THE VIABILITY OF ULTRALIGHT BOSONIC DARK MATTER IN DWARF GALAXIES

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ARXIV:2205.XXXXX

2022 MITCHELL CONFERENCE ON COLLIDER, DARK MATTER, AND NEUTRINO PHYSICS

ULTRALIGHT DARK MATTER

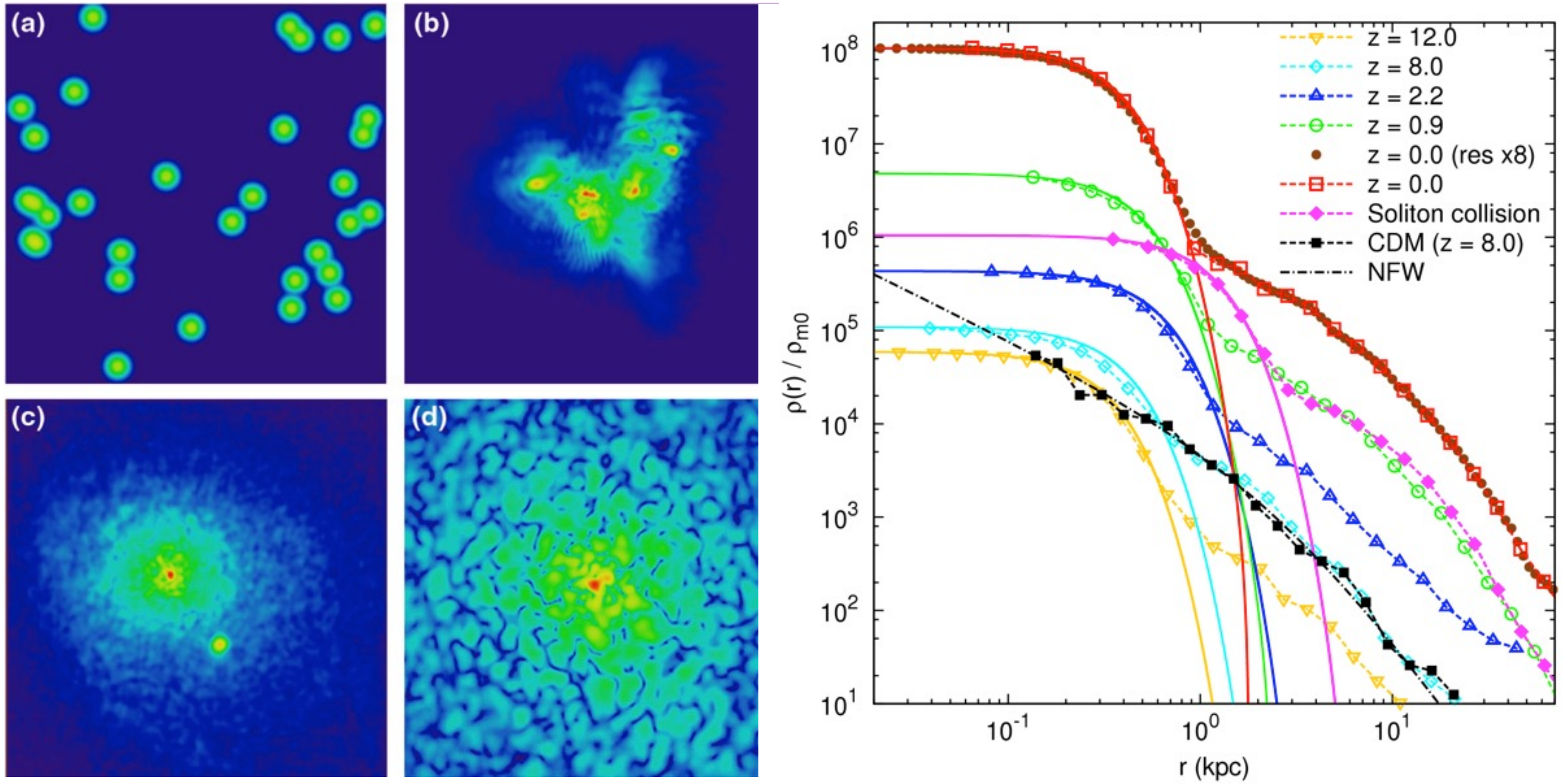
- **Ultralight bosonic dark matter** is a boson of mass $m \sim 10^{-22}$ eV
  - Often written as $m_{22} = m / 10^{-22}$ eV

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

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

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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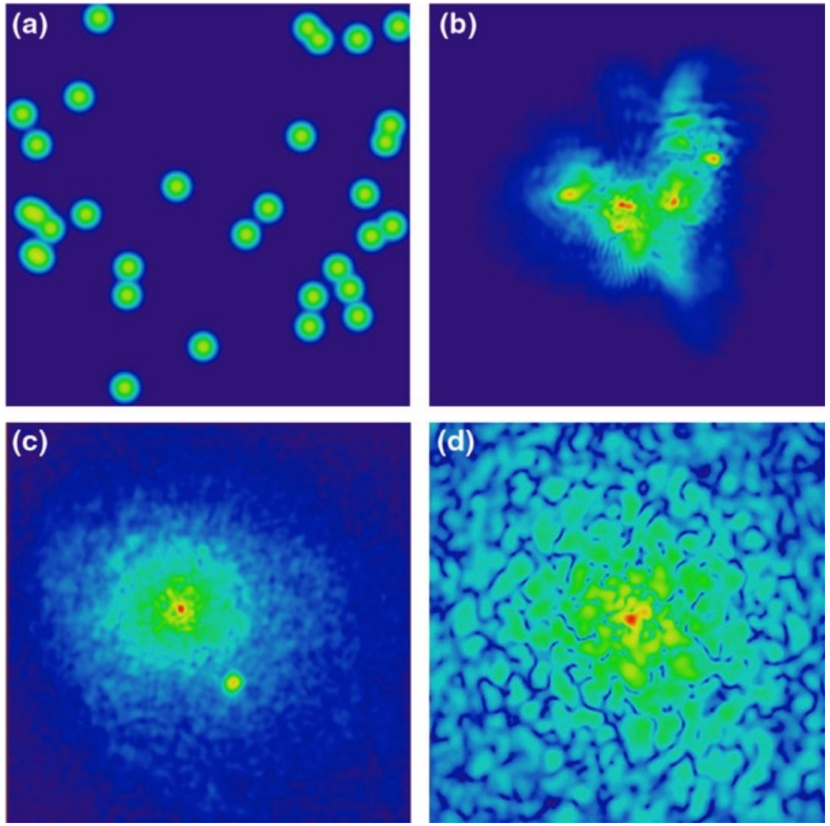

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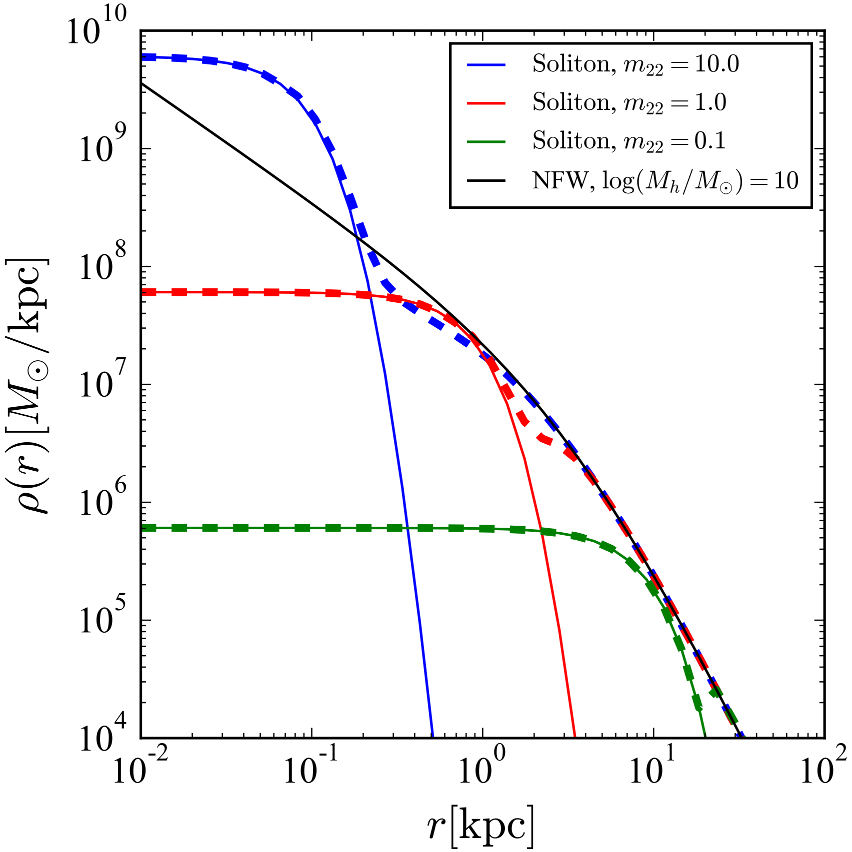

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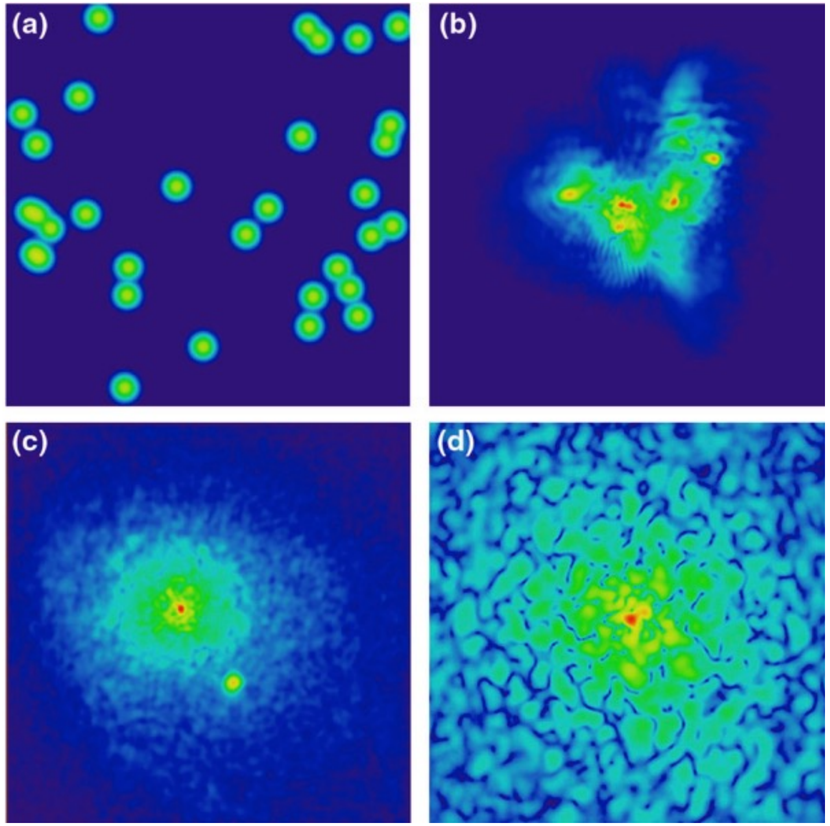
ULTRALIGHT DARK MATTER

- 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
- Connects to an outer NFW for the full density profile



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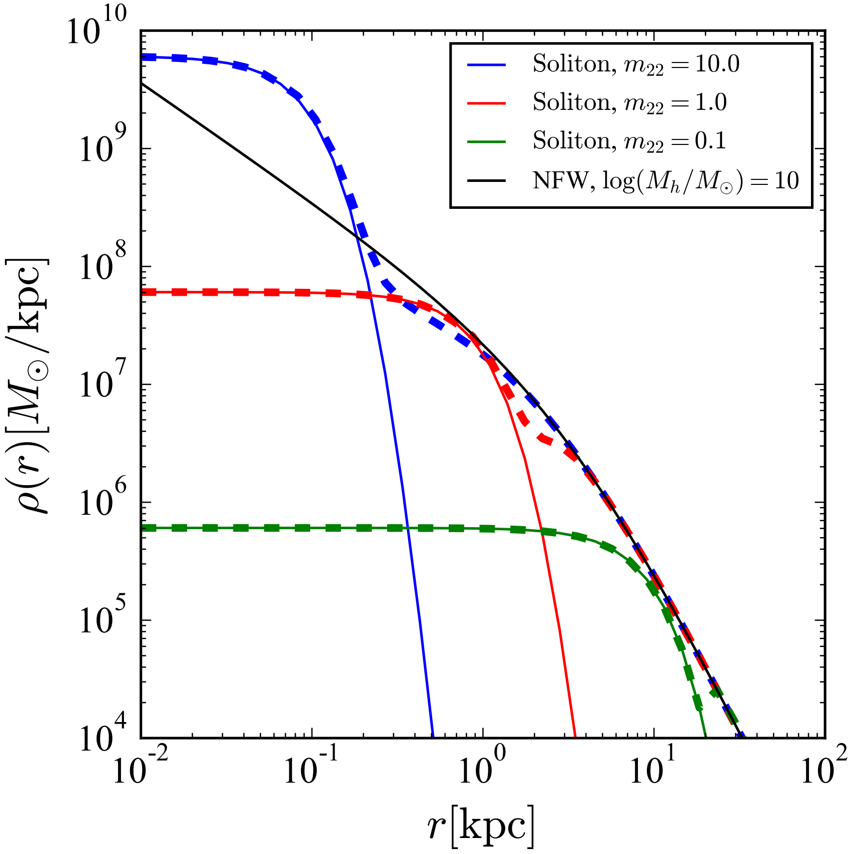

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ANALYSIS

Soliton core only	NFW is physically unconstrained	González-Morales, Marsh, Peñarrubia, and Ureña-López, MNRAS **472**, 1346 (2017)
NFW parameters chosen independent of soliton parameters	Most general, but mass is not necessarily conserved	Safarzadeh and Spergel, ApJ **893**, 21 (2020).
Parameterized transition with density continuity	Transition radius is allowed to vary	Marsh Pop, 2015, MNRAS, **451**, 2479
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

- 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

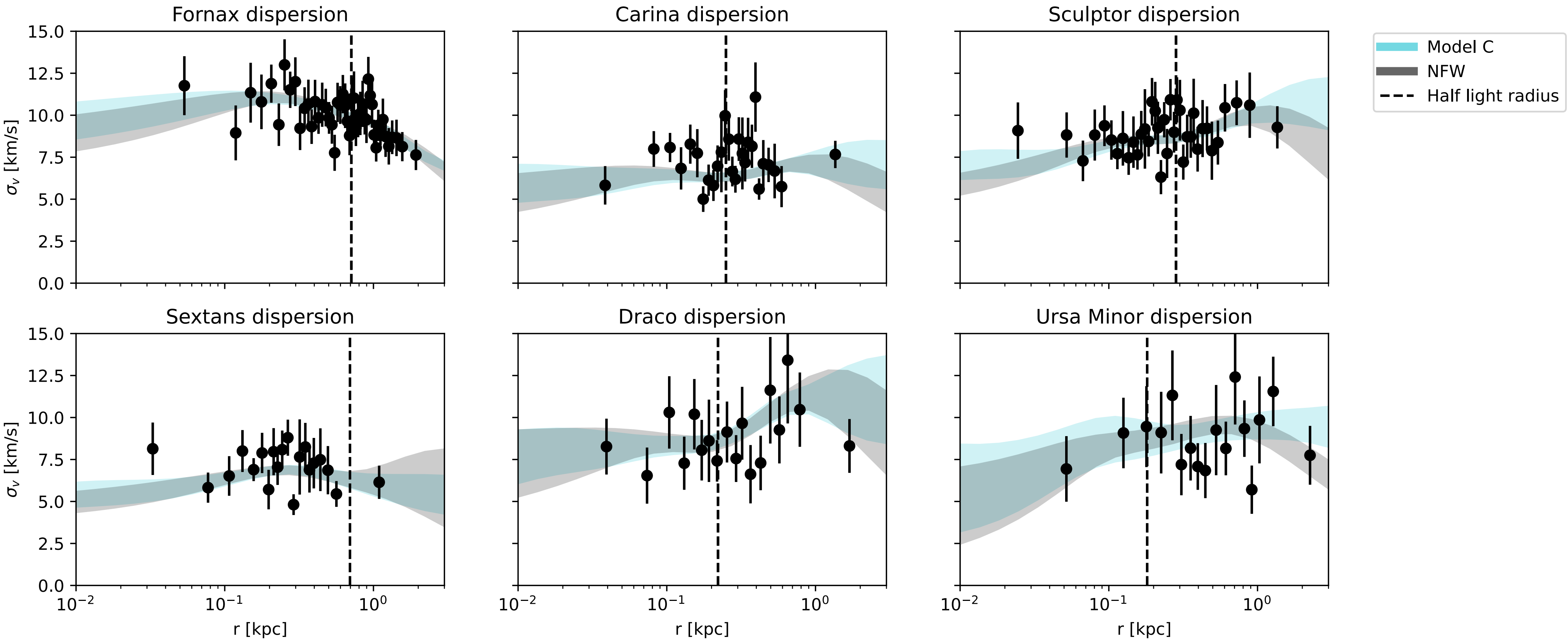
  - Past work has done this with CDM, WIMPs
- Run with `MultiNest` Feroz, Hobson, and Bridges, MNRAS **398**, 1601 (2009), choosing a:
  - Dark matter density profile
  - Particle mass, halo mass, velocity anisotropy

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

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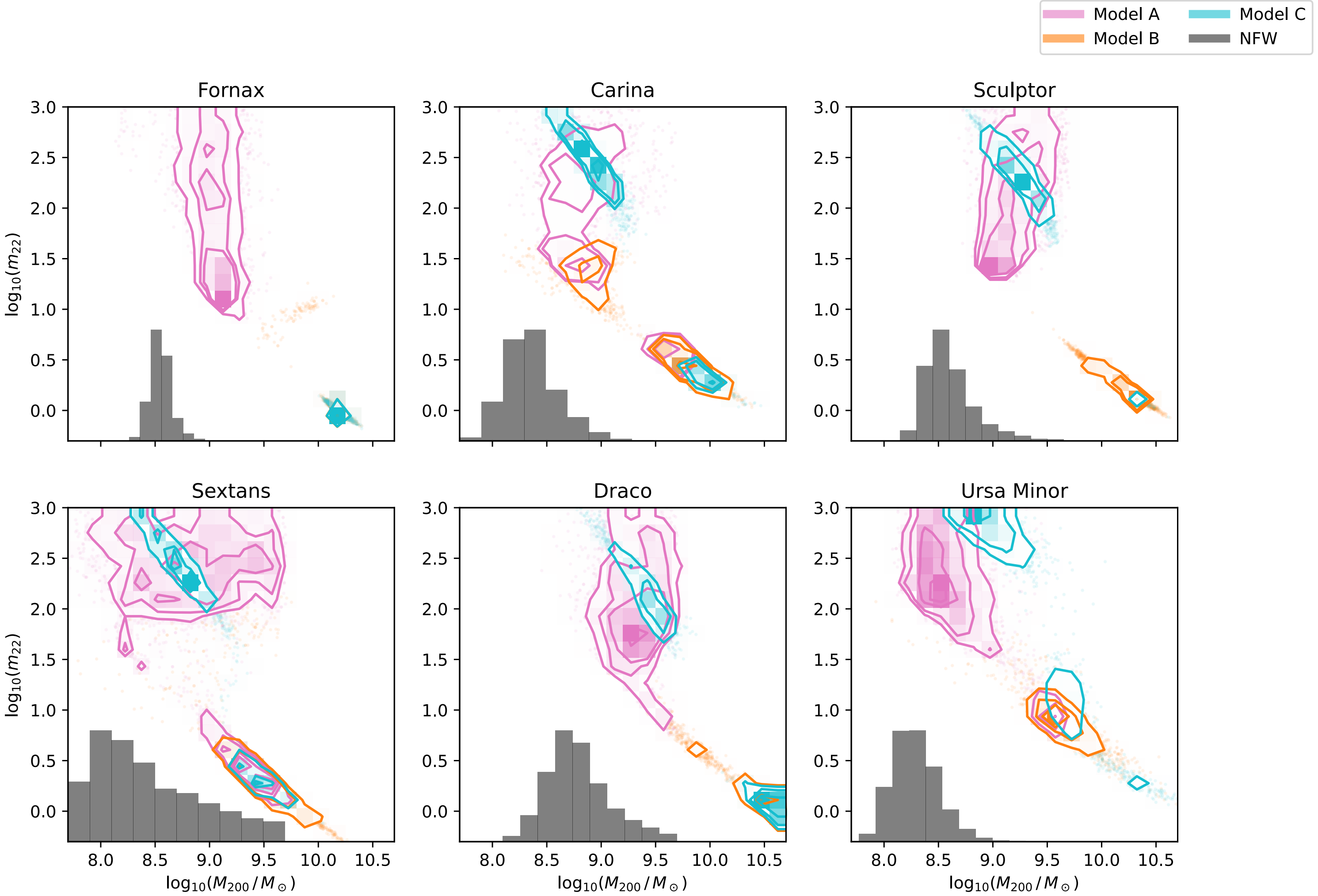
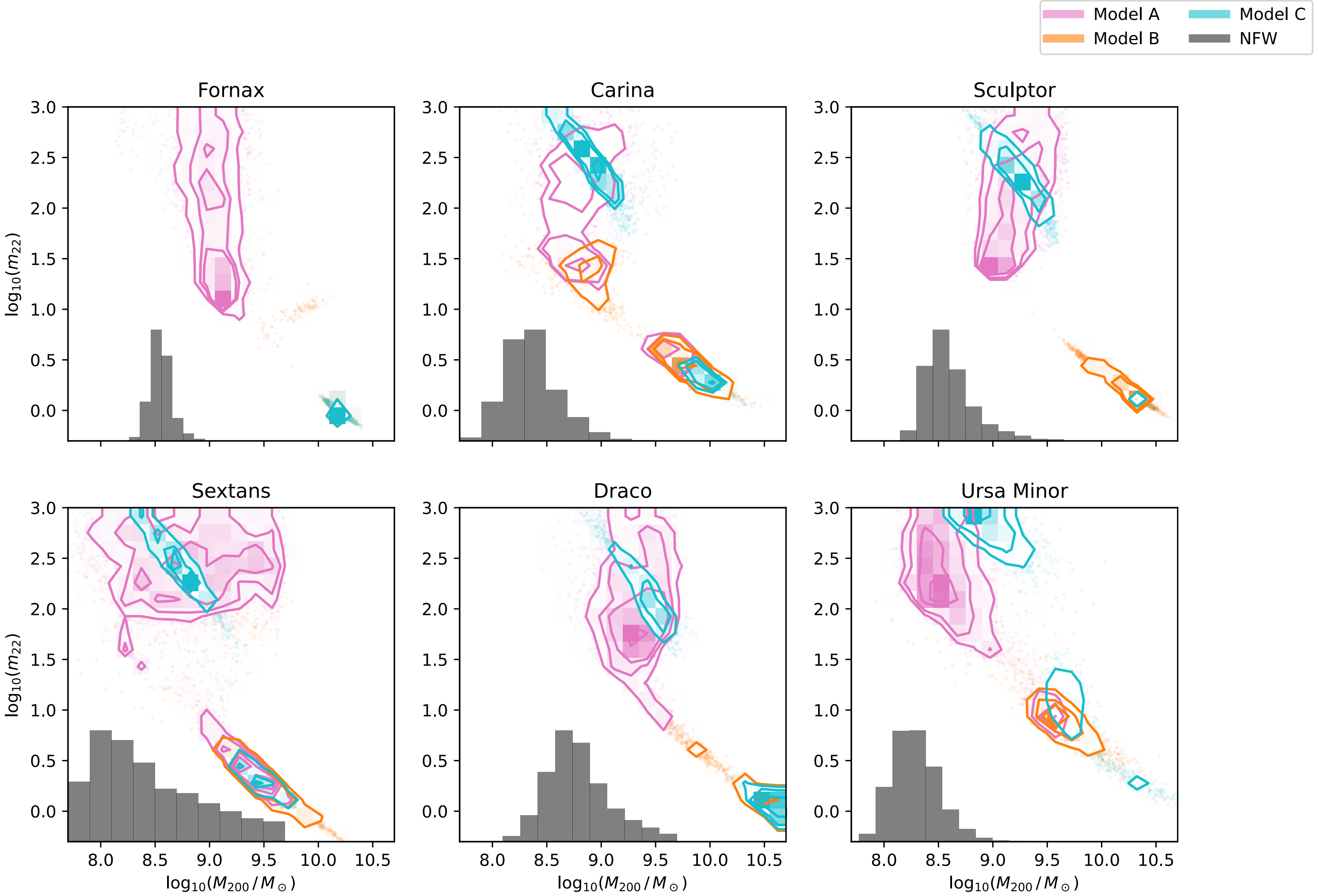

Model A
Model B
Model C
NFW
Fornax
Carina
Sculptor
Sextans
Draco
Ursa Minor
$\log_{10}(m_{22})$
$\log_{10}(M_{200}/M_\odot)$

RESULTS

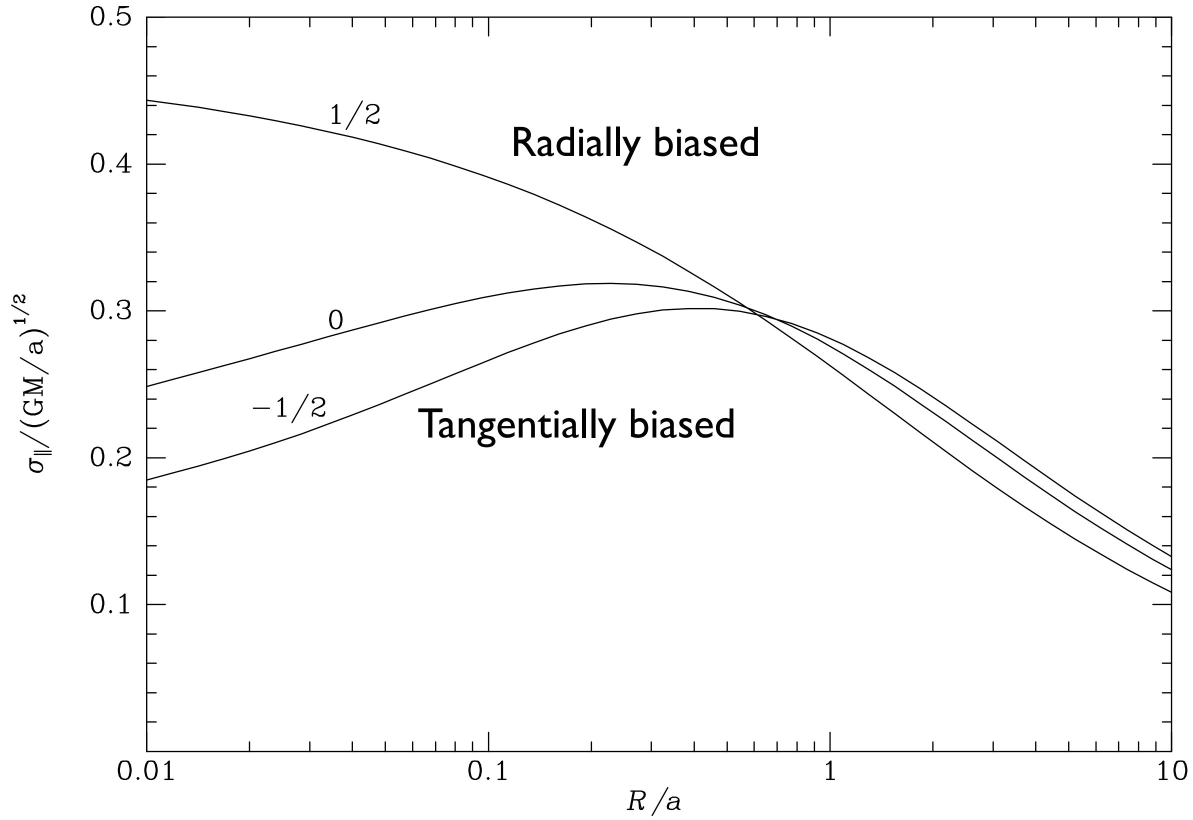
- Degeneracy between particle mass and halo mass



ANISOTROPY

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

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



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

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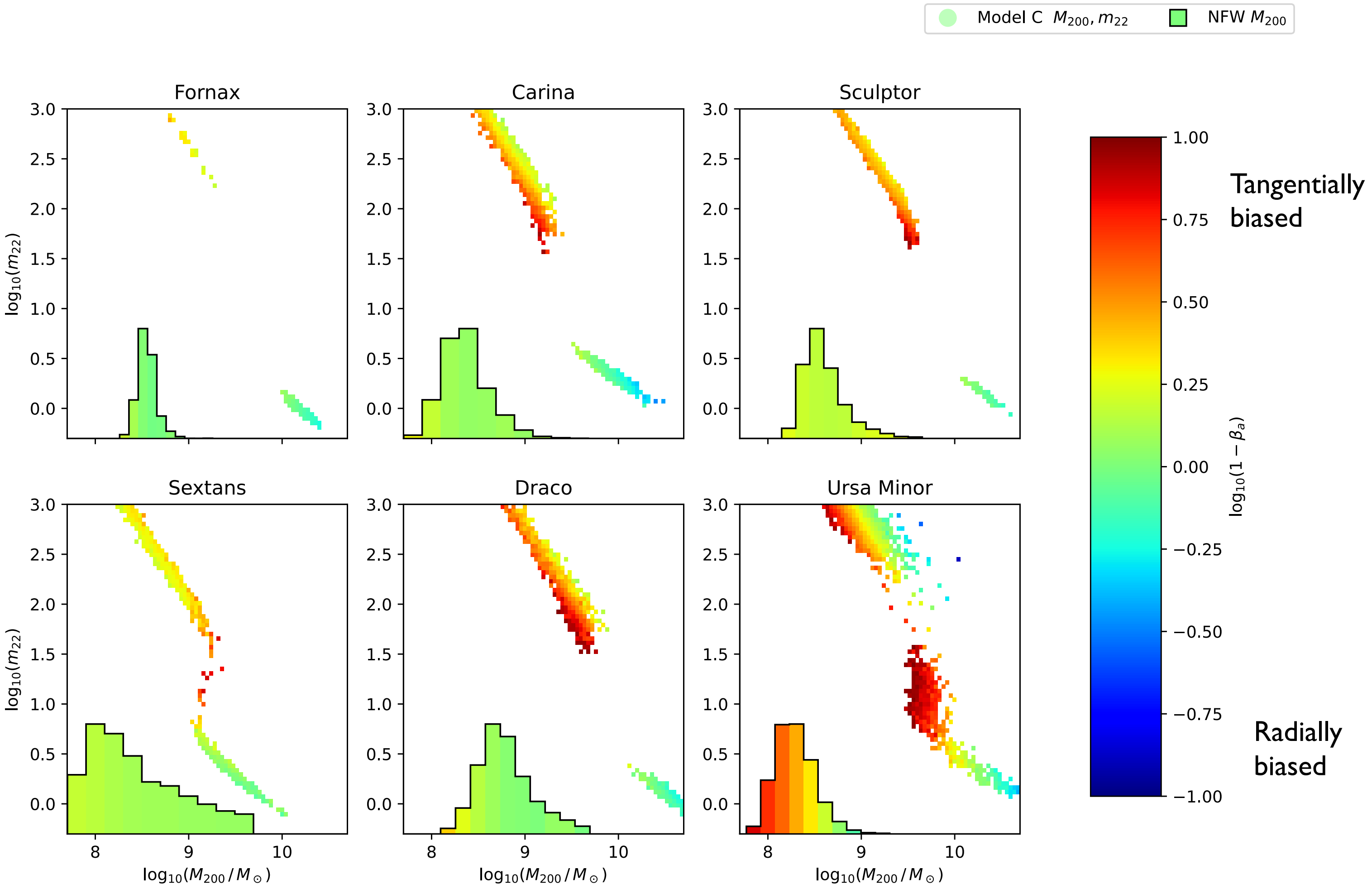
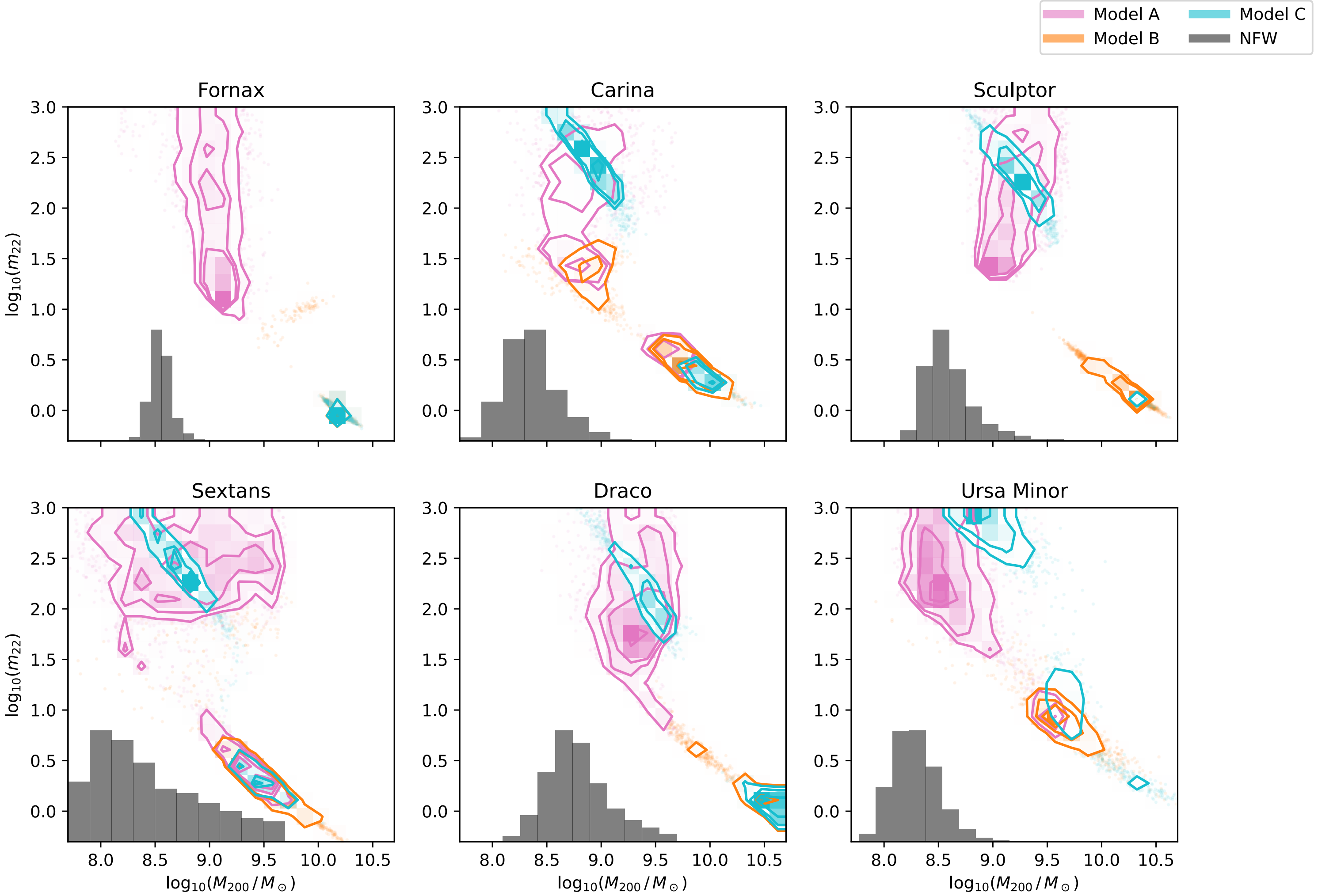


RESULTS

- Degeneracy between particle mass and halo mass

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



RESULTS: CENTRAL BLACK HOLE

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

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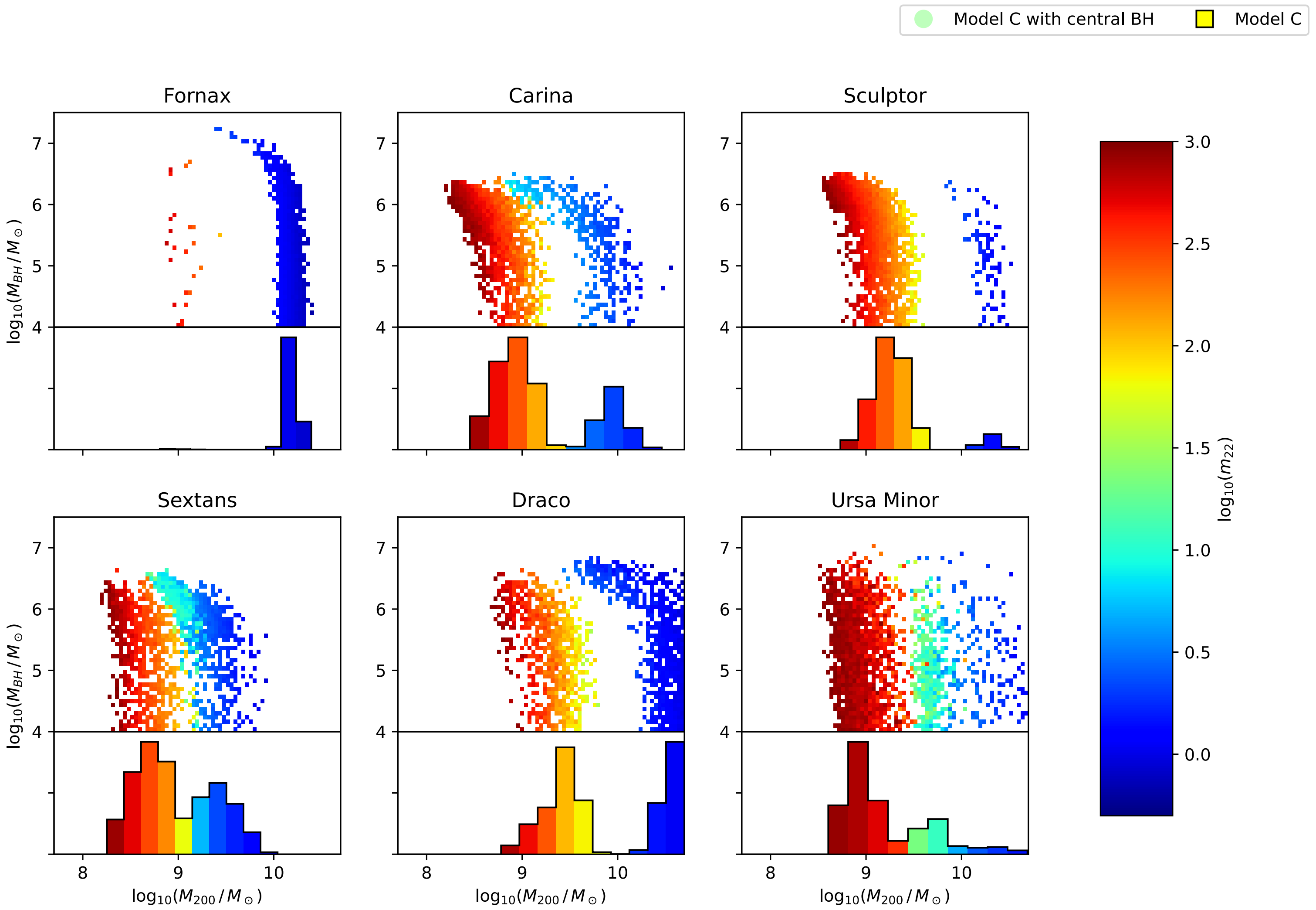
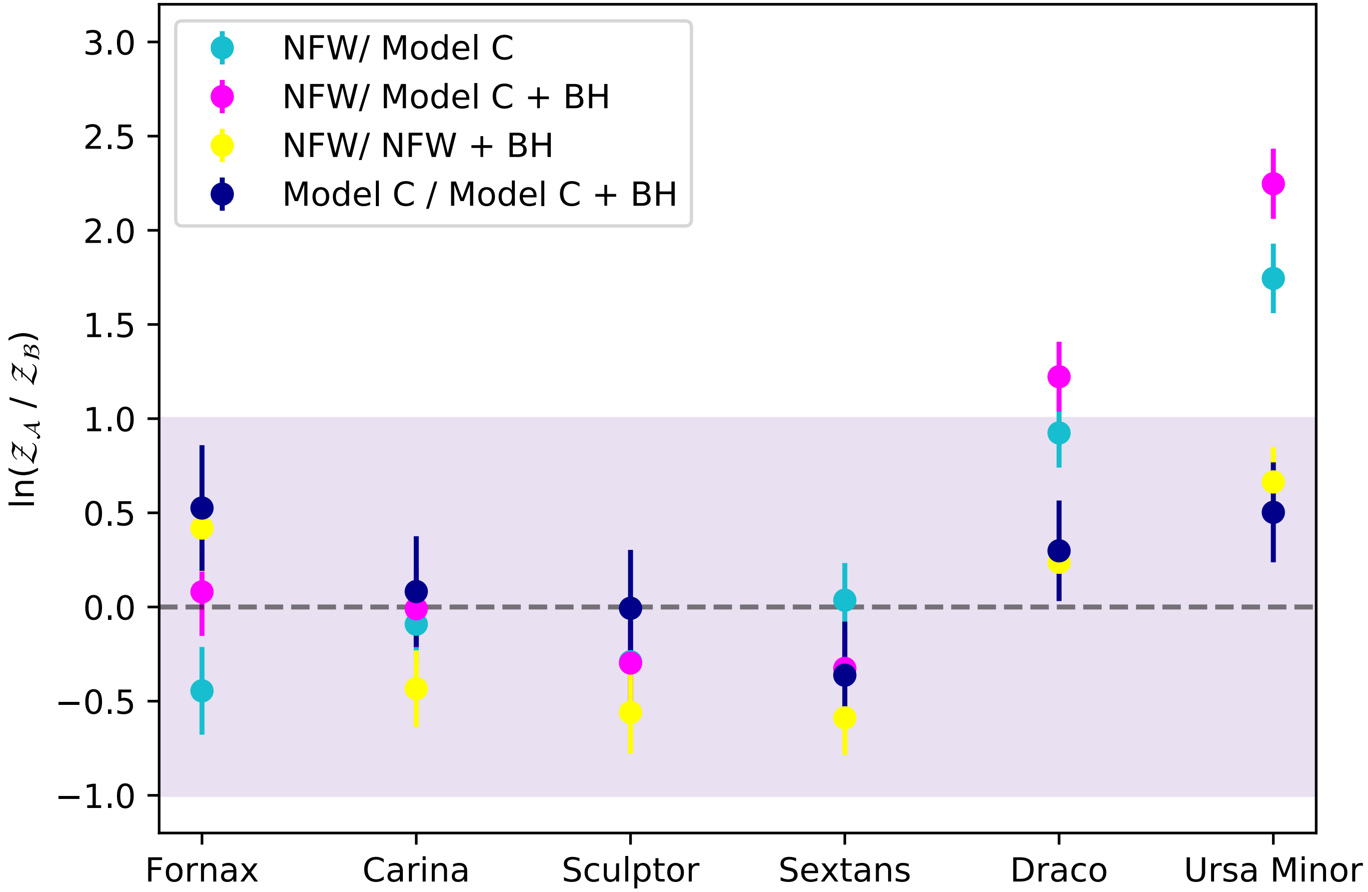
- Add a black hole (point mass) to the dwarf galaxy center
- Allows for lower particle mass, lower halo mass posteriors



EVIDENCE

- Evidence is the sum of likelihood over the prior volume



EVIDENCE

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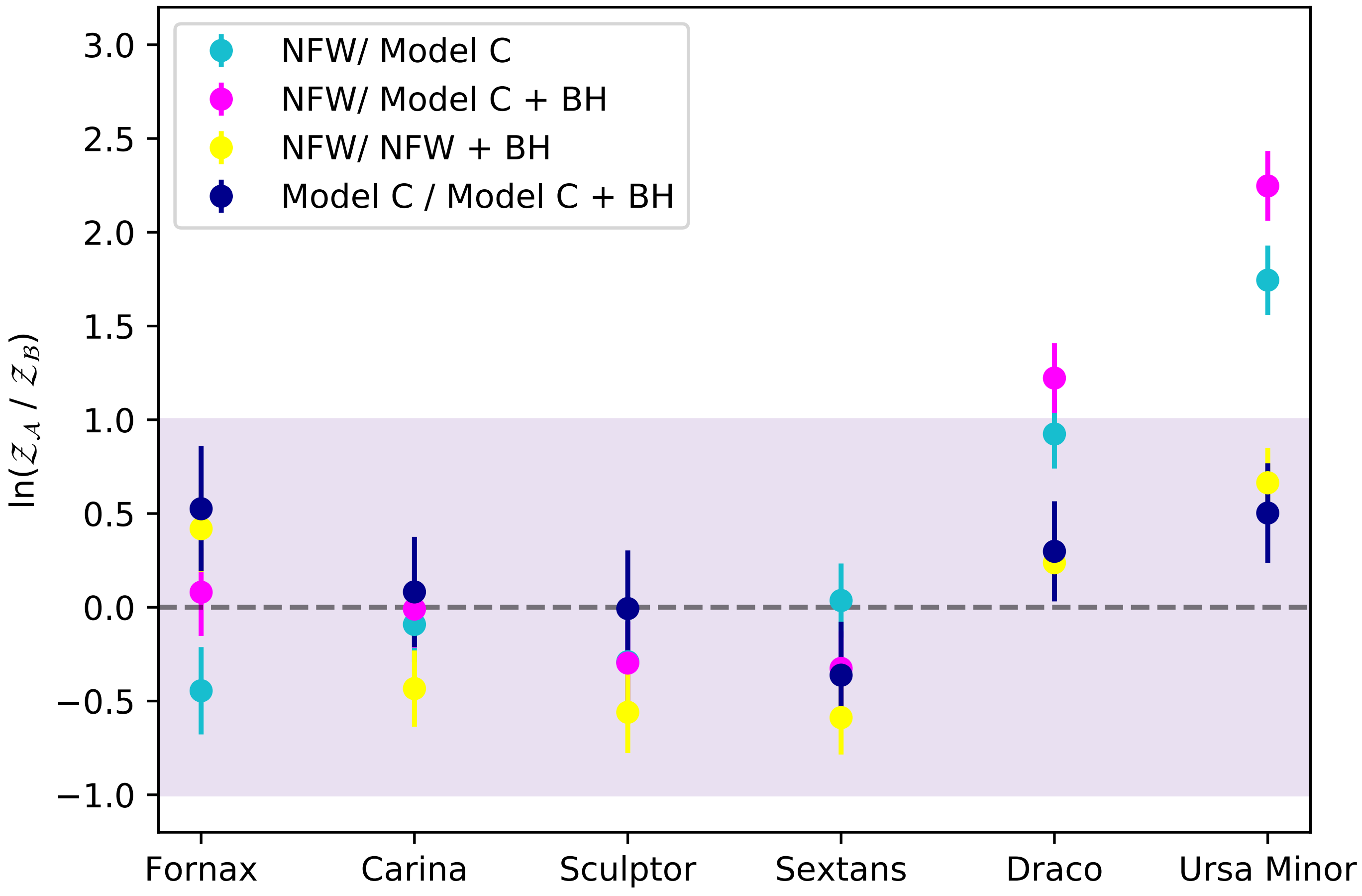
- Note that Ursa Minor has the smallest number of stars, and is the most irregular of the dwarfs analyzed



CONCLUSIONS

- 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.

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- 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: PRIORS

Generalized NFW:

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

Model C ULB:

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

ADDITIONAL MATERIAL