

# Looking for the Dark through the Light

Xiuyuan Zhang,

Based on work with Lina Necib and Denis Erkal: 2504.13247

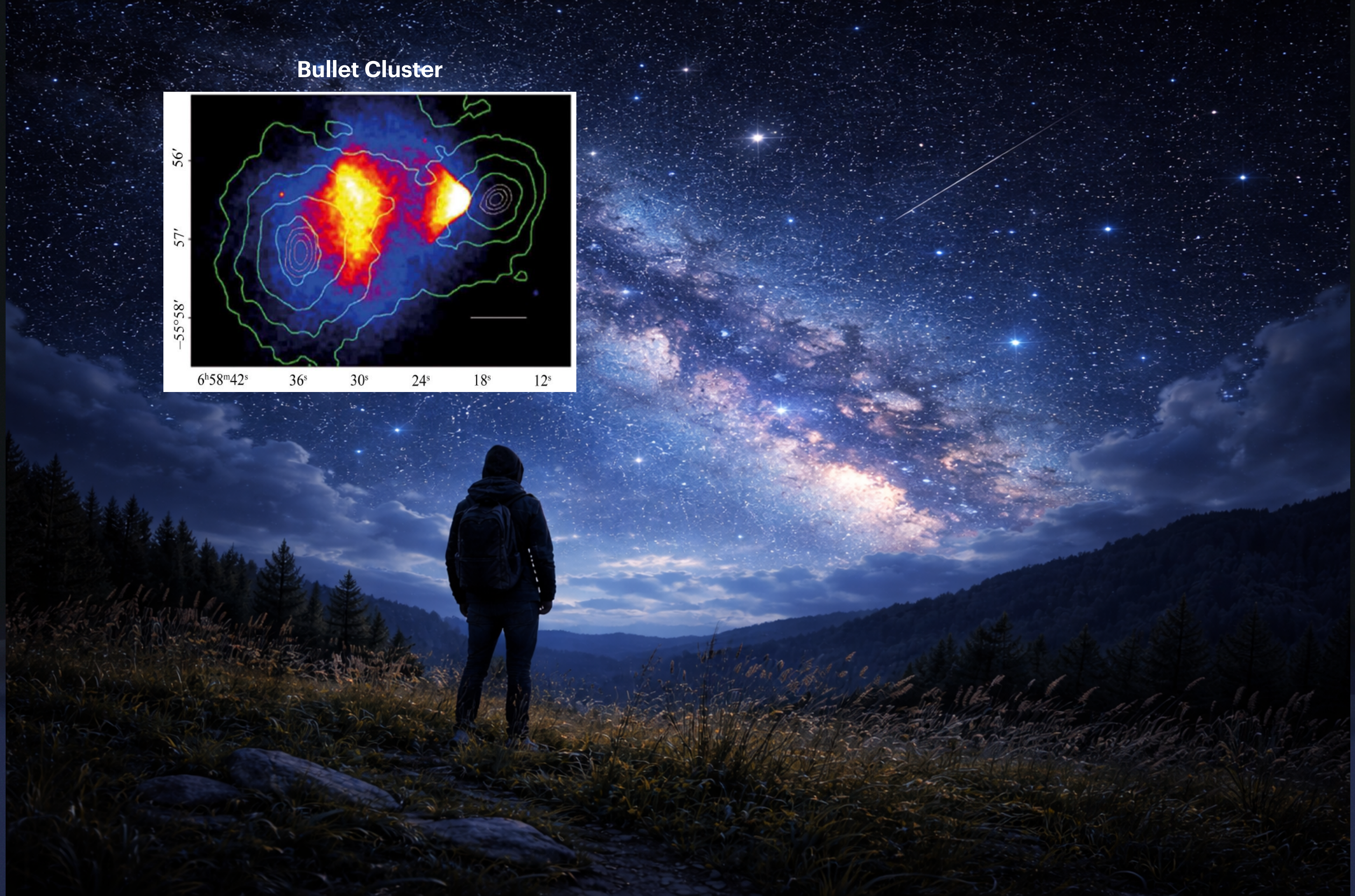
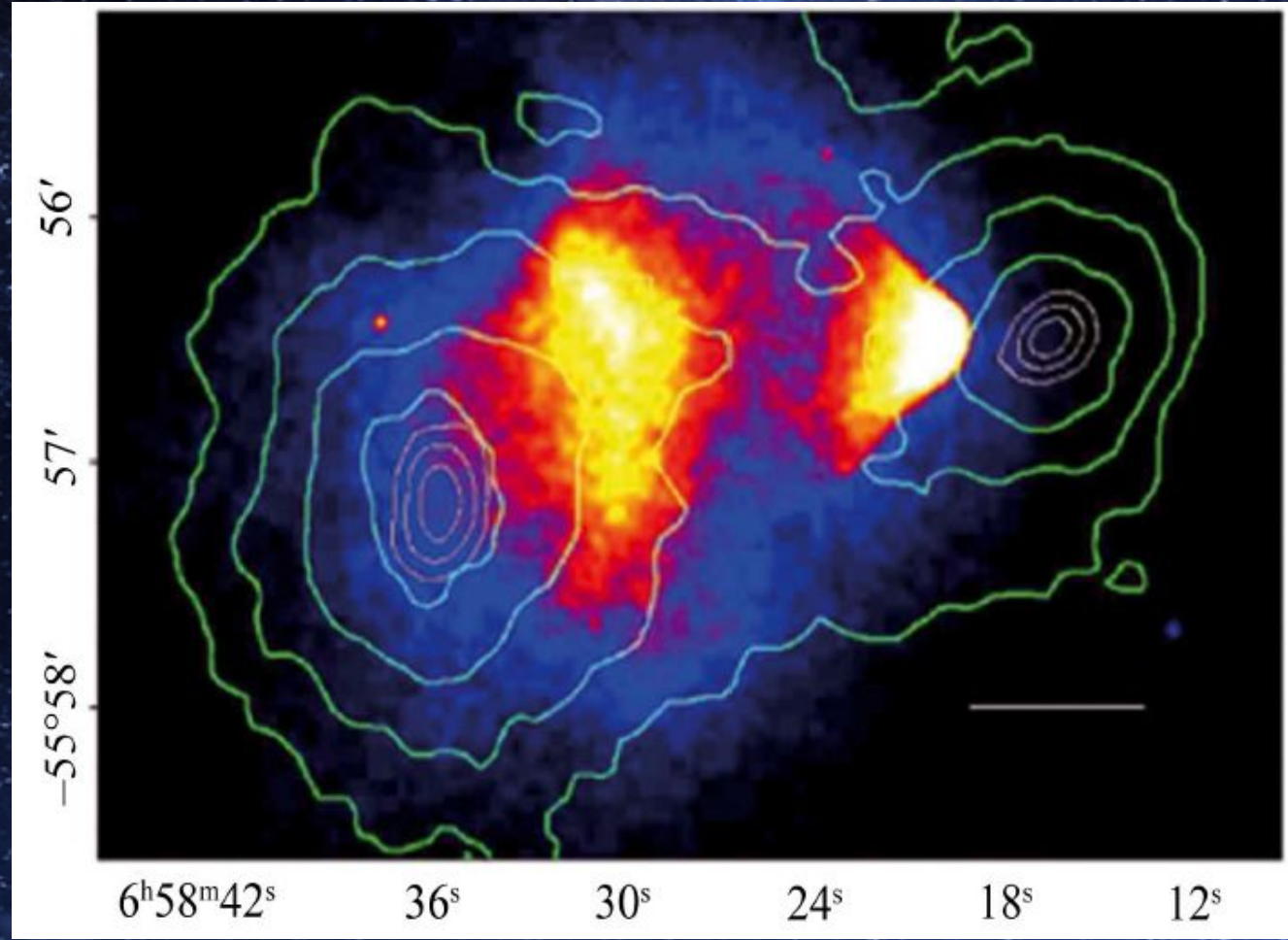
And with Andreas Thoyas, Lina Necib, Andrew Wetzel and Arpit Arora: 2603.25783

MIT / FIRE Collaboration

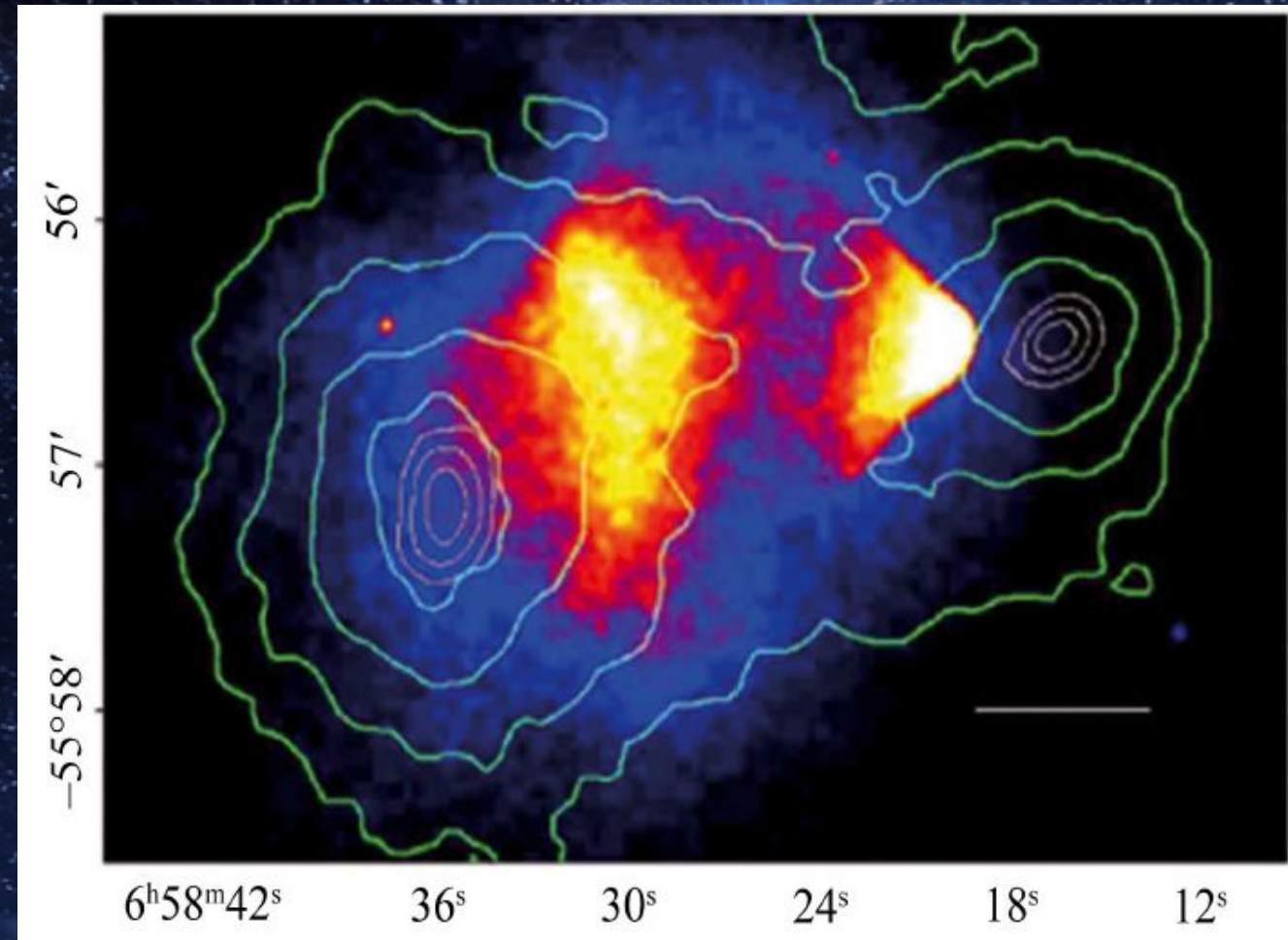




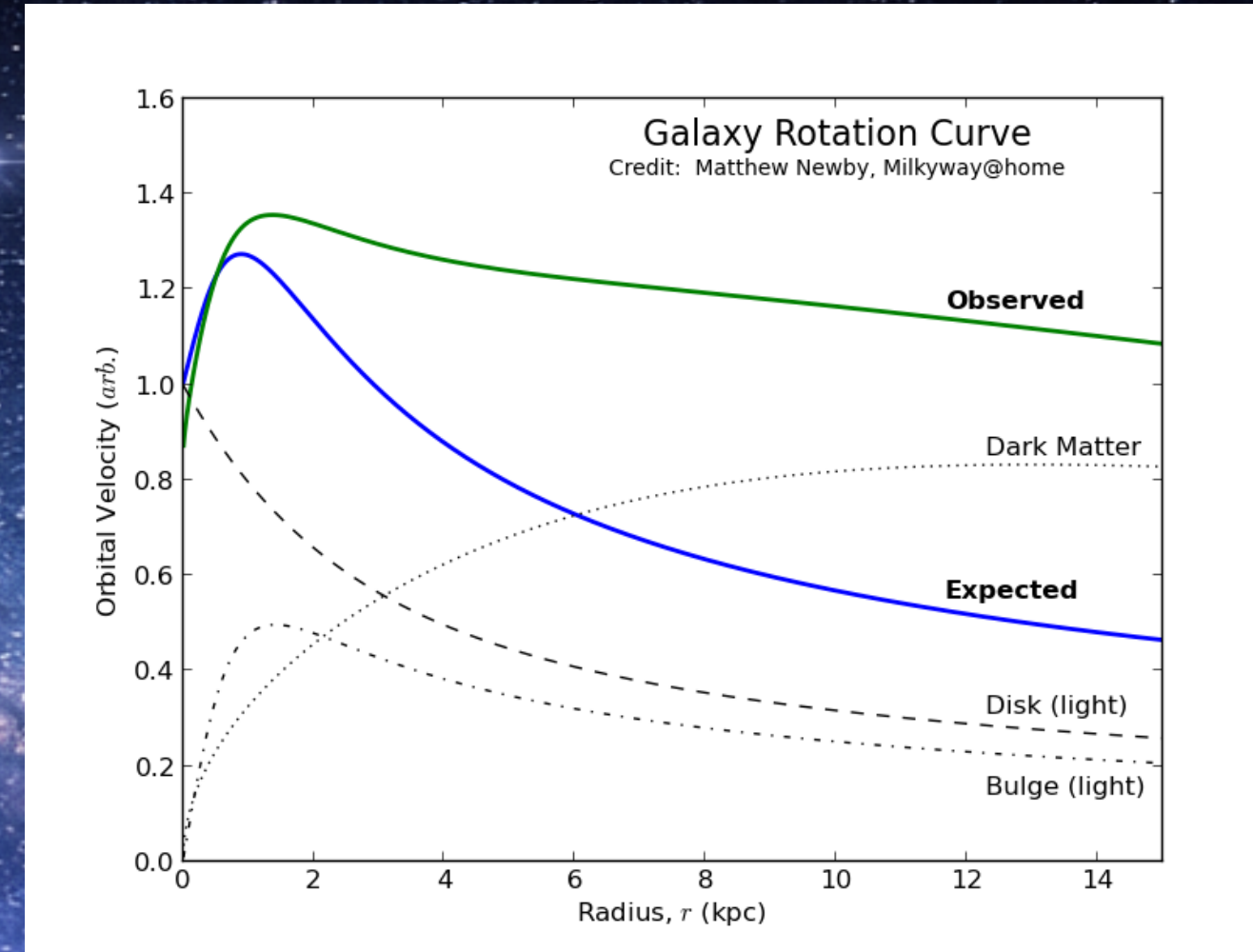
# Bullet Cluster



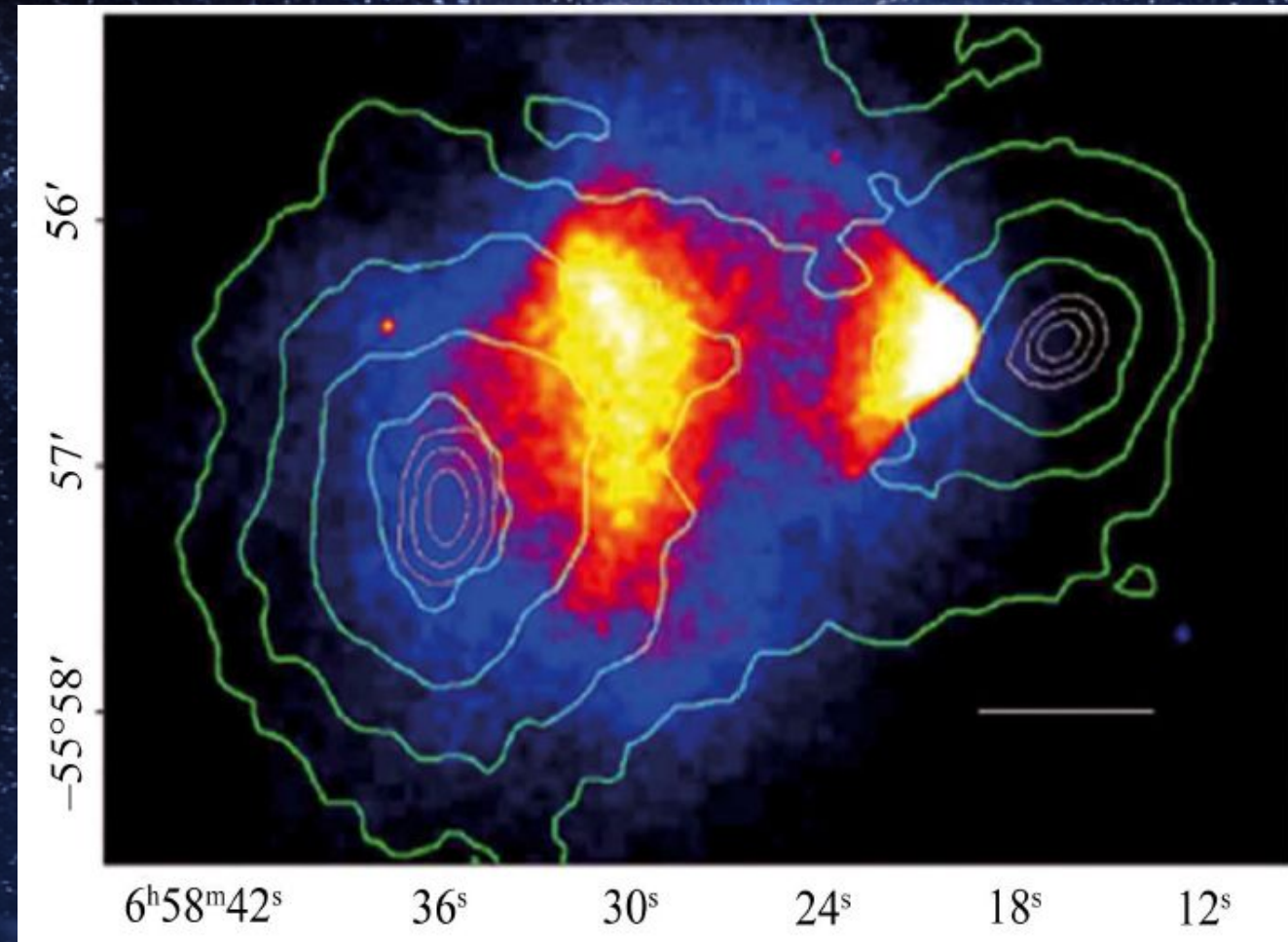
## Bullet Cluster



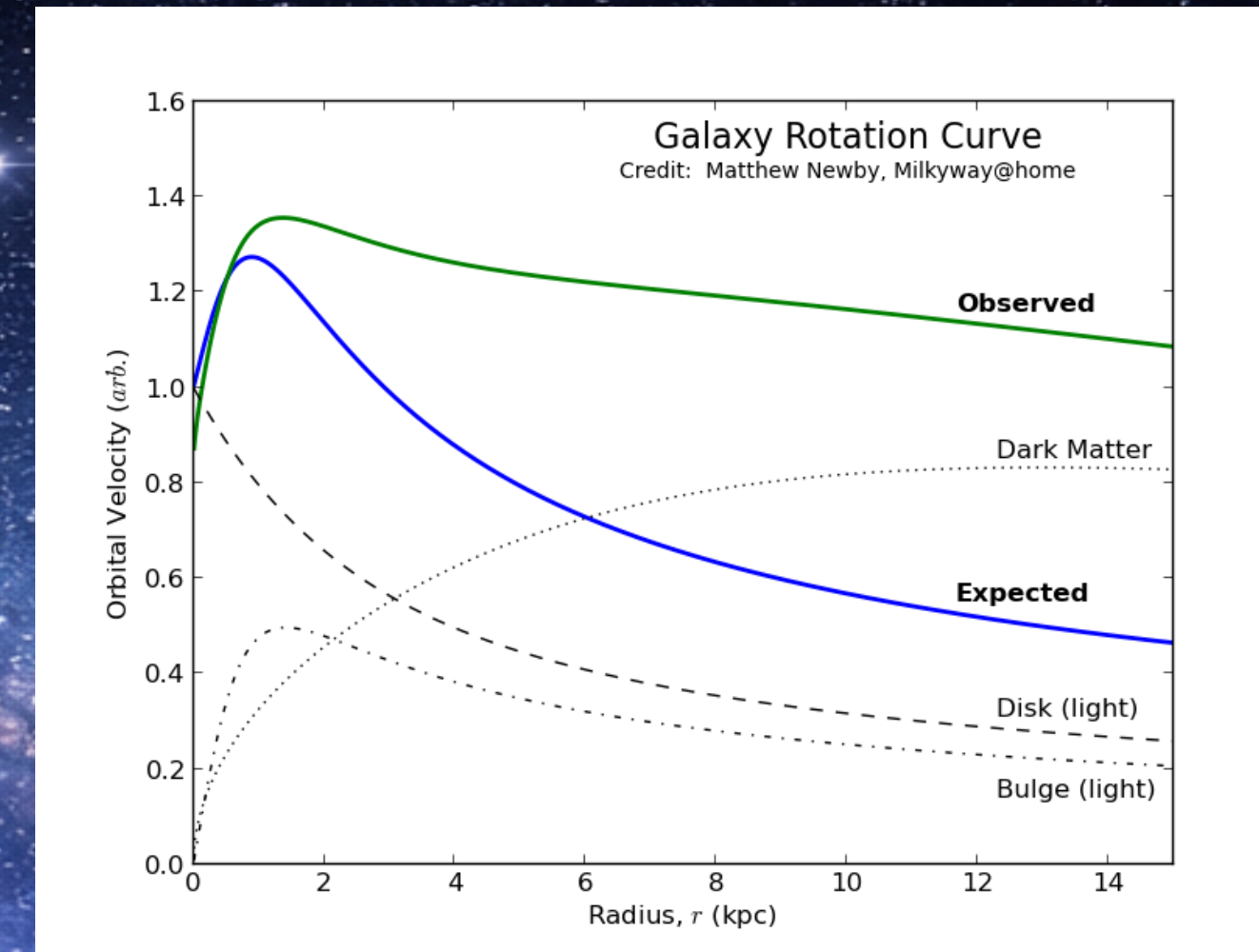
## Rotation Curve



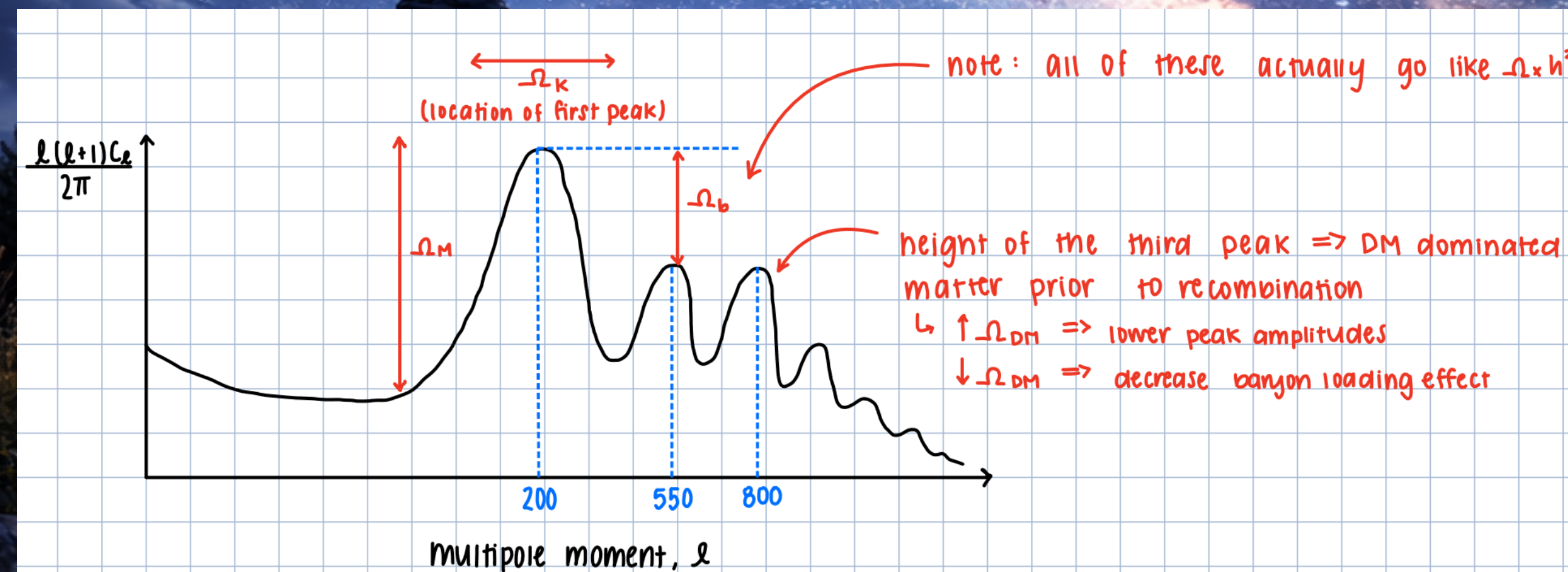
## Bullet Cluster



## Rotation Curve

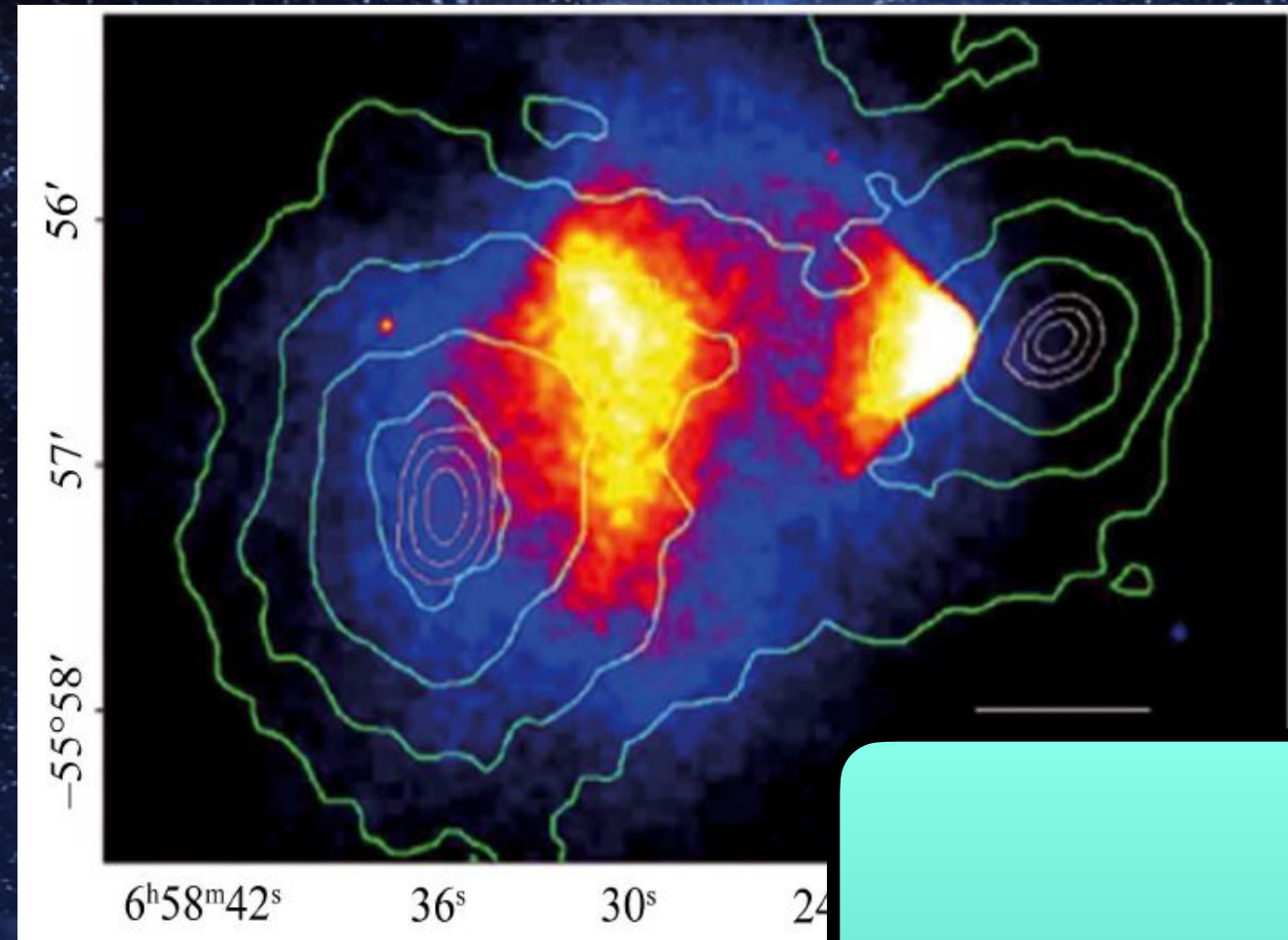


## CMB

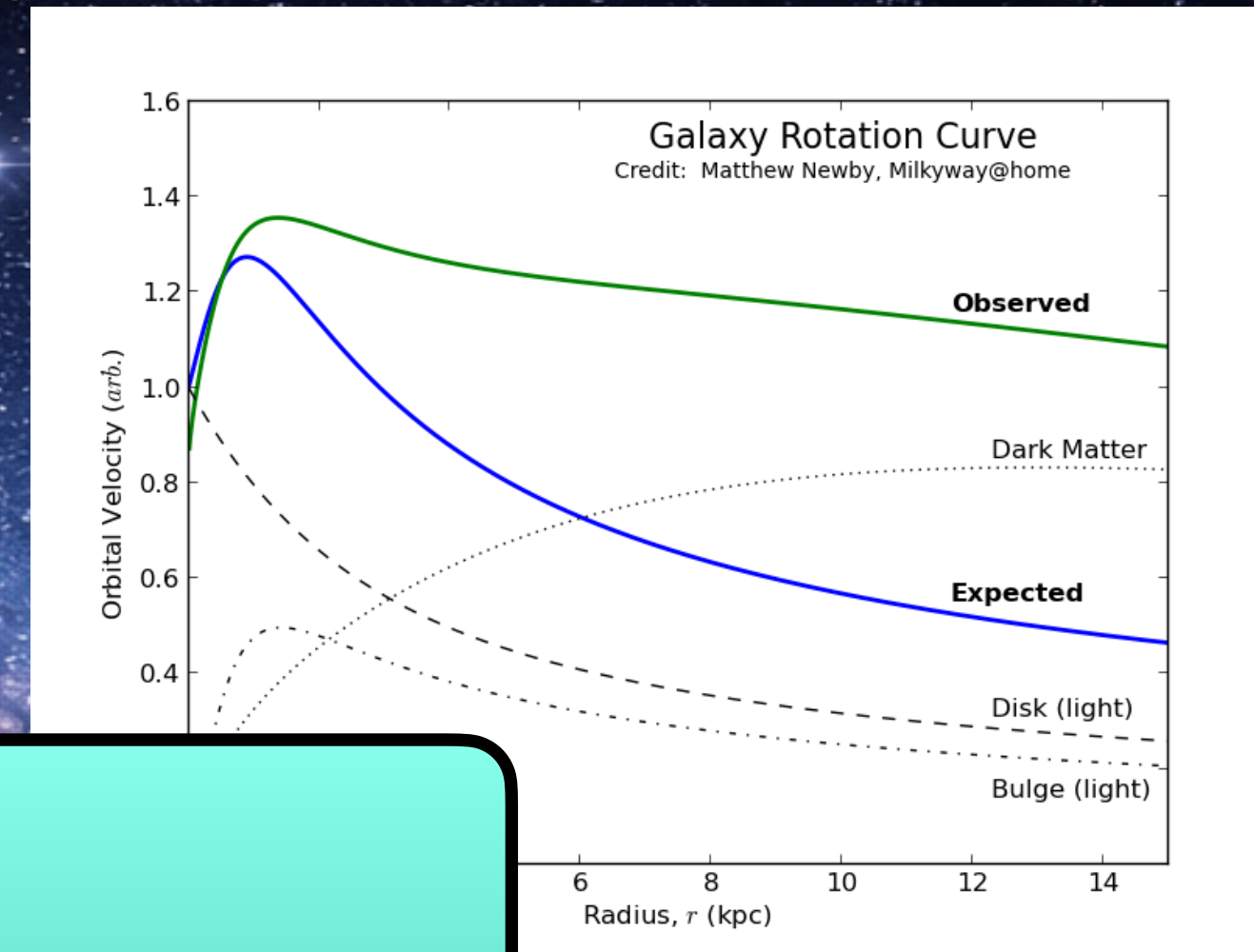


Megan Materson: astrowiki

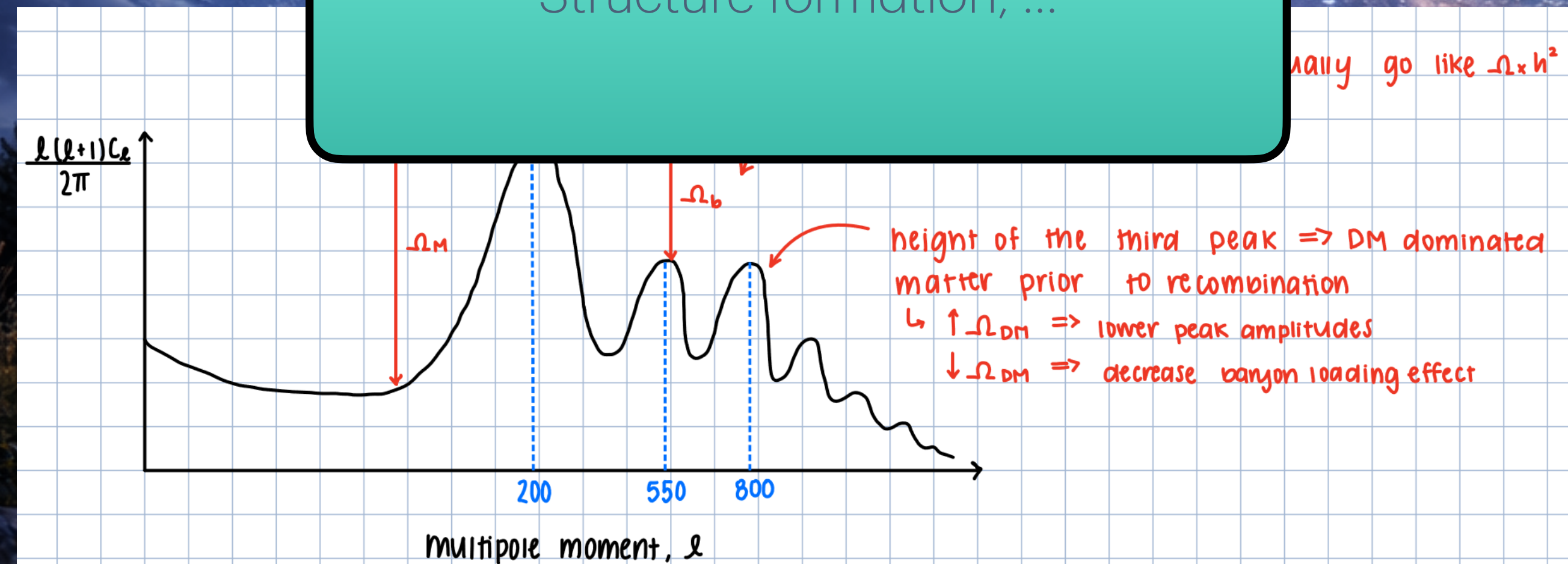
## Bullet Cluster



## Rotation Curve

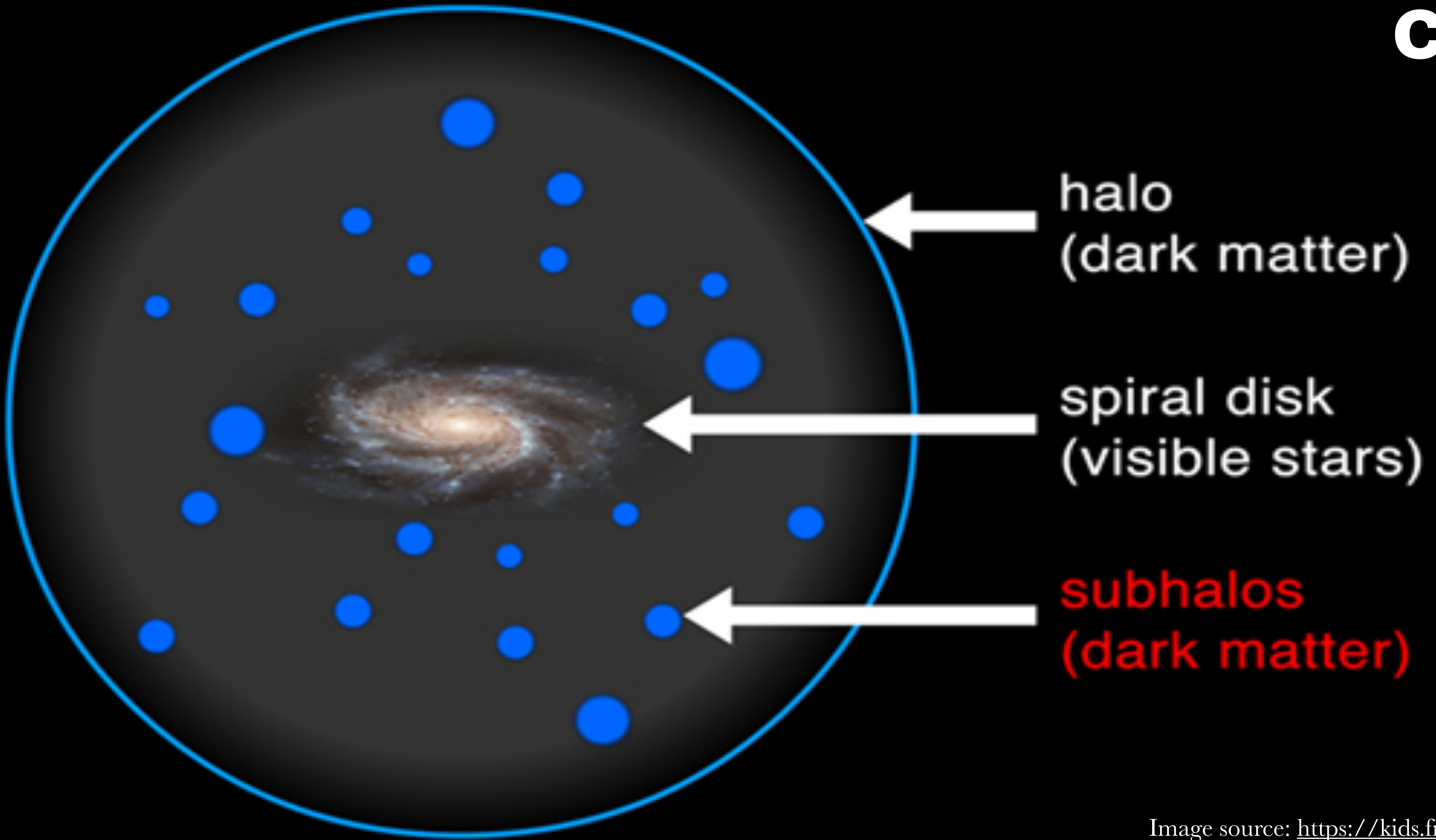


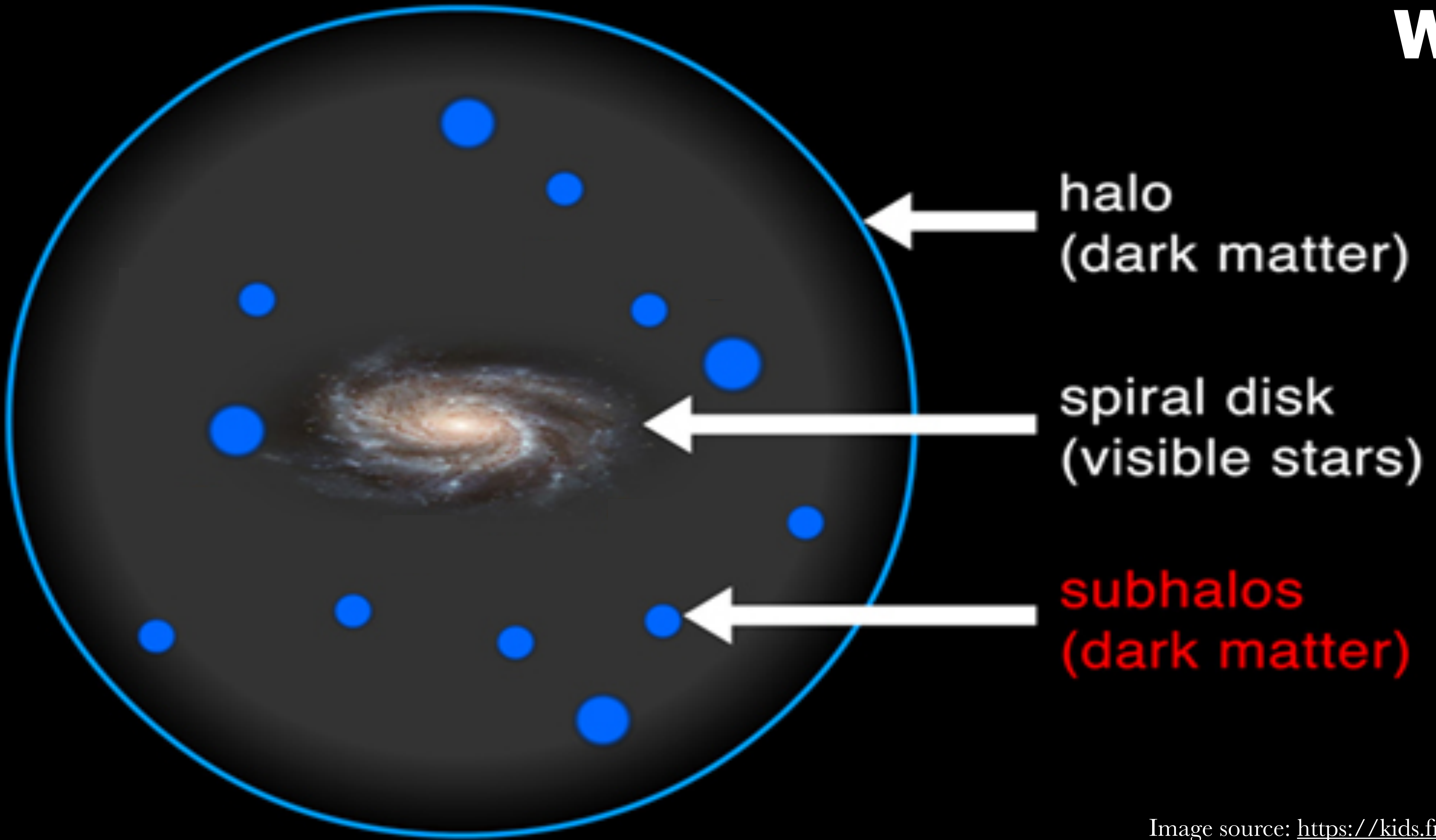
And so much more!  
Velocity dispersion, Lyman Alpha,  
Structure formation, ...



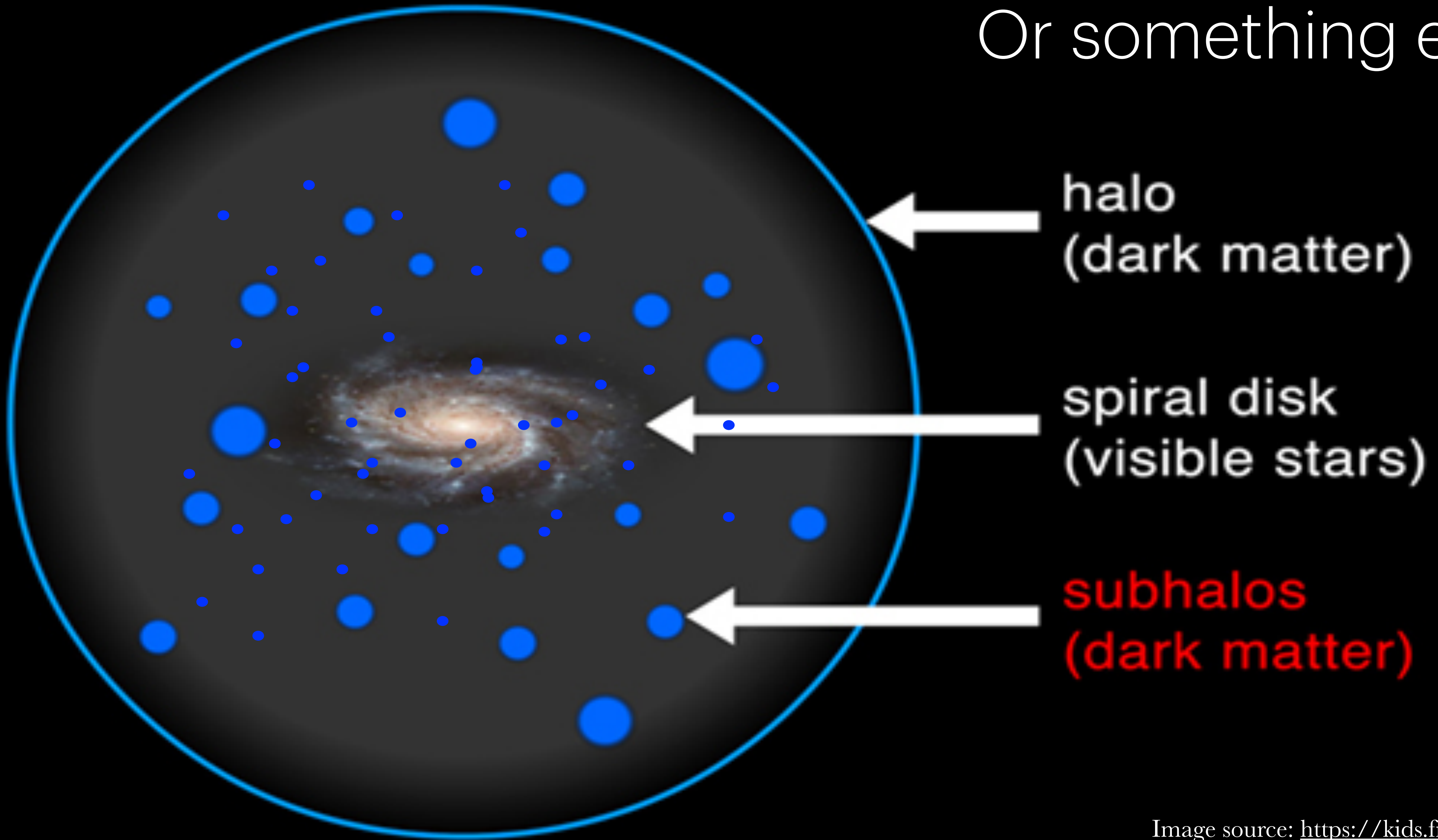
Megan Materson: astrowiki

# CDM

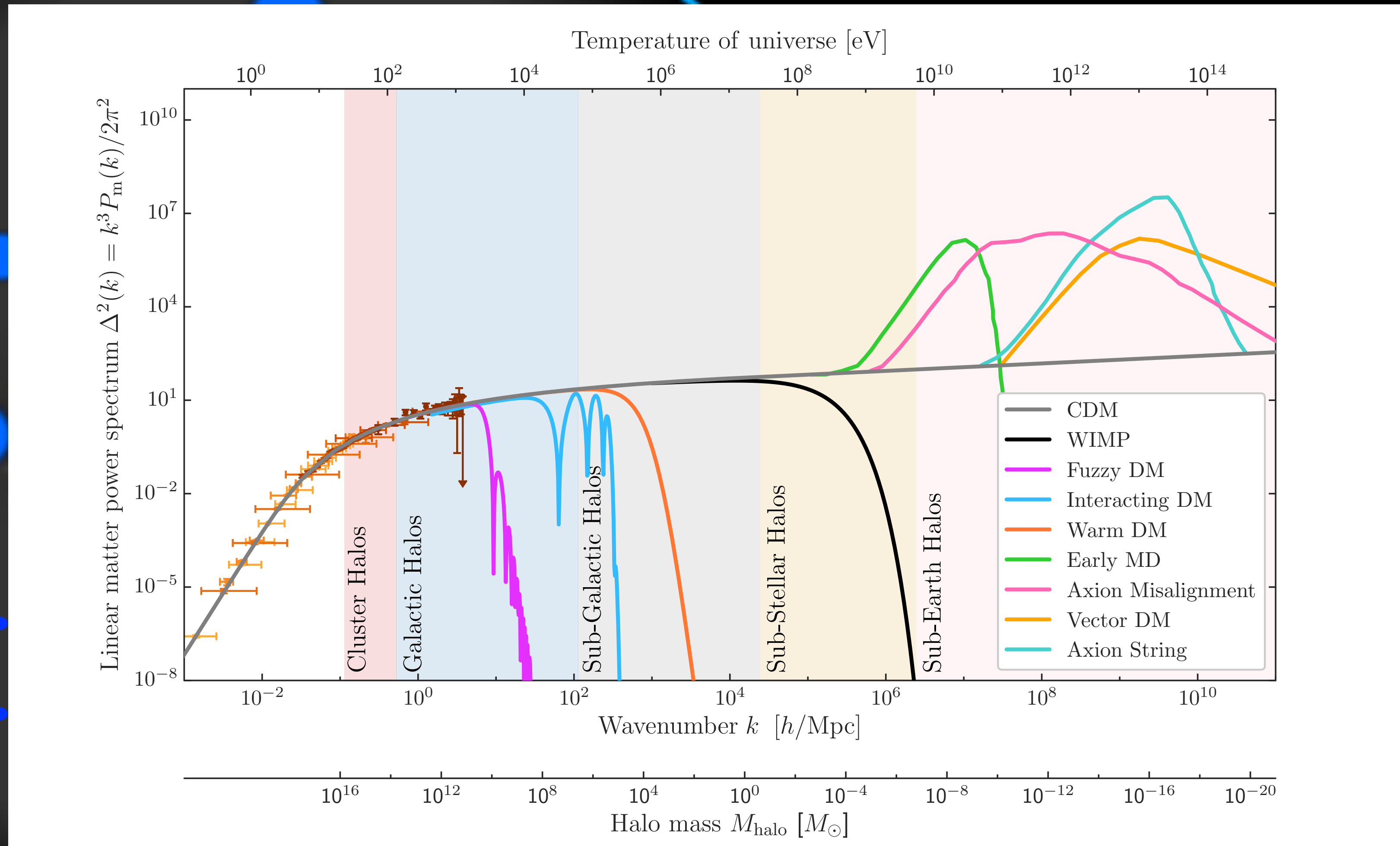




Or something else?



# Or something else?



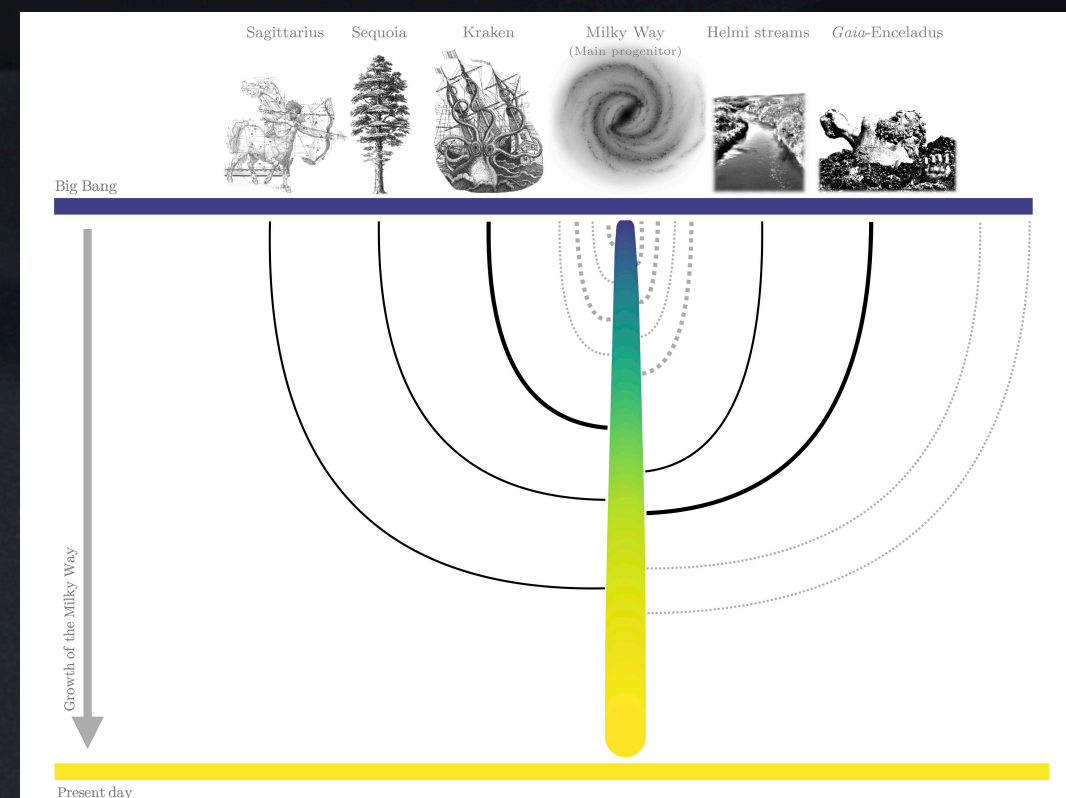
Snowmass Cosmic Probes of Dark Matter Report (2209.08215)

# Contents

Looking for subhalos using Paleo-detectors



Stellar Tracers of the Local Dark Matter Velocity Distribution



Distribution





# Looking for subhalos using Paleo-detectors

1. Estimating yearly Encounter rate
2. Paleo-detectors
3. Constraining subhalo properties

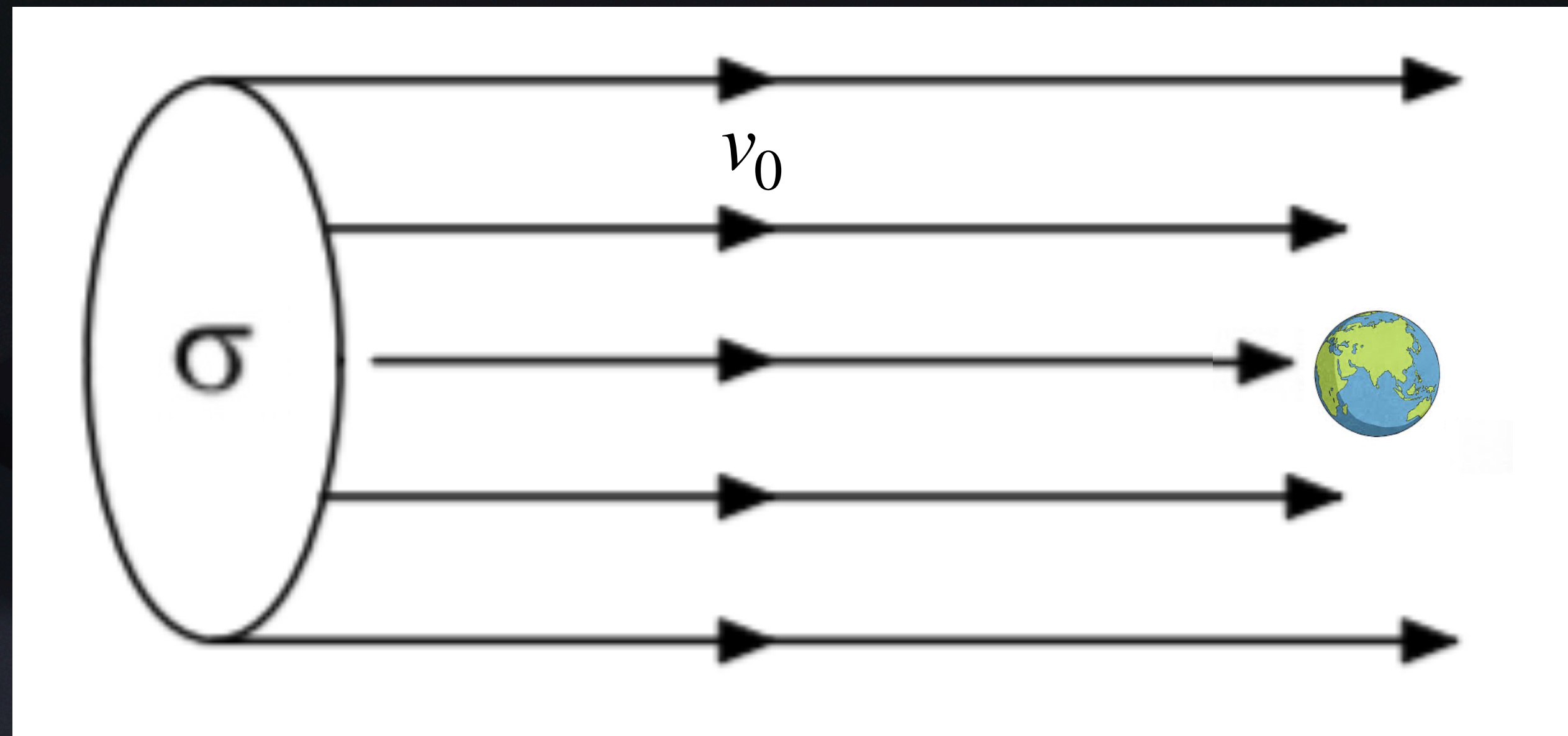
***So how much more ???***



# Subhalo Encountering Rate

$$\frac{dR_{sub}}{dM_{sub}} = \int \frac{dn_{sub}}{dM_{sub}} f(v) v \sigma(v, M_{sub}) dv$$

- $\frac{dR_{sub}}{dM_{sub}}$  is the differential rate of subhalo encountering events in unit of counts per year per solar mass



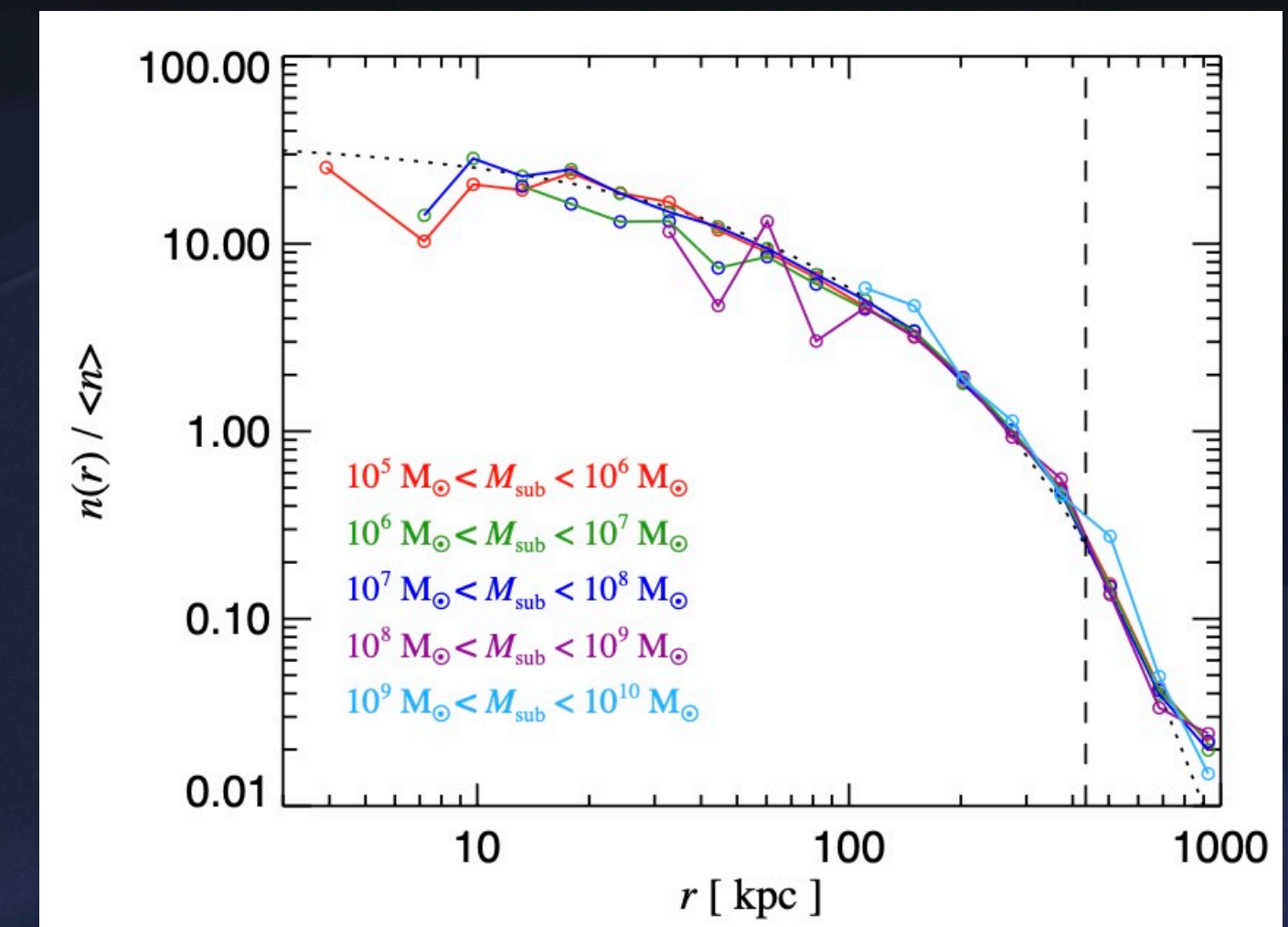
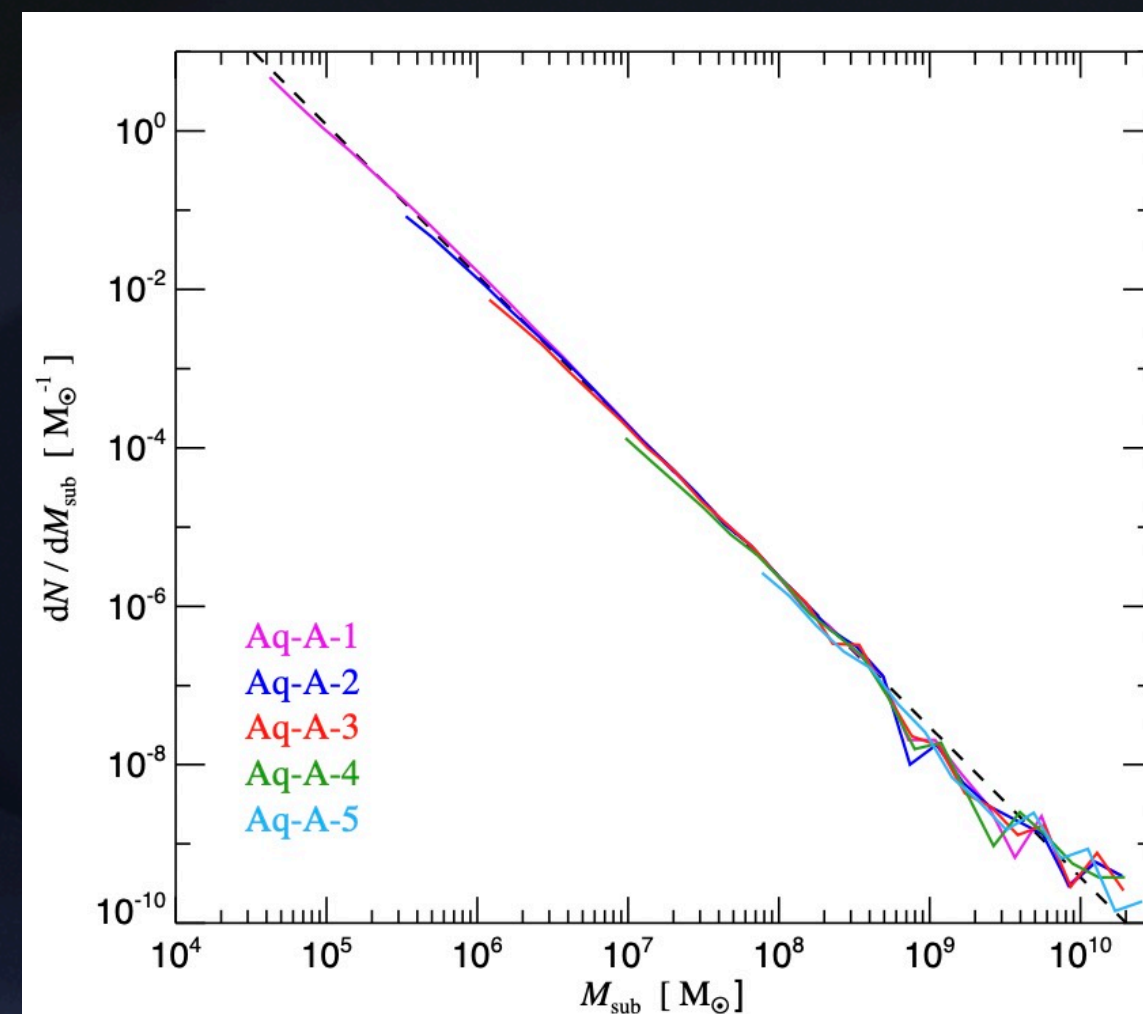
# Local Differential Number Density

$$\frac{dR_{sub}}{dM_{sub}} = \int \frac{dn_{sub}}{dM_{sub}} f(v) v \sigma(v, M_{sub}) dv$$

- $\frac{dn_{sub}}{dM_{sub}}$  is the local differential number density of subhalos in unit of number of subhalos per  $pc^3$  per solar mass

$$\frac{dN_{sub}}{dM_{sub}} = a_0 \left( \frac{M_{sub}}{m_0} \right)^\beta$$

$$n_{sub} \propto \exp\left[-\frac{2}{\alpha} \left( \left( \frac{r}{r_{-2}} \right)^\alpha - 1 \right)\right]$$



# Encounter Cross Section

$$\frac{dR_{sub}}{dM_{sub}} = \int \frac{dn_{sub}}{dM_{sub}} f(v) v \sigma(v, M_{sub}) dv$$

- Cross-Section:

$$\sigma(v, M_{sub}) = \int_0^{2\pi} d\phi \int_0^{b_{max}} b db = \pi b_{max}^2$$

- $b_{max}$  is the maximum impact parameter such that the closest approach point of the subhalo has a density higher than the local dark matter density  $0.3 \text{ GeV}/\text{cm}^3$



# Direct Detentional

The num

What're the odds of winning the lottery



The odds of winning a lottery can vary significantly depending on the specific game and its rules. For example:

- **Powerball:** The odds of winning the Powerball jackpot are about 1 in 292.2 million.
- **Mega Millions:** The odds of winning the Mega Millions jackpot are about 1 in 302.6 million.
- **Smaller Lotteries:** State lotteries or local games often have better odds, but the prizes are usually smaller. For instance, smaller games might have odds of winning the top prize that are about 1 in several million or even less.

**DM**

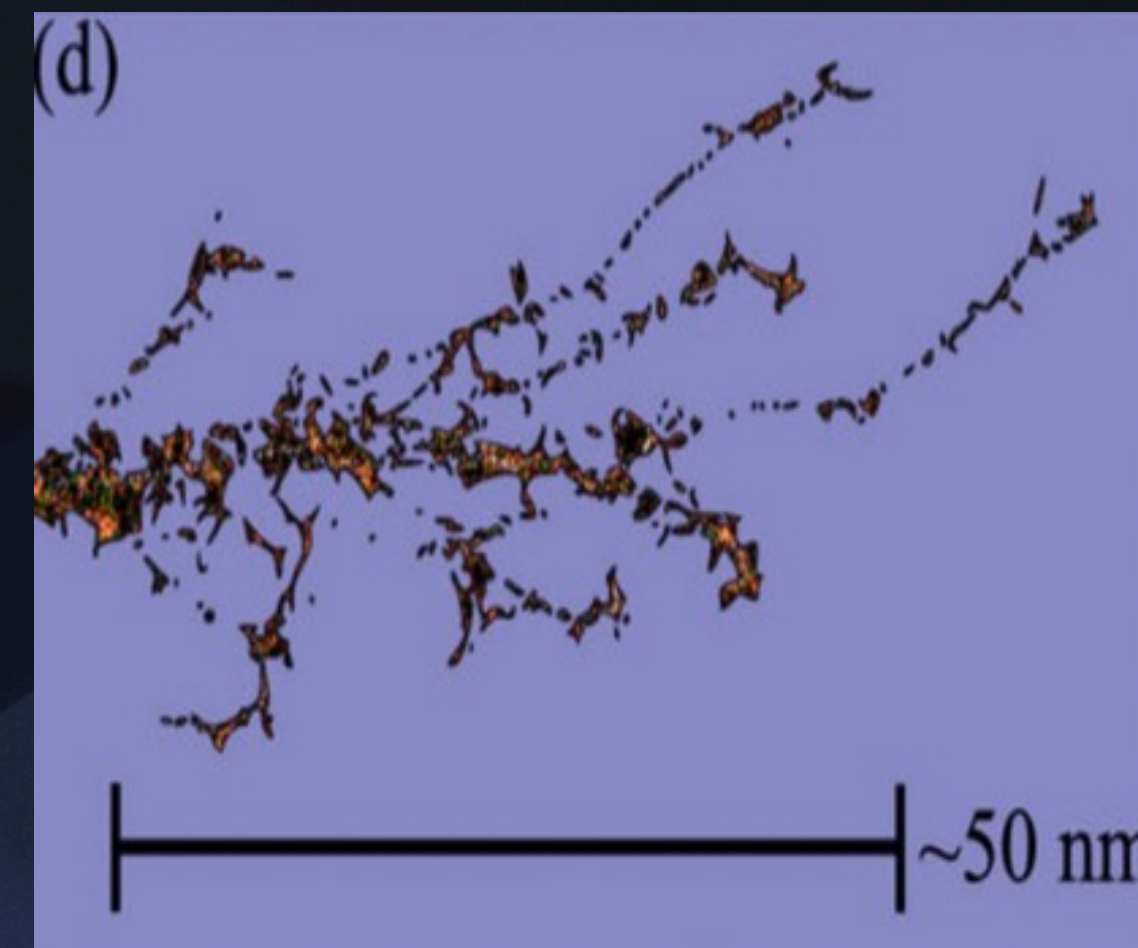
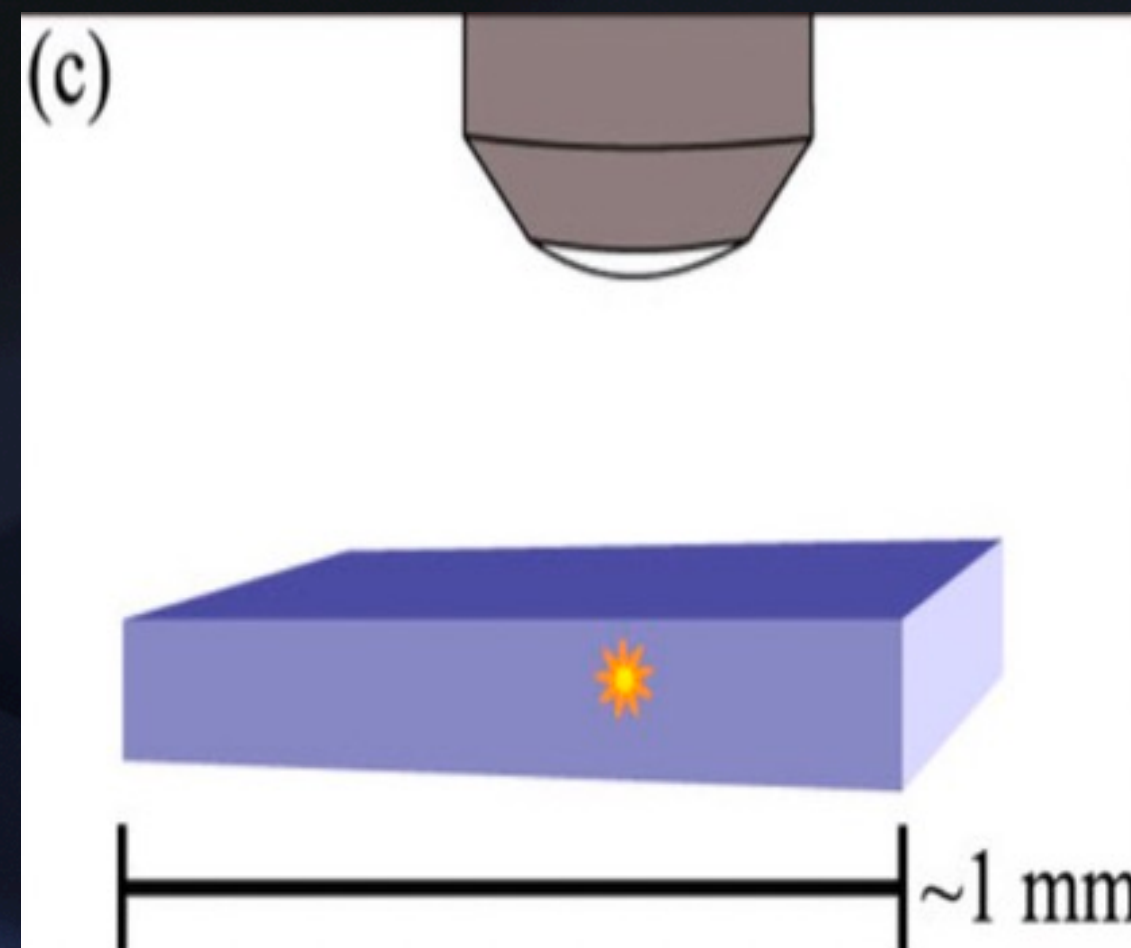
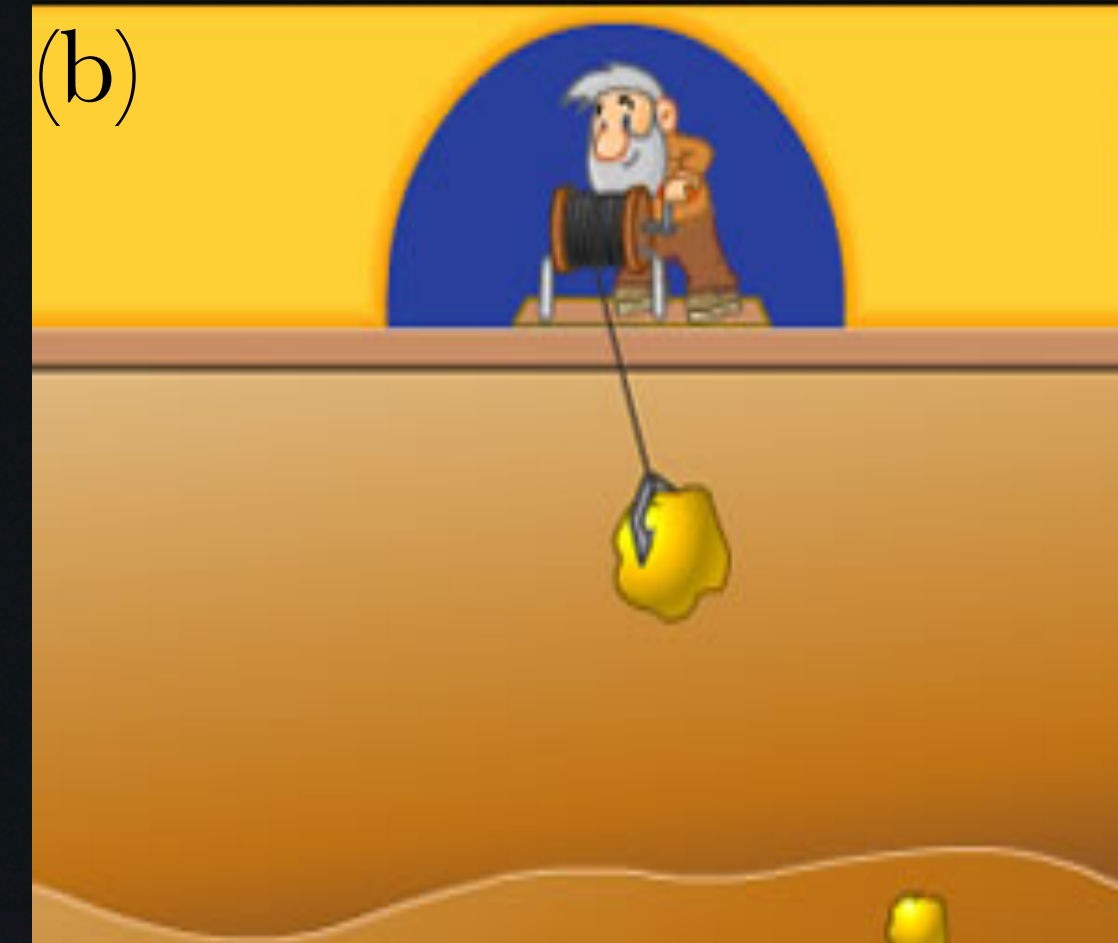
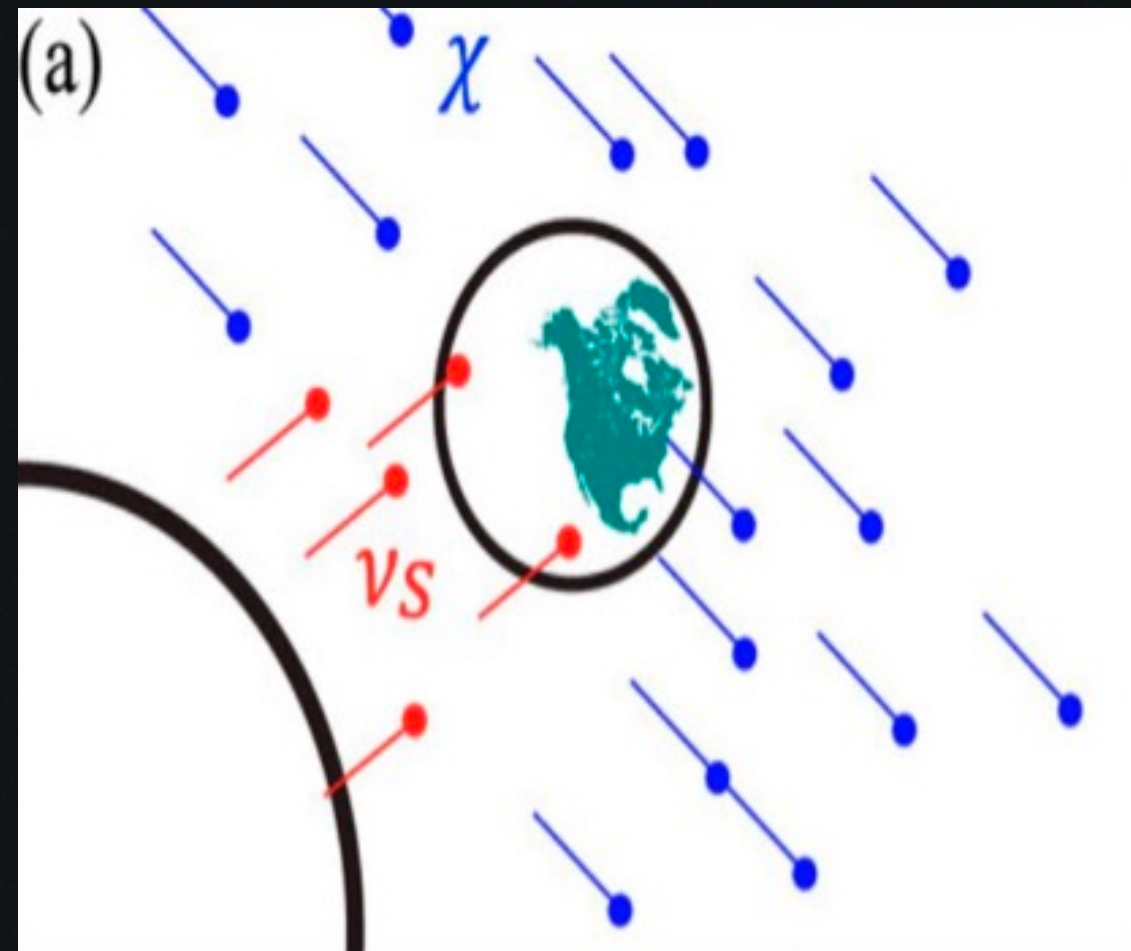


Overall, while the potential payout can be enticing, the chances of winning the top prize in major lotteries are extremely low.

# Paleo-Detectors

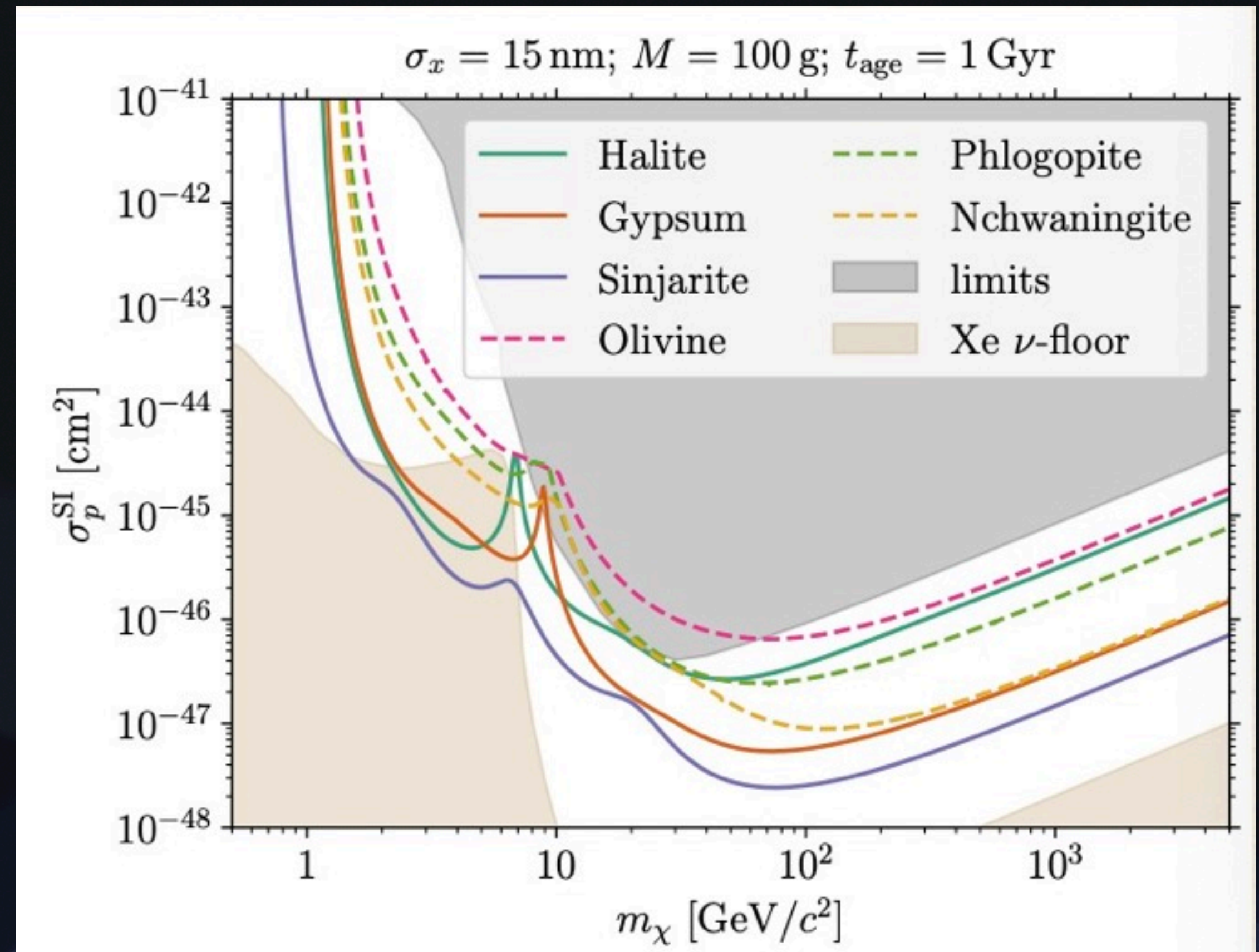
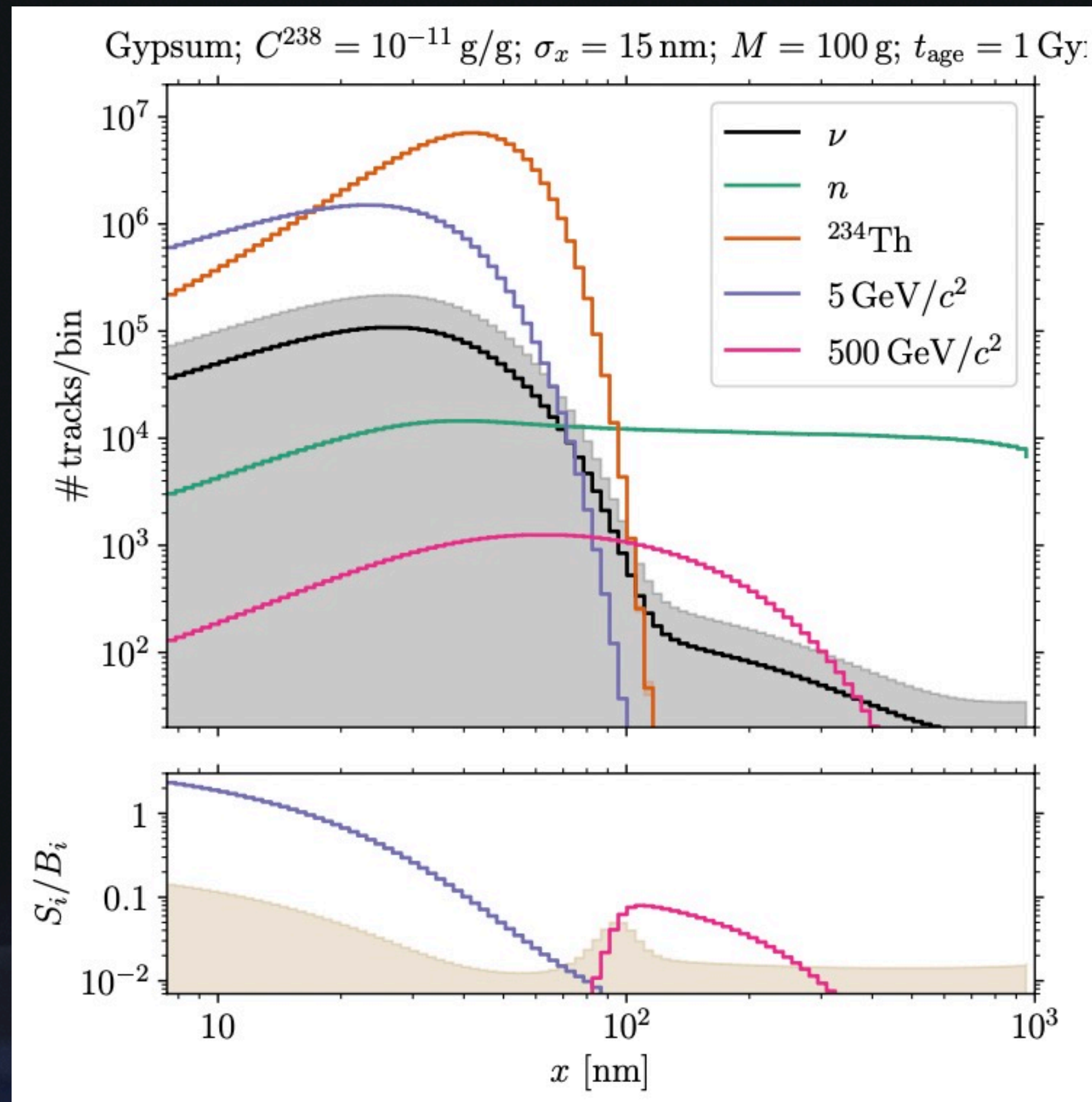


# Paleo-Detectors



Marshall et al, arXiv: 2009.01028

# Paleo-Detectors

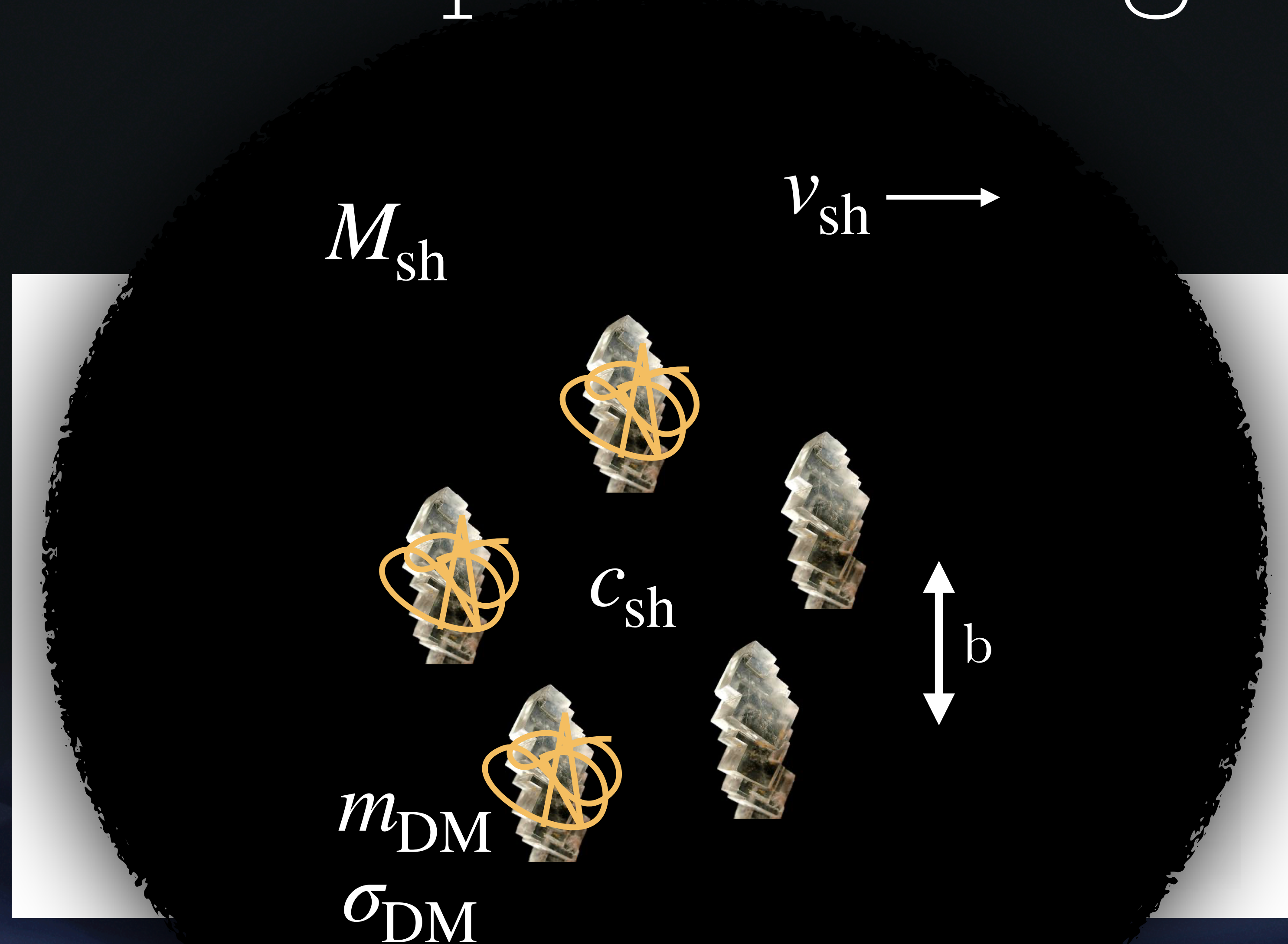


Baum et al, arXiv: 2106.06559

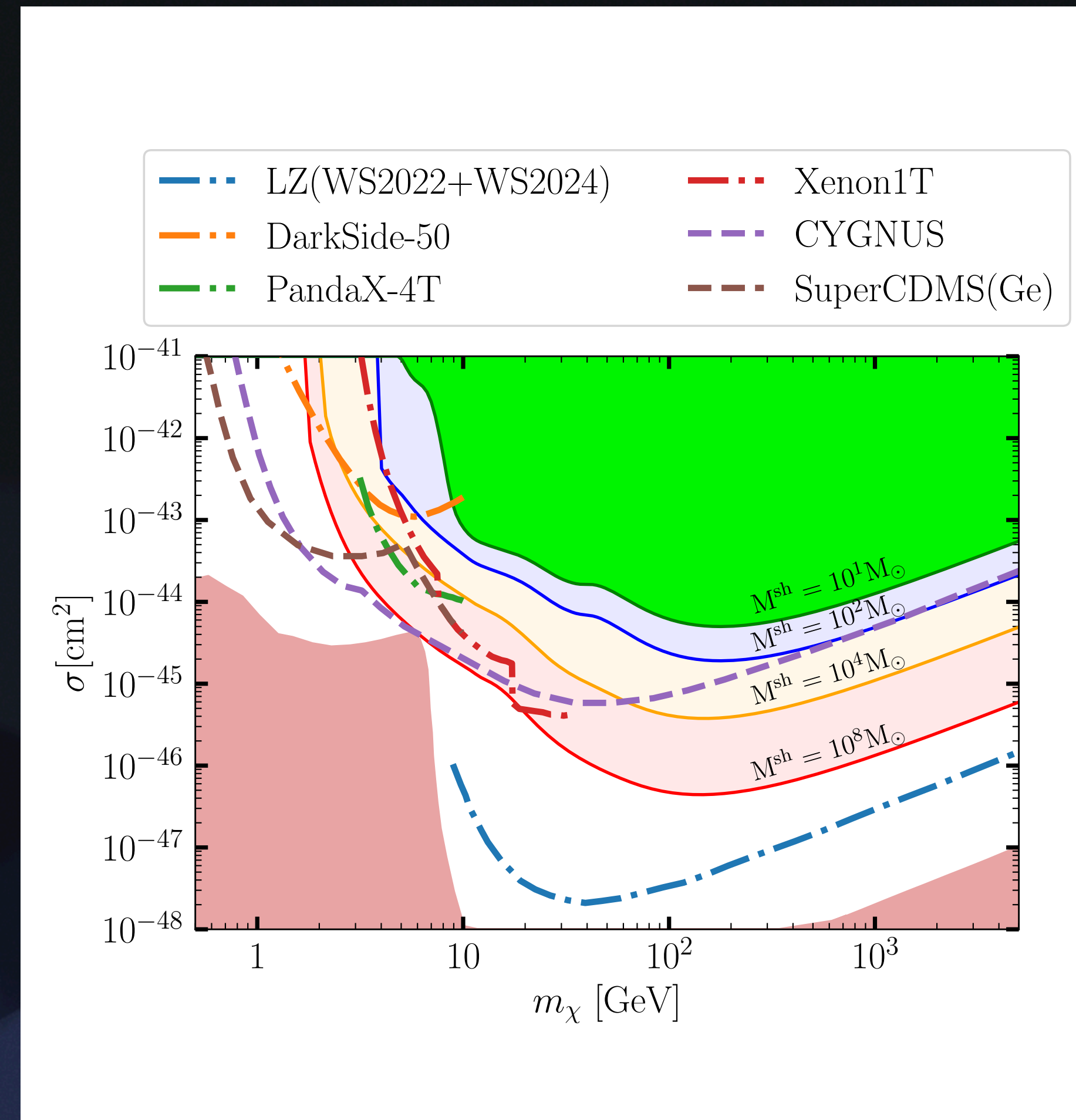
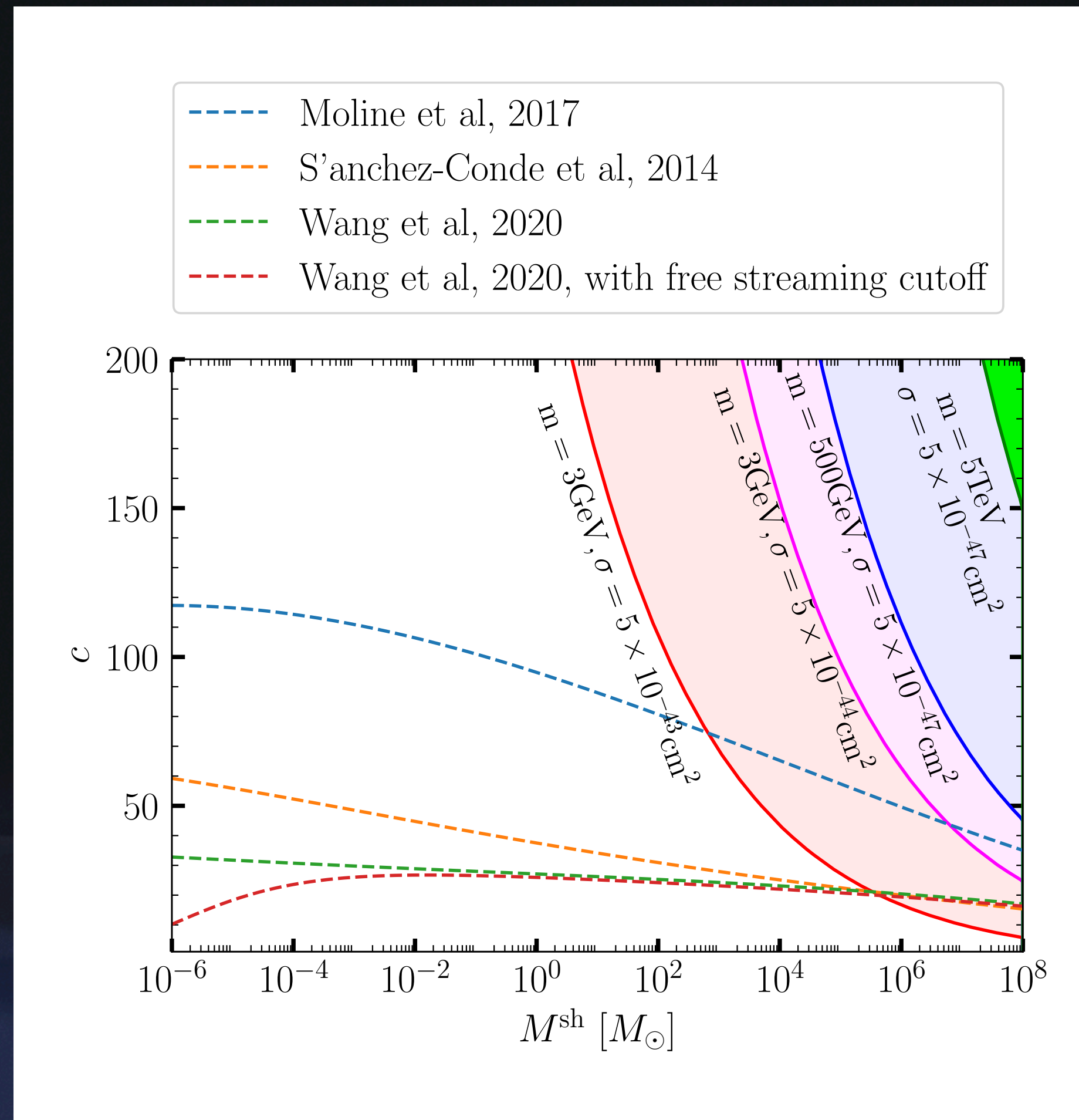
# Time Dependent Signal



# Time Dependent Signal

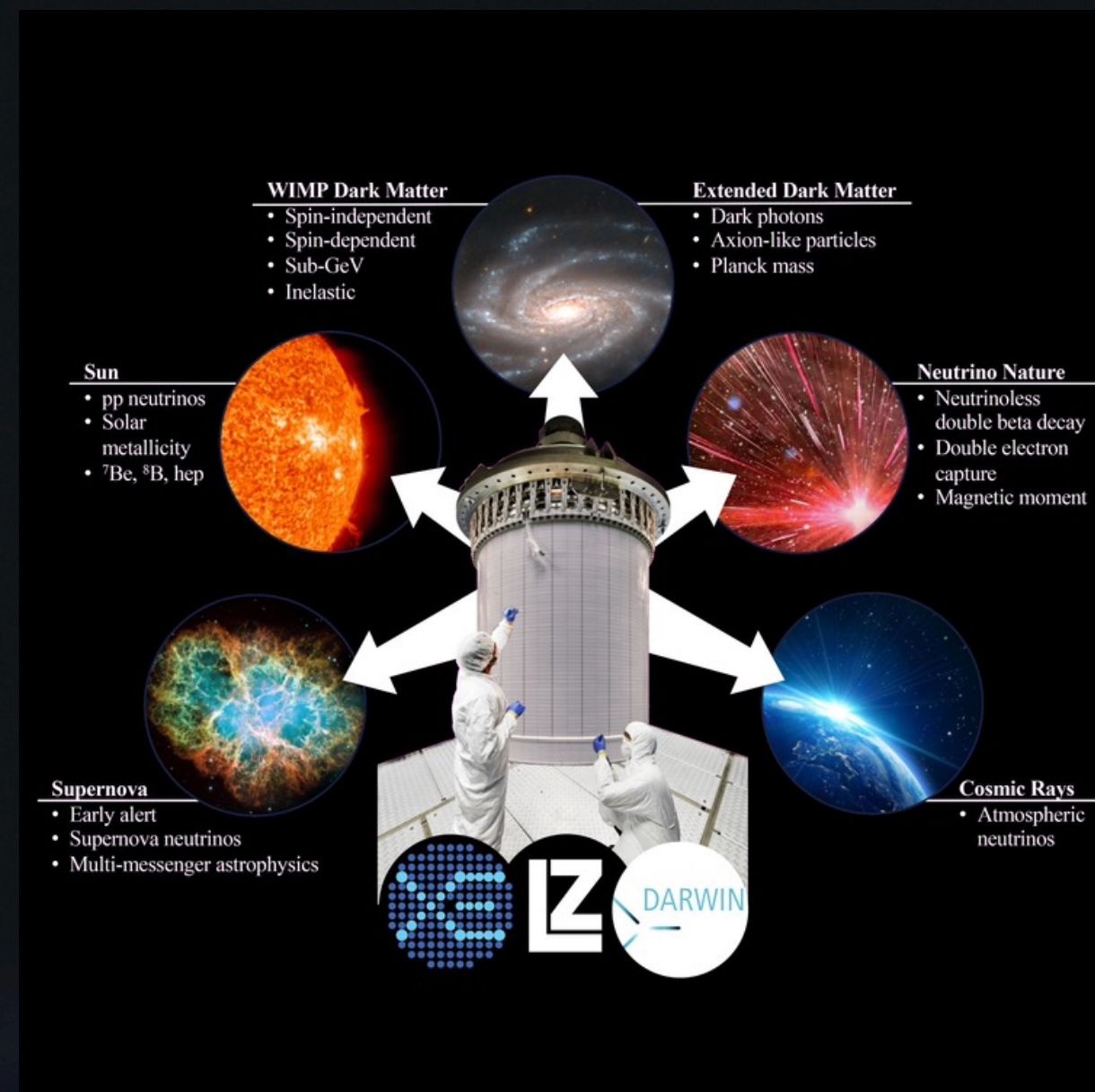


# Time Dependent Signal



$$\frac{dR_{sub}}{dM_{sub}} = \int \frac{dn_{sub}}{dM_{sub}} f(v) v \sigma(v, M_{sub}) dv$$

### Direct Detection



Credit: XLZD

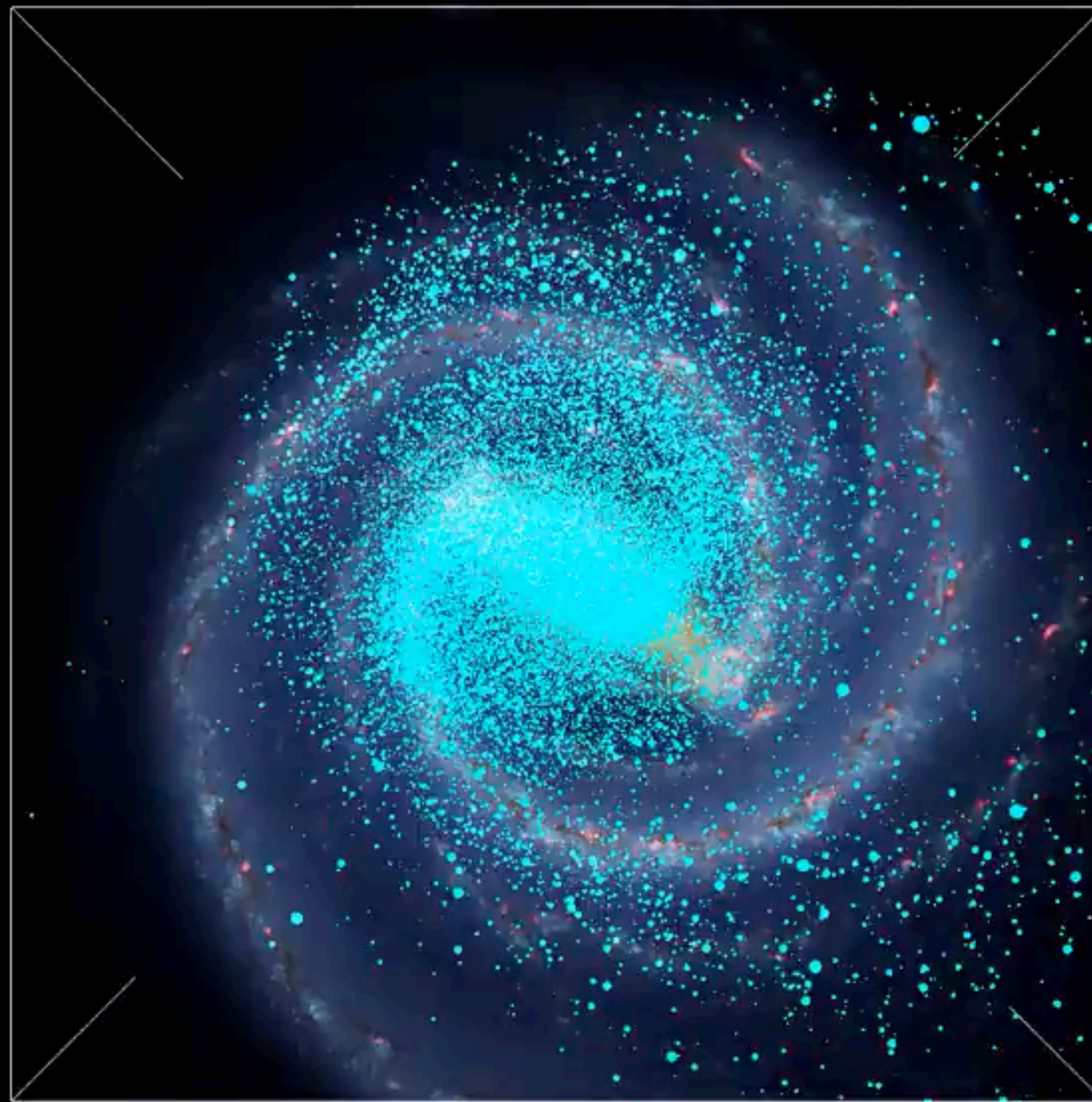
### Axion Detection



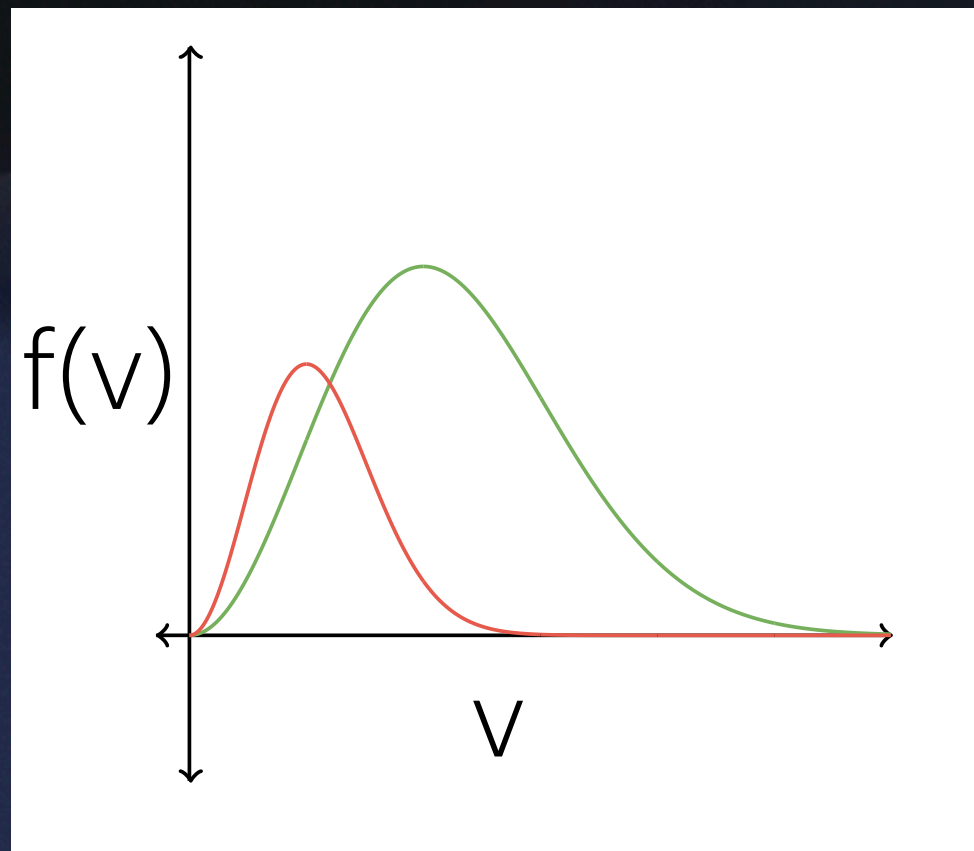
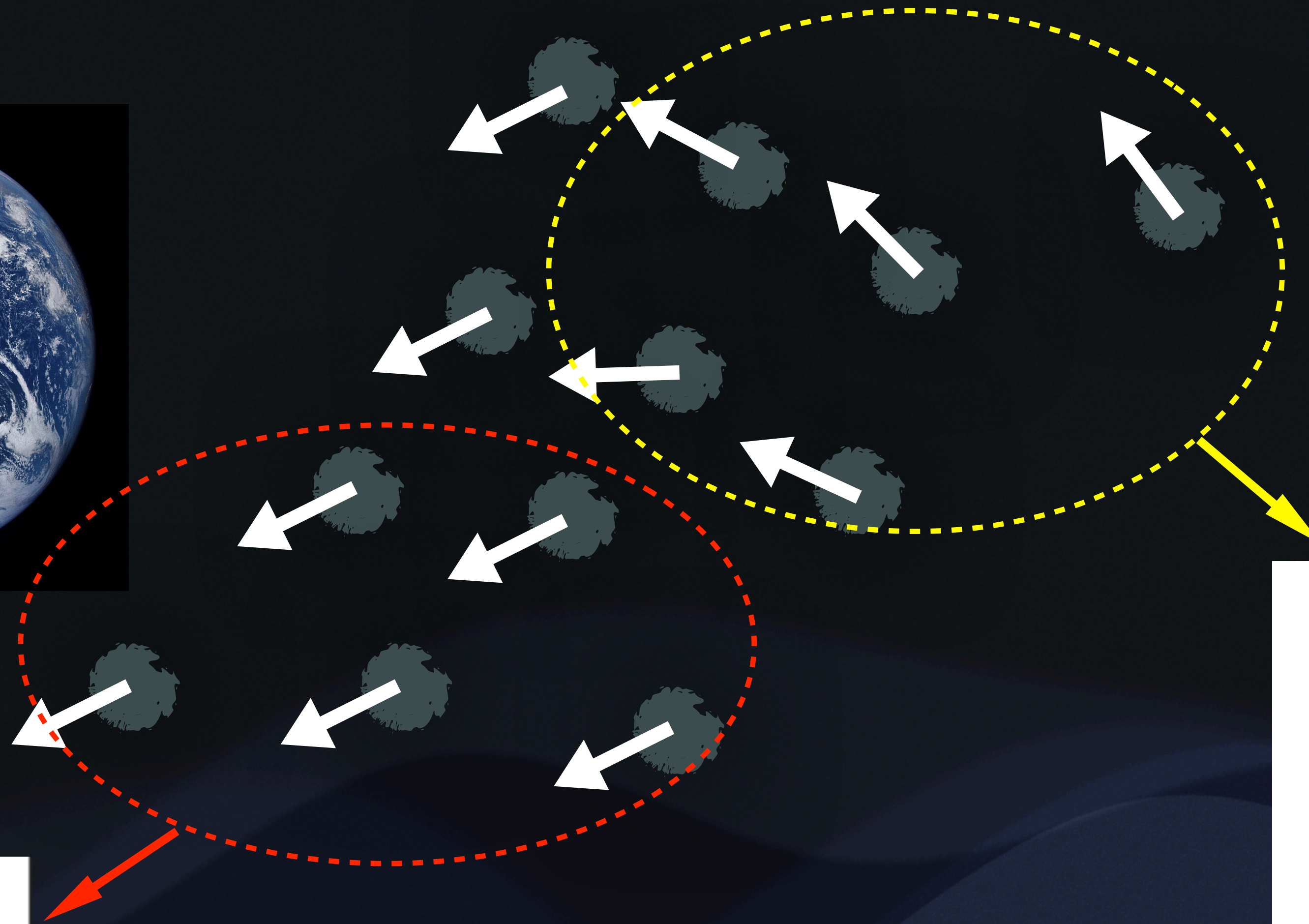
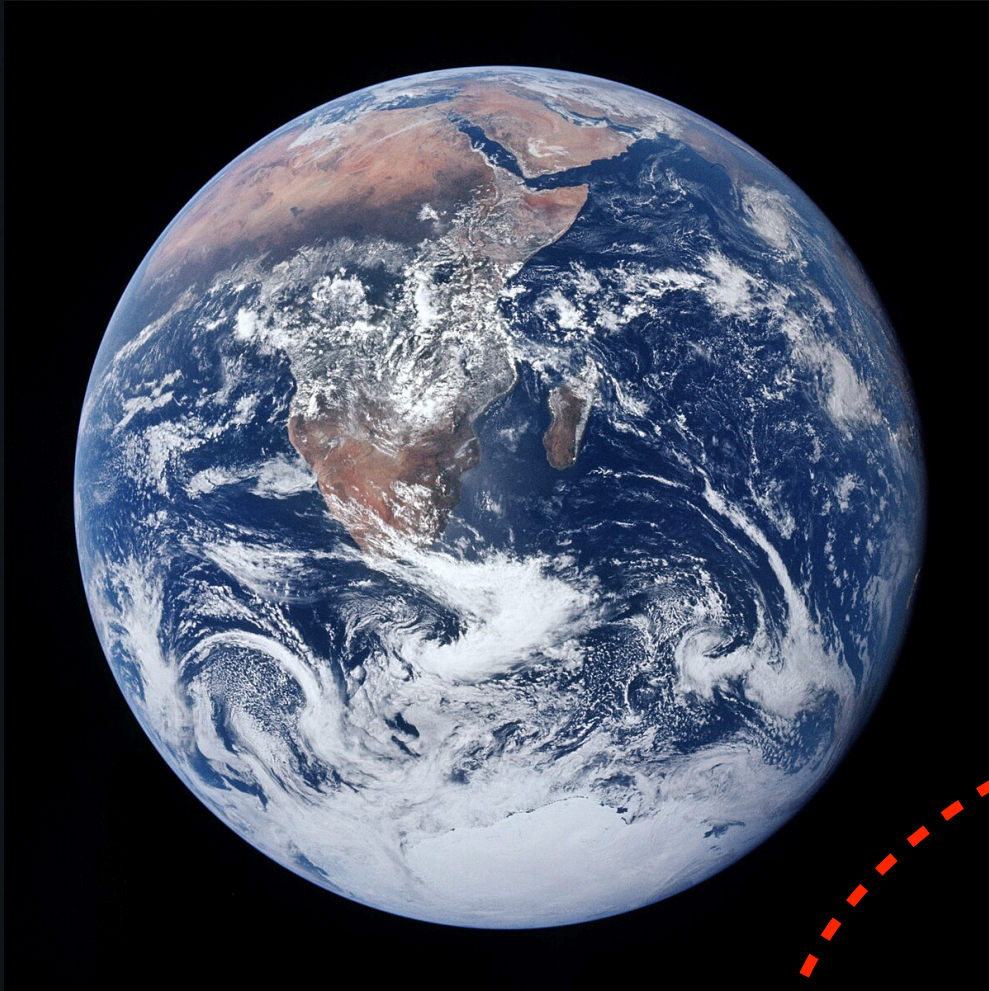
Credit: ABRACADABRA

$$\frac{dR_{dd}}{dQ} = \frac{\sigma\rho}{2m_\chi m_r^2} F(Q)^2 \int \frac{f(v)}{v} dv$$

$$a(t) = \frac{\sqrt{\rho}}{m_a} \int \sqrt{f(v)} \cos\left[m_a\left(1 + \frac{v^2}{2}\right)t + \phi t\right] dv$$



<https://www.youtube.com/watch?v=hVPZhATLDKY>

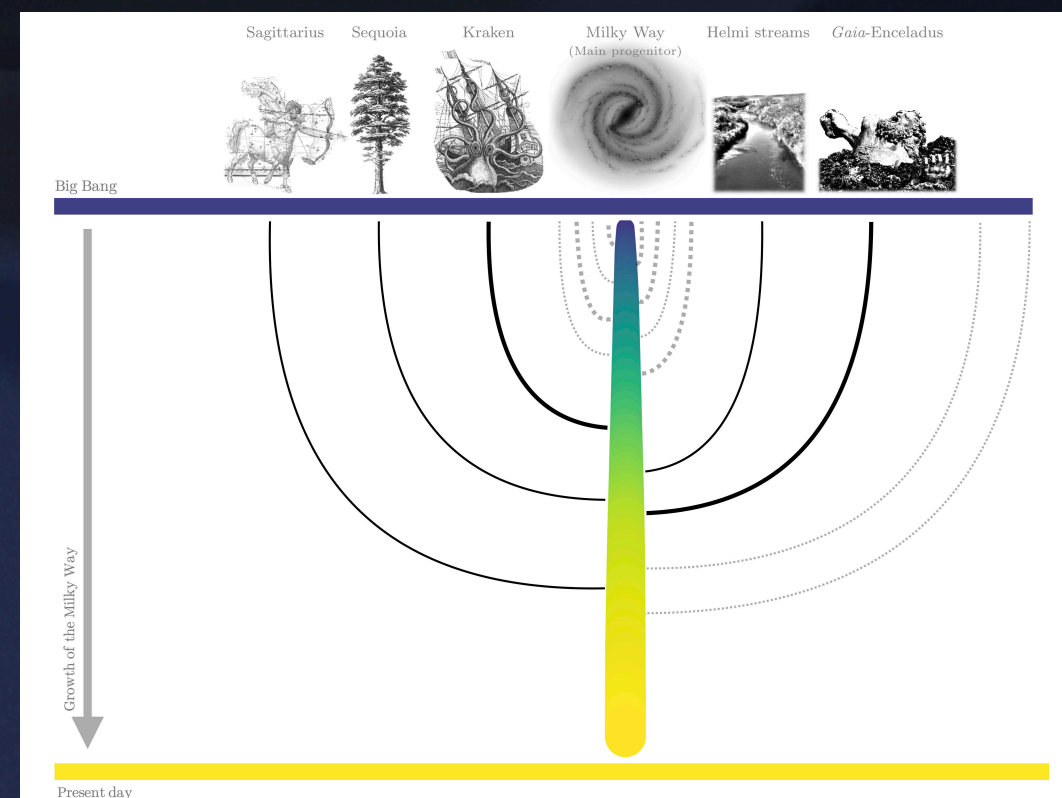




# Stellar Tracers of the Local Dark Matter Velocity Distribution

1. FIRE Milky Way Simulations

2. Building Merger History of Milky Way-like Galaxies

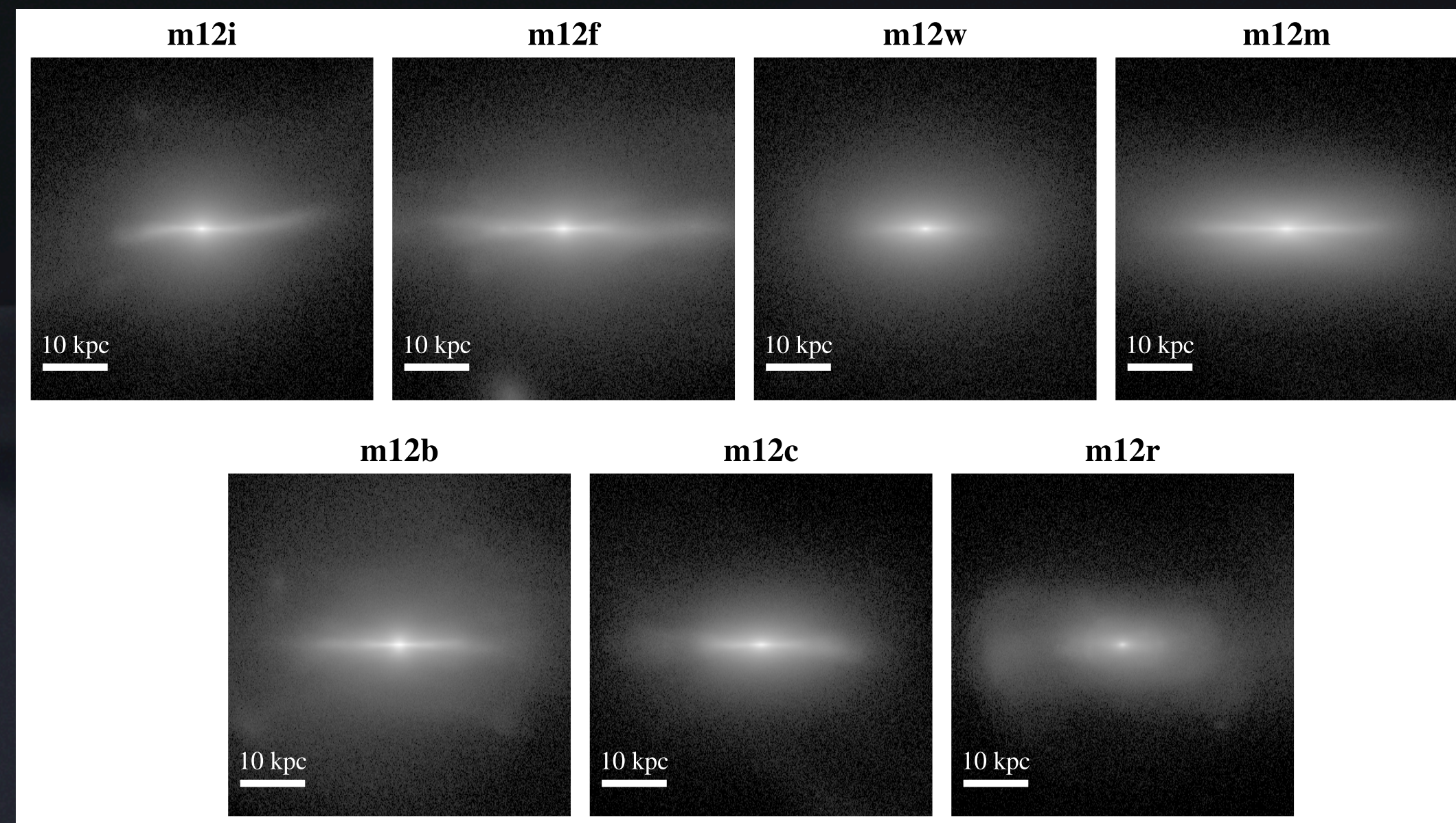


3. Velocity correlation



# FIRE Milky Way Simulations

- FIRE-2 Latte Simulations (Andrew et al. 2016): High-resolution, cosmological zoom-in simulation of Milky Way-mass galaxies using FIRE-2 physics model (Phil et al. 2018)
- In this study, we study six of the m12 simulations, namely m12i, m12f, m12m, m12w, m12b, m12c



**m12i**

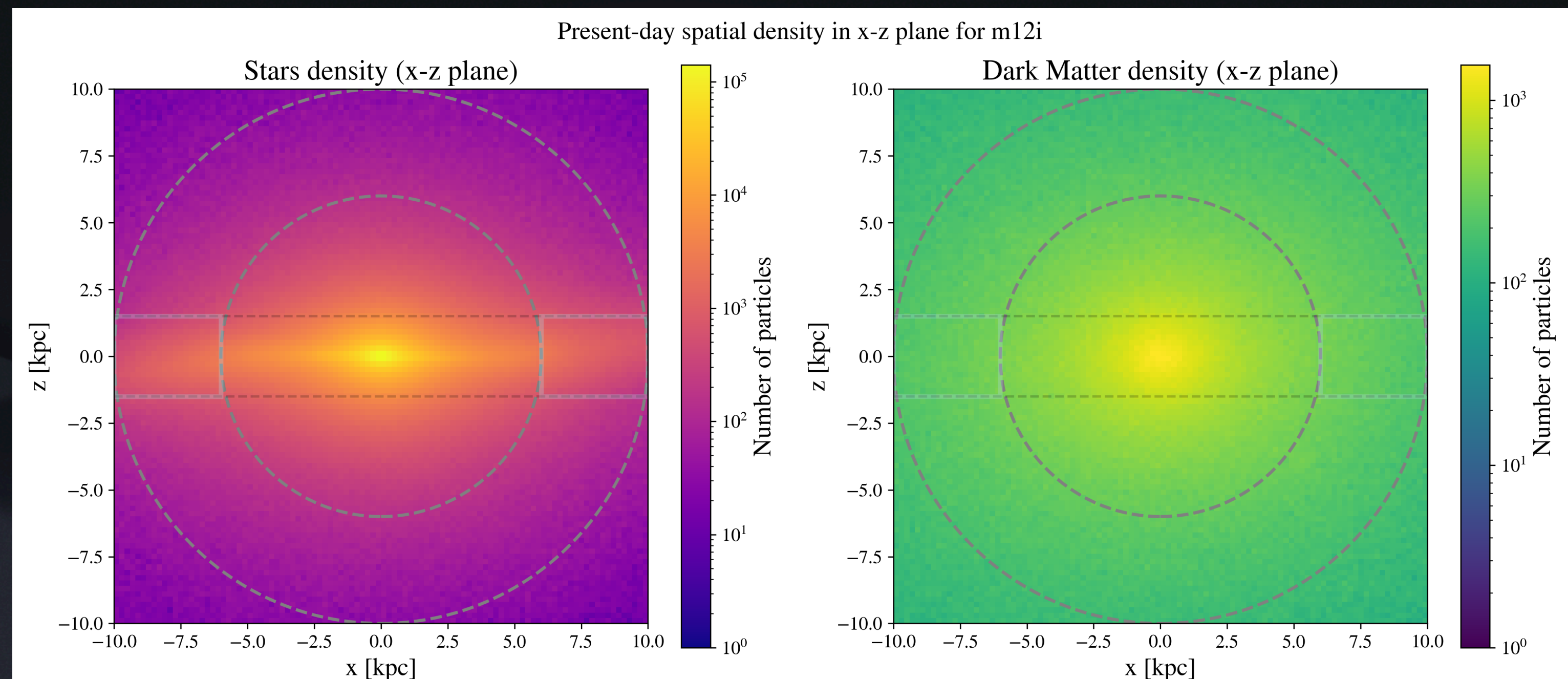
z=19.0

10 kpc

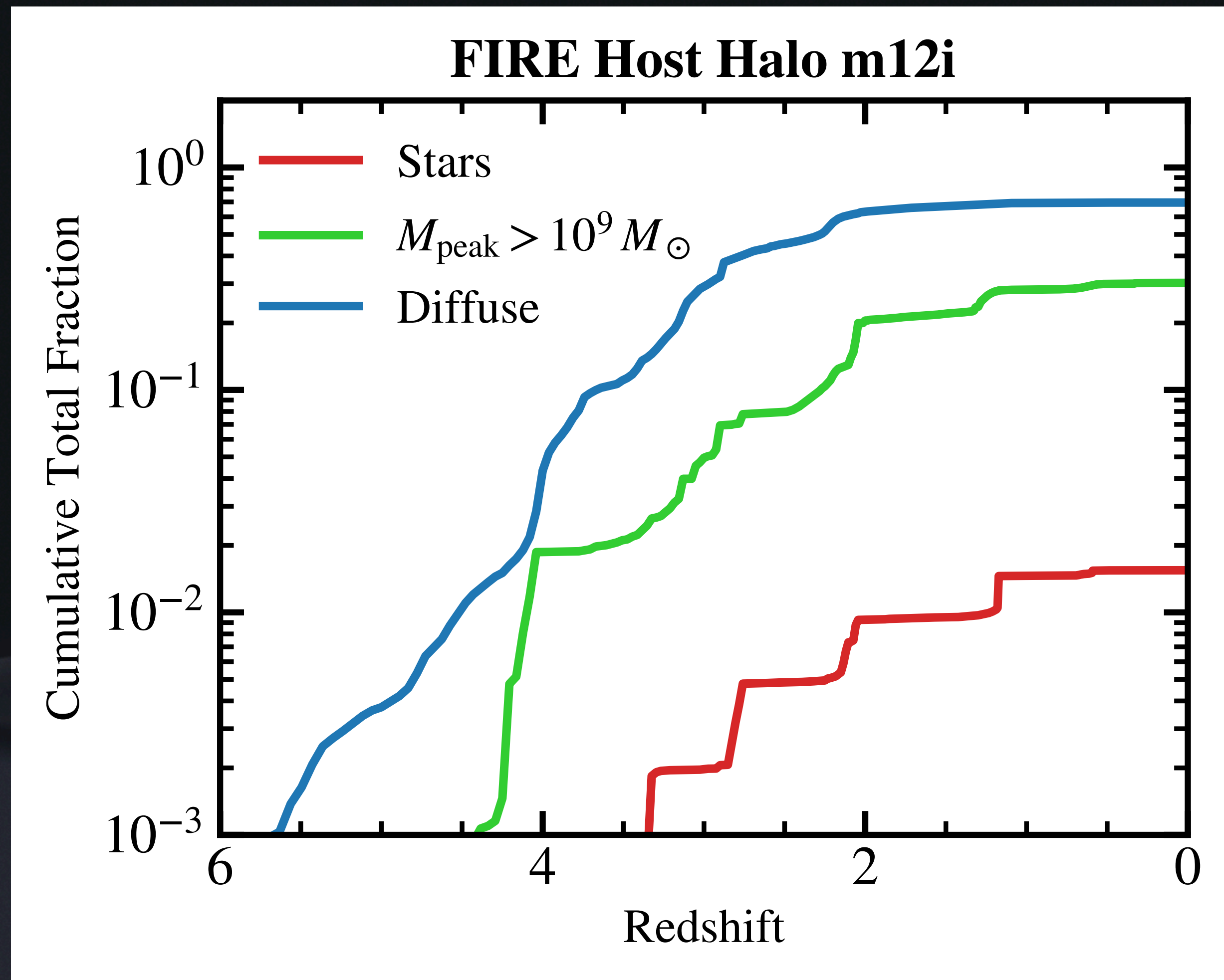
<http://www.tapir.caltech.edu/~phopkins/Site/animations/a-gallery-of-milky-way/>

# Building Merger History

- Particle information is directly read from the simulations
- Subhalo information is generated using Rockstar
- Stars and DM near the solar cycle at  $z = 0$ :  $|r - r_{\odot}| < 2\text{kpc}$  and  $|z| \leq 1.5\text{kpc}$



# Building Merger History



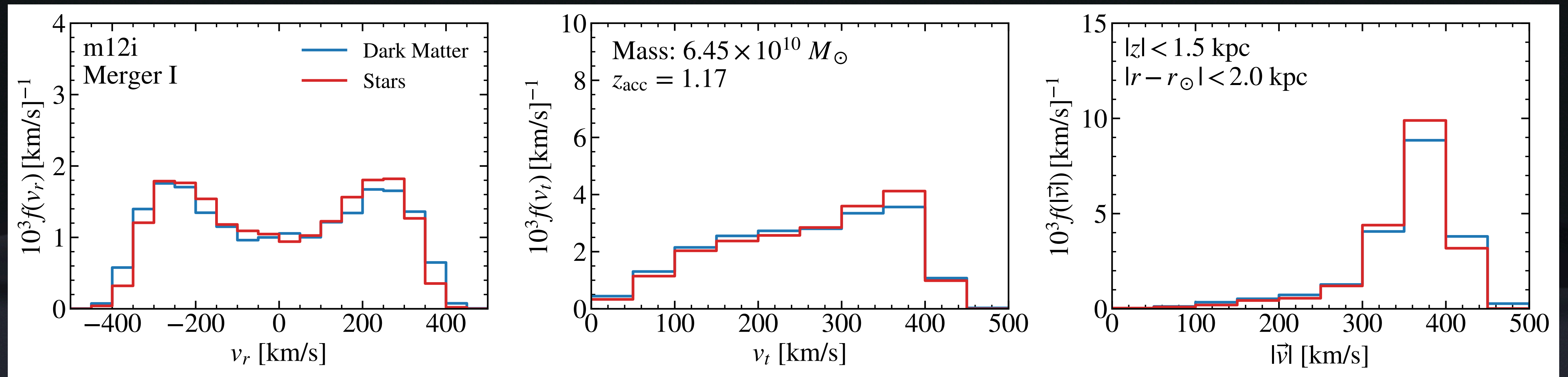
$z=19.0$

10 kpc

# Analysis and Results

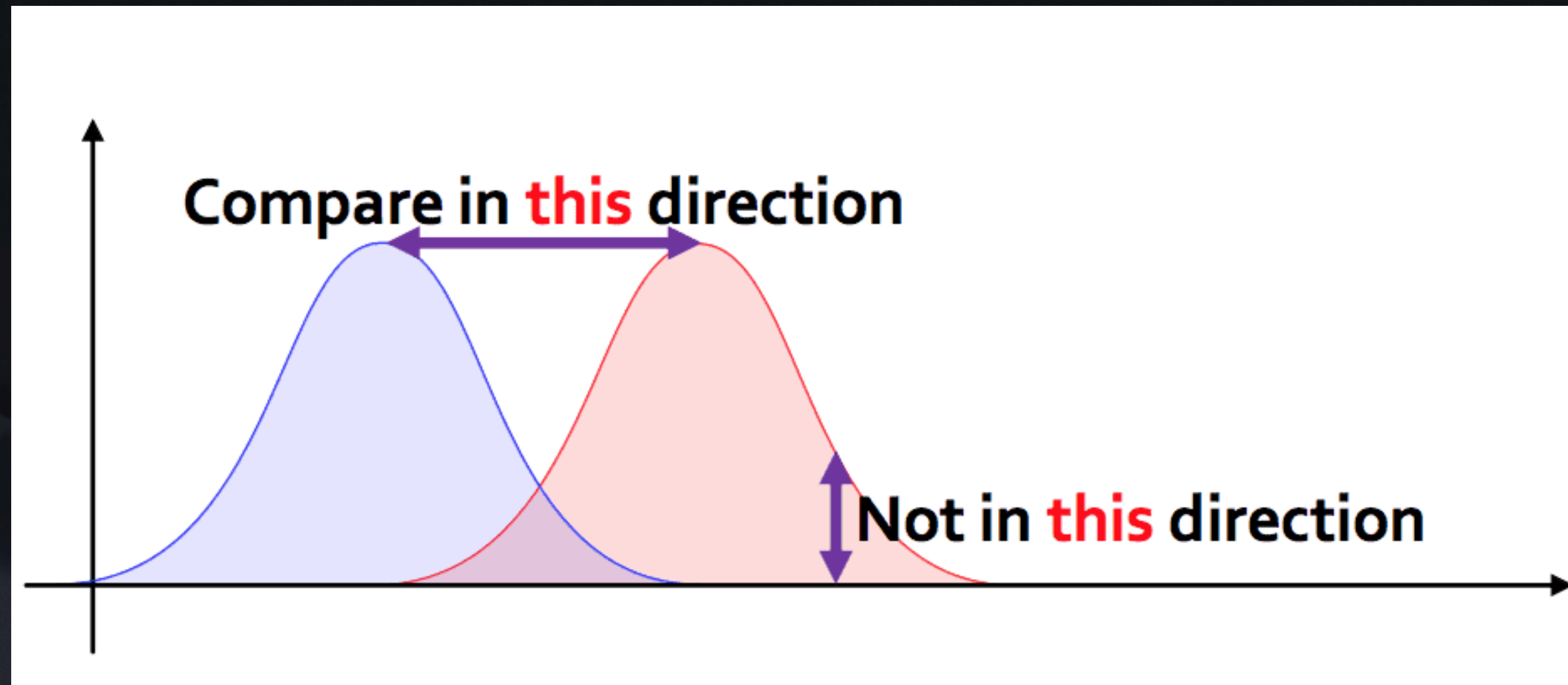
## Resolved Component

- We pick top four mergers that contribute the greatest fraction of accreted stellar population in each simulation.
- We compare the dark matter and stellar velocity distribution from the same merger



# Earth Mover's Distance

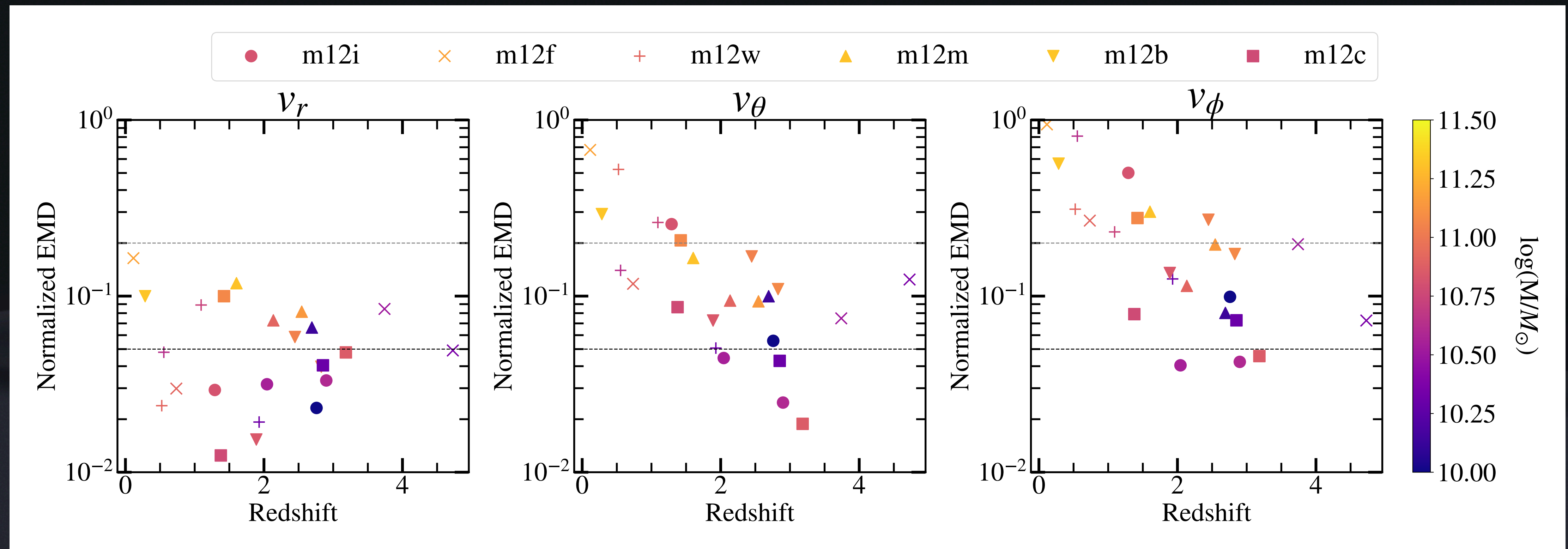
- Earth Mover's Distance (EMD) test measures how many steps it takes to transfer one distribution into another.
- The larger the EMD, the more different the two distributions are



# Analysis and Results

## Resolved Component

- We compare the EMD for each of the top four mergers in 5 m12 simulations
- Different simulations are marked by different shapes; markers are colored by their mass

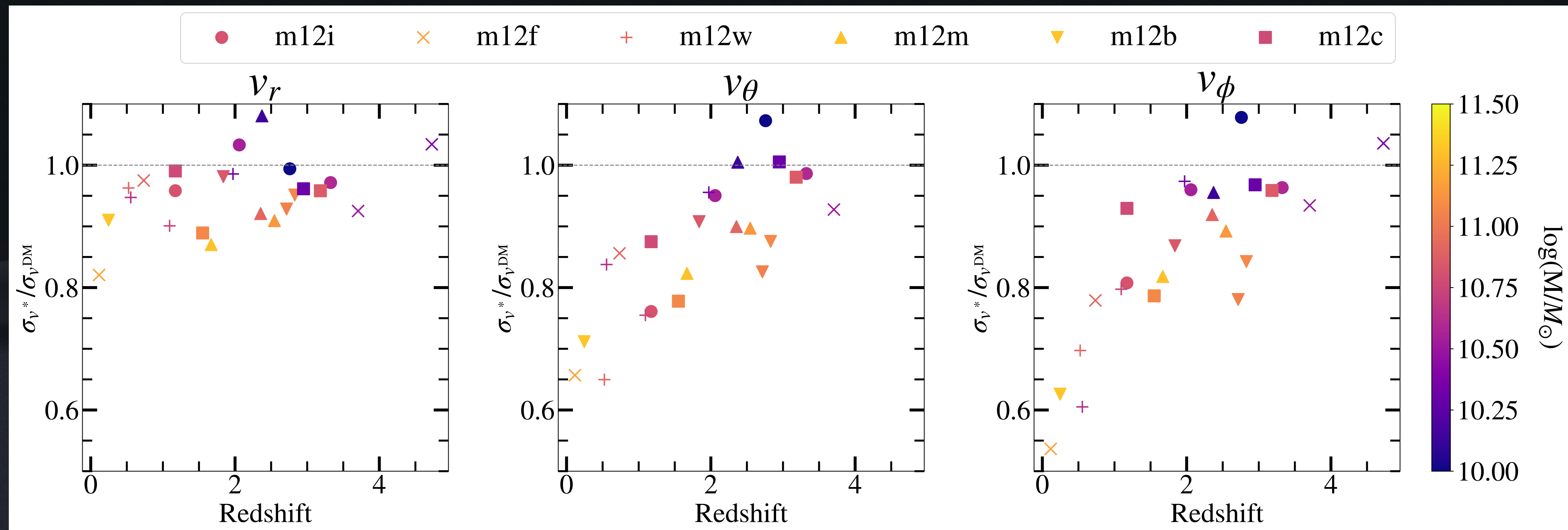


# Analysis and Results

## Resolved Component

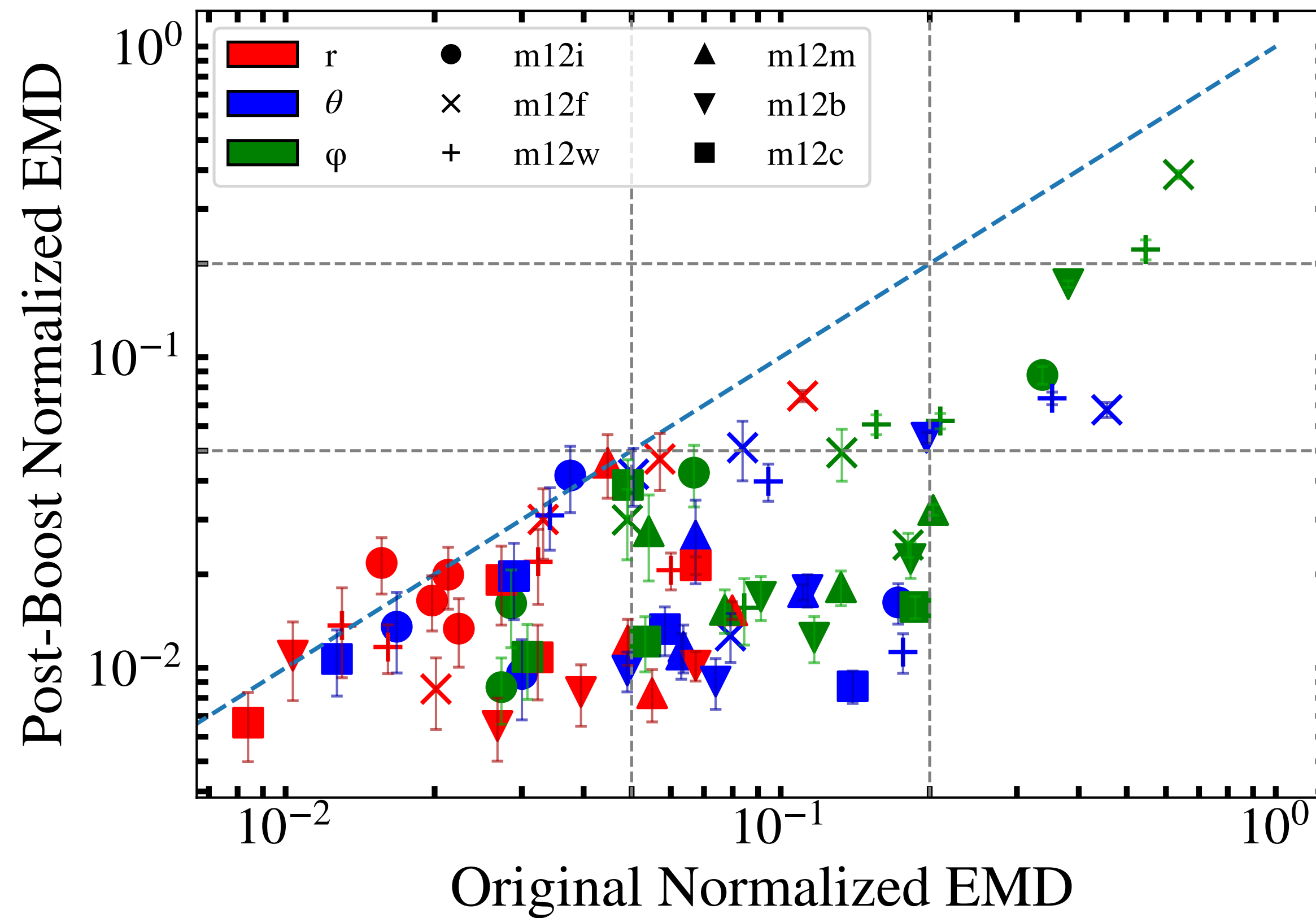
- Stellar velocity dispersion is smaller than DM velocity dispersion in general and scales with redshift

- $f_*(v) = f_{\text{DM}}(v) * \mathcal{N}(0, \sigma(z))$



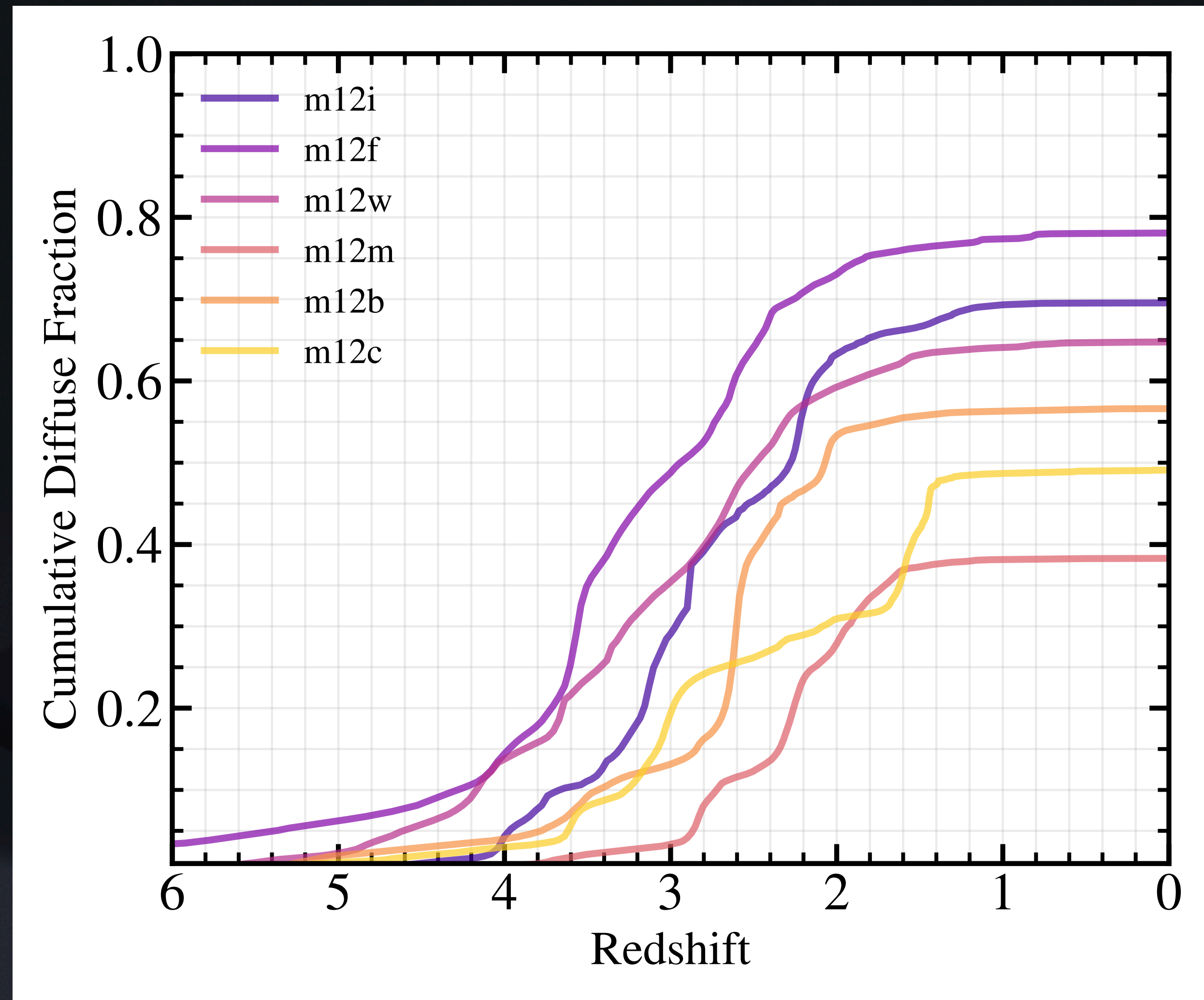
# Analysis and Results

## Resolved Component



# Analysis and Results

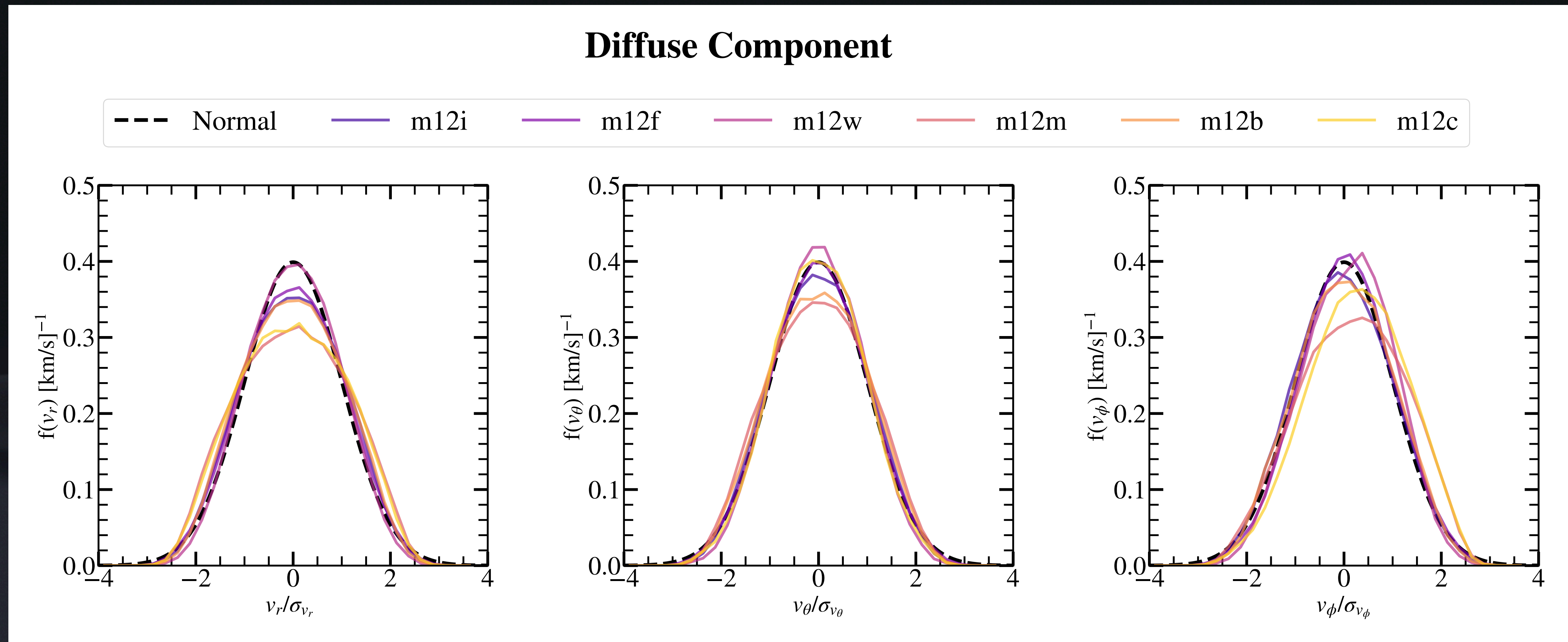
## Diffuse Component



# Analysis and Results

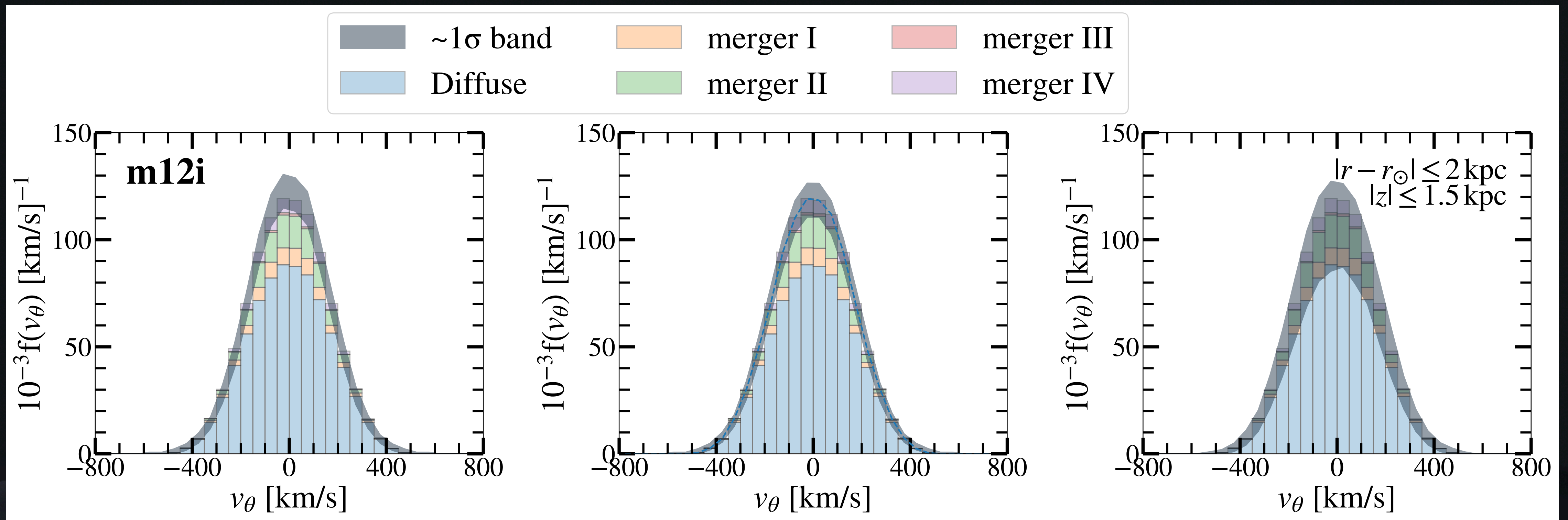
## Diffuse Component

- Diffused component includes smooth accretions and smaller subhalos that are not well resolved





# Analysis and Results



# Conclusion & Outlook

- Paleo-detectors can be an interesting tool in studying substructures
- Local DM velocity distribution can be improved over SHM
- For future reference, we will reconstruct the DM velocity distribution of MW based on observational data; we will also study the effects of the modification on direct detections and annual modulation
- Thank you all for listening!



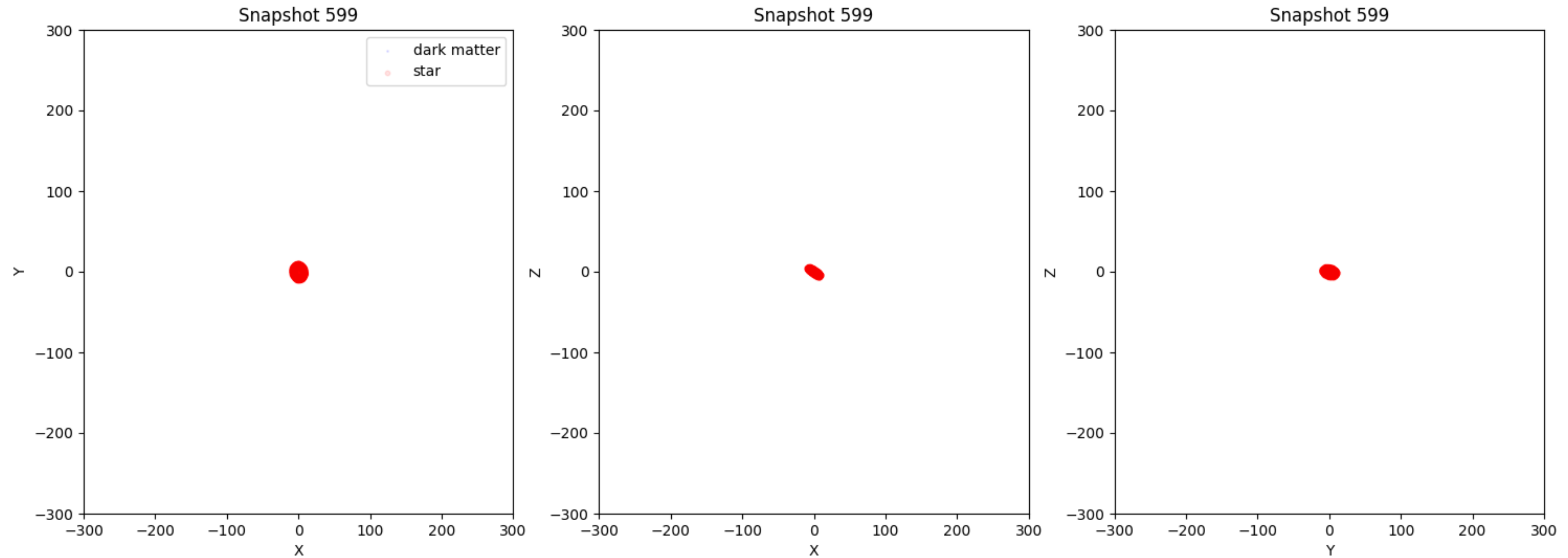
m12r

z=19.0

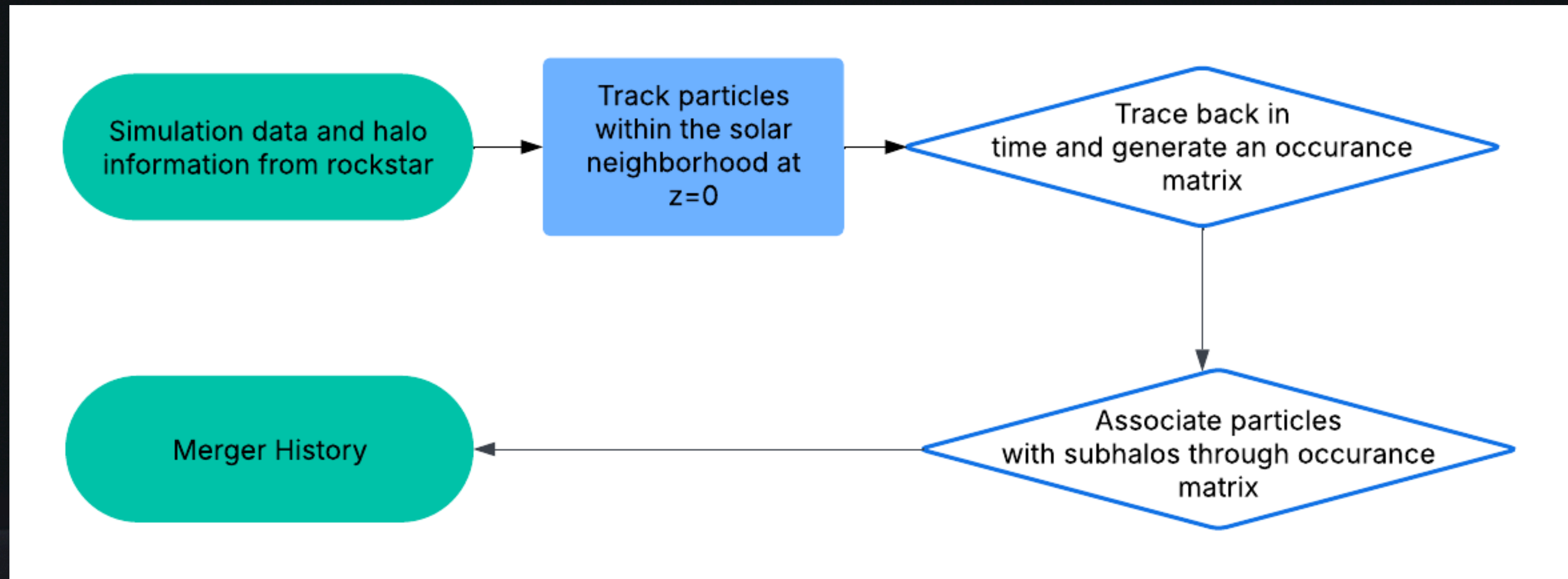
10 kpc

# Backup Slides

# Building Merger History



# Building Merger History



# Building Merger History

- We go backwards in time snapshot by snapshot
- At each snapshot, for each particle, we find the halo closest to it and check if its position is within the viral radius of the halo and if its velocity is within 2.5 standard deviations of the halo velocity

<b>Particle ID</b>	<b>...</b>	<b>Snapshot 478</b>	<b>Snapshot 479</b>	<b>Snapshot 480</b>	<b>Snapshot 481</b>	<b>...</b>	<b>Snapshot 599</b>	<b>Snapshot 600</b>
		1	0	1	1		0	0
		0	1	1	1		0	0
		0	0	0	1		0	0
		1	1	1	0		0	0
...		...	...	...	...		...	...

m12f

z=19.0

10 kpc

