Constraining Dwarf Galaxy Dark Matter Distributions: Spherical Jeans Analyses for Line-of-Sight and 3D Velocity Data

Isabelle Goldstein

THE INSTITUTE
FOR UNDERGROUND SCIENCE
AT SURF

CETUP WORKSHOP 2024

JUNE 20, 2024

TEXAS A&M
UNIVERSITY

1. **The Viability of Ultralight Bosonic Dark Matter in Dwarf Galaxies**
   Work done in collaboration with Savvas Koushiappas and Matthew Walker
   Phys. Rev. D **106**, 063010

2. **3D Jeans Analyses**

ULTRALIGHT DARK MATTER

- **Ultralight bosonic dark matter** is a boson of mass $m \sim 10^{-22}$ eV
  - Often written as $m_{22} = m / 10^{-22}$ eV

ULTRALIGHT DARK MATTER

- **Ultralight bosonic dark matter** is a boson of mass $m \sim 10^{-22}$ eV
  - Often written as $m_{22} = m / 10^{-22}$ eV

- Motivated by non QCD axions, GUT scale physics & string theory

ULTRALIGHT DARK MATTER

- **Ultralight bosonic dark matter** is a boson of mass m~10^{-22} eV
  - Often written as $m_{22} = m / 10^{-22}$ eV
- Motivated by non QCD axions, GUT scale physics & string theory
- Quantum effects become macroscopic: **~kpc scale**

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

ULTRALIGHT DARK MATTER

- Why is this interesting?
  - ΛCDM is well tested at large scales, but not small scales
  - Small scale problems: cores vs cusps, missing satellites, too big to fail

ULTRALIGHT DARK MATTER

- Why is this interesting?
  - ΛCDM is well tested at large scales, but not small scales
  - Small scale problems: cores vs cusps, missing satellites, too big to fail
- Baryons could explain this, but because of the complexity of baryons it's hard to be sure
- Dwarf galaxies are perfect tests

ULTRALIGHT DARK MATTER

- Simulated with the Schrödinger-Poisson Equations:

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi,$$

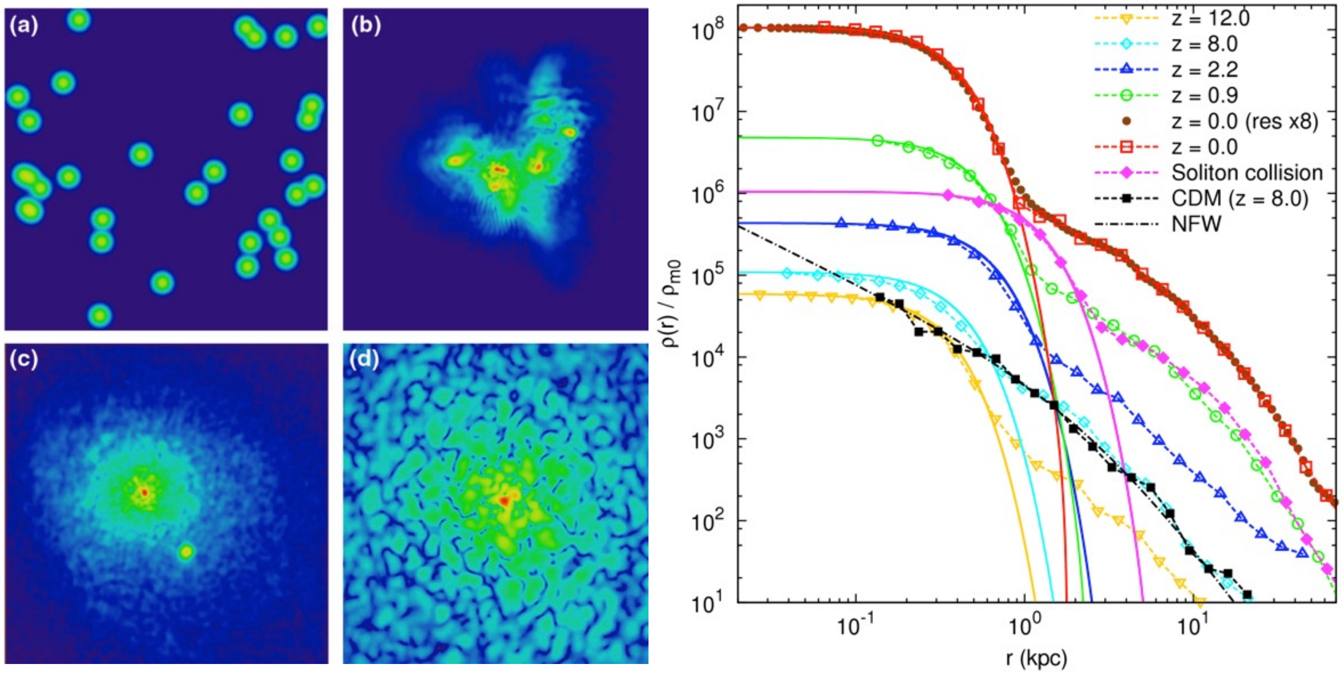
$$\nabla^2 V = 4\pi G(\rho - \bar{\rho}),$$

- Describes a self-gravitating quantum superfluid
  - No viscosity, flows without losing kinetic energy

Schive et al., Phys. Rev. Lett. **113**, 261302 (2014).
Mocz et al., Phys. Rev. D **97**, 083519 (2018).

ULTRALIGHT DARK MATTER

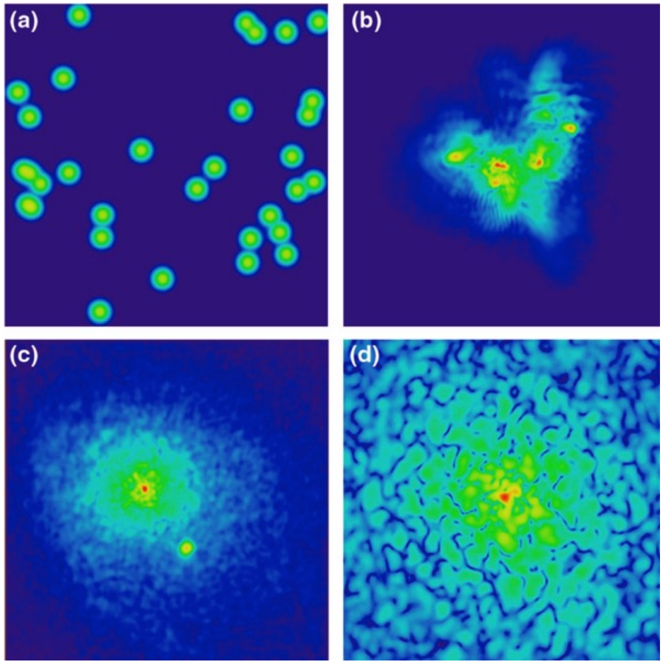
- Simulations have found an analytical form for the core (Schive et al. 2014, Mocz et al. 2018)
  - Soliton core depends on particle mass and halo mass



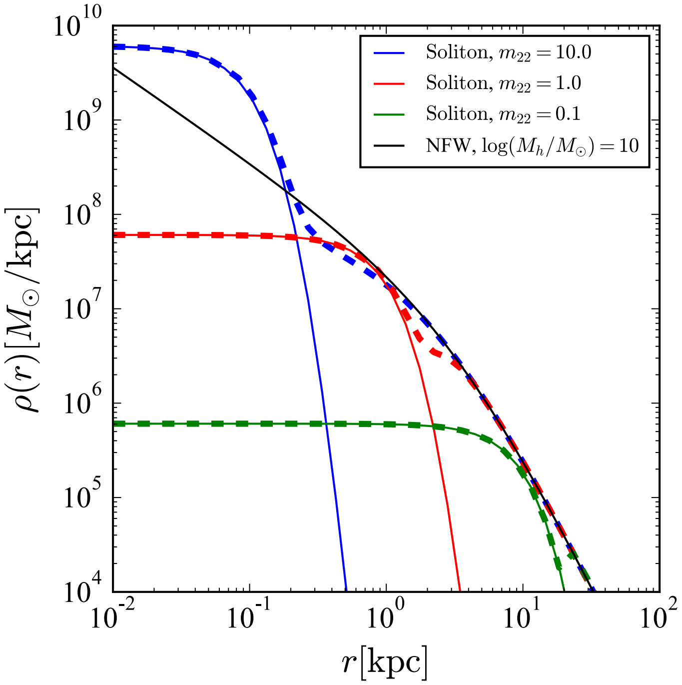
Schive et al., Phys. Rev. Lett. **113**, 261302 (2014).

ULTRALIGHT DARK MATTER

- Simulations have found an analytical form for the core (Schive et al. 2014, Mocz et al. 2018)
  - Soliton core depends on particle mass and halo mass



Schive et al., Phys. Rev. Lett. **113**, 261302 (2014).



M. Safarzadeh and D. N. Spergel, ApJ **893**, 21 (2020).

ANALYSIS

- Reconstruct a stellar velocity dispersion with a Jeans kinematic analysis

3D gravitational potential → Projected (2D) velocity dispersion

  - Past work has done this with CDM, WIMPs

ANALYSIS

- Reconstruct a stellar velocity dispersion with a Jeans kinematic analysis

3D gravitational potential → Projected (2D) velocity dispersion

  - Past work has done this with CDM, WIMPs

- Run with `MultiNest` choosing a:
  - Dark matter density profile
  - Particle mass, halo mass, velocity anisotropy

JEANS ANALYSIS

Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

Collisionless Boltzmann equation:

$$\boxed{\frac{\partial f}{\partial t} + \dot{\mathbf{q}}\frac{\partial f}{\partial \mathbf{q}} + \dot{\mathbf{p}}\frac{\partial f}{\partial \mathbf{p}} = 0}$$

Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

Observables?

Stellar distribution function: P(star at location x per unit volume)

$$\nu(\mathbf{x}) \equiv \int d^3v\, f(\mathbf{x}, \mathbf{v})$$

Velocity dispersion tensor:

$$\sigma_{ij}^2(\mathbf{x}) \equiv \int d^3v\, (v_i - \bar{v}_i)(v_j - \bar{v}_j)\frac{f(\mathbf{x}, \mathbf{v})}{\nu(\mathbf{x})}$$
$$= \overline{v_i v_j} - \bar{v}_i \bar{v}_j$$

Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

Assuming a spherical and time-independent system,

$$\boxed{\frac{d(\nu\overline{v_r^2})}{dr} + 2\frac{\beta}{r}\nu\overline{v_r^2} = -\nu\frac{d\phi}{dr}}$$

Spherical Jeans Equation

Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

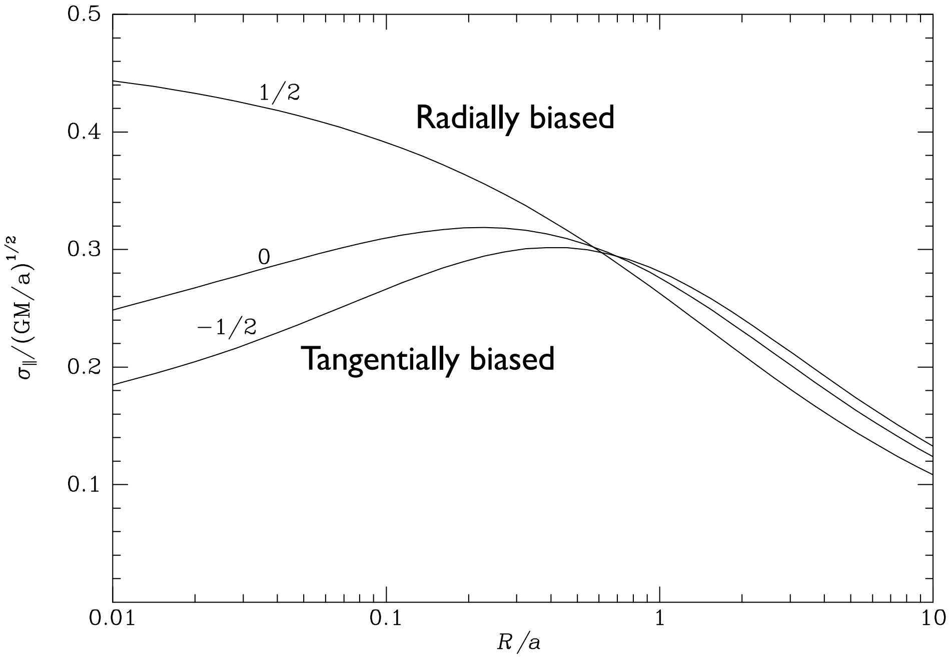
Assuming a spherical and time-independent system,

$$\boxed{\frac{d(\nu\overline{v_r^2})}{dr} + 2\frac{\beta}{r}\nu\overline{v_r^2} = -\nu\frac{d\phi}{dr}}$$

Anisotropy parameter: $$\beta_a \equiv 1 - \frac{\overline{v_\theta^2} + \overline{v_\phi^2}}{2\overline{v_r^2}}$$

Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

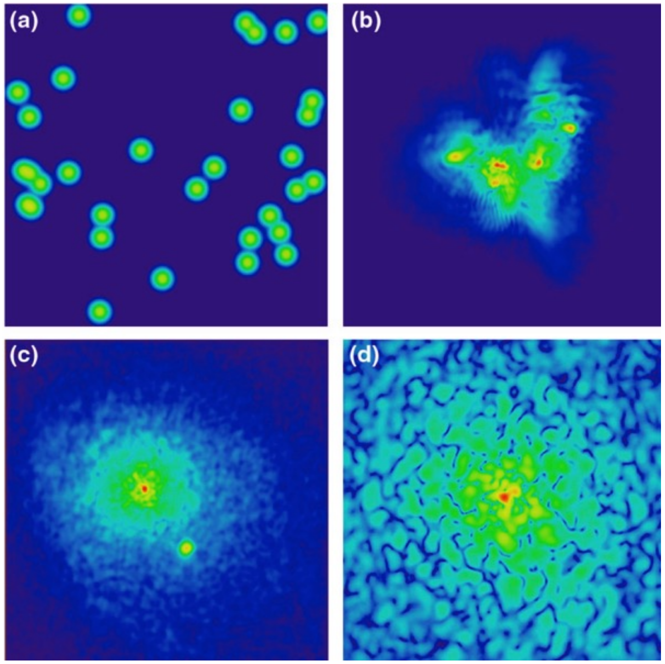


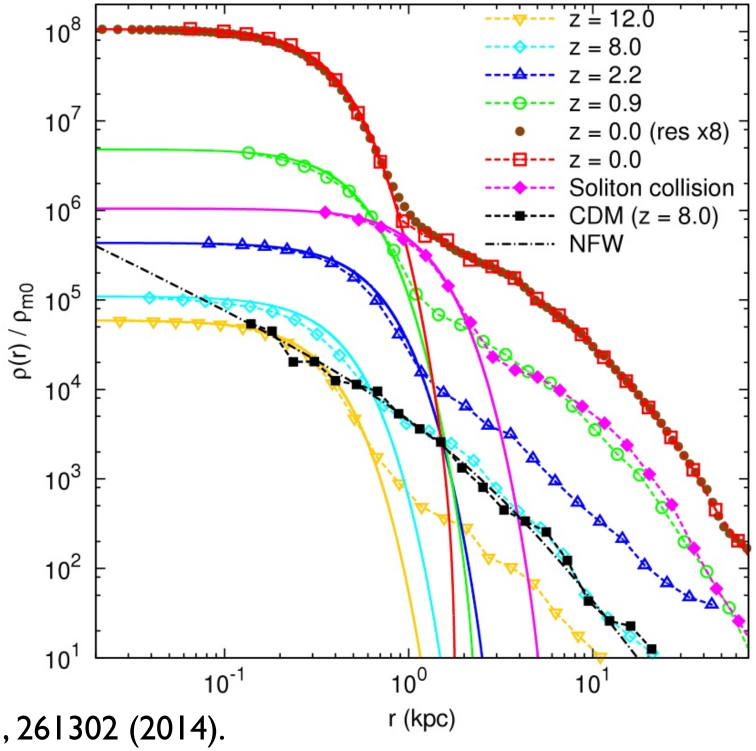
Binney and Tremaine, *Galactic Dynamics: Second Edition* (2008).

JEANS ANALYSIS

$$\boxed{\frac{d(\nu\overline{v_r^2})}{dr} + 2\frac{\beta}{r}\nu\overline{v_r^2} = -\nu\frac{d\phi}{dr}}$$

ANALYSIS





Schive et al., Phys. Rev. Lett. **113**, 261302 (2014).

ANALYSIS

	Soliton core only	NFW is physically unconstrained	González-Morales, Marsh, Peñarrubia, and Ureña-López, MNRAS **472**, 1346 (2017)
A	NFW parameters chosen independent of soliton parameters	Most general, but mass is not necessarily conserved	Safarzadeh and Spergel, ApJ **893**, 21 (2020).
B	Parameterized transition with density continuity	Transition radius is allowed to vary	Marsh Pop, 2015, MNRAS, **451**, 2479
C	**Density continuity,** **Mass conservation** $\mathbf{M_{halo} = M_{core} + M_{NFW}}$	**Total mass = core defining mass** **Enforces a minimum halo mass for a given particle mass**	**Robles, Bullock, and Boylan-Kolchin MNRAS 483, 289 (2019), 1807.06018.**

ANALYSIS

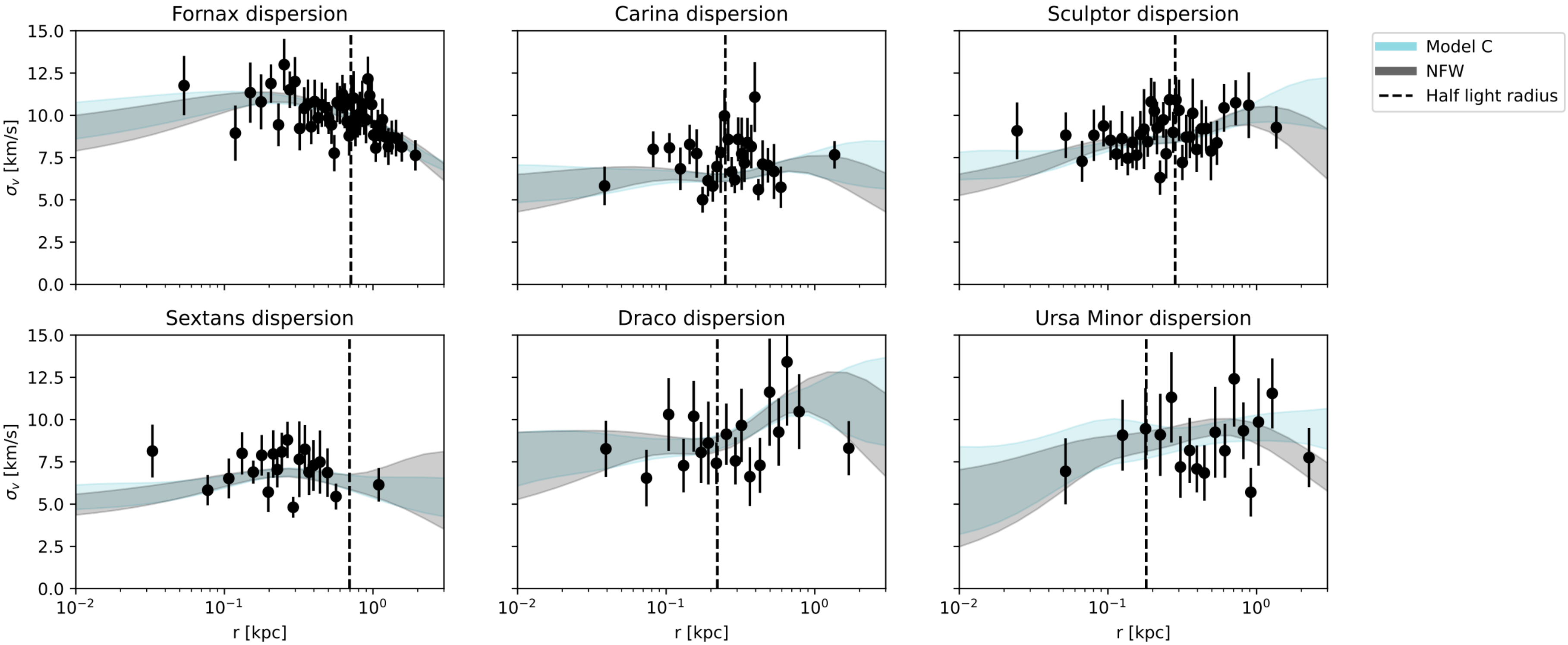
	Soliton core only	NFW is physically unconstrained	González-Morales, Marsh, Peñarrubia, and Ureña-López, MNRAS **472**, 1346 (2017)
A	NFW parameters chosen independent of soliton parameters	Most general, but mass is not necessarily conserved	Safarzadeh and Spergel, ApJ **893**, 21 (2020).
B	Parameterized transition with density continuity	Transition radius is allowed to vary	Marsh Pop, 2015, MNRAS, **451**, 2479
C	**Density continuity,** **Mass conservation** $\mathbf{M_{halo} = M_{core} + M_{NFW}}$	**Total mass = core defining mass** **Enforces a minimum halo mass for a given particle mass** **Very light halos can't form**	**Robles, Bullock, and Boylan-Kolchin MNRAS 483, 289 (2019), 1807.06018.**

DATA

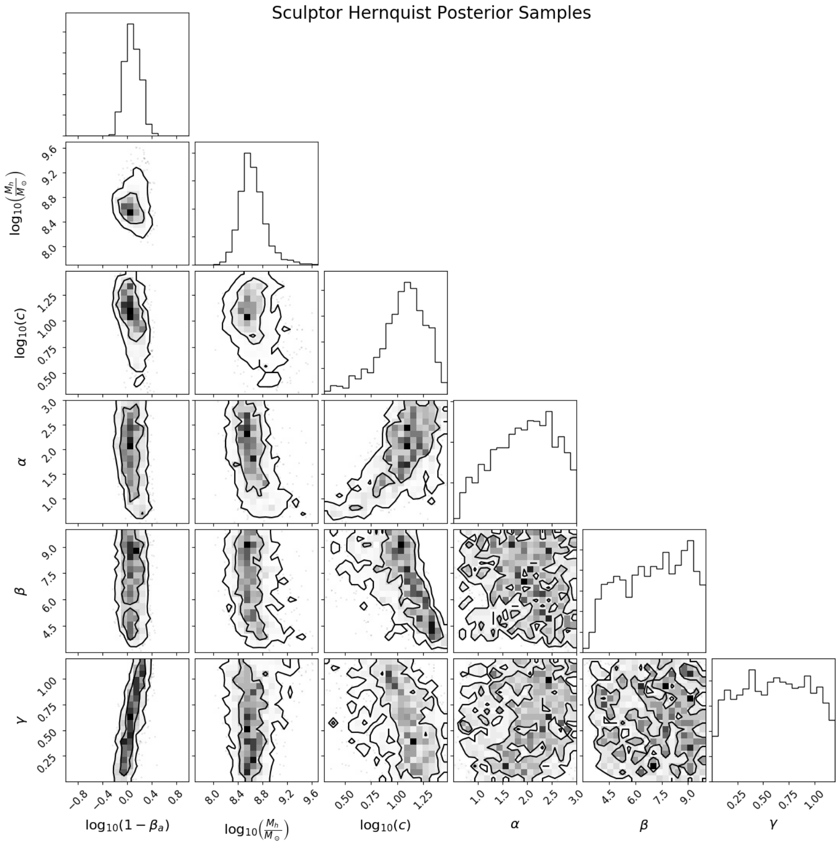
Data from:

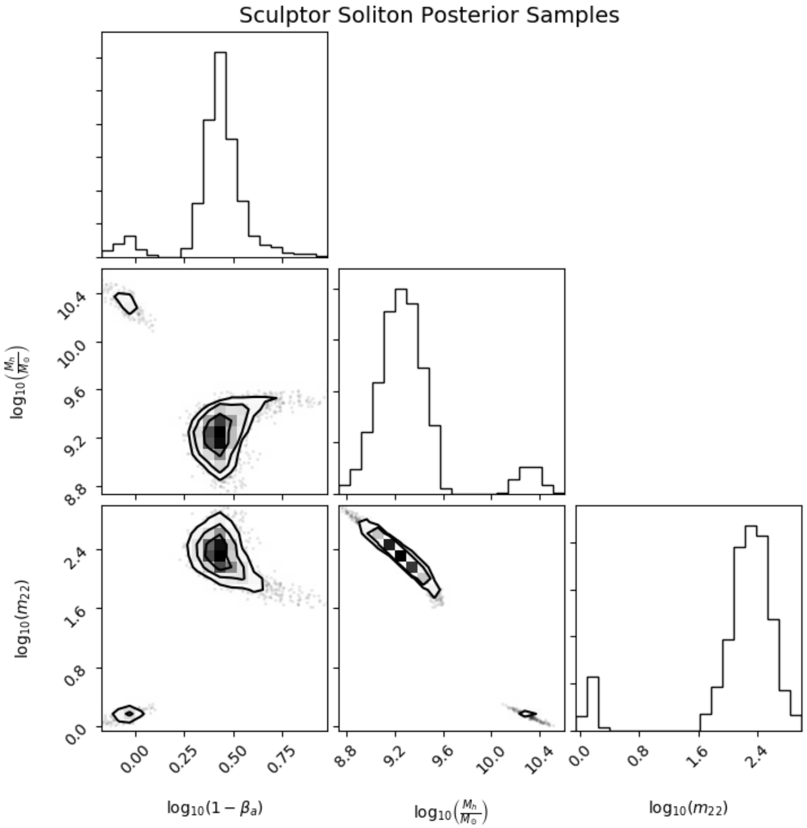
- Walker, Mateo, and Olszewski, ApJ **137**, 3100 (2009).
- Walker, Mateo, Olszewski, Bernstein, Sen, and Woodroofe, ApJS **171**, 389 (2007).
- Spencer, Mateo, Olszewski, Walker, McConnachie, and Kirby, ApJ **156**, 257 (2018).

DATA

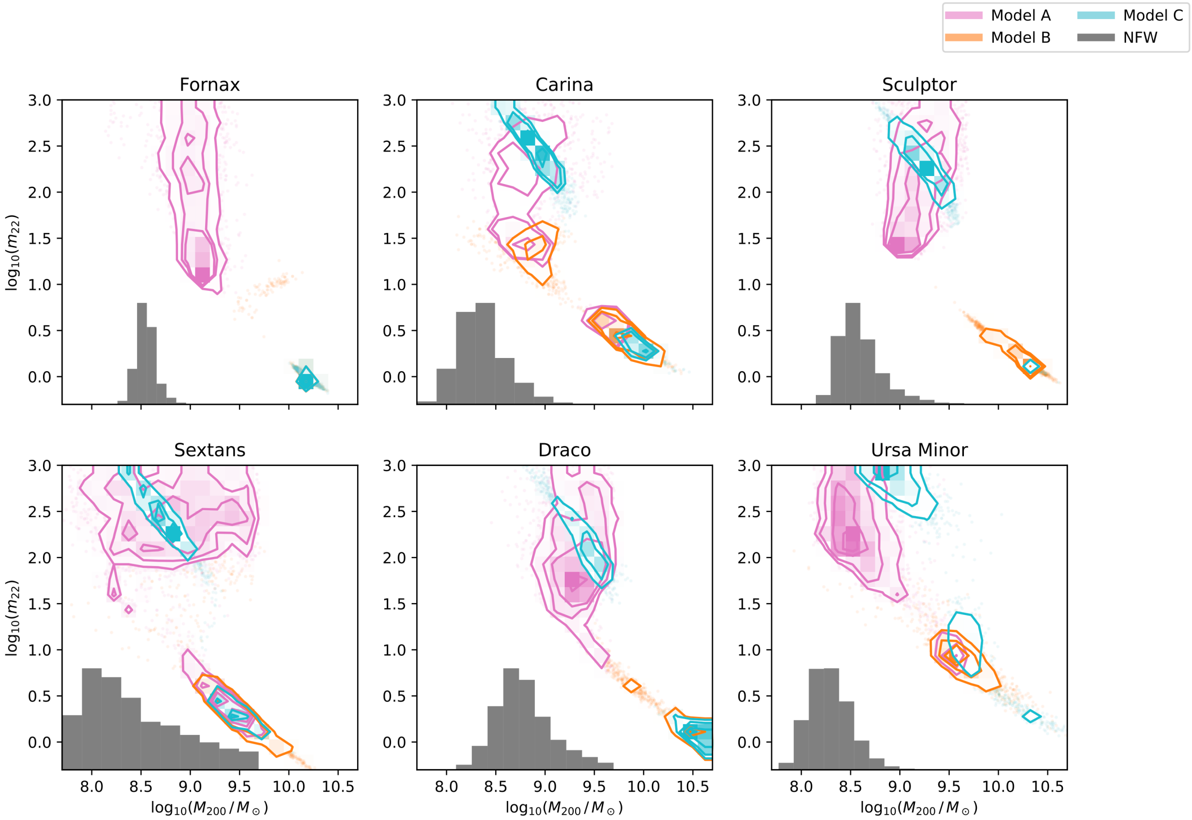

Fornax dispersion
Carina dispersion
Sculptor dispersion
Sextans dispersion
Draco dispersion
Ursa Minor dispersion
σ_v [km/s]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
10^{-2}
10^{-1}
10^{0}
r [kpc]
Model C
NFW
Half light radius

RESULTS


Sculptor Hernquist Posterior Samples

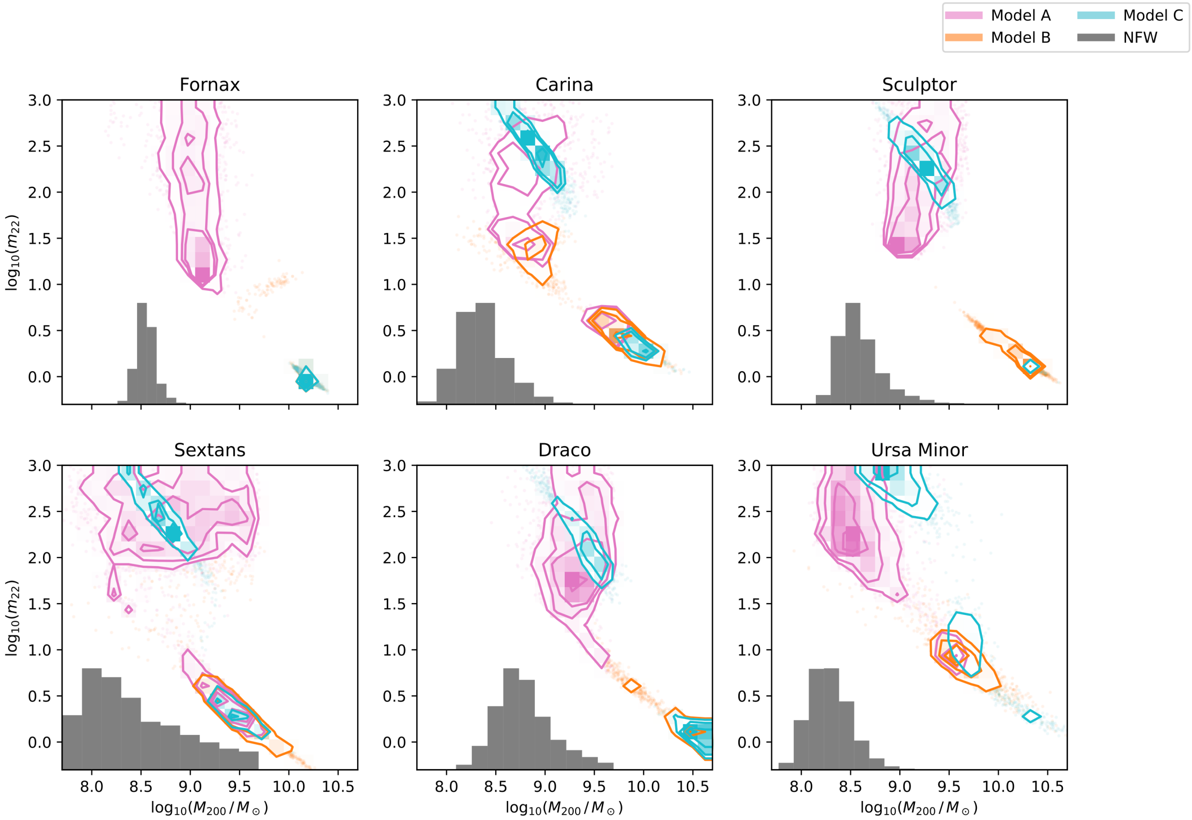

Sculptor Soliton Posterior Samples

RESULTS


Model A
Model C
Model B
NFW
Fornax
Carina
Sculptor
Sextans
Draco
Ursa Minor
$\log_{10}(m_{22})$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
8.0
8.5
9.0
9.5
10.0
10.5
$\log_{10}(M_{200}/M_\odot)$

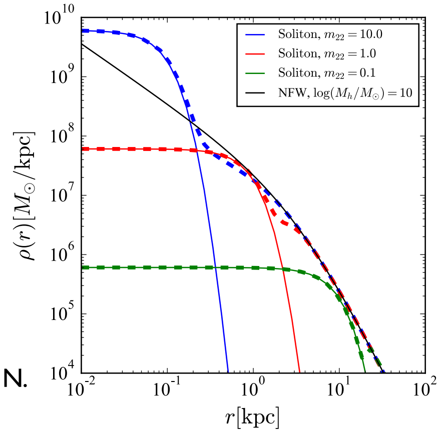
RESULTS

- Degeneracy between particle mass and halo mass

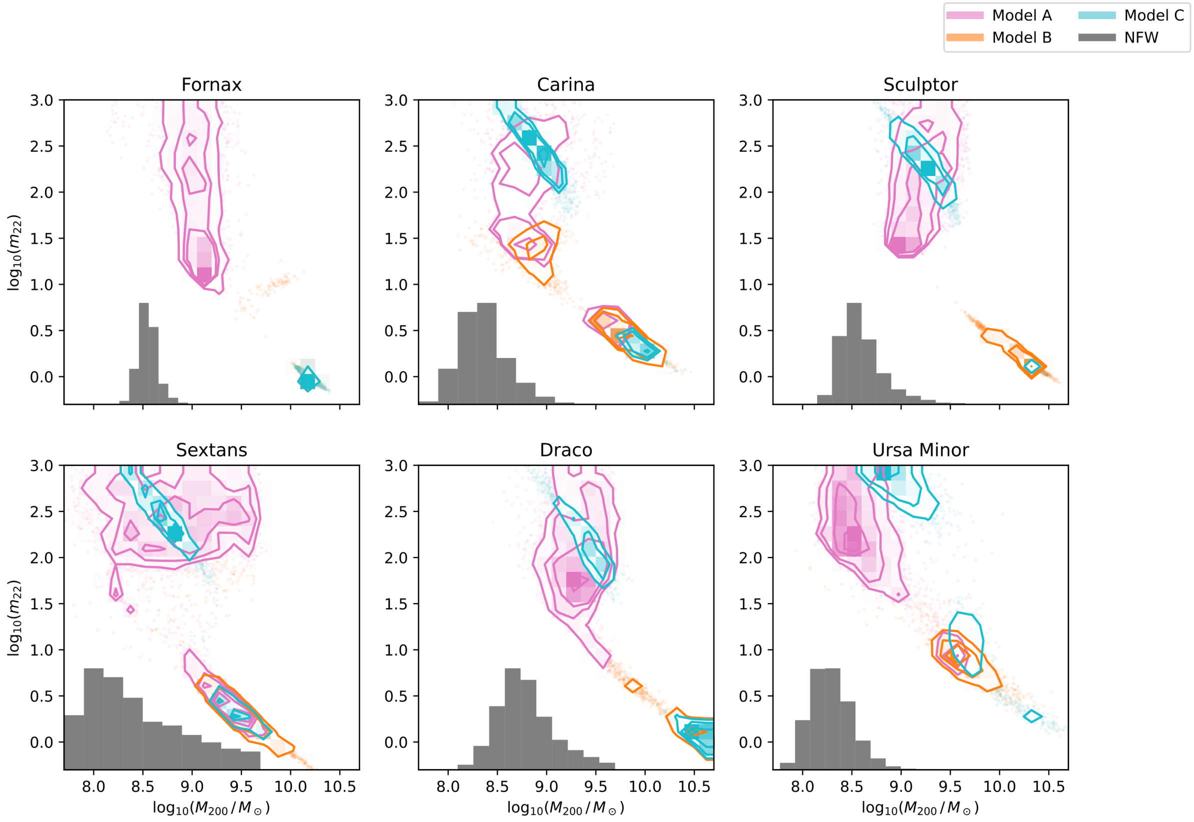


RESULTS

- Degeneracy between particle mass and halo mass
  - Cuspier profiles will have more mass concentrated in the center

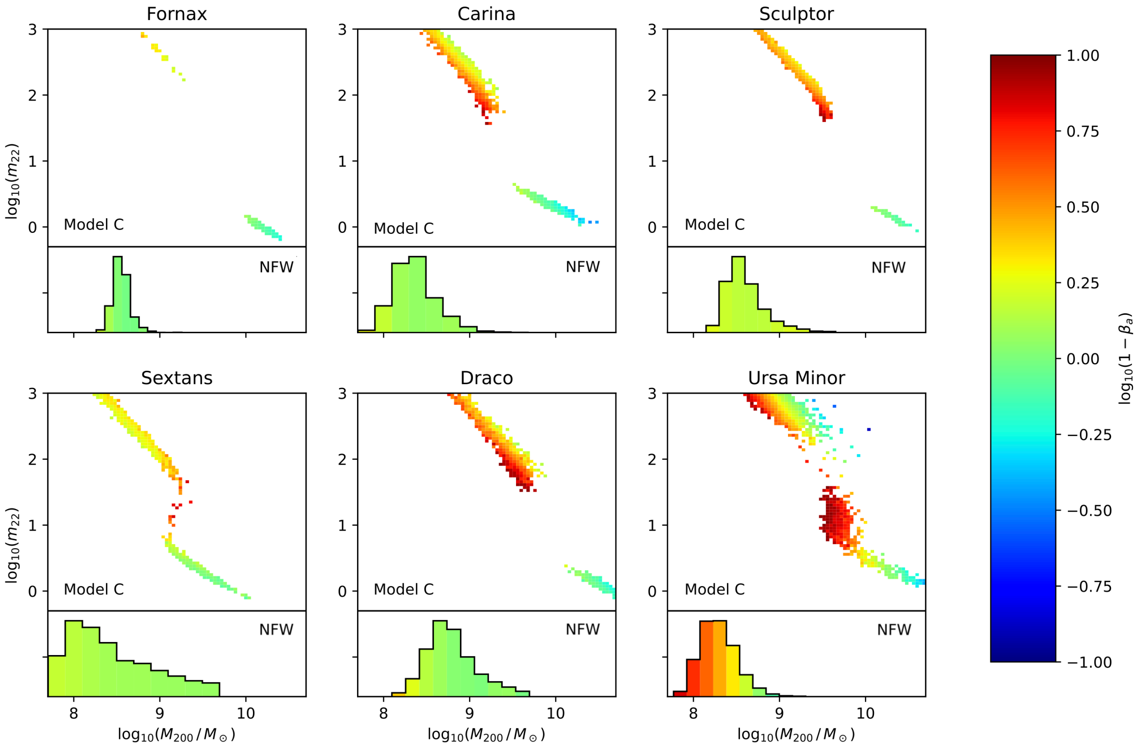


M. Safarzadeh and D. N. Spergel,
ApJ **893**, 21 (2020).



ANISOTROPY

- Velocity anisotropy β_a is a measure of the difference between tangential and radial velocity dispersion

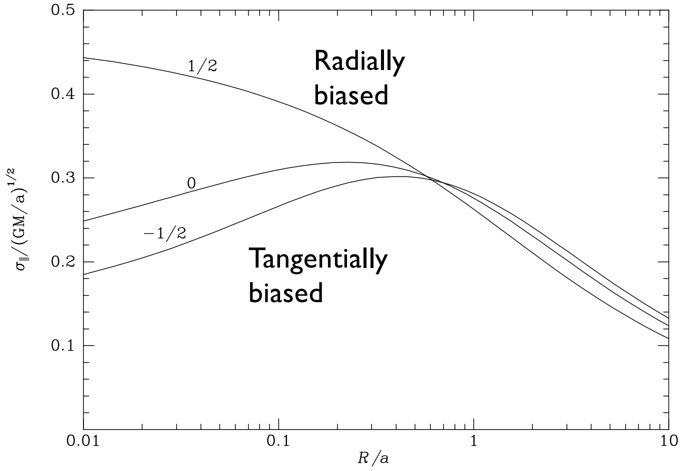


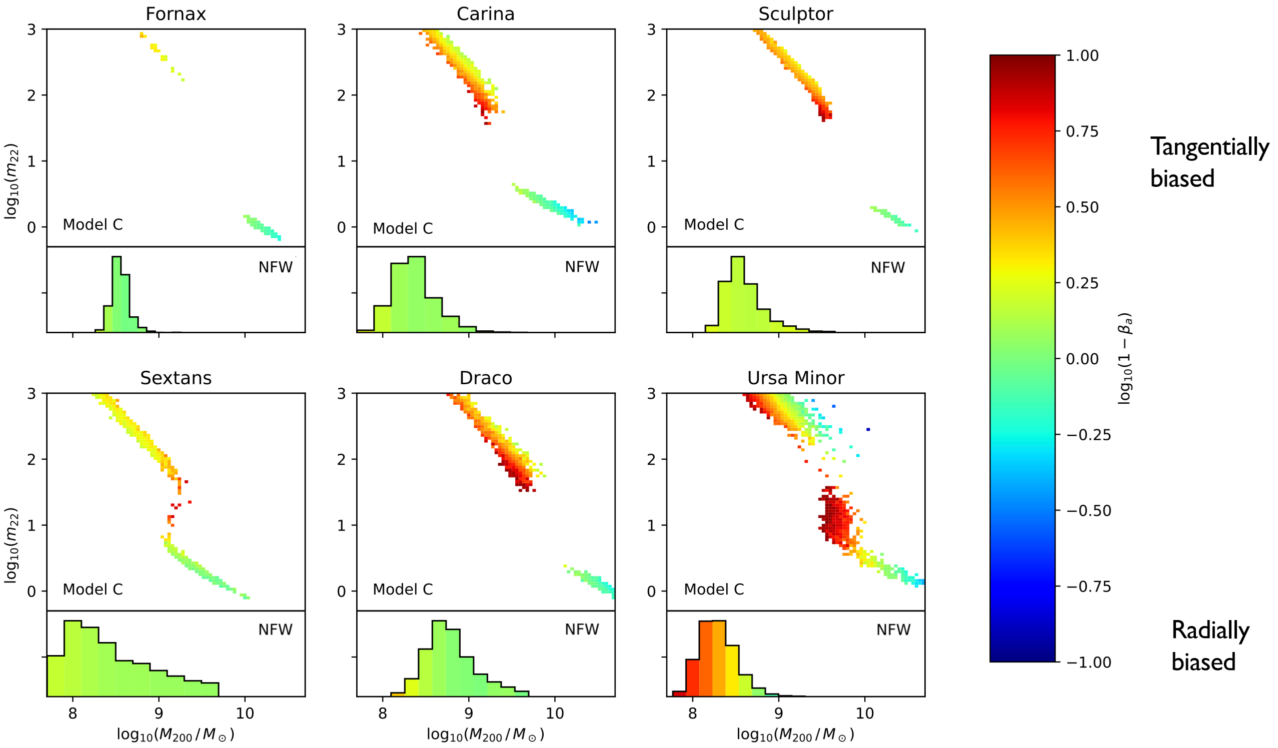
Tangentially biased

Radially biased

ANISOTROPY

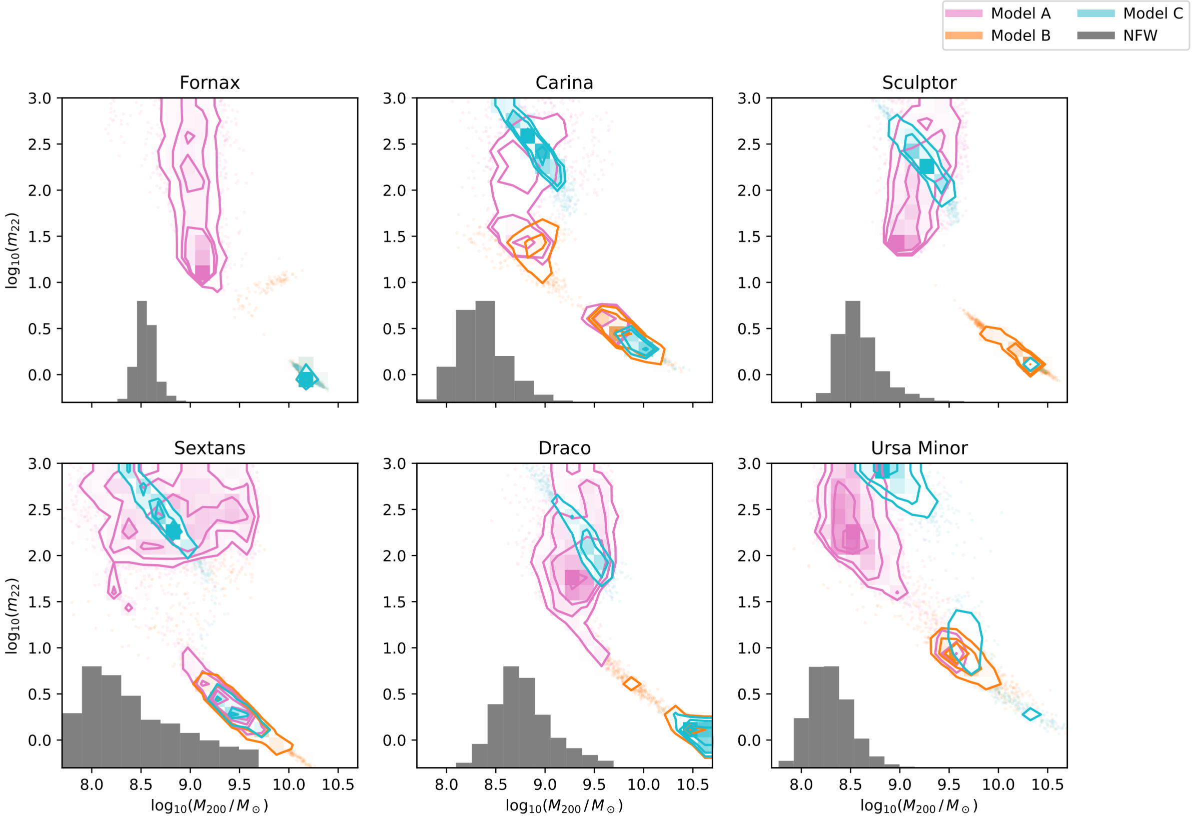
- Velocity anisotropy β_a is a measure of the difference between tangential and radial velocity dispersion





RESULTS

- Degeneracy between particle mass and halo mass
- Probability of 6 objects that mass merging with a Milky Way sized halo is very small (P~10^{-6}), would need to be an atypical galaxy



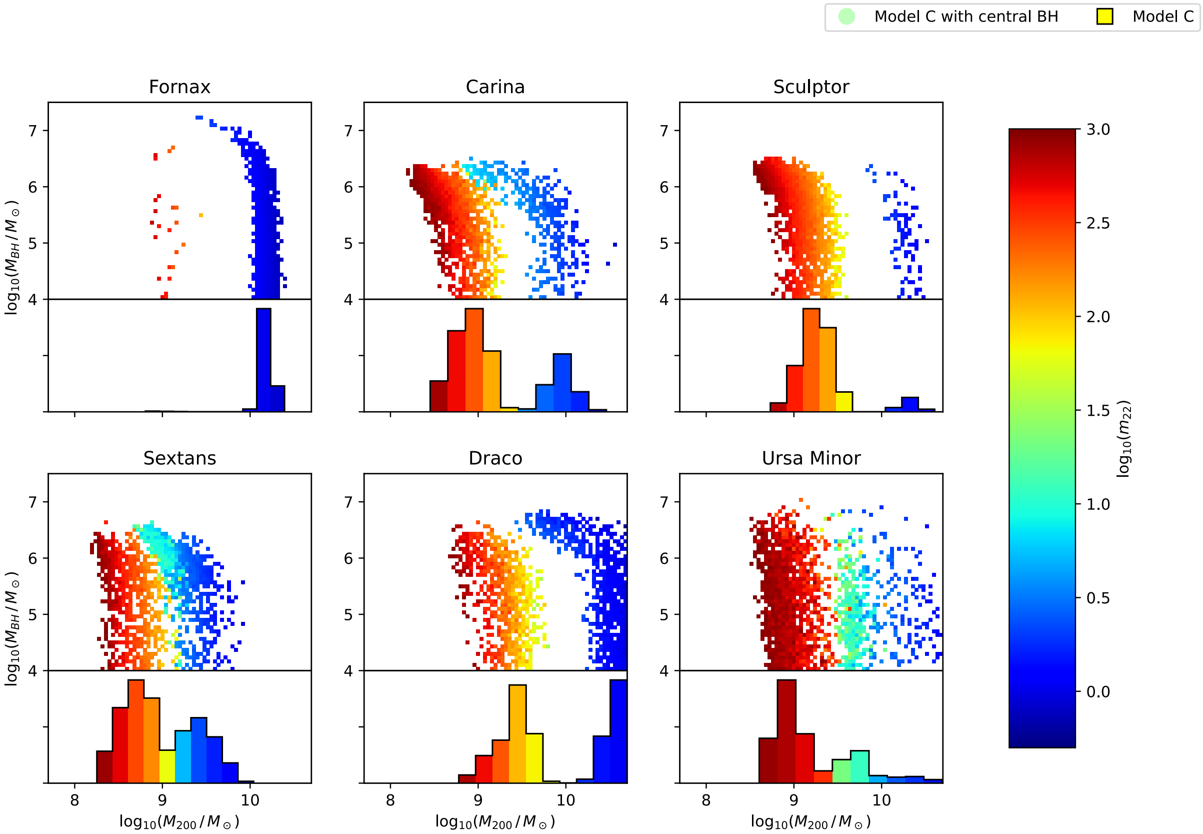
RESULTS: CENTRAL BLACK HOLE

- Add a black hole (point mass) to the dwarf galaxy center

RESULTS: CENTRAL BLACK HOLE

- Add a black hole (point mass) to the dwarf galaxy center

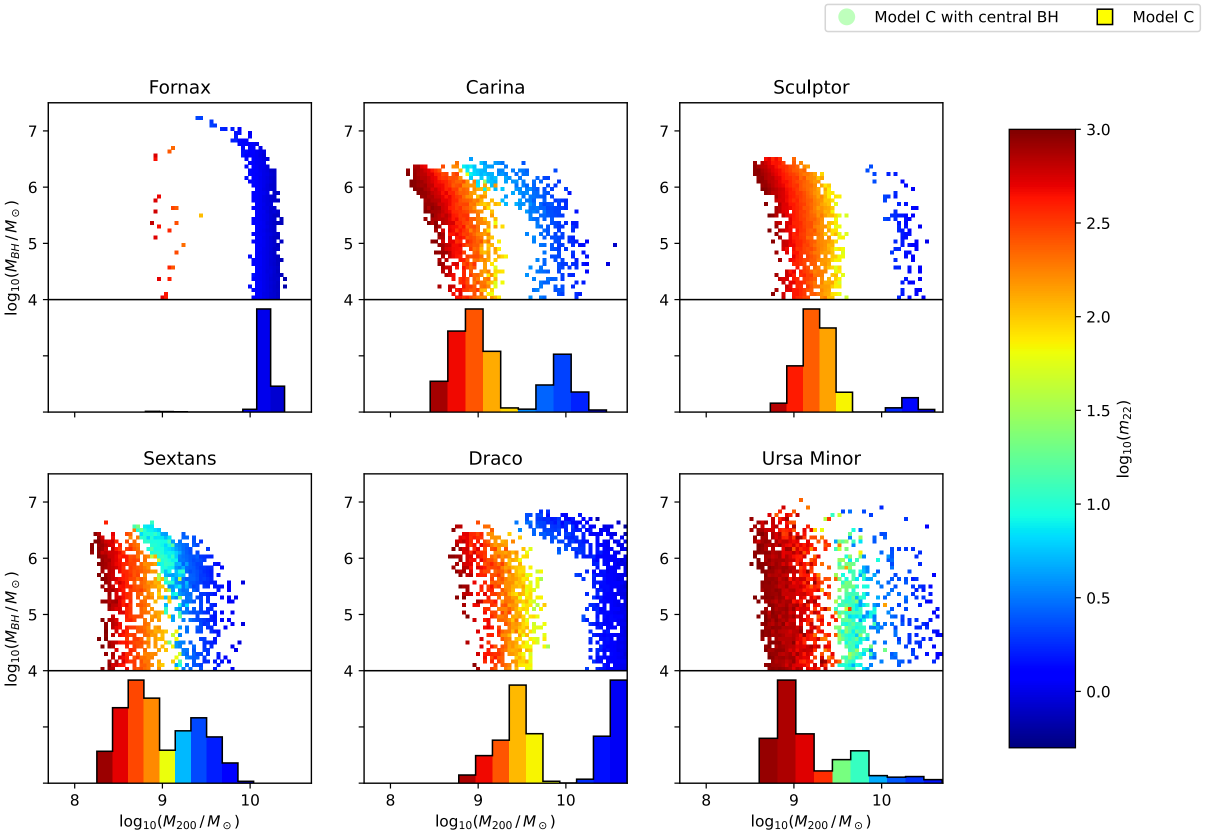
- Allows for lower particle mass, lower halo mass posteriors



RESULTS: CENTRAL BLACK HOLE

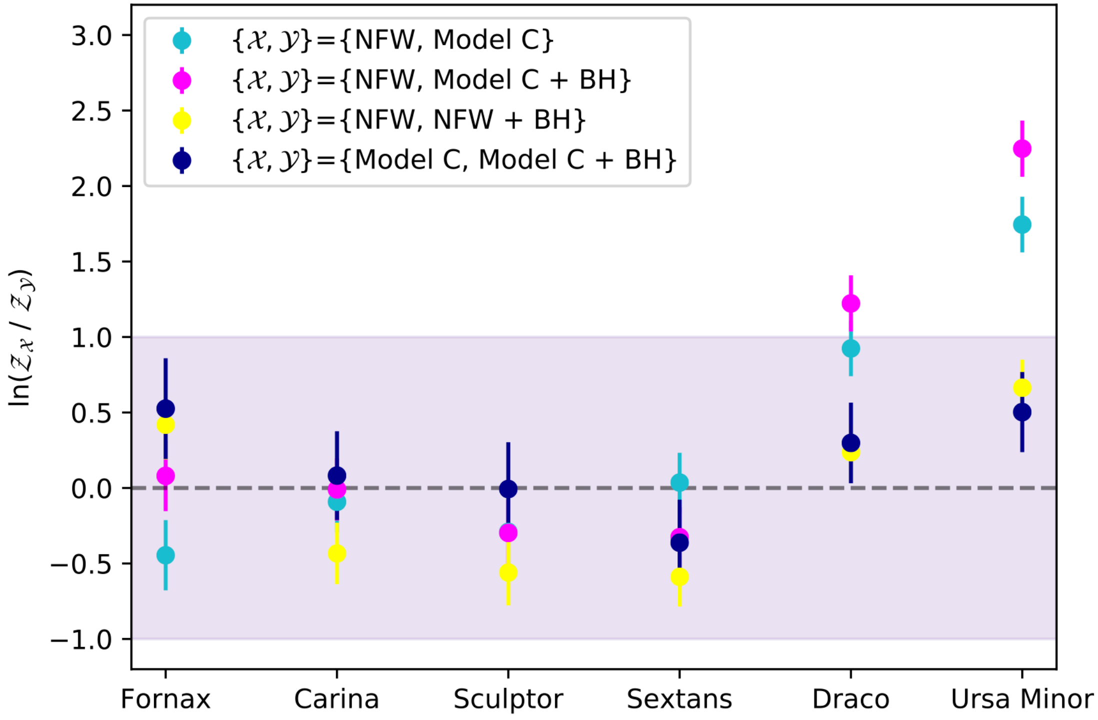
- Add a black hole (point mass) to the dwarf galaxy center
- Allows for lower particle mass, lower halo mass posteriors
- Requires proportionally massive black holes

[S. M. Koushiappas, J. S. Bullock, and A. Dekel, MNRAS **354**, 292 (2004), astro-ph/0311487.]



EVIDENCE

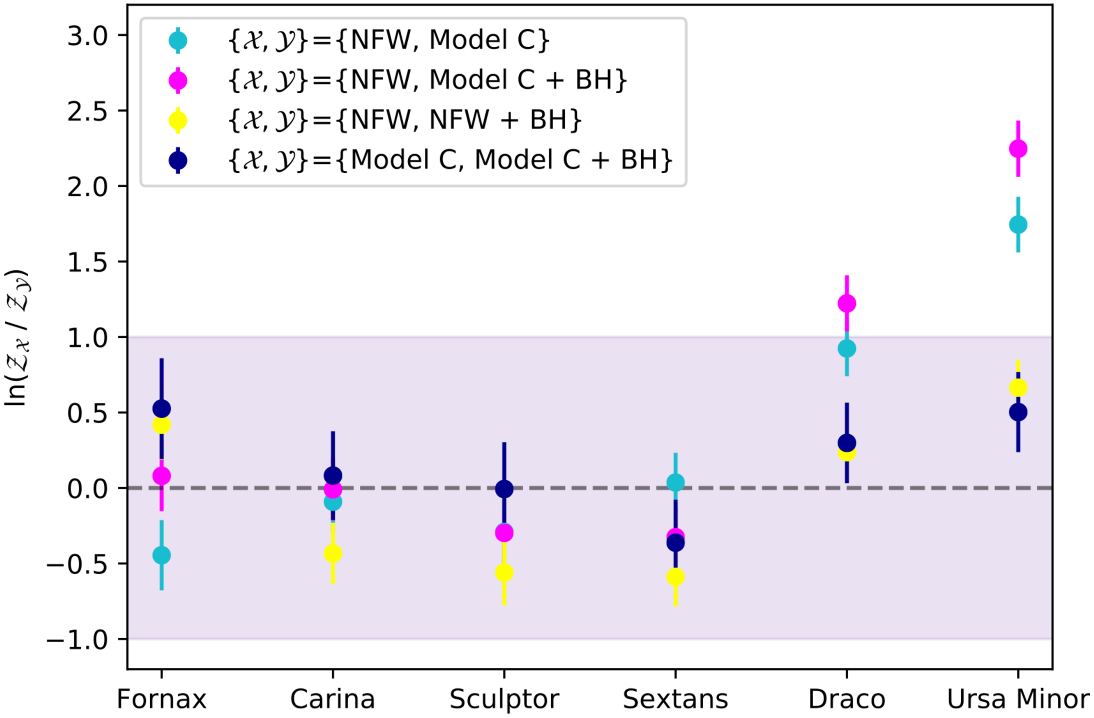
- Evidence is the sum of likelihood over the prior volume



51. Additional material: unbinned
52. Additional material: Multinest

EVIDENCE

- Evidence is the sum of likelihood over the prior volume
- Note that Ursa Minor has the smallest number of stars, and is the most irregular of the dwarfs analyzed



WHAT'S THE TAKE AWAY?

- Particle masses of $m<10^{-20}$ eV are not kinematically viable in dwarfs unless:
  - The Milky Way is an atypical halo.
  - All dwarfs contain a central black hole of mass ~0.1% their halo mass.

WHAT'S THE TAKE AWAY?

- Particle masses of $m<10^{-20}$ eV are not kinematically viable in dwarfs unless:
  - The Milky Way is an atypical halo.
  - All dwarfs contain a central black hole of mass ~0.1% their halo mass.

- Particle masses of $m>10^{-20}$ eV are allowed, but more CDM-like.

WHAT'S THE TAKE AWAY?

- Particle masses of $m<10^{-20}$ eV are not kinematically viable in dwarfs unless:
  - The Milky Way is an atypical halo.
  - All dwarfs contain a central black hole of mass ~0.1% their halo mass.
- Particle masses of $m>10^{-20}$ eV are allowed, but more CDM-like.
- There is no strong preference for any of the models in most dwarfs

1. **The Viability of Ultralight Bosonic Dark Matter in Dwarf Galaxies**
   Work done in collaboration with Savvas Koushiappas and Matthew Walker
   Phys. Rev. D **106**, 063010

2. **3D Jeans Analyses**

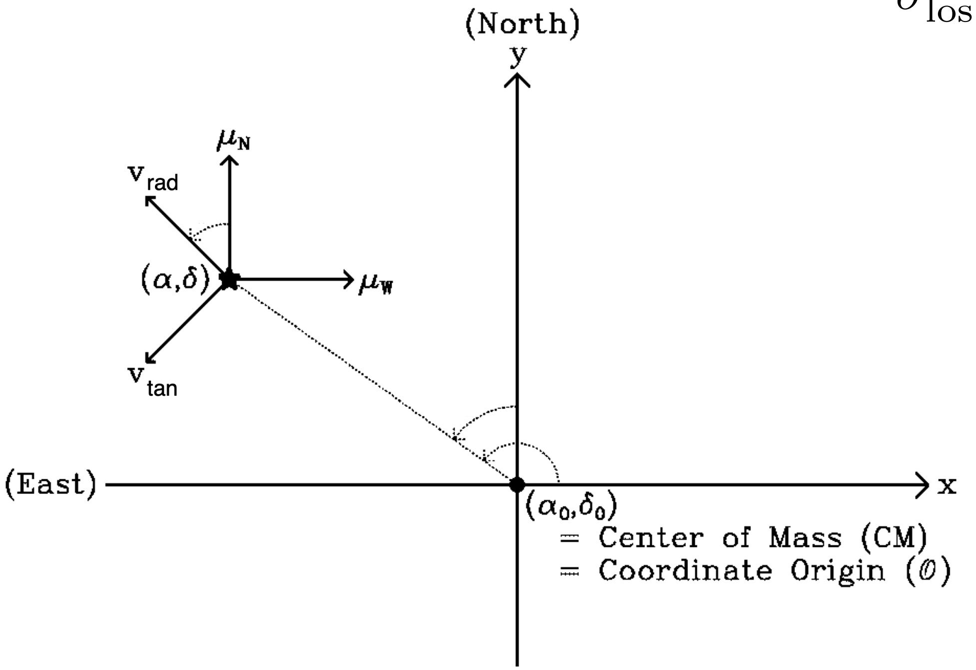
3D JEANS ANALYSIS

$$\sigma^2_{\rm los}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

Louis E. Strigari *et al* 2007 *ApJ* **669** 676

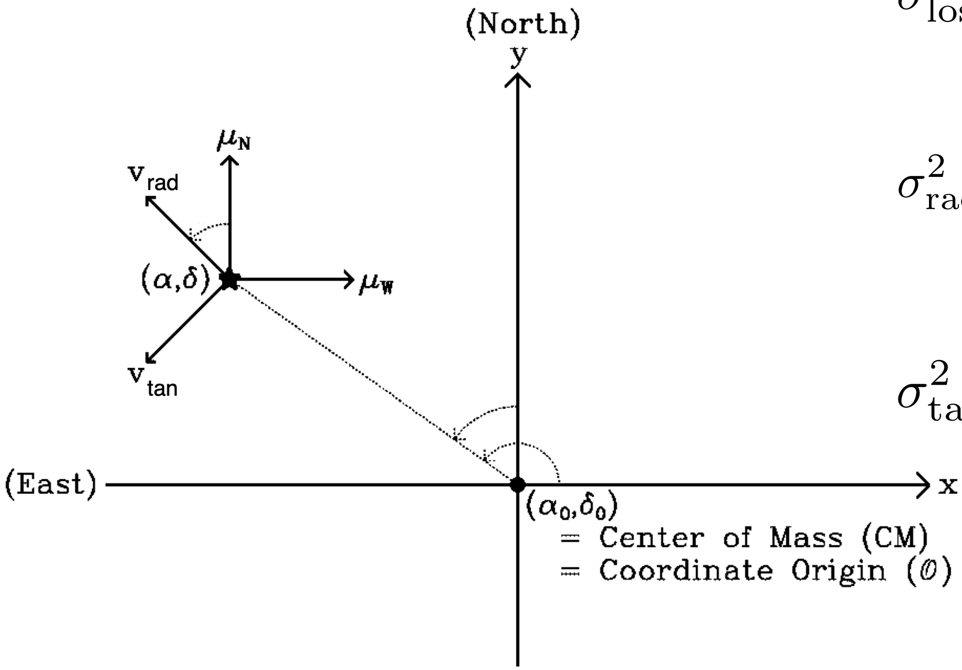
3D JEANS ANALYSIS

$$\sigma^2_{\mathrm{los}}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$



Louis E. Strigari *et al* 2007 *ApJ* **669** 676

3D JEANS ANALYSIS



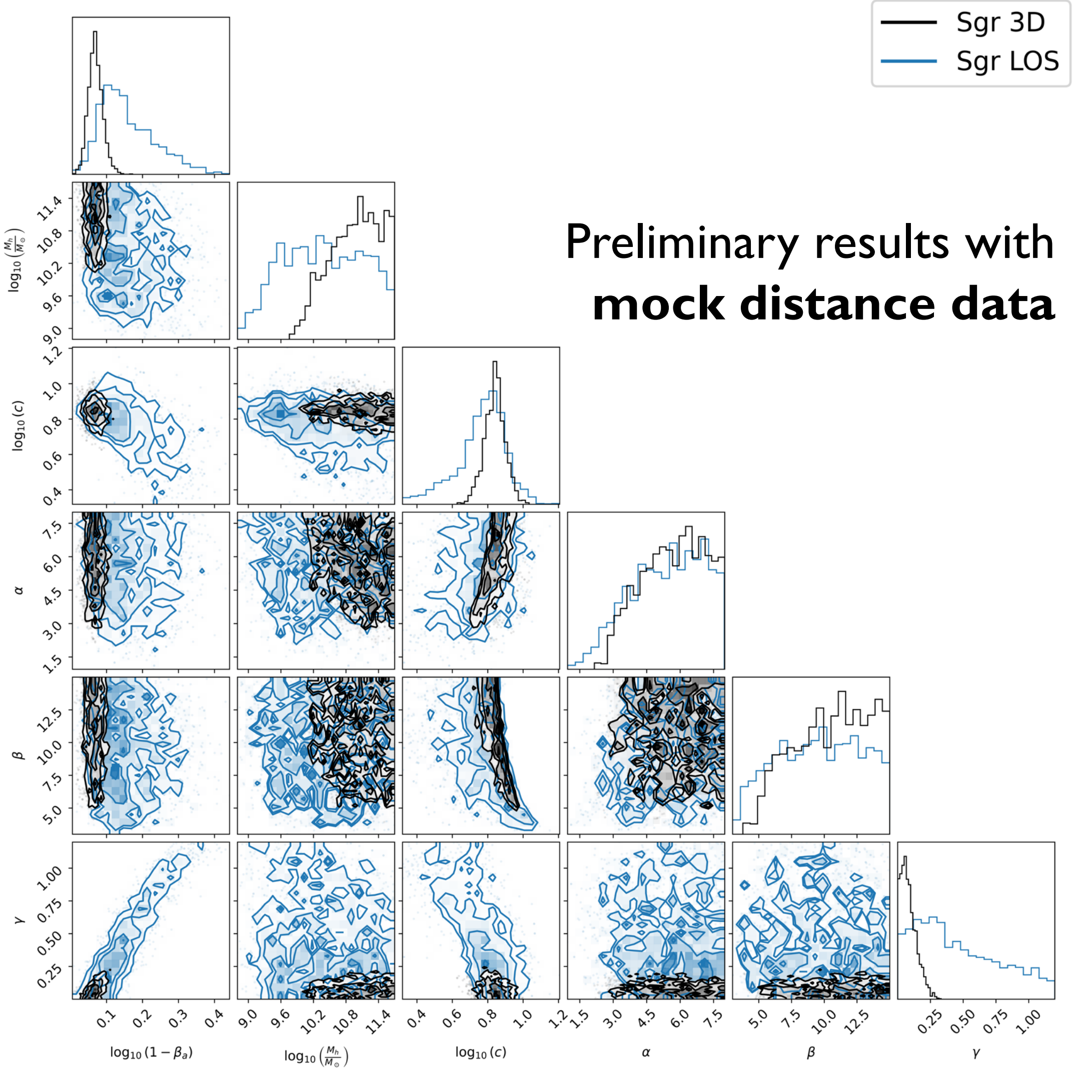
$$\sigma^2_{\rm los}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

$$\sigma^2_{\rm rad}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta + \beta \frac{R^2}{r^2}\right) \frac{\nu_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

$$\sigma^2_{\rm tan}(R) = \frac{2}{I_*(R)} \int_R^\infty (1 - \beta) \frac{\nu_* \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

Louis E. Strigari *et al* 2007 *ApJ* **669** 676

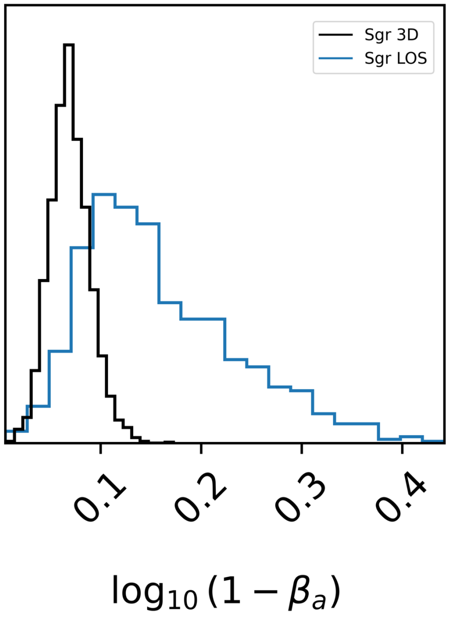
3D JEANS ANALYSIS

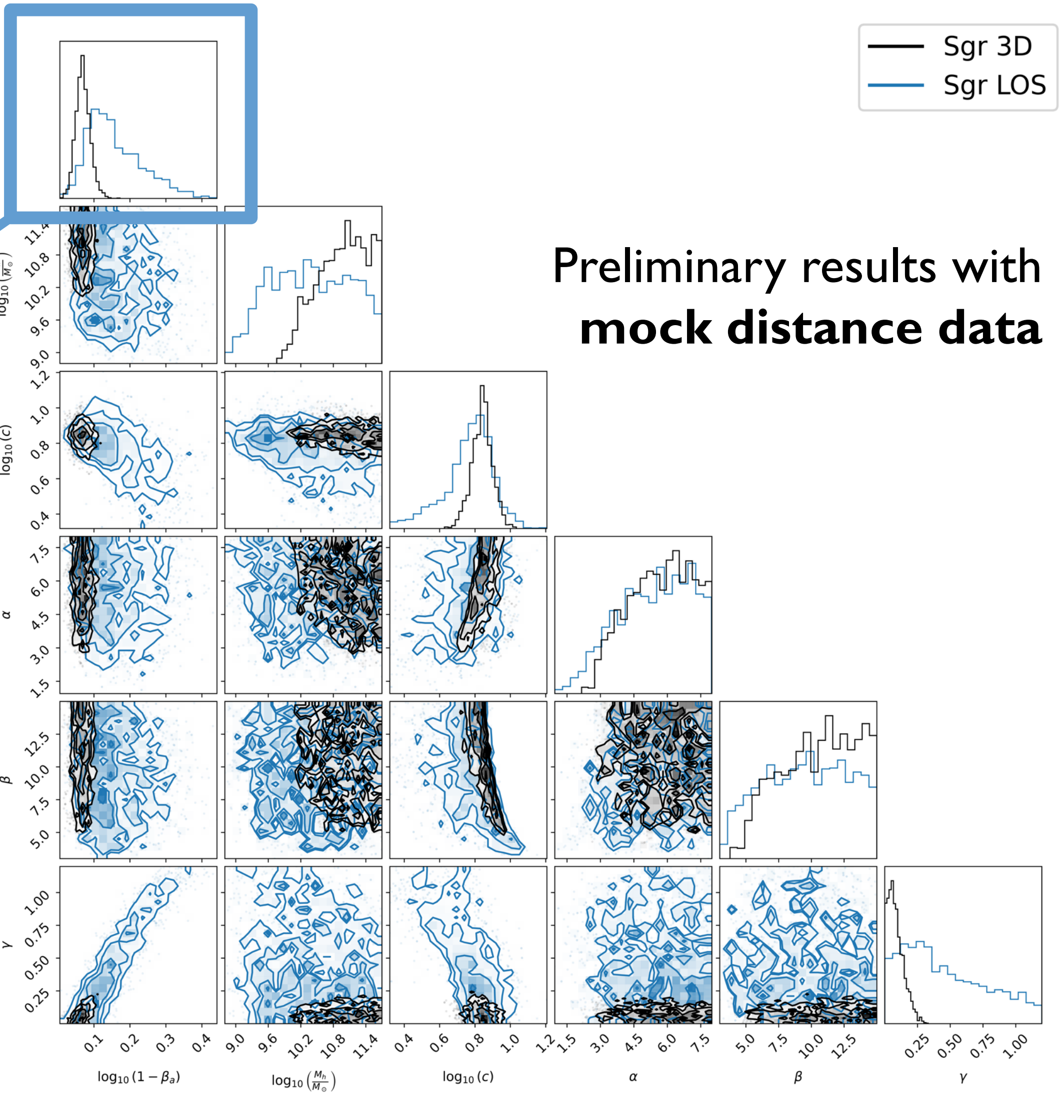


Preliminary results with **mock distance data**

61. Additional material: Generalized nfw

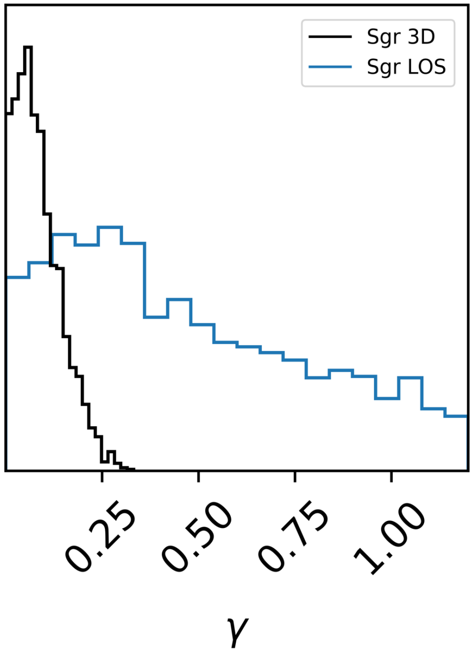
3D JEANS ANALYSIS

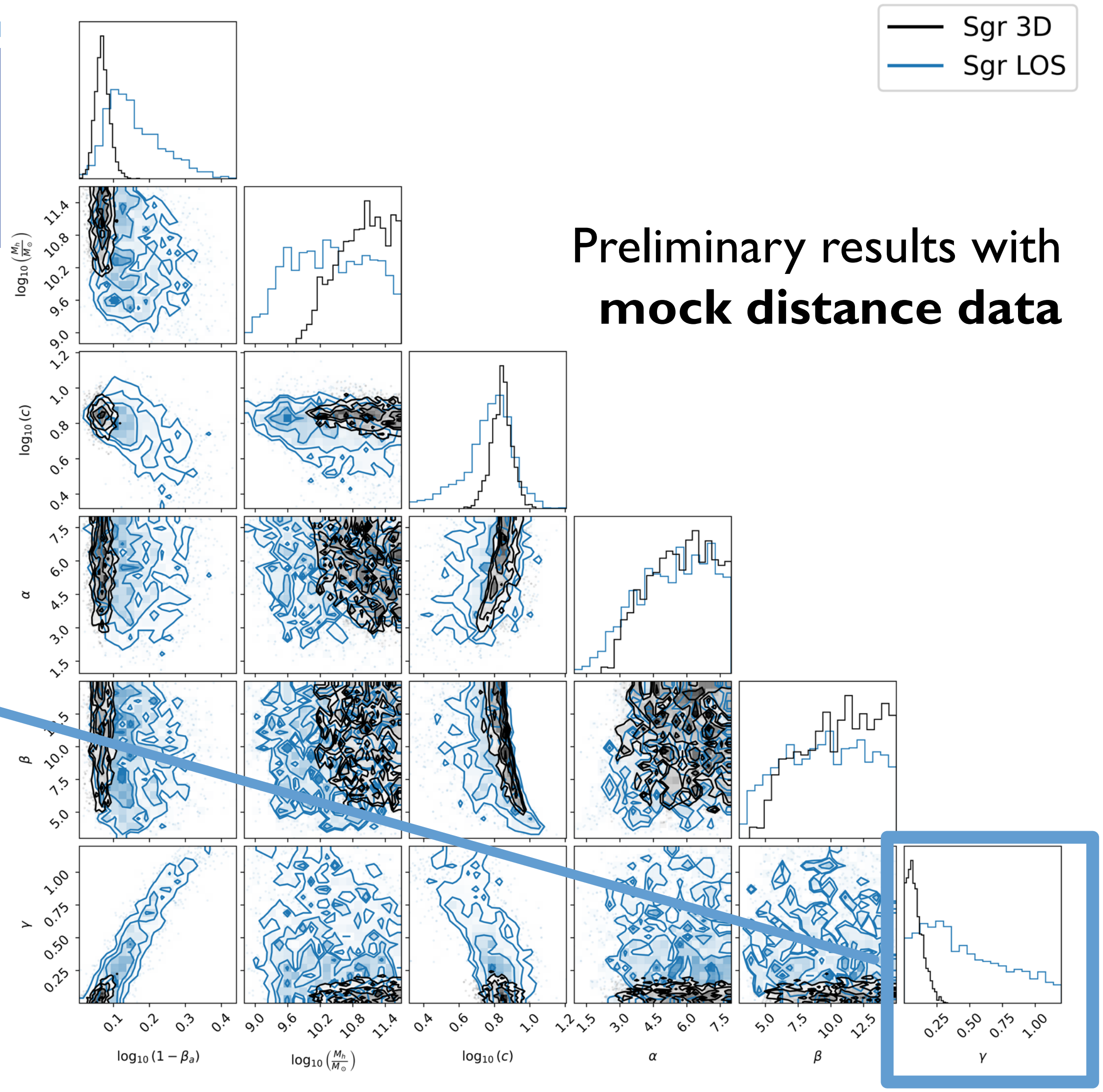




Preliminary results with
mock distance data

3D JEANS ANALYSIS





Preliminary results with
mock distance data

3D JEANS ANALYSIS

Uncertainties in **radial and tangential velocities** are highly dependent on uncertainty in **distance measurements**