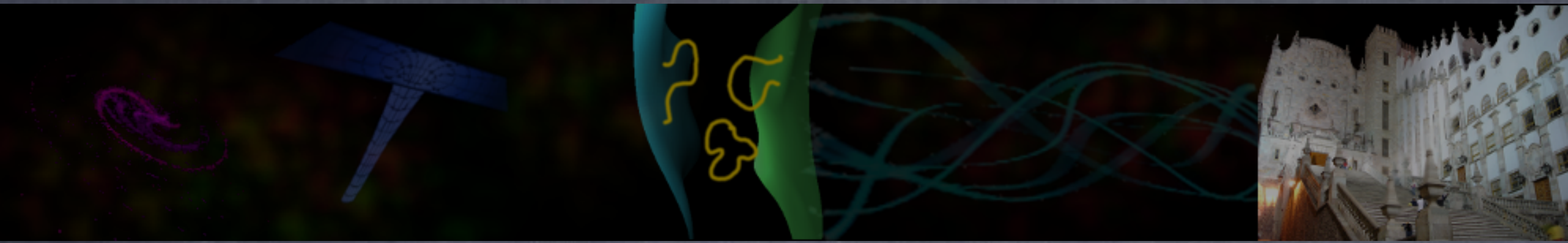

# Unbiased Constraint to the mass in axion-like dark matter models.

AXGM, D. Marsh, J. Peñarrubia & L. Ureña 2016

MNRAS stx1941/arXiv:1609.05856


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COSMO17

# **Axion-like Dark Matter** (a.ka. SFDM, BECDM, FuzzyDM, etc…)

- Dark Matter is described by a scalar field. Can be coupled to the SM: ej. Axion for QCD. Or it can be only coupled gravitationally: Ultra-Light axion. Axion like particles can also appear in String theory.

Hu et. al 2000, Matos & Ureña 2002, P. Sikivie and Yang, 2009. Marsh &Silk 2013, Shive et. al 2014, and many others.

Most recent review on the subject: H. Lam, J. Ostriker, S. Tremaine, Edward Witten arXiv:

ULA's allows a field representation; one specifies a field potential. Here $V(\phi) = m_a^2\phi^2$

# MOTIVATION

Ultra Light Axion Dark Matter, can provide, or may be not, a solution to the small scale issues. In any case, so far it is a compelling candidate to be the DM, as any CDM, worth to be tested .

# Missing Satellite "problem" since 2000's

- N-Body Simulations of only CDM predicts much more substructure than observed.
- Observational problem: Determine the precise number of satellite galaxies. Luminosity below detection threshold, non-complete samples, etc.
- Theoretical problem: What makes a halo not to host/produce stars so that they are undetectable. Or else, what inhibits the creation of small halos?

"Is theres a missing satellite problem with CDM ? The answer is likely to be not in the era of DES and LSST"

Hargis et. al 2014

# Cusp Vs Core "problem" since 2000's

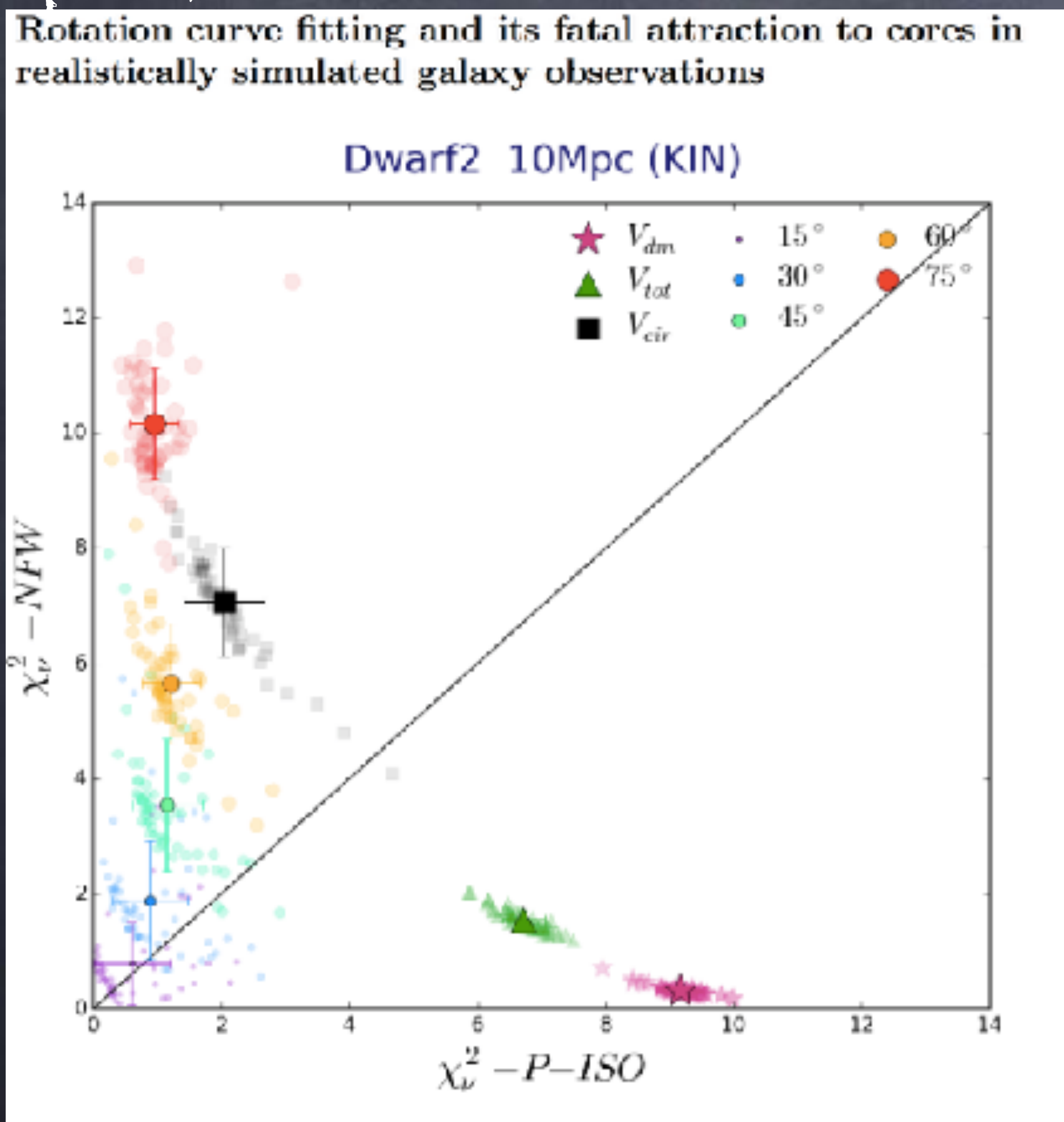
- N-Body Simulations of only CDM predicts cusp density profiles (down to simulation resolution). Some galaxy's observations present evidence for a core profile.

- Baryonic effects are very important, two effects compite: Contraction Vs Feedback. Some groups find cores, some others find cusps, in simulations of DM+Baryons. Sawala et al. 2016; Zhu et al. 2016, Peñarrubia et al. 2012 , Read et al. 2016

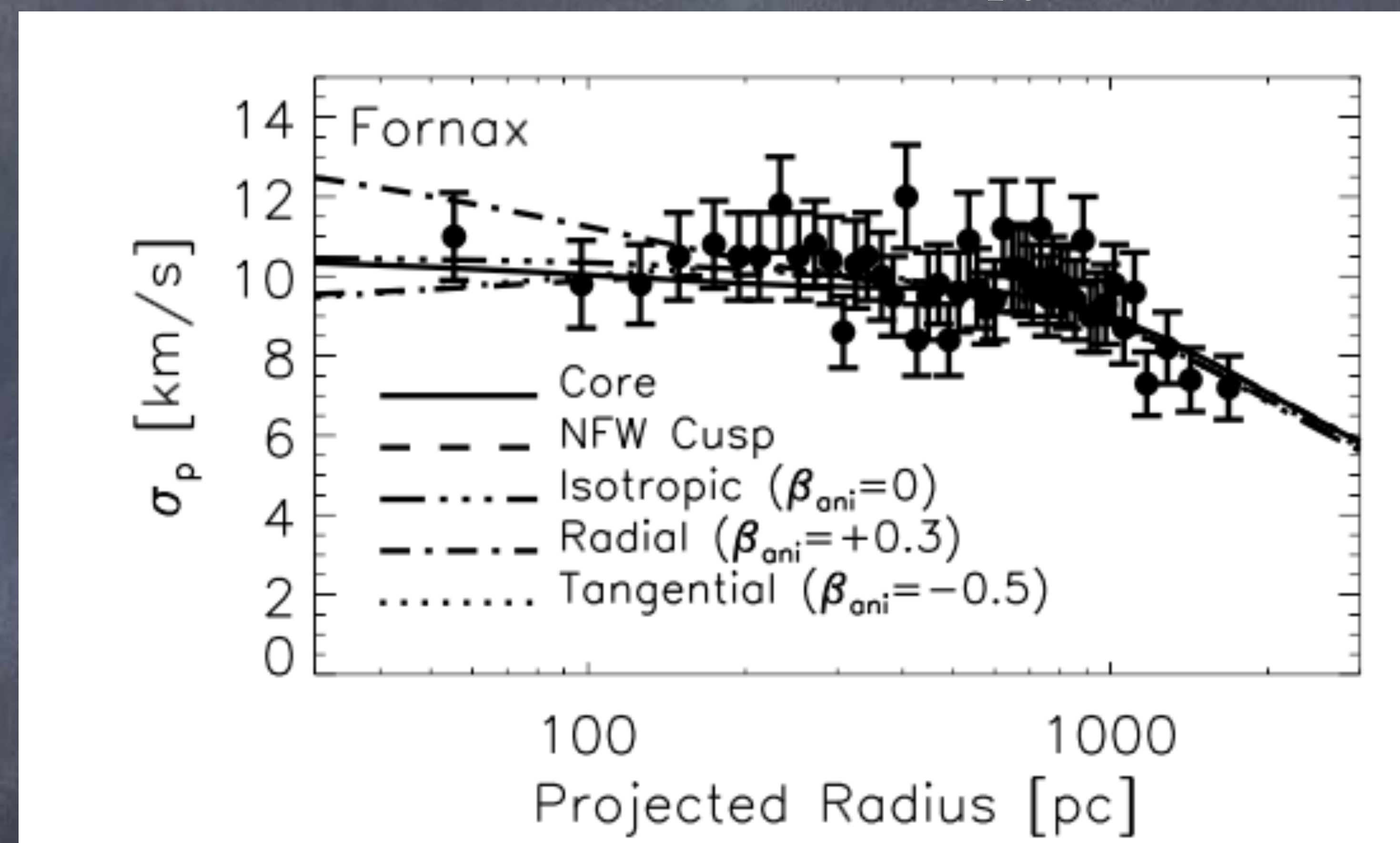
- Some DM candidates predicts core profiles (ignoring baryonic effects), ¿what is the final density profile in the presence of barions?.

# Cusp Vs Core status: No consensus

Observational problem: Degeneracies between different effects makes not trivial to recover the "true" density profile.




In dSph's, a strong degeneracy with stellar orbital anisotropy. (more later)

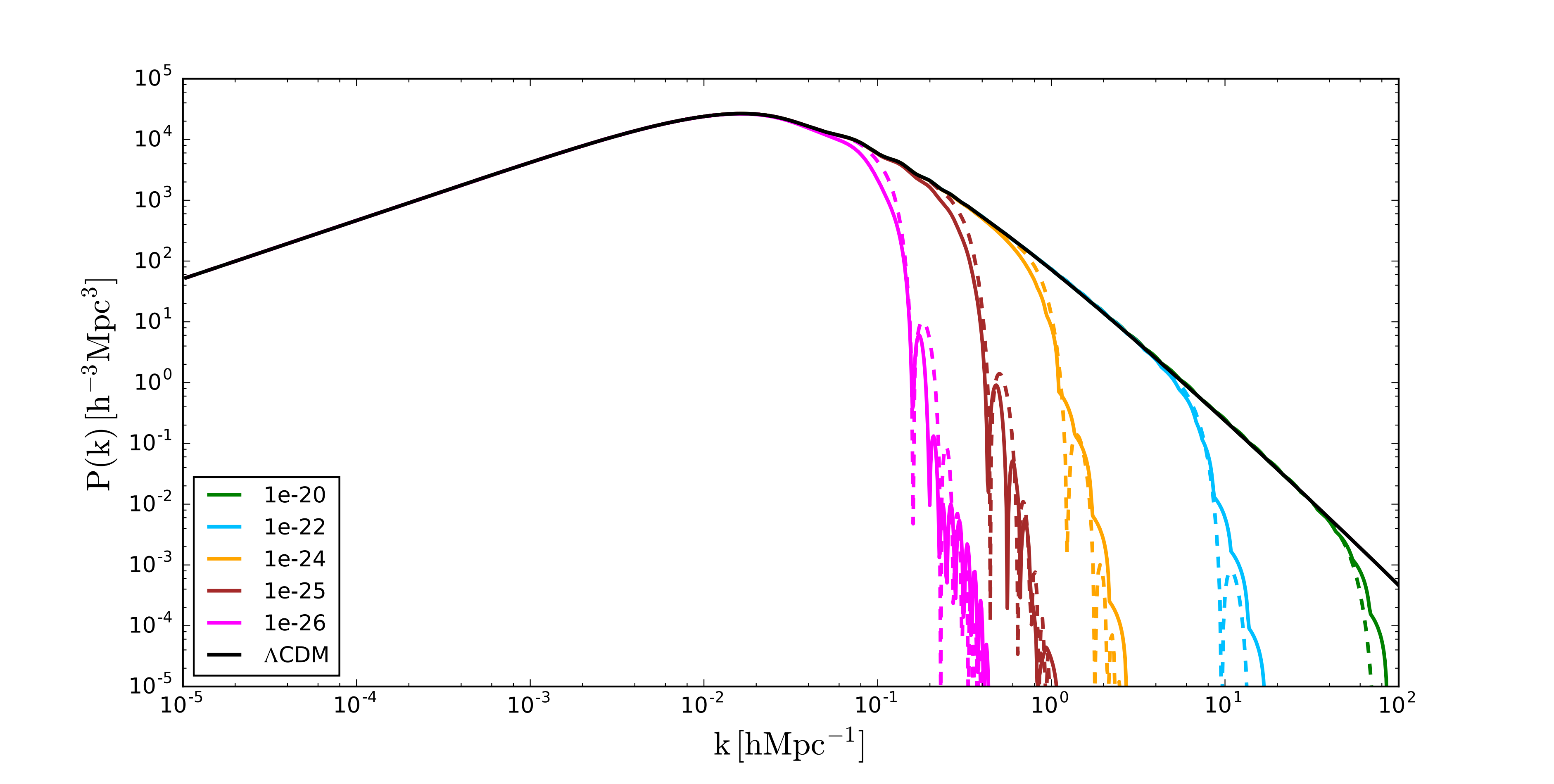



arXiv: 1108.2404v3

- In disk/irregular Galaxies:
  - Gas pressure effect in the center.
  - Projection effects
  - Finite Spatial

arXiv: 1602.07690v1

# UL-Axion DM at large scales




The mass of the scalar field sets a cut-off in the mass power spectrum. Which means less to no structure formed below cut-off scale

L. Ureña & AXGM, JCAP 2016

## Constraints

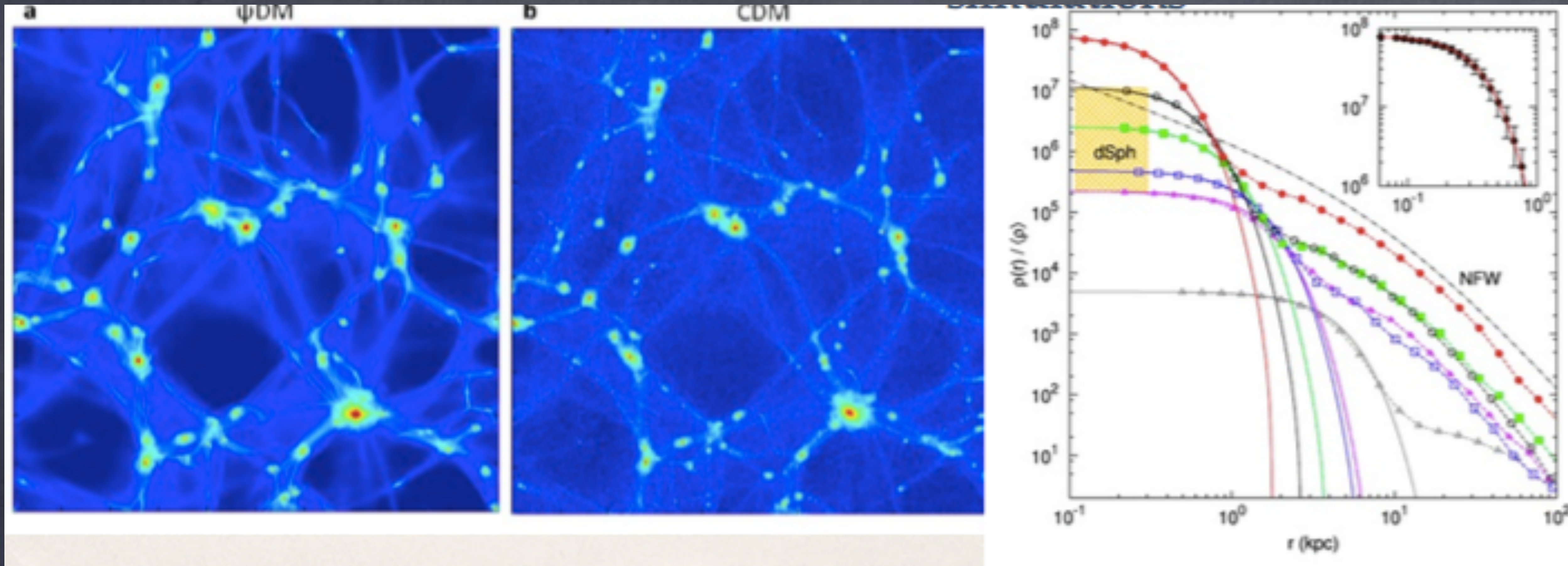
$m_a > 10^{-24}\text{eV}$ CMB Matos & Ureña 2002, 2009. Marsh &Silk 2013, Hlozek et al. 2015

$m_a > 2 \times 10^{-21}\text{eV}$ Ly-alpha Armengaud et. al.2017, Irsic et. al. 2017

$m_a < 1.1 \times 10^{-22}\text{eV}$ Marsh & Pop 2015

$m_a \approx 3.7 - 5.6 \times 10^{-21}\text{eV}$ Calabrese & Spergel 2016

# UL-Axion DM halo model




Hsi-Yu Schive1, Tzihong Chiueh & Tom Broadhurst, Nature,06/2014

$$\rho(r) = \rho_{\rm sol} \begin{cases} \dfrac{1}{(1+(r/r_{\rm sol})^2)^8} & \text{for} \quad r < r_\epsilon \\ \dfrac{\delta_{\rm NFW}}{r/r_s\,(1+r/r_s)^2} & \text{for} \quad r \geqslant r_\epsilon \end{cases} .$$

where

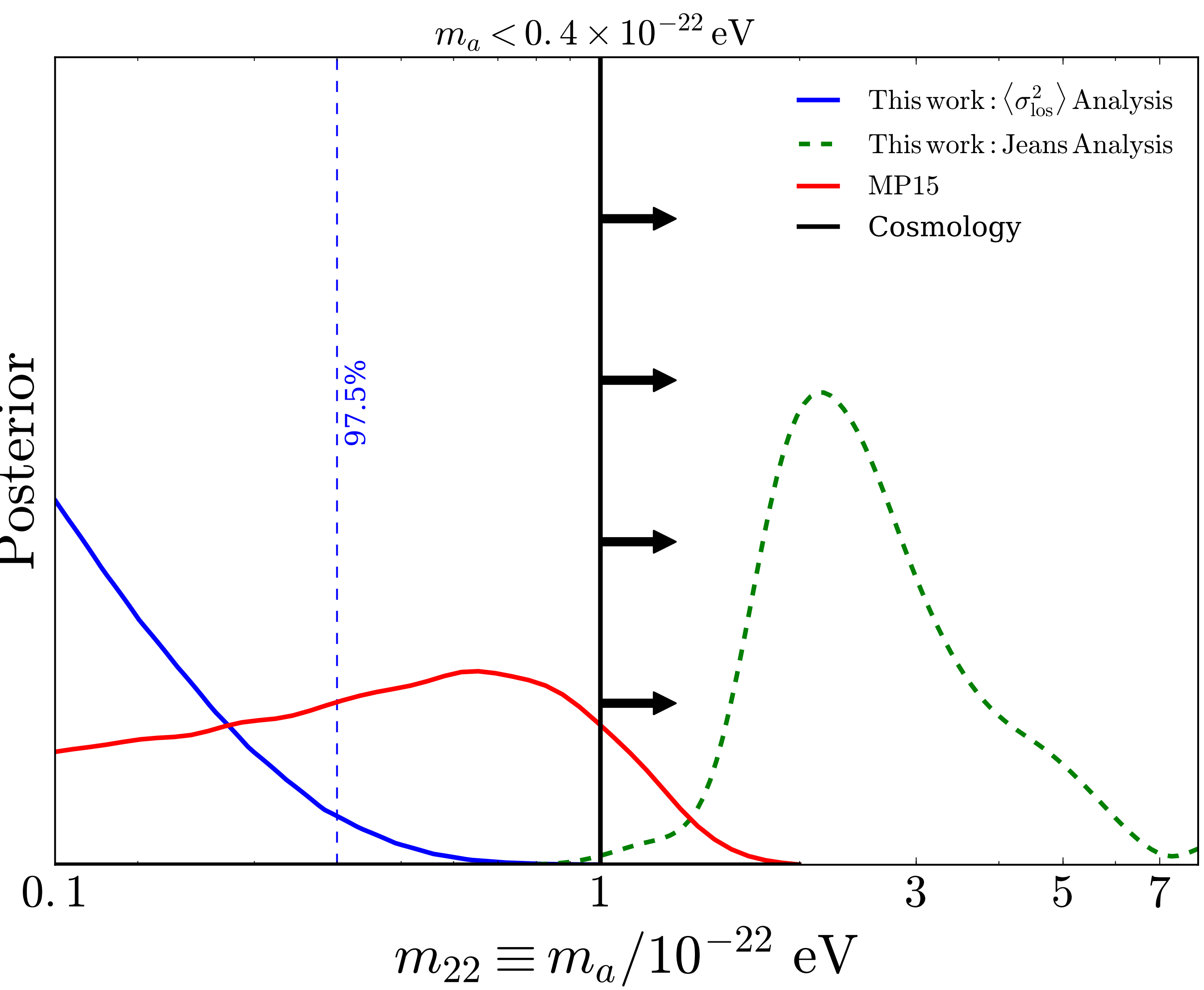
$$r_\epsilon = r_{\rm sol}(\epsilon^{-1/8} - 1)^{1/2},$$

and

$$\delta_{\rm NFW} = \epsilon \rho_{\rm sol} \left( \frac{r_\epsilon}{r_s} \left(1 + \frac{r_\epsilon}{r_s}\right)^2 \right) .$$

$$r_{\rm sol} = \left[ \frac{\rho_{\rm sol}}{2.42 \times 10^9\ {\rm M_\odot kpc^{-3}}} \left( \frac{m_a}{10^{-22}{\rm eV}} \right)^2 \right]^{-0.25}$$

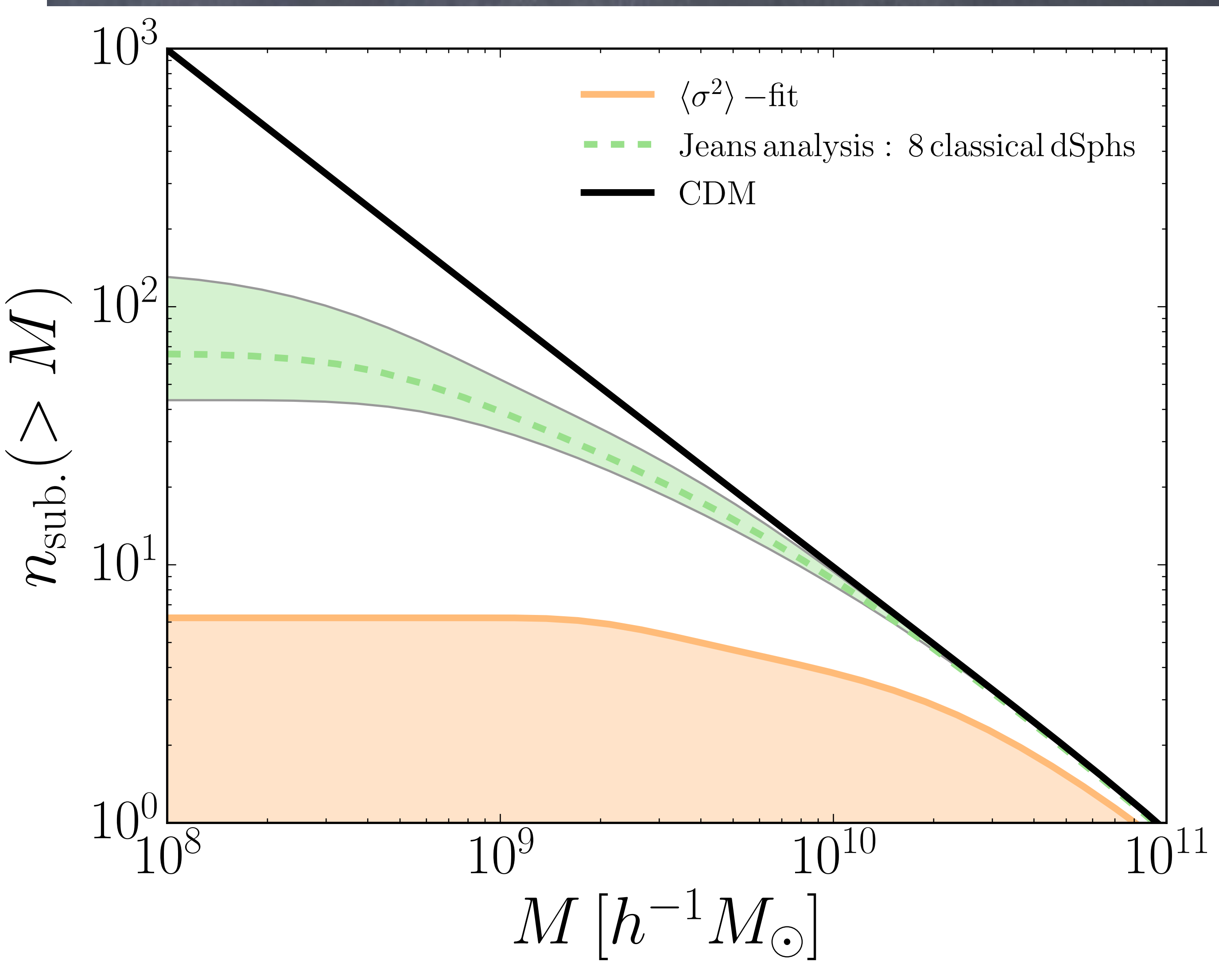
2 free parameters per halo + free anisotropy.
we treat the axion mass as universal parameter.




# Long story short:

New unbiased constraint in axion DM model, from dSph's kinematics, is in tension with previous analysis of galaxy kinematics.

A, VERY, simple calculation of the number of substructures shows that with this mass the ULA-DM suffers a catch 22 problem. Needs of simulations to be confirmed.



# dSph's kinematics & constraints to Axion DM mass

# Dwarf Spheroidal Galaxies & Axion Dark Matter

$$L_* \approx 10^6 L_\odot$$

$$\Upsilon_* = 100 - 1000$$

to reproduce kinematics with only stellar component

$$< \sigma_* > \approx 10 \mathrm{km/s}$$

We only observe one component of the velocity dispersion along the line of sight.

$\beta = 0$ Isotropic

$\beta$ Non-isotropoic. Not necessarily constant anisotropy

# dSph's kinematics: Constraints to axion DM

## Stars and the Jeans eqn.

e.g. Binney and Tremaine
Assuming spherical symmetry

Relate DM mass, to stellar dist. ν and velocity anisotropy β:

$$\frac{1}{\nu}\frac{d}{dr}\left(\nu\langle v_r^2\rangle\right) + 2\frac{\beta\langle v_r^2\rangle}{r} = -\frac{GM}{r^2}.$$

Integrate density

Assume constant β and Plummer profile for stars:

$$\nu(r) = \frac{3L}{4\pi r_{\rm half}^3}\frac{1}{[1+(r/r_{\rm half})^2]^{5/2}}.$$

measured for dSphs as single population

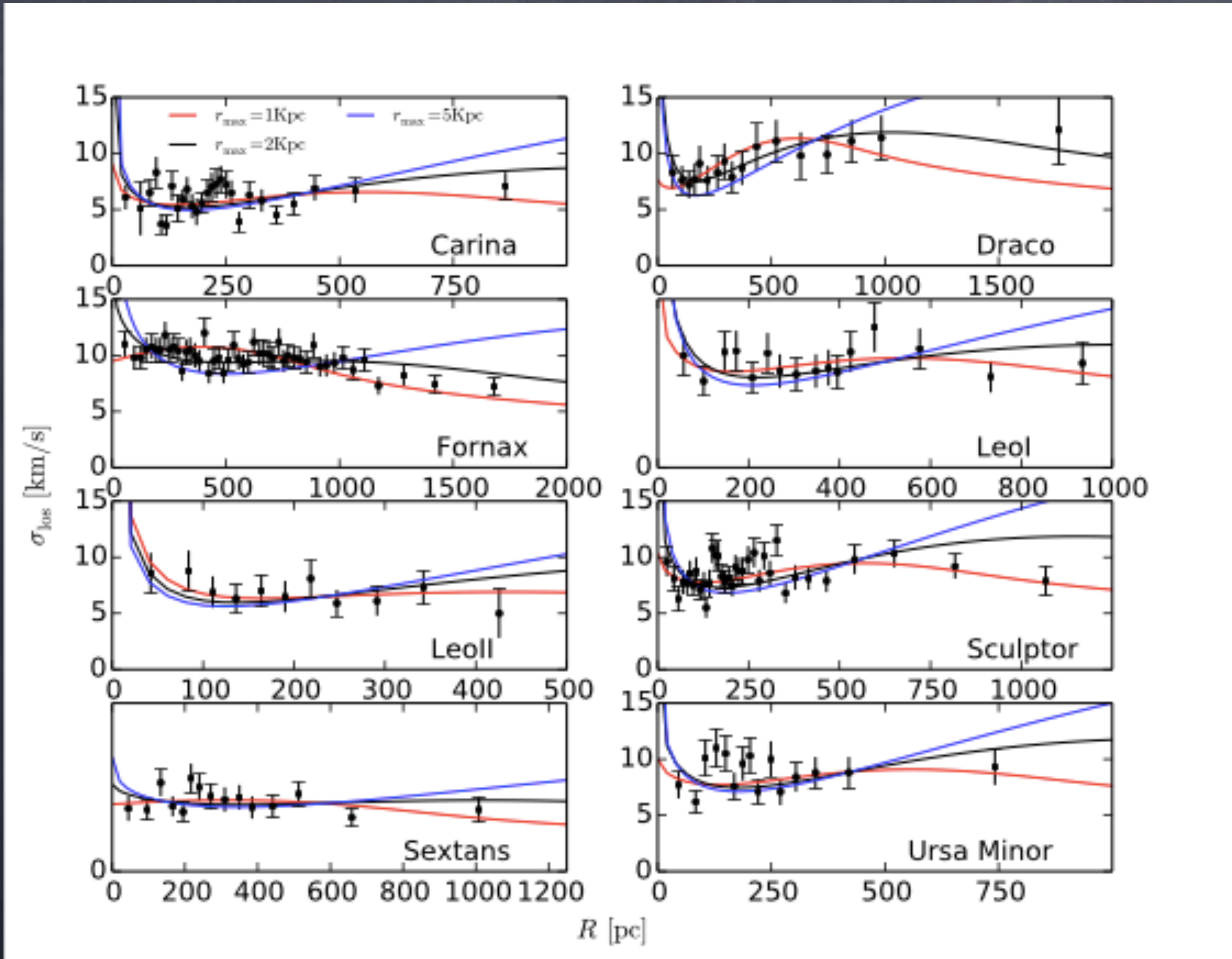
→ Projected l.o.s. velocity dispersion with β as free param.

$$\sigma_{\rm los}^2 = \frac{2G}{I(R)}\int_R^\infty dr'\nu(r')M(r')(r')^{2\beta-2}F(\beta,R,r').$$

DATA: Walker et al (2009)

From Plummer

Projection




Axion Like DM soliton only.

First done (for different profile) in
A. Diez-Tejedor, AXGM, S. Profumo, 1404.1054v2. Now done with the ULA+NFW profile.

# Soliton+NFW halo model Joint/Individual Analysis Comparison

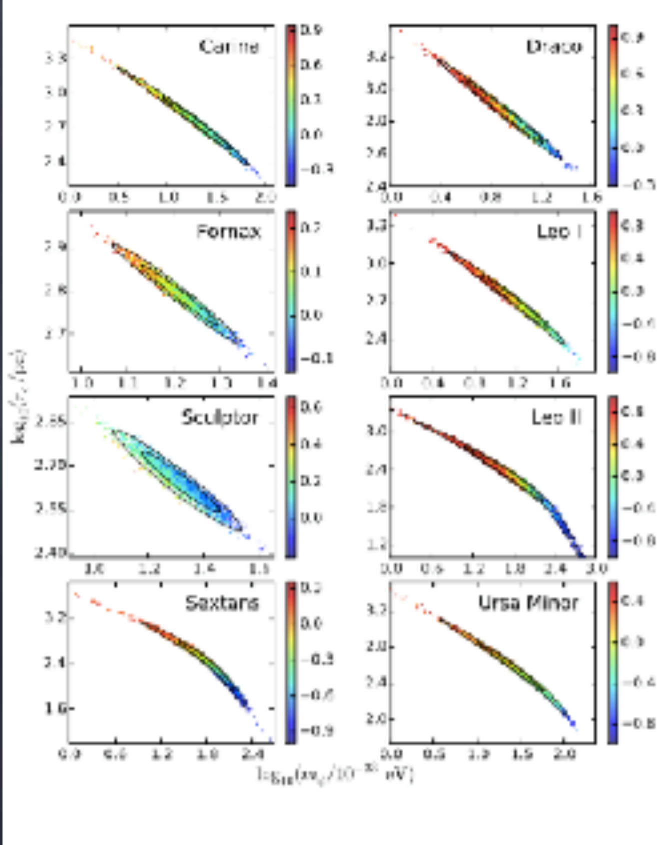



Figure 2. Posterior distributions of $m_B$ and $r_c$ colored by $\beta$ for each dSph in our MCMC analysis. Contours show the $1\sigma$ and $2\sigma$ confidence regions. The confidence intervals of the model parameters for each dSph are also listed in Table 1.

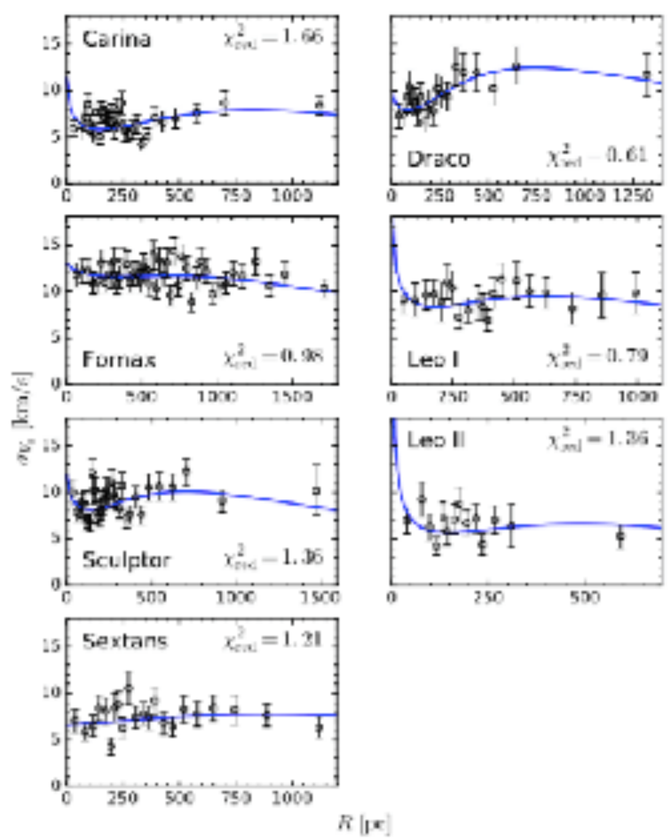
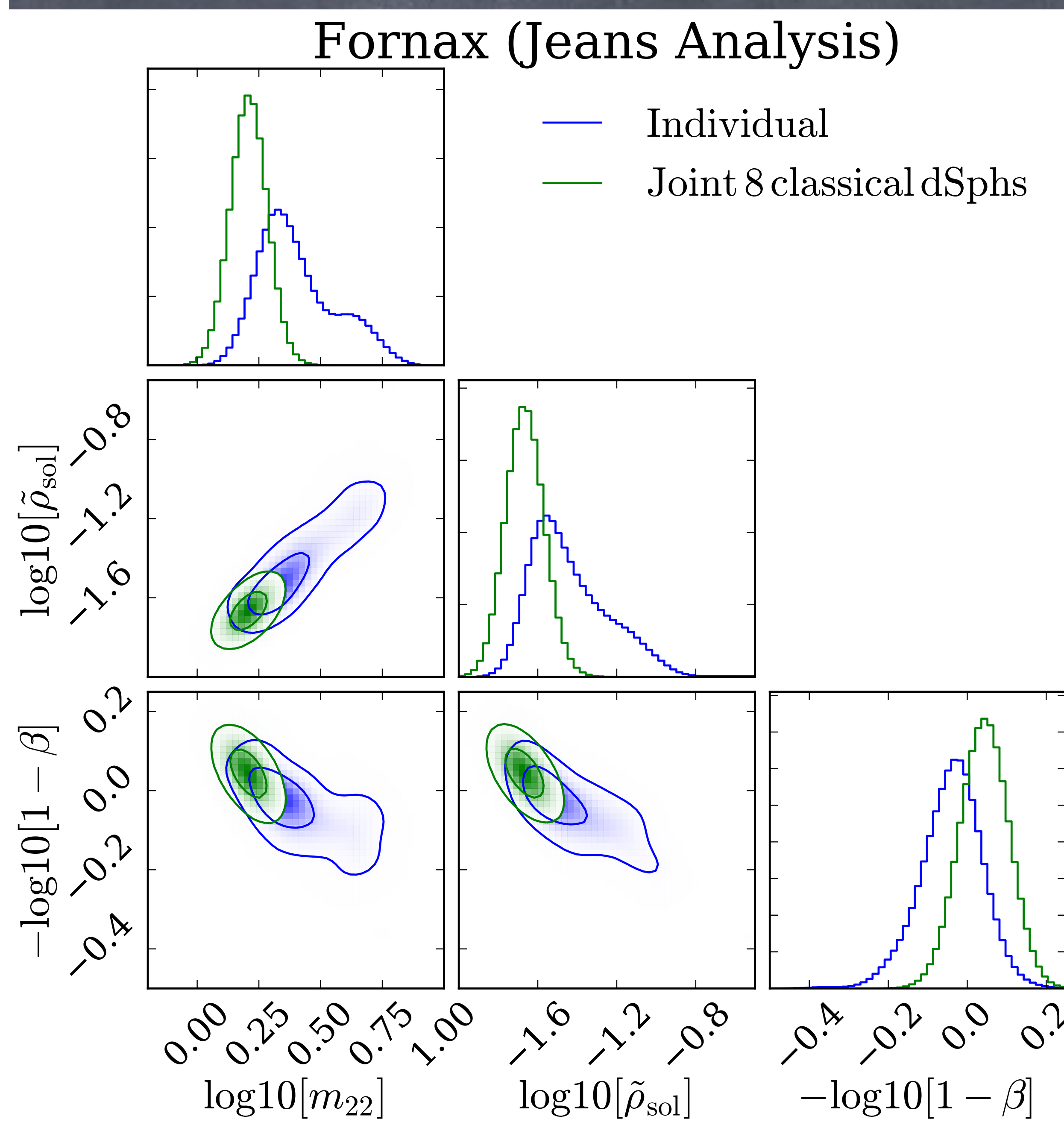



Figure 3. Same as Figure 1 but for the observational data set of Walker et al. (2007). The confidence intervals of the model parameters for each dSph are listed in Table 1.

$$m_a \approx 2.4 \times 10^{-22} eV$$

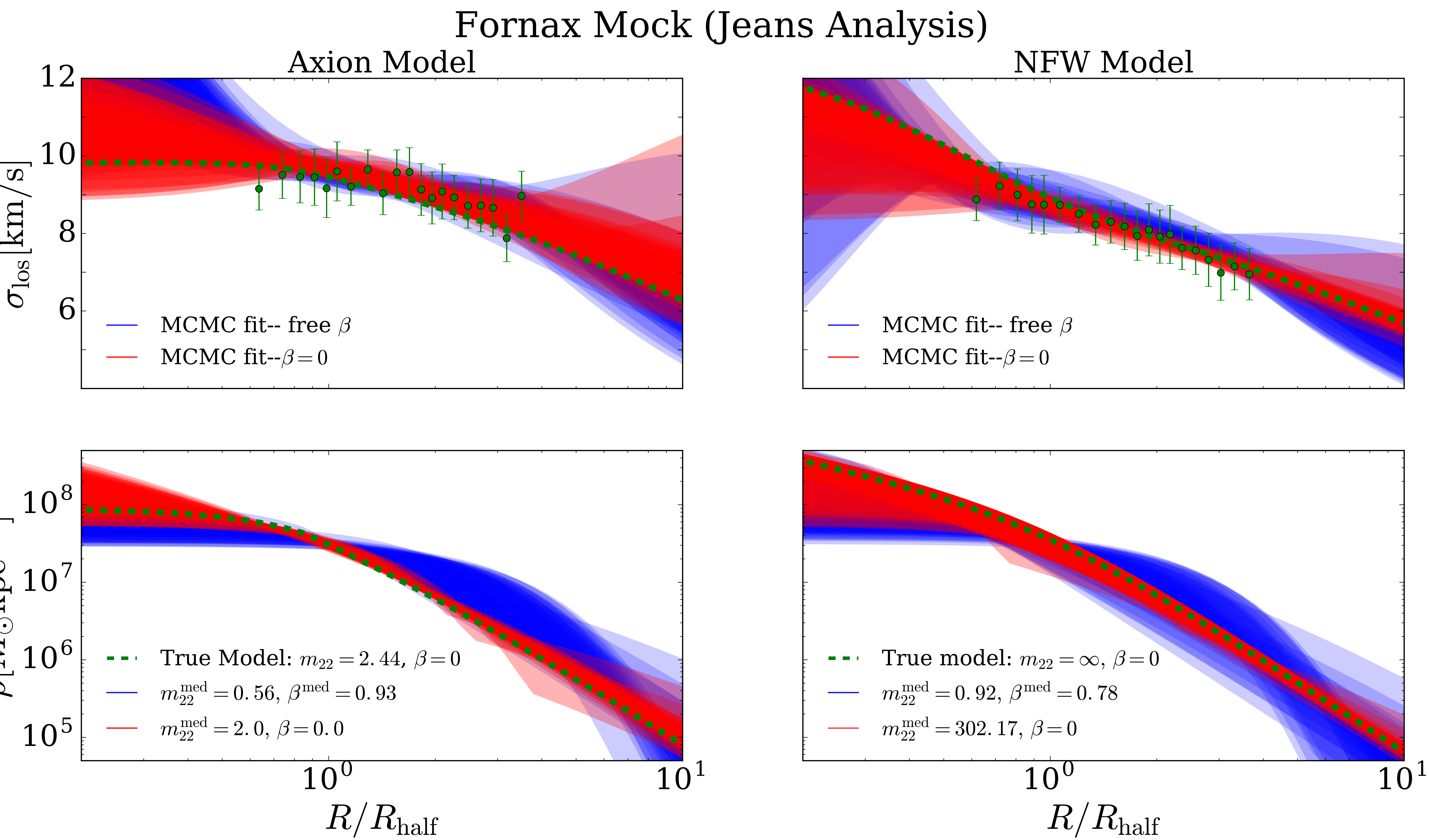



Chen. et. al arXiv 1606.09030v1

Looks nice but it is completely biased. Fortunately we knew it before trying to publish.

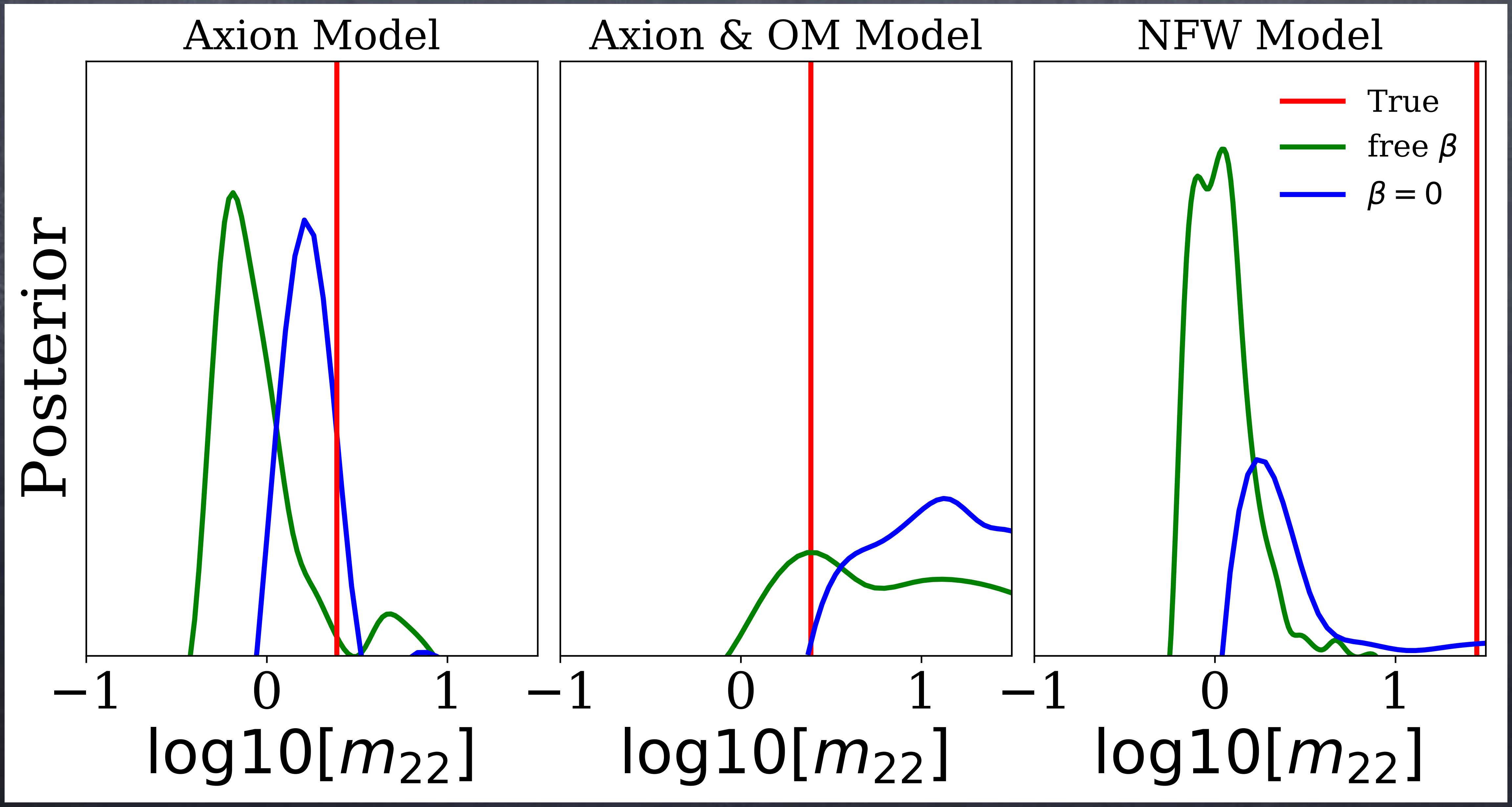
# What is wrong? Density Profile Vs Anisotropy

Test: Apply Jeans analysis using the axion density profile to simulated galaxies with different density profiles and isotropy.

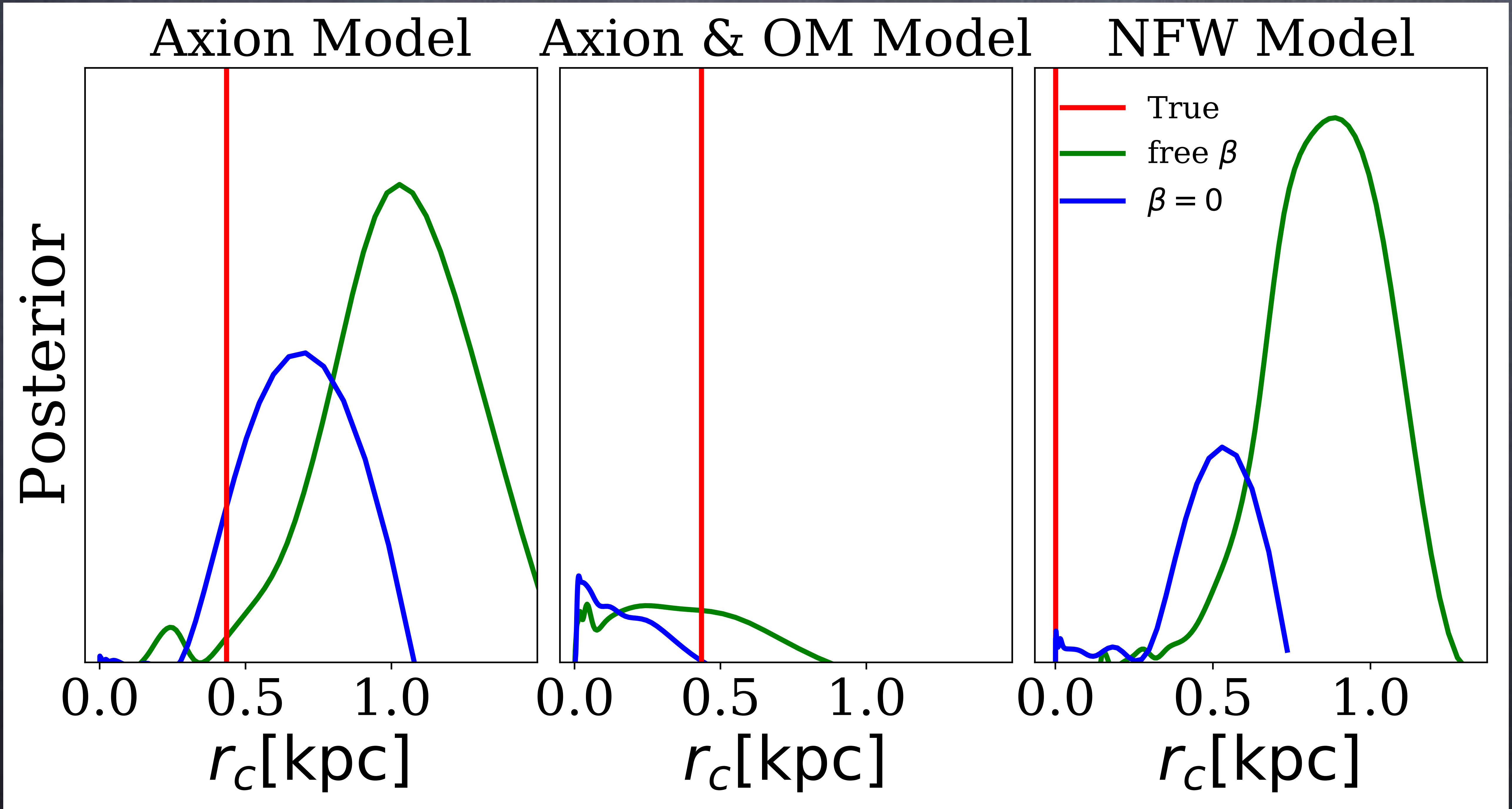


- Analysis of galaxy mock with the corresponding density profile, returns a biased result.

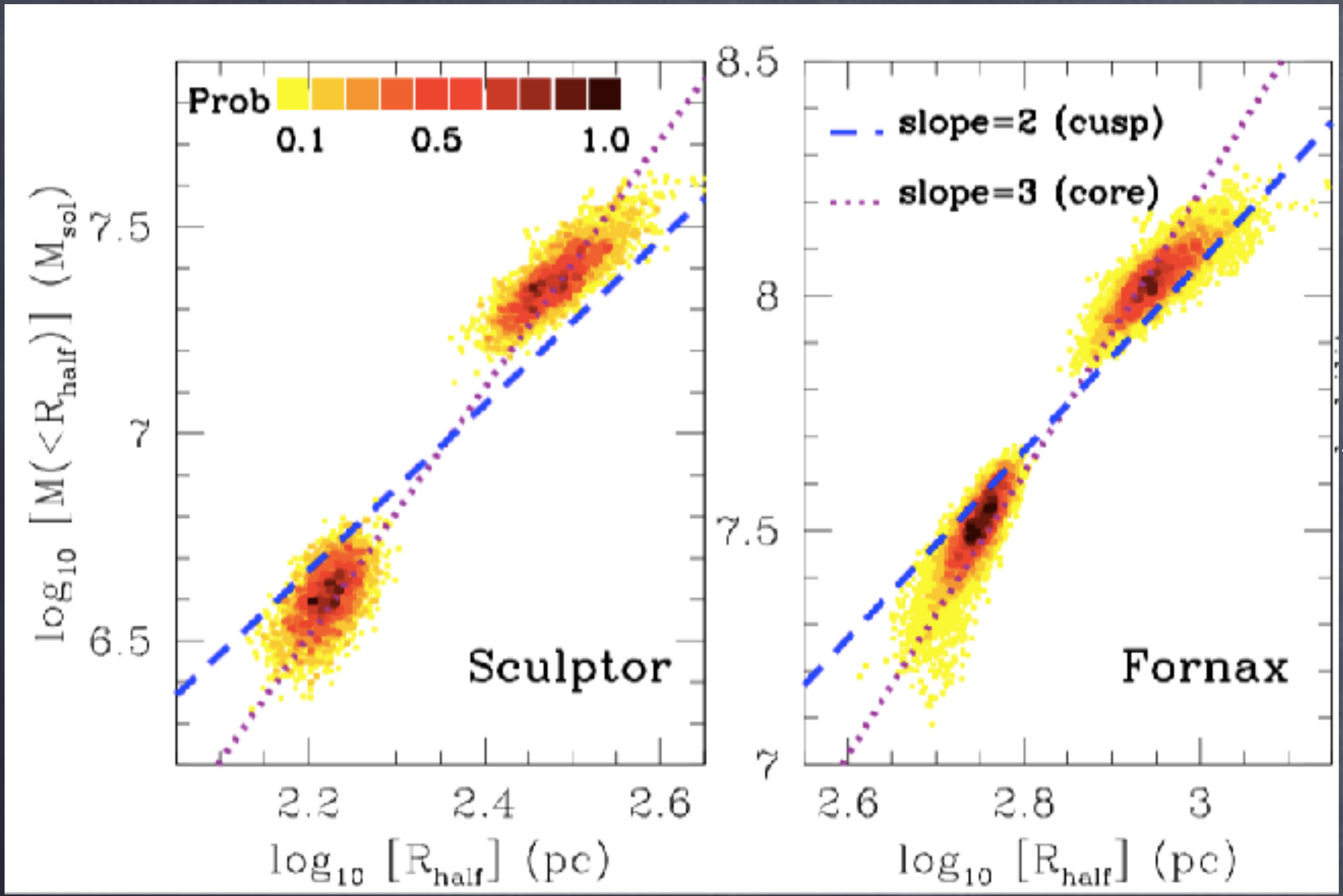
- We tend to recover a different axion mass even when a cusp (large axion mass and large central density) is the density profile of the simulated galaxy.



We tend to recover a large core radius (~0.3 r_sol) even when a true density profile of the simulated galaxy have no core (NFW).



# Then what?... review another observable




Walker &Peñarrubia 2011

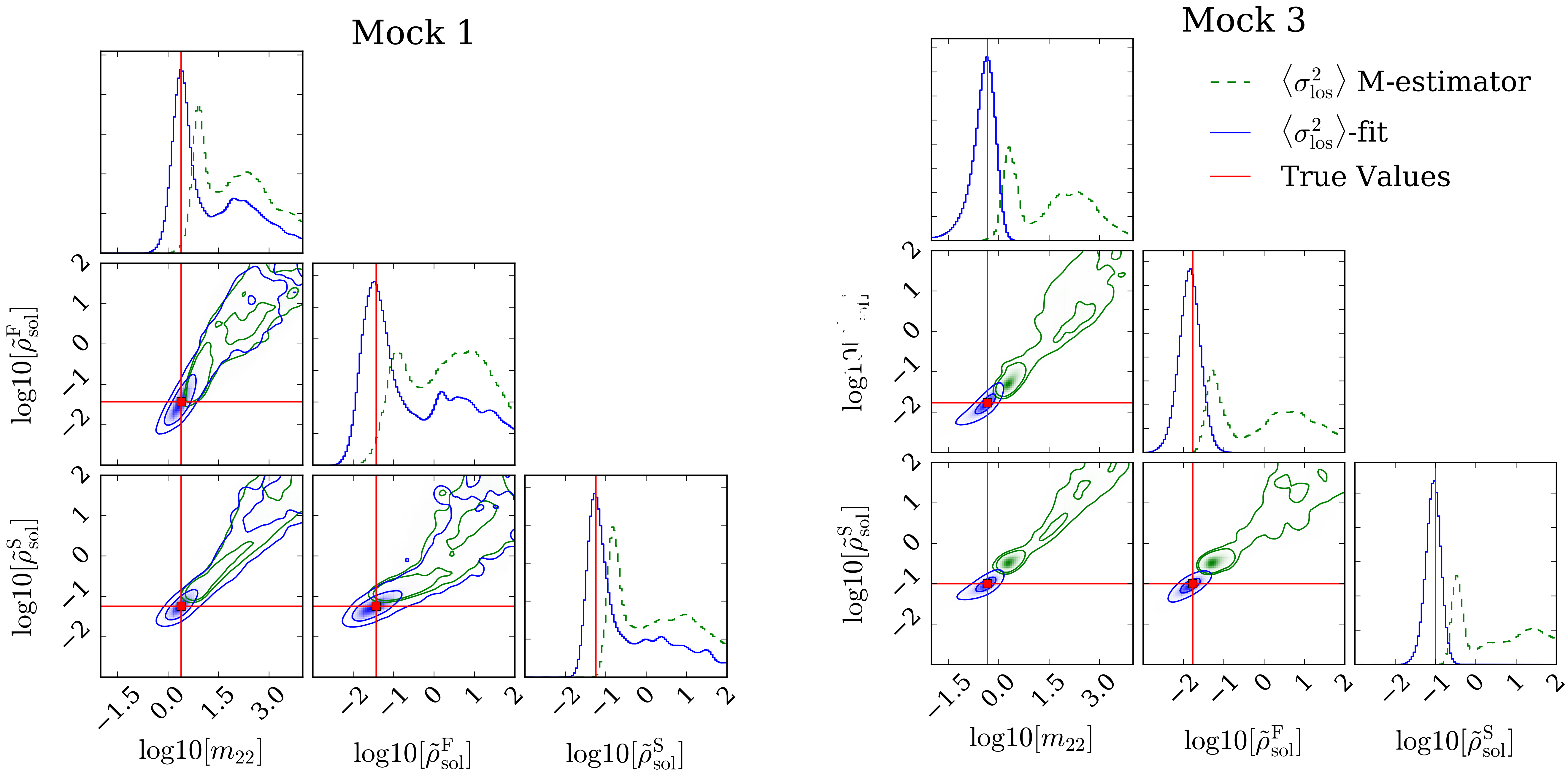
Use mass estimator

$$< \sigma^2_{\rm los}(r_{\rm half}) >= \frac{2GM(< r_{\rm half})}{5r_{\rm half}}$$

We propose to compute the mean velocity dispersion as

$$< \sigma^2_{\rm los}(r_{\rm half}) >= \frac{\int_0^\infty \sigma^2_{\rm los}(R')I(R')R'dR'}{\int_0^\infty I(R')R'dR'}$$

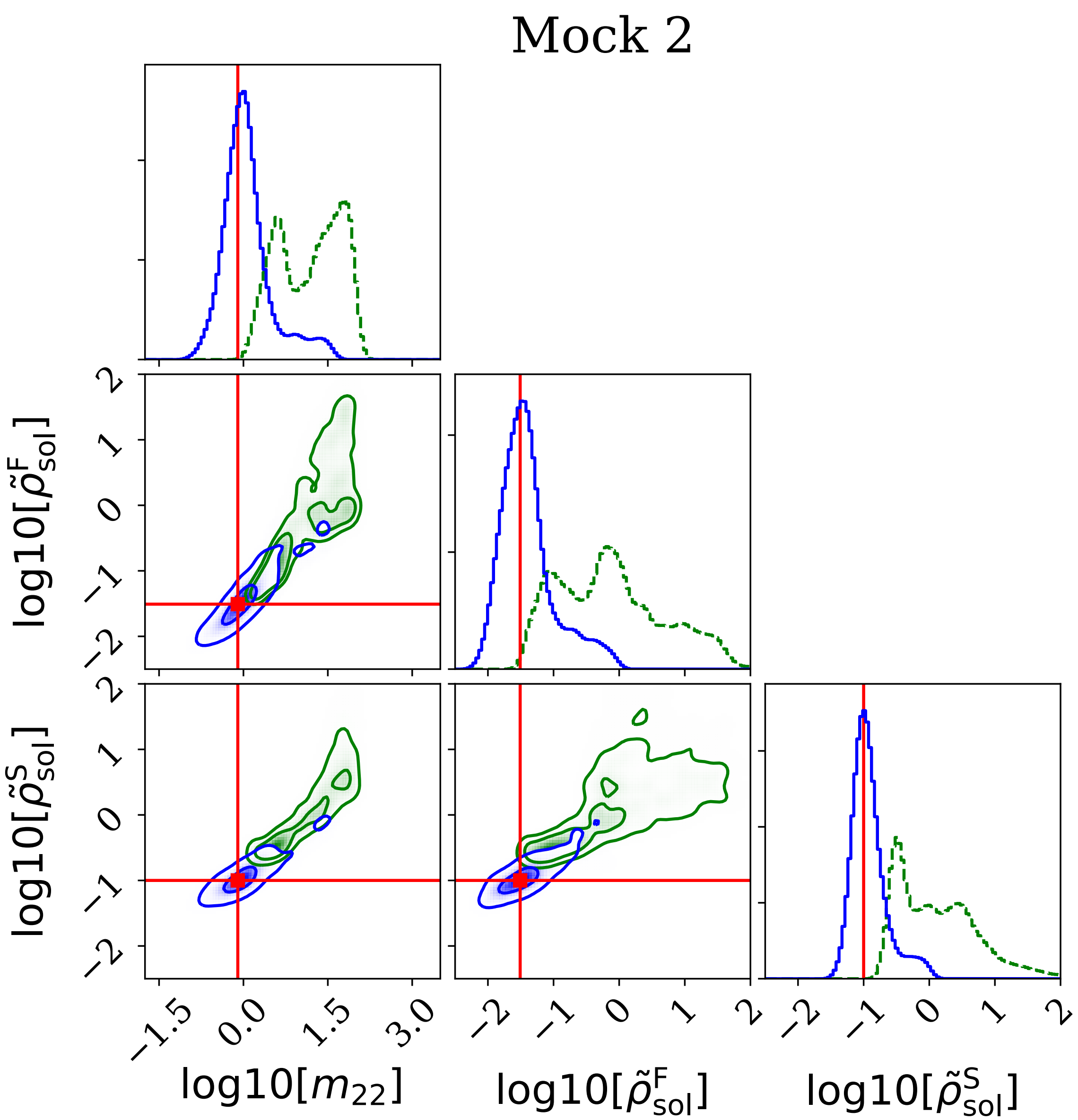
# Again, we test both estimators in synthetic data. Isotropic mocks

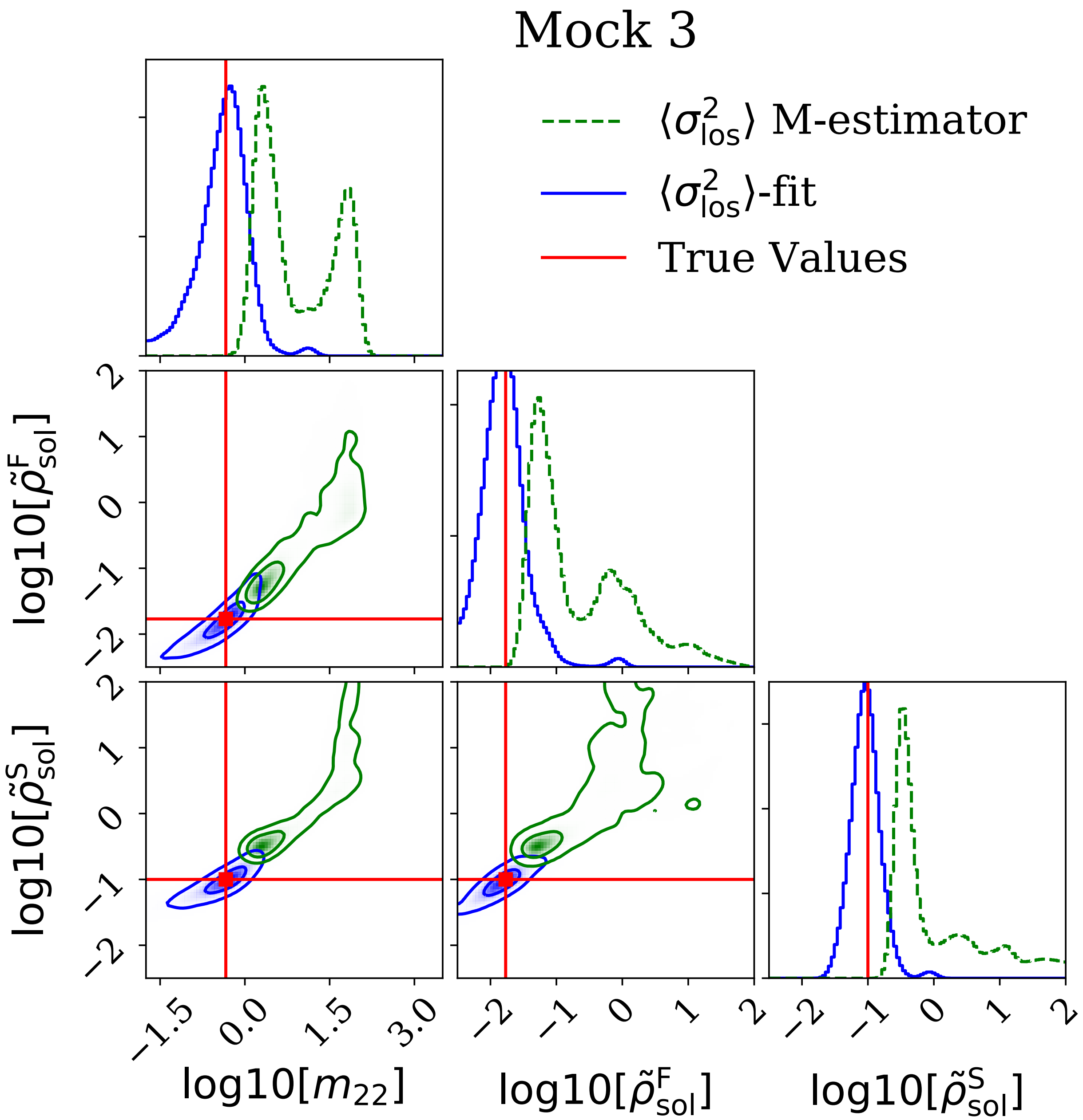



$$< \sigma^2_{\rm los}(r_{\rm half}) >= \frac{\int_0^\infty \sigma^2_{\rm los}(R')I(R')R'dR'}{\int_0^\infty I(R')R'dR'}$$

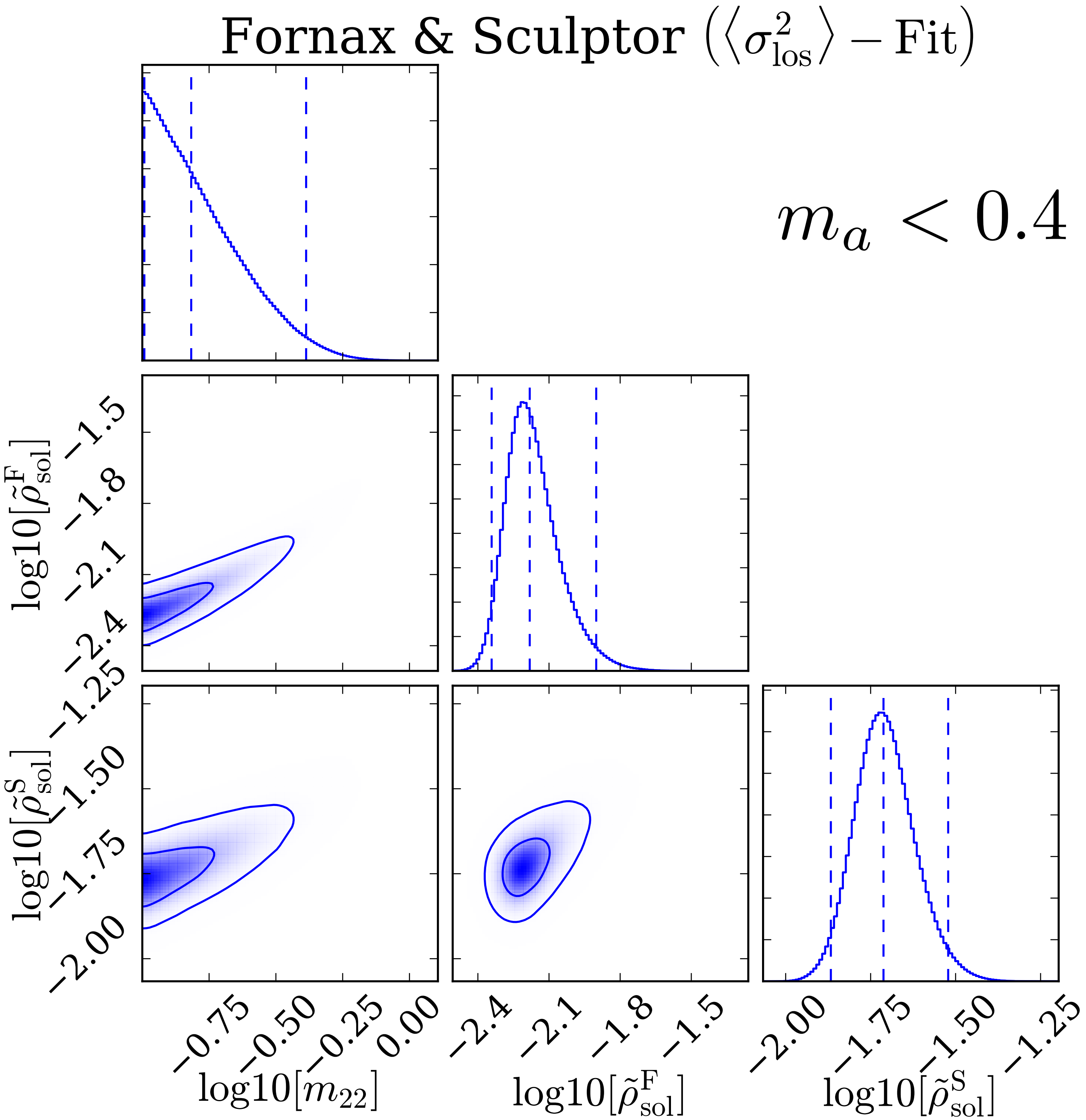
Use emcee (Foreman et. al 2013). Check convergence with spectral analysis (Dunkley et al. 2005)

# Non-isotropic mock data



# Now applied to real data




$$m_a < 0.4 \times 10^{-22} eV$$

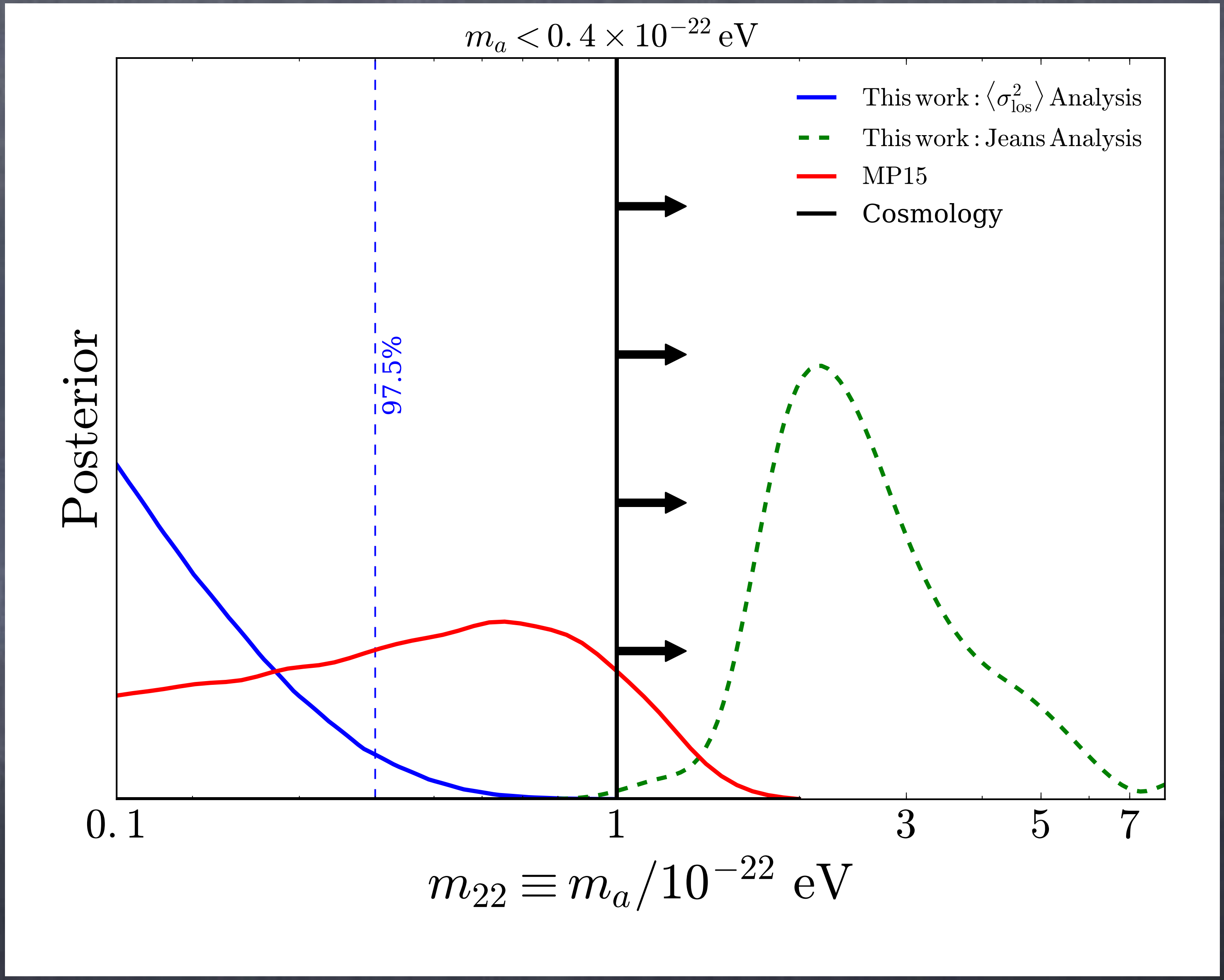
The axion mass is a common parameter to Fornax & Sculptor. Fit to the 2 stellar population in each galaxy simultaneously.

# Final remarks

- The galactic scales are very promising to find constraints to DM candidates. Need to be careful about degeneracies and consider the dynamical interaction between DM and Baryons.

- Constraints to Axion Mass using dSph's can be highly biased. We proposed a method to extract unbiased constraints.

- Our limit for the axion mass is at the edge of compatibility with other observables.



# FIG FESTIVAL, León, Gto, November


Thanks