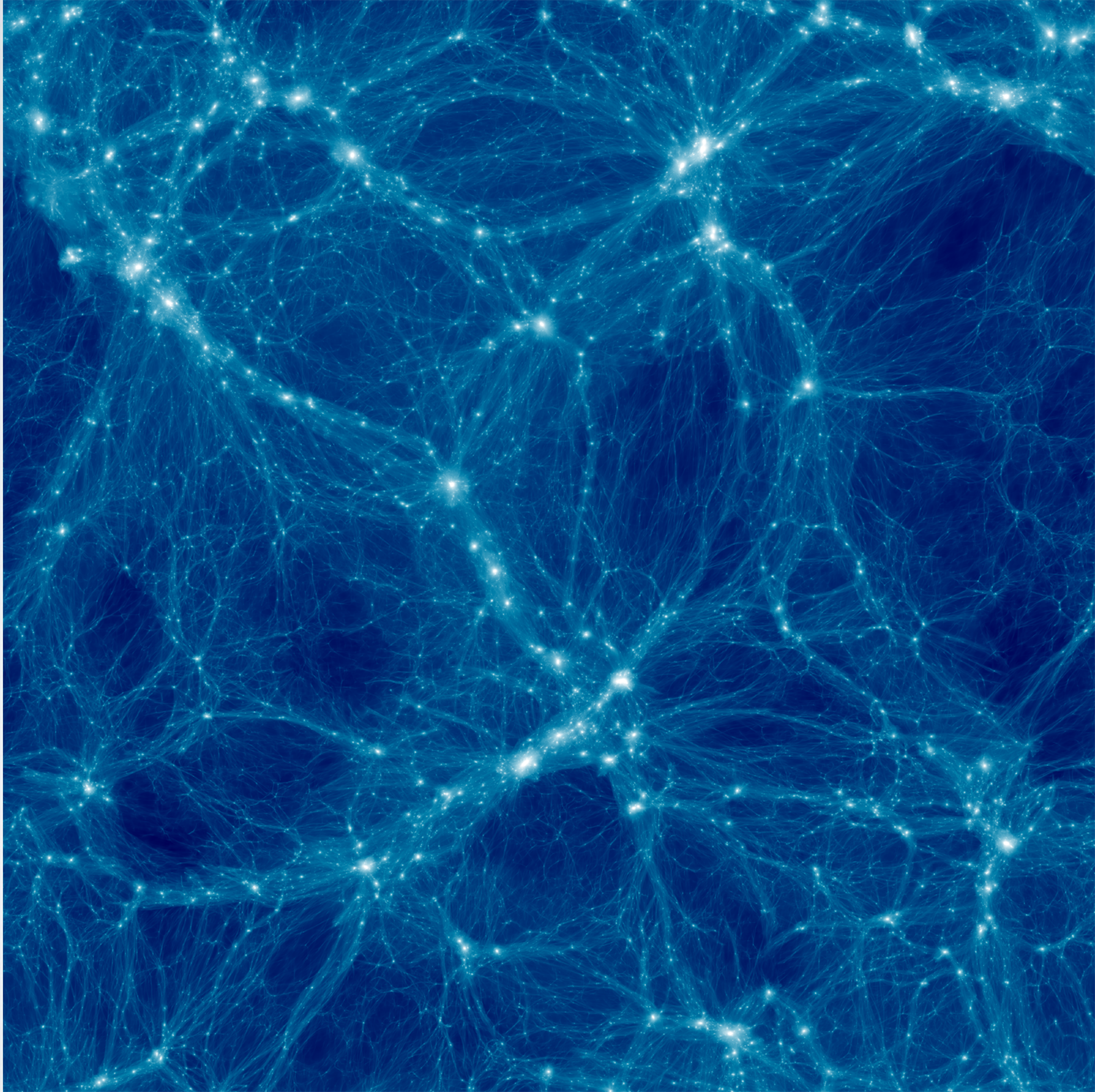
Where does the cosmic web end and the halo begin?

Benedikt Diemer
University of Maryland

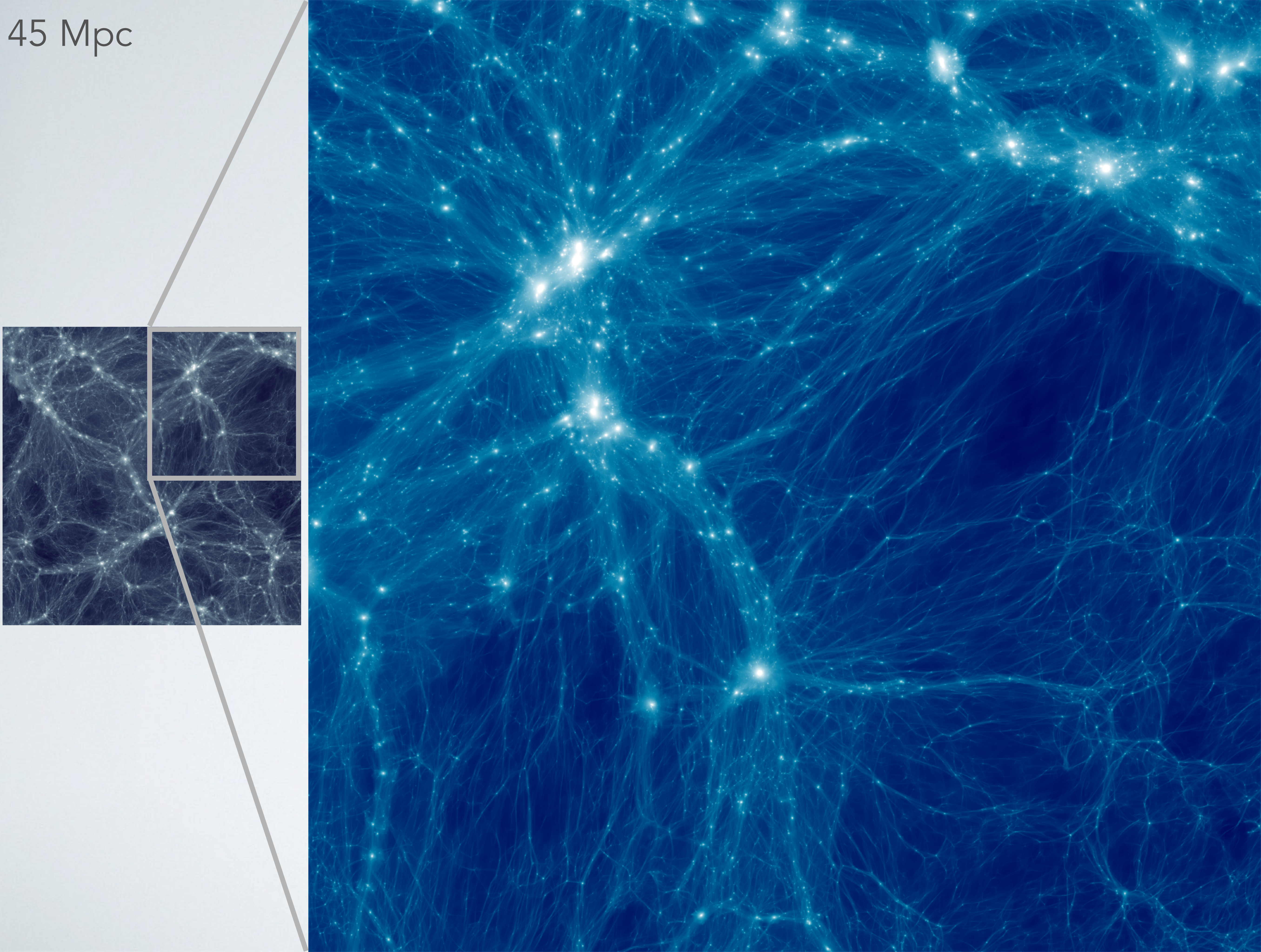
The Cosmic Web: Connecting Galaxies to Cosmology at High and Low Redshift

KITP • 1/10/2023

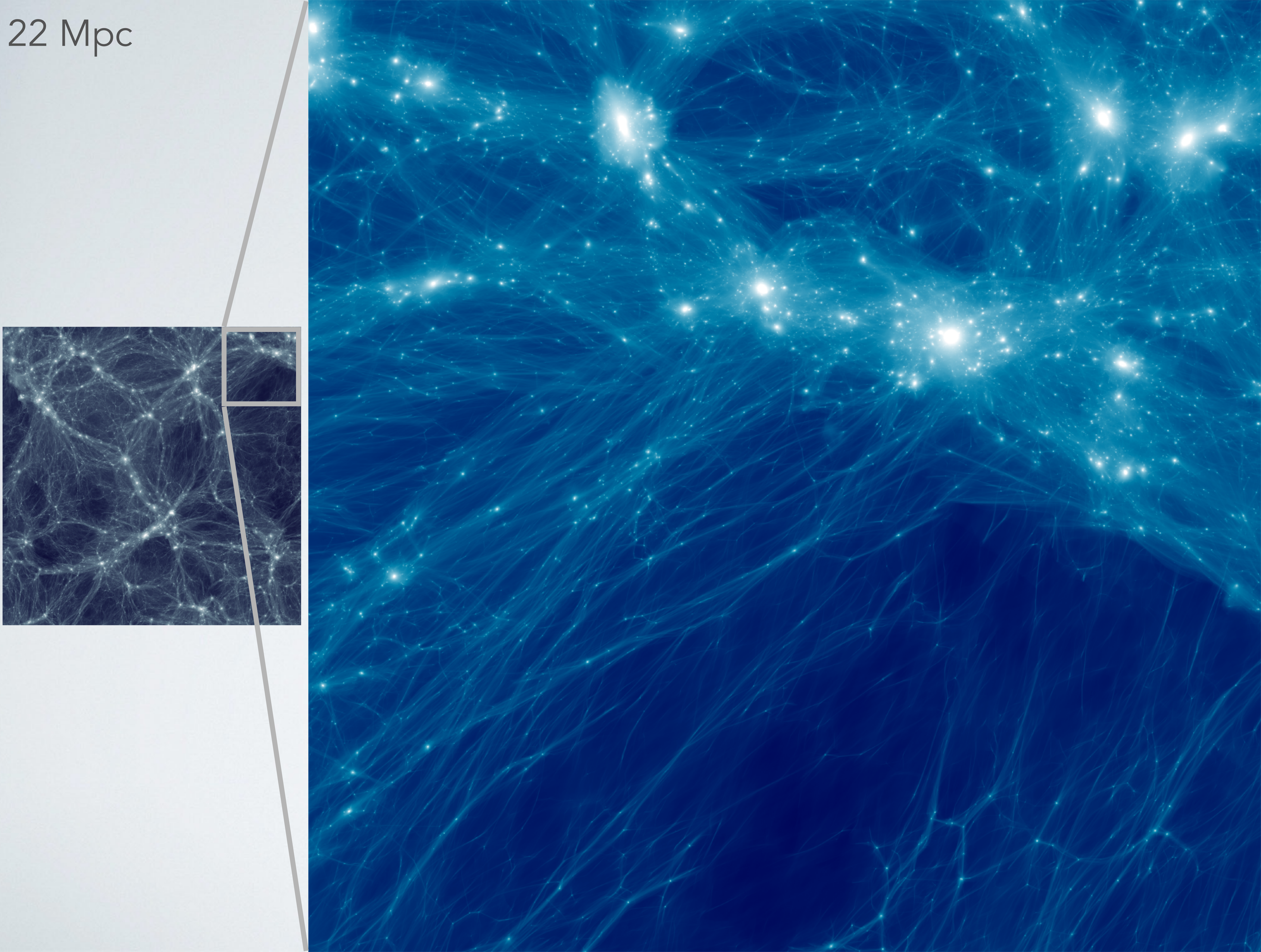
89 Mpc



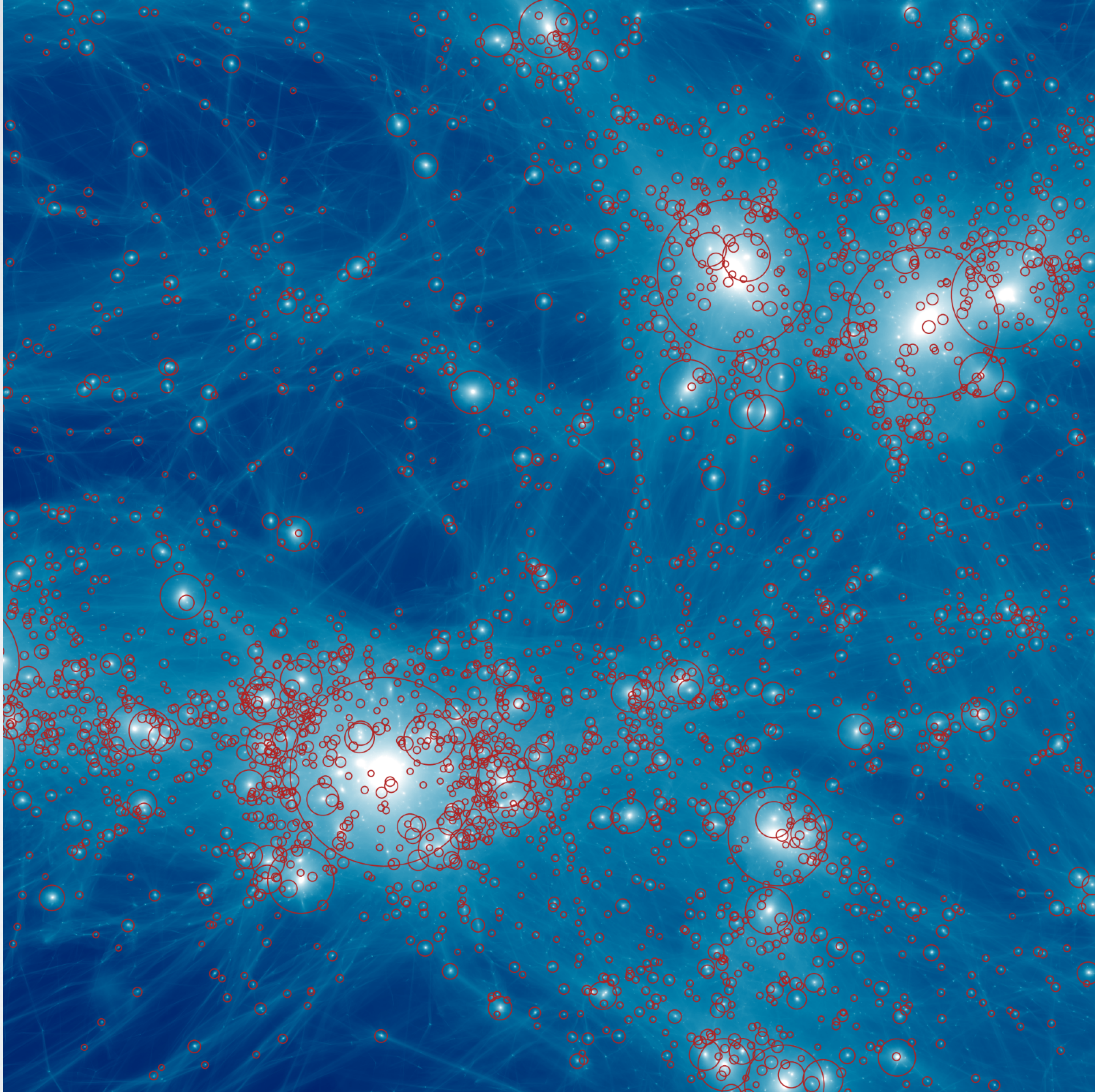
Visualization code:
Phil Mansfield

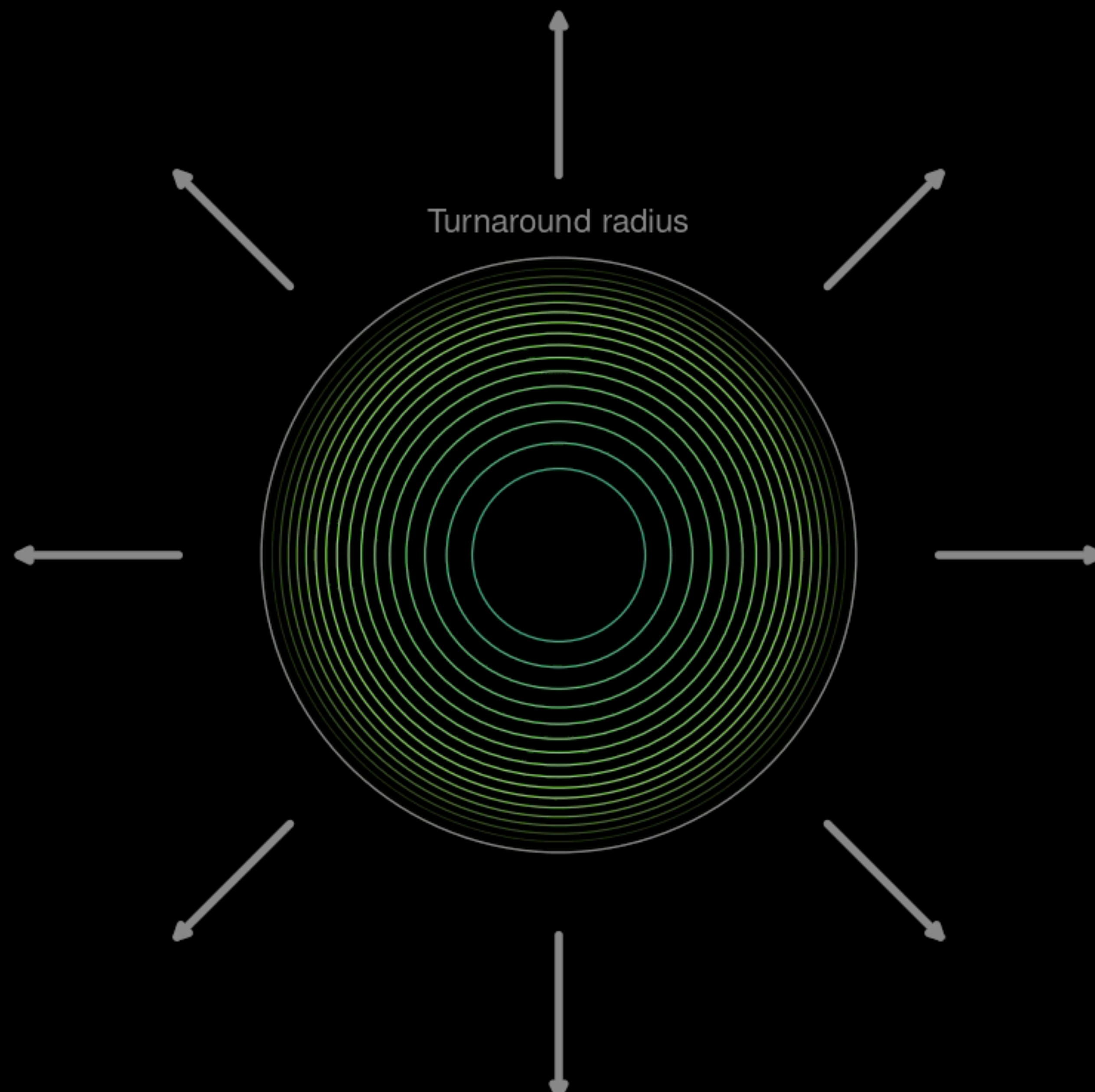

45 Mpc

22 Mpc

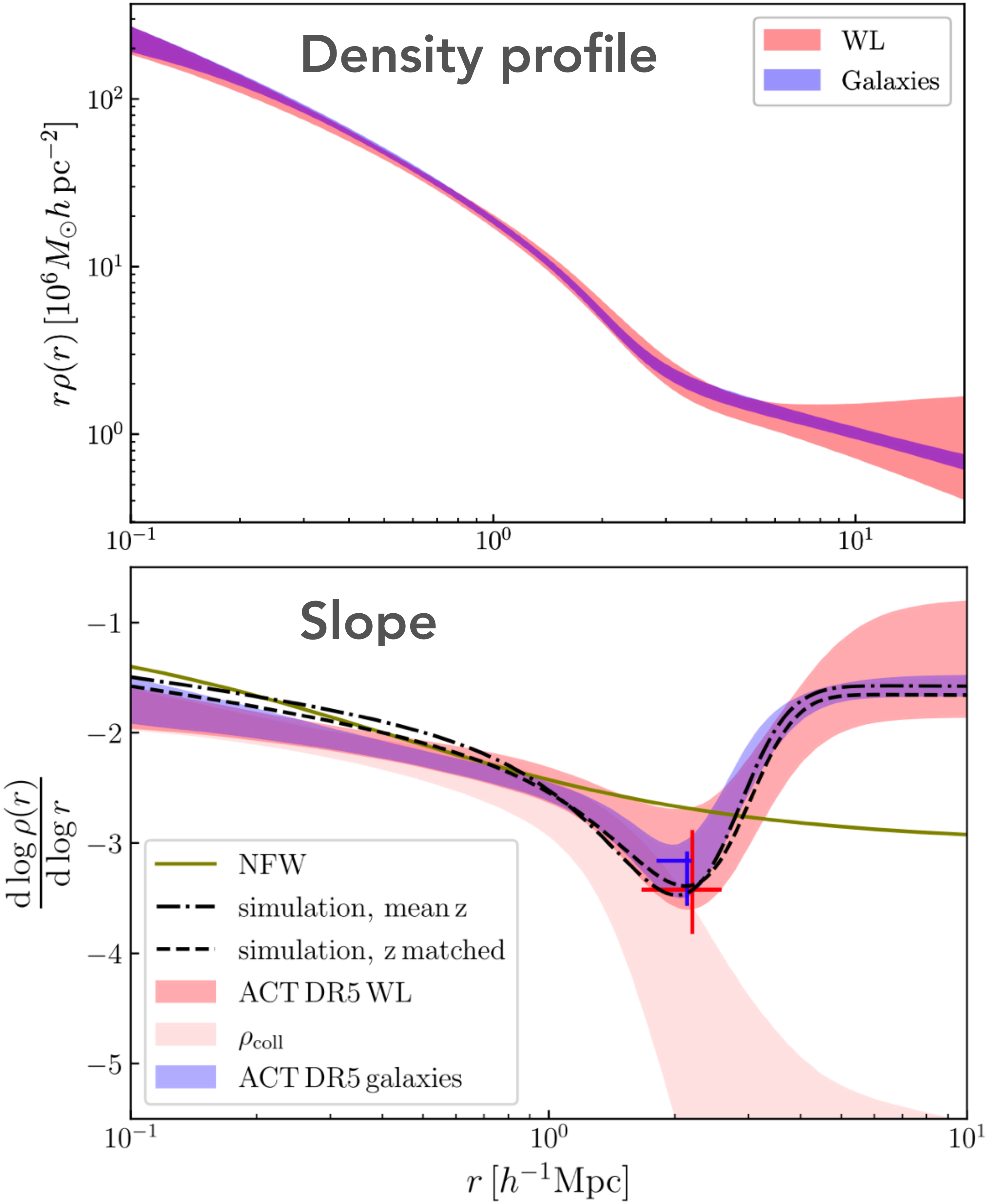


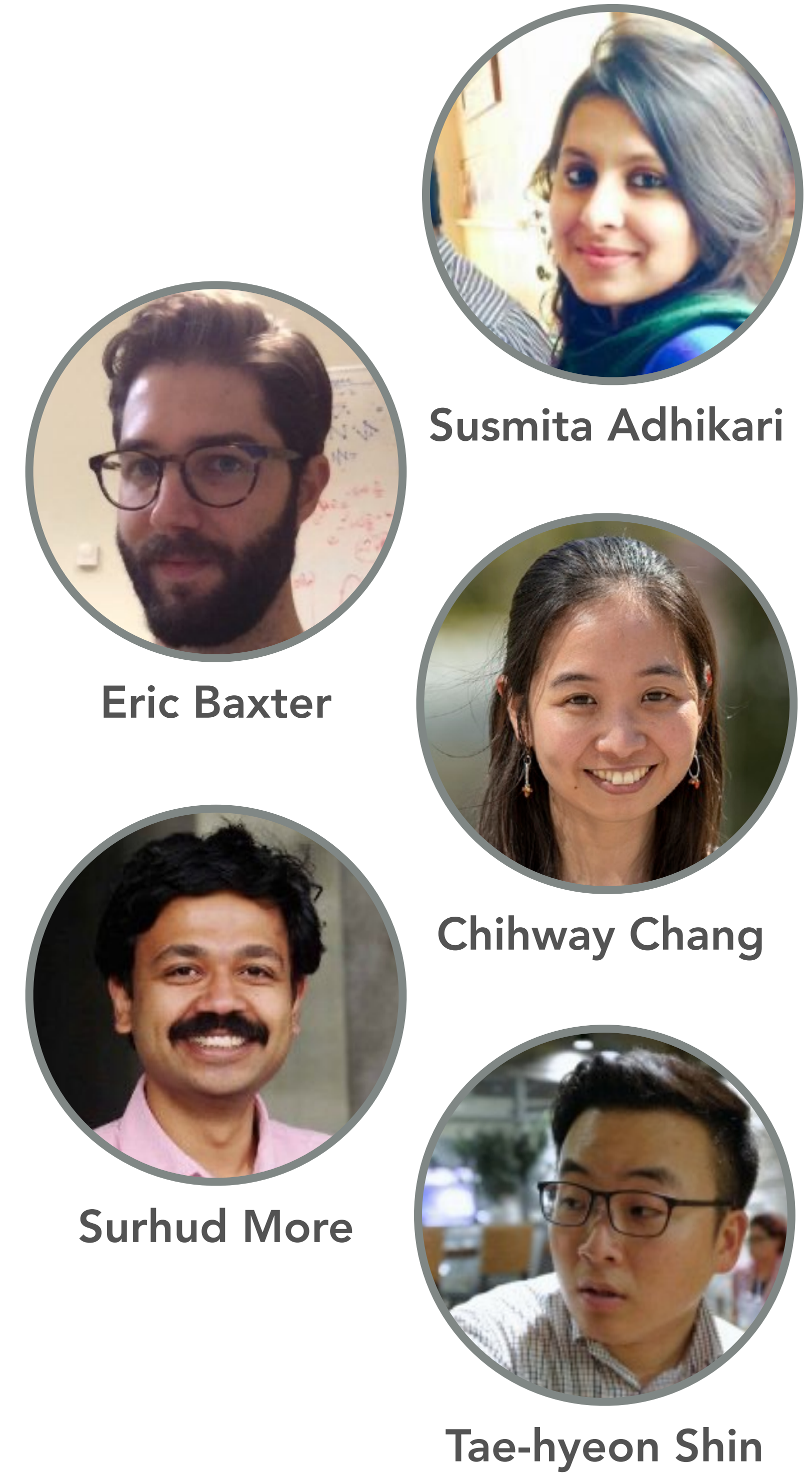
11 Mpc





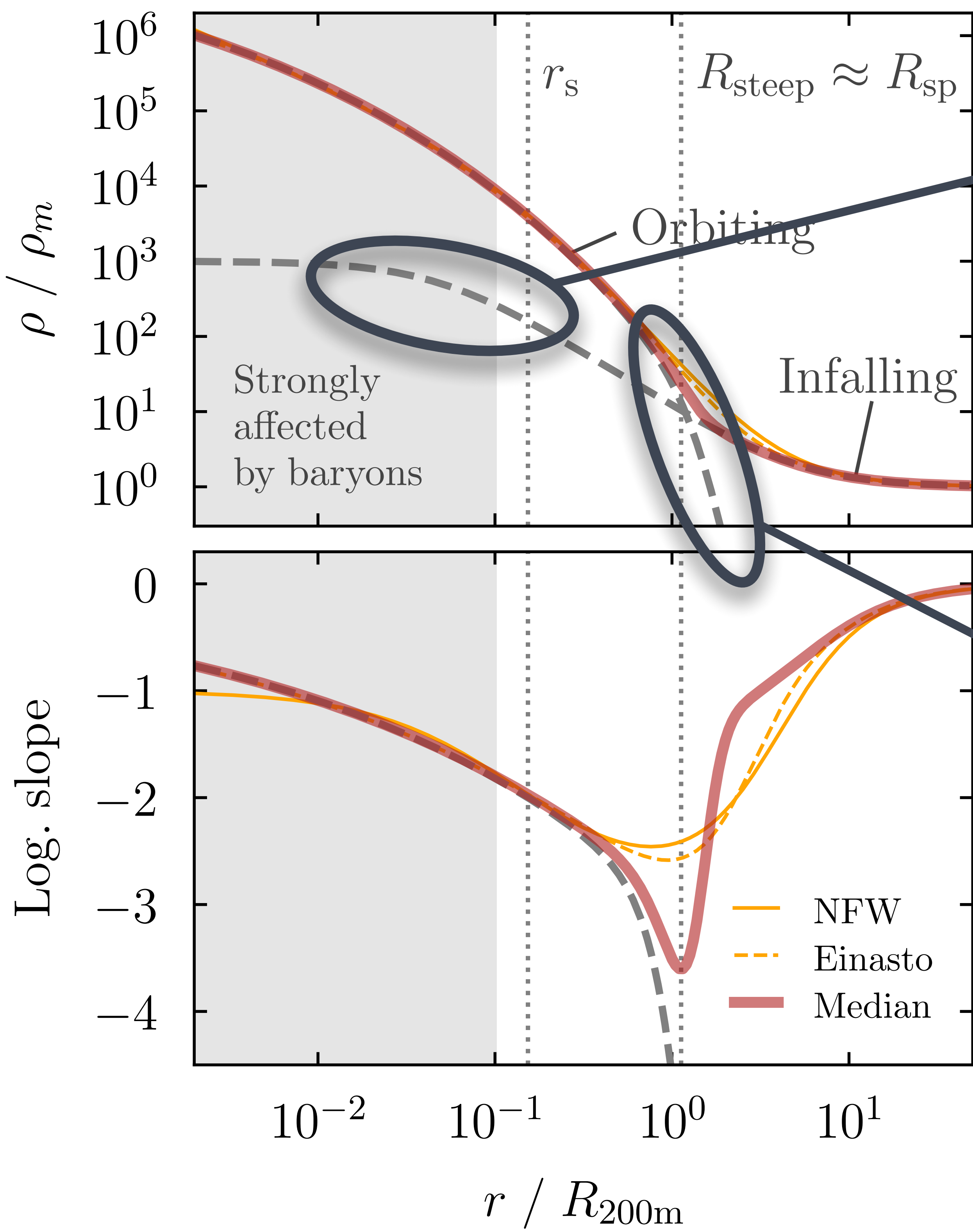
Fillmore & Goldreich 1984 • Bertschinger 1985 • Lu et al. 2006 • Diemand & Kuhlen 2008
Vogelsberger et al. 2011 • Lithwick & Dalal 2011 • Adhikari et al. 2014 • Shi 2016





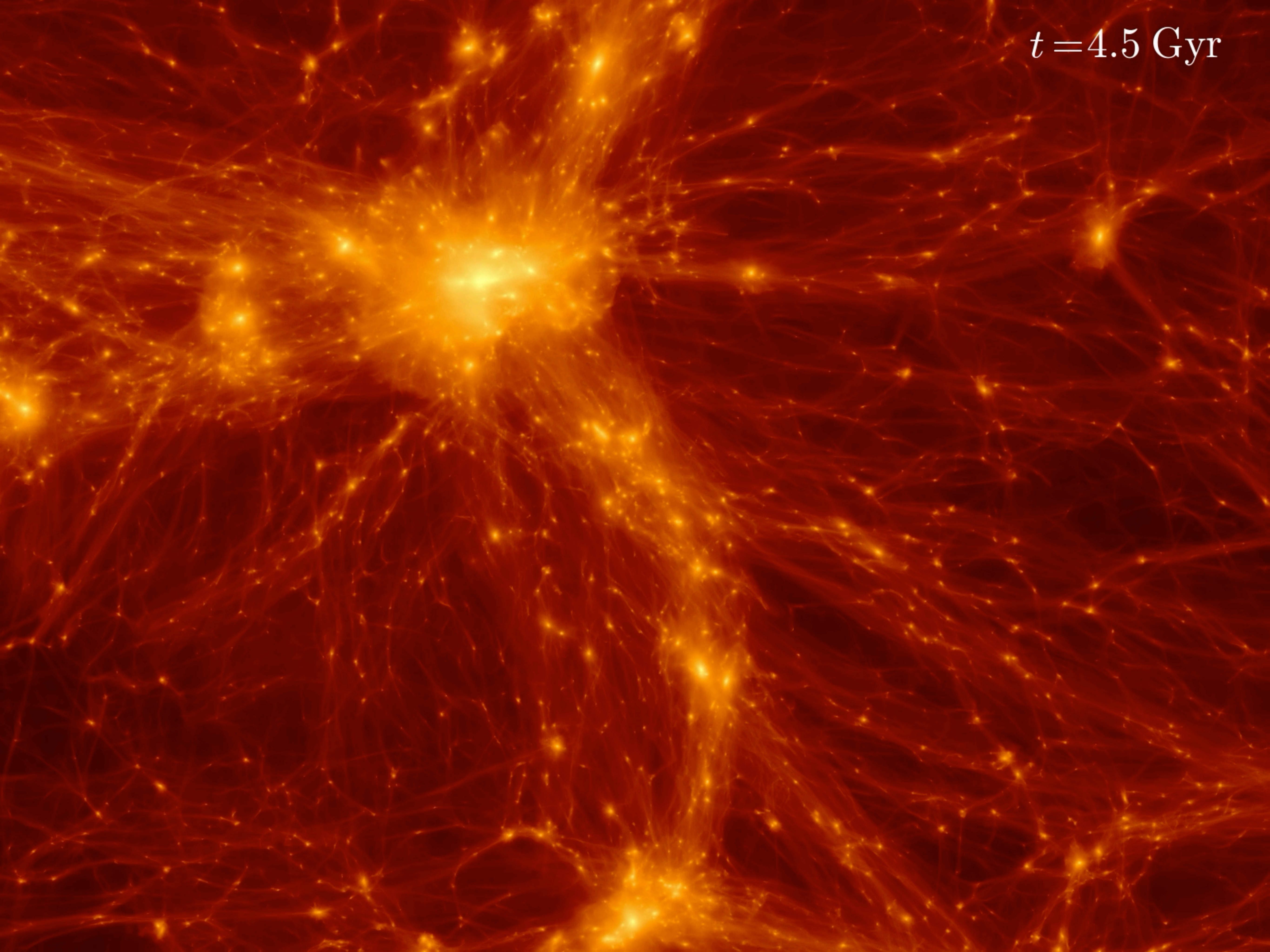
Observations: More et al. 2016 • Adhikari et al. 2016, 2018, 2020 • Baxter et al. 2017 • Chang et al. 2017 • Shin et al. 2019, 2021 • Zuercher & More 2019 • Murata et al. 2020 **See also:** Tully 2015 • Zu et al. 2017 • Busch & White 2017 • Patej & Loeb 2016 • Umetsu & Diemer 2017

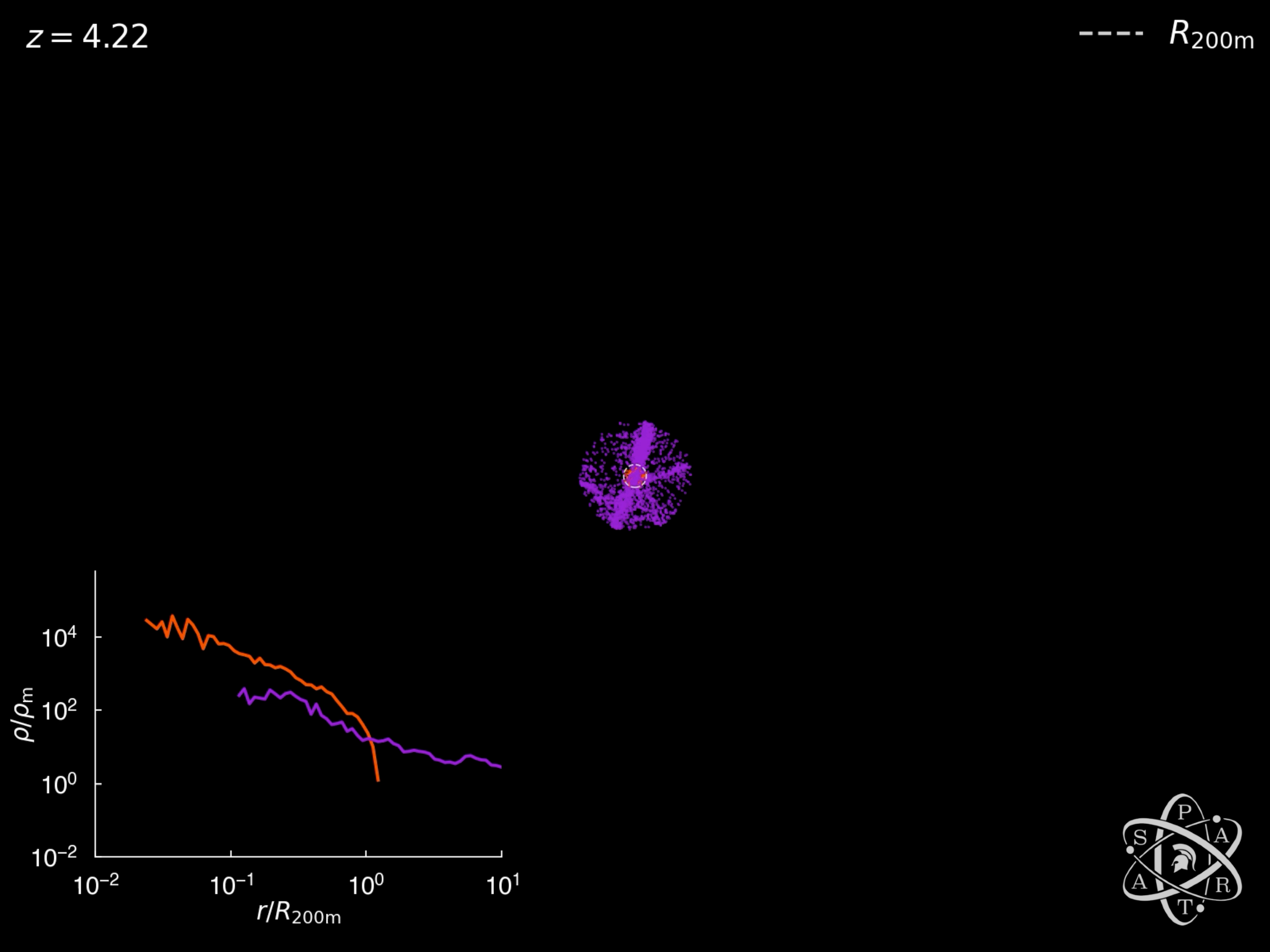
So what's the problem?



Shape of infalling term at small radii is unknown!

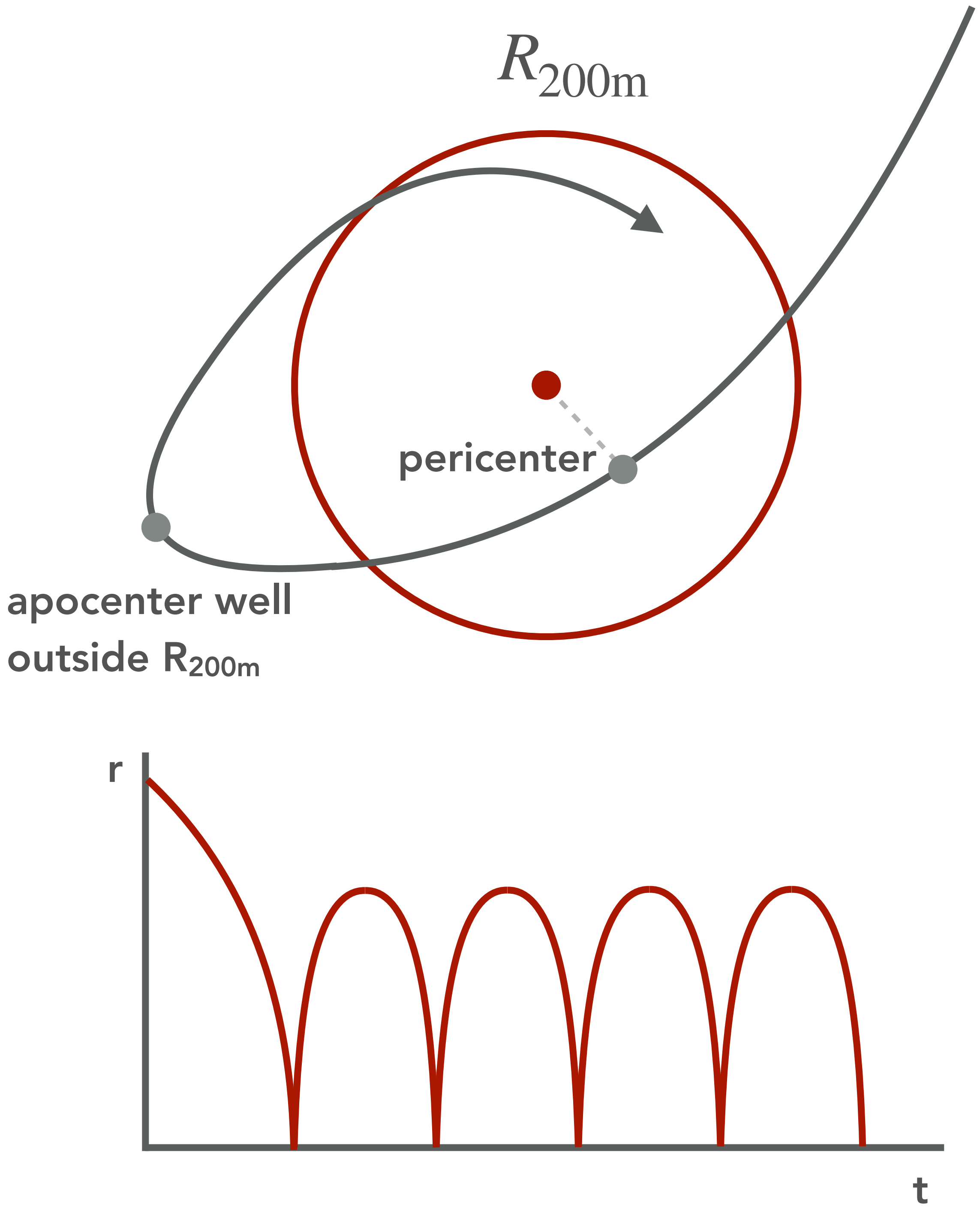
Shape of orbiting term at large radii is unknown!


$t = 4.5$ Gyr

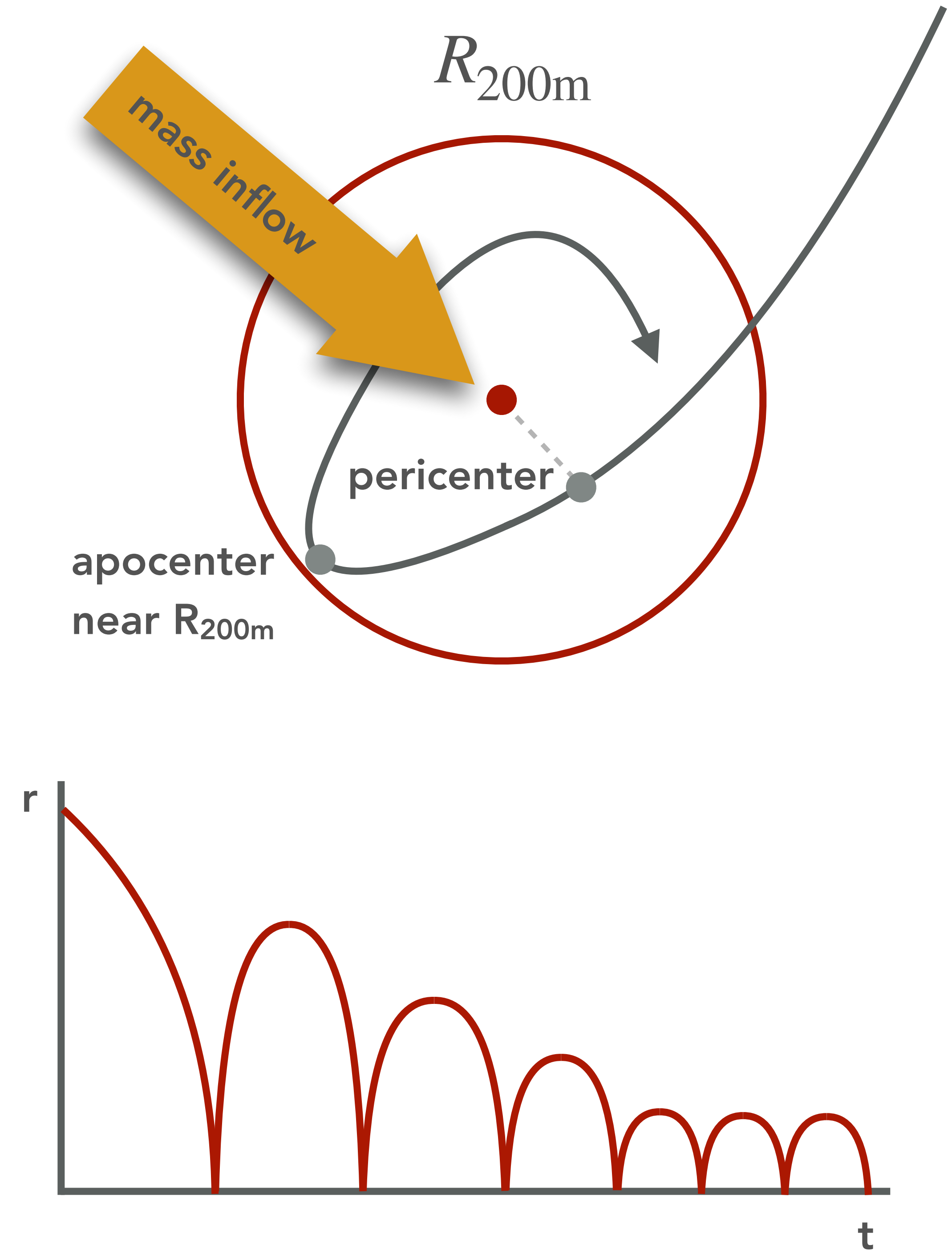

z = 4.22
R200m
10^4
10^2
10^0
10^-2
ρ/ρm
10^-2
10^-1
10^0
10^1
r/R200m
S P A R T A

Why does mass accretion rate matter?

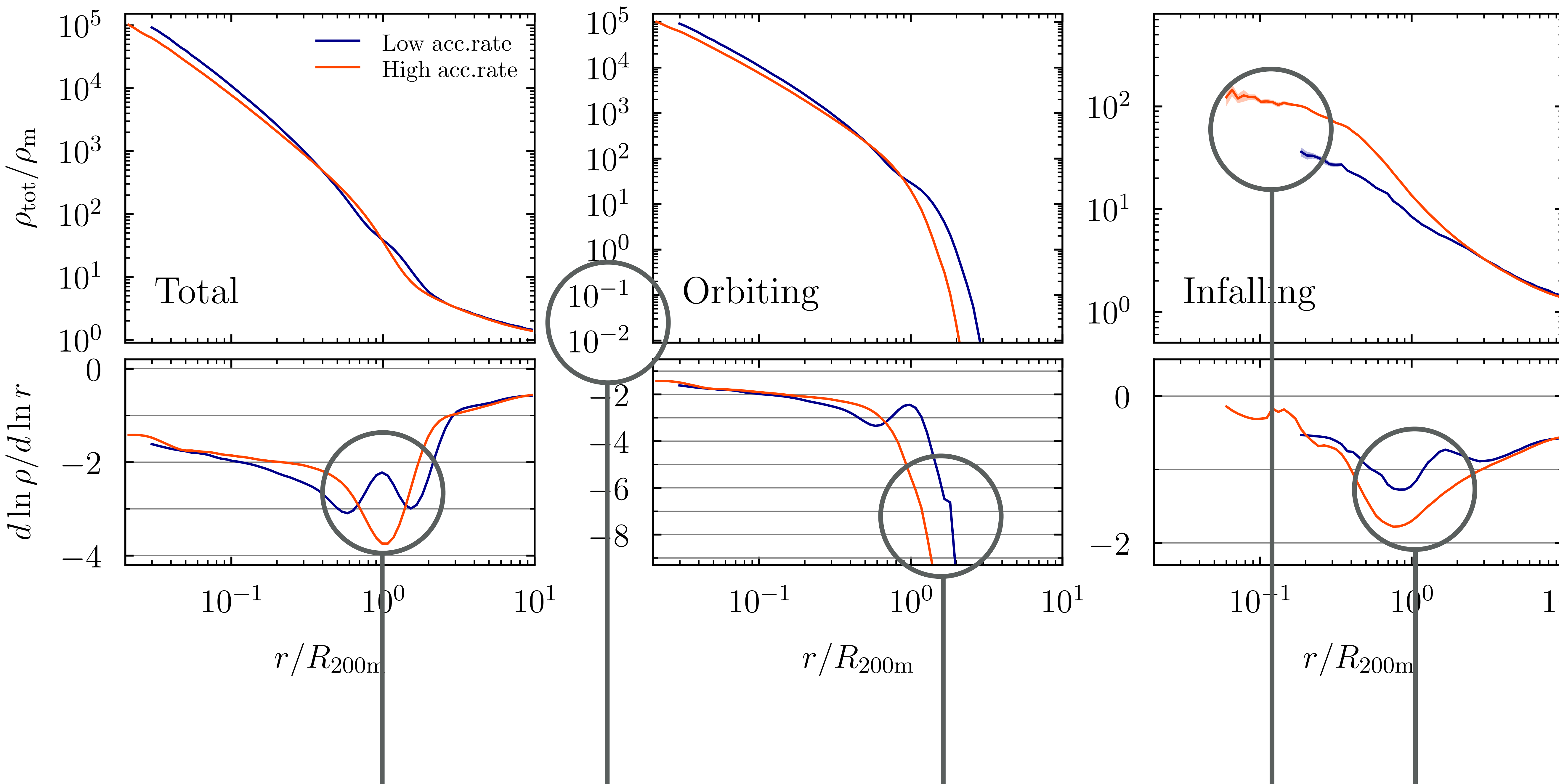
Low accretion rate



High accretion rate



Bertschinger 1985 • Adhikari et al. 2014 • Shi 2016



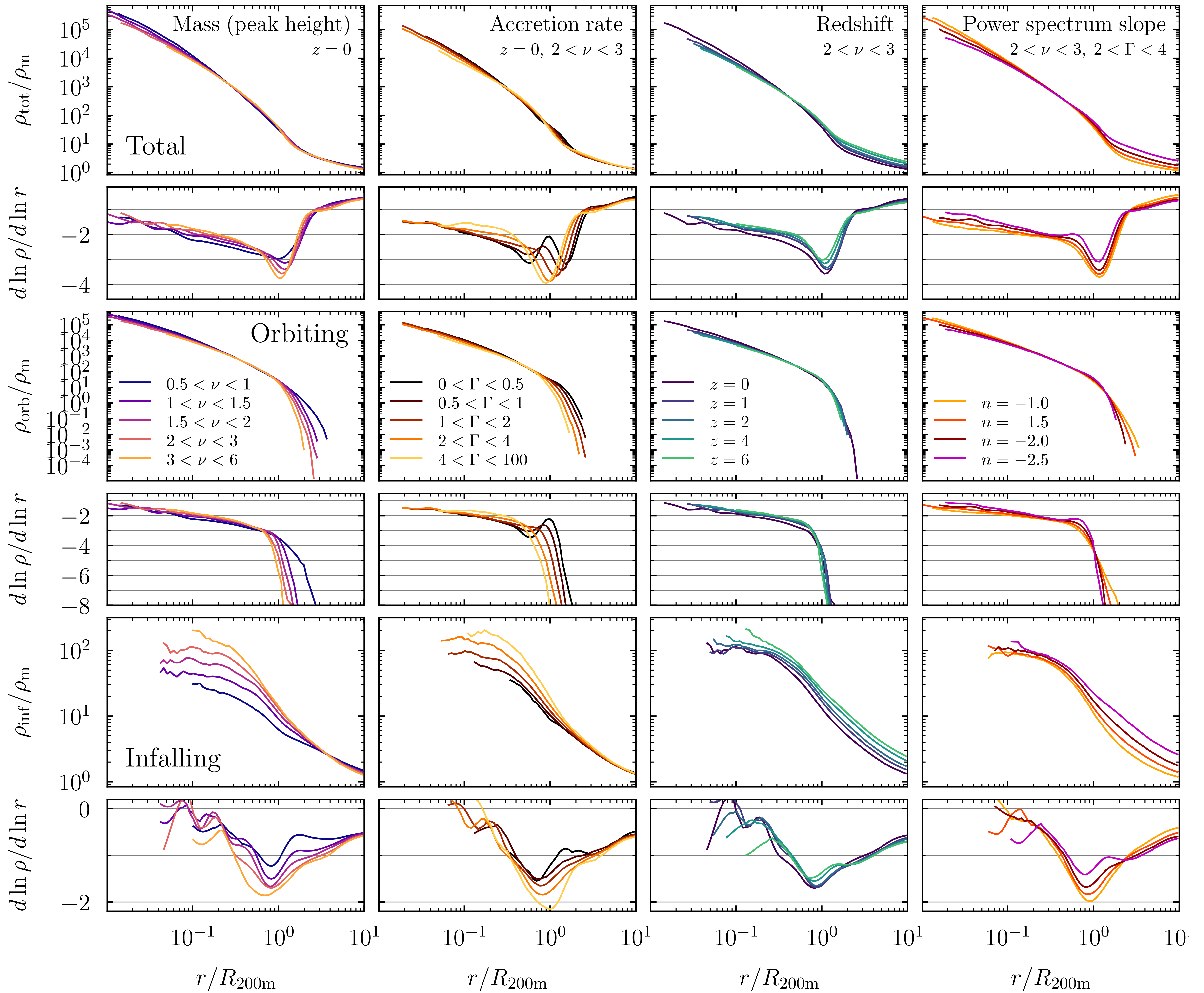
- splashback most prominent in fast-accreting halos
- second caustic in slowly accreting halos

- very steep truncation of orbiting term
- higher accretion rate means smaller trunc. radius

- infalling profiles approach fixed central density
- shape of infalling term depends on acc. rate

Diemer 2022 • see also Diemer & Kravtsov 2014 • Adhikari et al. 2014
Aung et al. 2022 • Lucie-Smith 2022ab • Garcia et al. 2022

Results: median density profiles



- What do profiles depend on?
  - **Accretion rate** (dynamical state)
  - **Power spectrum slope** (cosmology)
- To a much lesser extent:
  - Mass
  - Redshift

Fitting functions

NFW

$$\rho \propto \frac{1}{\left(\frac{r}{r_s}\right)\left(\frac{r}{r_s}+1\right)^2}$$

Einasto

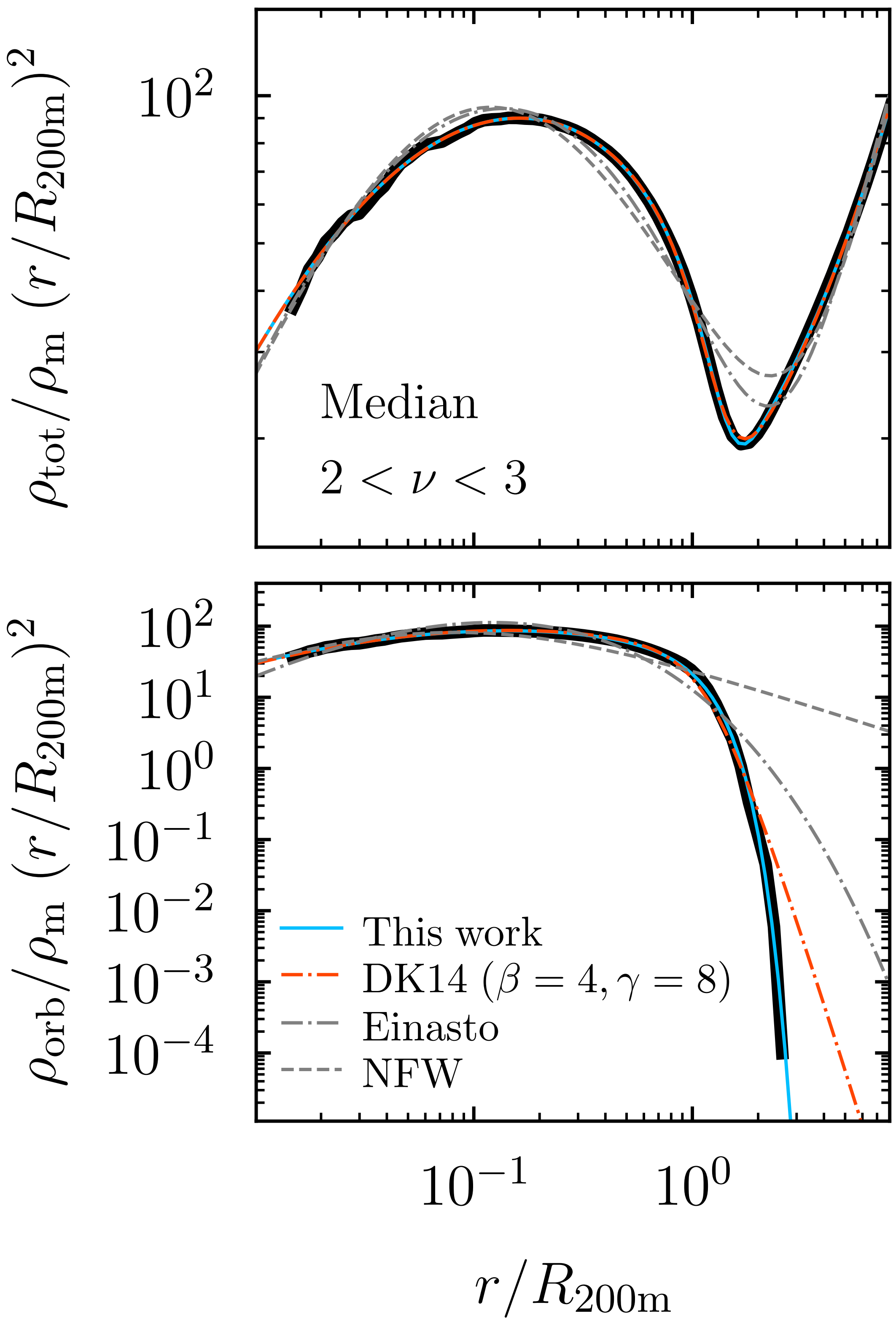
$$\rho \propto \exp\left[-\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha}\right]$$

Diemer & Kravtsov 2014

$$\rho \propto \exp\left[-\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha}\right] \times \left[1+\left(\frac{r}{r_t}\right)^{\beta}\right]^{-\gamma/\beta}$$

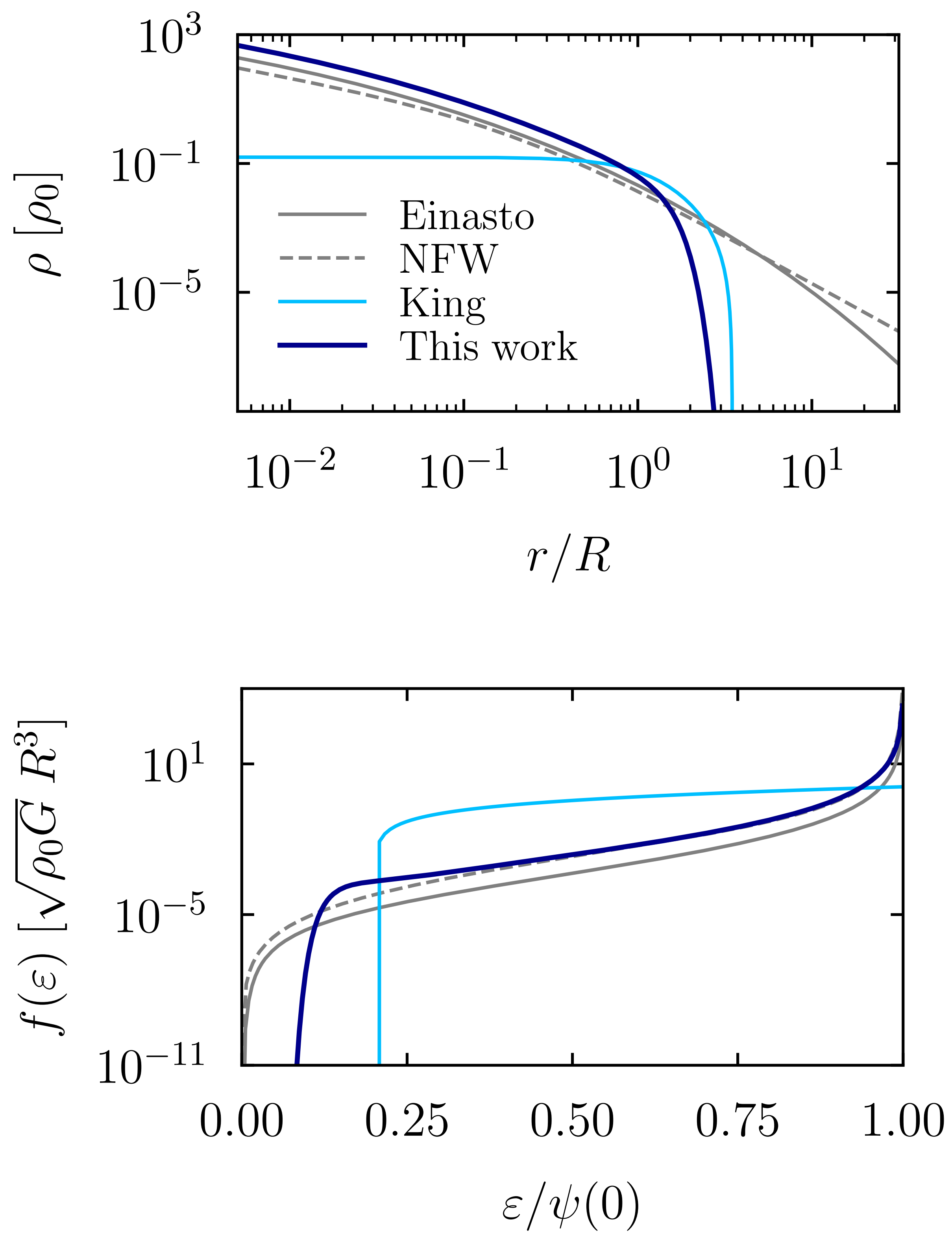
New model

$$\rho \propto \exp\left[-\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - \frac{1}{\beta}\left(\frac{r}{r_t}\right)^{\beta}\right]$$



Diemer 2023

Distribution function



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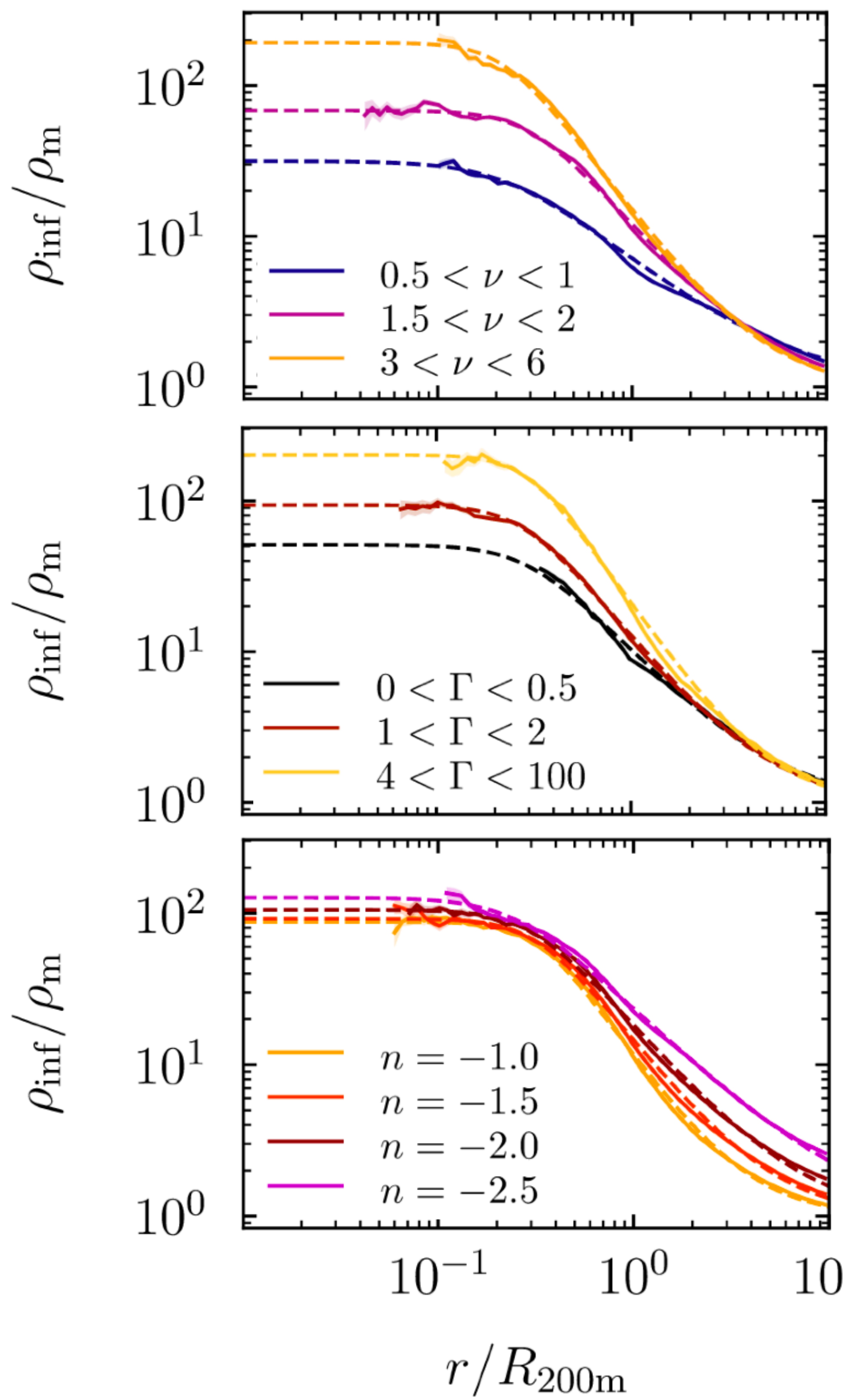
New fitting function - Infalling term

Mean + power law + maximum

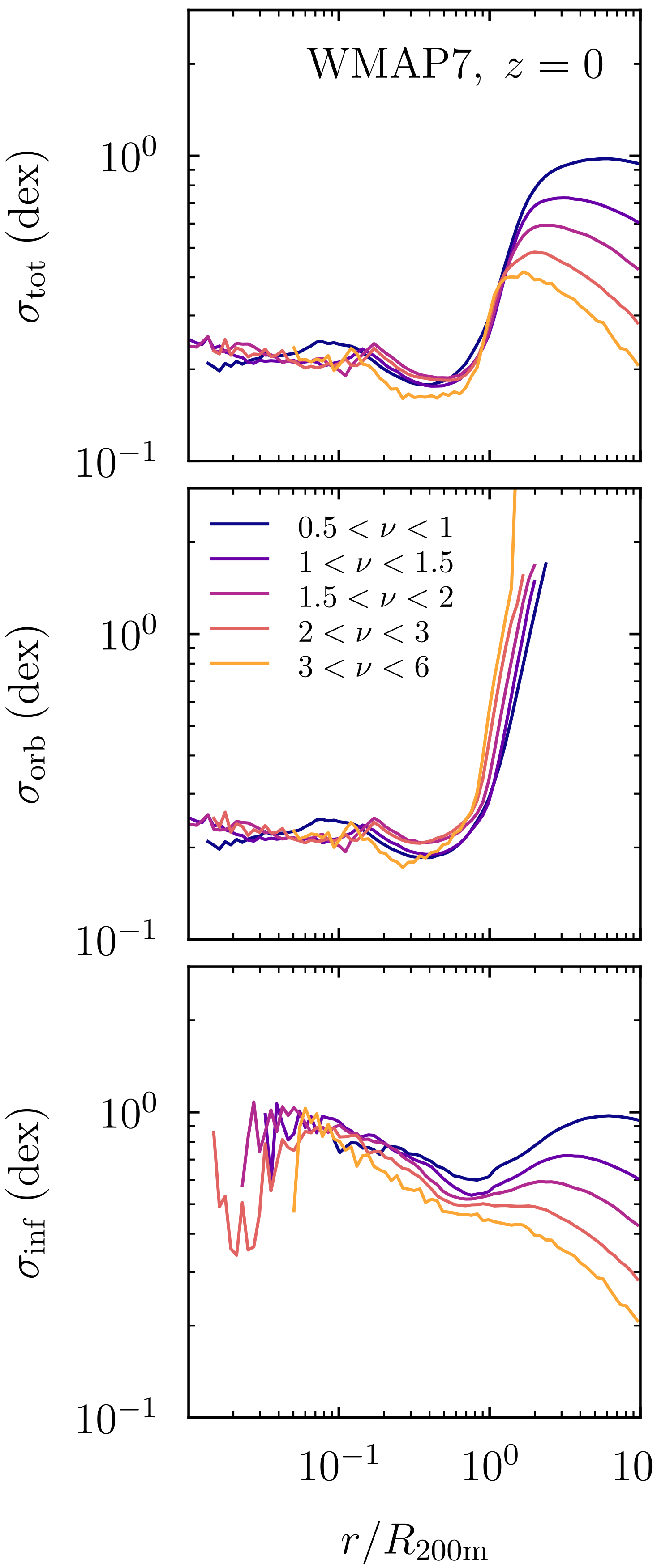
$$\rho_{\rm inf} = \rho_{\rm m} \left(\frac{\delta_1}{\sqrt{(\delta_1/\delta_{\rm max})^2 + (r/R)^{2s}}} + 1 \right)$$

$$\rightarrow \rho_{\rm m} \left[\left(\frac{r}{R} \right)^{-s} + 1 \right]$$



Diemer 2023

Halo-to-halo scatter



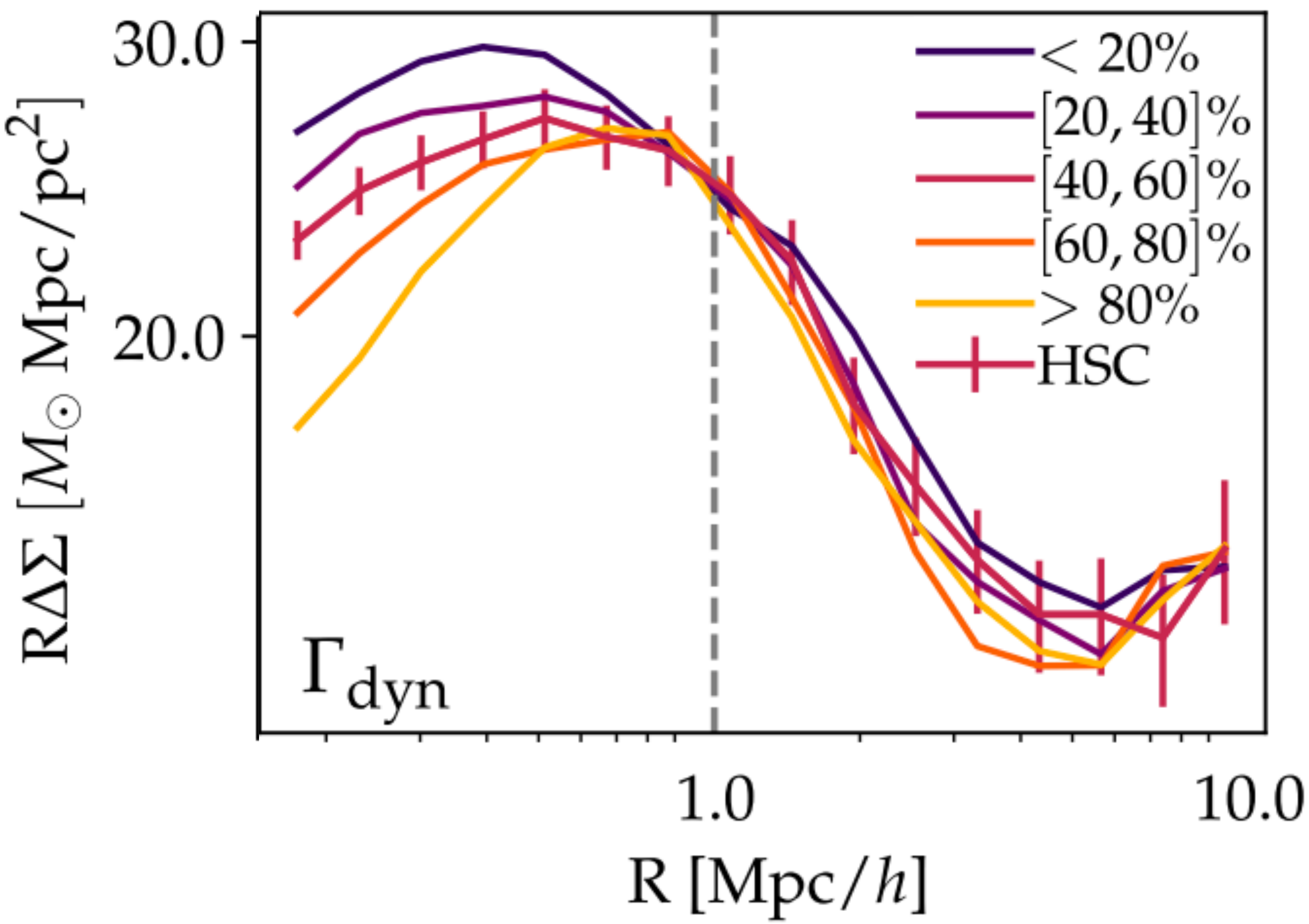
Total profile

Orbiting

Infalling

Diemer 2022

Measuring the accretion rate with weak lensing



Enia Xhakaj

Katya Leidig

Alexie Leauthaud

Xhakaj, Leauthaud, Diemer et al. 2020 / 2022

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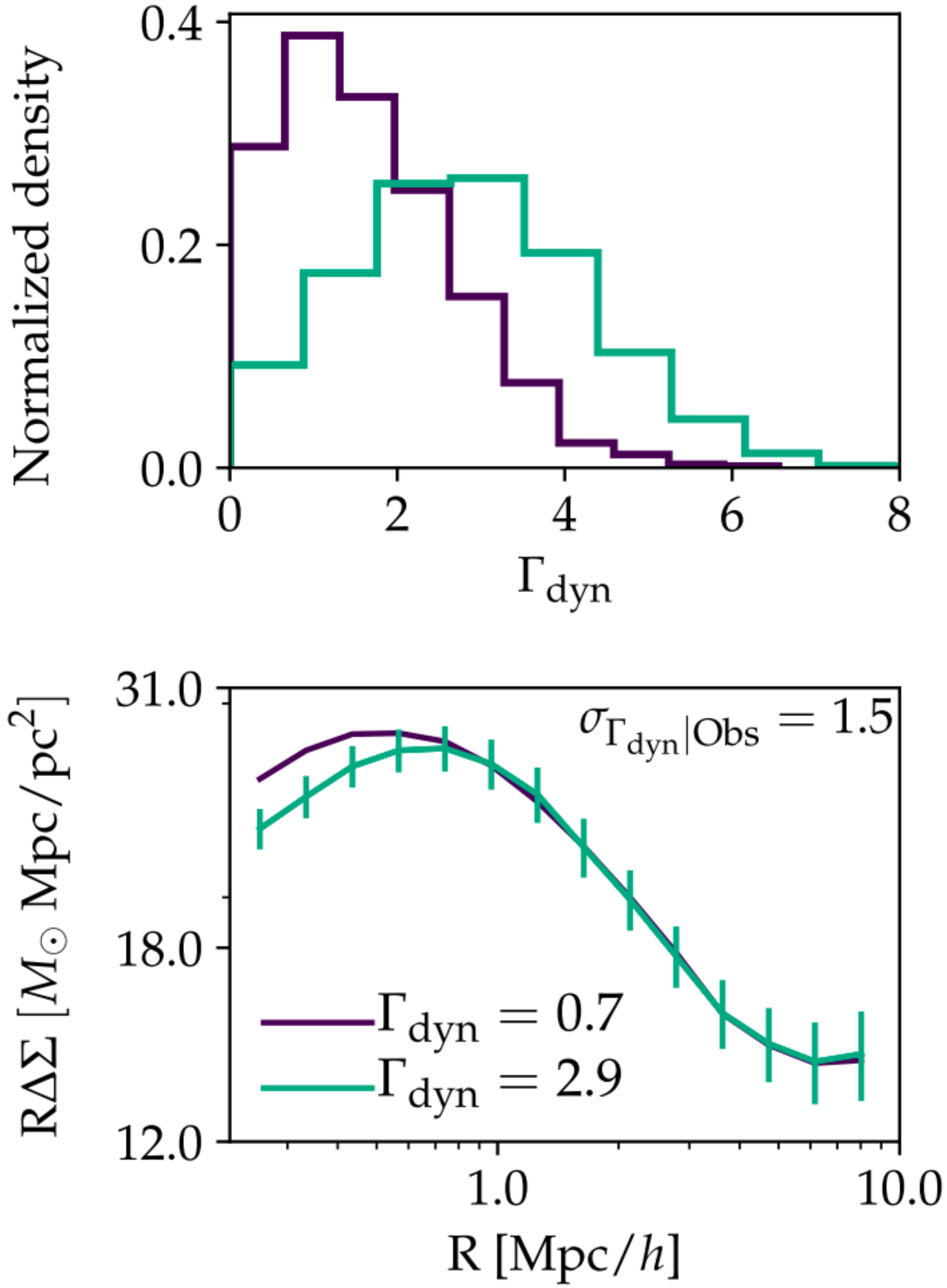

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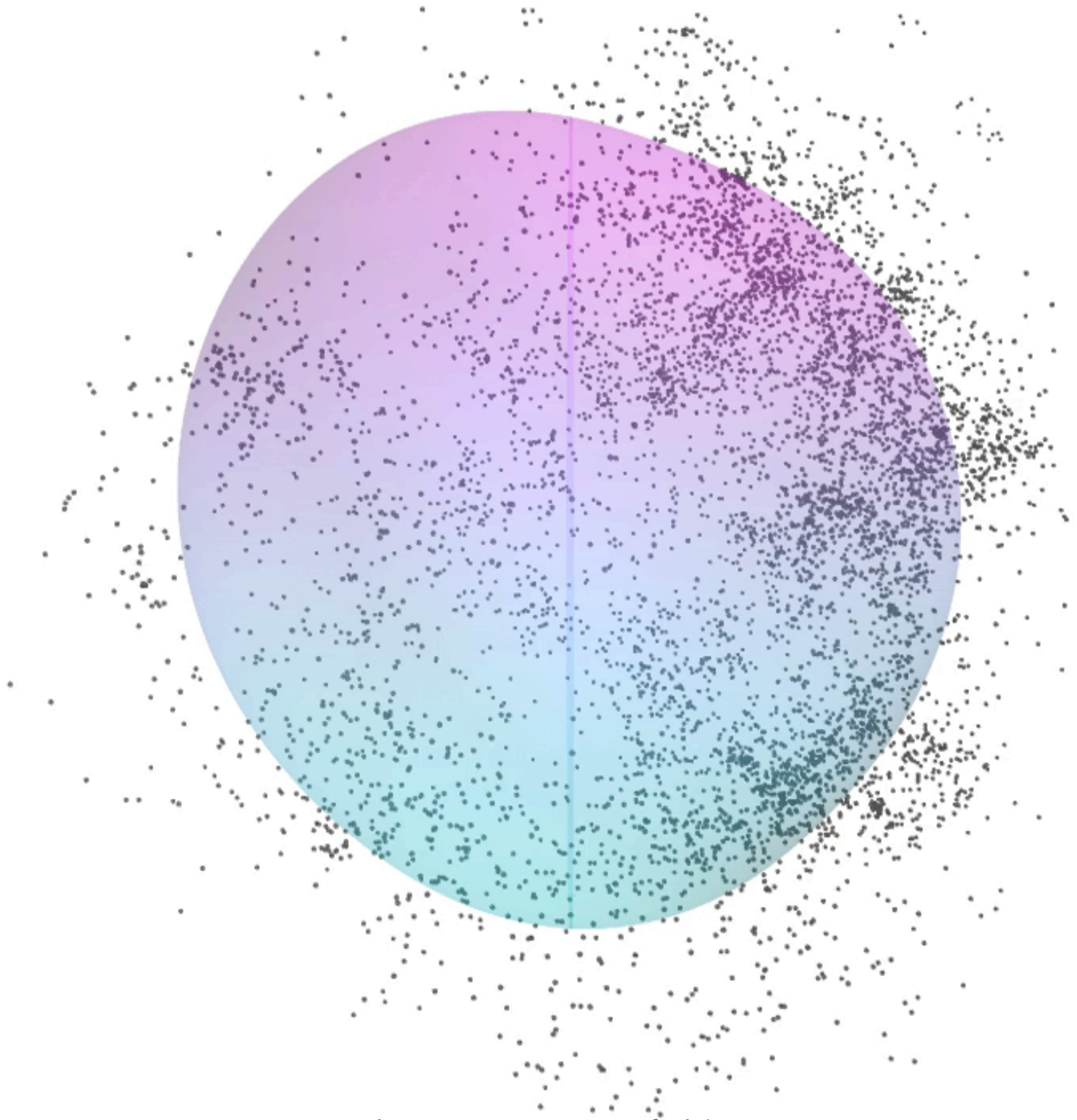
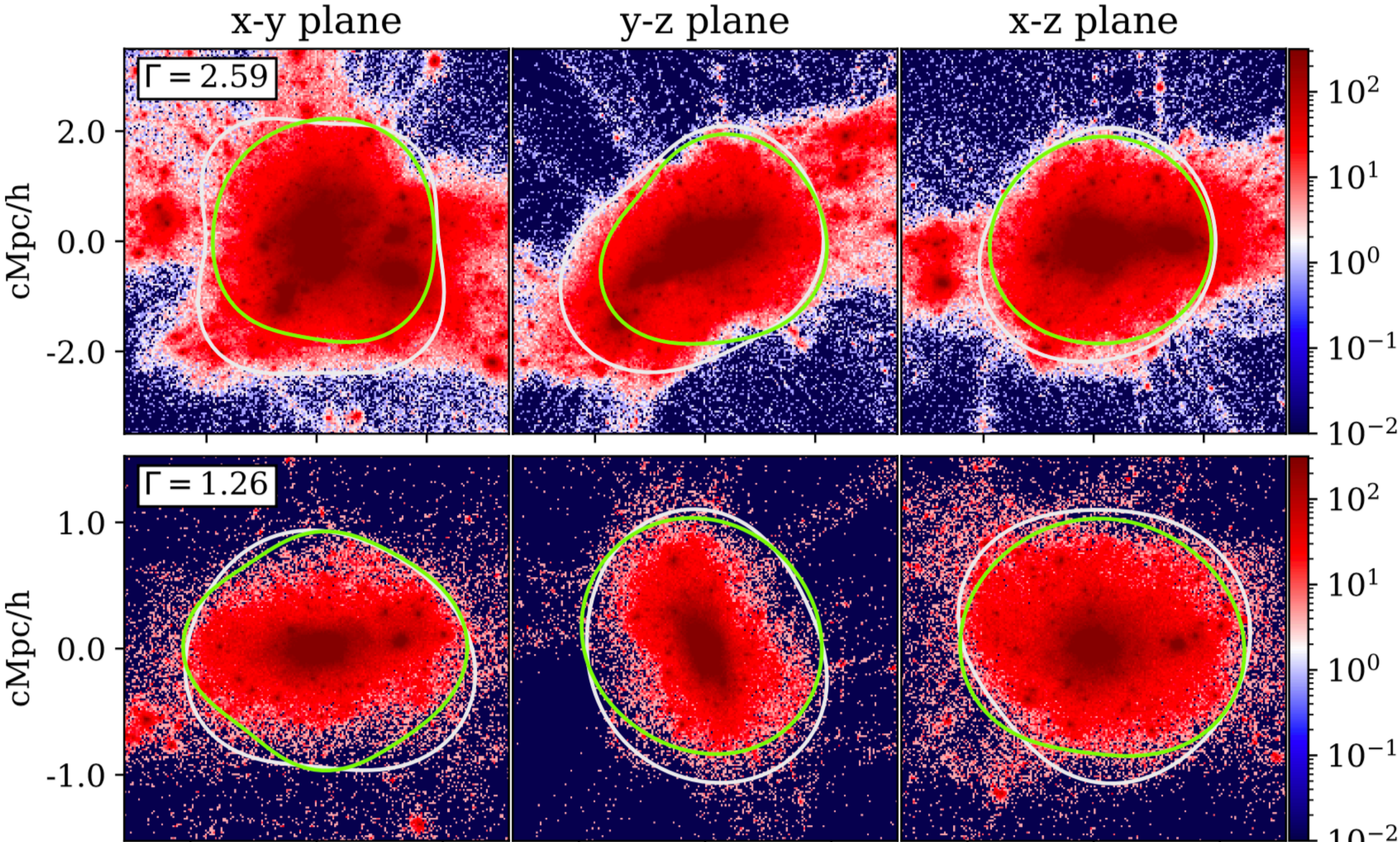
Xhakaj, Leauthaud, Diemer et al. 2020 / 2022



Calvin Osinga

Osinga et al. (in prep.) • Mansfield, Kravtsov & Diemer 2017 • Penna & Dines 2007



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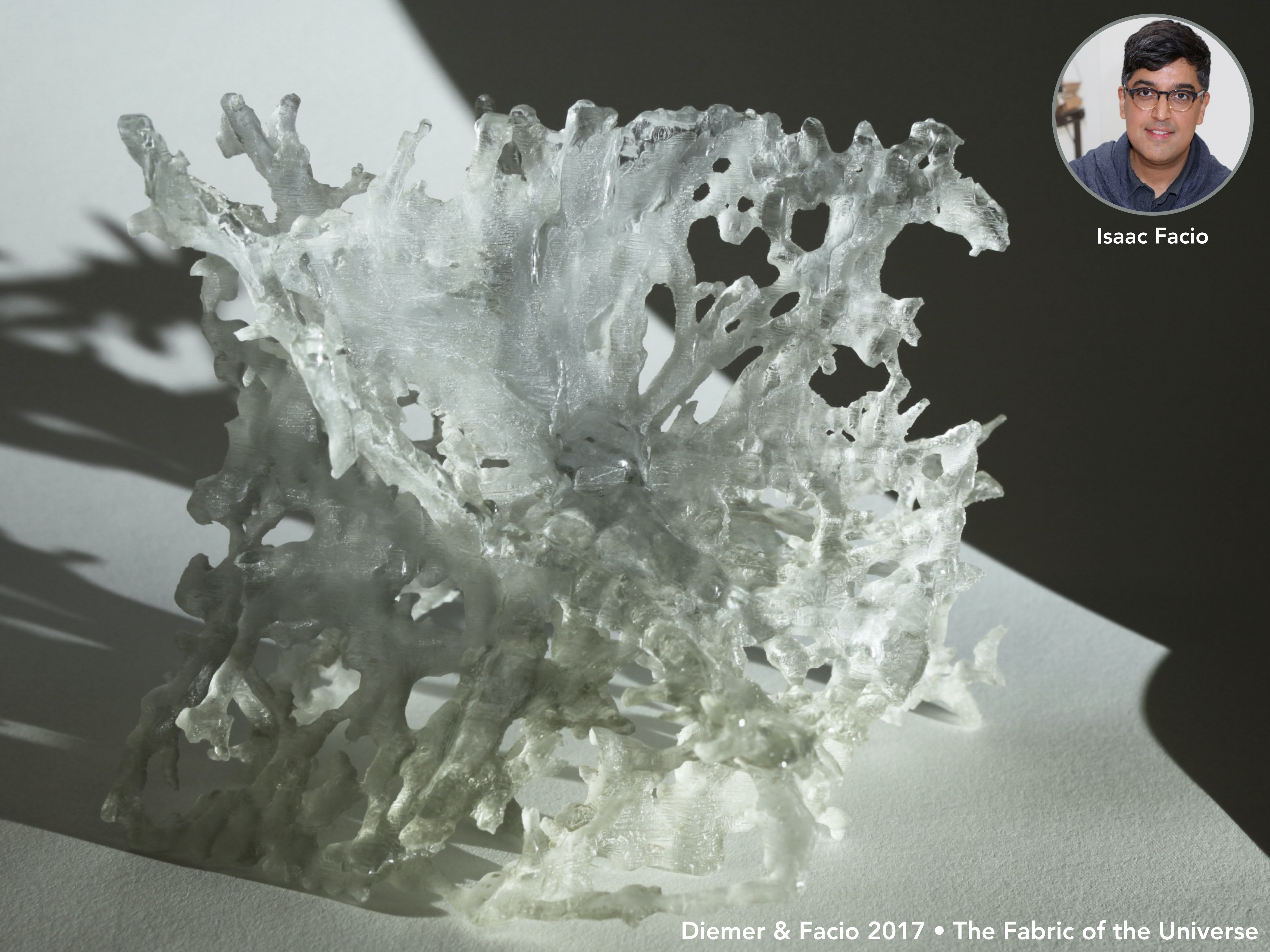
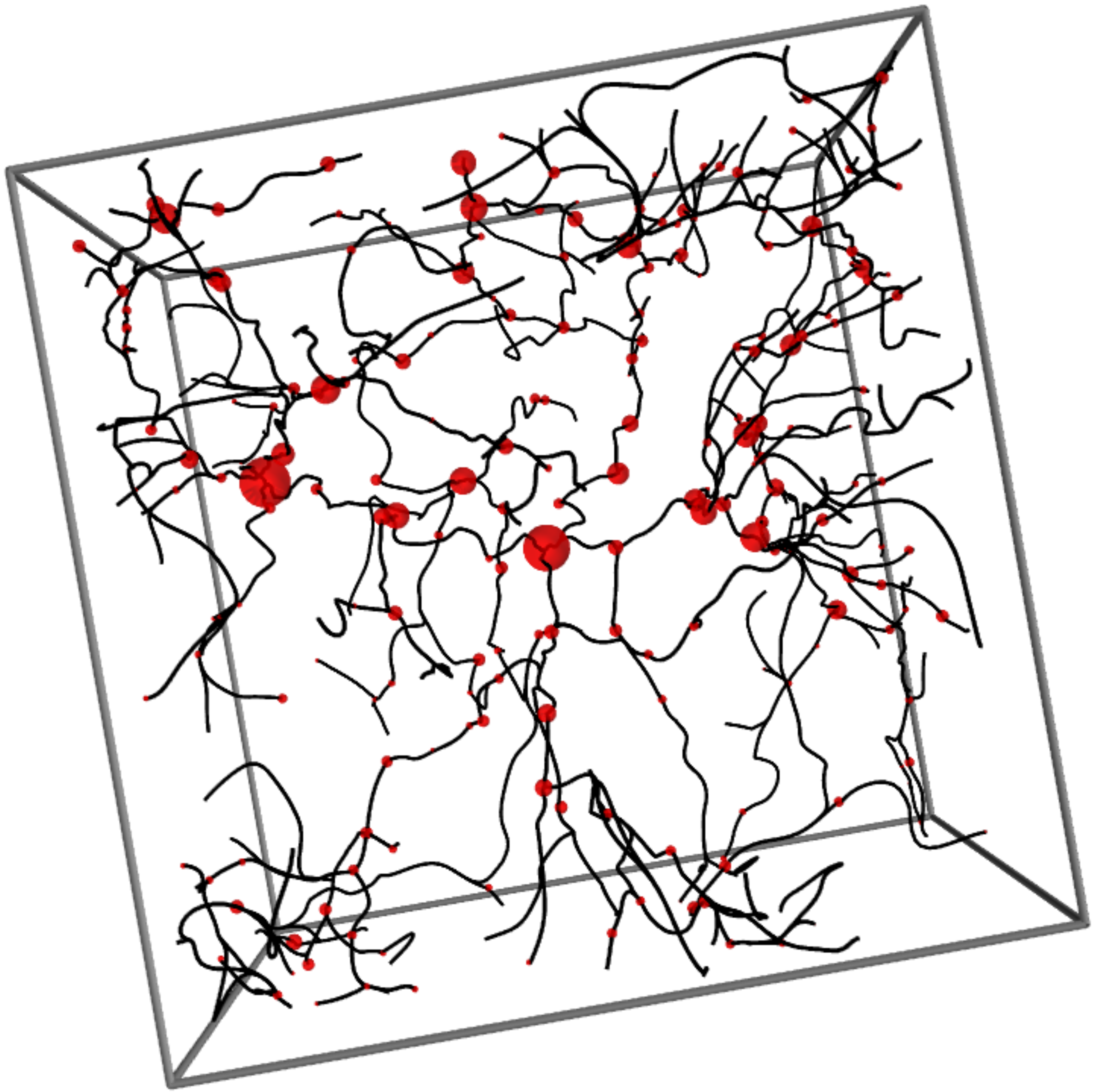
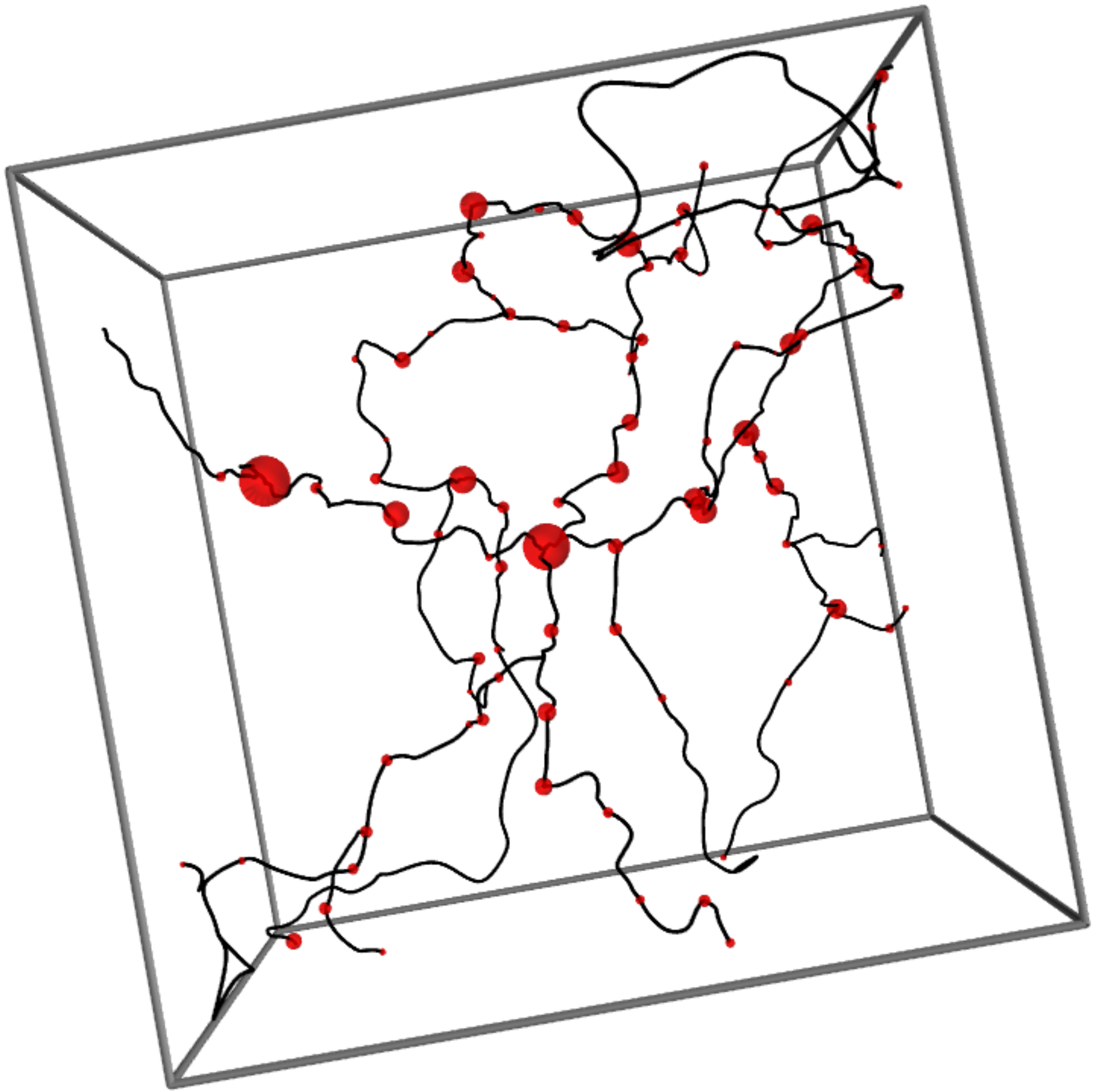

Isaac Facio
Diemer & Facio 2017 • The Fabric of the Universe



DISPERSE, Sousbie 2011



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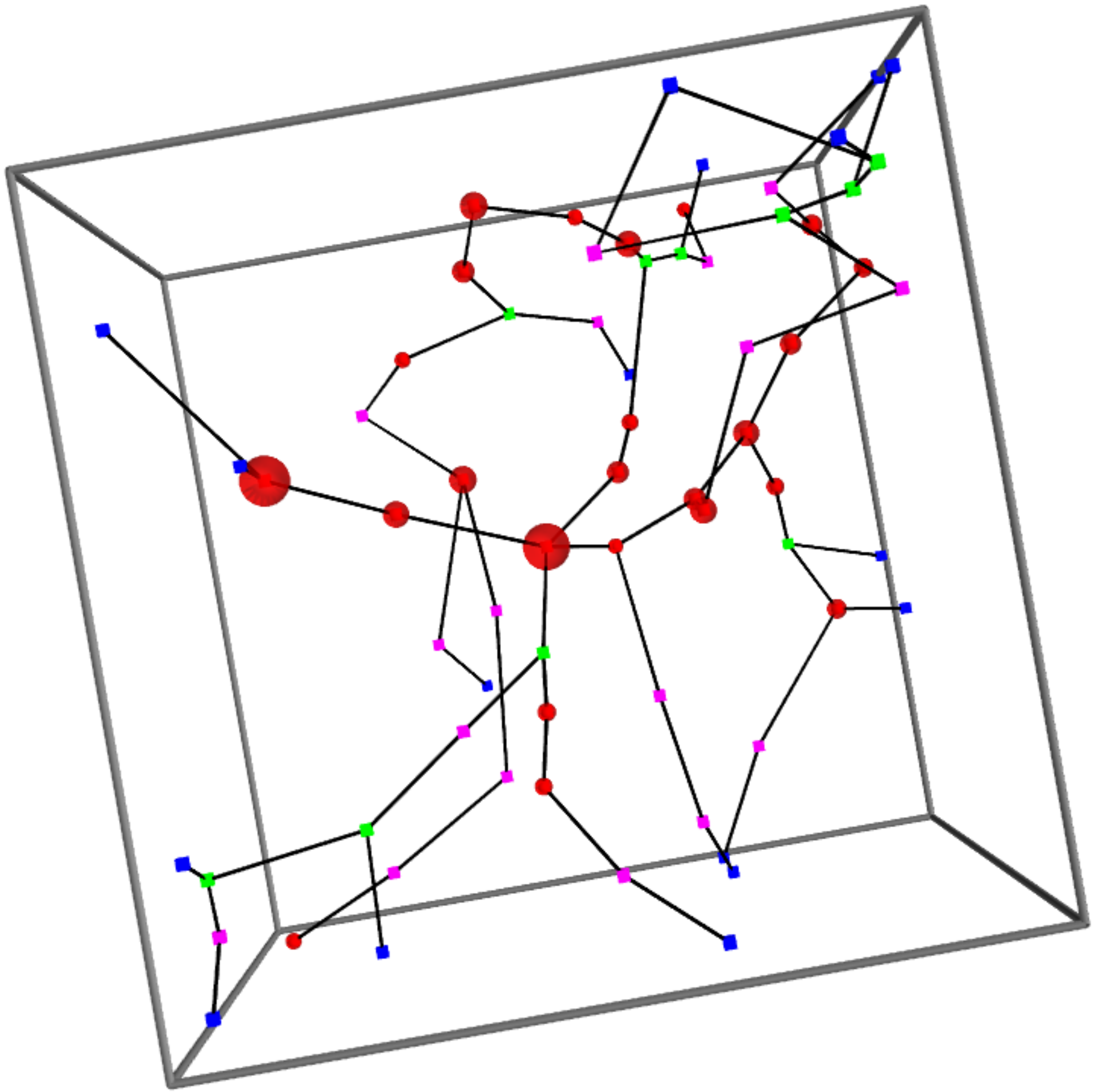
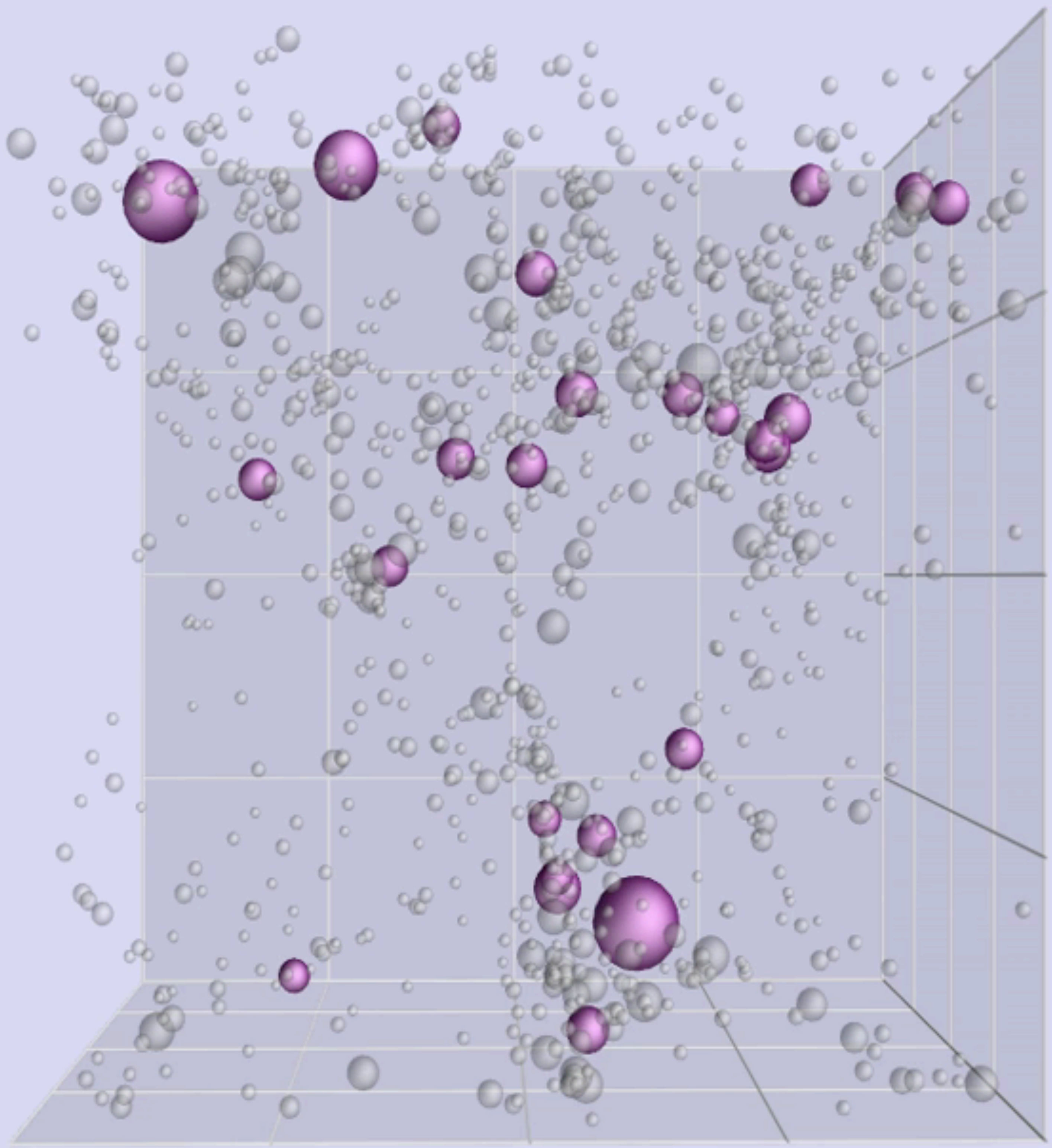
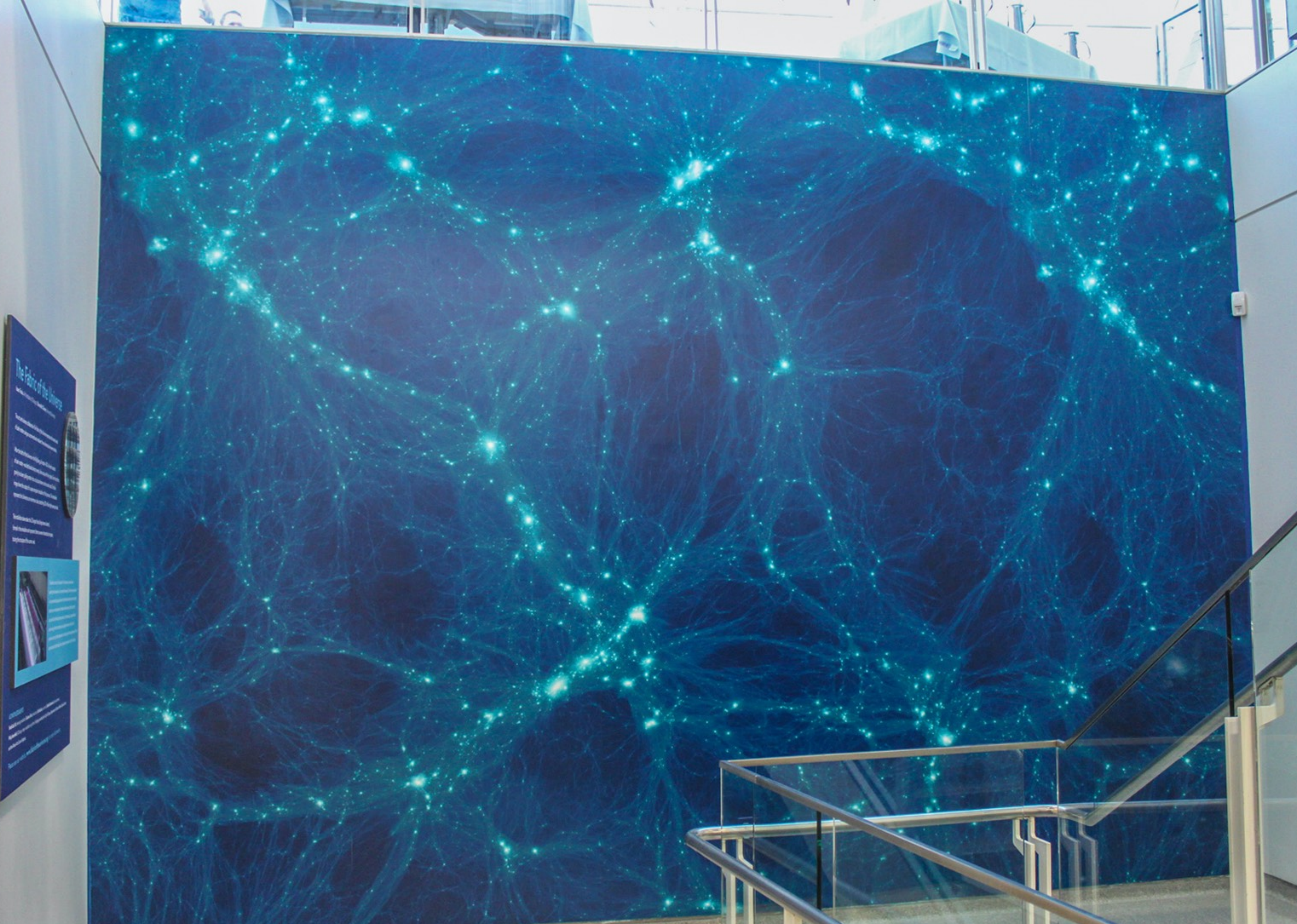




The Fabric of the Universe



The Fabric of the Universe

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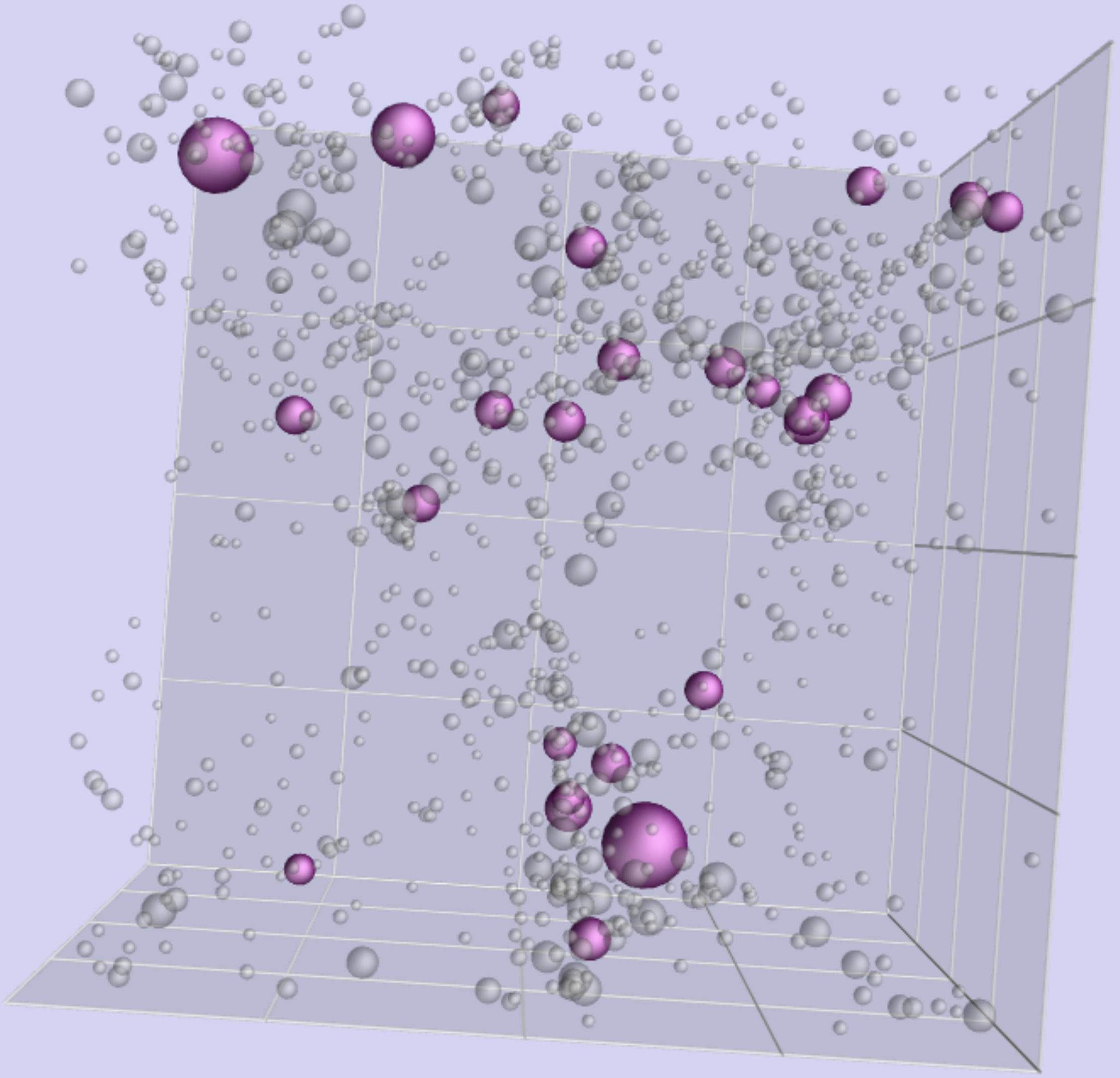

The Fabric of the Universe

Take-aways

- Splitting density into the **orbiting and infalling** terms finally lets us “see” their true structure
- Profiles depend on **accretion rate** and power spectrum slope, and less on mass/redshift/cosmology
- The new **fitting function** (Einasto + exponential truncation) captures the profiles accurately
- The halo outskirts are potential **cosmic laboratories** for accretion and fundamental physics