Universidad Zaragoza 1542

Direct dark matter detection and *Gaia*

Ciaran O'Hare
Universidad de Zaragoza

Topics for today

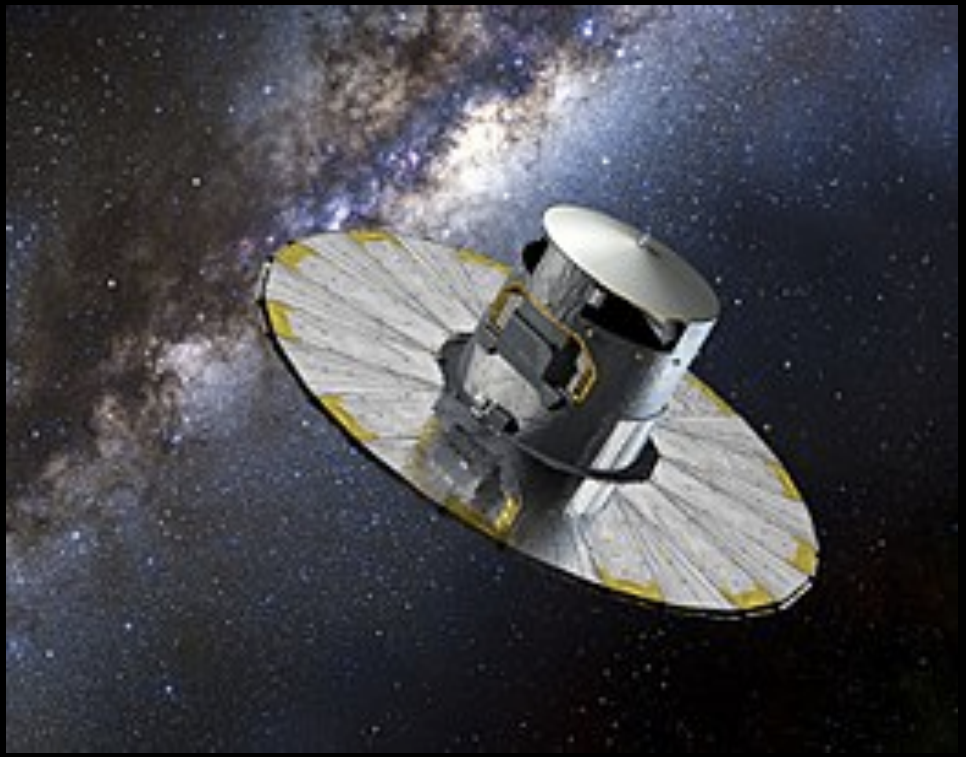
Gaia

The MW halo

Impact on WIMP searches

Impact on axion searches

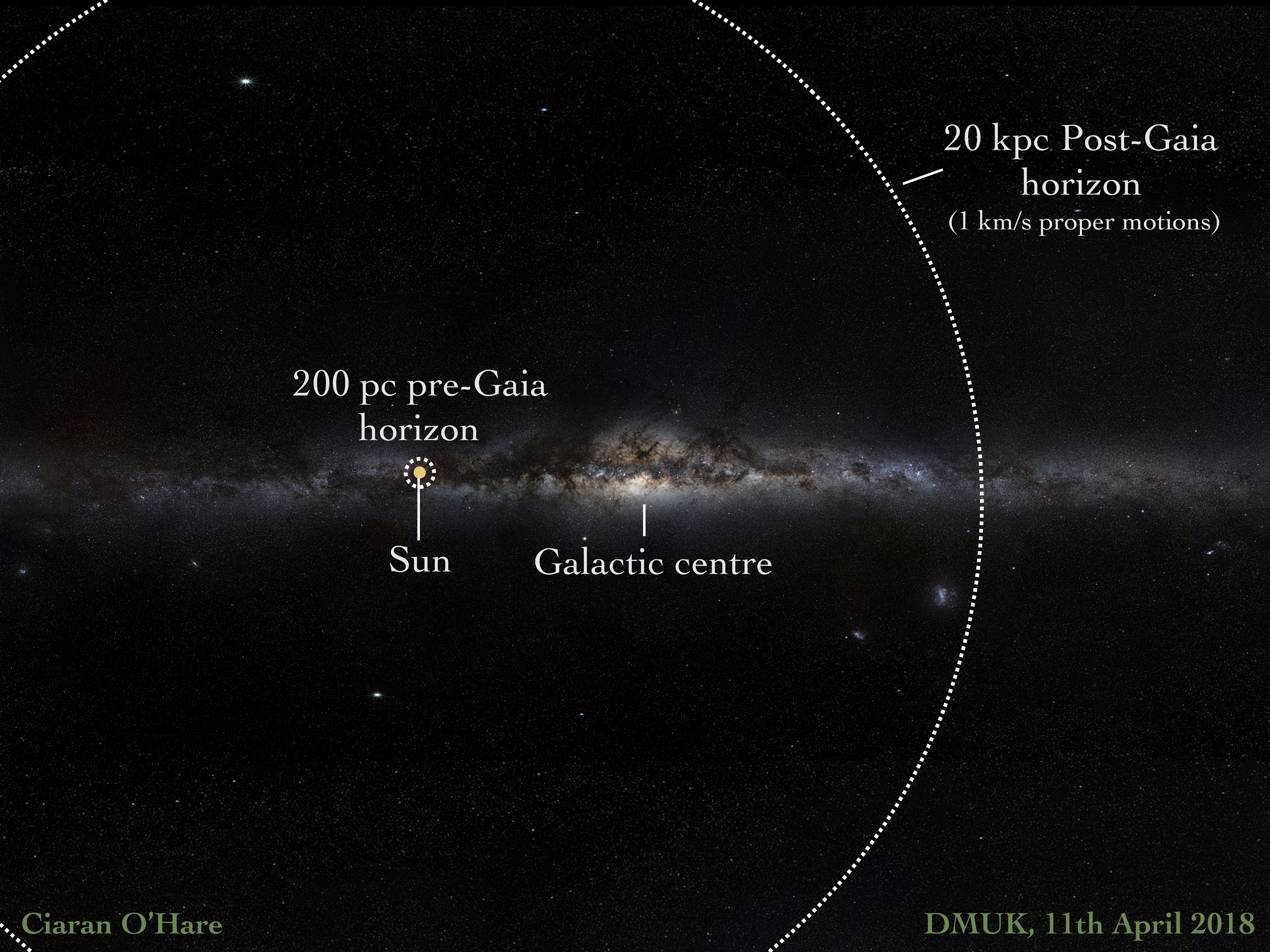
Gaia



- 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

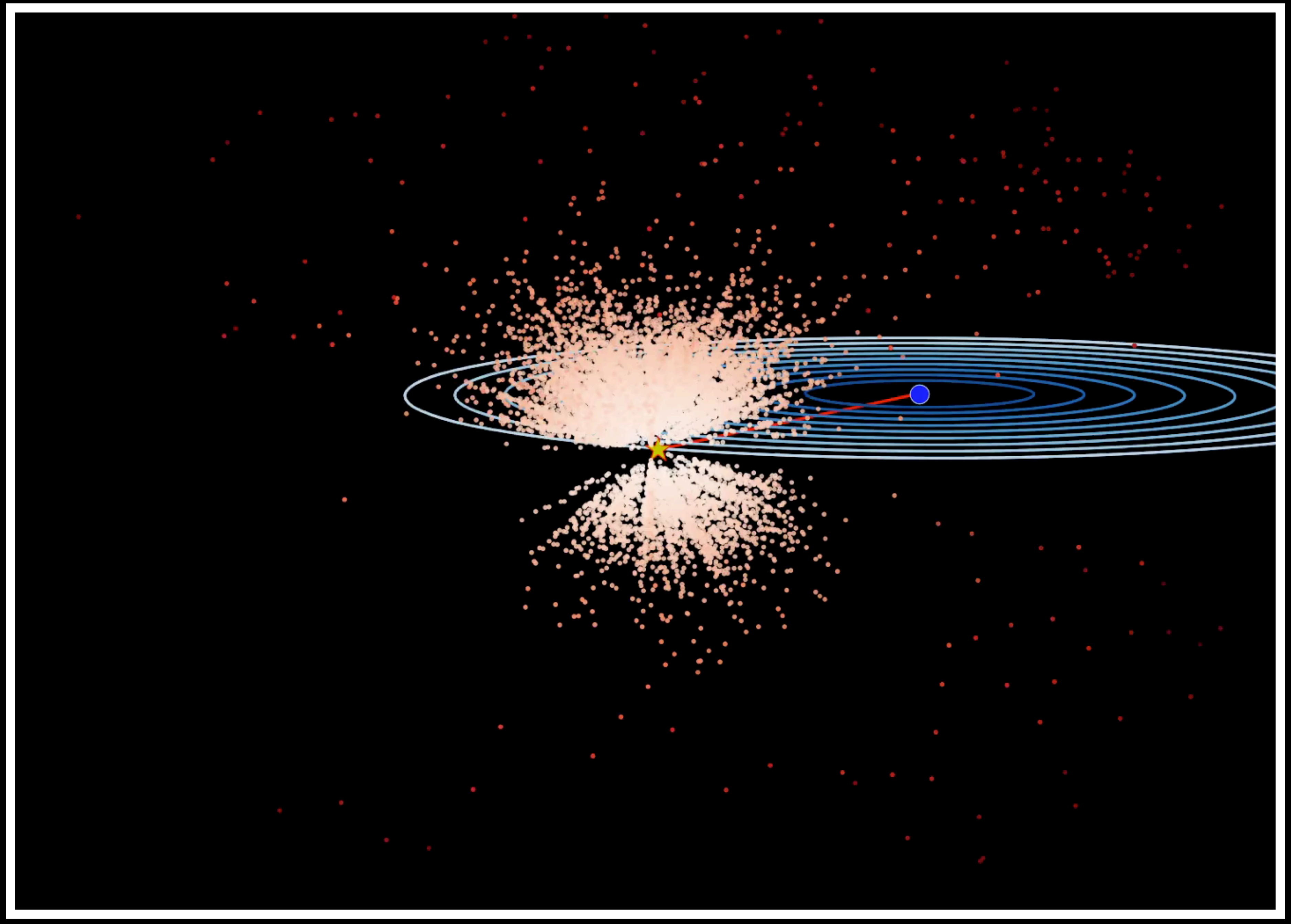


20 kpc Post-Gaia
horizon
(1 km/s proper motions)
200 pc pre-Gaia
horizon
Sun
Galactic centre
Ciaran O'Hare
DMUK, 11th April 2018

Sample of the stellar halo in SDSS-*Gaia*:

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

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



All stars in 6D

x, y, z, v_x, v_y, v_z

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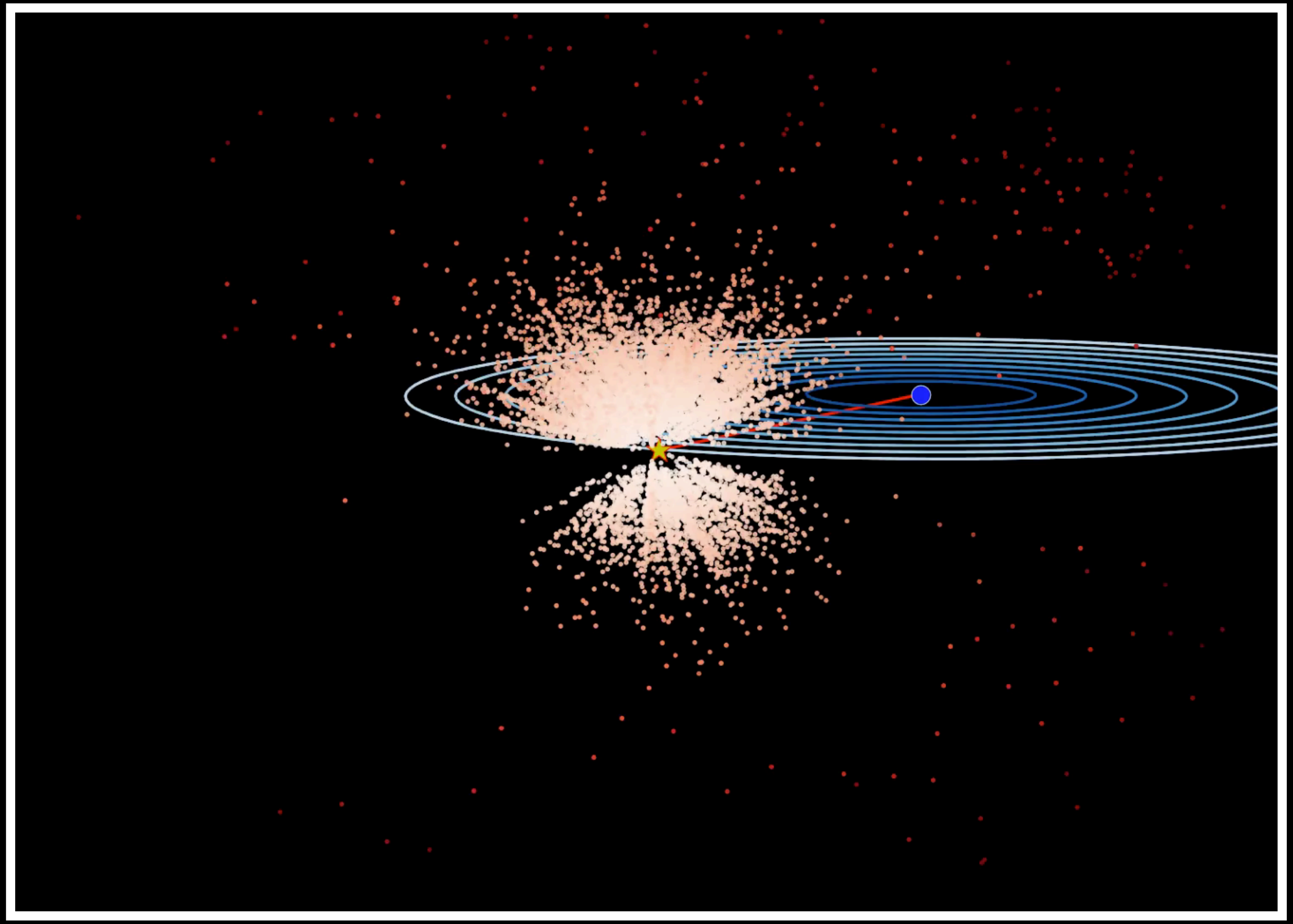
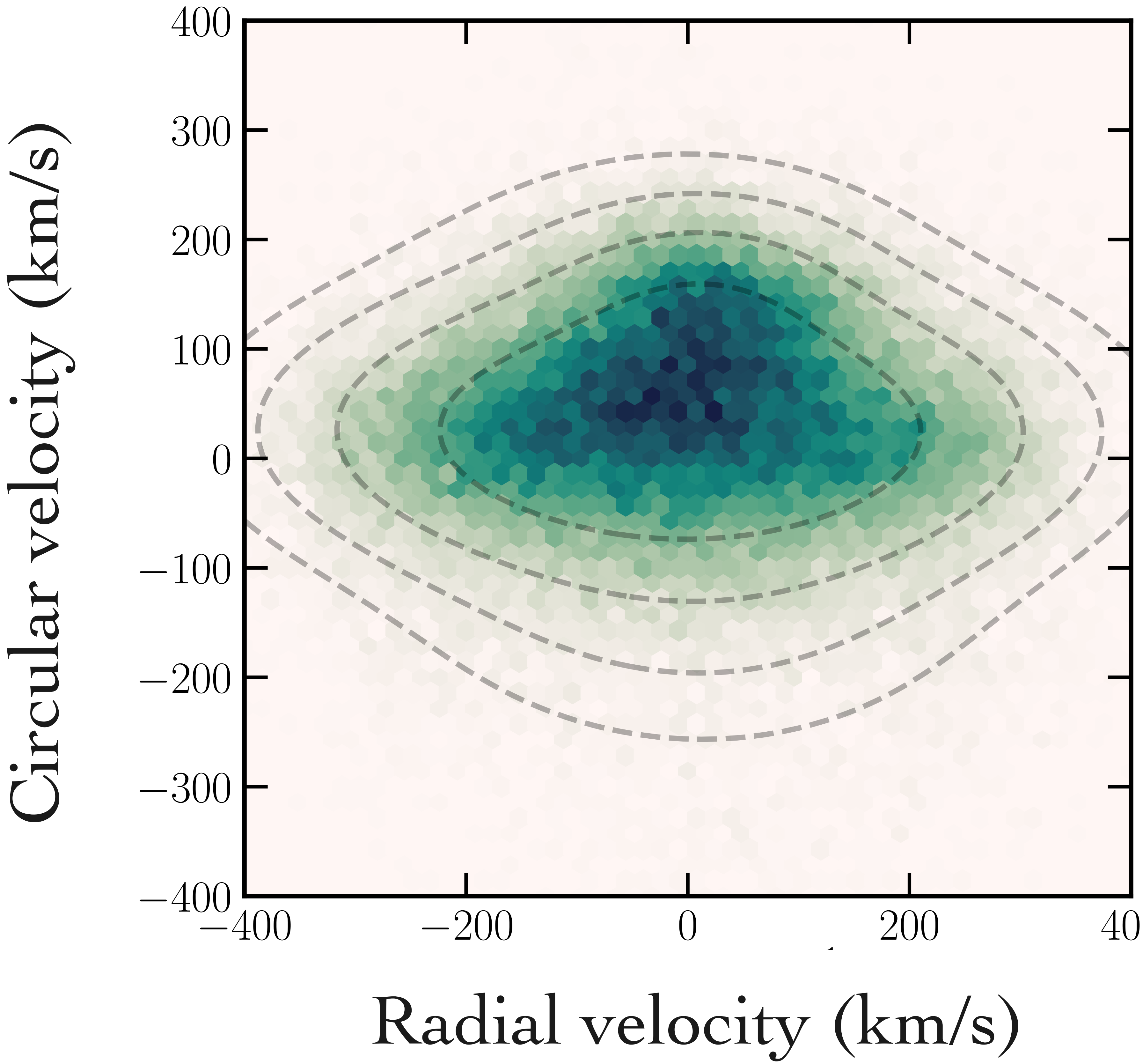


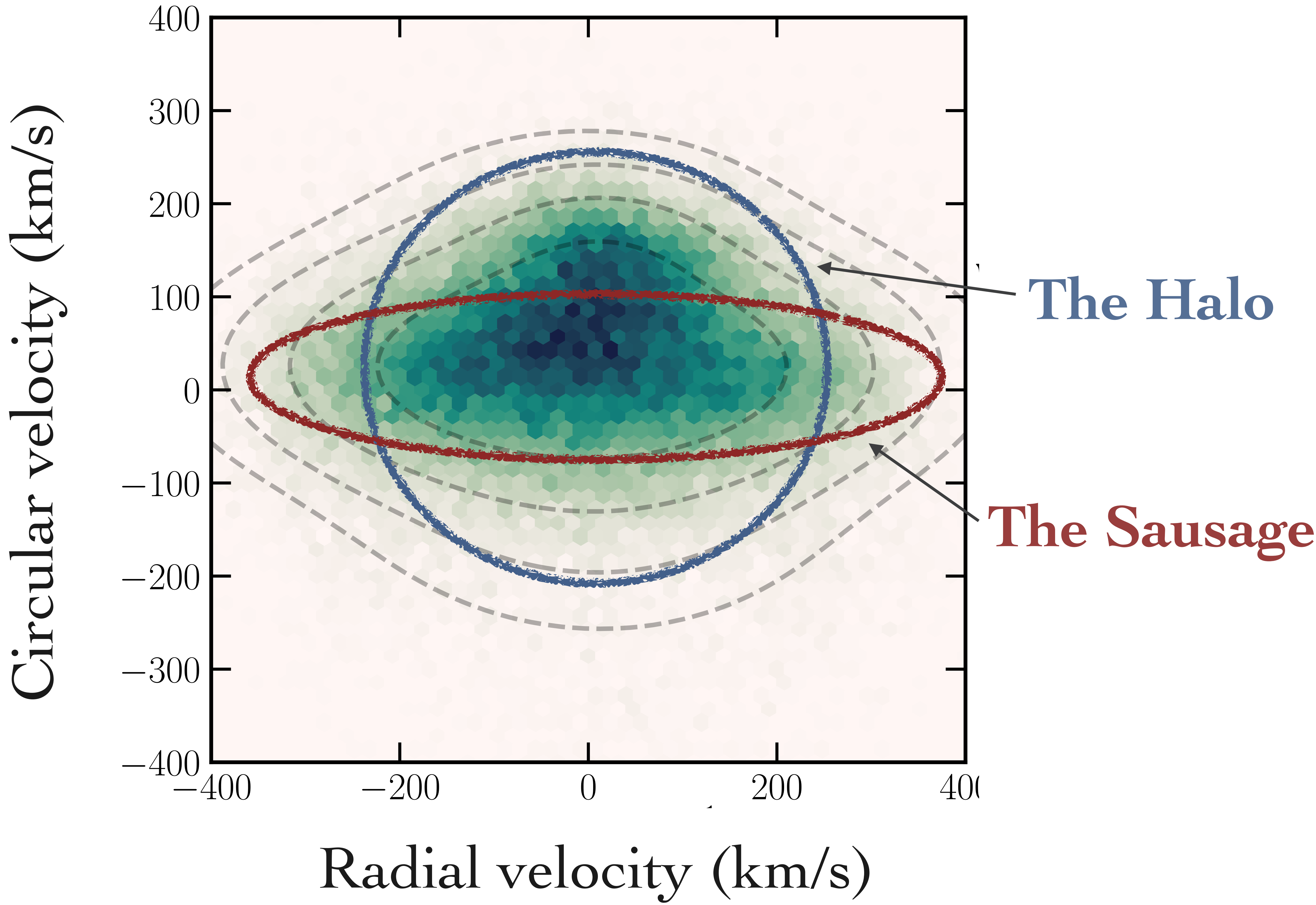
All stars in 6D

x, y, z, v_x, v_y, v_z

Evidence for two component halo



Evidence for two component halo



Gaia Sausage

From Wikipedia, the free encyclopedia

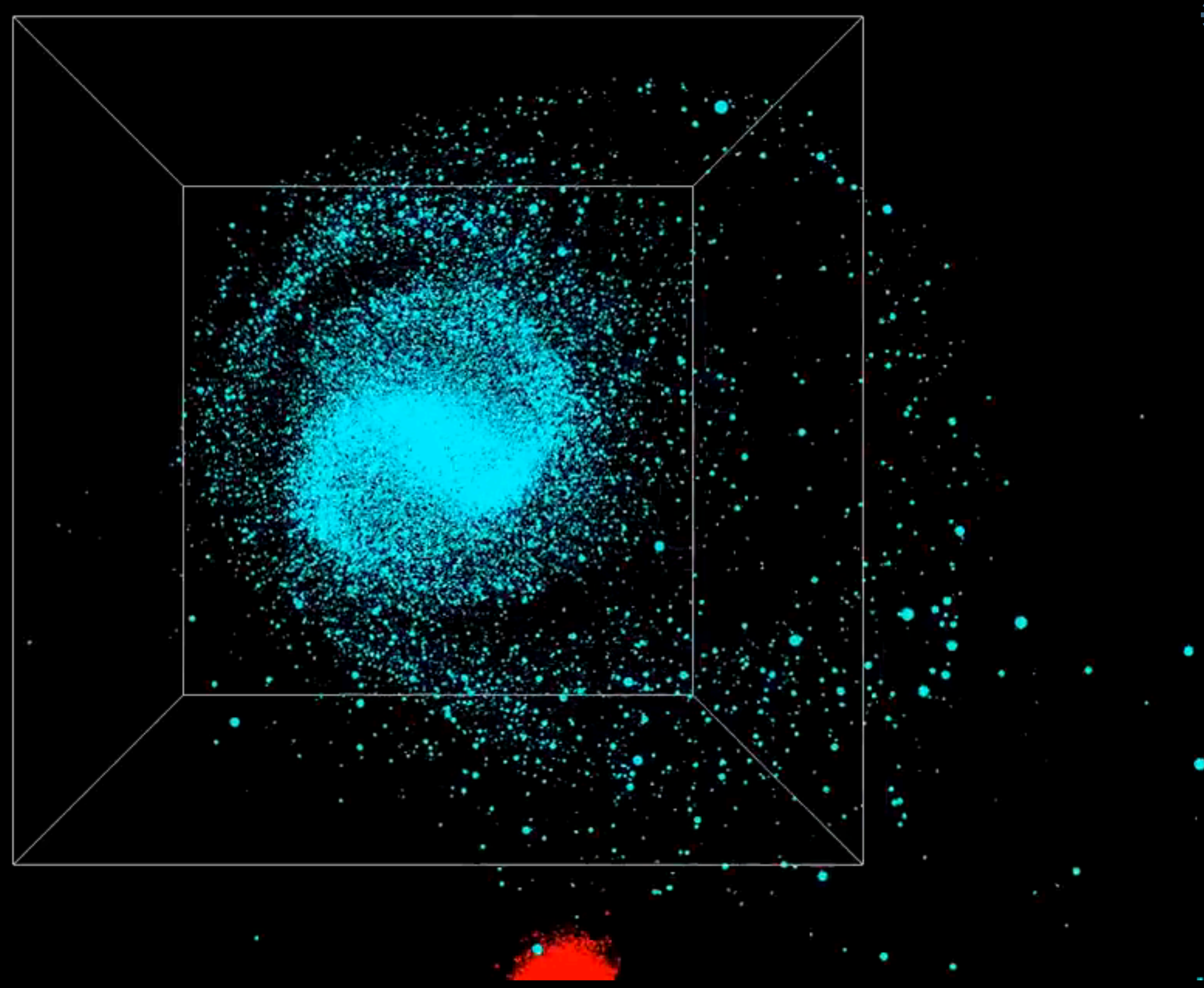
The **Gaia Sausage** is the remains of a dwarf galaxy, the "Sausage Galaxy" or **Gaia-Enceladus-Sausage** or just **Gaia-Enceladus**, that merged with the Milky Way about 8 - 11 billion years ago. At least eight globular clusters were added to the Milky Way along with 50 billion solar masses of stars, 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

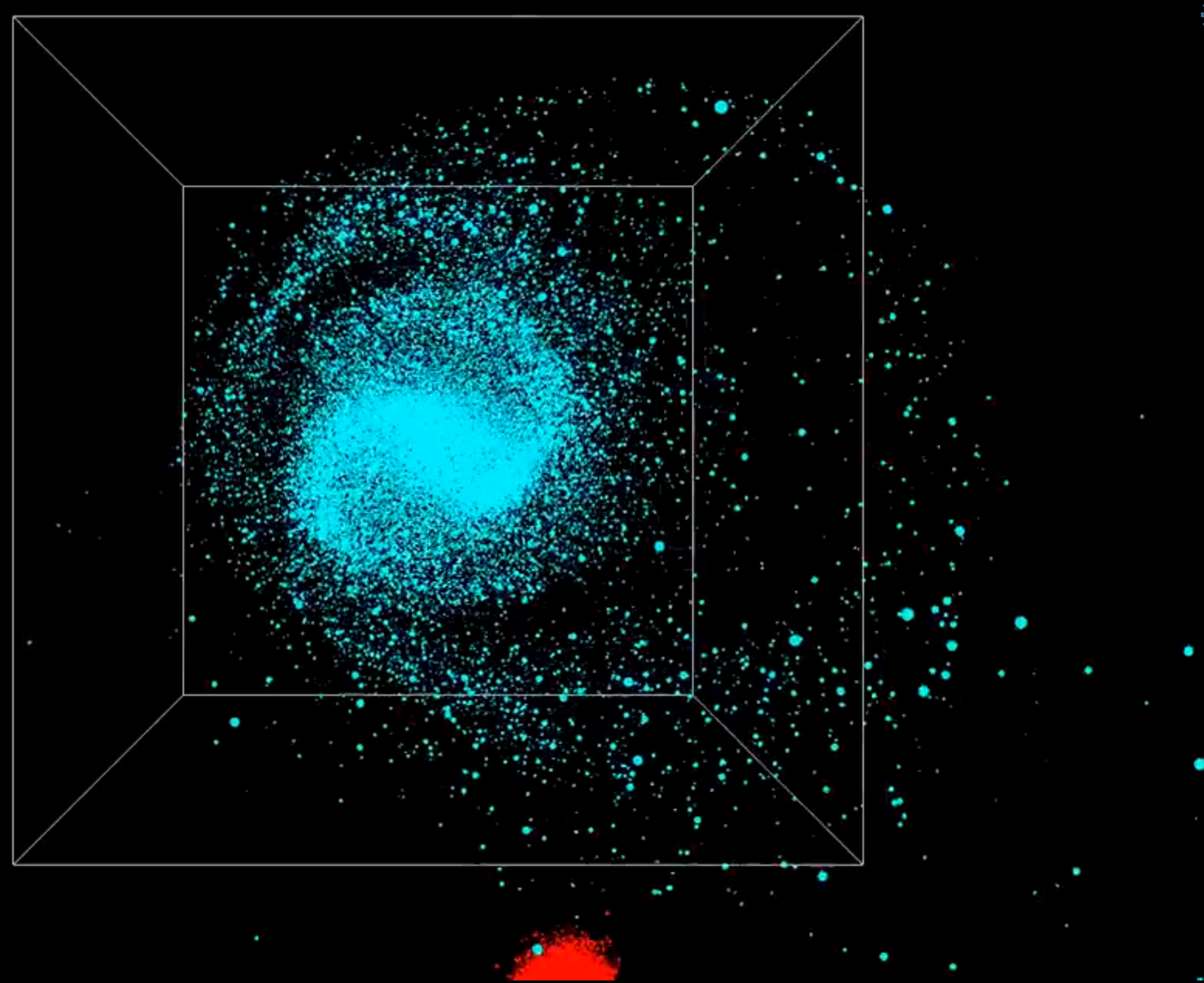


- Highly radial orbits suggest head-on collision with small impact parameter
- Leading to stars with highly radial orbits today

Anisotropy parameter of stars today: $\beta \sim 0.9$

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



- Highly radial orbits suggest head-on collision with small impact parameter
- Leading to stars with <u>highly radial</u> orbits today

Anisotropy parameter of stars today: $\beta \sim 0.9$

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*

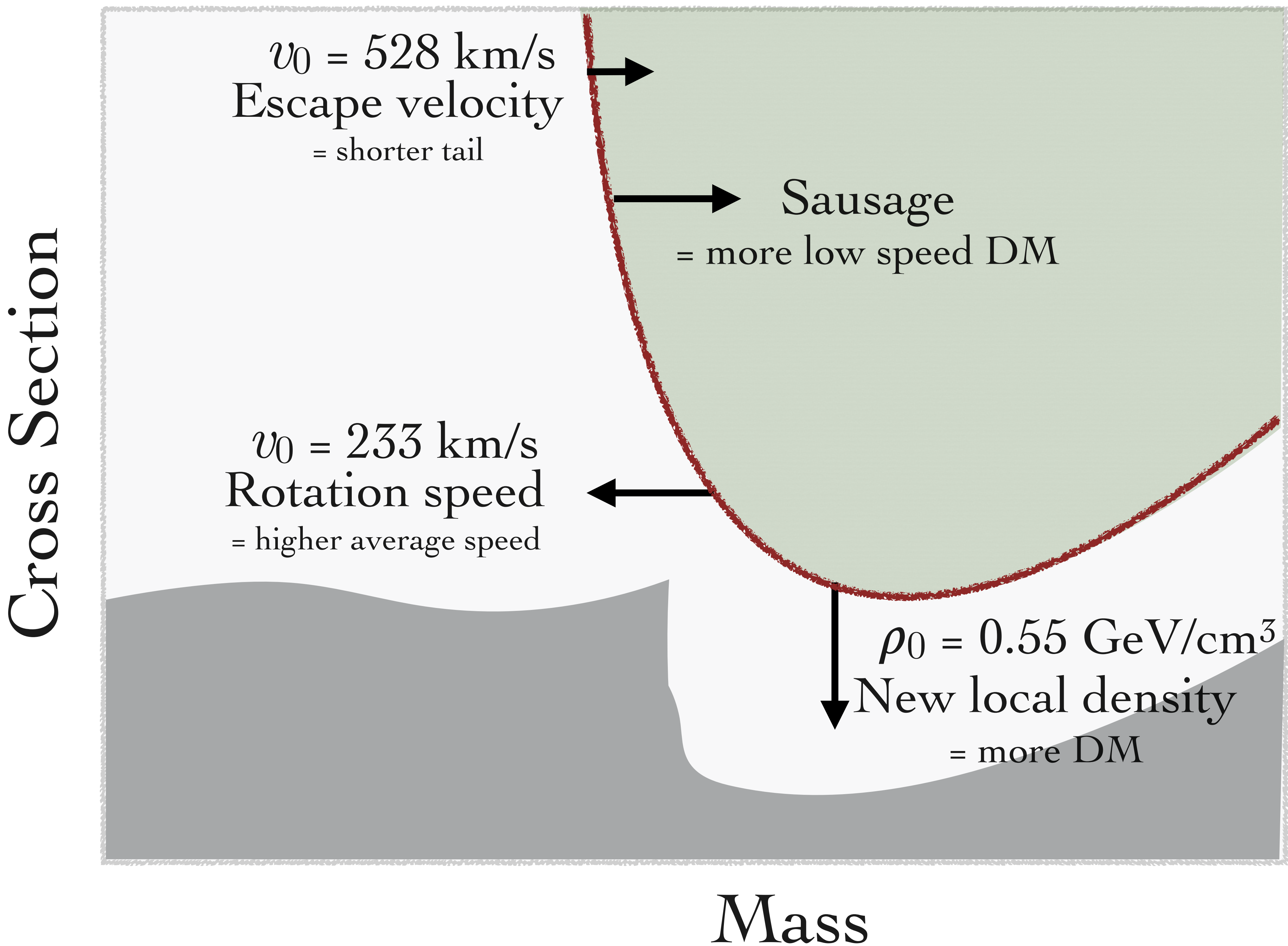
(Dated: October 30, 2018)

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

$g(v_{\rm min})$ files included for easy implementation into analysis codes

Impact of new model on WIMPs

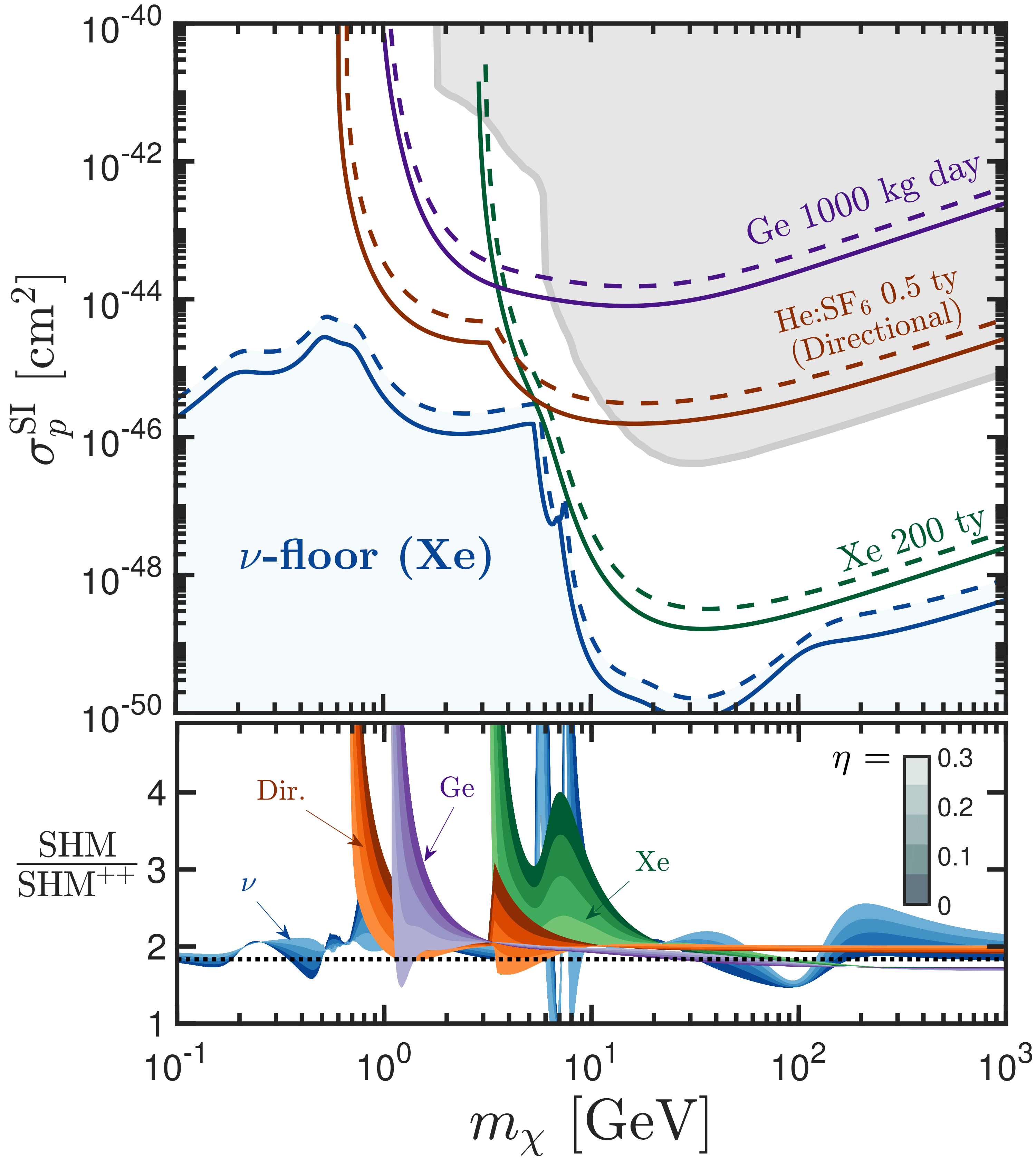
Summary of the updates included in the **SHM^{++}**



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

- - **SHM**

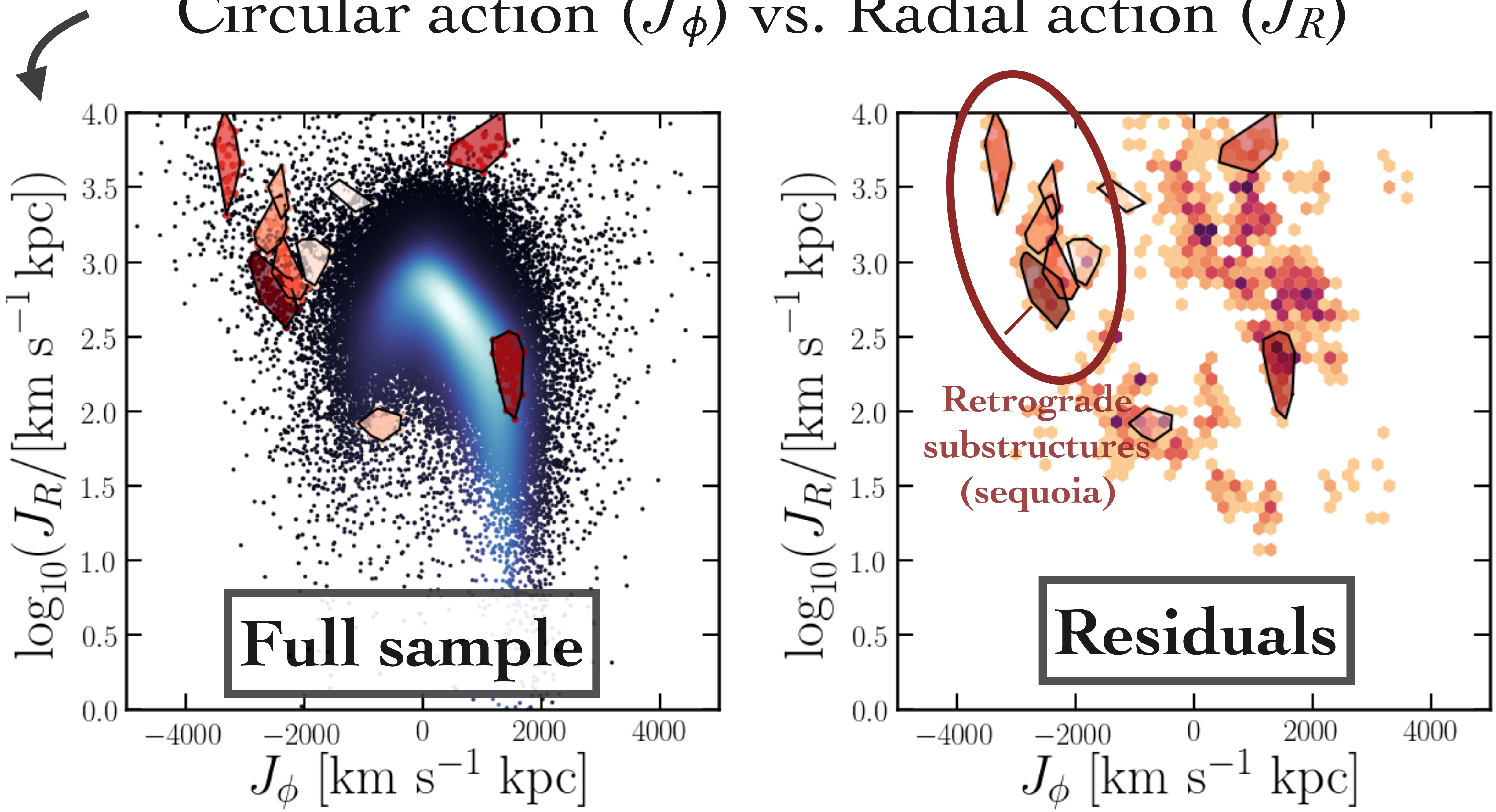
— **SHM^{++}**



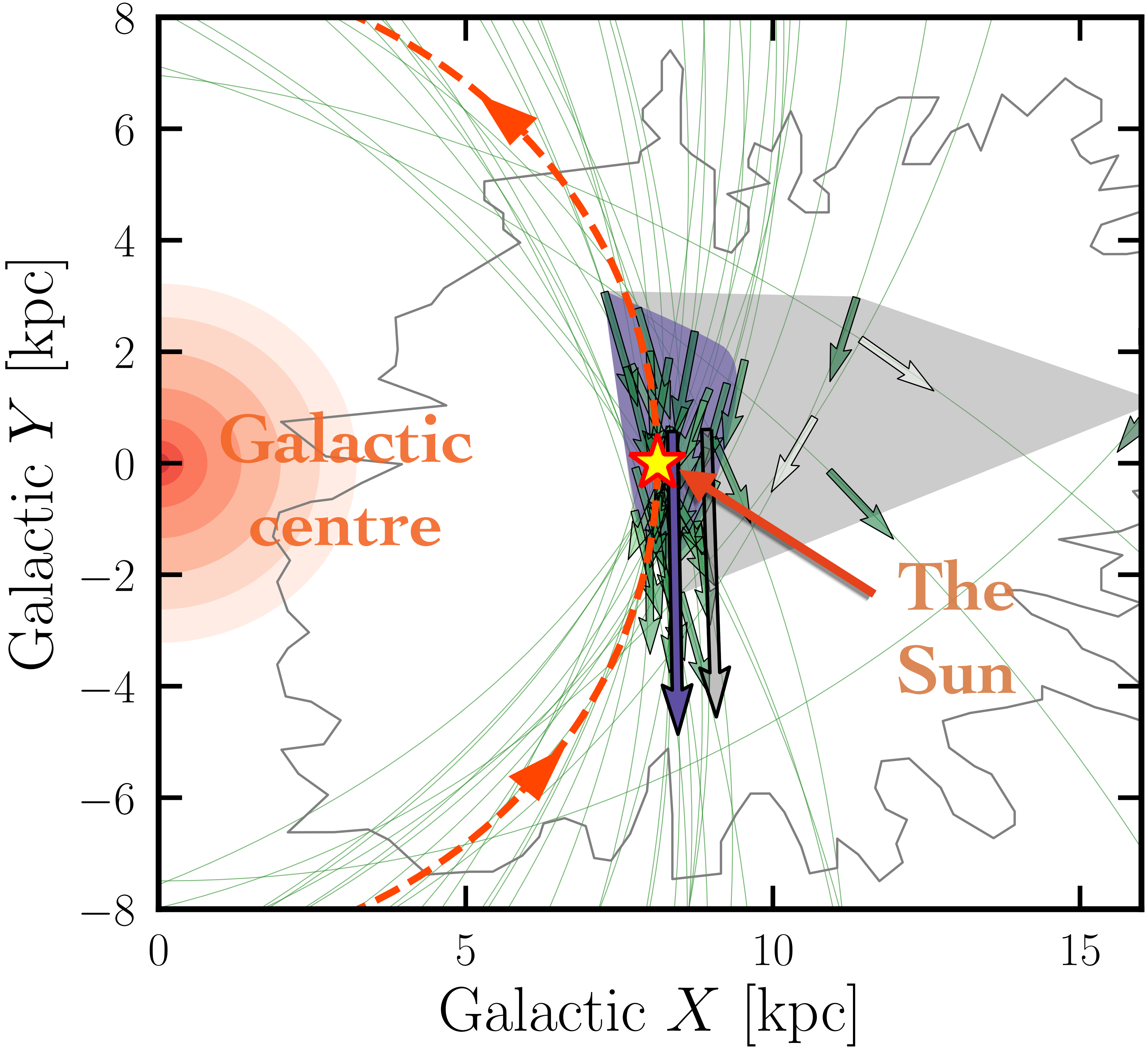
Evidence for substructure

Substructure appears as clusterings in **orbital actions**

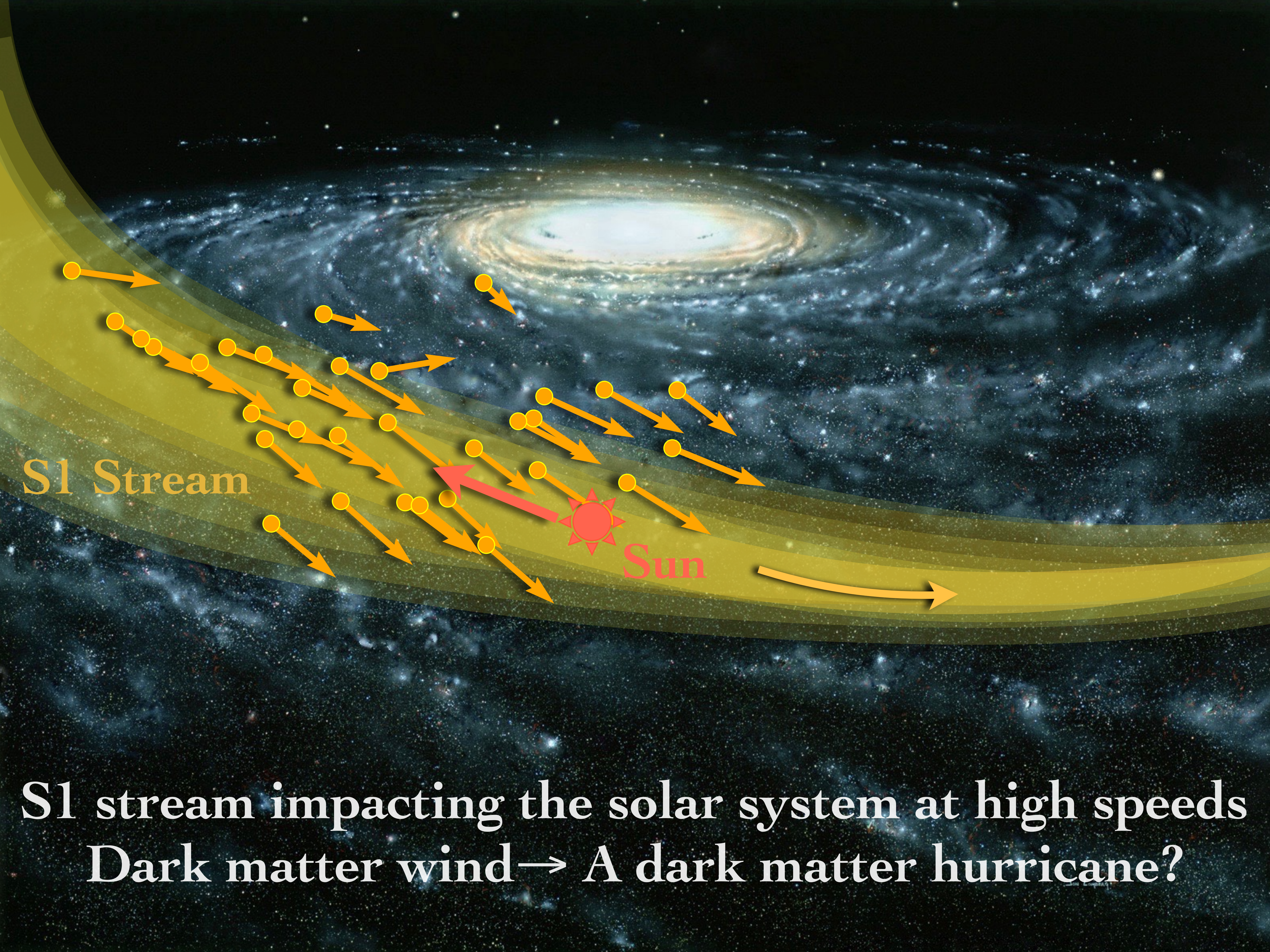
Circular action (J_ϕ) vs. Radial action (J_R)



The S1 stream



- Most prominent "sequoia" substructure encompassing the Solar System
- Likely the remnant of a large dwarf spheroidal accreted around the same time as the Sausage event (see 1904.03185)



S1 stream impacting the solar system at high speeds
Dark matter wind→ A dark matter hurricane?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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' blowing at 310 miles per SECOND is on a collision course with Earth and may finally offer proof the mysterious material exists
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Dark matter hurricane to hit Earth with speeds of up to 31
per SECOND
A Dark Matter "Hurricane" Is Blowing Past The Earth Right Now
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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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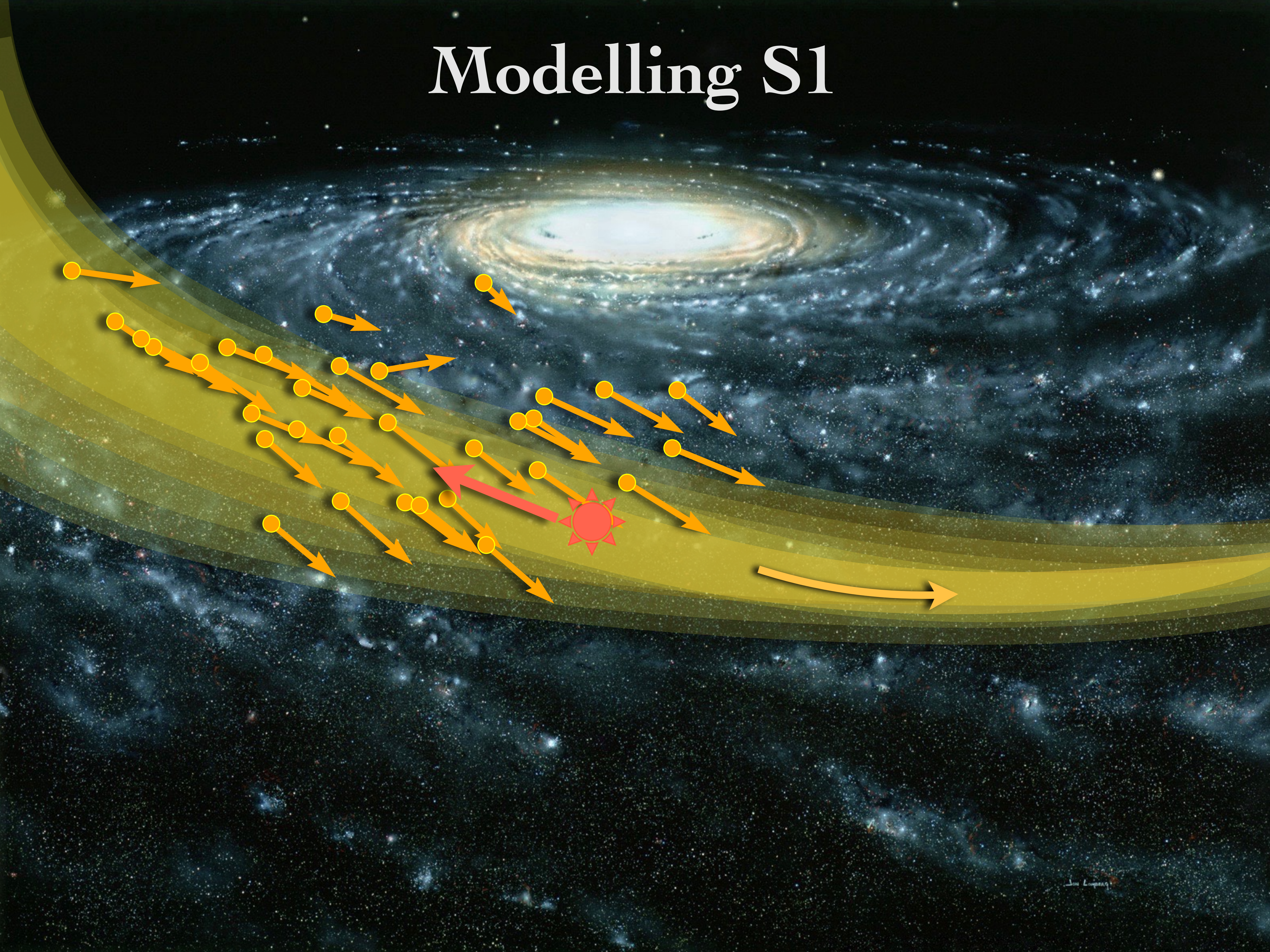
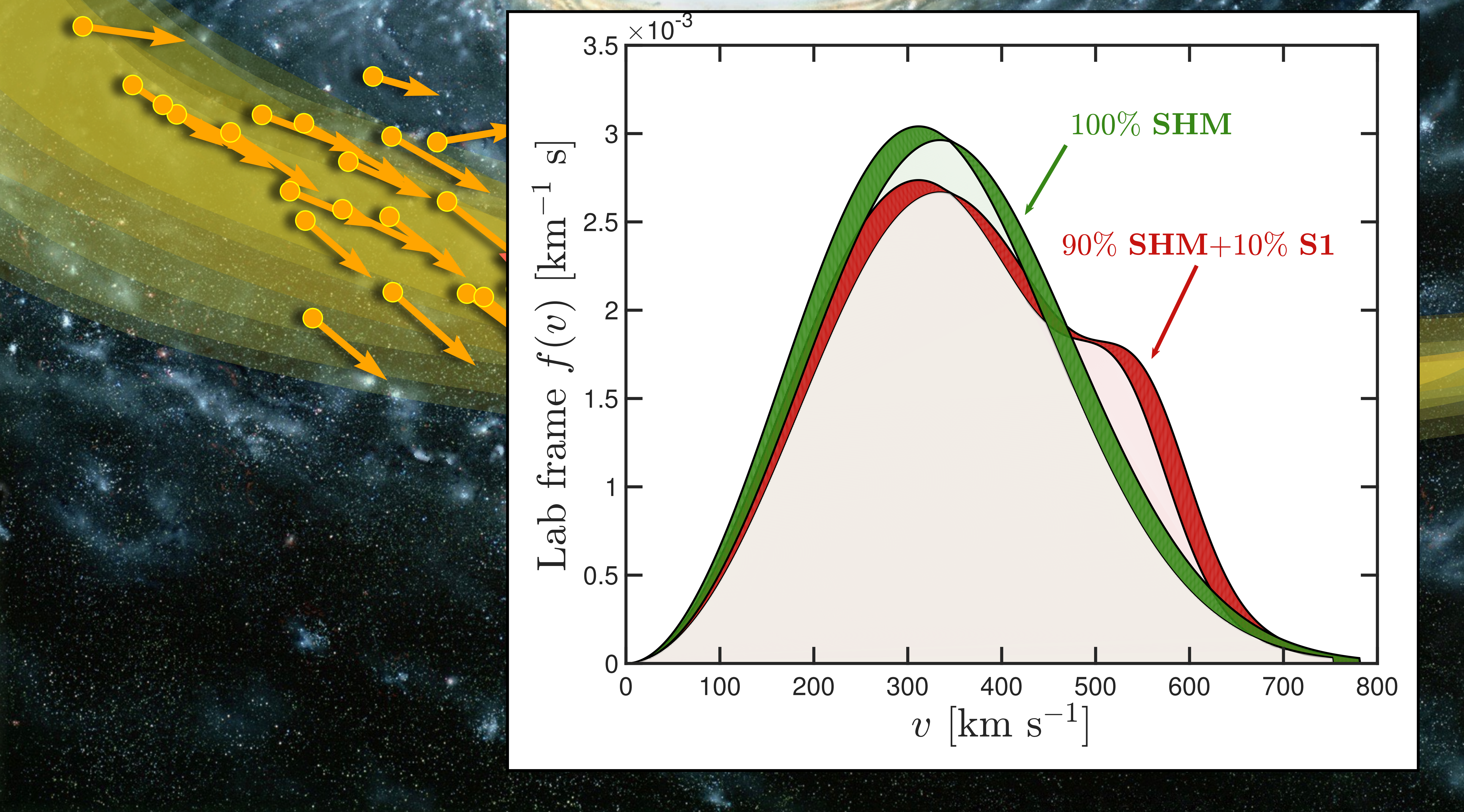
Approaching dark matter hurricane will collide with earth, predict scientists

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

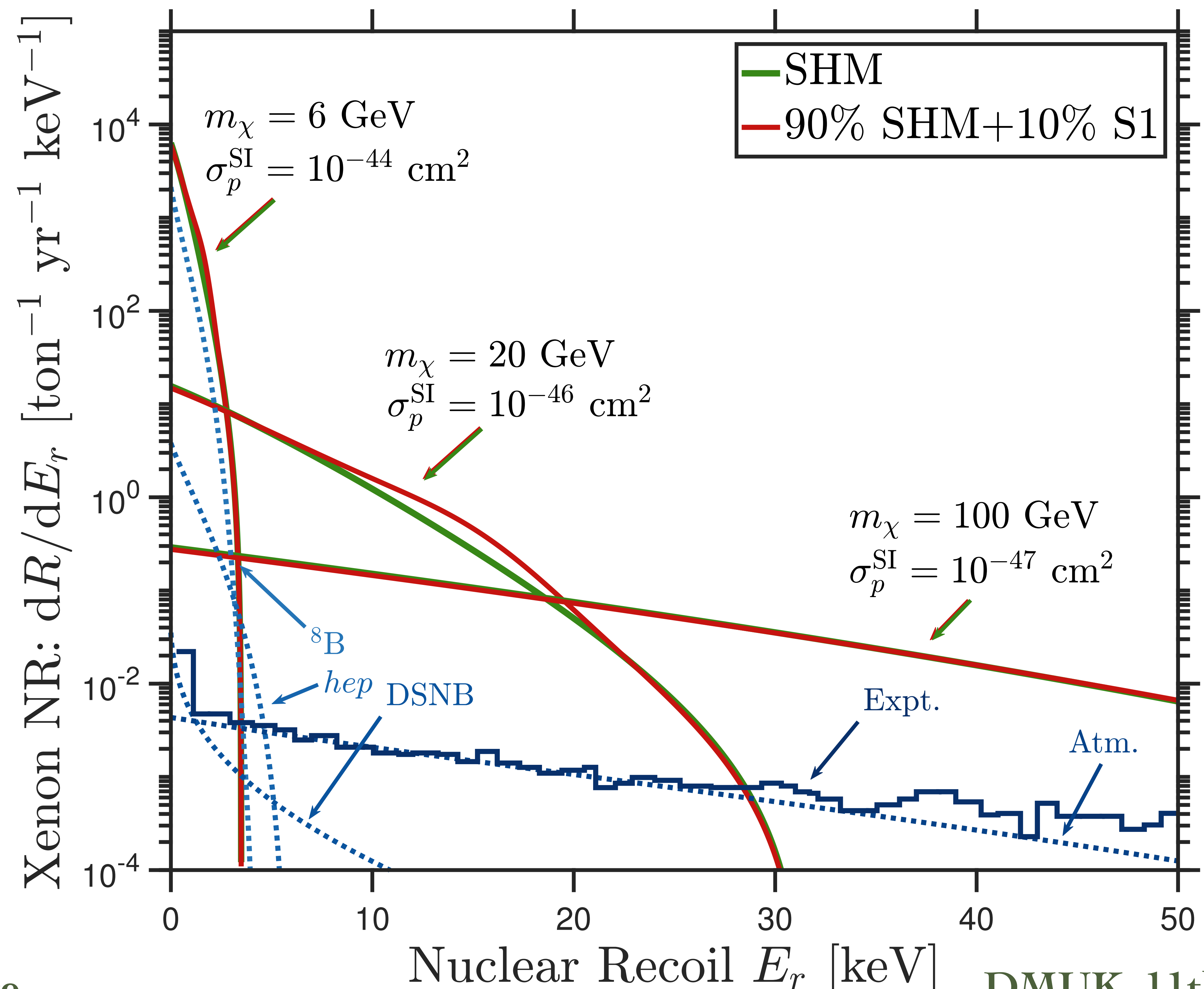
Modelling S1



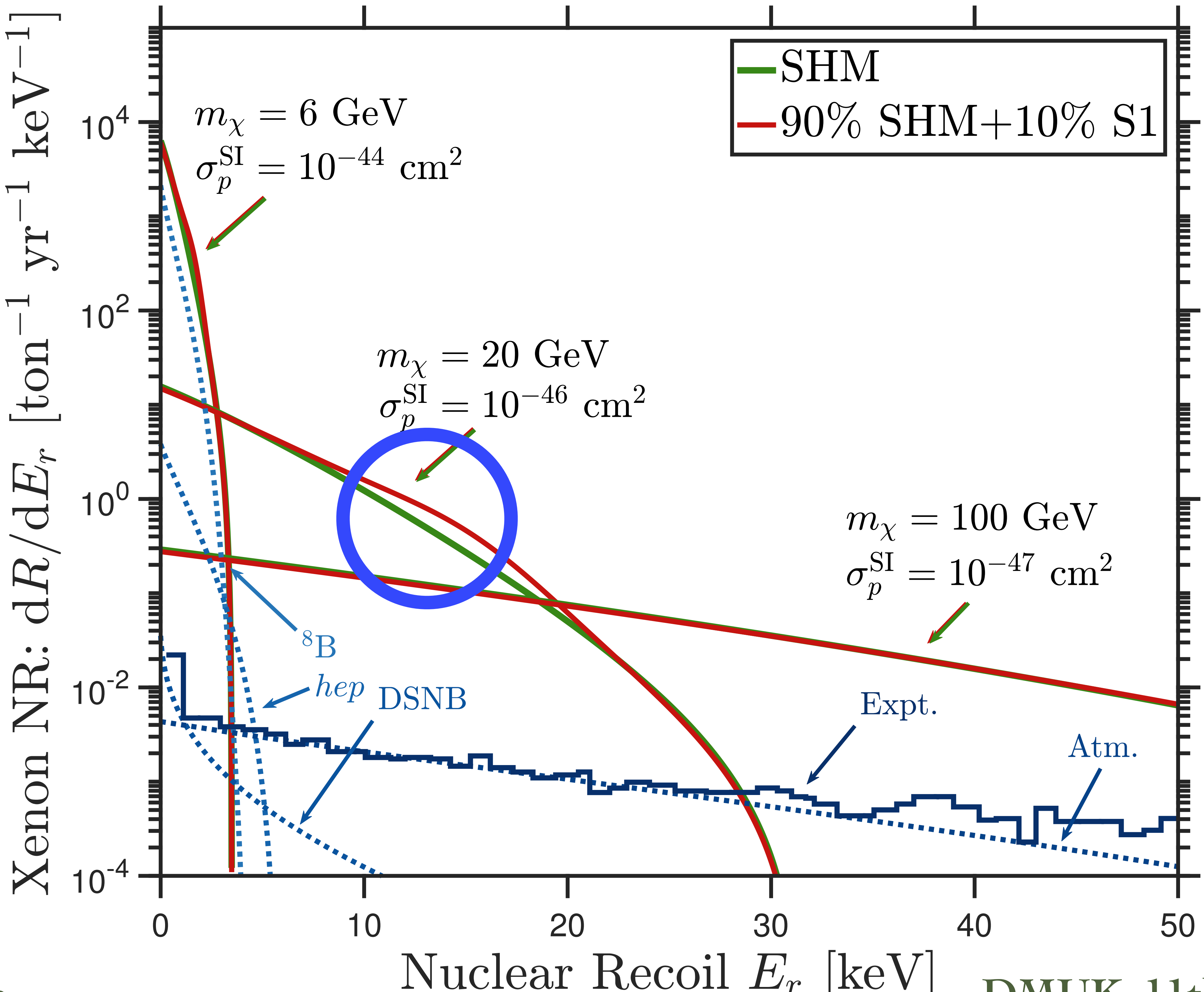
Modelling S1



How strong does the hurricane need to be for it to show up in a DM experiment (e.g. w/ Xenon)

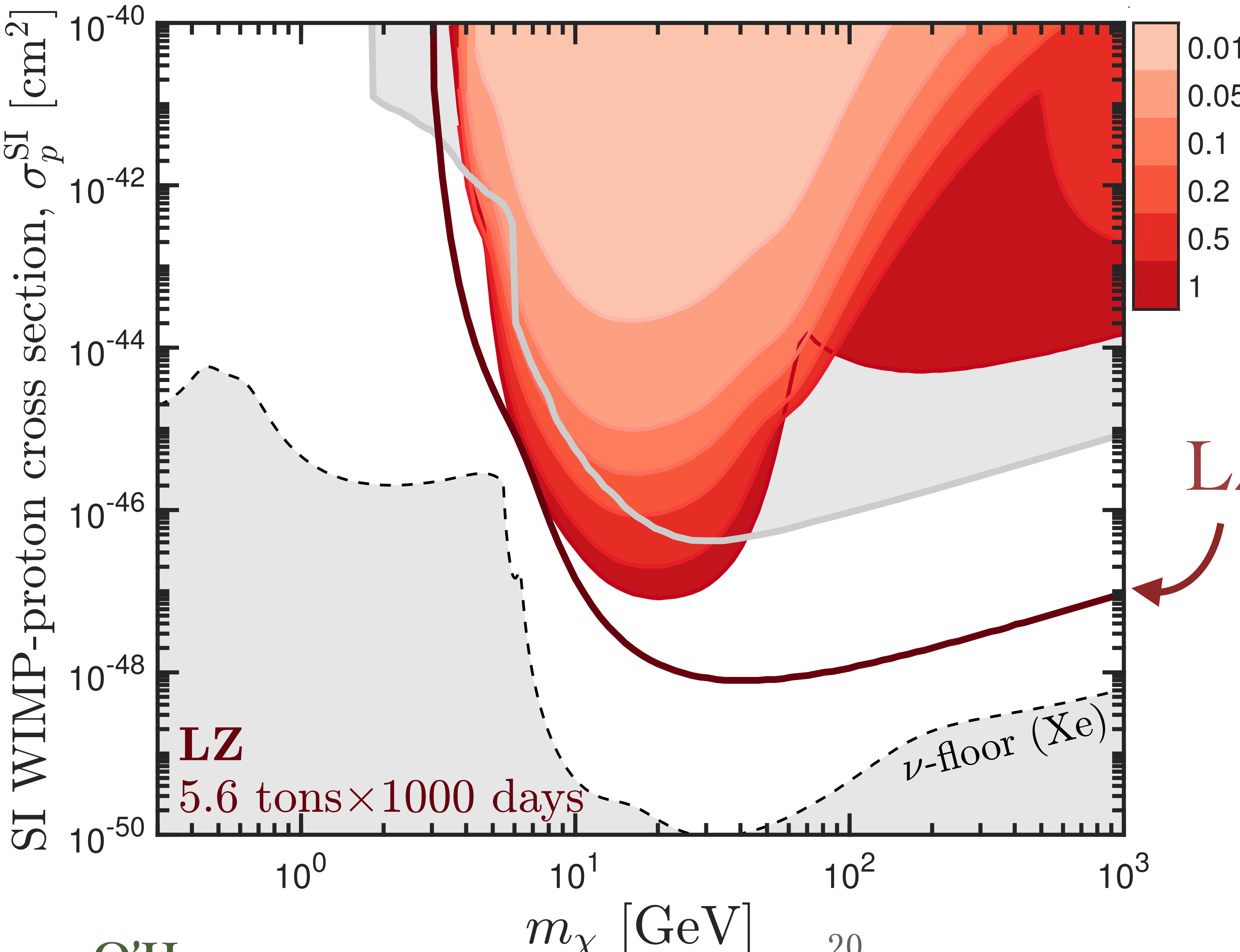


In other words: How big does this bump need to be for the experiment to tell the difference?



S1 in LZ

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

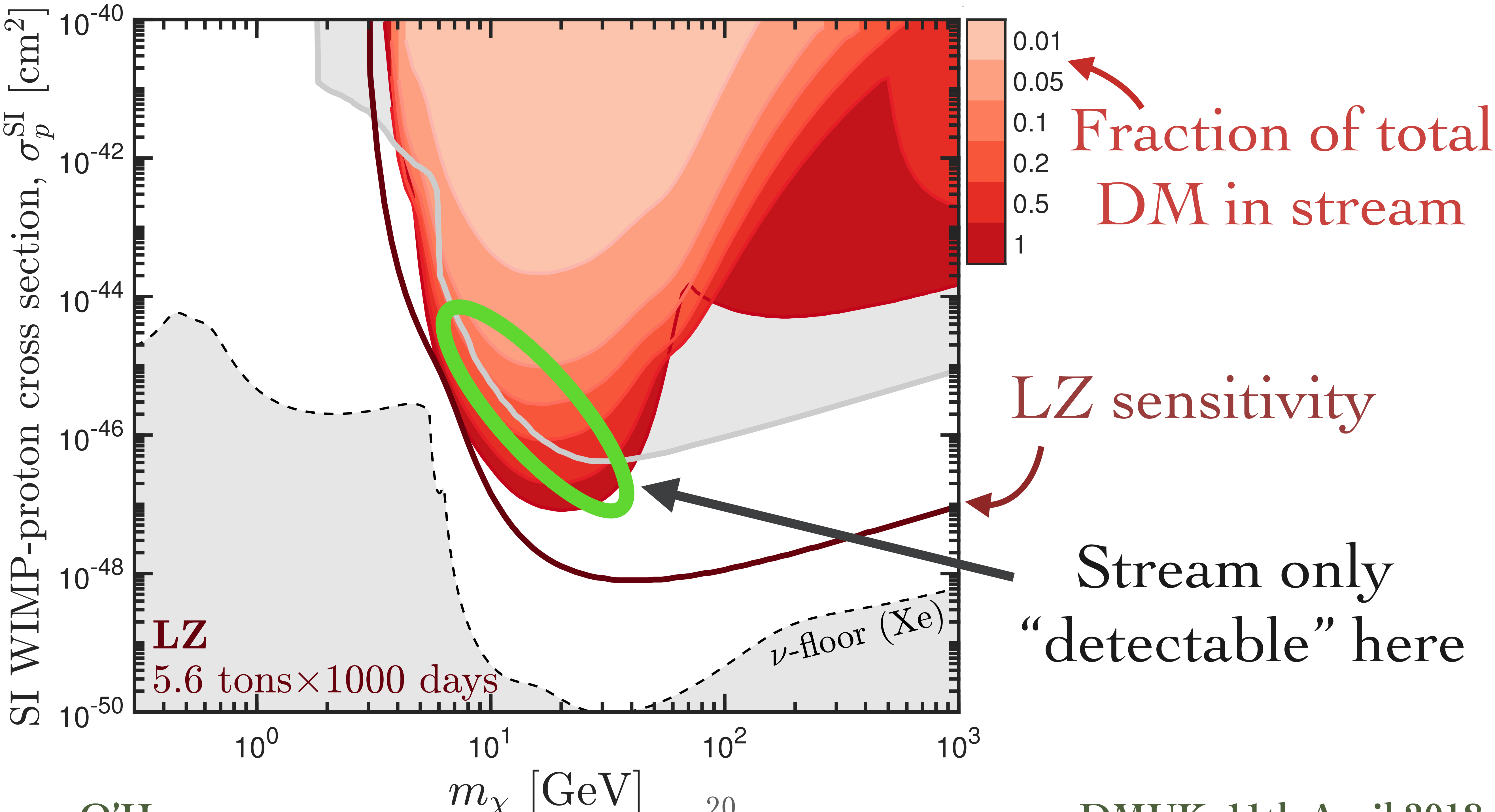


Fraction of total DM in stream

LZ sensitivity

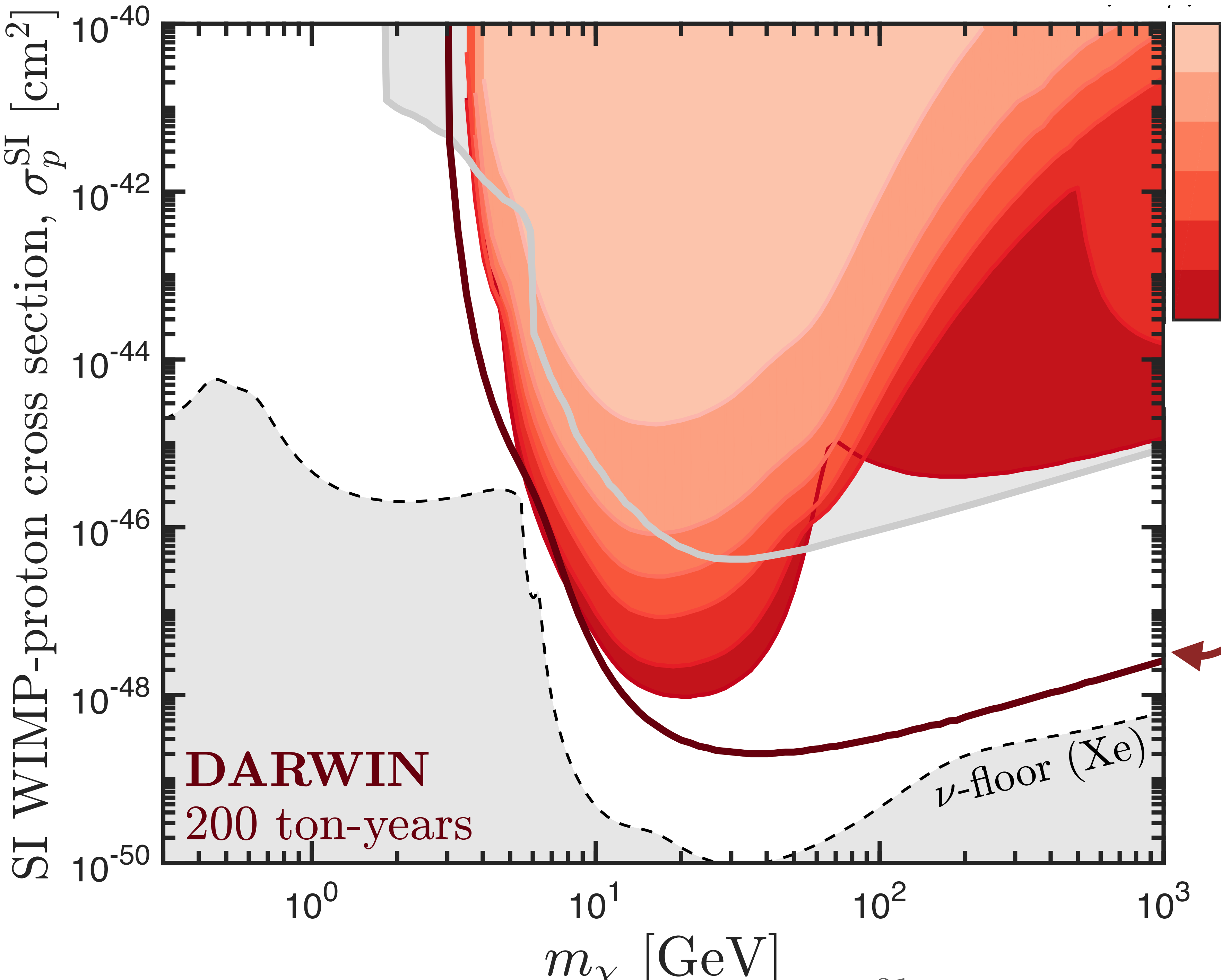
S1 in LZ

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



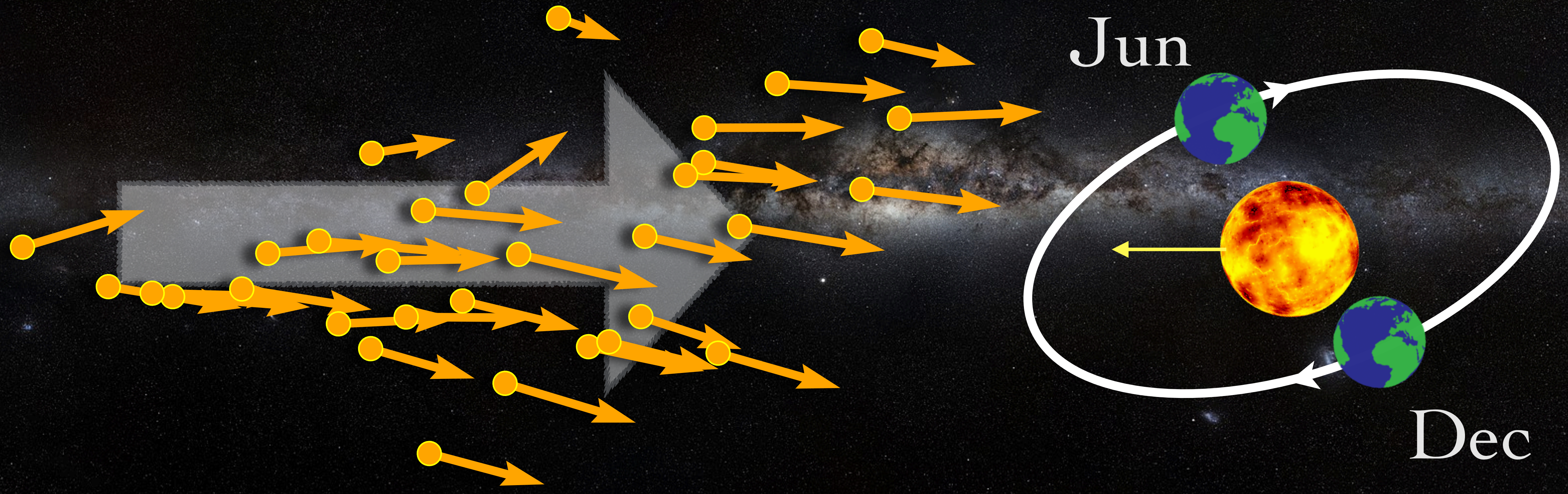
Fraction of total DM in stream

DARWIN sensitivity

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

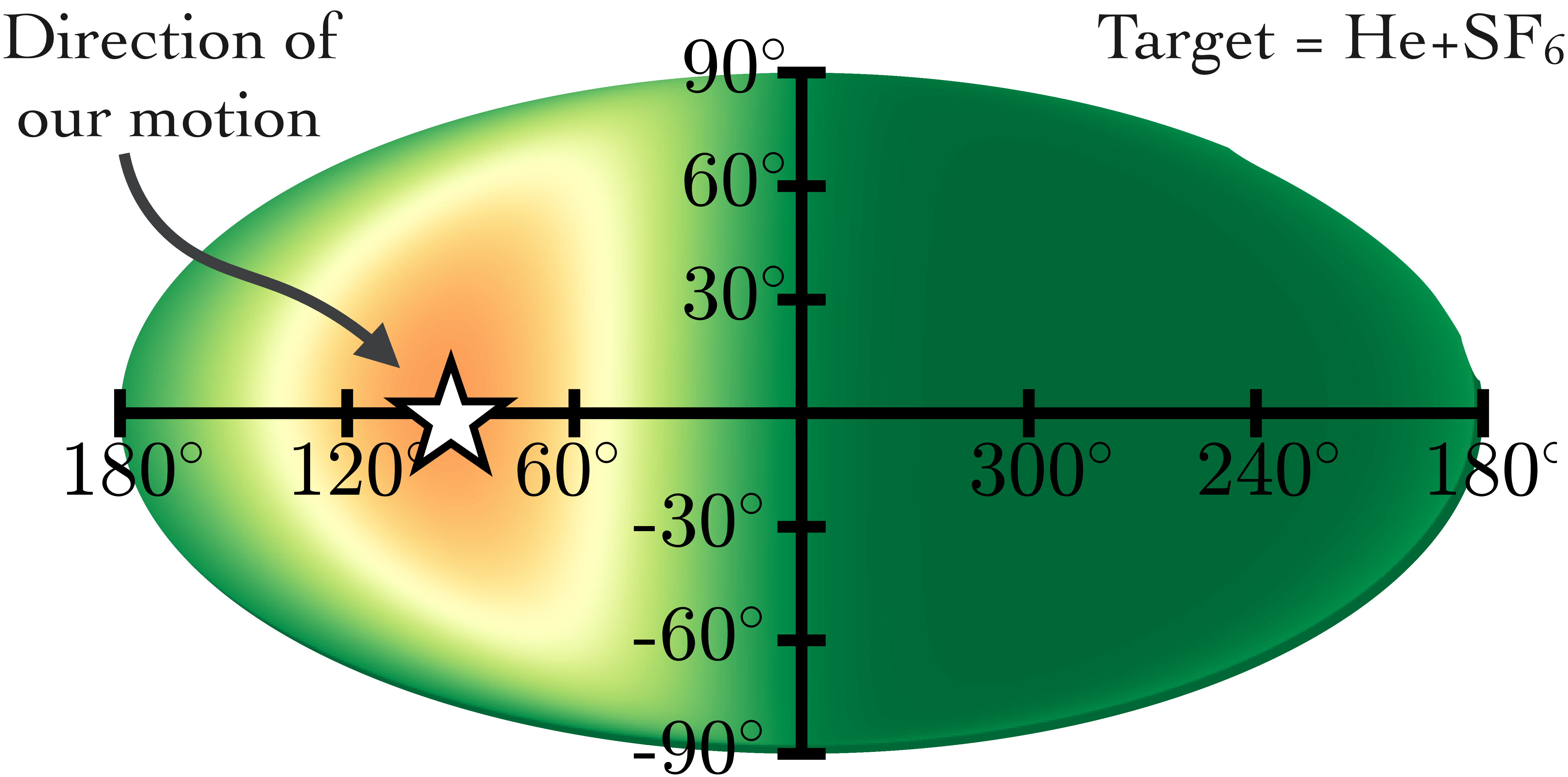
(also means that the phase of annual modulation is the same)

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

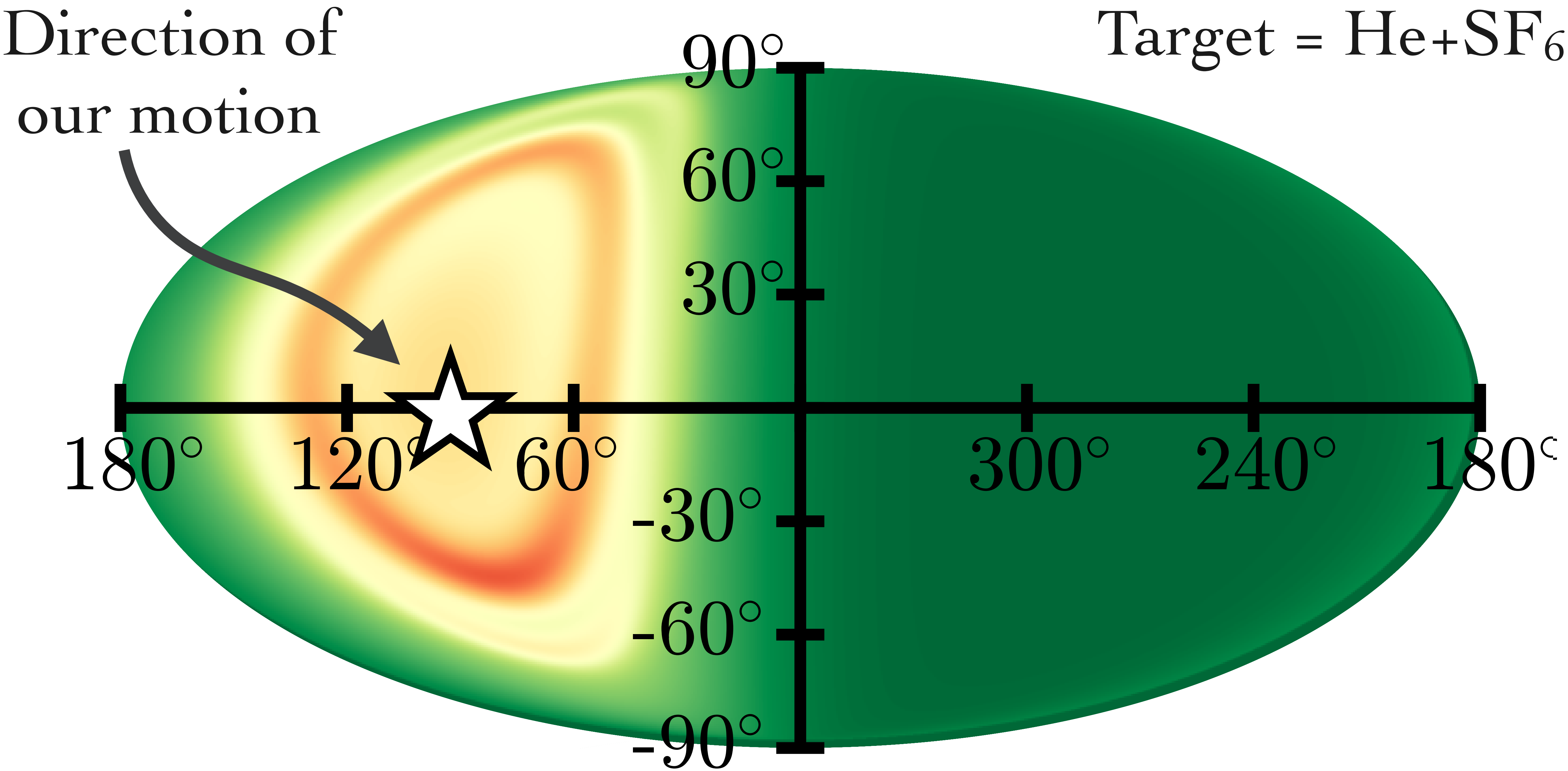


(also means that the phase of annual modulation is the same)

Directional detection of WIMPs



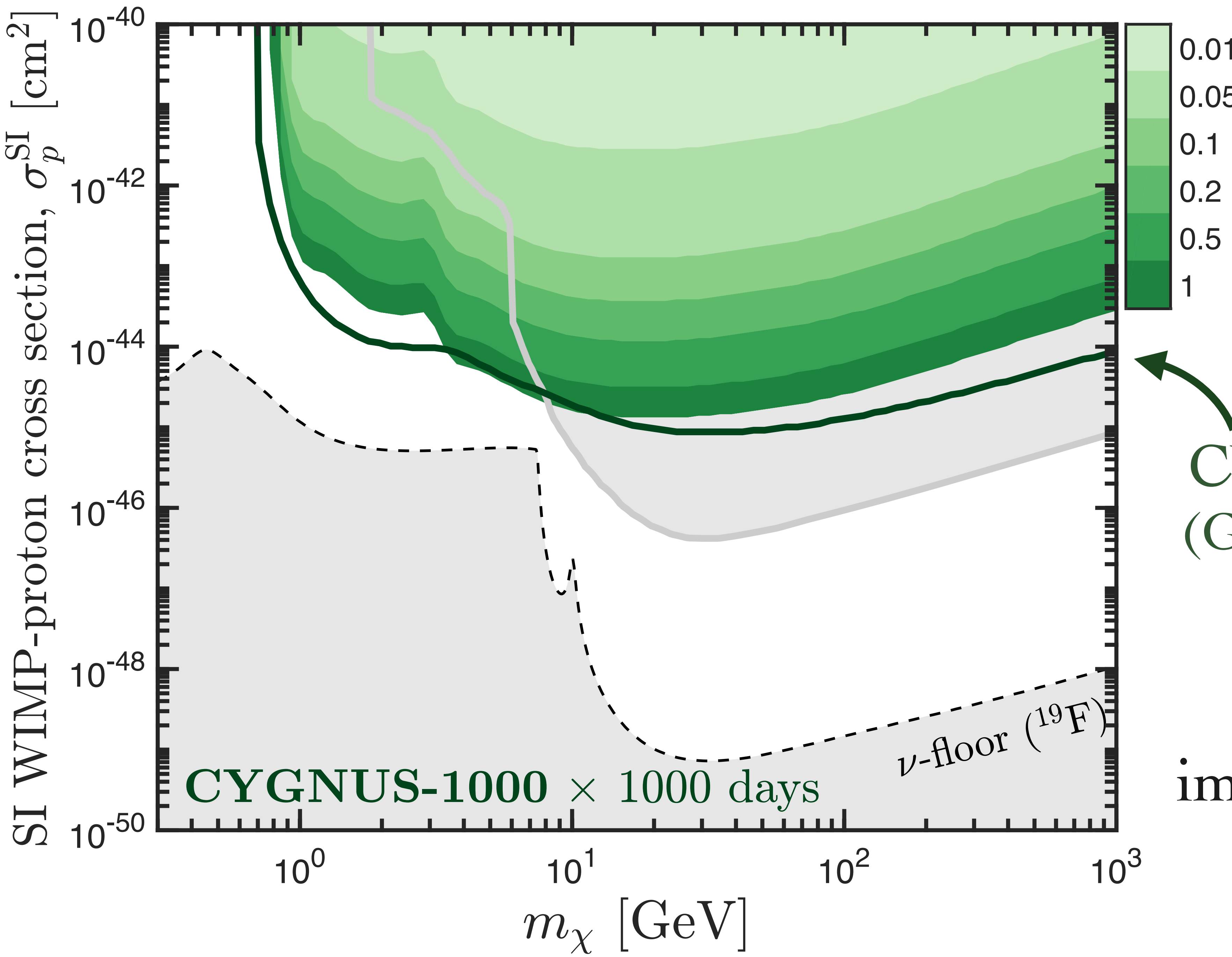
Directional detection of WIMPs



Halo + 10% S1

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

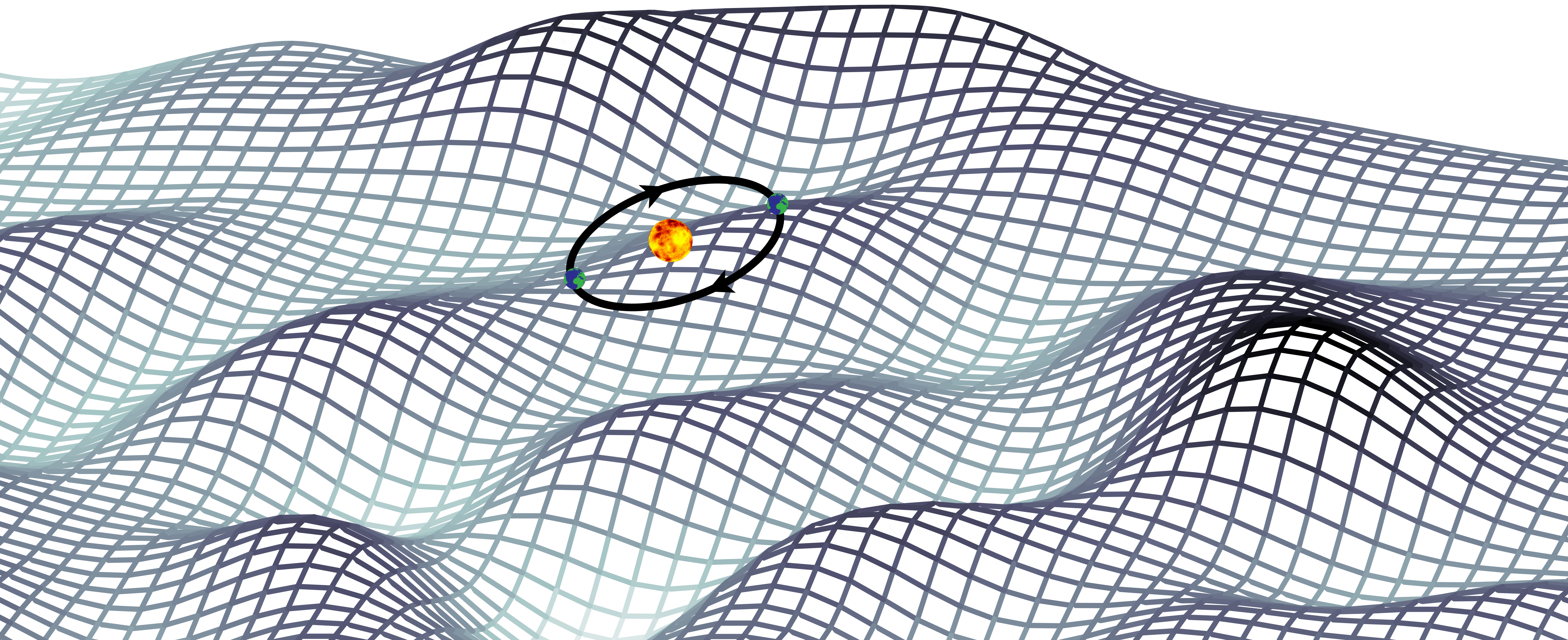
CYGNUS sensitivity (Gas TPC with He+SF_6)

Directionality improves sensitivity to stream

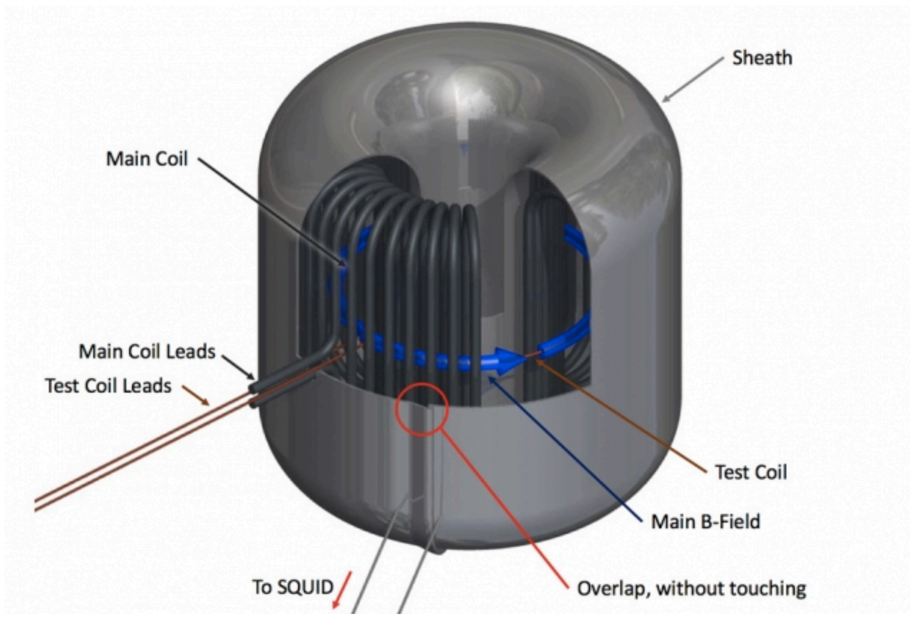
Detecting substructure: axions

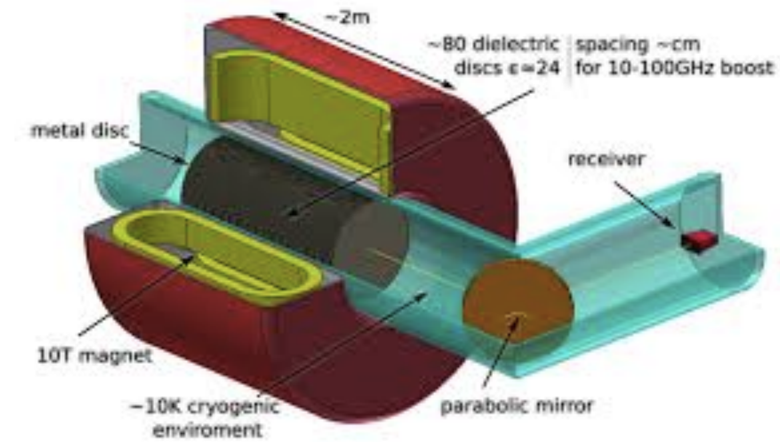
$$a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos\left(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha\right)$$

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



(some) Axion haloscopes





ABRACADABRA	ADMX	MADMAX
DM-Radio	CAPP	ORGAN
KLASH	HAYSTAC	BRASS

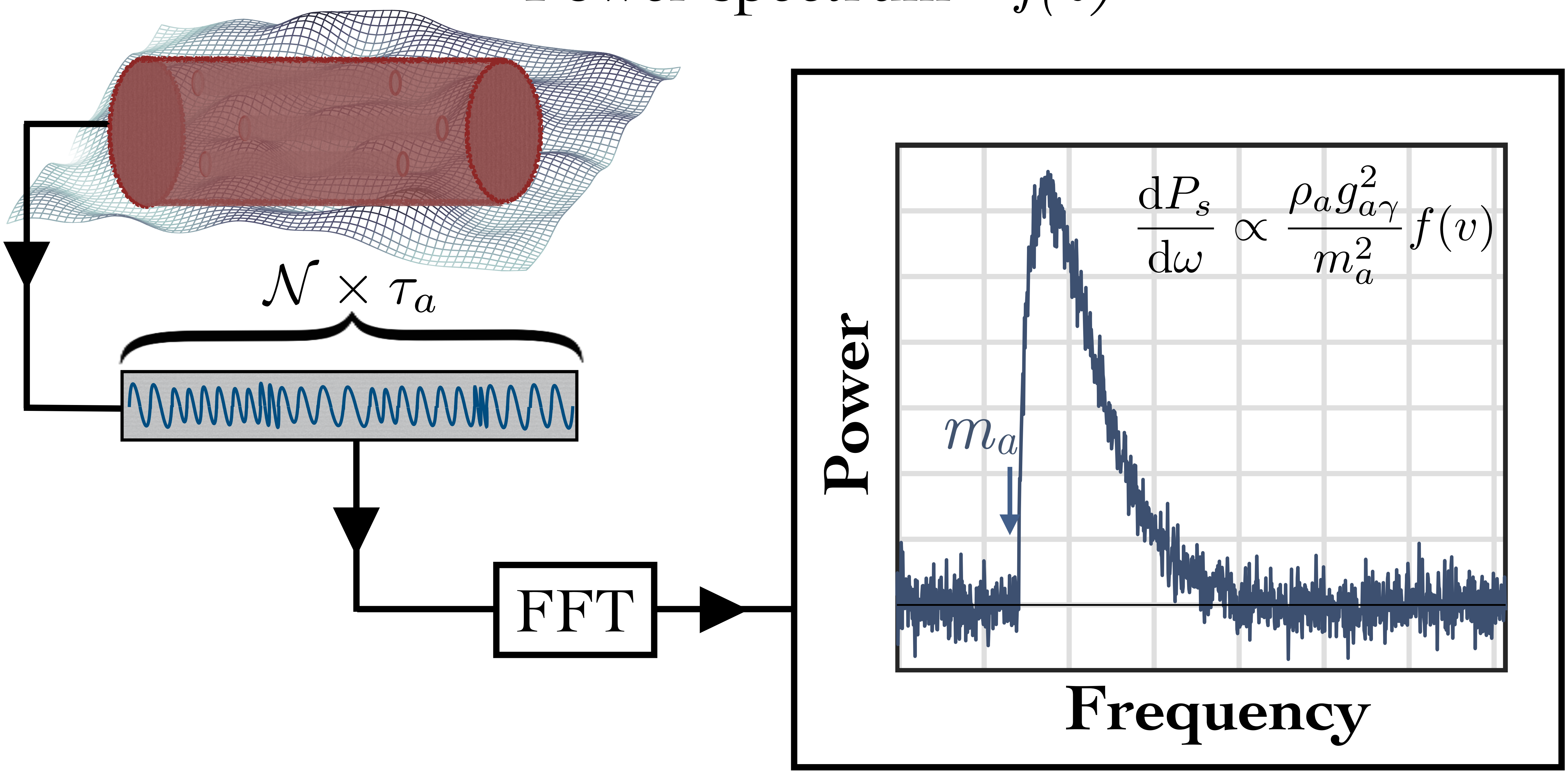
m_a [eV]

$<10^{-7}$	10^{-6} - 10^{-5}	10^{-4}

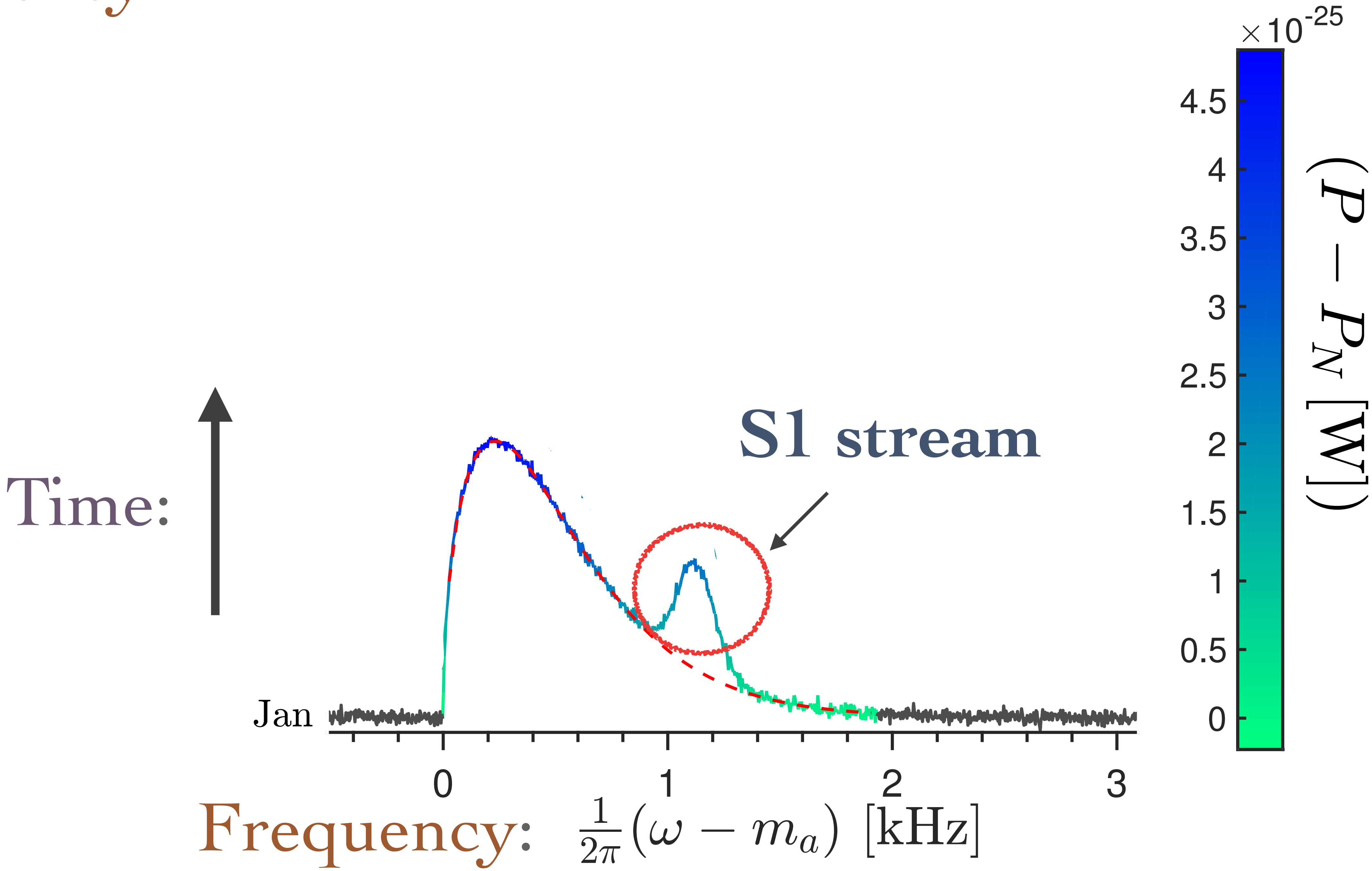
Measuring the axion distribution

Sampling axion field over many, N, coherence times:

→ Power spectrum ~ $f(v)$



Axion haloscope:
Signal power
vs time
vs frequency



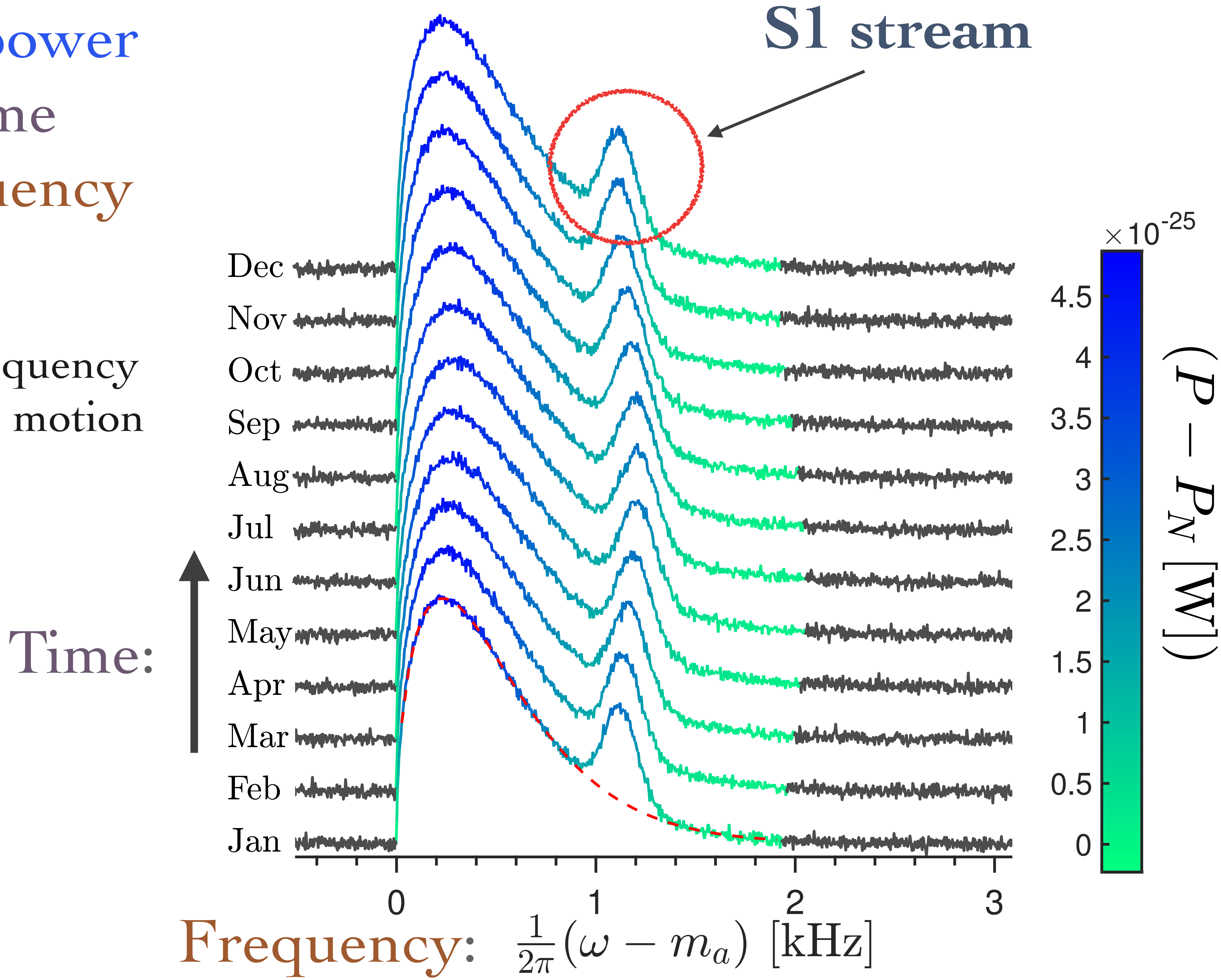
Axion haloscope:

Signal power

vs time

vs frequency

Wobble in frequency due to Earth's motion



Final thoughts

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

Local halo shows evidence for several significant merger and accretion events. More analysis coming.

Halo is a more complicated cow: the Sausage and the S1 stream have consequences for experiments on Earth - expect them to show up!

Once we detect dark matter, *Gaia*+DD experiments form a multimessenger probe of the history of our galaxy

Extras

Importance for DM

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

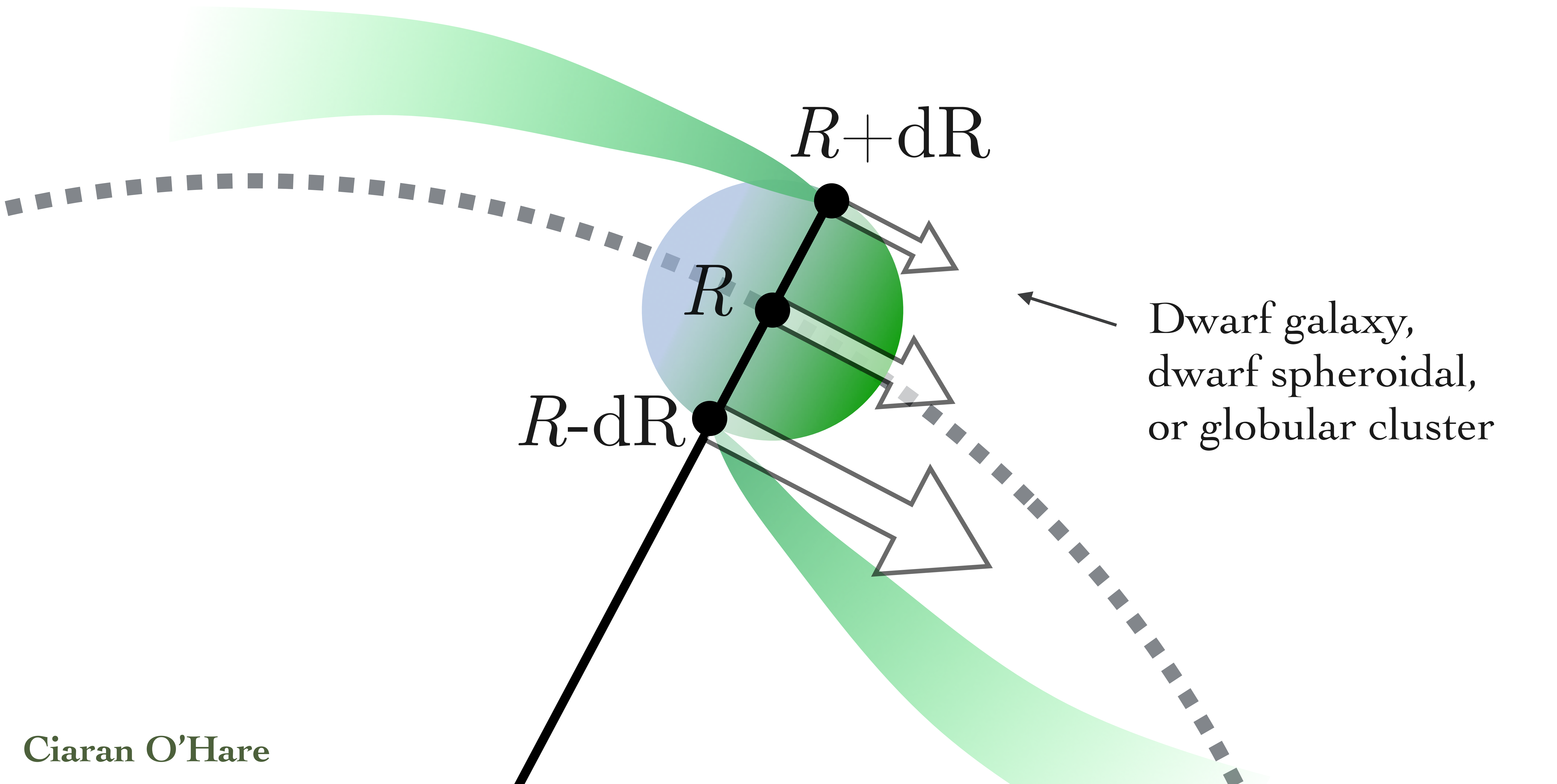
Streams → Informs about the granularity of DM halo
→ Traces the shape of MW potential
→ Can be used to constrain fuzzy DM

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

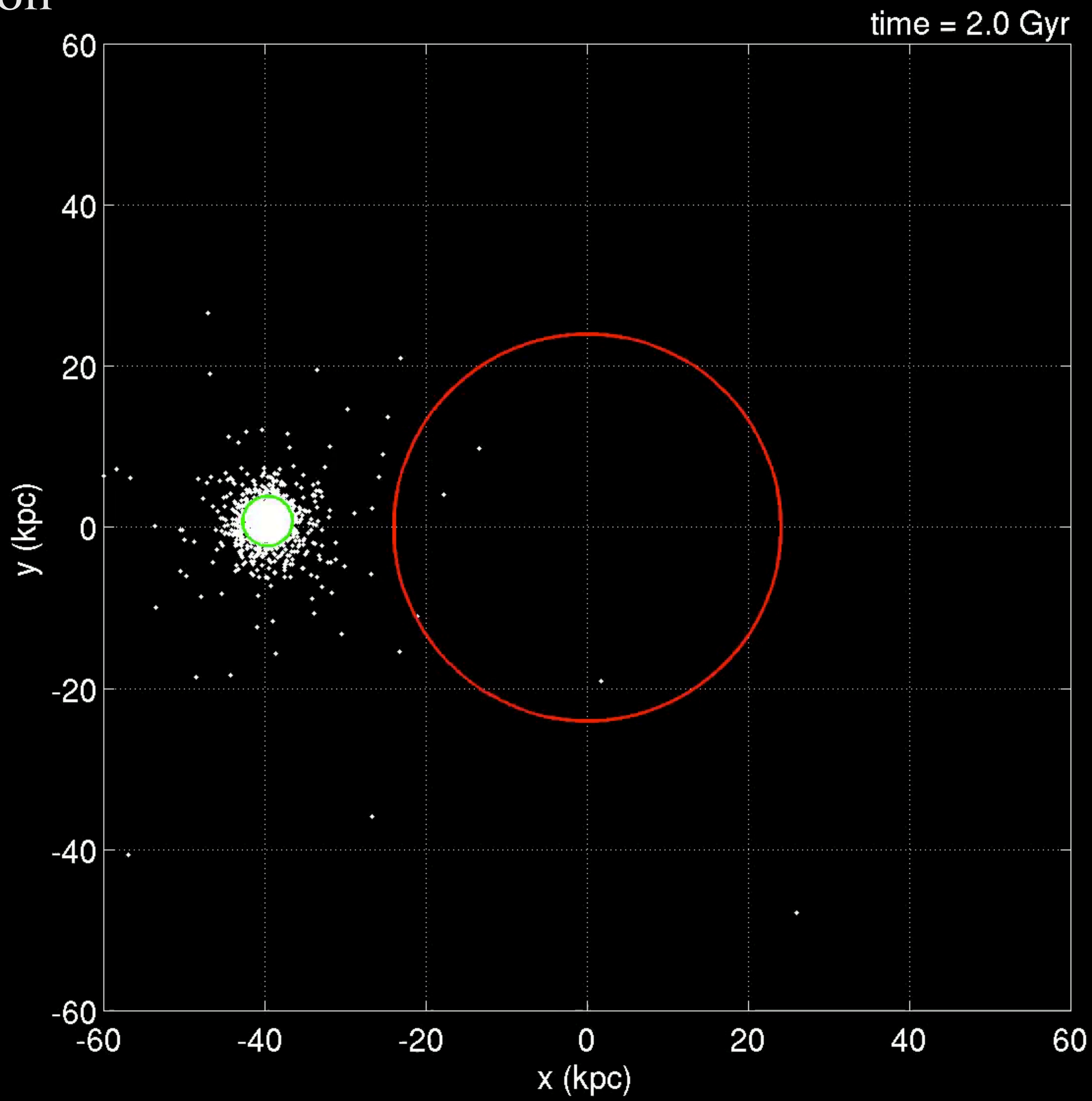
Ciaran O'Hare

Forming tidal streams

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



R. Sanderson



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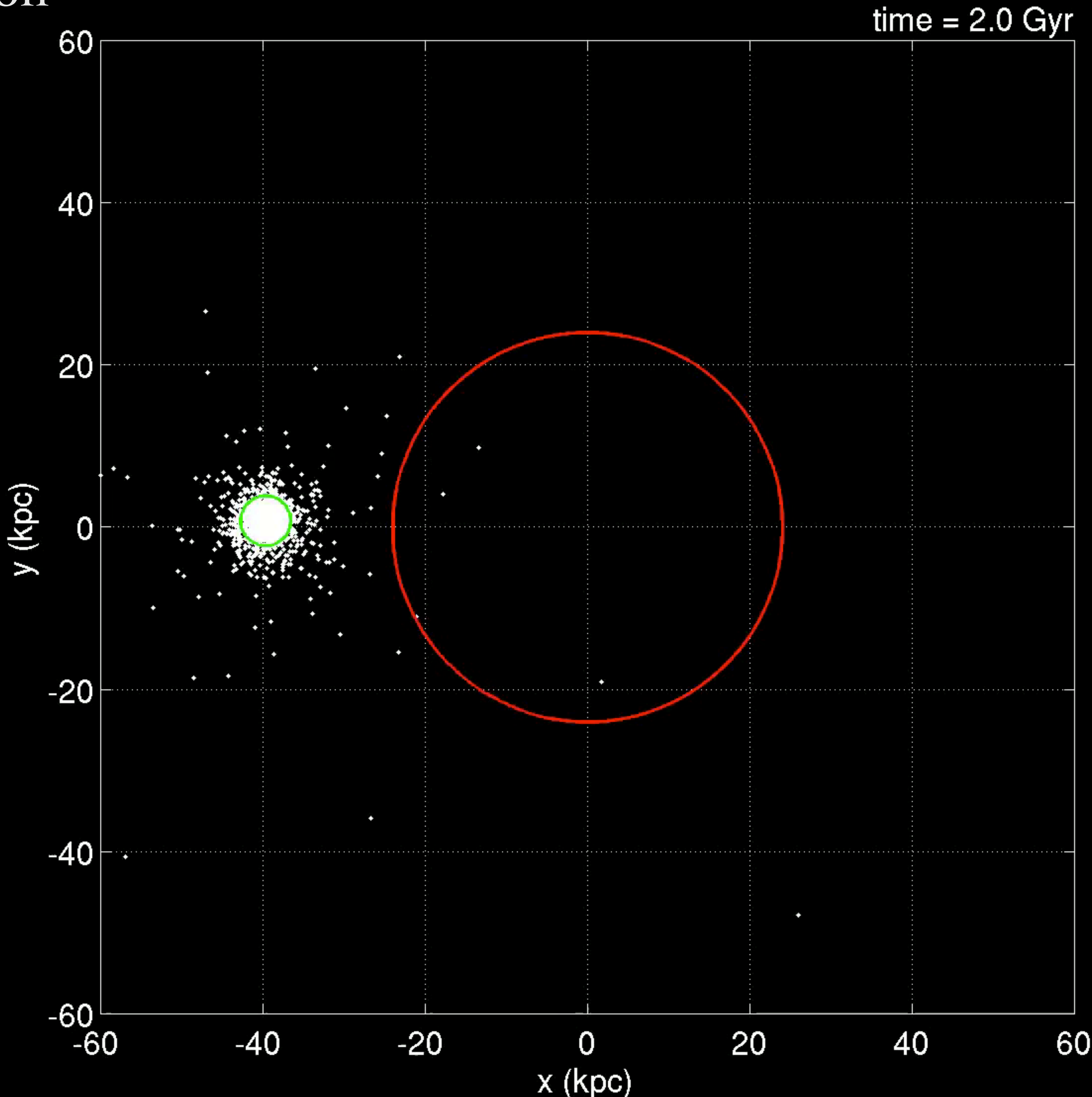
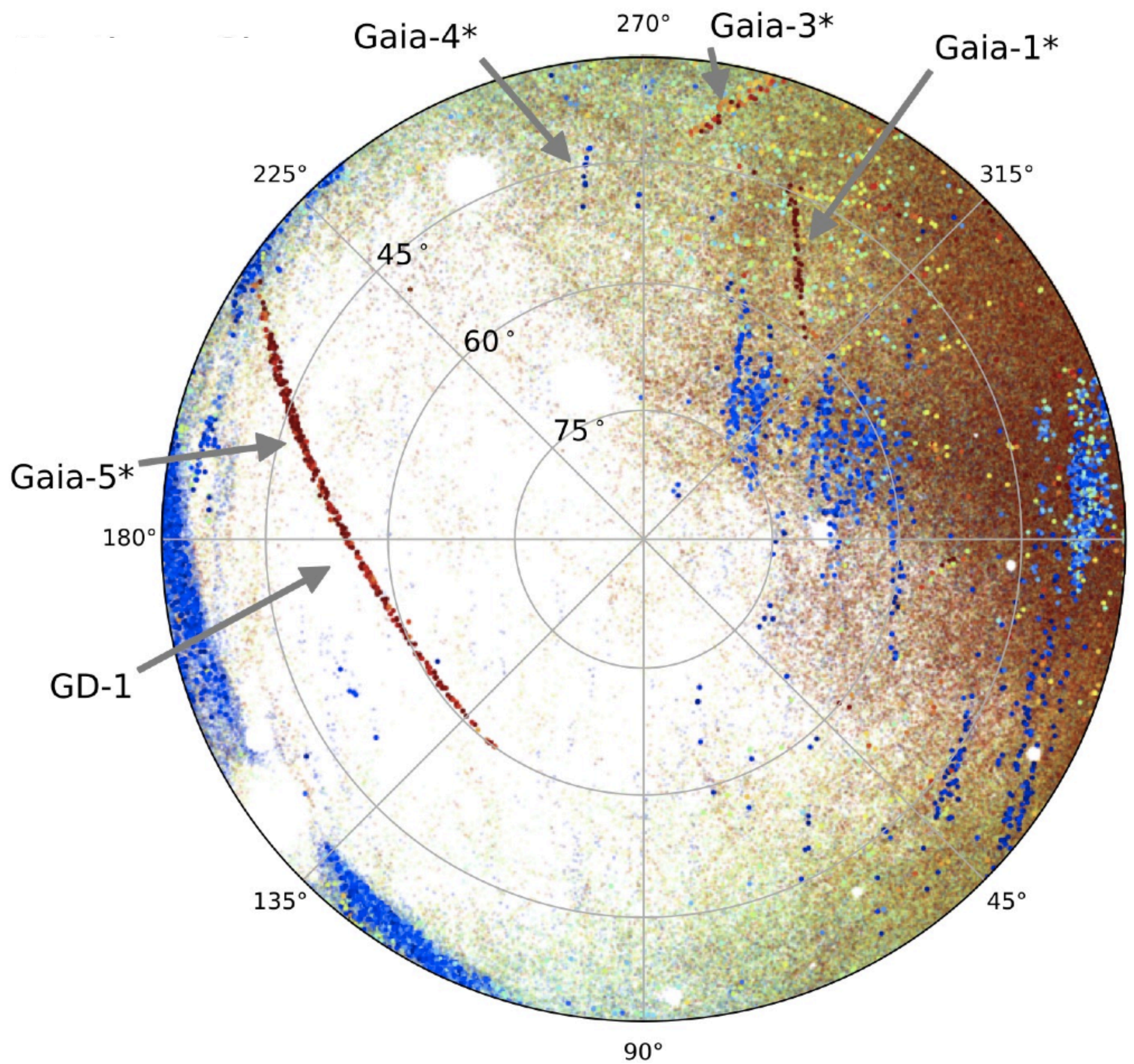


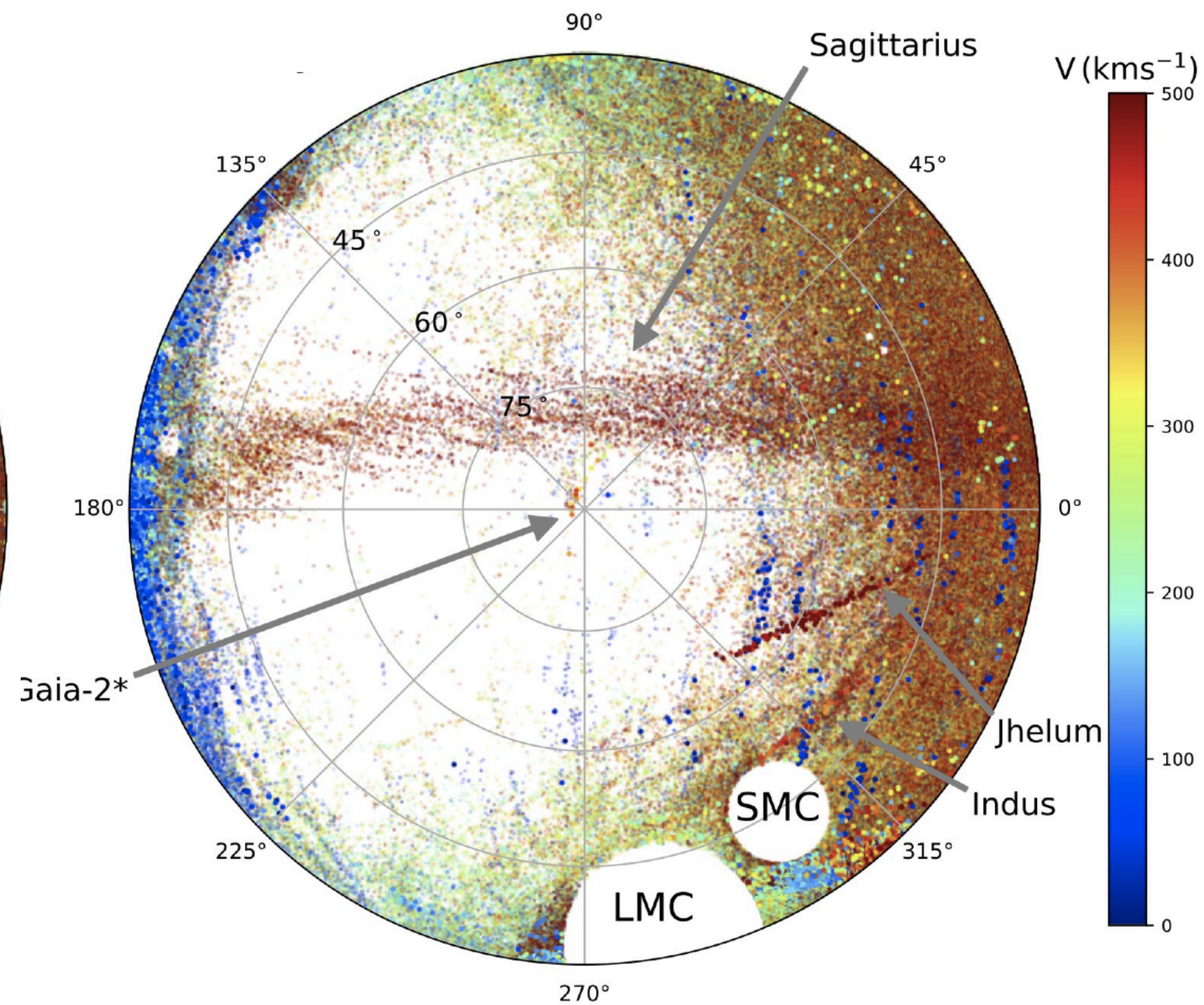
Finding streams spatially

Northern sky



Southern sky

ESA

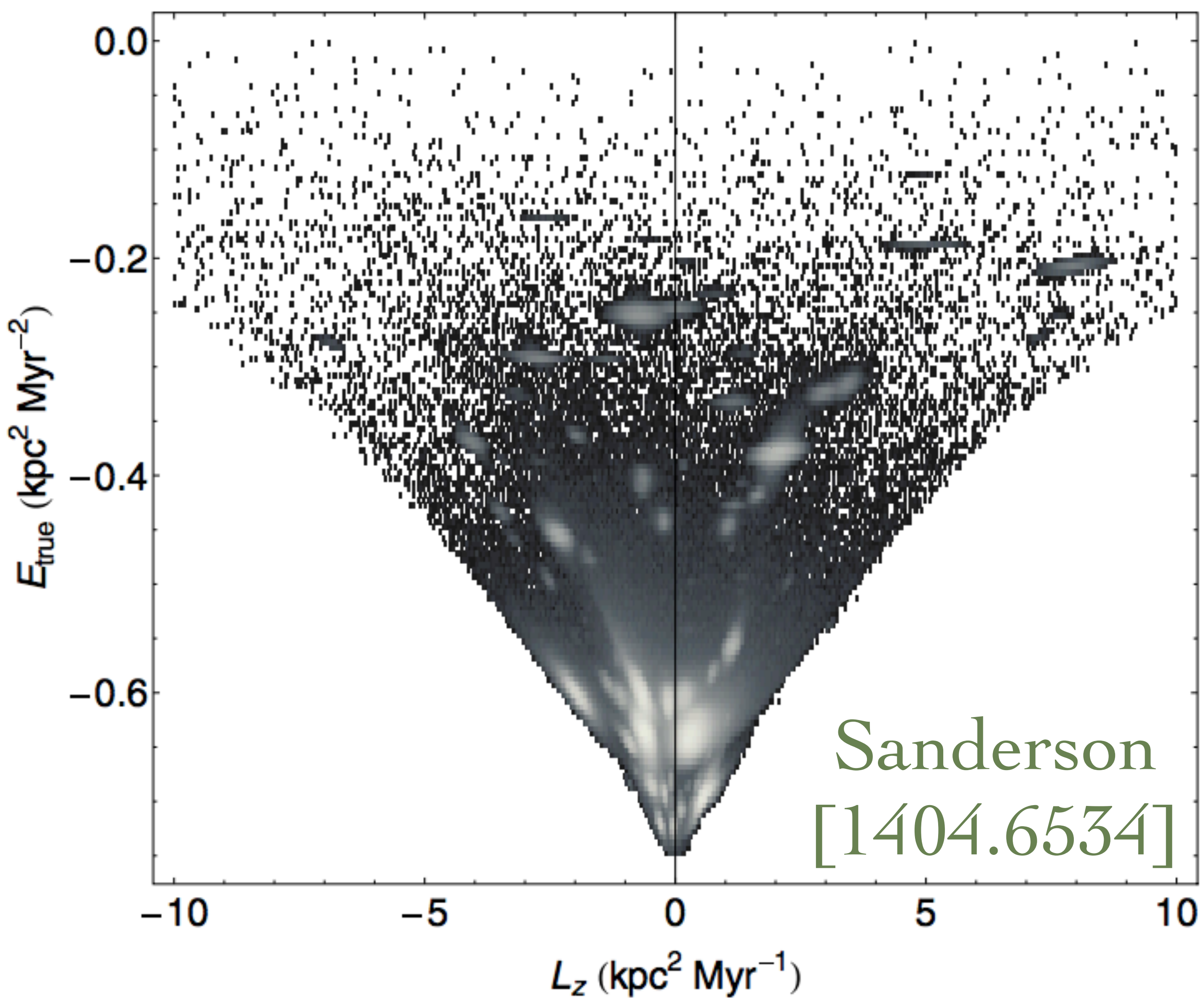


Ciaran O'Hare

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

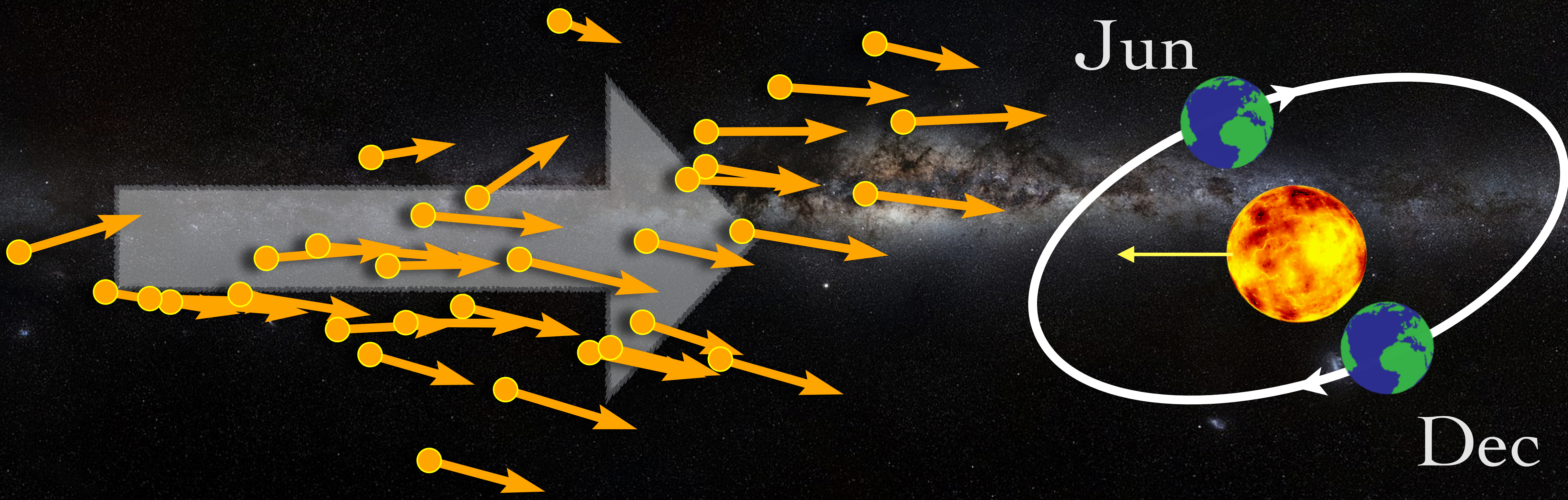
Galactic velocity: $\mathbf{v}_{\rm str} = (8.6,\ -286.7,\ -67.9)\ {\rm km\,s^{-1}}$
→ Stream on a strongly retrograde orbit, so DM impacts us at high velocity ~ 500 km/s

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

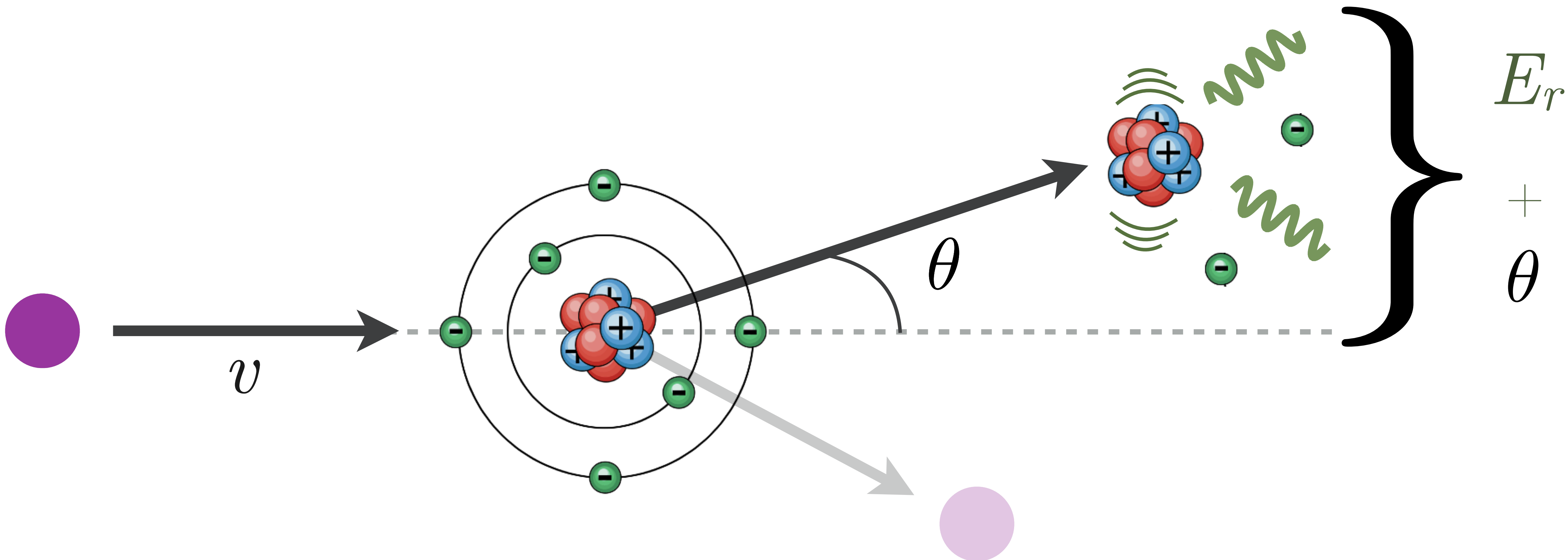
Dark matter content: $0 + \epsilon < \rho_{\rm str} < 0.55\,{\rm GeV\,cm^{-3}}$
→ Upper bound: is probably the local DM density probed over length scales smaller than the stream
→ Lower bound: Progenitor very likely had dark matter but other than that we cannot say, must remain agnostic

Annual modulation?

Annual modulation?



Directional detection of WIMPs



$$E_r = \frac{2 m_N m_\chi^2}{(m_N + m_\chi)^2} v^2 \cos^2\theta$$

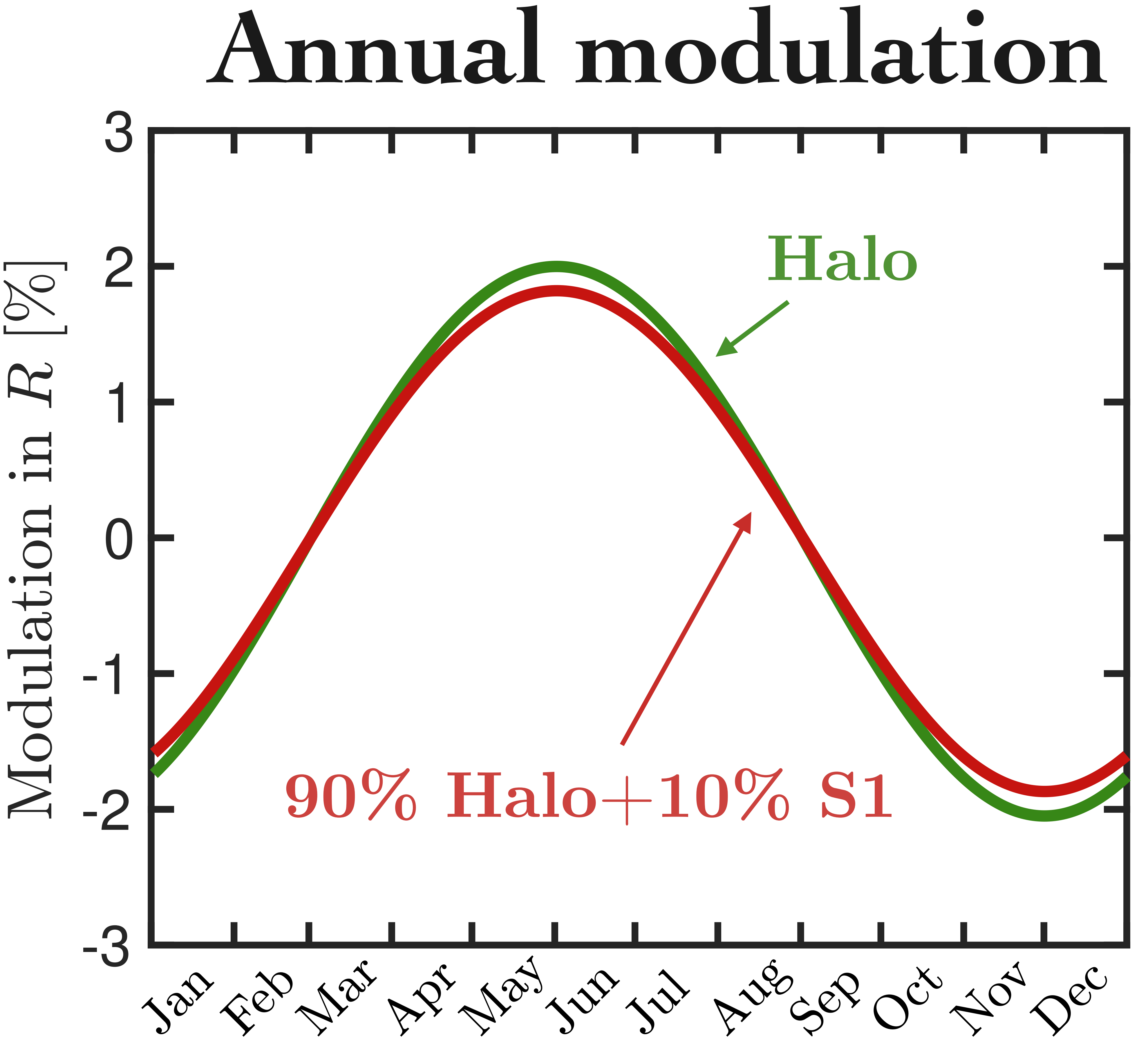
If both energy and angle are measurable $\rightarrow$ solve for v

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
- <u>Secondary goal: study DM astrophysics</u>
- 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
Modulation in R [%]
3
2
1
0
-1
-2
-3
Halo
90% Halo+10% S1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

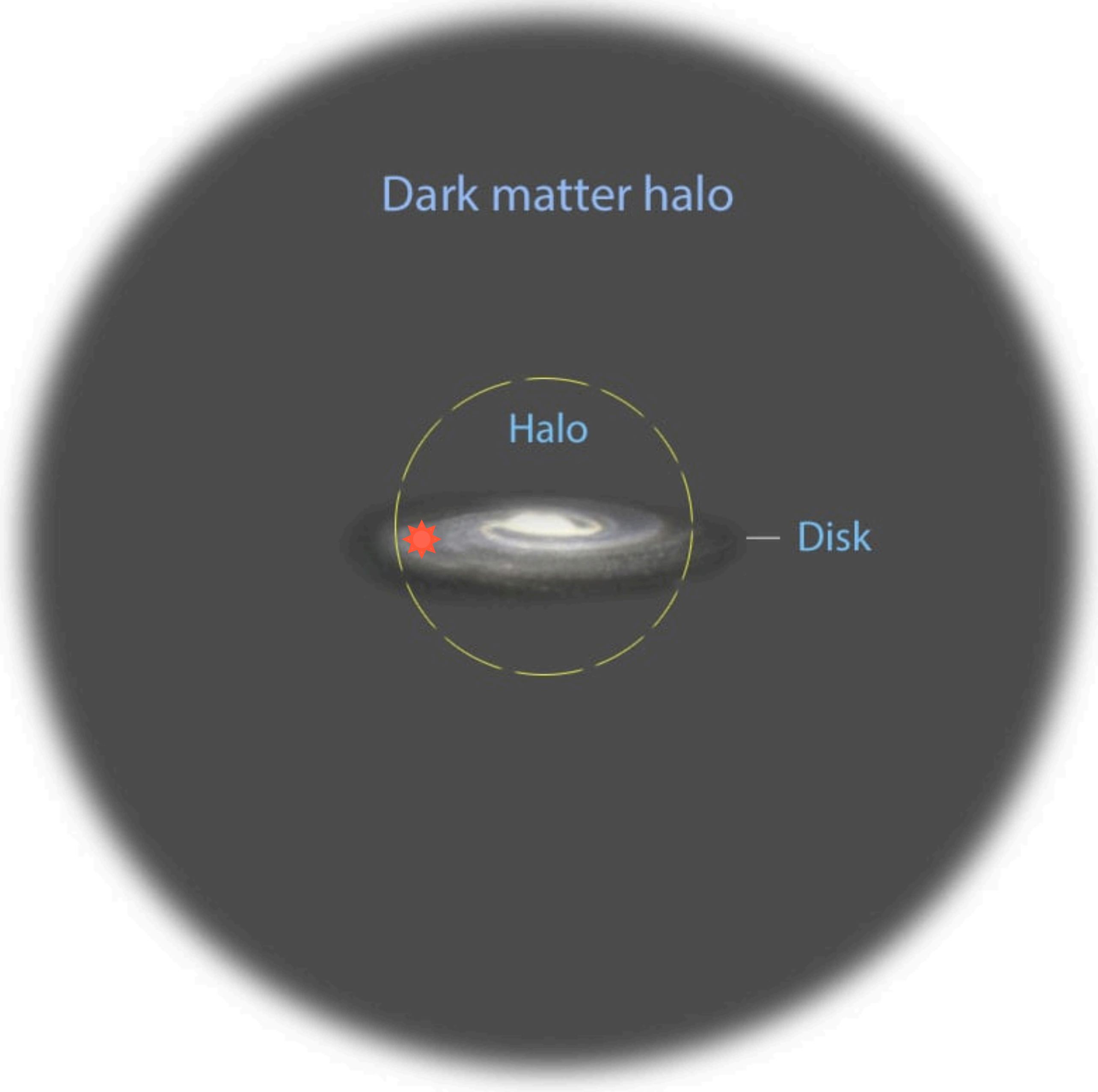
The Standard Halo Model

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

- → Density ~ $1/r^2$
- → Isothermal
- → Gaussian velocities
- → Truncated at $v_{\rm esc}$

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

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



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]

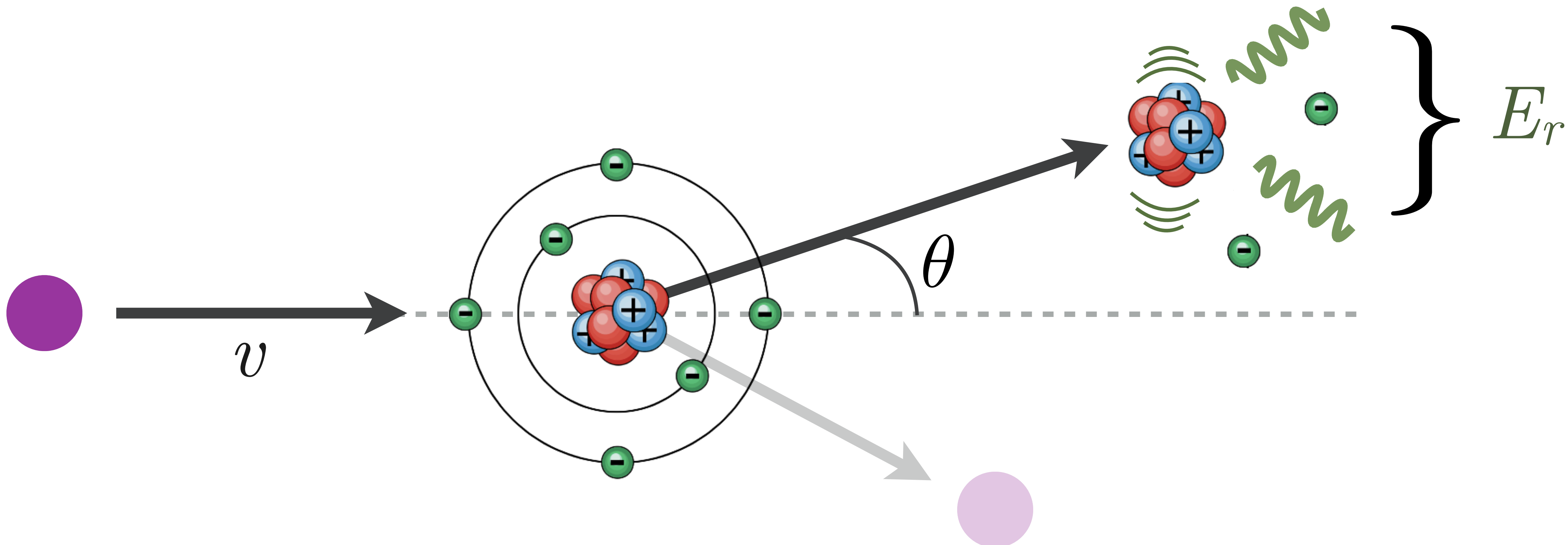
III) **Local density**

→ 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…**

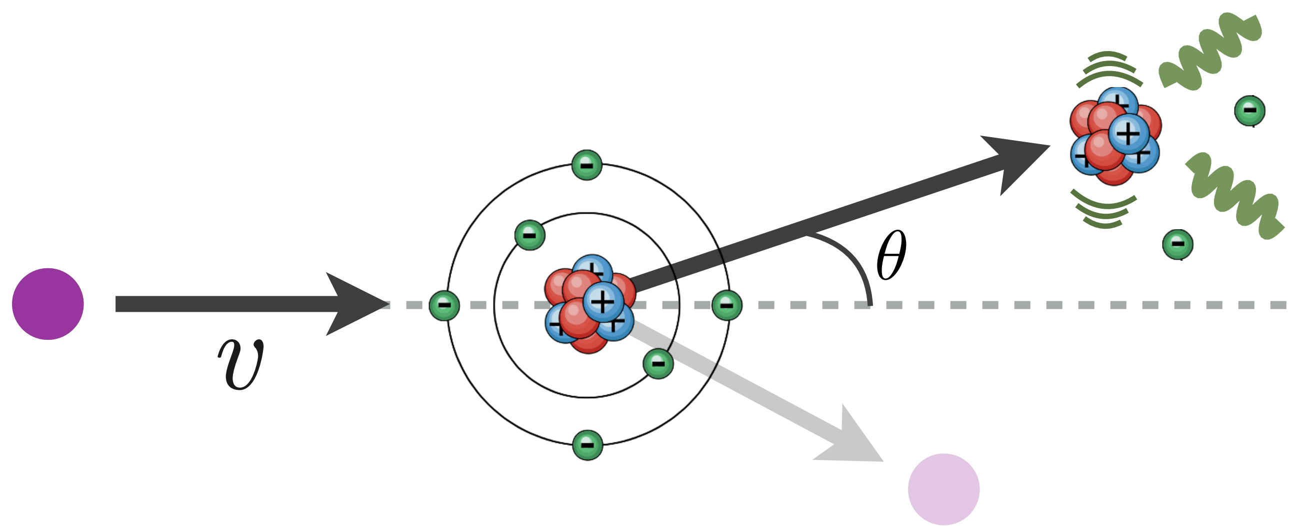
WIMP direct detection



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

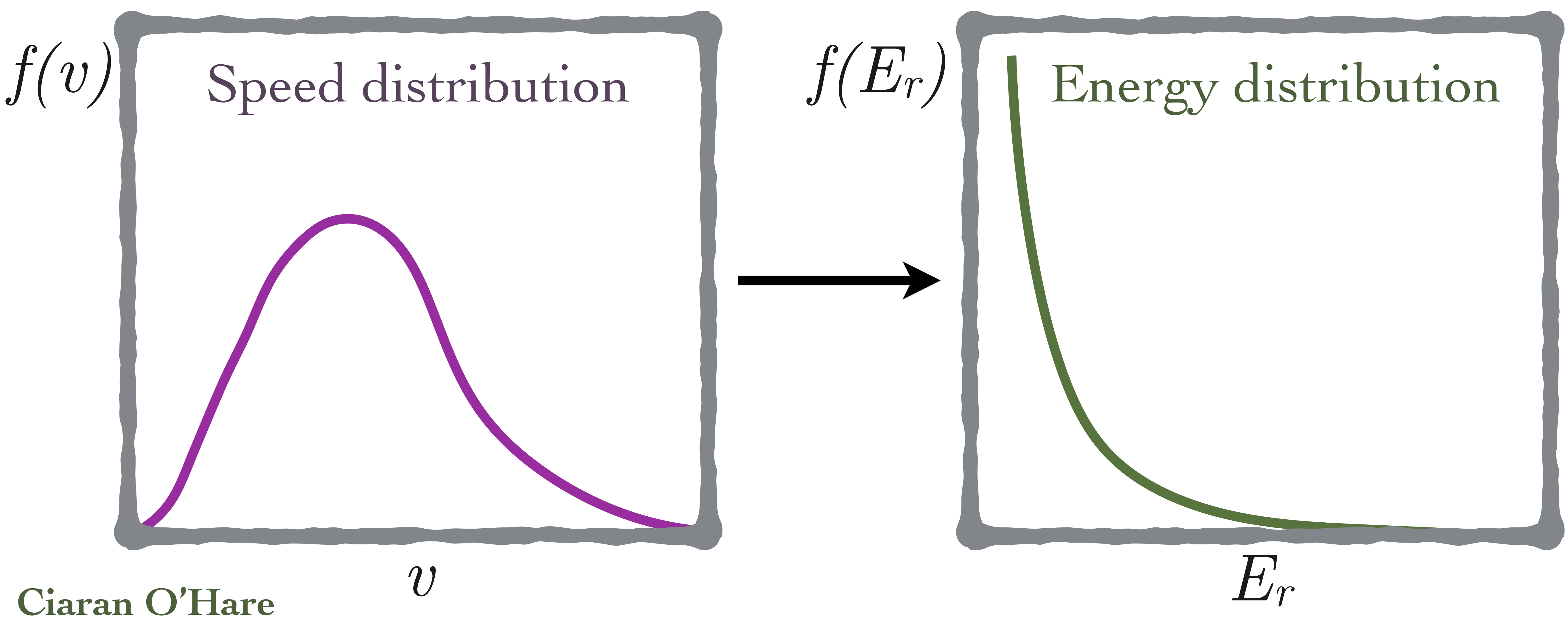
m_N = Nucleus mass
m_χ = WIMP mass

WIMP direct detection



Angle not measurable so for a given speed:

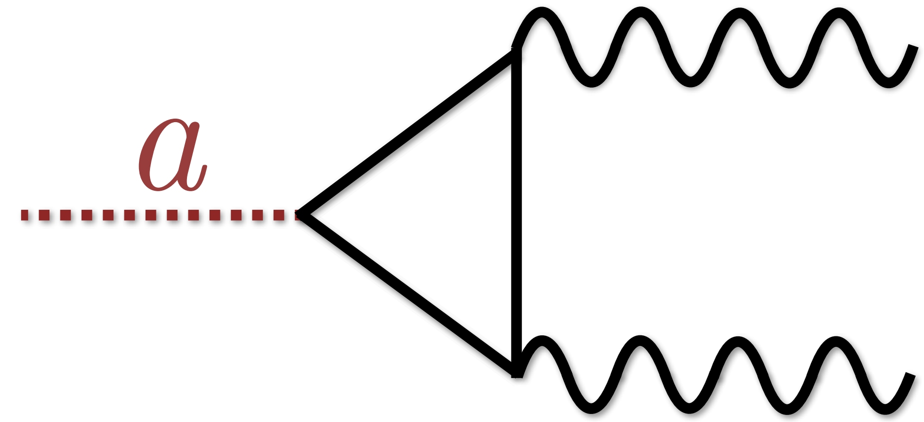
$$E_r \in \left[0,\ v^2 \frac{2 m_N m_\chi^2}{(m_N + m_\chi)^2}\right]$$



Ciaran O'Hare

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: $g_{a\gamma} \propto m_a$

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

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

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

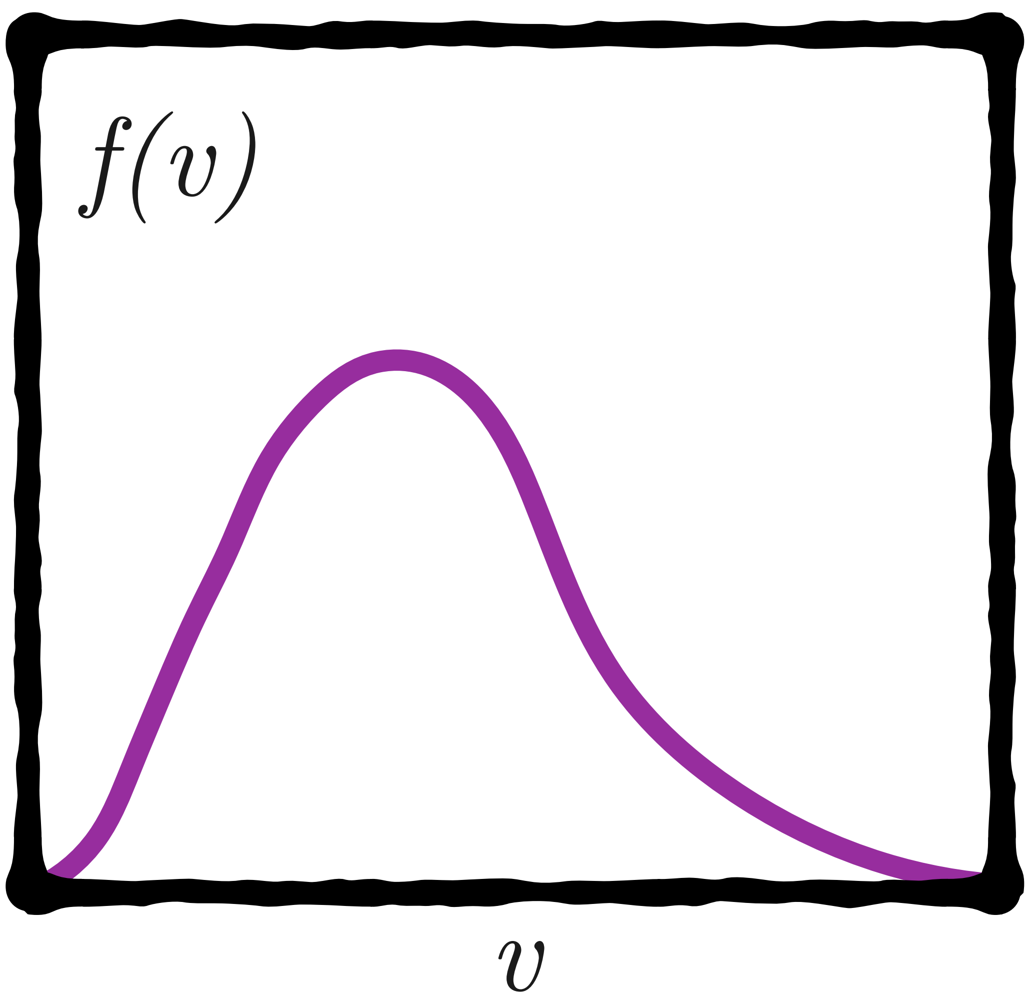
$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

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

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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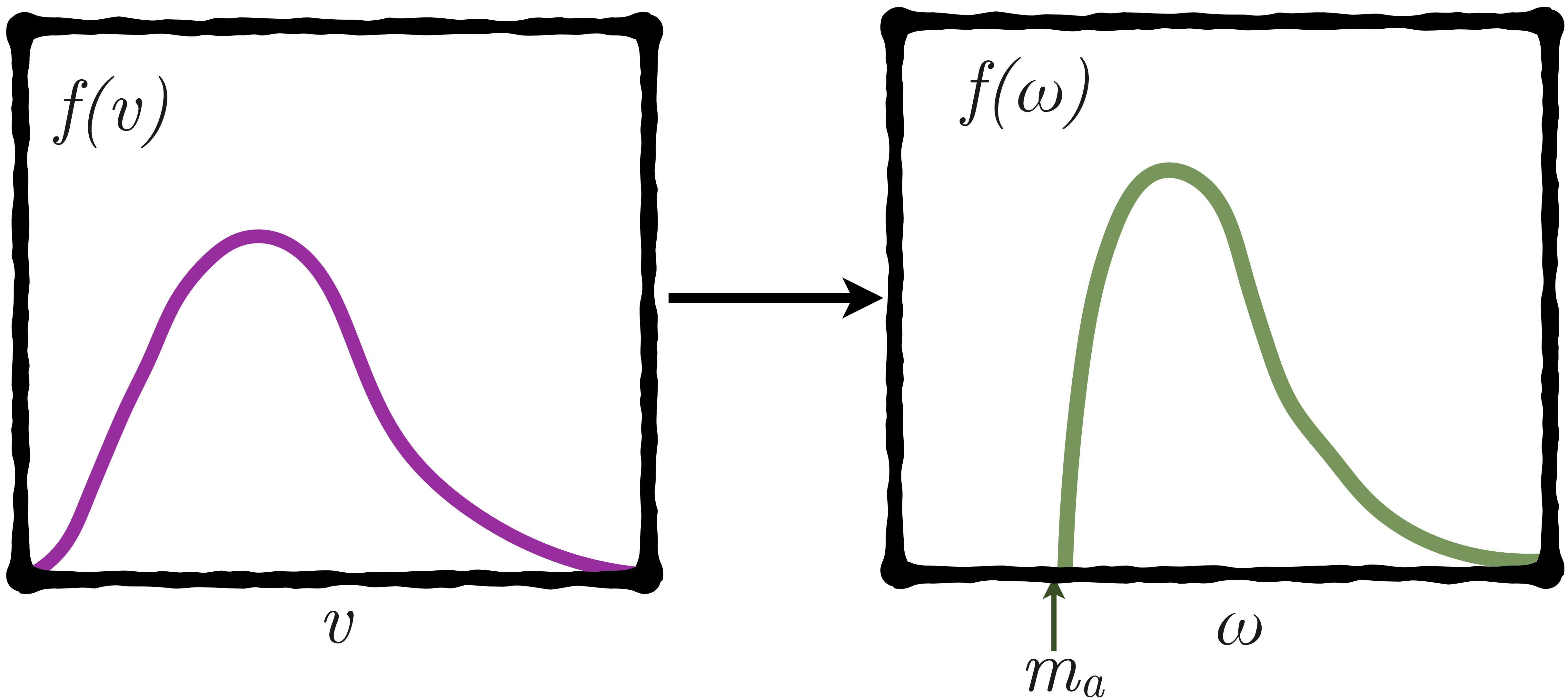
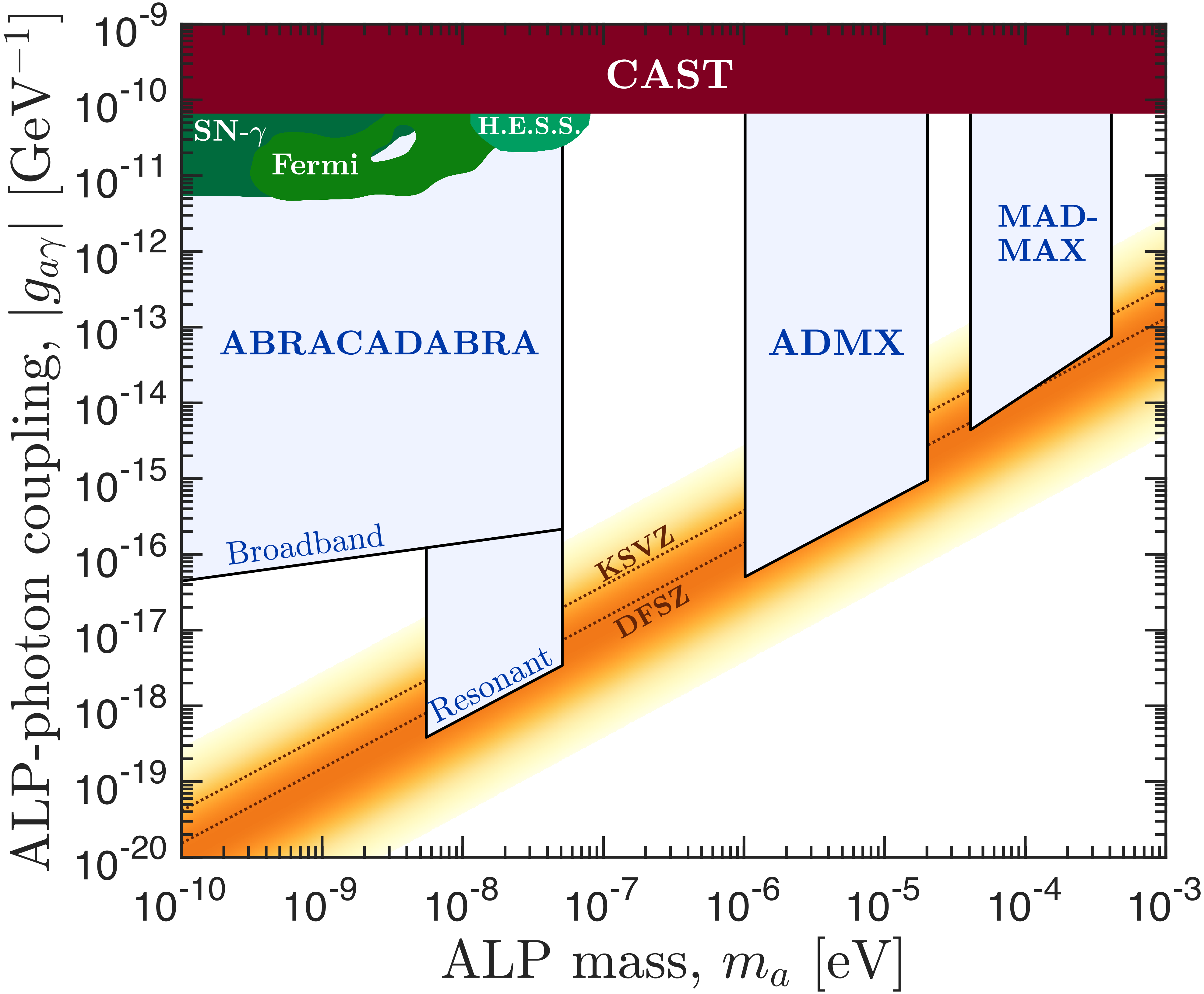
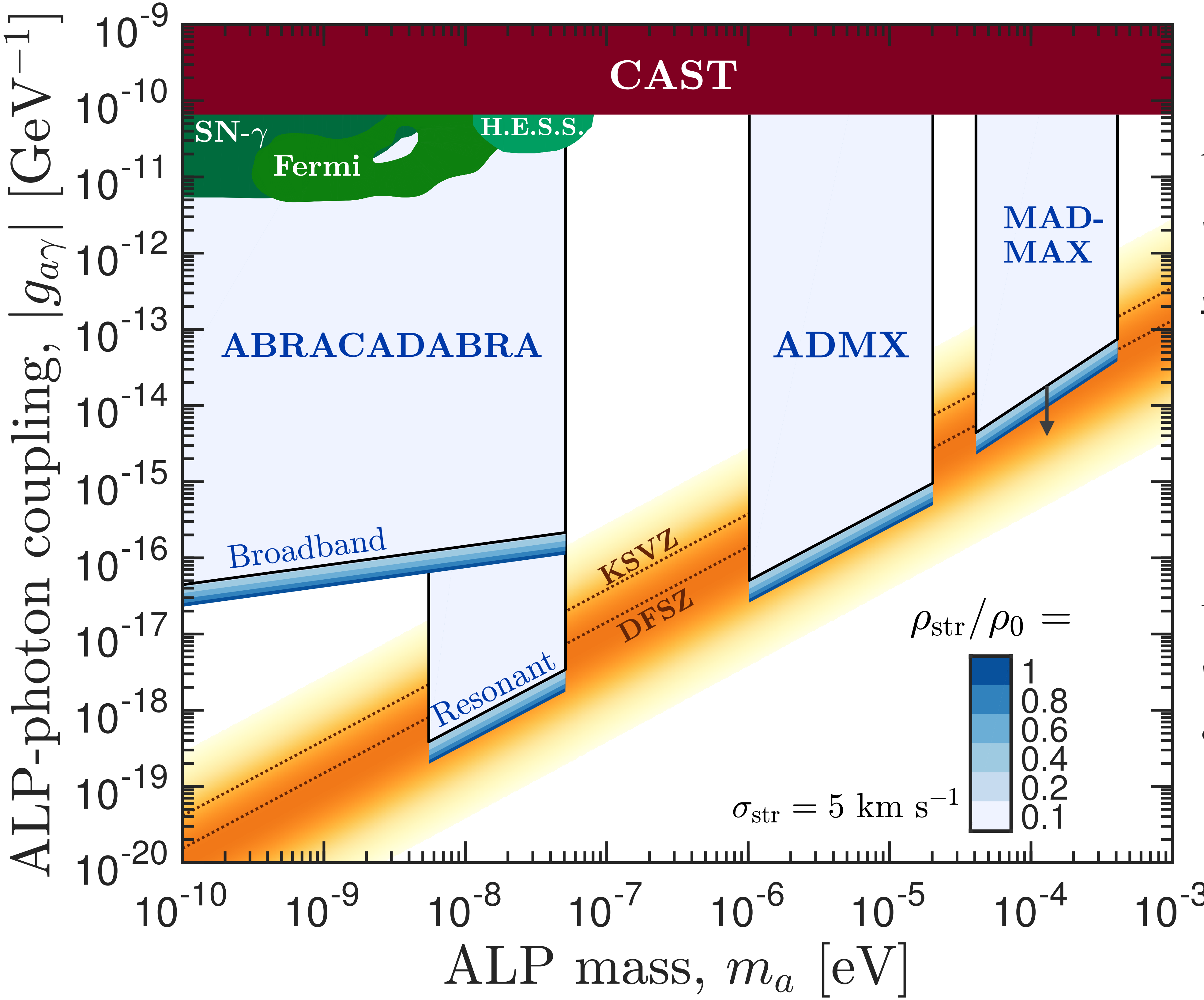


Axion experimental projections



Impact of streams on axion searches:



Axion searches like sharp signals

A cold S1 stream improves axion sensitivity