Galaxy Cluster Cosmology:

High-angular resolution follow-up studies in X-ray and SZ

Florian Ruppin

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In collaboration with: The NIKA2, the MaDCoWS, and the SPT cluster teams

Galaxy cluster cosmology

Cluster observables and cosmological analysis

Mass - Observable scaling relation

Systematic effects and cosmological impacts

Mass functions from simulations

Systematic effects and observational constraints

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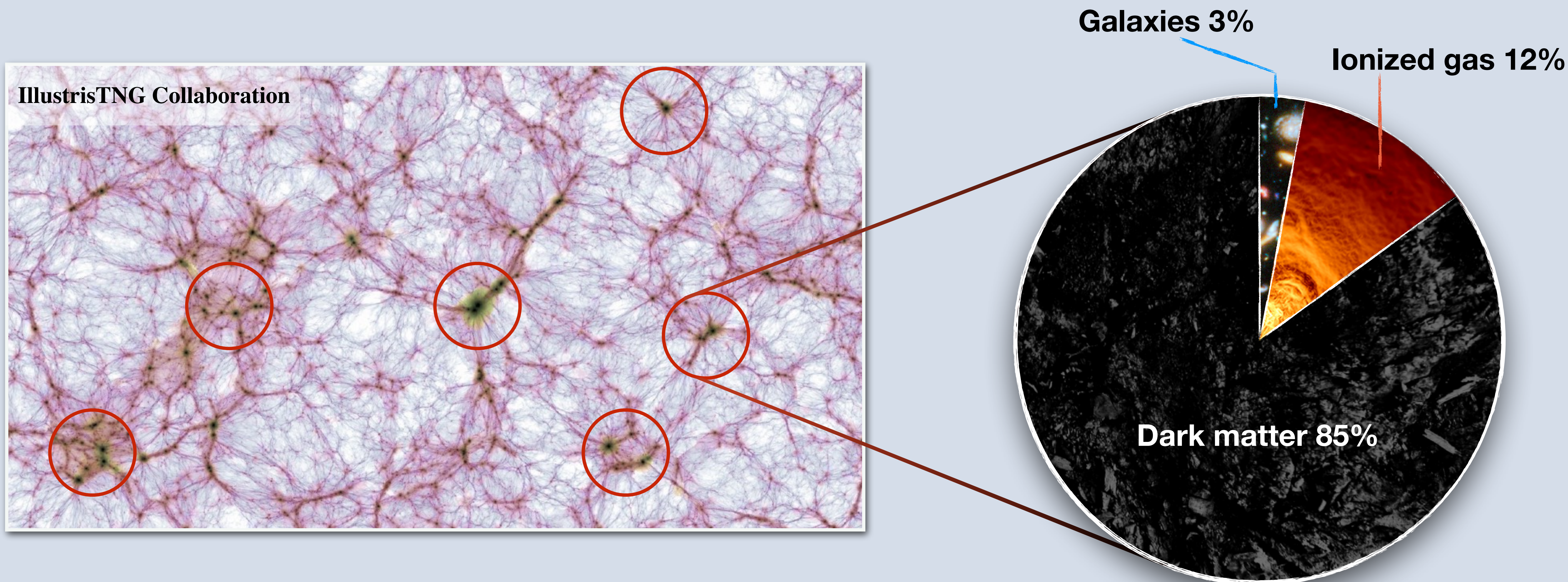
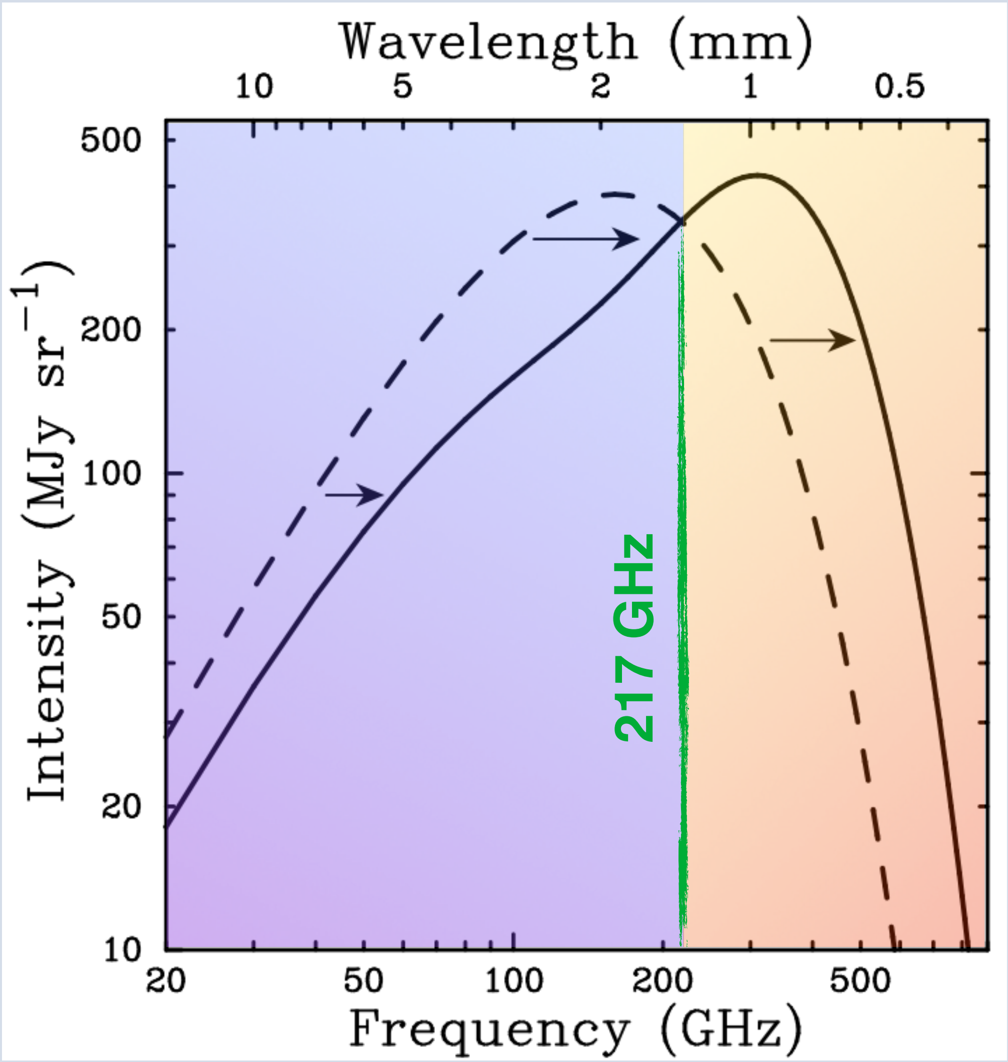
Clusters of Galaxies

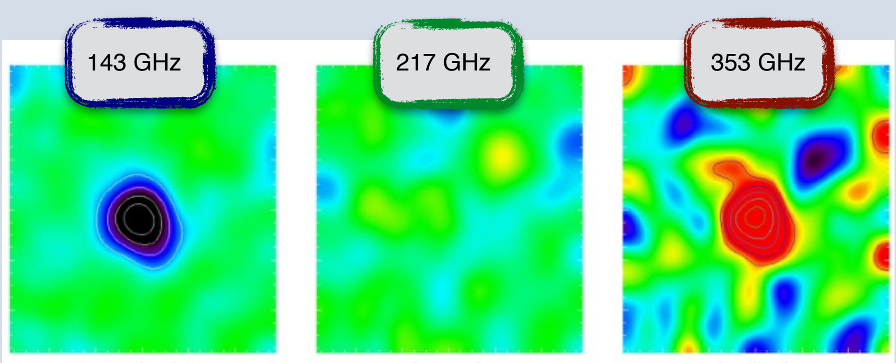


- **Clusters of Galaxies**
  - Largest gravitationally bound structures in the Universe
  - Dominated by dark matter
  - Intra-Cluster Medium (**ICM**) :
    Hot ionized gas $\sim 5 - 10 \text{ keV}$
  - Total mass: $M_{\text{tot}} \sim 10^{14} - 10^{15} M_{\odot}$
  - Typical redshift: $z \in [0, 3]$

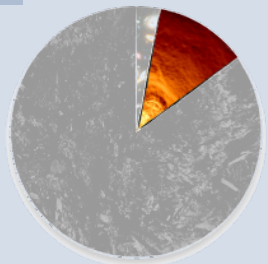
Galaxy cluster observables: SZ effect



Carlstrom *et al.* ARA&A (2002)



A 2319
(*Planck*)



- **Sunyaev-Zel'dovich effect** (SZ)

  Sunyaev & Zel'dovich CoASP (1972)

Compton scattering of CMB photons by high-energy ICM electrons

→ CMB photons gain energy

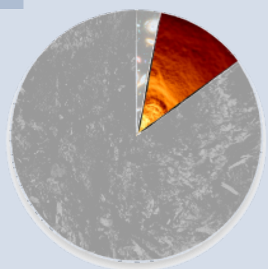
CMB spectral distortion

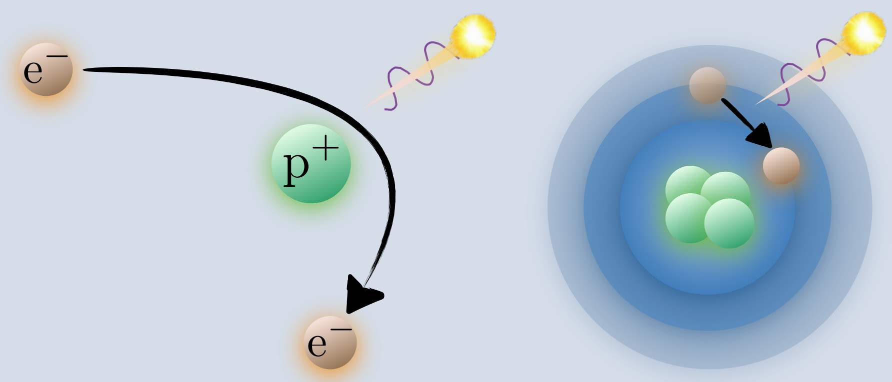
→ SZ effect is **redshift independent**

SZ effect Amplitude : Compton parameter

$$y_{SZ} \propto \int P_e \, dl \longrightarrow \boxed{\text{ICM electronic } \textbf{Pressure}}$$

Galaxy cluster observables: X-ray emission





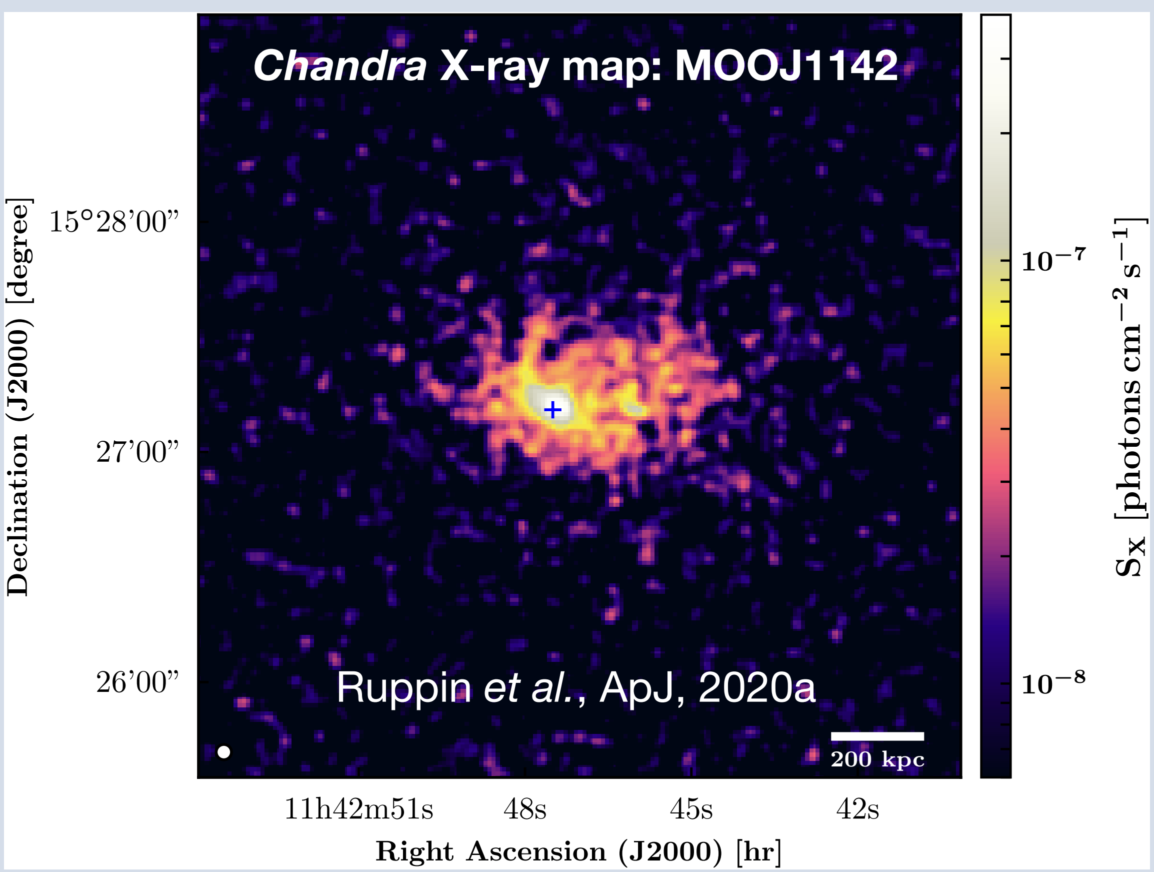
- **X-ray emission**

Bremsstrahlung emission induced by hot ICM electrons

→ Continuous spectrum

Change of electron quantum state in heavy elements

→ Emission lines



X-ray surface brightness: $S_X \propto \int n_e^2\, \Lambda(T_e, Z)\, dl$

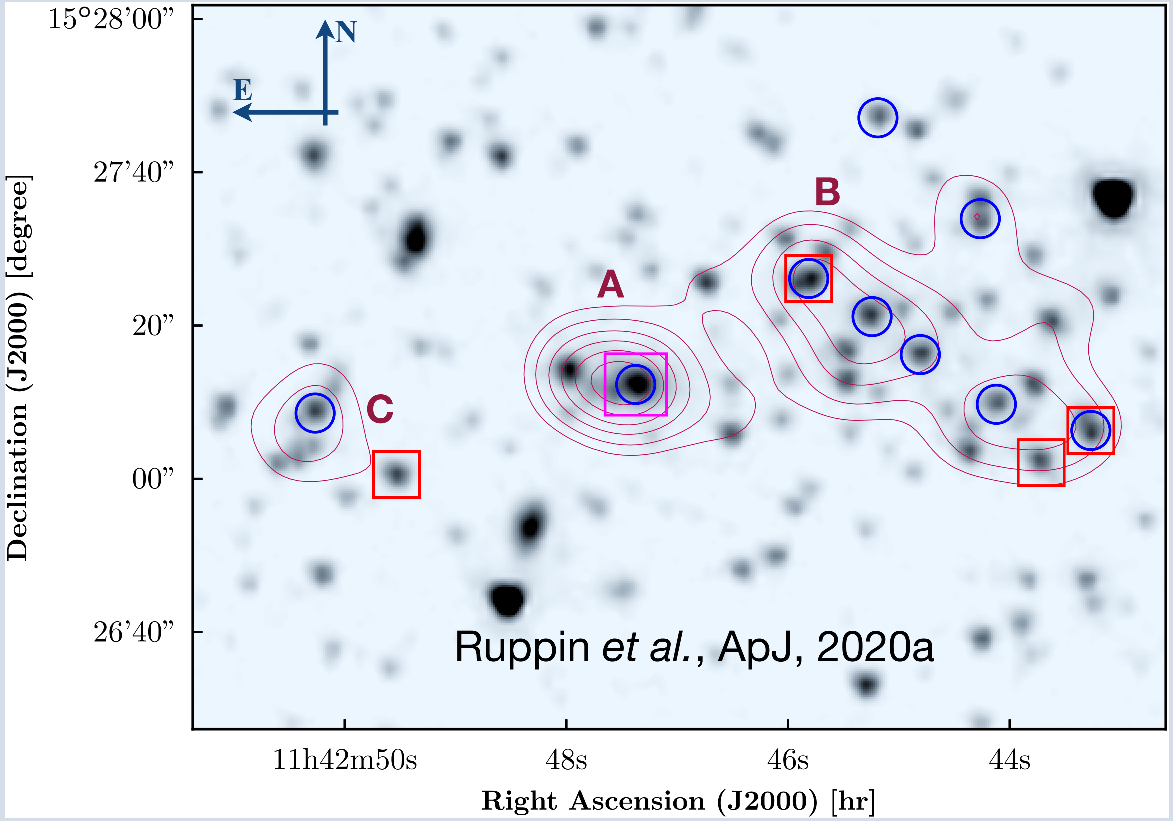
→ $\boxed{\text{ICM electron } \textbf{Density} \text{ and } \textbf{Temperature}}$

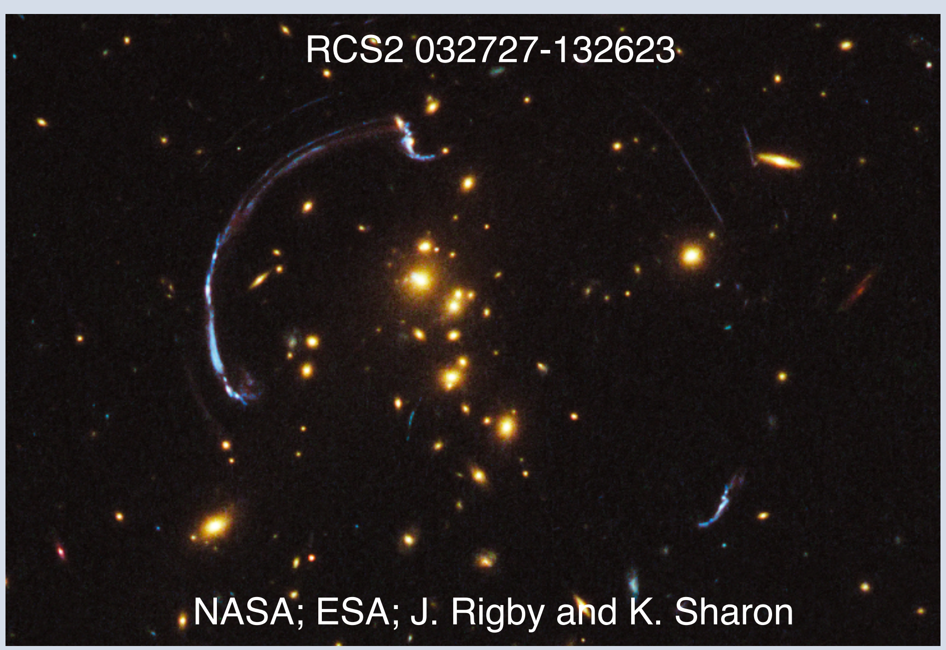
Hydrostatic mass: combination of Pressure / Density

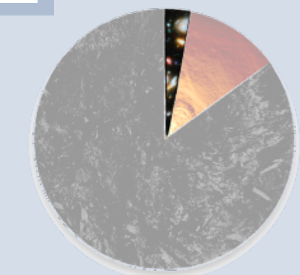
$$M_{HSE}(r) \propto \underbrace{\frac{r^2}{n_e(r)}}_{\text{X-rays}} \times \overbrace{\frac{d\,P_e(r)}{dr}}^{\text{SZ effect}}$$

Galaxy cluster observables: optical/IR emission

Spitzer infrared map: MOOJ1142







- **Optical/IR emission**

Light coming from stars and interstellar medium

→ Continuous spectrum + emission / absorption lines

Best observable to know cluster redshift
(essential for cosmology / astrophysics)

Galaxy distribution of cluster members
(very useful to study merger dynamics)

Gravitational lensing

→ Matter distribution + cluster **total mass**

Cosmology with galaxy clusters

Large galaxy cluster survey

- Catalog of detected clusters:
  - observable $\mathcal{O}_{500}$
  - signal-to-noise ξ_m
  - mass M_{500}
  - redshift z
  - position (l, b)
- Abundance of clusters in bins of **observable** and **redshift** $\dfrac{d^2N}{d\mathcal{O}_{500}dz}$
- Examples of surveys : **in SZ** with *Planck*, SPT, ACT
  in X-ray with eROSITA
  in optical/IR with *Euclid* and the Rubin Observatory

Large number of galaxy clusters to do **cosmology**

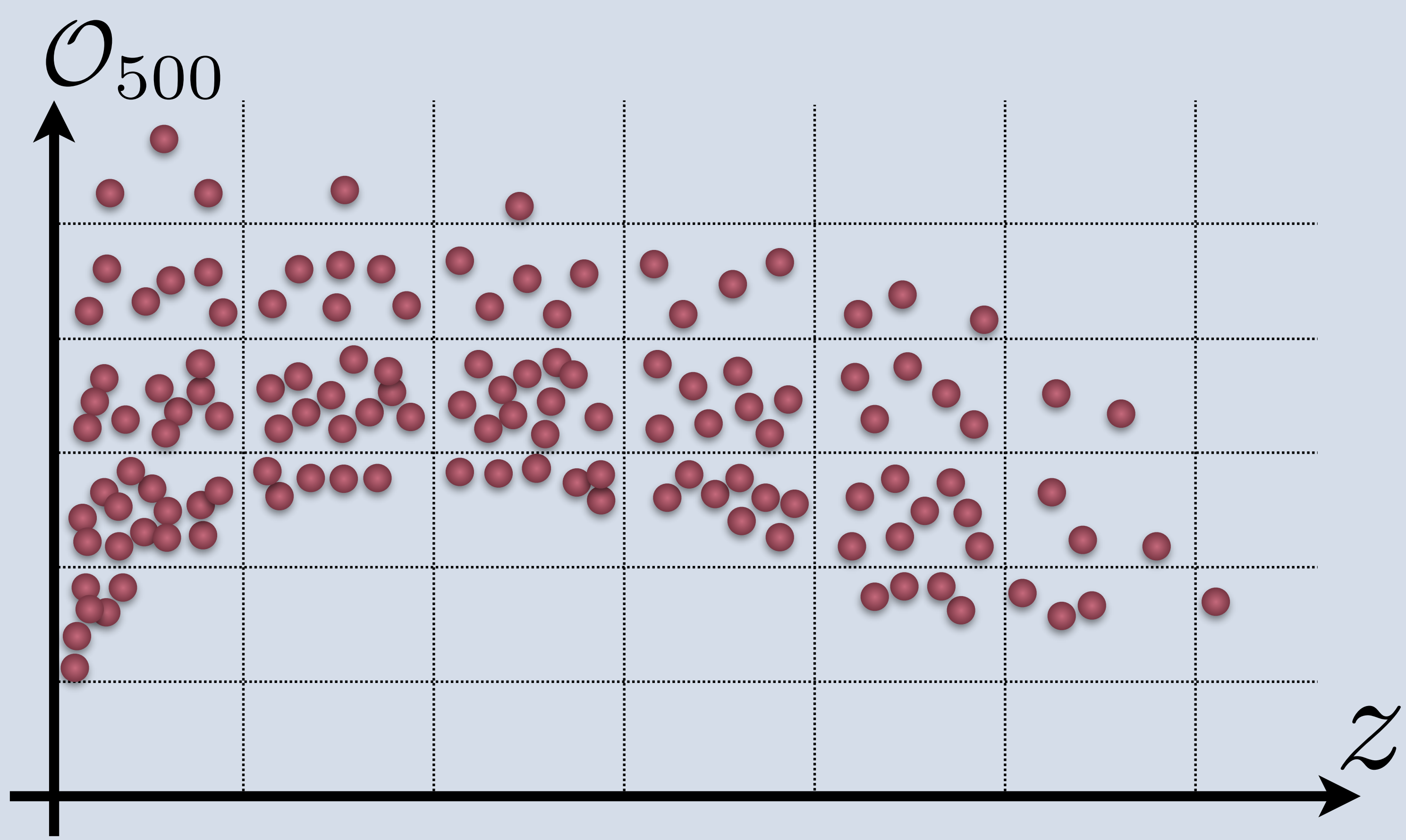
Cosmology with galaxy clusters

Expected cluster abundance:
Per unit of mass and redshift

Selection function | Mass-Observable scaling relation | Comoving volume | Mass function

$$\frac{d^2N}{dM_{500}dz}(\xi > \xi_{\rm cat}) = \int d\Omega \int d\mathcal{O}_{500} \int_{\xi_{\rm cat}}^{\infty} d\xi \boxed{P[\xi|\xi_m(\mathcal{O}_{500}, l, b)]} \boxed{P[\mathcal{O}_{500}|z, M_{500}]} \boxed{\frac{d^2V}{dzd\Omega}} \boxed{\frac{dn}{dM_{500}}}$$

Probability to detect a cluster



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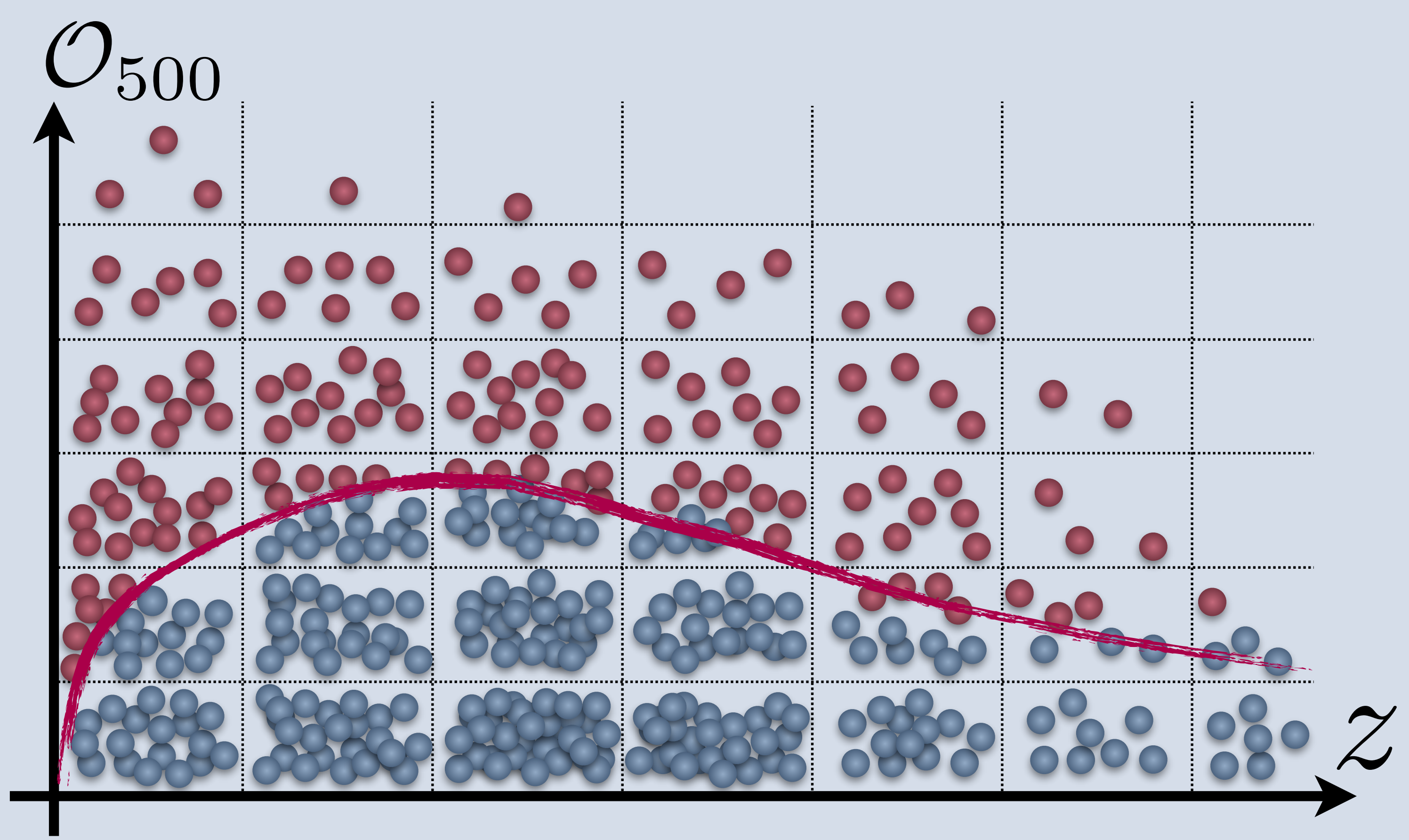

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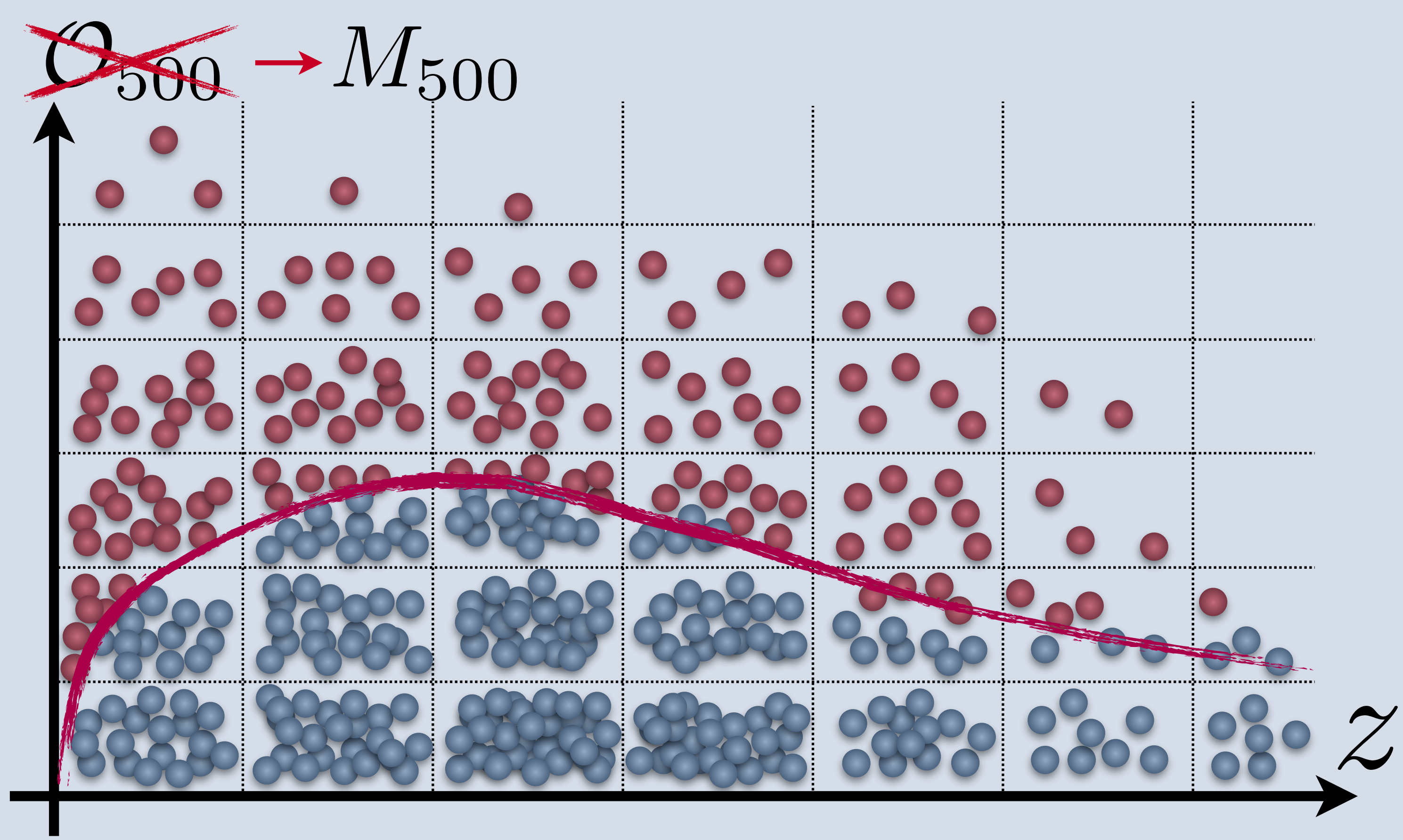

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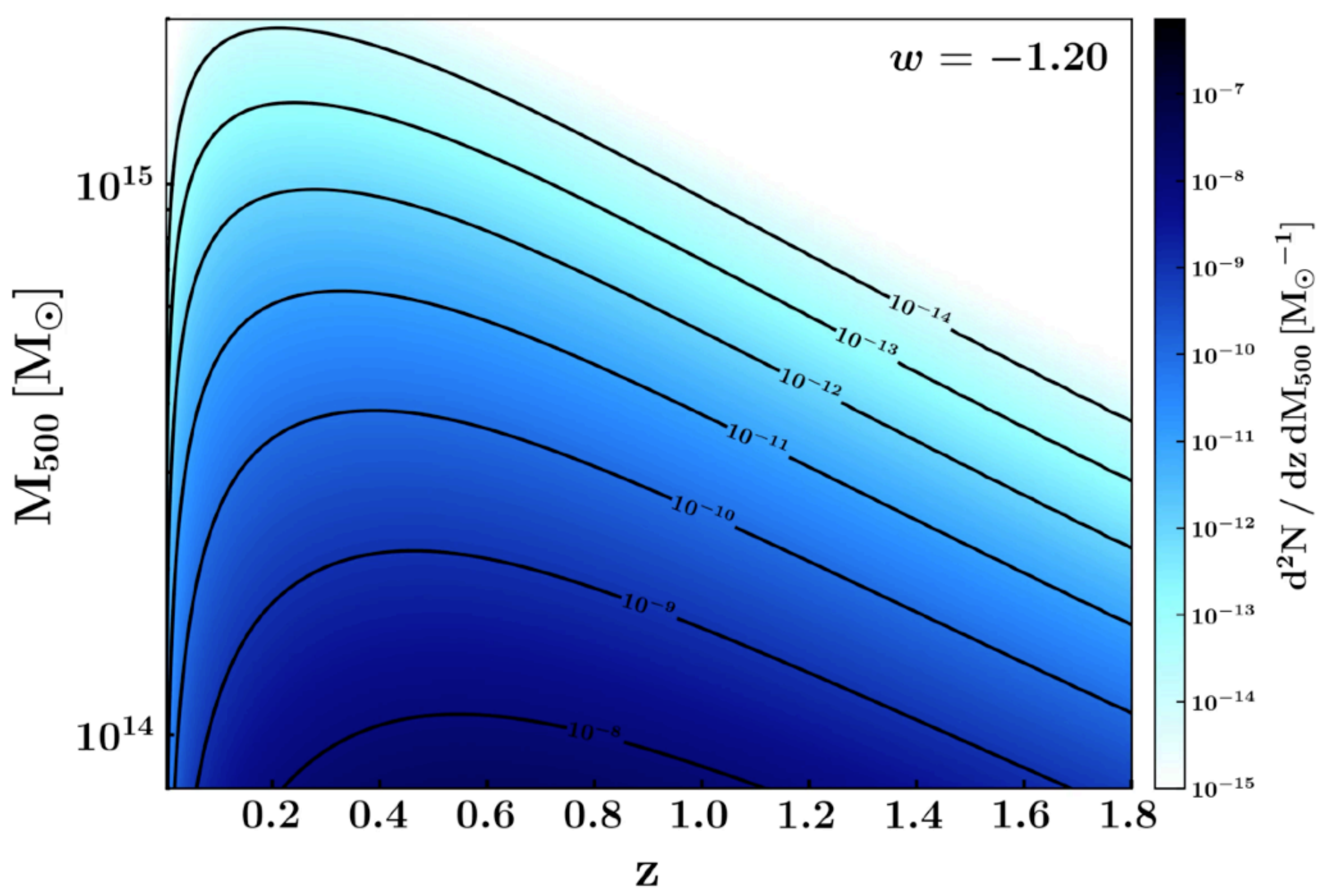
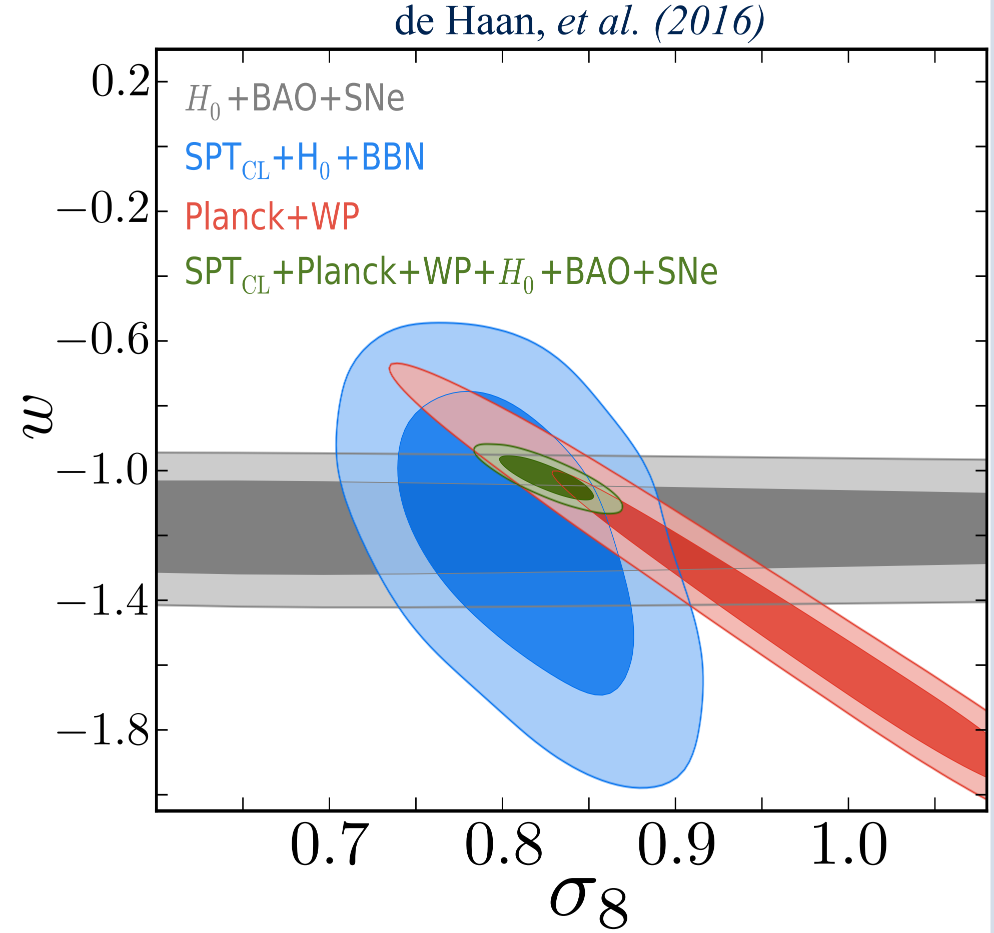
Depends on cosmological parameters $\sigma_8, \Omega_m, H_0, w, N_{eff}, \sum m_\nu, f_{NL}$





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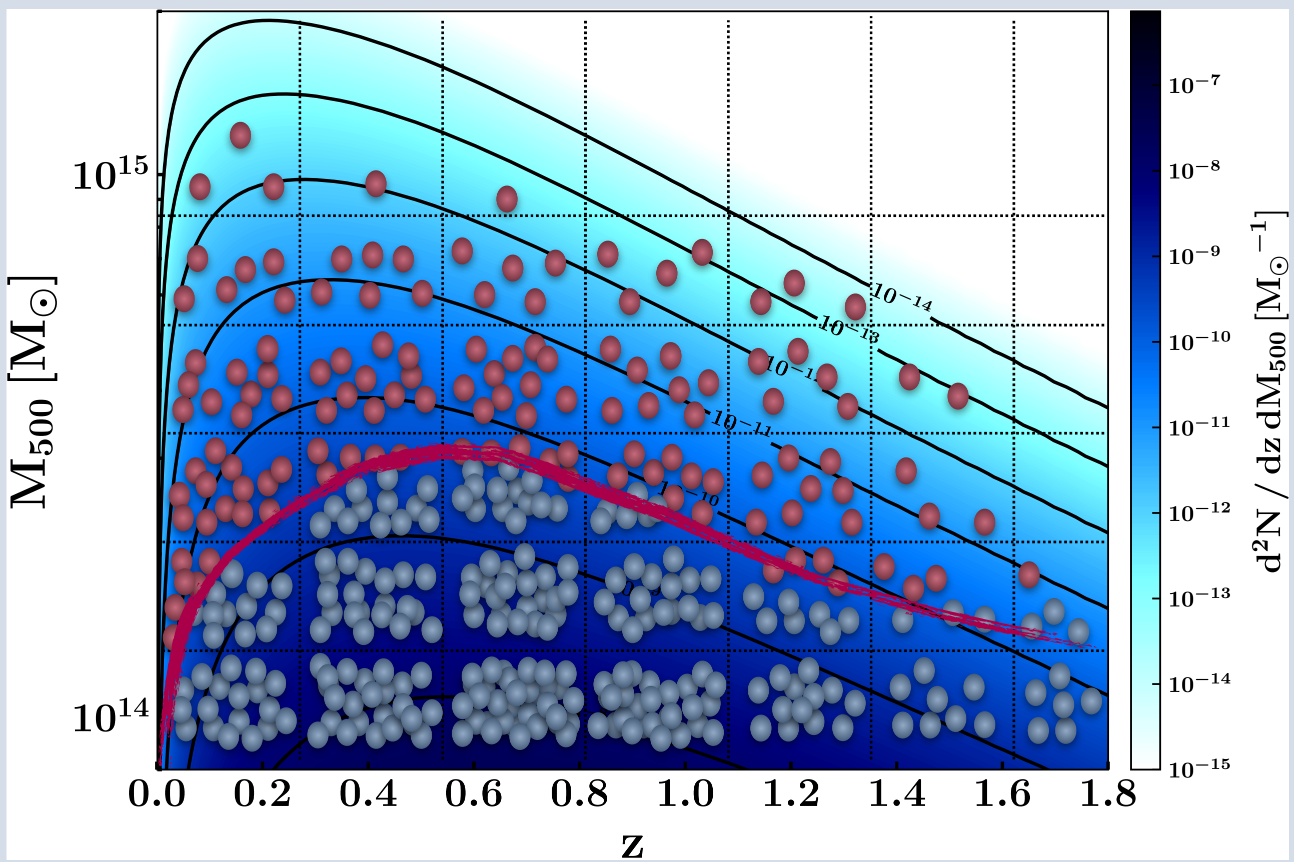

Systematic uncertainties for each element in $\frac{d^2N}{dM_{500}dz}(\xi > \xi_{\rm cat})$

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Systematics on the SZ-mass scaling relation

Scaling relation: $\boxed{\mathrm{P}[\mathcal{O}_{500}|z, M_{500}]}$

- SZ observable: integrated Compton parameter $Y_{500} \propto \int_0^{R_{500}} P_e \, d^3r$

SZ survey

Mean pressure profile

Observable: Y_{500}

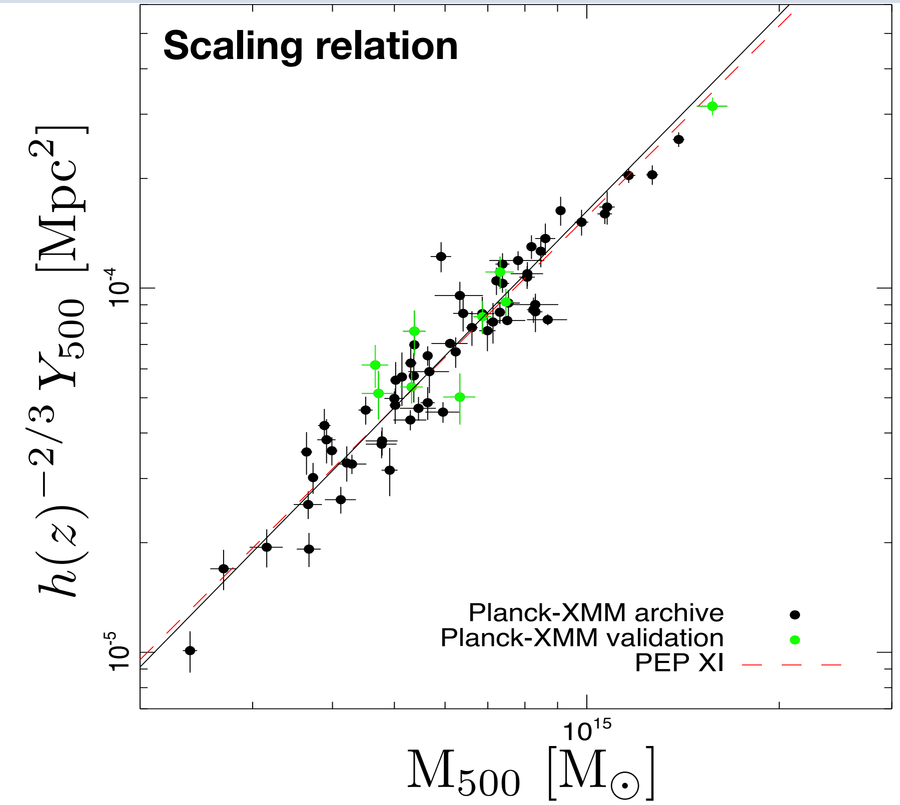
Scaling relation

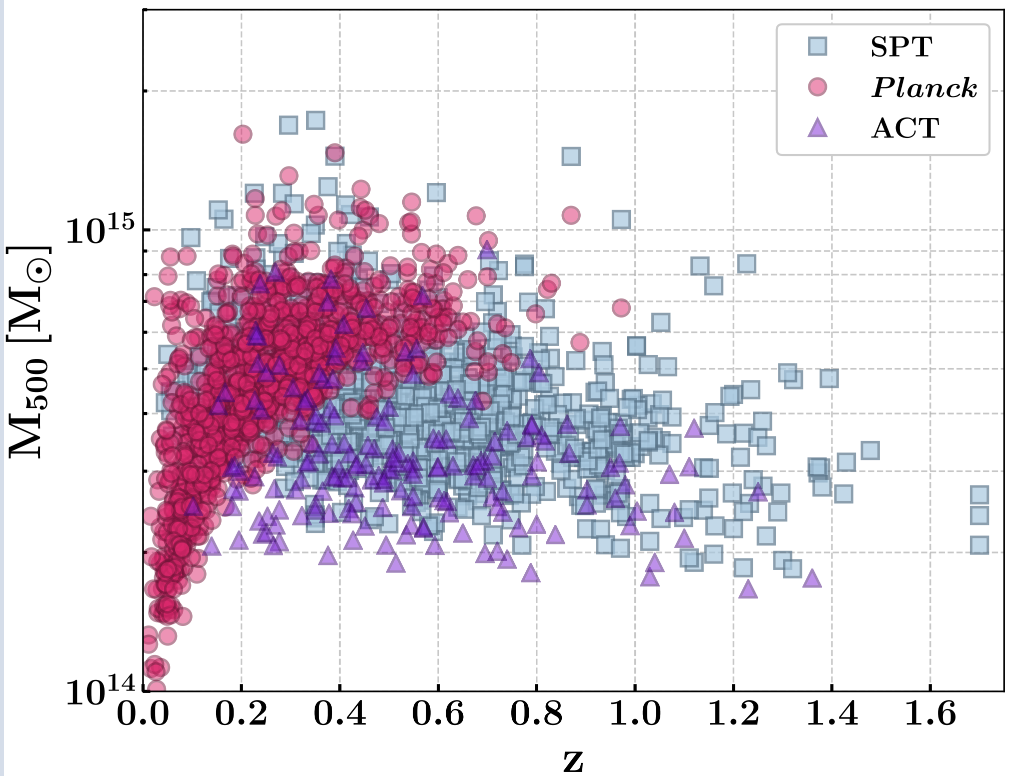
Mass: M_{500}

Main ingredients: **pressure profile** and **scaling relation**

- **Calibration** of ***current*** scaling relations:
  - **low-redshift** cluster samples ($z < 0.5$)
- **Self-similar assumption:** cluster = scaled objects
  - Main ingredients considered for **entire cluster population**

Redshift / Mass evolution of cluster properties?





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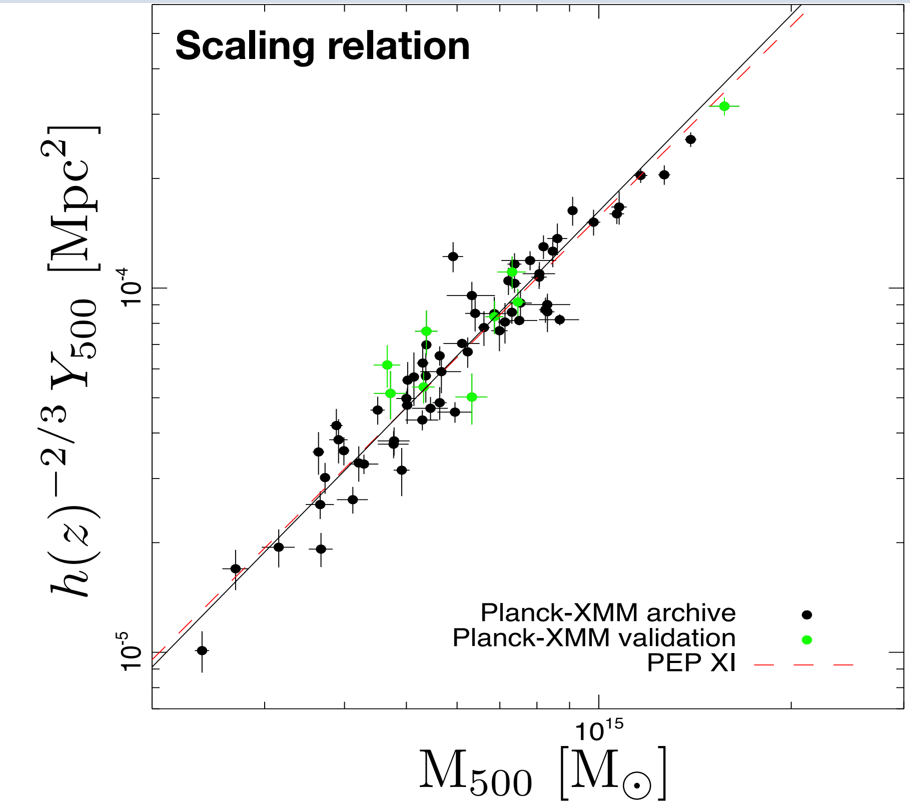

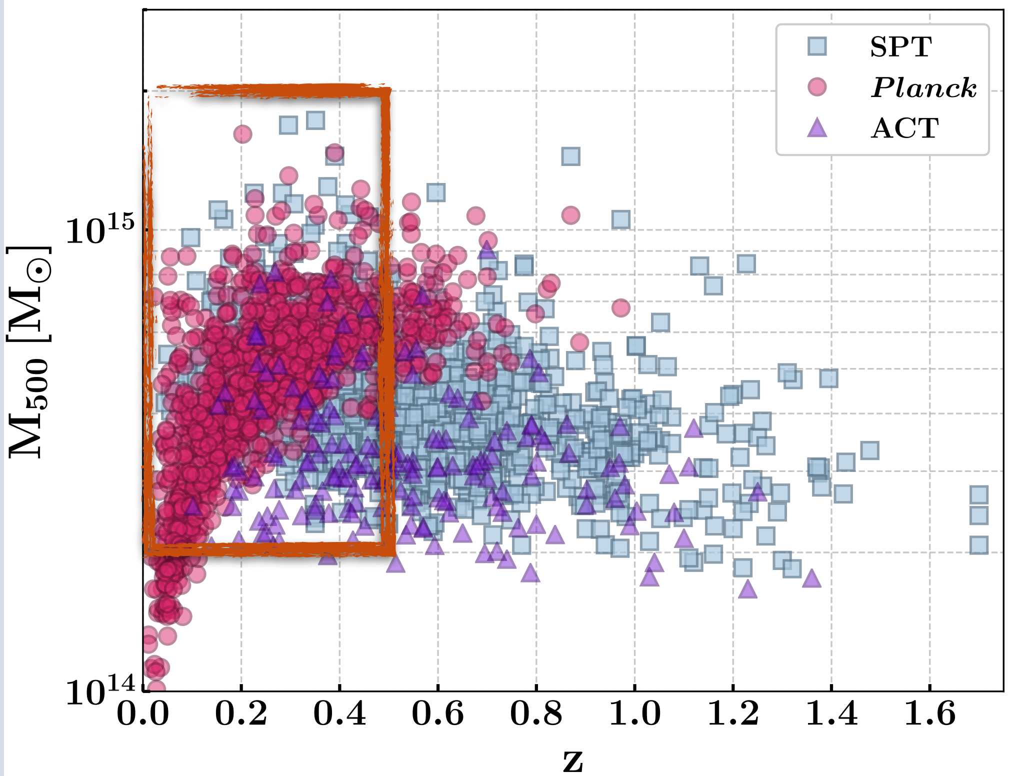

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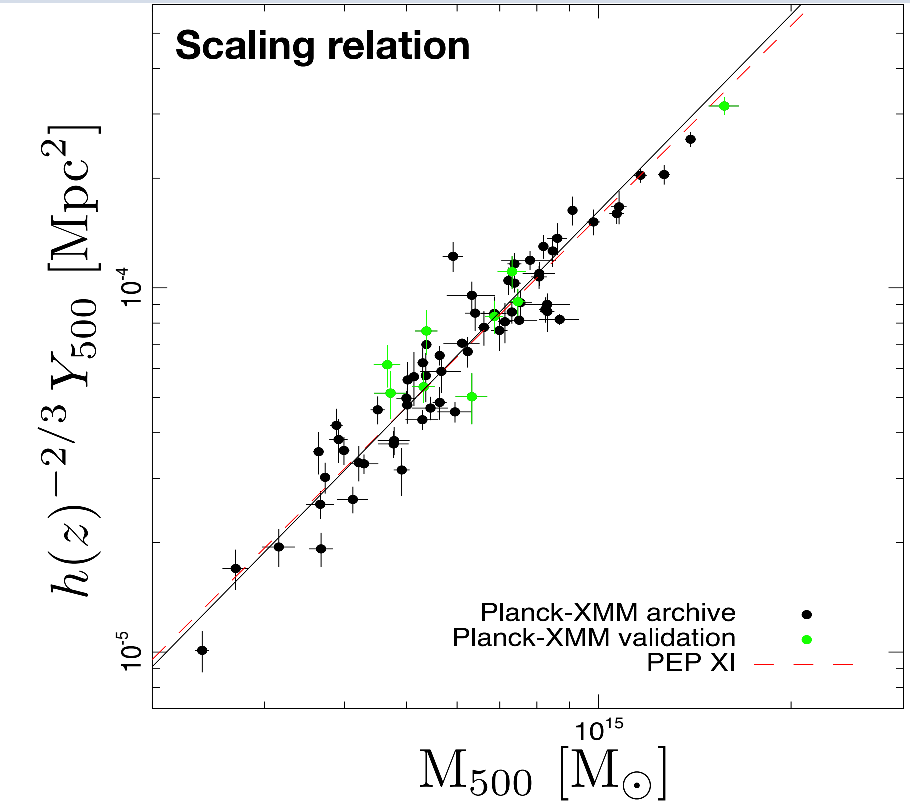
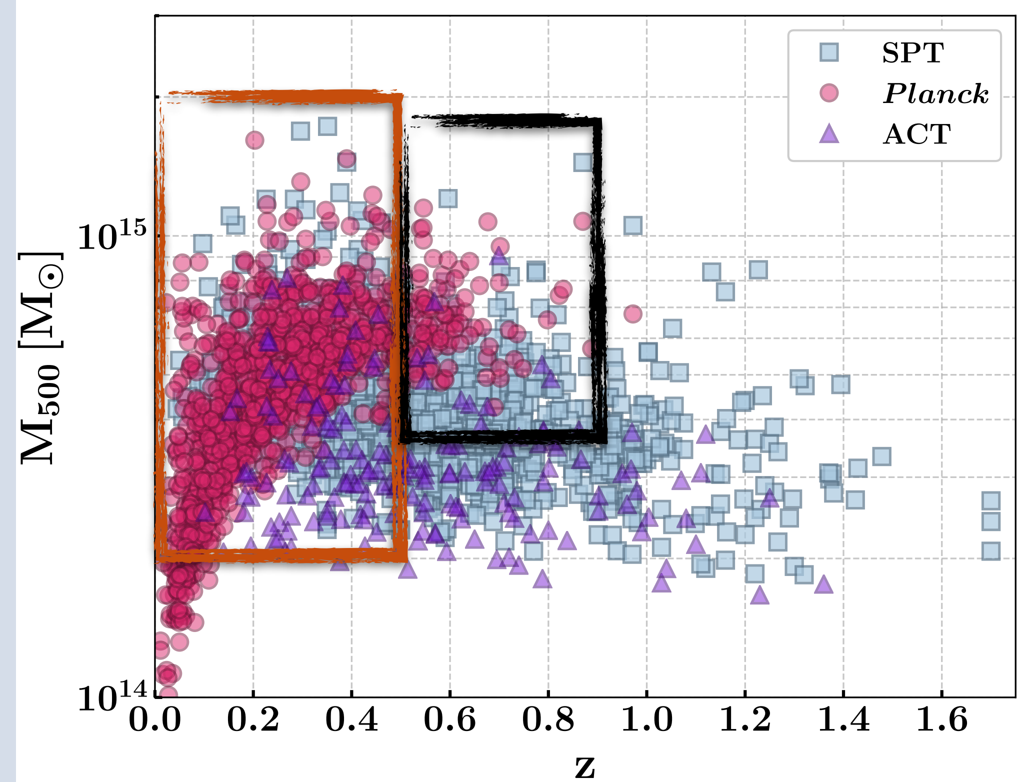
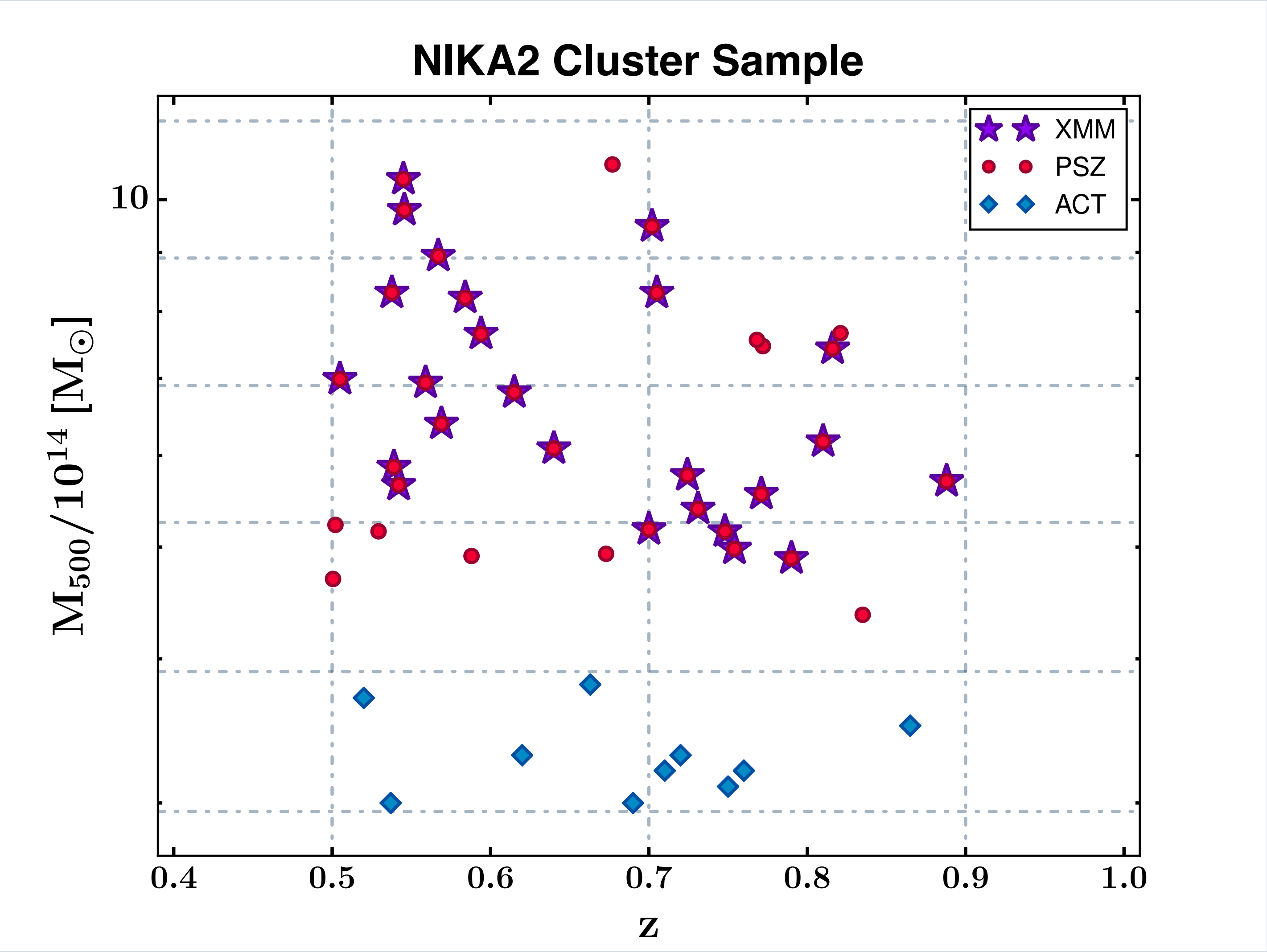


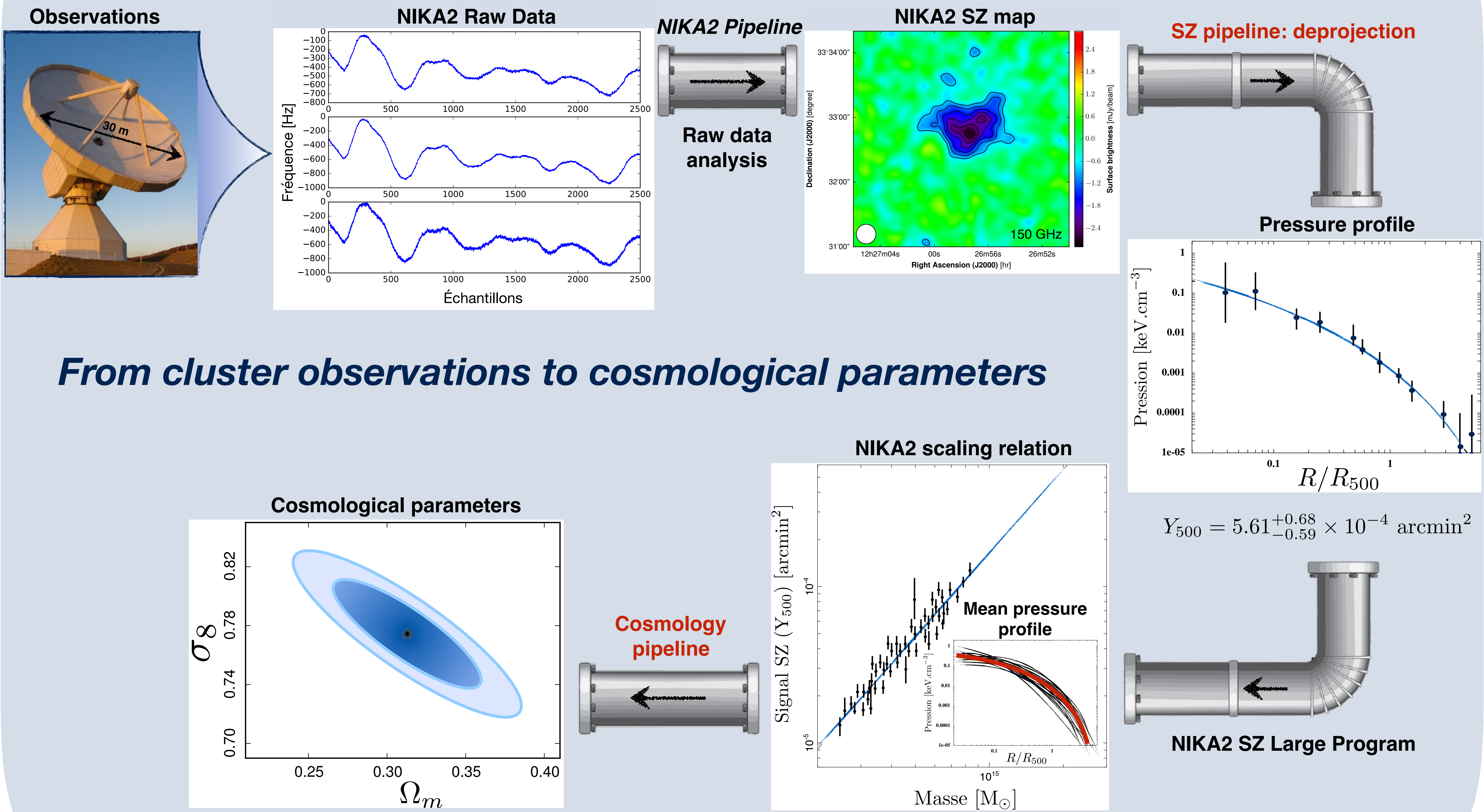


The NIKA2 SZ Large Program



- **High-angular resolution SZ observations of 50 galaxy clusters at high redshift:** $z \in [0.5, 0.9]$
  - 300 hours of guaranteed time at the IRAM 30-m telescope
  - Representative sample of clusters extracted from the *Planck* and ACT catalogs
  - X-ray / SZ combination with XMM-*Newton* and NIKA2 → SZ observable + mass

The NIKA2 SZ Large Program in one diagram



$$Y_{500} = 5.61^{+0.68}_{-0.59} \times 10^{-4}\ \mathrm{arcmin}^2$$

Analysis of systematic effects at each step of the program

Estimation of the pressure profile

Estimation of the pressure profile

- **Standard method:** parametric model
  Adapted to relaxed clusters

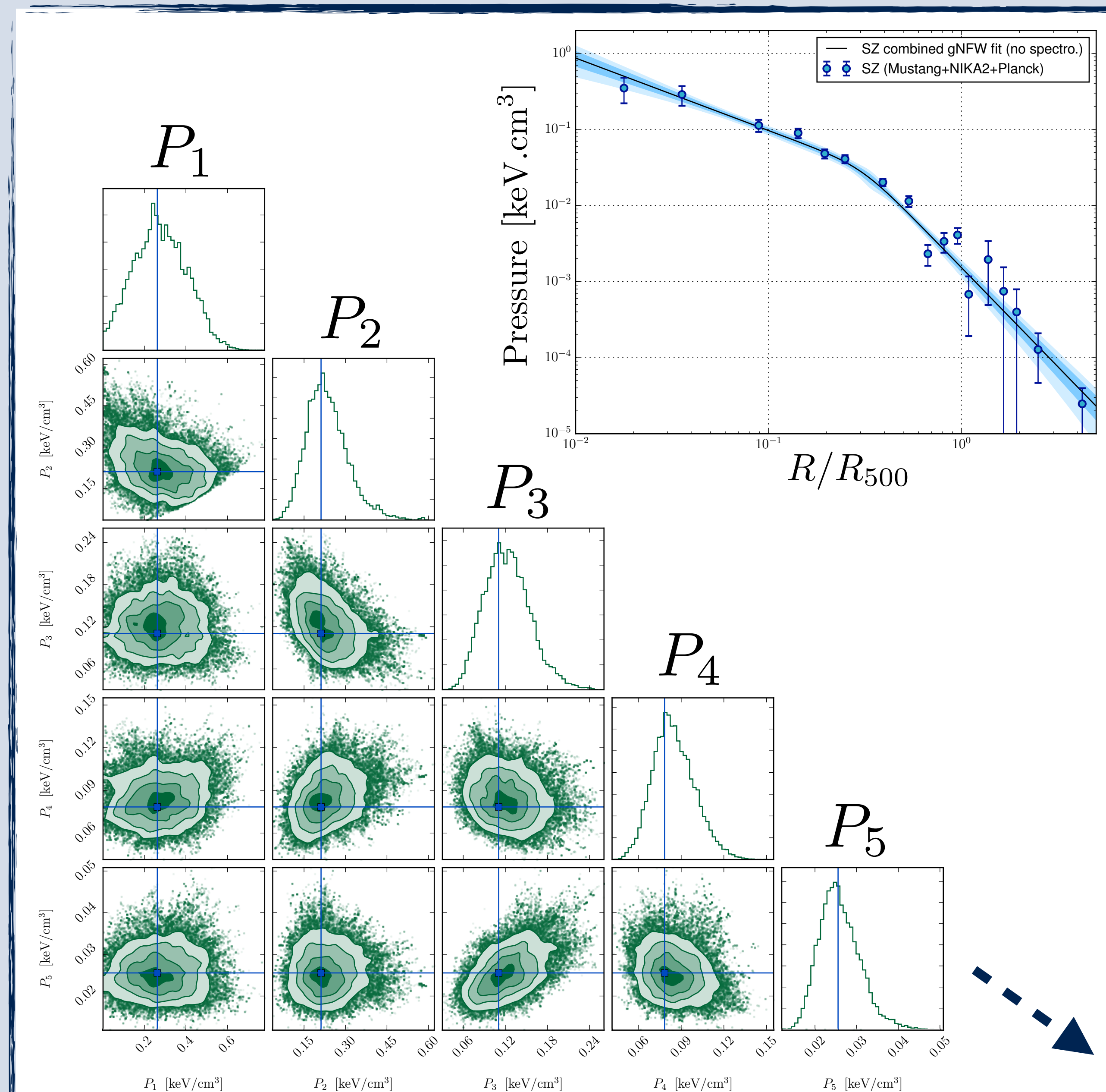
- **New method:** non-parametric deprojection

  Markov Chain Monte Carlo analysis (MCMC)
  N constrained points + power law interpolation

Decrease of computation time *(analytical integration)*

Shock identification *(pressure profile discontinuities)*

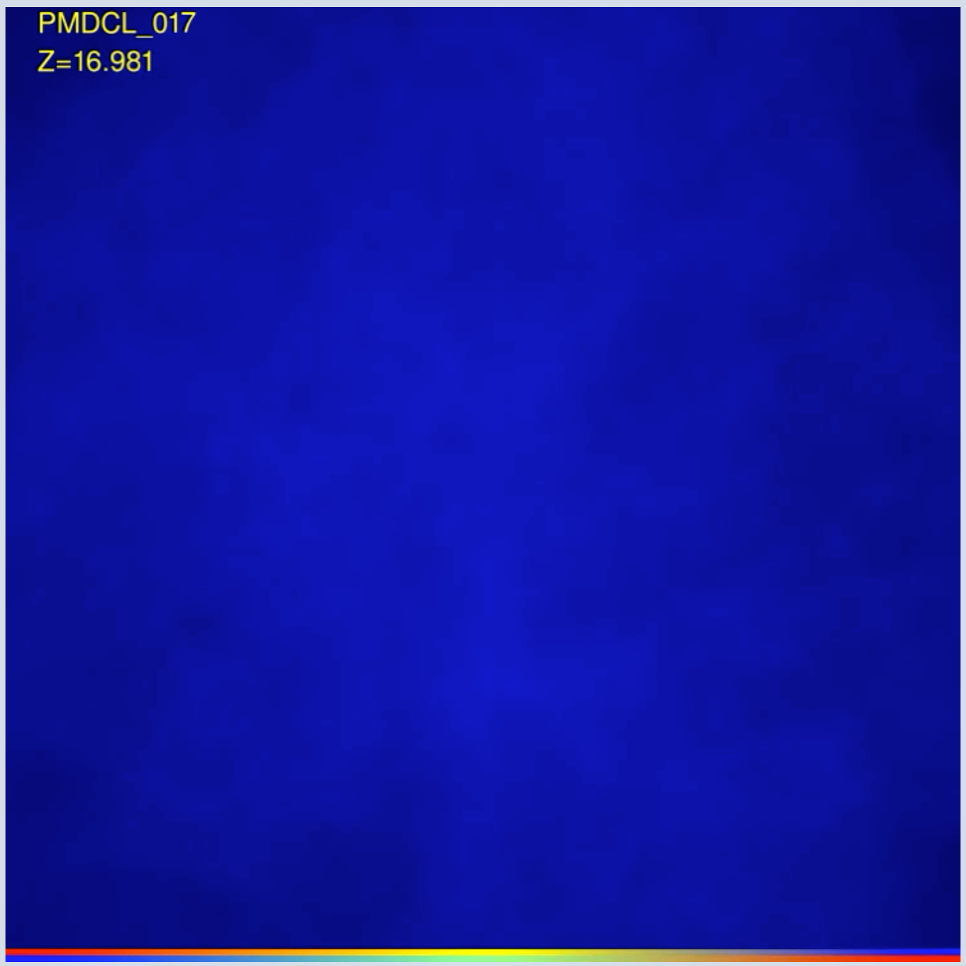
Multi-probe analysis code: official NIKA2 SZ pipeline



F. Ruppin *et al.*, Astron. Astrophys. 597, A110 (**2017**)

F. Ruppin *et al.*, Astron. Astrophys. 615, A112 (**2018**)

Hydrodynamic simulation: prospective studies



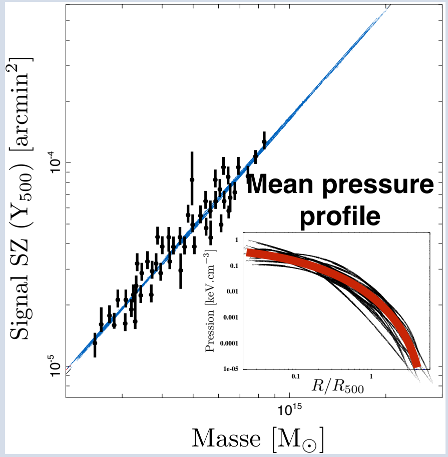
- Work with MUSIC **hydrodynamic simulation**
- Collaborators in Rome and Madrid
- Study of a twin sample of the NIKA2 SZ Large Program: **Mean pressure profile** and intrinsic scatter

▶ Impact of ICM dynamics on the mean pressure profile

F. Ruppin *et al.*, Astron. Astrophys. 631, A21 **(2019a)**

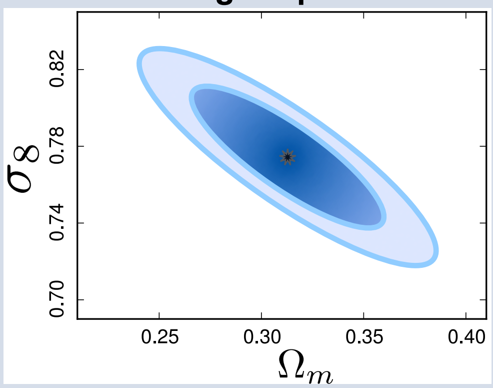
From the mean pressure profile to cosmology

NIKA2 scaling relation



Cosmology pipeline

Cosmological parameters

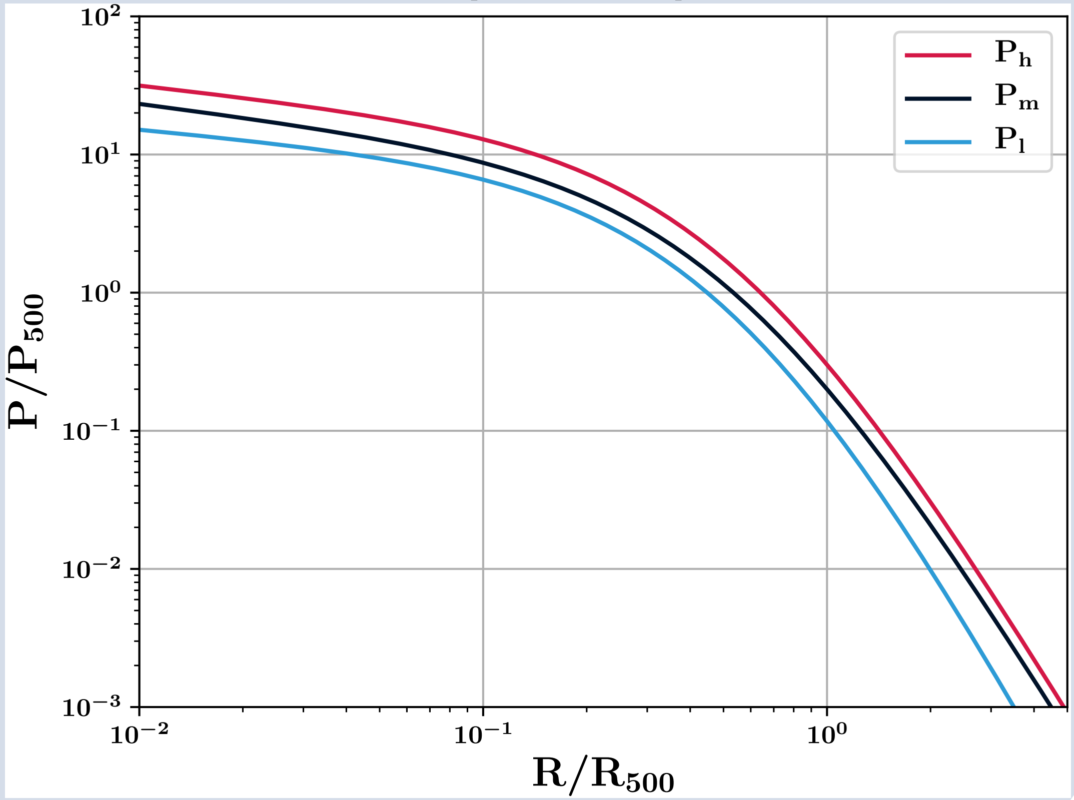


Cluster Cosmology: *Planck* SZ power spectrum

▶ Impact of a modification of the mean pressure profile on σ_8 and Ω_m

- **SZ power spectrum:** depends on cosmological parameters and the mean pressure profile
- Cosmological analysis: MCMC for each profile
- Comparison with *Planck* CMB results

Mean pressure profiles



- Significant impact on the estimation of **cosmological parameters**
- Cancel the **tension** between the CMB and cluster constraints

F. Ruppin *et al.*, MNRAS 490, 784 (**2019b**)

From the mean pressure profile to cosmology

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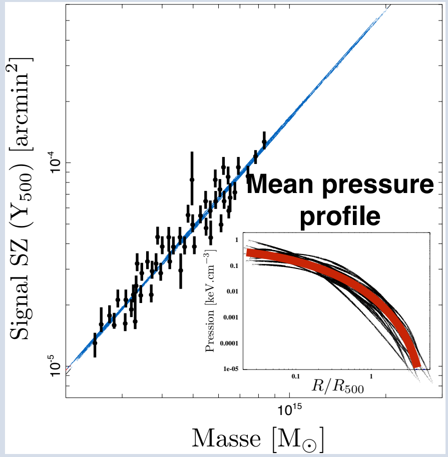

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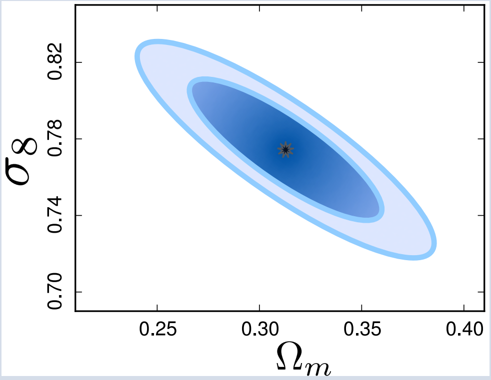

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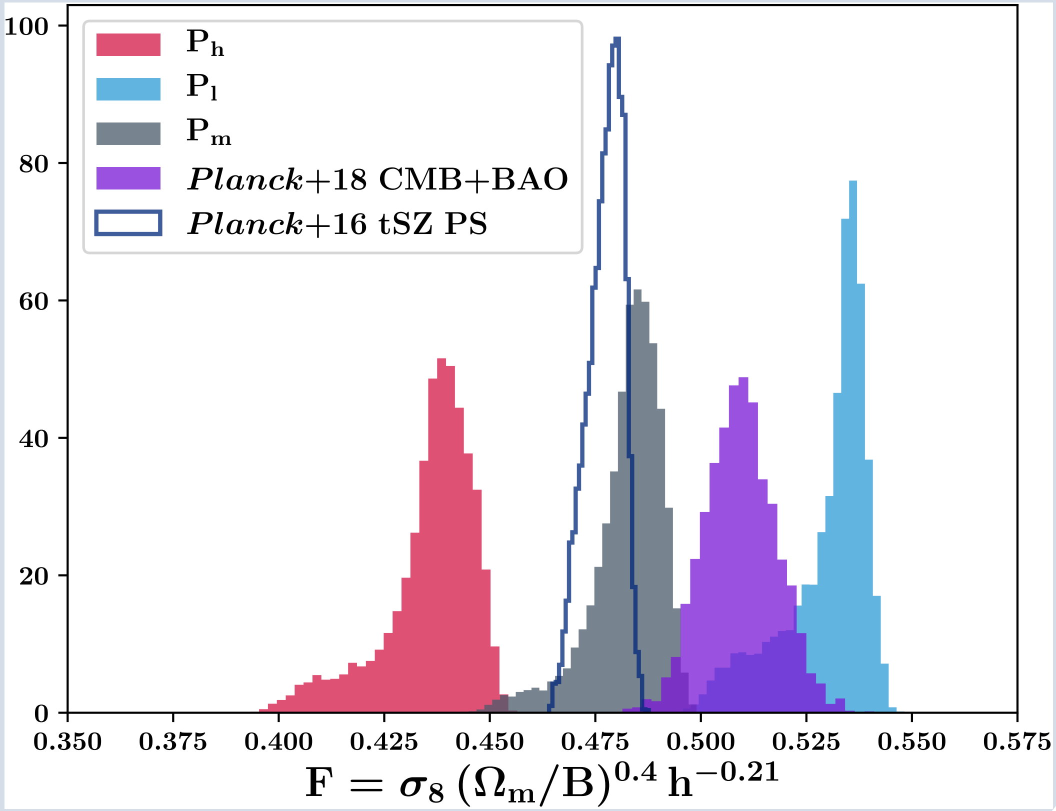
Cosmological constraints



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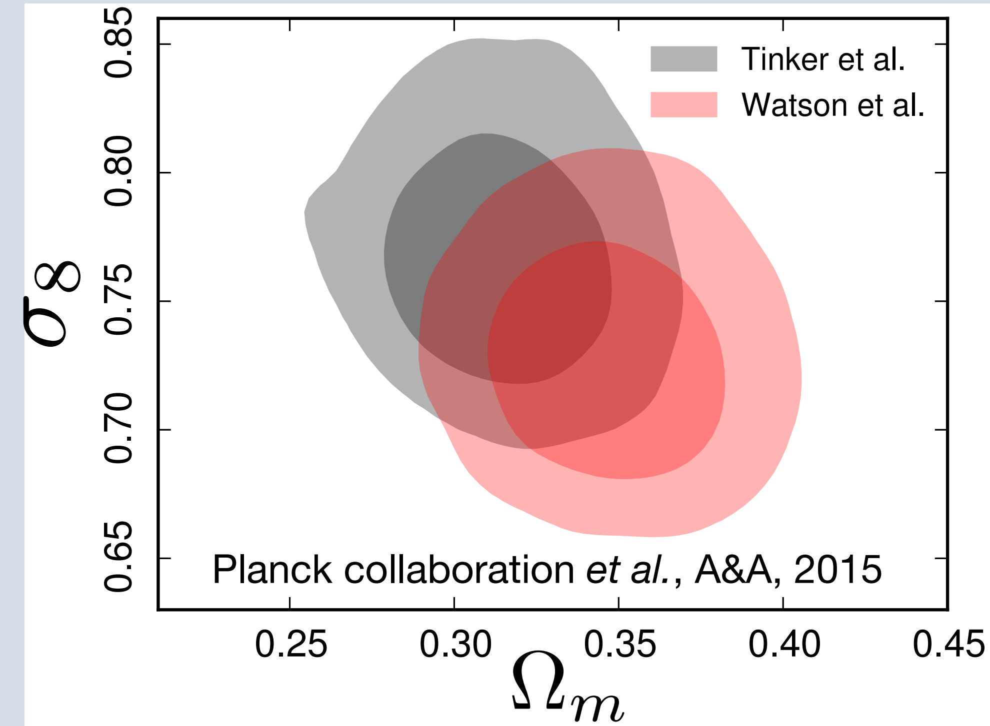
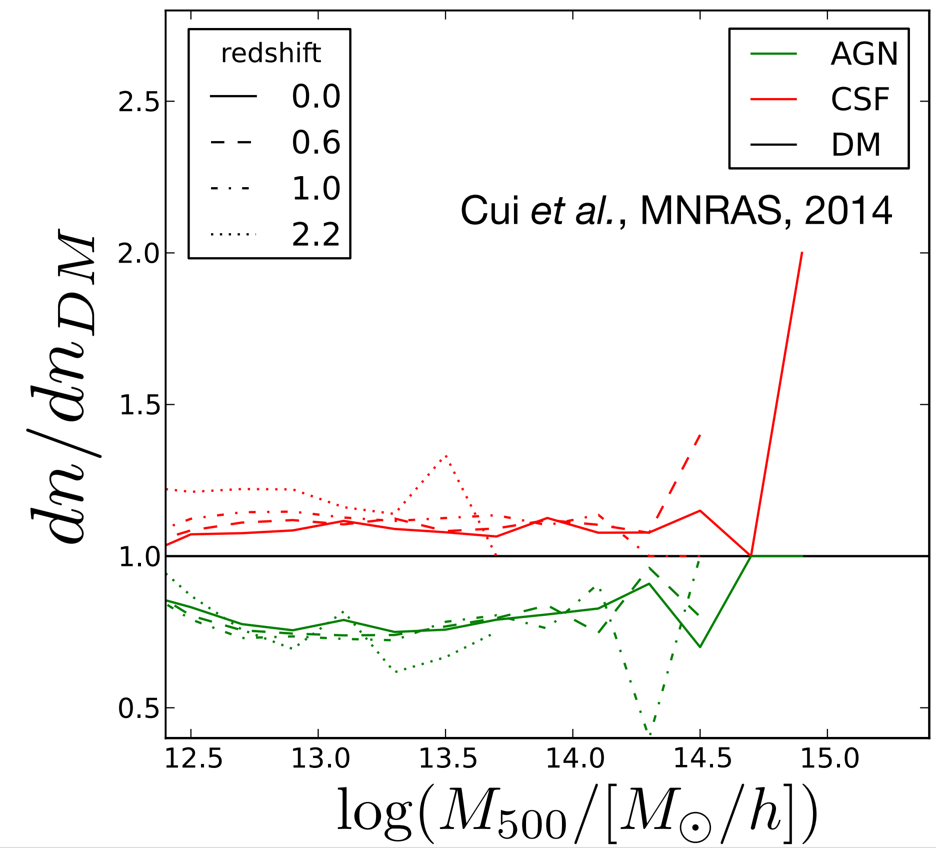
Systematic effects on the mass function: $\boxed{\dfrac{dn}{dM_{500}}}$

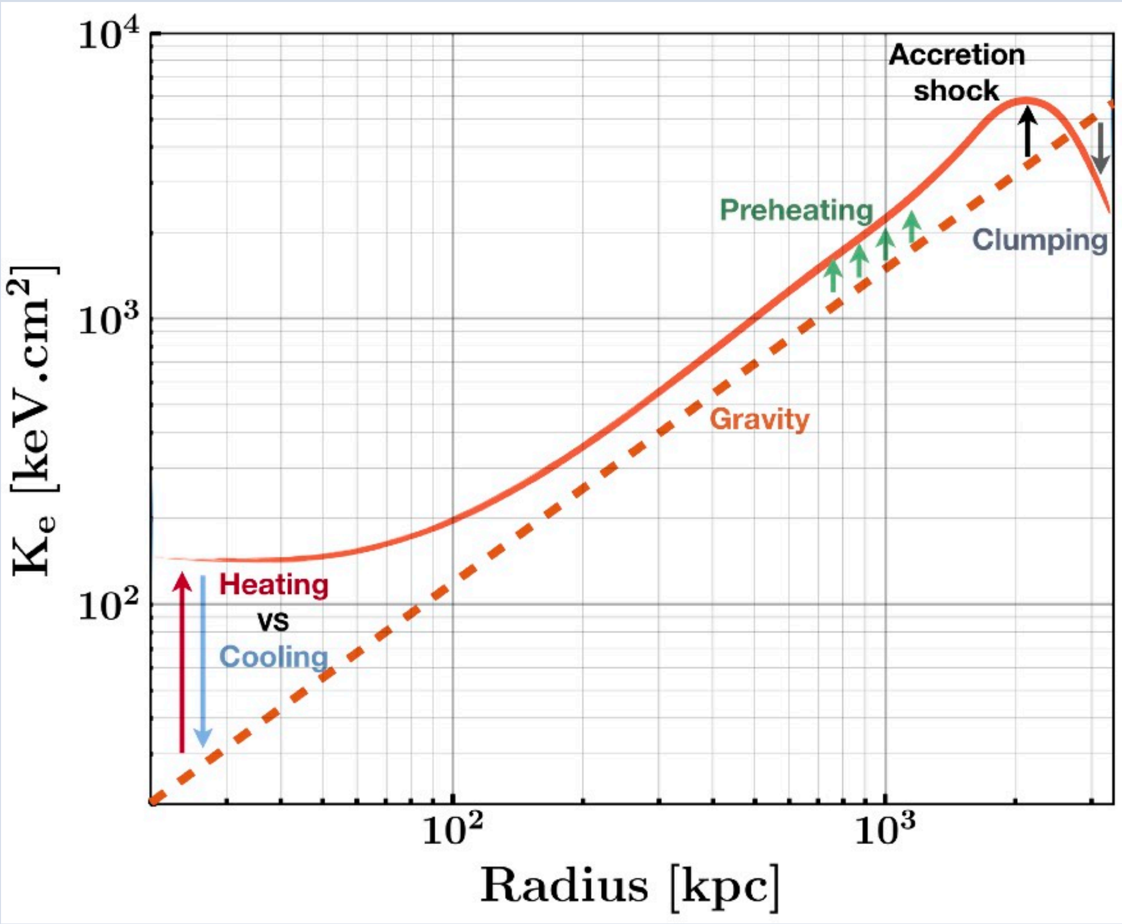
- Calibrated from numerical simulations *(mostly N-body)*
- Significant cosmological impact
- Hydrodynamic simulations: different cluster abundance
  Impact of gas properties and feedback on cluster abundance
- Not enough knowledge on: - AGN feedback
  - heat dissipation within the ICM

→ Observational priors to improve cosmological simulations





Observational priors for simulations

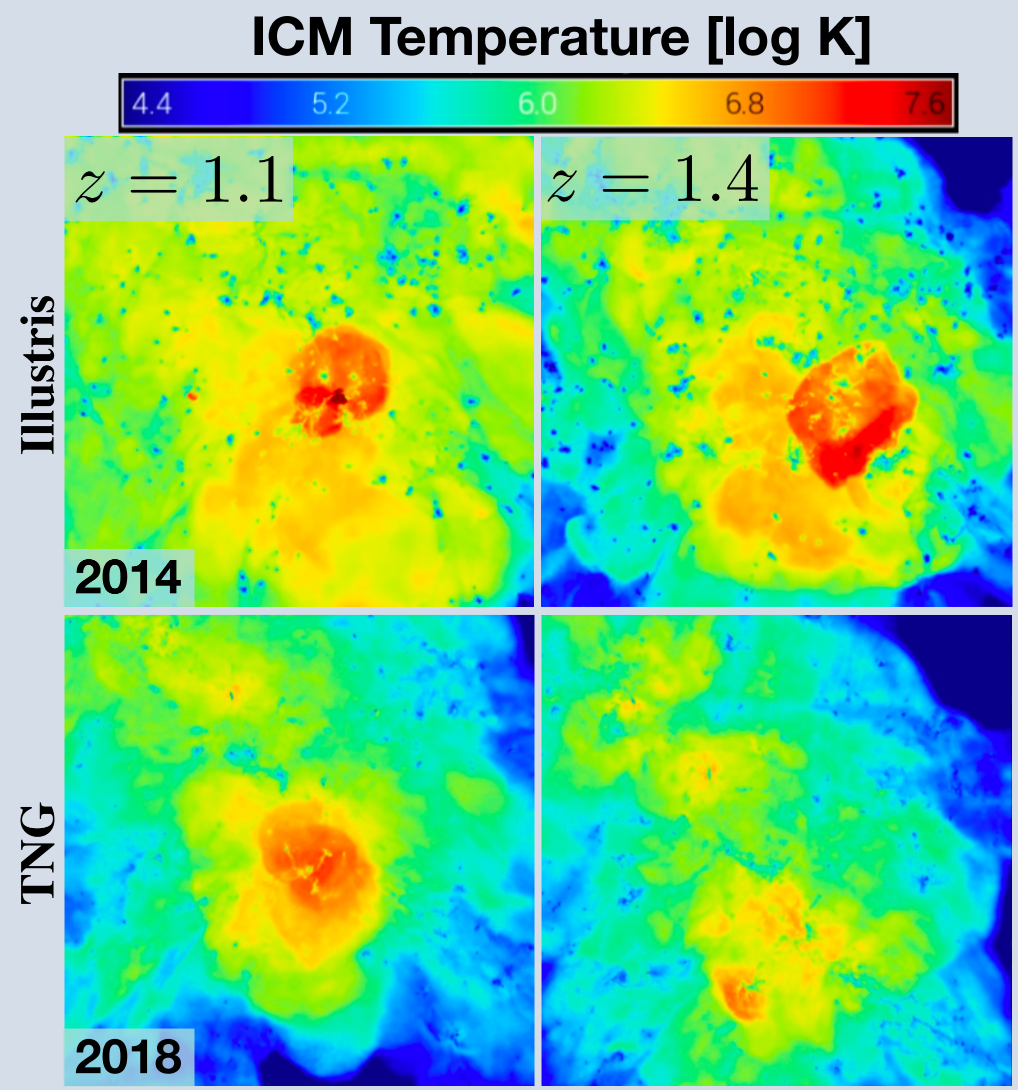


- Radial distribution of gas entropy

SZ effect X-rays

$$K_e(r) = P_e(r)/n_e(r)^{5/3}$$

- Shape and amplitude: energy inputs in the ICM



- ICM temperature map:

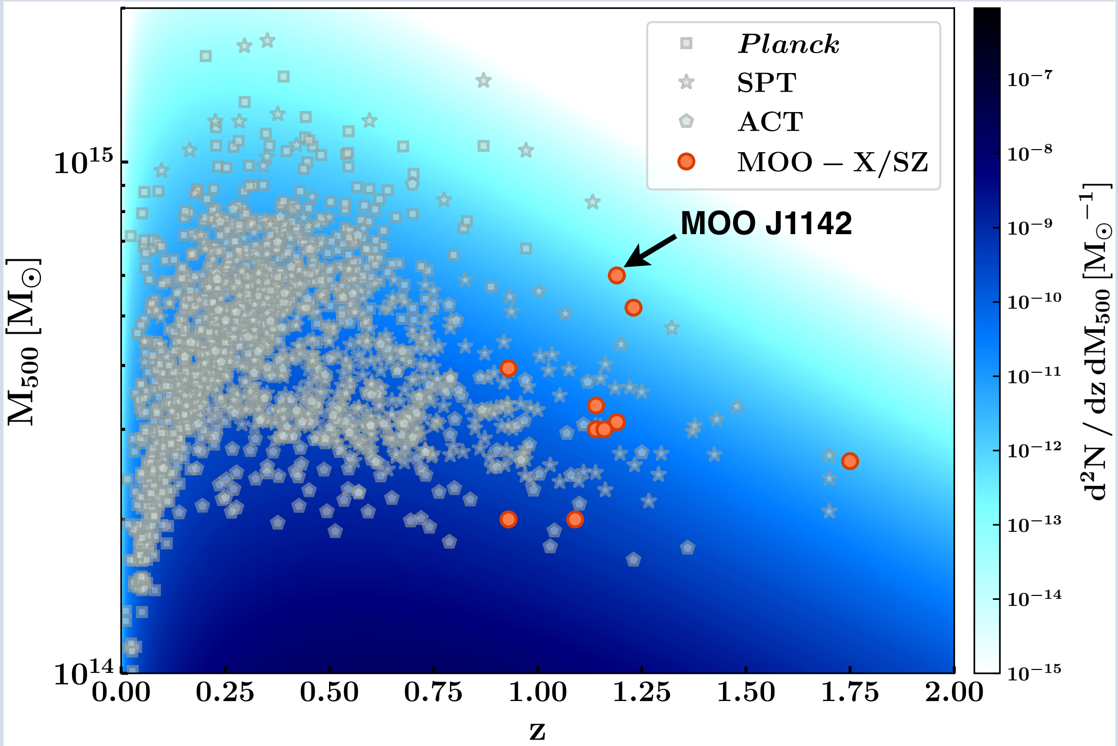
SZ effect X-rays

$$k_B T_e(x,y) = P_e(x,y)/n_e(x,y)$$

- Merging substructure thermalization with the main halo

Need high-angular resolution X-ray/SZ observations at z > 1
→ Improvement of the simulations

Properties of massive clusters at z > 1

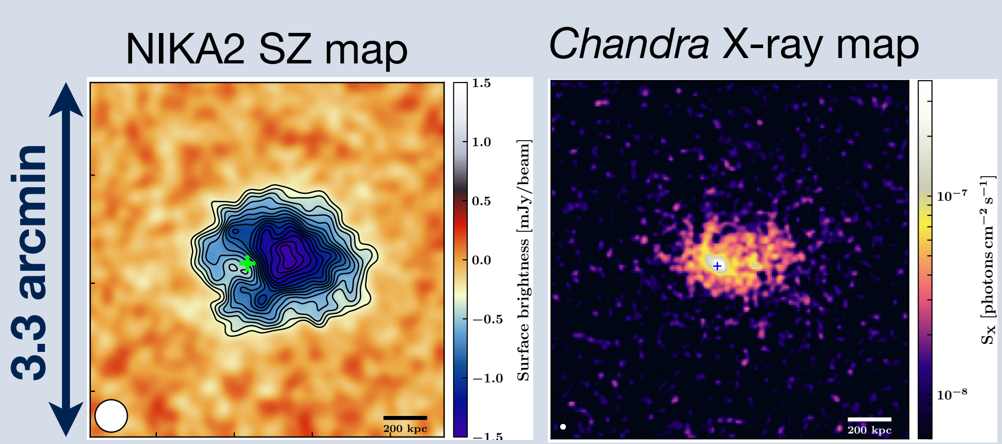


Large program of X-ray and SZ observations at z > 0.9 :

- Clusters discovered in Optical/IR: MaDCoWS and IDCS surveys
- Sample of 10 clusters at **0.93 < z < 1.75**

The case of MOO J1142: merging cluster at z = 1.2

- **X-ray/SZ pipeline:** entropy profile + temperature map



X-ray/SZ analysis

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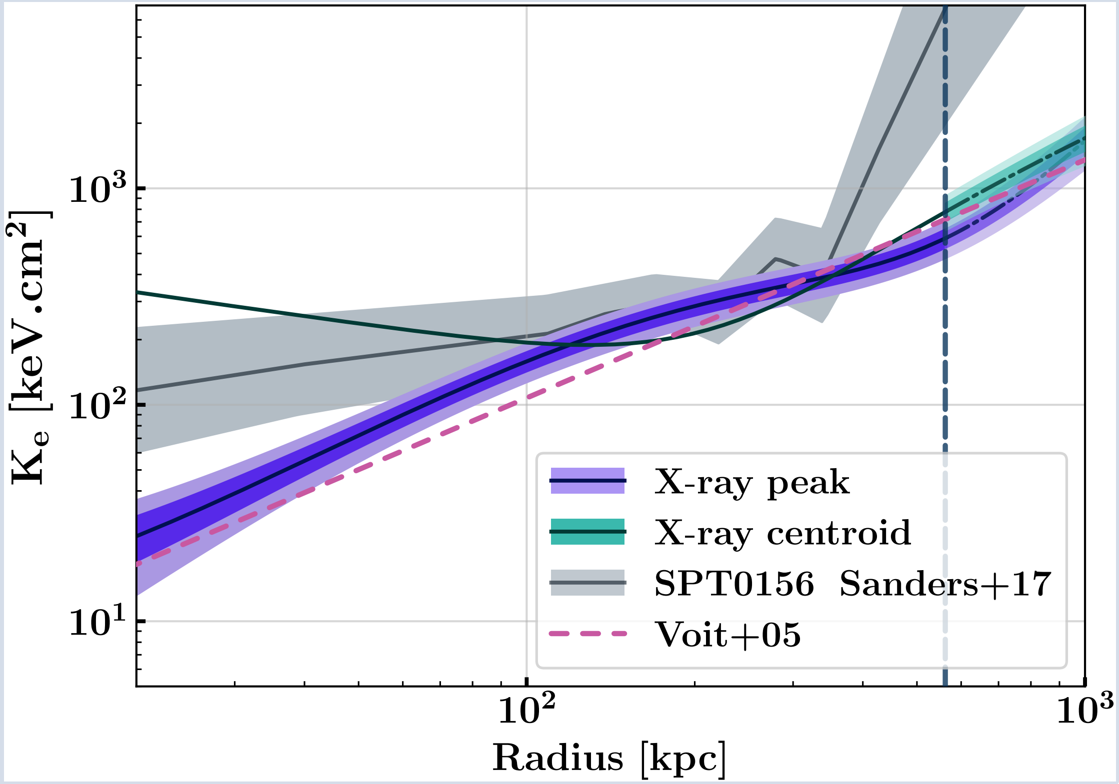

- Entropy: profile 3 times more constrained than X-ray results
- Temperature: map of a merging cluster

F. Ruppin *et al.*, ApJ 893, 74 (**2020a**)

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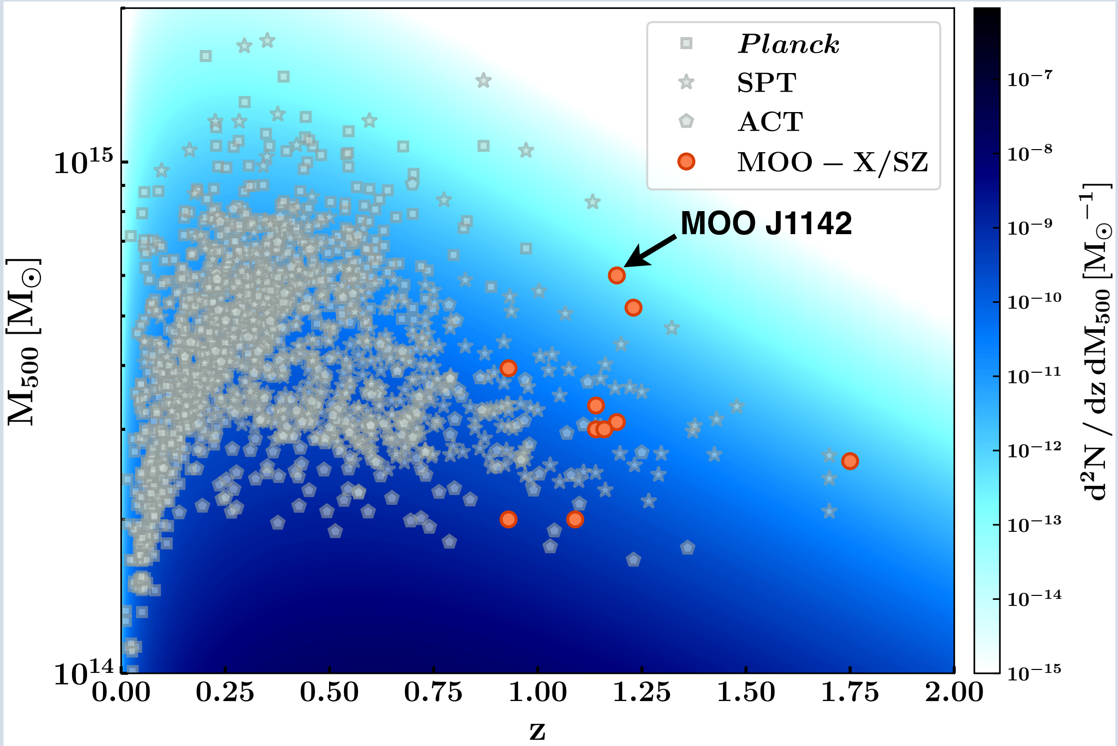

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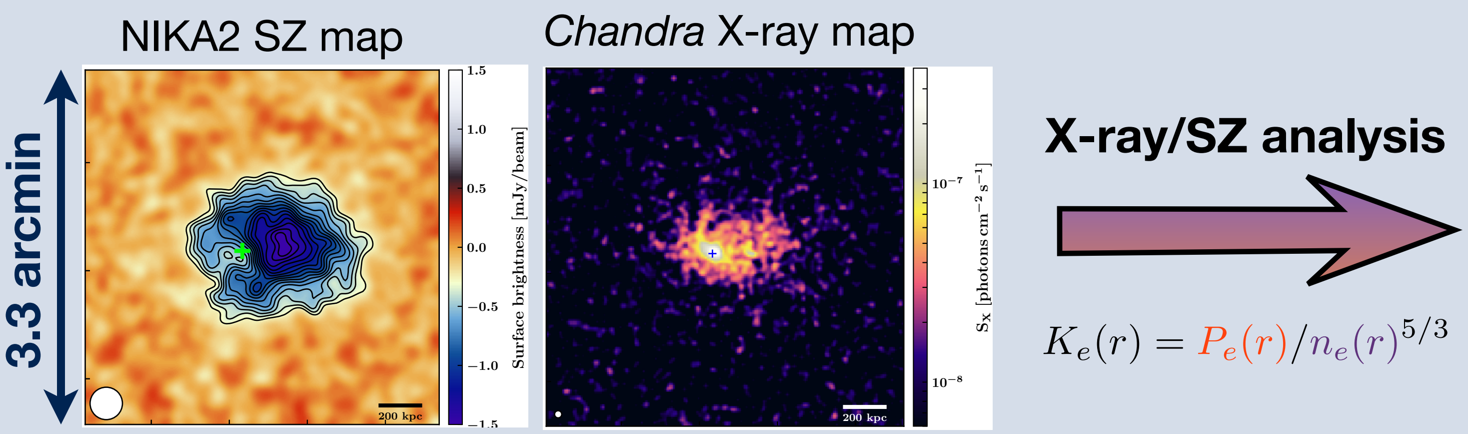

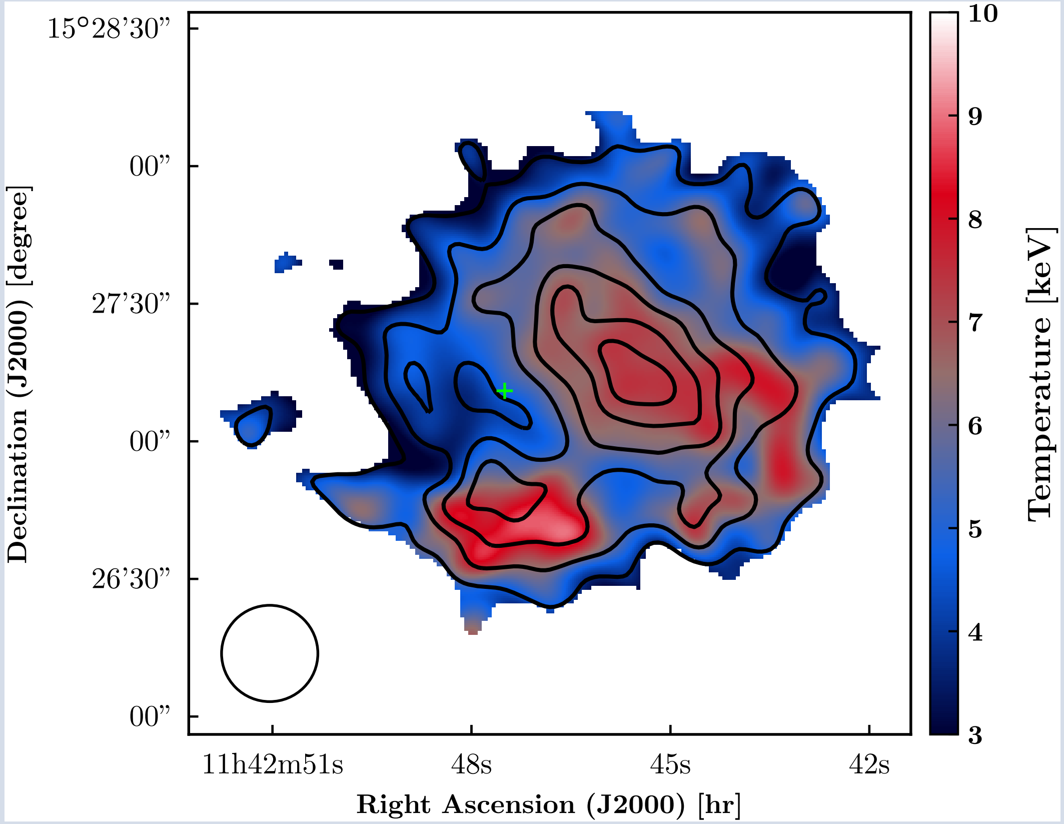

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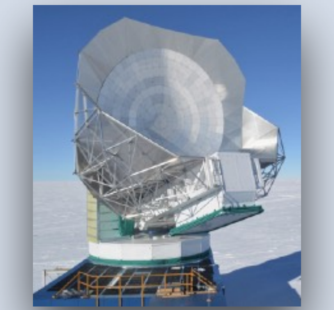
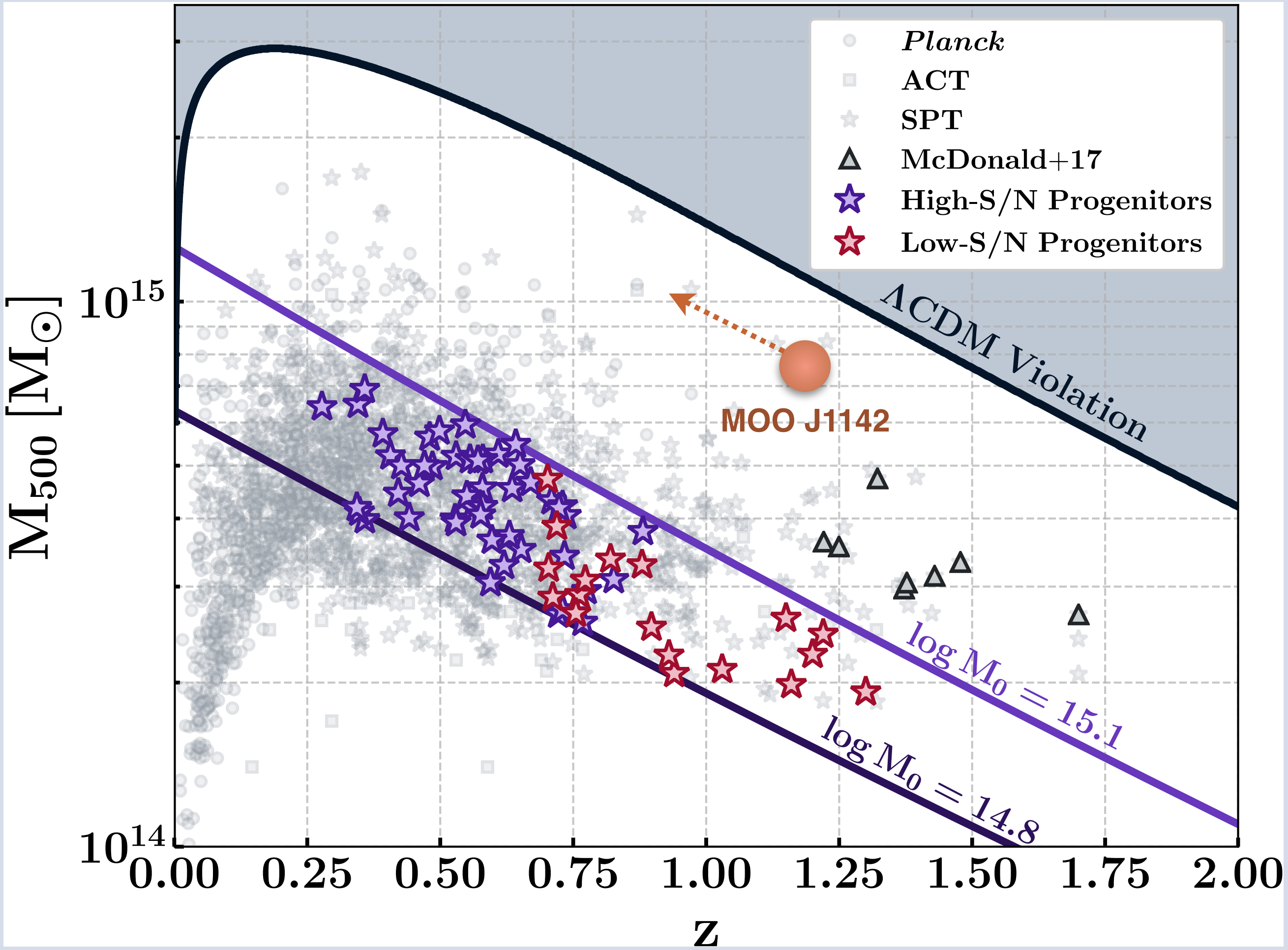
F. Ruppin *et al.*, ApJ 893, 74 (**2020a**)

ICM evolution along a common evolutionary track



Large program of *Chandra* X-ray observations:

- Sample of 67 clusters: progenitors of the most well-know clusters at z = 0
- SPT: South Pole Telescope for CMB observations
- New pipeline for the collaboration: SPT/*Chandra* combination ⟶ divide by 10 the requested *Chandra* exposures



Cool-core fraction: stable for 9 Gyr of cluster growth
Incompatible with results from recent simulations

F. Ruppin *et al.*, under reviewing (**2020b**)

Conclusions

- **Galaxy Clusters:** cosmological probe complementary to BAO, SNe, CMB → - Robust constraints *(systematics)*
  - Precise constraints *(degeneracies)*
  - Tensions *(new physics)*

- **Systematics on cluster abundance:** - measurement of the observable
  - mass calibration *(scaling relation)*
  - halo mass function *(simulations)*
  - selection function *(instrument + analysis)*

- **NIKA2 SZ Large Program:** new insights on redshift evolution of SZ-mass scaling relation → impact on cosmology

- **Joint X-ray/SZ analyses:** push the investigation of ICM evolution to low mass and high redshift → simulations

High-angular resolution multi-wavelength follow-ups of clusters are essential to next generation cluster surveys


Thank you
Credit: Geoffrey Chen
http://www.mit.edu/~ruppin/