# Direct dark matter detection and *Gaia*

Ciaran O'Hare
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# Topics for today

## *Gaia*

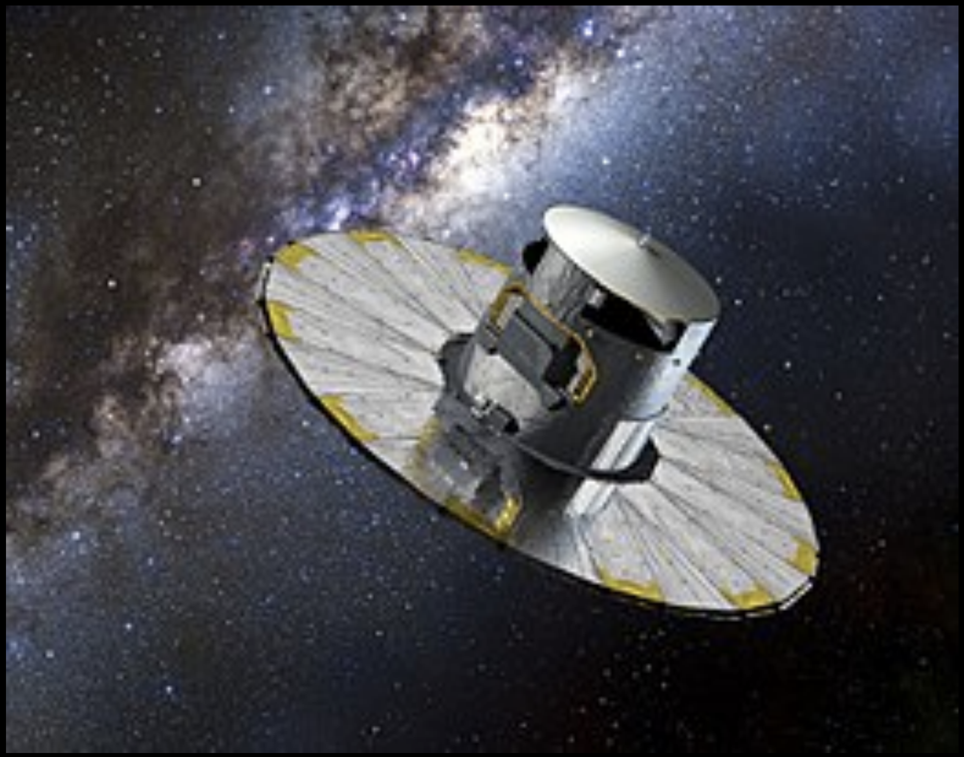
## Structure in the MW halo

## Impact on WIMP searches

## Impact on axion searches

[1807.09004], [1810.11468] and ongoing work

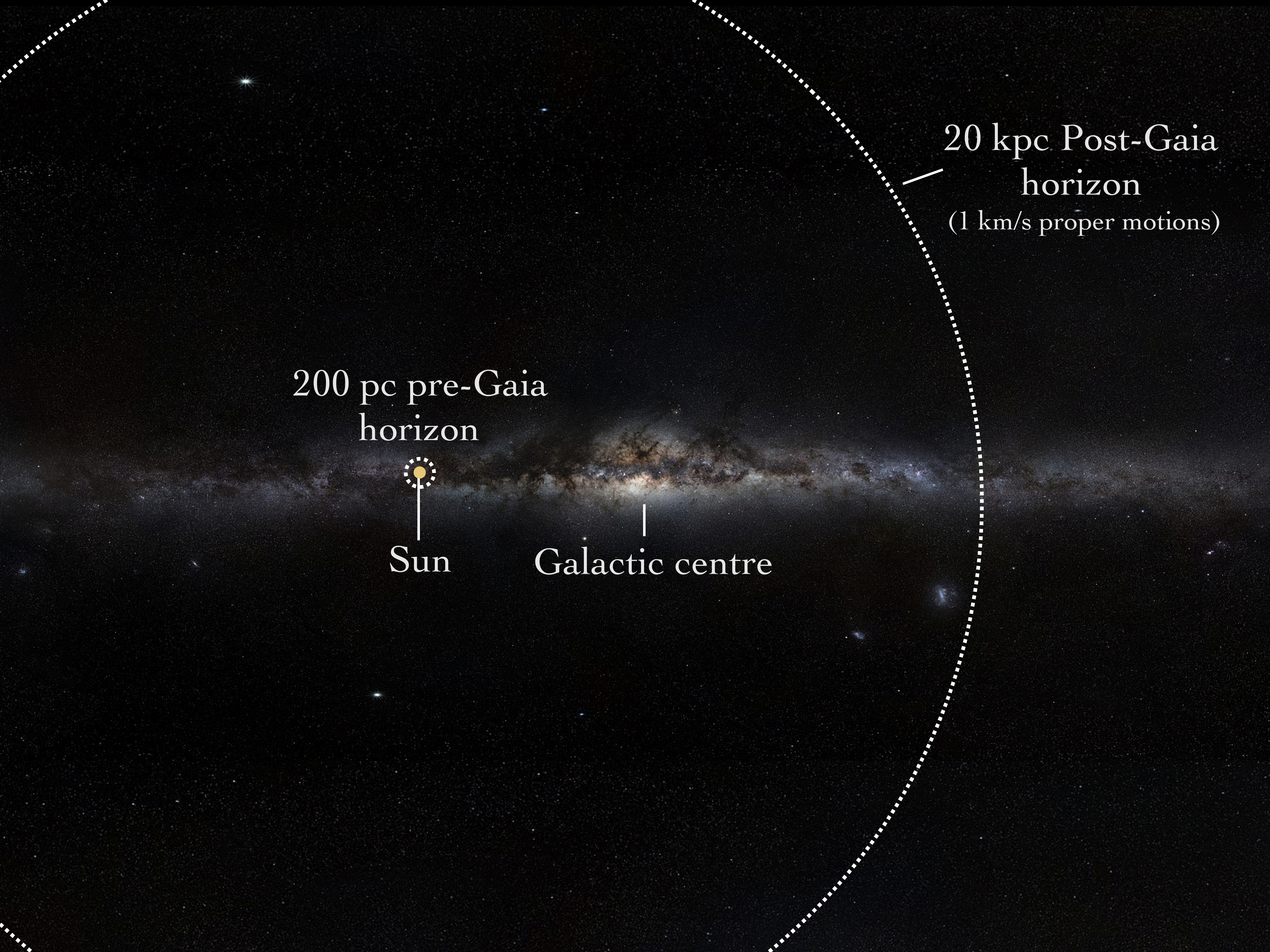
# *Gaia*



- Launched in 2013
- Will operate until ~2022
- 1.7 billion stars (1% of MW)
- Parallax+proper motion on 1.3 billion
- 20 million stars with distance precise to 1%
- 40 million stars with tangential velocity precise to < 0.5 km/s
- 7 million stars with full 6D solution $(x, y, z, v_x, v_y, v_z)$

**Compared to predecessor, Gaia has 10,000 times more stars, over a volume 100,000 times larger, with 1000 times better accuracy**


200 pc pre-Gaia
horizon
Sun
Galactic centre


20 kpc Post-Gaia
horizon
(1 km/s proper motions)
200 pc pre-Gaia
horizon
Sun
Galactic centre

# Sample of the stellar halo in *Gaia*:

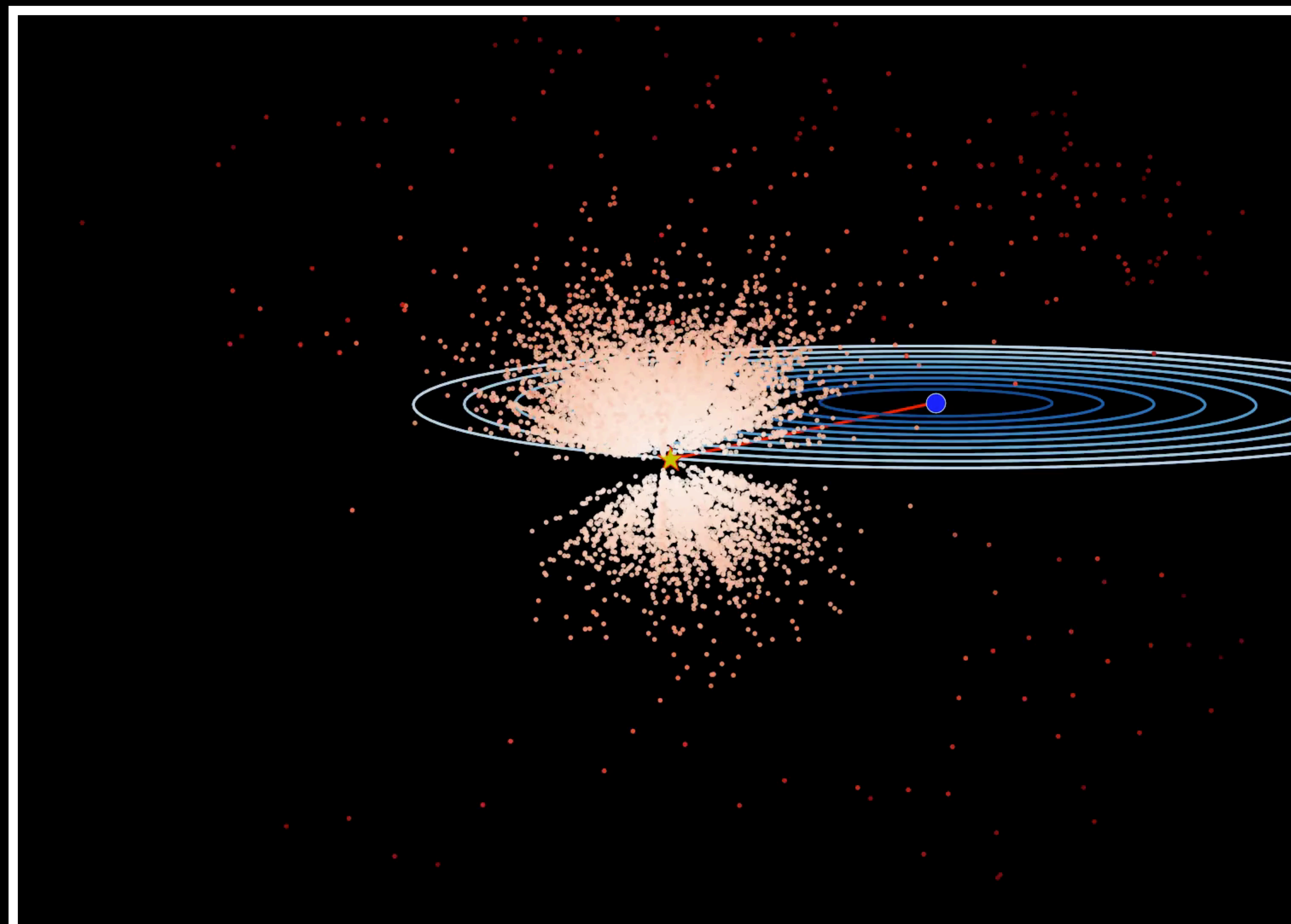
(can be cross-matched with spectroscopic surveys too: SDSS, LAMOST, APOGEE, RAVE-*On*)

~62,000 Main sequence turn off stars out to 10 kpc

All stars in "7D"

$x, y, z, v_x, v_y, v_z,$

+ metallicity [Fe/H]



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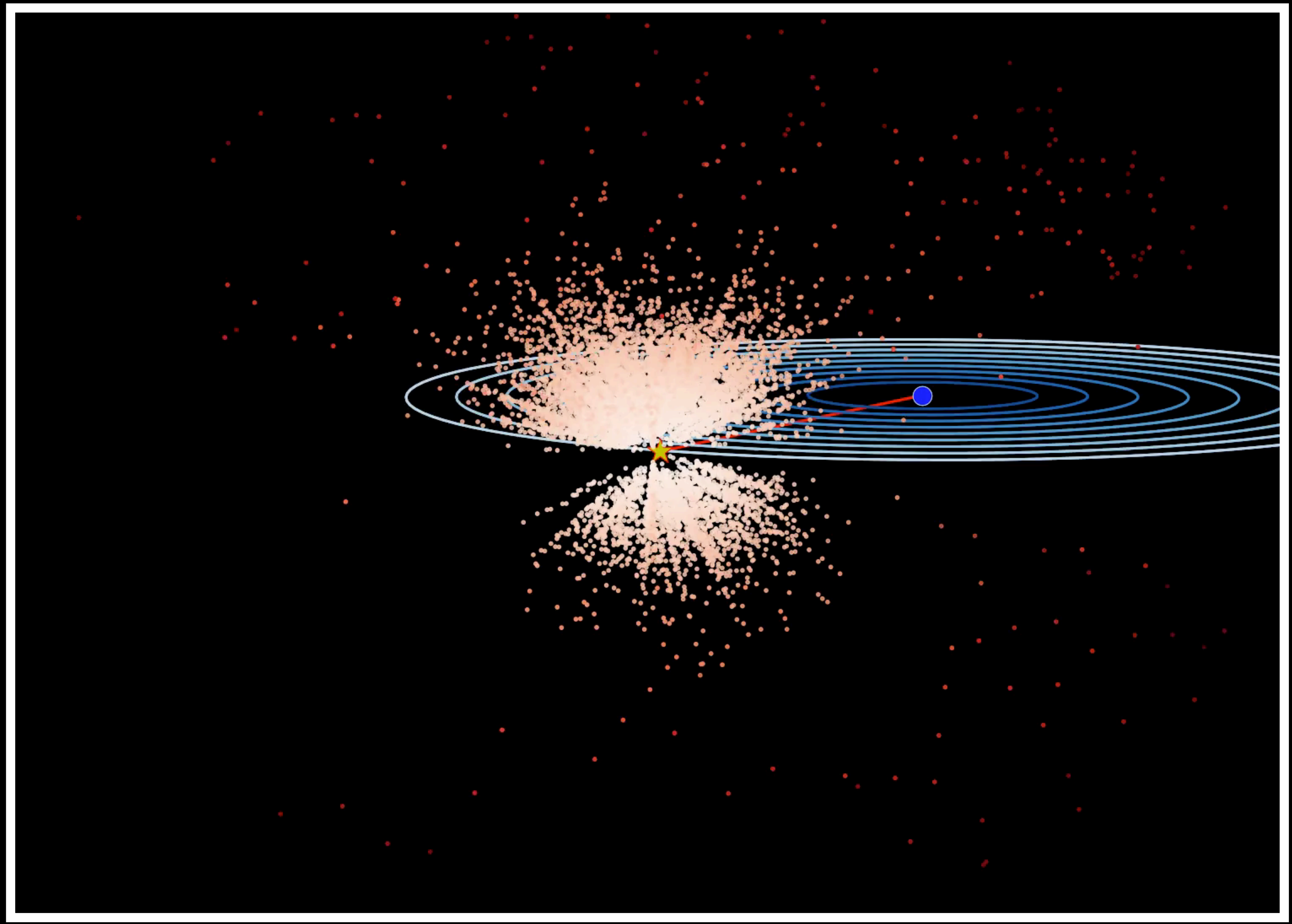

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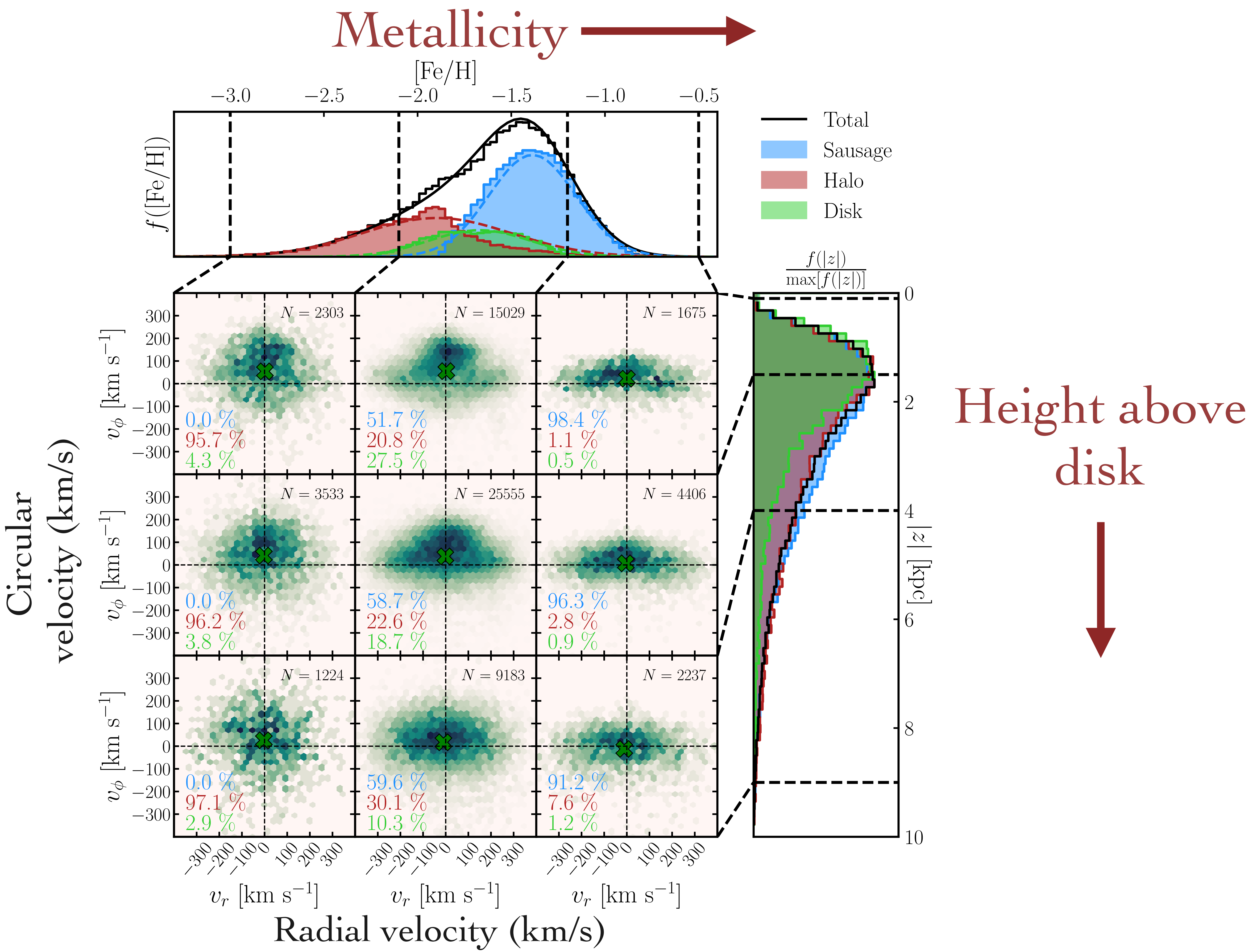
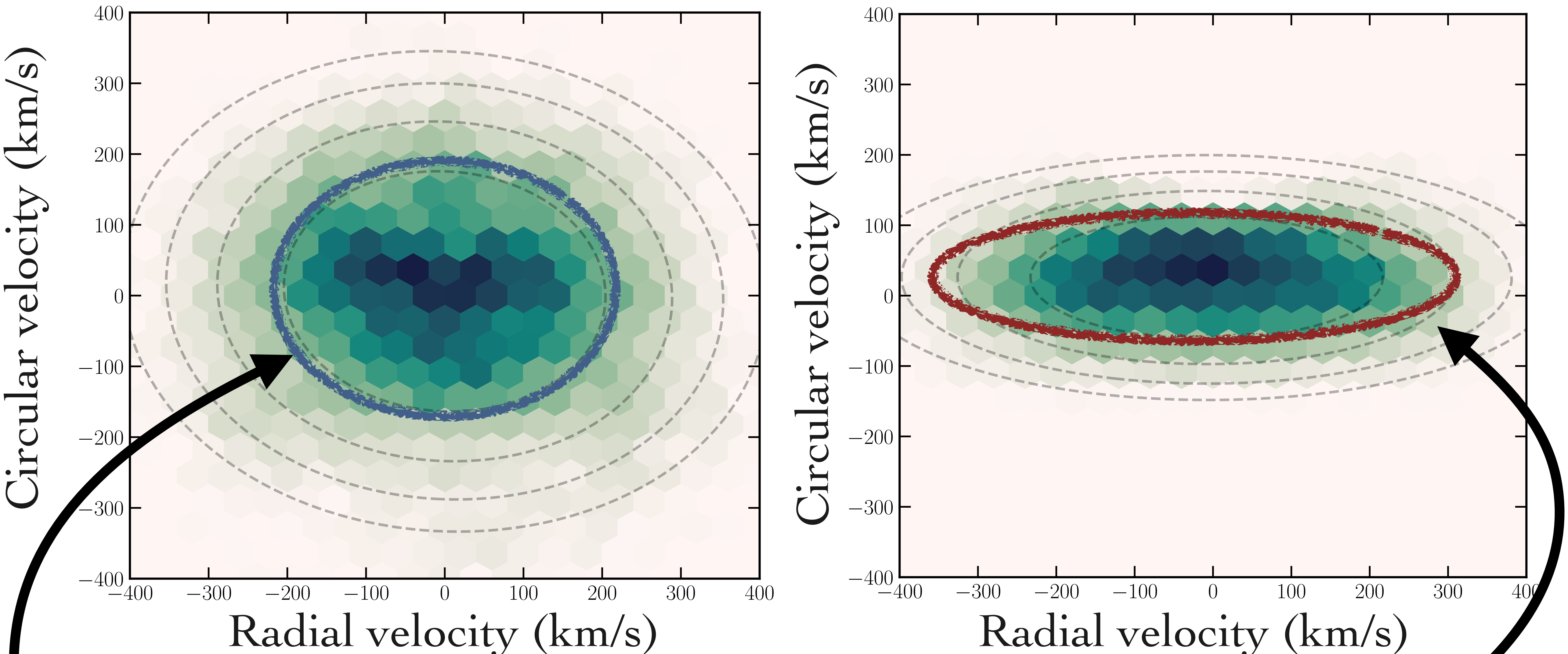


Metallicity
[Fe/H]
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
f([Fe/H])
Total
Sausage
Halo
Disk
f(|z|) / max[f(|z|)]
N = 2303
N = 15029
N = 1675
N = 3533
N = 25555
N = 4406
N = 1224
N = 9183
N = 2237
0.0 %
95.7 %
4.3 %
51.7 %
20.8 %
27.5 %
98.4 %
1.1 %
0.5 %
0.0 %
96.2 %
3.8 %
58.7 %
22.6 %
18.7 %
96.3 %
2.8 %
0.9 %
0.0 %
97.1 %
2.9 %
59.6 %
30.1 %
10.3 %
91.2 %
7.6 %
1.2 %
Height above disk
|z| [kpc]
Circular velocity (km/s)
$v_\phi$ [km s$^{-1}$]
$v_r$ [km s$^{-1}$]
Radial velocity (km/s)

## Metal-poor halo [Fe/H]<-1.5

## Metal-rich halo [Fe/H]>-1.5




## The "Halo"

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

## The "Sausage"

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

# Gaia Sausage

From Wikipedia, the free encyclopedia

The **Gaia Sausage** is the remains of a dwarf galaxy, the "Sausage Galaxy" or **Gaia-Enceladus-Sausage** or just **Gaia-Enceladus**, that merged with the Milky Way about 8 - 11 billion years ago. At least eight globular clusters were added to the Milky Way along with 50 billion solar masses of stars, gas and dark matter.[1] The "Gaia Sausage" is so-called because of the characteristic sausage shape of the population in velocity space, the appearance on a plot of radial versus azimuthal and vertical velocities of stars measured in the Gaia Mission.[1] The stars that have merged with the Milky Way have orbits that are highly radial. The outermost points of their orbits are around 20 kiloparsecs from the galactic centre at what is called the halo break.[2]

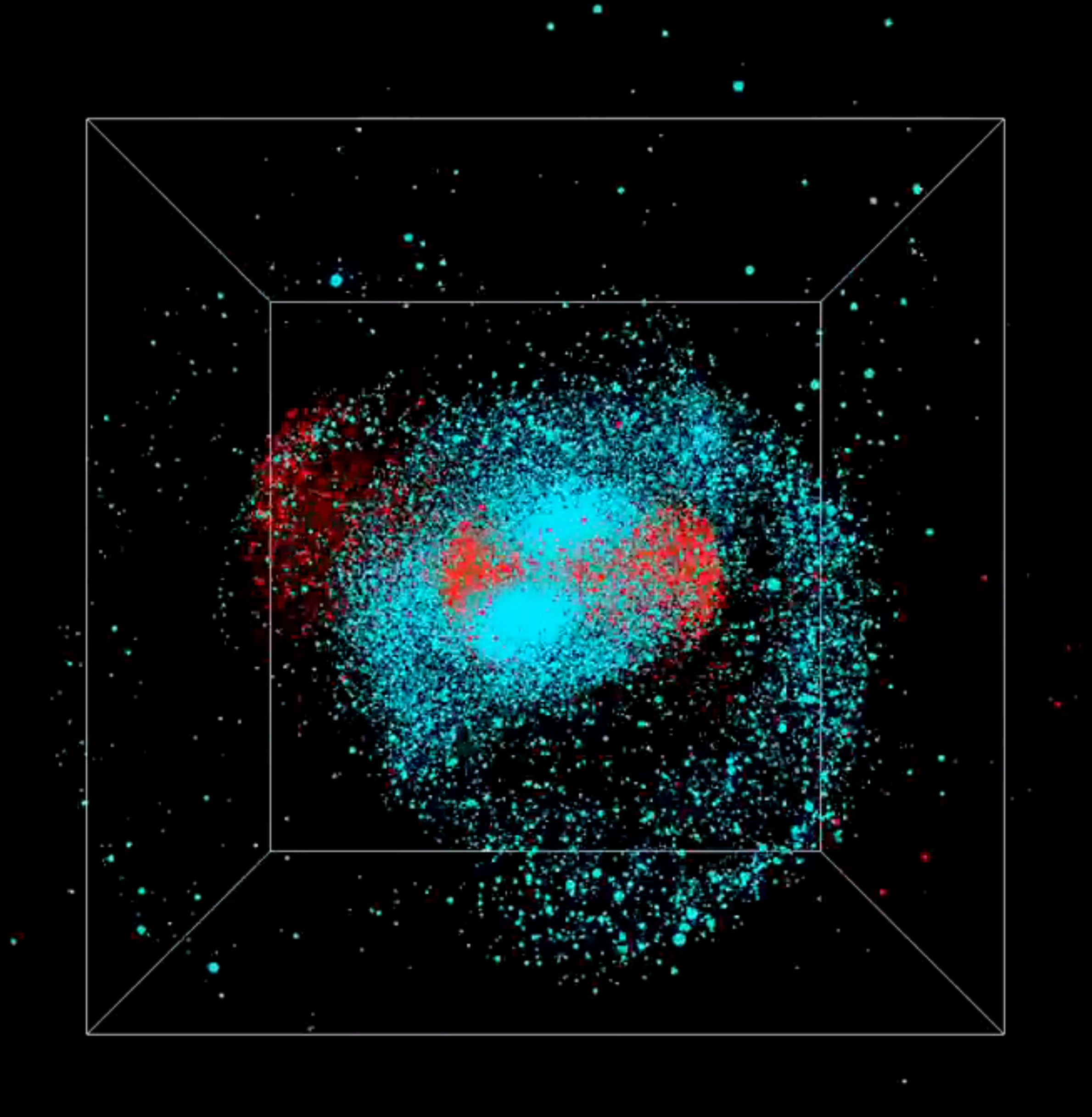
**Contents** [hide]



## Components [ edit ]

The Sausage globular clusters are NGC 1851, NGC 1904, NGC 2298, NGC 2808 (possibly the old galactic core), NGC 5286, NGC 6864, NGC 6779, and NGC 7089.[1]

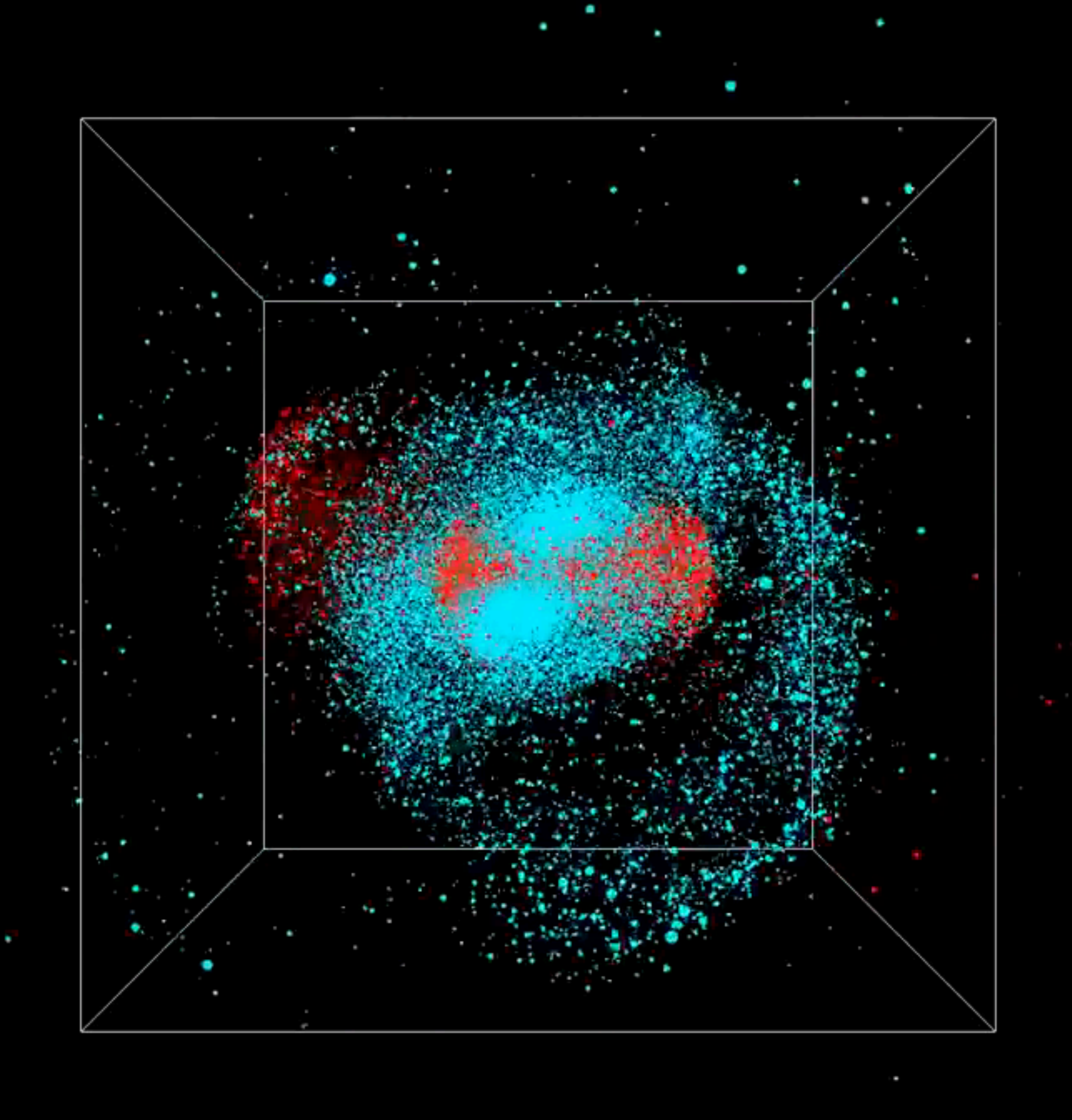
# Distinct chemodynamical signature implies that the **Gaia sausage** formed after a large merger with a $10^{11}$ $M_{\odot}$ dwarf galaxy, 8-10 billion years ago



- Highly radial orbits $\beta \sim 0.9$ suggest head-on collision with small impact parameter
- Interpretation consistent with the break in stellar density at 20 kpc → pileup of stars at apocentre
- Associated with 8 known globular clusters

**Helmi et al. 1806.06038**

Distinct chemodynamical signature implies that the **Gaia sausage** formed after a large merger with a $10^{11}$ $M_\odot$ dwarf galaxy, 8-10 billion years ago



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Helmi et al. 1806.06038

# New understanding of Milky Way halo
# → New signal model for dark matter experiments

arXiv:[1810.11468]

KCL-PH-TH-2018-49

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

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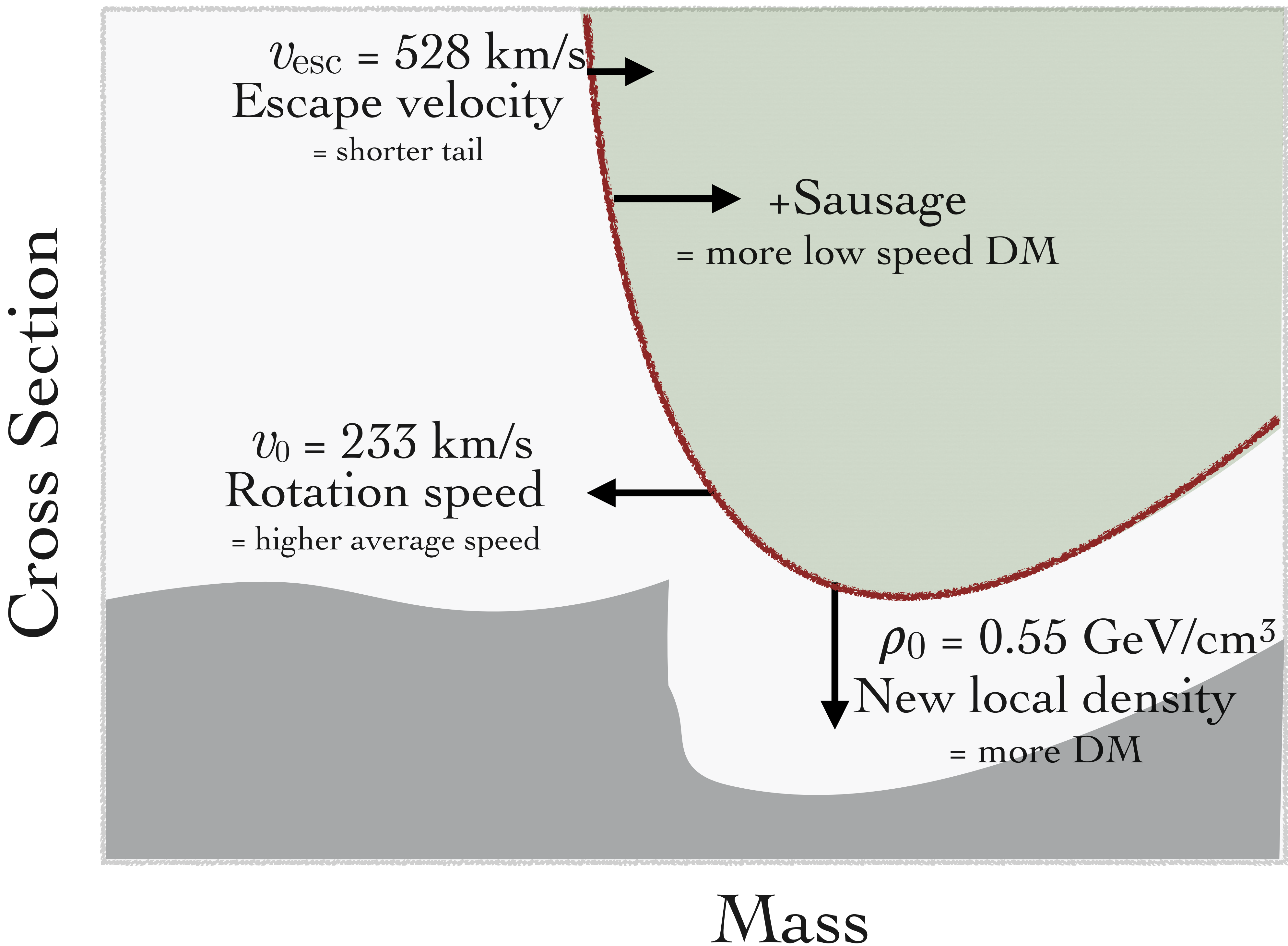
[2]*Departamento de Física Teórica, Universidad de Zaragoza, Pedro Cerbuna 12, E-50009, Zaragoza, España*
[3]*Department of Physics, King's College London, Strand, London, WC2R 2LS, United Kingdom*

(Dated: October 30, 2018)

Predicting signals in experiments to directly detect dark matter (DM) requires a form for the local DM velocity distribution. Hitherto, the standard halo model (SHM), in which velocities are isotropic and follow a truncated Gaussian law, has performed this job. New data, however, suggest that a substantial fraction of our stellar halo lies in a strongly radially anisotropic population, the '*Gaia* Sausage'. Inspired by this recent discovery, we introduce an updated DM halo model, the

# Impact of new model on WIMPs

## Summary of the updates included in the **SHM**$^{++}$



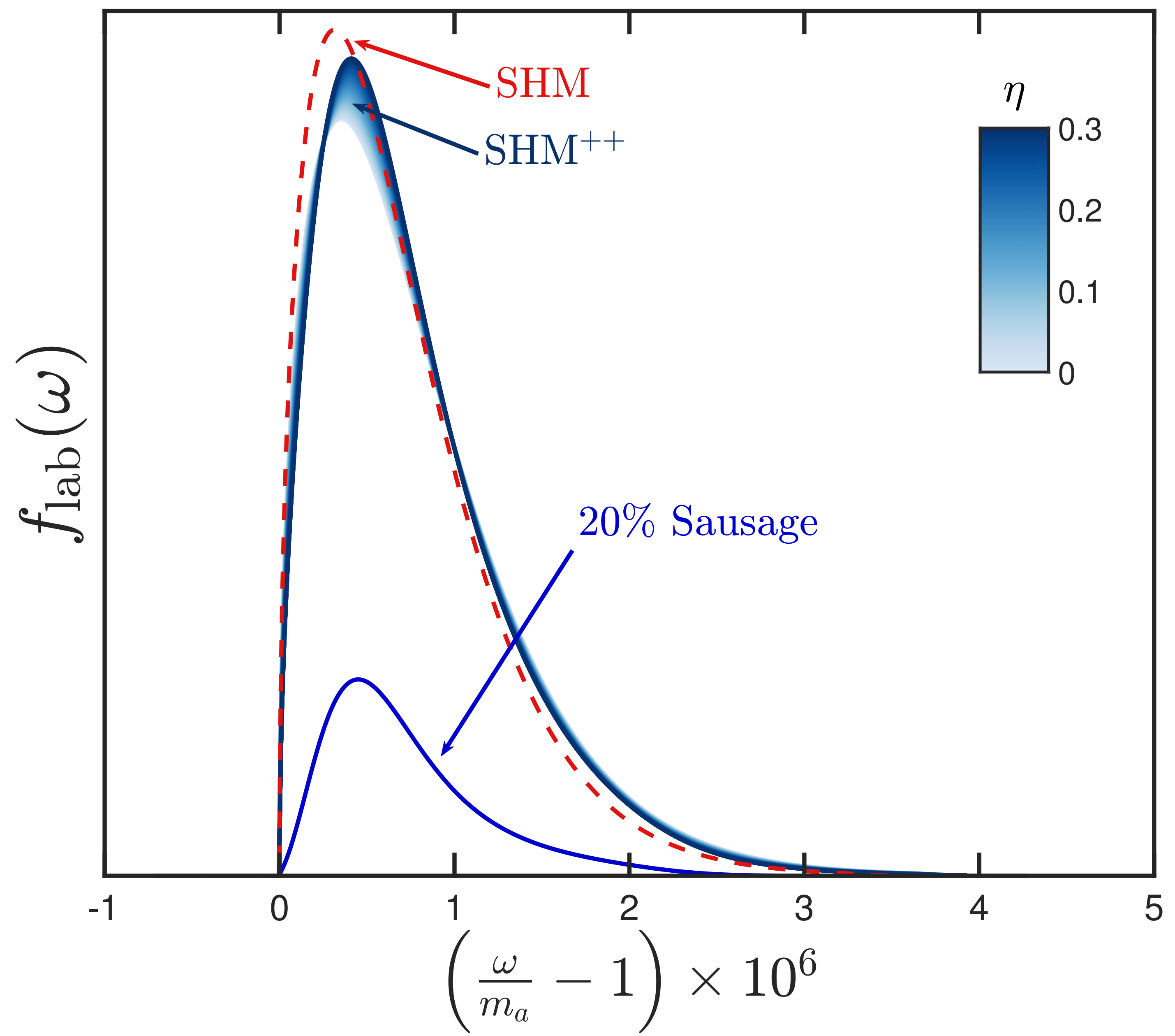
# For axions…

- Increase in axion linewidth → weaker limits
- Increase in local density → stronger limits
- Overall, SHM++ limits only about 8% stronger

**SHM still ok for axions,**

**However…**

→ Presence of the Sausage means the lineshape is much wider along the Galactic radial direction. Potentially important for axion wind and modulation-based experiments



# Substructure

# A galaxy is built from orbits

**Phase space**

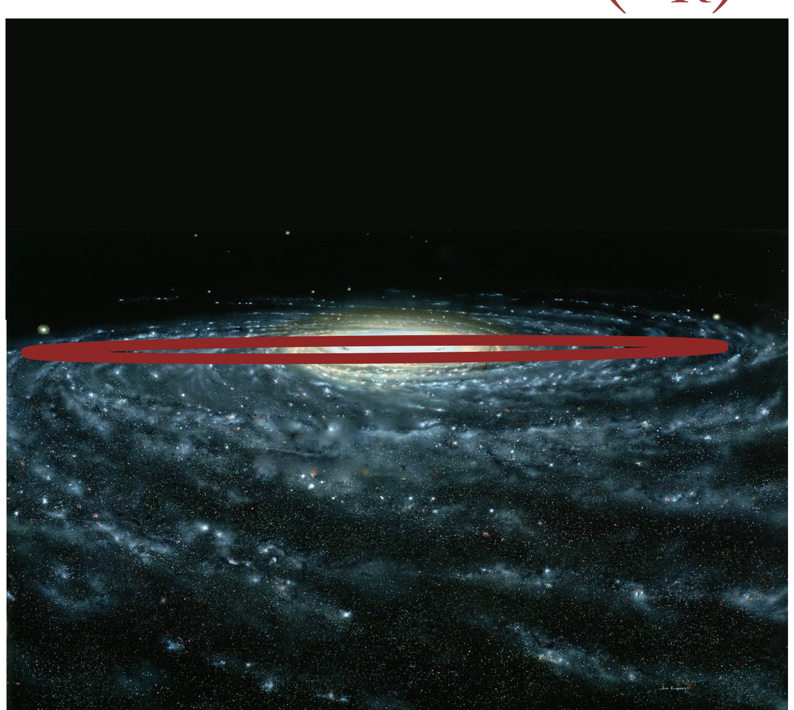
Each star sits at a location in 6D $(x, y, z, v_x, v_y, v_z)$

(integrate orbit assuming model for grav. potential)

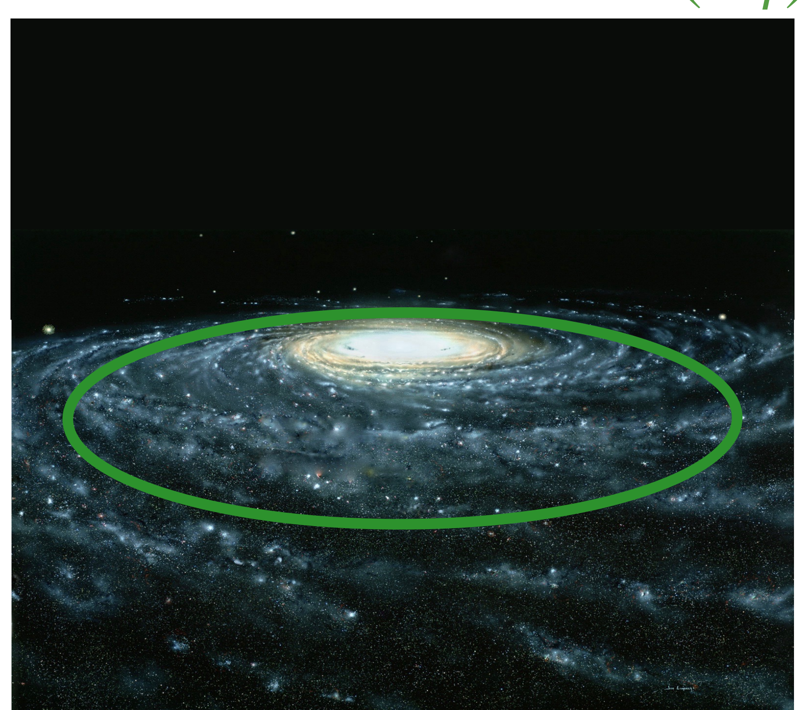
**Action space**

Stars are locations in 3D space of orbits

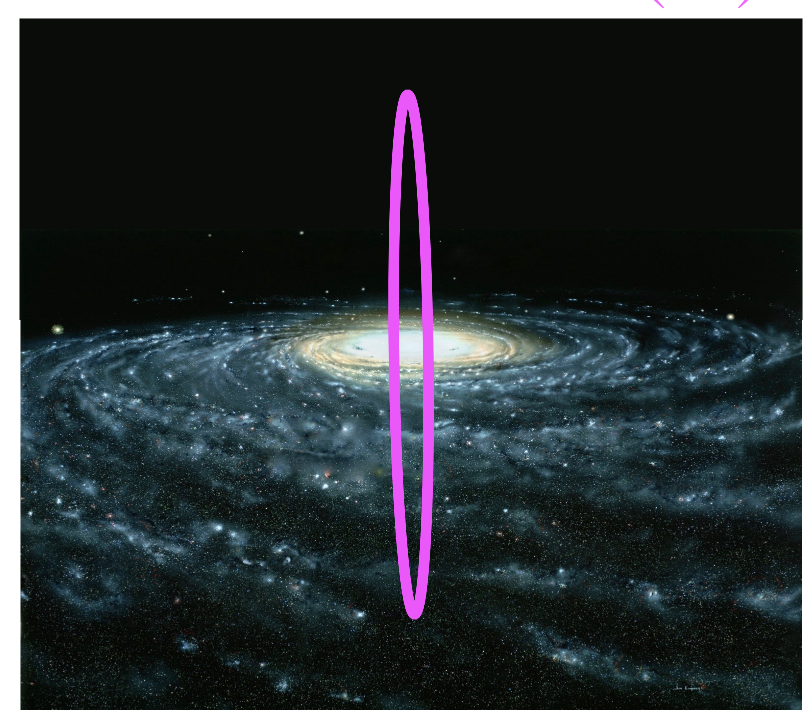
Radial action $(J_R)$



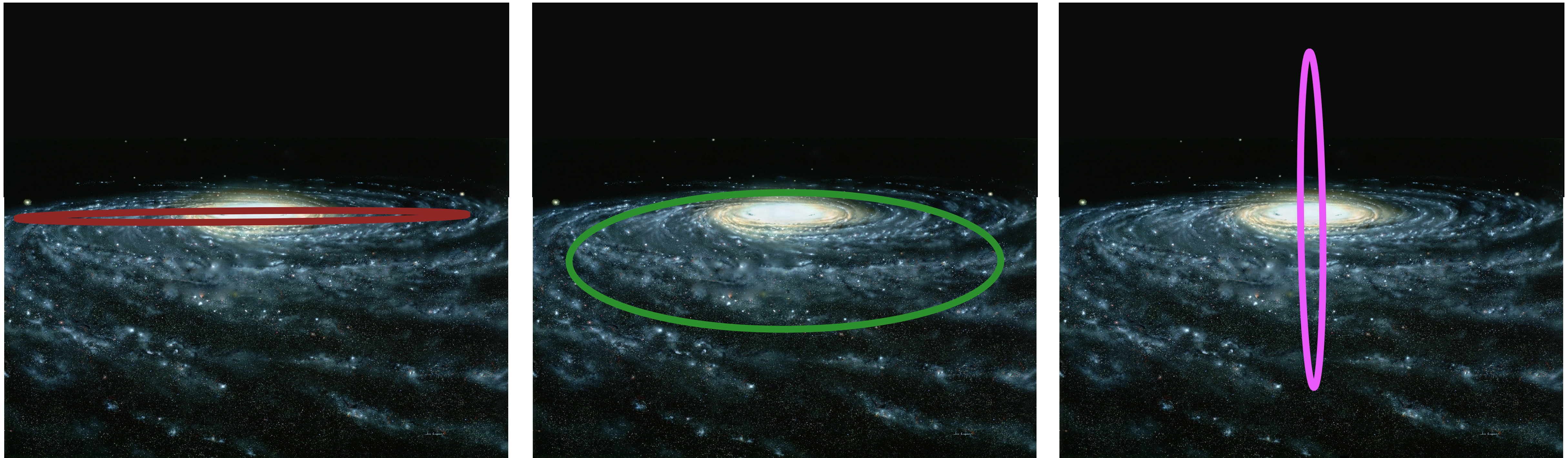
Azimuthal action $(J_\phi)$



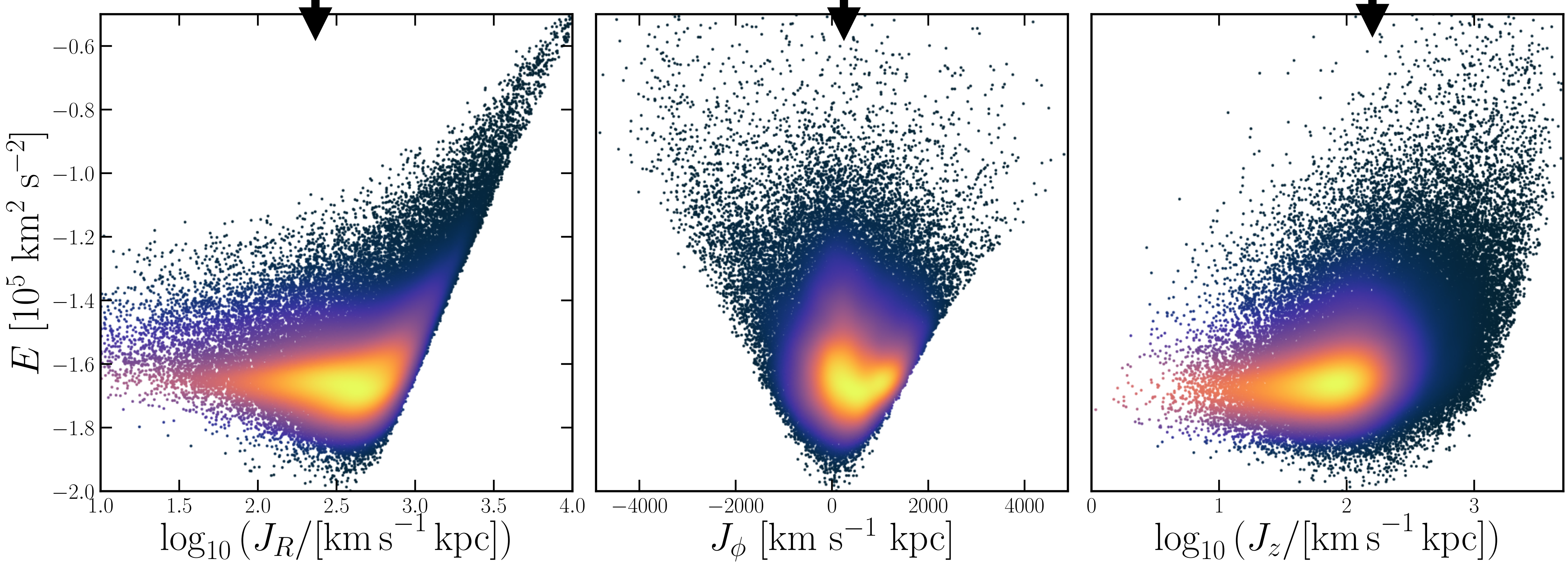
Vertical action $(J_z)$



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



**Actions in cylindrical polars vs orbital energy (E)**



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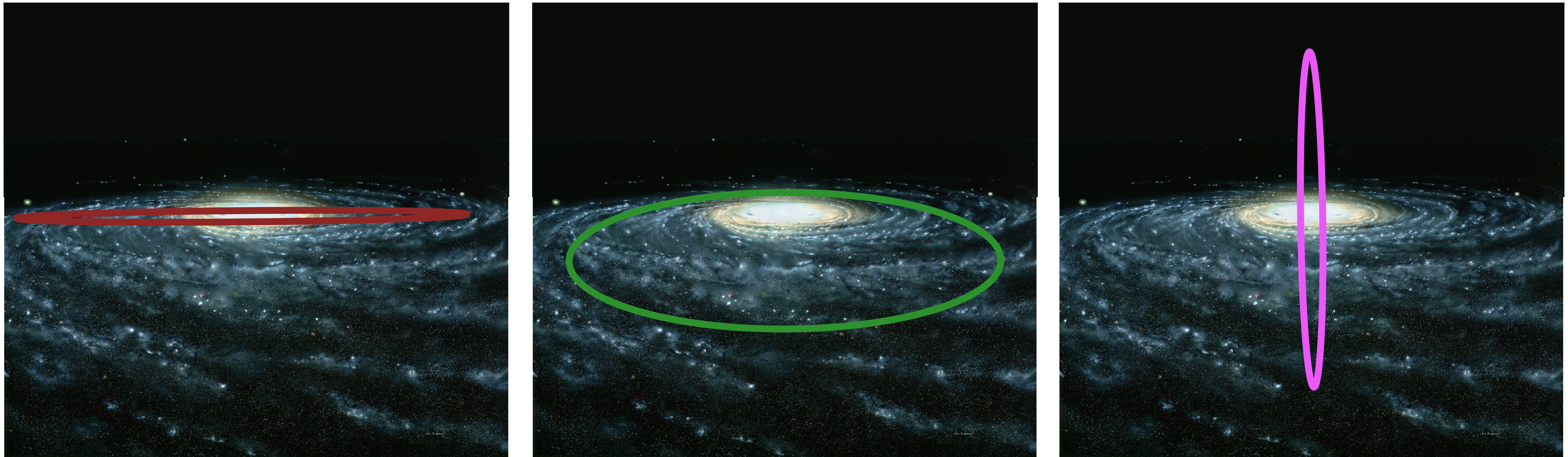

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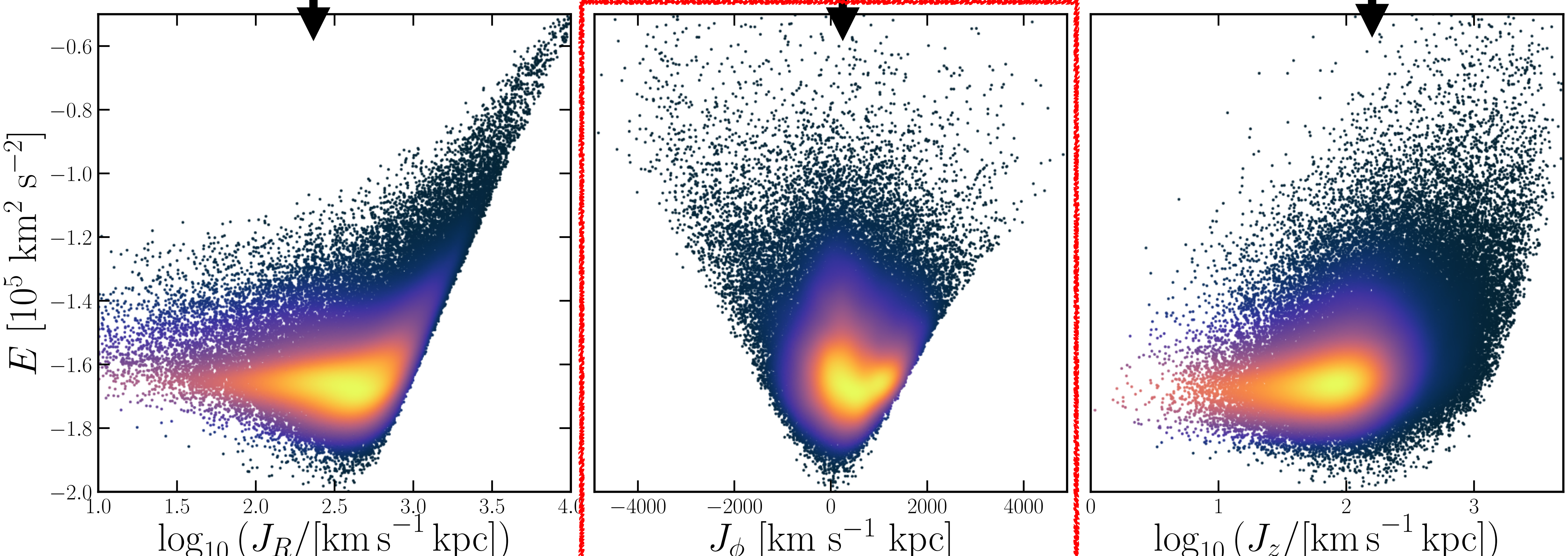
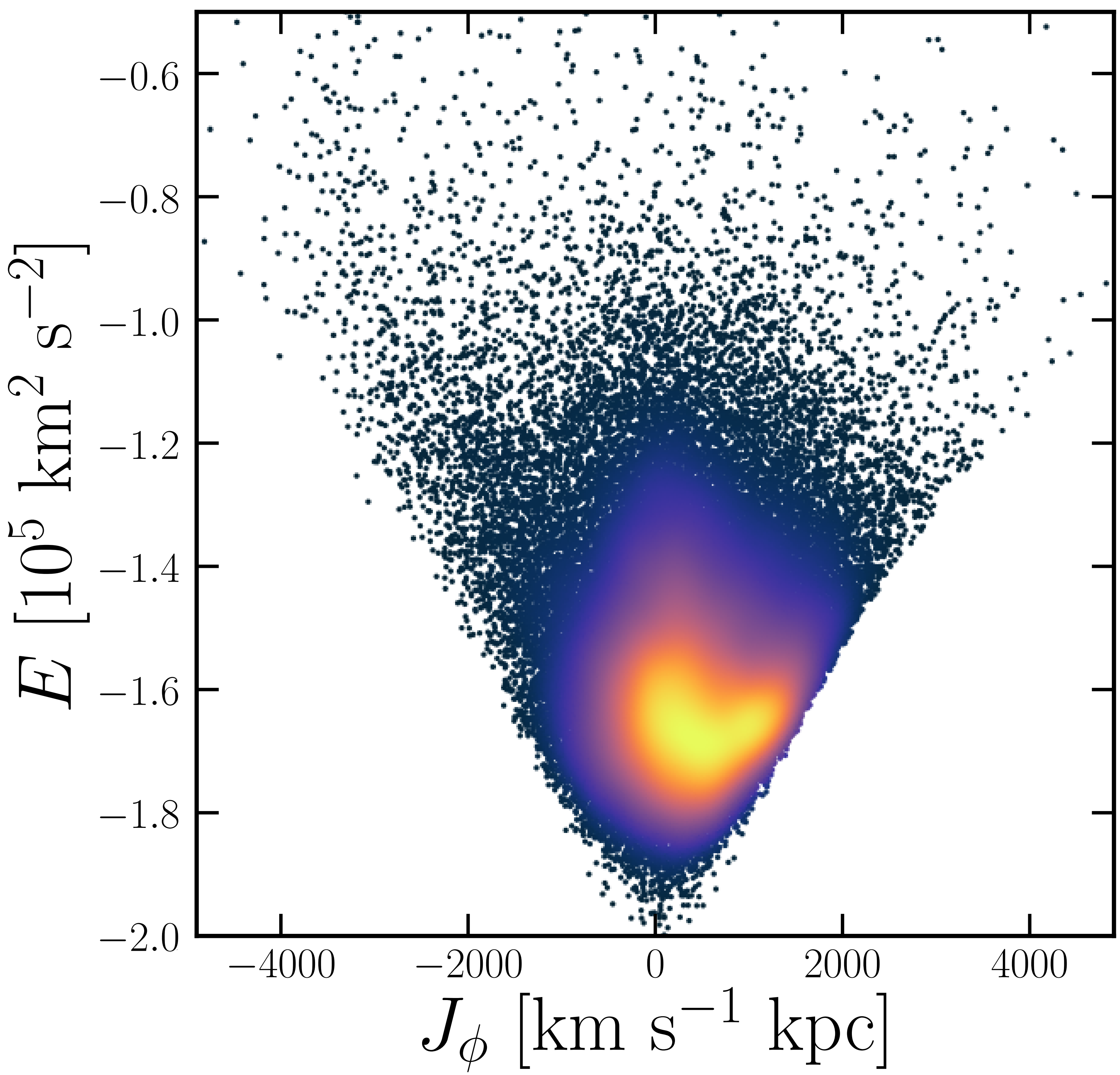
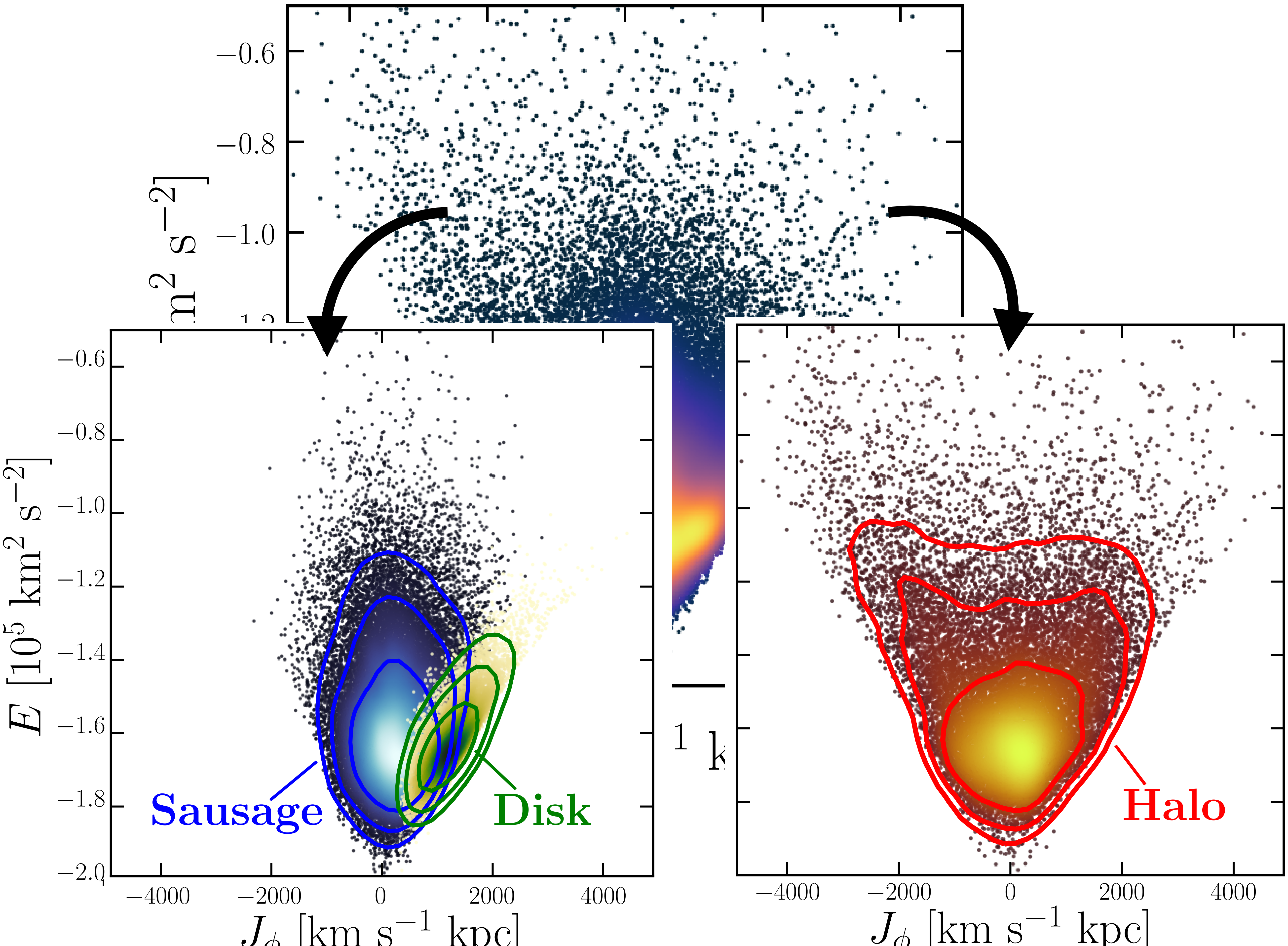
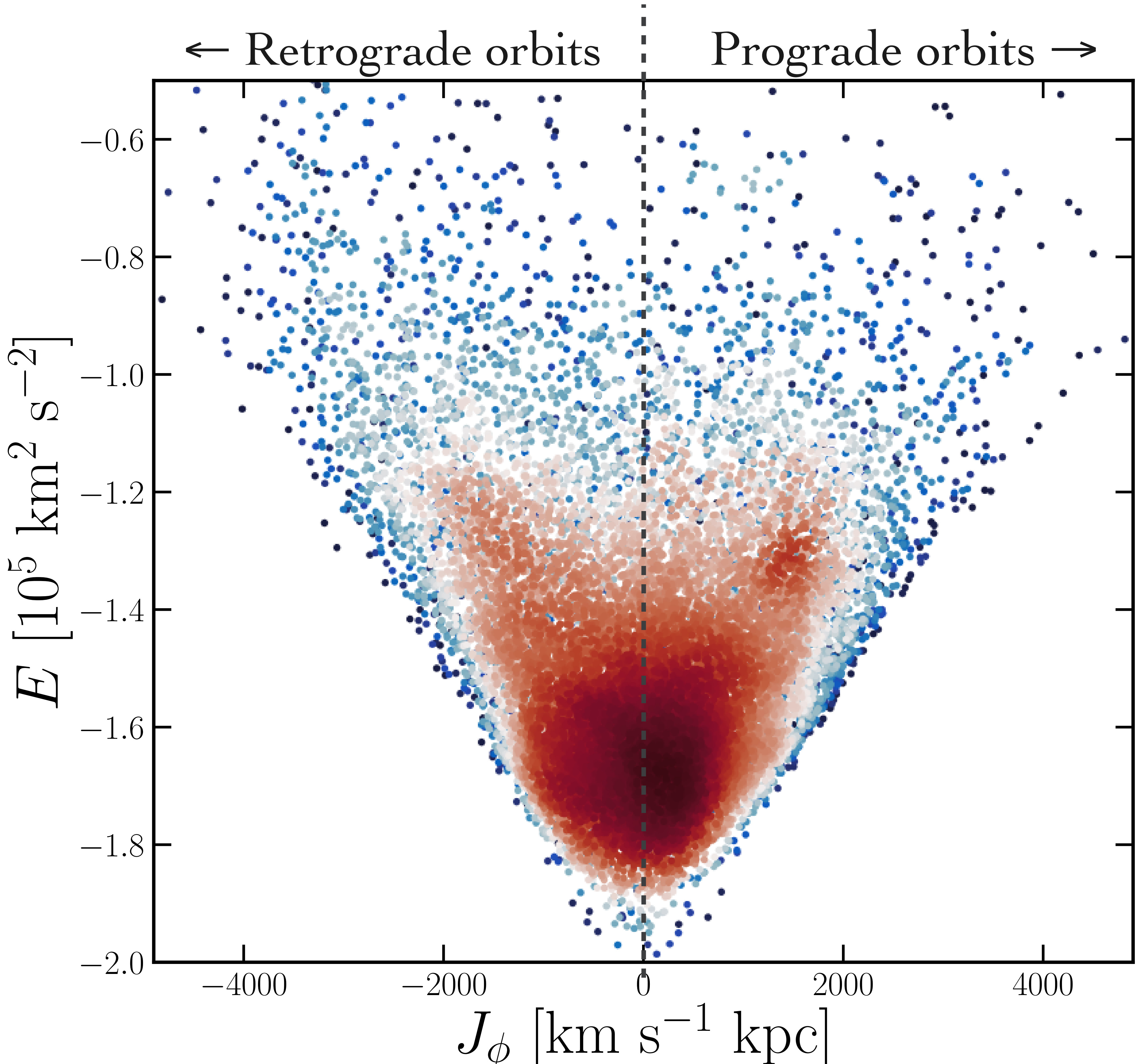




$-0.6$
$-0.8$
$-1.0$
$-1.2$
$-1.4$
$-1.6$
$-1.8$
$-2.0$
$E\ [10^5\ \mathrm{km}^2\ \mathrm{s}^{-2}]$
$-4000$
$-2000$
0
2000
4000
$J_\phi\ [\mathrm{km\ s}^{-1}\ \mathrm{kpc}]$



$E$ [$10^5$ km$^2$ s$^{-2}$]
$J_\phi$ [km s$^{-1}$ kpc]
Sausage
Disk
Halo



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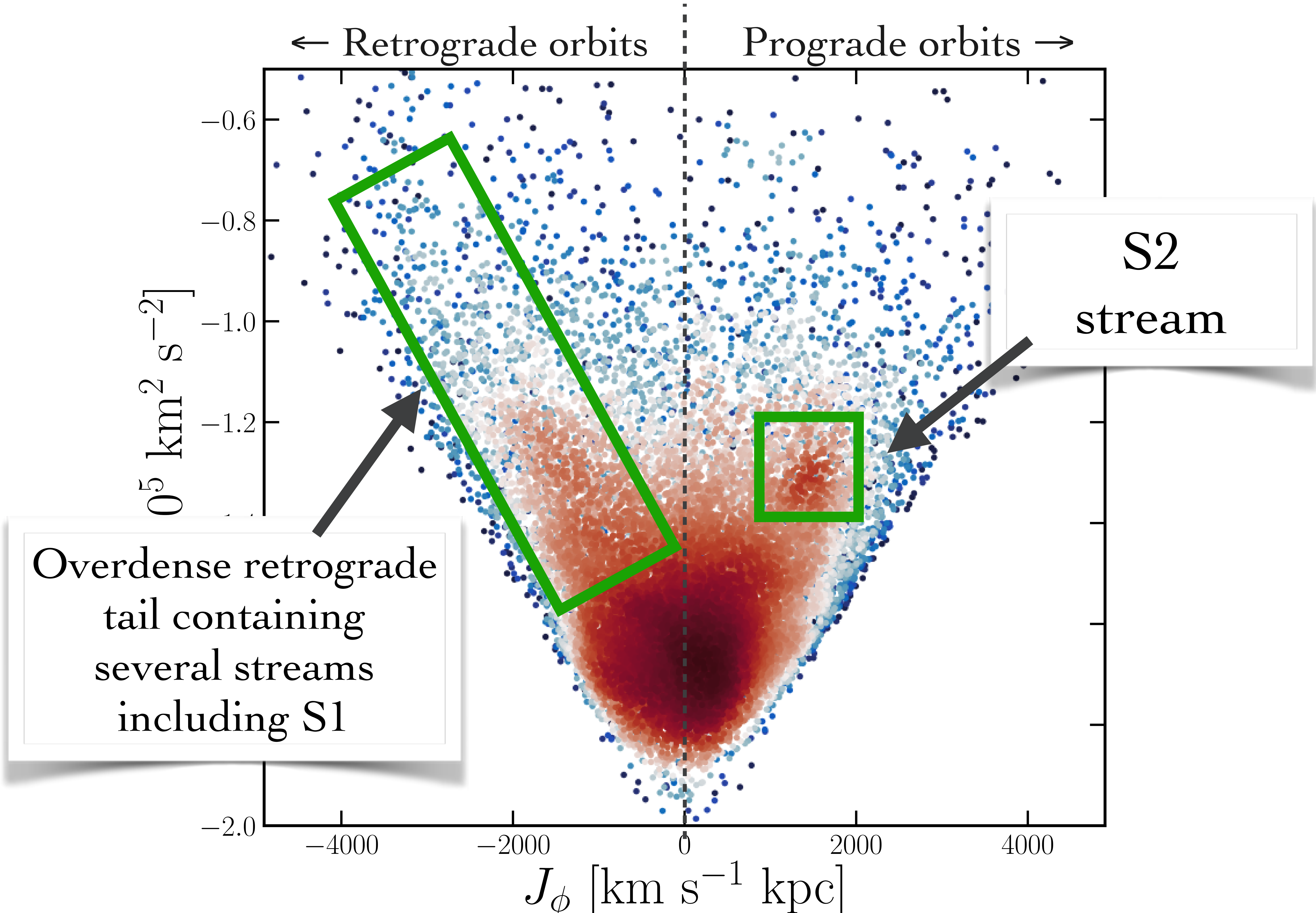




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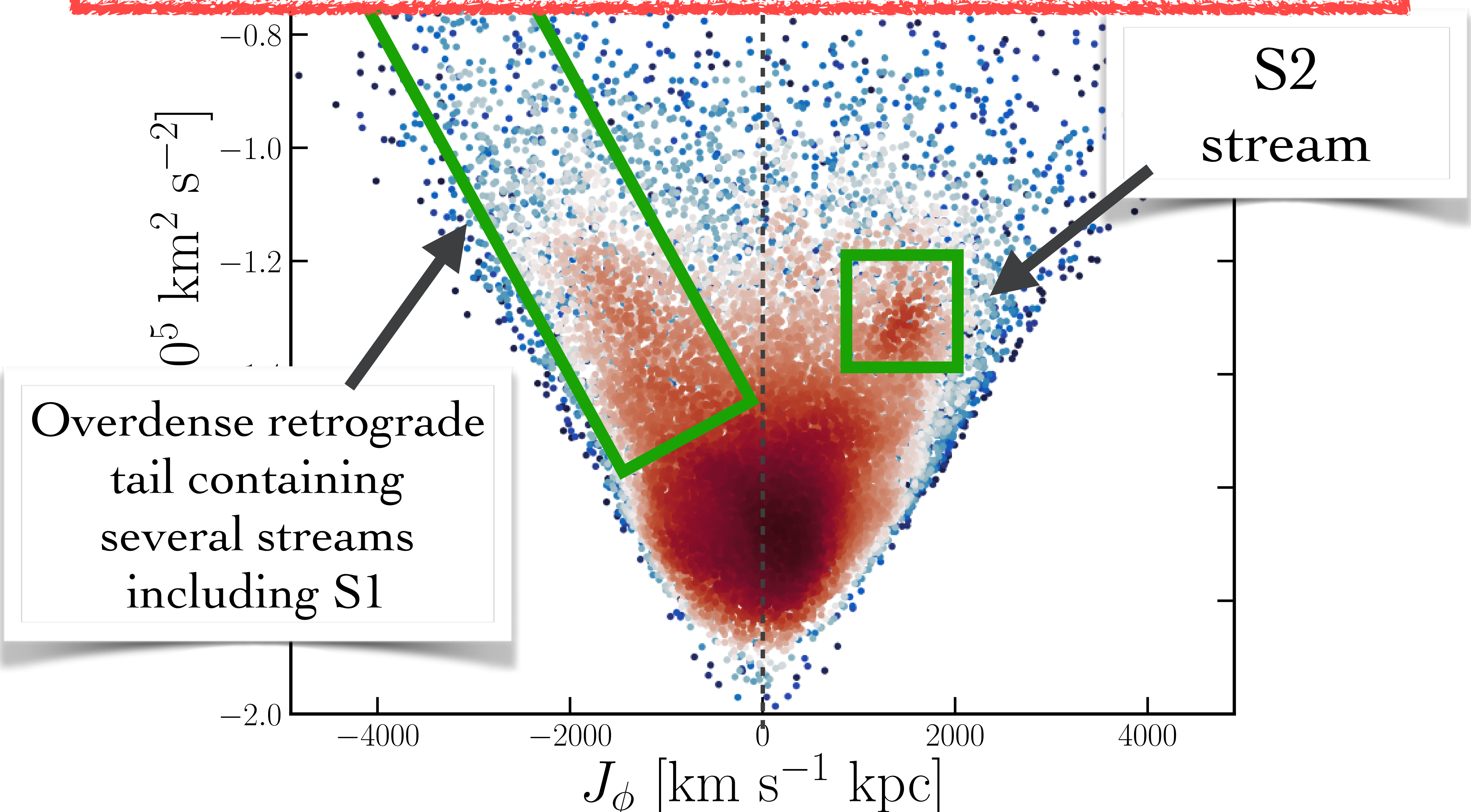
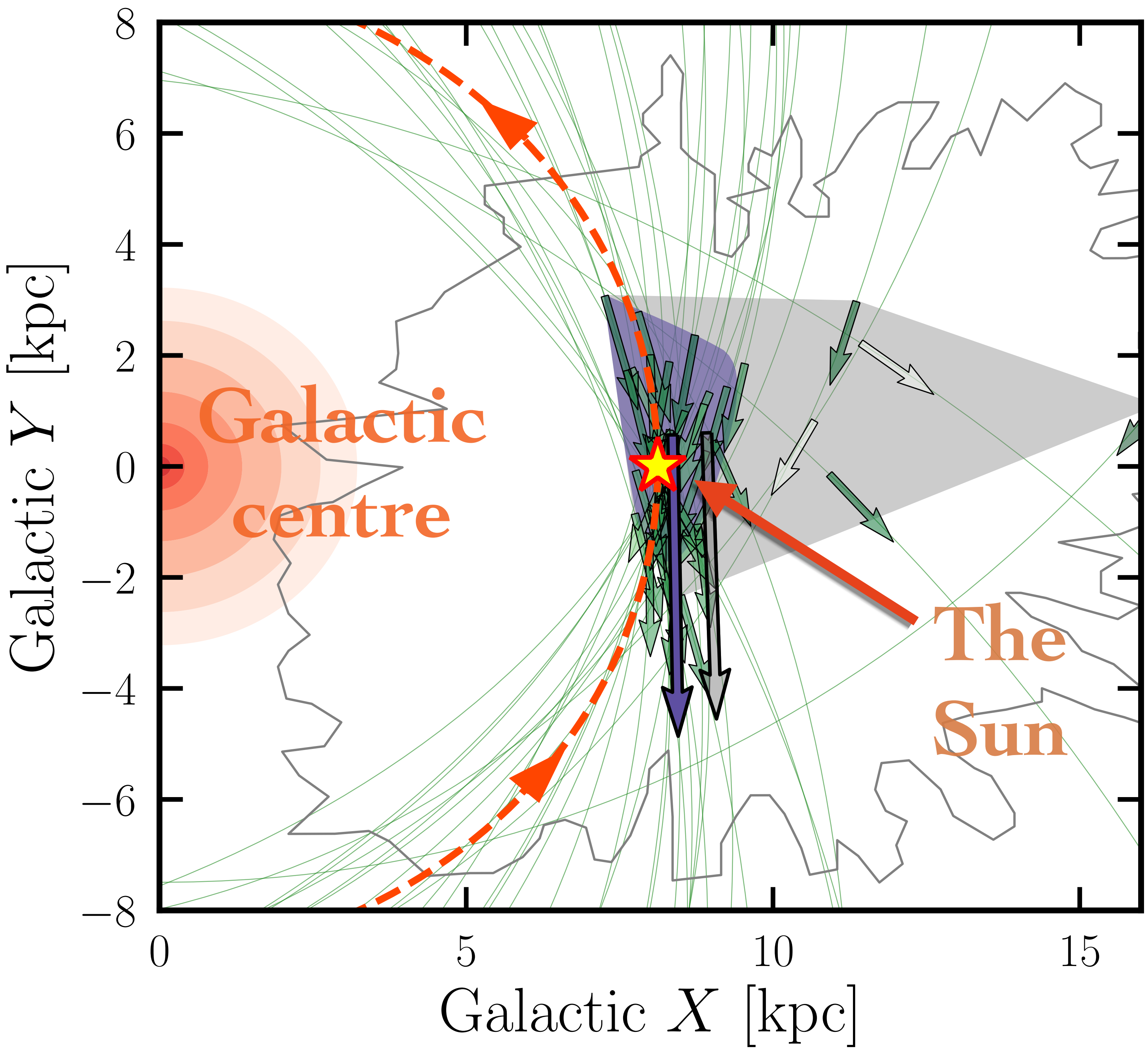
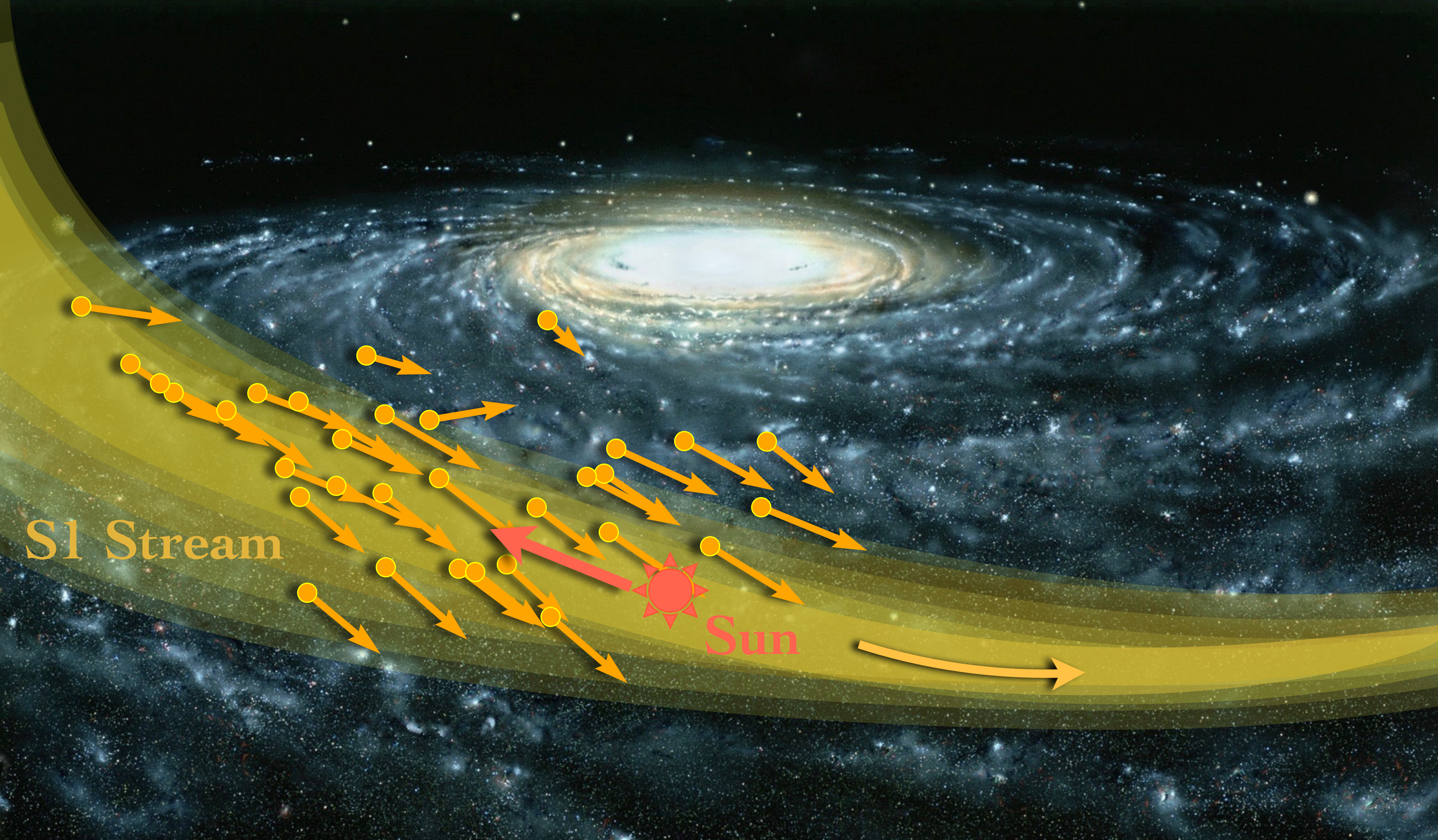
Substructures cluster in action space even when they are not clustered in phase space or visible on the sky
→ **we can see streams that we are inside of**



# The S1 stream




- Most prominent substructure encompassing the Solar System
- Likely the remnant of a large (Fornax-sized) dwarf spheroidal accreted around the same time as the Sausage event
- S1 and other retrograde stars possibly linked to a larger "Sequoia" event. Also responsible for several anomalous retrograde GCs (see 1904.03185)




S1 is on a retrograde infall, so impacts the solar system at high speeds

Dark matter wind→ A dark matter hurricane?

BBC Menú

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Qué es el "huracán de materia oscura" en el que se encuentra la Vía Láctea y qué permitirá saber sobre uno de los mayores misterios de la ciencia

Astronomy

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A 'dark matter hurricane' is storming past

*And it could help scientist detect the strange substance.*

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Dark matter hurricane to hit Earth with speeds of up to 31
per SECOND

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'Dark matter hurricane' blowing at 310 miles per SECOND is on a collision course with Earth and may finally offer proof the mysterious material exists

A Dark Matter "Hurricane" Is Blowing Past The Earth Right Now

SPACE / NOV 15, 2018 / NIKOS DIMITRIS FAKOTAKIS / 0 COMMENT

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So What's Going on With That 'Hurricane of Dark Matter?'

Ryan F. Mandelbaum

11/14/18 12:10pm • Filed to: DARK MATTER

67.1K 17 4


Urgent: "Scientist "Claim Dark Matter Hurricane" Is Coming

28,497 views

701 62 SHARE SAVE

**Paul Begley**

Published on Nov 14, 2018

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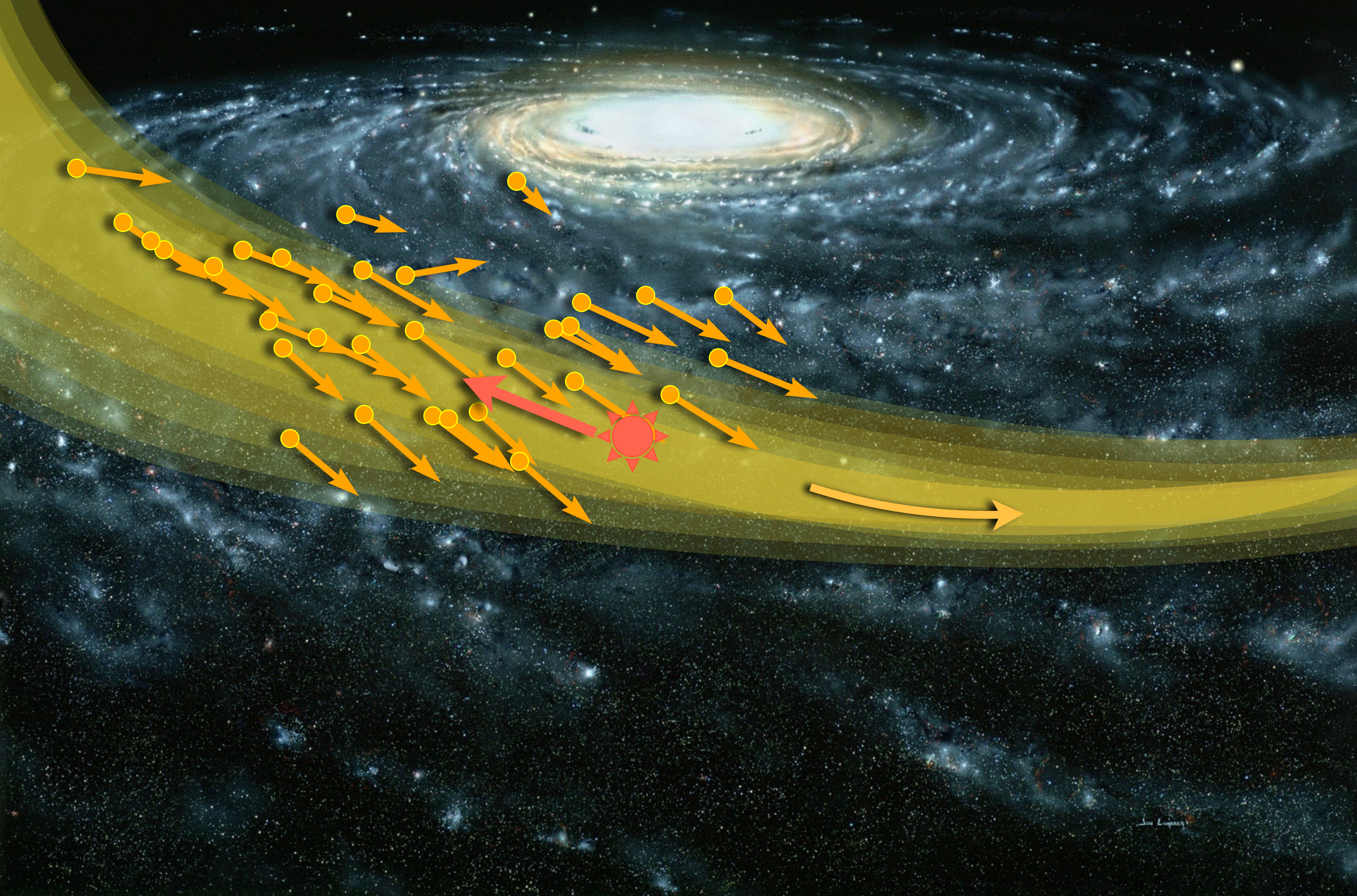
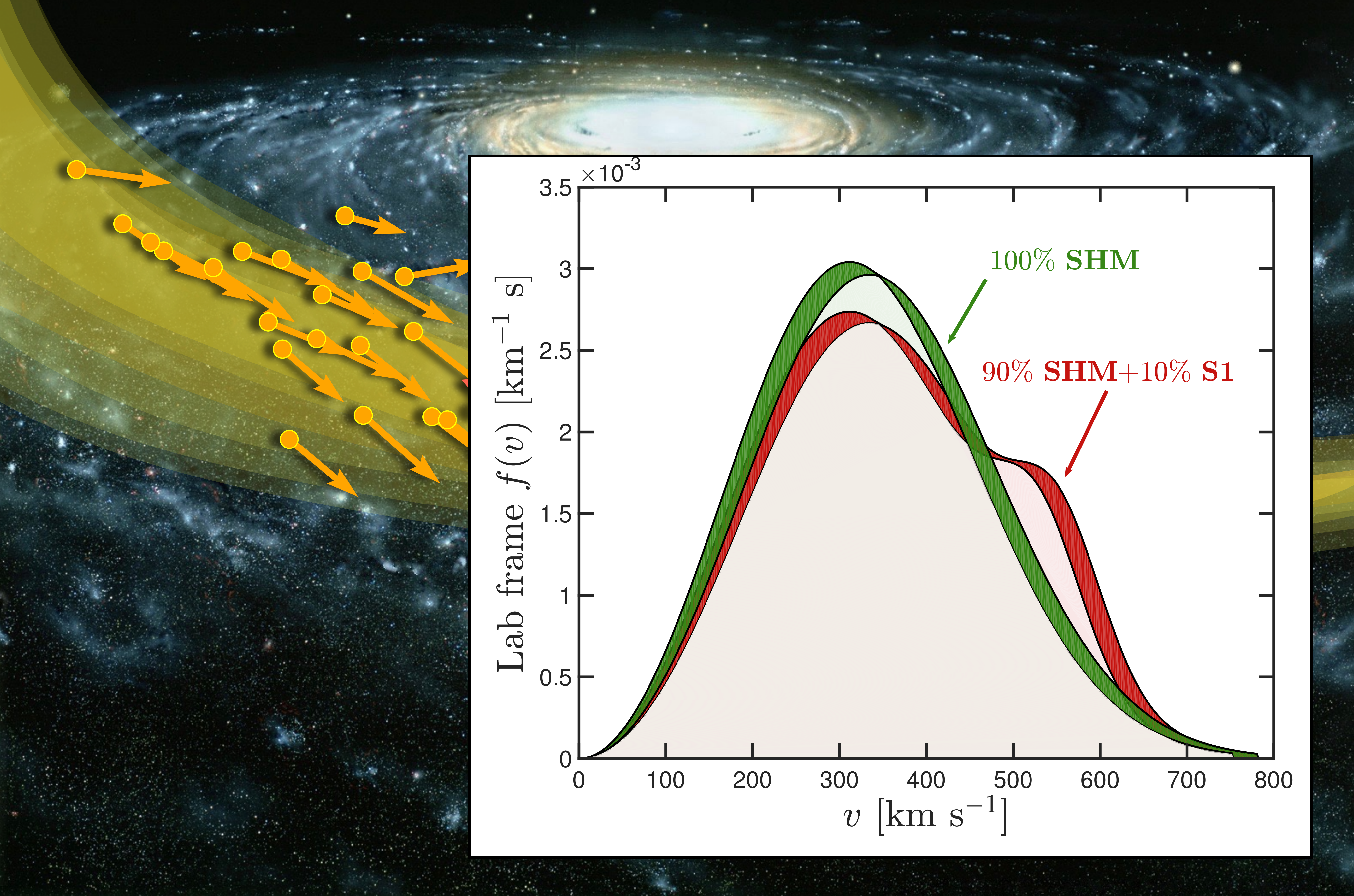
# Approaching dark matter hurricane will collide with earth, predict scientists

- Conspiracy theorists believe that the dark matter hurricane will result in an imminent apocalypse on earth.

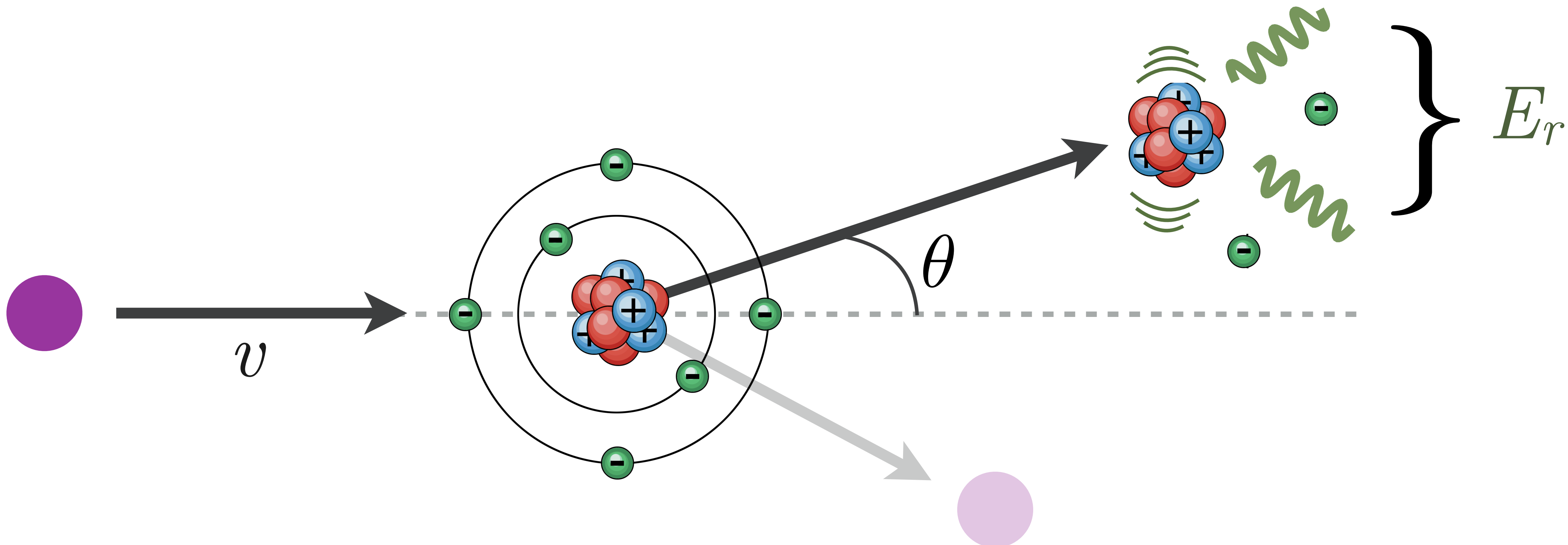
# Modelling S1



# Modelling S1



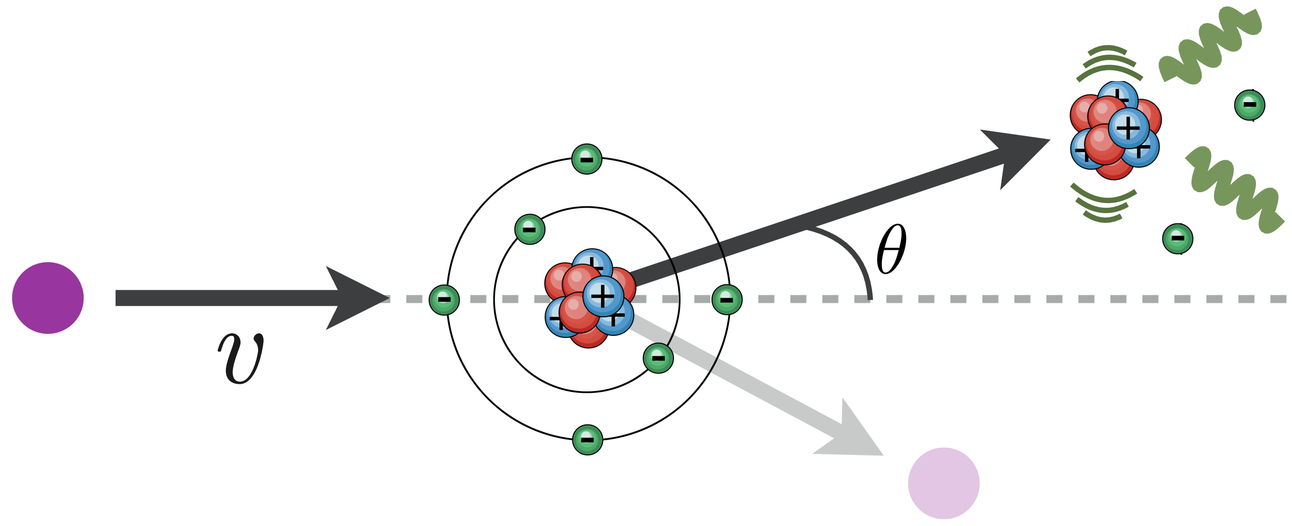
# WIMP direct detection




$$\text{“Signal”} \propto E_r = \frac{2 m_N m_\chi^2}{(m_N + m_\chi)^2} v^2 \cos^2\theta$$

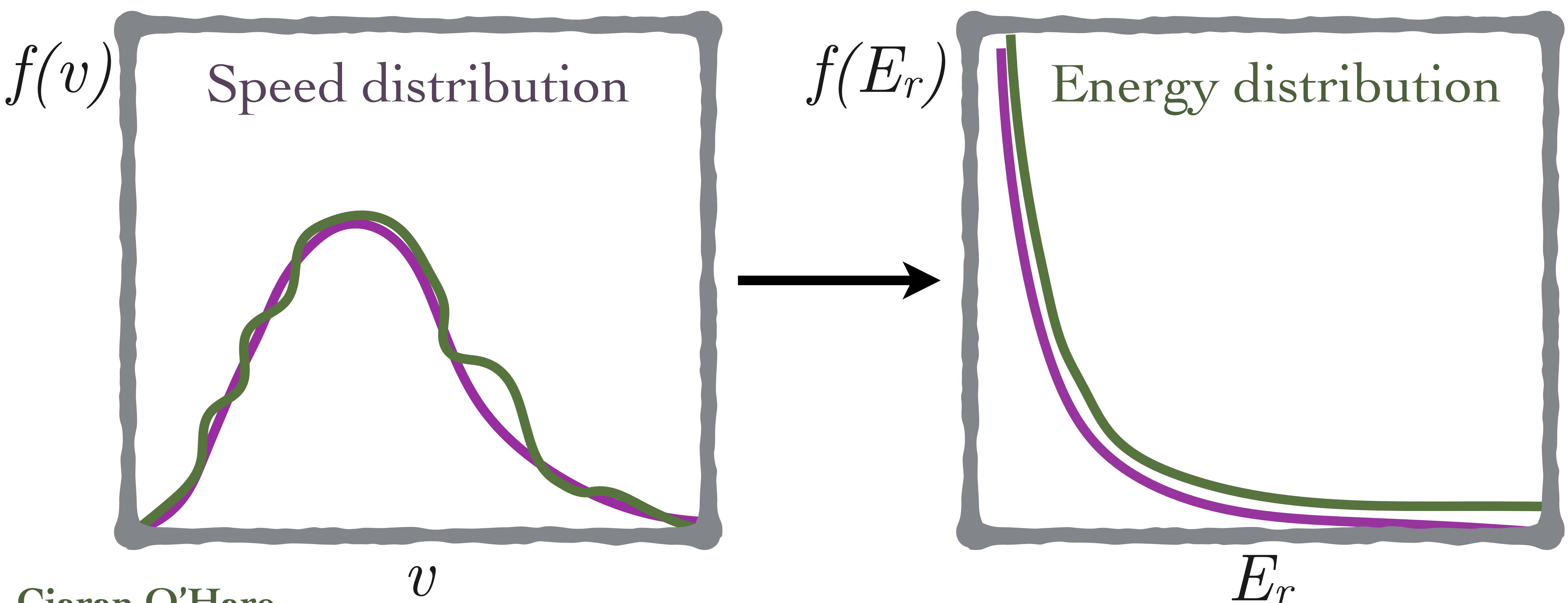
$m_N$ = Nucleus mass
$m_\chi$ = WIMP mass

# Substructure hard to see with WIMPs




Why? → Angle usually not measurable so:

$$E_r \in \left[0,\ v^2 \frac{2 m_N m_\chi^2}{(m_N + m_\chi)^2}\right]$$

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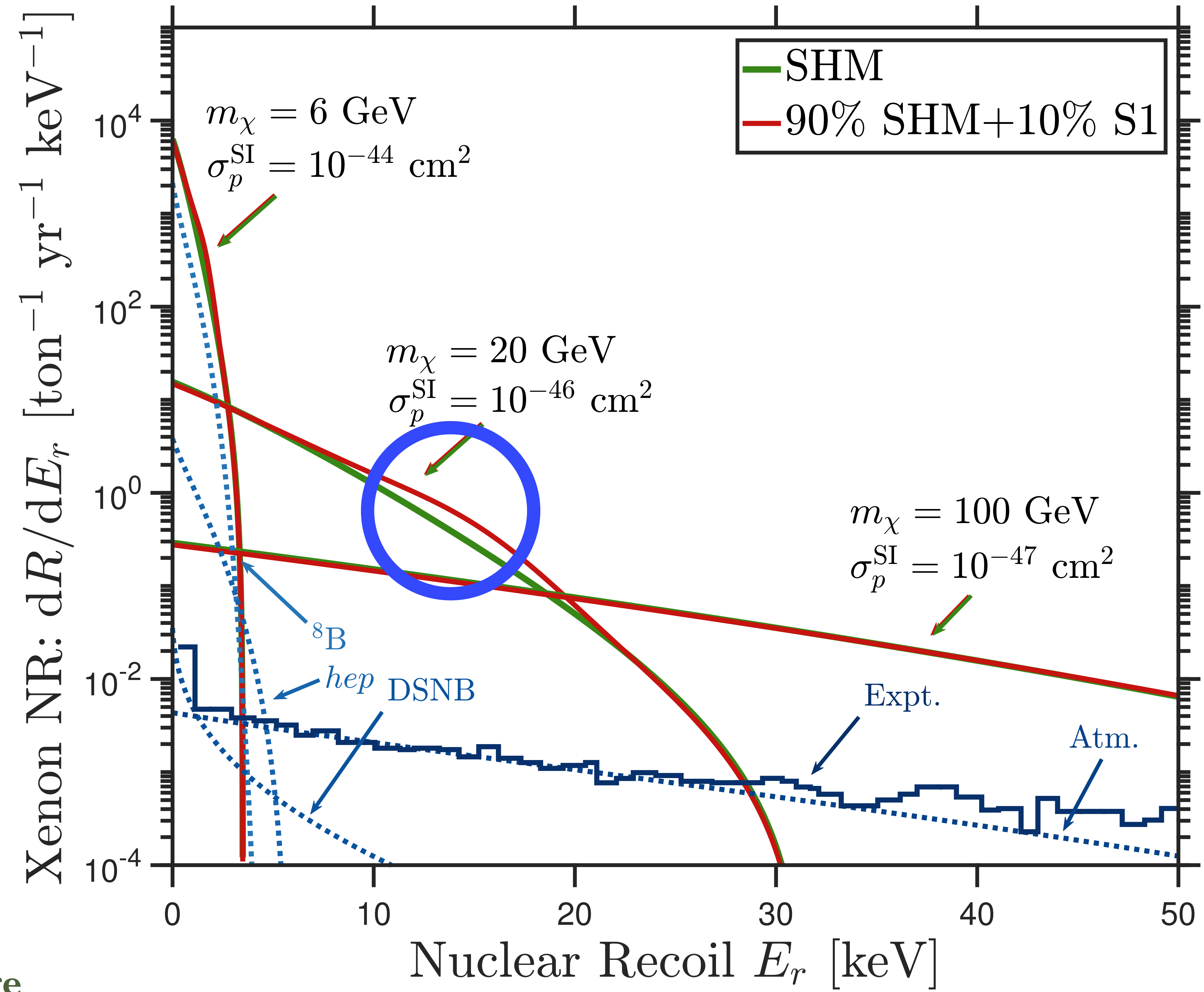
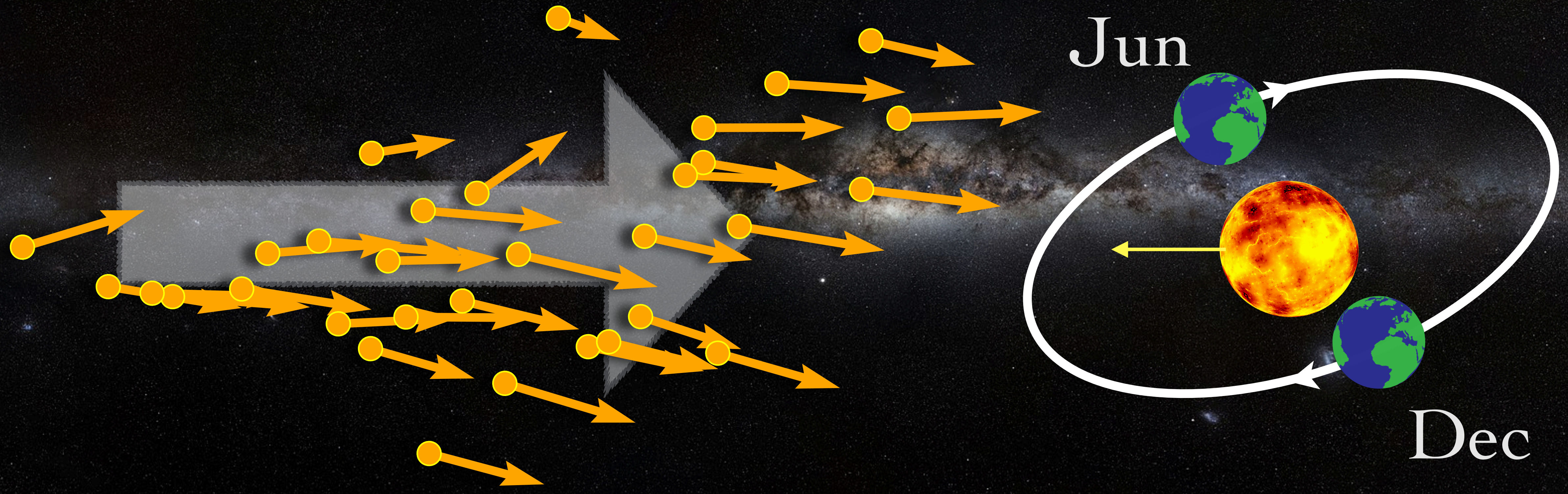
**To detect S1 with xenon, e.g. LZ, Xenon, DARWIN:**

- *O*(1-10%) of the local density would need to be from the stream
- WIMP mass between 5—50 GeV (see 1807.09004 for finer details)



# Stream is counter-rotating, so will enhance the anisotropy of the dark matter flux



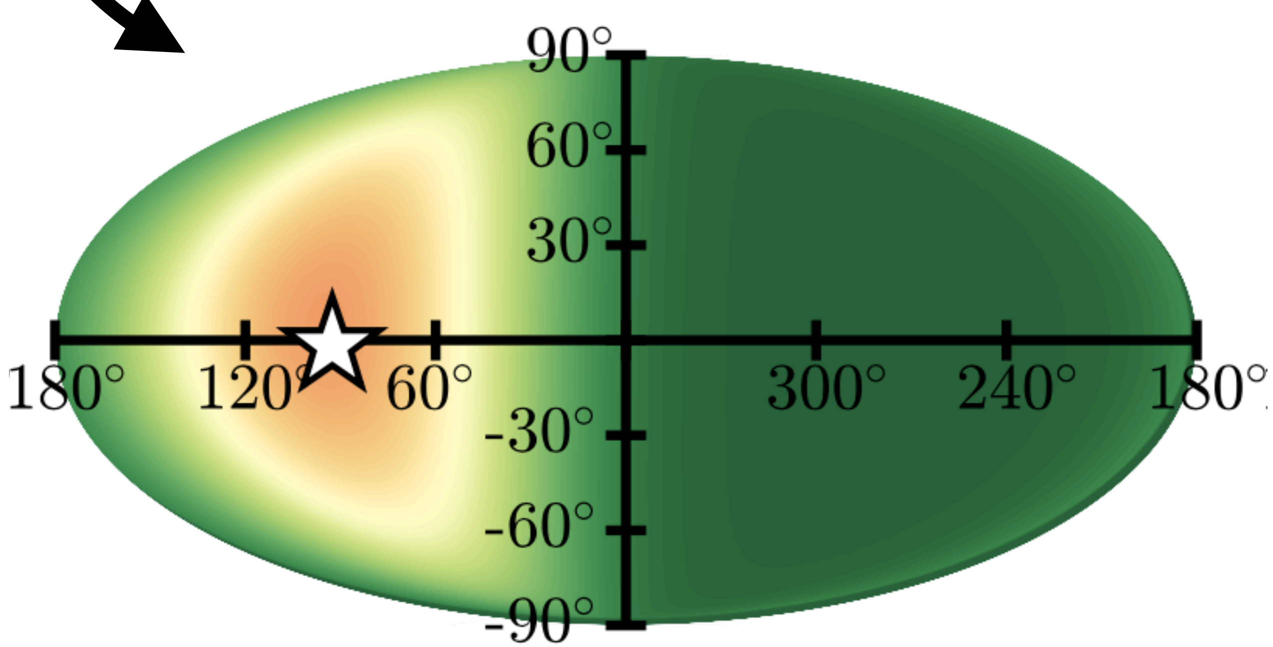

(also means that the phase of annual modulation is the ~same)

# Detecting substructure: WIMPs

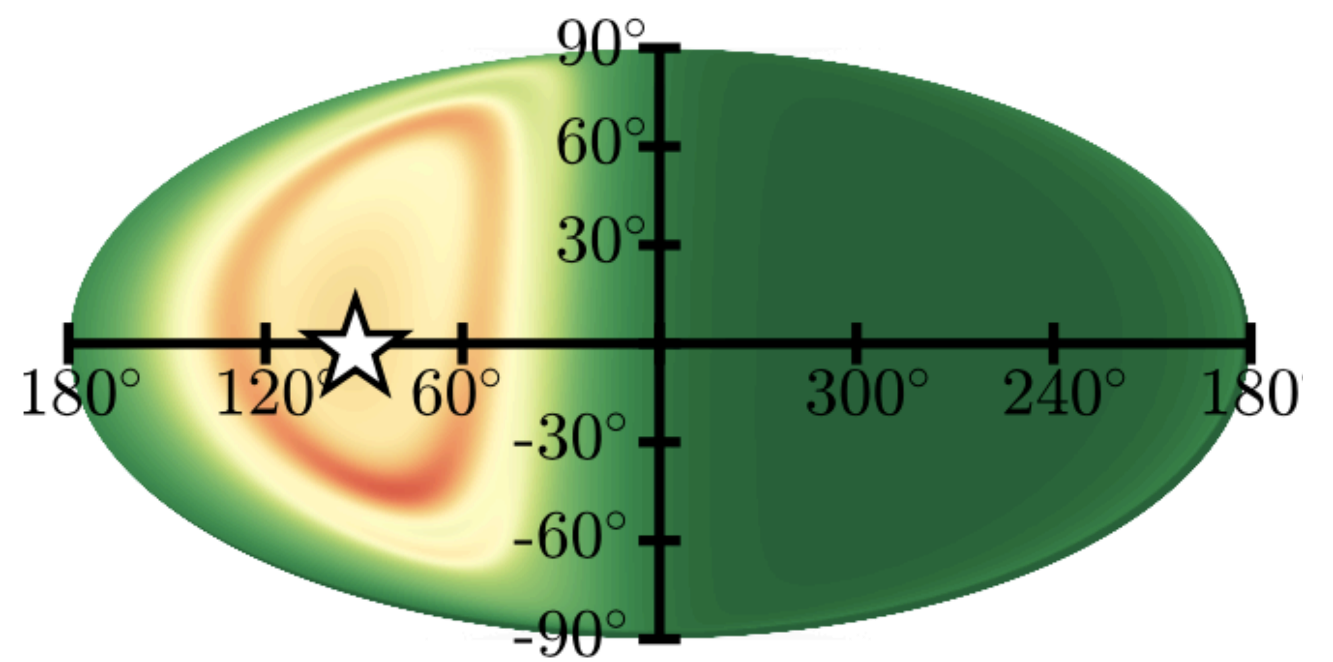
DM velocity is measurable, if
scattering angle is measurable

Directional distribution on the sky of nuclear recoils.
For CYGNUS expt: a gas TPC with $He+SF_6$ fill gas, see Elisabetta's talk on Friday

## Halo:



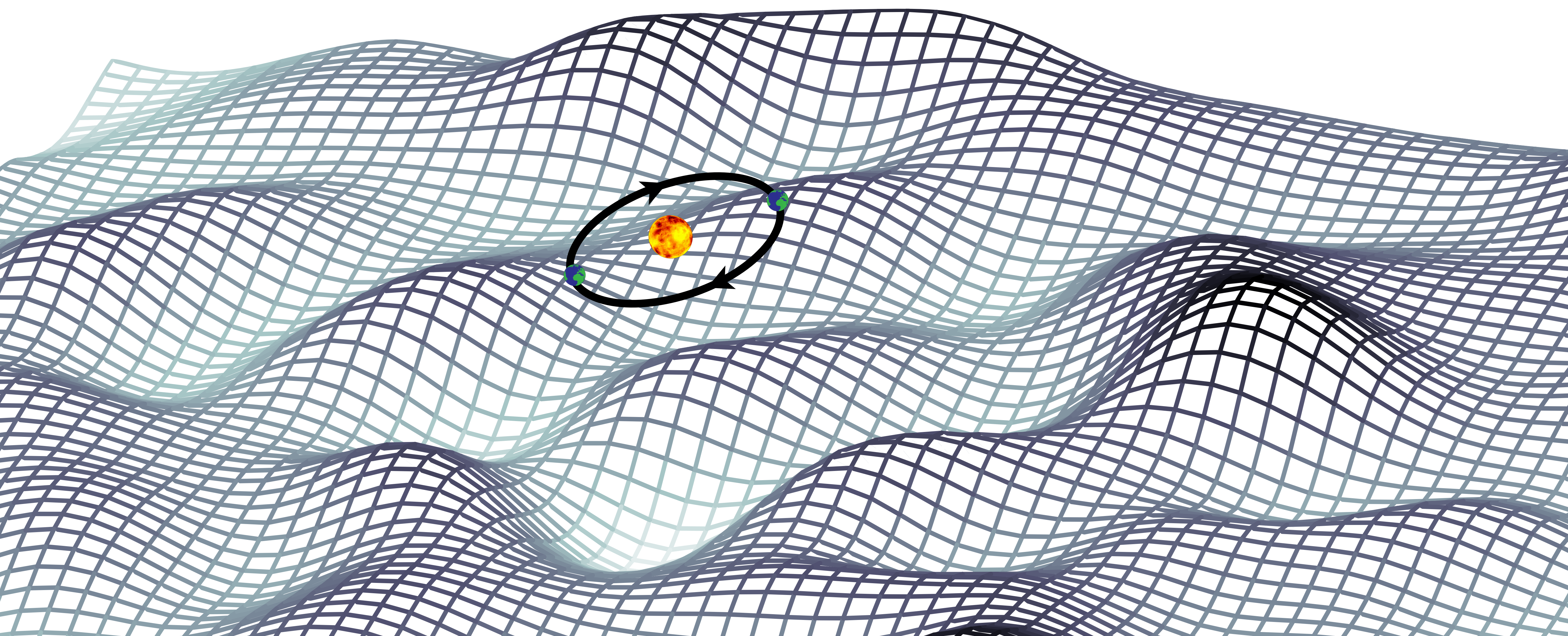

## Halo with S1:



# Detecting substructure: axions

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

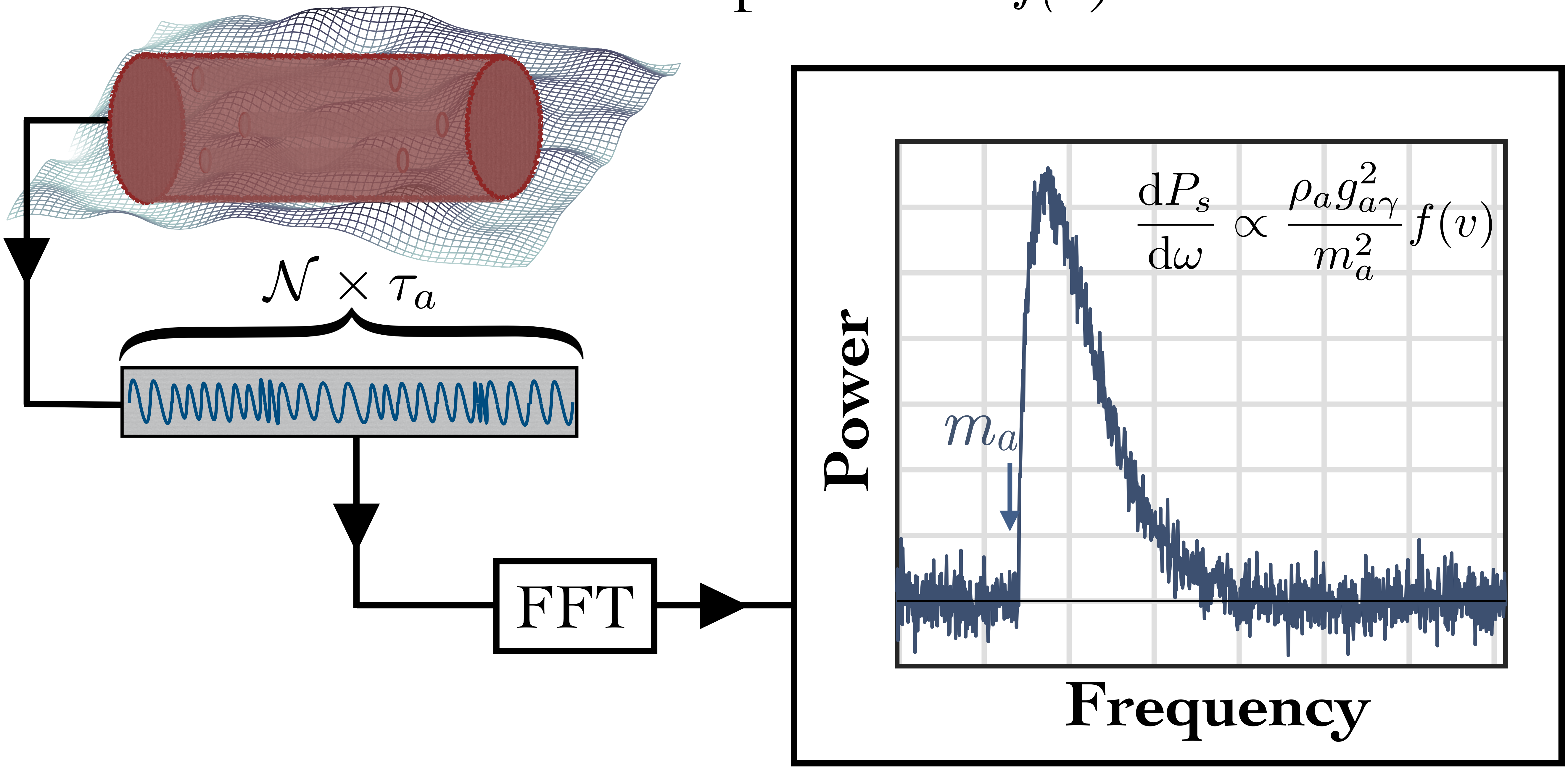
Oscillating at ~the axion mass with coherence time $\tau \sim \frac{1}{m_a \langle v \rangle^2}$



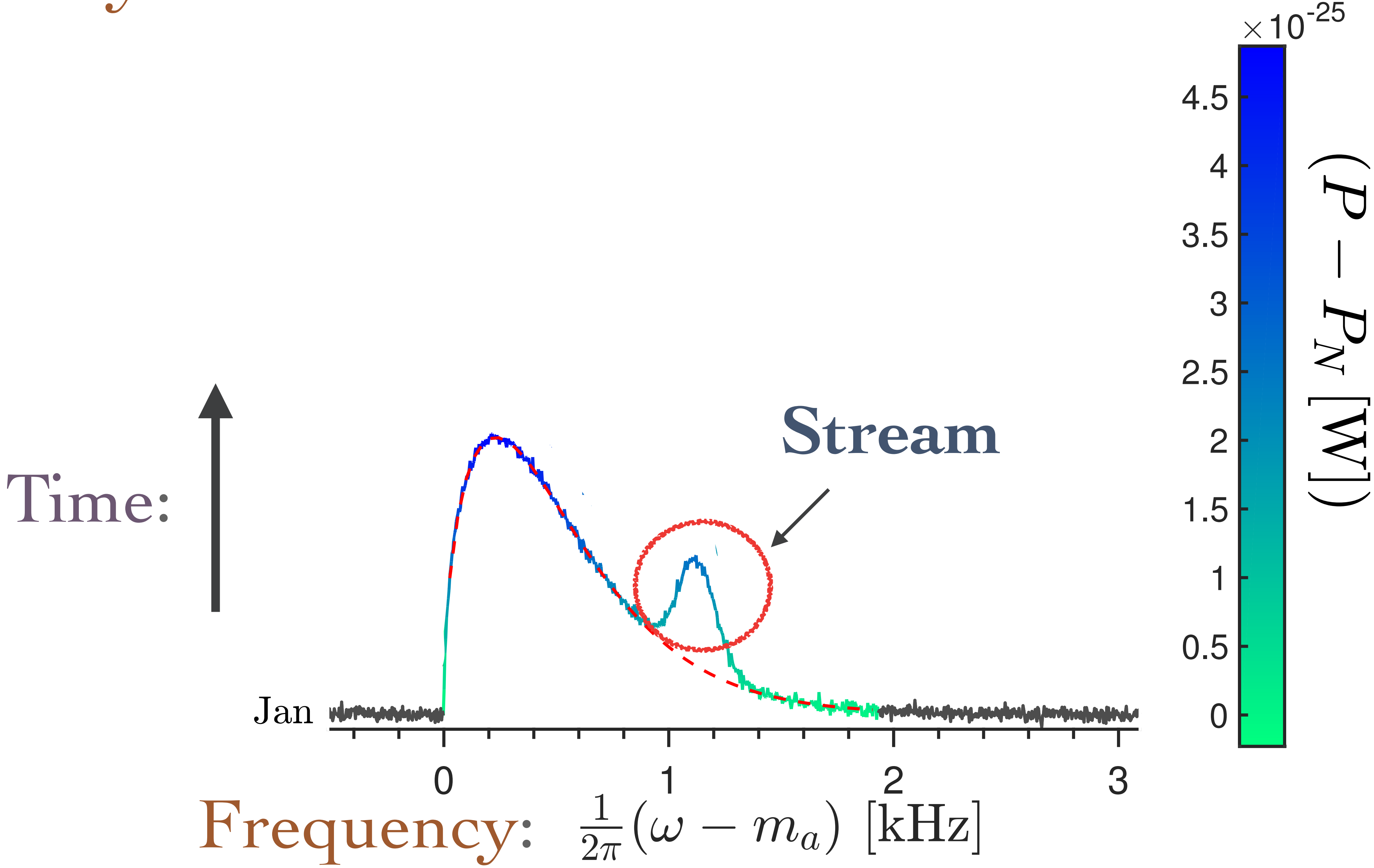
# Measuring the axion distribution

Sampling axion field over many, $N$, coherence times:

→ Power spectrum ~ $f(v)$



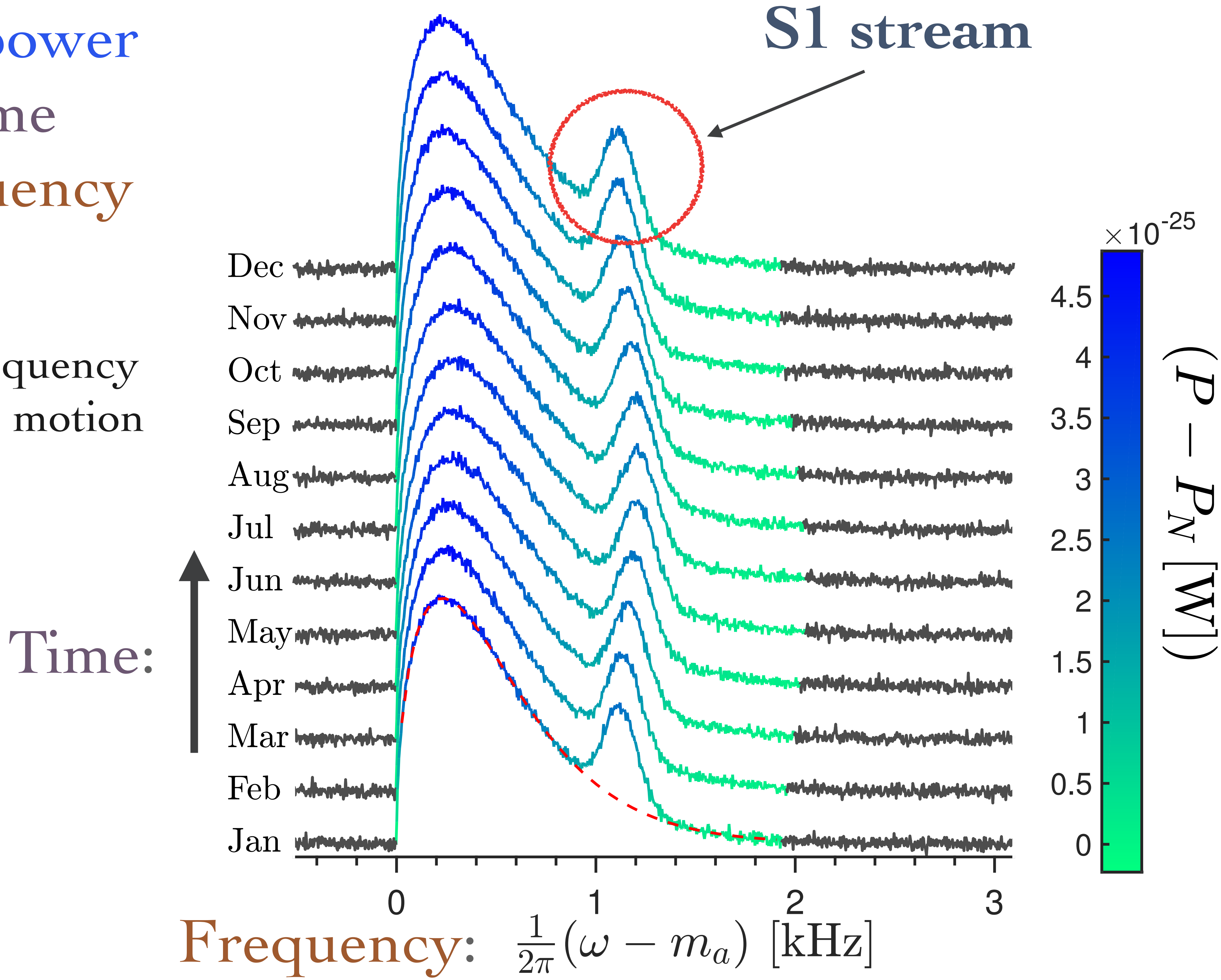
# Axion haloscope:
Signal power
vs time
vs frequency



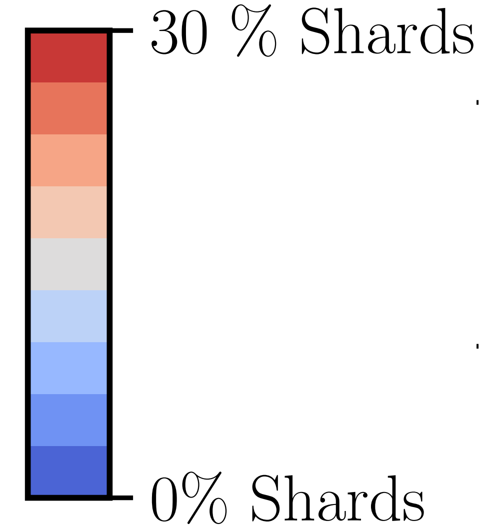
# Axion haloscope:

Signal power
vs time
vs frequency

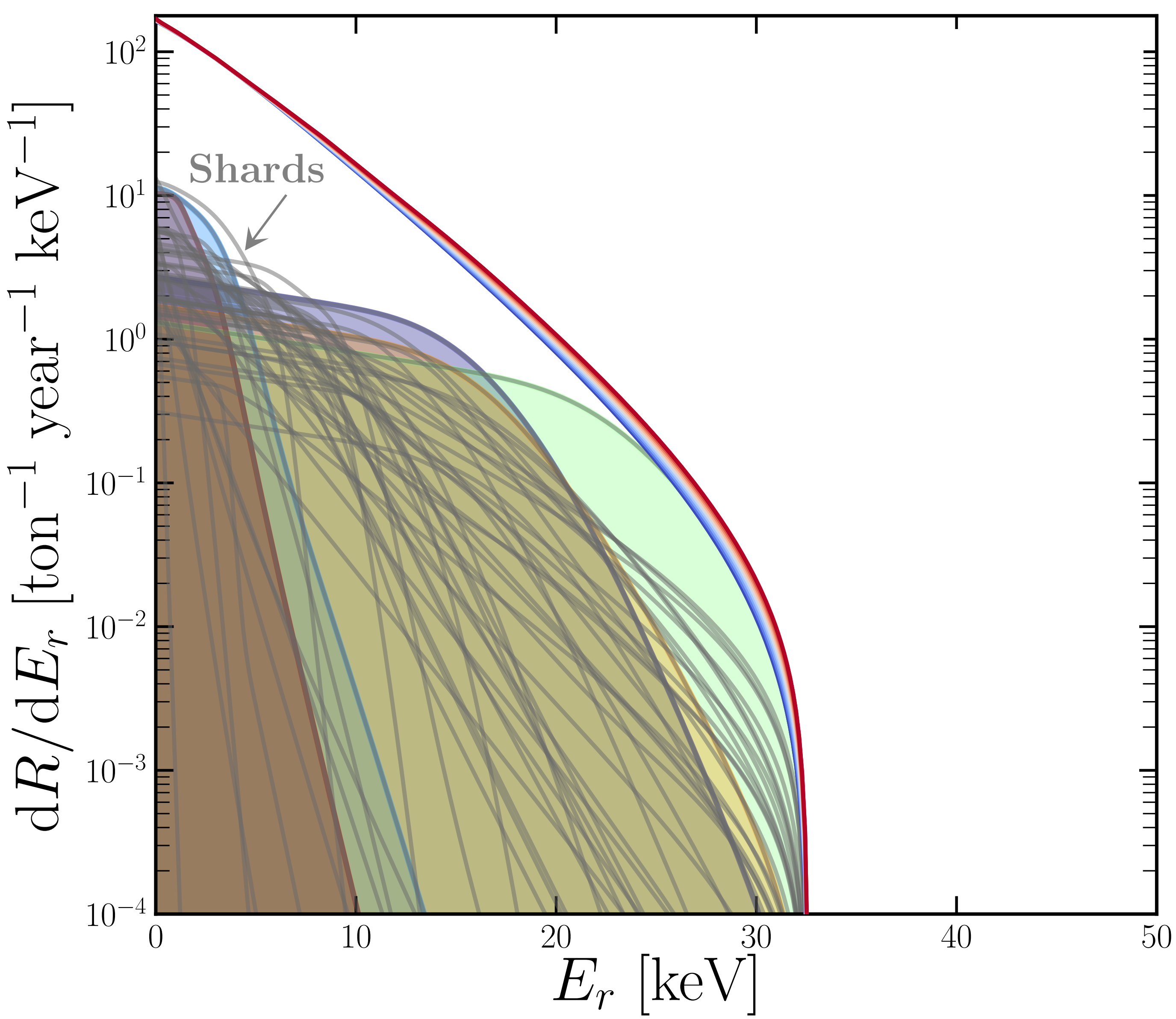
Wobble in frequency due to Earth's motion



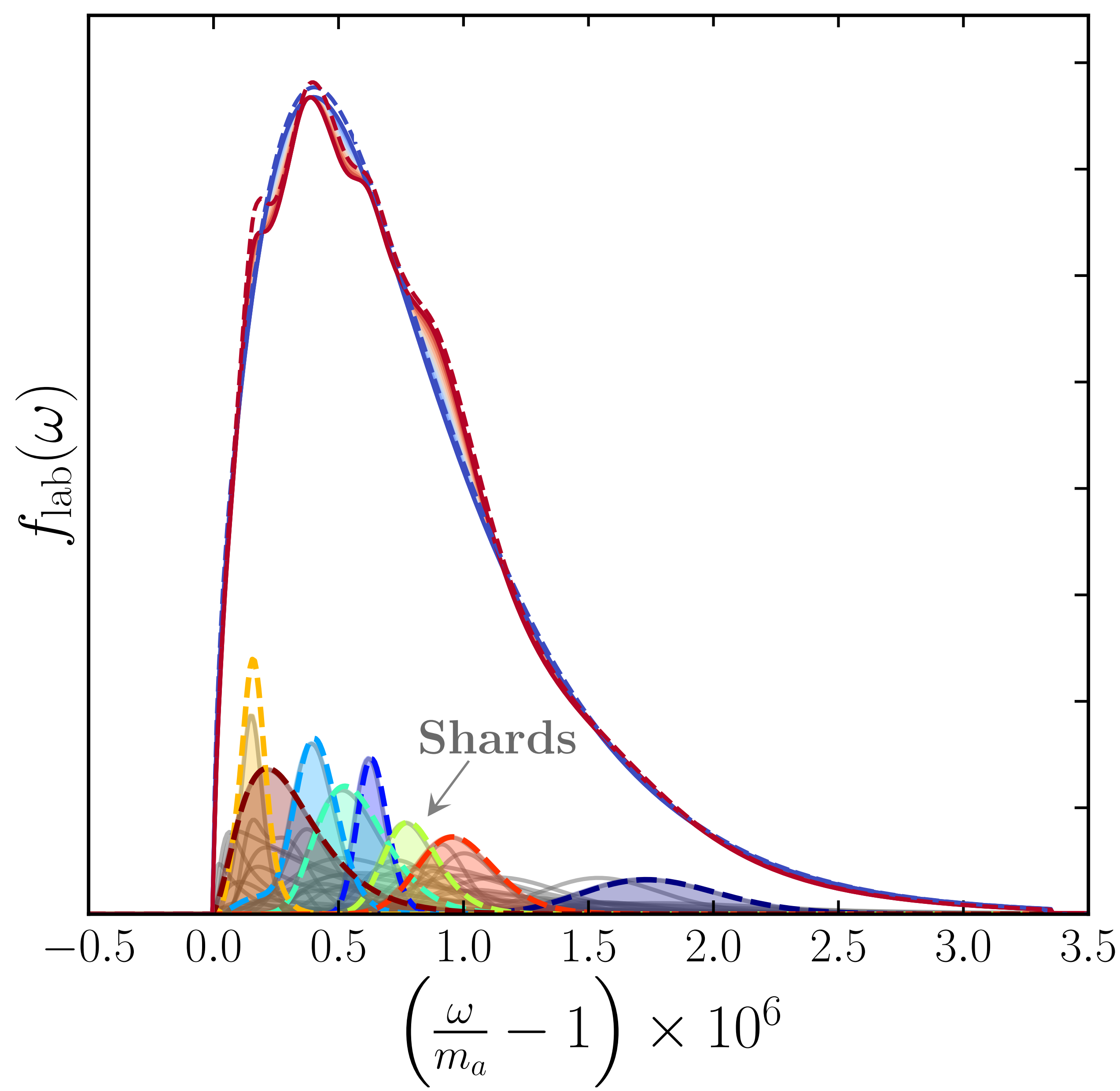
# Accounting for all the detected substructures intersecting Solar position, "Shards"




WIMP recoil rate vs. energy




Axion lineshape vs. frequency



# Take home points

Measurements of parameters describing the local distribution of DM are improving. Assumptions used for DD experiments are being put on more solid ground

*Gaia* is changing our understanding of the events that shaped the Milky Way's past

Local halo shows evidence for several significant merger and accretion events — Sausage, S1, Sequoia and more…

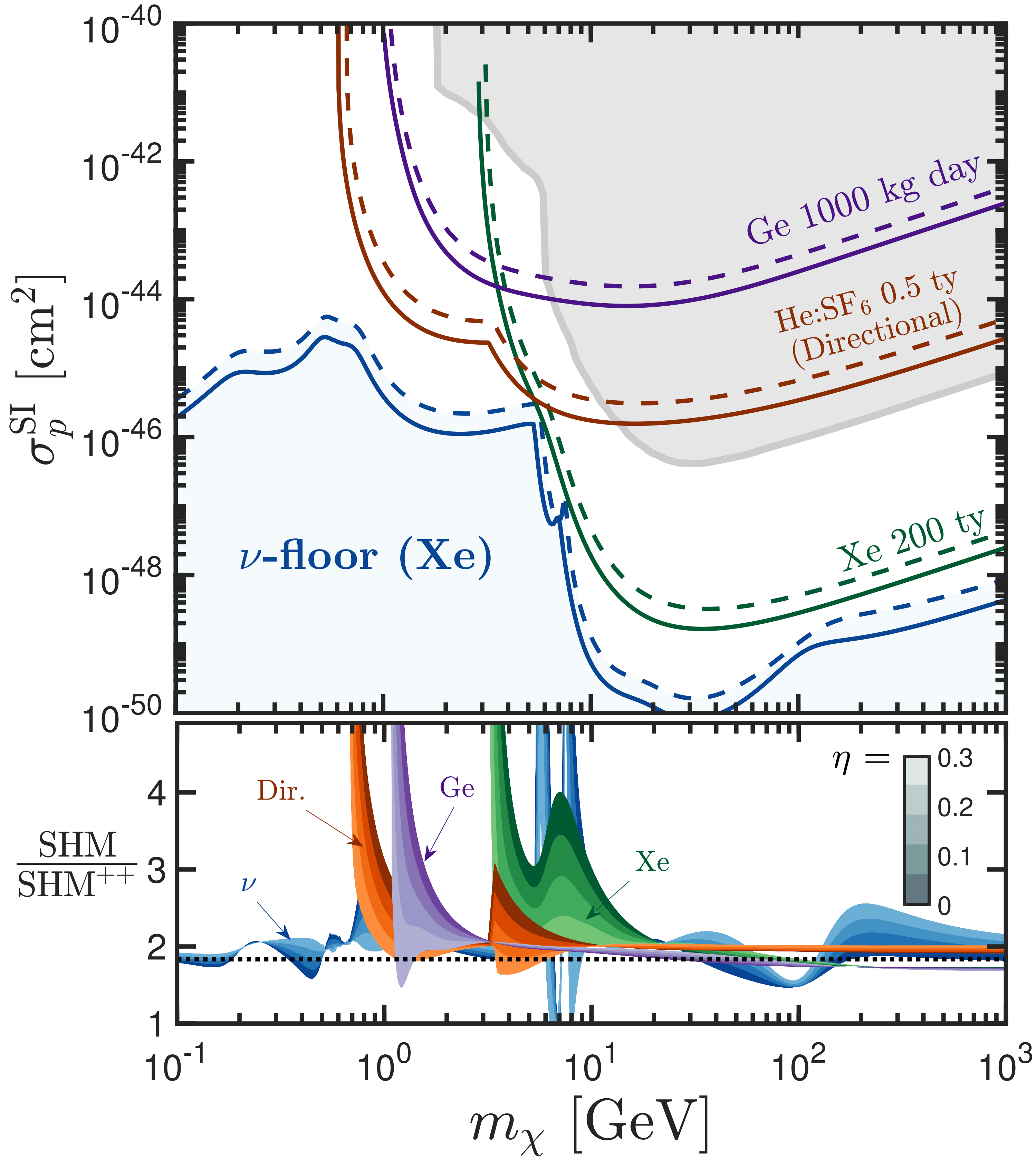
Halo is a more complicated cow: substructures have consequences for experiments on Earth, expect them to show up!

# Extras

→ Multiple competing effects mean that the differences between the two models are smaller than expected

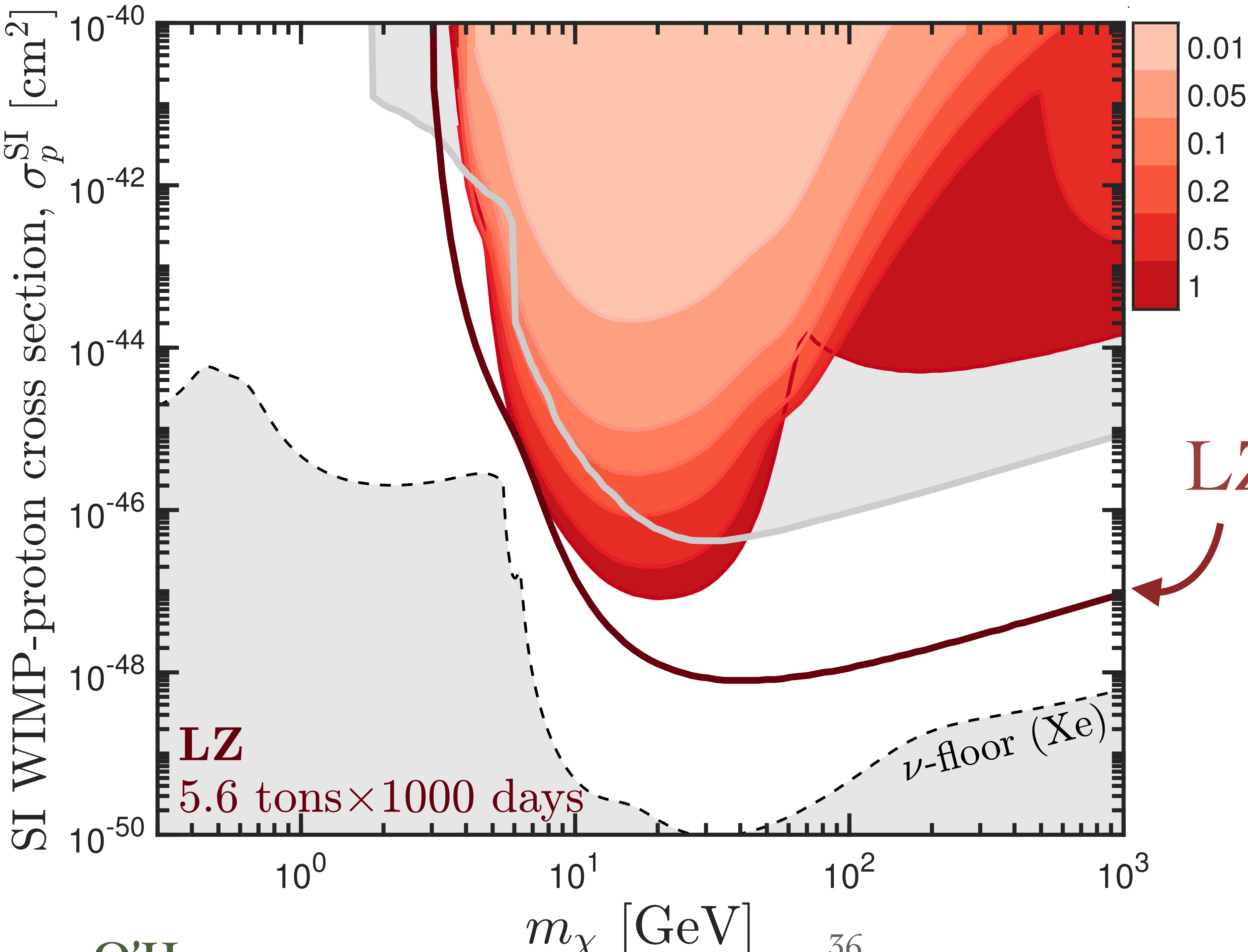
- - **SHM**

— **SHM$^{++}$**



# S1 in LZ

Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma

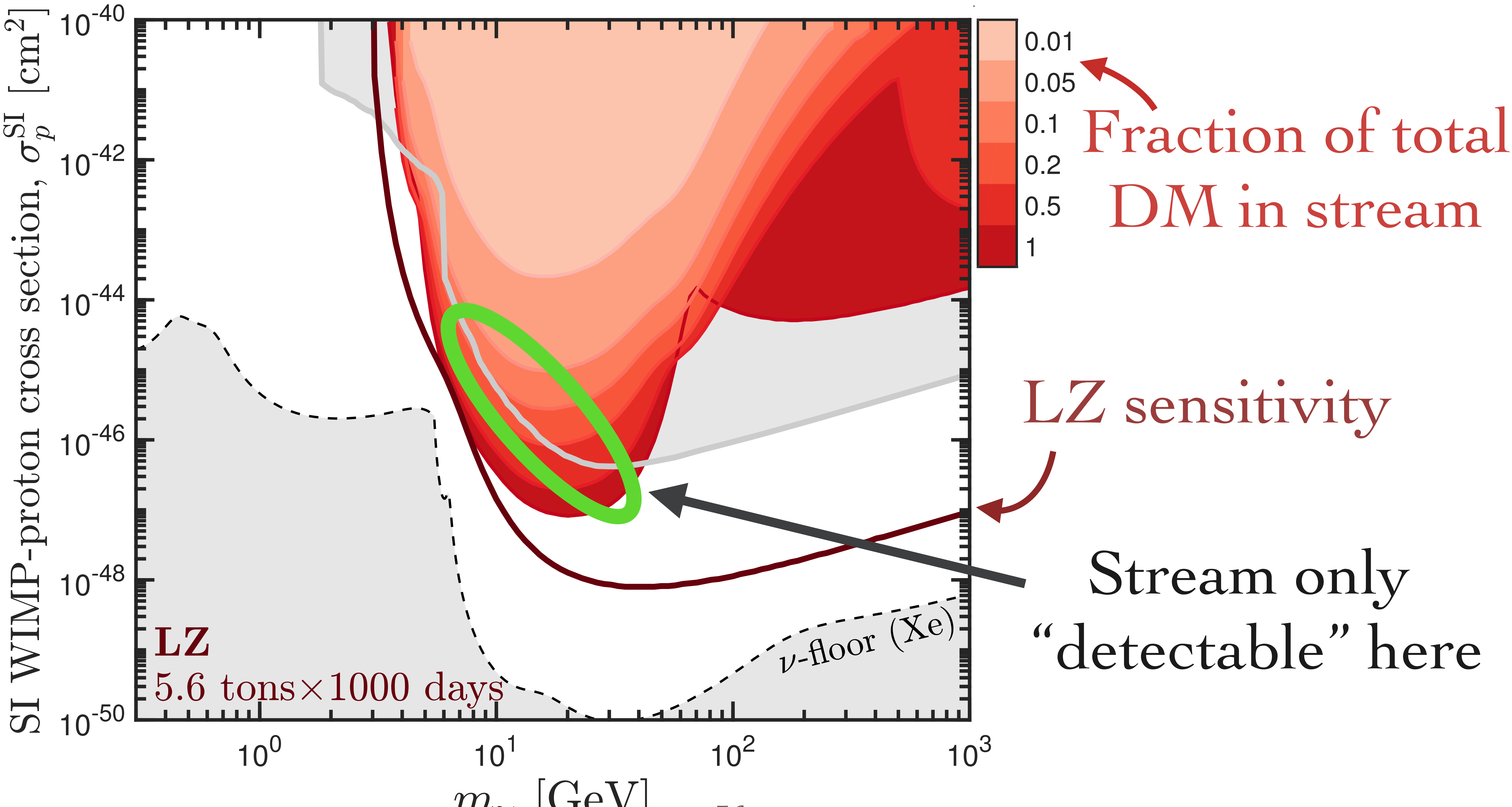



Fraction of total DM in stream

LZ sensitivity

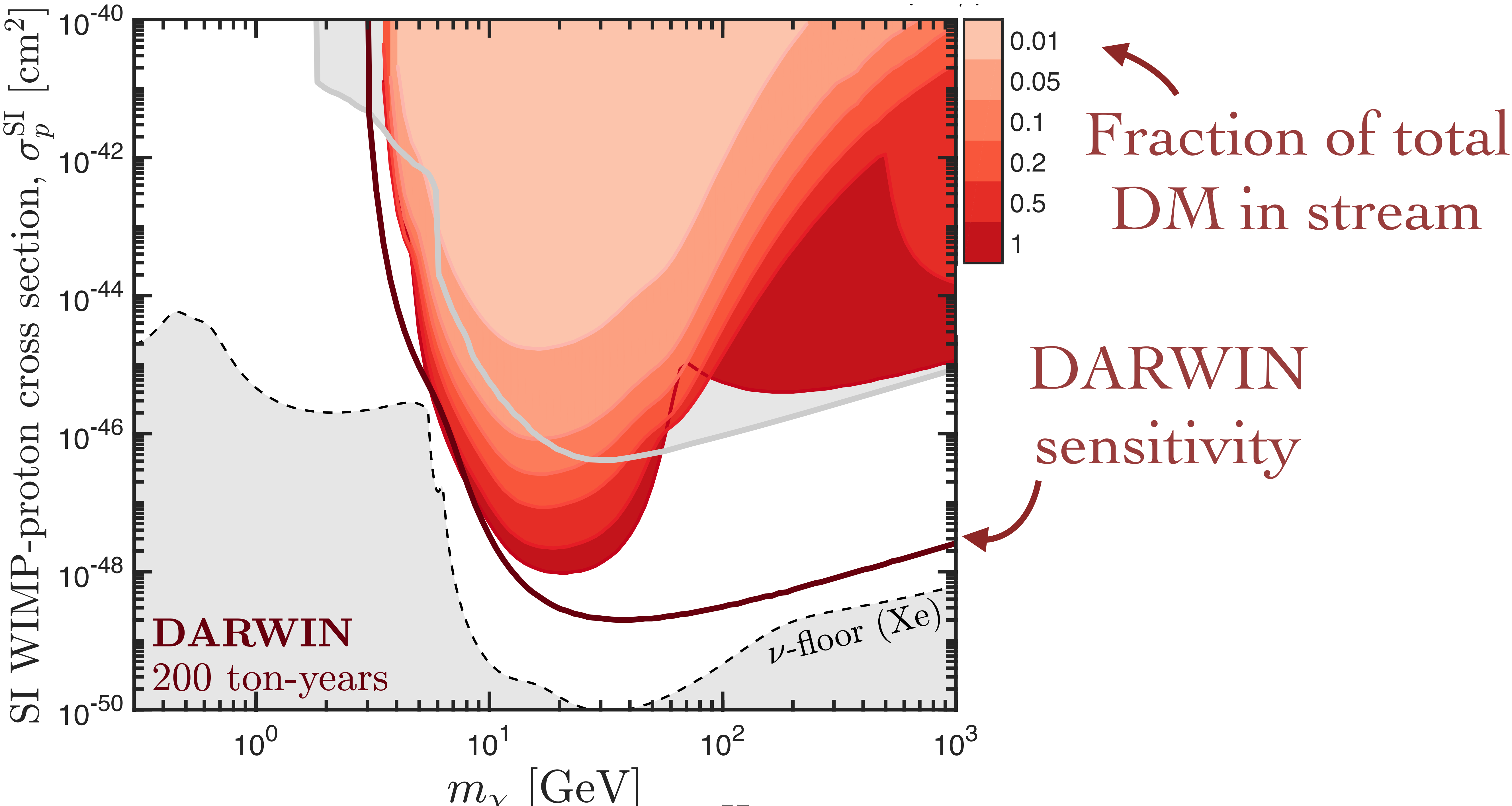
# S1 in LZ

Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma



# S1 in DARWIN

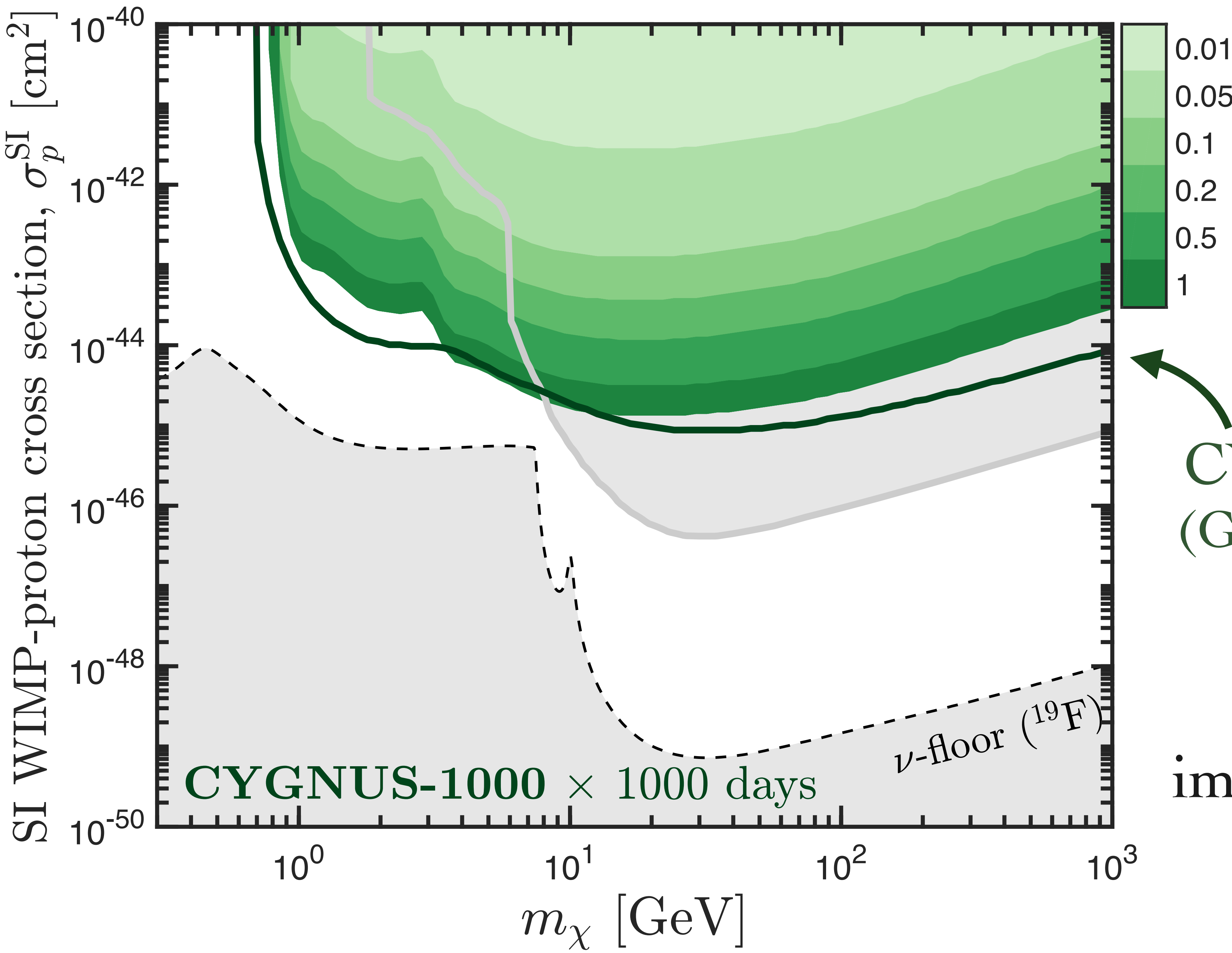
Red regions: range of WIMP models for which the stream can be distinguished from the halo in DARWIN at 3 sigma




Ciaran O'Hare

# S1 in a directional detector

Green regions: range of WIMP models for which the stream can be distinguished from the halo in CYGNUS at 3 sigma




Fraction of DM in stream

CYGNUS sensitivity (Gas TPC with He+$SF_6$)

Directionality improves sensitivity to stream



Ciaran O'Hare

# Importance for DM

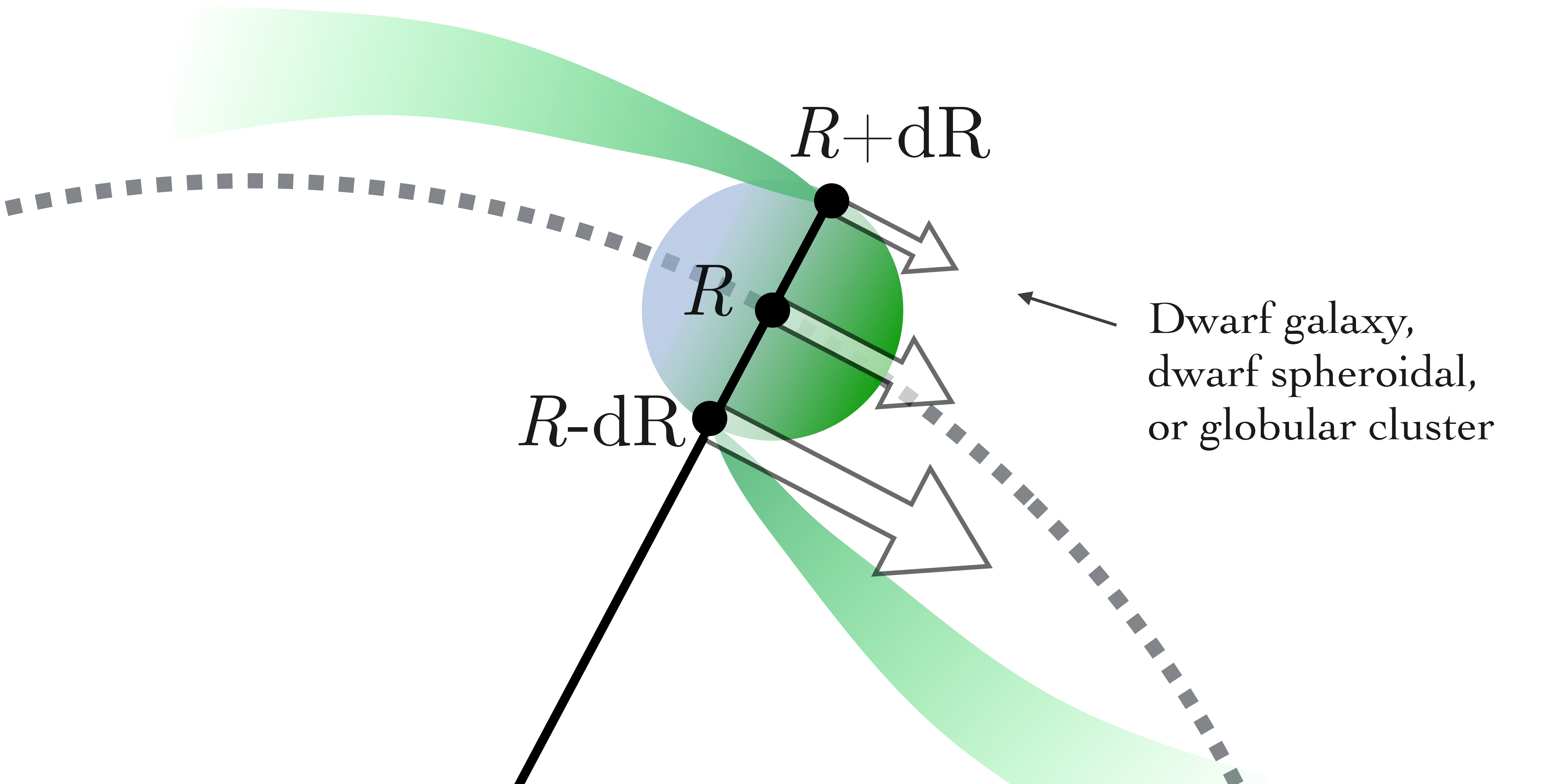
**Satellites** → Distinguishing warm/cold DM
→ Targets for DM annihilation or decay

**Streams** → Informs about the granularity of DM halo
→ Traces the shape of MW potential
→ Can be used to constrain fuzzy DM

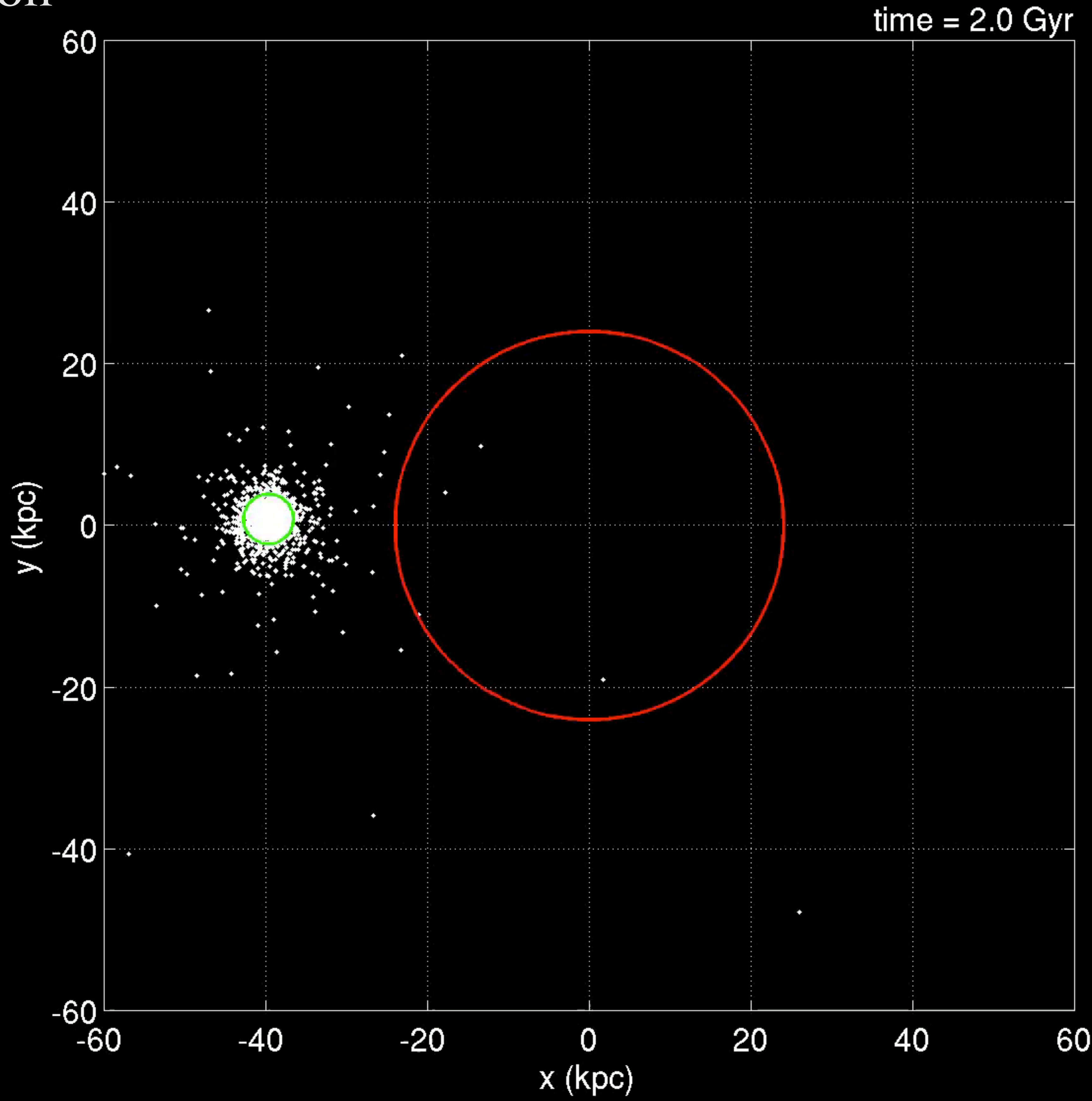
**Scramble** → Clumpiness of the dark matter halo
→ Crucial input for all direct DM searches

# Forming tidal streams

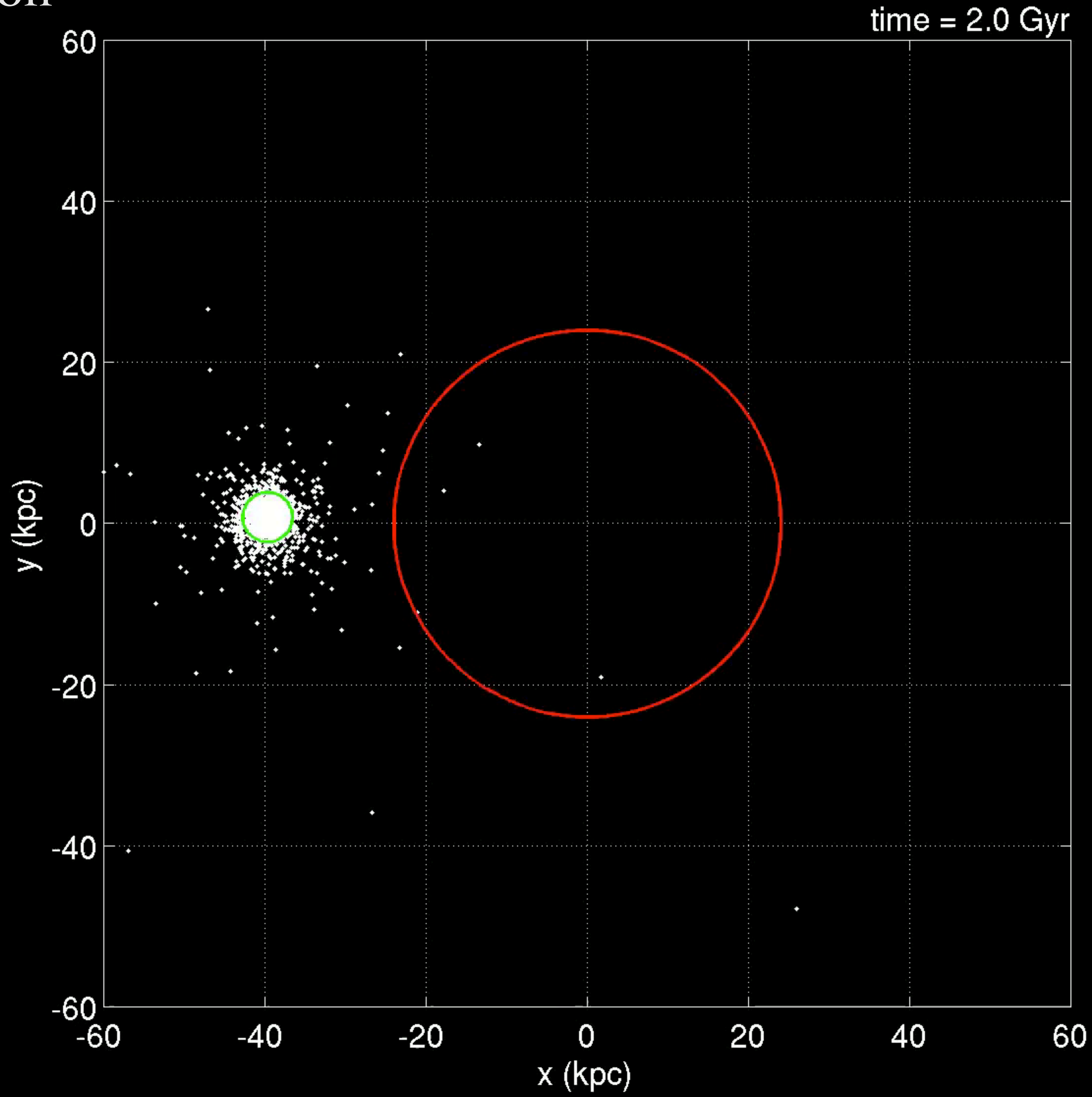
Satellite is pulled apart when the tidal force across it overcomes its own self-gravity



R. Sanderson



R. Sanderson

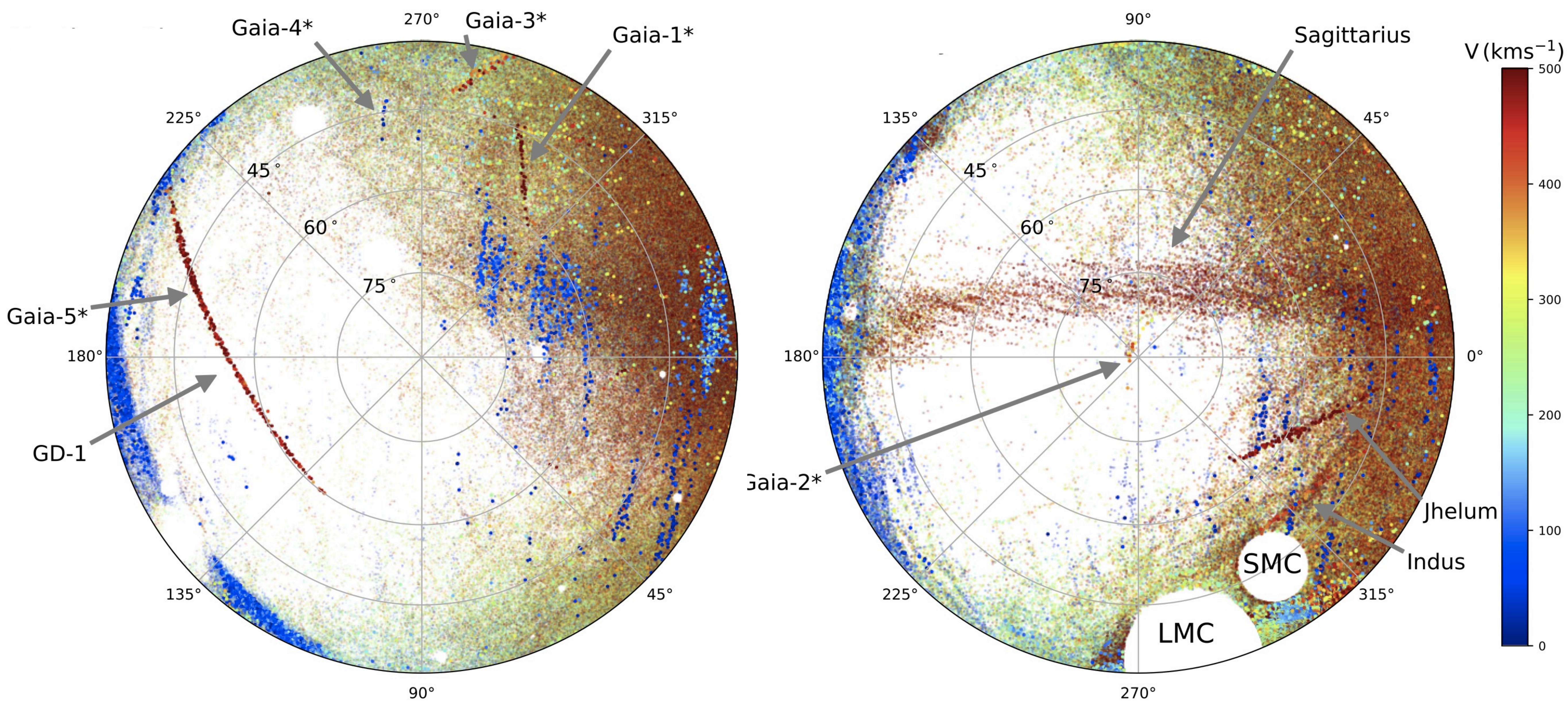


# Finding streams spatially

## Northern sky

## Southern sky

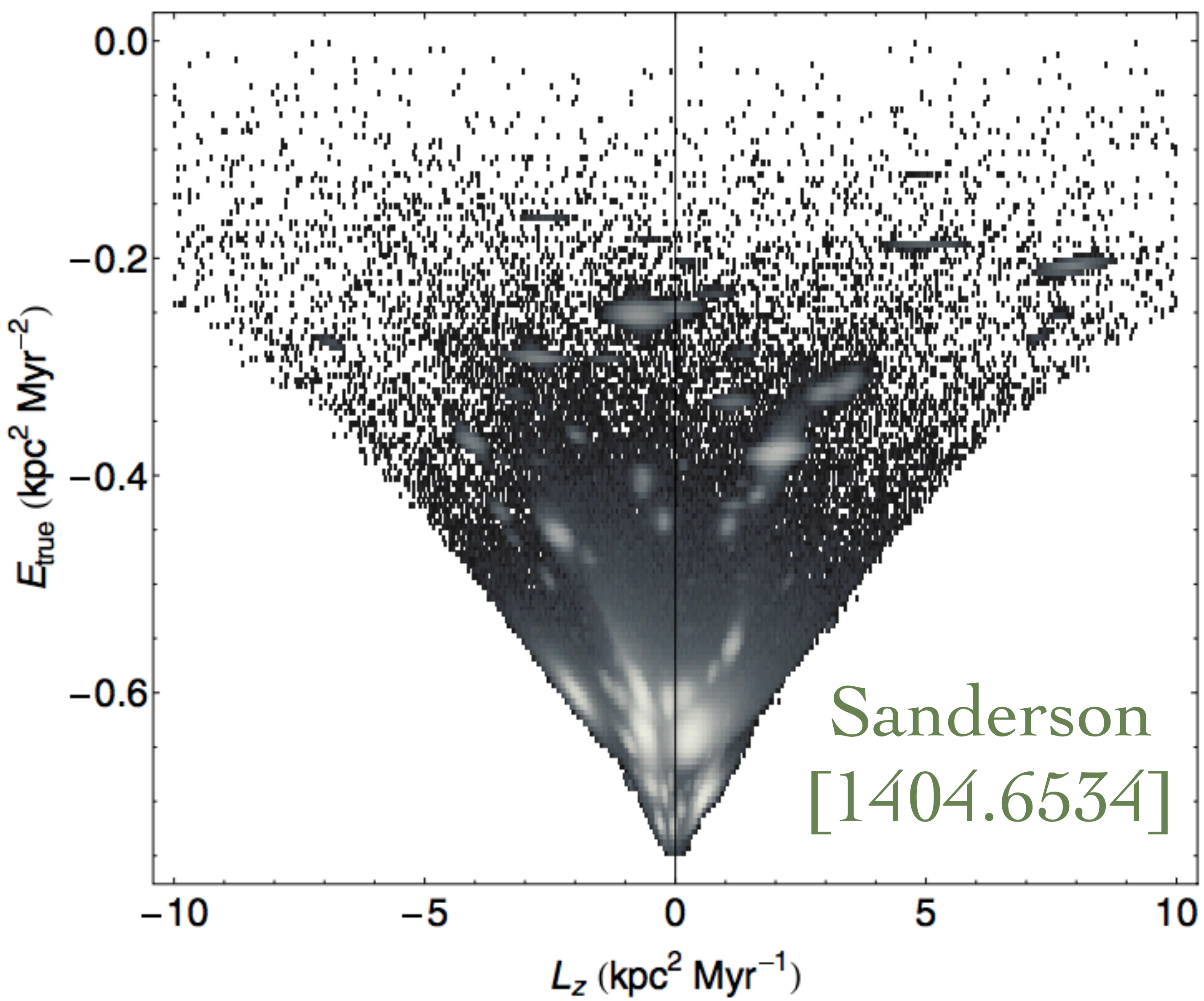
ESA



# Finding streams kinematically

"**Angle-Actions**" - map orbital parameters into variables that are conserved for orbits in slowly varying potentials
→ hence streams remain clustered in "<u>action space</u>" long after they have ceased to be visible in star counts

Computing these variables for stars requires full orbital information
→ **Need complete 6D kinematic data to find streams this way…**




Sanderson [1404.6534]

# S1 stream: what we know so far

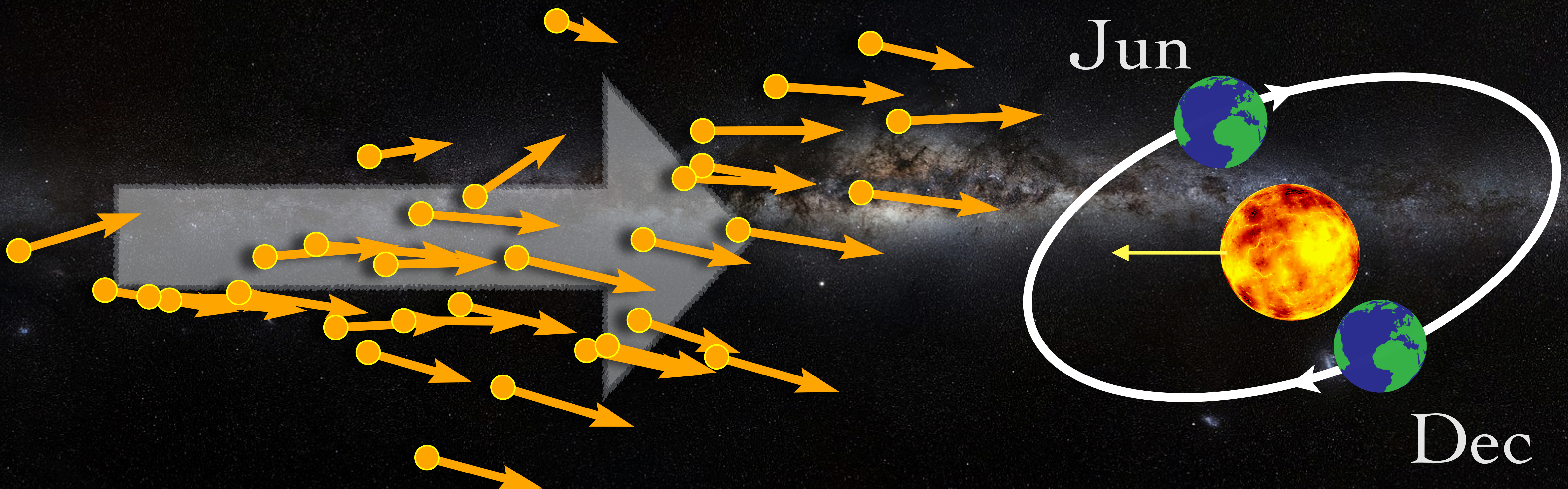
**Galactic velocity:** $\mathbf{v}_{\rm str} = (8.6,\ -286.7,\ -67.9)\ \mathrm{km\,s^{-1}}$
→ Stream on a strongly retrograde orbit, so DM impacts us at high velocity ~ 500 km/s

**Velocity dispersion:** $\sigma_{\rm str} = 46\,\mathrm{km\,s^{-1}}$
→ Suggests a dwarf spheroidal origin, around the mass of the present day Fornax satellite galaxy accreted over 8-10 billion years

**Dark matter content:** $0 + \epsilon < \rho_{\rm str} < 0.55\,\mathrm{GeV\,cm^{-3}}$
→ Upper bound: is probably the local DM density probed over length scales smaller than the stream
→ Lower bound: Progenitor very likely had dark matter but other than that we cannot say, must remain agnostic

# Annual modulation?

# Annual modulation?

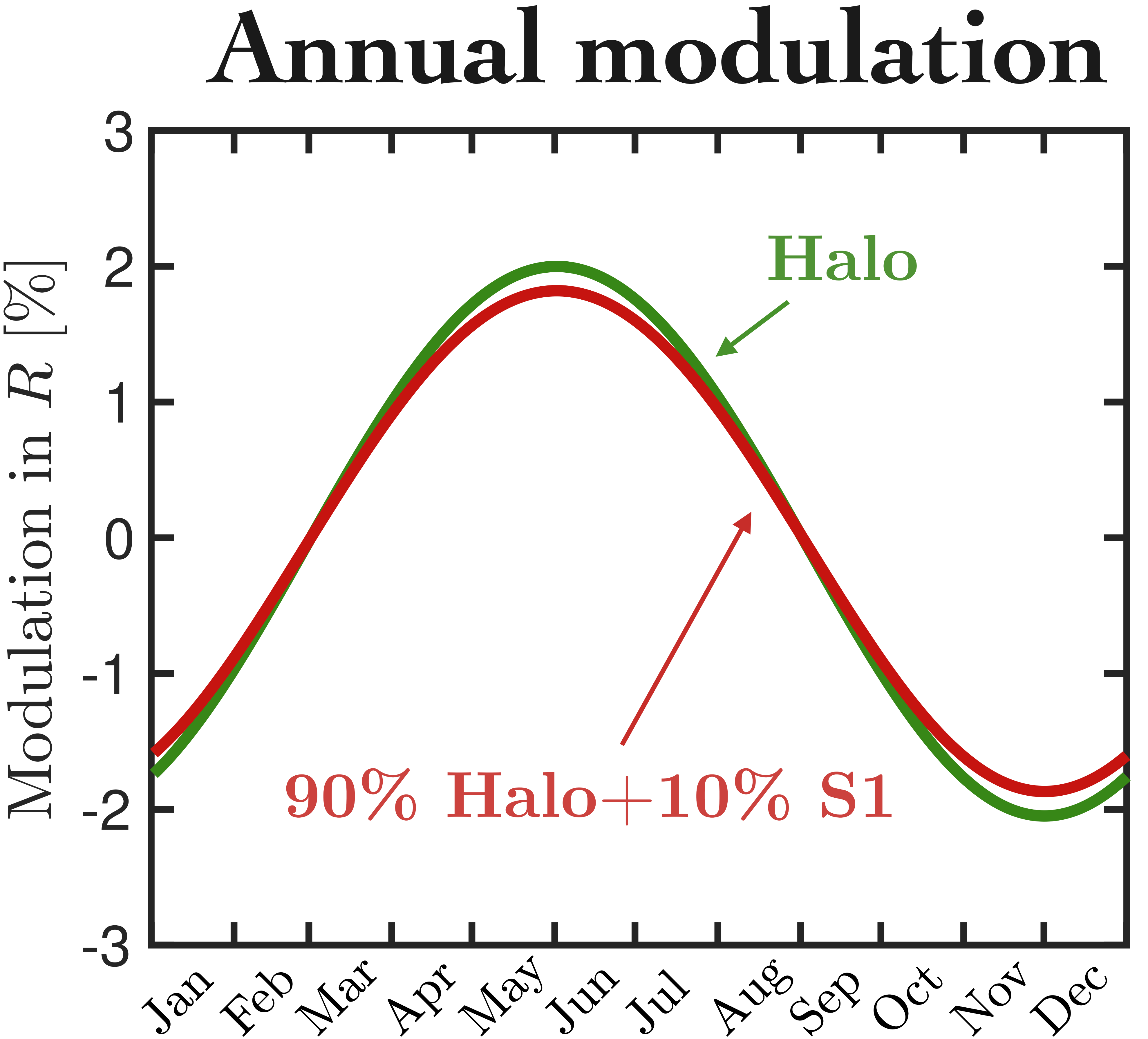


# CYGNUS

- A low pressure gas TPC
- Current plan: $SF_6$ at 20 torr and He at 740 torr
- Various readout technologies being compared
  (MWPCs, μPIC, pixel chips, optical, micromegas)
- Main goal: circumvent the neutrino floor
- Secondary goal: study DM astrophysics
- Paper coming soon…

**CYGNUS: Feasibility of a Nuclear Recoil Observatory with Directional Sensitivity to Dark Matter and Neutrinos**

E. Baracchini,[1,2,3] P. Barbeau,[4] J. B. R. Battat,[5] B. Crow,[6] C. Deaconu,[7] C. Eldridge,[8]
A. C. Ezeribe,[8] D. Loomba,[9] W. A. Lynch,[8] K. J. Mack,[10] K. Miuchi,[11] N. S. Phan,[12]
C. A. J. O'Hare,[13,14] K. Scholberg,[4] N. J. C. Spooner,[8] T. N. Thorpe,[6] and S. E. Vahsen[6]



Annual modulation
Halo
90% Halo+10% S1
Modulation in $R$ [%]
3
2
1
0
-1
-2
-3
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

# The Standard Halo Model

<u>Motivation</u>: Simplest spherical model with asymptotically flat rotation curve

→ Density ~ $1/r^2$

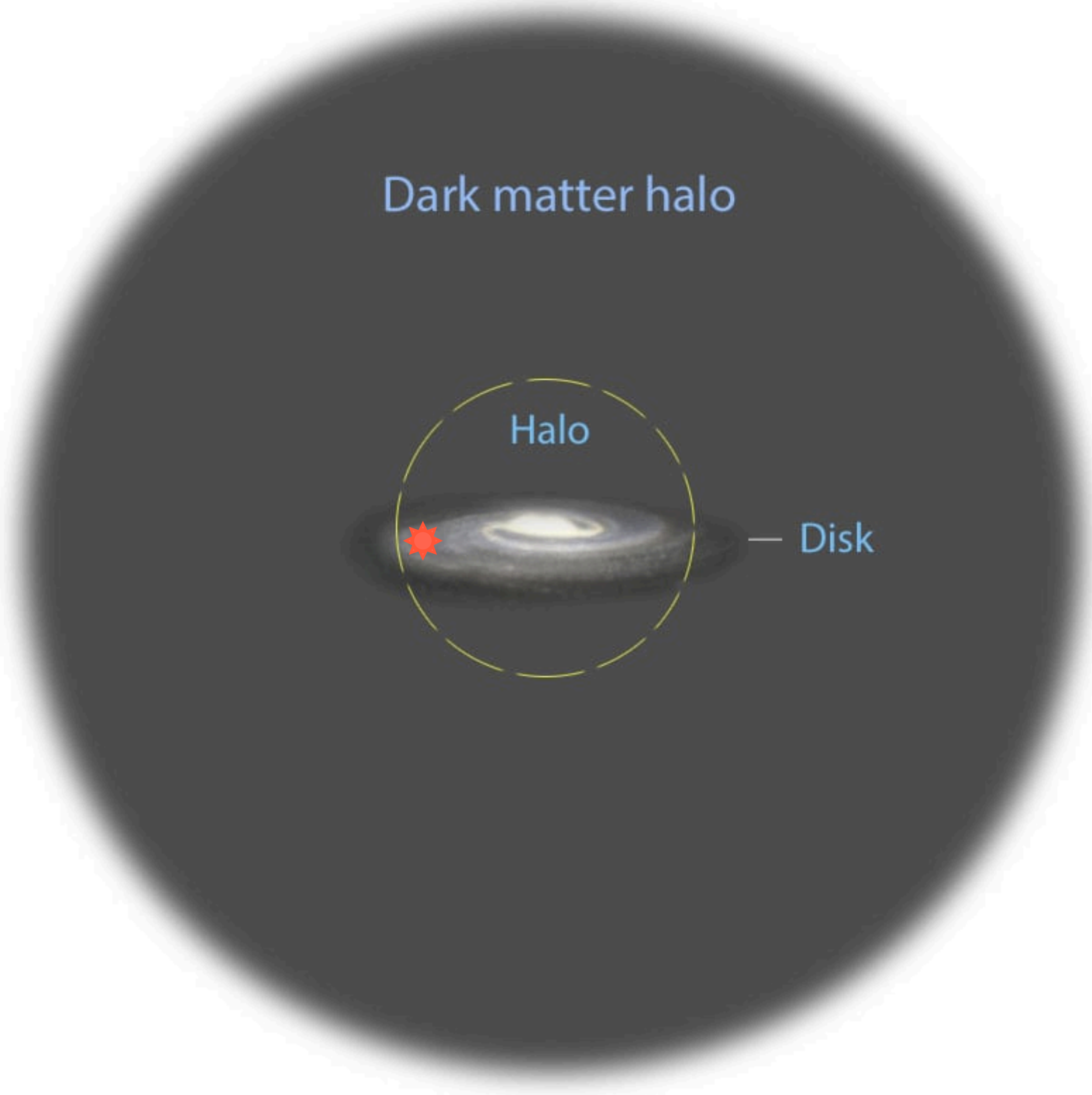
→ Isothermal

→ Gaussian velocities

→ Truncated at $v_{\rm esc}$

$$f(\mathbf{v}) \sim \exp\left(-\frac{|\mathbf{v}|^2}{v_{\rm rot}^2}\right)$$

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



**SHM** is a *standard*, i.e. it's okay for it to be wrong in certain aspects, but we should still want to refine the model with data

## I) Sphericity

→ Most recent Jeans analysis with RR lyraes continue to favour a very spherical halo for the inner most 15 kpc [1806.09635]

## II) Rotation speed $v_0 = v_{\rm rot}(r = 8\ {\rm kpc})$

→ Proper motion of Sgr A* → $v_0$ = 233 ± 3 km/s (±1% sys.) [1602.07702]

→ 23,000 APOGEE/*Gaia* red giants → $v_0$ = 229 ± 0.2 km/s (±5% sys.) [1810.09466]

## III) Local density

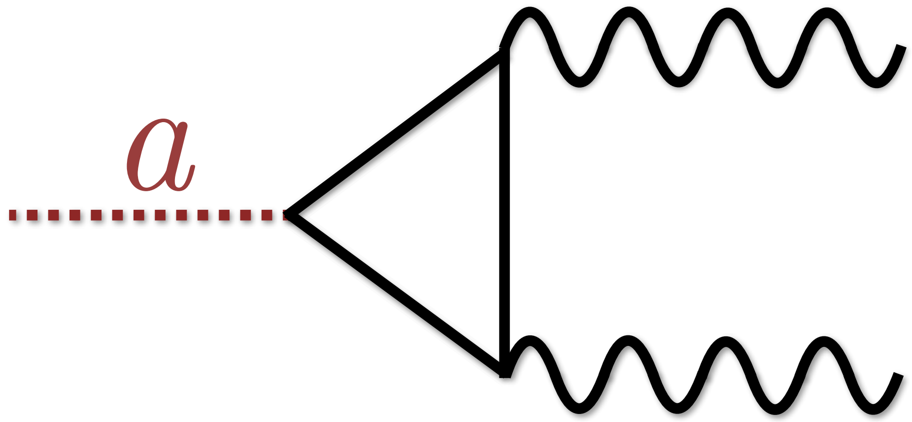
→ Recent analyses give higher values (~0.5) than canonical 0.3 GeV/cm$^3$

→ More Gaia analyses forthcoming, no big surprises are expected

## IV) Isotropic? → Definitely not…

# Axion-photon coupling: $g_{a\gamma}$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$




For QCD axion: $g_{a\gamma} \propto m_a$

$$\nabla \cdot \mathbf{E} = \rho_q - g_{a\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma}(\mathbf{B}\,\dot{a} - \mathbf{E} \times \nabla a)$$

$$\nabla \cdot \mathbf{B} = 0$$

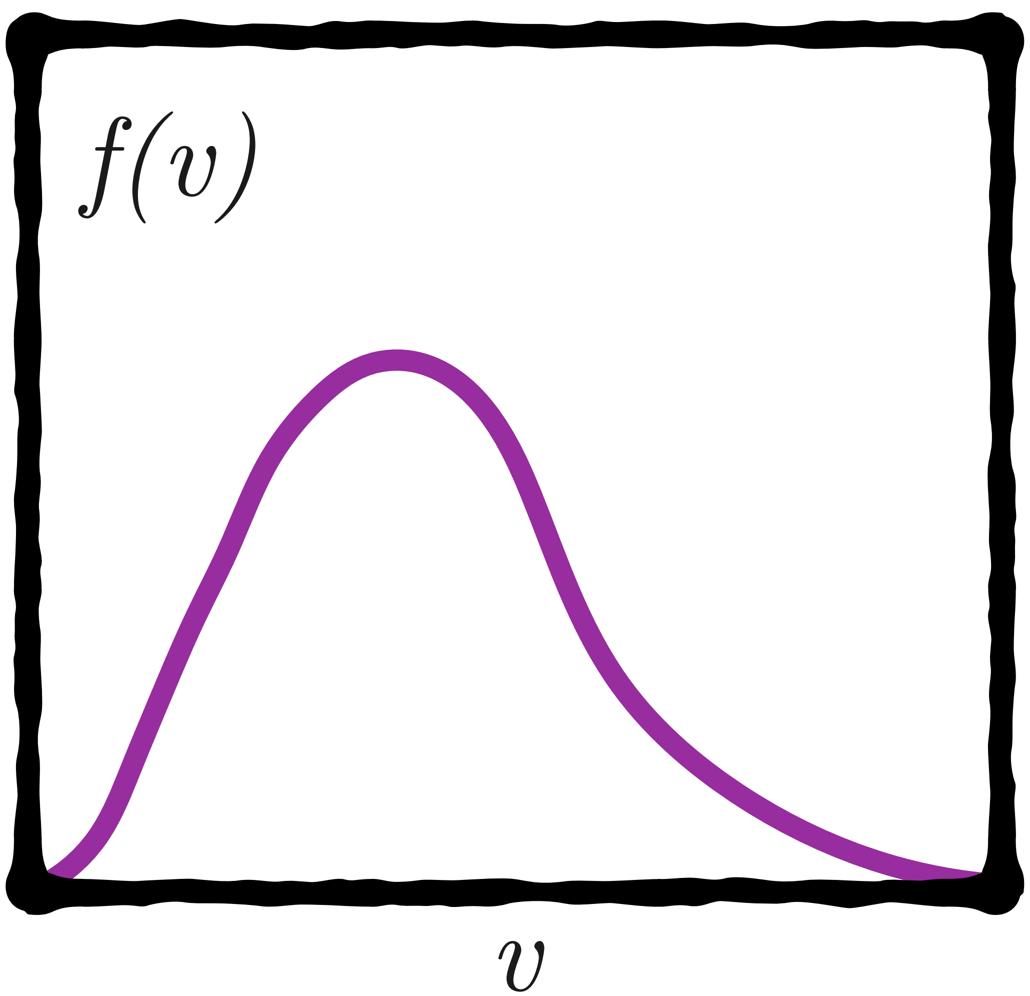
$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

$$(\Box + m_a^2) a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}$$

# Measuring $f(v)$ in a haloscope

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

A haloscope can effectively make a direct measurement of the astrophysical speed distribution



# Measuring $f(v)$ in a haloscope

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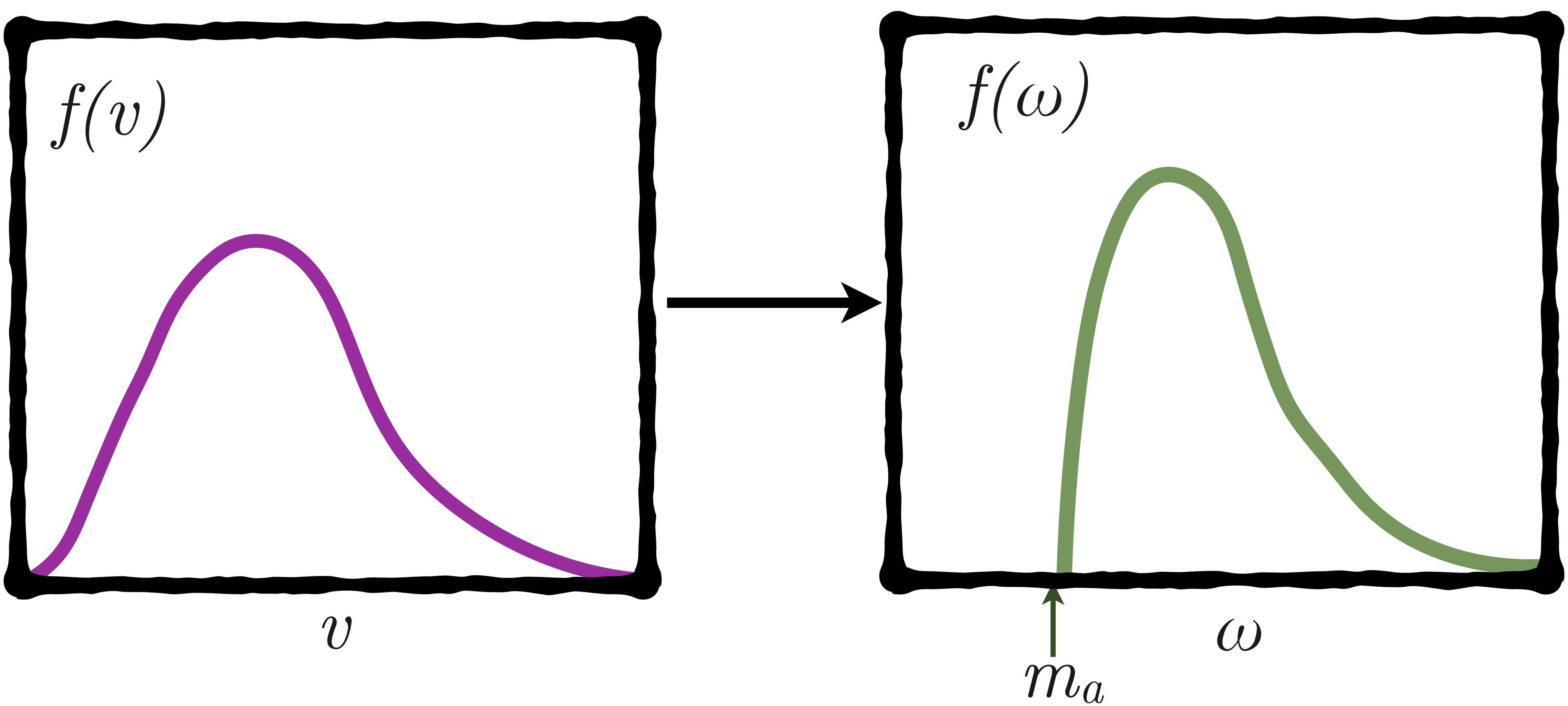
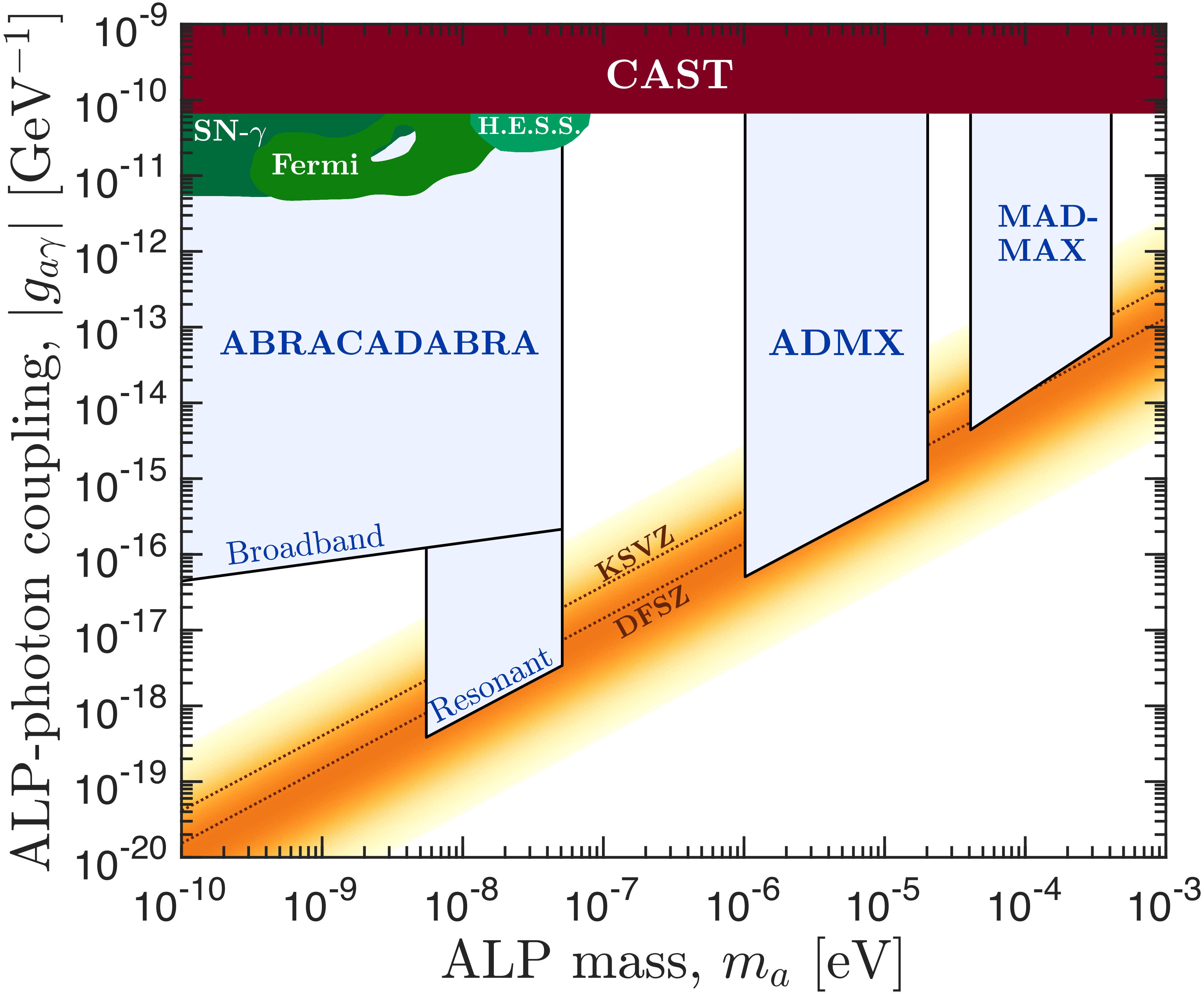
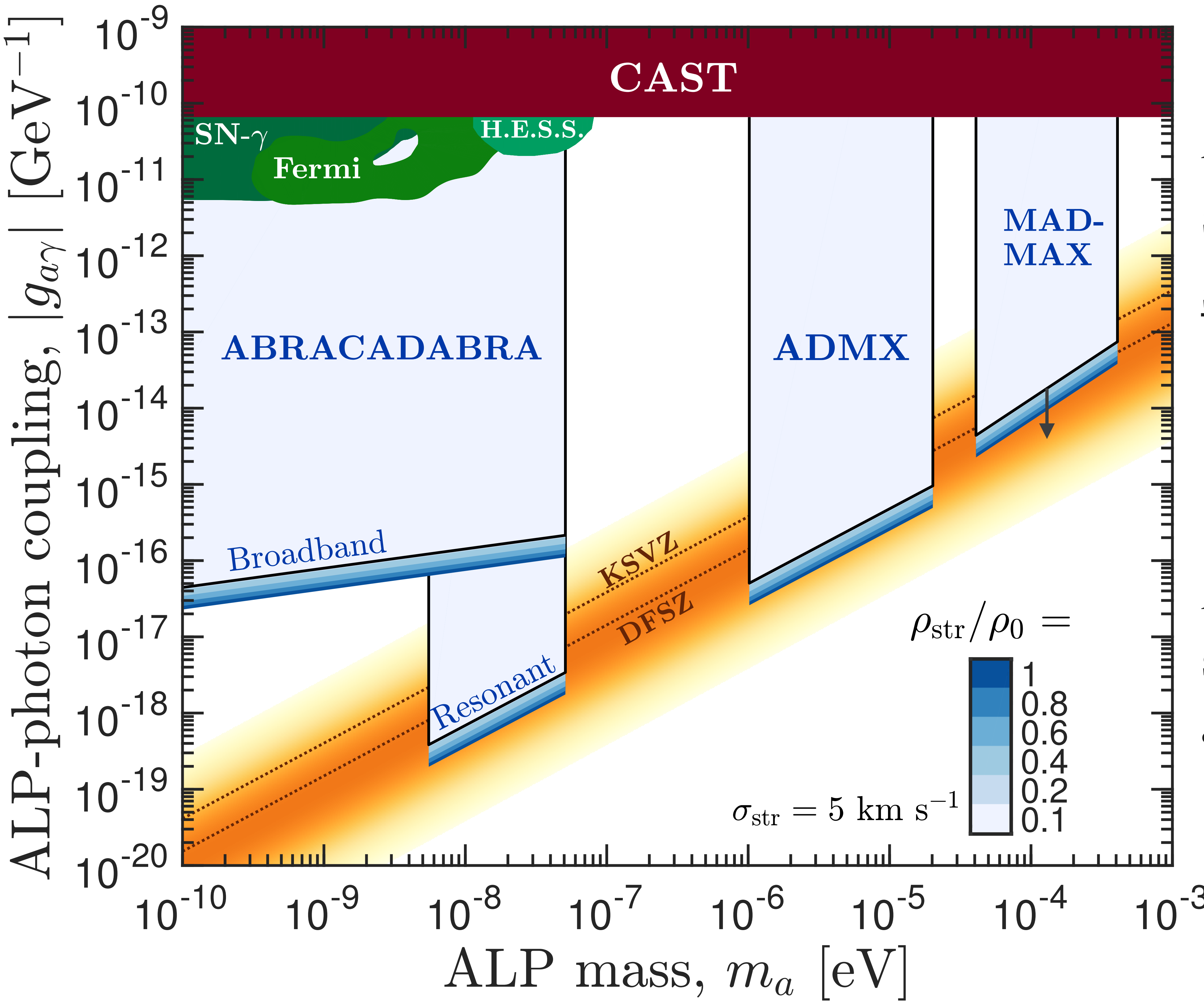


# Axion experimental projections



# Impact of streams on axion searches:




Axion searches like <u>sharp</u> signals

↓

A cold S1 stream <u>improves</u> axion sensitivity