Bayesian reconstruction of the Milky Way dark matter distribution

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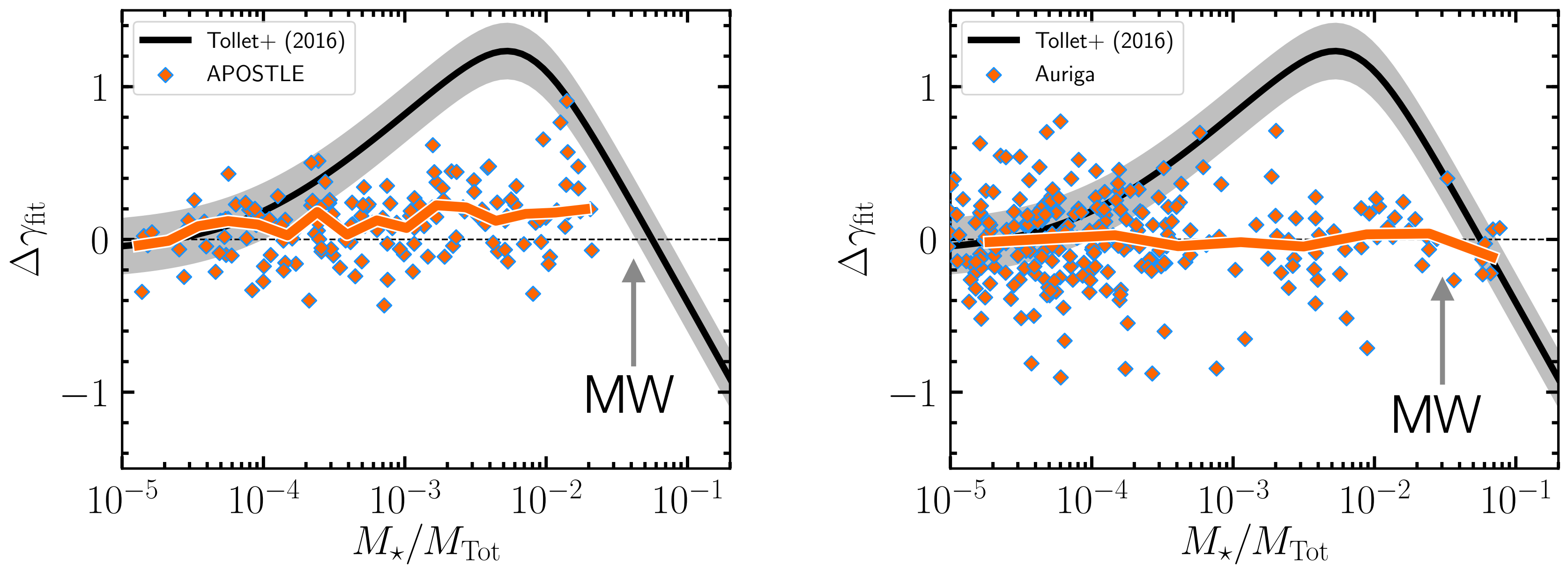
arXiv:1901.02463

AstroCeNT

CAMK PAN

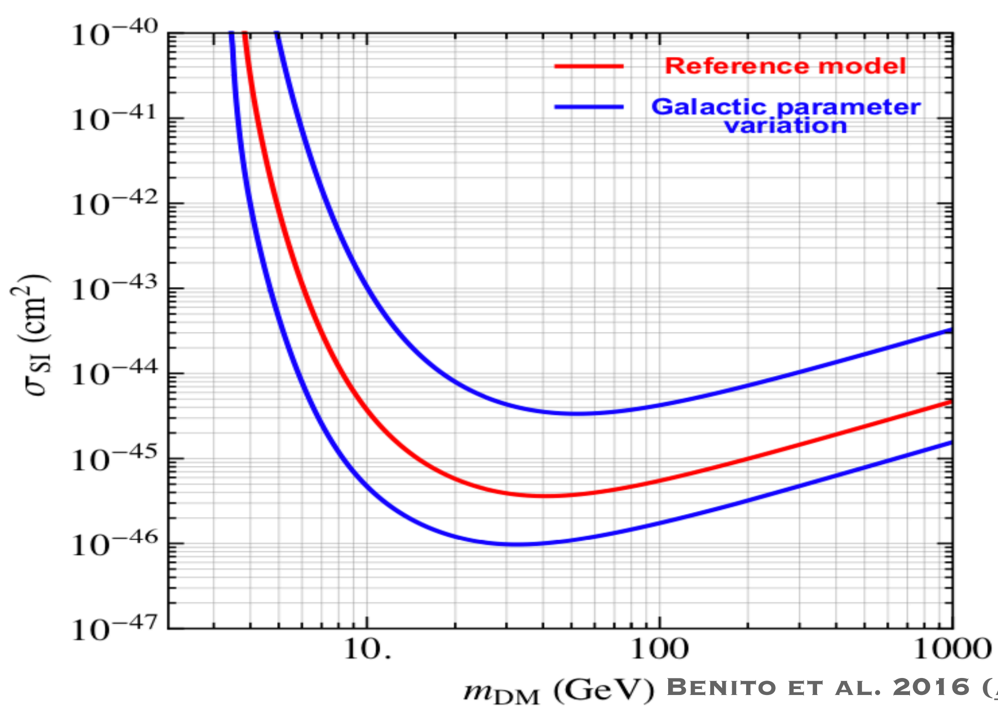
Motivations

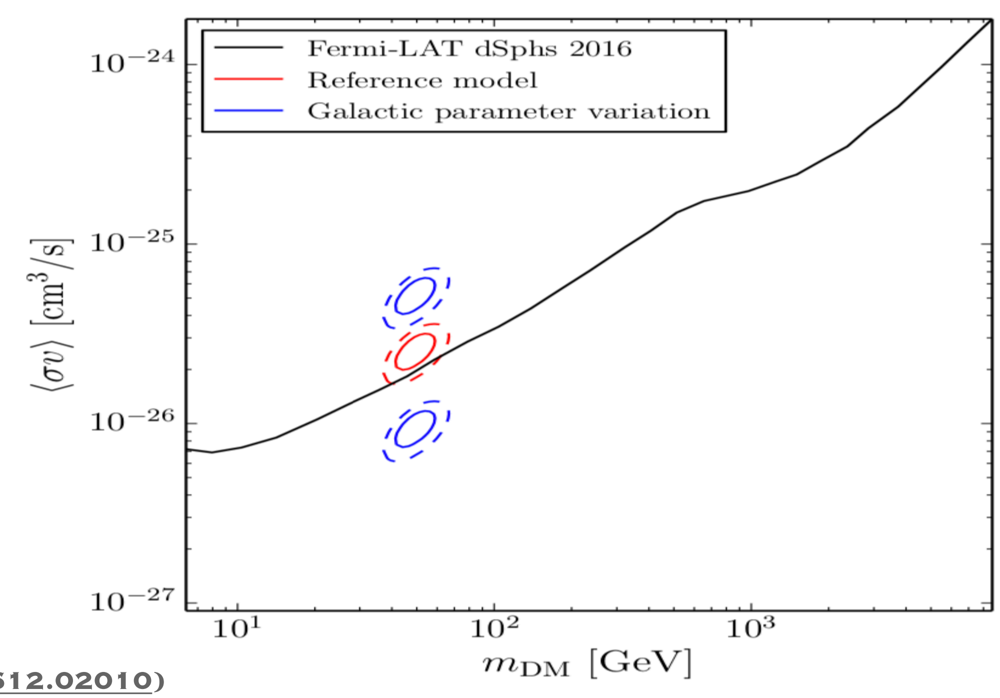
Placing MW in LCDM paradigm



Bose et al. 2018 (arXiv:1810.03635)

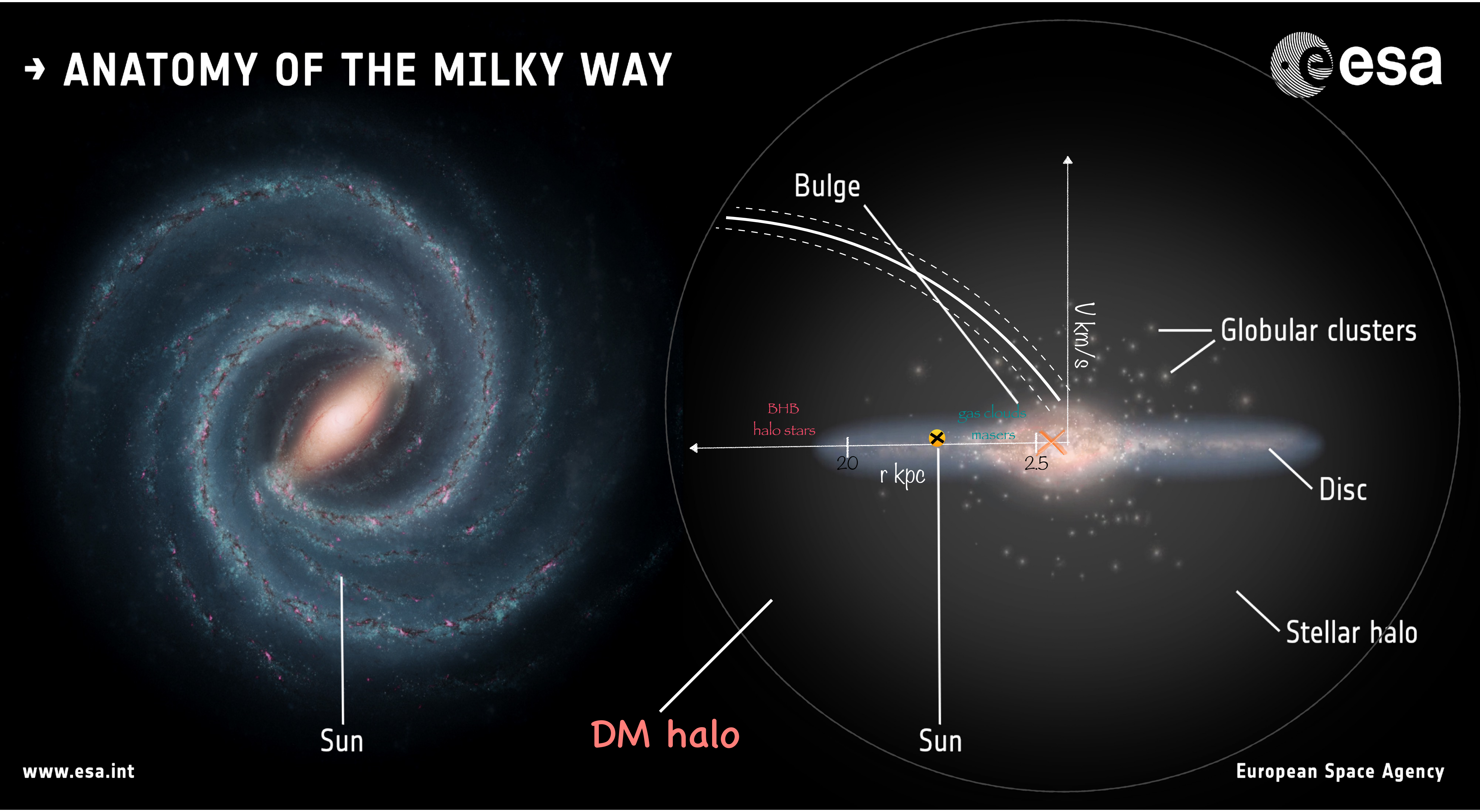
Direct and indirect dark matter searches



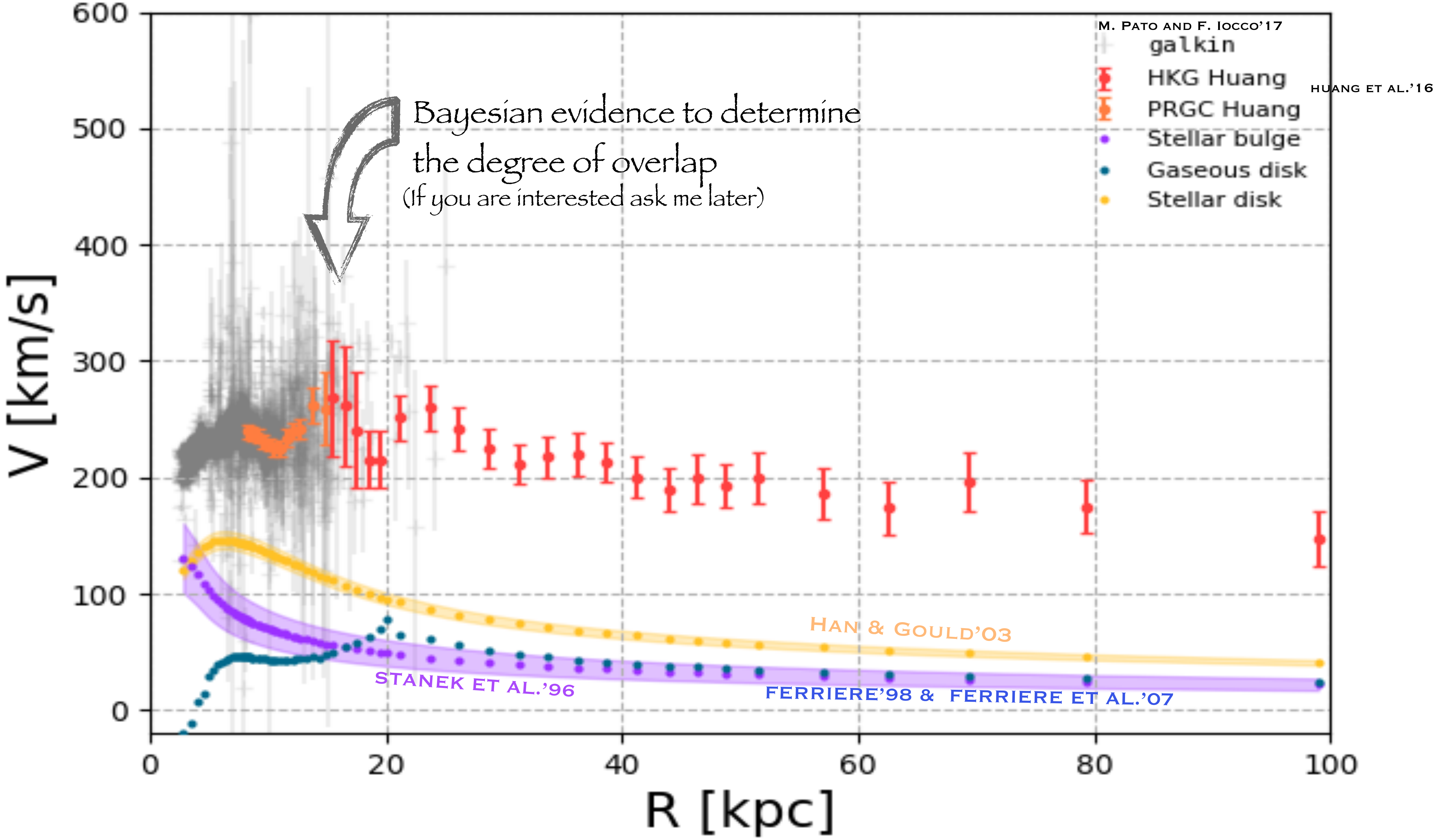


Benito et al. 2016 (arXiv:1612.02010)

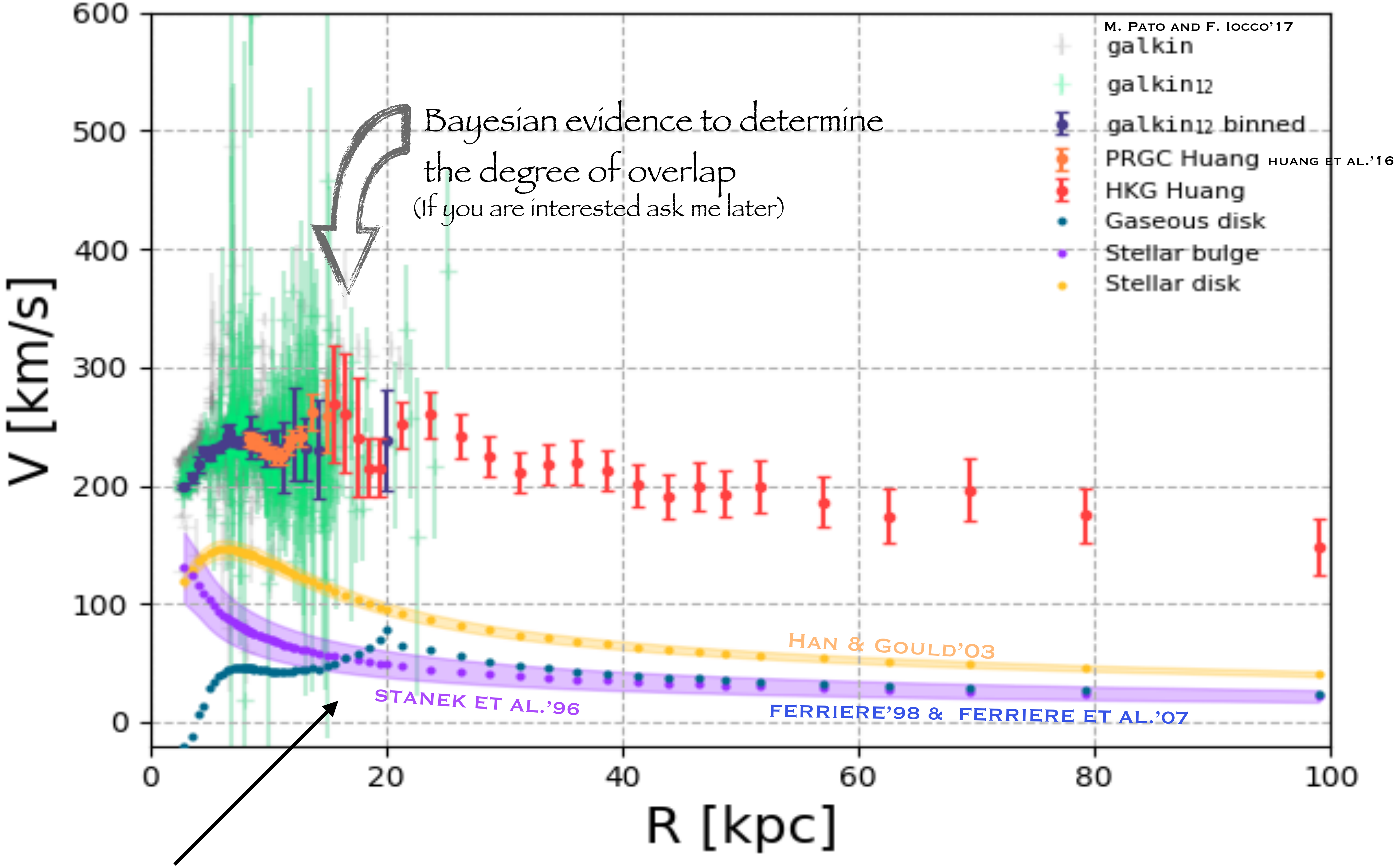
MW overview


→ ANATOMY OF THE MILKY WAY
esa
Bulge
V km/s
Globular clusters
BHB
halo stars
gas clouds
masers
20
2.5
r kpc
Disc
Stellar halo
Sun
DM halo
Sun
www.esa.int
European Space Agency

Compilation of MW RC



Compilation of MW RC



30 combinations of different stellar disk and bulge morphologies

Methodology

standard approach

see e.g. Sofue & Rubin'01, Catena & Ullio'09...

total gravitational potential:

$$\phi_{total} = \phi_{bar} + \phi_{dm}$$

DM potential assuming spherical symmetry:

$$\phi_{dm} = -\frac{GM_{dm}(r)}{r} \longleftarrow M_{dm}(r) = 4\pi \int_0^R \rho_{dm}(r) r^2 dr$$

gNFW DM density profile:

$$\rho(R) = \frac{\rho_s}{(R/r_s)^\gamma \, (1 + R/r_s)^{3-\gamma}} \longrightarrow \rho_s = \rho_0 \left(\frac{R_0}{r_s}\right)^\gamma \left(1 + \frac{R_0}{r_s}\right)^{3-\gamma}$$

R_0 - Sun's position
ρ_0 - density at Sun's location

MCMC-based reconstruction

Bayes theorem:

$$POSTERIOR \propto PRIOR \times LIKELIHOOD$$

we adopt flat priors

Likelihood function:

$$\mathrm{P(d|\Theta)} = \prod_{i=1}^{m} \left\{ \frac{1}{\sqrt{2\pi}\sigma_{\bar{\omega},i}} \exp\left[-\frac{1}{2} \frac{\left(\omega_c(r_i,\Theta) - \bar{\omega}^i\right)^2}{\sigma^2_{\bar{\omega},i}} \right] \right\}$$

$$\times \frac{1}{\sqrt{2\pi}\sigma_{\langle\tau\rangle}} \exp\left[-\frac{1}{2} \frac{\left(\langle\tau\rangle - \langle\tau\rangle^{obs}\right)}{\sigma^2_{\langle\tau\rangle}} \right] \Longleftarrow 2.17 \pm 0.47$$

$$\times \frac{1}{\sqrt{2\pi}\sigma_{\Sigma_*}} \exp\left[-\frac{1}{2} \frac{\left(\Sigma_* - \Sigma_*^{obs}\right)}{\sigma^2_{\Sigma_*}} \right] \Longleftarrow 38 \pm 4\, M_\odot/pc^2$$

PATO ET AL.'15

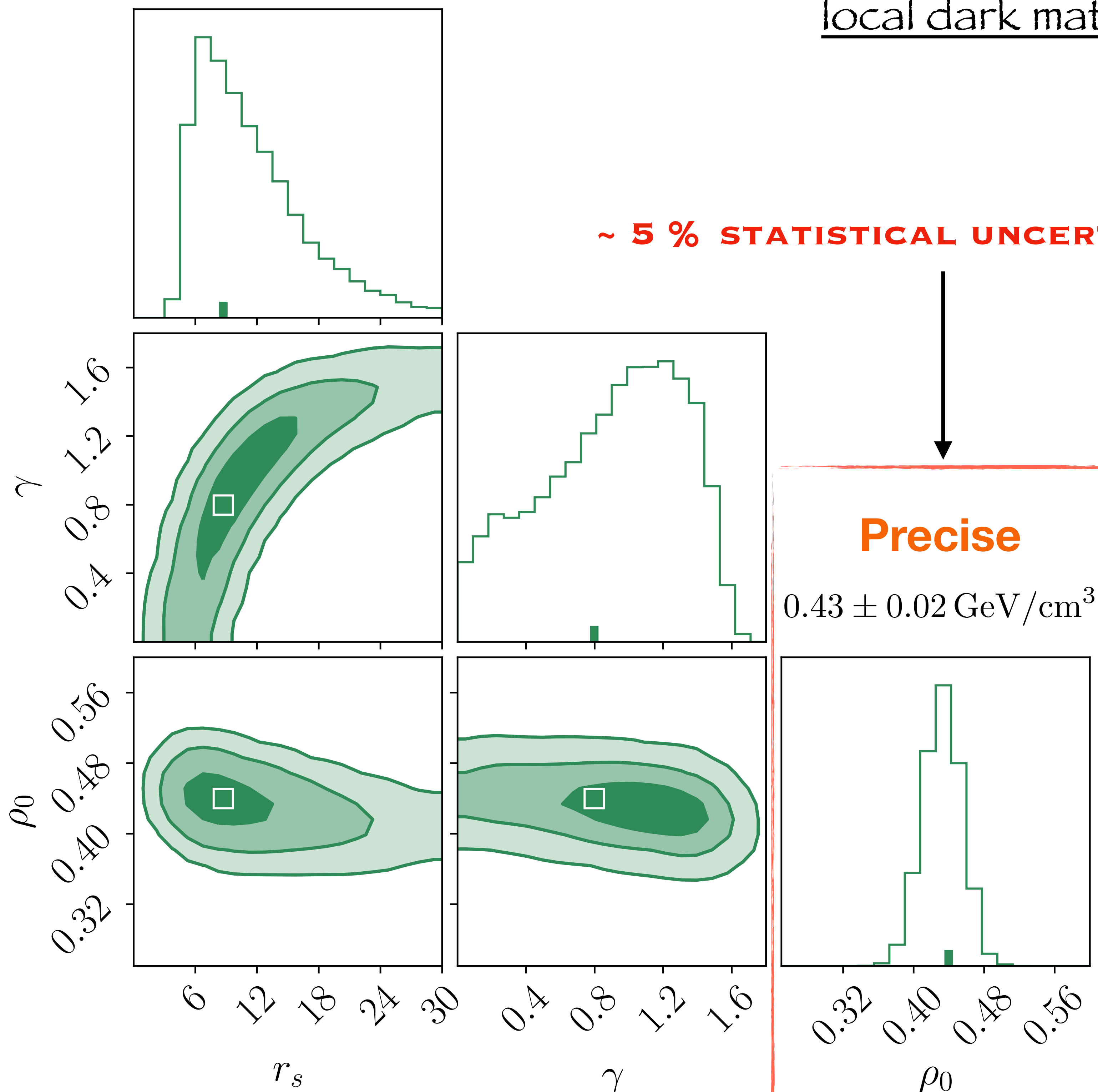
Note that the angular velocity ω_c is used instead of the actual circular velocity $V_c \equiv r\omega_c$

IN THE WAKE OF STANDARD APPROACH

Results

local dark matter density

~ 5 % STATISTICAL UNCERTAINTY



Precise

$0.43 \pm 0.02\,\mathrm{GeV/cm^3}$

Accurate

(validated on a suite of mock rotation curves)

and does not depend on the assumed baryonic morphology

Results

virial Milky Way mass

$$M_{vir} = \frac{4\pi}{3} 200 \rho_{crit} R_{vir}^3$$

We need to rewrite gNFW profile in terms of γ, c and M_{vir}

$$\rho(R) = \frac{\rho_s}{(R/r_s)^{\gamma}\,(1 + R/r_s)^{3-\gamma}}$$

← $r_s(c, M_{vir})$ and $\rho_s(\gamma, c, \rho_{crit})$

Results

virial Milky Way mass

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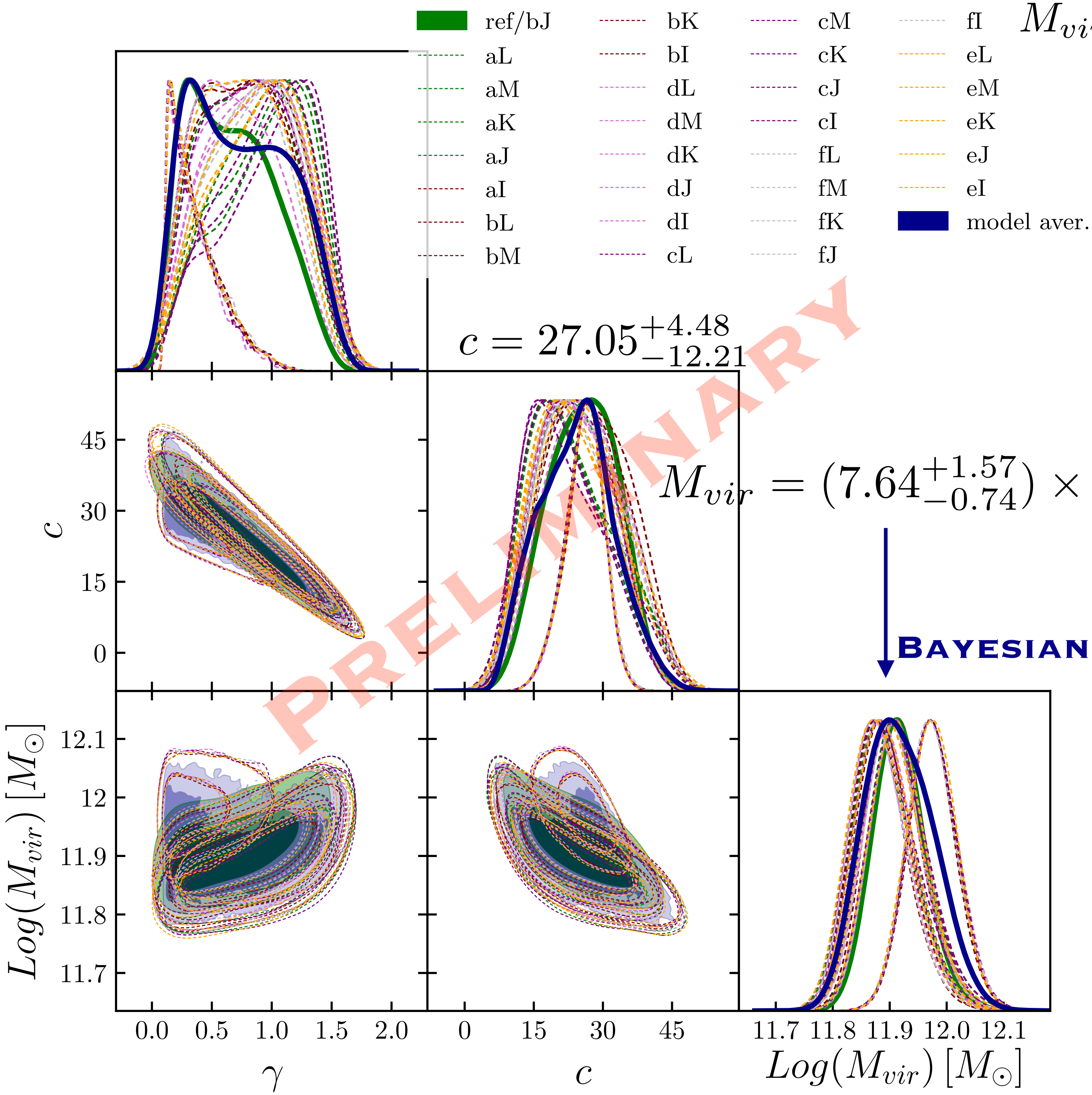

$$M_{vir} = (7.64^{+1.57}_{-0.74}) \times 10^{11}\ M_\odot$$

Bayesian model averaging

Summary

Bayesian reconstruction of the Milky Way dark matter distribution:

- precise reconstruction of the dark matter density distribution;
- high accuracy on the local dark matter density;
- determination of the local dark matter density is independent of the assumed baryonic morphology;
- weak accuracy on the inner dark matter density slope γ and scale radius r_s .

Preliminary

- accurate and precise estimation of the Milky Way virial mass;
- determination of the virial mass weakly depends on the assumed baryonic morphology.

Backup slides

Compilation of MW RC

Compatibility of data sets via the Bayesian evidence

$$B = \frac{p(d_1, d_2|\mathcal{M})}{p(d_1|\mathcal{M}\ )p(d_2|\mathcal{M}\ )}$$

$p(d|\mathcal{M})$ is the Bayesian evidence for data given model $\mathcal{M}$

galkin 12 data sets

+

2 data sets of Huang et al.

for details on the methodology see e.g. arXiv: 1101.1521, astro-ph/0203259, 0807.4512, 0903.2487

Bayesian model averaging

$$p(\theta|d) = p(M_j|d) \sum_i B_{ij} p(\theta|d, M_i)$$

posterior within each model

$$B_{ij} = \frac{p(d|M_i)}{p(d|M_j)}$$

Model's evidence ratio wrt the reference model (assuming equal priors for all models)

MCMC-based reconstruction and mock RCs

The idea is to test the MCMC-based reconstruction by creating mock rotation curves based on "underlying known" DM profiles (+ visible) and with the same statistical properties of the observed RC

We use the following way to create the mock data:

$$\omega_c^{\mathrm{mock}(i)} = \omega_c^{\mathrm{fid}(i)} + \delta_i$$

with

$$\omega_c^{\mathrm{fid(i)}} = \left(\omega^2_{\mathrm{gNFW}}(r_s, \gamma, \rho_0, r^{(i)}) + \omega^2_{\mathrm{baryons}}(\Sigma_*, \langle\tau\rangle, r^{(i)})\right)^{1/2}$$

- i is the index number of a bin
- $r_s, \gamma, \rho_0, \Sigma_*, \langle\tau\rangle$ are the fiducial parameters
- δ_i is a random sample from a normal distribution with mean 0 and variance equal to the observational error

MCMC-based reconstruction and mock RCs

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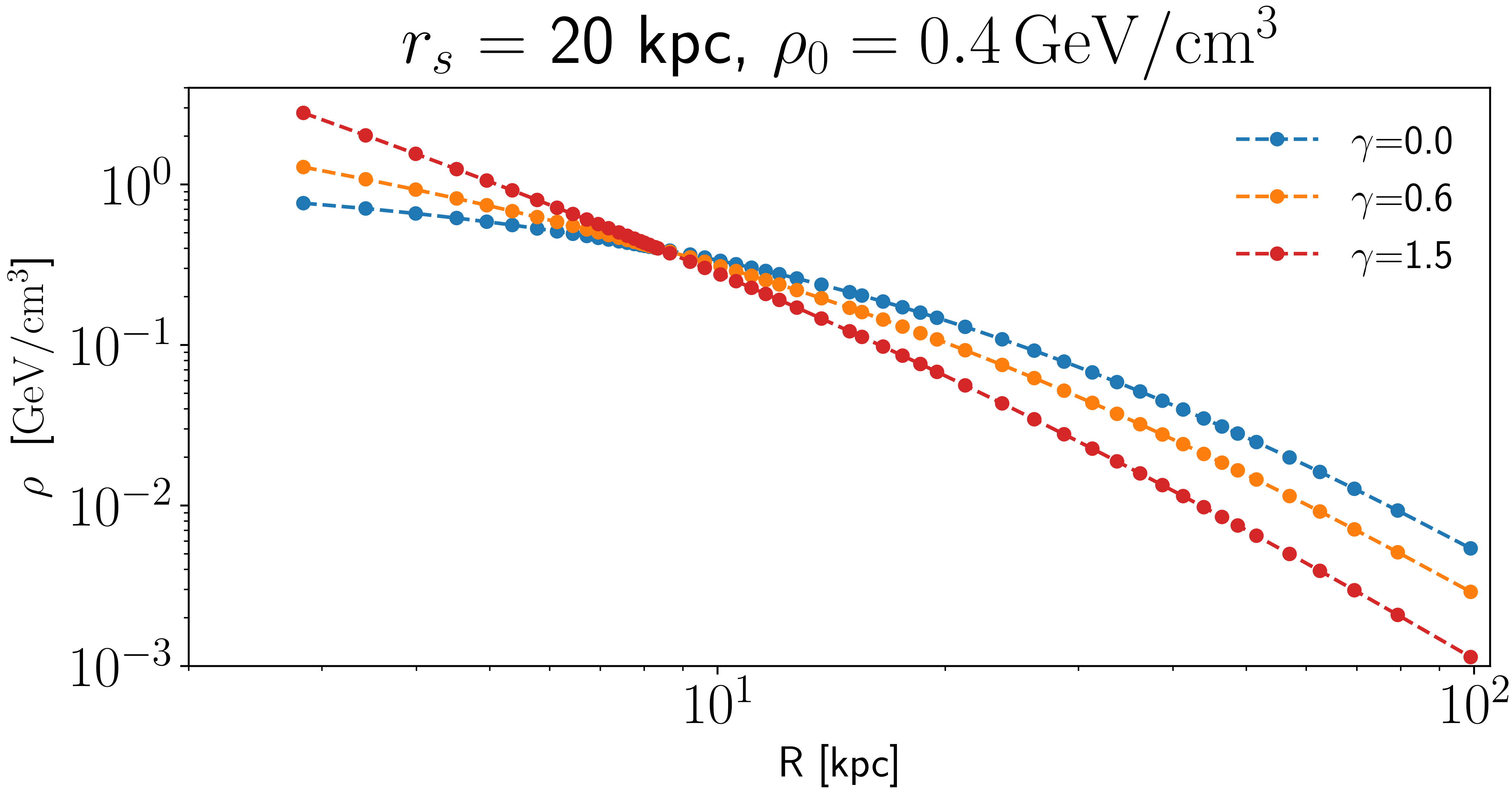
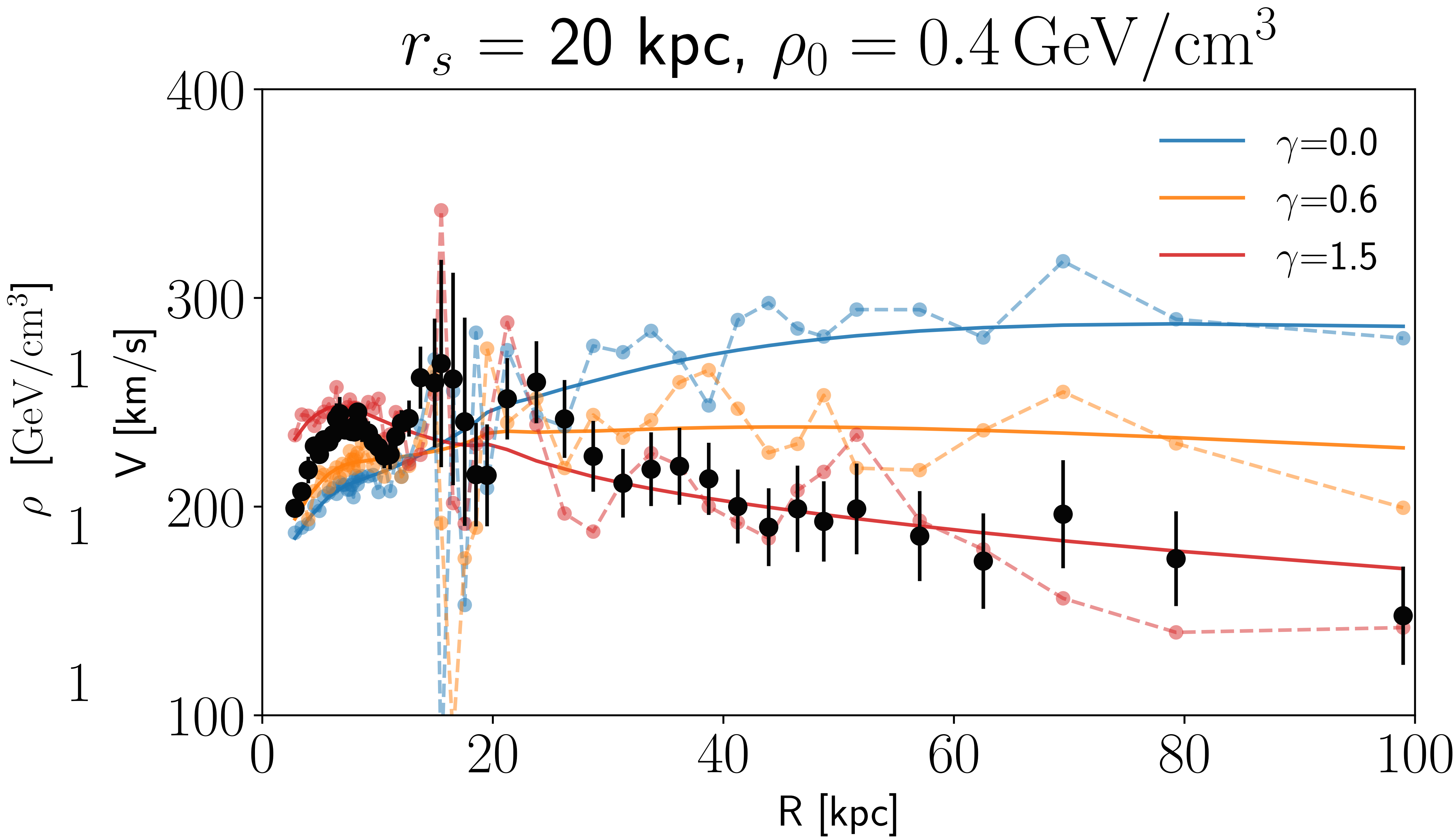


MCMC-based reconstruction and mock RCs

r_s [kpc]	5	8.5	12.5	16.5	20
γ	0.1	0.4	0.8	1.2	1.5
ρ_0, [GeV/cm^3]	0.4				
Σ_*, [M$_\odot$/kpc^2]	38×10^6				
$\langle\tau\rangle$	2.17×10^{-6}				

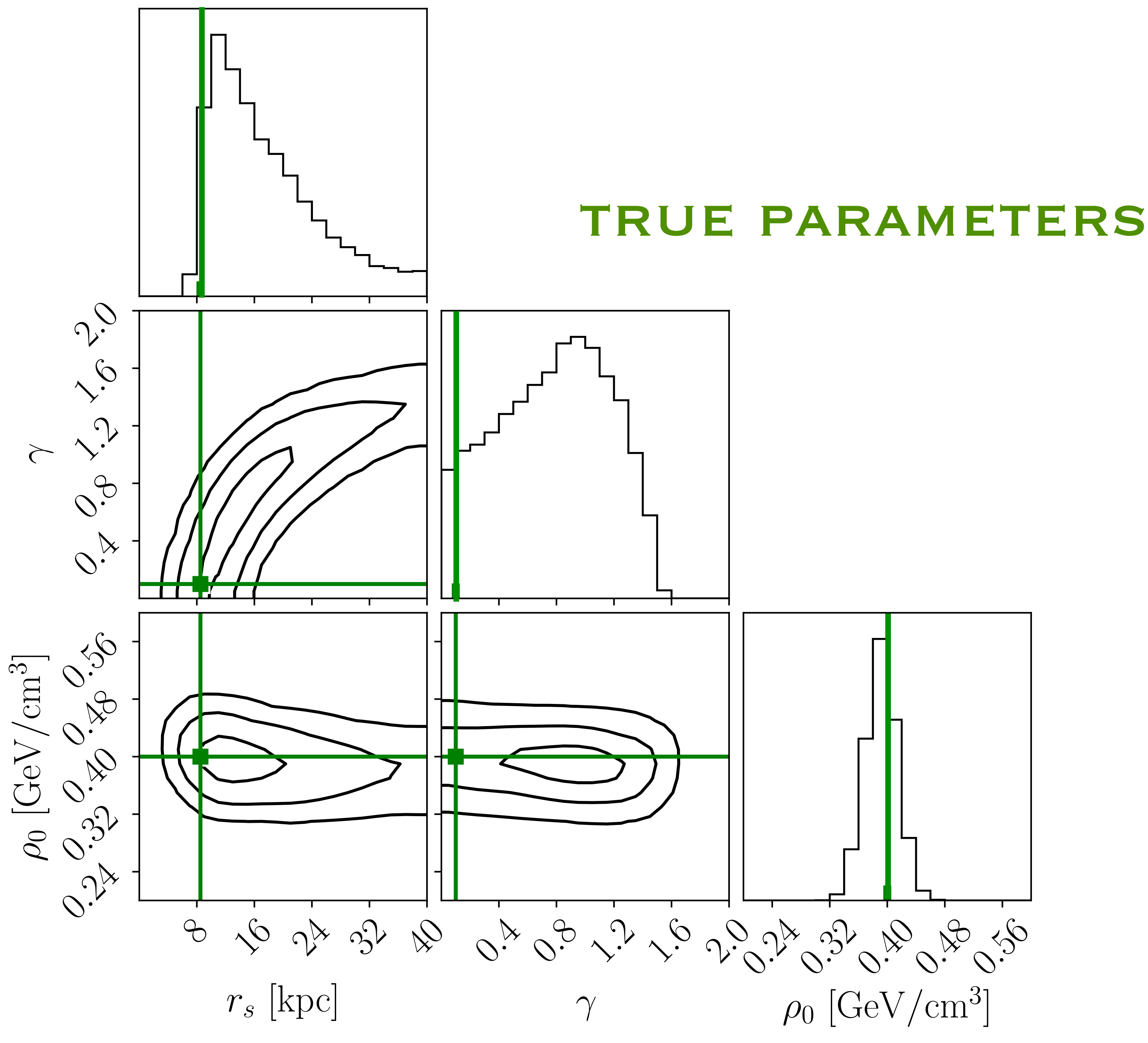
$$\omega_c^{\mathrm{mock}(i)} = \omega_c^{\mathrm{fid}(i)} + \delta_i$$



Results

100 mock realisations

25 points in the parameter space



Results

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