NIKA2 observations of 3 low mass clusters at z~1

Pressure profile and SZ flux -mass relation

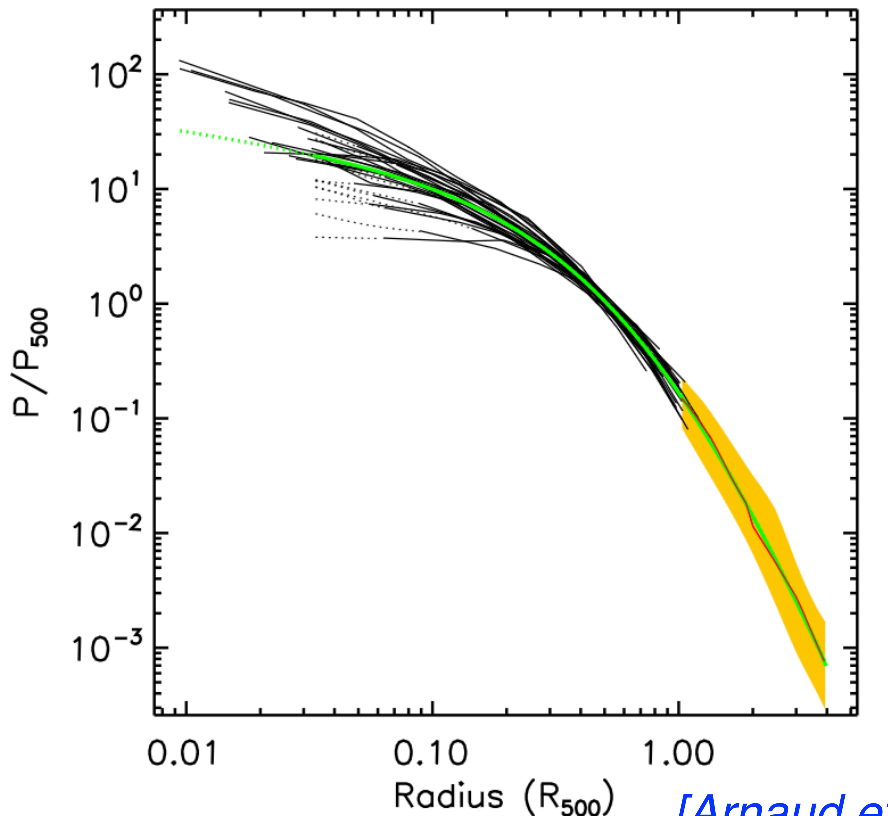
Rémi Adam

Main contributors: D. Eckert, M. Ricci et al.

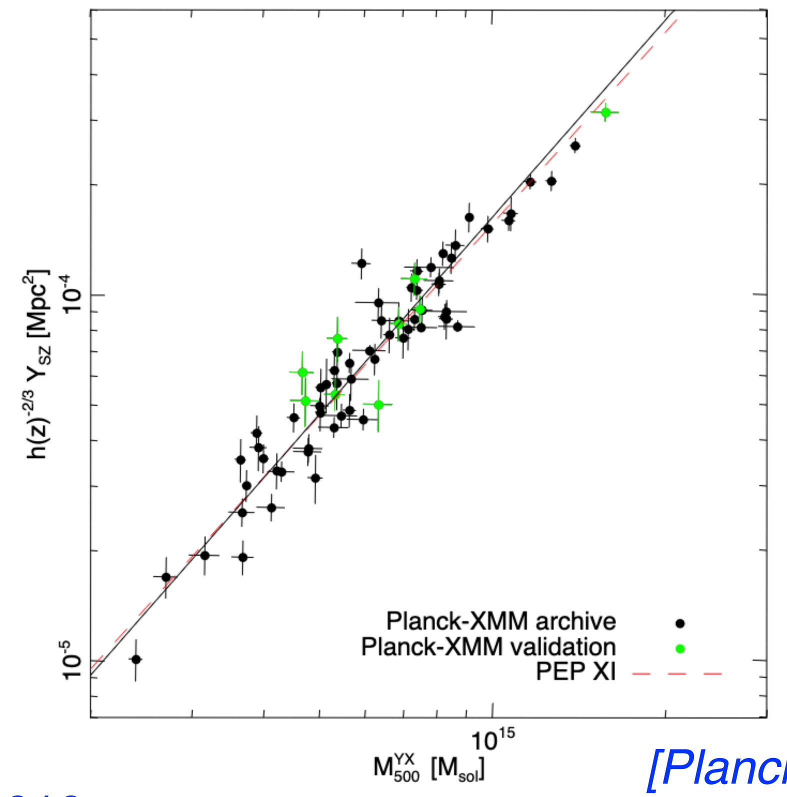
mmUniverse Conference, June 26, 2023

Pressure profile and SZ flux (Y_{SZ}) - mass relation

The pressure profile and the Y_{SZ}-M relation are key ingredients for cluster cosmology (e.g. detection, cluster counts, power spectrum) and astrophysics (e.g. feedback, dynamics)



[Arnaud et al. 2010, and many others]



[Planck XX 2013, and many others]

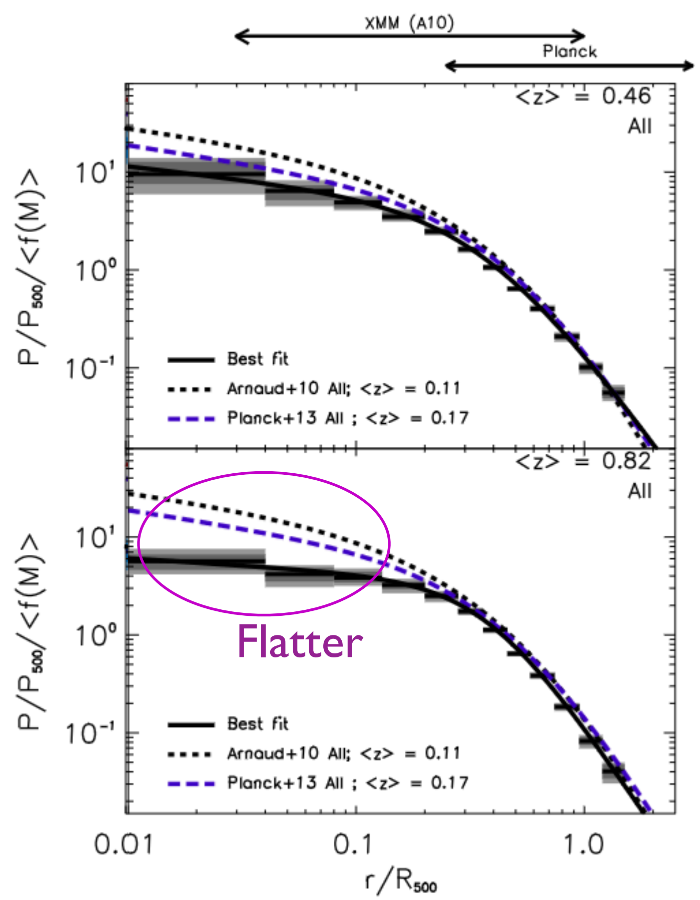
- These quantities are well investigated at low z and high M
- But the bulk regime of future surveys is at higher z and lower M *[e.g. CMB-S4, eROSITA, Euclid]*
- These clusters are also key for constraining cosmology *[e.g. Sartoris et al. 2016 for Euclid]*

Pushing the ICM characterization at high redshifts down to lower masses is essential

Non-standard evolution in mass and redshift?

Non-trivial redshift evolution may be expected:

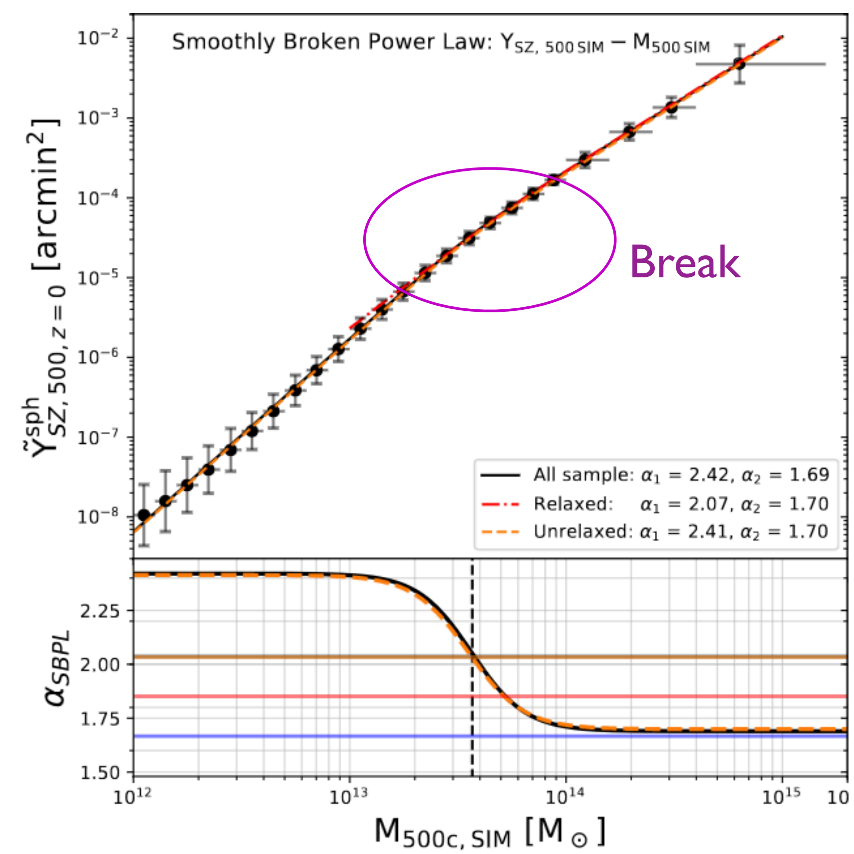
- Enhanced AGN and star formation activity
- Changes in mass accretion and merger rate



[80 massive SPT-clusters with CXO; McDonald et al. 2014]

Evolution in mass is expected:

- Shallower potential well
- Enhanced gas dynamics



[Illustris TNG clusters at z=0; Pop et al. 2023]

But we do not have detailed SZ measurement at low mass and high z

We aim for a detailed characterization of low-M clusters at high-z in a regime nearly unexplored with deep resolved SZ data

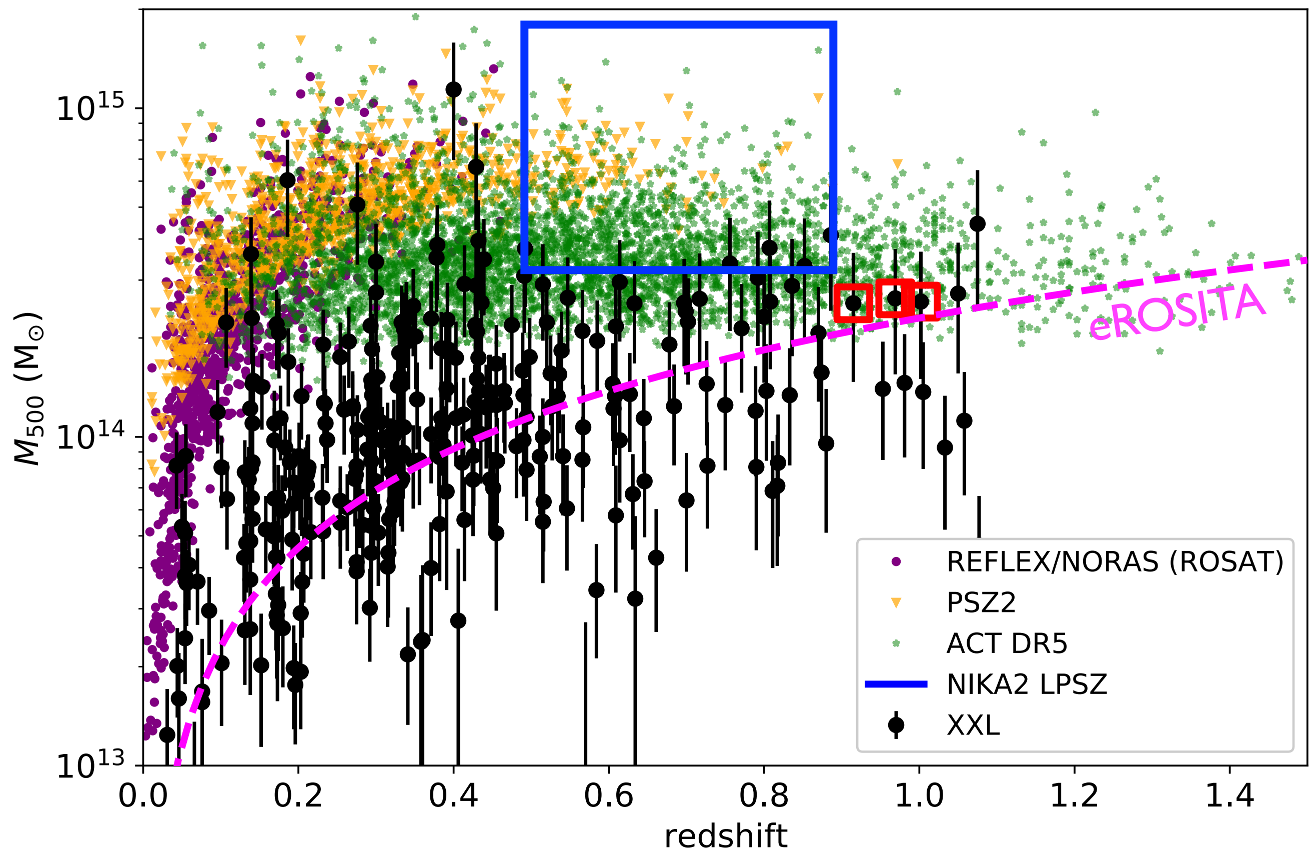
XXL-survey and target selection

XXL in a nutshell *[Pierre et al. 2016]*

- Depth and area allow exploring low-M clusters at high-z
- Intensive multiwavelength coverage:
  - Optical: CFHTLS and HSC
  - Radio: NVSS, FIRST, GMRT
  - Submm: Herschel/SPIRE for some of the clusters
  - X-ray: Chandra snapshot for some of the clusters

Selection criteria

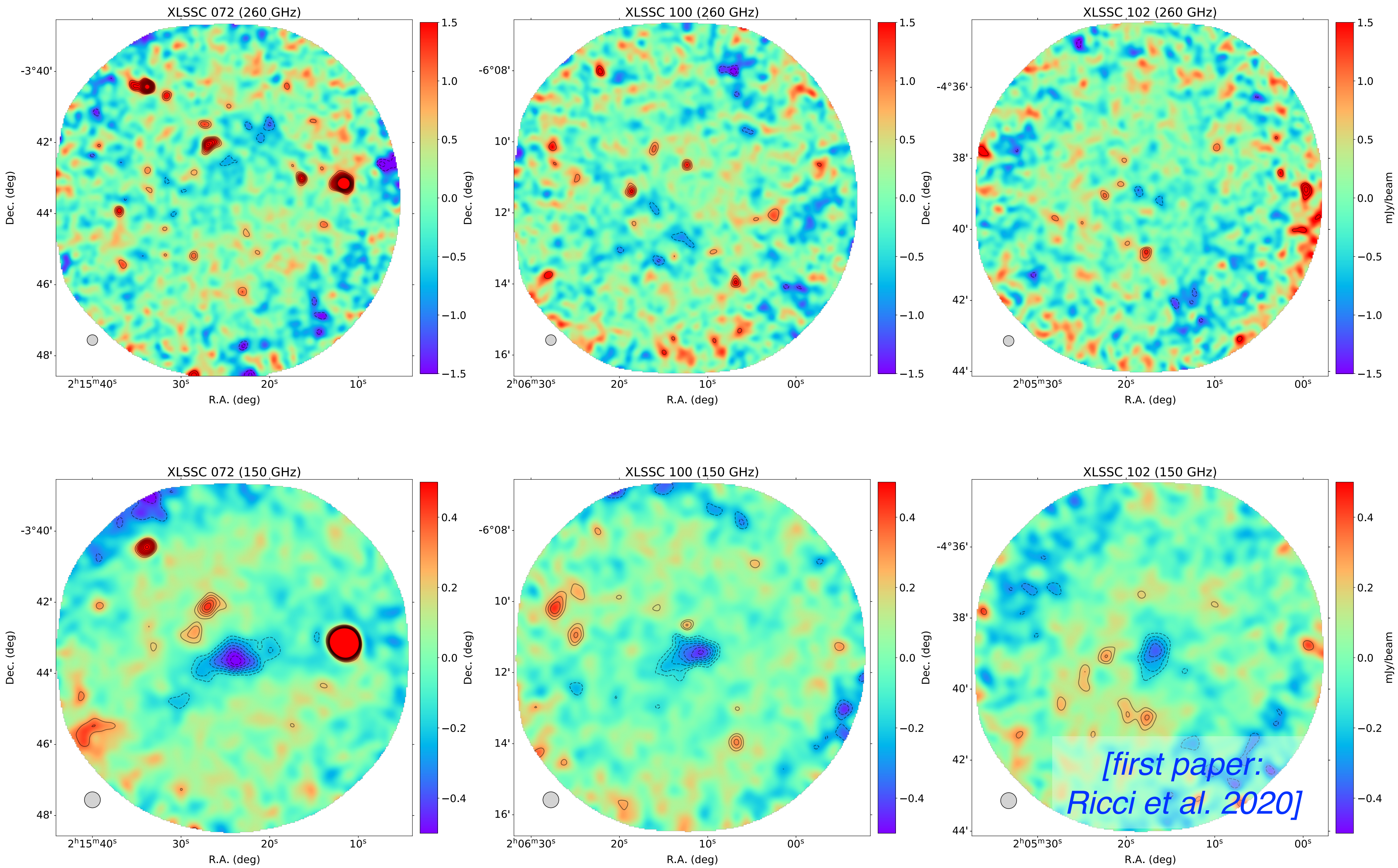
- Focus on clusters with redshift > 0.9
- Secured XXL detections
- Independent detection in optical overdensity
- Robust spectroscopic redshifts
- XXL-North, for observability reasons
- Reasonable observing time



Selection of 3 XXL clusters at z~1 & M~10^{14} M_{sun}

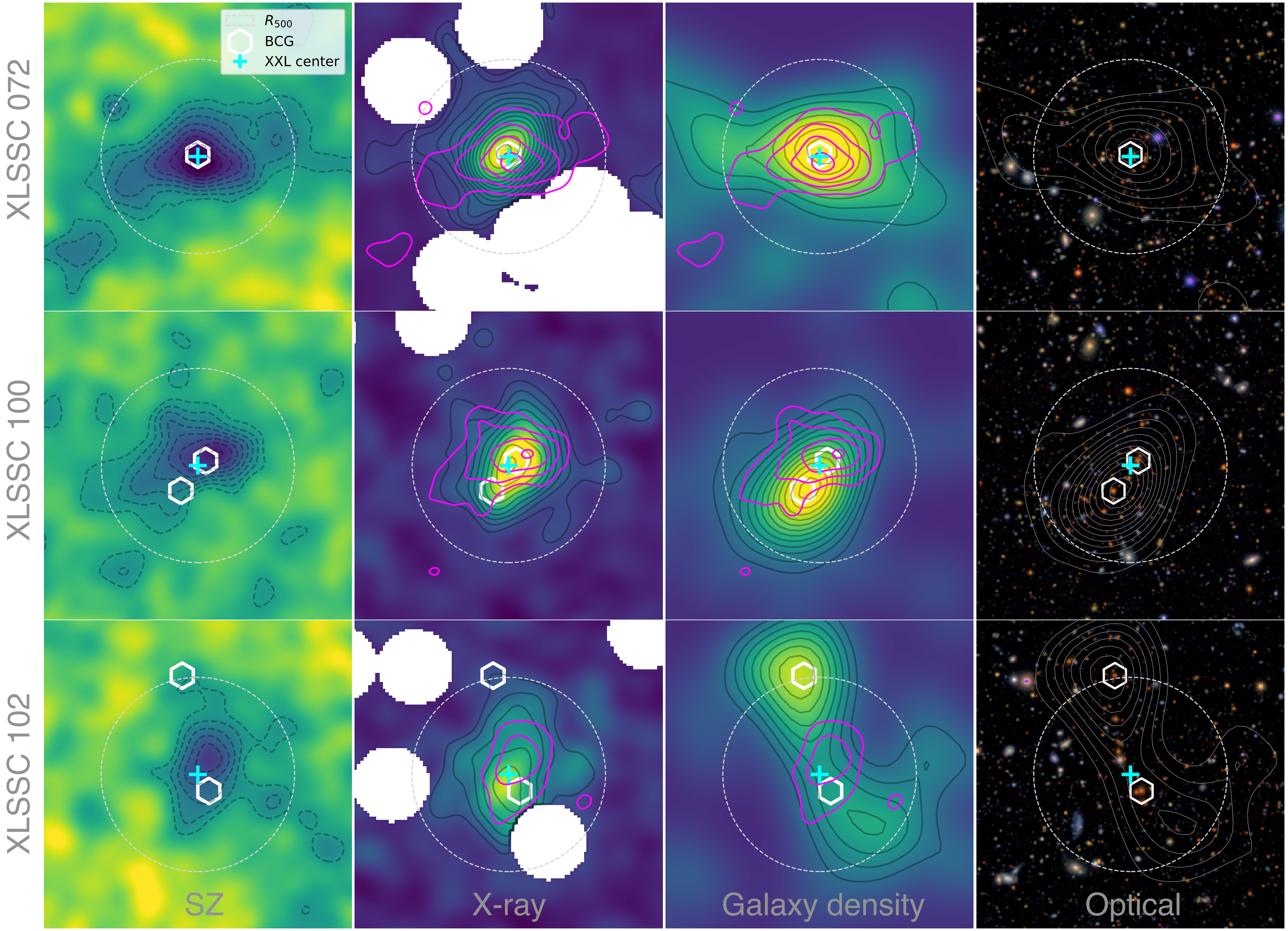
NIKA2 observations and data

- 26.6h of projected time *[PI: Ricci & Adam, projects 179-17,094-18,208-18,093-19,218-19,076-20]*
- Data quality in line with commissioning *[Adam et al. 2018, Perotto et al. 2020]*
- No bias from point sources (40 at S/N>4) *[Adam et al. 2016, and following NIKA(2) papers for the method]*



Clean significant SZ detection for the 3 targets

Multiwavelength comparison



- Disturbed morphology
- Elongated & flat core
- Good match in all bands
  - Likely disturbed

- Disturbed morphology
- Multiple BCGs
- ICM/galaxies mismatch
  - Merging

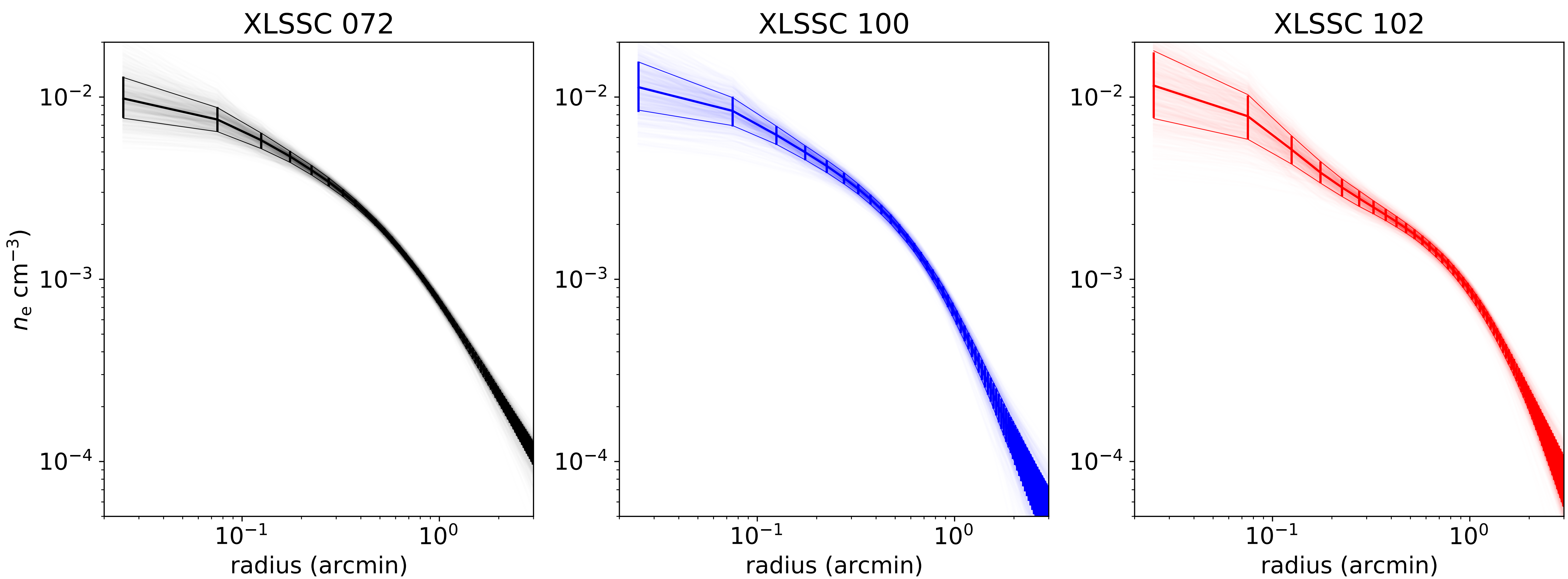
- Disturbed morphology
- SZ/X small scale offset
- Large ICM/galaxy offset
- 2-peaks galaxy density
  - Strongly merging

[see also Ricci et al. 2020]

Evidence for morphologically disturbed ICM in all targets
(confirmed by the offset between different components)

Thermal gas density profiles

The electron density profile is a key ingredient for the analysis (e.g. to get the mass)
Pyproffit package *[Eckert et al. 2020]* used for extraction, plus 1000 MC realizations



Density profile available with robust uncertainty propagation

Thermal pressure profile modeling and fitting

1) gNFW

- Standard gNFW modeling
- 5 parameters

[as in Adam et al. 2015, and following NIKA(2) papers]

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

2) binned

- Binned profile defined at 5 fixed radii
- log-log interpolation to compute the profile
- 5 parameters

[similar to Ruppin et al. 2017]

$$P_e(r) = \mathrm{interp}([P_e(r_i)])$$

3) HSE + mass model

- Assume the HSE
- NFW mass model +density profile
- 2 parameters

[see also Eckert et al. 2022]

$$M_{\mathrm{HSE}}(r) = -\frac{r^2}{\mu_{\mathrm{gas}} m_{\mathrm{p}} n_{\mathrm{e}}(r) G} \frac{dP_{\mathrm{e}}(r)}{dr}$$

$$P_e(r) = P_e(r_0) + \int_r^{r_0} \frac{\mu_{\mathrm{gas}} m_{\mathrm{p}} G n_e(r') M_{\mathrm{HSE}}(r')}{r'^2} dr'$$

Observable

- SZ map from $P_e(r)$, plus the instrument response
- Modeling, projection and sampling via the MINOT software

[see Adam et al. 2020 for MINOT]

$$\Delta I_\nu \propto \mathrm{Instrument\ response\ function} * \int P_{\mathrm{e}} d\ell$$

Fitting

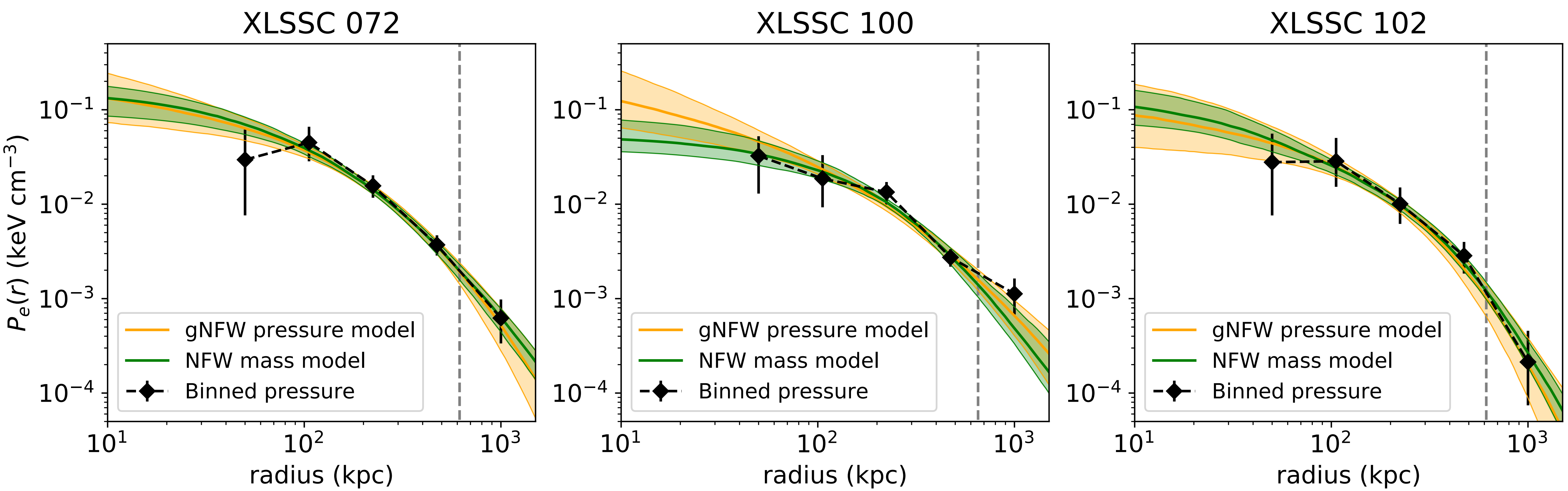
- Gaussian likelihood including noise covariance
- Pressure parameters plus map offset level
- Emcee sampling of the parameter space *[Foreman et al. 2013]*

$$\ln \mathscr{L} \propto \sum (D - M)^T C^{-1} (D - M)$$

[as in Adam et al. 2016, and following NIKA(2) papers]

3 different models for checking systematic uncertainties

Thermal pressure profile modeling and fitting



- Reliable constraints from ~50 kpc to ~ 2 R_{500}
- Excellent agreement between the different methods

High quality measurement down to low mass and high z

Mass estimates

HSE masses:

- a) Combine pressure and density profiles
- b) Direct HSE mass modeling (NFW)
  - The only direct mass measurement

$$M_{\mathrm{HSE}}(r) = -\frac{r^2}{\mu_{\mathrm{gas}} m_{\mathrm{p}} n_{\mathrm{e}}(r) G} \frac{dP_{\mathrm{e}}(r)}{dr}$$

[as in Adam et al. 2015, and following NIKA(2) papers]

UPP masses:

- Pressure expressed as a function of M_{500}
- Fit for M_{500} as the only parameter
  - Rely on *Arnaud et al. (2010)* UPP calibration

$$P_e(r) = P_{500} f_M \frac{P_0}{\left(c_{500}\frac{r}{R_{500}}\right)^c \left(1 + \left(c_{500}\frac{r}{R_{500}}\right)^a\right)^{\frac{b-c}{a}}}$$

Y_X-M and Y_{SZ}-M masses:

- The SZ flux Y_{SZ} and Y_X (= M_{gas} T) scale with the mass
- Use the Y profile and iterate about the scaling low to get M_{500}
  - Rely on local scaling relations, mostly at high mass

$$E(z)^{-2/3}\left(\frac{Y_{\mathrm{X},500}}{2\times 10^{14}\mathrm{M}_\odot \mathrm{keV}}\right) = 10^{0.376} \times \left(\frac{M_{\mathrm{HSE},500}}{6\times 10^{14}\mathrm{M}_\odot}\right)^{1.78}$$

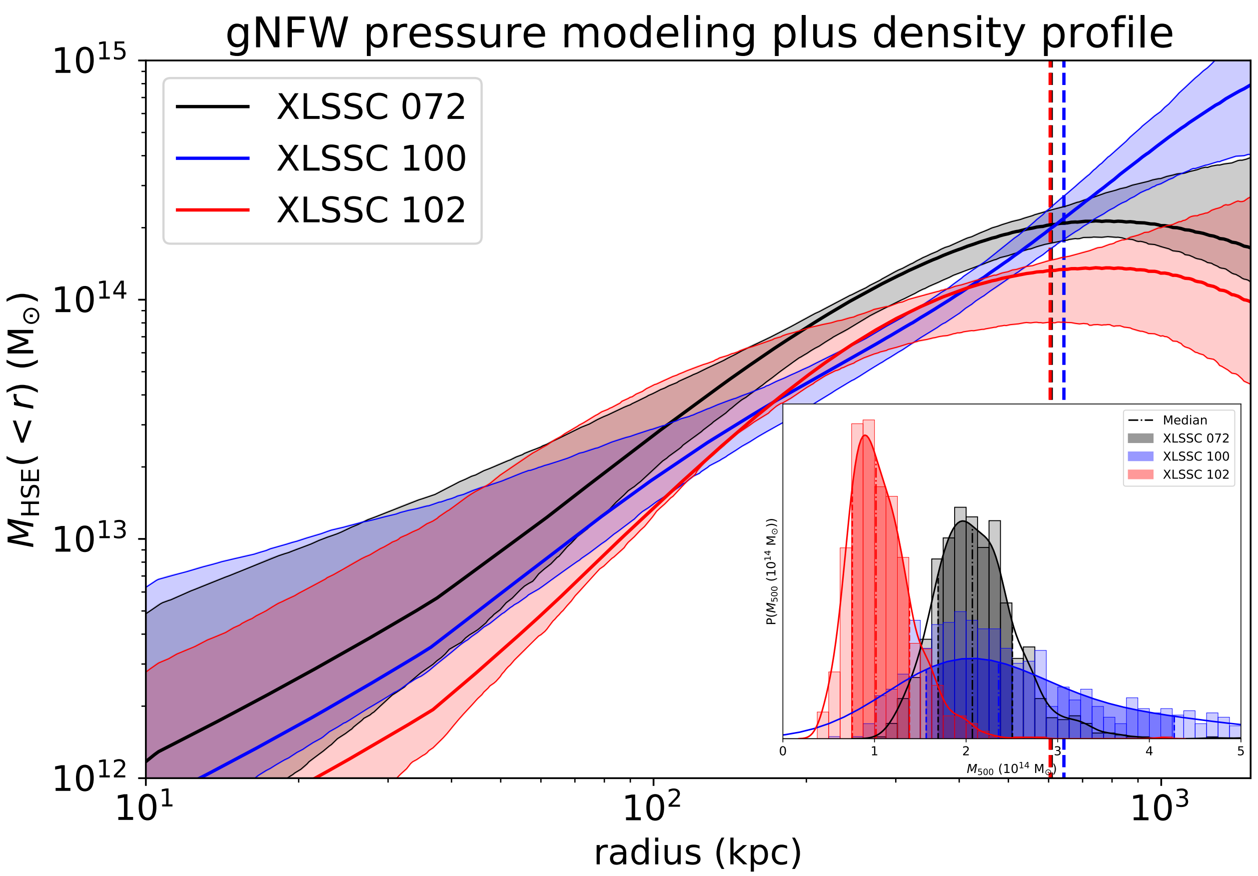
$$E(z)^{-2/3}\left(\frac{D_A^2 Y_{\mathrm{SZ},500}}{10^{-4}\mathrm{Mpc}^2}\right) = 10^{-0.19} \times \left(\frac{M_{\mathrm{HSE},500}}{6\times 10^{14}\mathrm{M}_\odot}\right)^{1.79}$$

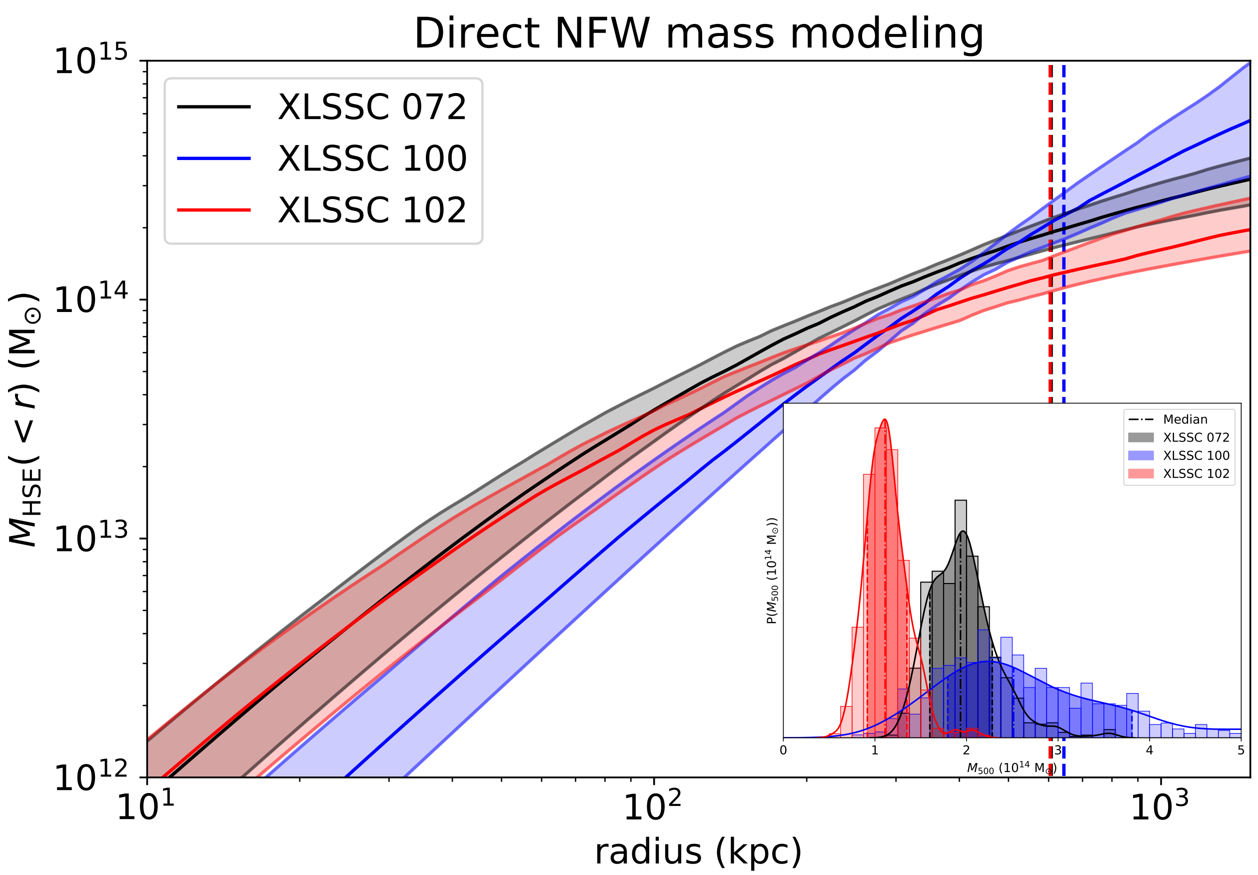
Masses from the literature:

- 2 clusters with ACT detections (UPP masses available) *[Hilton et al. 2018,Hilton et al. 2021]*
- XXL masses from the M-T relation as calibrated using WL *[Lieu et al. 2016]*
- XXL masses using count rates plus a set of scaling relations *[Adami et al. 2018]*

Various mass estimates with different assumptions

Direct measurement of the mass profile

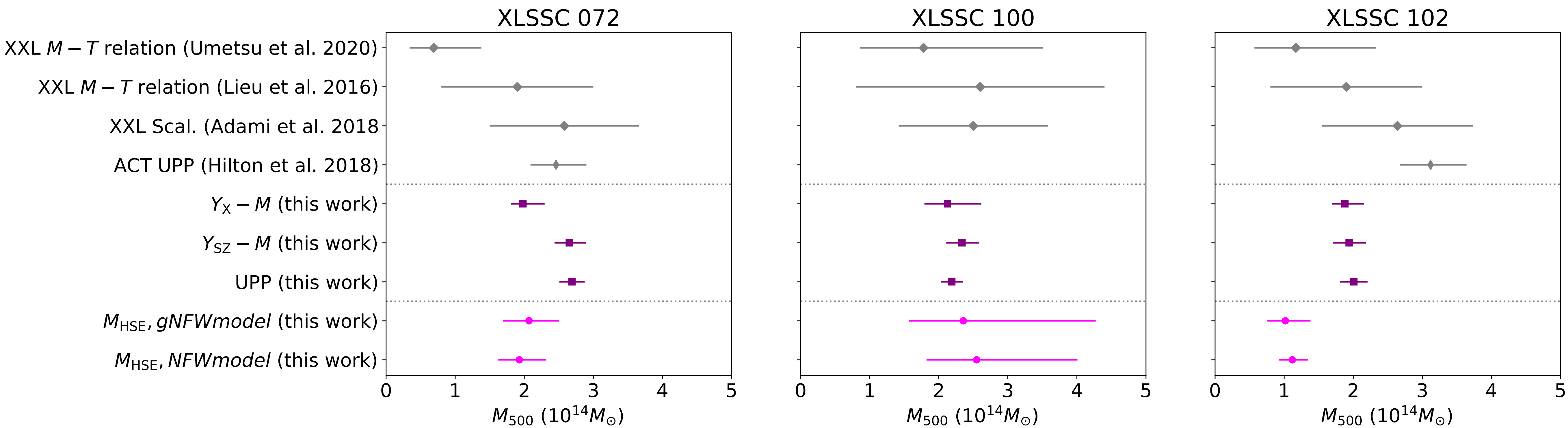




- Larger uncertainty for XLSSC 100 due to the shape of the profile
- Possible systematics due to cluster geometry and clumping (they are mergers)

High quality HSE masses given the mass and z range explored

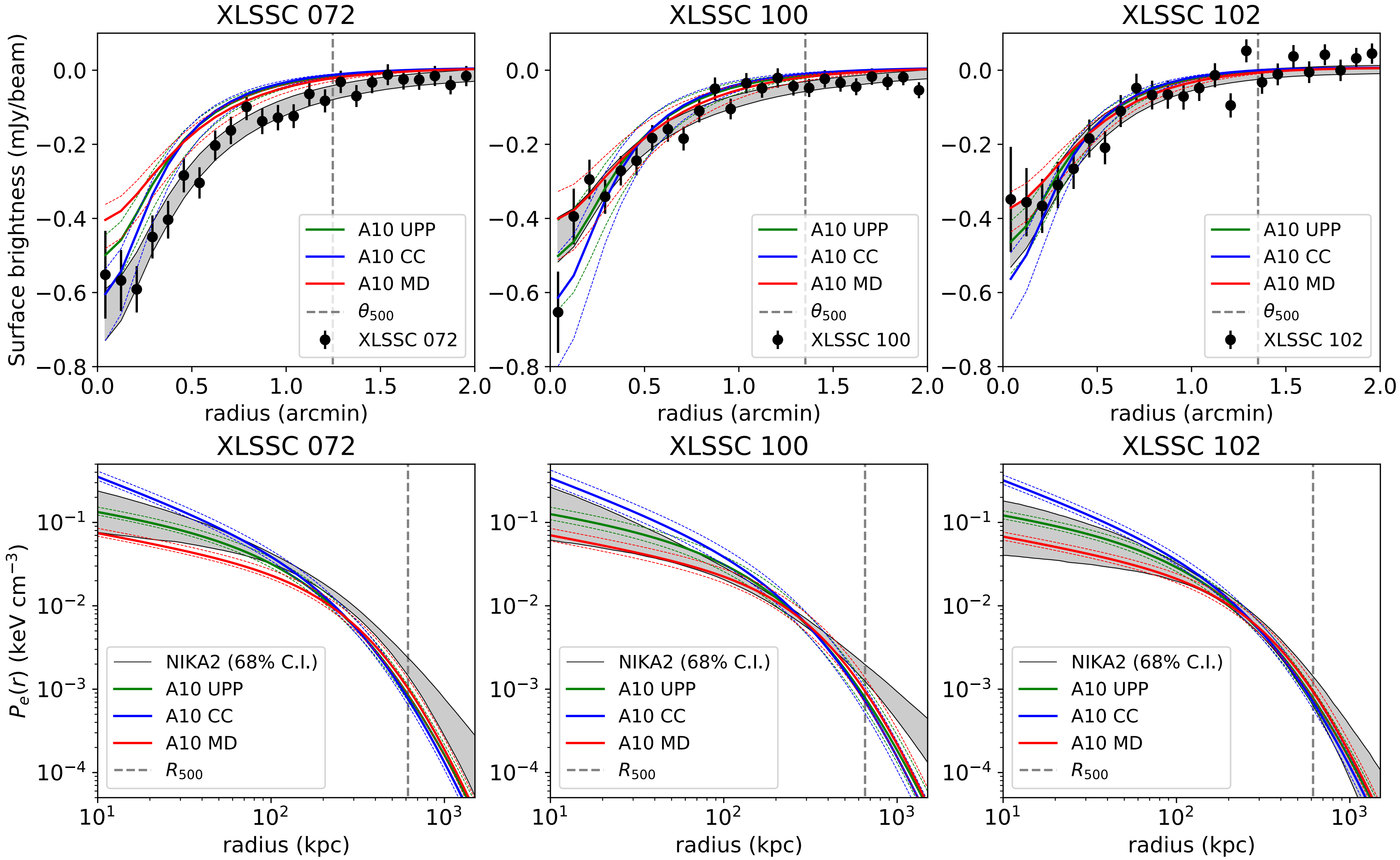
Comparison of the recovered masses



- Excellent agreement between the different methods
- UPP masses are the most precise, but rely on strong assumptions
- Direct HSE masses are lower for XLSSC 102
  - Indication for a large HSE bias, systematics due to the geometry? *[see also Ricci et al. 2020]*

Different masses available to test the UPP and the Y-M relation

Comparison with Arnaud et al. (2010) using M_{Y_X}

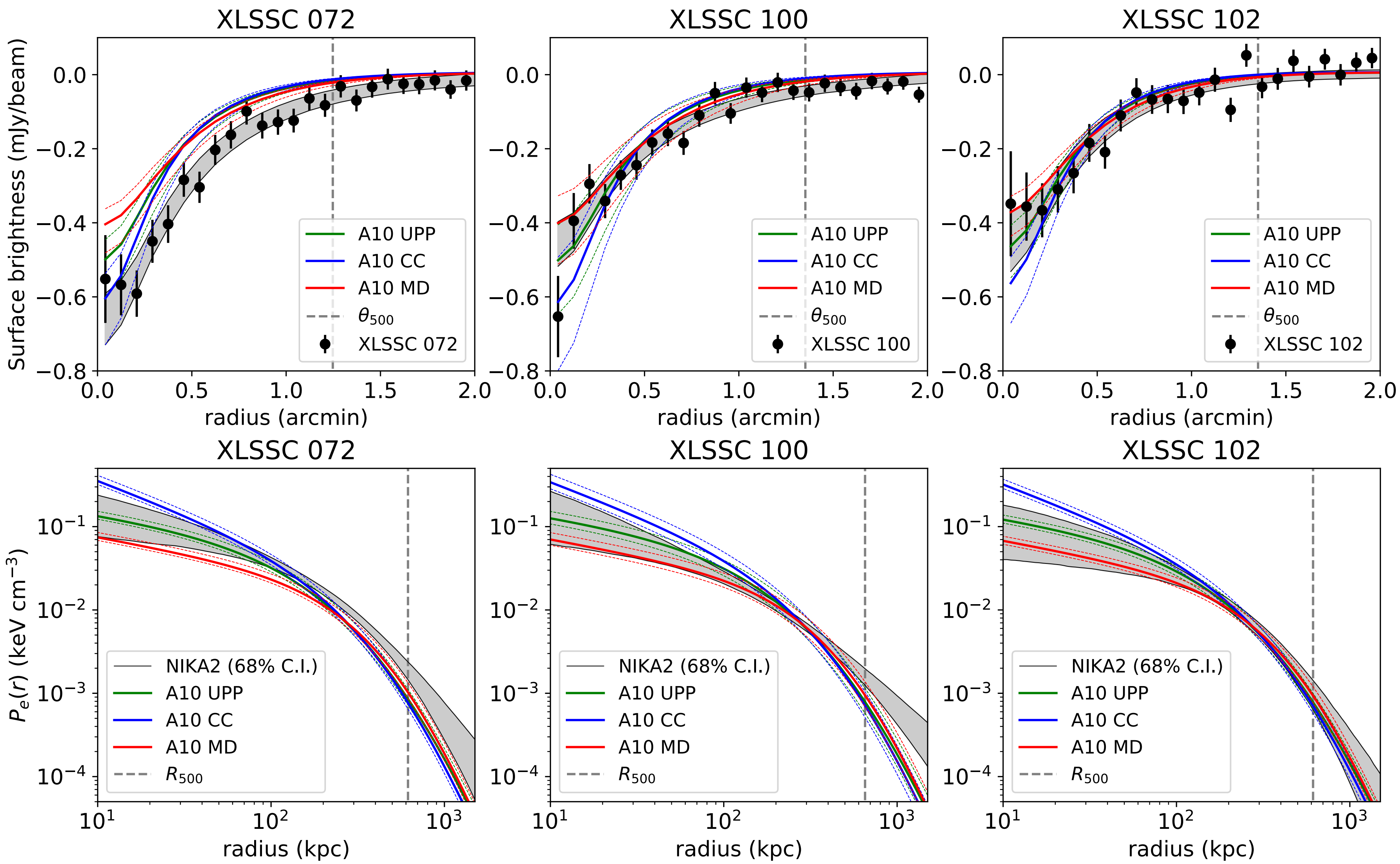


Best with a mass 2σ higher | Shallower outer slope | Perfect match

- Assuming local measurement, P(r) agrees with the dynamical state
- Given the dynamical state, our targets follow well standard extrapolations

Agreement with extrapolation from low z systems at higher M

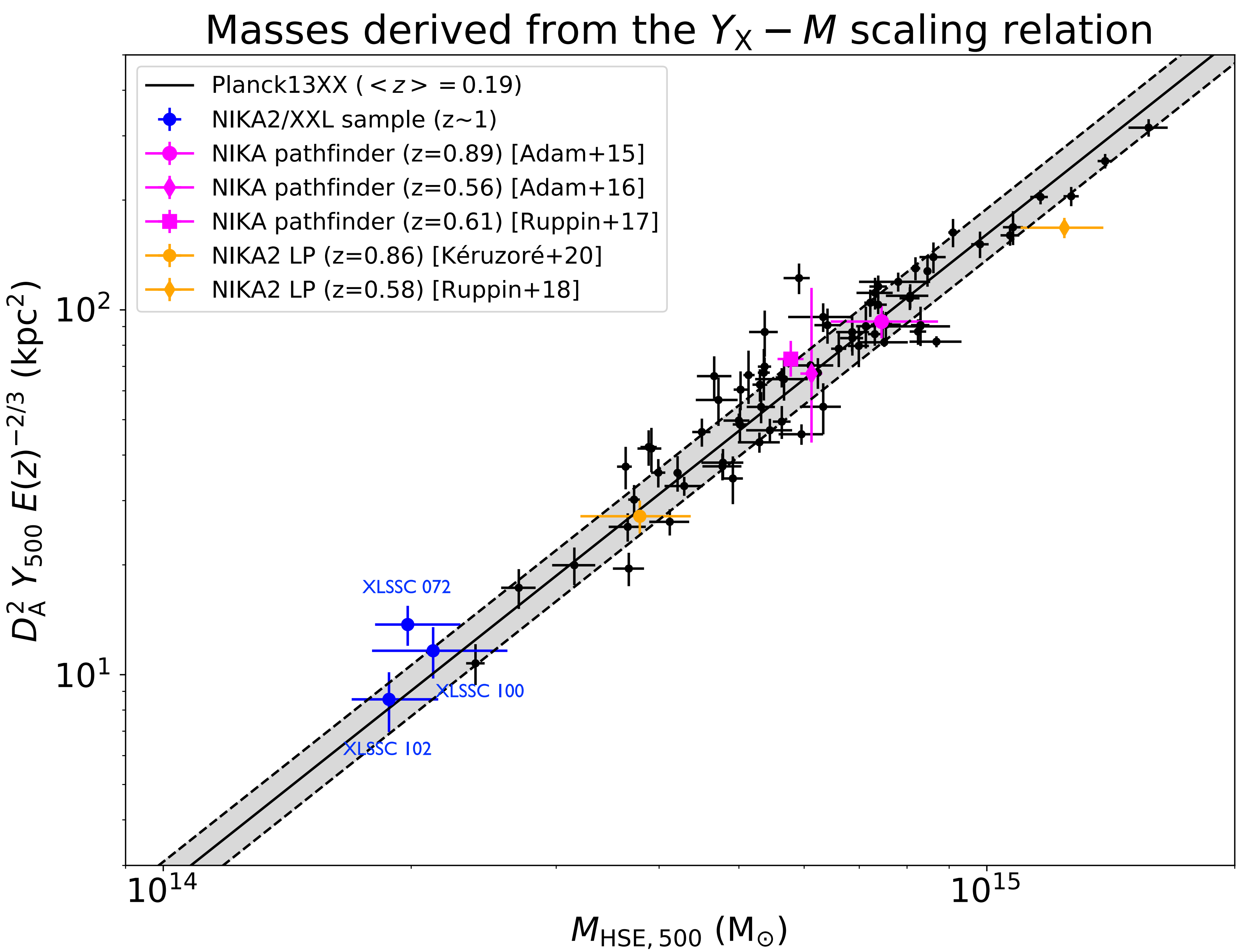
Comparison with Arnaud et al. (2010) using M_{HSE}



But most of the uncertainty comes from the mass

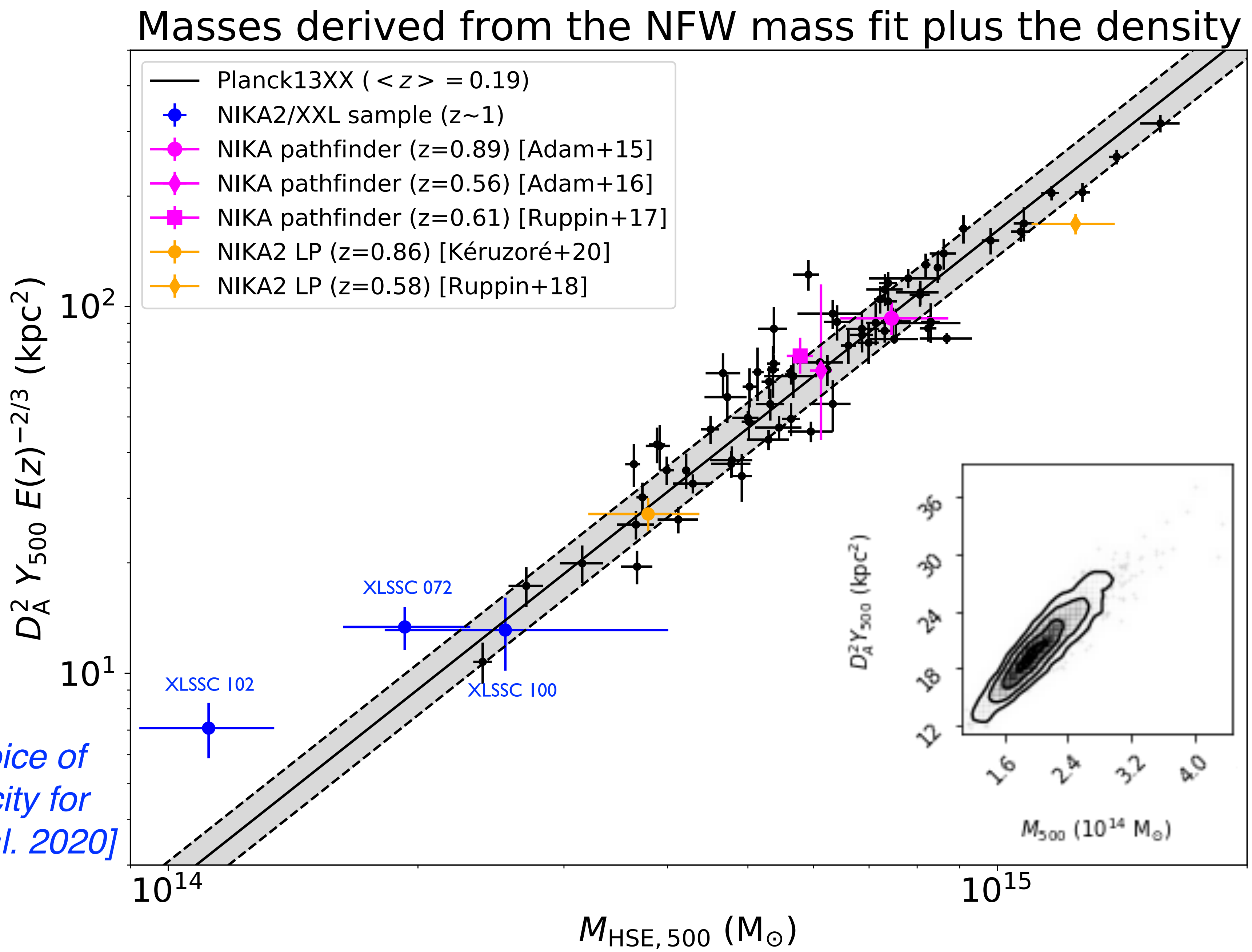
Agreement with extrapolation from low z systems at higher M

The SZ flux - M_{Y_X} relation



The 3 XXL clusters follow remarkably well the Y_X - Y_{SZ} relation

The SZ flux - $M_{HSE\ direct}$ relation



[~1σ syst. from the choice of center and non-sphericity for XLSSC 102 ; Ricci et al. 2020]

Consistency with the Y_{SZ} - M relation

Summary and conclusions

- **Context**
  - ICM physics is driven by gravitational collapse plus rich astrophysical processes
  - Little is known at low-M & high-z despite the importance for future/ongoing surveys

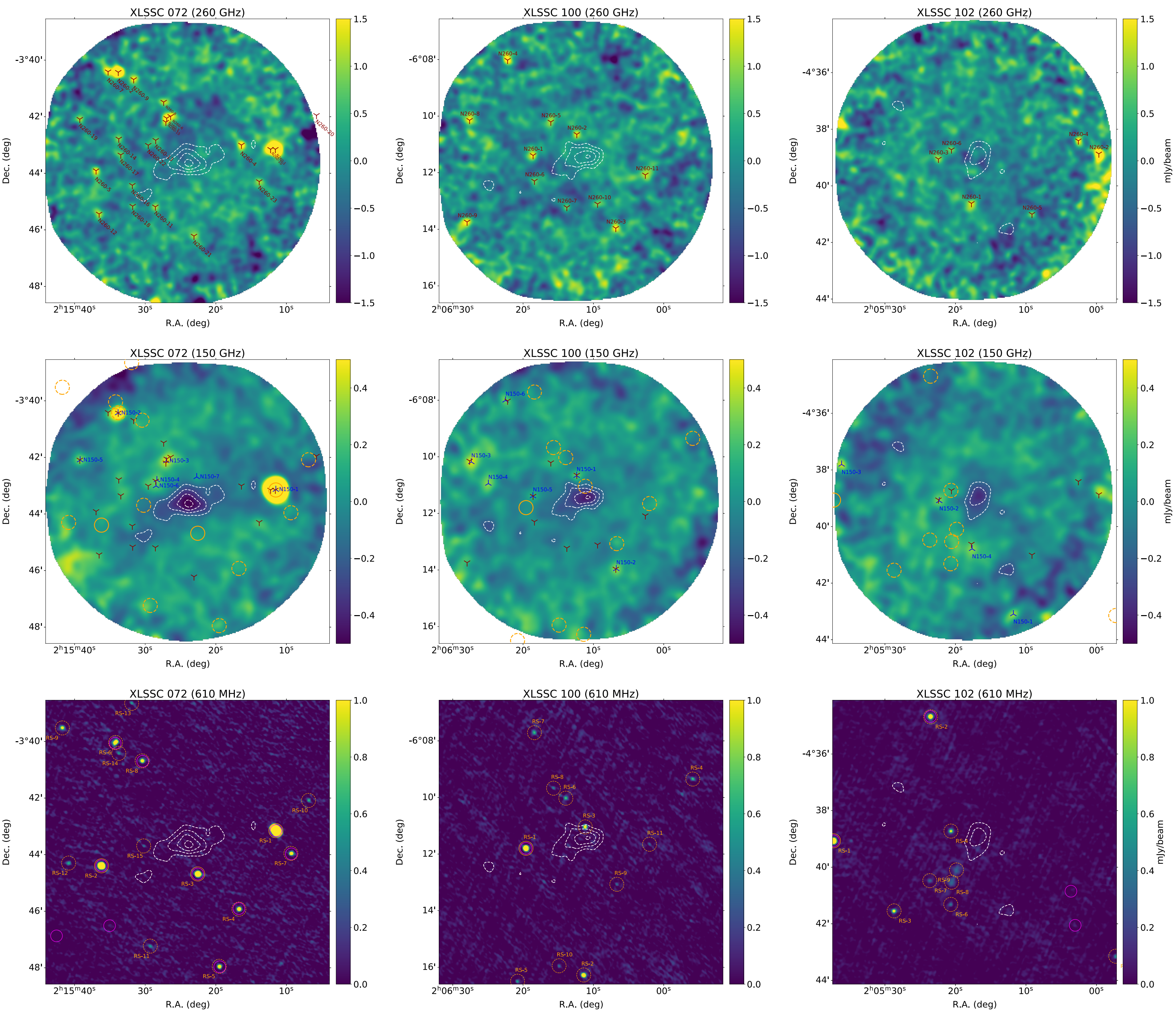
- **Methodology**
  - Selection of 3 XXL clusters at z ~ 1 & M ~ 10^{14} M_{sun}
  - SZ imaging with NIKA2
  - Multiwavelength analysis, extraction of the pressure and the Y-M relation

- **Outcomes**
  - The 3 clusters are consistent with morphologically disturbed systems
  - Pressure profile consistent with that of higher M & lower z clusters
  - Y_{SZ} - M and Y_x - Y_{SZ} relations agree with local calibration
  - Main uncertainty due to the difficulty in having precise & robust mass measurements

- **Conclusion**
  - This suggests stable cluster formation physics down to z ~ 1 & M ~ 10^{14} M_{sun}

Thank you

Contamination from submm & radio sources



- **Submm sources**:
  $S/N_{260} \sim 2xS/N_{150}$, no significant sources missed at 150 GHz
- **Radio source**:
  NVSS (1.4 GHz), FIRST (1.4 GHz) and GMRT (610 MHz)
- **Catalog**
  We built a catalog of 40 sources (S/N>4)

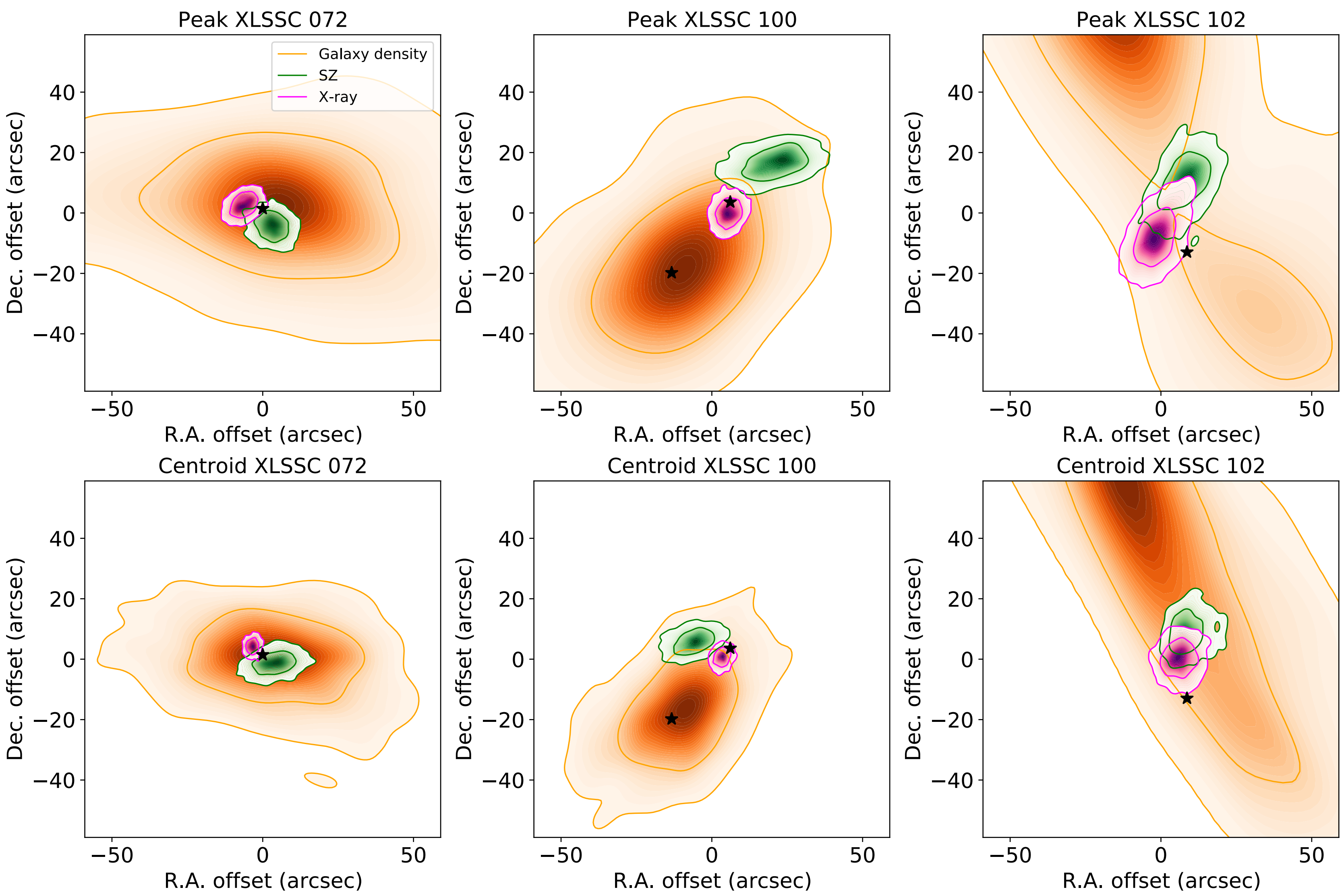
[Adam et al. 2016, and following NIKA(2) papers for the methodology]

No significant contaminating source should bias the SZ signal

Peak and centroid offset

The offset between the different cluster components is a quantitative dynamical state indicator *[e.g., Rossetti et al. 2016, and many other]*

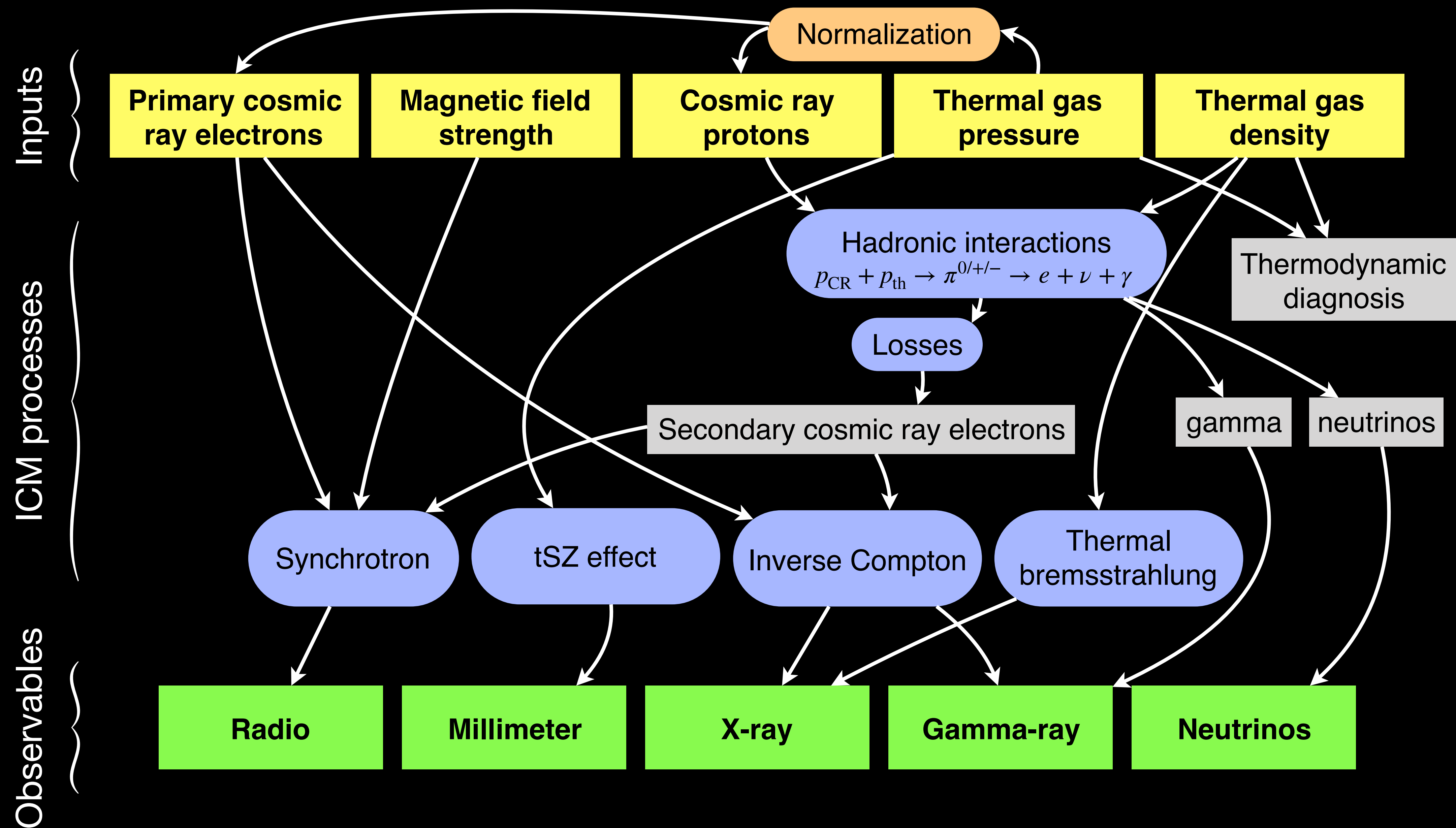
- BCG(s), SZ, X-ray, optical peak and centroid offsets estimates



- XLSSC 072: agrees with a single common center
- XLSSC 100 and XLSSC 072: tension for SZ vs X-ray, clear disagreement with the BCG

Dynamical state confirmed by the offset

The MINOT software



MINOT public software *[Adam et al. 2020]*

Self-consistent multi-wavelength framework implemented