Mass profiles of WINGS clusters
& orbital shapes of their E, S0 and S galaxies

Mamon, Cava, Biviano et al. 19

an observer's perspective

Andrea Biviano
OATS, Trieste

Antonio CAVA
formerly Univ. of Geneva

54 WINGS regular clusters

WIde Field Nearby Galaxy Survey

X-ray selected

all-sky $|b| > 20^\circ$

Fasano+06

77 clusters and 550 000 galaxies

spectroscopic followup

Cava+09; Moretti+14

z=0.055
log $(M/M_\odot) \approx 14.8$

irregular clusters removed

Cava+17

4700 member galaxies ($R < r_{vir}$): 1600 E, 1800 S0, 1200 S

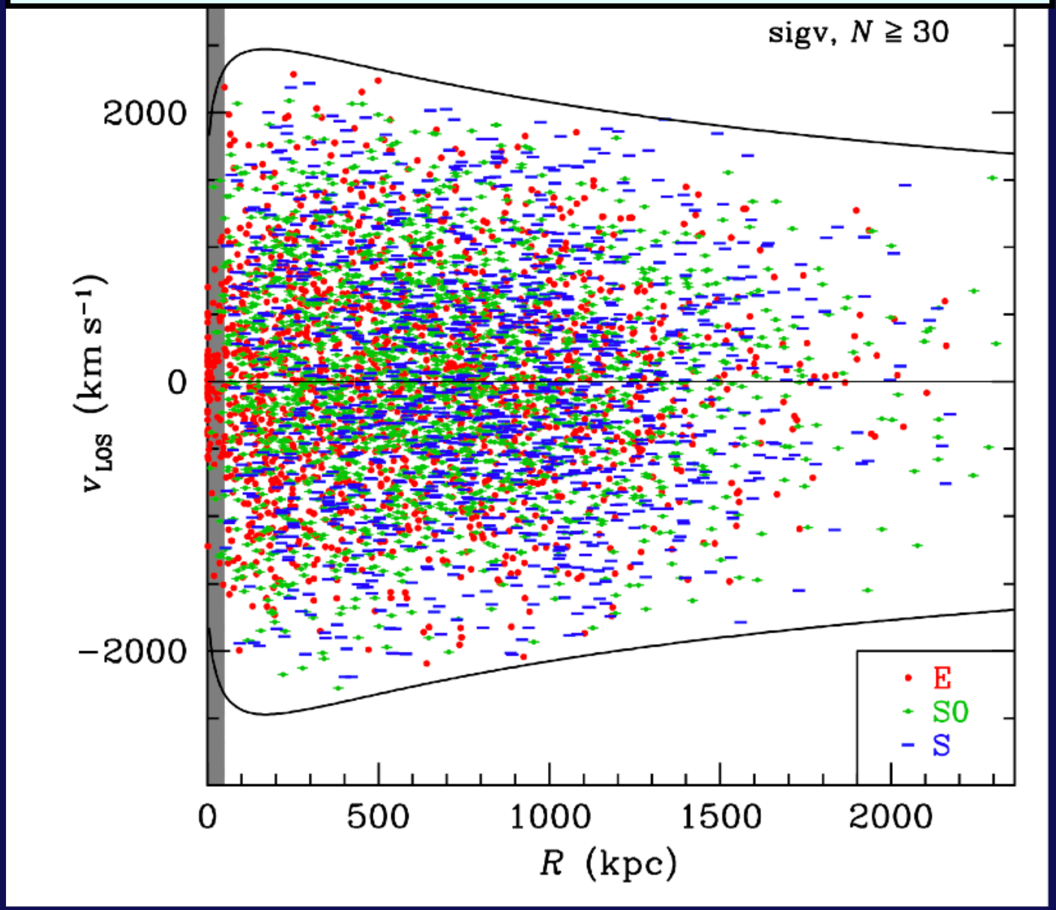
stack by virial radius

Cava+17

3 ways to estimate virial radius:
1) velocity dispersion "`sigv`"
2) richness "`Num`"
3) X-ray temperature "`tempX`"

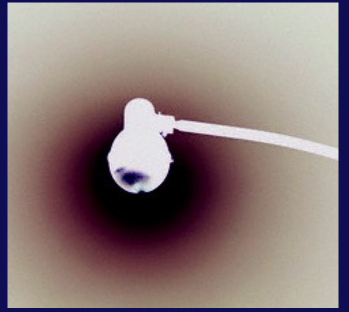
wider $\{v_{LOS}\} \Rightarrow$ more mass

cuspier $\{v_{LOS}\} \Rightarrow$ more radial orbits



MAMPOSSt:
Modeling Anisotropy & Mass Profiles of Observed Spherical Systems

Mamon, Biviano & Boué



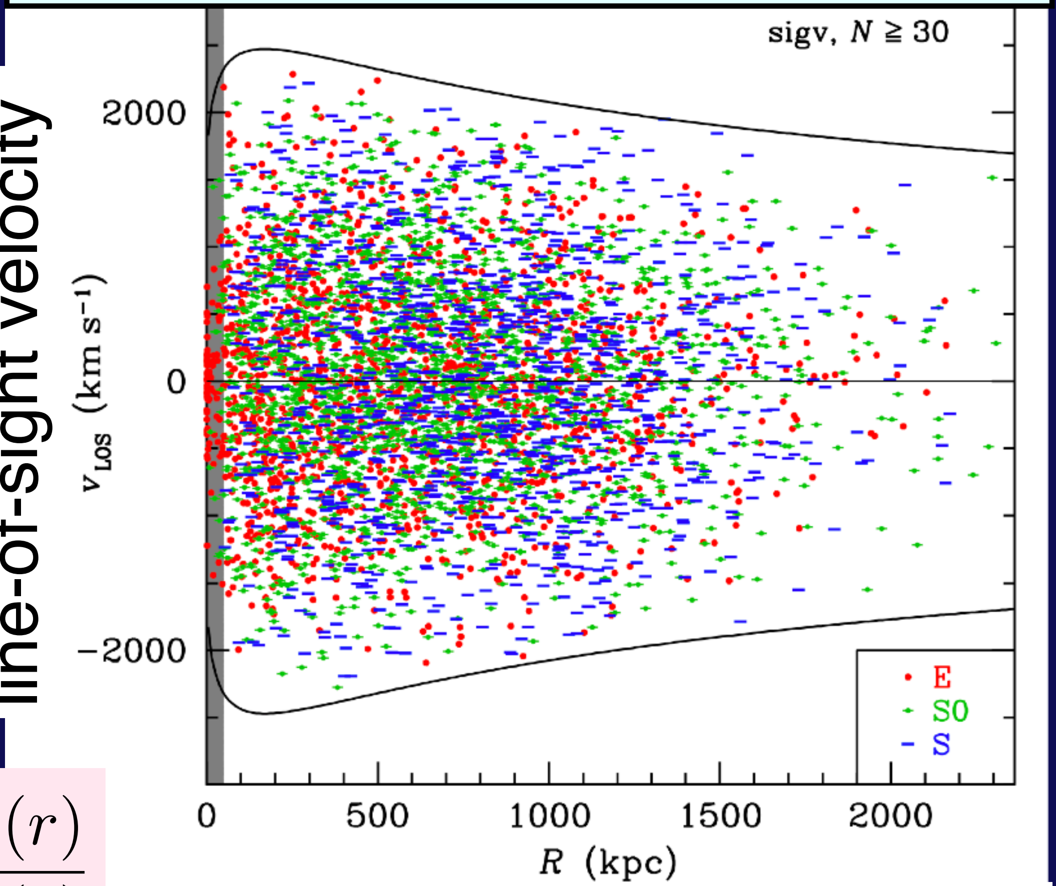
wider $\{v_{LOS}\} \Rightarrow$ more mass
cuspier $\{v_{LOS}\} \Rightarrow$ more radial orbits

PDF of distribution in projected phase space

$$p(R, v_z) = \frac{4\pi R}{\Delta N_{\rm p}} \int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2 - R^2}}\, h(v_z|R, r)\, {\rm d}r$$

tracer density

line-of-sight velocity



projected distance to center

Gaussian 3D velocities:

$$h(v_z|R, r) = \frac{1}{2\pi\sigma_z^2(R, r)} \exp\left[-\frac{v_z^2}{2\,\sigma_z^2(R, r)}\right]$$

$$\sigma_z(R, r) = \sqrt{1 - \beta(r)\left(\frac{R}{r}\right)^2}\ \sigma_r(r)$$

velocity anisotropy

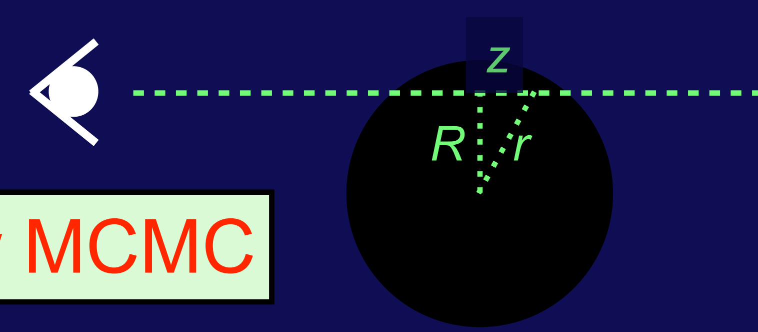
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

solution to Jeans equation of local dynamical equilibrium

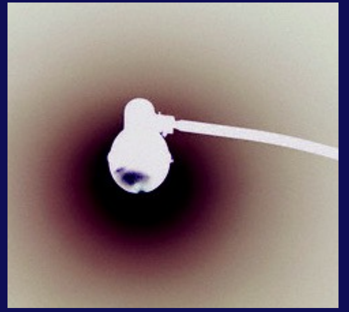
$$\sigma_r^2(r) = \frac{1}{\nu(r)} \int_r^\infty \exp\left[2\int_r^2 \beta(t)\frac{{\rm d}t}{t}\right] \nu(s) \frac{GM(s)}{s^2}\, {\rm d}s$$

very fast!

Bayesian w MCMC



MAMPOSSt: *Modeling Anisotropy & Mass Profiles of Observed Spherical Systems*



Mamon, Biviano & Boué 13

PDF of distribution in projected phase space

$$p(R,v_z) = \frac{4\pi R}{\Delta N_\mathrm{p}} \int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2-R^2}}\, h(v_z|R,r)\,\mathrm{d}r$$

tracer density

assume $M(r)$ & $\beta(r)$ w free-parameters

pre-determine tracer densities $\nu(r)$ for each morphological type

Gaussian 3D velocities:

$$h(v_z|R,r) = \frac{1}{2\pi\sigma_z^2(R,r)} \exp\left[-\frac{v_z^2}{2\,\sigma_z^2(R,r)}\right]$$

$$\sigma_z(R,r) = \sqrt{1-\beta(r)\left(\frac{R}{r}\right)^2}\,\sigma_r(r)$$

velocity anisotropy

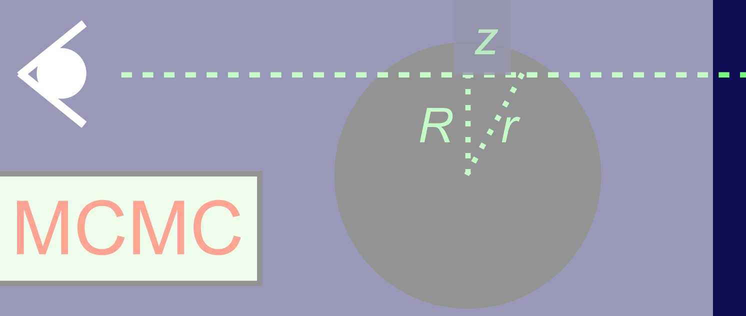
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

solution to Jeans equation of local dynamical equilibrium

$$\sigma_r^2(r) = \frac{1}{\nu(r)} \int_r^\infty \exp\left[2\int_r^2 \beta(t)\frac{\mathrm{d}t}{t}\right] \nu(s)\frac{GM(s)}{s^2}\,\mathrm{d}s$$

very fast!

Bayesian w MCMC



Cluster density profiles traced by galaxies

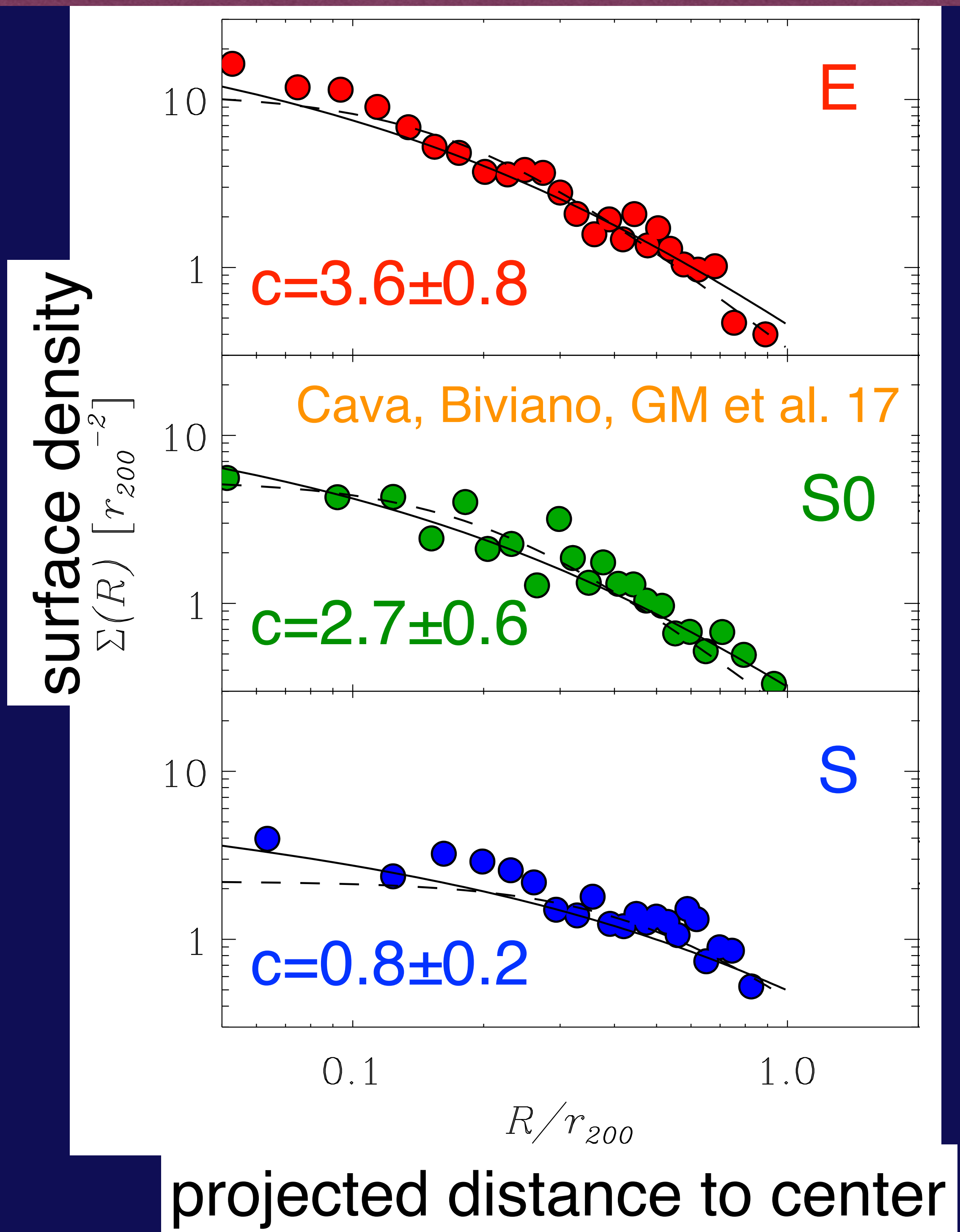
$$\text{concentration } c = \frac{r_{\rm vir}}{r_{-2}}$$

Stack of 54 z~0.05 regular (WINGS) clusters

ΛCDM simulations: $c_{\rm mass} = 4$
Navarro+97

projected NFW fits well surface number density profile with $c = 4$ Carlberg+97

$c_{\rm red} = 4$, $c_{\rm blue} = 1.3$
Collister & Lahav 05



⇒ number profiles consistent with NFW ∀ types
⇒ Ellipticals follow mass, spirals 4x wider distribution

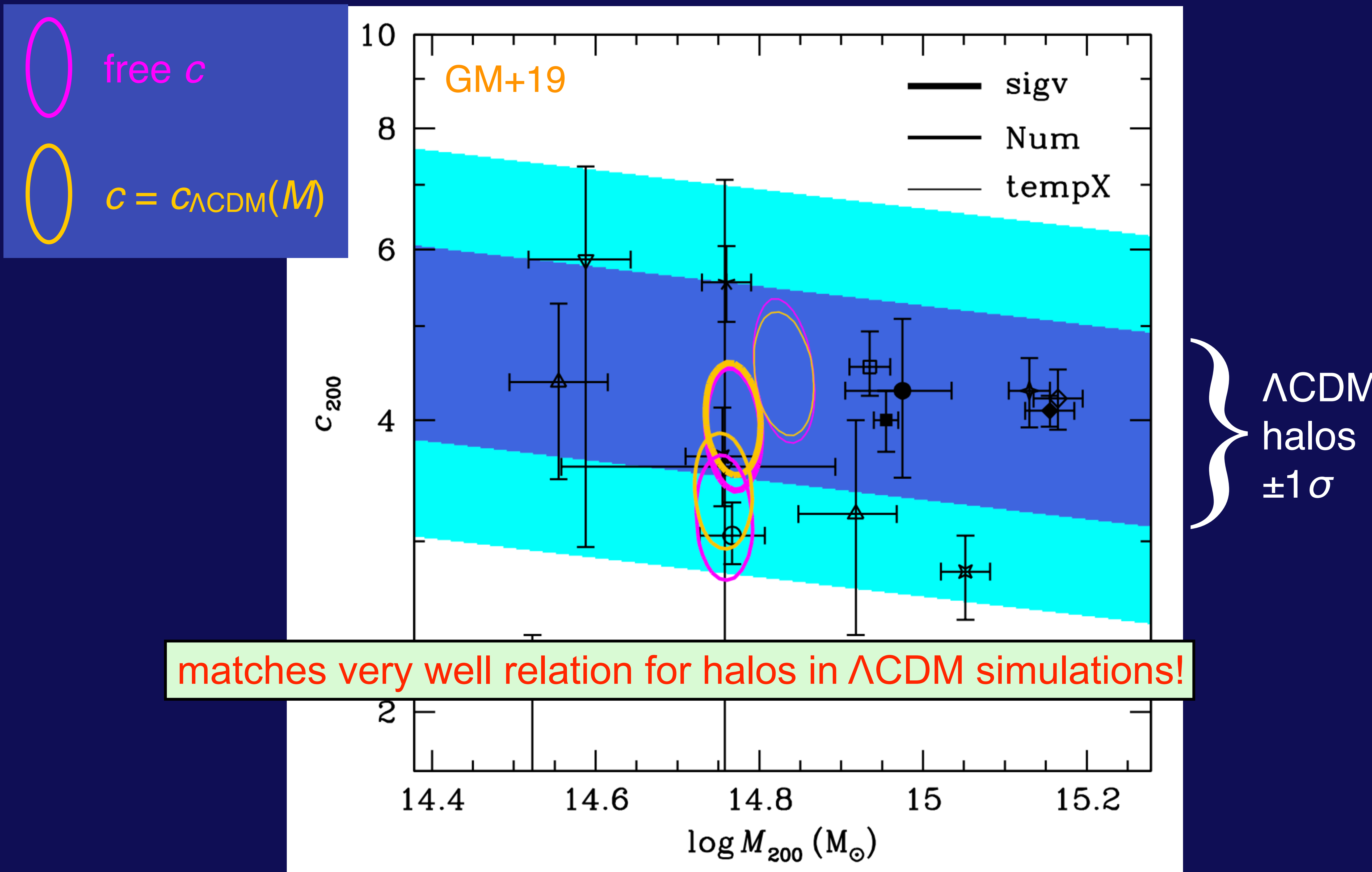
Not 1, not 2

model	mass model		anis.	inner anisotropy			outer anisotropy			TAND	R^{-1}	$-\ln \mathcal{L}_{\rm MLE}$	#	AIC	BIC
	cluster	BCG	model	E	S0	S	E	S0	S				free		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	posterior	(14)	Bayesian evidence	
1	gNFW	–	T	F	F	F	F	F	F	Y	0.004	**33526.28**	12	67076.62	67154.32
2	NFW	NFW	T	F	F	F	F	F	F	N	*0.065*	33526.47	16	67085.05	67188.62

Not 1, not 2, but 30 sets of priors!

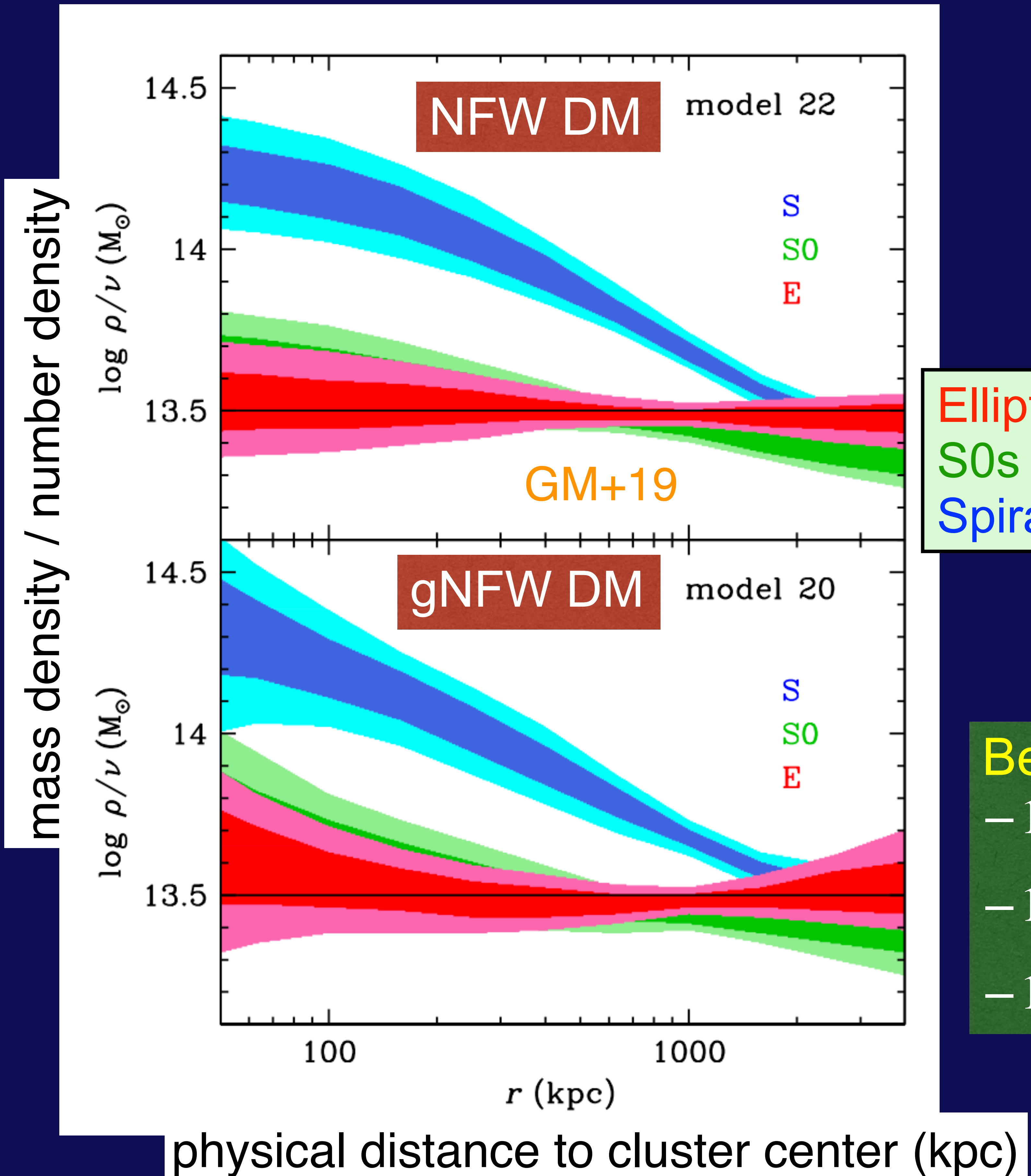
model	mass model		anis.	inner anisotropy			outer anisotropy			TAND	R^{-1}	$-\ln \mathcal{L}_{\rm MLE}$	#	AIC	BIC
	cluster	BCG	model	E	S0	S	E	S0	S			posterior	free	Bayesian evidence	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		(14)		
1	gNFW	–	T	F	F	F	F	F	F	Y	0.004	**33526.28**	12	67076.62	67154.32
2	NFW	NFW	T	F	F	F	F	F	F	N	*0.065*	33526.47	16	67085.05	67188.62
3	NFW	NFW	T	F	F	F	F	F	F	Y	0.012	33526.50	13	67079.08	67163.24
4	gNFW	–	T	F	0	0	F	F	F	Y	0.005	33526.50	10	*67073.05*	67137.80
5	NFW	NFW	gOM	F	F	F	F	F	F	Y	0.007	33526.55	13	67079.18	67163.34
6	gNFW	–	gOM	F	F	F	F	F	F	Y	0.011	33526.79	12	67077.65	67155.34
7	gNFW	–	T	F	F	F	F	F	F	N	*0.040*	33526.91	15	67083.92	67181.01
8	NFW	PS4	T	F	F	F	F	F	F	Y	0.005	33528.33	13	67082.74	67166.90
9	NFW	–	T	F	F	F	F	F	F	Y	0.002	*33528.36*	11	*67078.77*	67150.00
10	NFW	–	T	F	0	0	F	F	F	Y	0.001	33528.41	9	67074.86	67133.14
11	gNFW	–	T	0	0	0	F	F	F	Y	0.005	33528.41	9	67074.86	67133.14
12	NFW	–	T	F	F	F	F	F	F	N	*0.031*	33528.50	14	67085.09	67175.72
13	NFW	–	T	0	0	0	F	F	F	Y	0.002	33528.54	8	67073.11	67124.92
14	NFW	PS4	T	F	F	F	F	F	F	N	*0.043*	33528.55	16	67089.21	67192.77
15	NFW	–	gOM	F	F	F	F	F	F	Y	0.003	33528.92	11	67079.90	67151.12
16	NFW	–	T	0	0	0	0	F	F	Y	0.003	33529.20	7	**67072.42**	67117.76
Einasto (free n)		–	T	0	0	0	0	0	F	Y	0.002	33529.74	6	67073.50	67118.84
18	gNFW	–	T	0	0	0	0	0	F	N	0.015	33529.90	8	67075.83	67127.64
19	gNFW	–	T	0	0	F	0	0	F	Y	0.003	33530.03	8	67076.09	67127.90
20	NFW	–	T	0	0	0	0	0	F	N	0.007	33530.23	7	67074.48	67119.82
21	gNFW	–	T	0	0	0	0	0	F	Y	0.002	33530.27	7	67074.56	*67119.90*
22	NFW	–	T	0	0	F	0	0	F	Y	0.002	33530.35	7	67074.72	67120.06
Einasto (n=6)		–	T	0	0	0	0	0	F	Y	0.002	33530.50	6	67073.02	**67111.88**
24	NFW	–	T	0	0	0	0	0	F	Y	0.001	33530.68	6	67073.38	*67112.24*
25	cNFW	–	T	0	0	0	0	0	F	Y	0.003	33532.30	6	67076.62	67115.48
Hernquist		–	T	0	0	0	0	0	F	Y	0.001	33534.44	6	67080.90	67119.76
27	NFW	–	gOM	0	0	0	0	0	F	Y	0.002	33537.09	6	67086.20	67125.06
28	NFW	–	iso	0	0	0	0	0	0	—	0.002	33538.52	5	67087.05	67119.44
29	NFW	–	T	0	0	0	0	F	0	Y	0.001	33539.46	6	67090.94	67129.80
30	NFW	–	T	0	0	0	F	0	0	Y	0.002	33539.56	6	67091.14	67130.00

concentration vs. mass



Which morphology traces best the mass?

sigv stack



Ellipticals trace well total mass
S0s fairly well
Spirals trace poorly the total mass

independently of stack

Best inner slopes of total mass:

$-1.6^{+0.7}_{-0.3}$ (sigv)

$-1.4^{+0.3}_{-0.2}$ (tempX)

$-1.8^{+0.4}_{-0.1}$ (Num)

effect of inner BCG?

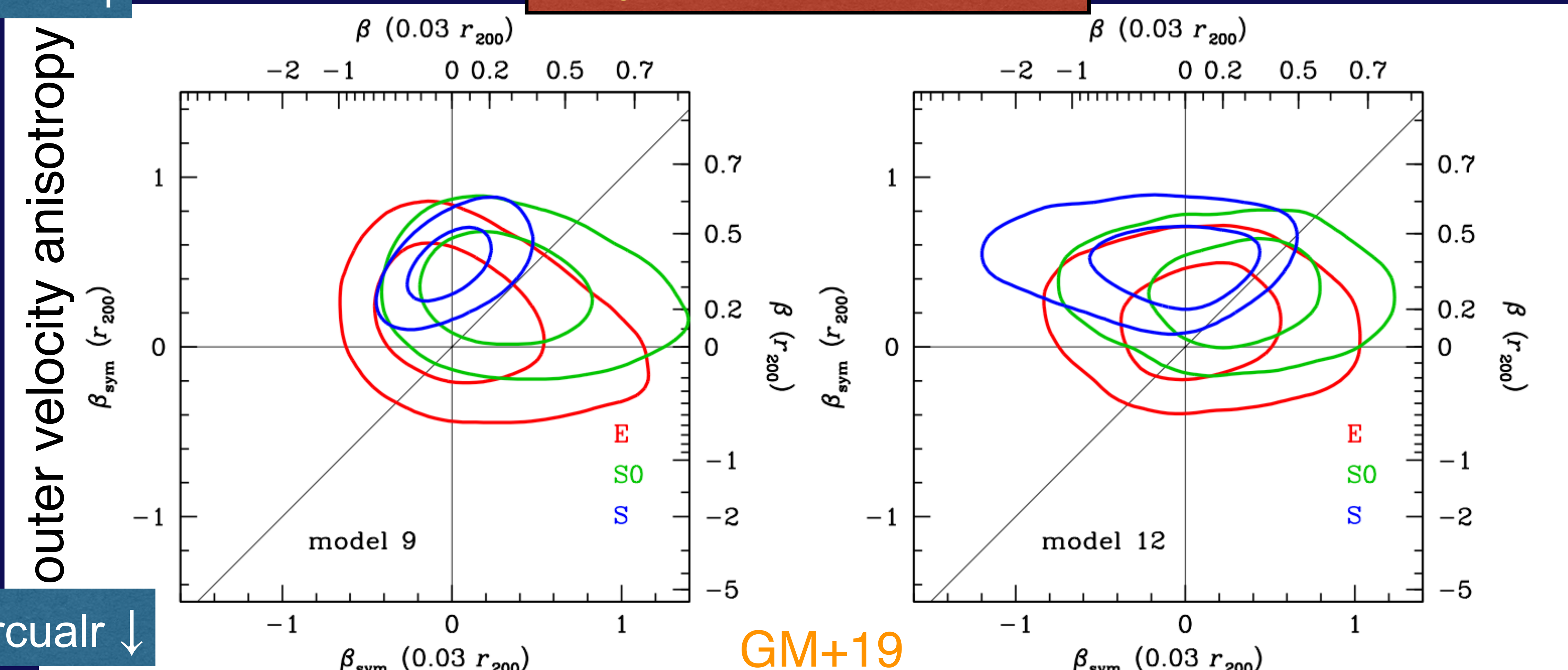
Outer vs. inner Velocity Anisotropy

sigv stack, NFW DM

radial ↑

outer velocity anisotropy

circualr ↓



GM+19

circular ← inner velocity anisotropy

inner velocity anisotropy radial →

anisotropy radius = density scale radius

free anisotropy radius

E: isotropic orbits

S: isotropic inner orbits & ~ radial outer orbits

S0: isotropic inner orbits & ~ less radial outer orbits

Effect of stacking method

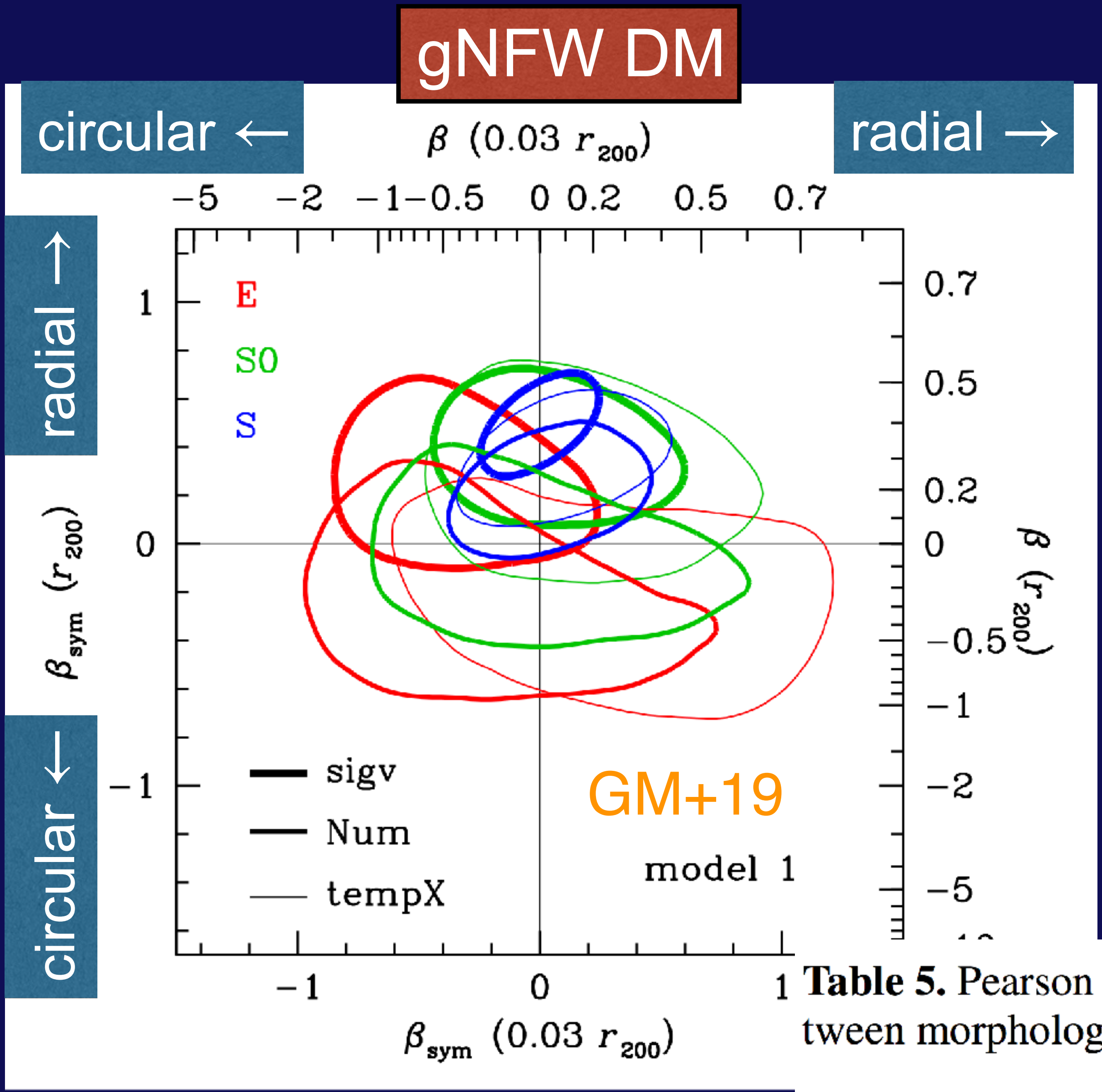


Table 5. Pearson correlation coefficients of inner-outer anisotropies between morphological types (for model 1)

stack	E vs. S0	E vs. S	S0 vs. S
sigv	0.51	0.23	0.69
Num	0.72	0.17	0.50
tempX	0.44	0.18	0.82

S0 orbits more like S (sigv & tempX) or more like E (Num)

Why do ellipticals & S0s have isotropic inner orbits?

morphologically transformed from infalling spirals

2-body relaxation → inefficient!

dynamical friction of parent infalling groups

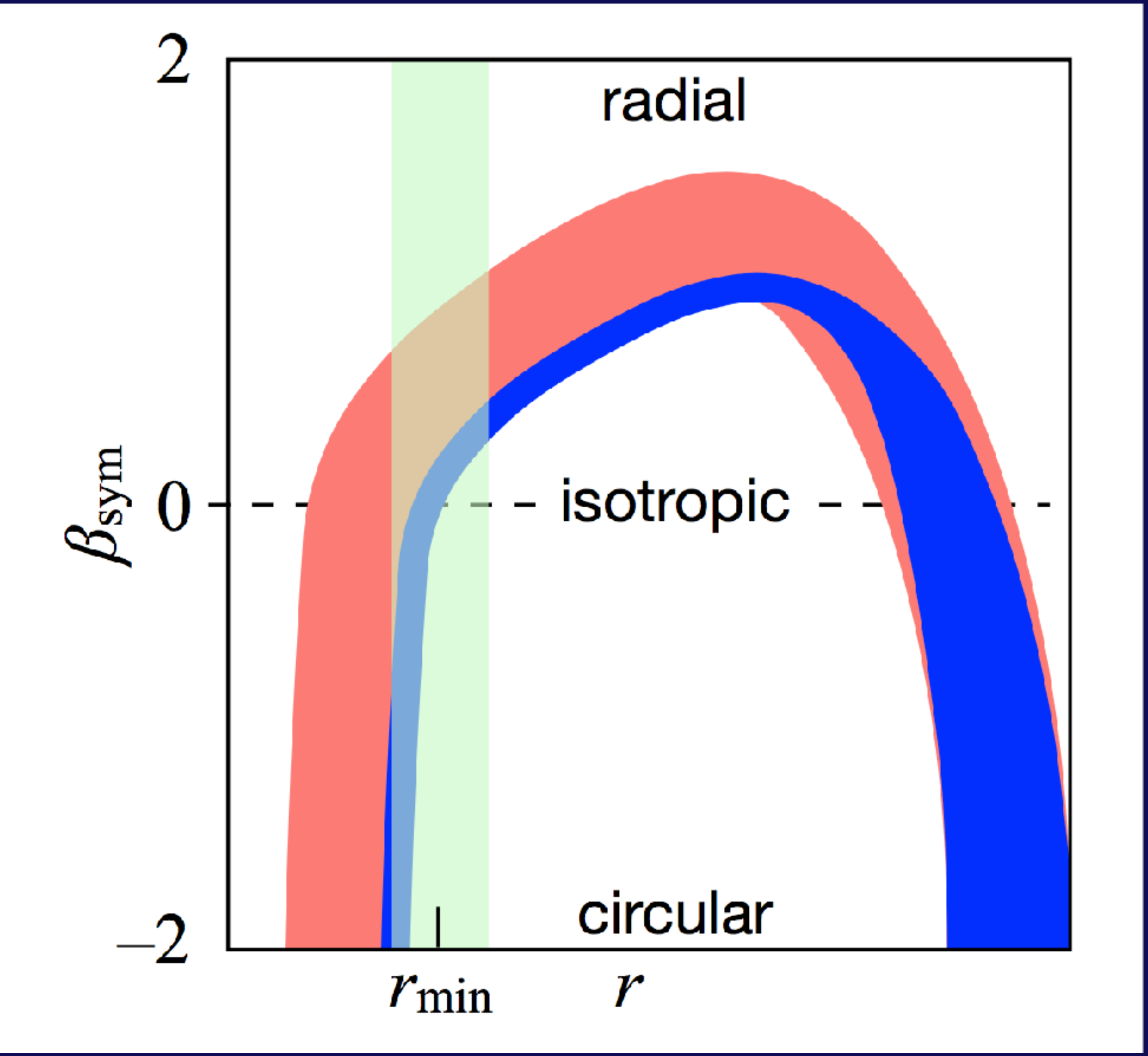
violent relaxation in merging clusters

1/3 of clusters undergo major mergers since z=1 (~1.5 galaxy orbits)

artificial phase mixing of imperfectly stacked halos

Why do spirals have isotropic inner orbits?

4x larger scale radius ⇒ rapid morphological transformation (< 1 orbit)
⇒ narrower range of pericenters (& apocenters)



selection effect from rapid morphological transformation of spirals!

Conclusions

Cluster number density profiles | well fit by NFW within r_{vir}
… and out to > 10 r_{vir}!
Trevisan, GM & Stalder 17

Cluster mass density profiles | NFW or possibly steeper (BCG?)

concentration vs. mass | consistent with simulations

Galaxies vs. mass | Ellipticals trace mass best, spirals poorly
S0s closer to ellipticals

Outer orbits in clusters | S more radial, E more isotropic, S0s closer to S(?)

Inner orbits in clusters | isotropic!
E/S0: dyn'l friction of groups + violent relax'n
S: selection effect of small range of pericenters