THE UNIVERSITY OF SYDNEY

Australian Government
Australian Research Council

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

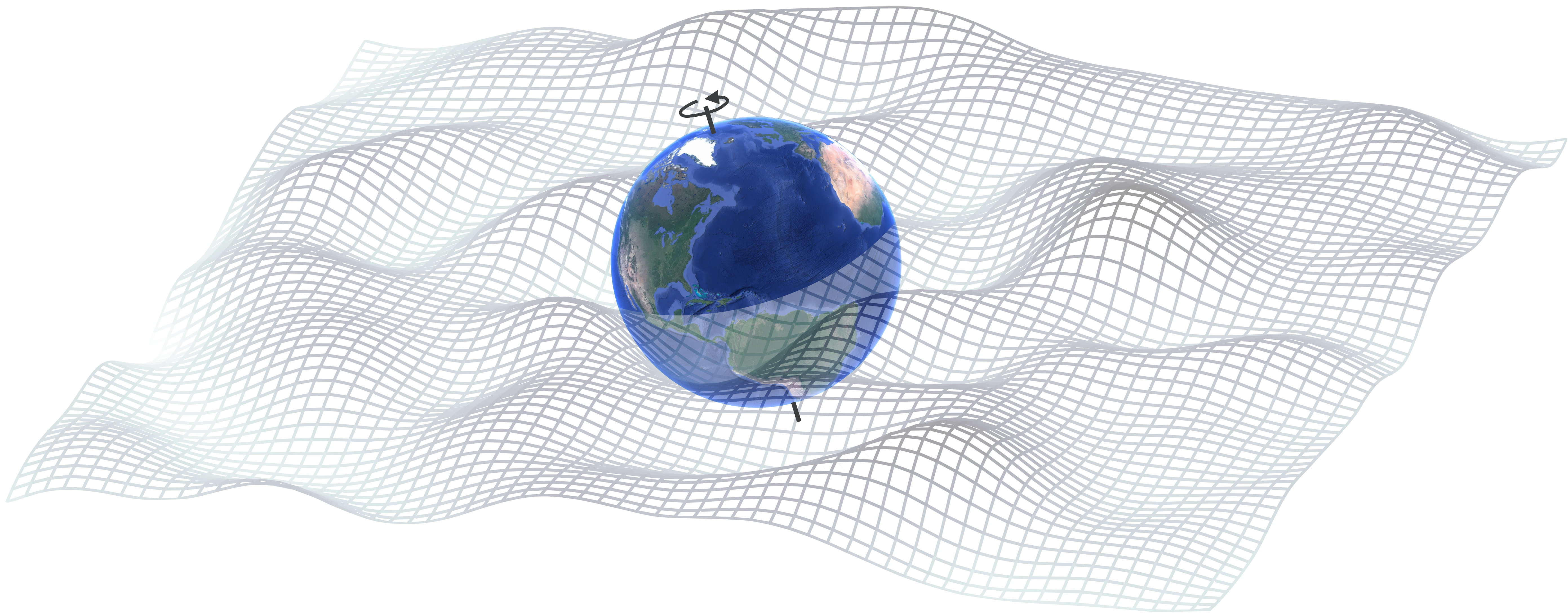
Dark matter in the Milky Way & implications for wave-like dark matter experiments

Ciaran O'Hare

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

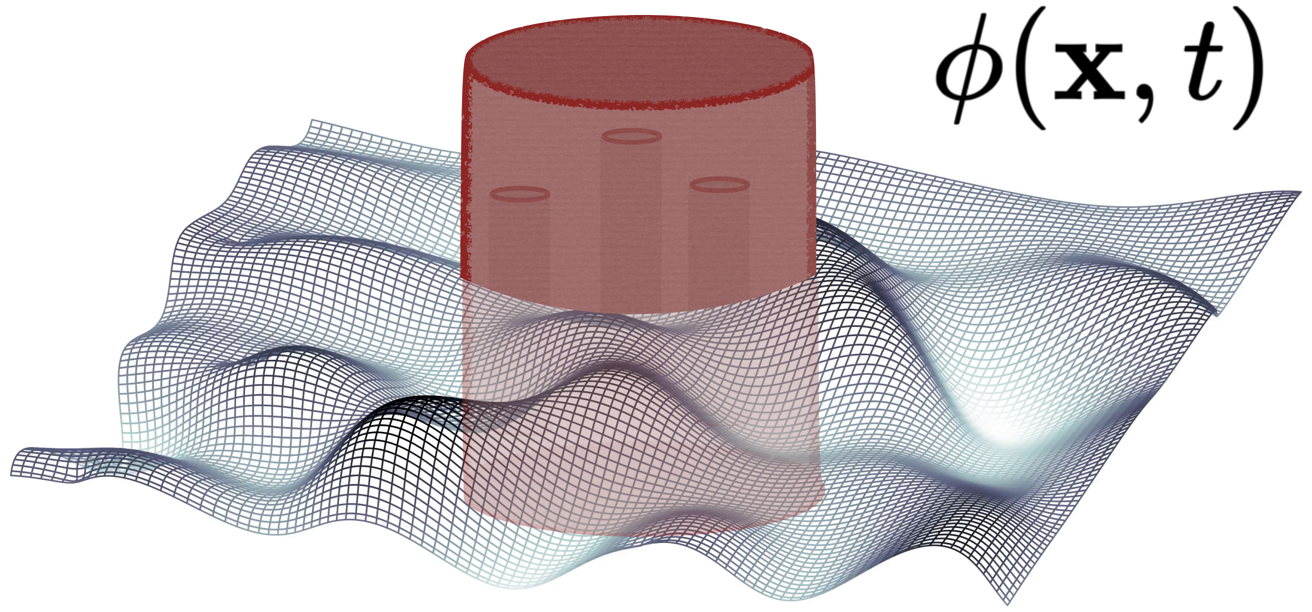
Particle-like

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

Flux $\Phi = v n_\chi$

Wave-like dark matter signal

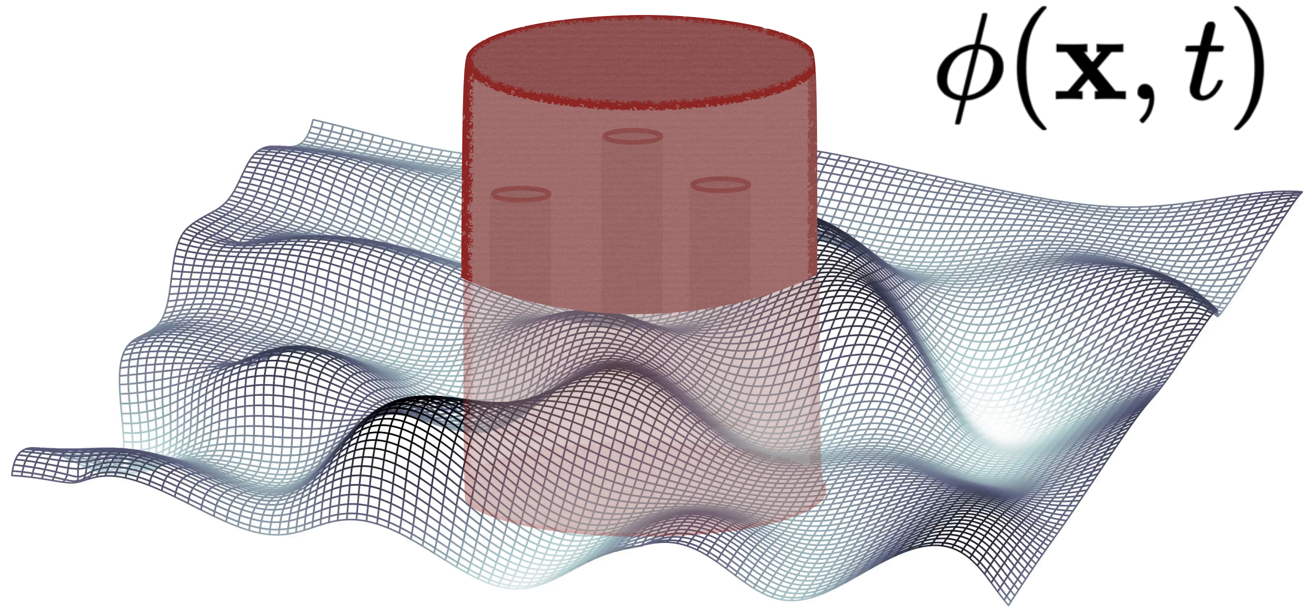
If field is coherent over experimental volume, and oscillates many times per observation duration → FT of signal timeseries approaches DM speed distribution



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

Wave-like dark matter signal

If field is coherent over experimental volume, and oscillates many times per observation duration → FT of signal timeseries approaches DM speed distribution

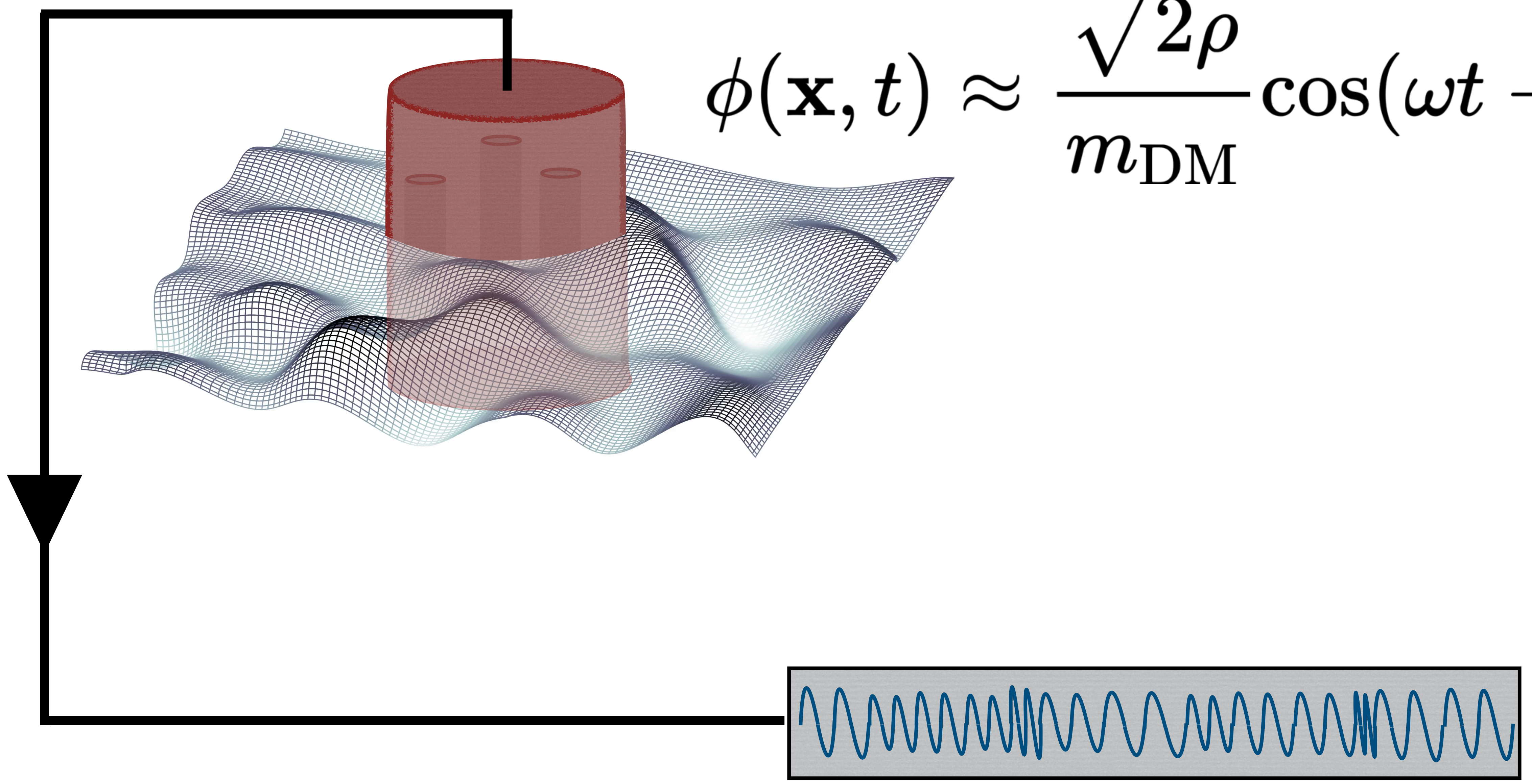


$$\phi(\mathbf{x}, t) \approx \frac{\sqrt{2\rho}}{m_{\rm DM}} \cos(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha)$$

Wave-like dark matter signal

If field is coherent over experimental volume, and oscillates many times per observation duration → FT of signal timeseries approaches DM speed distribution

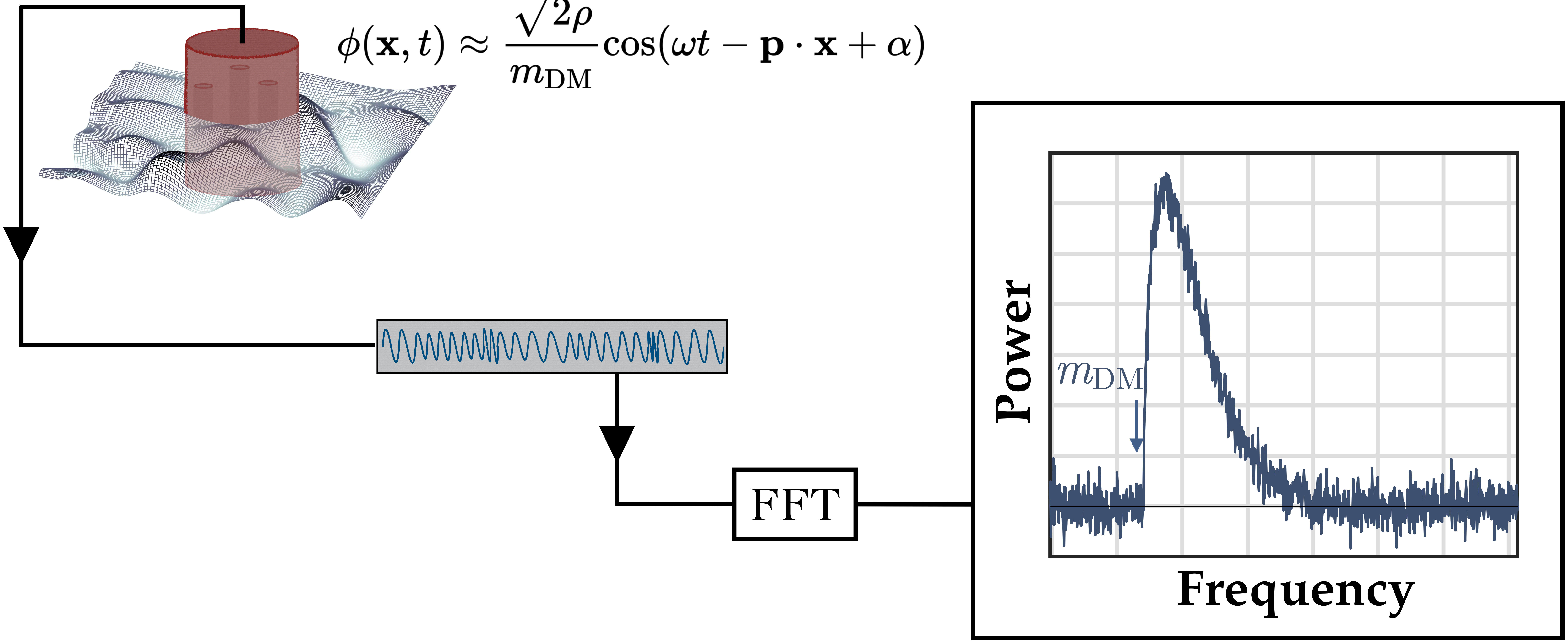
$$\phi(\mathbf{x},t) \approx \frac{\sqrt{2\rho}}{m_{\mathrm{DM}}}\cos(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha)$$



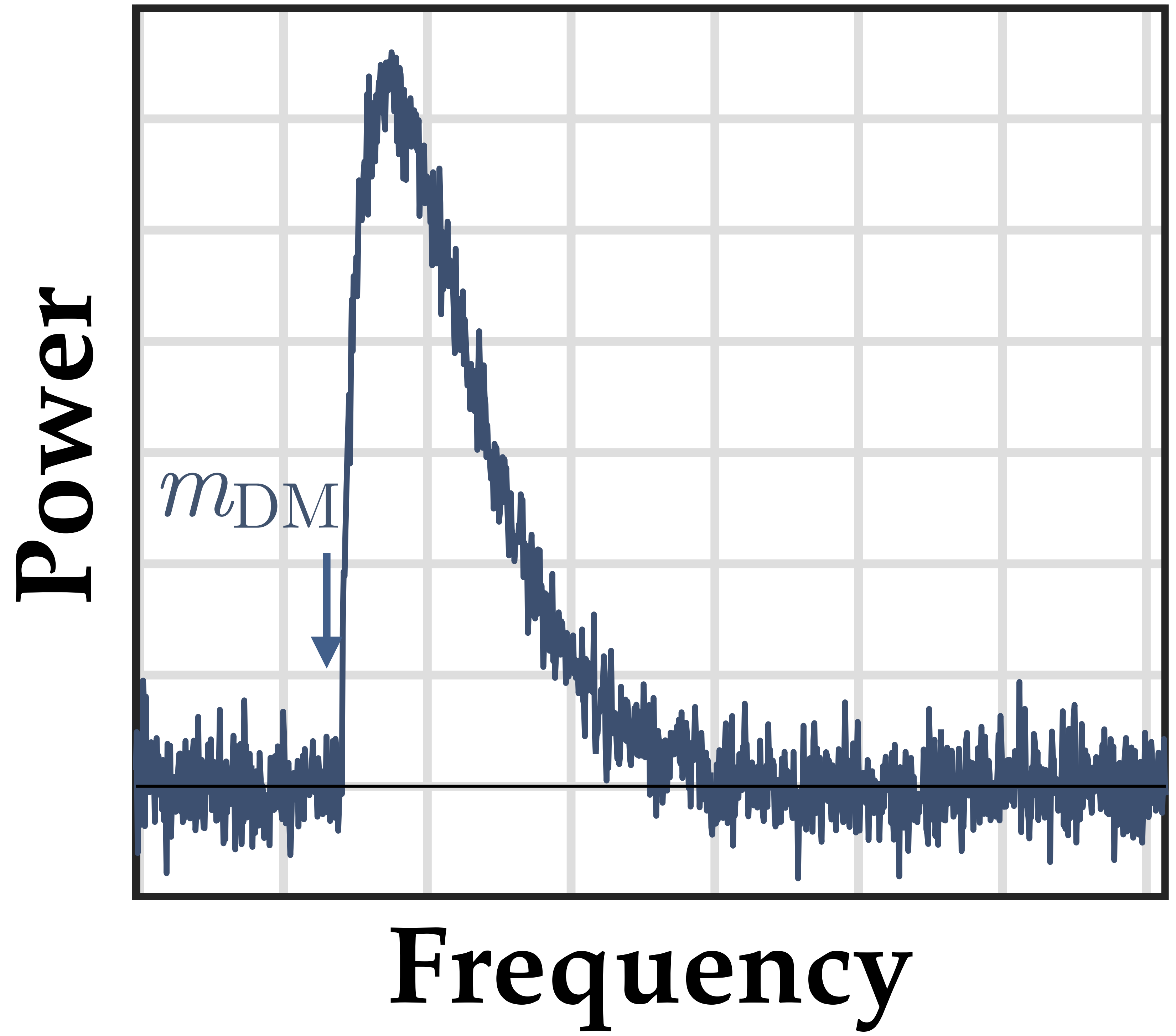
Wave-like dark matter signal

If field is coherent over experimental volume, and oscillates many times per observation duration → FT of signal timeseries approaches DM speed distribution

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

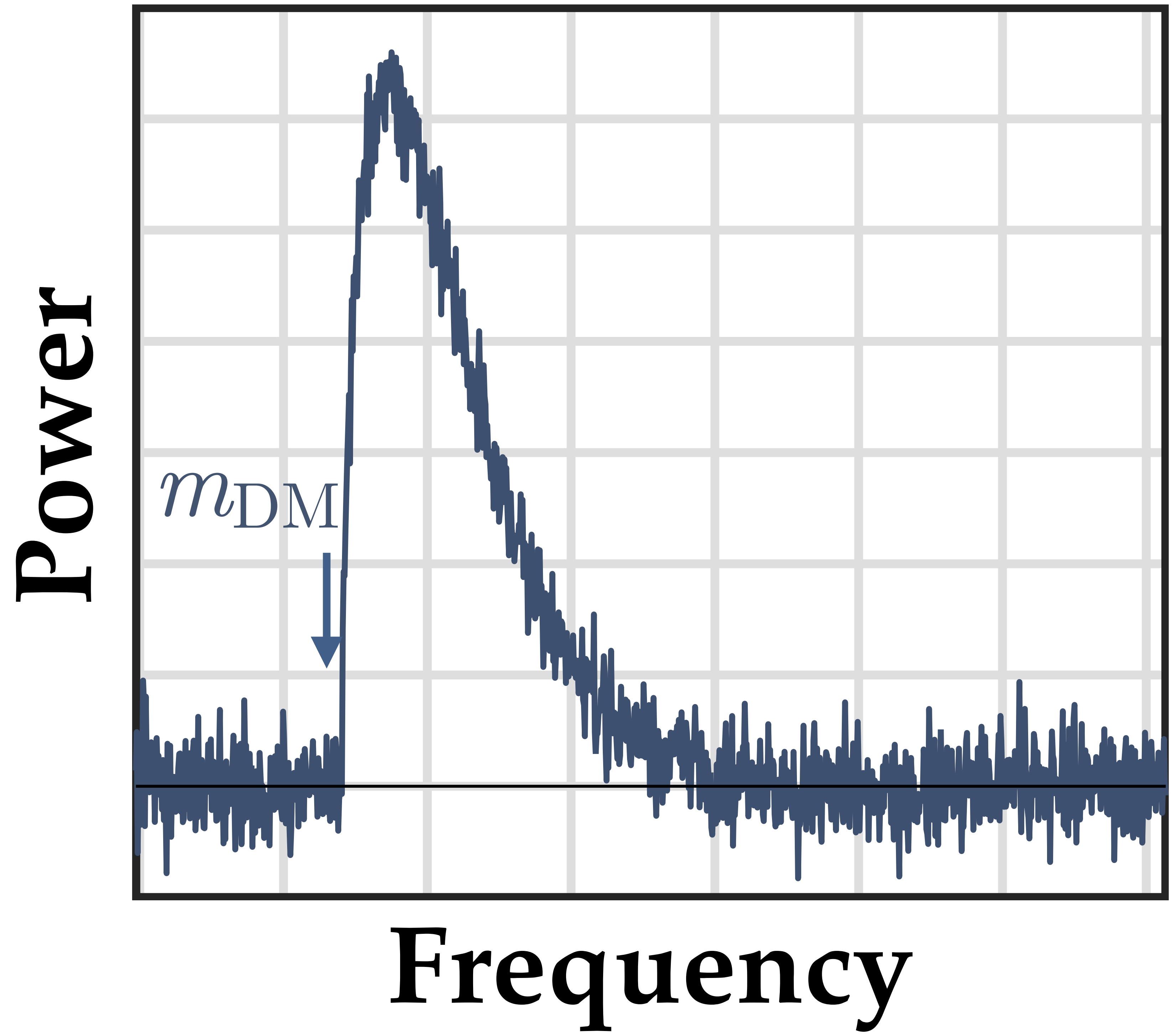


For wave-like DM detected through oscillatory signatures, the signal is stronger for *higher* densities and *narrower* speed distributions



$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_{\rm DM}\, g^2}{m_{\rm DM}^2} f(v)$$

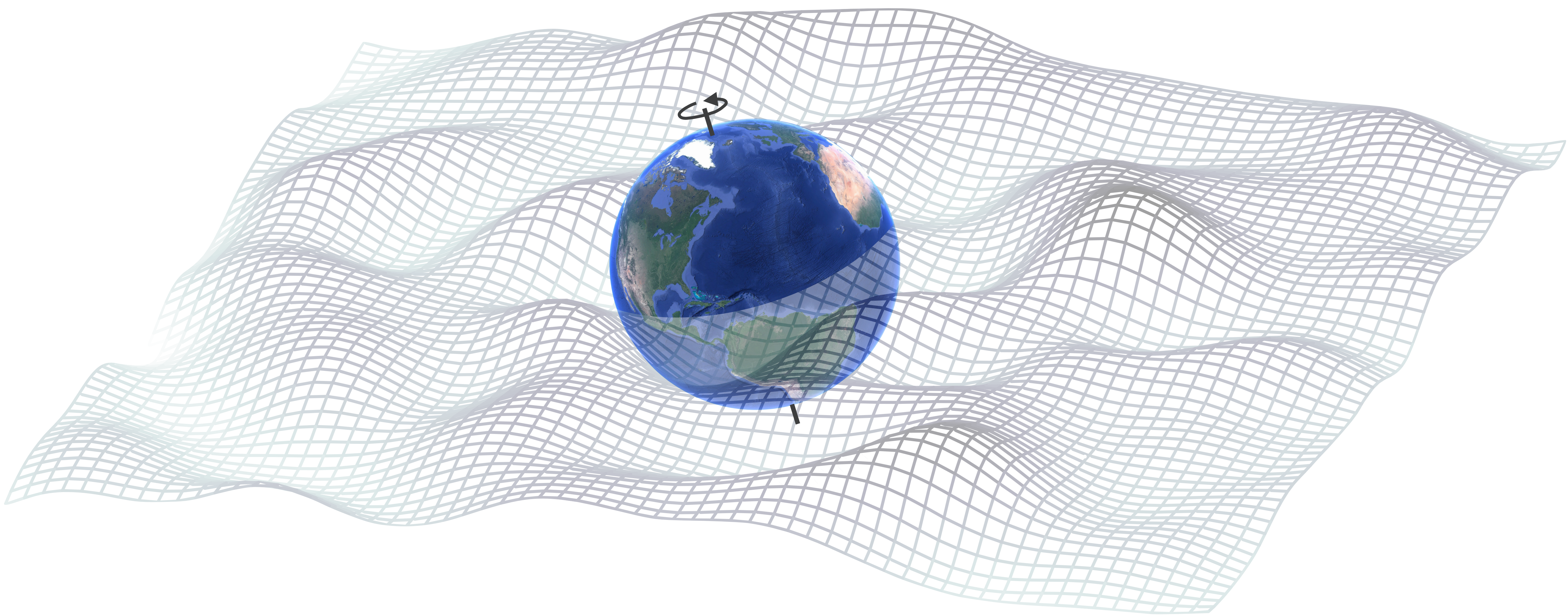
For wave-like DM detected through oscillatory signatures, the signal is stronger for *higher* densities and *narrower* speed distributions



$$\frac{{\rm d}P_s}{{\rm d}\omega} \propto \frac{\rho_{\rm DM}\, g^2}{m_{\rm DM}^2} f(v)$$

+ Annual modulation
+ Direction dependence
+ Polarisation dependence (DPs)
+ Fundamental noise from incoherent distribution of phases*

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



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

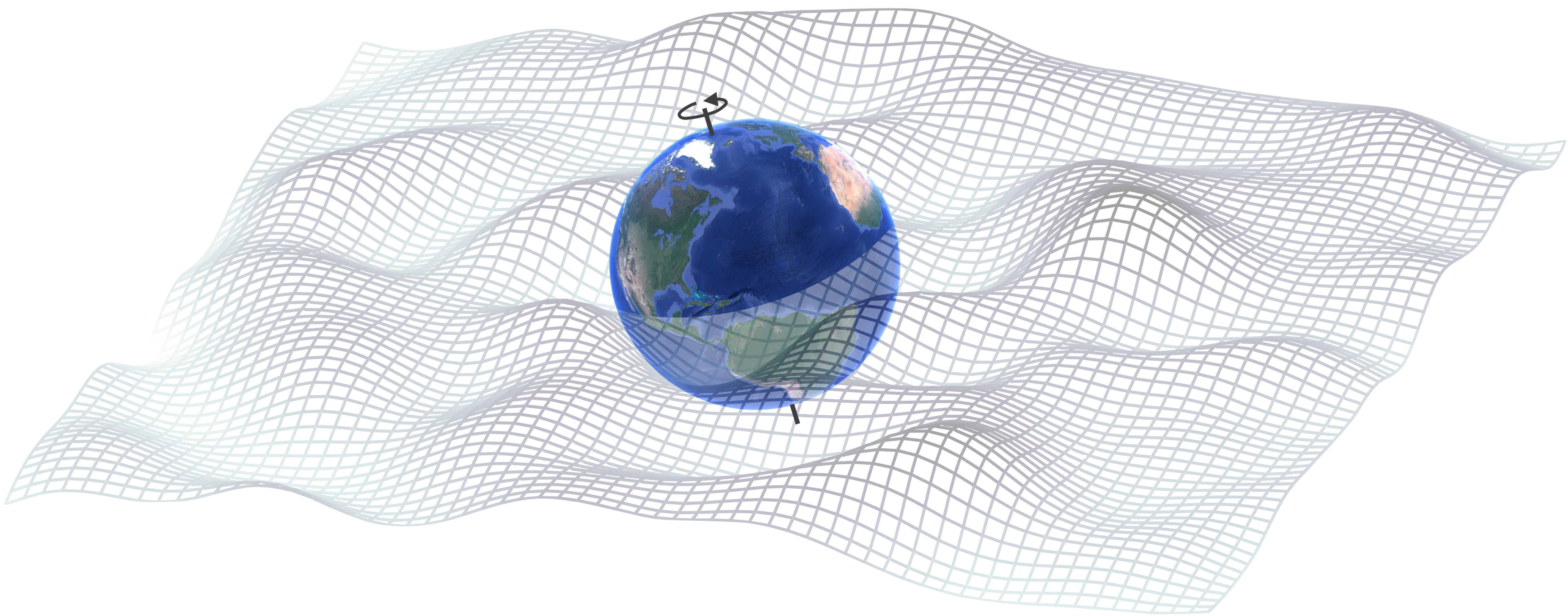
Frequency $\omega = m_\chi + \frac{1}{2} m_\chi v^2$

Local density

$\rho_{\rm DM}$

Velocity distribution

$f(\mathbf{v})$



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

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

Local density

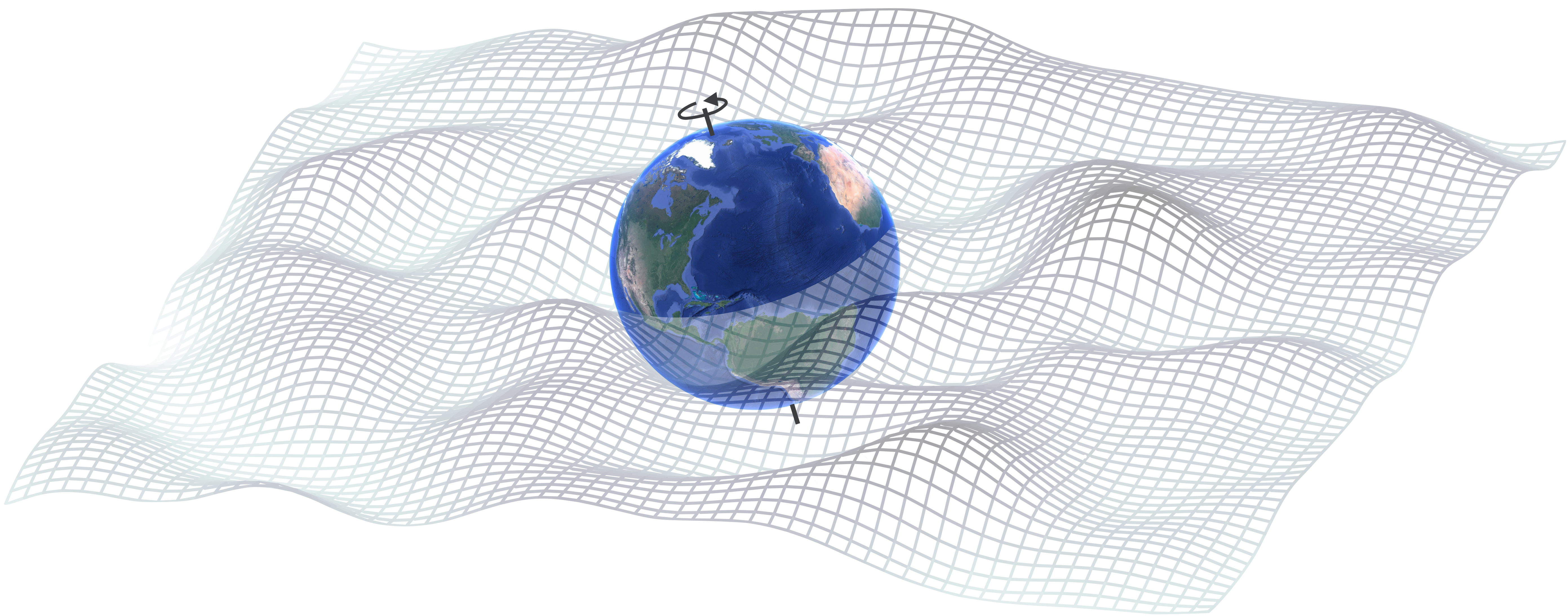
ρ_{DM}

Velocity distribution

$f(\mathbf{v})$

Distribution function

$f(\mathbf{x}, \mathbf{v})$



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

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

Local density

ρ_{DM}

Velocity distribution

$f(\mathbf{v})$

↓

Distribution function

$f(\mathbf{x}, \mathbf{v})$

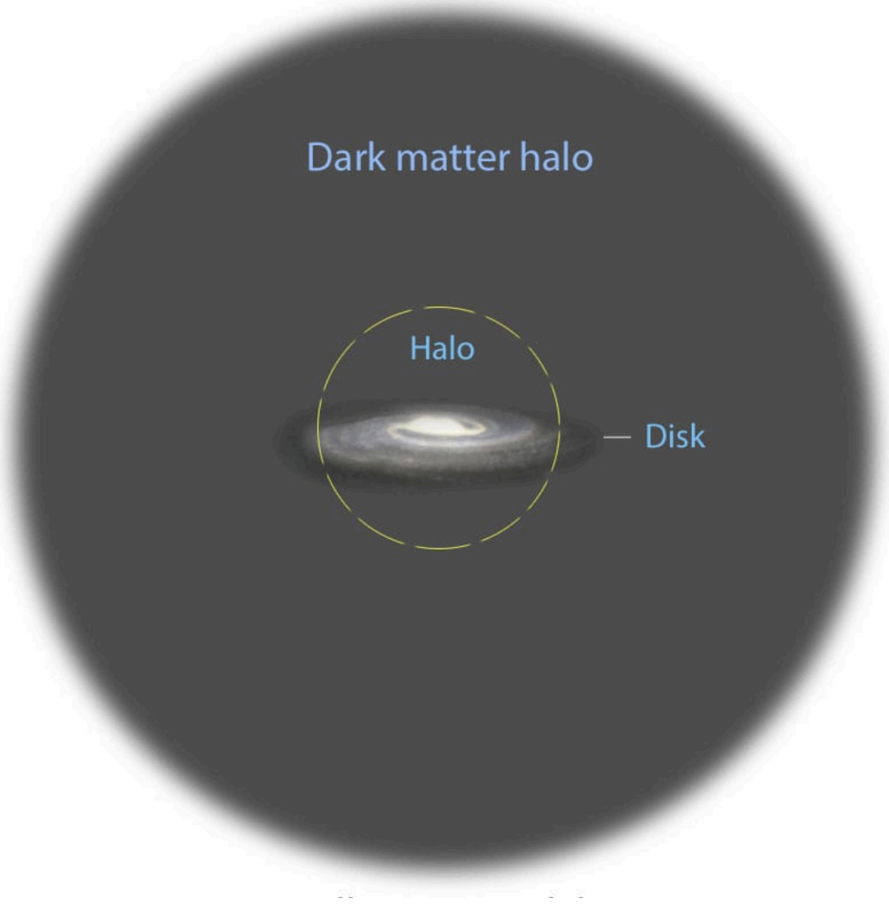
↓

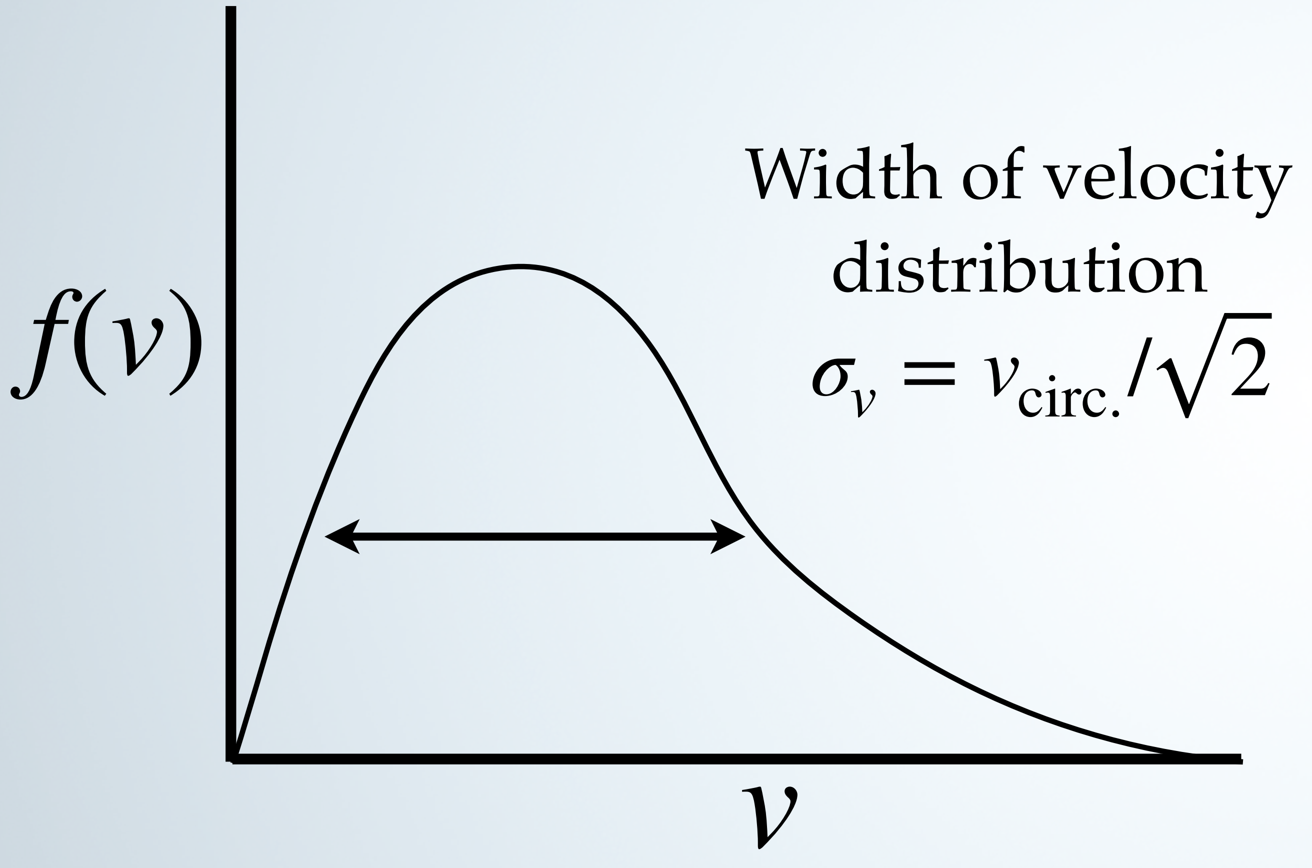
Halo model

The usual assumption: the Standard Halo Model (SHM)

- Infinite isothermal sphere → Simplest halo model that gives a flat asymptotic rotation curve: $v_{\rm circ}(R) \to$ const
- We observe it after a boost into our frame of reference by $v_{\rm lab} \approx v_{\rm circ}$

$\rho \sim 1/r^2$

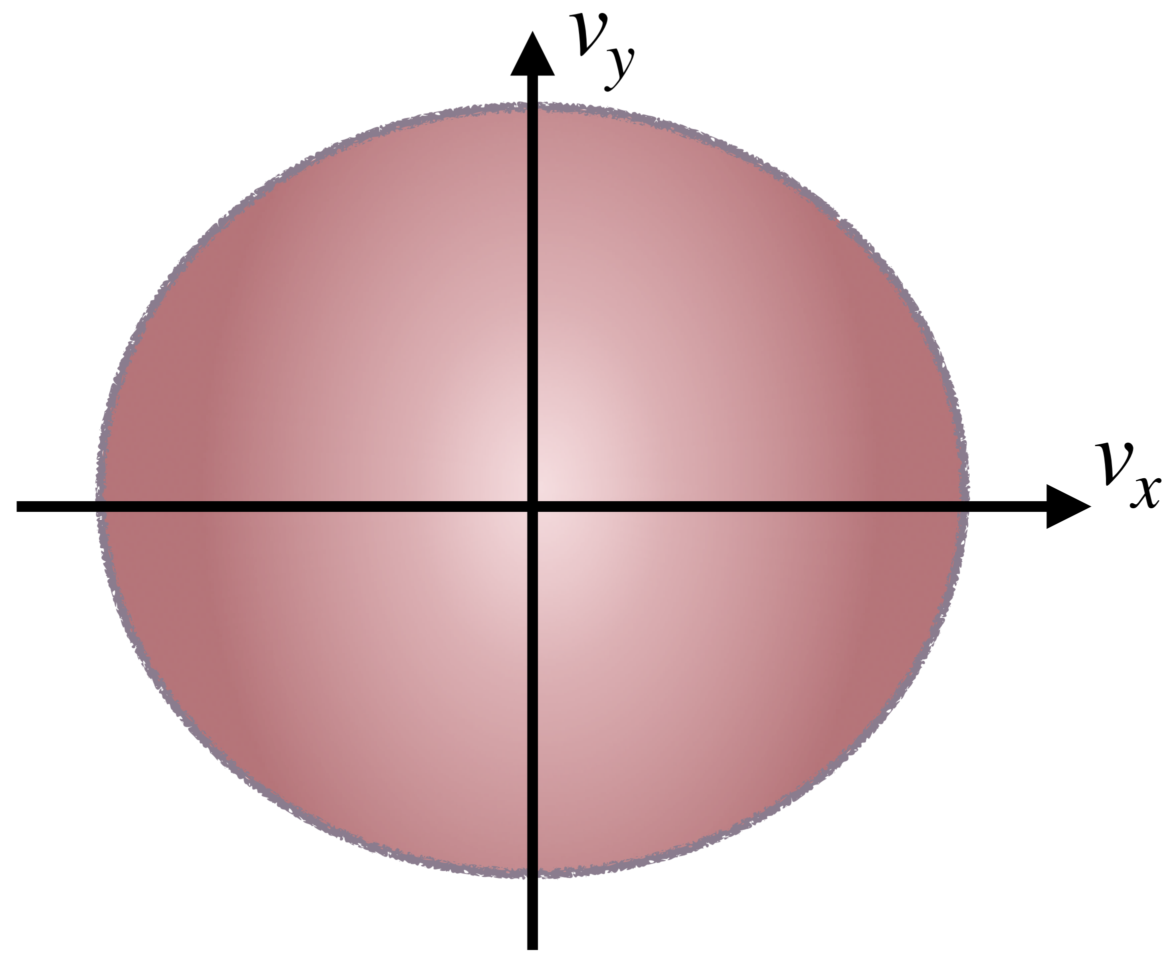




$@\, R = 8$ kpc:

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

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



What’s the issue?

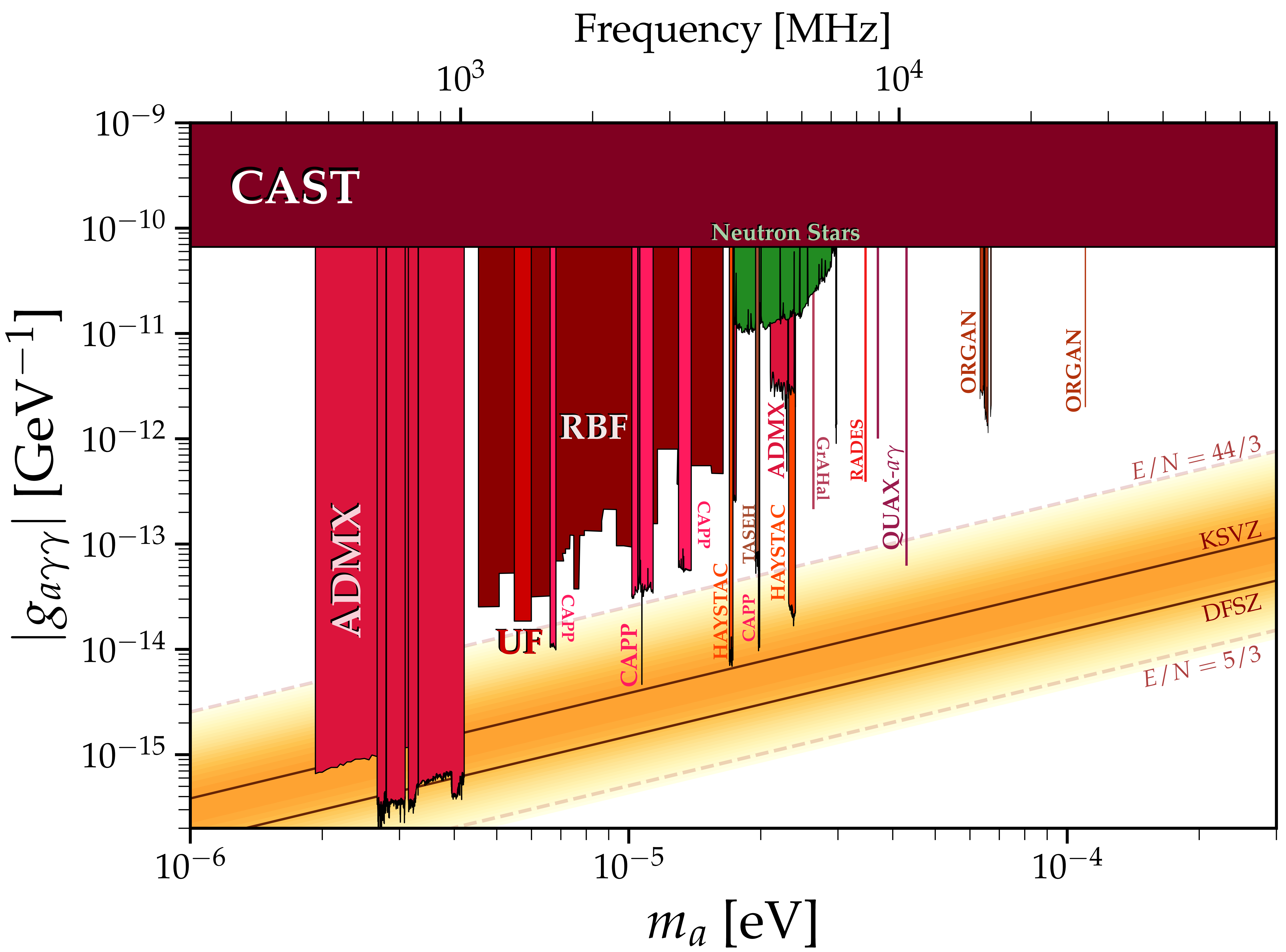
The SHM is unlikely to be accurate in detail, but as long as we agree on it as a benchmark, does the precise model matter?

$\rightarrow$ Can’t we just rescale things?

What's the issue?

The SHM is unlikely to be accurate in detail, but as long as we agree on it as a benchmark, does the precise model matter?

→ Can't we just rescale things?

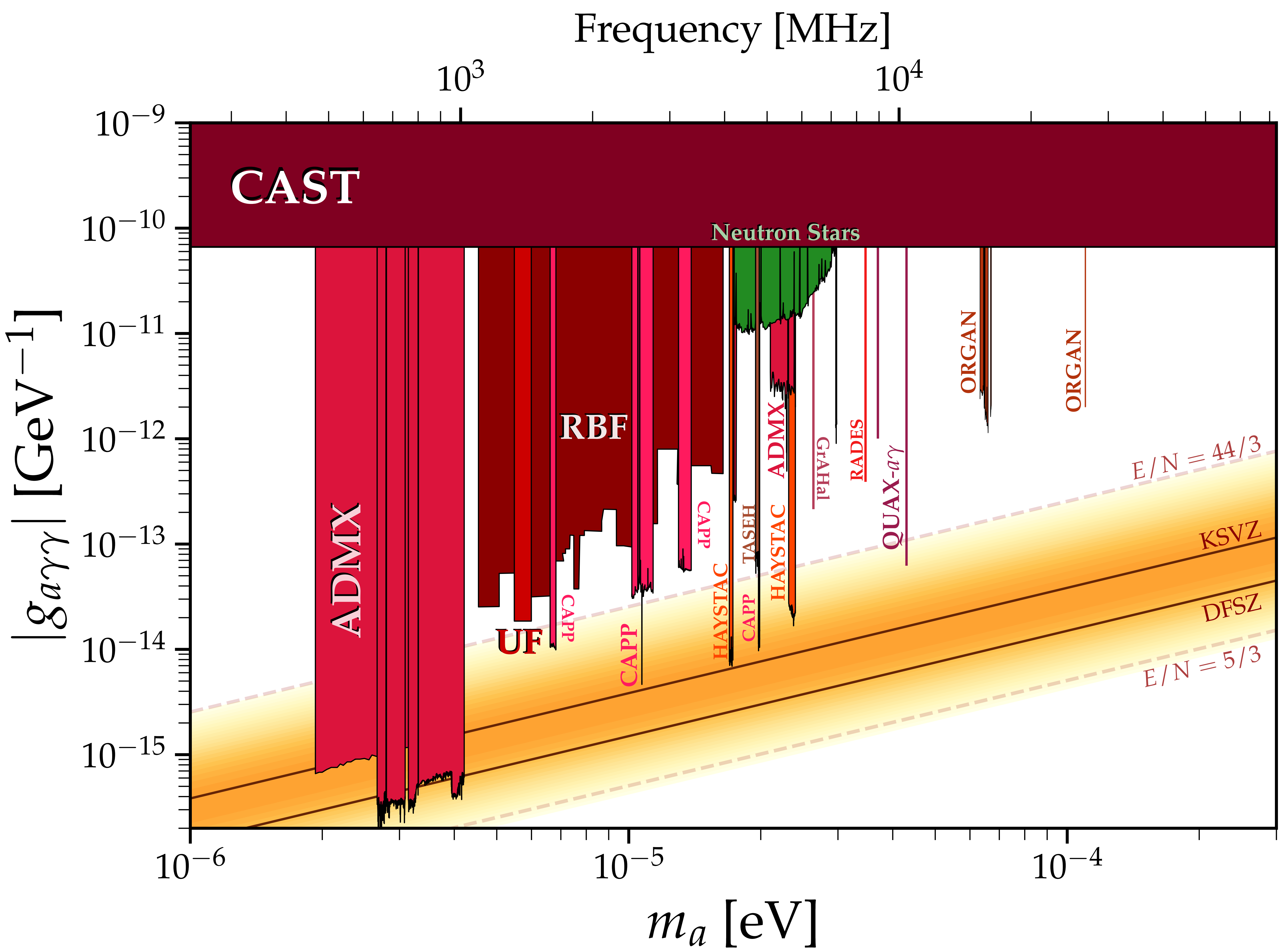


What's the issue?

The SHM is unlikely to be accurate in detail, but as long as we agree on it as a benchmark, does the precise model matter?
→ Can't we just rescale things?

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

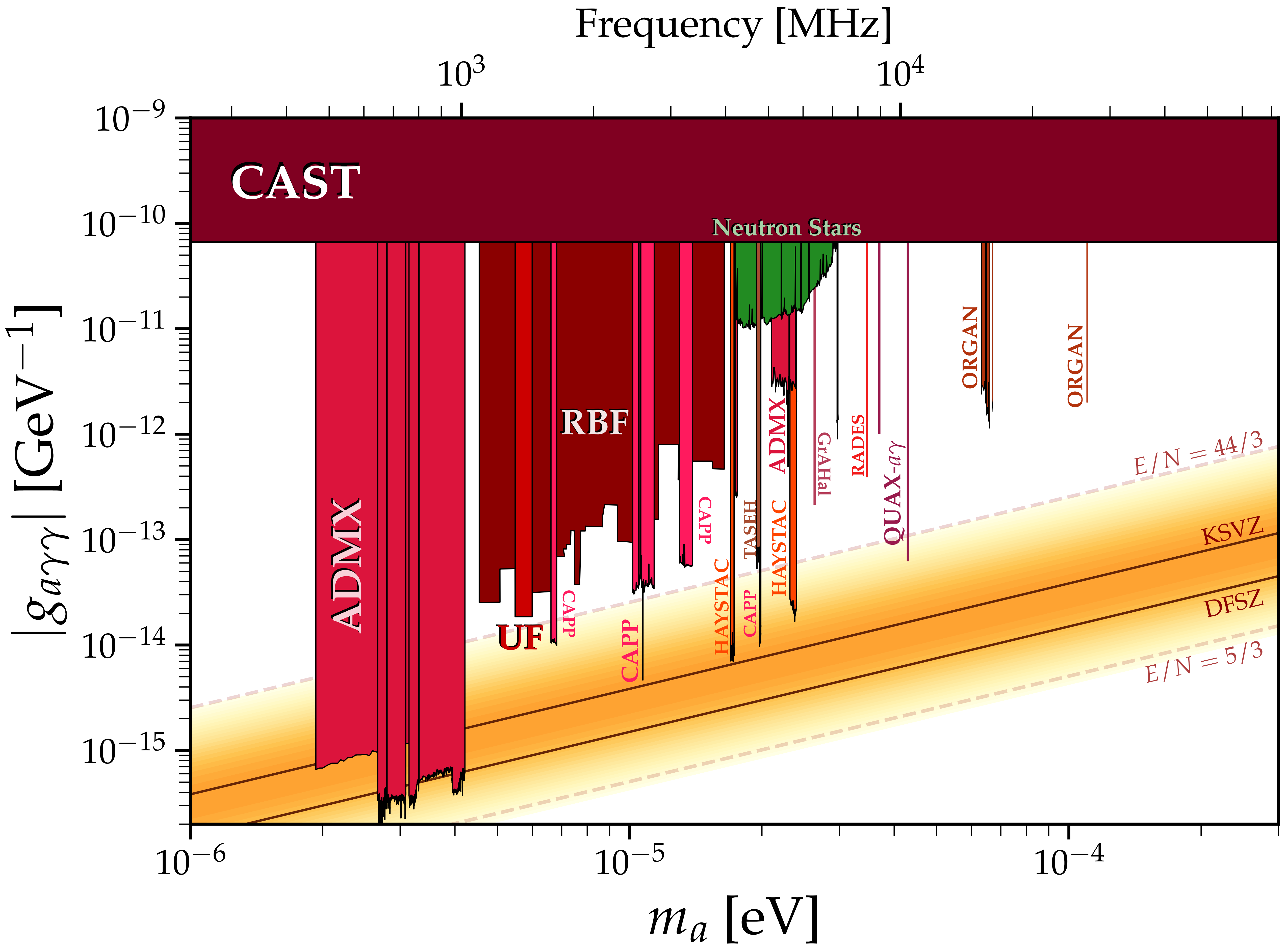
Absorb into vertical axis?



What's the issue?

The SHM is unlikely to be accurate in detail, but as long as we agree on it as a benchmark, does the precise model matter?
→ Can't we just rescale things?

For some DM, yes, but for axions no!
→ Not if you are shooting for specific models, e.g. KSVZ/DFSZ. You cannot break the degeneracy between coupling and the DM density/lineshape



E.g. A resonant axion search: the scan rate required for a cavity to reach a specific axion model with some fixed $(E/N - 1.92)$

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

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

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

So what value should we use?

History of the local DM density used in haloscope publications

1987 RBF
0.3 GeV / cm³

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/cm³. 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 $g_{a\gamma\gamma}<2\times10^{-30}$ $\mathrm{MeV}^{1/2}\ \mathrm{cm}^{3/2} \approx 10^{-11}\ \mathrm{GeV}^{-1}$.

2009 ADMX
0.45 GeV / cm³

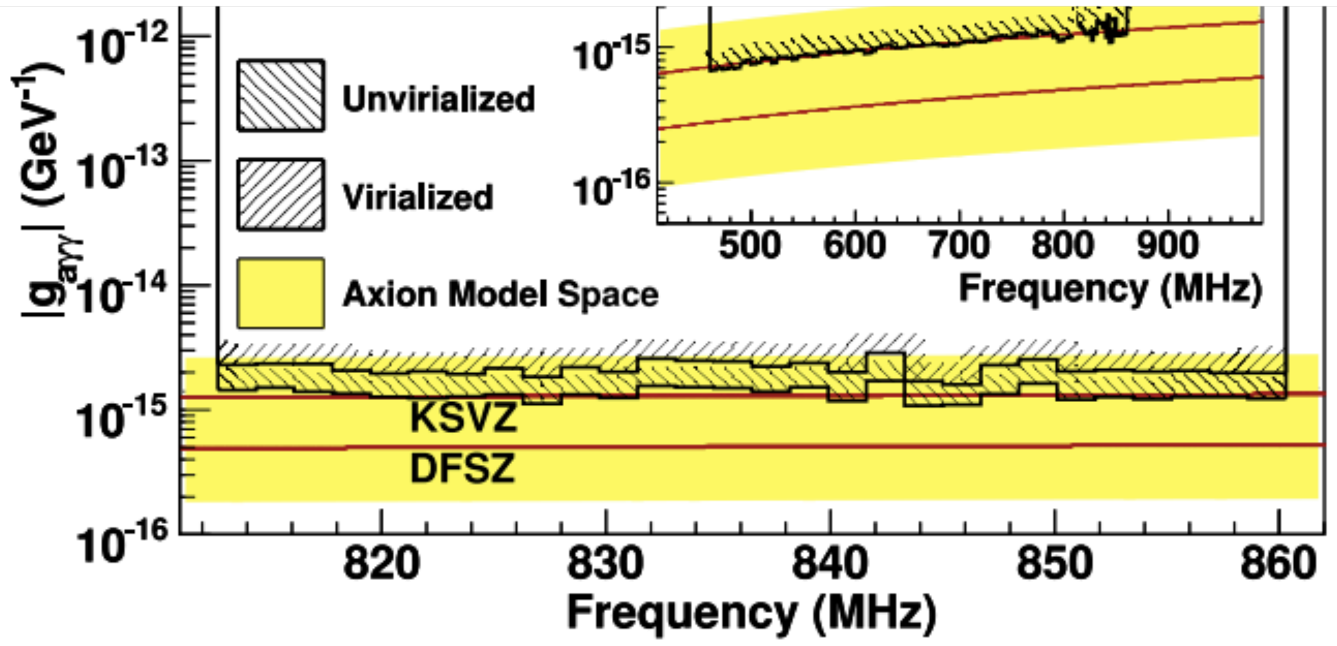


FIG. 5: Axion-photon coupling excluded at the 90% confidence level assuming a local dark matter density of 0.45 GeV/cm³ for two dark matter distribution models. The

2018 ADMX
0.63 GeV / cm³

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/cm³ 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

We can estimate the local dark matter density using stars

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

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

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

Poission eq.
Grav. potential → matter density

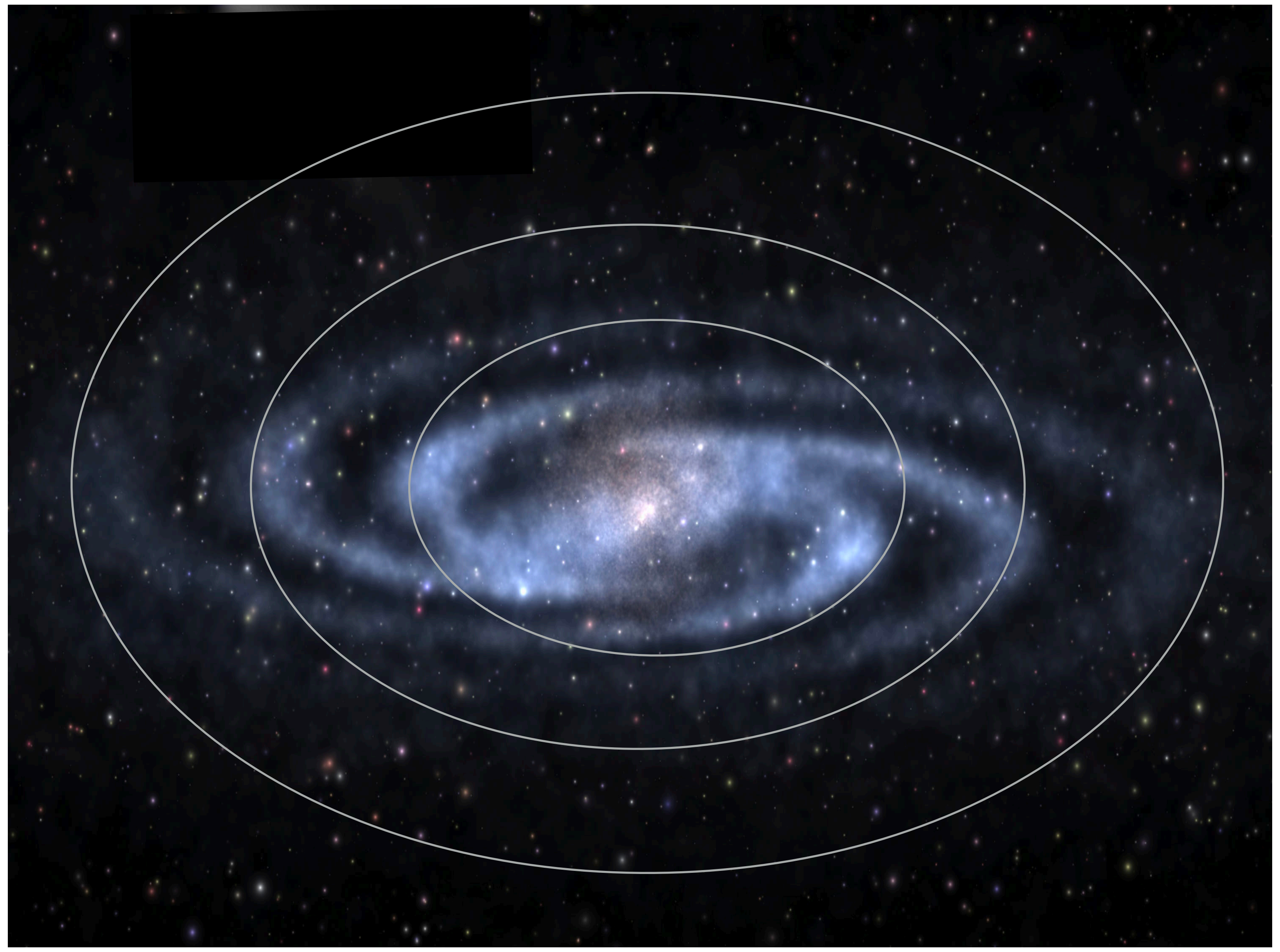
Local measure

(kinematics of nearby stars)

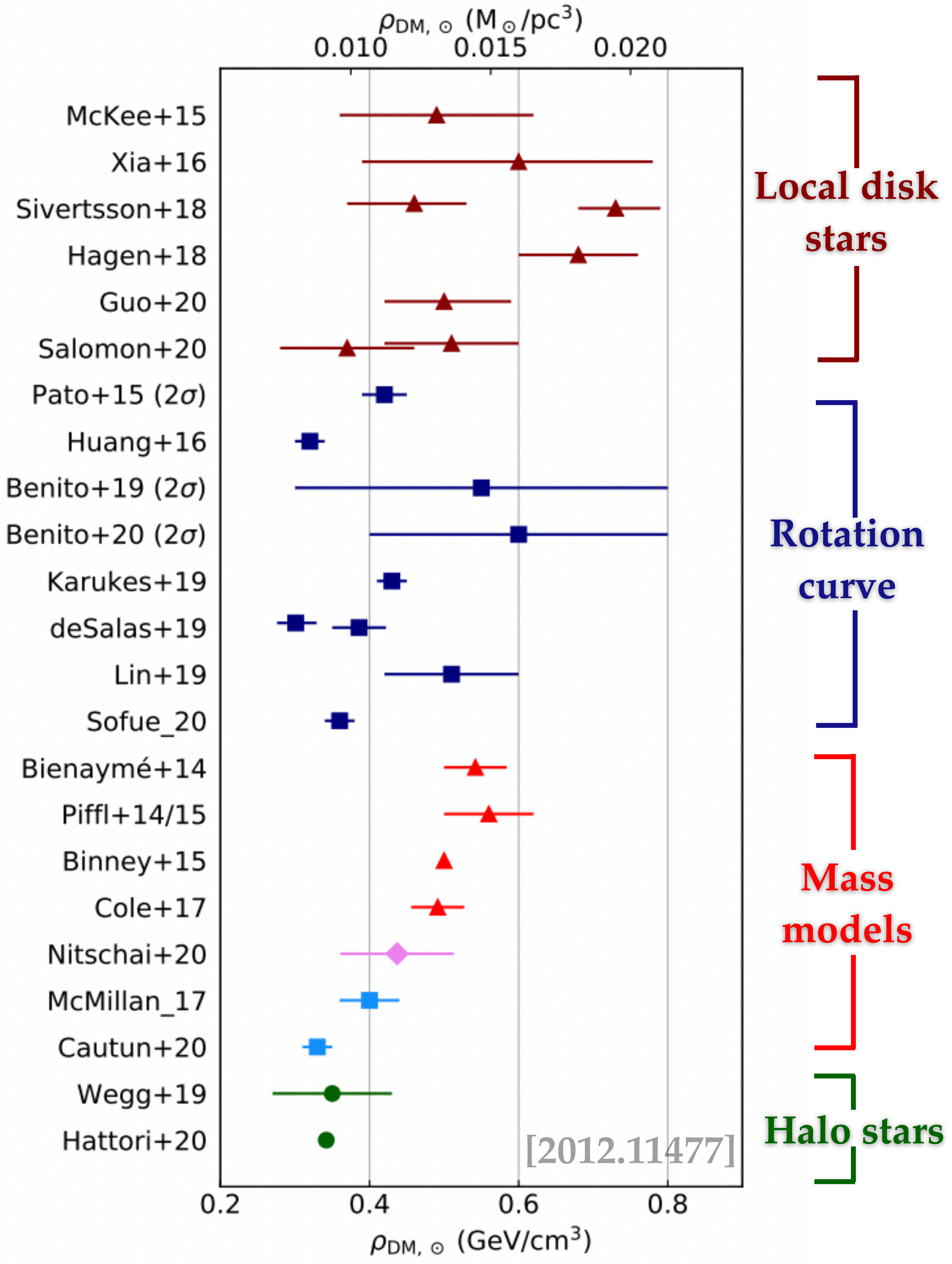
Pro: density that we are interested in
Con: sensitive to baryonic density model

Global measure

(build mass model for MW)



Pro: Average over a lot of halo/disk
Con: less direct measure of local density



Some recent estimates

Hagen+[1802.09291]

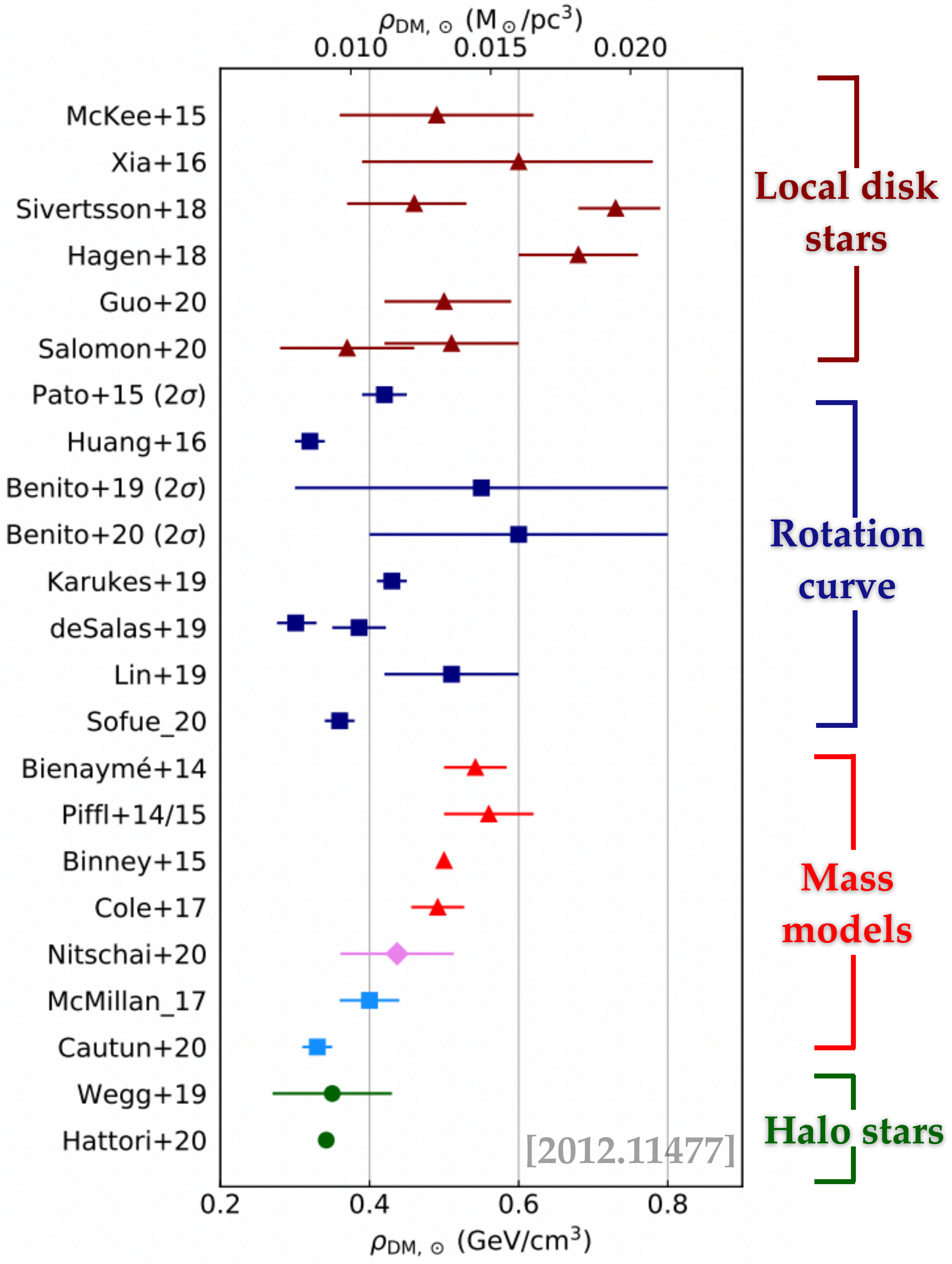
Buch+ [1808.05603]

Widmark [1811.07911]

de Salas+ [1906.06133]

Eilers+ [1810.09466]

Benito+ [1901.02460]



Some recent estimates

Hagen+[1802.09291]

Buch+ [1808.05603]

Widmark [1811.07911]

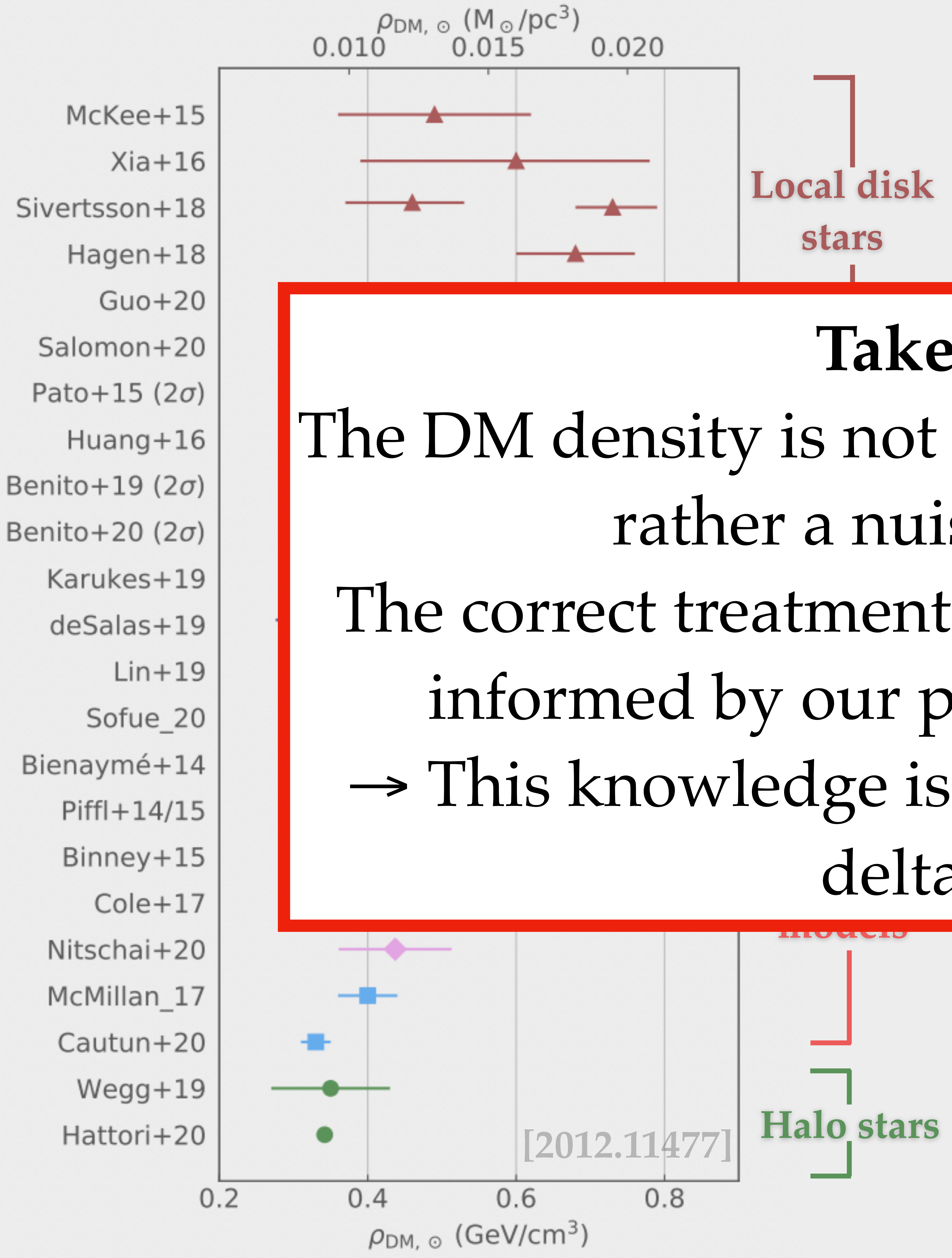
de Salas+ [1906.06133]

Eilers+ [1810.09466]

Benito+ [1901.02460]

Values span the range 0.3—0.7 GeV cm^{-3} depending on the method and dataset used

→ Most datasets (e.g. *Gaia*) are now huge in size, so the fundamental problem is modelling and systematics



Take home #1

The DM density is not a fundamental constant but rather a nuisance parameter.

The correct treatment would be to adopt a prior informed by our present knowledge of it.

→ This knowledge is currently quite far from a delta function

Some recent estimates

Hagen+[1802.09291]

Buch+ [1808.05603]

Widmark [1811.07911]

s+ [1906.06133]

s+ [1810.09466]

o+ [1901.02460]

span the range
pending on the
d dataset used

→ Most datasets (e.g. *Gaia*) are now huge in size, so the fundamental problem is modelling and systematics

What about the velocity distribution?

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

A Gaussian velocity distribution (i.e. Maxwellian speed distribution) is the basic assumption everyone uses.

What about the velocity distribution?

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

A Gaussian velocity distribution (i.e. Maxwellian speed distribution) is the basic assumption everyone uses.

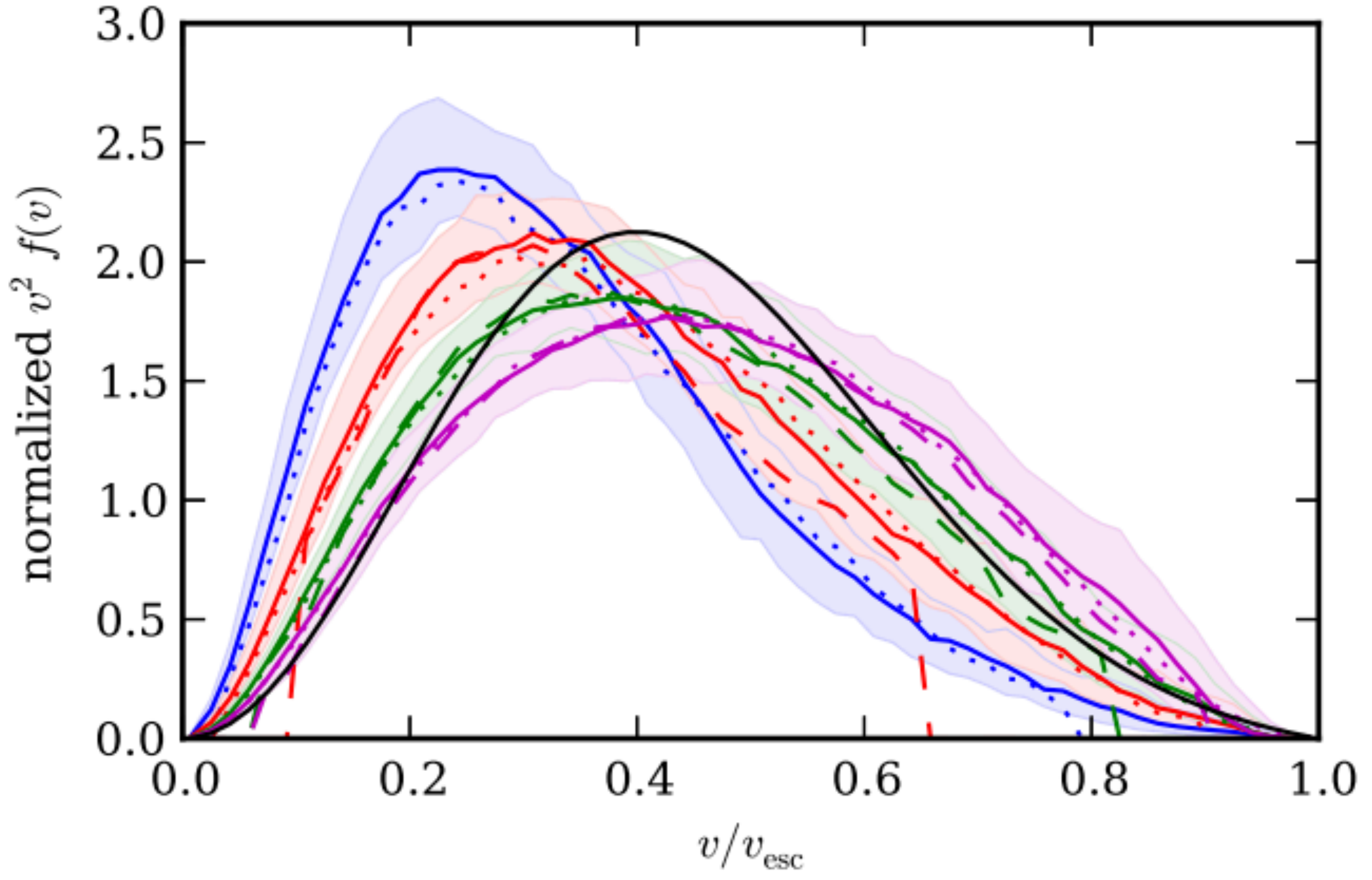
Seems reasonable, but how sure are we that the local DM distribution is:

→ Gaussian?
→ Isotropic?
→ Devoid of substructure?
→ Normalised? (i.e $f(\mathbf{x}, \mathbf{v}) = \text{const}\,.$)

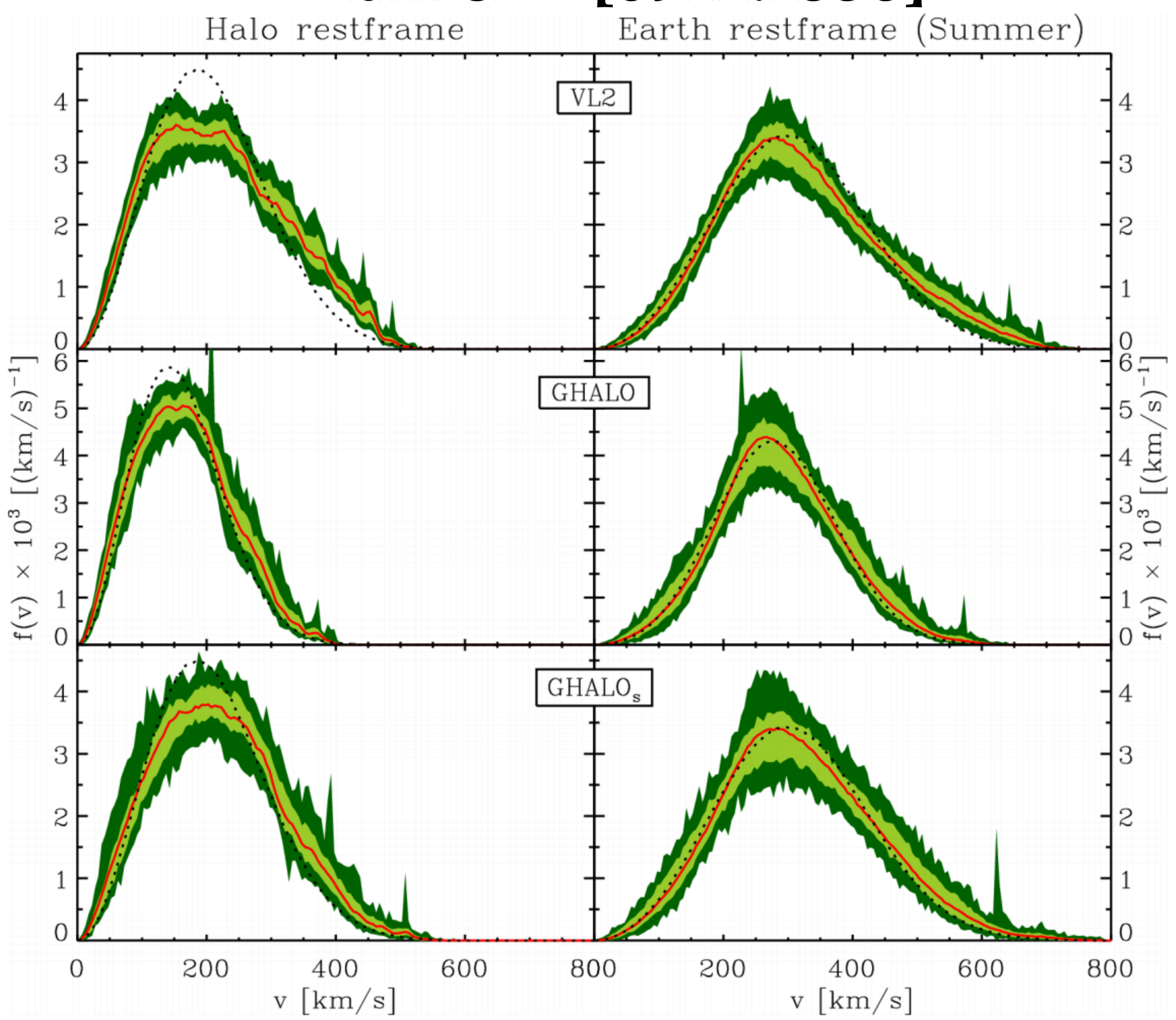
What do we expect a more accurate halo model to look like?

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

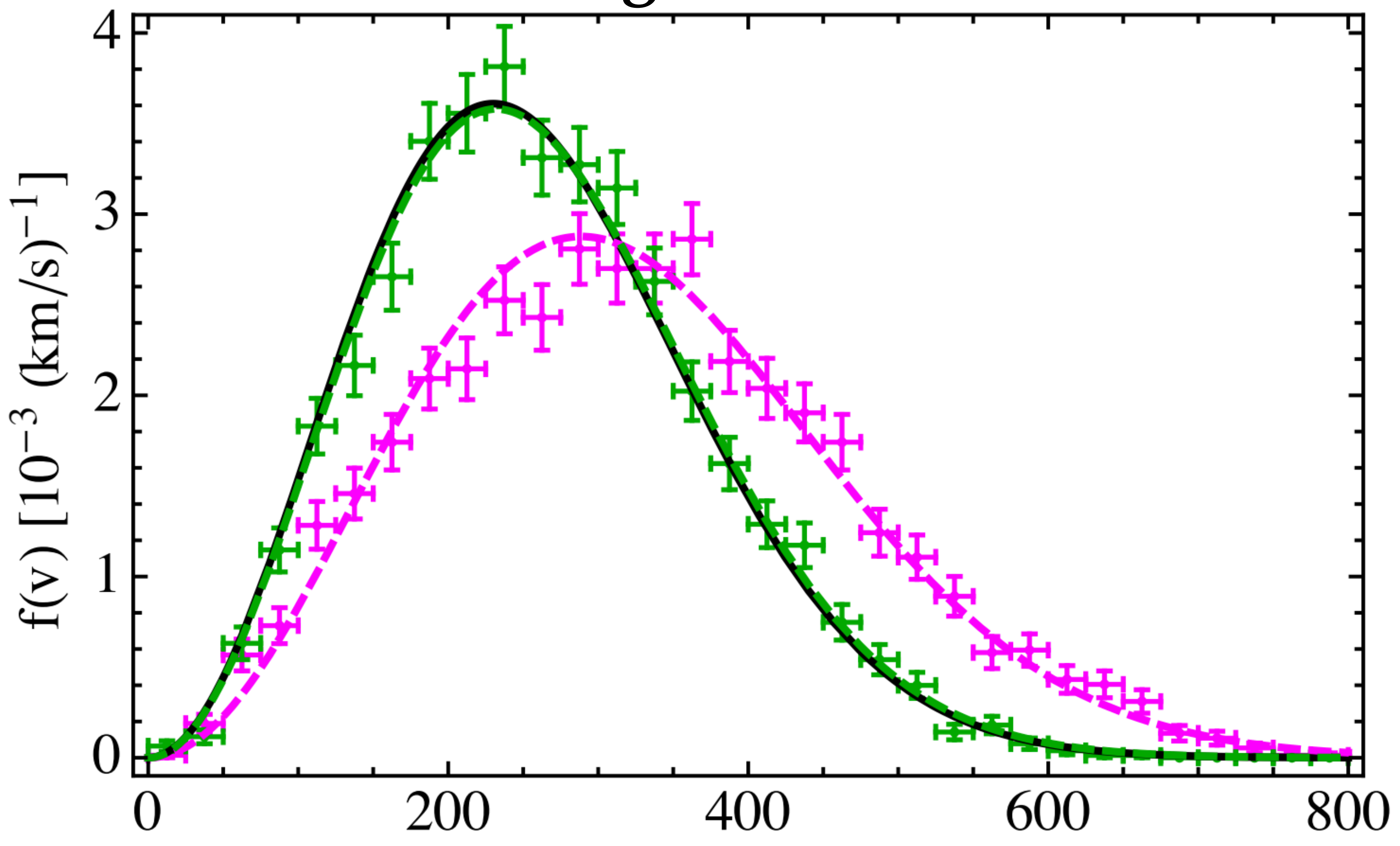
Mao+ [1210.2721]



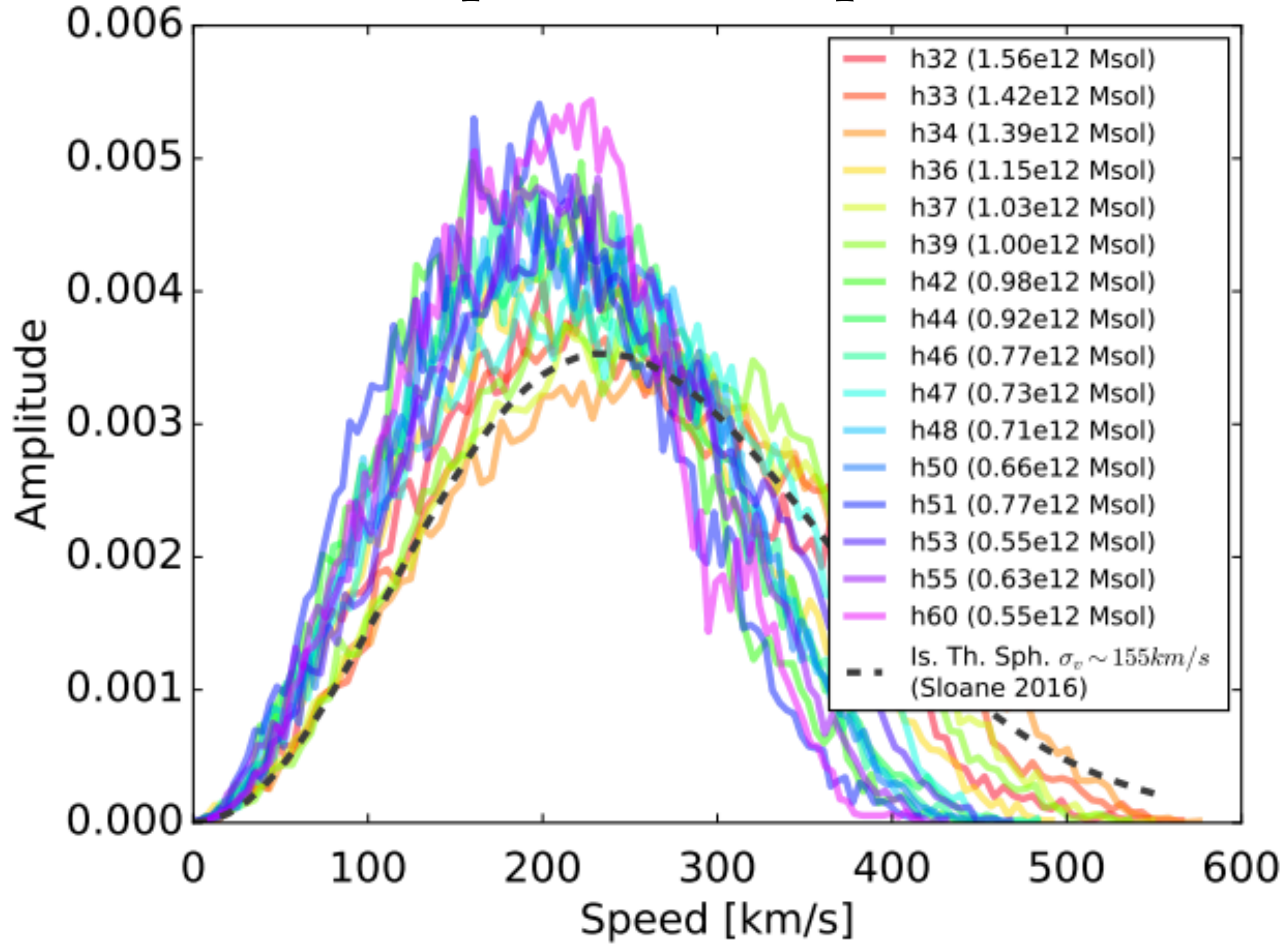
Kuhlen+ [0912.2358]



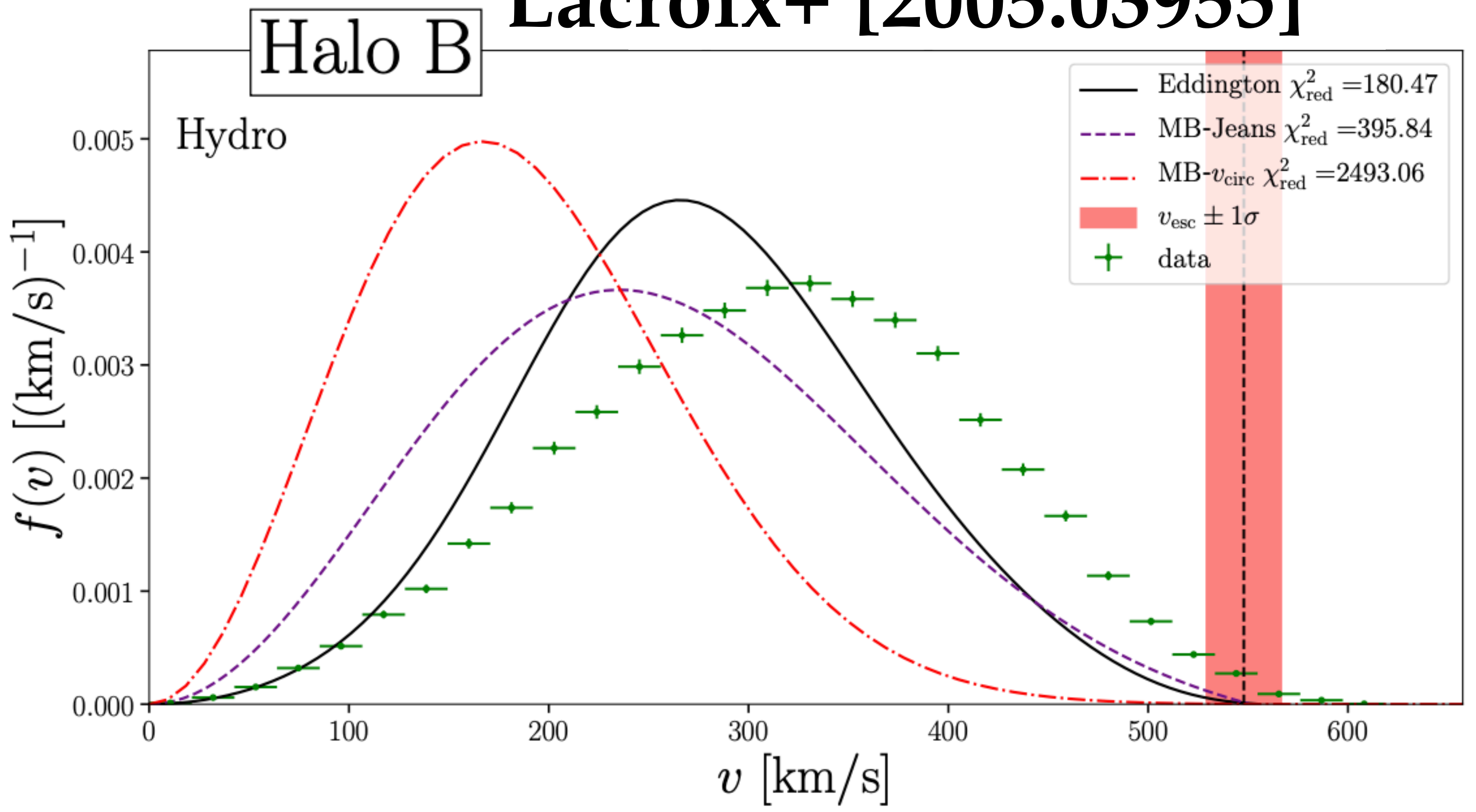
Bozorgnia+ [1601.04707]



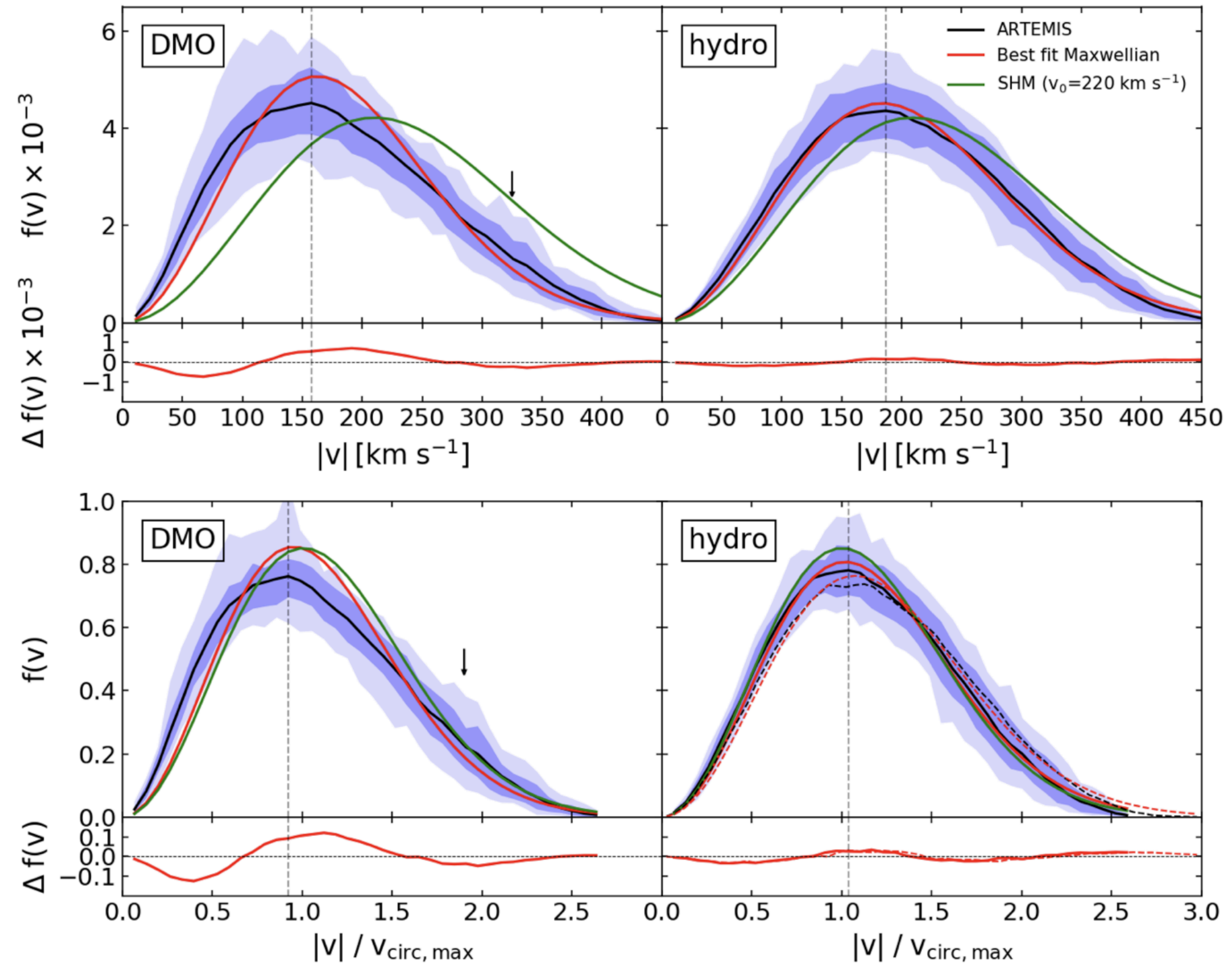
Lentz+ [1703.06937]



Lacroix+ [2005.03955]



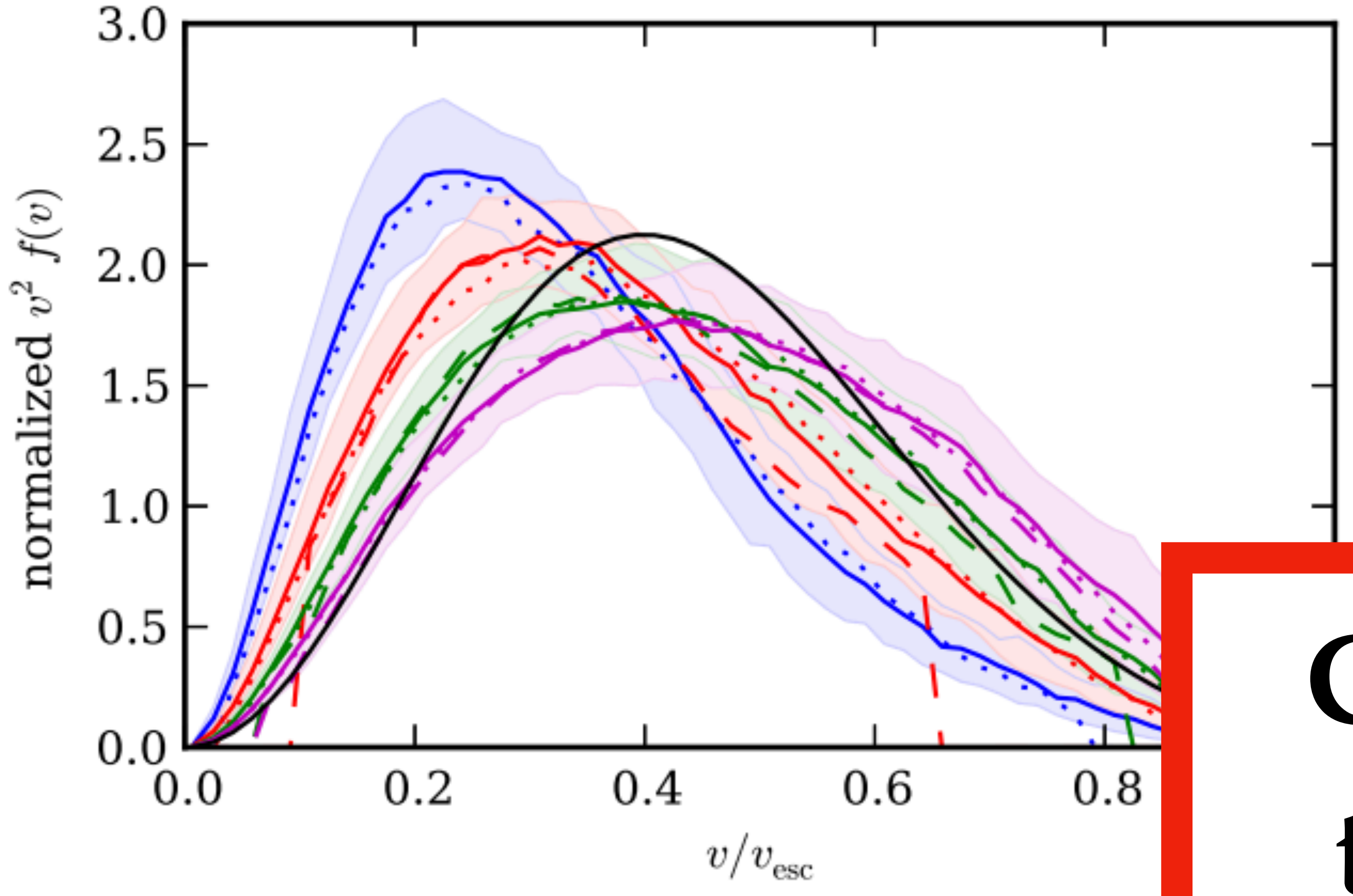
Poole-Mackenzie+ [2006.15159]



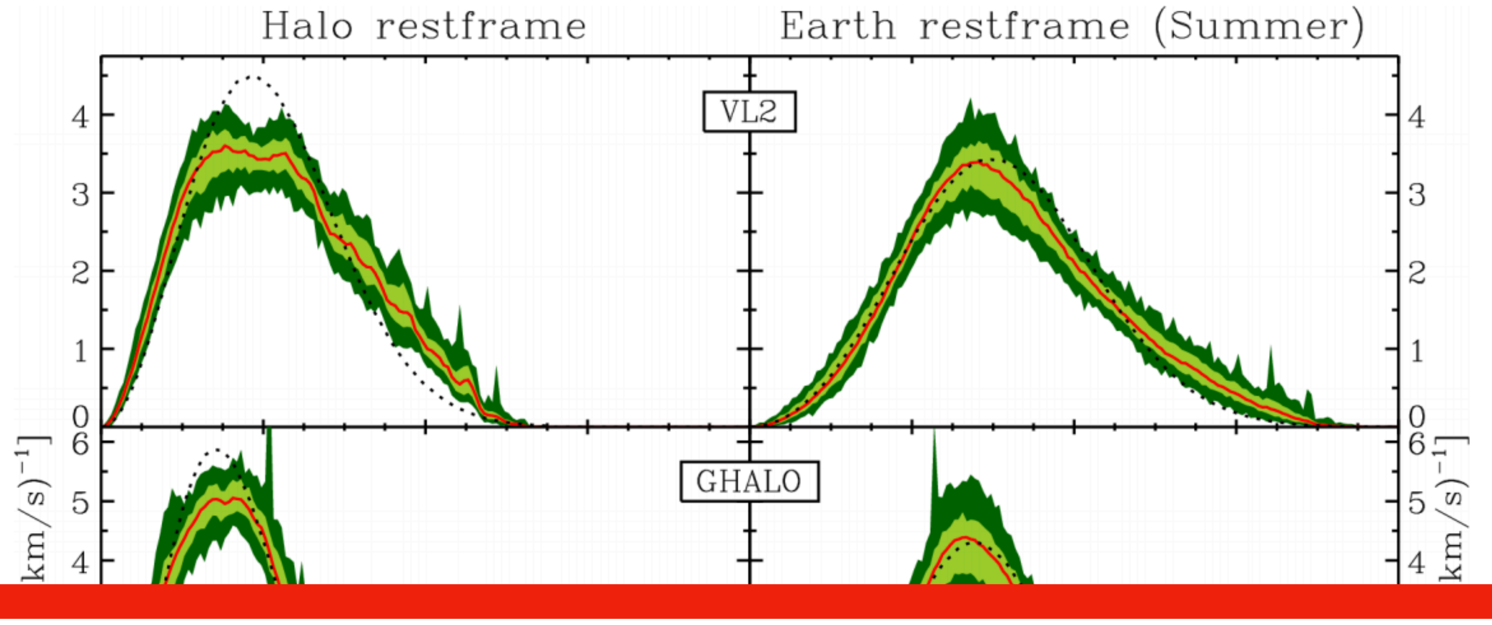
What do we expect a more accurate halo model to look like?

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

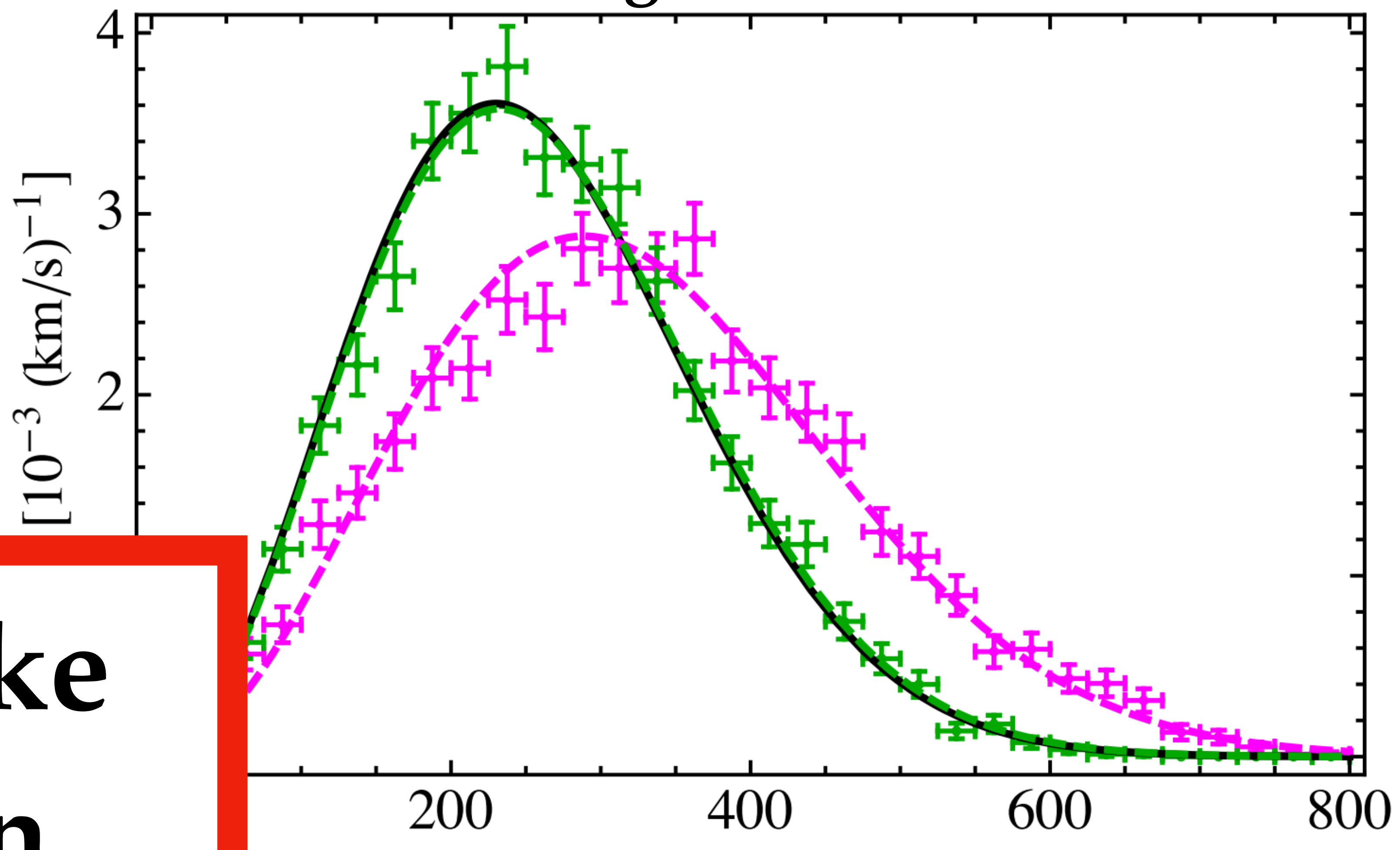
Mao+ [1210.2721]



Kuhlen+ [0912.2358]

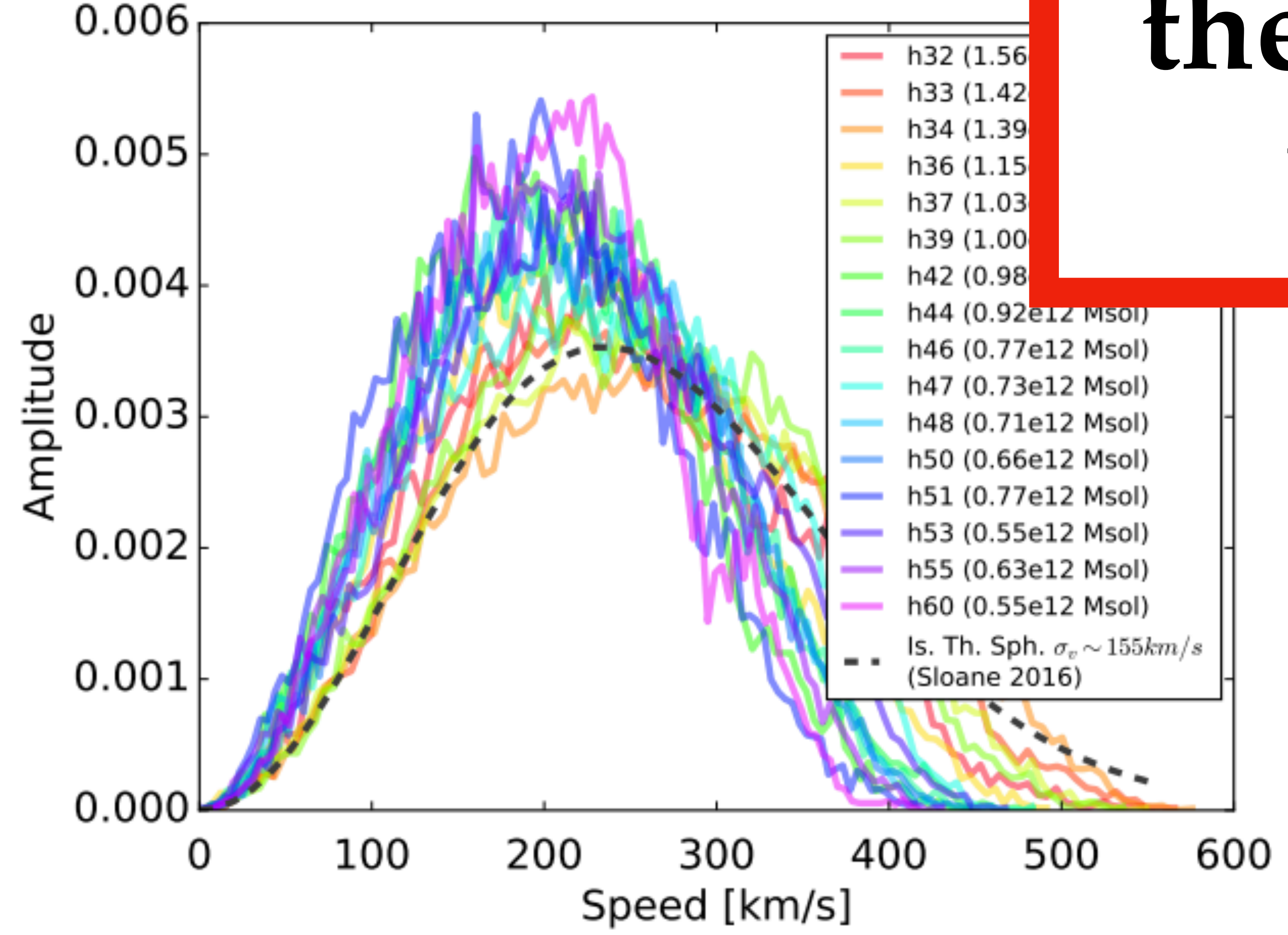


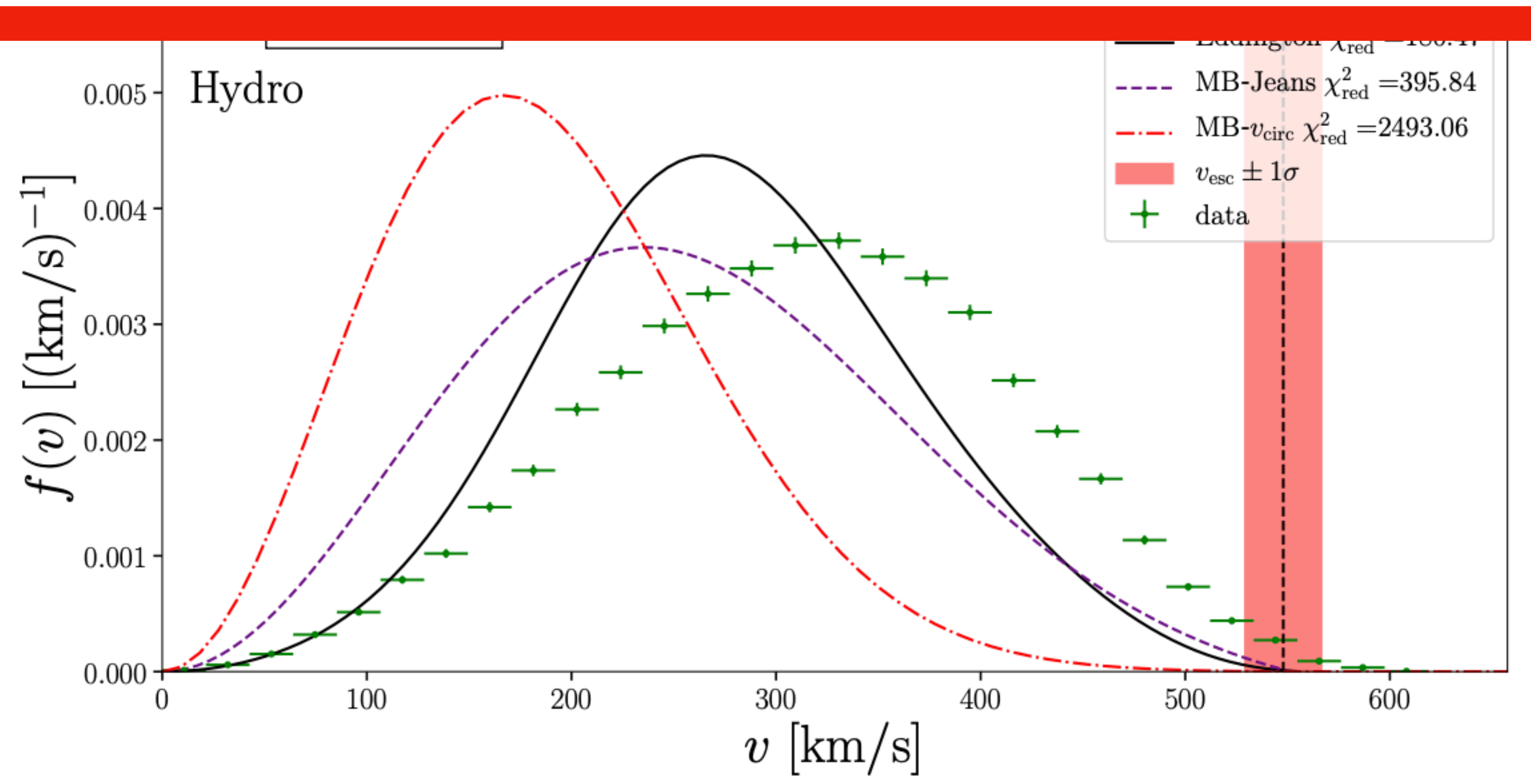
Bozorgnia+ [1601.04707]



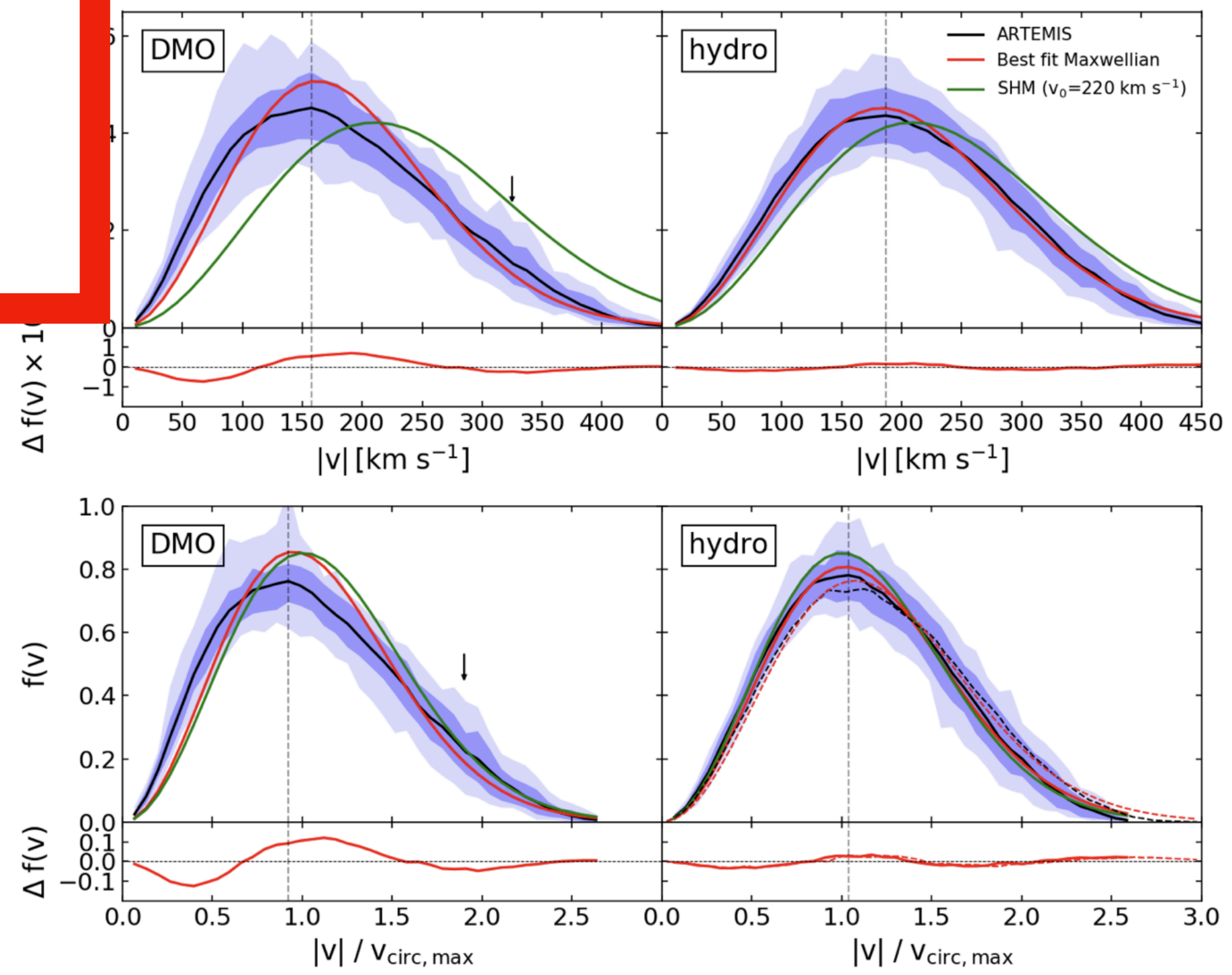
Central problem is that, unlike the DM's *spatial* distribution, there are no luminous tracers of DM's *velocity* distribution

Lentz+ [1703.06937]





Poole-Mackenzie+ [2006.15159]



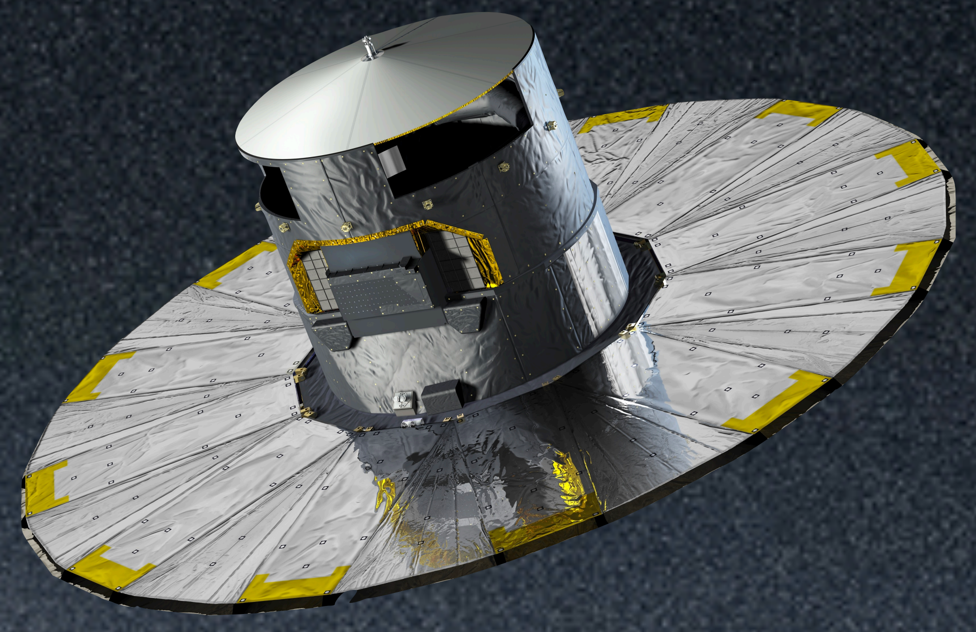
Luminous tracers of the DM halo?

universetoday.com

Luminous tracers of the DM halo?

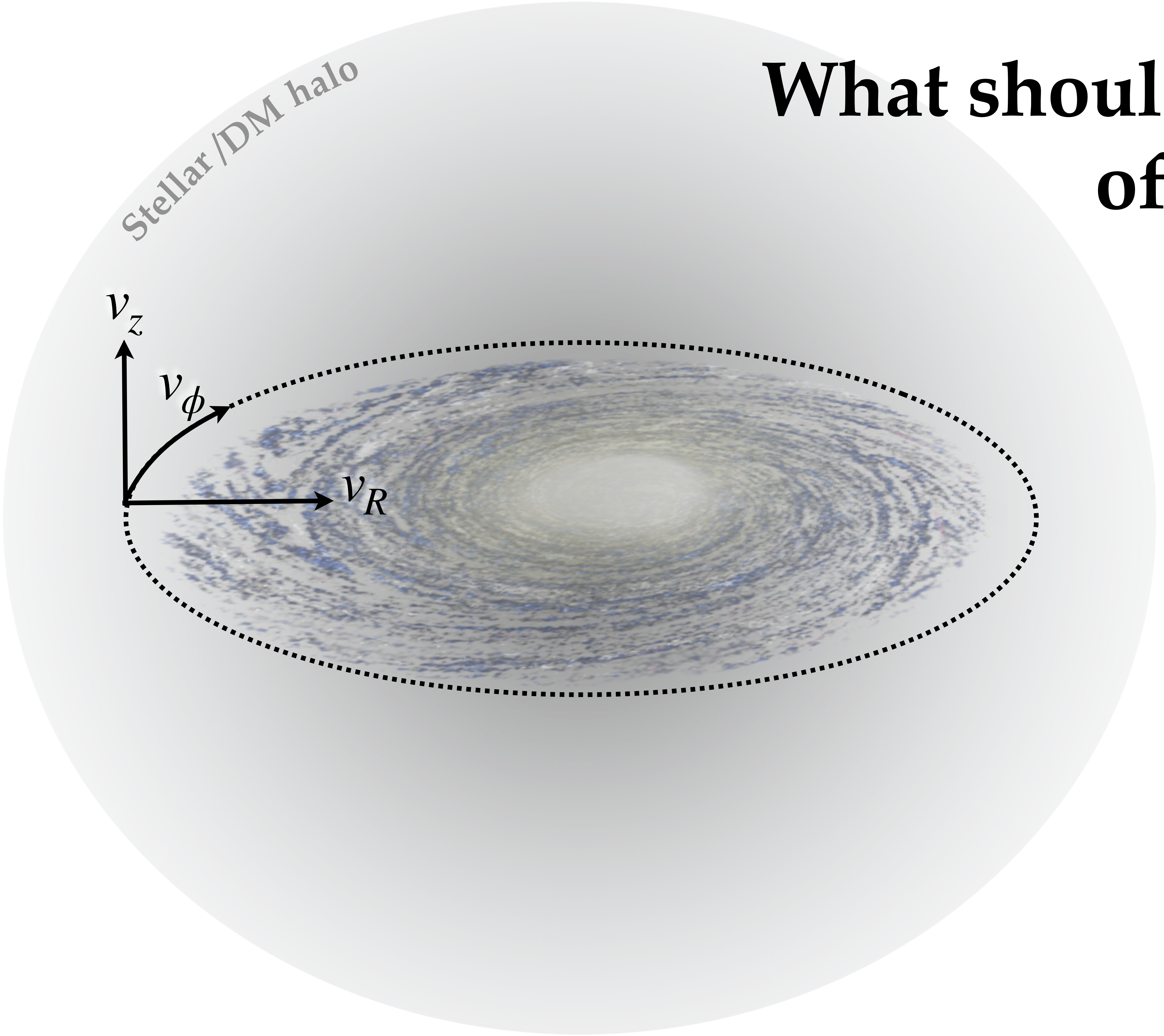
universetoday.com

Gaia



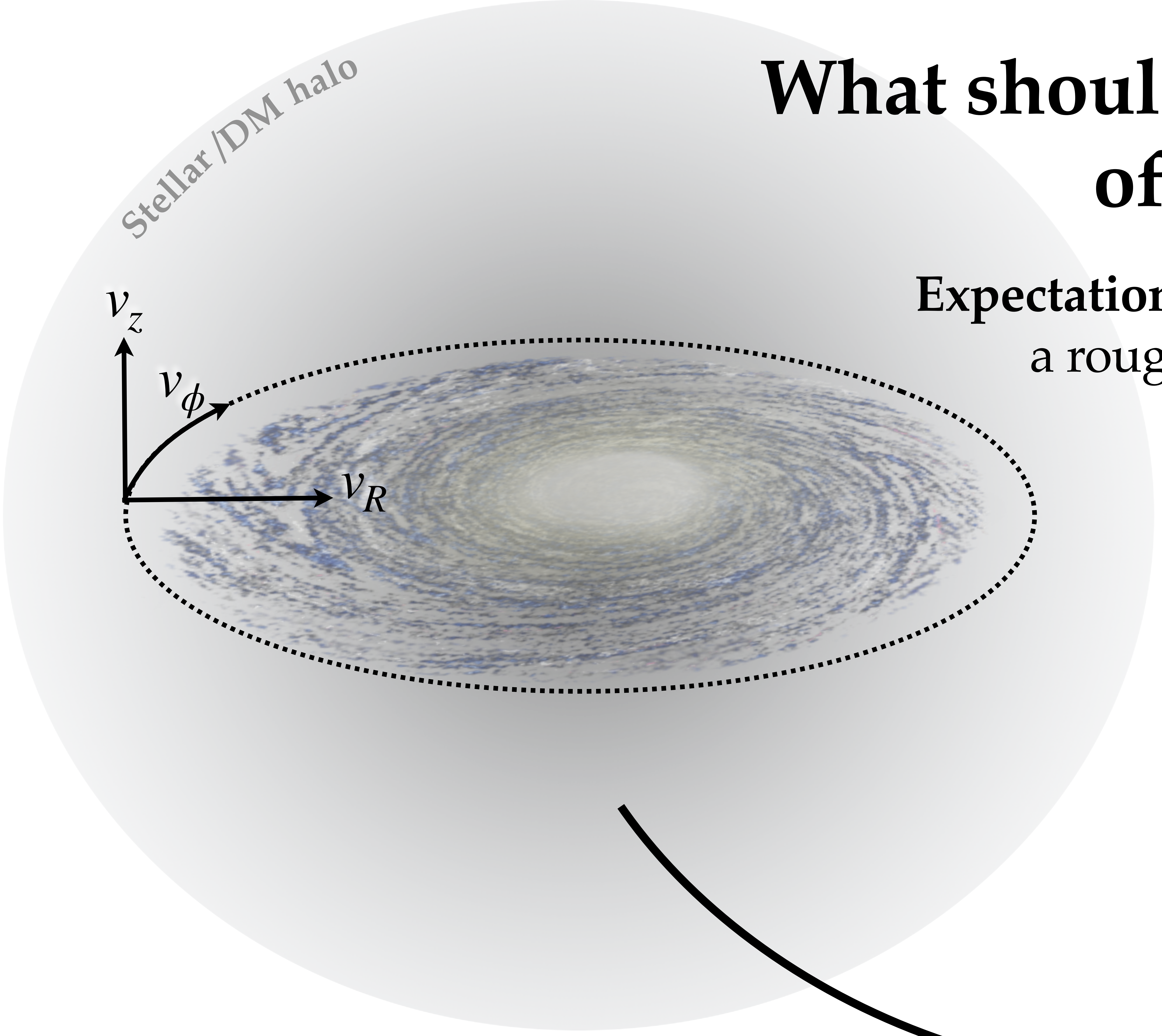
- 1.7 billion stars in 2D (positions)
- 1.3 billion in 5D (positions + distances + plane of the sky motions)
- 33 million in 6D (positions + distances+ plane of the sky motions + line of sight motion)

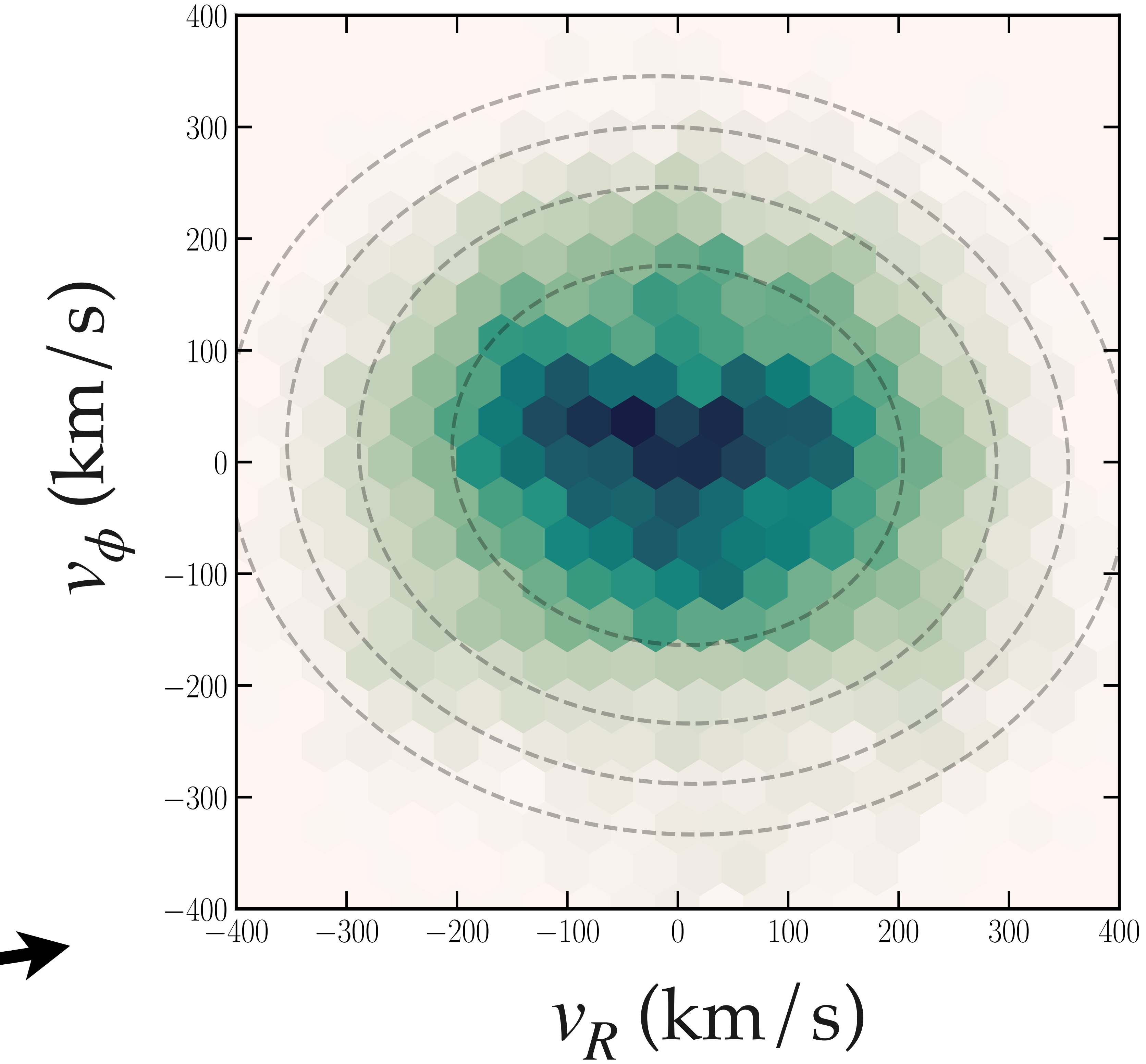
What should the velocity distribution of the *stellar* halo look like?

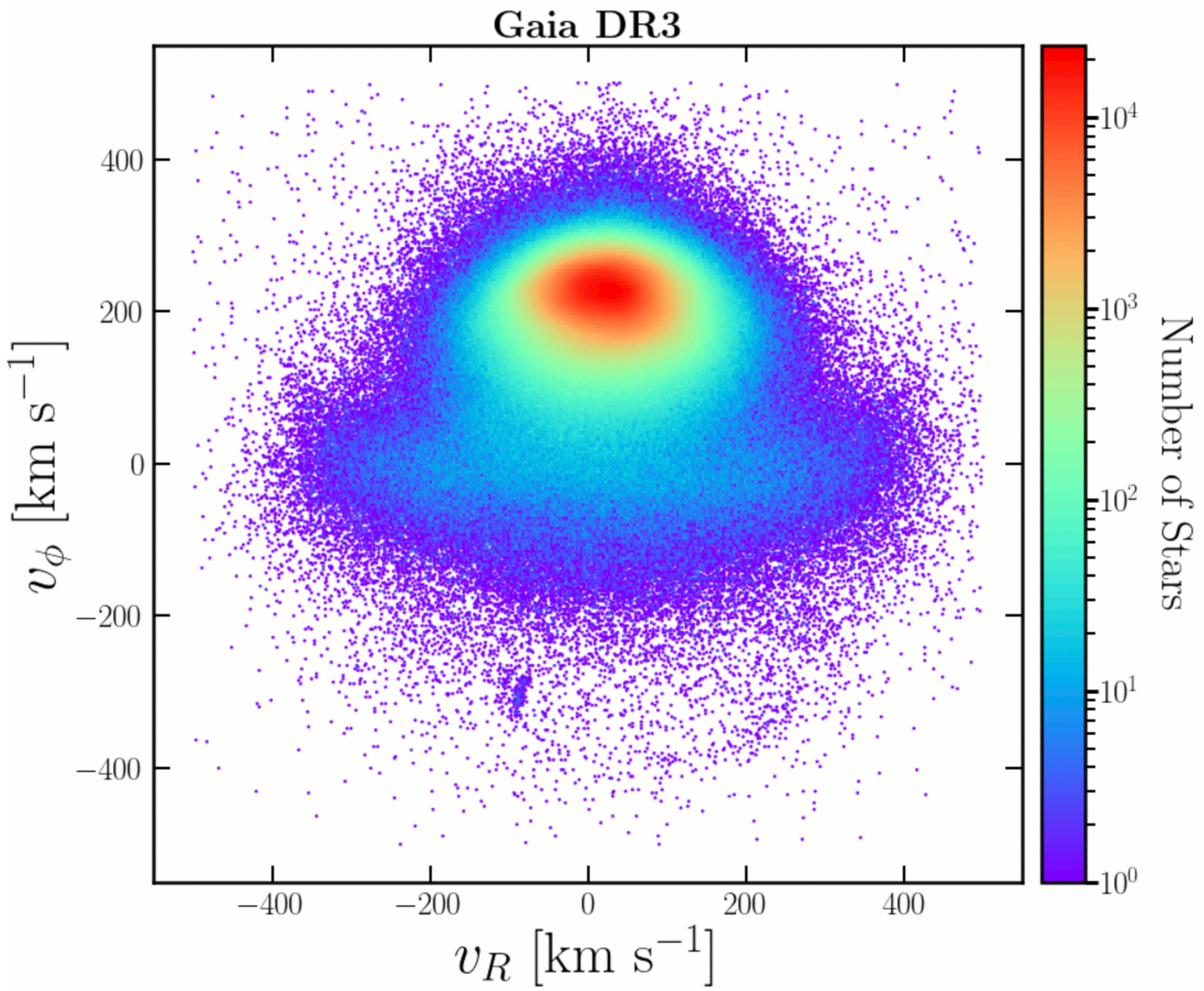


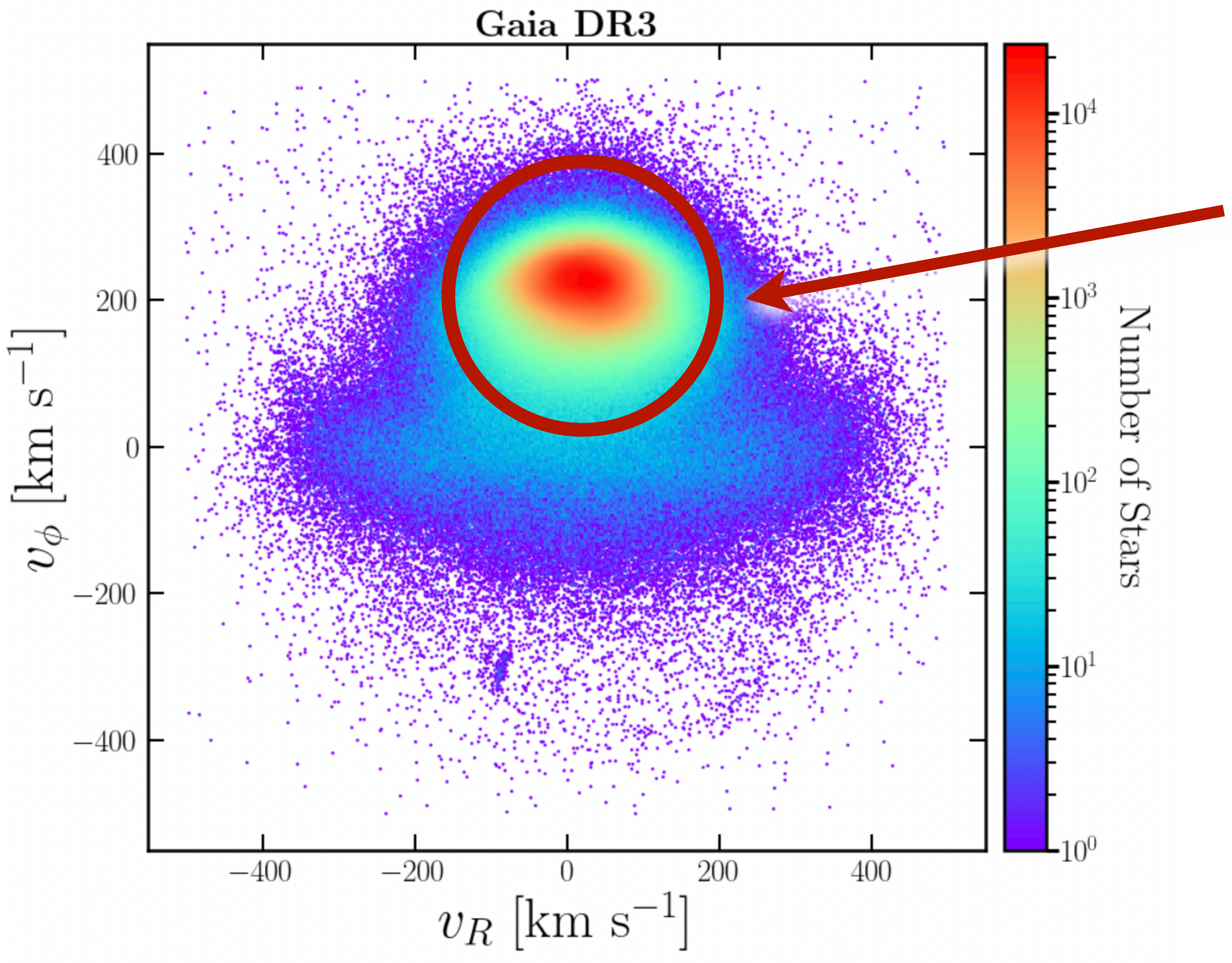
What should the velocity distribution of the *stellar* halo look like?

Expectation: stellar halo is round so should also have a roughly round (isotropic) velocity distribution

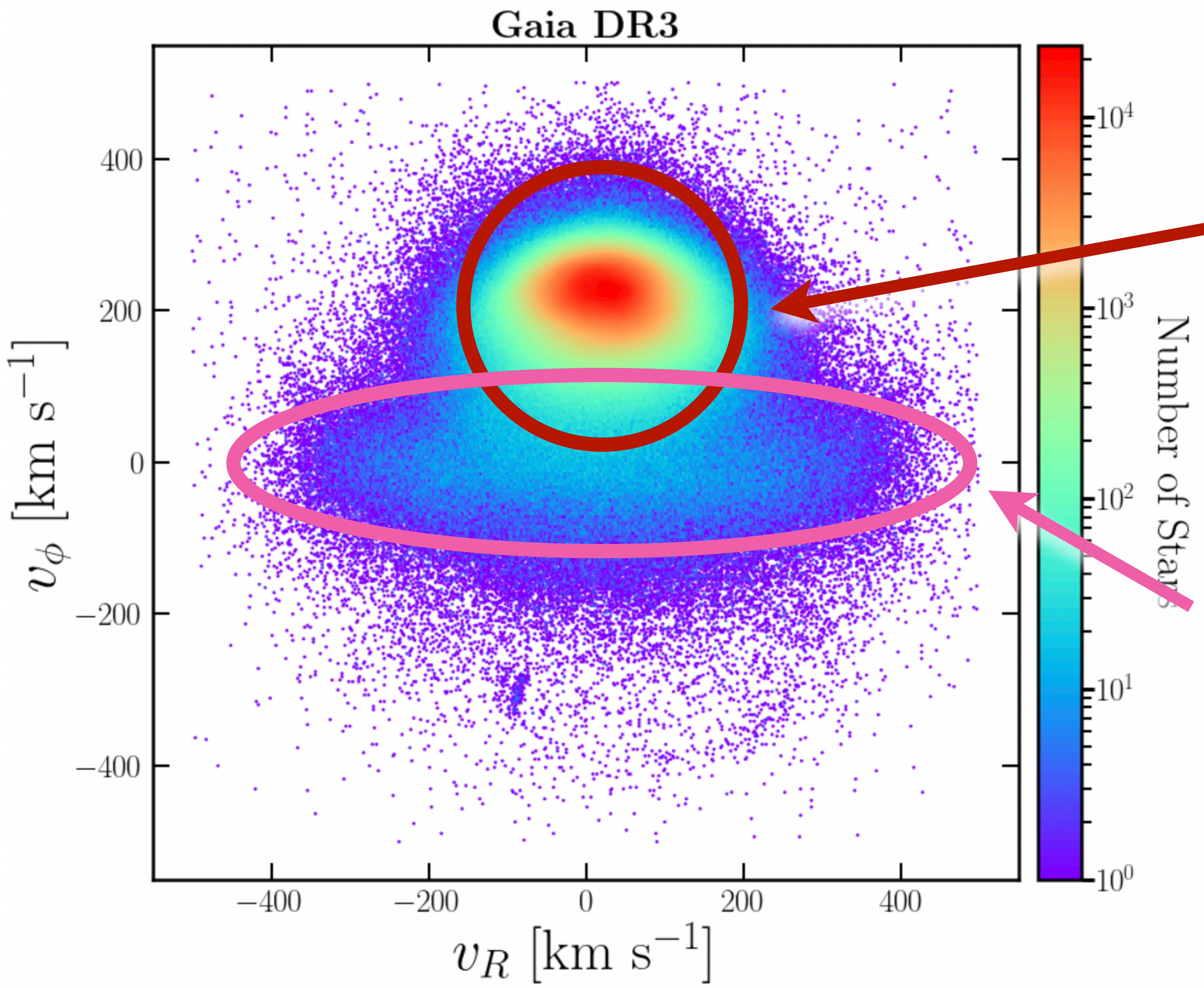





Gaia DR3
400
200
0
−200
−400
−400
−200
0
200
400
v_ϕ [km s^{-1}]
v_R [km s^{-1}]
10^4
10^3
10^2
10^1
10^0
Number of Stars



Stars in the galactic disk are rotating at $v_\phi \approx 220$ km/s



Stars in the galactic disk are rotating at $v_\phi \approx 220$ km/s

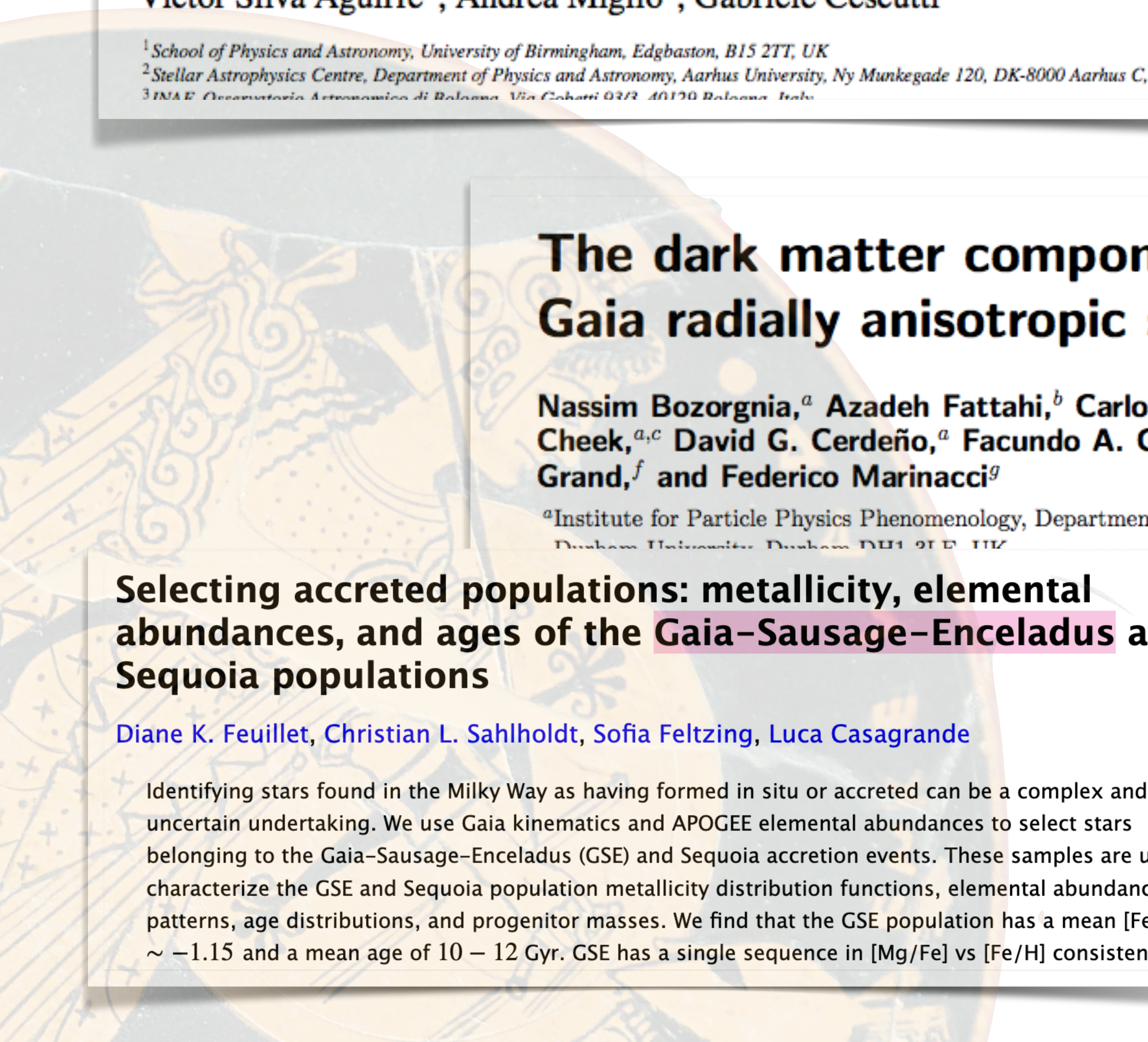
The stellar halo is not rotating ($v_R \approx 0$ km/s, $v_\phi \approx 0$ km/s) but its velocity *distribution* is shaped like a sausage

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

arXiv.org > astro-ph > arXiv:2001.06009

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,

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

Astrophysics > Astrophysics of Galaxies

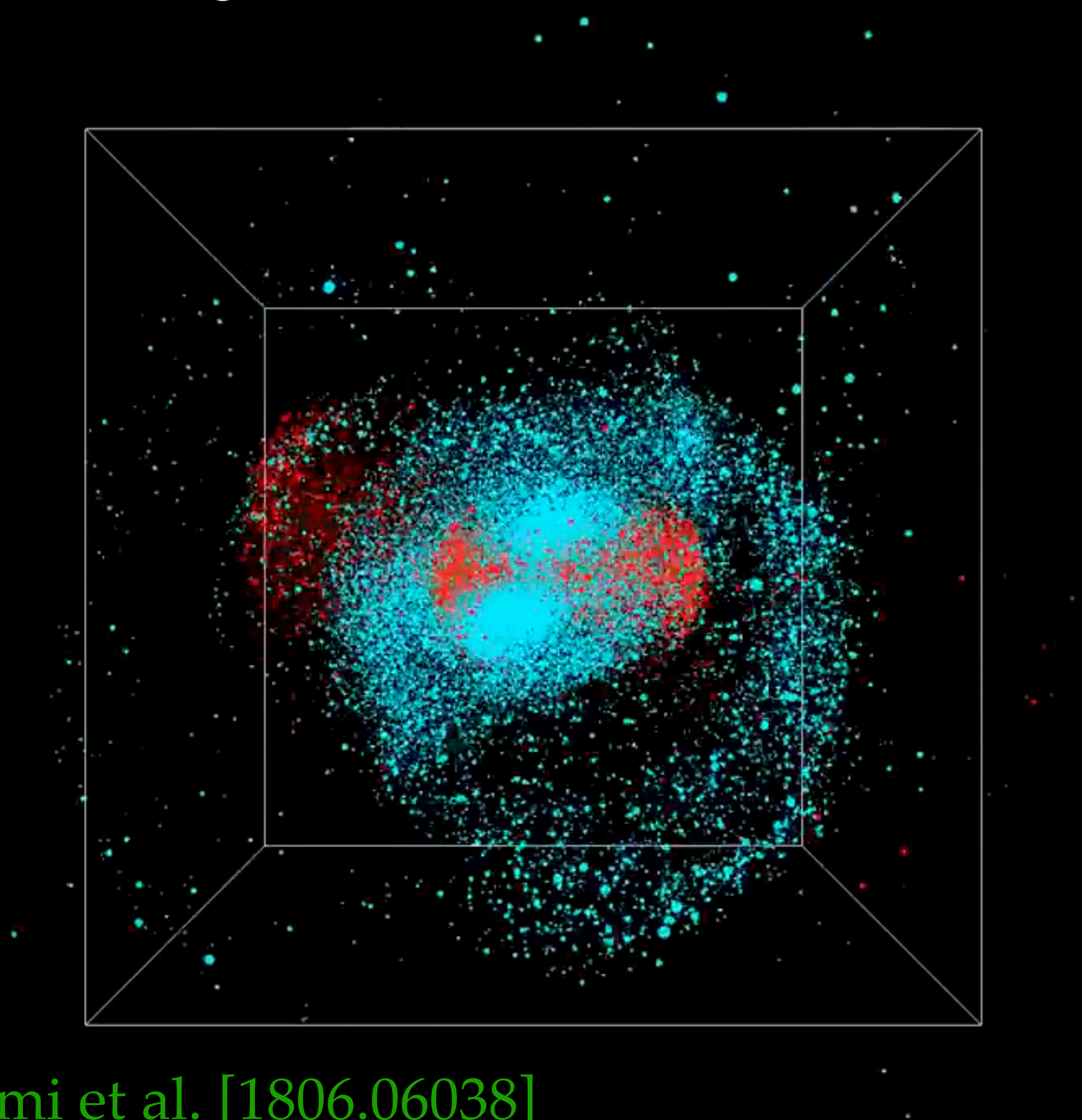
Cosmological insights into the assembly of the radial and compact stellar halo of the Milky Way

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

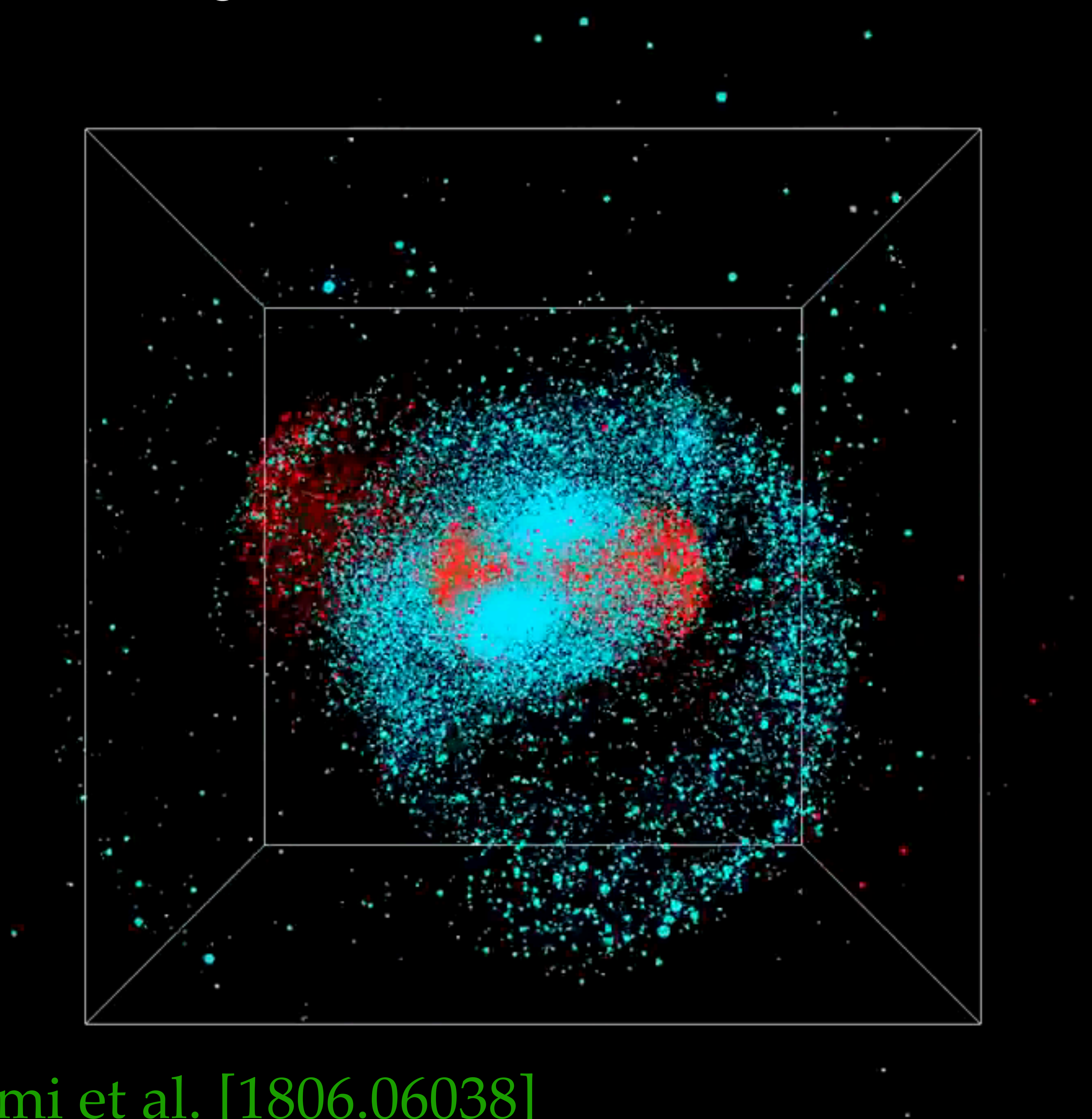
Gaia-Sausage-Enceladus (GSE) consists of a huge number of stars on highly eccentric orbits that were brought in by a 4:1 merger with a $10^{9\text{-}10}\, M_{\odot}$ stellar mass galaxy, 8-10 billion years ago



Helmi et al. [1806.06038]

→ Highly radial orbits suggest low-inclination head-on collision
→ Stars are also distributed in a triaxial figure (i.e. the halo is not round)
→ Dominates the inner stellar halo, and probably accounts for around O(10-40%) of DM at the Solar position

Gaia-Sausage-Enceladus (GSE) consists of a huge number of stars on highly eccentric orbits that were brought in by a 4:1 merger with a $10^{9\text{-}10}\, M_\odot$ stellar mass galaxy, 8-10 billion years ago

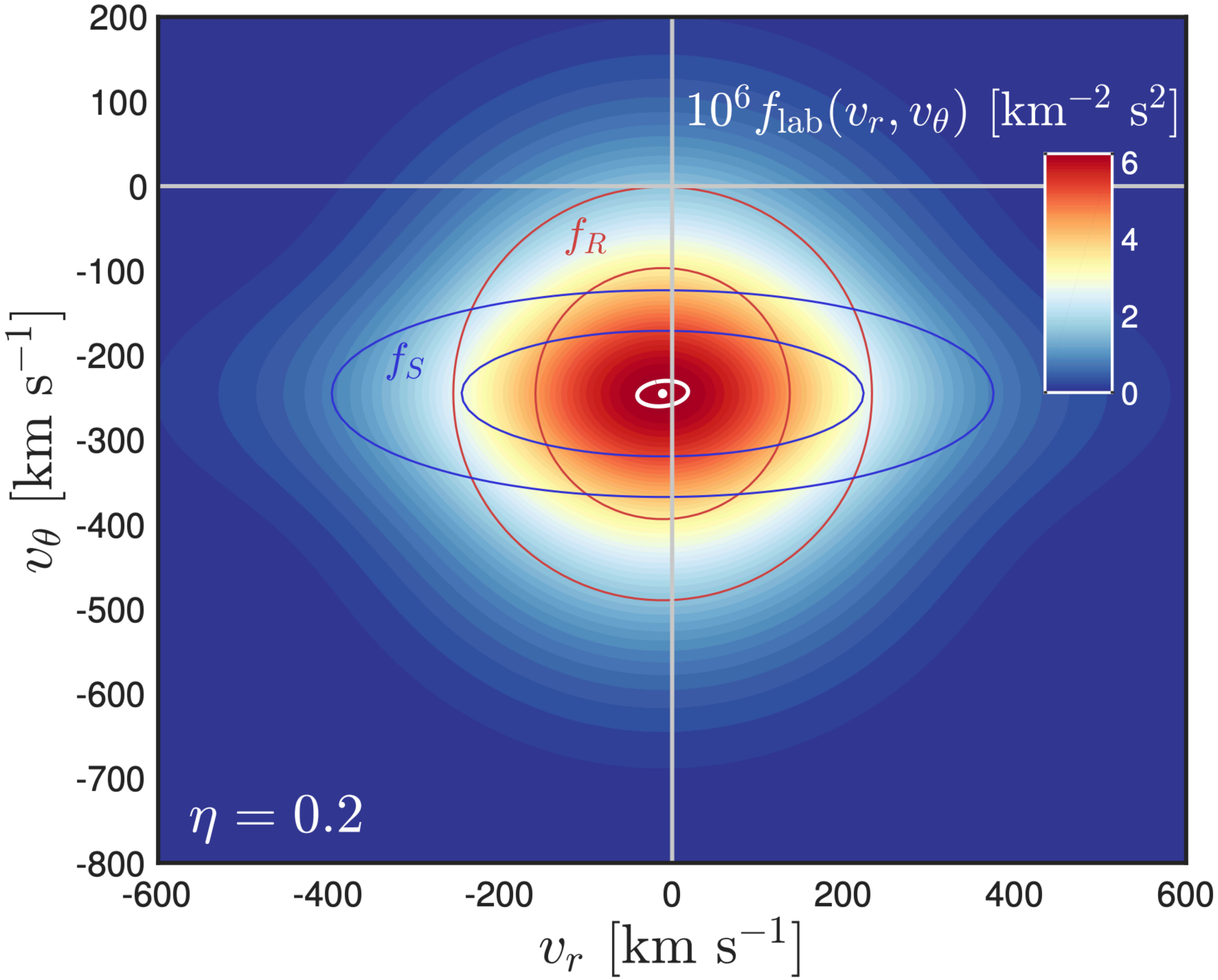


Helmi et al. [1806.06038]

→ Highly radial orbits suggest low-inclination head-on collision
→ Stars are also distributed in a triaxial figure (i.e. the halo is not round)
→ Dominates the inner stellar halo, and probably accounts for around O(10-40%) of DM at the Solar position

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 a DM velocity distribution that includes the GSE:

$$f(\mathbf{v}) = (1-\eta) f_R(\mathbf{v}) + \eta f_S(\mathbf{v})$$

→ Sum of a round halo part (f_R), and a radially anisotropic Sausage part (f_S)

→ f_S makes up $\eta \approx 20\,\%$ of DM

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

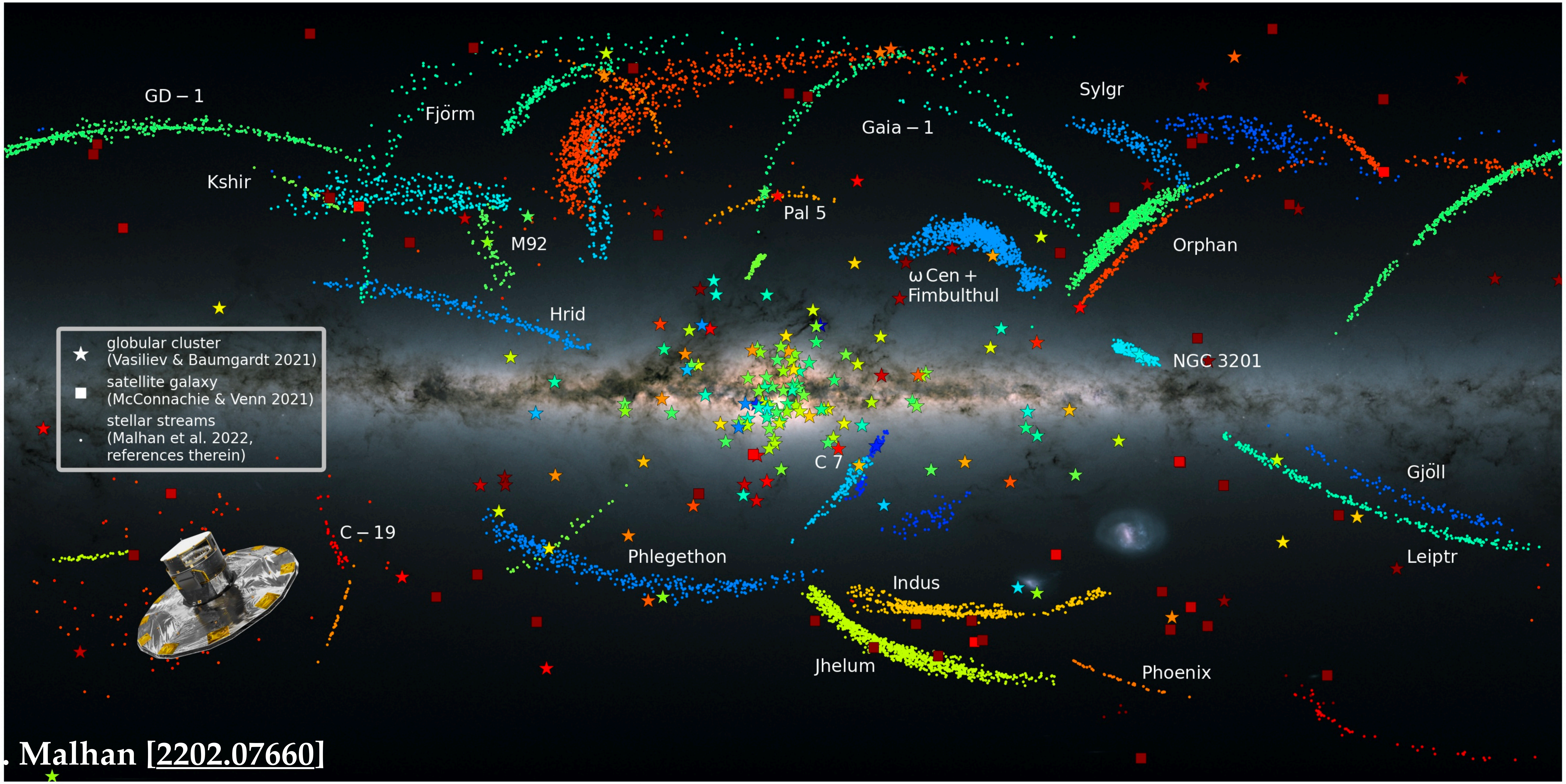
N. Wyn Evans,[1,*] Ciaran A. J. O'Hare,[2,†] and Christopher McCabe[3,‡]

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

Substructure part 2: Streams

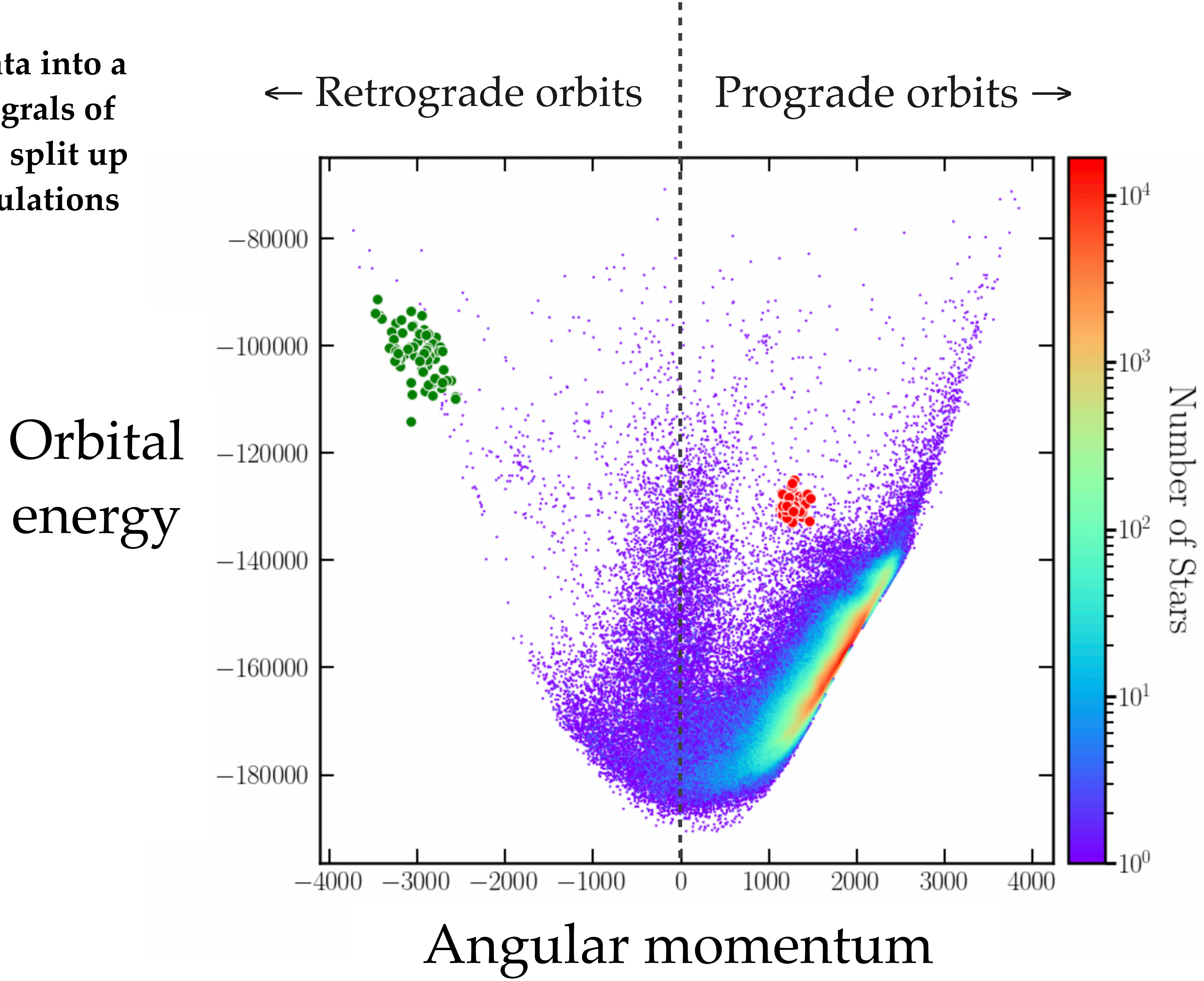
→ Generic result of hierarchical structure formation

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

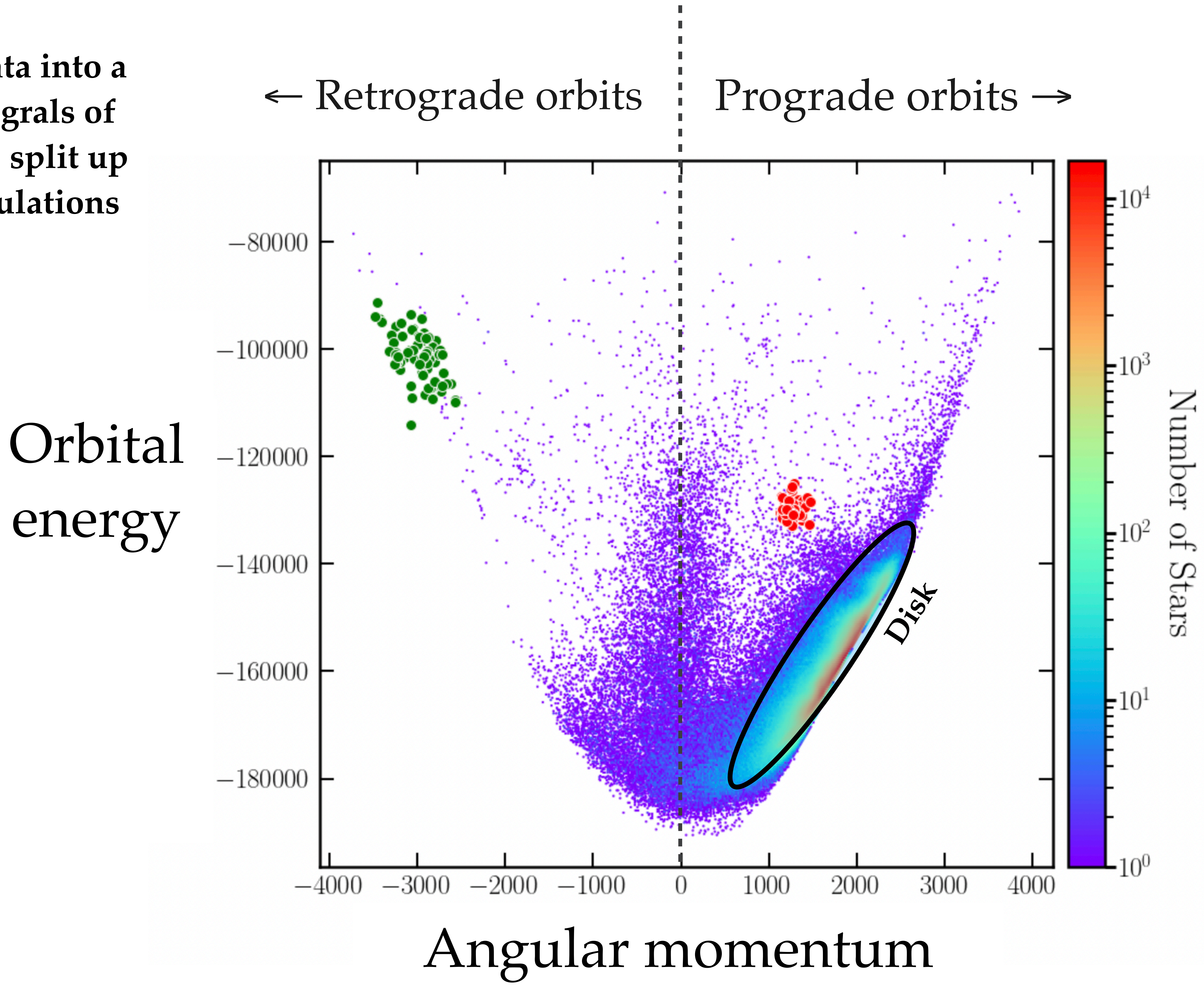


. Malhan [2202.07660]

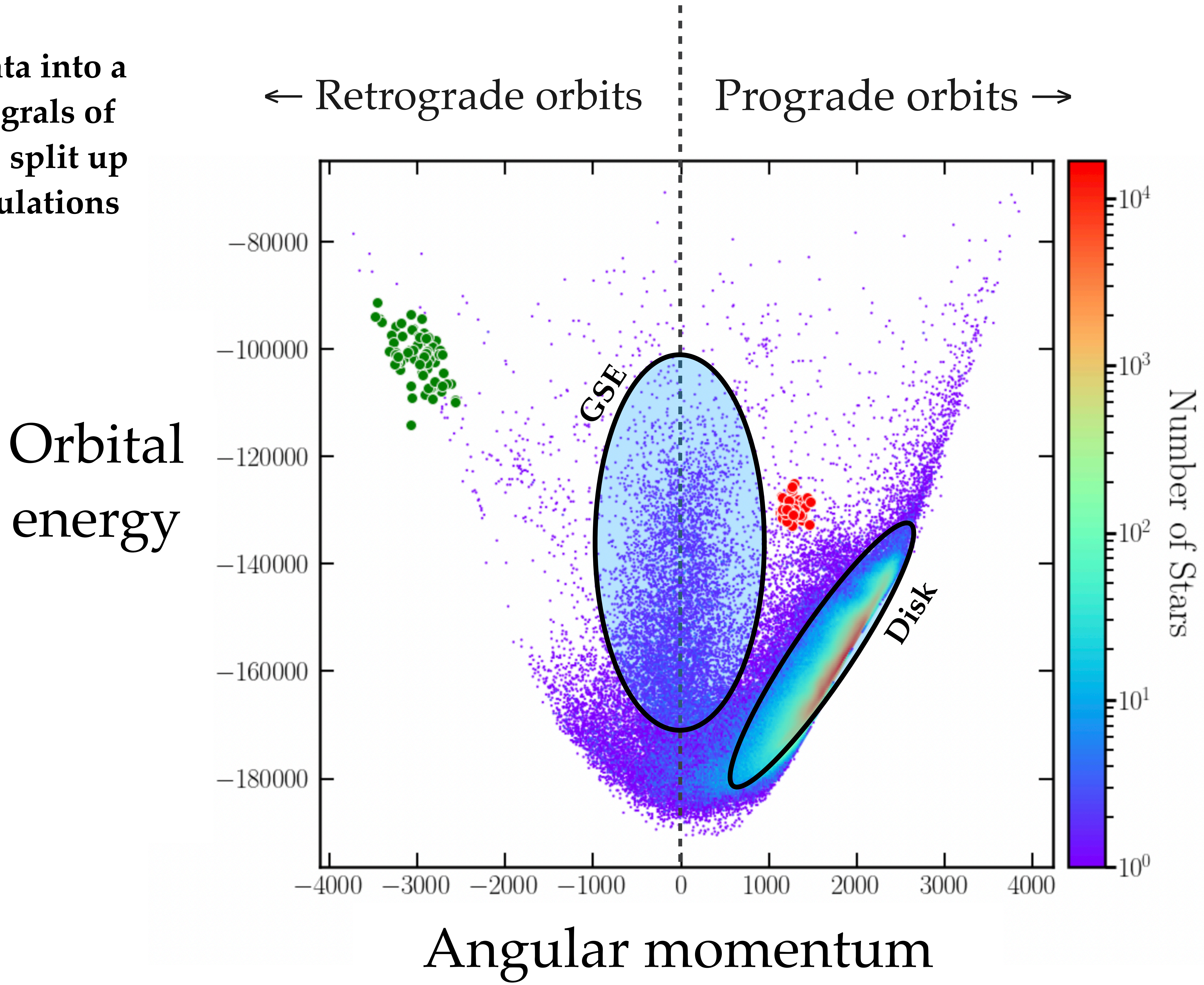
Casting the data into a space of "integrals of motion" helps split up different populations



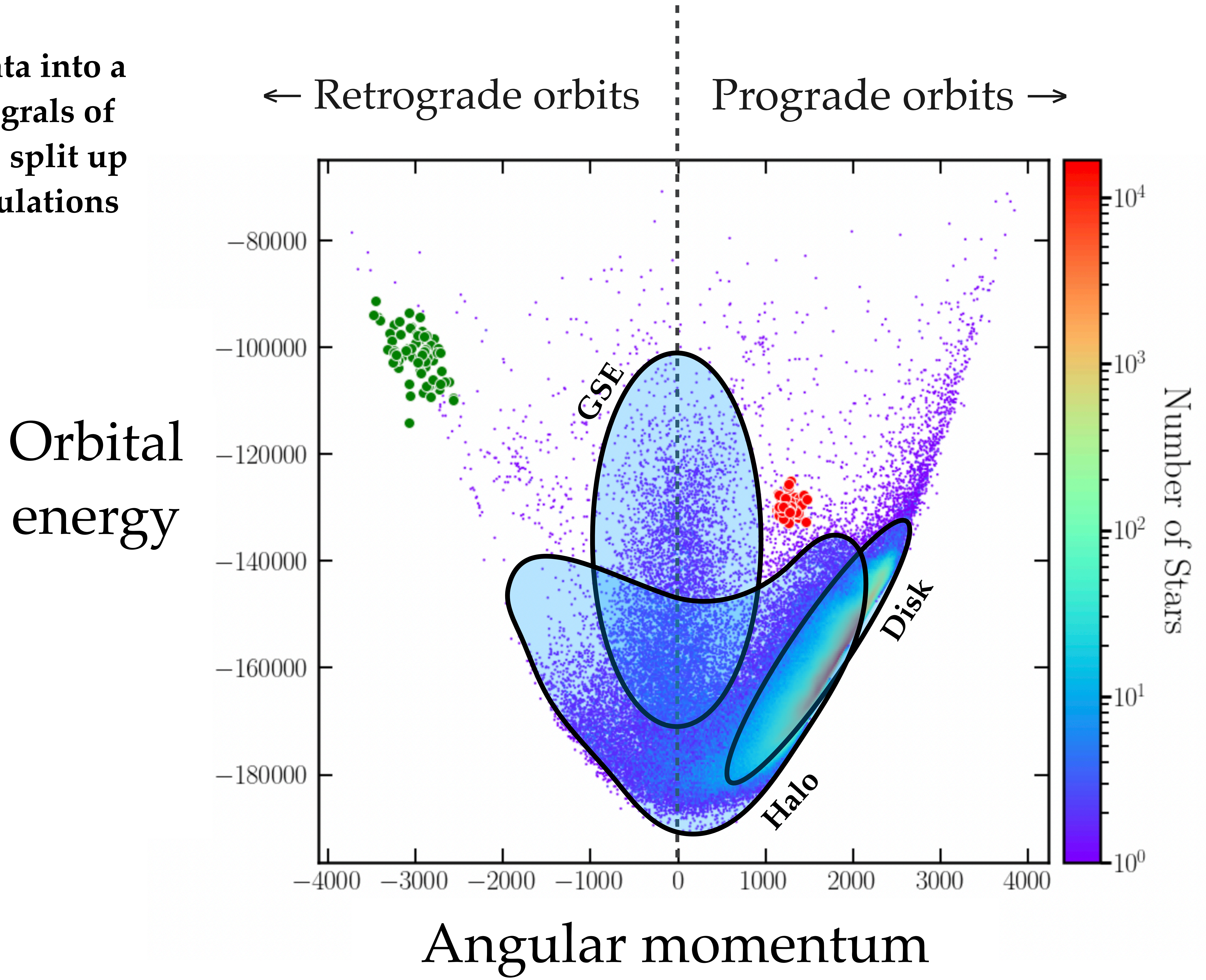
Casting the data into a space of "integrals of motion" helps split up different populations



Casting the data into a space of "integrals of motion" helps split up different populations



Casting the data into a space of "integrals of motion" helps split up different populations




Casting the data into a space of "integrals of motion" helps split up different populations
← Retrograde orbits
Prograde orbits →
Orbital energy
Angular momentum
−80000
−100000
−120000
−140000
−4000
−3000
−2000
−1000
0
1000
2000
3000
4000
GSE
Disk
Halo
10^4
10^2
10^1
10^0
er of Stars
Prograde overdensity: "Helmi streams"
Retrograde overdensity "Sequoia"

Several important substructures detected in the inner stellar halo

→ **Gaia-Sausage-Enceladus:** a large population of halo stars on highly radial, eccentric orbits. Cautious estimate ~20% of local DM

→ **Sequoia**: stars on high-energy, highly retrograde orbit. <10% of local DM

→ **Helmi streams:** stars on prograde+polar orbits. <10% of local DM

Several important substructures detected in the inner stellar halo

→ **Gaia-Sausage-Enceladus:** a large population of halo stars on highly radial, eccentric orbits. Cautious estimate ~20% of local DM

→ **Sequoia**: stars on high-energy, highly retrograde orbit. <10% of local DM

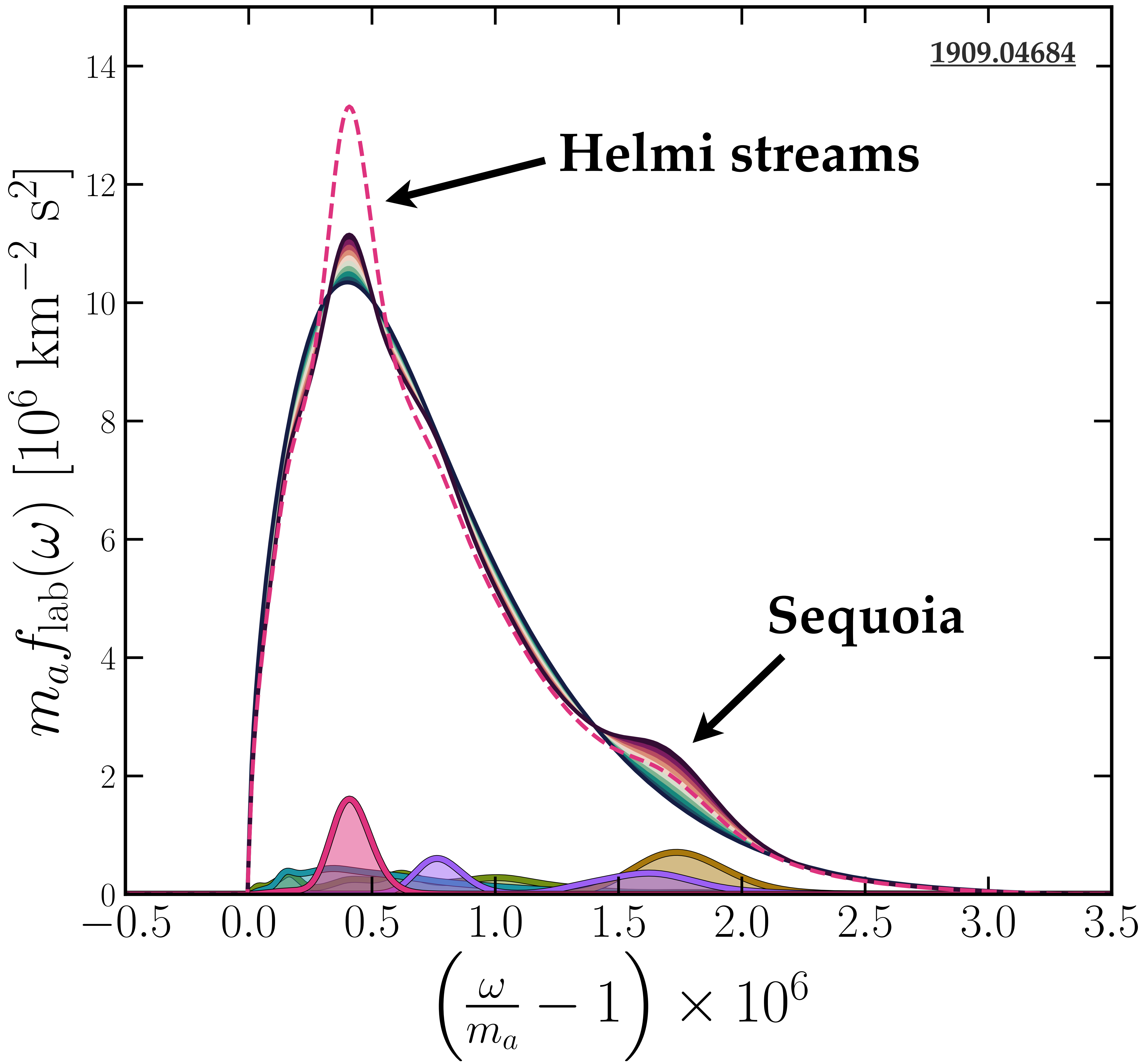
→ **Helmi streams:** stars on prograde+polar orbits. <10% of local DM

There are potentially more, but these are the ones that have:

1. been detected at high significance
2. intersect the solar position, and
3. come from dwarf-galaxy progenitors

(i.e. will have associated DM components)

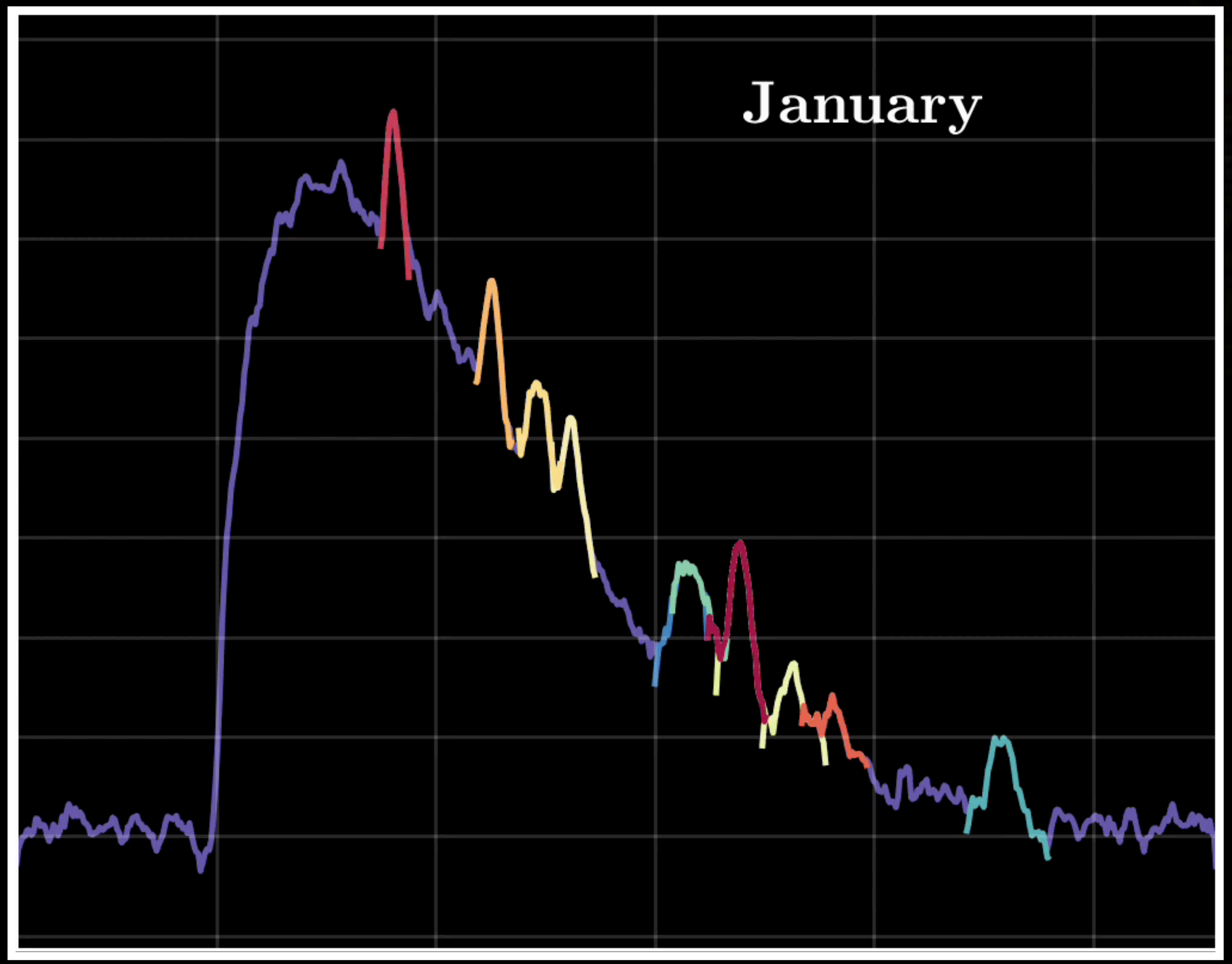
Substructure in the wave-like DM line

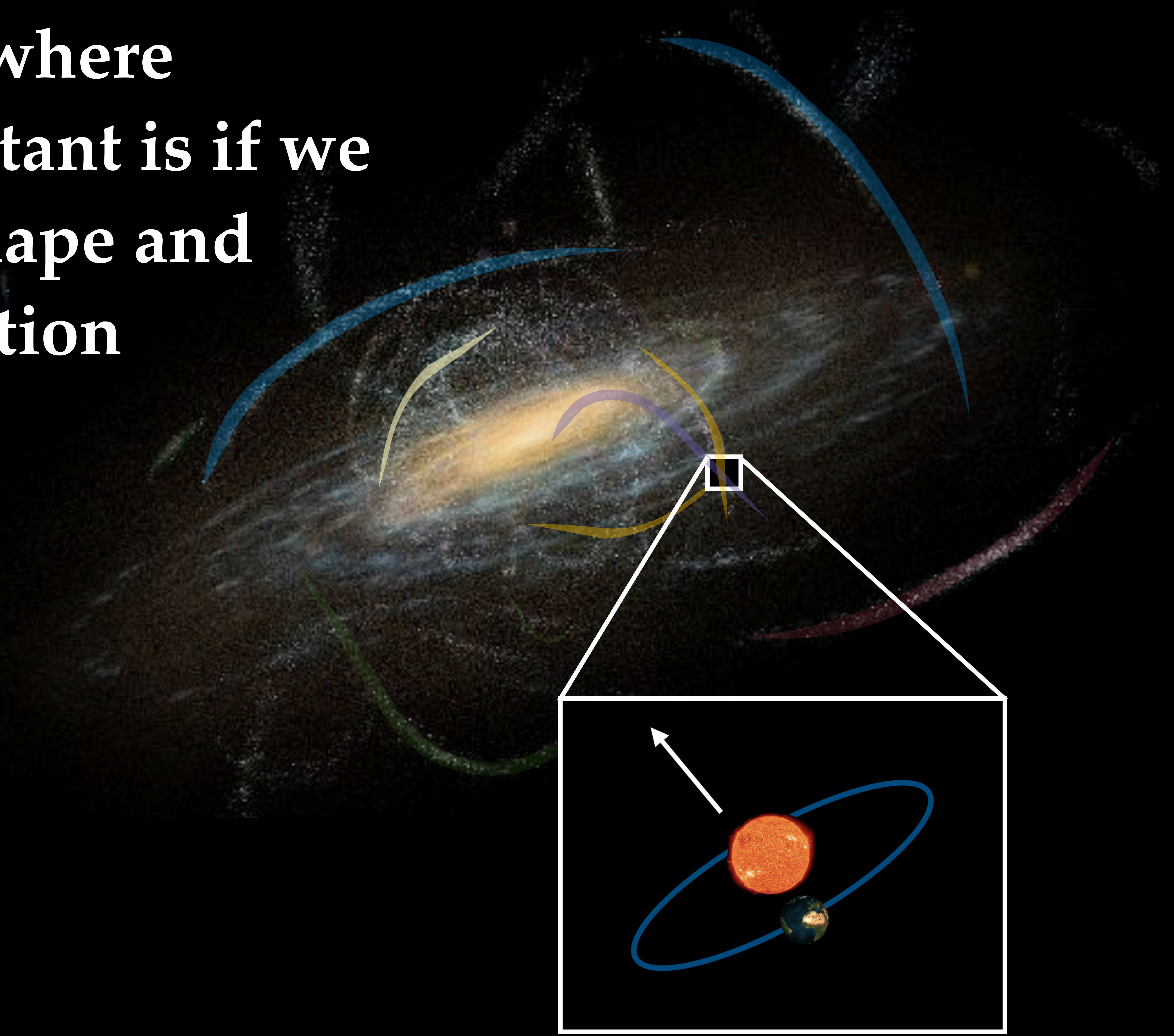


Helmi streams are at ~280 km/s which means it would show up almost precisely at the peak of the lineshape.
→ **Enhances wave-like DM signal**

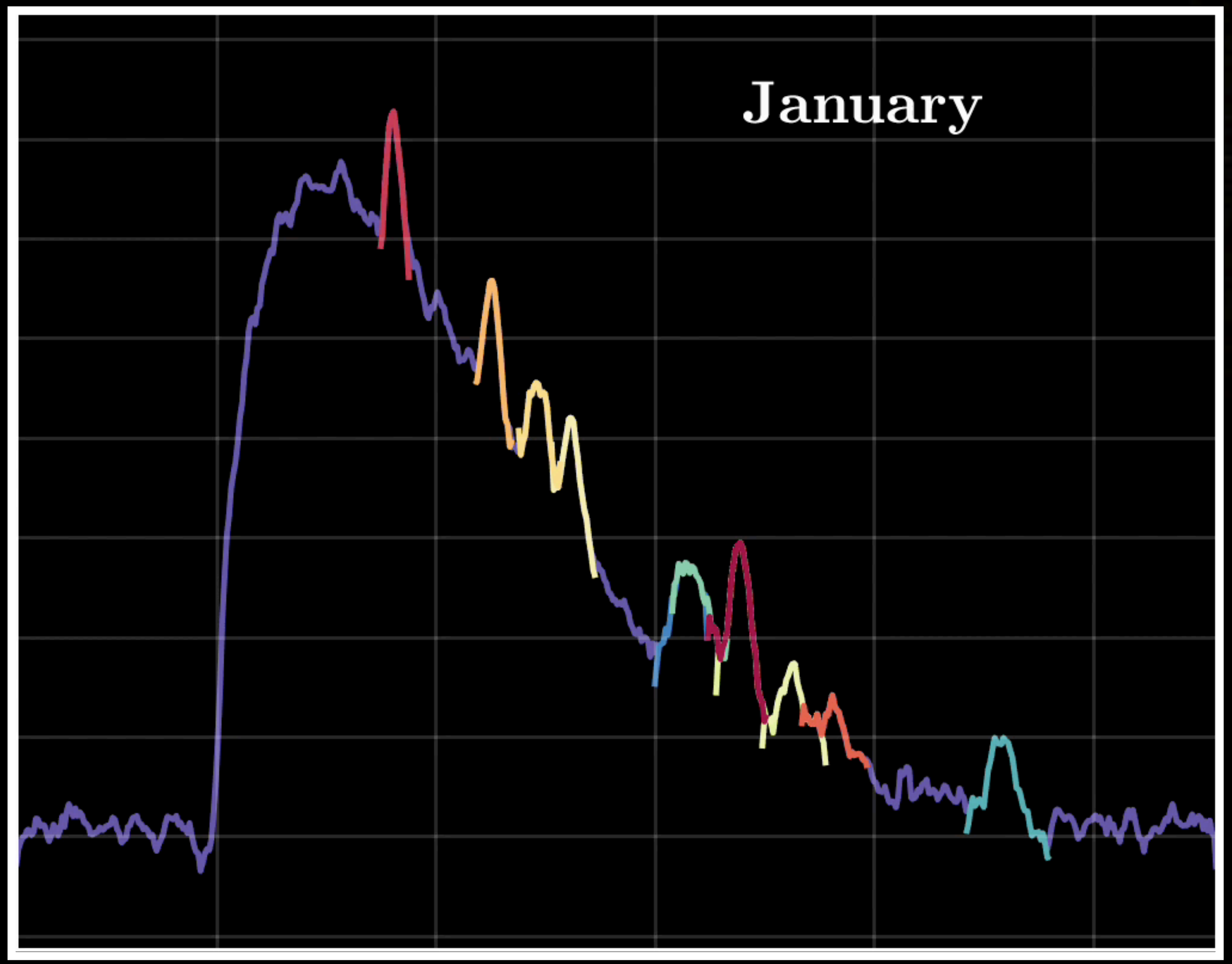
Sequoia exists at high speeds so acts to make the distribution wider
→ **Weakens wave-like DM sensitivity**

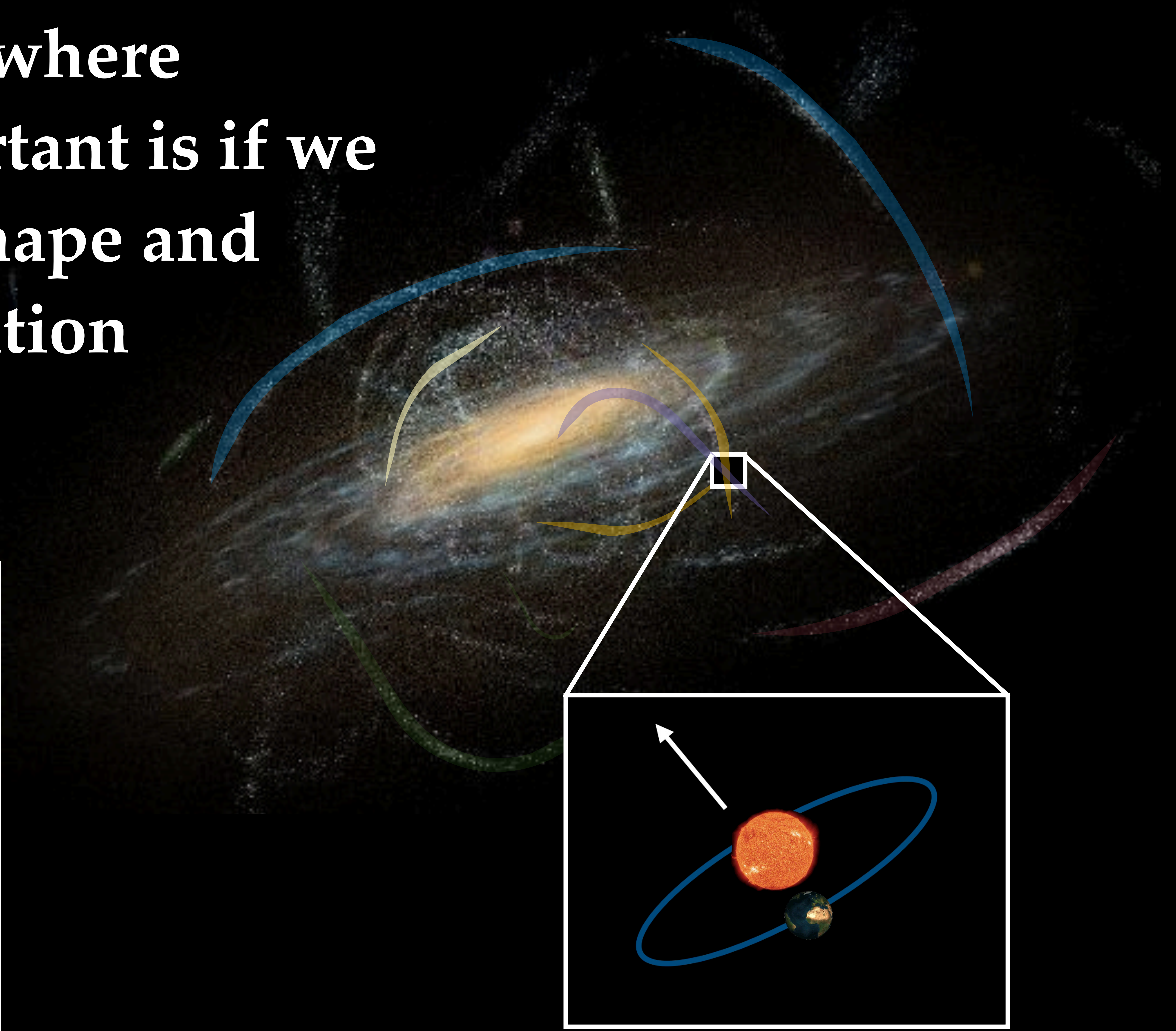
Ultimately the place where substructure is important is if we can resolve the lineshape and study annual modulation



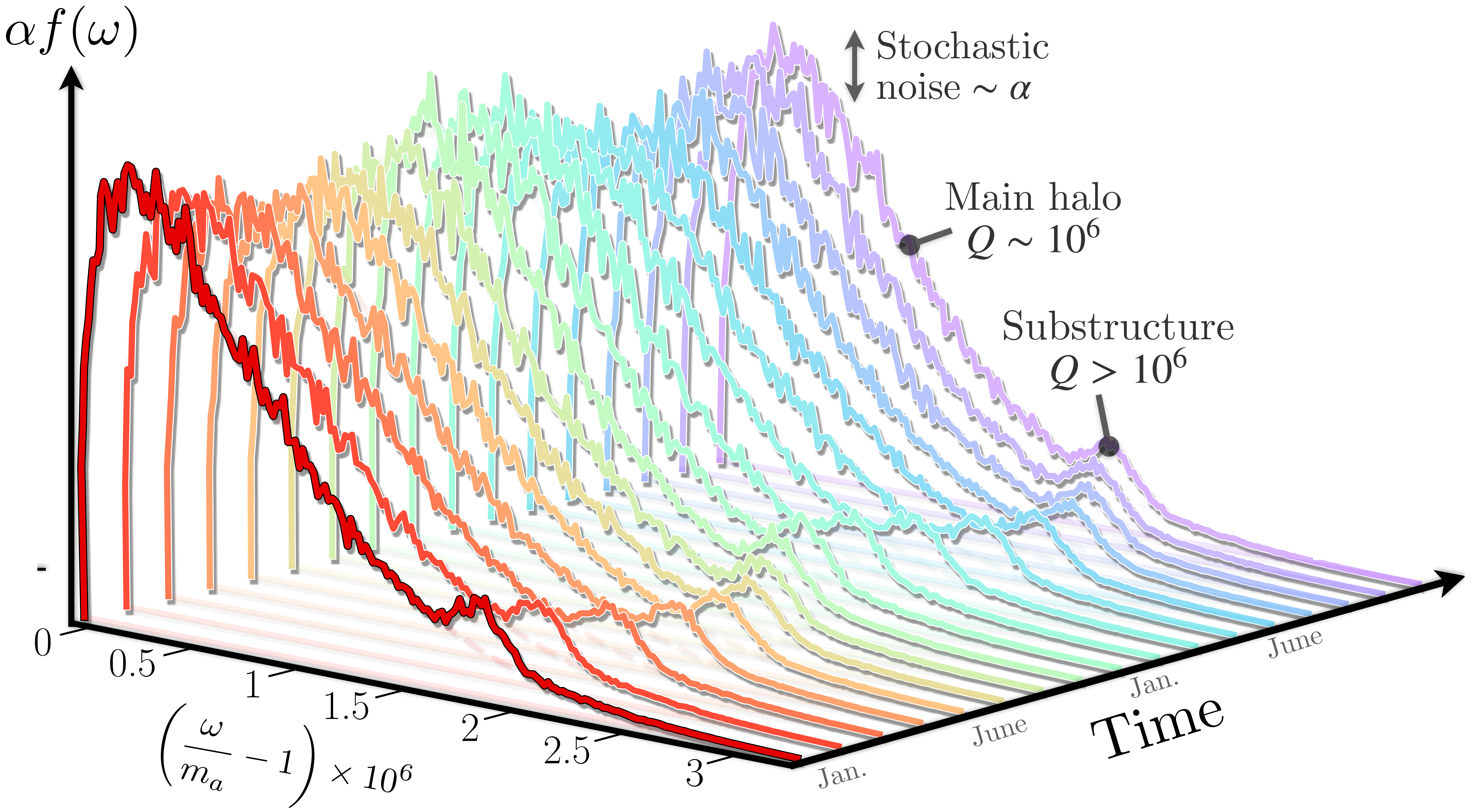


Ultimately the place where substructure is important is if we can resolve the lineshape and study annual modulation

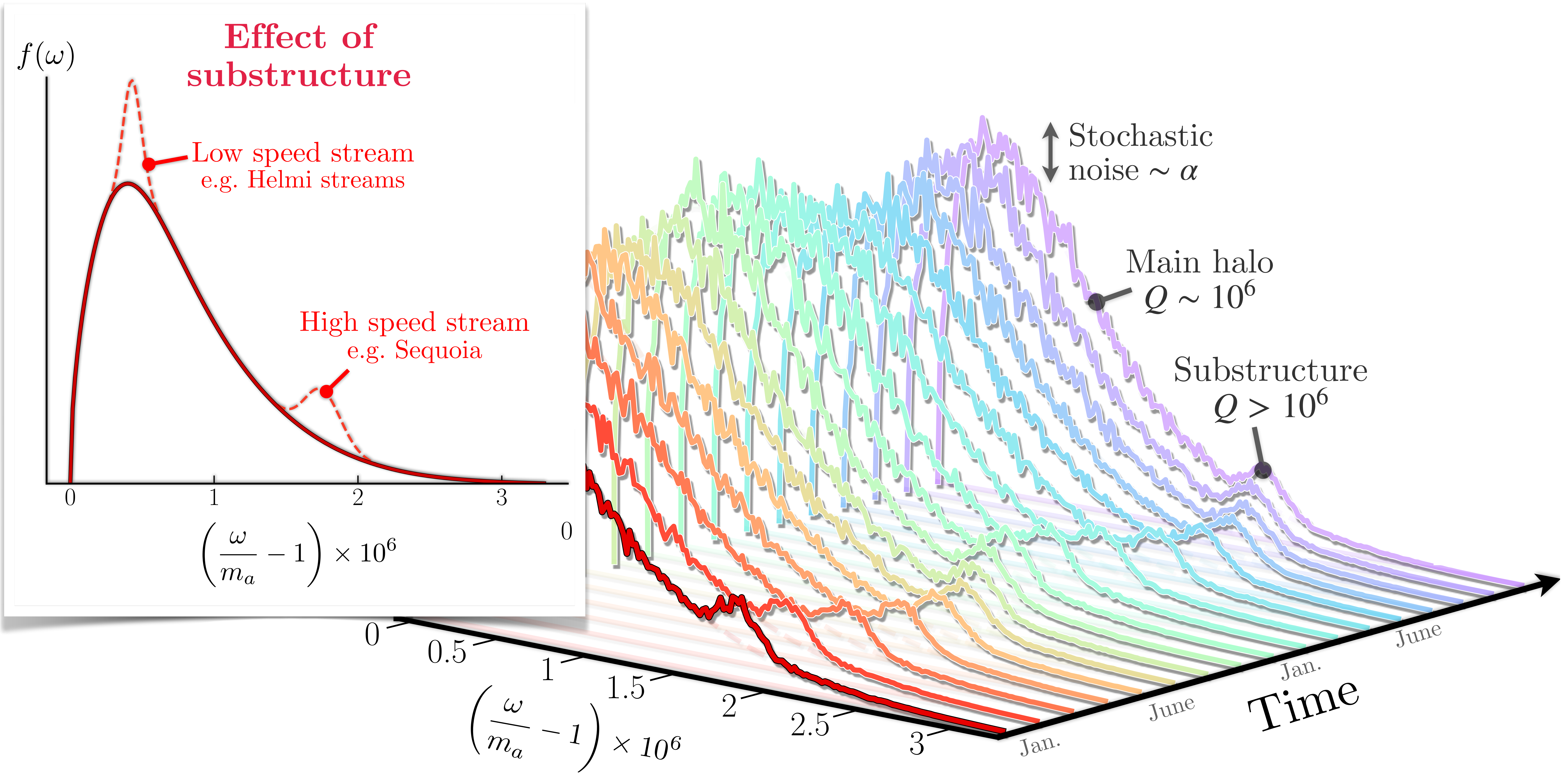




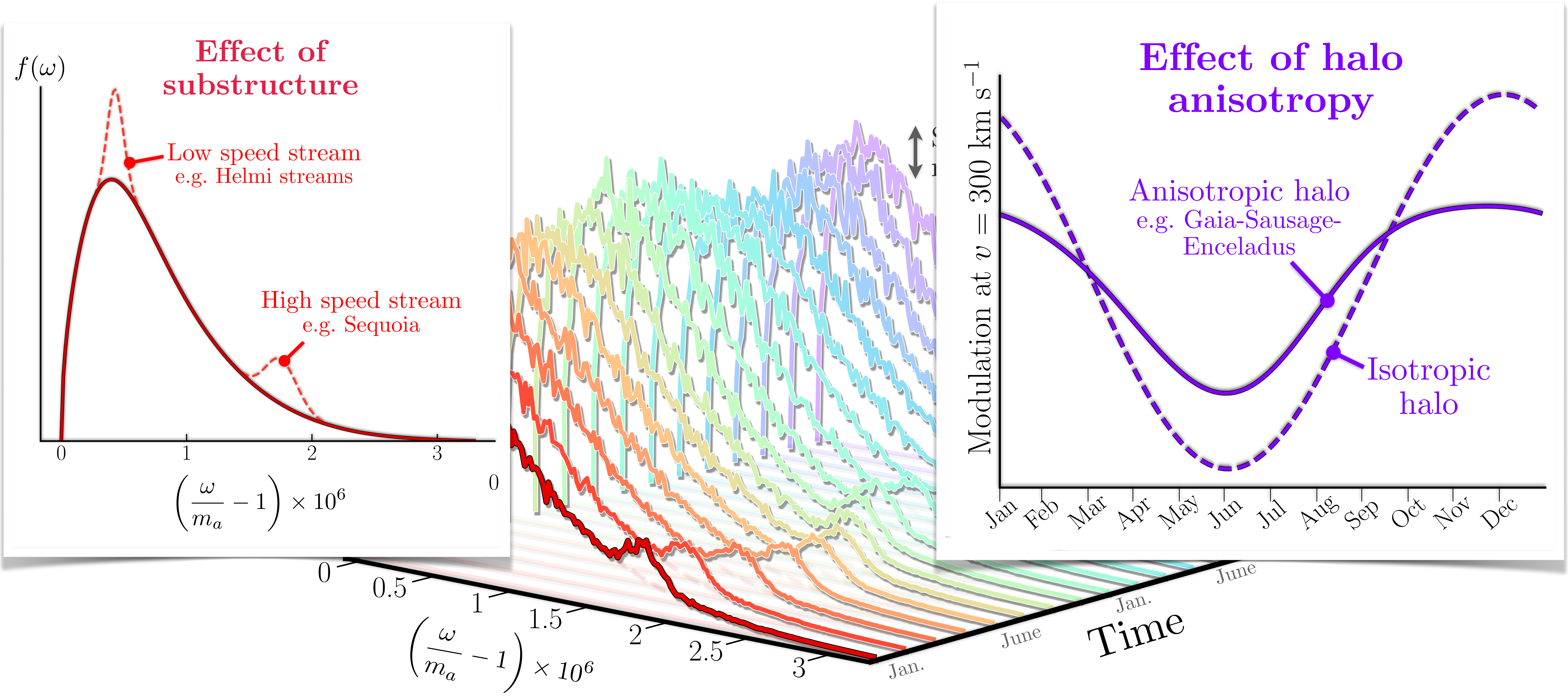
Substructure in the DM line + annual modulation



Substructure in the DM line + annual modulation



Substructure in the DM line + annual modulation



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

Take home messages:

1. **Astrophysical uncertainties are just that, uncertainties,** they must be reckoned with when one claims to rule out specific particle physics predictions. The correct approach is to treat the DM density/ lineshape as nuisance parameters.
2. **So far there are no nasty surprises in the *Gaia* data as far as DM searches go.** The velocity distribution will have modest amounts of substructure that could impact direction/time-dependent expts., but not enough to radically alter search strategies for the time being.

But wait, there's more…

Q: How do we know the DM content of halo substructures?
Q: What about the polarisation distribution for the dark photon case?
Q: What about axion miniclusters for the post-inflationary scenario?
Q: Can there be transient signals, or time-dependence beyond annual modulation?

Dark photons

Dark photon electrodynamics

DP-photon Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu v}F^{\mu v} - \frac{1}{4}X_{\mu v}X^{\mu v} + eJ^{\mu}_{\text{EM}}A_{\mu} + \frac{m_X^2}{2}(X^{\mu}X_{\mu} + 2\chi X_{\mu}A^{\mu})$$

Solution is a wave equation: $-K^2 A^{\mu} = \chi m_X^2 X^{\mu}$ $K = (\omega, \mathbf{k})$

↓

$$|\mathbf{E}| = \left|\frac{\chi m_X}{\epsilon}\mathbf{X}\right|$$

Dark photon sources E-field with direction given by the DP polarisation, **X**

Dark photon electrodynamics versus Axion electrodynamics

Axions source an effective current in a similar way, but via $a\,\mathbf{E}\cdot\mathbf{B}_{\rm ext}$ meaning DPs can searched for with exactly the same techniques only they do not require a B-field to convert into photons

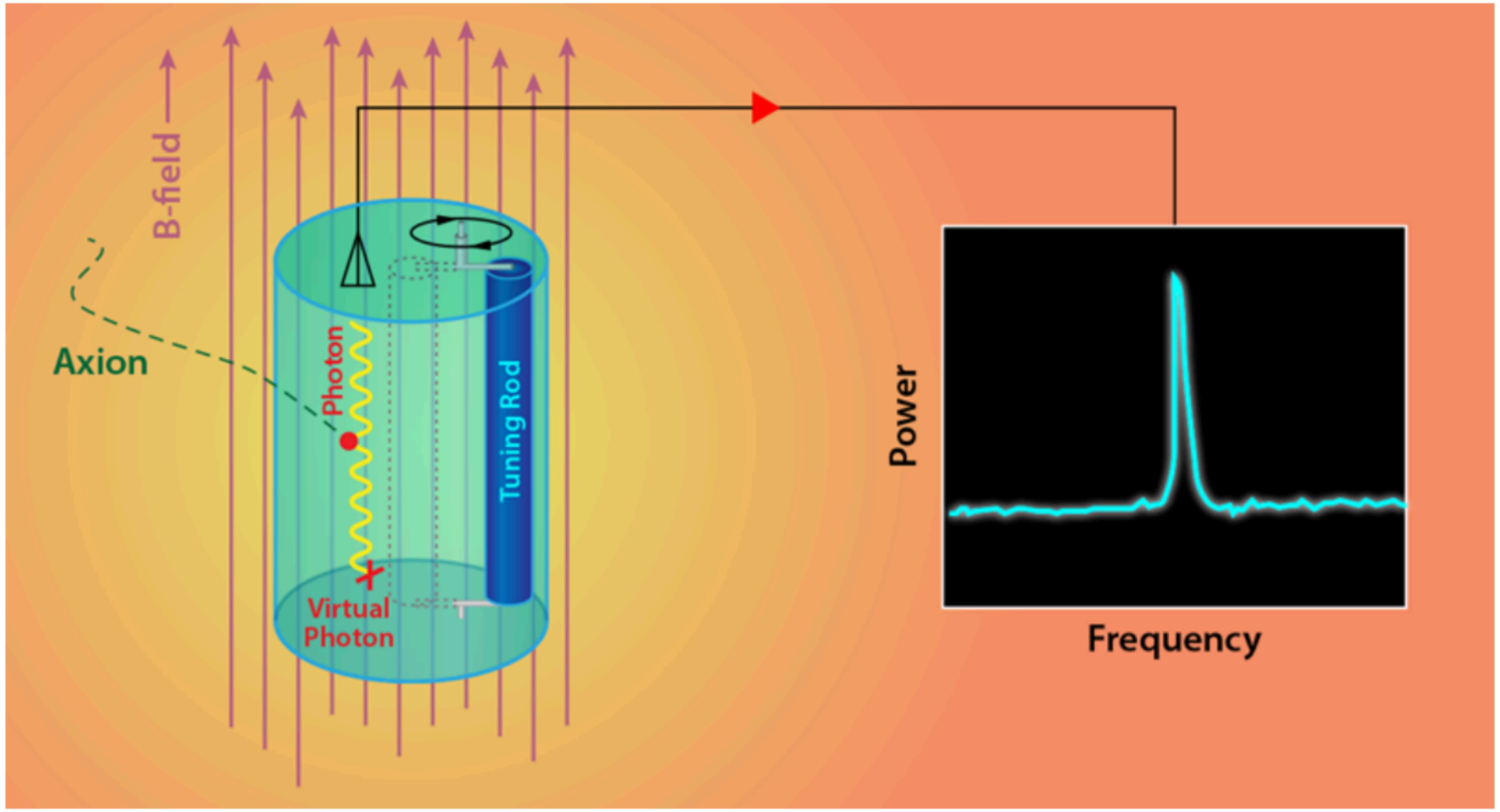
Example: cavity haloscope

Sikivie formula for resonant cavity power from axions:

$$P_{\rm axion} = \kappa\,\mathcal{G}\,V Q \rho_{\rm DM}\,\frac{g_{a\gamma}^2 B^2}{m_a}$$

$$P_{\rm DP} = \kappa\,\mathcal{G}\,V Q \rho_{\rm DM}\,\chi^2 m_X$$

$$\boxed{\chi m_X \leftrightarrow g_{a\gamma} B}$$



C. BOUTAN/PACIFIC NORTHWEST NATIONAL LABORATORY; ADAPTED BY APS/ALAN STONEBRAKER

Have to be careful!

There is a very subtle difference between these formulae

$$P_{\mathrm{DP}} = \kappa\, \mathcal{G}\, V Q \rho_{\mathrm{DM}}\, \chi^2 m_X$$

$$P_{\mathrm{axion}} = \kappa\, \mathcal{G}\, V Q \rho_{\mathrm{DM}}\, \frac{g_{a\gamma}^2 B^2}{m_a}$$

Have to be careful!

There is a very subtle difference between these formulae

$$P_{\mathrm{DP}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \chi^2 m_X$$

$$P_{\mathrm{axion}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \frac{g_{a\gamma}^2 B^2}{m_a}$$

Have to be careful!

There is a very subtle difference between these formulae

$$P_{\rm DP} = \kappa \mathcal{G} V Q \rho_{\rm DM} \chi^2 m_X$$

$$P_{\rm axion} = \kappa \mathcal{G} V Q \rho_{\rm DM} \frac{g_{a\gamma}^2 B^2}{m_a}$$

Cavity form factor

$$\mathcal{G}^{\rm axion} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \mathbf{B}_{\rm ext}\right)^2}{V B^2 \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

$$\mathcal{G}^{\rm DP} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \hat{\mathbf{X}}\right)^2}{V \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Have to be careful!

There is a very subtle difference between these formulae

$$P_{\mathrm{DP}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \chi^2 m_X$$

$$P_{\mathrm{axion}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \frac{g_{a\gamma}^2 B^2}{m_a}$$

Cavity form factor

$$\mathcal{G}^{\mathrm{axion}} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \mathbf{B}_{\mathrm{ext}}\right)^2}{V B^2 \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Axion case relies on overlap between the cavity mode $\mathbf{E}_\alpha$ and applied B-field

$\rightarrow$ Dependent only on the cavity itself

$$\mathcal{G}^{\mathrm{DP}} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \hat{\mathbf{X}}\right)^2}{V \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Have to be careful!

There is a very subtle difference between these formulae

$$P_{\rm DP} = \kappa \mathcal{G} V Q \rho_{\rm DM} \chi^2 m_X$$

$$P_{\rm axion} = \kappa \mathcal{G} V Q \rho_{\rm DM} \frac{g_{a\gamma}^2 B^2}{m_a}$$

Cavity form factor

$$\mathcal{G}^{\rm axion} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \mathbf{B}_{\rm ext}\right)^2}{V B^2 \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Axion case relies on overlap between the cavity mode $\mathbf{E}_\alpha$ and applied B-field
→ **Dependent only on the cavity itself**

$$\mathcal{G}^{\rm DP} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \hat{\mathbf{X}}\right)^2}{V \frac{1}{2} \int dV \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Appearing here is the DP polarisation!

$$|\mathbf{E}| = \left|\frac{\chi m_X}{\epsilon} \mathbf{X}\right|$$

Axions differ from dark photons in two respects

1) Dark photons don't require an applied B-field.

2) Dark photon signal depends upon its polarisation state.

So the actual recasting looks like this:

$$\chi m_X |\cos\theta| \leftrightarrow g_{a\gamma} B$$

In the cavity example $\cos\theta$ is the angle between the DP polarisation and the applied B-field.

But what is the DP polarisation???

→ this is yet another astrophysical uncertainty!

But what is the dark photon’s polarisation state?

But what is the dark photon's polarisation state?

…No one seems to know

But what is the dark photon's polarisation state?

…No one seems to know

Seems to be a badly understudied aspect of DPDM, but we can bound some possibilities:

Scenario 1: The DP polarisation is totally random in every coherence time, i.e. a random direction is drawn every $\sim 10^6$ oscillations.

But what is the dark photon's polarisation state?

…No one seems to know

Seems to be a badly understudied aspect of DPDM, but we can bound some possibilities:

Scenario 1: The DP polarisation is totally random in every coherence time, i.e. a random direction is drawn every $\sim 10^6$ oscillations.

Scenario 2: The DP polarisation is fixed over length/time-scales probed by experiments, i.e. $t <$ year, and $L <$ mpc

(A mixture of purely random and purely fixed is possible of course, but these two scenarios are the extremes)

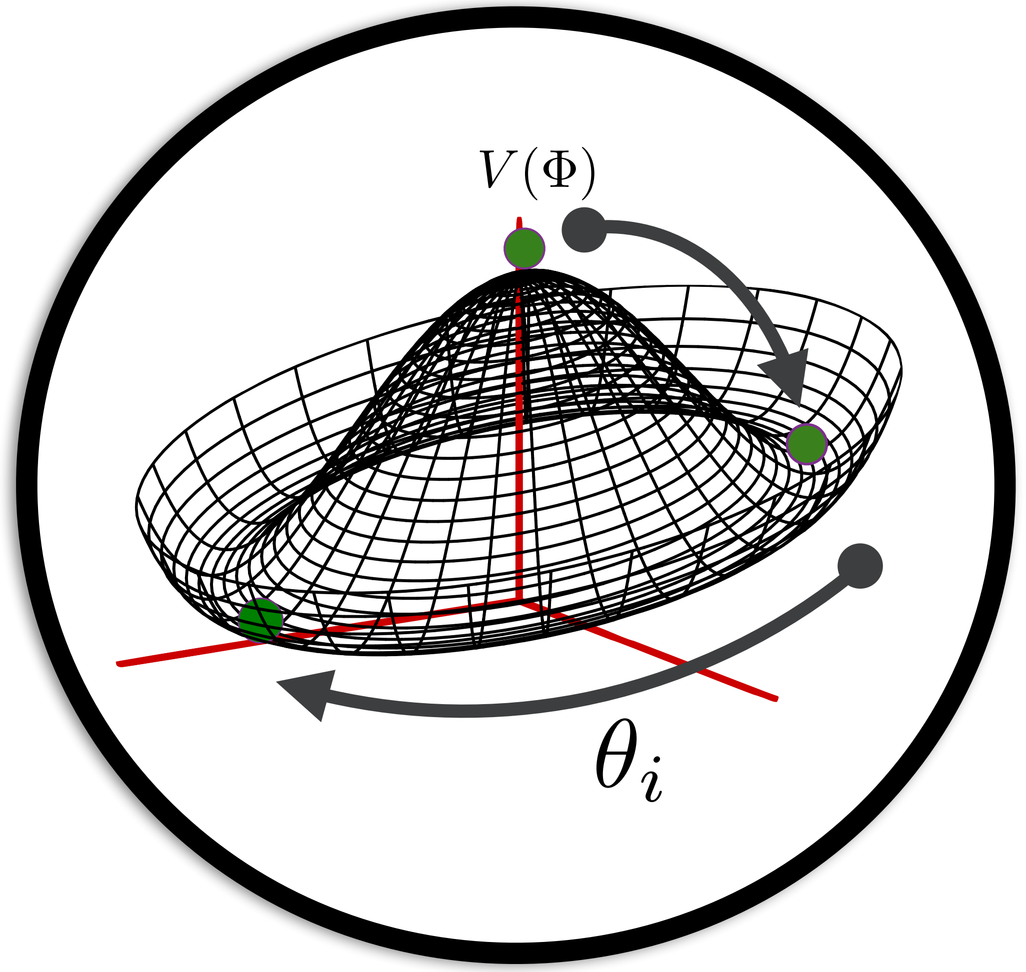
Which scenario is correct?

The answer depends on:

1) DP production mechanism → What was the primordial polarisation distribution?
2) Structure formation → Can gravity rotate the DP polarisation?

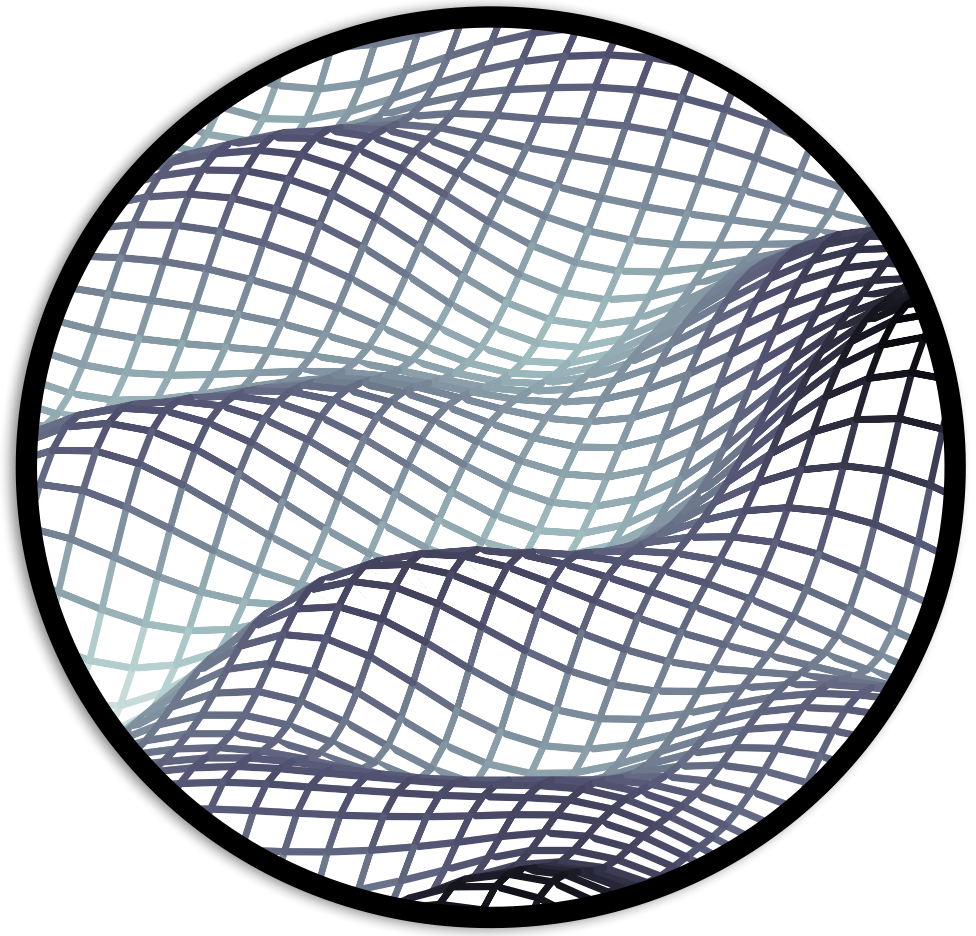
Misalignment mechanism

e.g. 1201.5902, 1905.09836



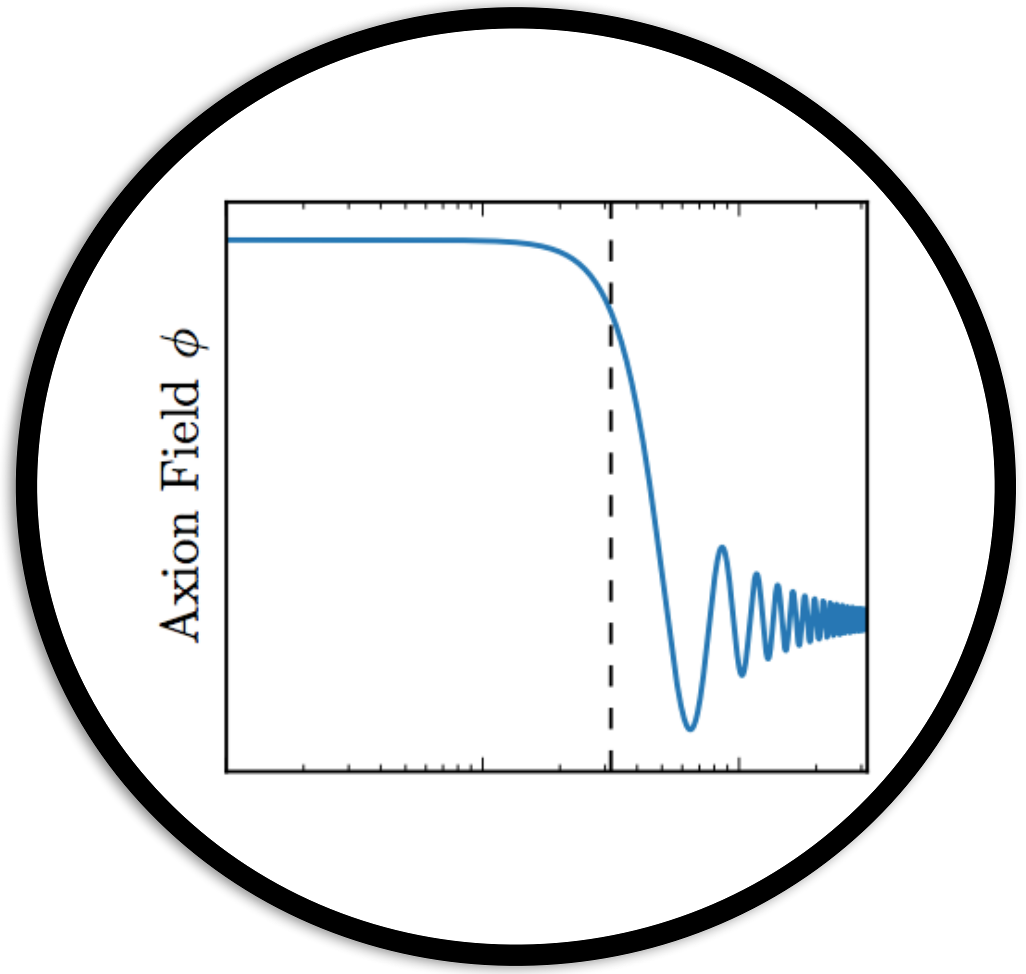
Inflationary perturbations

e.g. 1504.02102, 2009.03828, 2005.01766, 2004.10743



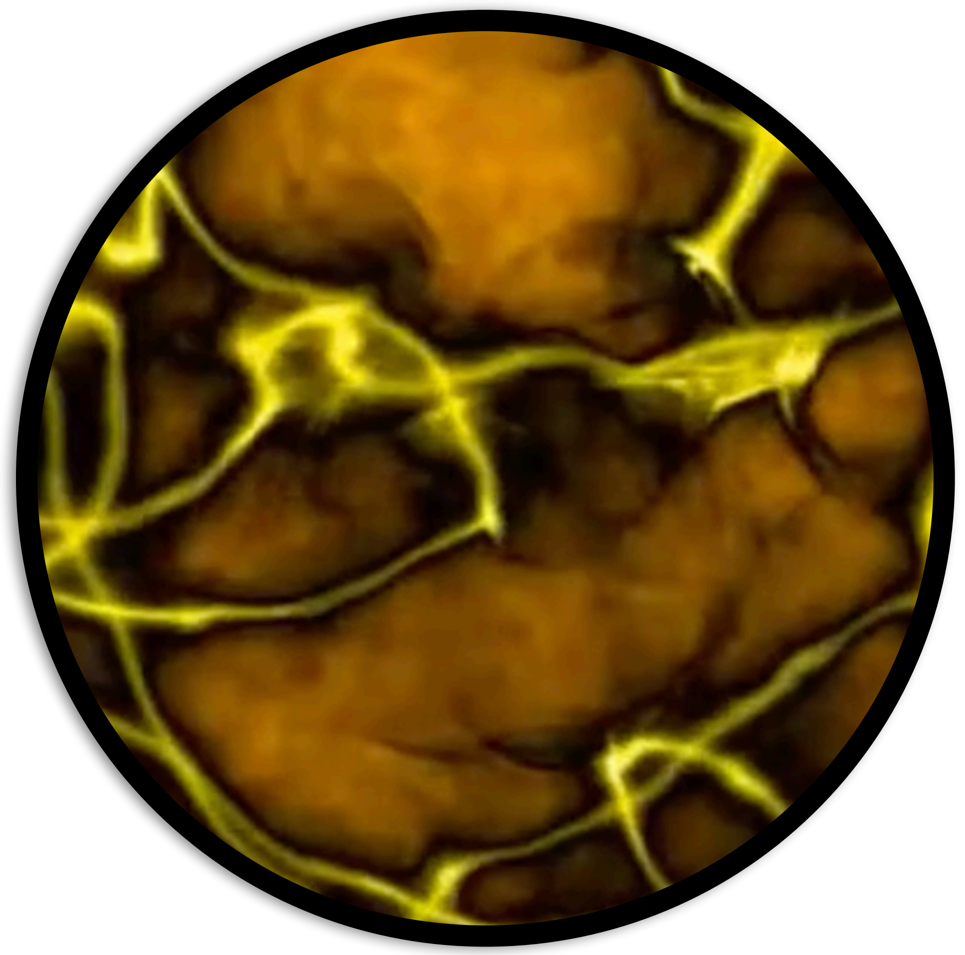
Via an axion

e.g. 1810.07188, 1810.07196



Cosmic string decay

e.g. 1901.03312



Probably fixed polarisation inside horizon (Scenario 1)

Very roughly…

Probably more randomised polarisation inside horizon (Scenario 2)

How to account for the DP polarisation: Scenario 1

Measured power is proportional to $\langle \cos^2\theta \rangle_T$ which is the time-averaged DP polarisation angle over the duration of the measurement being made

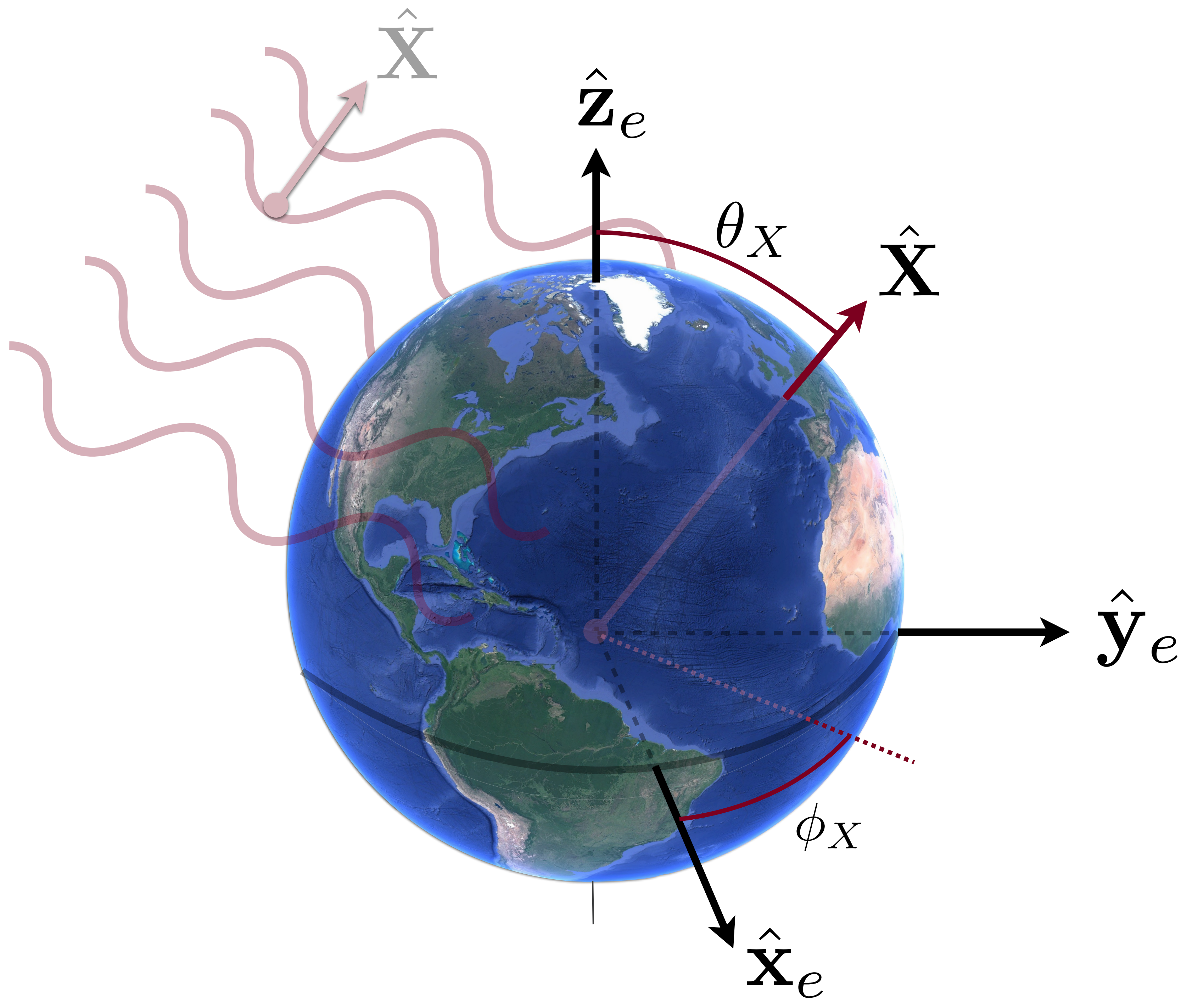
If measurements last many coherence times and we randomly sample angles across the sky, then $\langle \cos^2\theta \rangle_T = 1/3$

(answer is 2/3 if expt. is sensitive to 2 polarisations)

And we're done.

How to account for the DP polarisation: Scenario 1

The Earth rotates with respect to the DP polarisation axis which is **fixed**, so $\cos^2\theta$ depends upon time/orientation in a non-trivial, but predictable way



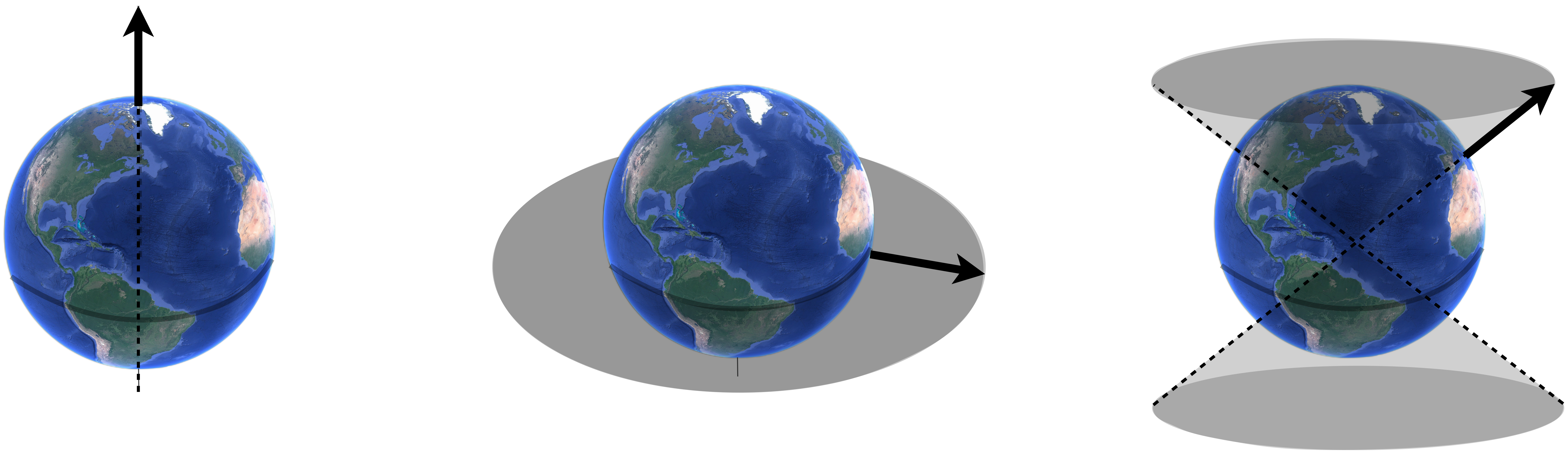
Since the DP signal is weaker in Scenario 2, it is always the more conservative option, worthwhile to use it as a baseline

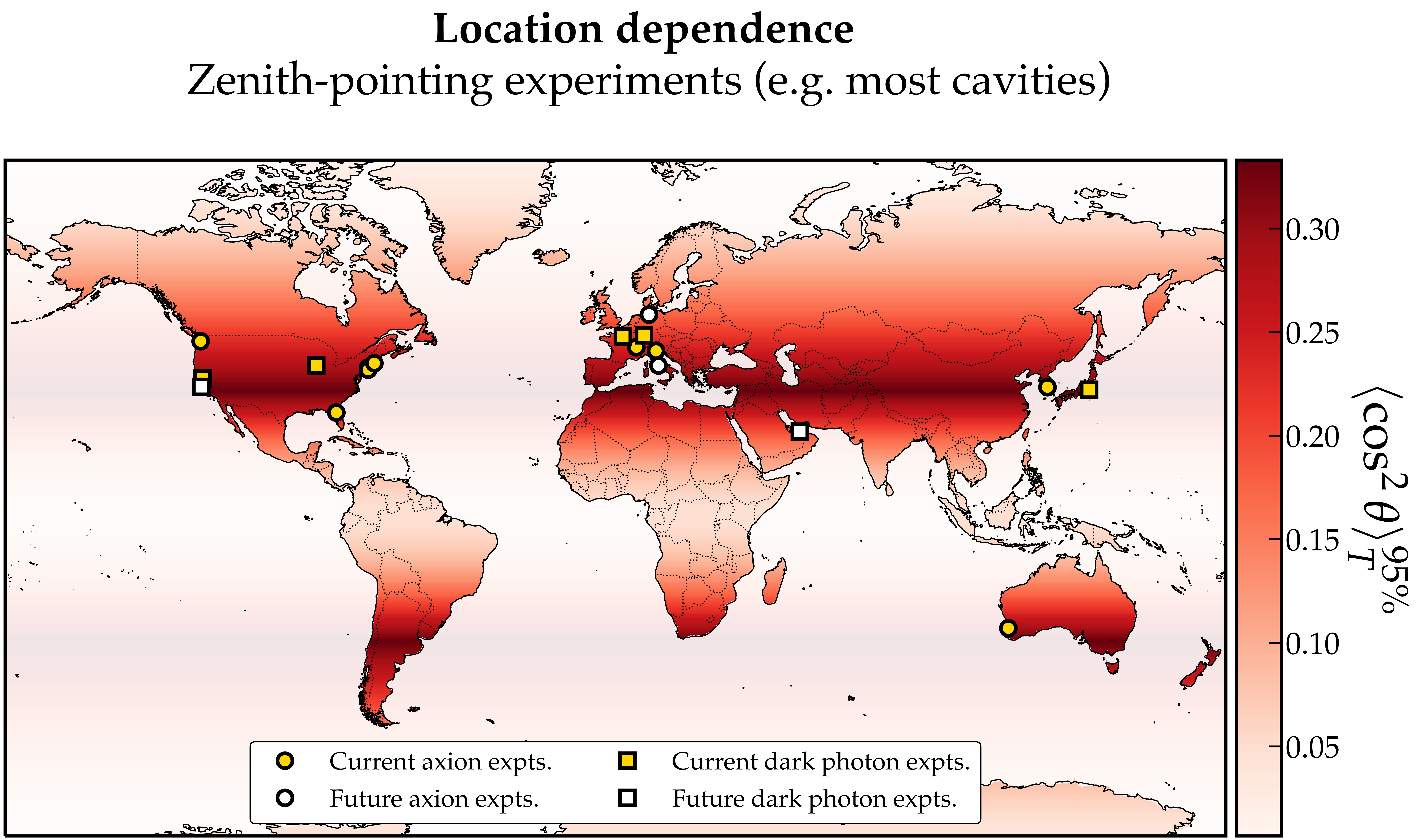
Scenario 2

This also means that the sensitivity of a DP search strongly depends upon the duration of observation, the location, and the orientation of the experiment

Take a **Zenith-pointing** experiment (e.g. a cavity with vertical B-field):

North Pole: **Worst** Equator: **Bad** Latitude~35°: **Best**

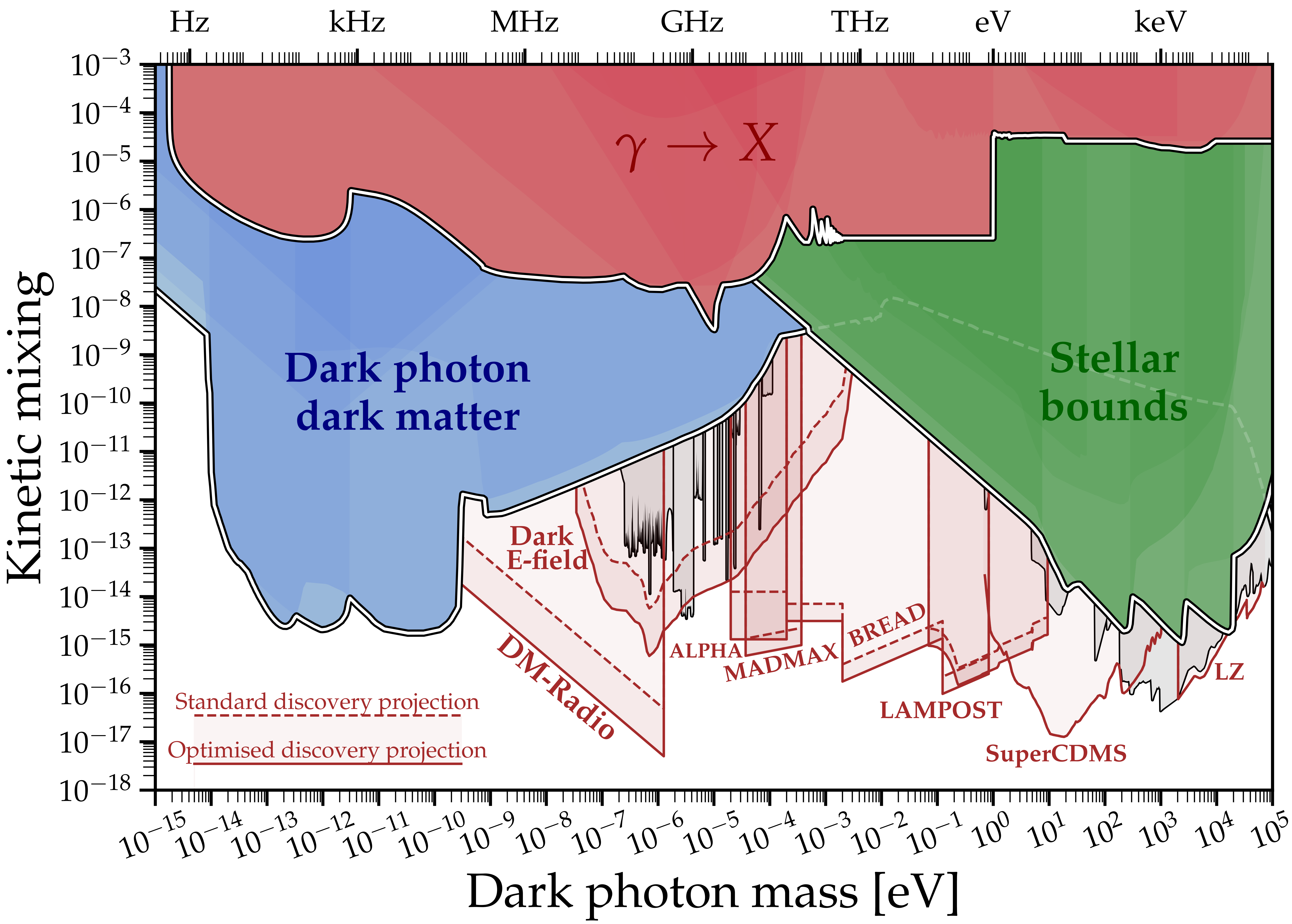




Location dependence
Zenith-pointing experiments (e.g. most cavities)
Current axion expts.
Future axion expts.
Current dark photon expts.
Future dark photon expts.
0.30
0.25
0.20
0.15
0.10
0.05
$\langle \cos^2\theta \rangle_T^{95\%}$

Distribution of time-averaged $\cos^2\theta$ versus the duration of observation

→ day-long measurements always optimal at any location



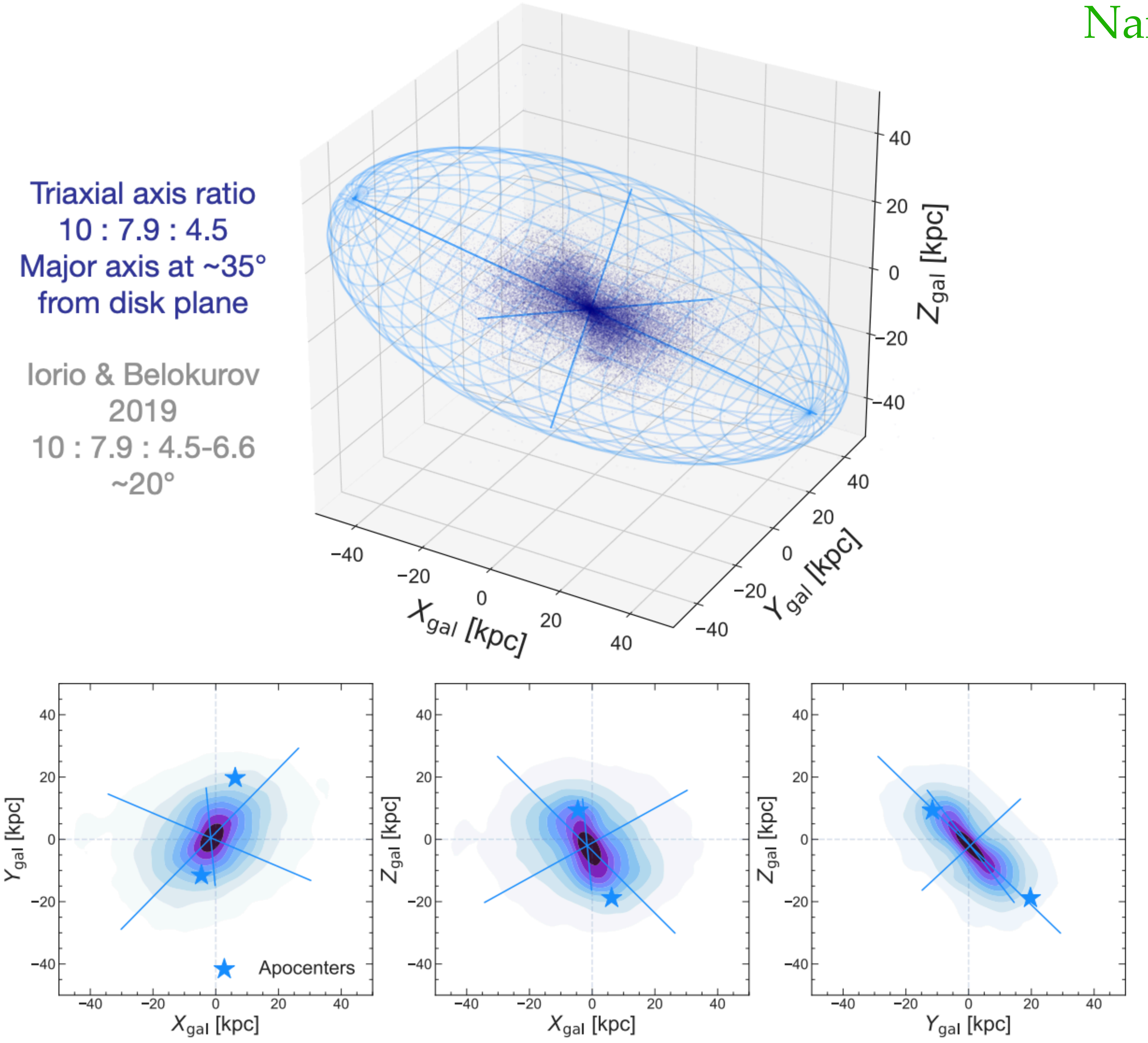
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
$\gamma \to X$
Dark photon dark matter
Stellar bounds
Dark E-field
DM-Radio
ALPHA
MADMAX
BREAD
LAMPOST
SuperCDMS
LZ
Standard discovery projection
Optimised discovery projection

Dark matter/Stellar halo connection

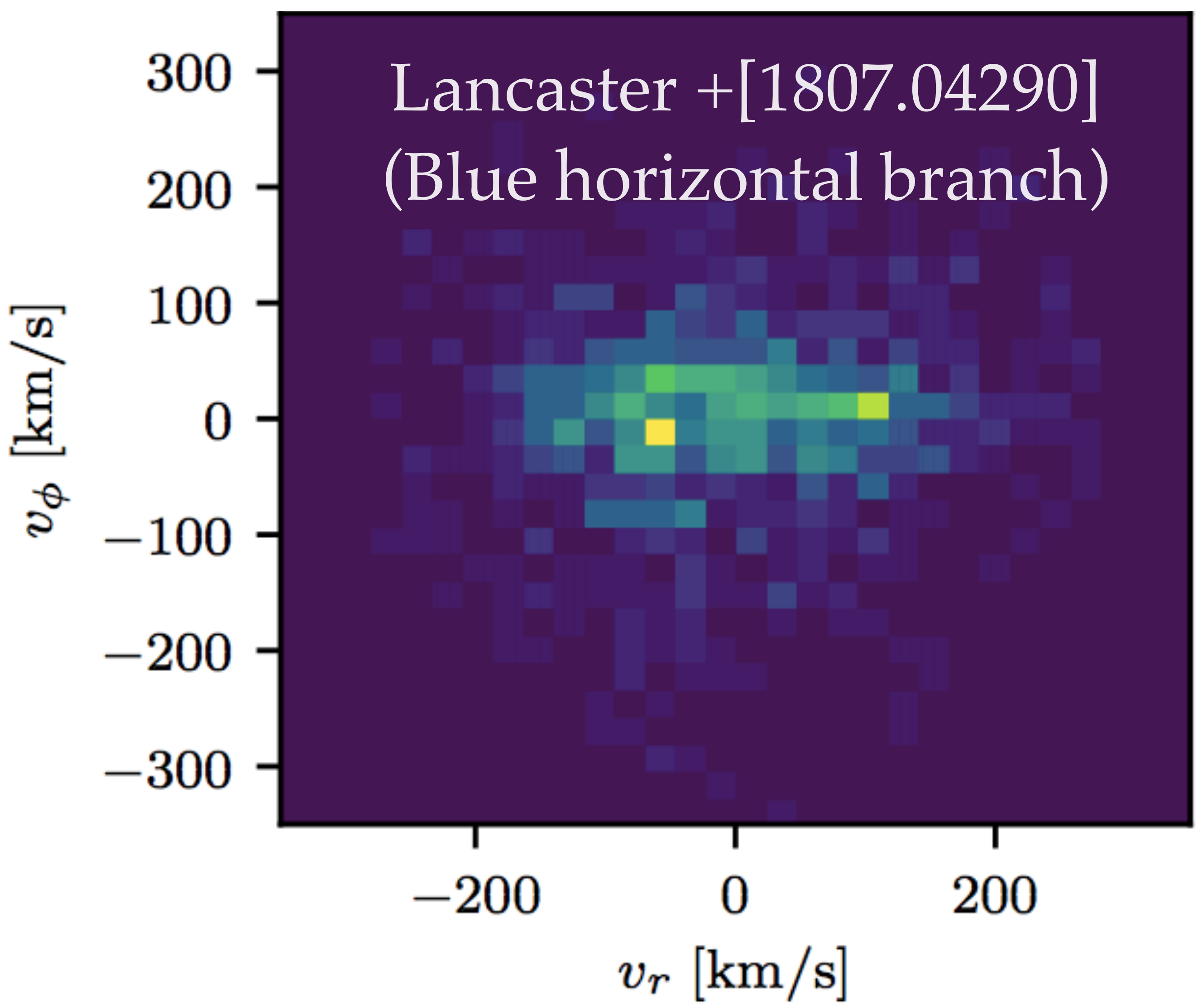
Naidu+[2103.03251]

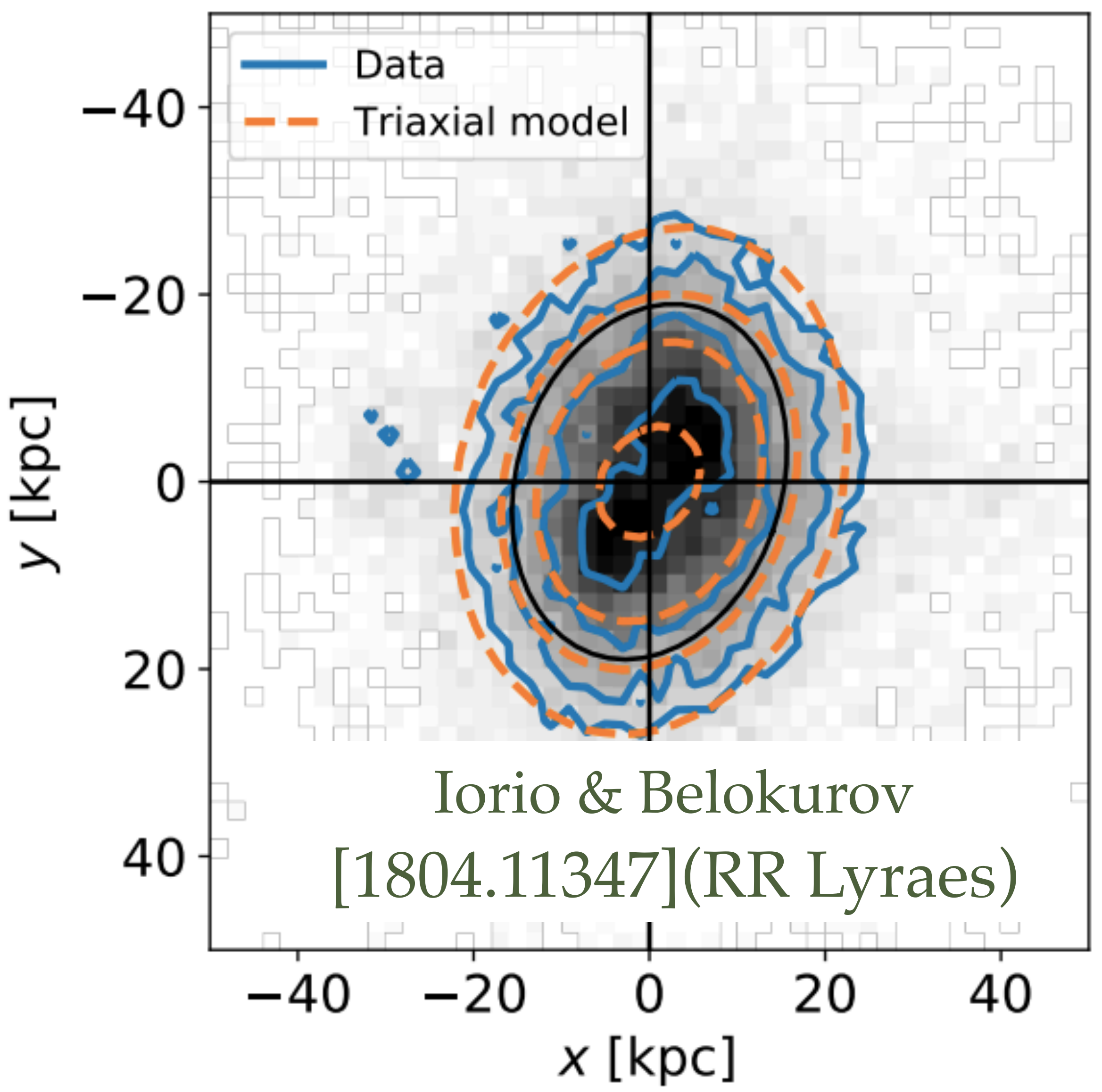
Triaxial axis ratio
10 : 7.9 : 4.5
Major axis at ~35°
from disk plane

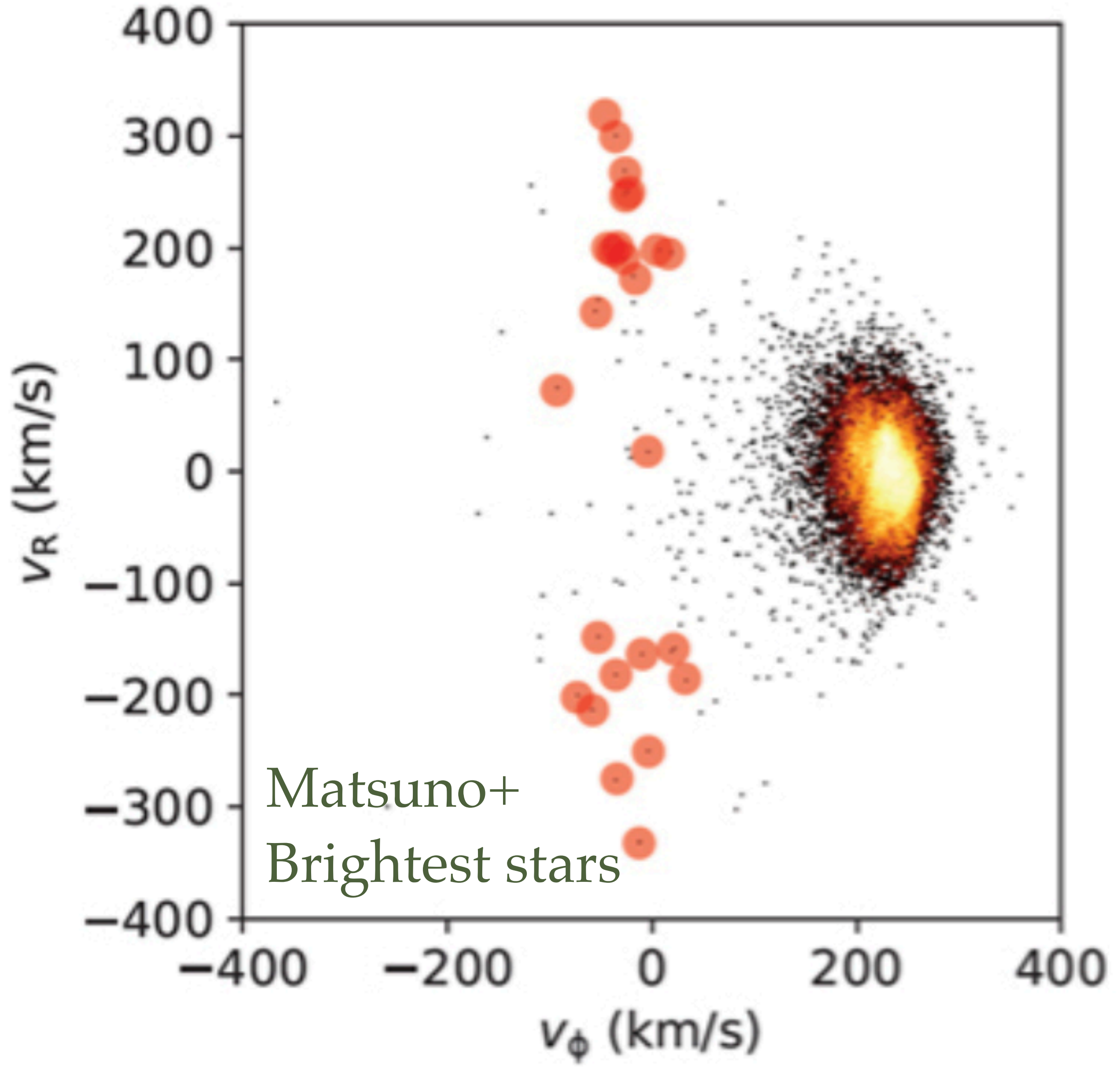
Iorio & Belokurov
2019
10 : 7.9 : 4.5-6.6
~20°

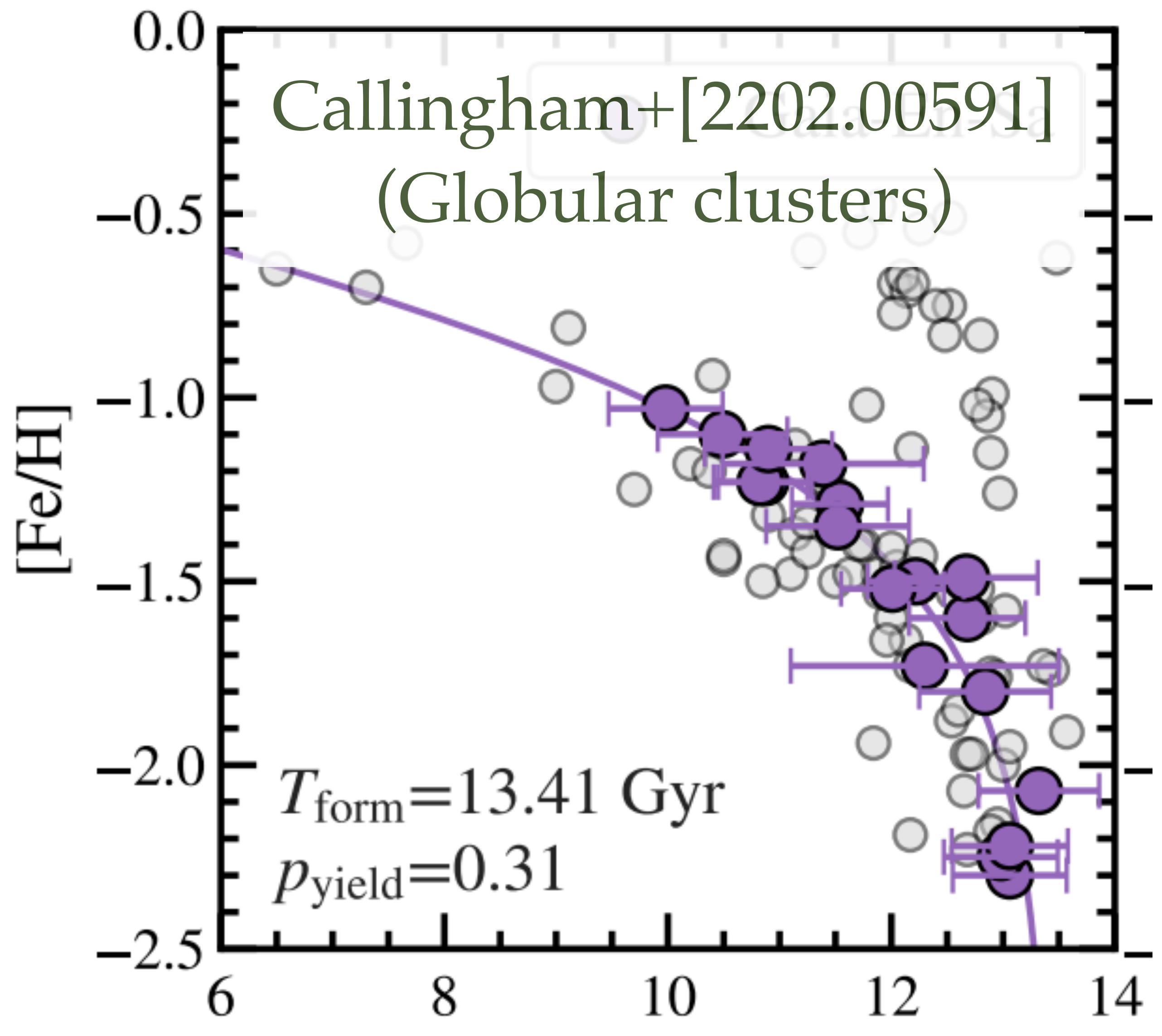


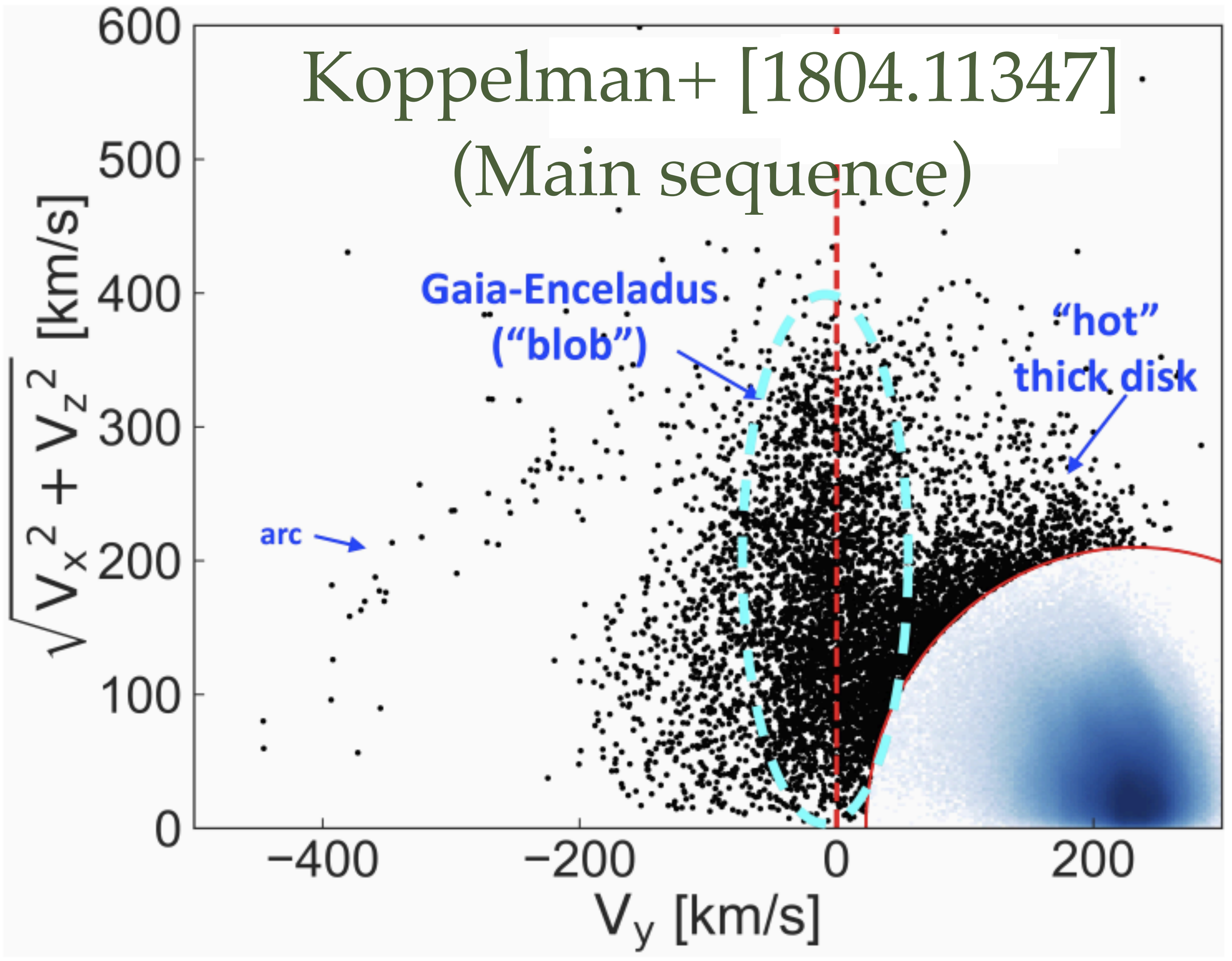
More on the sausage…

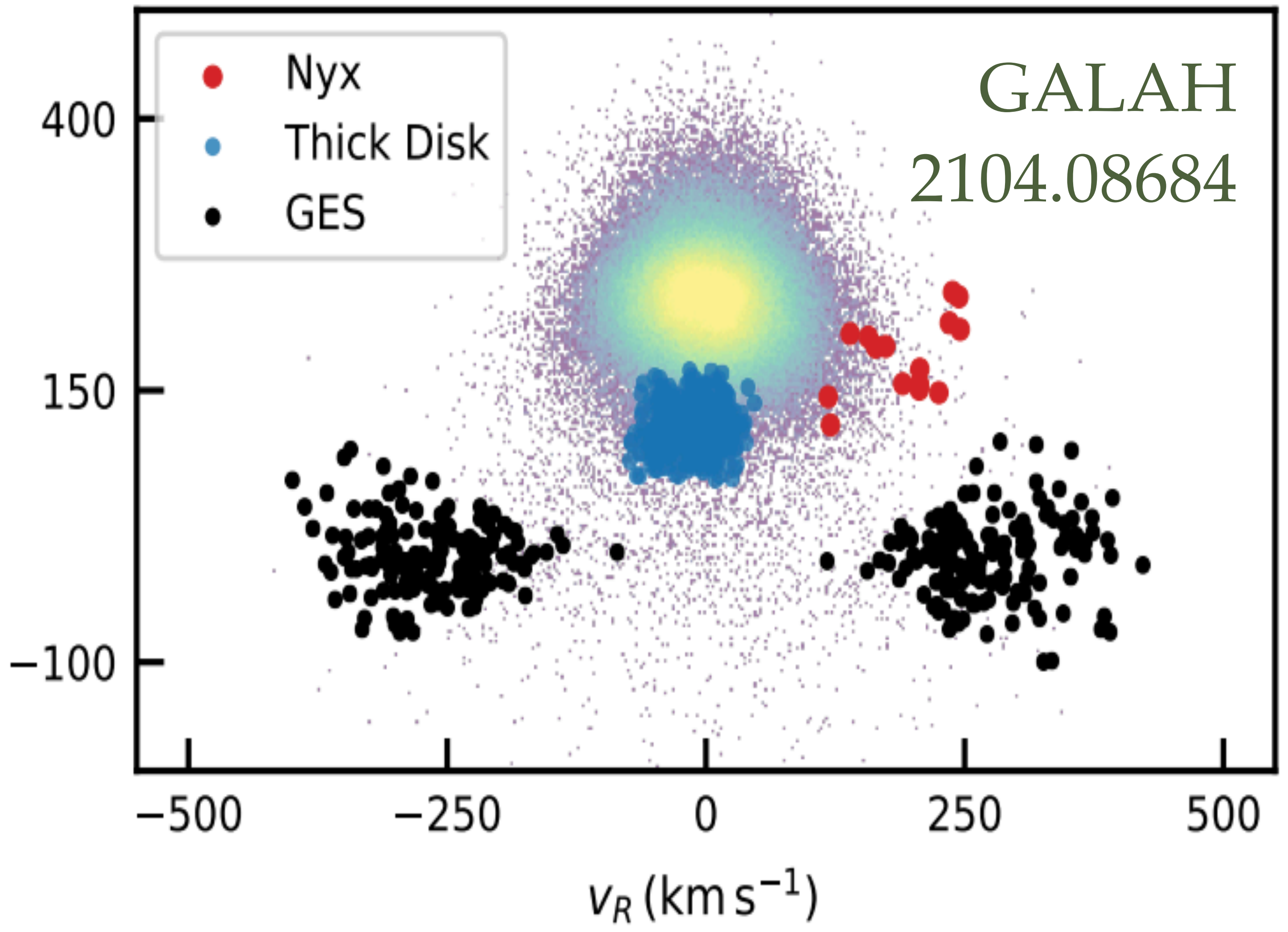












Q: What % of the local dark matter halo is made of sausage?

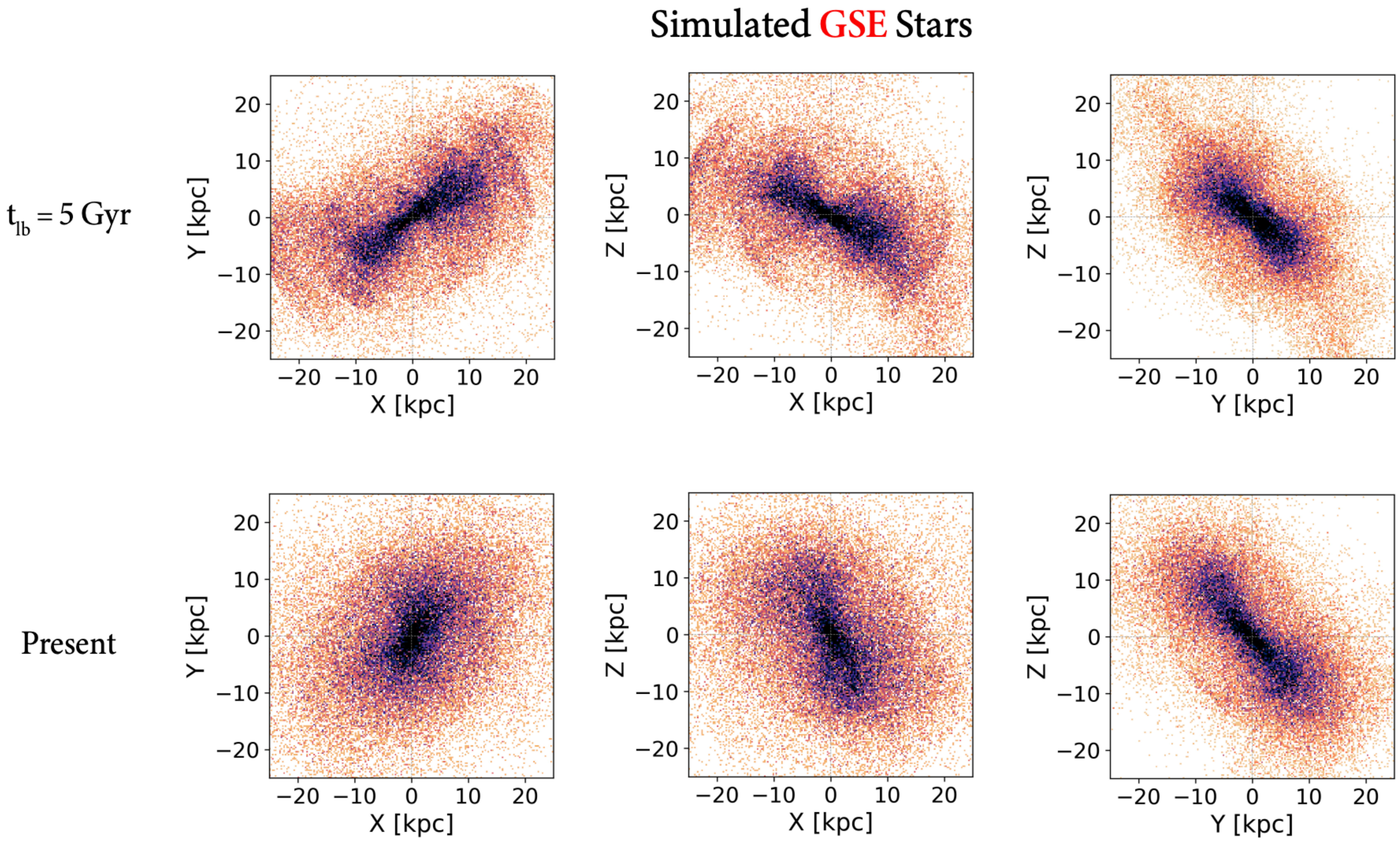
>0% is very likely

- **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)
- **Naidu+[2103.03251]:** suite of bespoke MW-GSE merger simulations reproduce stellar halo well and suggest 10—20% of inner halo is from GSE.

There are upper bounds however:

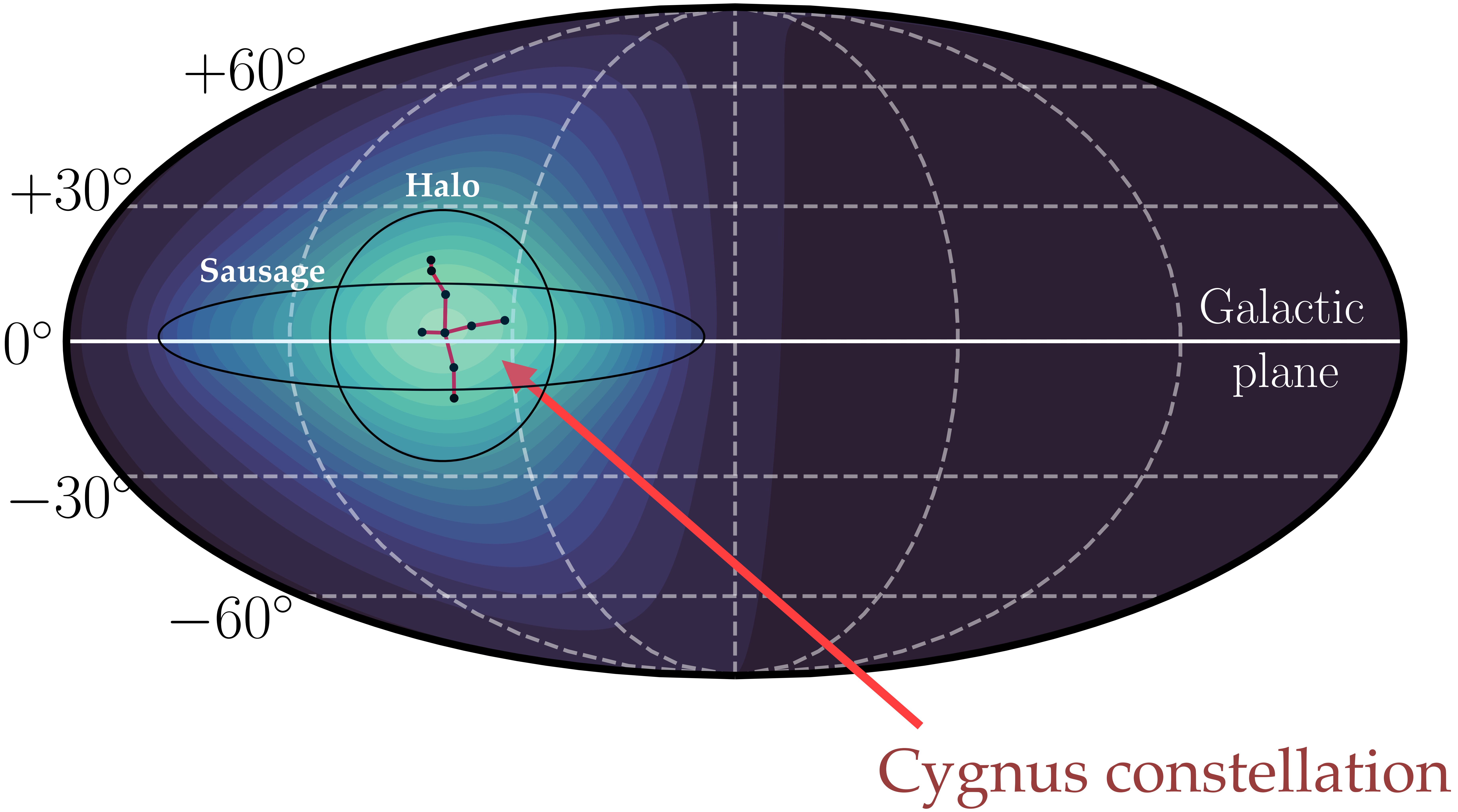
- **Fattahi+ [1810.07779]:** $\lesssim$ 10% of local DM within 20 kpc brought in by Sausage-like events (Auriga sims)
- **Evans+ [1810.11468]:** sphericity of equipotentials means that fraction of halo mass in a triaxial figure should be $\lesssim$ 20%

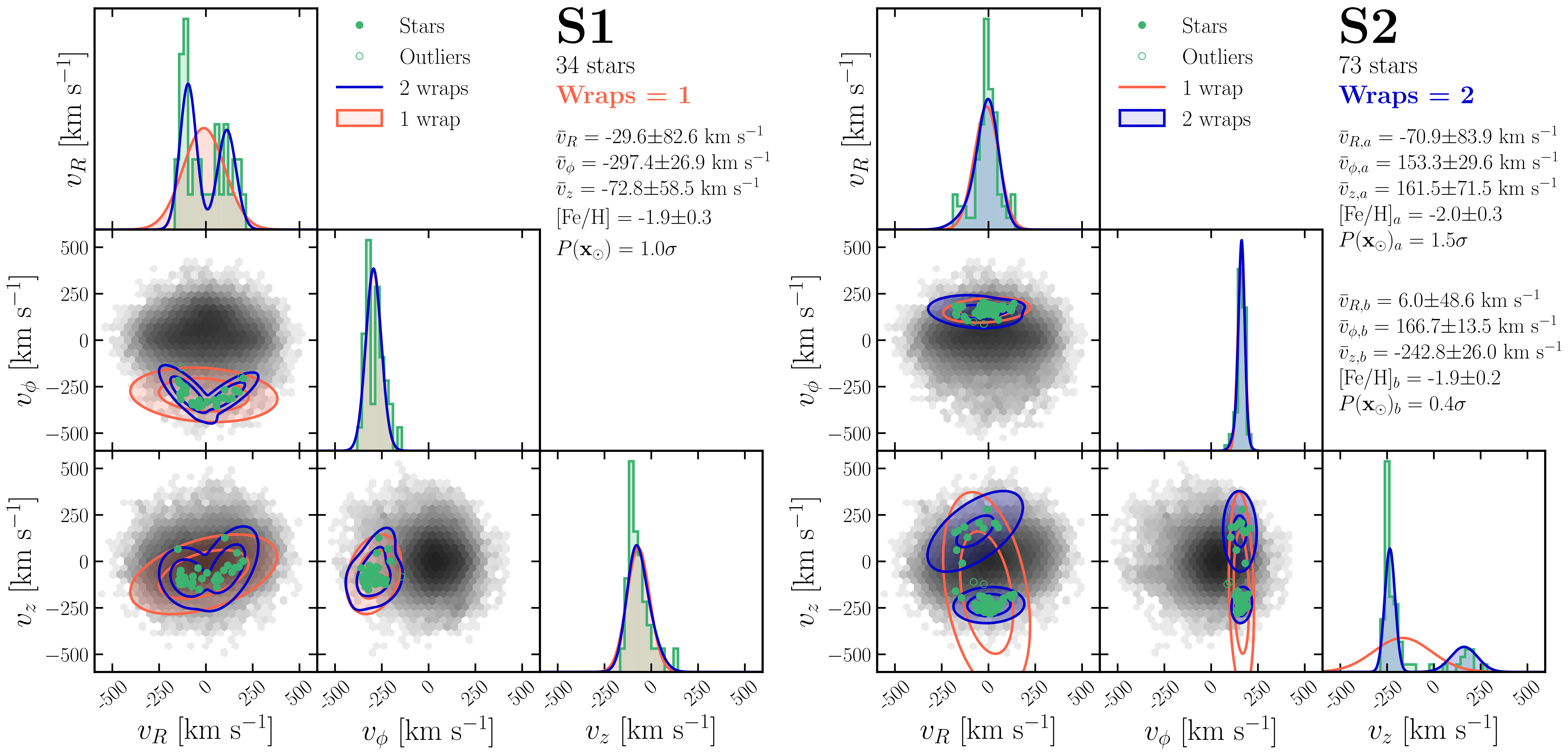
Dark matter halo should have a noticeable tilt due to GSE (seen also in stellar halo via RR Lyraes)



Han+ [2202.07662]

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



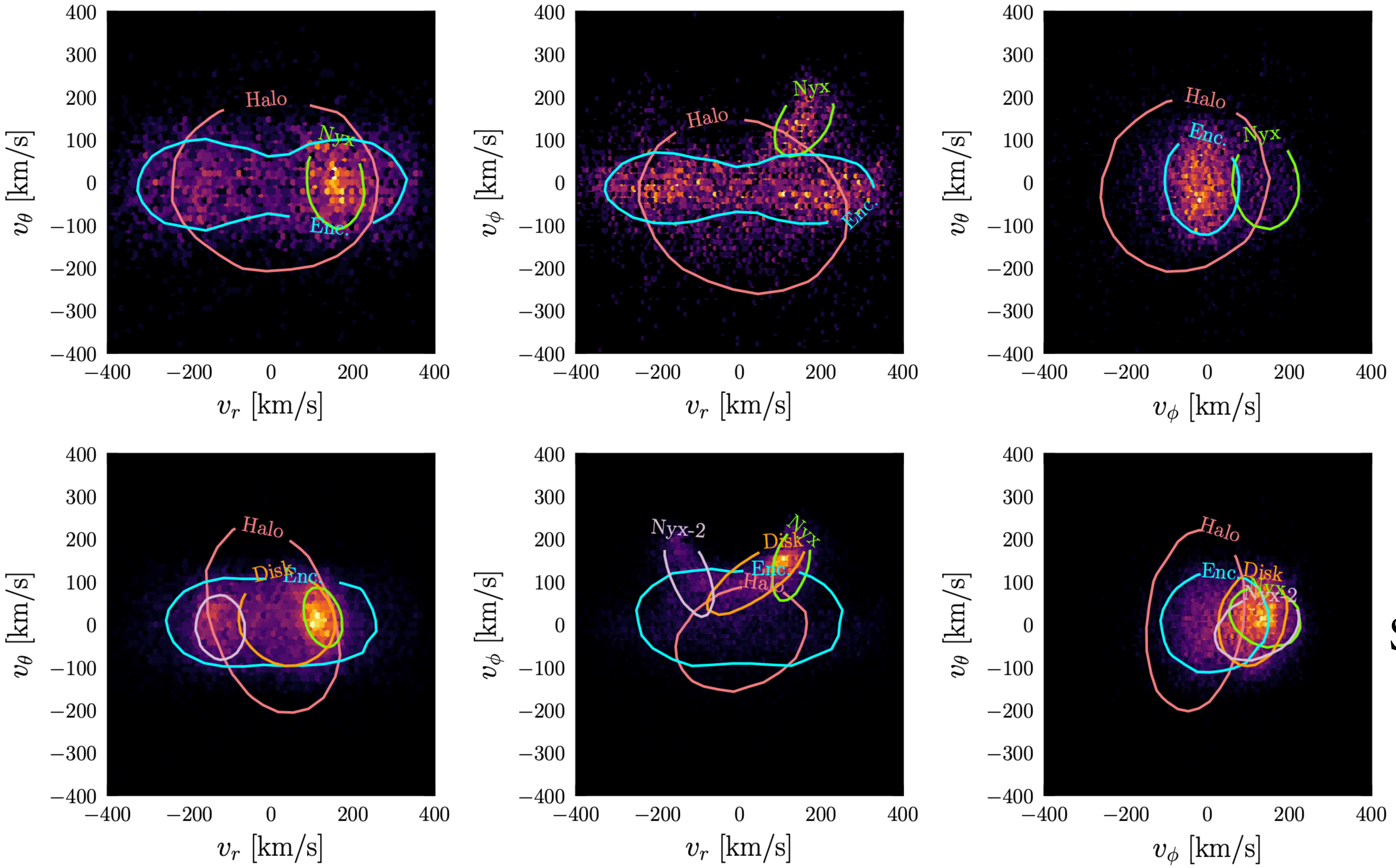


S1
34 stars
Wraps = 1
$\bar{v}_R$ = -29.6±82.6 km s^{-1}
$\bar{v}_\phi$ = -297.4±26.9 km s^{-1}
$\bar{v}_z$ = -72.8±58.5 km s^{-1}
[Fe/H] = -1.9±0.3
$P(\mathbf{x}_\odot) = 1.0\sigma$
Stars
Outliers
2 wraps
1 wrap
S2
73 stars
Wraps = 2
$\bar{v}_{R,a}$ = -70.9±83.9 km s^{-1}
$\bar{v}_{\phi,a}$ = 153.3±29.6 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"

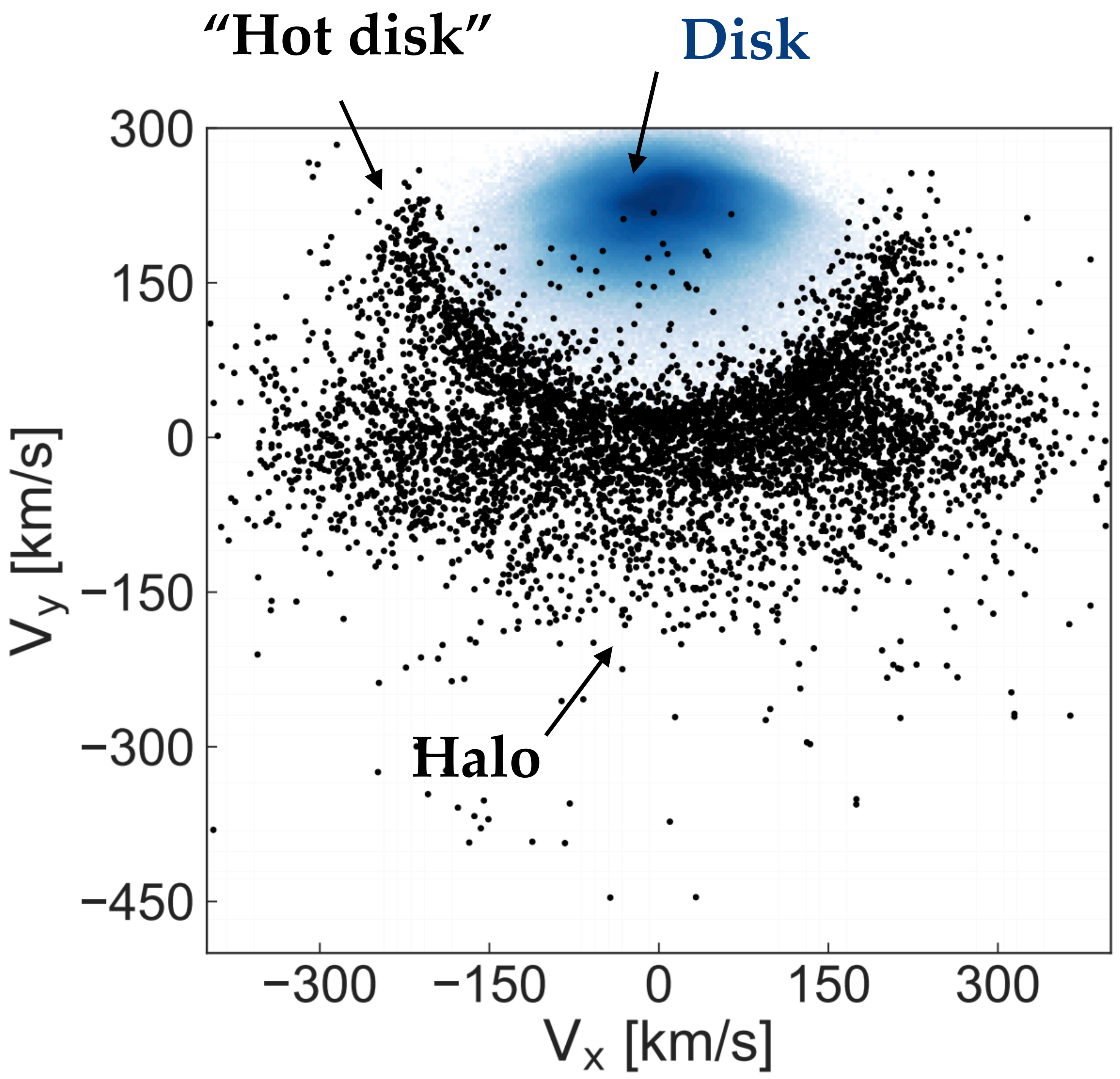
Ostdiek, Necib+ [1907.07681, 1907.07190]



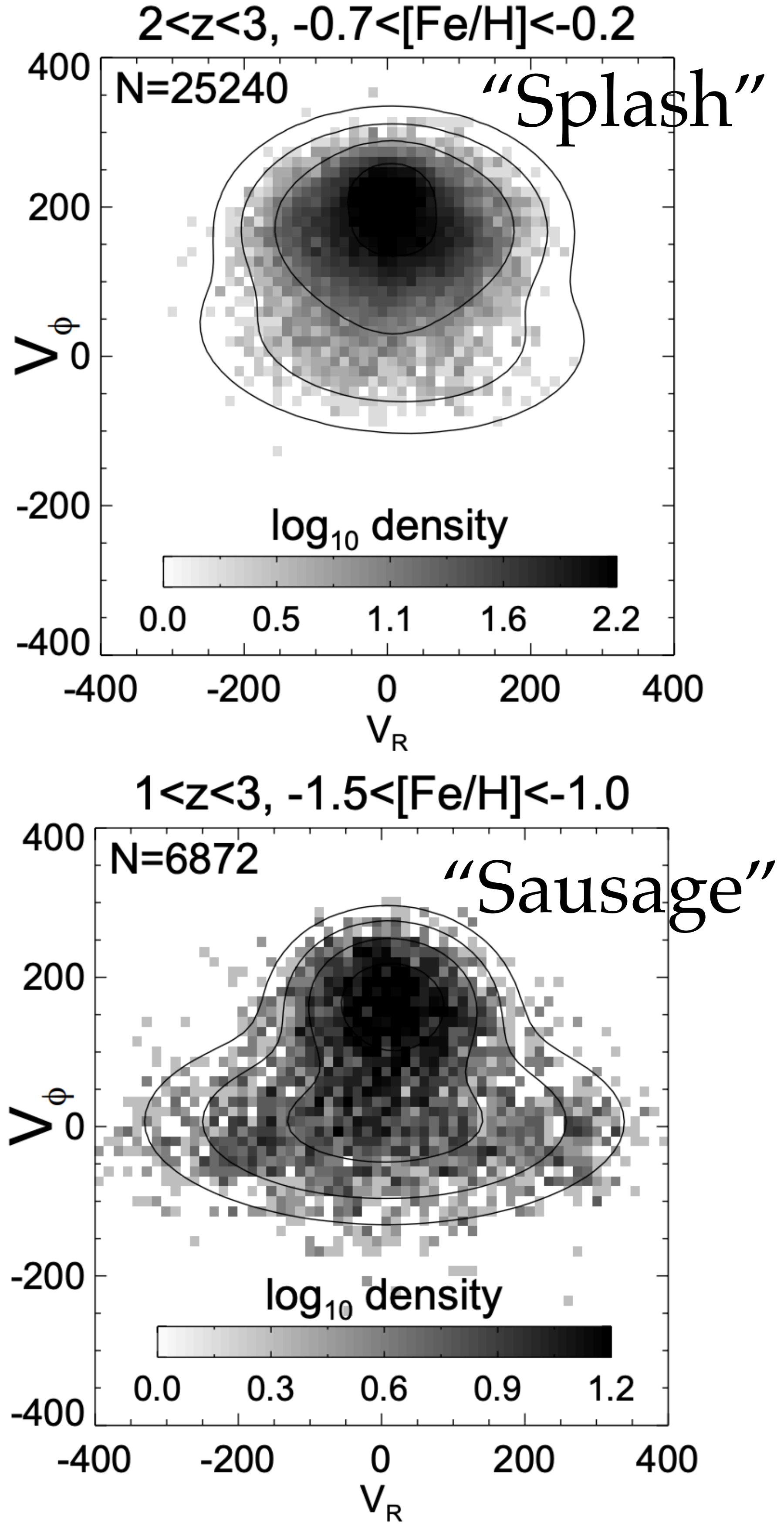
High purity sample

Semi-pure sample

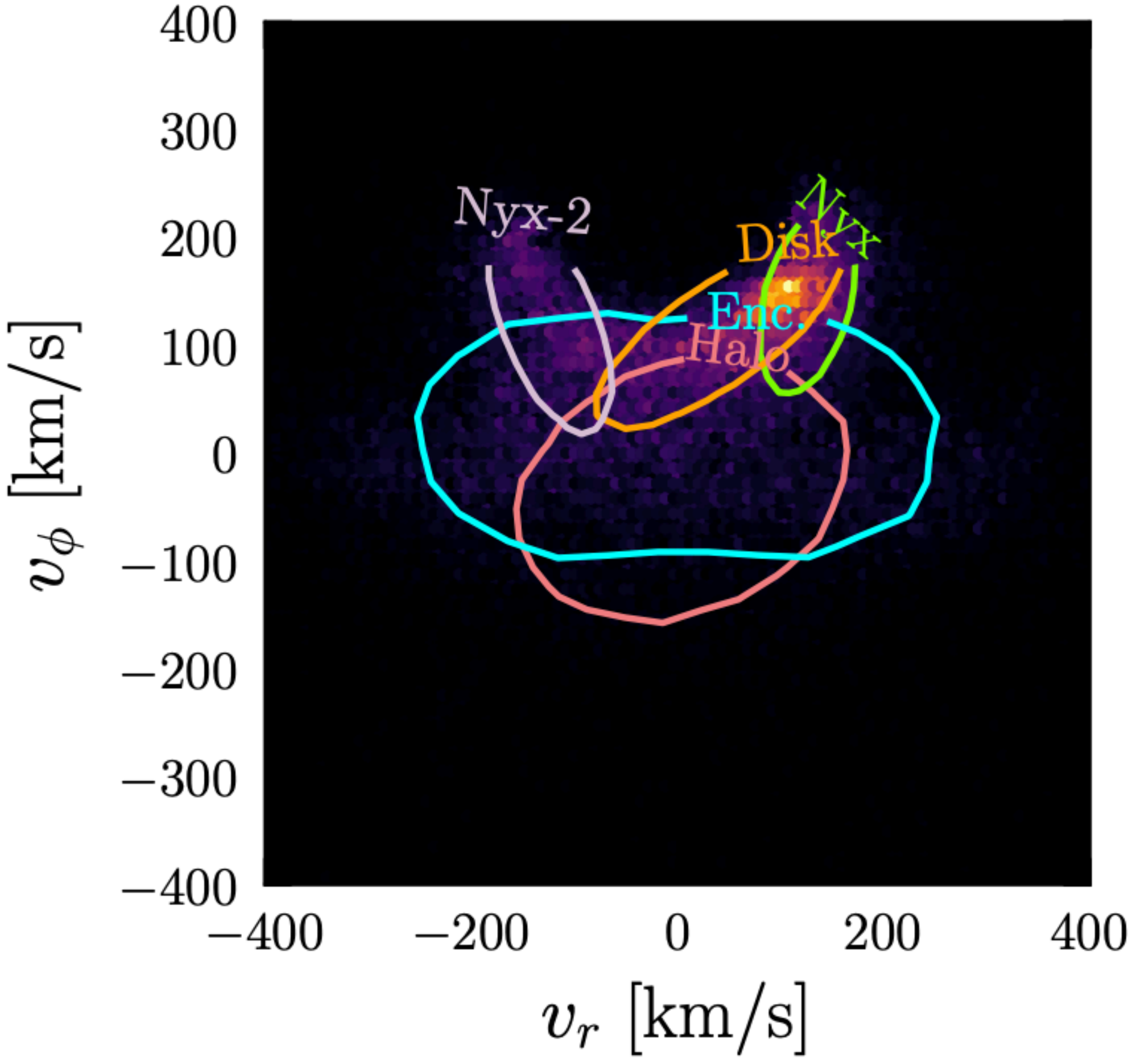
From Helmi's review of substructure in the MW [2002.04340]



Belokurov et al. [1909.04679]

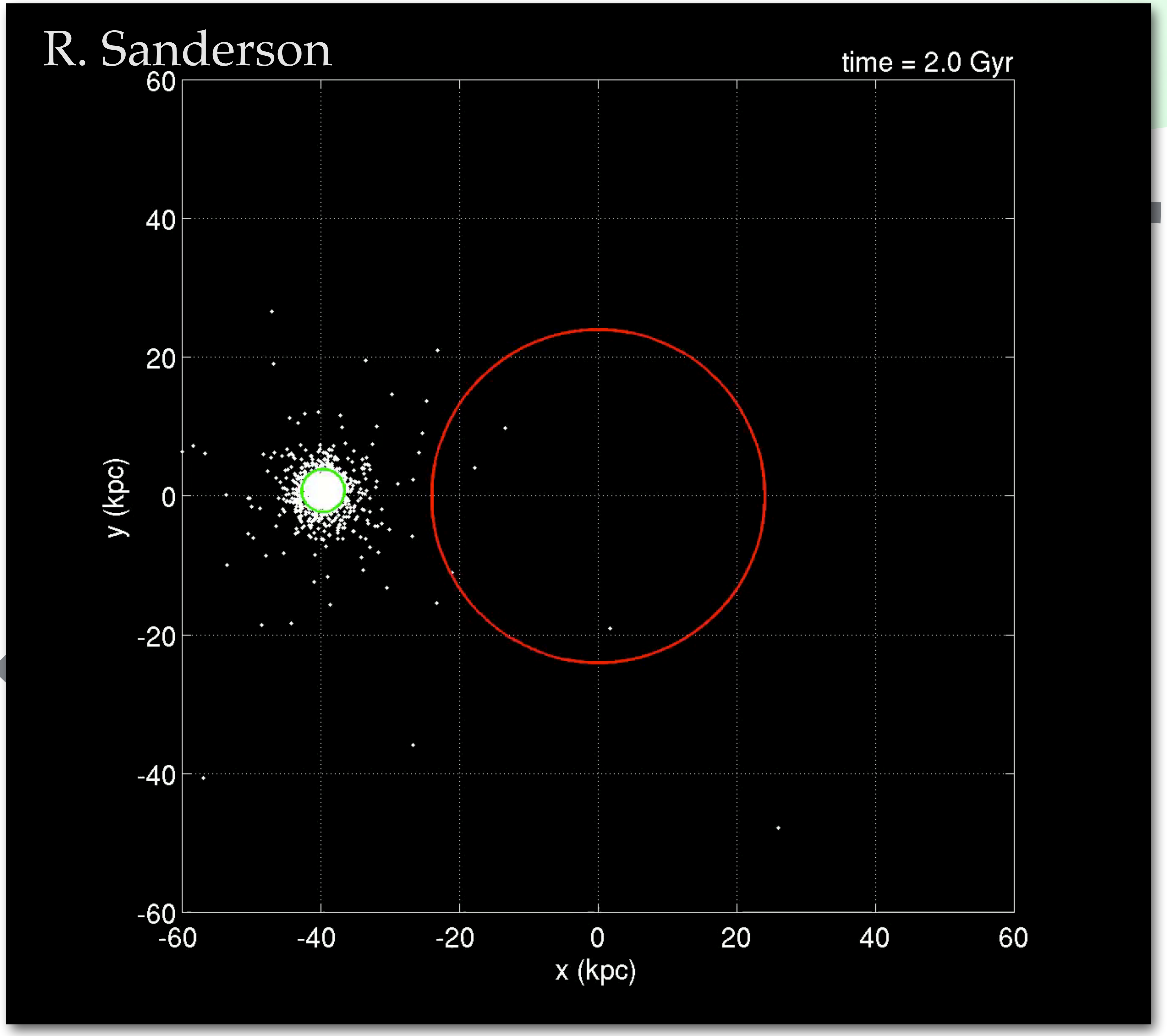


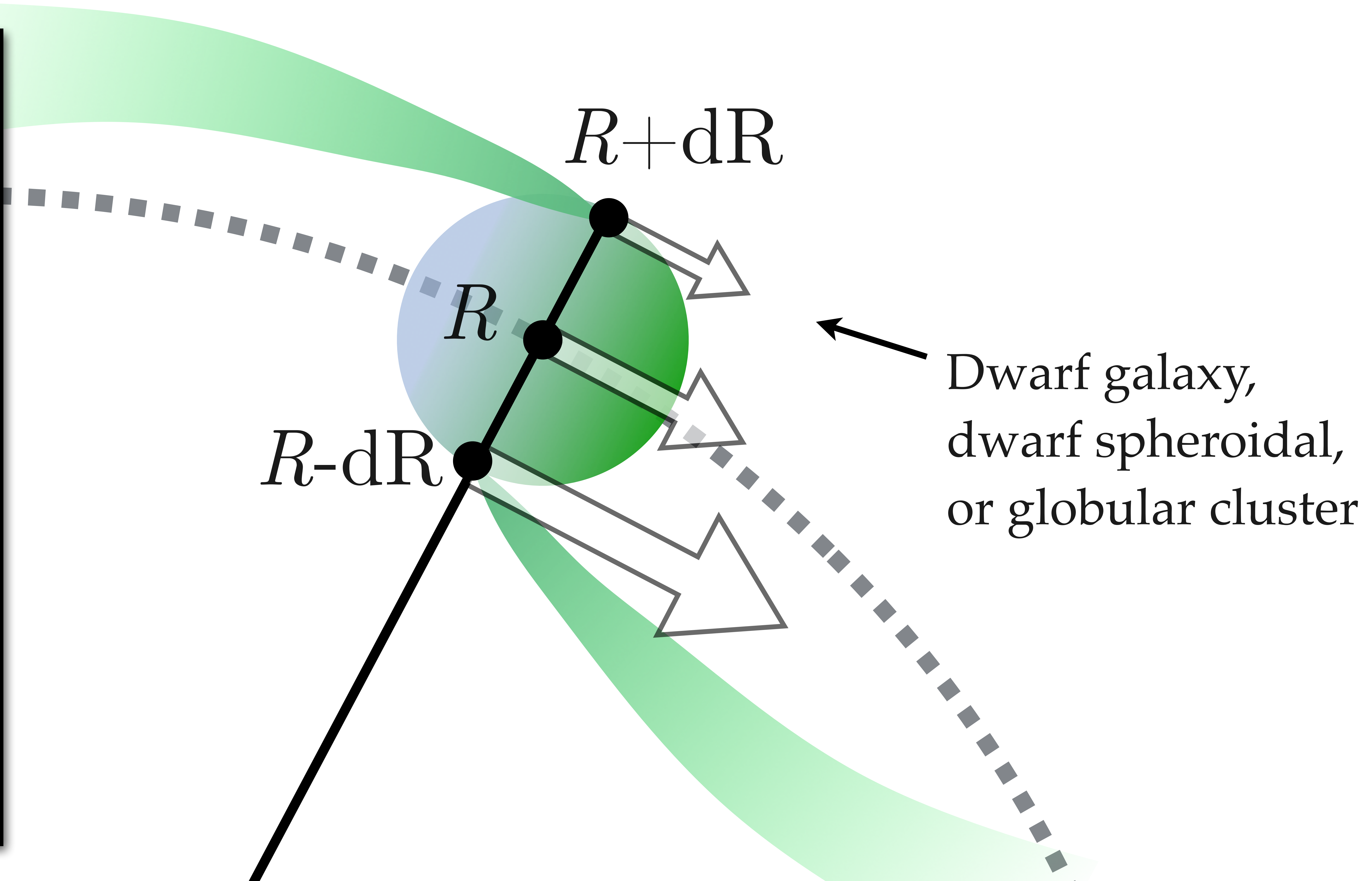
Nyx stream



Forming tidal streams

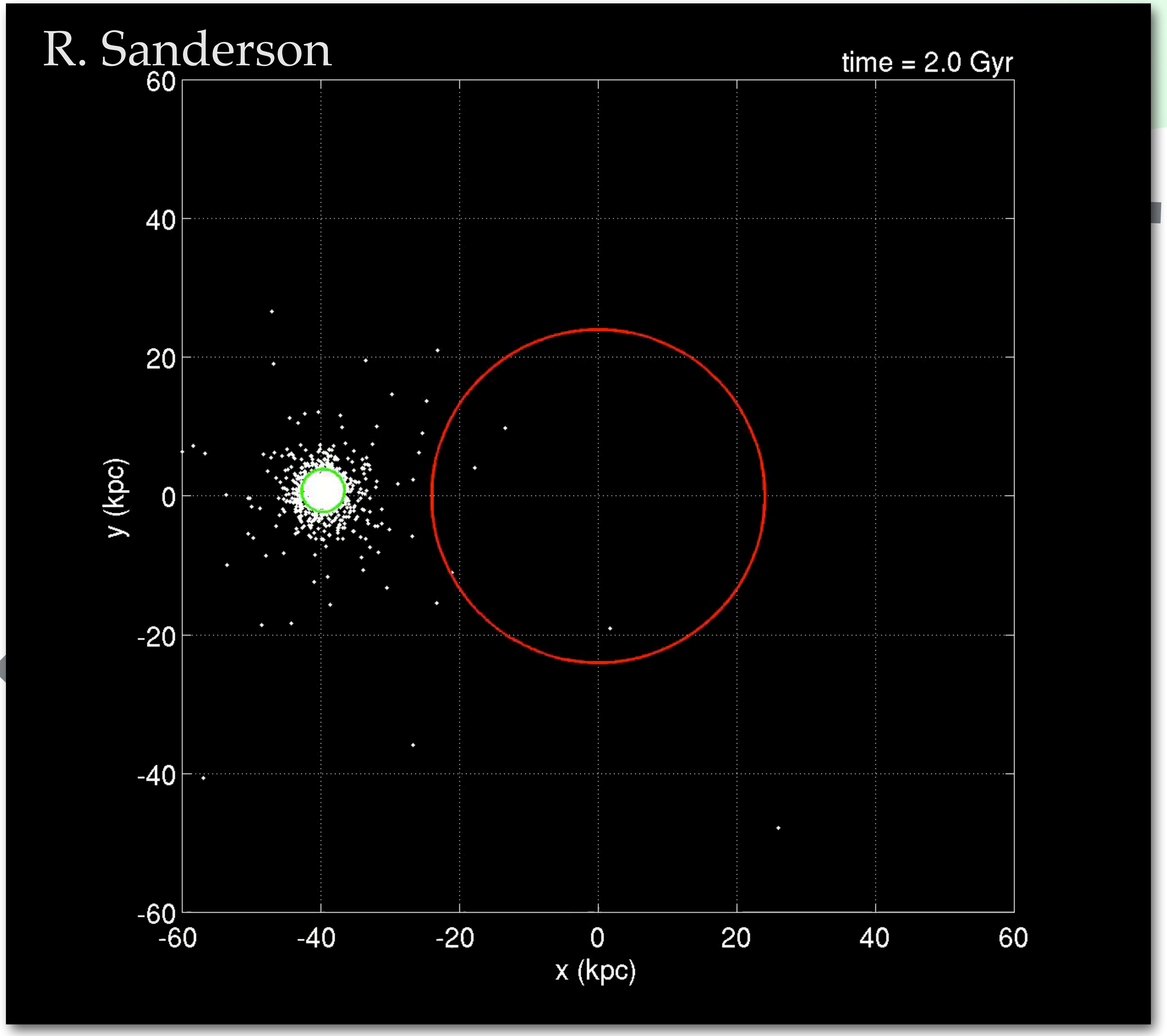
Satellite is pulled apart when the tidal force across it overcomes its own self-gravity

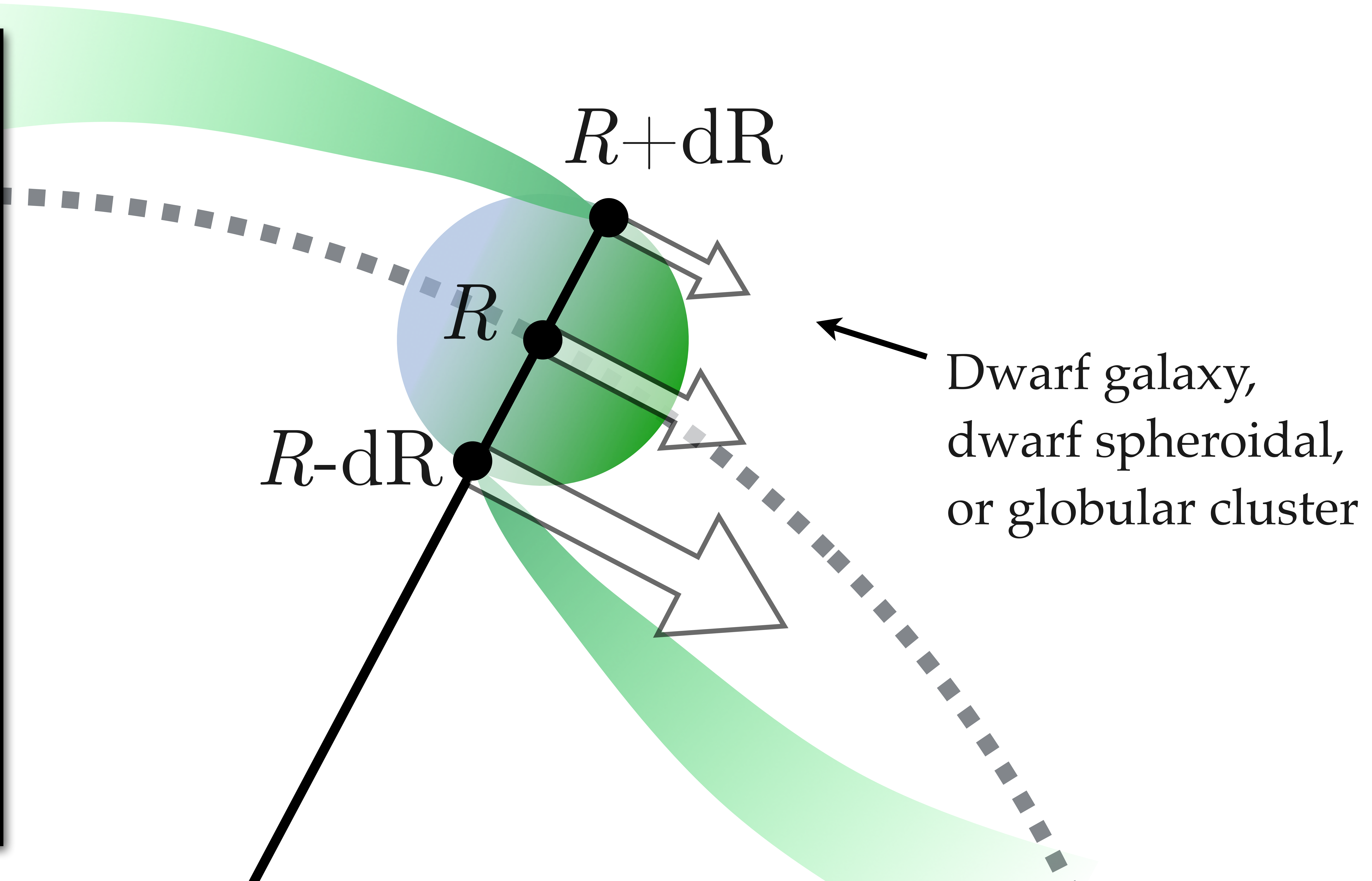




Forming tidal streams

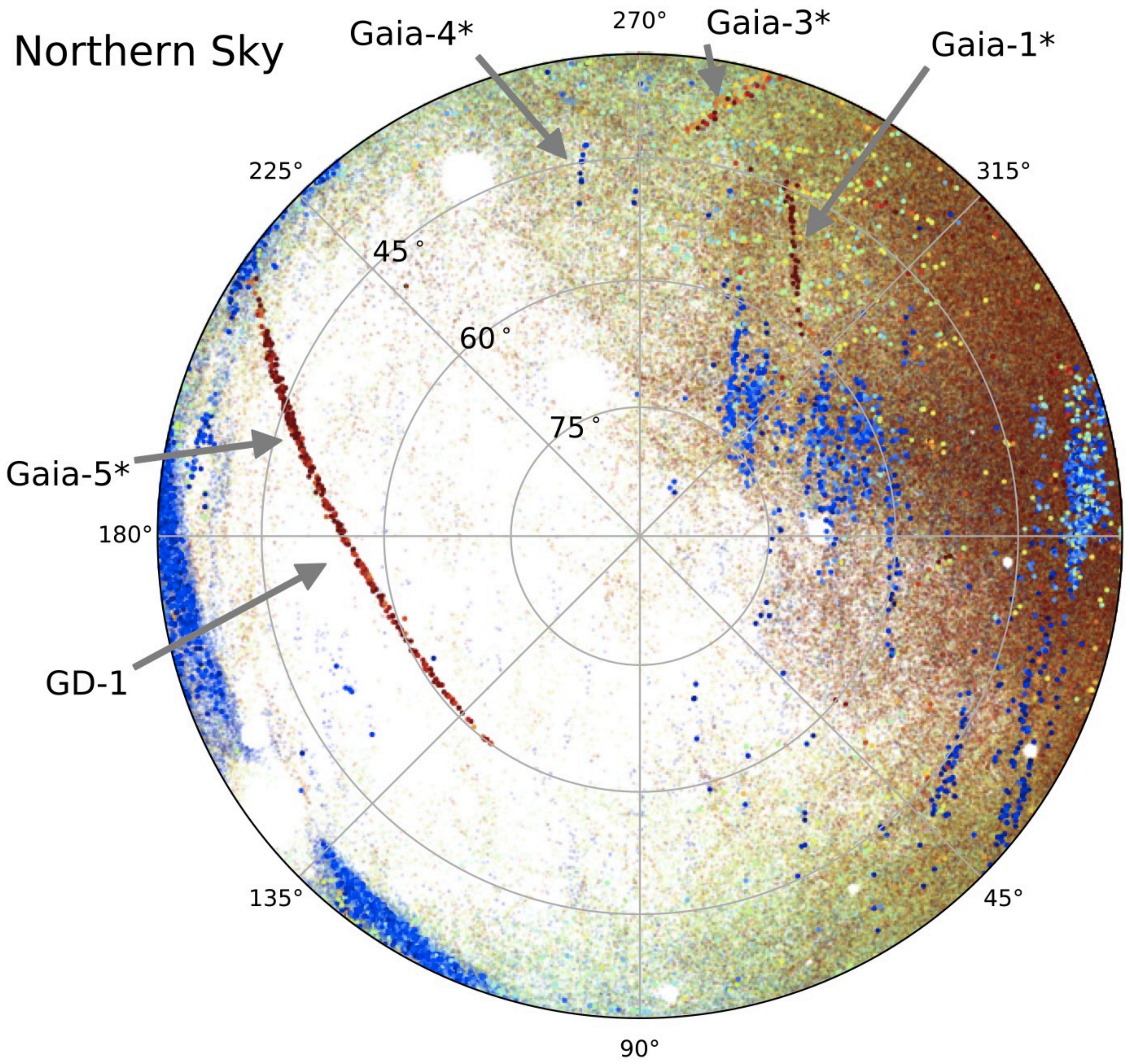
Satellite is pulled apart when the tidal force across it overcomes its own self-gravity



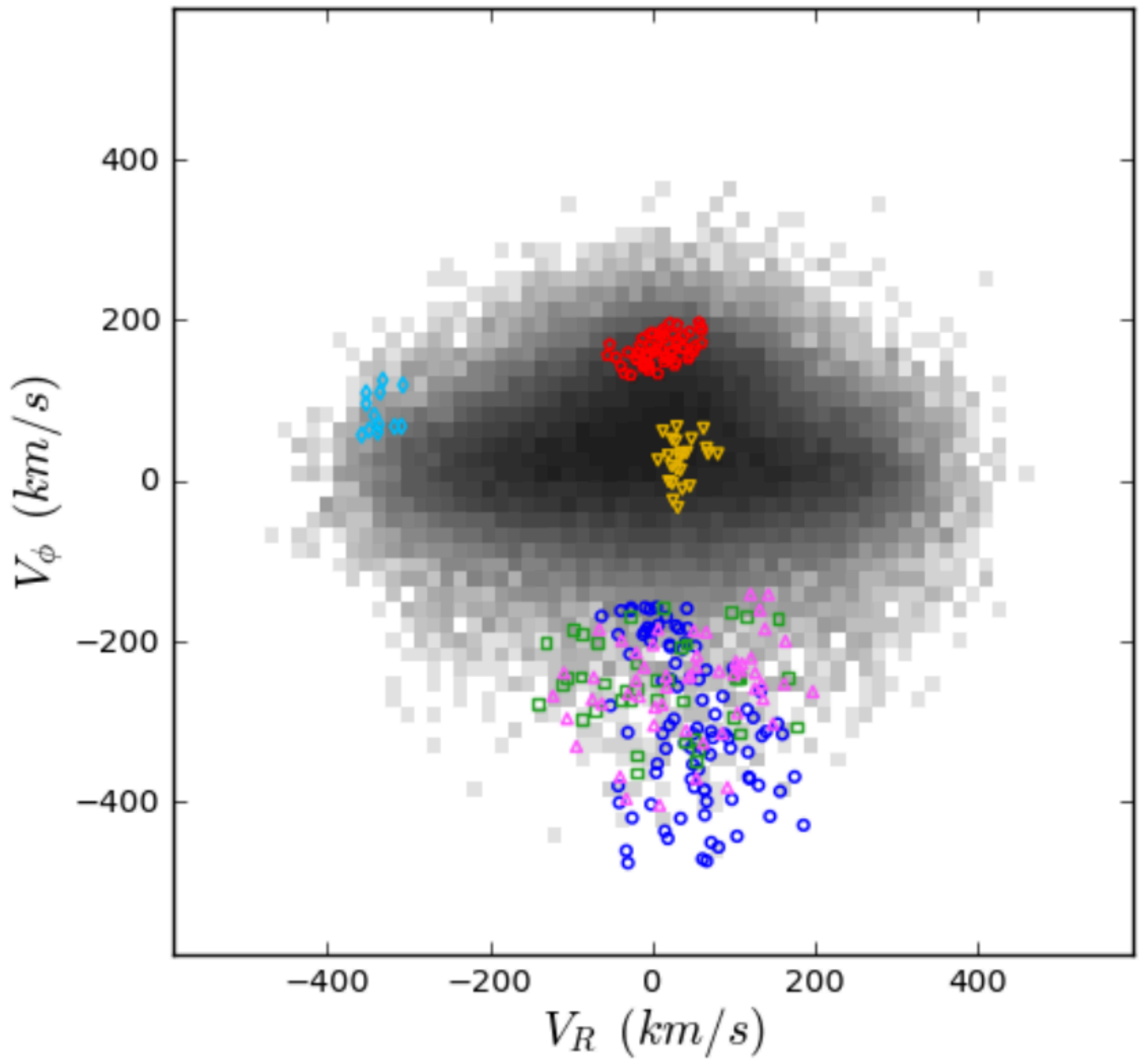


Finding streams

- 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

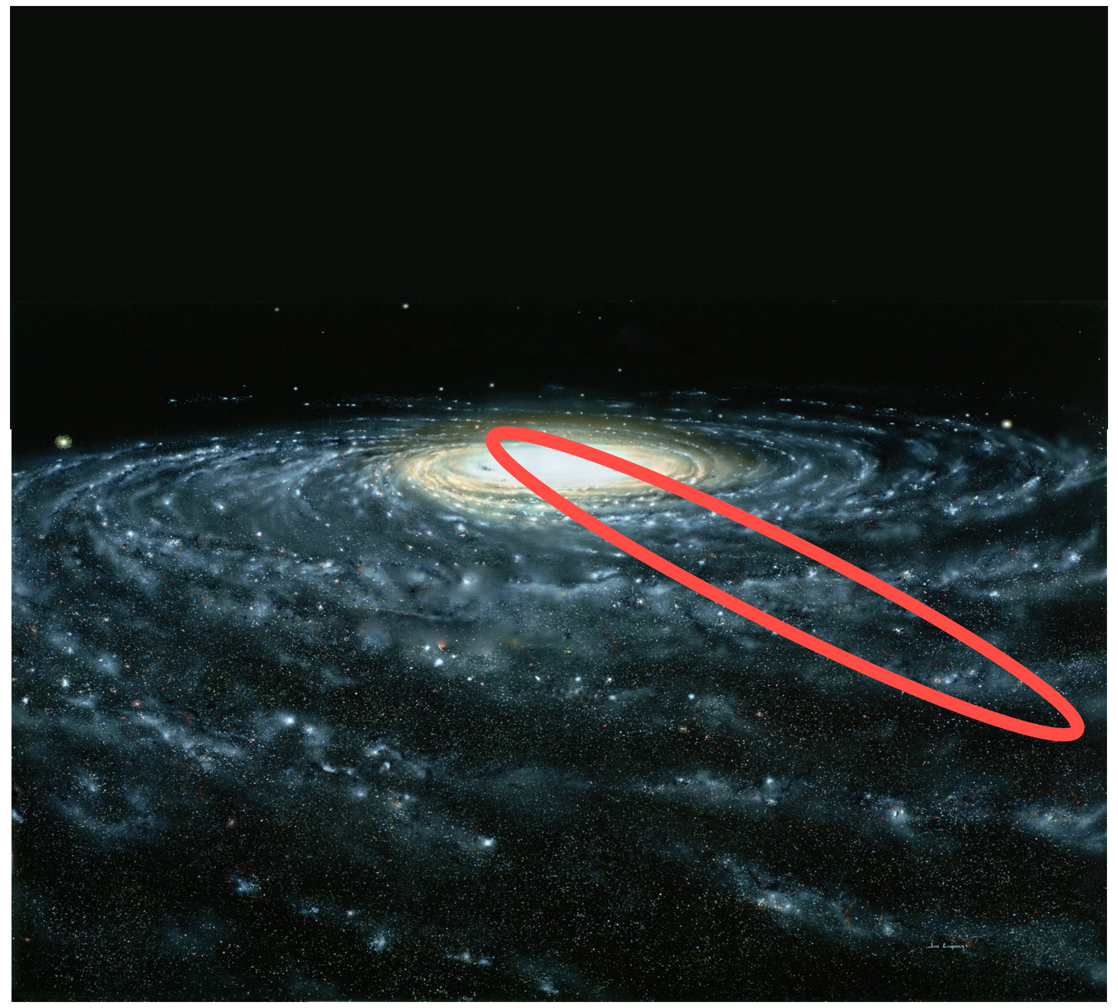
Each star sits at a location in 6D (x, y, z, v_x, v_y, v_z)

↓ (integrate orbit assuming grav. potential)

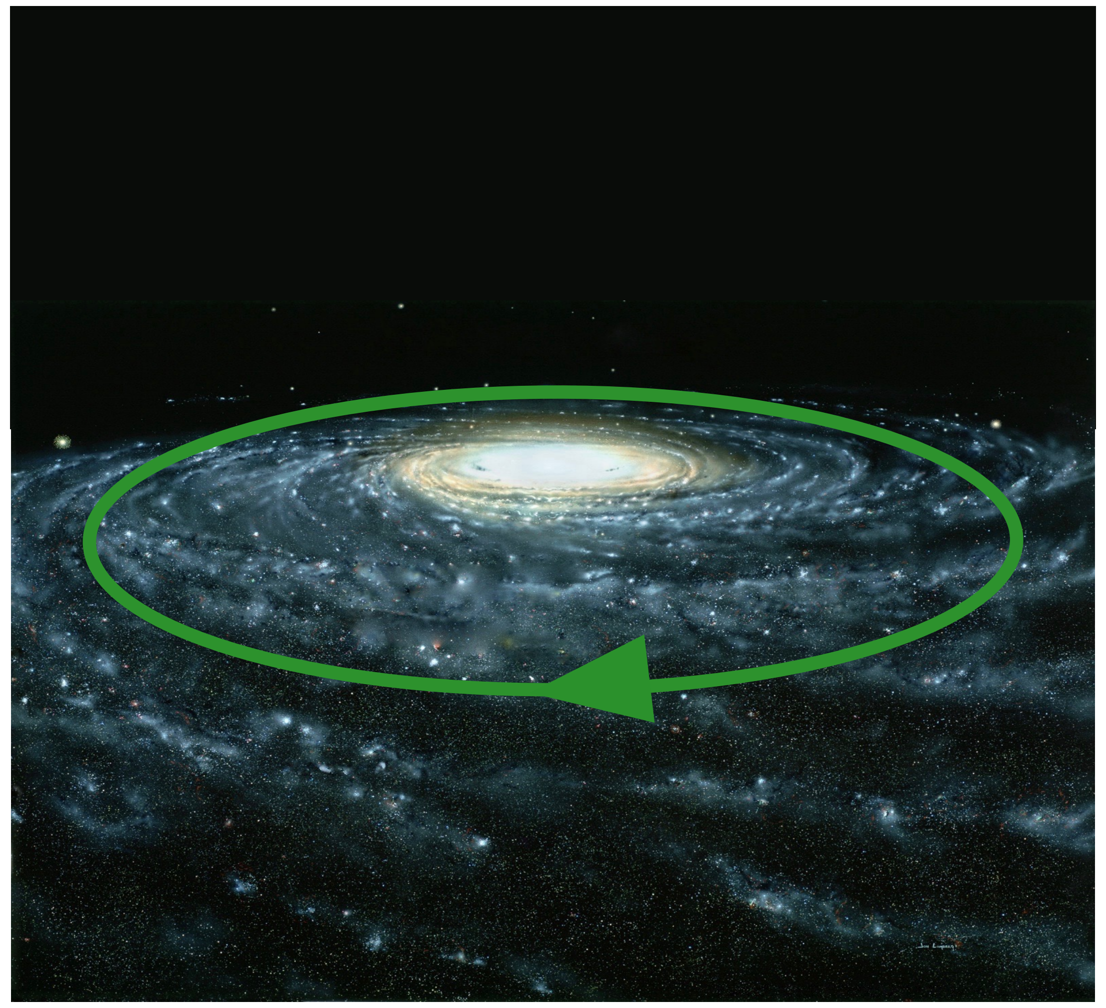
Action space

Stars are locations in 3D space of orbits

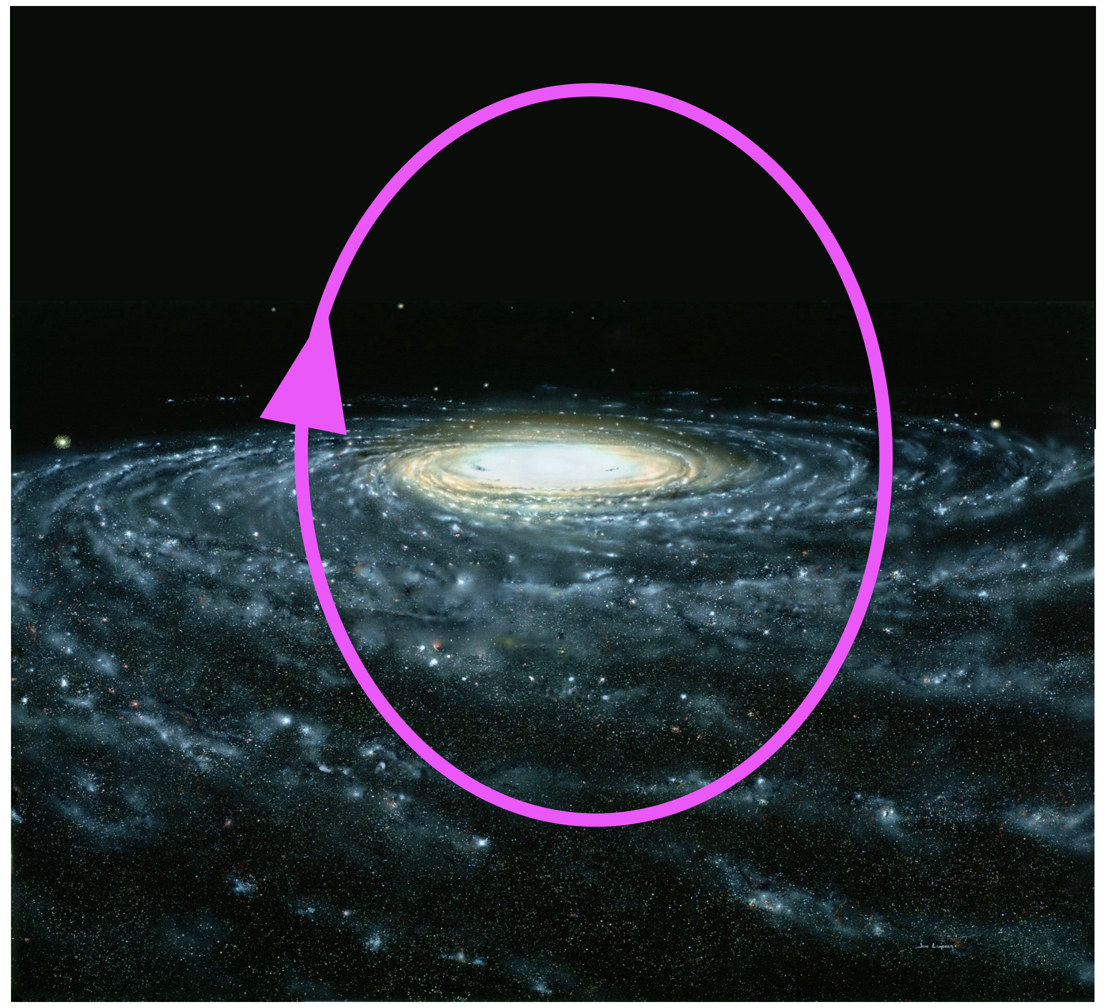
Radial action (J_R)

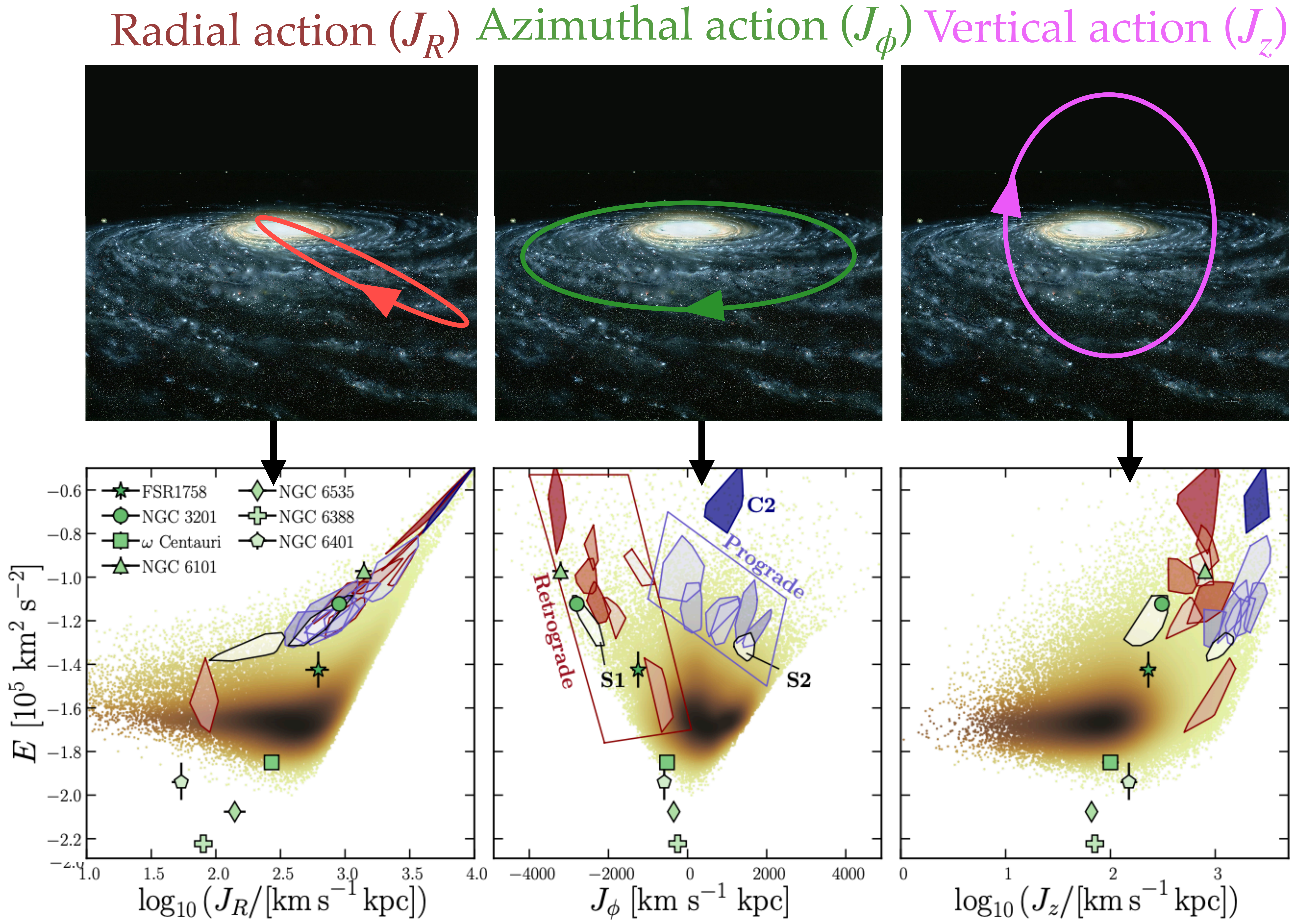


Azimuthal action (J_ϕ)



Vertical action (J_z)

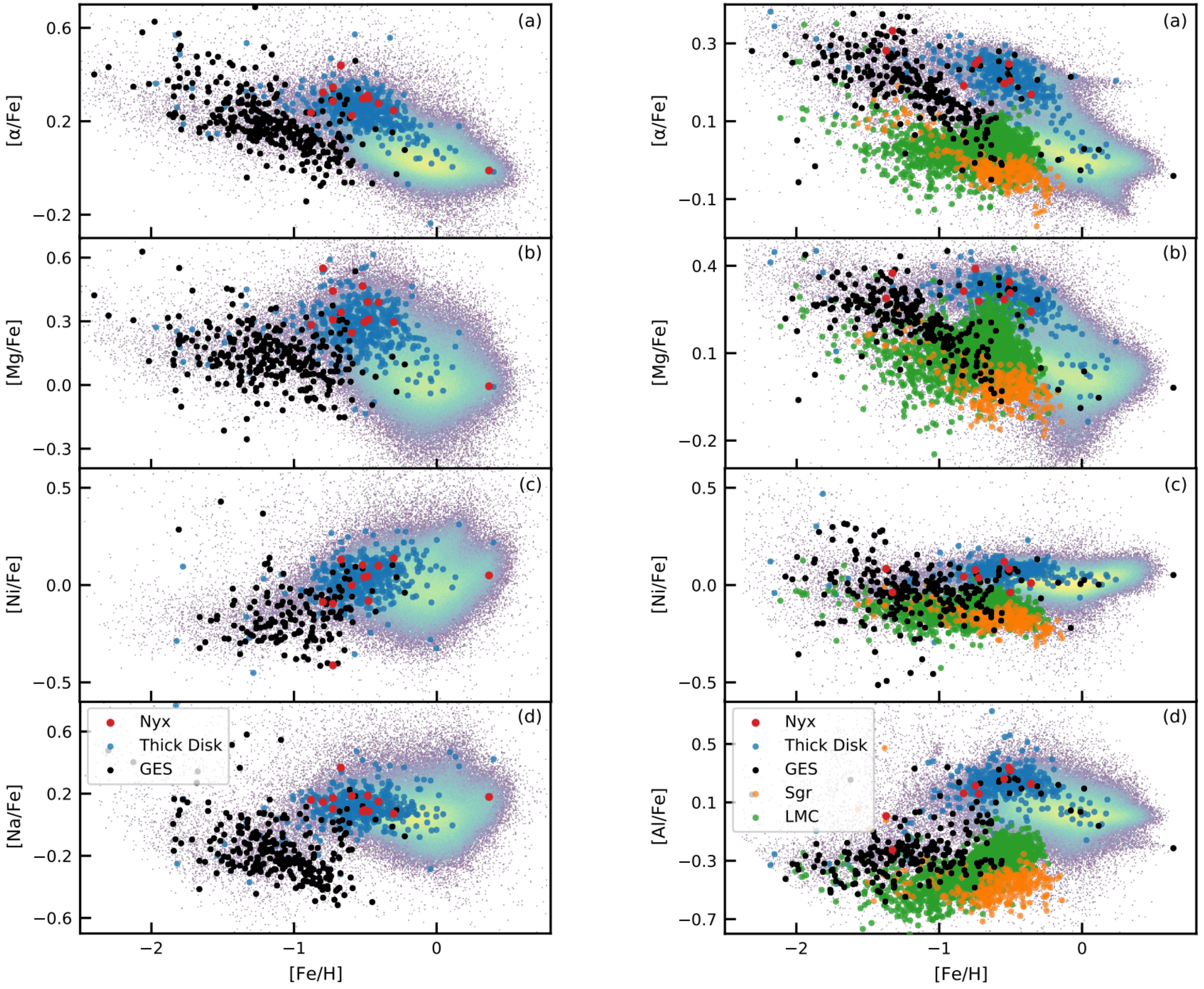




Radial action (J_R)
Azimuthal action (J_ϕ)
Vertical action (J_z)
FSR1758
NGC 3201
ω Centauri
NGC 6101
NGC 6535
NGC 6388
NGC 6401
E [10^5 km^2 s^{-2}]
$\log_{10}(J_R/[\mathrm{km\,s^{-1}\,kpc}])$
C2
Prograde
Retrograde
S1
S2
J_ϕ [km s^{-1} kpc]
$\log_{10}(J_z/[\mathrm{km\,s^{-1}\,kpc}])$

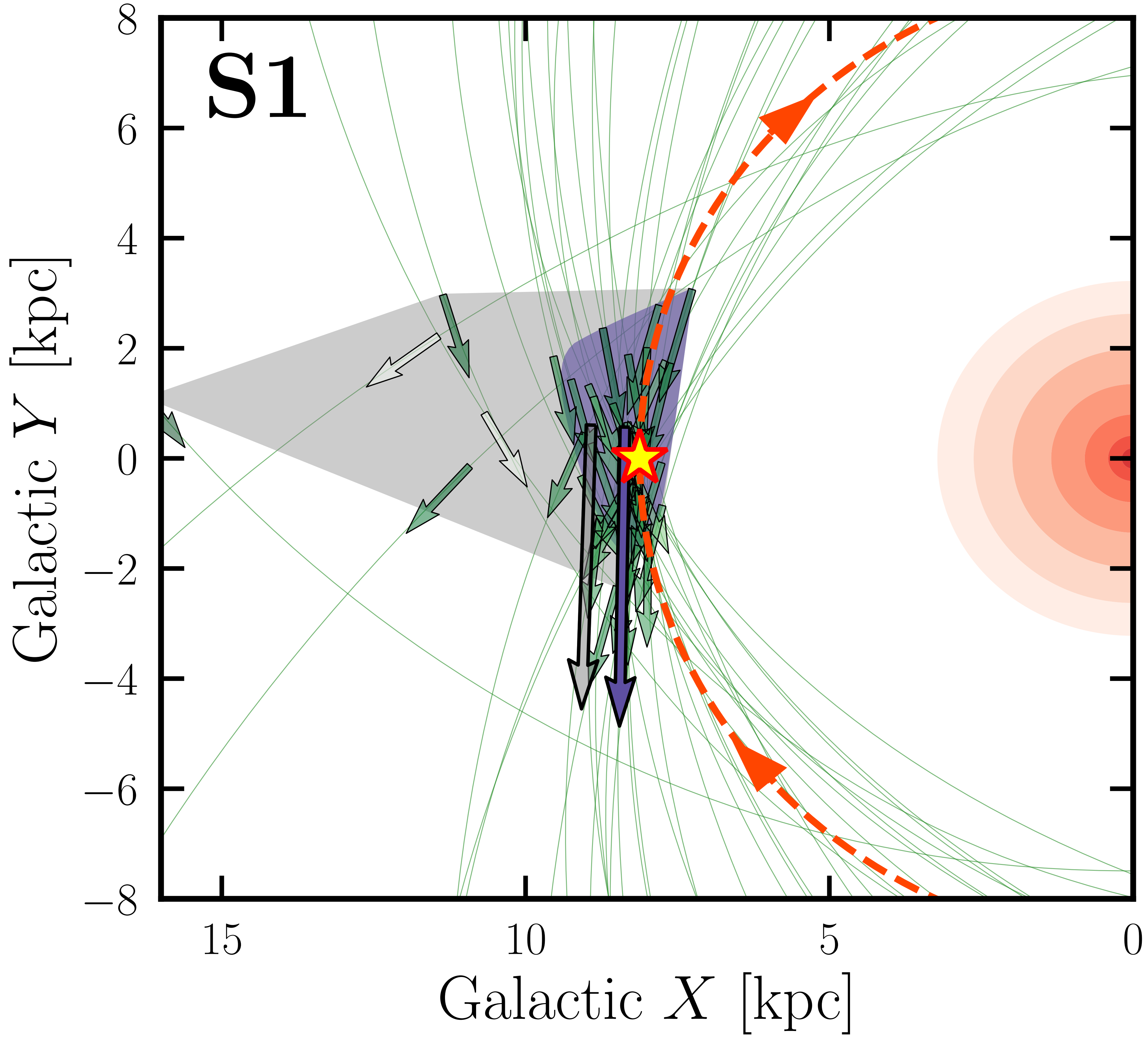
Zucker+ [2104.08684]

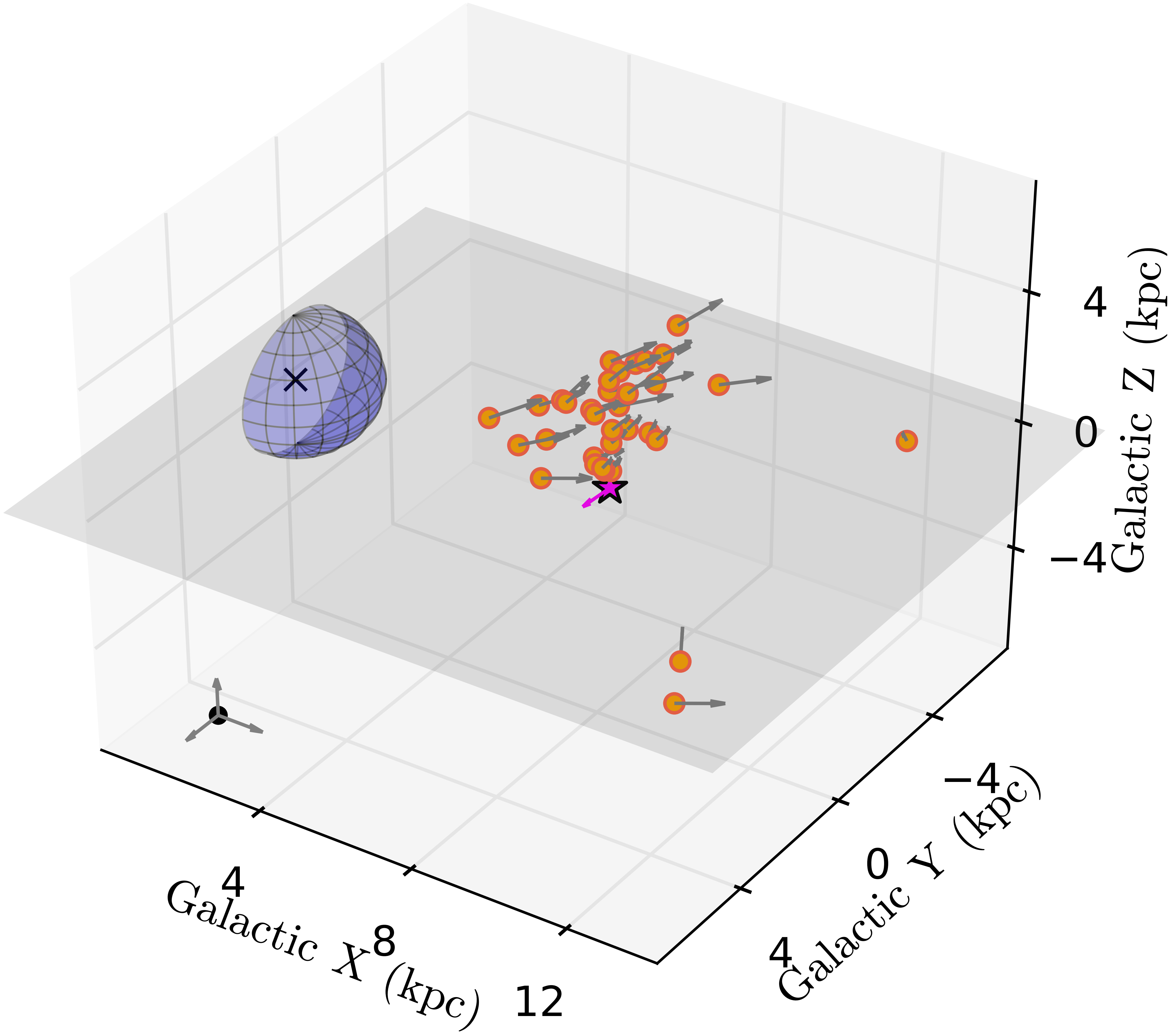
No chemical evidence that Nyx stars are from an accreted dwarf, likely part of the hot-thick disk



S1/Sequoia

O'Hare+ [1909.04684]

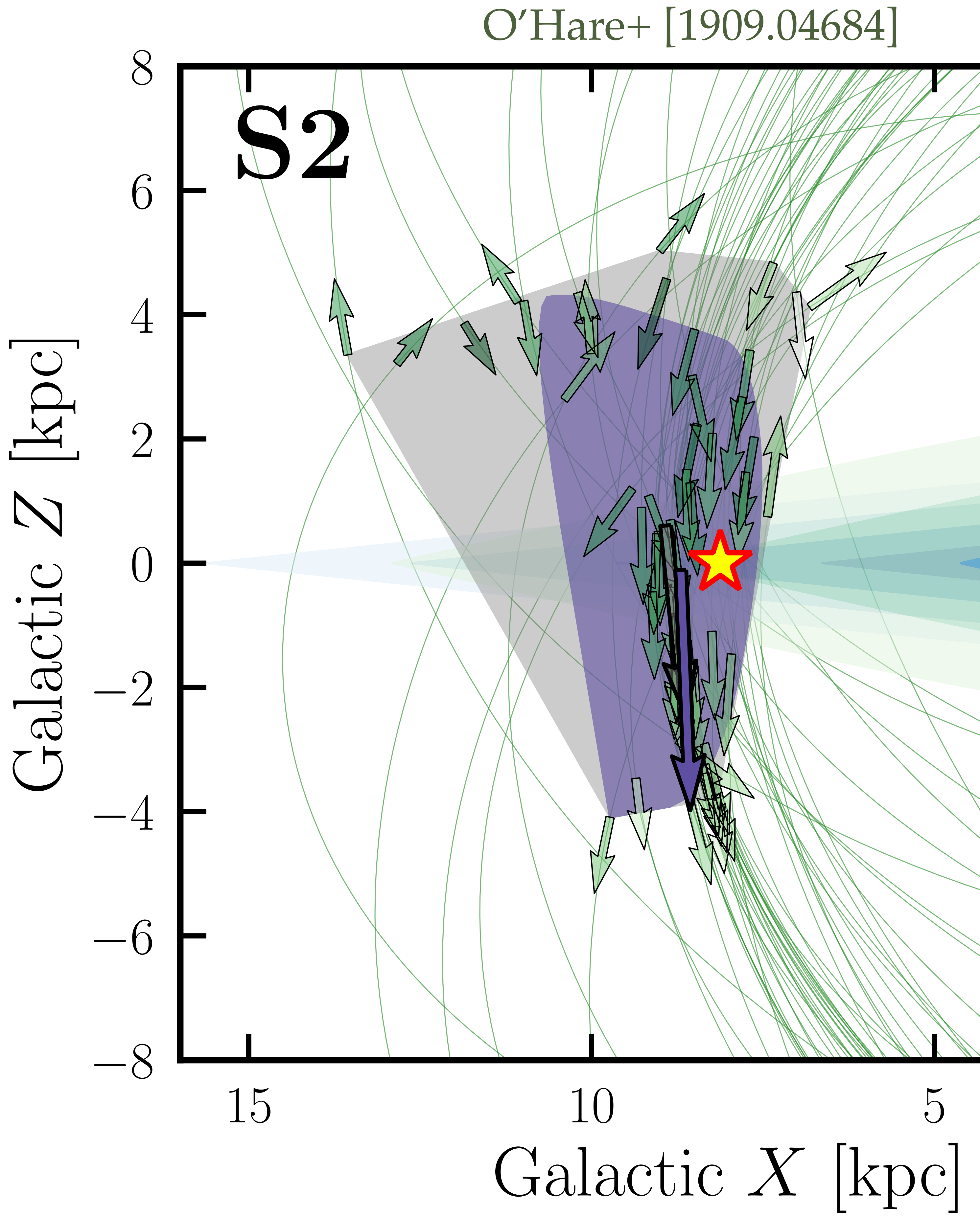


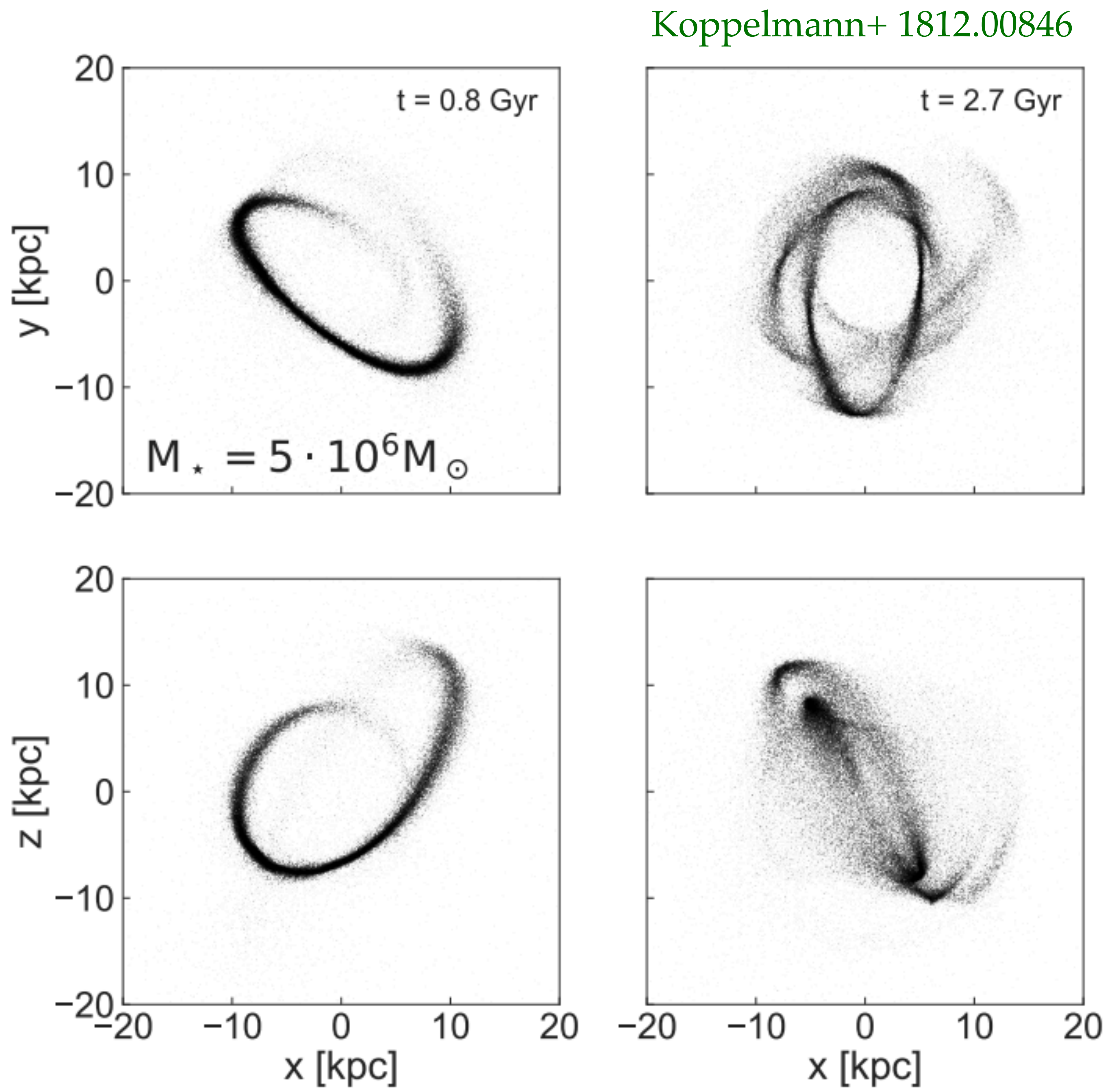


→ High-energy, retrograde-moving material

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

S2/Helmi streams





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

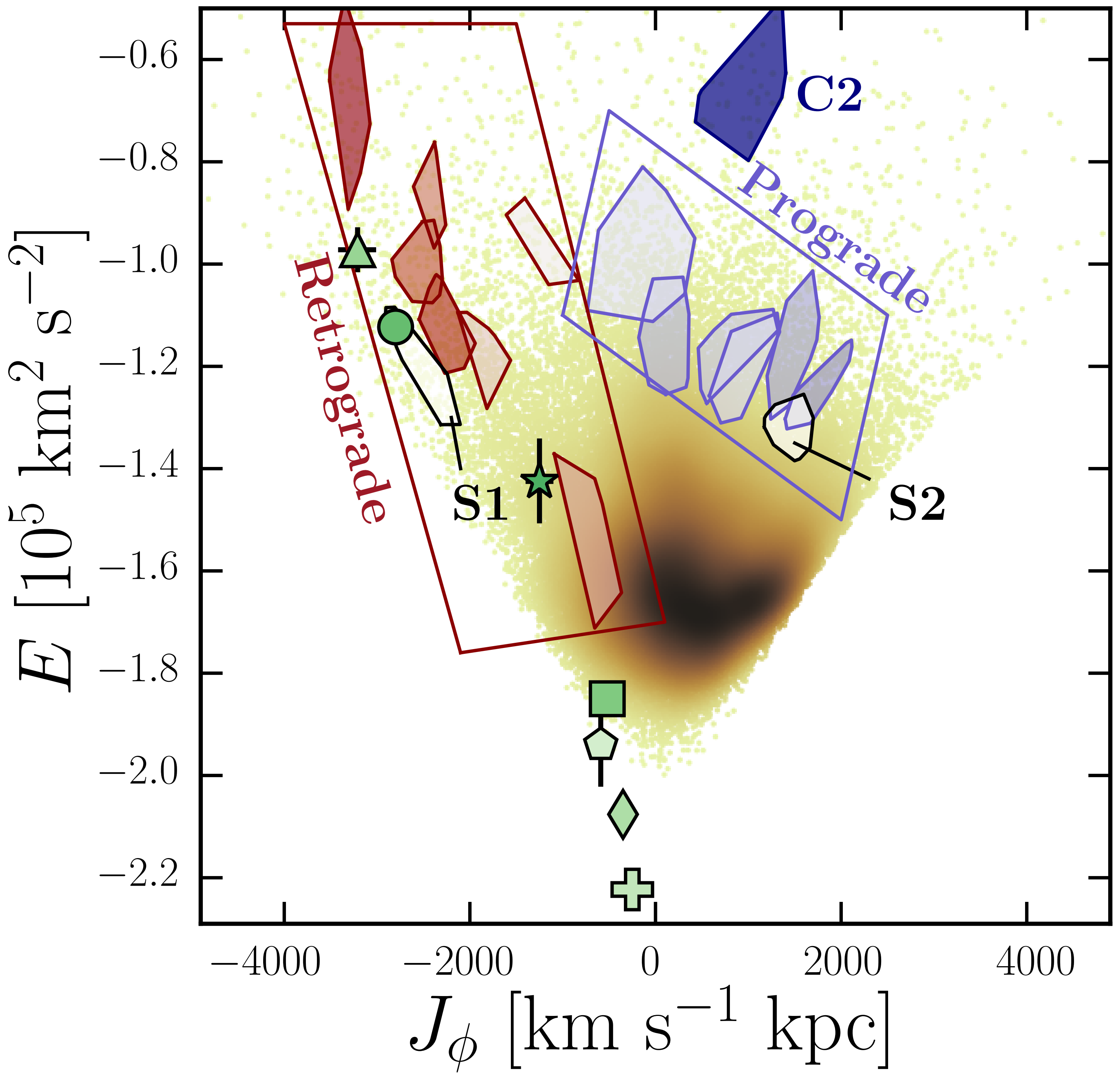
→ Two components with $\pm v_z$

→ Interpreted as multiple wraps of a larger stream

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

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"

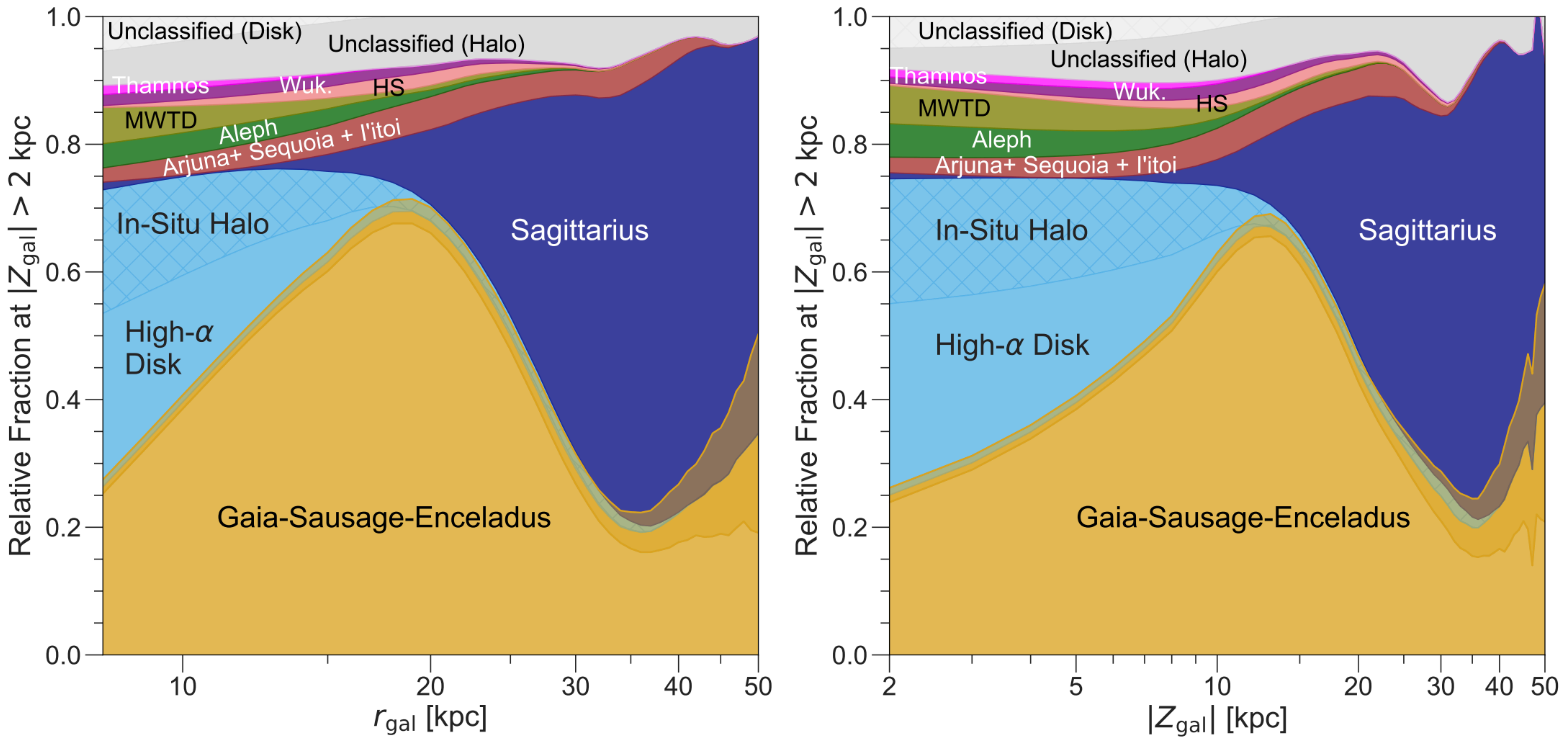


	Name	Number of stars	(X,Y,Z) kpc	$(\Delta X,\Delta Y,\Delta Z)$ kpc	(v_R,v_ϕ,v_z) km s^{-1}	$(\sigma_R,\sigma_\phi,\sigma_z)$ km s^{-1}	⟨[Fe/H]⟩
S1		28	$(8.4, 0.6, 2.6)$	$(0.7, 1.8, 2.2)$	$(-34.2, -306.3, -64.4)$	$(81.9, 46.3, 62.9)$	-1.9 ± 0.3
S2	a	46	$(8.7, 0.4, 0.1)$	$(0.7, 1.2, 6.9)$	$(5.8, 163.6, -250.4)$	$(45.9, 13.8, 26.8)$	-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

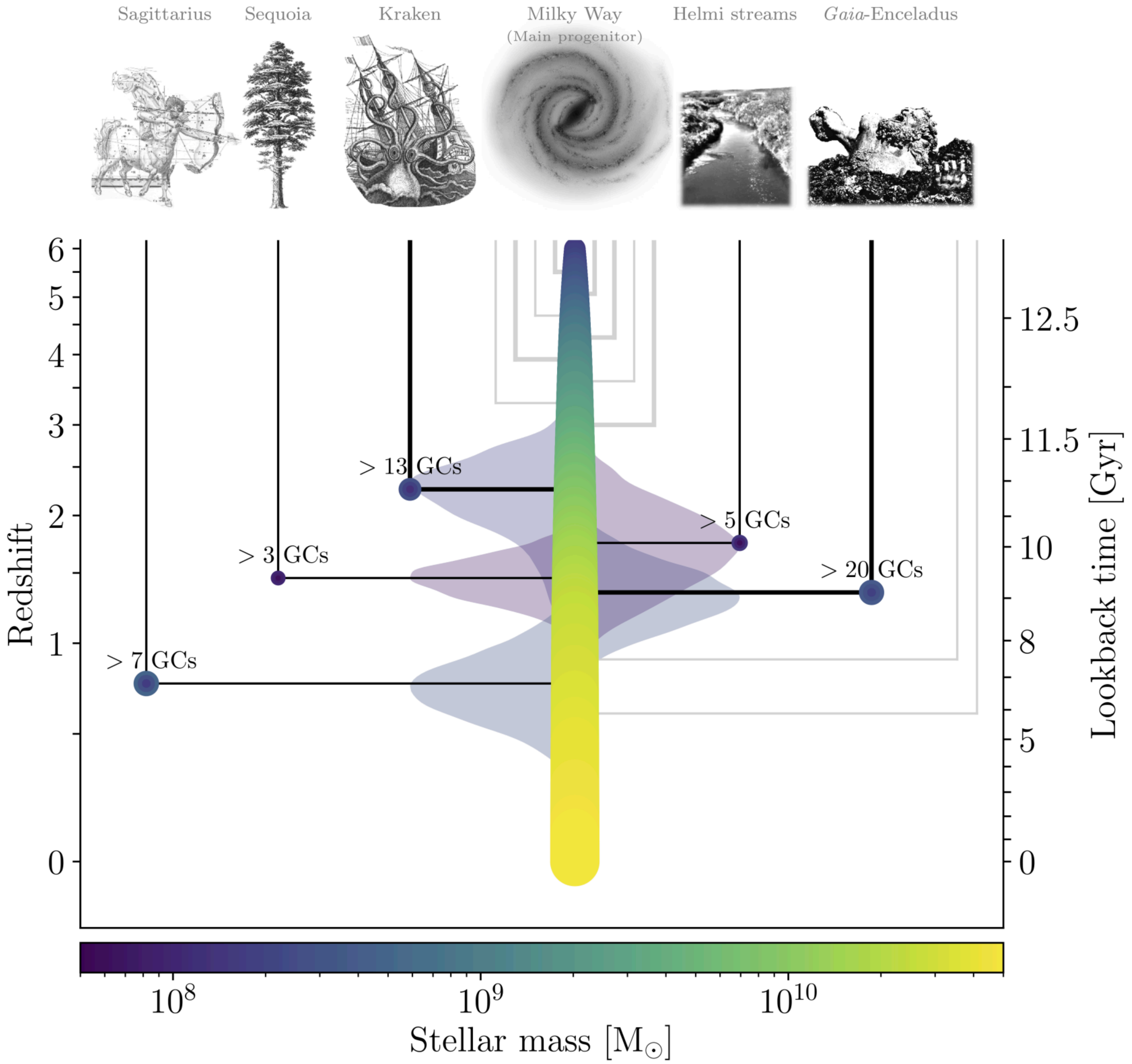
A lot of substructures discovered and re-discovered with different datasets, stellar samples, search methods,
→ a few prominent cases are emerging

More thorough taxonomy of stellar halo with H3 survey

Naidu et al. 2006.08625



2003.01119



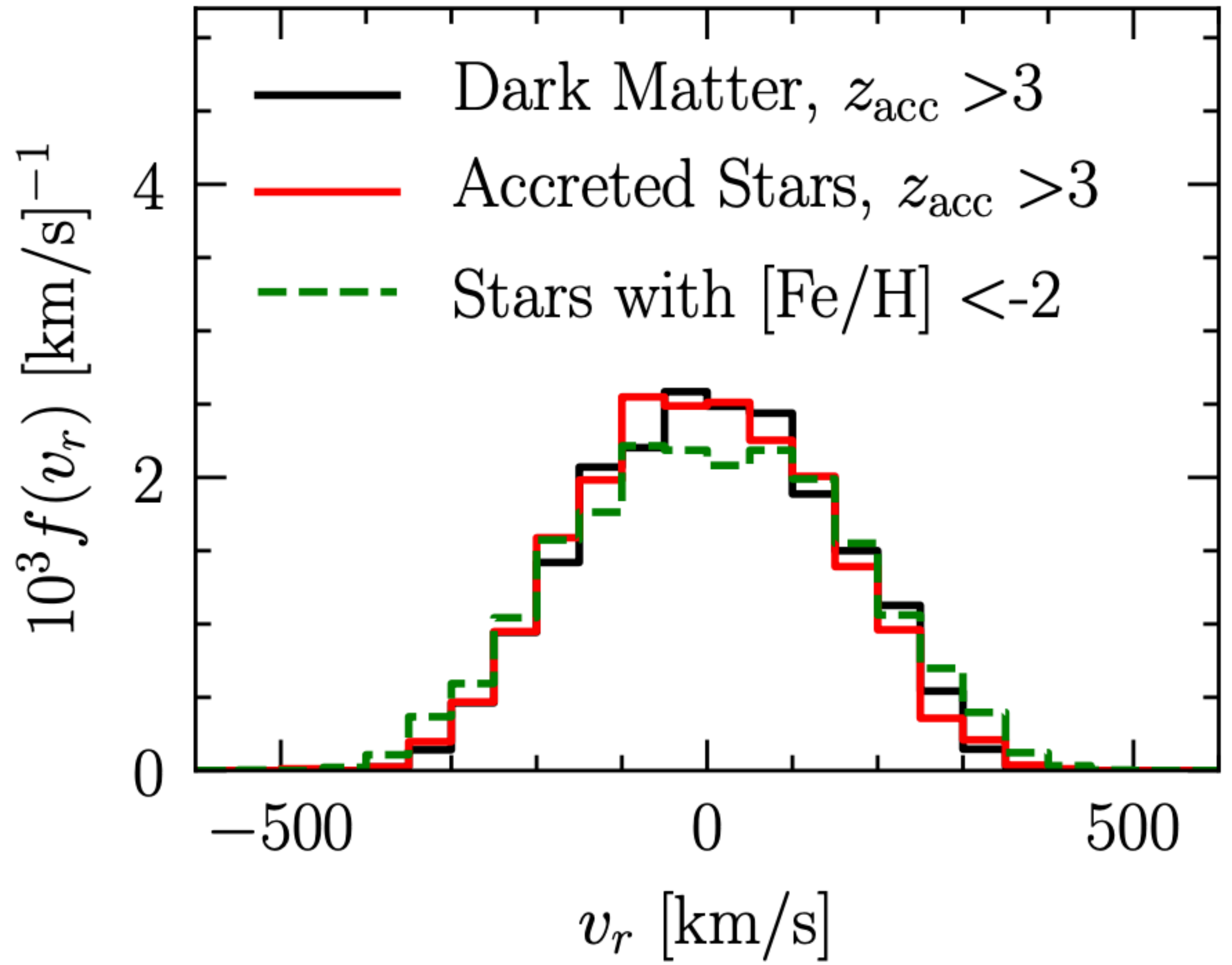
Sagittarius
Sequoia
Kraken
Milky Way
(Main progenitor)
Helmi streams
Gaia-Enceladus
> 13 GCs
> 5 GCs
> 3 GCs
> 20 GCs
> 7 GCs
Redshift
6
5
4
3
2
1
0
Lookback time [Gyr]
12.5
11.5
10
8
5
0
10^8
10^9
10^{10}
Stellar mass [$M_\odot$]

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

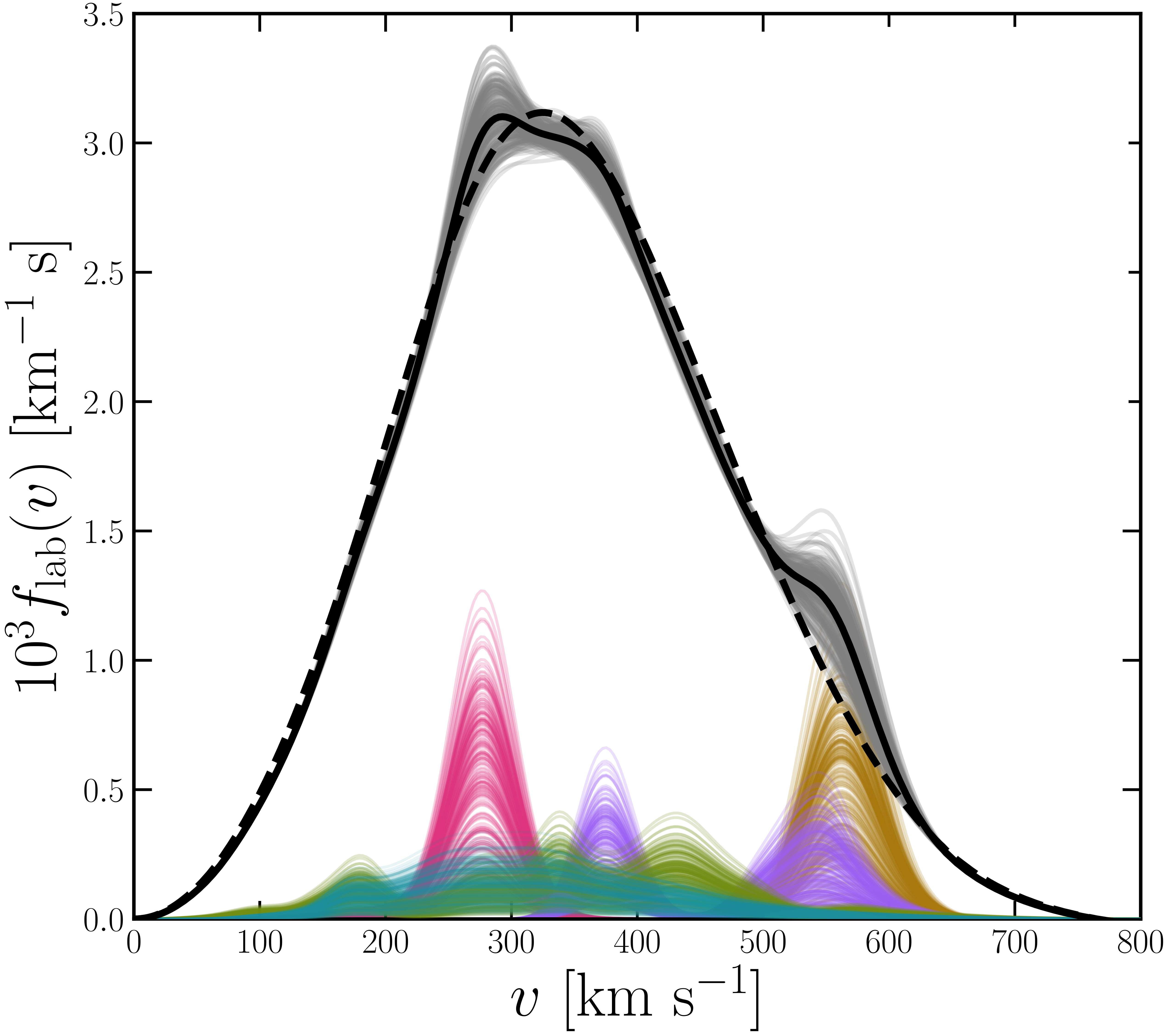
Necib+ [1810.12301]

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

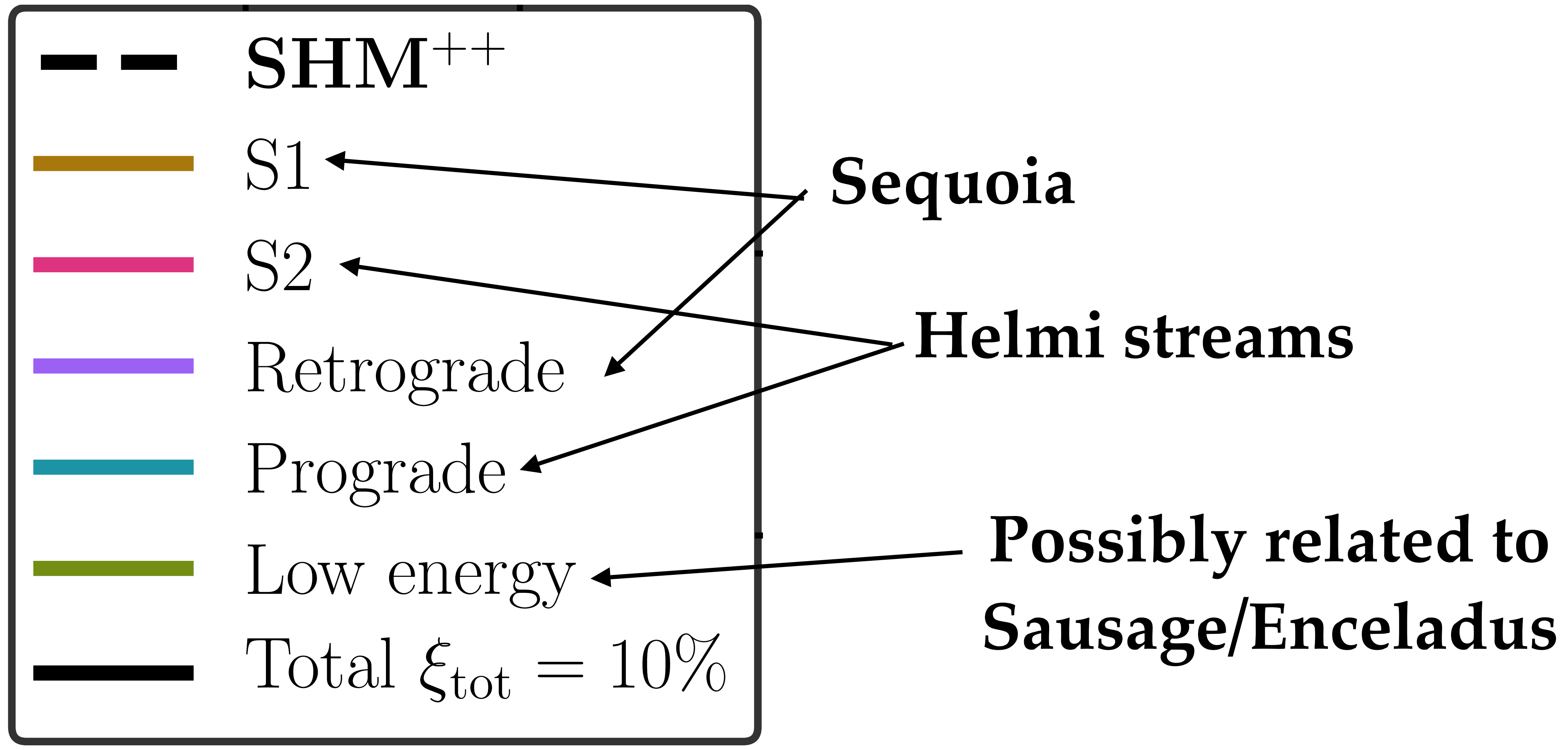


Dark shards

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



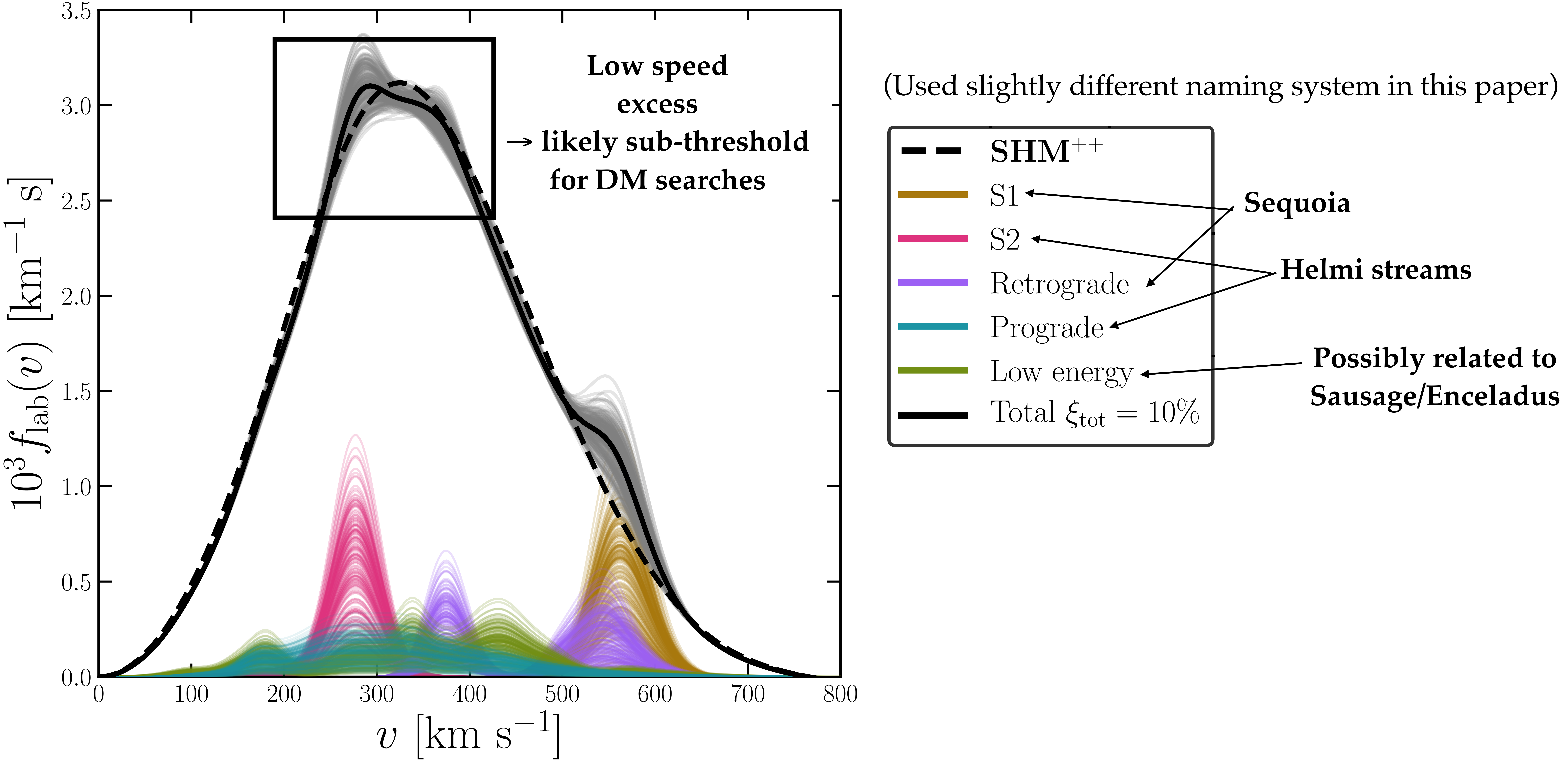
(Used slightly different naming system in this paper)



1909.04684

Dark shards

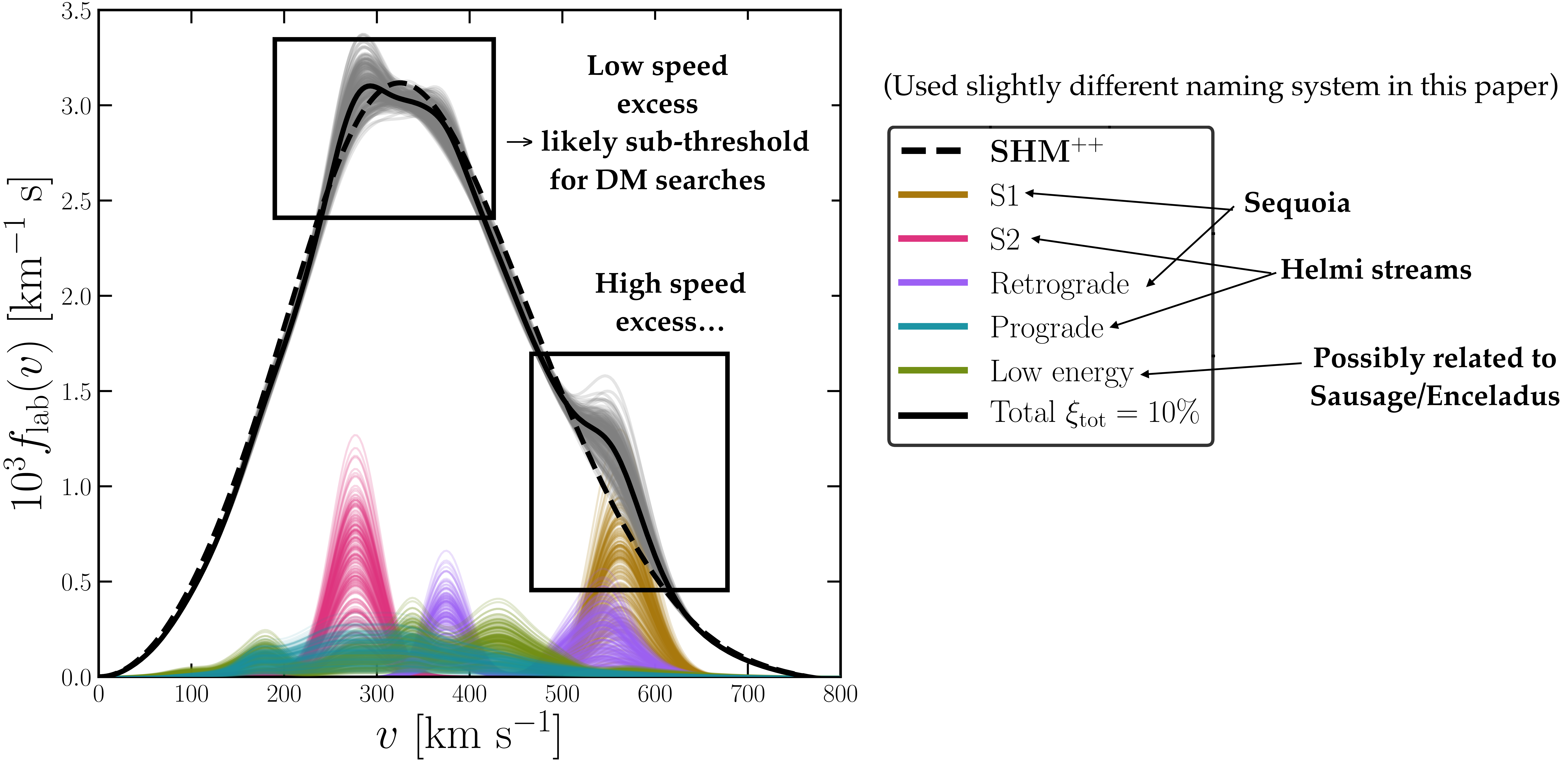
→ Take all the velocity substructures observed in the halo and build a potential DM velocity distribution out of them



(Used slightly different naming system in this paper)

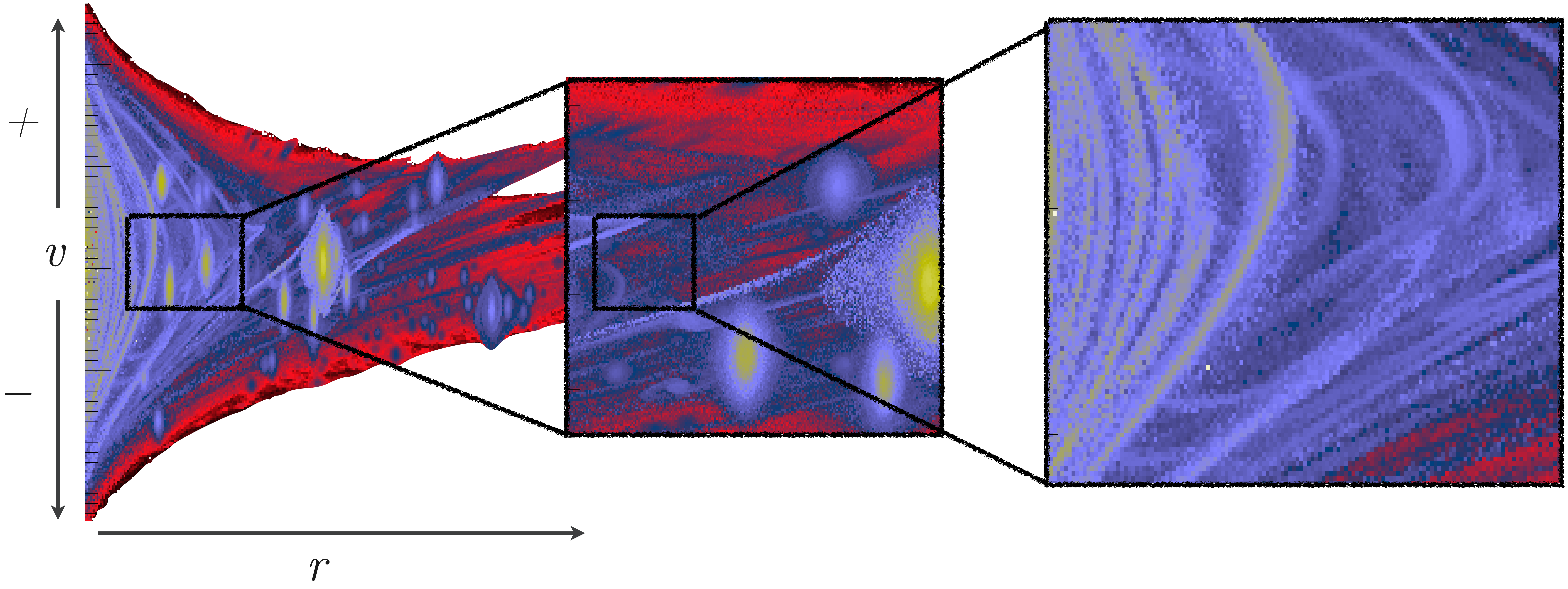
Dark shards

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

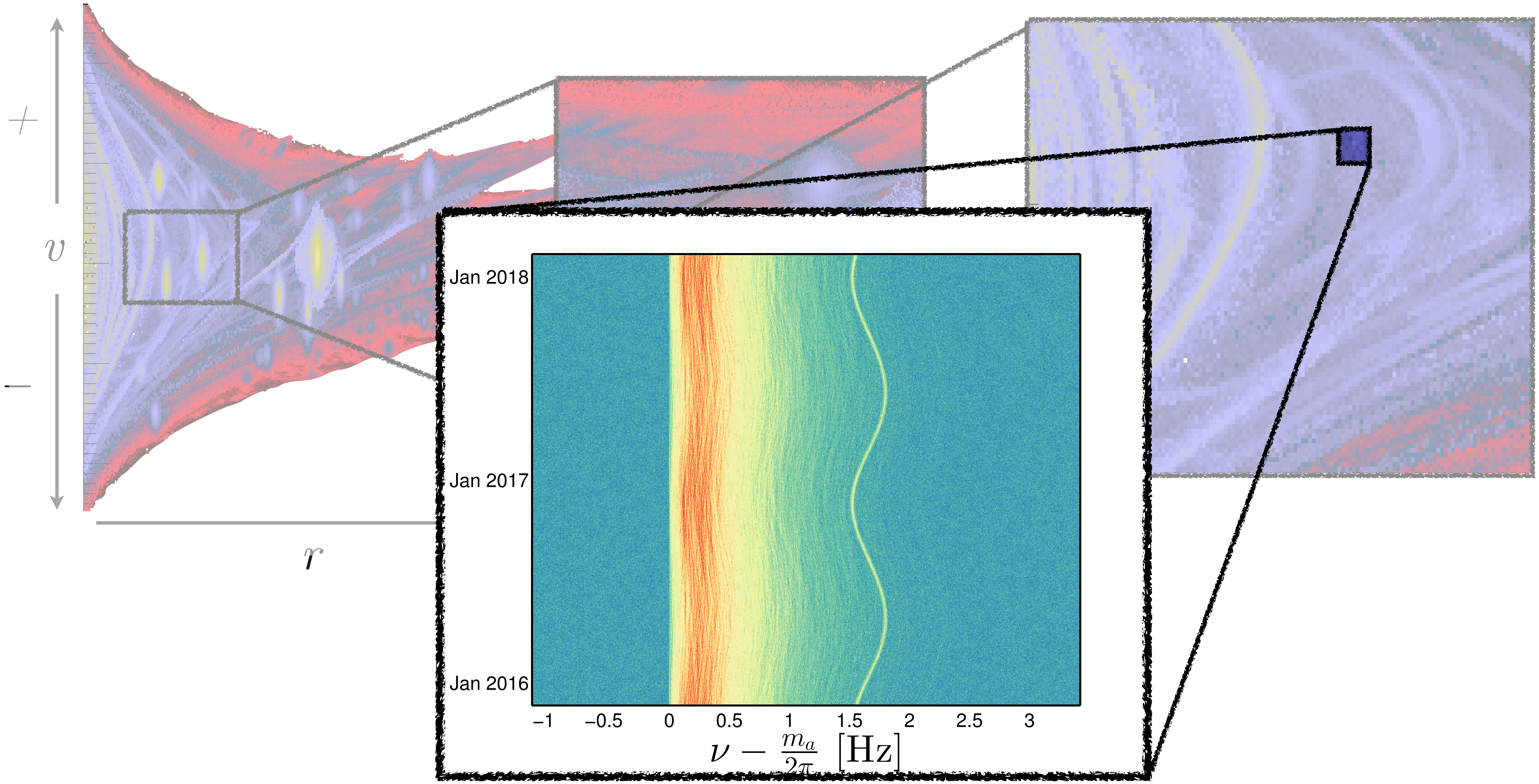


Substructure

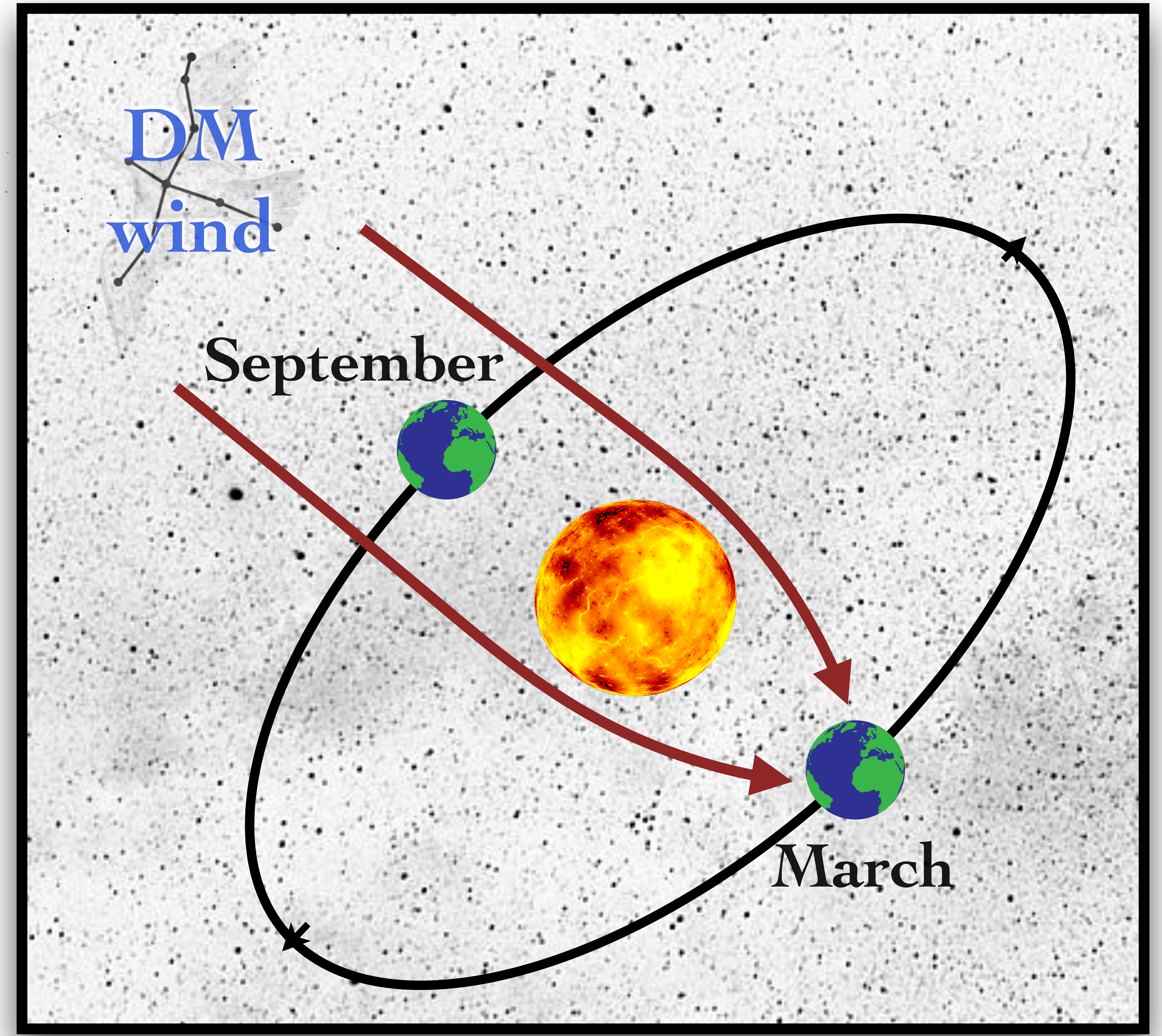
Assuming perfectly cold DM, at some level the halo will have ultra-fine grained substructure, even if it consists of millions of overlapping streams Vogelsberger+ [1002.3162]



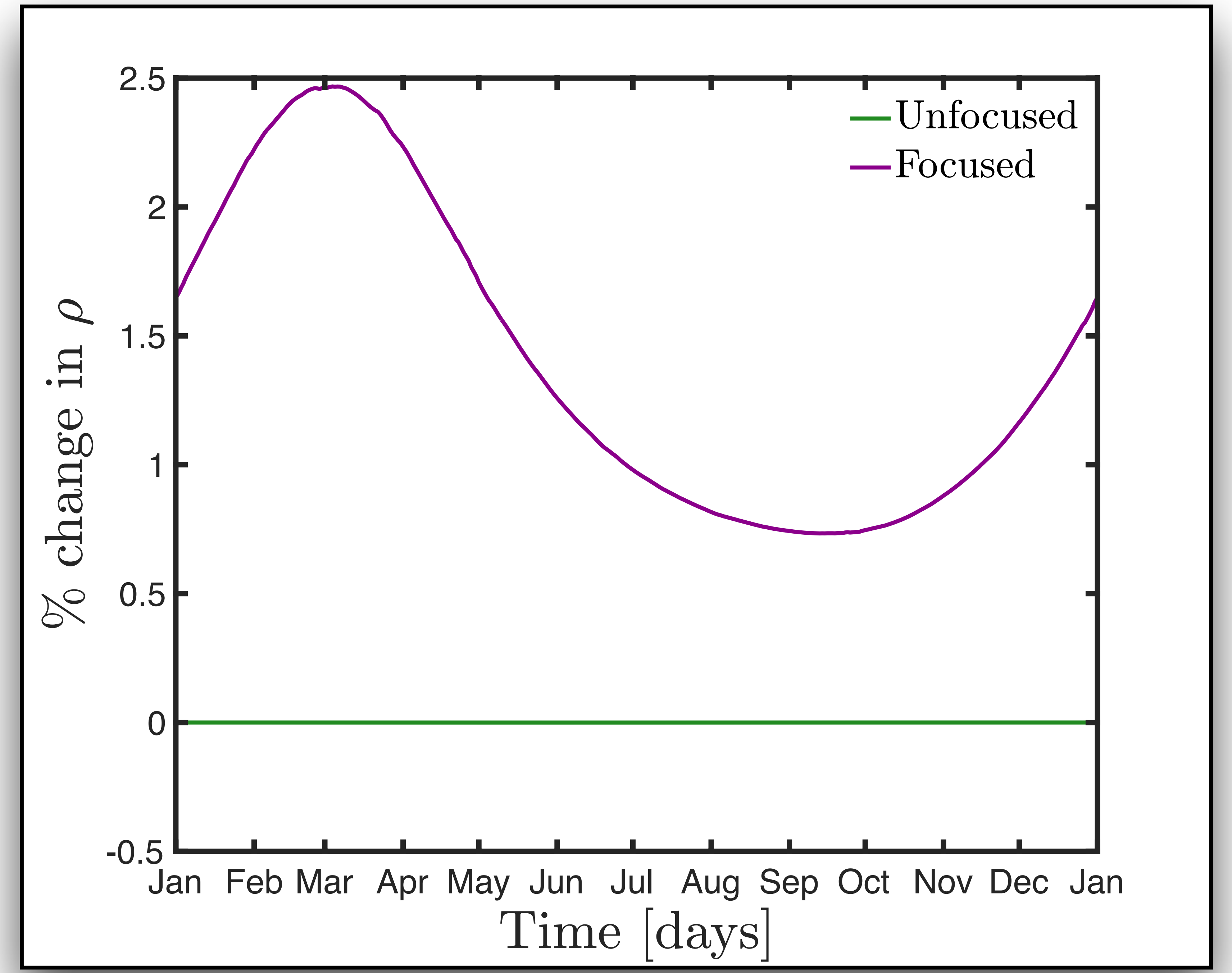
Assuming perfectly cold DM, at some level the halo will have ultra-fine grained substructure, even if it consists of millions of overlapping streams Vogelsberger+ [1002.3162]



Gravitational focusing

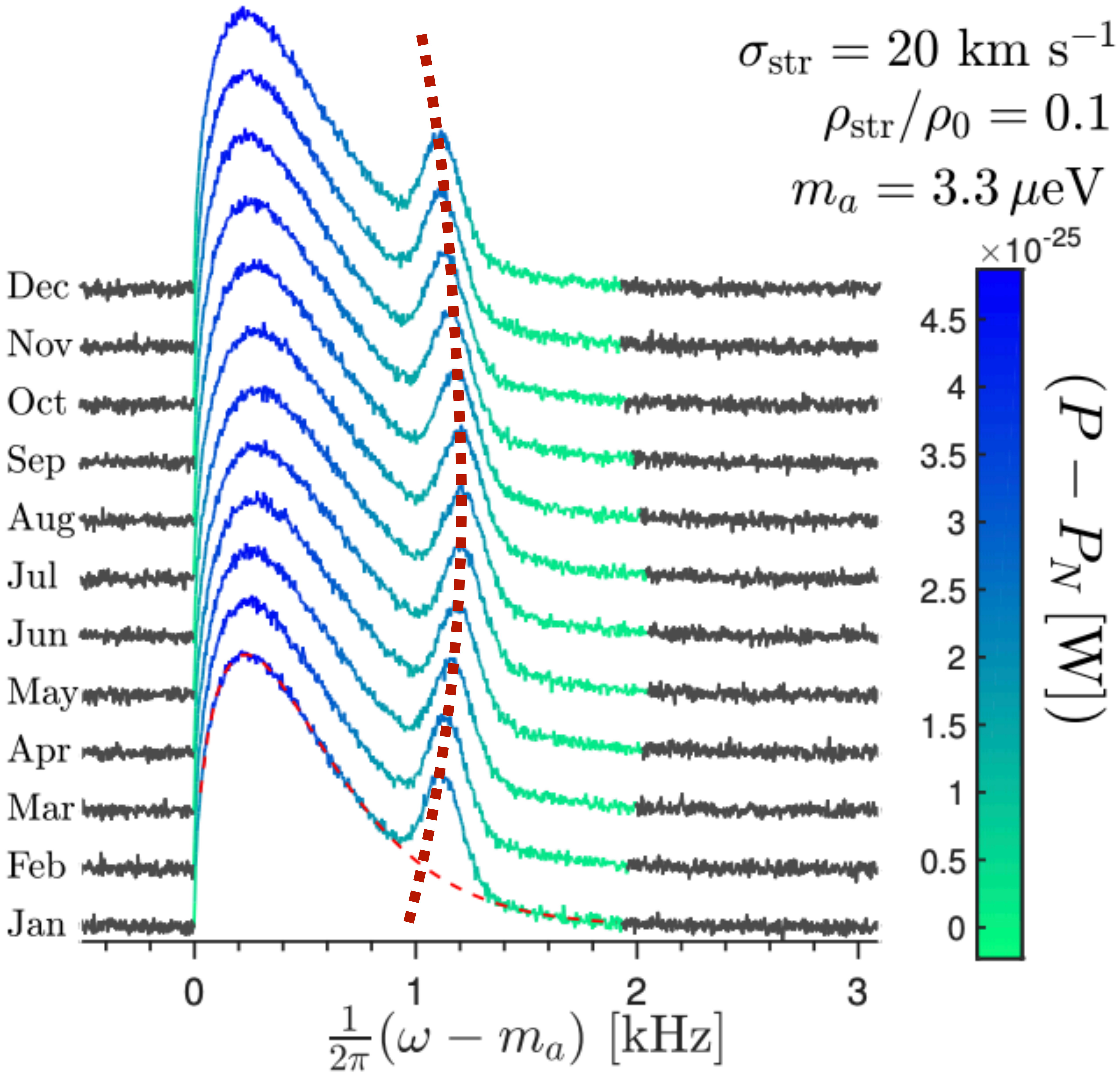


Additional ~2% modulation in DM density (+shift of $f(v)$ at small v)



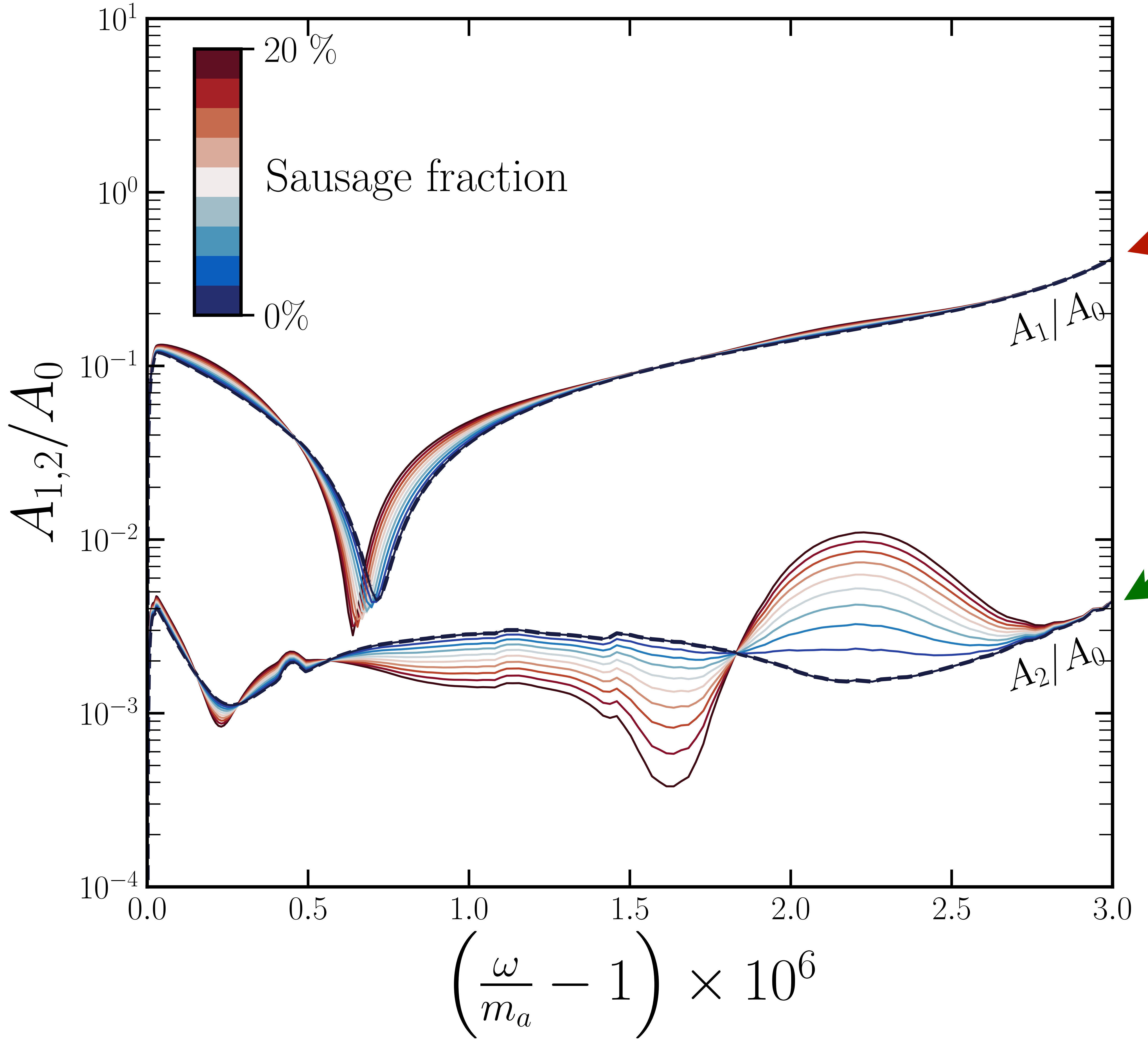
Axion "astronomy": identifying streams

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



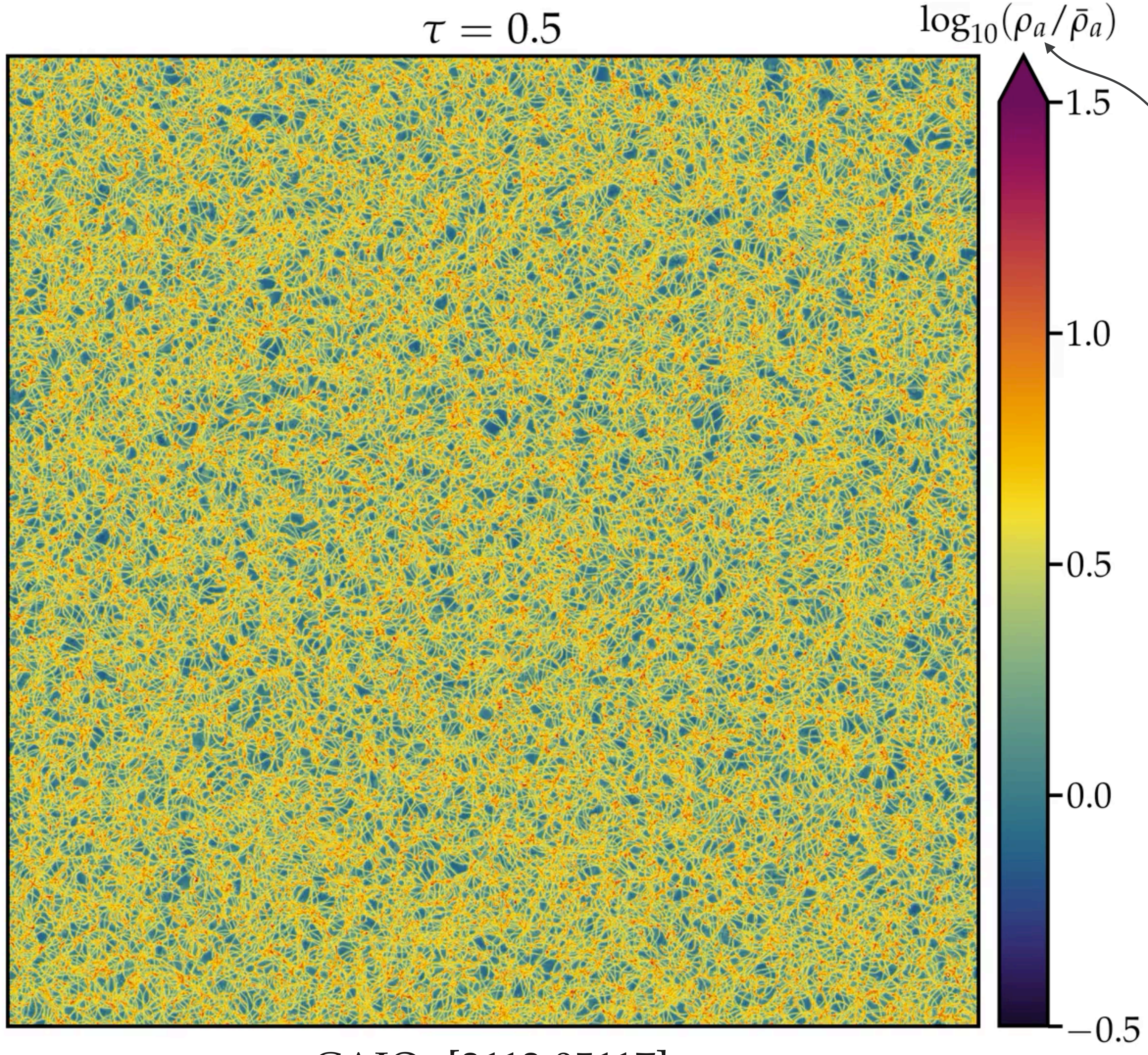
$$f(\omega) = A_0 + \sum_{n=1}^{\infty} \left[A_n \cos\left(\frac{2\pi n\,(t - t_n)}{1\,\text{year}} \right) \right]$$

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

Axion miniclusters

Evolution of the axion field in the post-inflationary scenario

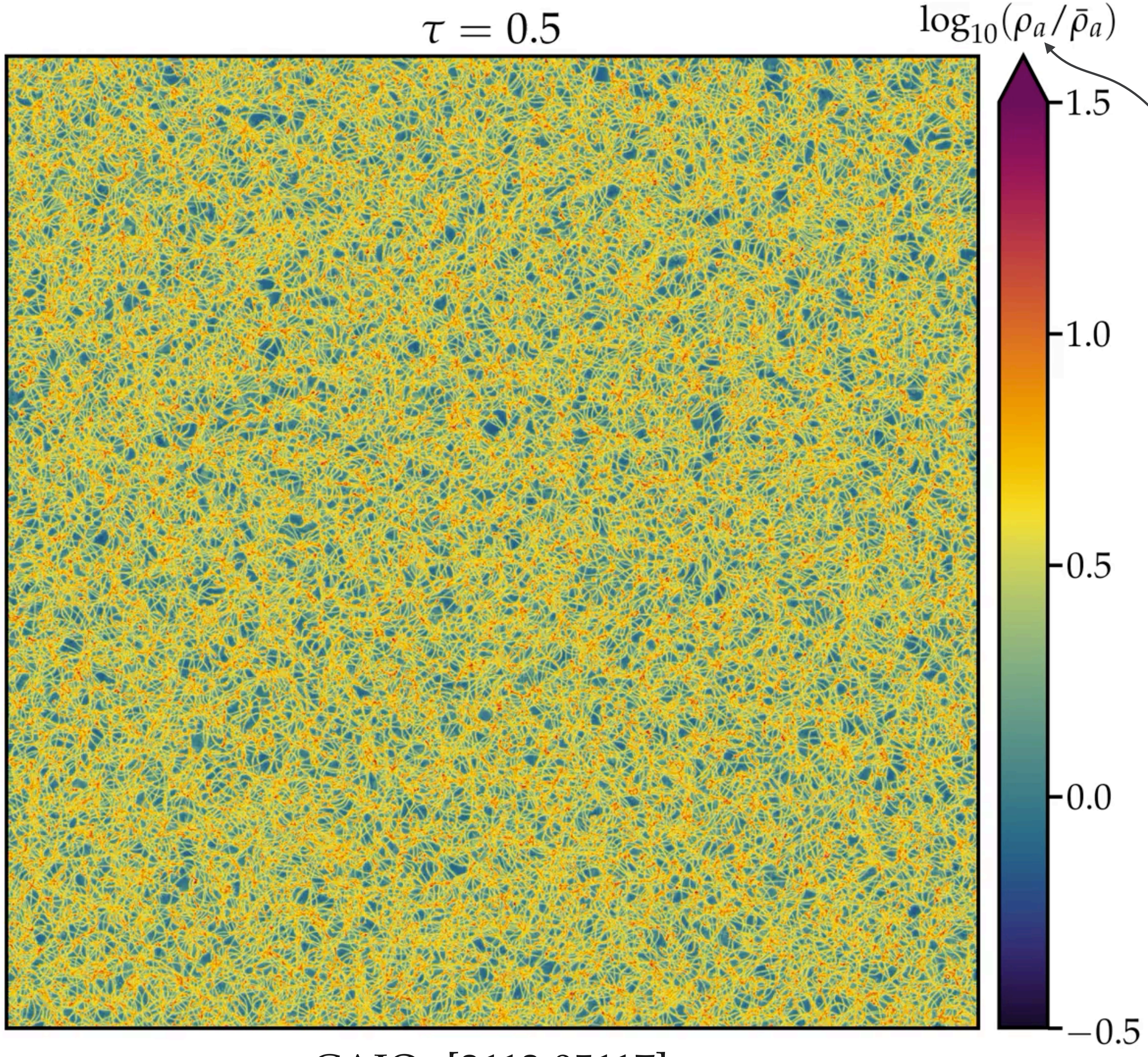


$$\rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2R^2}(\nabla a)^2 + \chi\,(1 - \cos a/f_a)$$

CAJO+[2112.05117]

(movie)

Evolution of the axion field in the post-inflationary scenario

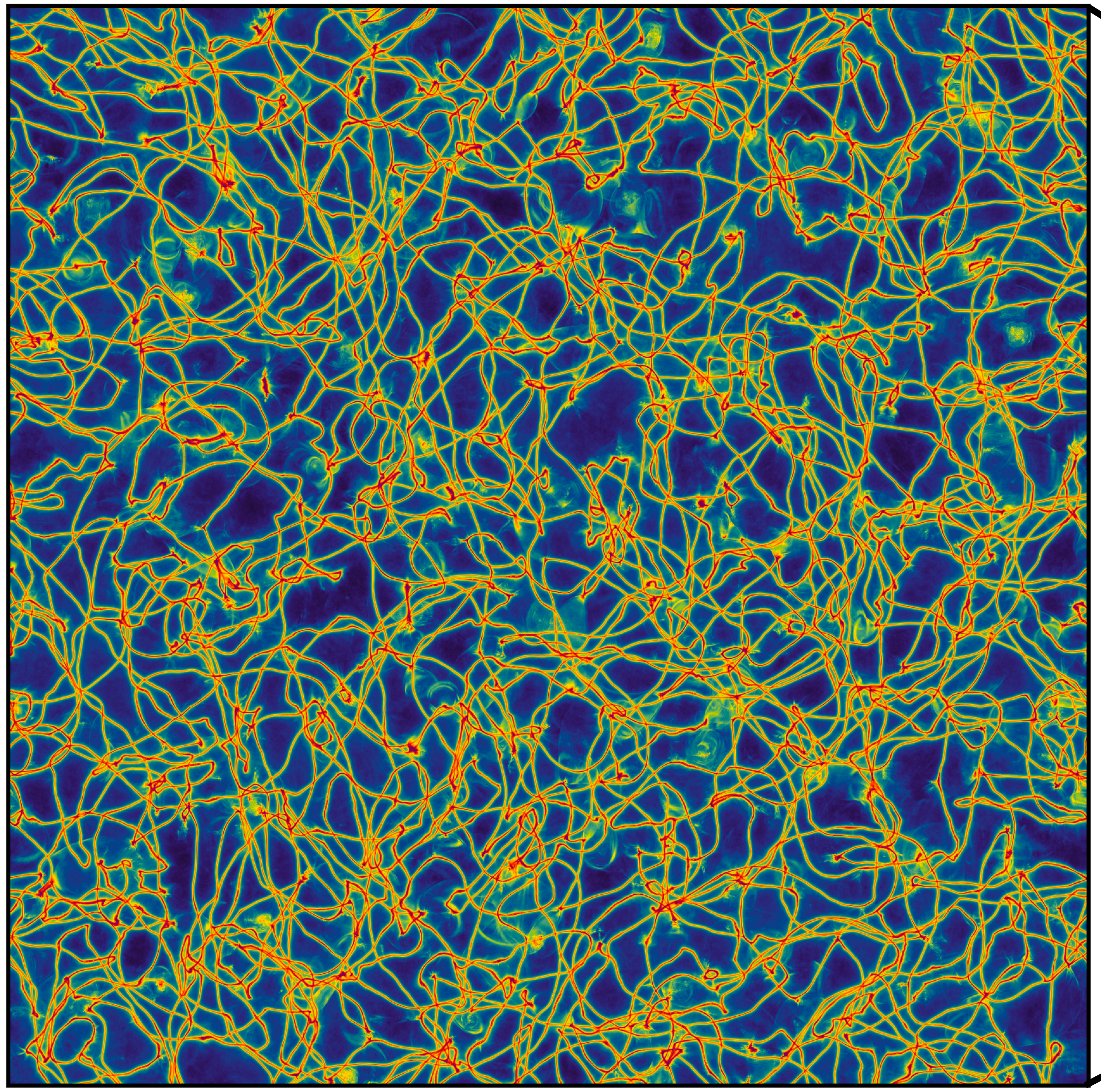


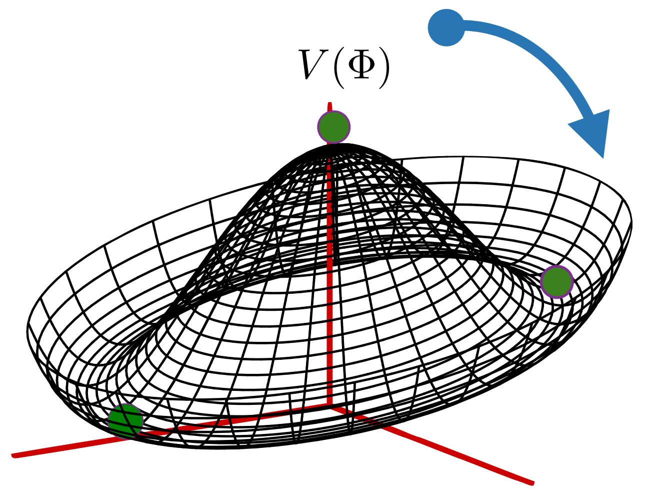
$$\rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2R^2}(\nabla a)^2 + \chi\,(1 - \cos a/f_a)$$

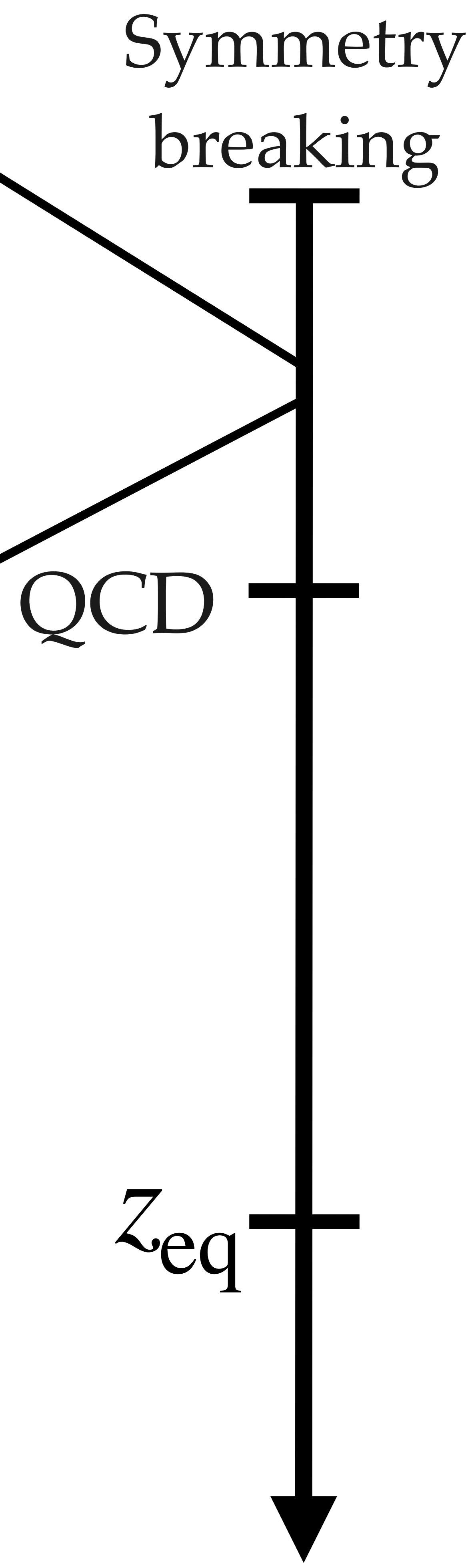
(movie)

CAJO+[2112.05117]

Evolution of the axion field in the post-inflationary scenario



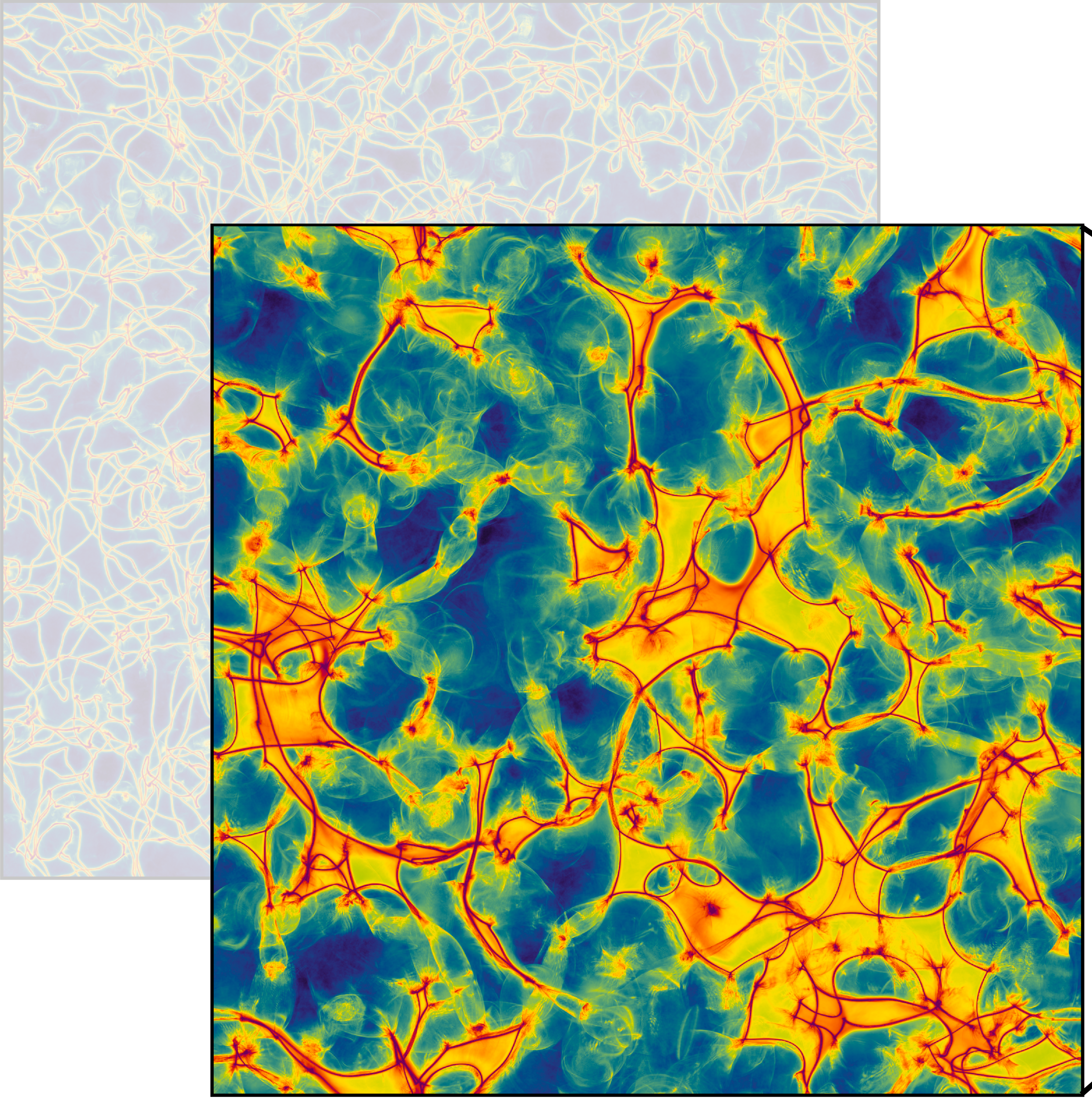


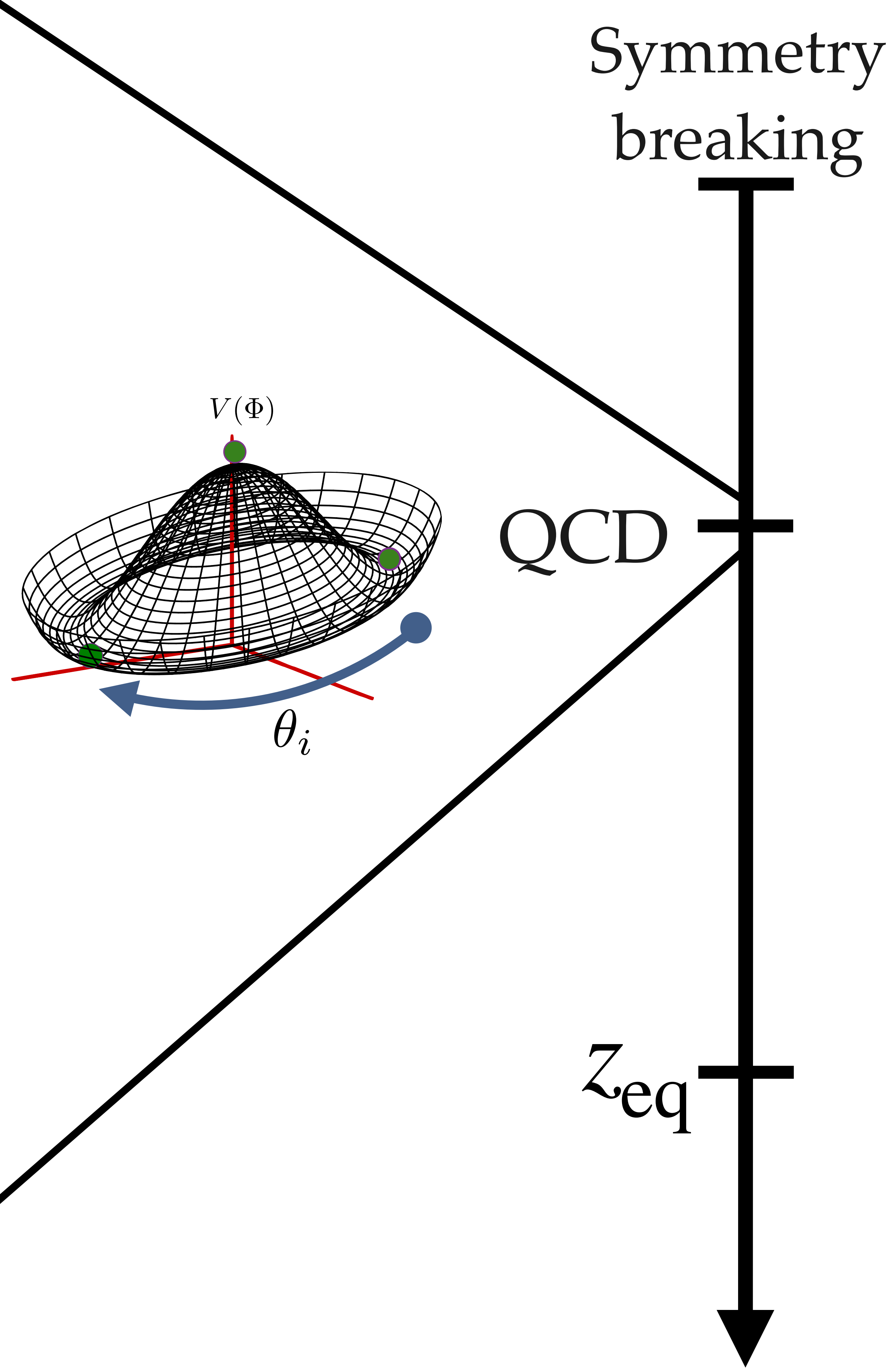


String network scaling

CAJO+[2112.05117]

Evolution of the axion field in the post-inflationary scenario



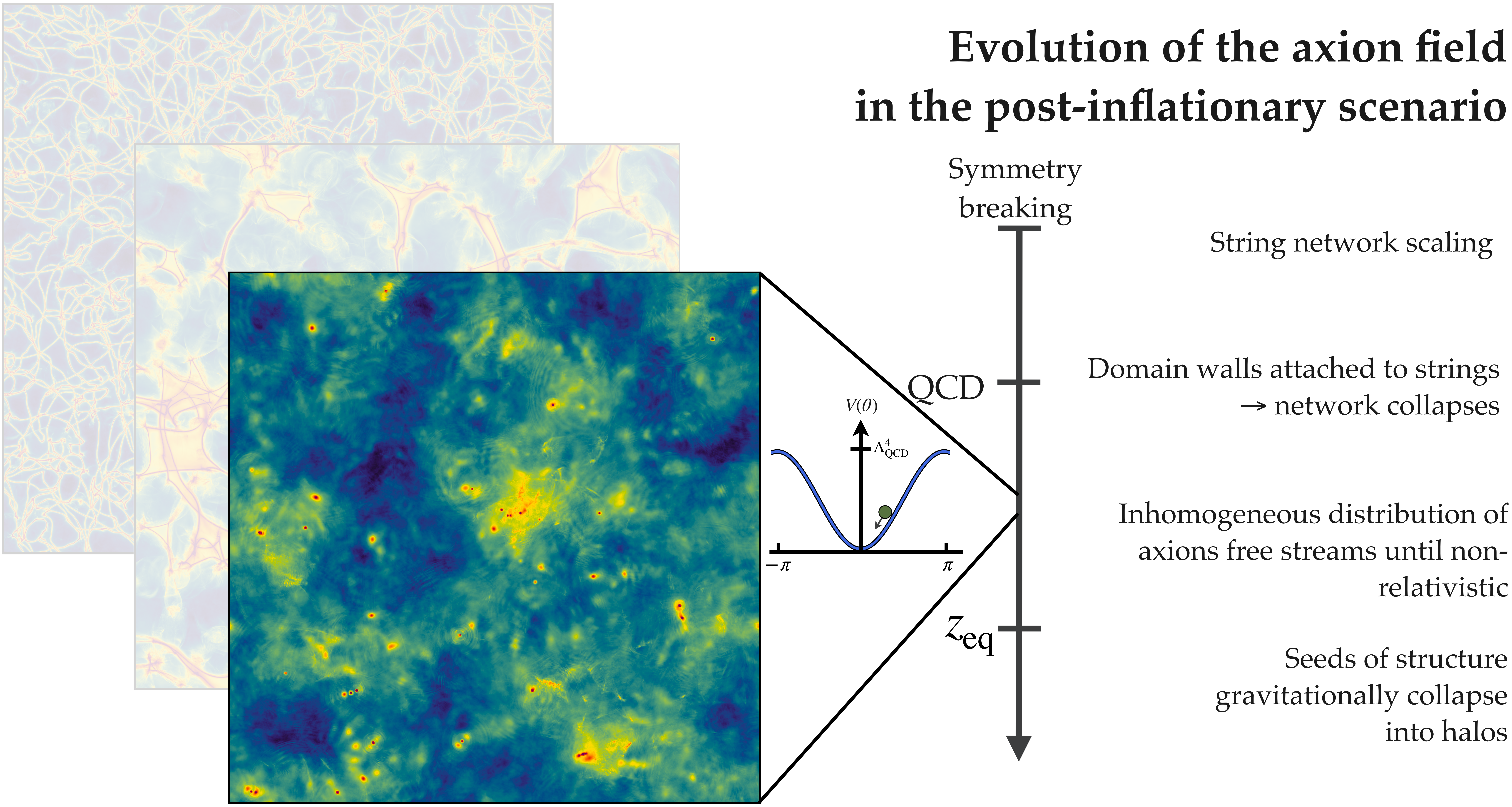


String network scaling

Domain walls attached to strings
→ network collapses

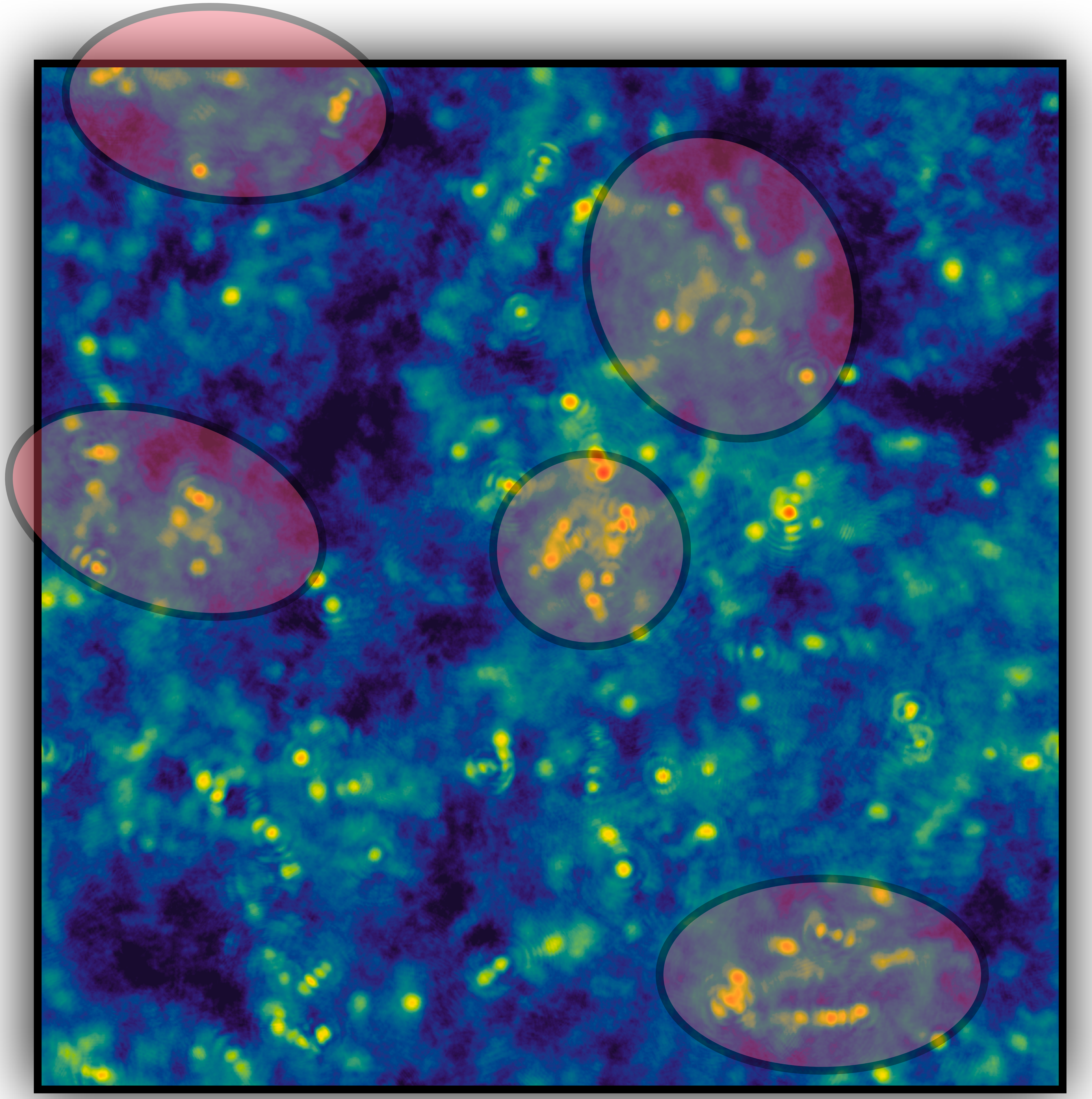
CAJO+[2112.05117]

Evolution of the axion field in the post-inflationary scenario

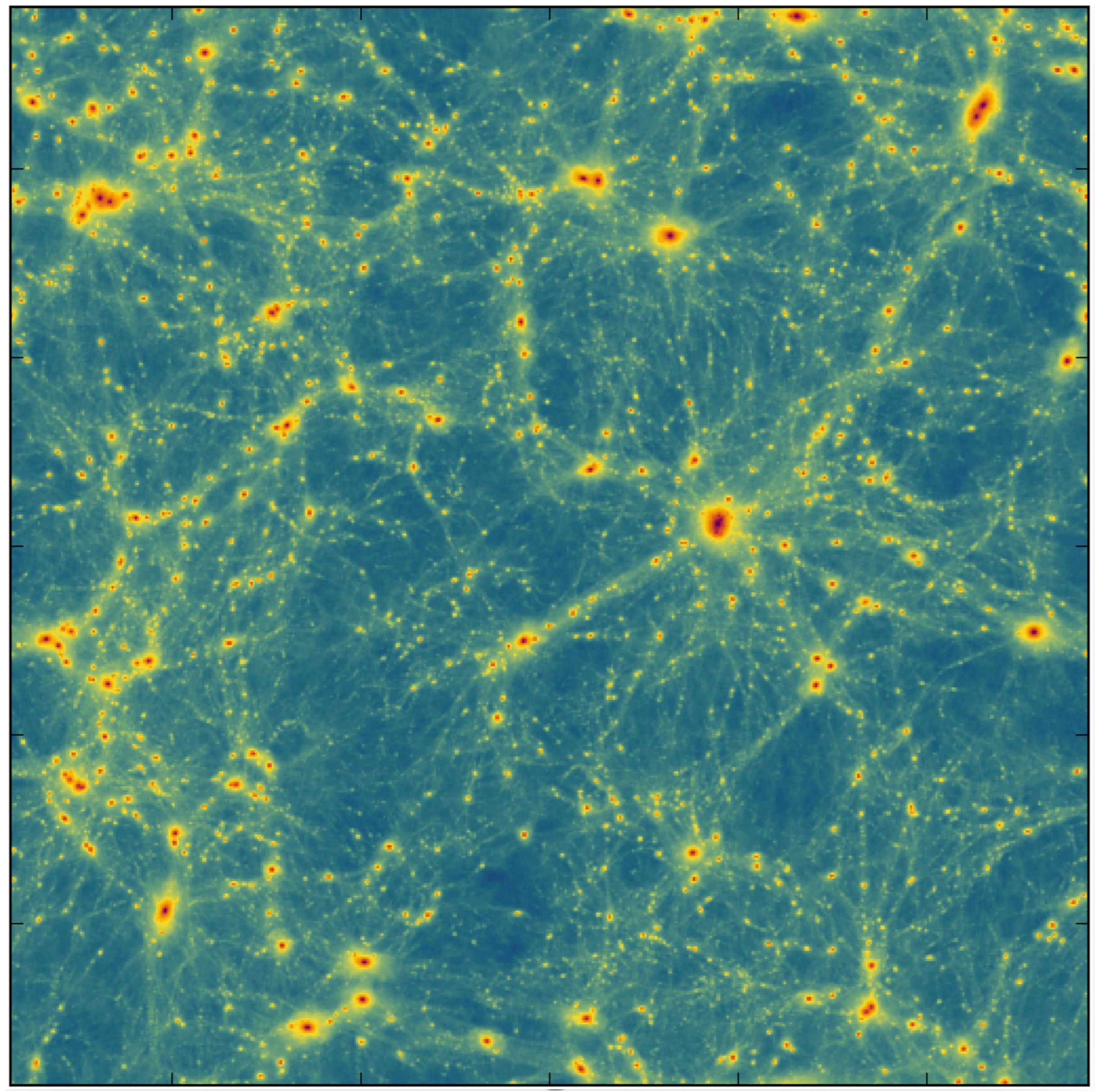


CAJO+[2112.05117]

What next? → Gravity



As we approach $z_{\rm eq}$, field has significant inhomogeneity on small scales $L \sim 0.1$ pc
→ Leads to gravitational collapse of structures much earlier than conventional thermal CDM
→ **Miniclusters**



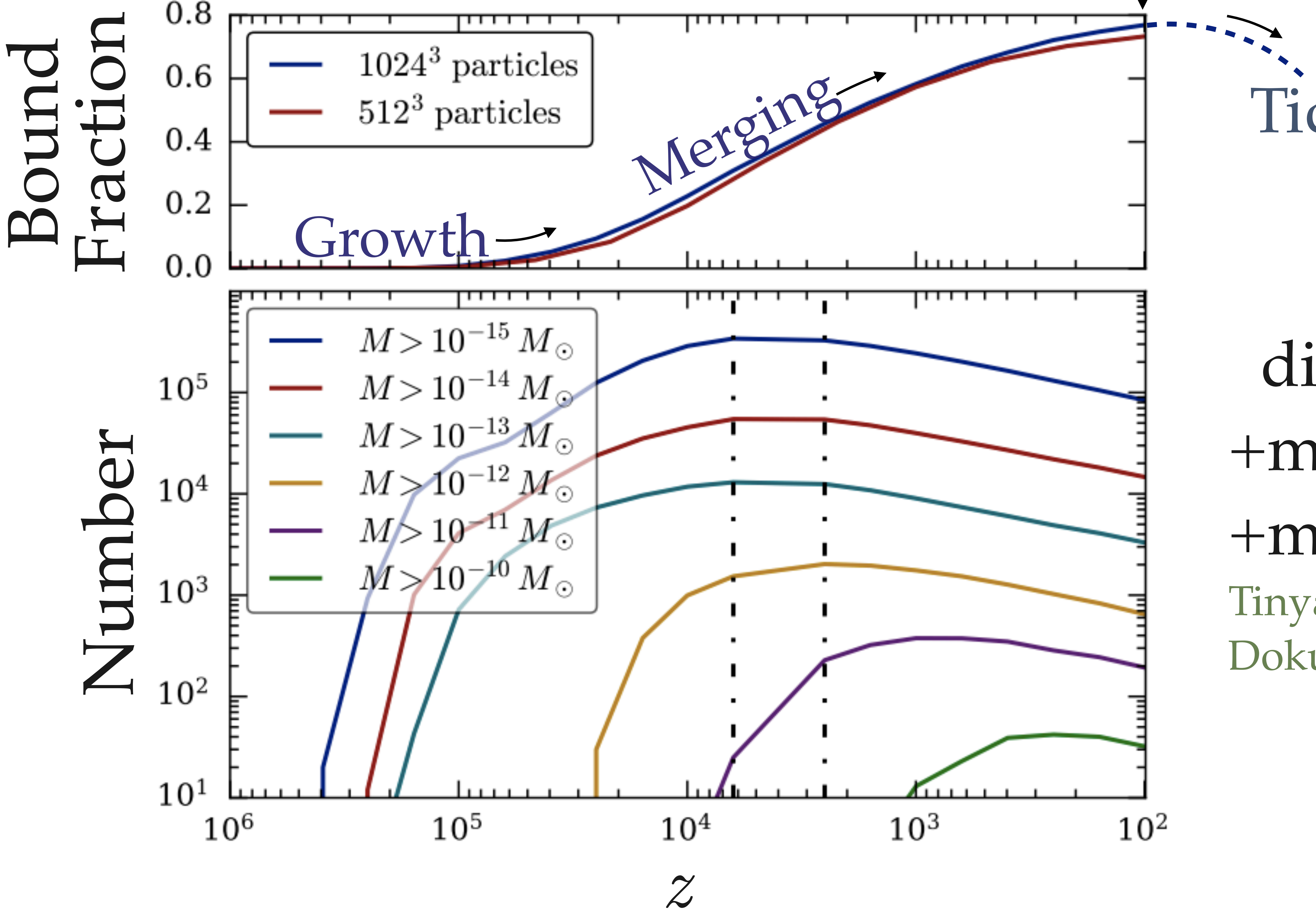
$M_{\rm mc} \sim 10^{-12} M_\odot$ $\rho_{\rm mc} \sim 10^4\,{\rm GeV\,cm}^3$

CAJO+[2112.05117]

Galaxies made of axion miniclusters+diffuse axions

Eggemeier+ [1911.09417]

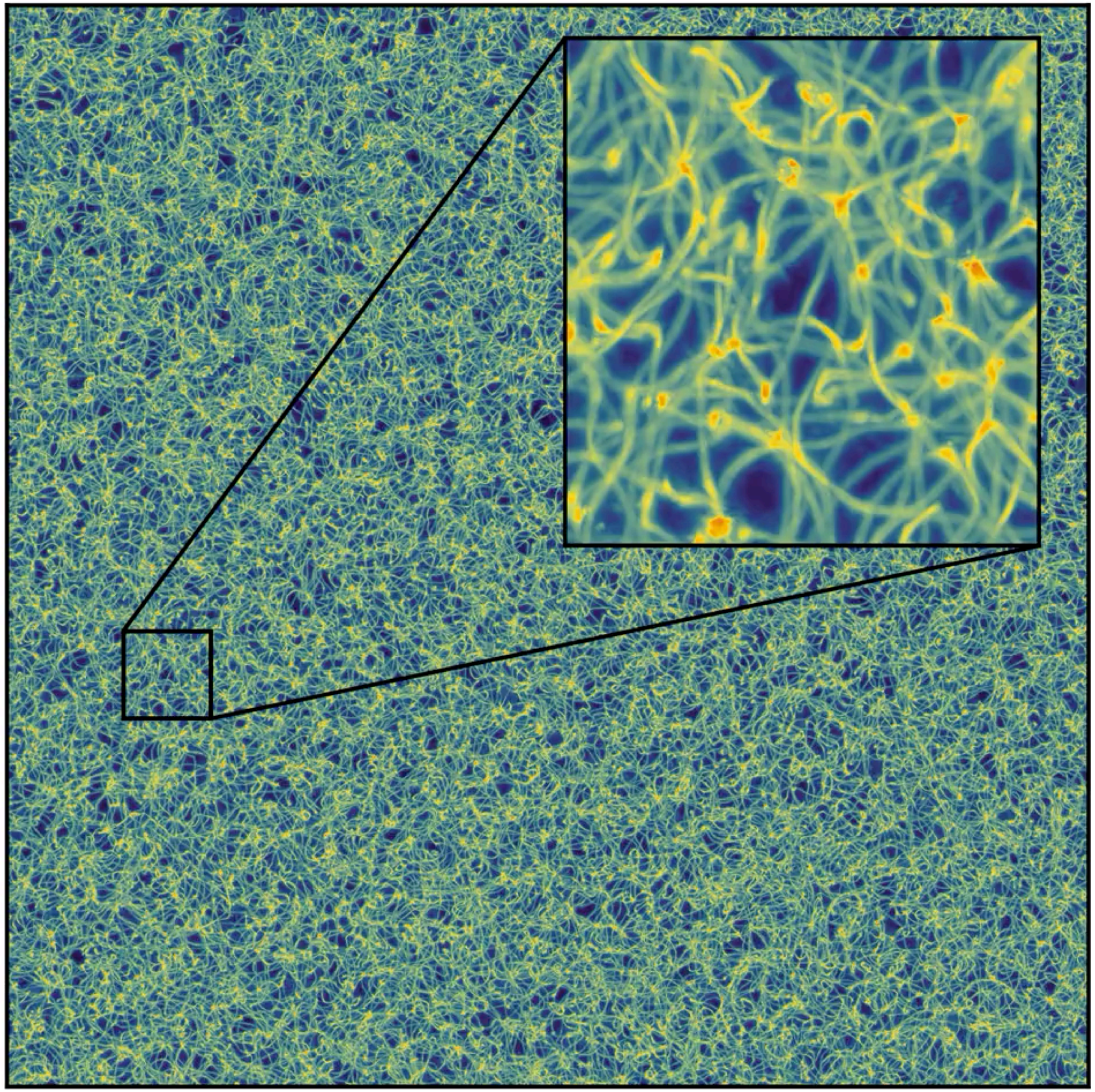
$f_{\rm clump}(z=100)=0.75$



Tidal disruption?

diffuse axions
+miniclusters
+ministreams ~ 1%?

Tinyakov+ [1512.02884]
Dokuchaev+ [1710.09586]

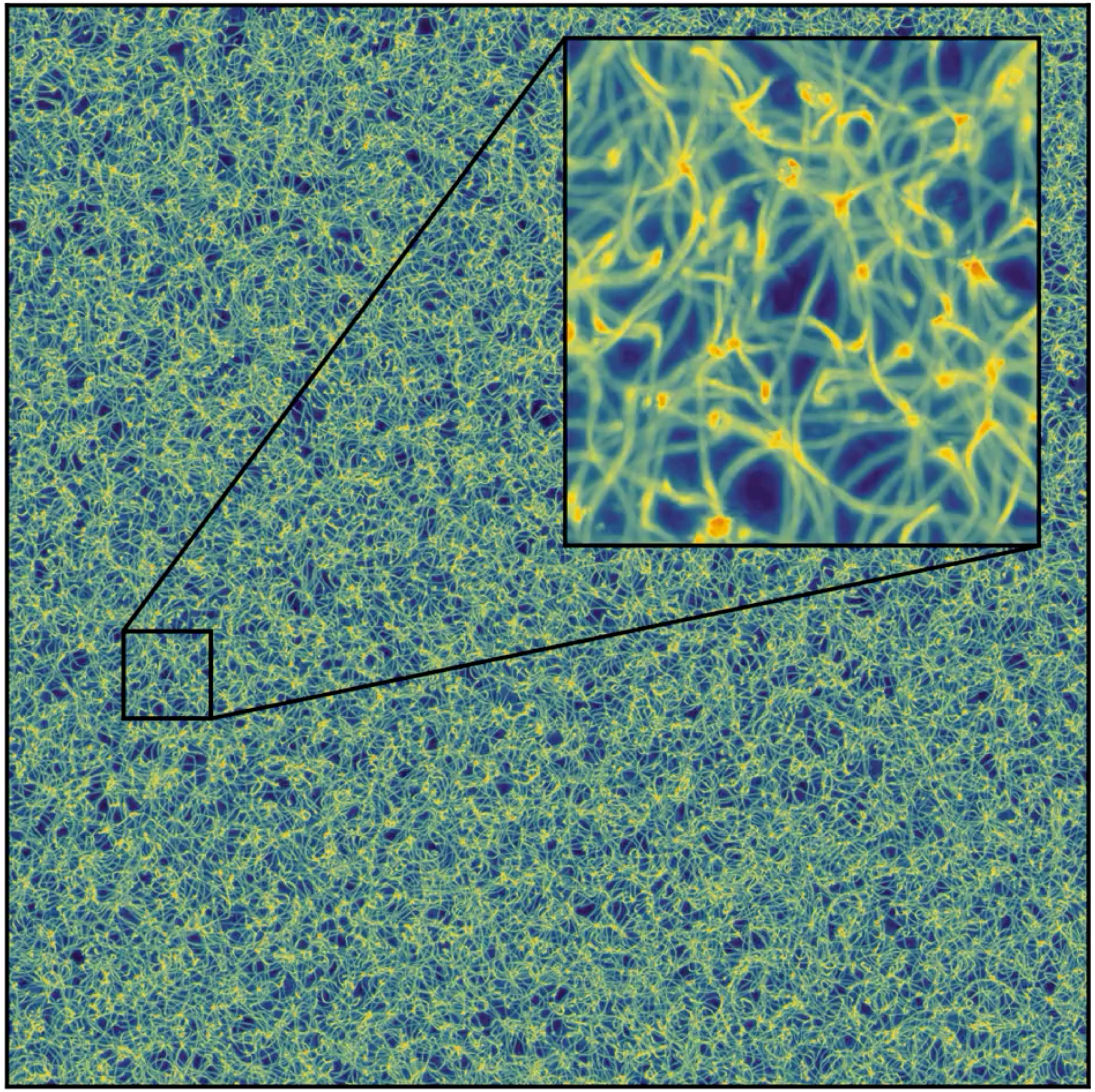


(Movie)

CAJO+[2112.05117]

Large numbers of high-density oscillating lumps are seeded towards the end of the simulation

“Axitons”

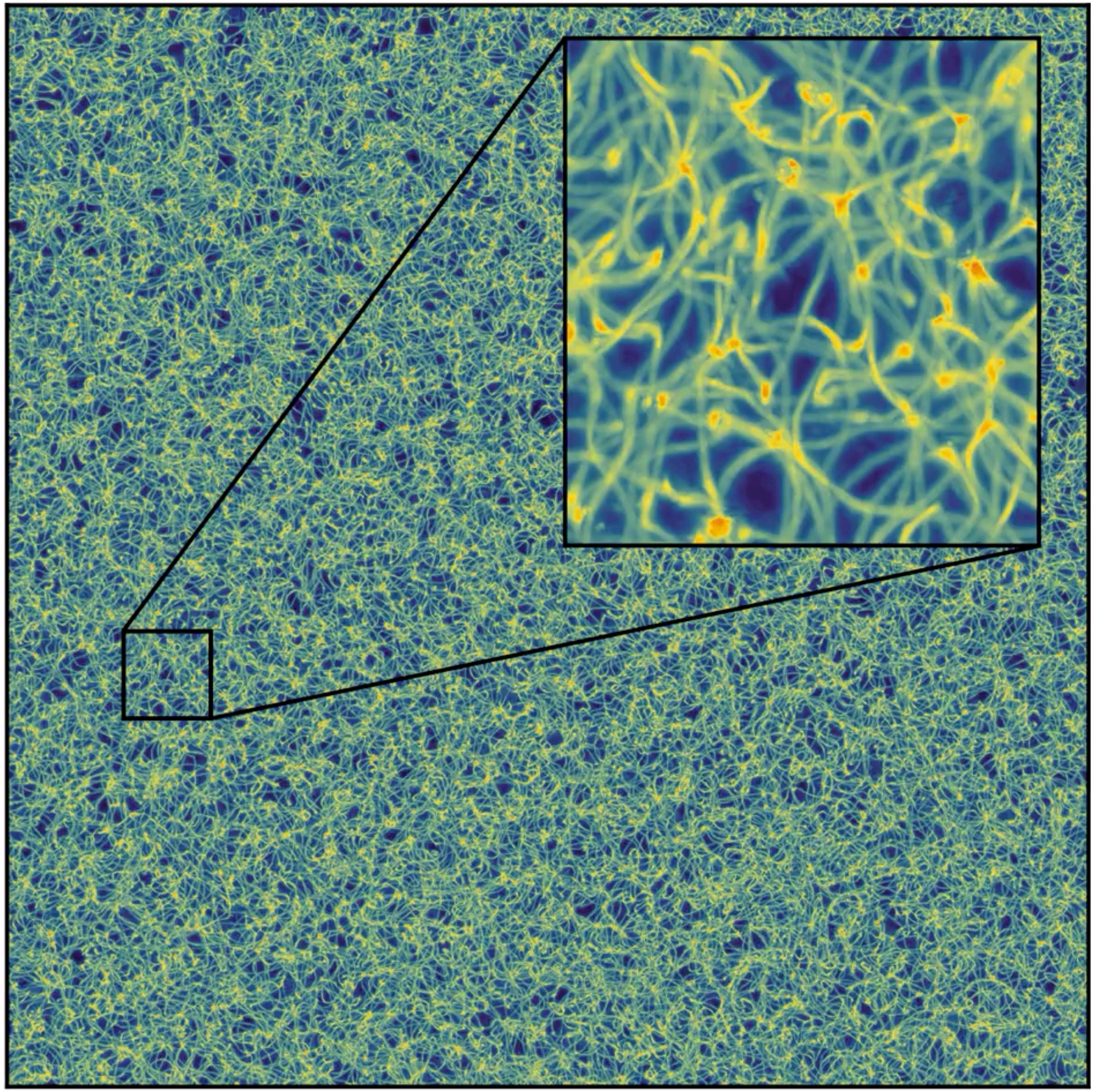


(Movie)

CAJO+[2112.05117]

Large numbers of high-density oscillating lumps are seeded towards the end of the simulation

“Axitons”



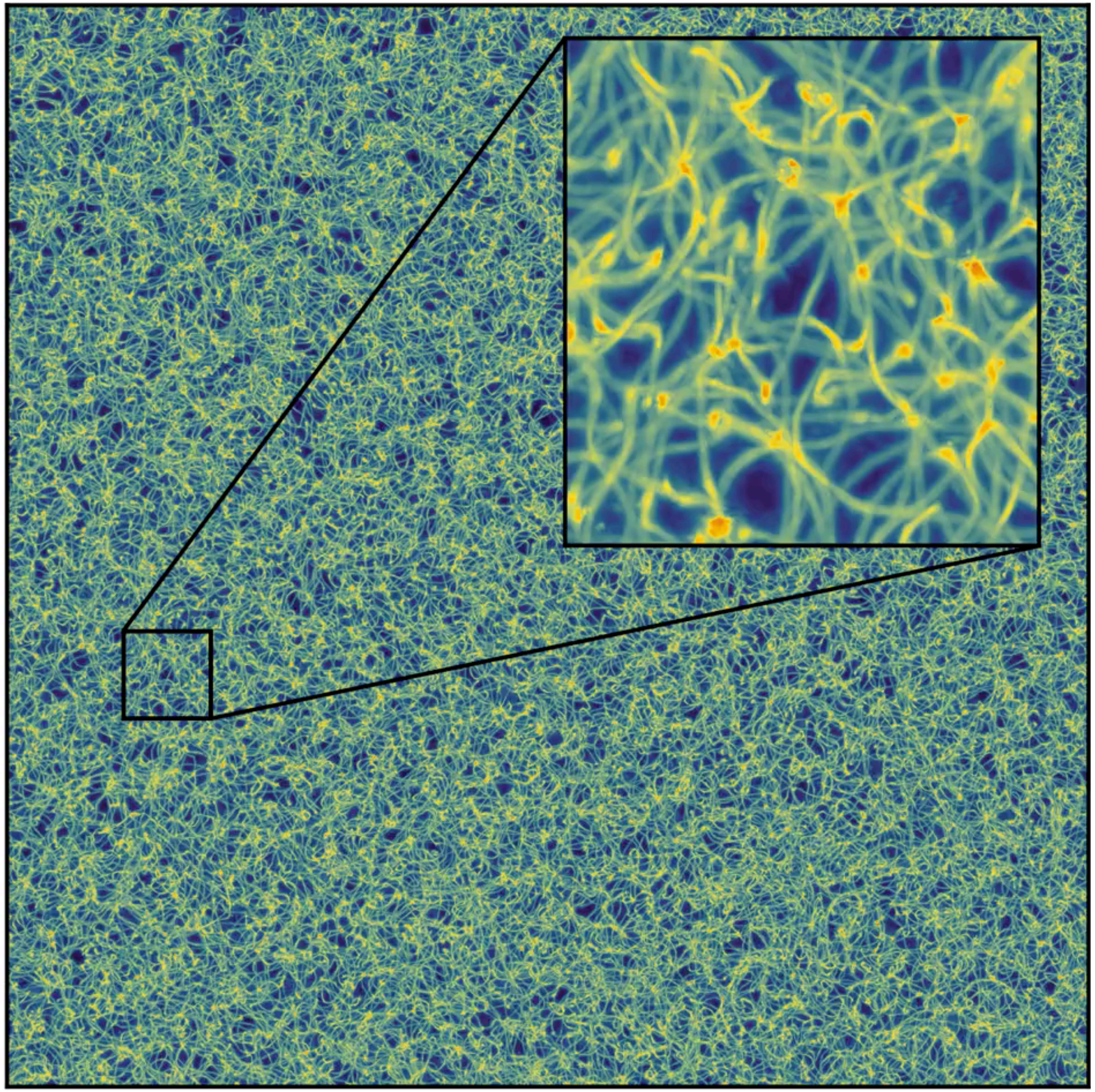
(Movie) CAJO+[2112.05117]

Large numbers of high-density oscillating lumps are seeded towards the end of the simulation

"Axitons"

→ Axion stars

→ Axion miniclusters



(Movie)

CAJO+[2112.05117]

Large numbers of high-density oscillating lumps are seeded towards the end of the simulation

“**Axitons**”

Axion stars

Axion miniclusters

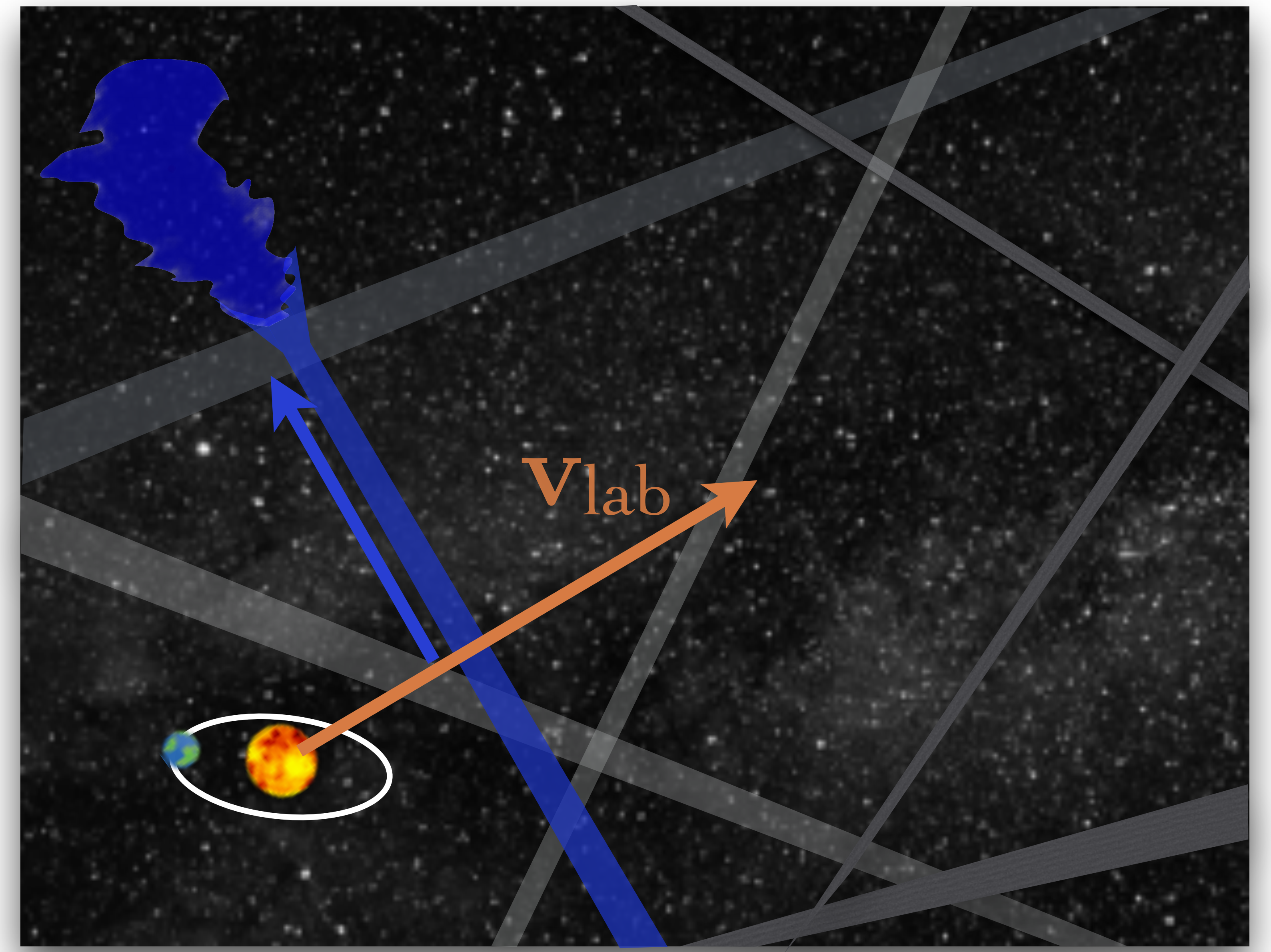
Additional astrophysics signatures…

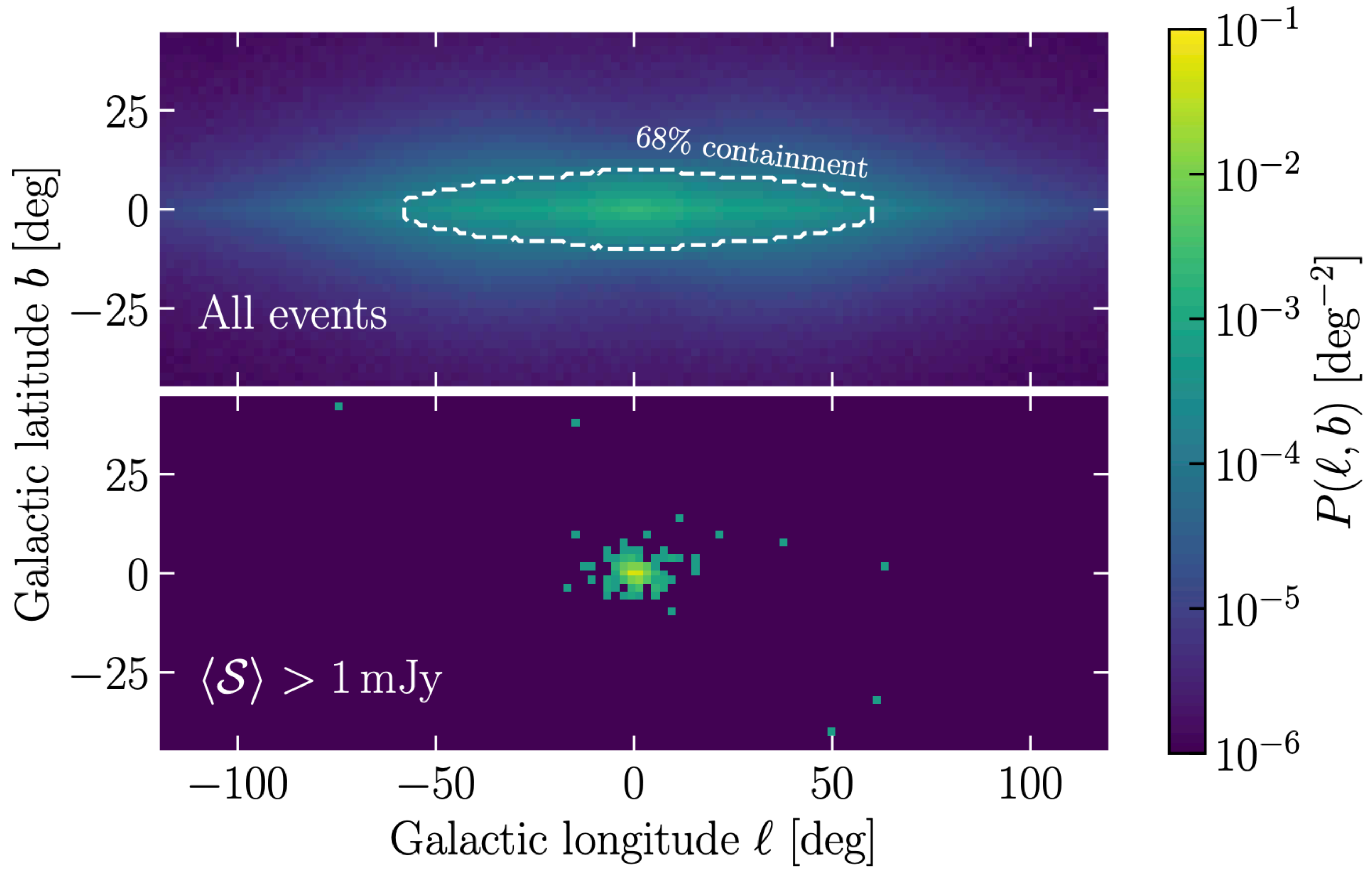
Outstanding problem: the DM distribution

Problems for direct detection

→ Encounter rate ~ once every 10^4—10^6 years.

→ If tidally disrupted by stars we could pass through streams [2011.05377], but this implies a radically different signal model for lab experiments





Opportunities for indirect detection

→ Collision of miniclusters with neutron stars, observe in radio [2011.05378]

→ Miniclusters passing line of sight (microlensing) [1908.01773], [1701.04787]

Directional detection

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

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

Directional axion detection

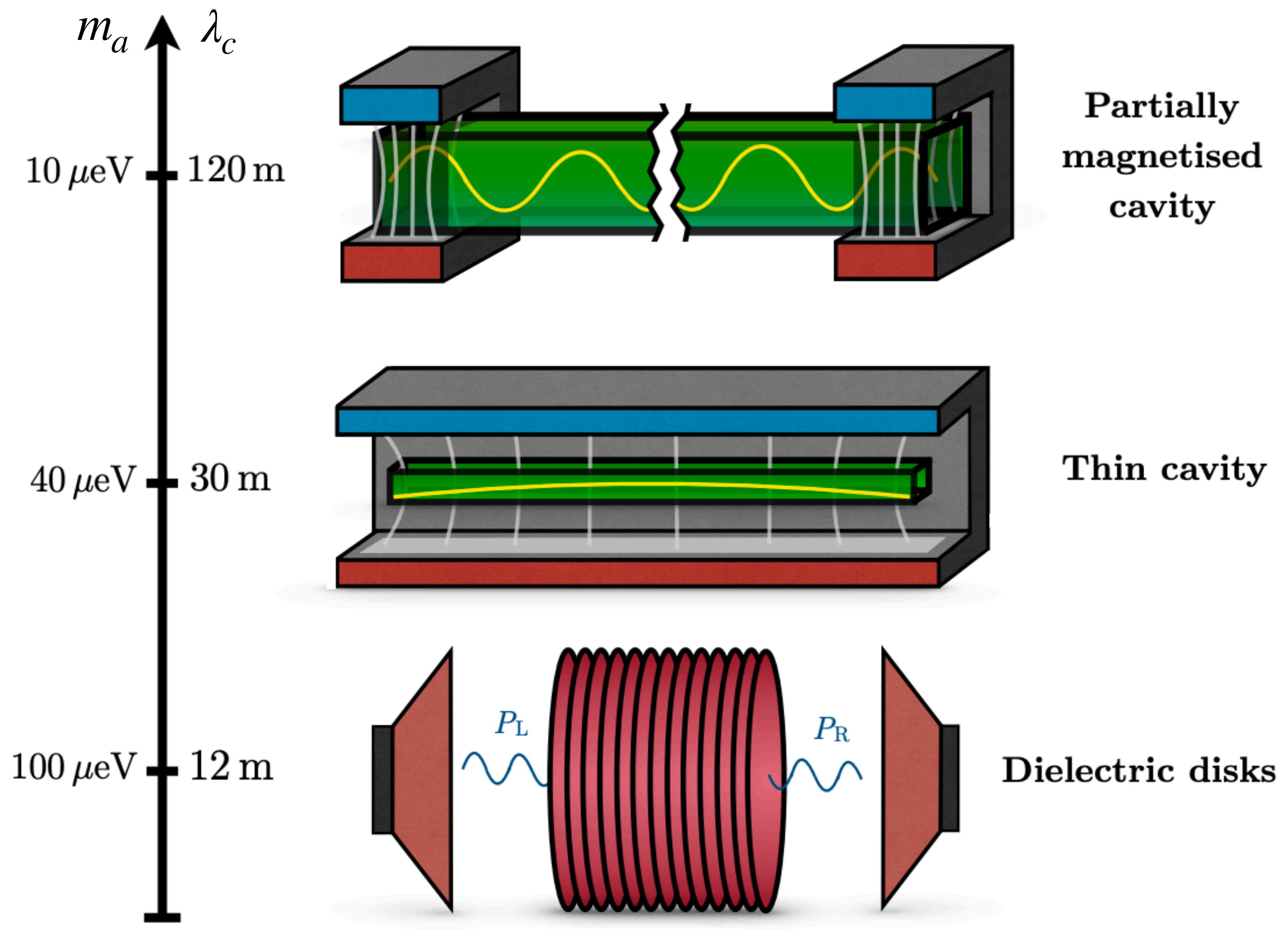
May also be possible to do some kind of directional measurement to extract even more information

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

Single experiment directionality

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

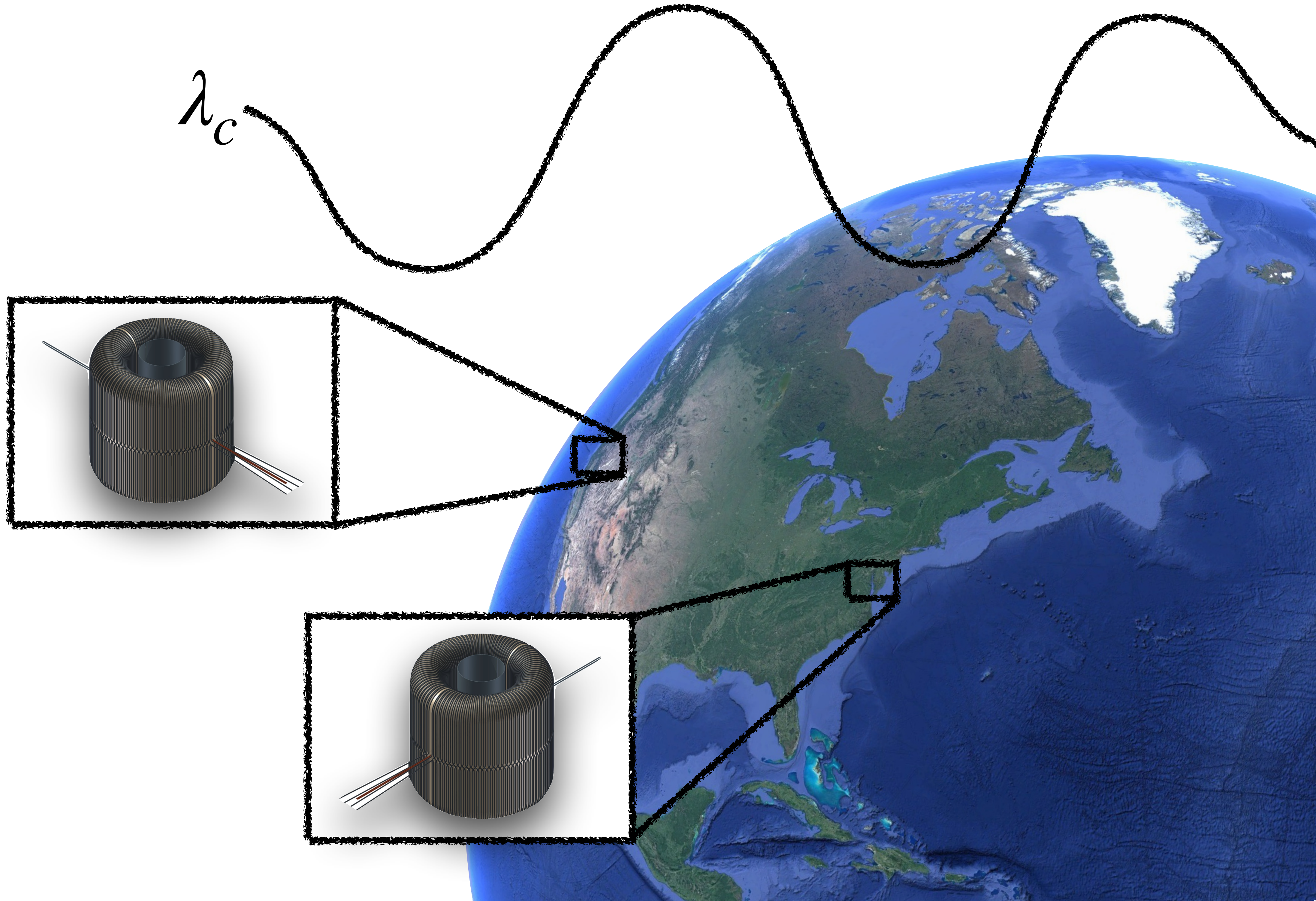
Knirck+ [1806.05927]



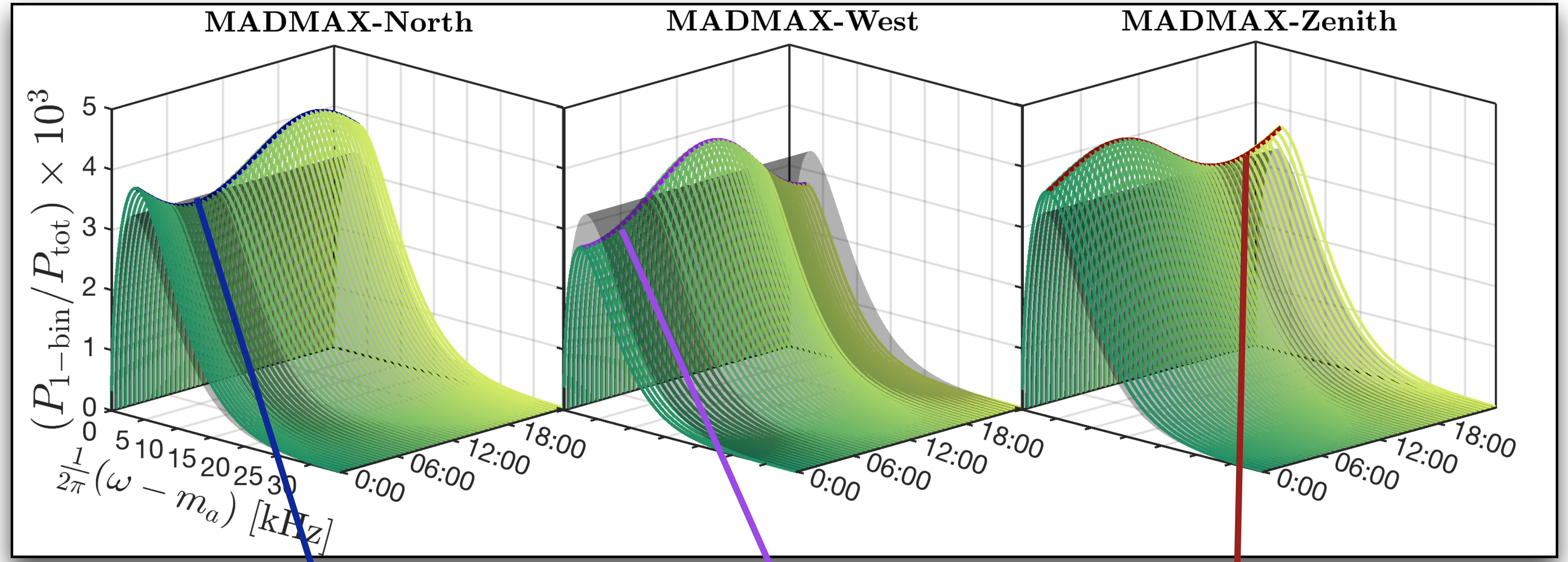
Multi-experiment directionality

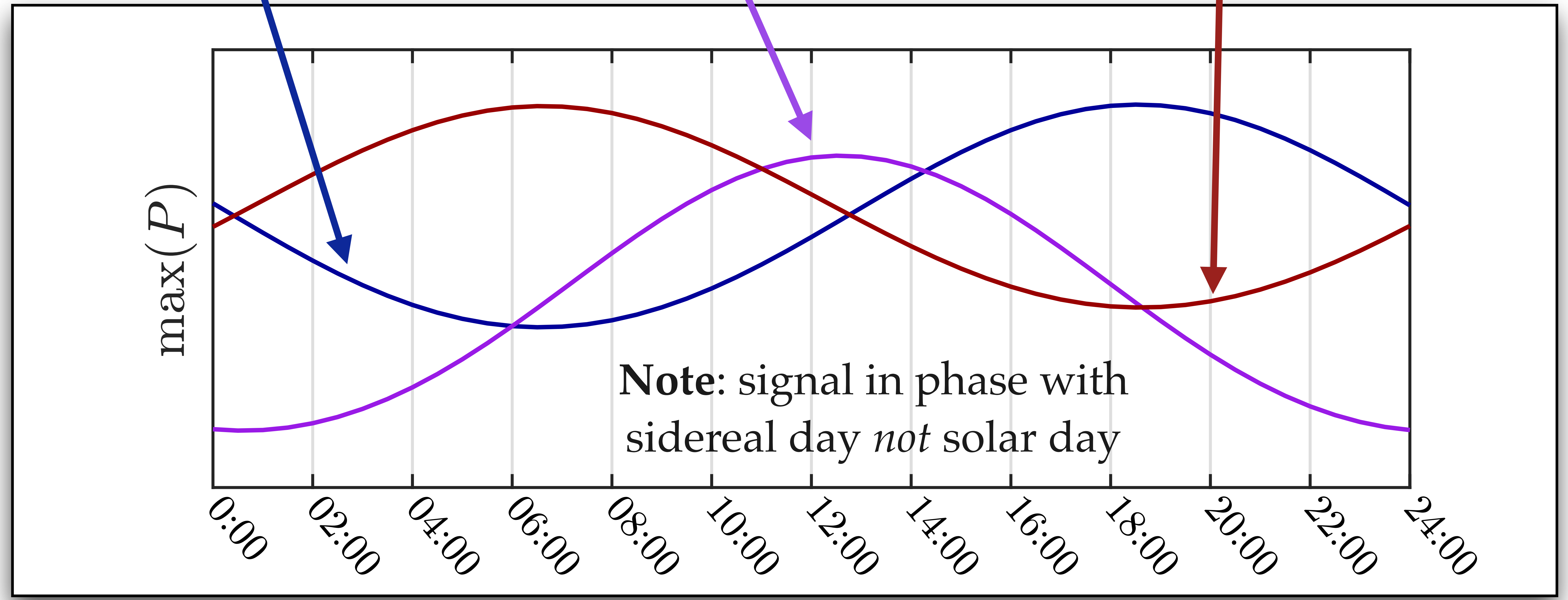
→ combine precise axion phase information at detectors separated by a few coherence lengths

Foster+ [2009.14201]



Daily modulation for a directional experiment

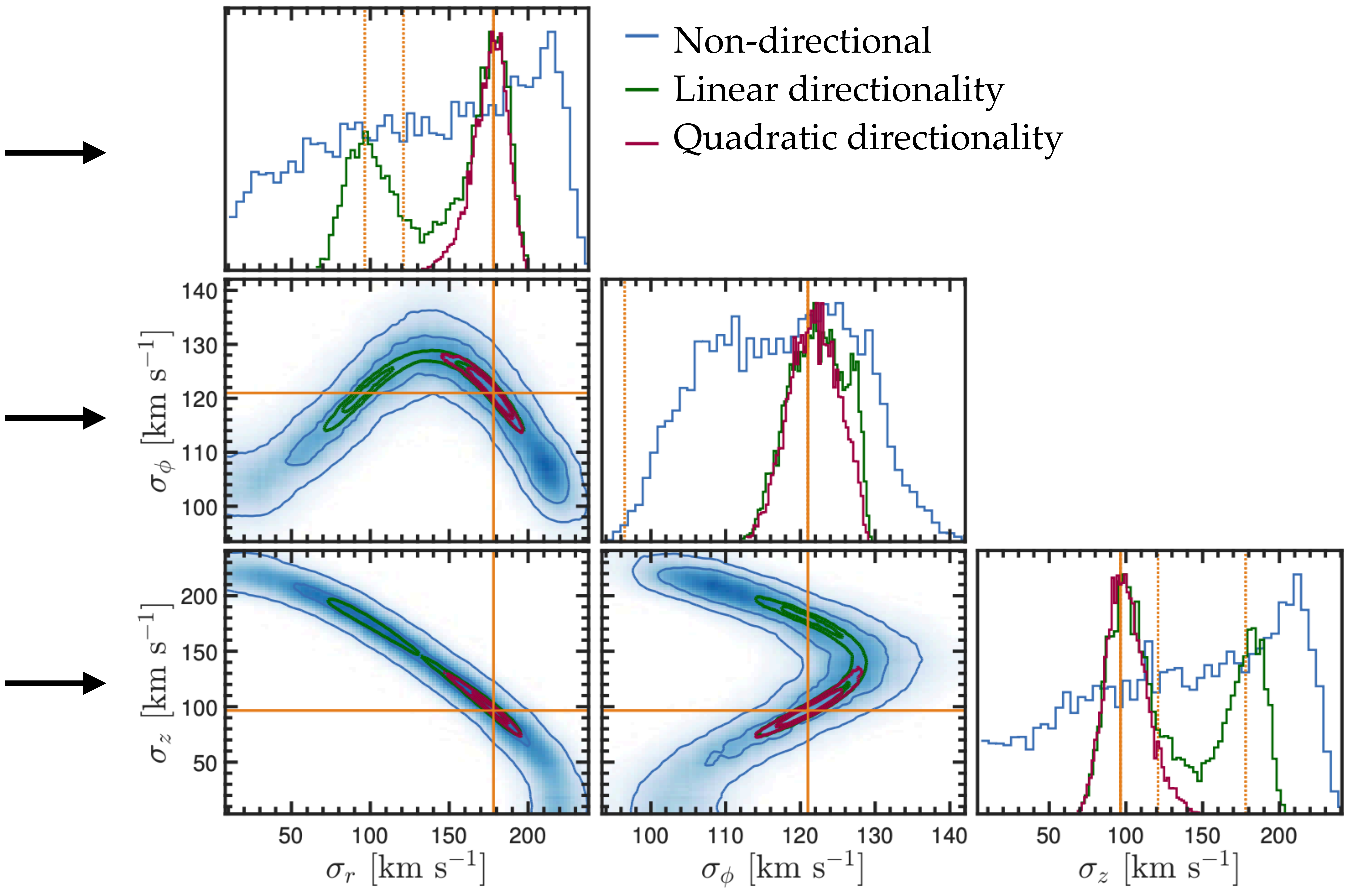




Directional axion detection: Sausage

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

Dispersion along 3 galactic axes

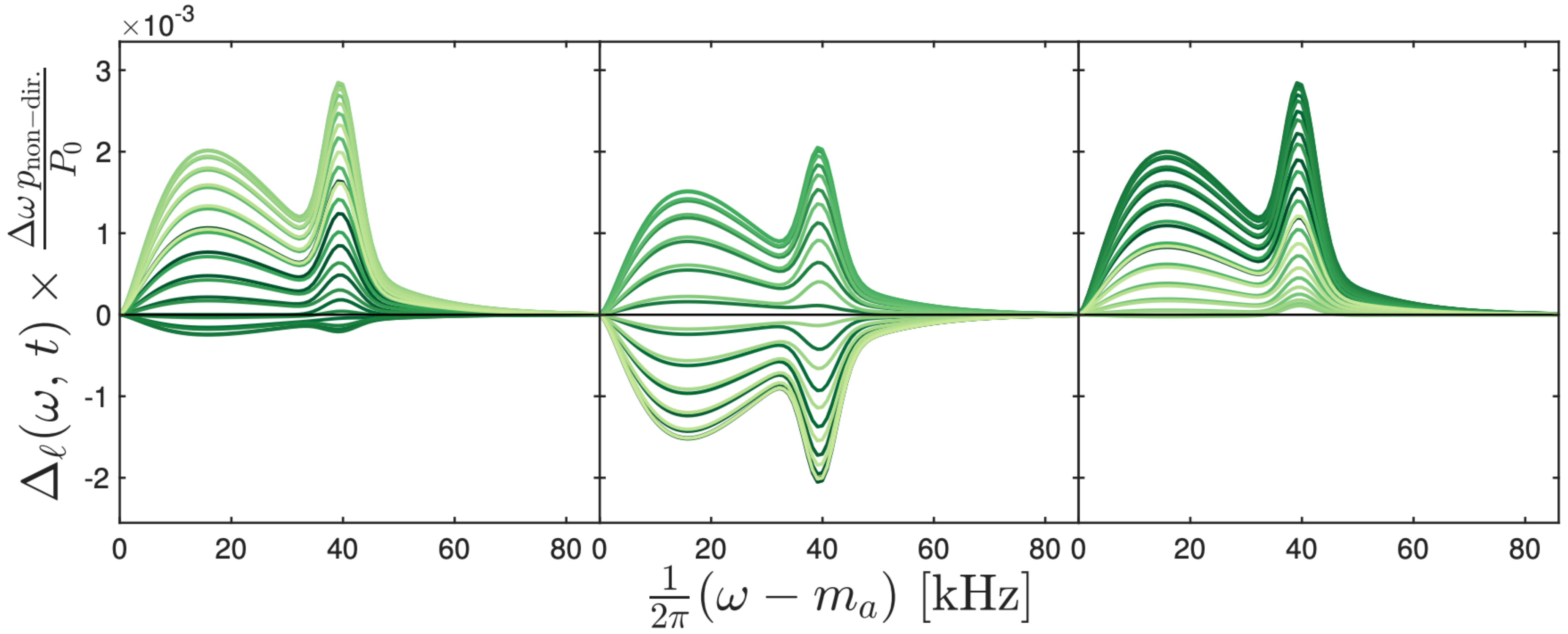


Directional axion detection: streams

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]