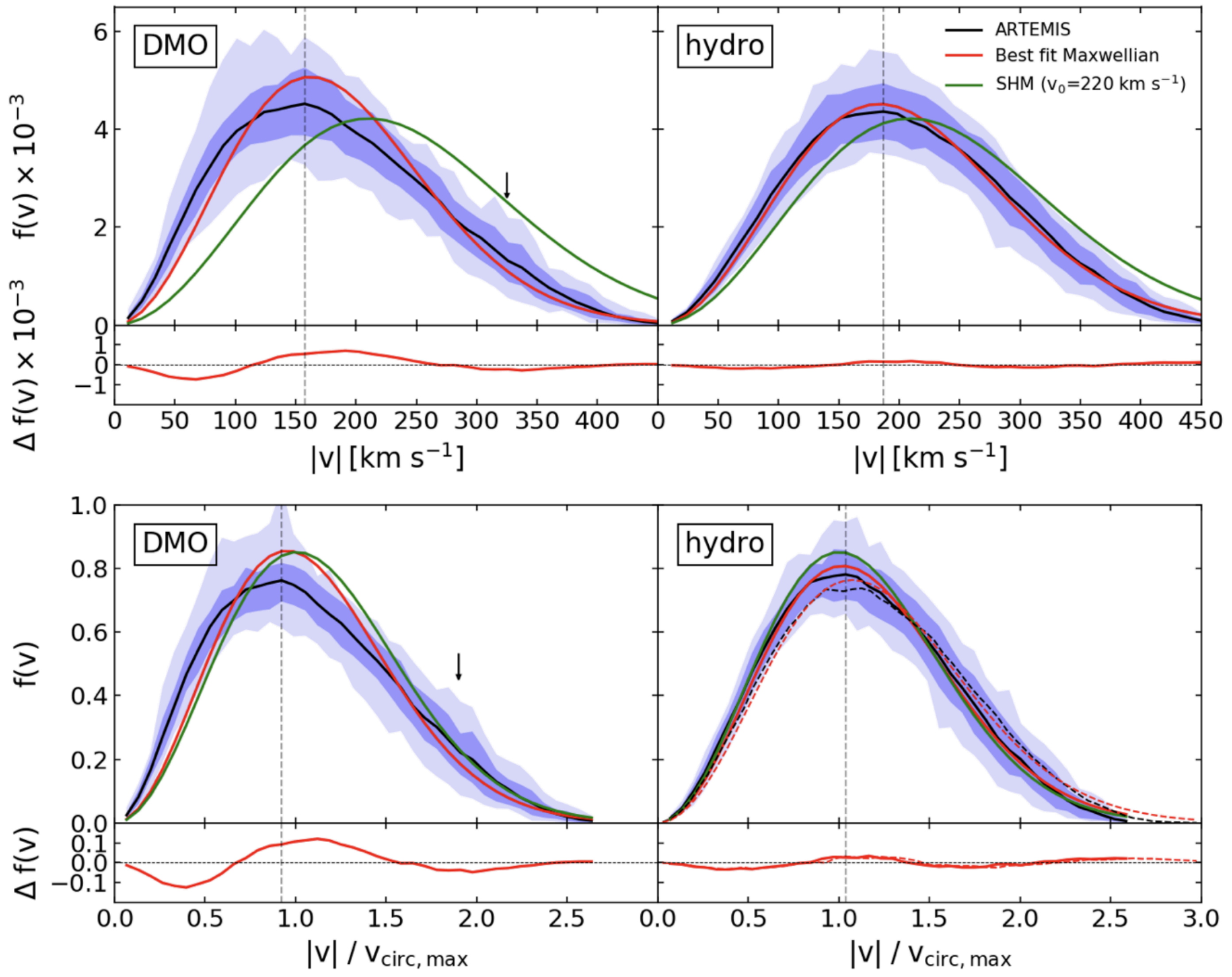
Lentz+ [1703.06937]



Lacroix+ [2005.03955]

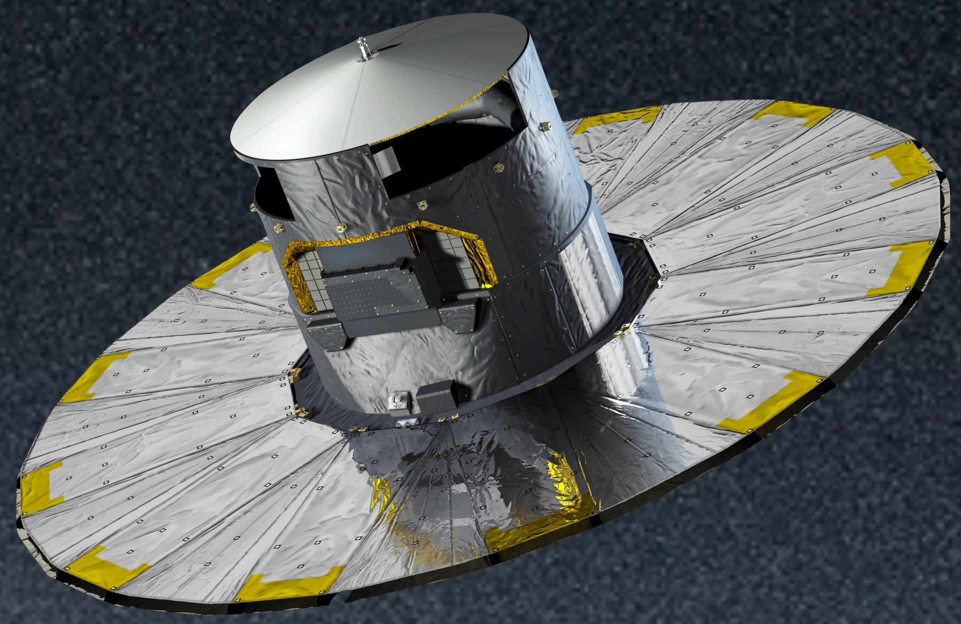


Poole-Mackenzie+ [2006.15159]



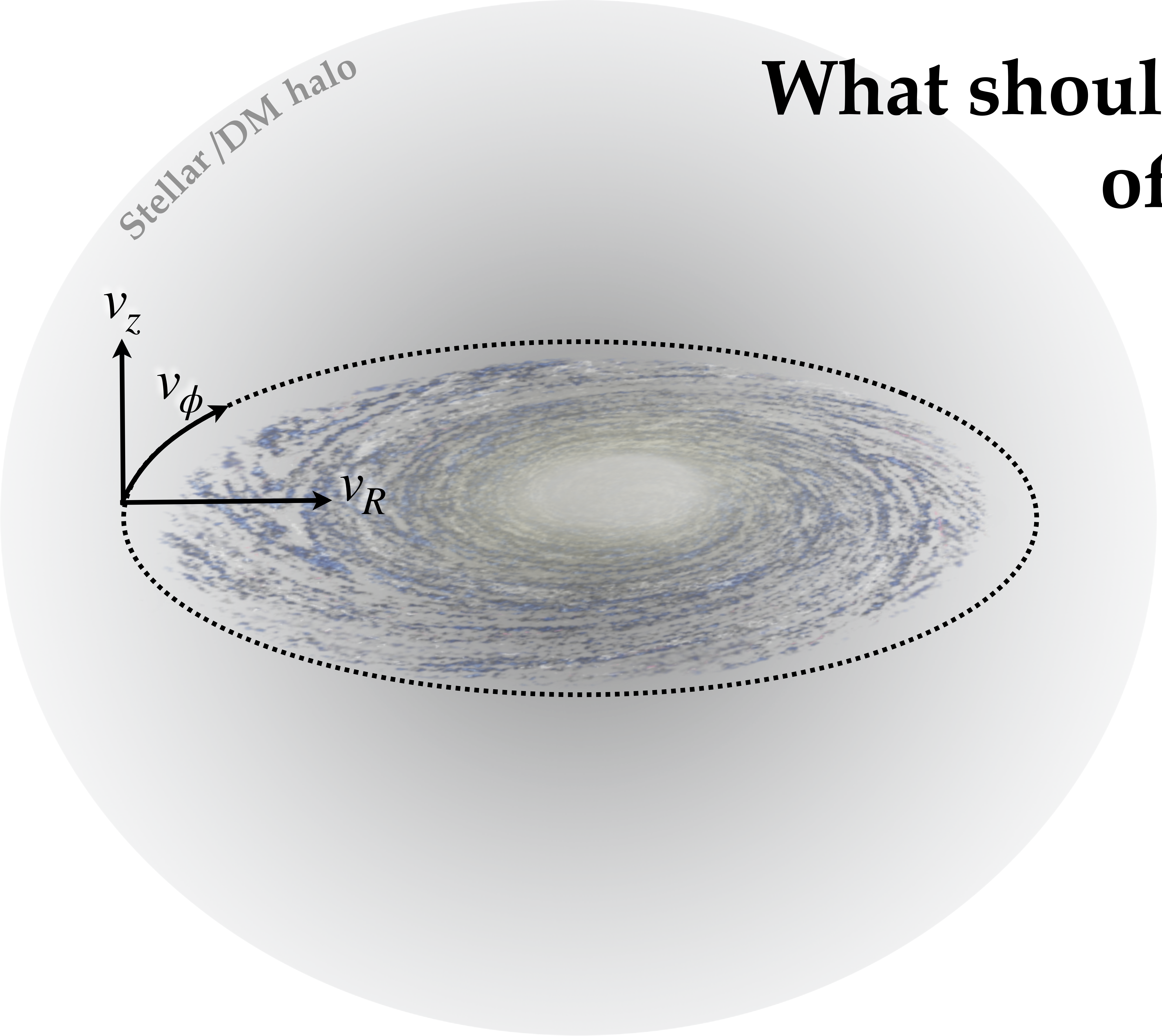
Luminous tracers of the DM halo?

Gaia

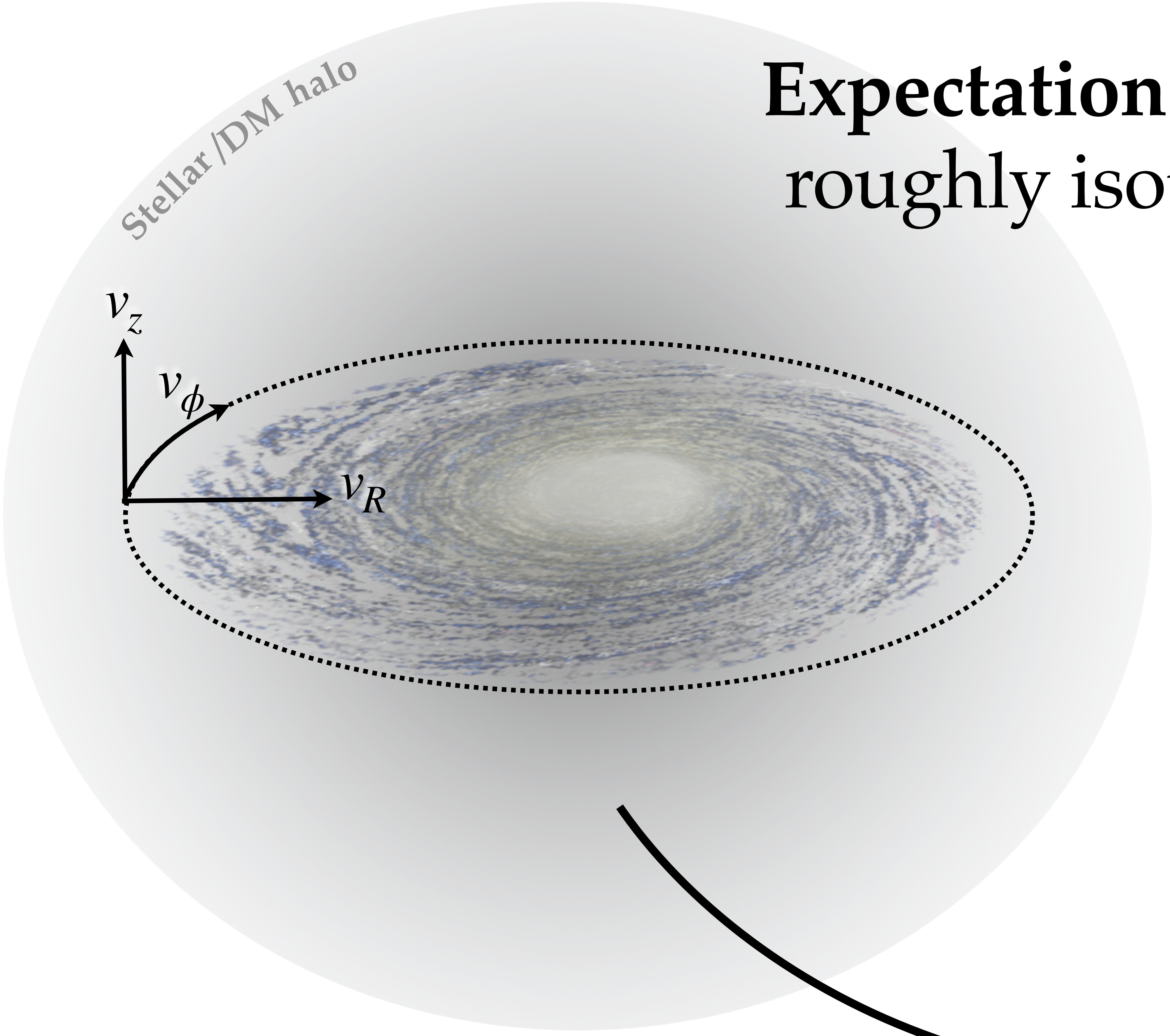


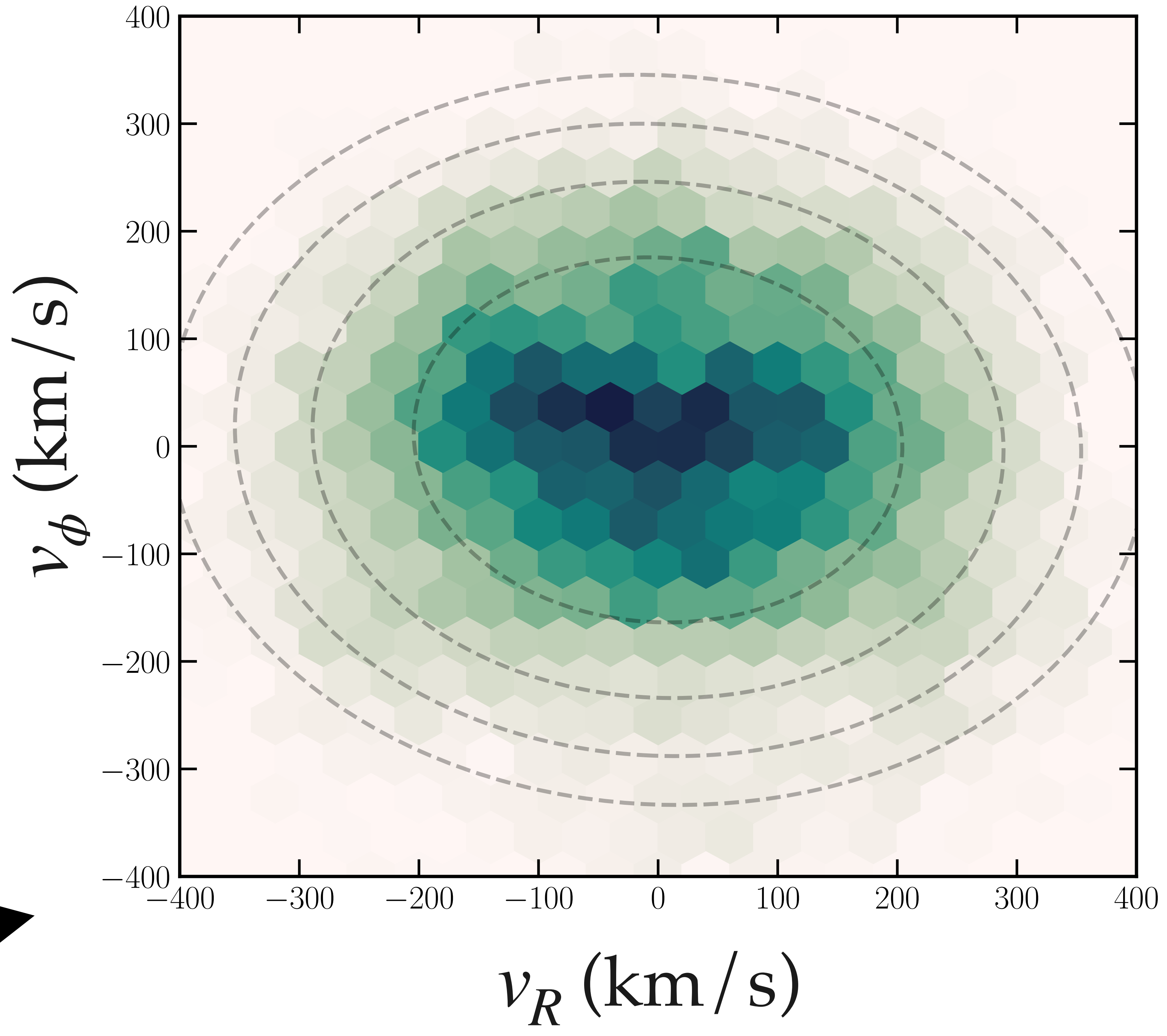
- 1.7 billion stars (1% of MW)
- 1.3 billion in 5D $(\alpha,\delta,\varpi,\mu_{\alpha^*},\mu_\delta)$
- 7 million in 6D (x,y,z,v_x,v_y,v_z)

What should the velocity distribution of the stellar halo look like?

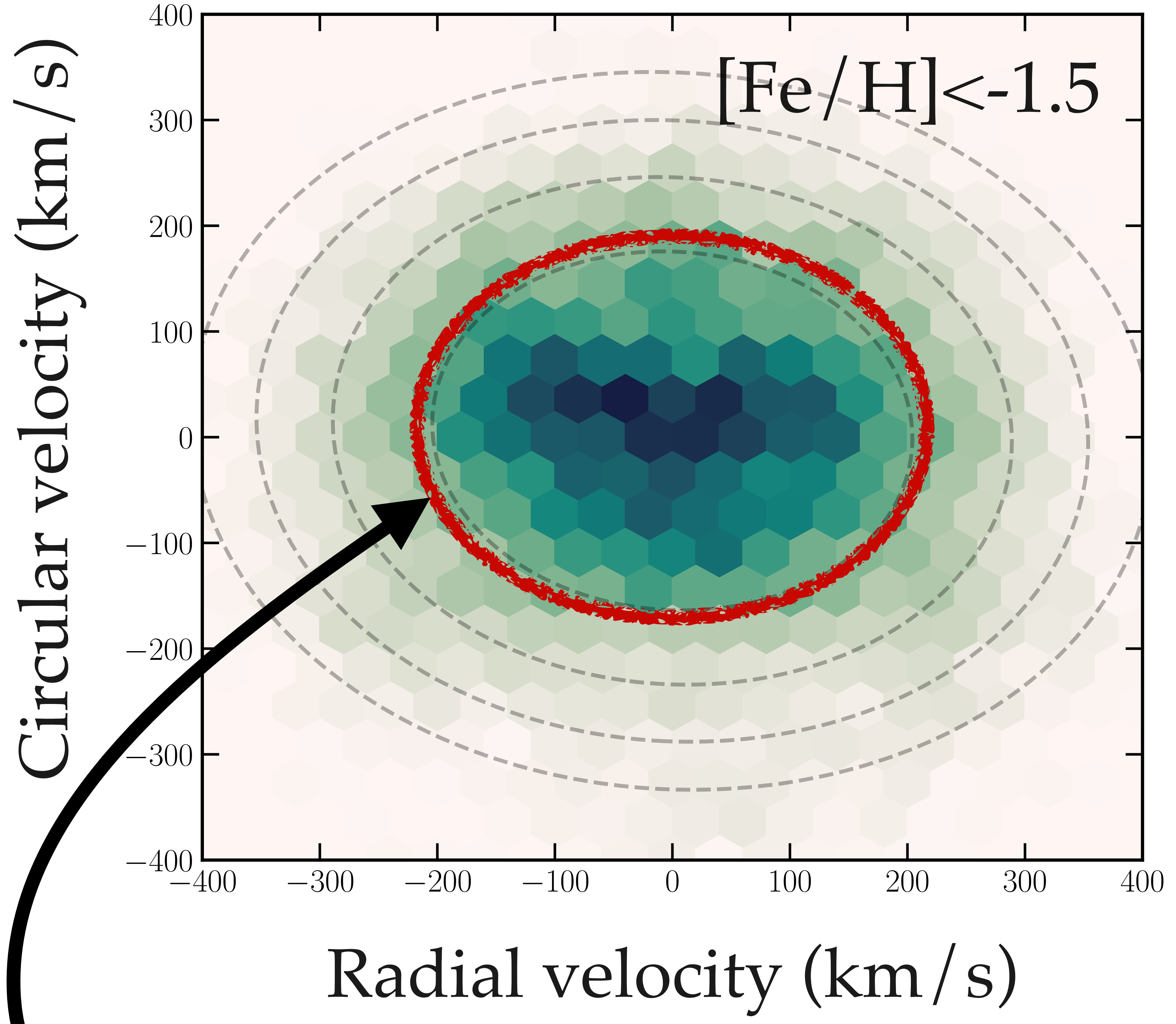


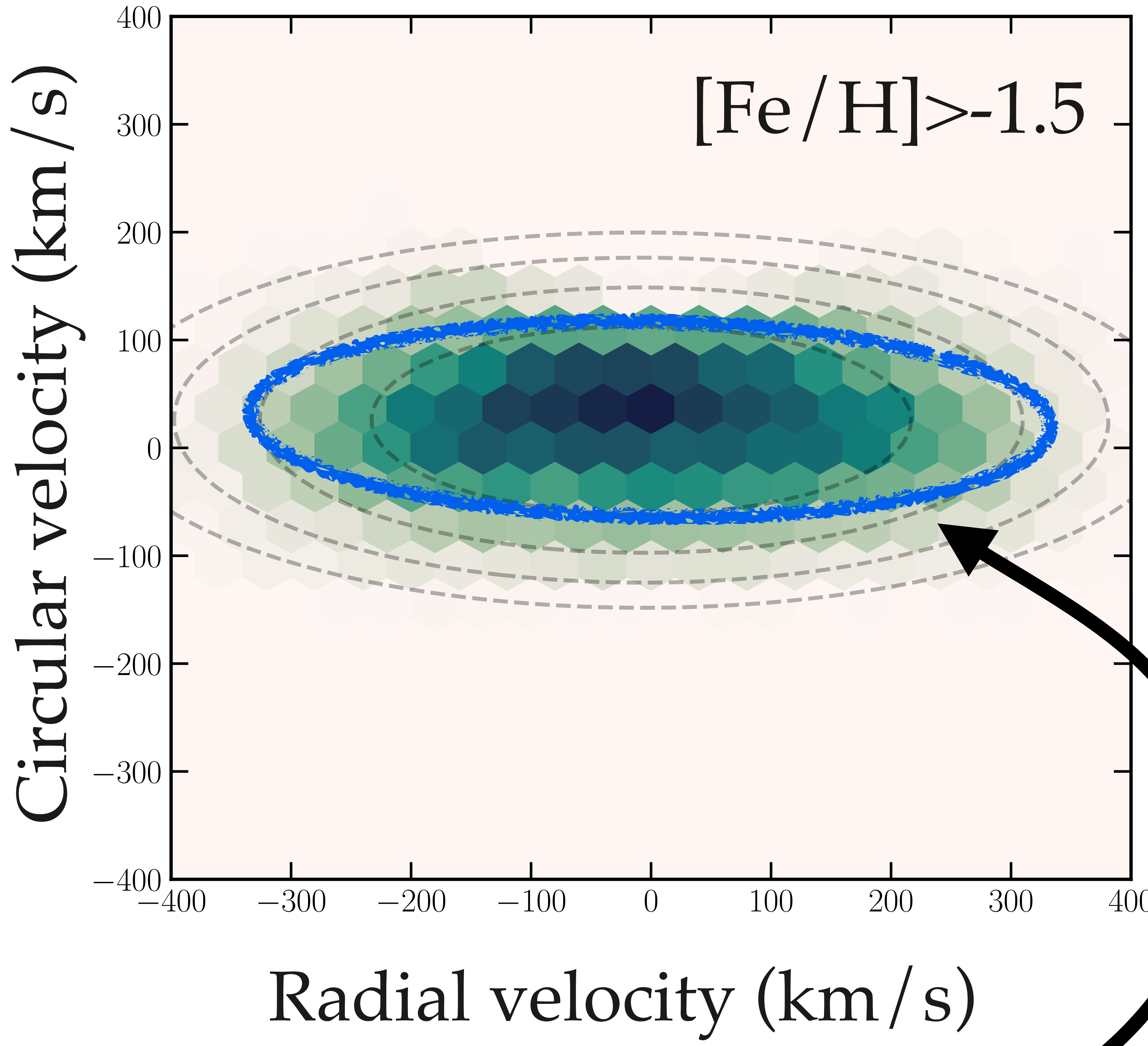
Expectation: stellar halo should have a roughly isotropic velocity distribution





What does the stellar halo *really* look like?





"Metal-poor" halo

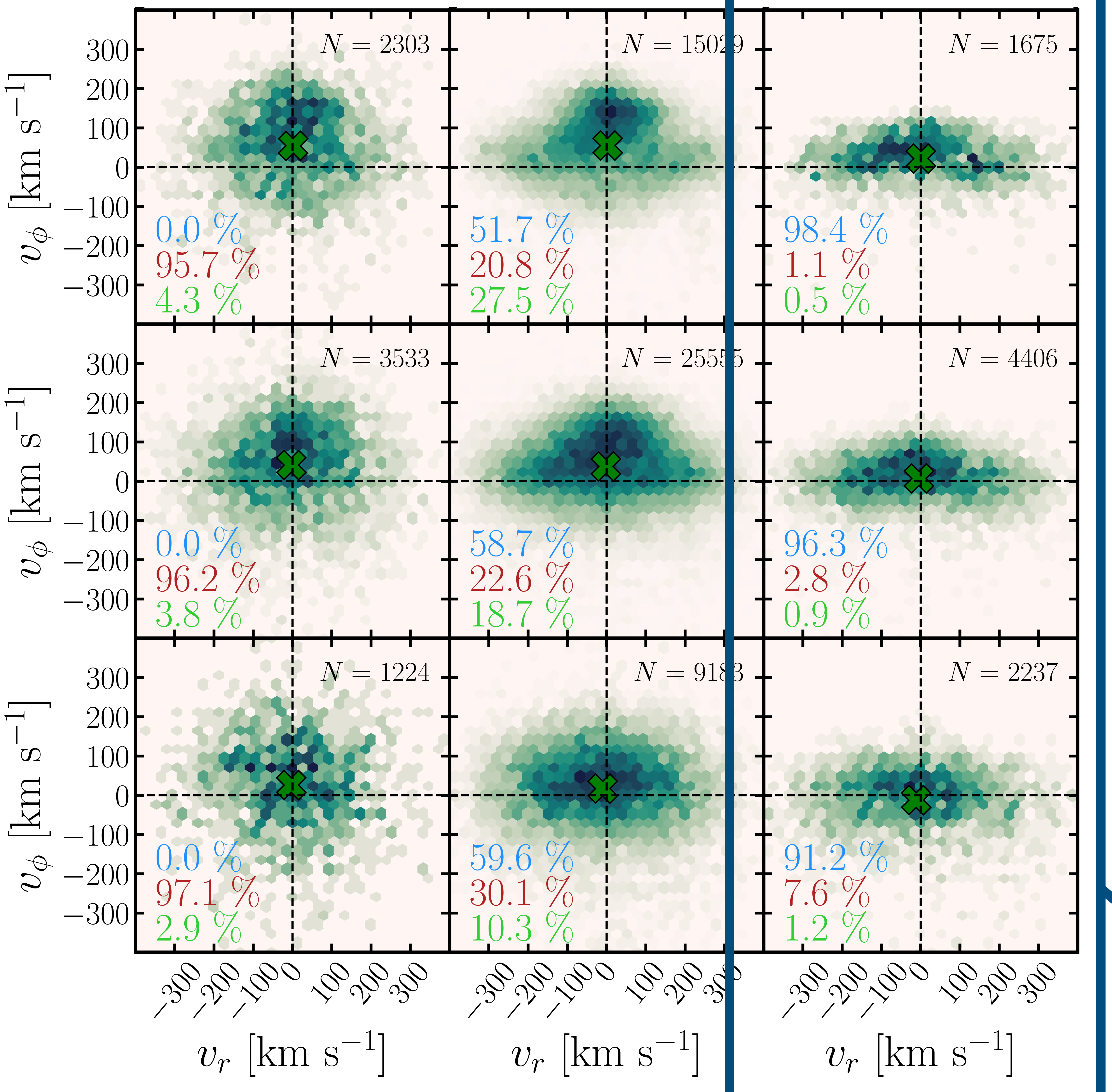
- Round velocity ellipsoid
- ~30% of main sequence halo sample
- More metal-poor on average

"Metal-rich" halo

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

Sample of *Gaia* main sequence stars from stellar halo within 10 kpc with distances provided by SDSS

Metallicity →



Height above disk ↓

“Sausage”-shaped velocity distribution?

“Gaia Enceladus”

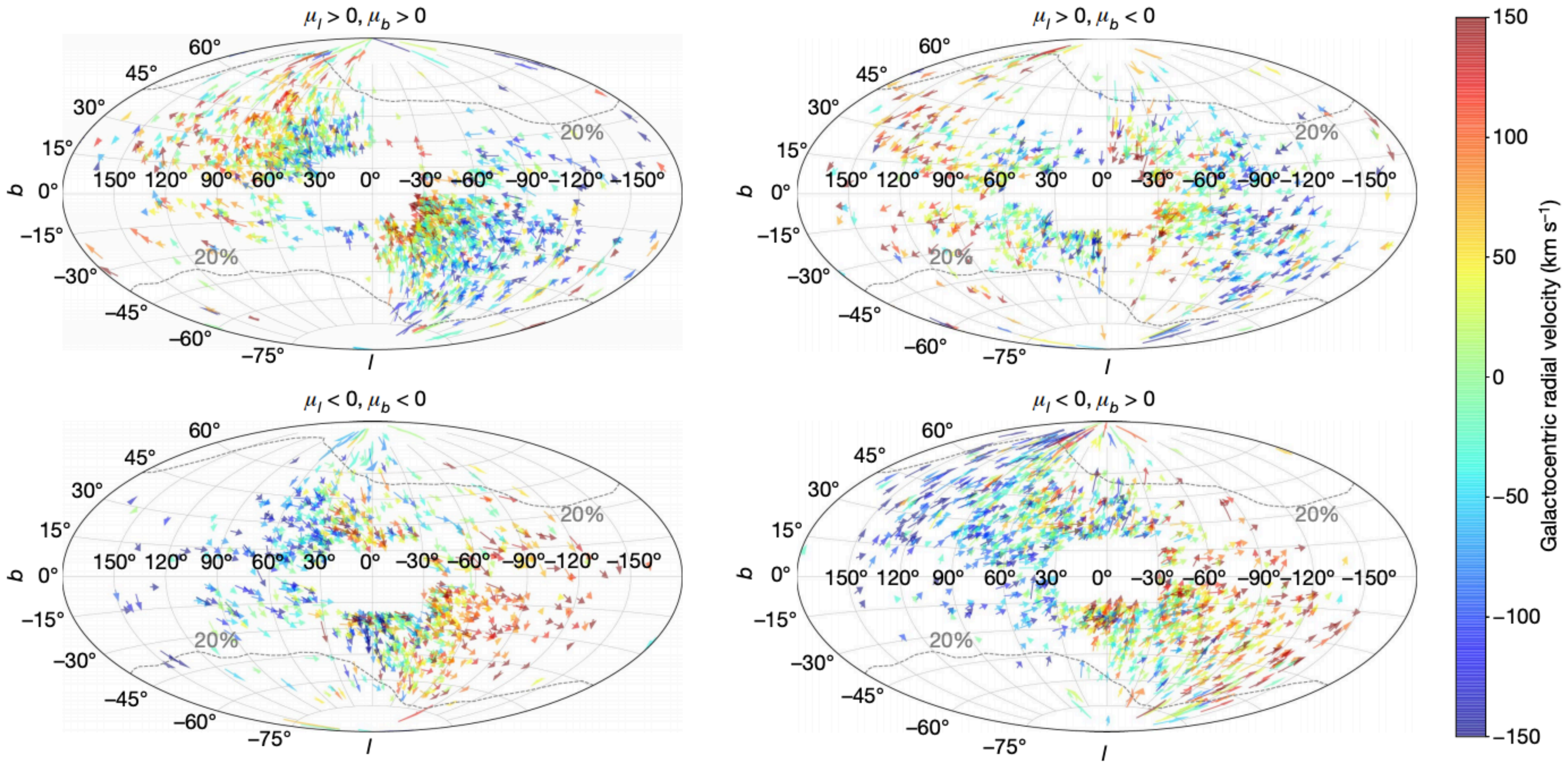
1806.06038

“Gaia Sausage”

1802.03414

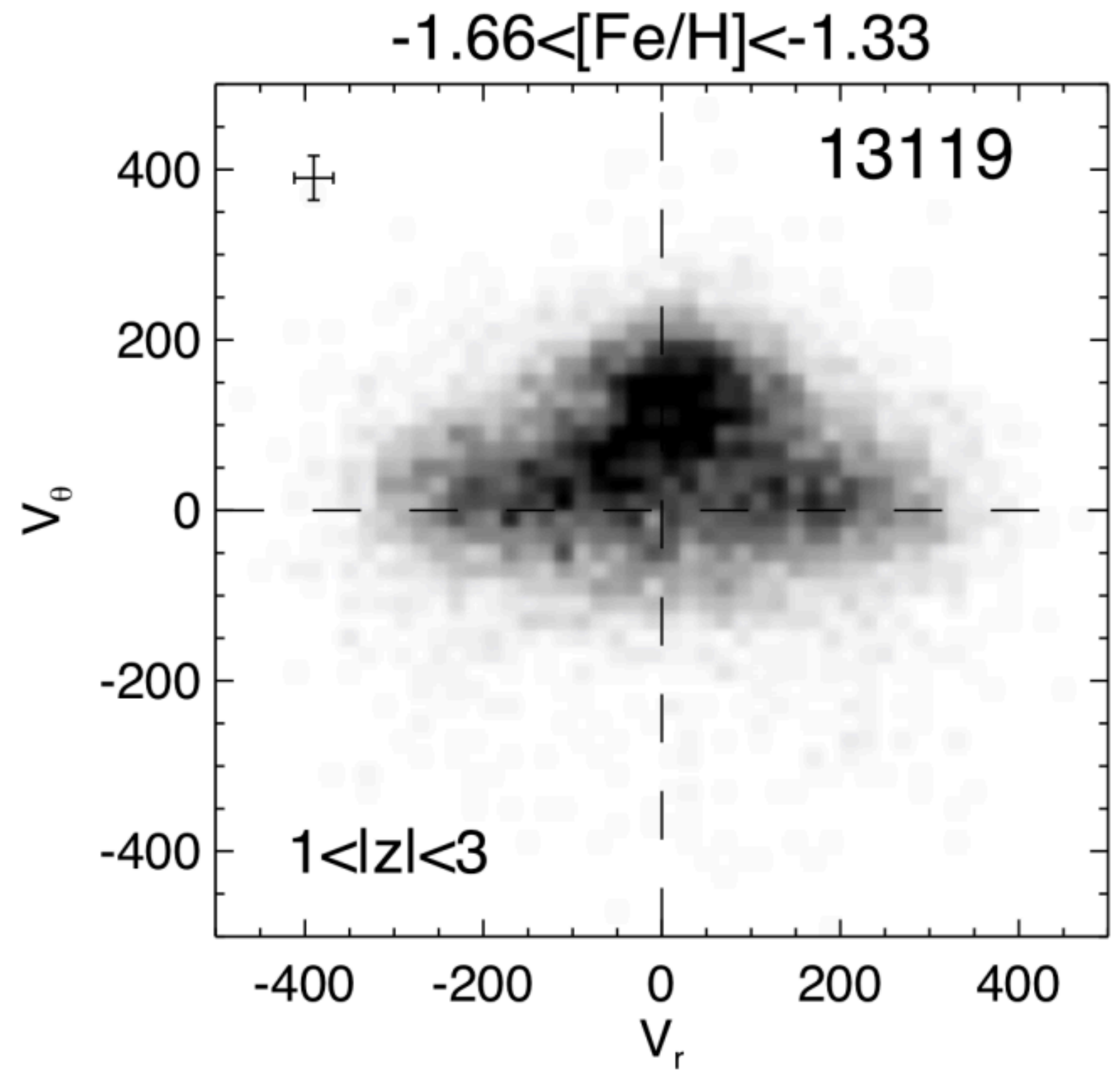
The merger that led to the formation of the Milky Way’s inner stellar halo and thick disk

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_θ) 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,

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*

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,

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,

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

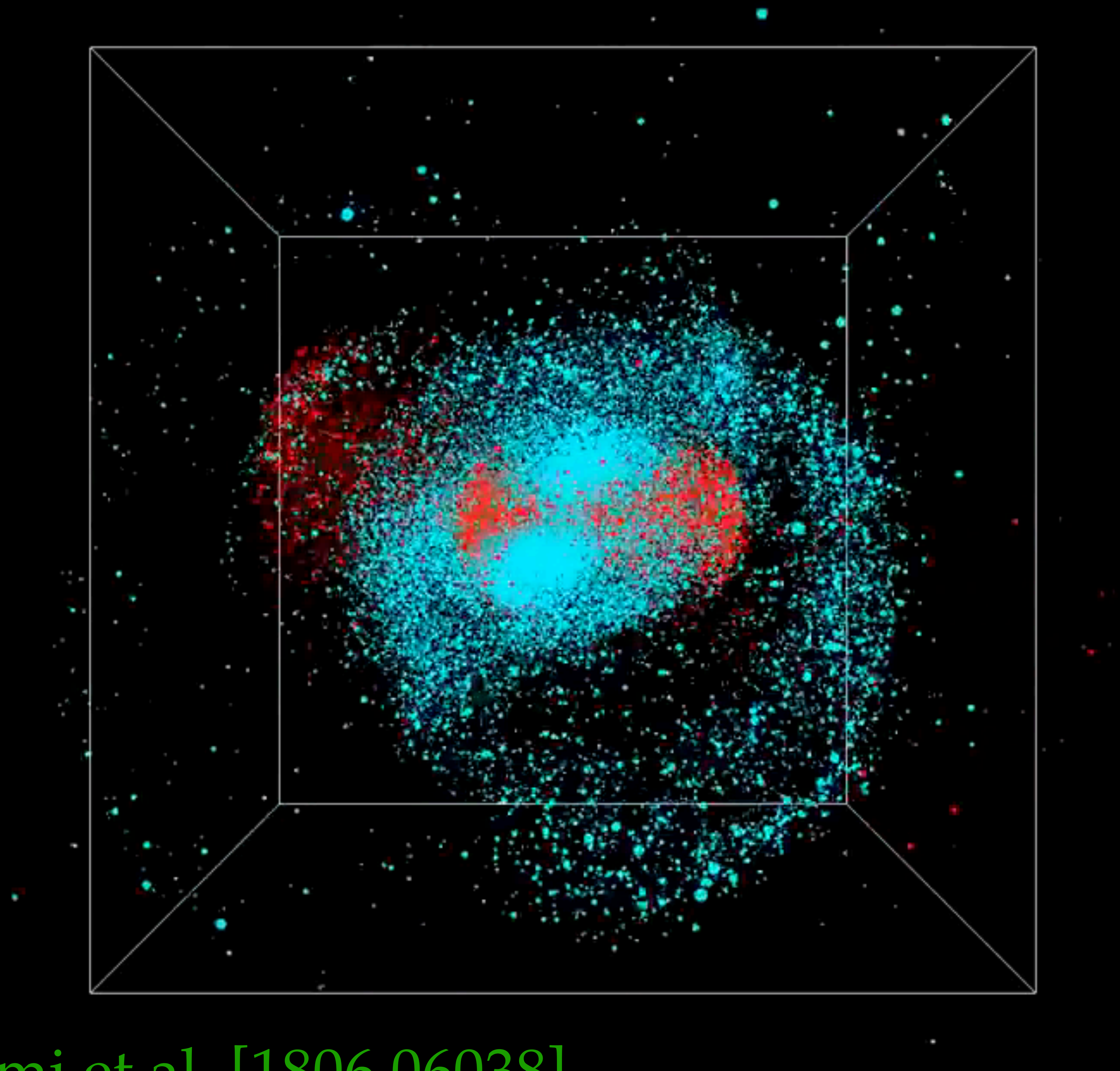
Selecting accreted populations: metallicity, elemental abundances, and ages of the Gaia-Sausage-Enceladus and Sequoia populations

Diane K. Feuillet, Christian L. Sahlholdt, Sofia Feltzing, Luca Casagrande

Identifying stars found in the Milky Way as having formed in situ or accreted can be a complex and uncertain undertaking. We use Gaia kinematics and APOGEE elemental abundances to select stars belonging to the Gaia-Sausage-Enceladus (GSE) and Sequoia accretion events. These samples are used to characterize the GSE and Sequoia population metallicity distribution functions, elemental abundance patterns, age distributions, and progenitor masses. We find that the GSE population has a mean [Fe/H] ~ -1.15 and a mean age of $10-12$ Gyr. GSE has a single sequence in [Mg/Fe] vs [Fe/H] consistent with

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

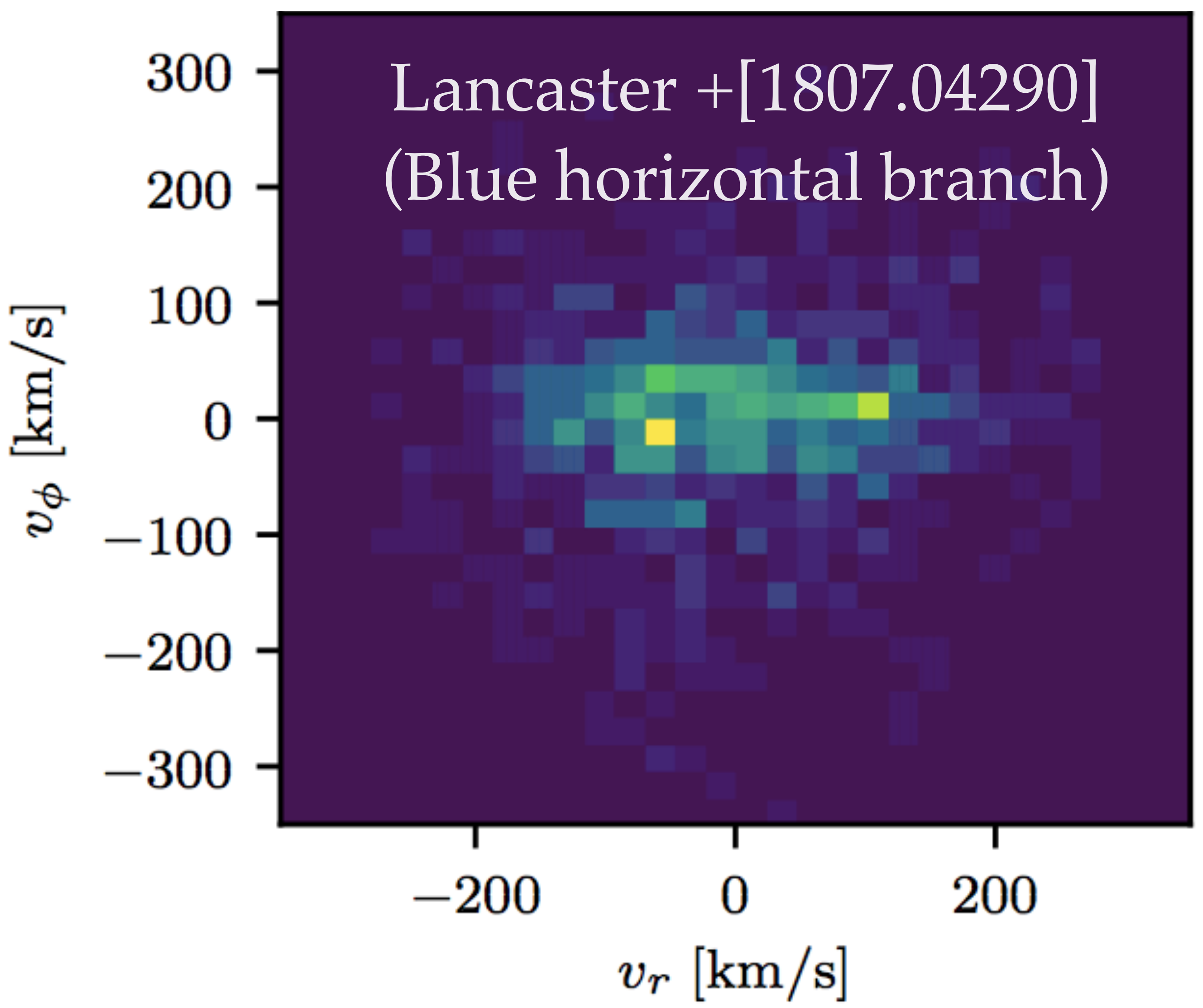


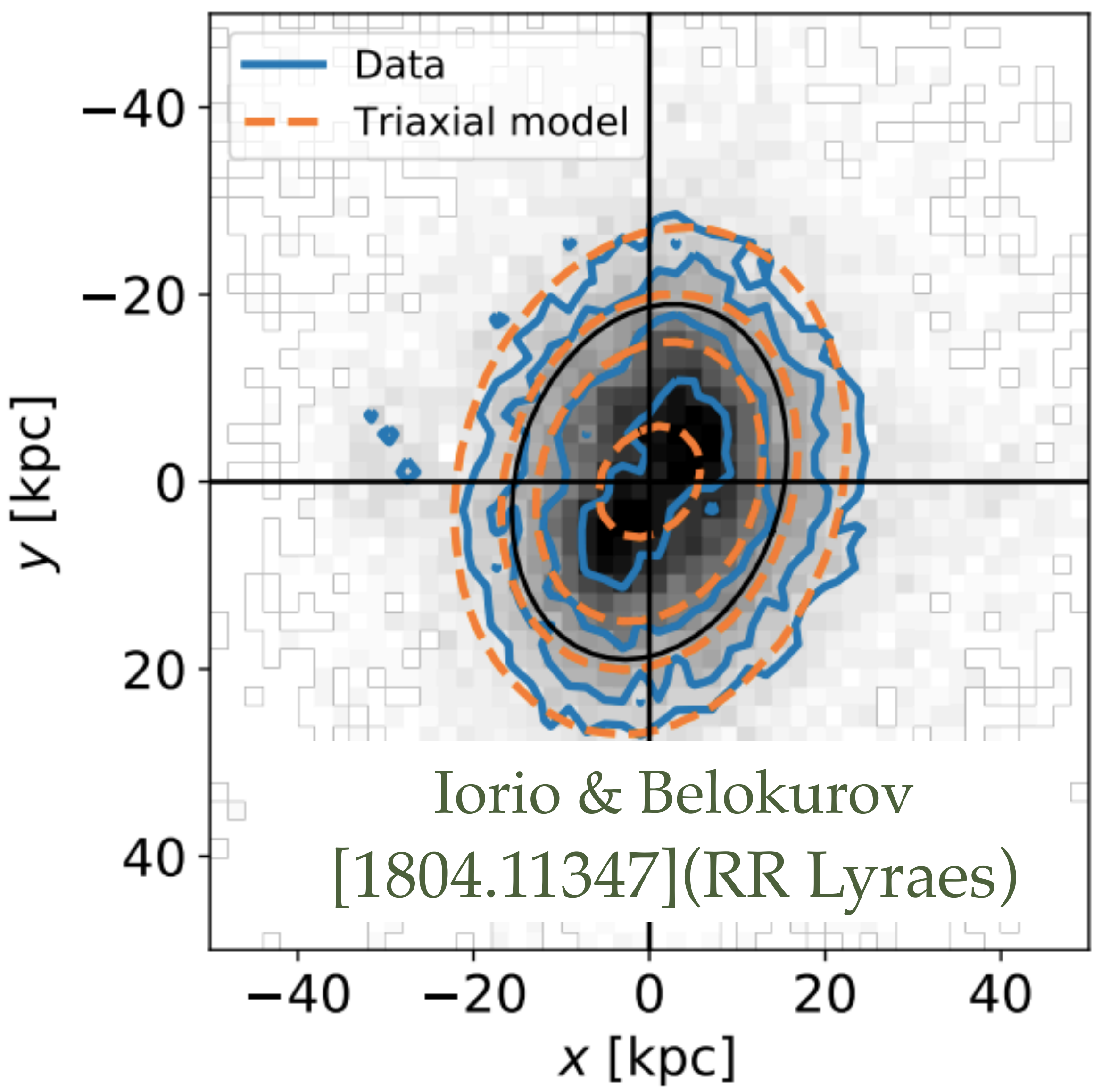
Helmi et al. [1806.06038]

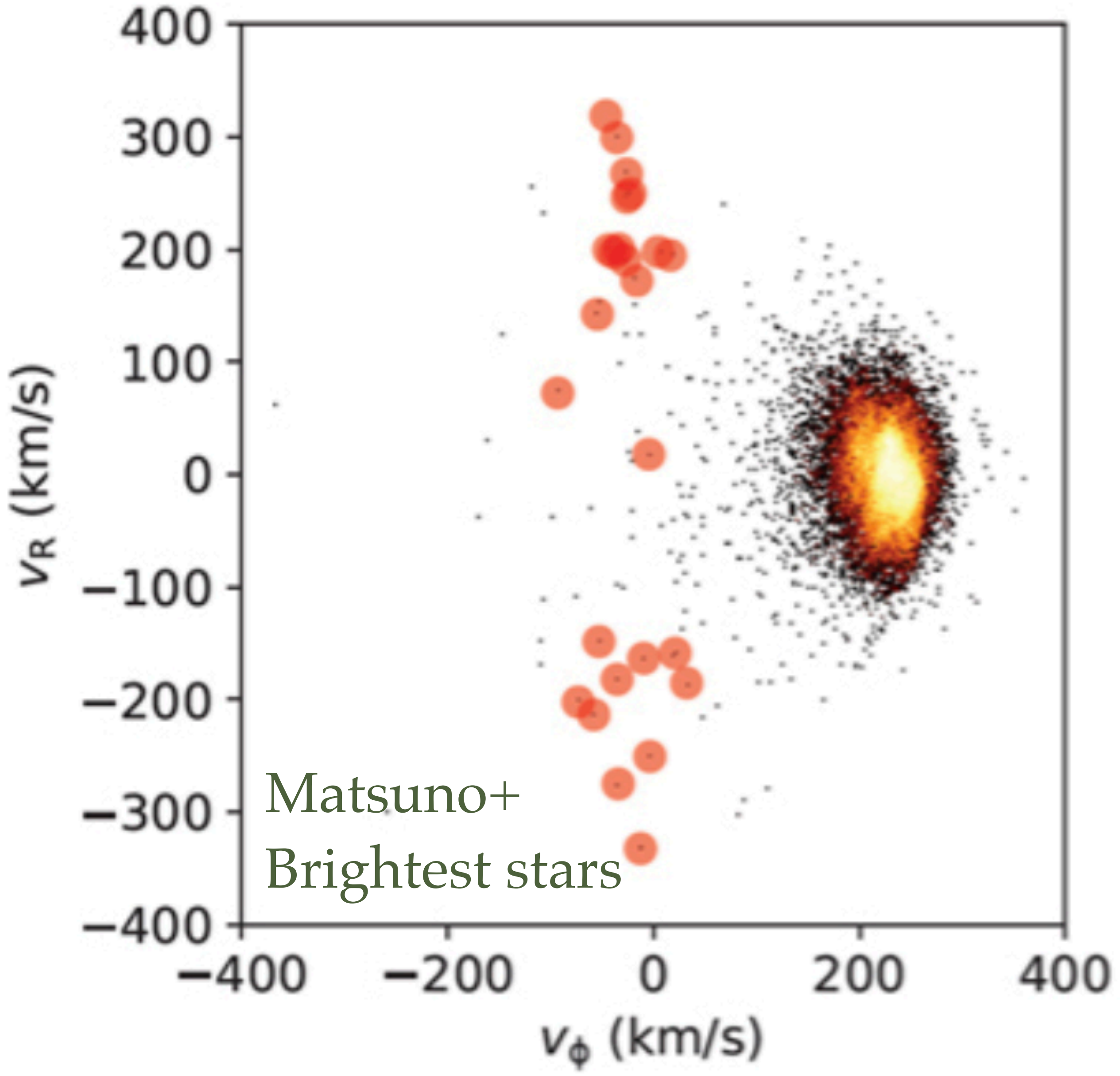
Further evidence:

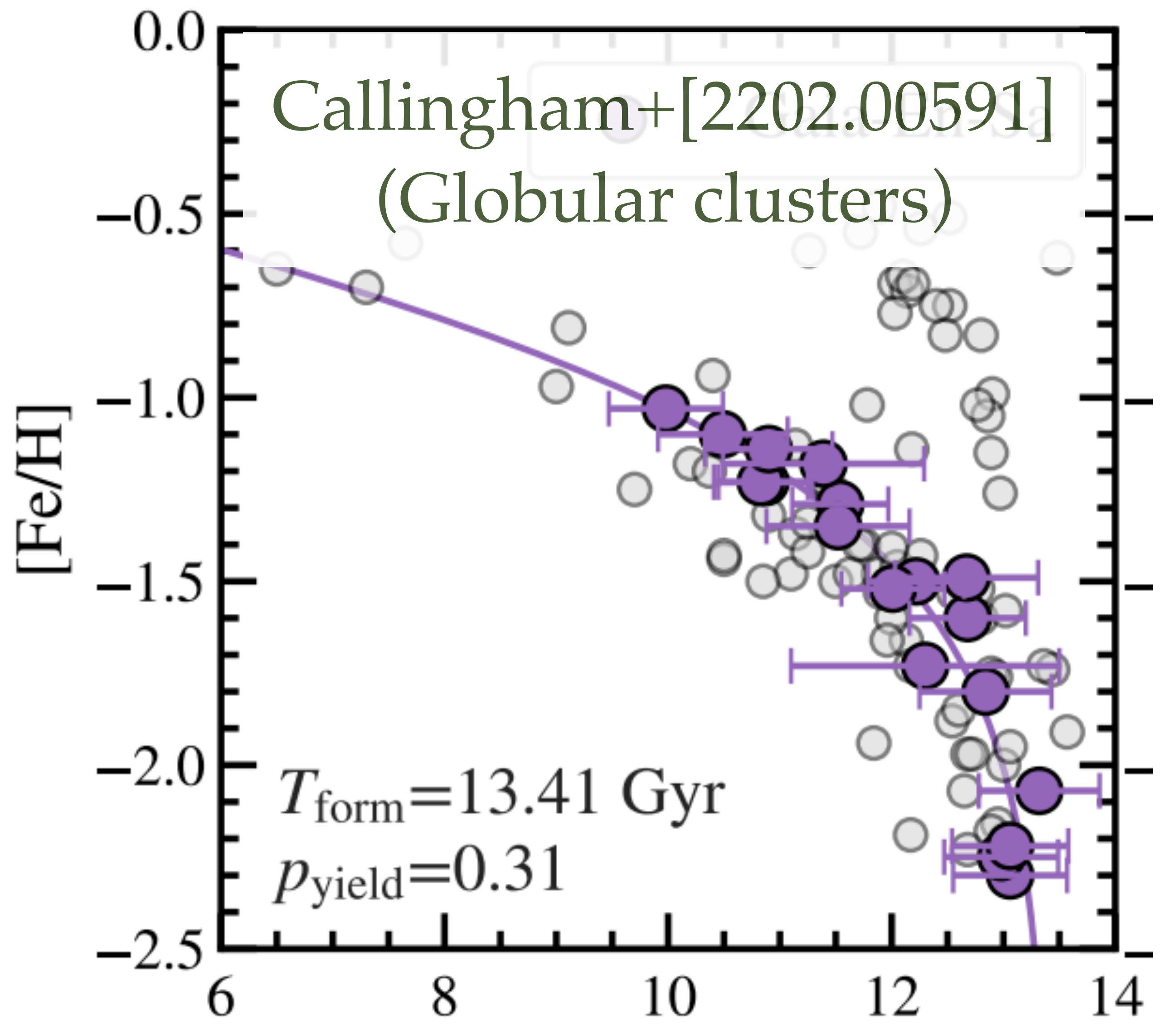
- Stellar density break at 20 kpc from pileup of stars at apocentre Deason+[1805.10288]
- Dynamical heating of thick disk stars into halo-like orbits (the “Splash”) Belokurov+ [1909.04679, 2008.02280]
- Connected to at least 16 known GCs Myeong+ [1805.00453], Callingham+[2202.00591]
- Explains previously observed over densities in the halo (Hercules-Aquila cloud / Virgo over density) Naidu+[2103.03251]

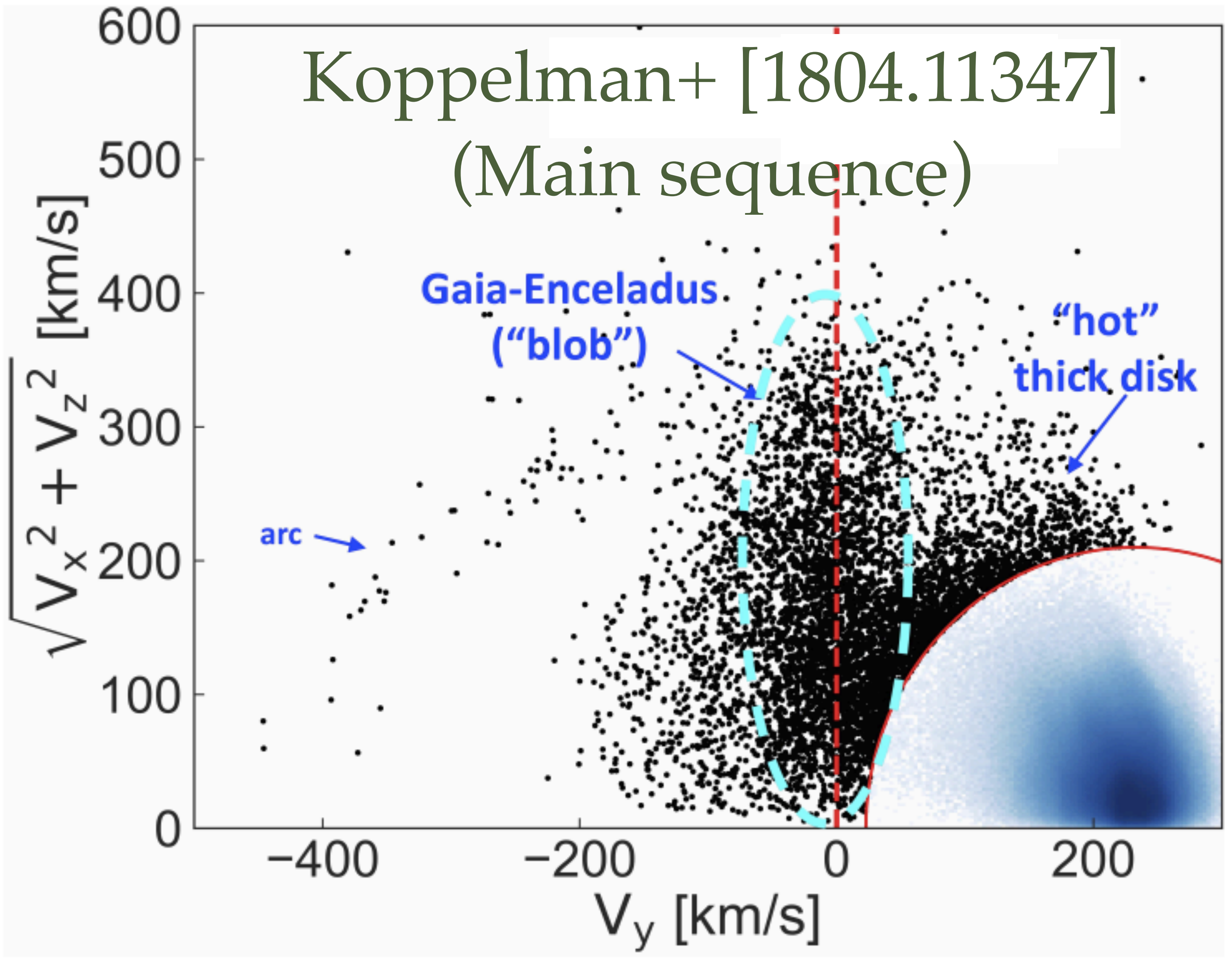
More on the sausage…

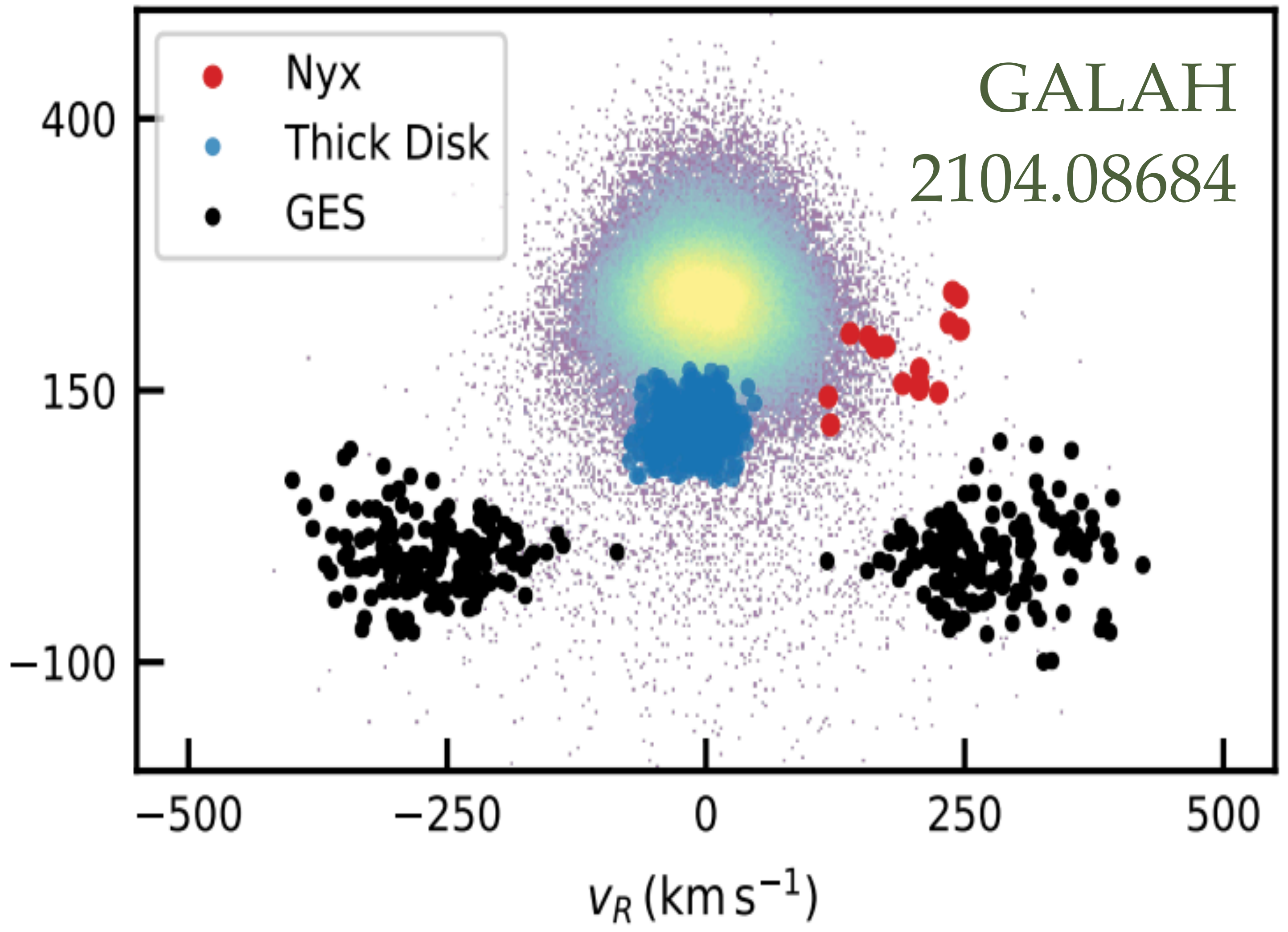








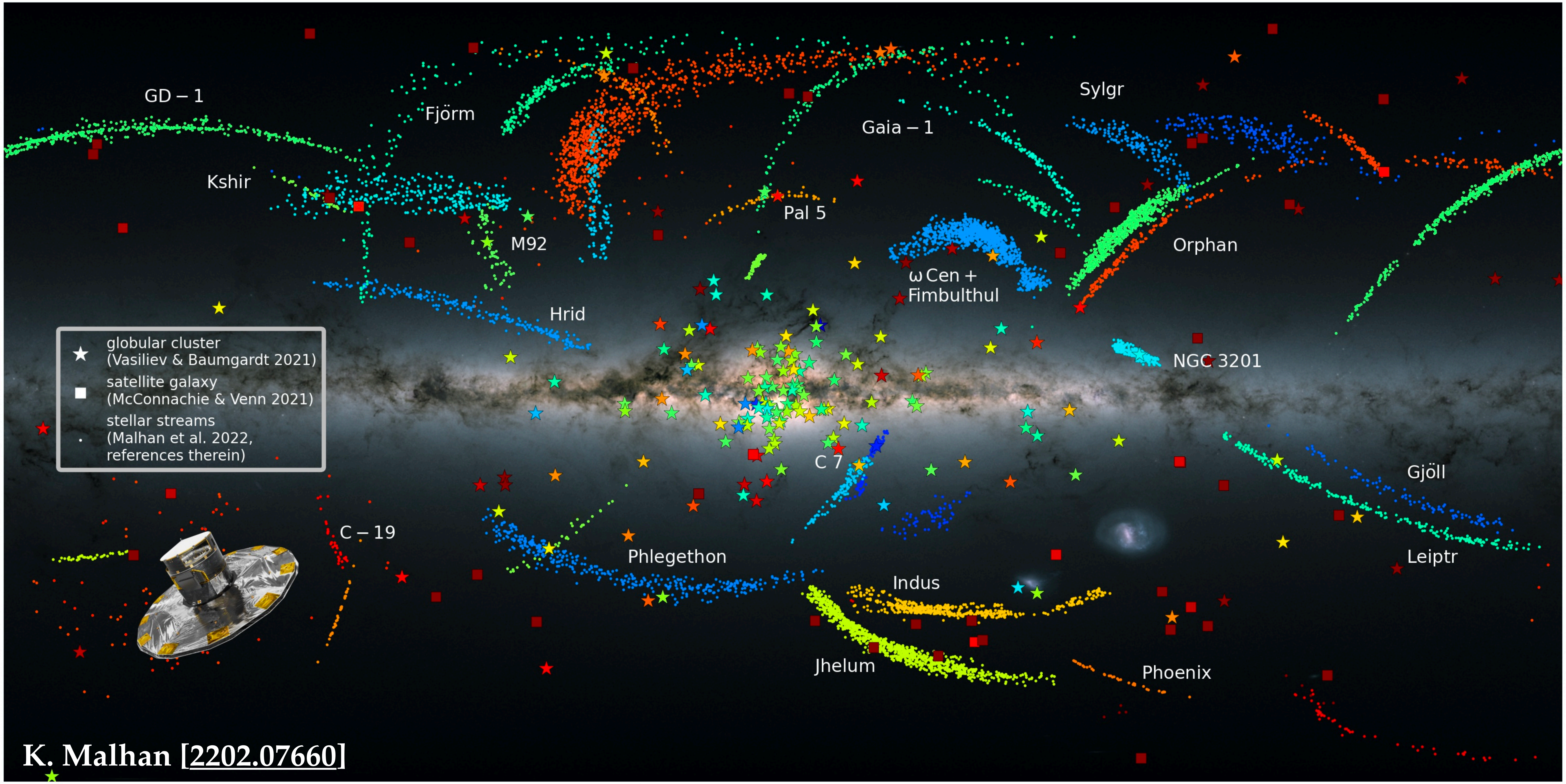




Streams

→ Generic result of hierarchical structure formation

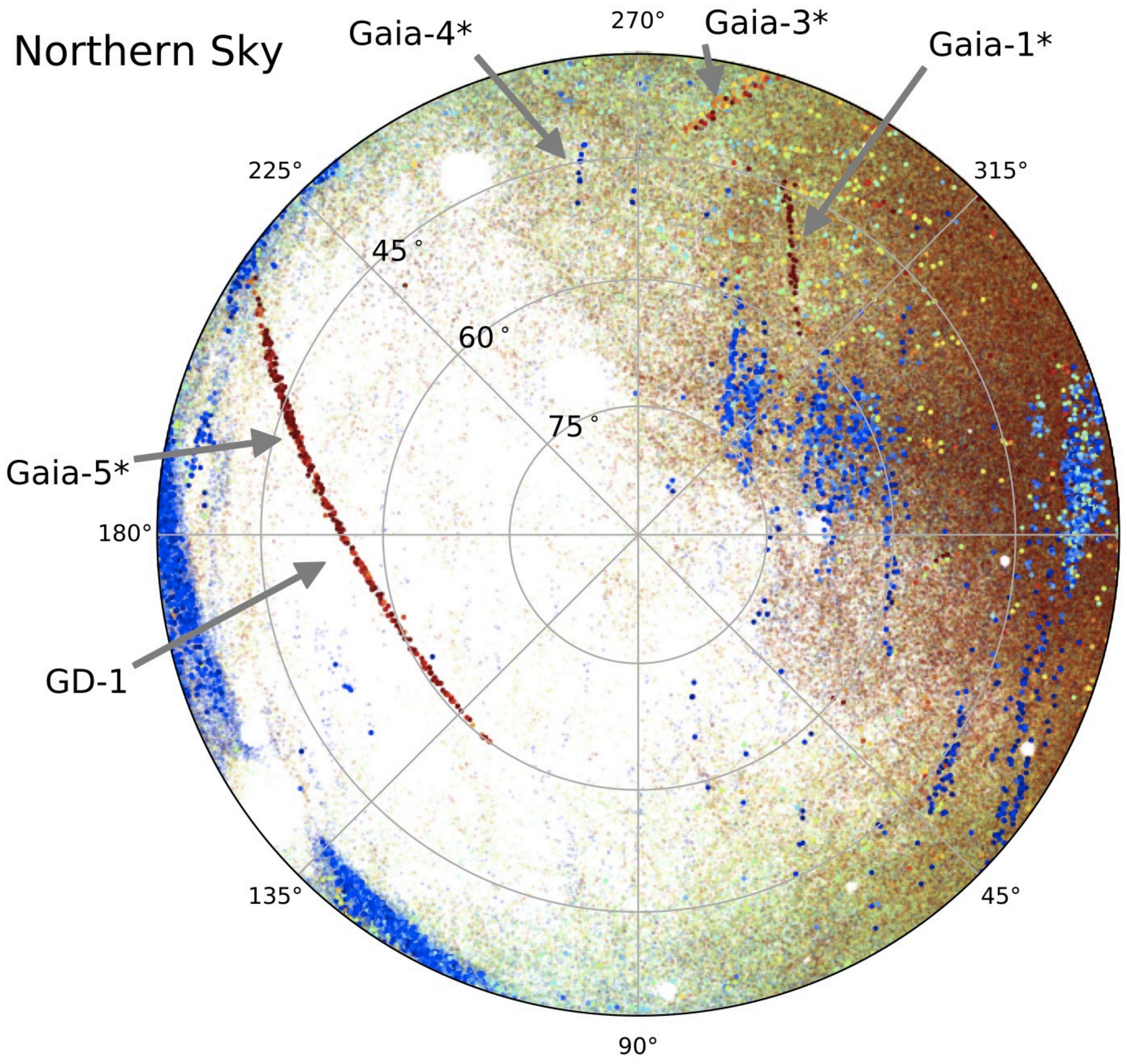
→ Formed of stars/DM from tidally stripped GCs, dwarfs, subhalos …



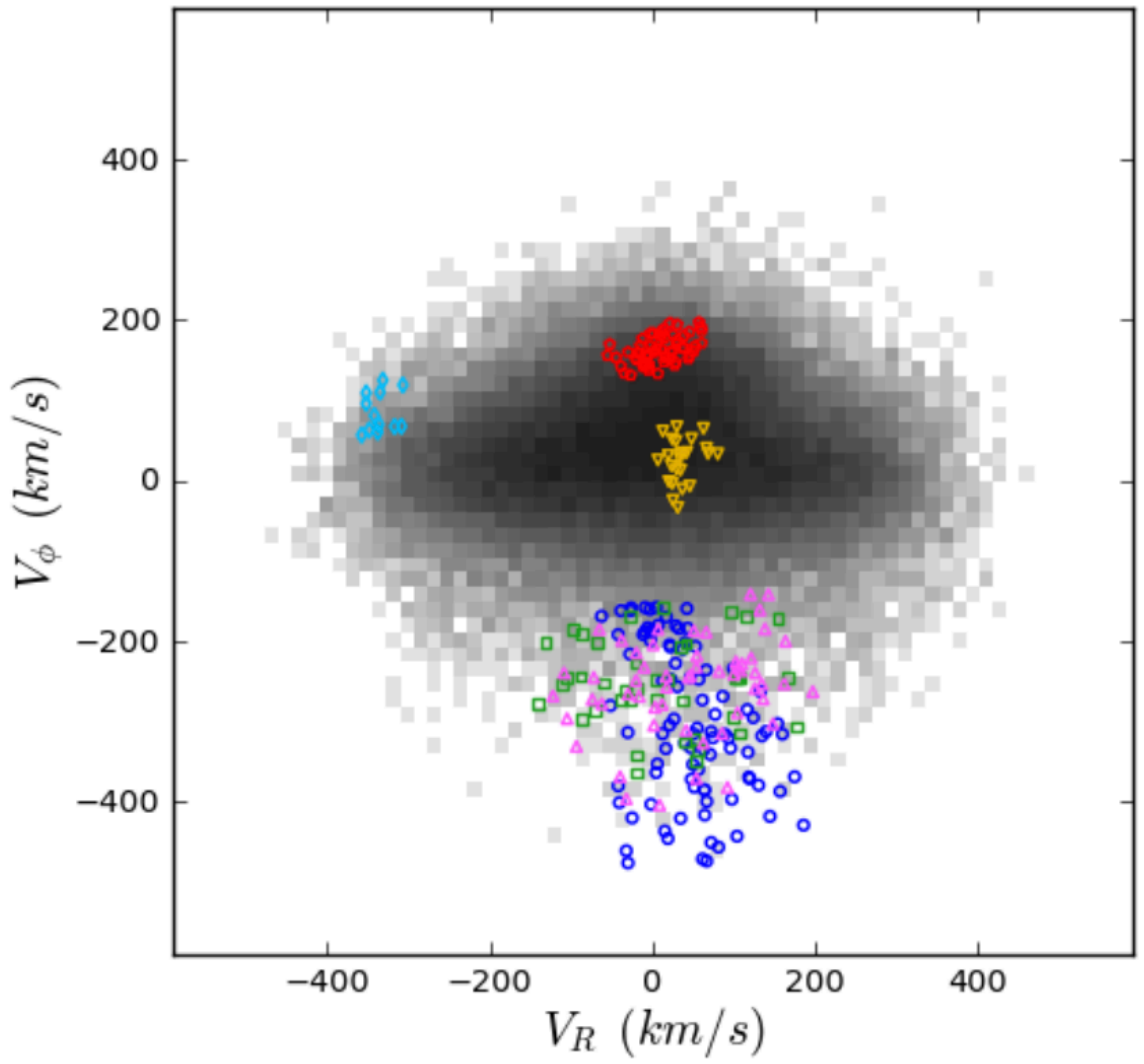
K. Malhan [2202.07660]

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

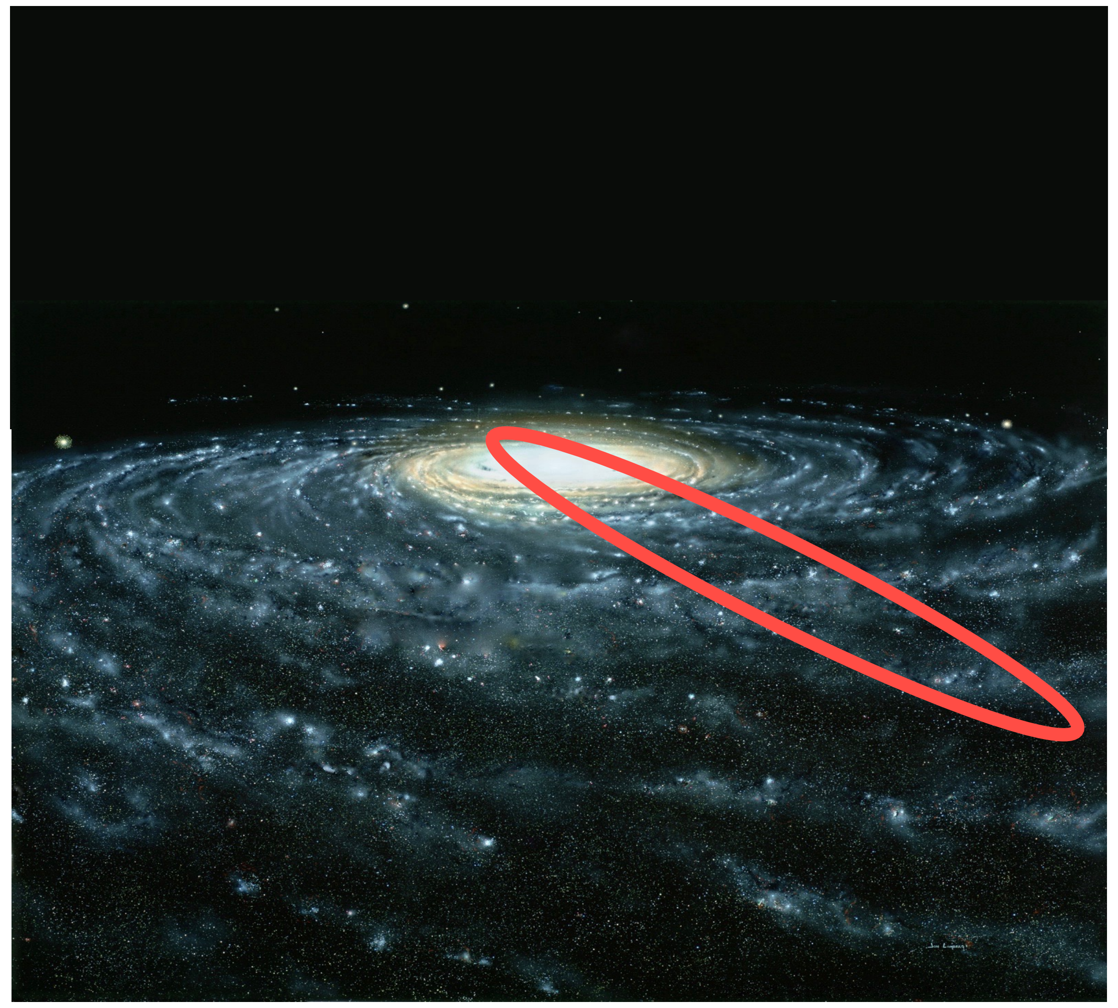
Each star sits at a location in 6D (x, y, z, v_x, v_y, v_z)

(integrate orbit assuming grav. potential)

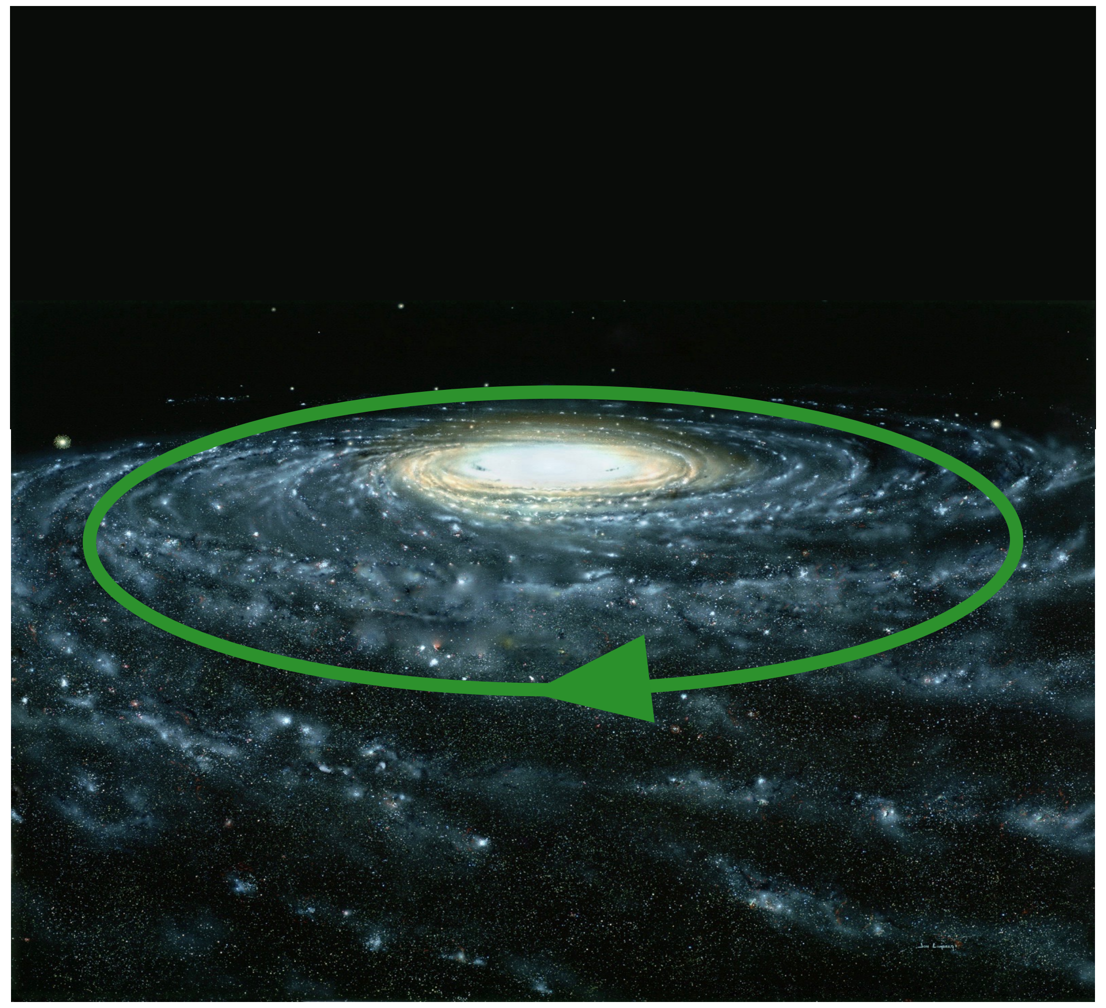
Action space

Stars are locations in 3D space of orbits

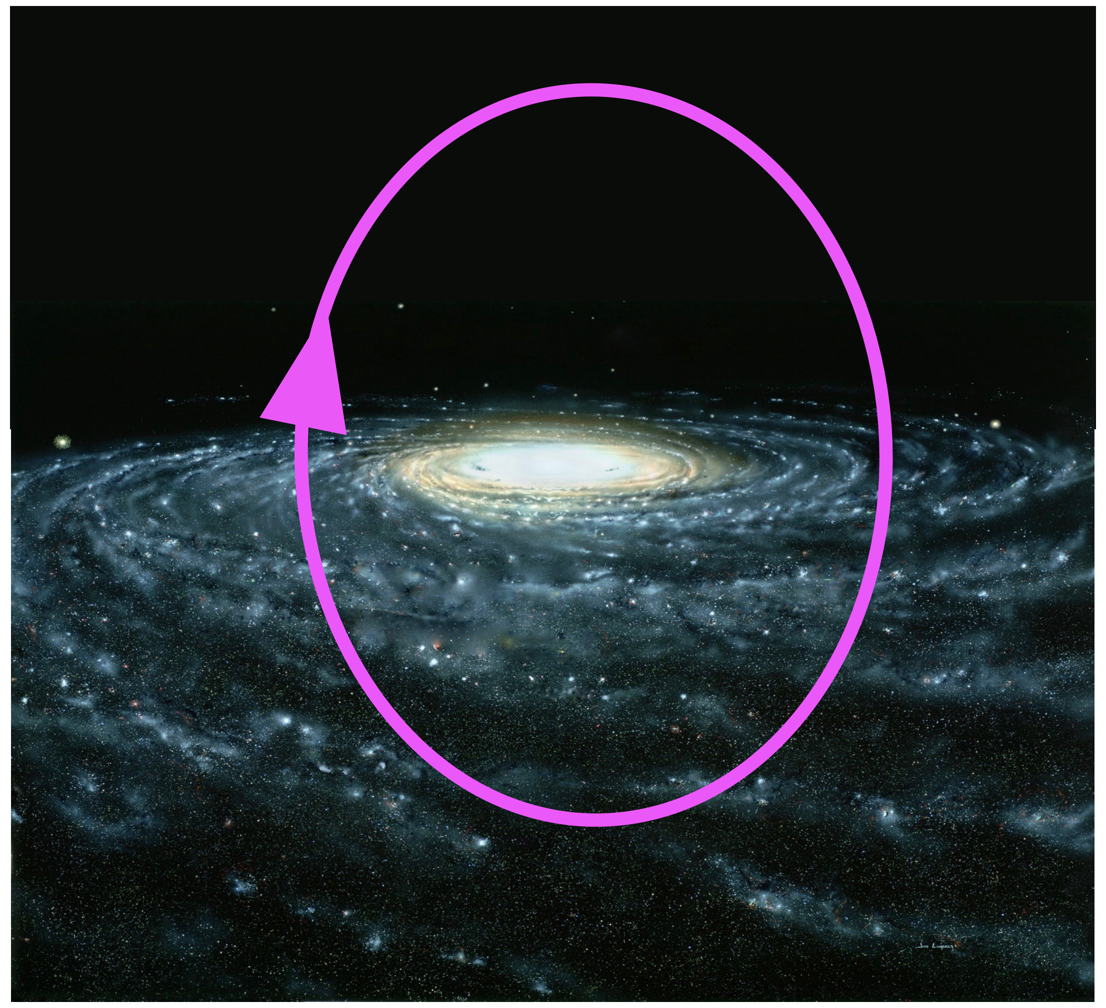
Radial action (J_R)

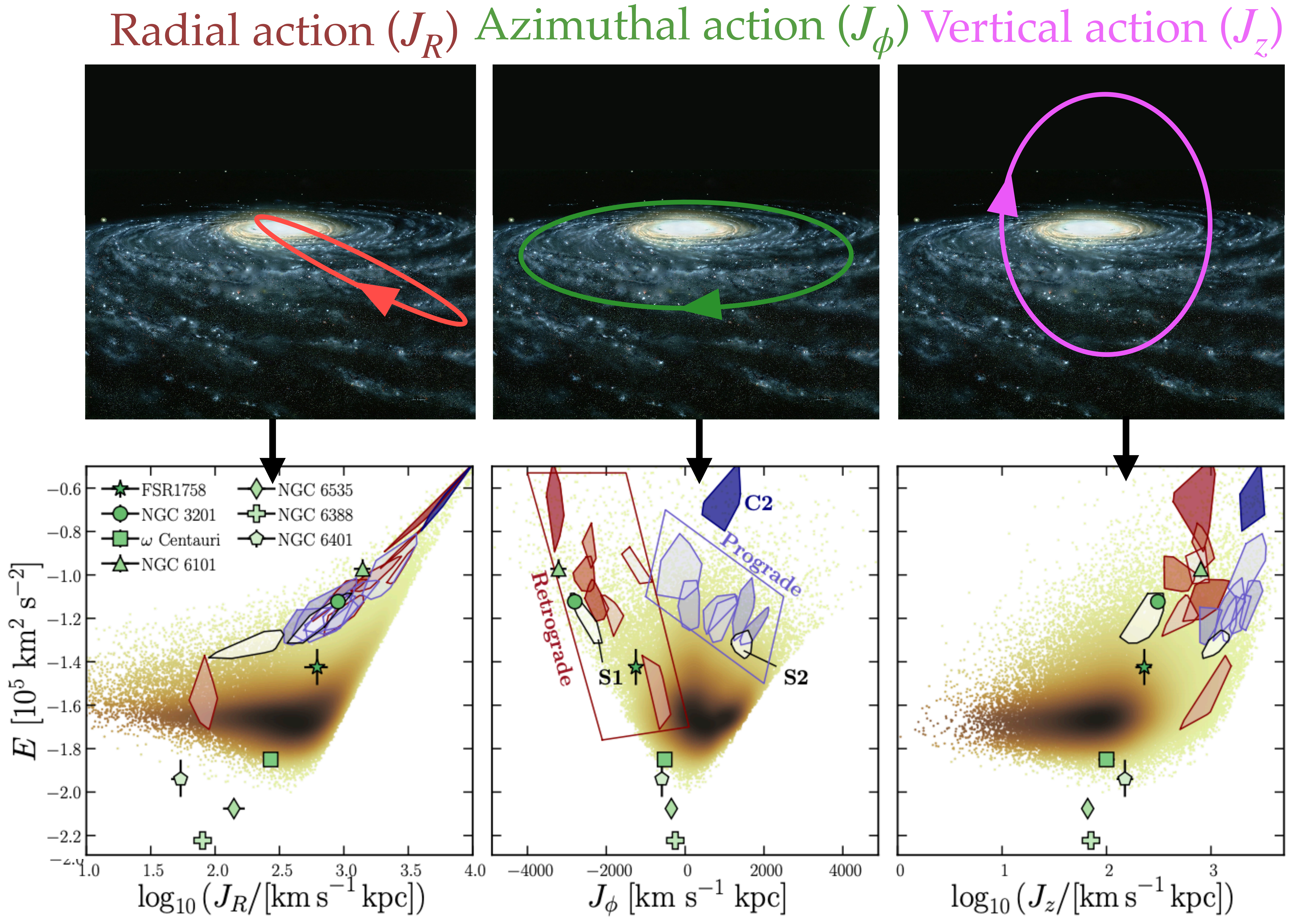


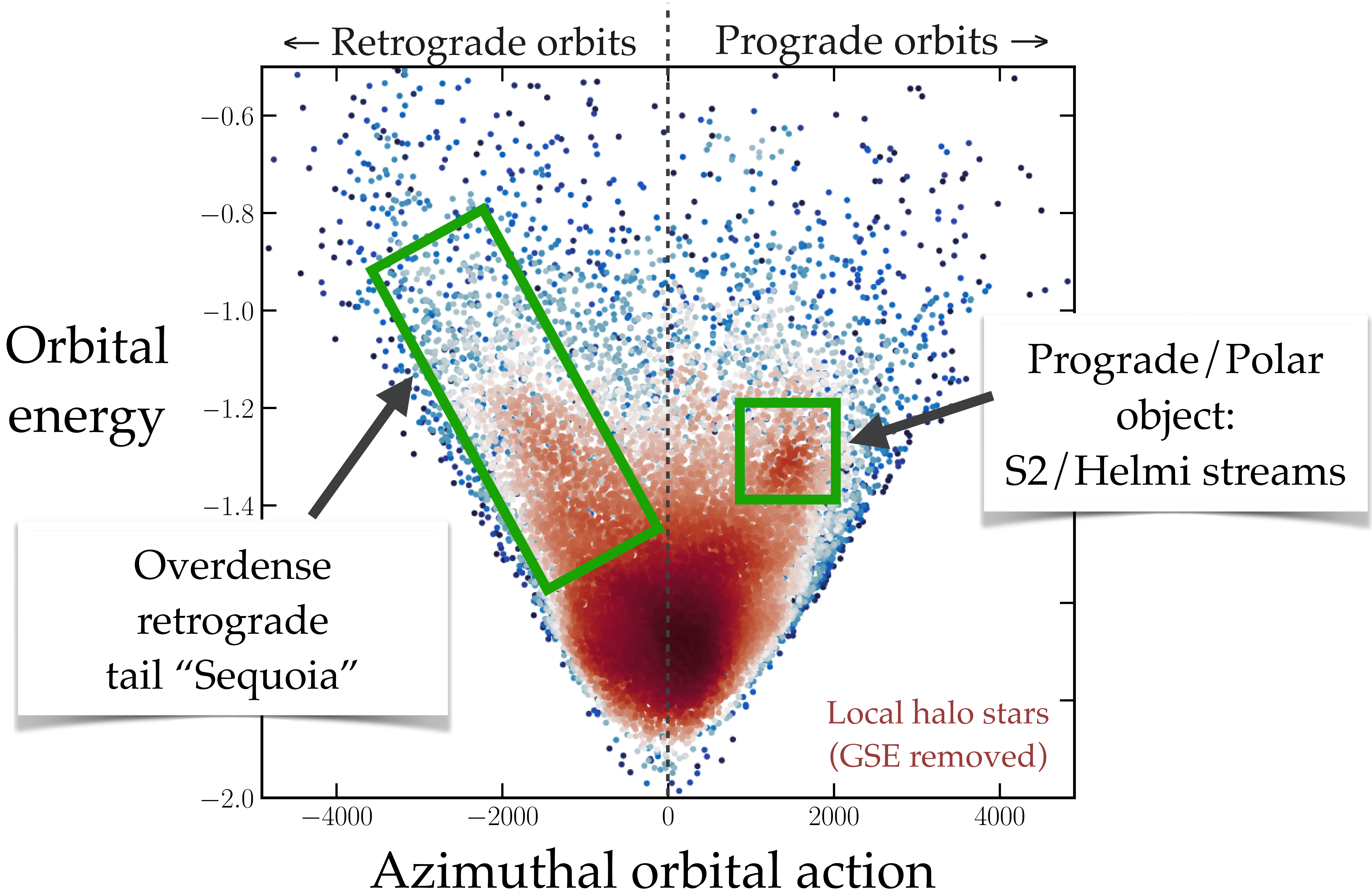
Azimuthal action (J_ϕ)



Vertical action (J_z)



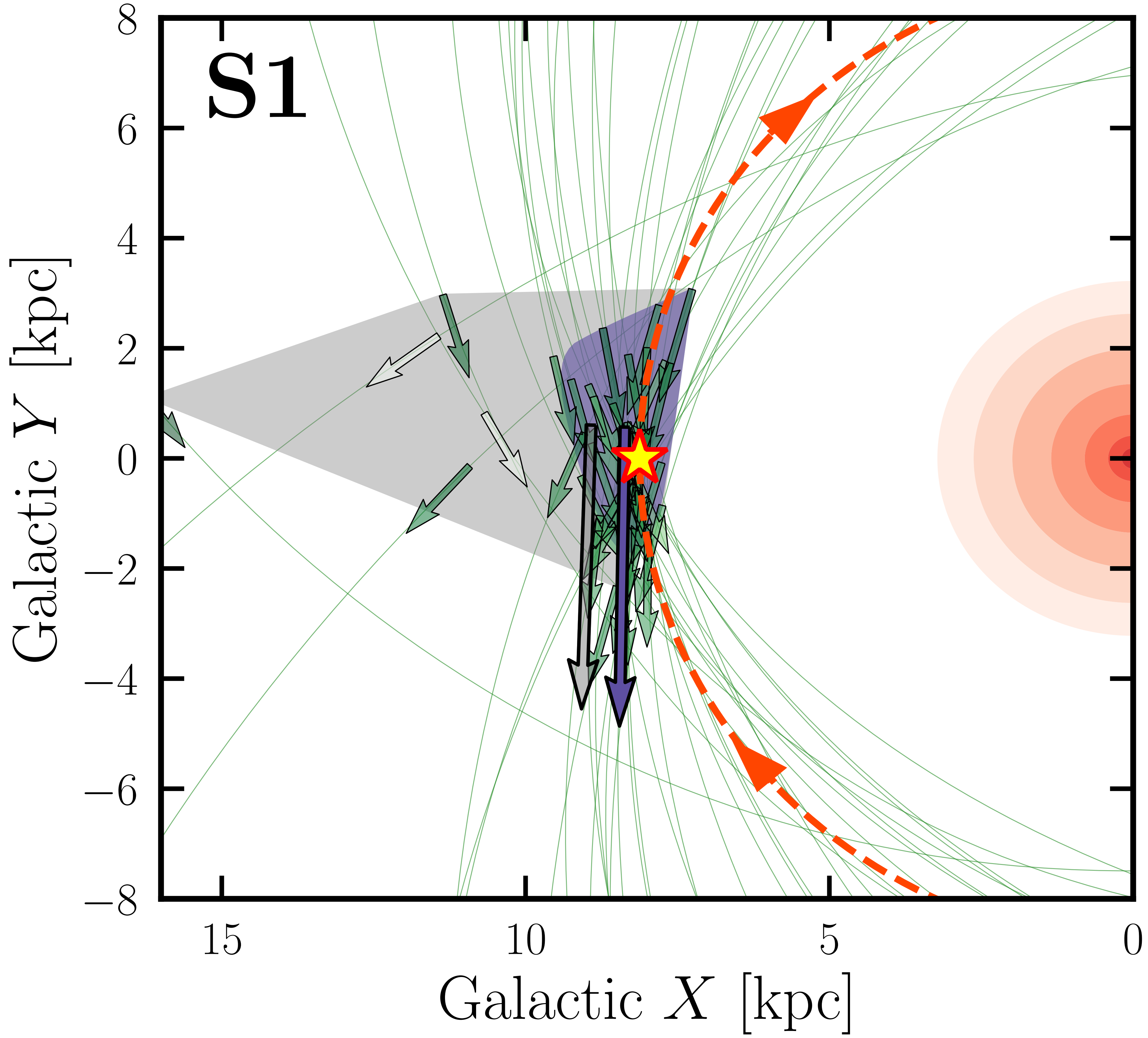

Radial action (J_R)
Azimuthal action (J_ϕ)
Vertical action (J_z)
FSR1758
NGC 3201
ω Centauri
NGC 6101
NGC 6535
NGC 6388
NGC 6401
C2
Prograde
Retrograde
S1
S2
E [10^5 km^2 s^{-2}]
$\log_{10}(J_R/[\mathrm{km\,s^{-1}\,kpc}])$
J_ϕ [km s^{-1} kpc]
$\log_{10}(J_z/[\mathrm{km\,s^{-1}\,kpc}])$

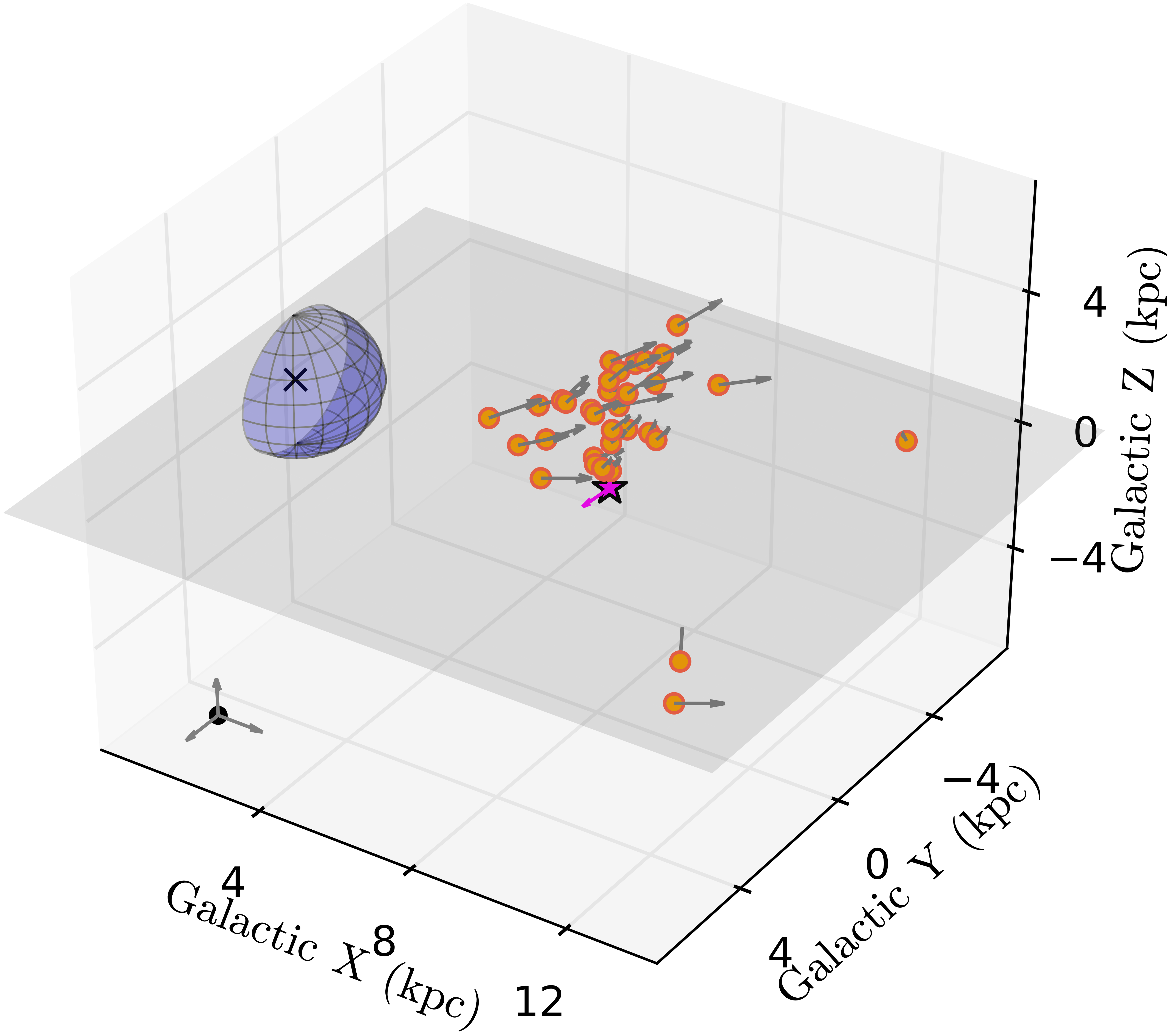


← Retrograde orbits
Prograde orbits →
Orbital energy
−0.6
−0.8
−1.0
−1.2
−1.4
−2.0
−4000
−2000
0
2000
4000
Azimuthal orbital action
Overdense retrograde tail “Sequoia”
Prograde / Polar object: S2 / Helmi streams
Local halo stars (GSE removed)

S1/Sequoia

O'Hare+ [1909.04684]



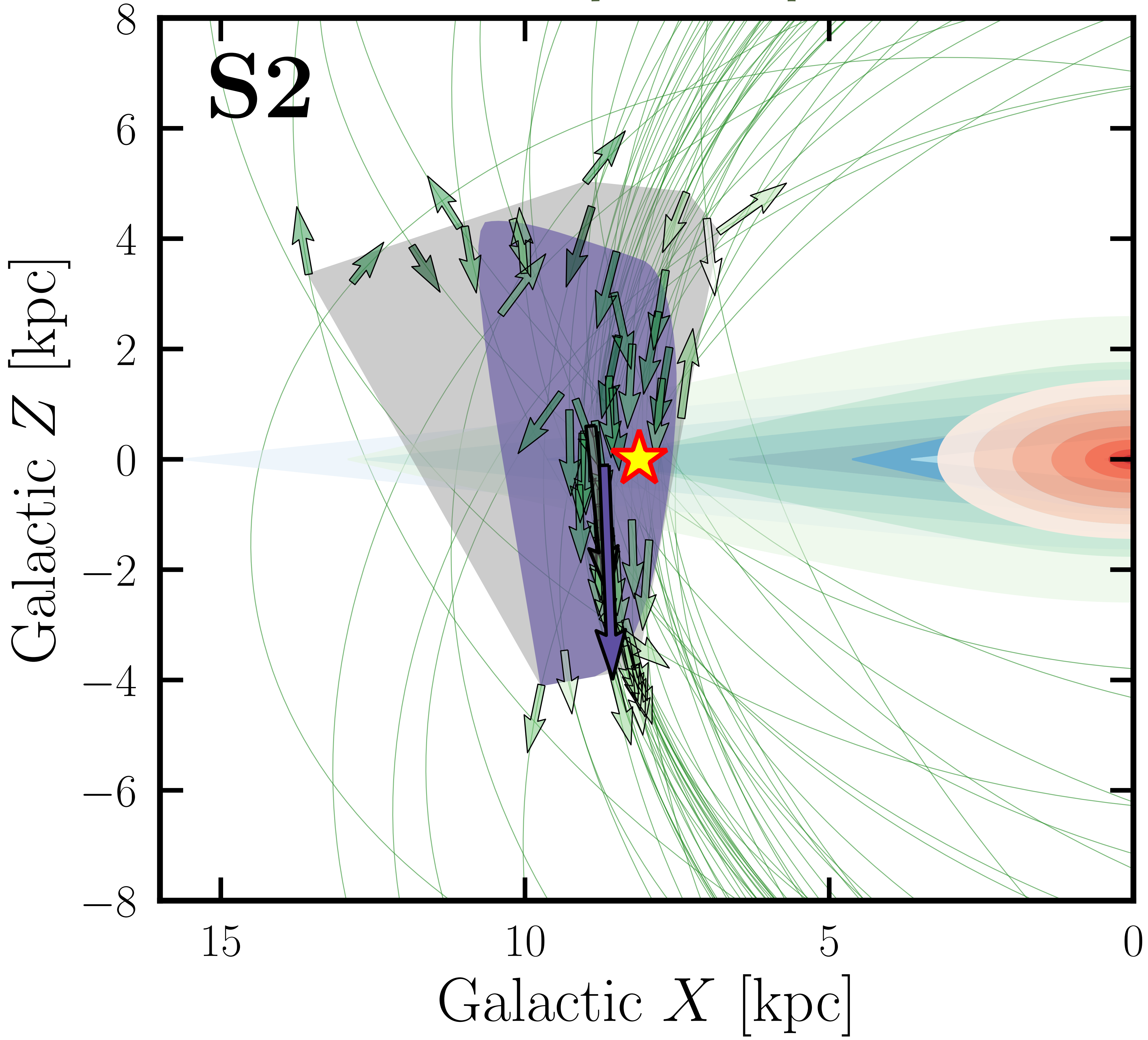


→ High-energy, retrograde-moving material

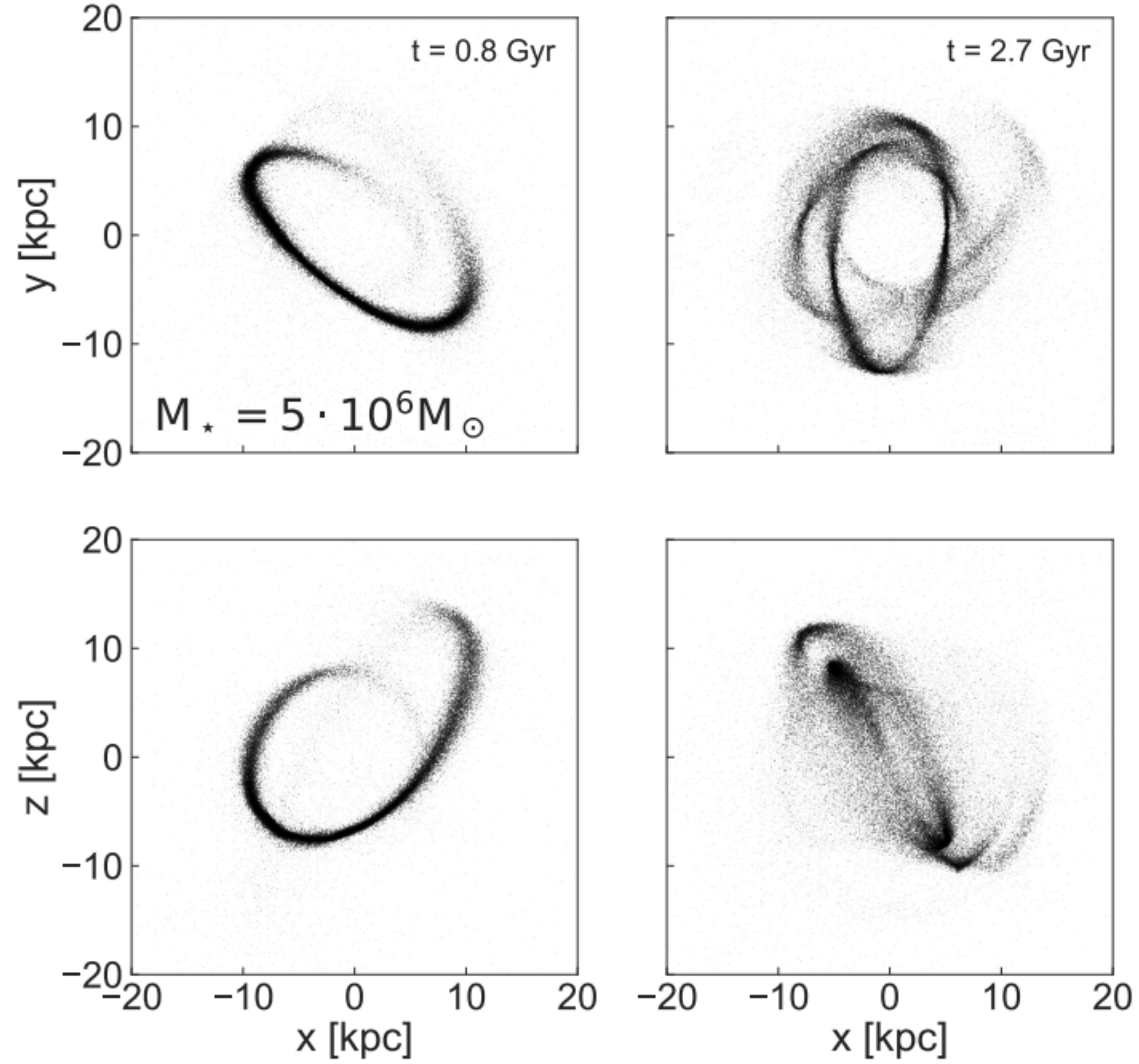
→ Linked to several globular clusters, and possibly ωCen Myeong+ [1904.03185, 1804.07050]

S2/Helmi streams

O'Hare+ [1909.04684]



Koppelmann+ 1812.00846



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

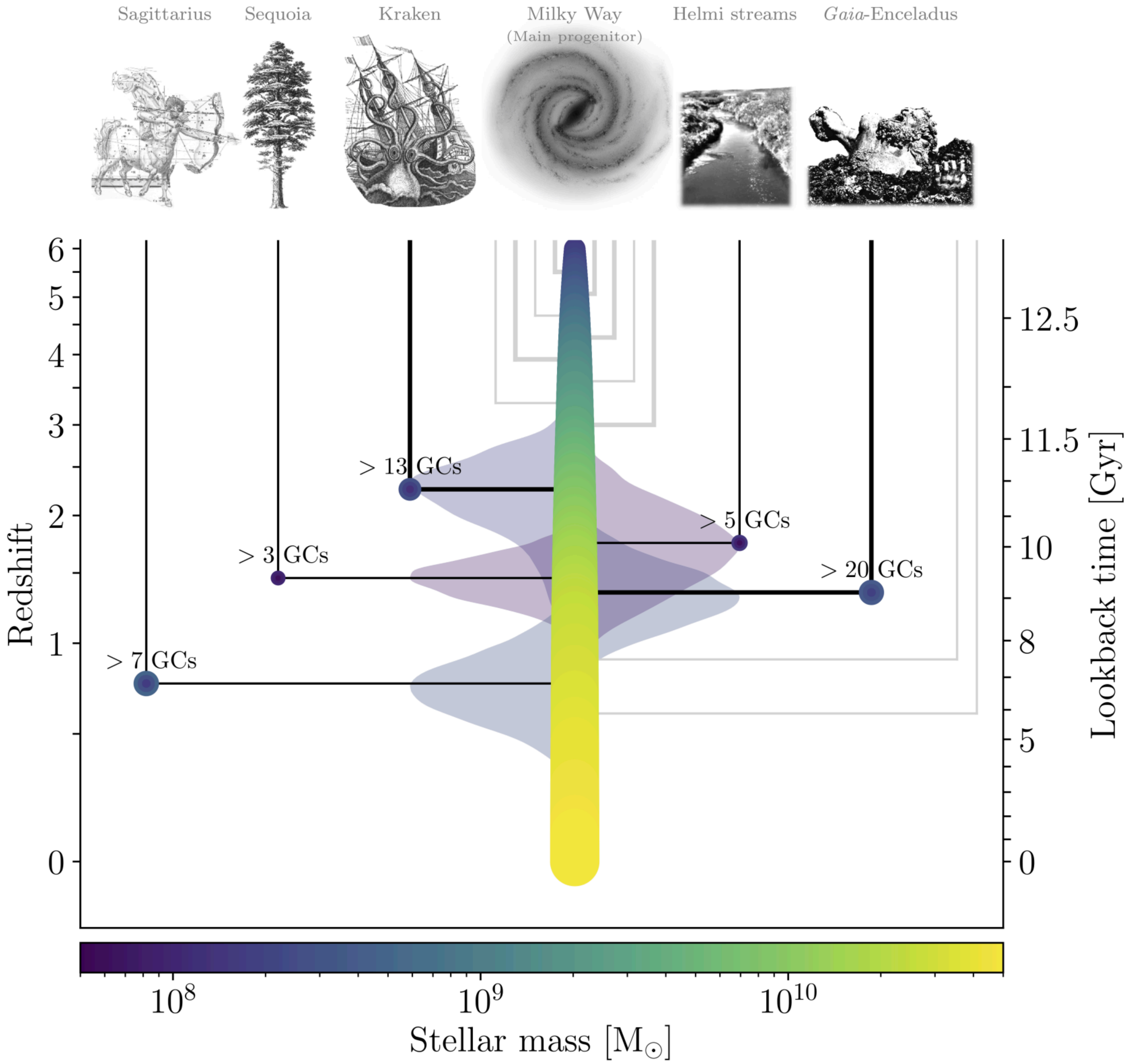
→ Two components with $\pm v_z$

→ Interpreted as multiple wraps of a larger stream

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

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

2003.01119



Sagittarius
Sequoia
Kraken
Milky Way
(Main progenitor)
Helmi streams
Gaia-Enceladus
> 13 GCs
> 5 GCs
> 3 GCs
> 20 GCs
> 7 GCs
Redshift
Lookback time [Gyr]
Stellar mass [M☉]

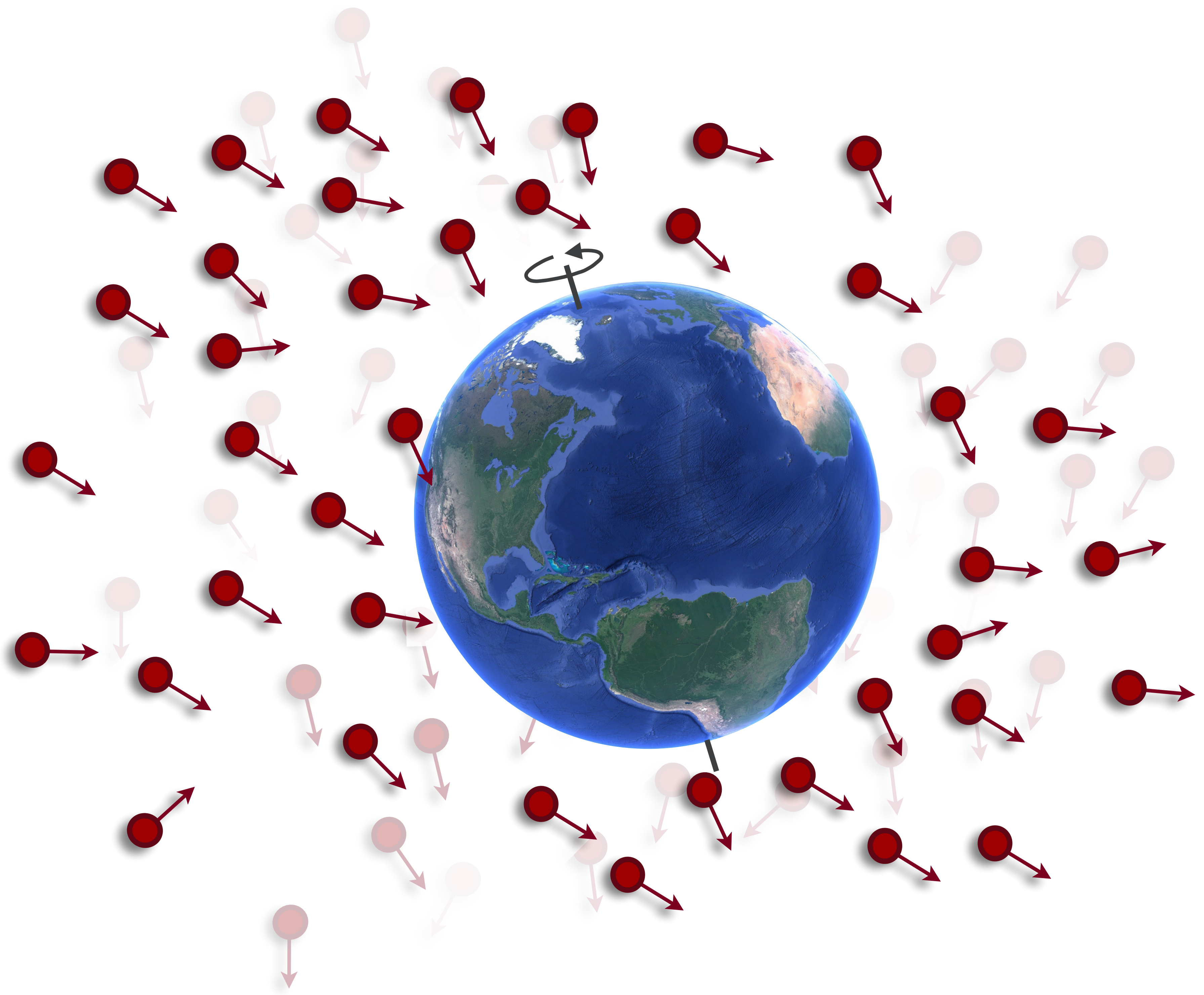
Several important substructures now detected at very high significance

→ **Gaia-Sausage-Enceladus:** a large population of halo stars on highly radically. Cautious estimate 10-20% of local DM
→ S1/**Sequoia**: stream of stars on high-energy, highly retrograde orbit. Cautious estimate <10% of local DM
→ S2/**Helmi streams:** stars on prograde/polar orbits, with multiple wraps of the stream intersecting the solar position. Cautious estimate <10% of local DM

+ potentially more…

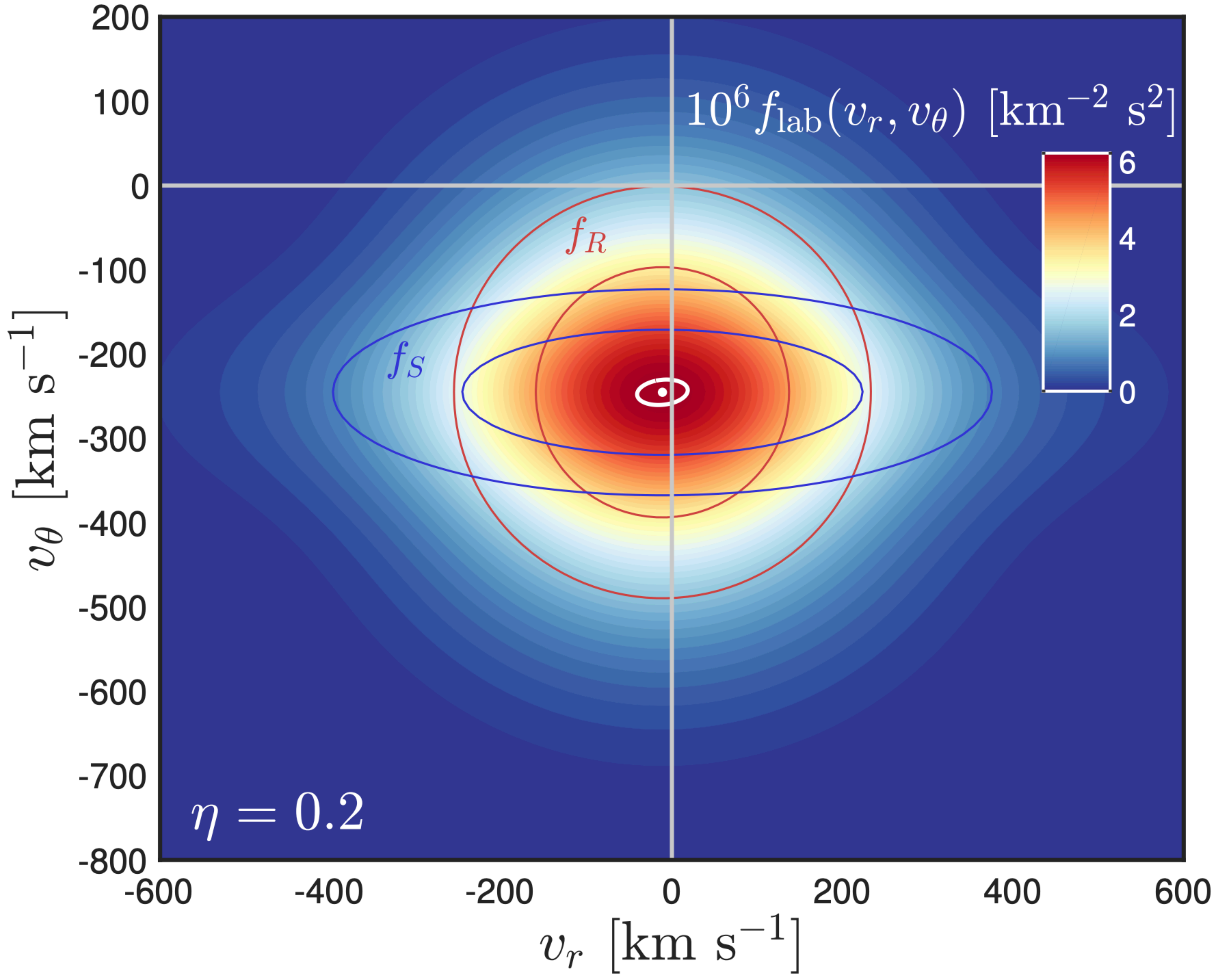
Particle-like (WIMP-like) DM

→ What we need is $f_{\text{DM}}(\mathbf{v})$



SHM^{++}: A Refinement of the Standard Halo Model for Dark Matter Searches

N. Wyn Evans,[1,*] Ciaran A. J. O'Hare,[2,†] and Christopher McCabe[3,‡]



Simple model for the DM halo velocity distribution composed of a round part (f_R), and the radially anisotropic sausage (f_S)

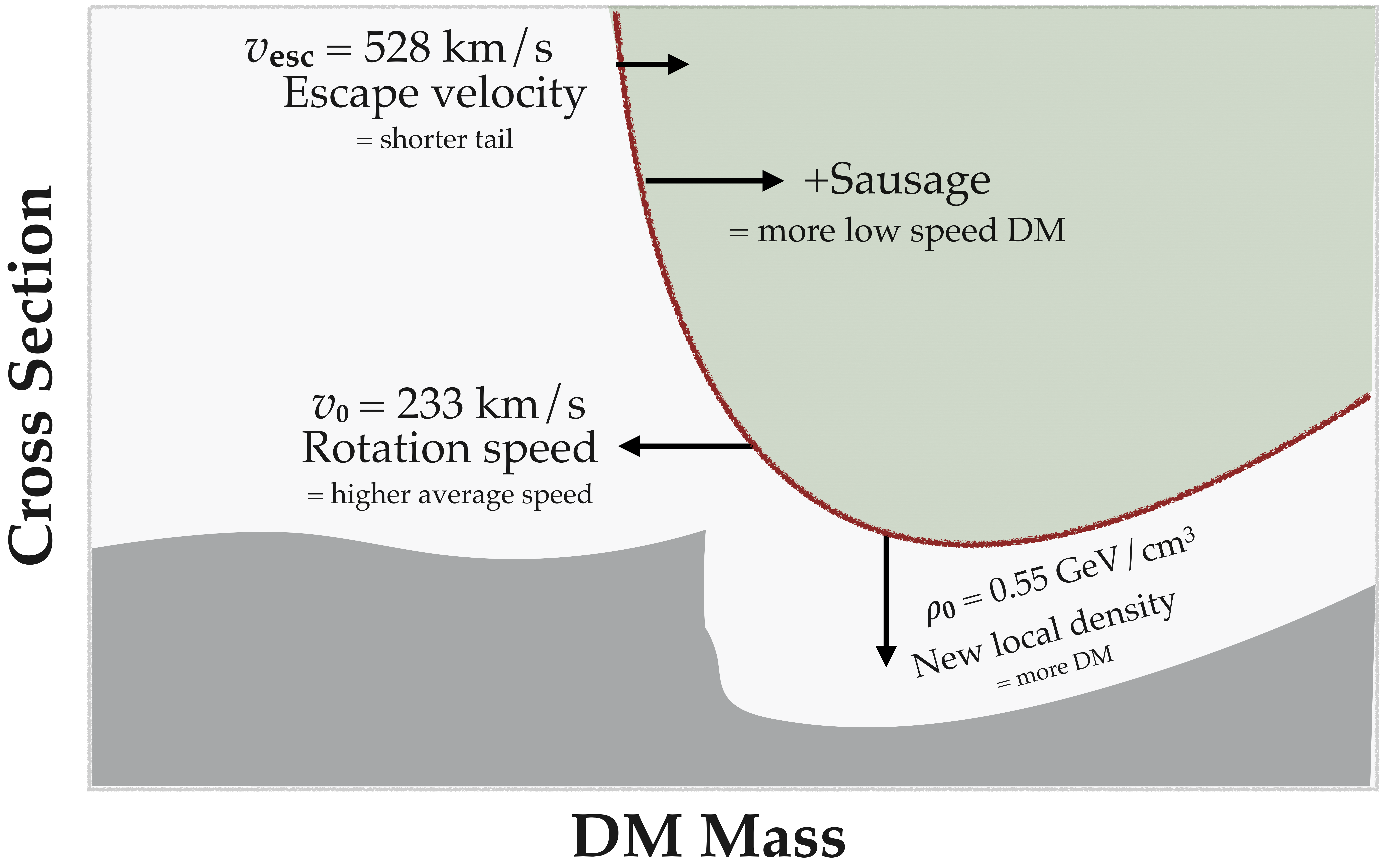
With Sausage making up ~ 10-20% of DM

SHM^{++}: A Refinement of the Standard Halo Model for Dark Matter Searches

N. Wyn Evans,[1,*] Ciaran A. J. O'Hare,[2,†] and Christopher McCabe[3,‡]

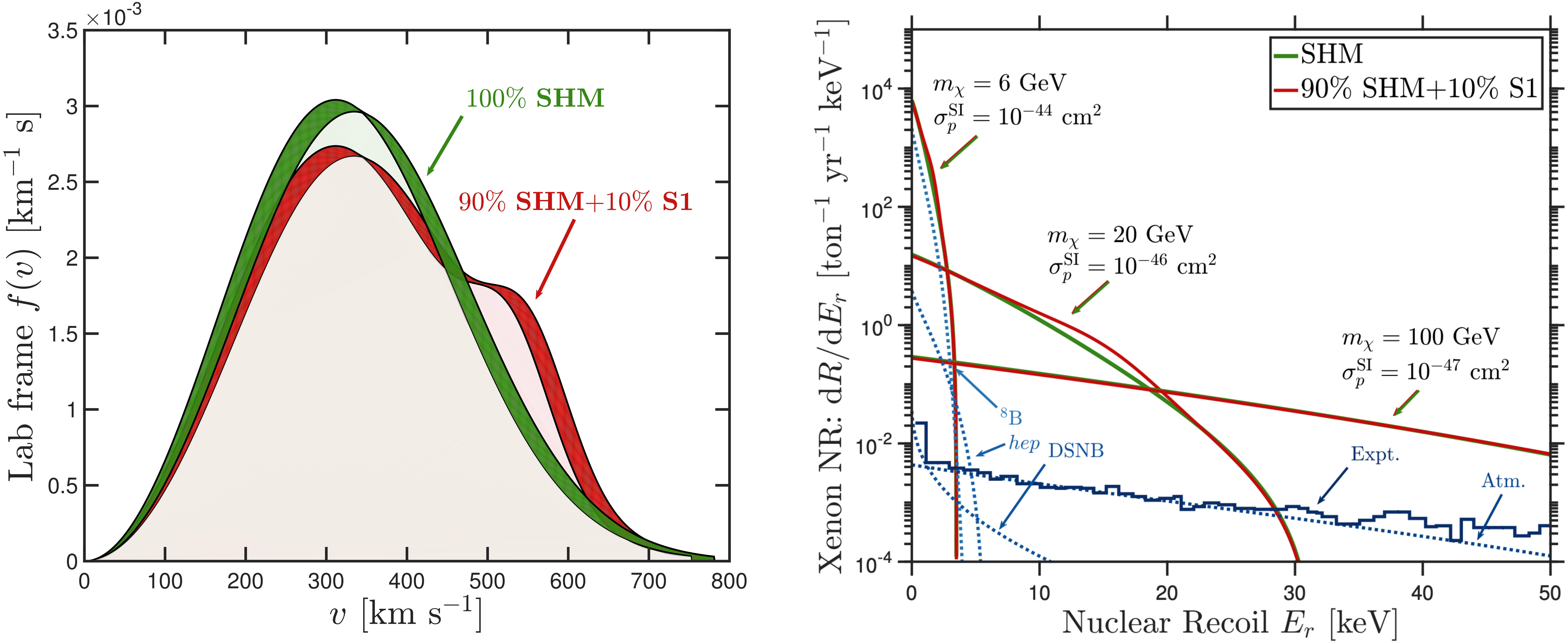
SHM	Local DM density	ρ_0	$0.3\,\mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	220 km s^{-1}
	Escape speed	$v_{\rm esc}$	544 km s^{-1}
	Velocity distribution	$f_{\rm R}(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	0.55 ± 0.17 GeV cm^{-3}
	Circular rotation speed	v_0	233 ± 3 km s^{-1}
	Escape speed	$v_{\rm esc}$	528^{+24}_{-25} km s^{-1}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)

Impact of SHM^{++} on DM limits



How do high-speed streams in the velocity distribution impact direct searches for WIMP-like DM?

→ Not very much, but this is a good thing, our simple model is okay

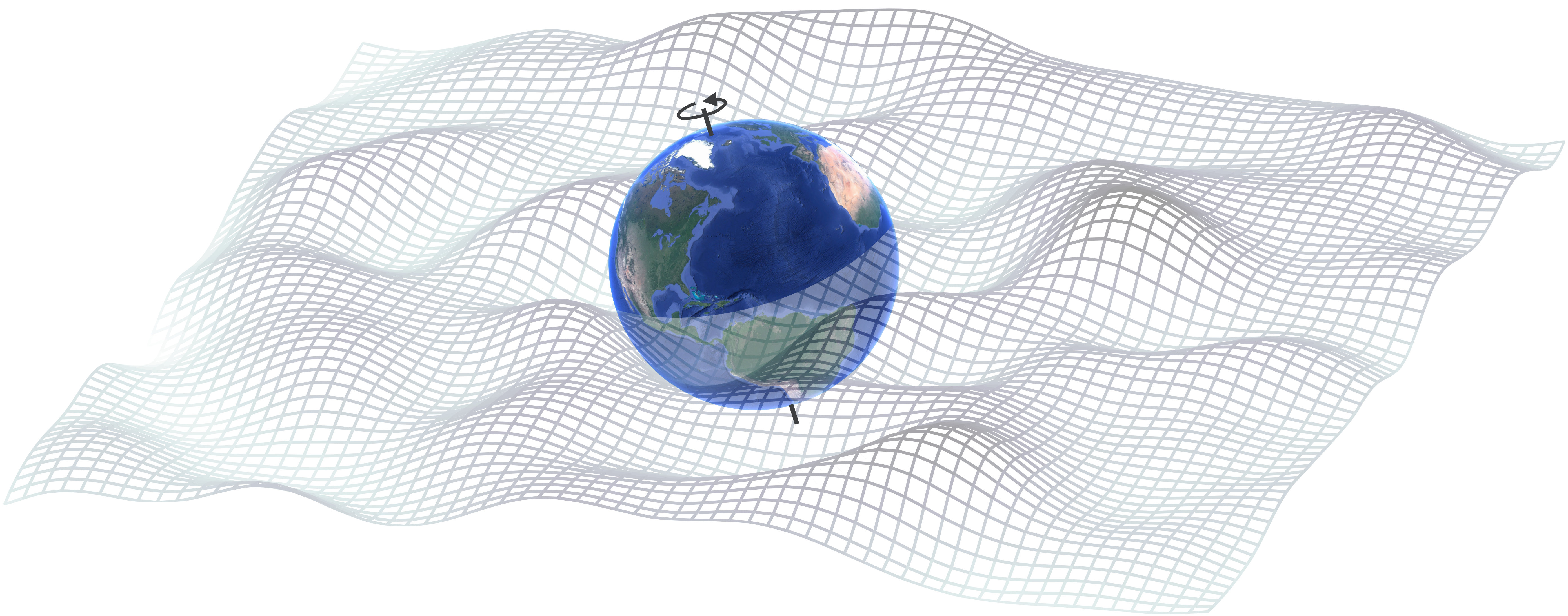


Standard WIMP signals are only dependent on

$$g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{f_{\rm lab}(v)}{v} {\rm d}v$$

→ So kinematic information has been lost

Wave-like DM (e.g. axions)



Dark matter waves

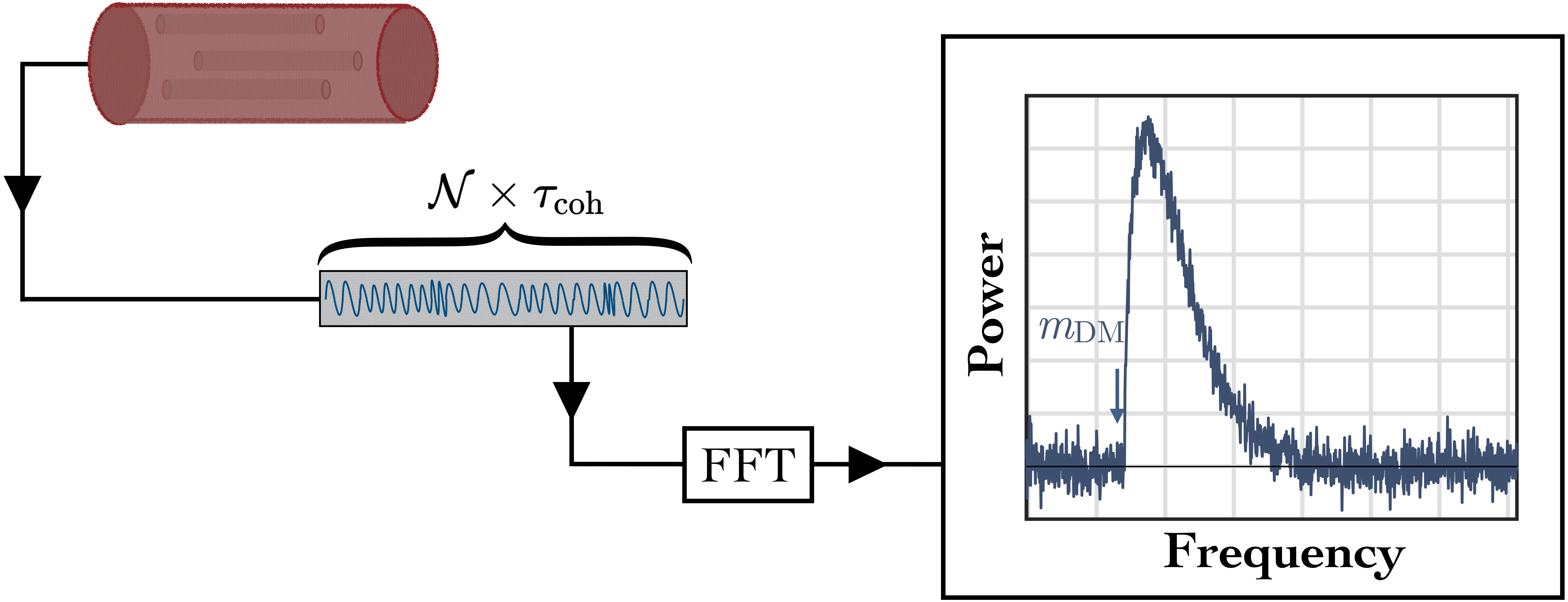
behave like a classical field : $\phi(\mathbf{x},t) \approx \frac{\sqrt{2\rho}}{m_{\rm DM}} \cos(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha)$

$\omega \approx m_{\rm DM}$

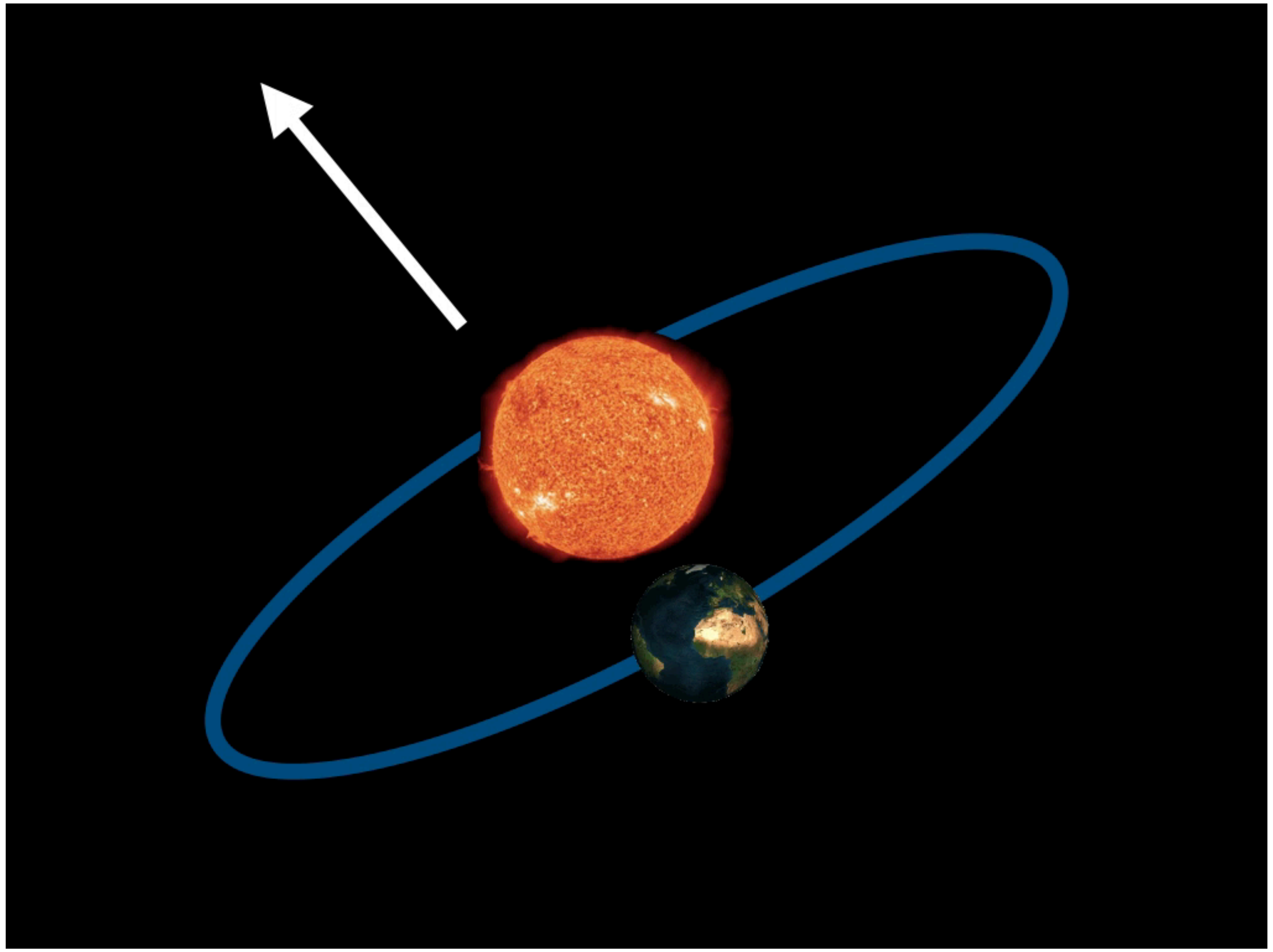
Oscillating at the DM mass

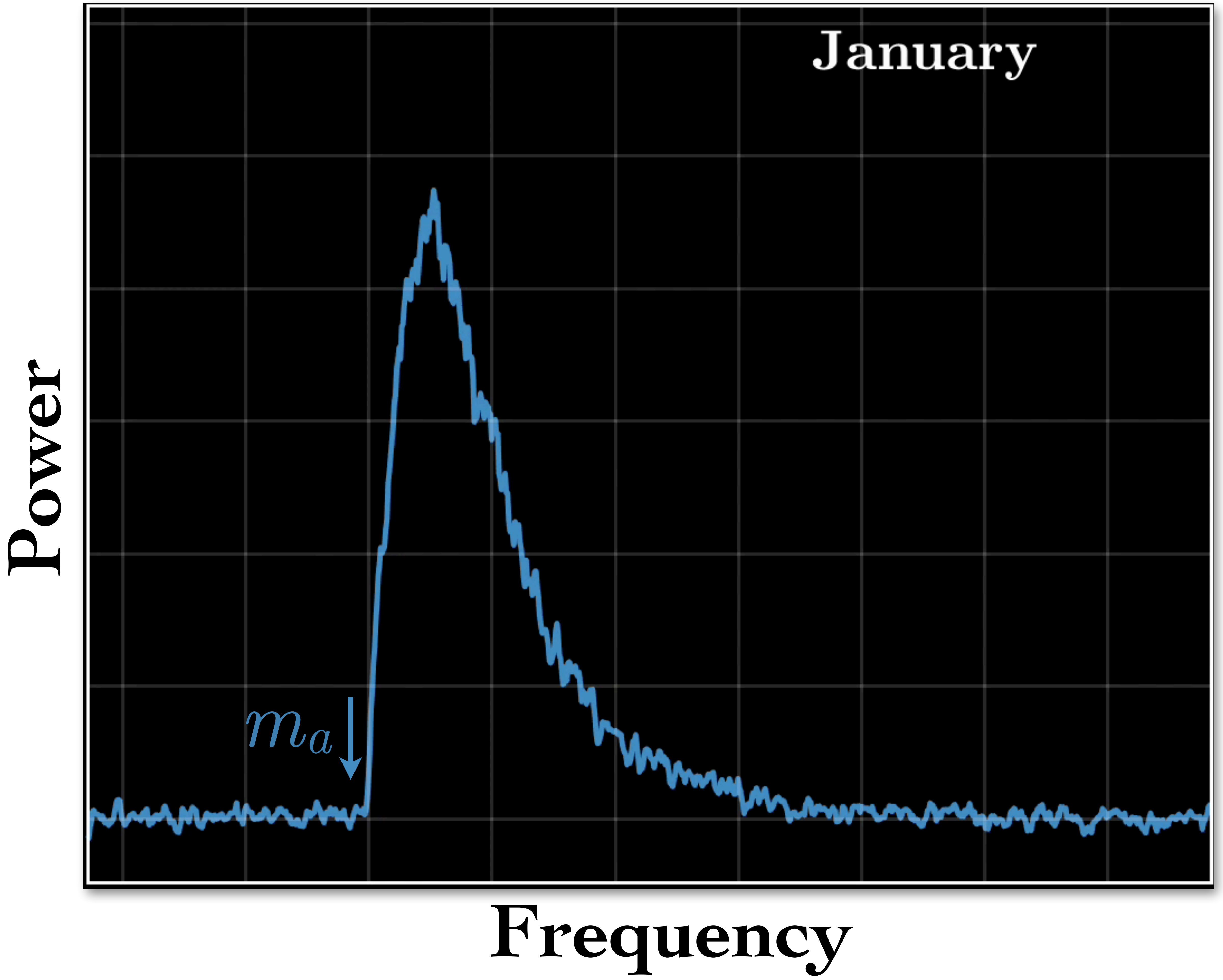
Most haloscopes observe over many coherence times, but well inside the coherence length → Fourier transform of signal timeseries approaches *f(v)*

$$\tau_{\rm coh} = \frac{2\pi}{m_{\rm DM}\sigma_v^2} \simeq 40\mu{\rm s}\left(\frac{100\mu{\rm eV}}{m_{\rm DM}}\right)$$

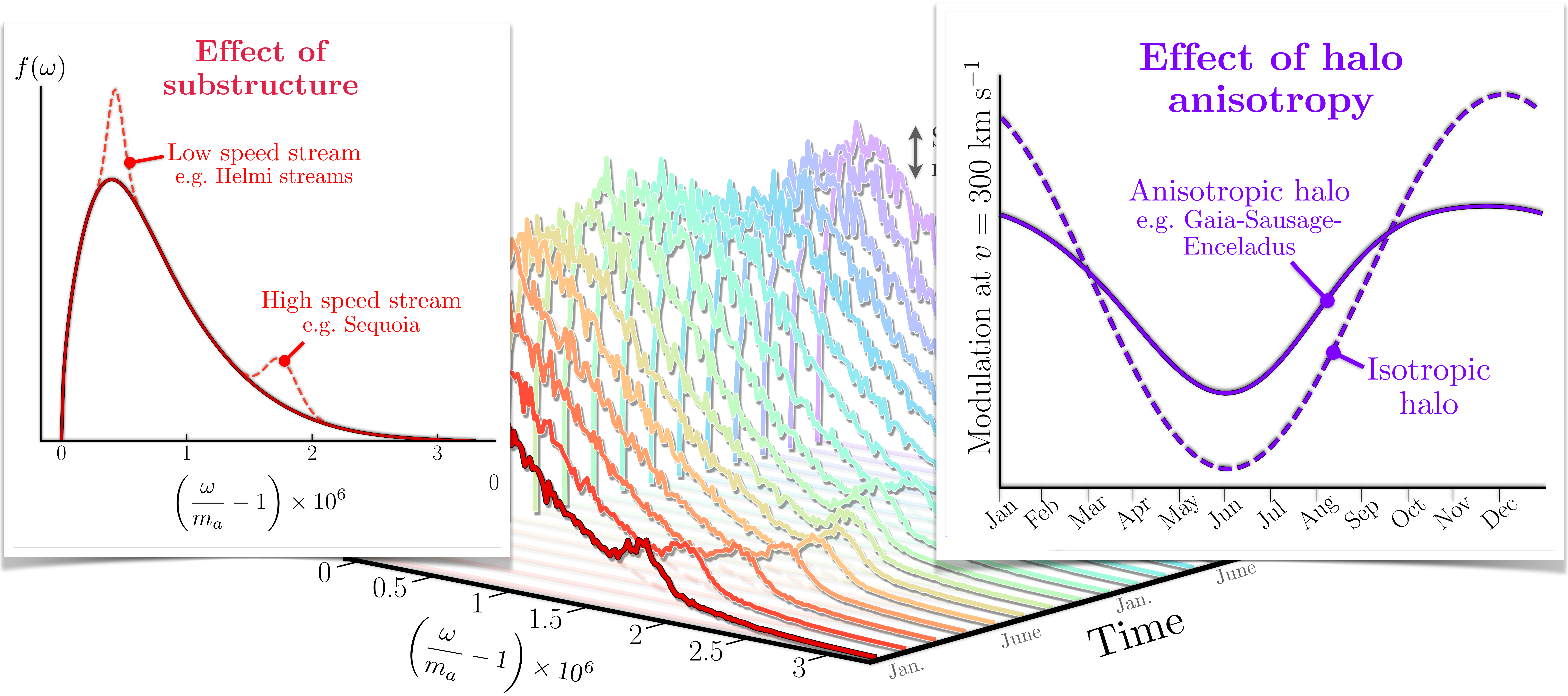


Annual modulation





Substructure in the axion line + annual modulation



Unlike particle-DM these variations are things that could actually be observed

Summing up

- Clear evidence for substructure in the inner halo (Gaia Sausage-Enceladus, Sequoia, Helmi streams)
- Substructure likely comes from accreted halos, and therefore should be associated with DM
- Substructure can be safely neglected in WIMP-like DM searches prior to detection, with the possible exception of direction-sensitive searches (e.g. CYGNUS)
- Substructure presents much more readily observable signals in axion experiments, with some like the Helmi streams, actually enhancing sensitivities.

Take home message: So far there are no nasty surprises in the Gaia data as far as DM searches go, and potentially a lot of interesting things to see once DM is detected…

THE UNIVERSITY OF SYDNEY
Australian Government
Australian Research Council
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

The story is not over for Gaia and dark matter…

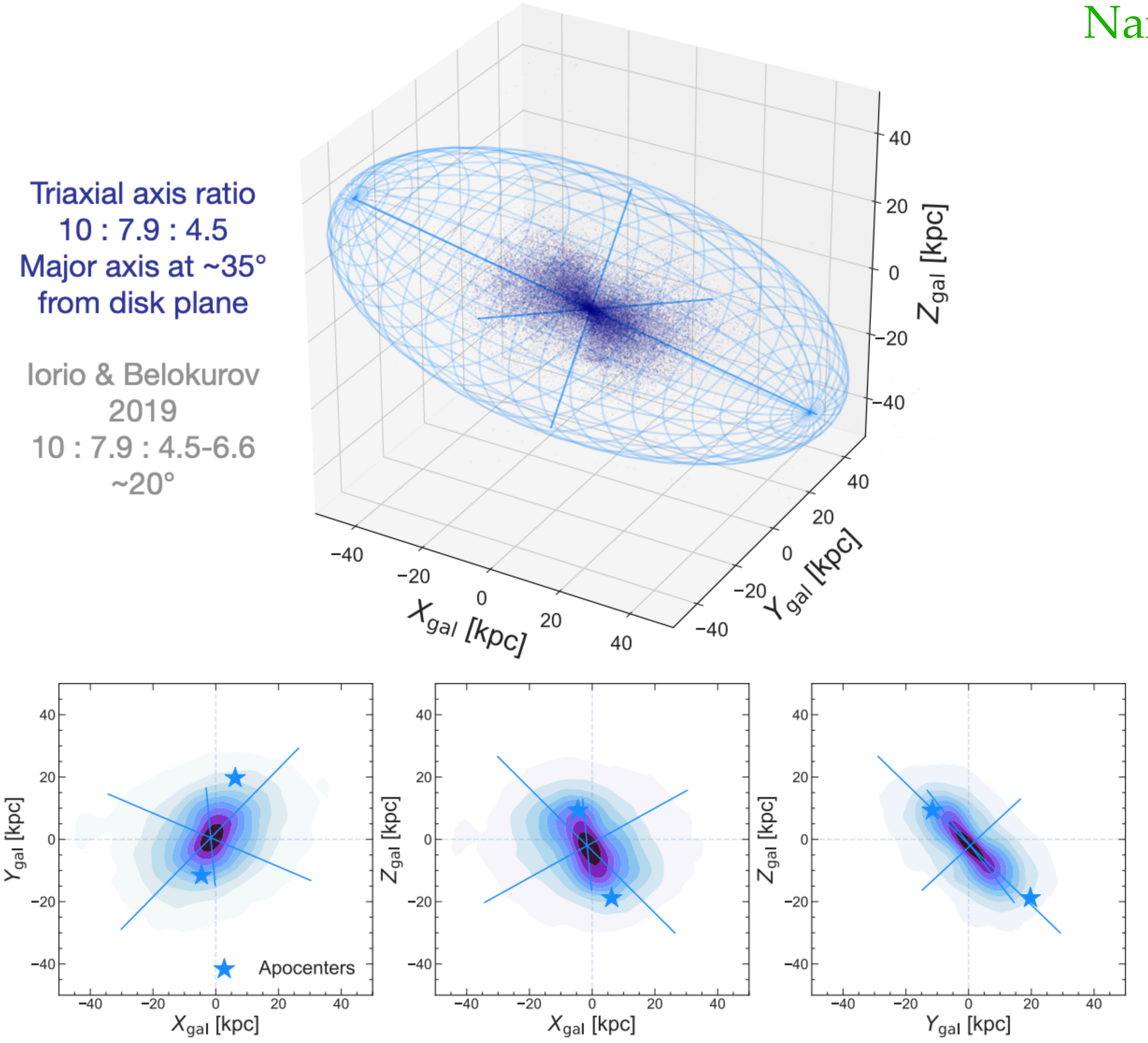
- Dark matter-stellar halo connection → how to precisely predict DM densities for each substructure from stellar data alone?
- Fine-grained substructure
- DM substructure specific to particle models (e.g. axion miniclusters, microhalos, boson stars, solitons)
- Impact on indirect DM searches (galactic centre, sub-halo mass function, microlensing, stellar stream perturbations)
- Gaia DR3 coming soon, with a much larger sample of radial velocities…

Extra

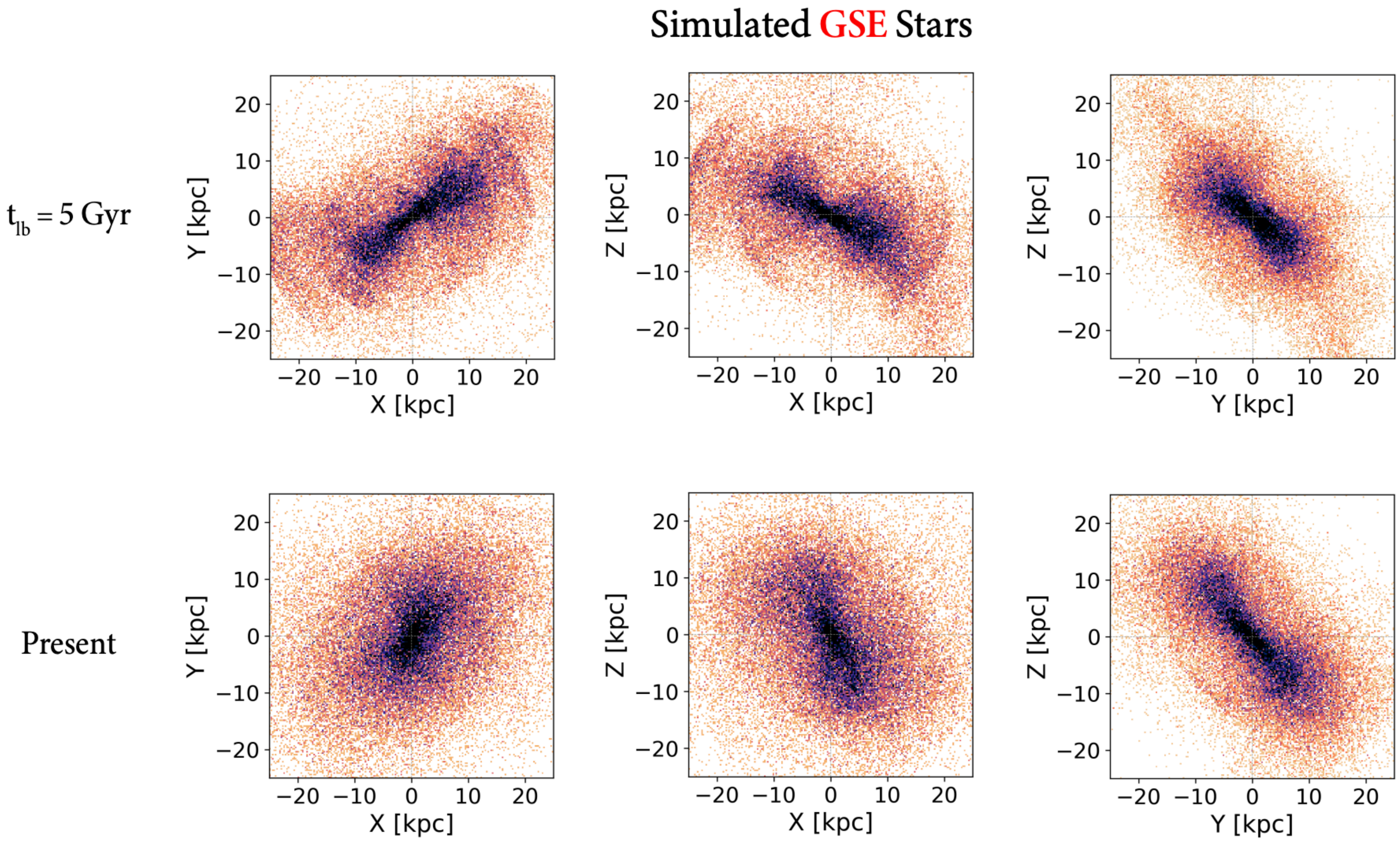
Naidu+[2103.03251]

Triaxial axis ratio
10 : 7.9 : 4.5
Major axis at ~35°
from disk plane

Iorio & Belokurov
2019
10 : 7.9 : 4.5-6.6
~20°

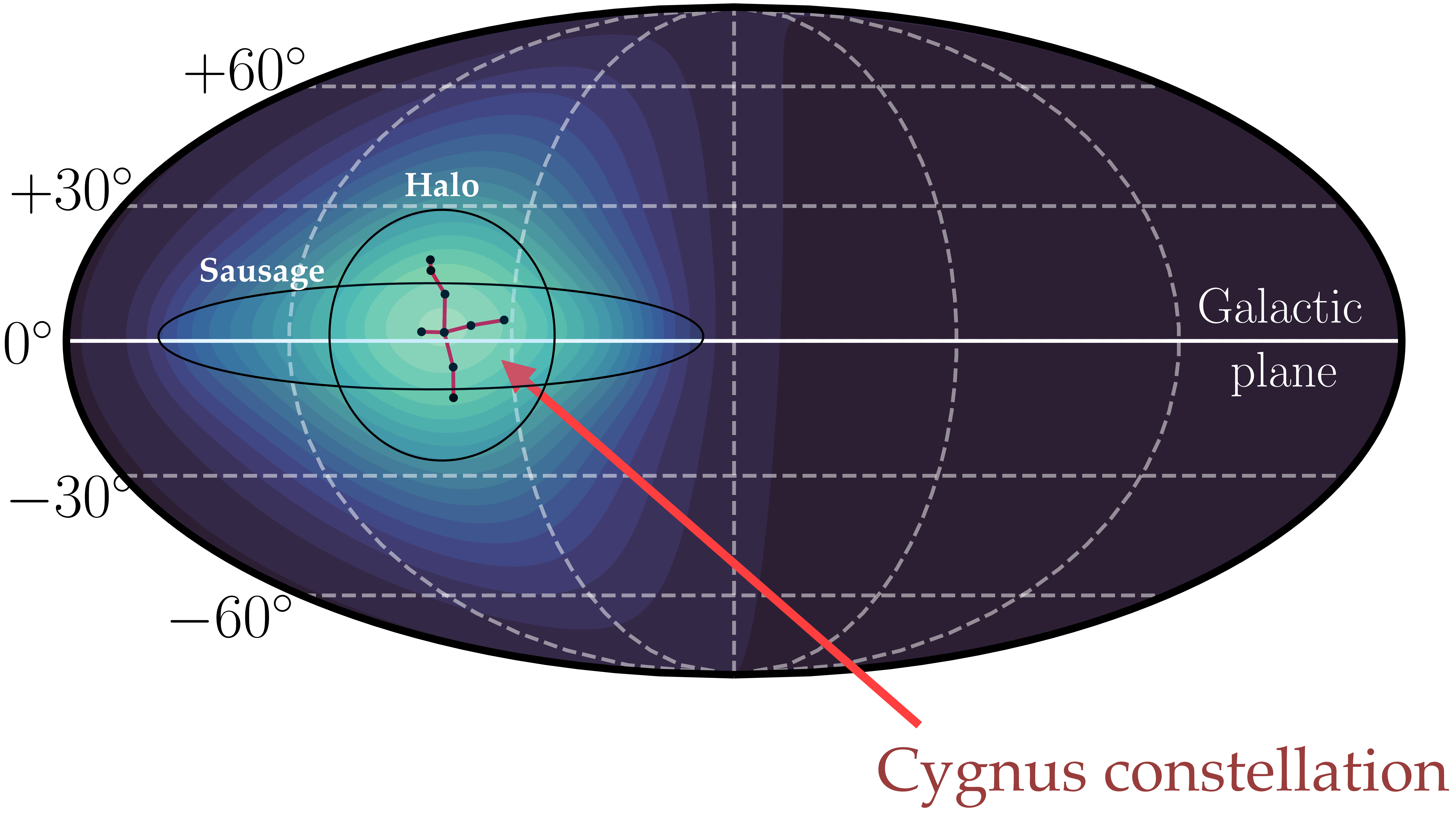


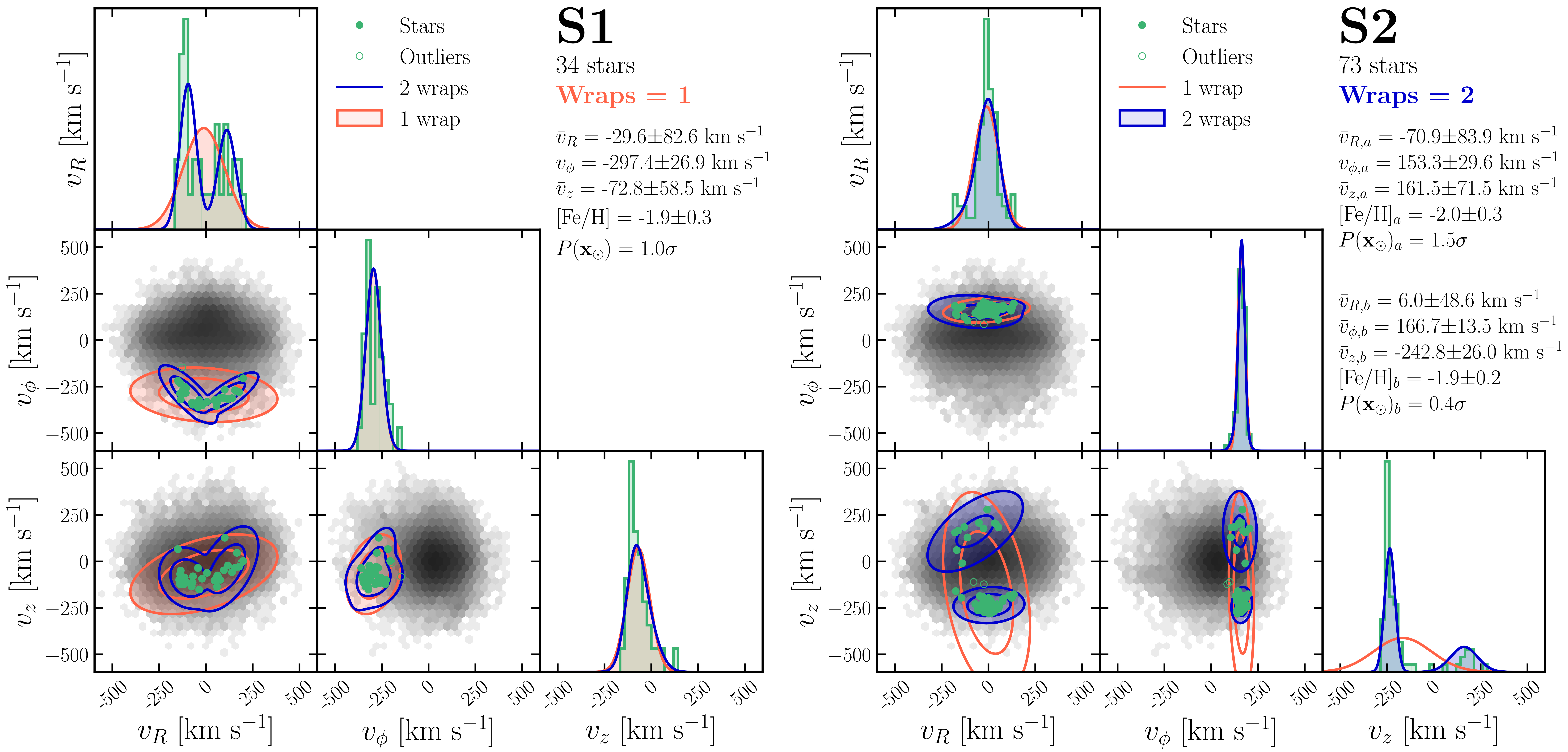
Dark matter halo should have a noticeable tilt due to GSE (seen also in stellar halo via RR Lyraes)



Han+ [2202.07662]

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



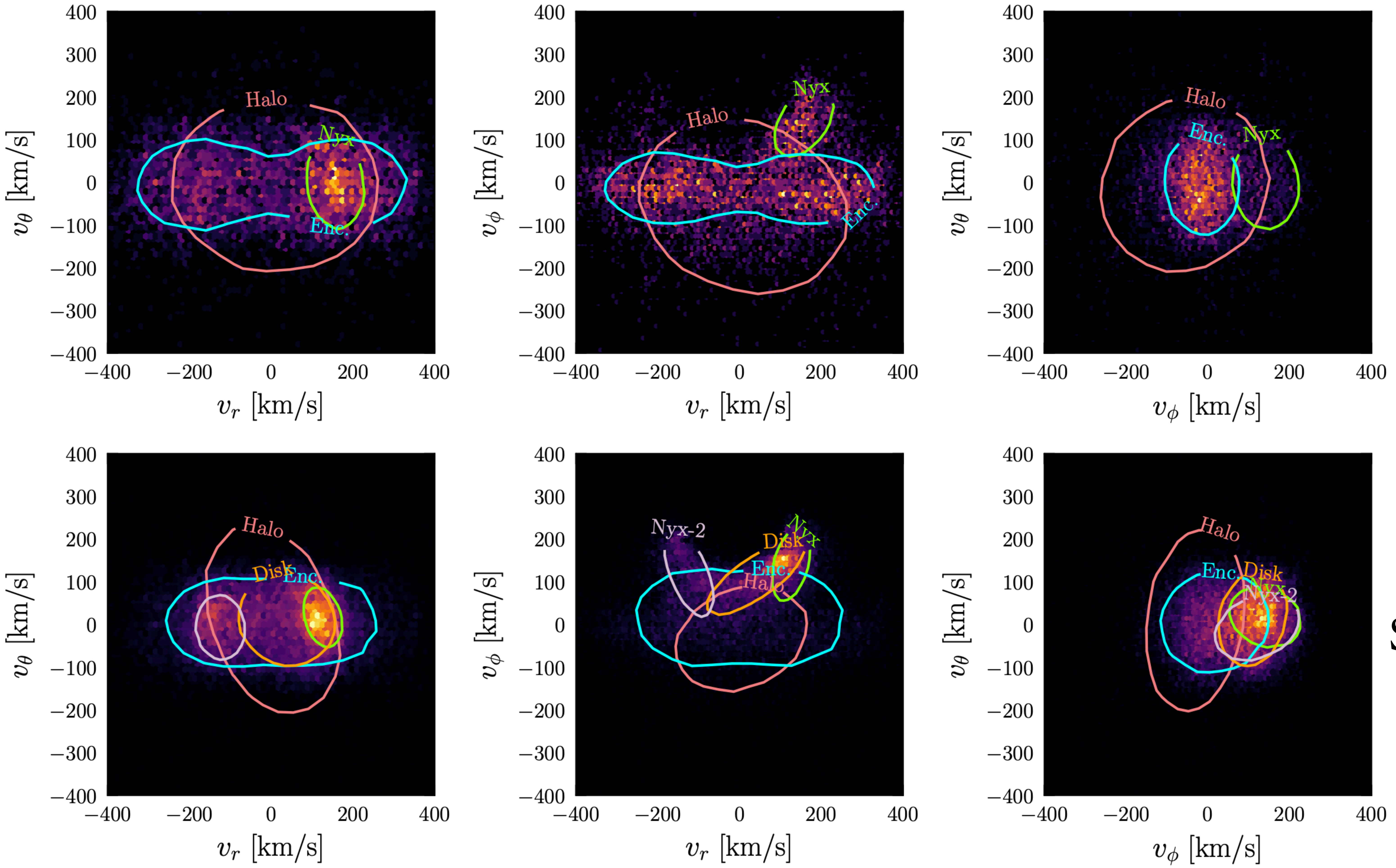


S1
34 stars
Wraps = 1
$\bar{v}_R$ = -29.6±82.6 km s^{-1}
$\bar{v}_\phi$ = -297.4±26.9 km s^{-1}
$\bar{v}_z$ = -72.8±58.5 km s^{-1}
[Fe/H] = -1.9±0.3
$P(\mathbf{x}_\odot) = 1.0\sigma$
Stars
Outliers
2 wraps
1 wrap
S2
73 stars
Wraps = 2
$\bar{v}_{R,a}$ = -70.9±83.9 km s^{-1}
$\bar{v}_{\phi,a}$ = 153.3±29.6 km s^{-1}
$\bar{v}_{z,a}$ = 161.5±71.5 km s^{-1}
[Fe/H]$_a$ = -2.0±0.3
$P(\mathbf{x}_\odot)_a = 1.5\sigma$
$\bar{v}_{R,b}$ = 6.0±48.6 km s^{-1}
$\bar{v}_{\phi,b}$ = 166.7±13.5 km s^{-1}
$\bar{v}_{z,b}$ = -242.8±26.0 km s^{-1}
[Fe/H]$_b$ = -1.9±0.2
$P(\mathbf{x}_\odot)_b = 0.4\sigma$
v_R [km s^{-1}]
v_ϕ [km s^{-1}]
v_z [km s^{-1}]

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"

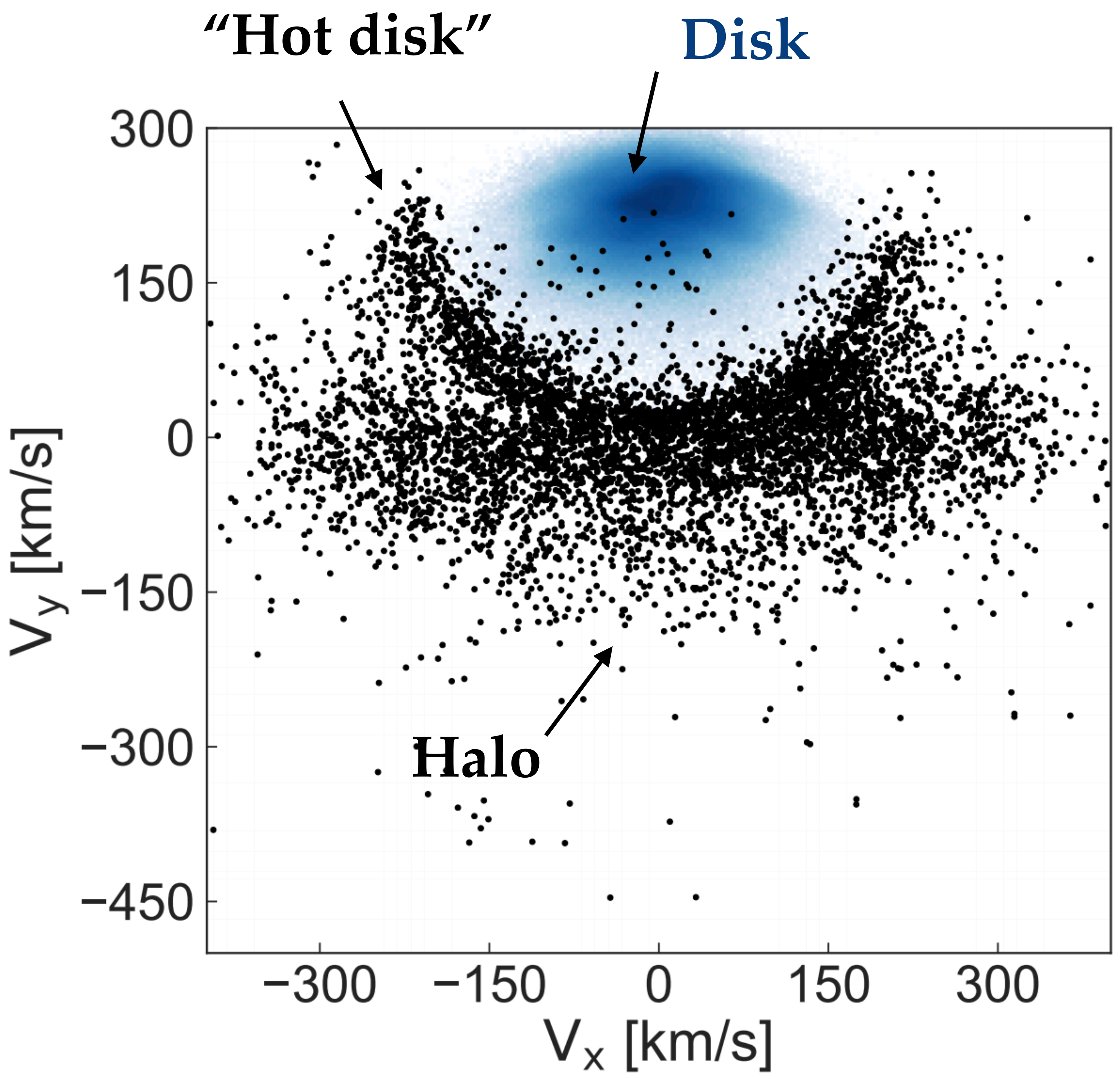
Ostdiek, Necib+ [1907.07681, 1907.07190]



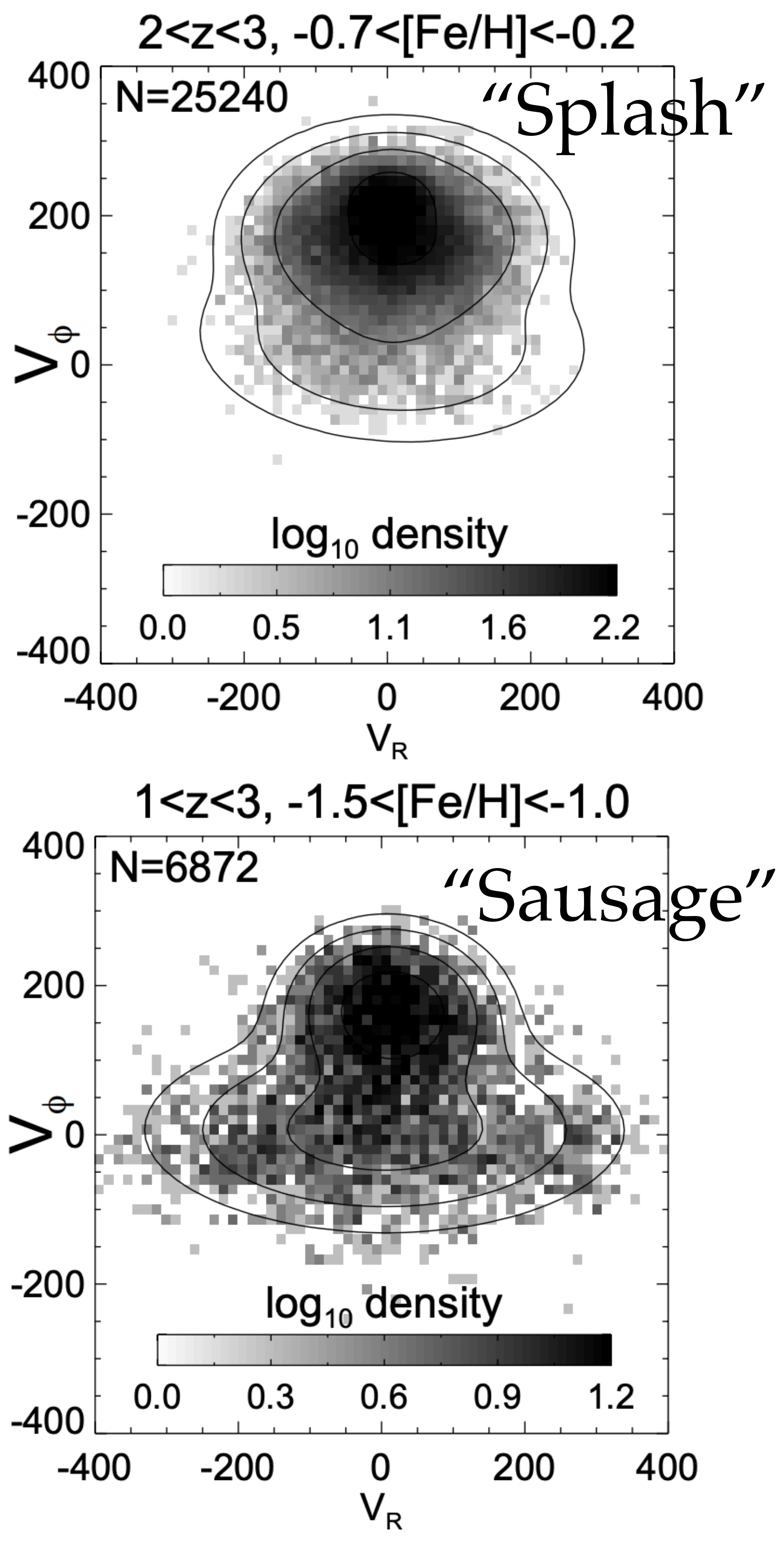
High purity sample

Semi-pure sample

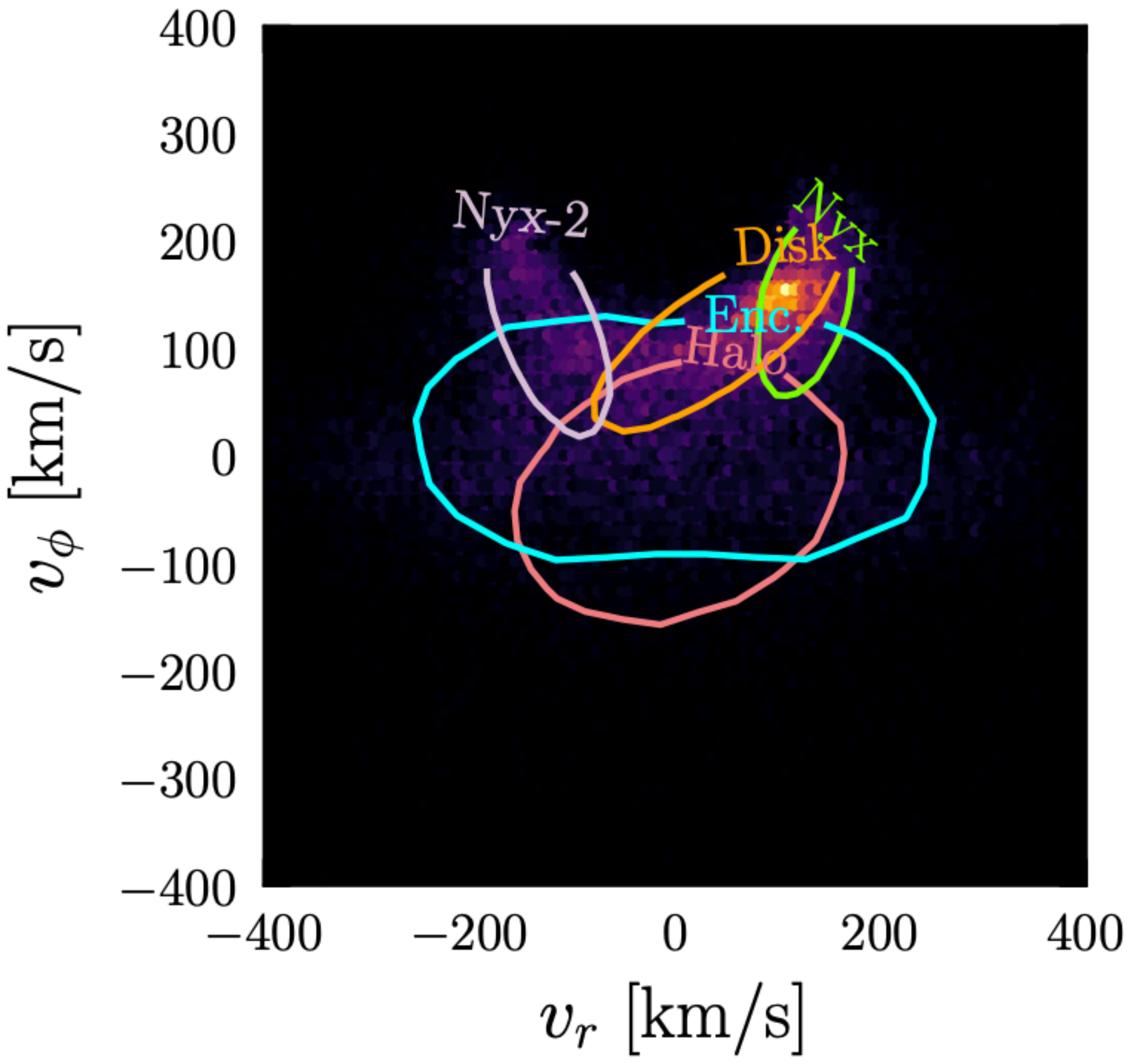
From Helmi's review of substructure in the MW [2002.04340]



Belokurov et al. [1909.04679]

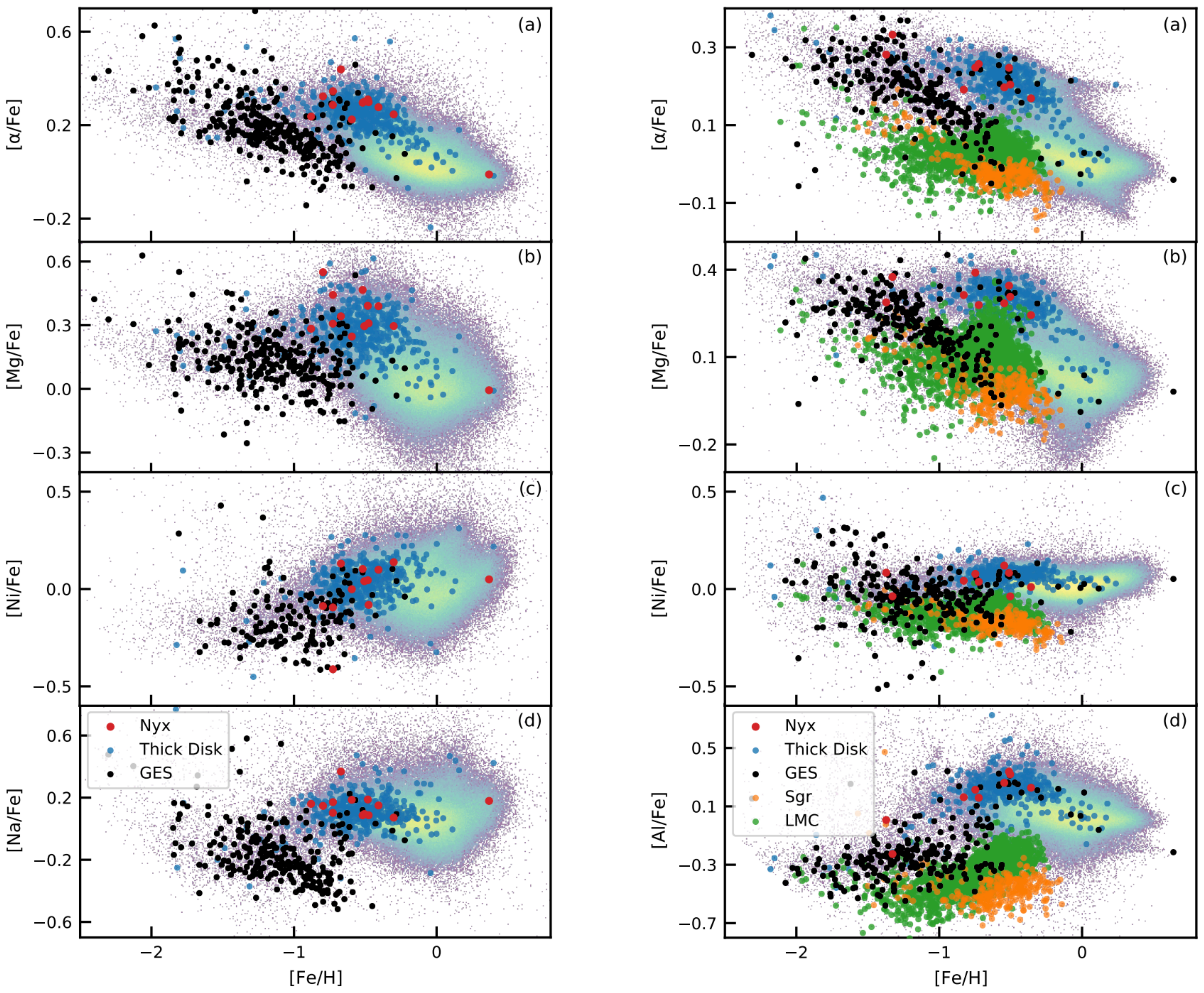


Nyx stream



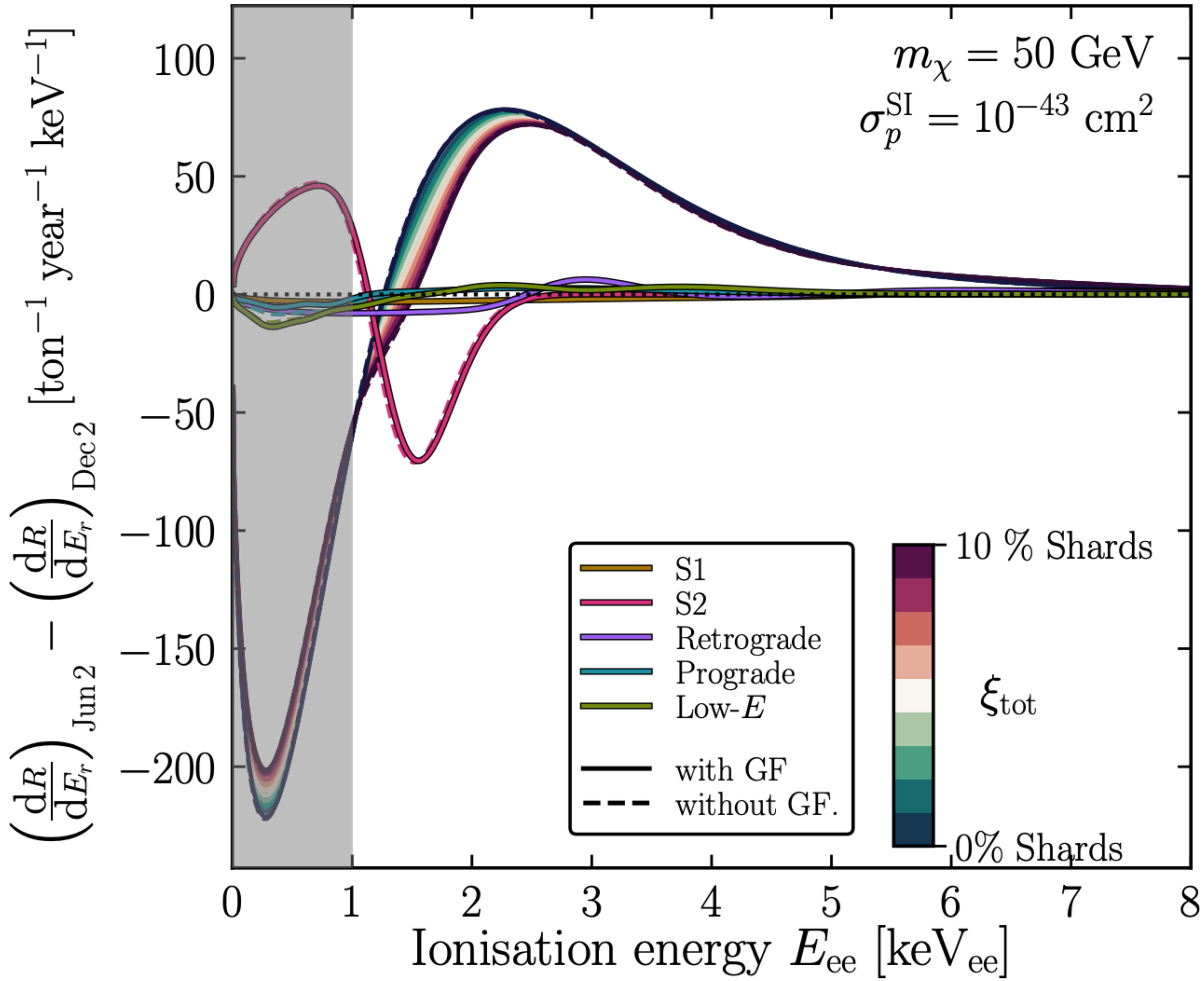
Zucker+ [2104.08684]

No chemical evidence that Nyx stars are from an accreted dwarf, likely part of the hot-thick disk

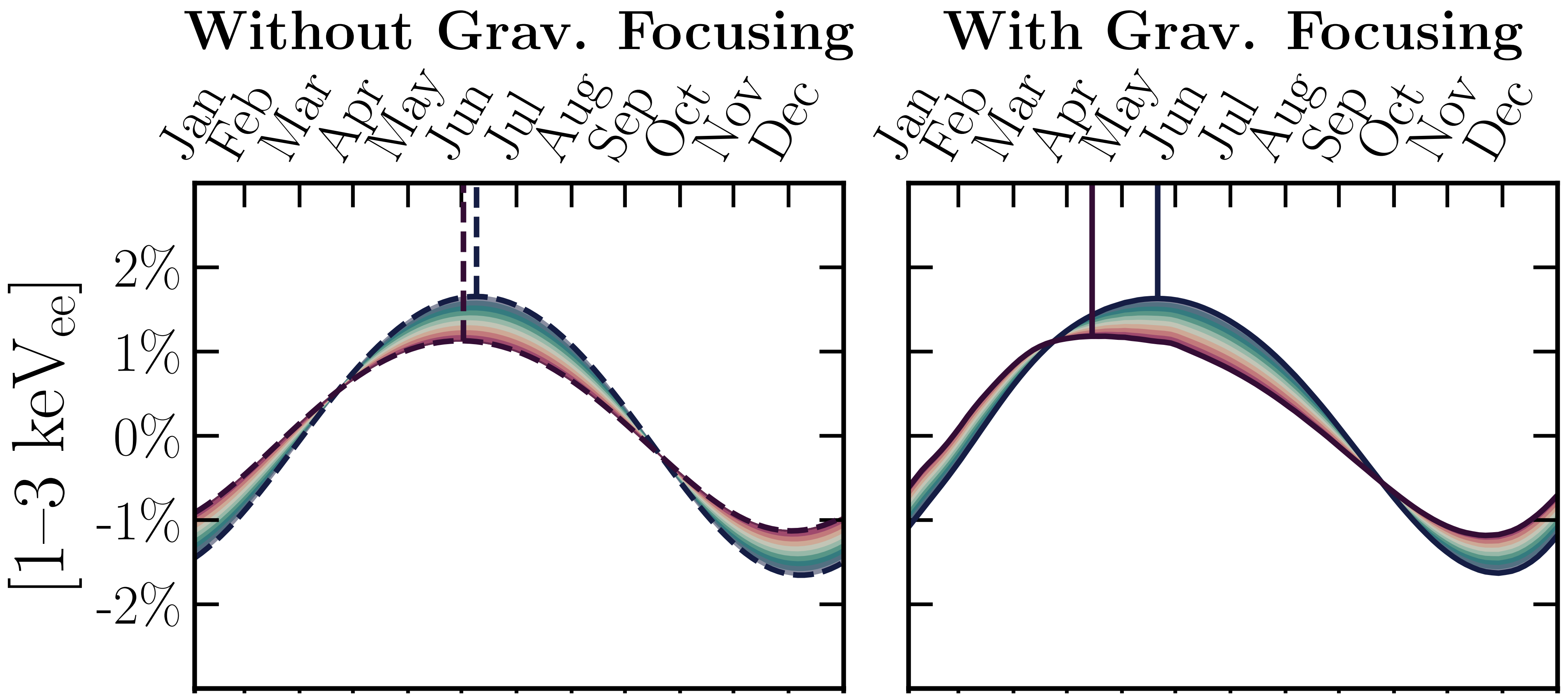


1909.04684

Annual modulation (NaI target)

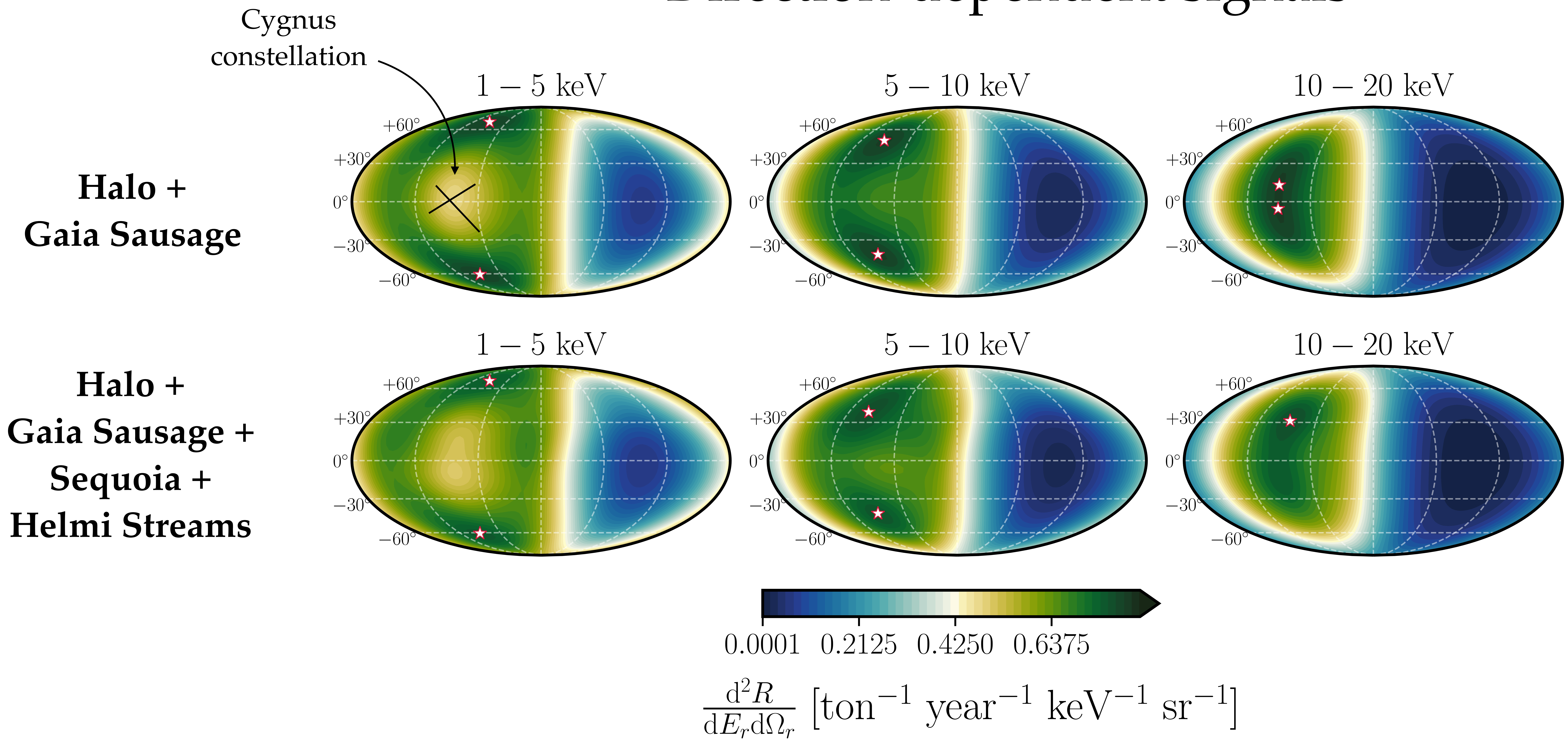


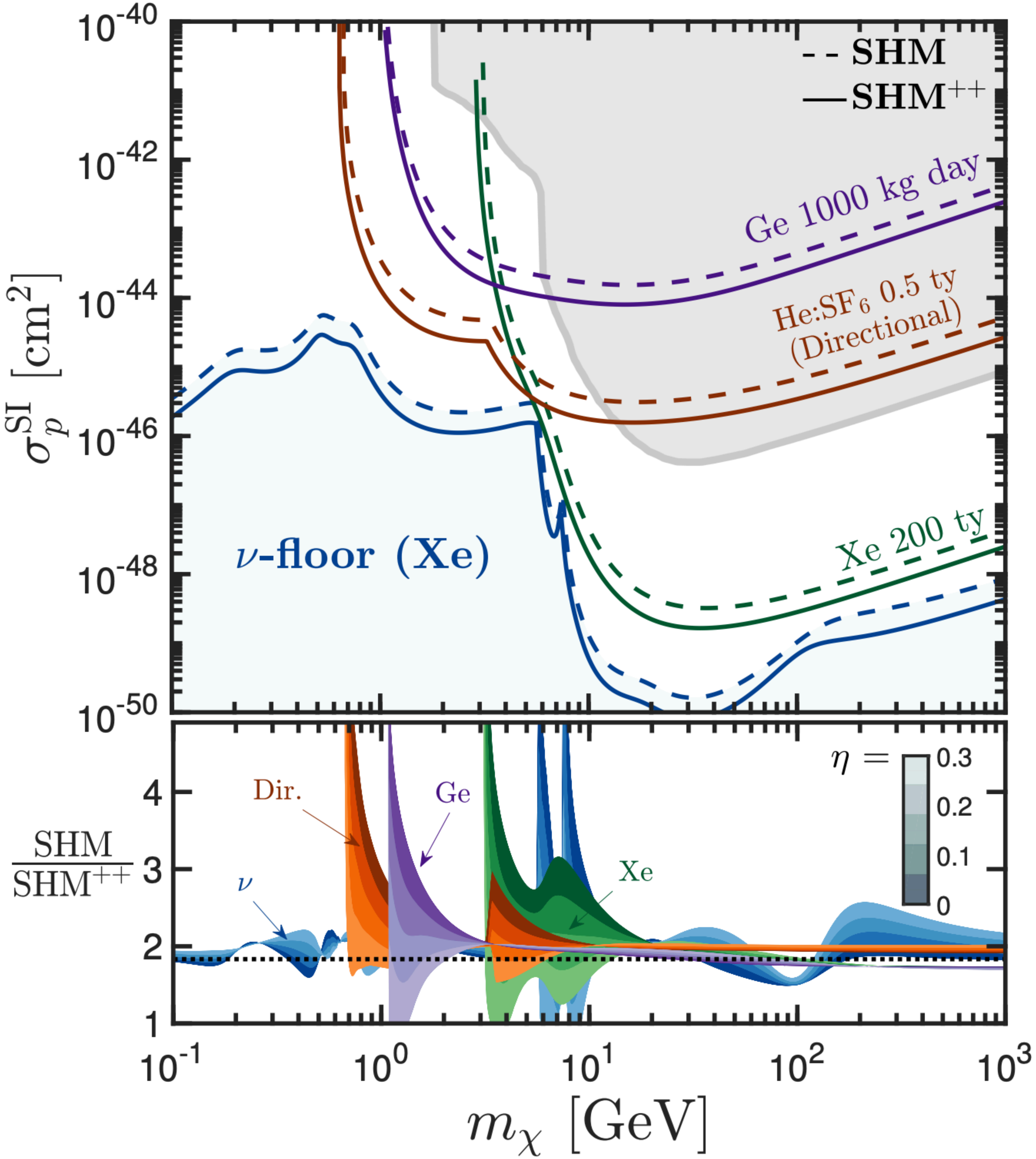
→ Most substructures do not substantially modify annual modulation signature, with the exception of S2 (Helmi streams)



→ S2 also leads to a significant departure from a sinusoidal modulation signal when accounting for gravitational focusing

Most substantial departure
→Direction-dependent signals

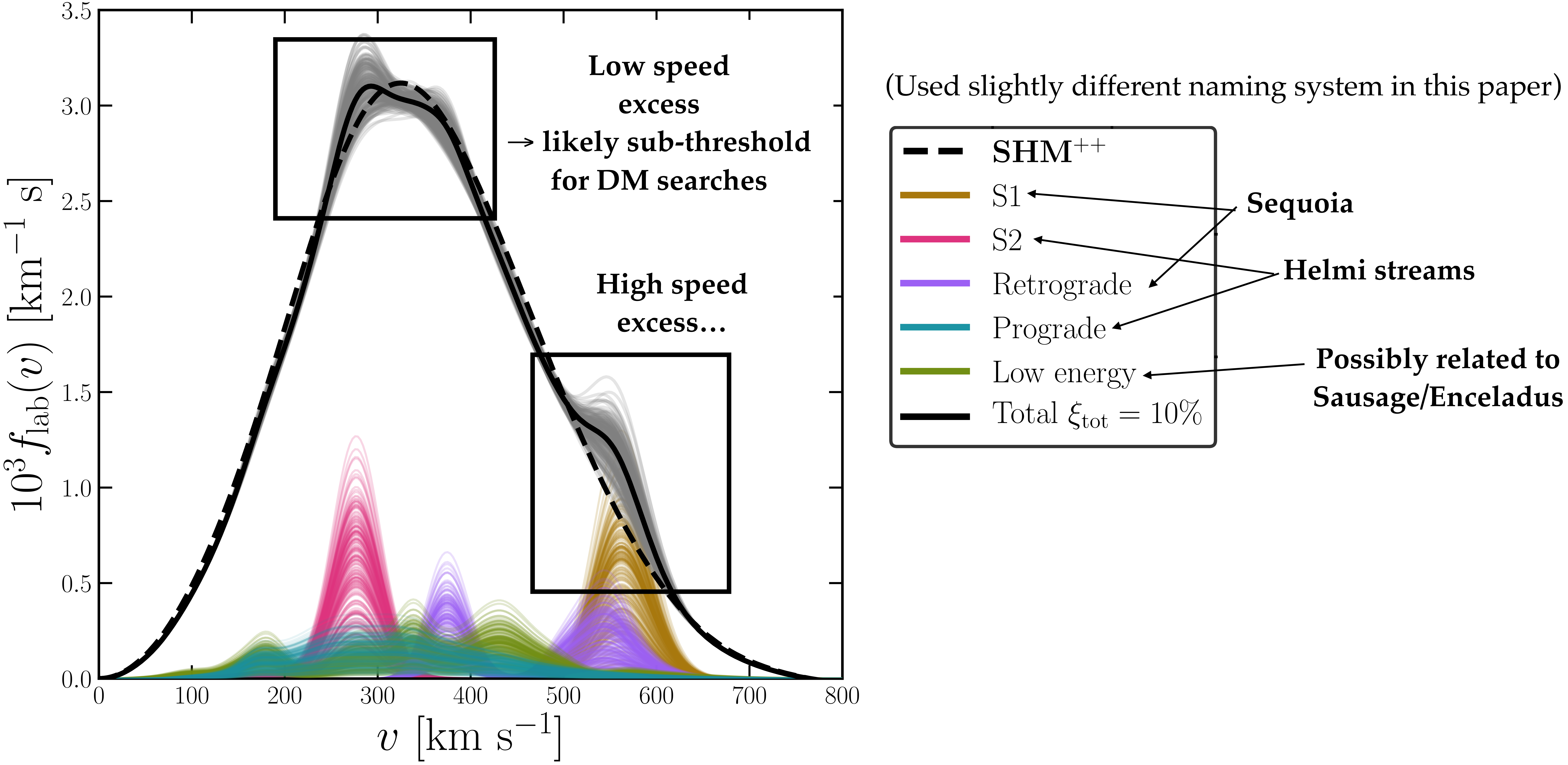




SHM	Local DM density	ρ_0	$0.3\,\mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	220 km s^{-1}
	Escape speed	$v_{\rm esc}$	544 km s^{-1}
	Velocity distribution	$f_{\rm R}(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	0.55 ± 0.17 GeV cm^{-3}
	Circular rotation speed	v_0	233 ± 3 km s^{-1}
	Escape speed	$v_{\rm esc}$	528^{+24}_{-25} km s^{-1}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)

Dark shards

→ Take all the velocity substructures observed in the halo and build a potential DM velocity distribution out of them



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 $f(\mathbf{v})$

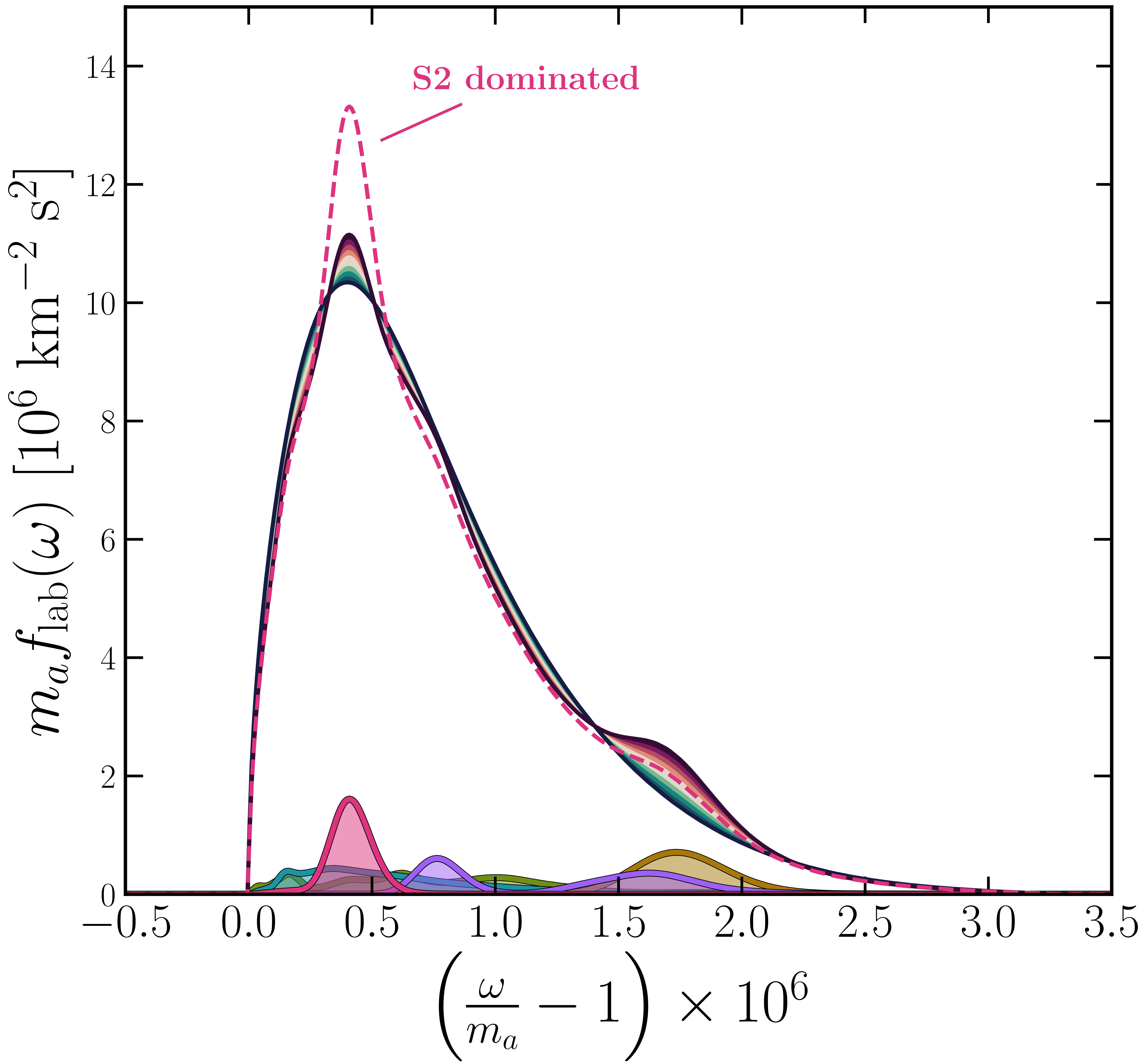
Coherence time: time scale for oscillation to dephase

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

Coherence length: length scale for oscillation to dephase

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

Streams in the axion line



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

1910.06356

Implications of the *Gaia* Sausage for Dark Matter Nuclear Interactions

Jatan Buch,[1,*] JiJi Fan,[1,†] and John Shing Chau Leung[1,‡]

[1] *Department of Physics, Brown University, Providence, RI, 02912, USA*

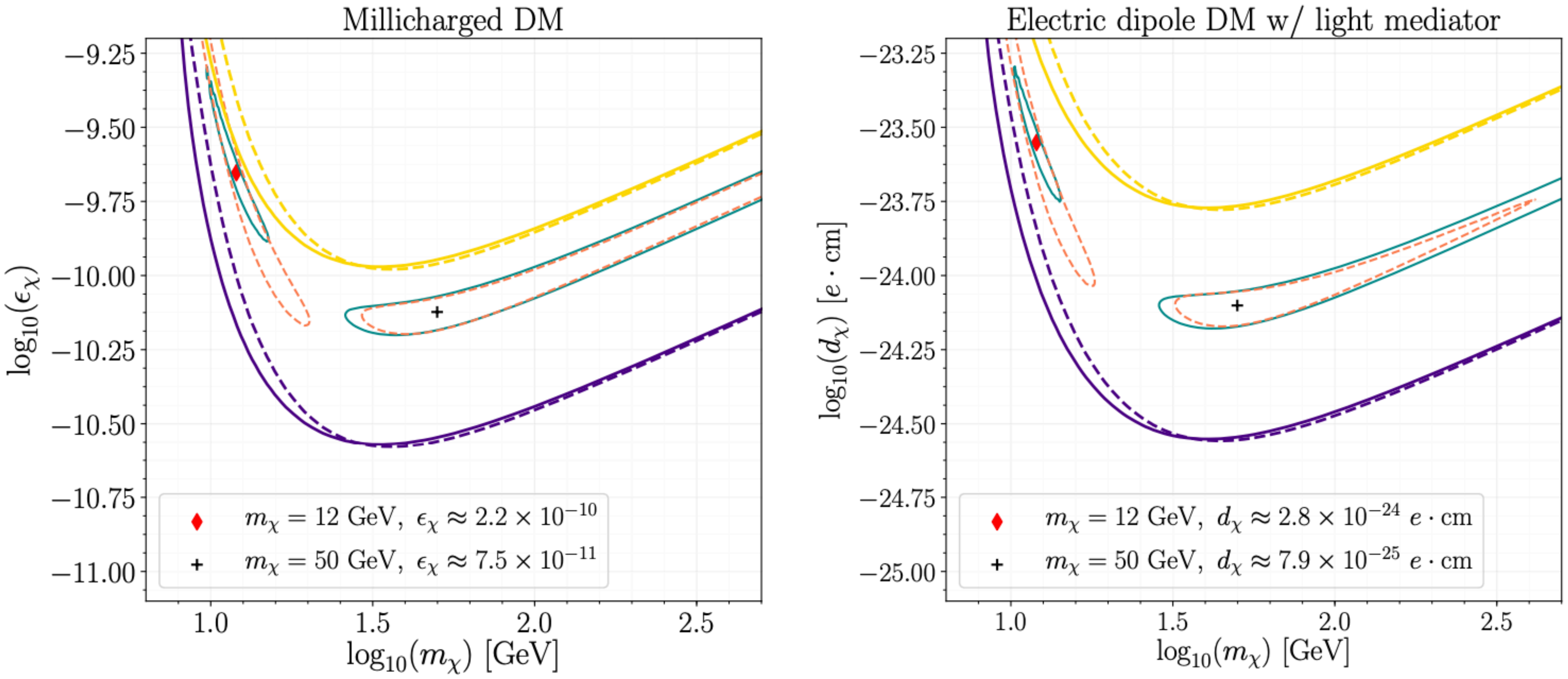
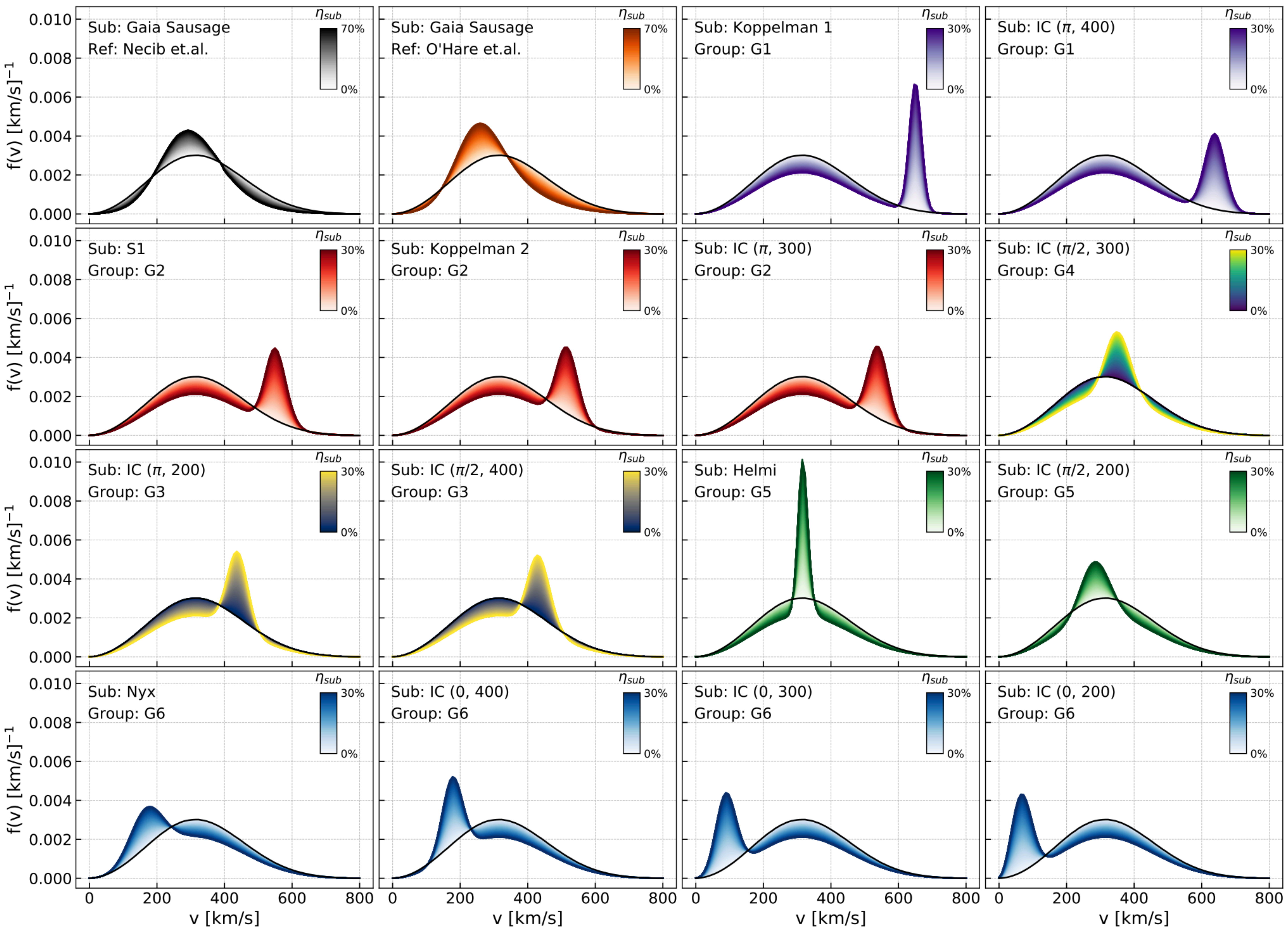


FIG. 7: Constraints and forecasts in the DM coupling-mass plane for all the benchmark models in Table II with varying q^2 and v^2 dependence. The 68% CL forecast contours for SHM (cyan, solid) and *Gaia* (orange, dashed) velocity distributions are shown for both light (red diamond, $m_\chi = 12$ GeV) and heavy (black cross, $m_\chi = 50$ GeV) DM. Also indicated for reference are 90% CL upper limits following the latest XENON-1T results (yellow) and projected upper limits for a DARWIN-like experiment (indigo) assuming SHM (solid) and *Gaia* (dashed) velocity distributions. The constraints for MD with heavy mediator are quoted in units of electron Bohr magneton, $\mu_e = \frac{e}{2m_e}$.

[2005.14667]

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

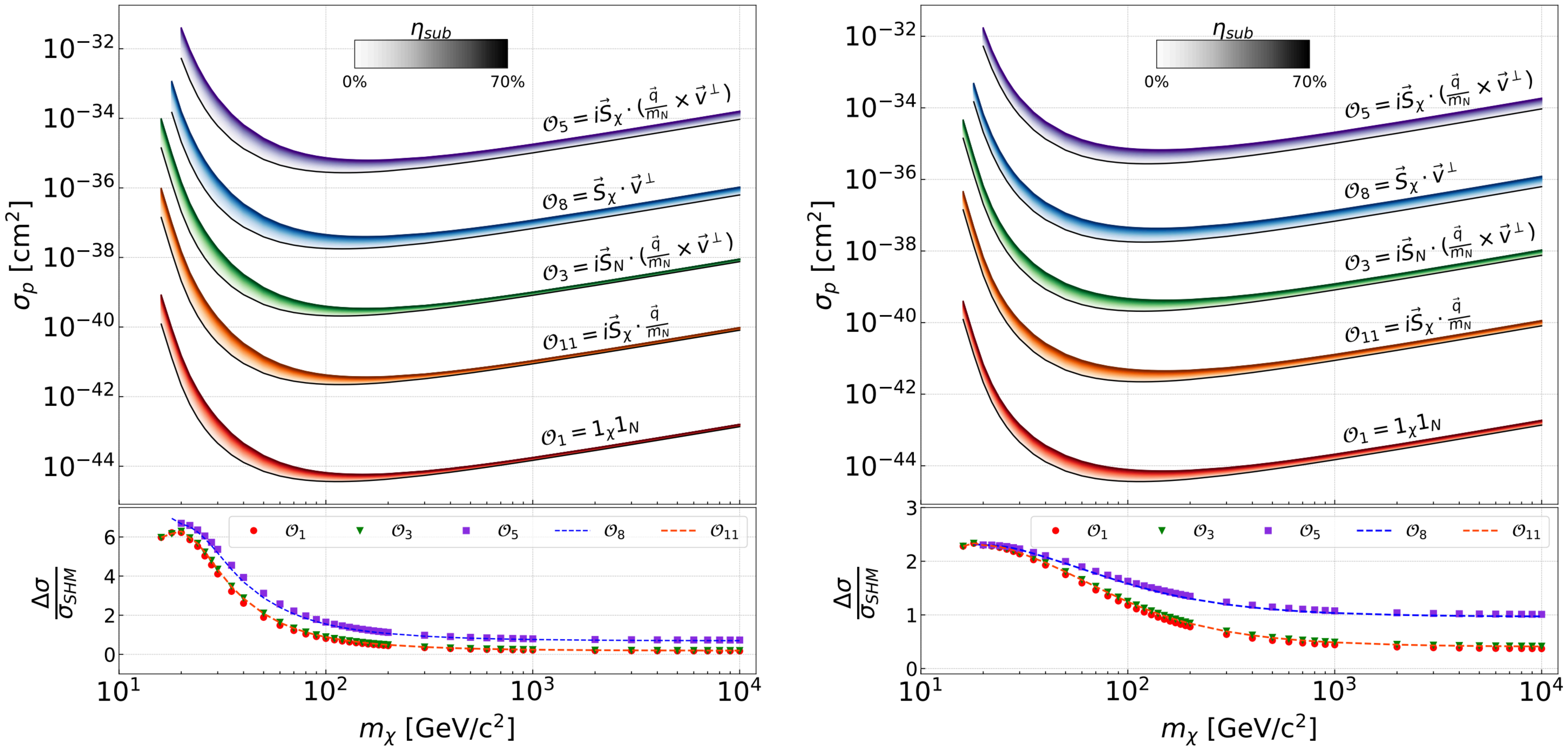
P. Adhikari,[5] R. Ajaj,[5,24] C. E. Bina,[1,24] W. Bonivento,[14] M. G. Boulay,[5] M. Cadeddu,[7,14] B. Cai,[5,24] M. Cárdenas-Montes,[4] S. Cavuoti,[6,13] Y. Chen,[1] B. T. Cleveland,[20,9] J. M. Corning,[17] S. Daugherty,[9] P. DelGobbo,[5,24] P. Di Stefano,[17] L. Doria,[15] M. Dunford,[5] A. Erlandson,[5,3]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



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]



(a) *Gaia* Sausage (Necib *et al.*) [61]   (b) *Gaia* Sausage (O'Hare *et al.*) [17]

FIG. 9. Upper limits (90 % C. L.) on DM-nucleon scattering cross sections for the $\mathcal{O}_1$, $\mathcal{O}_{11}$, $\mathcal{O}_3$, $\mathcal{O}_8$, and $\mathcal{O}_5$ effective operators, in the presence of VDFs corresponding to both *Gaia* Sausage models, G1 streams, and G2 streams, with $\eta_{\rm sub}$ of the DM contained in the specified substructure. Beneath each set of exclusion curves is the relative deviation of each operator with the given substructure at its maximum value compared to the SHM and where $\Delta\sigma = \sigma_{\rm sub} - \sigma_{\rm SHM}$.

2007.13750

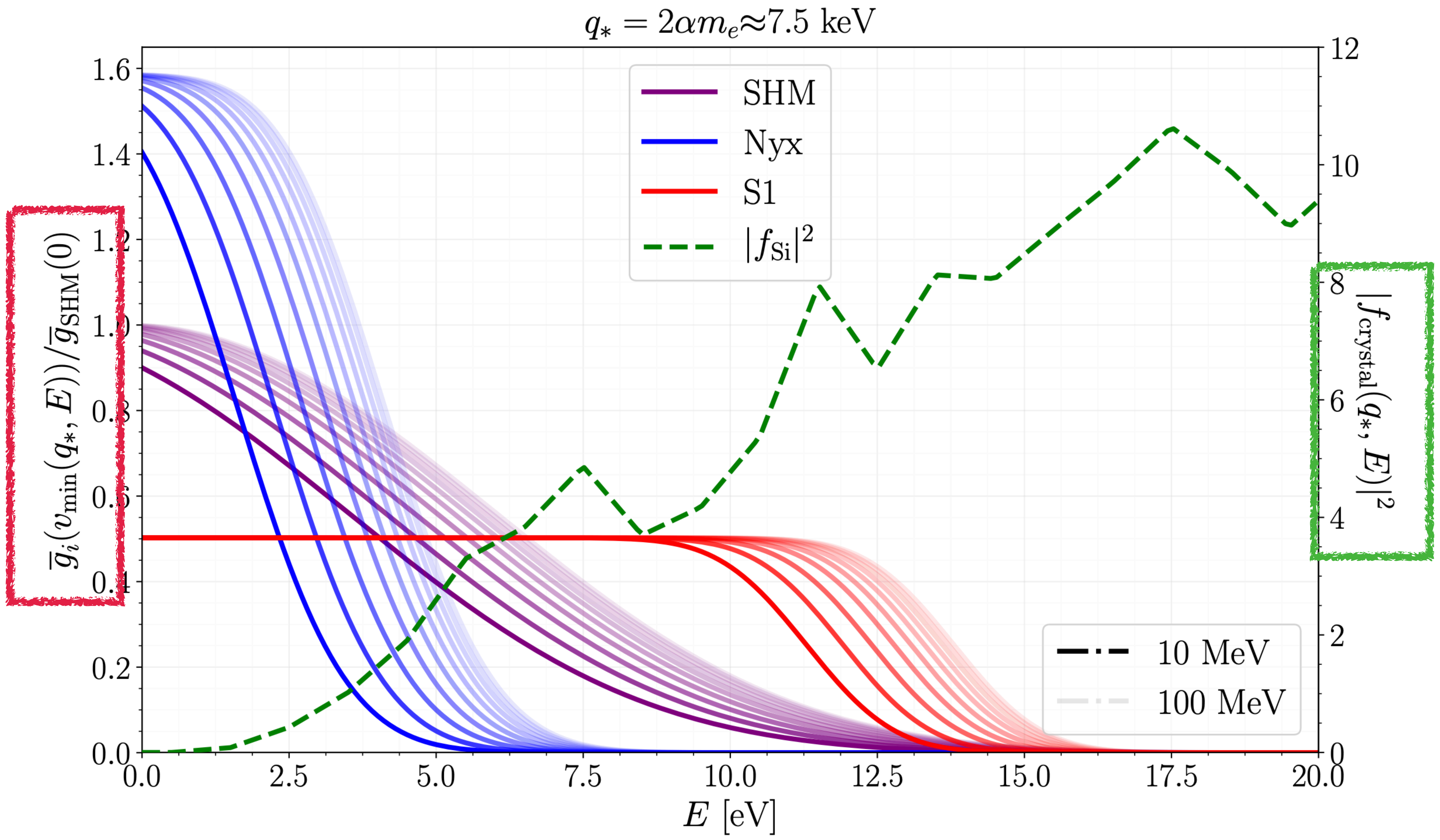
Dark Matter Substructure under the Electron Scattering Lamppost

Jatan Buch,* Manuel A. Buen-Abad,† JiJi Fan,‡ and John Shing Chau Leung§
Department of Physics, Brown University, Providence, RI, 02912, USA

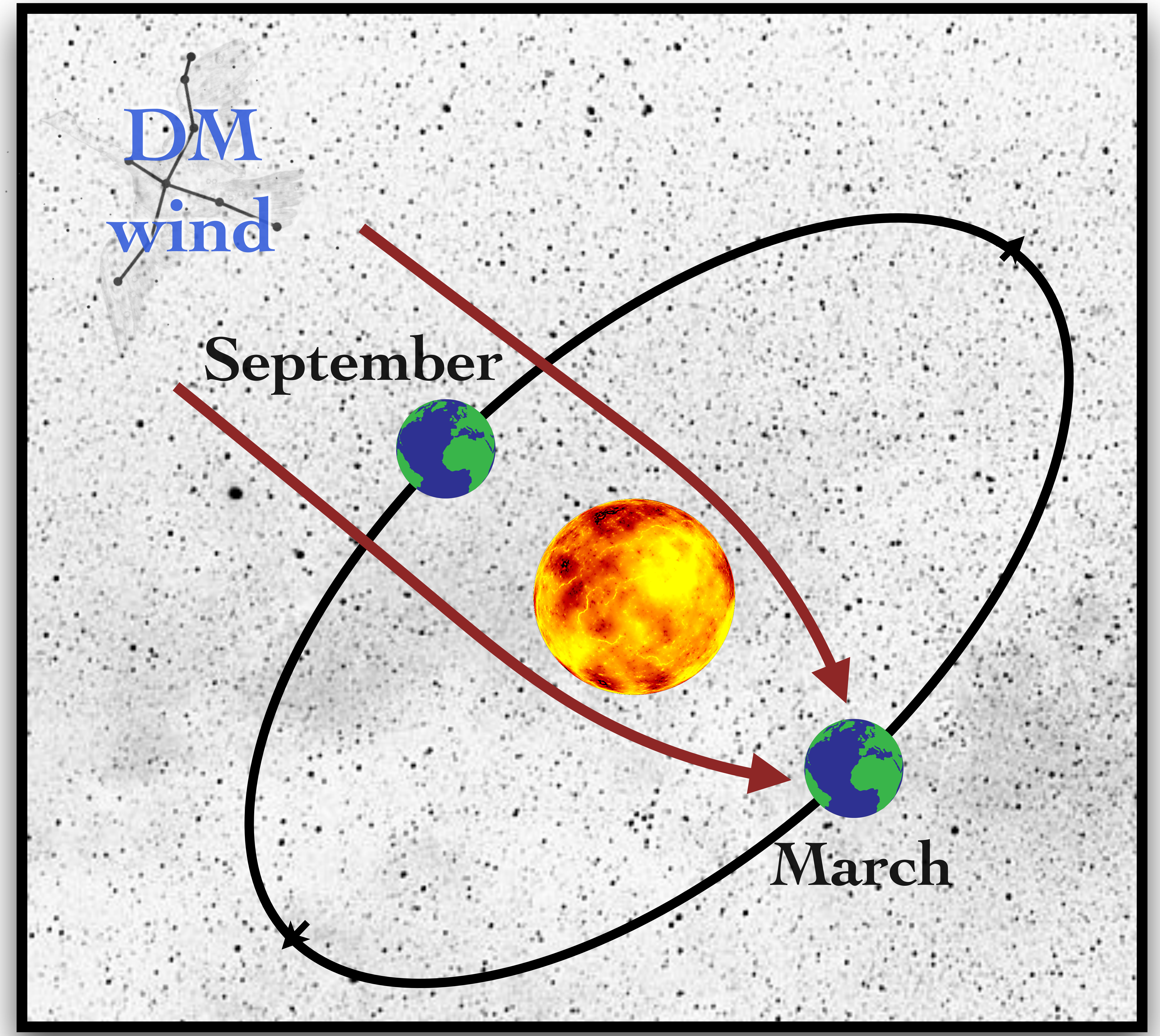
(Dated: July 29, 2020)

Rate of electron recoils in semiconductor:

$$\frac{\mathrm{d}R}{\mathrm{d}\ln E} = N_{\rm cell}\frac{\rho_\chi}{m_\chi}\overline{\sigma}_e\alpha\frac{m_e^2}{\mu_{\chi e}^2}\int \mathrm{d}q\ \frac{E}{q^2}F_{\rm DM}^2(q)|f_{\rm crystal}(q,E)|^2\, g(v_{\rm min}(q,E),t)$$



Gravitational focusing



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