Beyond the Standard Halo Model

Christopher McCabe

Together with Ciaran O'Hare, Wyn Evans, G. Myeong and V. Belokurov

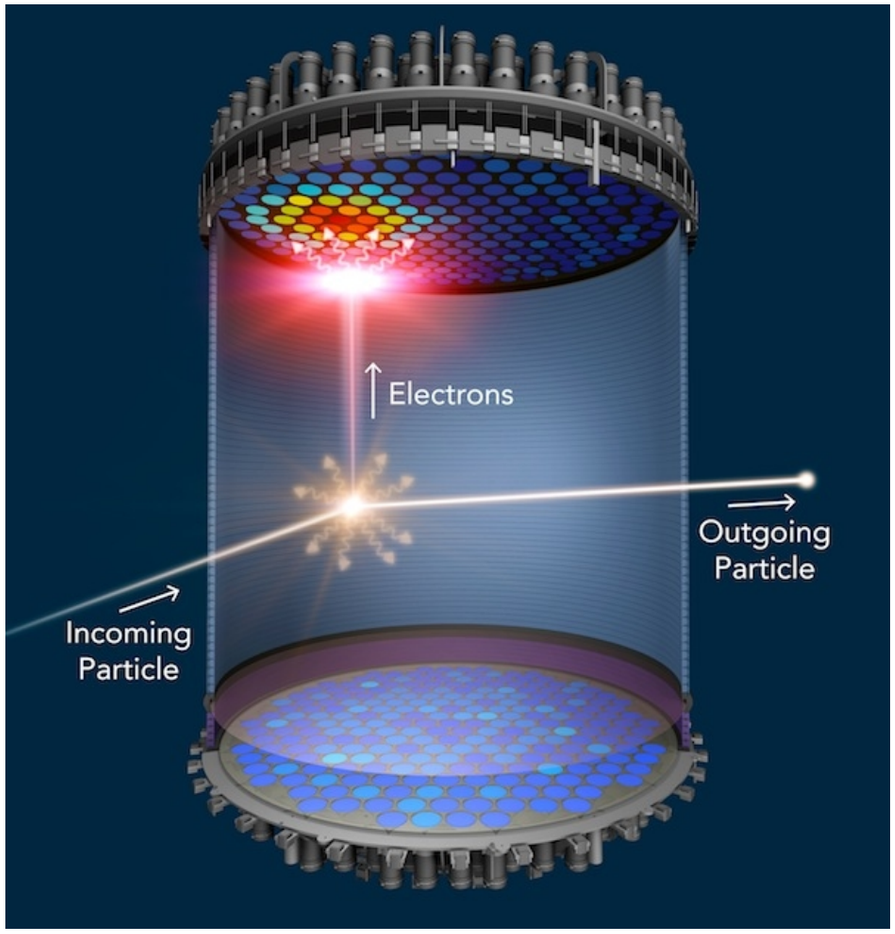
Based around arXiv:1807.09004 (PRD), 1810.11468 (PRD), 1909.04684

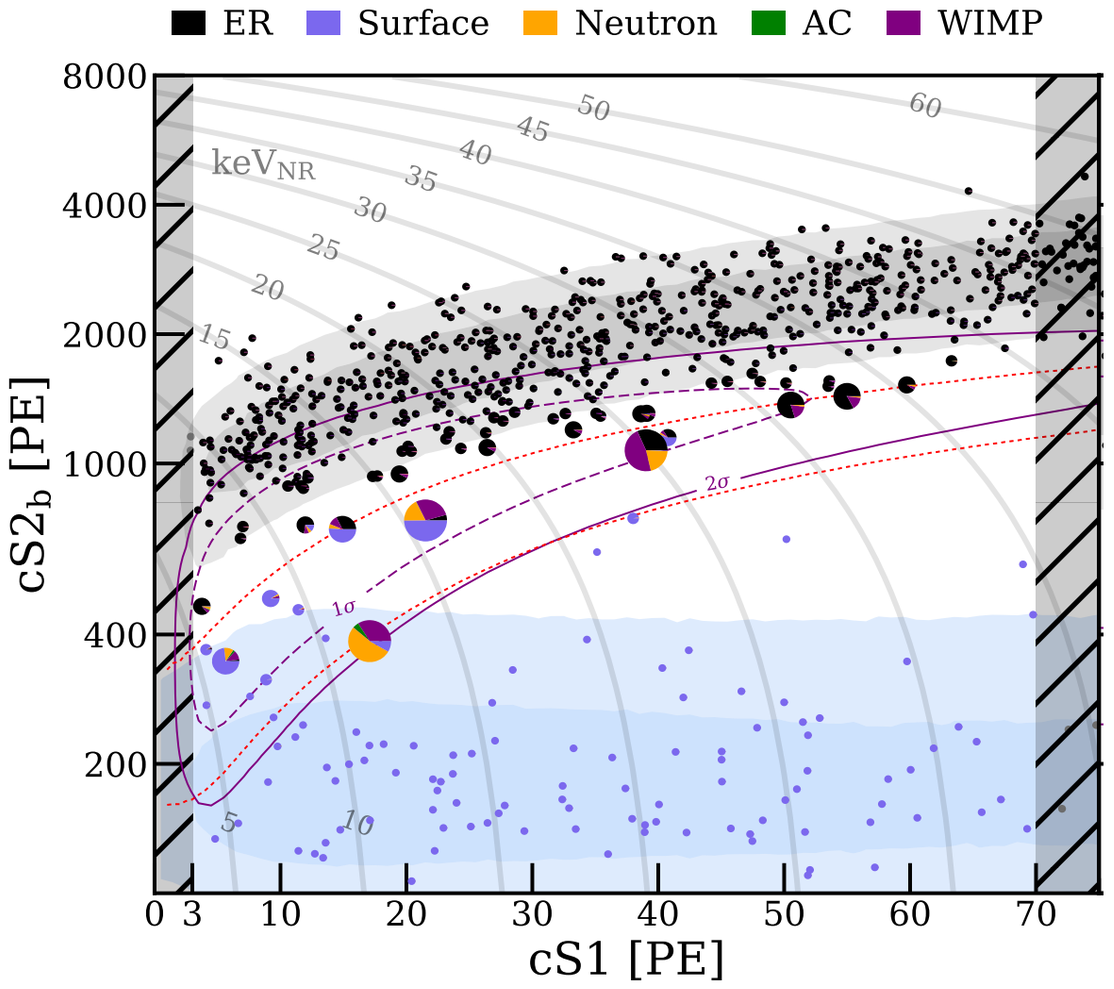
Light Dark Matter - Venice - 20th November 2019

Motivation

‘Traditional’ direct detection experiments

Good event-by-event discrimination

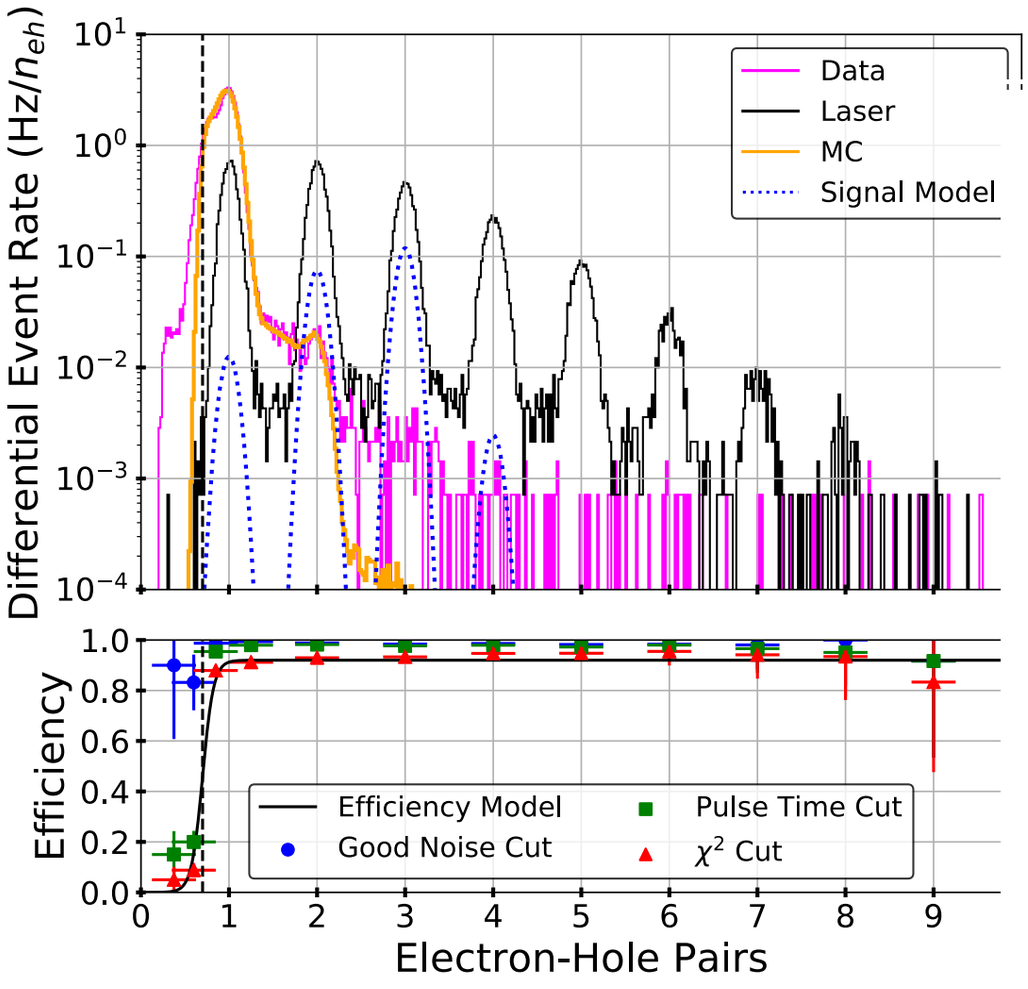


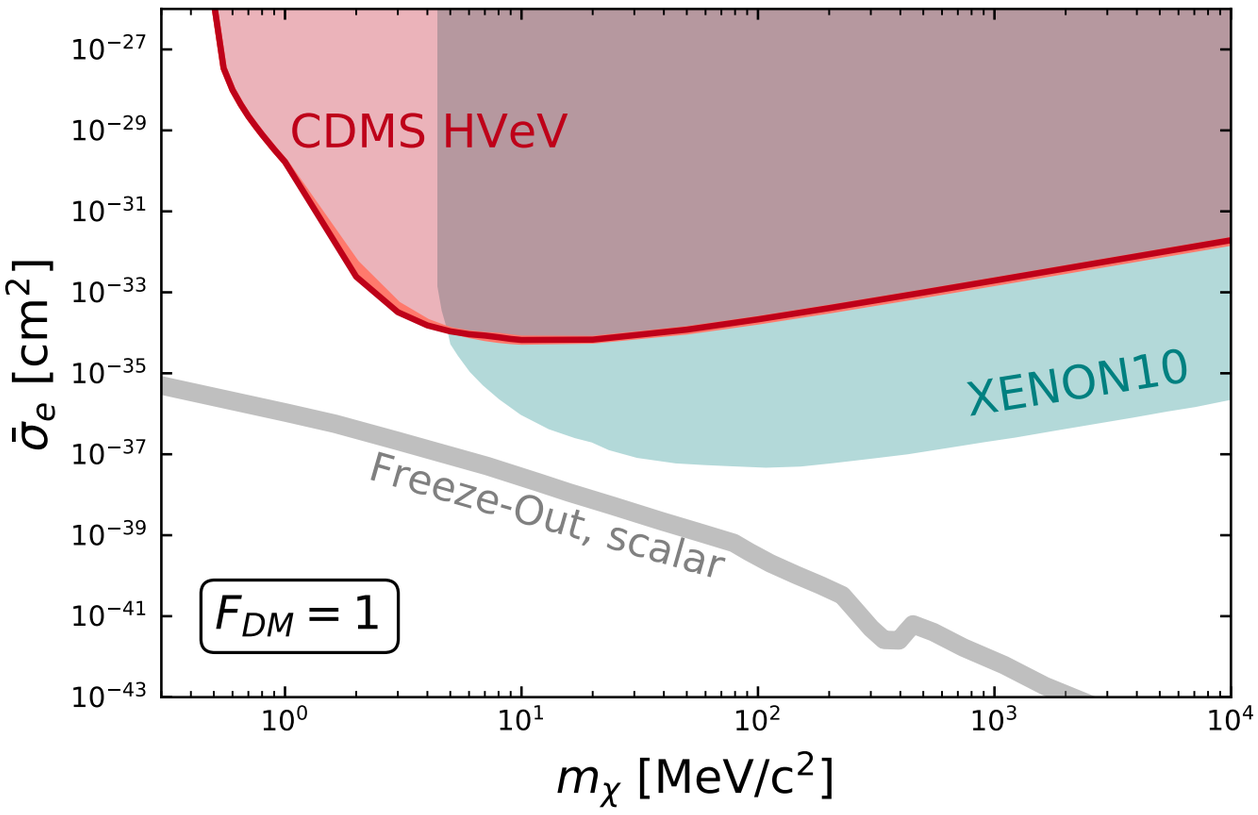


XENON1T, PRL, arXiv:1805.12562

Lower mass searches lose discrimination

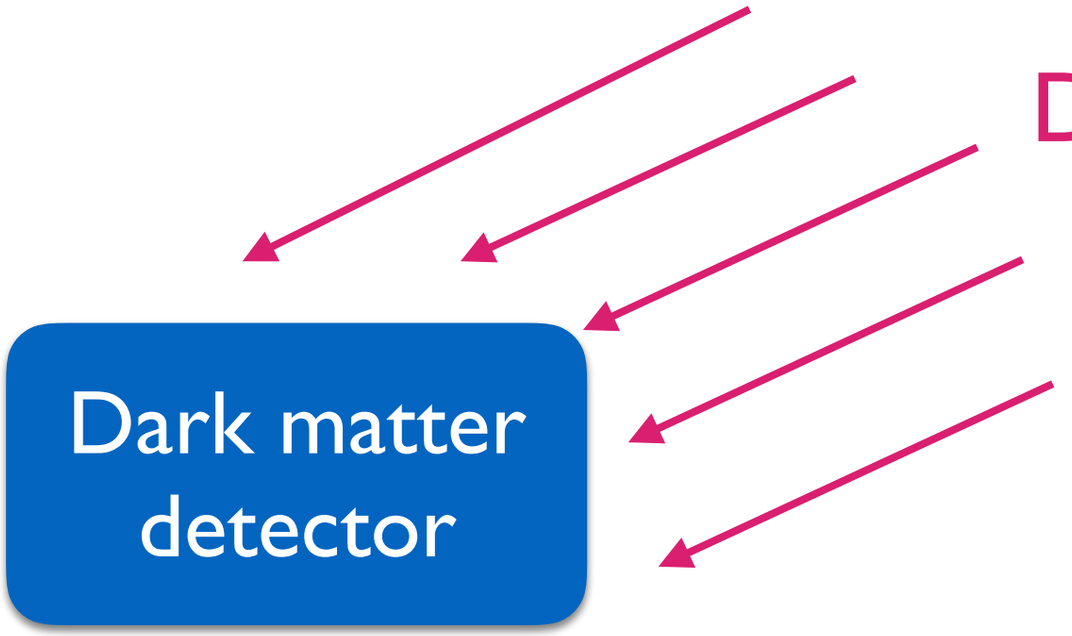
SuperCDMS, PRL
arXiv:1804.10697





Need to ensure the signal model is accurate

Generic direct detection experiment



Dark matter flux

$$\sim \rho_{\rm DM} \int d^3v \, f_{\rm DM}(\mathbf{v}) \, v$$

Event rate = *DM flux* × *particle physics*

Need to accurately model the DM flux to accurately predict signals

The Standard approach

Standard Halo Model

Simple spherical model with (asymptotically) flat rotation curve

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2} \right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & : |\mathbf{v}| < v_{\rm esc} \\ 0 & : \text{otherwise} \end{cases}$$

Assumptions:

- *Round halo*
- *Gaussian (Maxwellian)*
- *Isotropic*
- *No substructure*

Standard Halo Model

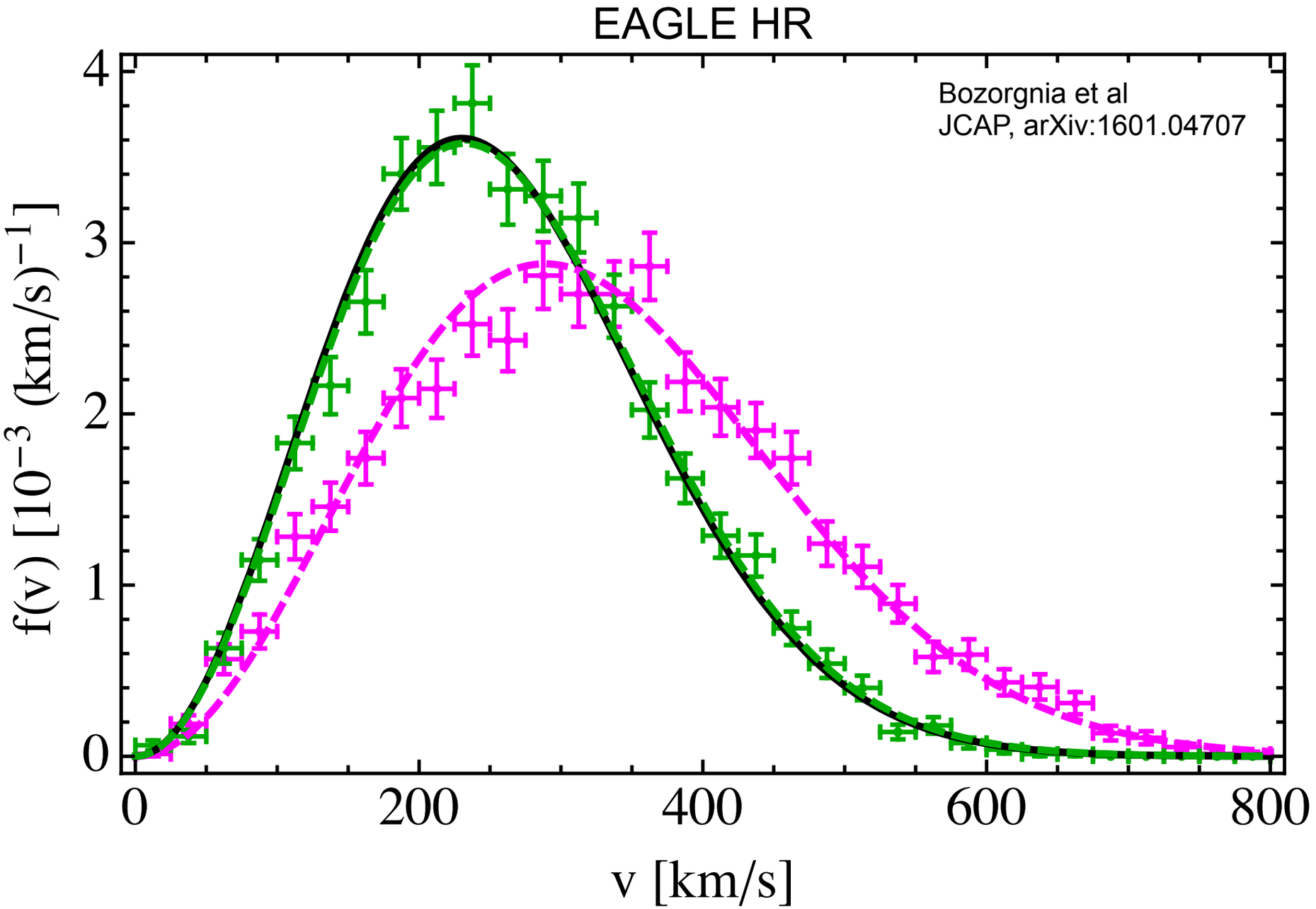
Simple spherical model with (asymptotically) flat rotation curve

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2} \right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & : |\mathbf{v}| < v_{\rm esc} \\ 0 & : \text{otherwise} \end{cases}$$

Advantages:

- *Simple*
- *Only 2 parameters*
- *Accurate(?)*

Gaussian form agrees well with simulated galaxies

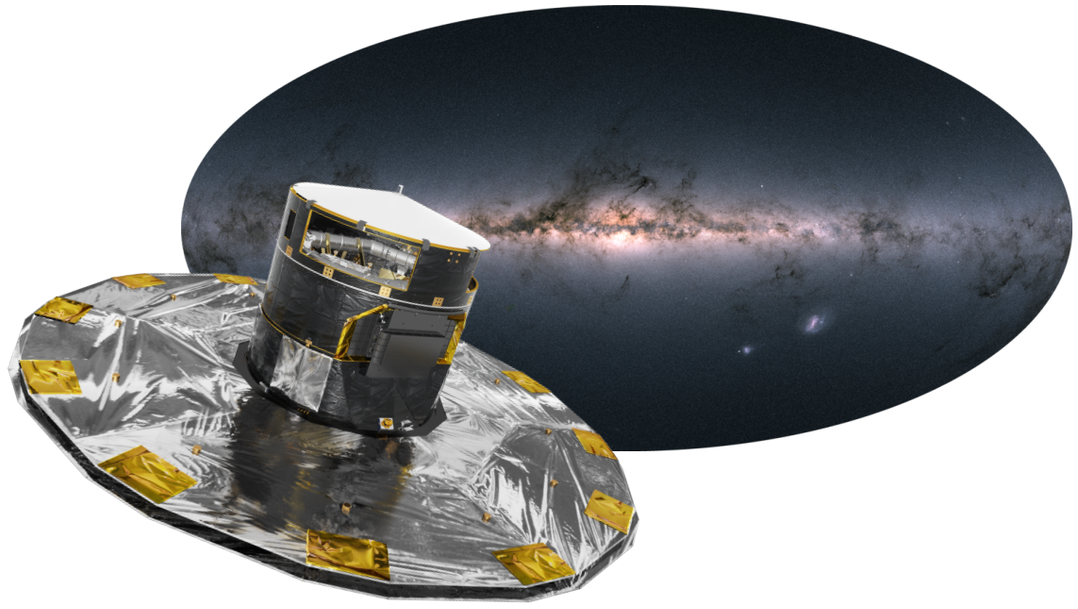


Green and magenta data points: *Milky Way-like* simulated halos

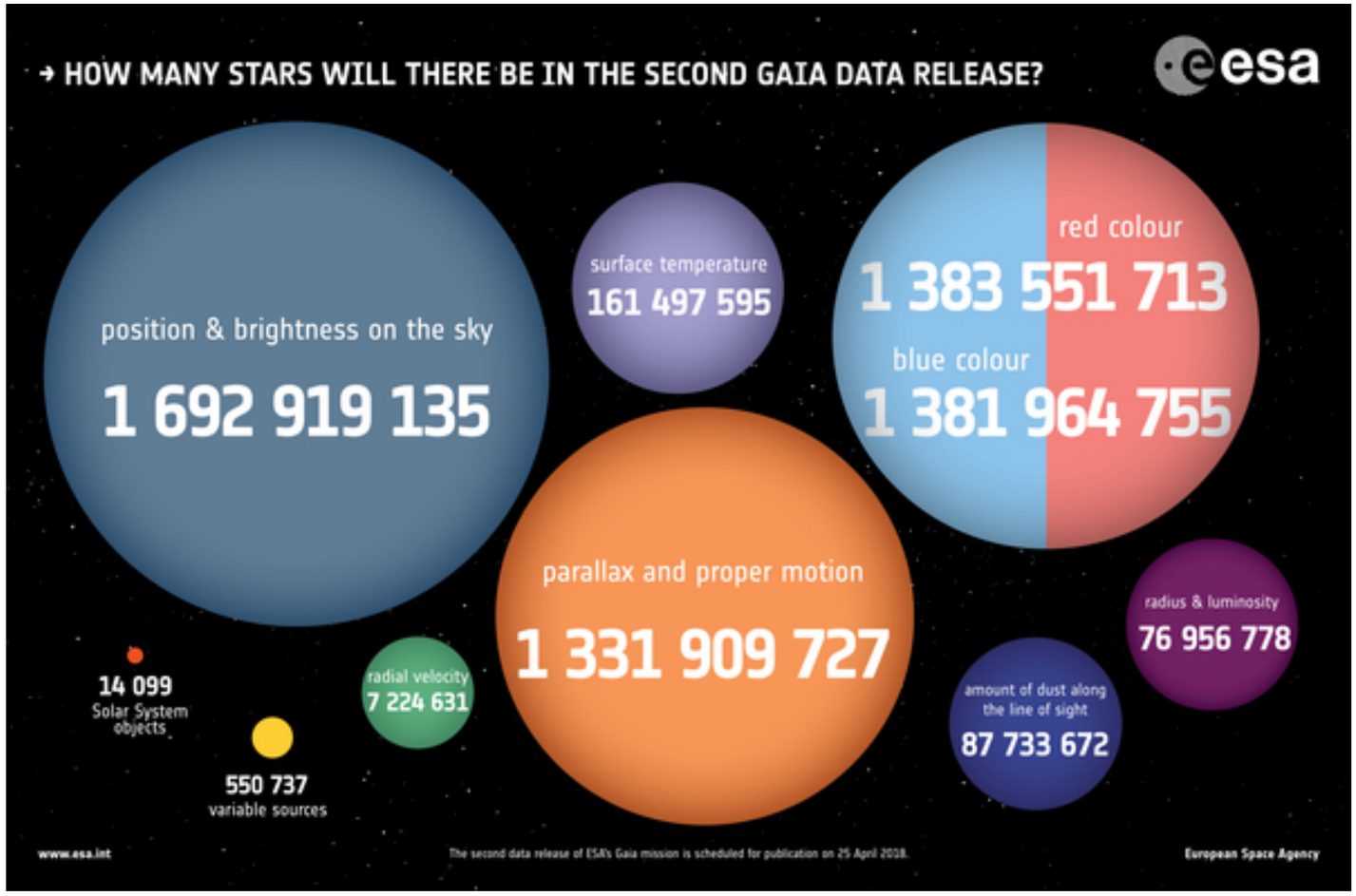
Lines: Standard Halo Model - *Agreement is reasonably good!*

Is our galaxy similar to a ‘Milky Way-like’ simulated halo?

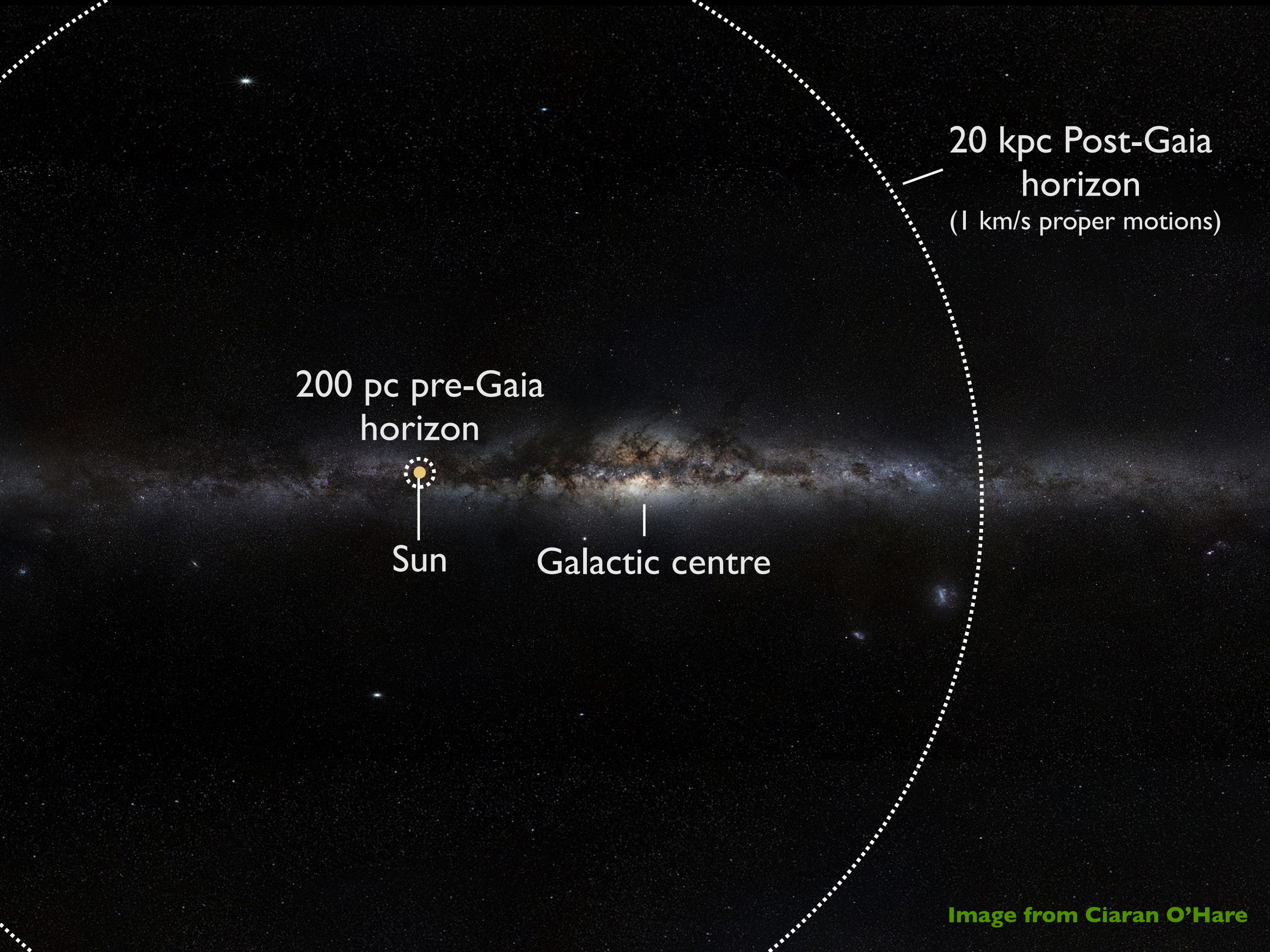
Gaia: a new era in mapping the Milky Way



Launched 2013
Operates until ~2022



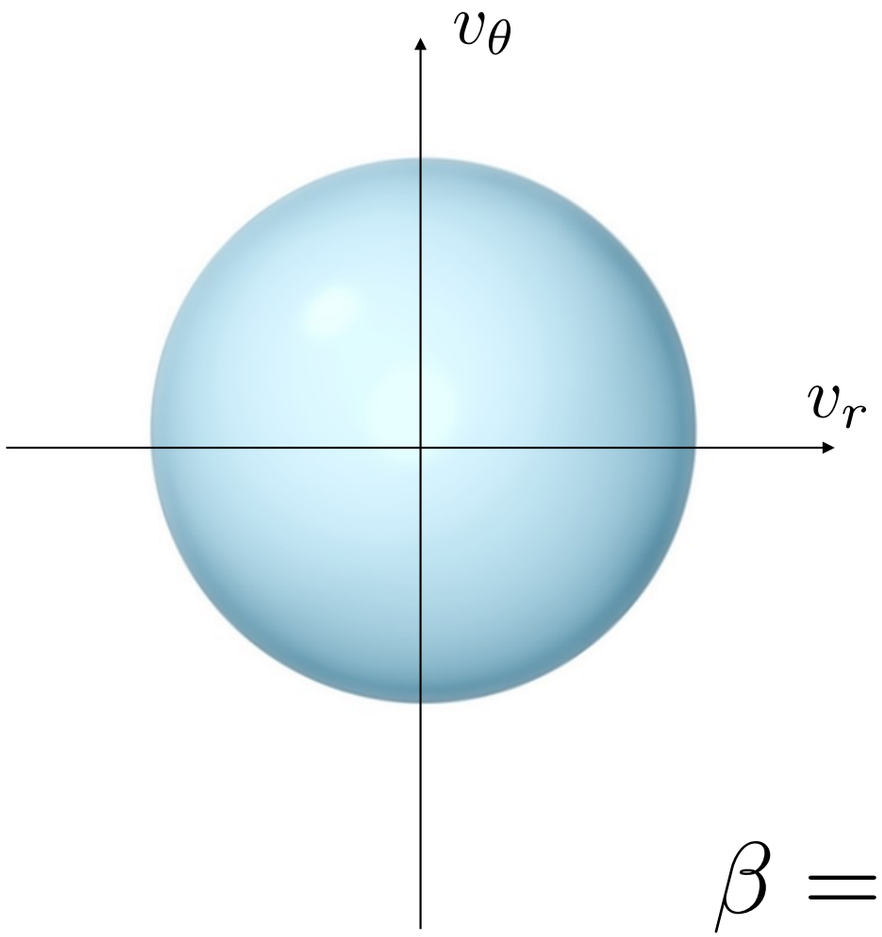
7 millions stars with full 6D phase space (x,v)


20 kpc Post-Gaia horizon
(1 km/s proper motions)
200 pc pre-Gaia horizon
Sun
Galactic centre
Image from Ciaran O'Hare

Meatballs and Sausages *in velocity space*

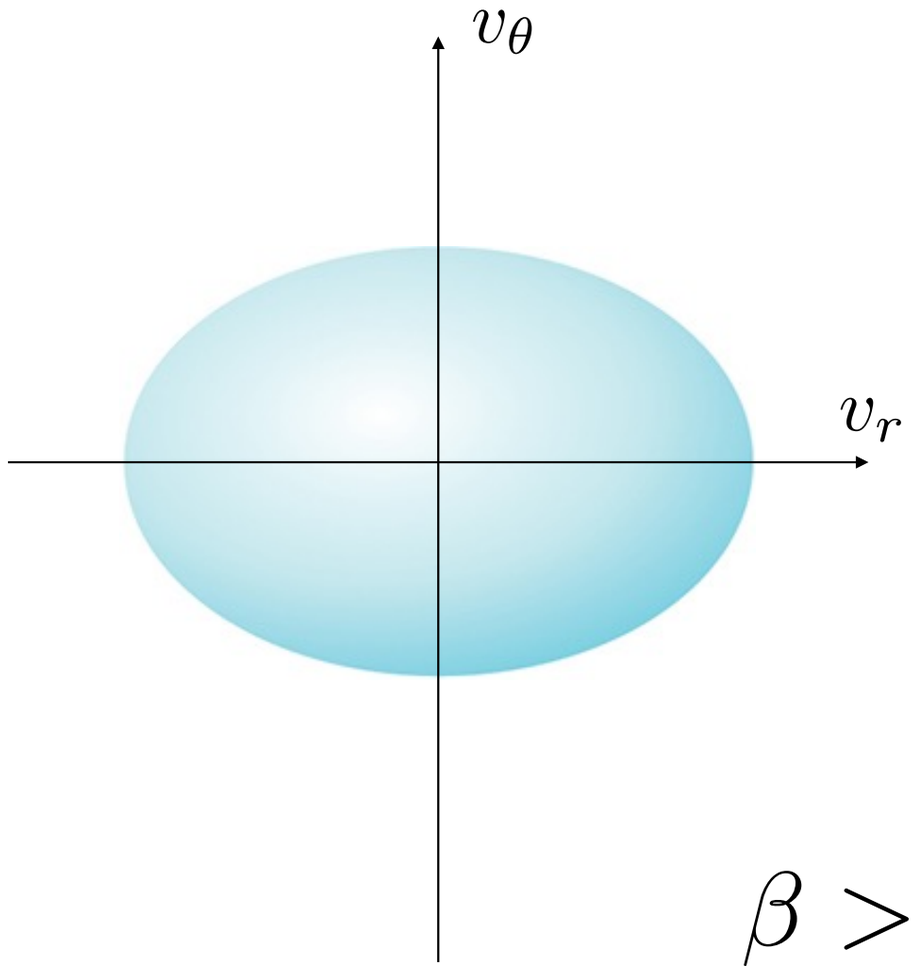
Meatball

Isotropic
SHM model

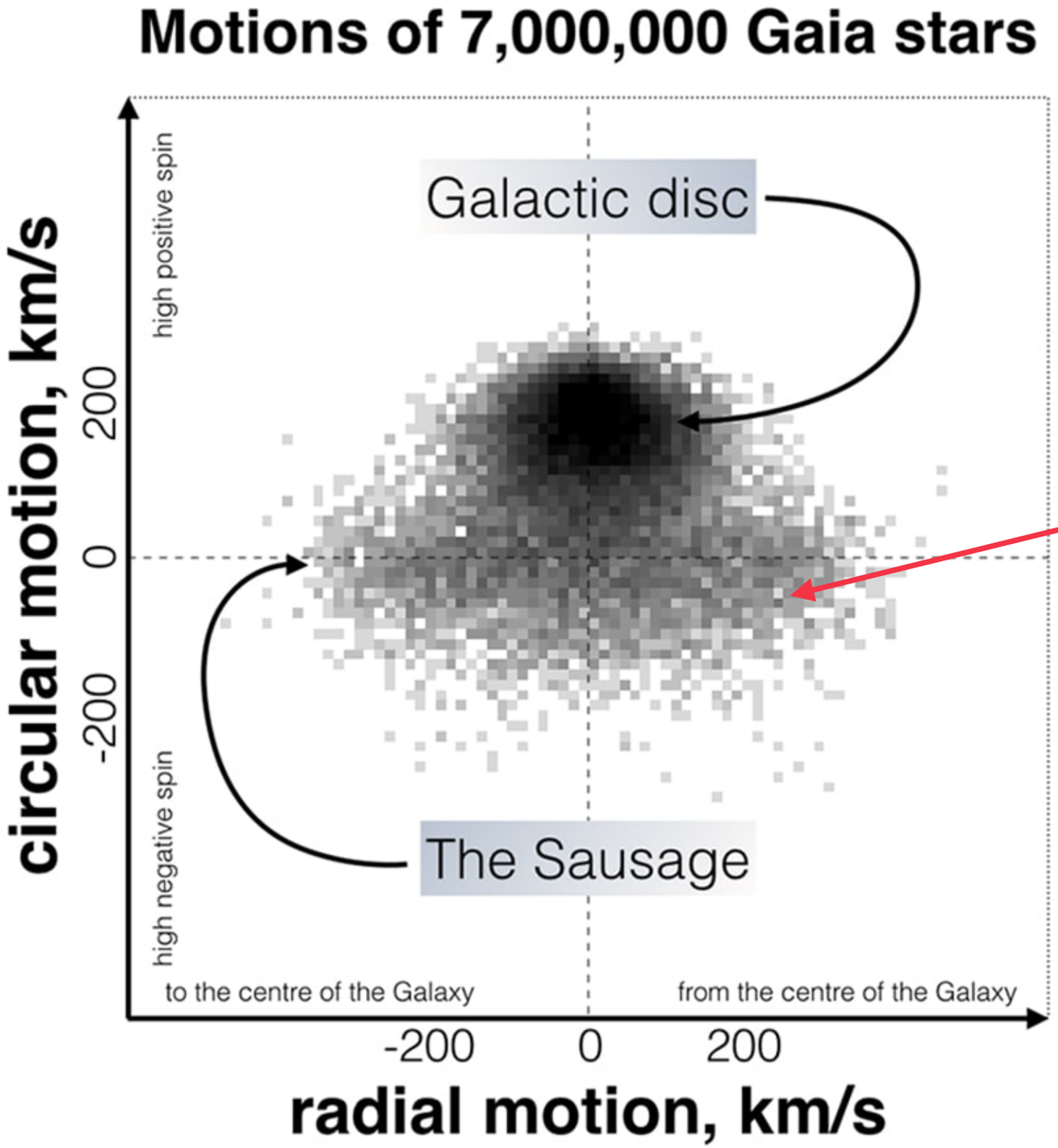


Sausage

Radially anisotropic
Beyond the SHM model



Gaia data contains a Sausage



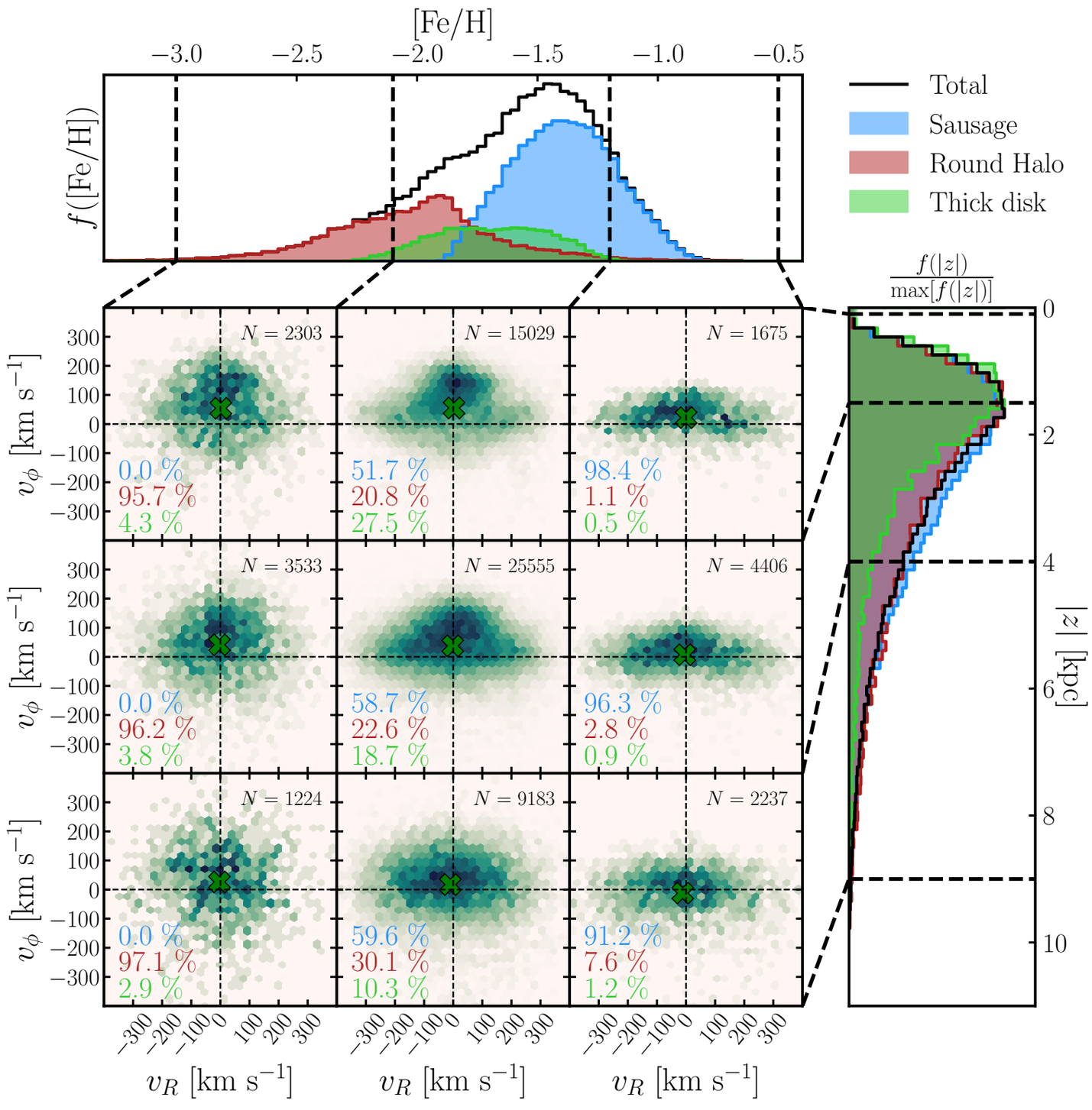
In the Sausage, stars move on highly radial orbits

Belokurov, Erkal, Evans, Koposov, Myeong… arXiv:1802.03414, 1805.10288, 1805.00453…

Gaia data contains a Sausage

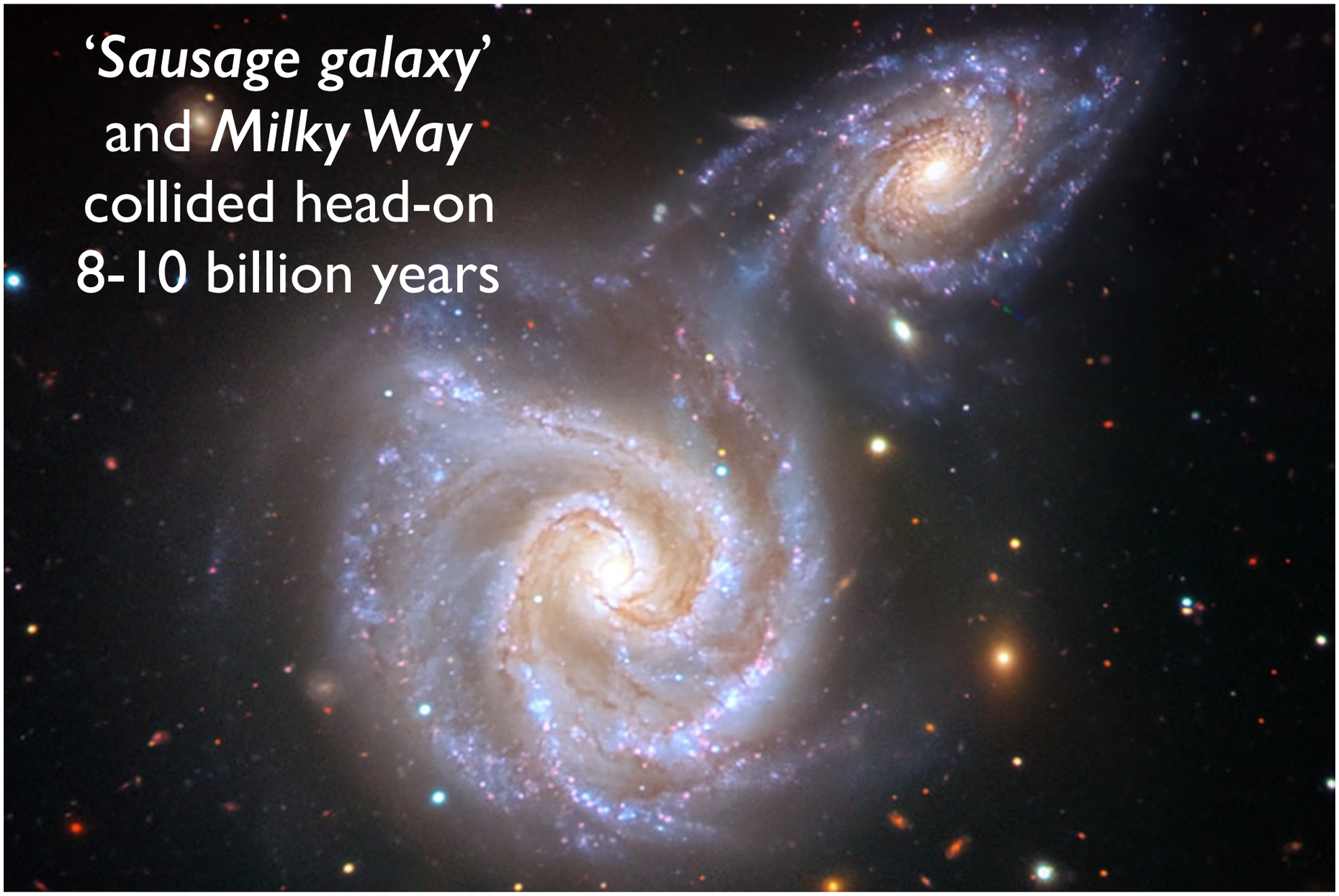
O'Hare, Evans, CM et al
arXiv:1909.04684

@ low metallicity: 'Meatballs'



@ higher metallicity: 'Sausages'

Extreme radial anisotropy arises from head-on collision

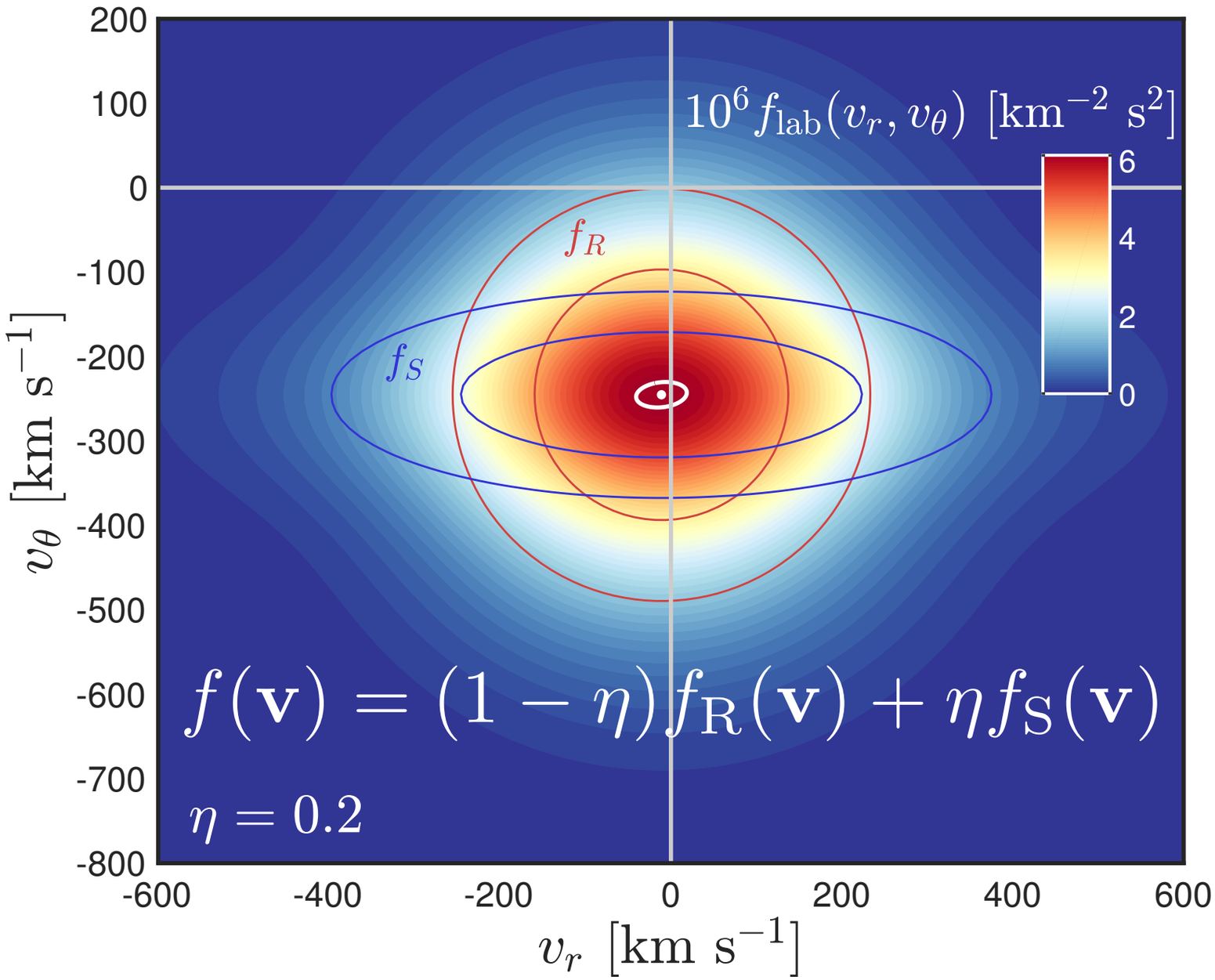


Sausage galaxy brought dark matter too…

…will also be on highly radial orbit

Modelling the Gaia Sausage dark matter

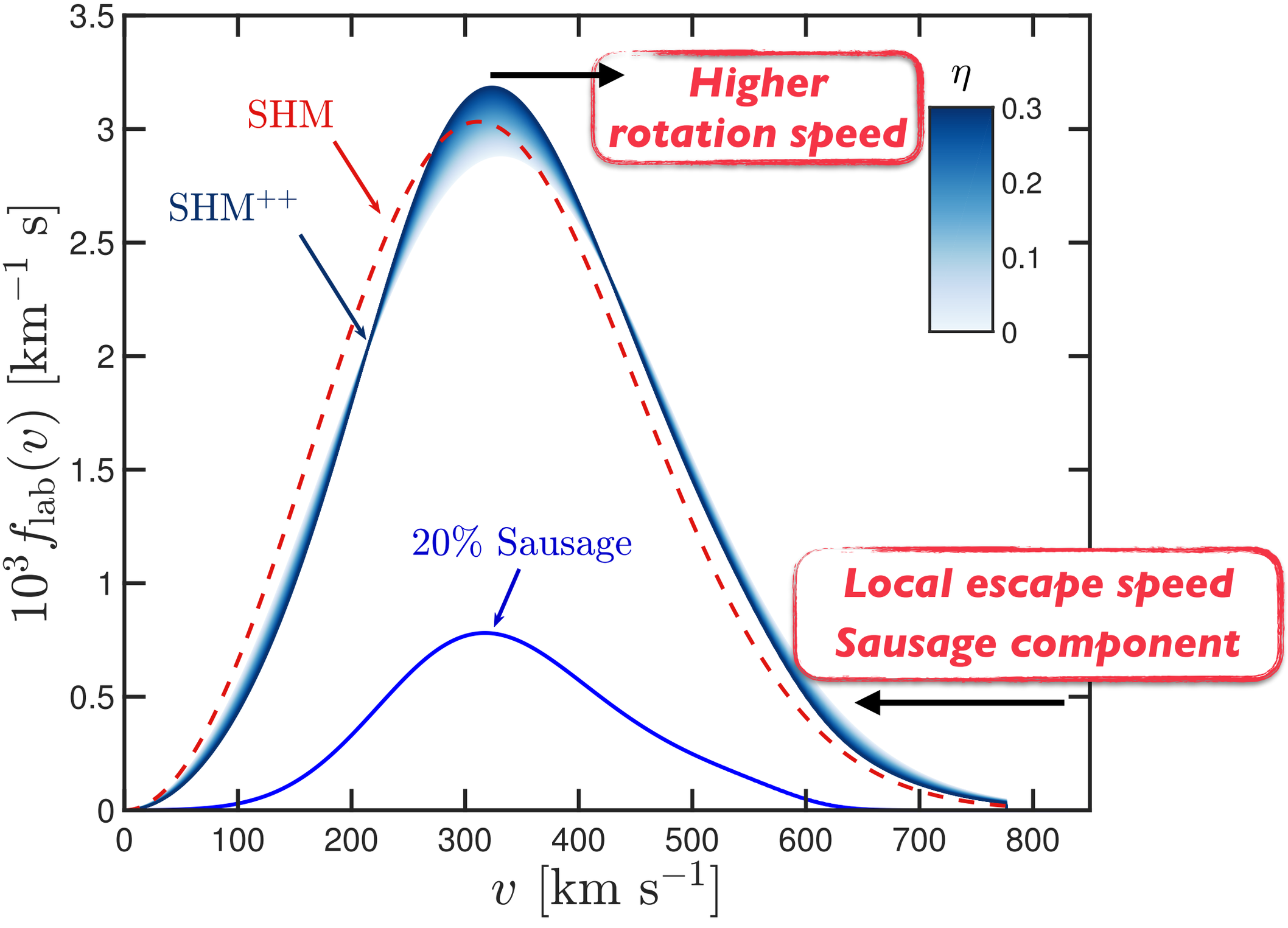
O'Hare, Evans, CM, arXiv:1810.11468, PRD



η is fraction of local DM in Sausage

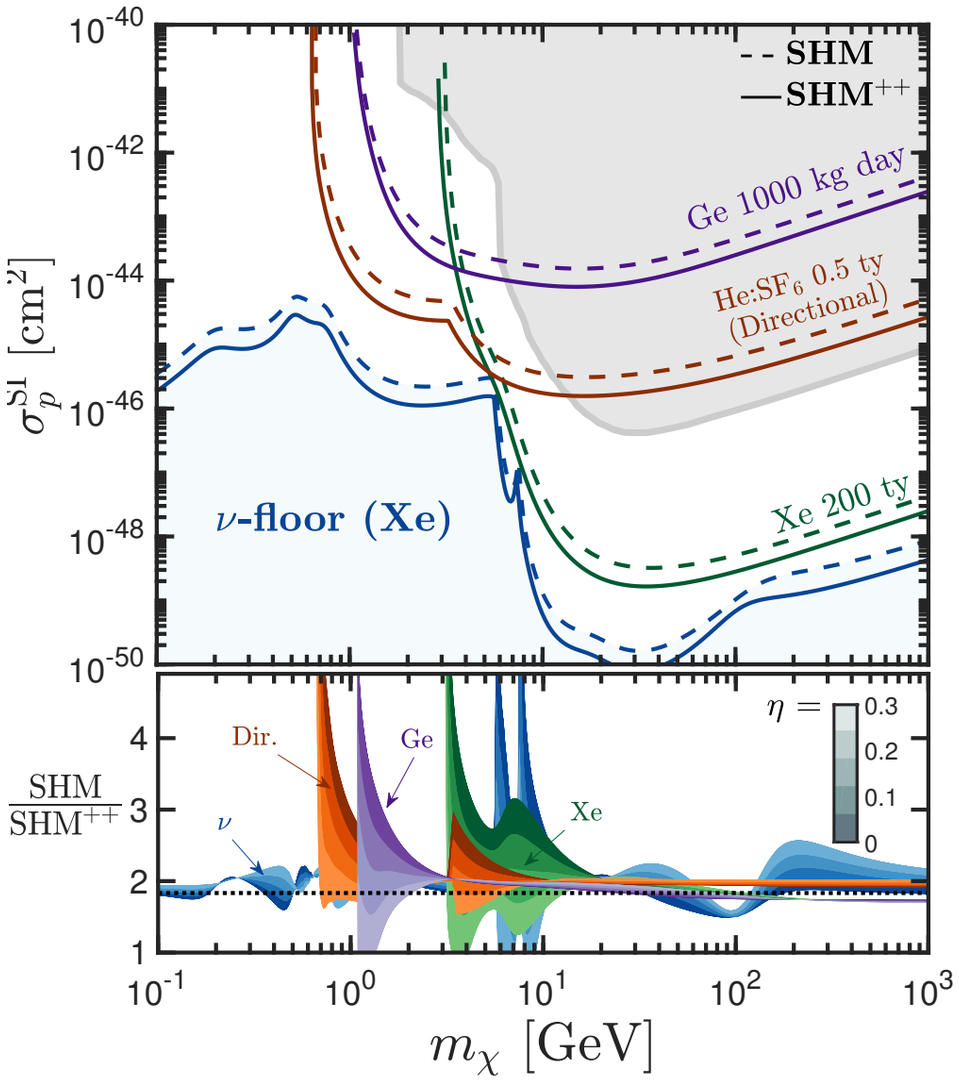
$$f_{\rm R}(\mathbf{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2} N_{\rm R,esc}} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma_v^2}\right), \quad f_{\rm S}(\mathbf{v}) = \frac{1}{(2\pi)^{3/2}\sigma_r\sigma_\theta^2 N_{\rm S,esc}} \exp\left(-\frac{v_r^2}{2\sigma_r^2} - \frac{v_\theta^2}{2\sigma_\theta^2} - \frac{v_\phi^2}{2\sigma_\phi^2}\right)$$

SHM++: 2 component model

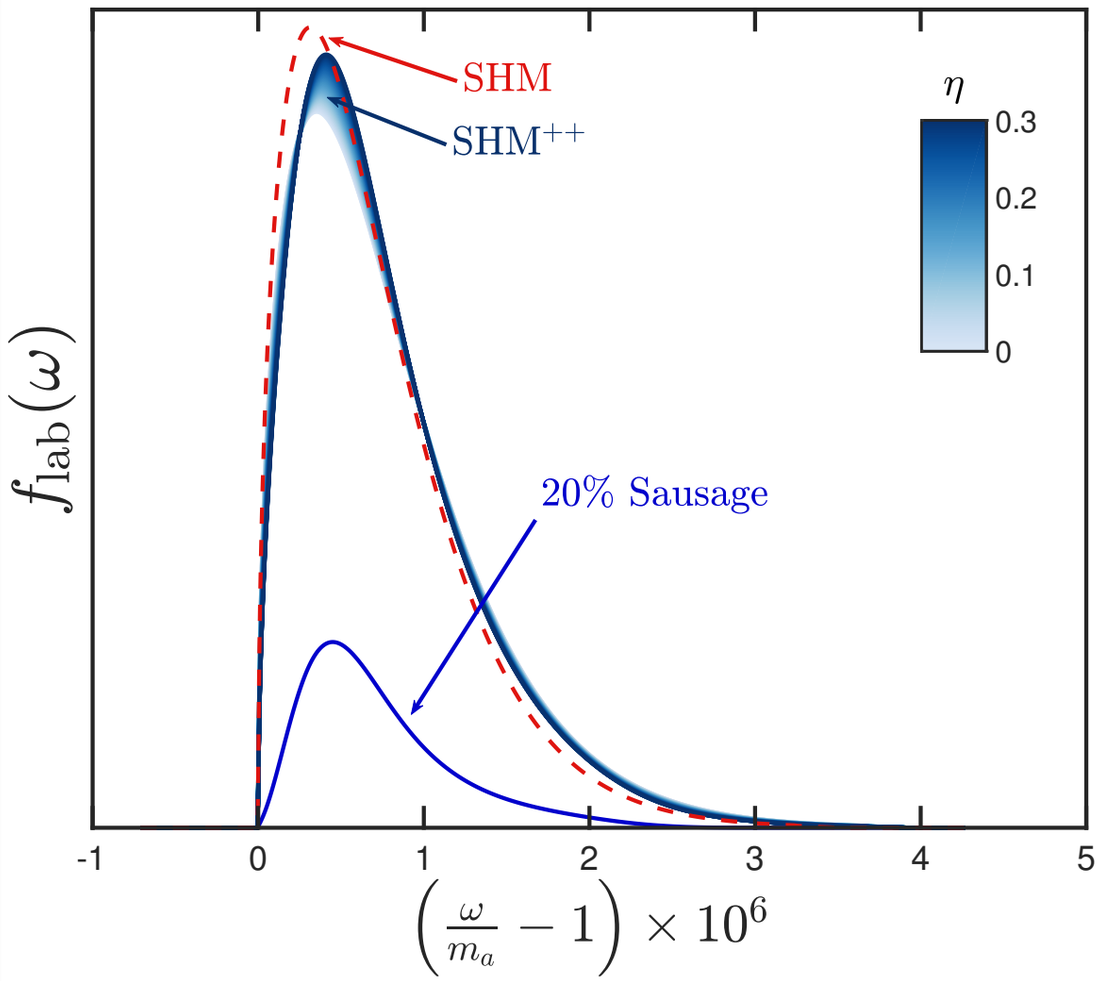


Sausage leads to modest changes

Higher-mass nuclear recoils



Axion-haloscope power spectrum



Gaia Sausage is Beyond the Standard Halo Model…

…but generally leads to modest changes in experimental signals

Going further beyond the SHM

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **475,** 1537–1548 (2018) doi:10.1093/mnras/stx3262
Advance Access publication 2017 December 20

Halo substructure in the SDSS–*Gaia* catalogue: streams and clumps

G. C. Myeong,[1] N. W. Evans,[1★] V. Belokurov,[1] N. C. Amorisco[2,3] and S. E. Koposov[1,4]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **478,** 5449–5459 (2018) doi:10.1093/mnras/sty1403
Advance Access publication 2018 June 7

Discovery of new retrograde substructures: the shards of ω Centauri?

G. C. Myeong,[1★] N. W. Evans,[1★] V. Belokurov,[1] J. L. Sanders[1] and S. E. Koposov[1,2]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2]*McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

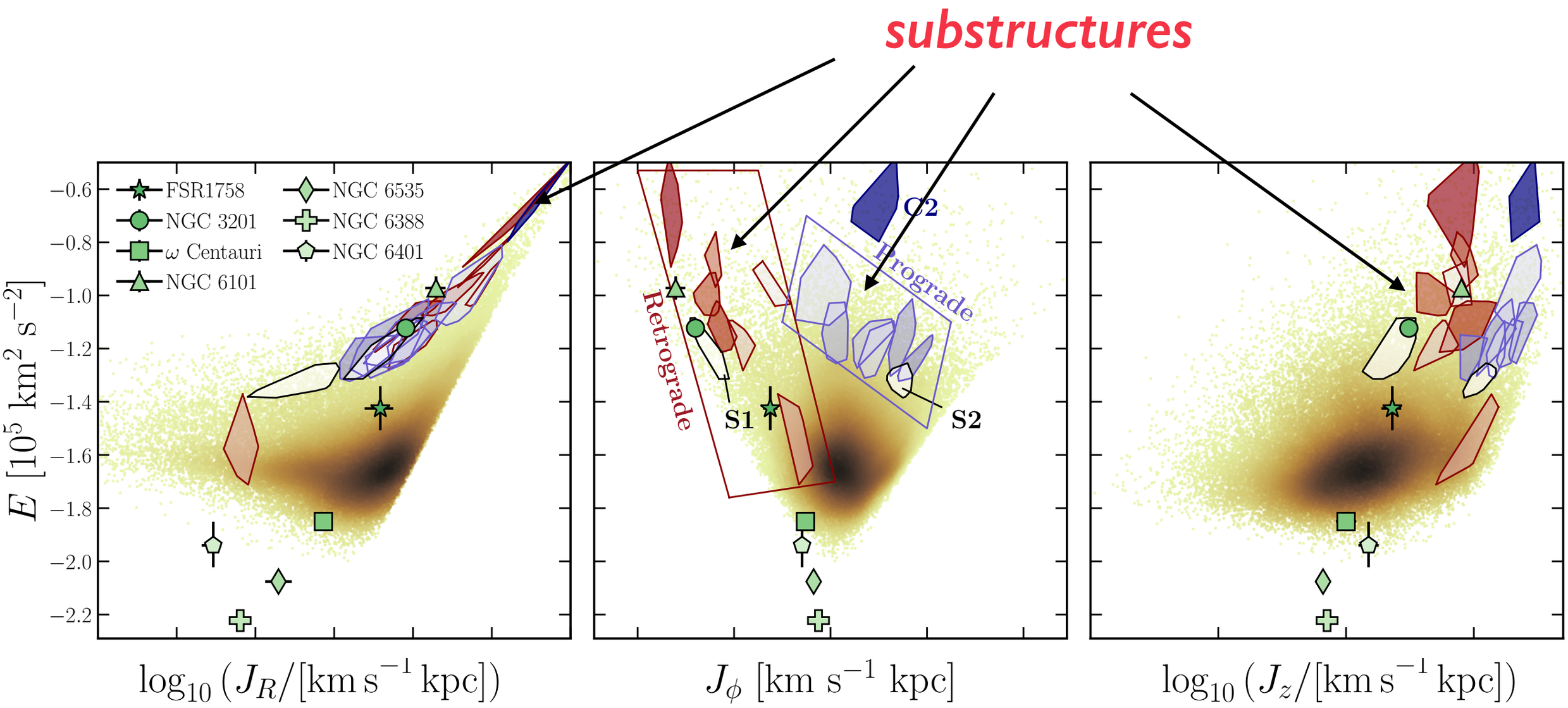
MNRAS **488,** 1235–1247 (2019) doi:10.1093/mnras/stz1770
Advance Access publication 2019 July 1

Evidence for two early accretion events that built the Milky Way stellar halo

G. C. Myeong,[1★] E. Vasiliev,[1,2] G. Iorio,[1] N. W. Evans[1★] and V. Belokurov[1]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2]*Lebedev Physical Institute, Leninsky Prospekt 53, Moscow 119991, Russia*

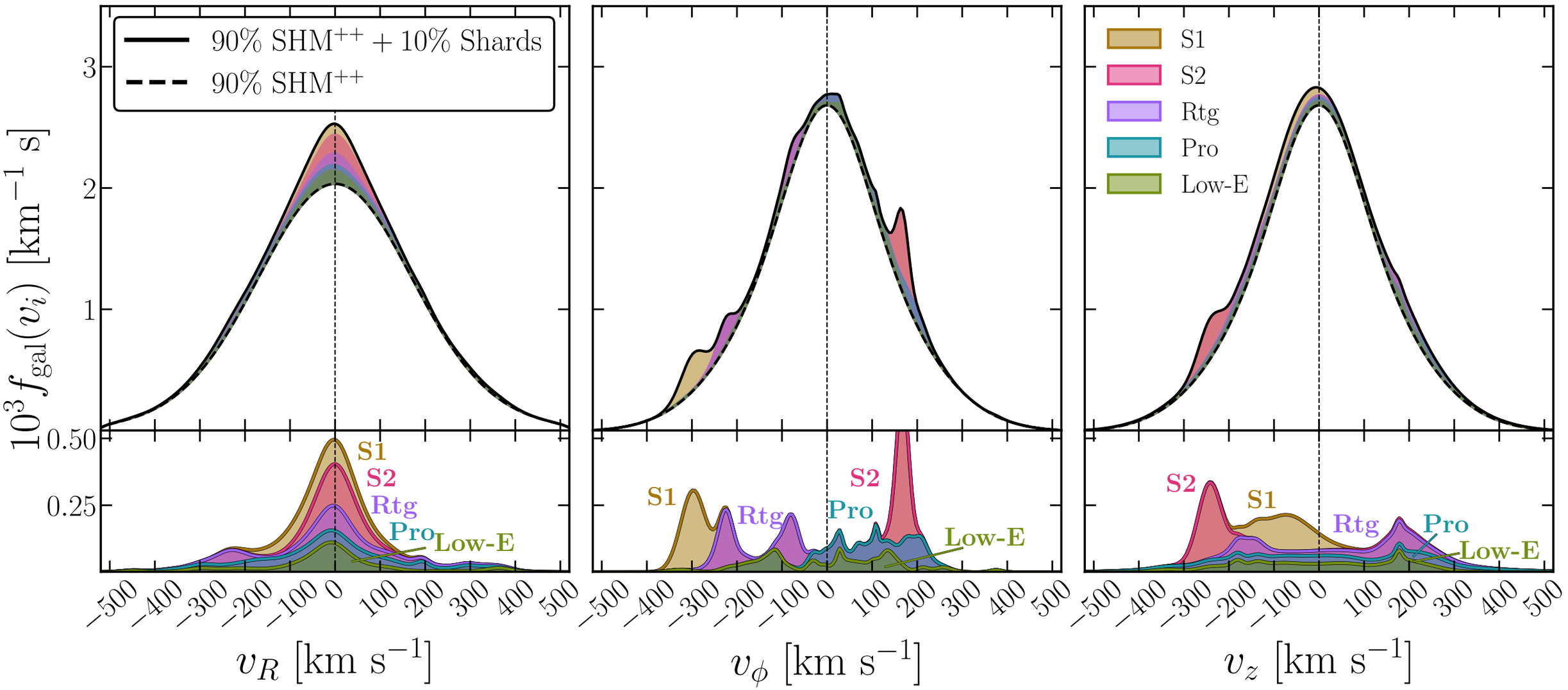
Finding local structure ‘Shards’ in action space



S1 and S2 are the most interesting for terrestrial experiments

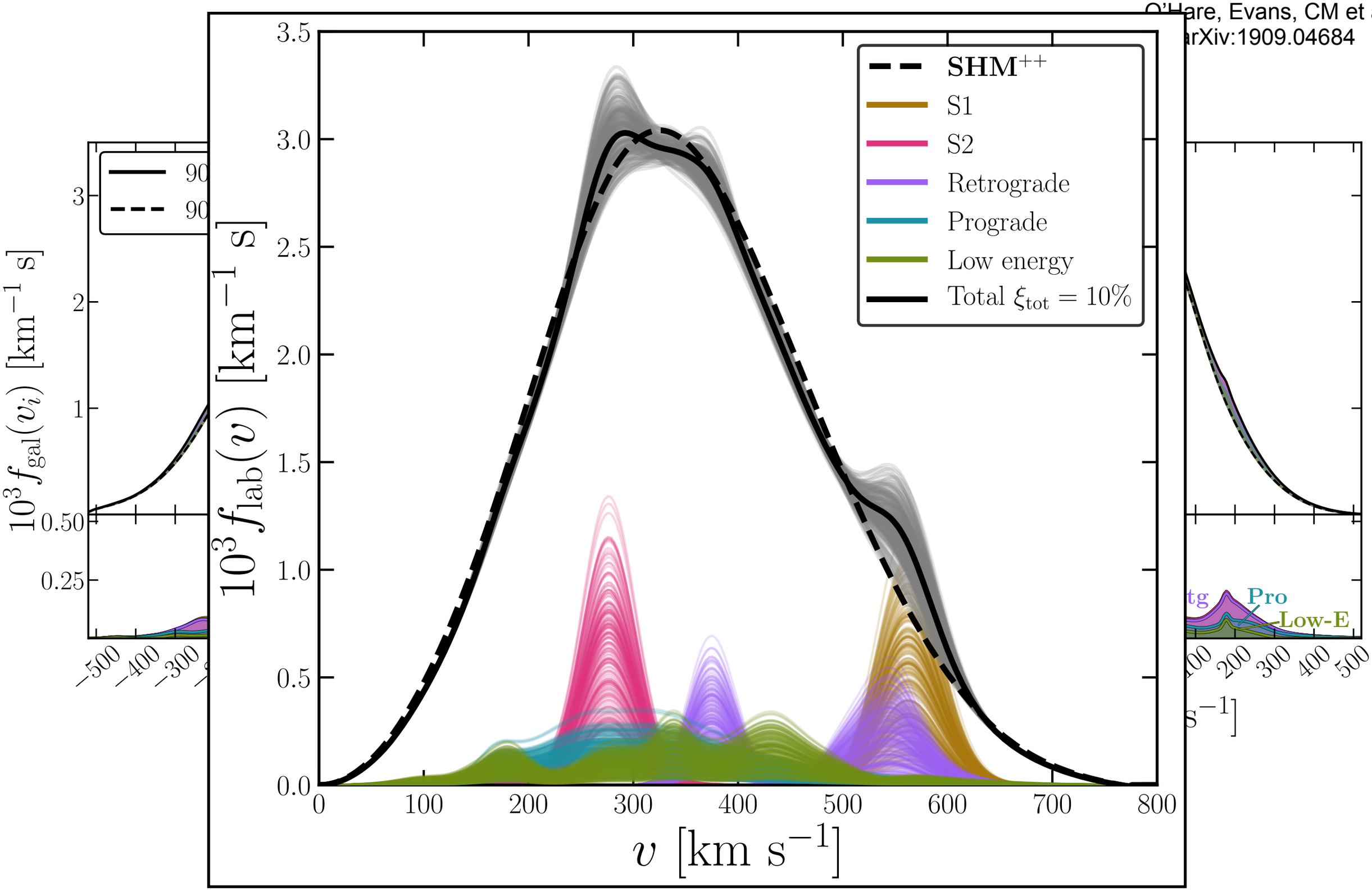
More general substructure: ‘Dark Shards’

O’Hare, Evans, CM et al
arXiv:1909.04684

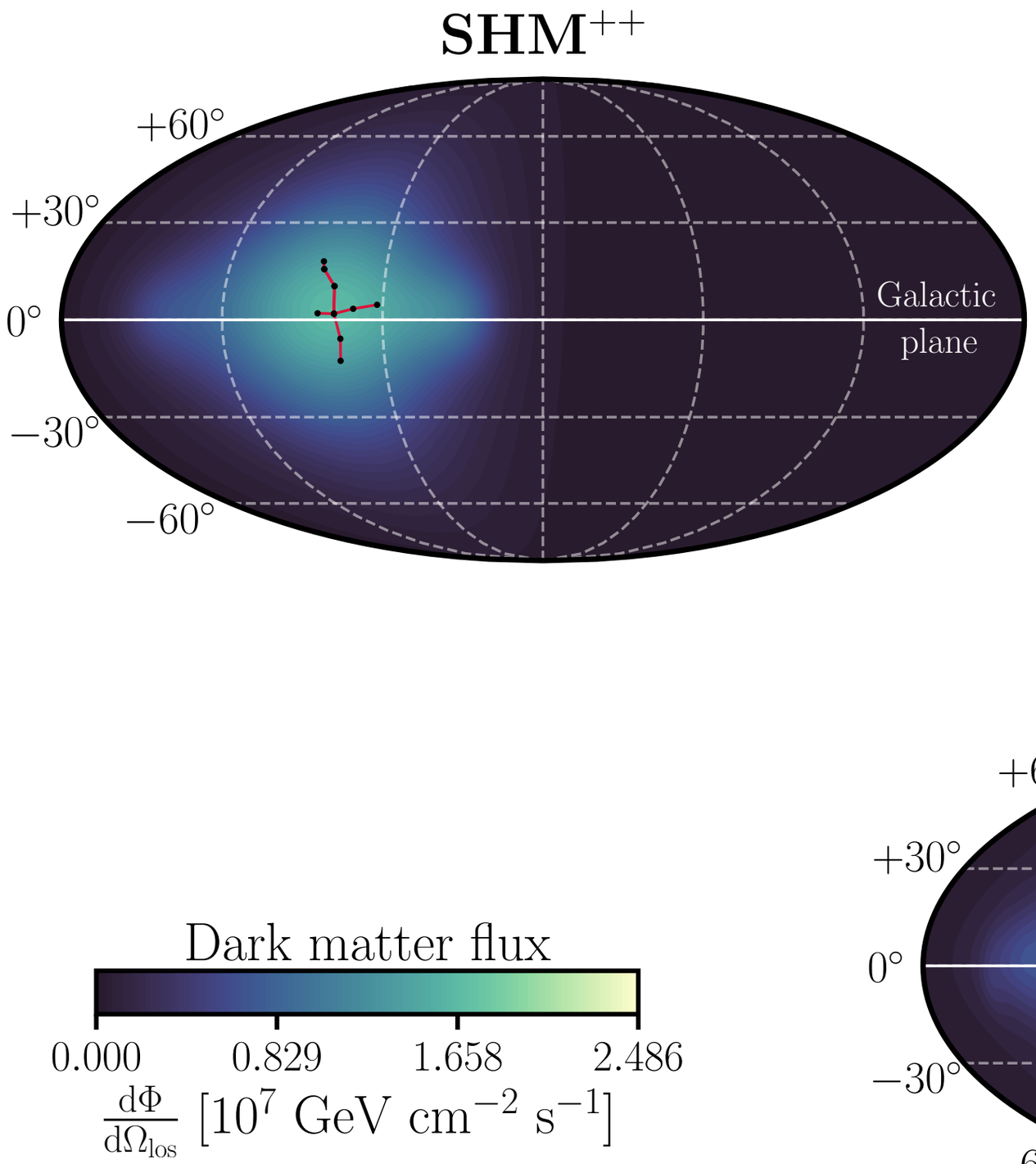


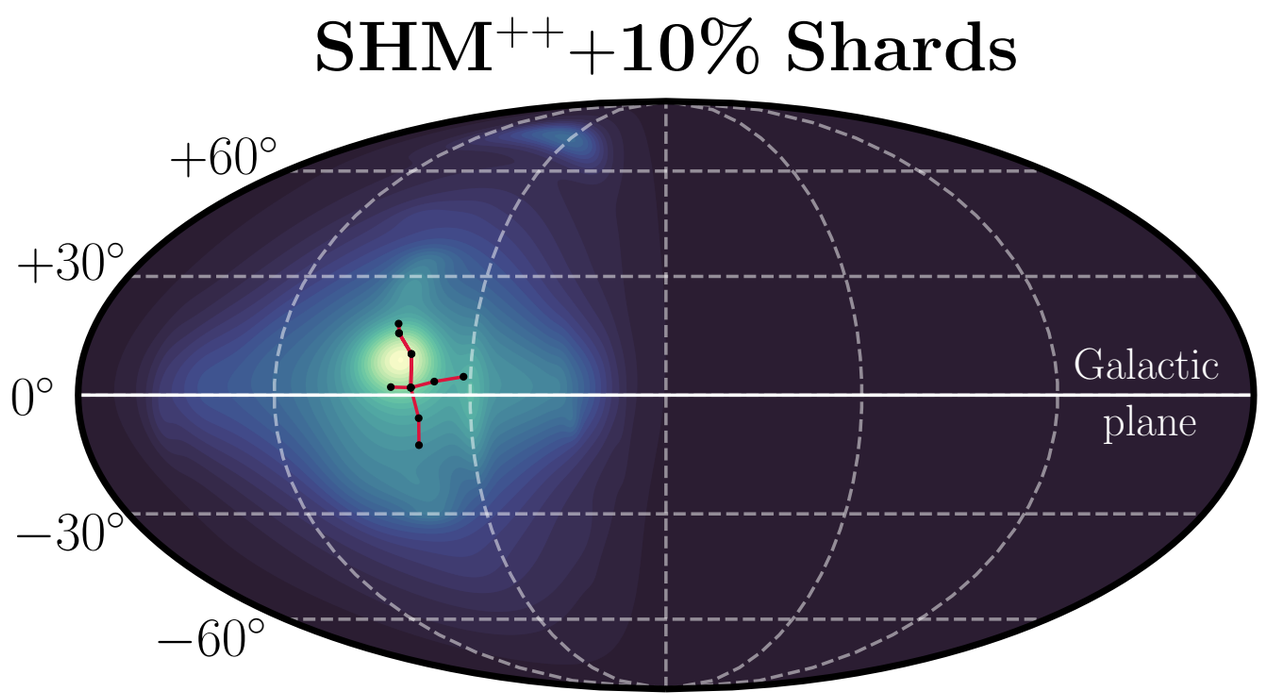
More general substructure: ‘Dark Shards’

O’Hare, Evans, CM et al
arXiv:1909.04684

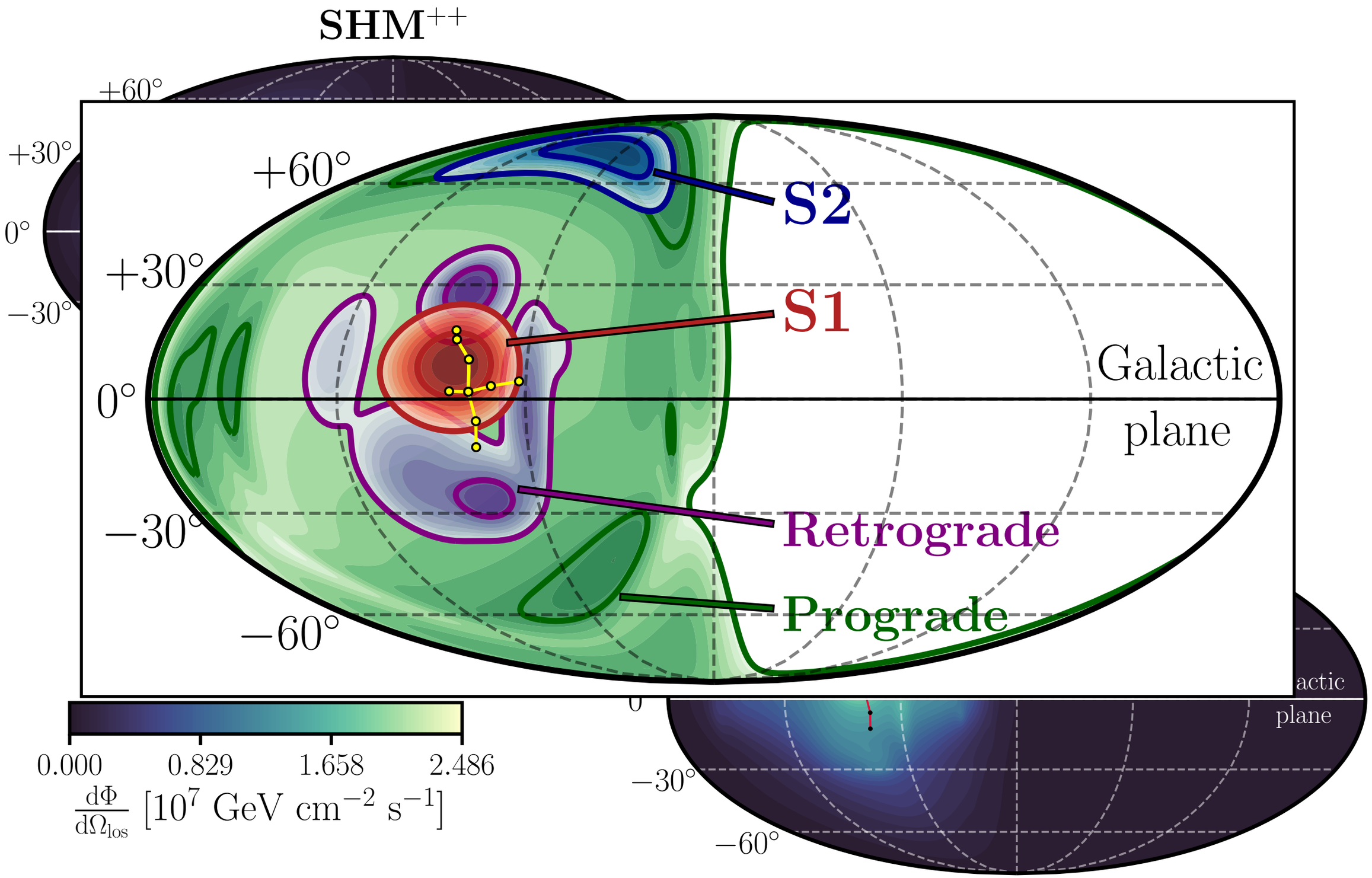


Directional signals: hotspots away from Cygnus





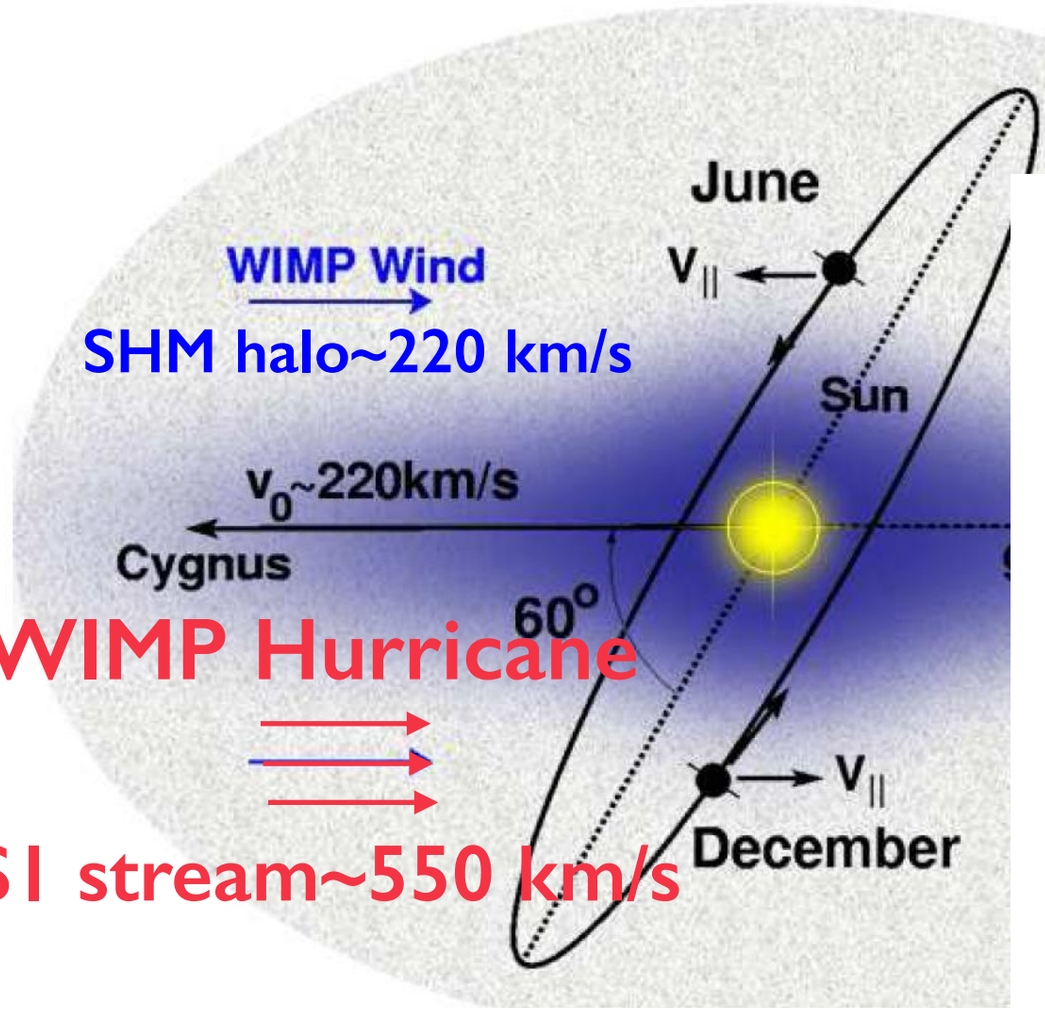
Directional signals: hotspots away from Cygnus

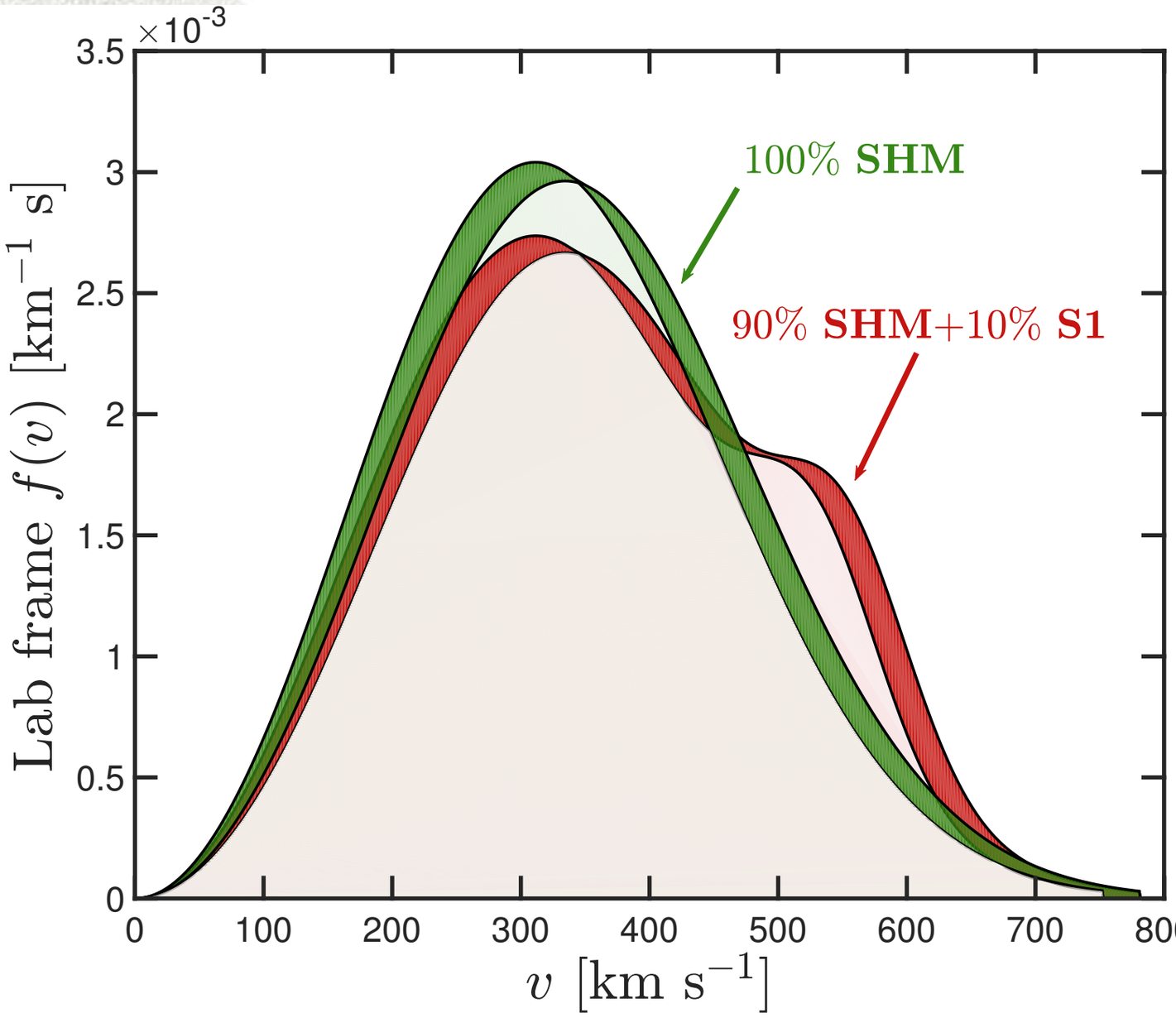


S1: 'Dark matter hurricane'

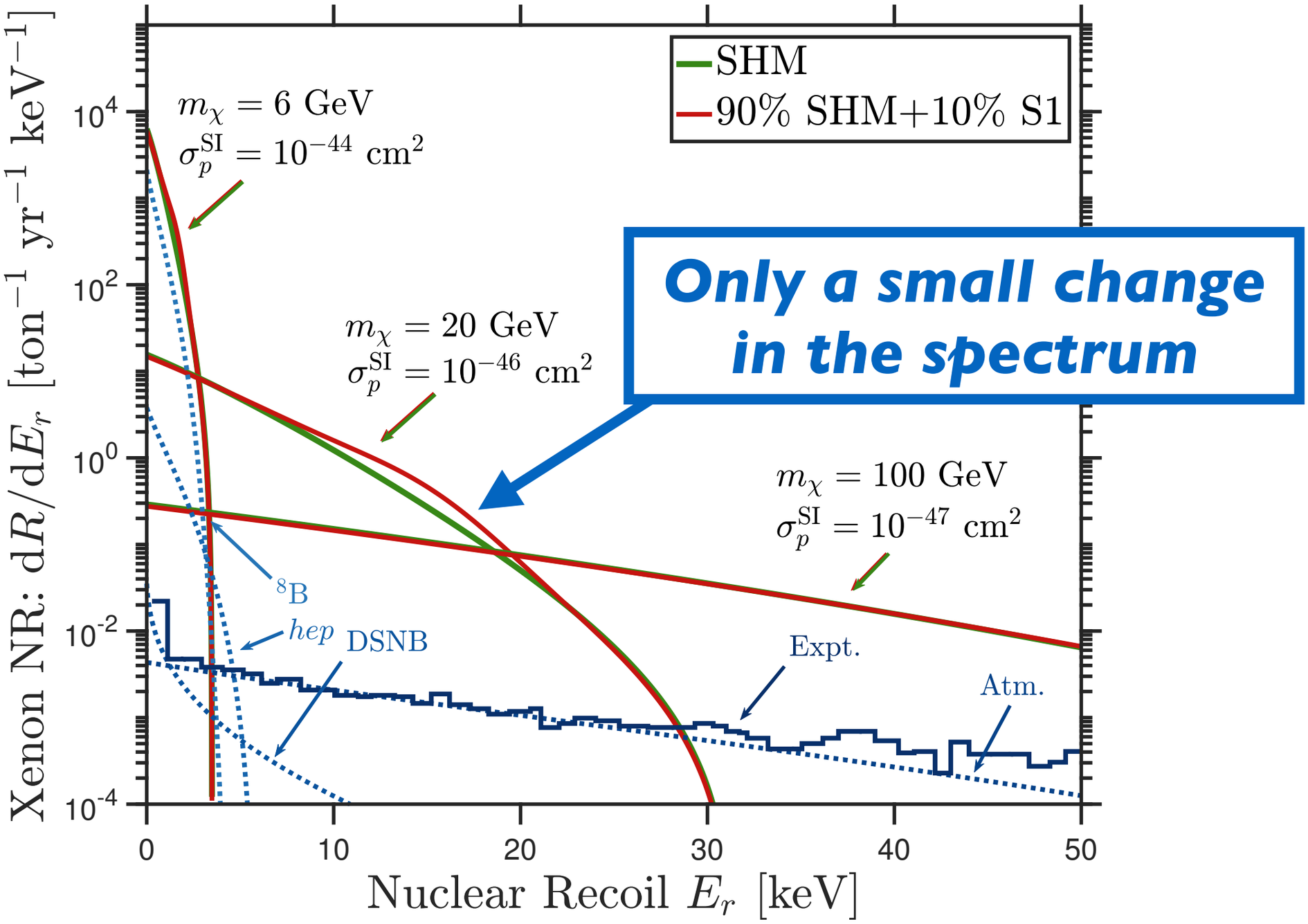
O'Hare, CM et al.1807.09004

A dark matter hurricane…





Small effect for high mass searches



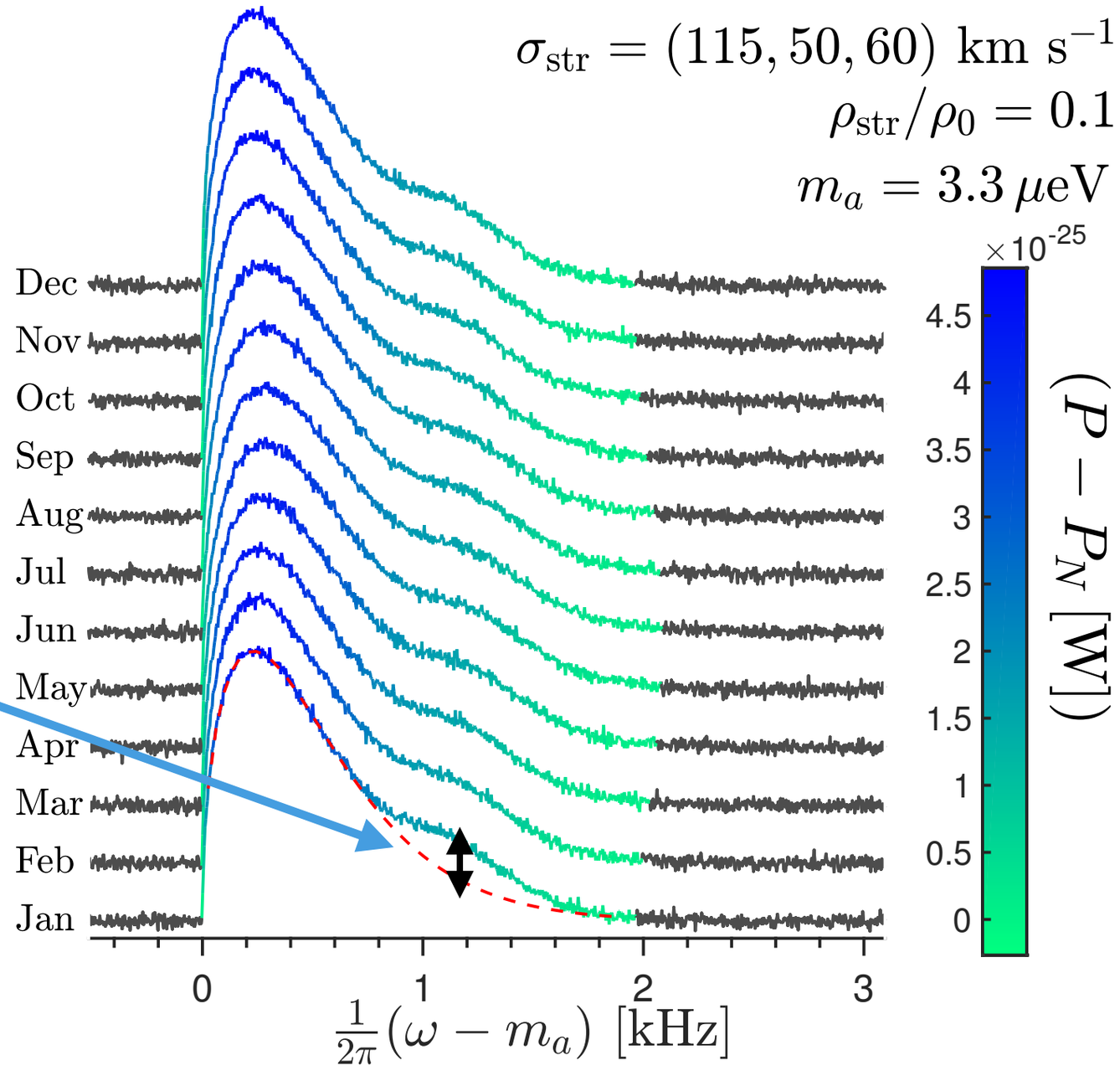
Spectrum is relatively featureless…

…except in a sweet spot around 20 GeV

Axion haloscopes: precision astronomy?

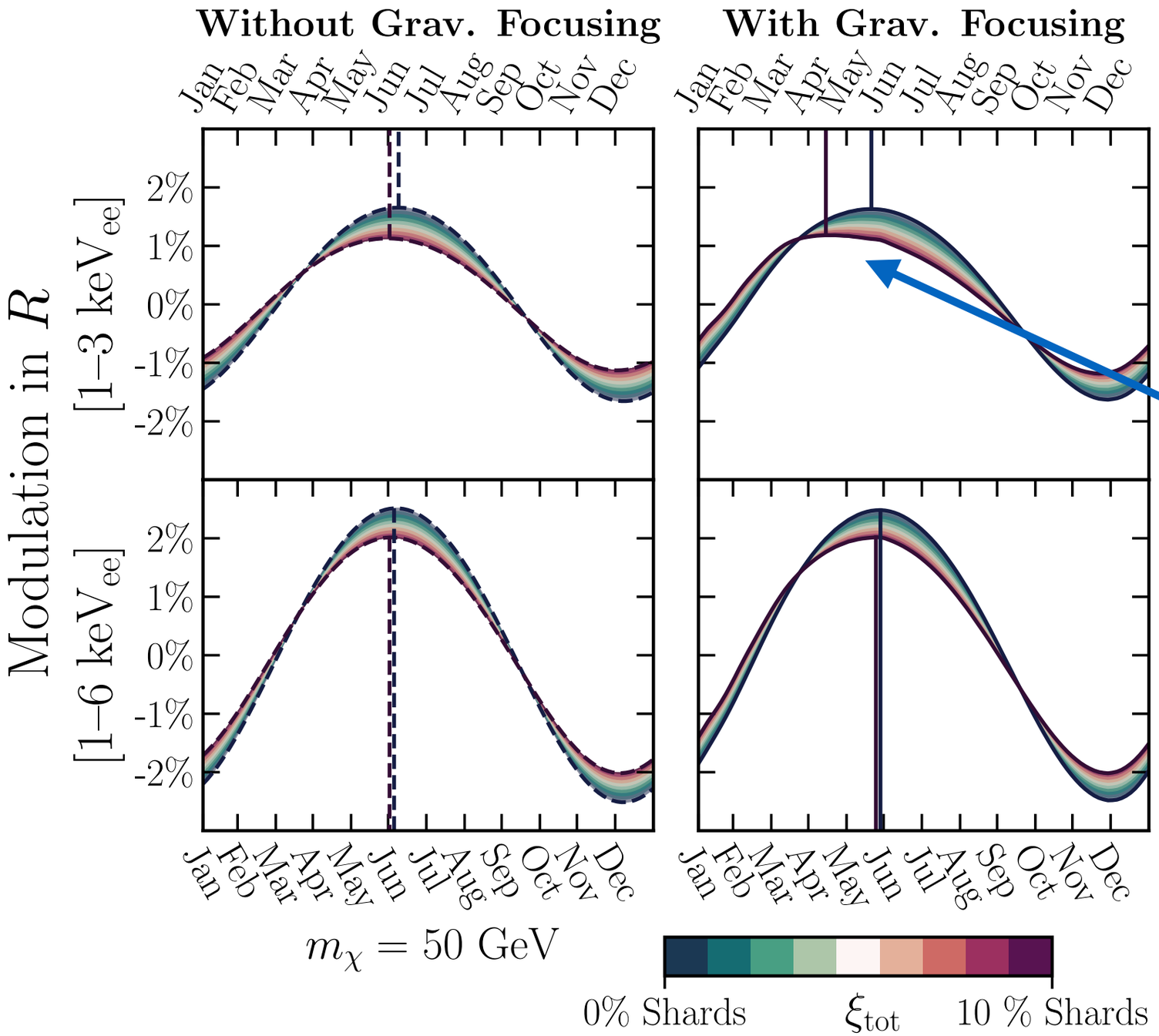
Height depends on $\frac{\rho_{\rm str}}{\rho_0}$

Sensitive even to ~percent level stream densities



SHM only (dashed) SHM+S1 (solid)

Modulation signals: peak day changes



Peak day shifts by ~ 1 month from S2

Summary

- Robust particle physics constraints/measurements requires robust halo model

- Gaia has opened a new era in understanding the Milky Way

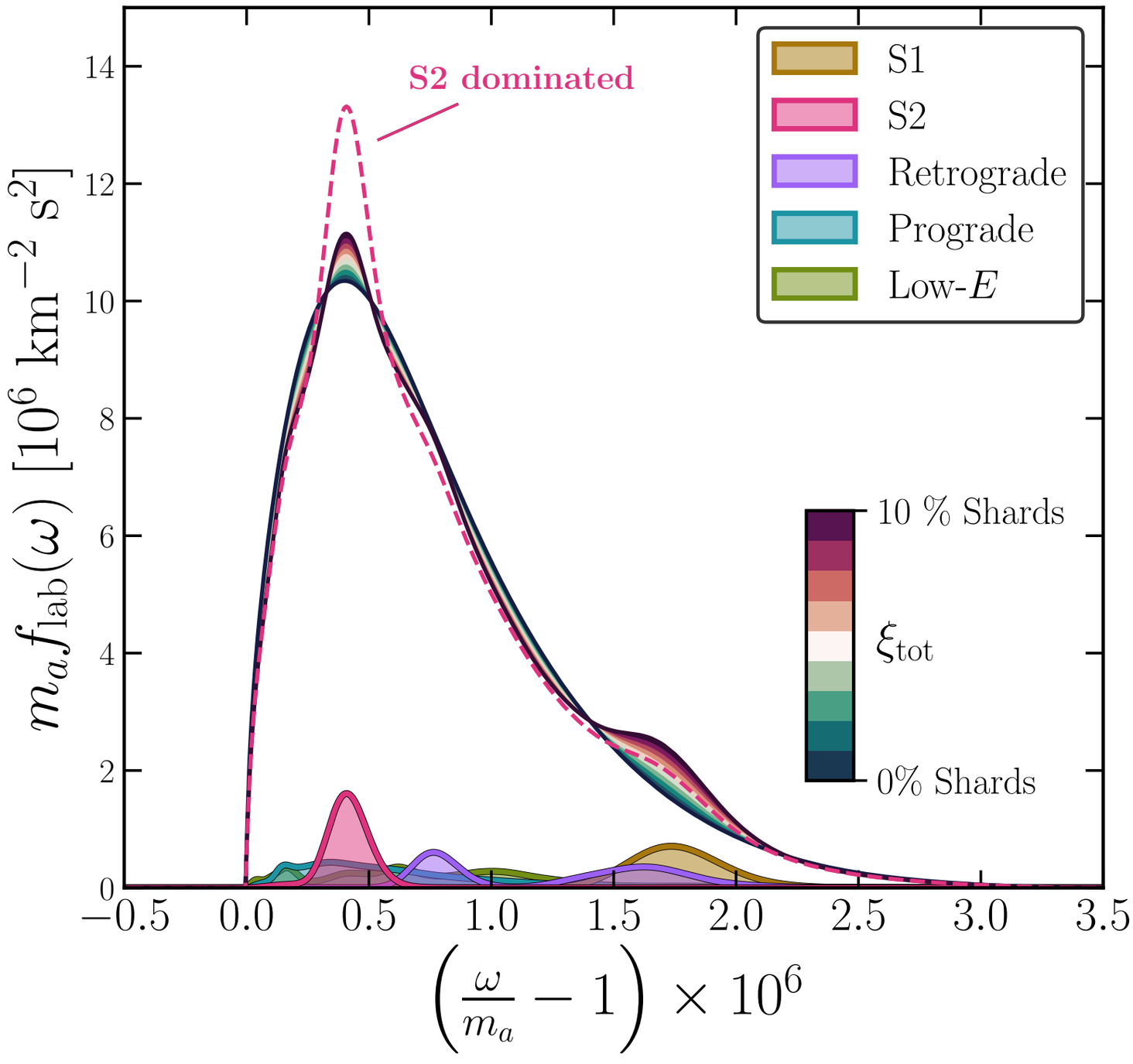
- We have investigated the impact on ***nuclear recoils*** and ***axion haloscopes*** of
  ★ ***the Gaia Sausage (modest)***
  ★ ***the S1, S2 streams and other substructure (more dramatic)***

Next:

- work with simulations to refine properties
- investigate properties on wider range of experiments

Thanks

Axion power spectrum: S1 and S2 leave distinctive features



SHM++: 2 component model

O'Hare, Evans, CM,
arXiv:1810.11468, PRD

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)

η here is consistent with values in simulations

β takes same values as stars in Sausage sample

Necib et al 1810.12301
Fattahi et al 1810.07779

Gaia Sausage or Gaia Enceladus?

Gaia Sausage

From Wikipedia, the free encyclopedia

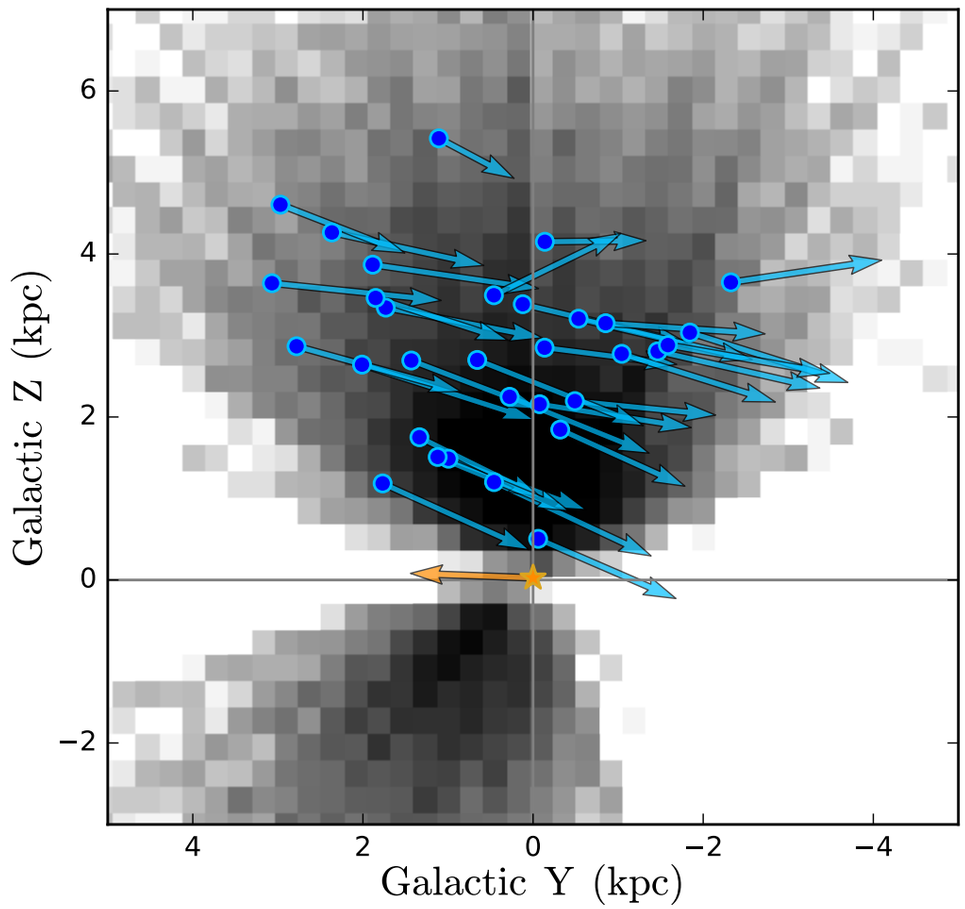
The **Gaia Sausage** is the remains of a dwarf galaxy, the "Sausage Galaxy" or **Gaia-Enceladus-Sausage** or just **Gaia-Enceladus**, that merged with the Milky Way about 8 - 11 billion years ago. At least eight globular clusters were added to the Milky Way along with 50 billion solar masses of stars,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

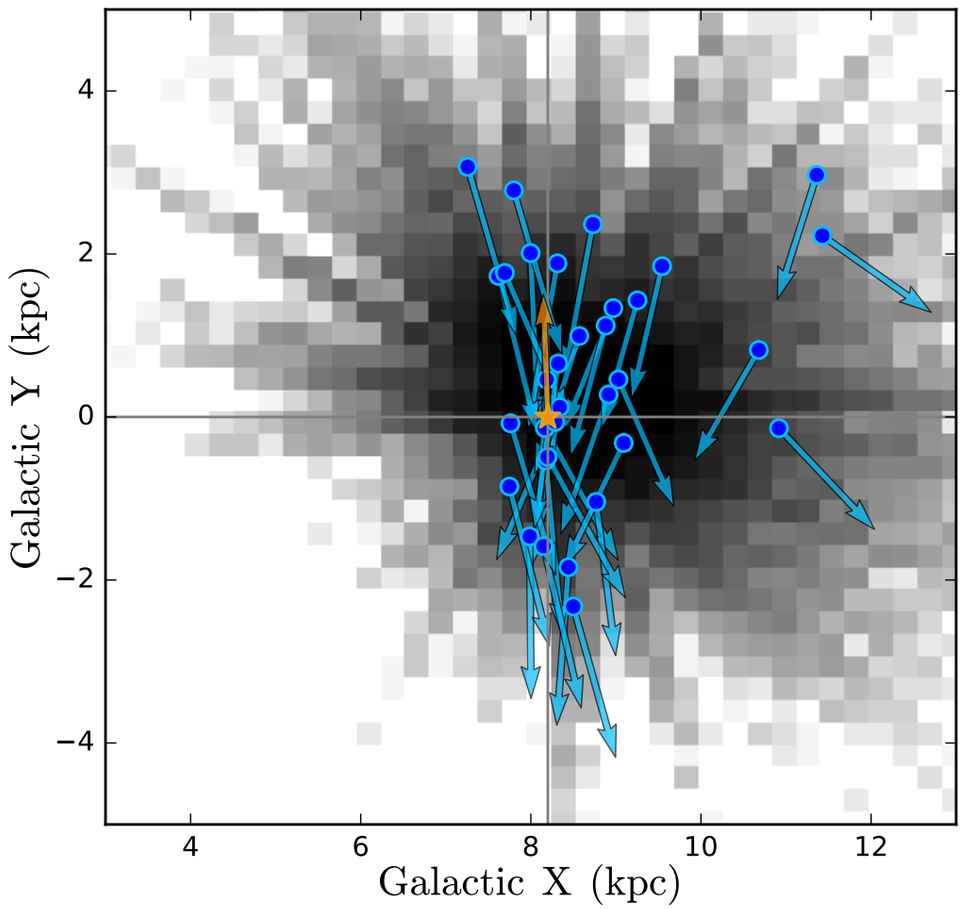
S1 stellar stream

S1: Identified with SDSS-Gaia (DR1) Catalogue

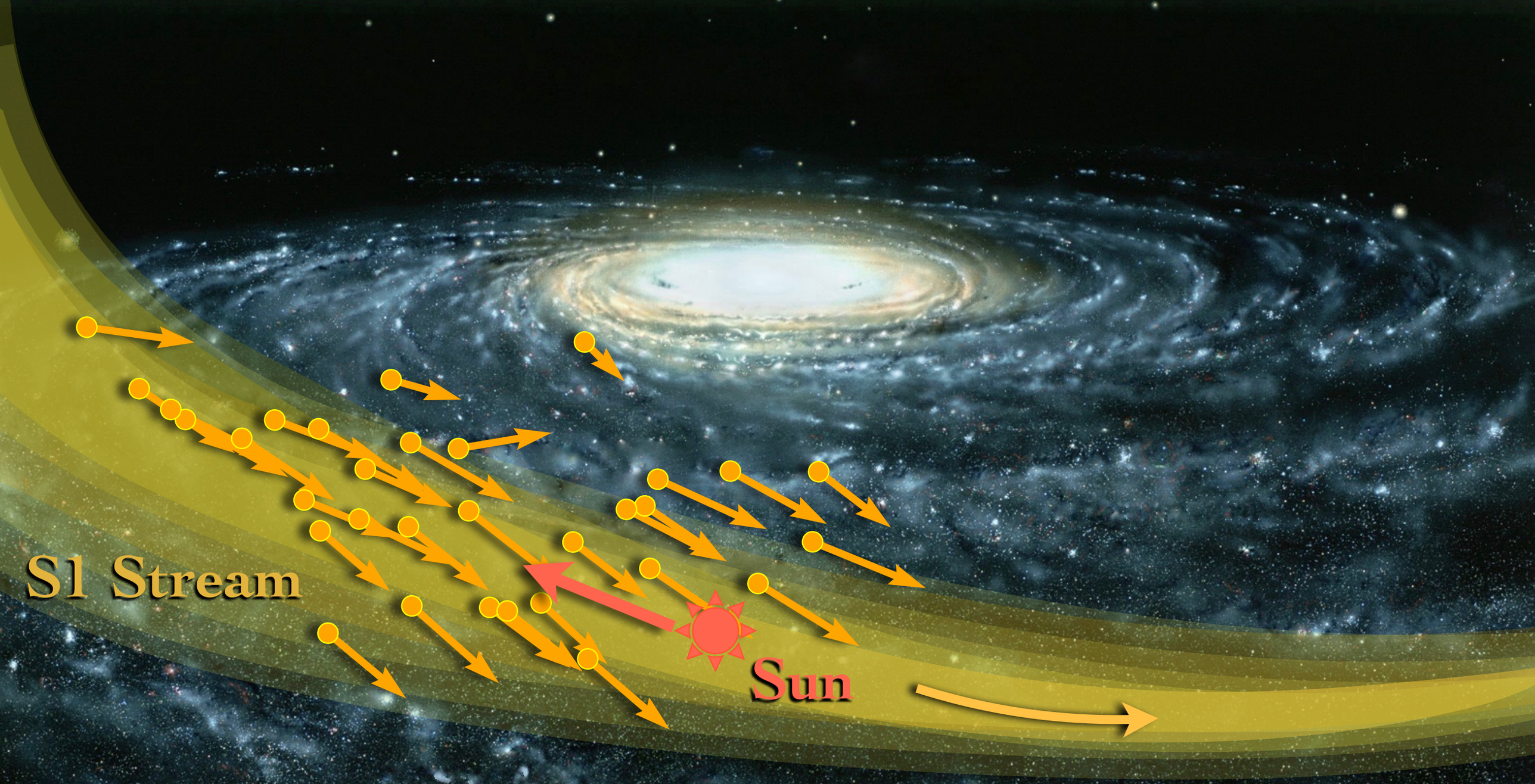
94 member stars

G. Myeong et al. 1712.04071





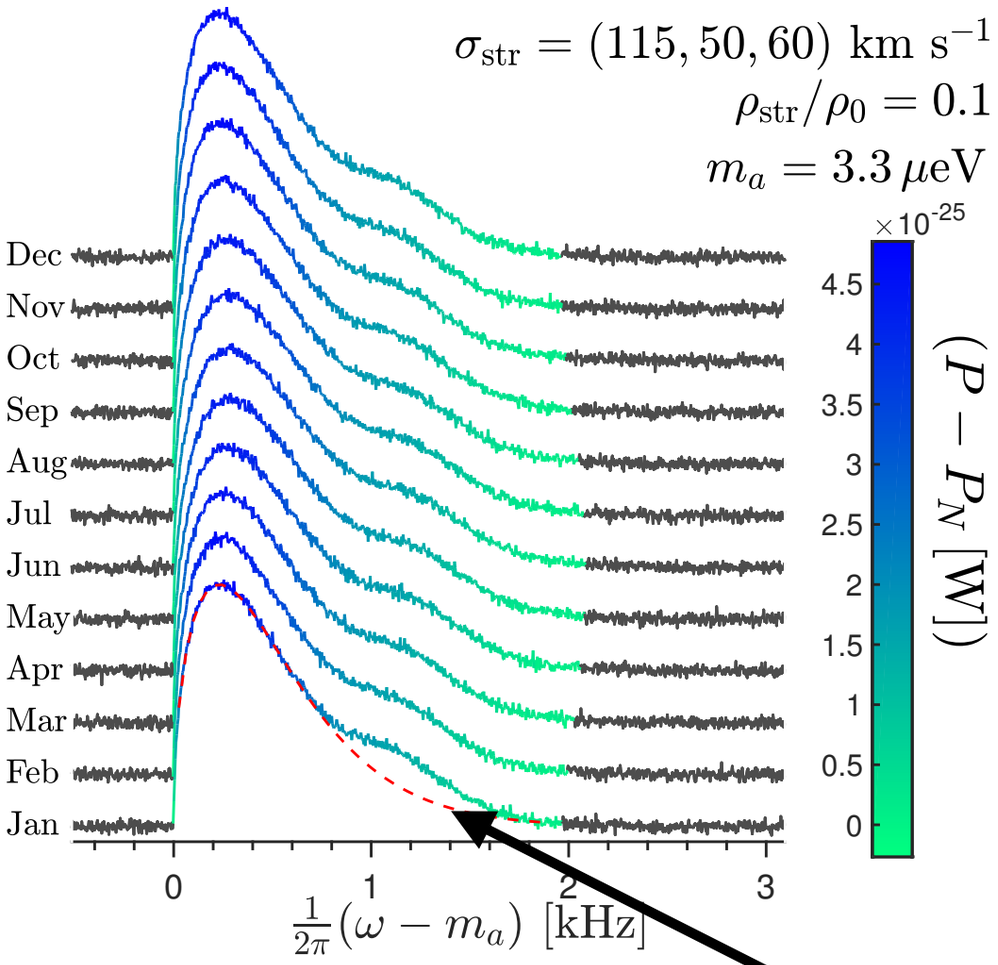
Passes very close to solar position (orange arrow)

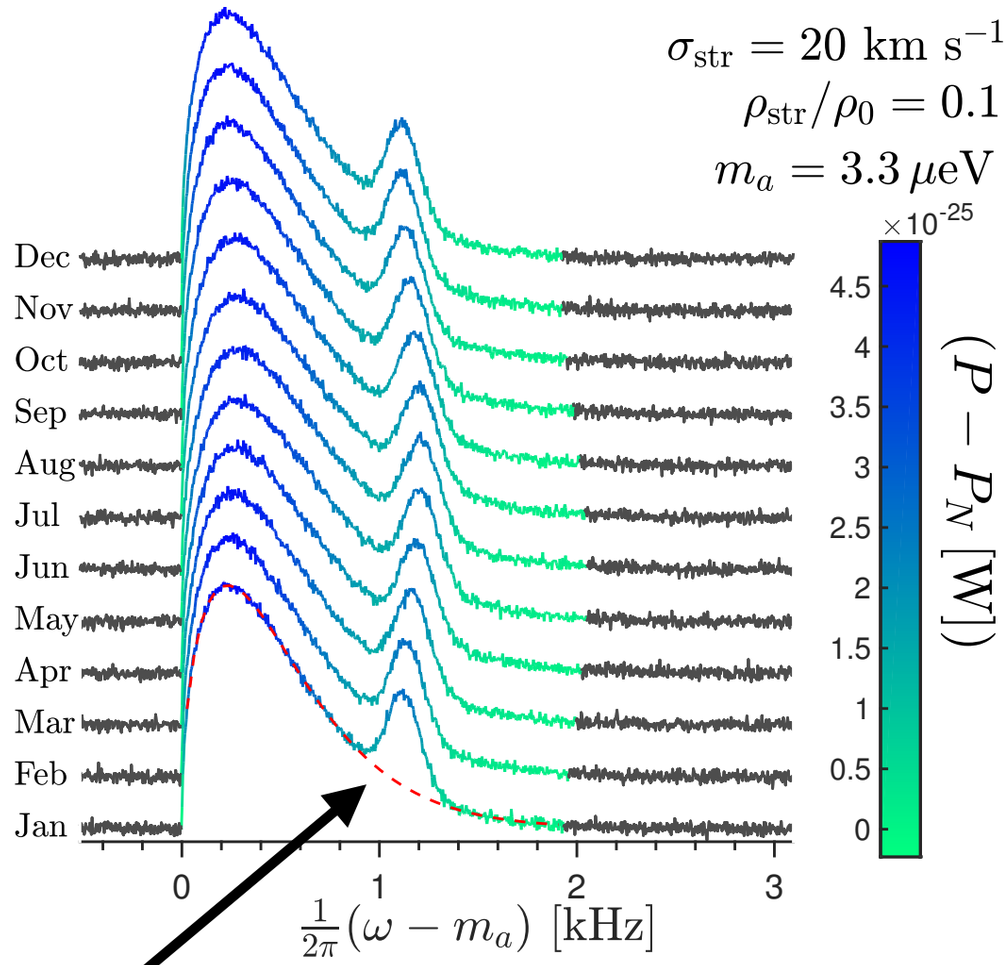


S1 stream: very fast moving DM subcomponent

ADMX: precision astronomy

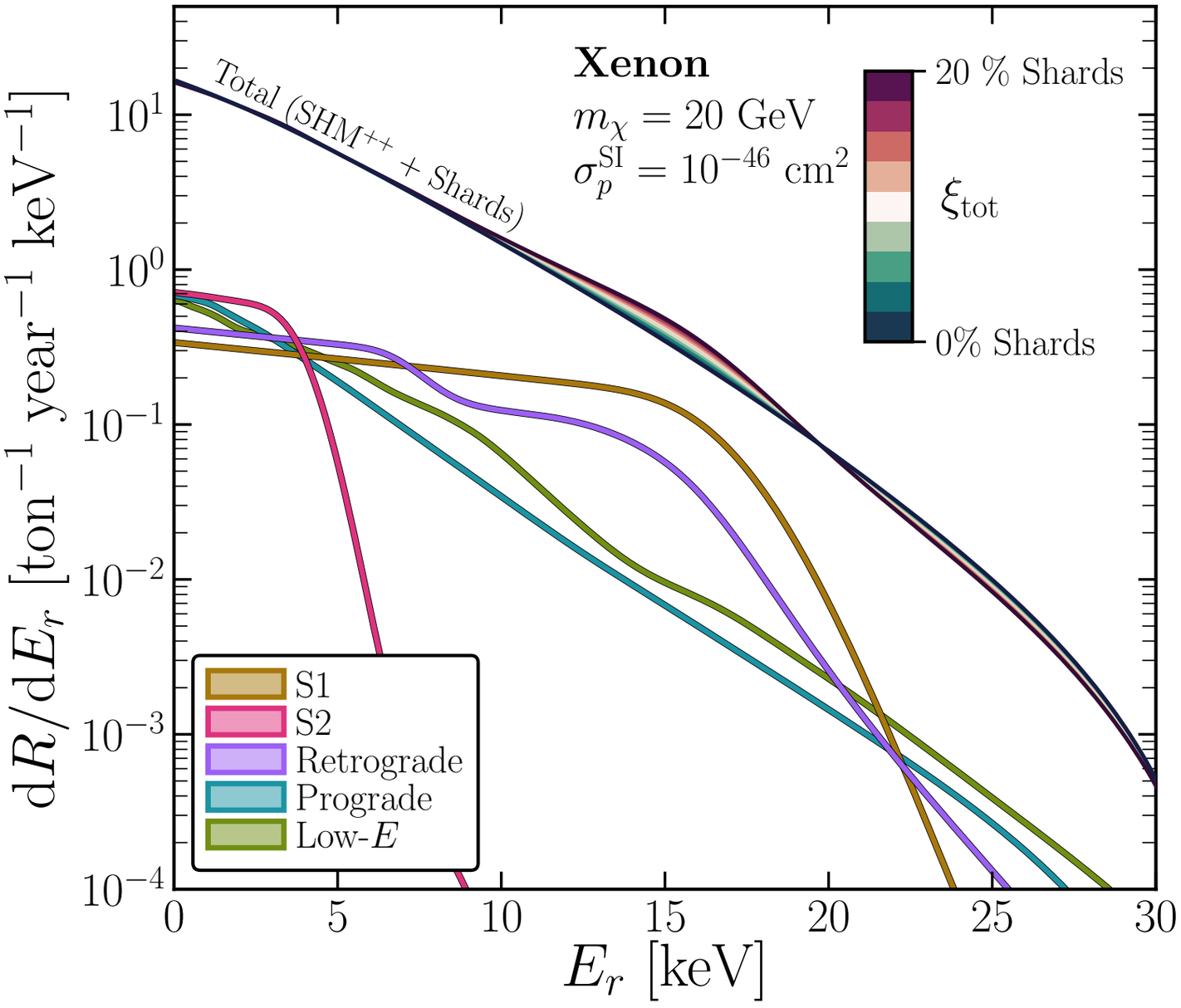
Could measure properties of S1 dark matter component
eg. velocity dispersion





Height of feature depends on S1 density and velocity dispersion

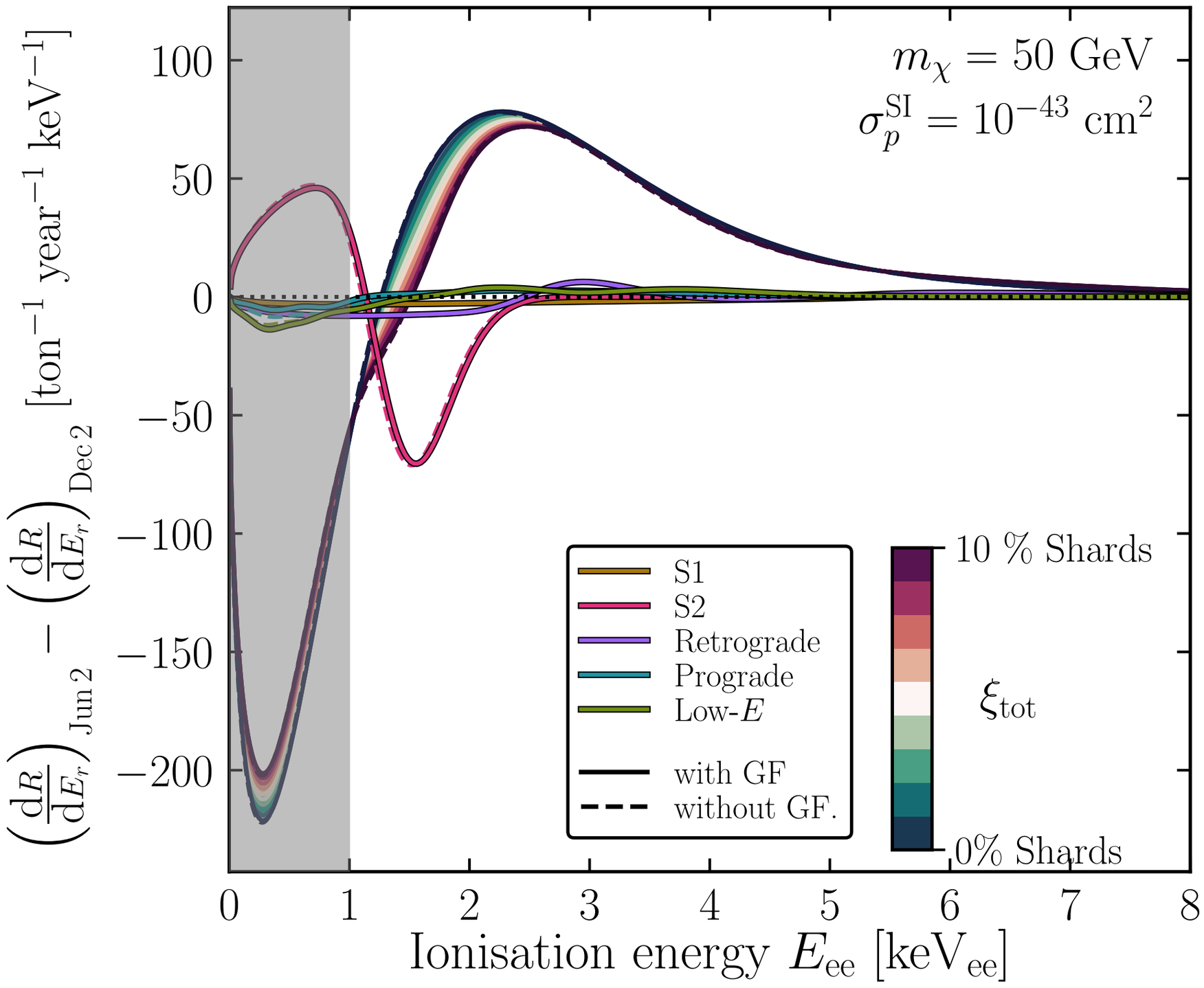
More general substructure



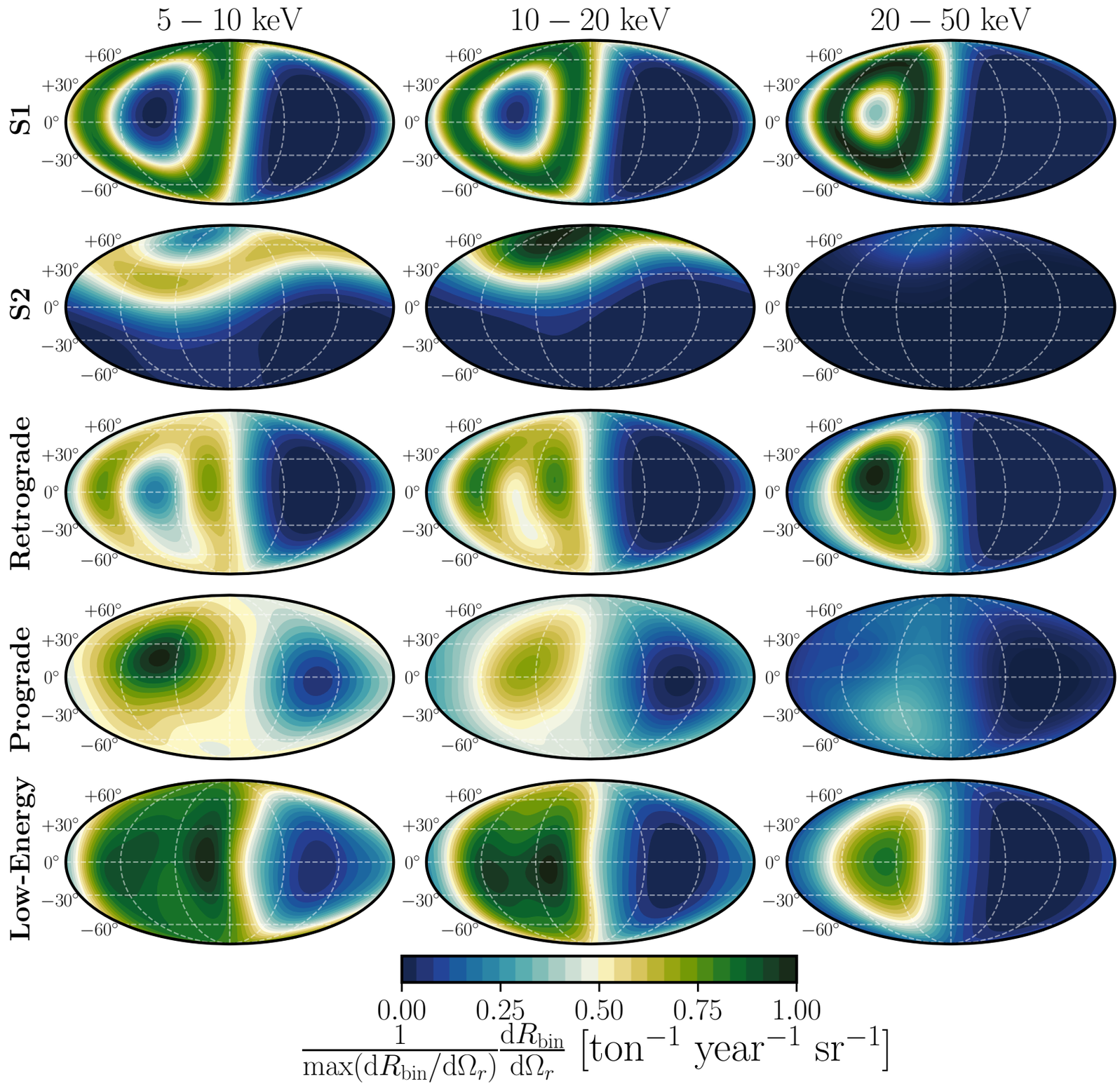
O'Hare, Evans, CM et al
arXiv:1909.04684

Impact on the nuclear recoil spectrum is always small

Modulation signals: amplitude changes



Directional signals: hotspots away from Cygnus



Directional signals: hotspots away from Cygnus