The velocity anisotropy of the Milky Way satellite system

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Gaia: the sliced bread of astronomy

Satellite	RA (deg)	Dec (deg)	M_V (mag)	$d_\odot$ (kpc)	$v_\odot$ (km s^{-1})	$\mu_{\alpha*}^{F18}$ (mas yr^{-1})	μ_{δ}^{F18} (mas yr^{-1})
Aquarius II	338.481	−9.327	−4.36	107.9 ± 3.3	−71.1 ± 2.5	[redacted]	[redacted]
Boötes I	210.015	14.512	−6.3	66 ± 3.0	102.2 ± 0.8	[redacted]	[redacted]
Boötes II	209.521	12.859	−2.3	42 ± 1.6	−117.1 ± 7.6	[redacted]	[redacted]
Canes Venatici I	202.016	33.559	−8.6	210 ± 6	30.9 ± 0.6	[redacted]	[redacted]
Canes Venatici II	194.292	34.321	−4.6	160 ± 7	−128.9 ± 1.2	[redacted]	[redacted]
Carina I	100.407	−50.966	−8.6	105.6 ± 5.4	222.9 ± 0.1	0.485 ± 0.038	0.131 ± 0.038
Carina II	114.107	−57.999	−4.5	37.4 ± 0.4	477.2 ± 1.2	[redacted]	[redacted]
Carina III	114.630	−57.900	−2.4	27.8 ± 0.6	284.6 ± 3.25	[redacted]	[redacted]
Coma Berenices I	186.746	23.908	−3.8	42 ± 1.5	98.1 ± 0.9	[redacted]	[redacted]
Crater II	177.310	−18.413	−8.2	117.5 ± 1.1	87.5 ± 0.4	[redacted]	[redacted]
Draco I	260.060	57.965	−8.75	76 ± 6	−291.0 ± 0.1	−0.012 ± 0.013	−0.158 ± 0.038
Draco II	238.198	64.565	−2.9	20 ± 3.0	−347.6 ± 1.75	[redacted]	[redacted]
Fornax	39.962	−34.511	−13.4	147 ± 9	55.3 ± 0.1	0.374 ± 0.035	−0.401 ± 0.035
Grus I	344.176	−50.163	−3.4	120.2 ± 11.1	−140.5 ± 2.0	[redacted]	[redacted]
Hercules	247.763	12.787	−6.6	132 ± 6	45.2 ± 1.09	[redacted]	[redacted]
Horologium I	43.882	−54.119	−3.5	79 ± 7	112.8 ± 2.55	[redacted]	[redacted]
Hydra II	185.425	−31.985	−4.8	151 ± 8	303.1 ± 1.4	[redacted]	[redacted]
Hydrus I	37.389	−79.309	−4.71	27.6 ± 0.5	80.4 ± 0.6	[redacted]	[redacted]
Leo I	152.122	12.313	−12.03	258.2 ± 9.5	282.5 ± 0.1	−0.086 ± 0.069	−0.128 ± 0.071
Leo II	168.370	22.152	−9.6	233 ± 15	78.5 ± 0.6	−0.025 ± 0.087	−0.173 ± 0.09
Leo IV	173.233	−0.540	−4.97	154 ± 5	132.3 ± 1.4	[redacted]	[redacted]
Leo V	172.784	2.222	−4.4	173 ± 5	172.1 ± 2.2	[redacted]	[redacted]
LMC	80.894	−69.756	−18.1	51.0 ± 2.0	262.2 ± 3.4	...	...
Pisces II	344.634	5.955	−4.1	183 ± 15	−226.5 ± 2.7	[redacted]	[redacted]
Reticulum II	53.949	−54.047	−3.6	31.4 ± 1.4	64.8 ± 0.5	[redacted]	[redacted]
Sagittarius I	283.831	−30.545	−13.5	26 ± 2.0	140.0 ± 2.0	−2.736 ± 0.036	−1.357 ± 0.036
Sculptor	15.039	−33.709	−10.7	83.9 ± 1.5	111.4 ± 0.1	0.084 ± 0.036	−0.133 ± 0.0356
Segue 1	151.763	16.074	−1.5	23 ± 2	208.5 ± 0.9	[redacted]	[redacted]
Segue 2	34.817	20.175	−2.5	36.6 ± 2.45	−40.2 ± 0.9	[redacted]	[redacted]
Sextans	153.268	−1.620	−9.3	92.5 ± 2.2	224.2 ± 0.1	[redacted]	[redacted]
SMC	13.187	−72.829	−16.8	64.0 ± 4.0	145.6 ± 0.6	...	...
Triangulum II	33.322	36.172	−1.2	28.4 ± 1.6	−381.7 ± 1.1	[redacted]	[redacted]
Tucana II	343.060	−58.570	−3.9	57.5 ± 5.3	−129.1 ± 3.5	[redacted]	[redacted]
Tucana III	359.150	−59.600	−2.4	25 ± 2	−102.3 ± 0.4	[redacted]	[redacted]
Ursa Major I	158.685	51.926	−6.75	97.3 ± 5.85	−55.3 ± 1.4	[redacted]	[redacted]
Ursa Major II	132.874	63.133	−3.9	34.7 ± 2.1	−116.5 ± 1.9	[redacted]	[redacted]
Ursa Minor	227.242	67.222	−8.4	76 ± 4	−246.9 ± 0.1	−0.184 ± 0.044	0.082 ± 0.042
Willman 1	162.341	51.053	−2.7	38 ± 7	−12.8 ± 1.0	[redacted]	[redacted]

Studying satellite kinematics

- Clustering of orbital poles
- Reconstructing orbits (needs potential)
- Velocity anisotropy β

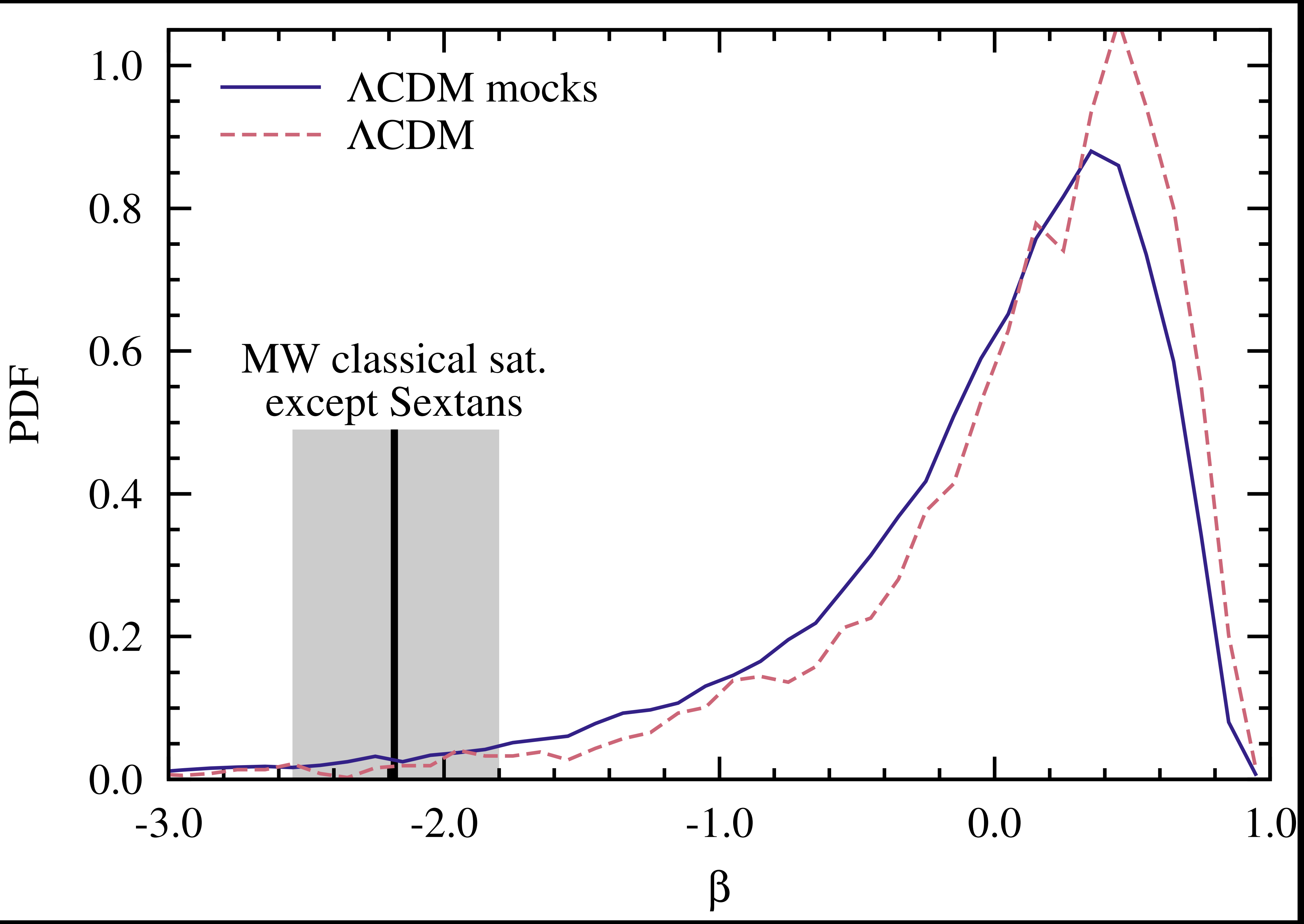
$$\beta(r) = 1 - \frac{\sigma_\theta(r)^2 + \sigma_\phi(r)^2}{2\sigma_r(r)^2}$$

Not affected by selection function!

β = 1: radial
β = 0: isotropic
β = -∞: tangential

Cautun & Frenk (2017)

- Found β = -2.2 ± 0.4 for 10 brightest satellites
- Significant deviation from ΛCDM (2.9% tail, semi-analytic model applied to Millenium-II)



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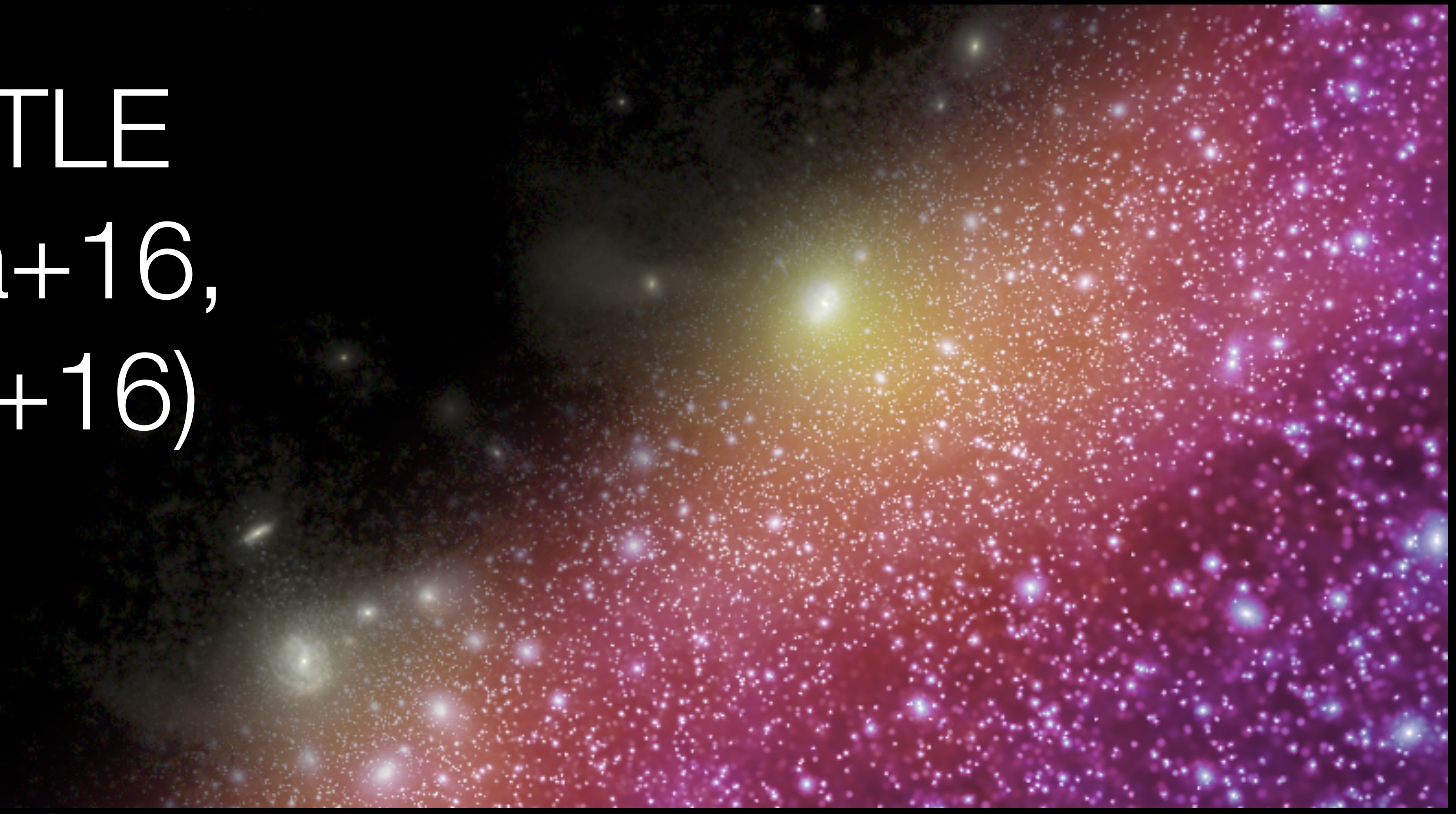
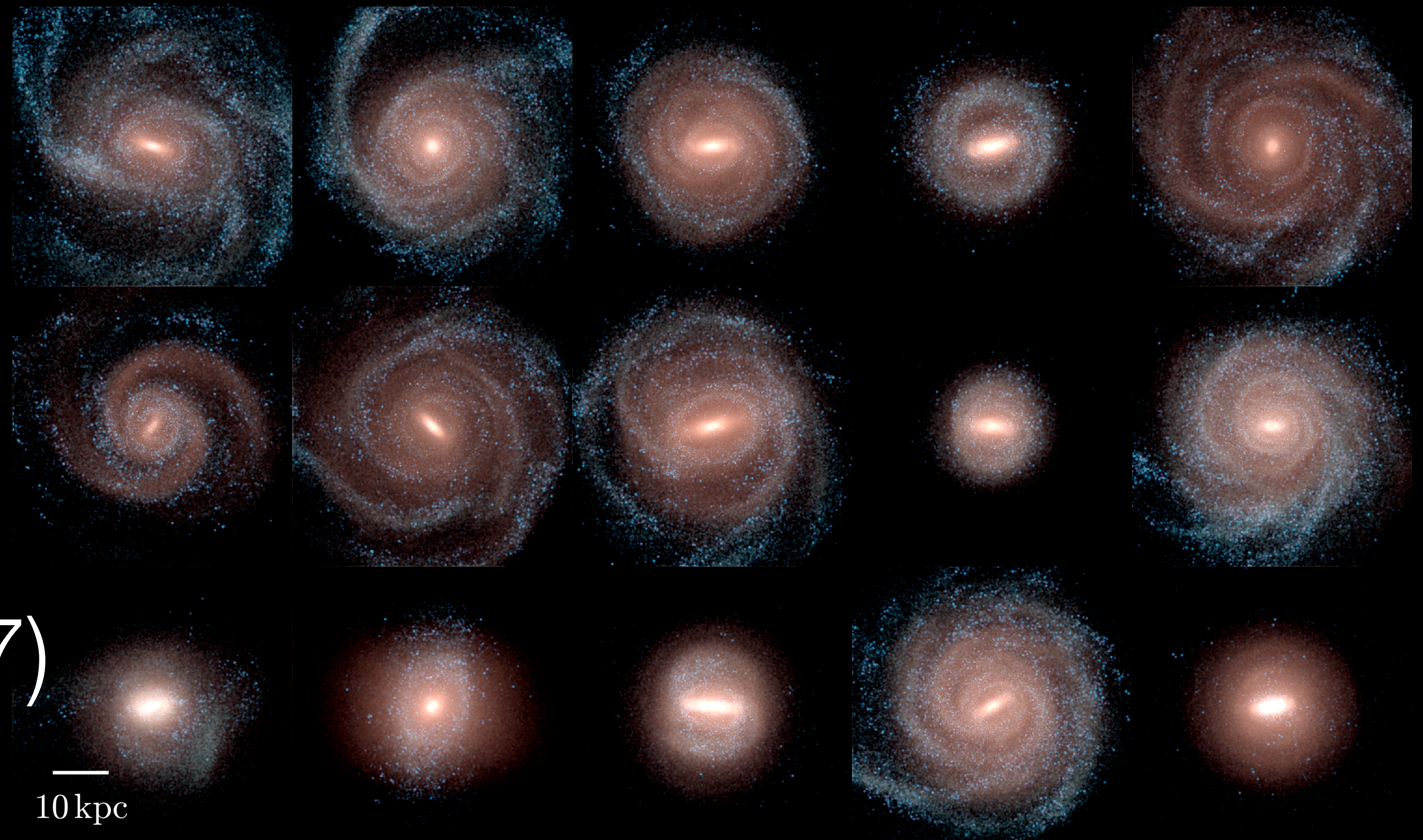
tx.ag/beta

Building on prior work

- More satellites (w/ PMs)
- Likelihood methodology for computing β
- Compare to sims w/ baryons

APOSTLE
(Sawala+16,
Fattahi+16)



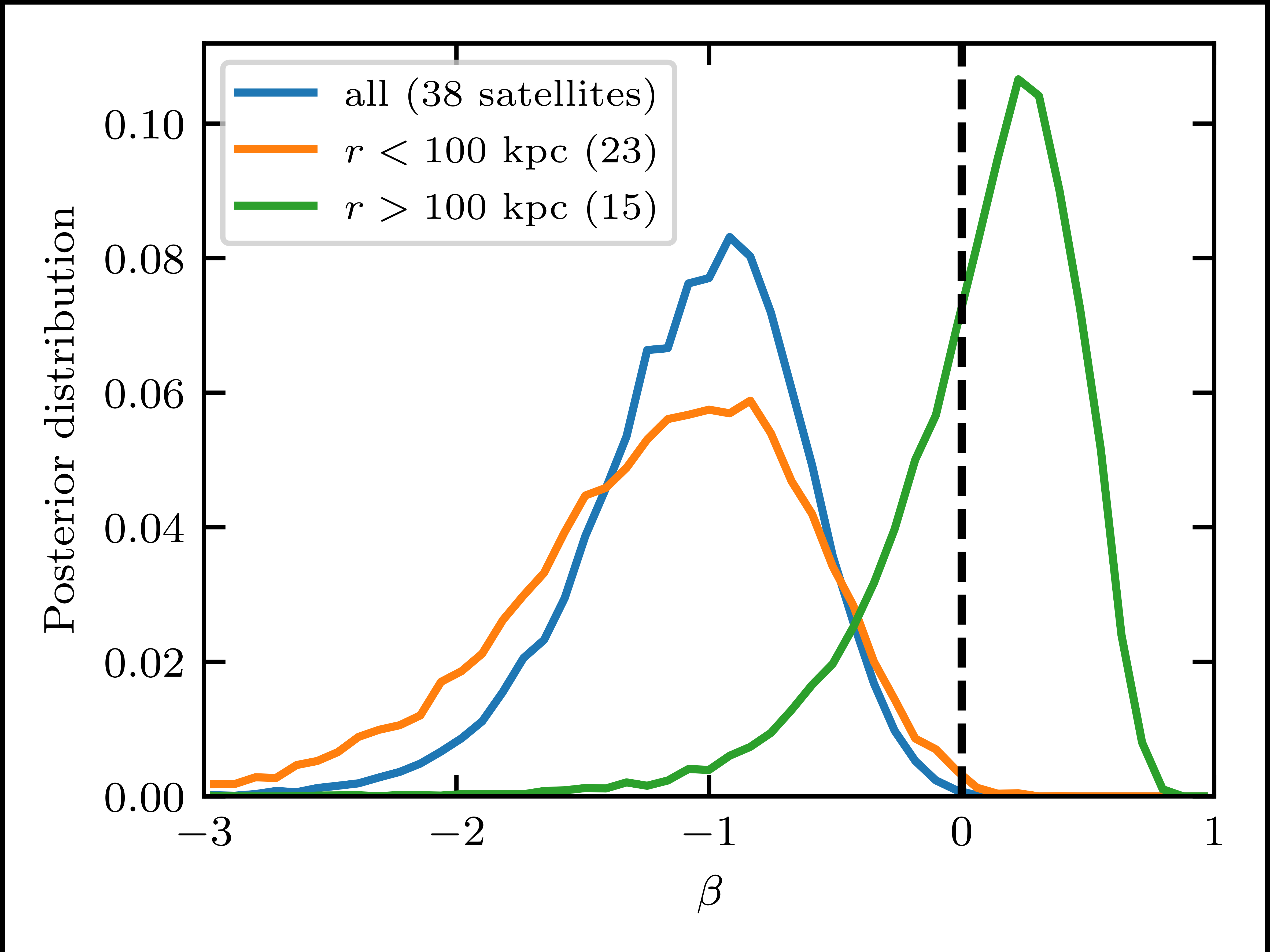


Auriga (Grand+17)

Results (uniform)

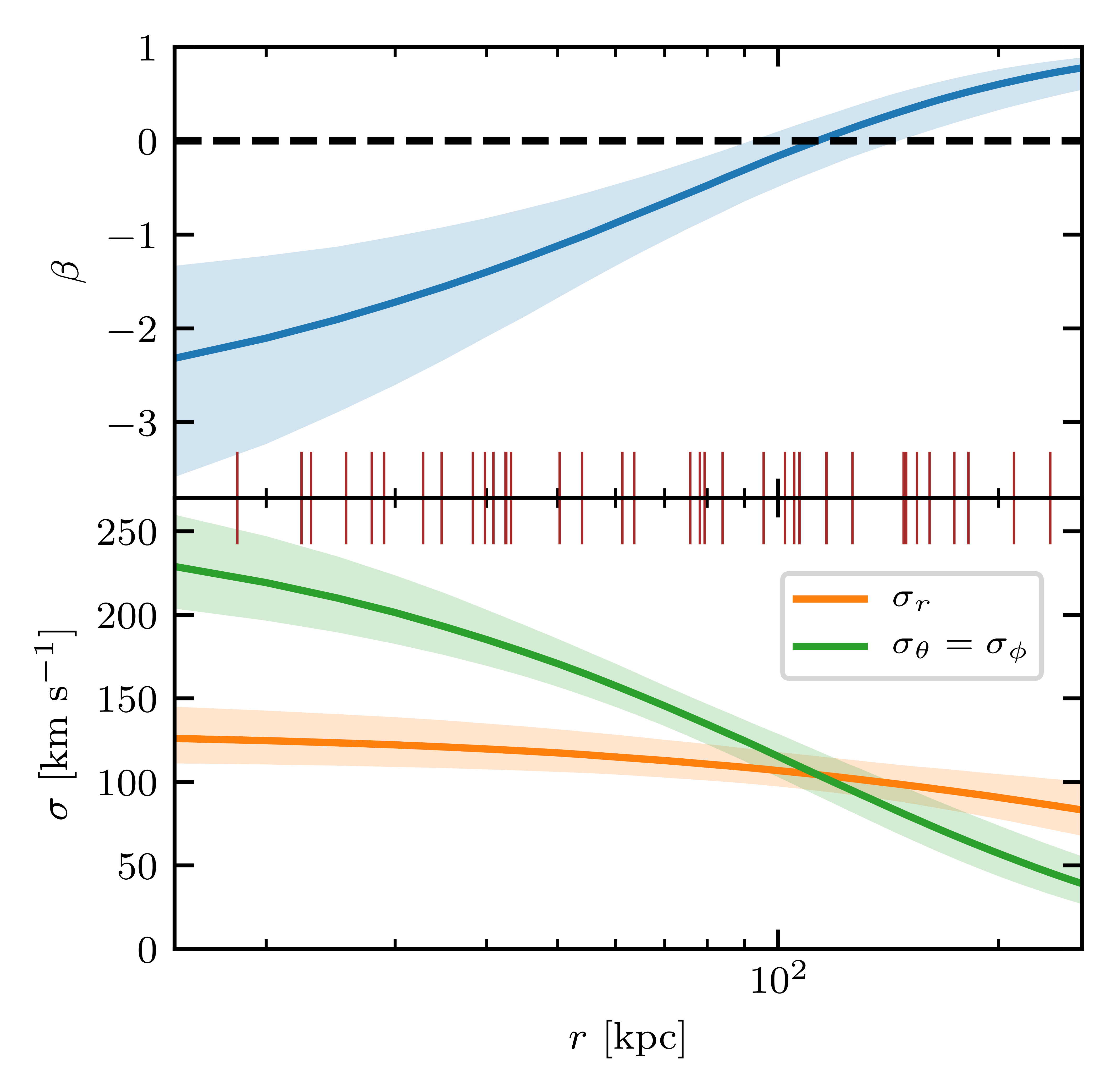
$$\beta = -1.02^{+0.37}_{-0.45}$$

- Consistent (2σ) with Cautun & Frenk (2017)
  - Same 10 bright satellites $\beta = -1.52^{+0.86}_{-1.23}$

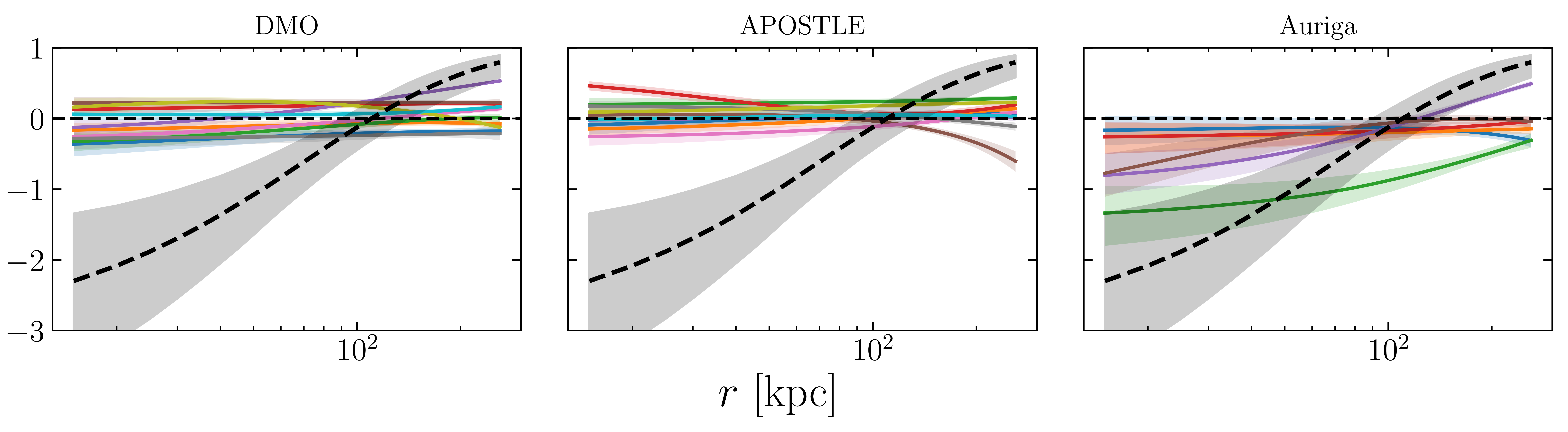


Results (variable)

$$\sigma(r) = \sigma_0 \left[1 + \frac{r}{r_0}\right]^{-\alpha}$$



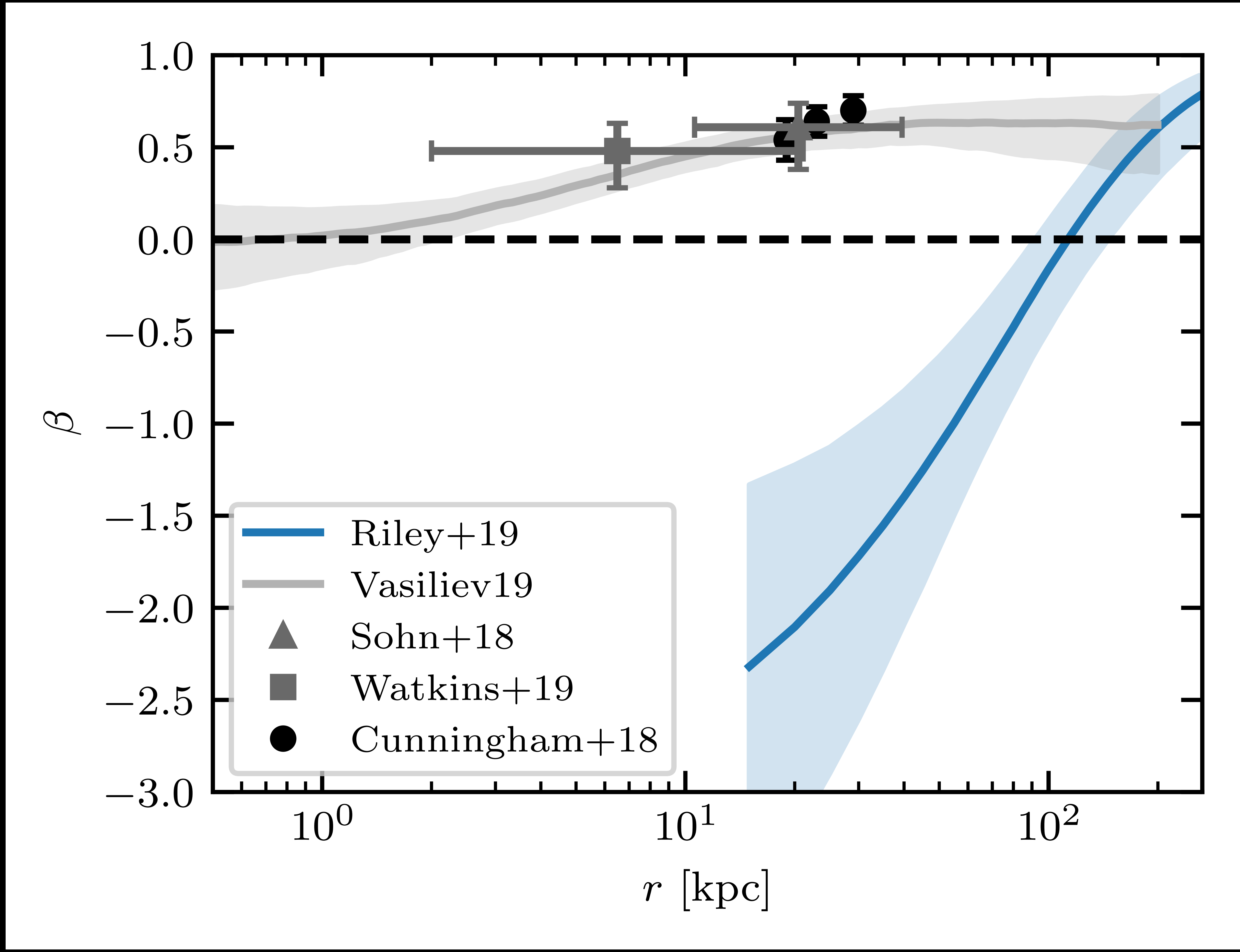
Results (simulations)



- DMO, APOSTLE β(r) curves are qualitatively similar
- Auriga haloes exhibit dip in centre, likely due to massive central disc (D'Onghia+10, Garrison-Kimmel+17, Kelley+19)

Tracer comparison

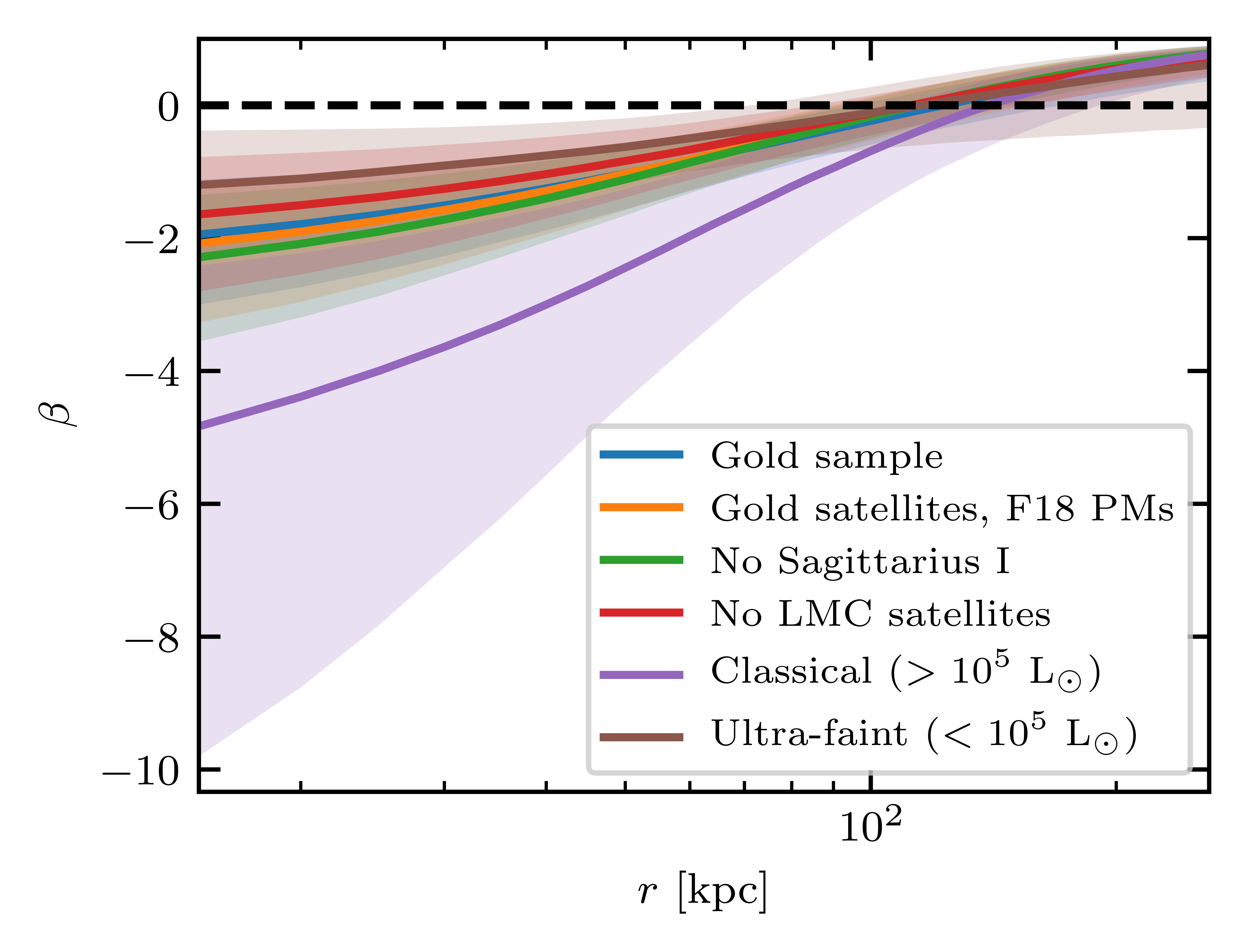
- Globular clusters and halo stars more radial
- Qualitatively agrees w/ destruction of satellites on radial orbits



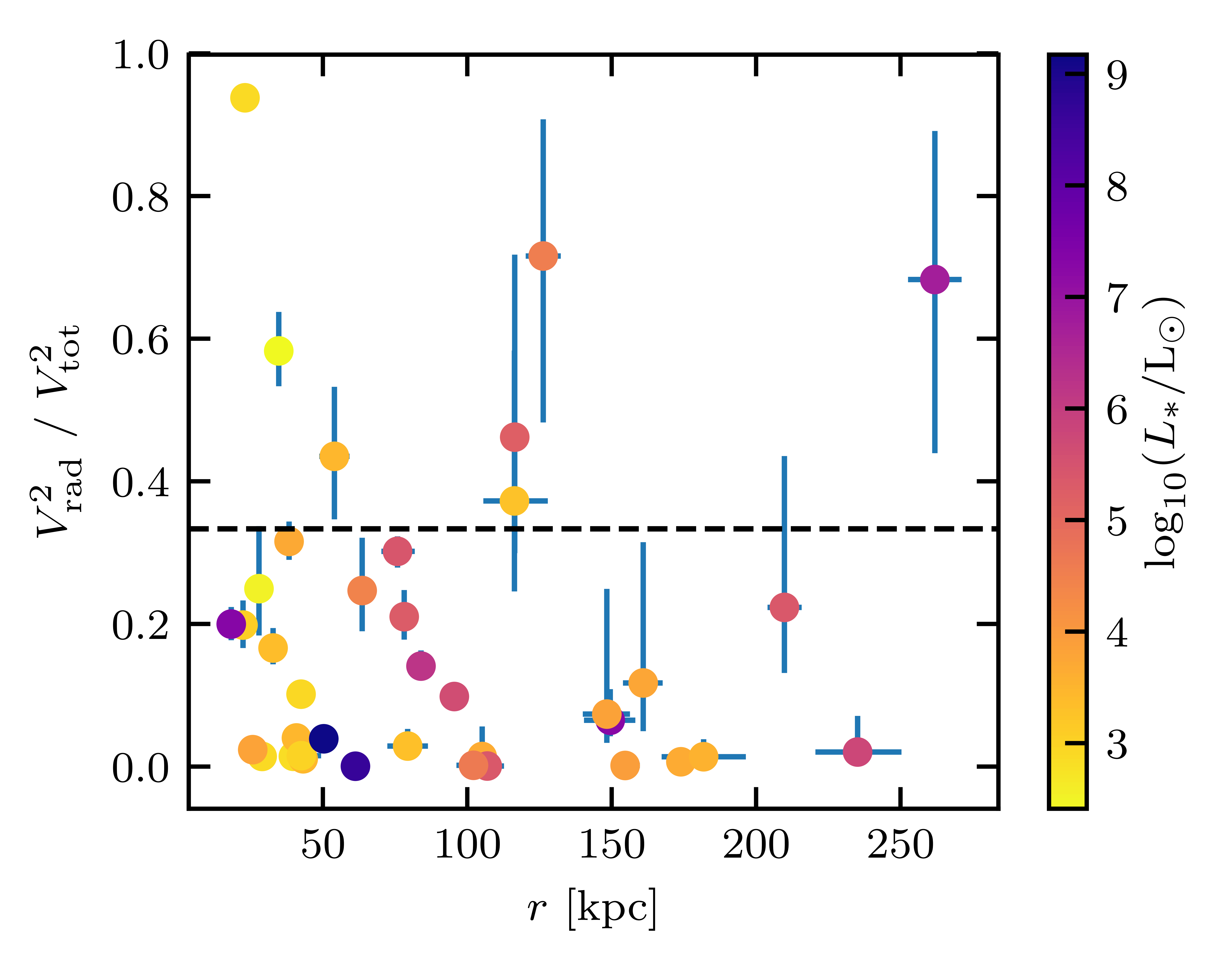
Summary

- Satellites **closer** to the Galactic centre have **more tangential motions**
- Likely due to **subhalo destruction** from the massive central galaxy
- Going forward: **joint analysis/modeling** of satellites, halo stars, and GCs
- Paper: **tx.ag/beta** — more from me: **tx.ag/alex**

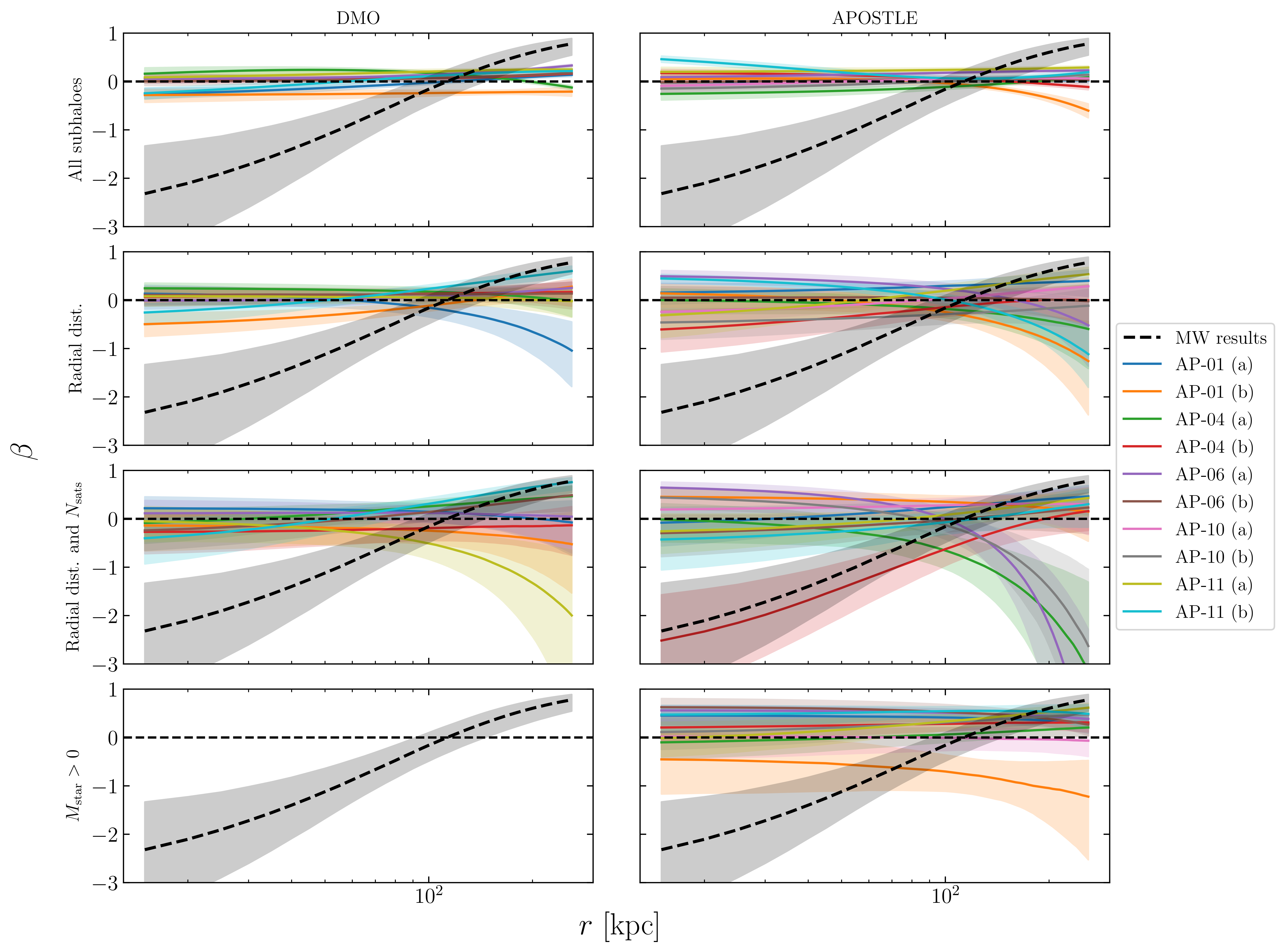
Different satellite populations



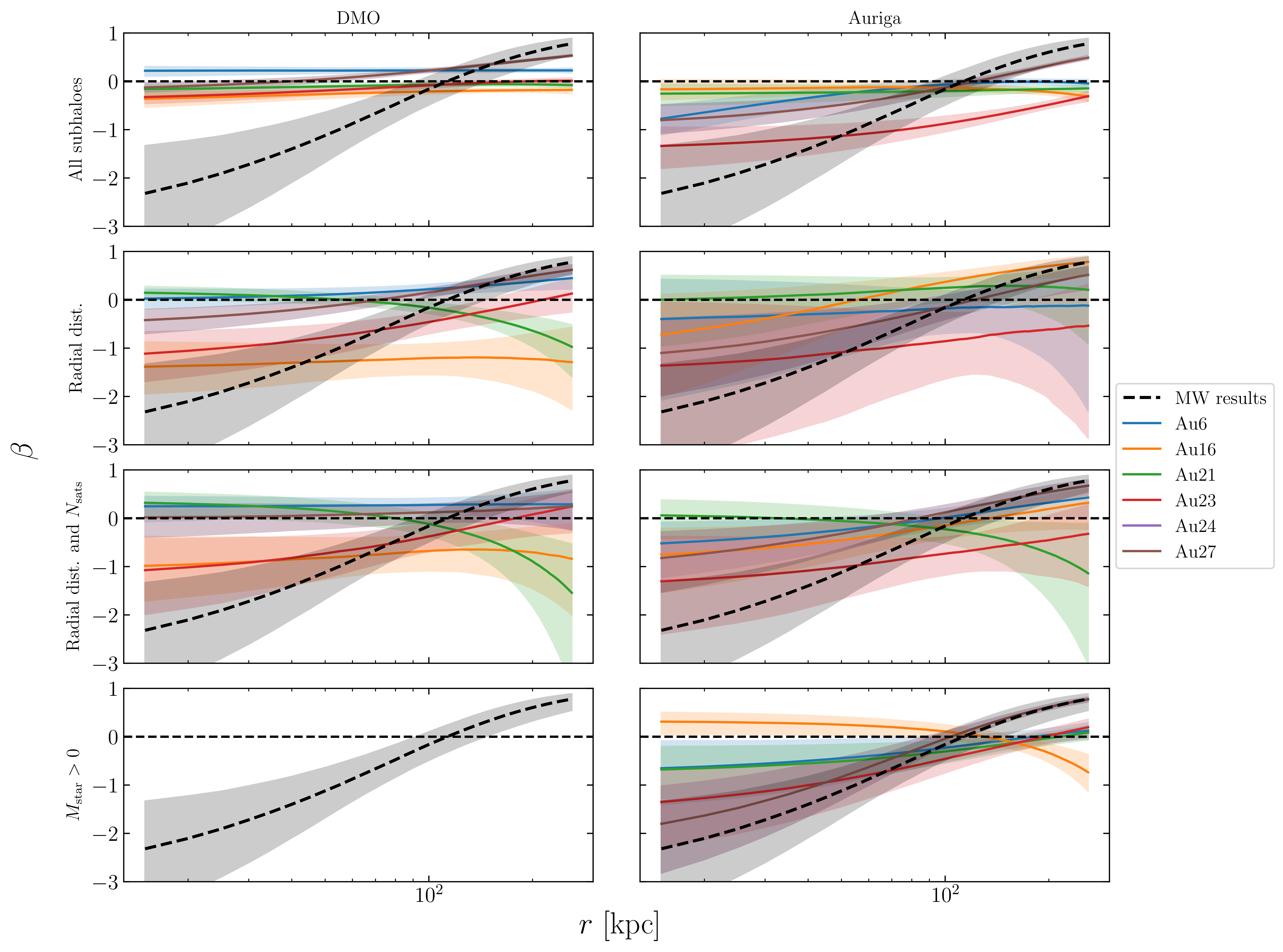
Tangential velocity excess



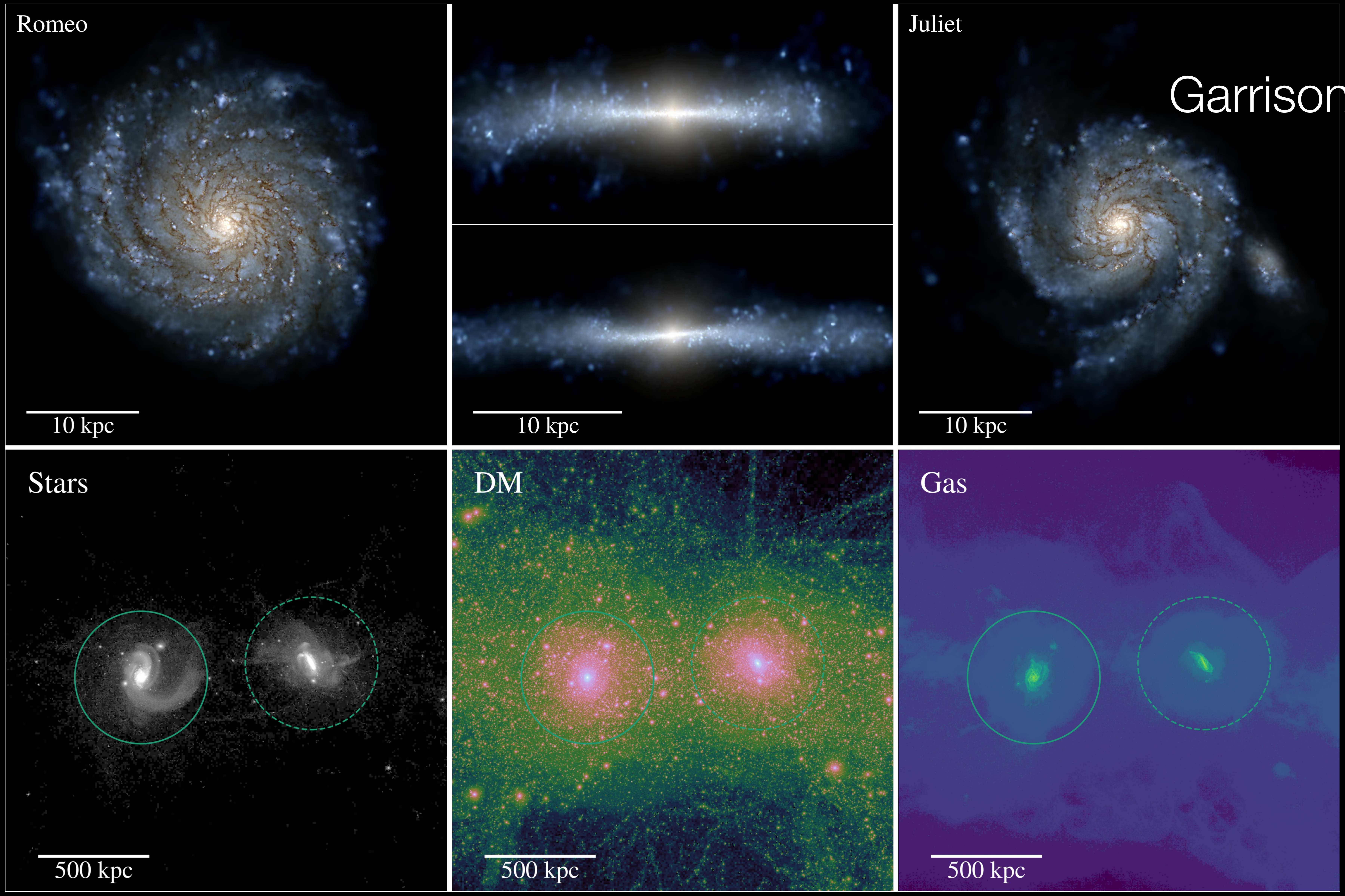
Subhalo selections (APOSTLE)



Subhalo selections (Auriga)



Simulations also improved substantially



Garrison-Kimmel+19