Direct measurement of the hydrostatic bias

The mass of CL J1226.9+3332 galaxy cluster

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on behalf of the NIKA2 collaboration

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Overview

- The mass of galaxy clusters for cosmology and the Large Program Sunyaev-Zel’dovich (LPSZ)
- The case of CL J1226.9+3332 galaxy cluster
  - Hydrostatic equilibrium (HSE) mass: systematic effects
  - Lensing mass
  - HSE-to-lensing mass bias
- SZ+X HSE-to-lensing mass bias
- Conclusions

Cosmology with galaxy cluster number counts

For SZ surveys, a precise SZ - mass scaling relation, *SR (Y | M)* needed

Scaling relation:
observable - mass

$$\frac{\mathrm{d}^2 N}{\mathrm{d}M\mathrm{d}z}(\xi > \xi_{\mathrm{cat}}) = \int \mathrm{d}\Omega \int \mathrm{d}\mathcal{O} \int_{\xi_{\mathrm{cat}}}^{\infty} \mathrm{d}\xi \times P(\xi|\mathcal{O}) \times SR(\mathcal{O}|M) \times \frac{\mathrm{d}^2 V_c}{\mathrm{d}\Omega\mathrm{d}z} \frac{\mathrm{d}n}{\mathrm{d}M}$$

Selection function of the experiment

Depends on the evolution of the universe and the structure formation rate

Most used scaling relations:

- SZ - X-ray hydrostatic (HSE) mass (e. g. Lovisari et al. 2020, Arnaud et al. 2010)
- SZ - CMB lensing mass (e. g. Planck 2015 results. XXIV)
- SZ - lensing mass (e. g. Planck 2015 results. XXIV)
- SZ - dynamical mass (e. g. Aguado-Barahona et al. 2022)

→ **Need** of **resolved high redshift clusters scaling relation**

The hydrostatic mass bias problem

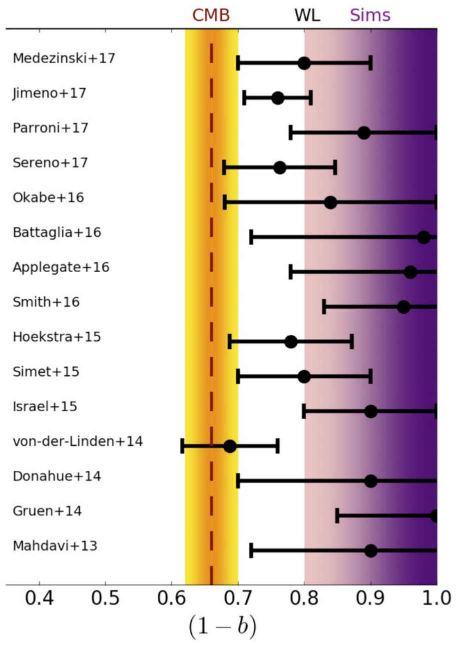
With SZ – $M^{X\text{-ray HSE}}$ scaling relations, cosmology with cluster number counts gives lower σ_8 and Ω_m than the CMB

→ Proving that hydrostatic masses of clusters are underestimated would solve this problem

$1 - b = M^{HSE} / M \sim 0.65$ would be needed

But, according to simulations: $1 - b = M^{HSE} / M \sim 0.9$

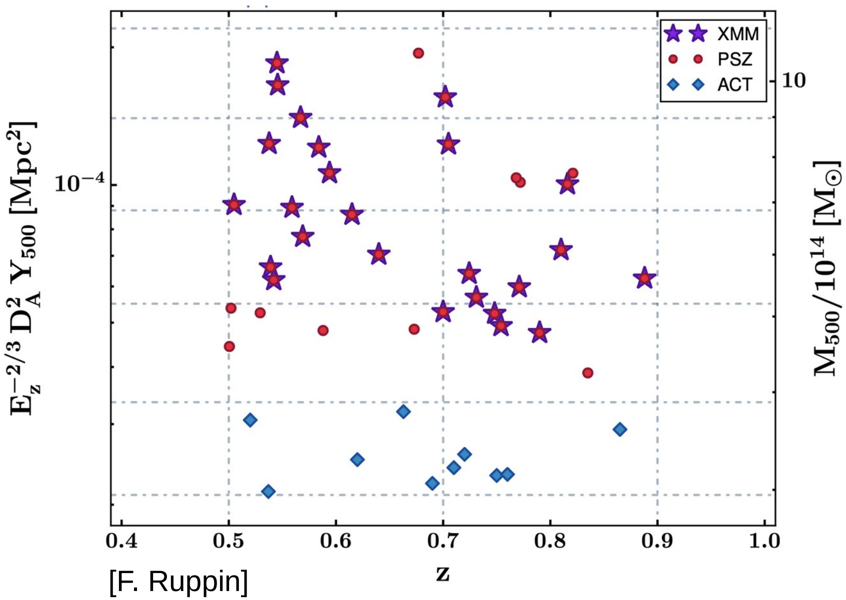
→ **Good measurement of hydrostatic masses needed**



[Salvati et al. 2018]

The NIKA2 Sunyaev Zel’dovich Large Program (LPSZ)

High angular resolution follow-up of 45 Planck and ACT galaxy clusters
[Mayet et al. 2020]



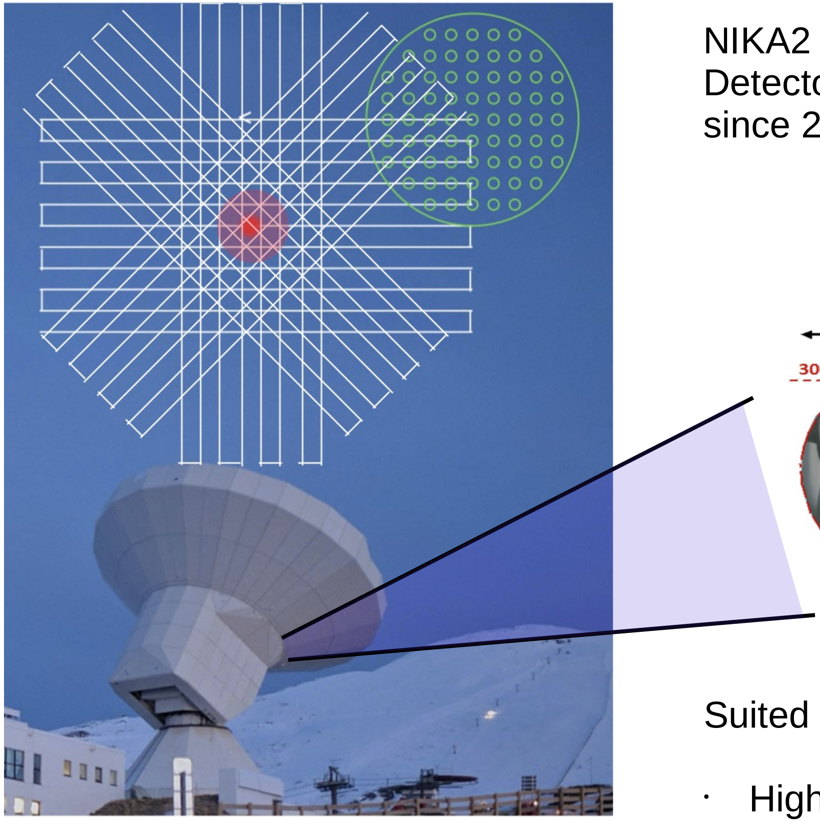
[F. Ruppin]

Precise characterization of the SZ - hydrostatic mass scaling relation:

- **Systematic** effects that affect the **SZ signal**?
  With the angular resolution below the arcminute, identification of:
  - point sources,
  - complex morphologies,
  - shocks
- **Precise** estimation of **hydrostatic masses**

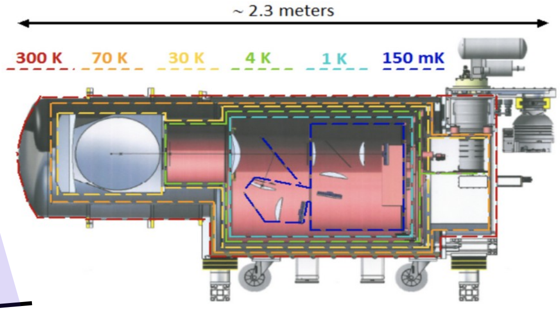
Higher redshift range than previous mass calibration samples

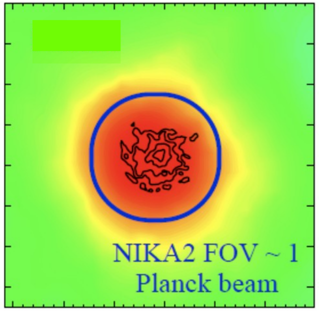
NIKA2



NIKA2 is a millimeter continuum camera of 2 900 Kinetic Inductance Detectors (KID) installed at the IRAM 30-meter telescope, and operating since 2017 [Adam et al. 2018, A&A, 609, A115]

NIKA2





Suited for observing the SZ effect of clusters:

- High angular resolution, below the arcminute (18’’ FWHM at 150 GHz)
- High sensitivity: detect the weak signal of clusters

Hydrostatic mass of a spherical cluster

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

Electron density from

- X-rays:

$$I_x \propto \int {n_e}^2$$

XMM-*Newton*

Electron pressure from

- SZ data:

$$y = \frac{\sigma_{\mathrm{T}}}{m_e c^2} \int P_e \, \mathrm{d}l$$

NIKA2

- or X-rays:

$$P_e \propto n_e T_e$$

XMM-*Newton*

The case of CL J1226.9+3332 galaxy cluster

Highest redshift cluster of the LPSZ, $z \sim 0.89$

« a very X-ray luminous galaxy cluster »

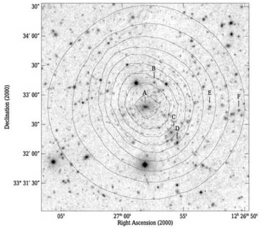
Appeared as a very spherical and massive cluster

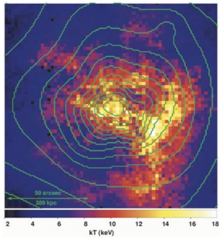
A hot region at ~ 40'' to the south-west

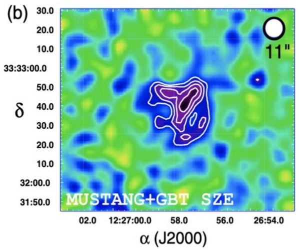
Substructure confirmed in optical and SZ

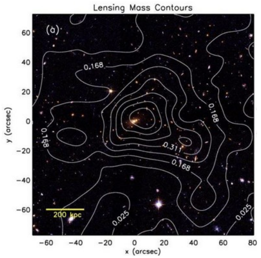
Diffuse radio emission

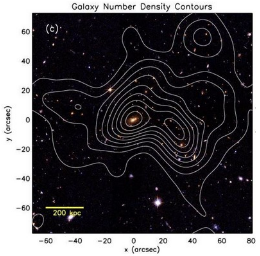
CL J1226.9+3332: evidence of disturbance in the core, but relaxed morphology at large scales

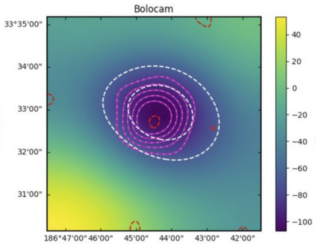


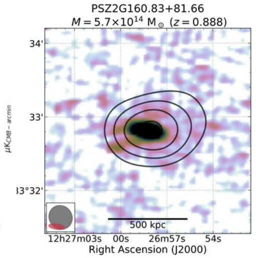






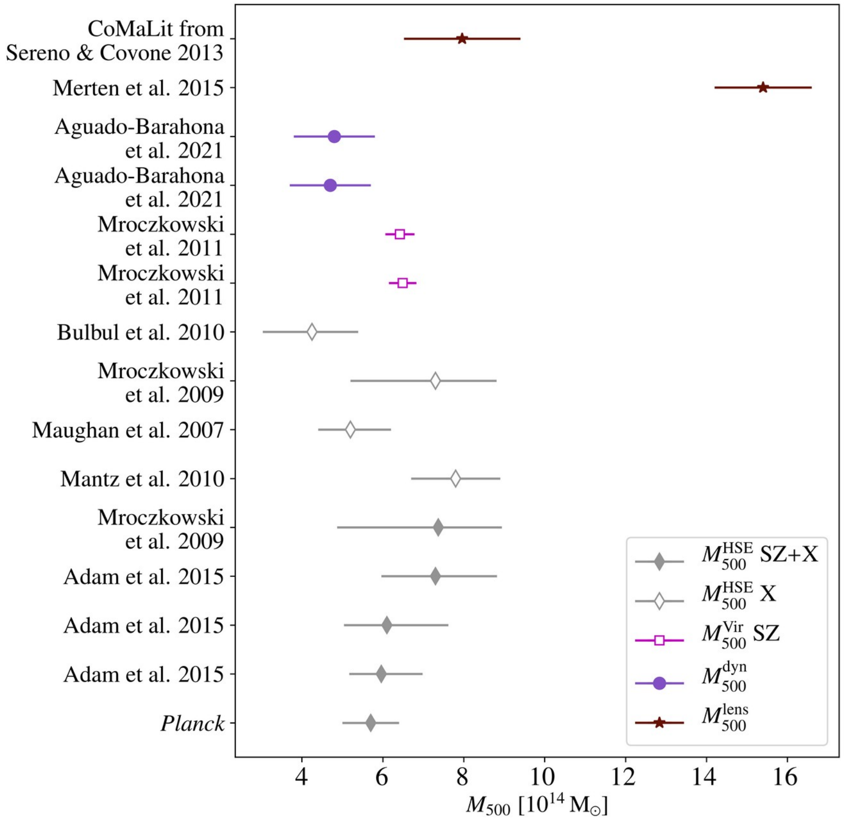






The mass of CL J1226.9+3332

M_{500} values in literature



- Different approaches to obtain HSE masses
- M_{500} HSE mass estimates vary from 4.2 to 7.8 x 10^{14} $M_\odot$
- M_{500} lensing estimates not consistent

The mass of CL J1226.9+3332

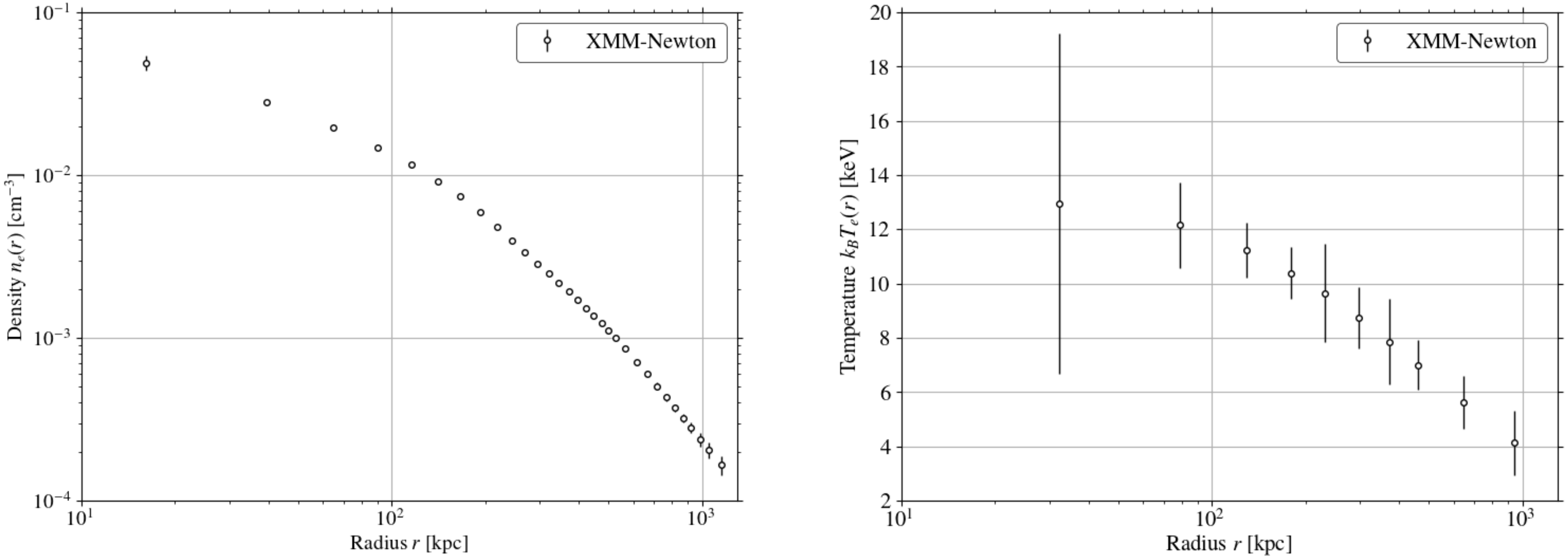
CL J1226.9+3332 widely analysed cluster, but:

- Which systematic effect has the strongest impact on HSE masses?
  - Raw NIKA2 data processing?
  - Modeling of the mass?
- How biased are the HSE estimates w.r.t. lensing?
- Which is its mass?

  $M\,(< R)$ - R correlation makes comparisons very tricky

CL J1226.9+3332 with XMM-*Newton*

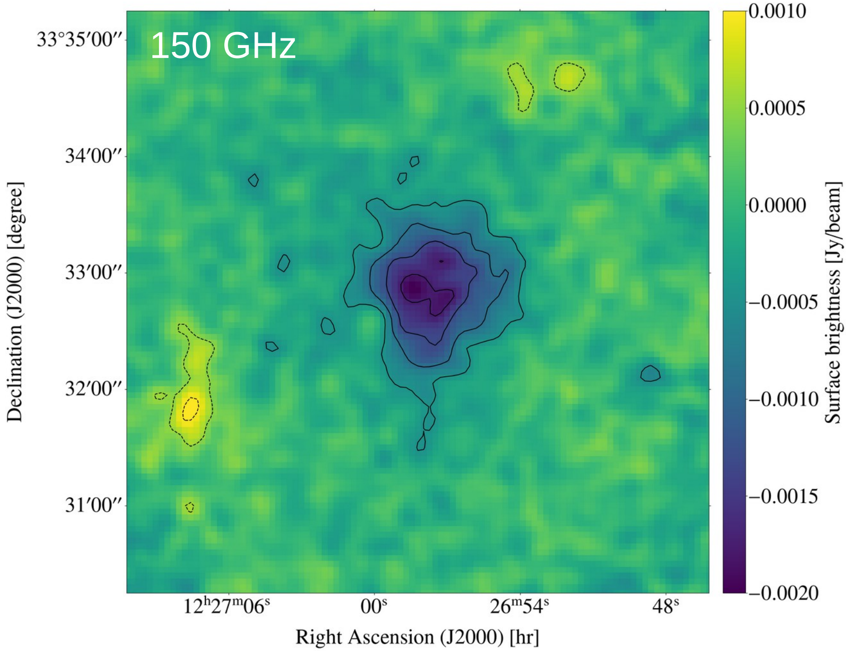
Electron density and temperature profiles centered in $(\text{R.A., Dec.})_{J2000} = (12h26m58.08s, +33d32m46.6s)$

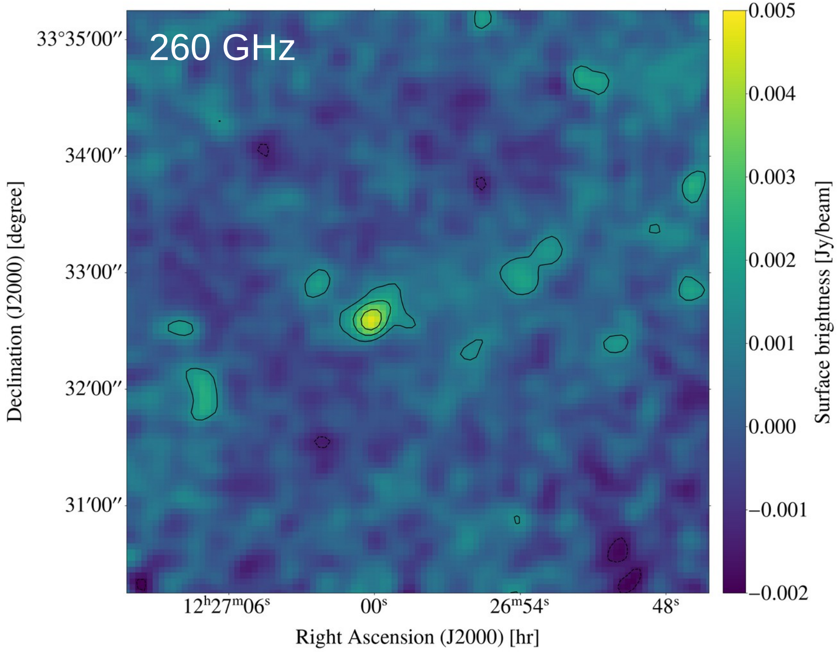


- X-ray measurements up to ~ 1000 kpc
- High temperature measured in the core

CL J1226.9+3332 with NIKA2

3.6 hours in 36 scans with angles of 0, 45, 90, and 135 degrees (w.r.t. Right Ascension axis)
Baseline data reduction method: common modes of most correlated detectors subtracted

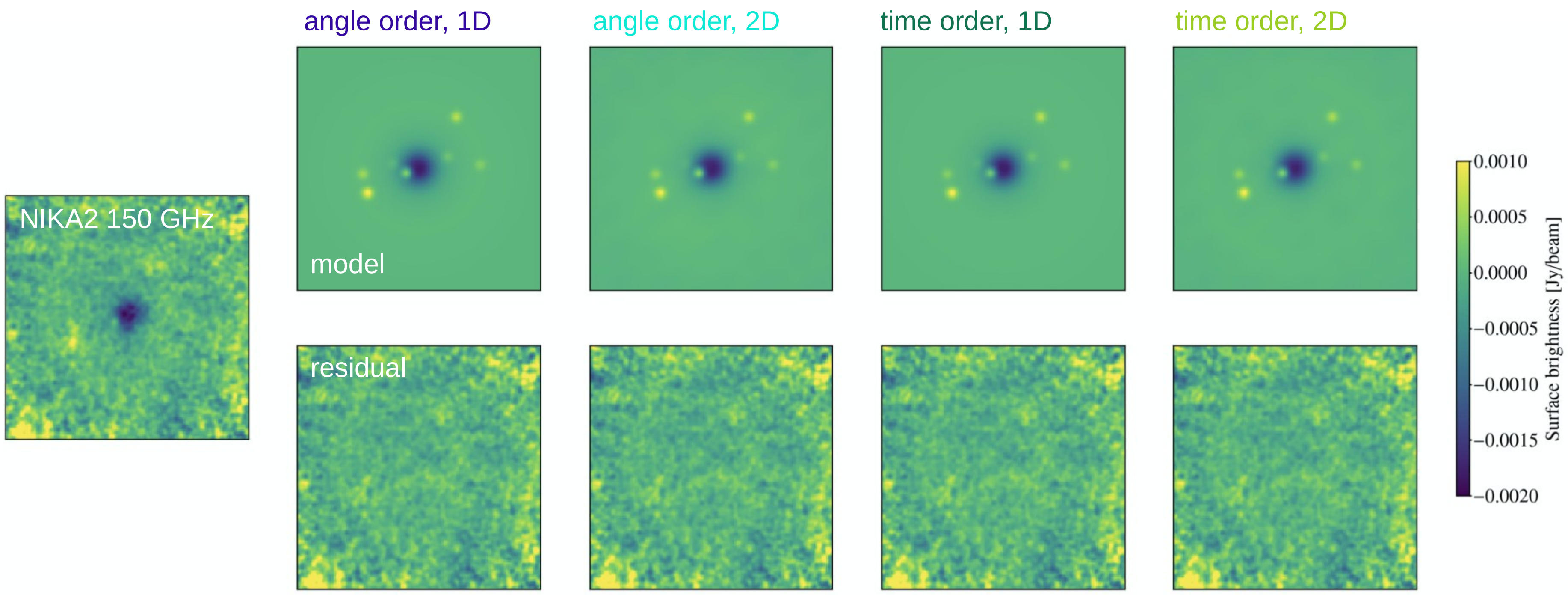




5’ maps, with a 10’’ FWHM smooth. Contours are multiples of 3σ starting from 3σ.

CL J1226.9+3332 with NIKA2: pressure profile determination

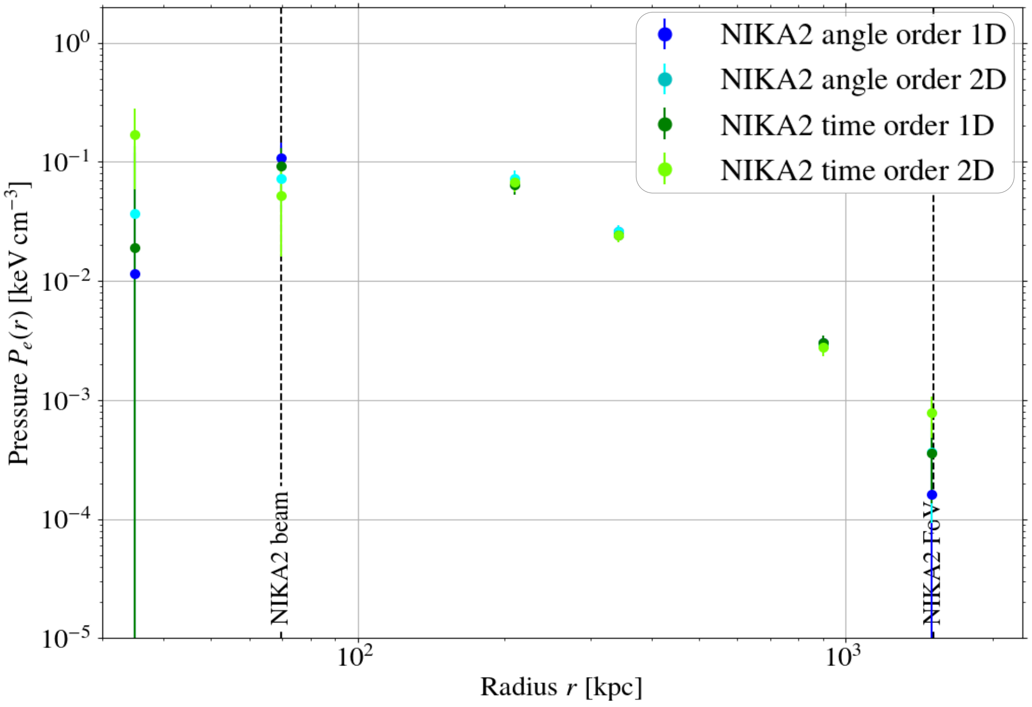
Four different analyses to evaluate the systematic effects from the NIKA2 raw data processing:
impact of the noise estimate and the processing-induced large-angular scales filtering



Equivalent results for the four fits, consistent pressure model and point source fluxes

CL J1226.9+3332 with NIKA2: pressure profile determination

NIKA2 pressure profiles



- Agreement between NIKA2 estimates:
  less realistic noise (angle order) and TF (1D) estimates give consistent results with precise estimates (time order and 2D)

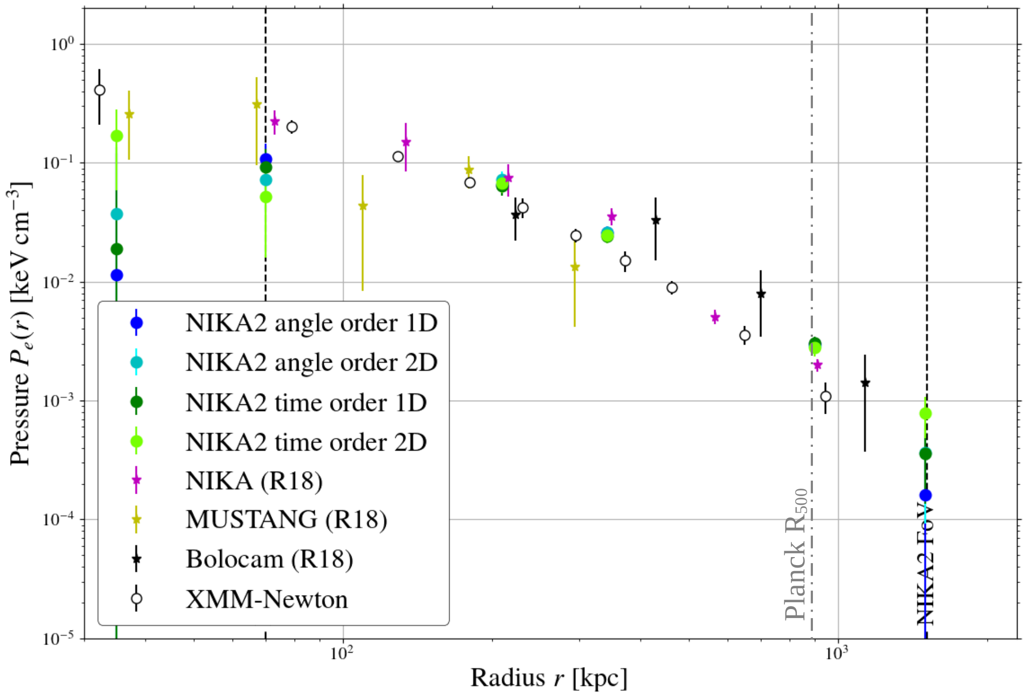
  Slightly larger uncertainties for more noisy estimates

- Last NIKA2 pressure bin (at FoV) completely affected by filtering from data processing, we can not rely on this value

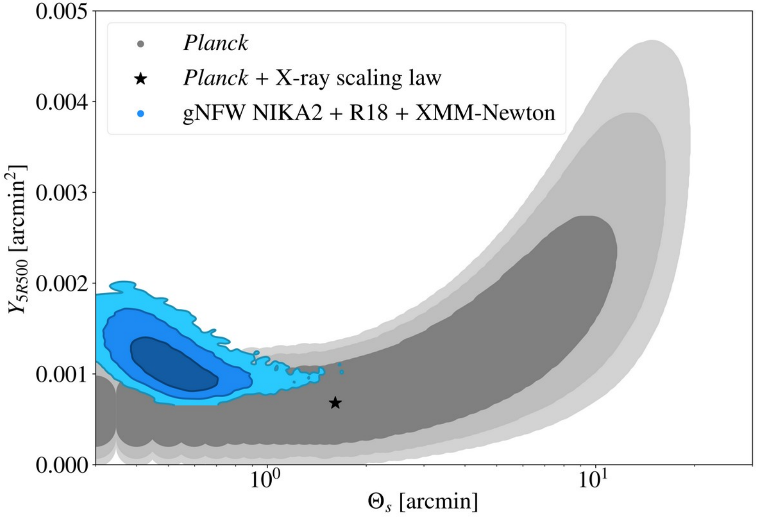
CL J1226.9+3332 with NIKA2: pressure profile determination

NIKA2 pressure profiles compared to XMM-*Newton*
and other SZ data from NIKA, MUSTANG and Bolocam [Romero et al. 2018, R18]

Between the NIKA2 beam and FoV, agreement with other instruments



Improvement in spatial resolution with NIKA2 allows to measure the size (Θ_s) of the cluster



SZ + X hydrostatic mass: fit of the pressure profile

Two different approaches to model the HSE mass

- Fit a smooth pressure profile, **gNFW**:

$$P_e(r) = \frac{P_0}{\left(\frac{r}{r_p}\right)^c \left(1 + \left(\frac{r}{r_p}\right)^a\right)^{(b-c)/a}}$$

free parameters: P_0, r_p, a, b, c

- HSE mass:

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

- Reverse the approach:

$$P(r_b) - P(r_a) = \int_{r_a}^{r_b} \frac{{\rm d}P(r)}{{\rm d}r} {\rm d}r = \int_{r_a}^{r_b} -\mu m_p G n_e(r) \frac{M_{\rm HSE}(< r)}{r^2} {\rm d}r$$

- Fit a density profile, **NFW**:

$$\rho_{\rm NFW}(R) = \frac{\rho_c \delta_c(c_{200})}{R/r_s(1 + R/r_s)^2}$$

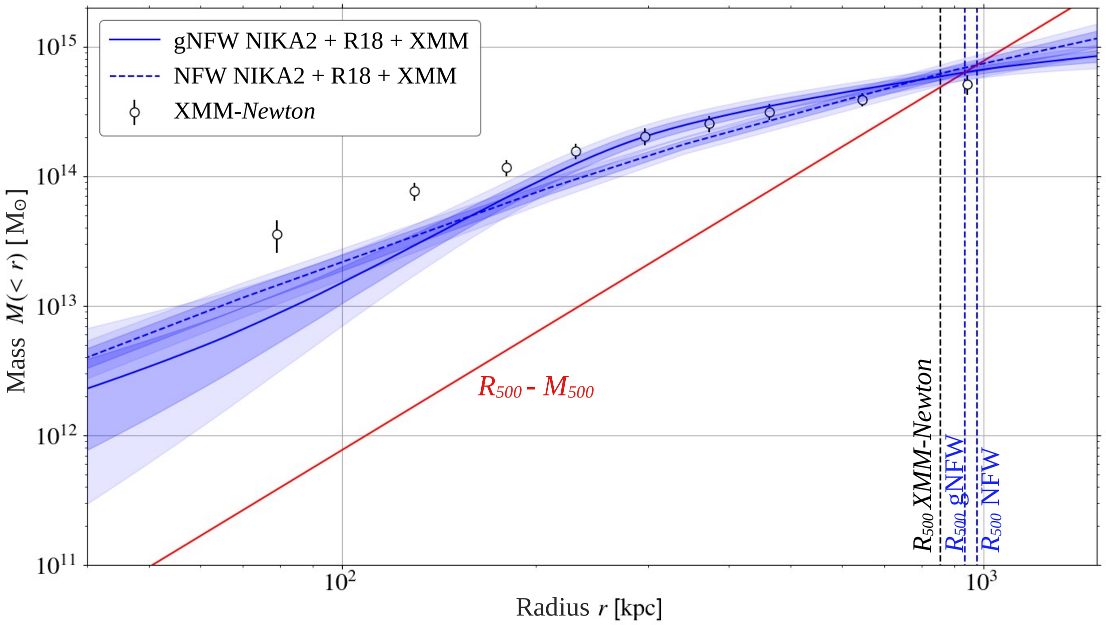
parameters: r_s, c_{200}, (P_{zero})

- Mass defined directly with NFW parameters

The hydrostatic mass of CL J1226.9+3332

Two different approaches to model the HSE mass

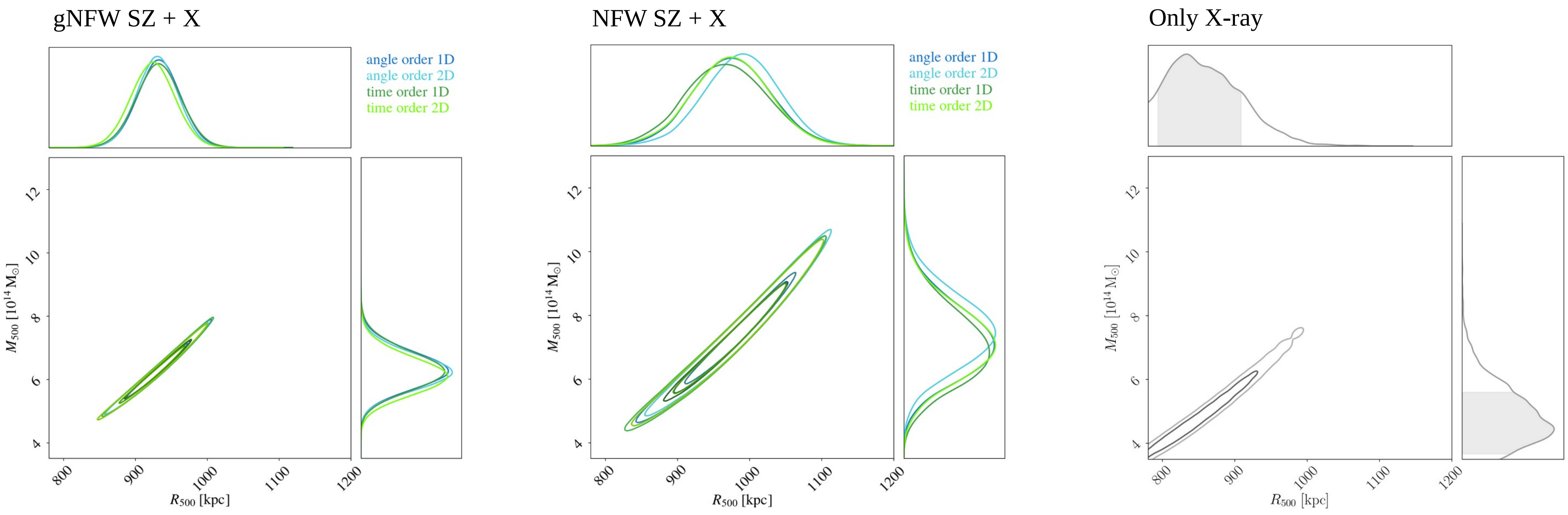
Showing only the results obtained with ‘angle order 1D’ NIKA2 bins



- Both gNFW and NFW models give consistent HSE mass profiles
- X-only and SZ+X masses consistent between ~ 300 and 1000 kpc
- For scaling relations in cosmology we use M_{500}, the mass inside a sphere of R_{500}

$$\langle \rho(r < R_{500}) \rangle = 500 \times \rho_c(z)$$

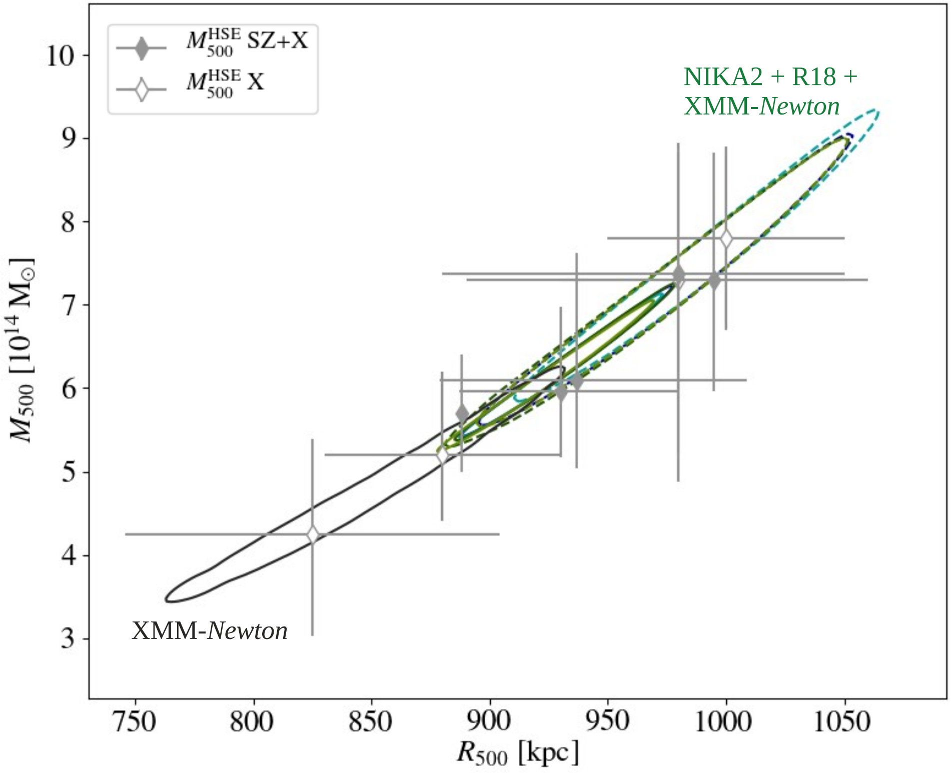
The hydrostatic mass of CL J1226.9+3332: R_{500} - M_{500}



- M_{500} consistent within 1σ
- But! Differences of the mass profile at ~ R_{500} crucial: higher profile at ~ R_{500} larger R_{500} → larger M_{500}
- Systematic effects from maps negligible compared to modeling and mass slope effects

The hydrostatic mass of CL J1226.9+3332: R_{500} -M_{500}

Contours obtained in this work compared to values given in literature



- M_{500} in agreement with previous works within 1σ
- For CL J1226.9+3332 at R_{500} X-ray only HSE masses prefer lower values than SZ+X
- NIKA2 LPSZ: capacity to study systematic effects on HSE mass reconstruction

The hydrostatic-to-lensing bias

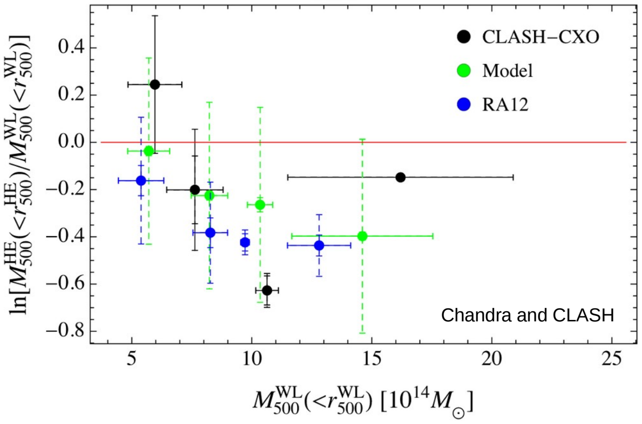
From the observational side: real HSE bias is unachievable

→ Approximated using mass estimates that do not rely on the HSE hypothesis and trace the total mass of the cluster

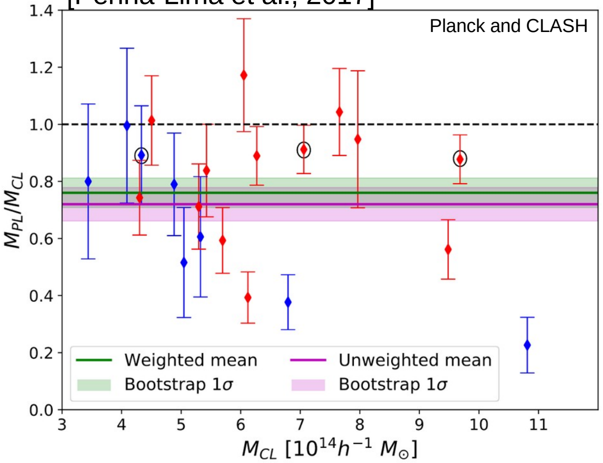
The hydrostatic-to-lensing mass bias:

$$1 - b_{\mathrm{HSE/lens}} = M^{\mathrm{HSE}} / M^{\mathrm{lens}}$$

[CoMaLit, Sereno & Ettori, 2015]



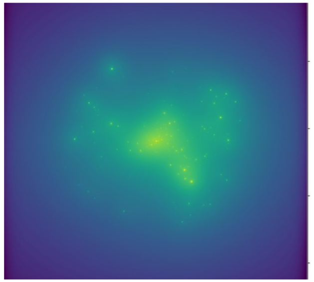
[Penna-Lima et al., 2017]



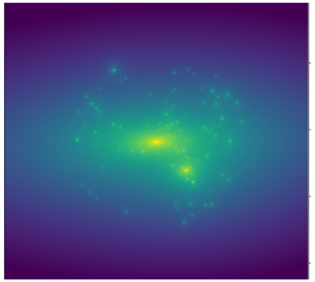
The lensing mass of CL J1226.9+3332

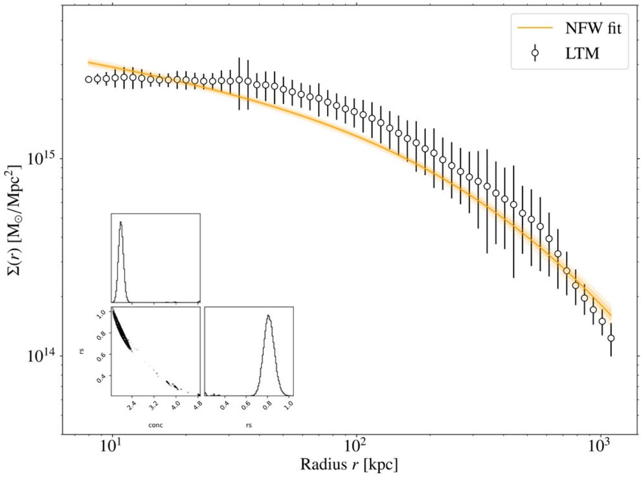
From the CLASH convergence maps, following the procedure in Ferragamo et al. 2022
Fit of a NFW density model to the convergence maps

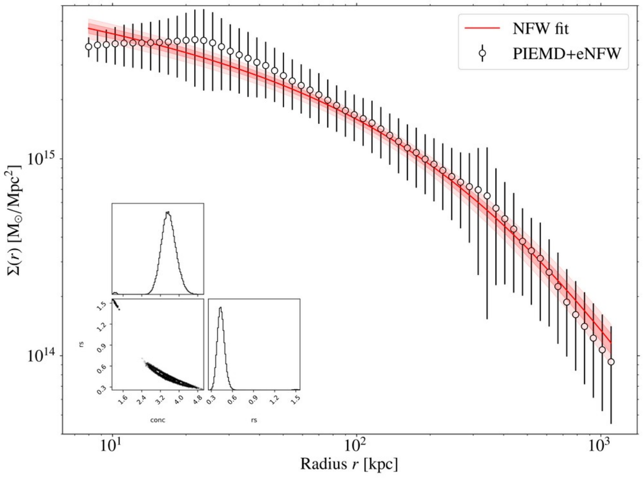
LTM



PIEMD
+eNFW







κ: convergence, Σ in critical density unities Σ_{crit}

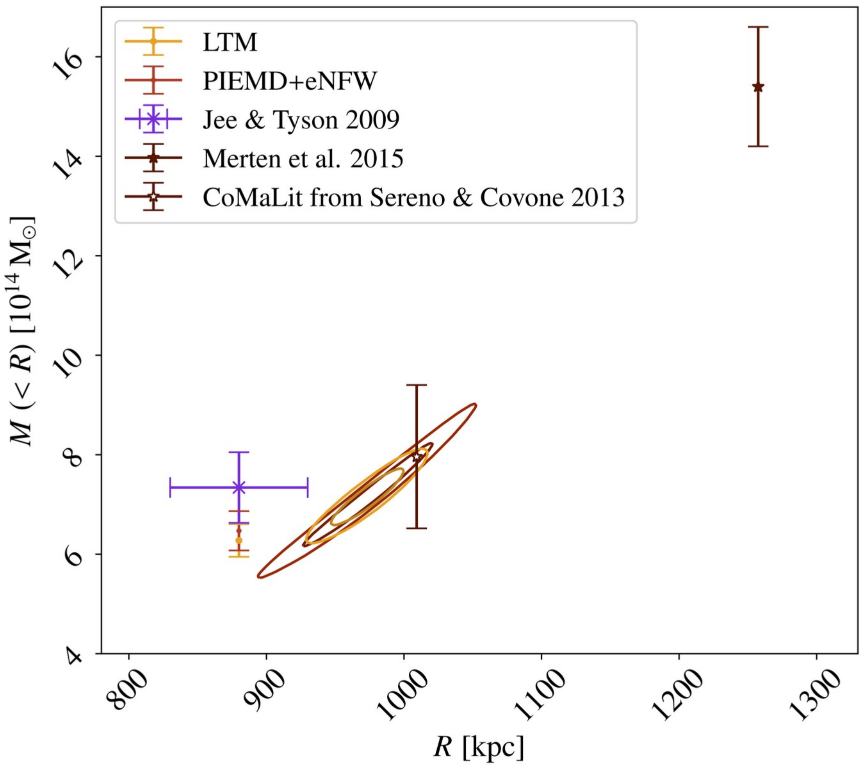
$$\kappa = \Sigma/\Sigma_{crit}$$

Σ: surface mass density
→ modeled with a NFW

Σ_{crit}: the density needed for strong lensing to occur

*Centering the profiles at the same position as SZ and X-ray profiles

The lensing mass of CL J1226.9+3332

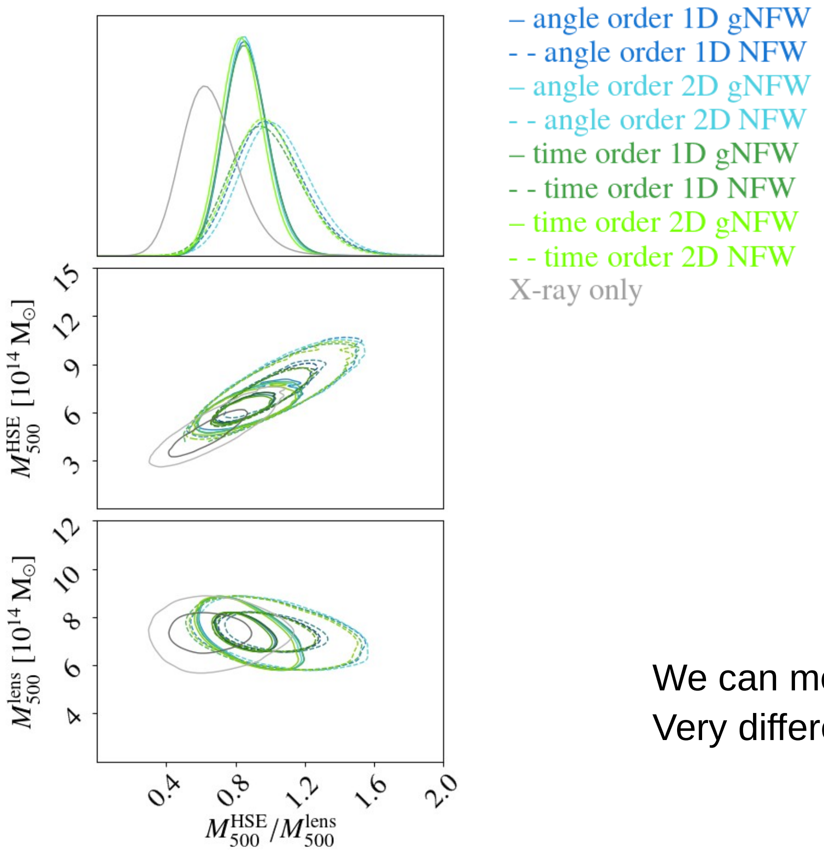


- Lensing mass reconstruction in agreement with CoMaLit and Jee & Tyson (2009) estimates
- Accounting for systematic uncertainties and the R_{500} - M_{500} degeneracy is mandatory

  → various independent estimates and consistent definitions needed

Hydrostatic-to-lensing mass bias

The ratio of HSE and lens masses at their R_{500}, supposing they are not correlated: $M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{lens}} = 1 - b_{\mathrm{HSE/lens}}$

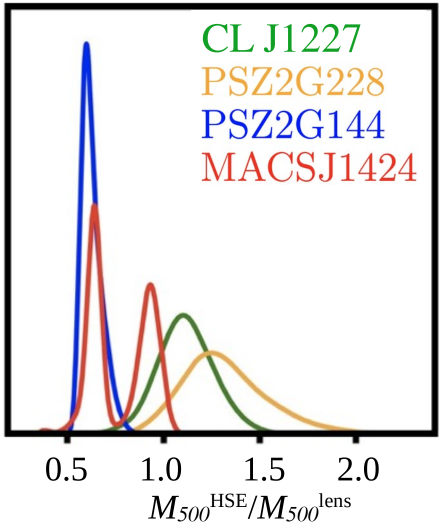


- We obtain for SZ+X:
  - $1 - b_{\mathrm{HSE/lens}} = 0.86^{+0.10}_{-0.11}$ for gNFW
  - $1 - b_{\mathrm{HSE/lens}} = 1.01^{+0.17}_{-0.19}$ for NFW
- And for X-ray only HSE mass:
  - $1 - b_{\mathrm{HSE/lens}} = 0.66^{+0.14}_{-0.14}$

We can measure the HSE-to-lensing mass bias for single clusters
Very different results for SZ+X and X-ray only

SZ+X hydrostatic-to-lensing mass bias

Common sample between LPSZ and CLASH



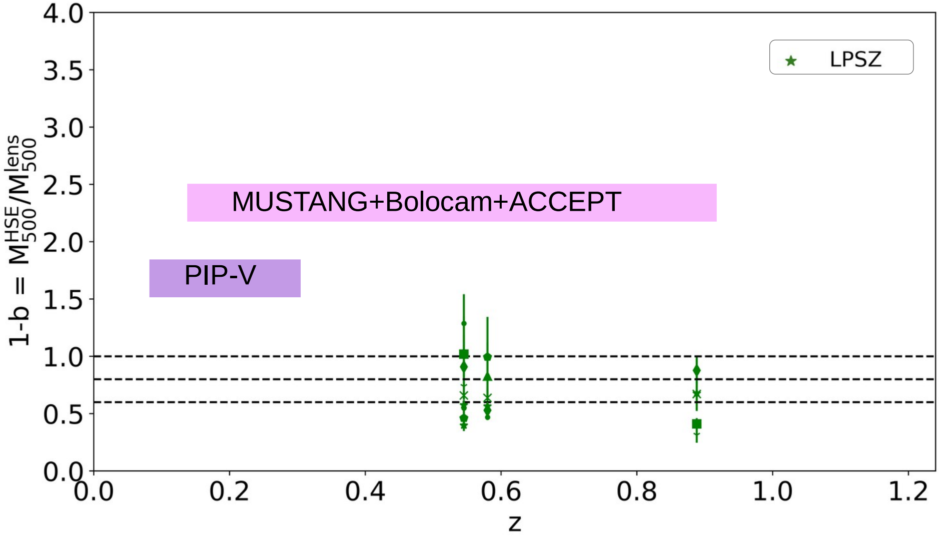
[Muñoz-Echeverría et al., arXiv:2111.01691]

- With this sample: nonlinear M_{500}^{HSE} - M_{500}^{lens} relation
- Cluster and data properties affect the bias
- Small but important sample:
  HSE-to-lensing bias of resolved clusters with SZ

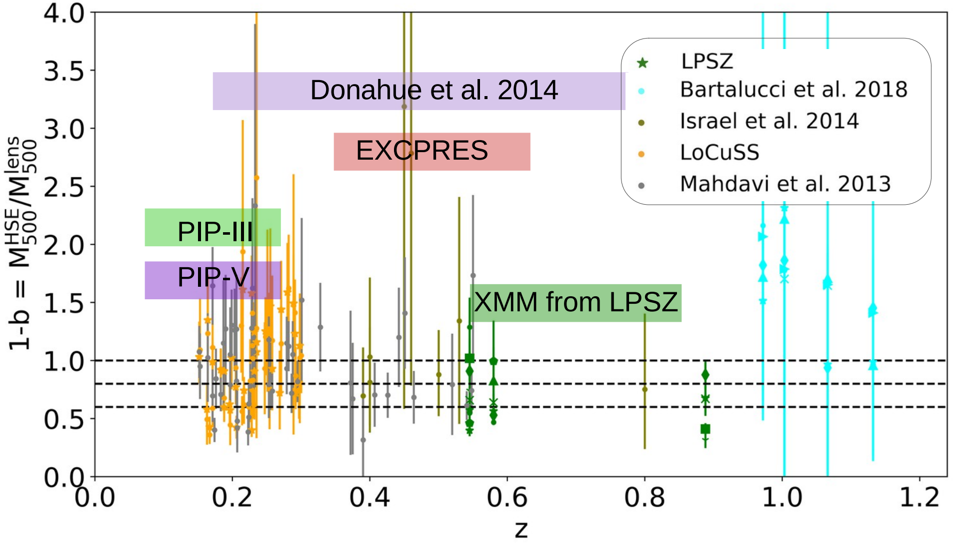
SZ+X hydrostatic-to-lensing mass bias

LPSZ clusters essential to understand the HSE bias in SZ

HSE: X+SZ



HSE: X only



Very few resolved clusters in SZ
* MUSTANG and Bolocam miss the intermediate radii and ACCEPT profiles don't reach R_{500}

* With Planck only low redshifts

Conclusions

- NIKA2 has been operating for the last 4 years: it is working fine
- LPSZ has observed 35/45 galaxy clusters at expected sensitivity
- LPSZ data allow to resolve intermediate to high redshift galaxy clusters in SZ and X-ray
- From pilot study: precise HSE mass reconstruction, even at high redshift
- LPSZ clusters would be important for HSE-to-lensing bias measurement
- Independent measurement of HSE bias can help to understand cosmological results
  → working on an extended sample