Dark matter in the Solar System

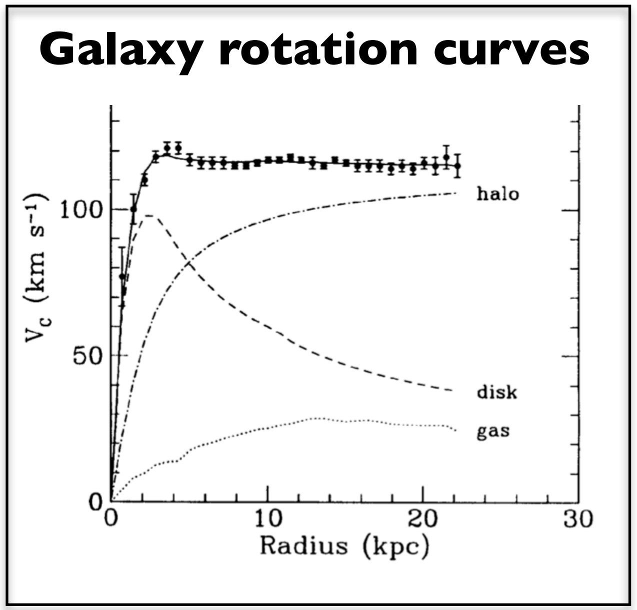
Christopher McCabe

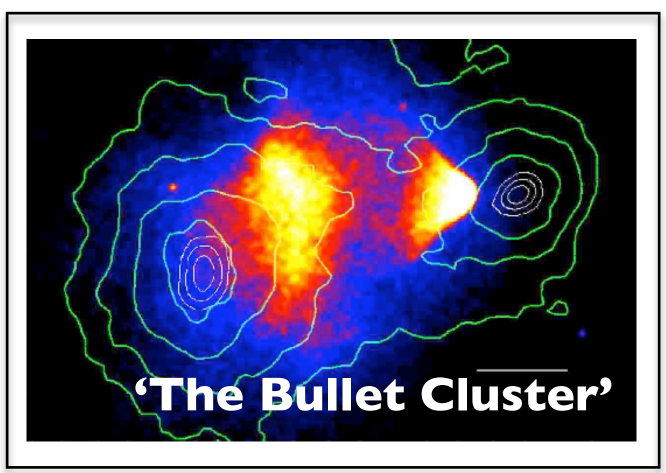
Together with Ciaran O'Hare, Wyn Evans, G. Myeong and V. Belokurov

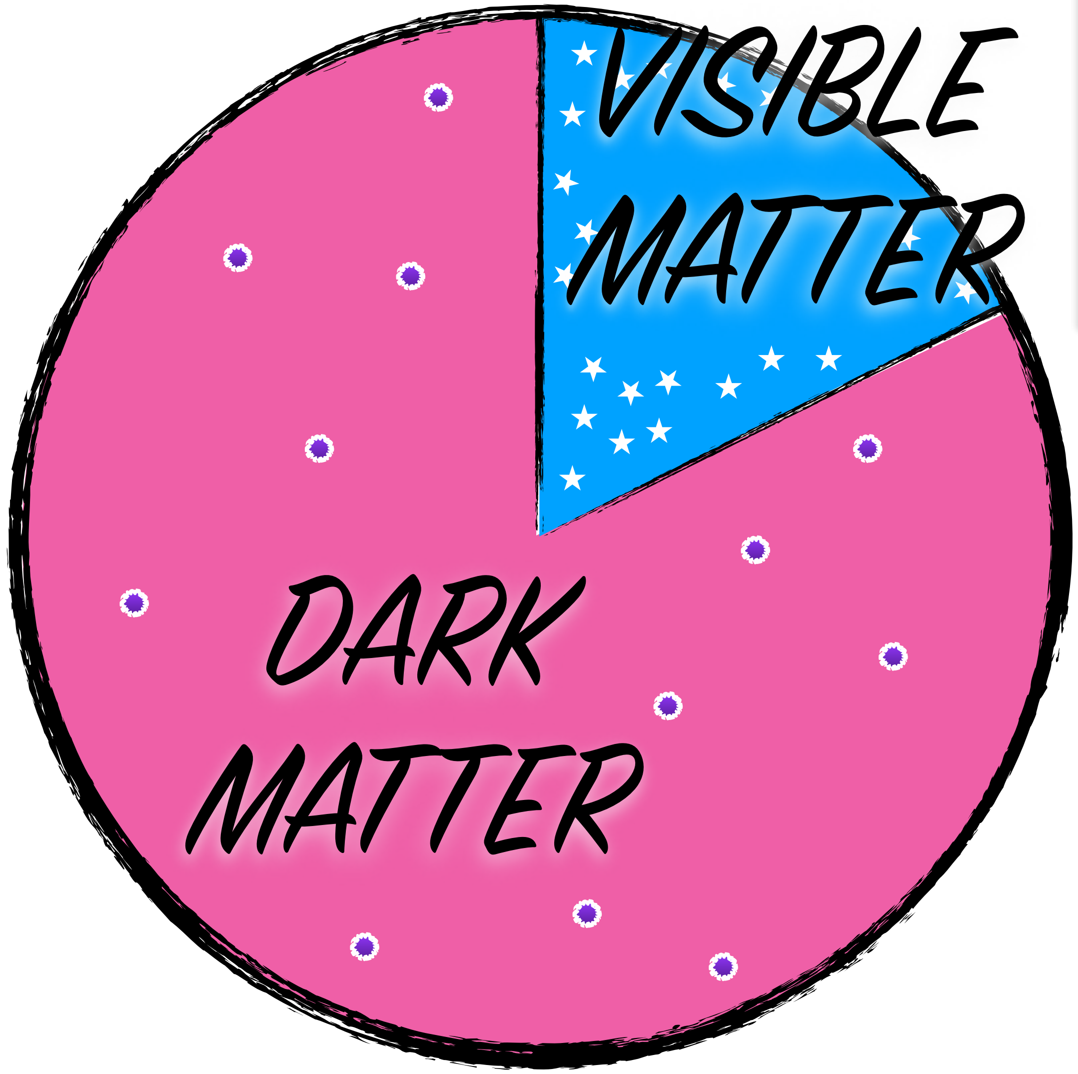
Based around arXiv:1807.09004 (PRD), 1810.11468 (PRD), 1909.04684

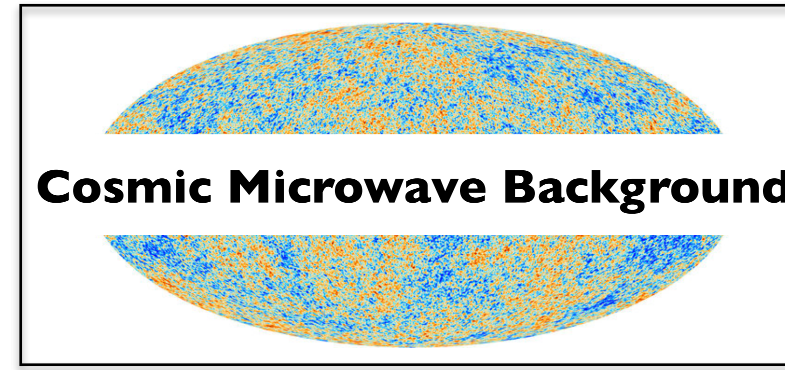
University of Birmingham - 13th November 2019

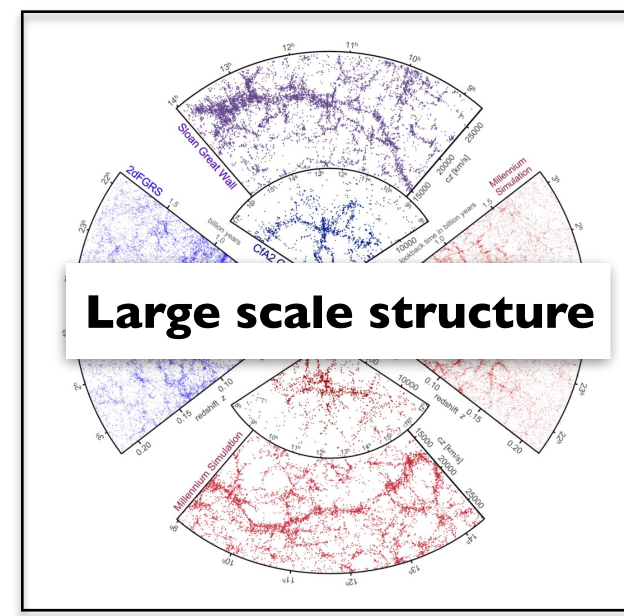
We have detected dark matter







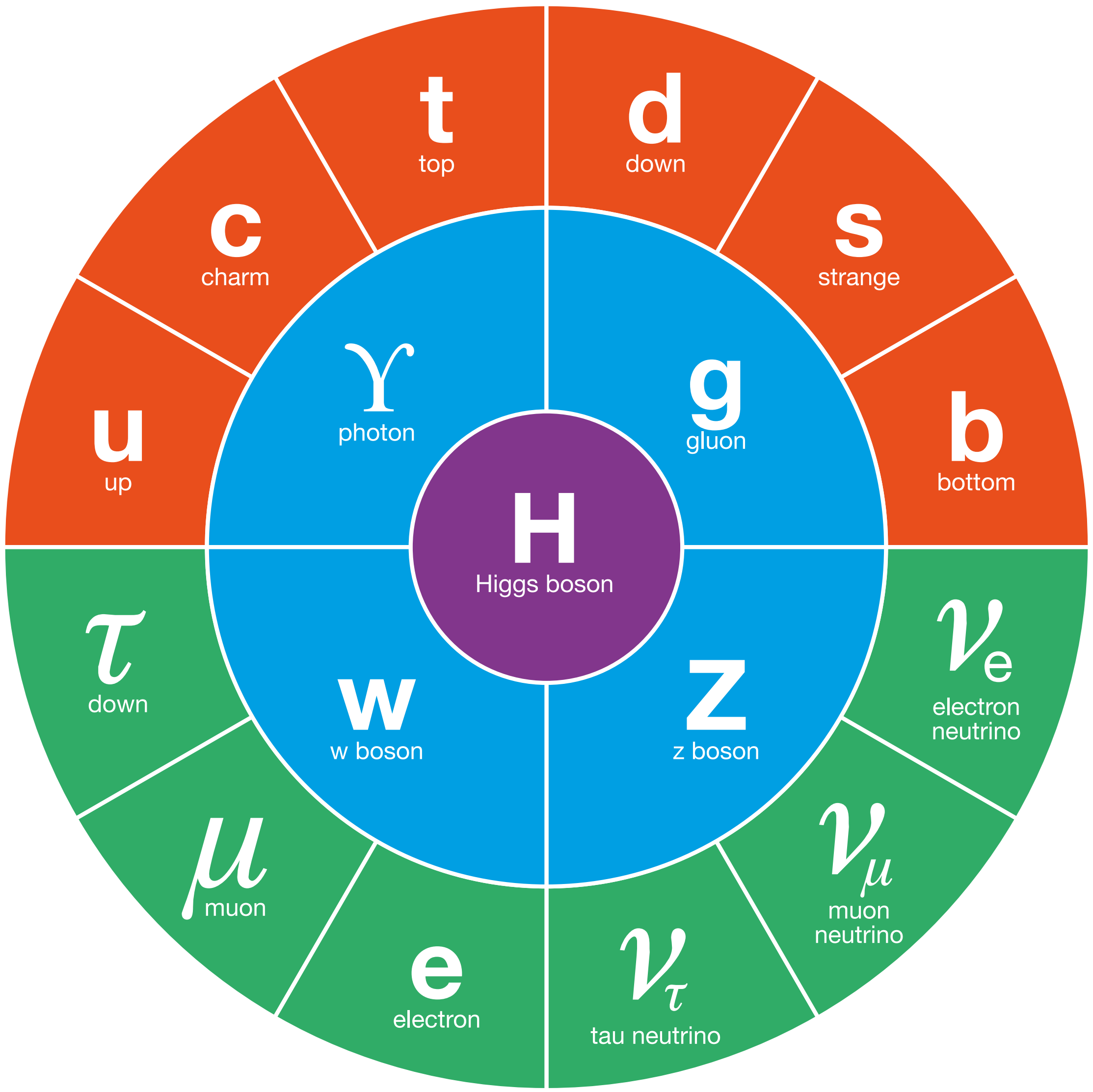




Evidence from gravitational interactions…

…over many distance scales

Job done?

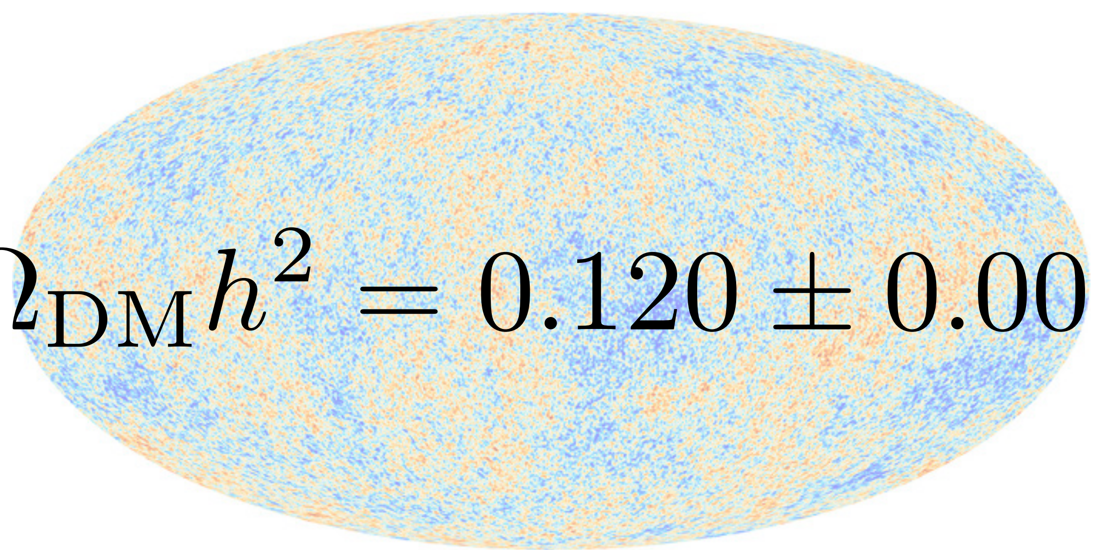


Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: $?$
X^0 production cross-section in hadron colliders: $?$
X^0 self-annihilation cross-section: $?$

Why should DM interact with the SM?

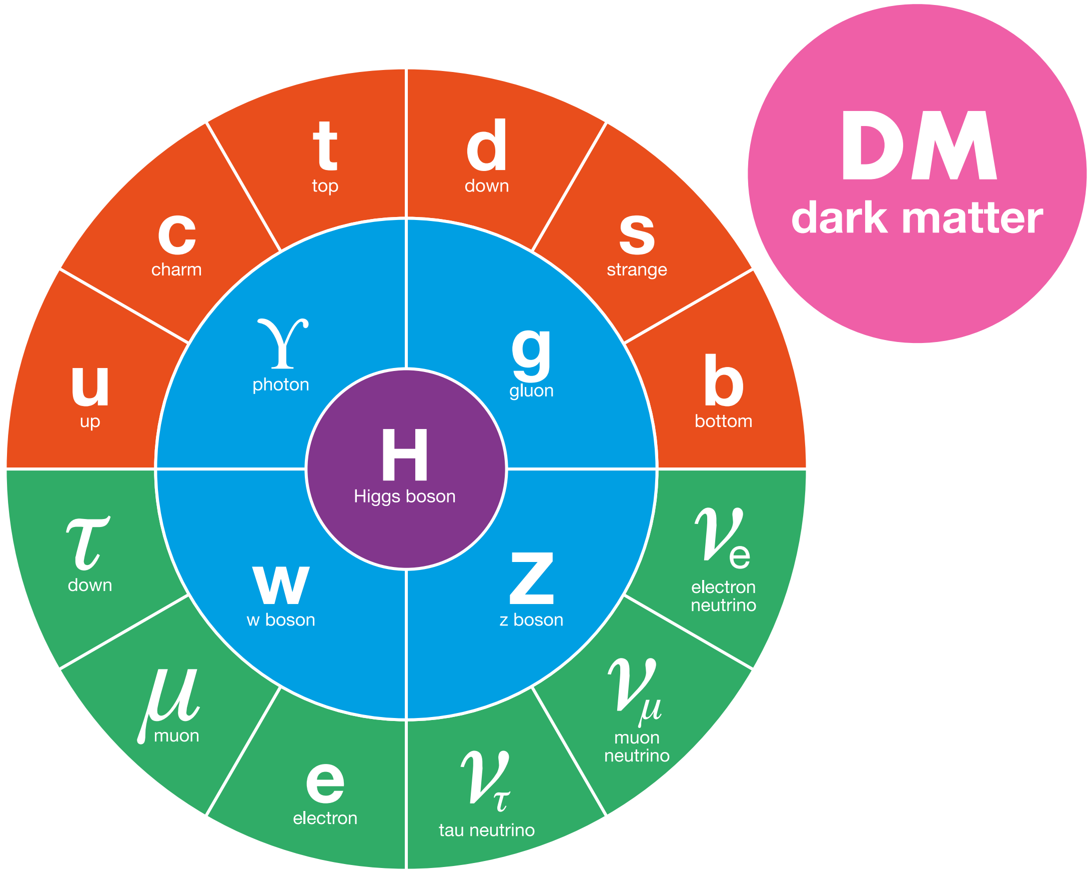
Cosmology



$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Suggests dark and visible matter interactions are generic

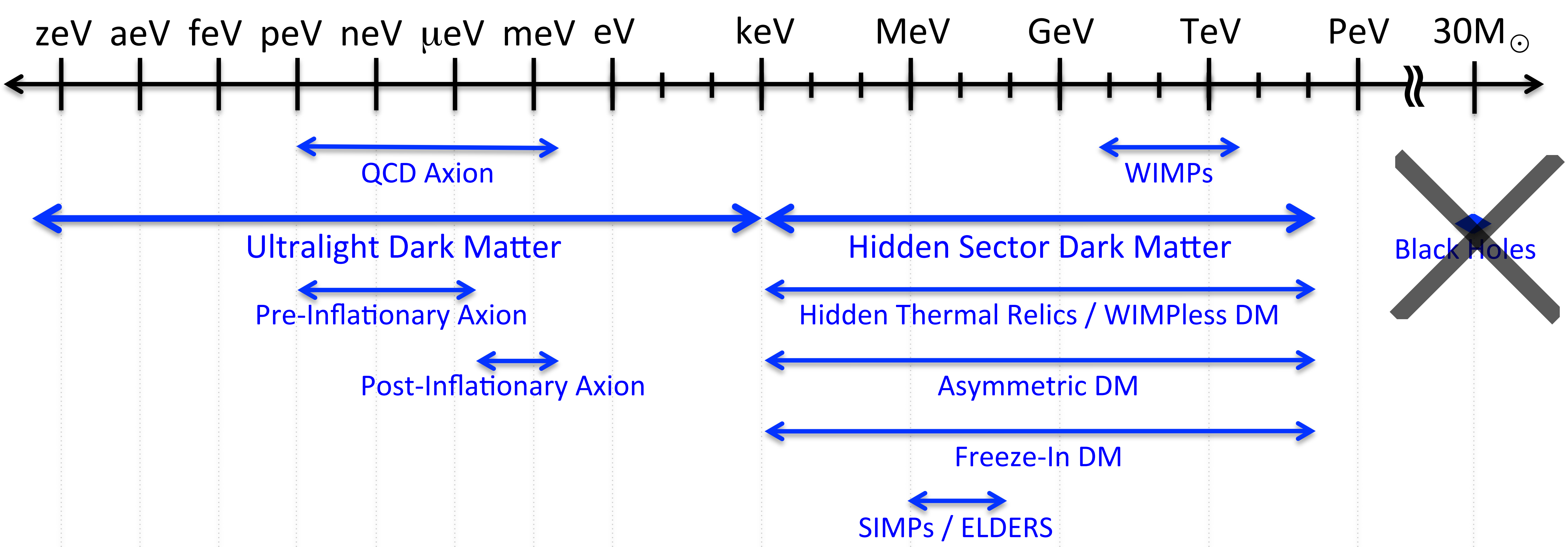
Particle Physics



&

Informs and limits the possible interactions

A wide landscape



US Cosmic Visions

Many candidates…

…all with SM interactions

Outline

- Why do we need to model the local dark matter?
- What is the 'standard approach'?
- Gaia!
- 

…why is this on Wikipedia?

- 

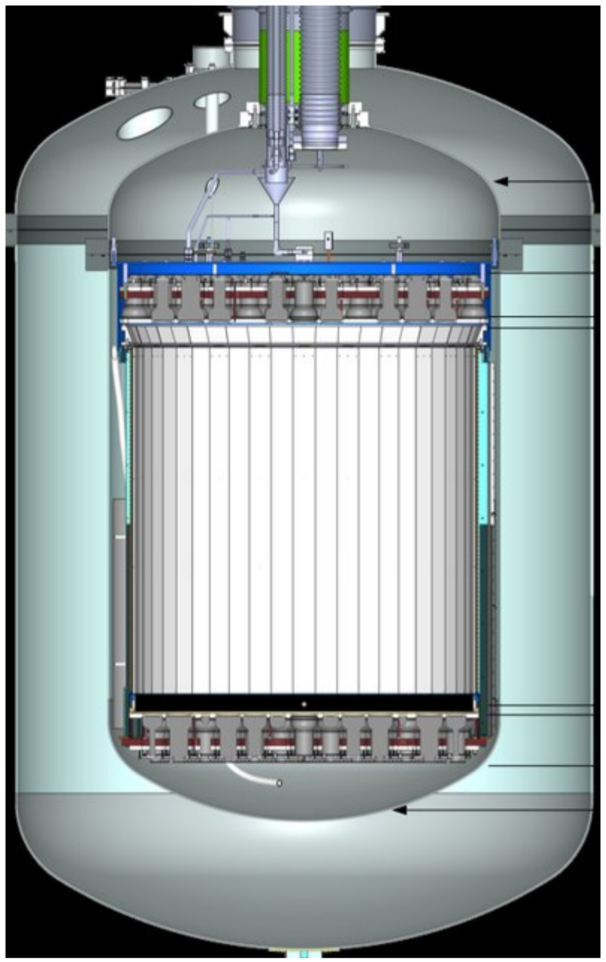
… ???

Motivation

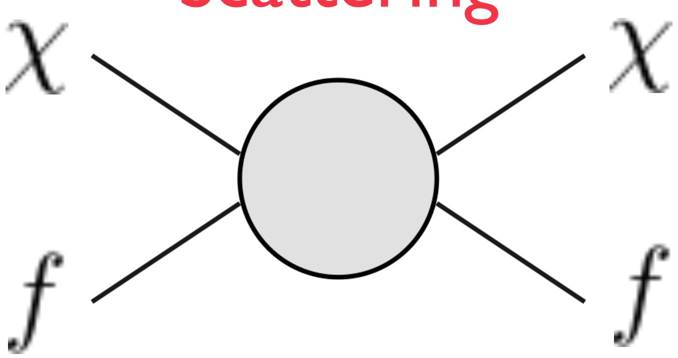
Why model dark matter near Earth?

Searching for dark and visible interactions

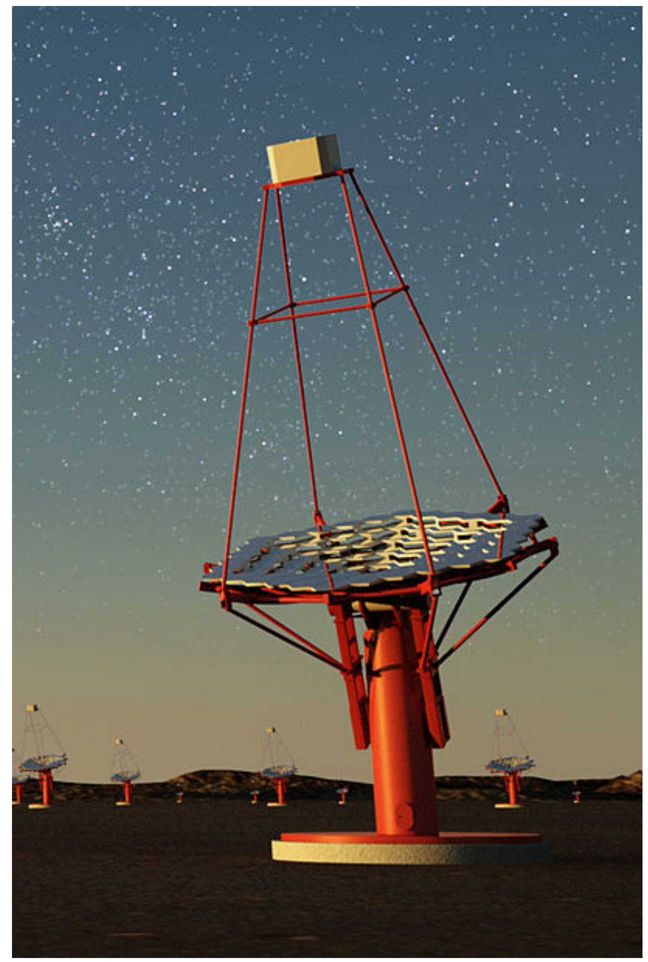
Direct detection



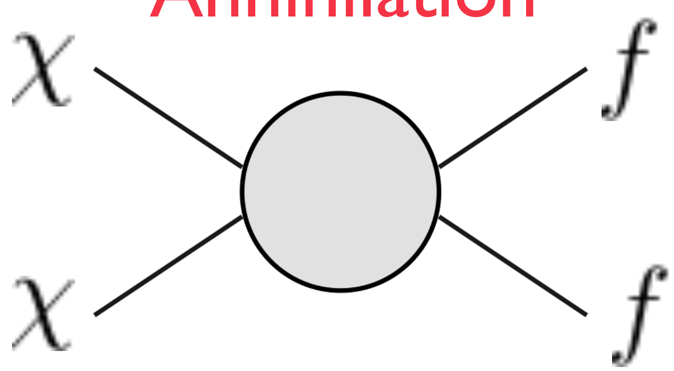
Scattering



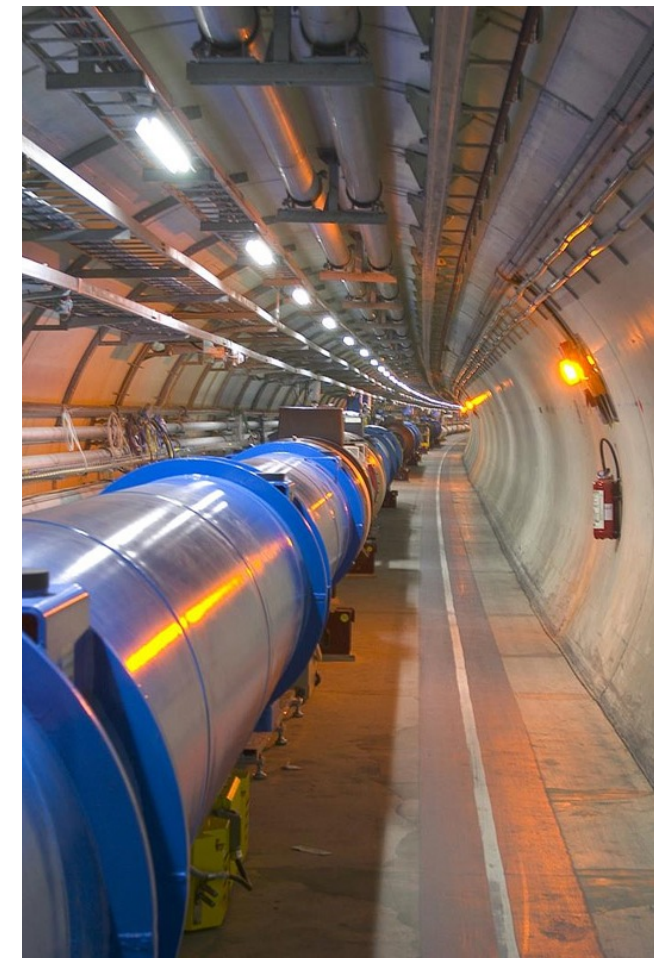
Indirect detection



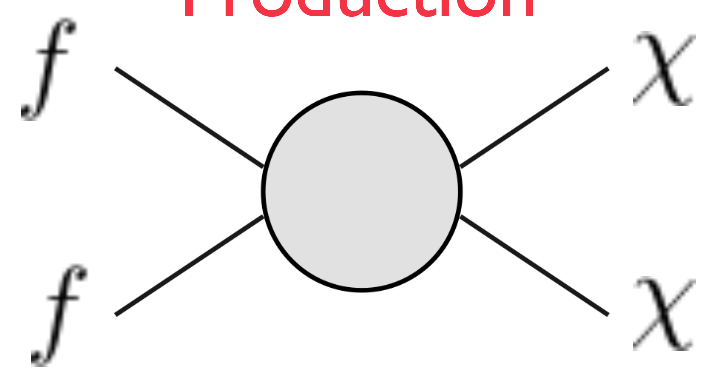
Annihilation



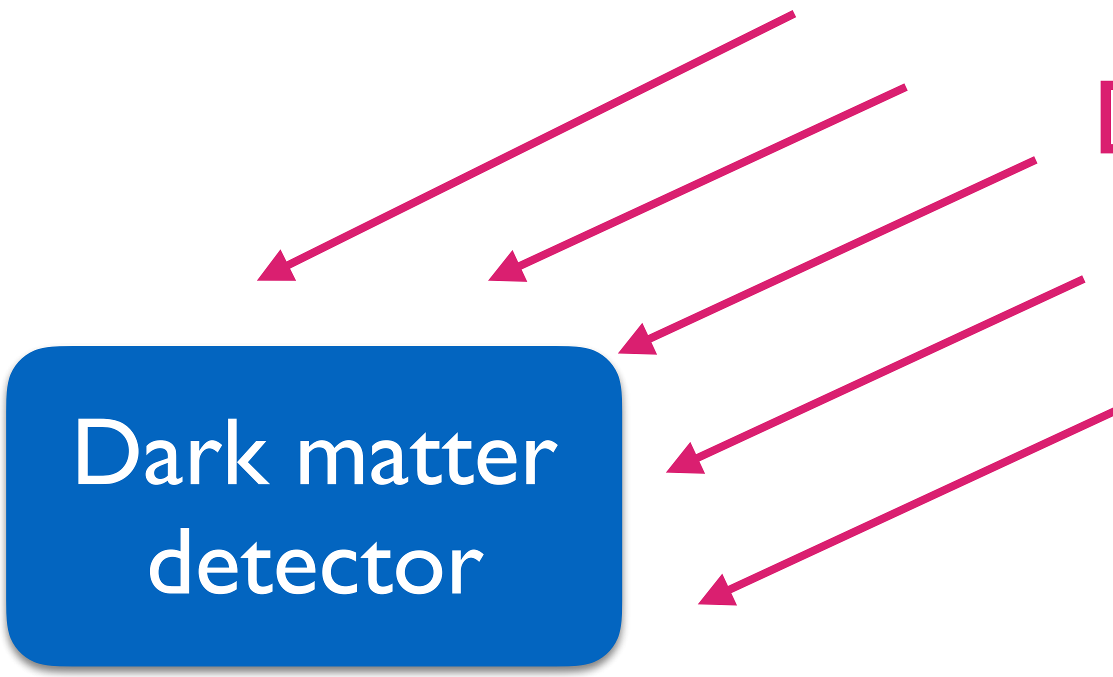
Collider



Production



Generic direct detection experiment



Dark matter flux

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

Event rate = DM flux $\times$ *particle physics*

Have to model the DM flux to extract the particle physics

The Standard approach

Standard Halo Model

Simplest 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

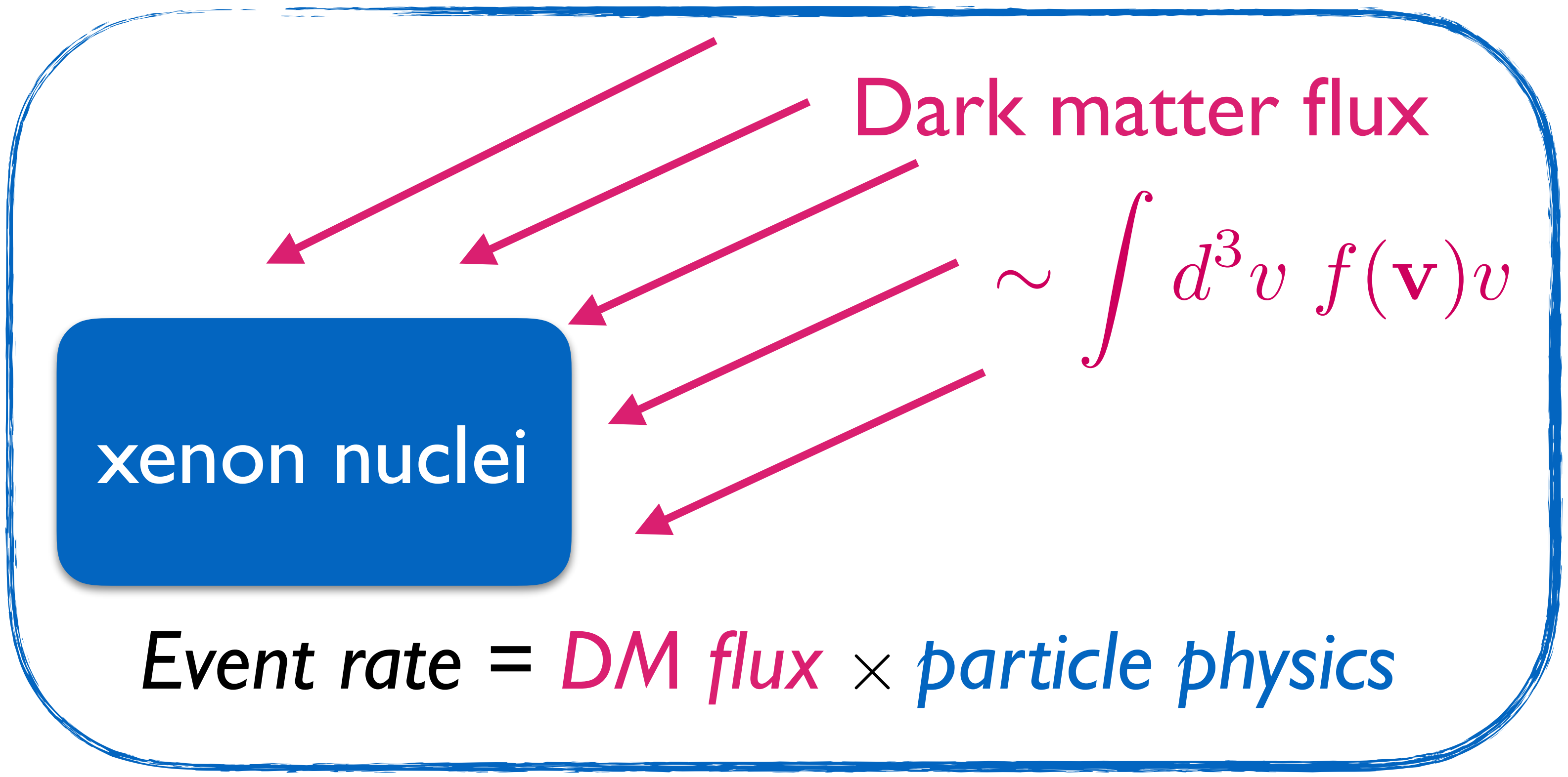
Simplest spherical model with (asymptotically) flat rotation curve

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

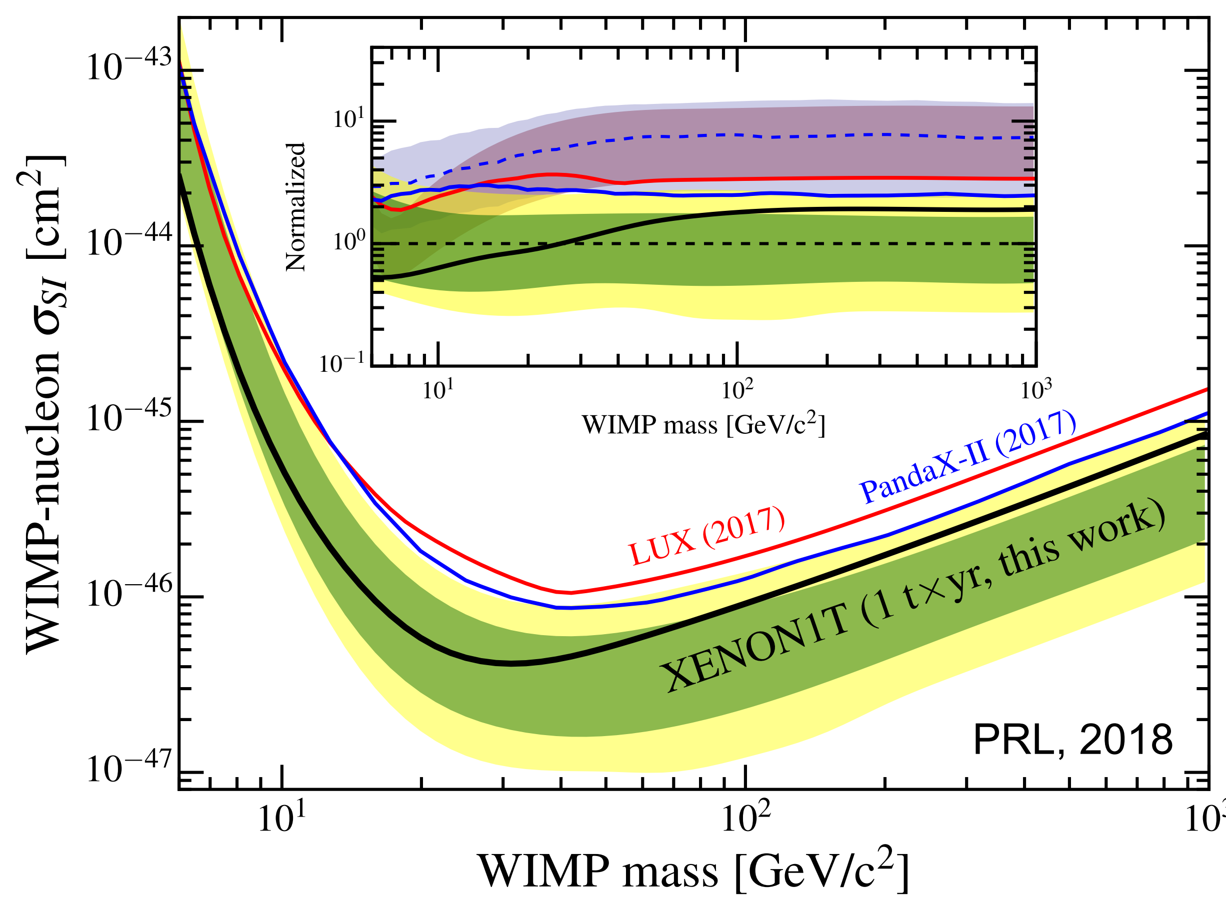
Advantages:

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

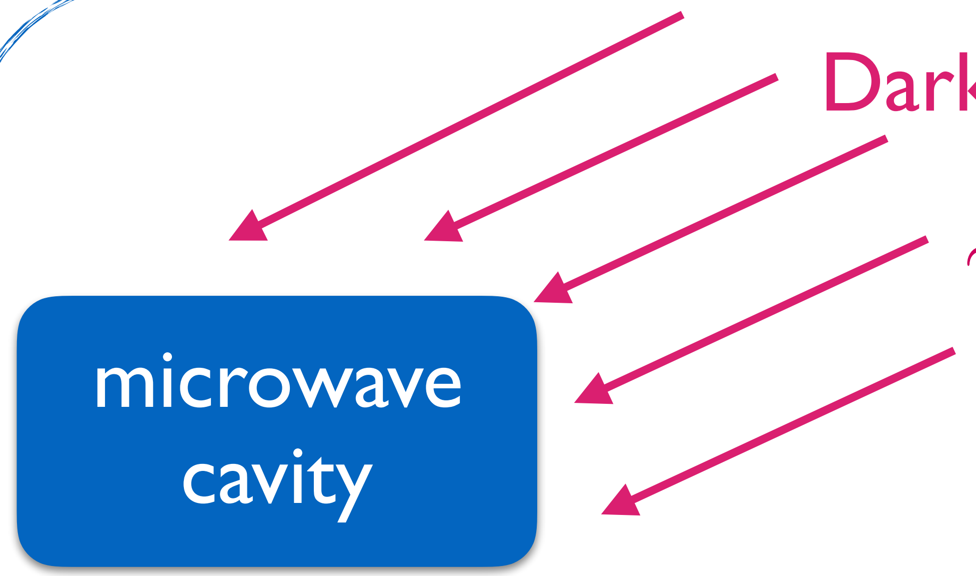
SHM in nuclear recoil signals



particle physics:
WIMP mass
& scattering cross section



SHM in axion searches

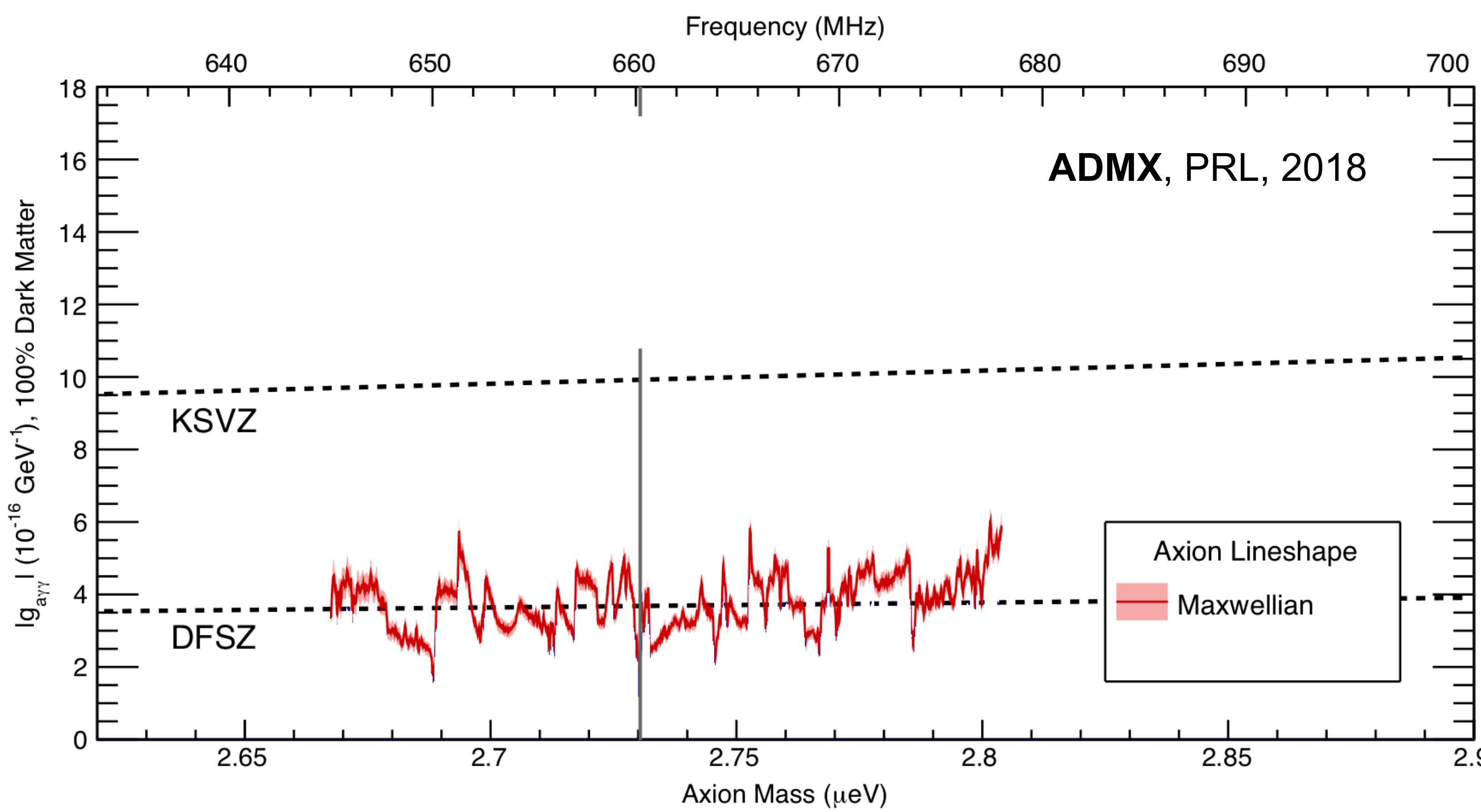


Dark matter flux

$$\sim \int d^3v \, f(\mathbf{v}) v$$

Event rate = DM flux $\times$ *particle physics*

particle physics:
axion mass
& axion-photon coupling

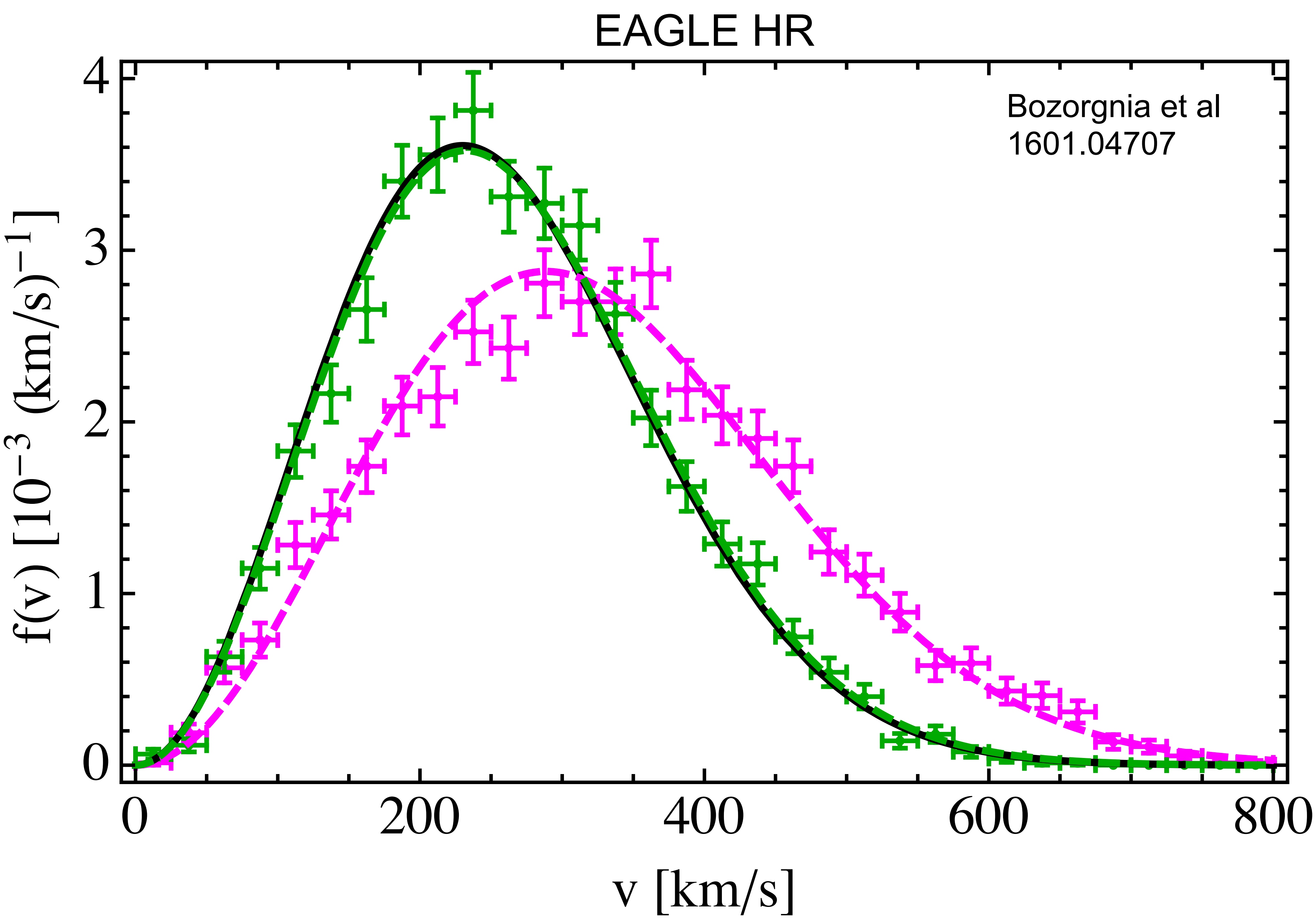


Is the Standard Halo Model correct?

Is the Standard Halo Model correct?

1. Compare with numerical simulations

Dark matter speed distribution from simulations



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

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

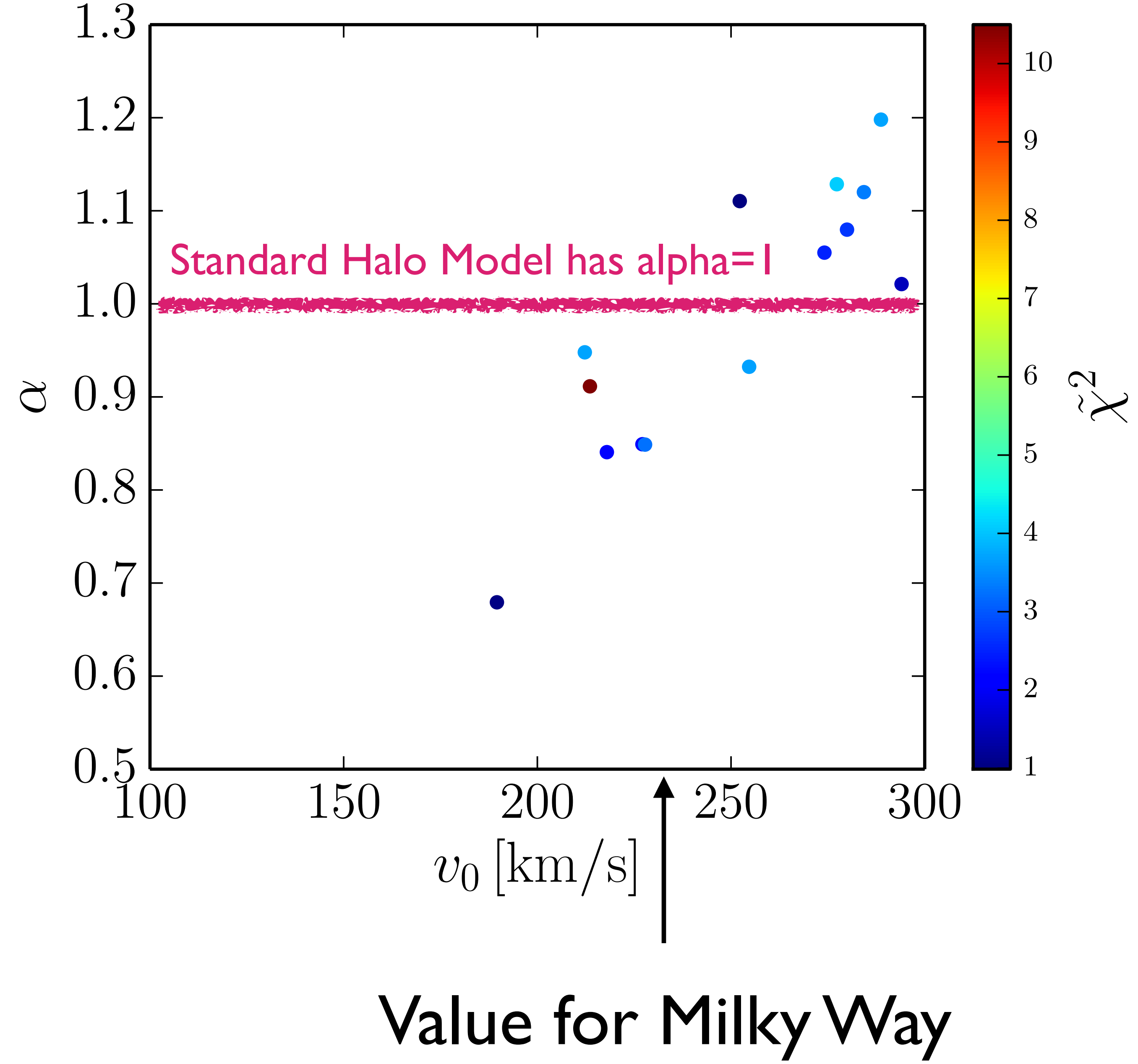
Speed distribution from simulations

Bozorgnia et al
1601.04707

Generalized Maxwellian distribution:

$$f(|\mathbf{v}|) \propto |\mathbf{v}|^2 \exp[-(|\mathbf{v}|/v_0)^{2\alpha}]\,,$$

Spread of results for Milky Way-like halos:

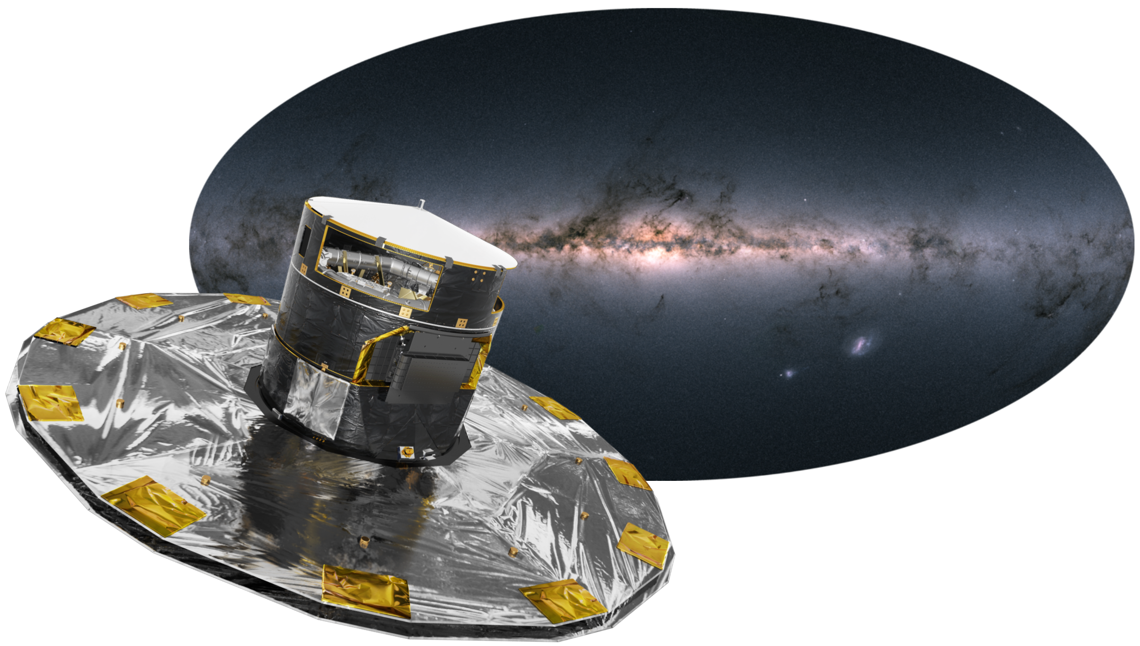


Alpha is close to 1. Simulations consistent with Standard Halo Model

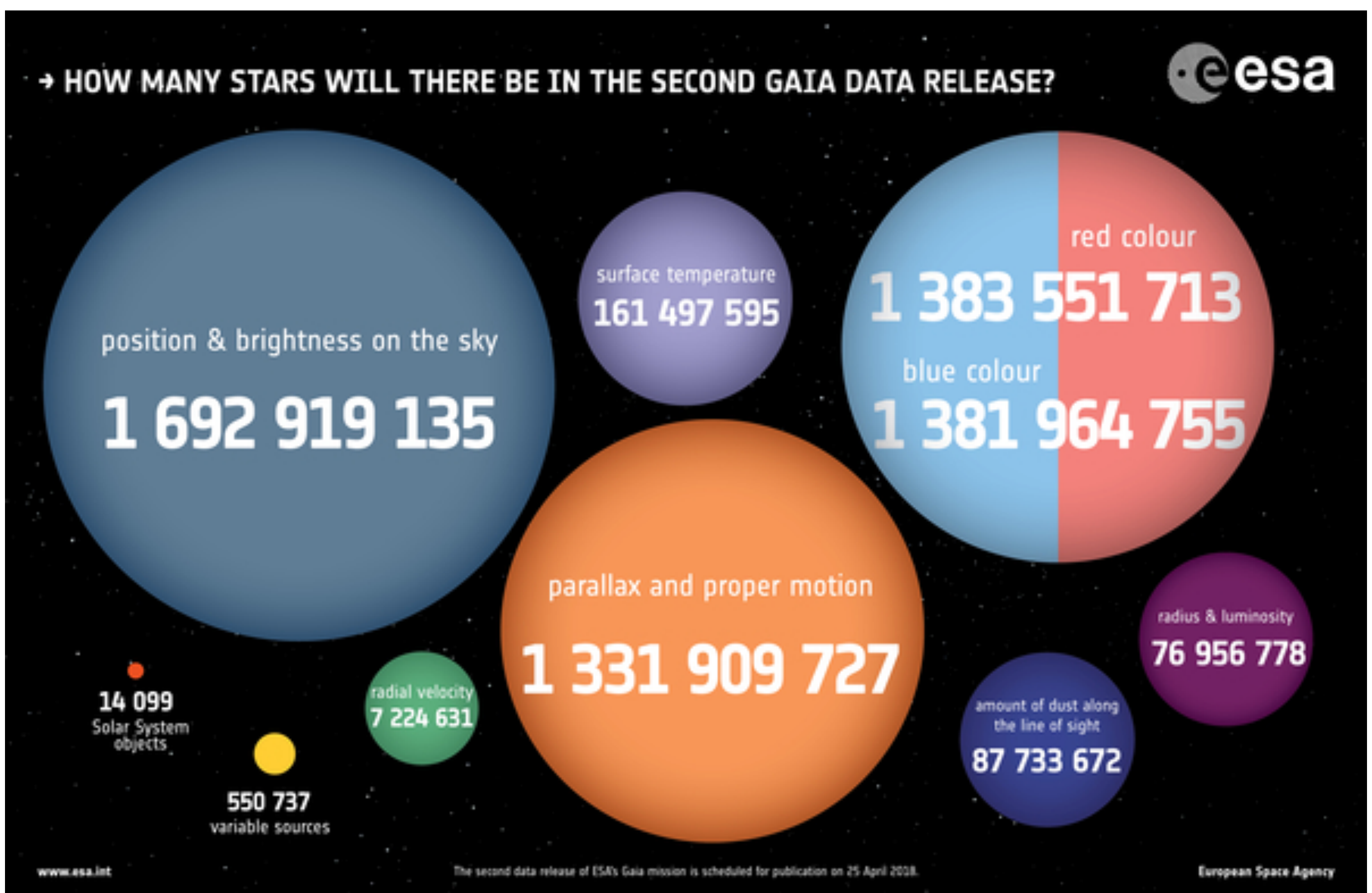
Is the Standard Halo Model correct?

1. Compare with numerical simulations
2. Compare with data from the Milky Way

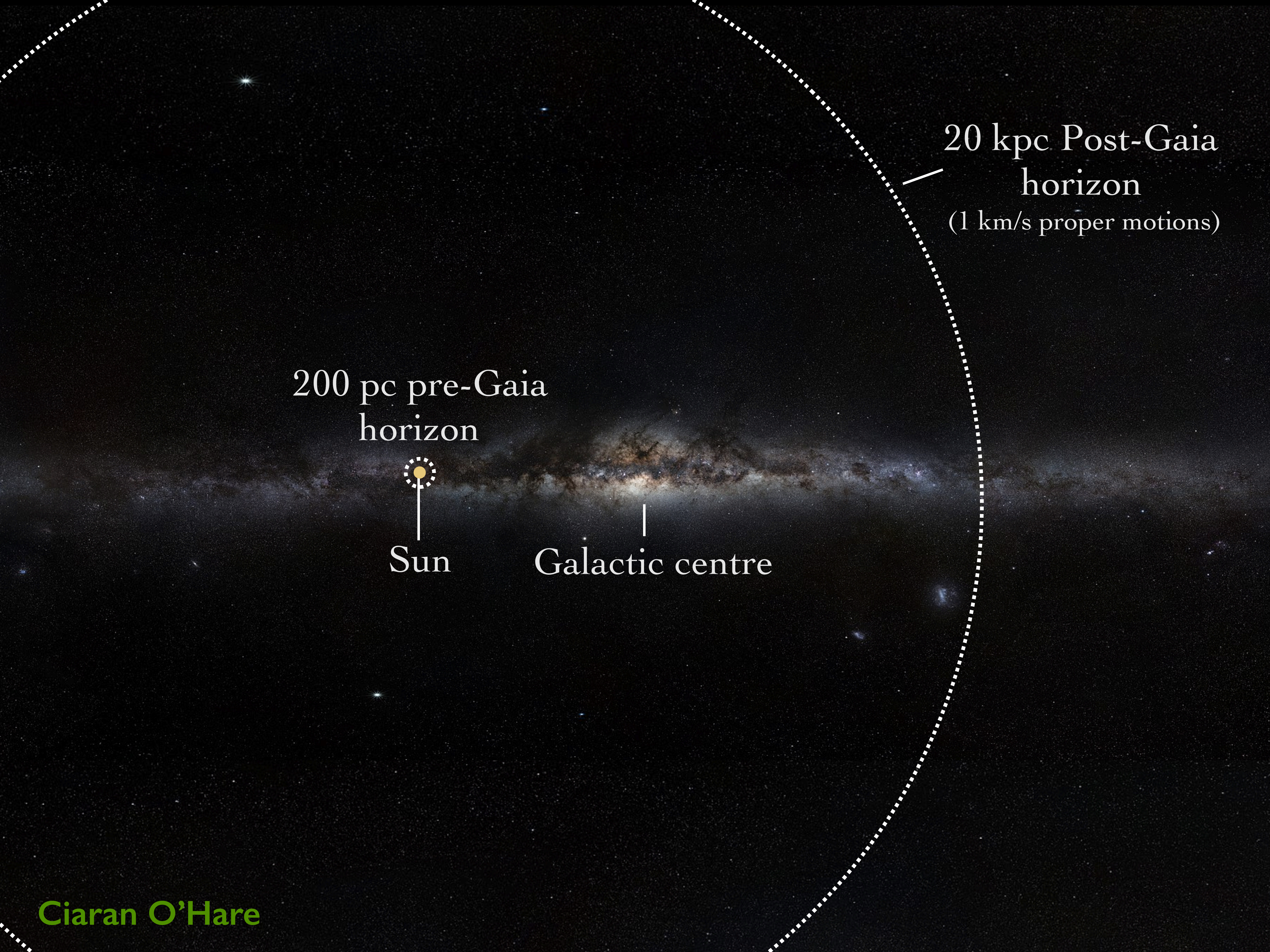
Gaia: a new era in mapping the Milky Way



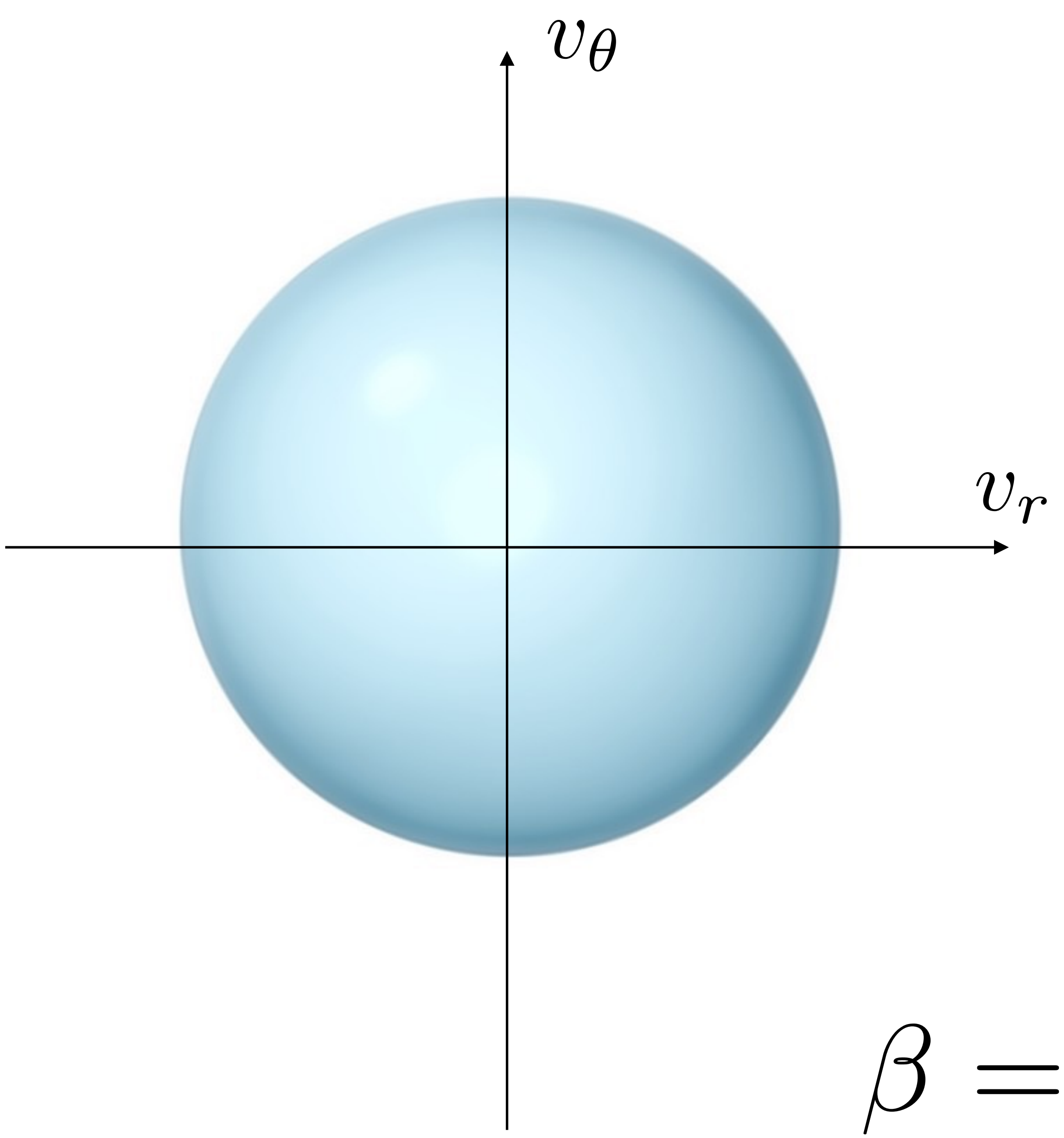
Launched 2013
Operates until ~2022



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
Ciaran O'Hare

Standard Halo Model assumes isotropic distribution



$$\beta = 0$$

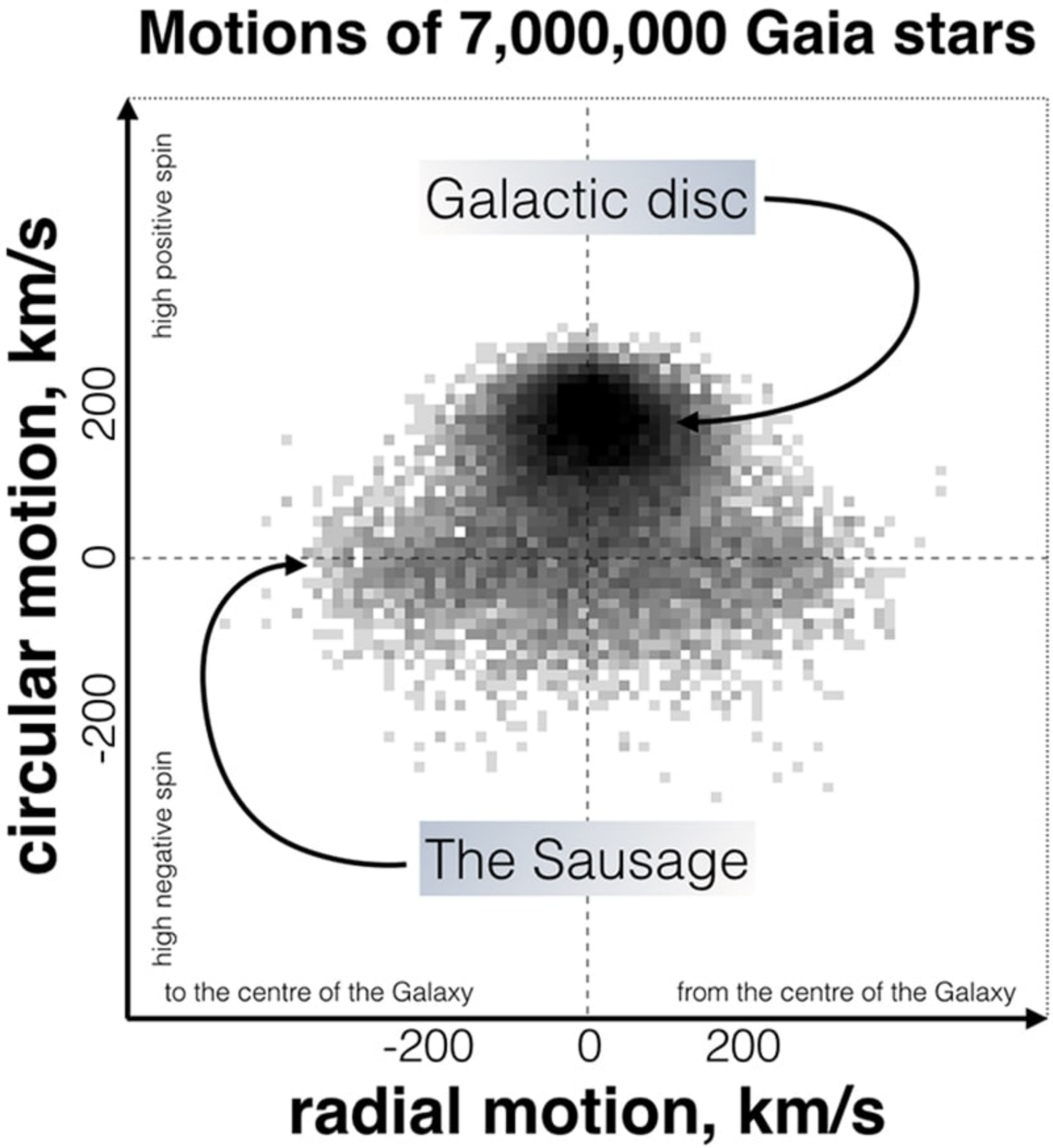
Anisotropic component: Gaia Sausage

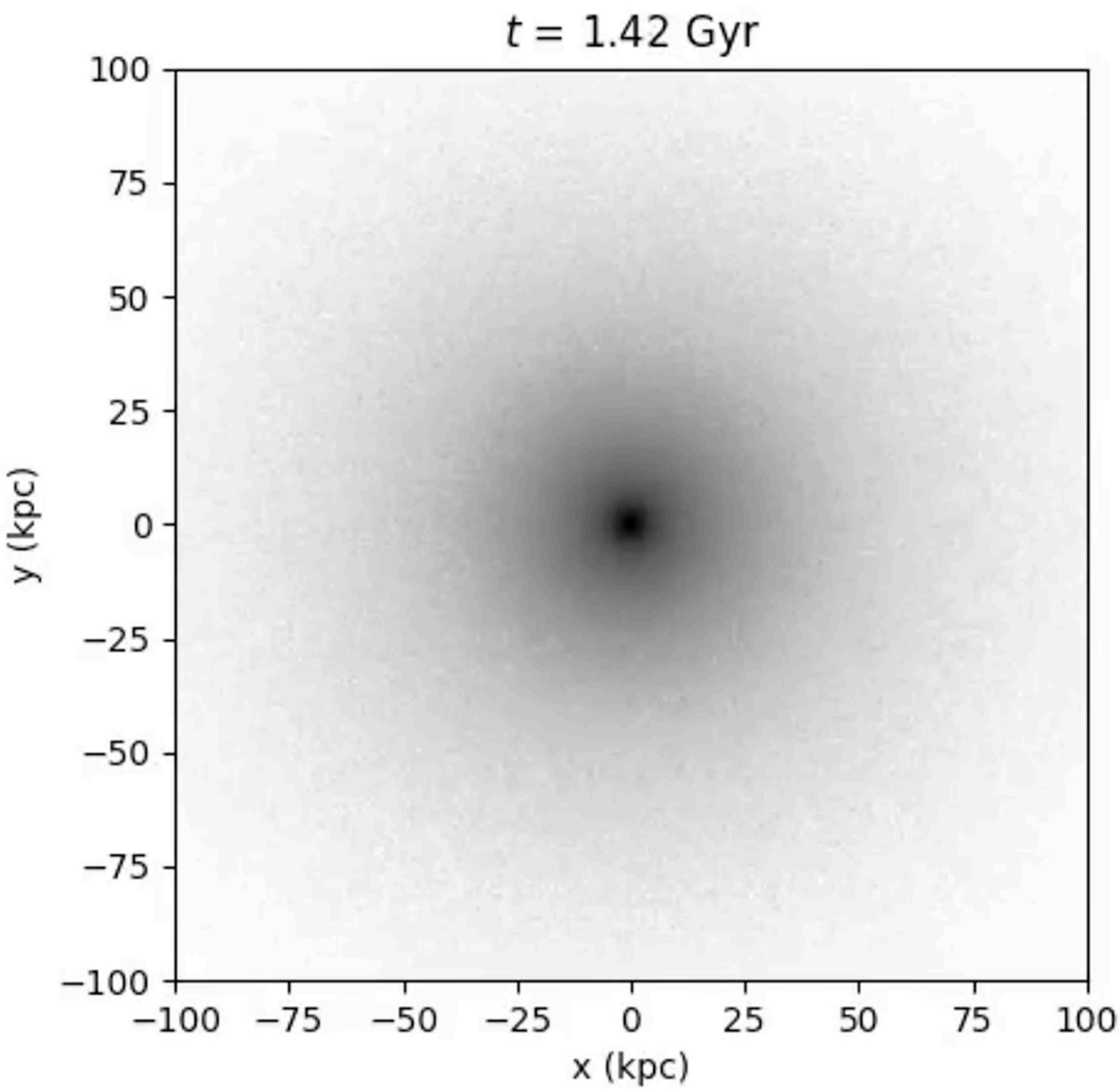
Major accretion event:

'*Sausage galaxy*'
and *Milky Way*
collided head on
8-10 billion years ago

Stars move on highly
radial orbits
not isotropic!

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

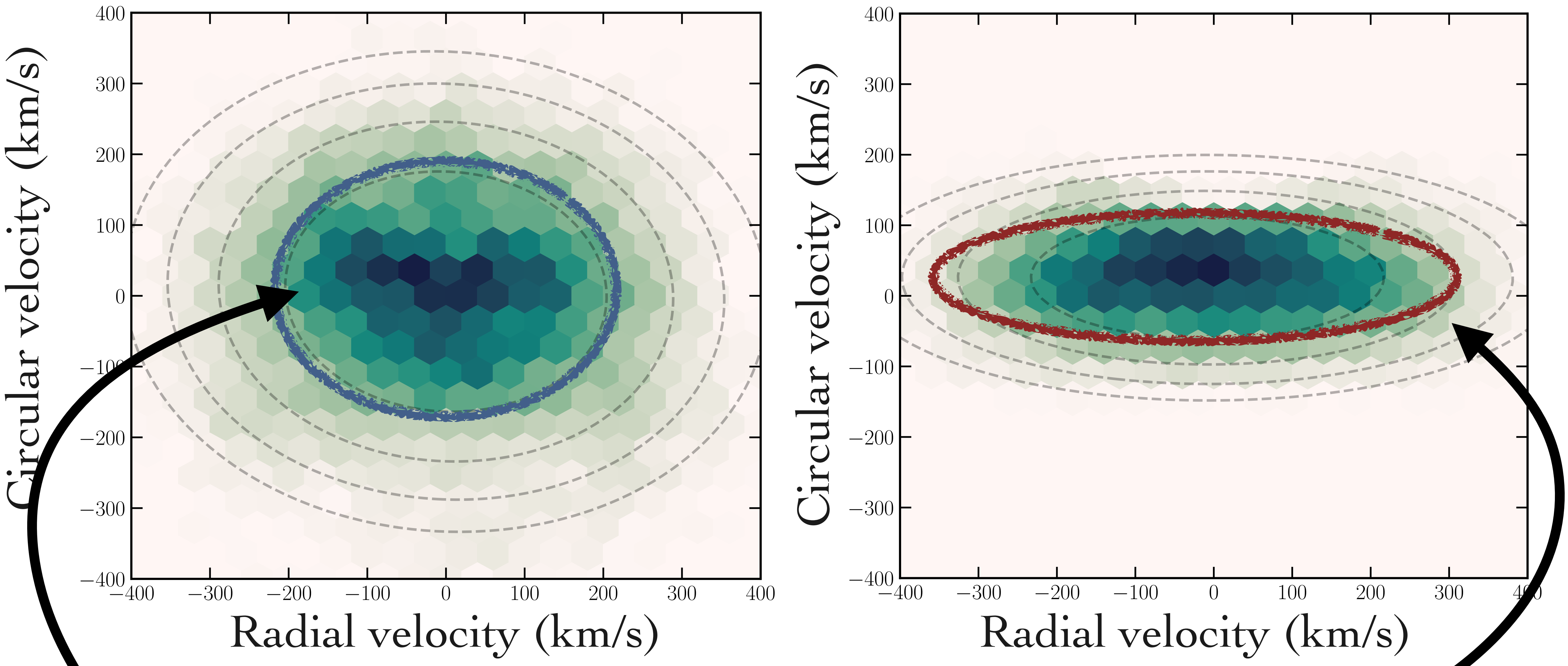




Denis Erkal: https://www.youtube.com/watch?v=8T2EdRZ_iE4

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

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



" Stellar Halo"

"Gaia Sausage"

Spherical, isotropic

Flattened, radially anisotropic

Ciaran O'Hare

Gaia Sausage or Gaia Enceladus?

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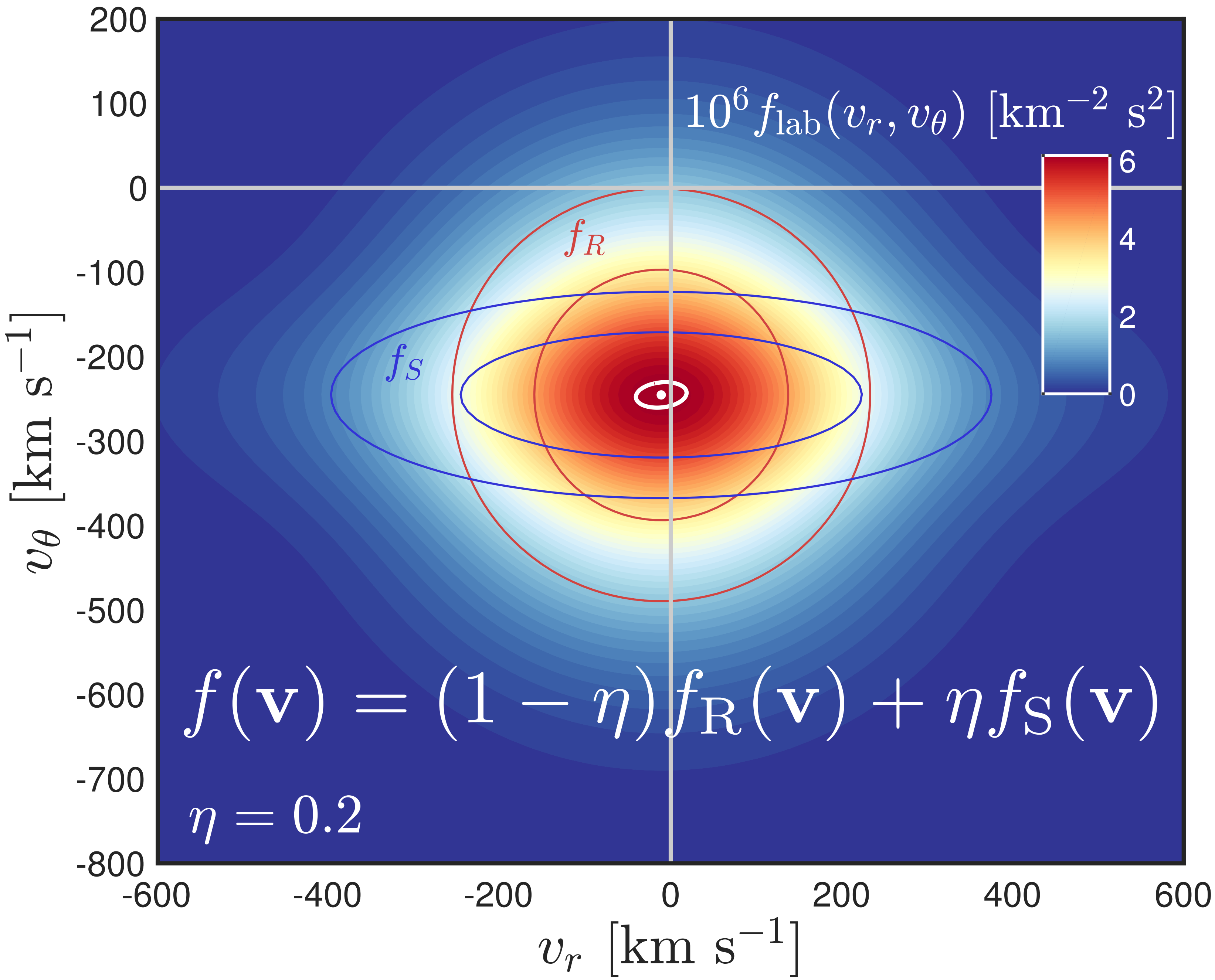
Gaia Sausage

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]

Including the Gaia Sausage

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

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

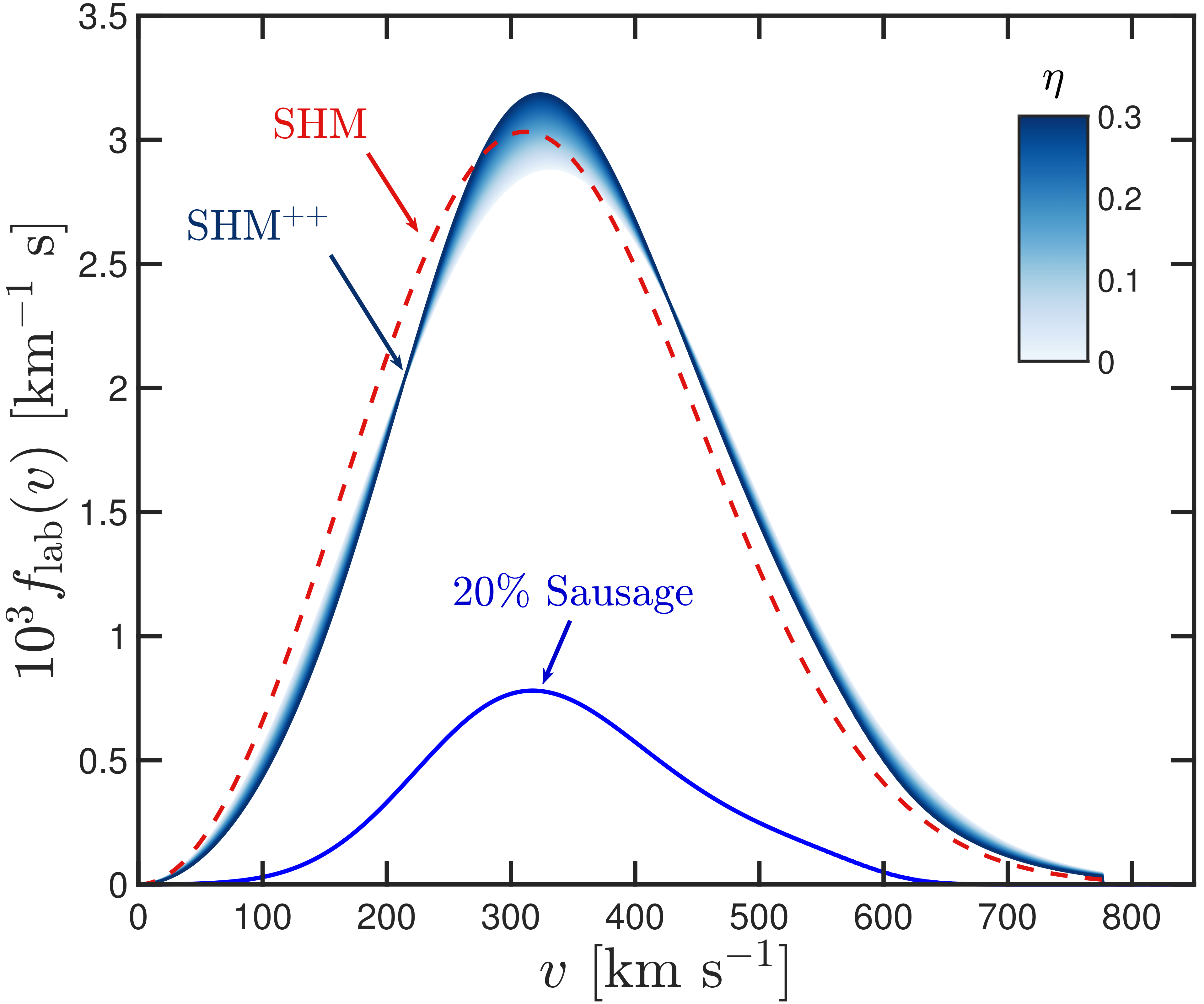
SHM	Local DM density	ρ_0	$0.3\,\mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$220\ \mathrm{km\ s^{-1}}$
	Escape speed	$v_{\rm esc}$	$544\ \mathrm{km\ s^{-1}}$
	Velocity distribution	$f_{\rm R}(\mathbf{v})$	Eq. (1)
$\mathbf{SHM}^{++}$	Local DM density	ρ_0	$0.55 \pm 0.17\ \mathrm{GeV\ cm^{-3}}$
	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

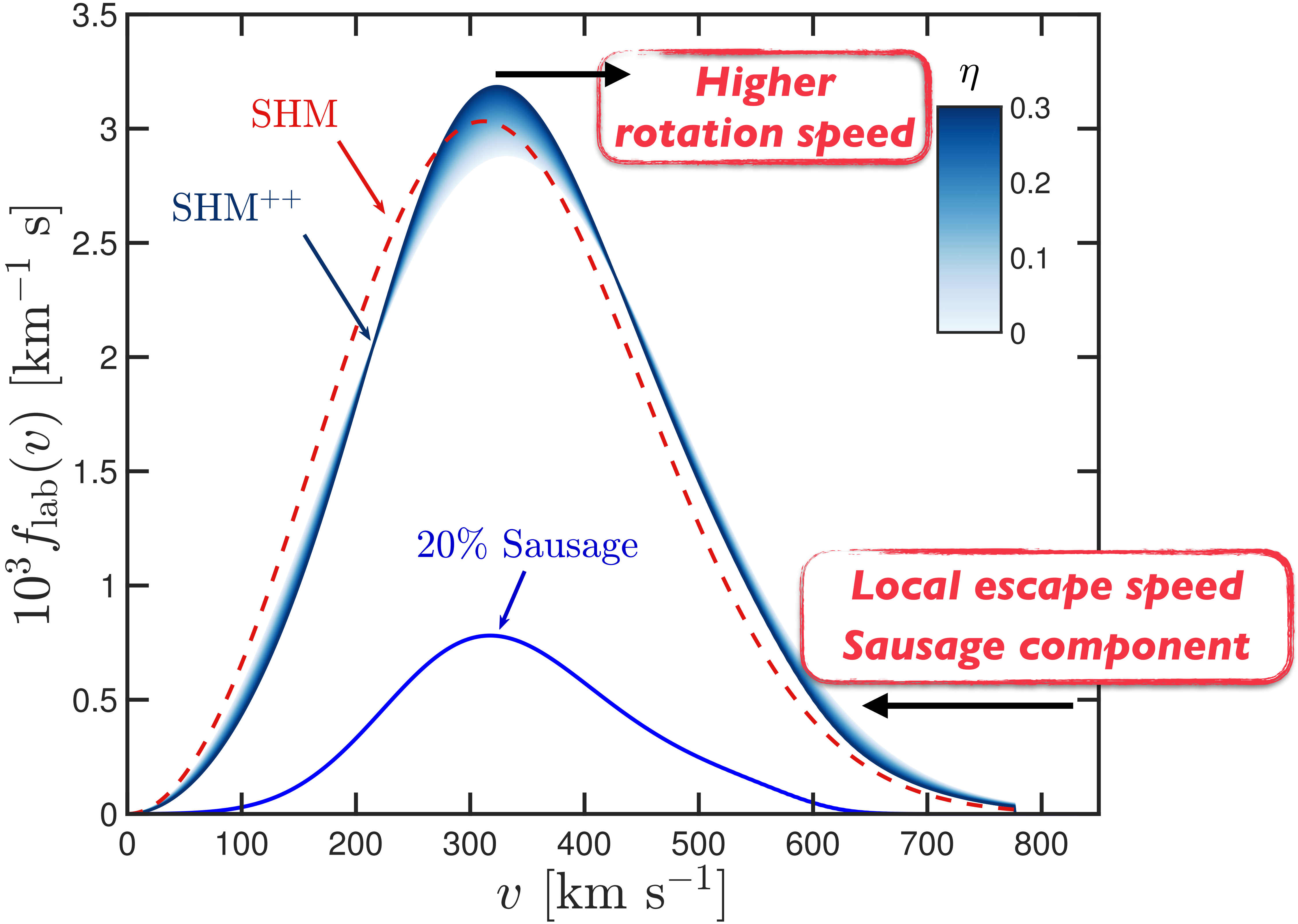
β takes same values as stars in Sausage sample

Necib et al 1810.12301
Fattahi et al 1810.07779

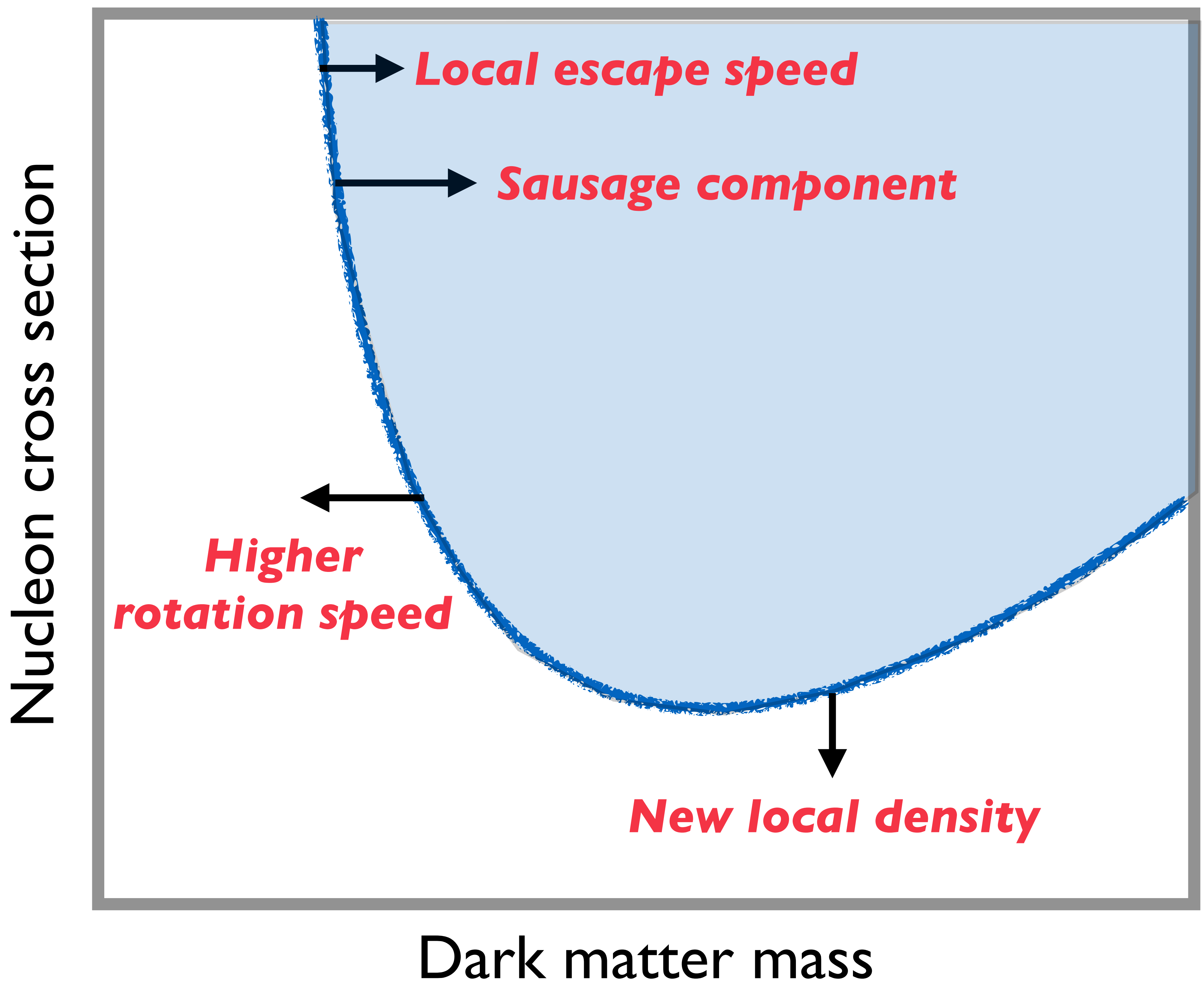
SHM++: 2 component model



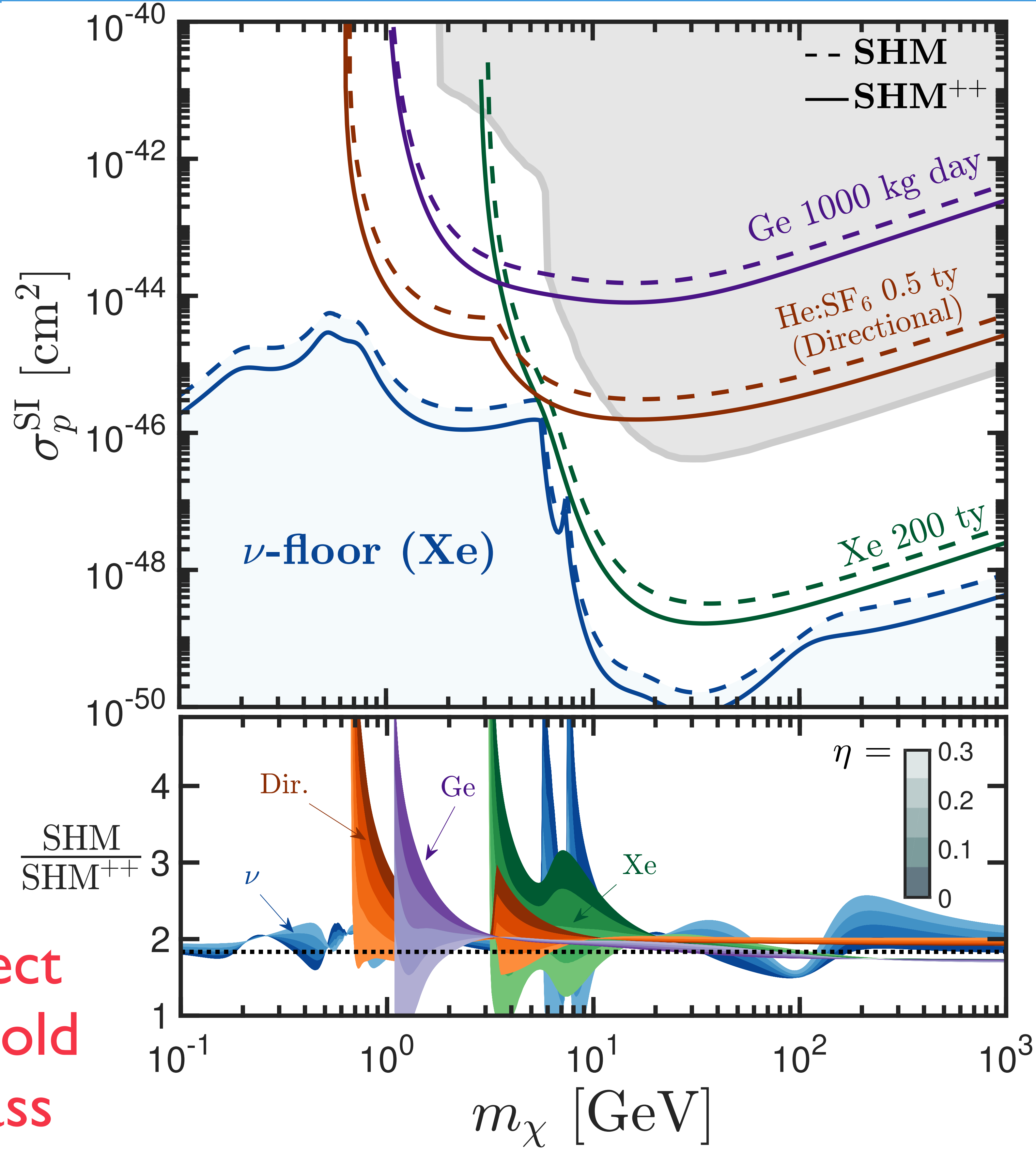
SHM++: 2 component model



Modest changes for nuclear recoils



Modest changes for nuclear recoils

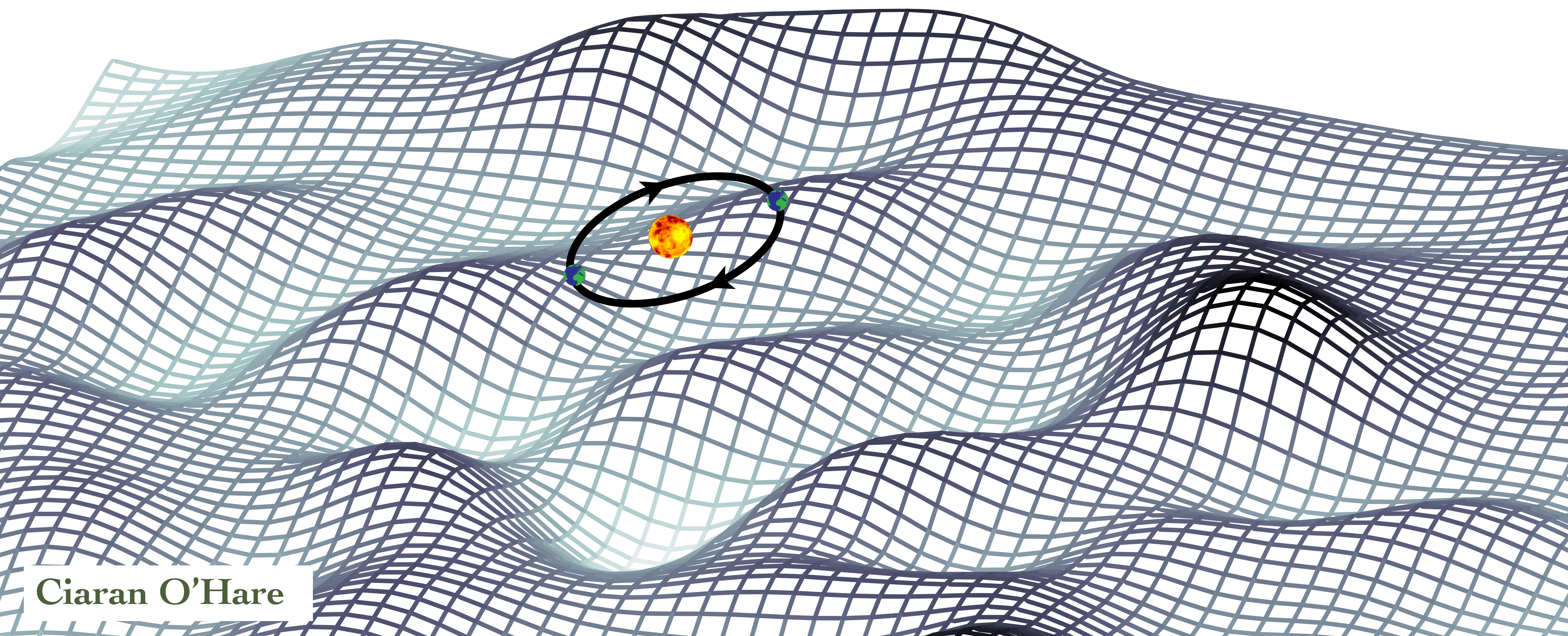


Biggest effect near threshold i.e. low mass

Detecting substructure: axions

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

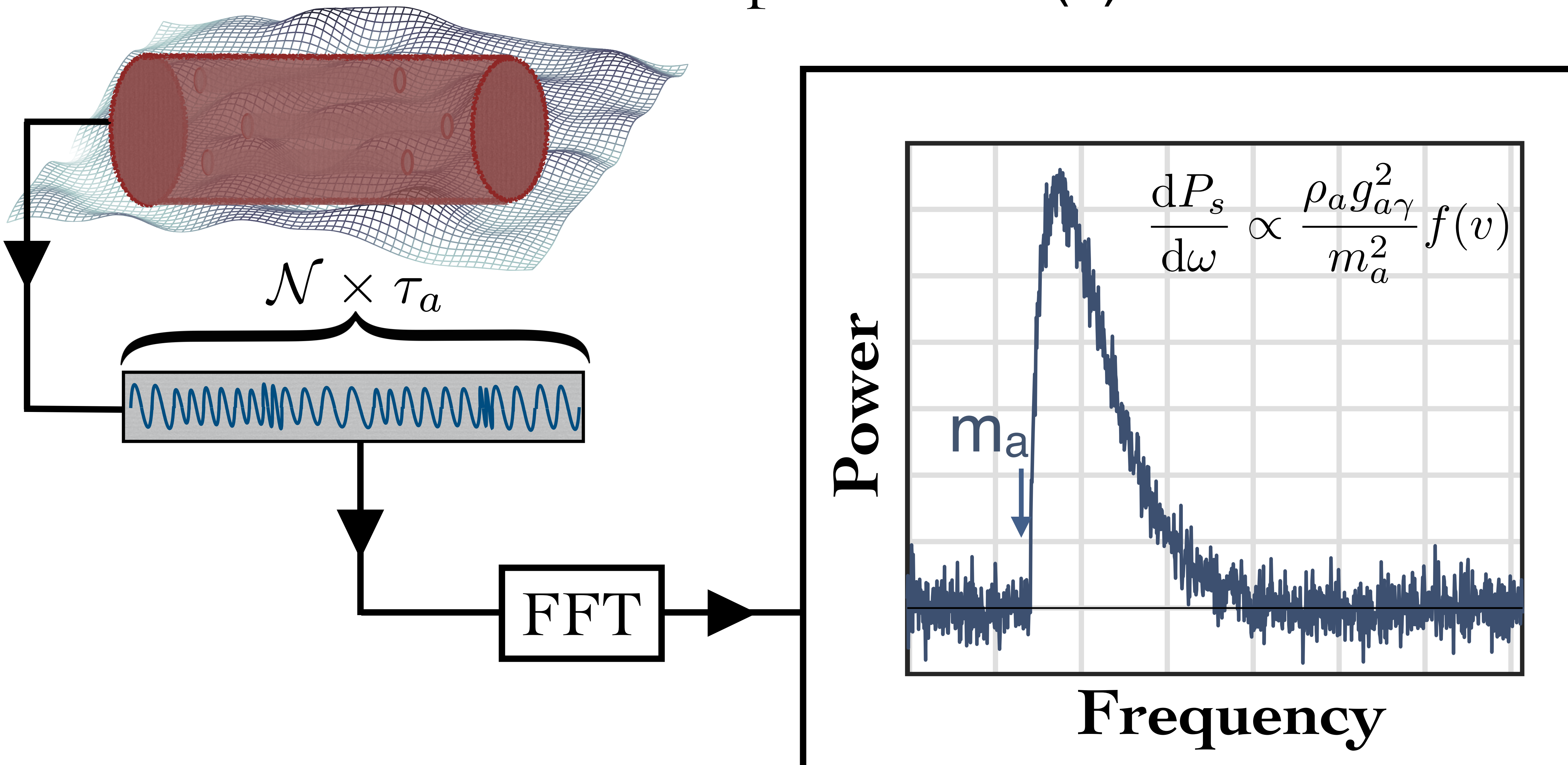
Oscillating at ~the axion mass with coherence time $\tau \sim \dfrac{1}{m_a\langle v\rangle^2}$



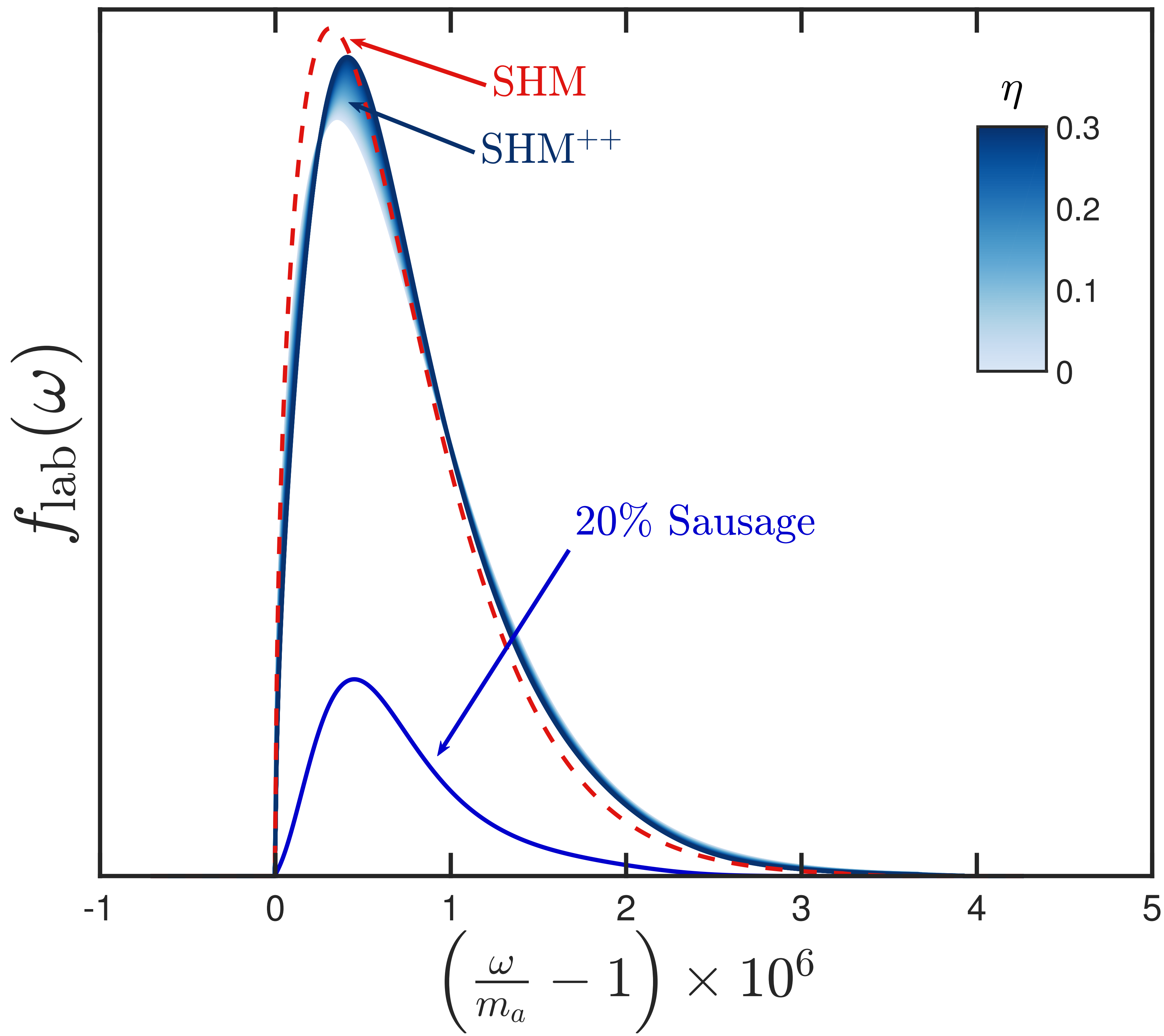
Ciaran O'Hare

Measuring the axion distribution

Sampling axion field over many, N, coherence times:
→ Power spectrum ~ f(v)



Modest changes for axion haloscopes



Gaia Sausage is clearly beyond the Standard Halo Model

…but generally leads to modest changes in experimental signals

Standard Halo Model

Simplest spherical model with (asymptotically) flat rotation curve

Assumptions:

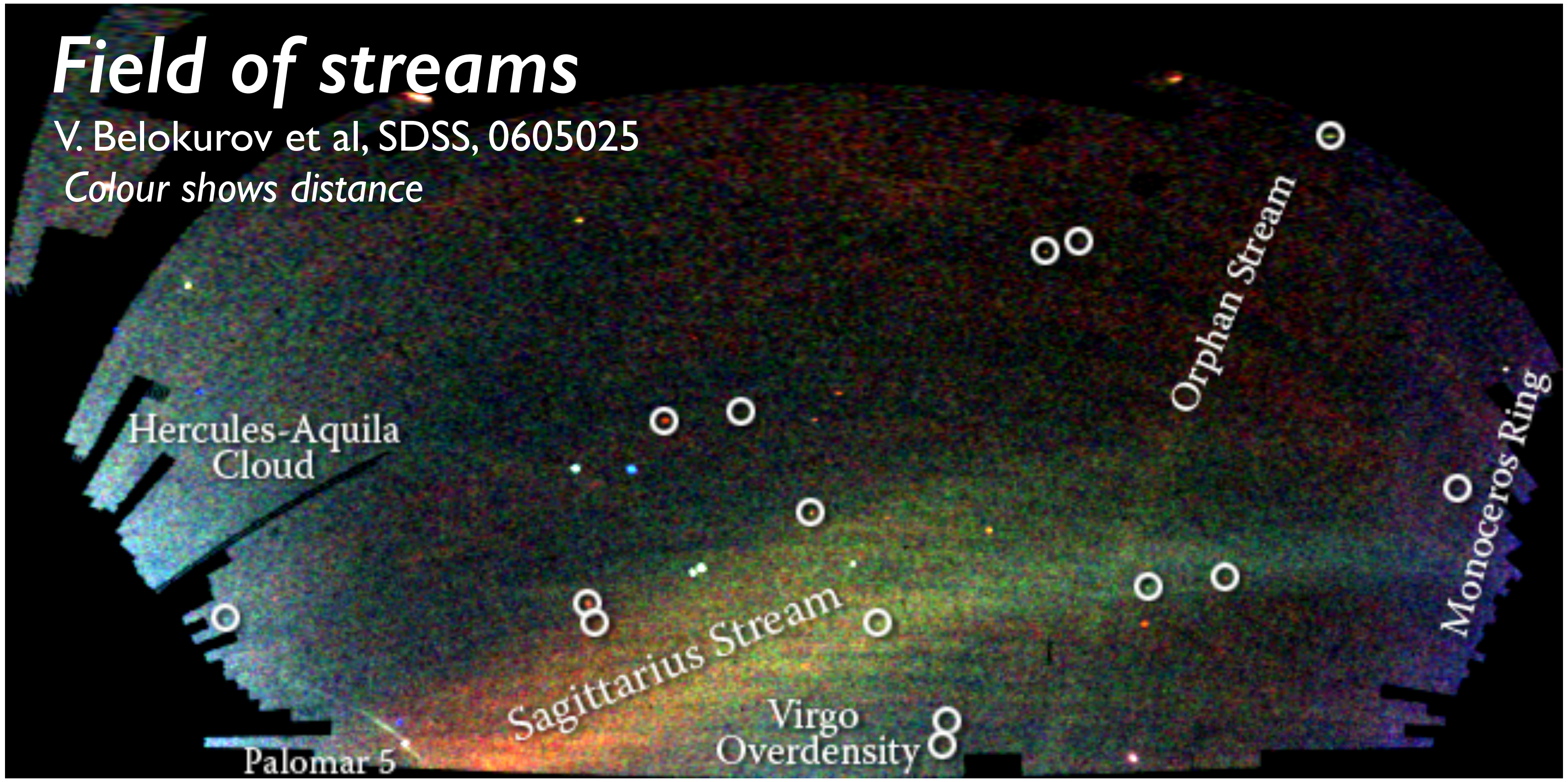
- ~~*Round halo*~~
- ~~*Gaussian (Maxwellian)*~~
- ~~*Isotropic*~~
- *No substructure*

Sausage component breaks assumptions

Is there also substructure?

Substructure: more extreme variations

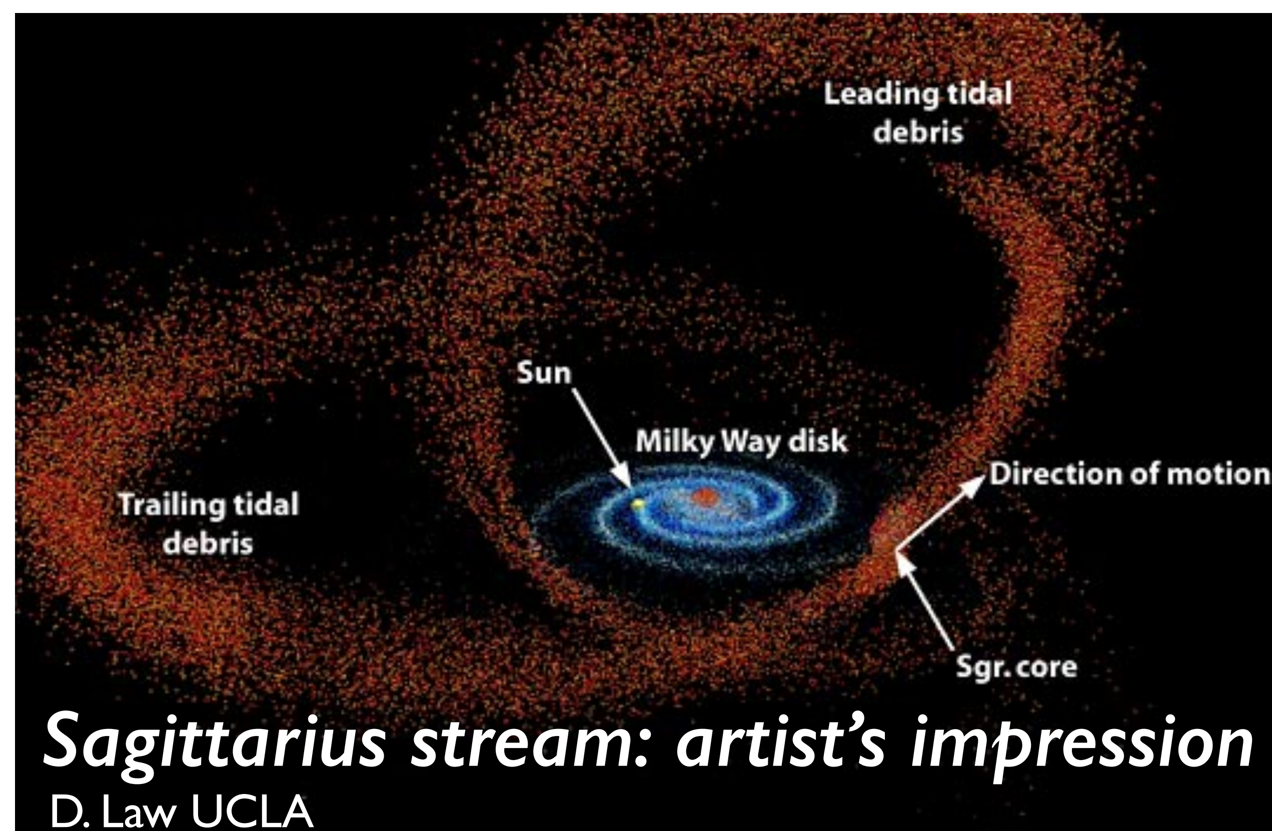
We know there is substructure: streams



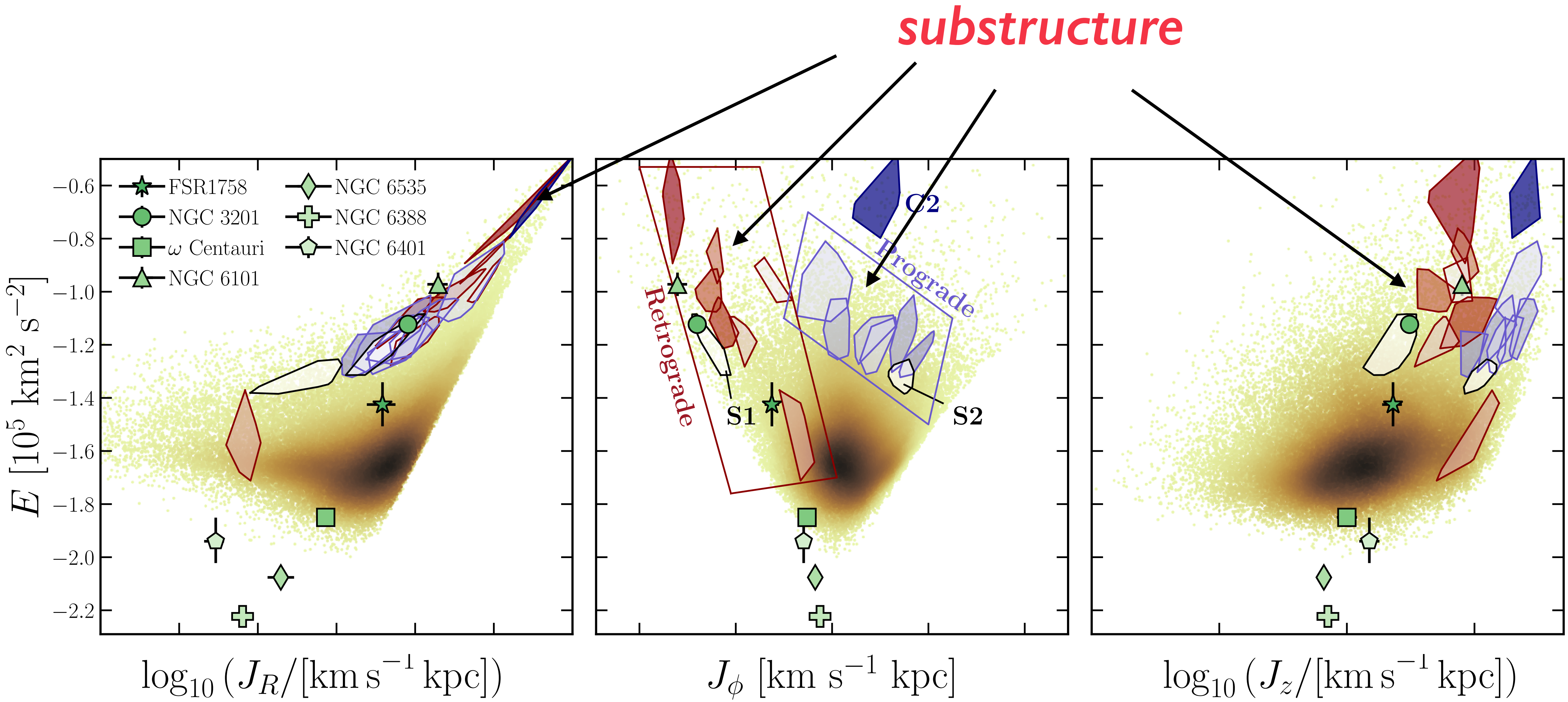
Famous example:
Sagittarius stream
(doesn't pass through solar system)

Streams produced by the accretion of smaller galaxies

Are there streams passing through the solar system?



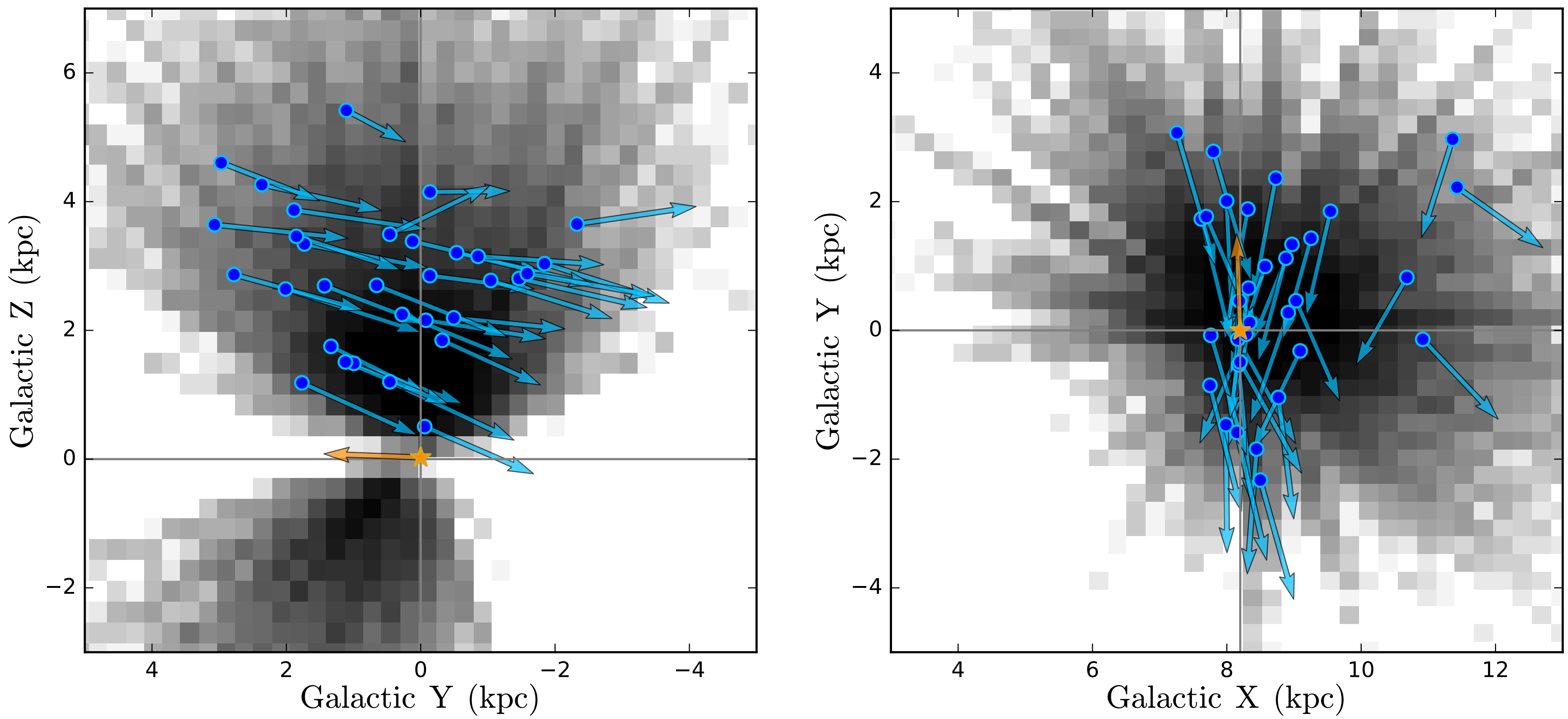
Finding structure in action space



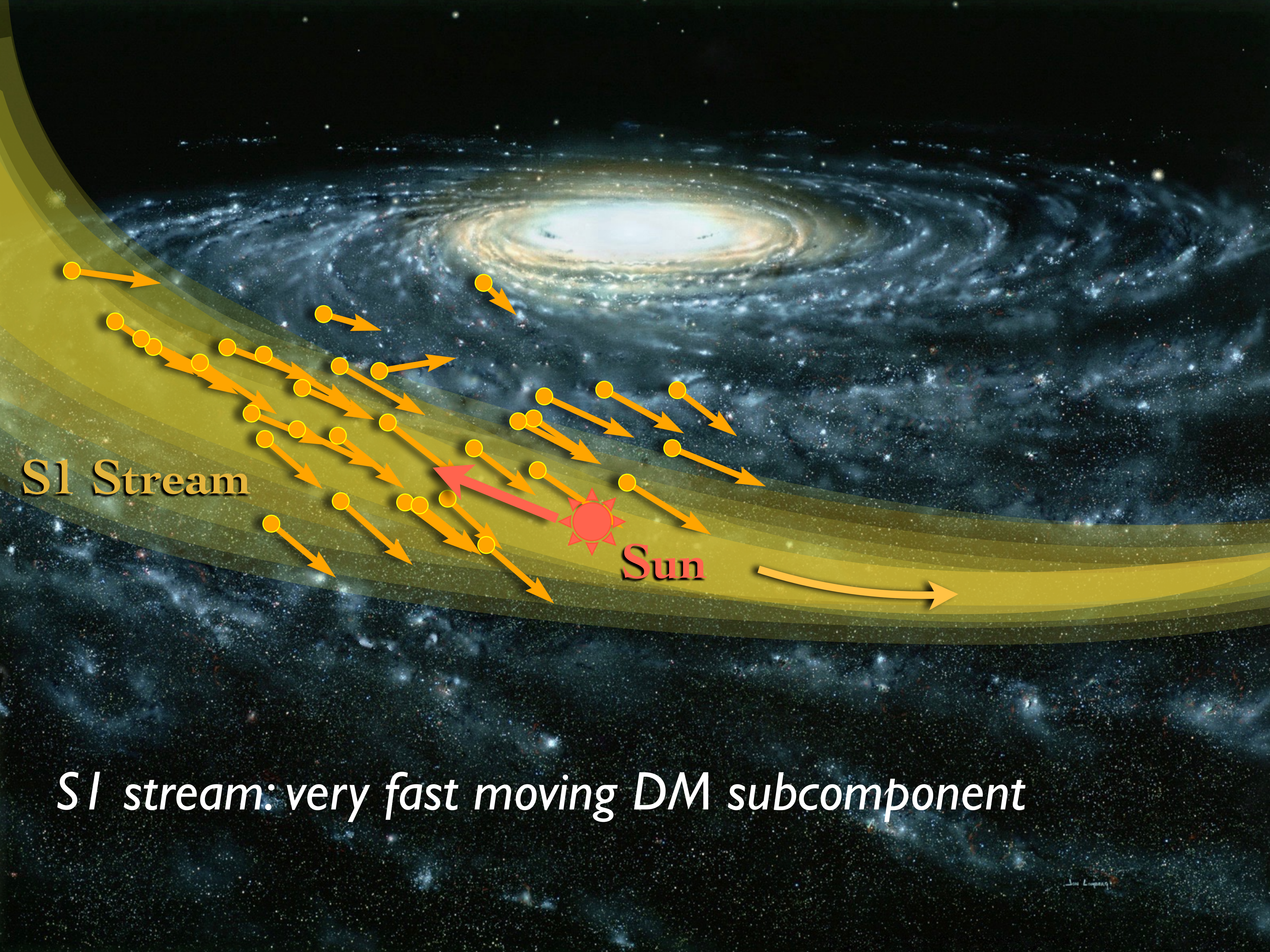
S1 is the most interesting for terrestrial experiments

S1 stellar stream

S1: Identified with SDSS-Gaia (DR1) Catalogue
94 member stars
G. Myeong et al. 1712.04071

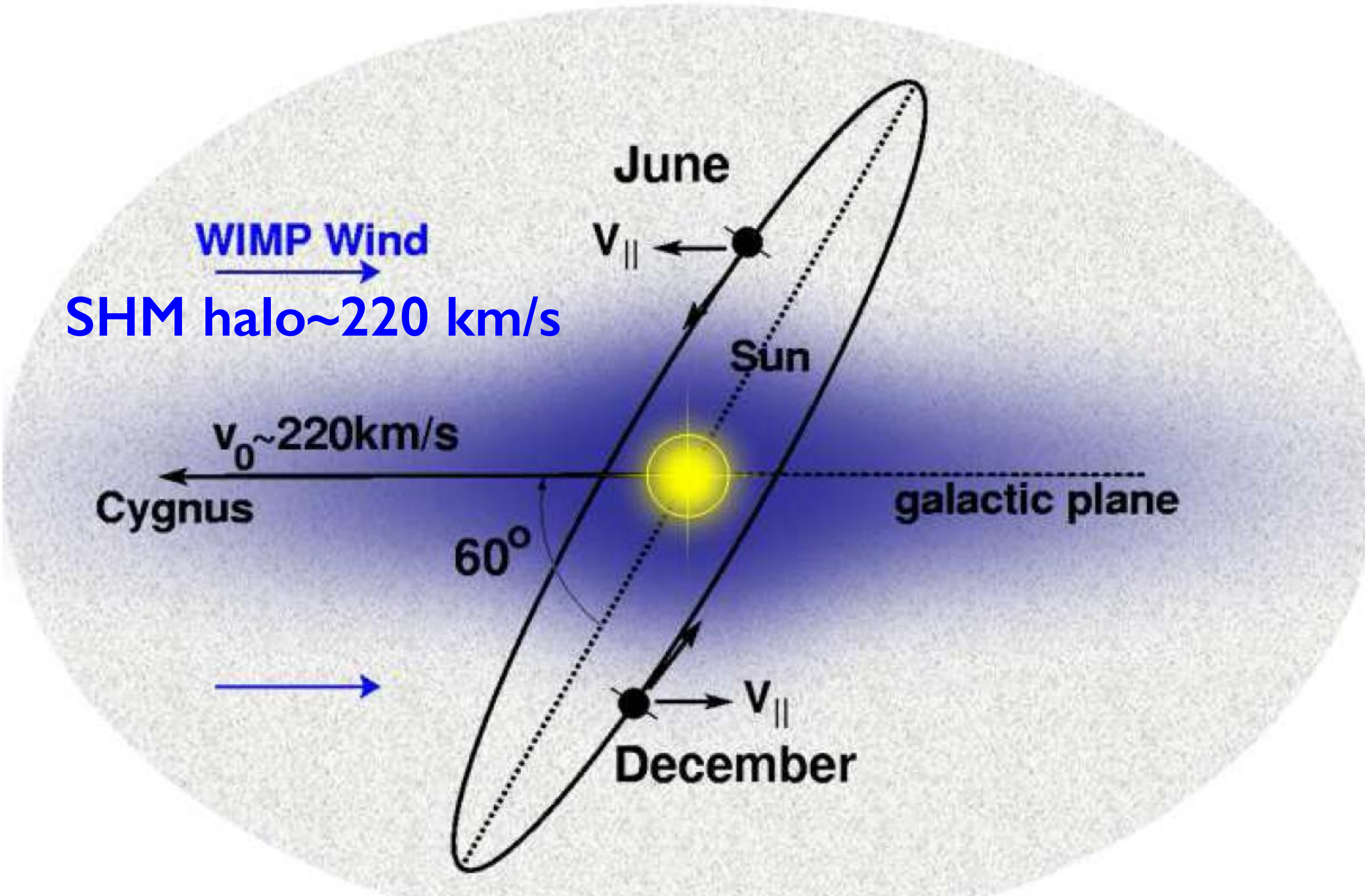


Passes very close to solar position (orange arrow)



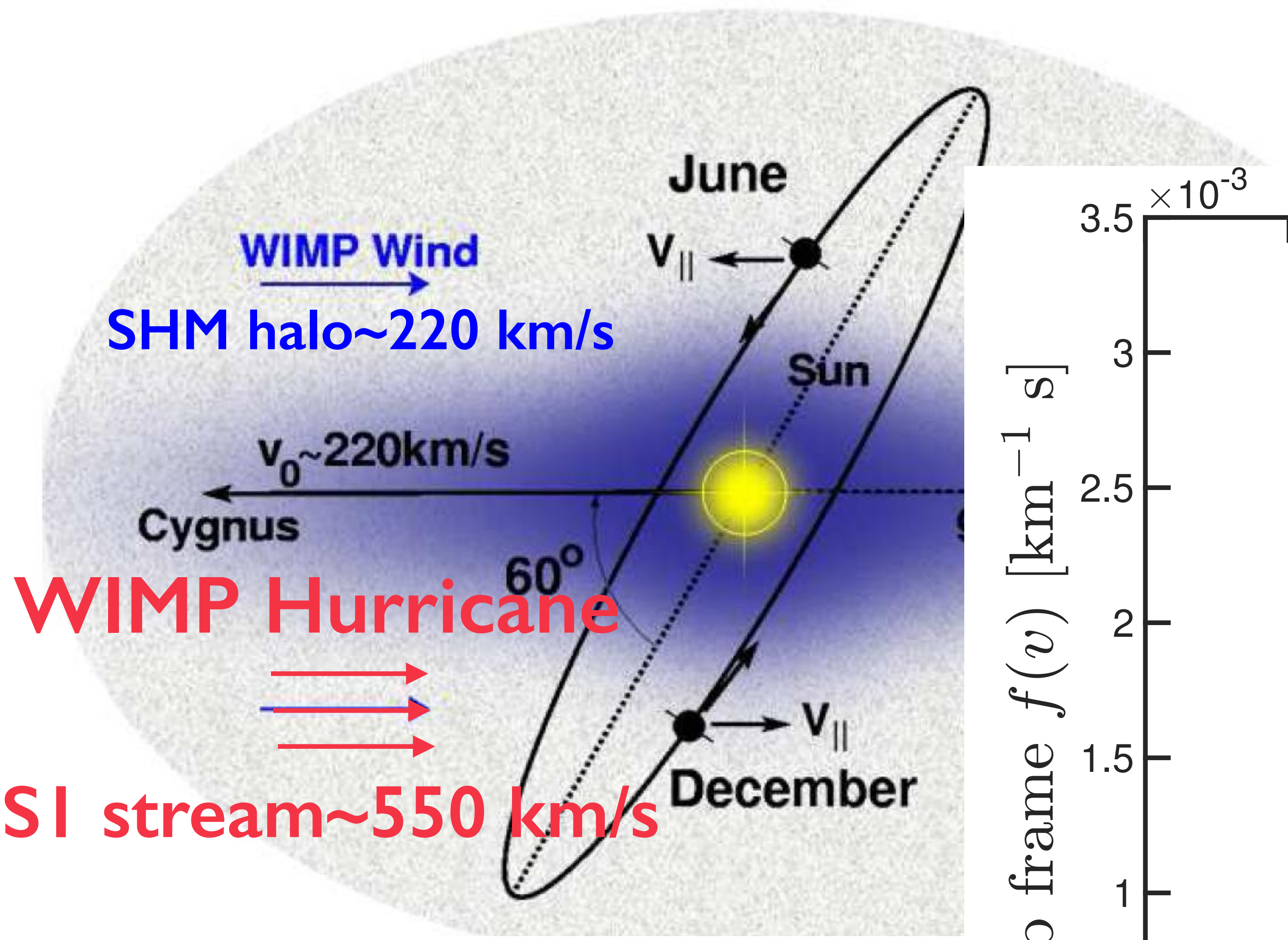
S1 stream: very fast moving DM subcomponent

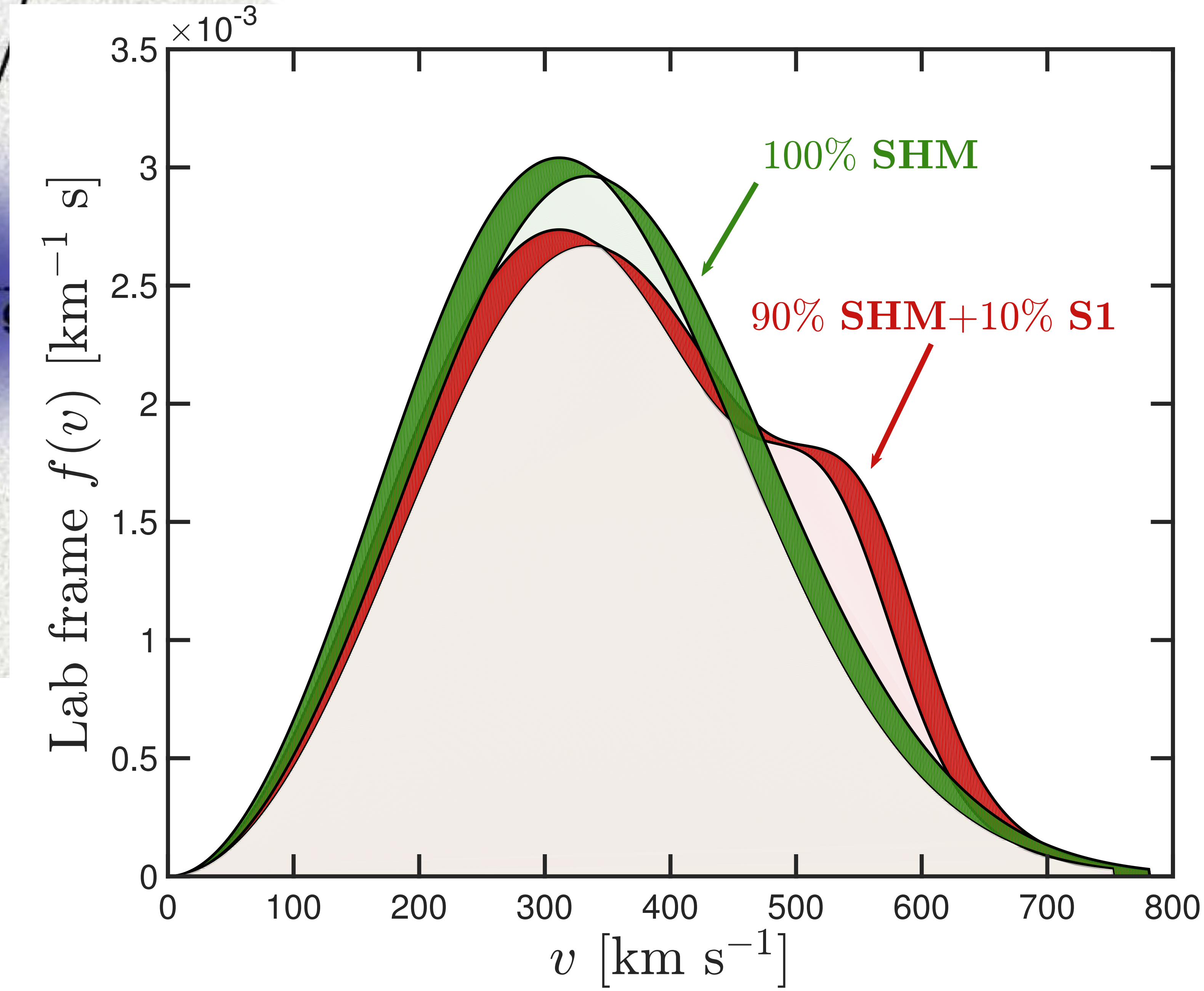
The dark matter wind



Dark matter hurricane?

O'Hare, CM et al.1807.09004
A dark matter hurricane…





Astronomy

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A 'dark matter hurricane' is storming

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 310 miles per SECOND

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

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3:29 / 5:38
Urgent: “Scientist “Claim Dark Matter Hurricane” Is Coming
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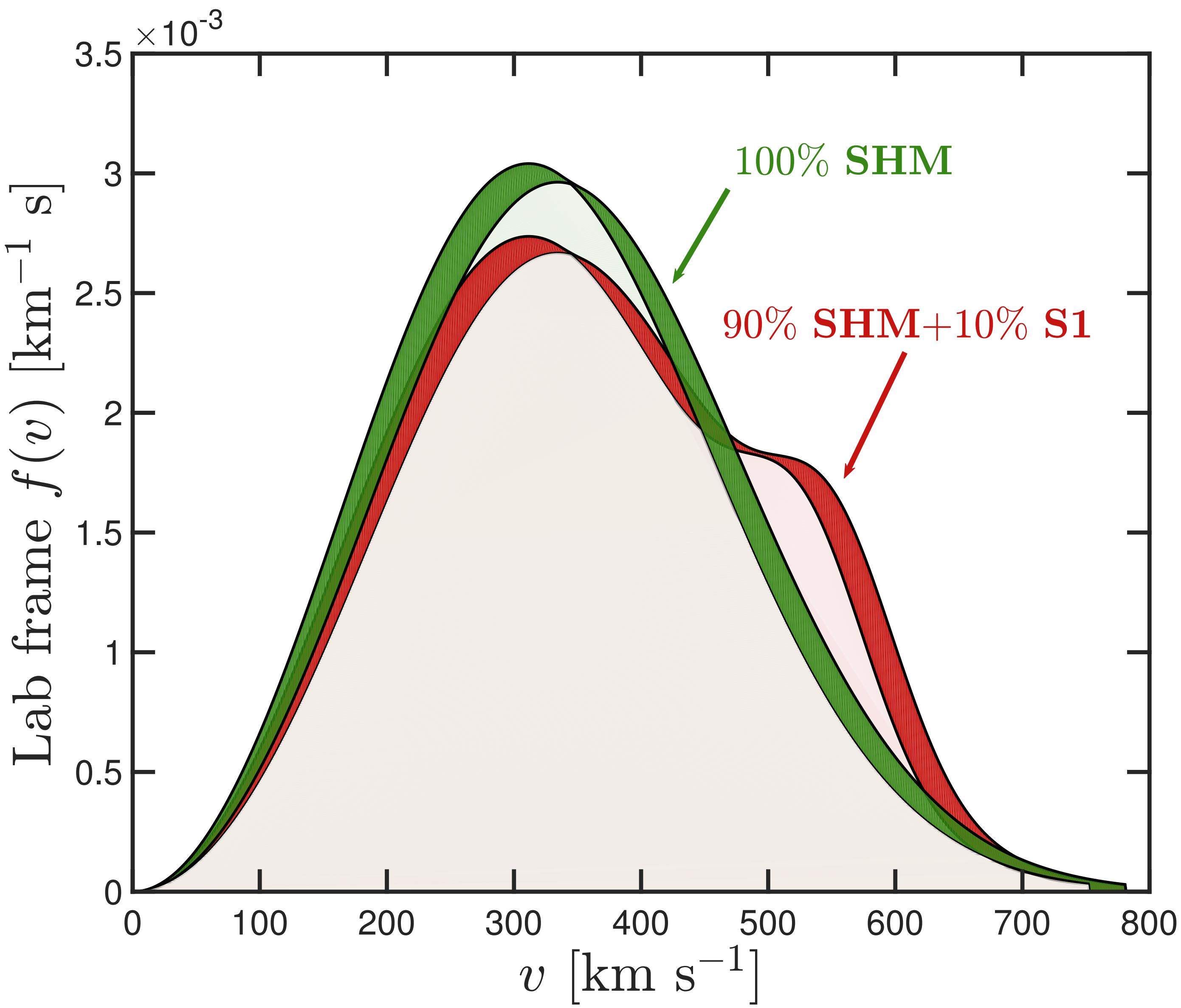
How much dark matter in S1?

We remain agnostic and ask:
What fraction of DM in S1 is needed to detect it in a DM experiment?

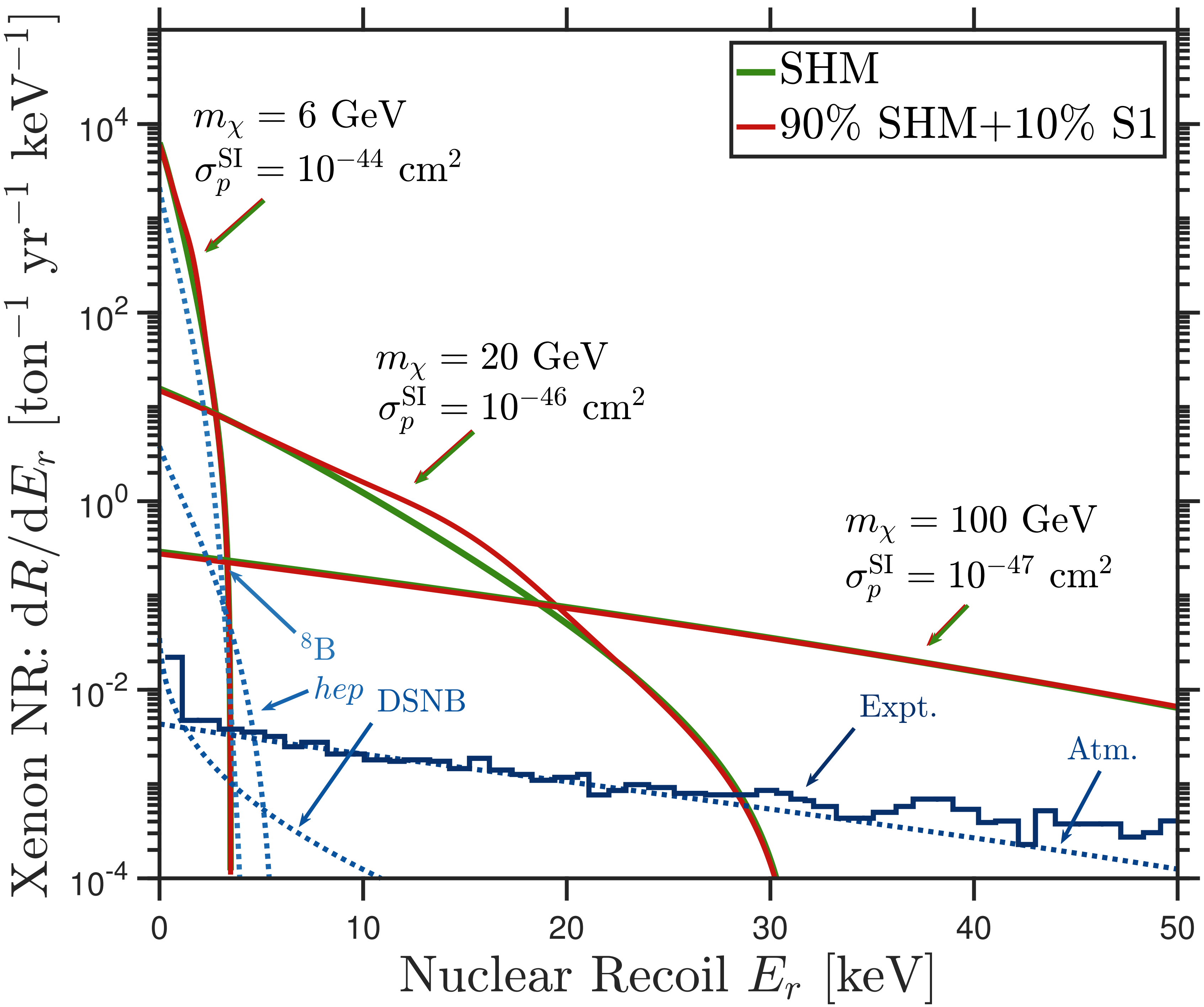
Model halo distribution as sum of 2 components:

$$f_{\mathrm{SHM+str}}(\mathbf{v}) = \left(1 - \frac{\rho_{\mathrm{str}}}{\rho_0}\right) f_{\mathrm{SHM}}(\mathbf{v}, t) + \frac{\rho_{\mathrm{str}}}{\rho_0} f_{\mathrm{str}}(\mathbf{v}, t)$$



$\frac{\rho_{\mathrm{str}}}{\rho_0}$: a free parameter

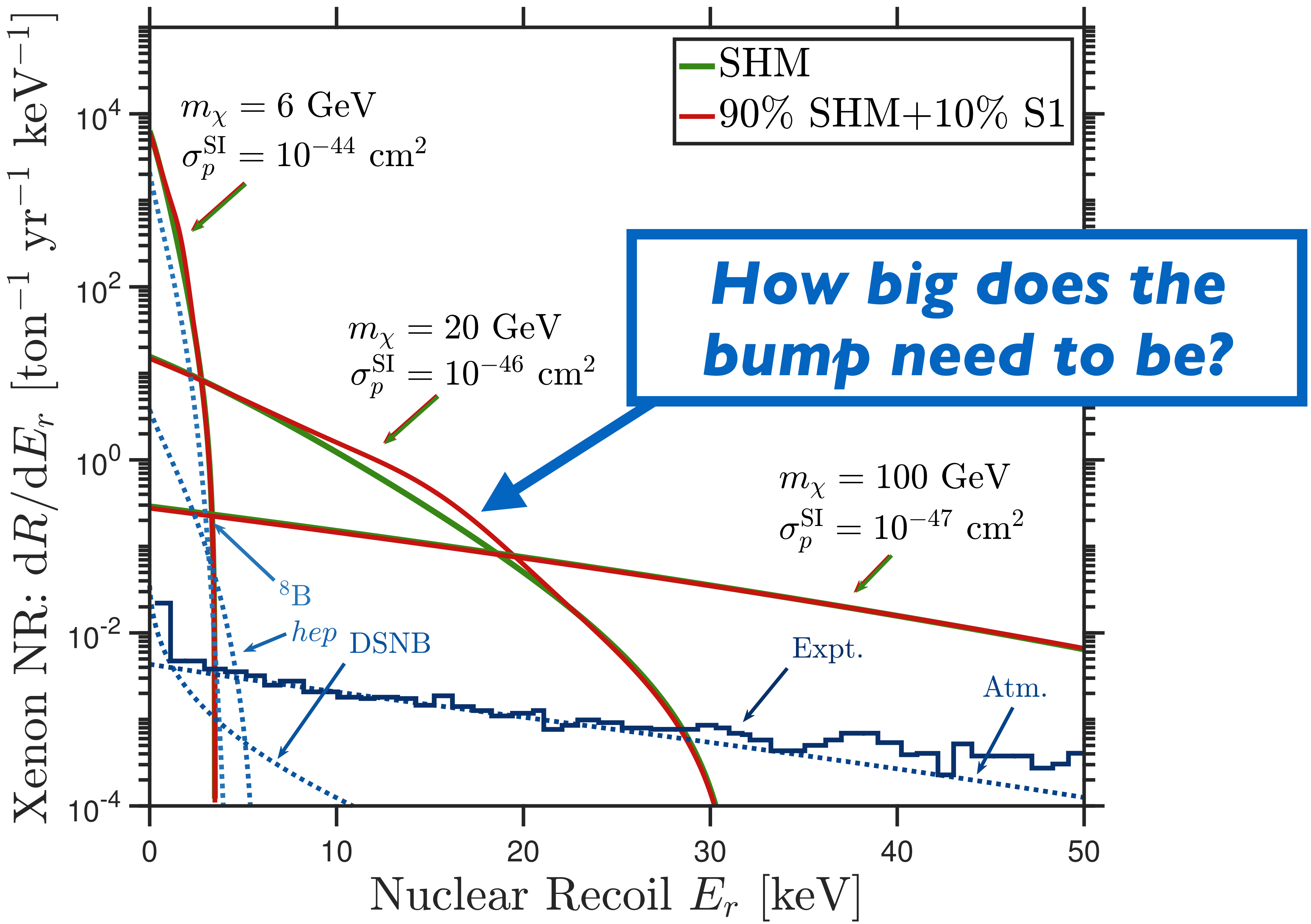
Xenon: what it measures



Spectrum is relatively featureless…

…except in a sweet spot around 20 GeV

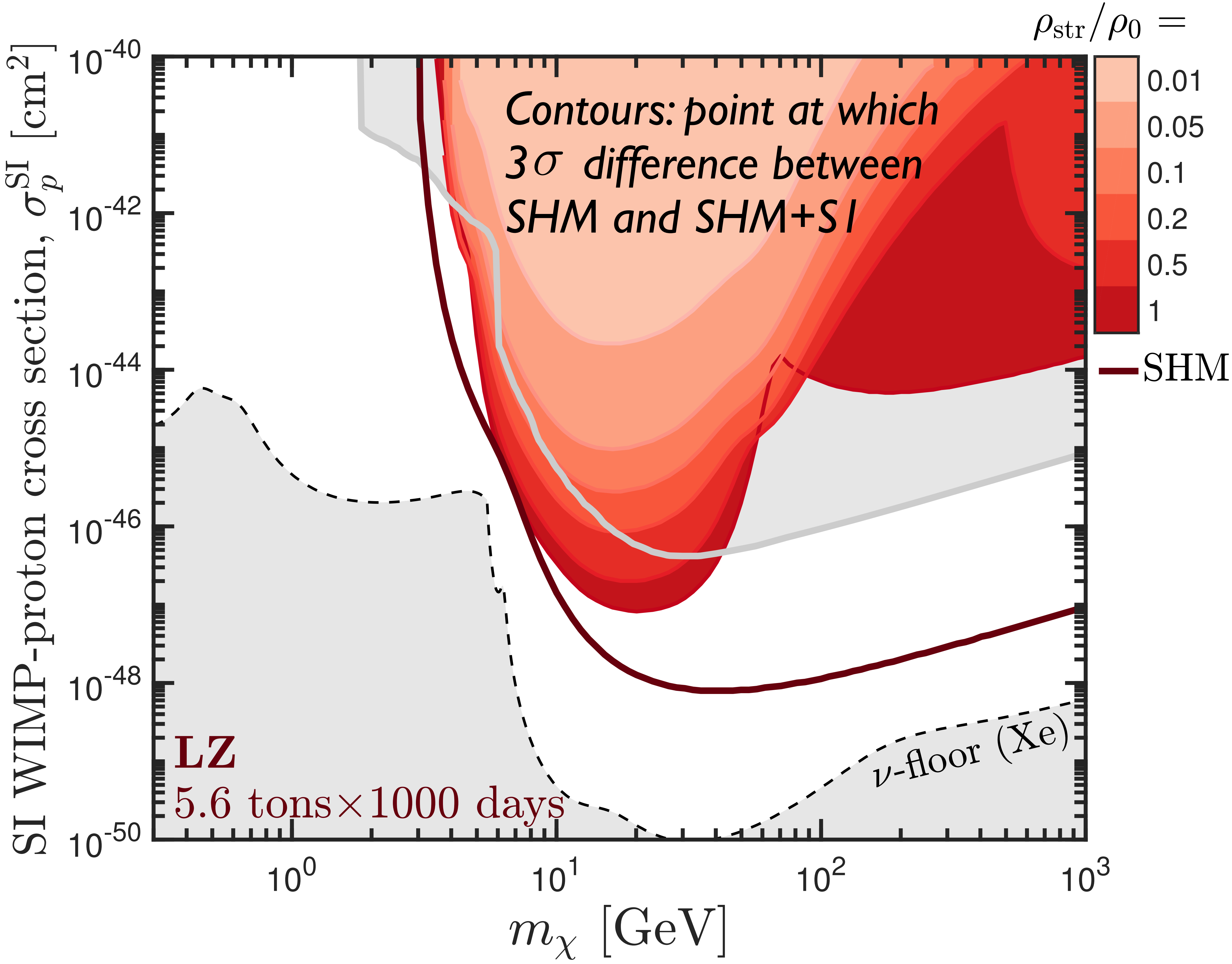
Xenon: what it measures



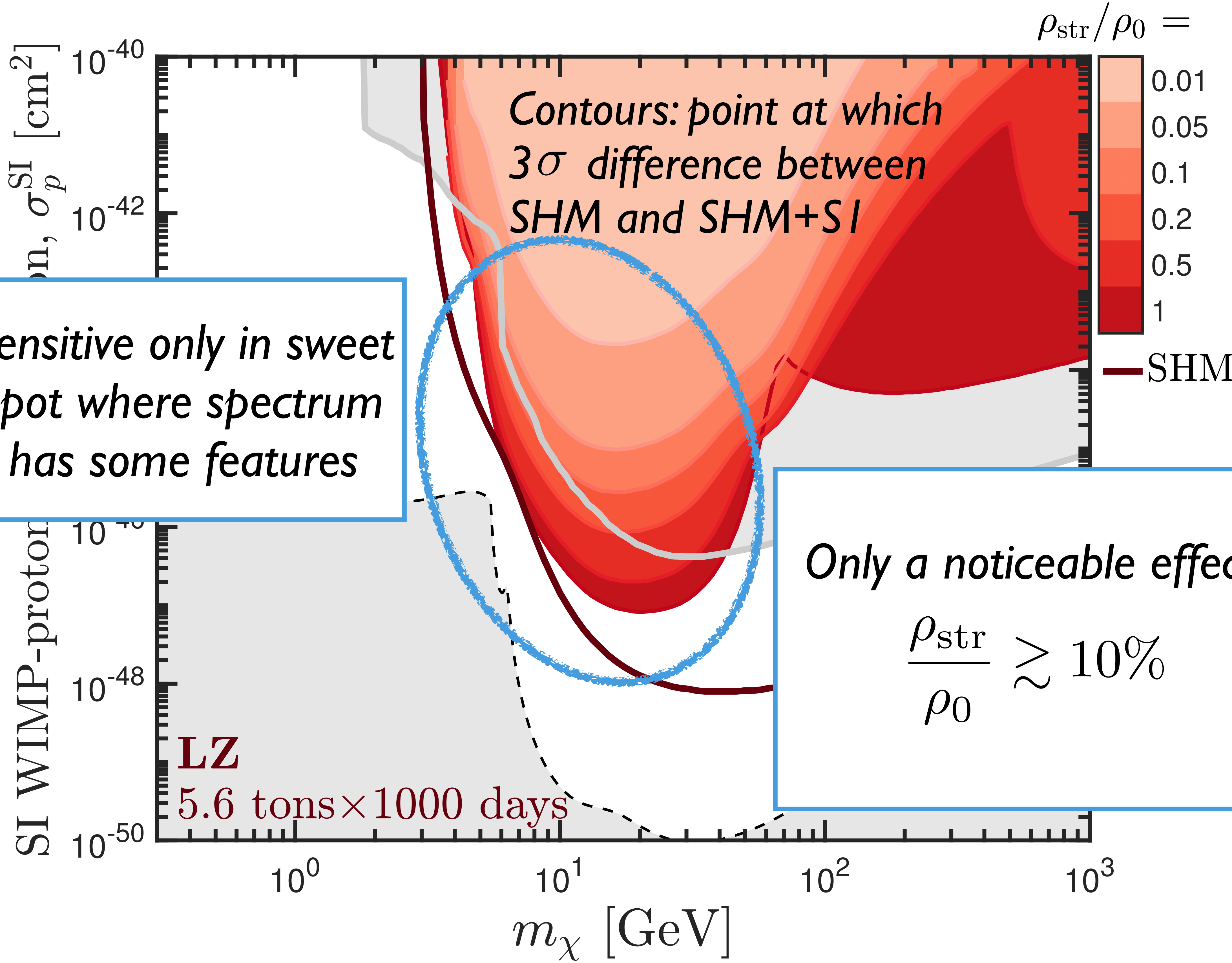
Spectrum is relatively featureless…

…except in a sweet spot around 20 GeV

Xenon: distinguishing SHM and SHM+S1



How big is the effect?

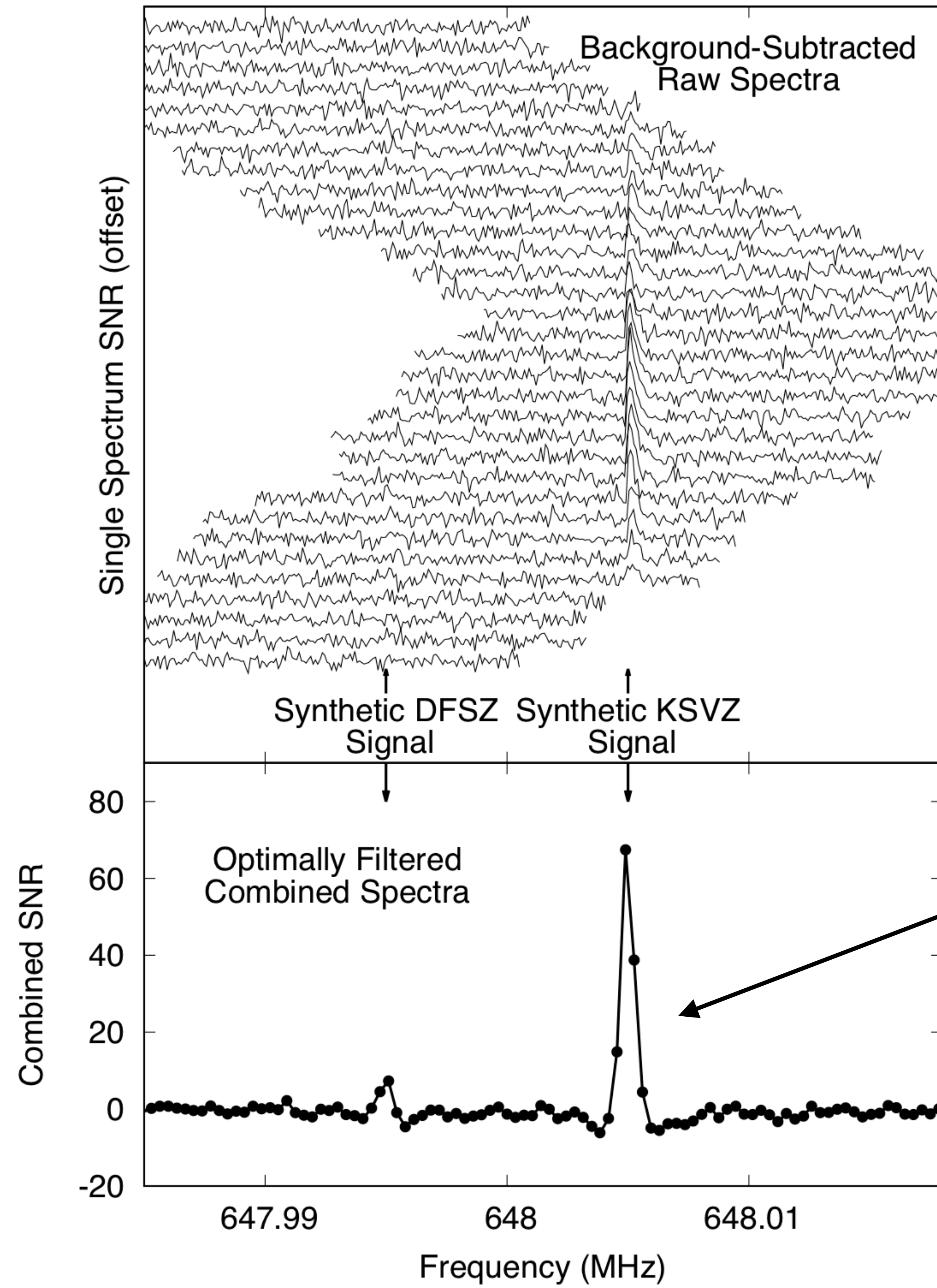


Sensitive only in sweet spot where spectrum has some features

Only a noticeable effect if

$$\frac{\rho_{\rm str}}{\rho_0} \gtrsim 10\%$$

Axion haloscope: example signal



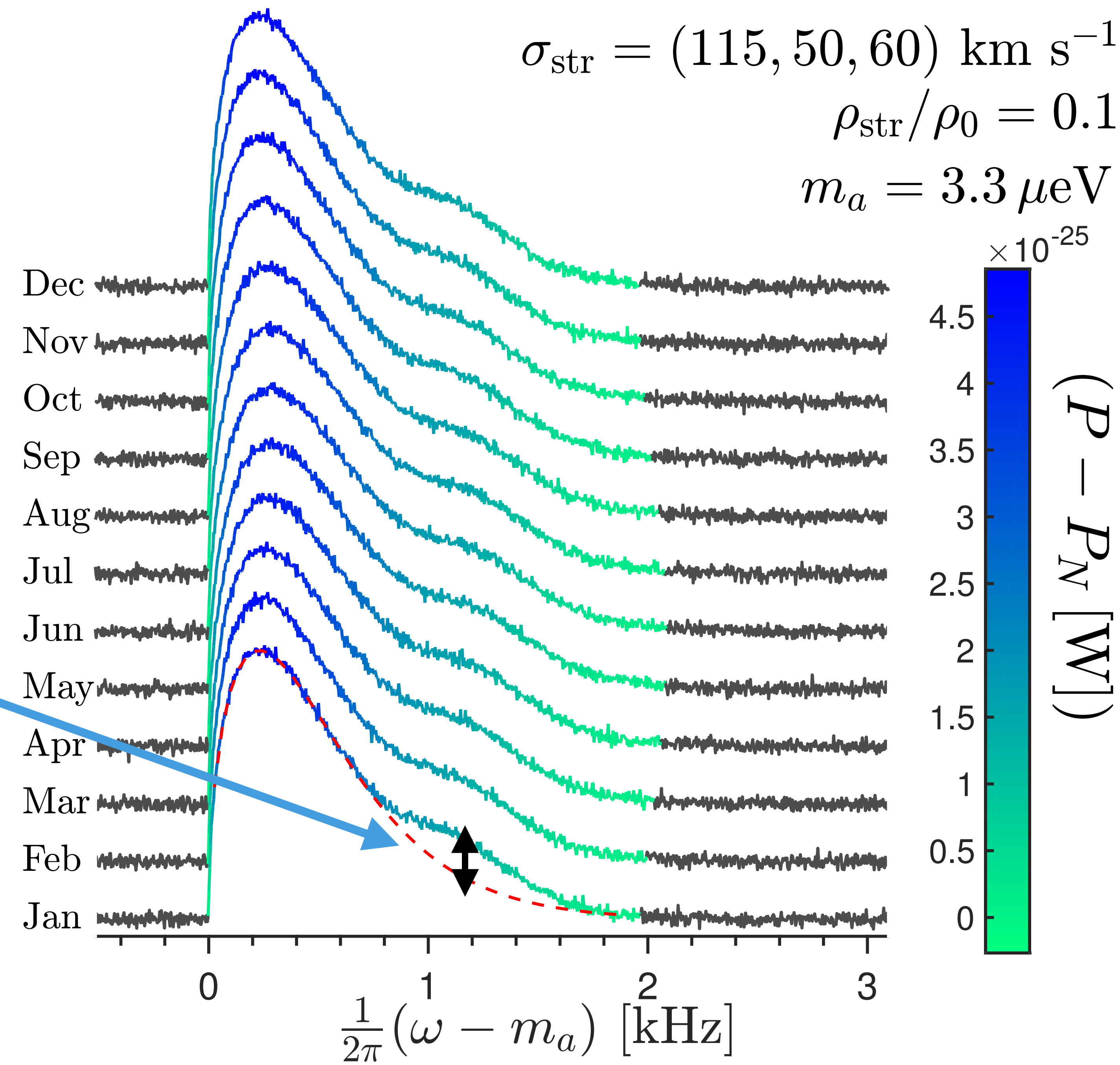
If signal detected, can tune to that frequency

ADMX: precision astronomy

Post discovery mode

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

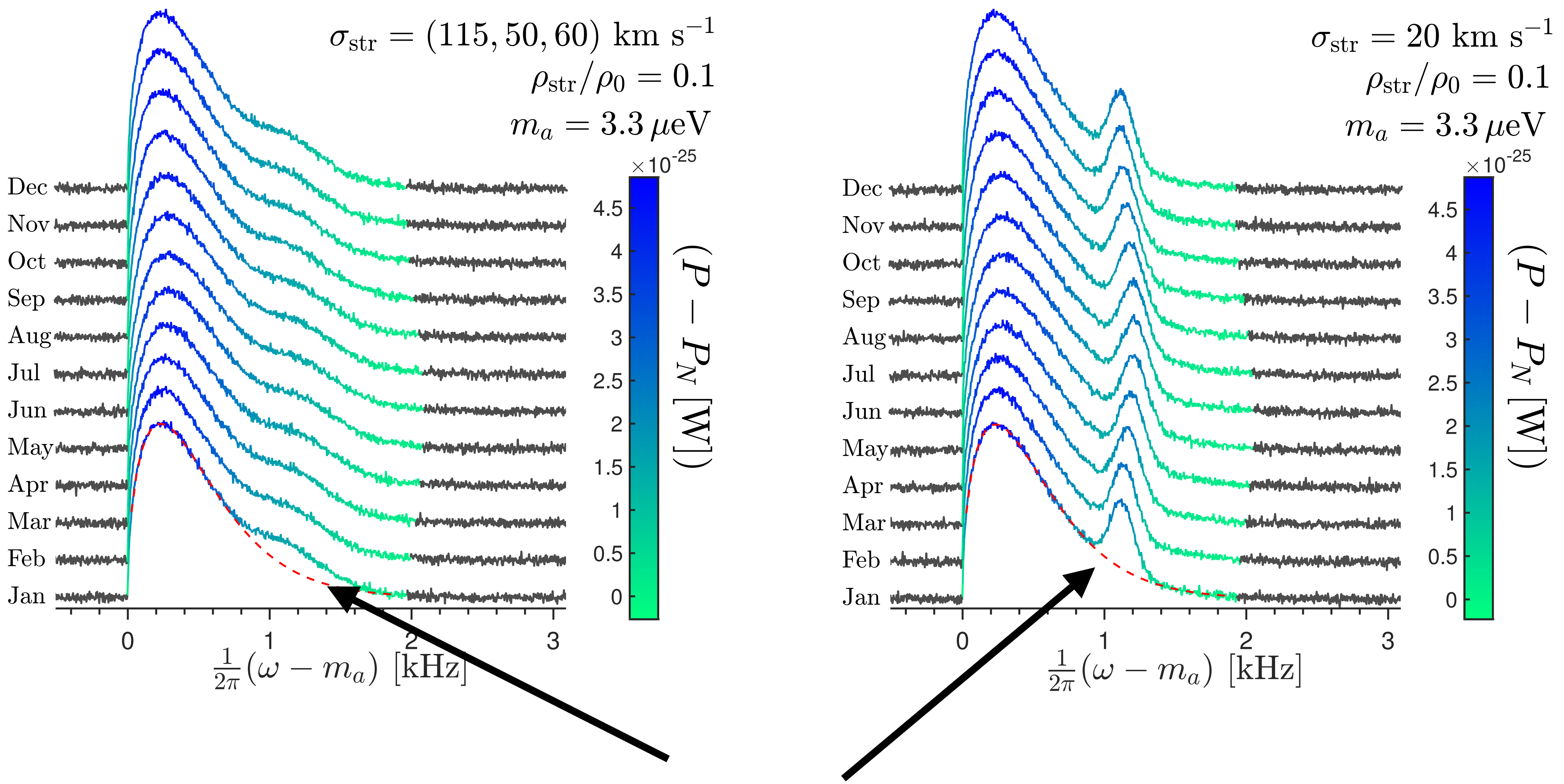
Sensitive even to sub-percent level



SHM only (dashed) SHM+S1 (solid)

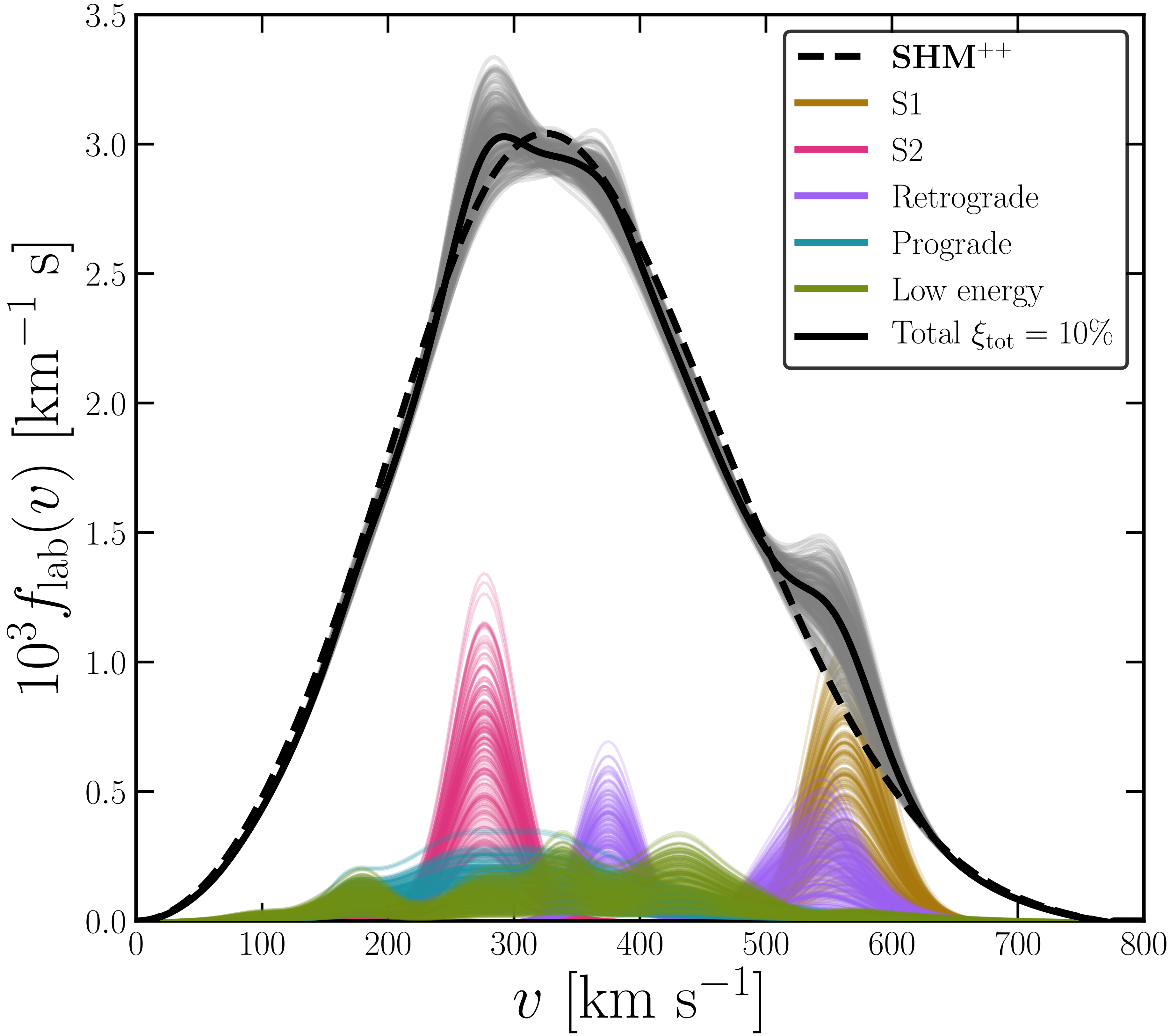
ADMX: precision astronomy

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



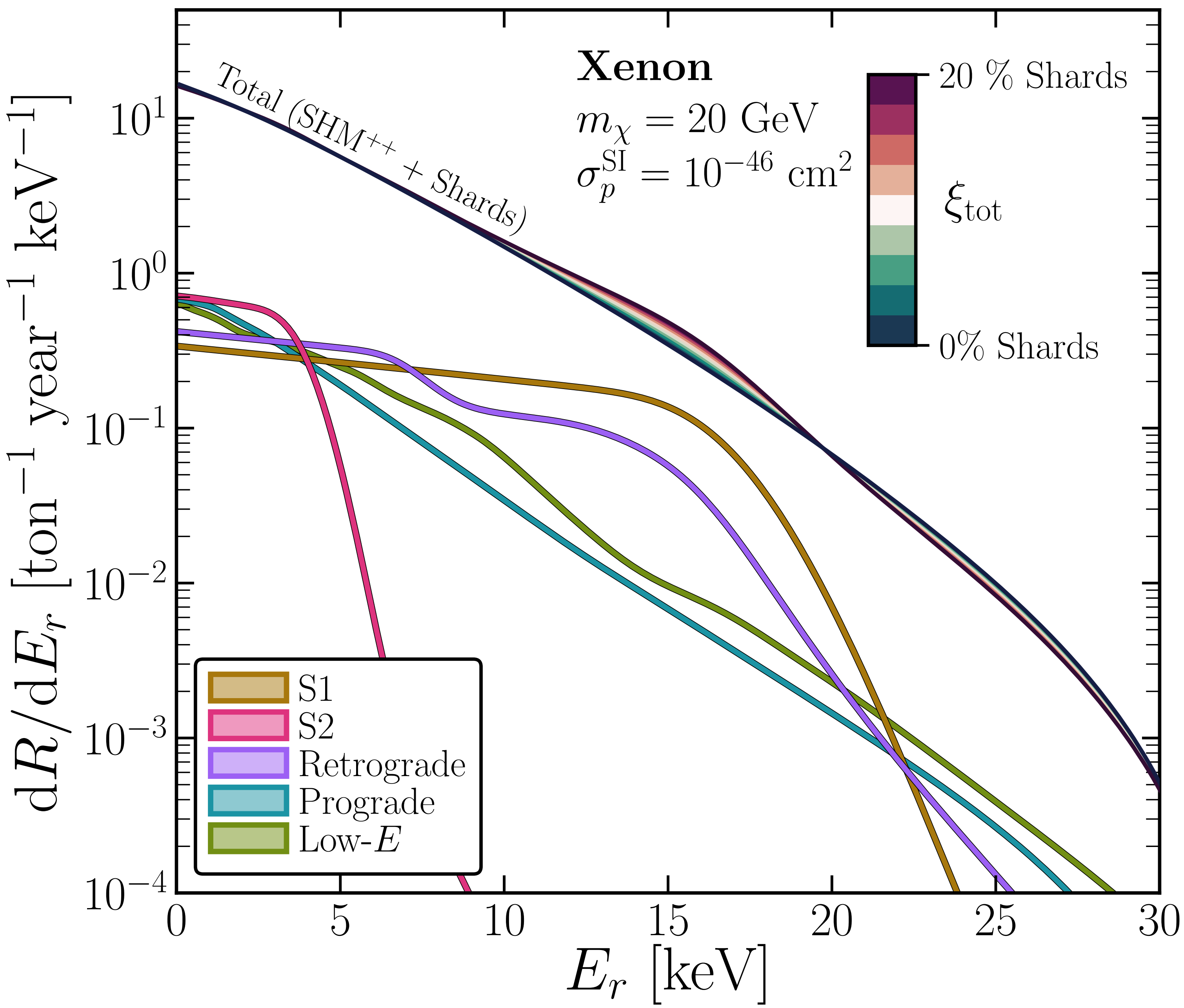
Height of feature depends on S1 density and velocity dispersion

More general substructure: 'Dark Shards'



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

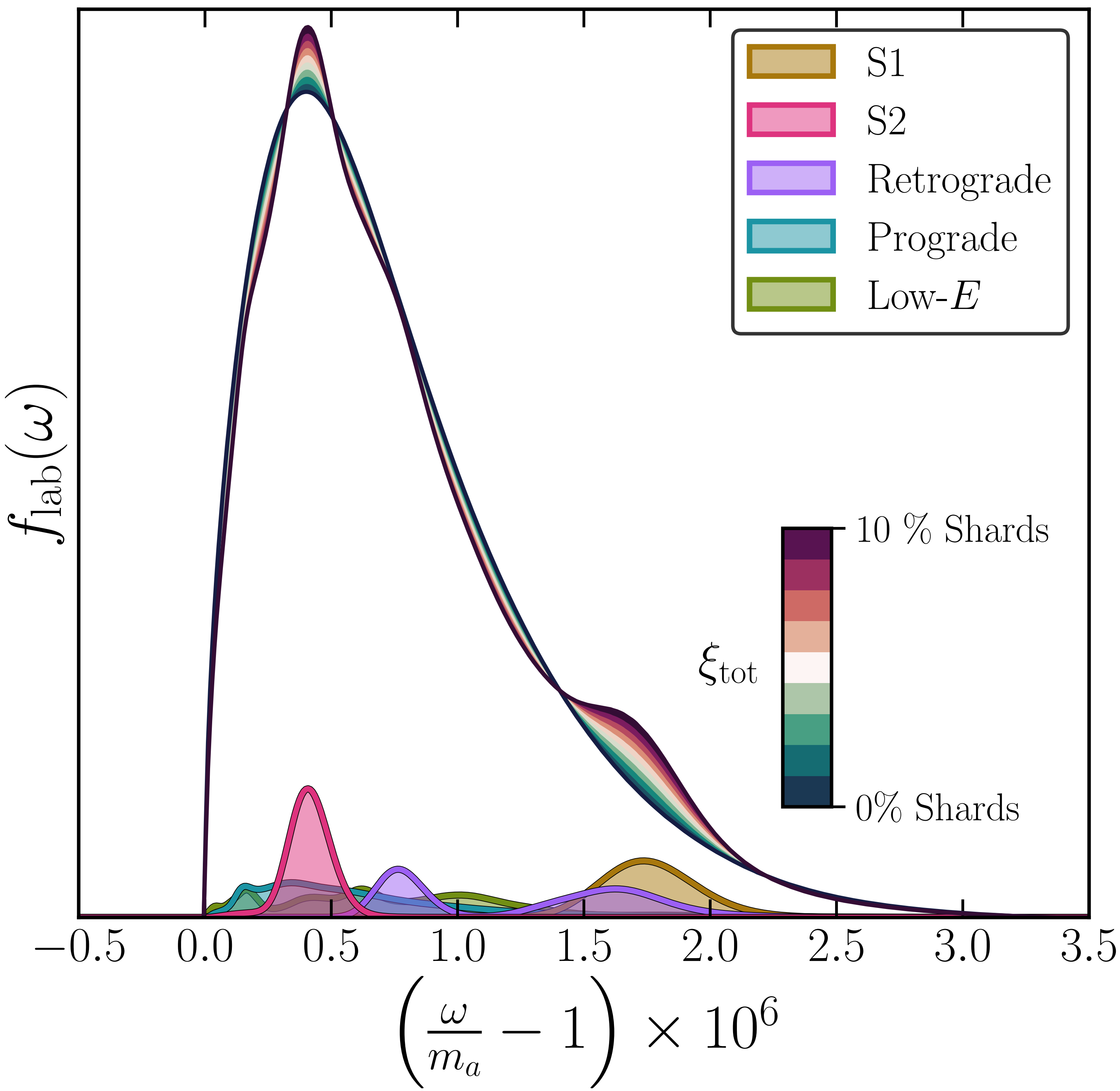
More general substructure



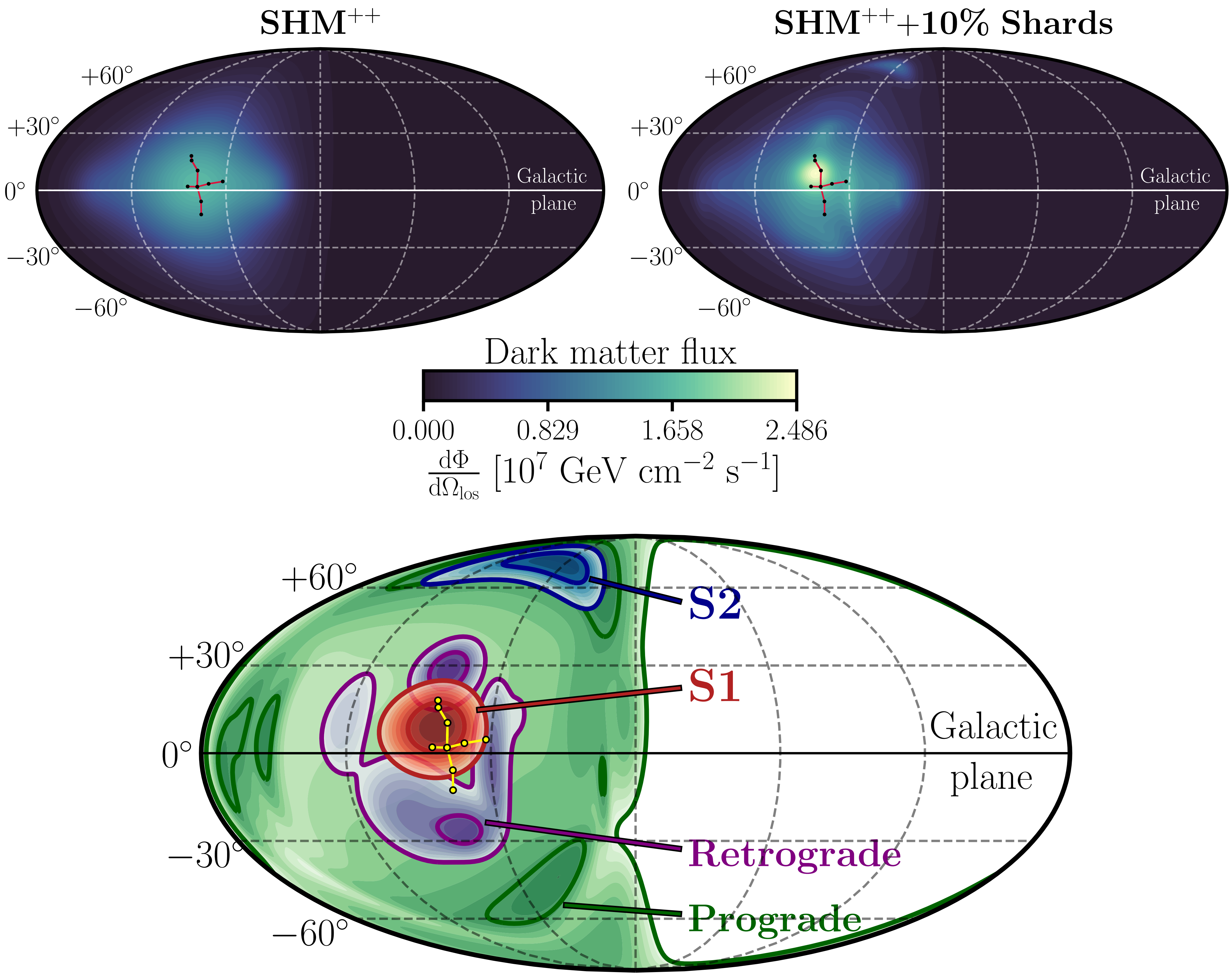
O'Hare, Evans, CM et al
arXiv:1909.04684

Impact on the nuclear recoil spectrum is always small

Axion haloscopes



Directional signals: hotspots away from Cygnus



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 stream and additional substructure (more dramatic)***

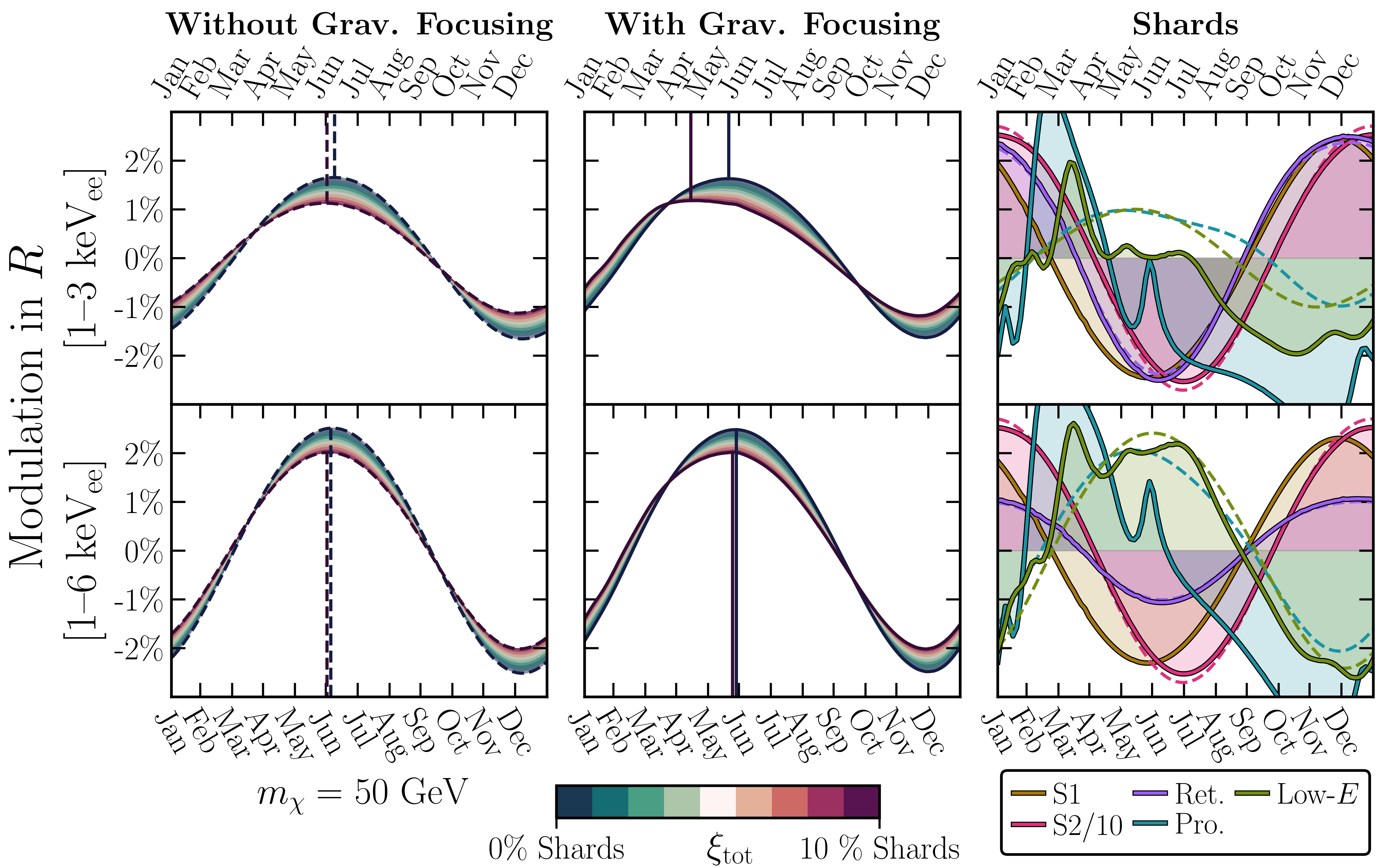
Next:

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

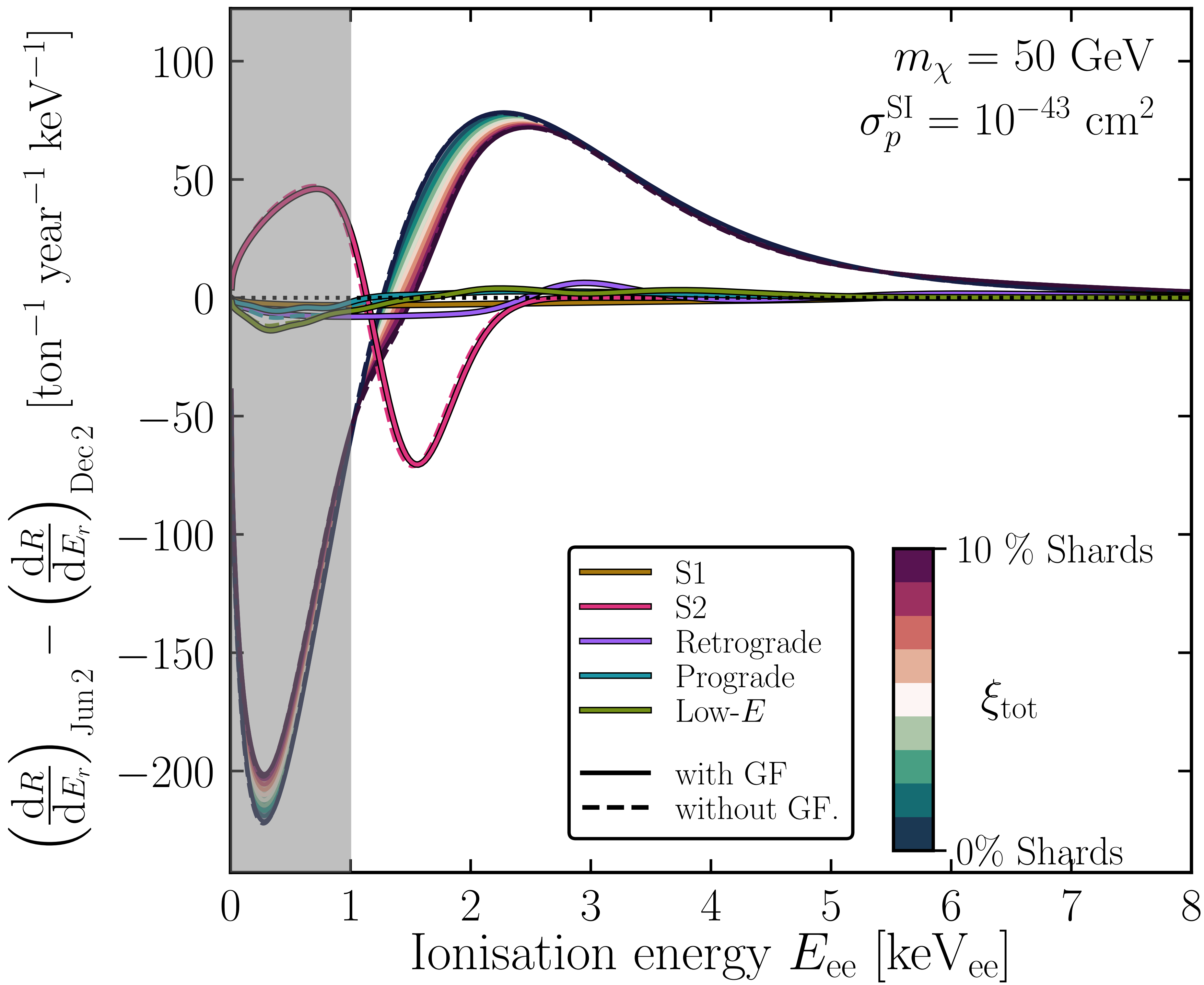
Thanks

Backup: effects of substructure can be important as the following slides show

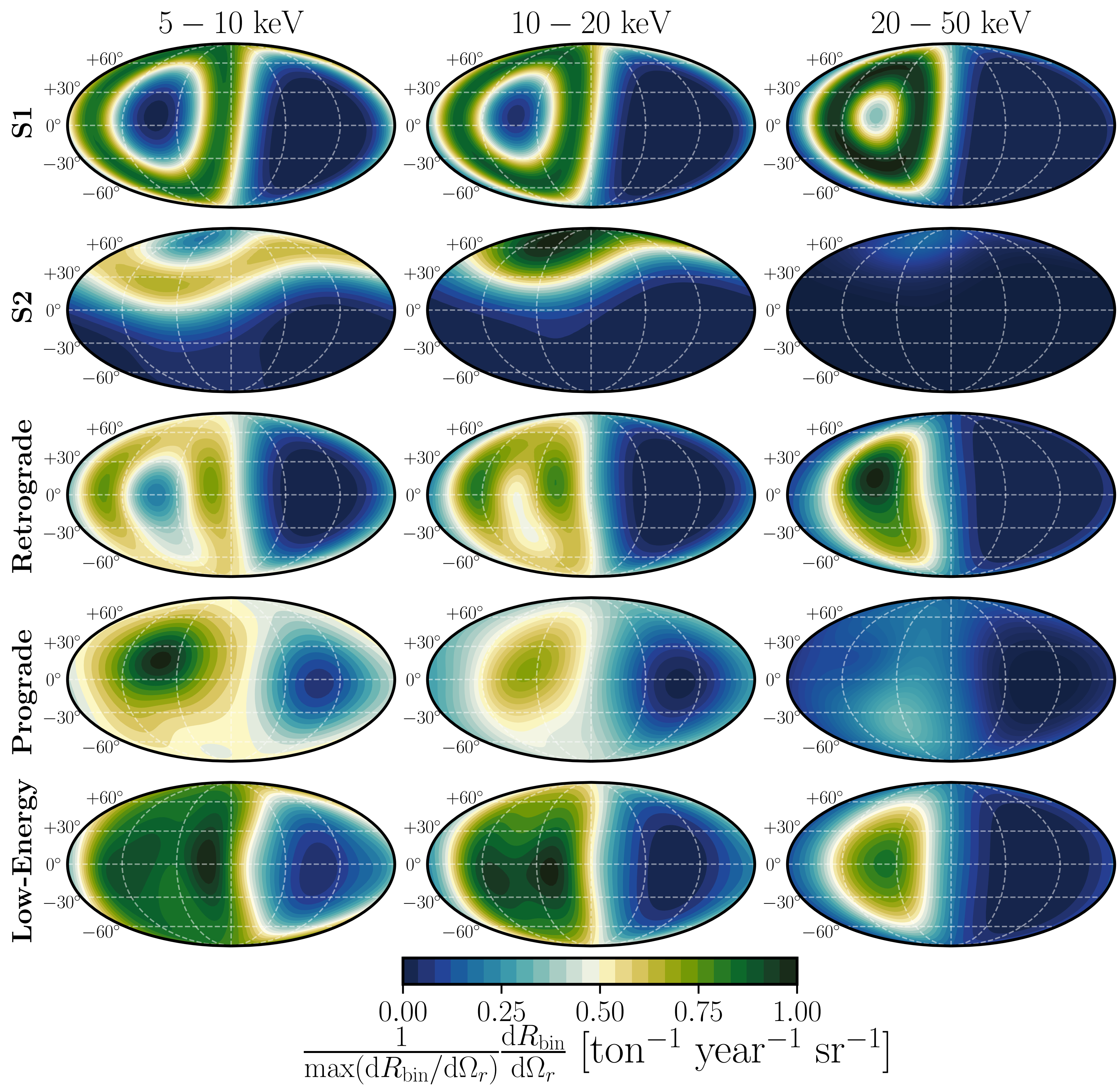
Modulation signals: peak day changes



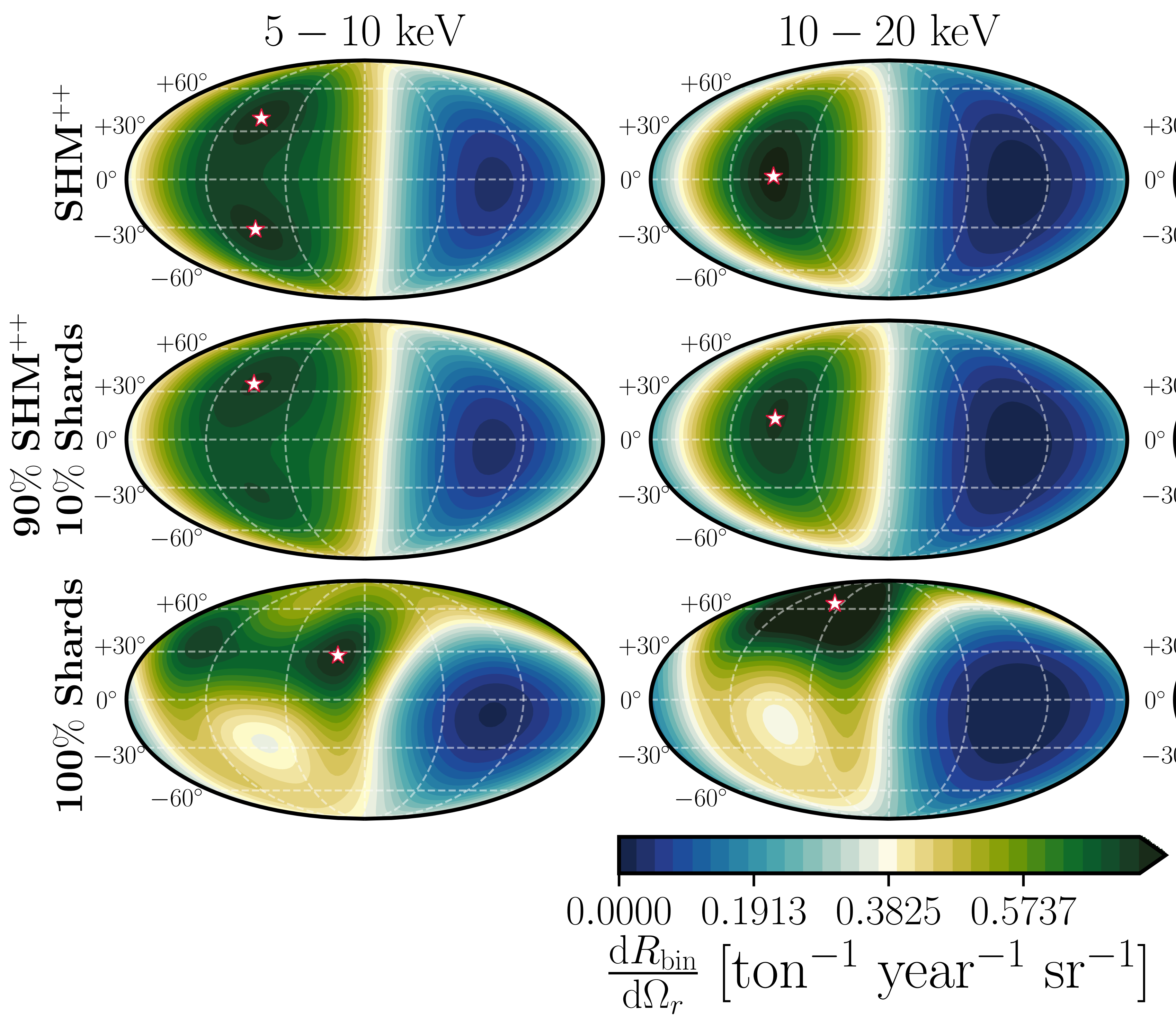
Modulation signals: amplitude changes



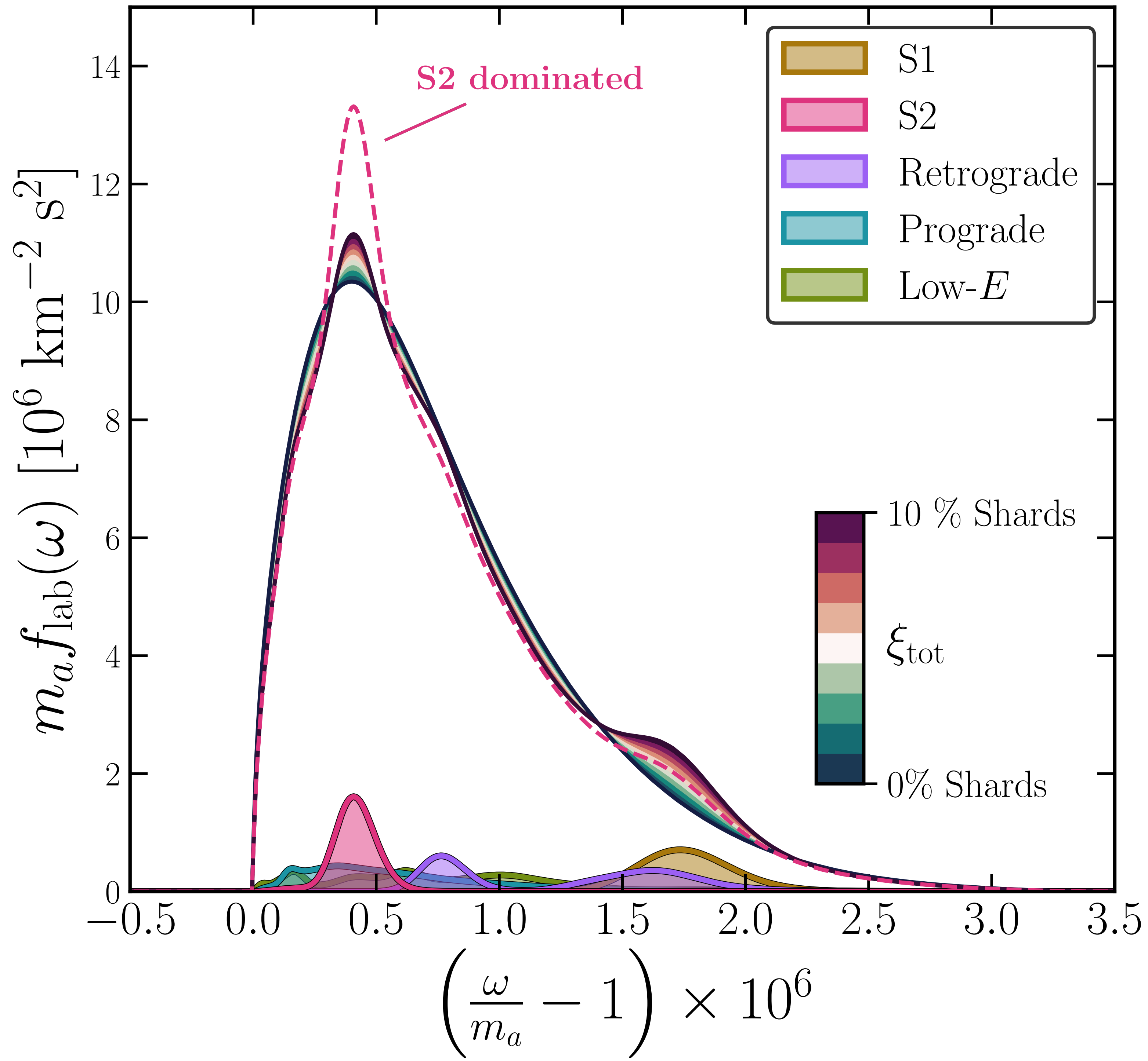
Directional signals: hotspots away from Cygnus



Directional signals: hotspots away from Cygnus



Axion power spectrum: S1 and S2 leave distinctive features



Sun's speed

$$f_{\mathrm{Earth}}(\mathbf{v},t) = f_{\mathrm{Gal}}(\mathbf{v} + \underbrace{\mathbf{v_0} + \mathbf{v_{pec}}} + \mathbf{v}_{\mathrm{E}}(t))$$

$$\frac{\vec{v}_{\mathrm{Sun}}}{R_0} = 30.24 \pm 0.12\ \mathrm{km\,s^{-1}\,kpc^{-1}}$$

Well known

Reid & Brunthalter
arXiv:0408107 [astro-ph]

Earth distance from Gal. Centre now well known!

$$v_0 + V_{\mathrm{pec}} = 247.4 \pm 1.4\ \mathrm{km/s}$$

Gravity Collaboration
arXiv:1904.05721

$$V_{\mathrm{pec}} = 12 \pm 2\ \mathrm{km/s}$$

Schoenrich et al
arXiv:0912.3693

v_0 far from 220 km/s !

Time to update v0 to 235 km/s?

Also consistent
with McMillan
arXiv:1608.00971
and Eilers et al
arXiv:1810.09466

Escape speed

Standard value from RAVE (2006): $v_{\rm esc} = 544^{+64}_{-46}$ km/s   arXiv:0611671

Better(?) RAVE result (2013): $v_{\rm esc} = 533^{+54}_{-41}$ km/s   arXiv:1309.4293

Best current value (with Gaia data): $v_{\rm esc} = 528^{+24}_{-25}$ km/s

Deason et al arXiv:1901.02016

Maintain the status-quo?
some preference for a lower value but 544 km/s still consistent

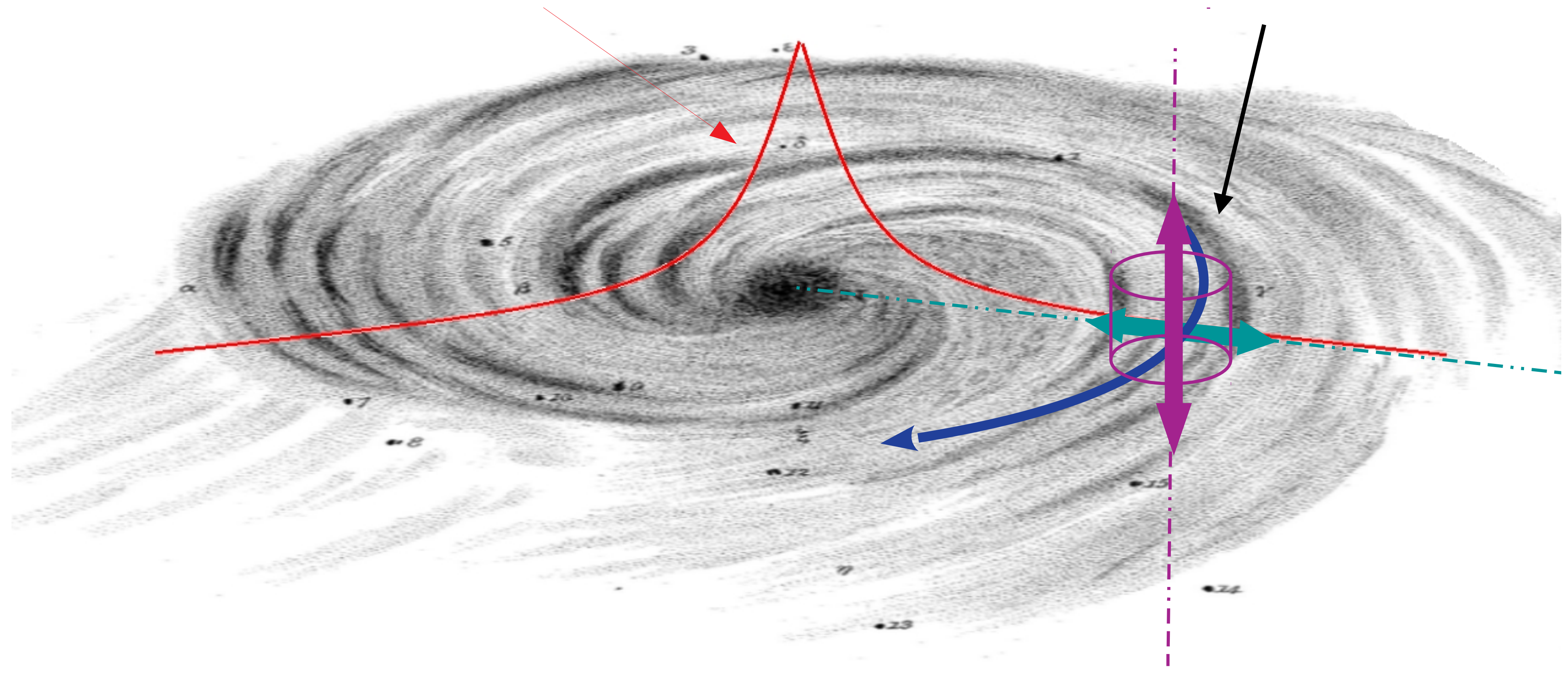
Local DM density

de Salas TAUP2019 talk

Two broad approaches to getting a value:

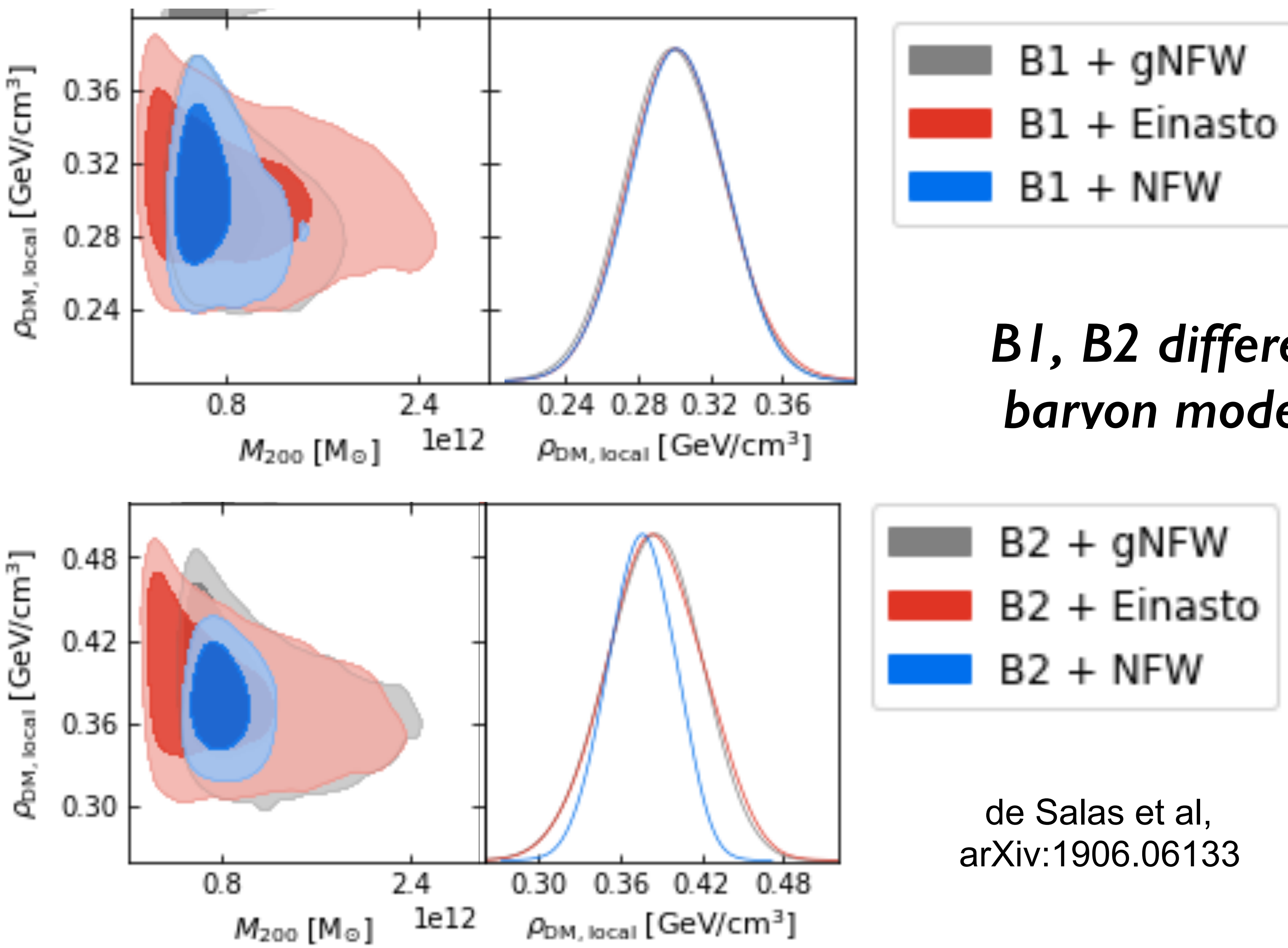
1. Global measurements
   e.g. fit rotation curves

2. Local measurements
   e.g. z Jeans equation



1. Global measurements

Model the whole of the Milky Way halo (baryons + dark matter)



B1, B2 different baryon models

de Salas et al, arXiv:1906.06133

Give values with smaller errors but with more model dependence

2. Local measurements

Model kinematics of stars near the Solar System

Sivertsson et al
arXiv:1708.07836

$$\rho_{\rm DM} = 0.46 \pm 0.1 \ {\rm GeV/cm^3}$$

Hagen et al
arXiv:1802.09291

$$\rho_{\rm DM} = 0.68 \pm 0.08_{\rm stat.} \pm 0.23_{\rm syst.} \ {\rm GeV/cm^3}$$

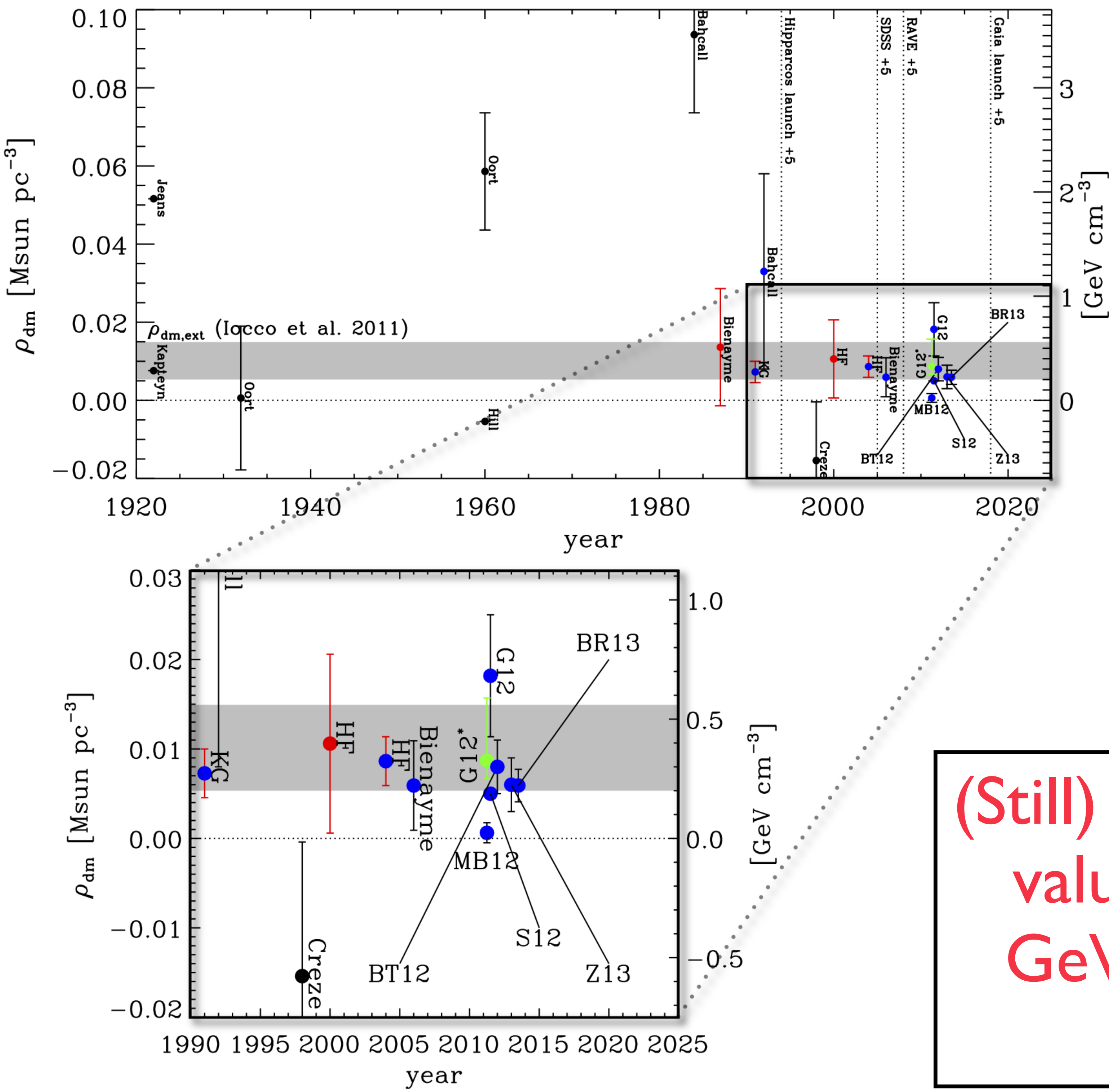
Buch et al
arXiv:1808.05603

$$\rho_{\rm DM} = 0.61 \pm 0.38 \ {\rm GeV/cm^3}$$

Give values with larger errors but with less* model dependence

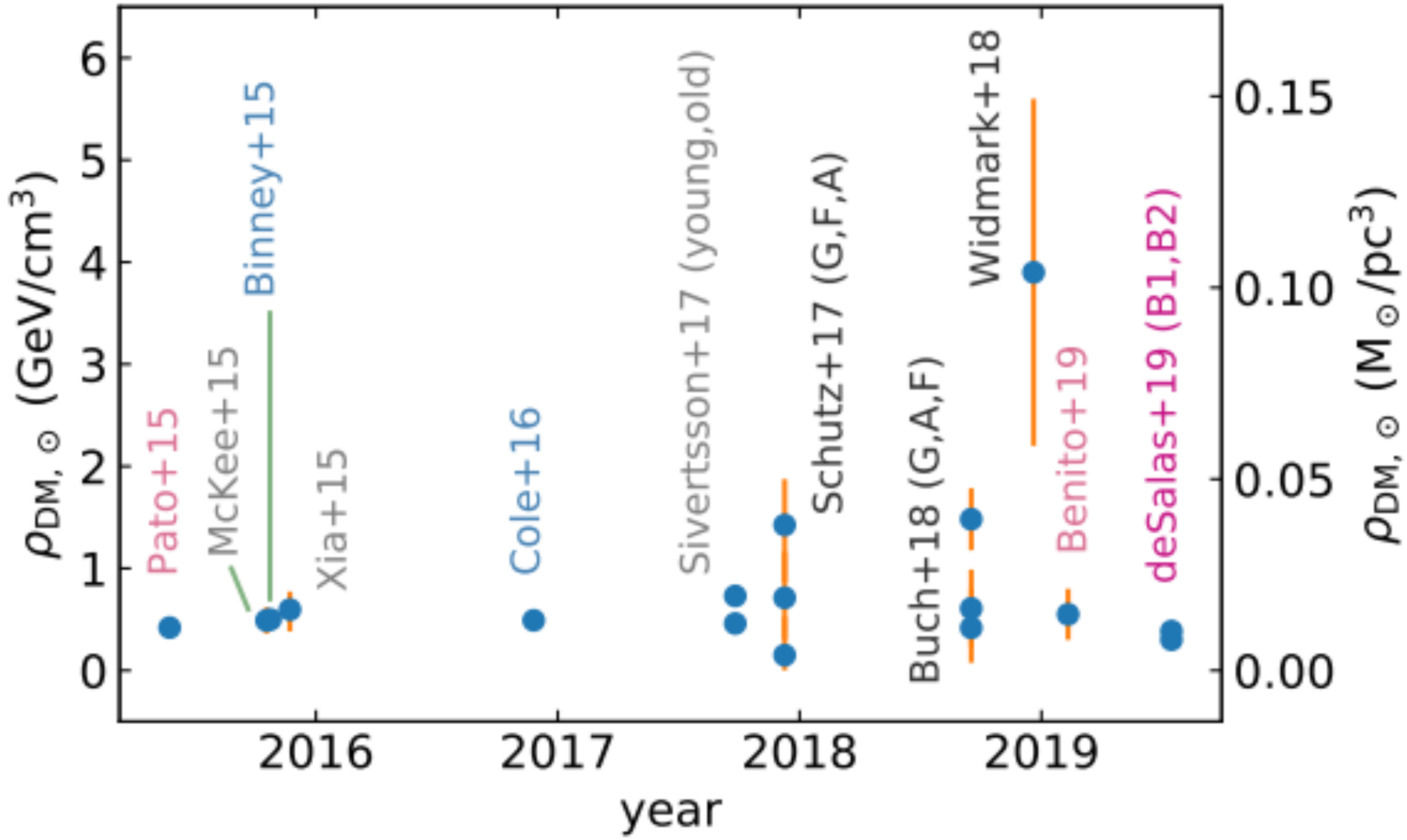
Local DM density over time

Excellent resource is the review by Justin Read (arXiv:1404.1938)



(Still) difficult to argue that any value in the range 0.2 - 0.6 GeV/cm³ is better than any other

Local DM density in recent years



Method:

- Rotation curve
- Distribution Function
- Vertical Jeans eq.

(dark colors: Gaia data)

de Salas TAUP2019 talk

(Still) difficult to argue that any value in the range 0.2 - 0.6 GeV/cm³ is better than any other