Fuzzy Dark Matter Confronts Rotation Curves of Nearby Dwarf Irregular Galaxies

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Axions as a Solution to Small-scale Challenges of ΛCDM

- Physically well-motivated (originally from QCD, also string theory)
- Core-cusp problem and "too big to fail": Observed dwarf galaxies show constant density cores at their centres, not high-density cusps
- Missing satellites problem: ΛCDM predicts a significantly larger number of satellite subhalos in the local group than we observe

$$\lambda_{dB} \approx 12 \left(\frac{v}{100\ \mathrm{km/s}}\right)^{-1} \left(\frac{m_a}{10^{-23}\ \mathrm{eV}}\right)^{-1} \mathrm{kpc}$$

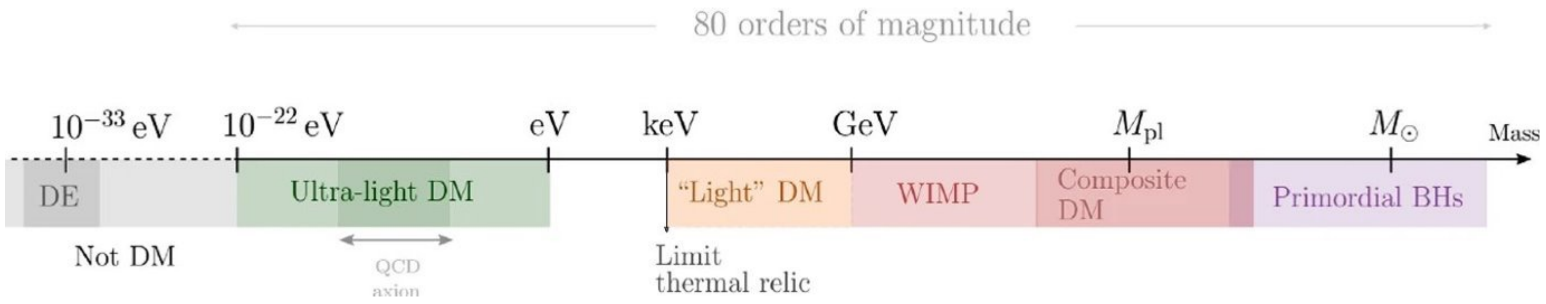


Image credit: Elisa G. M. Ferreira (2021)

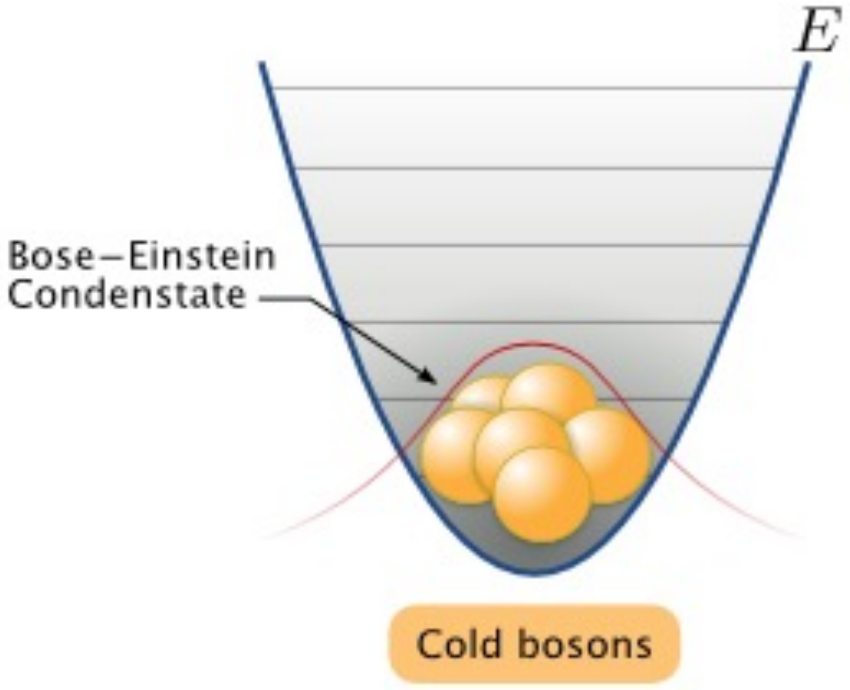
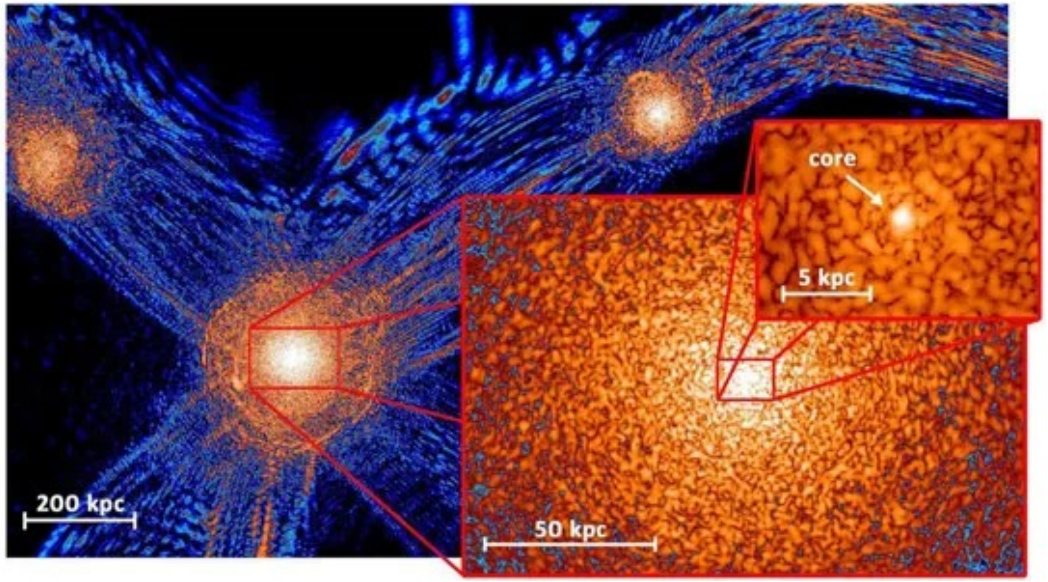


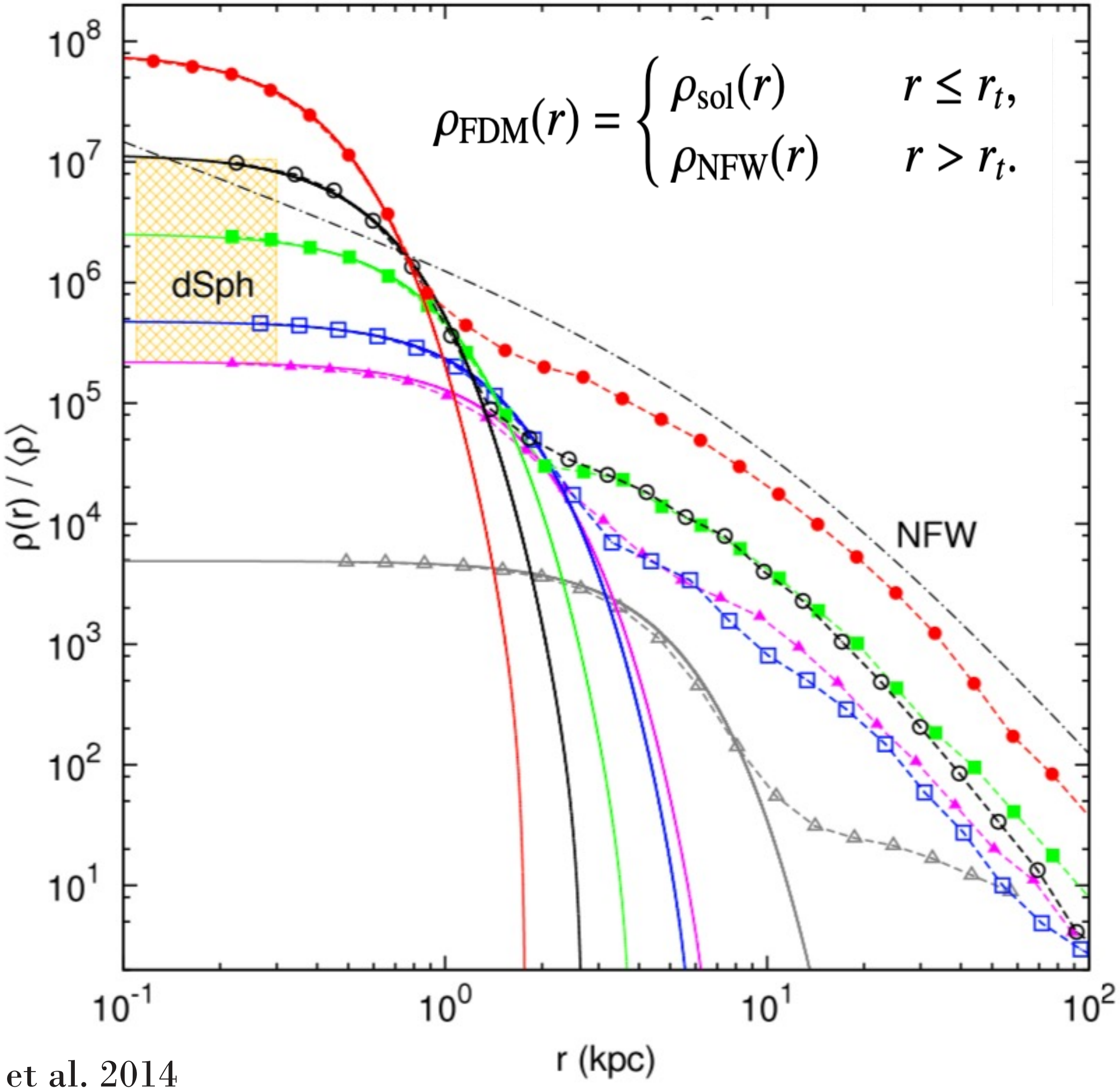
Image credit: Frédéric Bellaiche (2012)

FDM Simulations and the Soliton Core + NFW Profile

Schrödinger-Poisson Equation

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi,$$
$$\nabla^2\Phi = 4\pi G|\psi|^2.$$





Schive et al. 2014

Soliton Scaling Relations

- Core radius – mass relation

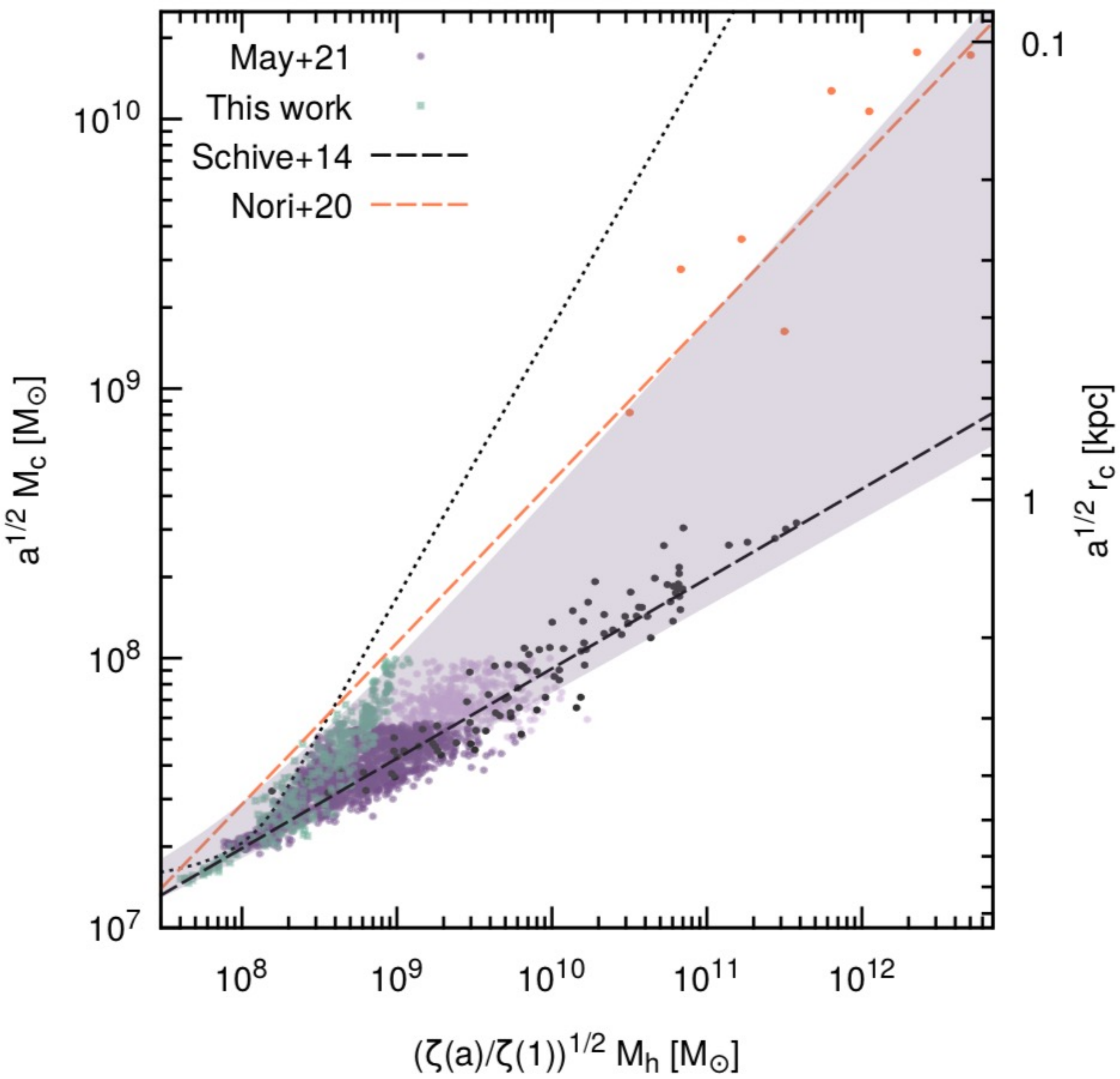
$$M_c \simeq 5.4 \times 10^9 \left(\frac{m_a}{10^{-23}\mathrm{eV}}\right)^{-2} \left(\frac{r_c}{\mathrm{kpc}}\right)^{-1} \mathrm{M}_\odot$$

- Core radius – central density relation:

$$\rho_c \simeq 1.9 \left(\frac{m_a}{10^{-23}\mathrm{eV}}\right)^{-2} \left(\frac{r_c}{\mathrm{kpc}}\right)^{-4} \mathrm{M}_\odot\,\mathrm{pc}^{-3}$$

- Core – halo mass relation (Schive et al. 2014):

$$M_c \approx 3.1 \times 10^9 (1+z)^{1/2} \left(\frac{m_a}{10^{-23}\ \mathrm{eV}}\right)^{-1} \left(\frac{M_h}{10^{12}\ \mathrm{M}_\odot}\right)^{1/3} \mathrm{M}_\odot$$



Chan et al. 2022

Probing FDM with LITTLE THINGS

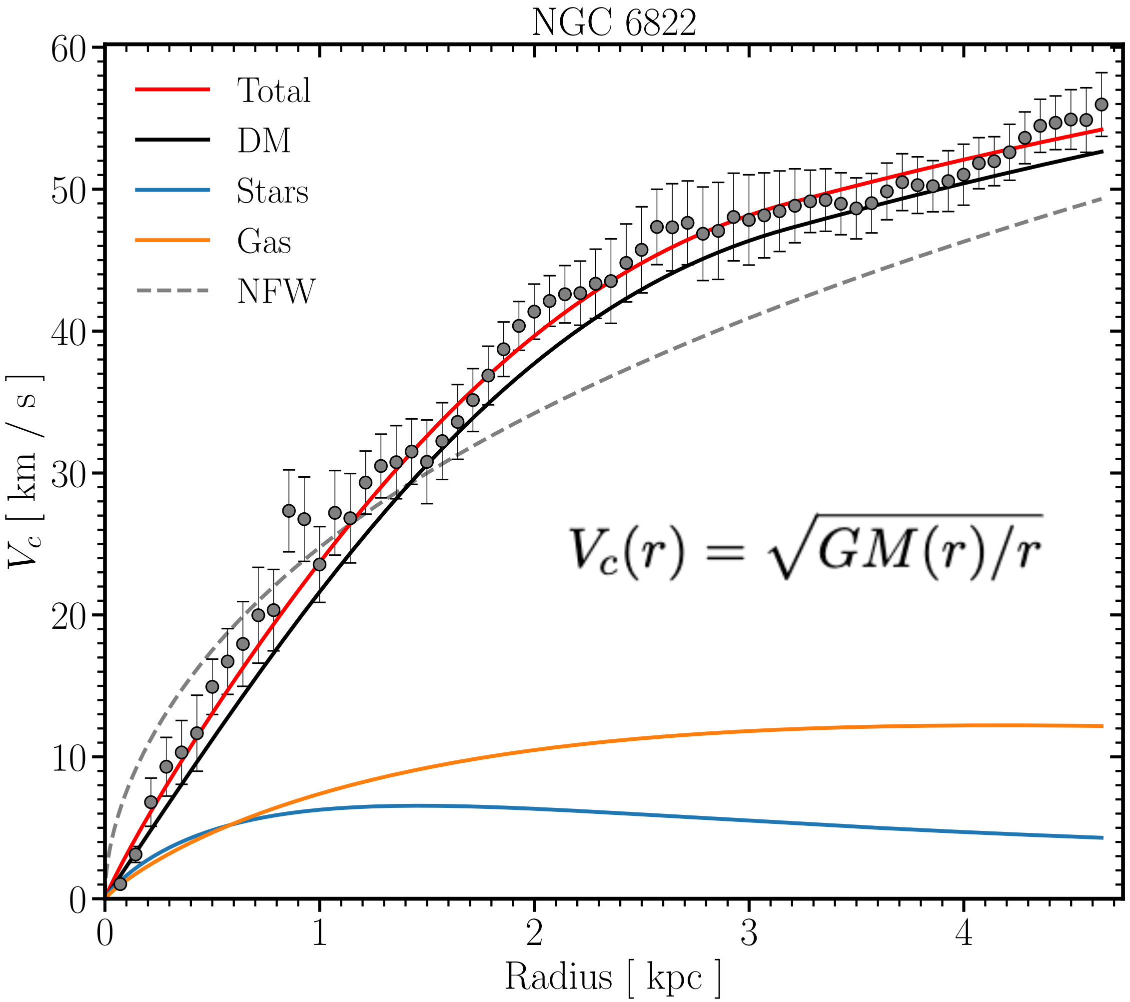
- Collaboration with G. Iorio using extensive analysis of RCs on a select group of 13 **isolated, DM-dominated** dwarf galaxies
- **Robust determination of uncertainties** with state-of-the-art 3D Barolo software
- One of the **highest quality** samples of dwarf galaxy RCs to date, ideal for FDM

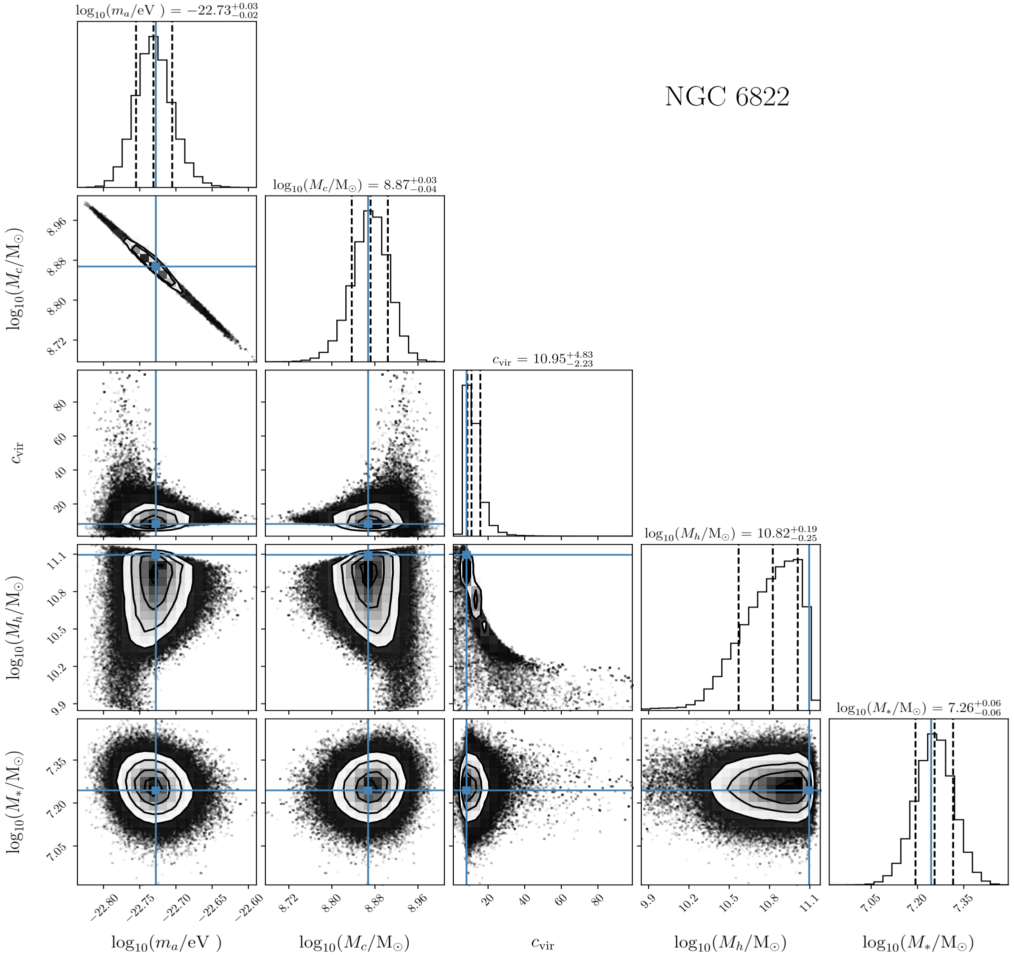
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **466,** 4159–4192 (2017) doi:10.1093/mnras/stw3
Advance Access publication 2016 December 17

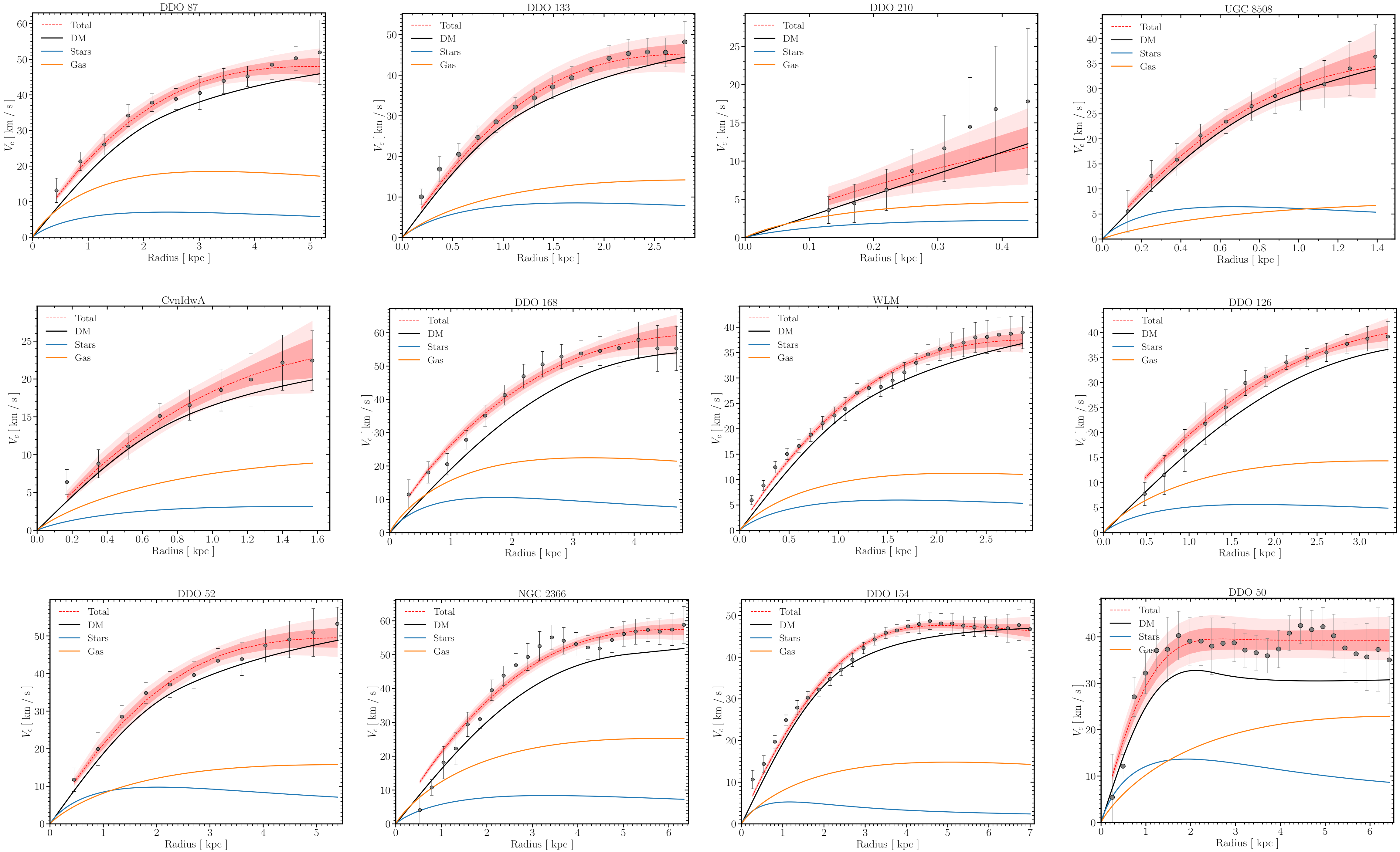
LITTLE THINGS in 3D: robust determination of the circular velocity of dwarf irregular galaxies

G. Iorio,[1,2★] F. Fraternali,[1,3] C. Nipoti,[1] E. Di Teodoro,[4] J. I. Read[5] and G. Battaglia[6,]

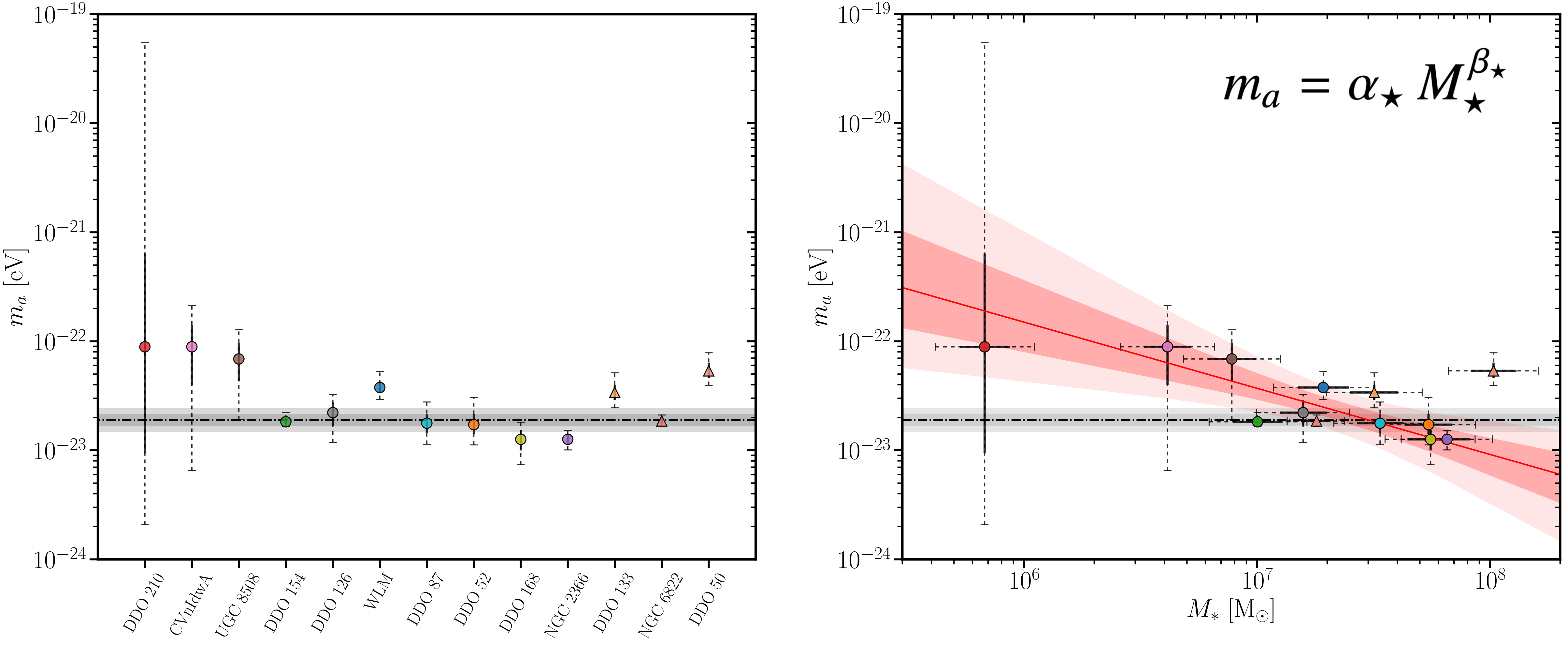
Some Results from MCMCs



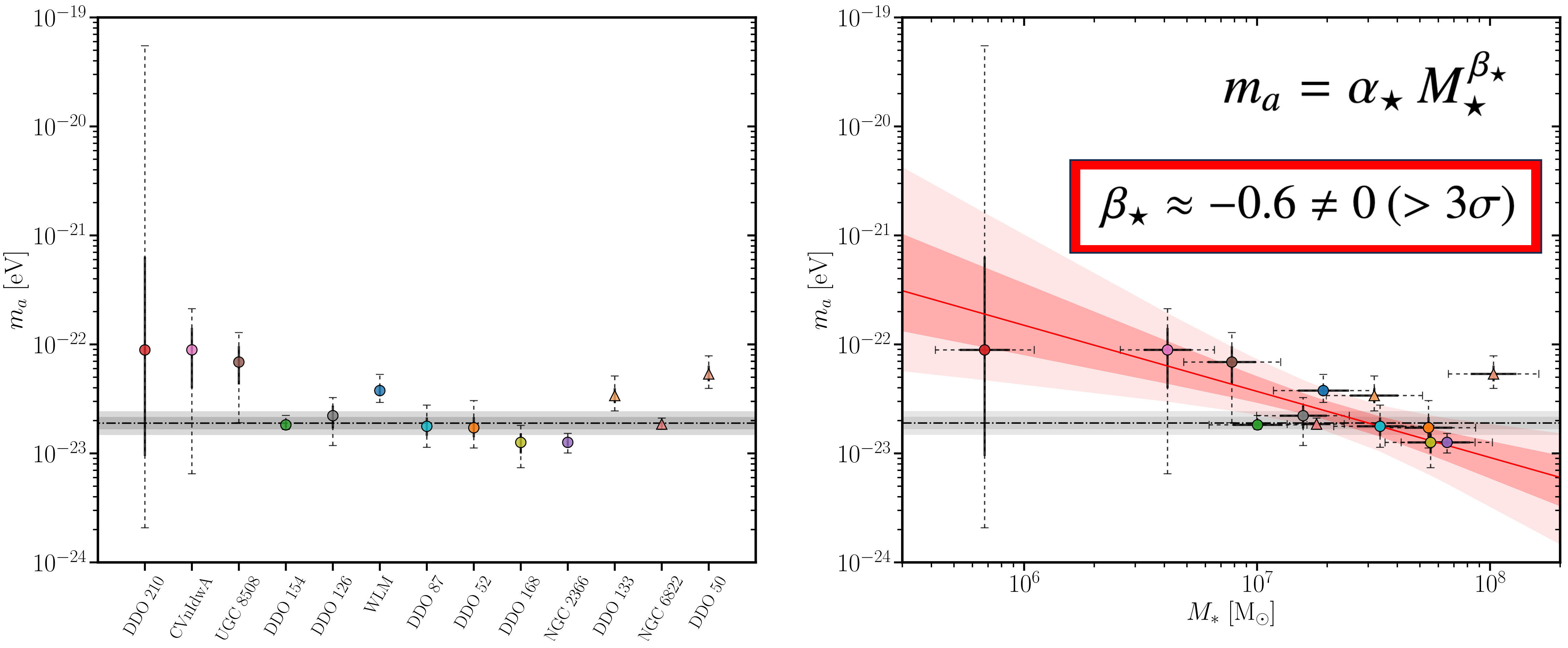



DDO 87
DDO 133
DDO 210
UGC 8508
CvnIdwA
DDO 168
WLM
DDO 126
DDO 52
NGC 2366
DDO 154
DDO 50
Total
DM
Stars
Gas
V_c [km / s]
Radius [kpc]

Universality of the Axion Mass



Universality of the Axion Mass

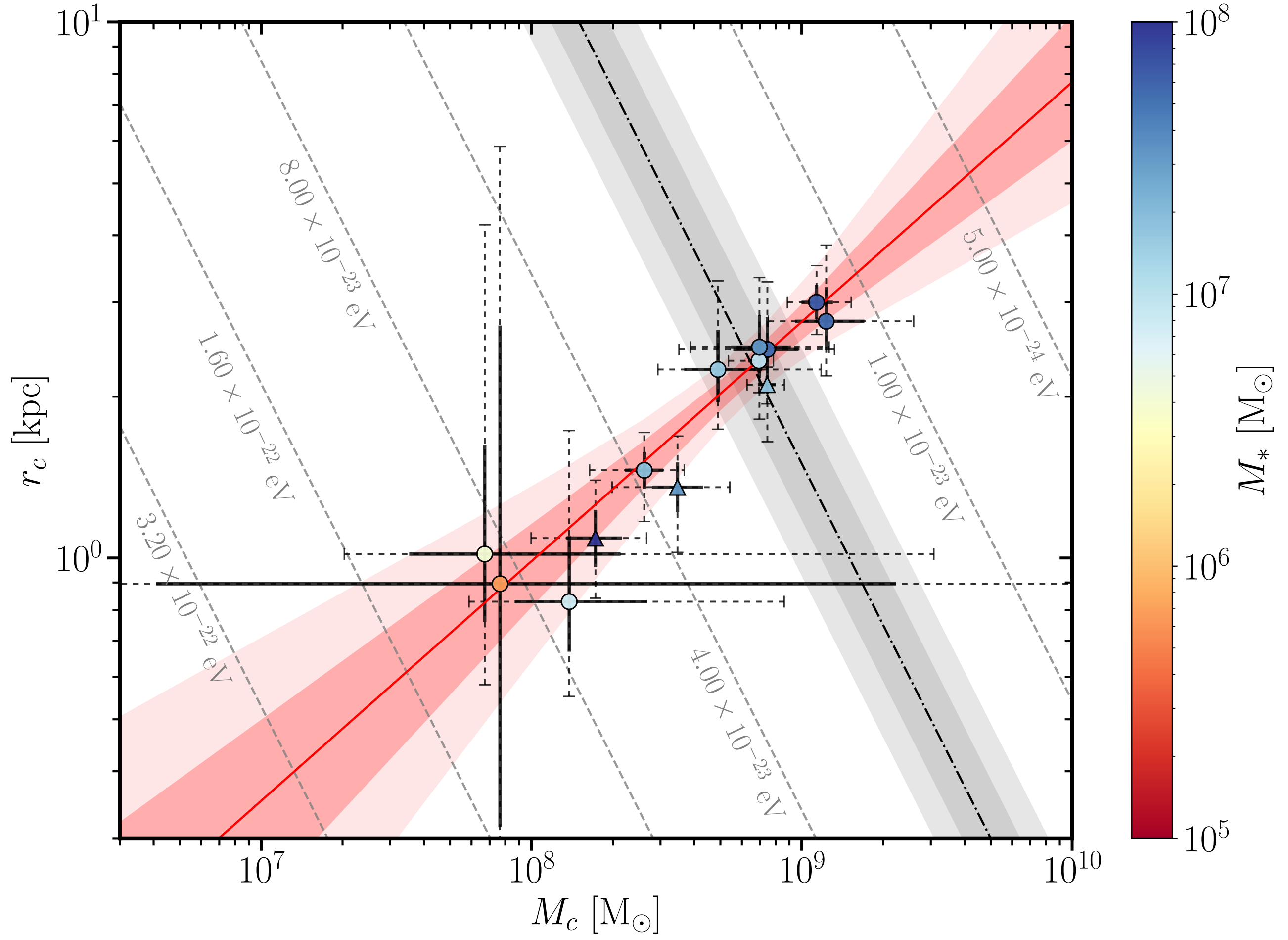


Core Radius – Mass Relation

- A statistically significant positive correlation is observed, inconsistent with theoretical expectations

$$r_c \propto M_c^{\beta}$$

- A similar discrepancy occurs with the central density – radius relation



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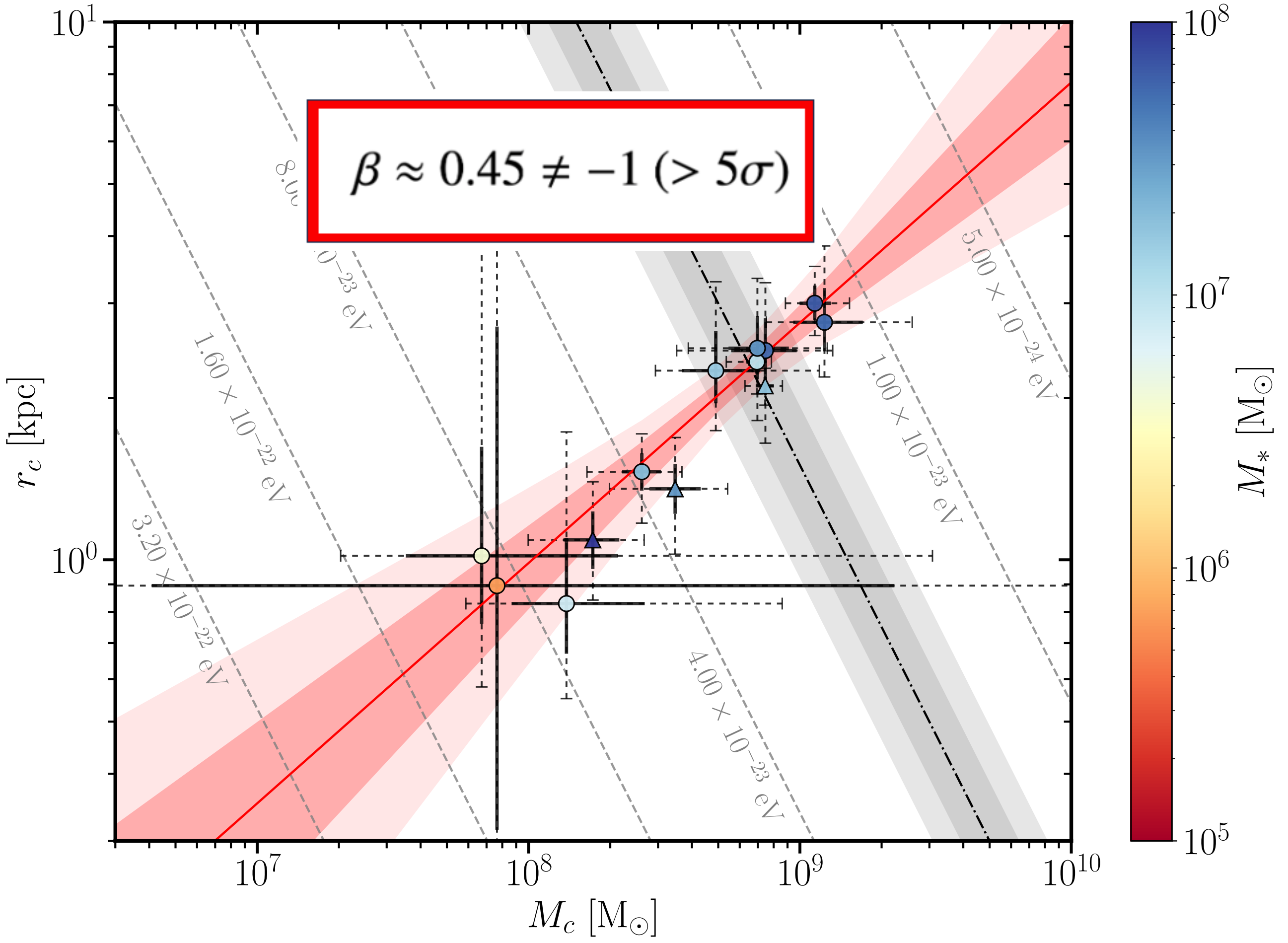
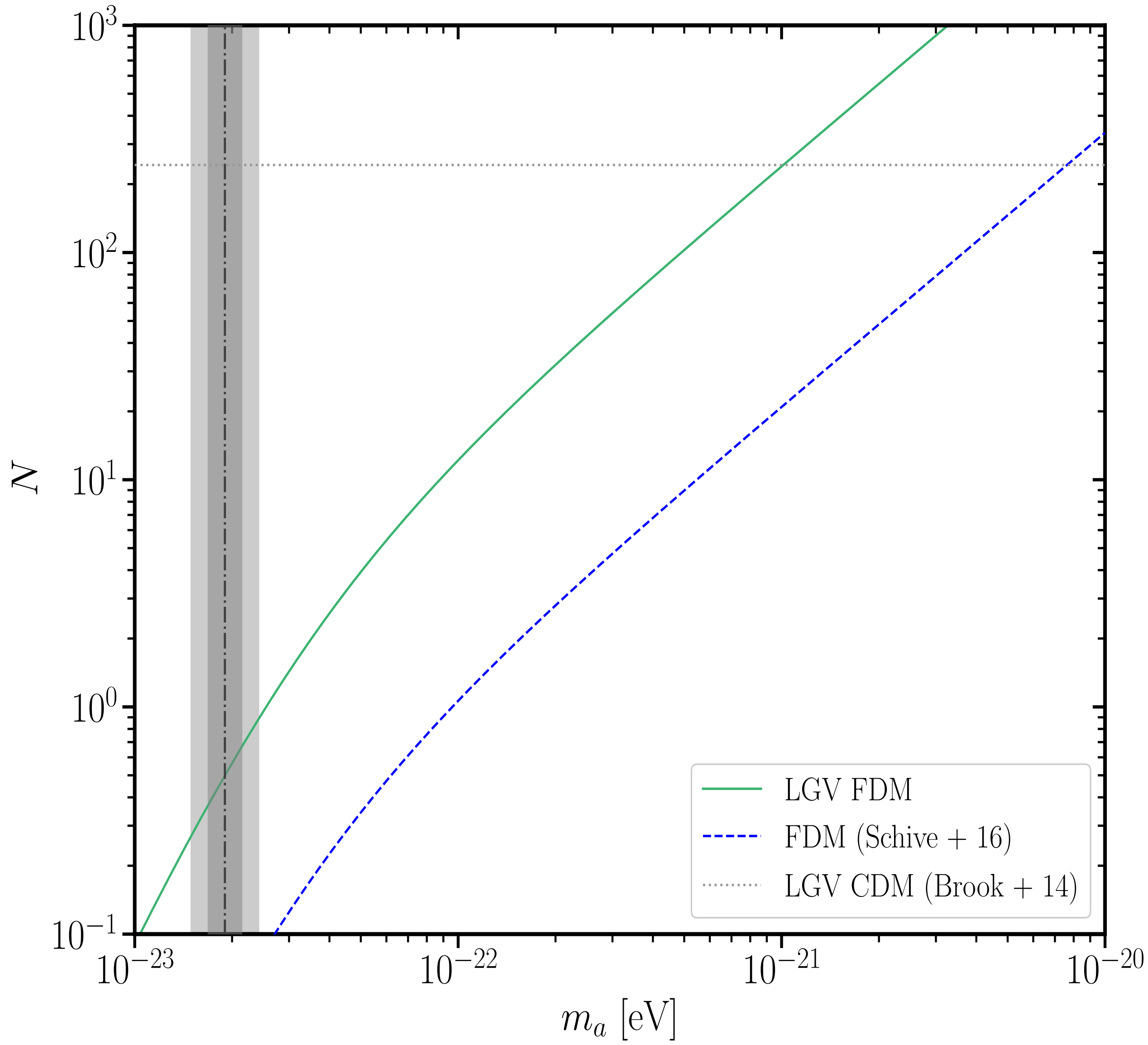


Halo Mass Function Suppression

- Our halos should not exist for axion masses below $\sim 4.3 \times 10^{-23}$ eV
- Including observed LG galaxies makes the bound stronger, reaching $\sim 5.5 \times 10^{-22}$ eV
- These bounds are inconsistent with the best-fit axion mass of $\sim 2 \times 10^{-23}$ eV



Conclusions

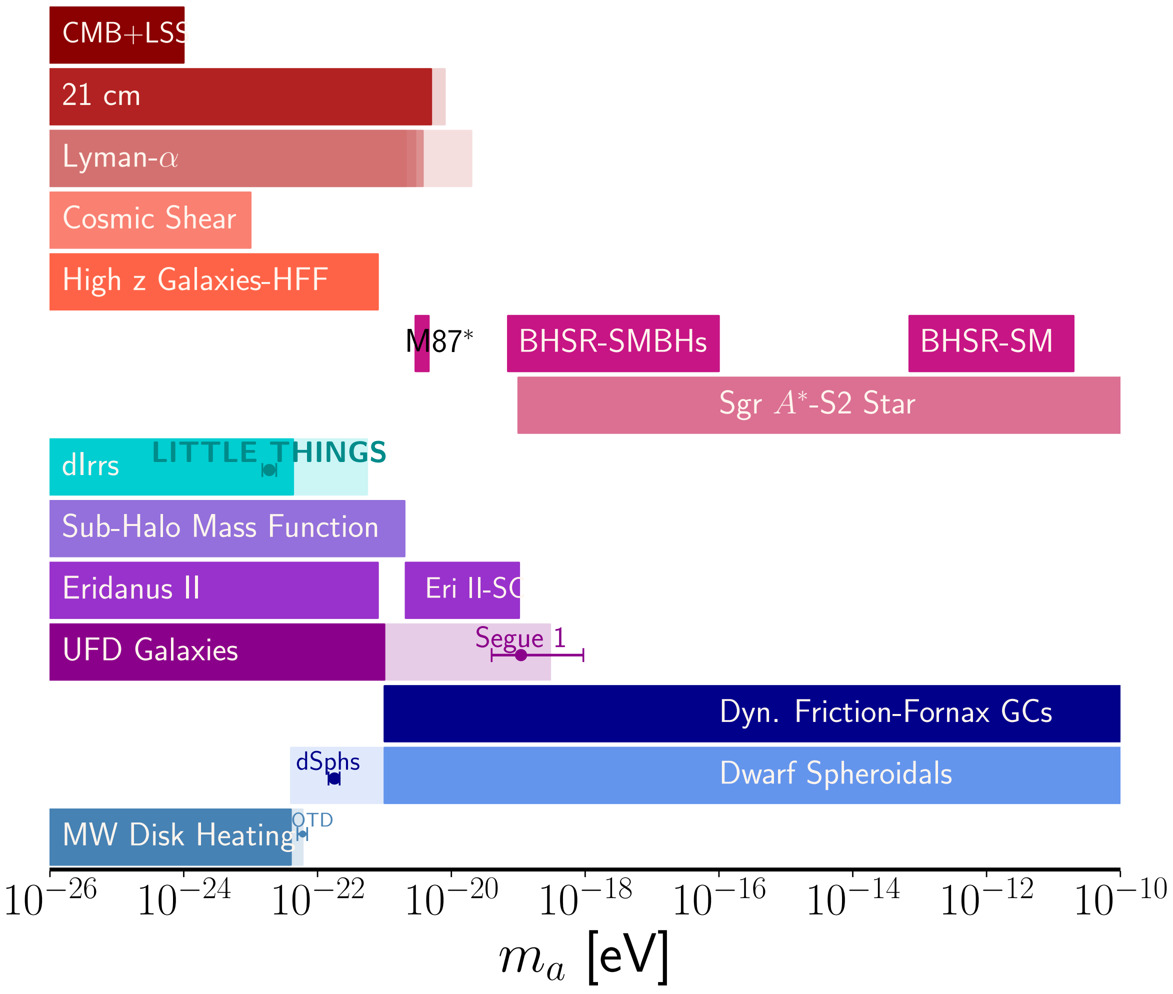
- Dwarf, isolated galaxies are ideal probes for testing fundamental properties of DM
- The FDM model predicts that DM consists of light, weakly-interacting wave-like particles that suppress small-scale structure and produce galactic cores

- While fits show excellent agreement with RC data, favoured axion masses are in tension with the strong suppression expected from the HMF (Catch-22 problem)
- Including baryonic effects only exacerbates this tension (see extra slides)

- Furthermore, scaling relations favoured by the fits are inconsistent with model predictions, suggesting physics extrinsic to FDM

Comments and Future Directions

- Other bounds exist in the literature, e.g. Lyman-α forest, weak lensing, LSS-CMB etc. (see figure)
- One may restrict FDM to be only a small fraction of all DM
- Baryonic feedback – driven CDM and self-interacting dark matter remain promising alternatives



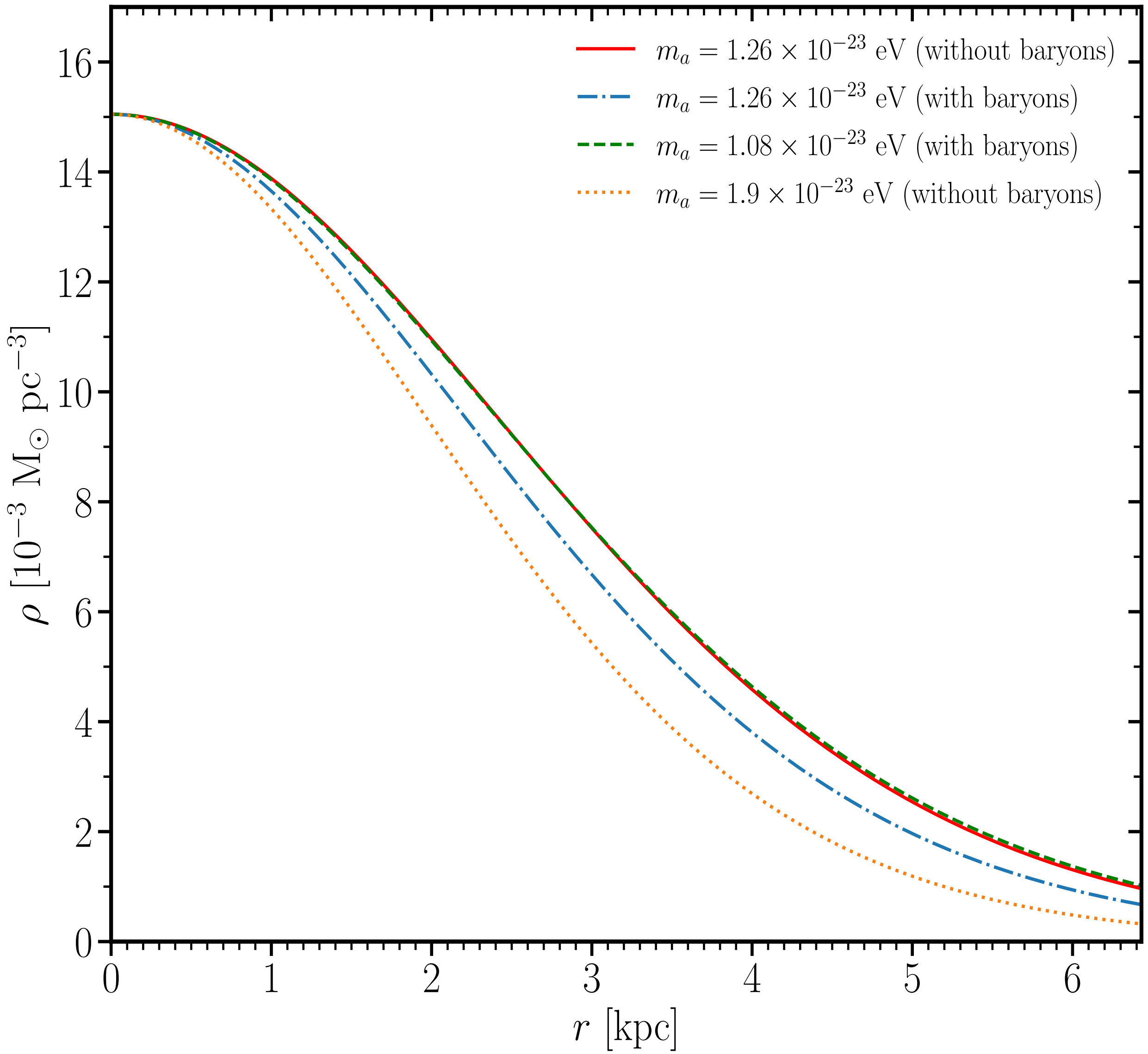
ll images are shown at the same linear scale (courtesy Kim Herrmann). HI (red), V (green), FUV (blue; a few are Hα or NUV instead)

Thank you!

Backup Slides

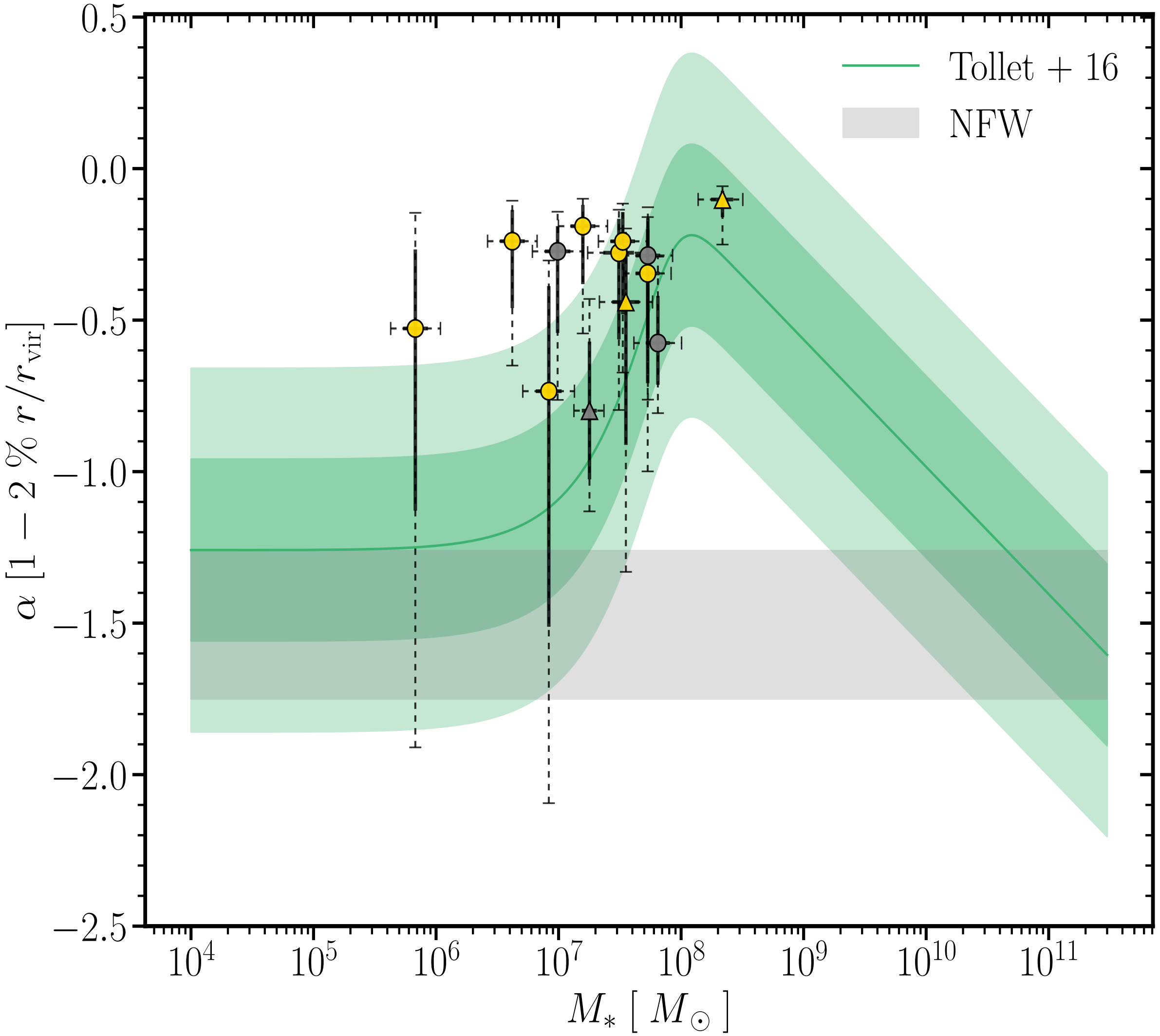
Including Baryonic Effects

- Solving S-P equation under a background baryonic potential yields a modified soliton
- This solution is consistent with FDM simulations including baryons (See Bar et al. 18,Veltmaat et al. 20)
- We find that this translates to a $\lesssim 15\ \%$ systematic drop in FDM mass in the fits
- This only aggravates the problem further



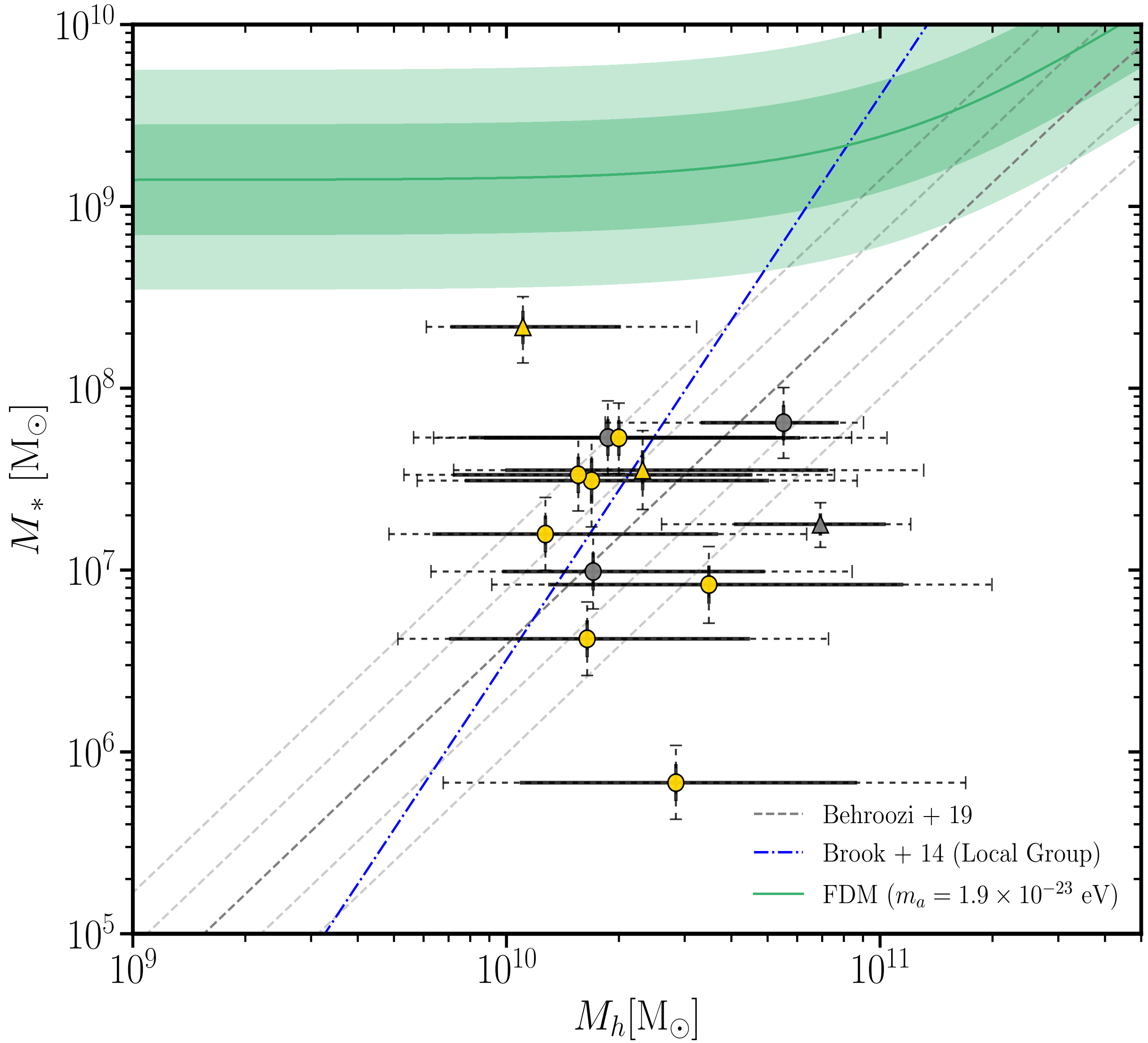
Baryonic Feedback

- The modified soliton profile has been found to be consistent with FDM simulations including feedback effects (Veltmaat et al. 20)
- Posterior distributions of inner (logarithmic) slopes show overlap with the predictions from CDM simulations including feedback (Tollet et al. 16, Di Cintio et al. 14)



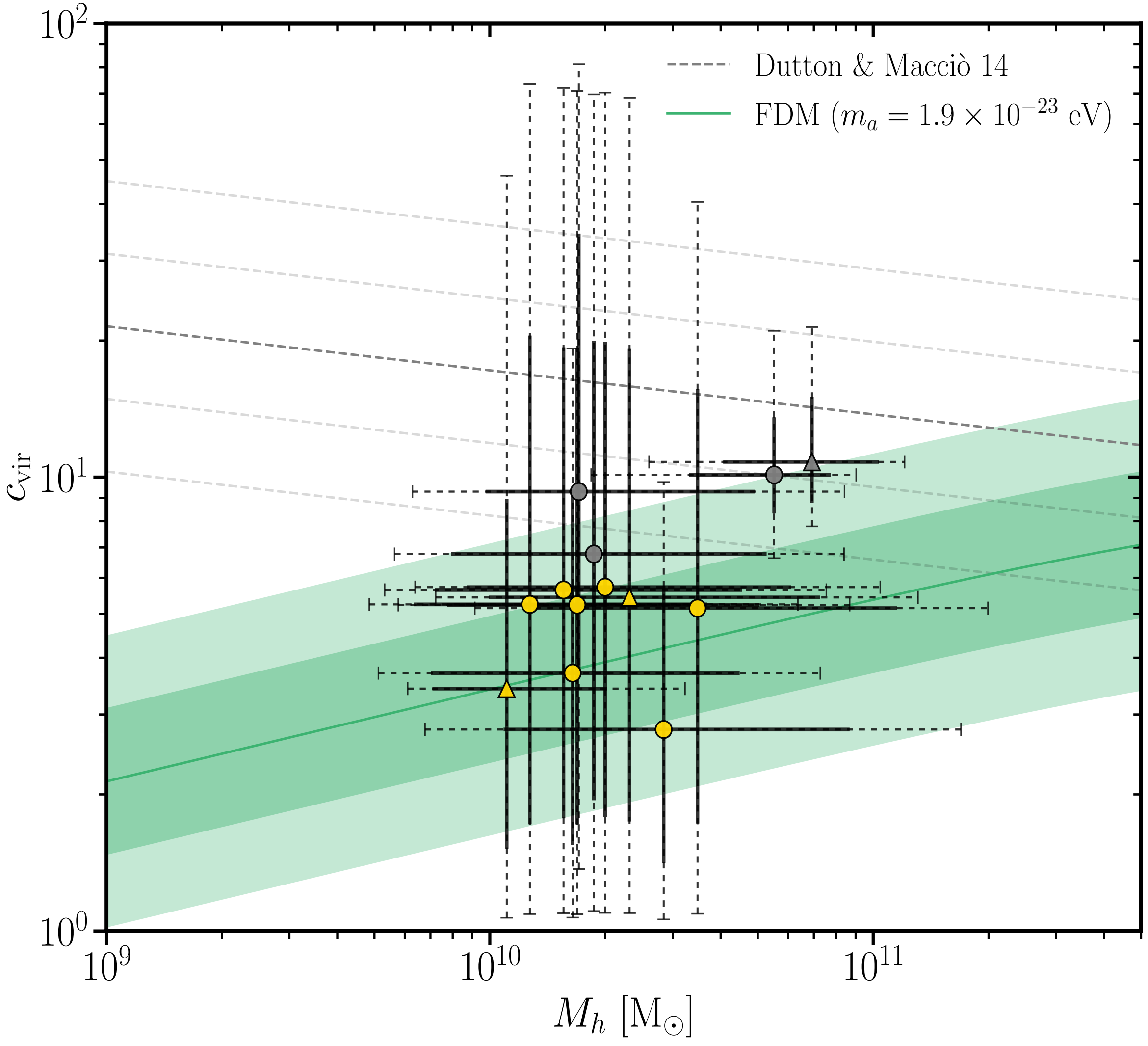
Abundance Matching

- The Schive et al. 16 FDM parametrization is applied to the HMF using Behroozi et al. 19 for the SMF
- For the favoured axion mass values of $\sim 10^{-23}$ eV, the HMF is strongly suppressed, excluding most galaxies
- Masses in the $\sim 10^{-22}$ eV range or greater may be compatible, but are disfavoured by the fits



c - M Relation

- We apply the correction factor relative to CDM from the FDM simulations in Dentler et al. 22 to Dutton & Macciò 14
- Suppression observed in the c - M relation is largely consistent, with most data points clustering around the best-fit axion mass value



Soliton + NFW Model

- Based on simulations, we adopt the soliton + NFW model with a transition point > core radius

$$\rho_{\rm FDM}(r) = \begin{cases} \rho_{\rm sol}(r) & r \le r_t, \\ \rho_{\rm NFW}(r) & r > r_t. \end{cases}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2},$$

$$\rho_{\rm sol} \approx \frac{\rho_c}{[1 + 9.1 \times 10^{-2}(r/r_c)^2]^8}$$

- We parametrize the DM profile with four variables: axion mass (m_a), core mass (M_c), concentration parameter (c) and halo mass (M_h)
- Baryonic components (gas + stars) are added to reproduce rotation curves

Real, massive bosonic scalar field (K-G equation.)

$$-\Box\phi + m^2\phi = 0$$

+

non-relativistic solution

$$\phi = \frac{1}{\sqrt{2m}}\left(\psi e^{-imt} + \psi^* e^{imt}\right)$$

+

minimally-coupled to gravity (Poisson equation)

$$\nabla^2\Phi = 4\pi G\rho \quad , \quad \rho = |\psi|^2$$

$\longrightarrow$

Schrödinger-Poisson Equation

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi,$$

$$\nabla^2\Phi = 4\pi G|\psi|^2.$$

Soliton Solution to the S-P Equation

- Searching for a quasi-stationary, phase-coherent solution

$$\psi(x,t) = \left(\frac{mM_{\rm pl}}{\sqrt{4\pi}}\right) e^{-i\gamma m t}\chi(x).$$

S-P spherical and stationary eq.

$$\partial_r^2(r\chi) = 2r(\Phi - \gamma)\chi,$$

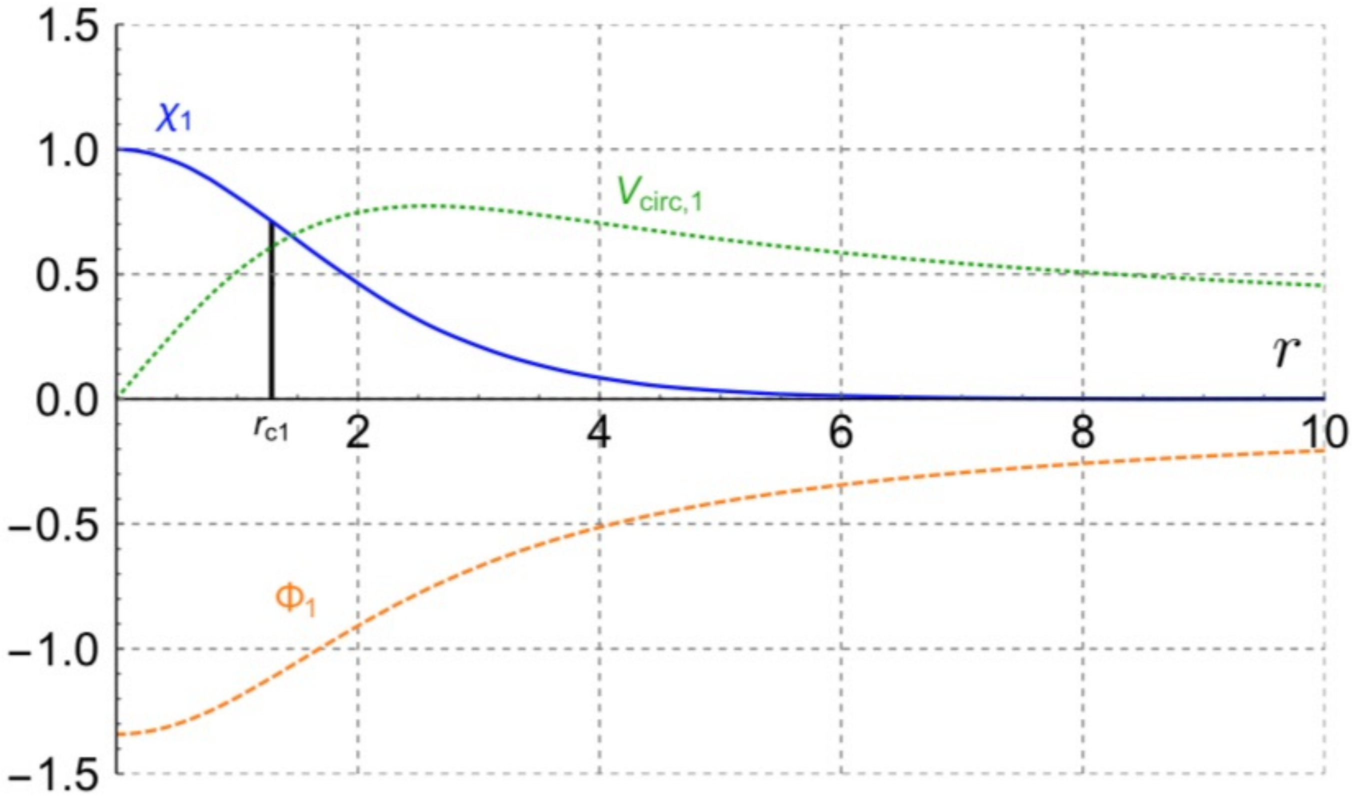
$$\partial_r^2(r\Phi) = r\chi^2.$$

Scaled solutions of S-P eq.

$$\chi_\lambda(r) = \lambda^2\chi_1(\lambda r),$$

$$\Phi_\lambda(r) = \lambda^2\Phi_1(\lambda r),$$

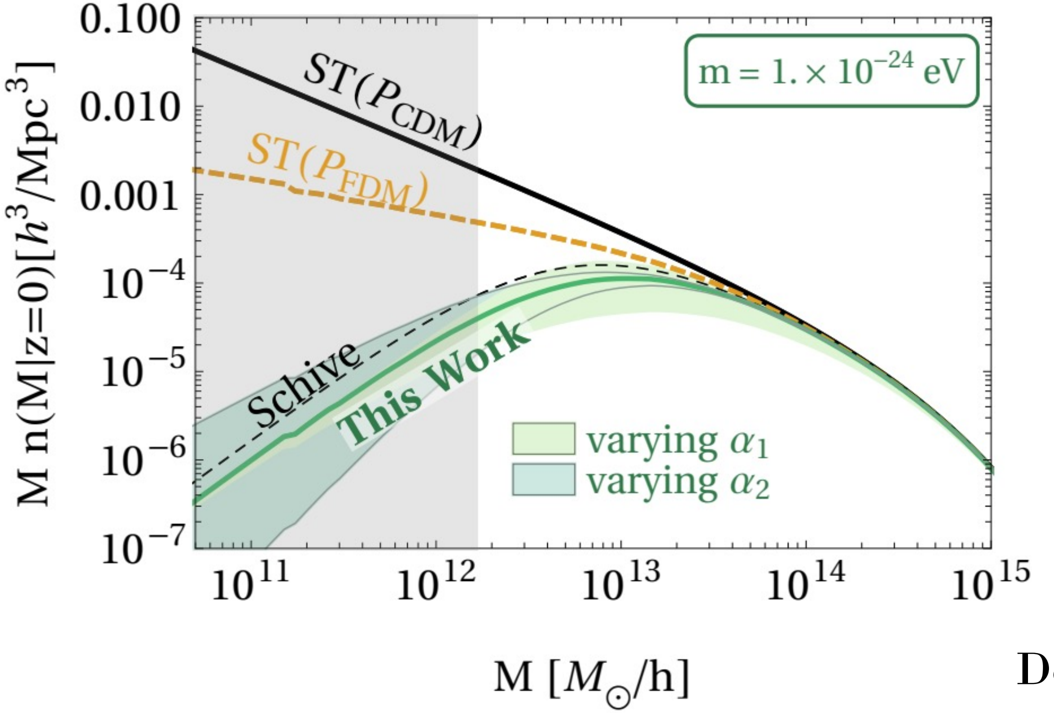
$$\gamma_\lambda = \lambda^2\gamma_1,$$

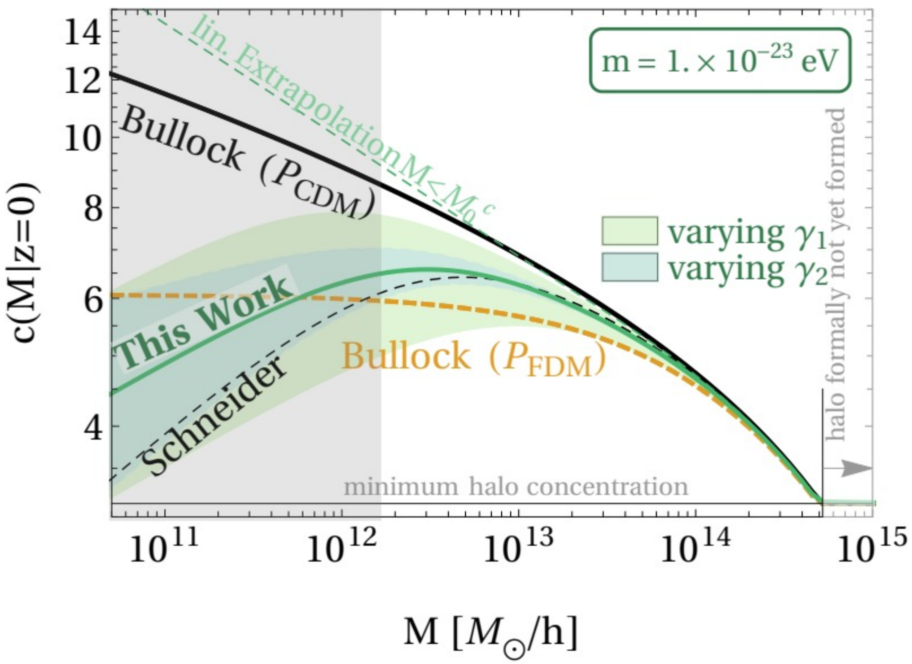


Bar et al. 2018

ΛCDM Challenges and FDM

- Wave behaviour causes core formation and suppression of the formation of halos below a certain mass (due to power spectrum suppression)
- This makes FDM an attractive candidate to address small-scale strucure issues in ΛCDM (i.e. core-cusp problem and missing satellites)

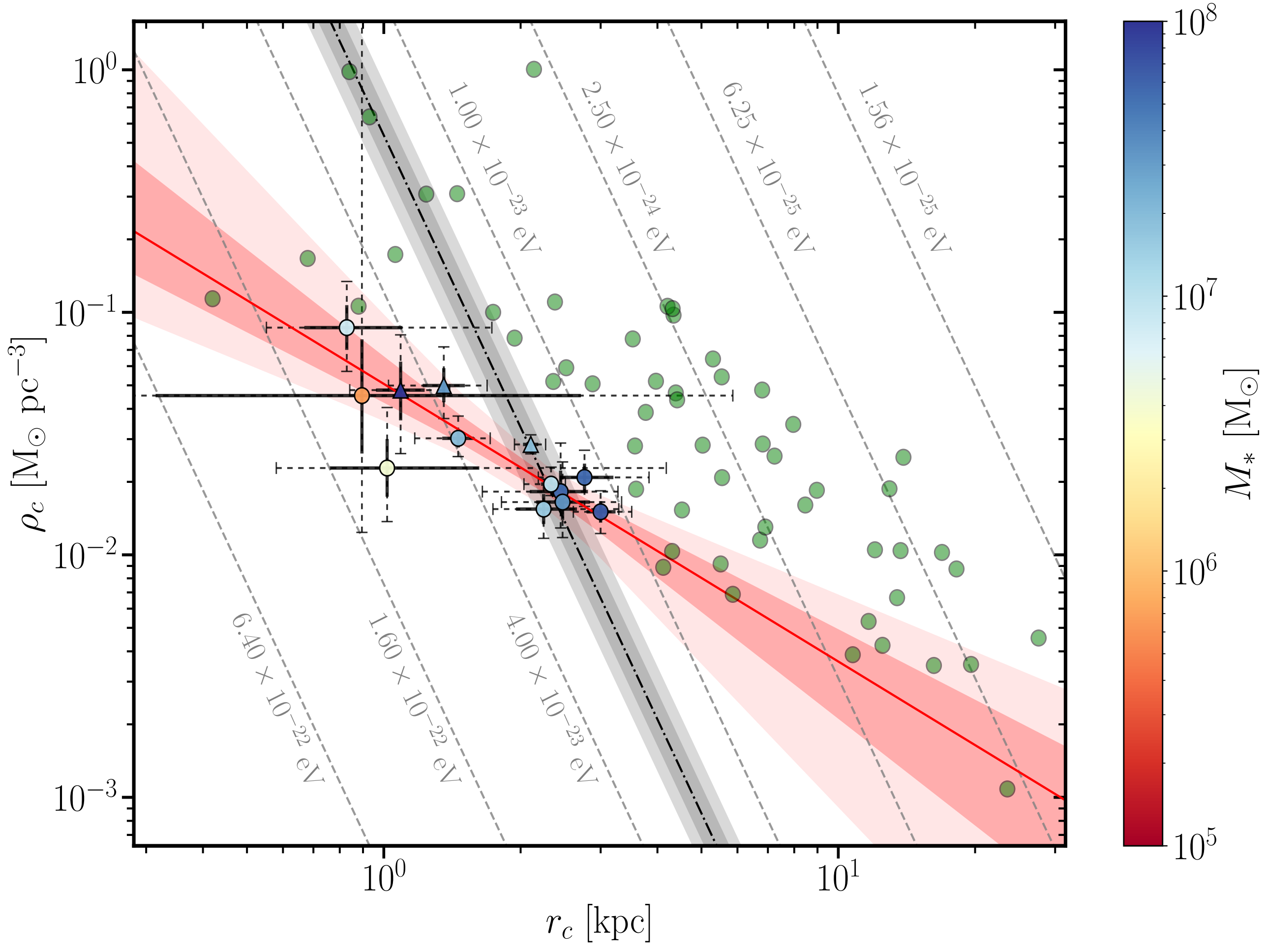




Dentler et al. 2022

Central Density – Core Radius Relation

- Galaxies tend to cluster along the expected best-fit axion mass relation
- But similarly, the preferred slope of the relation differs significantly from the (steeper) expected one
- Agreement with Rodrigues et al. 17, Deng et al. 18 (green dots) further suggests astrophysical relevance



Core - Halo Mass Relation

- **We impose the core-halo mass relation from Chan et al. 22 as a general constraint from simulations**
- **Range of allowed masses is quite broad, spanning circa an order of magnitude in scatter**
- **We perform an analysis using the favoured best-fit axion mass (right)**