Multifield Ultralight Dark Matter

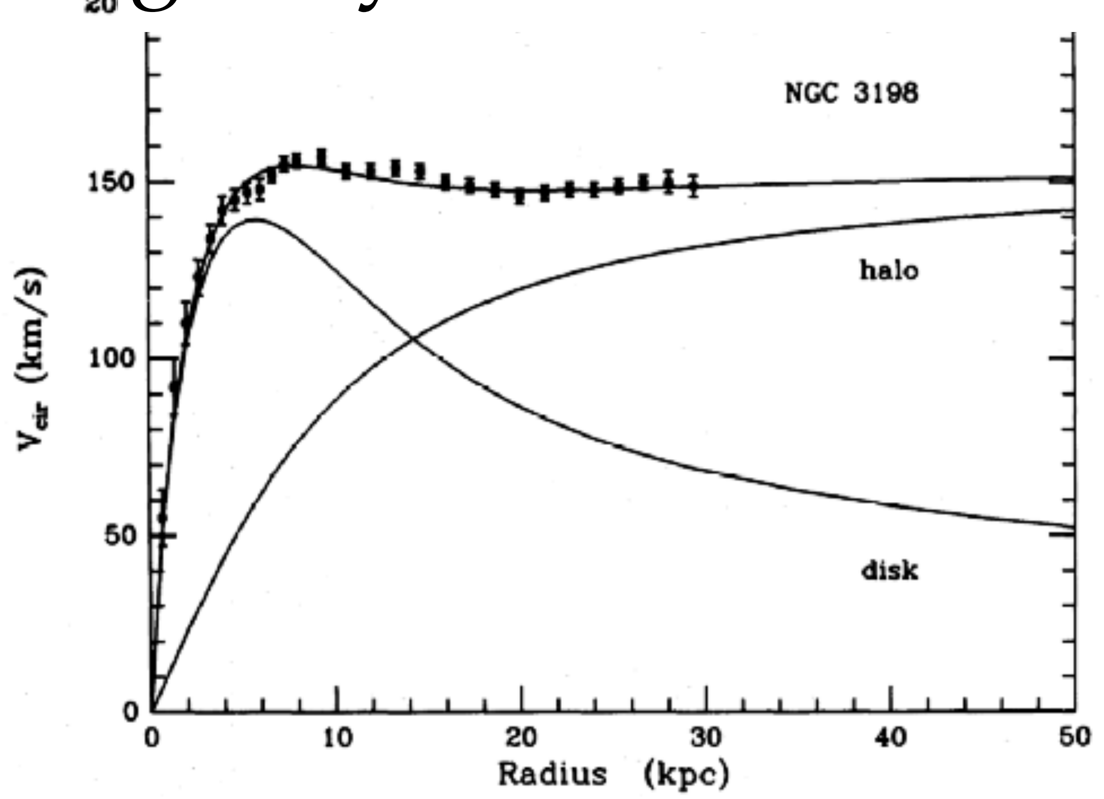
Mateja Gosenca **University of Vienna**

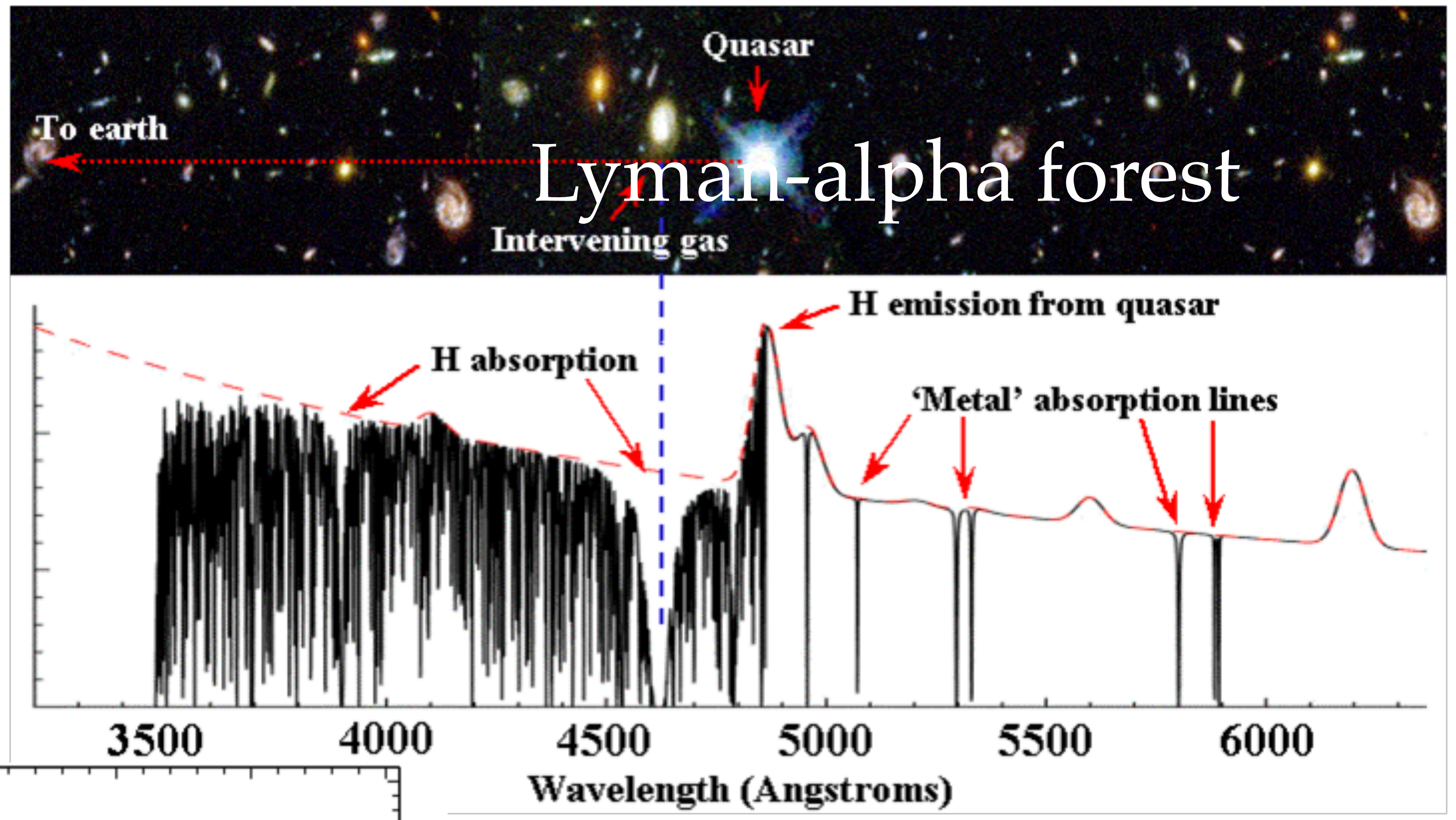
Collaborators: Richard Easther, Andrew Eberhardt, Benedikt Eggemeier, Peter Hayman, Emily Kendall, Jens Niemeyer, Frank Schindler, Bodo Schwabe, Yourong Wang, J. Luna Zagorac

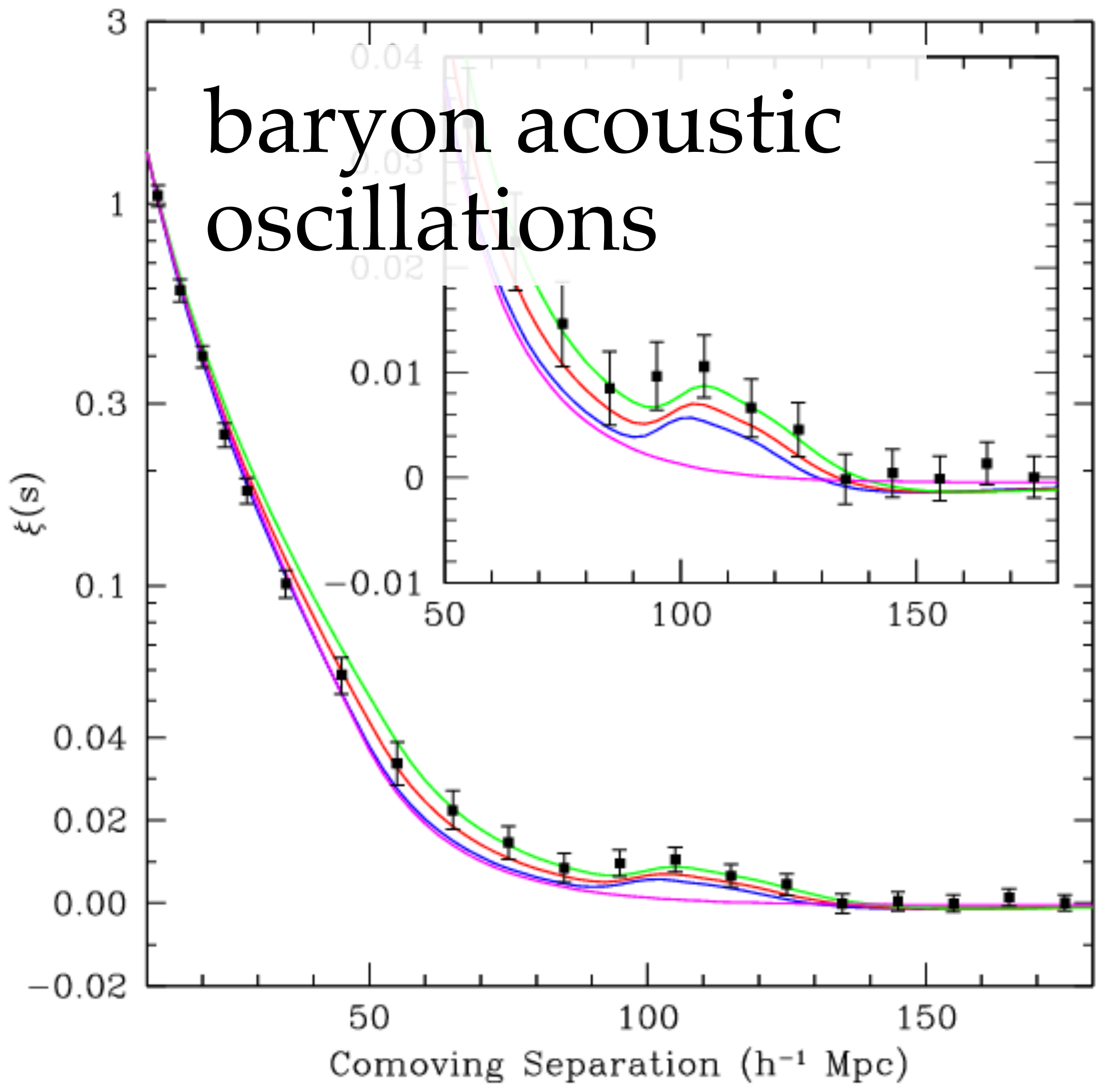
Cosmology 2023 in Miramare

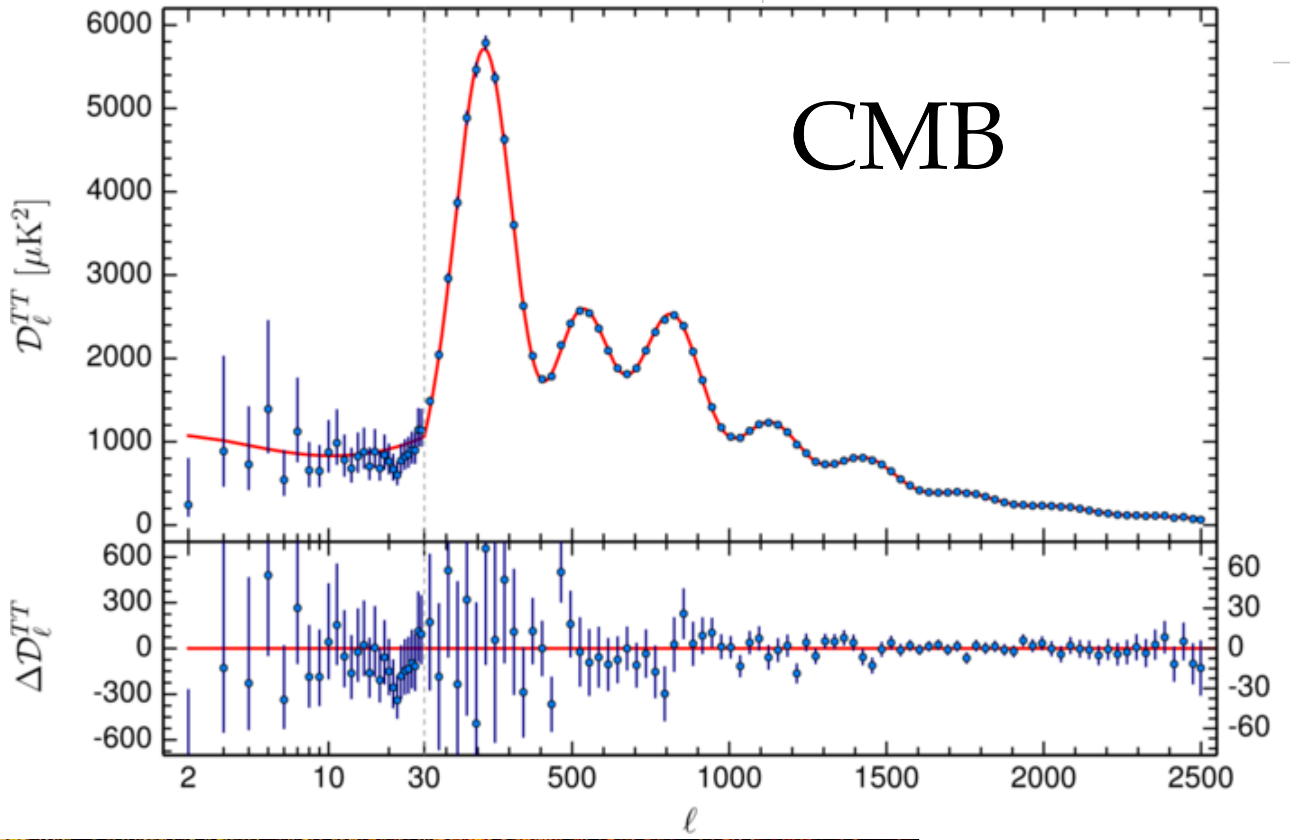
30 August 2023

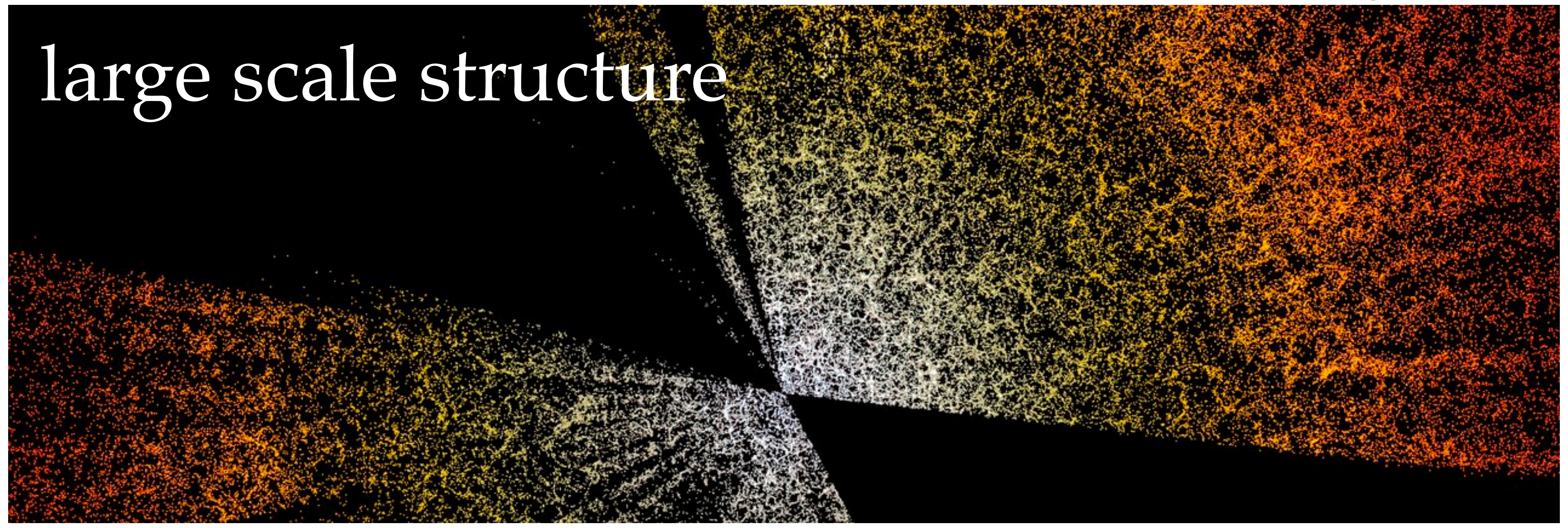
Observational evidence for dark matter









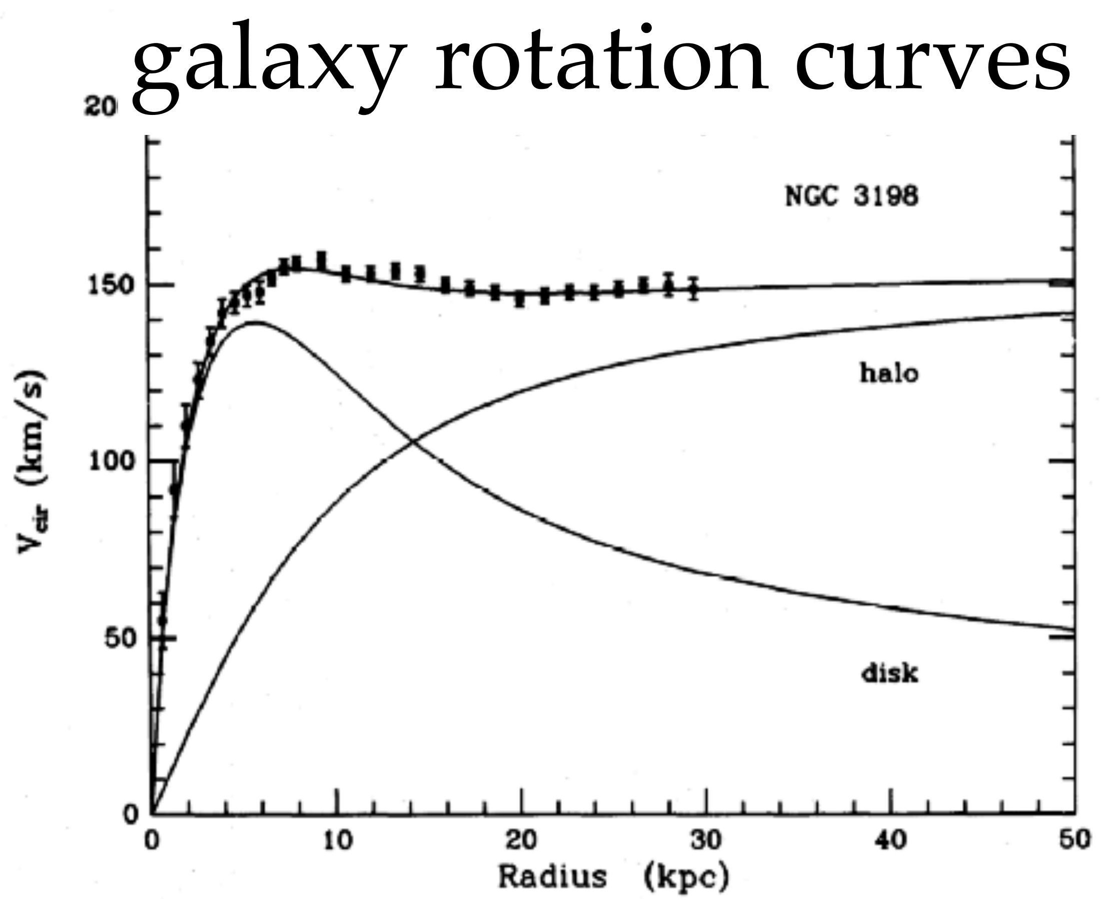


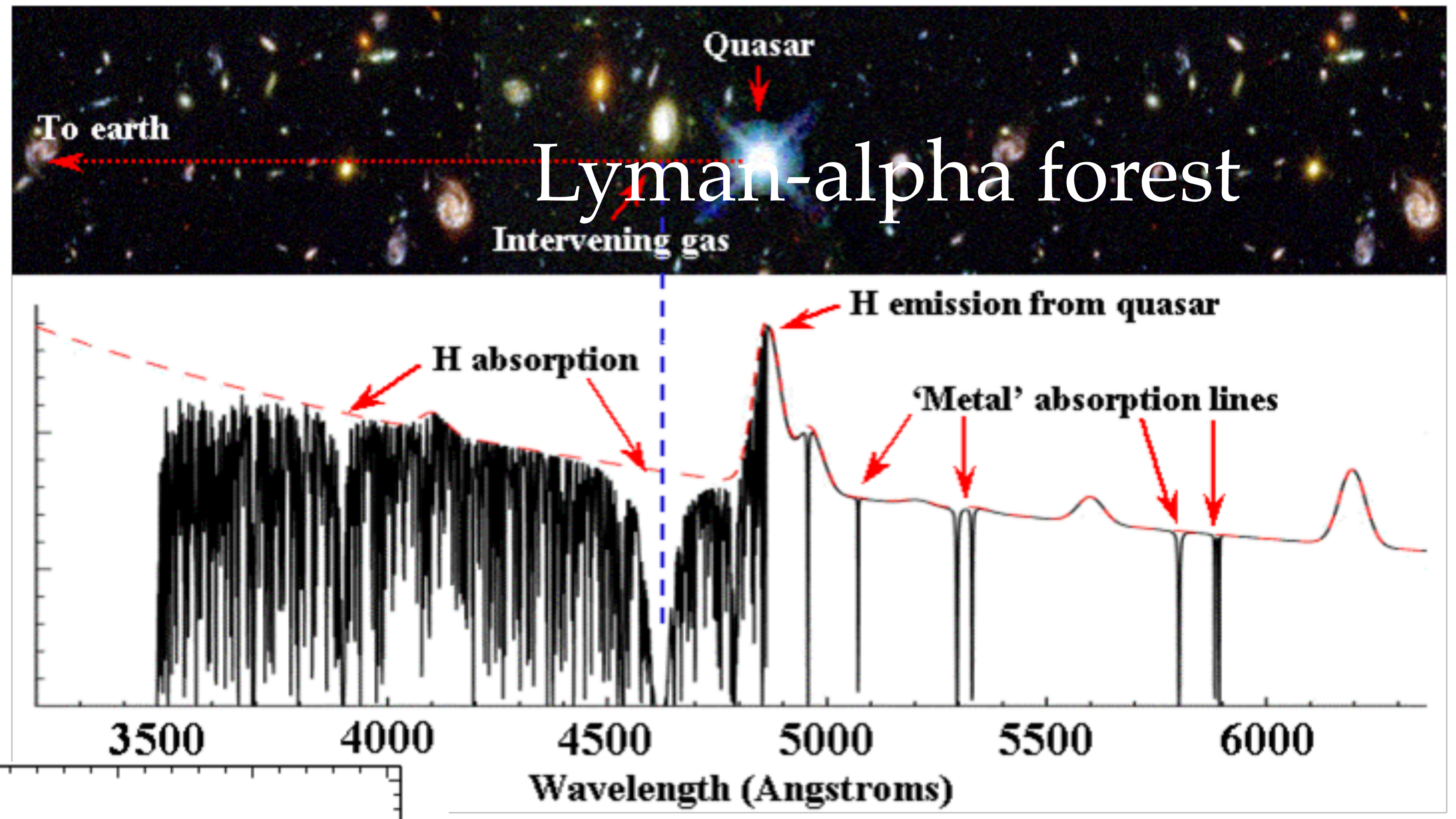
85% of the matter in the Universe is dark

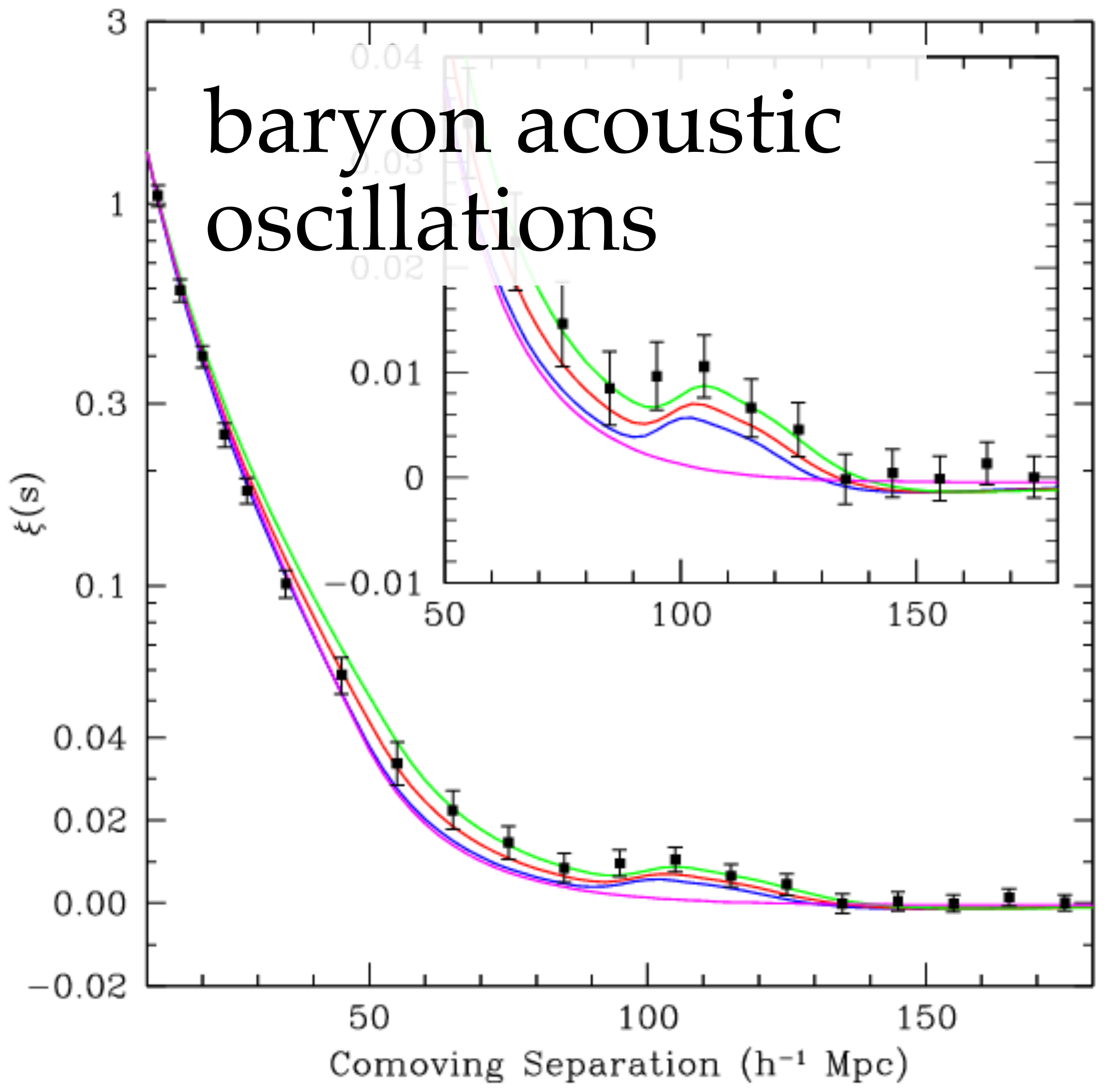
Described by the cold dark matter (CDM):

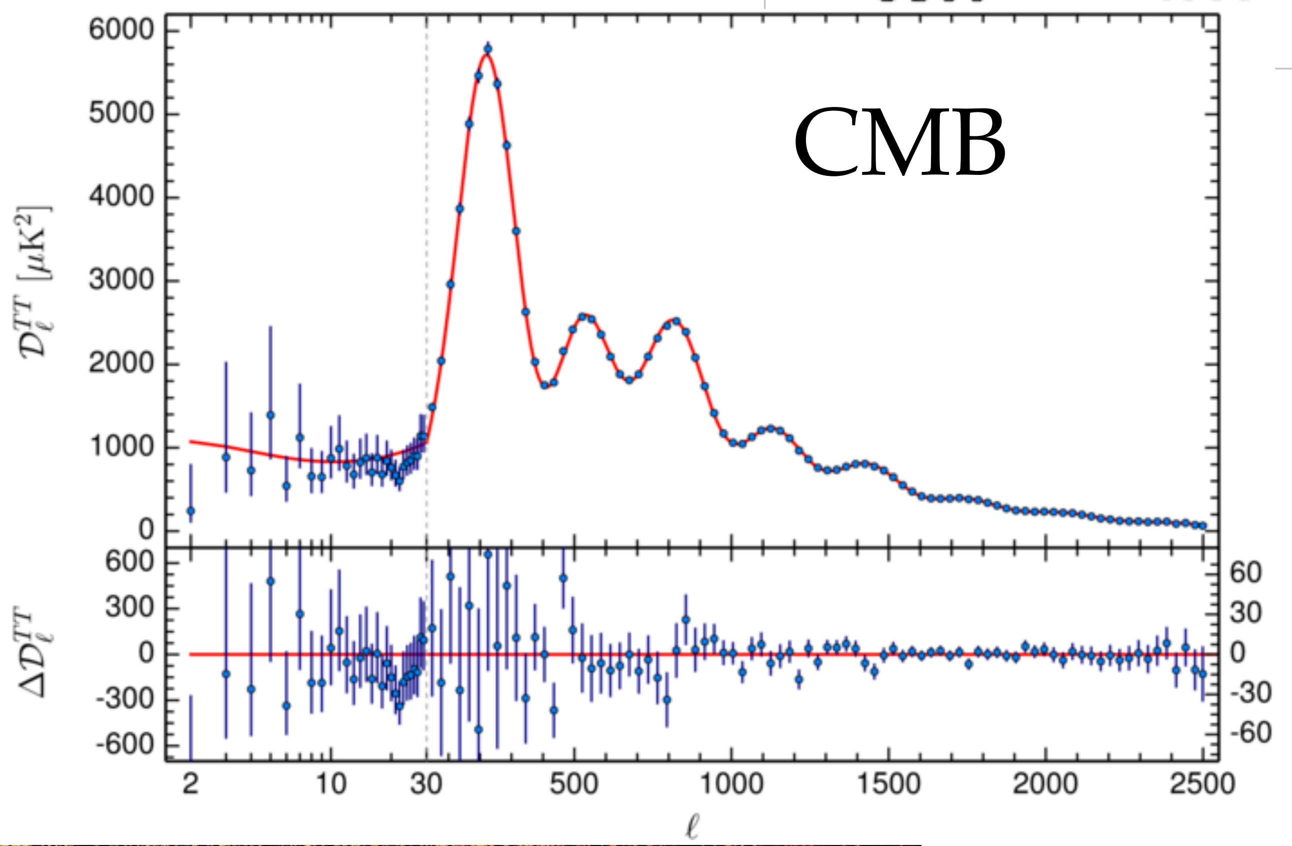
- cold
- dark
- collisionless

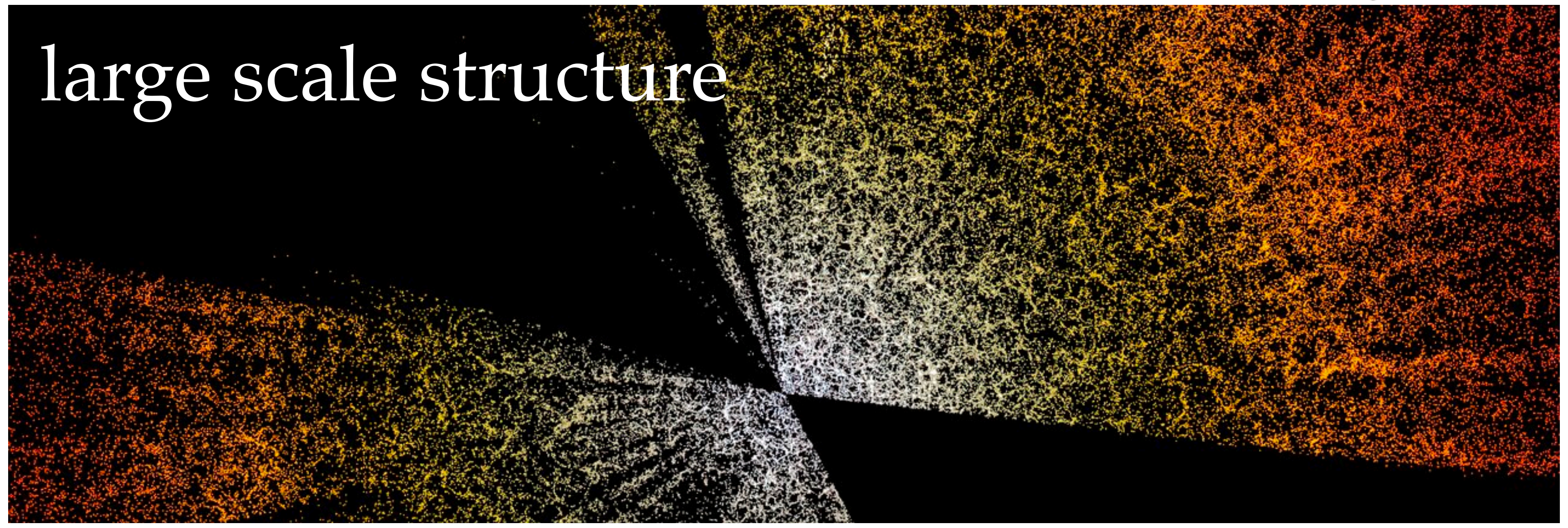
Observational evidence for dark matter











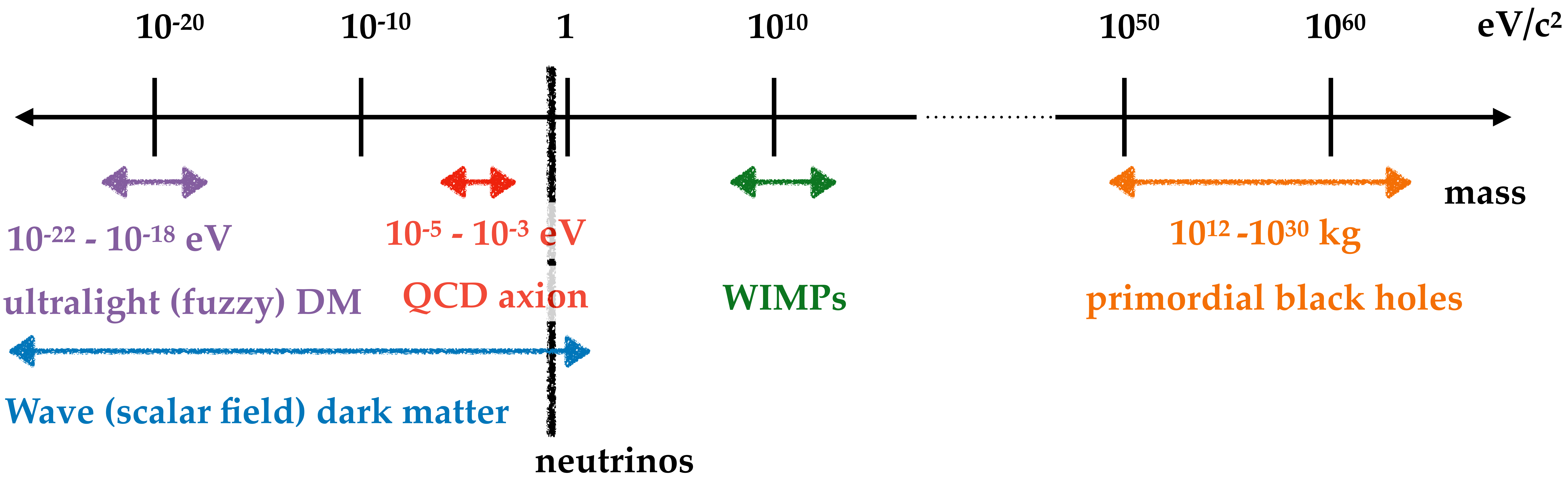
85% of the matter in the Universe is dark

CDM:
- cold
- dark
- collisionless

Challenged by:
- warm, fuzzy DM
- milicharged DM
- self-interacting DM

Theoretical explanation for dark matter?

- a new kind of massive particle or object
- gravity doesn't behave the same on galactic or extra galactic scales as in the Solar system or on the Earth



scalar field Lagrangian:

$$\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2}m^2\phi^2 + \frac{1}{4!}g\phi^4$$

self-interaction term

non-relativistic limit: $$\phi = \frac{1}{\sqrt{2m}}\left(\Psi e^{-imt} + \Psi^* e^{imt}\right)$$

Schrödinger-Poisson system

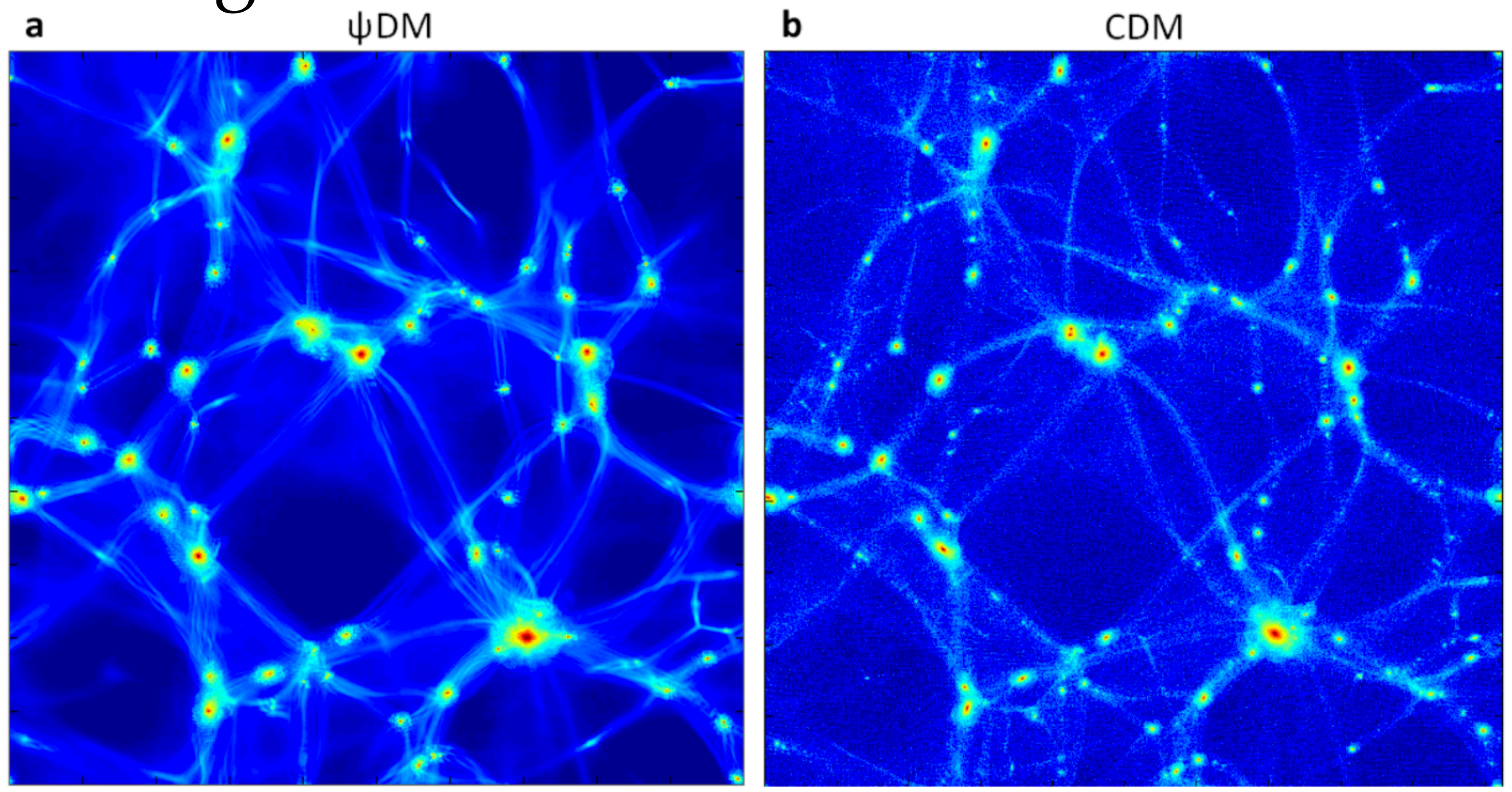
$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\Psi + mV\Psi$$

$$\nabla^2 V = \frac{4\pi G}{a}(\rho - \bar{\rho})$$

$$\rho = |\Psi|^2$$

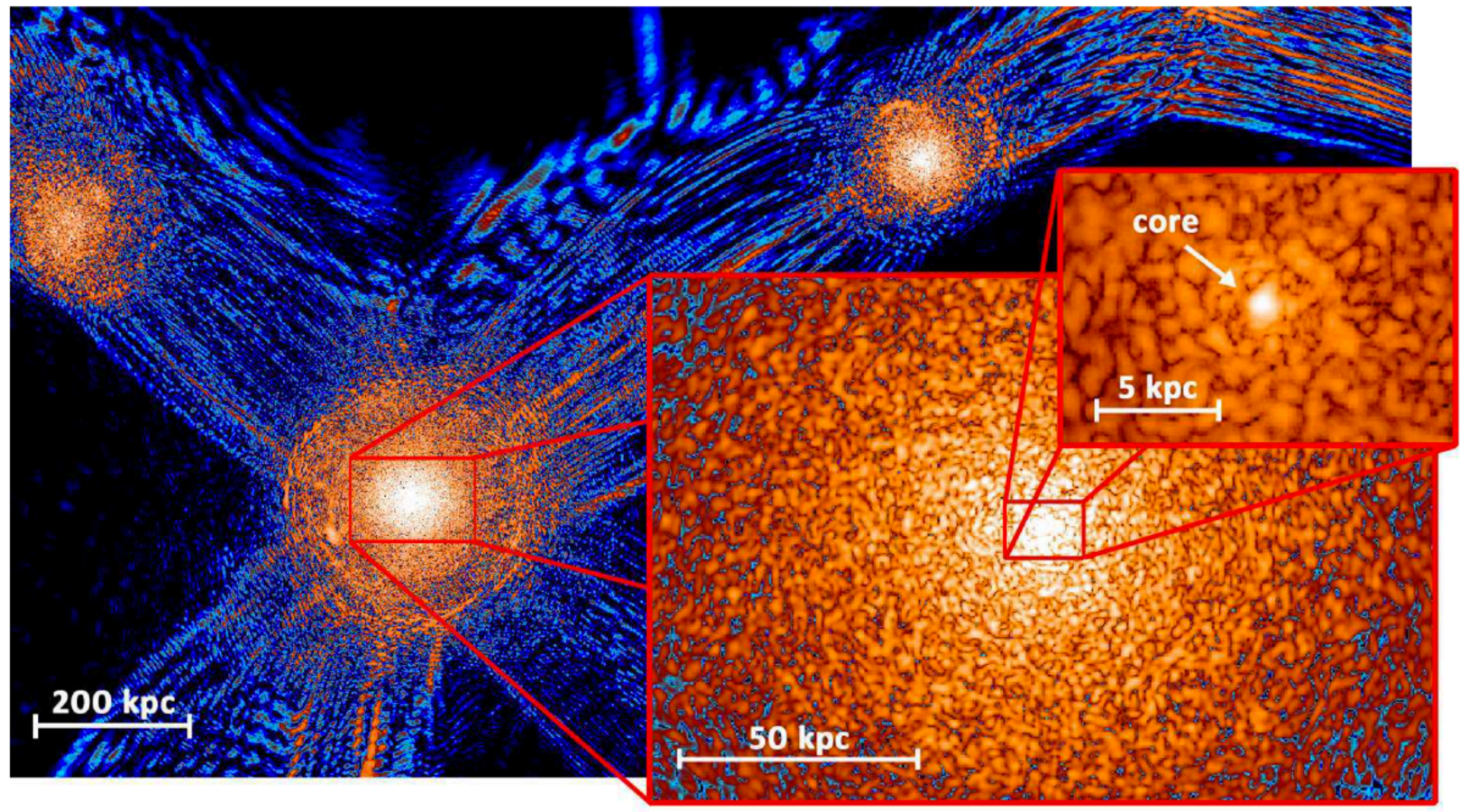
de Broglie wavelength: $$\lambda_{\mathrm{dB}} = \frac{\hbar}{mv}$$

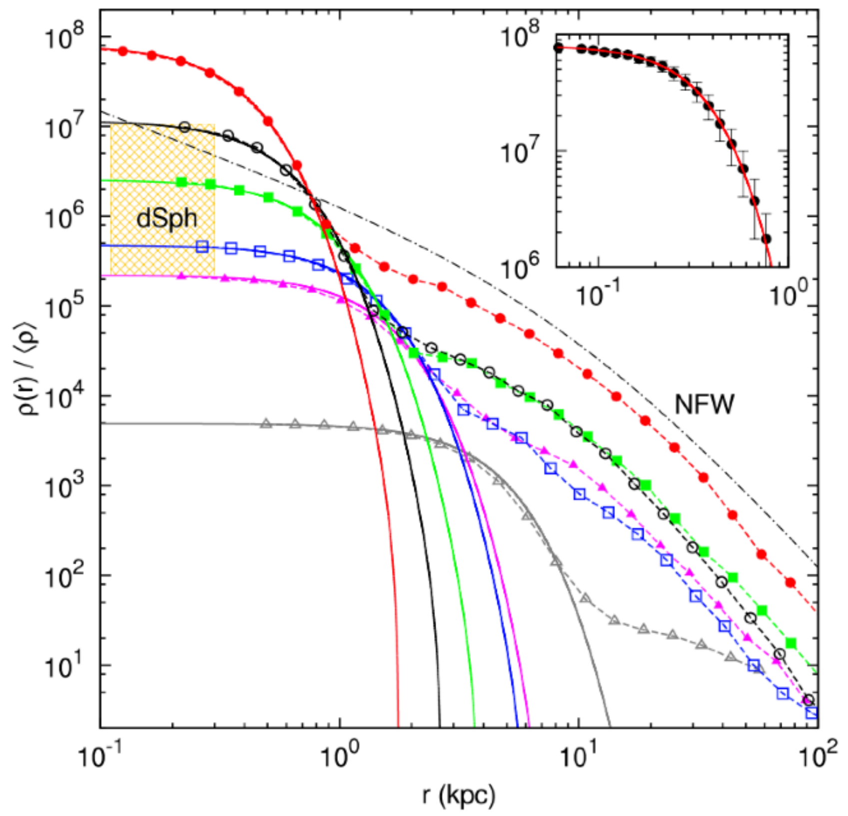
Large scales: ULDM behaves like CDM
(Schrödinger-Poisson — Vlasov-Poisson correspondence)



Schive, et al., *Nature Physics*, 2014

Small scales: wavelike effects present





AxioNyx

Schwabe, MG, Behrens, Niemeyer, Easther, *2020*

- Based on AMReX and Nyx
  - https://amrex-codes.github.io/amrex/
  - https://amrex-astro.github.io/Nyx/
- solves the Schrödinger-Poisson system on a grid (with a cosmological background)
- uses adaptive mesh refinement (AMR) in regions of interest
- can easily parallelise to high number of processes
- publicly available
  - https://github.com/axionyx/axionyx_1.0

Construction of isolated halos

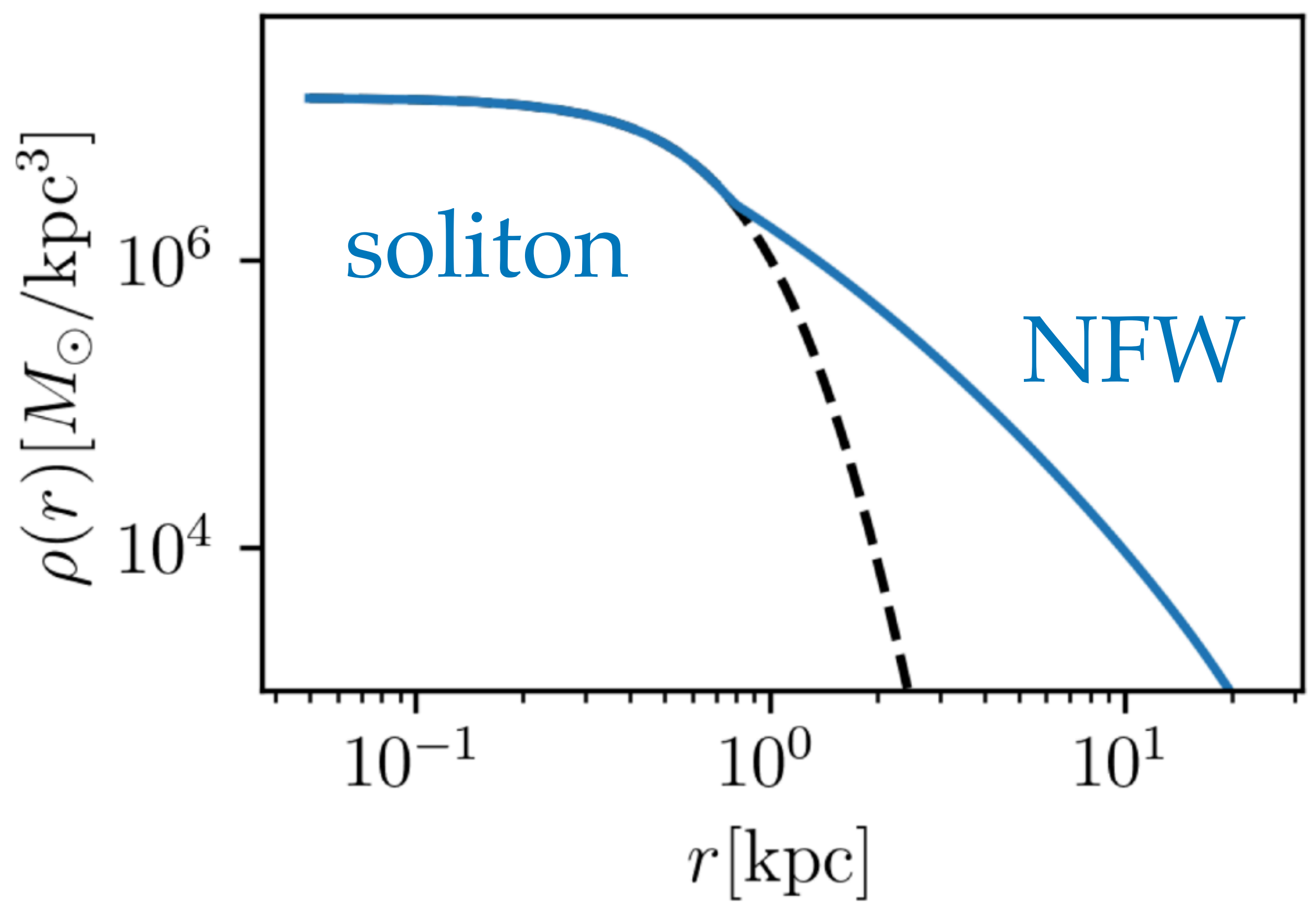
- use the eigenfunction method

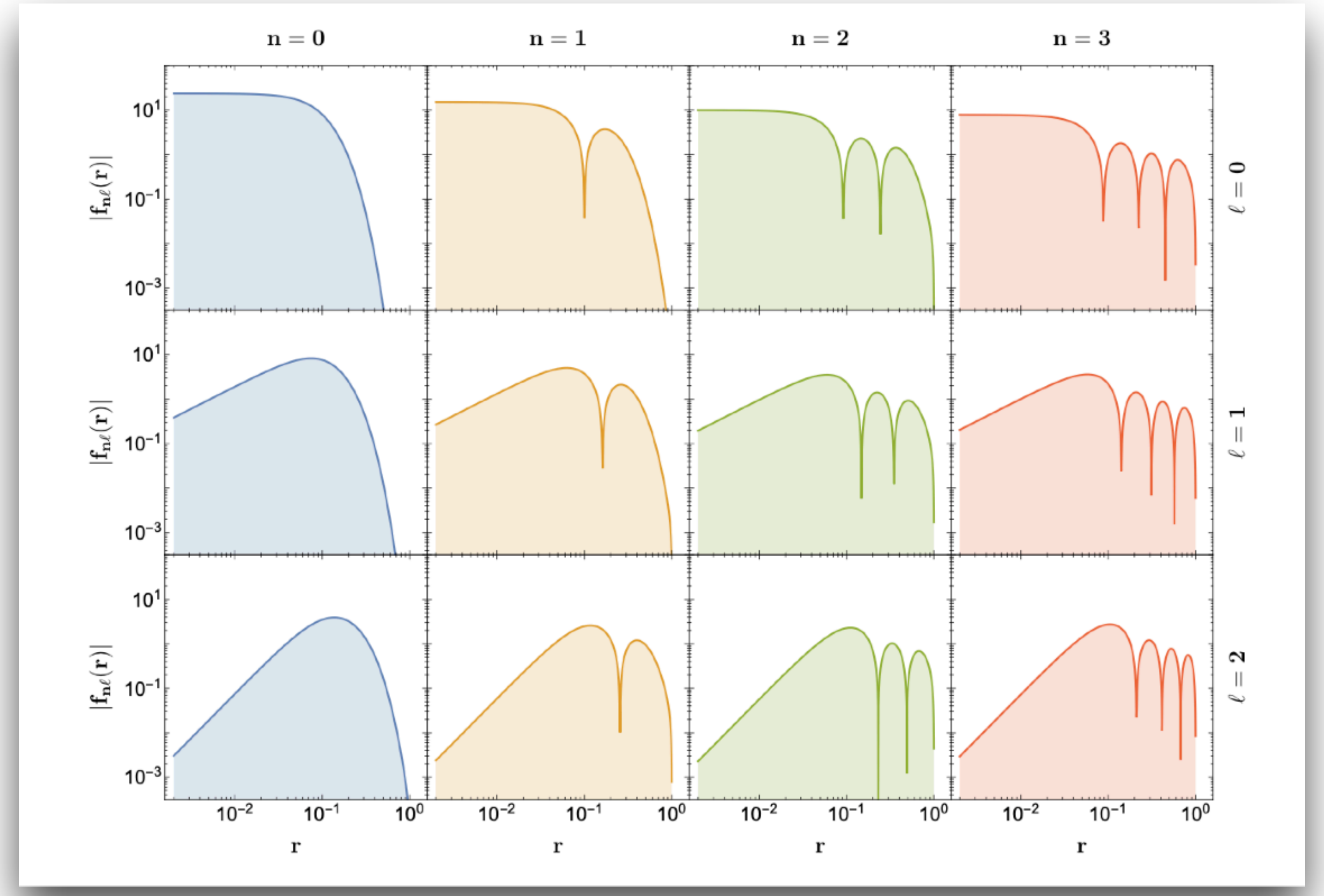
Yavetz, Li, Hui, Phys. Rev. D 105, 023512

$$\Psi(\mathbf{r}, t) = \sum_j a_j \psi_j(\mathbf{r}) e^{-iE_j t/\hbar}$$

$$\psi_j(r, \theta, \phi) = R_{n\ell}(r) Y_\ell^m(\theta, \phi)\, e^{if_{n\ell m}}$$

random phase



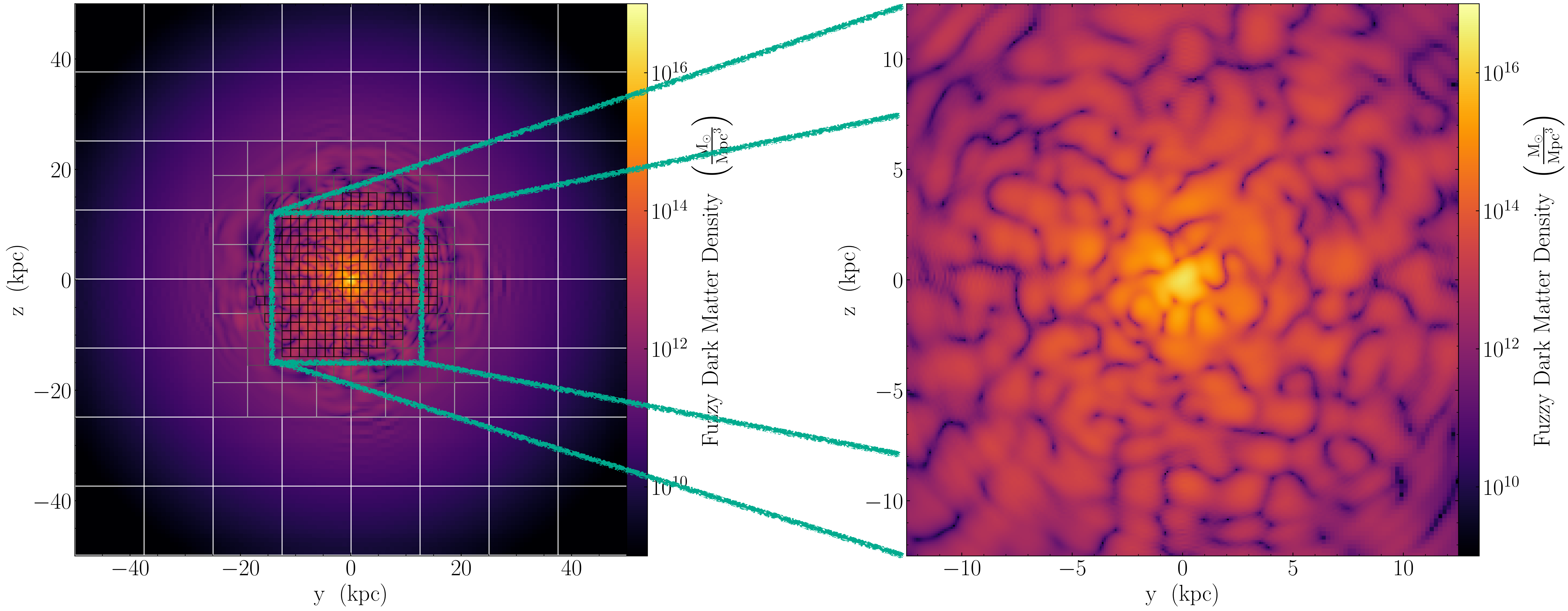


Zagorac et al, Phys. Rev. D 105, 103506

Construction of isolated halos

random phase

constructed 3D wave function: $\Psi(r,\theta,\phi) = \sum_{n\ell} a_{n\ell} R_{n\ell}(r) Y_\ell^m(\theta,\phi)\, e^{i f_{n\ell m}}$



$m_{\text{axion}} = 5 \times 10^{-22}$ eV

Multifield Ultralight Dark Matter

Theoretical motivation for ULDM comes from string theory axions

- ~30 axion fields are expected
- masses distributed uniformly on the logarithmic scale

Arvanitaki et al., ***2009***

- the model:

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\Psi + m\Phi\Psi$$

$$\nabla^2\Phi = \frac{4\pi G}{a}(\rho - \bar{\rho})$$

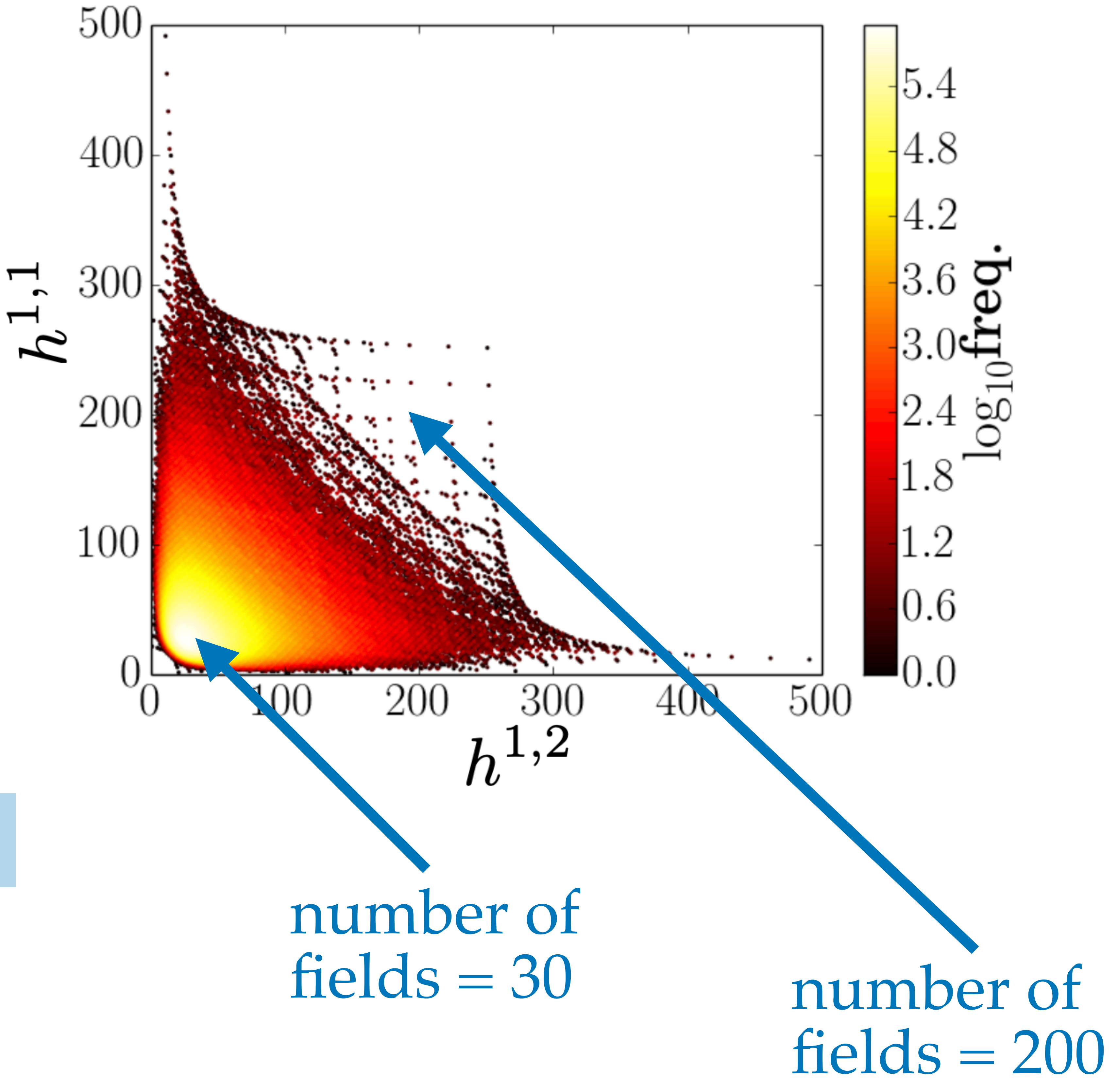
$$\rho = |\Psi|^2$$

⇒

$$i\hbar\frac{\partial\Psi_i}{\partial t} = -\frac{\hbar^2}{2m_i a^2}\nabla^2\Psi_i + m_i\Phi\Psi_i$$

$$\nabla^2\Phi = \frac{4\pi G}{a}(\rho - \bar{\rho})$$

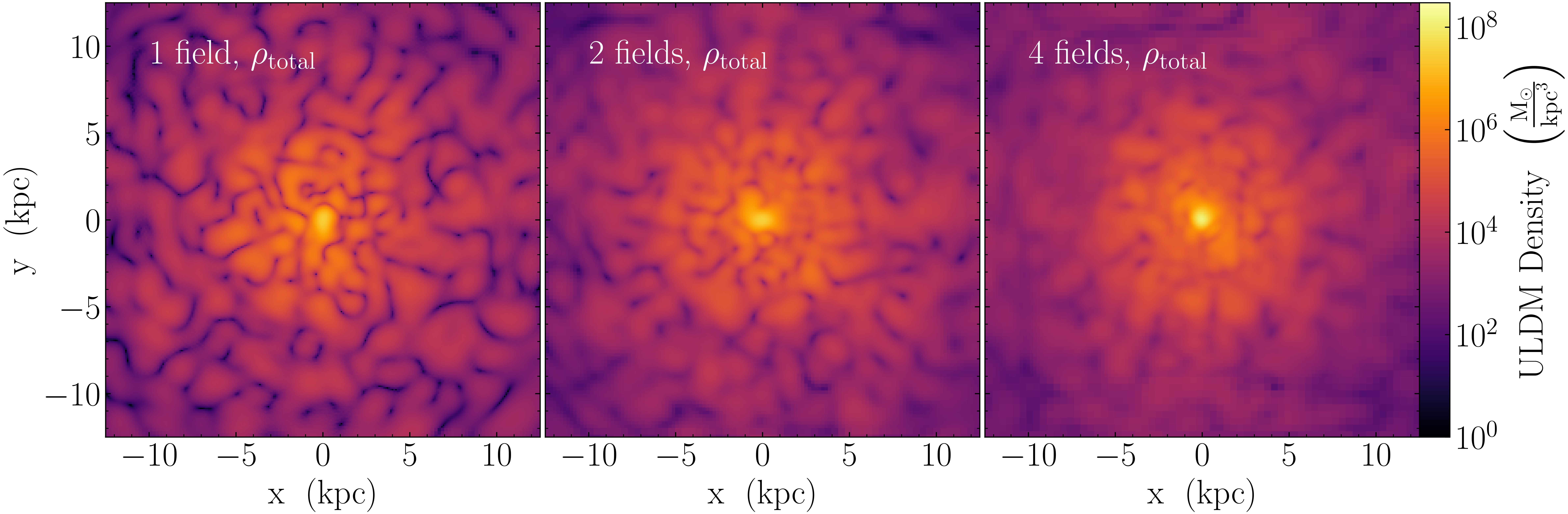
$$\rho = \sum_{i=1}^{N}|\Psi_i|^2$$



Marsh, ***2016***

Multifield halos: total density is smoother

- Equal ULDM mass



$$\rho = \sum_{i=1}^{N} |\Psi_i|^2$$

MG, Eberhardt, Wang, Eggemeier, Kendall, Zagorac, Easther

PRD, 2023

Multifield halos: how much smoother?

- Equal ULDM mass

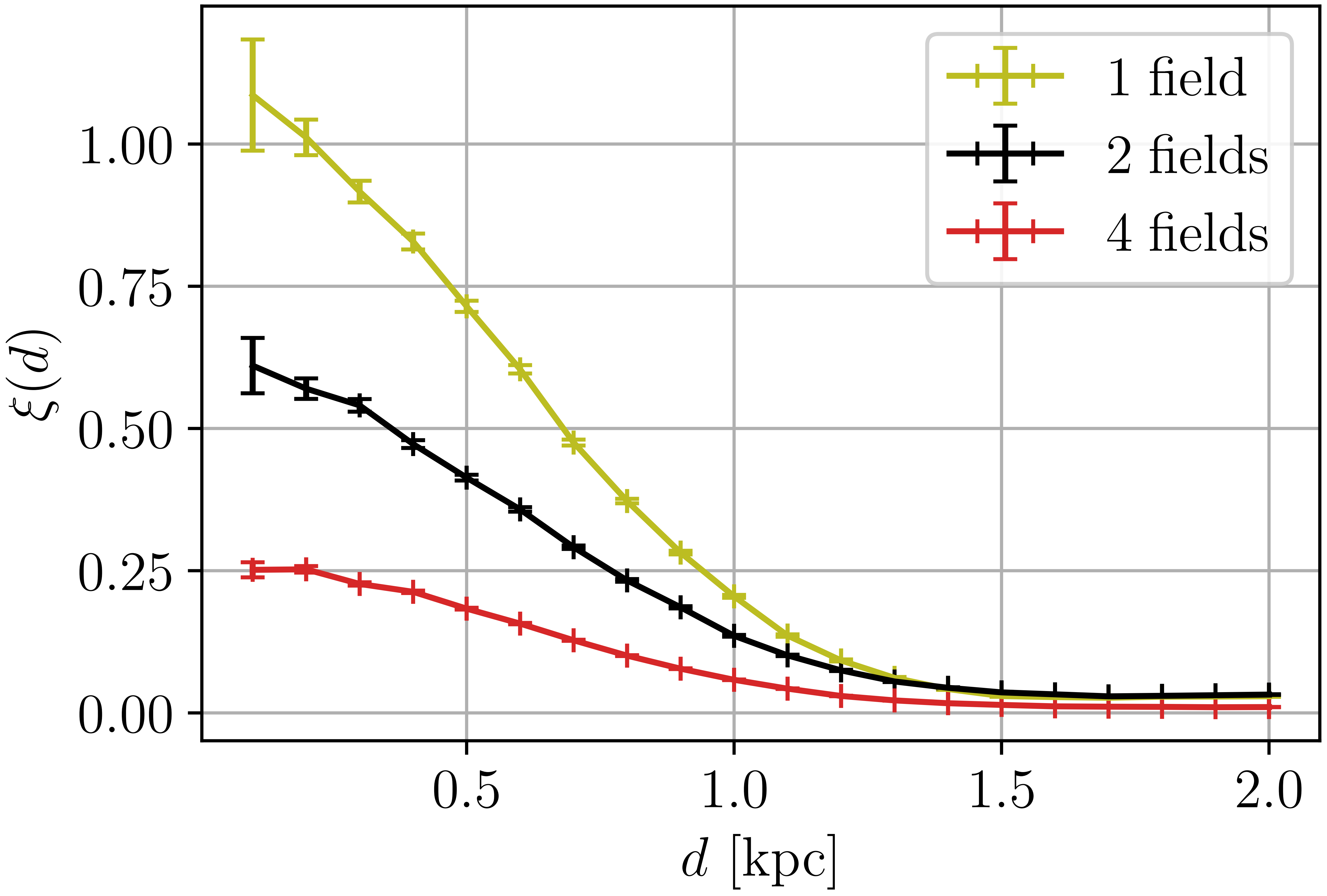
Density with more fields looks more smooth, but is it?

Overdensity: $$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}(x)}{\bar{\rho}(x)}$$

2-pt correlation function:

$$\xi(d) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{d}) \rangle = \frac{1}{V}\int \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{d})\mathrm{d}^3\mathbf{x}$$

$$\xi \sim \frac{1}{N} \longrightarrow \delta(\mathbf{x}) \sim \frac{1}{\sqrt{N}}$$



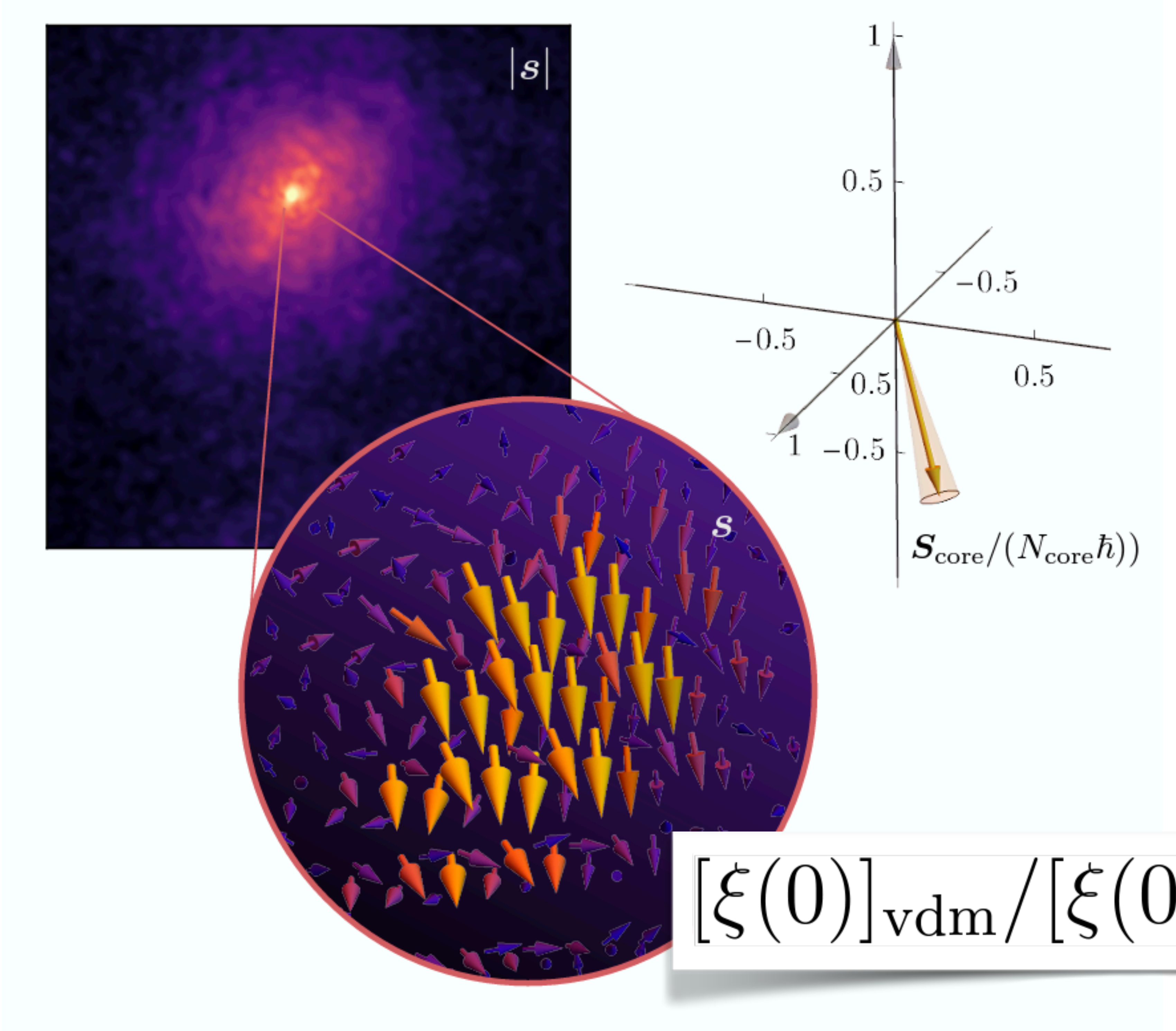
MG, Eberhardt, Wang, Eggemeier, Kendall, Zagorac, Easther
***PRD*, 2023**

Multifield halos: how much smoother?

- Equal ULDM mass

This is in agreement with VECTOR DARK MATTER

Density with more fields looks more smooth, but is it?



Overdensity: $\delta(\mathbf{x}) = \dfrac{\rho(\mathbf{x}) - \bar{\rho}(x)}{\bar{\rho}(x)}$

$[\xi(0)]_{\rm vdm}/[\xi(0)]_{\rm sdm} \sim 1/3$

2-pt correlation function:

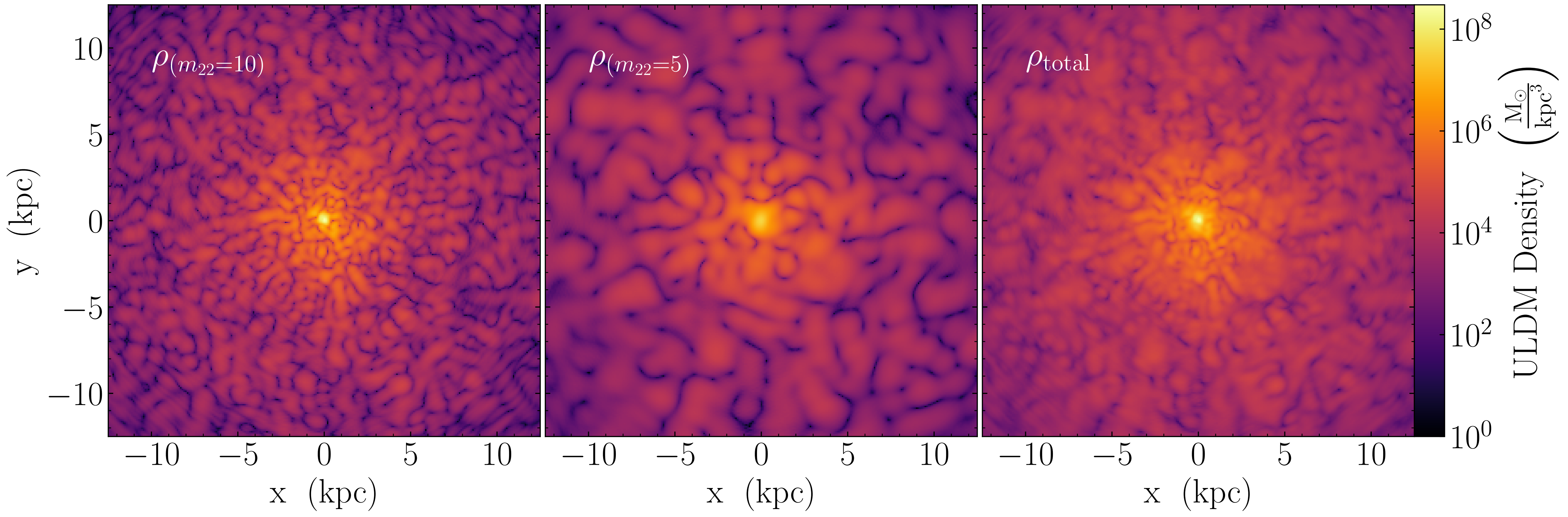
$$\xi(d) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{d})\rangle = \frac{1}{V}\int \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{d})\mathrm{d}^3\mathbf{x}$$

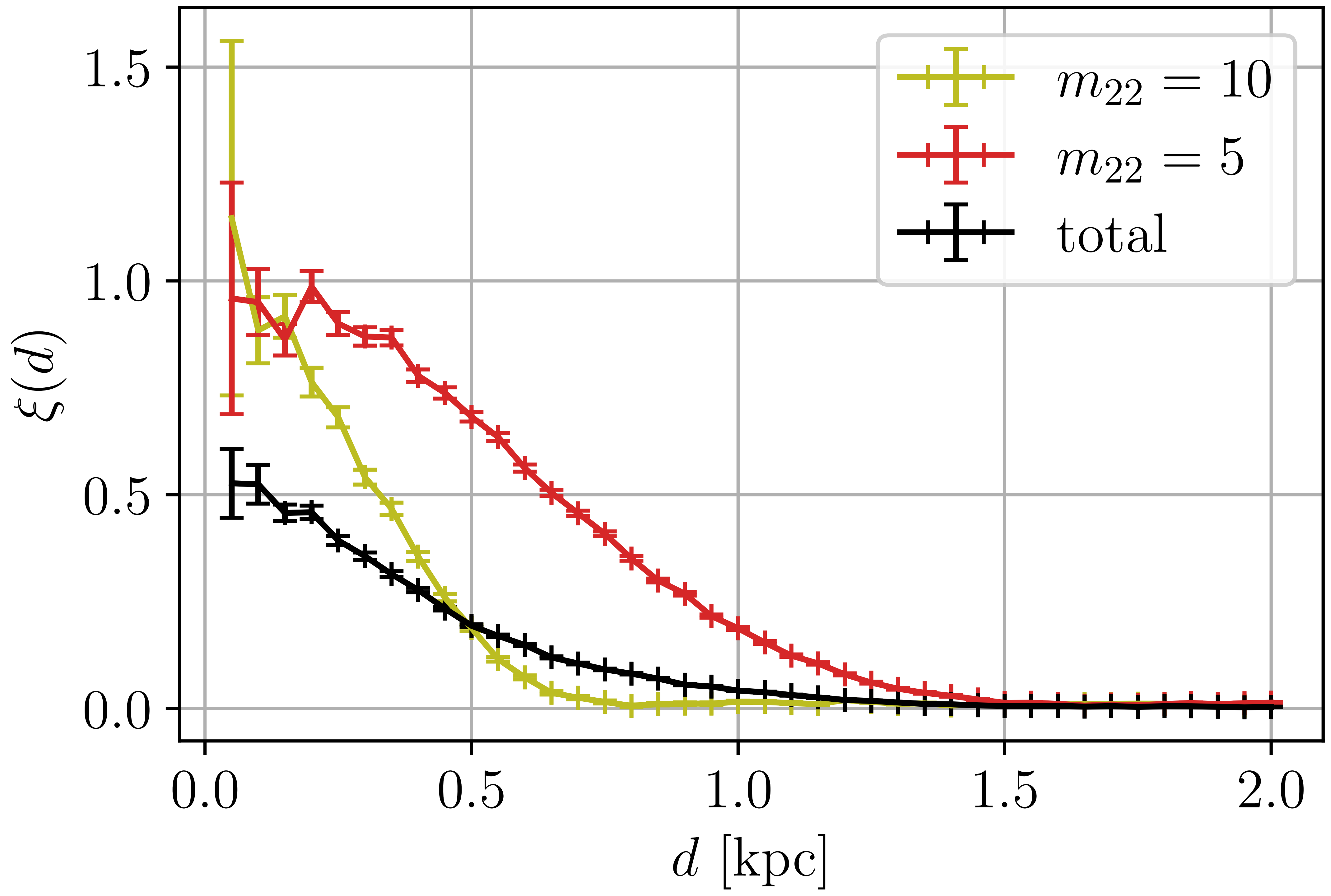
Amin et al., JCAP 2022

$$\xi \sim \frac{1}{N} \longrightarrow \delta(\mathbf{x}) \sim \frac{1}{\sqrt{N}}$$

Multifield halos: how much smoother?

- Different ULDM masses





$$\xi \sim \frac{1}{N} \longrightarrow \delta(\mathbf{x}) \sim \frac{1}{\sqrt{N}}$$

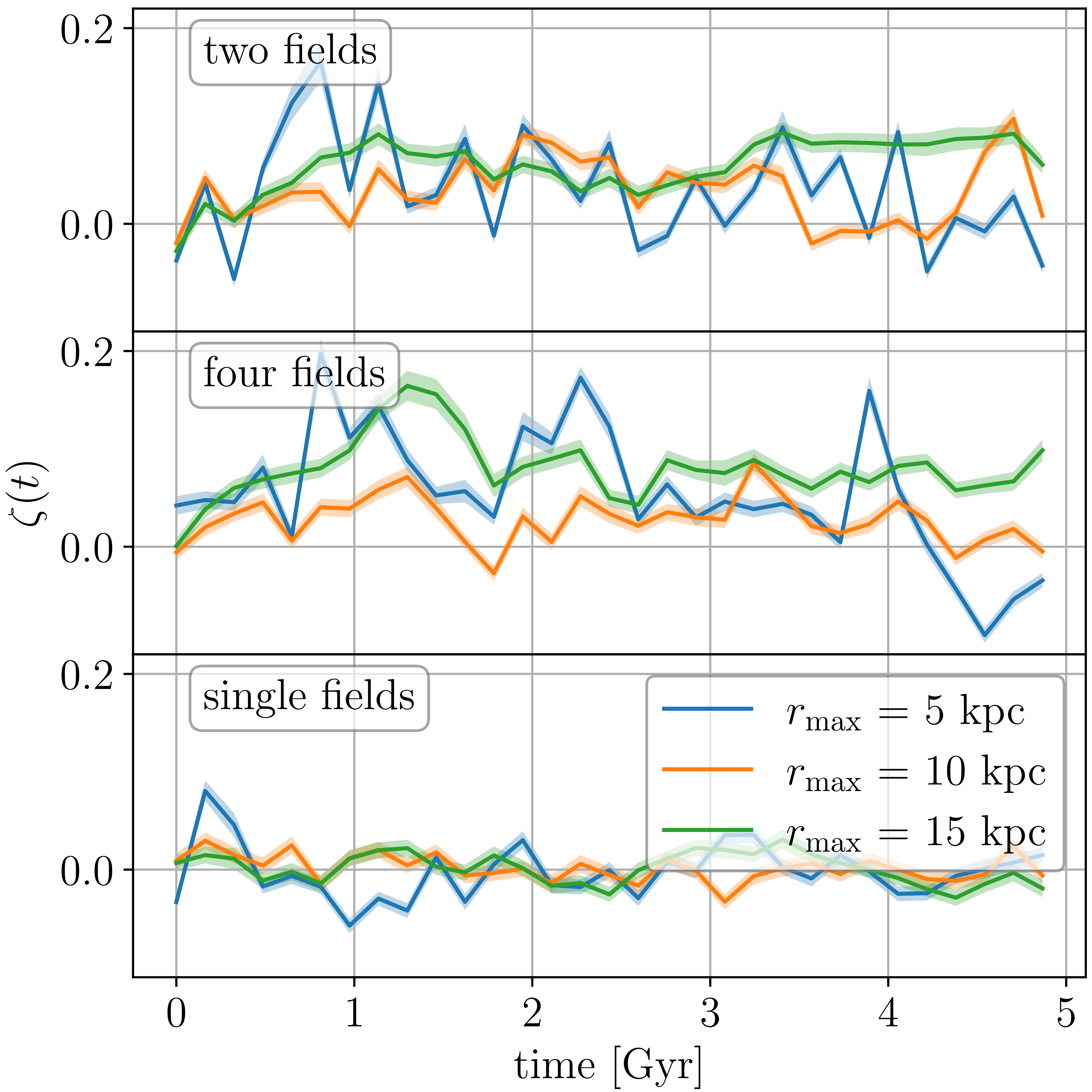
MG, Eberhardt, Wang, Eggemeier, Kendall, Zagorac, Easther
***PRD*, 2023**

Multifield halos: do they stay smoother?

Overdensity: $\delta(\mathbf{x}) = \dfrac{\rho(\mathbf{x}) - \bar{\rho}(x)}{\bar{\rho}(x)}$

1-point covariance: $\zeta = \dfrac{\langle \delta_1(\mathbf{x})\delta_2(\mathbf{x})\rangle}{\sqrt{\langle \delta_1(\mathbf{x})^2\rangle}\sqrt{\langle \delta_2(\mathbf{x})^2\rangle}}$

= { 1 if two fields maximally correlated
0 if there is no correlation
-1 if two fields perfectly anti-correlated



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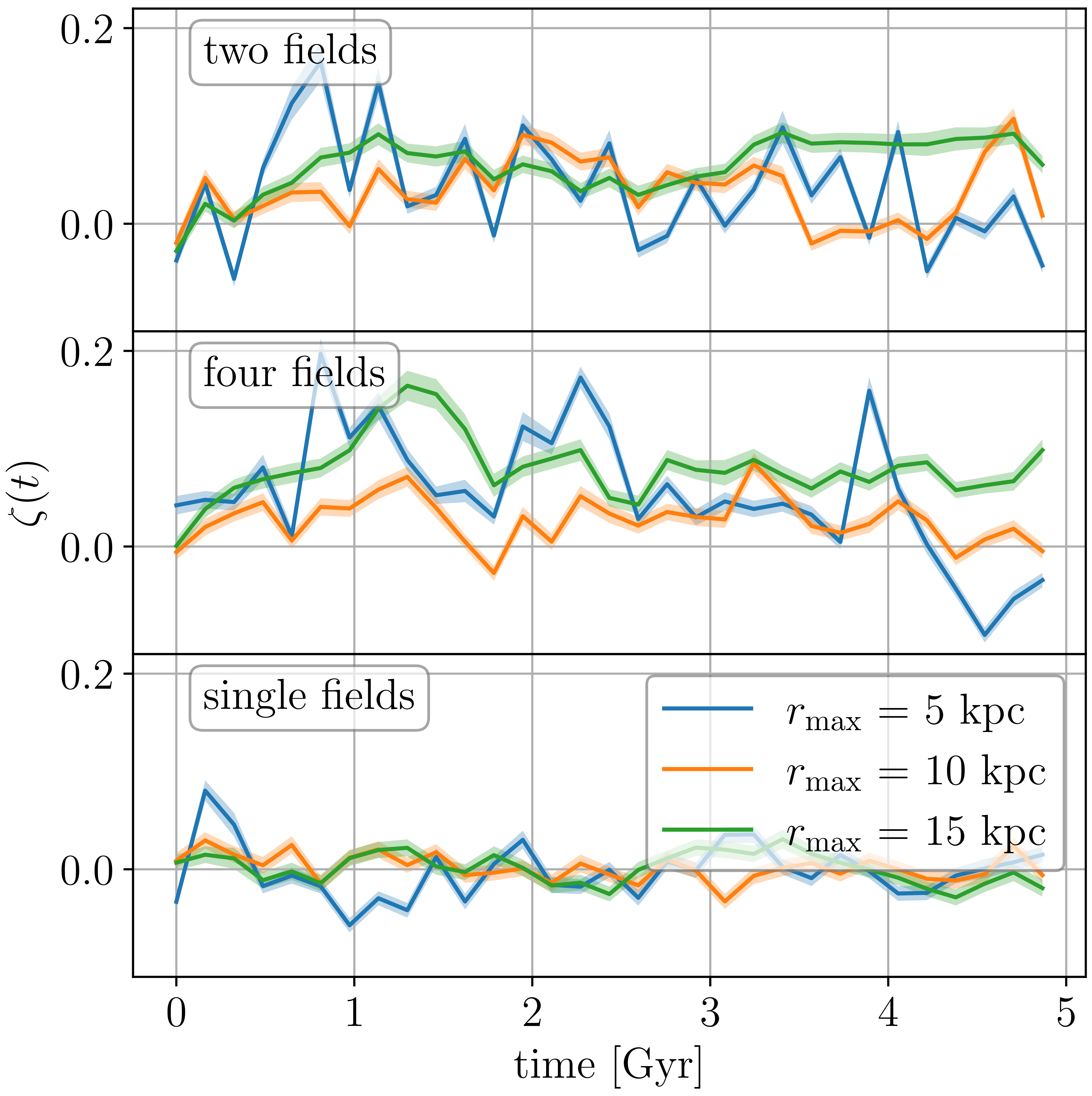
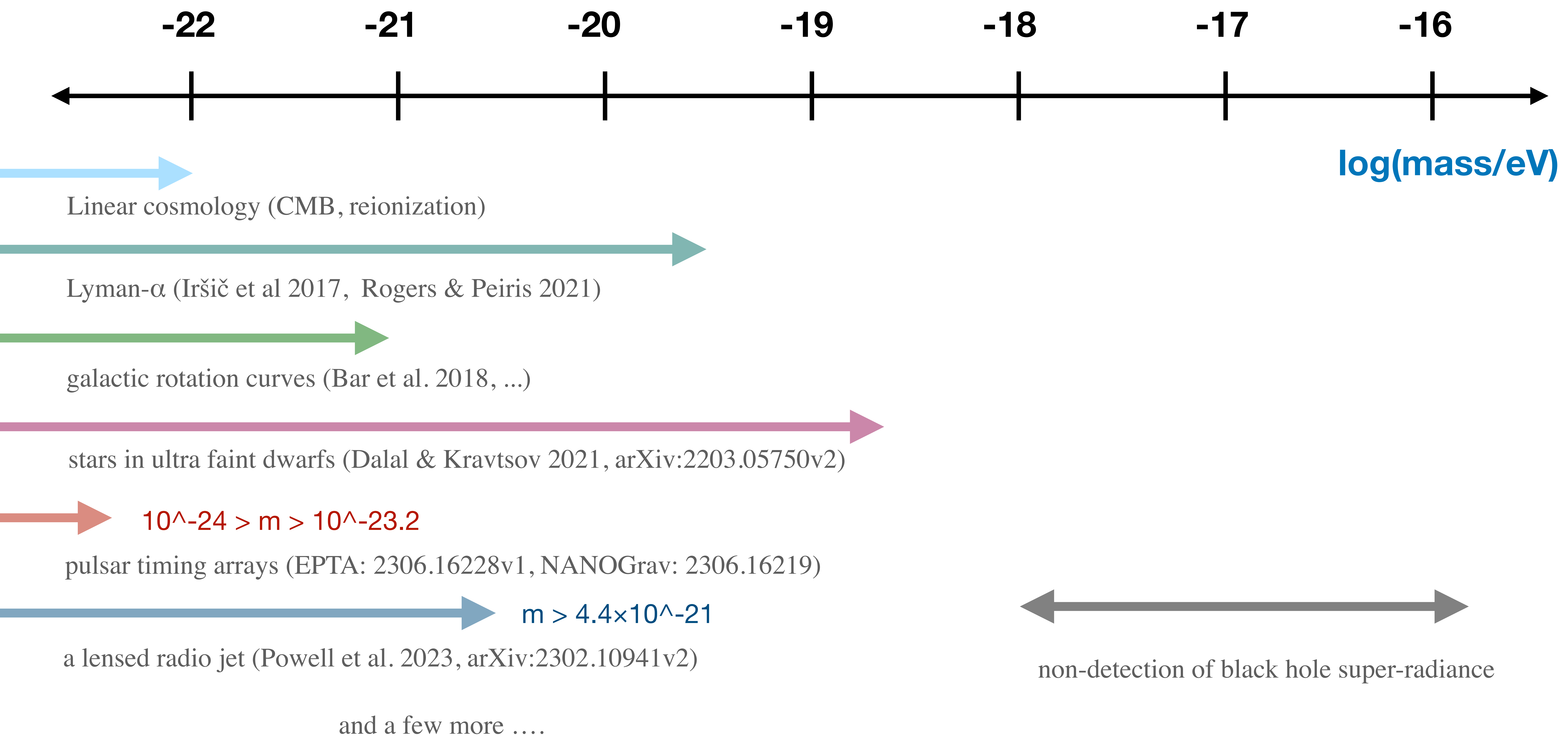
$$= \begin{cases} 1 \text{ if two fields maximally correlated} \\ 0 \text{ if there is no correlation} \\ -1 \text{ if two fields perfectly anti-correlated} \end{cases}$$

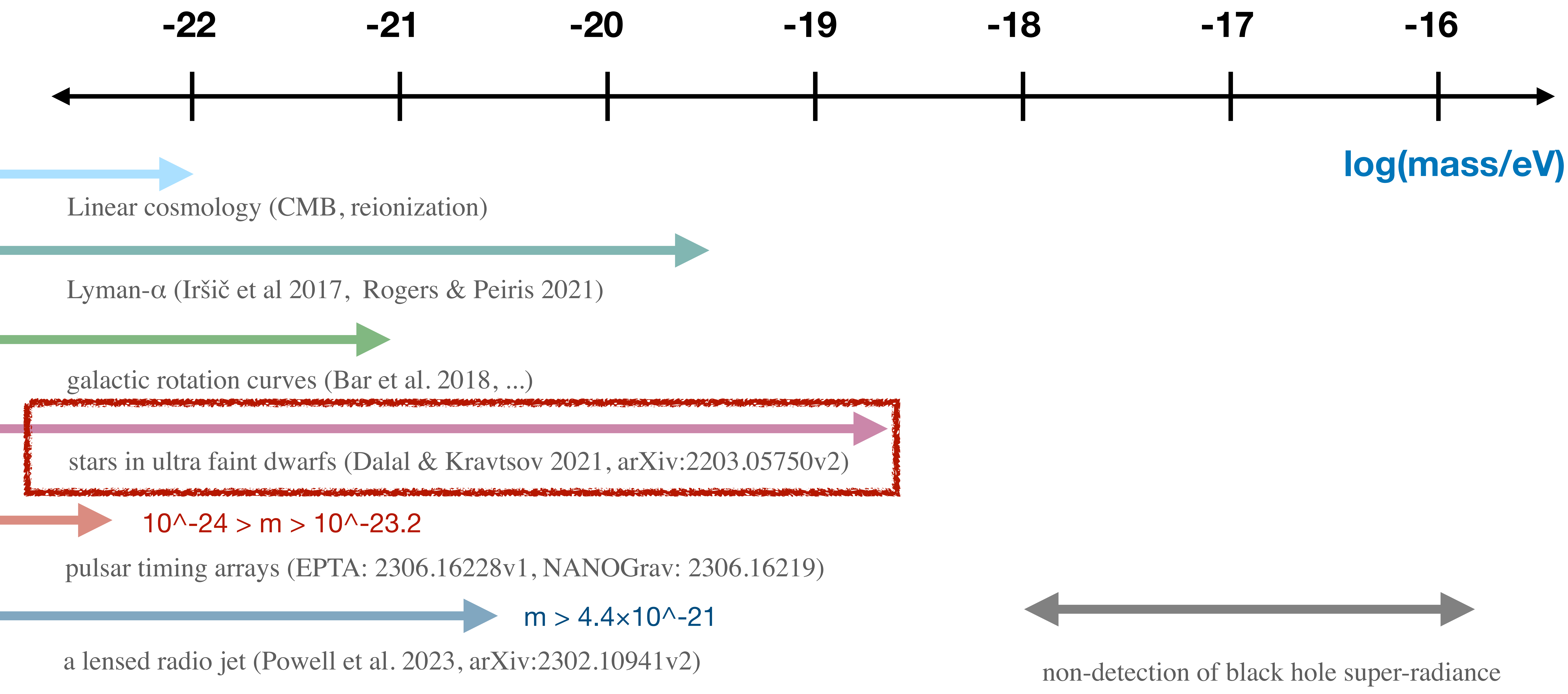
- very small amount of correlation develops
- correlation remains ≲ 0.1 meaning that smoothness persists over time



Observational constraints on ULDM

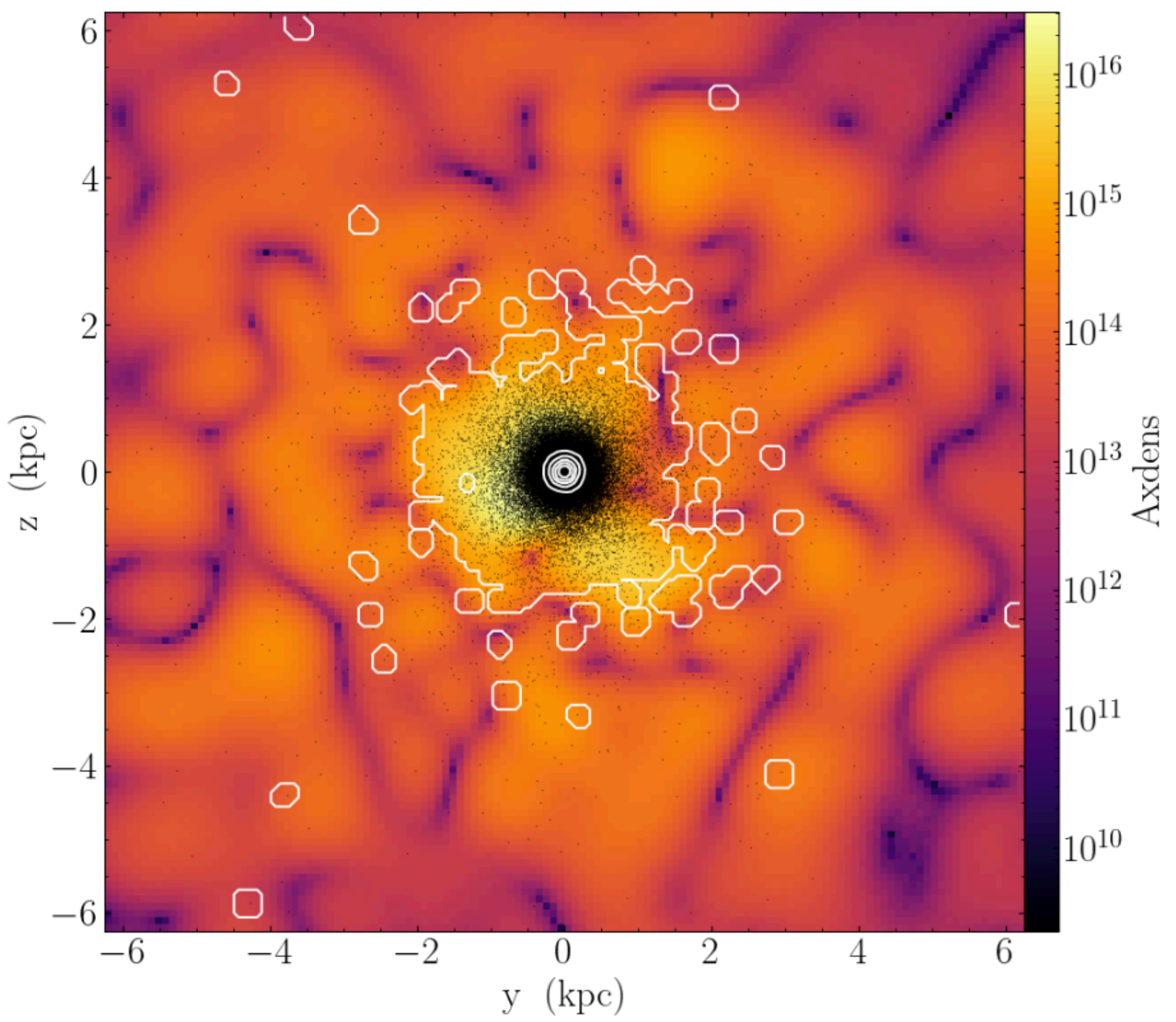


Observational constraints on ULDM



and a few more ….

Stellar heating constraints



$$\delta v = \frac{2G\,\delta M}{\lambda\,\sigma_{\rm DM}}$$

mass of a granule

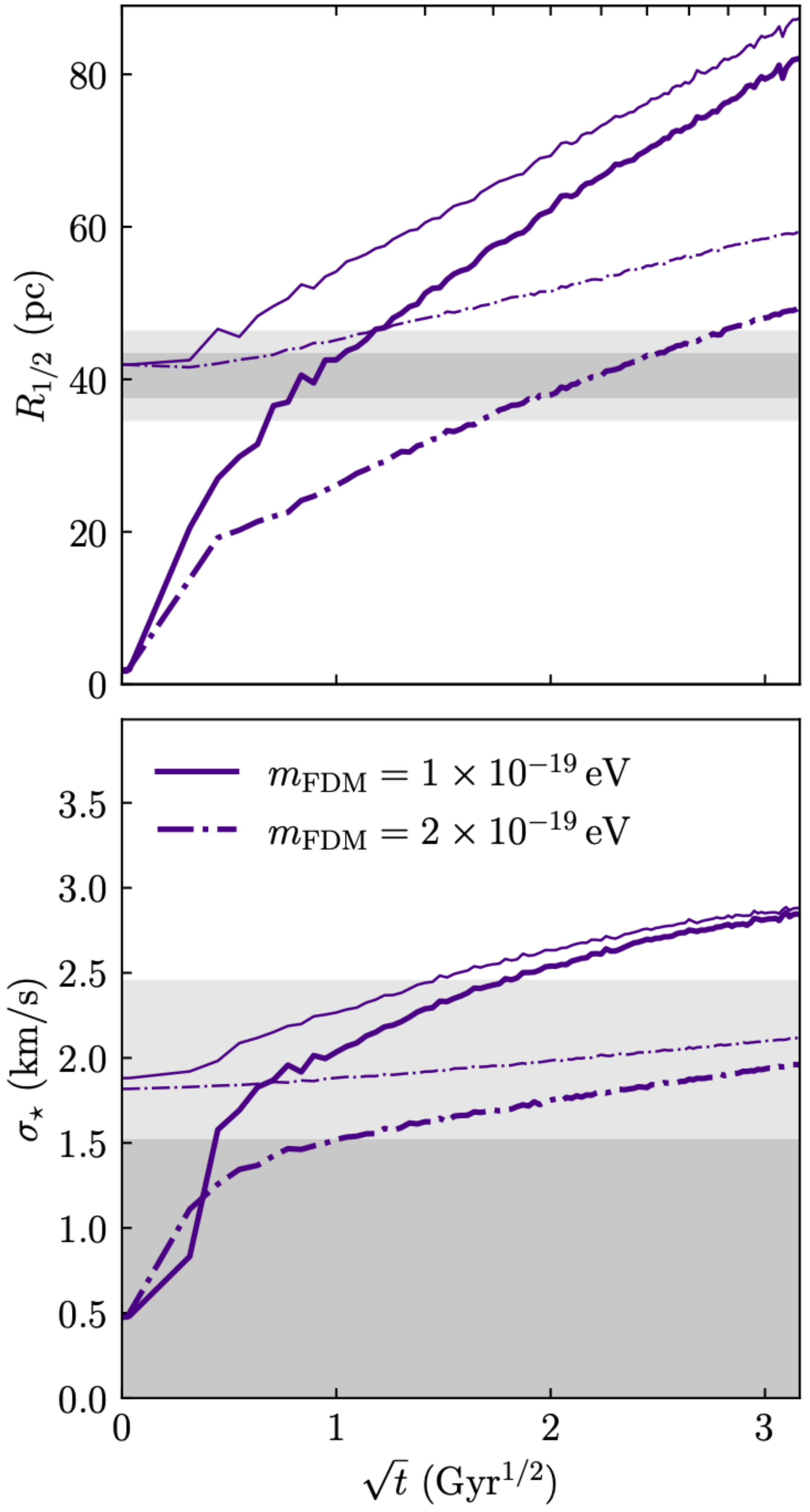
$$\Delta\sigma^2_{\rm granules} \sim n(\delta v)^2$$

Velocity dispersion of stars due to the encounters with n granules

A model with mass m must satisfy:

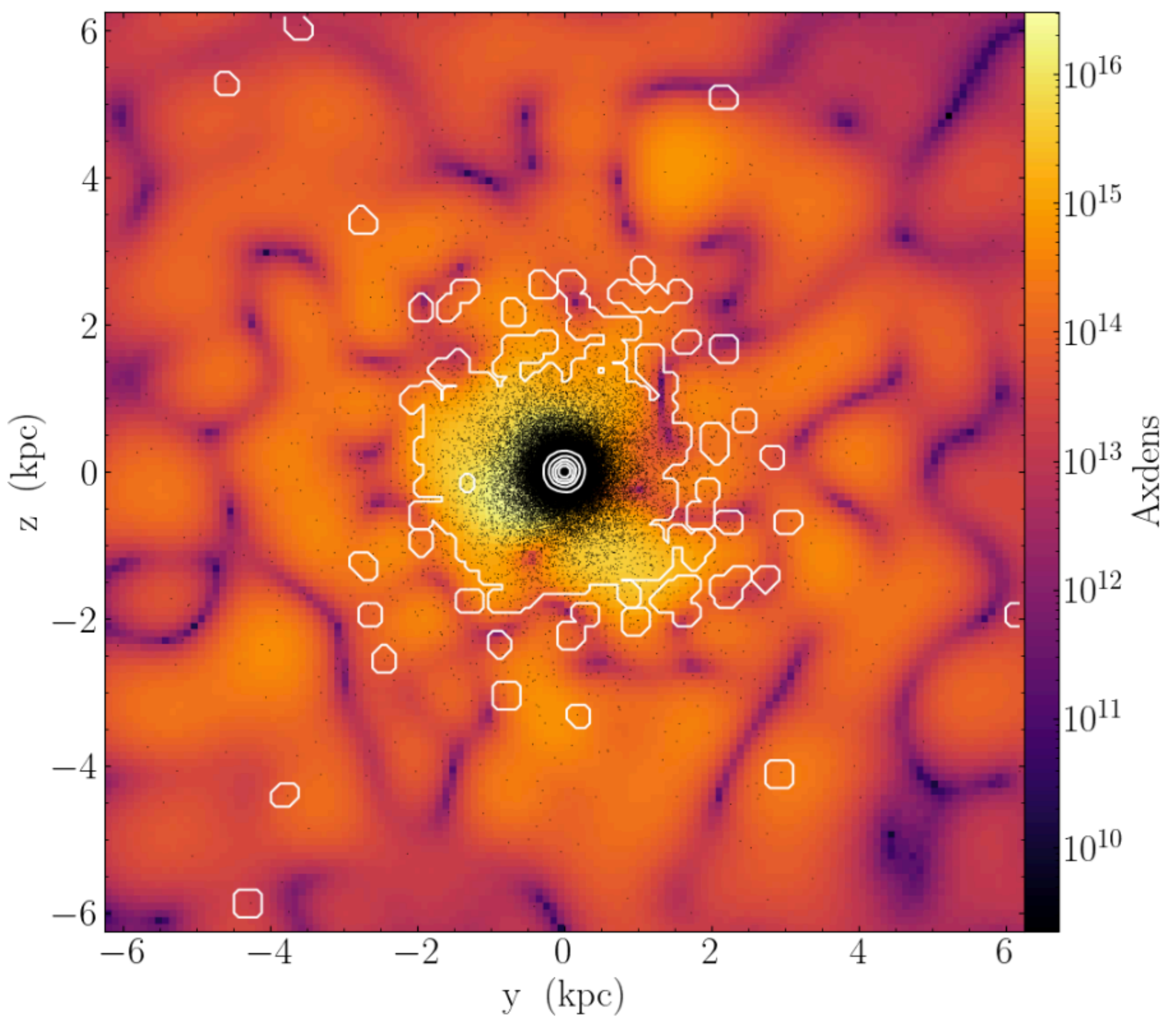
$$\Delta\sigma^2_{\rm obs} > \Delta\sigma^2_{\rm granules}$$

$$\Delta\sigma^2_{\rm obs} \geq n(\delta v)^2 \sim \frac{1}{m^3}$$



Dalal & Kravtsov 2021

Stellar heating constraints



$$\delta v = \frac{2G\,\delta M}{\lambda\,\sigma_{\rm DM}}$$ ← mass of a granule

$$\Delta\sigma^2_{\rm granules} \sim n(\delta v)^2$$

↑ Velocity dispersion of stars due to the encounters with n granules

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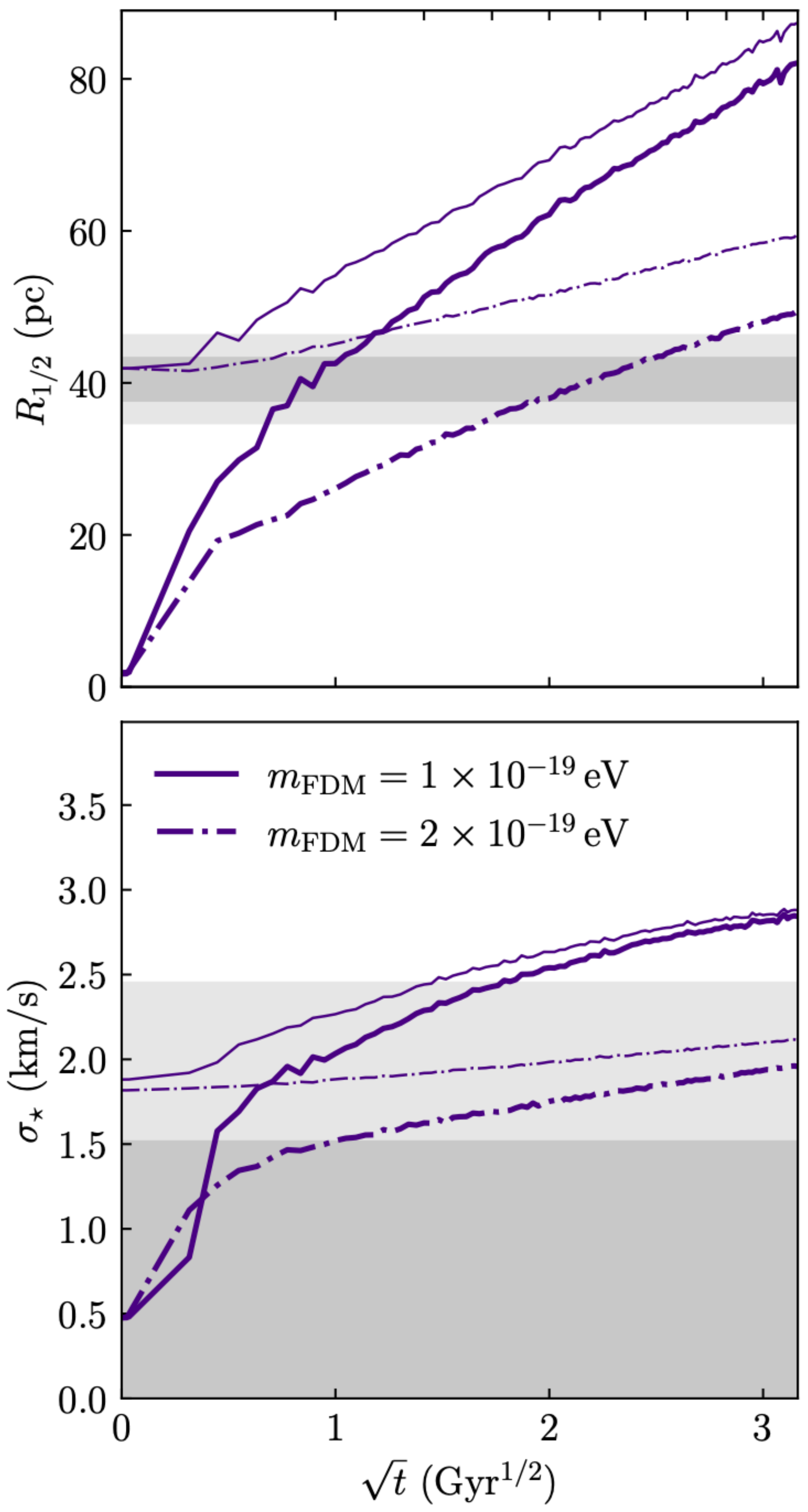


Dalal & Kravtsov 2021

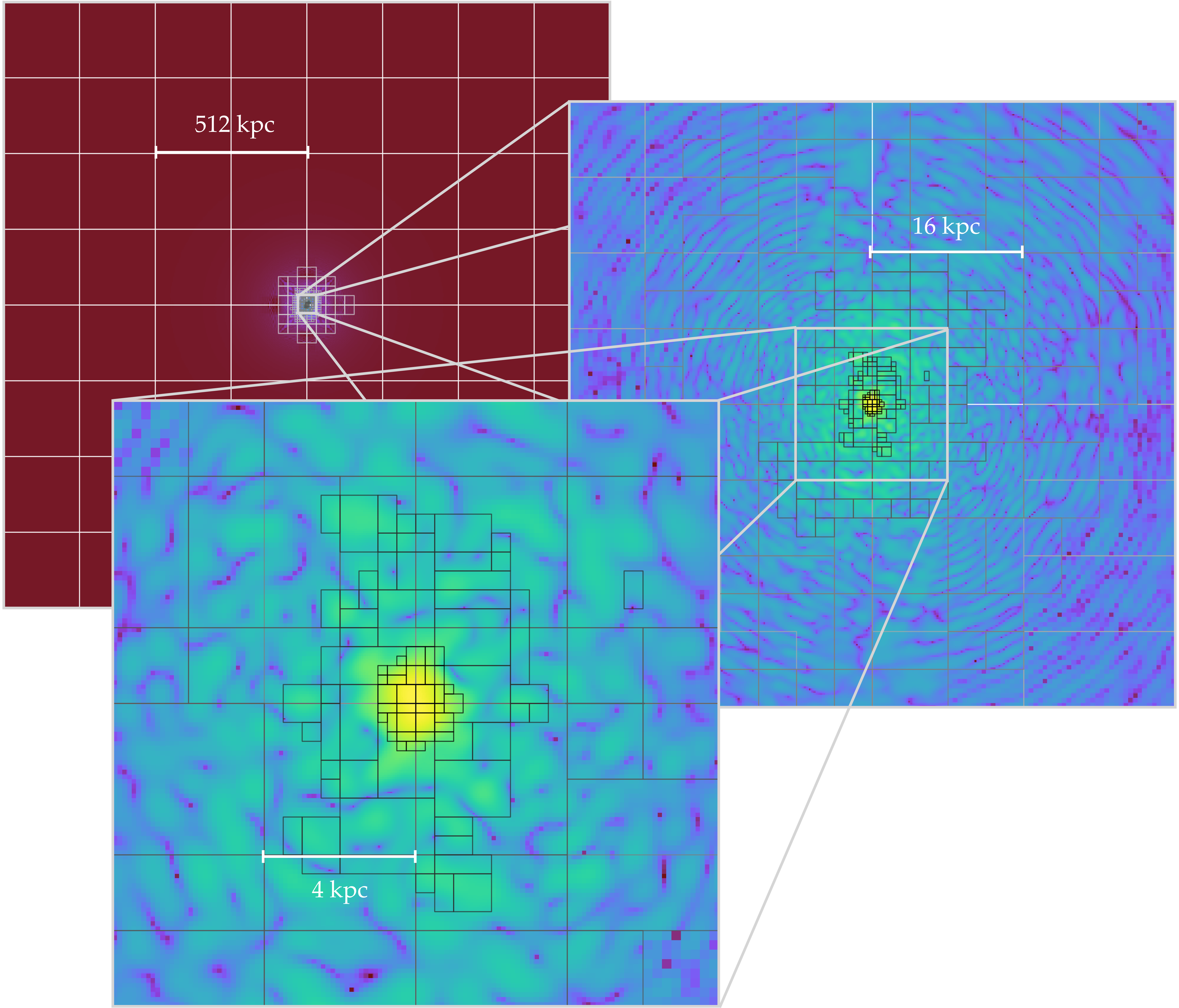
Multifield case:

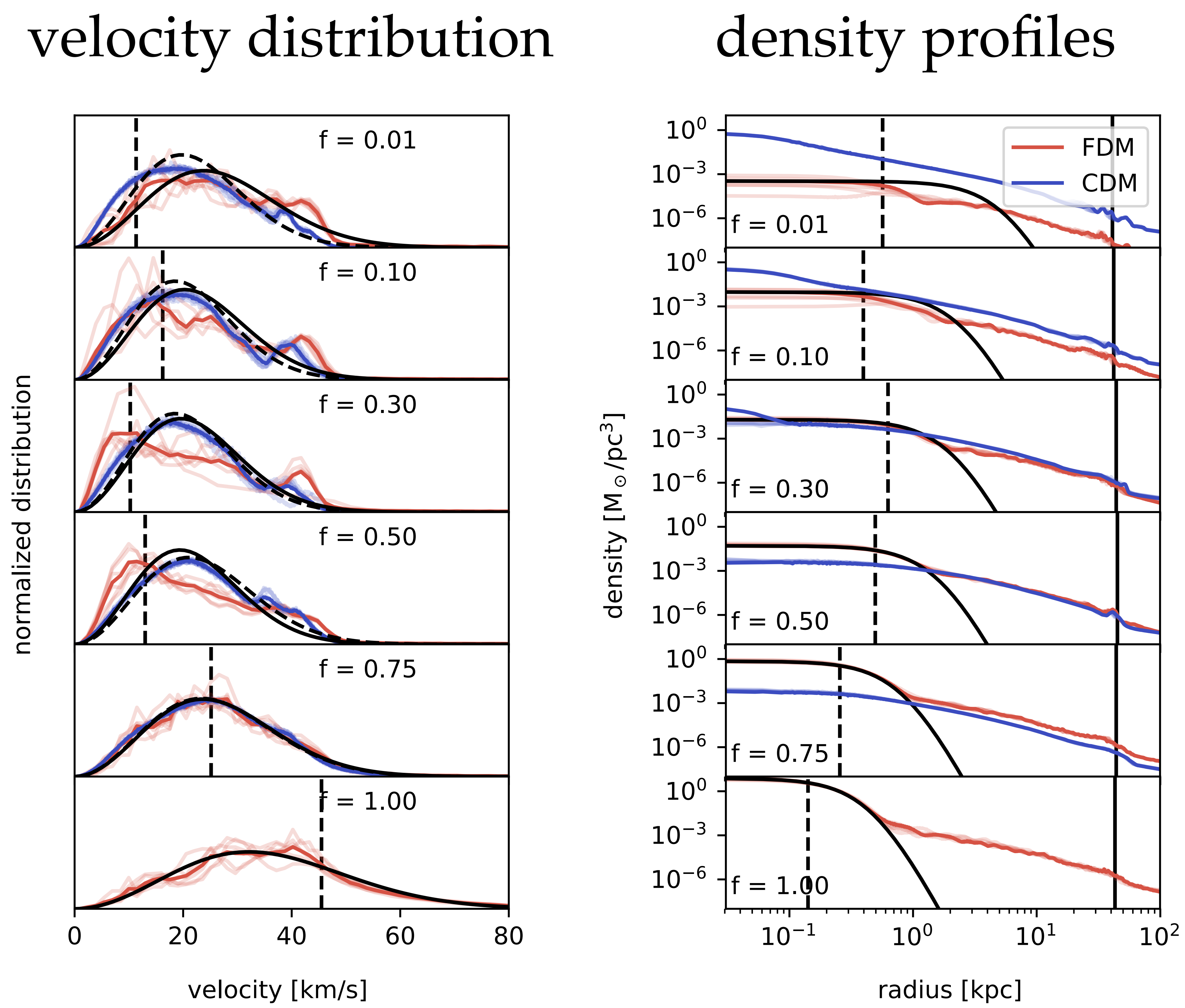
$$n \to nN \qquad \delta M \to \delta M/N \qquad \Delta\sigma^2_{\rm obs} \geq n(\delta v)^2 \sim \frac{1}{N\,m^3}$$

If one field is much lighter then the others:

$$m_{\rm L} \ll m_i \qquad \Delta\sigma^2_{\rm obs} \geq n(\delta v)^2 \sim \frac{1}{N^2\,m_{\rm L}^3}$$

Mixed cold and ultralight dark matter





- on smaller scales, around de Broglie wavelength, wave effect are present if FDM constitutes at least ~10% of total dark matter

Schwabe, MG, Behrens, Niemeyer, Easther, arXiv:2007.08256v1, 2020

Conclusions

- ULDM represents a compelling DM explanation
- Constraints are closing the gap of the allowed mass of the particle
- Simulations of multifield scenario show consistent smoothing of the total density
- Although small correlations between fields may develop, the timescale on which they grow is large compared to the age of the universe
- Multifield scenario therefore has the potential to alleviate observational constraints, in particular the ones based on the granular structure of the inner parts of the halo