A view of clusters of galaxies via the SZ effect
with KID cameras

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KISS

Outline

I. Clusters of galaxies and the Sunyaev-Zeldovich effect

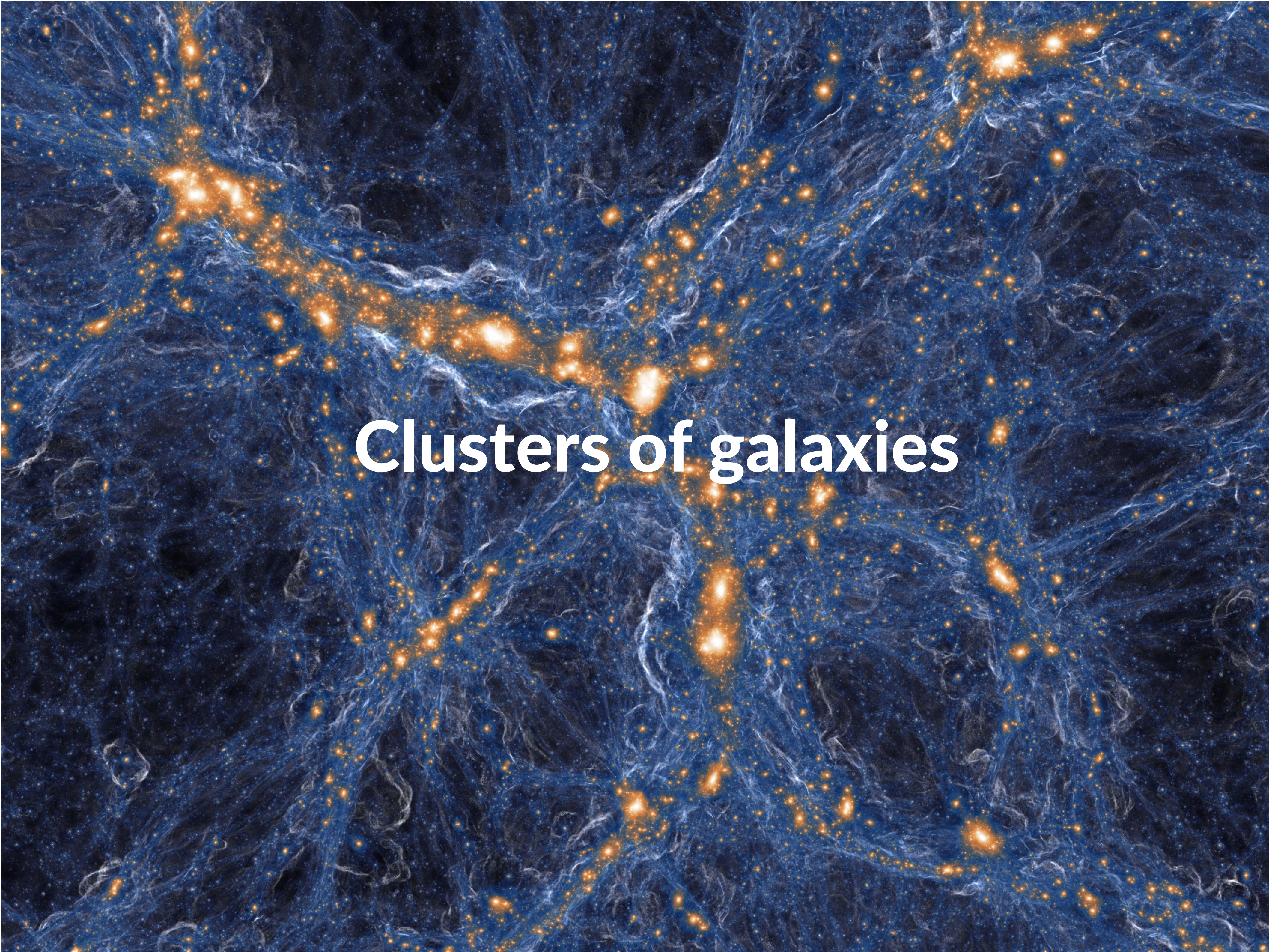
II. SZ cluster cosmology with Planck

III. KID cameras and spectrometers for SZ

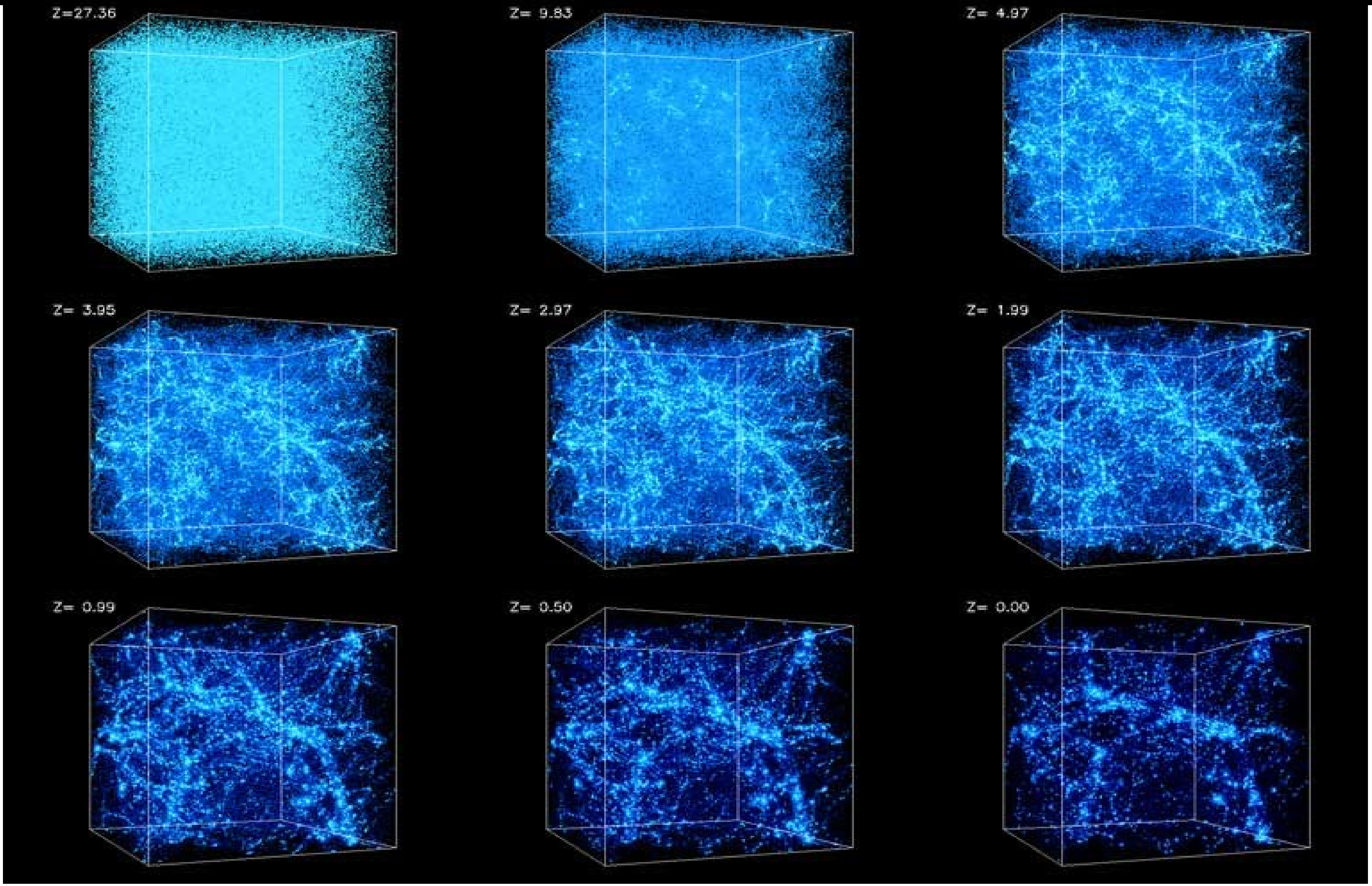
IV. NIKA SZ results

V. NIKA2 SZ large program

VI. SZ science with KISS and CONCERTO


Clusters of galaxies

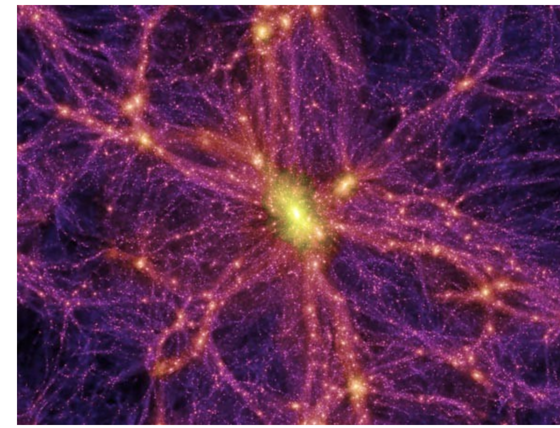
Large scale structure formation

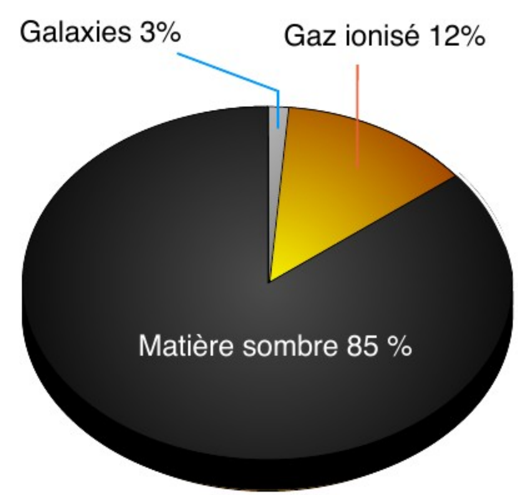


Credit: Center for Cosmological Physics

Clusters of galaxies

- Formed by gravitational collapse at the intersection of cosmic filaments, correspond to massive dark matter halos
  - Self-similar scenario: clusters are scaled copies one of each others
  - However, baryonic physics plays a significant role
- First observed by Zwicky in 1930's who inferred that their total mass was larger than the sum of its luminous components
- Largest gravitationally bound structures in the Universe
  - Dominated by dark matter
  - Most baryonic matter is in the form of gas, the Inter Cluster Medium (ICM)
  - Galaxies count for only 3 % of the total mass
- Total mass 10^{13}- 10^{16} $M_{\odot}$, redshift $0 < z < 3$





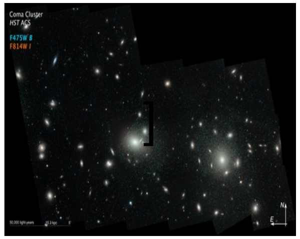
Cluster observables and physics

Cluster observables: detect them and/or measure their physical properties

Visible and IR emission

Light from stars in galaxies

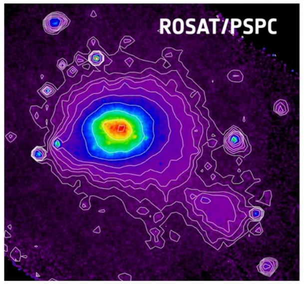
Mass:
- Richness (number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing



X-ray emission

Free-free emission from free electrons in the ICM

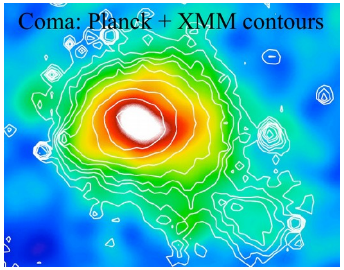
Density, temperature, entropy, mass:
- surface brightness
- spectroscopy



Sunyaev-Zeldovich effect

Interaction of hot electrons in the ICM with CMB photons

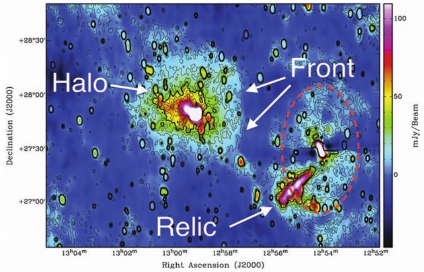
Pressure, mass, shocks:
- Compton parameter



Radio emission

Non thermal emission from accelerated particles

Shocks:
- Surface brightness



Cluster physics from multi-wavelength observations

Coma cluster

Sunyaev-Zel'dovich (SZ) effect

Two main components:

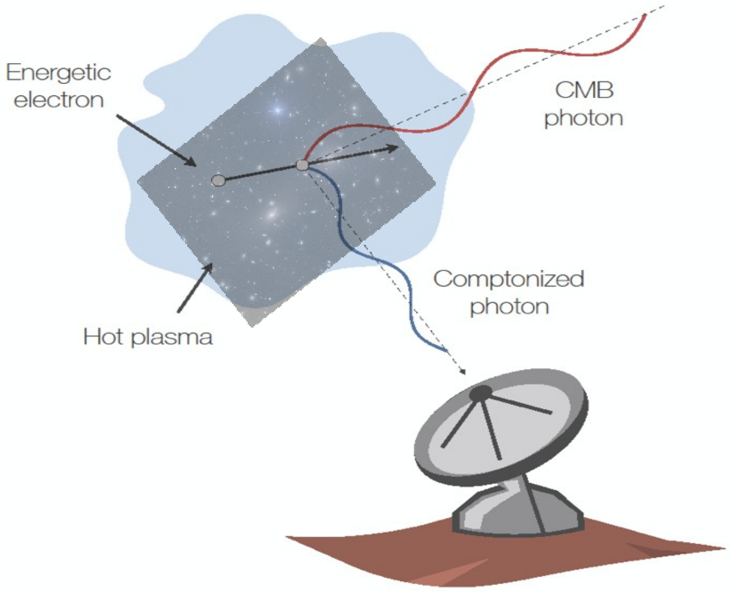
$$\frac{\Delta I_\nu}{I_0} = f_\nu y_{tSZ} + g_\nu y_{kSZ}$$

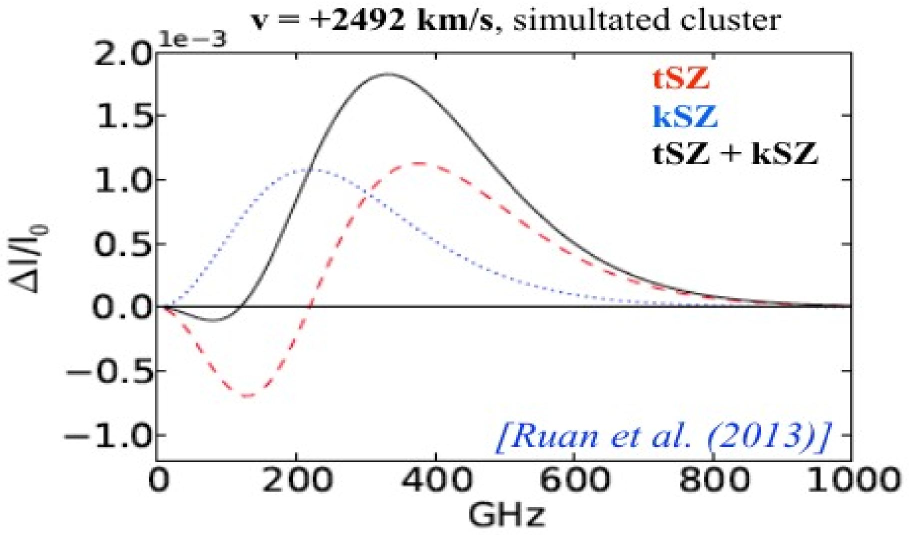
thermal SZ: CMB spectral distortion induced by inverse Compton interaction of CMB photons with clusters hot electrons

$$y_{tSZ} = \frac{\sigma_T}{m_e c^2} \int P_e d\ell$$

Kinetic SZ: CMB Doppler shift from bulk motion of cluster electrons (about tSZ/10)

$$y_{kSZ} = \sigma_T \int \frac{-v_z}{c} n_e d\ell$$





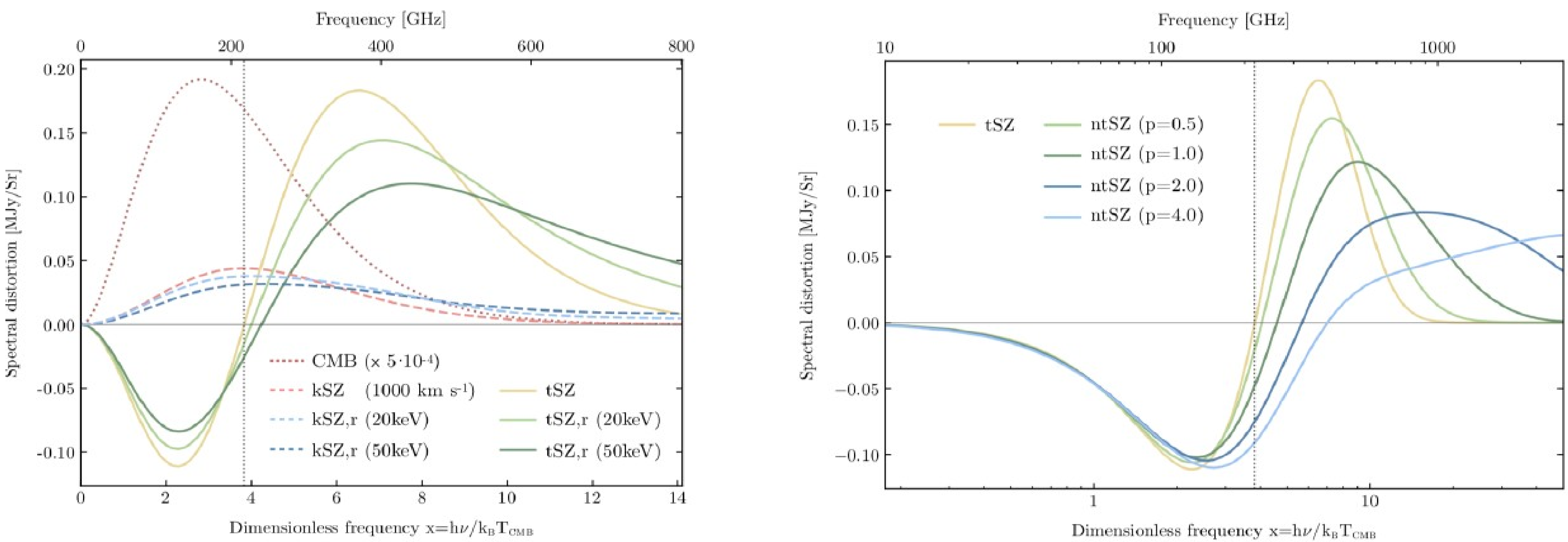
No affected by cosmological diming

Probe for intercluster gas, mass and velocity tracer

Sunyaev-Zeldovich (SZ) effect

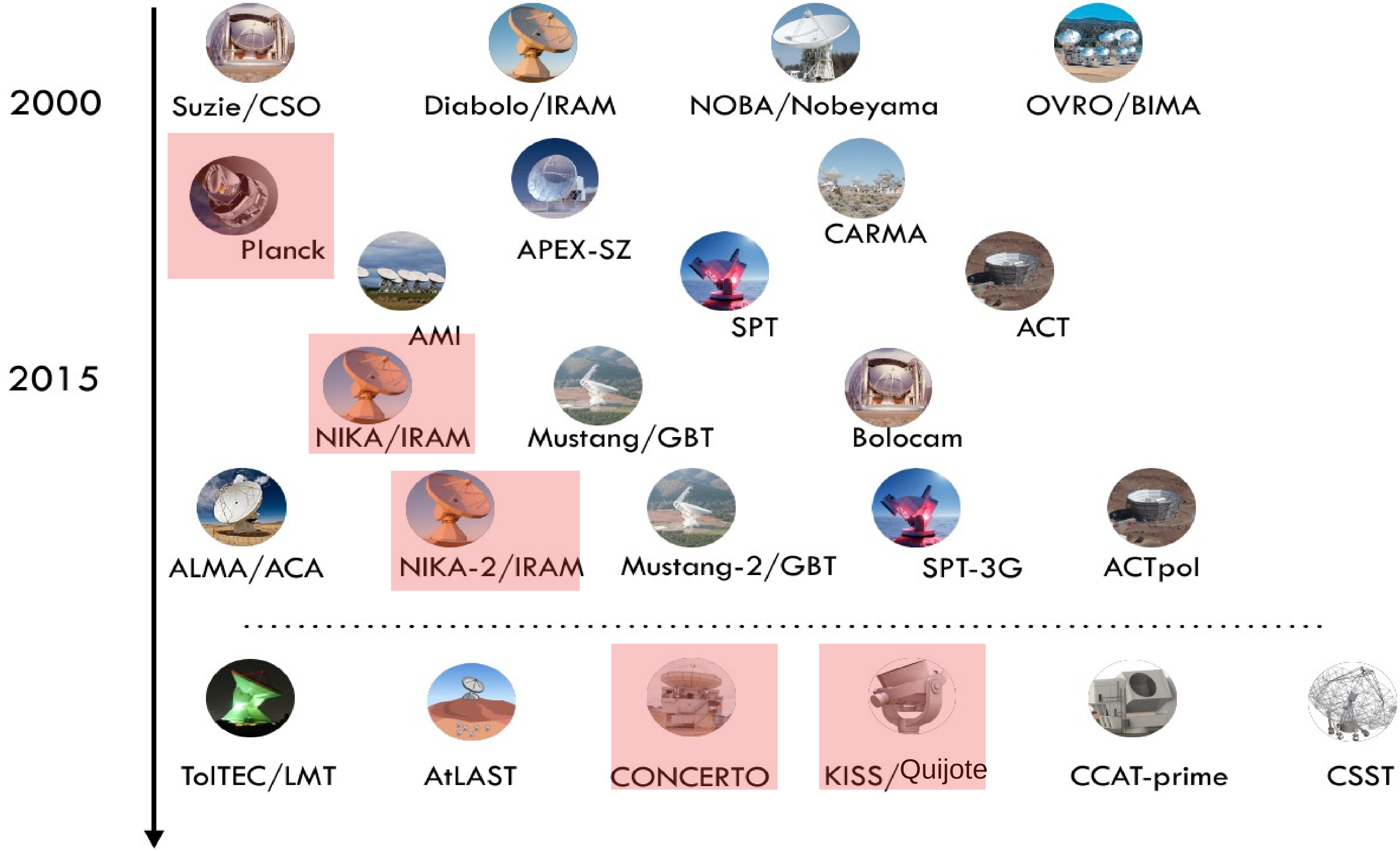
$$\Delta I_\nu^{th} + \Delta I_\nu^{kin} + \Delta I_\nu^{rel} + \Delta I_\nu^{non-th} + \Delta I_\nu^{pol} + \Delta I_\nu^{m-scat}$$

Thermal | Kinetic | Relativistic corrections | Non-thermal | Polarised | Multiple Scattering



Mroczkowski+2019

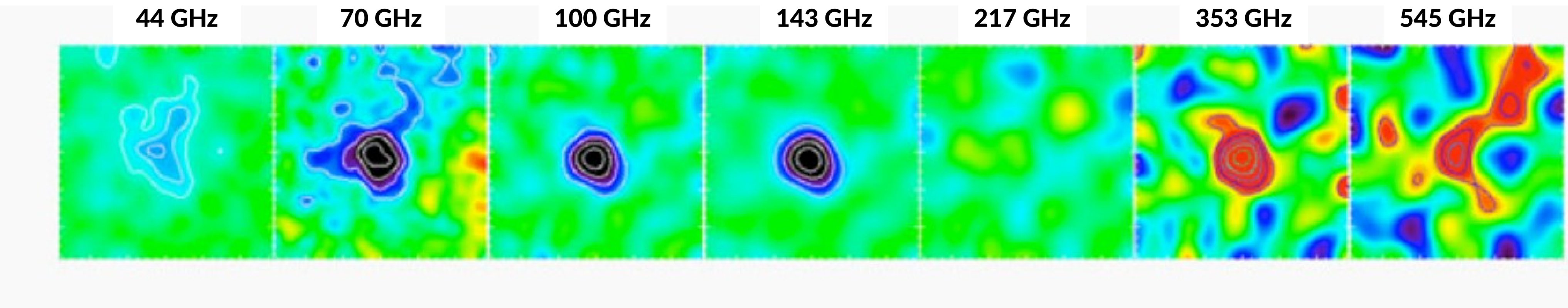
SZ observations ?



SZ cluster cosmology: the Planck example

SZ with the Planck satellite

Planck satellite has been specifically designed to extract the tSZ signal on clusters



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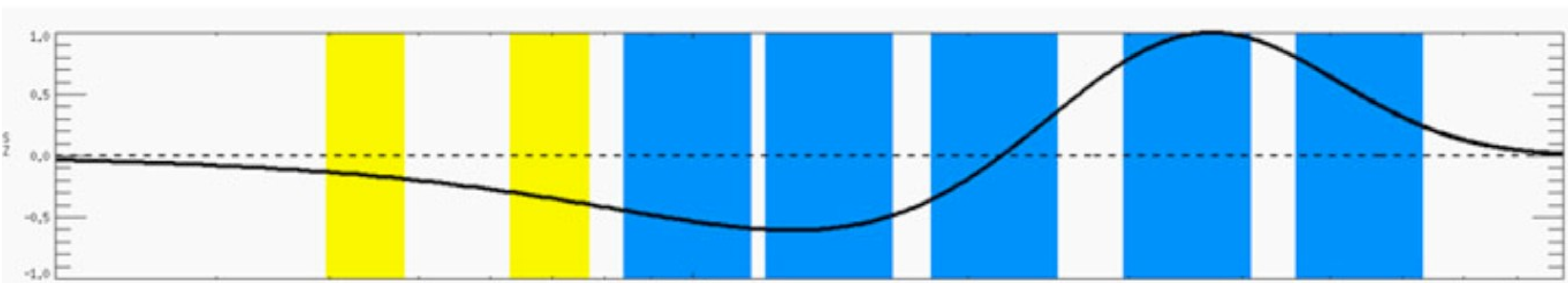
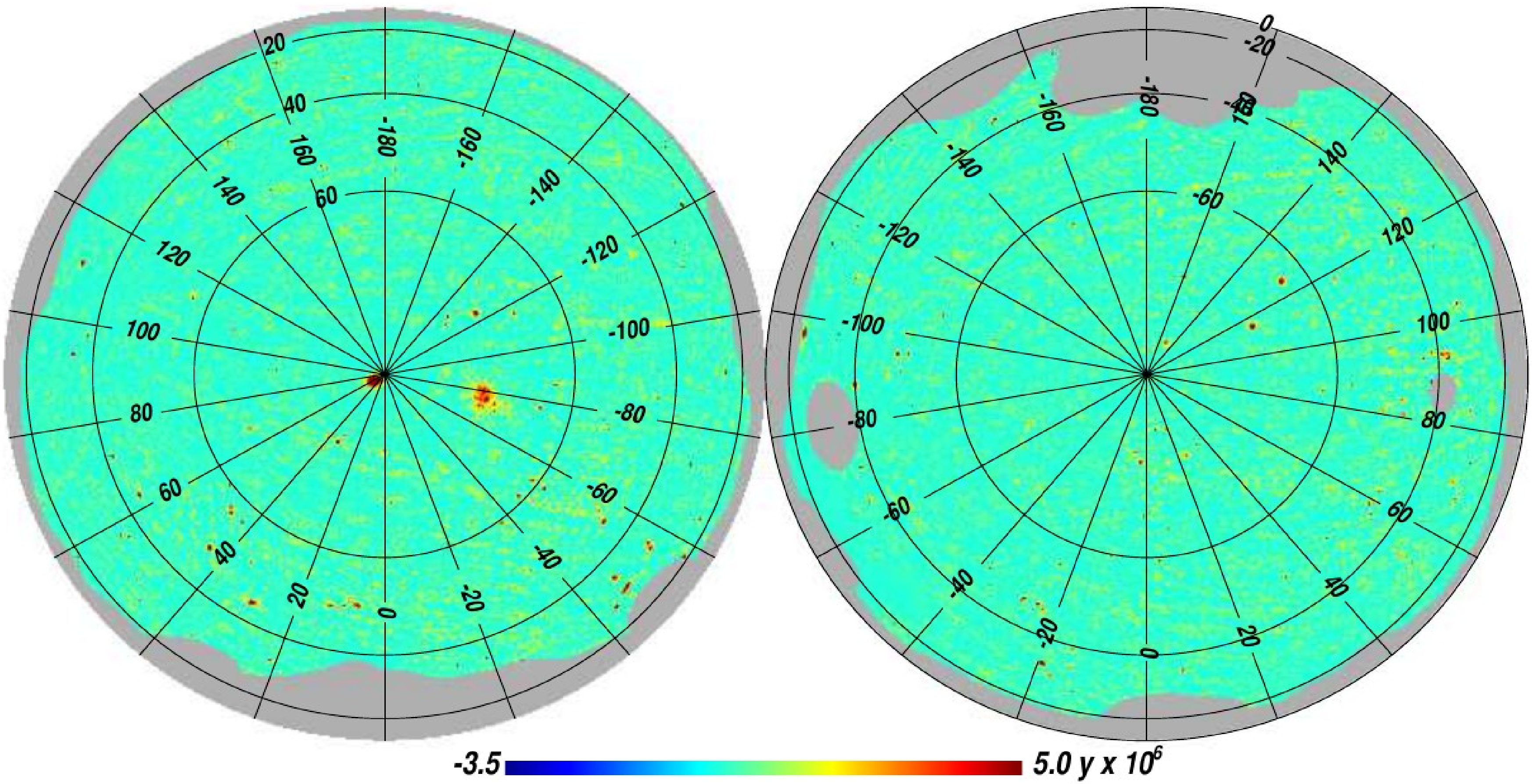


Use both specific cluster size and shape as well as spectral form

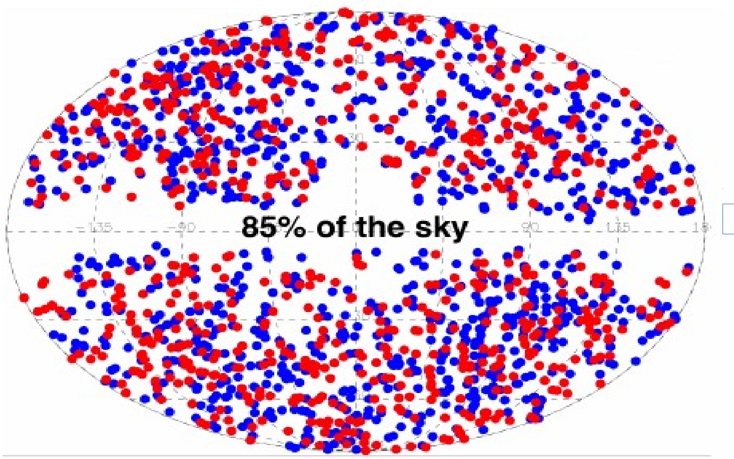
Compton parameter map (y-map)

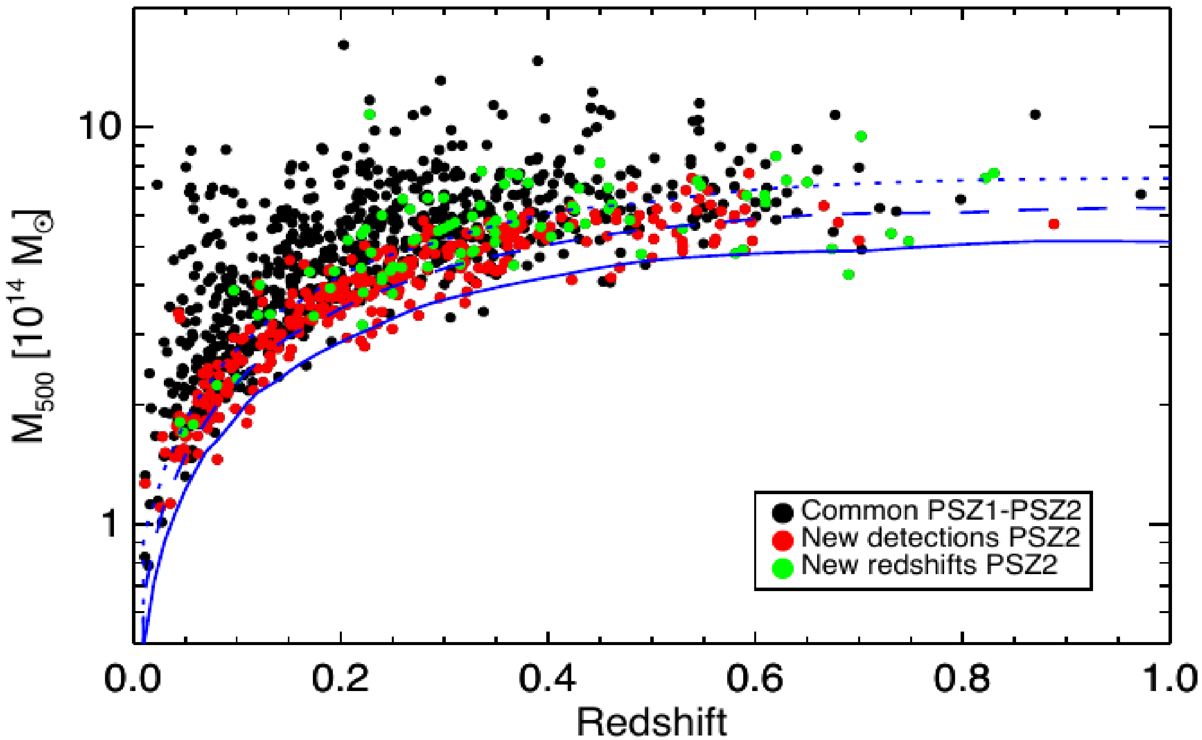
- Develop adapted component separation algorithms: **MILCA** and **NILC** preserve tSZ signal and nullify CMB emission
- First full-sky map of the tSZ emission



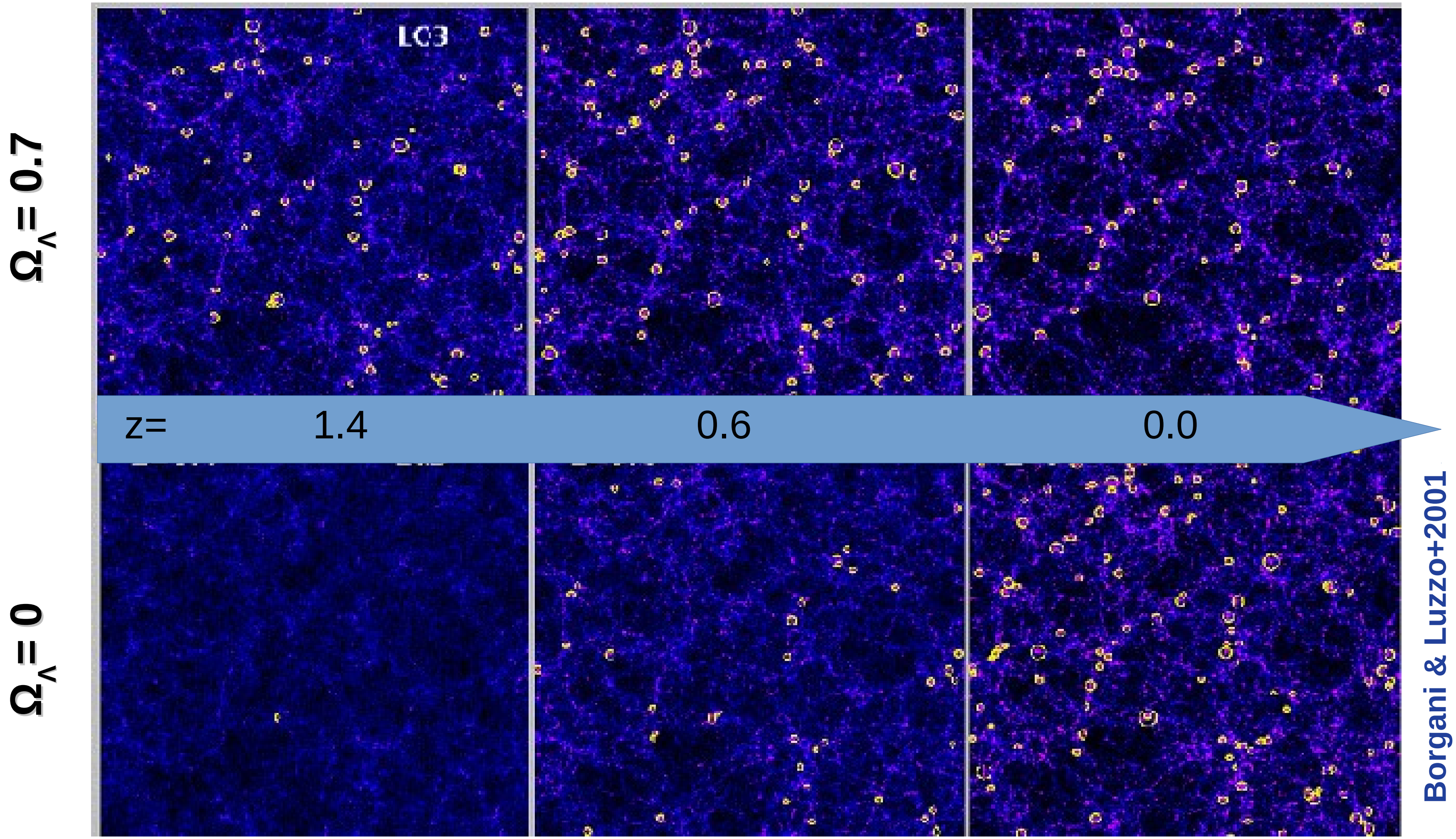
Planck cluster sample

- Use specific multi-scales and multi-wavelengths filters to detect clusters
- Three catalogs has been released: ESZ(2011), PSZ1 (2013), PSZ2 (2015)
- PSZ2: 1653 clusters detected
- 1203 confirmed from existing surveys and follow-up programs in X-rays (XMM newton) and optical/IR (several telescopes)





Cosmology with clusters



Cluster distribution in mass and redshift depends on cosmological parameters

A bit of tSZ cluster cosmology theory

Cluster number counts

$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b) \frac{dN}{dz\, dM_{500}\, d\Omega}$$

tSZ power spectrum

$$C_\ell^{1\mathrm{halo}} = \int_0^{z_{\max}} dz \frac{dV_c}{dz\, d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2$$

Universe properties:

Volume of the Universe

Mass and redshift cluster distribution

Cluster properties and dynamical state:

Hydrostatic to total mass bias

Cluster pressure distribution

tSZ flux to hydrostatic mass relation

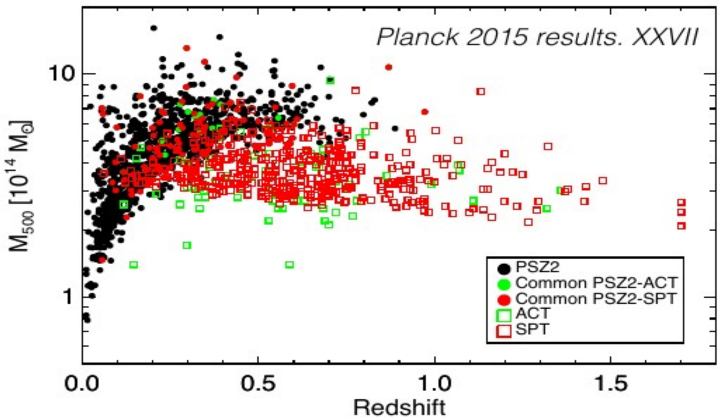
Data analysis

Cluster selection function

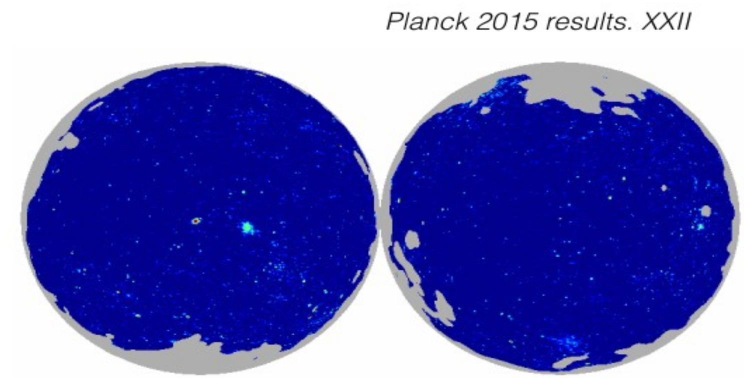
Noise distribution in the y-map

Planck tSZ cluster cosmology

Cluster number counts



tSZ power spectrum



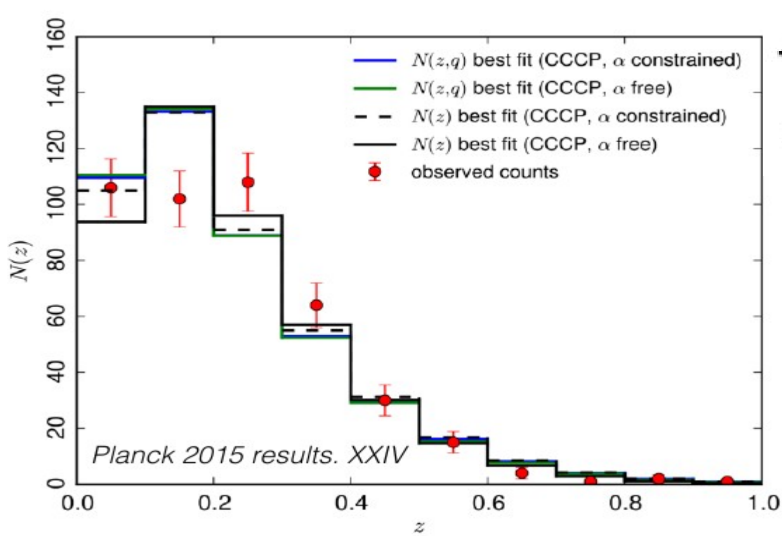
$\frac{dV_c}{dzd\Omega}$ (H0,Ωm,ΩΛ,Ων) Volume

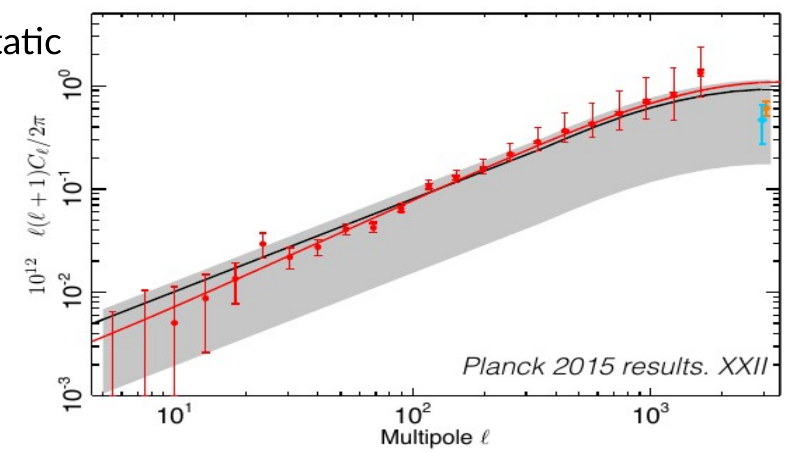
$\frac{dn(\sigma_8, \Omega_m)}{dM}$ Mass function

$P_e(r)$ Pressure profile

$Y_\Delta = A M_\Delta^\alpha$ Scaling relation

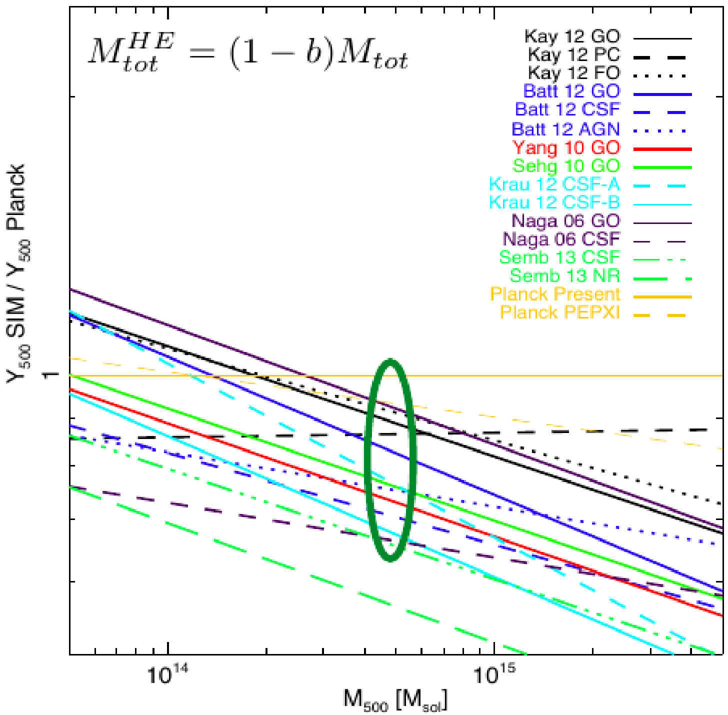
$M_{tot}^{HE} = (1-b) M_{tot}$ Hydrostatic bias





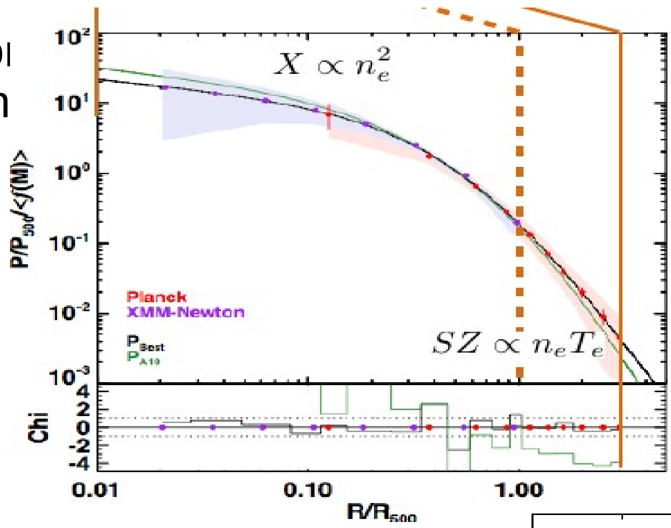
A bit of cluster complexity

- Hydrostatic bias and mass function fro[m] hydrodynamic cosmological simulation



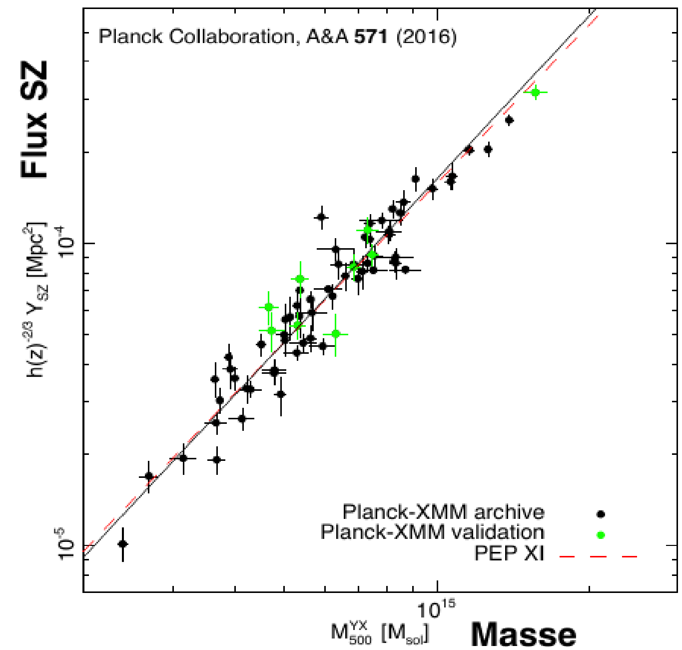
[Planck 2013 results XX]

[Planck intermediate results V (2013)]



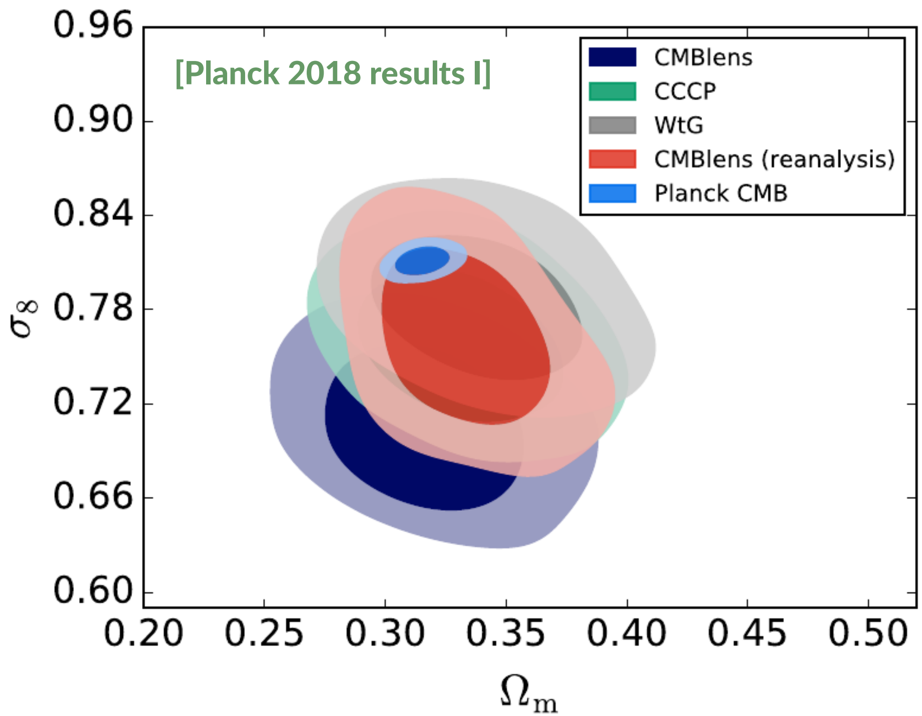
- Pressure profile from tSZ (Planck), X-rays (XMM) low redshift clusters

- Scaling relation from tSZ (Planck), X-rays (XMM) low redshift clusters

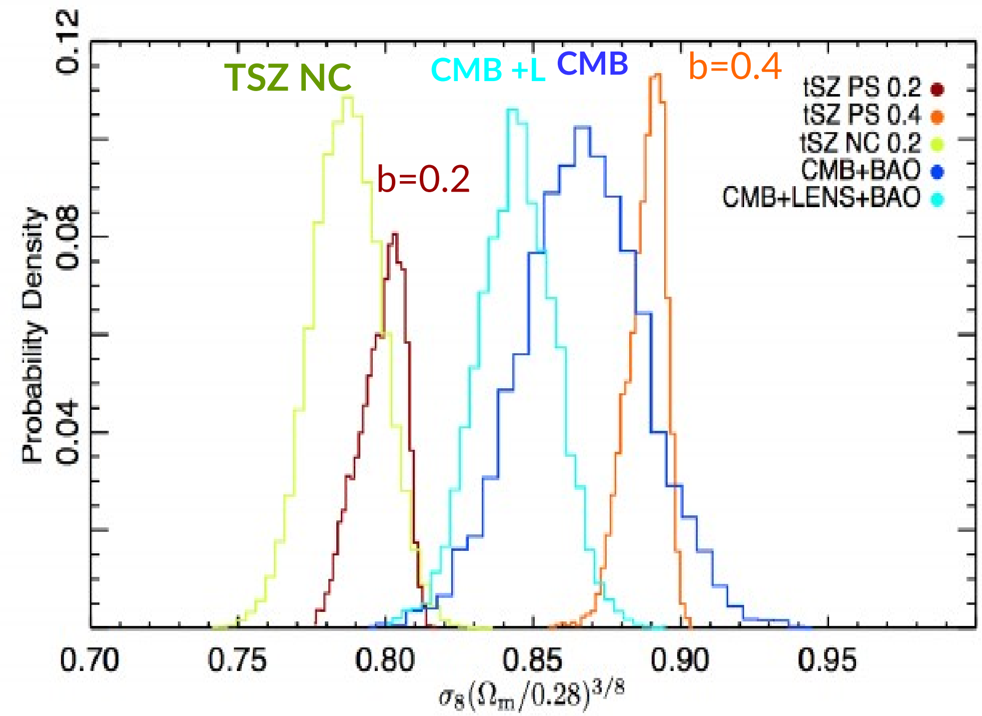


Planck tSZ cluster cosmology results

Cluster number counts



tSZ power spectrum



Current “quasi-consistency” with primary CMB given by large uncertainties in cluster masses when using lensing estimates or by systematic effects in hydrostatic mass estimes

Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, ...

Need for accurate cluster masses

- Cluster cosmology requires accurate mass and matter distribution estimates
- Two complementray approaches :

WL masses		baryonic mass proxies
no bias !!?	vs	unknown bias
large scatter		low scatter

Weak lensing provides absolute mass normalisation

Many observational efforts :
CCCP, Weighing the Giants, 400d WL, CFHTLenS, 400d WL, LoCuSS, WISCy

LSST + EUCLID 2021
+
CMB lensing in clusters

$Y - M_{tot}$ & P(r)

bias
scatter
evolution

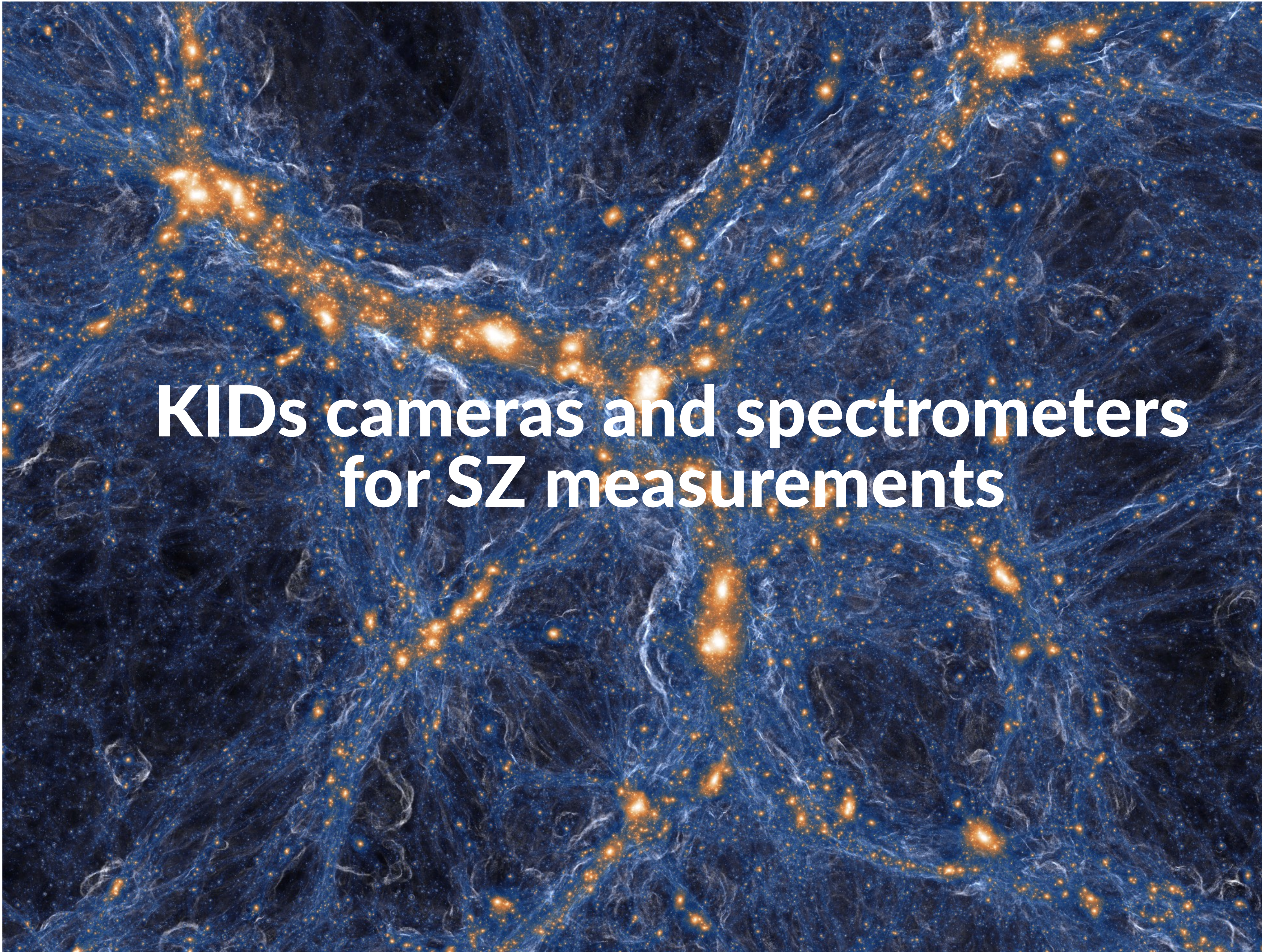
vs

dynamics
z

Cluster detection
X-rays : e-ROSITA
SZ : SPT-3G (2016-2019), Advanced ACTPOL

Scaling relations
X-rays : XMM, Chandra
SZ : **NIKA2 (2017-2021),** MUSTANG2 (2018),

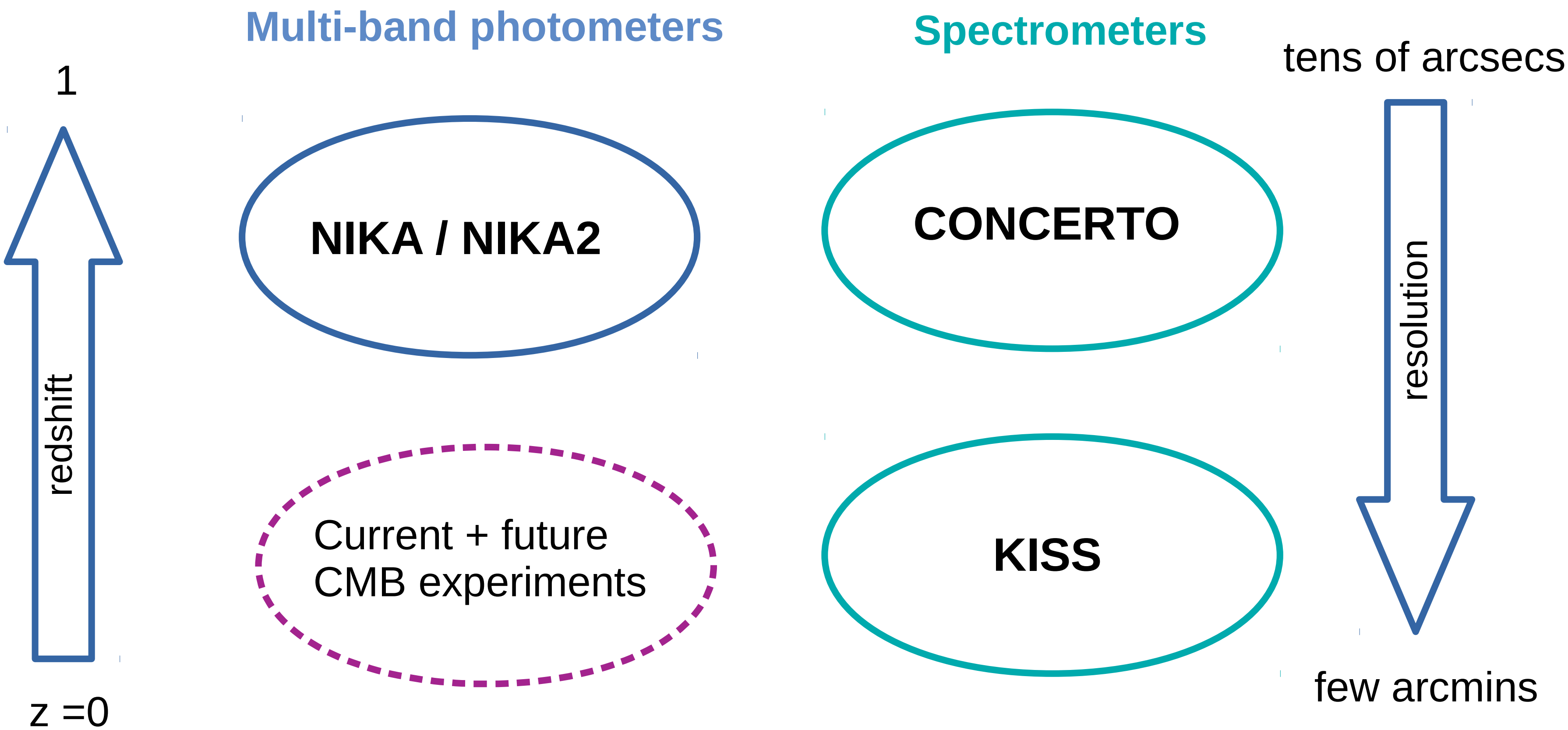
We expect baryonic mass proxies to be affected by cluster physics and dynamical state, which may evolve with redshift and depend on cluster dynamical state



KIDs cameras and spectrometers for SZ measurements

Our SZ science approach

Develop new instruments to carry out complementary SZ observations targeting the improvement of cluster mass estimates at low and high redshift

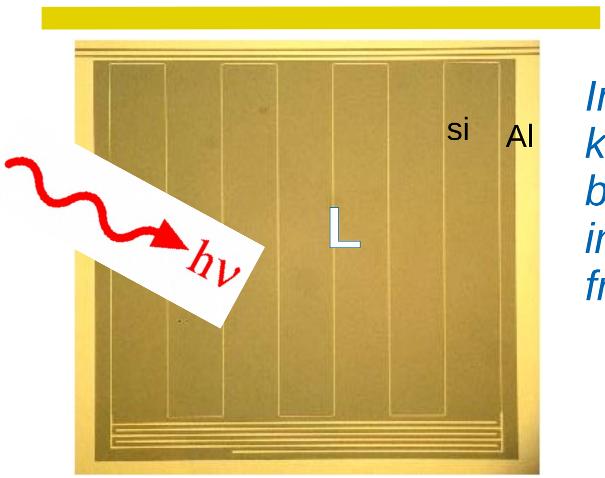


For this we need large arrays of detectors in the millimeter domain

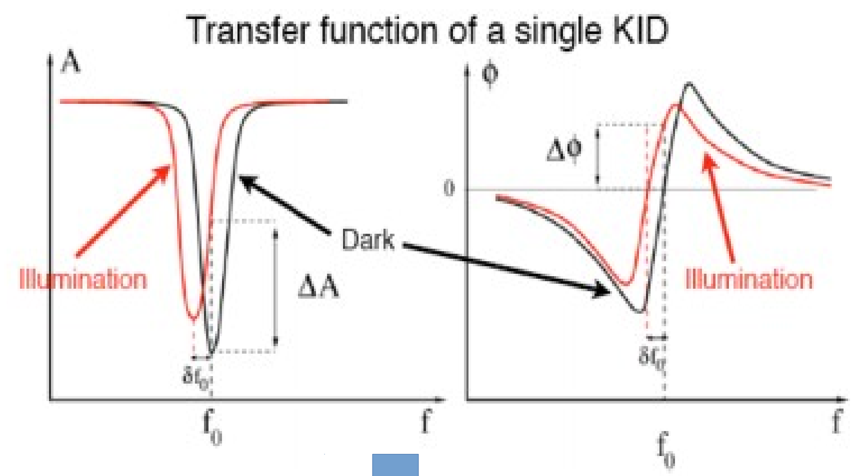
Kinetic Inductance Detectors (KIDs)

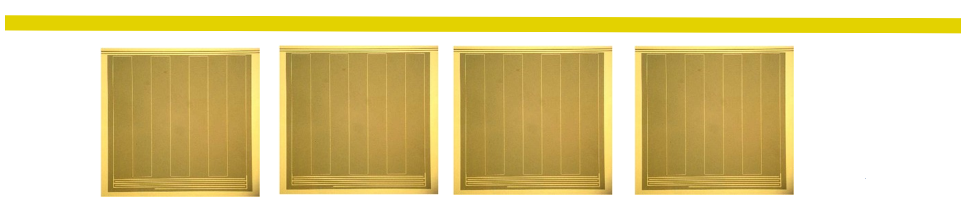
KIDs are superconducting RLC resonators operated at $T_b \sim 100 \text{ mK} \ll T_c \sim 1.5 \text{ K}$

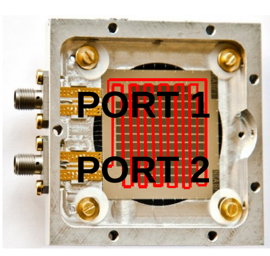
In out

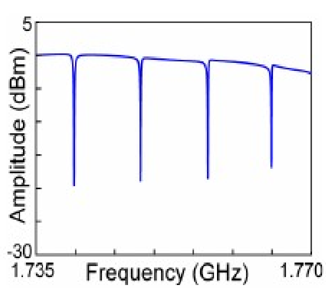


Incoming light changes kinetic inductance by breaking Cooper pairs and induces a resonance frequency shift







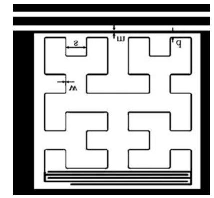


Monfardini, Benoit, Bideaud et al. 2011

KIDs a are good alternative to bolometers

- Fast detectors, time constant << 1 ms
- Relatively simple fabrication procedure
- Natural frequency domain multiplexing
- Simultaneous real-time readout

KIDs developments in Grenoble (Institut Néel, LPSC, IPAG, IRAM)



Hilbert geometry (dual polarisatic

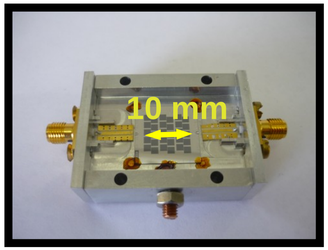
2000
KID Concept
(Caltech-JPL)

NIKA0

NIKA1

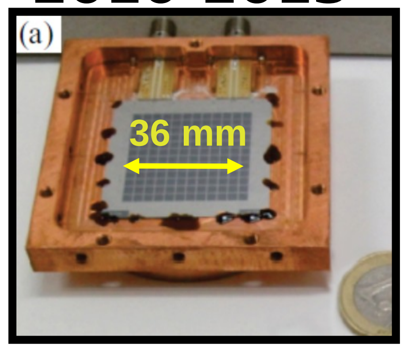
NIKA2

2009



30 pixels

2010-2013



300 pixels

2014-2017

1100 pixels

2008

Grenoble “join” the KID community

2009

30 pixels → NIKA0 (first ever KID camera)

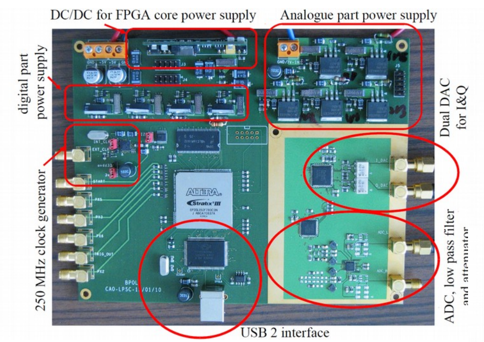
2014 - 2017

- Background-limited **(NEP < 10^{-17} W/Hz$^{0.5}$)**
- Readout line 2.5 m long !! Litho !!
- Al high-quality, uniform thickness film (≈10nm)

[Monfardini+2010, 2011, Adam+2019]

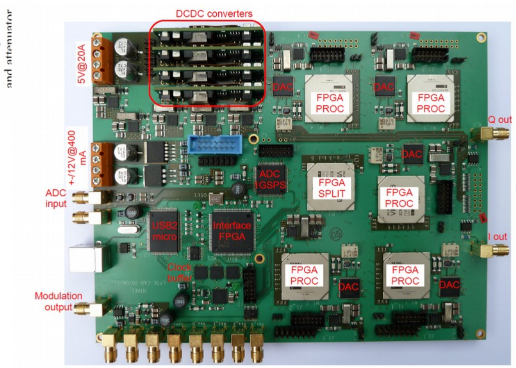
Readout developments in Grenoble (LPSC, Institut Néel, IPAG, IRAM)

2011: NIKEL proto



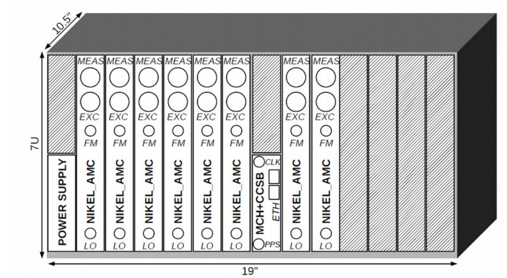
128 pixels
500 MHz bandwidth
external RF

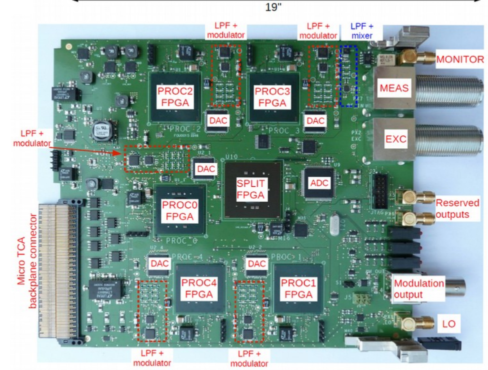
2012: NIKEL (NIKA)



400 pixels
500 MHz bandwidth
external RF

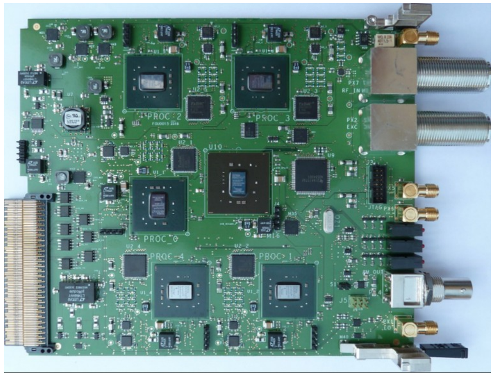
2016: NIKEL AMC (NIKA2/KISS)





400 pixels
500 MHz bandwidth
RF in the board
Compact crate with up to 10 boards

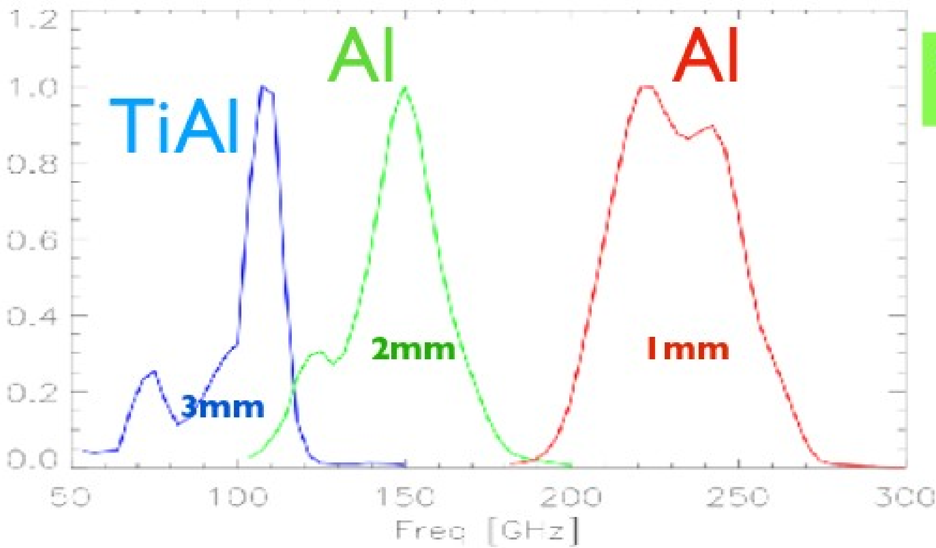
2020: NIKEL AMC v2 (CONCERTO)

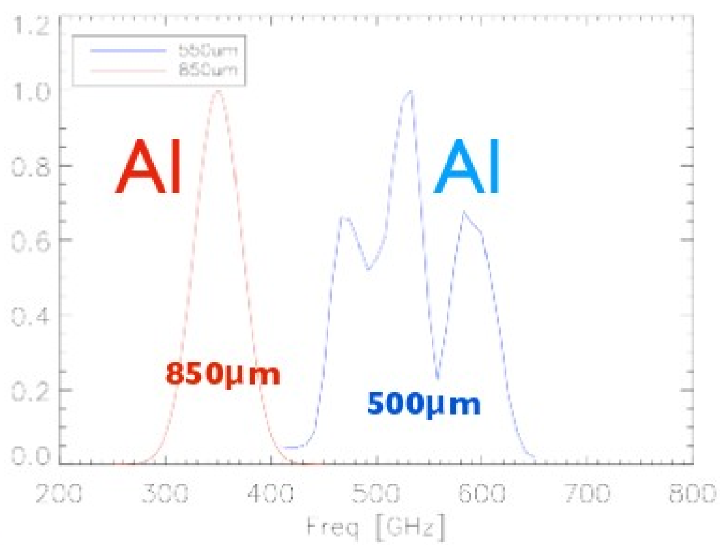


1 GHz bandwidth
30 watts power

[Bourrion+2011, 2012, 2016]

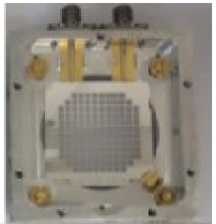
KIDs spectral response



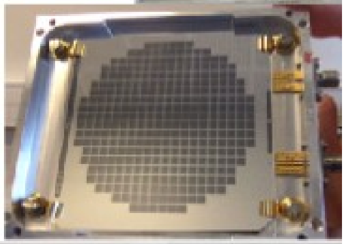


[Catalano+2018, Goupy+2017]

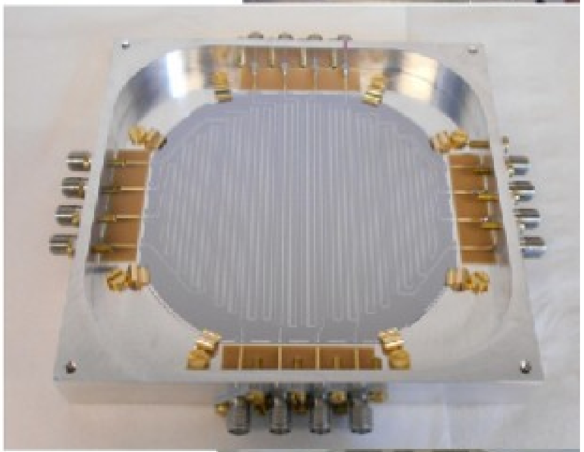
LEKID Demonstrators for space (132pix)
3mm - 2mm - 1mm - 850µm - 500µm



LEKID Array for KISS Interferometer (300pix) TiAl@3mm



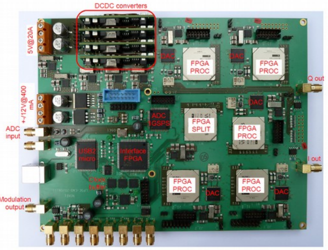
LEKID Array for NIKA2 (2000pix) Al@3mm

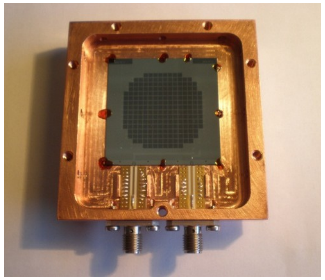


LEKID Array for Ballon (500 pix) Al@500µm

The NIKA camera

- prototype of NIKA2
- operated at the IRAM 30 m telescope from 2009-2014
- Dual band camera with 336 KIDs
- Polarisation capabilities in both bands
- First KID based camera to provide scientific grade results





NIKA	150 GHz	260 GHz
# KIDs	132	224
FOV diameter	1.8 arcmin	2.0 arcmin
Sensitivity	14 mJy/s$^{1/2}$	40 mJy/s$^{1/2}$
Angular res.	18 arcsec	12 arcsec

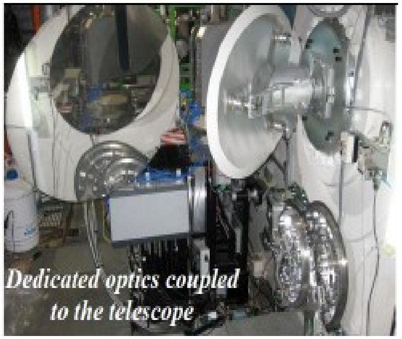
[Calvo & NIKA collaboration, 2012, Adam & NIKA collaboration, 2014, Catalano & NIKA collaboration 2014]

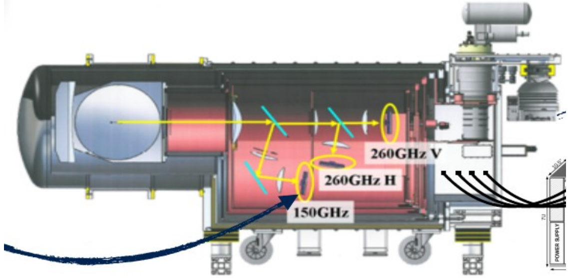
The NIKA2 camera

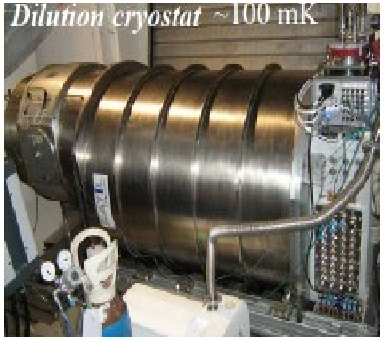
IRAM 30-m telescope
at Pico Veleta (Spain)

Dual band mm camera made of Kinetic Inductance Detector (KID) arrays

Resident instrument open to the astrophysical community





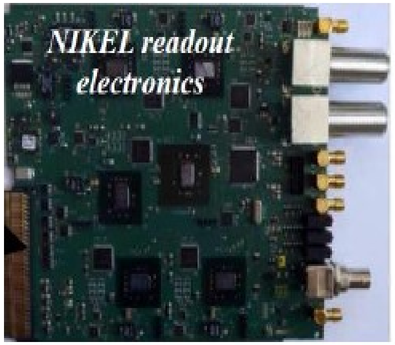


Arrays of 1140 (666) KIDs:
8 (4) independent feedlines
with up to 200 KID each

[Adam+ NIKA2 collaboaration 2019, Perotto + NIKA2 collaboration 2020, & mm conference proceedings]

Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	8±1 mJy/s$^{1/2}$	33±2 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

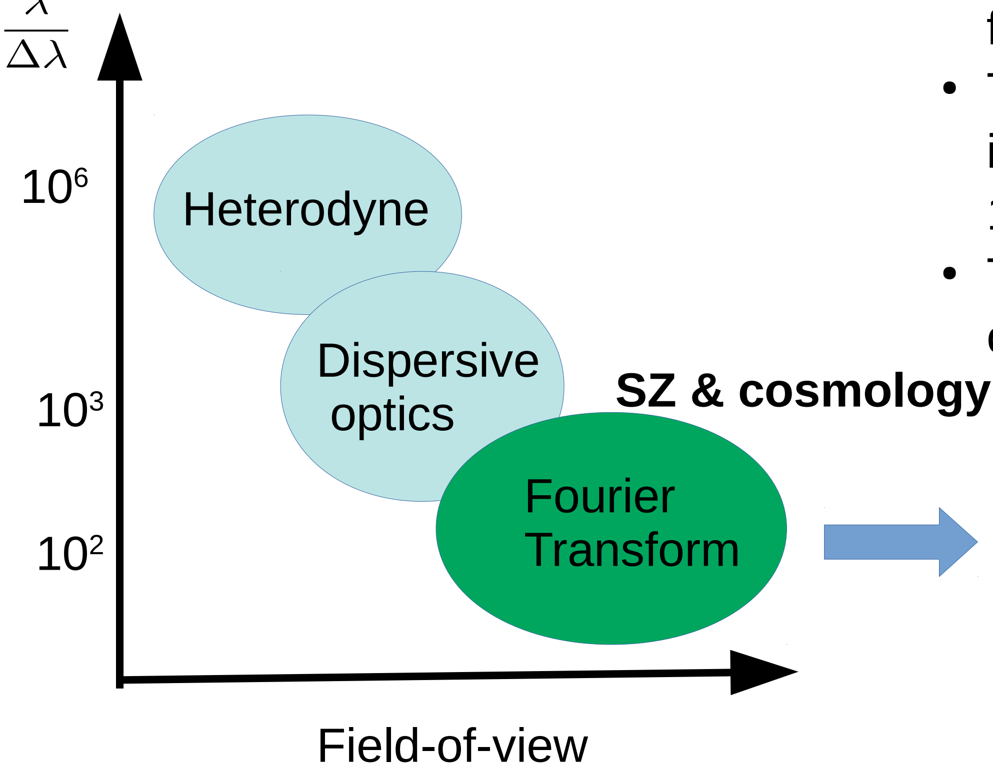
20 boxes (one per feedline) arranged in 3 crates (one per array)



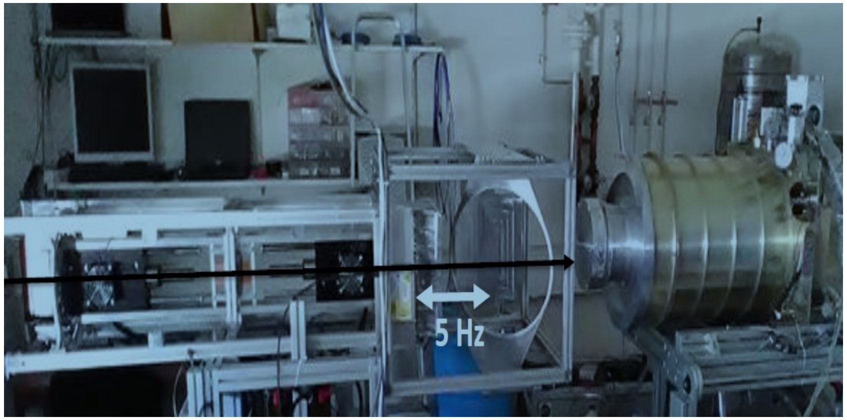
Large FOV ground-based mm spectrometers

For a large FOV best is:

$$R = \frac{\lambda}{\Delta\lambda}$$

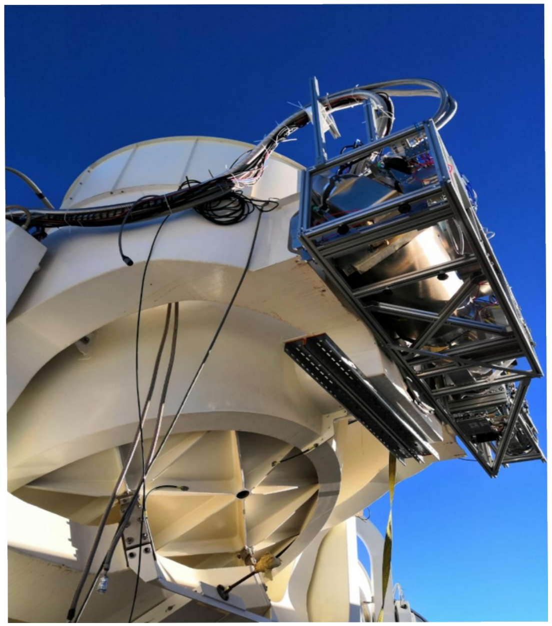


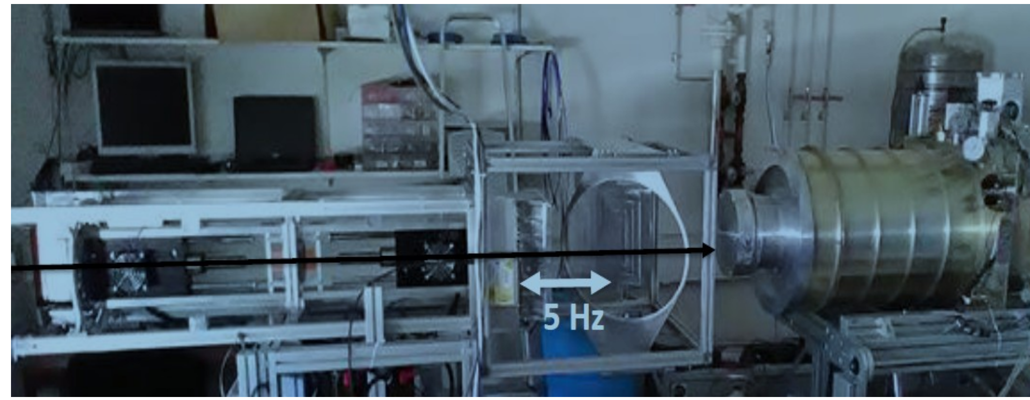
- Fourier transform spectrometer can be achieved via Martin-Puplett interferometers
- To reduce atmospheric noise we need to go **faster than the atmosphere**
- Typically we want one interferogram/spectrogram per pixel each 100 ms!!, about 4 kHz sampling reate
- This can only be achieved with KIDS, time constant << 0.25 ms



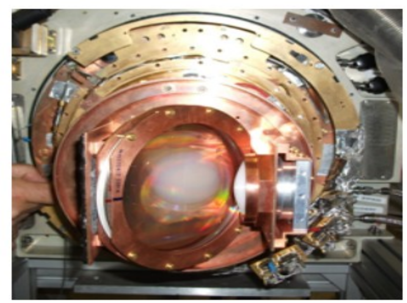
Our solution: couple Martin-Puplett interferometer to KIDs camera

The KISS spectrometer

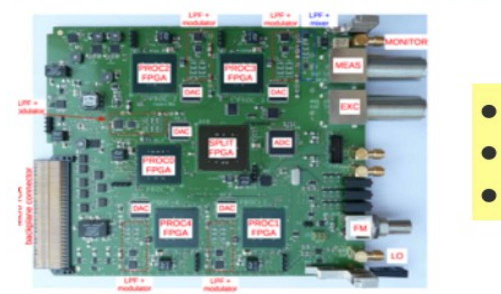




Dilution Cryostat ^3He-^4He (100 mK)



Frequency Multiplexing Read-Out Electronics : NIKEL



Measure physical properties of nearby cluster via the SZ effect

Low resolution MP spectrometer from 120 to 260 GHz

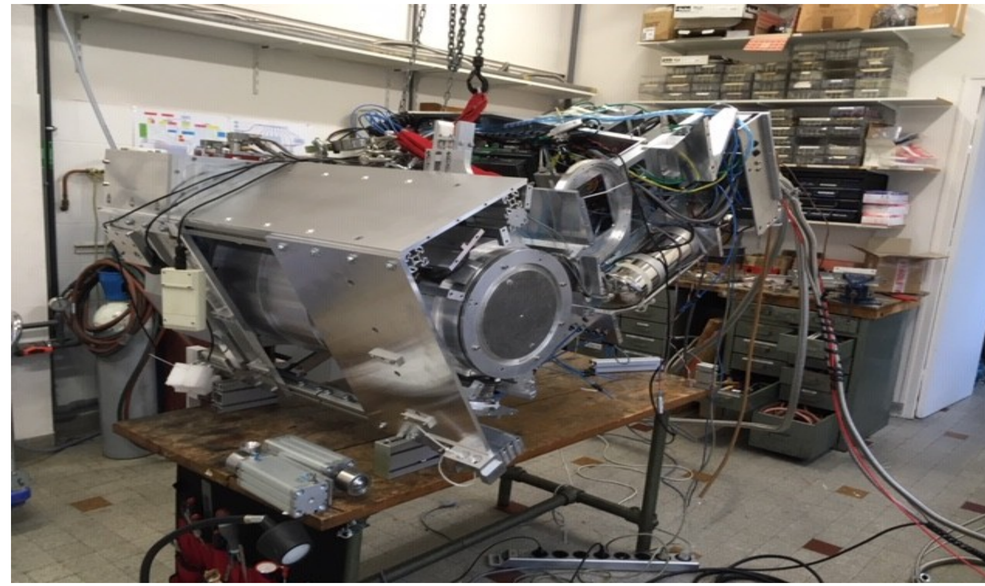
600 KIDs @ QUIJOTE telescope in Teide Observatory

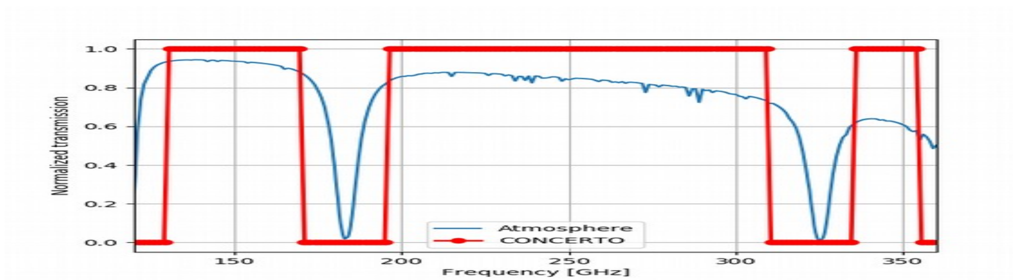
In commissioning phase

Scientific goal:
Low resolution spectroscopy observations of known low redshift galaxy clusters at mm wavelengths to map cluster physical properties from spectral distortions

[Fasano+ KISS collaboration 2019, 2020]

CONCERTO spectrometer





Intensity mapping of CII lines at high redshift to measure SFR + detection of clusters with SZ

Low resolution MP spectrometer from 120 to 350 GHz

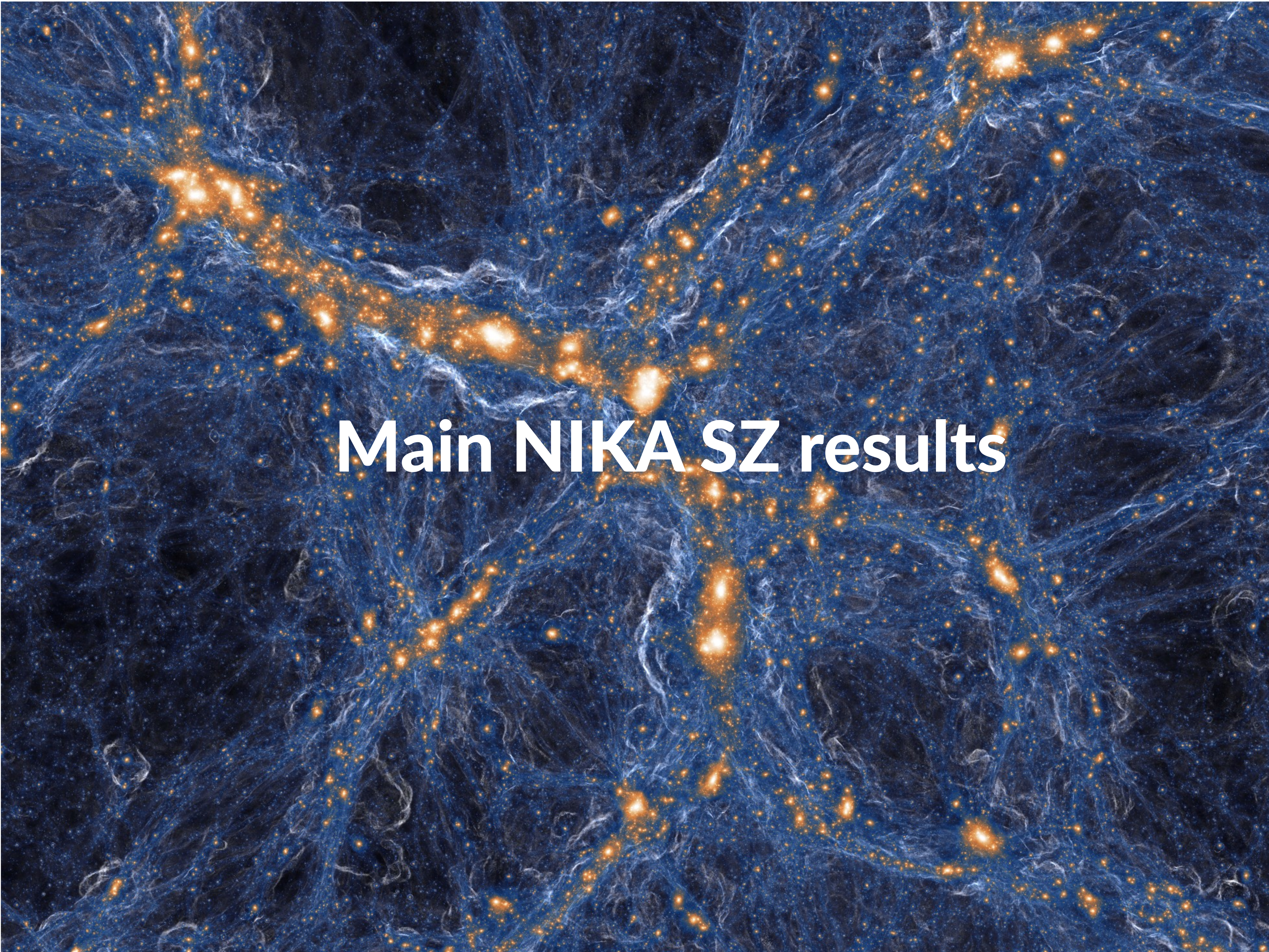
Instrumental design as KISS but with 5000 KIDs @ APEX telescope in Atacama

Installation expected in 2021

Scientific goal:

1) CII intensity mapping for reionization studies
2) high redshift galaxy clusters mm wavelengths spectroscopy to map cluster physical properties from spectral distortions

Main NIKA SZ results

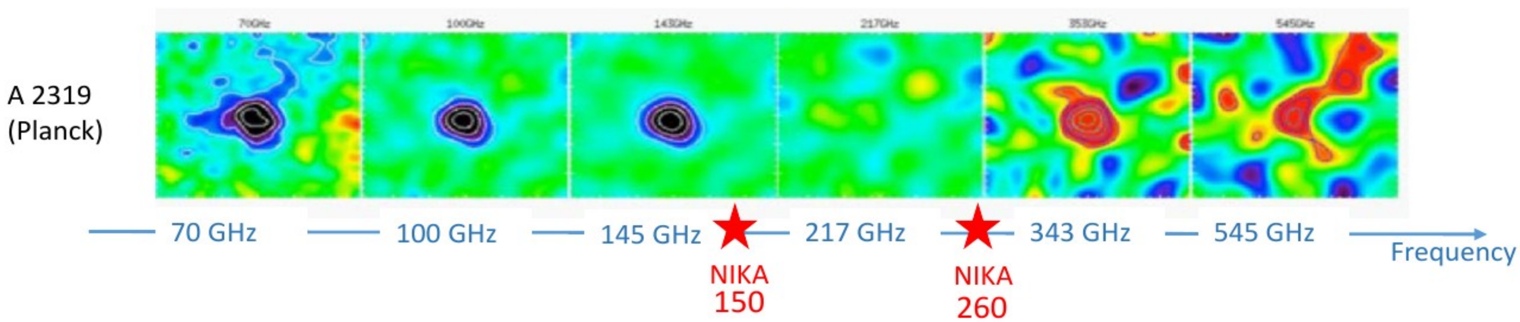


SZ with NIKA/NIKA2

NIKA2 is well adapted for SZ observations of intermediate and high redshift clusters

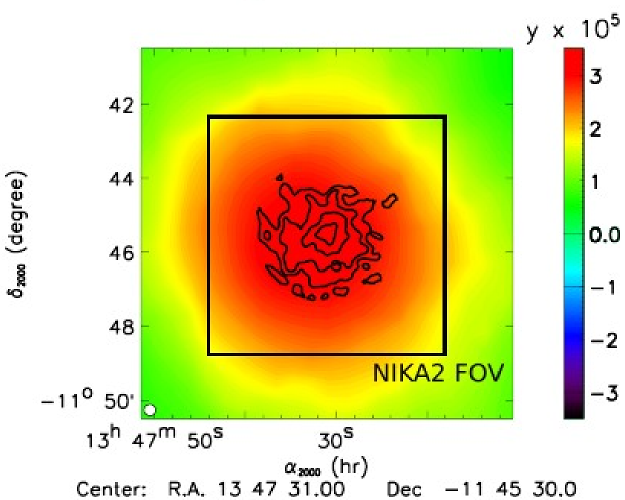
Ideal spectral coverage

Simultaneous mapping of SZ and possible contaminants

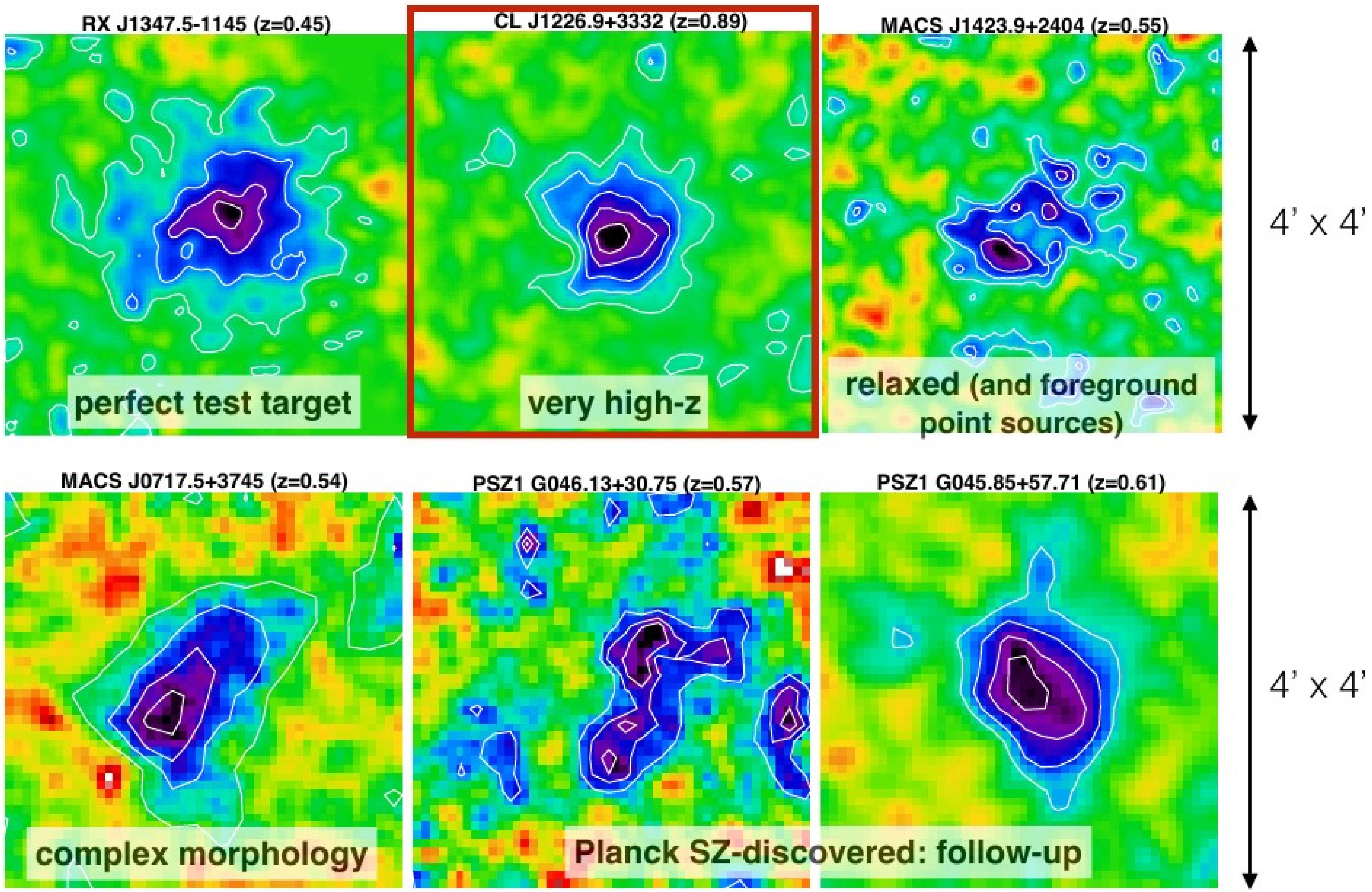


High resolution and large FOV

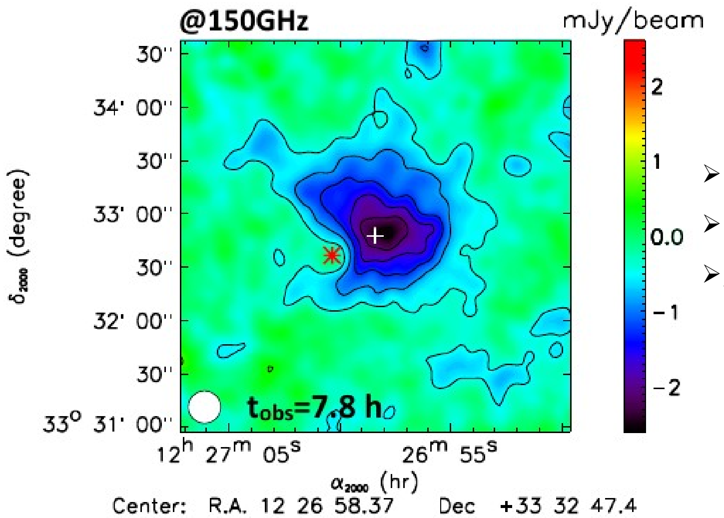
Can map both cluster inner regions and outskirts

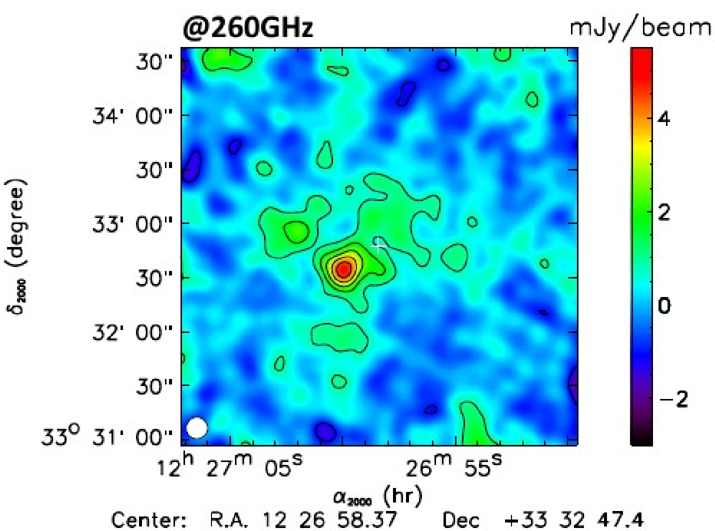


The NIKA cluster sampe



High redshift cluster (z=0.89)

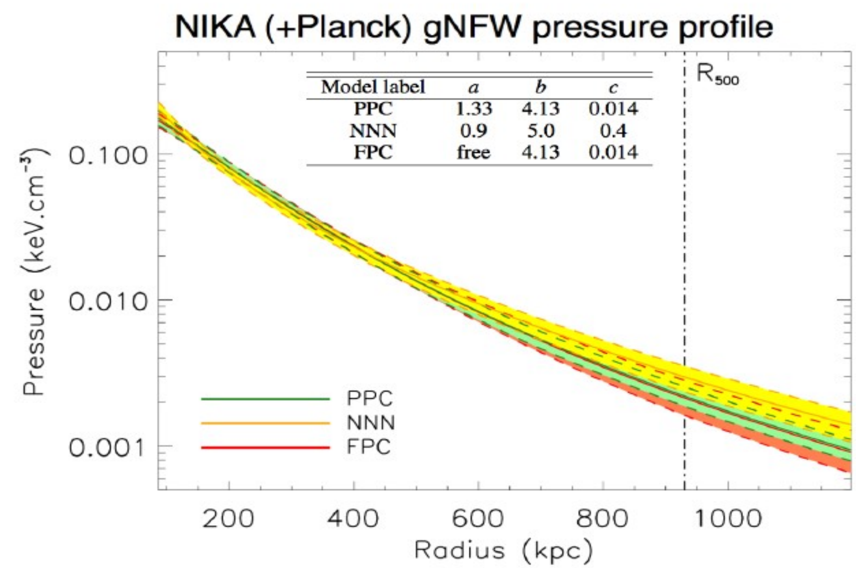


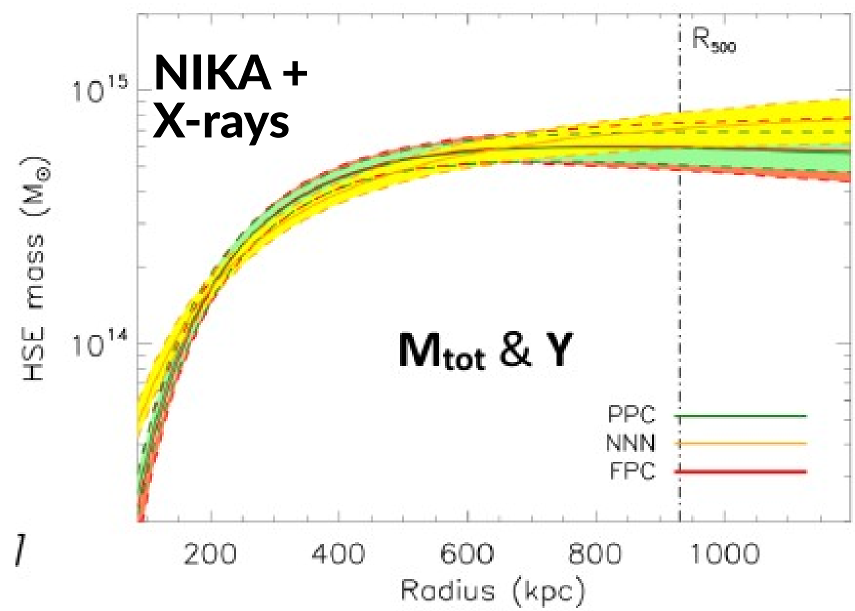


CL1226.8+3332

- Relaxed and massive
- 18-σ peak detection
- Strong point source

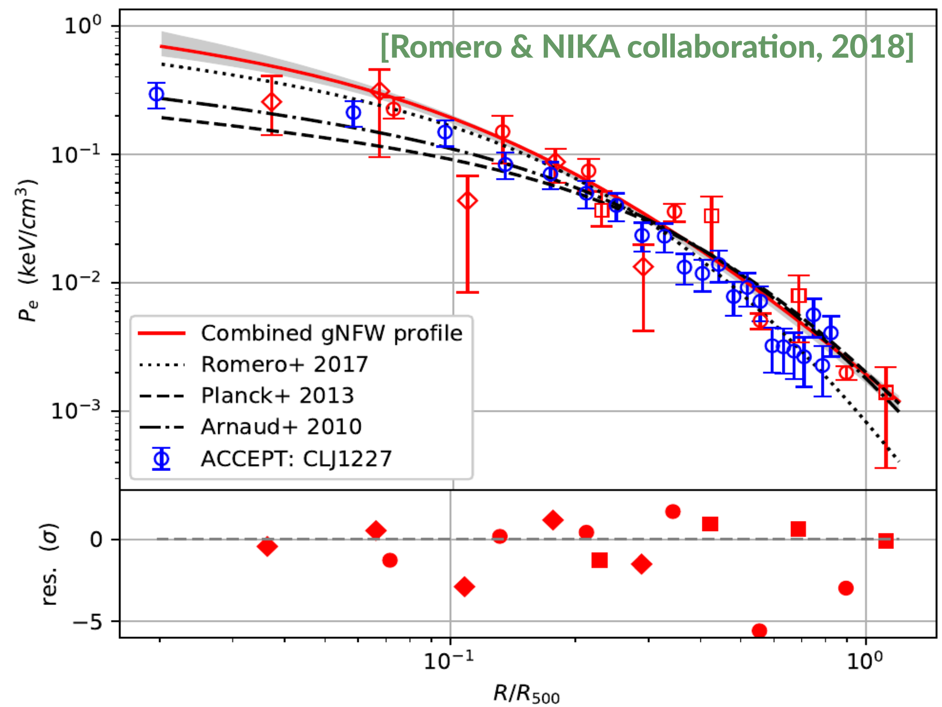
Measure cluster thermodynamic properties and HSE mass





[Adam & NIKA collaboration, 2015]

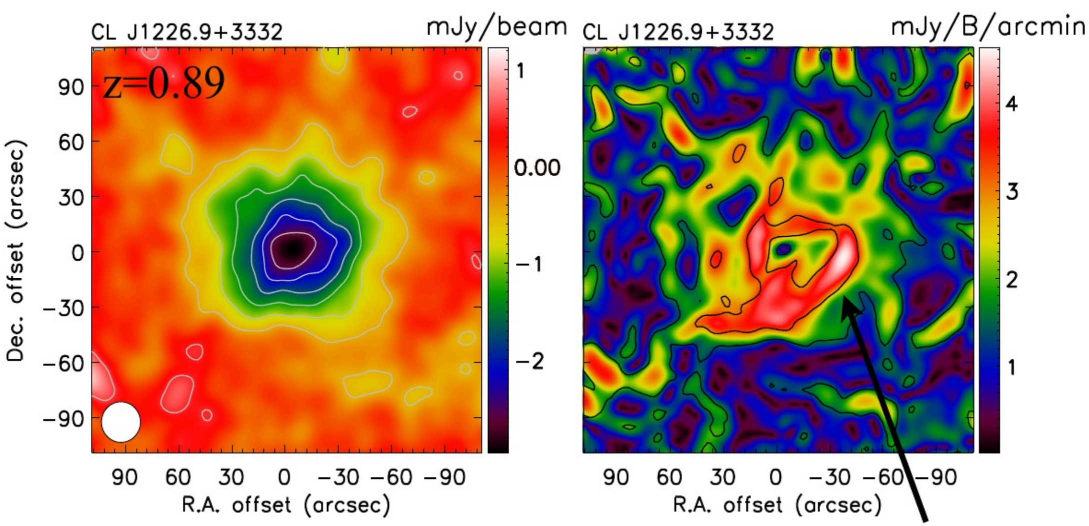
High redshift cluster (z=0.89)



- **Joint NIKA, MUSTANG, BOLOCAM and PLANCK tSZ analysis** pressure profile from the inner cluster region to the outskirts.

NIKA map

Gradient filtered map

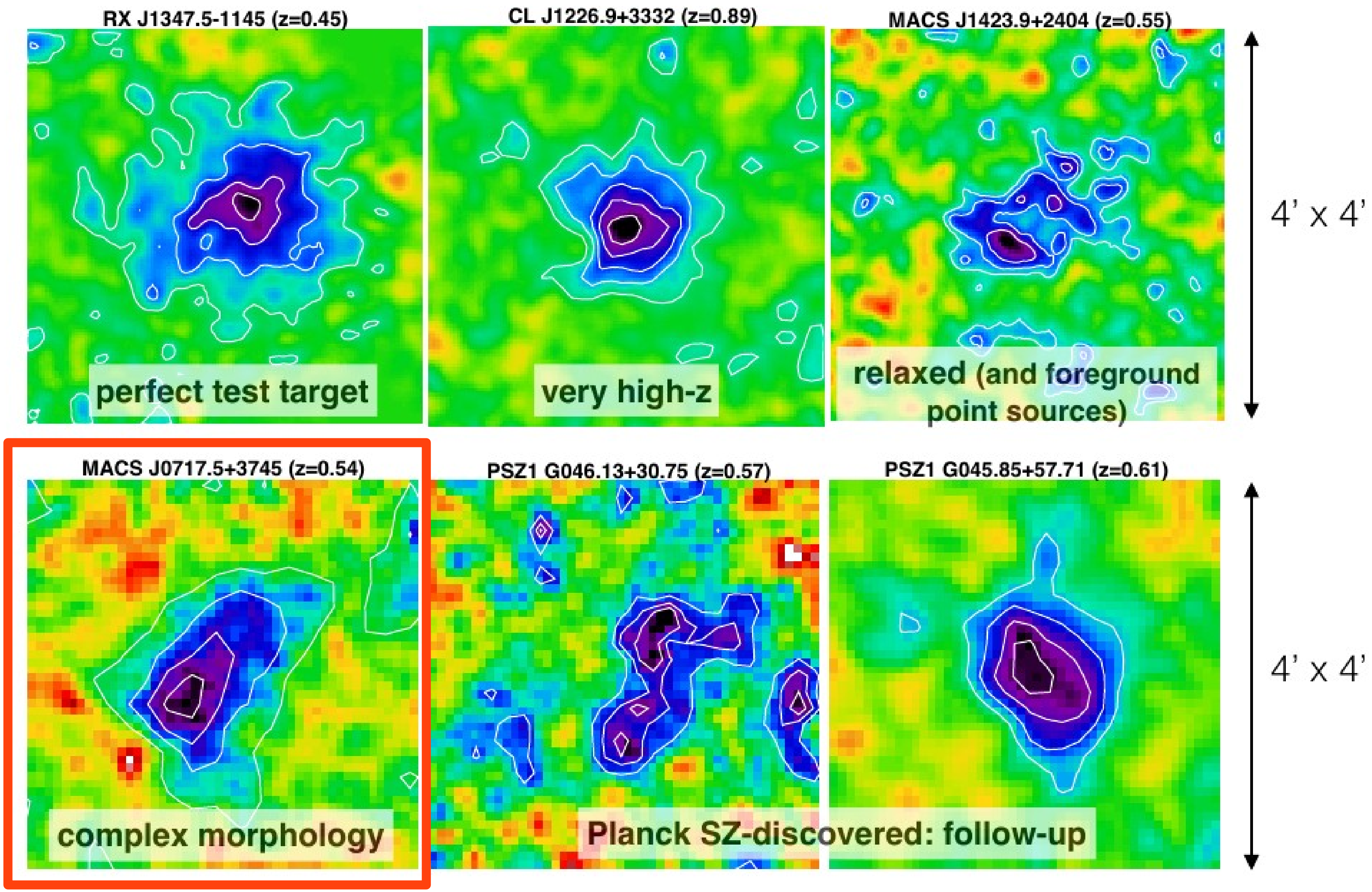


Pressure jump caused by merger

- ICM physical state determination: Direct detection of pressure jump induced by merging events

[Adam & NIKA collaboration, 2017]

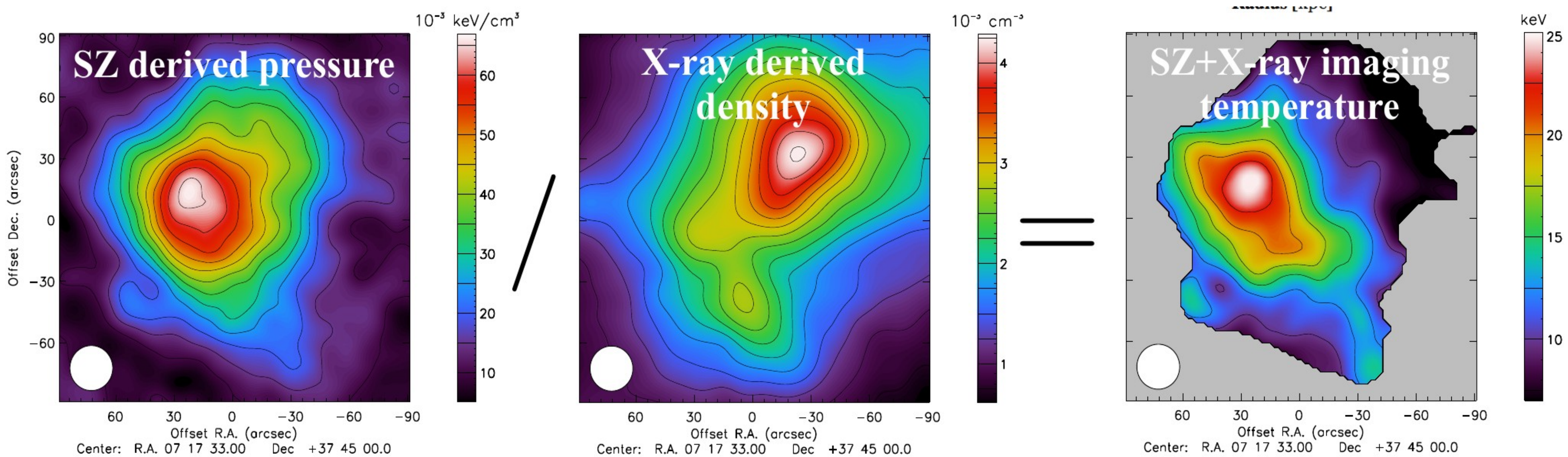
Complex physics

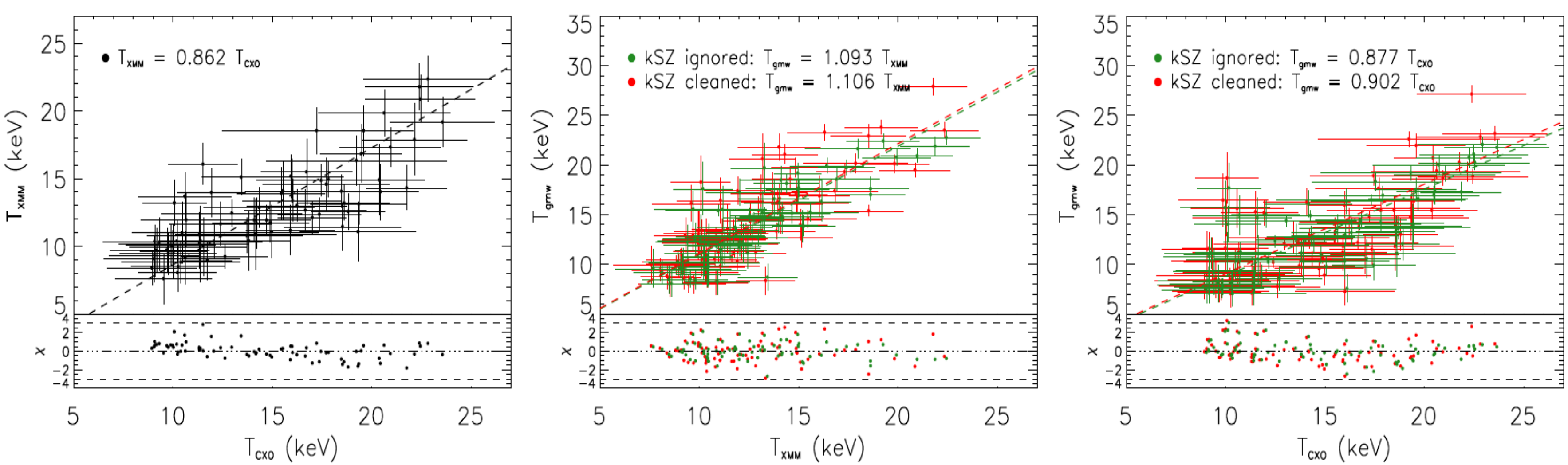


Temperature map from tSZ + X-rays

[Adam & NIKA collaboration, 2017]

$P_e = n_e T_e$ ⇨ *First 2D temperature map from combined tSZ and X-ray imaging*





MACS J0717-3745 and kSZ

- High sensitivity NIKA data (12 hours on source)
  + High quality X-ray, optical and IR data

- However, mapping kSZ is very challenging:

  Complex system (5 subclusters
  Foreground emission
  Degeneracy relativistic tSZ and kSZ

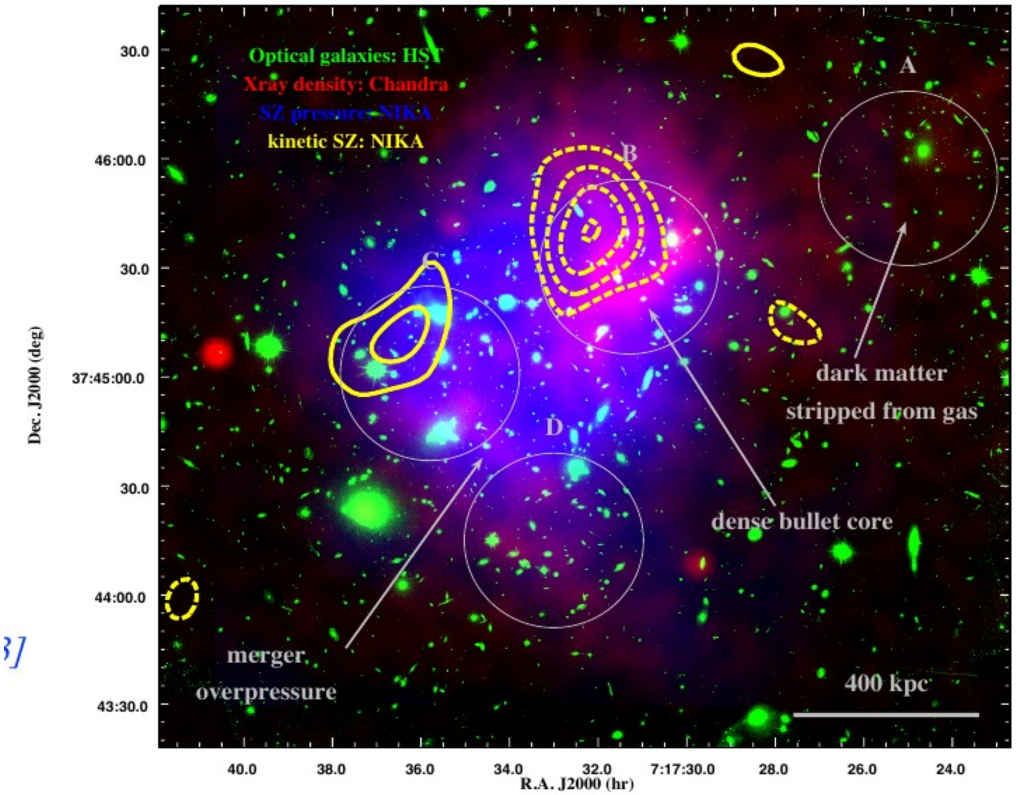
- Use the two NIKA channel maps
  + temperature map from X-rays

spectral dependencies

$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

gas pressure — *gas velocity and density*

MACS J0717-3745



kSZ mapping with NIKA

- High sensitivity NIKA data (12 hours on source)
  + High quality X-ray, optical and IR data
- However, mapping kSZ is very challenging:

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  Foreground emission
  Degeneracy relativistic tSZ and kSZ

- Use the two NIKA channel maps
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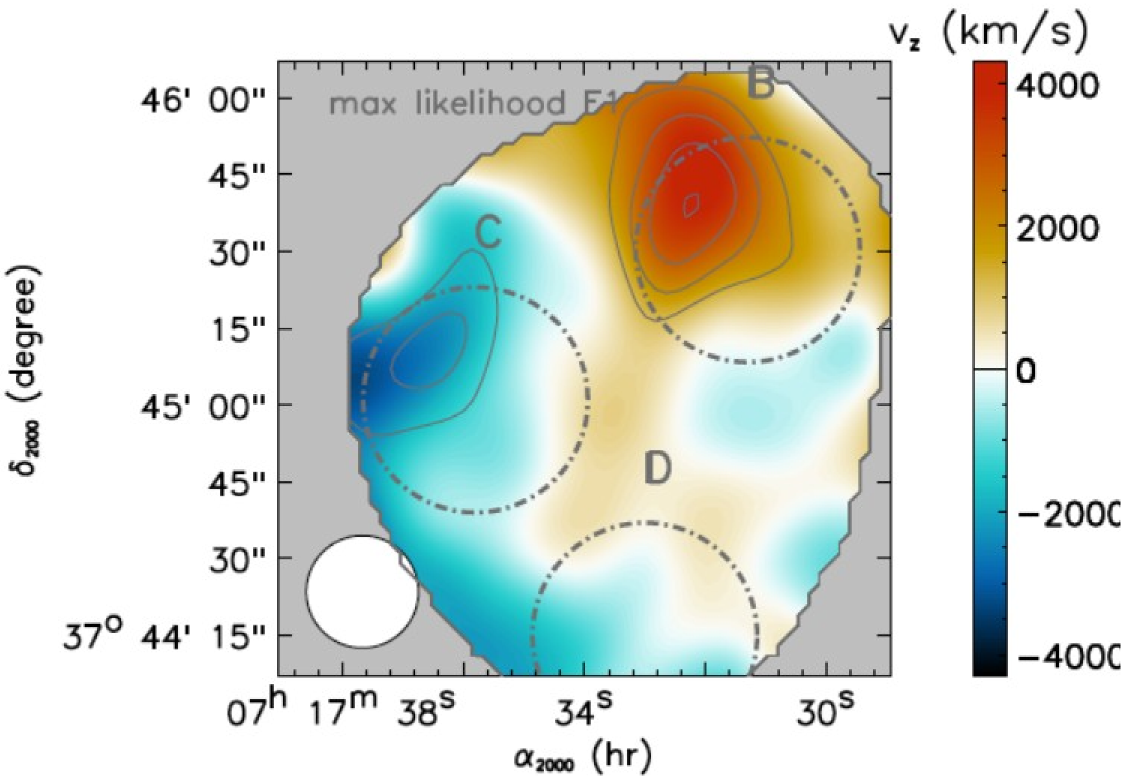
spectral dependencies

$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

gas pressure *gas velocity and density*

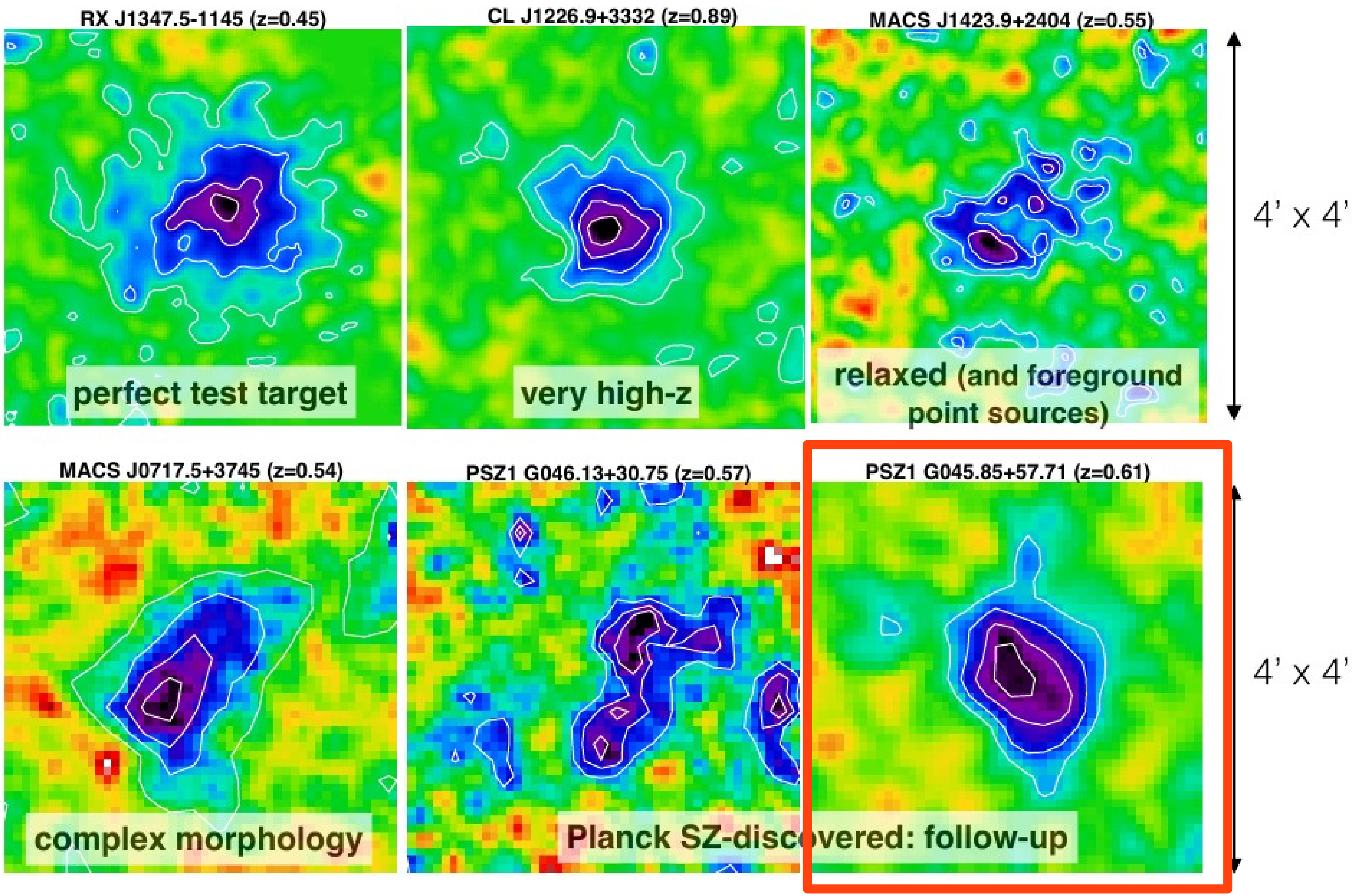
MACS J0717-3745 velocity map



First direct mapping of kSZ emission

[Adam & NIKA collaboration, 2016]

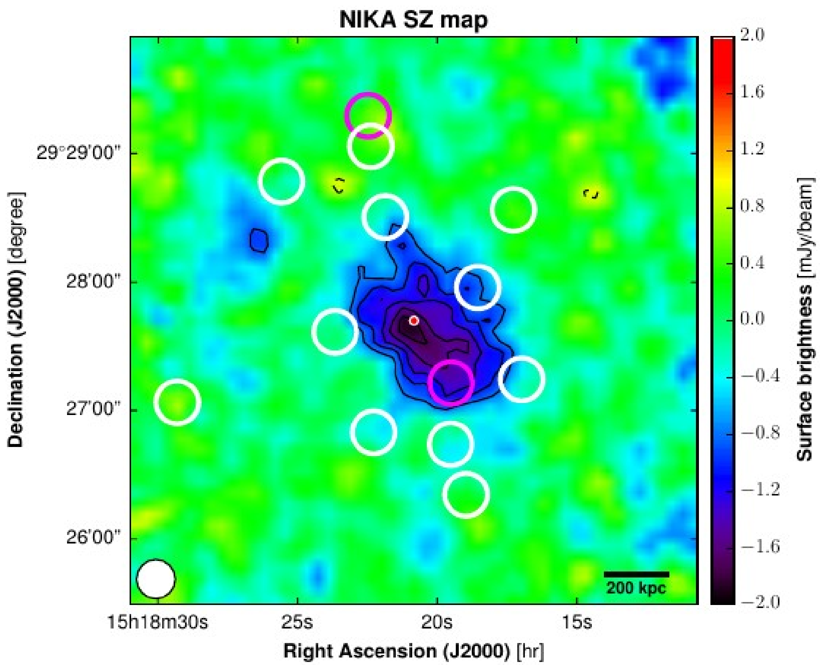
Follow-up of Planck clusters

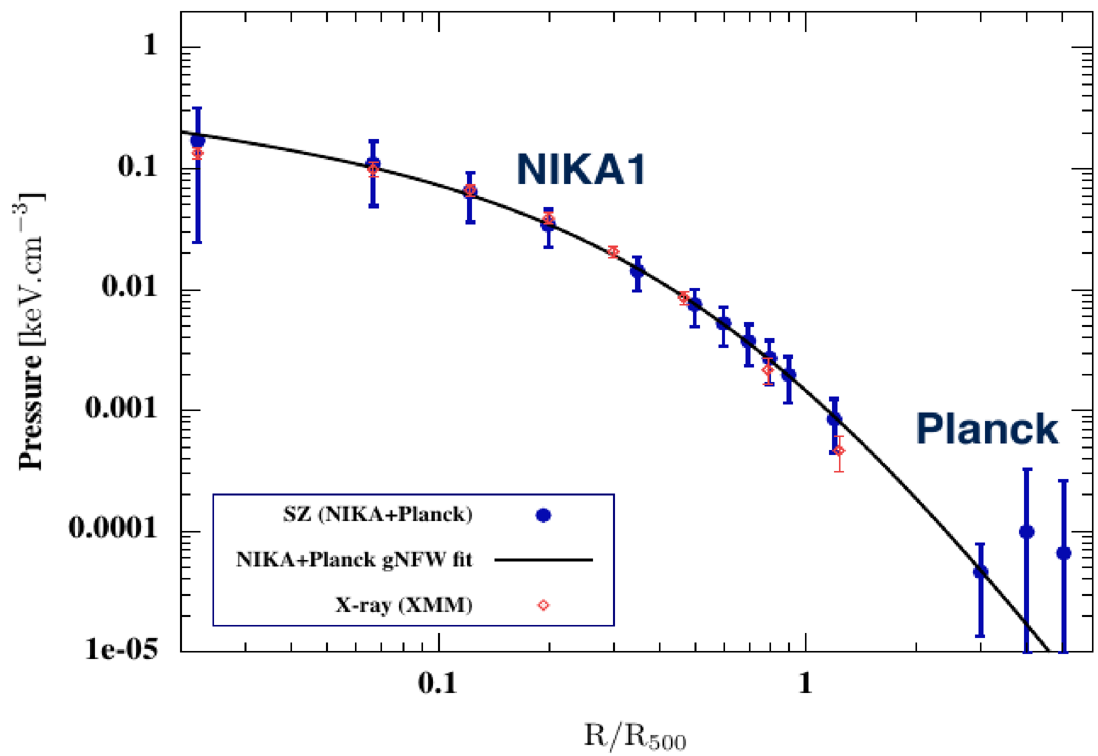


Follow-up of Planck clusters

PSZ1 G045.85+57.71

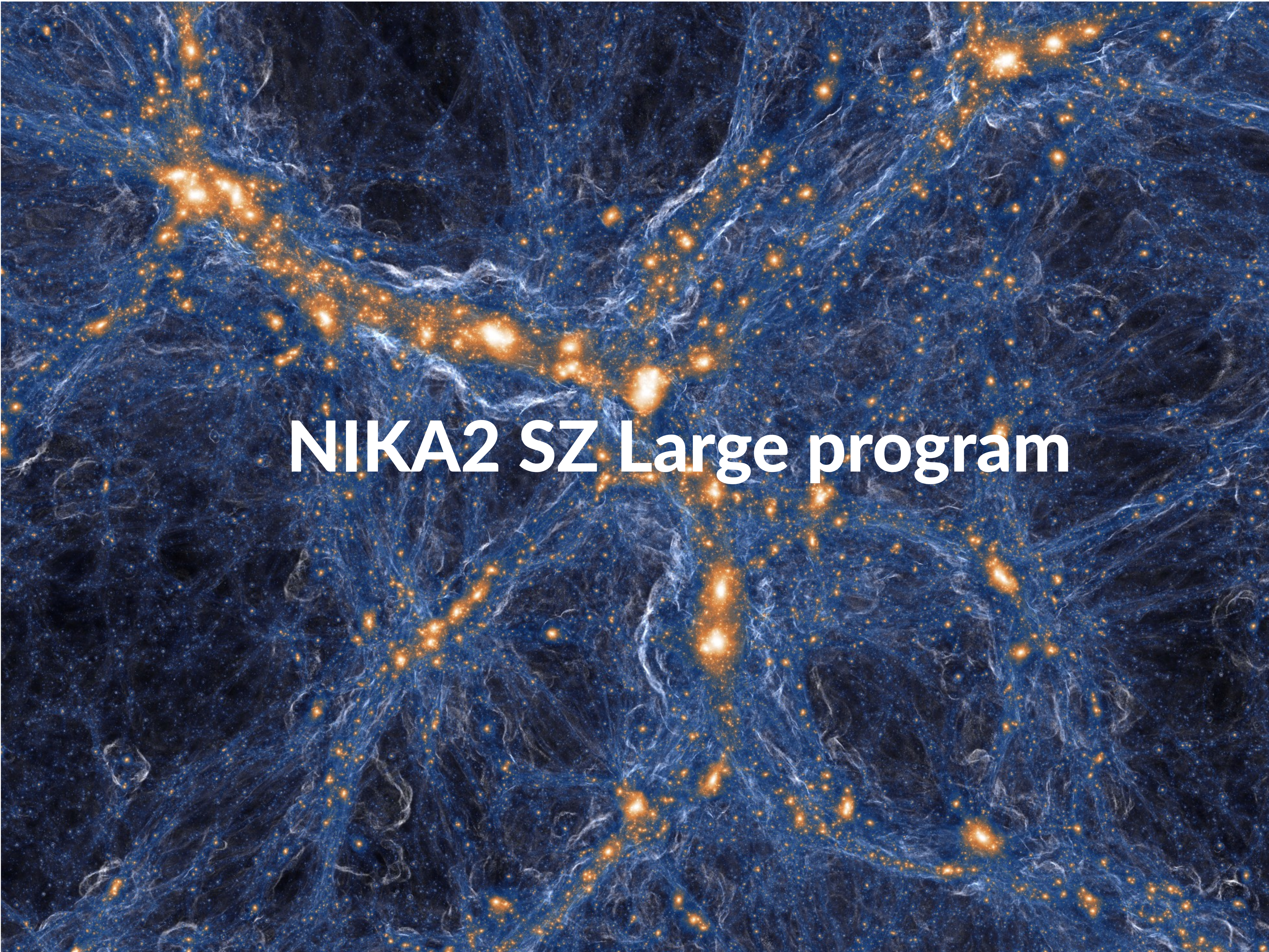
- Planck tSZ detected cluster at high redshift, z = 0.61
- 5h41m observations with NIKA1 in moderate weather conditions



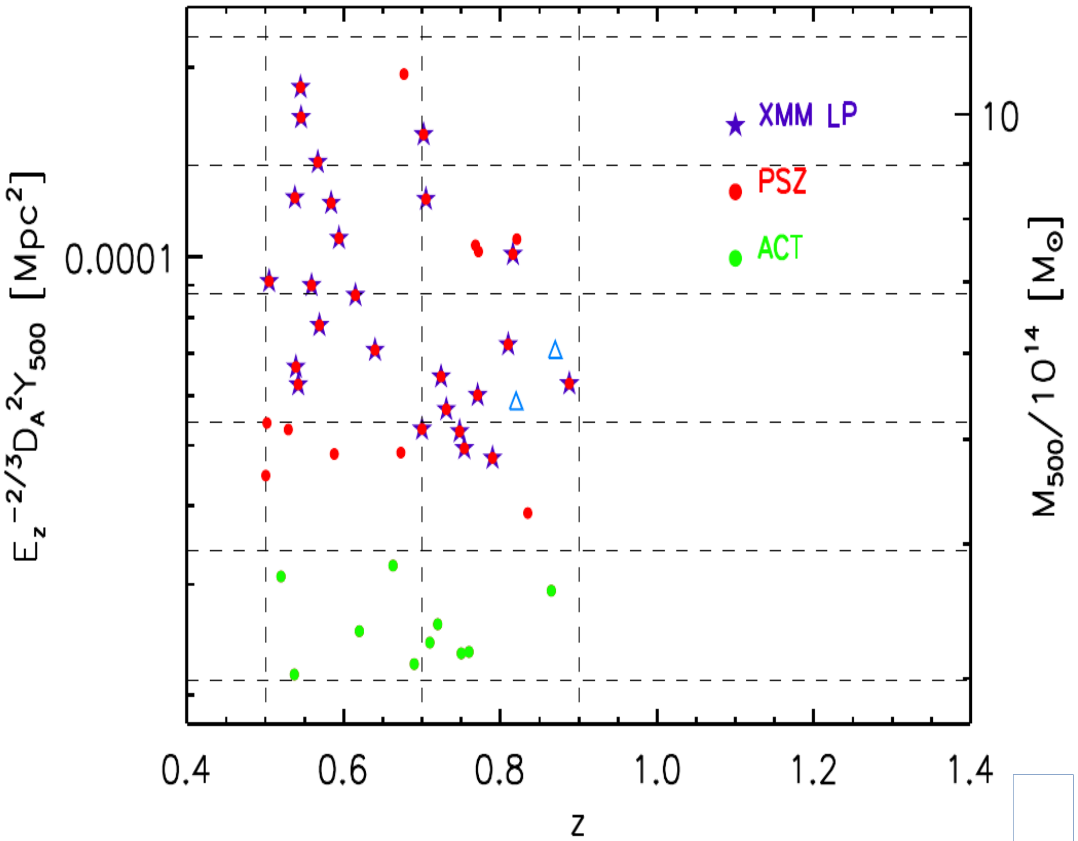


[Ruppin & NIKA collaboration, 2017]

First non-parametric reconstruction of the pressure profile for high redshift cluster


NIKA2 SZ Large program

NIKA2 SZ Large program



One of the 5 NIKA2 LP (1300h in total)

- **300 hours** of tSZ observation
- **50 high redshift clusters 0.5 < z < 1.0**
- tSZ selected clusters from Planck and ACT catalogues

Ancillary data

- X-ray follow-up with XMM
- Optical data using GranTeCan
- MUSIC hydrodynamic simulations

Main goals

- In-depth study of ICM
- Thermodynamic properties: pressure, density, temperature and entropy profiles
- Mass – tSZ flux relationship

Redshift evolution of:

- Thermodynamic quantities profiles
- Scaling laws and hydrostatic bias

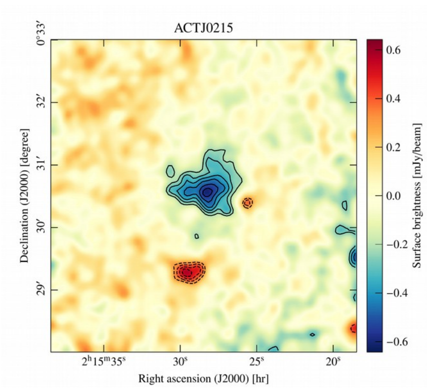
Variation of cluster properties with:

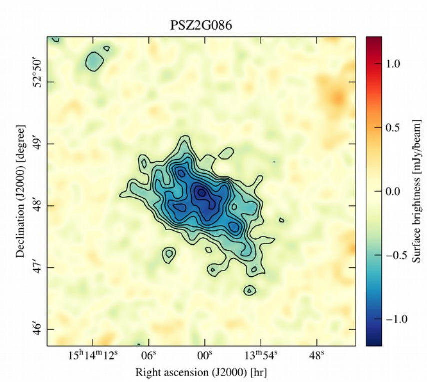
- Dynamical state (mergers)
- Morphology (ellipticity)

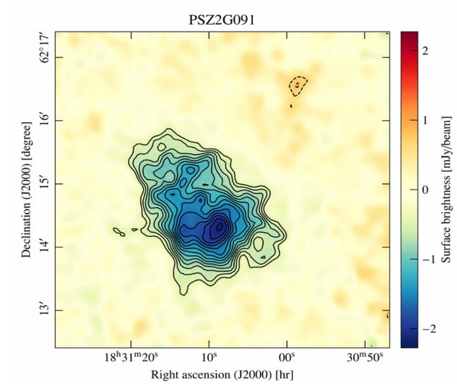
[Comis, 2016]

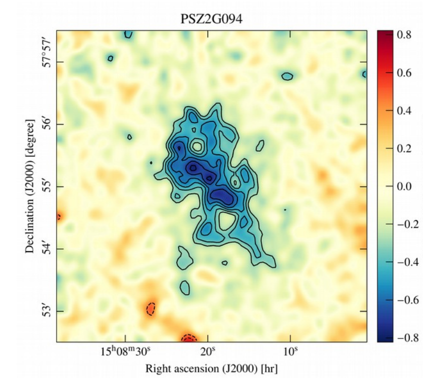
[JFMP & NIKA2 collaboration 2017, arXiv:171107088]

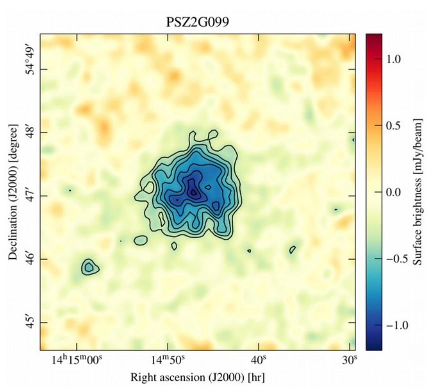
Observed NIKA2 LP clusters

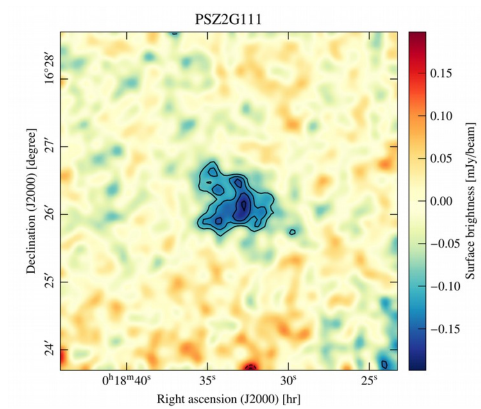


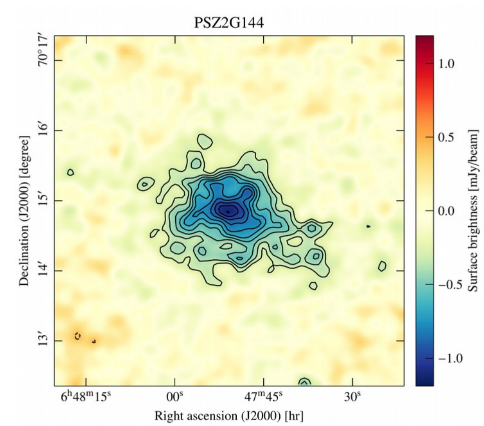


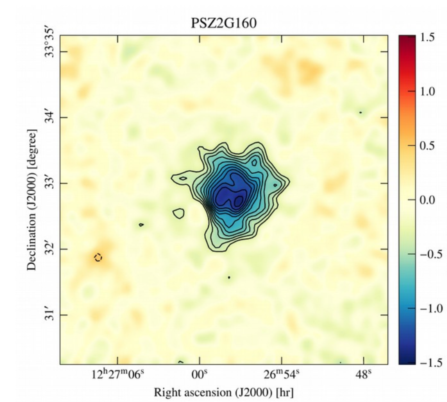


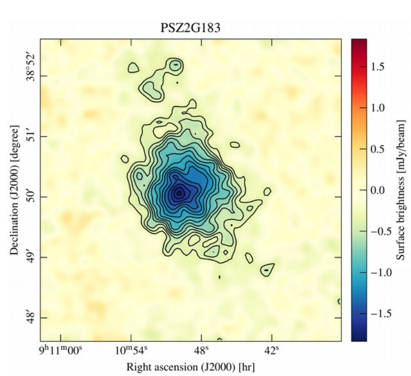




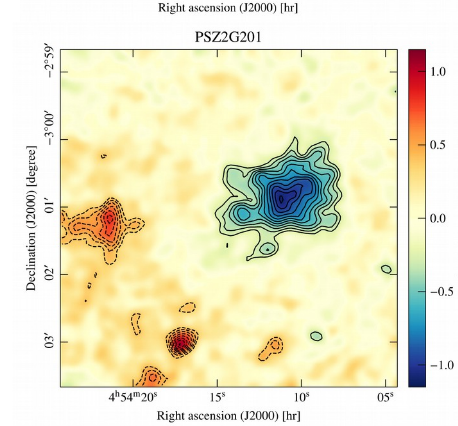








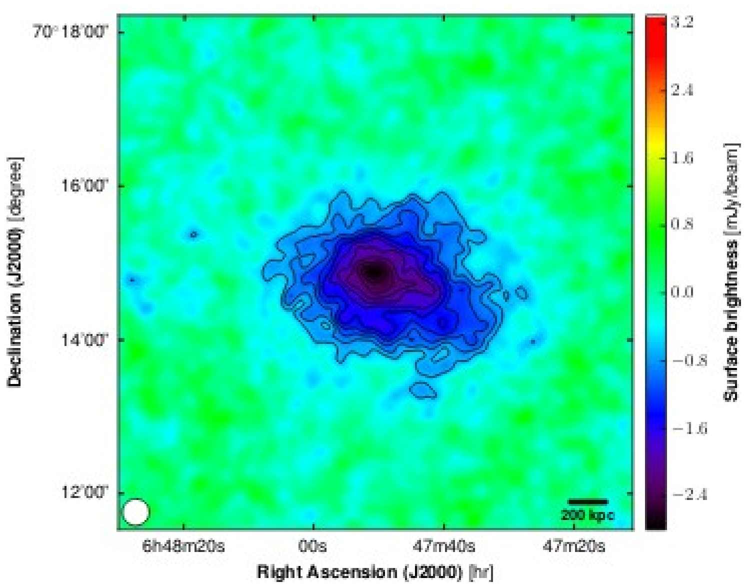
More than 20 clusters observed, very promising results, detailed analysis on going

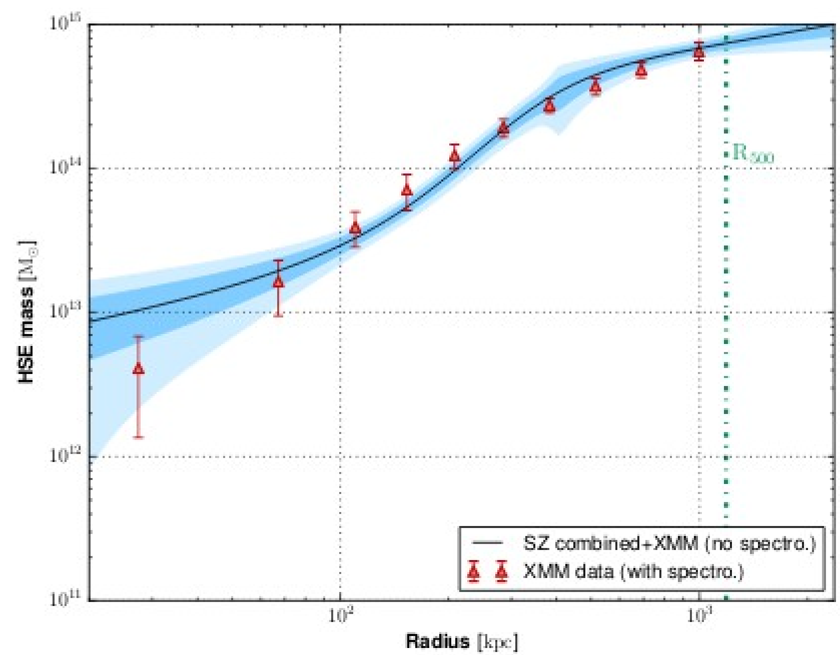


Mass measurements with NIKA2

PSZ2 G144 [Ruppin et al, AA, 2018]

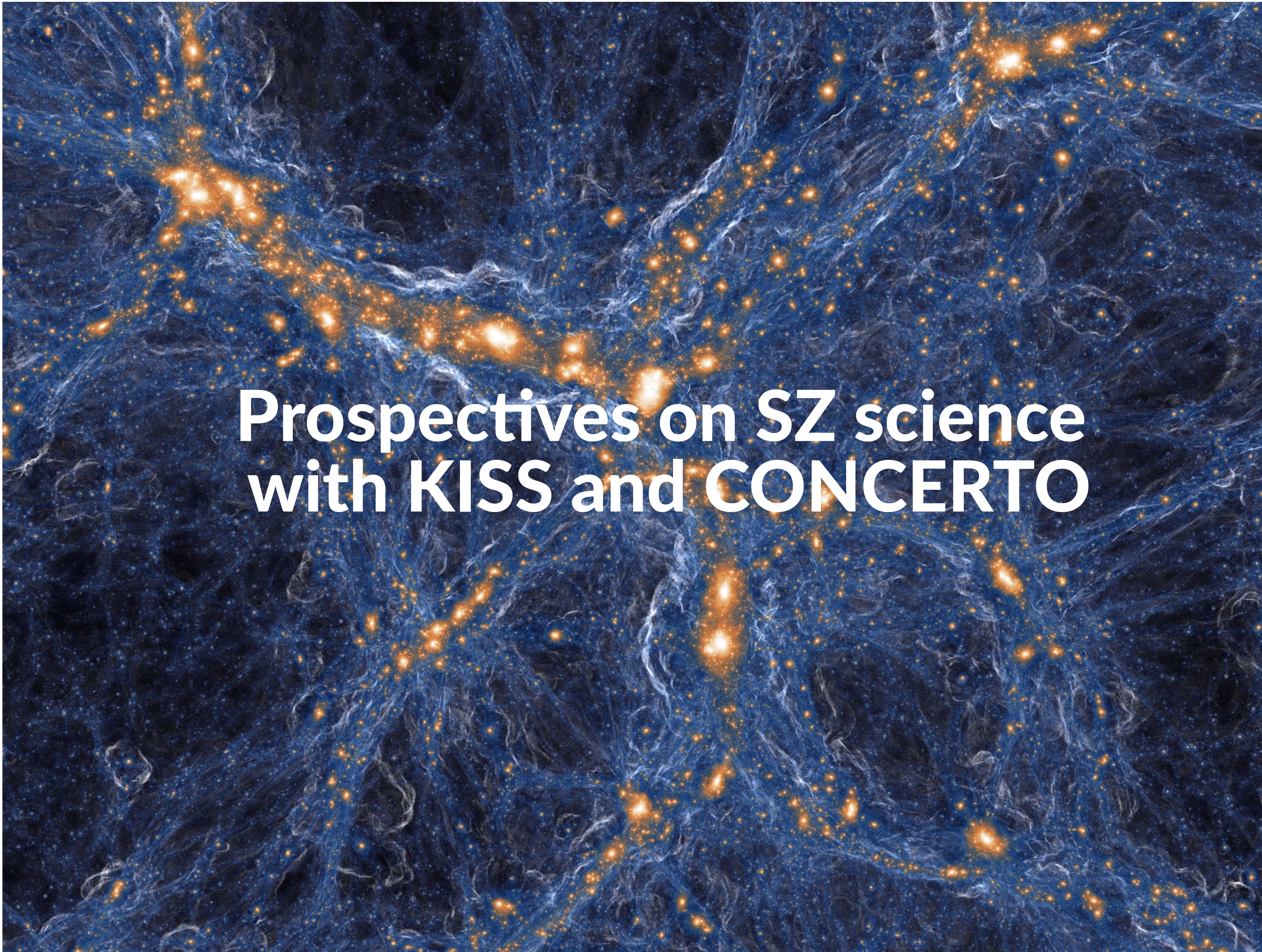
- Planck tSZ detected cluster at redshift, z = 0.58, high mass $M_{500} = 7.8 \times 10^{14}\ M_{\odot}$
- 11h observations with NIKA2 in poor weather conditions (atmospheric opacity 0.3@225 GHz)
- Already observed: SZ – MUSTANG & Bolocam, X-rays - XMM



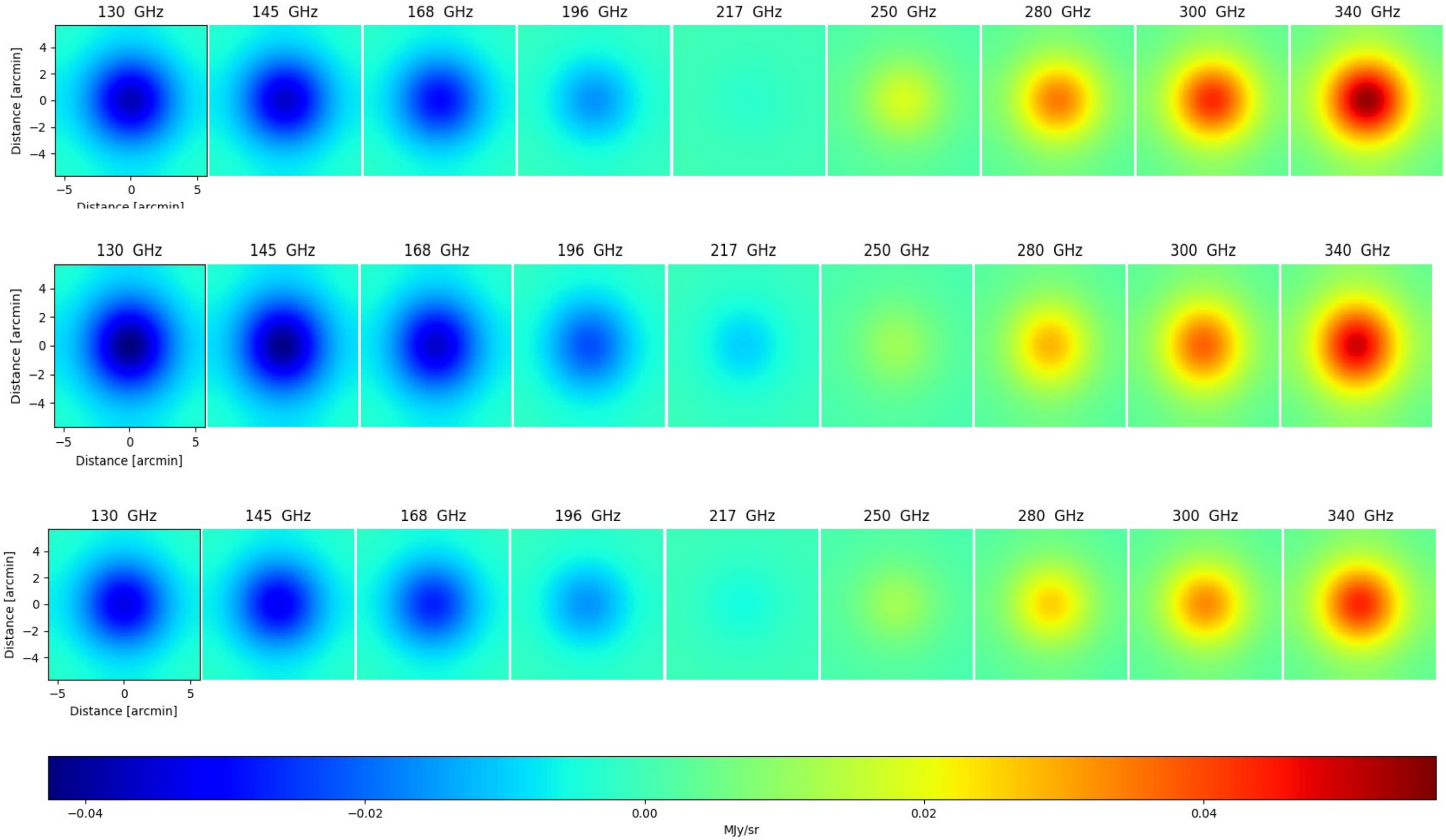


Detailed characterization of the cluster pressure profile – overpressure found
Hints of dependence of the hydrostatic mass bias with cluster physics

Prospectives on SZ science with KISS and CONCERTO



Spectral imaging SZ science



tSZ

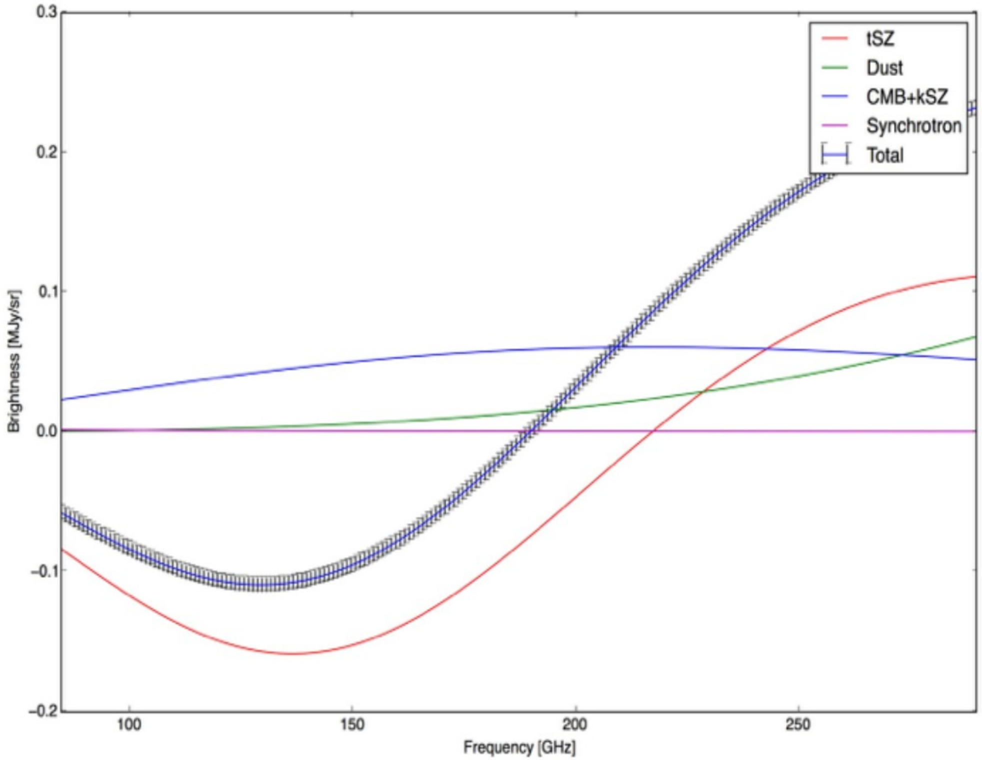
tSZ + kSZ

tSZ + rSZ

Direct mapping of cluster pressure, temperature and velocity distributions via the tSZ, kSZ and relativistic corrections

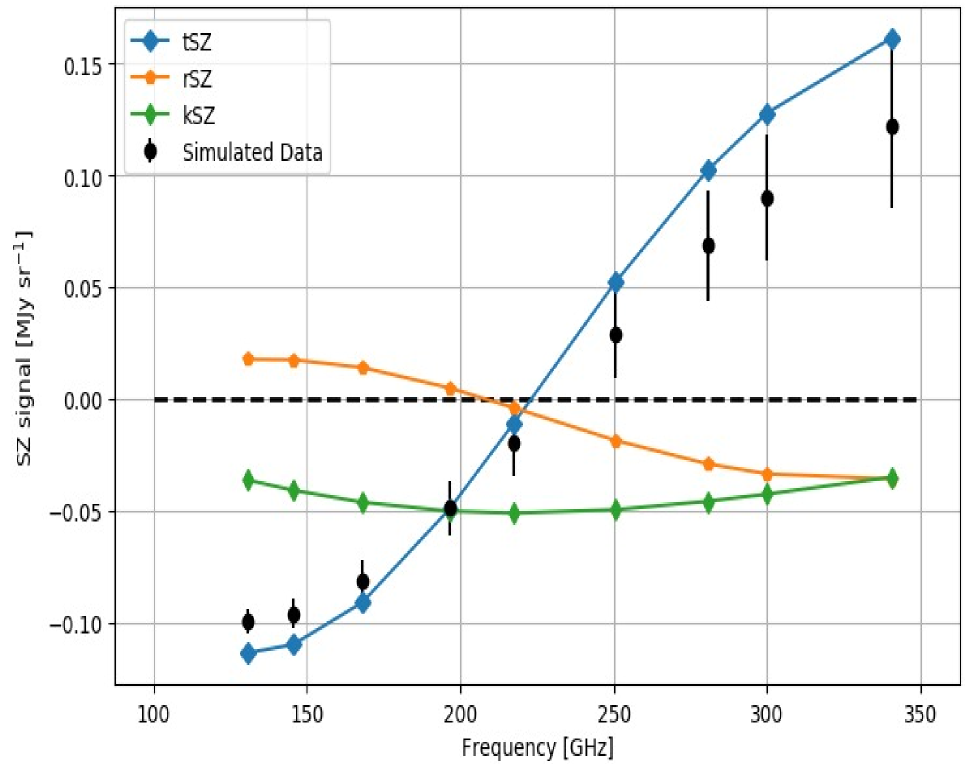
KISS and CONCERTO SZ performance

KISS



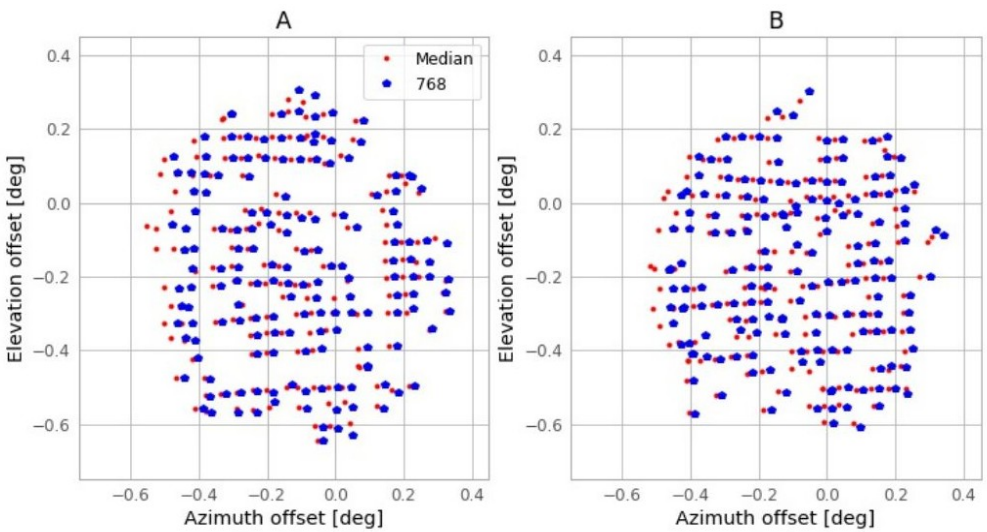
About 30 hours of observations for a Coma like cluster

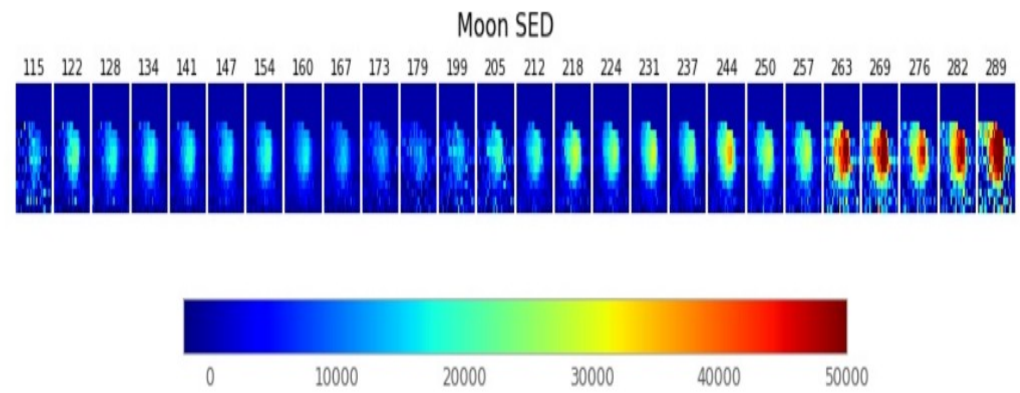
Concerto

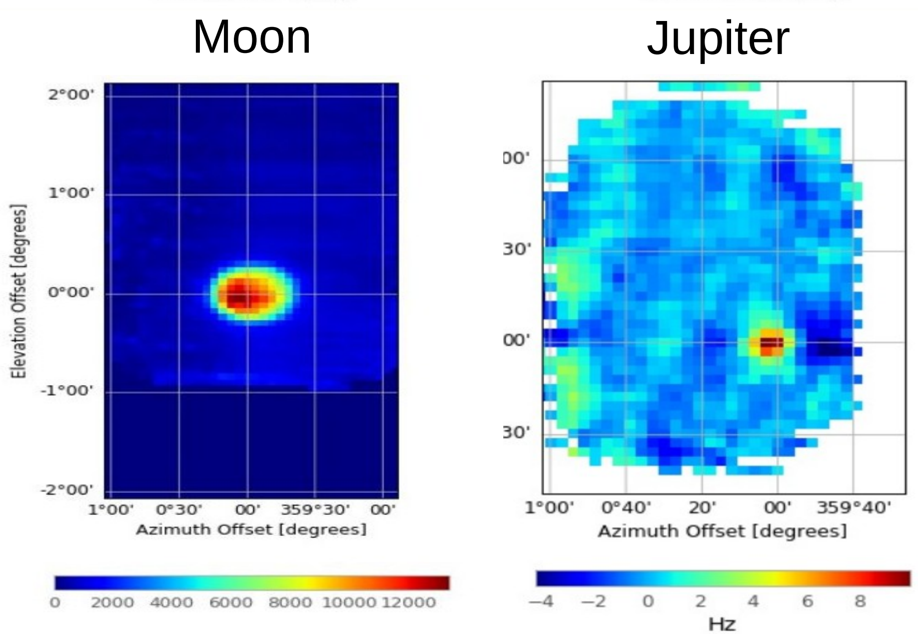


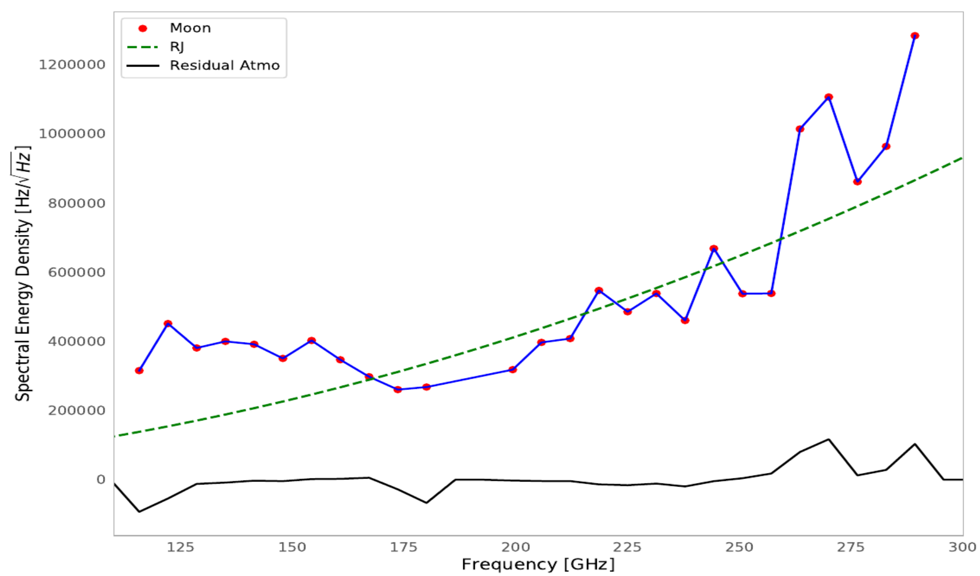
About 20 hours of observations for a z=0.5 clusters of mass 10^{15} $M_{\odot}$

KISS first light









Conclusions

- Current science drivers in mm astronomy and cosmology needs high sensitivity and wide-field multi-color observations with large arrays of detectors
- KIDs have achieved sufficient technical maturity to be a credible option to build those large arrays (tens of thousands pixels) of photon noise limited detectors
- Cluster physics and cosmology via the SZ effect are a target of choice for KID cameras
- NIKA first, and now NIKA2, have demonstrated that KID based mm cameras can achieve state-of-art performance for SZ science
- A new generation ground-based mm spectrometers are possible thanks to KIDs technology: KISS already installed and CONCERTO should come soon
- KID activities in Grenoble are now organized in a GIS (Groupement d'Intérêt Scientifique) to try to tackle new challenges in CMB science

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

NIKA http://ipag.osug.fr/nika2

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LAM Laboratoire d'Astrophysique de Marseille

Lagache Guilaine

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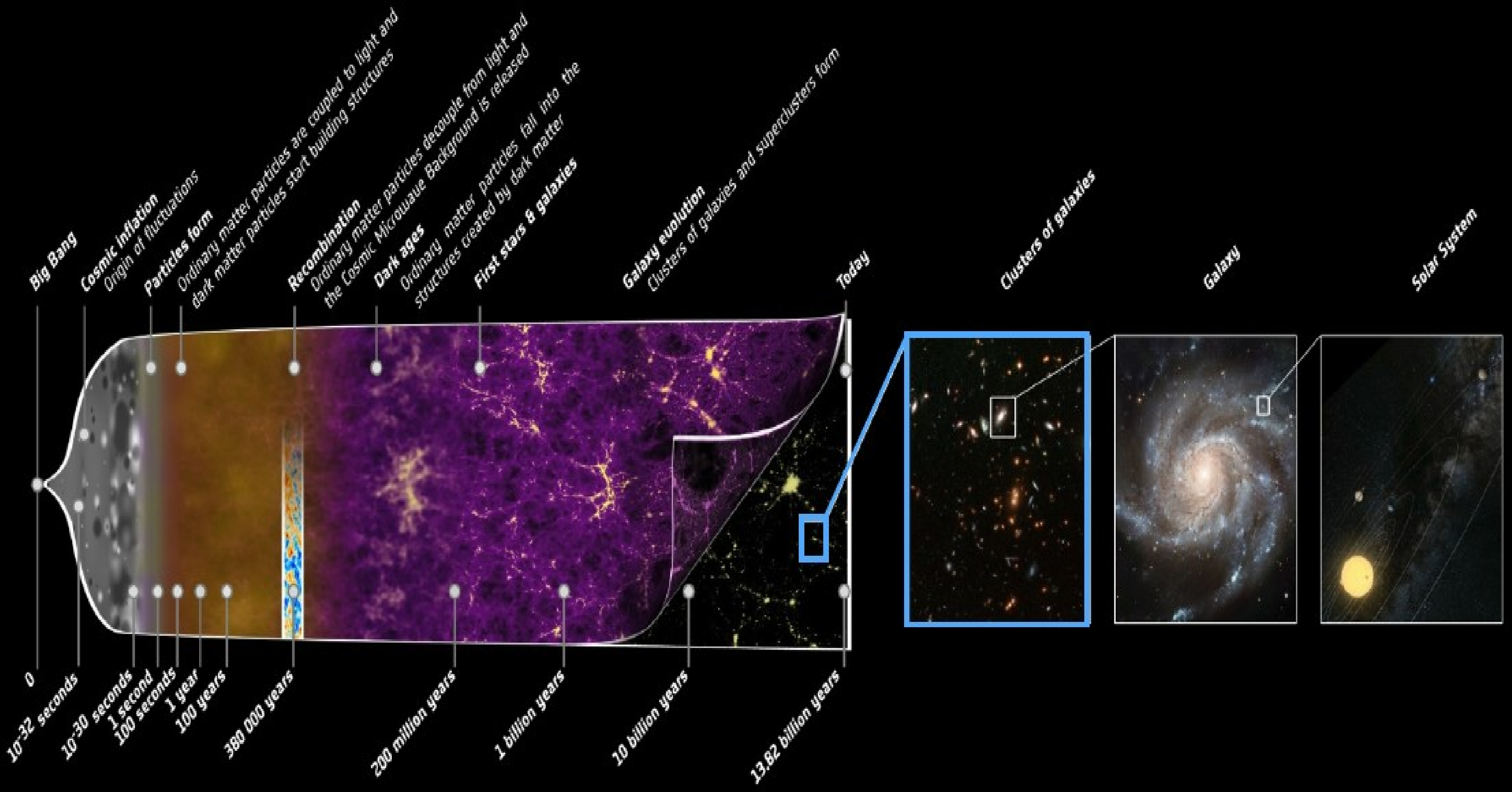
Brief history of the Universe



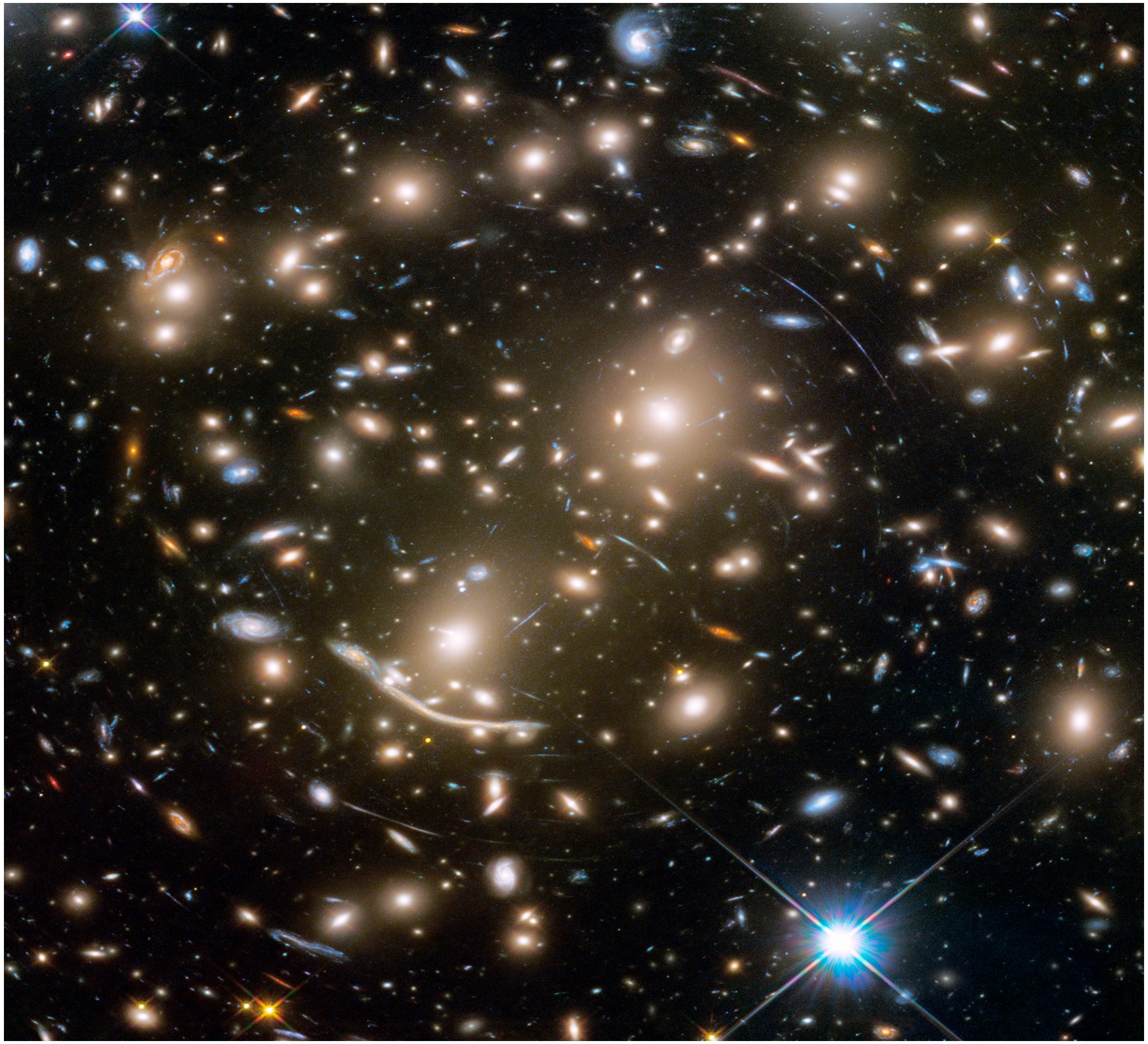
Visible & Infrared

Visible and IR emission

Light from stars in galaxies

Mass:

- Richness (~ number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing



Abell 370 with HST

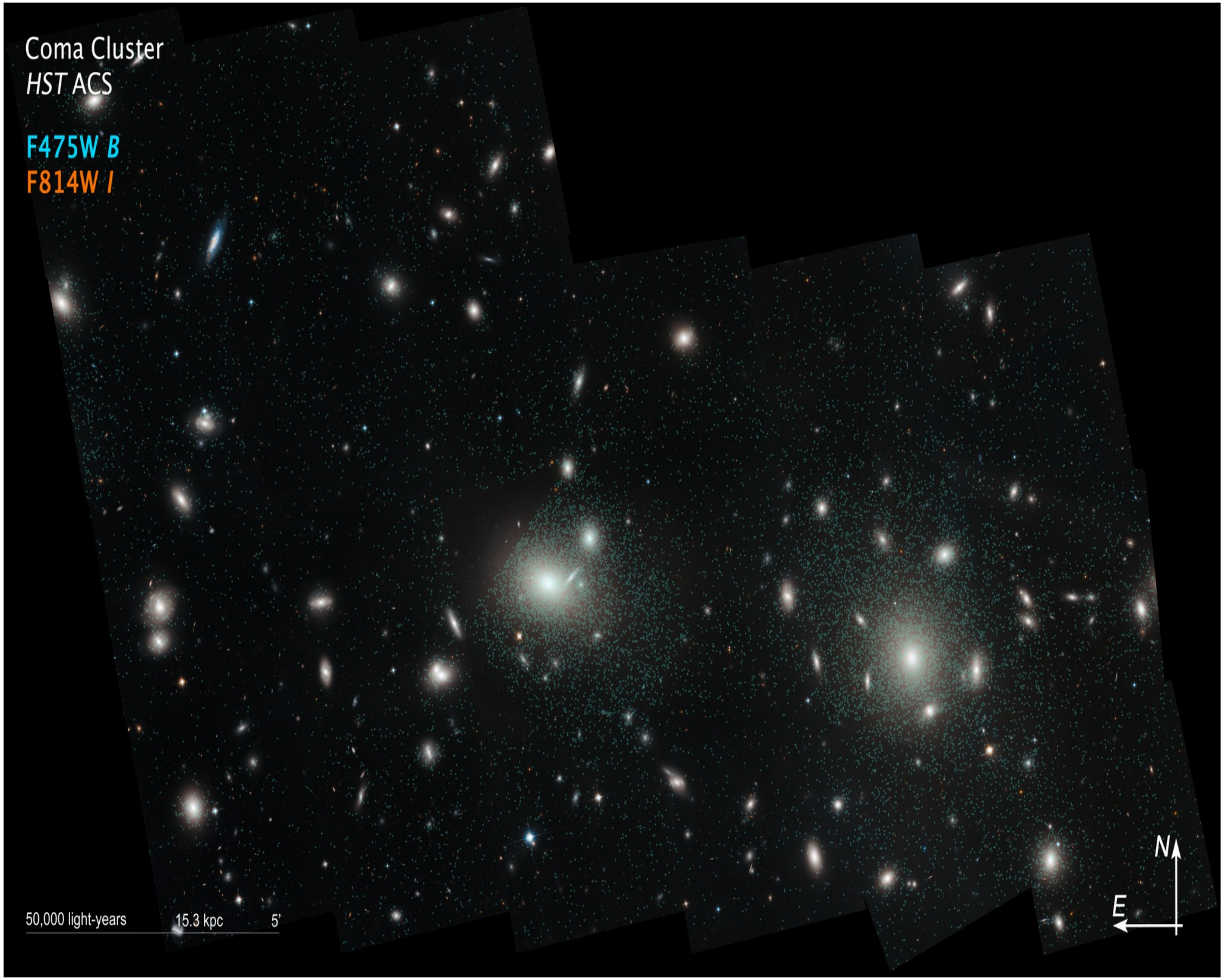
Visible & Infrared

Visible and IR emission

Light from stars in galaxies

Mass:

- Richness (number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing



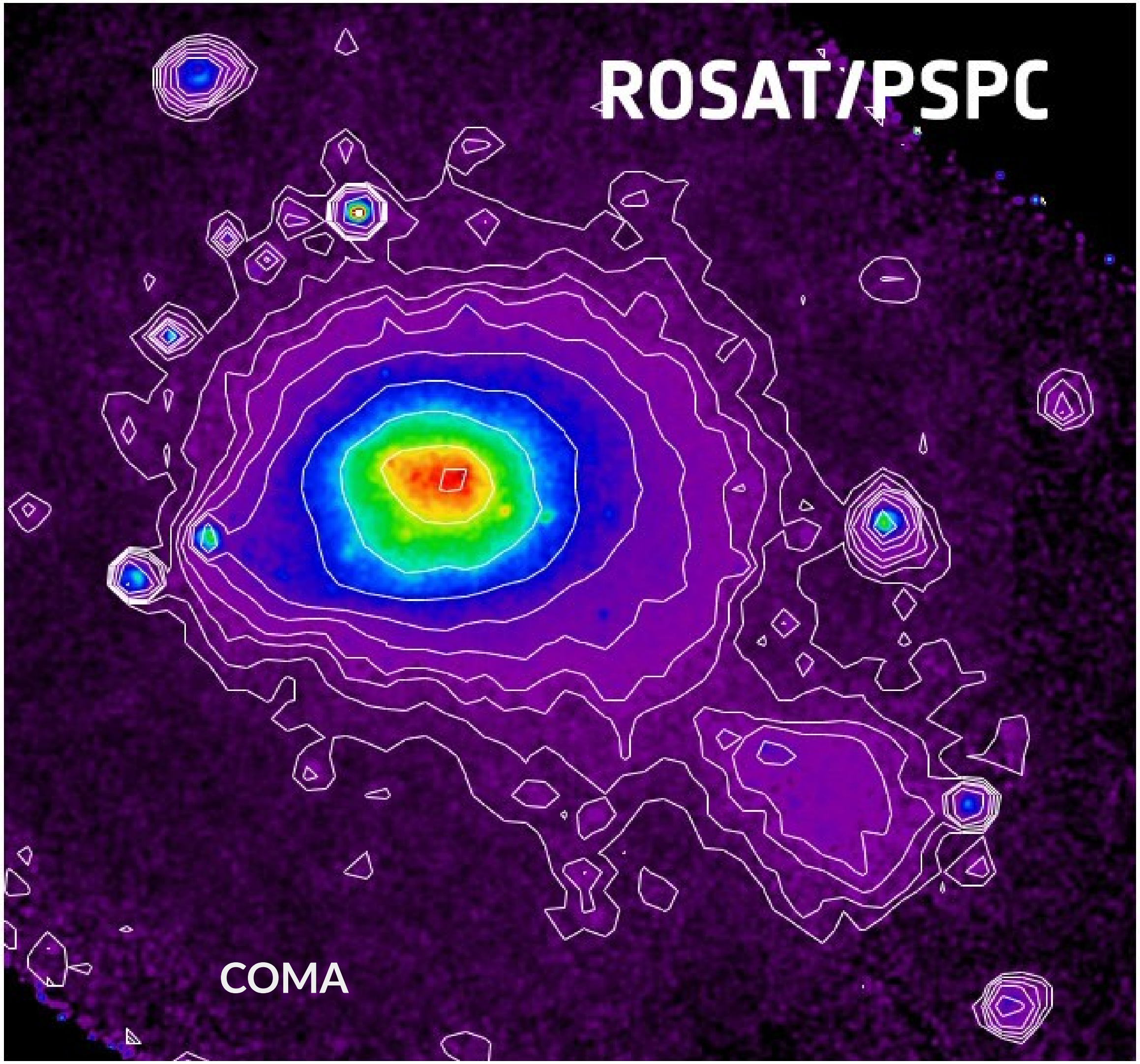
X-rays

X-ray emission

Free-free emission from free electrons in the Intra Cluster Medium (ICM)

Density, temperature, entropy, mass:

- surface brightness
- spectroscopy



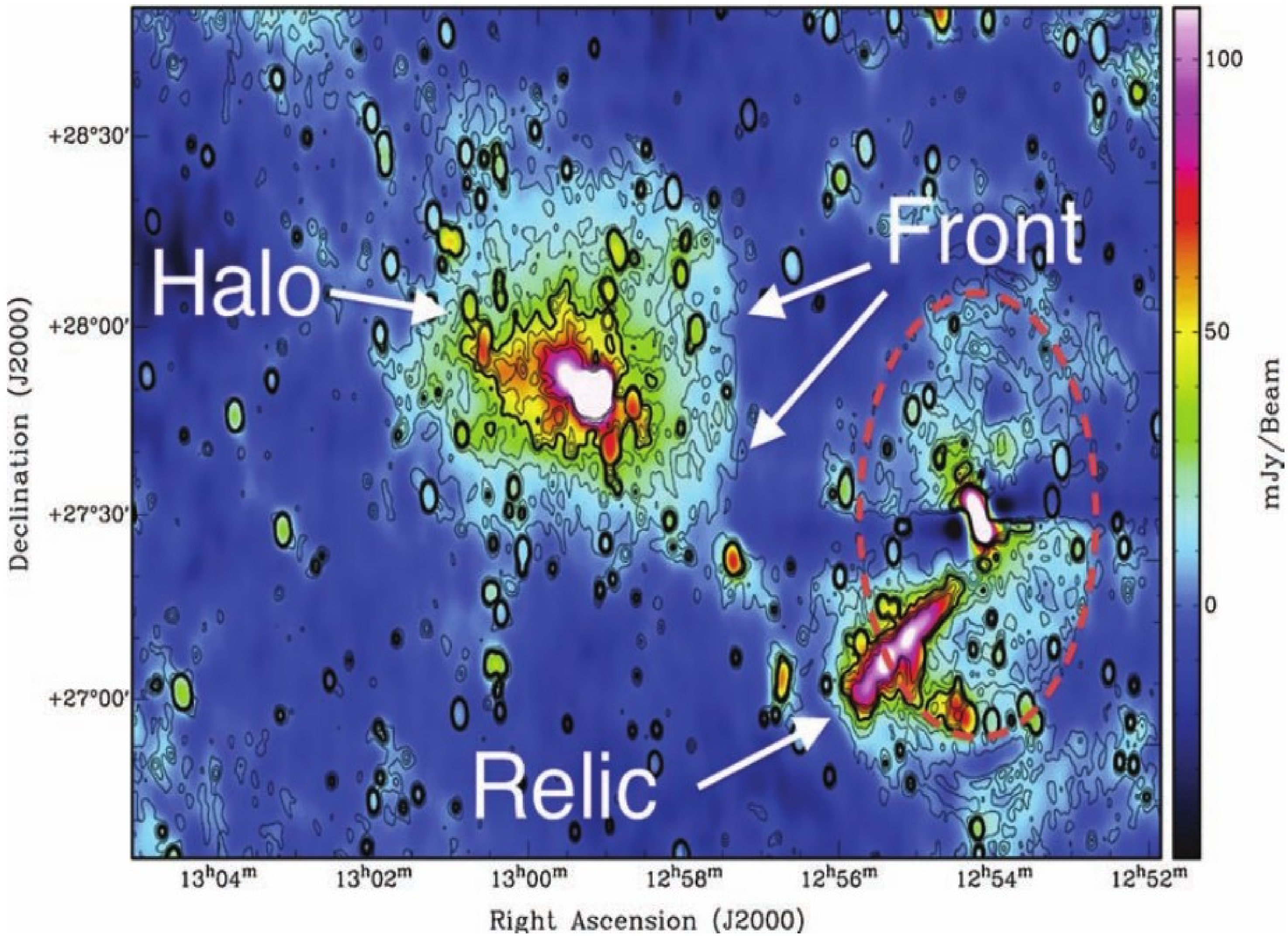
Radio emission

Radio emission

Non thermal emission from accelerated particles

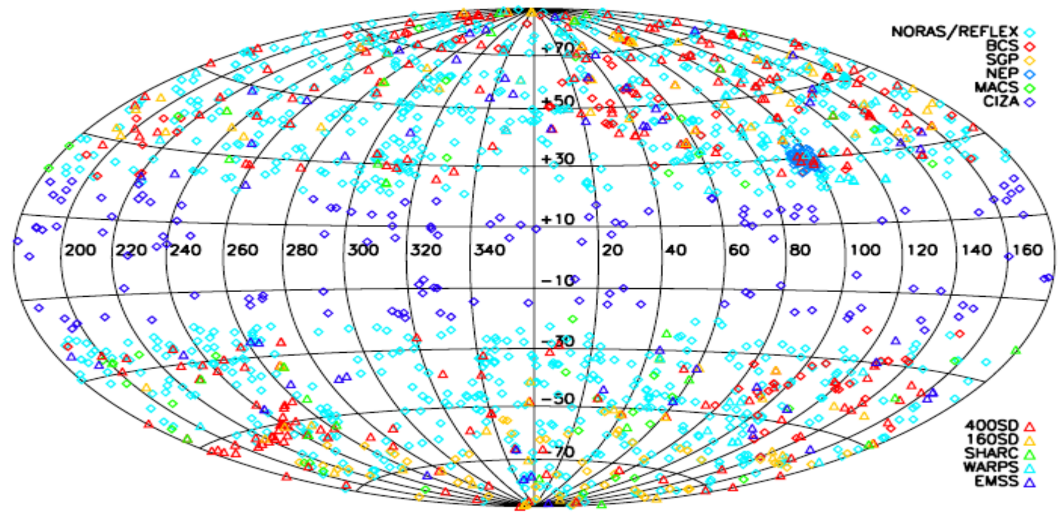
Shocks:

- Surface brightness



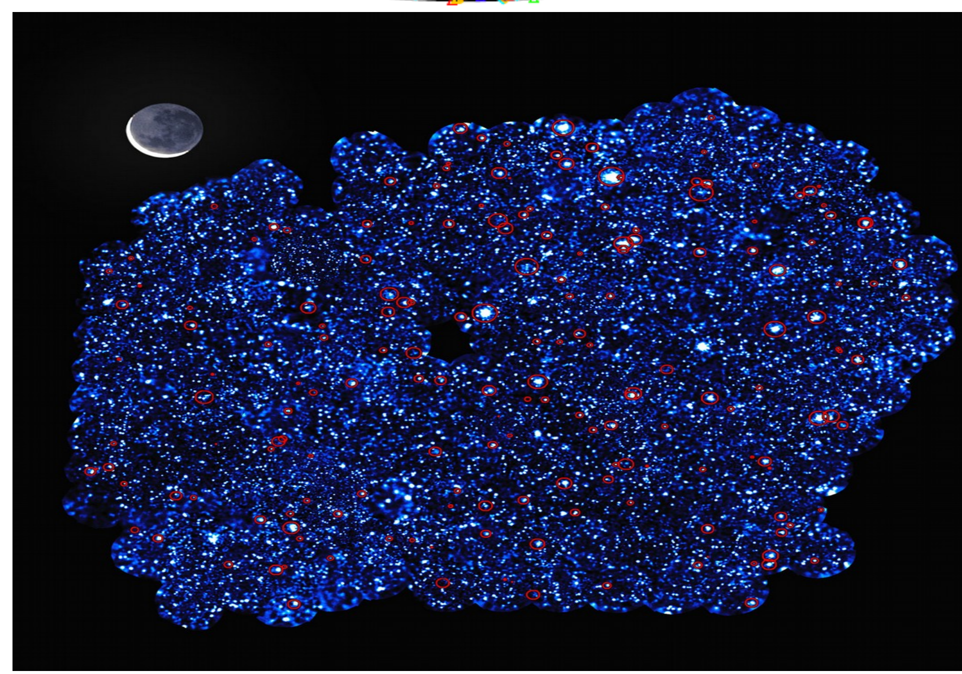
X-ray catalogues

MCXC (Metacatalogue of CG): 1743 clusters from ROSAT All-sky survey public data + serendipitous catalogues, Piffaretti+2011

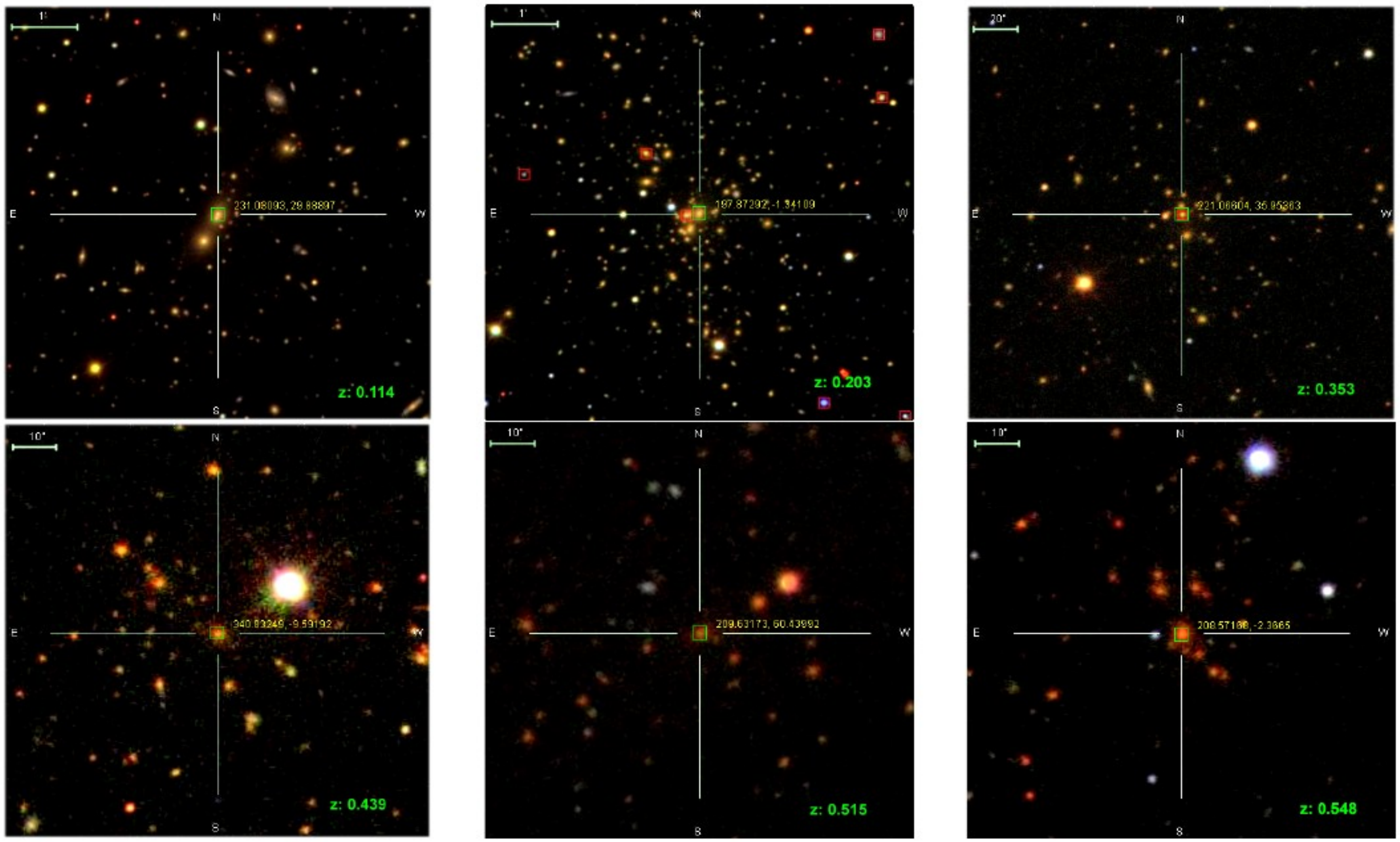


X-CLASS: few hundreds of clusters from serendipitous observations with XMM, Sabidekova+ 2014

XXL survey: 365 clusters from a 50° survey with XMM, Adami+2018



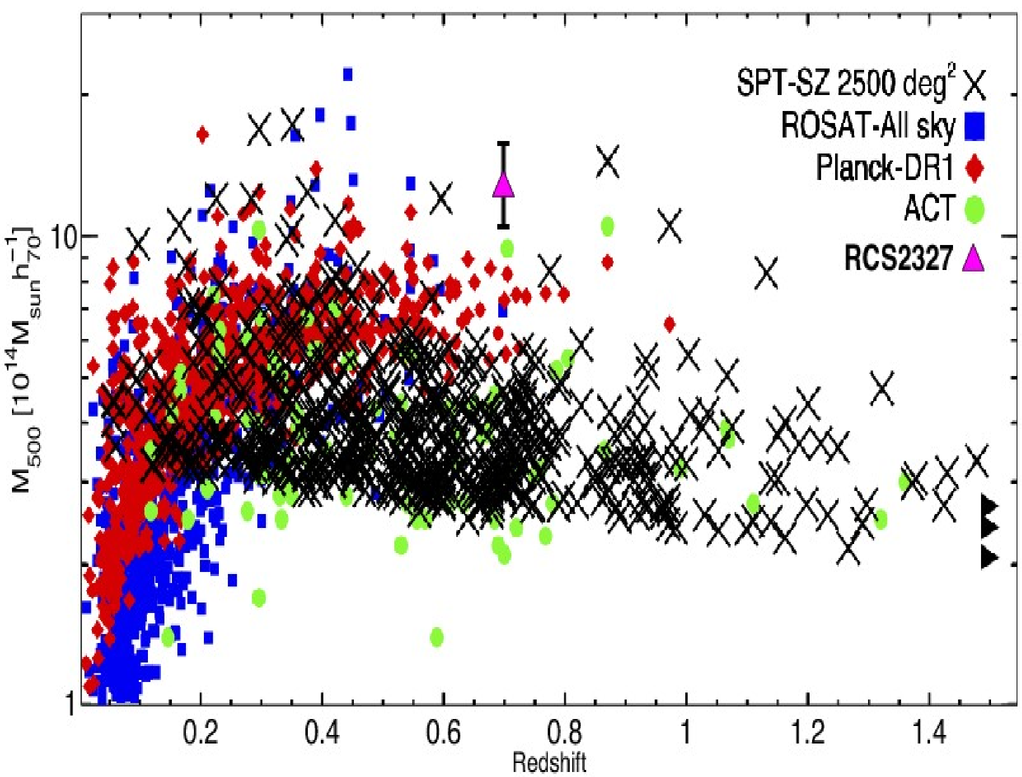
Infrared and optical catalogues



MAXBCG: 13823 clusters from Sloan Digital Sky Survey (SDSS), Koester+2007
GMBCG: extension of MAXBCG to redshift beyond 0.3, Hao+2010
RedMaPPer: 26000 clusters from SDSS DR8, z {0.08-0.5}, Rykoff+2014,2016
786 clusters from Dark Energy Survey (DES) SV, Rykoff+2016

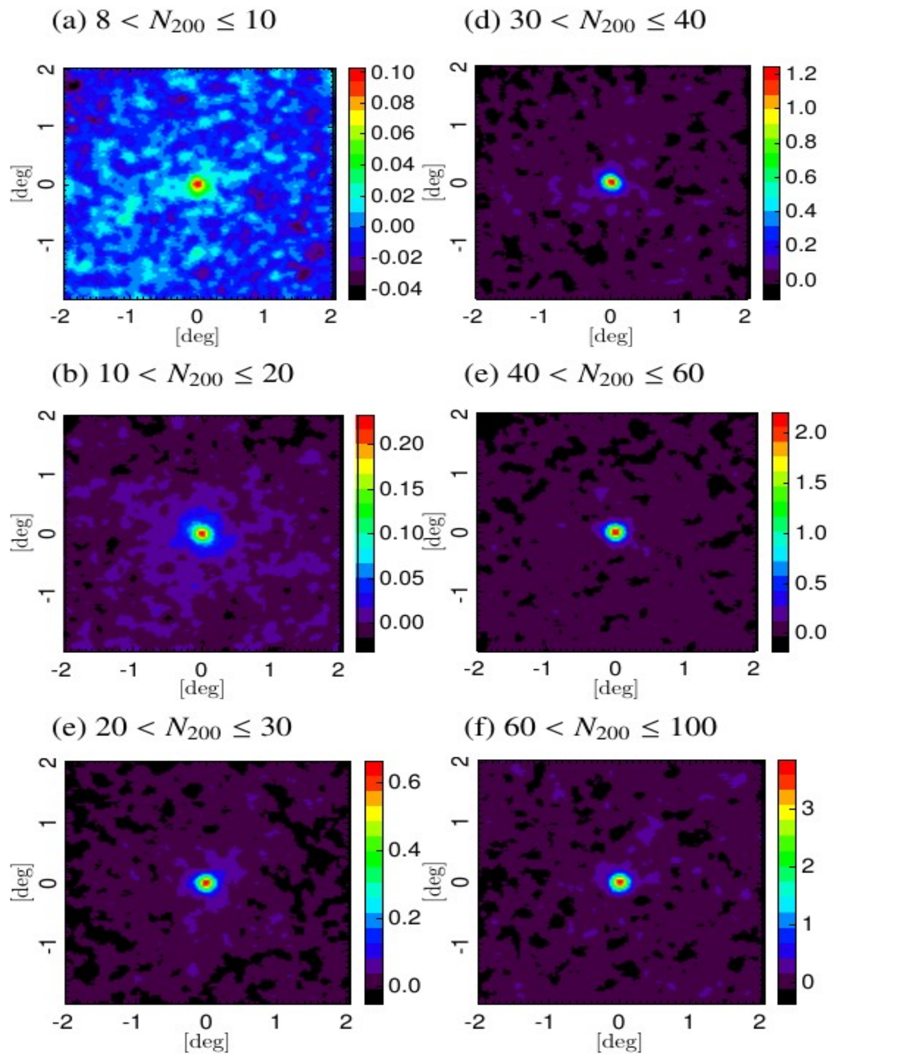
Multi-wavelength comparisons

Xray vs SZ



Planck 2015 results XXII
Wen +2011

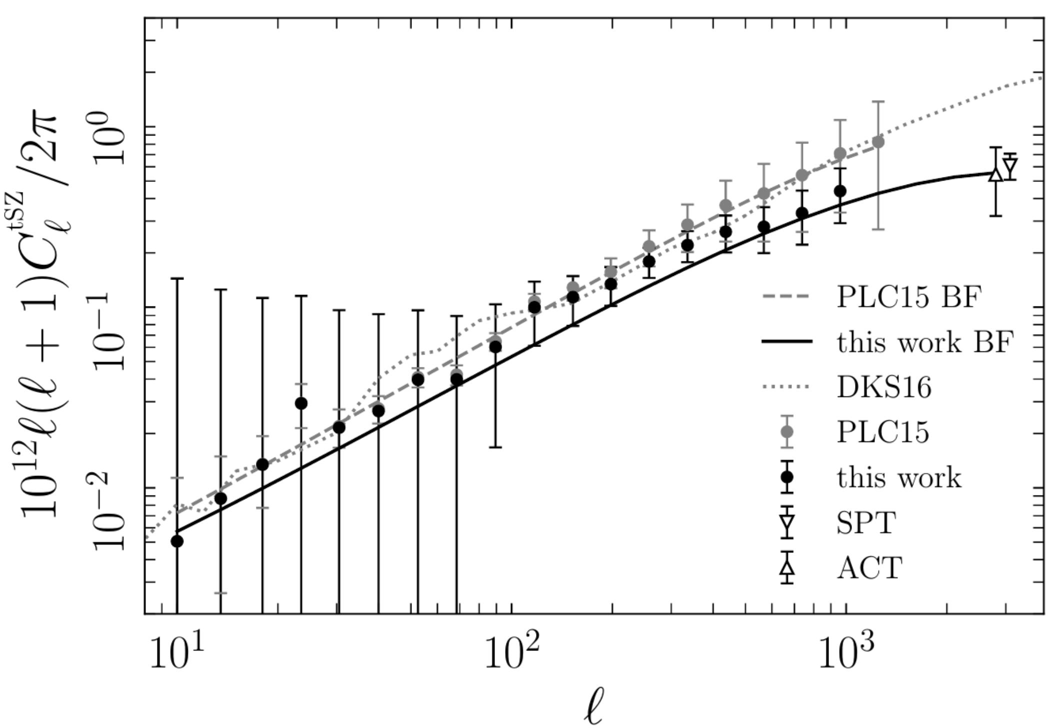
SDSS8 vs Planck SZ

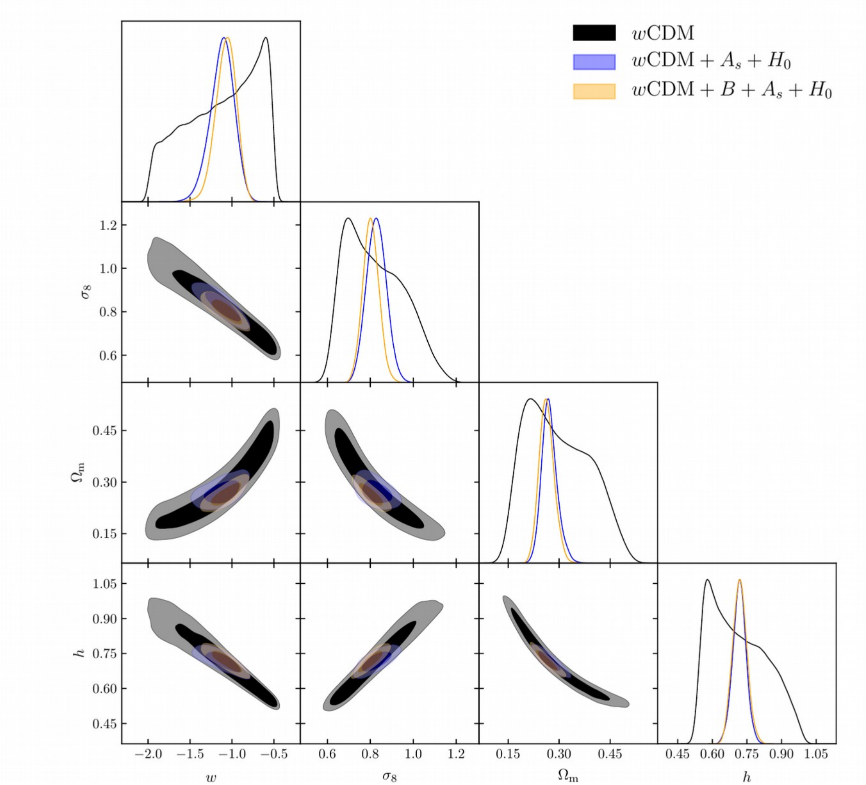


Planck tSZ cluster cosmology II: recent updates

- Considering non-Gaussian uncertainties: trispectrum
- Testing different mass functions
- Revisiting mass computation
- Going beyond mass bias parameter
- Exploring other cosmological parameters as **dark energy equation of state**

[Bocquet, Saro, Dolag & Mohr 2016, Horowitz & Seljak 2017, Hurier & Lacasa 2017, Bolliet, Comis, Komatsu & JFMP 2017]



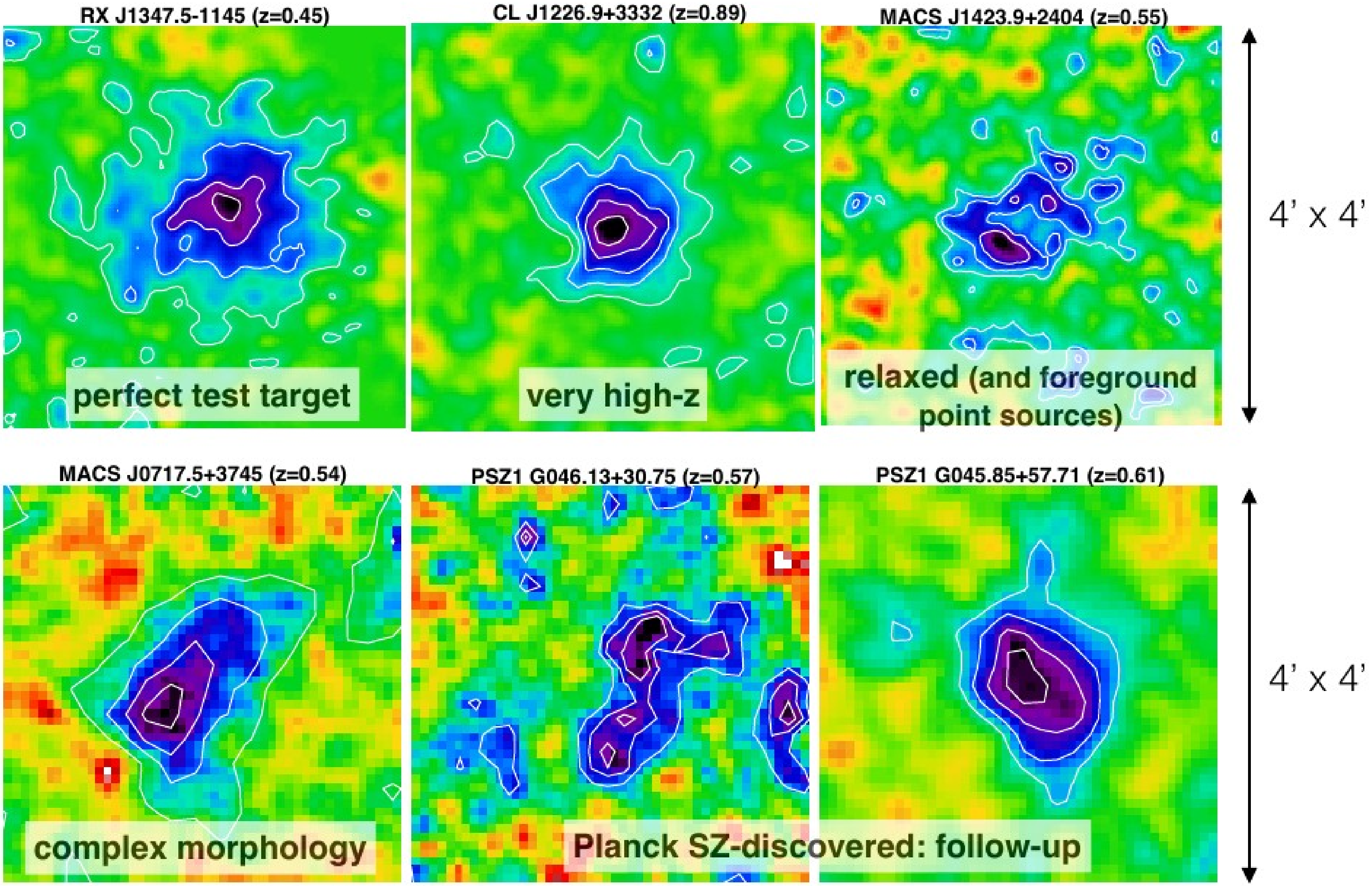


New tSZ power spectrum computation code integrated with CLASS

[Bolliet, Comis, Komatsu & JFMP 2017, arXiv:1712.00788]

w = −1.15 ± 0.15 (68% CL) for 1.11 < B < 1.67
w = −1.10 ± 0.12 (68% CL) for B = 1.25

NIKA SZ pilot sample

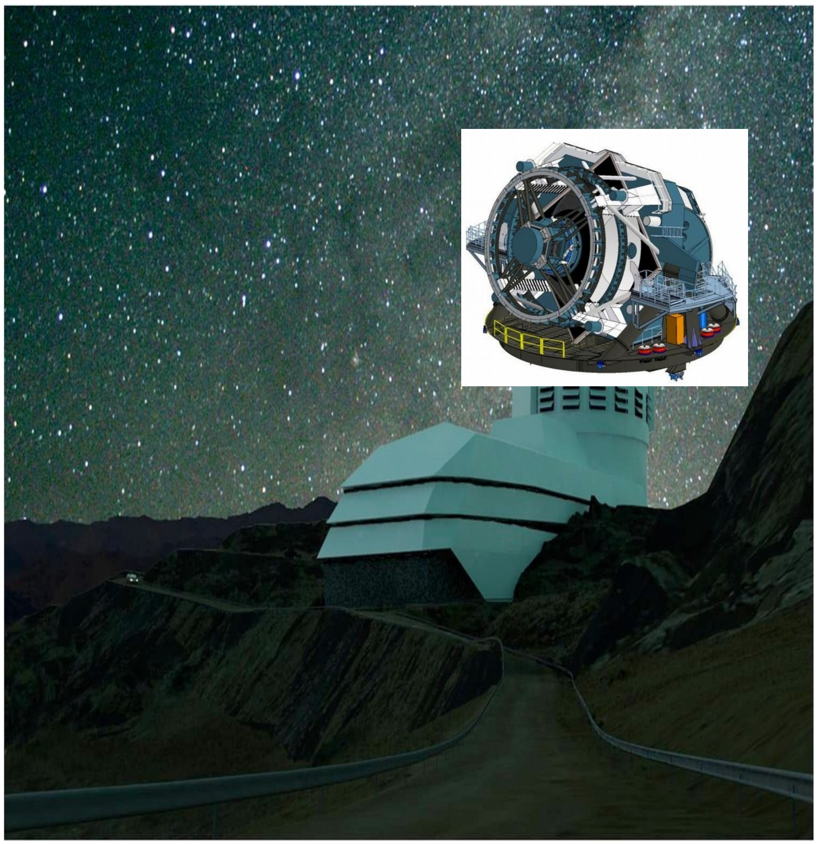


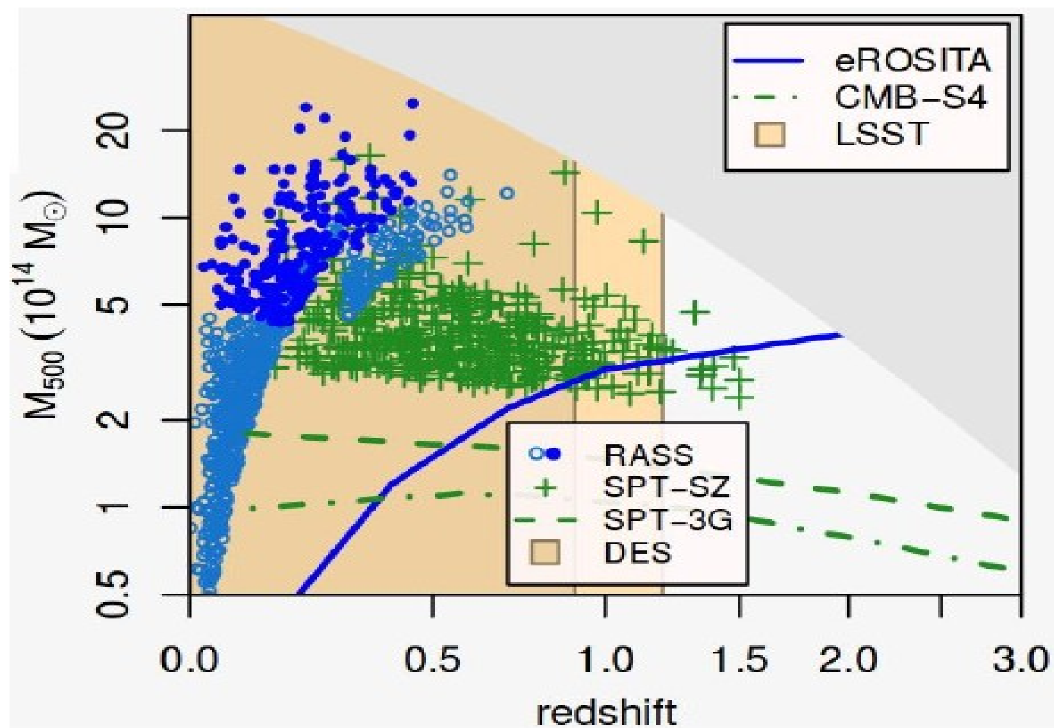
LSST

First lights 2019
Survey from 2022 to 2032

Deep survey of 18 000 deg²

Accurate photometric redshift with 6 bands (ugrizy)





www.lsst.org/lsst/scibook

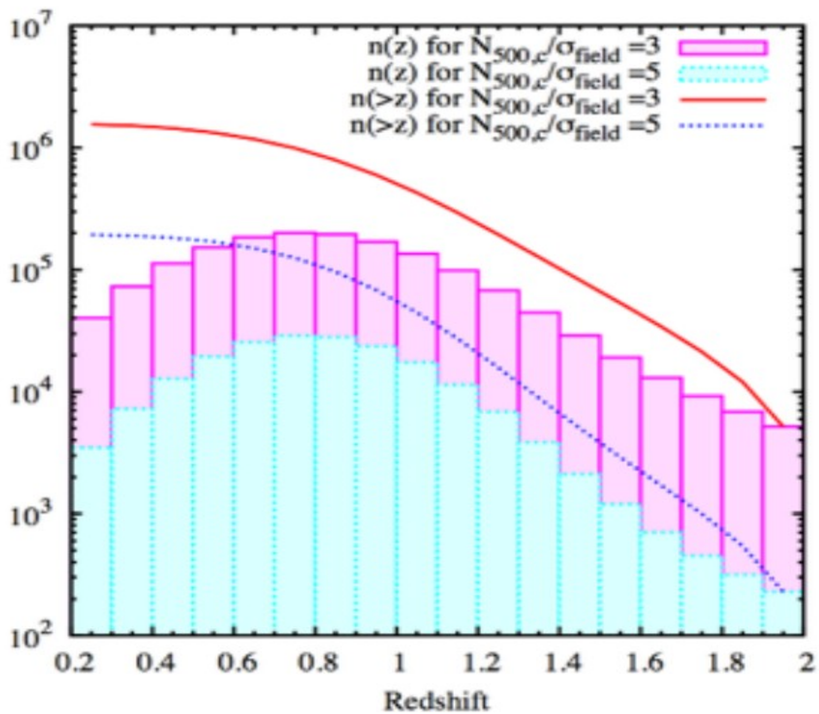
EUCLID satellite

M-class ESA mission, launch in 2021, 7 years mission

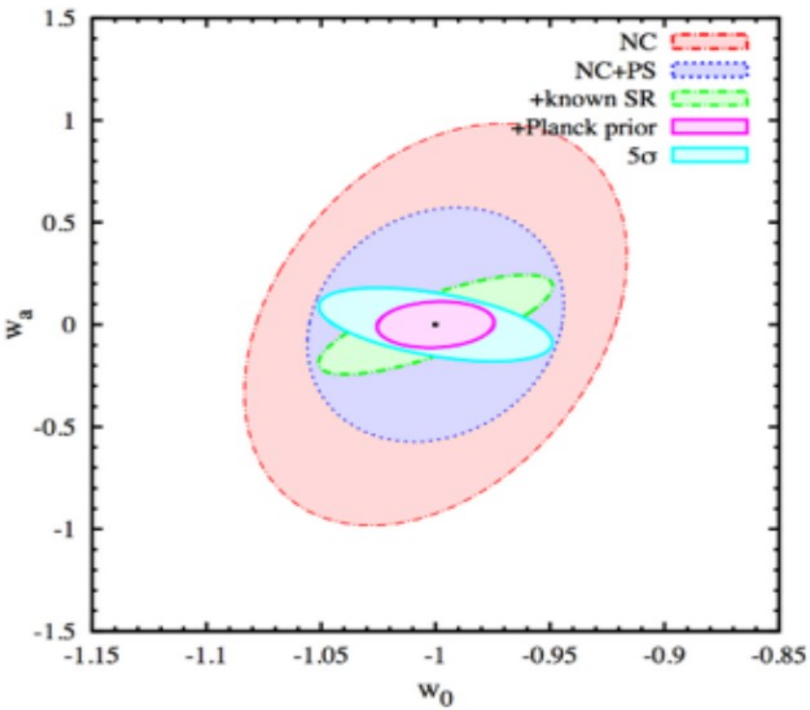
Survey of 15 000 deg^2

Visible photometer for state of art lensing

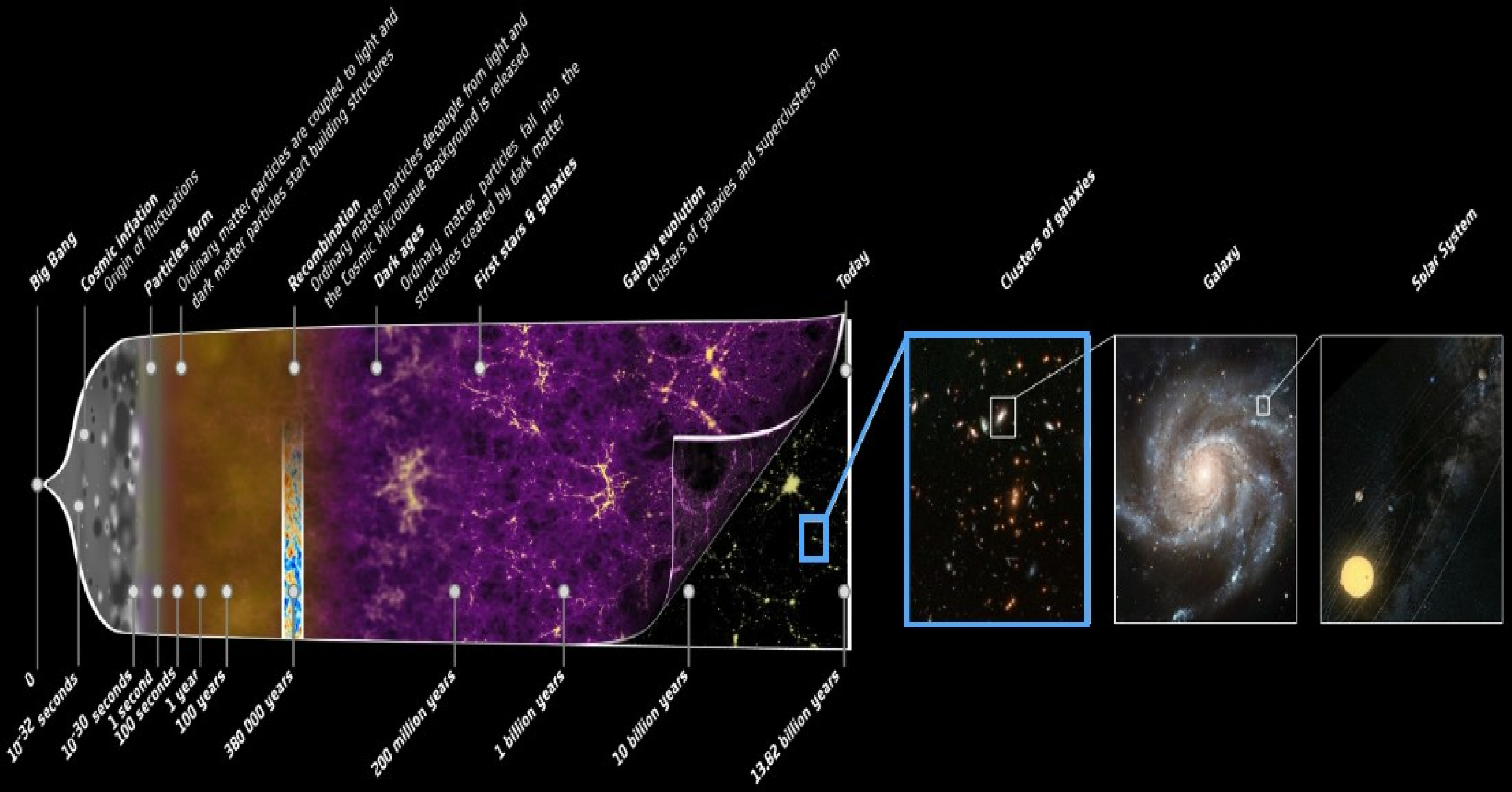
IR 3 bands photometer (Y,J,H) + slitless spectroscopy



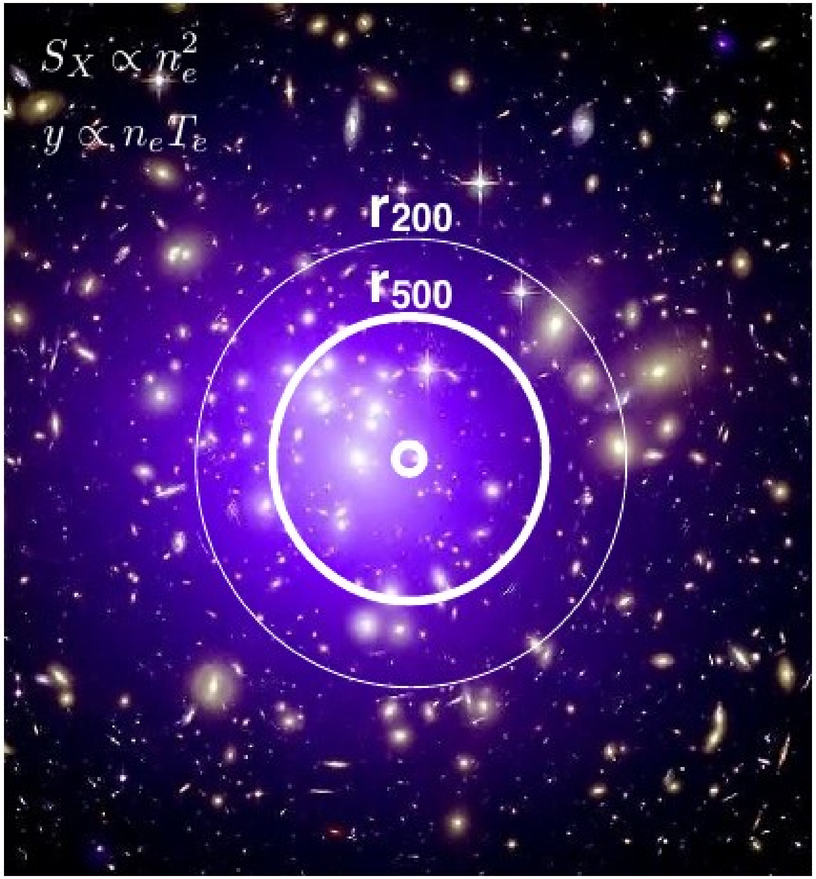
Dark energy constraints



Brief history of the Universe



Cluster self-similarity vs radius

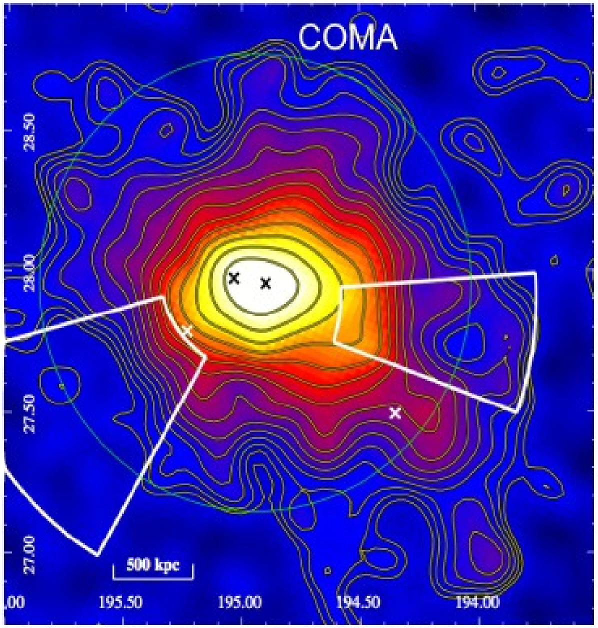


$r \lesssim 0.1 r_{500}$ ⇒ baryonic physics
(e.g. cooling, feedback, affect the normalization)

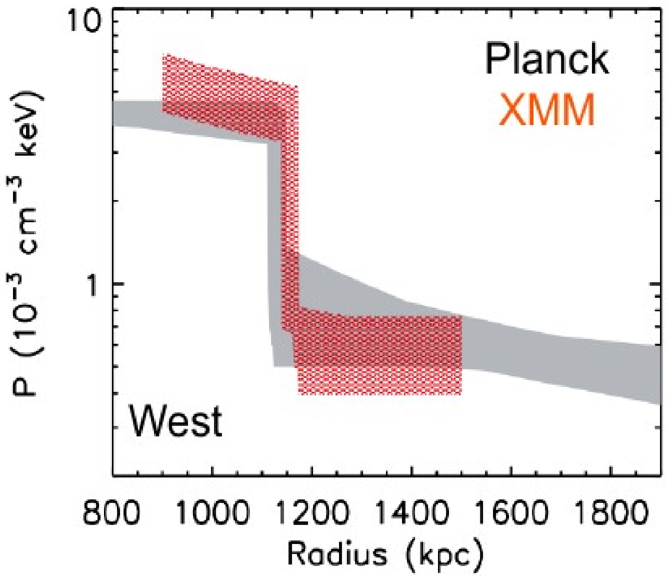
$0.1 r_{500} \lesssim r \lesssim r_{500}$ ⇒ gravity

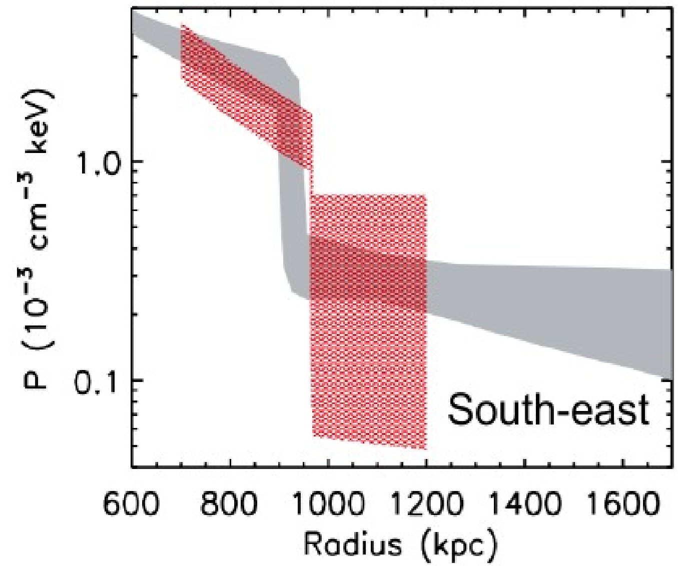
$r \gtrsim r_{500}$ ⇒ deviations from equilibrium, on-going formation
(e.g. non-thermal pressure support, affects the normalization)

A new look at cluster dynamics



Planck Int. Result X, 2013





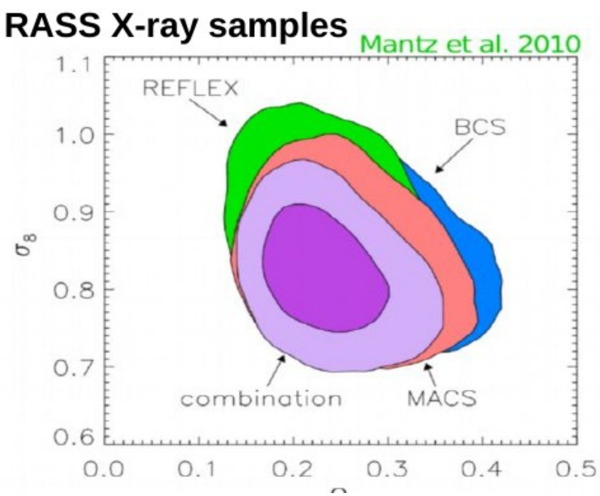
Mach number:

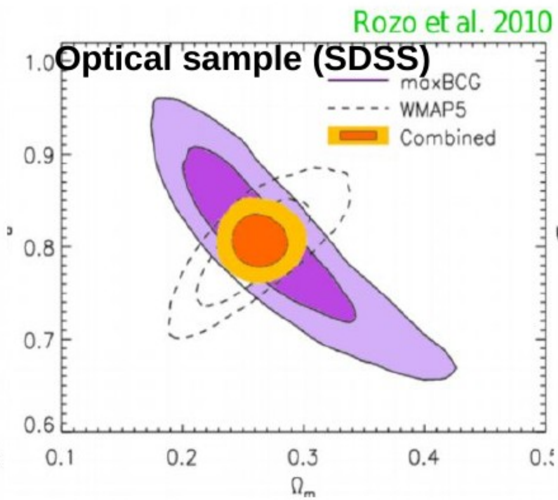
$M_W = 2.03\ [+0.09, -0.04]$

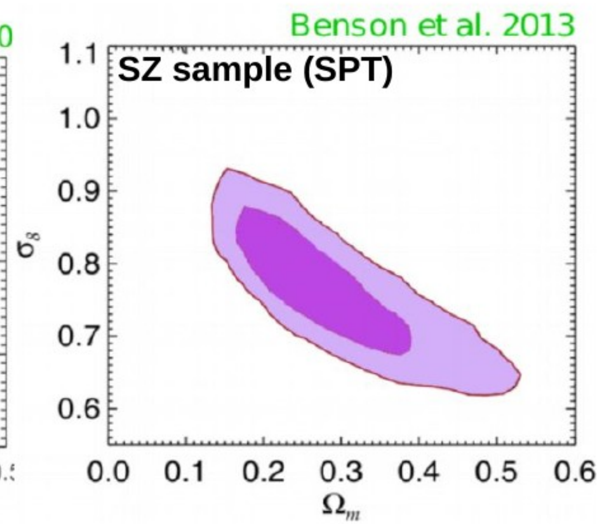
$M_{SE} = 2.05\ [+0.25, -0.02]$

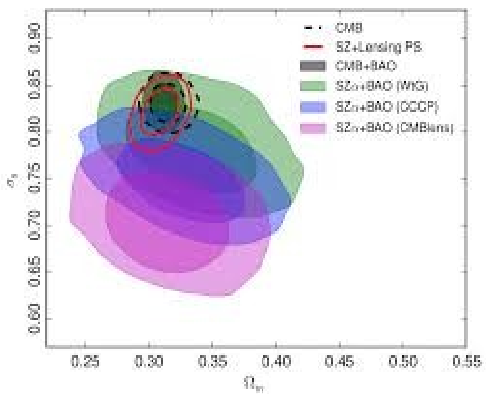
- Pressure jumps sign the presence of shocks

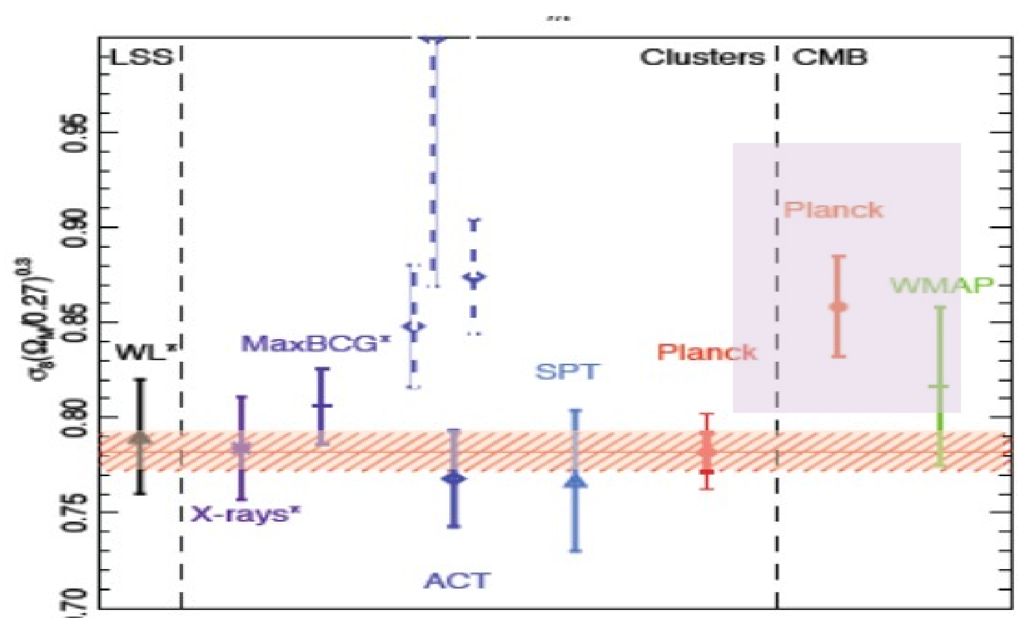
Multi-wavelength cluster cosmology





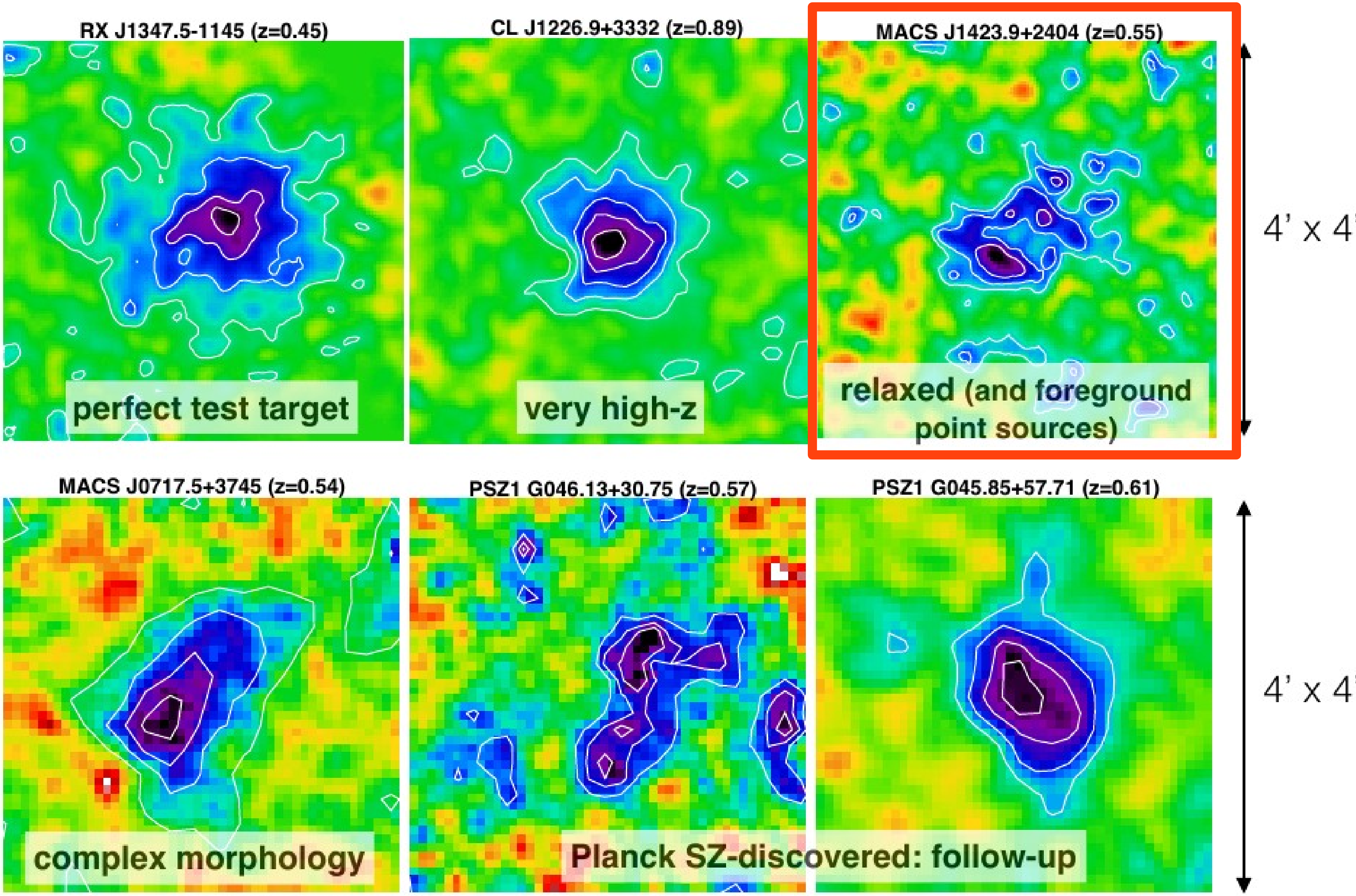






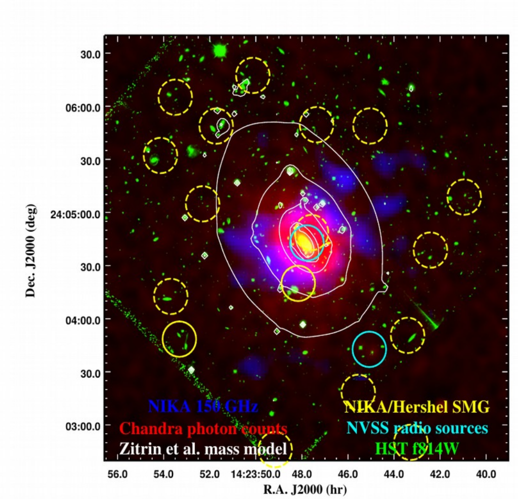
- Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, …

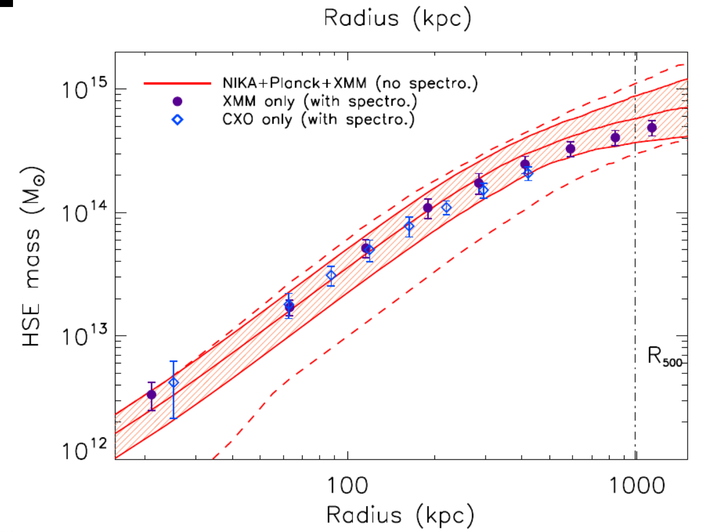
Rich environment

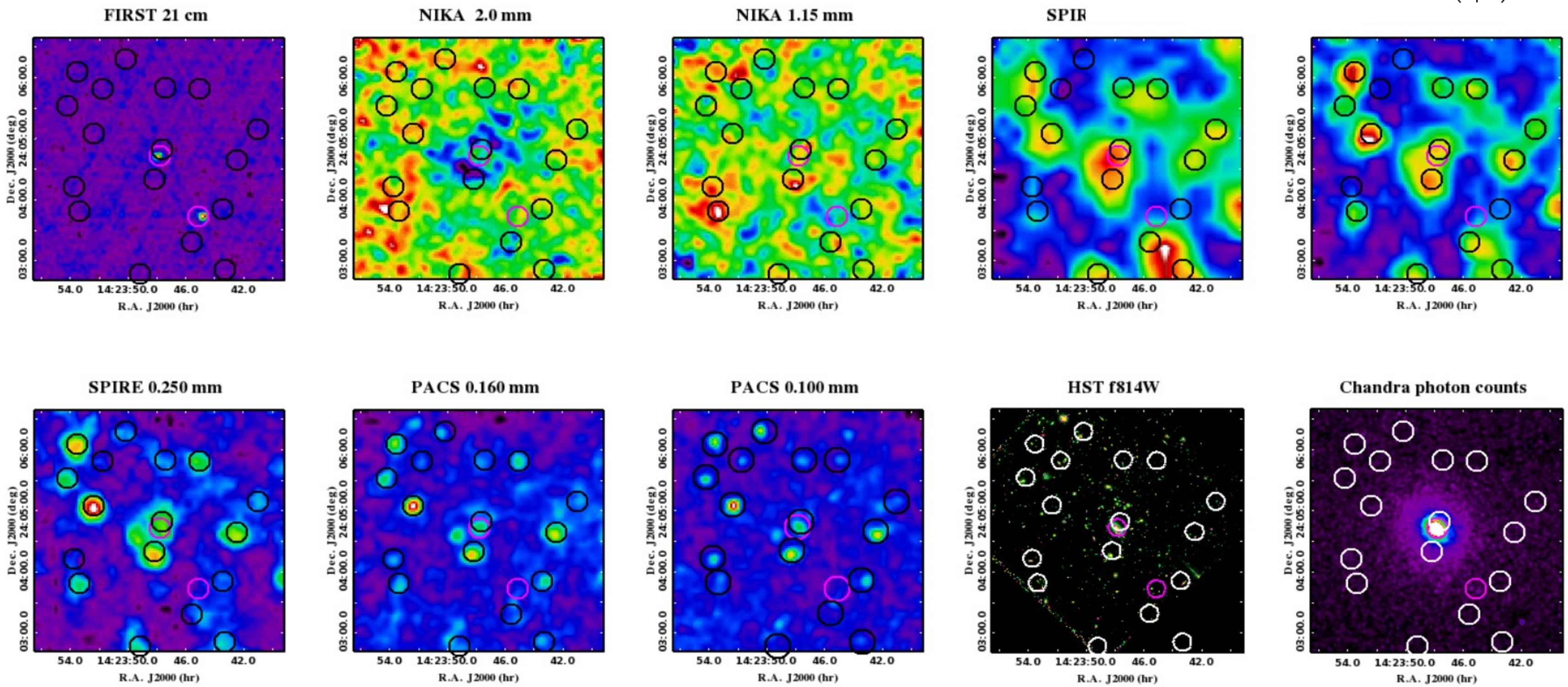


Rich environment

- 17 SMG + 2 RS but still possible to reconstruct thermodynamics properties and mass
- Multi-wavelength analysis







J.