Simulations of mixed dark matter

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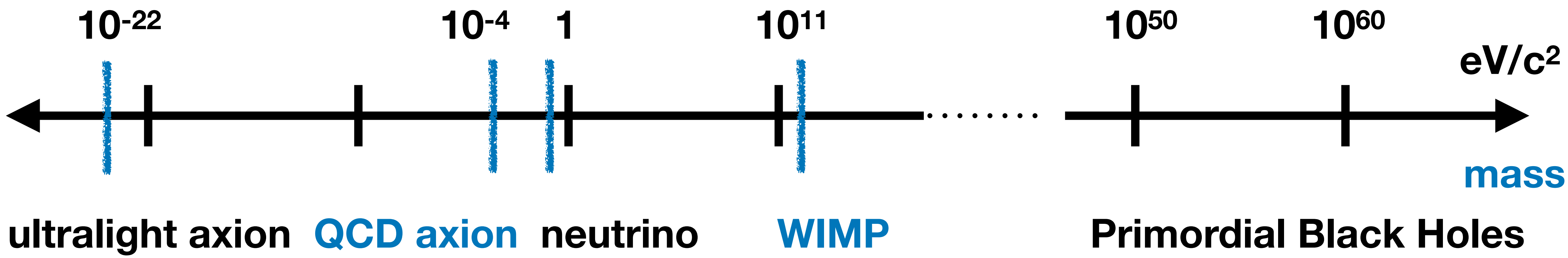
Collaborators: Bodo Schwabe, Christoph Behrens, Jens Niemeyer, Richard Easther, Julian Adamek, Christian Byrnes, Shaun Hotchkiss

The search for the dark matter particle



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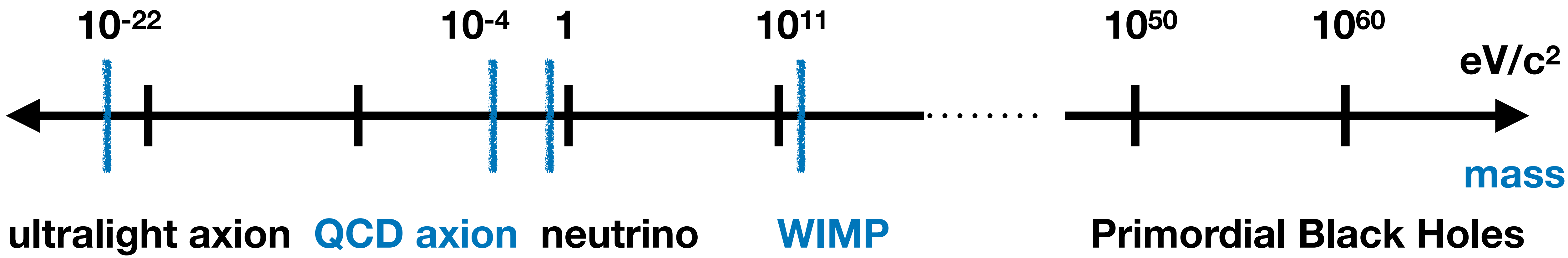
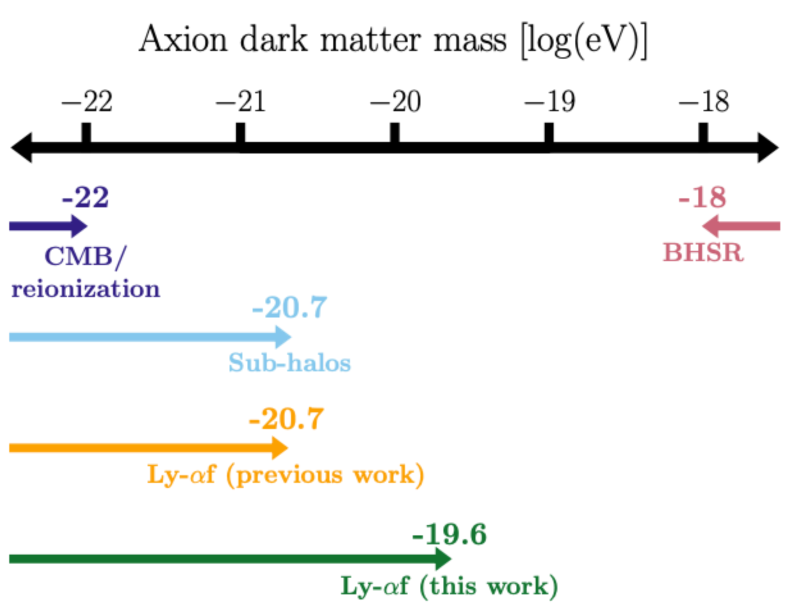
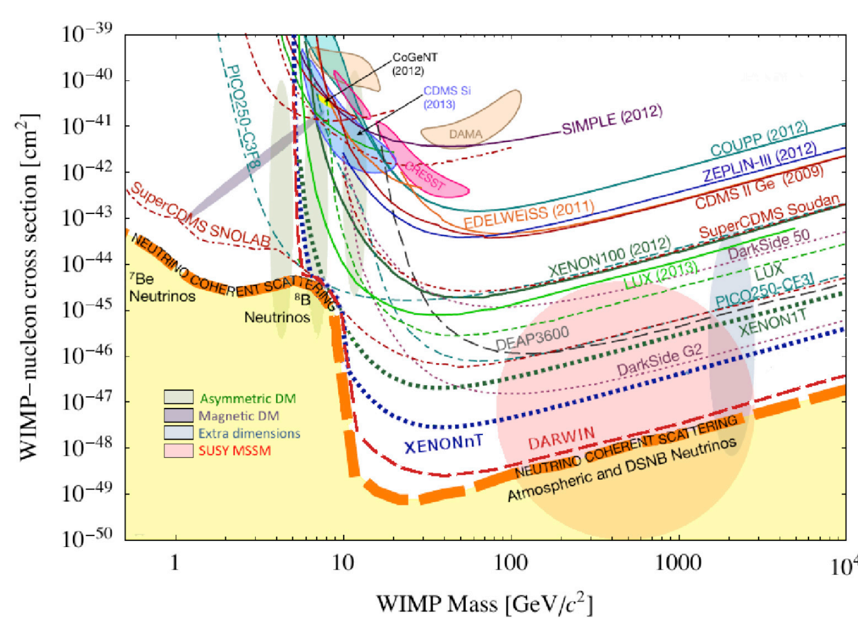


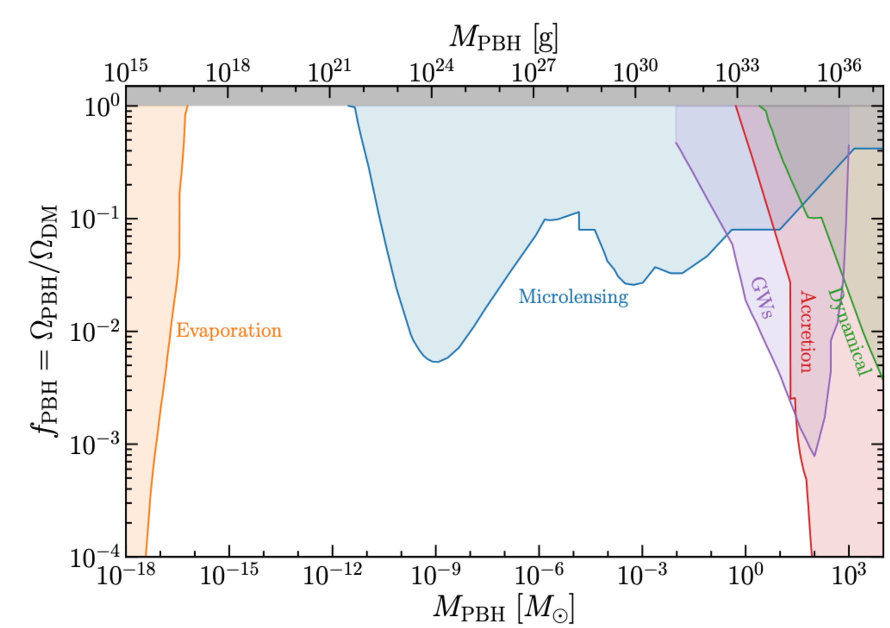
… so far only gave constraints:



Rogers, Peiris, 2020



Cushman et al., 2013



Green, Kavanagh, 2020

In this talk I will present two ideas:

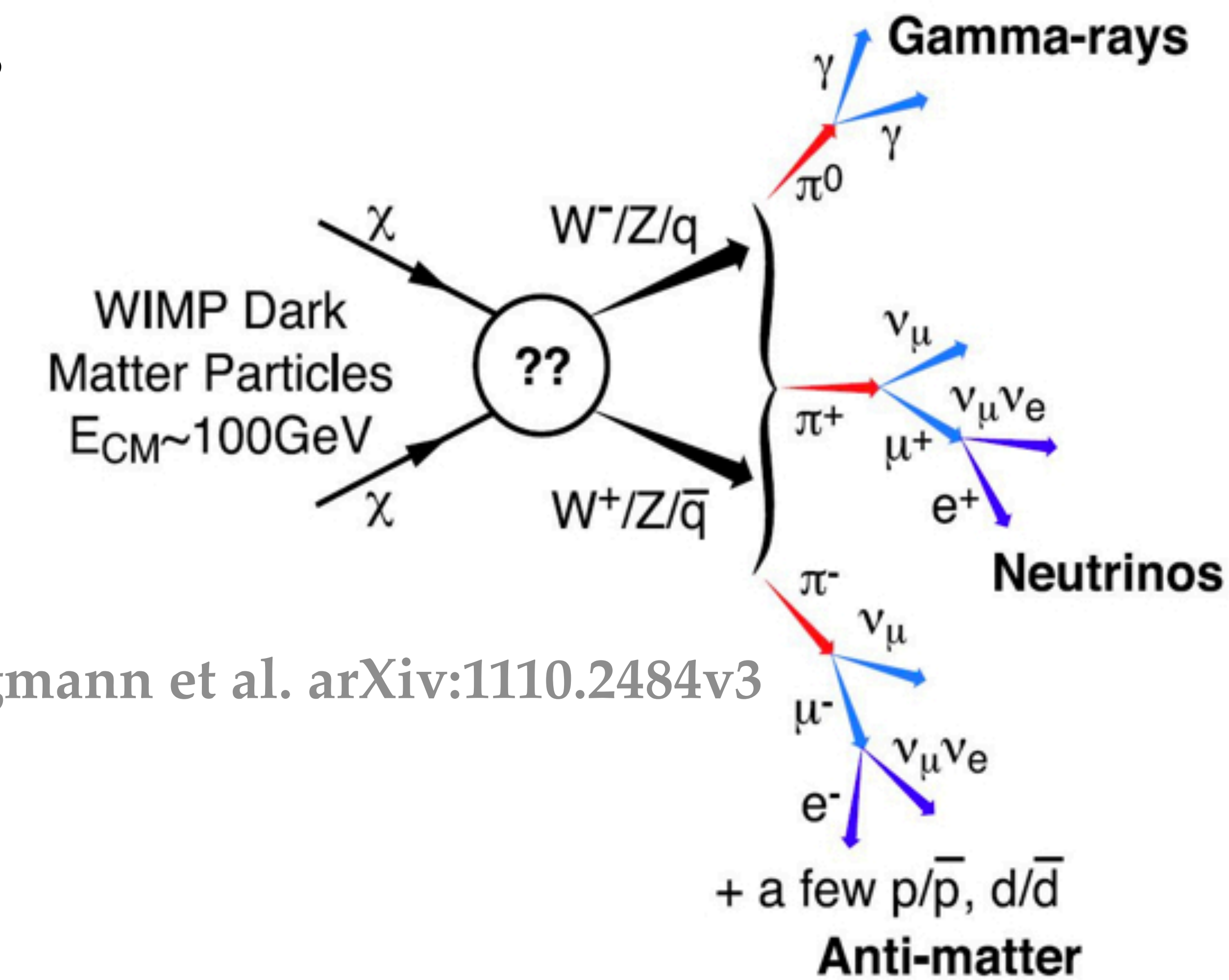
- Primordial Black Holes + Cold Dark Matter (WIMPs)
- Fuzzy Dark Matter + Cold Dark Matter

Motivations for mixed dark matter models:

- the “bright” sector has many different particles - why expect that the “dark” sector would only have one?
- axions likely created at many different masses simultaneously: FDM composed of a continuous mass spectrum of particles
- single-mass particle scenarios strongly constrained

Primordial black holes

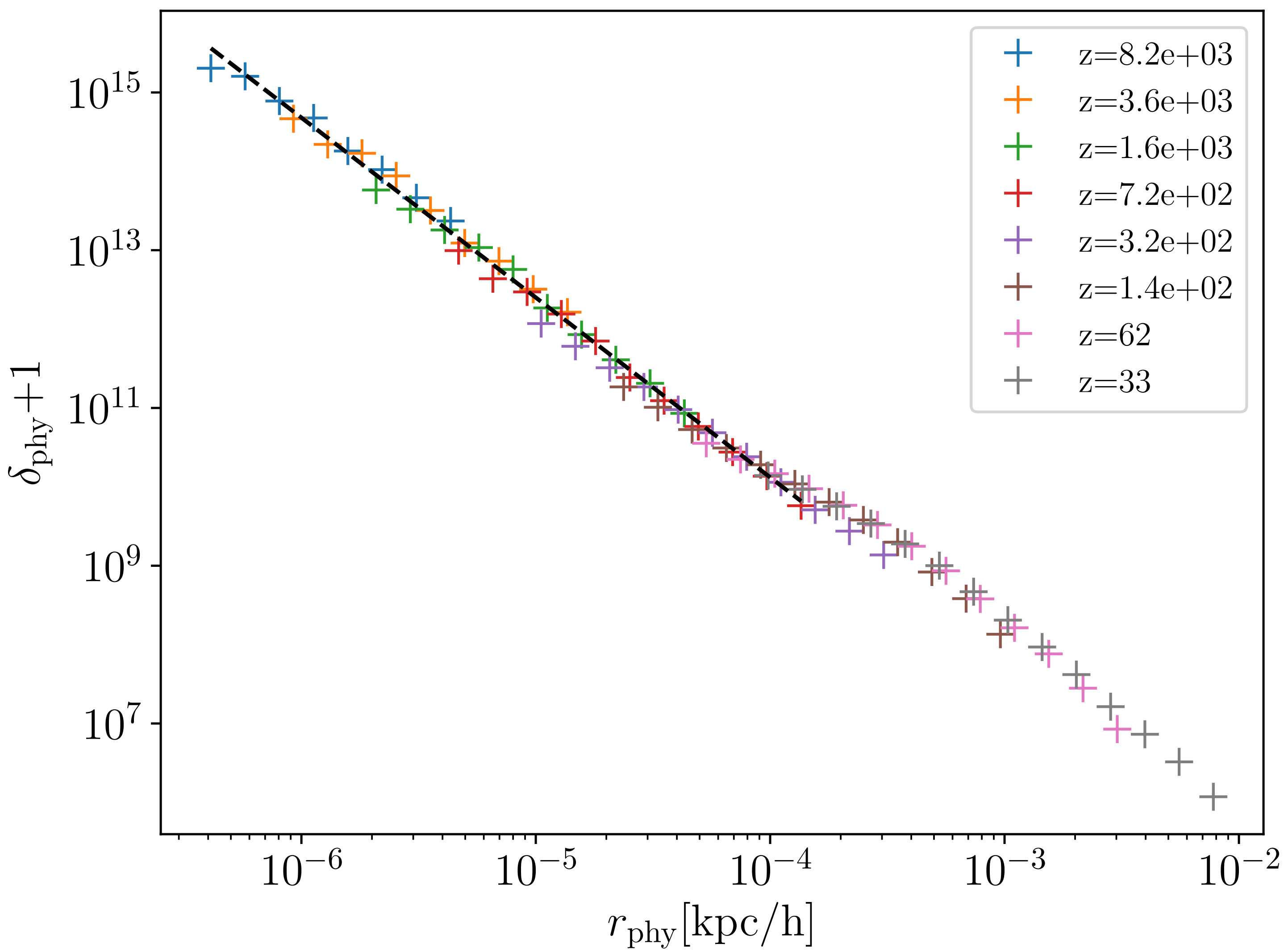
- form in the early Universe by gravitational collapse if $\delta \sim 1$
- strong constraints exist on the fraction of dark matter in PBHs
- if PBHs are only a fraction of DM, the rest has to be something else, e.g. WIMPs
- WIMPs form halos around PBHs
- WIMPs annihilate and produce gamma rays
- non-detection of gamma ray background translates to constraints on PBH



Bringmann et al. arXiv:1110.2484v3

WIMP halos arounds primordial black holes

- consider a hybrid model: PBHs with ~ solar mass constitute small proportion of dark matter, the rest is WIMPs.
- simulations show steep power-law density profiles in the centre



$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

- Using Fermi gamma-ray background to constrain:

$$f_{\rm PBH} = \frac{\Gamma_{\rm DM} M_{\rm PBH}}{\Gamma_{\rm PBH}\, m_\chi}$$

$$\Gamma_{\rm PBH} \sim \int_0^\infty \rho(r)^2 r^2 dr$$

Adamek, Byrnes, MG, Hotchkiss, *PRD*, 2019

m_χ	10 GeV	100 GeV	1 TeV
$f_{\rm PBH} \lesssim$	10^{-9}	2×10^{-9}	4×10^{-9}

Fuzzy dark matter

- cold scalar field: $$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + m\Phi\psi$$

Schrödinger-Poisson

- coupled to gravity: $$\nabla^2\Phi = \frac{4\pi G}{a}(\rho - \bar{\rho}) \qquad \rho = m\psi\psi^*$$

- axion particles are predicted in string theory

- ultralight axion: $10^{-22}\mathrm{eV} \lesssim m_a \lesssim 10^{-18}\mathrm{eV}$

  may help alleviate small-scale problems in astronomy

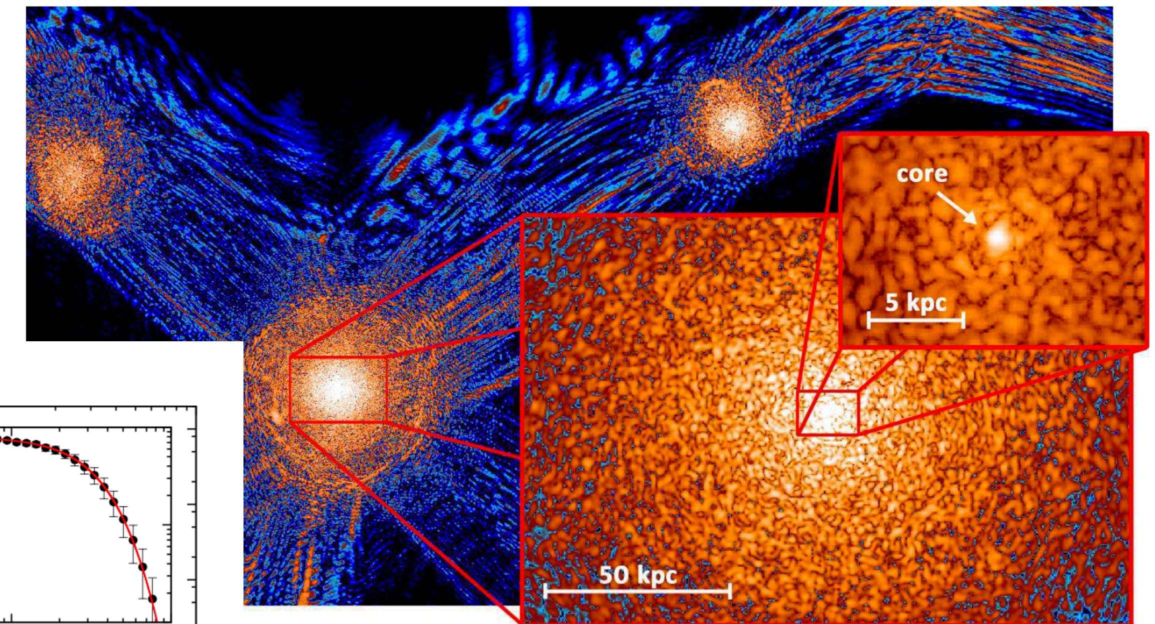
- de Broglie wavelength: $$\lambda_{\mathrm{dB}} = \frac{h}{m_a v}$$

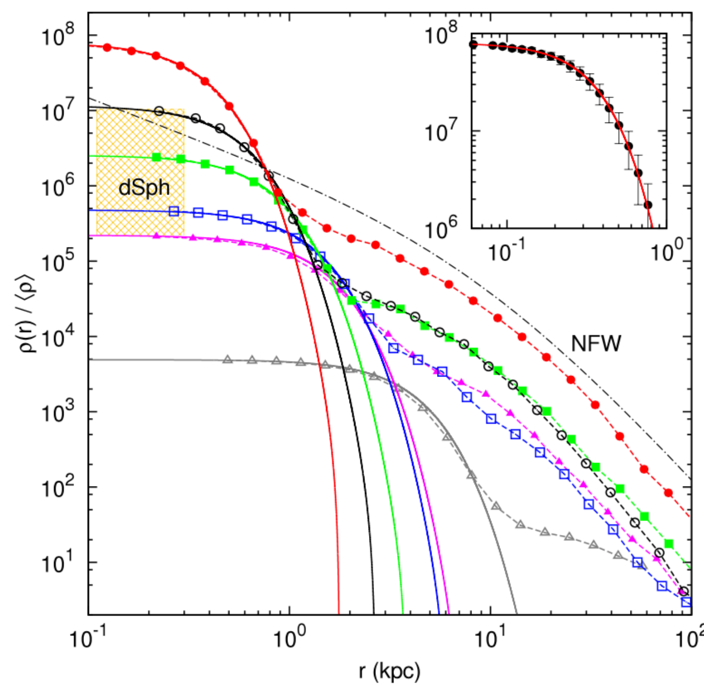
Simulations of fuzzy dark matter

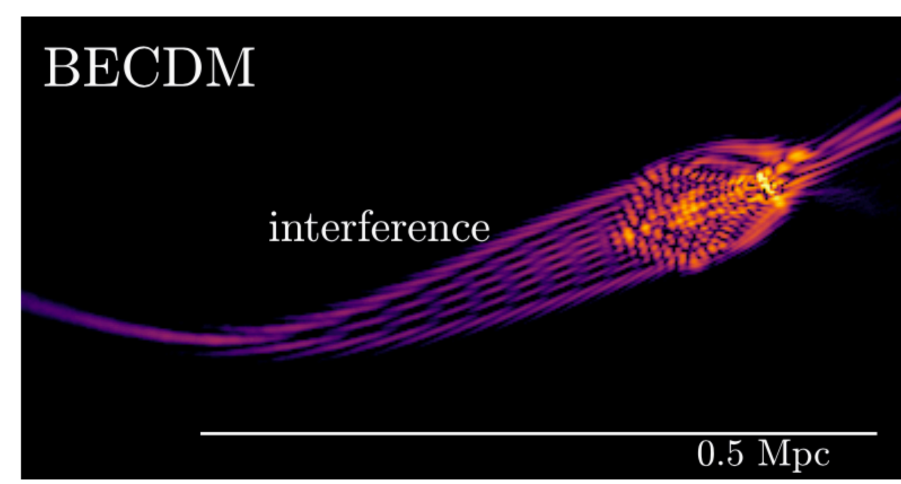
Schive, Chiueh, Broadhurst, *Nature Physics*, 2014

- on large scales, FDM behaves like CDM
- solitonic cores in halos centres
- interference patterns around solitons and in filaments
- FDM predicts less structure on small scales (fewer subhalos)

$$\lambda_{\mathrm{dB}} = \frac{h}{m_a v}$$

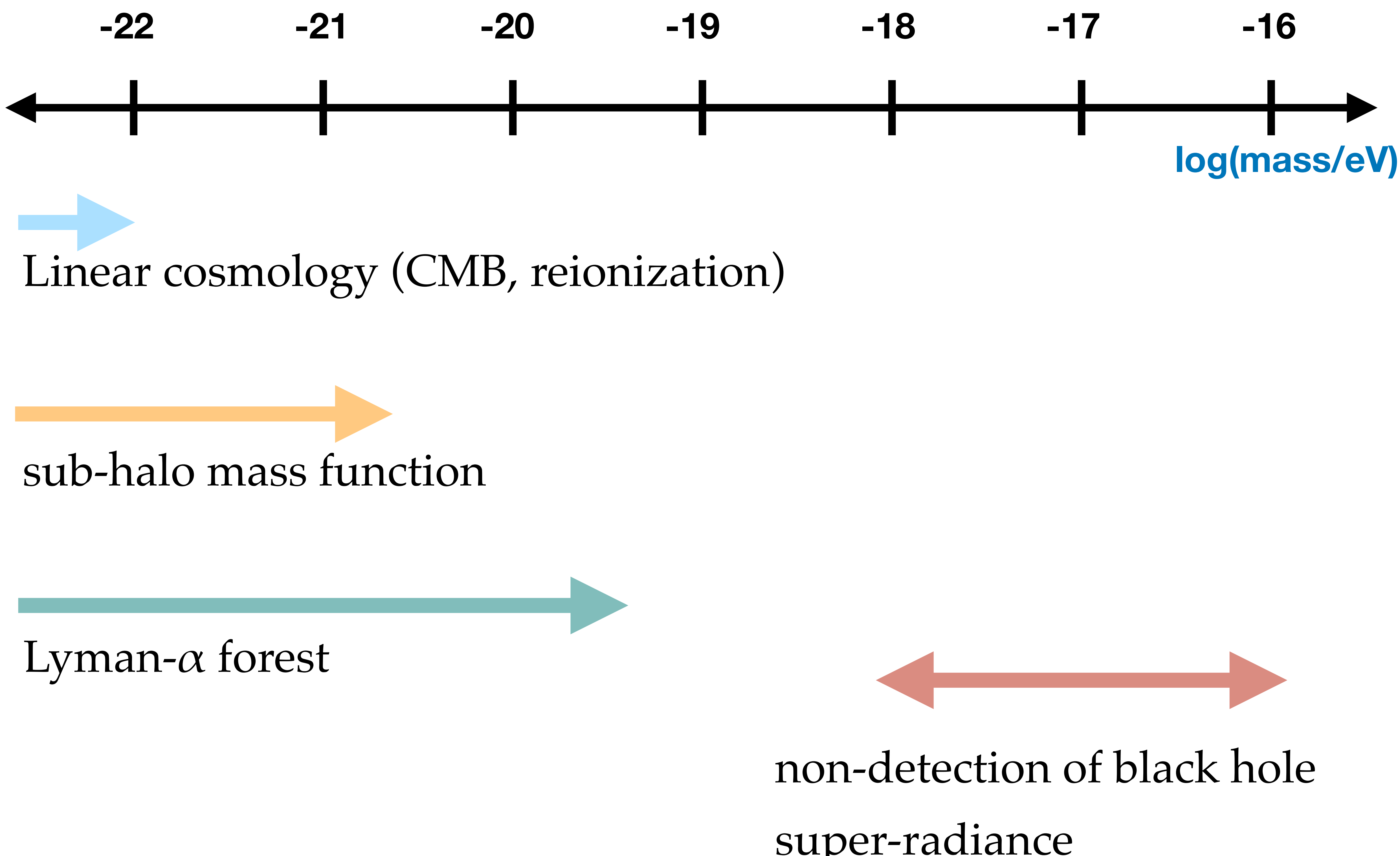






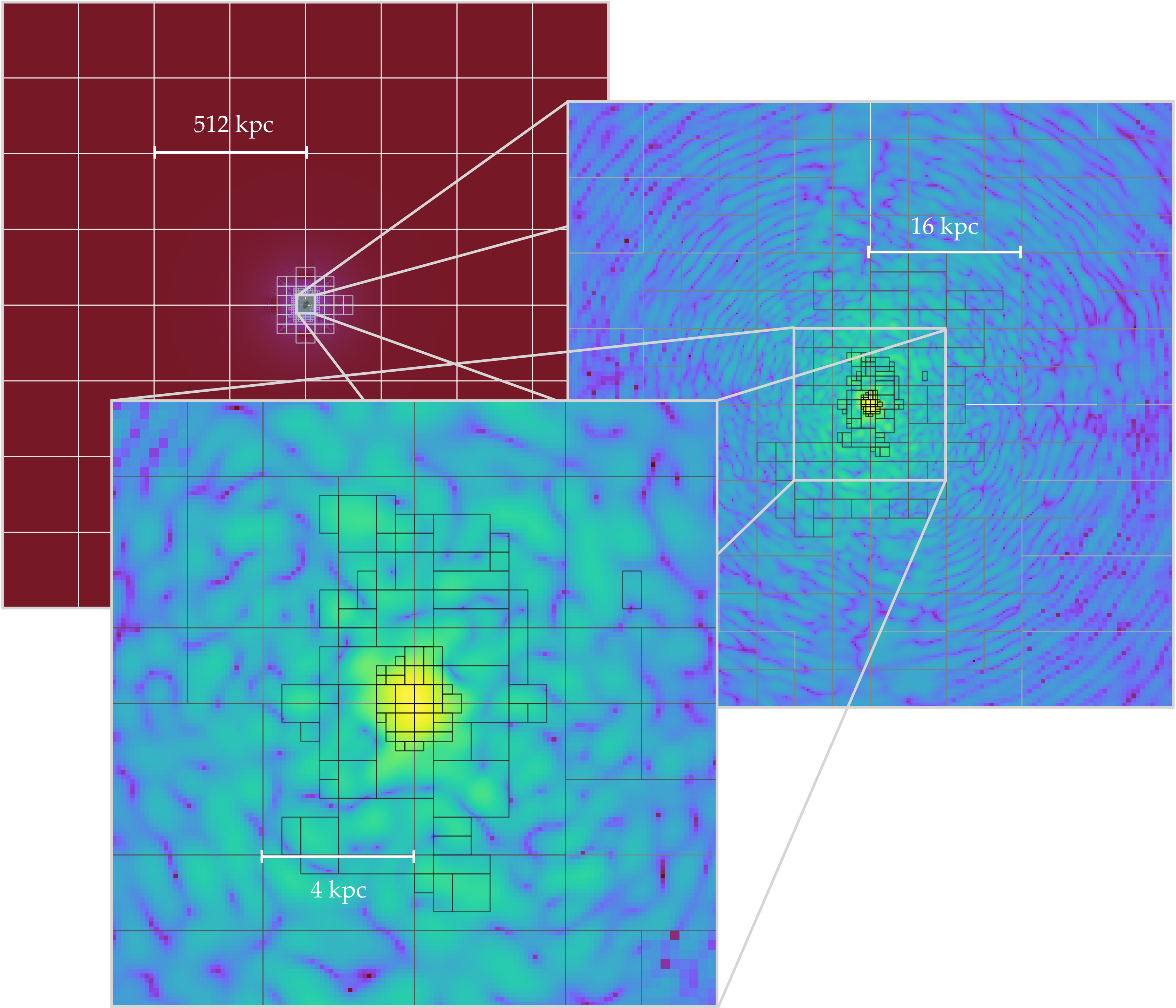
P. Mocz et al., *Mon. Not.*, 2019

Constraints on the Fuzzy Dark Matter mass



AxioNyx : simulations of FDM + CDM with AMR

- solves the Schrödinger-Poisson system in a cosmological background
- uses adaptive mesh refinement in regions of interest
- mixed dark matter with various fractions of cold and fuzzy dark matter
- can easily parallelise to high number of processes
- publicly available



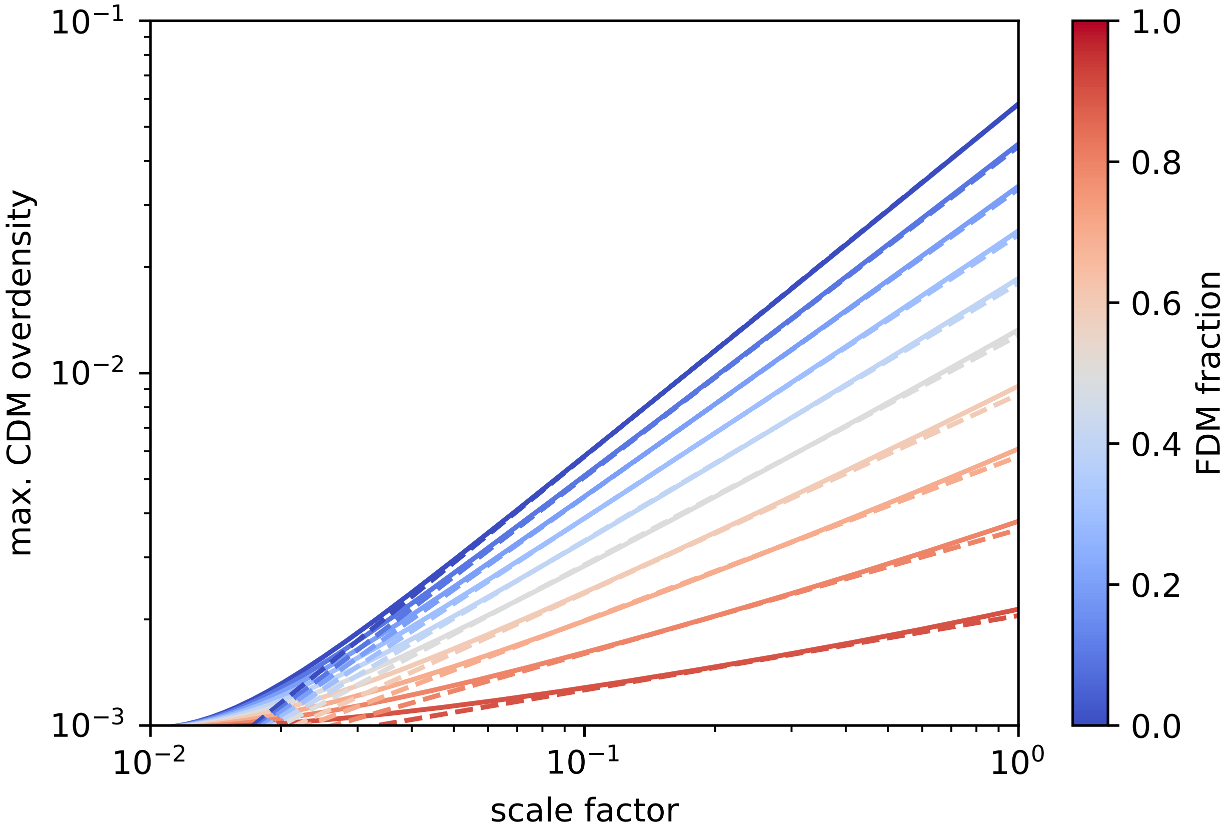
Schwabe, MG, Behrens, Niemeyer, Easther, arXiv:2007.08256v1, 2020

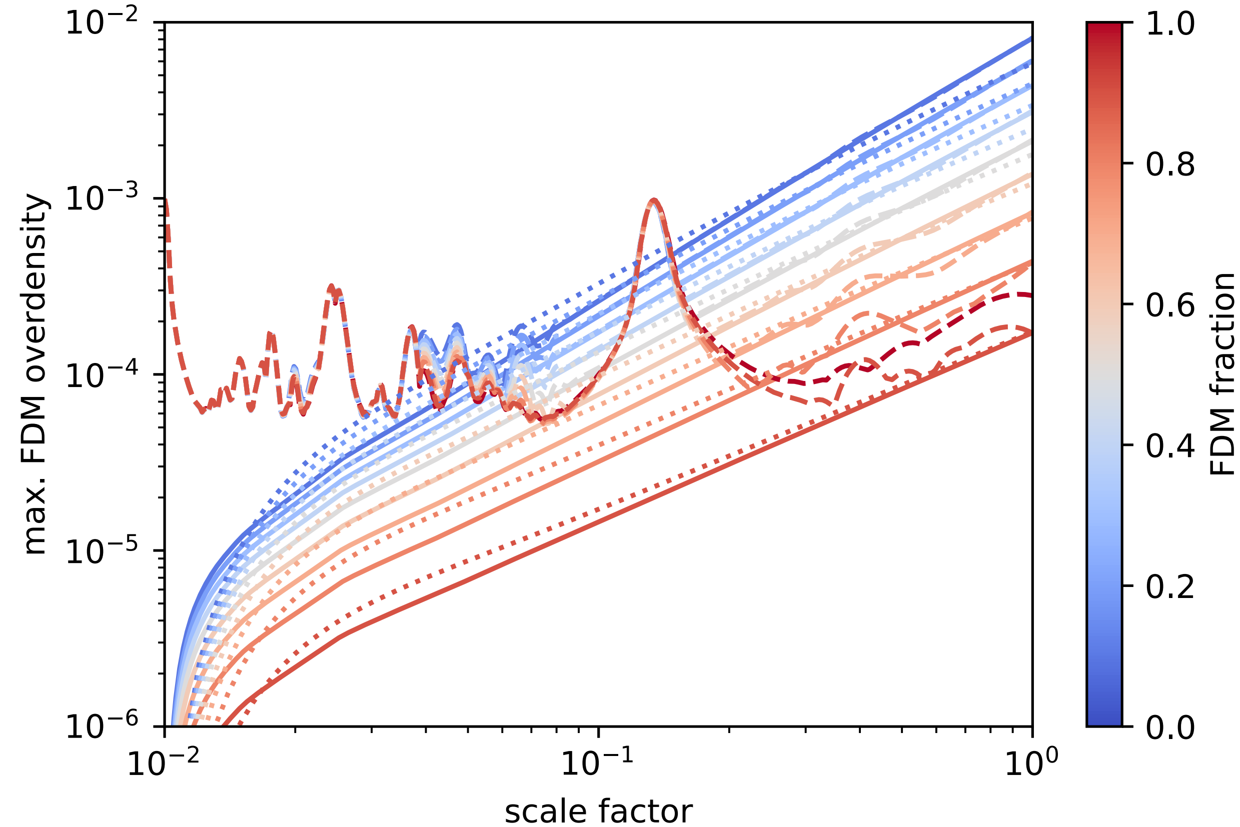
Spherical collapse - linear

$$\ddot{\delta}_{\mathrm{CDM}} + 2H\dot{\delta}_{\mathrm{CDM}} - 4\pi G(1-f)\overline{\rho}\delta_{\mathrm{CDM}} = 4\pi G f\overline{\rho}\delta_{\mathrm{FDM}}$$

$$\ddot{\delta}_{\mathrm{FDM}} + 2H\dot{\delta}_{\mathrm{FDM}} + \left(\frac{k^4\hbar^2}{4m^2a^4} - 4\pi G f\overline{\rho}\right)\delta_{\mathrm{FDM}} = 4\pi G(1-f)\overline{\rho}\delta_{\mathrm{CDM}}$$

$$f = \frac{\rho_{\mathrm{FDM}}}{\rho_{\mathrm{FDM}} + \rho_{\mathrm{CDM}}}$$

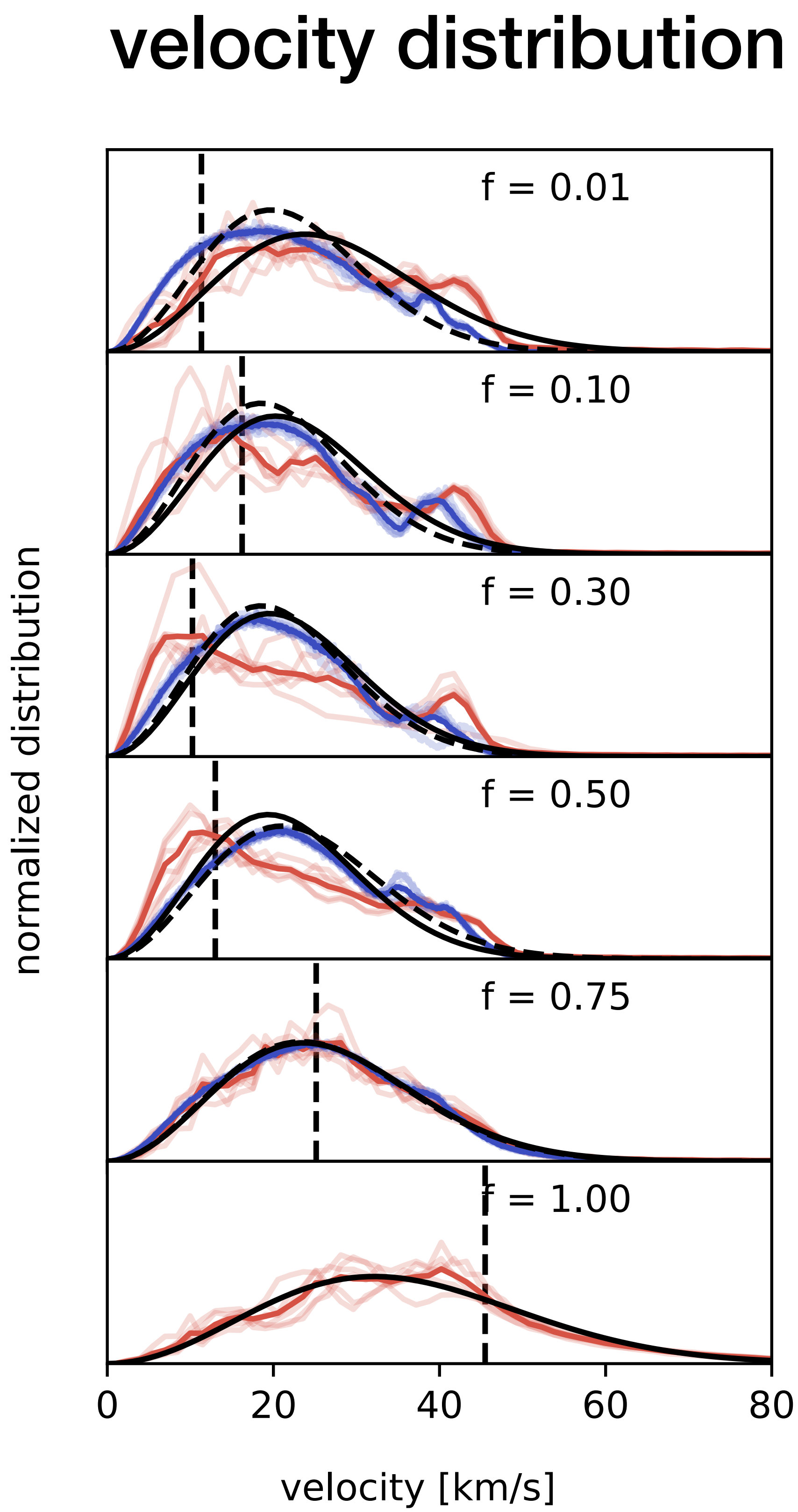


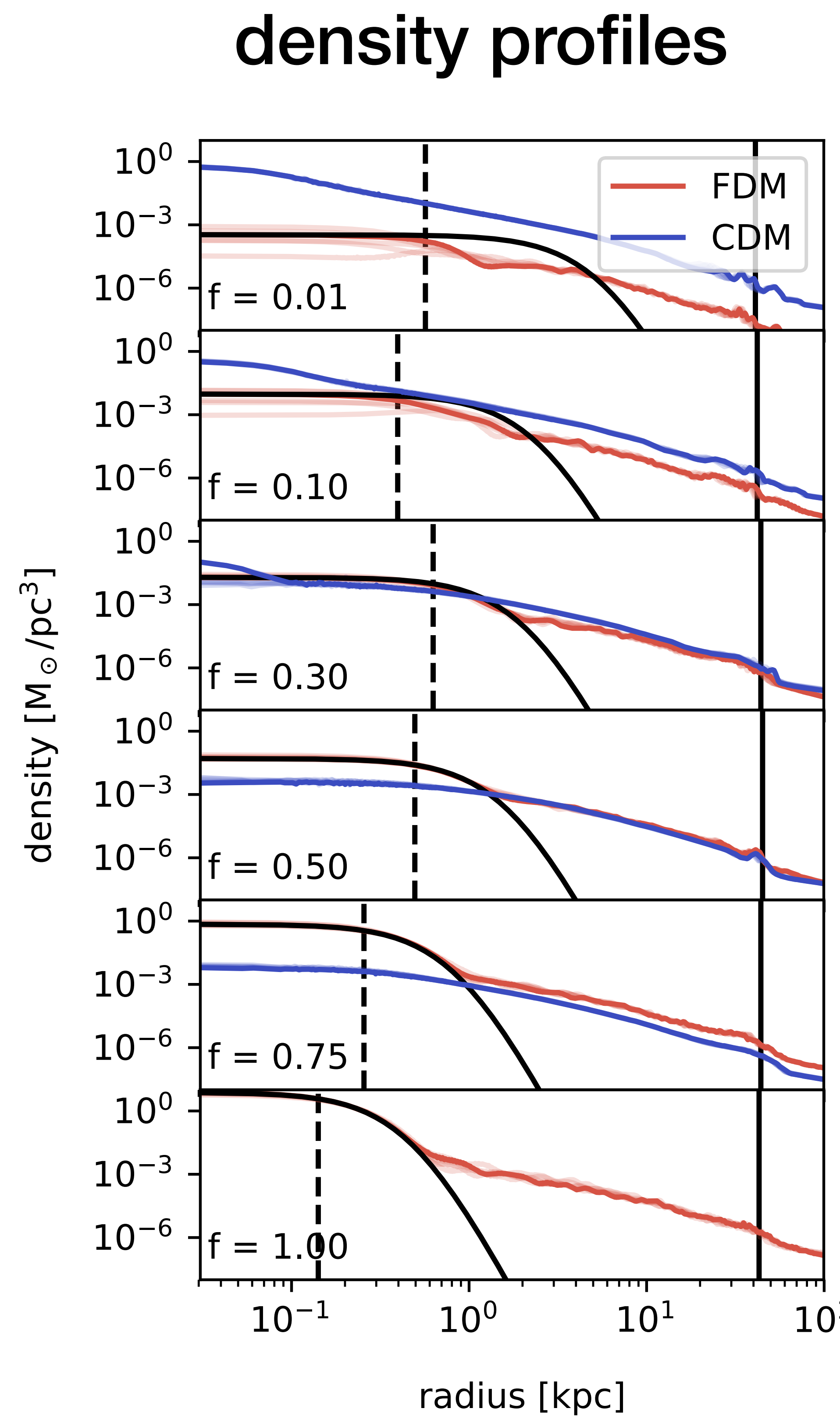


$$\delta_{\mathrm{CDM}}(a) \propto a^{\left(\sqrt{1+24(1-f)}-1\right)/4}$$

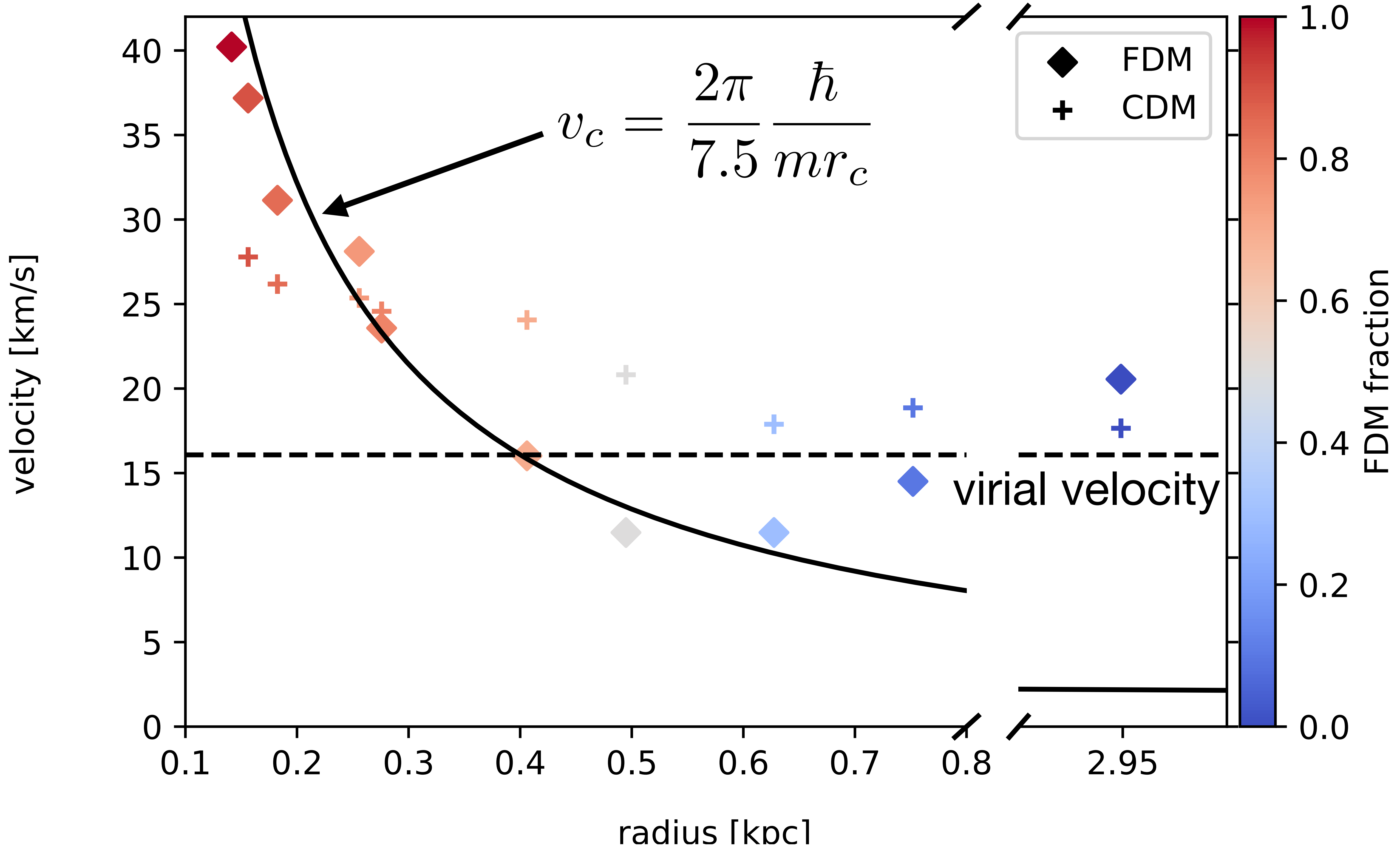
$$\delta_{\mathrm{FDM}}(a) \propto a^{\left(\sqrt{1+24(1-f)}+3\right)/4}$$

Spherical collapse - non-linear



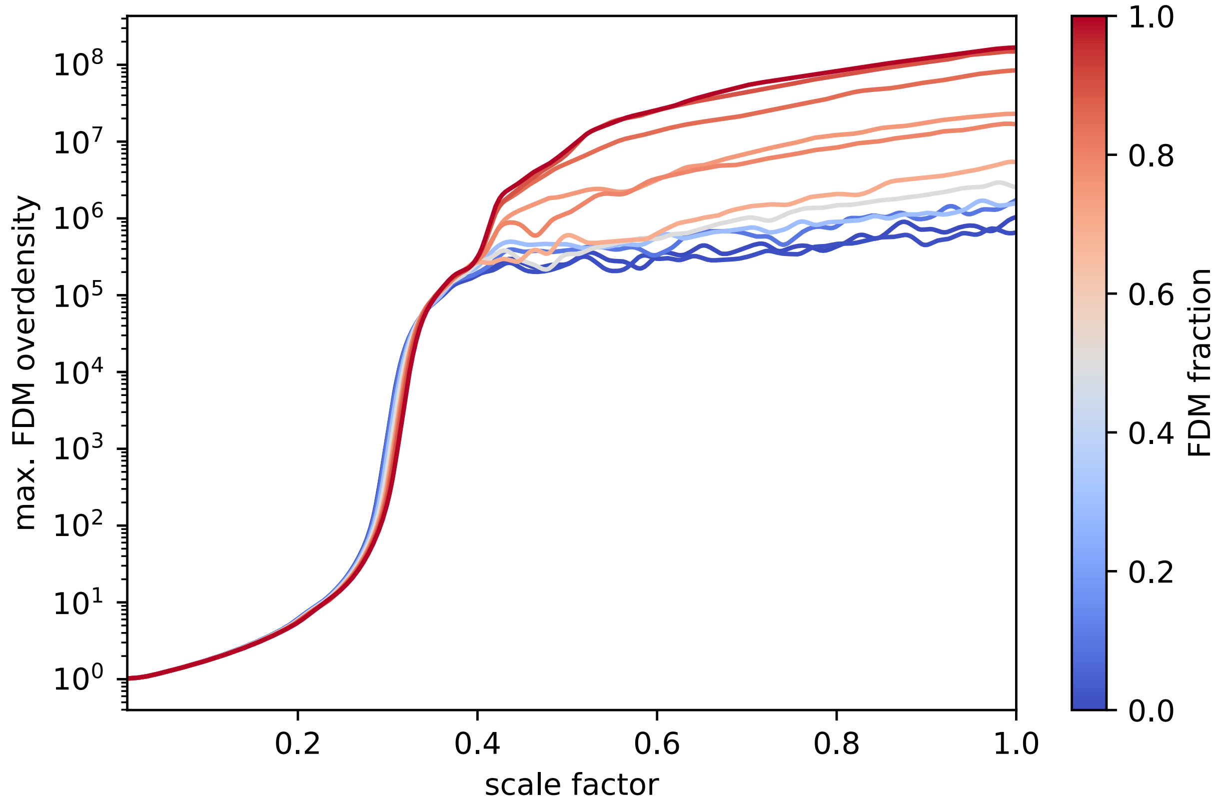


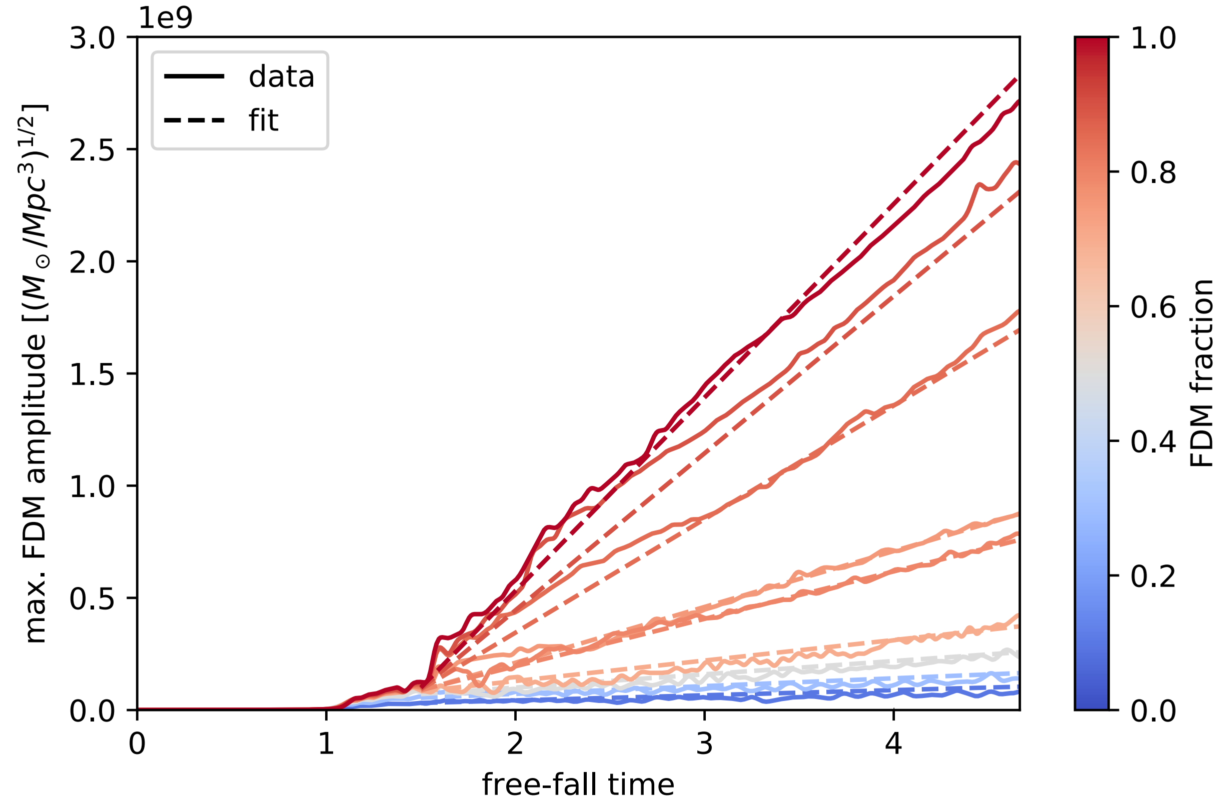
$$v_c = \frac{2\pi}{7.5}\frac{\hbar}{m r_c}$$



$v_c = \frac{2\pi}{7.5}\frac{\hbar}{m r_c}$
FDM
CDM
virial velocity
velocity [km/s]
radius [kpc]
FDM fraction
0
5
10
15
20
25
30
35
40
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
2.95
0.0
0.2
0.4
0.6
0.8
1.0

Spherical collapse - non-linear





$$A(t) = A_1 \cdot (t - t_0)/\tau_{\rm gr} + A_0 f^{1/2}$$

$$\tau_{\rm gr} = \frac{0.7\sqrt{2}}{12\pi^3}\frac{m^3 v_c^6}{G^2\rho_c^2\Lambda}$$

Levkov et al., 2018

Summary

- the search for dark matter has so far only given us constraints
- mixed dark matter models should be considered
- PBH + WIMP simulations show:
  - if most of dark matter is WIMPs, then PBH with ~ solar mass can not exist
- FDM + CDM simulations show:
  - on large scales we confirm the Schrödinger-Vlasov correspondence
  - on smaller scales, around de Broglie wavelength, fuzzy effect are present if FDM constitutes at least ~10% of total dark matter
- baryonic effects must also be taken into account