A Bayesian Hierarchical Model for estimating the heterogeneity of pressure profiles within a population of galaxy clusters

Castagna Fabio (INAF Brera - Milano)
Andreon Stefano (INAF Brera - Milano)
Trombetta Alberto (Insubria University - Varese/Como)
Landoni Marco (INAF Brera - Merate)

IASF-MI Seminar - October 30th, 2024

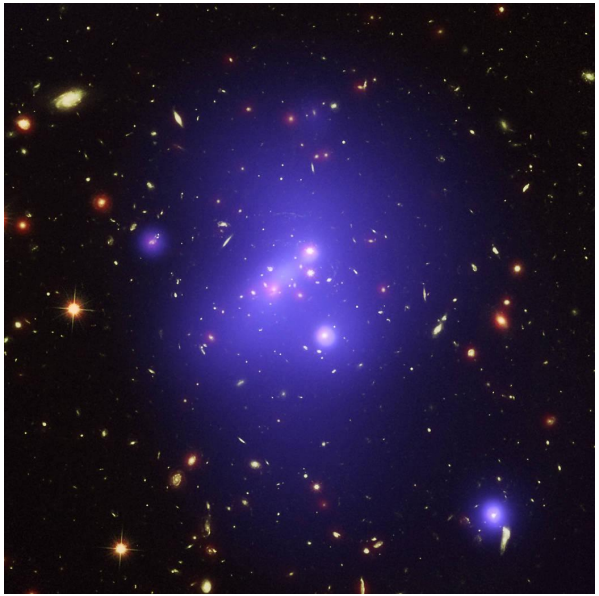
INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Finanziato dall'Unione europea
NextGenerationEU

Galaxy clusters

- **Largest** gravitationally bound structures in the universe

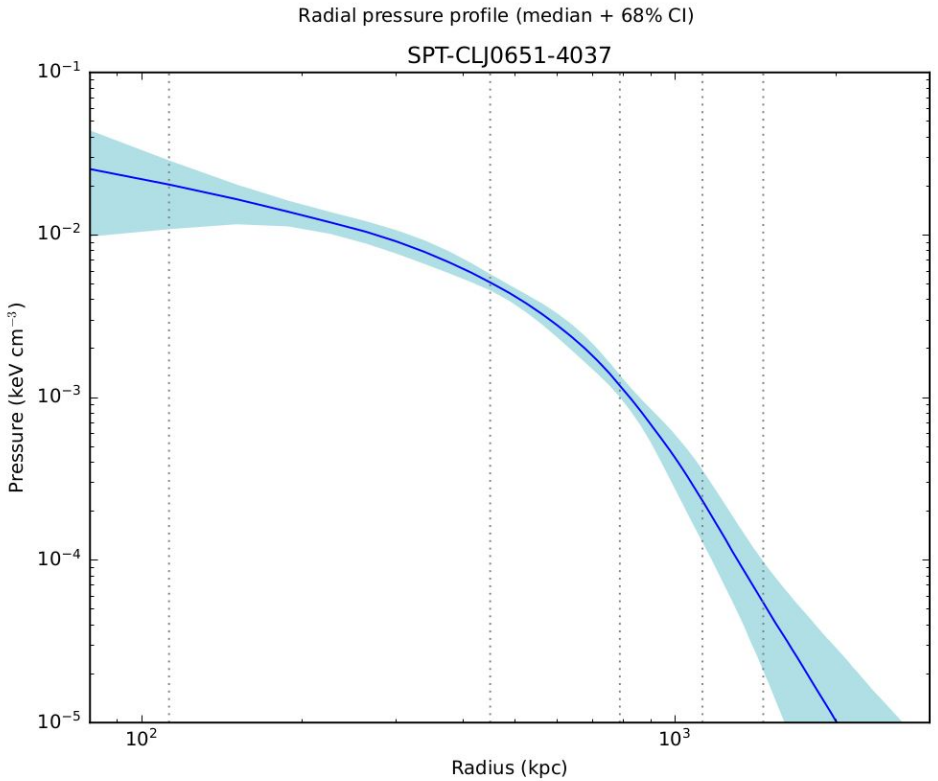
- Crucial to probing the **evolution** of the **universe** at the largest scales



INAF
Finanziato dall'Unione europea
NextGenerationEU

Pressure profile

- Along with other **thermodynamic properties**, it is a valuable asset to **investigate** the structure of galaxy clusters:
  - e.g., **shock fronts**
  - e.g., constraints on **cosmological** parameters estimation

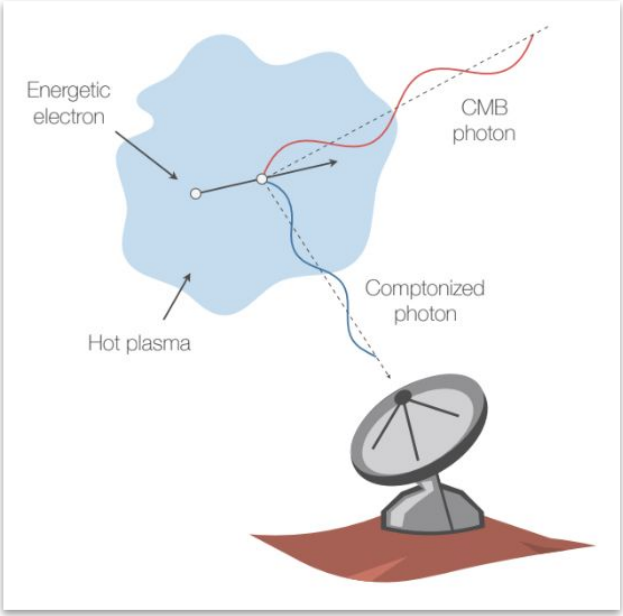


INAF
Finanziato dall'Unione europea
NextGenerationEU

The Sunyaev-Zeldovich effect

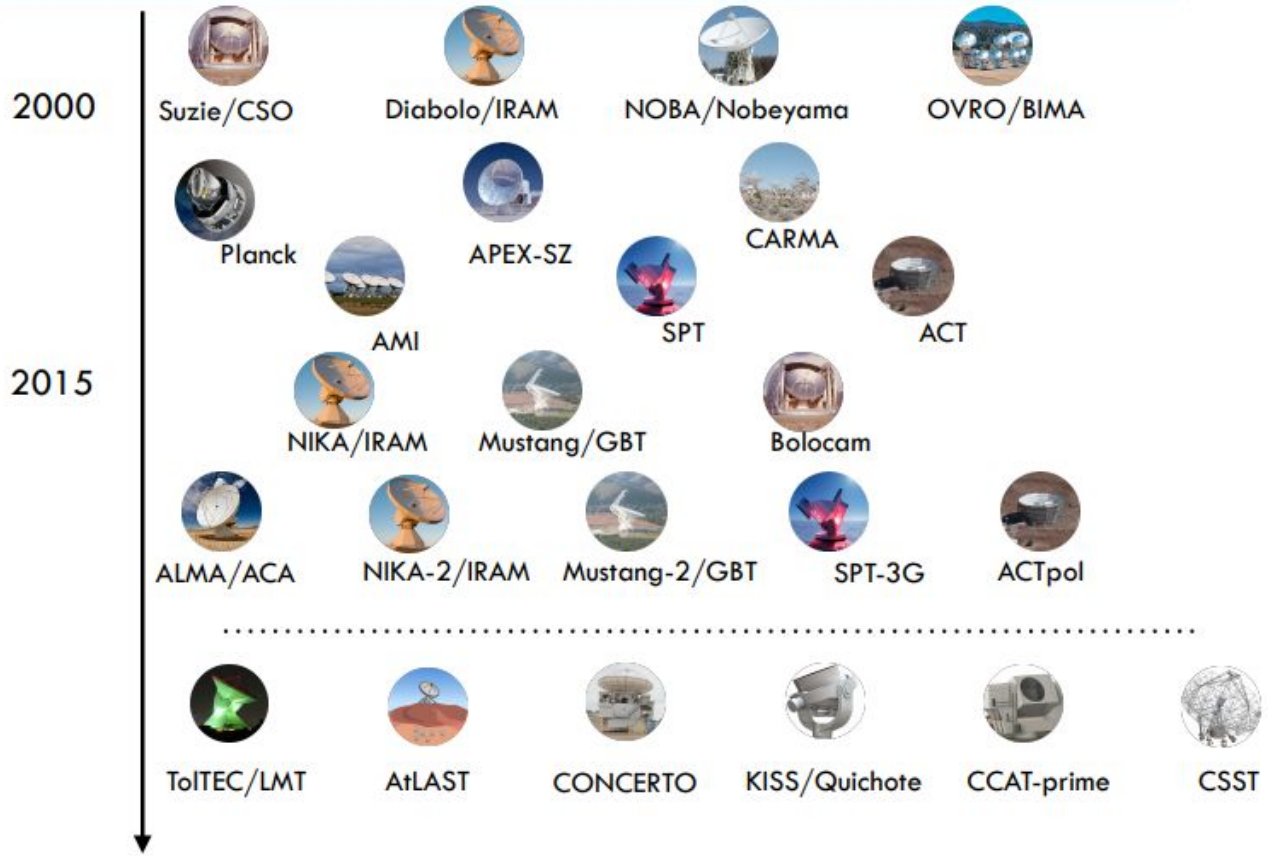
- Spectral **distortion** of the **CMB** radiation

- Arises from **inverse Compton** scattering of photons with high-energy electrons in the ICM.



The thermal SZ effect (Mroczkowski et al. 2019)

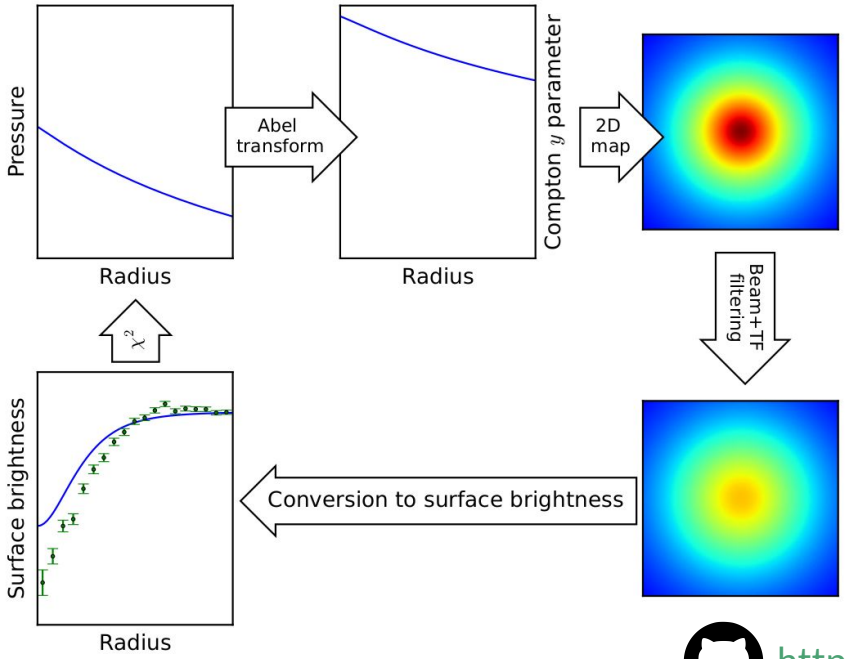
INAF
Finanziato dall'Unione europea
NextGenerationEU



Huge increment of high-resolution SZ instruments (Pointecouteau 2019)

INAF
Finanziato dall'Unione europea
NextGenerationEU

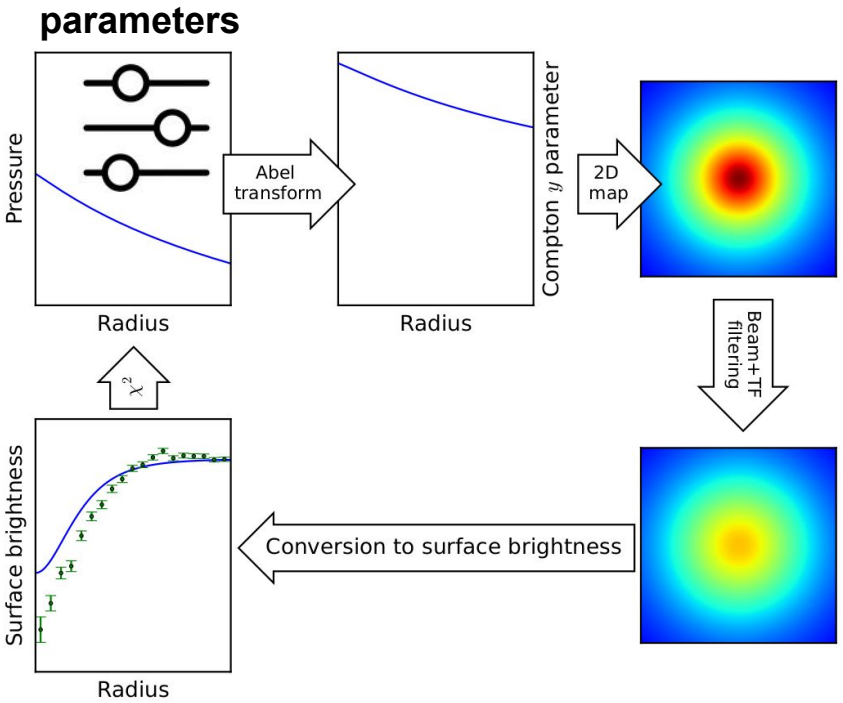
PreProFit - Pressure Profile Fitter for galaxy clusters



https://github.com/fcastagna/preprofit

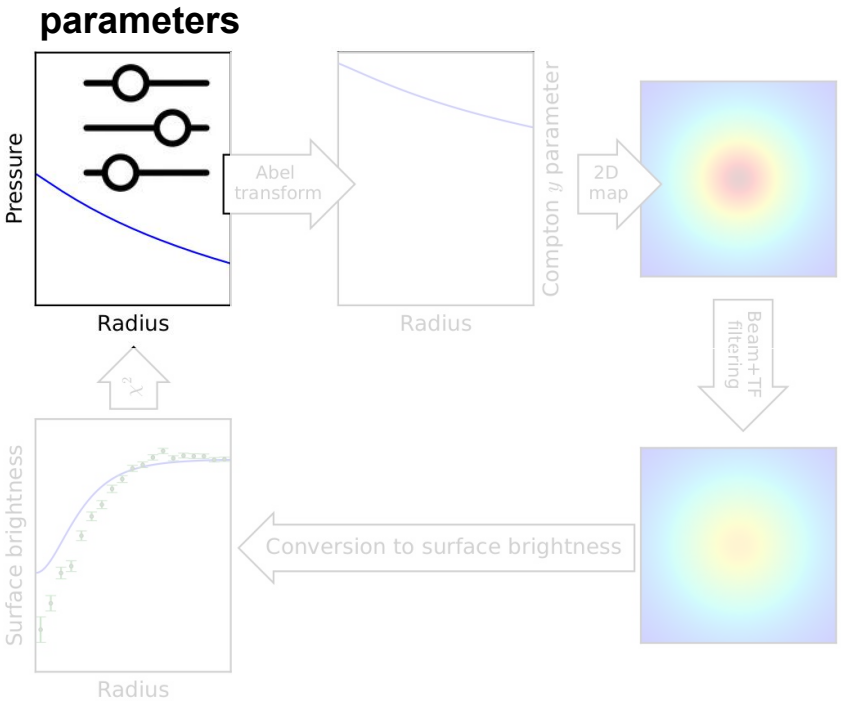
INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Forward modelling approach



INAF
Finanziato dall'Unione europea
NextGenerationEU

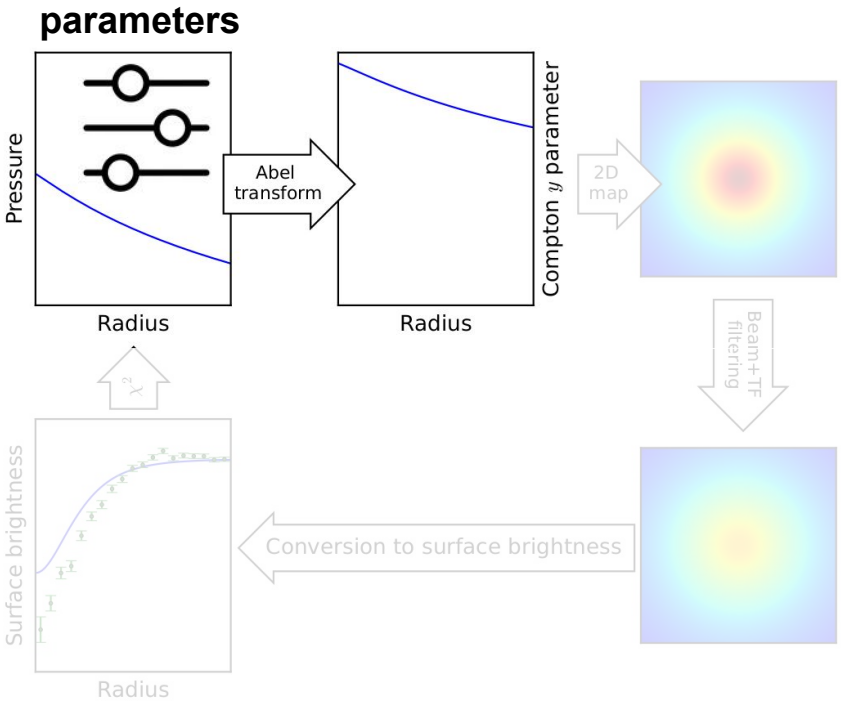
PreProFit - Pressure Profile



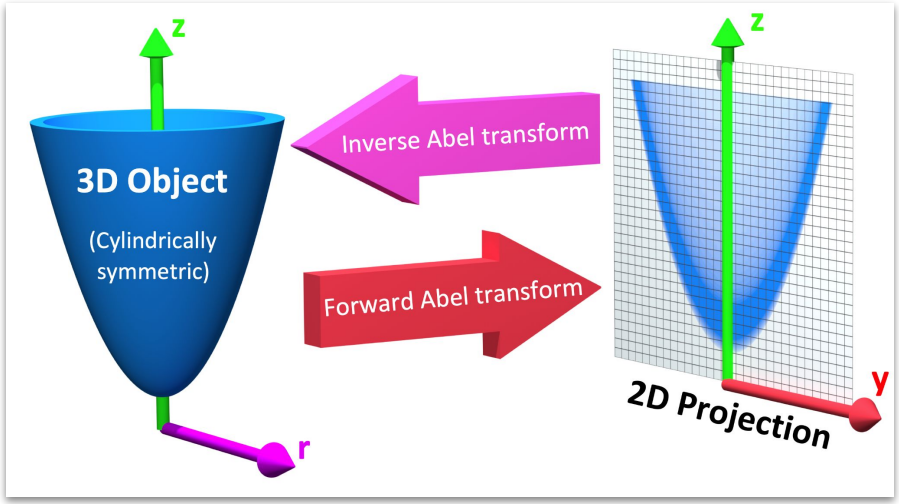
$$P(r) = \alpha + \beta_0 r + \sum_{j=1}^{K-2} \beta_j f(r, R_j)$$

Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Abel transform

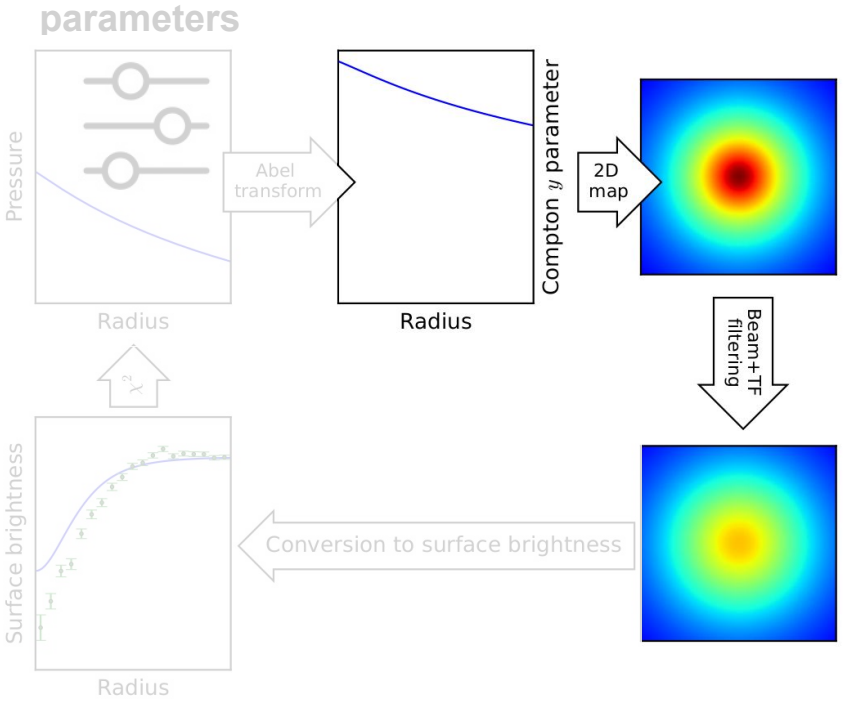


$$F(y) = 2\int_y^\infty \frac{f(r)r}{\sqrt{r^2 - y^2}}dr$$



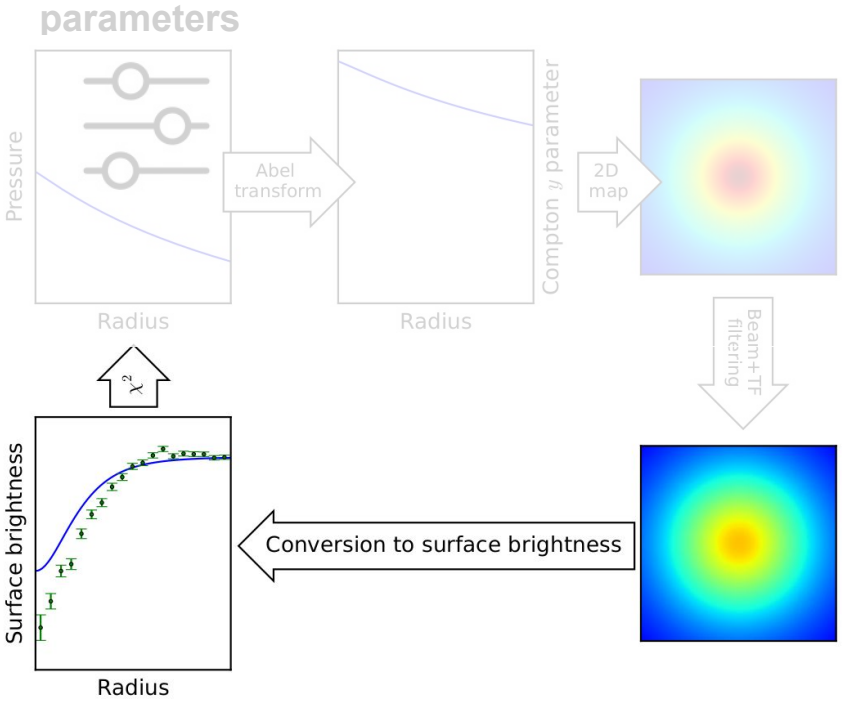
INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - 2D Convolution through Fast Fourier Transform



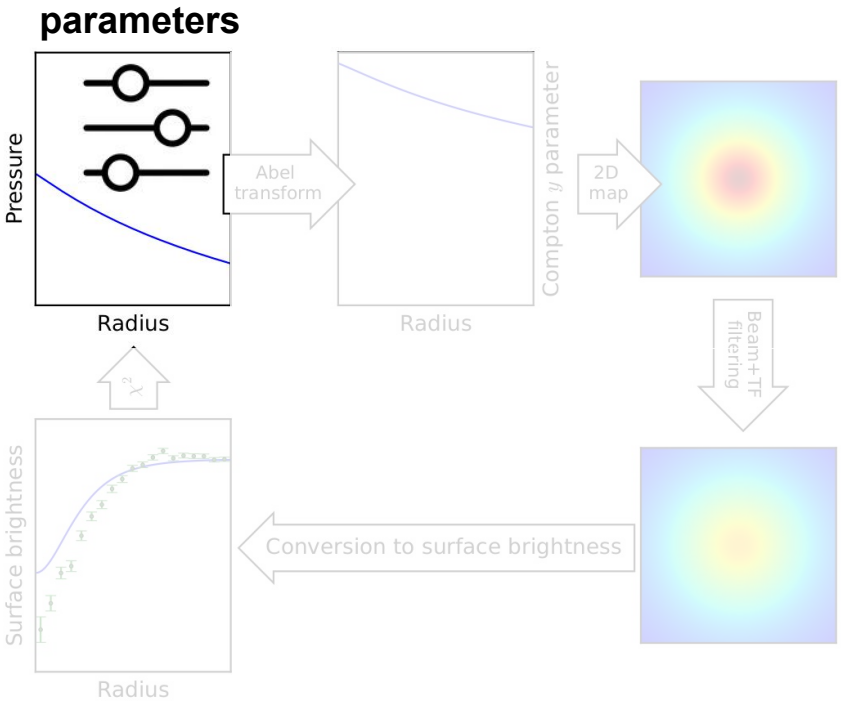
INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Profile extraction and likelihood computation



INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Forward modelling Bayesian estimation



Prior knowledge

P (param)

Likelihood evaluation

P (data | param)

Bayes theorem

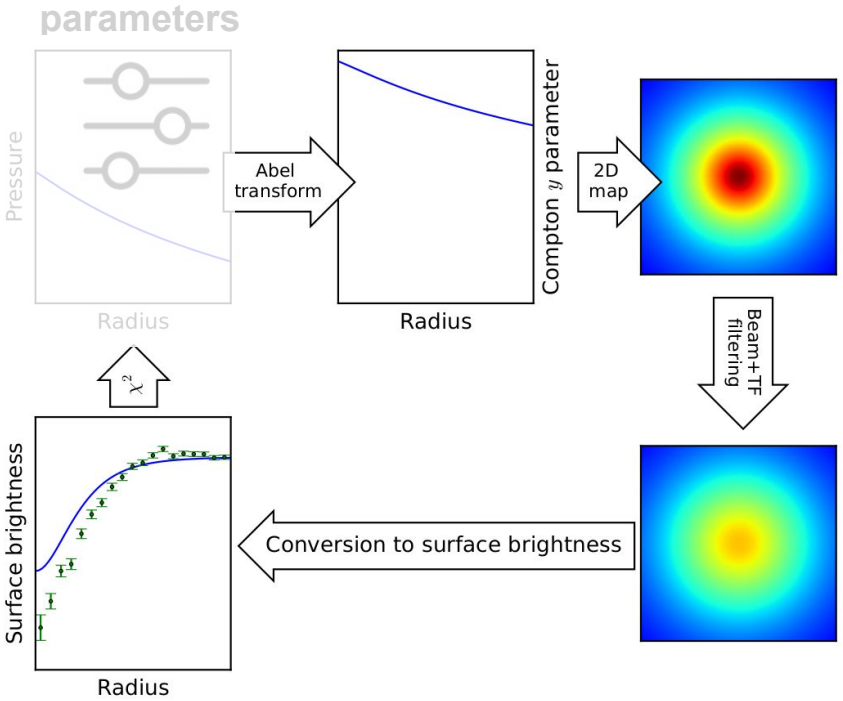
P (param | data) ∝ P (data | param) * P (param)

Posterior knowledge

P (param | data)

INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Forward modelling Bayesian estimation



Prior knowledge

P (param)

Likelihood evaluation

P (data | param)

Bayes theorem

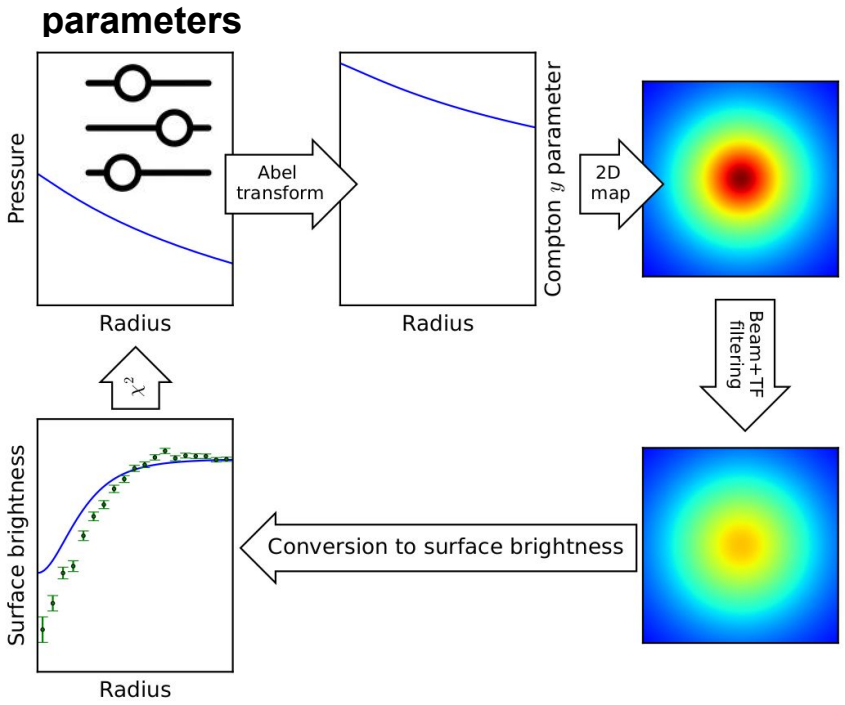
P (param | data) ∝ P (data | param) * P (param)

Posterior knowledge

P (param | data)

INAF
Finanziato dall'Unione europea
NextGenerationEU

PreProFit - Forward modelling Bayesian estimation



Prior knowledge

P (param)

Likelihood evaluation

P (data | param)

Bayes theorem

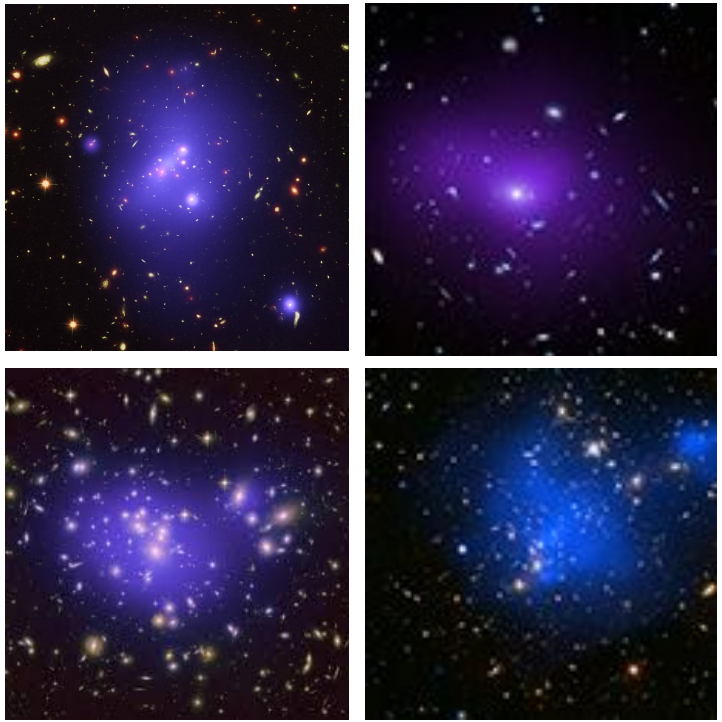
P (param | data) ∝ P (data | param) * P (param)

Posterior knowledge

P (param | data)

INAF
Finanziato dall'Unione europea
NextGenerationEU

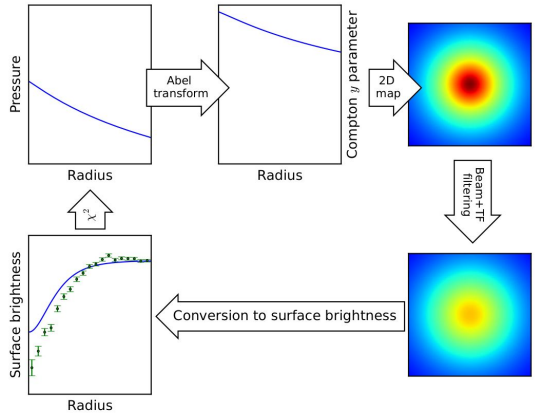
Extension from single-cluster to population analysis

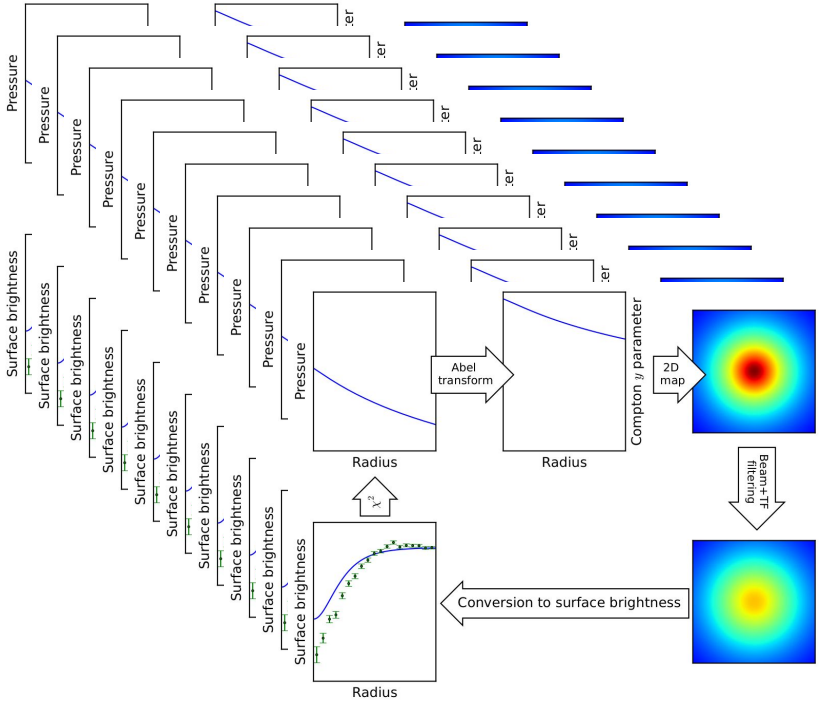


INAF
Finanziato dall'Unione europea
NextGenerationEU

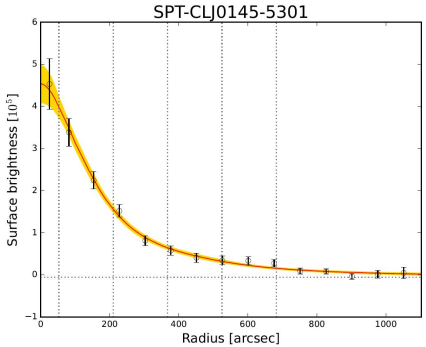
Extension from single-cluster to population analysis

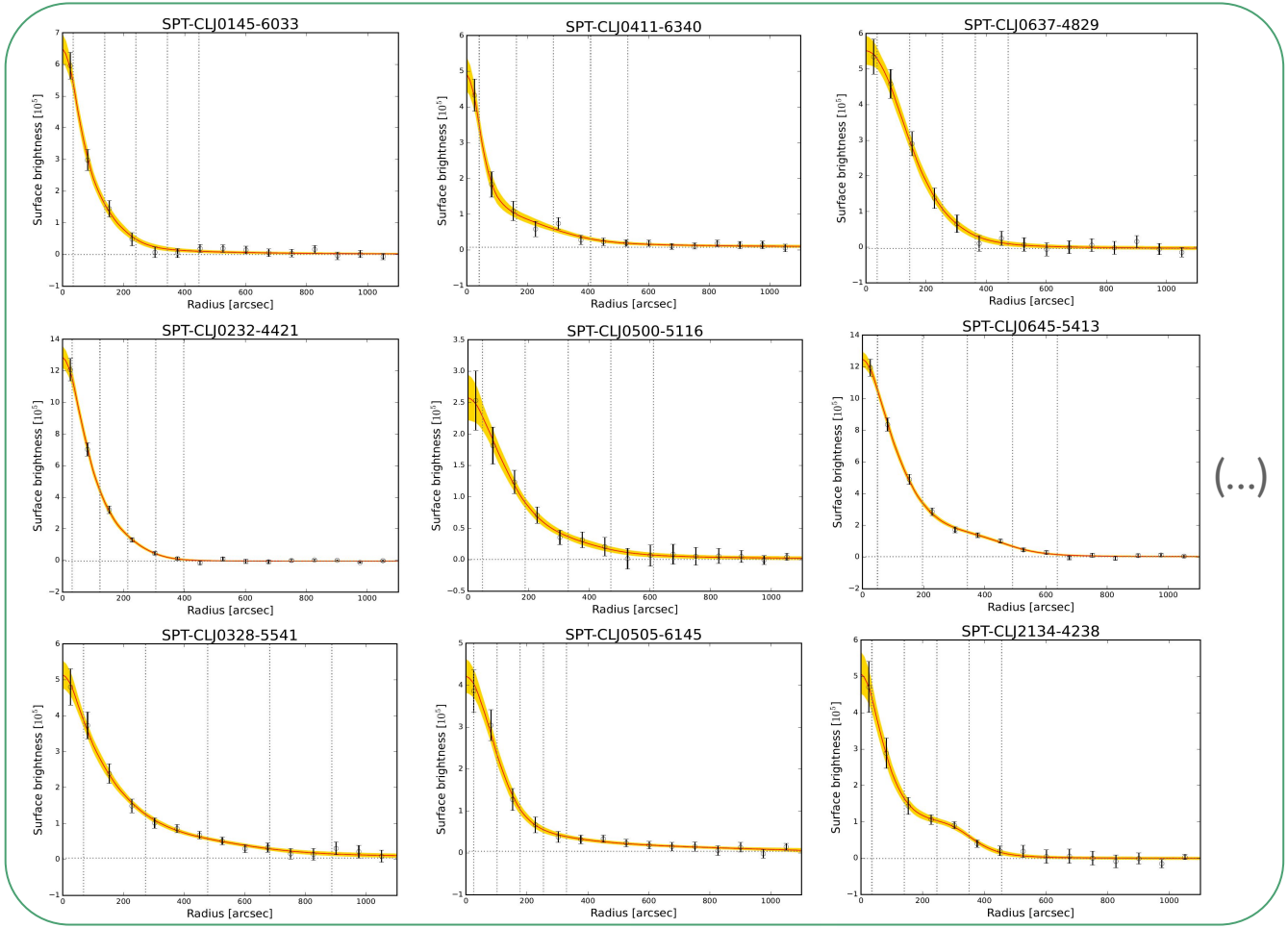
- Dramatically **increases** likelihood **computation time**





INAF
Finanziato dall'Unione europea
NextGenerationEU





(...)

INAF
Finanziato dall'Unione europea
NextGenerationEU

Extension from single-cluster to population analysis

- Dramatically **increases** likelihood **computation time**

- Requires to implement a **Bayesian hierarchical model**
  - ➔ focus on the **intrinsic scatter**

INAF ISTITUTO NAZIONALE DI ASTROFISICA
Finanziato dall'Unione europea NextGenerationEU

Bayesian hierarchical model

Population level estimate

(*k*-th knot)

$$\sigma_k^{\mathrm{ind}} \sim HN(\sigma)$$

$$\sigma_k^{\mathrm{mean}} \sim HN(\sigma)$$

$$\mu_k \sim N(\mu, \sigma)$$

$$\log(P_k) \sim N(\mu = \mu_k, \sigma = \sigma_k^{\mathrm{mean}})$$

Single object level estimates

(*k*-th knot, *i*-th cluster)

$$\log(P_{k,i}) \sim T_{\nu=10}\left(\mu = \log(P_k), \sigma = \sigma_k^{\mathrm{ind}}\right)$$

$$\log(ped_i) \sim N(\mu = 0, \sigma = \sigma_{ped})$$

INAF
Finanziato dall'Unione europea
NextGenerationEU

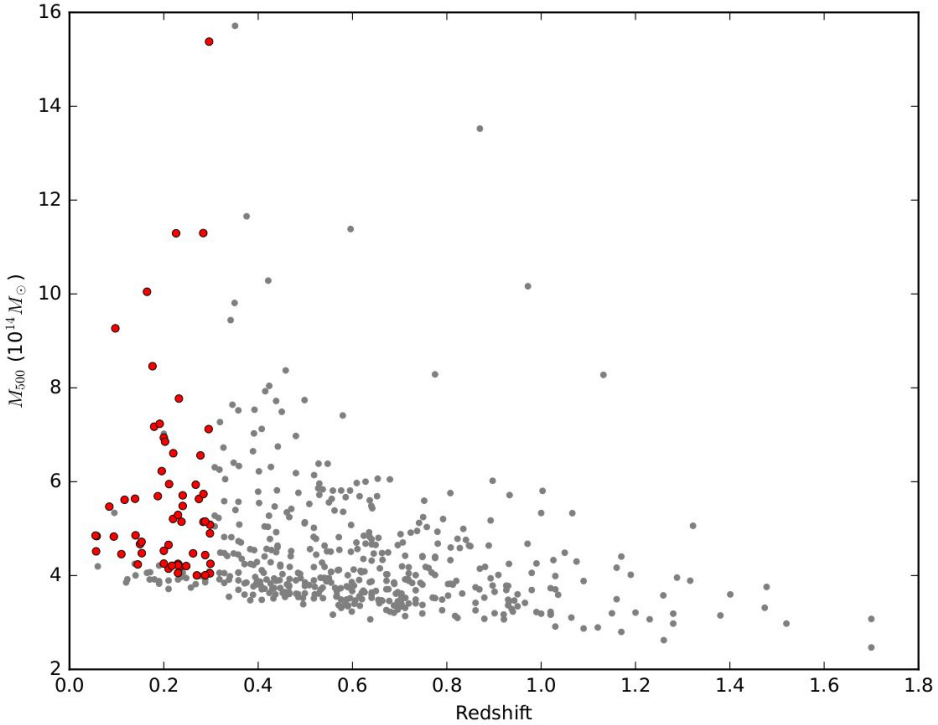
An application to SPT data

Sample selection

2500 deg^2 SPT-SZ Survey

- $z < 0.3$
- $M_{500} > 4 \times 10^{14} M_\odot$
- S/N > 5

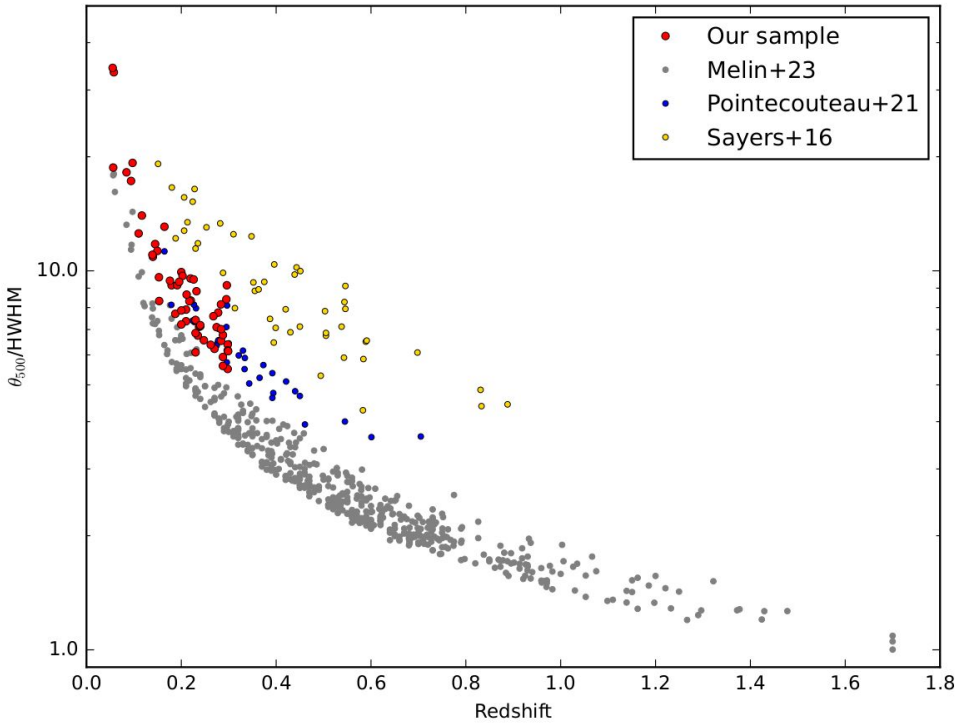
57 galaxy clusters



INAF
Finanziato dall'Unione europea
NextGenerationEU

Data resolution at the cluster redshift

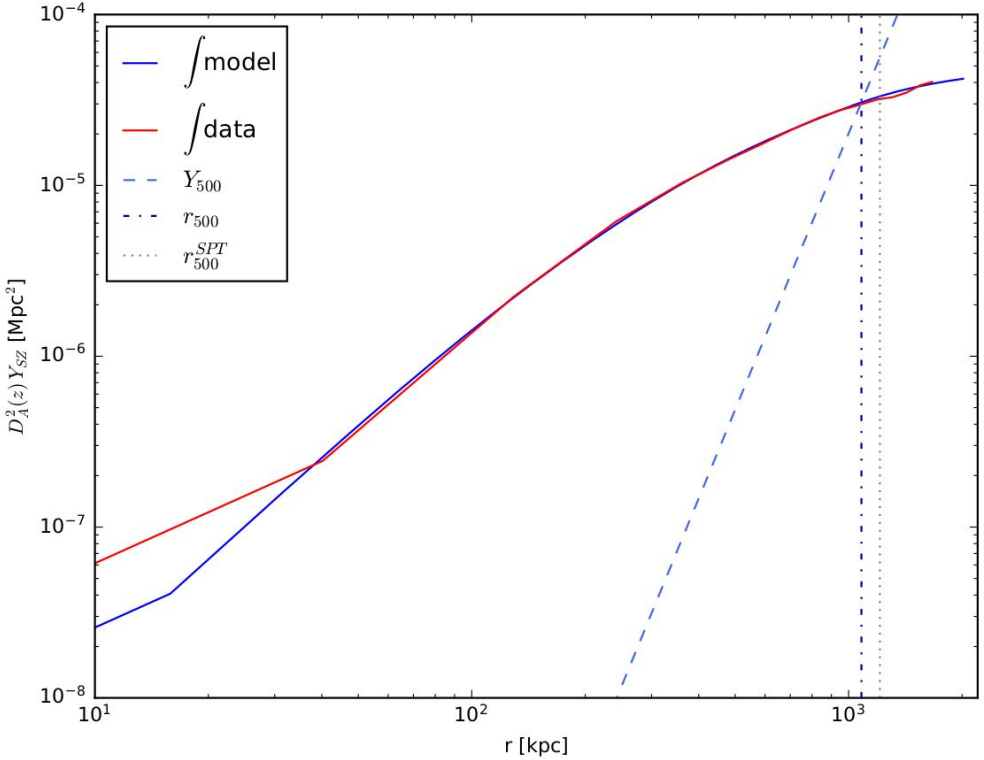
SPT FWHM = 1.25 arcmin



INAF
Finanziato dall'Unione europea
NextGenerationEU

r_{500} derivation

- Compute the spherical integrated Y_{SZ} from SZ flux
- Intersect the integral curve according to Y_{500} - M_{500} scaling relationship
- Derive r_{500}

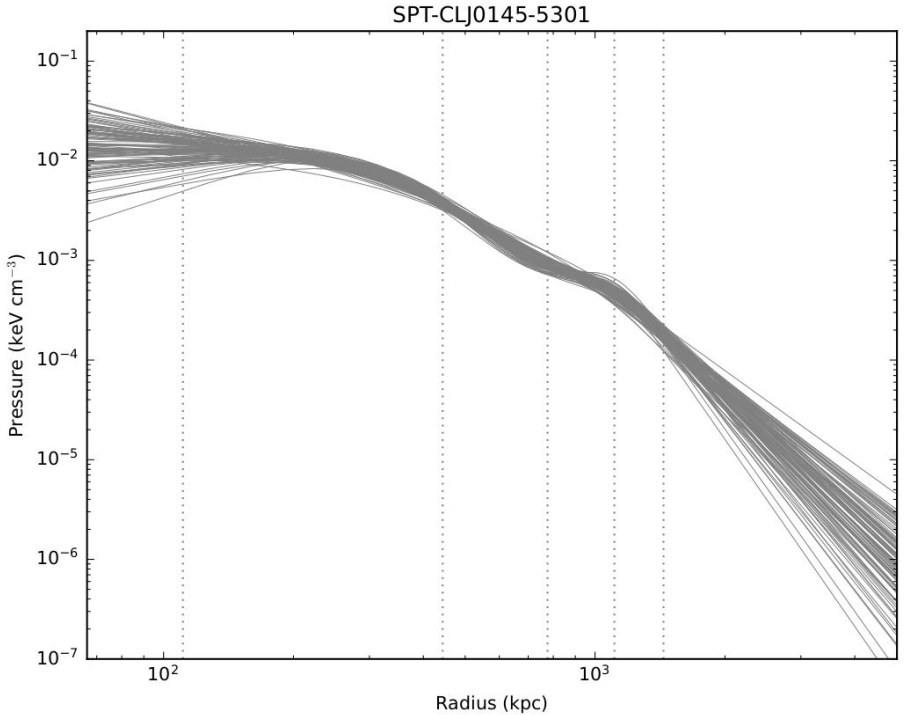


INAF
Finanziato dall'Unione europea
NextGenerationEU

Pressure profile - Restricted cubic splines modelization

- High **flexibility**
  - elasticity of the **cubic** interpolation
  - **linear** interpolation at the extremities **avoids** undesired twists at radii basically unconstrained by data

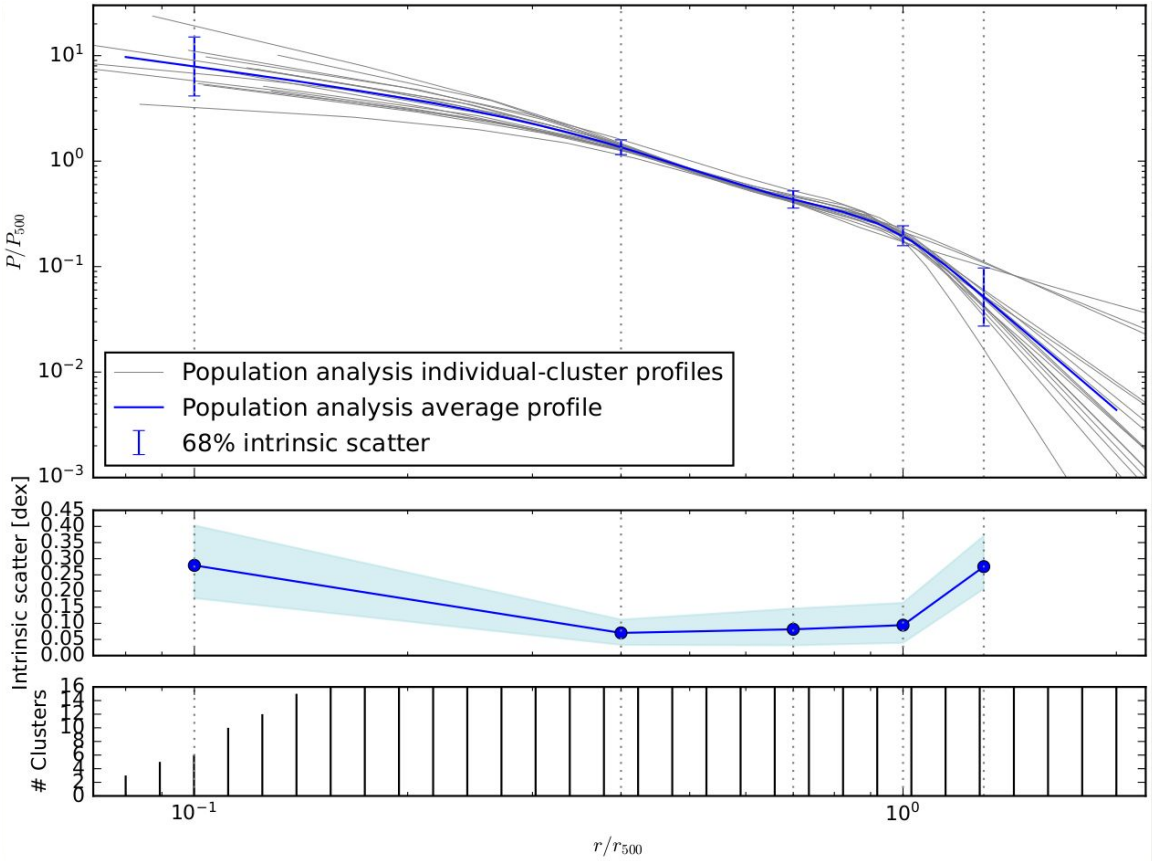
- **Knots** placement
  - [0.1, 0.4, 0.7, 1, 1.3] × r_{500}
  - 5 knots for >5 elements of resolution



INAF
Finanziato dall'Unione europea
NextGenerationEU

Population estimates

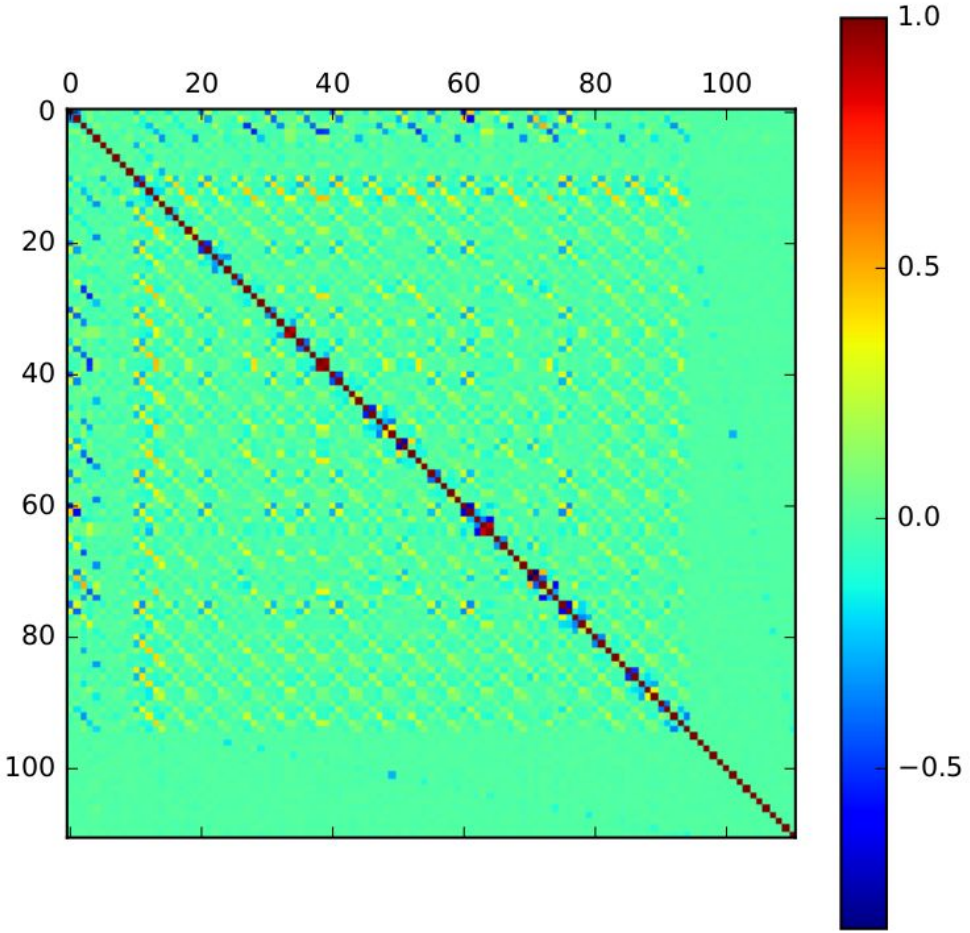
- Preliminary results on 16 galaxy clusters



INAF
Finanziato dall'Unione europea
NextGenerationEU

Diagnostics plots: correlation matrix

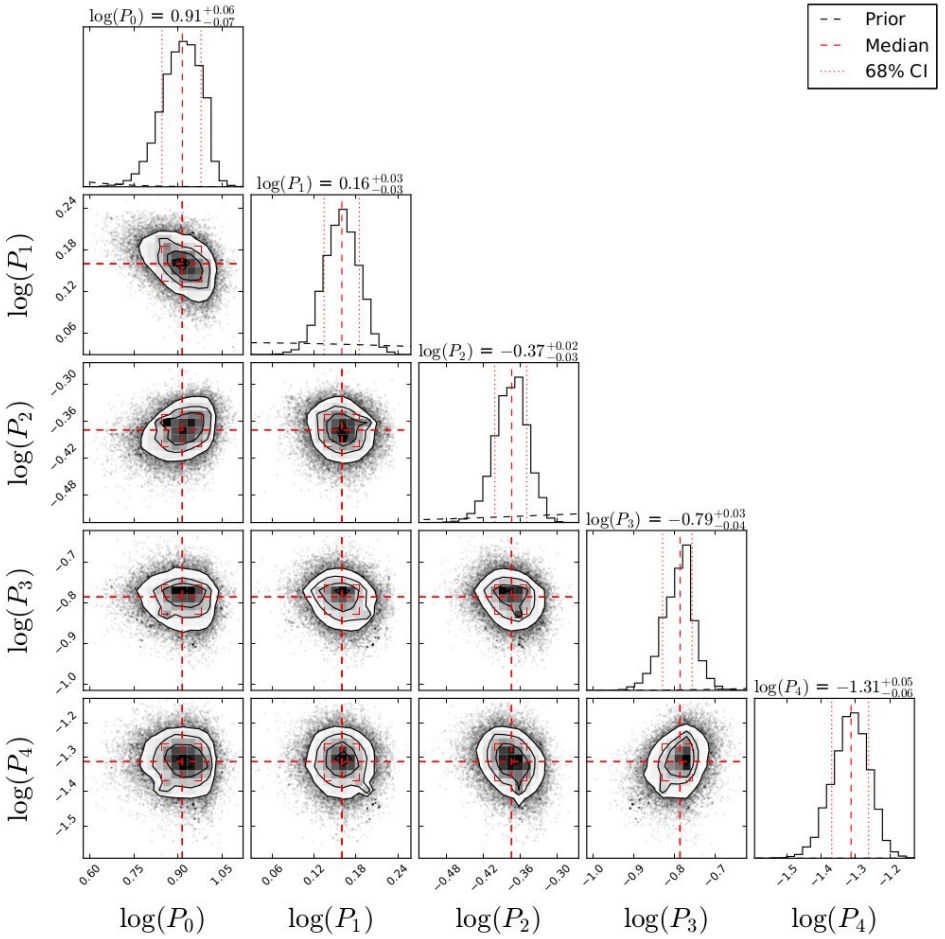
- #param > #clus x #knots



INAF
Finanziato dall'Unione europea
NextGenerationEU

Diagnostics plots: cornerplot

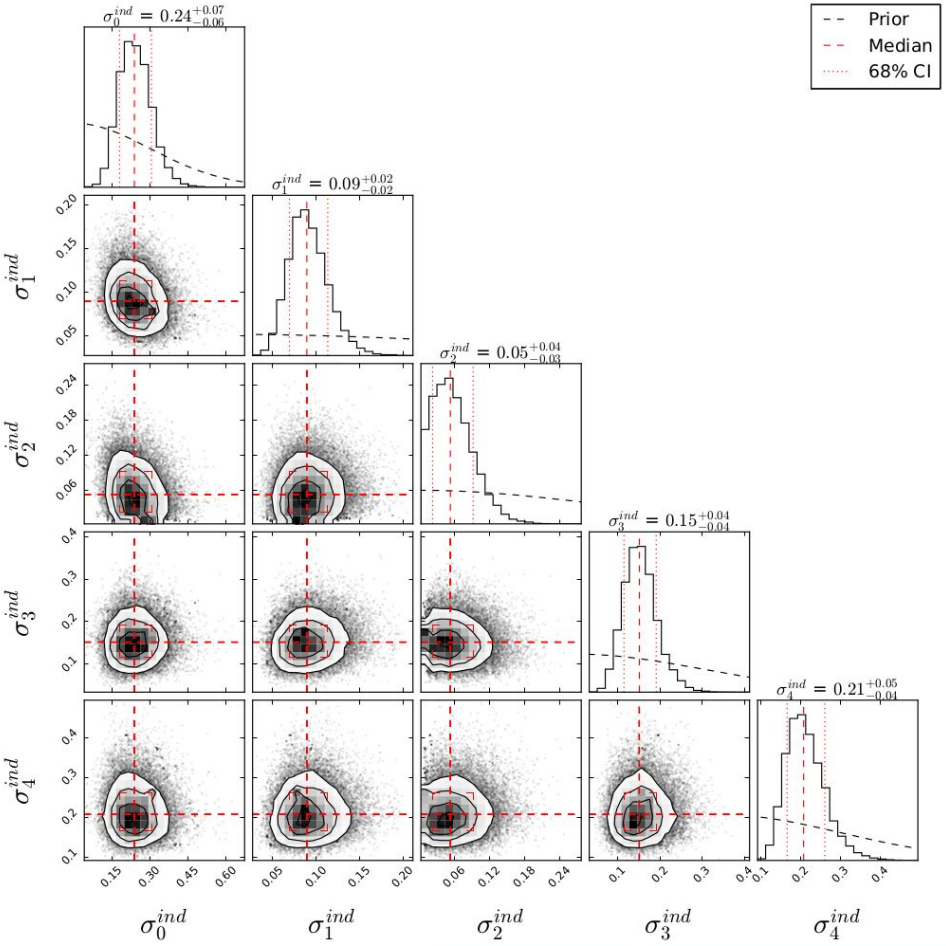
- Population-level pressure estimates



INAF
Finanziato dall'Unione europea
NextGenerationEU

Diagnostics plots: cornerplot

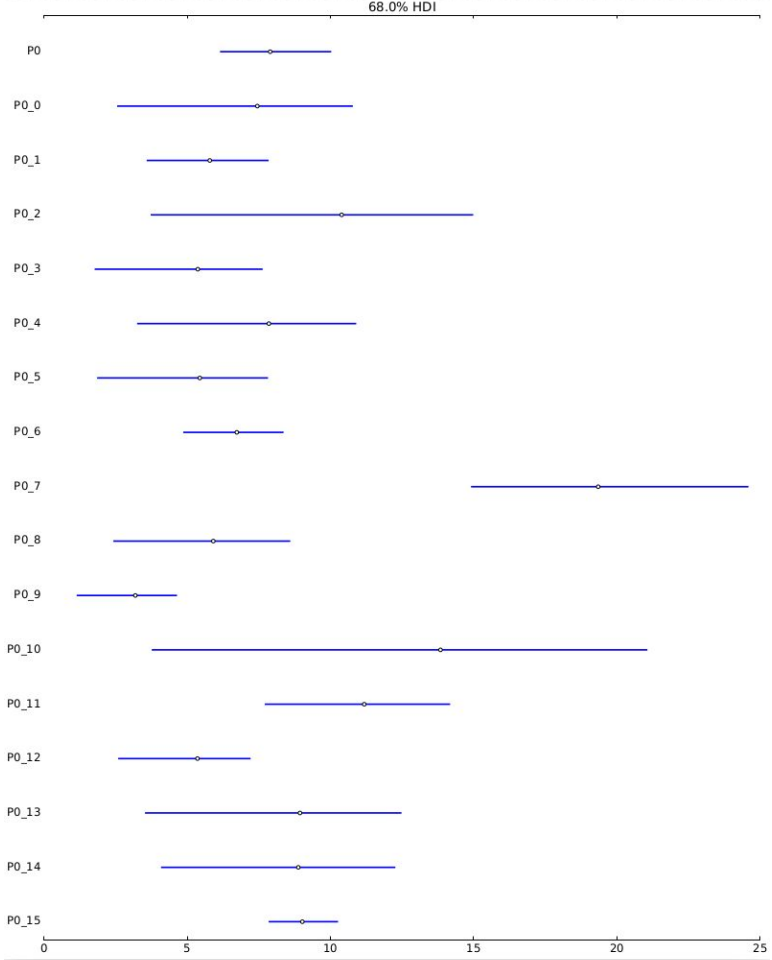
- Intrinsic scatter estimates



INAF
Finanziato dall'Unione europea
NextGenerationEU

Diagnostics plots: forest plot

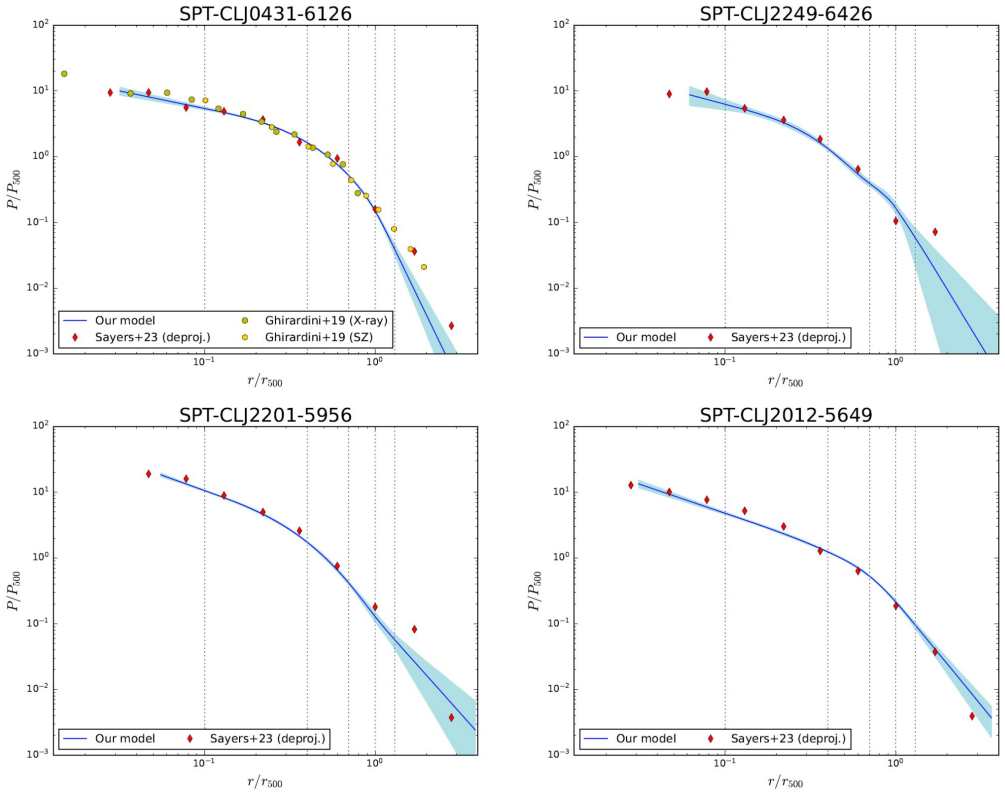
- Both levels of the hierarchical model visualized together
- First knot shown as an example



INAF
Finanziato dall'Unione europea
NextGenerationEU

Literature comparison: cluster-specific estimates

- NOTE: deprojection data shown here differ from the data upon which our model has been fitted

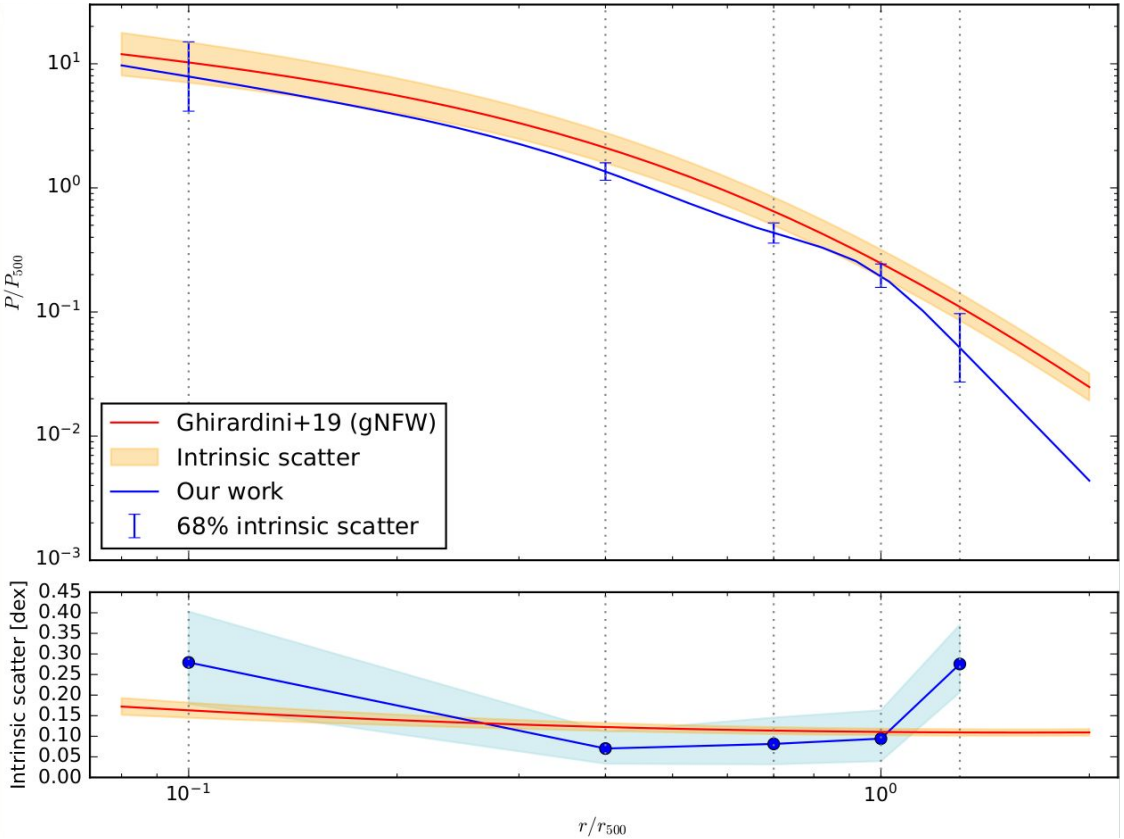


INAF
Finanziato dall'Unione europea
NextGenerationEU

Literature comparison: population estimates

Discrepancy can arise from

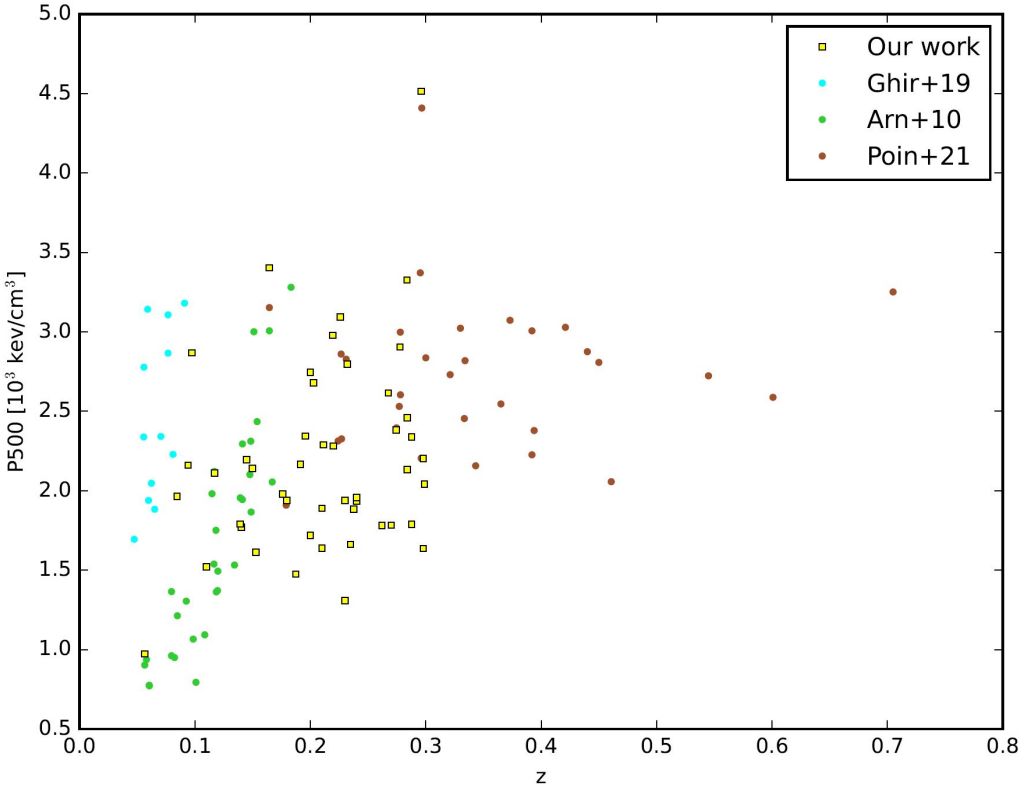
- different modelizations
- sample selection
- different derivation methods for P_{500}



INAF
Finanziato dall'Unione europea
NextGenerationEU

Subset-specific comparisons

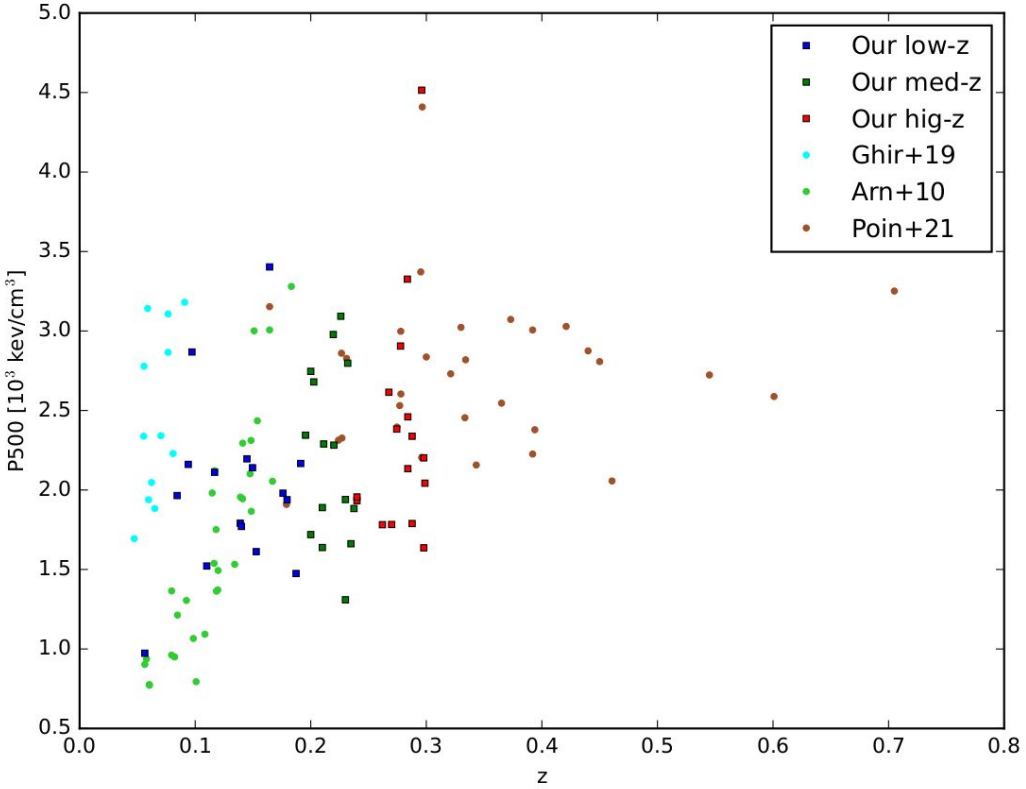
- Consider the z vs P_{500} distribution
- How the variation of such measures affects our results?
- How does it relate to other works in the literature?



INAF
Finanziato dall'Unione europea
NextGenerationEU

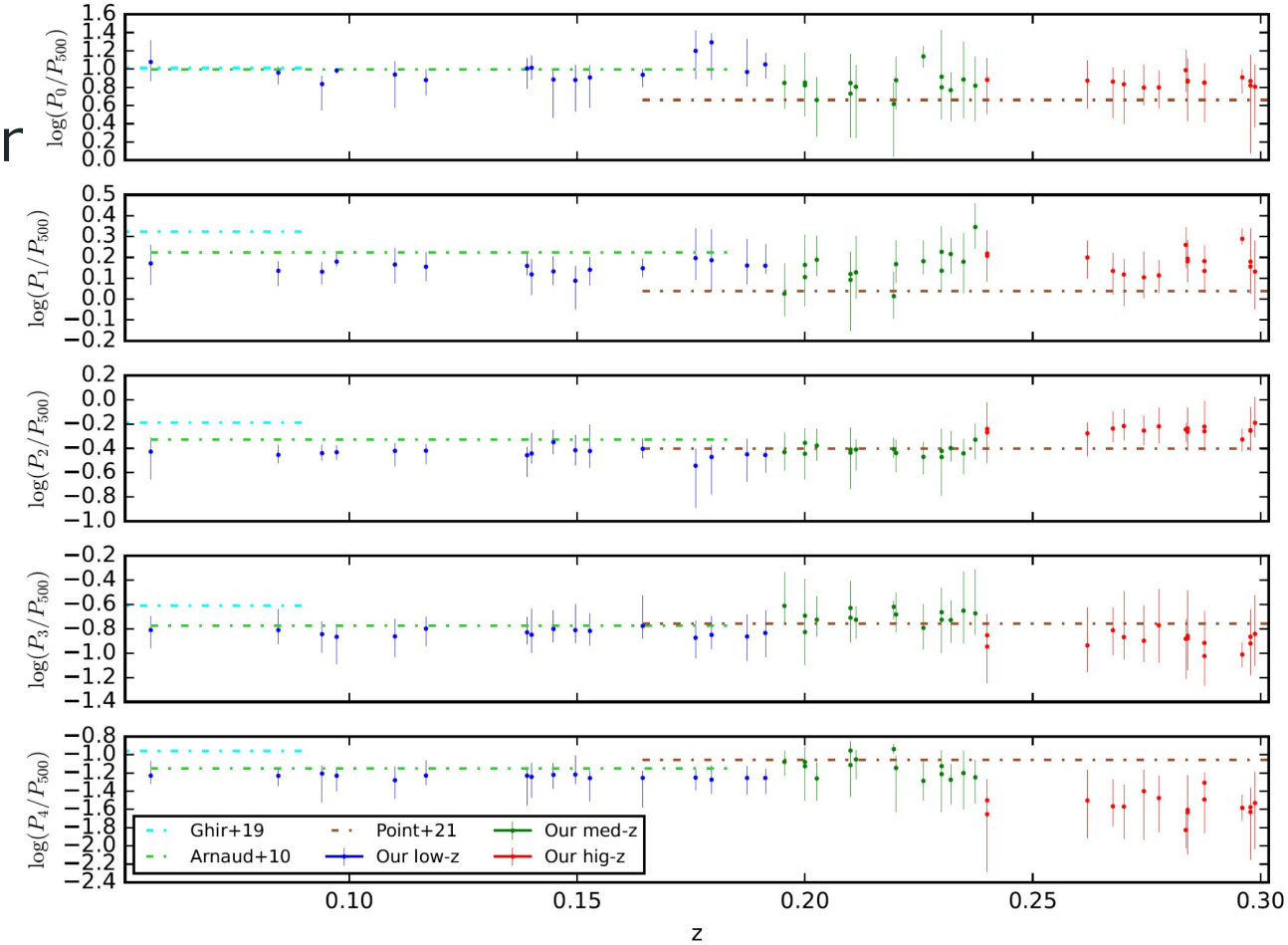
Tertiles subdivision

- 3 classes of either *z* (see plot) or P_{500}
- 3 different estimations



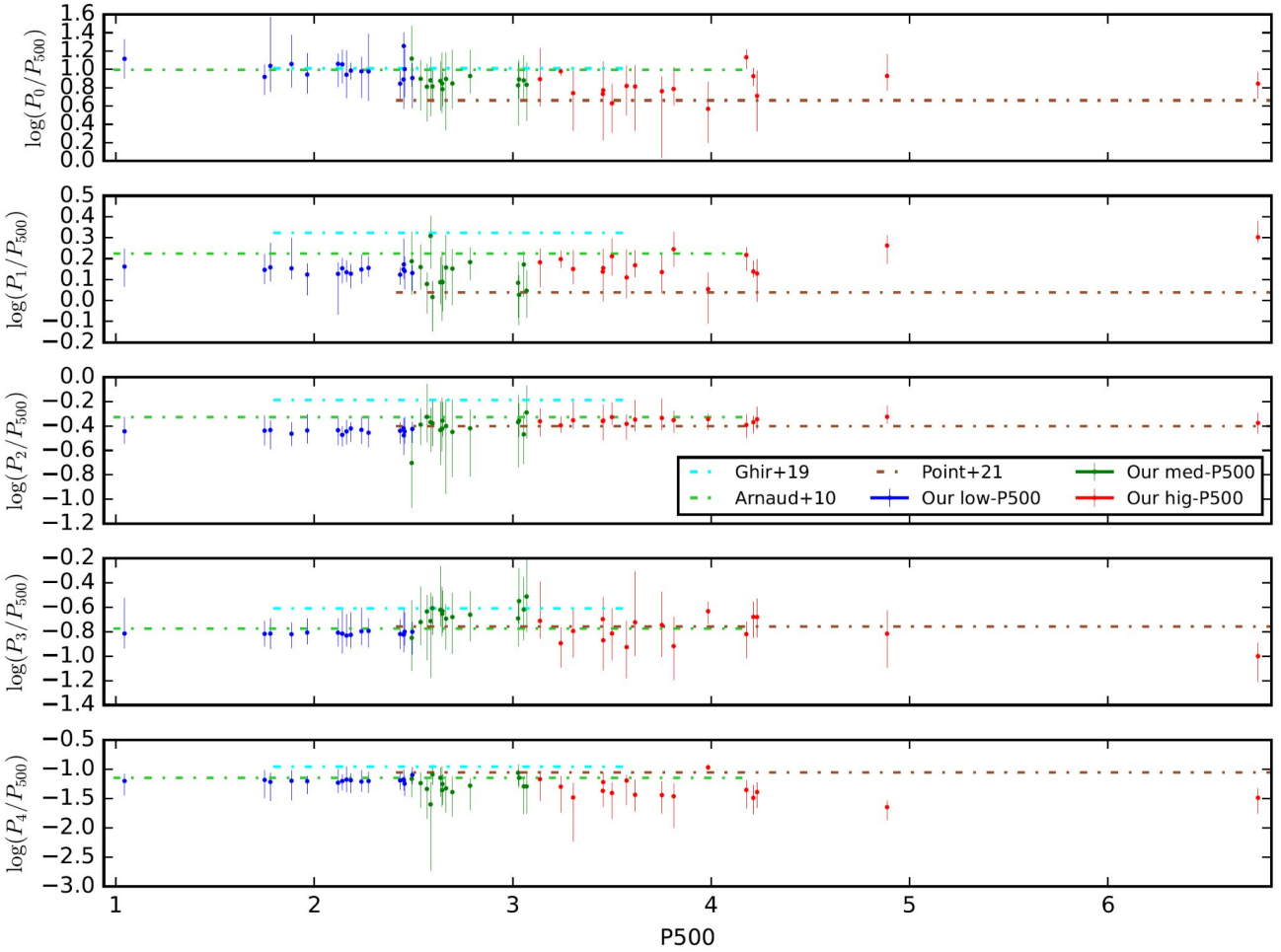
INAF
Finanziato dall'Unione europea
NextGenerationEU

Dependence on *z*?



INAF
Finanziato dall'Unione europea
NextGenerationEU

Dependence on P_{500}?



Finanziato dall'Unione europea
NextGenerationEU

Current and forthcoming developments

- Increase the **capillarity** of the **model** to improve the estimation **accuracy**
  - e.g. model the P_{500} scaling of profiles in order to capture possible deviations from self-similarity
- Consider **selection effects**
  - e.g. evaluate the influence of cluster morphology on results
- Extend the population analysis to the **entire sample** of 57 objects

INAF
Finanziato dall'Unione europea
NextGenerationEU

Future developments

- Extend the population analysis to **larger amounts** of objects
- Extension from analyzing data gathered by a single **SZ** instrument to considering observations coming from **multiple facilities** (e.g., **ACT** data)
- **Multiwavelength** analysis that allows the estimation of thermodynamic properties
  - joint **X-ray** and **SZ** analysis (see *JoXSZ* for single-object analysis)
  - add the **weak lensing** component

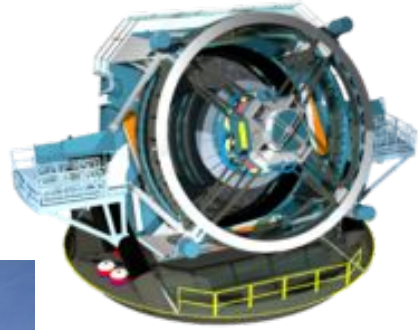
https://github.com/fcastagna/JoXSZ

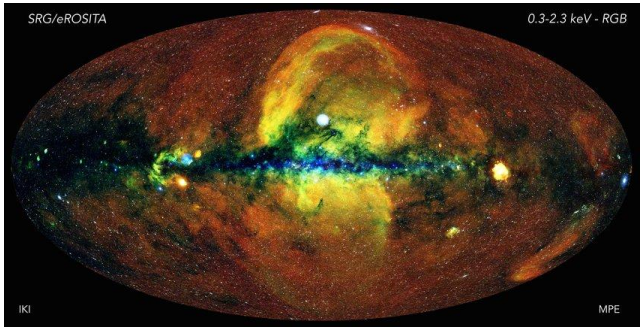
INAF ISTITUTO NAZIONALE DI ASTROFISICA
Finanziato dall'Unione europea NextGenerationEU

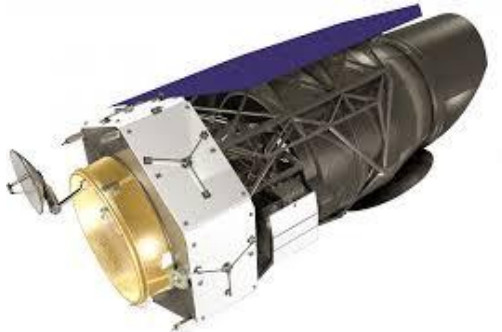
Towards the big data era in astrophysics

Towards the big data era in astrophysics

New-generation surveys are collecting **unprecedented** amounts of **heterogeneous data** that require **ad hoc analyses** to answer scientific questions







INAF
Finanziato dall'Unione europea
NextGenerationEU