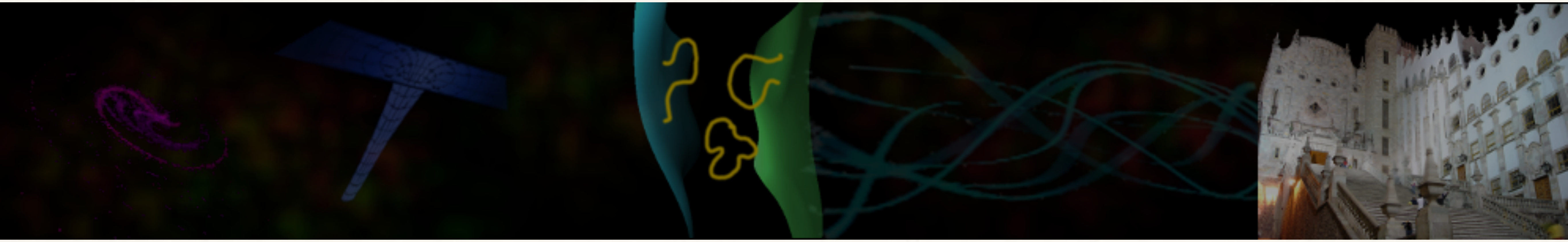

Signals?/Constraints for axion-like particles in dSph's

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Guanajuato


ZACATECAS
NAYARIT
SAN LUIS
POTOSÍ
GUANAJUATO
JALISCO
HIDALGO
MICHOACÁN
COLIMA
PUEBLA
GUERRERO
Google

Campus León

Cosmology Group

Other members working in string theory, particle physics, GR ,etc..

León

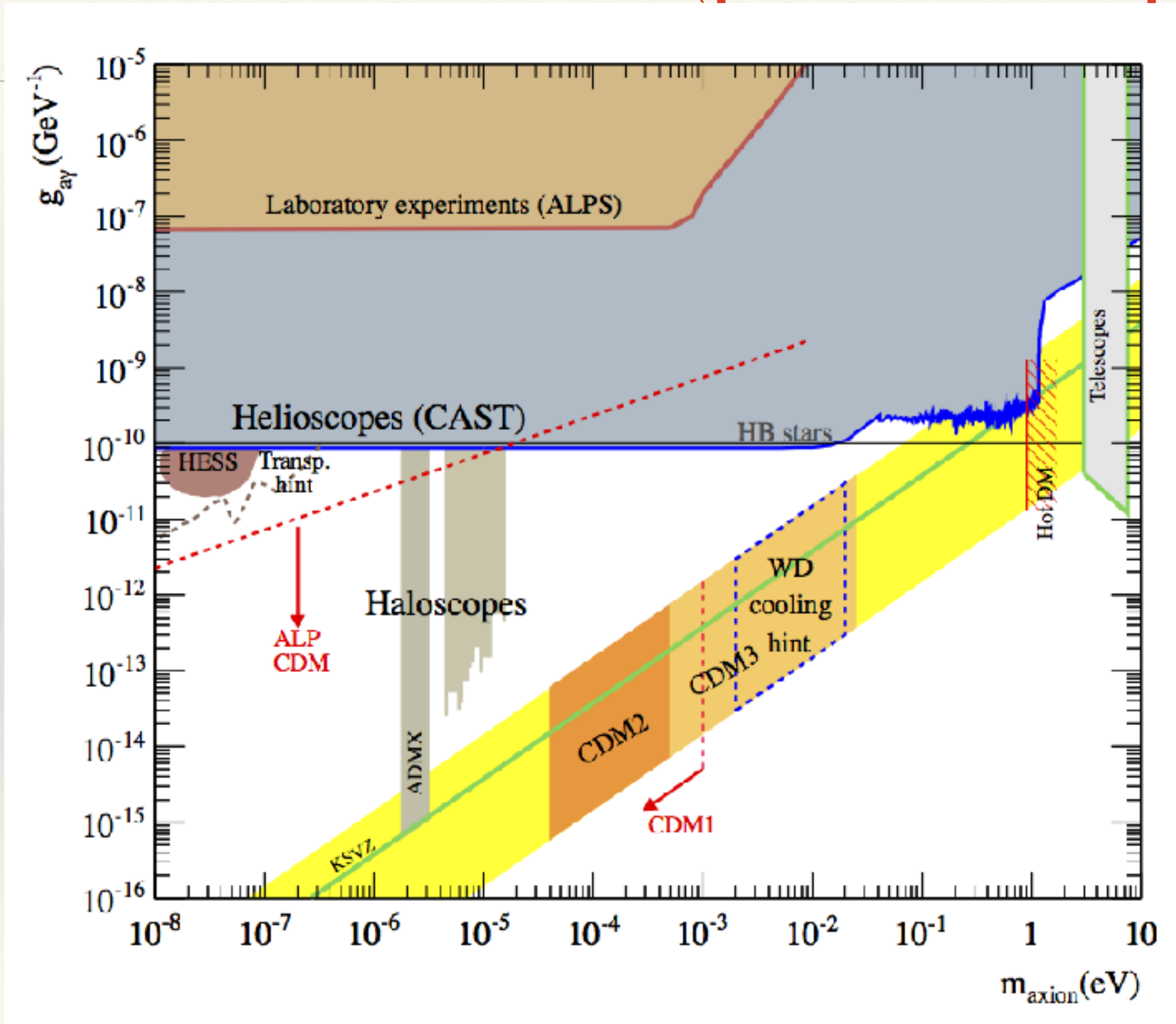
Axion Dark Matter

- First proposed to solve the strong CP problem in QCD. The axion mass is given by:

$$m_{a,QCD} \approx 6 \times 10^{-6} \frac{(10^{12} GeV)}{f_a/C}$$

Axion production can be either thermal or non-thermal. Axions can be very light, stable, and still be cold.

Axion detection limits (photon coupling)



The International Axion Observatory IAXO, *Letter of Intent 2013*

Axion / Axion like

- QCD axion. Mass is fixed by f_a.

- In string theory and supergravity is more general and can refer either to matter fields, or to pseudoscalar fields associated to the geometry. It requires to fix both (m_a, f_a)

- In a more general case the term refers to light scalar field (or pseudo scalar field, for cosmology the distinction is not relevant in most cases.) It is also a two parameter model. (m_a, f_a)

- Occupation numbers are large and can be modeled by classical field equations. Provided we specify a scalar field potential. One common choice is

$$V(\phi) = \Lambda_a^4 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$

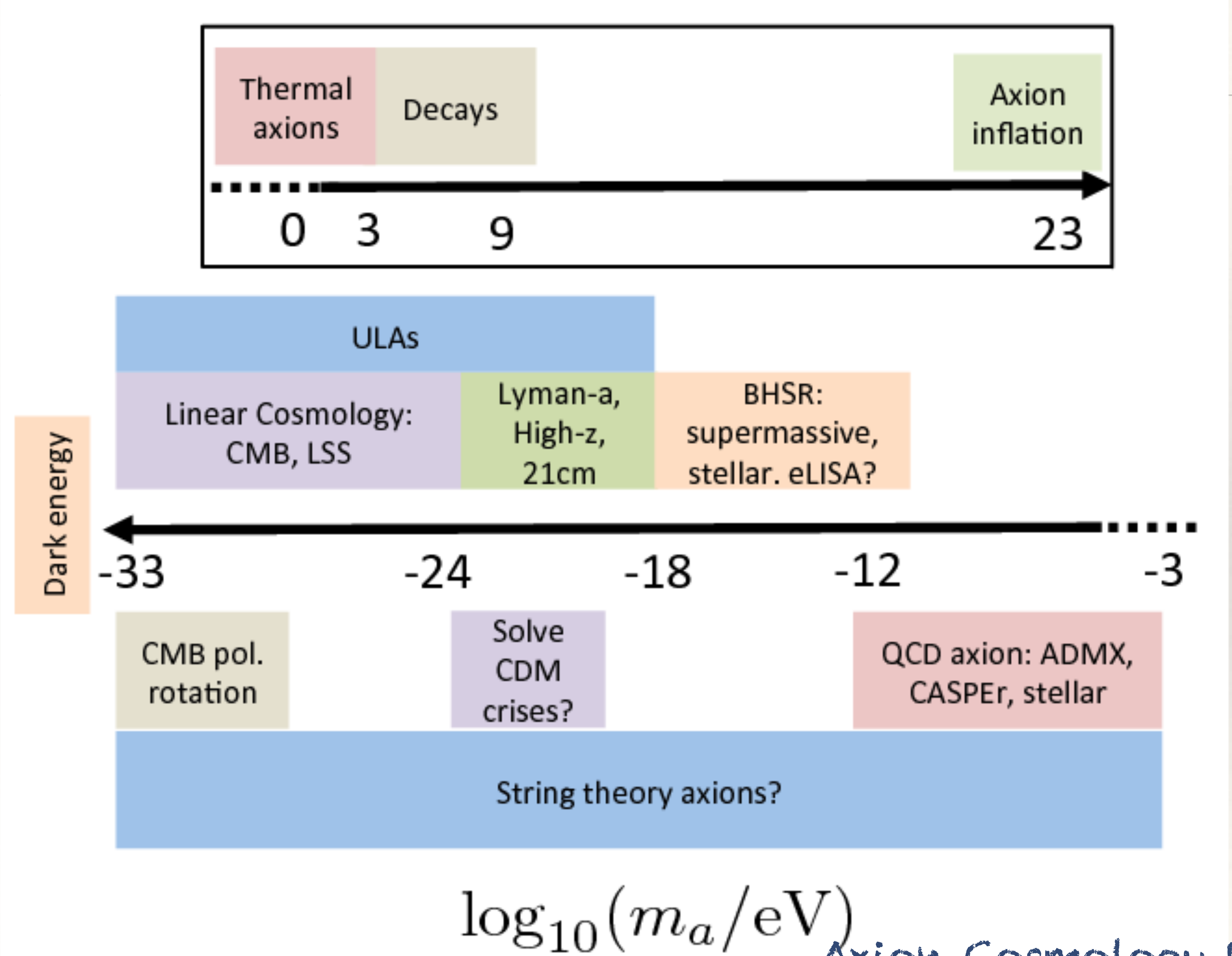
Λ_a : non-perturbative scale

- One can study axions in a model independent way if considers small displacements $\phi < f_a$ in which case the dominant term is

$$V(\phi) \approx m_a^2 \phi^2$$

$$m_a = \Lambda_a^4 / f_a$$

Axion like and ultra light axions (ULA's)



Axion Cosmology Review

Ultra light axions (ULA's). AKA

Scalar Field DM

Fuzzy DM

Wave DM

Bose Einstein Condensate DM

Press, Ryden & Spergel 1990, Sin 1994; Sahni & Wang 2000; Arbey, Lesgourgues & Salati 2001, Hu et. al 2000, Matos & Ureña 2002, P. Sikivie and Yang, 2009. Marsh &Silk 2013, Shive et. al 2014, etc.

Most recent influential paper on ULA's. Lam, J. Ostriker, S. Tremaine, Edward Witten, 2016

Most recent extensive review on Axions. Axion Cosmology, David Marsh, 2015.

- IMPORTANT: There are many constraints in the literature, not all refers to the same model, and sometimes are presented as if they were all the same.

Axion Cosmology

Field equation in a FRW Universe.

$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

If $H < m_a$ the field oscillates around the minimum and behaves like CDM. $\rho_a \approx a^{-3}$ $\left(\rho_a = 1/2\dot{\phi}^2 + V(\phi)\right)$

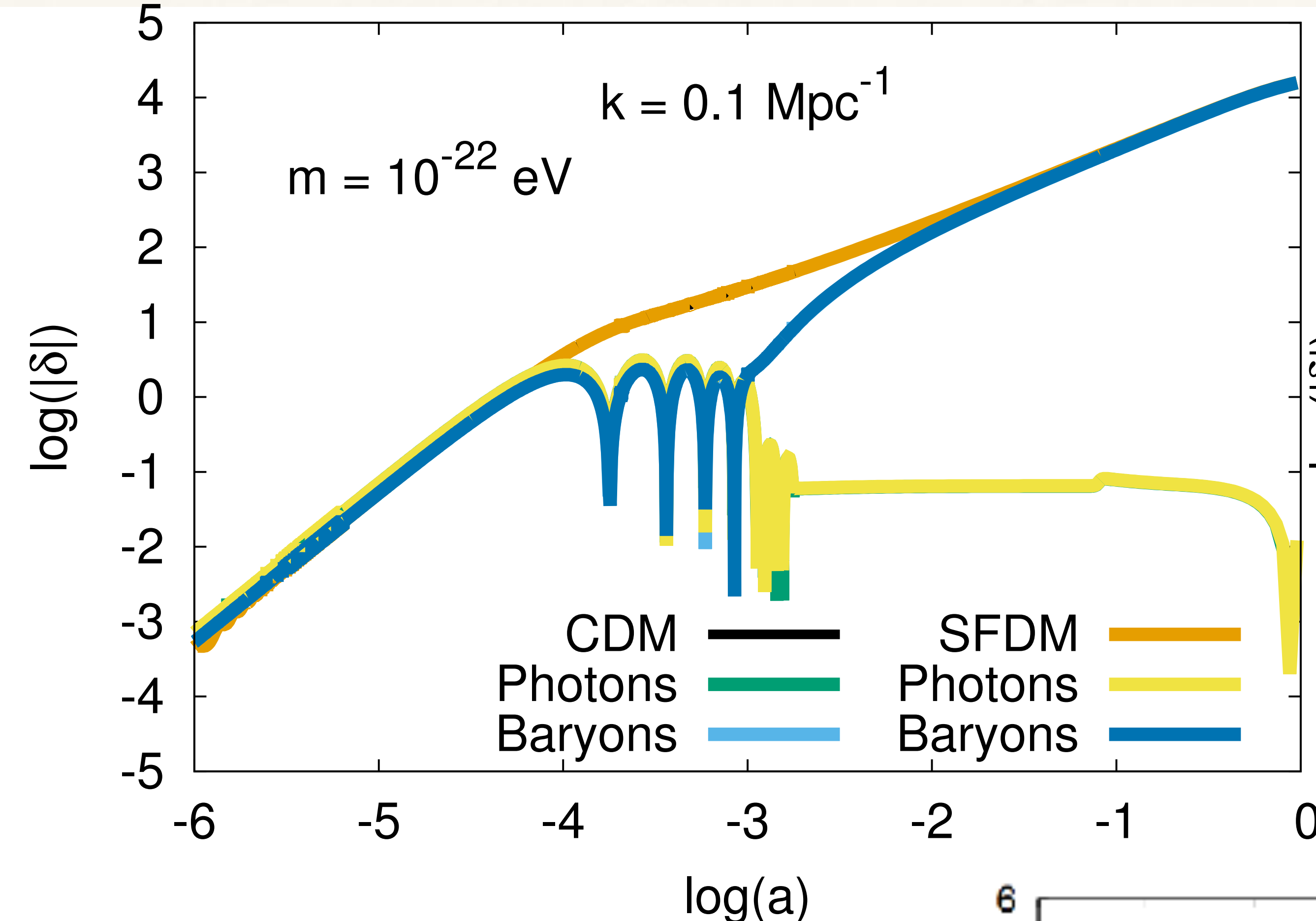
Linear Perturbation Theory $\phi(\mathbf{x}, t) = \phi(t) + \psi(\mathbf{x}, t)$

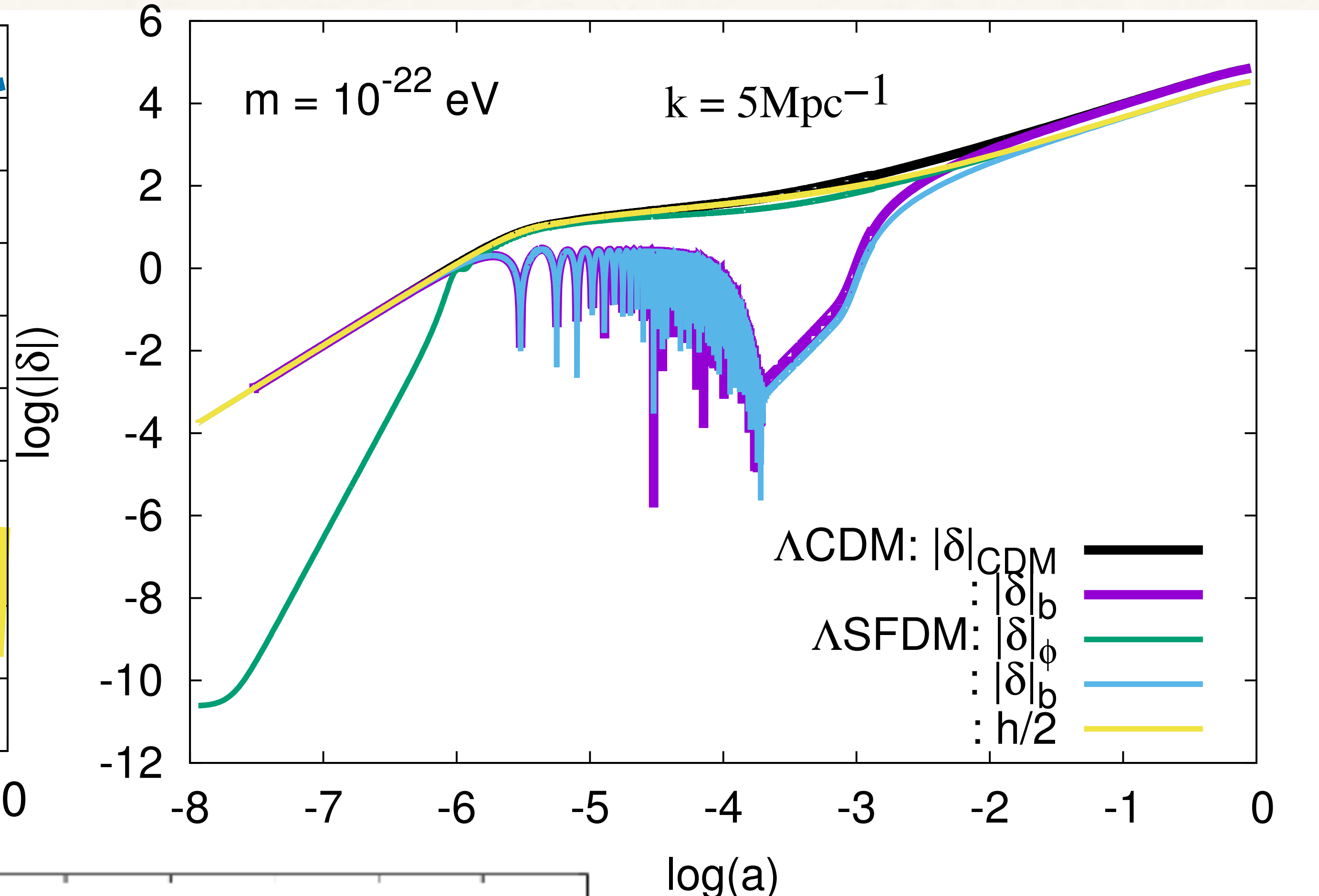
$$\ddot{\phi} = -3H\dot{\phi} - [k^2a^{-2} + m_a^2]\phi - 1/2\dot{\phi}\dot{h}$$

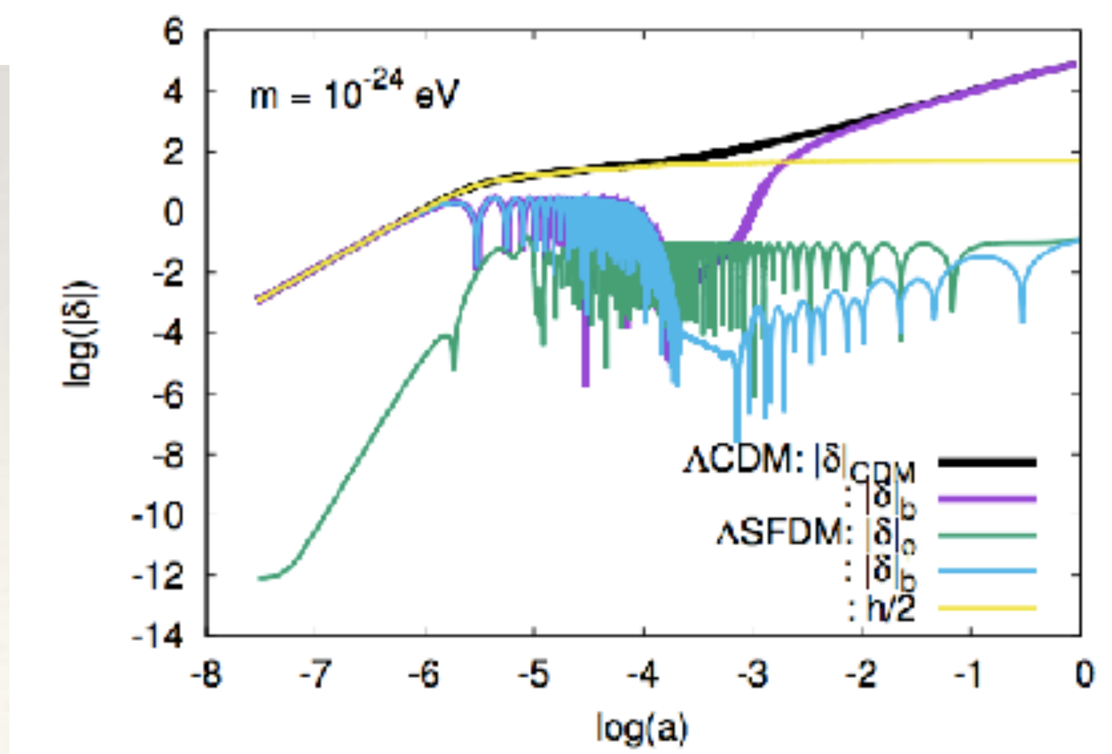
(Fourier space and Syncronous Gauge)

Solved using codes as CLASS (github/class.FreeSF) and CAMB (github/axionCAMB)

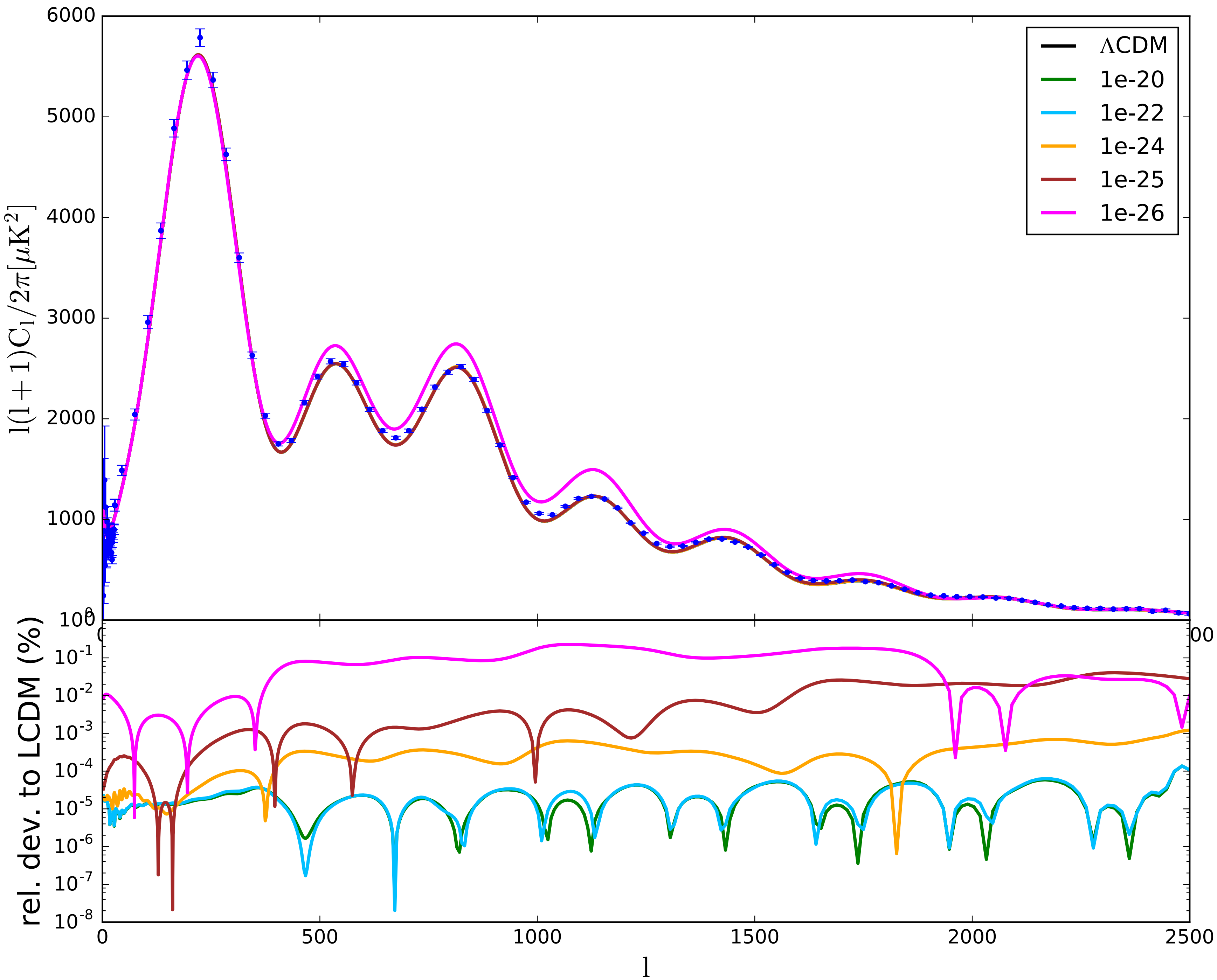
ULA Cosmology—Free SF







ULA Cosmology—Free SF



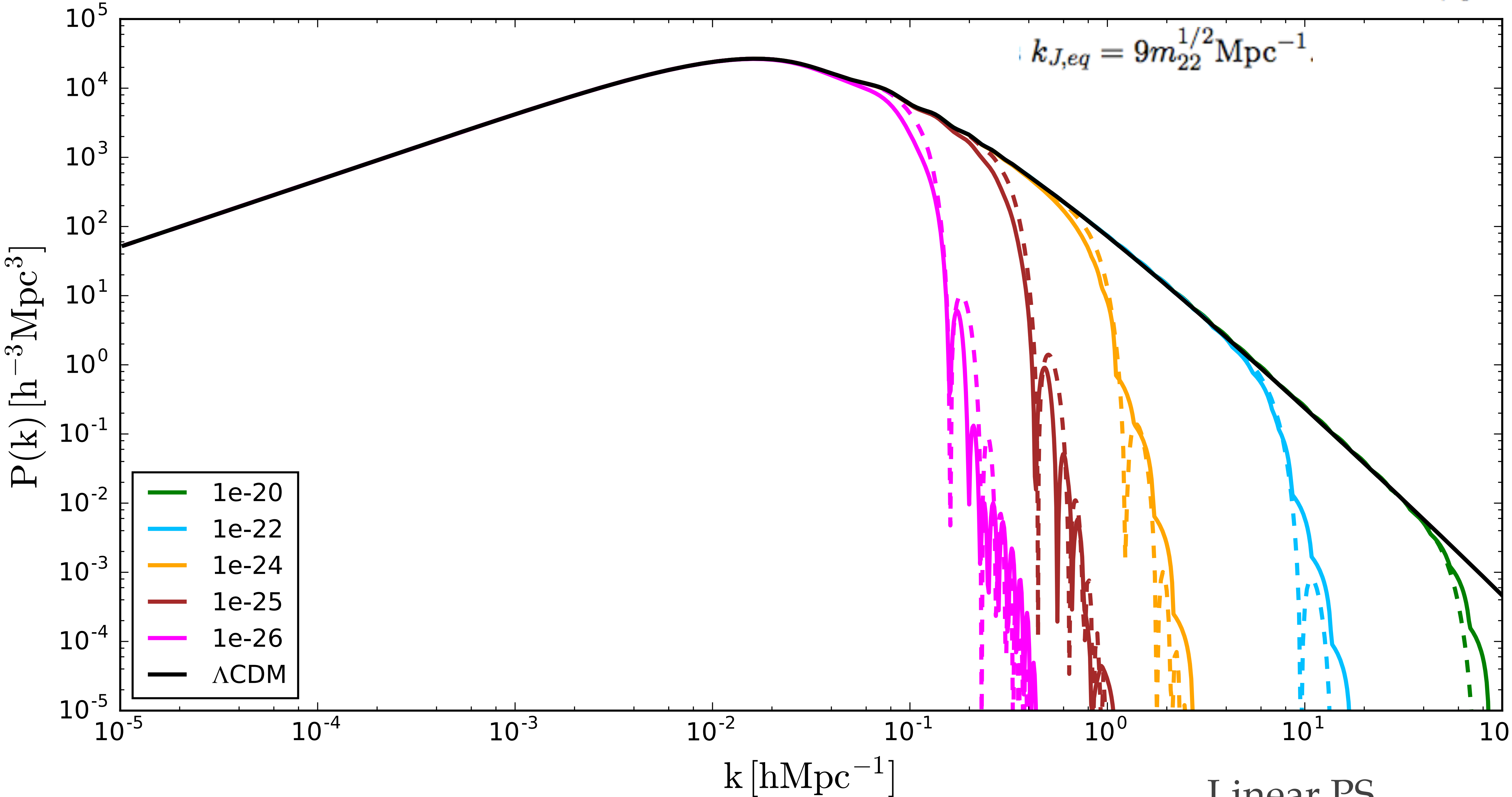
ULA Cosmology—Free SF

Dotted Lines corresponds to the approximation

$$P_{\rm SFDM}(k,z) = T^2(k) P_{\Lambda\rm CDM}(k,z)$$

$$T(k) = \frac{\cos(x^3)}{(1+x^8)}, \quad x = 1.61 \left(\frac{m}{10^{-22}\rm eV}\right)^{1/18} \frac{k}{k_{J,eq}}$$

$$k_{J,eq} = 9 m_{22}^{1/2} \rm Mpc^{-1}.$$



Linear PS.

ULA Cosmology—Free SF- Current Constraints

$m_a > 10^{-24}\text{eV}$ CMB Matos & Ureña 2002, 2009. Marsh &Silk 2013, Hlozek et al. 2015, L. Ureña & AXGM 2016,

$m_a < 10^{-22}\text{eV}$ high-z galaxies luminosity finctuon, Bozek2015, Schive 2016

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

$m_a = 2.5 \times 10^{-23} eV$ disfavored by Ly-alpha Jiajun Zhang et.al 2017 but argue larger masses can not be excluded with current status of simulations/data

Constraints from dSph's

$m_a = 0.2 - 1 \times 10^{-22}\mathrm{eV}$

$m_a = 0.12 - 8 \times 10^{-22}\mathrm{eV}$

Use the longevity of cold clumps in UMi&Sextants (soliton only)

Lora et. al2012

$m_a = 8.1 \pm^{1.6}_{1.7} \times 10^{-23}\mathrm{eV}$

Use only intermediate metallicity population in Fornax from Amorisco 2013

Schive 2014

$m_a < 1.1 \times 10^{-22}\mathrm{eV}$

slope analysis Fornax & Sculptor

Marsh & Pop 2015

$m_a \approx 3.7 - 5.6 \times 10^{-21}\mathrm{eV}$

Ultrafaint dwarfs, DracoII & Triangulum II, use mean vel. disp, and maximum mass estimates.

Calabrese & Spergel 2016

$m_a = 1.79 \pm^{0.35}_{0.33} \times 10^{-22}\mathrm{eV}$ (Jeans analysis)

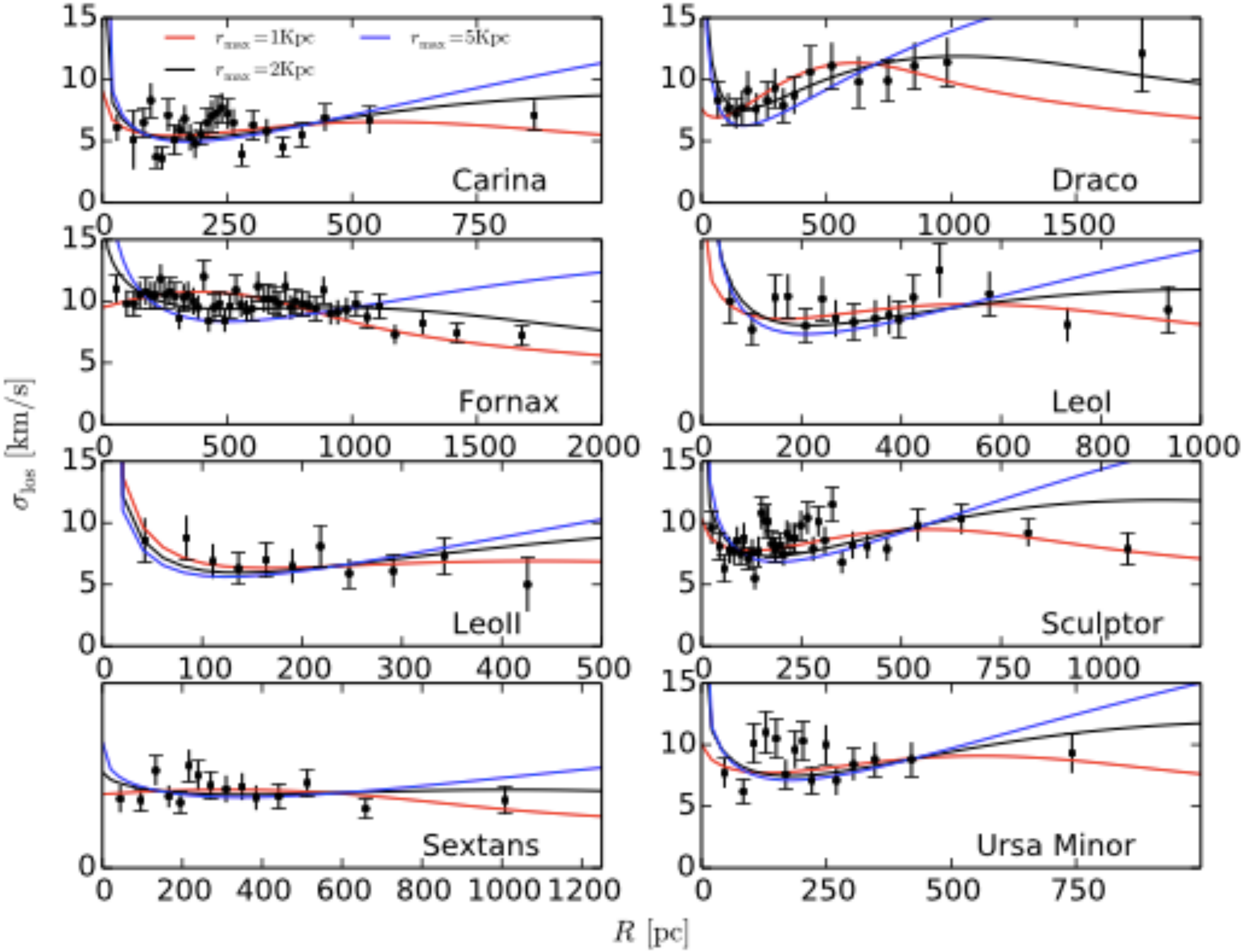
Chen et. al 2016

$m_a = 2.4 \pm^{1.3}_{0.6} \times 10^{-22}\mathrm{eV}$ (Jeans analysis)

AXGM et. al 2016

$m_a < 4 \times 10^{-23}\mathrm{eV}$ (Revised slope analysis)

ULA Constraints from dSph’s



Axion DM soliton only.

First done in A. Diez-Tejedor, AXGM, S. Profumo, 1404.1054v2.

$$\rho(r) = \begin{cases} \rho_c \dfrac{\sin(\pi r/r_{\max})}{(\pi r/r_{\max})} & \text{for} \quad r < r_{\max} \\ 0 & \text{for} \quad r \geq r_{\max} \end{cases}$$

The lesson we learned is that we needed a full density profile to model different types of galaxies consistently

Surprisingly not pointed out in most of previous work in LSB and other types of galaxies., e.g Arbey 2001, Harko 2015, Matos et. al 2000-2013 , etc.. etc

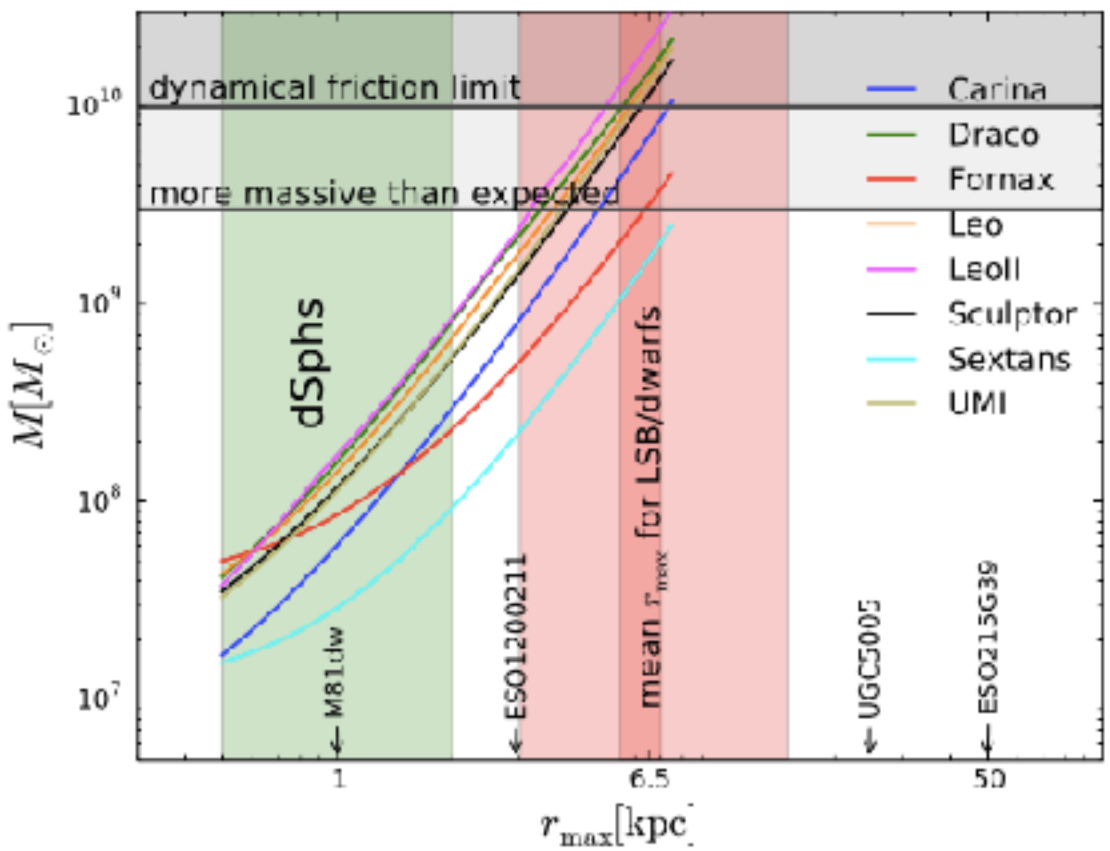


FIG. 4: Total mass for the best fits as a function of the scale radius. The line at $M = 3 \times 10^9 M_\odot$ corresponds to the virial mass of Draco (the most massive object in the sample) obtained from a NFW profile consistent with the observations in the velocity dispersions [34, 40]. The line at $M = 1 \times 10^{10} M_\odot$ comes from an upper limit to the mass of this same galaxy as required from the dynamical friction decay time to be larger than one Hubble time [36, 41].

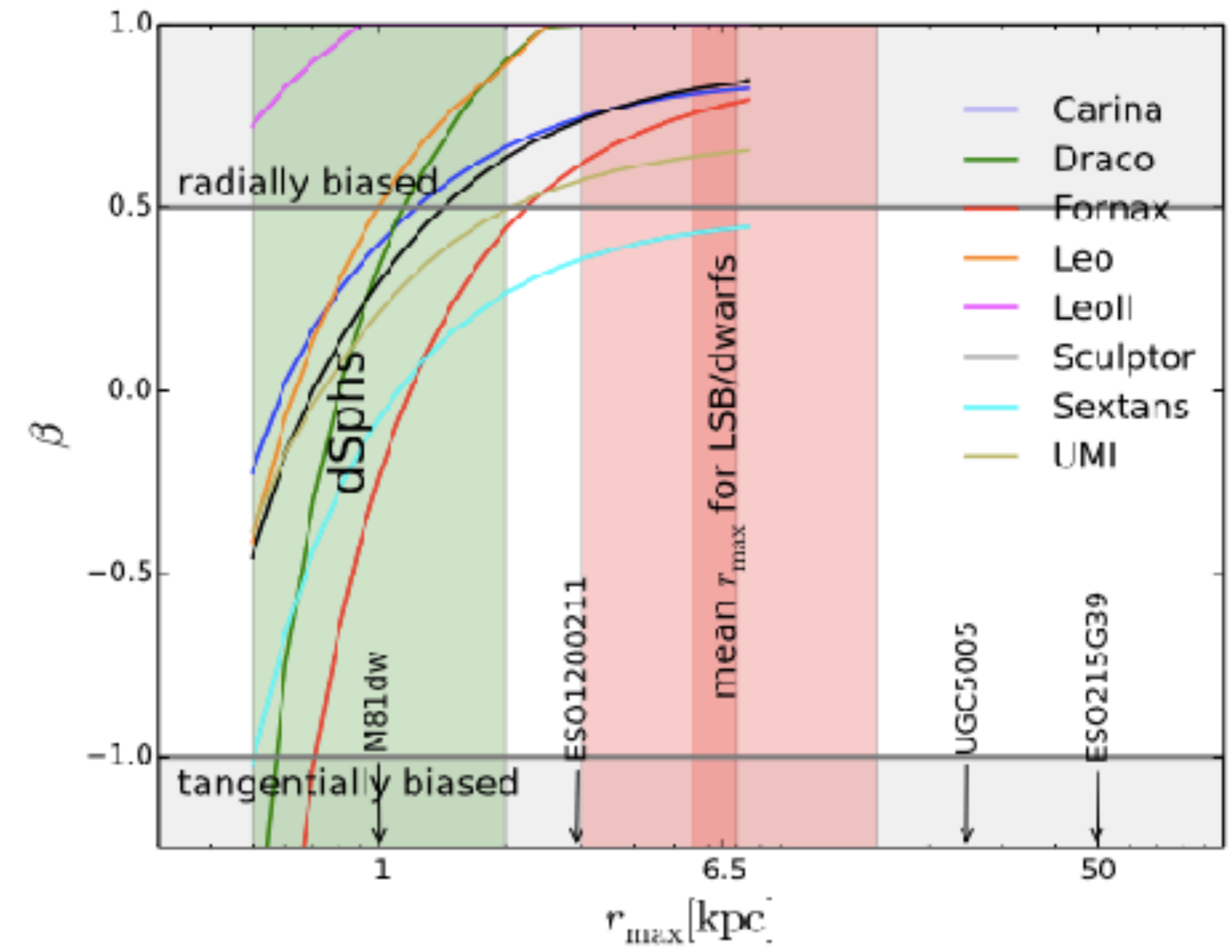
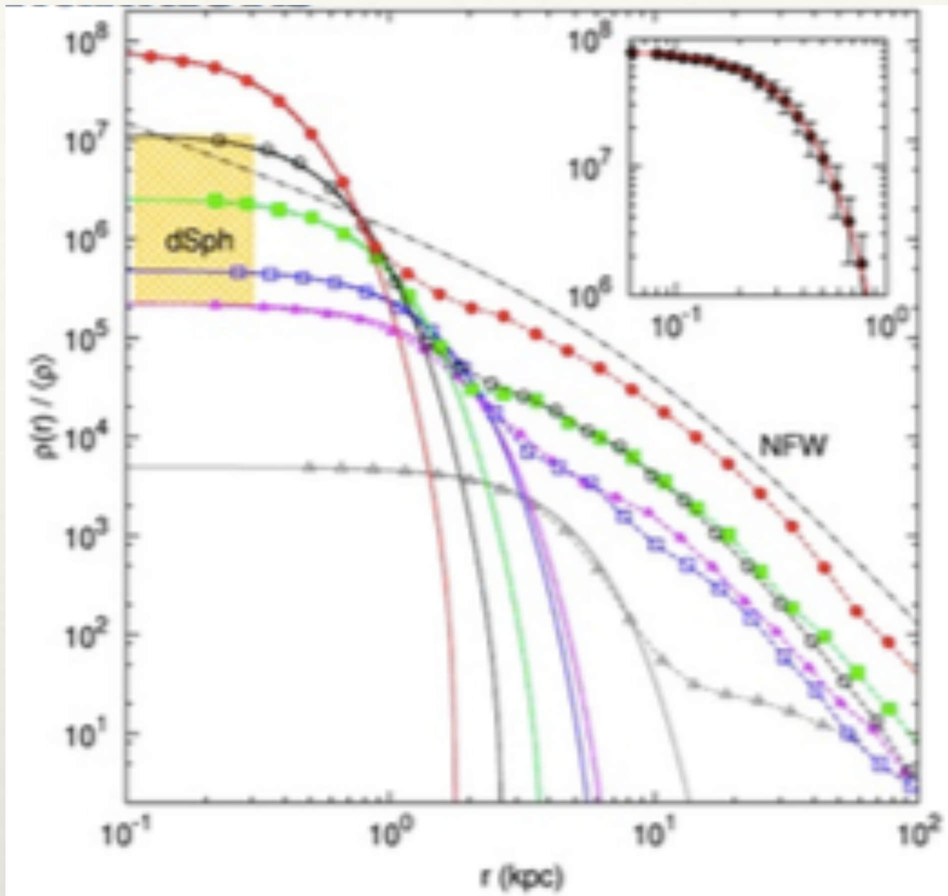
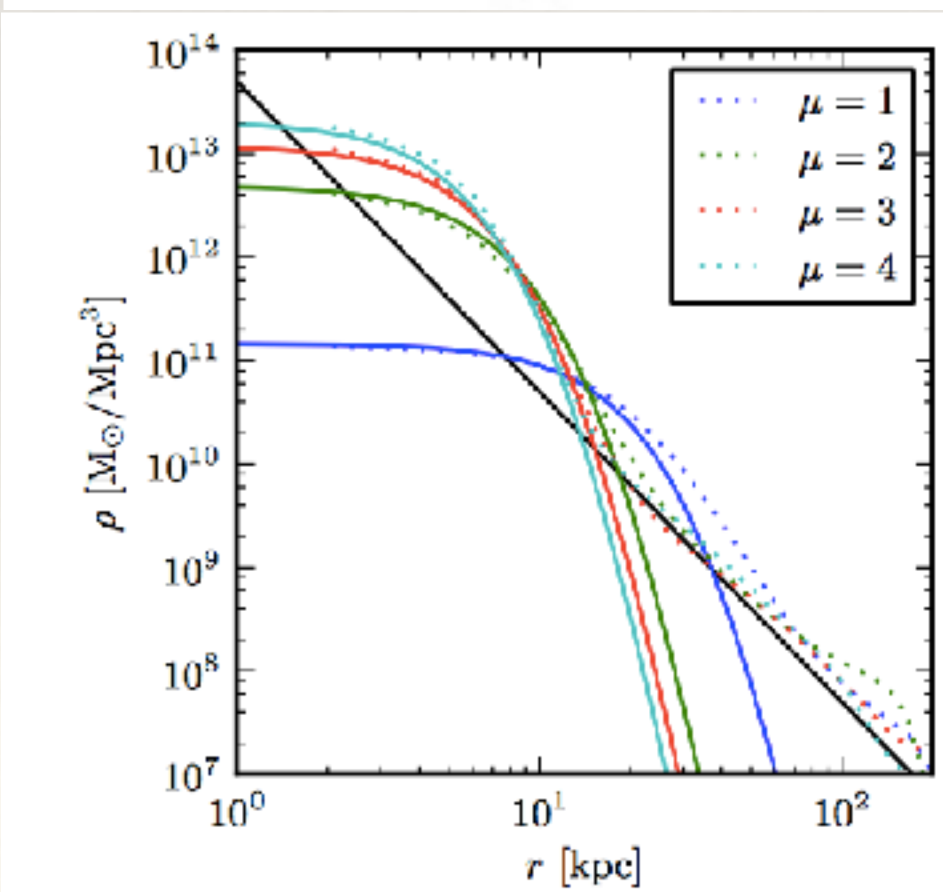


FIG. 3: Preferred orbital anisotropy for the best fits as a function of the scale radius. The lines at $\beta = 0.5$ and $\beta = -1$ correspond to $\langle v_r^2 \rangle = 2\langle v_\theta^2 \rangle$ and $\langle v_\theta^2 \rangle = 2\langle v_r^2 \rangle$, respectively.

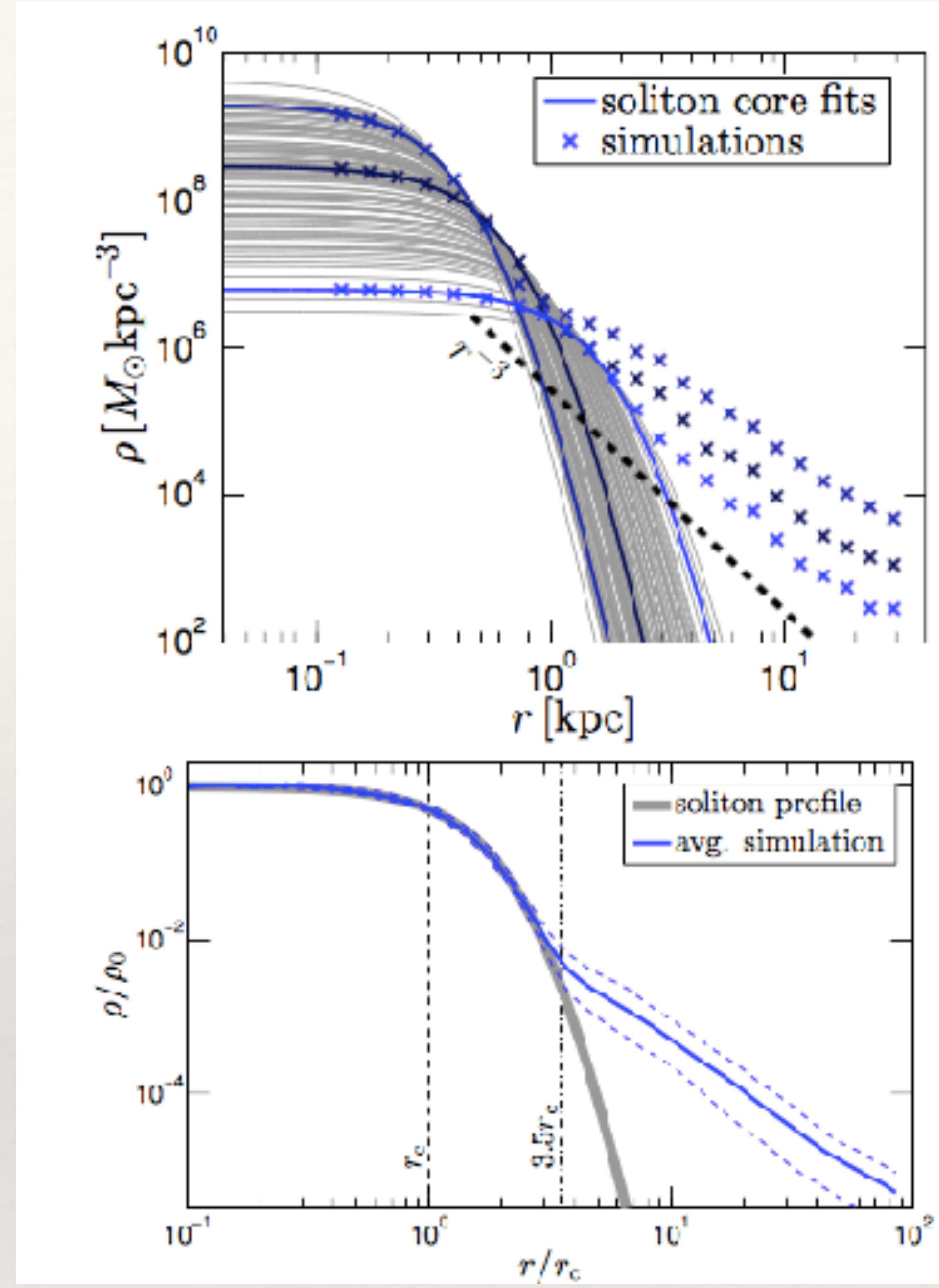
ULA DM halo model



Schive et. al 2013



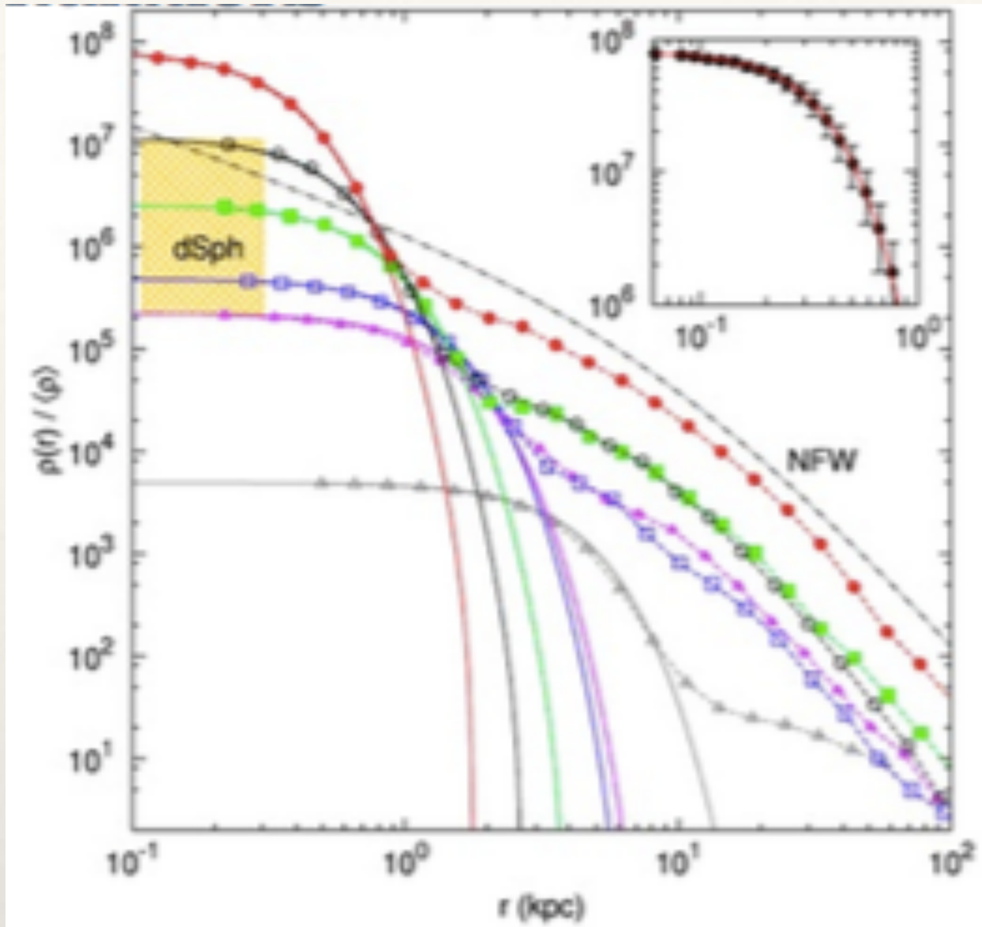
Veltmaat and Niemeyer 2016



Philip Mocz 2017

MOVIE

ULA DM halo model



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

where

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

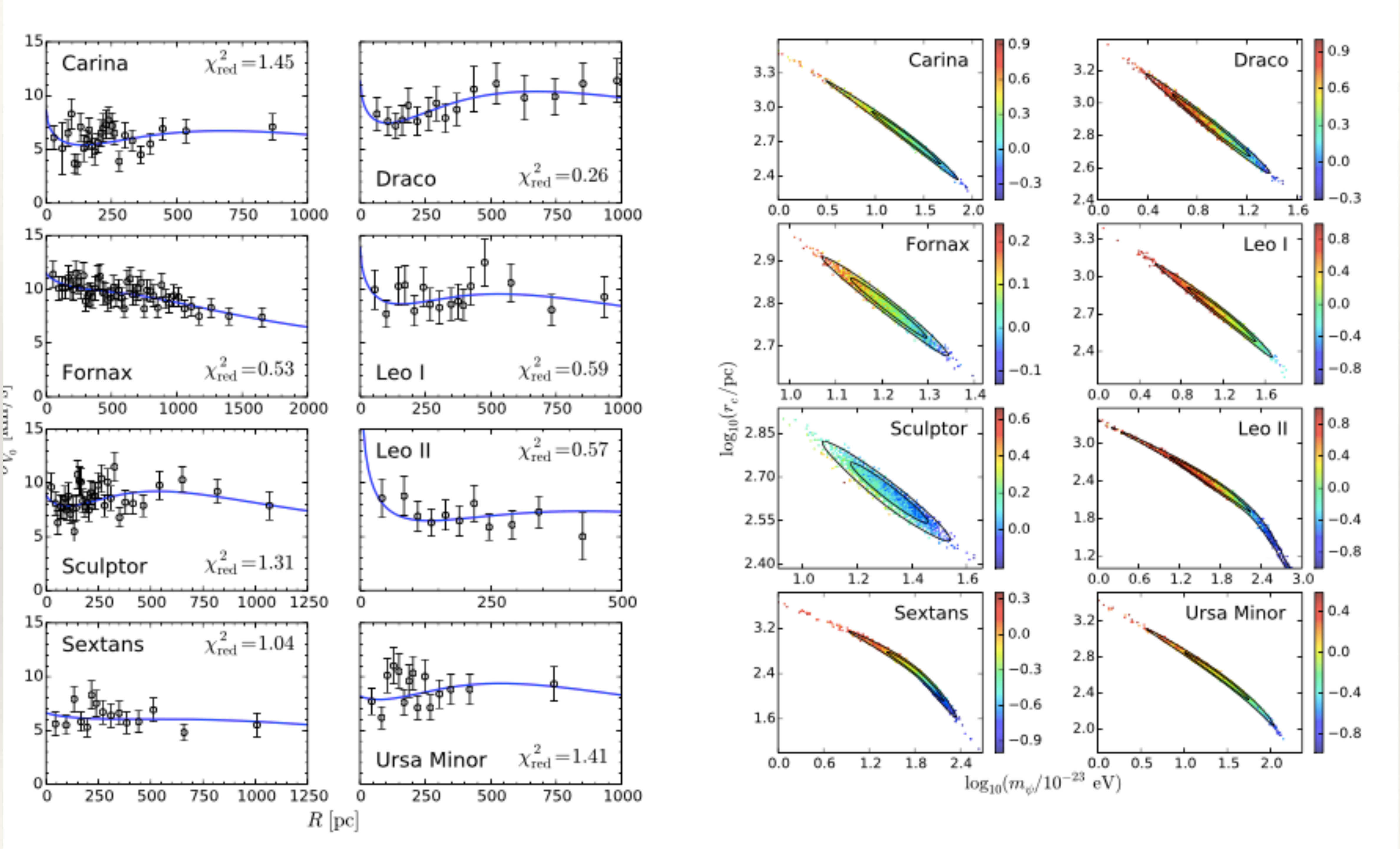
and

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

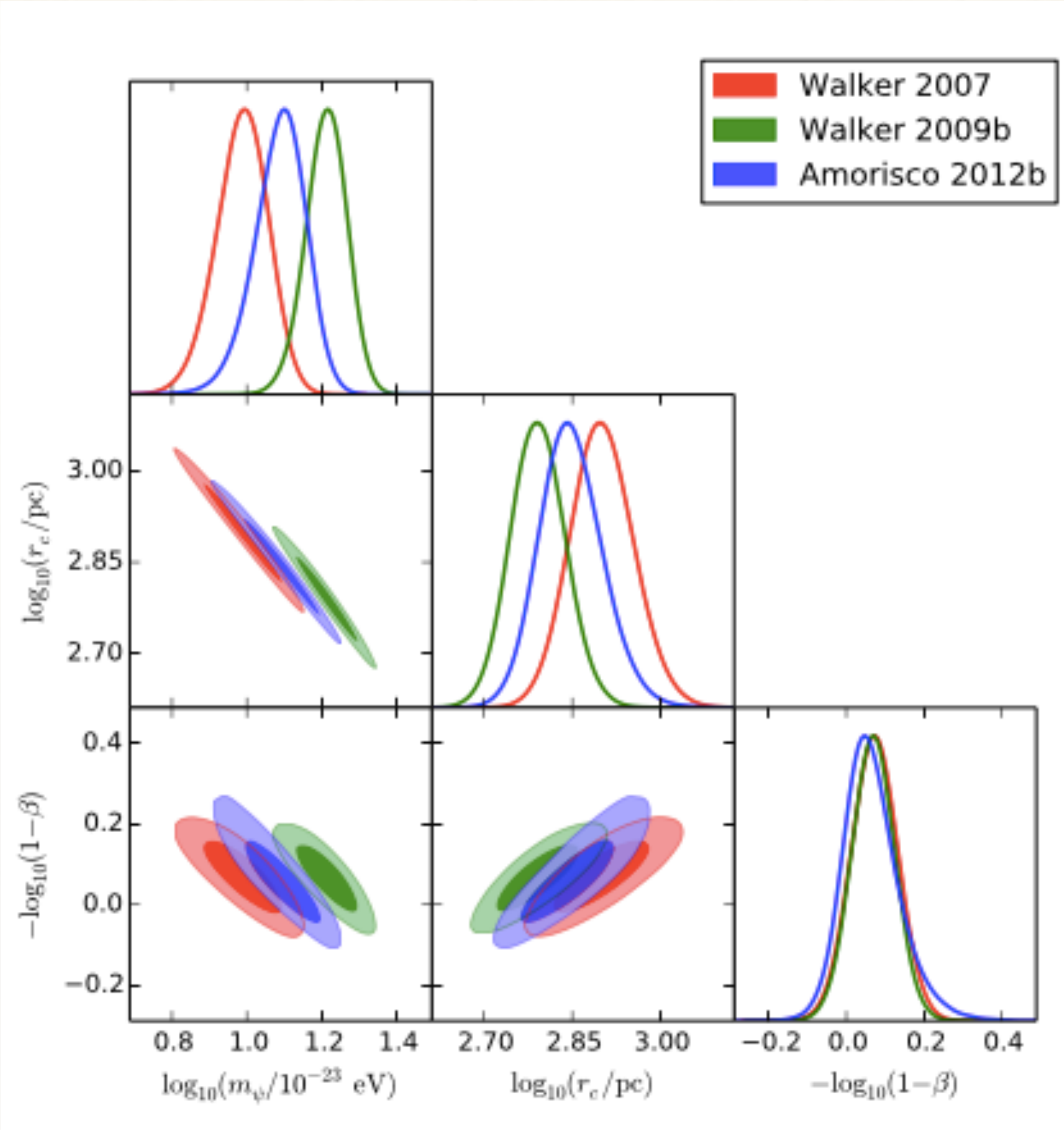
$$r_{\rm sol} = \left[\frac{\rho_{\rm sol}}{2.42 \times 10^9 \ {\rm M_\odot kpc^{-3}}} \left(\frac{m_a}{10^{-22}{\rm eV}} \right)^2 \right]^{-0.25}$$

2 free parameters per halo + free anisotropy (for Jeans analysis). We treat the axion mass as universal parameter.

Jeans analysis, Chen. et. al 2016

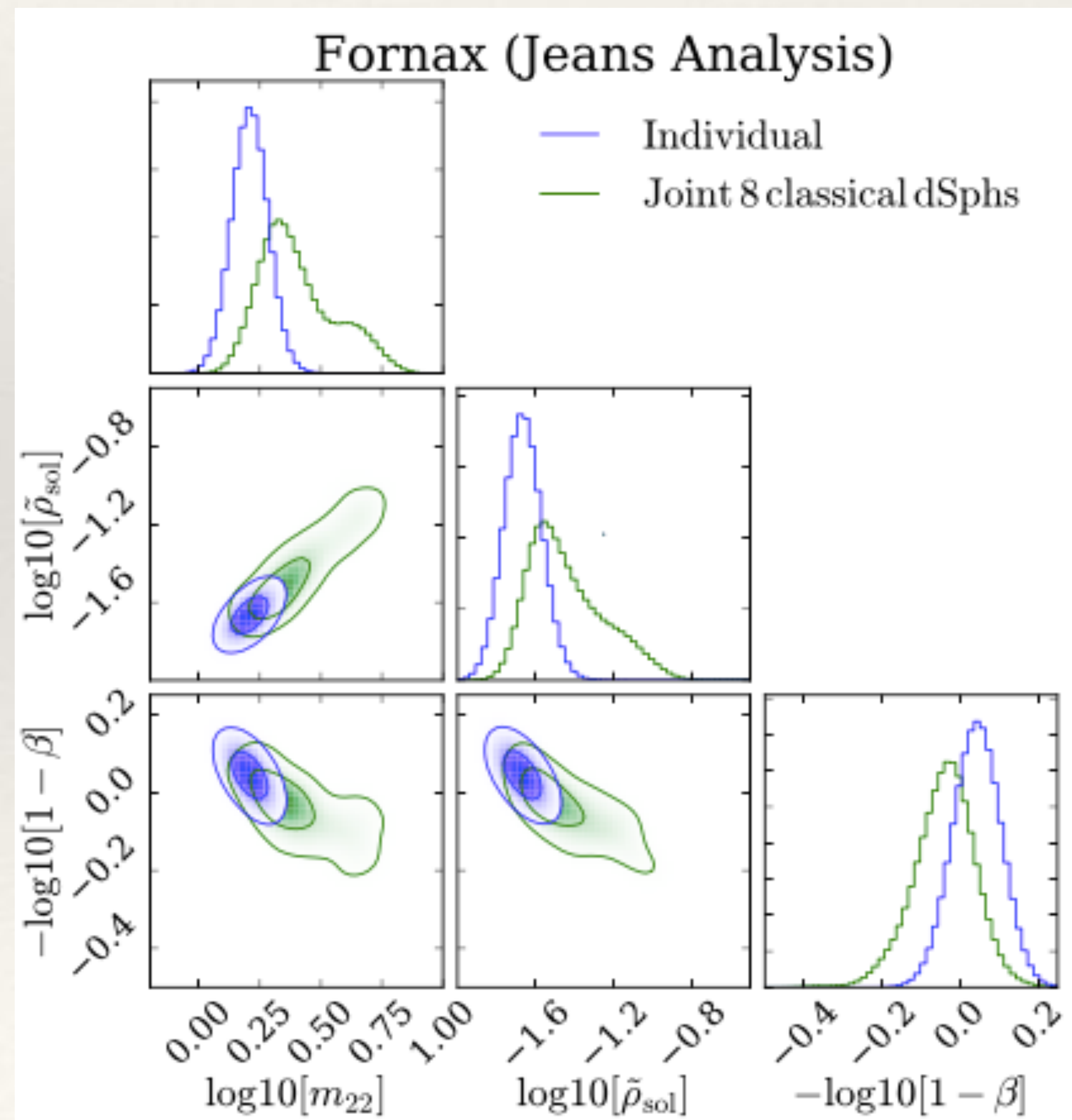


Jeans analysis



Chen. et. al 2016 . They tested for different anisotropy profile, and different stellar density: Plummer and King. After all, they found a robust constraint of :

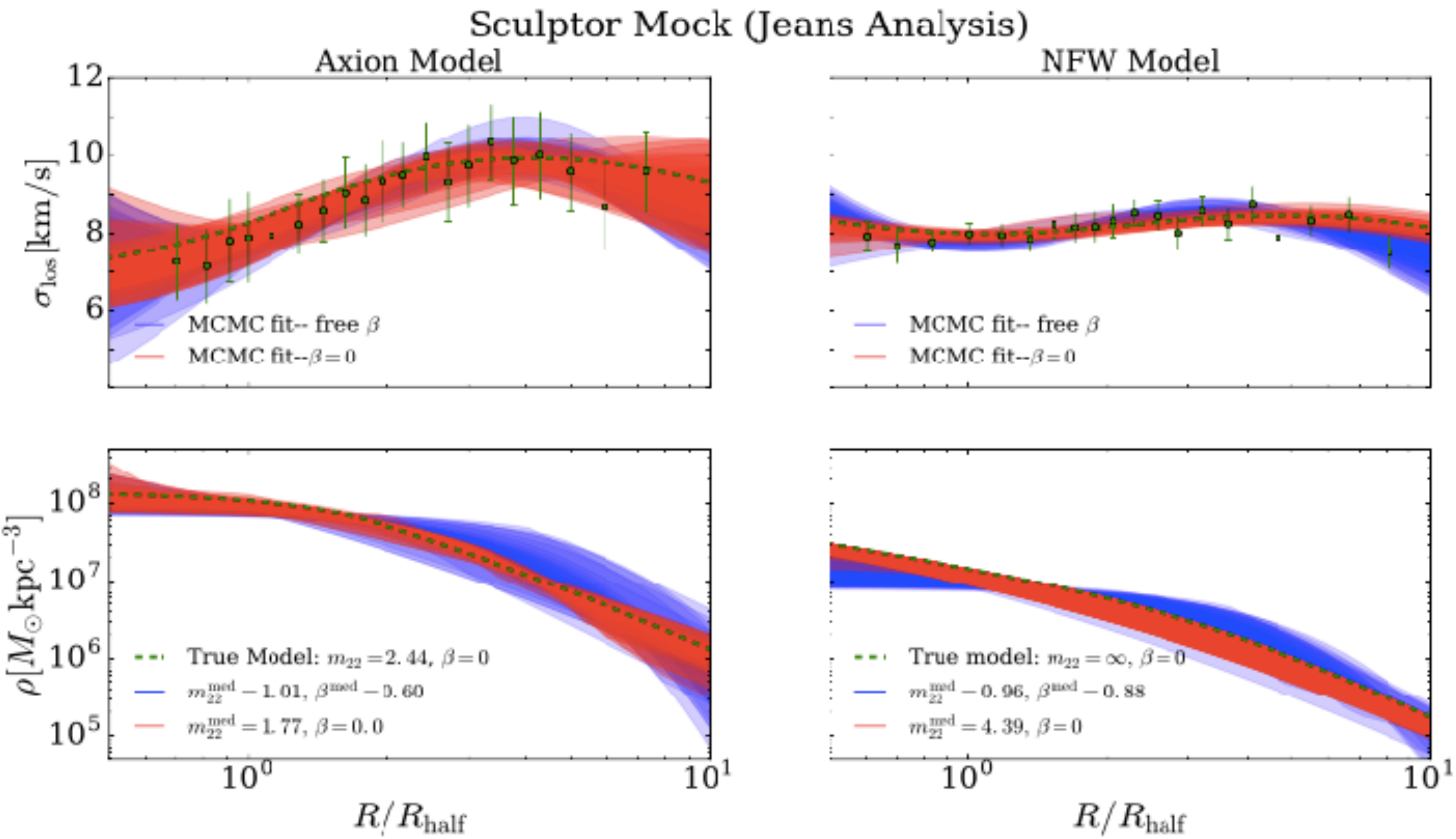
$$m_a = 1.79 \pm^{0.35}_{0.33} \times 10^{-22}\mathrm{eV}$$

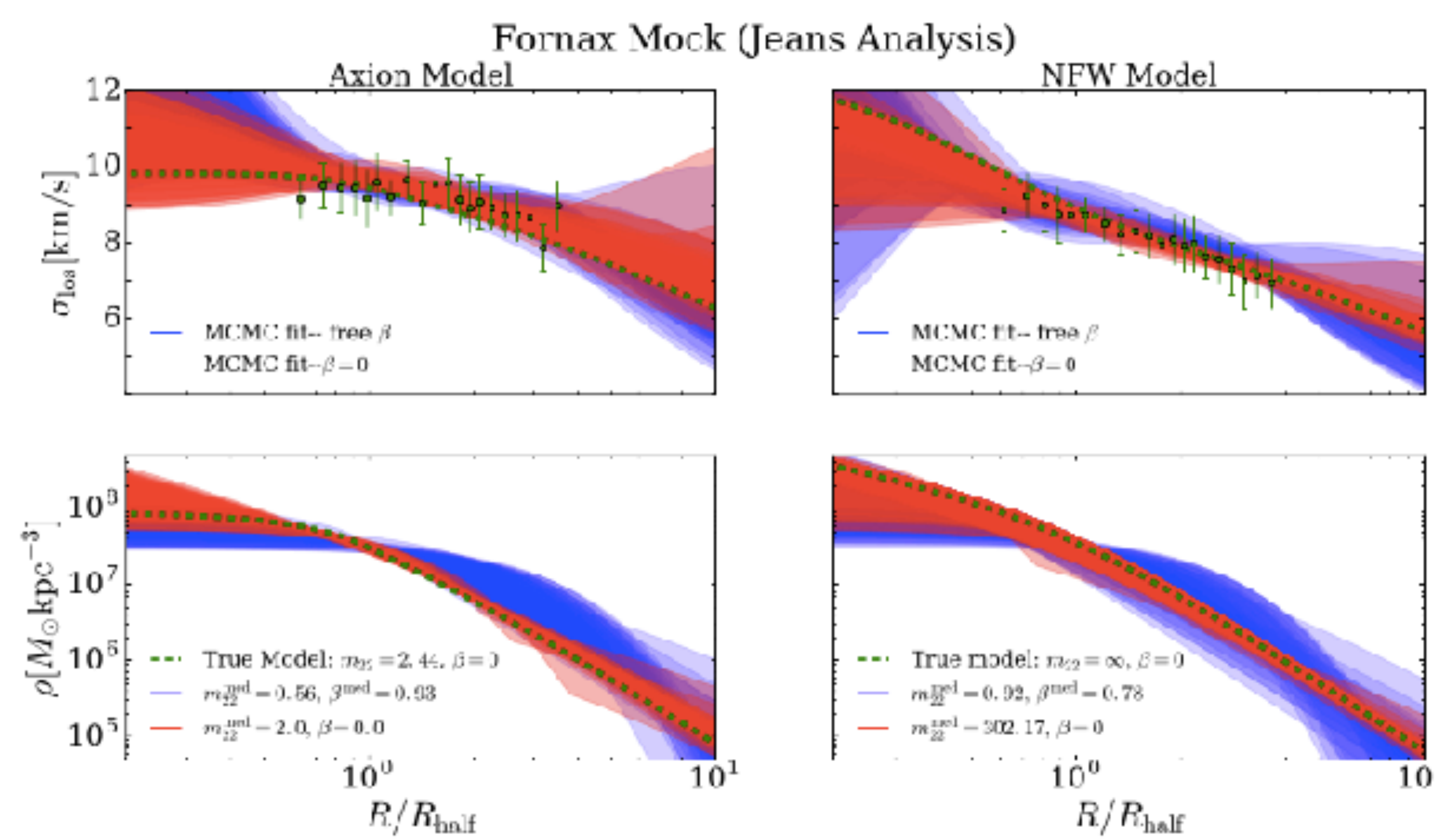


AXGM et. al 2016. With one of the data sets, different priors, different mcmc implementation and a joint analysis, we found:

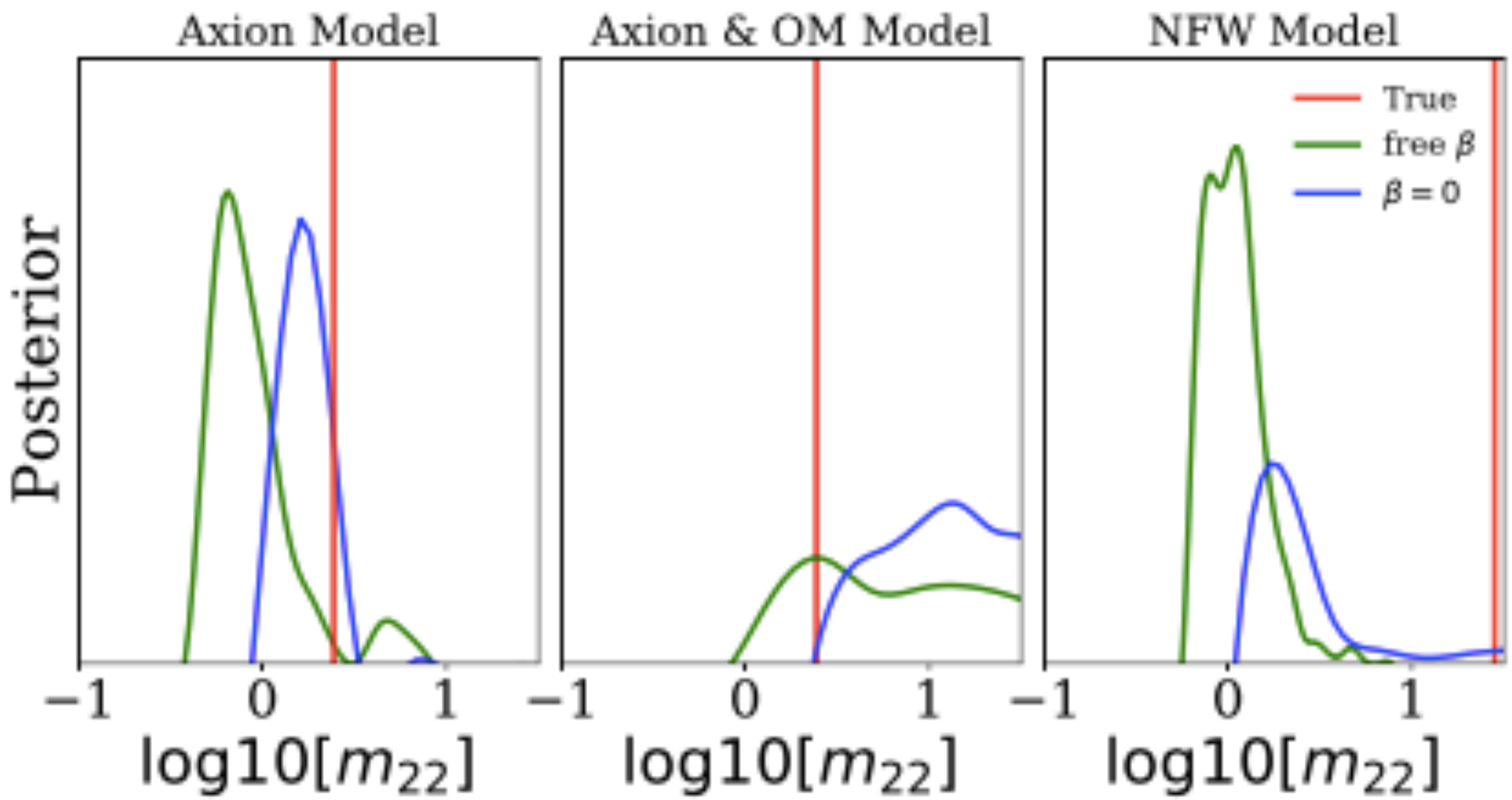
$$m_a = 2.4 \pm^{1.3}_{0.6} \times 10^{-22}\mathrm{eV}$$

Jeans analysis in Mock data

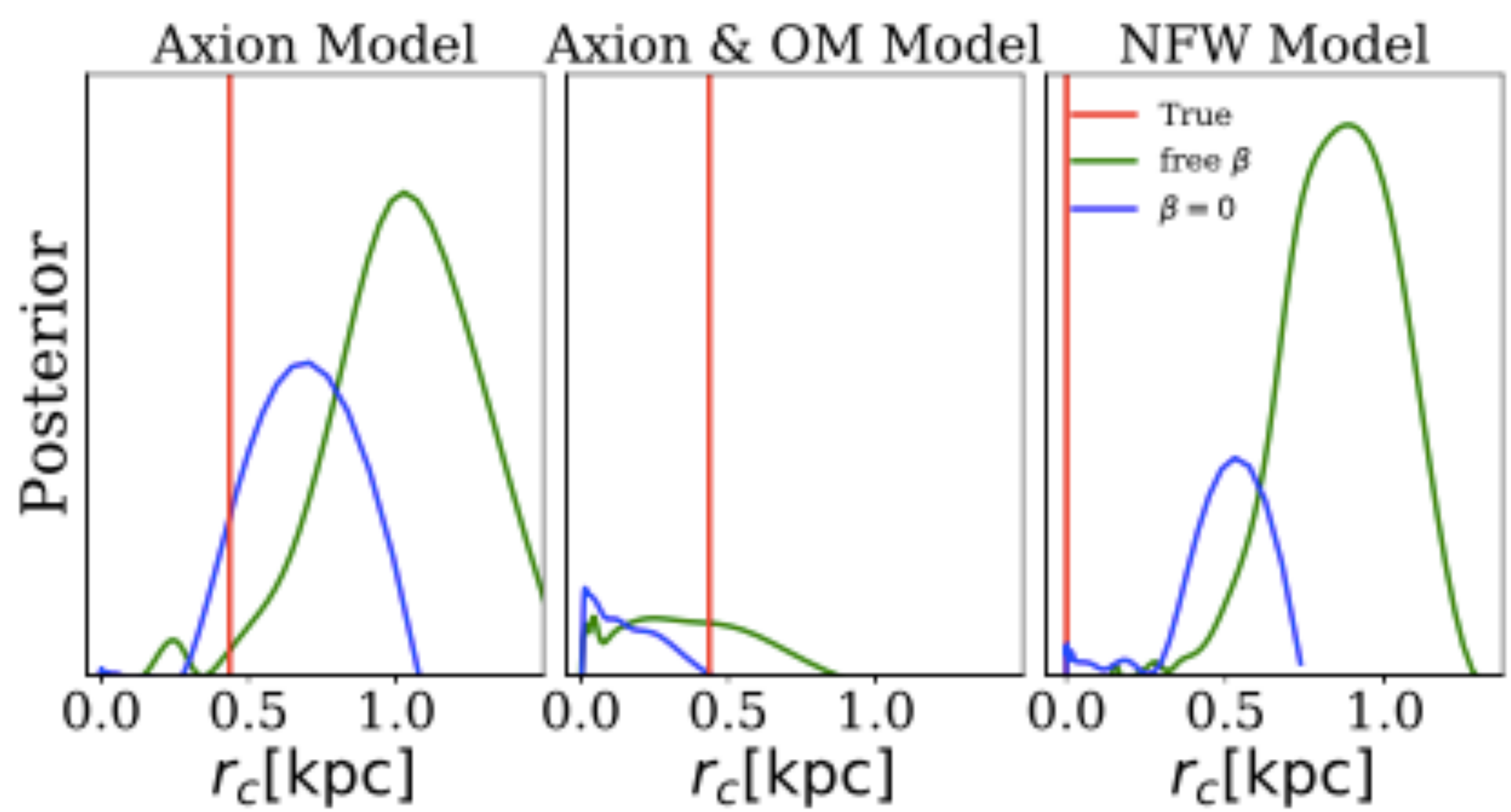




Use emcee (Foreman et. al 2013).
Check convergence with spectral analysis (Dunkley et al. 2005)

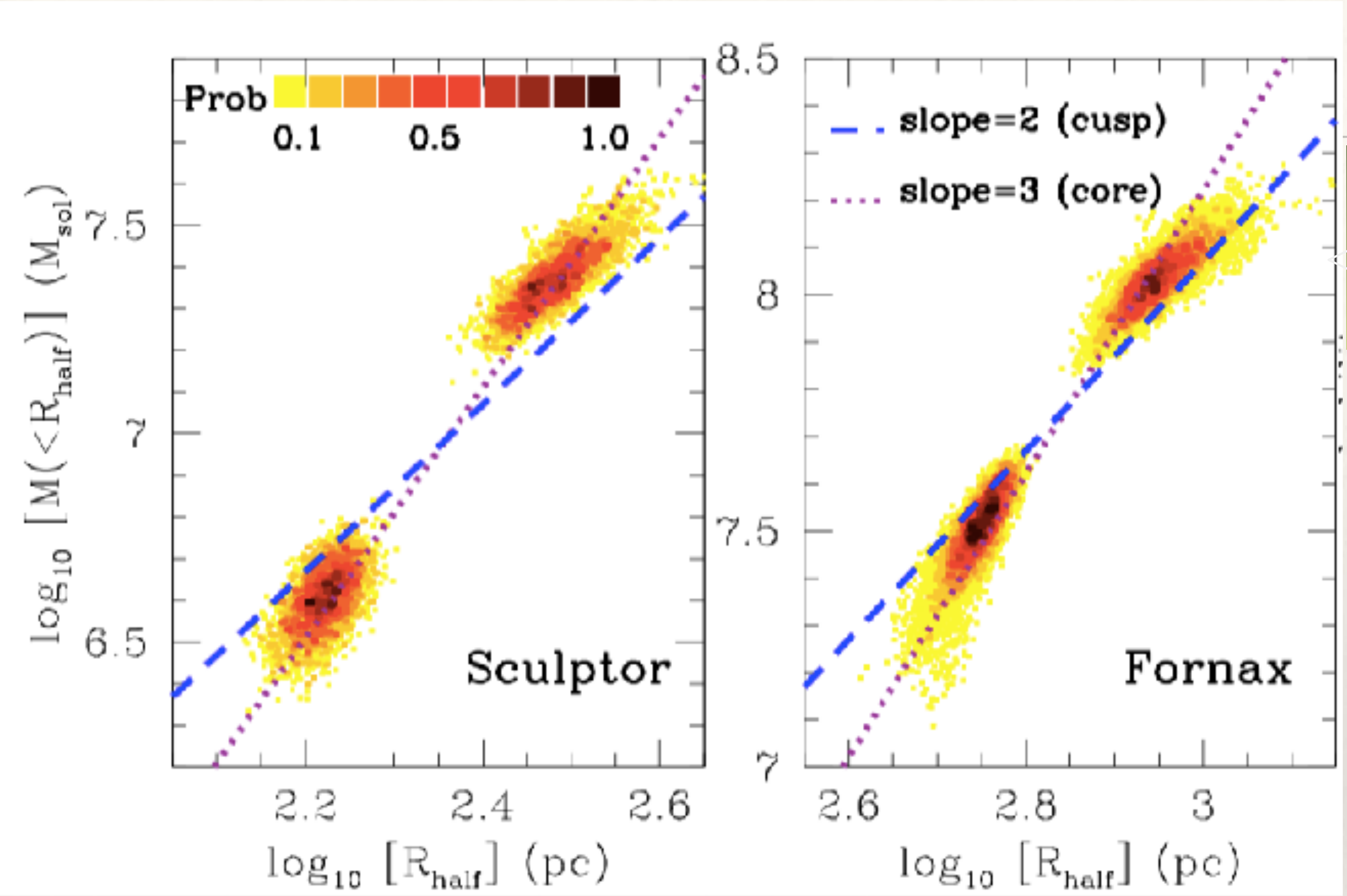


Jeans analysis in Mock data shows the results are biased in the best case, but also could be totally wrong



Slope Analysis Revisted

(Walker &Peñarrubia 2011)



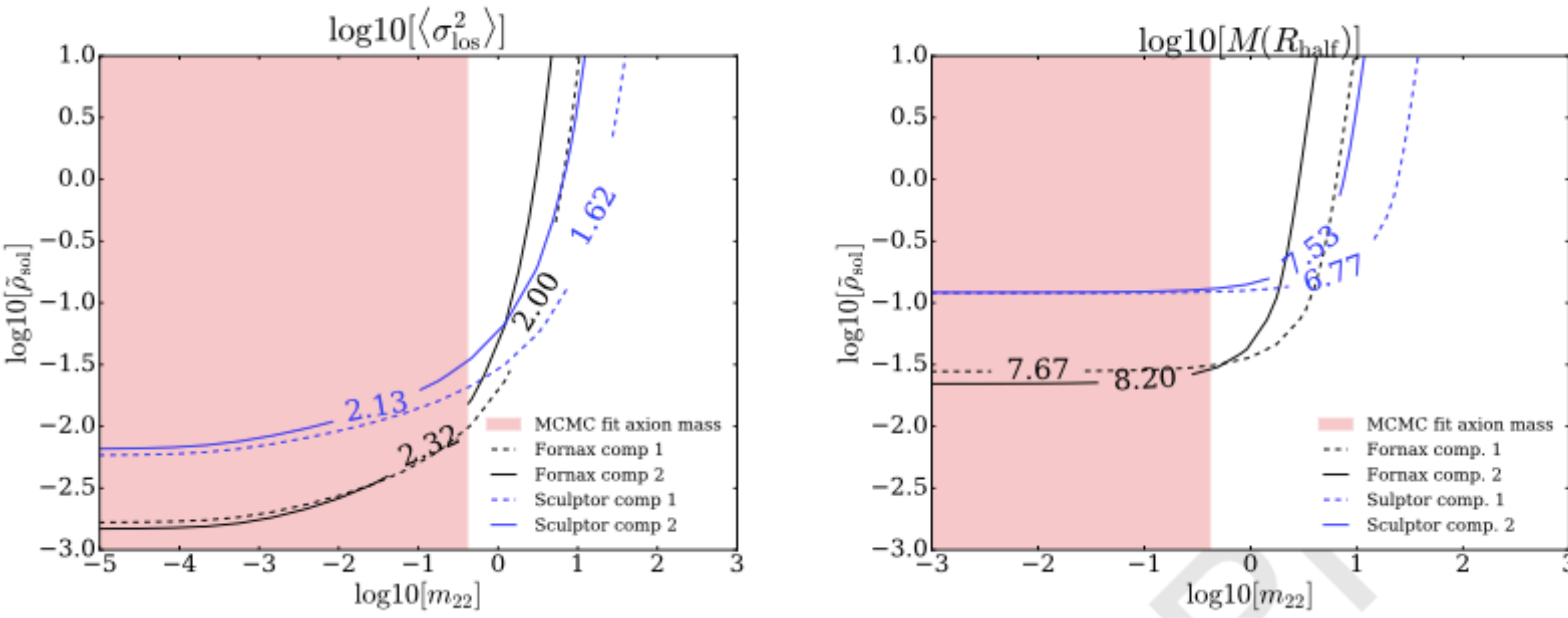
WP 2011 use mass estimator

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

We propose to compute the mean velocity dispersion as

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

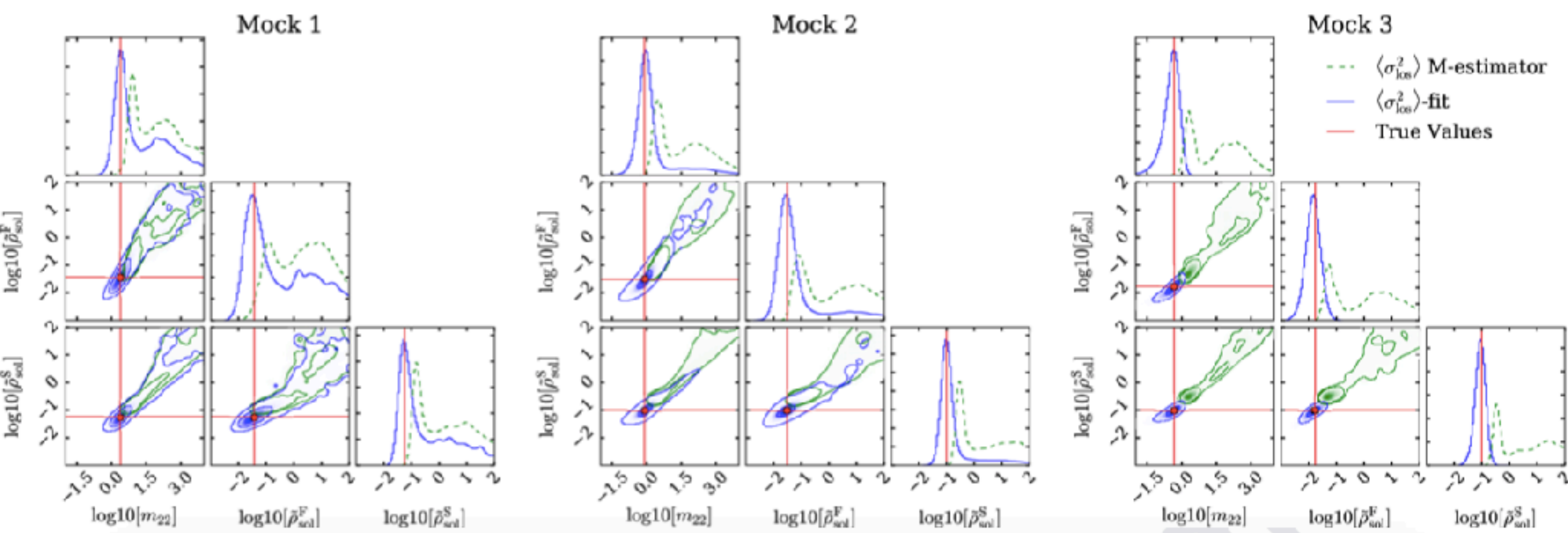
Slope Analysis Revisted



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

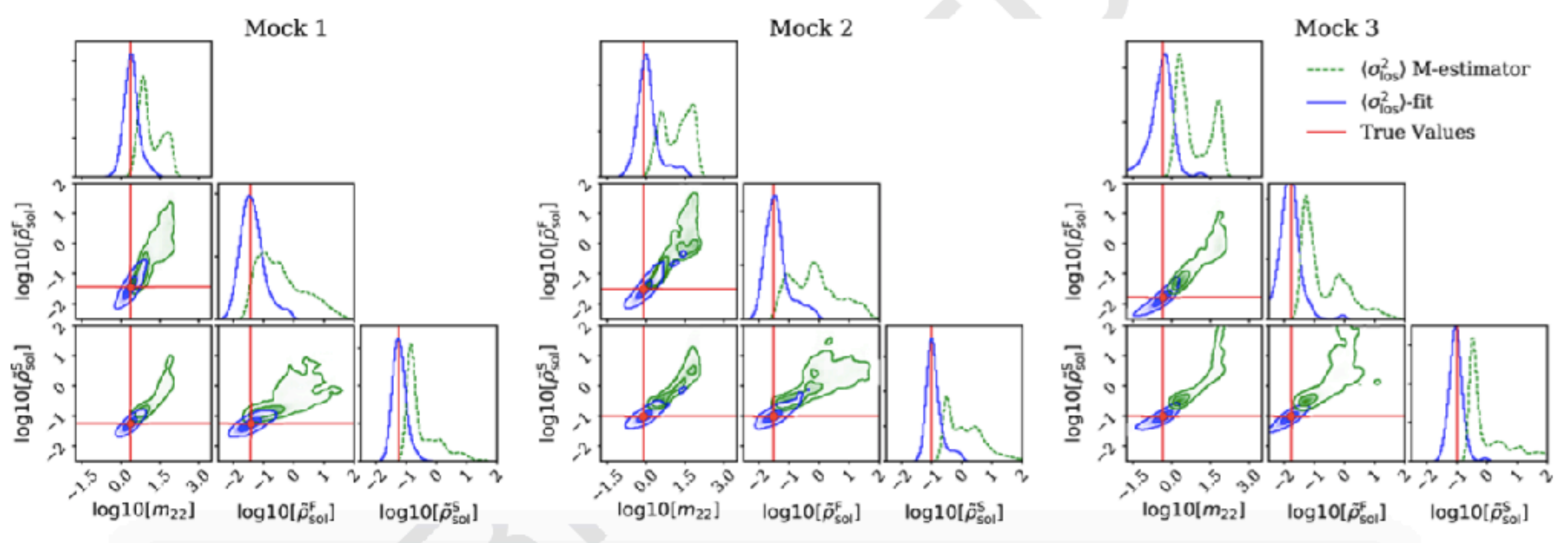
$$< \sigma^2_{\rm los}(r_{\rm half}) >= \frac{2GM(< r_{\rm half})}{5r_{\rm half}}$$

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

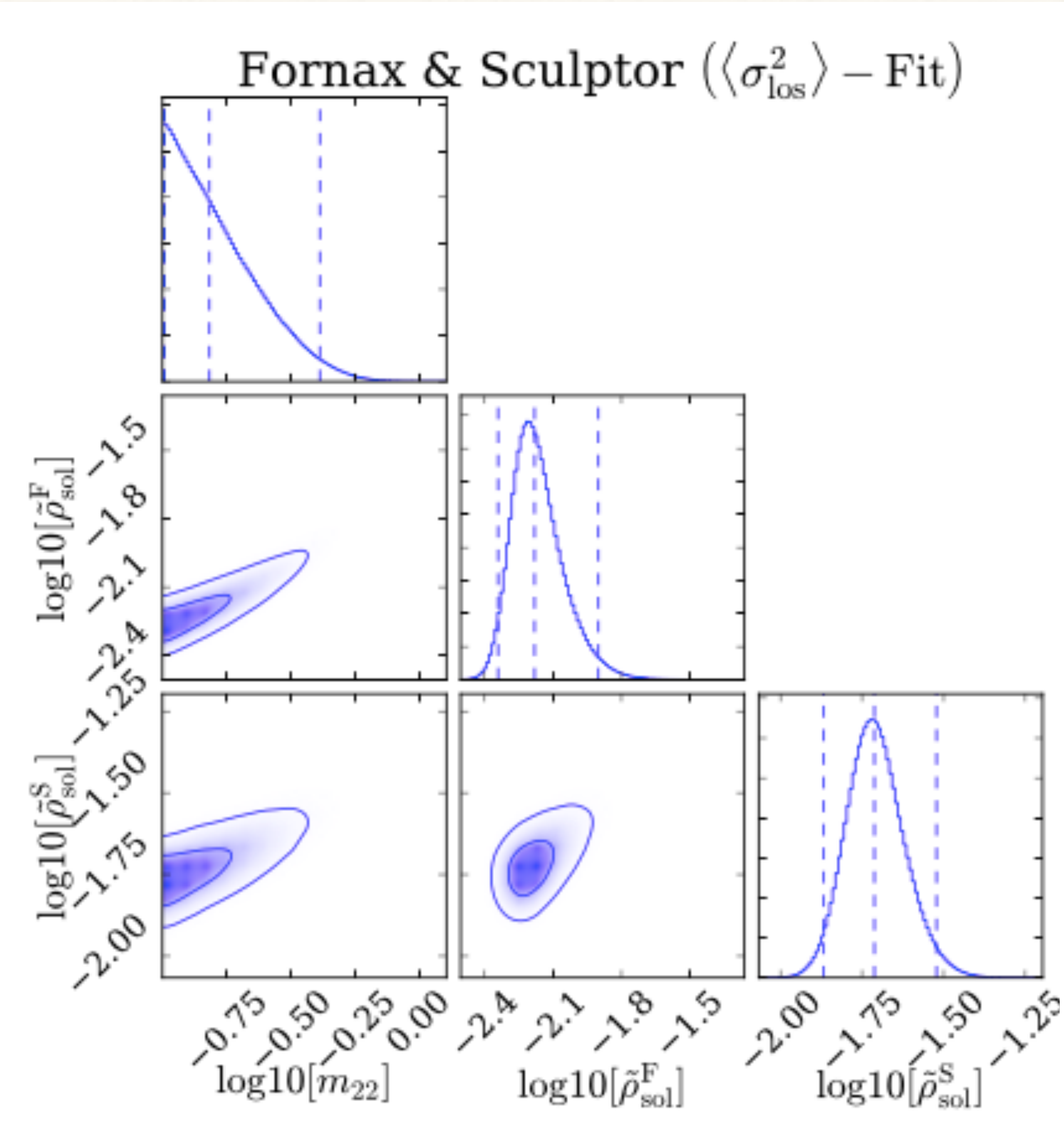


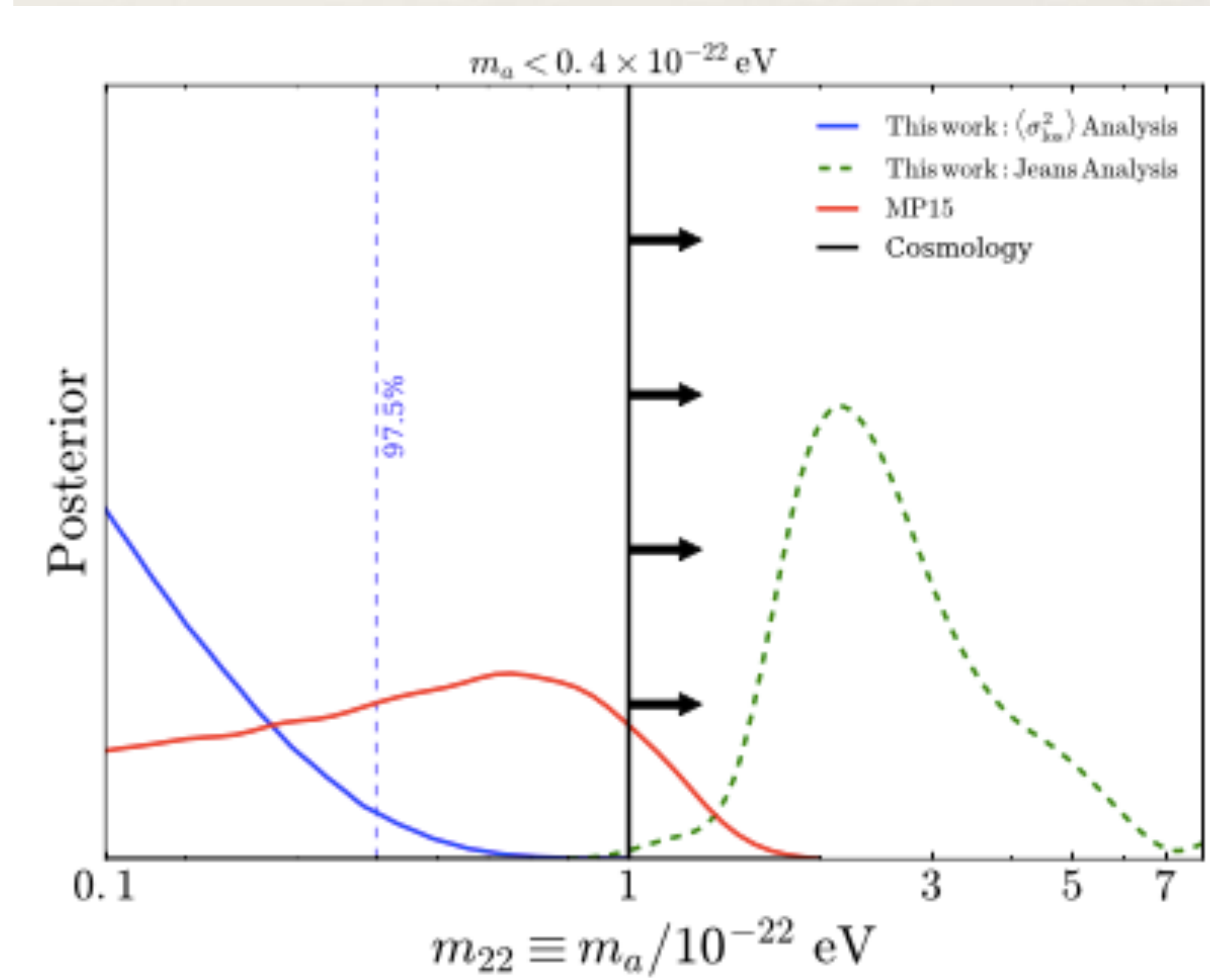
$$<\sigma^2_{\rm los}(r_{\rm half})> = \frac{\int_0^{\infty} \sigma^2_{\rm los}(R')I(R')R'dR'}{\int_0^{\infty} I(R')R'dR'}$$

and non-Isotropic mocks



Final Result

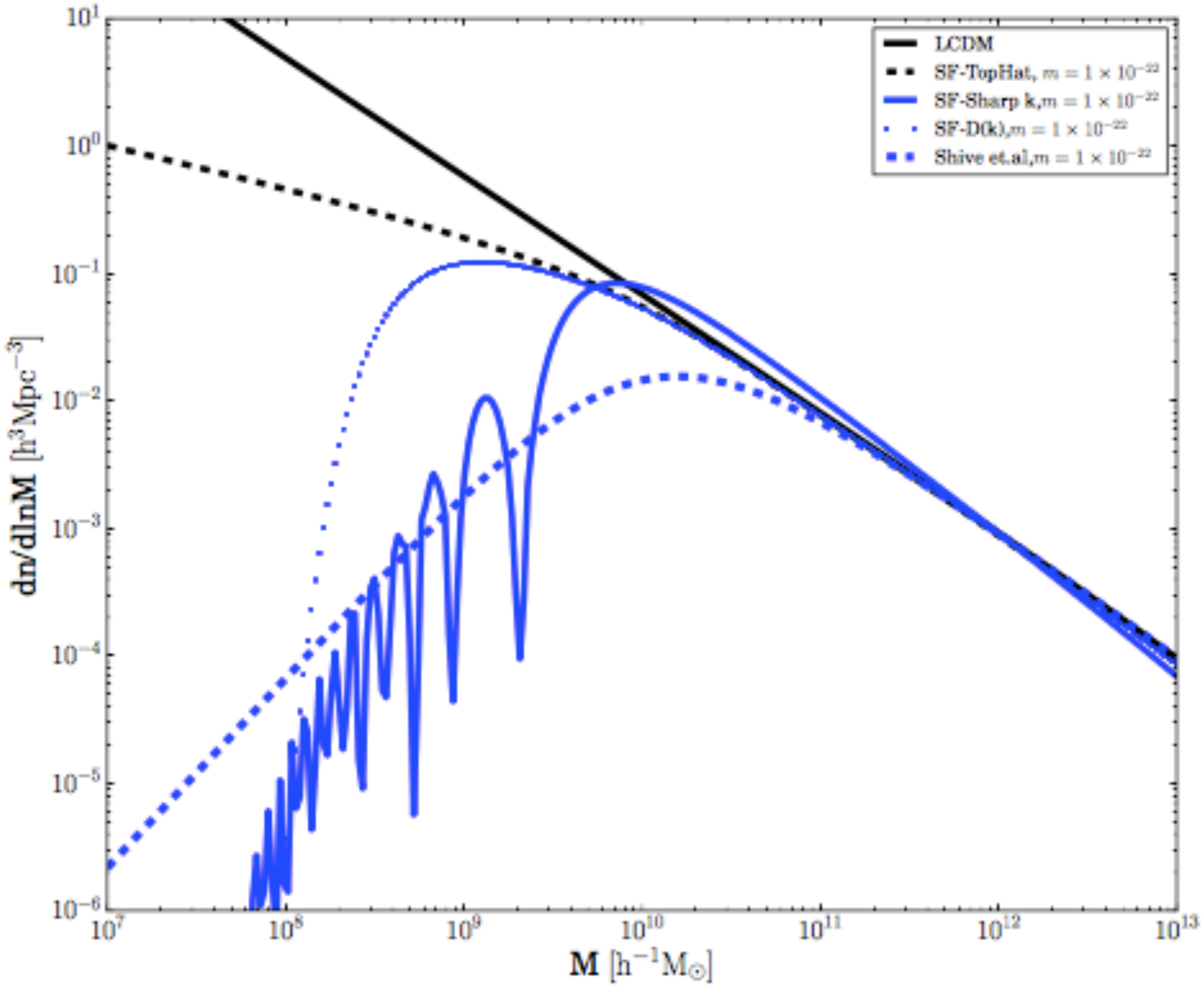


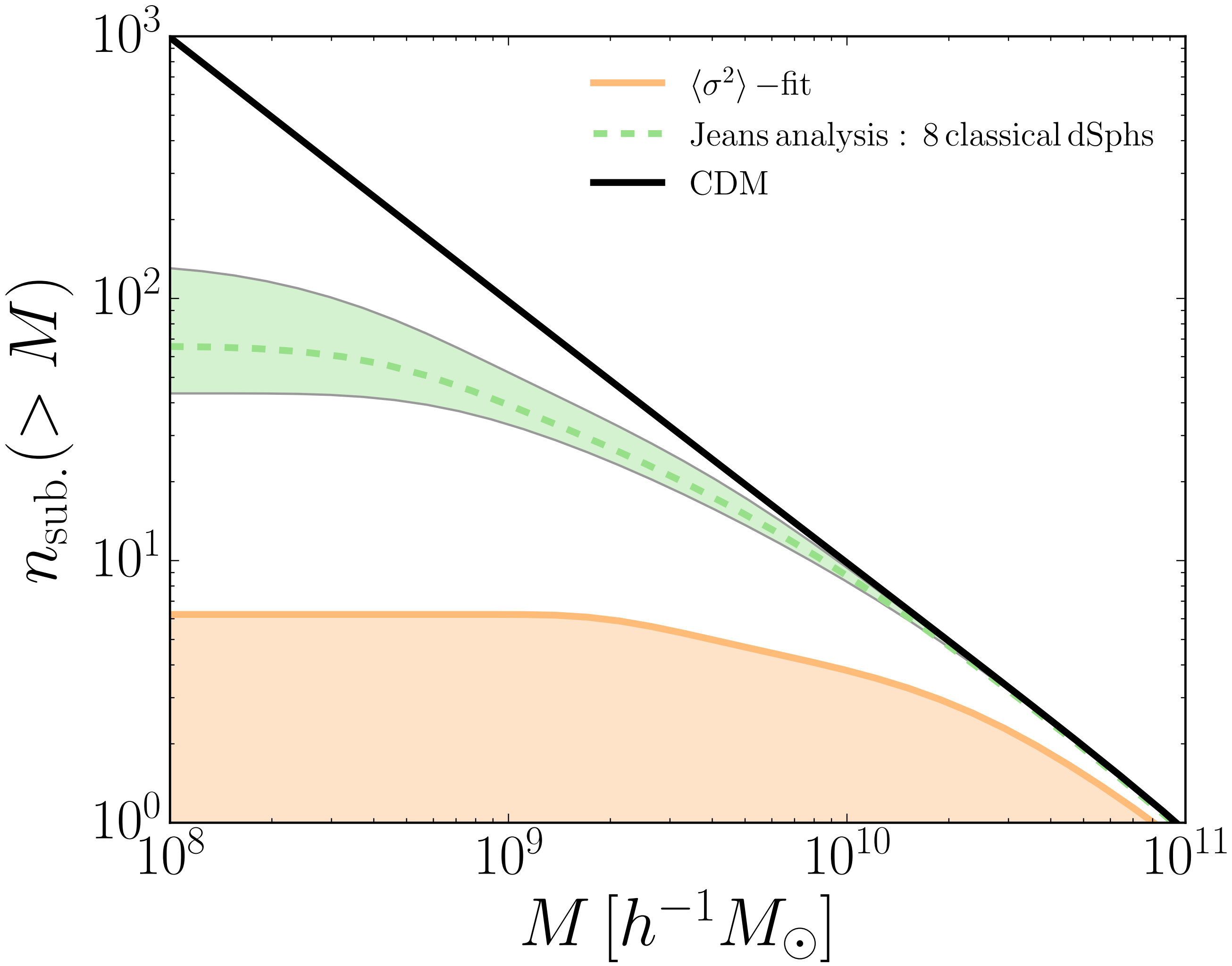


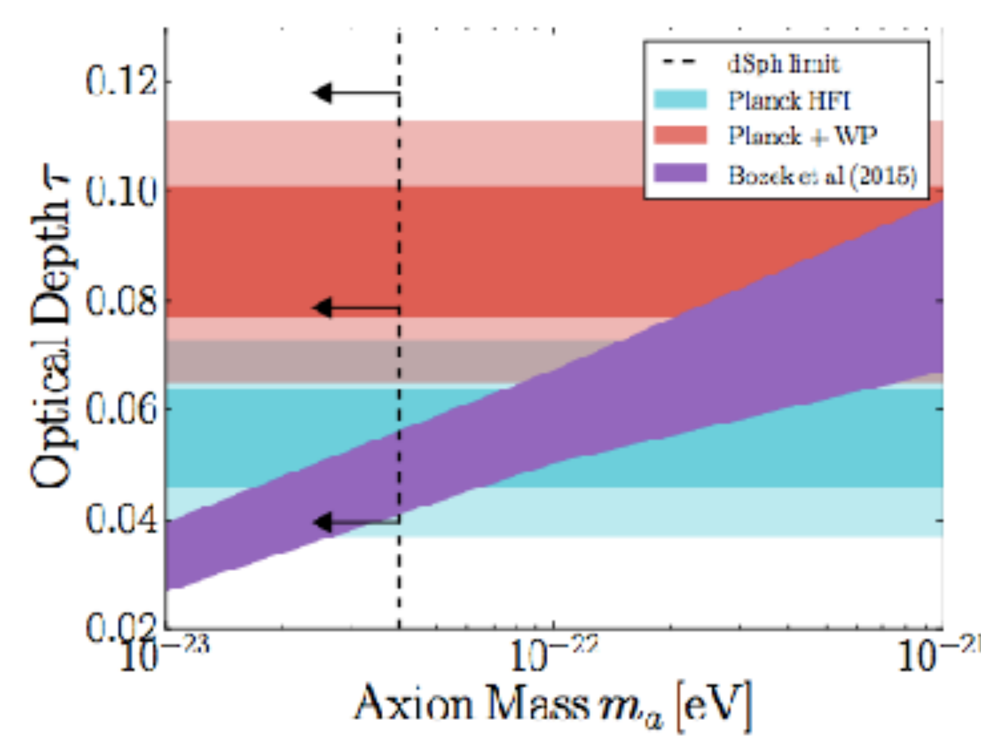
rc > 1.5 kpc (Fornax)

rc > 1.2 (Sculptor)

How it looks for cosmology?

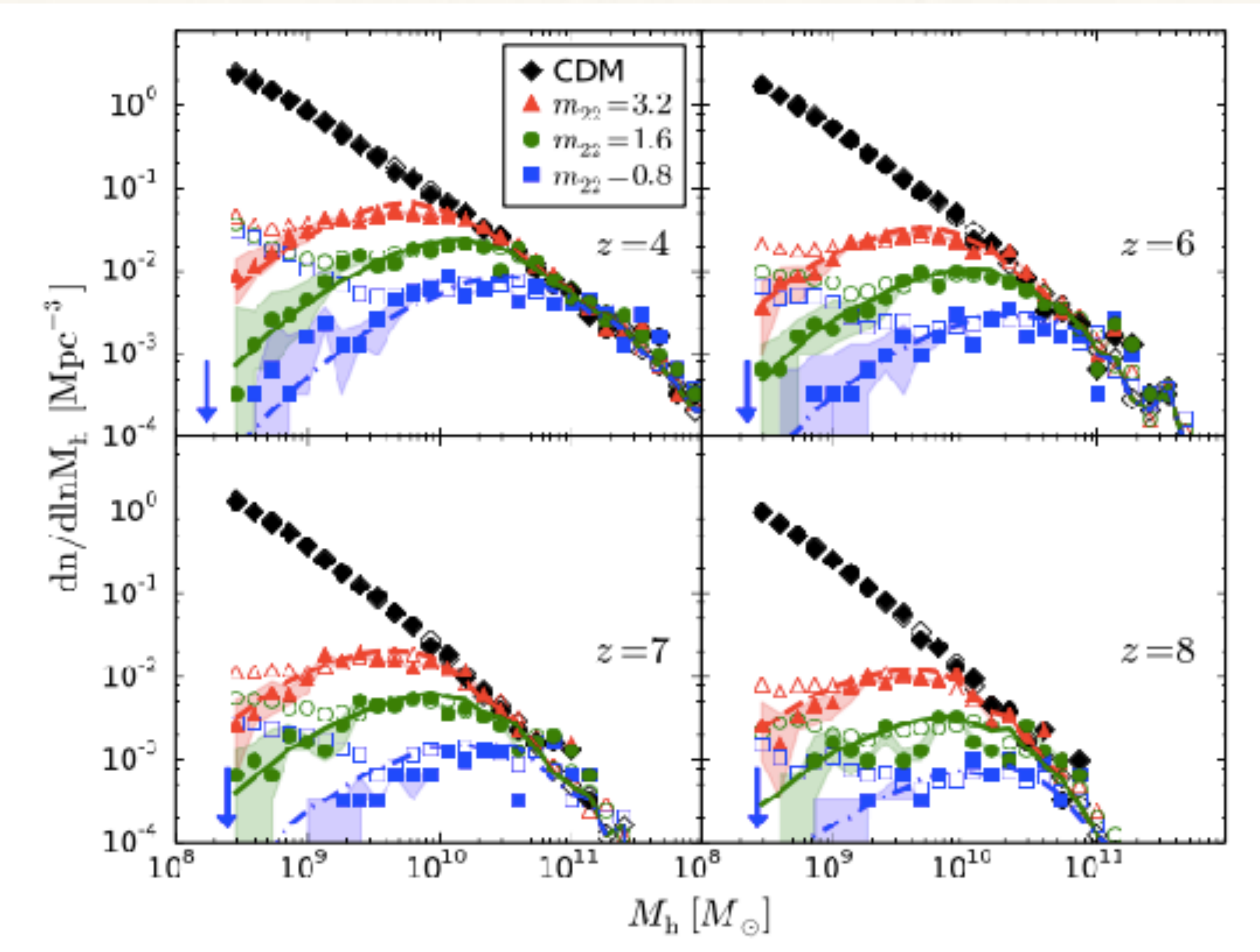




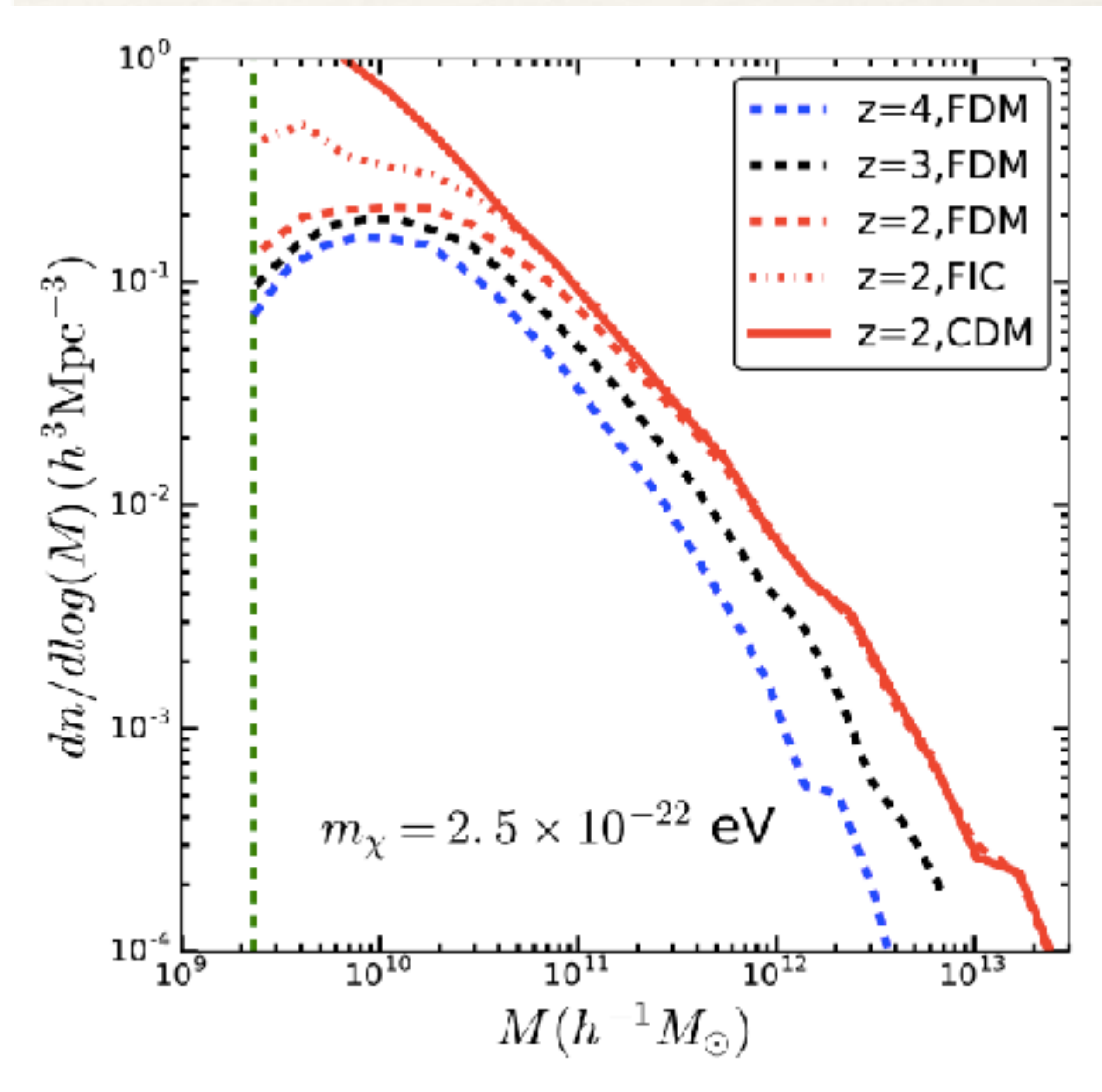


Our simple estimates show it suffers from a catch 22. Also in tension with optical depth from Planck+WP

Mass function from Simulations

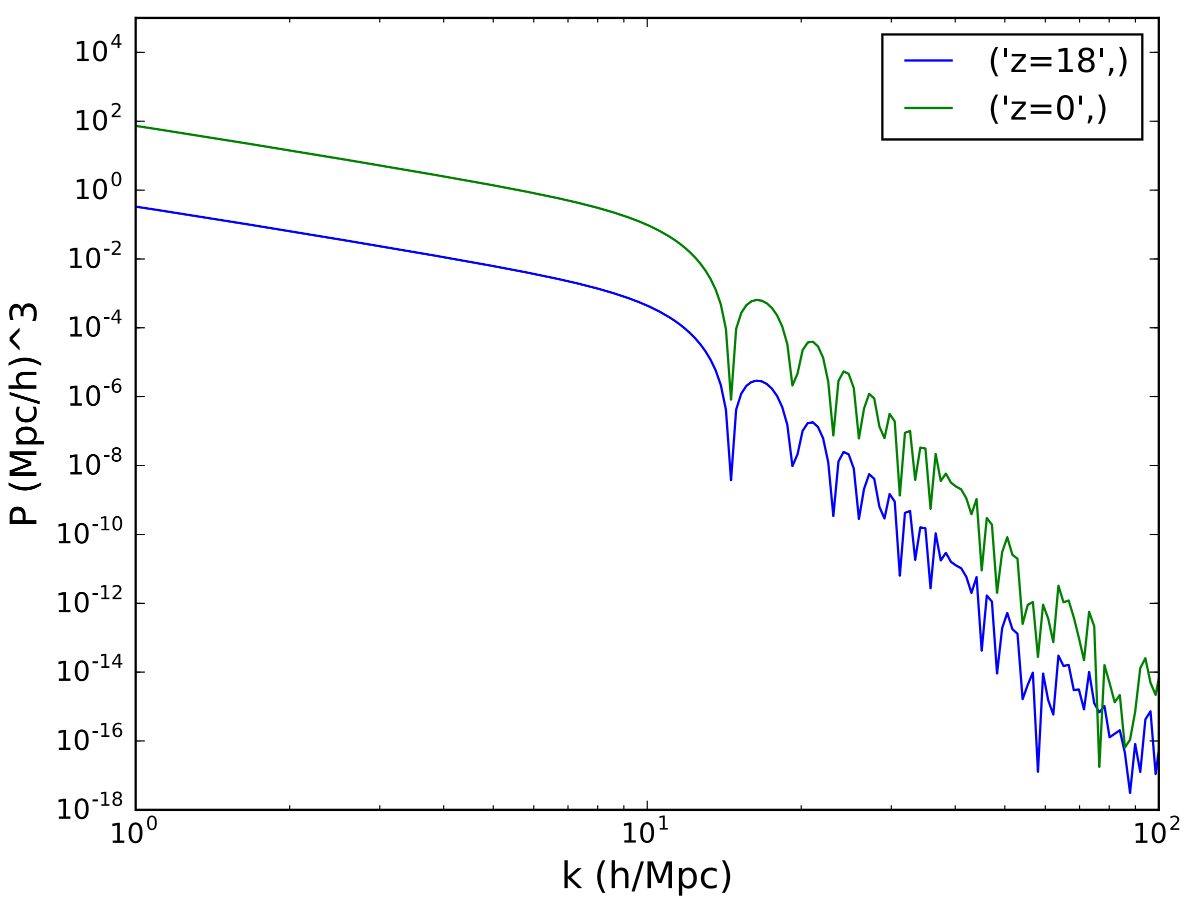


Schive et. al 2015



Zhang et. al 2017

Simulated P(k)



AXGM using CLASS (linear theory)

$$m_a = 2.5 \times 10^{-22}\text{eV}$$

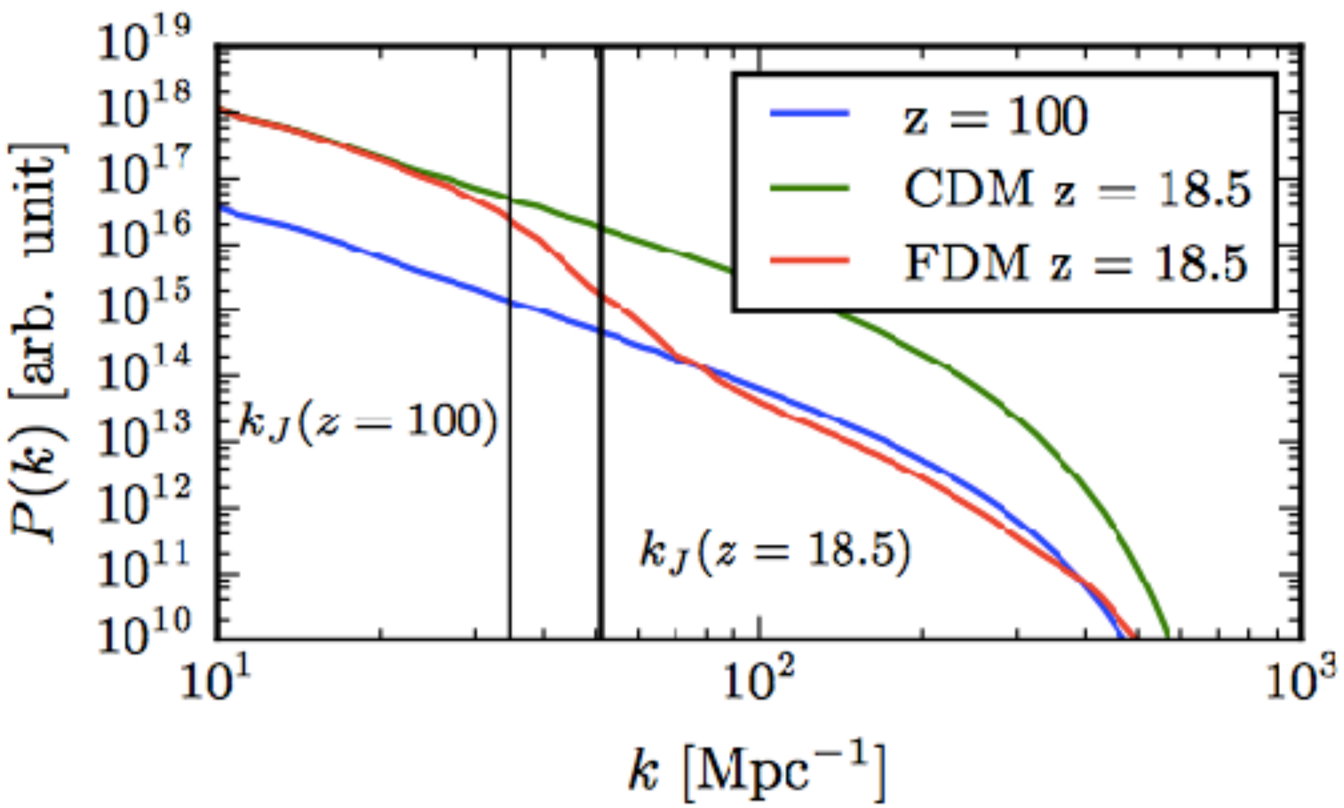
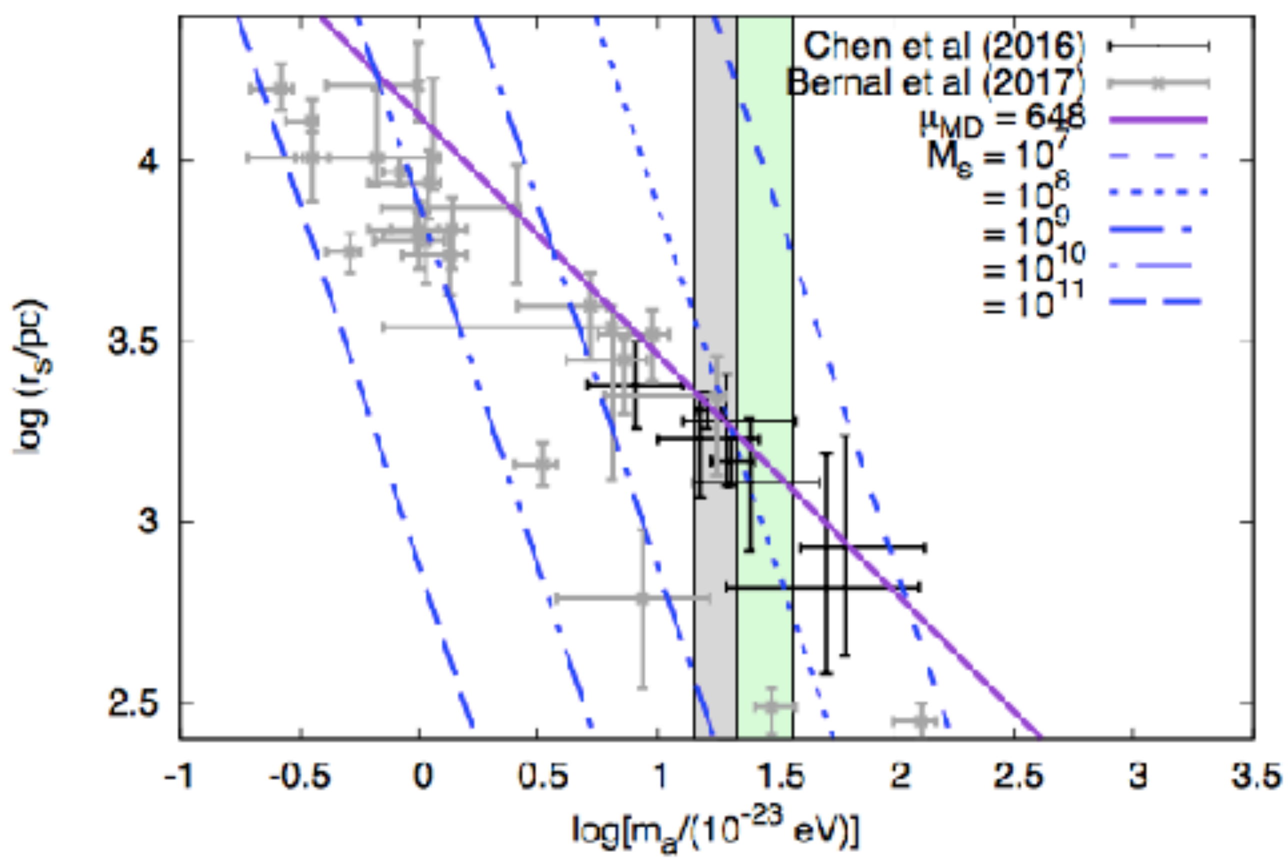
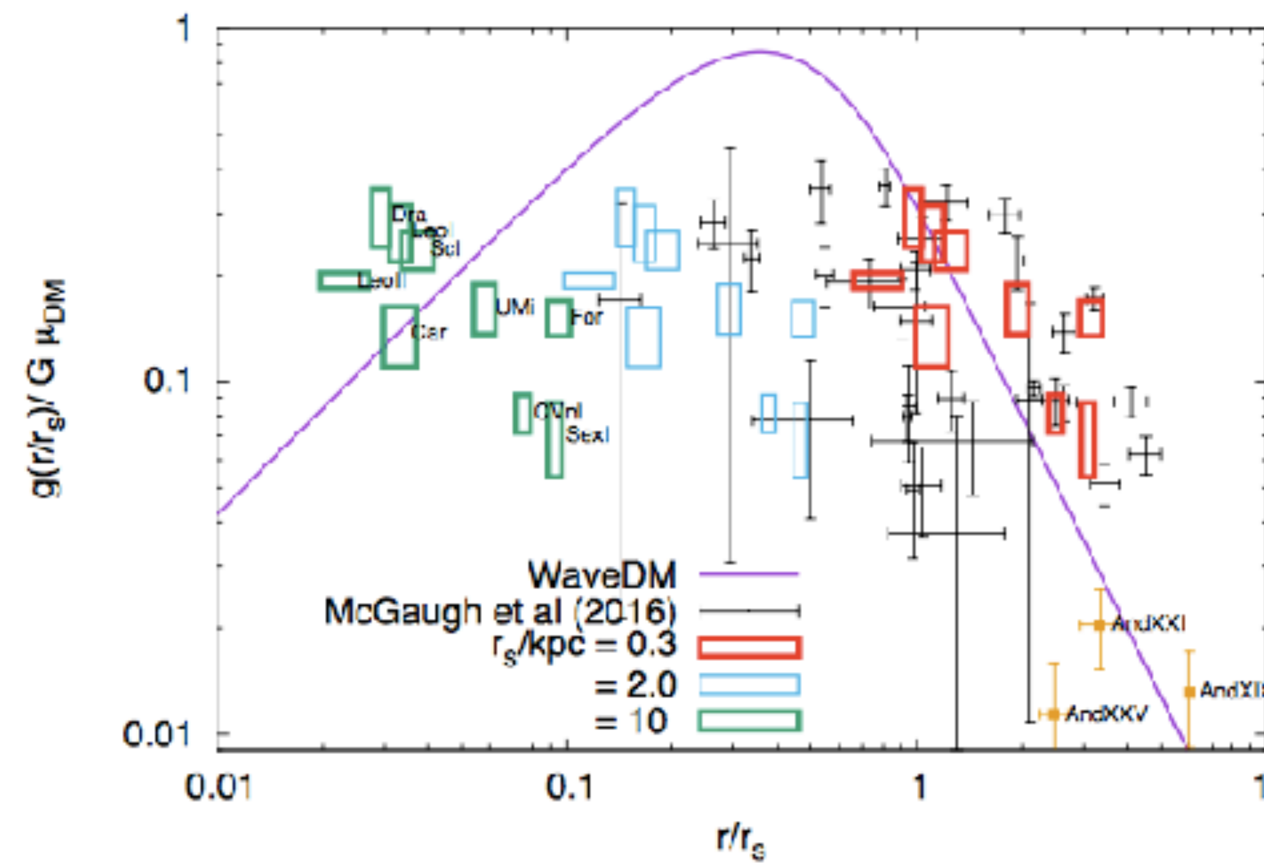


FIG. 5. Power spectra in simulations with an initial CDM power spectrum at $z = 100$ and the Jeans scales k_J at $z = 100$ and $z = 18.5$.

Other recent work





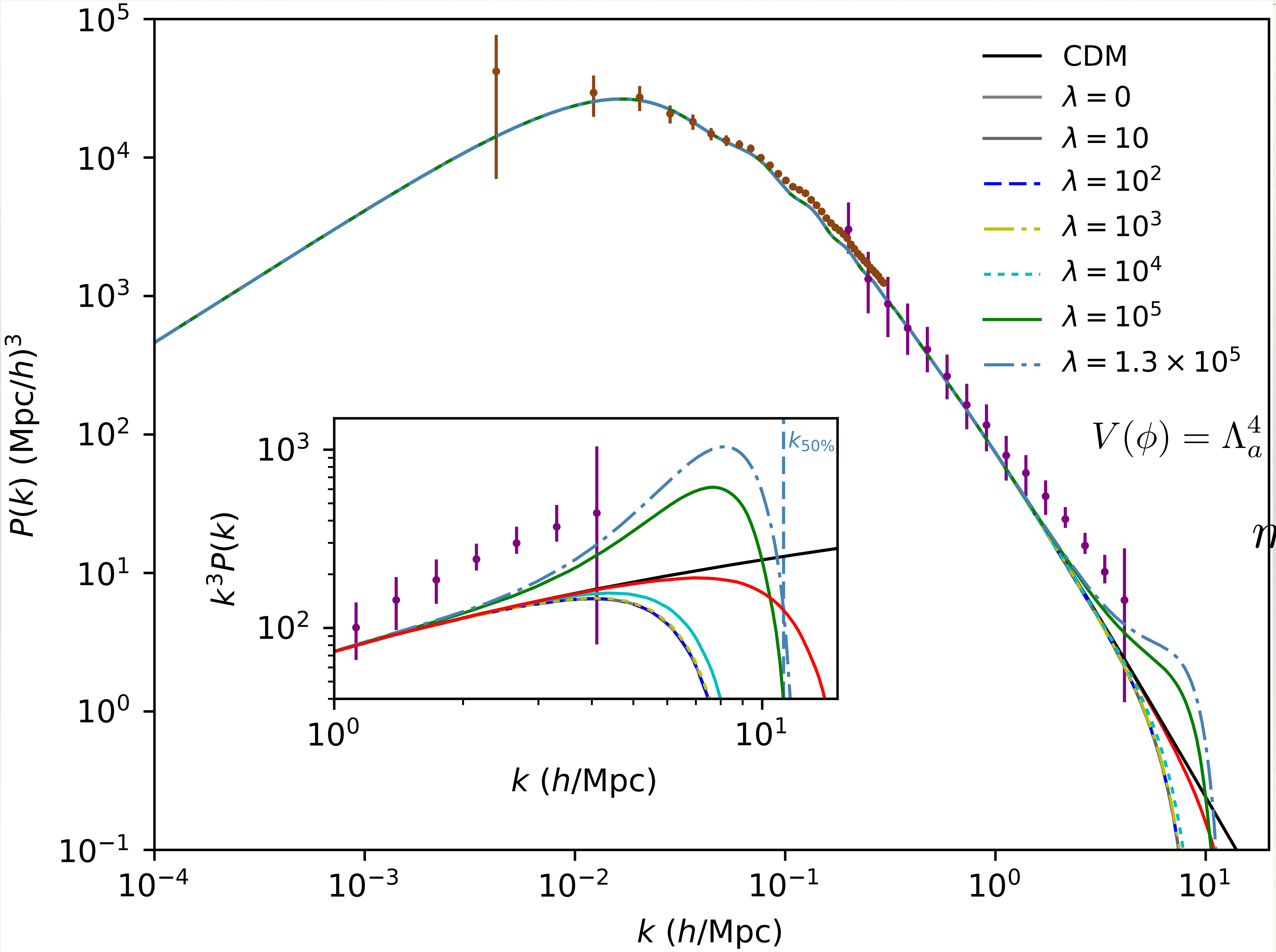
Ureña, Martinez, Matos 2016. Requieres $m_a \approx 10^{-21}\mathrm{eV}$ to follow McGaugh acceleration relation.

$$\left(\frac{r_s}{\mathrm{pc}}\right)^{-3}\left(\frac{m_a}{10^{-23}\mathrm{eV}}\right)^{-2} = 4.1\times 10^{-15}\left(\frac{\mu_{DM}}{M_\odot \mathrm{pc}^{-2}}\right)$$

$$\mu_{DM} = 648\ M_\odot \mathrm{pc}^{-2}$$

$$\mu_{DM} = \rho_s r_s$$

ULA Cosmology—not-free SF



$$V(\phi) = \Lambda_a^4 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$

$$m_a = \Lambda_a^4 / f_a$$

Linear PS.

X. Linares, **AXGM,** L. Ureña
Phys.Rev.D rapid, 2017

Open questions

- We might be measuring an effective core radius, not really the axion mass. This depend on the ULA density profile reacts to baryonic process as SN feedback. ¿ How tides affect our estimates?
- What is the role/interpretation of the transition radius from soliton to NFW profile? (Is the parametrization in terms of NFW the best to use?)
- We would like to test our inference on m_a in less idealized mock data.
- Look for consistency with bigger galaxies.
- Many more…