Quantifying the Local Dark Matter Distribution with 1000 Simulated Milky Ways

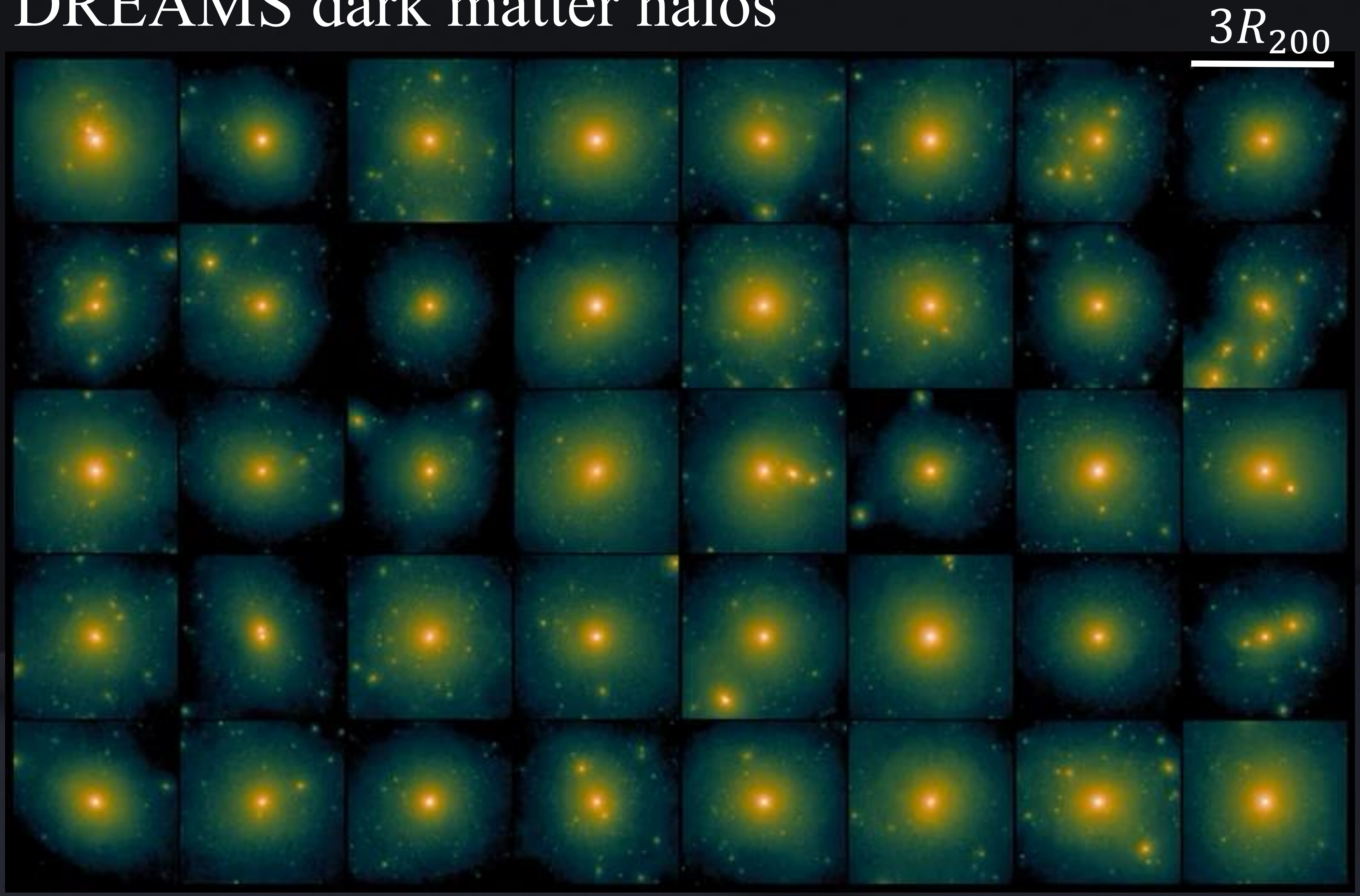
Ethan Lilie, June 11th, 2026

arXiv:2512.04157

Princeton Physics

Local Dark Matter Phase Space

DREAMS dark matter halos



Positions → $\rho(\vec{r})$

See A. Garcia et al. [2512.03132]

Velocities → $f(\vec{v})$

(at 8 kpc)

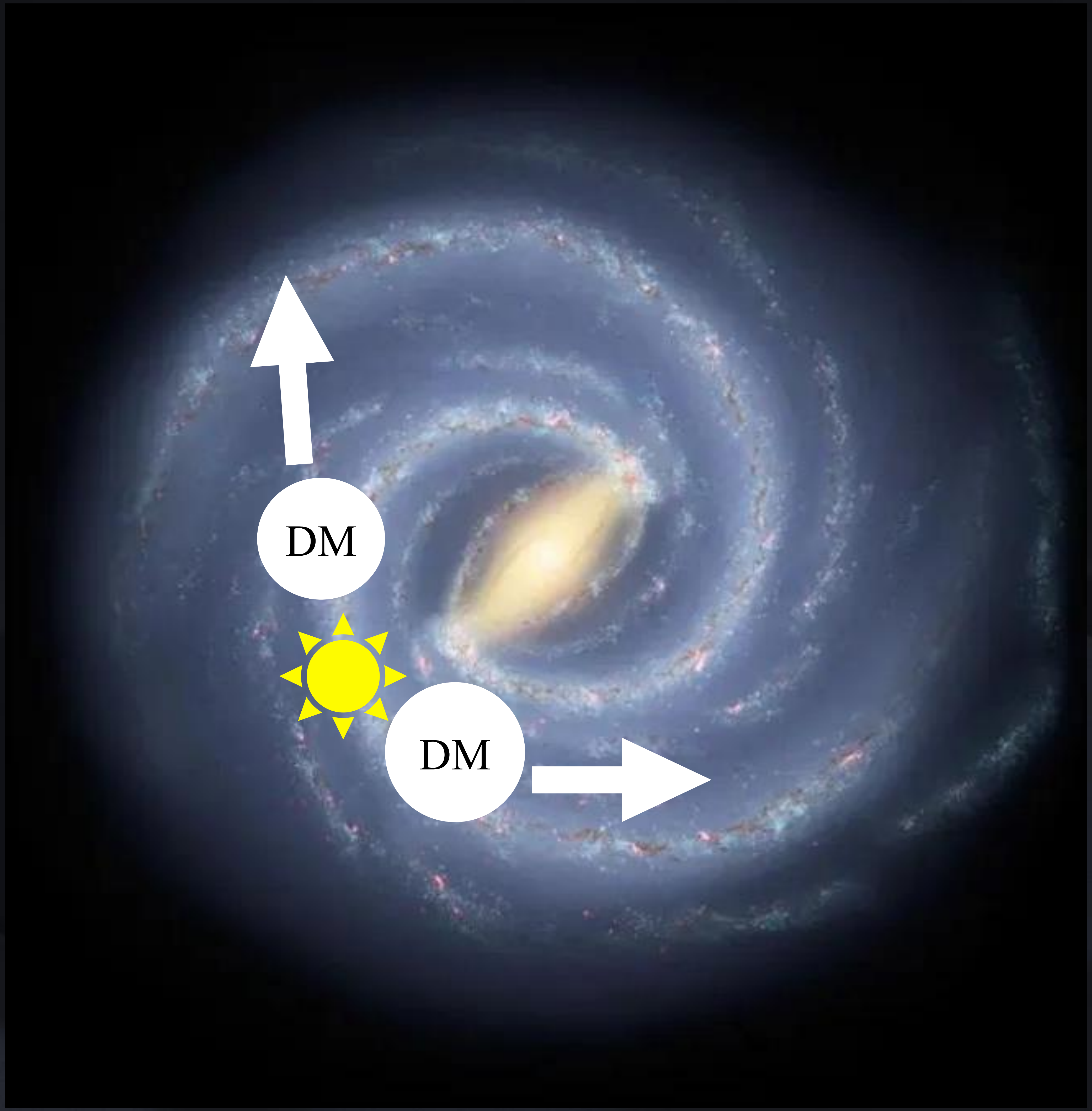
[Alex Garcia]

Contributions to Speed Distributions

Baryonic disk

Galactic properties

Unique formation history



[NASA/JPL-Caltech]

Dark Matter Direct Detection

Differential event rate for direct detection

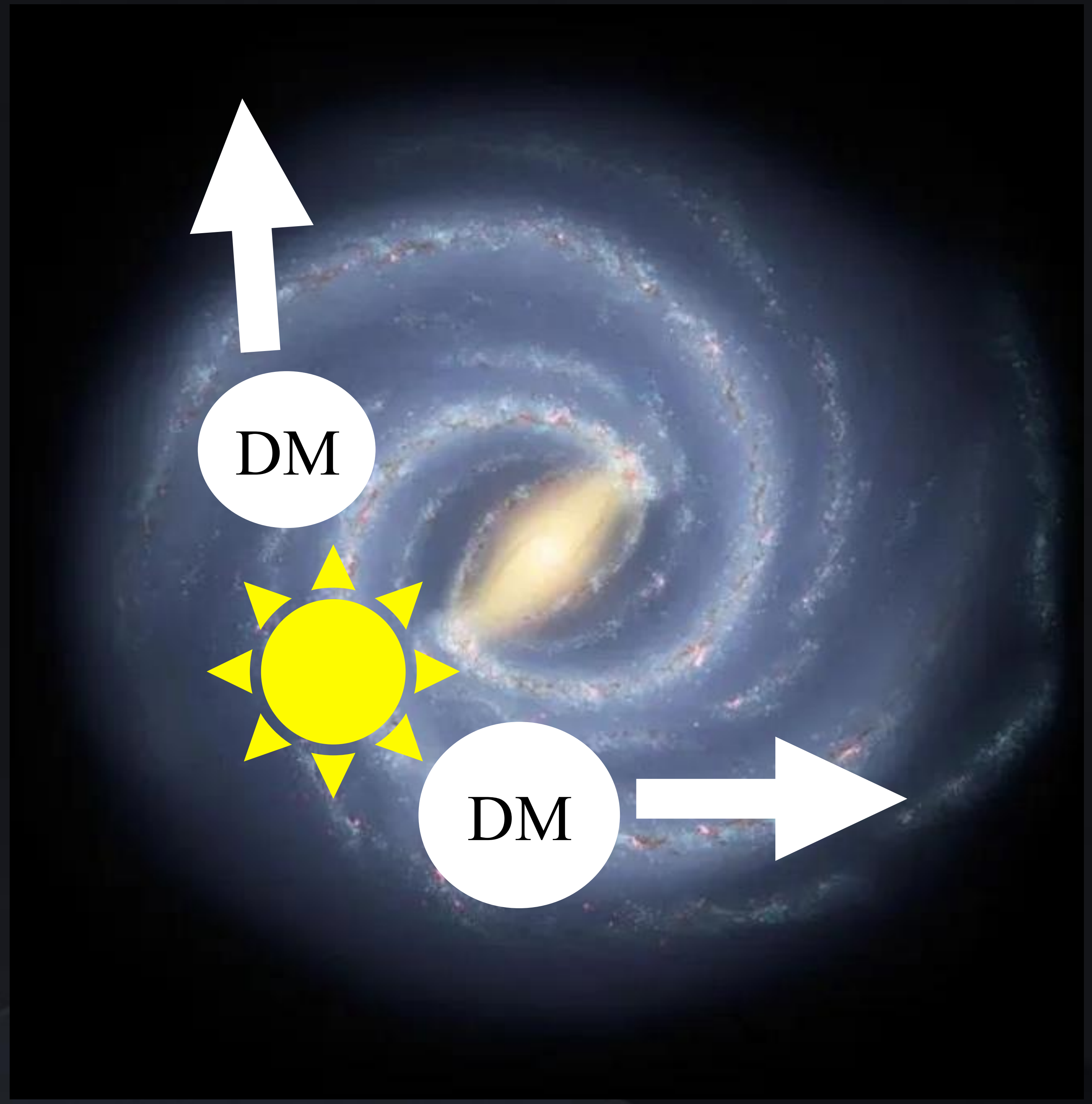
$$\frac{dR}{dE_R} \propto \rho_\chi \int_{v_{\min}}^{v_{\max}} d^3\vec{v}\; v\, f(\vec{v} - \vec{v}_{\mathrm{earth}}) \frac{d\sigma}{dE_R}$$

E_R: Nuclear recoil energy

$\frac{d\sigma}{dE_R}$: Differential scattering cross section

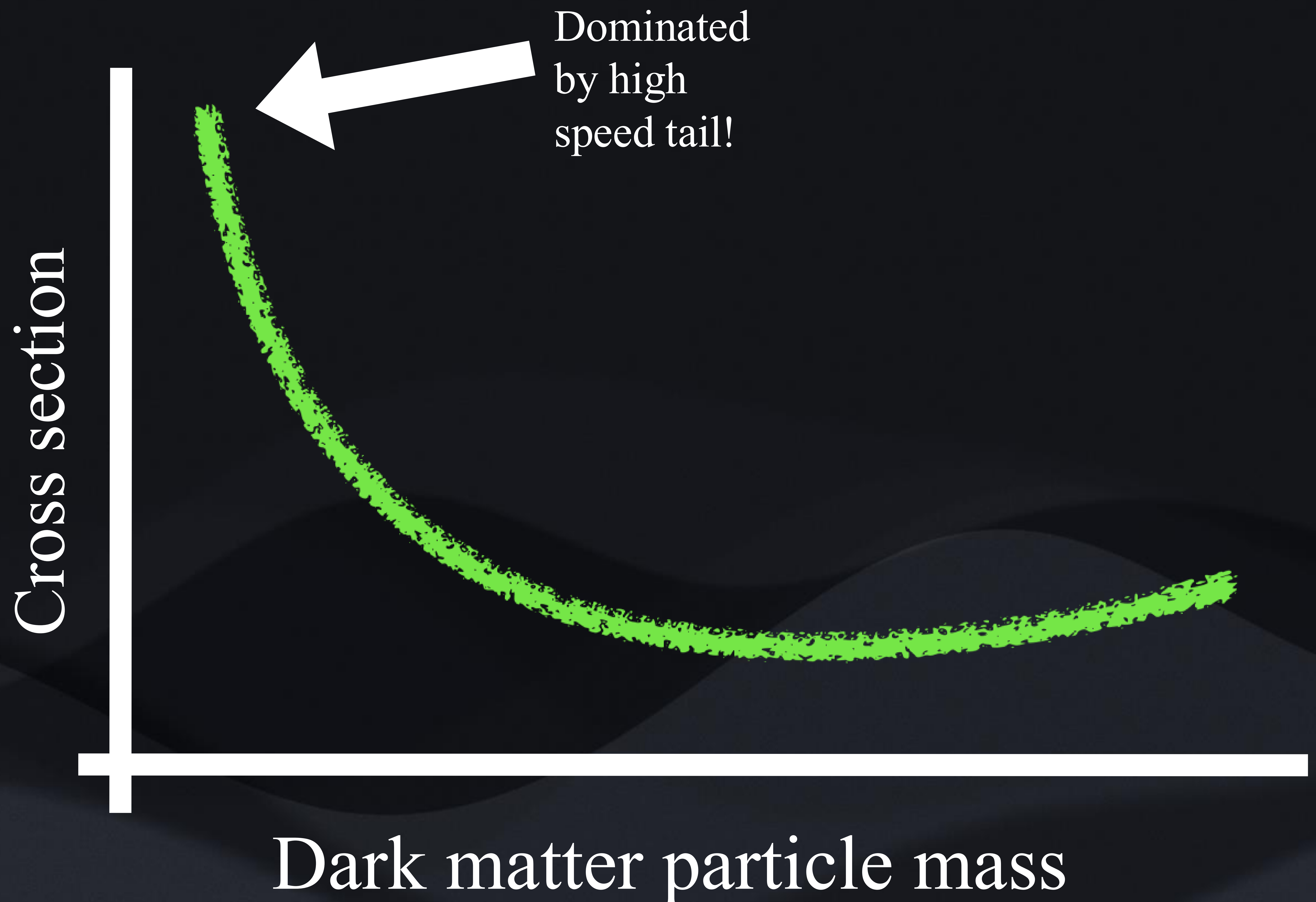
Local dark matter density $\rho_\chi = 0.3 - 0.6\mathrm{GeV/cm^3}$

Local velocity distribution near the Sun

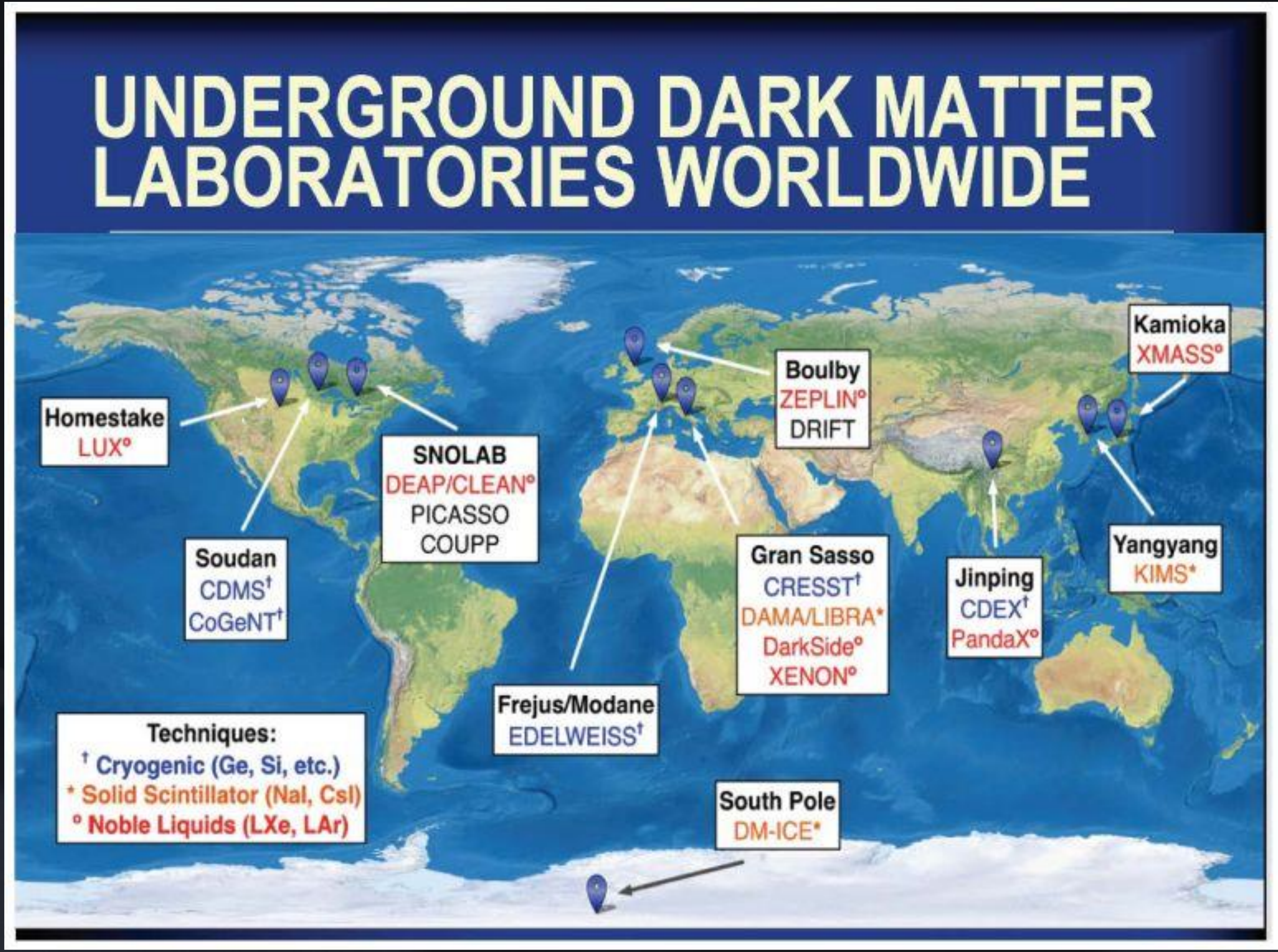


P. de Salas and A. Widmark [2012.11477]
[NASA/JPL-Caltech]

Dark Matter Direct Detection



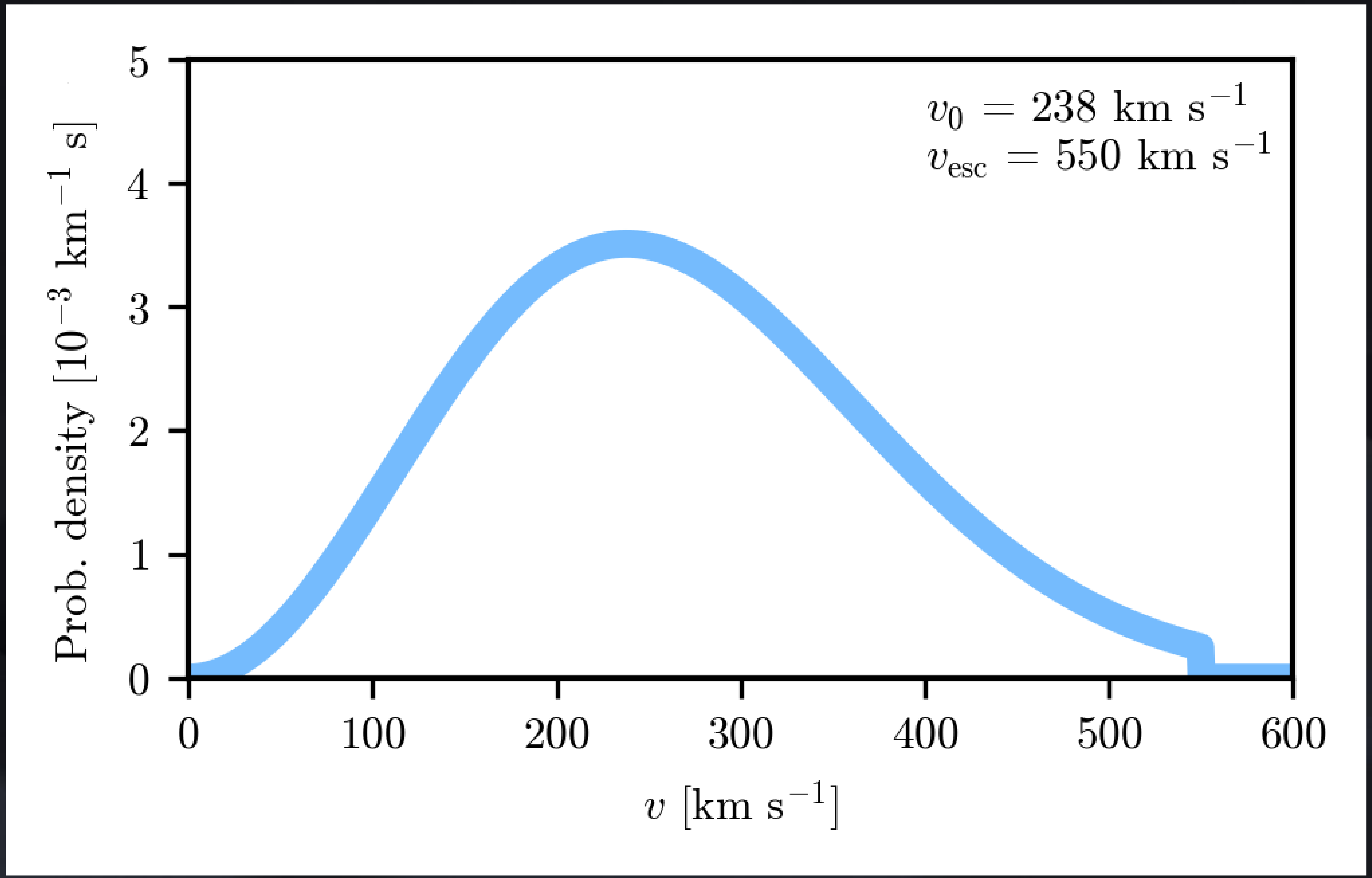
Dark Matter Direct Detection



[M. Tripathi and M. Wood]

Standard Halo Model

$$f(\vec{v}) = \frac{1}{N(v_0)} \exp\left(-\frac{\vec{v}^2}{v_0^2}\right) \Theta(v_{\mathrm{esc}} - |\vec{v}|)$$

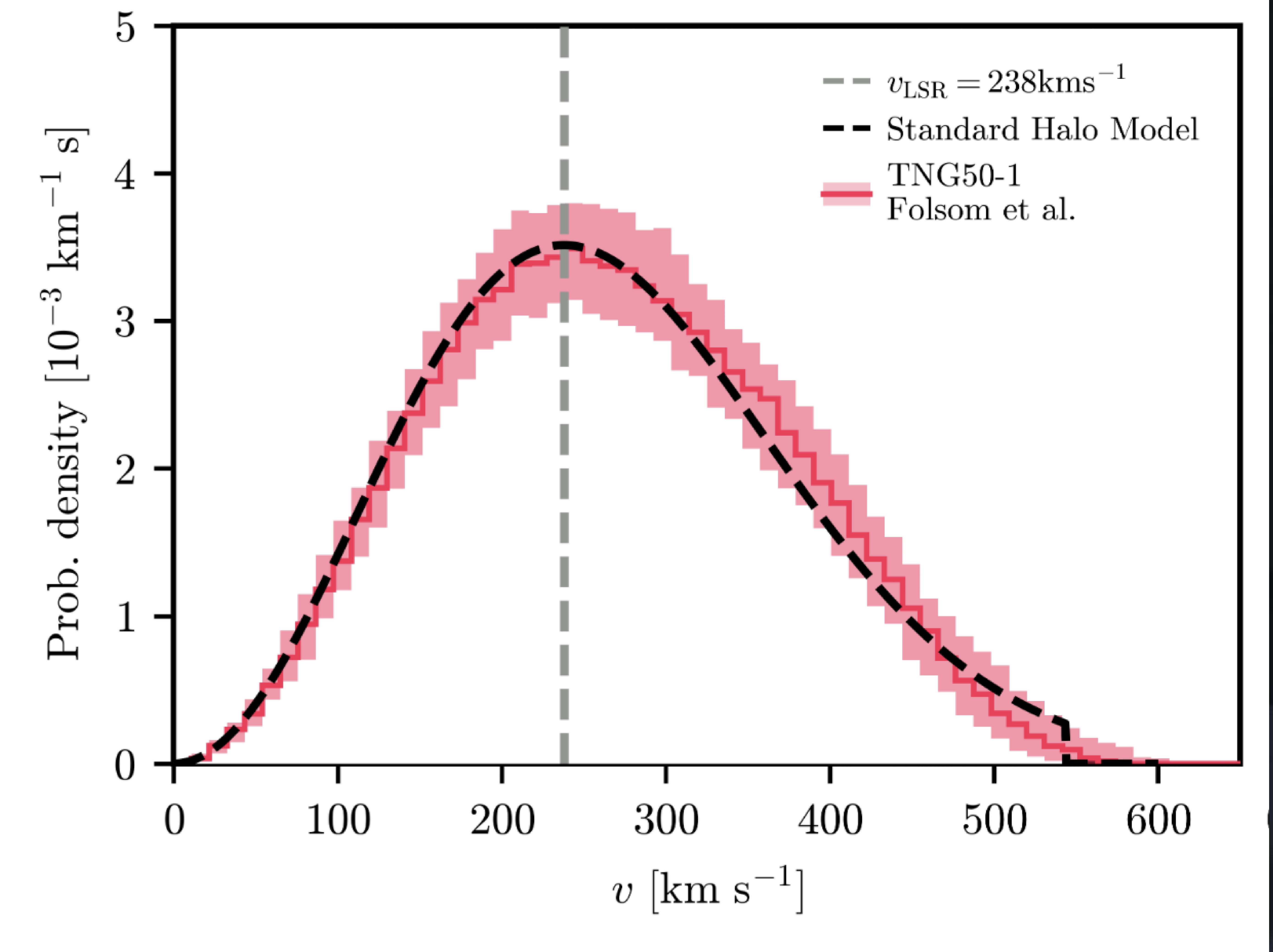


J. Bland-Hawthorn and O. Gerhard [1602.07702]
M.C. Smith et al. [0611671] [A. Drukier, K. Freese, D. Spergel 1986]

Speed Distributions in IllustrisTNG

98 Milky Way halos in TNG50-1

Ensemble consistent with the Standard Halo Model



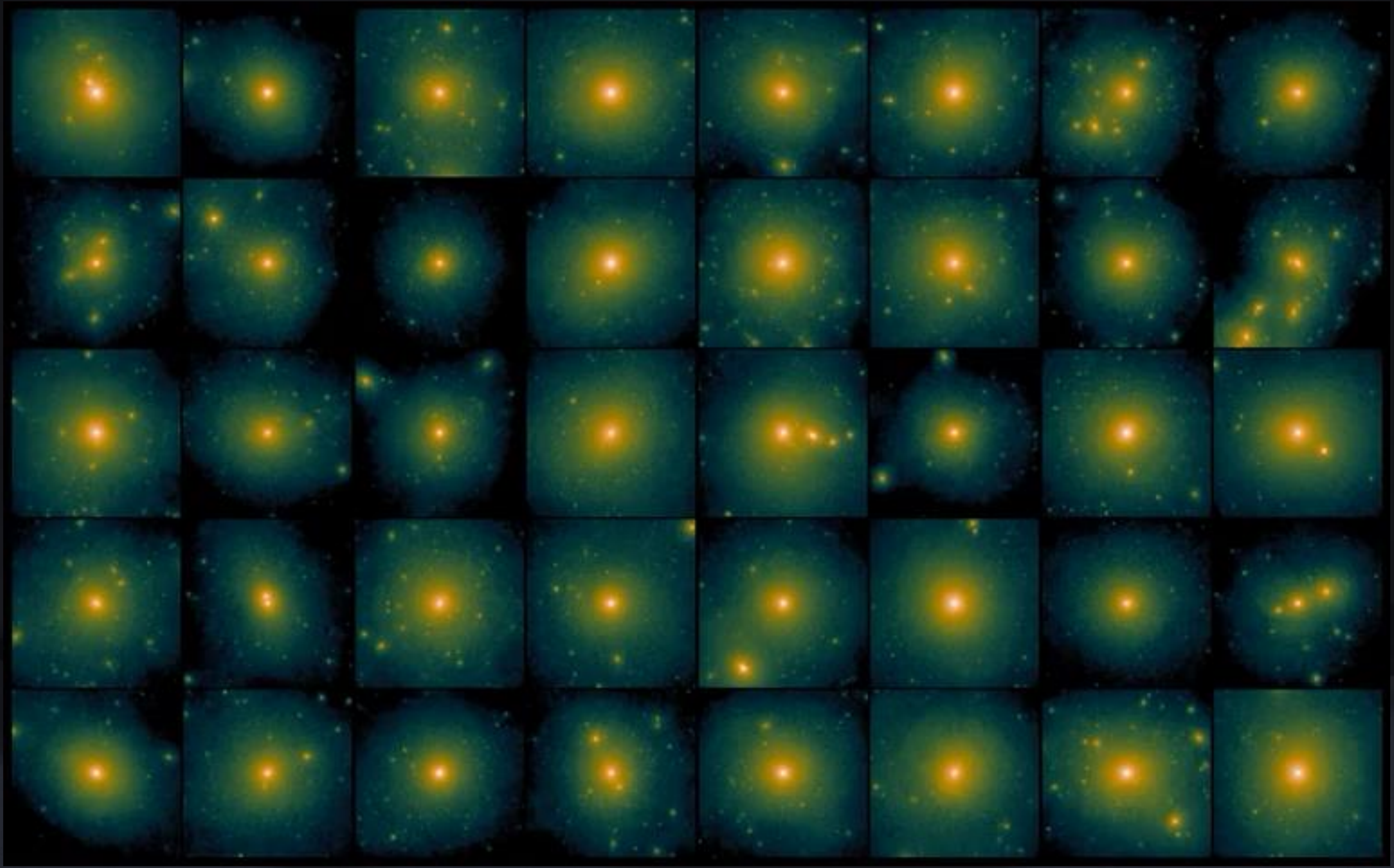
D. Folsom et al. [2505.0792]

DREAMS CDM Suite

1024 Milky Way-mass halos in cosmological boxes

TNG feedback model with varied parameters

Large halo-to-halo variation



J. Rose et al. [2512.00148]

[Alex Garcia]

Baryonic Feedback

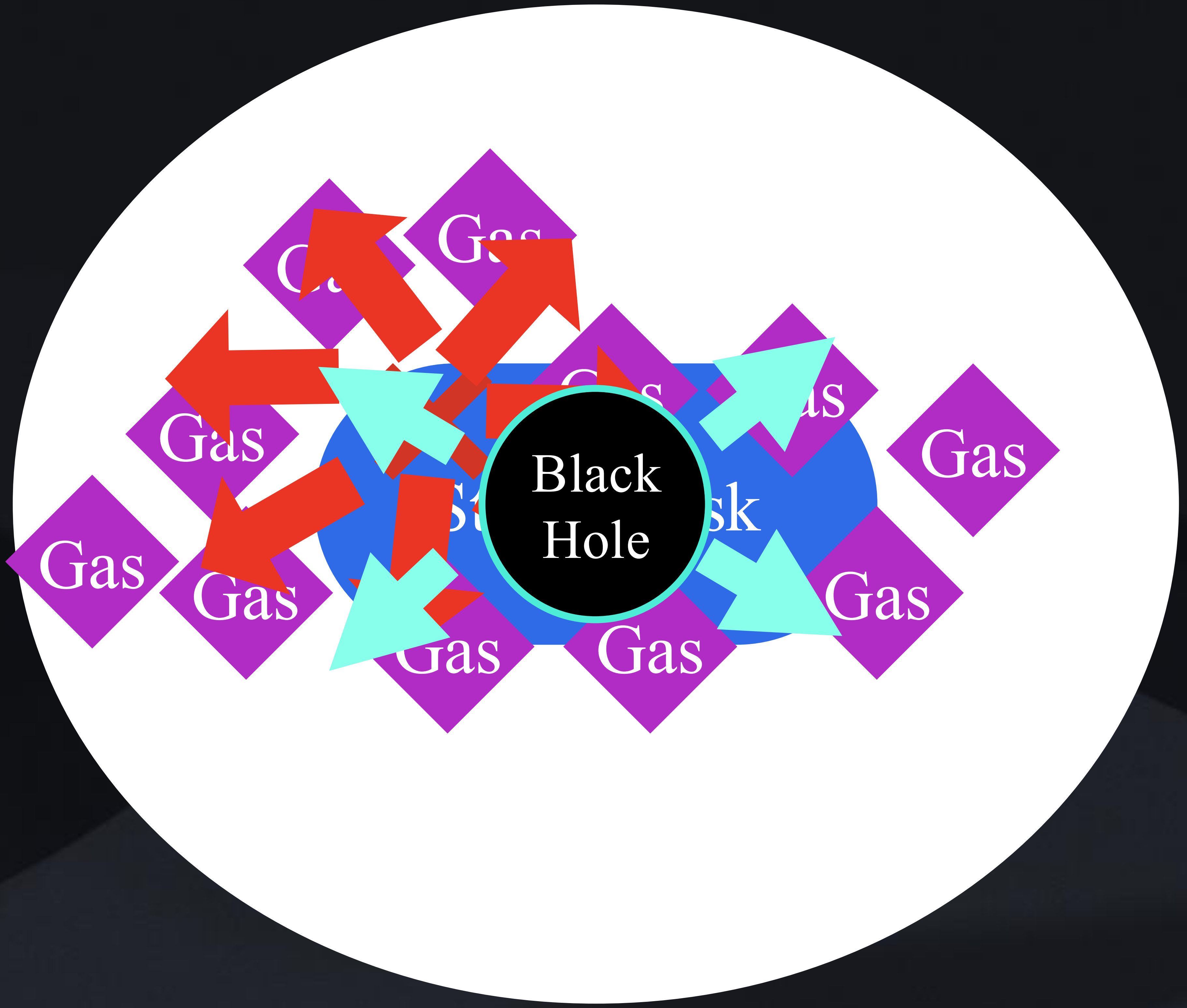
DREAMS suite varies over baryonic feedback parameters

Wind energy: $\bar{e}_w$

Wind speed: κ_w

AGN feedback: $\epsilon_{f,\mathrm{high}}$

Dark Matter Halo



A. Pillepich et al. [1703.02970]

Normalizing Flows Emulator

$\log \kappa_w$

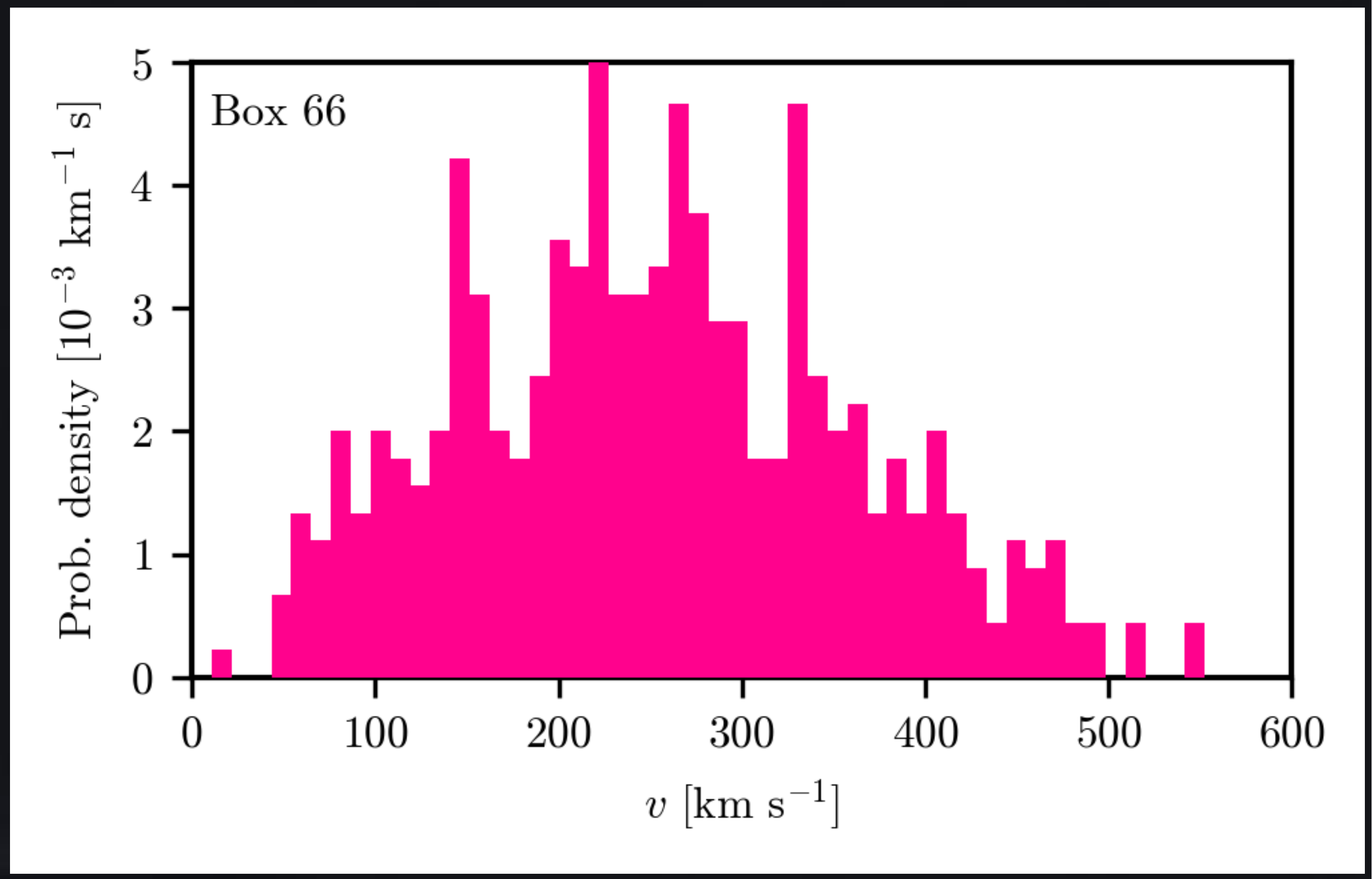
$\log \bar{e}_w$

$\log \epsilon_{f,\mathrm{high}}$

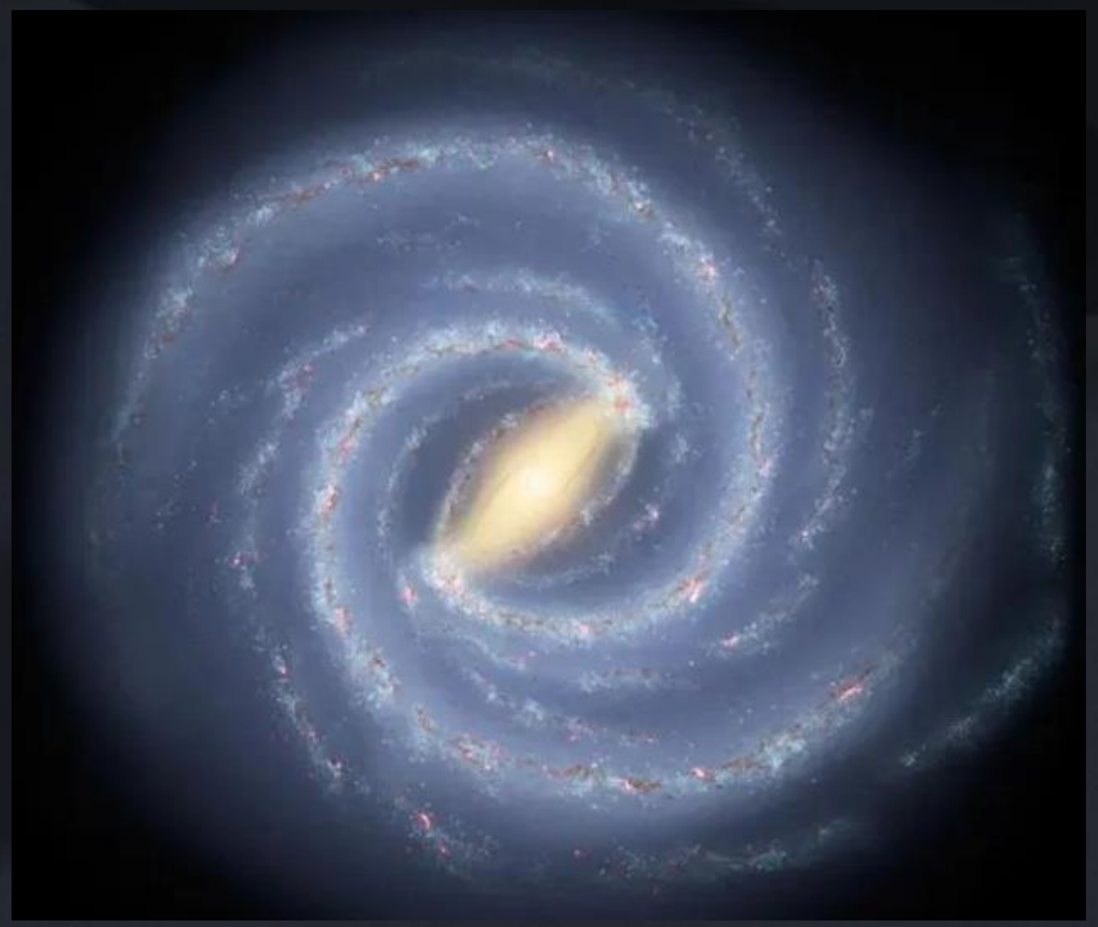
$\log M_{\mathrm{halo}}$

Emulator

Local Velocity Distribution



Milky Way Properties

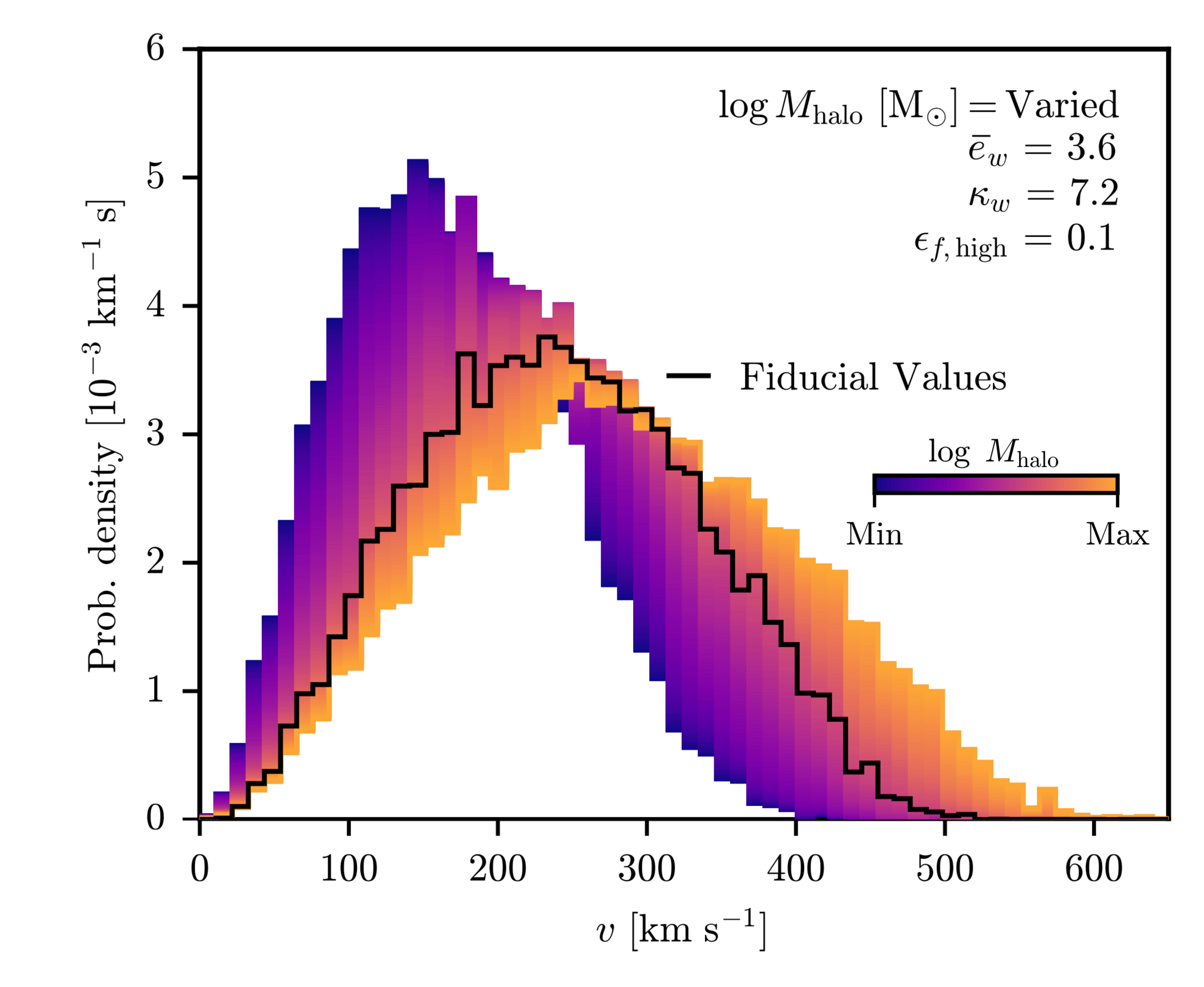


Halo Mass

$\log M_{\mathrm{halo}}/\mathrm{M}_{\odot} \in [11.6, 12.2]$

As halo mass increases, peak speed shifts from 150 kms^{-1} to 270 kms^{-1}

Fiducial Values:
$\log M_{\mathrm{halo}}/\mathrm{M}_{\odot} = 12$
$\bar{e}_w = 3.6$
$\kappa_w = 7.2$
$\epsilon_{f,\mathrm{high}} = 0.1$

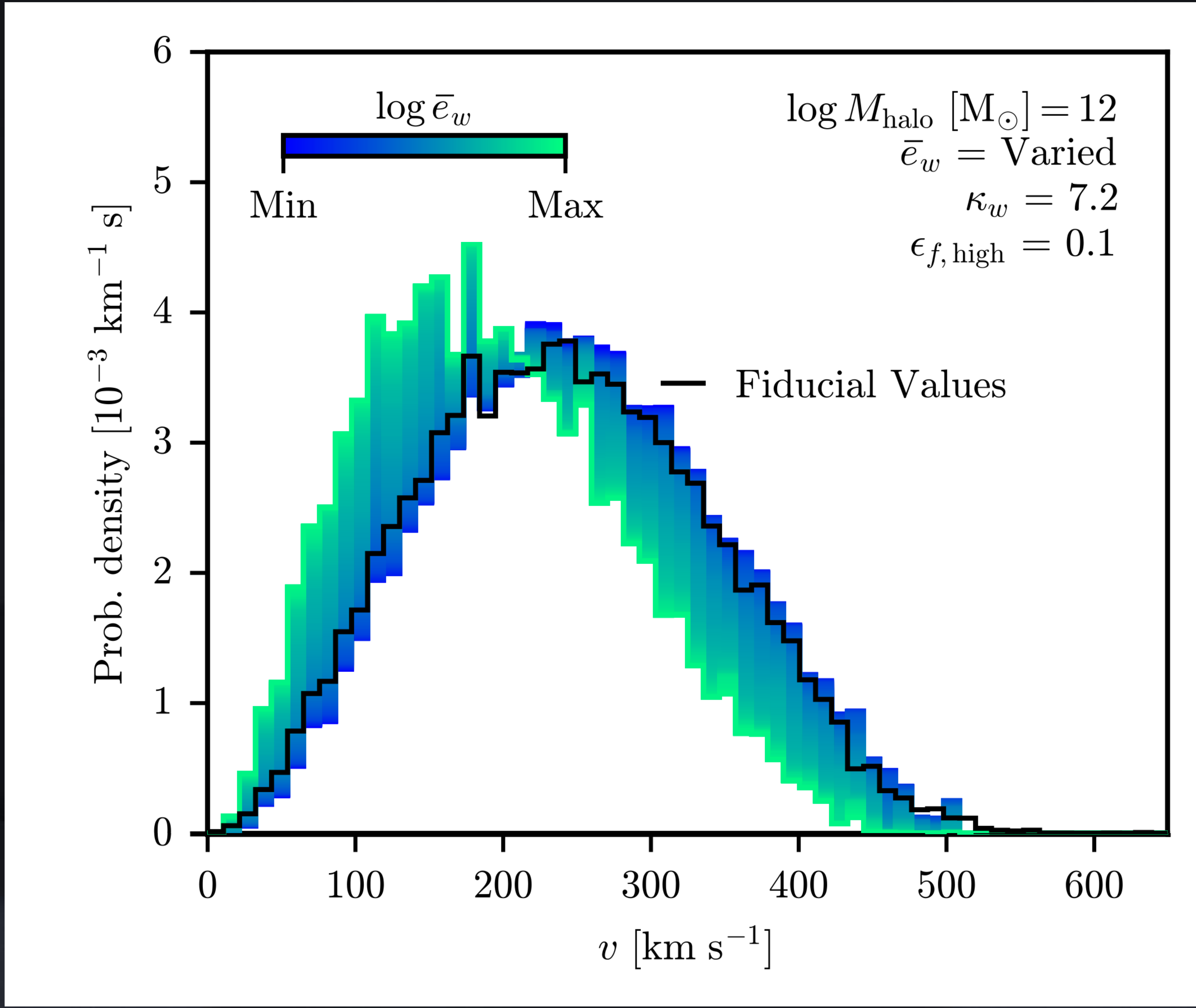


J. Bland-Hawthorn and O. Gerhard [1602.07702]

Supernova Wind Energy

$\bar{e}_w \in [0.9, 14.4]$

As $\bar{e}_w$ increases, peak speed shifts from 240 $\mathrm{kms^{-1}}$ to 160 $\mathrm{kms^{-1}}$



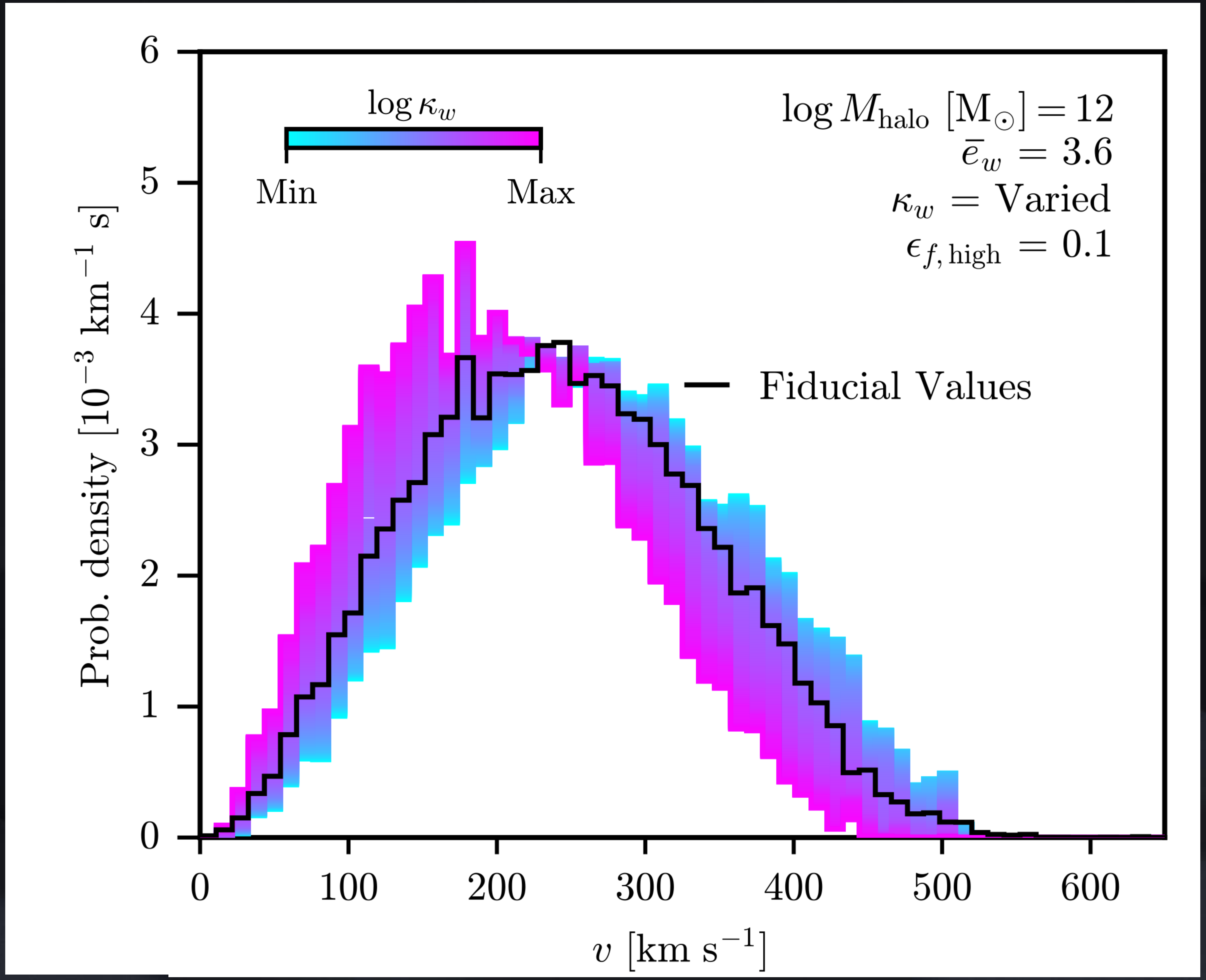
M. Vogelsberger et al. [1305.2913]

J. Rose et al. [2512.00148]

Supernova Wind Speed

$\kappa_w \in [3.7, 14.8]$

As κ_w increases, peak speed shifts from 260 kms^{-1} to 180 kms^{-1}



M. Vogelsberger et al. [1305.2913]

J. Rose et al. [2512.00148]

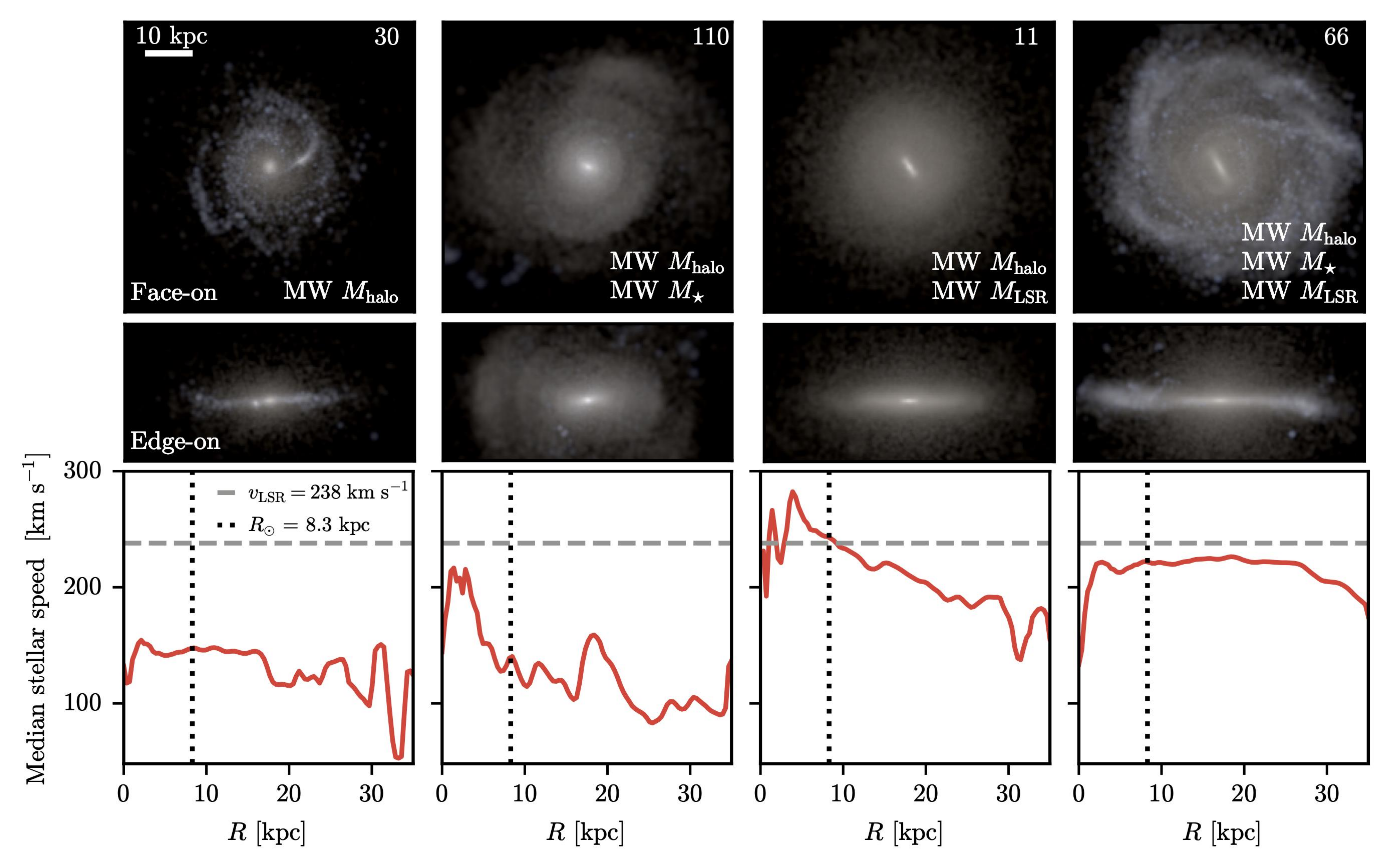
Milky Way Analogs

Halo mass : M_{halo}

Stellar mass : $M_{\star}$

Mass enclosed : M_{LSR}

Milky Way is a compact galaxy



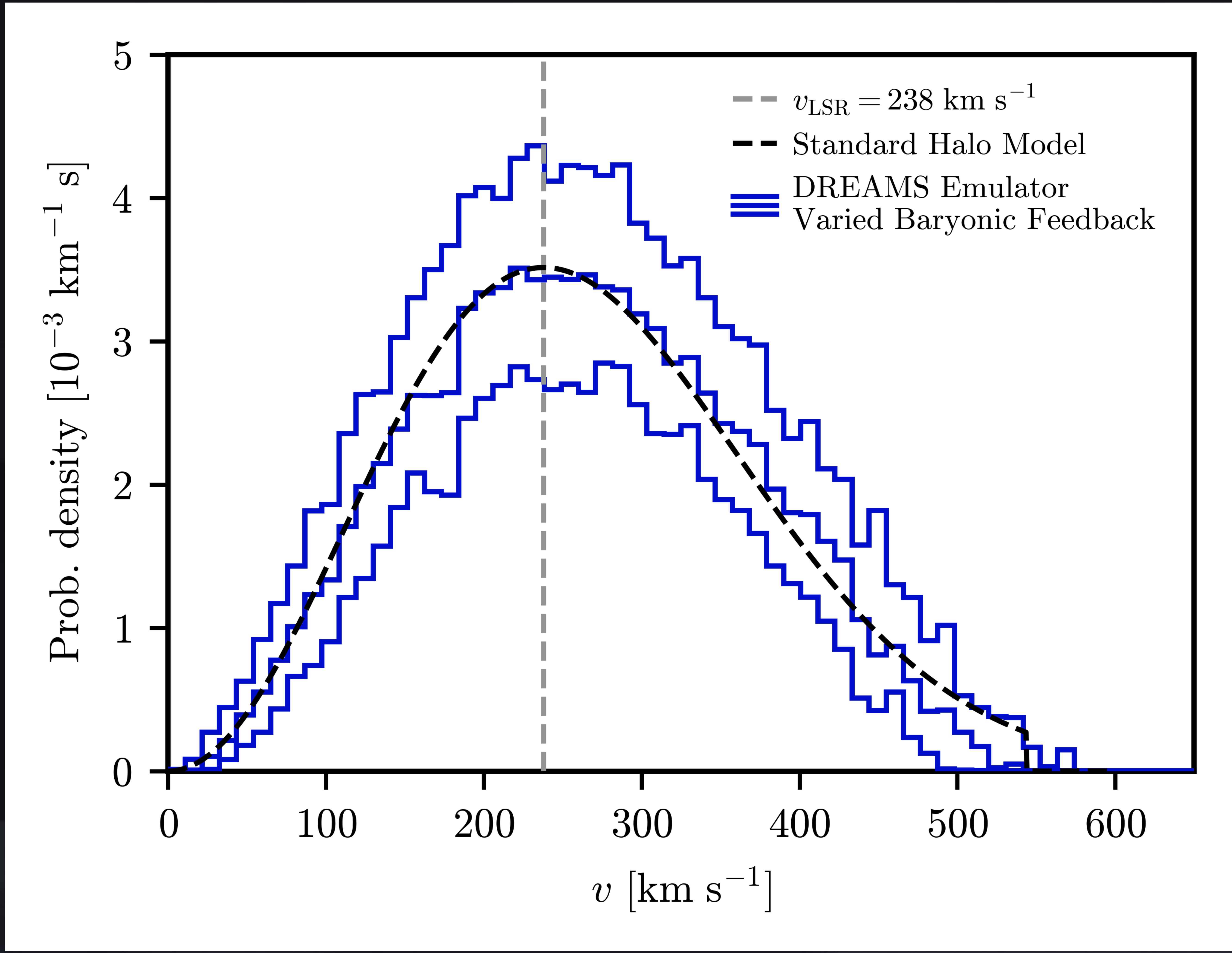
F. Hammer et al. [0702585]
T. Licquia et al. [1610.05769]

Milky Way Speed Distribution

$10.60 \leq \log M_{\star}/\mathrm{M}_{\odot} \leq 10.78$
$10.98 \leq \log M_{\mathrm{LSR}}/\mathrm{M}_{\odot} \leq 11.09$

Standard Halo Model consistent with ensemble of emulated Milky Ways

Uncertainty is dominated by halo-to-halo variance

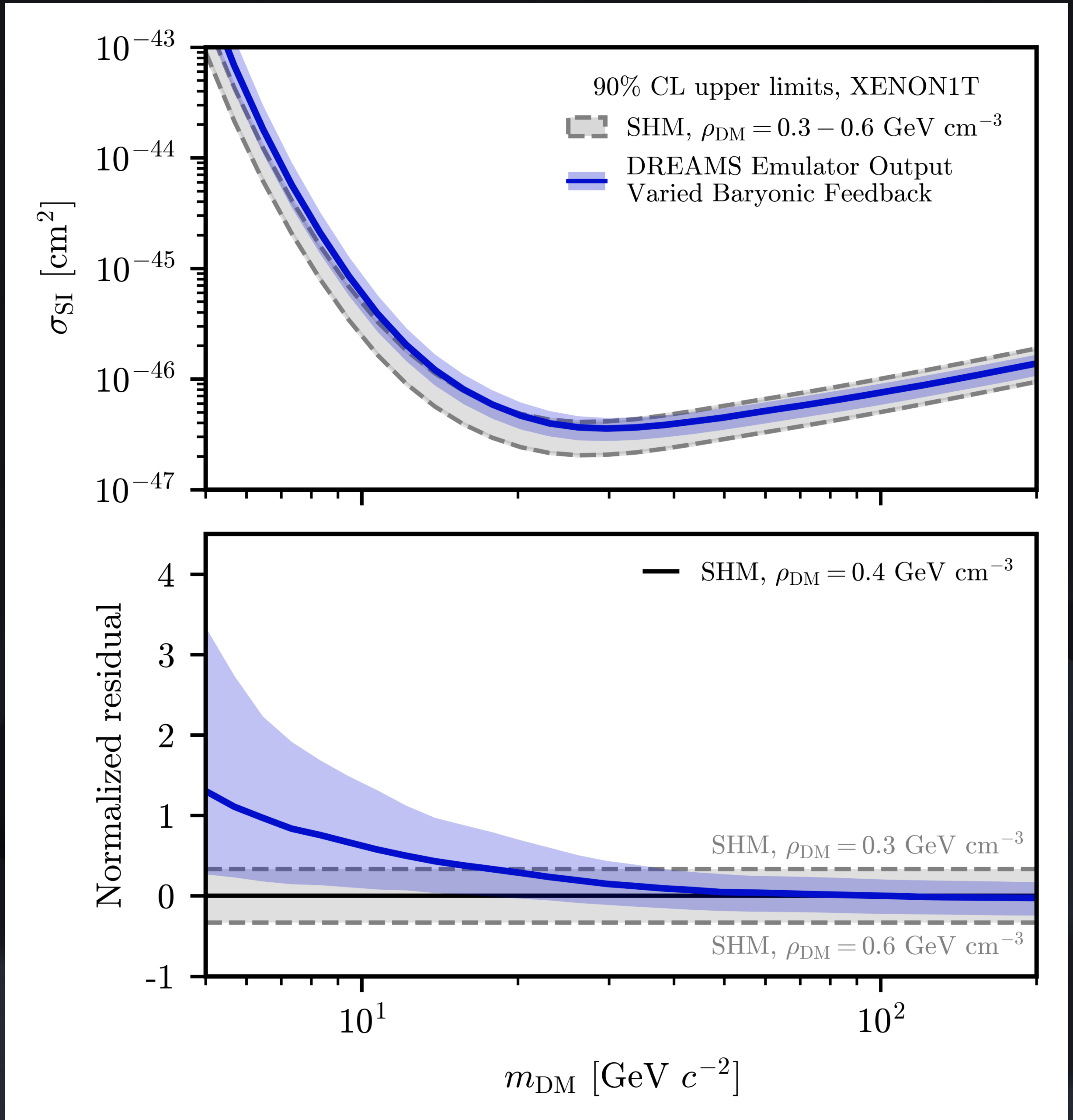


J. Bland-Hawthorn and O. Gerhard [1602.07702]

Direct Detection Constraints

Uncertainty comparable to the XENON1T systematic uncertainty

$$\frac{\sigma_{SI} - \sigma_{SHM}}{\sigma_{SHM}}$$



Aprile et al. [1805.12562]

Conclusions

The DREAMS suite is an unprecedented sample size to analyze astrophysical uncertainties with machine learning methods

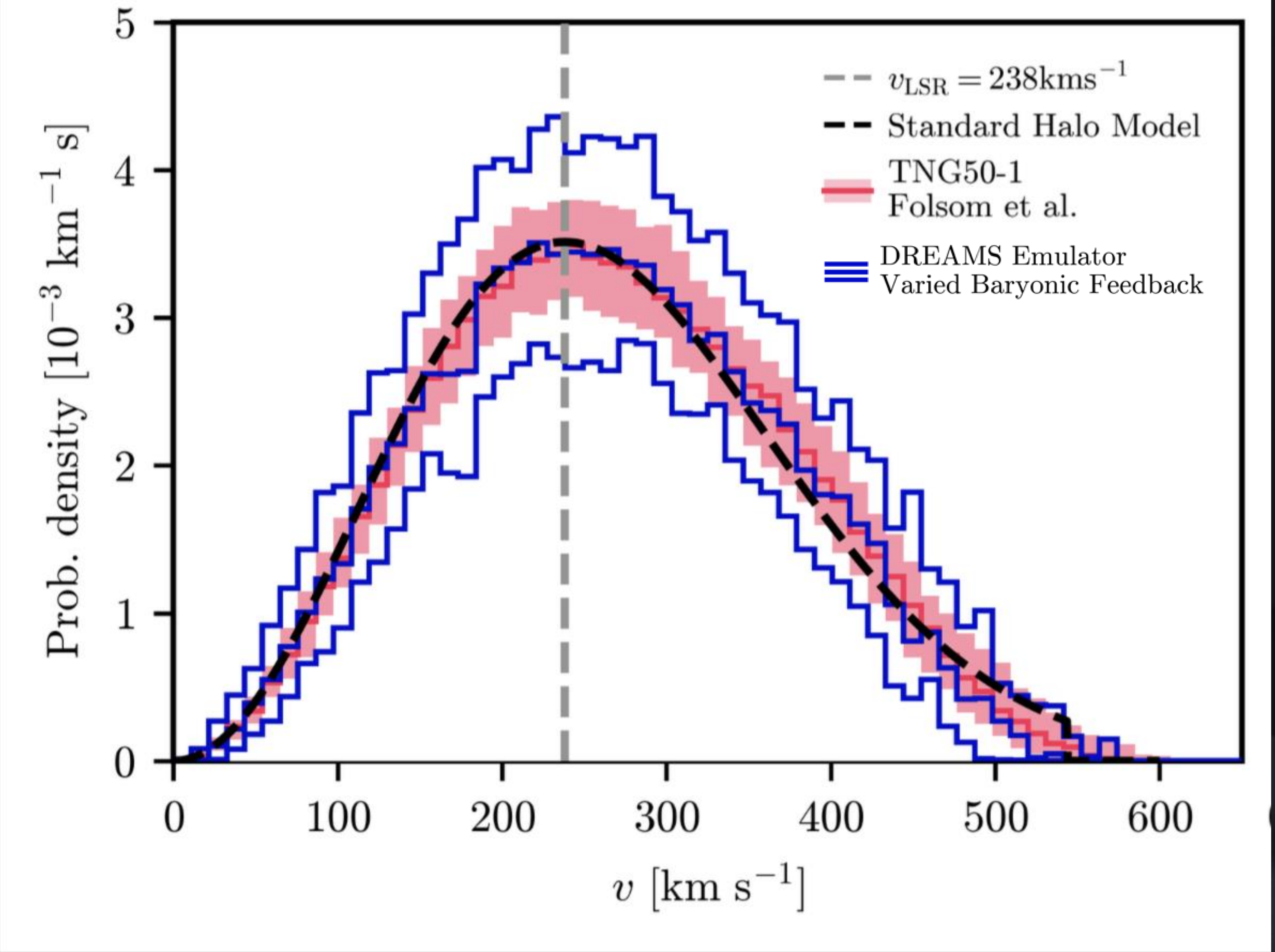
The local dark matter speed distribution uncertainty is dominated by halo-to-halo variance within TNG baryonic physics

More analyses to be done on resolution affects, sub-grid models, and formation histories

Bonus Slides

TNG50 Previous Result

Larger uncertainty band compared to TNG50 result and lower high-speed tail



D. Folsom et al. [2505.0792]

TNG50 Comparison

Use emulator to match number of galaxies, halo masses, stellar masses to TNG50

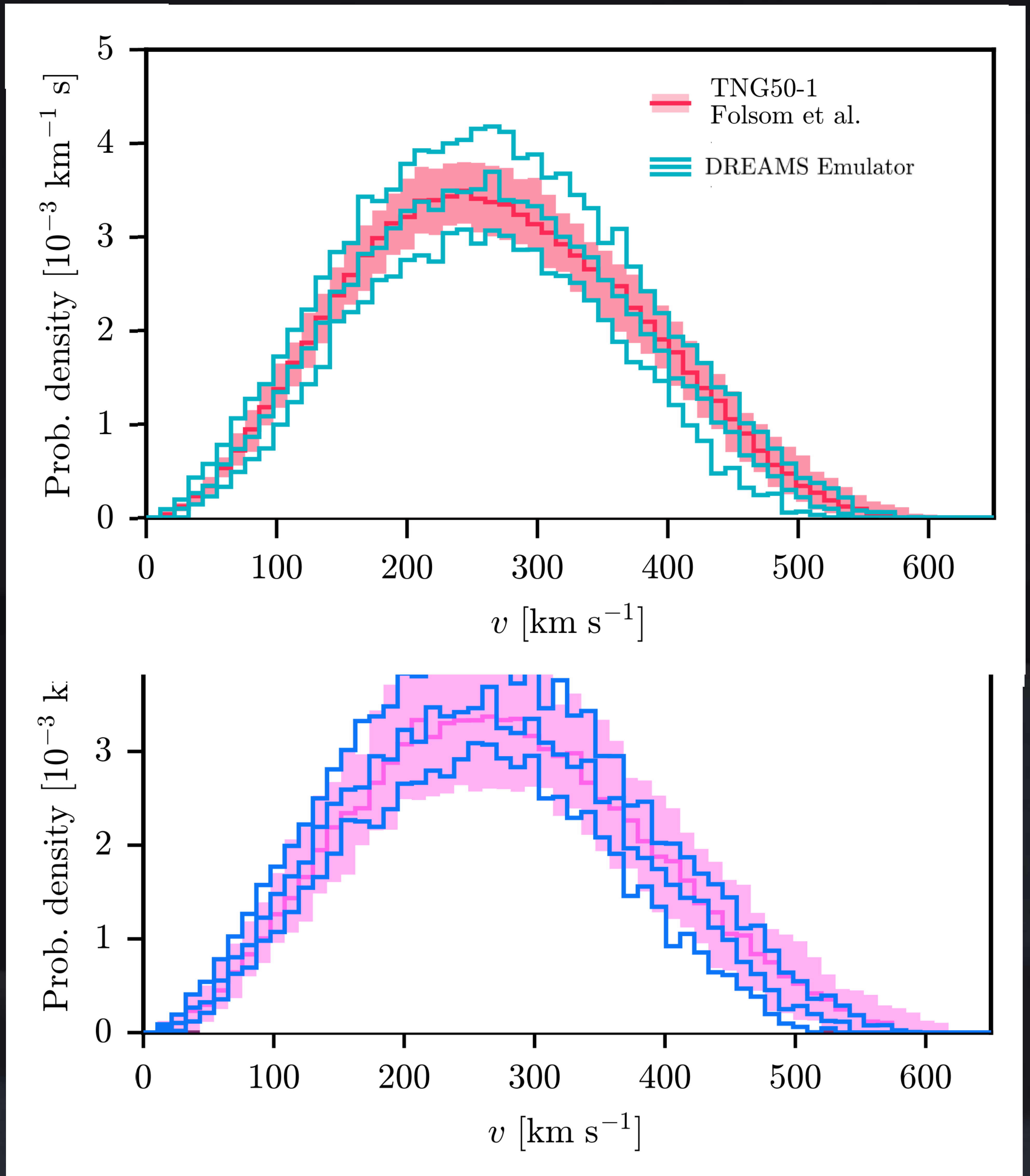
Uncertainty band increases as resolution decreases

DM mass resolution:

TNG50-2 ~ $2.5 \times 10^6 M_\odot$

DREAMS ~ $1.8 \times 10^6 M_\odot$

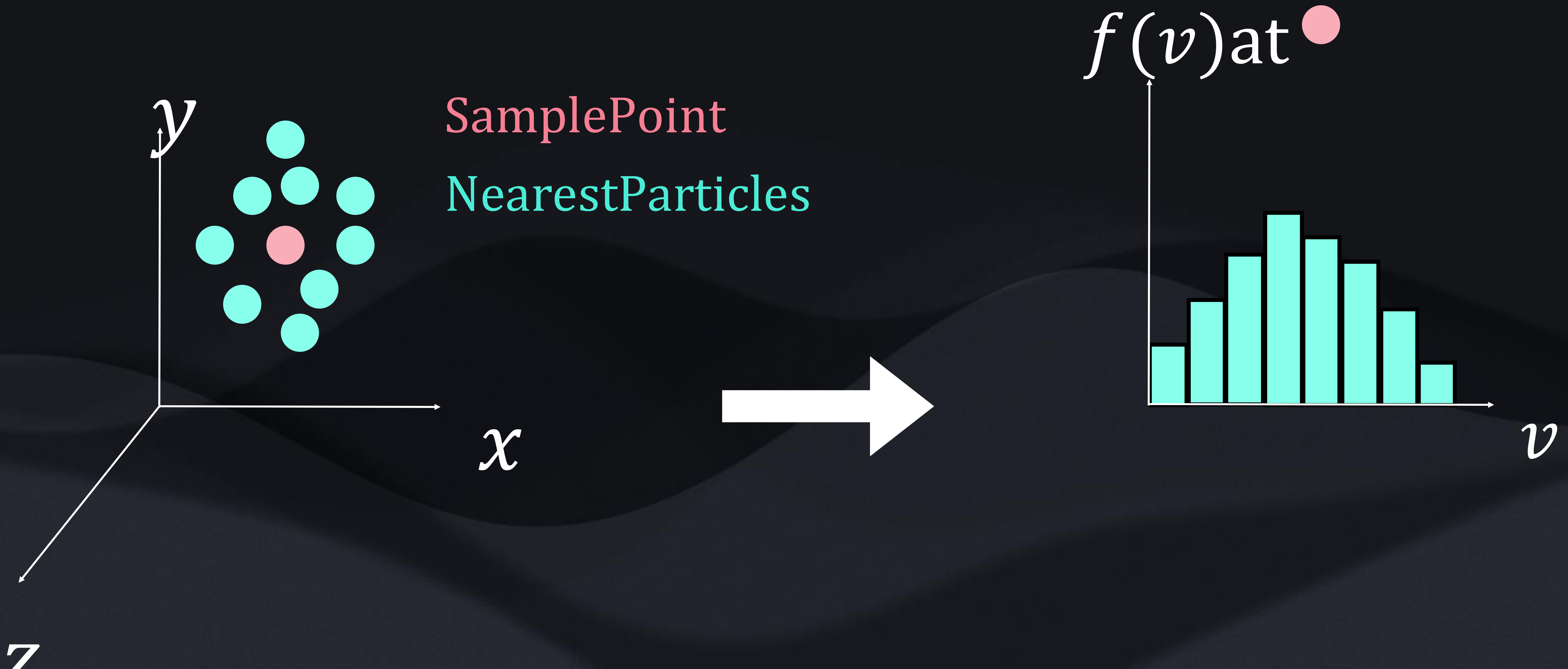
TNG50-1 ~ $4.5 \times 10^5 M_\odot$



Kernel Density Estimation

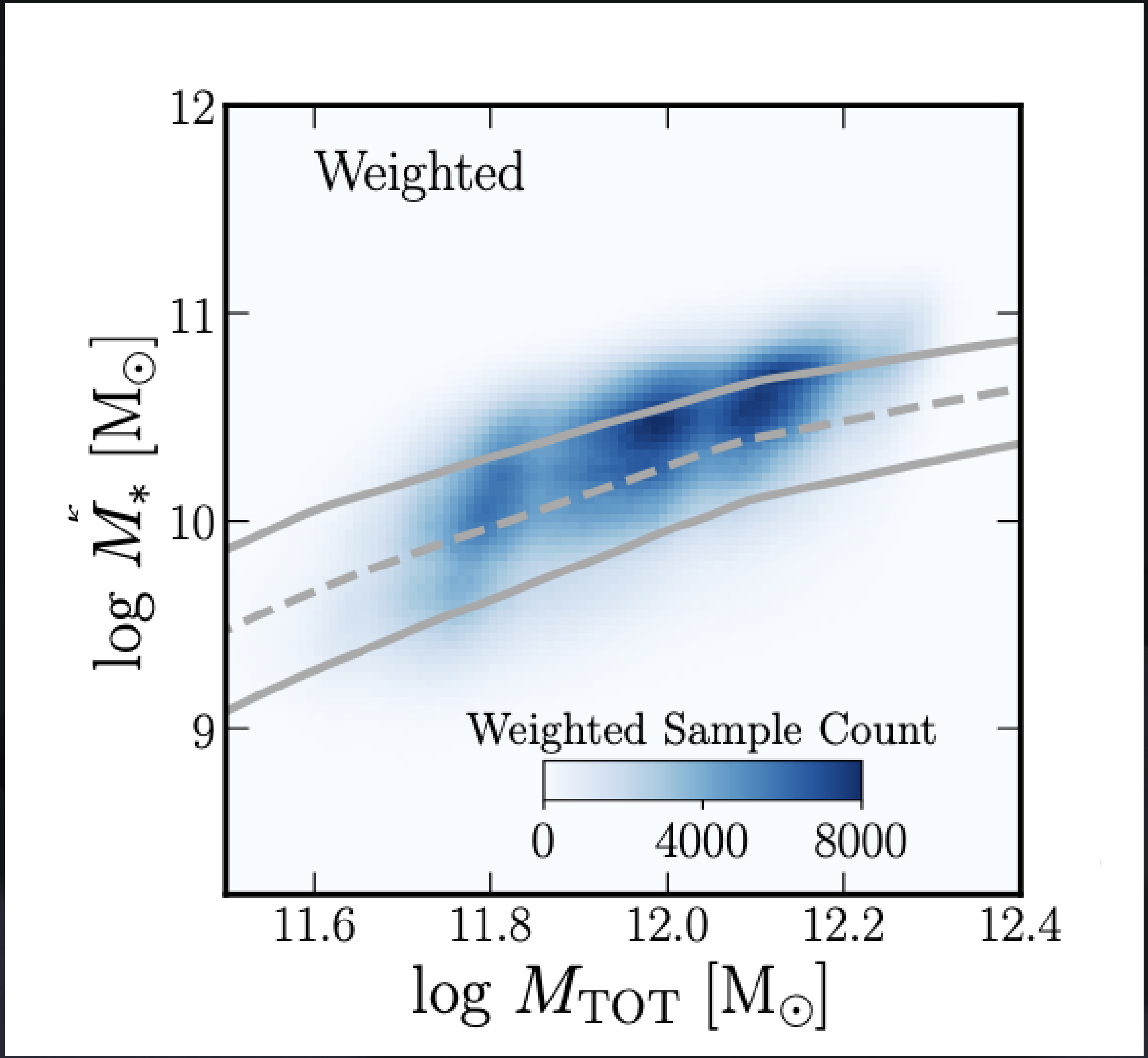
Estimate $f(v)$ at a point using nearby particles given a weight based on their distance to the point

Kernel Function $K(r)$ gives weight



DREAMS Weights

Regions of parameter space inconsistent with observations



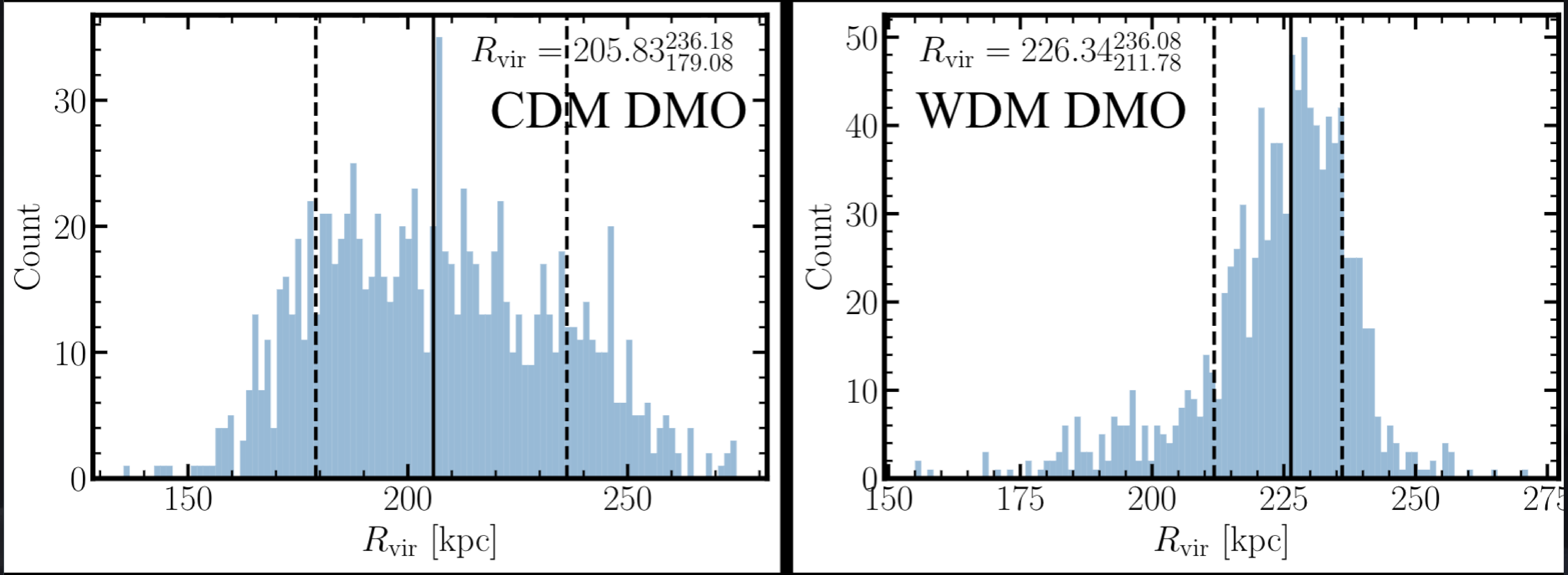
J. Rose et al. [2512.00148]

DREAMS Weights

J. Rose et al. [2512.00148]

Assumptions

- Fixed fraction of virial radius ⟵ $R_{\rm Vir}^{\rm MW} = 250$ [kpc]



[Alex Garcia]

Baryonic Feedback

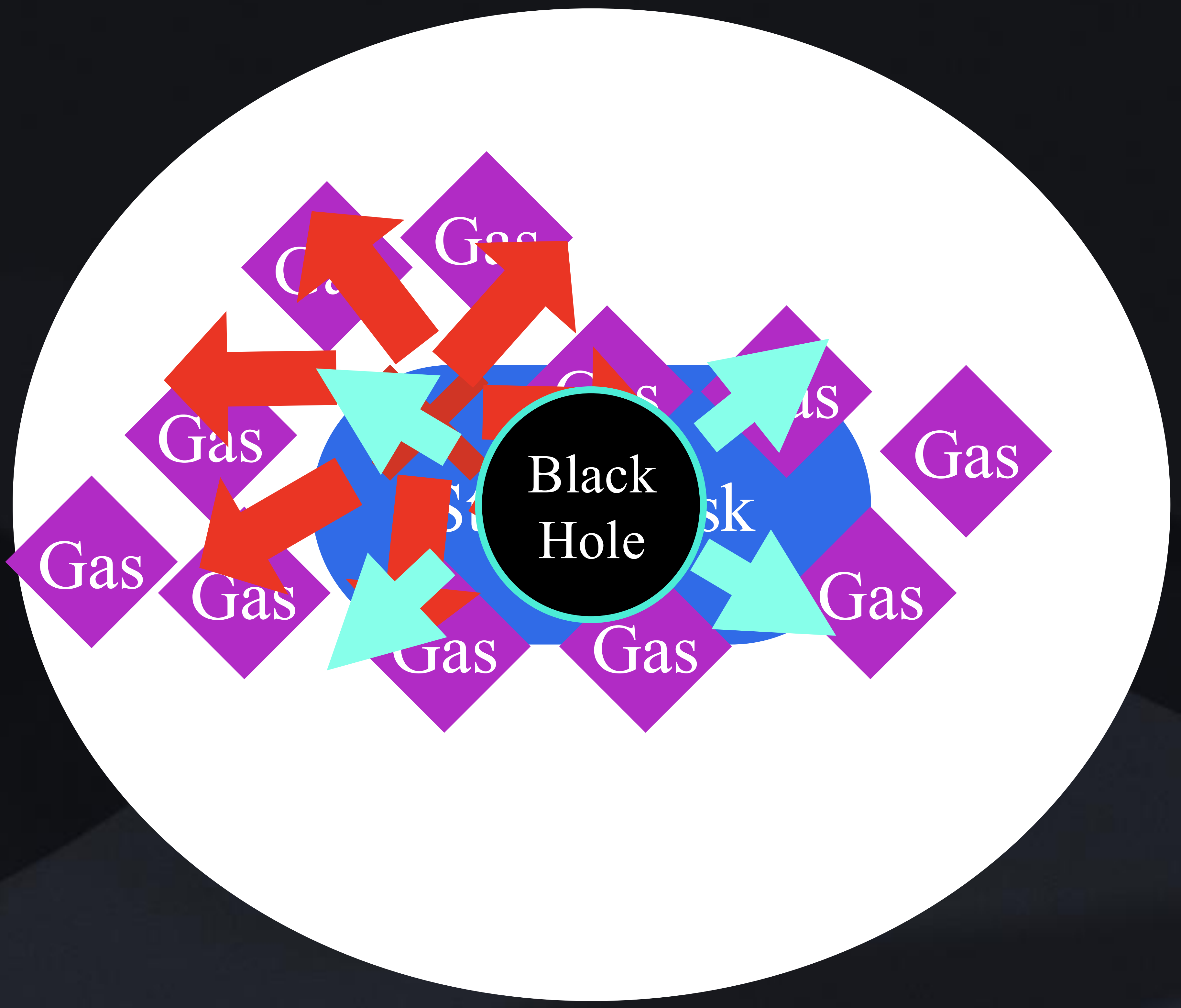
DREAMS suite varies over baryonic feedback parameters

Wind energy: $\overline{e}_w$

Wind speed: κ_w

AGN feedback: $\epsilon_{f,\mathrm{high}}$

Dark Matter Halo



A. Pillepich et al. [1703.02970]

Emulator Architecture

$f(v)$ Distribution

Normalizing Direction

Generative Direction

$$f_1 \circ f_2 \circ \cdots \circ f_T(SN1, SN2, AGN, M)$$

$$p_T(y)$$

Emulator Architecture 2

Suppose you have a probability density $p(\mathbf{u})$ and a variable $\mathbf{y} = f(\mathbf{u})$, you can get $p(\mathbf{y})$ by:

$$p(\mathbf{y}) = p(f^{-1}(\mathbf{y}))\left|det\left(\frac{\partial f^{-1}}{\partial \mathbf{y}}\right)\right|$$

(In 1D this is just saying $p(y)dy = p(u)du$)

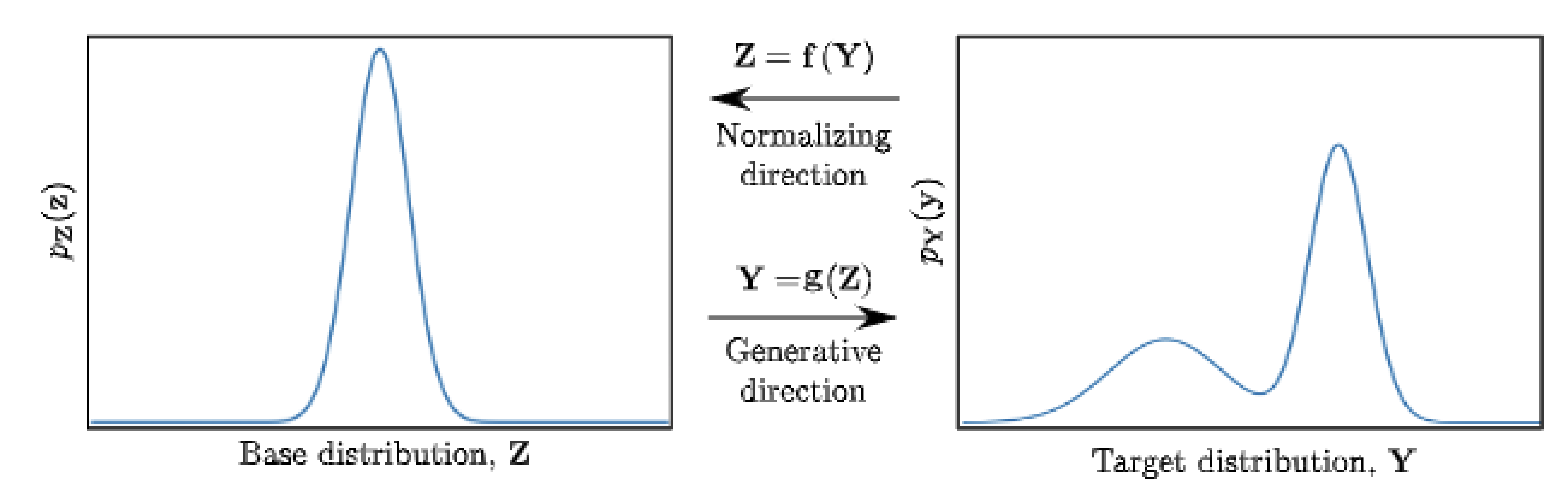
We can repeat this for many transformations:

$$f = f_1 \circ f_2 \circ \cdots \circ f_T$$

$$p_T(y) = p_0(u_0)\prod_{i=1}^{T}\left|det\left(\frac{\partial f_i^{-1}}{\partial u_i}\right)\right|$$

T. Nguyen et al. [2409.02980]

Emulator Architecture 3



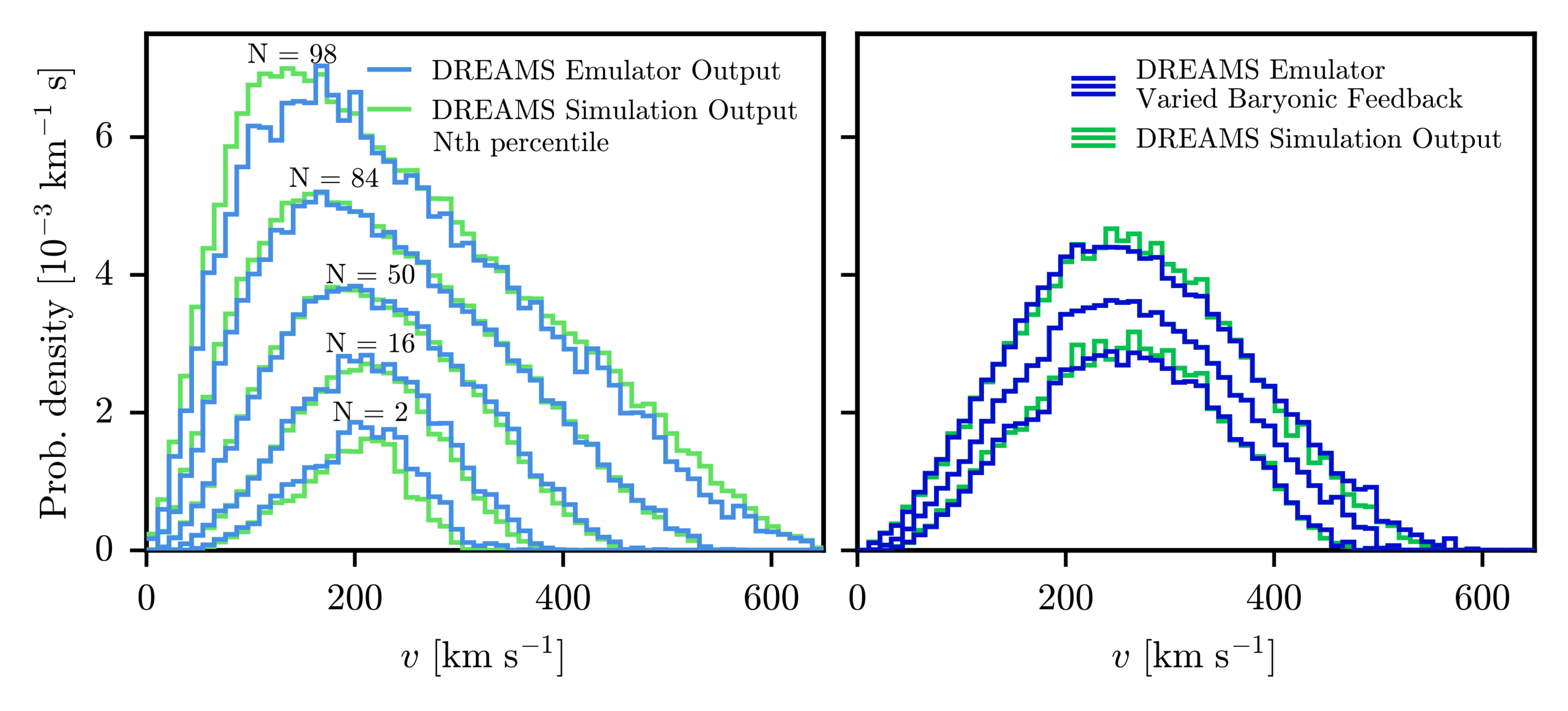
I. Kobyzev et al. [1908.09257]

f_i is parameterized by a neural network with parameters ϕ_i .

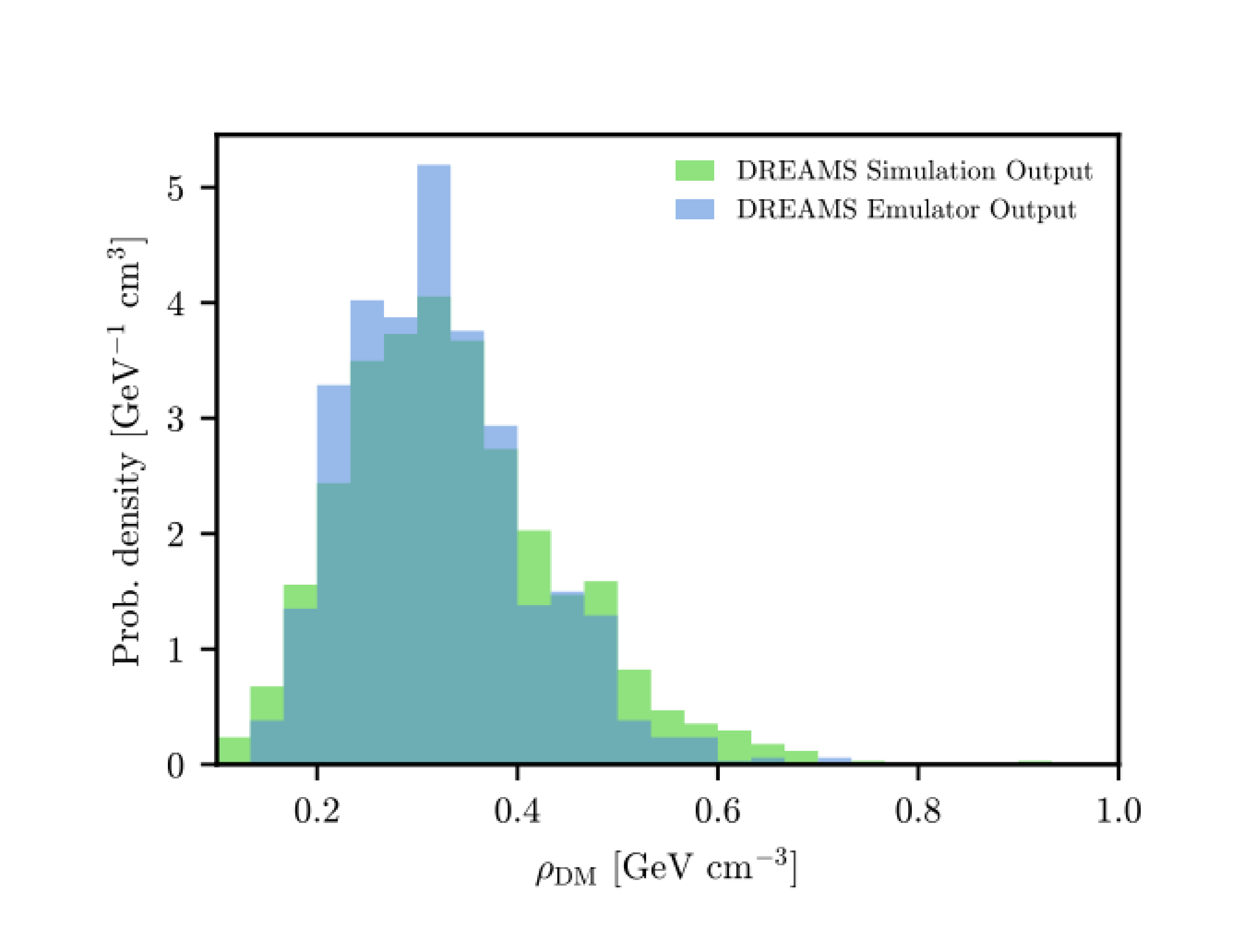
If we want to condition on some variable θ, then we must consider $f_i(y, \theta)$.

$$\mathcal{L}_{\text{flows}}(y) = -\log p_0(u) - \sum \log \left| det \frac{\partial f_i^{-1}}{\partial u_i} \right|$$

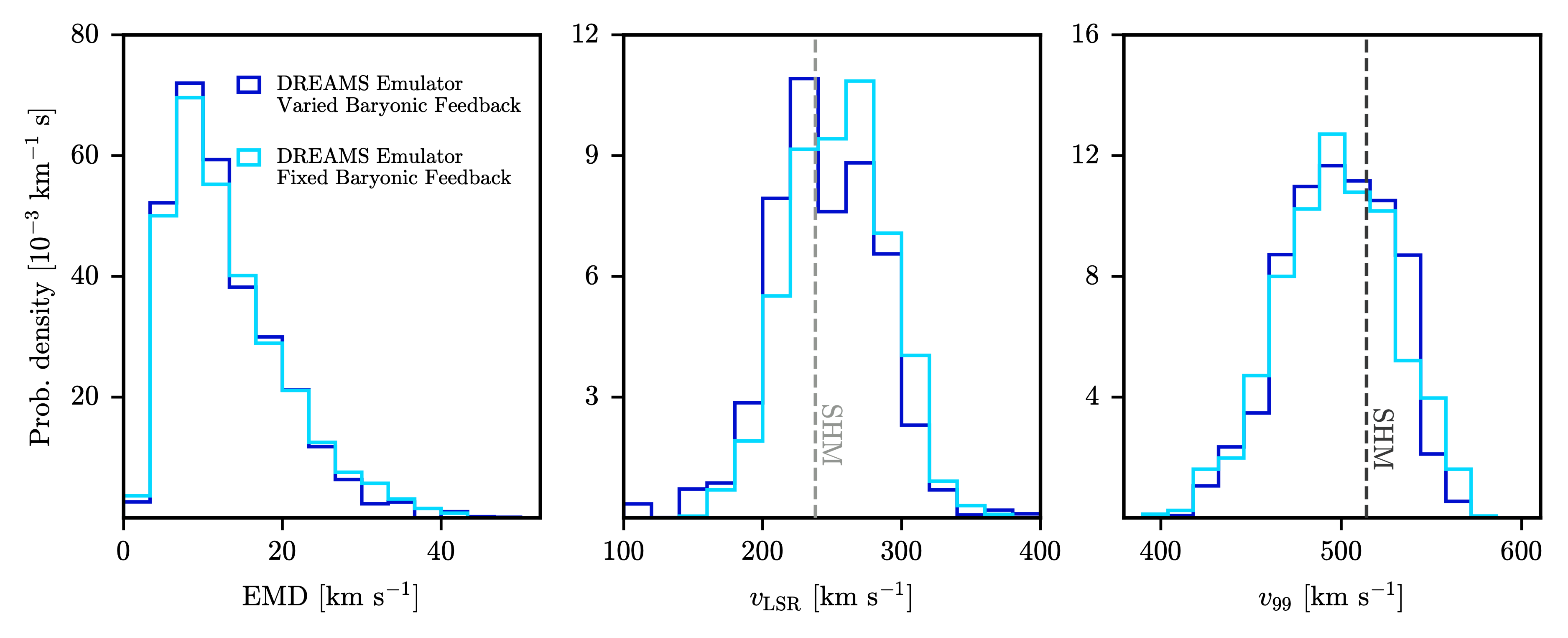
Emulator Reconstruction



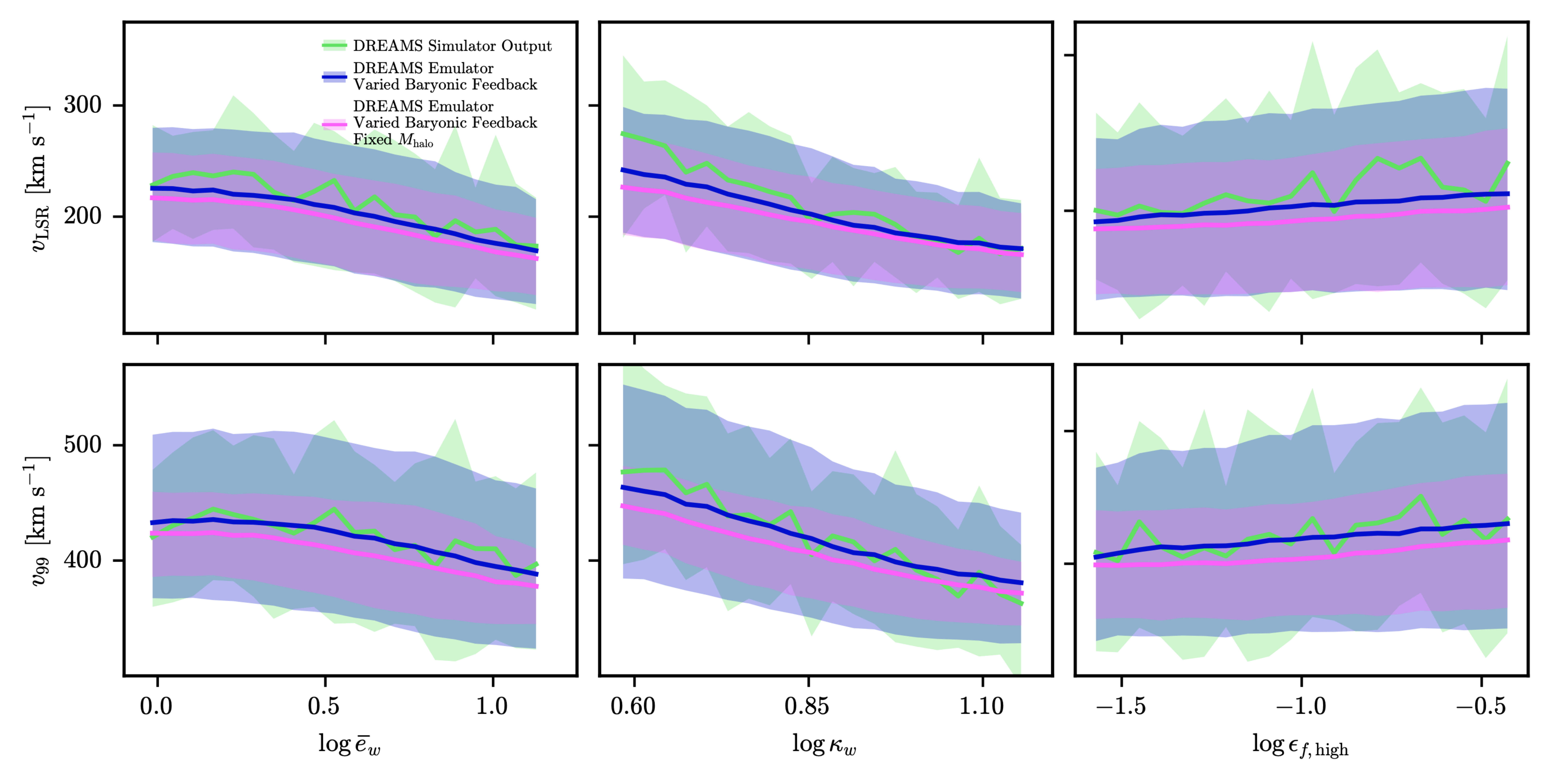
Emulator Reconstruction



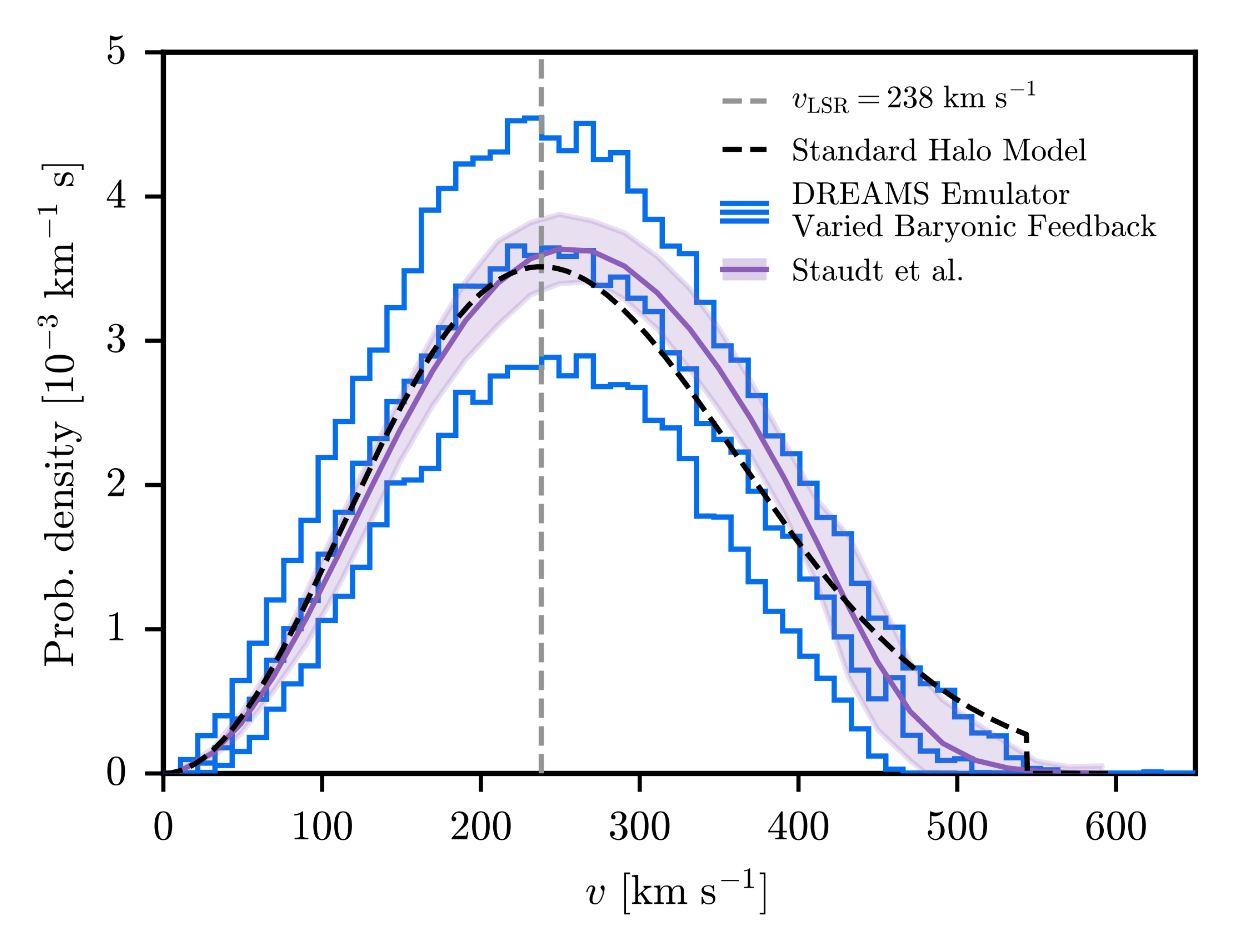
SHM Comparisons



Baryonic Parameters



FIRE-2 Comparison



TNG50 results

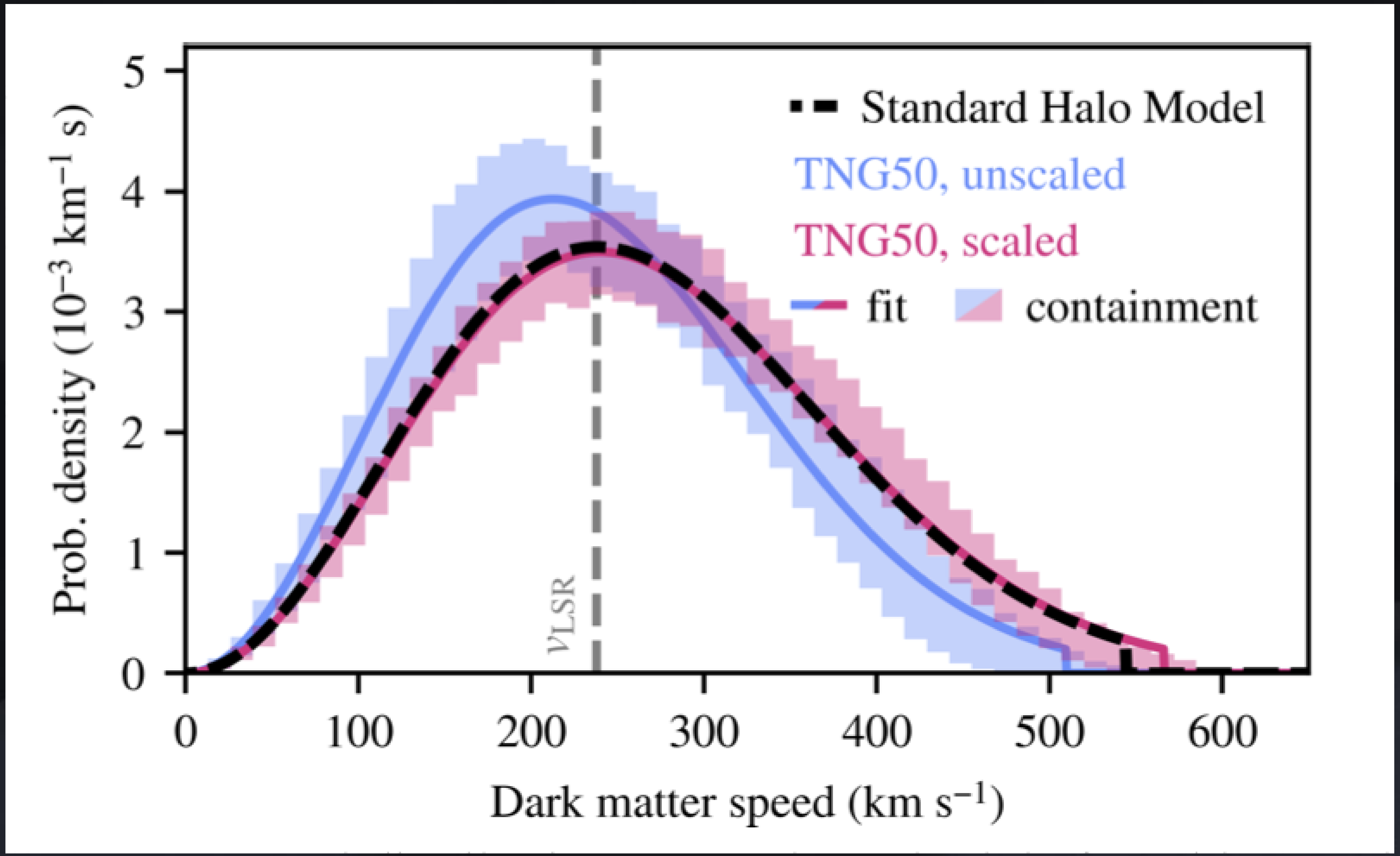
Use mass inside solar radius, $R_\odot$, as $M_{\mathrm{LSR}} = 1.09 \times 10^{11} \mathrm{M}_\odot$

For simulated halo find radius R_M that encloses mass M_{LSR}

Scale phase space while conserving energy as

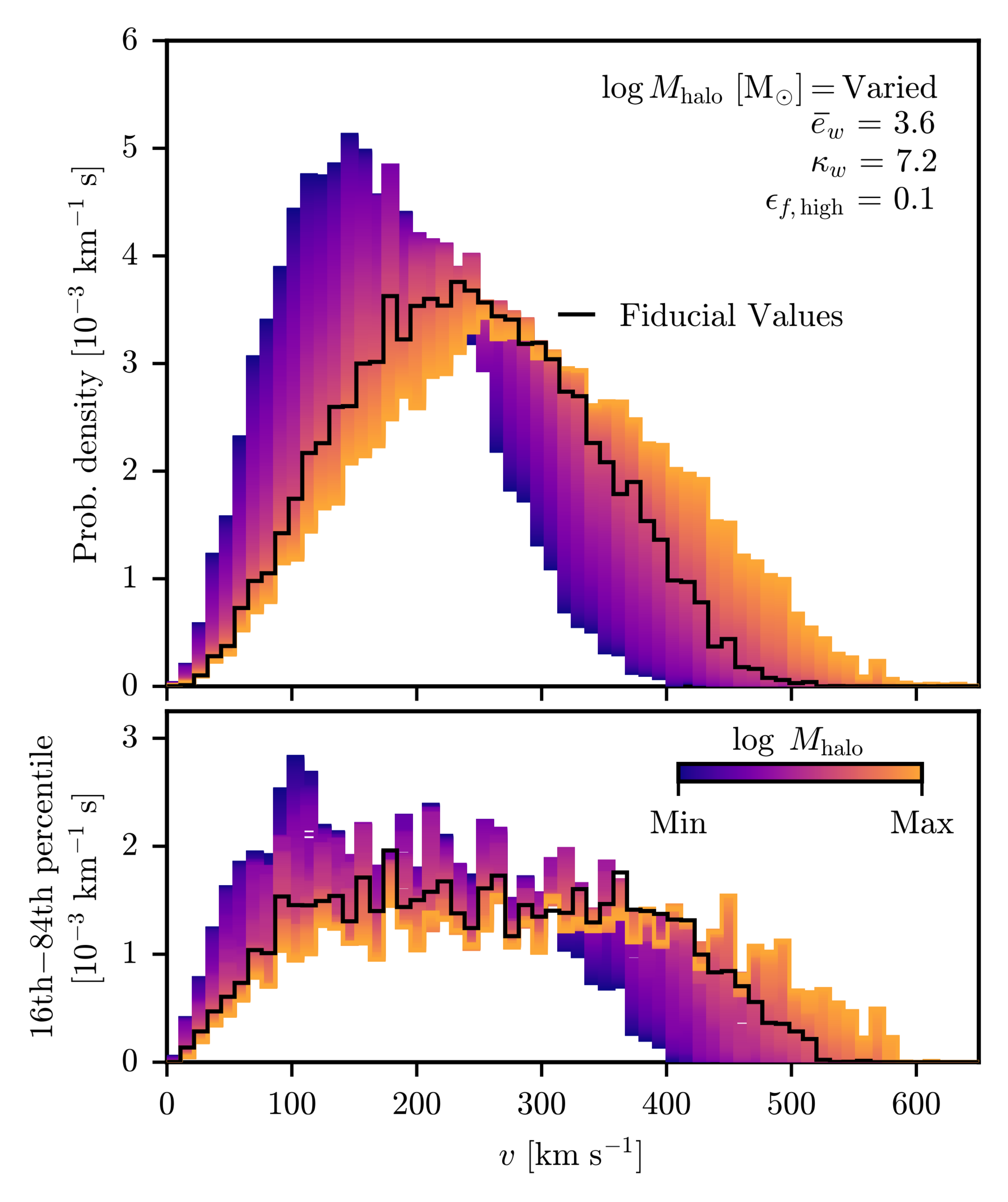
$$r \to r \frac{R_\odot}{R_M}$$

$$v \to v \sqrt{\frac{R_M}{R_\odot}}$$



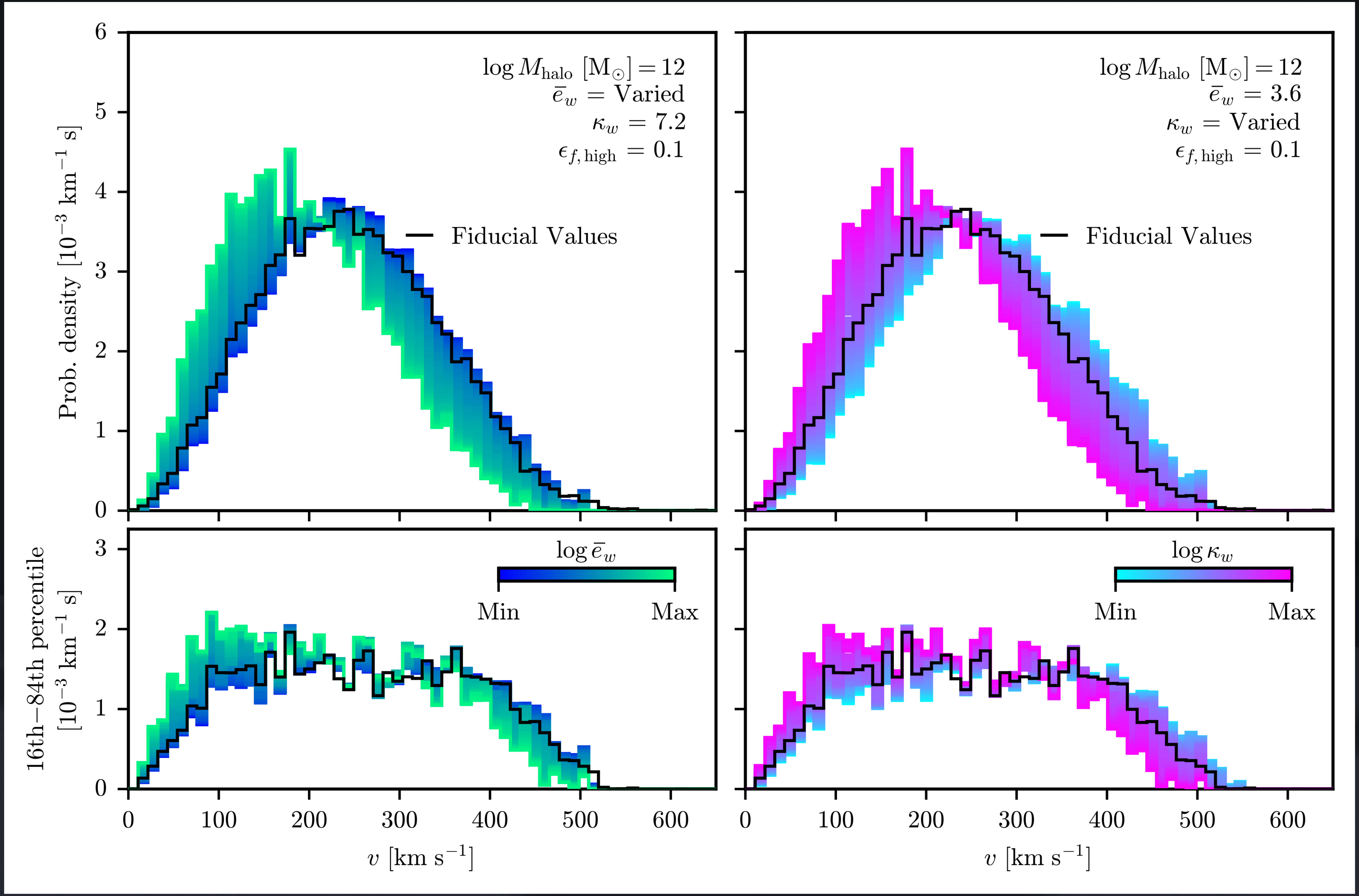
D. Folsom et al. [2505.0792]

Halo Mass

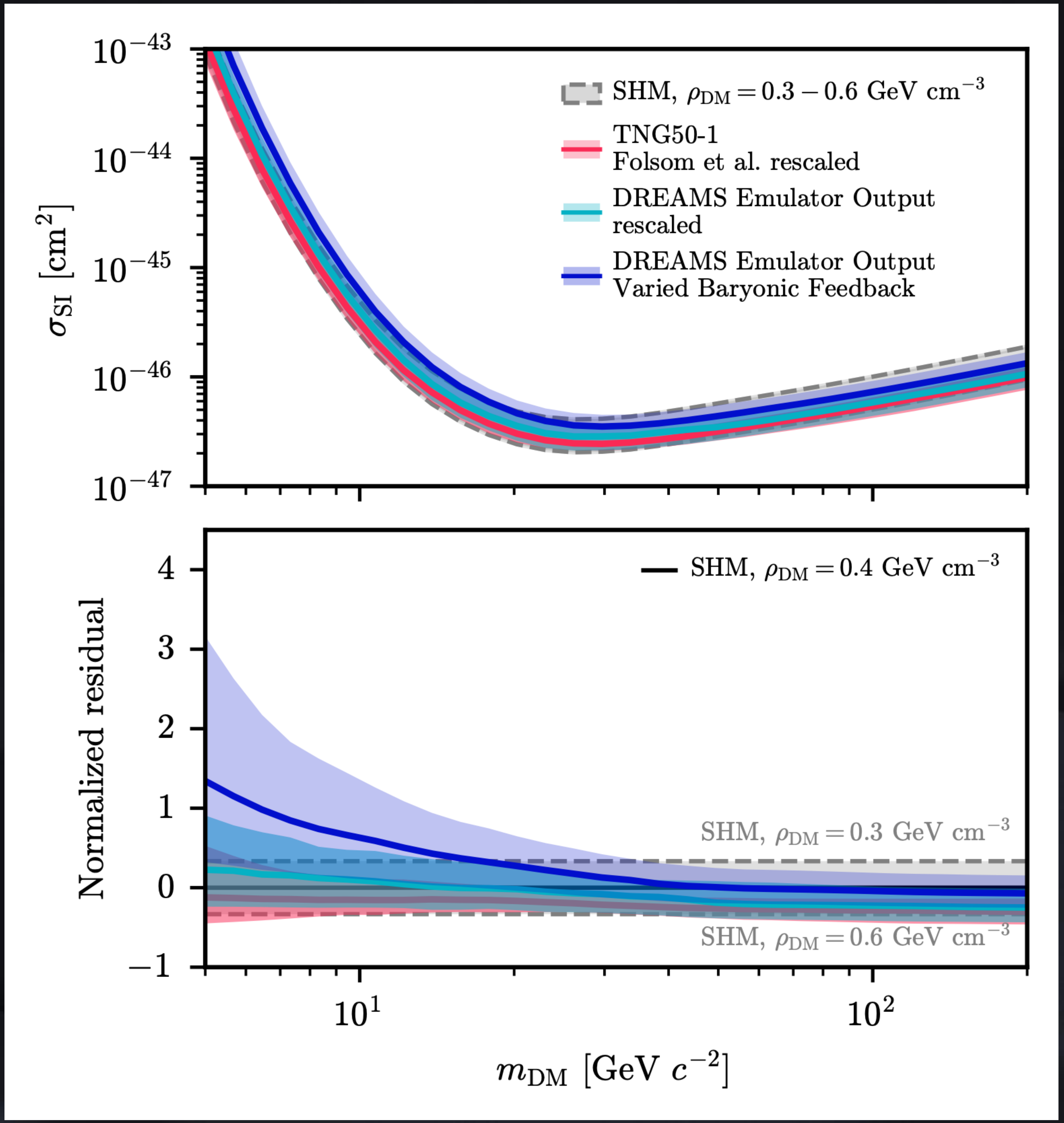


$\log M_{\rm halo}\ [\mathrm{M}_\odot] = $ Varied
$\bar{e}_w = 3.6$
$\kappa_w = 7.2$
$\epsilon_{f,\,\rm high} = 0.1$
Fiducial Values
Prob. density [10^{-3} km^{-1} s]
$\log\ M_{\rm halo}$
Min
Max
16th–84th percentile [10^{-3} km^{-1} s]
v [km s^{-1}]
0
1
2
3
4
5
6
100
200
300
400
500
600

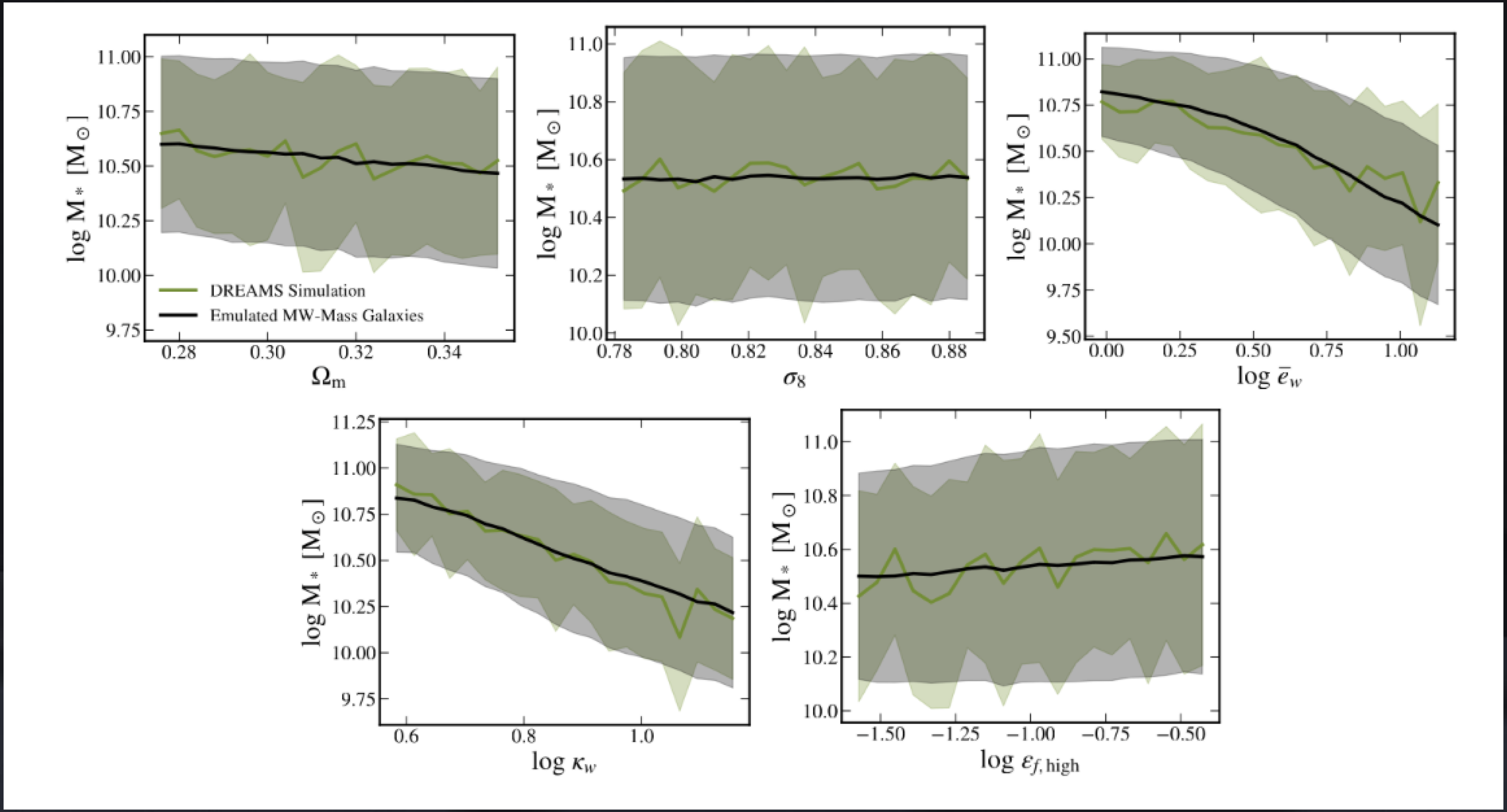
Supernovae Parameters



Direct Detection

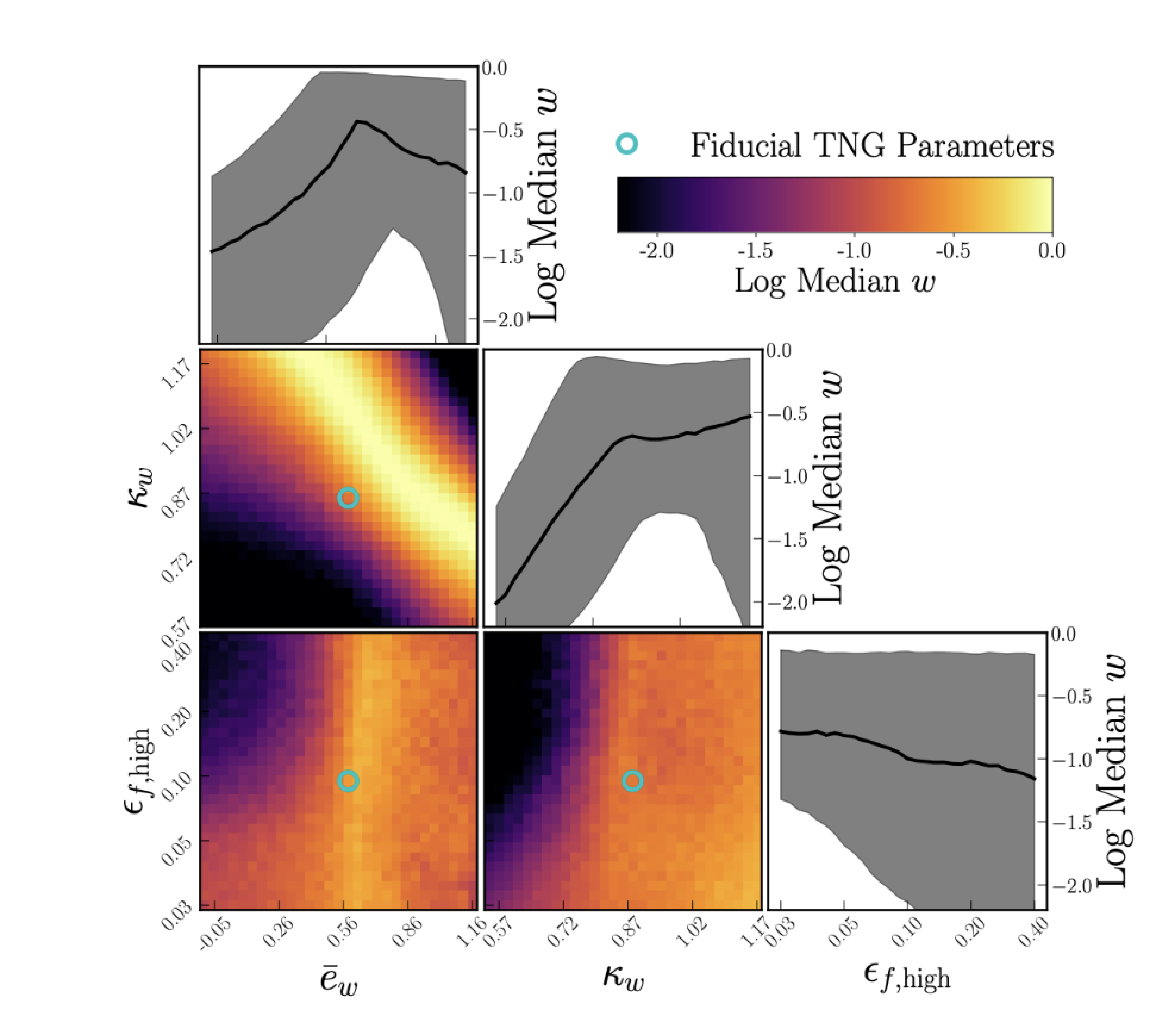


Stellar Mass



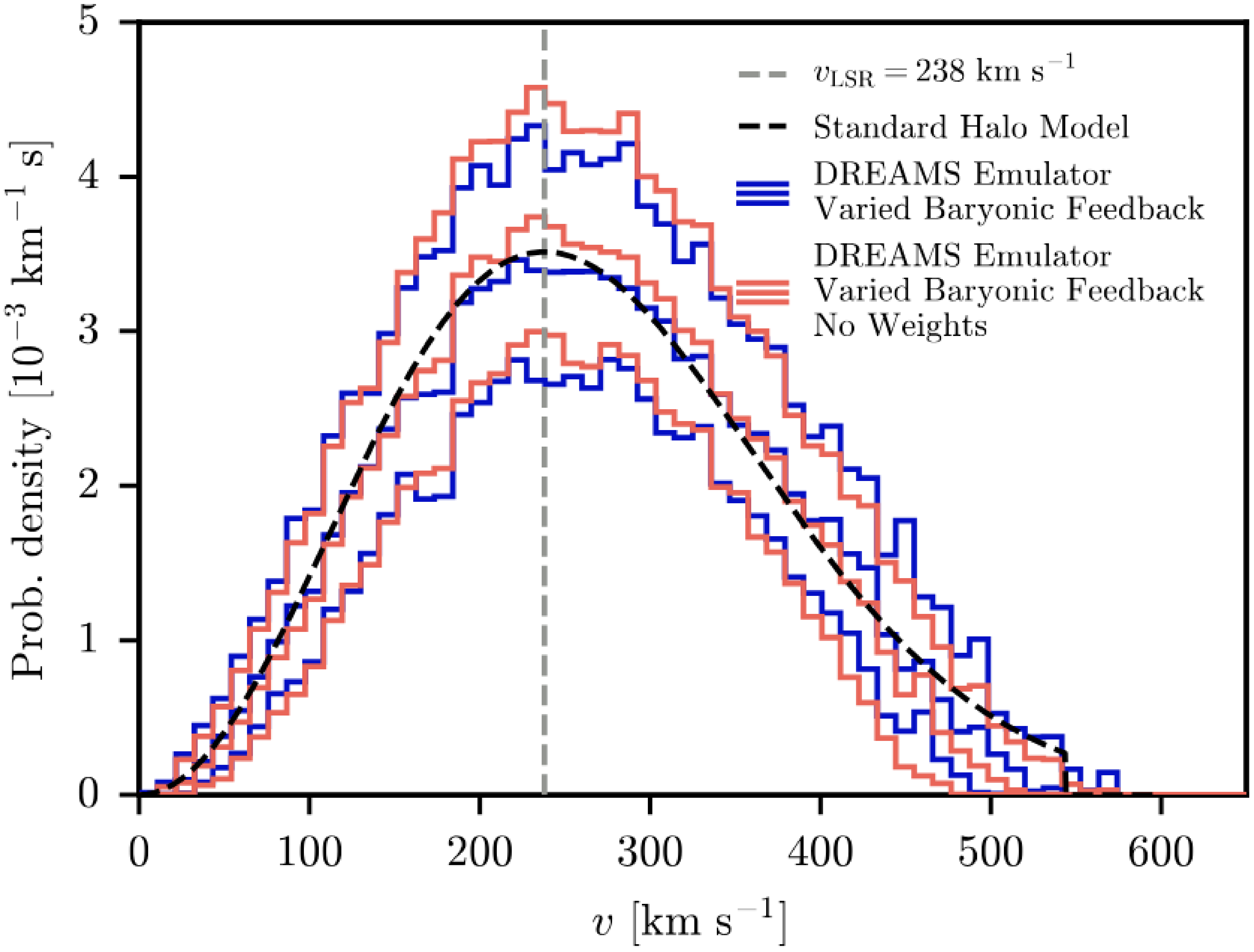
J. Rose et al. [2512.00148]

DREAMS Weights



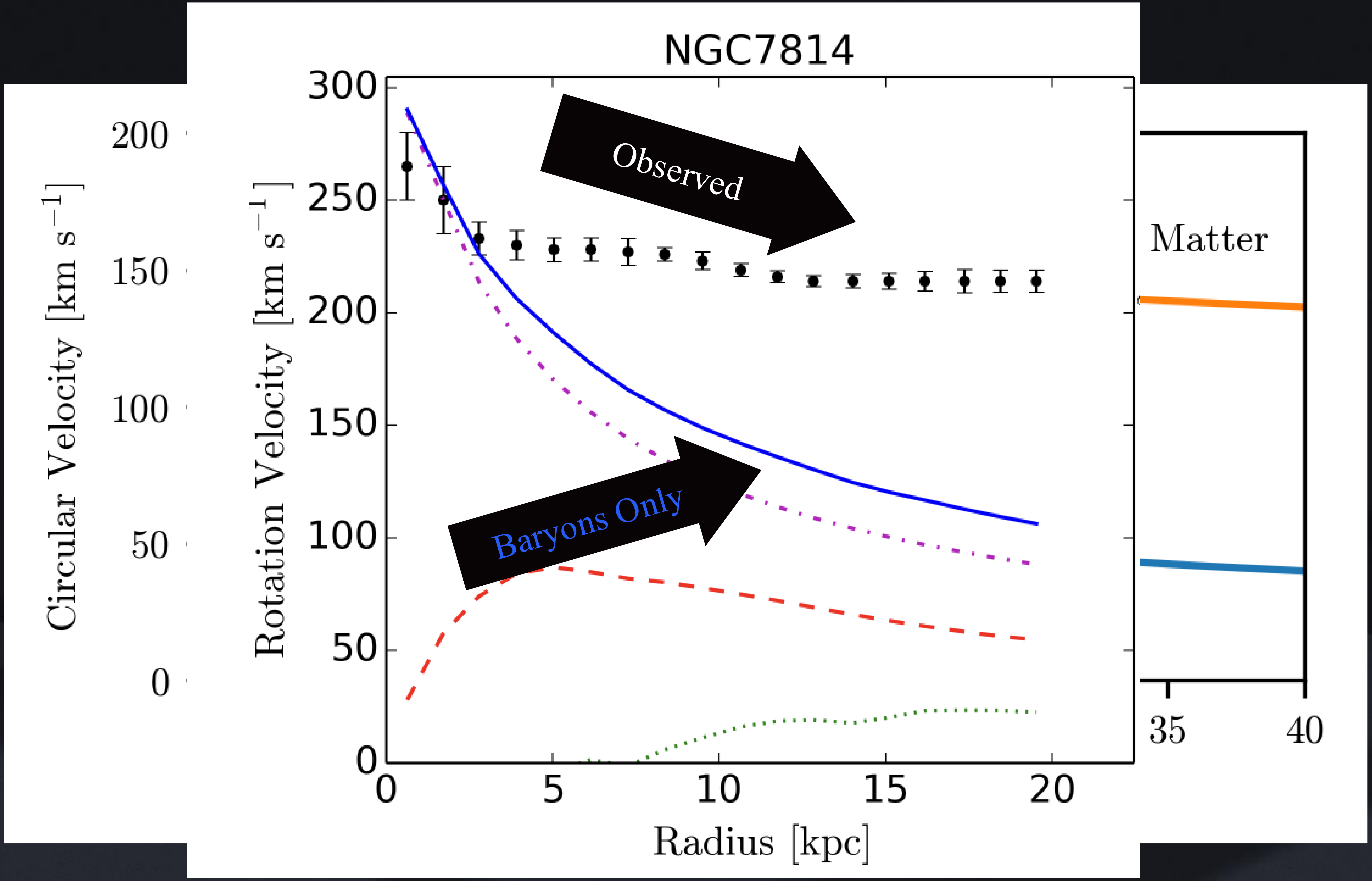
J. Rose et al. [2512.00148]

Weights



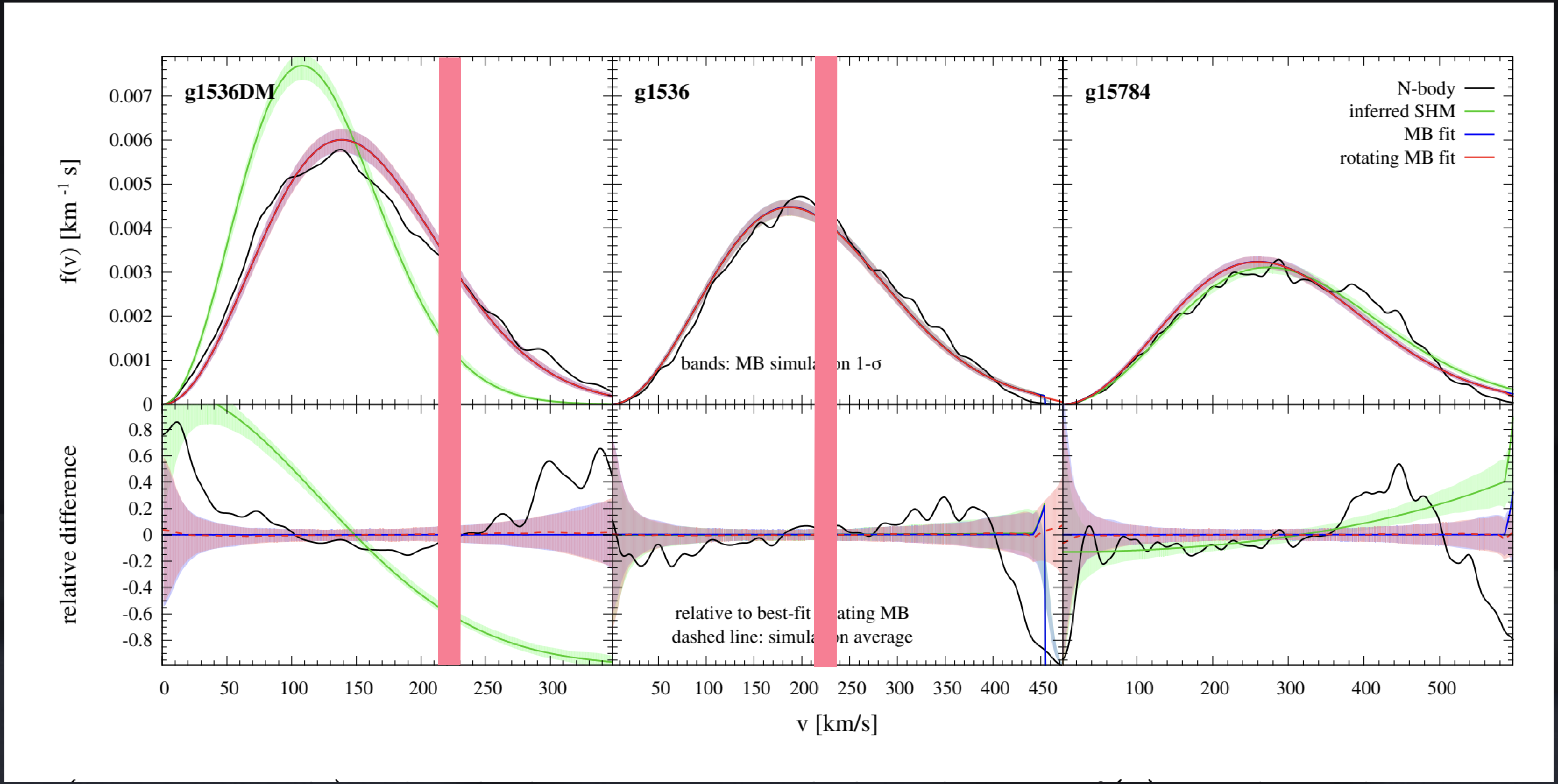
$v_{\rm LSR} = 238$ km s^{-1}
Standard Halo Model
DREAMS Emulator
Varied Baryonic Feedback
DREAMS Emulator
Varied Baryonic Feedback
No Weights
Prob. density [10^{-3} km^{-1} s]
v [km s^{-1}]
0
1
2
3
4
5
0
100
200
300
400
500
600

Rotation Curves



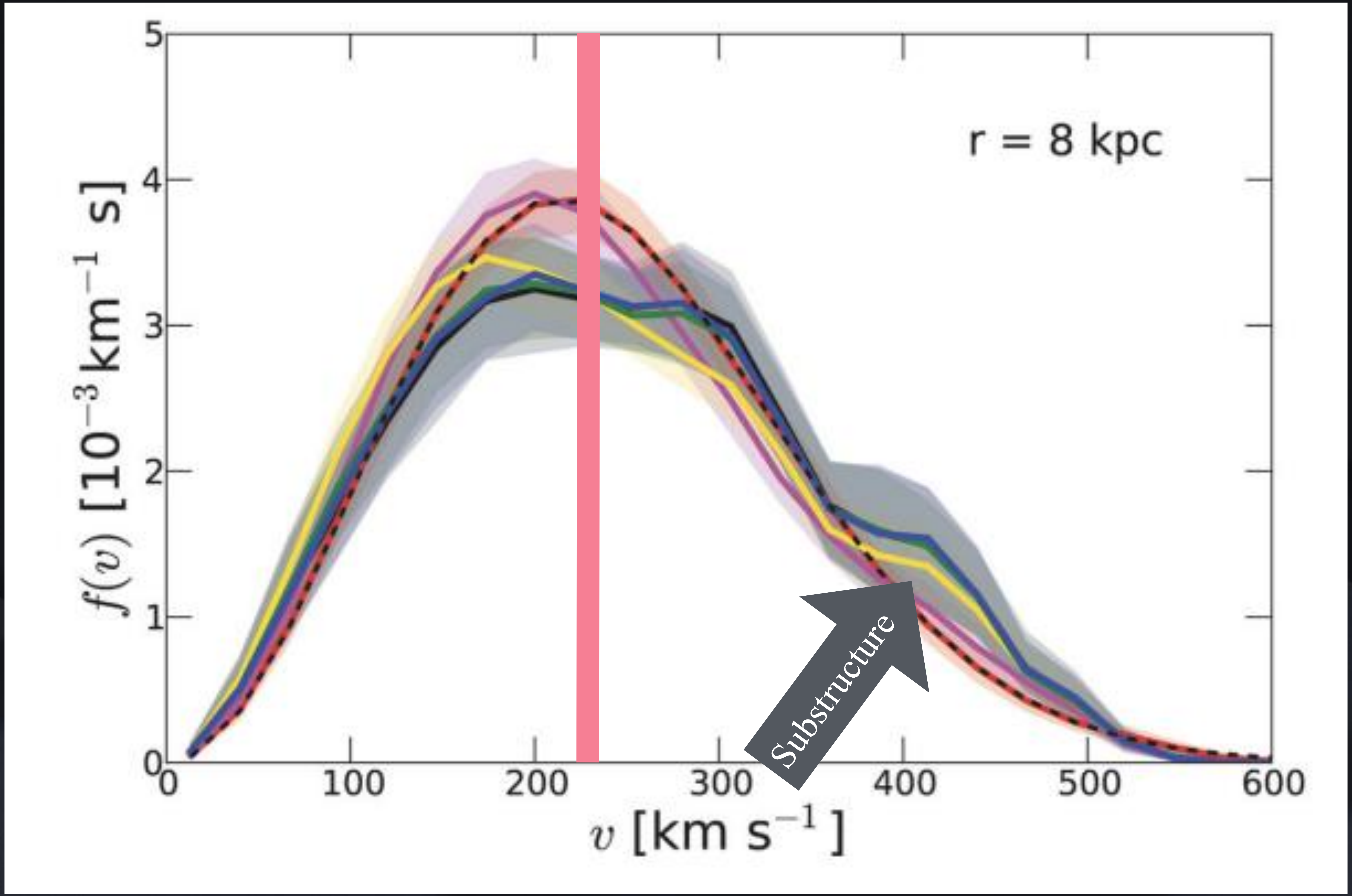
F. Lelli et al. [1610.08981]

Hydrodynamical Simulations



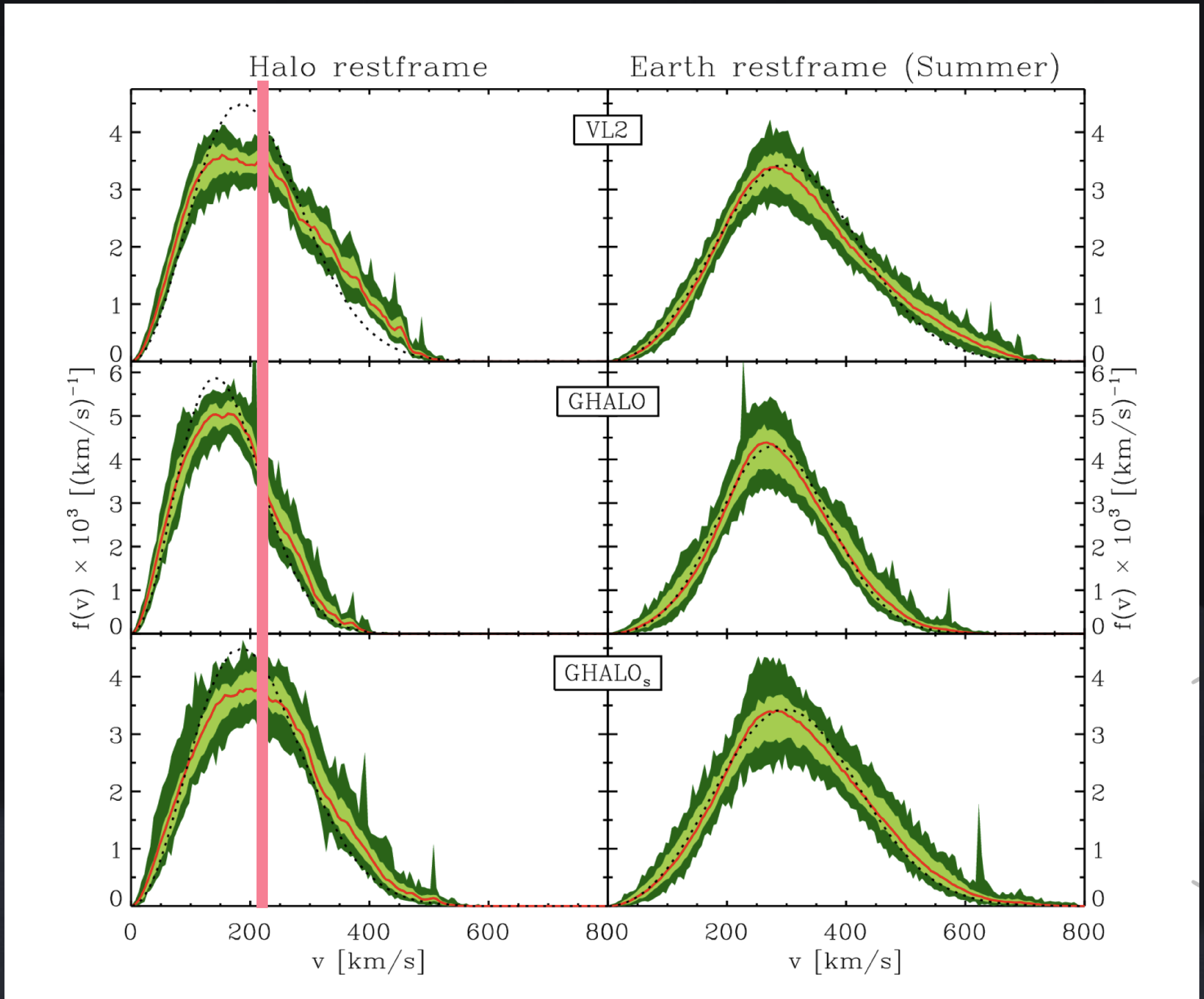
C. Kelso et al. [1601.04725]

Previous N-body Results



M. Vogelsberger, J. Zavala [1211.1377]

Previous N-body Results



M. Kuhlen et al. [0812.0362]