THE VIABILITY OF ULTRALIGHT BOSONIC DARK MATTER IN DWARF GALAXIES

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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
  - **Scalar field** dark matter

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

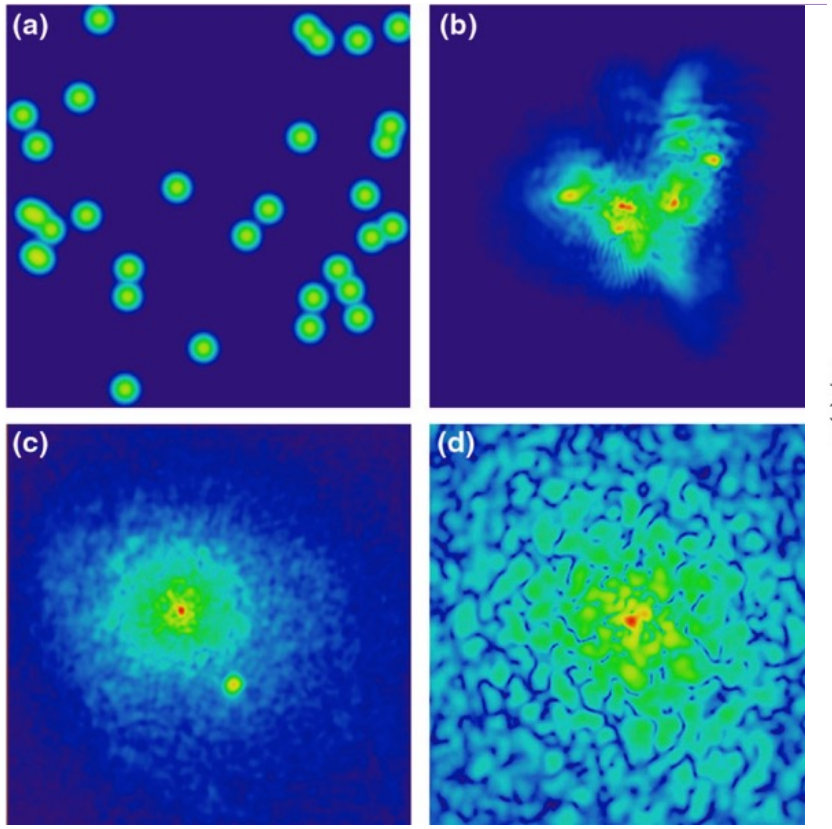
- Quantum effects become macroscopic: **~kpc scale**
  - Forms a Bose-Einstein condensate

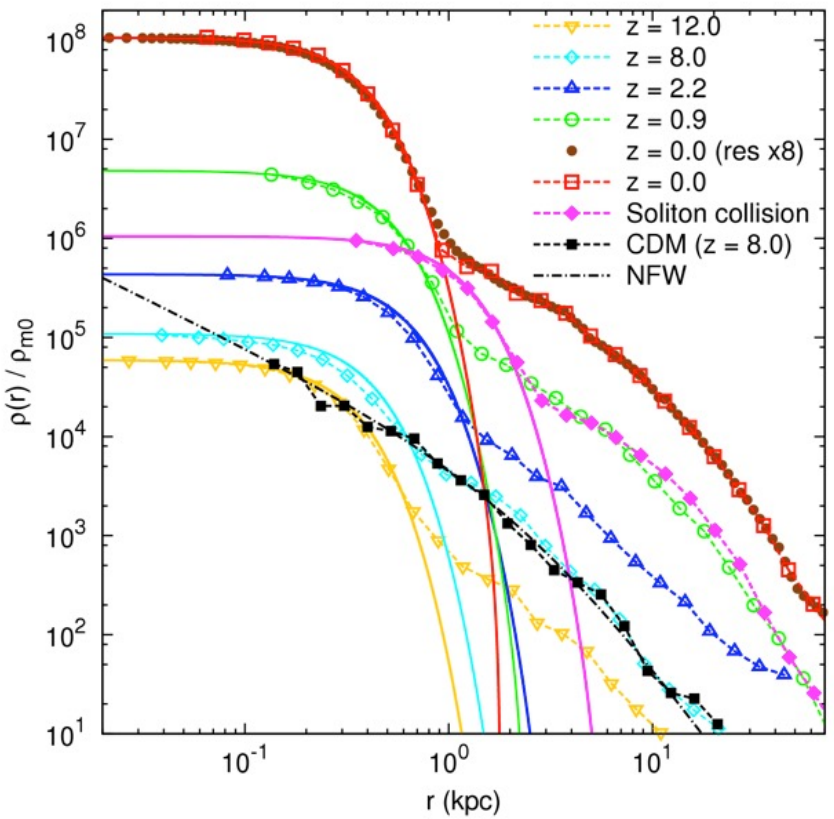
ULTRALIGHT DARK MATTER

- 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

- 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





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ULTRALIGHT DARK MATTER

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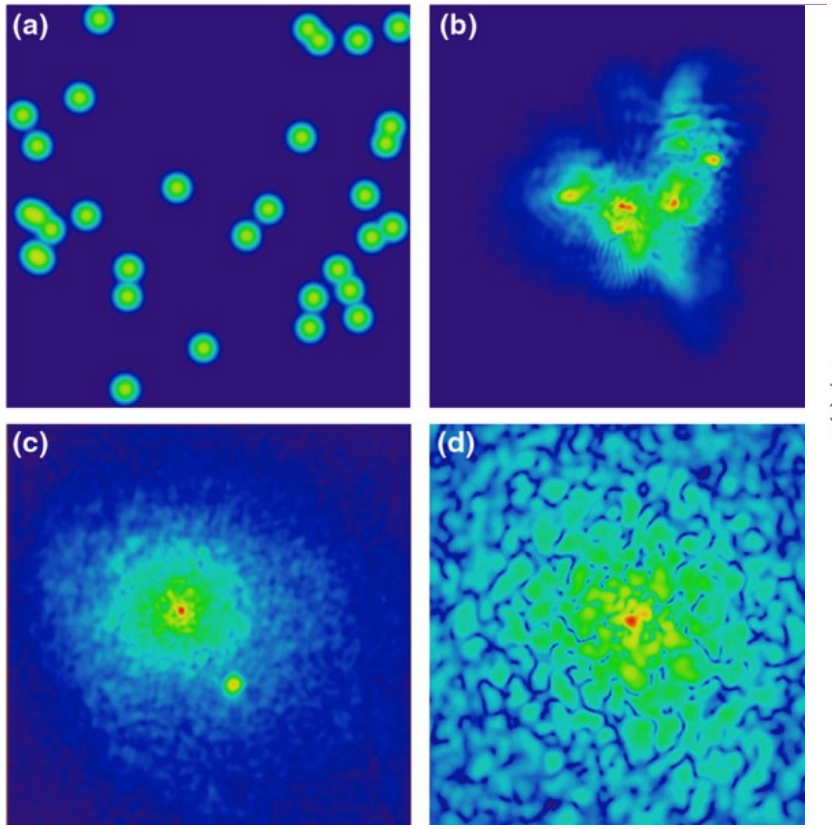
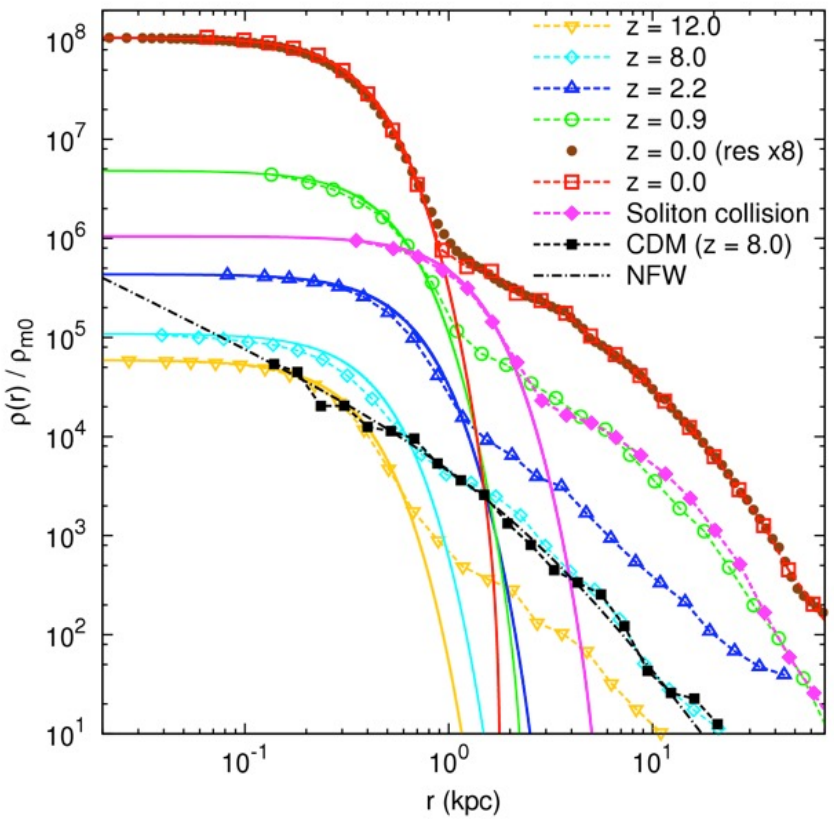
  - Soliton core depends on particle mass and halo mass
- Connects to an outer NFW for the full density profile





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ANALYSIS

- Focus on full density profile from Robles, Bullock, and Boylan-Kolchin MNRAS 483, 289 (2019), 1807.06018. (Model C)

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

  - Past work has done this with CDM, WIMPs
- Run with `MultiNest` Feroz, Hobson, and Bridges, MNRAS **398**, 1601 (2009), choosing a:
  - Dark matter density profile
  - Particle mass, halo mass, velocity anisotropy

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 $M_{halo} = M_{core} + M_{NFW}$**	**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.**

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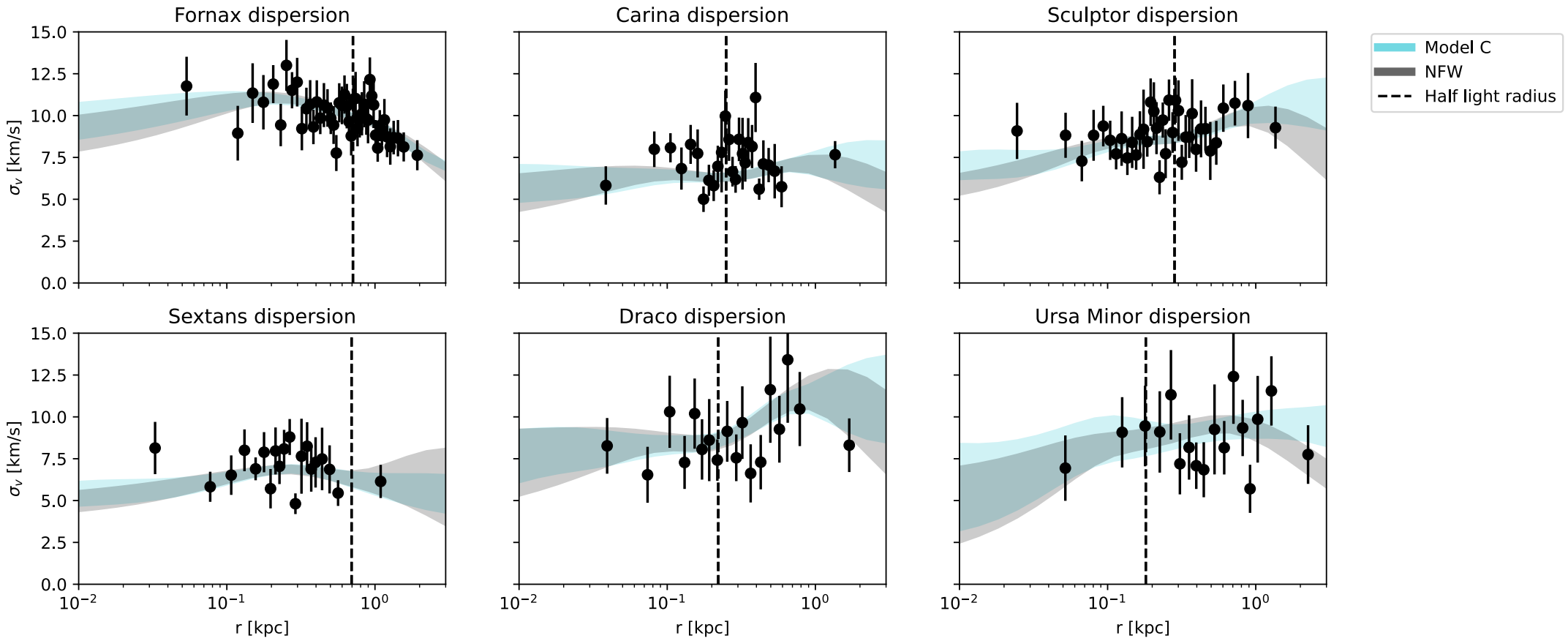
C	**Density continuity,** **Mass conservation** **$M_{halo} = M_{core} + M_{NFW}$**	**Total mass = core defining mass** **Enforces a minimum halo mass for a given particle mass** **Very light halos can't form**	**Robles, Bullock, and Boylan-Kolchin MNRAS 483, 289 (2019), 1807.06018.**

DATA

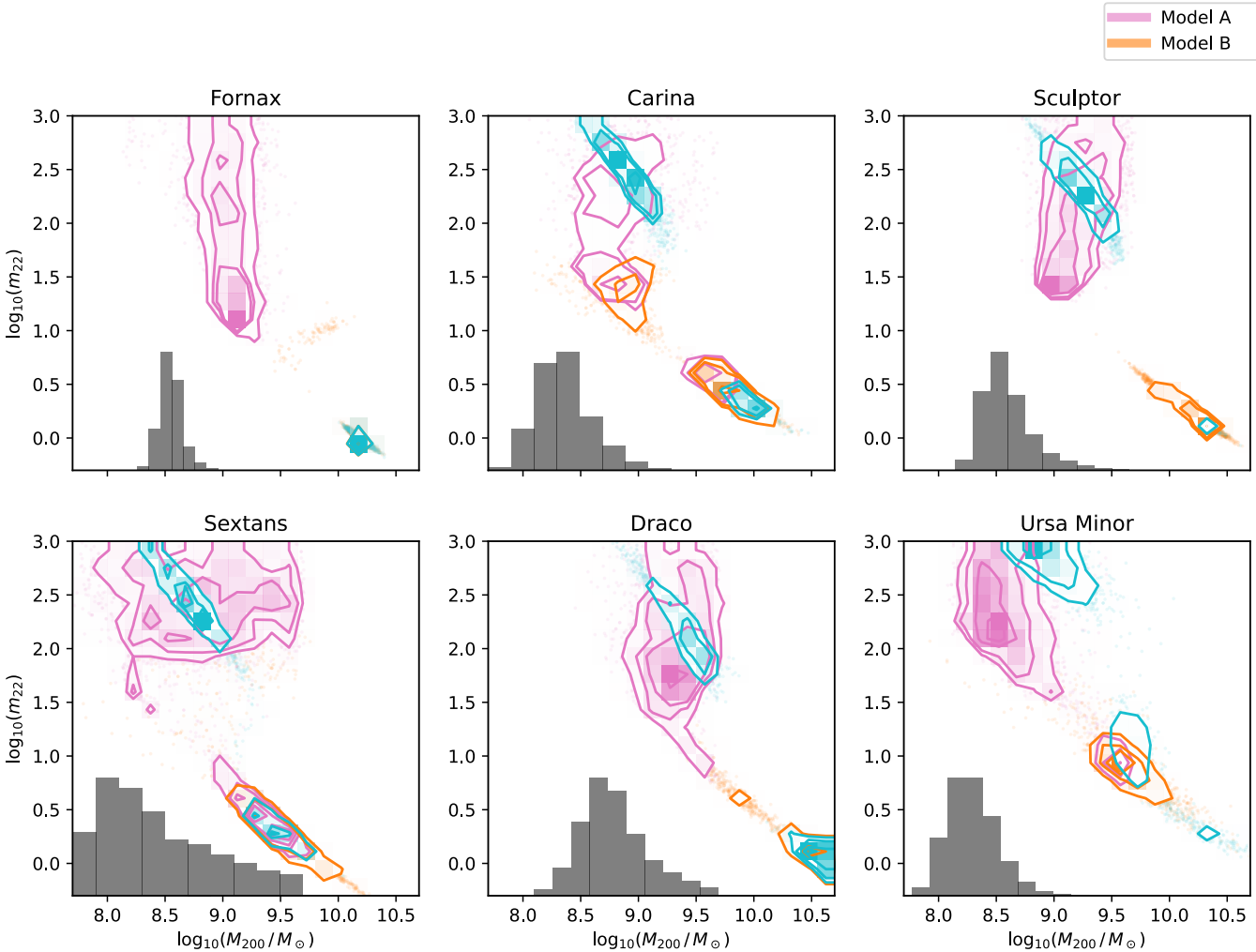
Data from:

- 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

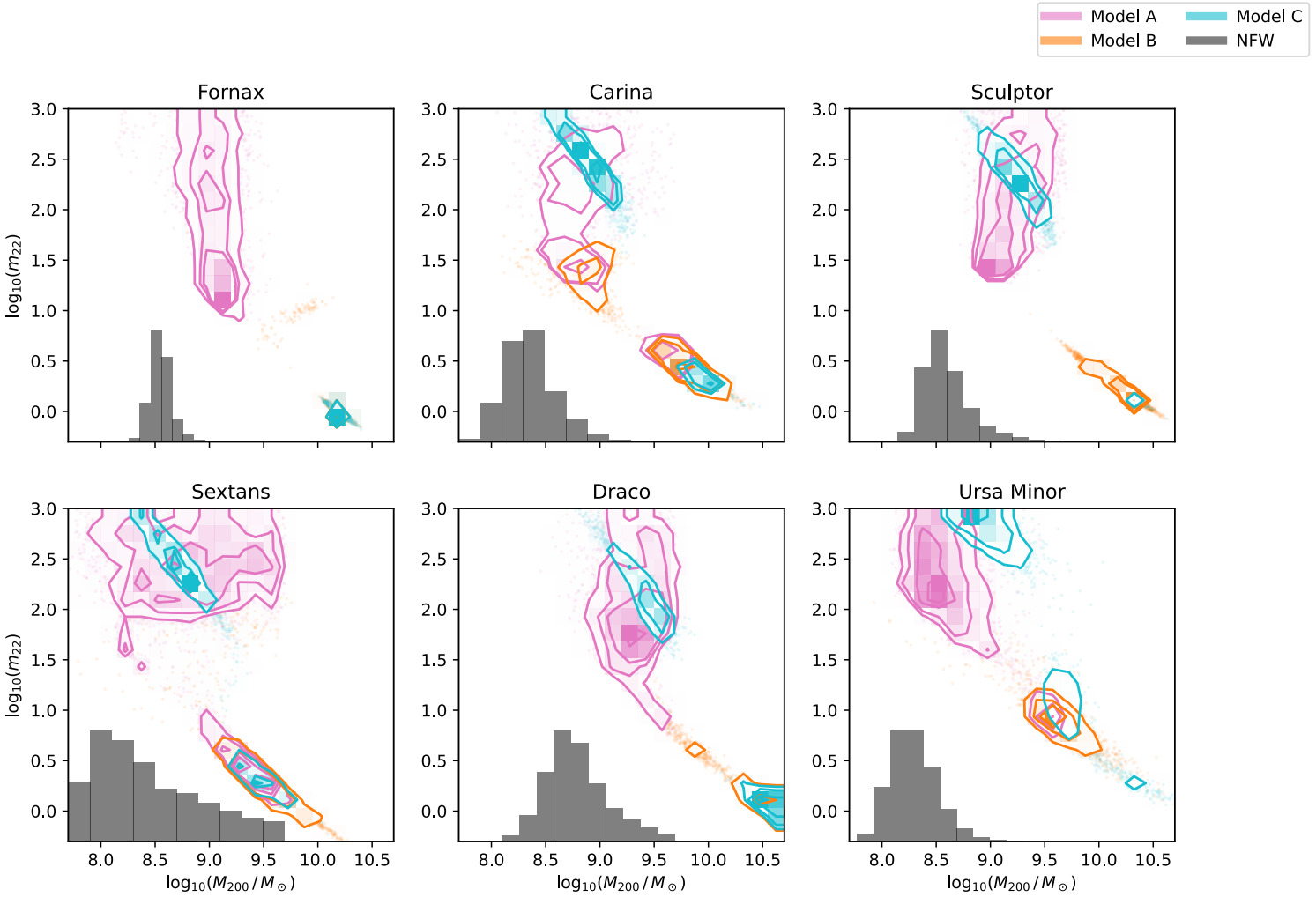

Fornax dispersion
Carina dispersion
Sculptor dispersion
Sextans dispersion
Draco dispersion
Ursa Minor dispersion
σ_v [km/s]
r [kpc]
Model C
NFW
Half light radius

RESULTS


Model A
Model B
Model C
NFW
Fornax
Carina
Sculptor
Sextans
Draco
Ursa Minor
$\log_{10}(m_{22})$
$\log_{10}(M_{200}/M_\odot)$
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

RESULTS

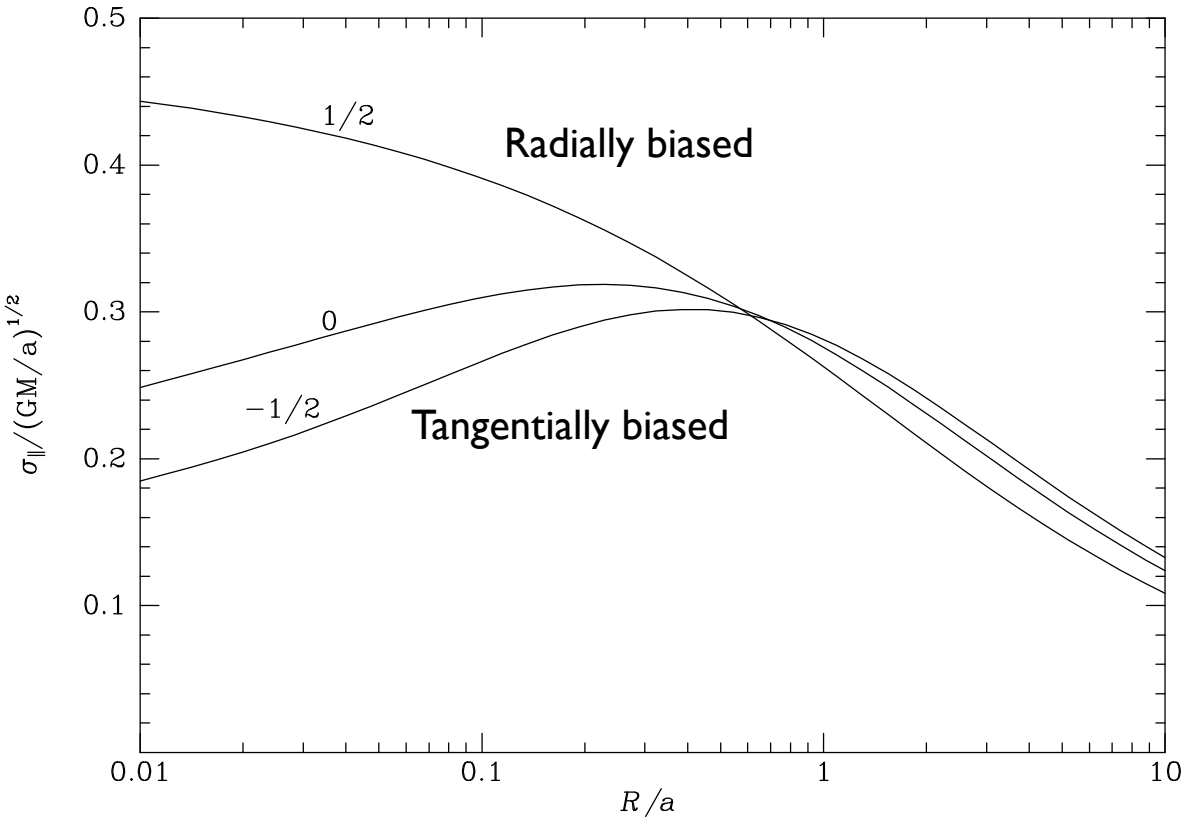
- Degeneracy between particle mass and halo mass



ANISOTROPY

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

$$\beta_a(r) \equiv 1 - \frac{2\overline{u_\theta^2}(r)}{\overline{u_r^2}(r)}$$



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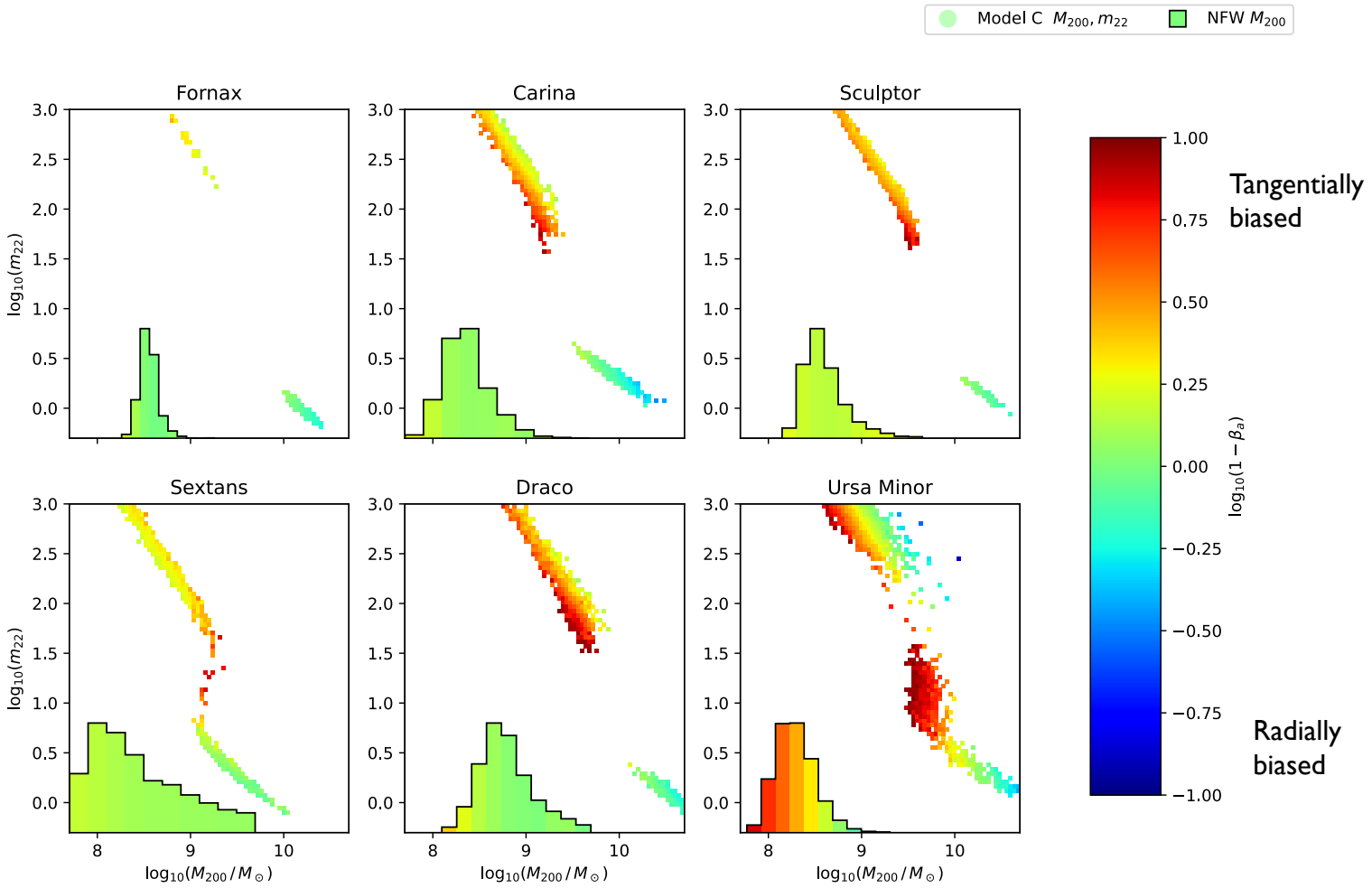

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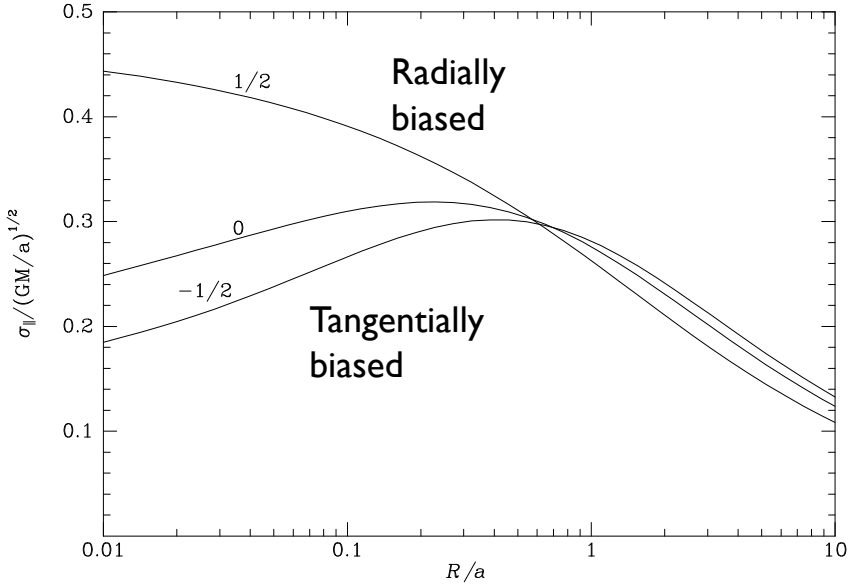

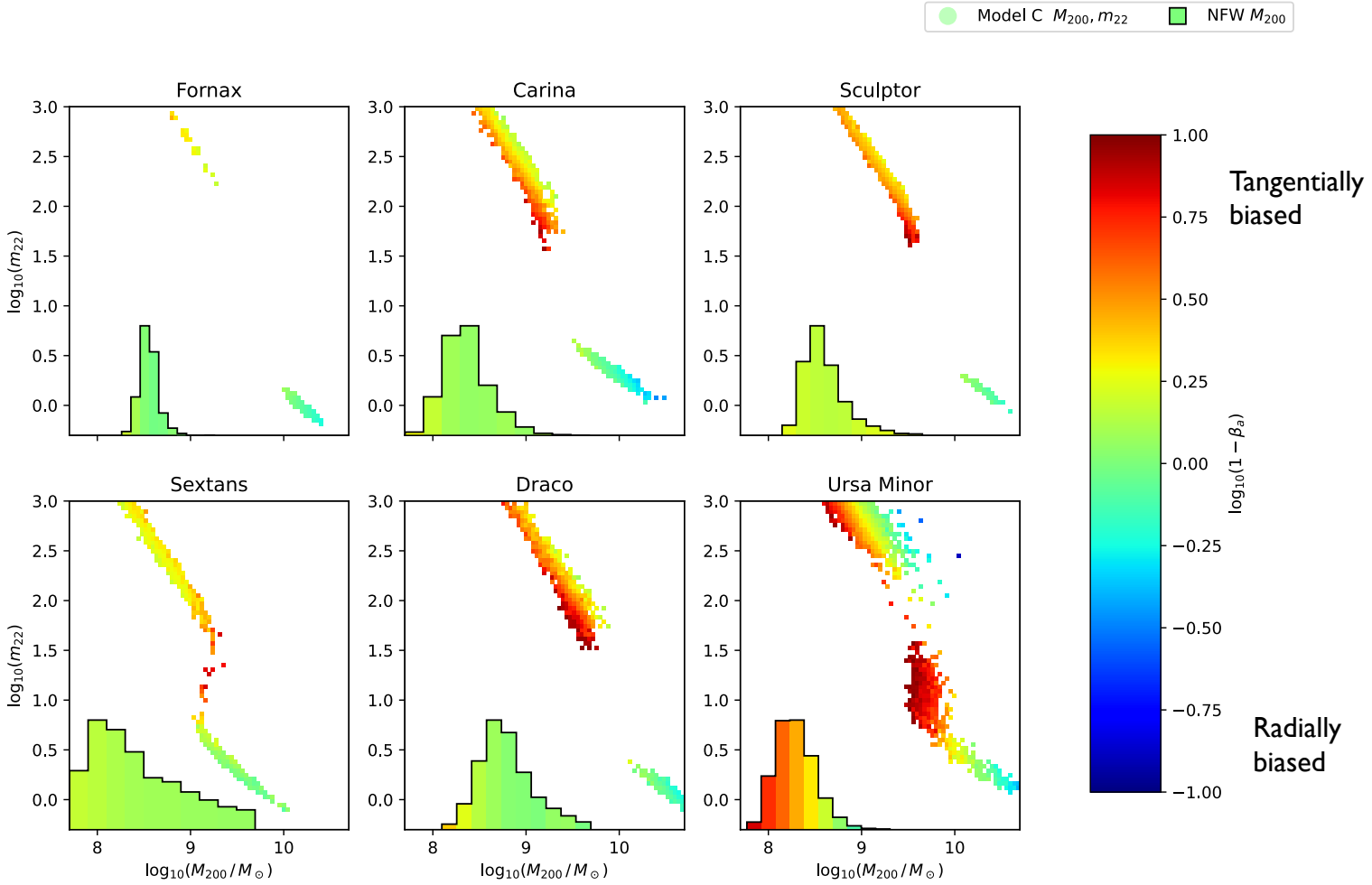

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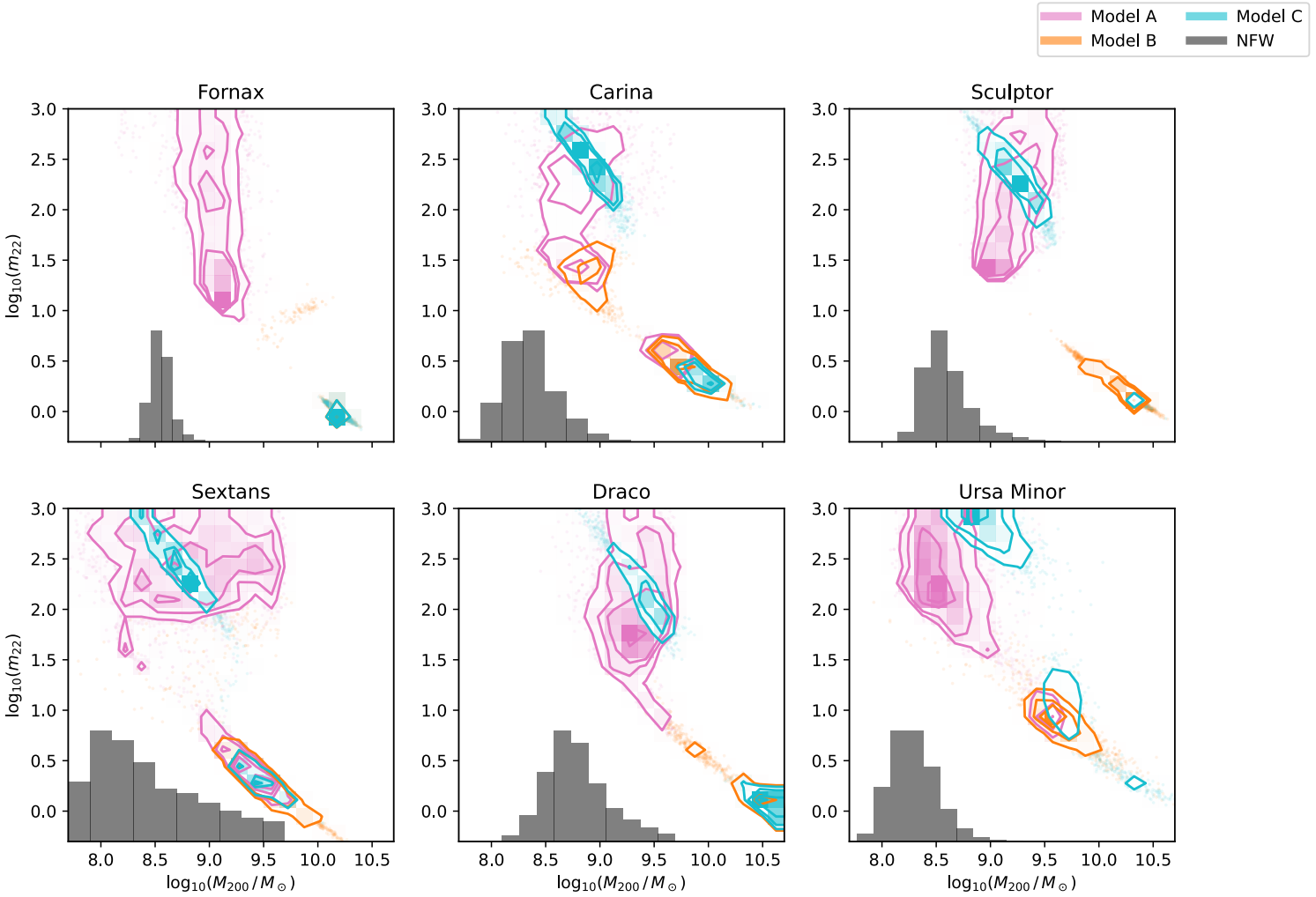
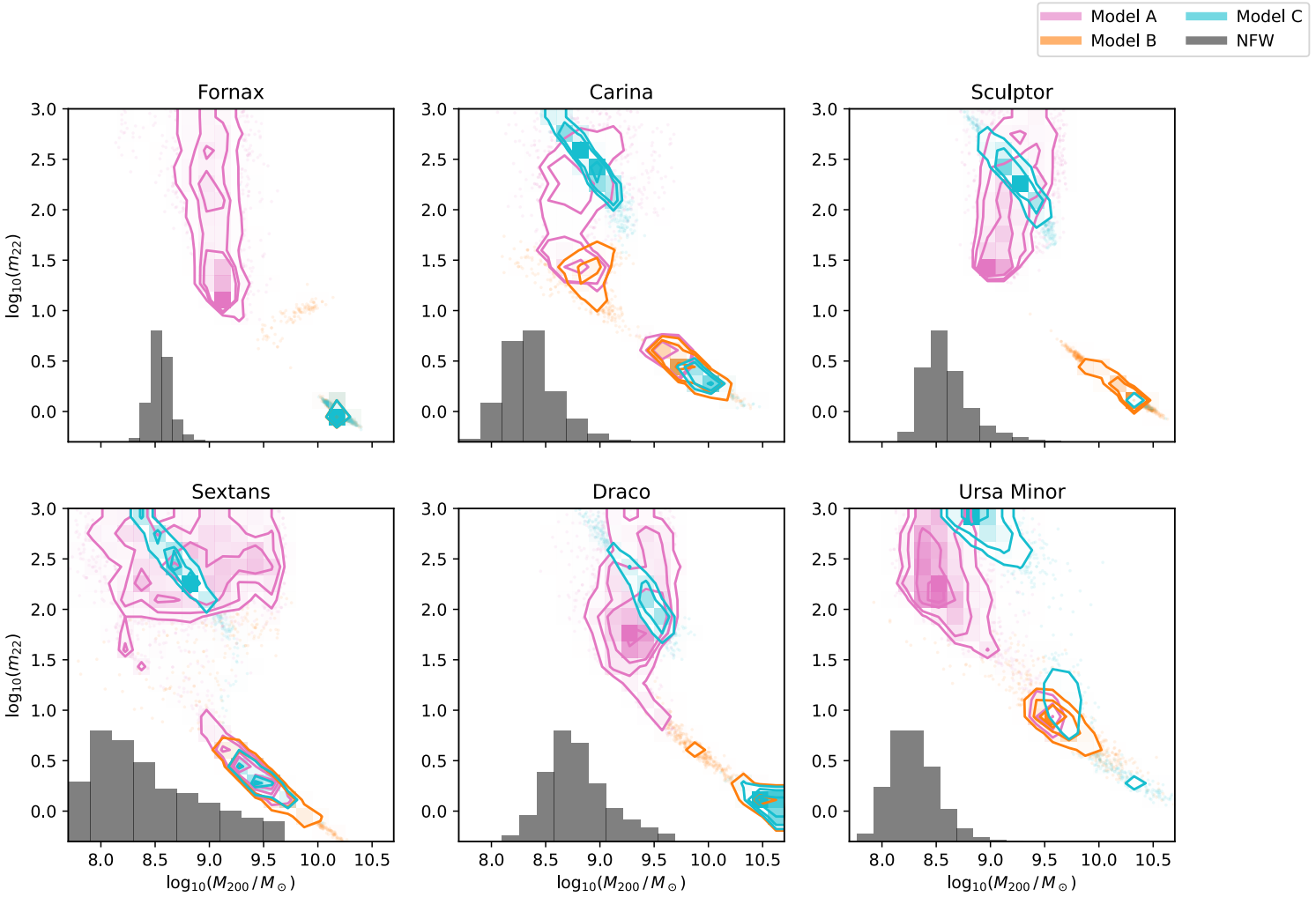


RESULTS

- Degeneracy between particle mass and halo mass

- Probability of 7 objects that size merging with a Milky Way sized halo is very small ($P \sim 10^{-6}$), would need to be an atypical galaxy



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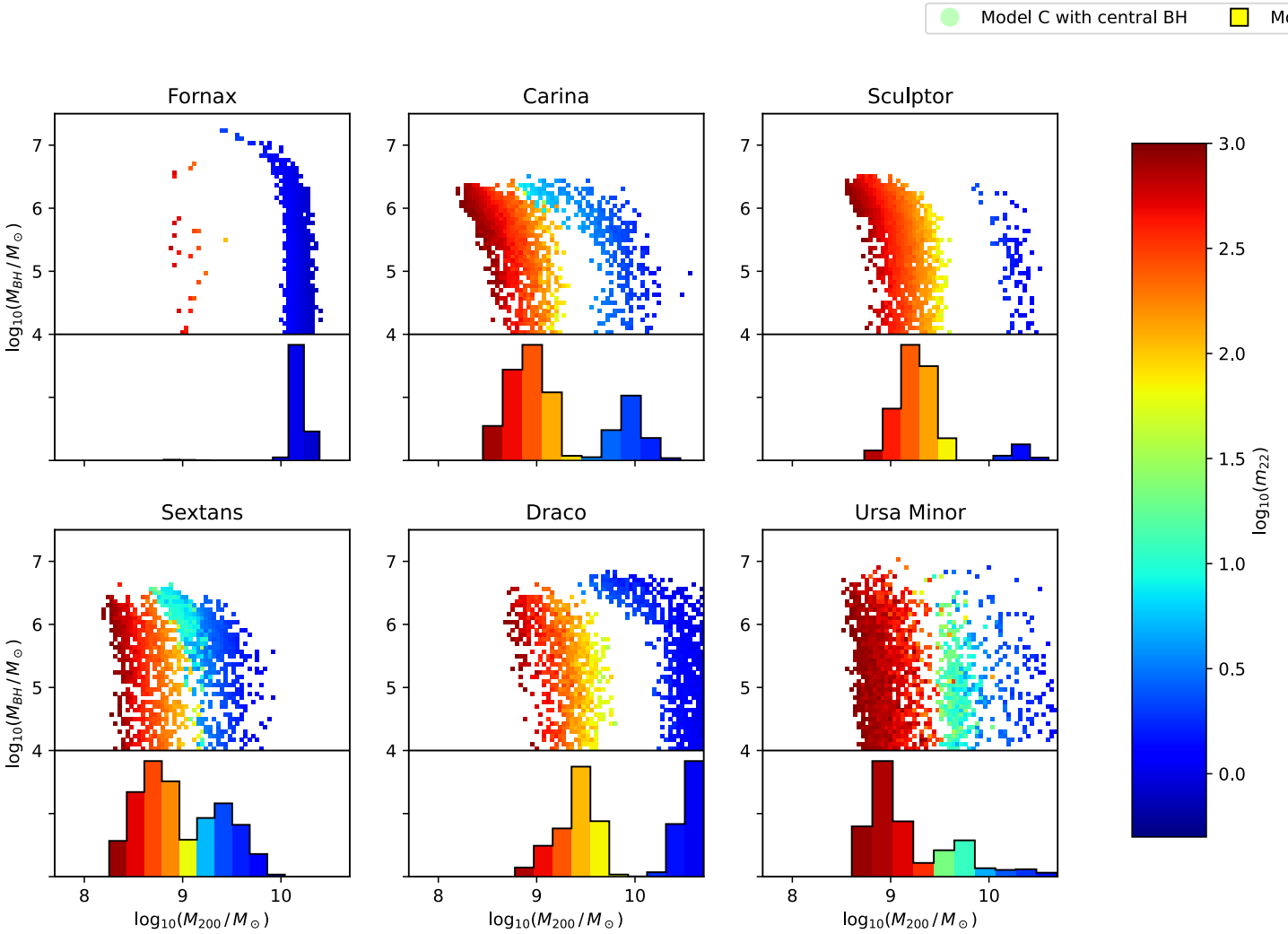
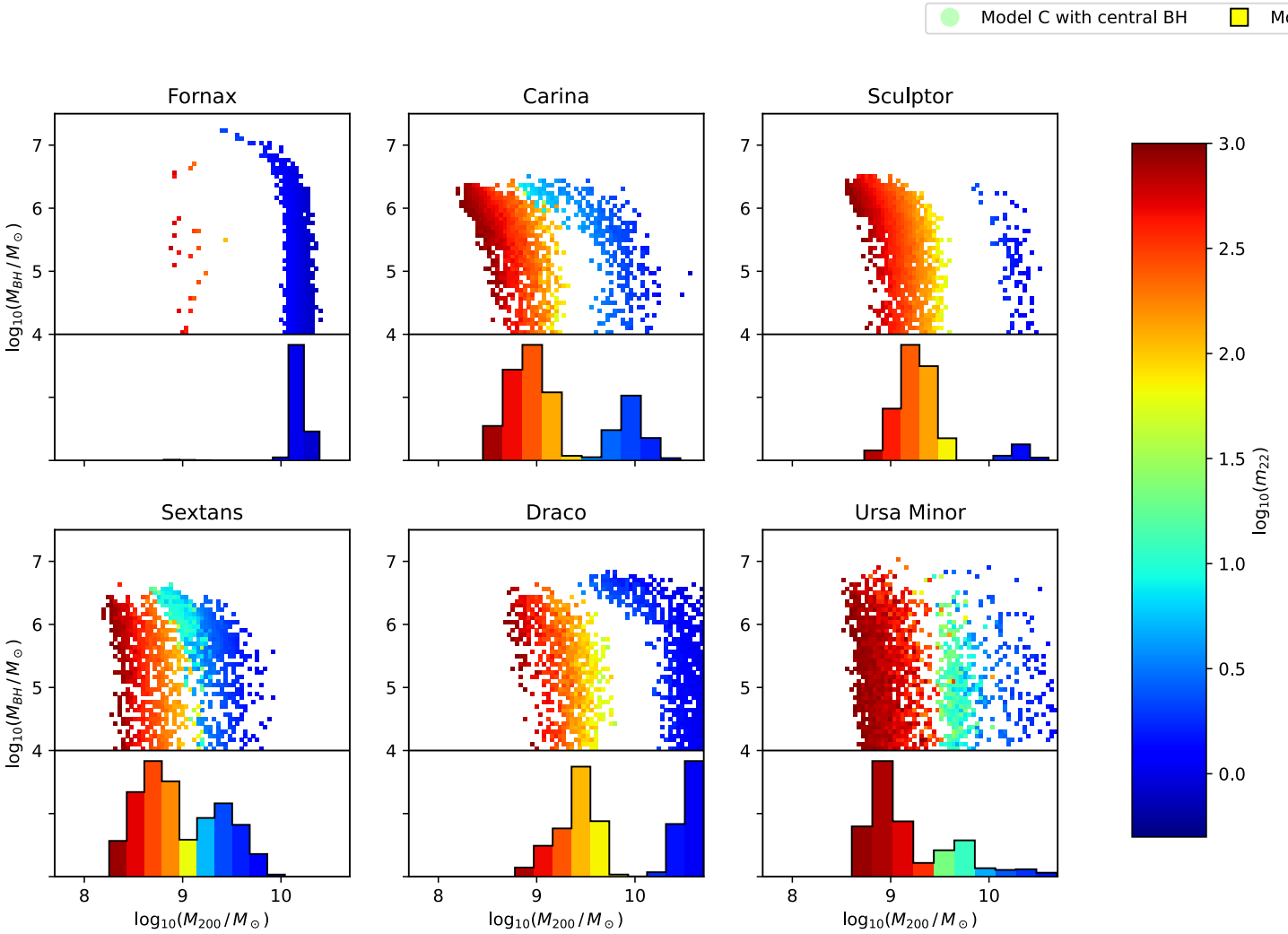


RESULTS: CENTRAL BLACK HOLE

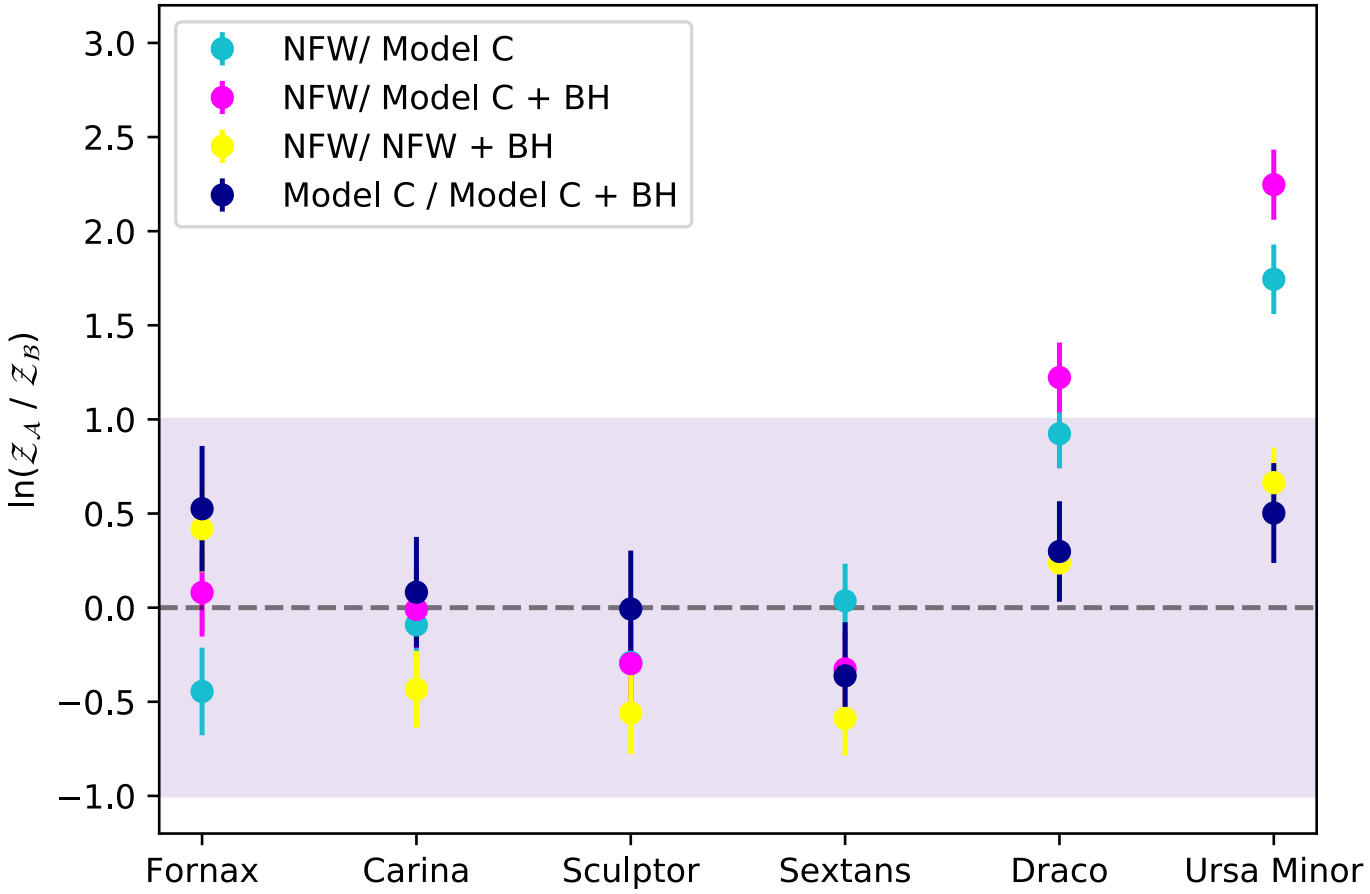
- Add a black hole (point mass) to the dwarf galaxy center
- Allows for lower particle mass, lower halo mass posteriors
- Requires proportionally massive black holes

[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



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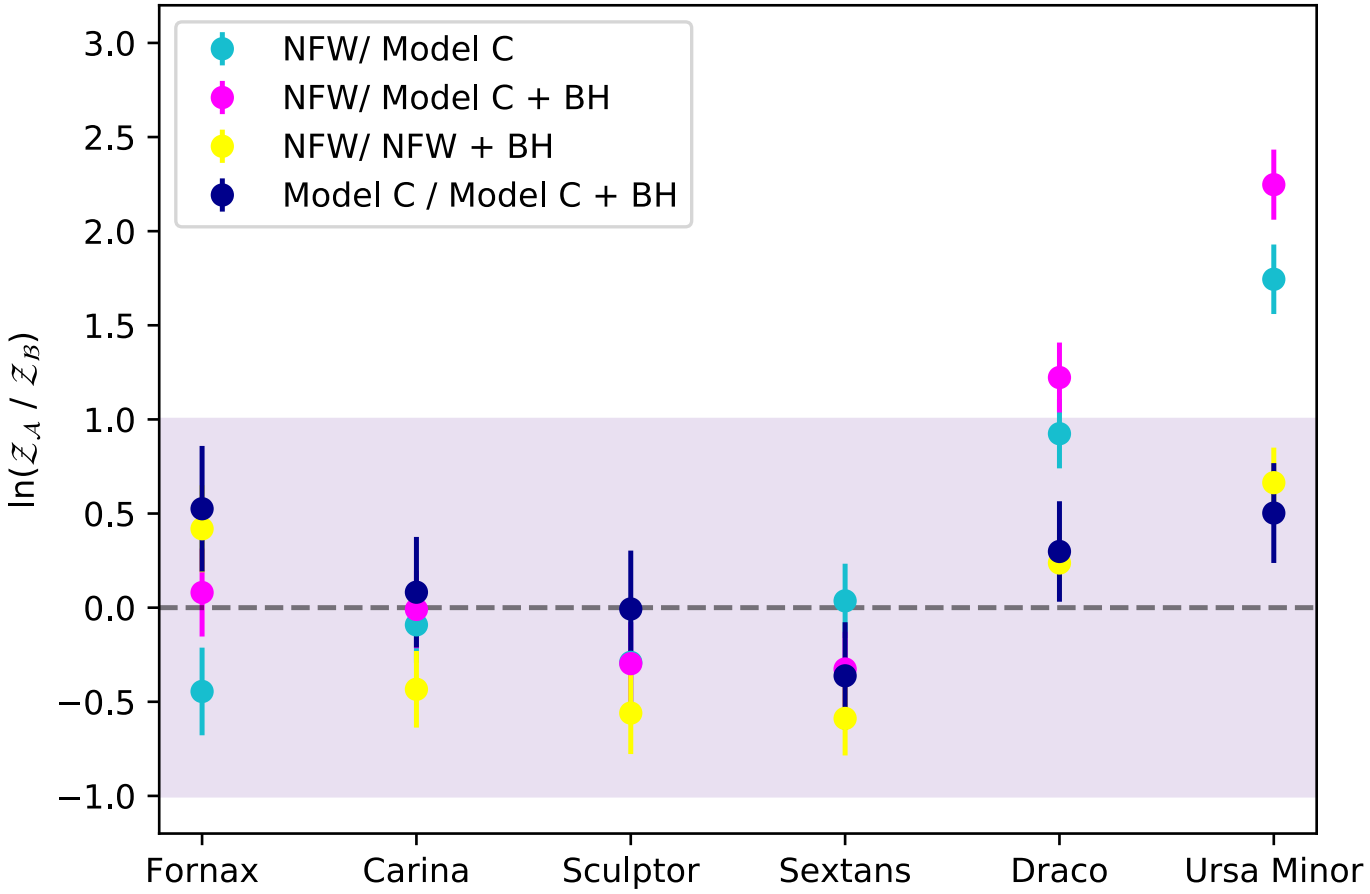
- Note that Ursa Minor has the smallest number of stars, and is the most irregular of the dwarfs analyzed



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- Particle masses of $m<10^{-20}$ eV are not kinematically viable in dwarfs unless:
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  - 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

ADDITIONAL MATERIAL

- ULB simulations are done with the Schrodinger-Poisson equations
  - Describes a self gravitating quantum superfluid

$$\left[i\frac{\partial}{\partial\tau} + \frac{\nabla^2}{2} - aV\right]\psi = 0$$

$$\nabla^2 V = 4\pi\left(|\psi|^2 - 1\right)$$

ADDITIONAL MATERIAL

- Start with the collisionless Boltzmann equation, then integrate over [velocity moments] to get the **Spherical Jeans Equation**:

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

- Assume anisotropy is constant over the system, and you get the solution:

$$\sigma^2(R)\Sigma(R) = 2\int_R^\infty \left(1 - \beta_a(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\overline{u_r^2}(r)r}{\sqrt{r^2 - R^2}}dr$$

with $\Sigma(R)$ the projected stellar density, $\overline{u_r^2}(r)$ the radial stellar velocity dispersion profile, R is the projected radial distance from the center

ADDITIONAL MATERIAL: UNBINNED

- Unbinned Gaussian likelihood function:

$$L = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi}\sqrt{\delta_{u,i}^2 + \sigma^2(R_i)}} \exp\left[-\frac{1}{2}\frac{(u_i - \langle u \rangle)^2}{\delta_{u,i}^2 + \sigma^2(R_i)}\right].$$

Here, u_i is the projected velocity, R_i is the projected position, and $\delta_{u,i}$ is the observational error in velocity of the ith star in the data set. $\langle u \rangle$ is the bulk velocity, which is marginalized over with a flat prior.

For more details, see:

A. Geringer-Sameth, S. M. Koushiappas, and M. Walker, The Astrophysical Journal **801**, 74 (2015).

ADDITIONAL MATERIAL: PRIORS

Generalized NFW:

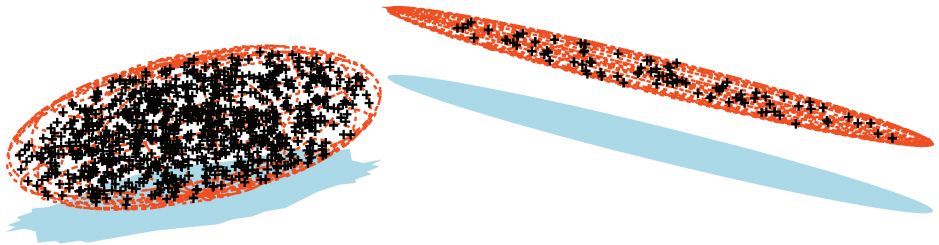
$$-1 \leq -\log_{10}(1-\beta_a) \leq +1,$$
$$\log_{10}(5\times 10^7) \leq \log_{10}(M_{200}/M_\odot) \leq \log_{10}(5\times 10^9),$$
$$\log_{10}(2) \leq \log_{10}(c_{200}) \leq \log_{10}(30),$$
$$0.5 \leq \alpha \leq 3,$$
$$3 \leq \beta \leq 10,$$
$$0 \leq \gamma \leq 1.2.$$

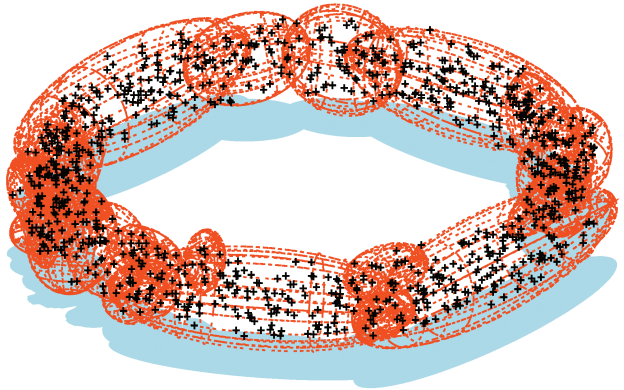
Model C ULB:

$$-1 \leq -\log_{10}(1-\beta_a) \leq +1,$$
$$-1 \leq \log_{10}(m_{22}) \leq 3$$
$$M_{200}^{\min}(m_{22}) \leq \log_{10}\left(M_{200}/M_\odot\right) \leq \log_{10}(5\times 10^{10}),$$

ADDITIONAL MATERIAL: MULTINEST

- `PyMultiNest` interface for the `MultiNest` Bayesian inference tool
  - N points sampled
  - Lowest likelihood L_0 point discarded
  - Replaced by a point if likelihood is $L>L_0$
  - Reduce prior volume





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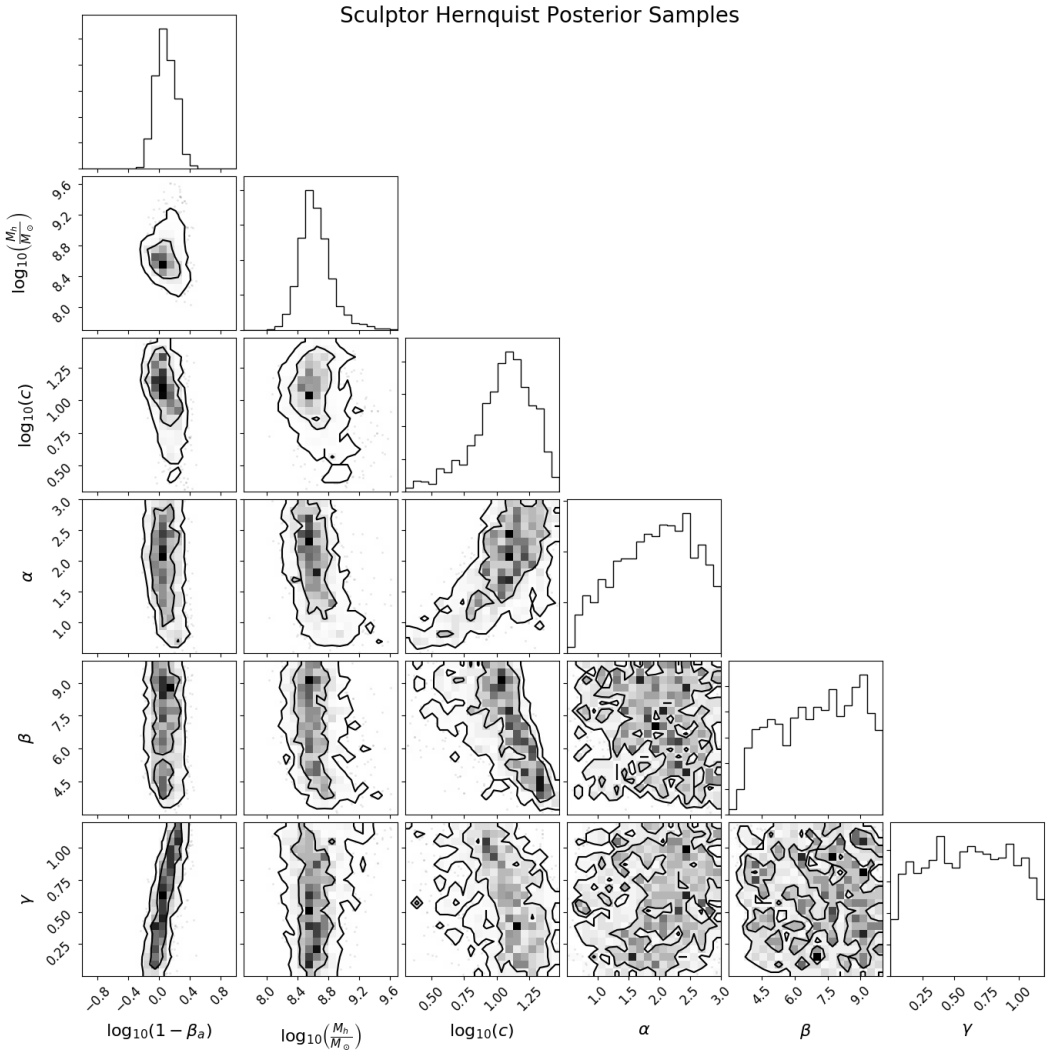
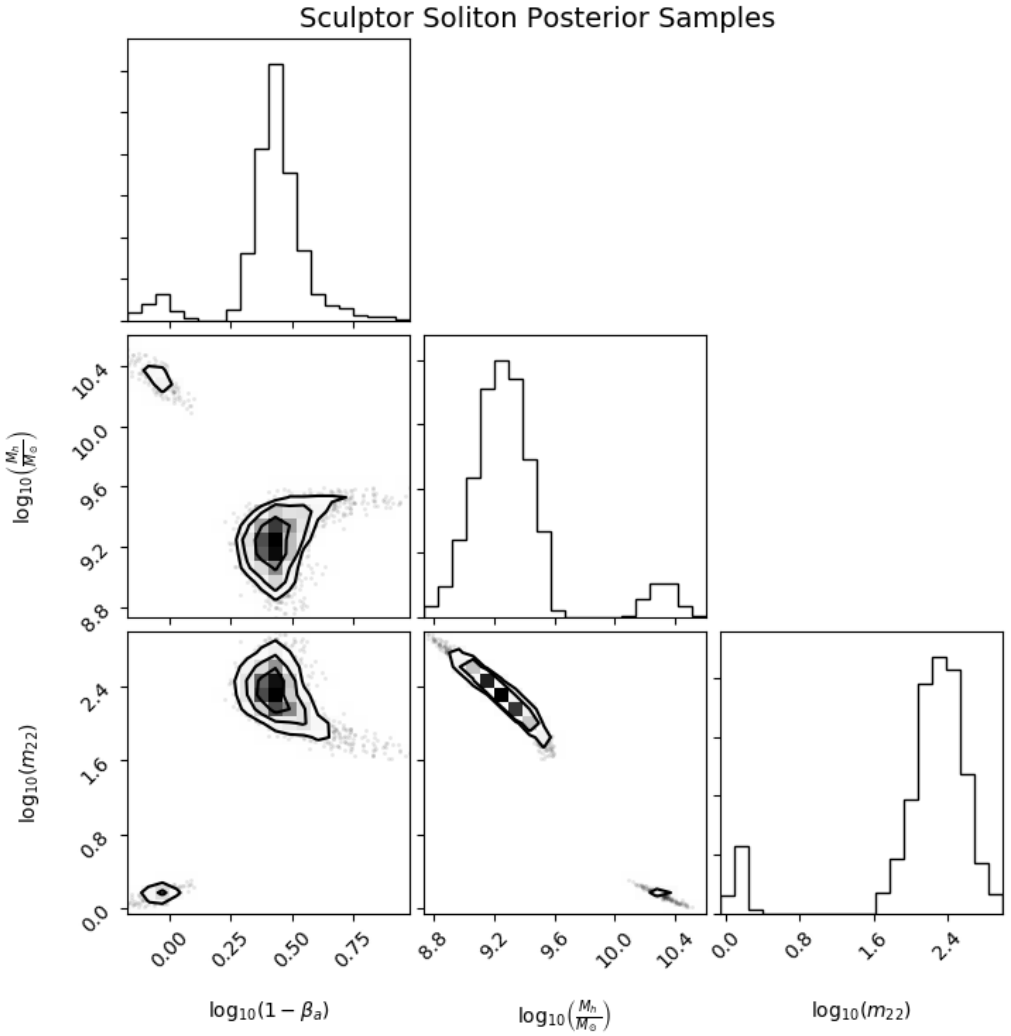
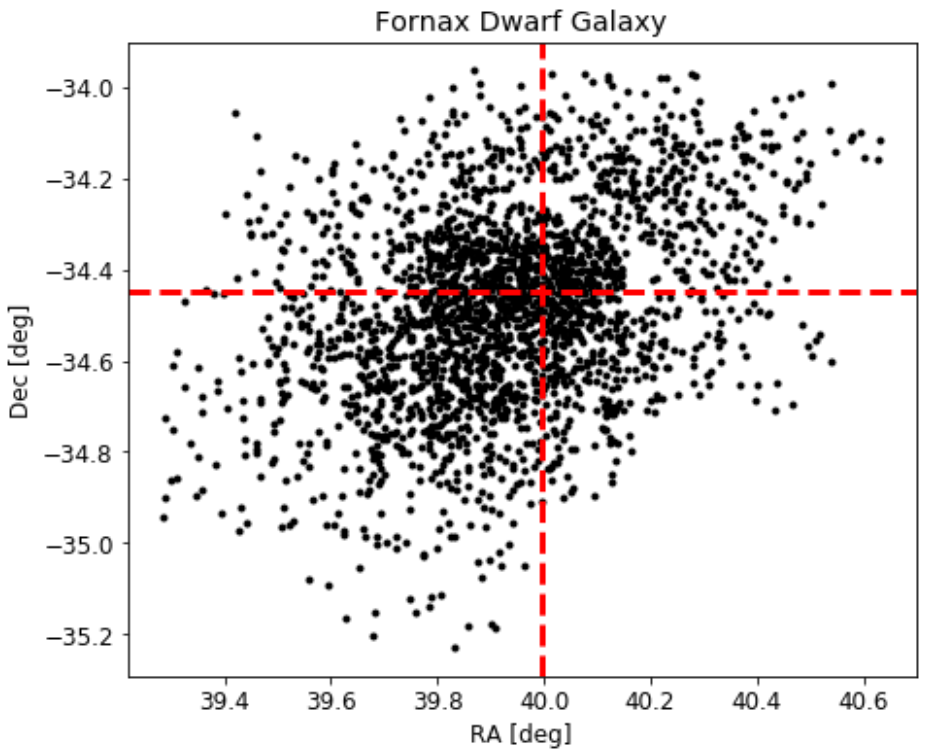
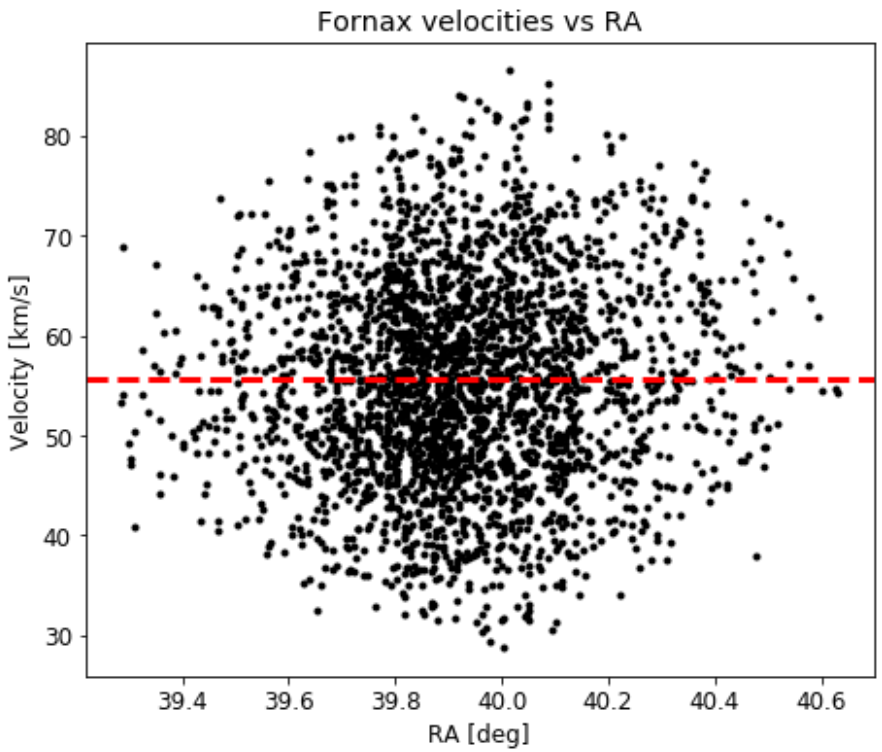




ADDITIONAL MATERIAL: FORNAX





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,

$$\boxed{\underbrace{\frac{d(\nu\overline{v_r^2})}{dr} + 2\frac{\beta}{r}\nu\overline{v_r^2}}_{\text{Pressure term}} = \underbrace{-\nu\frac{d\phi}{dr}}_{\text{Gravity term}}}$$

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).