3D (Y, M, Δ) scaling laws and projection effects in The300-NIKA2 Sunyaev-Zeldovich Large Program Twin Samples

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Outline

- Motivation
- The NIKA2 Sunyaev-Zeldovich Large Program (LPSZ) and The300
- Data: The300-NIKA2 twin sample
- Analysis and results
- Ongoing/future work
- Takeaway

Motivation

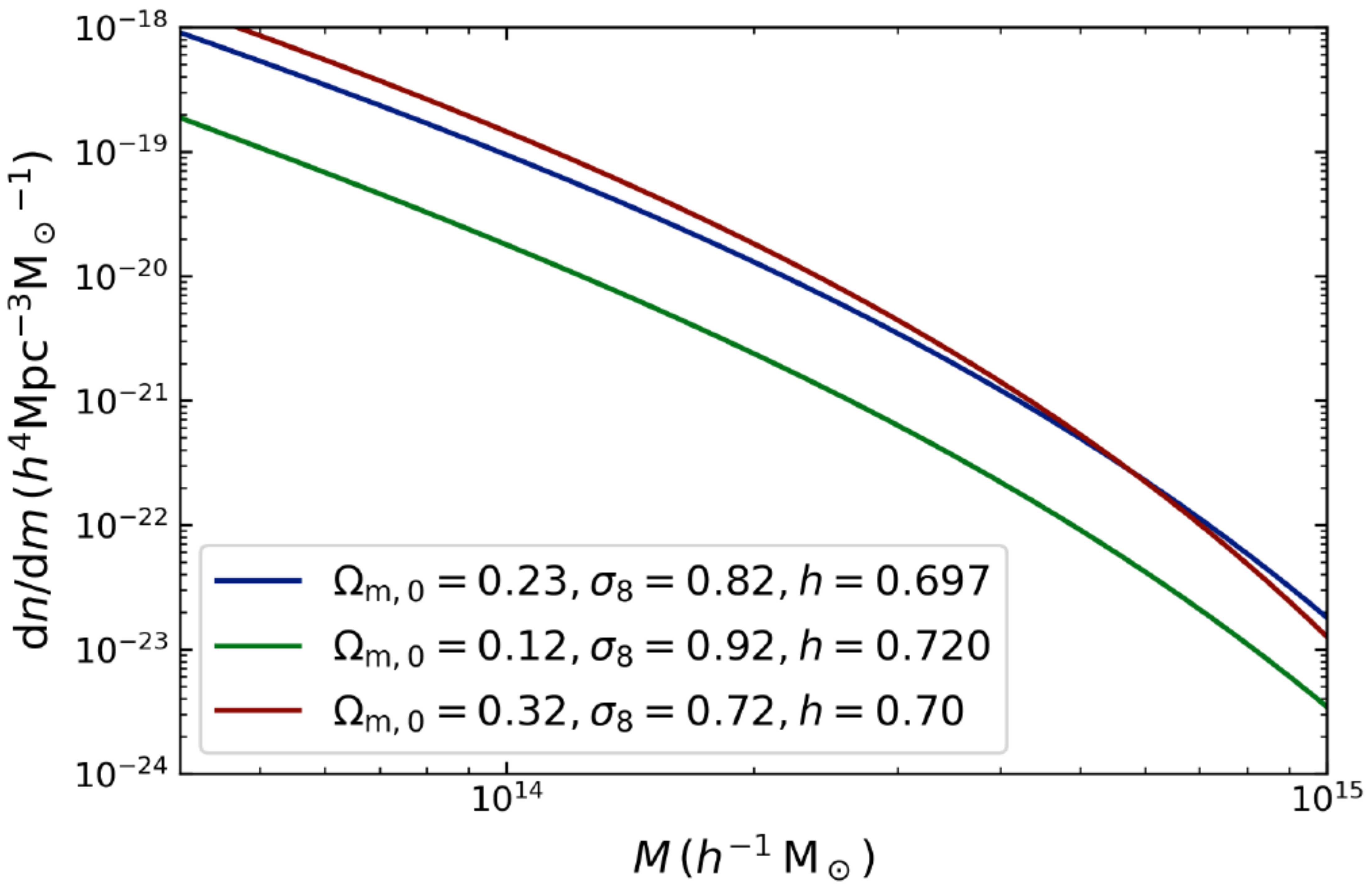
- Galaxy clusters are the **most massive**, gravitationally **collapsed structures in the Universe**, serve as good as growth of structure **tools to study cosmology** (see e.g. Planck Collaboration 2016a; Reiprich et al. 2021)

- Galaxy cluster **number density** and distribution **carries the imprint of** structure formation and **the underlying cosmology**

- Requires **accurate mass estimates** with high precision but, mass is **not directly observable**:

  =>Need for good calibration of observable-mass scaling relations
  =>Need to acquire detailed astrophysical information

- This requires a combination of **high sensitivity and high angular resolution observations, with detailed hydrodynamical simulations**



Theoretical galaxy cluster mass functions for different sets of cosmological parameters.

The NIKA2 Sunyaev–Zeldovich Large Program (LPSZ)* an The300**

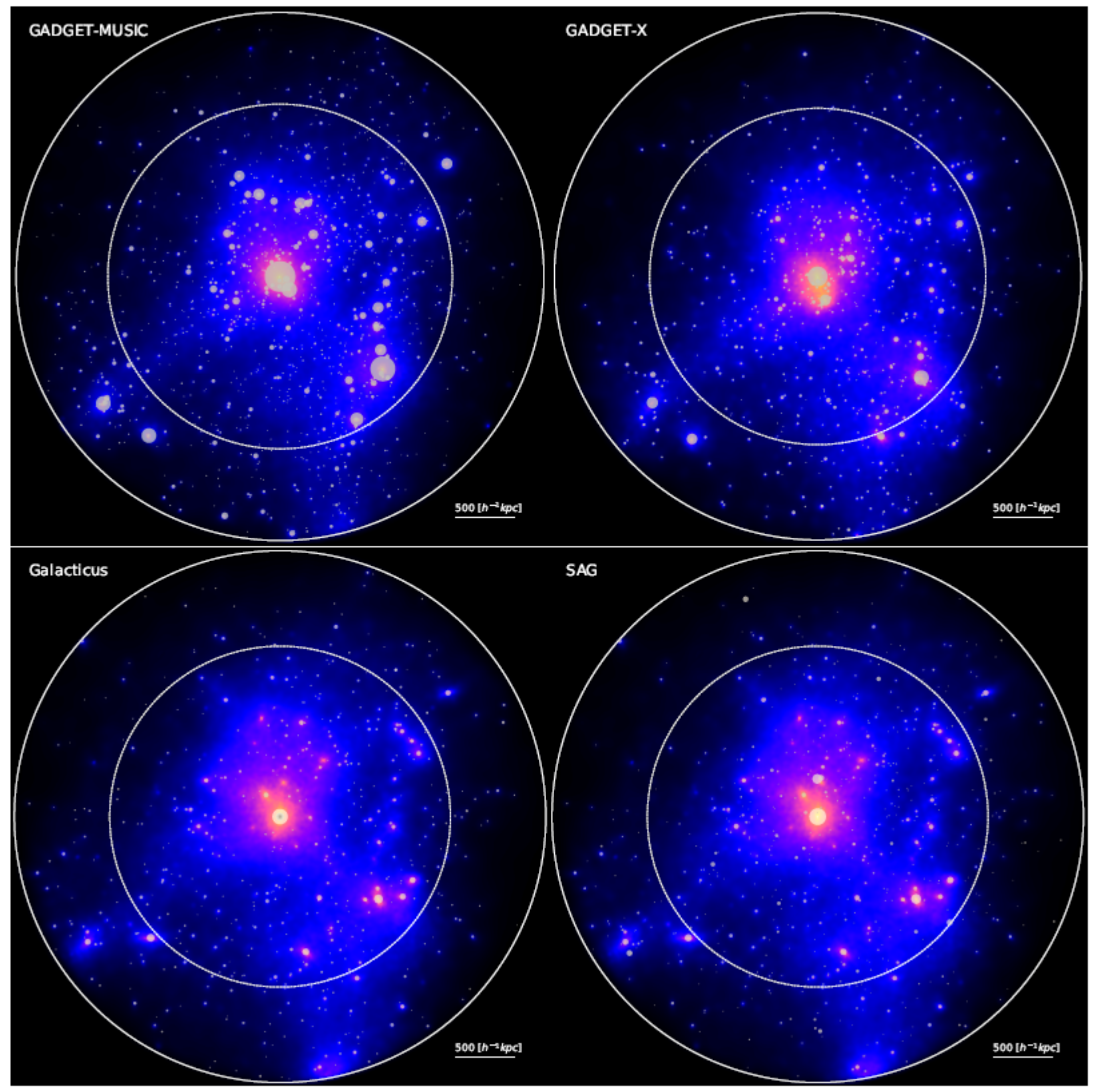
LPSZ (talk by L. Perotto)**:** Guaranteed time program of NIKA2, dedicated to SZ observations of clusters

- Sample of 38 clusters with $0.5 < z < 0.9$, covering about one order of magnitude in mass
- Follow-up of SZ-selected clusters from the Planck and Atacama Cosmology Telescope (ACT) catalogs

The300 (talk by W. Cui)**:** large sample of simulated galaxy clusters and their environment modelled using a range of simulation packages and physics modules that provides mock maps of the clusters in X-ray, optical, gravitational lensing, radio, and Sunyaev-Zeldovich (SZ) wavelengths

- 324 regions of radius 15 Mpc/h having a cluster identified at $z = 0$ with mass $M\_200 > 6.42 \times 10^{14}\ M_\odot/h$, at its centre
- Hydrodynamical simulations run for each region using standard SPH (GADGET-MUSIC) and modern SPH (GADGET-X, GIZMO-Simba)
- Semi-analytical model (SAM) counterparts produced using Galacticus, SAG, and SAGE

The IRAM 30-Meter telescope at Pico Veleta, Spain: site of the NIKA2 camera



An example of the clusters from The300. The coloured maps show the projected dark matter density, galaxy colours are calculated from the SDSS band magnitudes, and the sizes represent their stellar mass. W. Cui et al. 2018.

*L. Perotto et al. 2021, **the300-project.org

The300-NIKA2 twin sample

The samples:

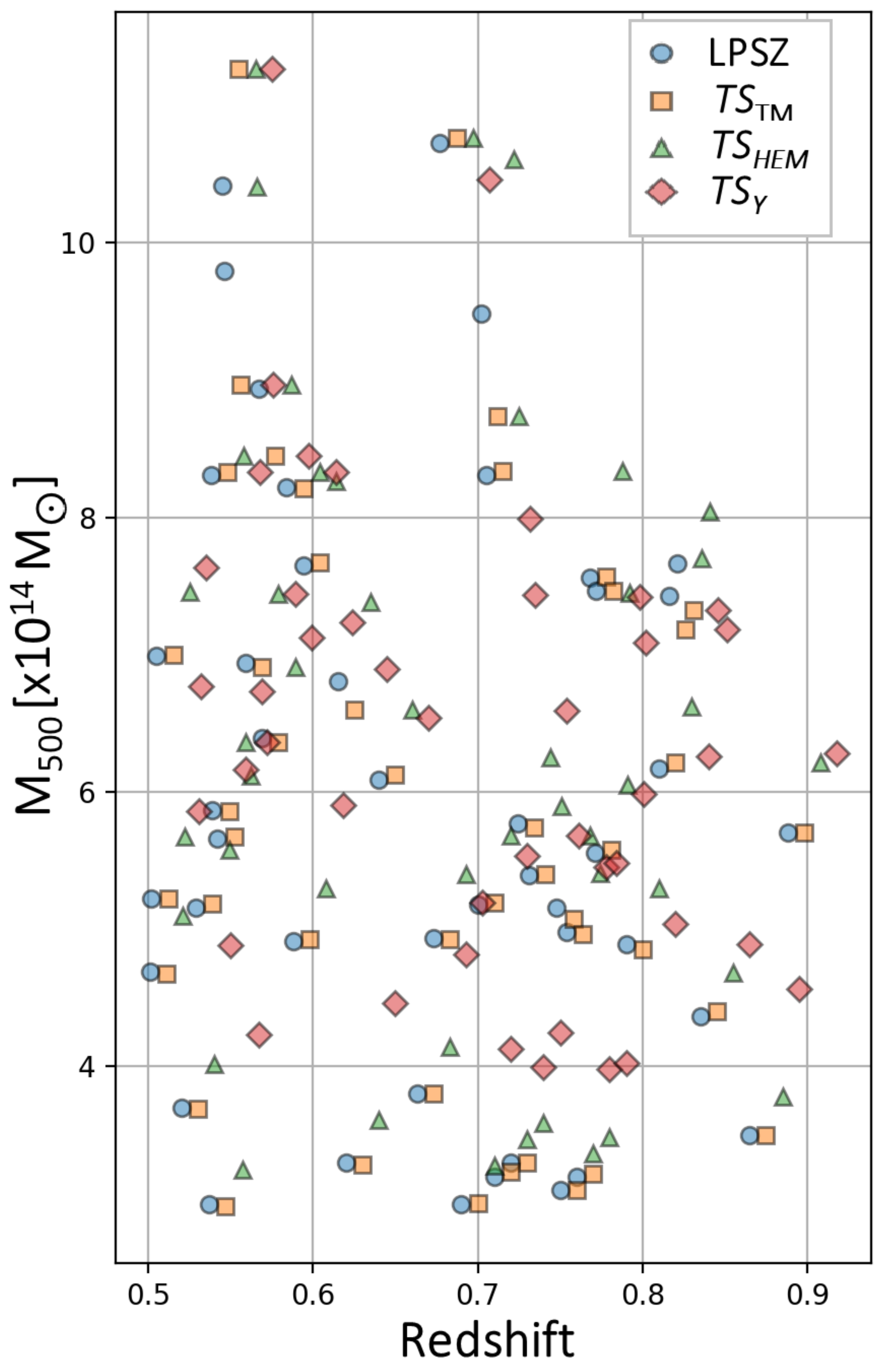
- Select snapshots in The300 with median z closest to z of each NIKA2 bin
- Create three “twin simples” (TS) based on following criteria
  - closest total M_500: **TS_TM**
  - closest hydrodynamical mass M_500: **TS_HEM**
  - closest integrated Compton parameter Y_500: **TS_Y**

Available data:

- y-maps (multiple projections)

$$y \equiv \int \frac{k_B T_e}{m_e c^2} \, d\tau_e = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl = \frac{\sigma_T}{m_e c^2} \int P_e \, dl.$$

- halo catalogues
- projected total mass density maps (multiple projections)
- ICM profiles (density, pressure, mass..)



A. Paliwal et al. 2021

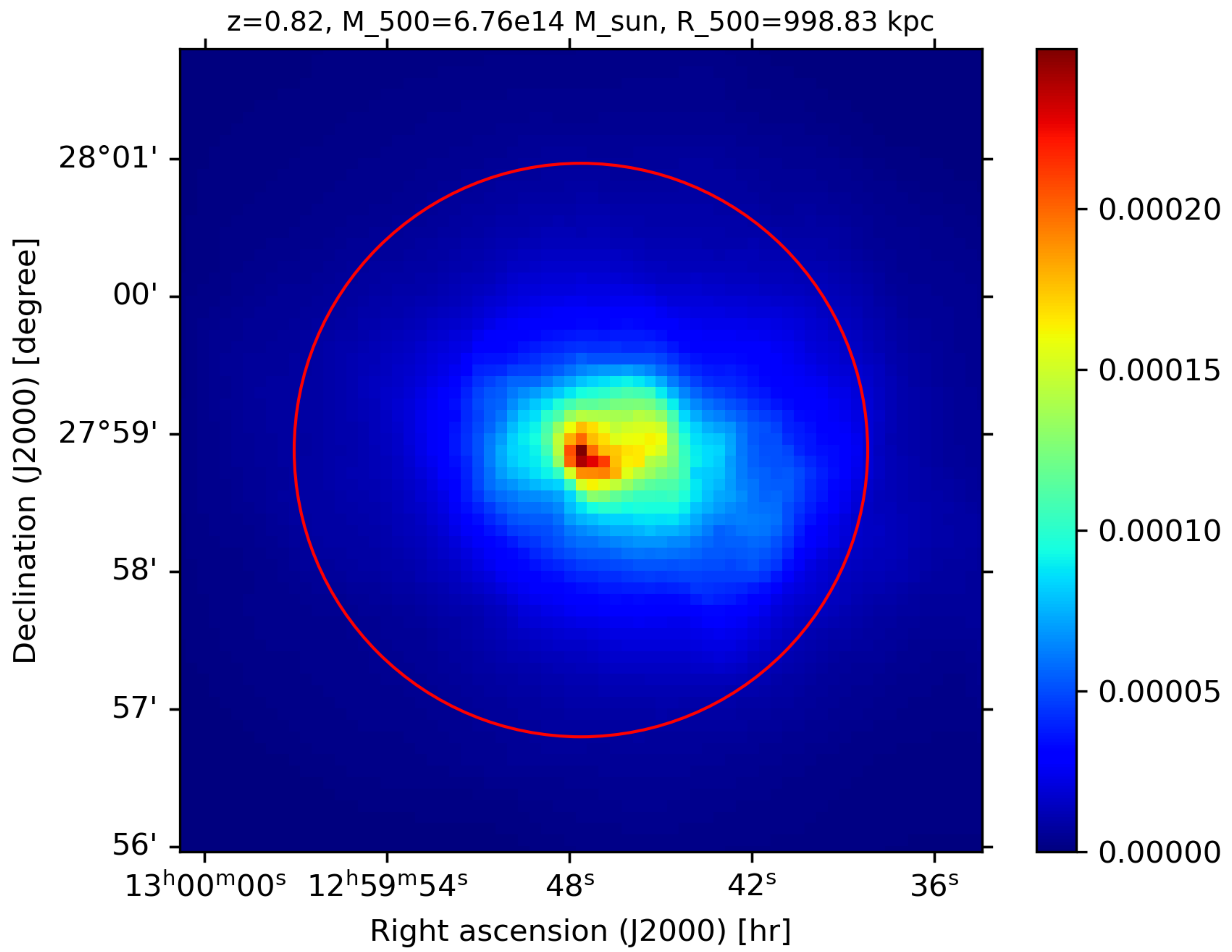
Integrated Y parameter estimates from y maps

For each twin sample we have y maps* along 29 different lines-of-sight, we estimate Y:

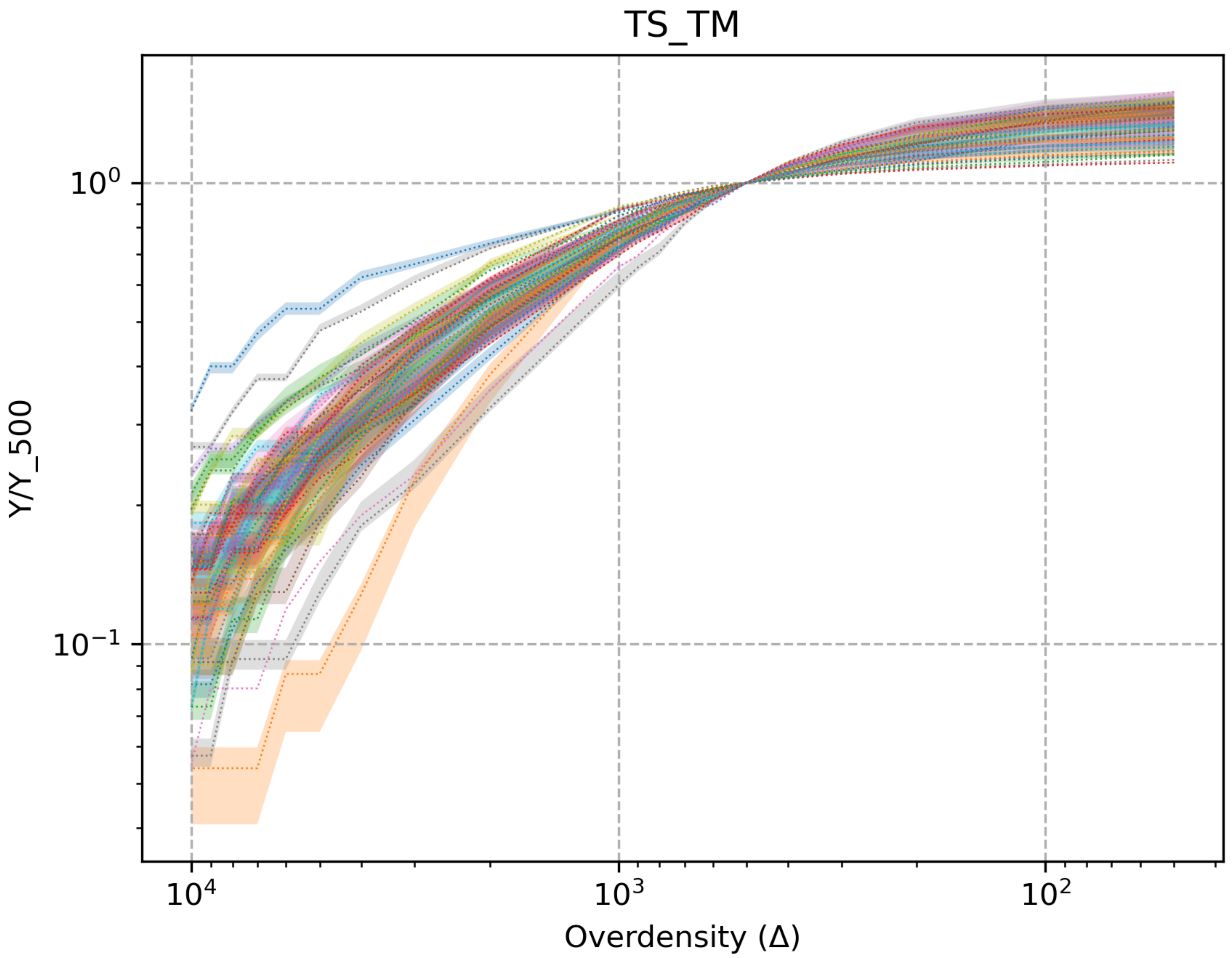
$$Y_\Delta \equiv \int_\Omega y_\Delta d\Omega$$

$$\Delta = \frac{M_\Delta/(\frac{4}{3}\pi r_\Delta^3)}{\rho_{crit}(z)}$$

at different overdensities for all clusters in a TS



Example of a simulated y map



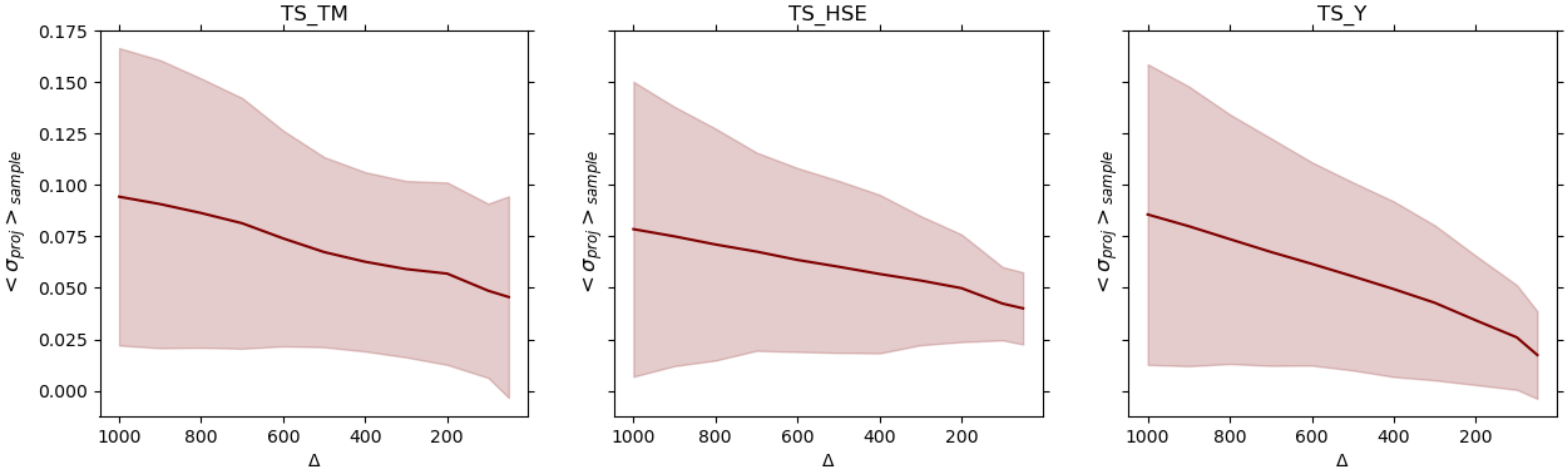
The shaded region indicates the spread of Y along the 29 LoS

To quantify: the spread in Y along different LoS and find the overdensity at which the spread is minimum

*All projected maps (y and M_total) from which the integrated (cylindrical) quantities are obtained, have an integration depth of 4 x r_200

Spread of Y along different LoS

The **scatter** induced on Y **due to projections is quantified** using the **standard deviation in the value of Y** calculated from **different LoS** maps at a given overdensity.
We calculated this scatter for each cluster in the TSs.
Here we show the **mean scatter** of the sample. The shaded area is the 1σ region.



We do not observe a special overdensity with minimum scatter in Y along different LoS: scatter decreases with decreasing overdensity

Correlation between spread in Y and cluster dynamical state

Is the spread in Y (quantified here using the NPR) along different LoS correlated with the cluster dynamical state?

We use the dynamical state parameter $\chi = \left[\frac{\Sigma_i \left(\frac{x_i}{x_{0,i}}\right)^2}{N}\right]^{-\frac{1}{2}}$ *

$$\text{Normalised percentile range } (NPR) = \left\langle \frac{Percentile_{84} - Percentile_{16}}{Median} \right\rangle_{sample}$$

There is no correlation between spread in Y along different LoS and χ, the former cannot be as a dynamical state indicator.

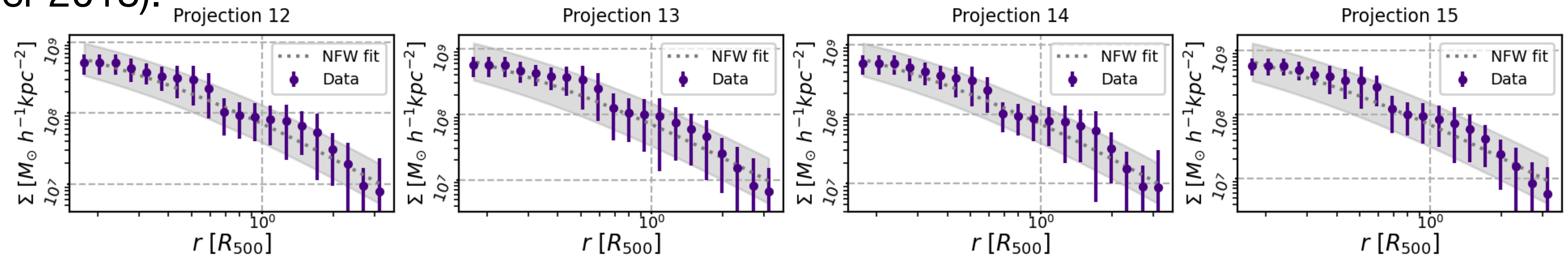
*De Luca et al. 2021

NB: we do find correlation between the spread in y and χ

Mass estimates

1. **Projected mass** estimates by directly integrating, within an aperture, the projected total mass density maps: **M_cyl**
2. We construct total projected mass density profiles from the corresponding simulated maps and fit them to projected NFW profiles (using Colossus, Diemer 2018):

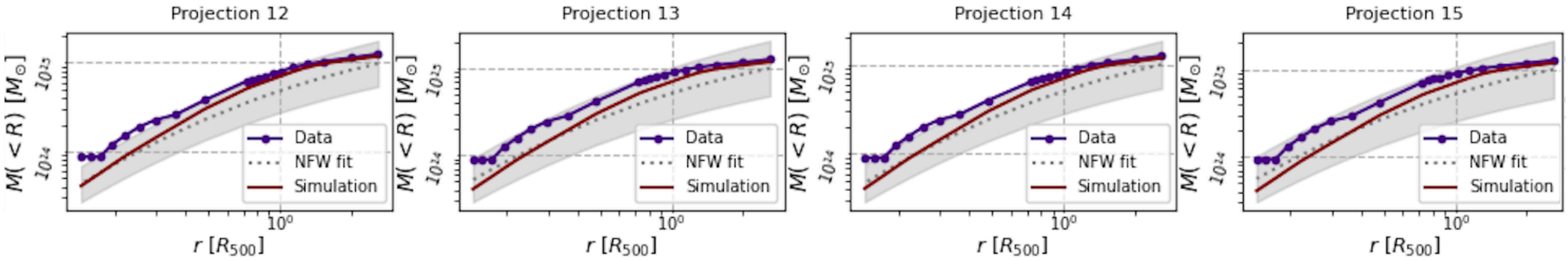
$$\Sigma(x) = \begin{cases} \frac{2\rho_s r_s}{x^2-1}\left(1 - \frac{2}{\sqrt{x^2-1}}\arctan\sqrt{\frac{x-1}{x+1}}\right) & (x > 1) \\ \frac{2\rho_s r_s}{x^2-1}\left(1 - \frac{2}{\sqrt{1-x^2}}\operatorname{arctanh}\sqrt{\frac{1-x}{1+x}}\right) & (x < 1) \\ \frac{2\rho_s r_s}{3} & (x = 1) \end{cases}$$



Examples of NFW fits obtained for some projections of cluster 27, snap 101, R_500 = 824.45 kpc, M_500 = 7.1 M_sol

And **de-project** the surface density profiles to 3D density profiles and consequently the **spherical mass**: **M_sph,NFW**

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

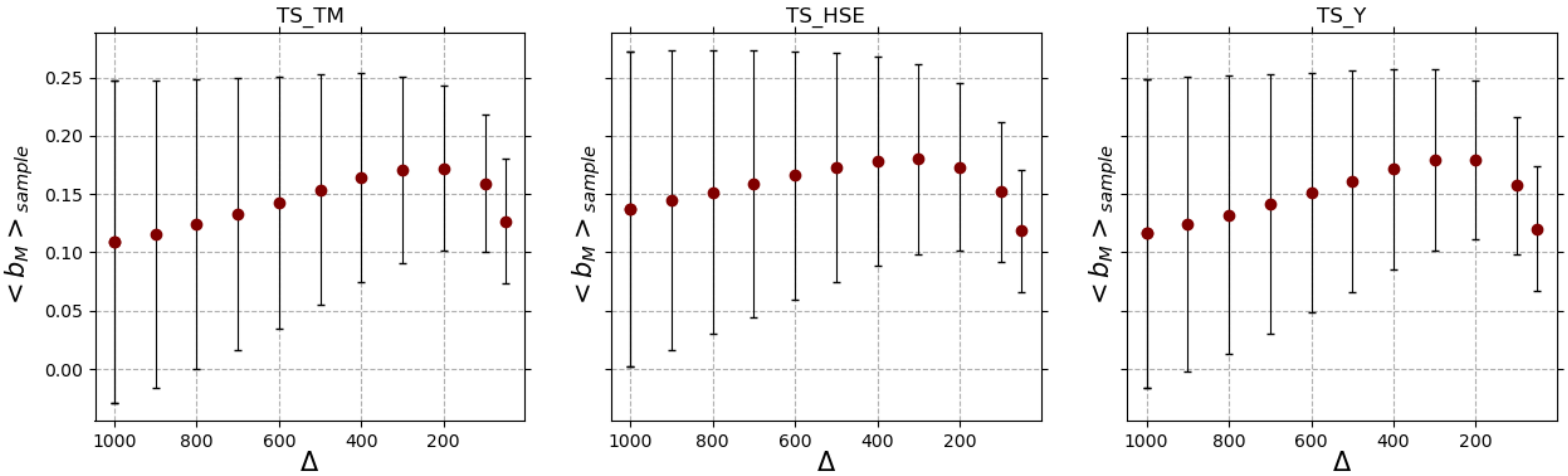


Examples of 3D mass profiles obtained for some projections of cluster 27, snap 101, R_500 = 824.45 kpc, M_500 = 7.1x10^14 M_sol

3. We have the **spherical mass** estimates from the simulation mass profile: **M_sph**; used to compare our mass estimates (1 and 2) with simulation

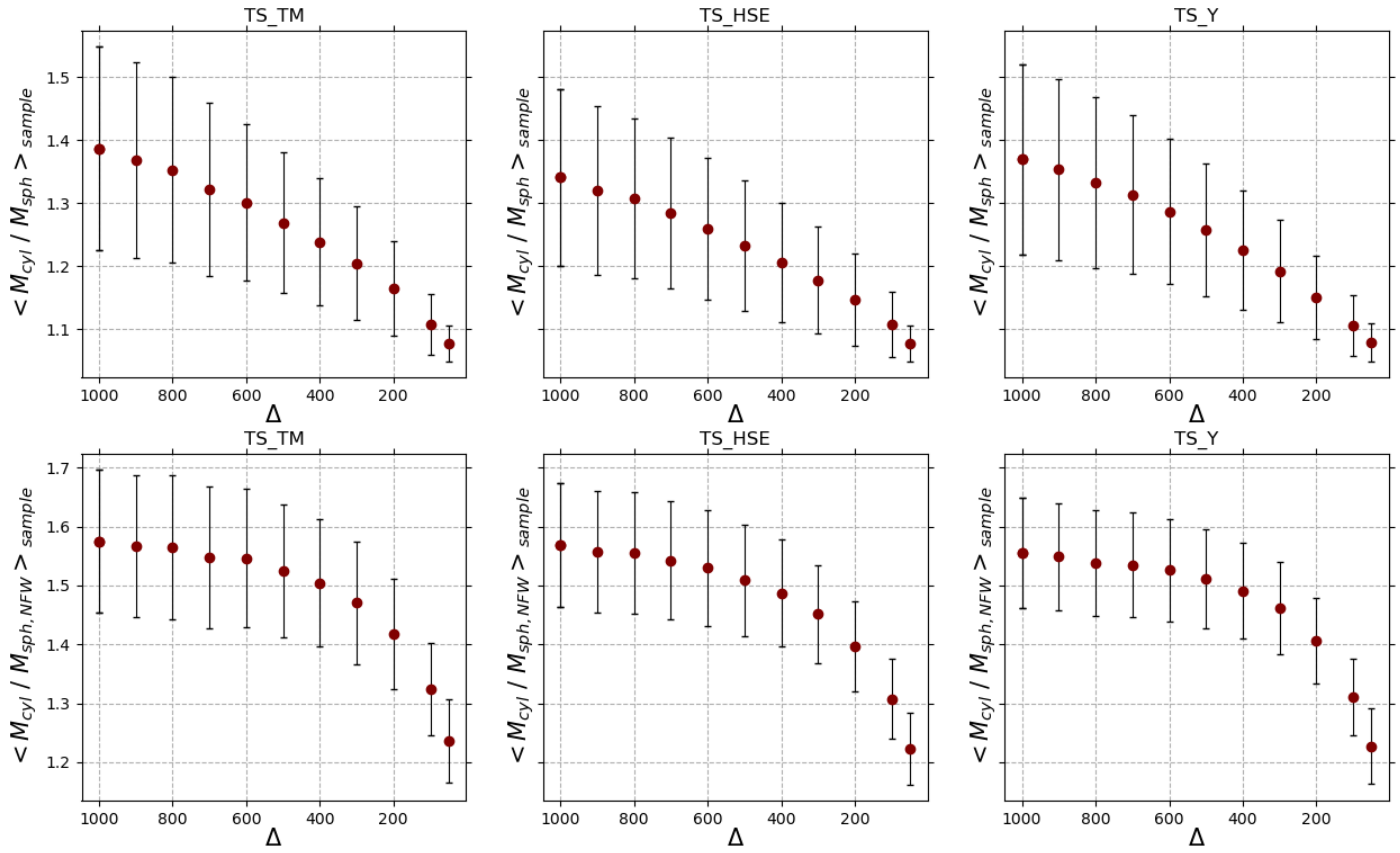
Mass estimates

Comparison between spherical mass values obtained from simulation and NFW fits: $b_M = \frac{M_{sph} - M_{sph_{NFW}}}{M_{sph}}$



Mass estimates

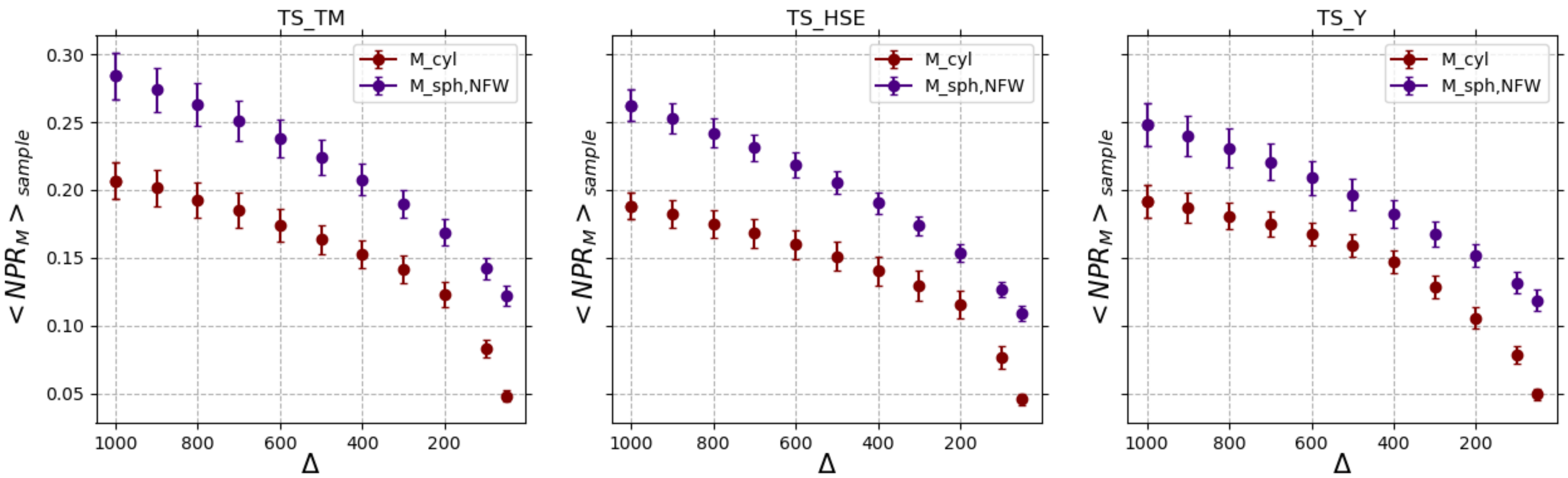
Comparison between cylindrical and spherical masses obtained from simulation and NFW fits: this comparison becomes relevant when comparing scaling laws built with M_cyl vs M_sph



As expected, the cylindrical masses are higher than the spherical ones, with the ratio decreasing with decreasing overdensity

Mass estimates

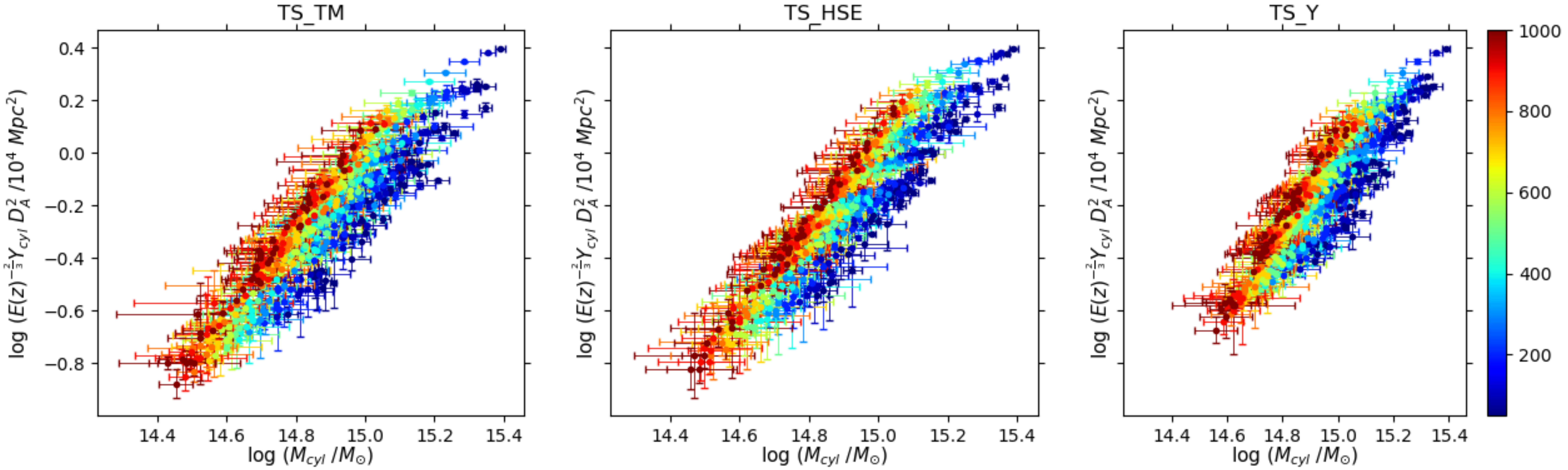
The scatter induced on mass due to the projection effect: higher in de-projected, spherical mass



3D scaling law: Y, M, Δ

We build a scaling laws between Y, M, Δ: $E(z)^{-\frac{2}{3}}\left[\frac{D_A^2 Y_\Delta}{10^{-4}\ \mathrm{Mpc}^2}\right] = A\left[\frac{M_\Delta}{6.10^{14}\ \mathrm{M}_\odot}\right]^B$ *

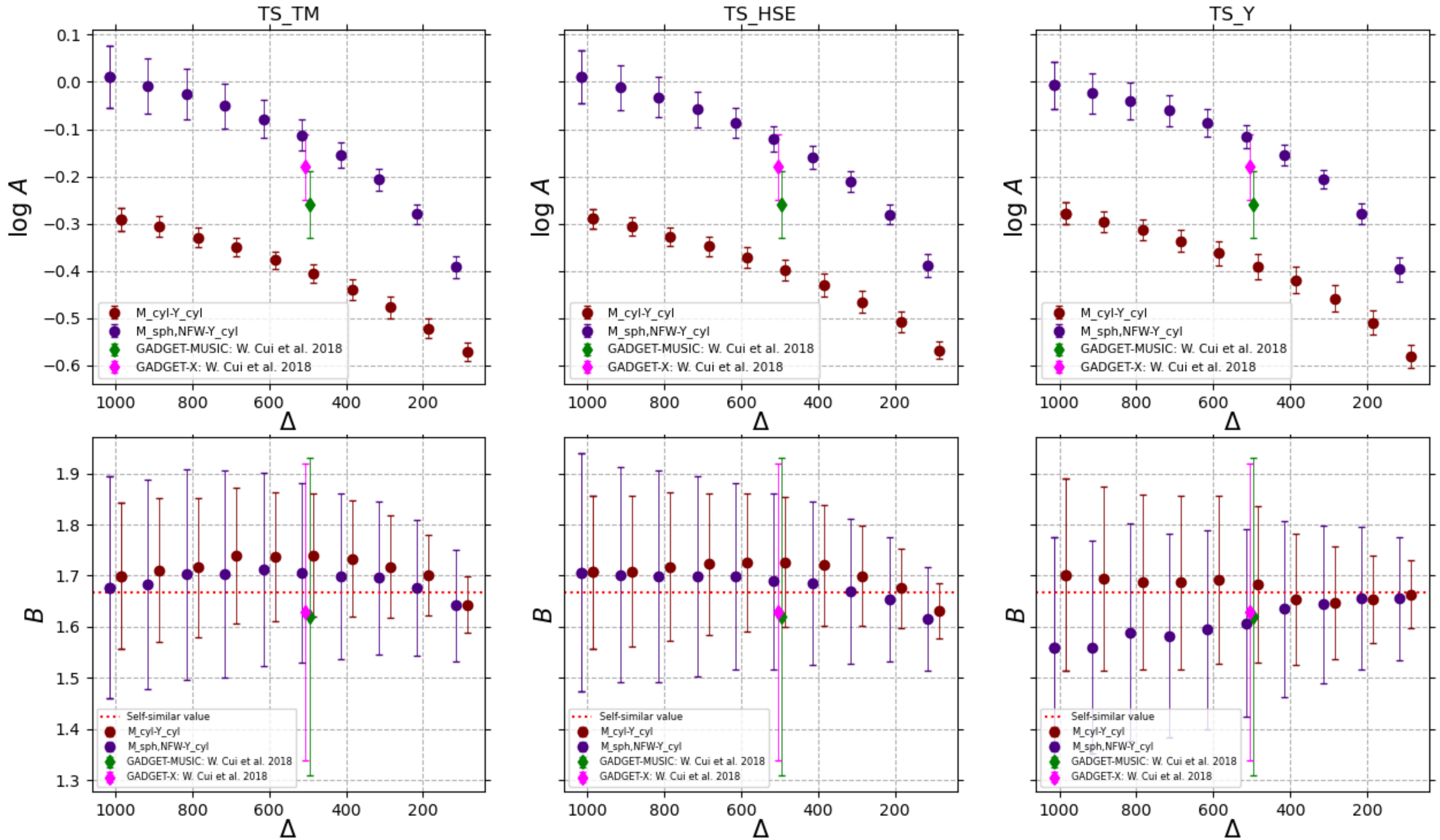
where M_Δ can either be M_cyl or M_sph,NFW and Y_Δ is Y_cyl



The Y-M distribution, at different overdensities, of the TSs. The errors are the scatter induced due to projection. We use pylira (https://github.com/fkeruzore/pylira), the python wrapper of the LIRA code (M. Sereno 2016) to fit the scaling laws. We assume no redshift evolution in the slope, normalisation, or the intrinsic scatter.

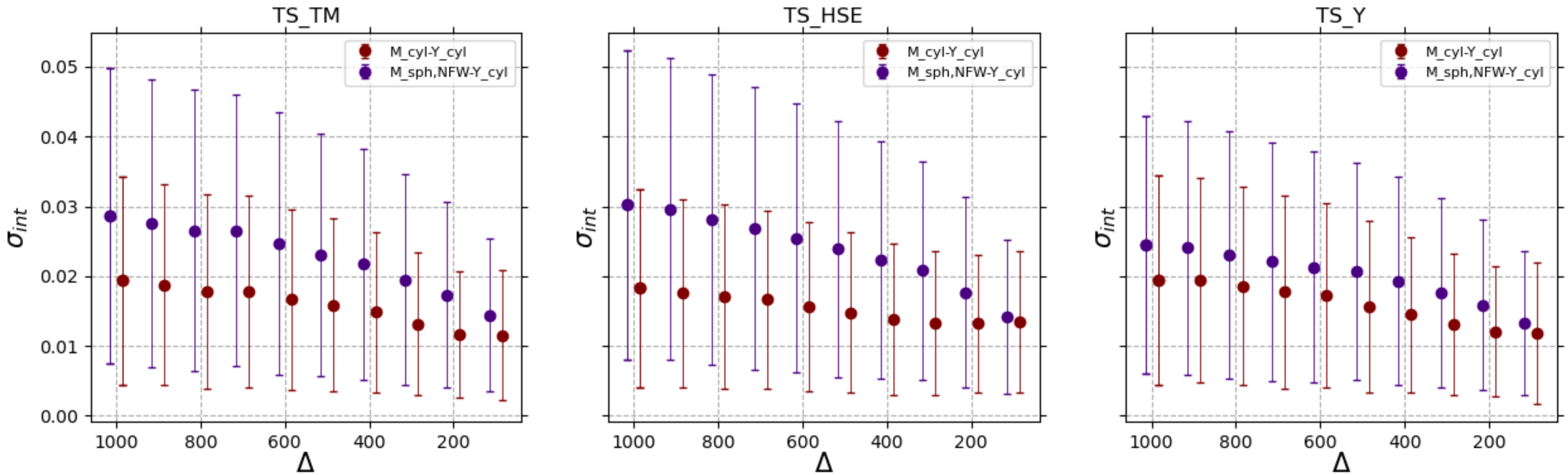
*Planck Collaboration *et al.* 2014

3D scaling law: best-fit parameters



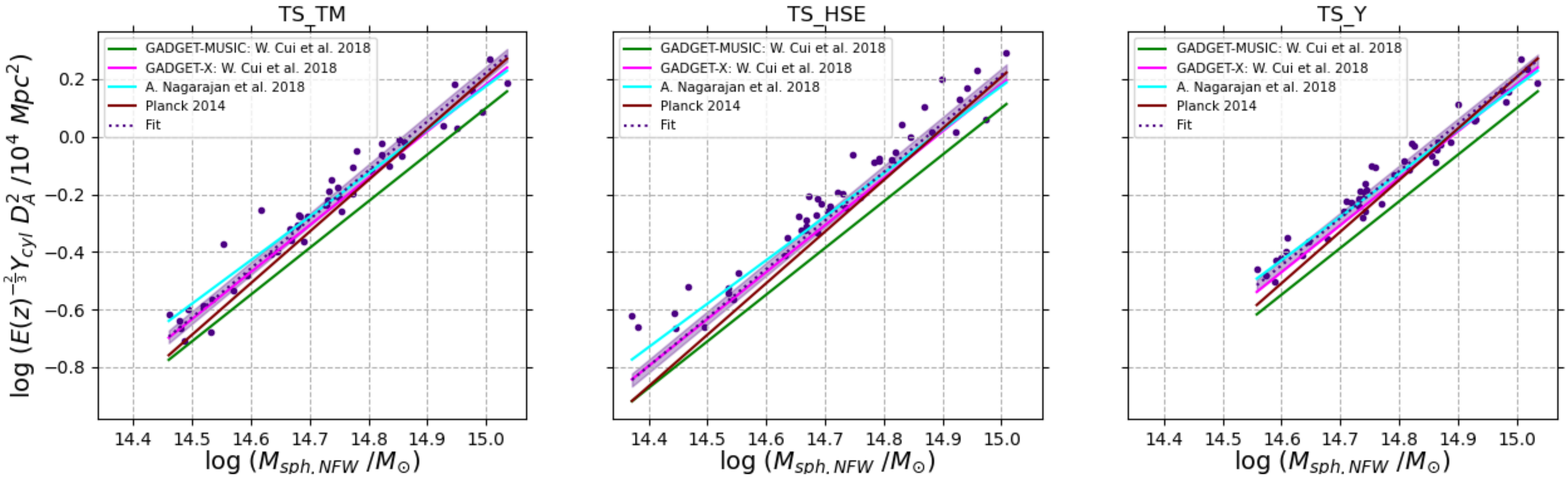
- The **normalisation decreases with decreasing overdensity** and is higher for SL calibrated using spherical mass
- No significant trend in the **slope** other than its **dispersion decreasing with decreasing overdensity**
- **No departure** in the value of **slope from the self-similar** value

3D scaling law: best-fit parameters



- The **intrinsic scatter** in the SL (at z=0) **decreases with decreasing overdensity**; e.g. the scatter at Δ(500)=1.2 x Δ(200)
- The scatter (and its dispersion) is **lower for M_cyl**
- The **scatter due to projection is comparable to intrinsic scatter**, hence cannot be ignored. Albeit, the intrinsic scatter is derived with no observational/instrumental error and hence maybe underestimated

3D scaling law: comparison with existing scaling laws



The M_sph,NFW-Y_cyl scaling laws compared to literature. The errors on individual data points are omitted for visualisation purpose.

Ongoing/future work

To include more realistic observational errors we extend this analysis in the following way

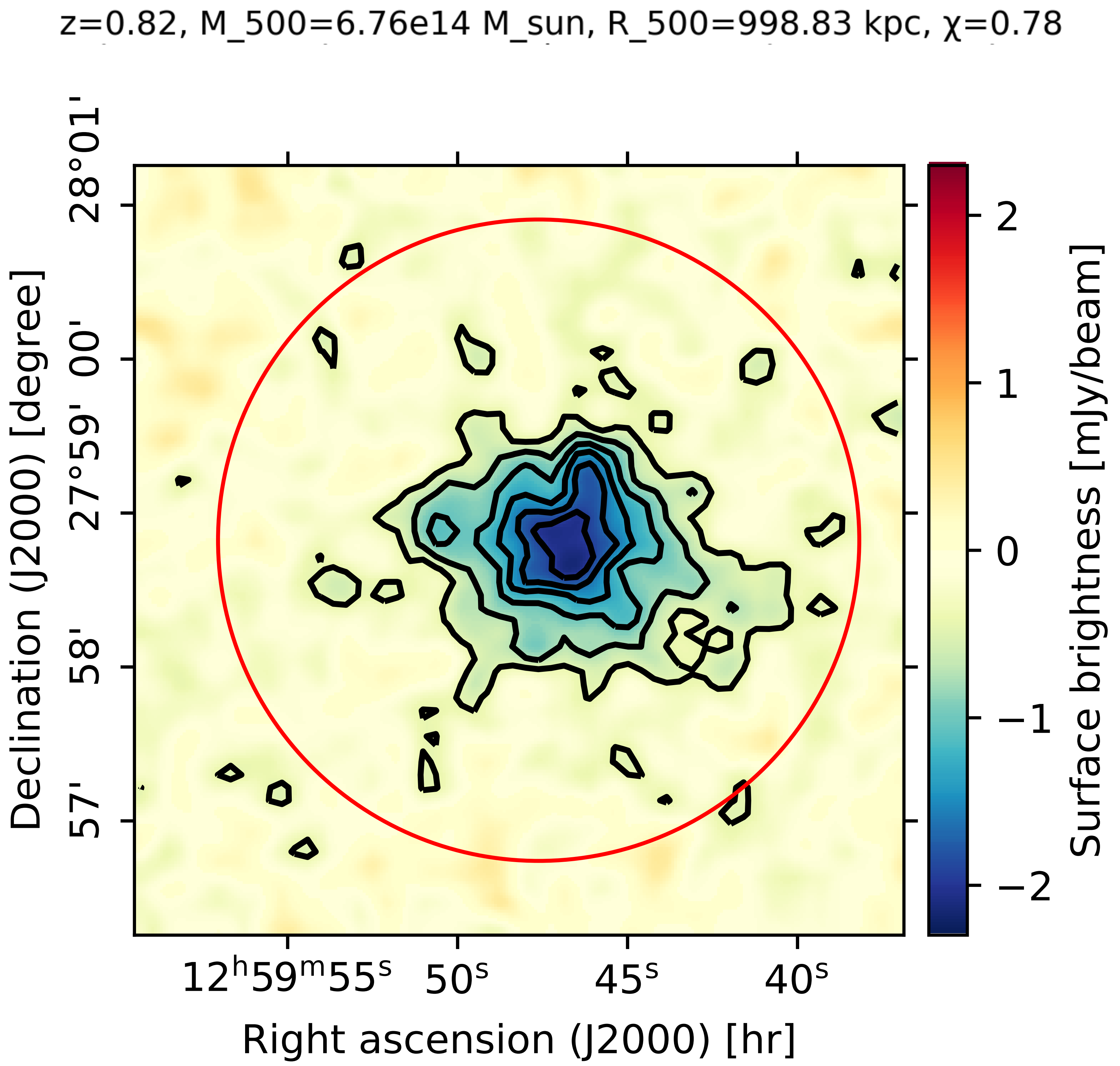
=> Create NIKA2 like maps for all the simulated y projections (example of one projection is shown on the right side for, cluster 29, snap 101)

=> Combine these maps with ICM electron density profiles from simulations to calculate HSE mass at different over-densities using:

$$M_{\mathrm{HSE}}(< r) = -\frac{1}{\mu m_p G}\frac{r^2}{n_e(r)}\frac{\mathrm{d}P_e(r)}{\mathrm{d}r}$$

with the standard procedure followed for the LPSZ clusters
(talk by C. Hanser, A. Moyer)

=> Fit the SL law using this mass estimate and compare the results to the present ones



Takeaway

- Optimal overdensity: the scatter induced on Y due to projection and the Y-M scaling law intrinsic scatter decrease with decreasing overdensity i.e. there is no special overdensity at which the scatter is minimum

- The projection induced scatter on both, Y and M is higher for de-projected mass values M_sph,NFW as compared to M_cyl

- The scatter induced due to projection is comparable to the intrinsic scatter of the Y-M scaling law hence can not be ignored
  Caveat: the scaling laws are calibrated without realistic observational errors and the intrinsic scatter may be underestimated

- The scatter induced on Y due to projection is not correlated with the cluster dynamical state

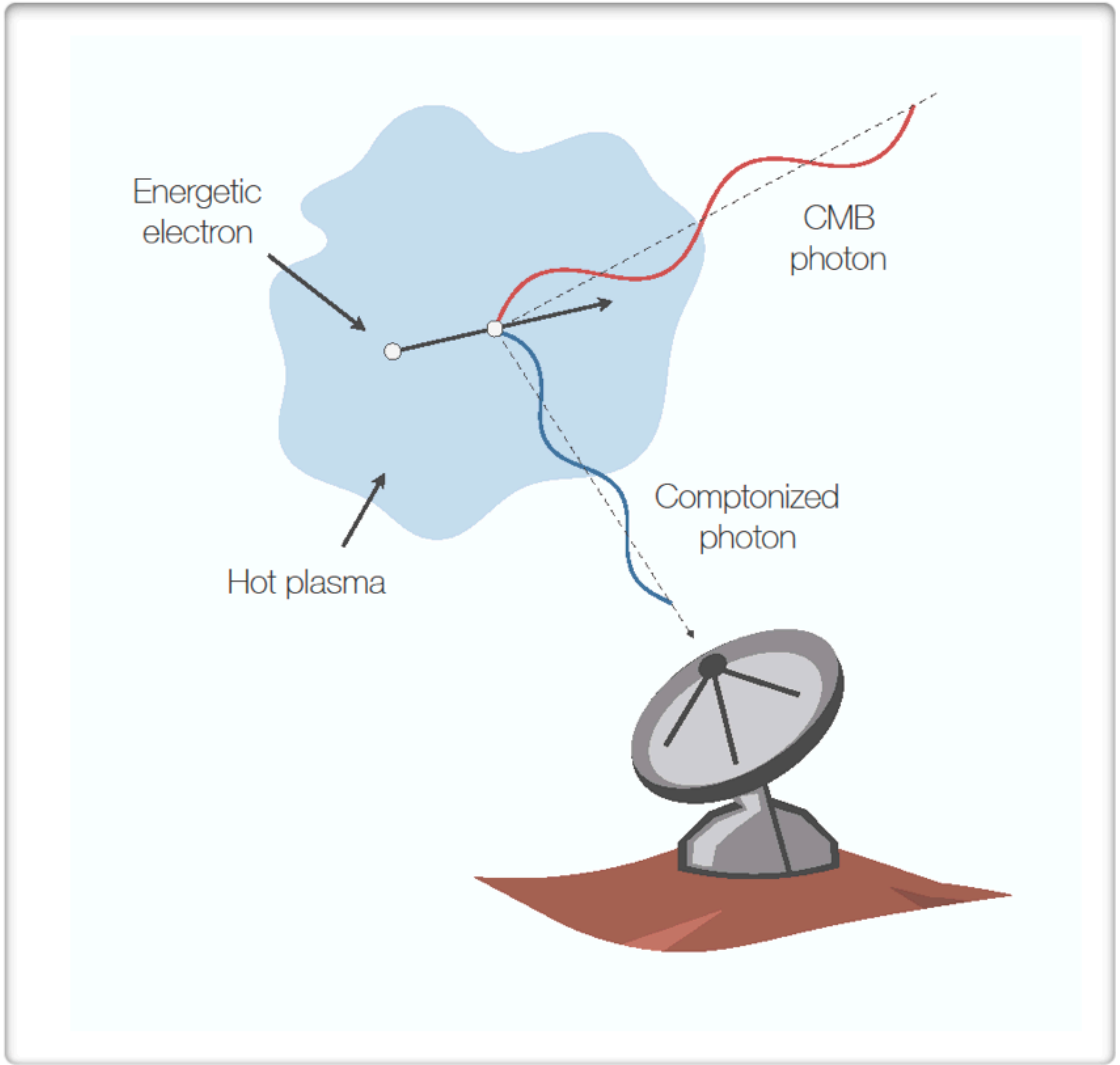
Backup: The Sunyaev-Zeldovich (SZ) effect in galaxy clusters

$$y \equiv \int \frac{k_B T_e}{m_e c^2} \mathrm{d}\tau_e = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T \mathrm{d}l = \frac{\sigma_T}{m_e c^2} \int P_e \, \mathrm{d}l.$$

The derived pressure (profile) can be used to estimate mass of the cluster using the hydrostatic equilibrium equation

Further, the integrated Compton parameter is tightly related to the mass of the cluster.

$$Y \equiv \int_\Omega y \, d\Omega$$



Mroczkowski et al. 2019

Correlation between chi and spread in y