Challenge in galaxy clusters for MOND: Measuring mass profiles with galaxy kinematics

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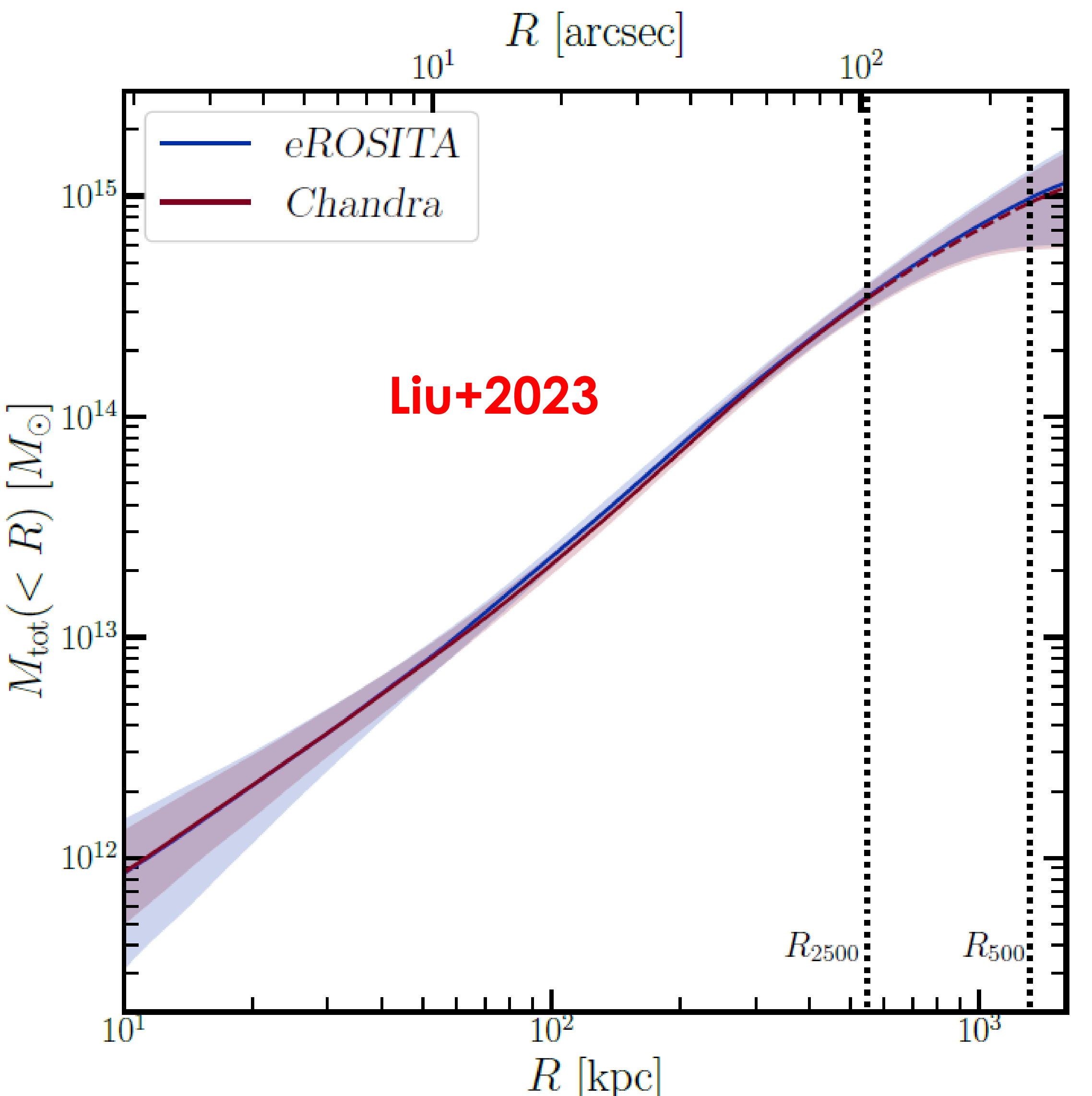
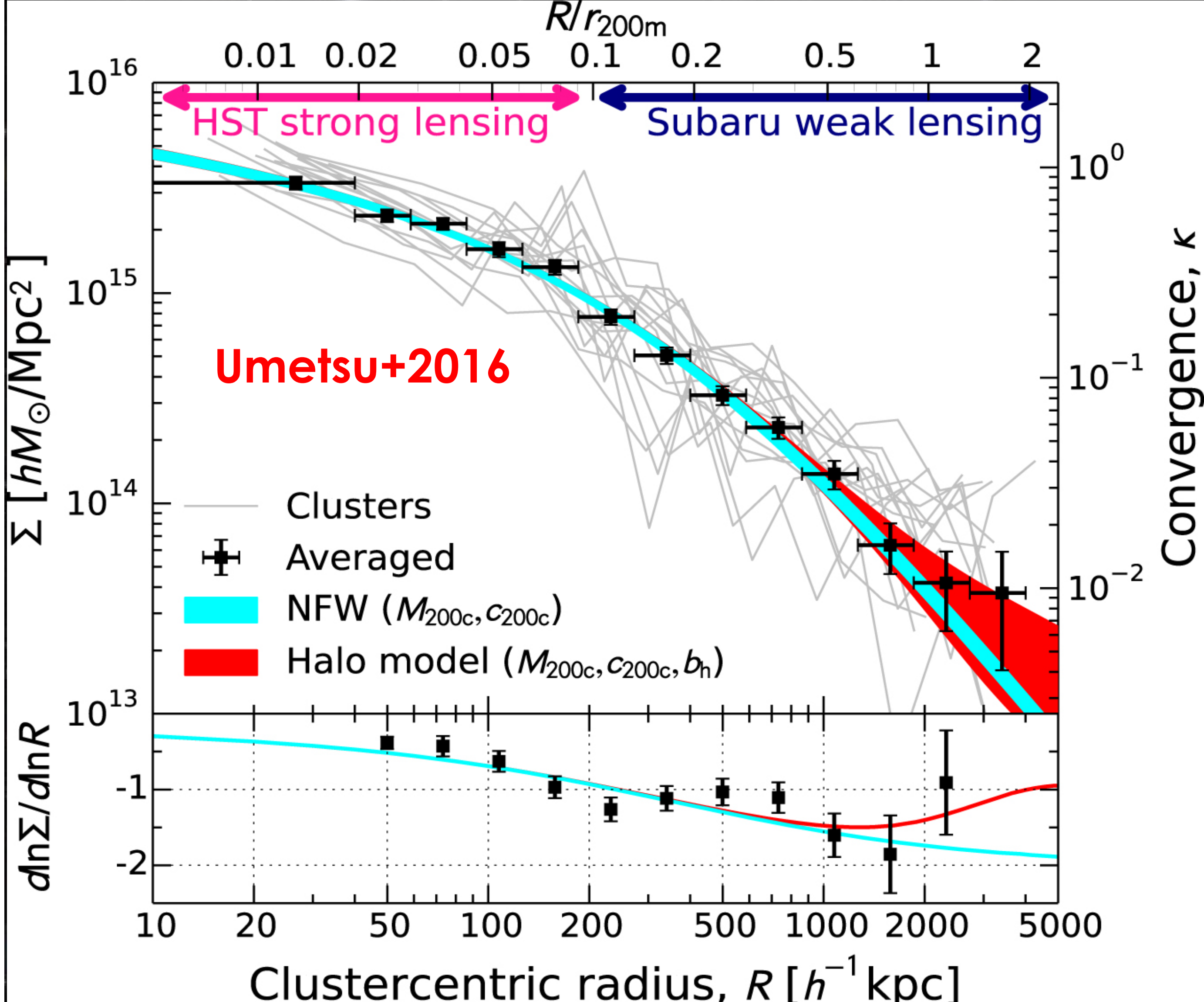
Measure the mass profiles of clusters





The third tracer: cluster galaxies

$$\frac{1}{\nu}\frac{\partial}{\partial r}\left(\nu\sigma_r^2\right)+\frac{2\beta(r)\sigma_r^2}{r}=-\frac{GM(<r)}{r^2}$$

$\nu(r)$: galaxy number density
σ_r^2 : radial velocity dispersion
$\beta(r)=1-\sigma_t^2/\sigma_r^2$: velocity anisotropy
$M(<r)$: total enclosed mass

Projection of integrated Jeans equation

$$\sigma_{los}^2(R) = \frac{2}{\Sigma_{gal}(R)} \int_R^{\infty} \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr$$

$\Sigma_{gal}(R)$: galaxy number density

σ_r^2 : radial velocity dispersion

$\beta(r) = 1 - \sigma_{\mathrm{t}}^2/\sigma_r^2$: velocity anisotropy

Break the $M - \beta$ degeneracy

Virial shape parameters (Merrifield & Kent 1990)

$$v_{s1} = \frac{2}{5}\int_0^\infty GM\nu(5-2\beta)\,\sigma_r^2 r\,dr = \int_0^\infty \Sigma_{gal}\langle v_{los}^4\rangle R\,dR$$

$$v_{s2} = \frac{4}{35}\int_0^\infty GM\nu(7-6\beta)\,\sigma_r^2 r^3\,dr = \int_0^\infty \Sigma_{gal}\langle v_{los}^4\rangle R^3\,dR$$

$\Sigma_{gal}(R)$: galaxy number density

σ_r^2 : radial velocity dispersion

$\beta(r) = 1 - \sigma_{\mathrm{t}}^2/\sigma_r^2$: velocity anisotropy

HIFLUGCS Sample:
Highest Flux Galaxy Cluster Sample

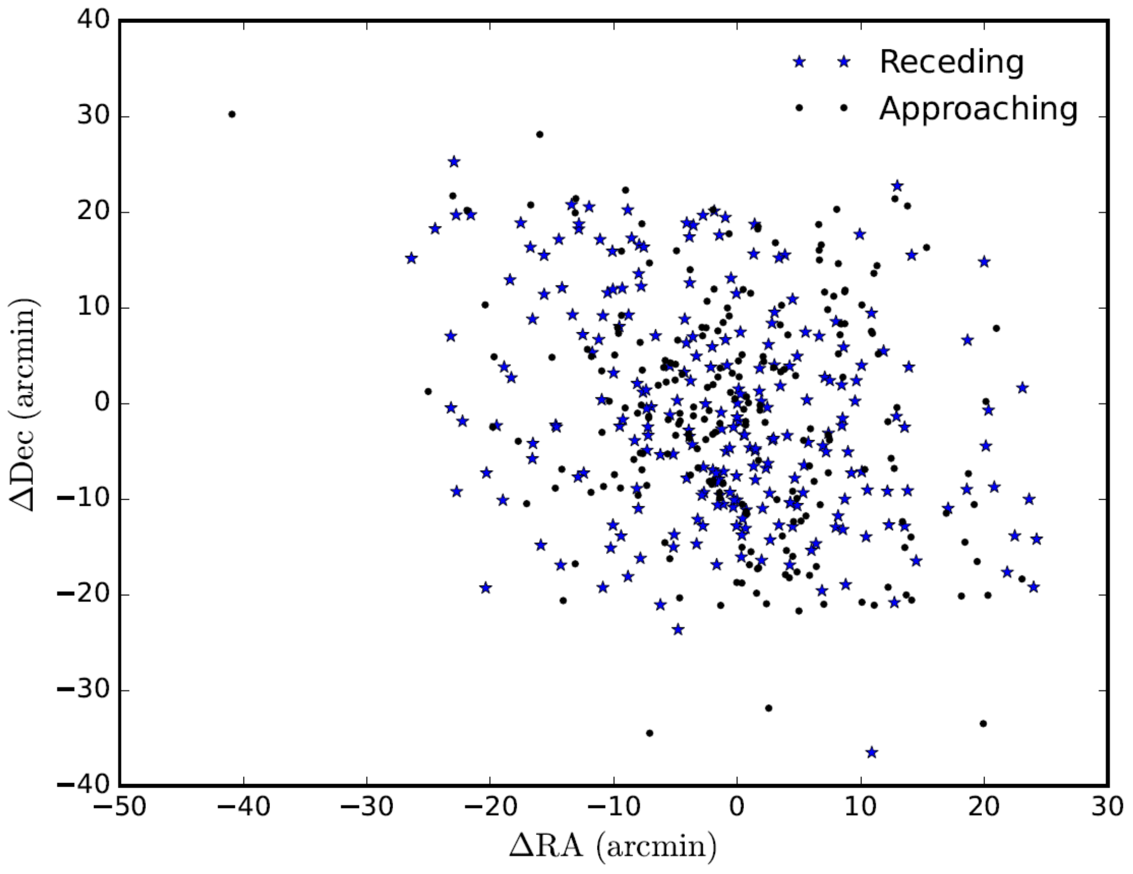
63 clusters (Reiprich+2002)
X-ray observations: ROSAT All-sky Survey
Optical data: Zhang+(2011) + Simbad -> Tian

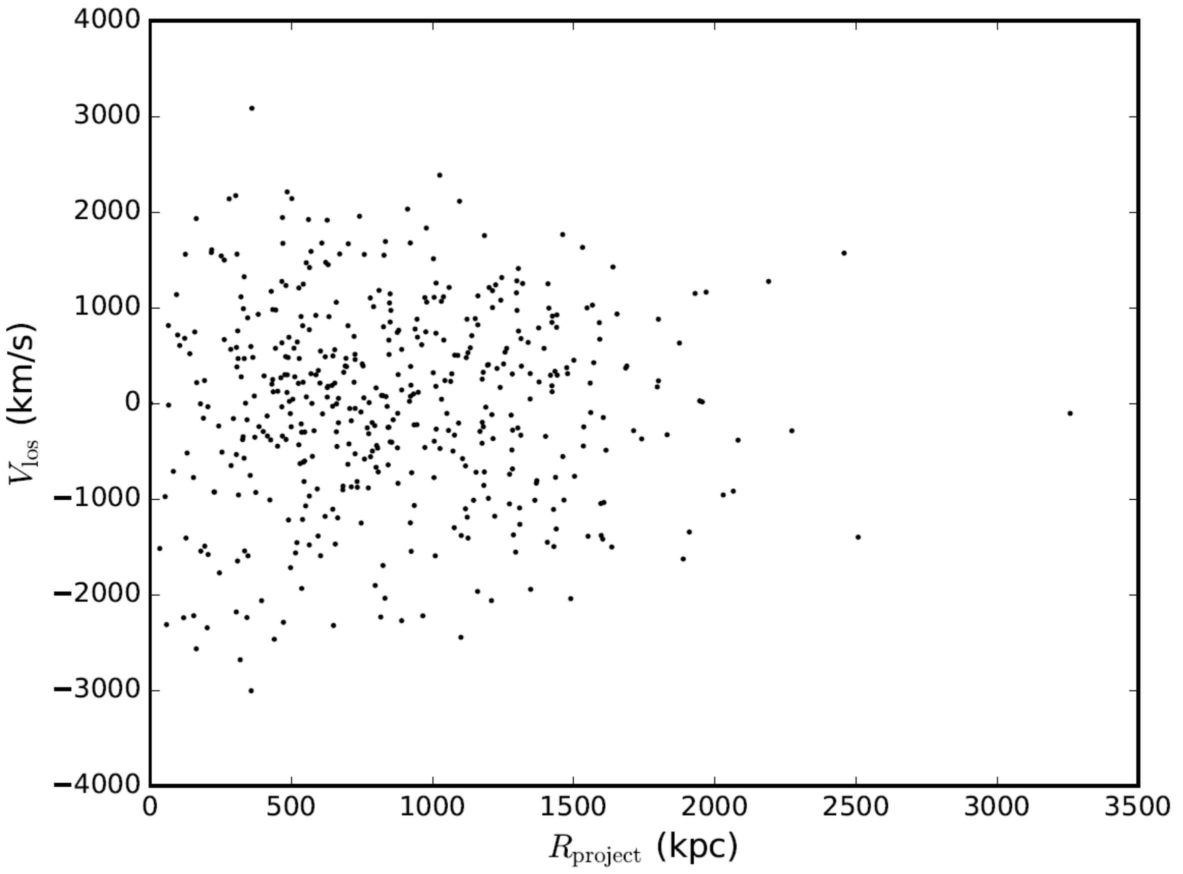
Requirements:
1. Offset between optical and X-ray centers < 60 kpc
2. >75 member galaxies

Retain 16 clusters of galaxies in total

Positions and line-of-sight velocity of galaxies

Example: A0085





Projected galaxy number density $\Sigma_{gal}(R)$

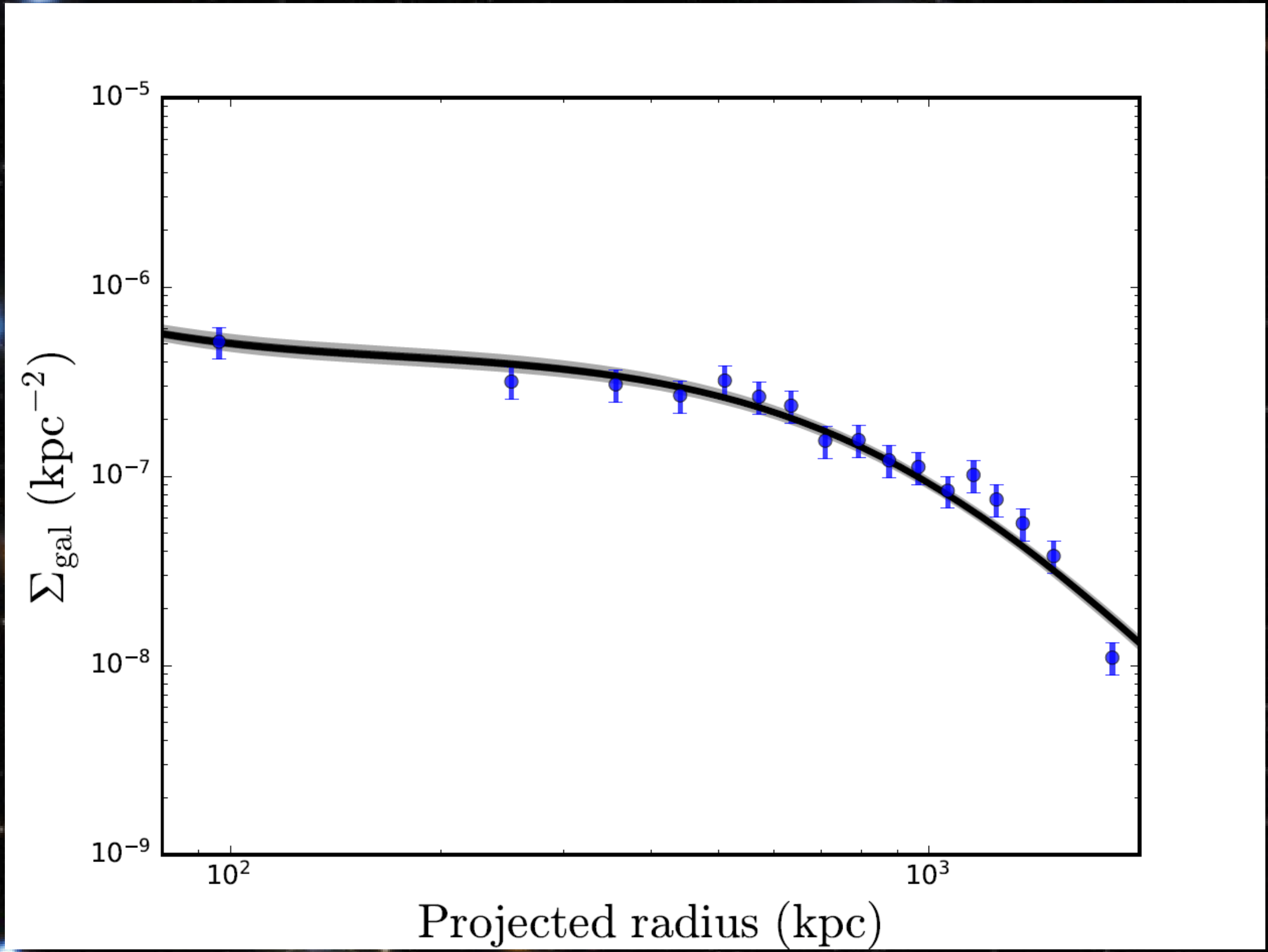
Galaxy number density

$$\upsilon = \int f \, d^3\vec{v}$$

Parameterized with three Plummer spheres:

$$\upsilon = \sum_{i=1}^{3} \frac{3N_i}{4\pi a_i^3} \left(1 + \frac{r^2}{a_i^2}\right)^{-5/2}$$

Then projection



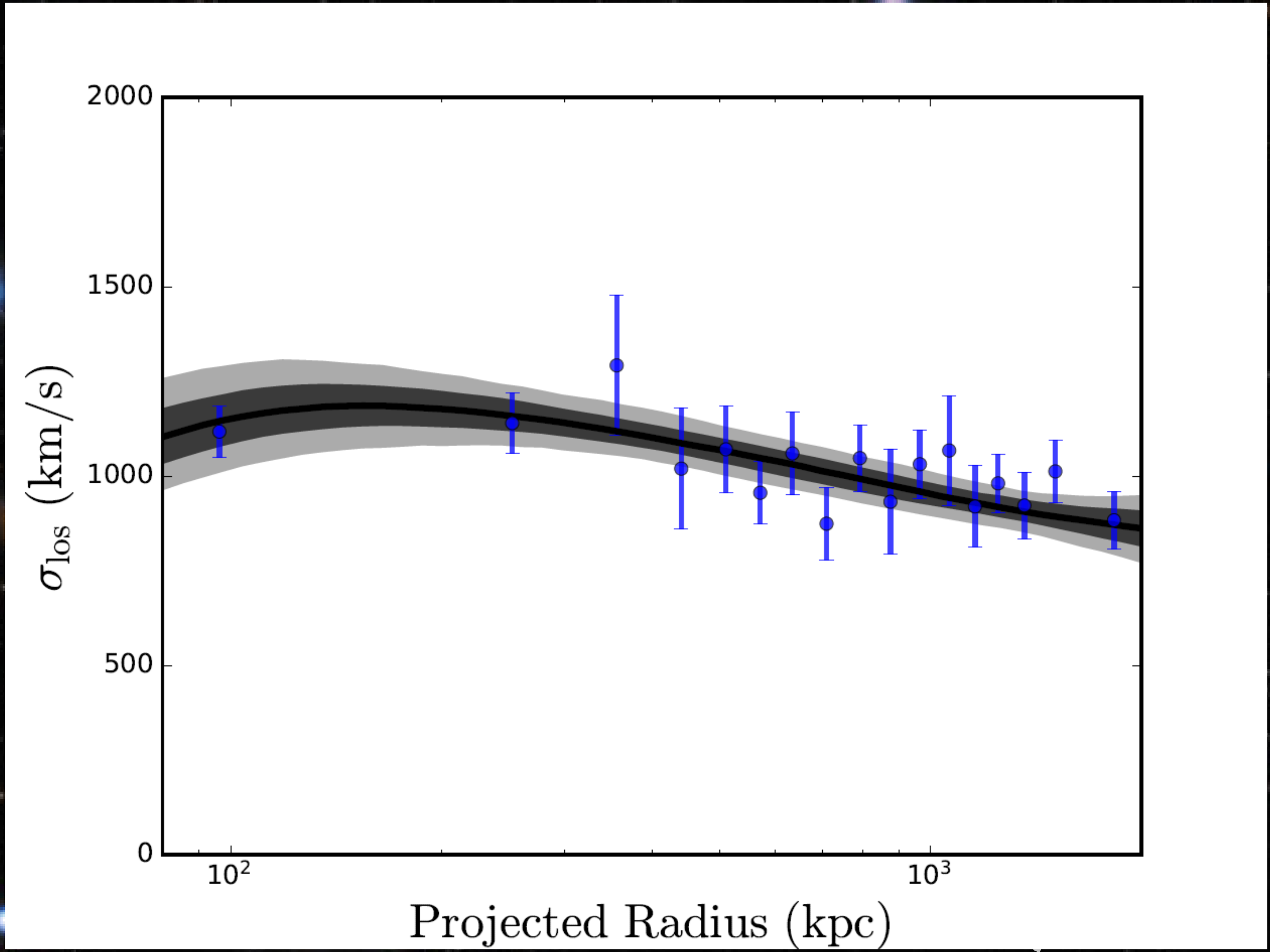
Mass profiles: cNFWt function

At r < r_t:

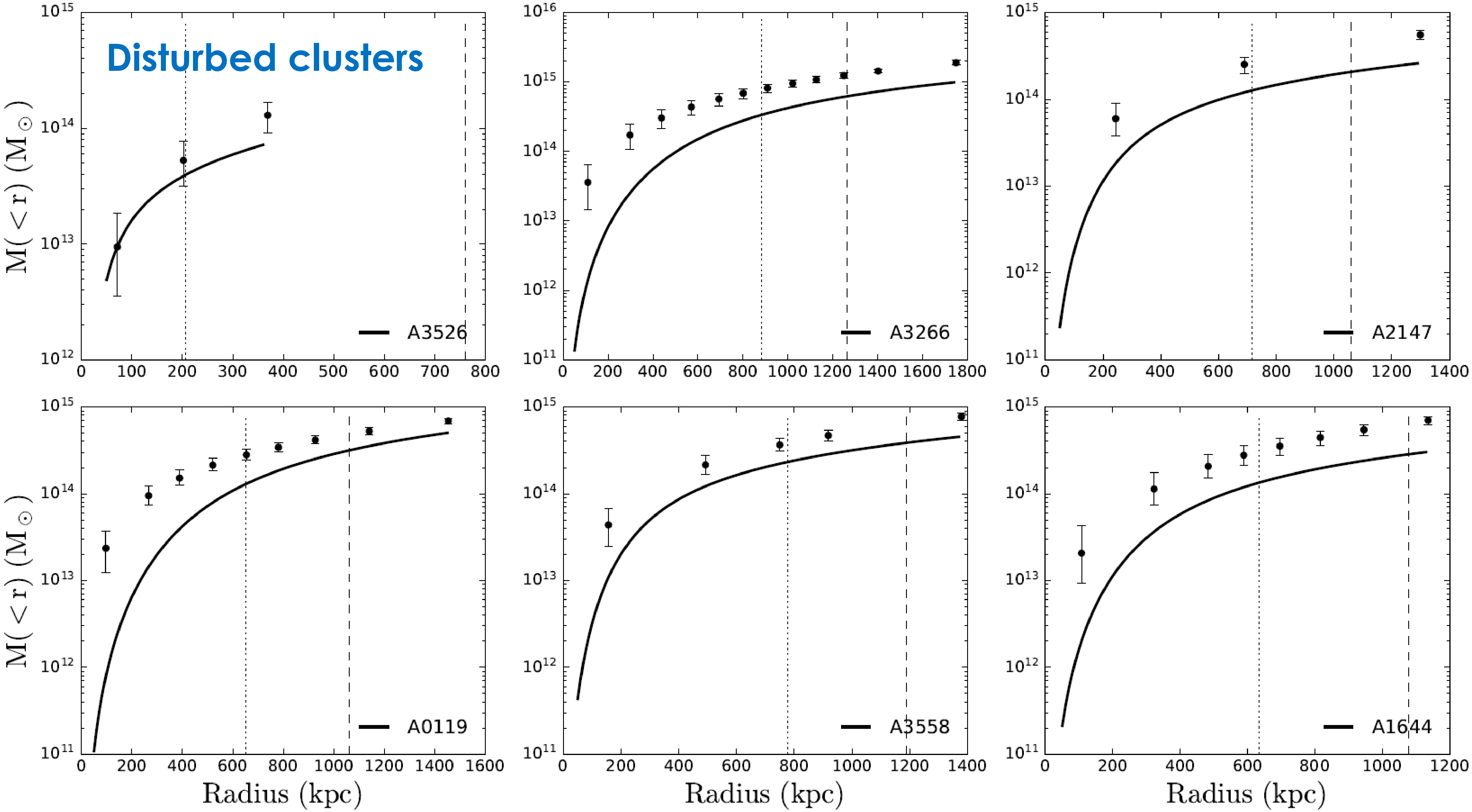
$$M_{cNFW}(<r) = M_{NFW}(<r)\left[tanh\left(\frac{r}{r_c}\right)\right]^n$$

At r > r_t:

$$M_{cNFWt}(<r) = M_{cNFW}(<r_t) + 4\pi\rho_{cNFW}(r_t)\frac{r_t^3}{3-\delta}\left[\left(\frac{r}{r_t}\right)^{3-\delta} - 1\right]$$

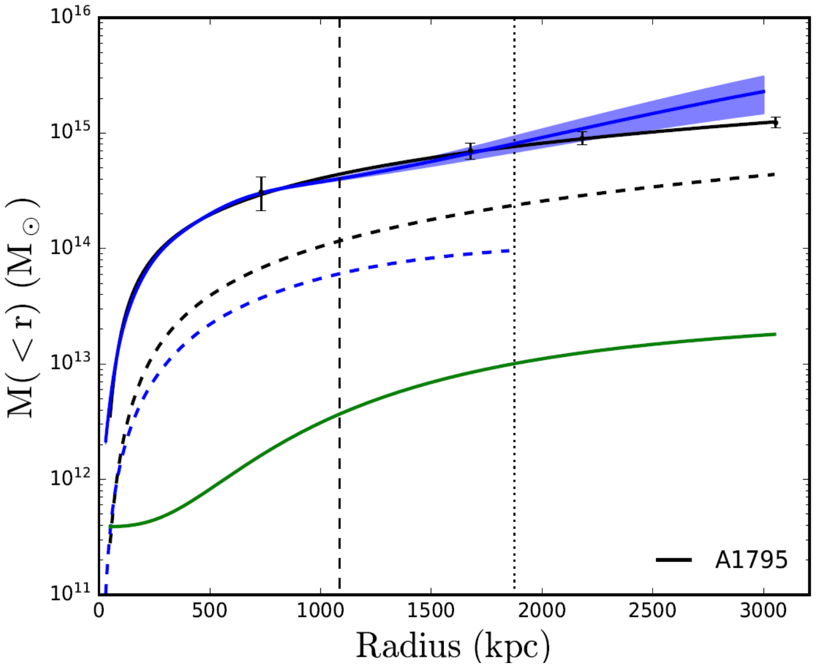


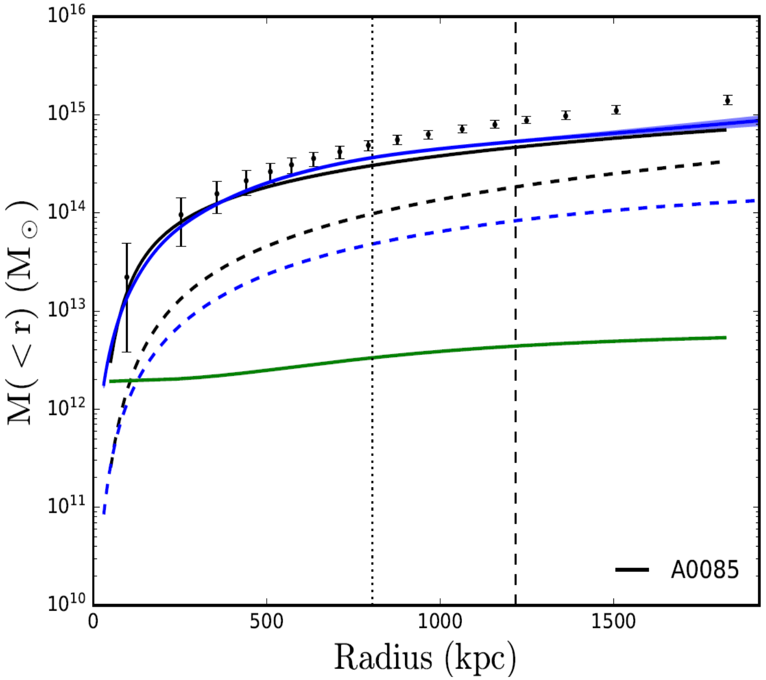
Six parameters with variable inner and outer slopes

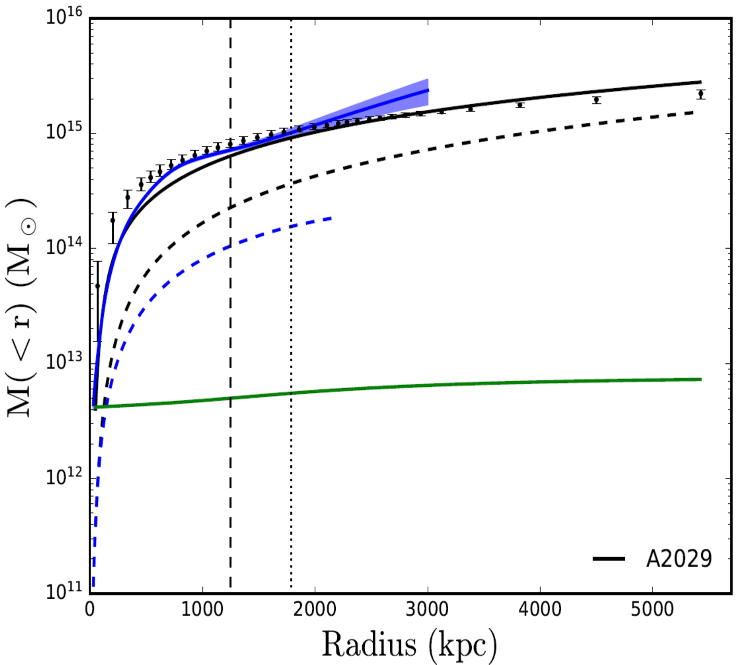

Disturbed clusters
A3526
A3266
A2147
A0119
A3558
A1644
M(<r) (M⊙)
Radius (kpc)

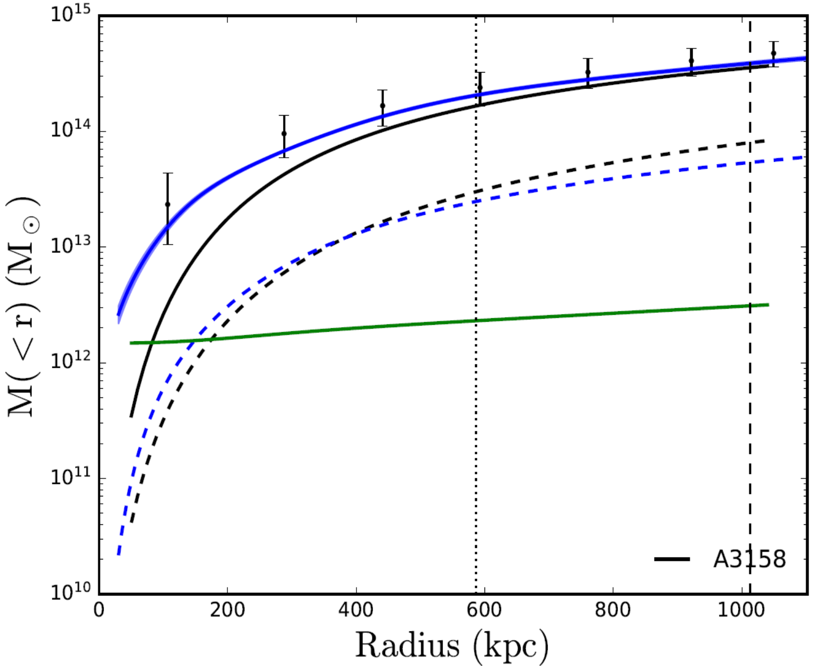
Total mass profiles:

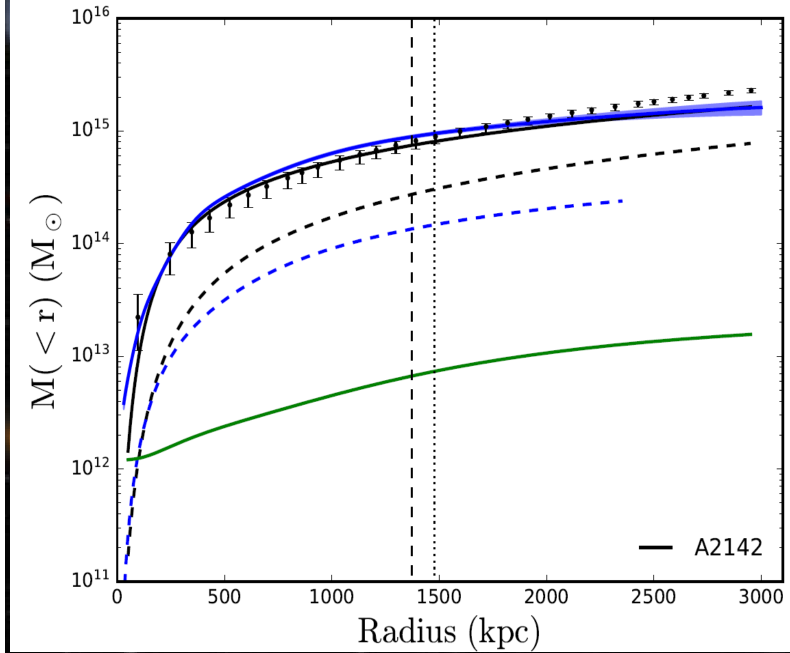
Five classical clusters with X-COP data





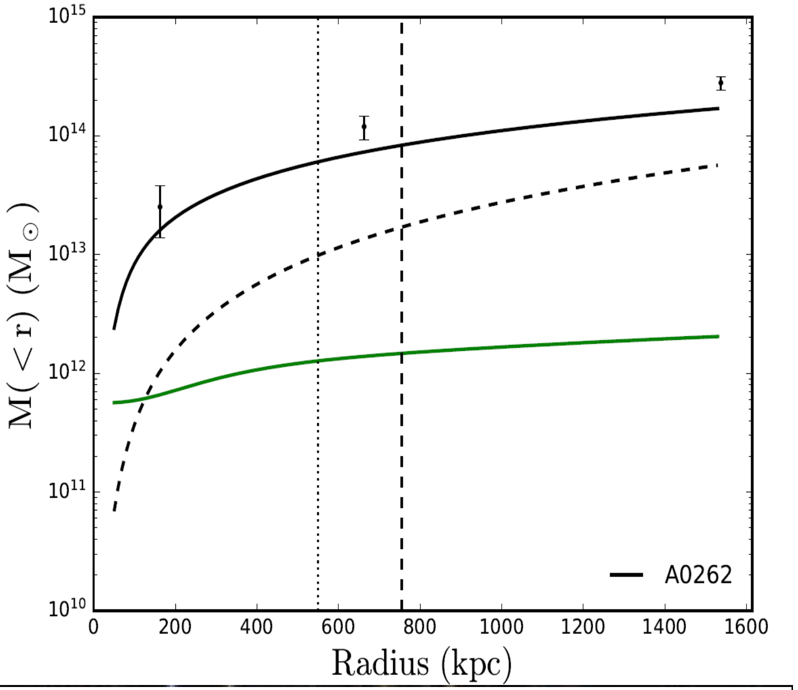


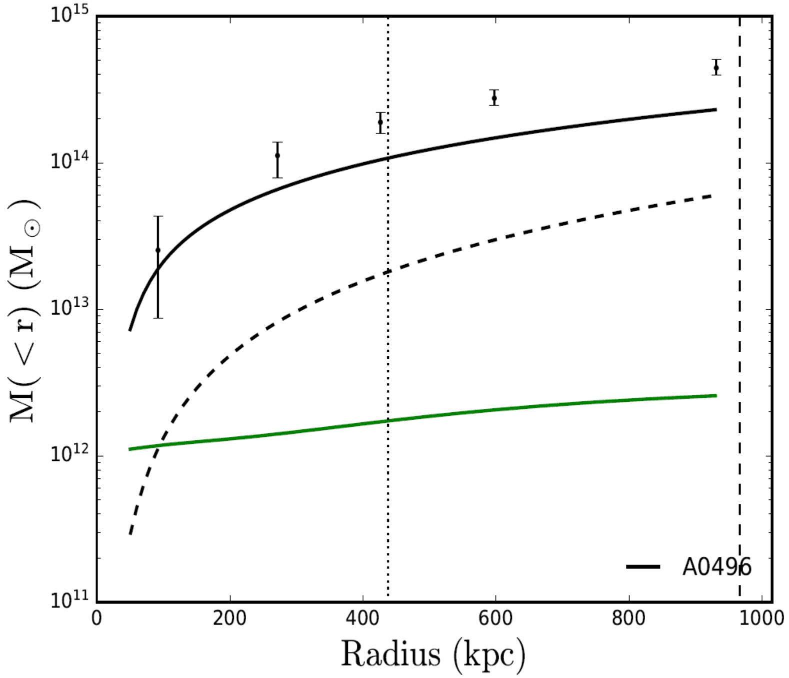


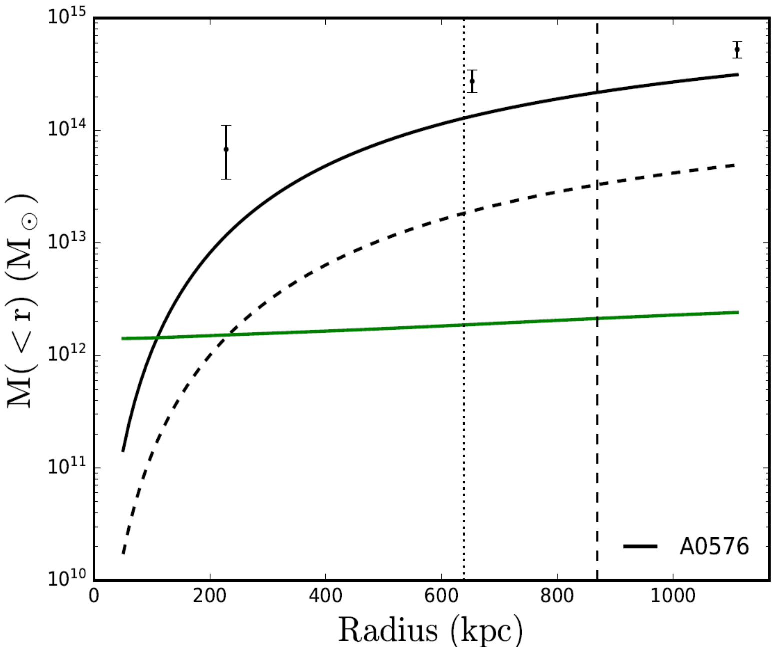


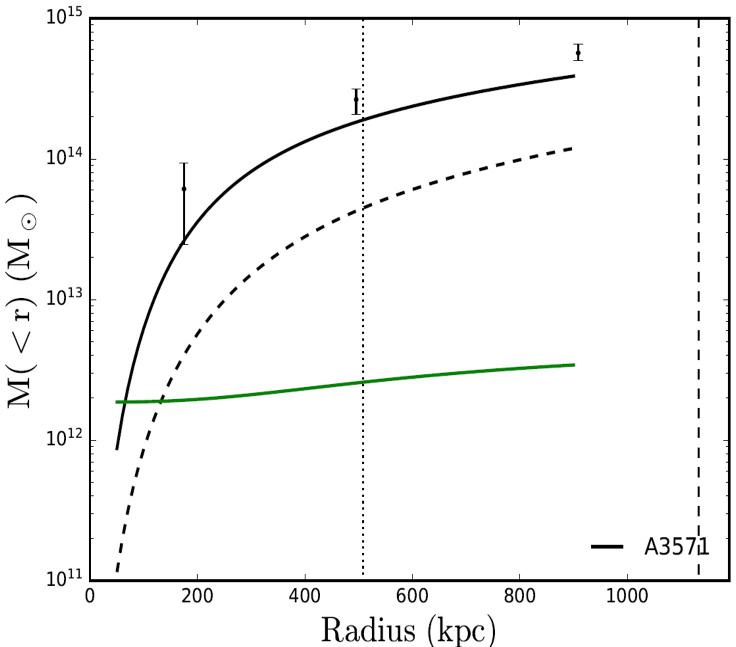
Total mass pofiles:

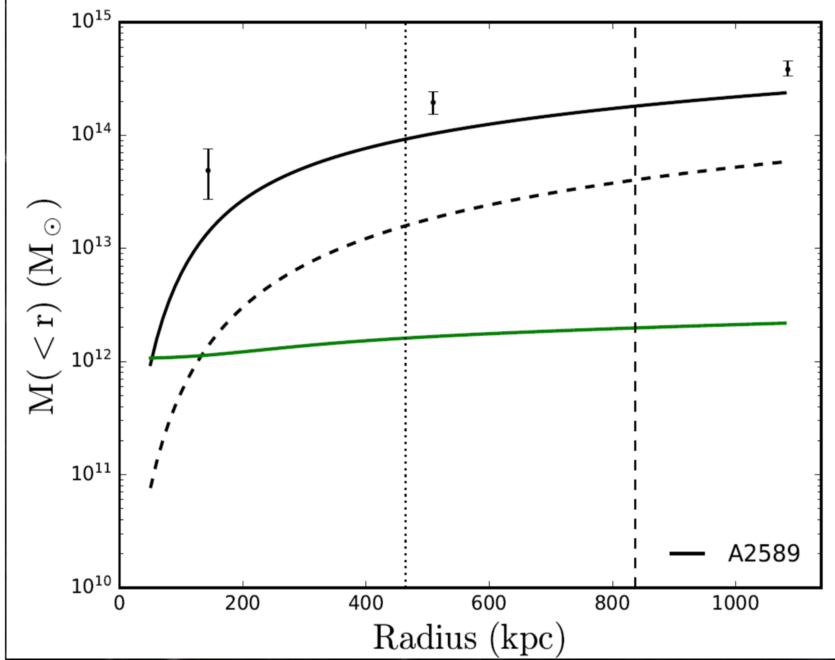
Five clusters without X-COP data









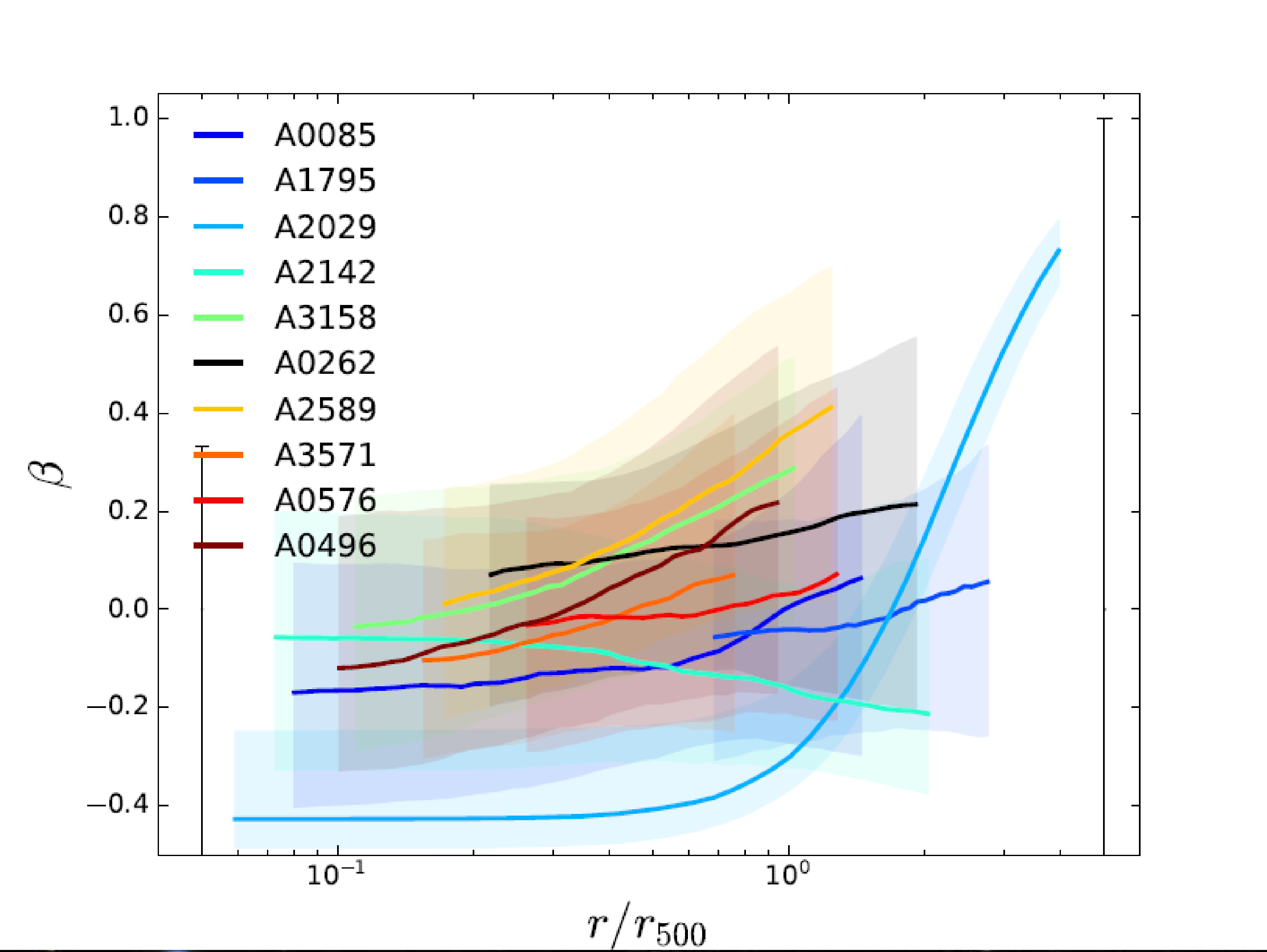


velocity anisotropy

$$\beta(r) = 1 - \sigma_t^2/\sigma_r^2$$

Degenerated with mass profile.

Broken with two virial shape parameters: 4th-order of velocity dispersion



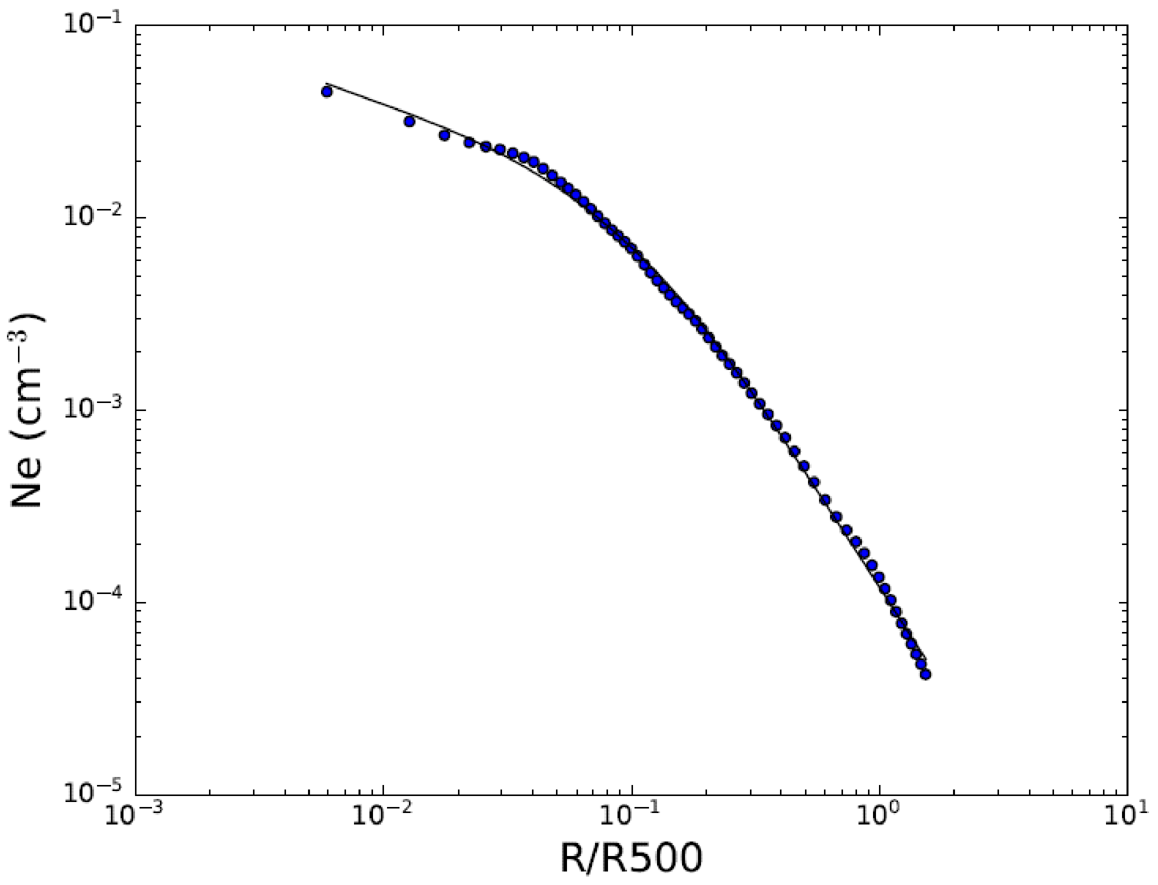
MASS BUDGET OF TEN RELAXED CLUSTERS

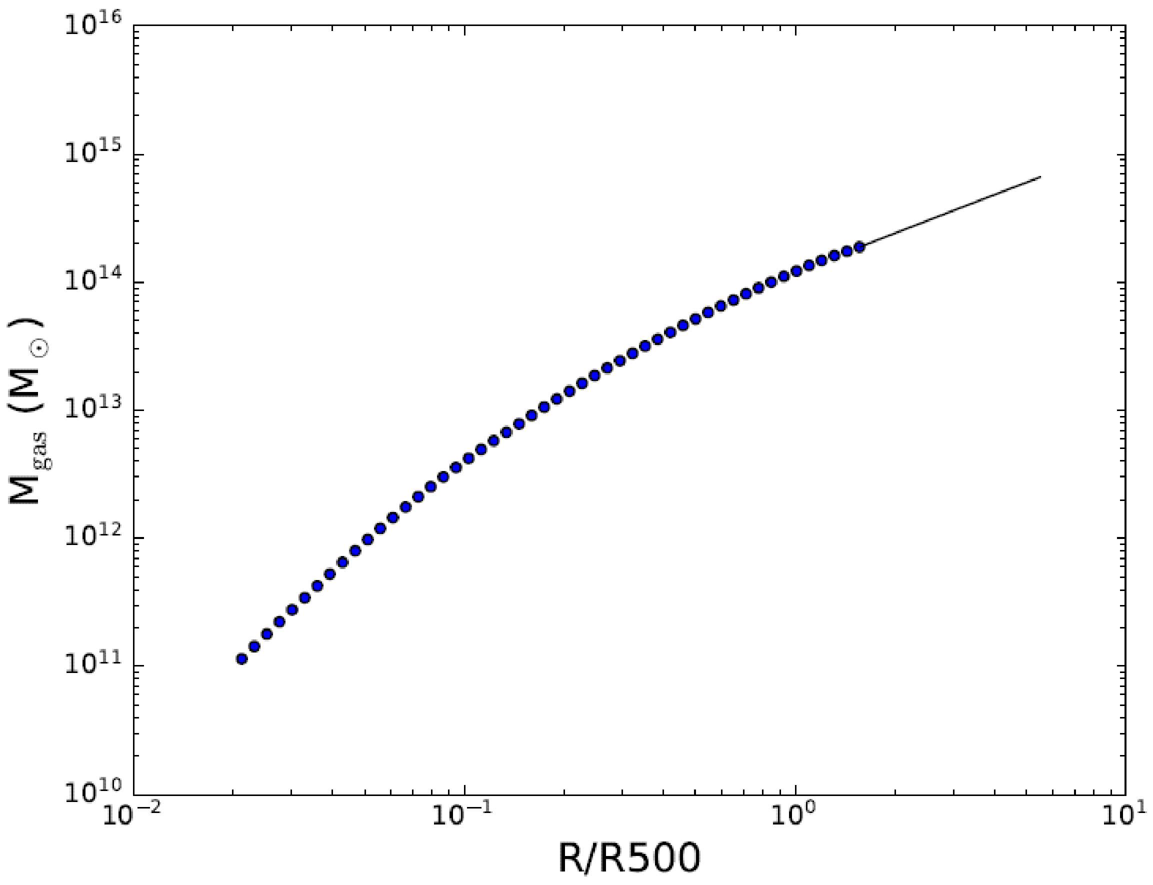
Cluster	r_{500} (kpc)	$M_{gas,500}$ ($10^{13} M_{\odot}$)	$M_{\star,500}$ ($10^{12} M_{\odot}$)	$M_{\star,BCG}$ ($10^{11} M_{\odot}$)	$M_{dyn,500}$ ($10^{14} M_{\odot}$)	$M_{hydro,500}$ ($10^{14} M_{\odot}$)	$M_{dyn,500}/M_{hydro,500}$	f_b
A0085	1217	6.67	4.39	19.05	8.44	4.66	1.81	0.086
A0262	755	1.08	1.47	5.62	1.37	0.83	1.64	0.094
A0496	967	2.79	2.60	10.72	4.61	2.39	1.92	0.069
A0576	869	2.00	2.13	14.13	3.94	2.18	1.80	0.060
A1795	1085	4.95	3.68	3.89	4.59	4.41	1.04	0.117
A2029	1247	8.24	4.99	41.69	8.07	6.37	1.27	0.113
A2142	1371	13.40	6.68	12.02	8.05	7.47	1.08	0.176
A2589	837	1.77	1.98	10.72	3.06	1.81	1.69	0.068
A3158	1013	3.75	3.11	14.79	4.59	3.55	1.29	0.091
A3571	1133	5.16	3.77	18.62	7.36	5.02	1.47	0.078

Testing RAR:
Break down baryonic mass

1. Stellar mass in BCG:
   K-band luminosity from 2MASS +
   scaling relation (Cappellari 2013)
2. Stellar mass in satellite galaxies:
   Gas-stellar mass relation (Chiu et al. 2018) +
   galaxy number density profiles
3. Gas mass
   Extrapolations using the β function or
   the modified β function

A2029: extrapolations for gas mass at large radii





Bayonic acceleration

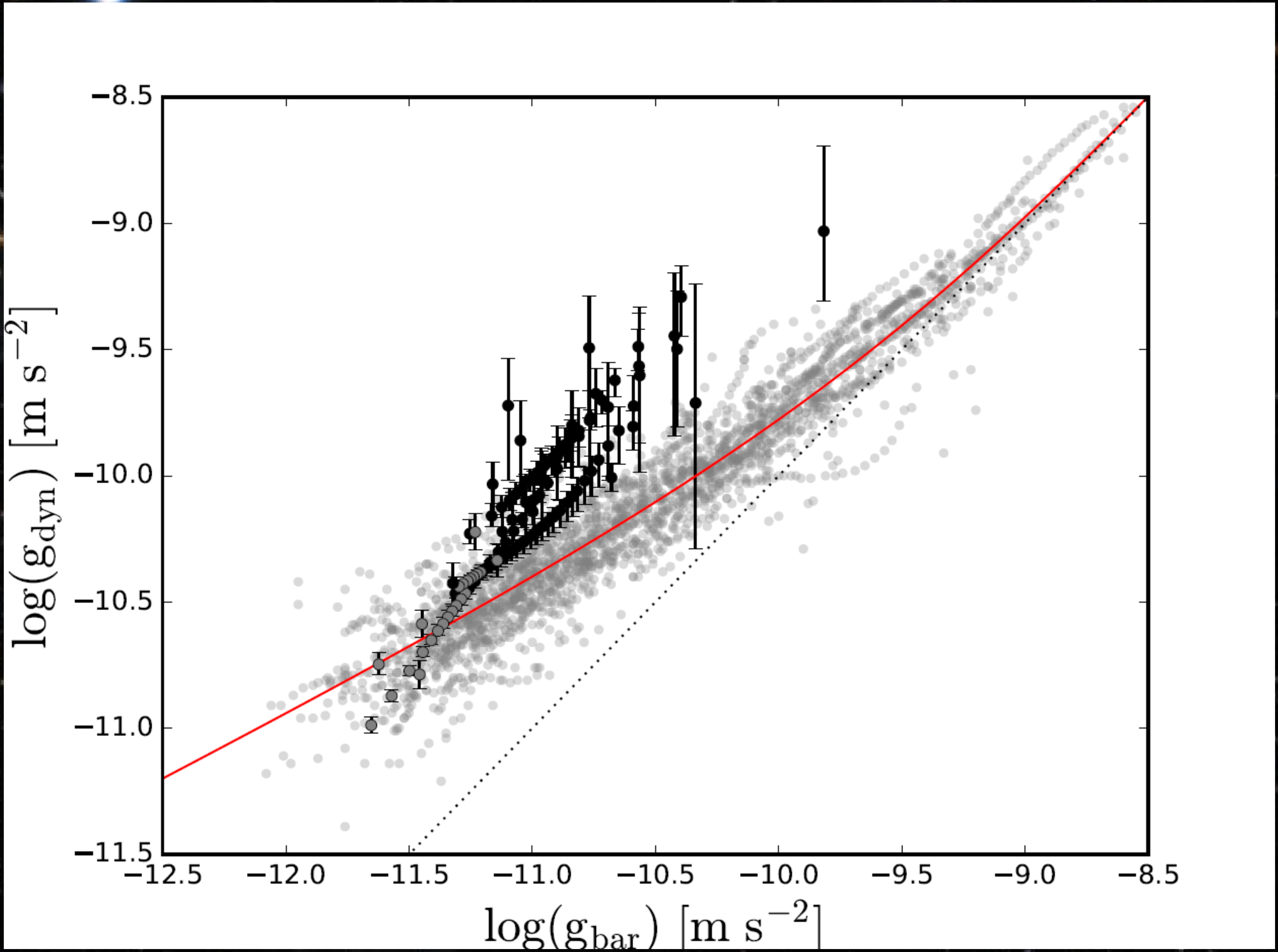
$$g_{bar} = \frac{GM_{bar}}{R^2}$$

Total acceleration from Galaxy kinematics:

$$g_{tot} = \frac{GM_{tot}}{R^2}$$

Room for extra mass closes towards large radii.

Due to extrapolations?



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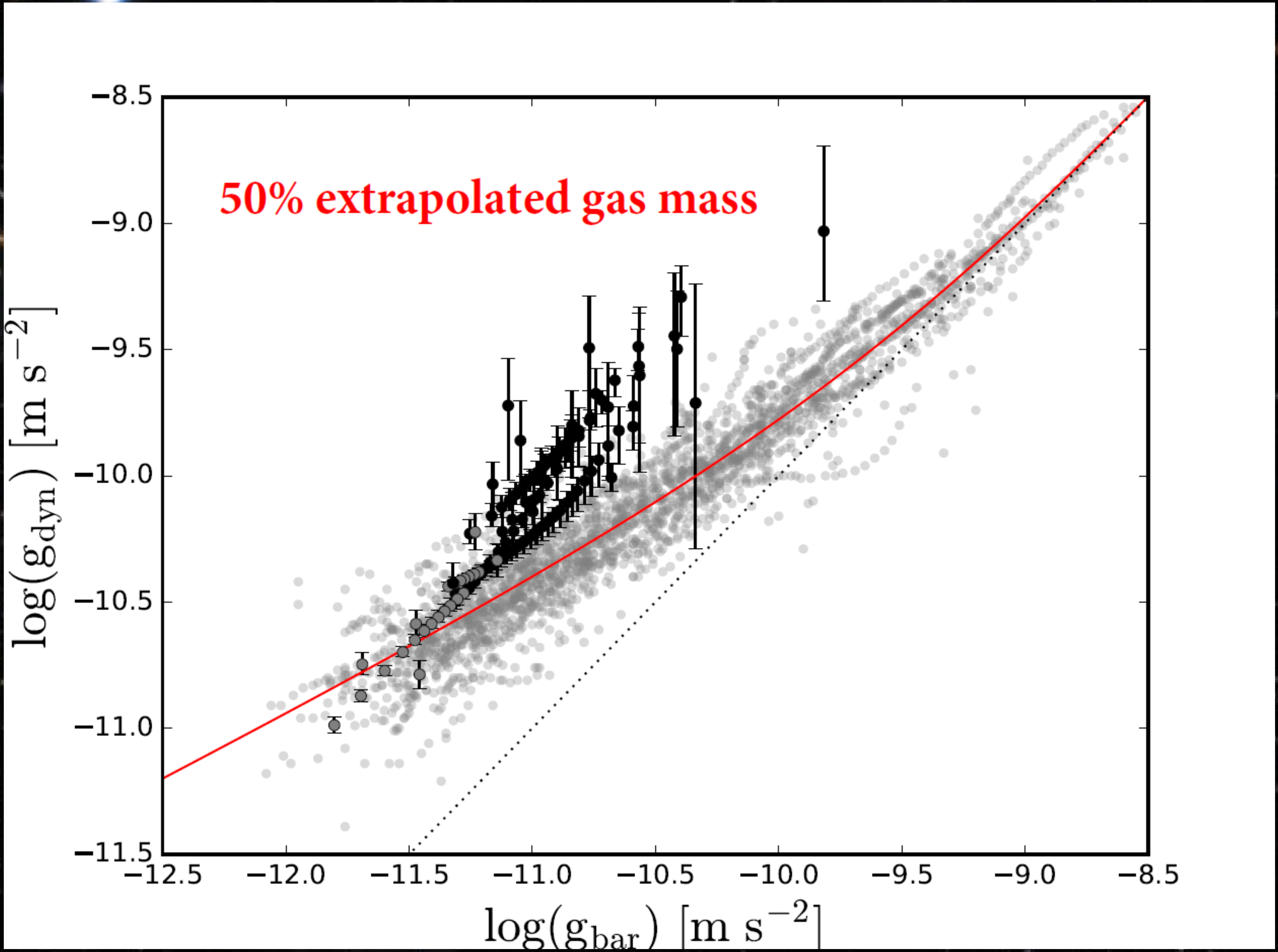

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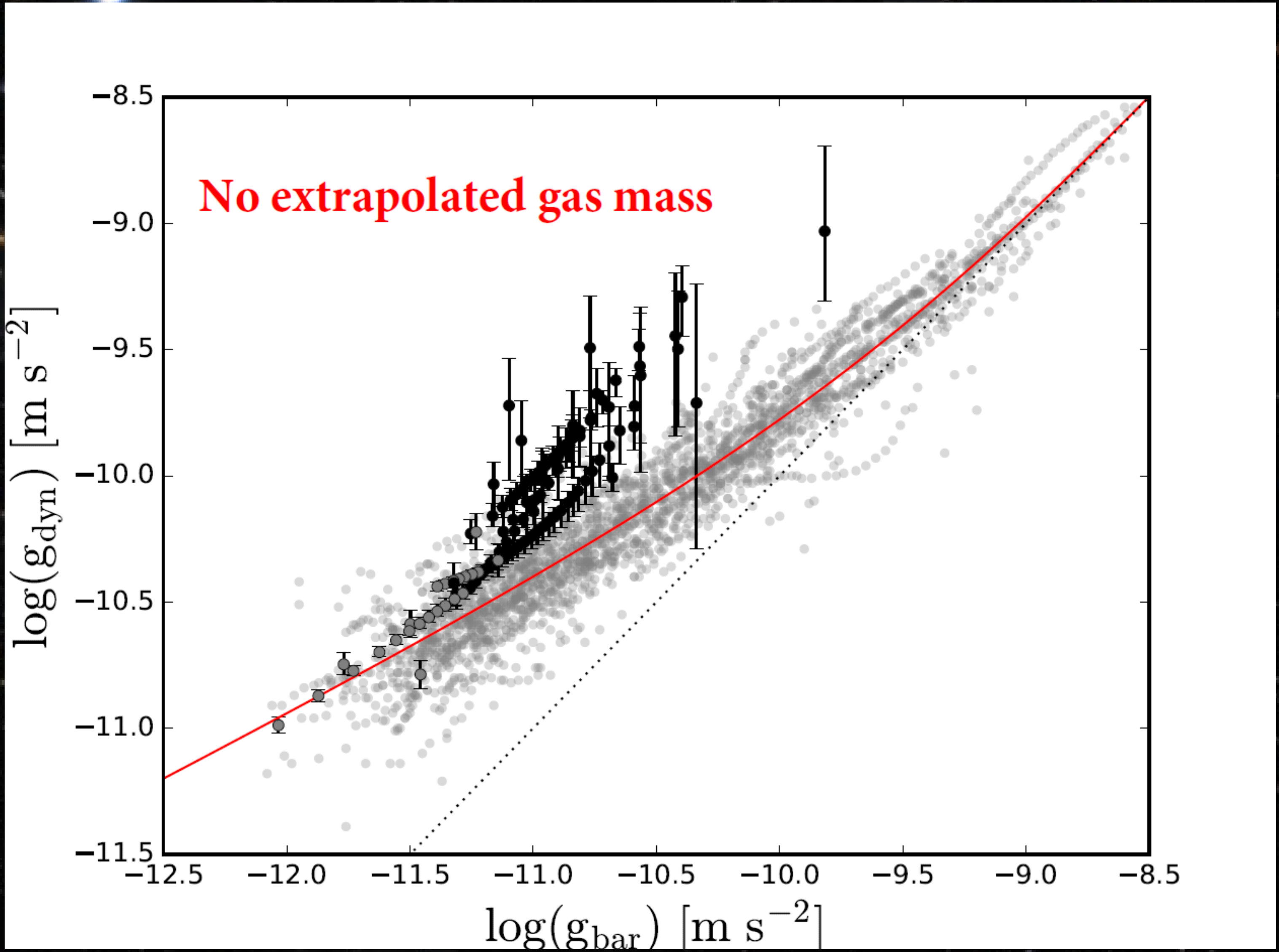


Missing mass profiles in MOND:

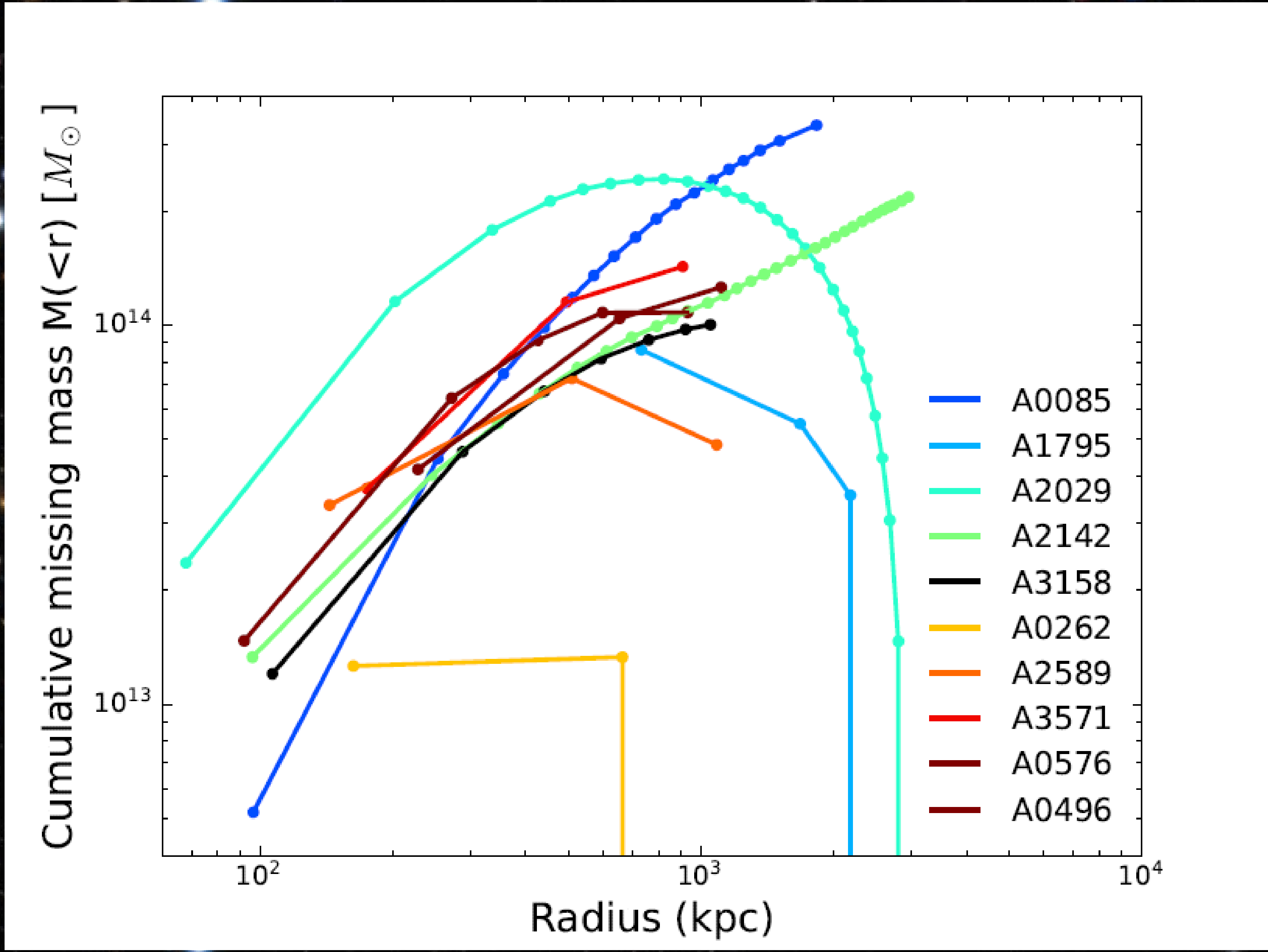
Assume the RAR

$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{+}}}}$$

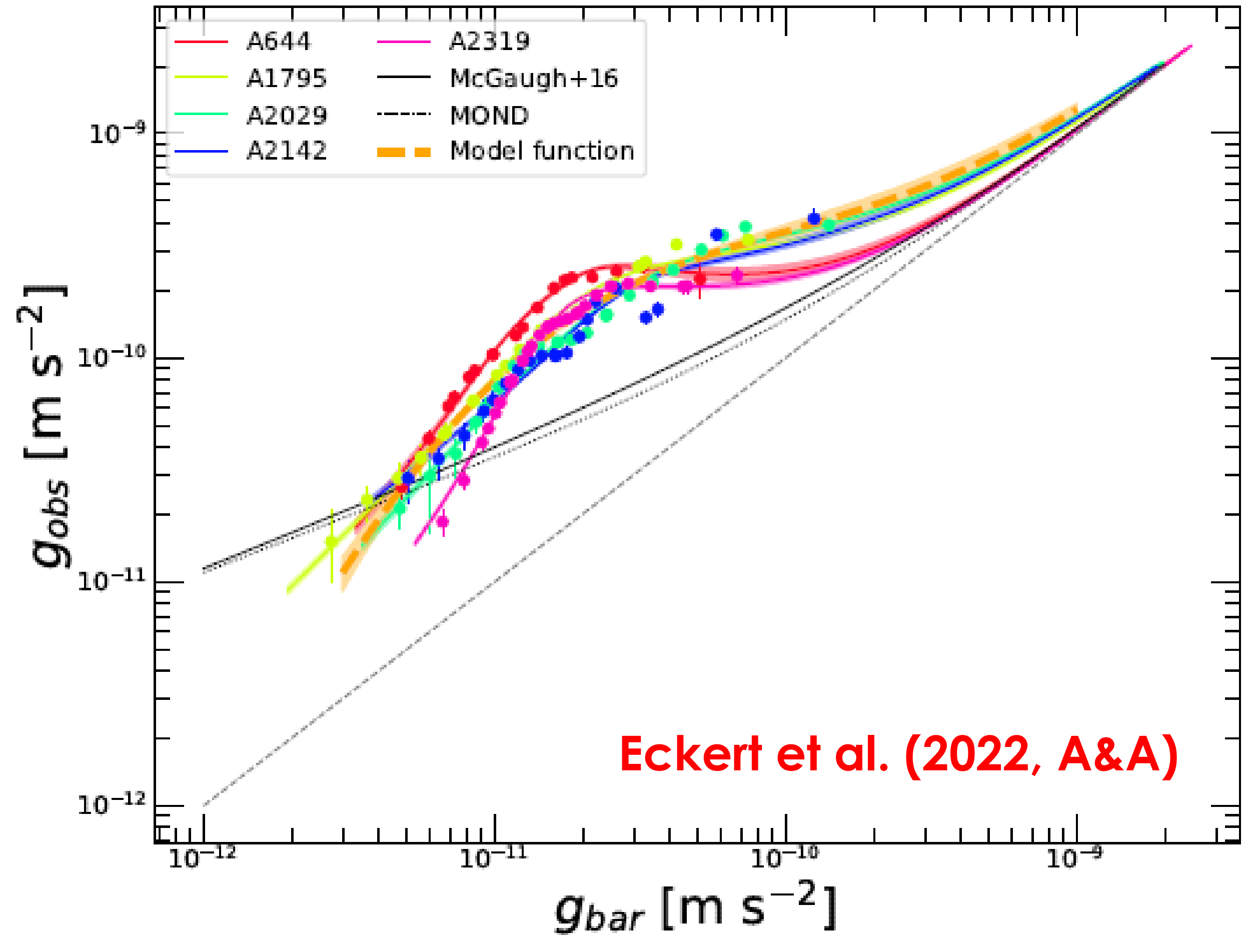
Derive g_{bar} from g_{obs}

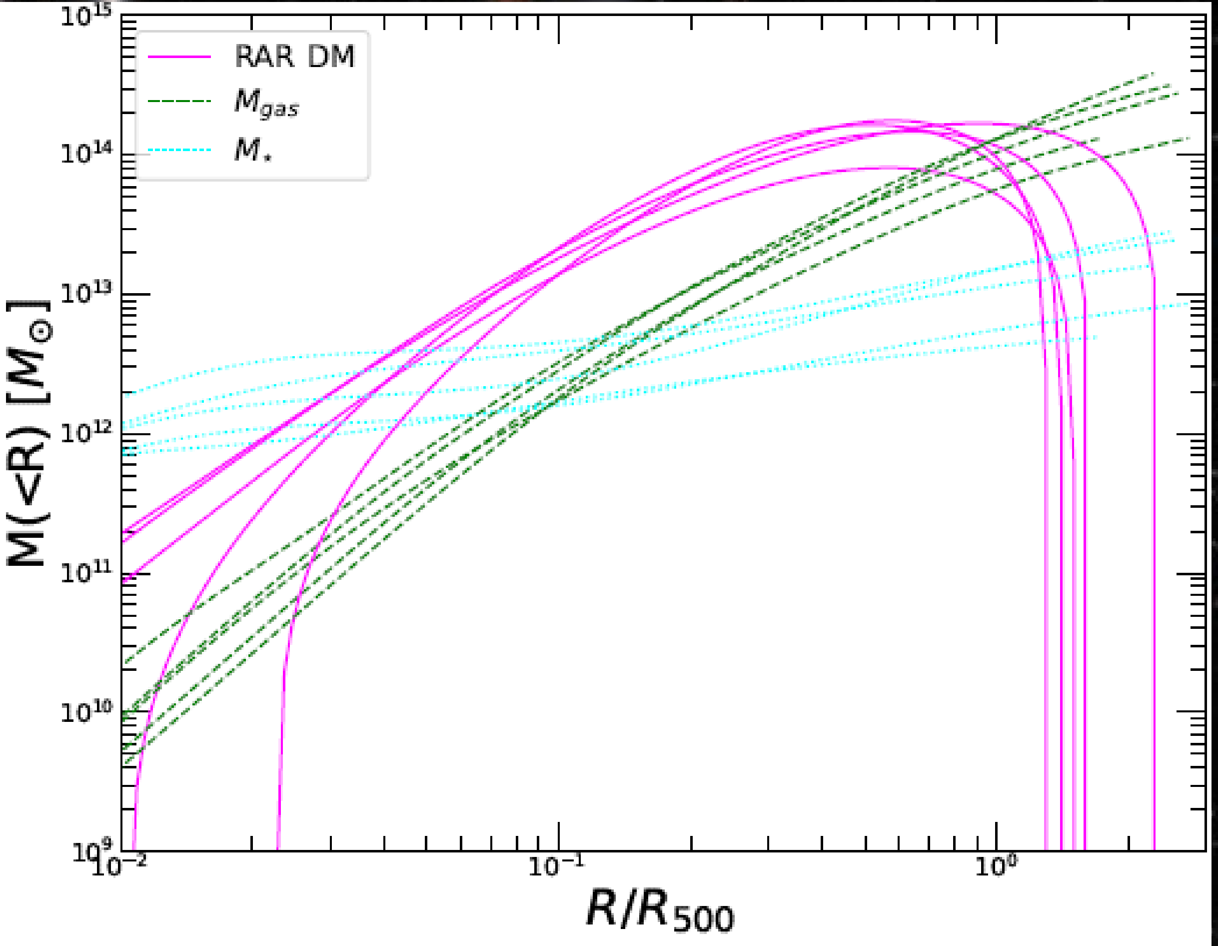
g_{bar} → total $M_{bar}(< \mathrm{r})$

$$M_{missing}(< r) = M_{total}(r) - M_{obs}(r)$$



Hydrostatic mass for X-COP clusters
XMM-Newton deep observations in the outskirts





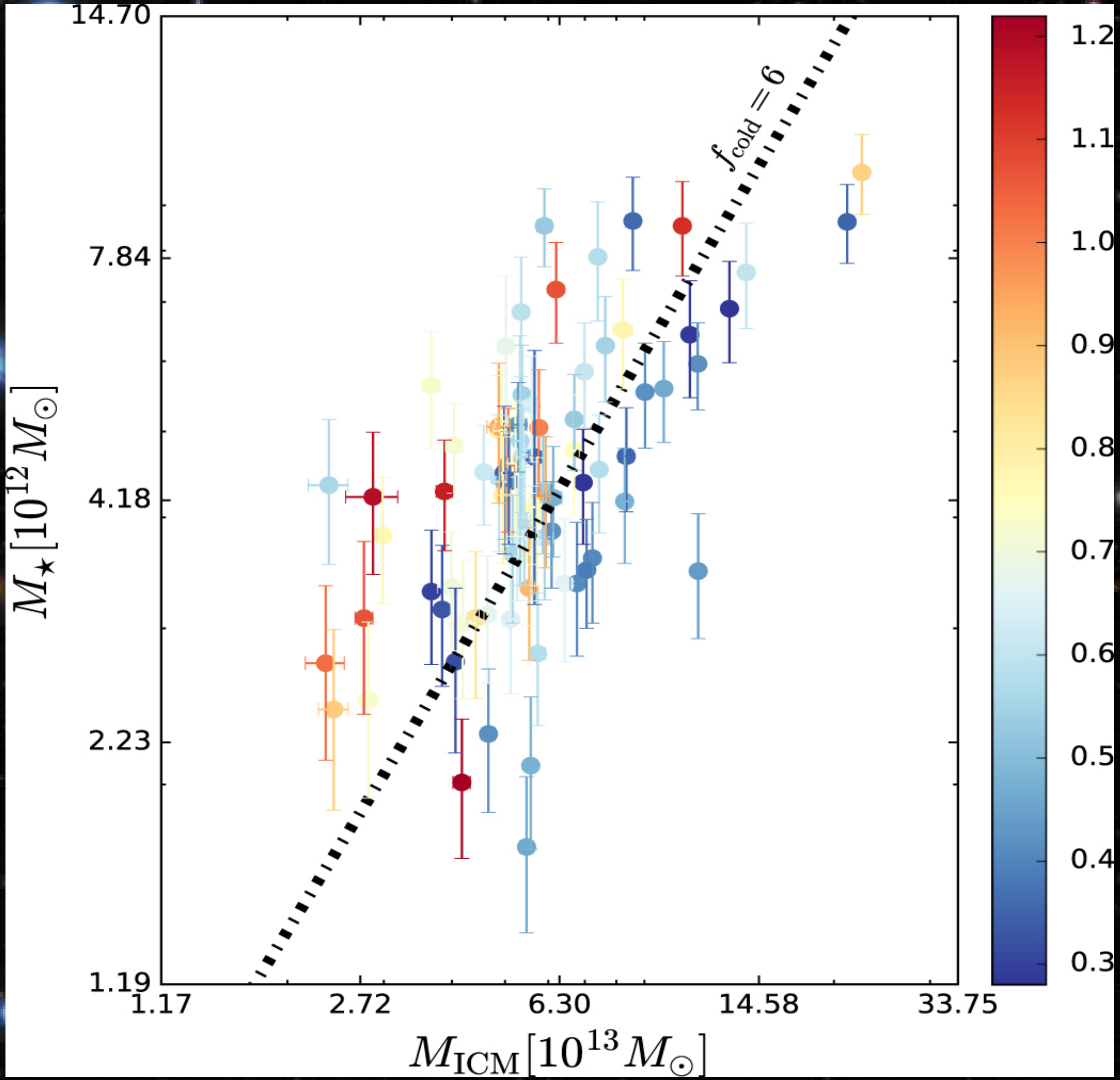
CONCLUSION

1. Dynamical equilibrium and hydrostatic equilibrium seem incompatible with MOND.
   How general and robust is the incompatibility?

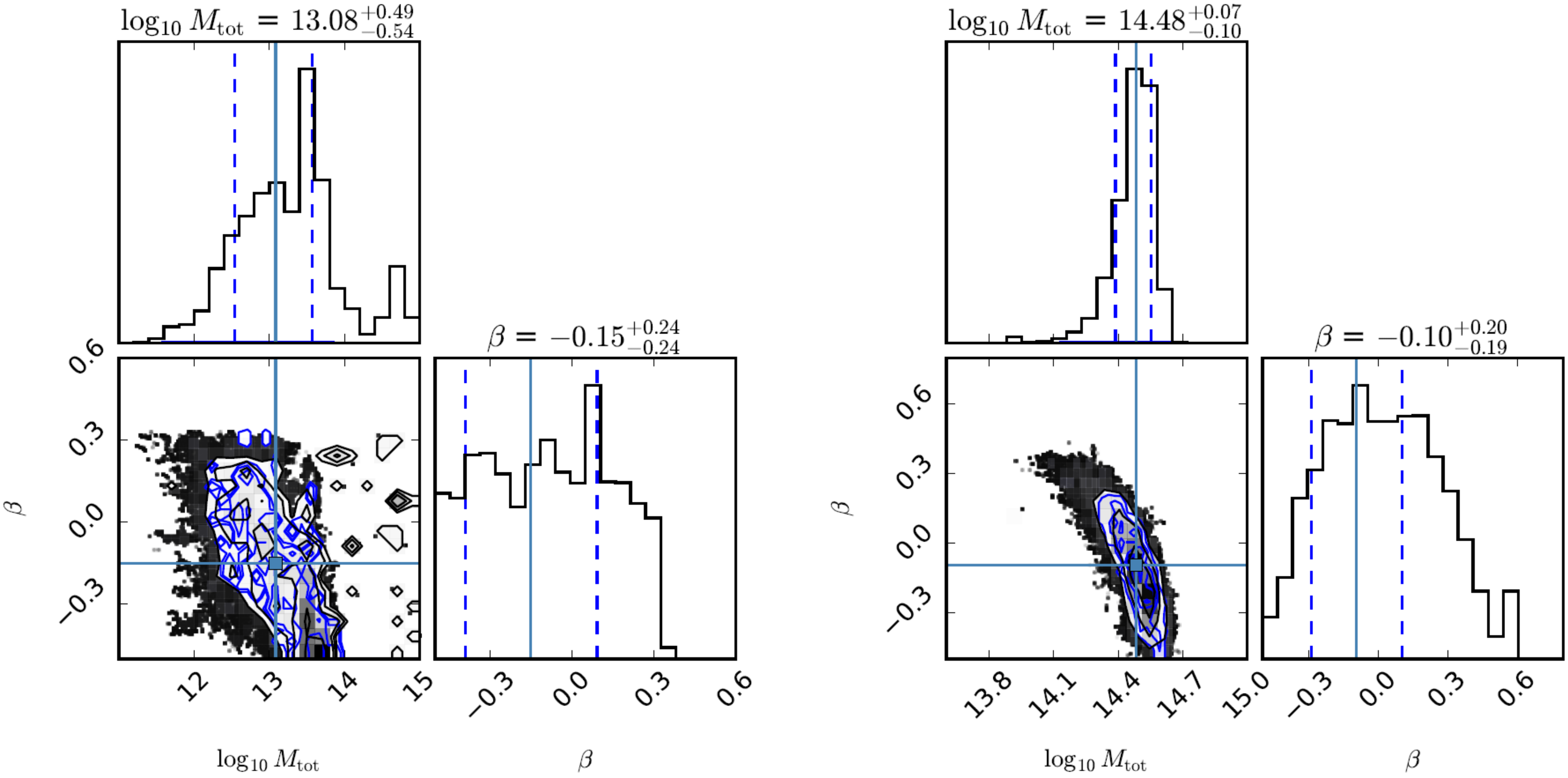
2. We can test MOND in galaxy clusters now.
   Don't have to wait decades for new observations for possible missing baryons.
   Derive cumulative missing mass profiles!

BACKUP

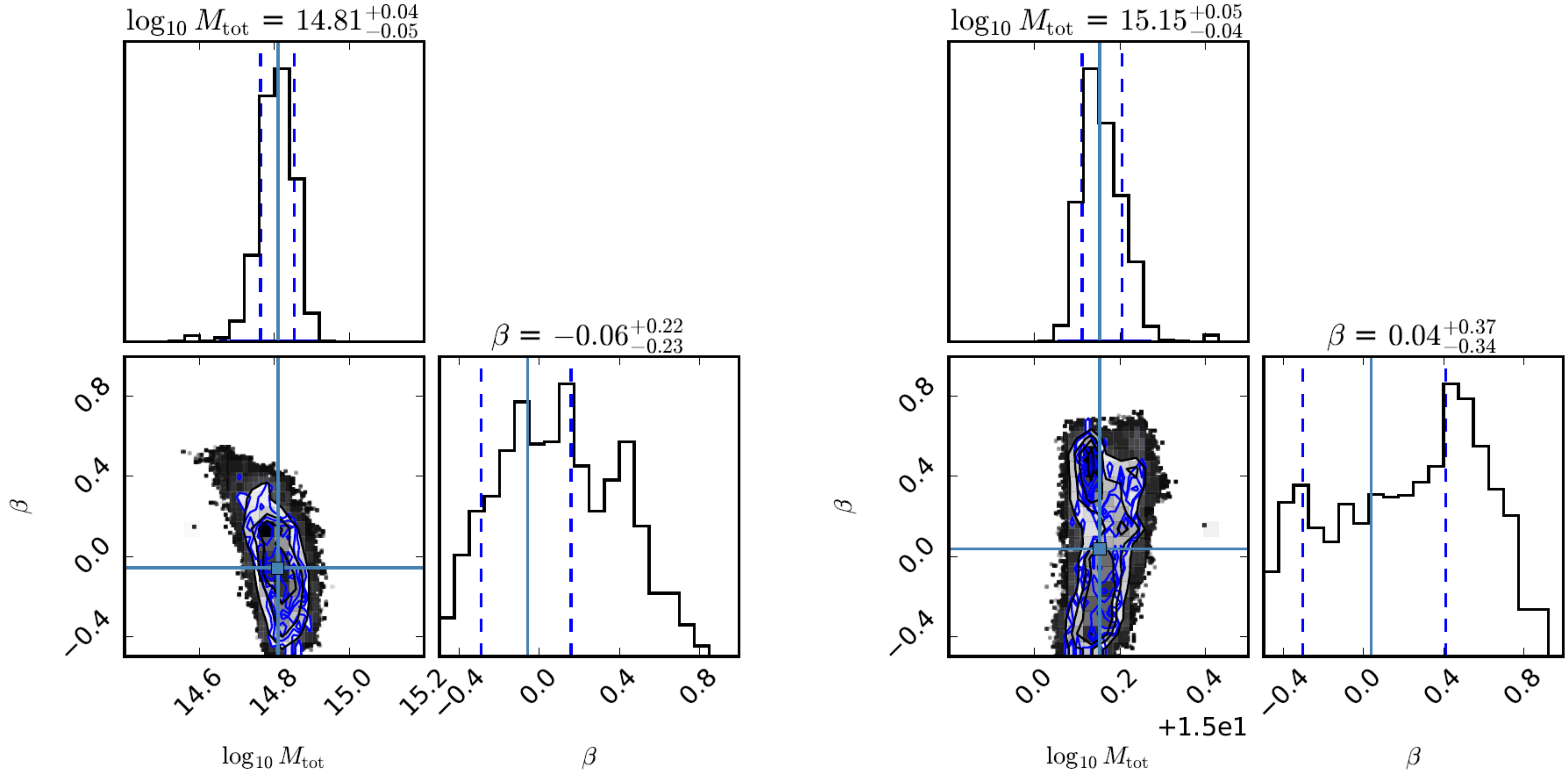
Gas mass – stellar mass Relation within r500. Chiu+(2018)



A0085: r=96 kpc; r= 570 kpc



A0085: r=965 kpc; r= 1827 kpc



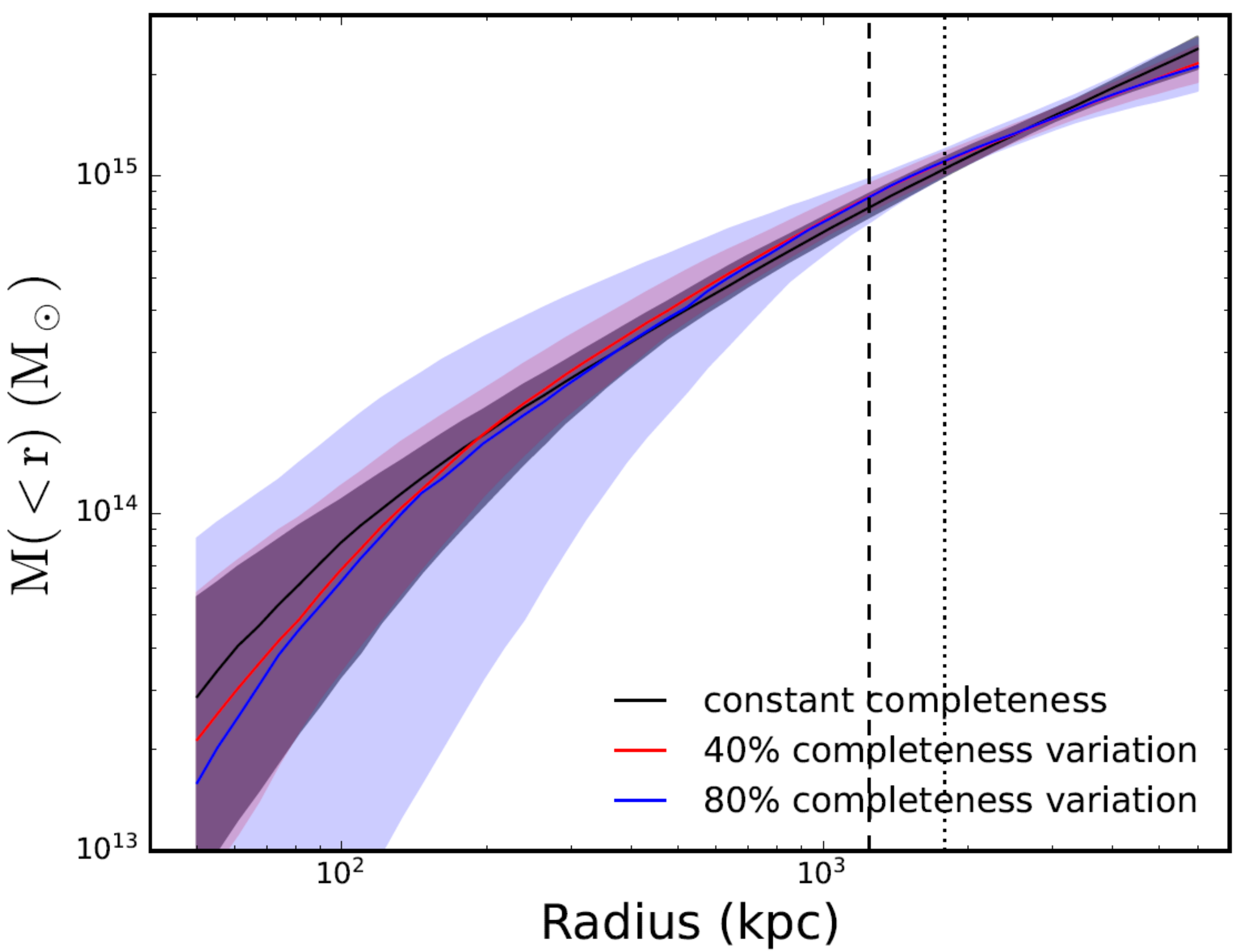
Effect of completeness:

$$\sigma_{los}^2(R) = \frac{2}{\Sigma_{gal}(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\upsilon(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr$$

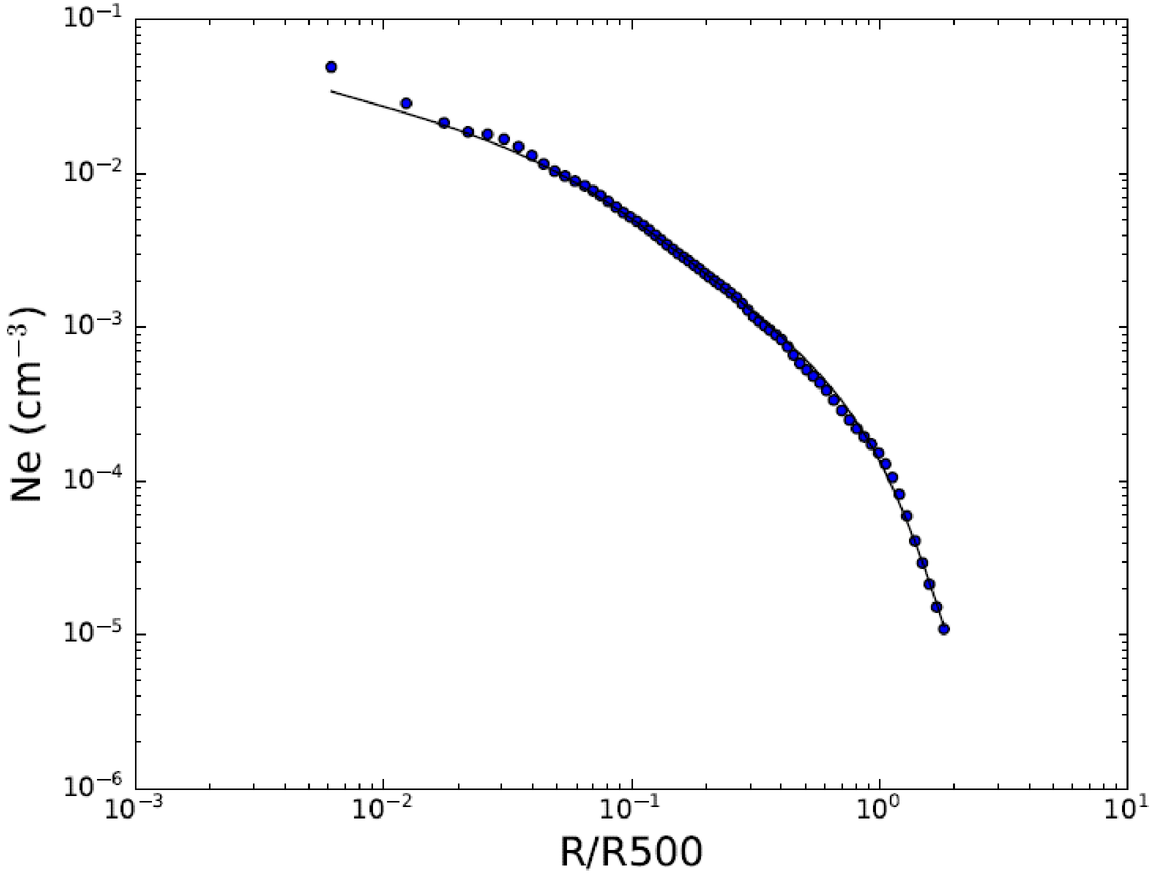
Radially varying completeness:

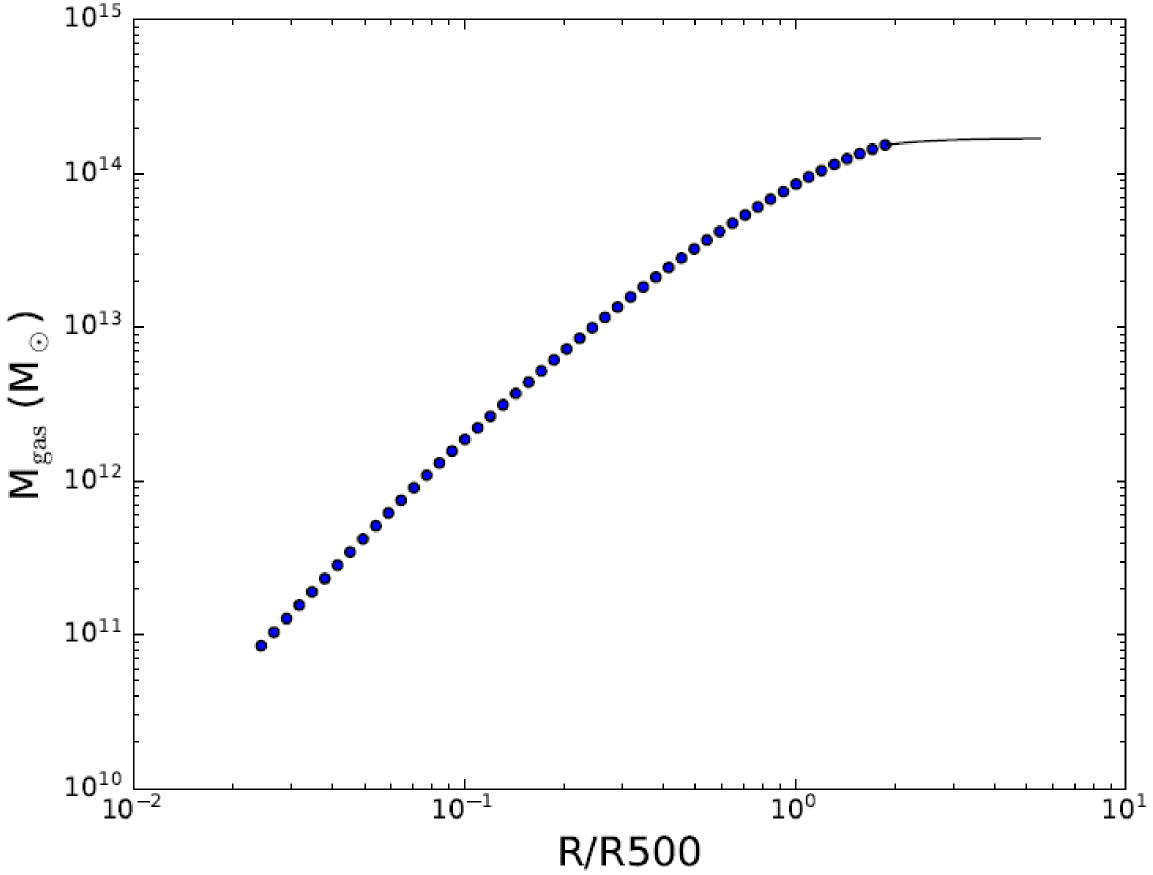
80% variation in completeness: 100% at small radii linearly decreases to 20% at outermost point;

40% variation in completeness: 100% at small radii linearly decreases to 60% at outermost point;

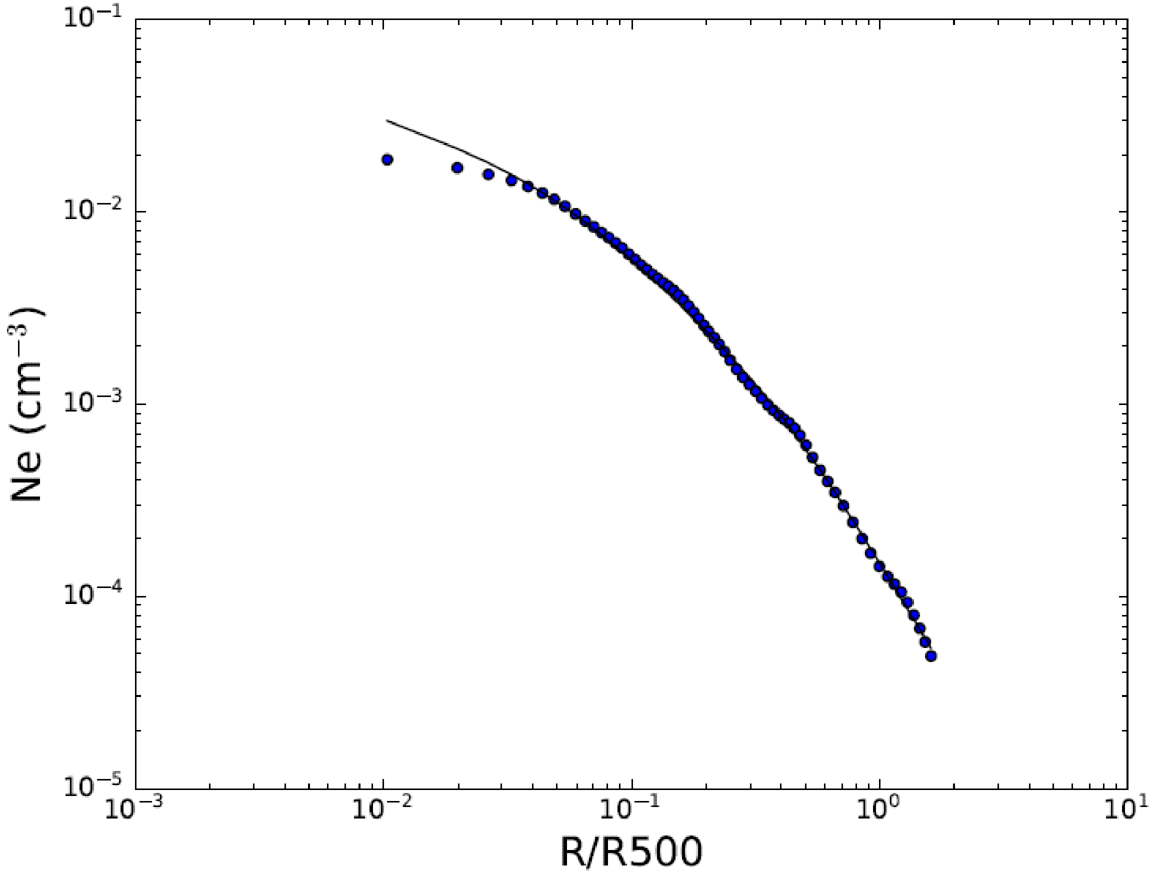


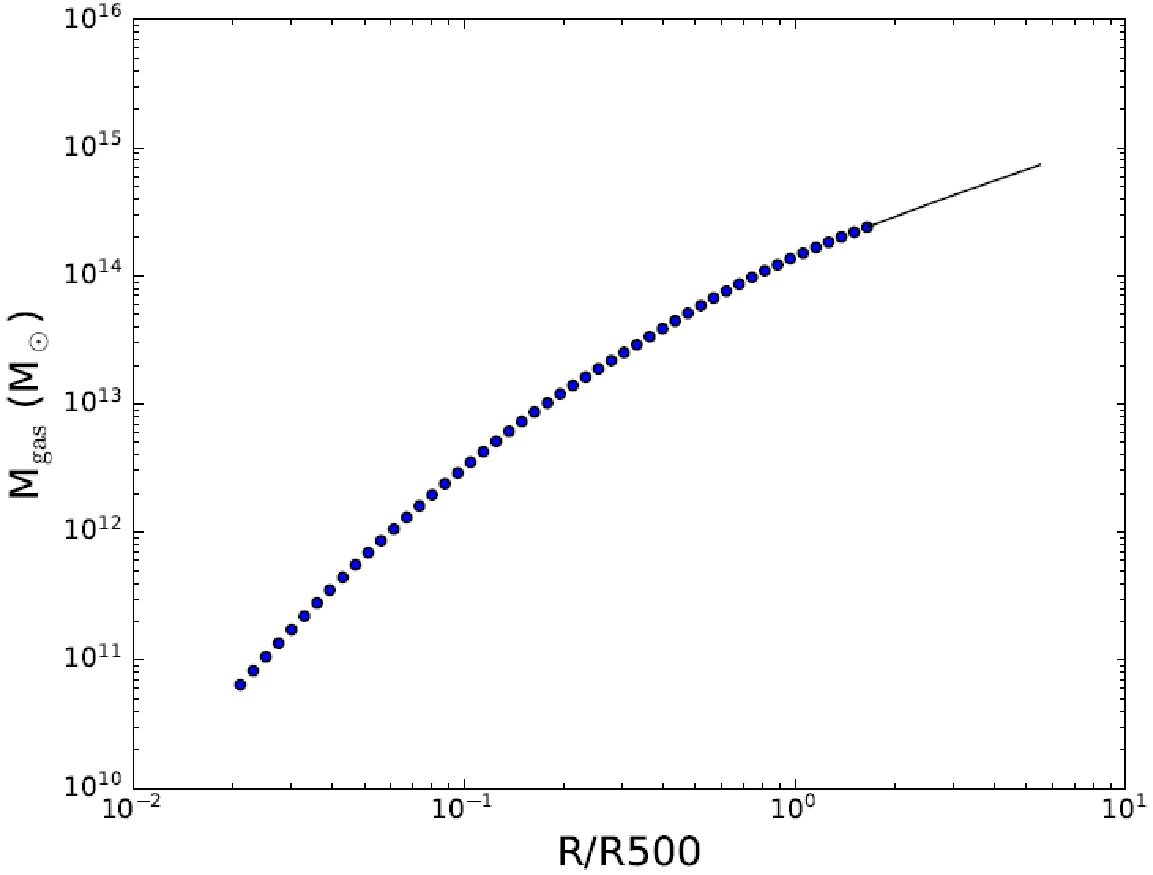
A0085: extrapolations for gas mass at large radii



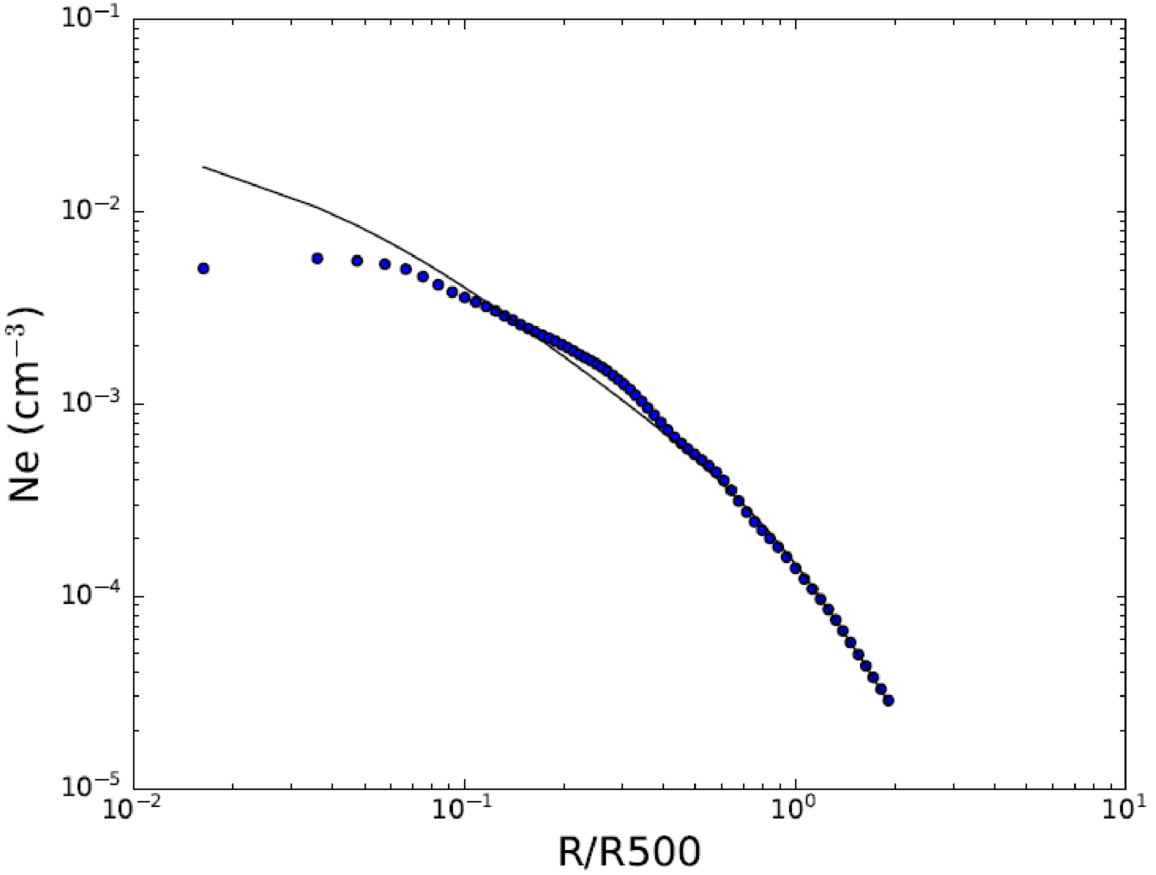


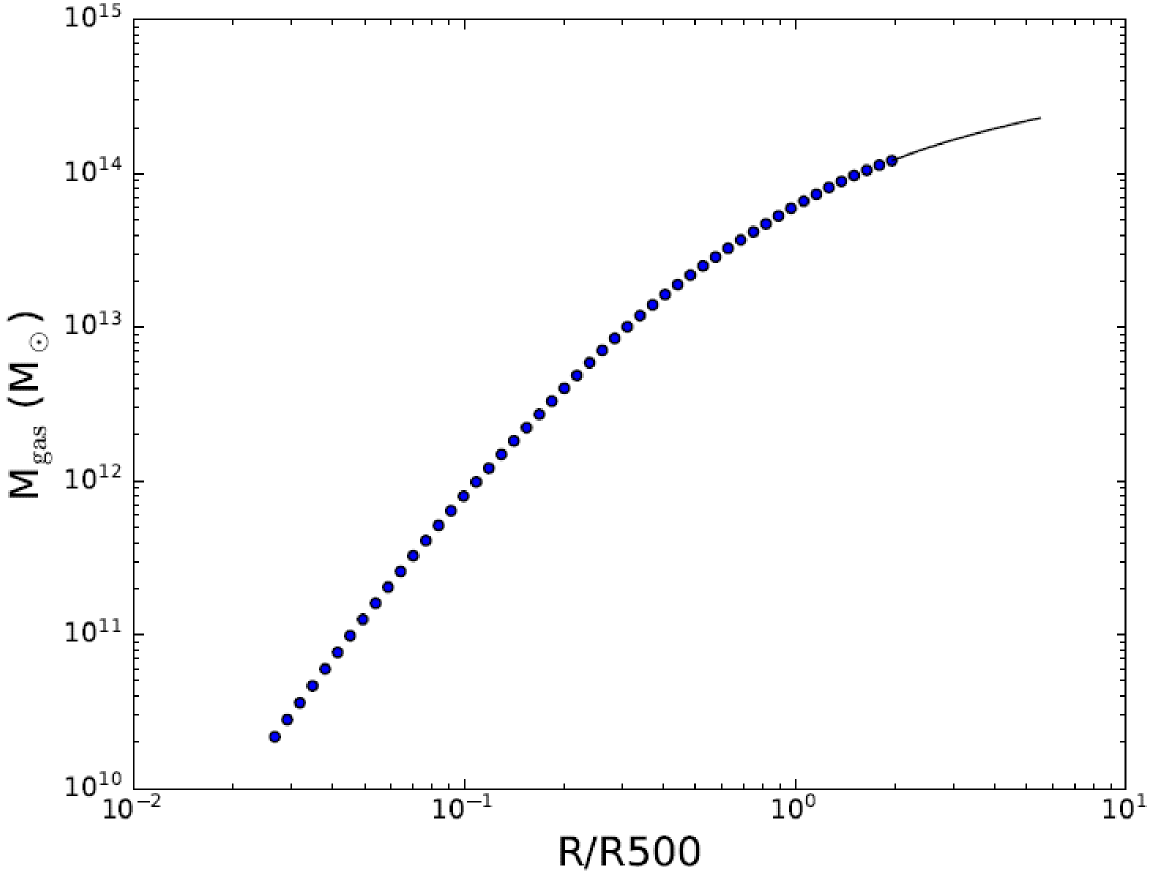
A2142: extrapolations for gas mass at large radii





A3158: extrapolations for gas mass at large radii





A1795: extrapolations for gas mass at large radii