Cosmology with clusters of galaxies and their Sunyaev-Zel'dovich effect signal

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Outline

Cosmology and cosmology with galaxy clusters

The thermal Sunyaev-Zel'dovich effect

SZ (cosmological) results from the Planck satellite

Future goals for SZ observation (with NIKA)

Conclusions

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.

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http://ipag.osug.fr/nika2

R. Adam, A. Adane, P. Ade, P. André, A. Beelen, B. Belier, **A. Benoît**, A. Bideaud, N. Billot, N. Boudou, **O. Bourrion, M. Calvo, A. Catalano**, G. Coiffard, **B. Comis, A. D'Addabbo, F.-X. Désert**, S. Doyle, **J. Goupy**, C. Kramer, S. Leclercq, **J. F. Macias-Perez**, J. Martino, P. Mauskopf, **F. Mayet, A. Monfardini**, F. Pajot, E. Pascale, **L. Perotto**, E. Pointecouteau, **N. Ponthieu**, V. Revéret, L. Rodriguez, F. Ruppin, G. Savini, K. Schuster, A. Sievers, C. Tucker, R. Zylka

also financed by

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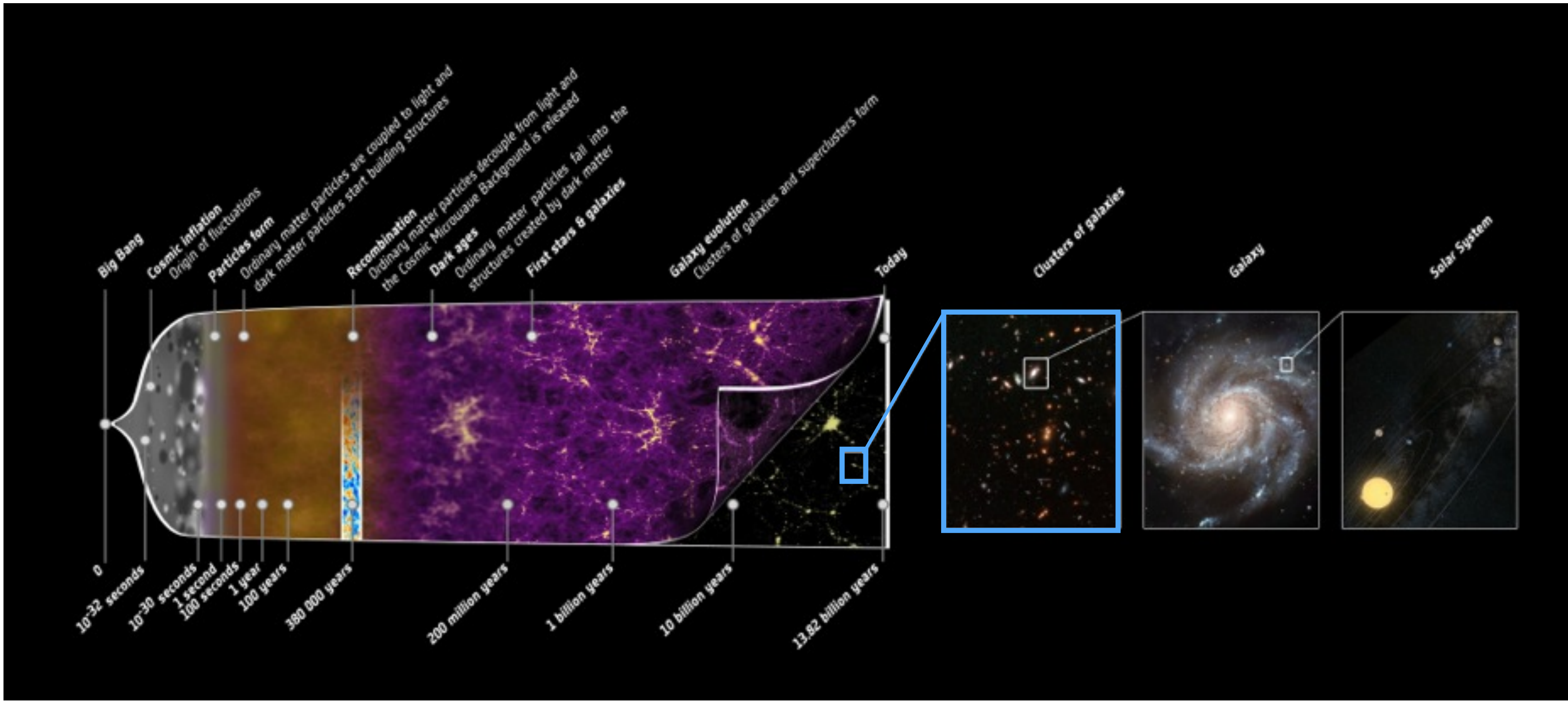
Cosmic history

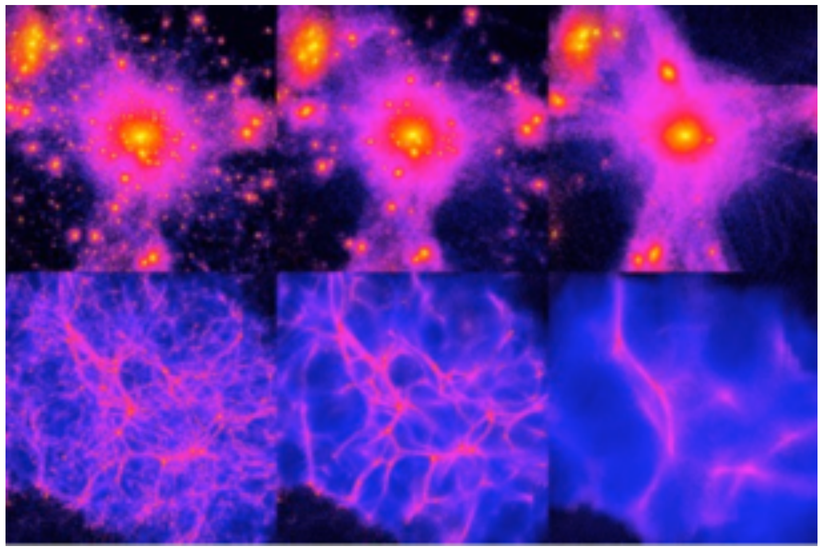


Galaxy clusters: strong cosmological probe, as tracers of the highest peaks in the matter density field

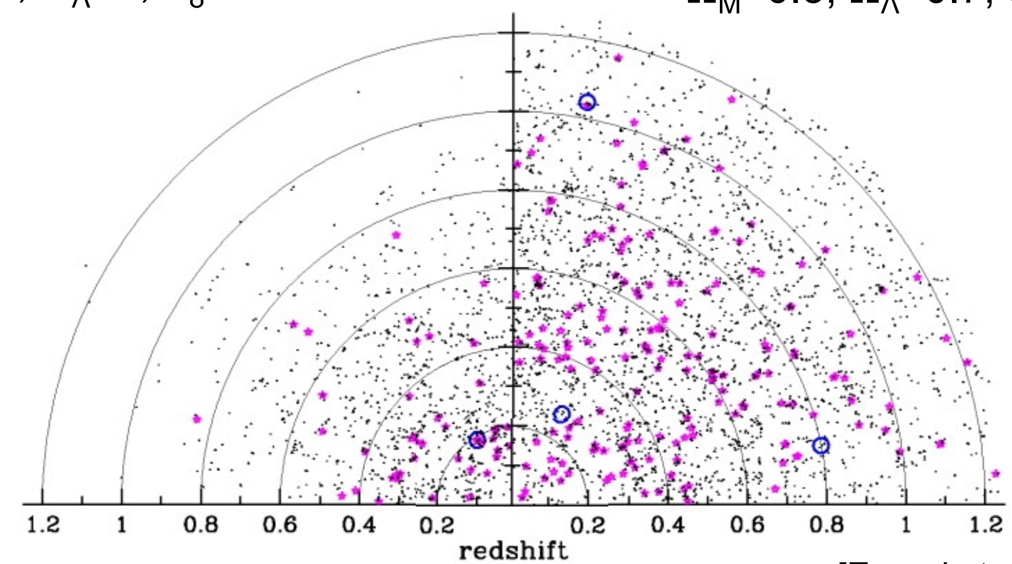
Clusters of galaxies

cold DM **warm DM** **hot DM**

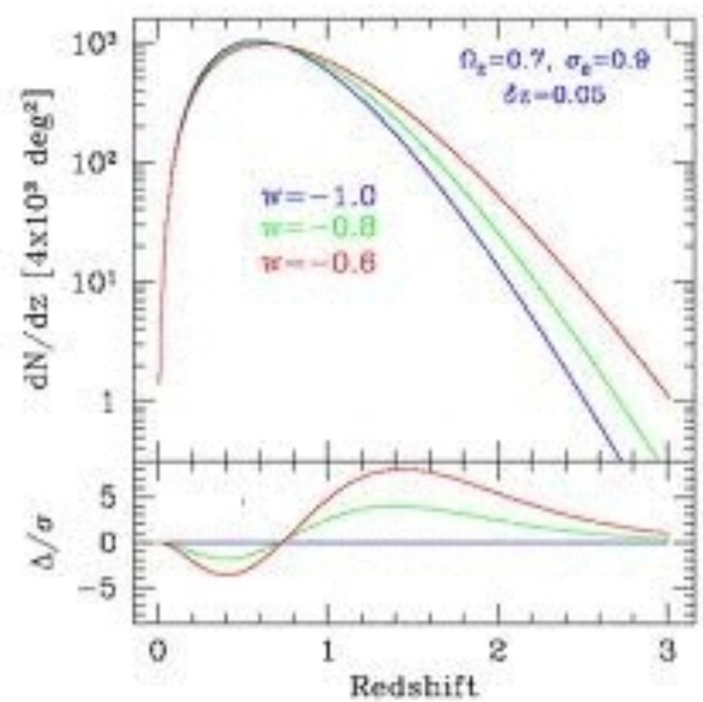
Λ-CDM



Ω_M=1, Ω_Λ=0, σ_8=0.6 Ω_M=0.3, Ω_Λ=0.7, σ_8=0.9



[Evrard et al. 2002]



cluster derived cosmological constraints:
limited by systematics associated with the use of direct observables as proxies for mass

Clusters of galaxies

Abell (1958)
Zwicky et al., 1961-1968

Optical catalogs were constructed by identifying clusters as **enhancements in the surface number density of galaxies**

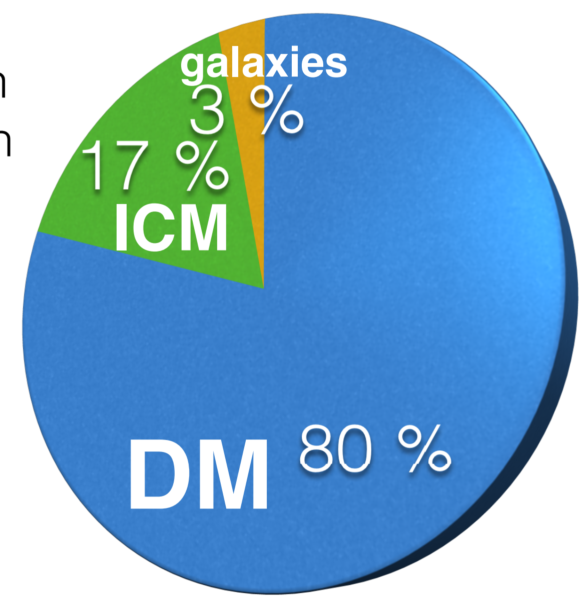
1966: **X-ray emission detected** in the center of the **Virgo cluster**
1971: X-ray sources were also detected in the directions of Coma and Perseus

Since these are three of the nearest rich clusters, it was suggested that clusters of galaxies might generally be X-ray sources *[Cavaliere et al. (1971)]*

X-ray satellites (Uhuru + Ariel V):

- many clusters were bright X-ray sources, L~10^{43-45} ergs/sec
- spatially extended (~ size of the galaxy distribution)
- brightness did not vary temporally
- consistent with thermal bremsstrahlung from hot gas

the space between galaxies in clusters seems to be filled with **very hot** (**T_e~10^{6-8} K**), **low-density** (**n_e~10^{-4} - 10^{-2} cm^{-3}**) **gas**



T_e in agreement with the mass inferred by Zwicky in the 1930's

[Sarazin, RevModPhys (1986)]

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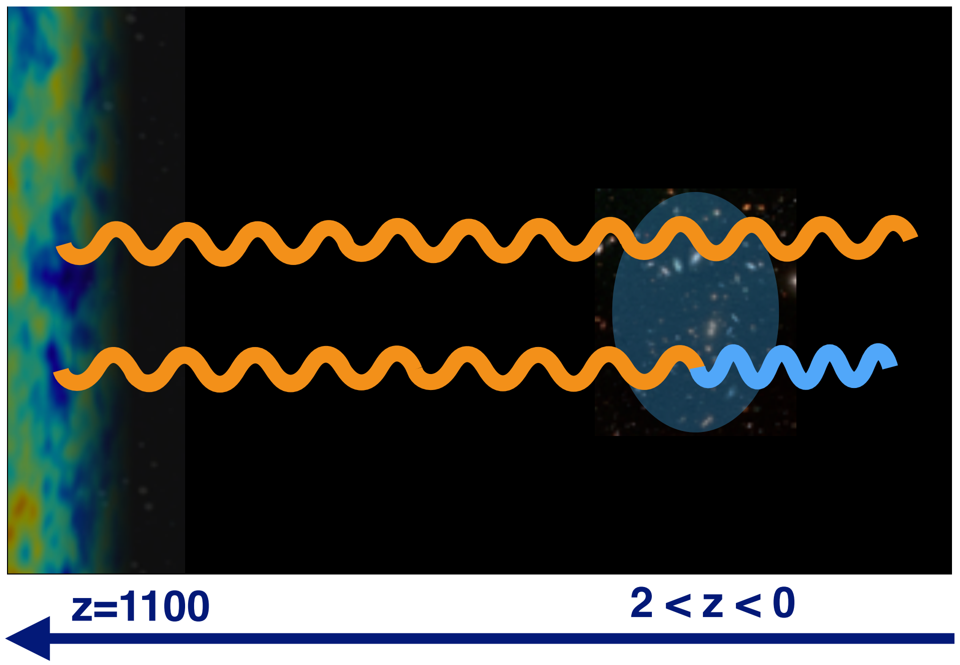
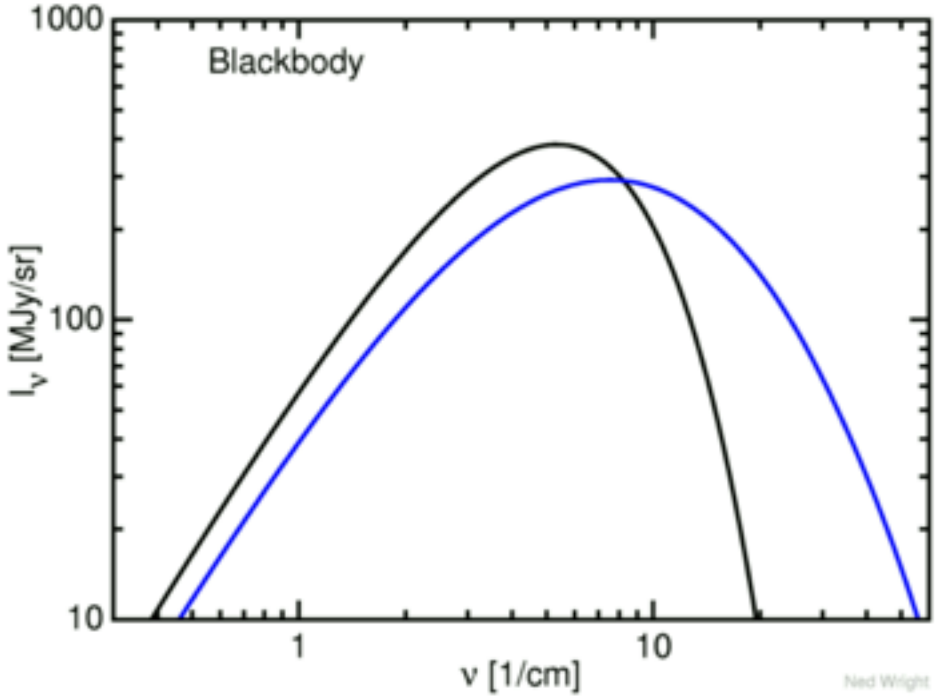
tSZ from clusters of galaxies

Sunyaev, R. A., & Zeldovich, Y. B. (1972)





- The SZ amplitude (**y**) is directly r**elated to the cluster thermal energy** ⟼ strongly related to the cluster potential wells
- Being a spectral deformation, its flux is **z-independent** ⟼ tool to detect/probe high-z clusters

Clusters tSZ (ICM) signal can provide a valuable cosmological tool

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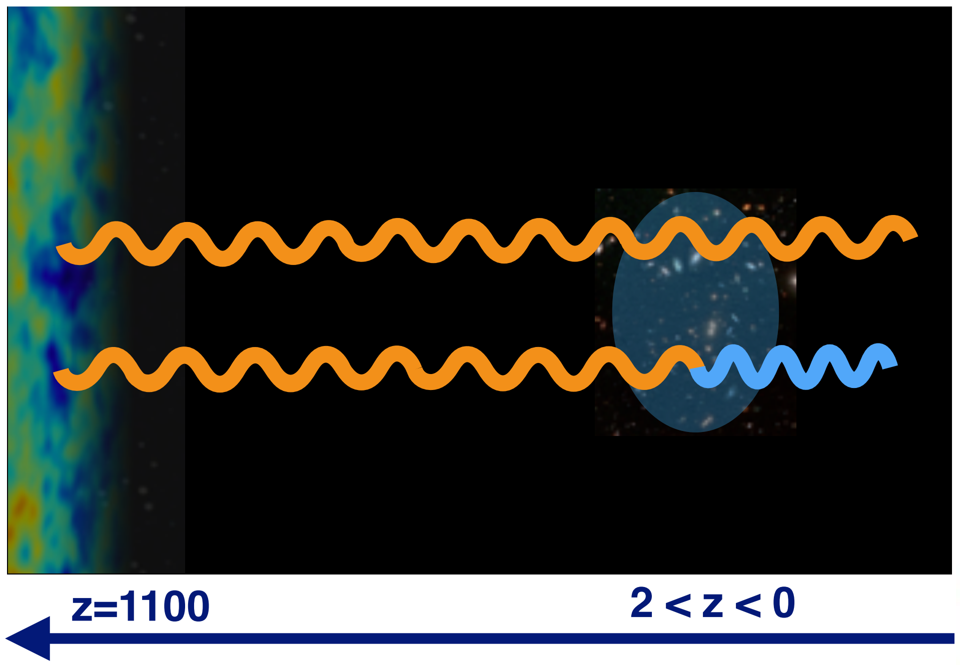

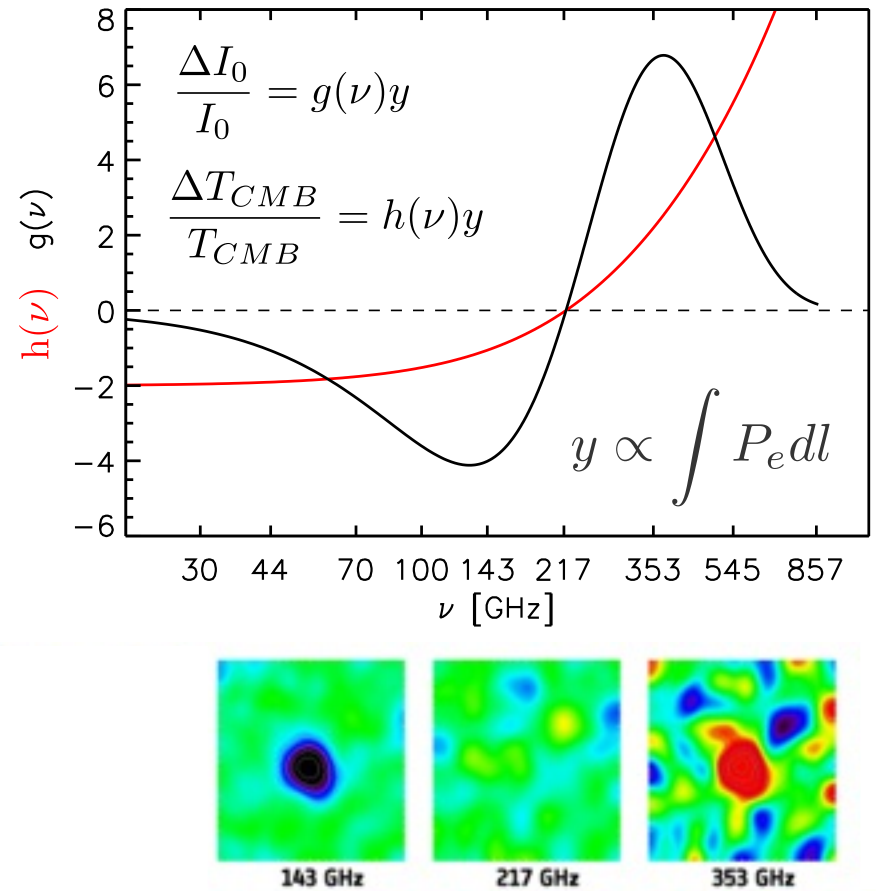

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Clusters tSZ (ICM) signal can provide a valuable cosmological tool

tSZ selected cluster catalogue

- tight relation between SZ signal and mass

$$\Delta I_{SZ} \propto Y = \int_{\Omega} y d\Omega \qquad Y \propto \int P(r) dV$$

- nearly z-independent mass limit
- less sensitive to morphology
  (biased selection function)

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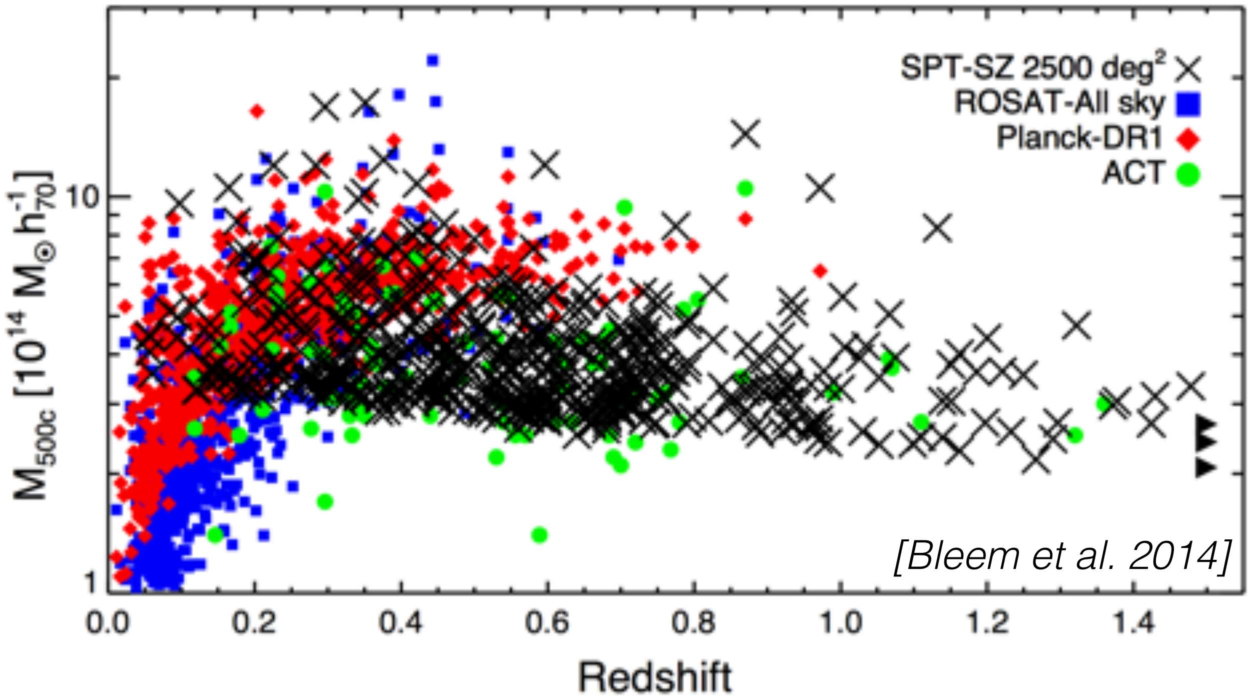

1972: predicted by Sunyaev & Zel'dovich

2009: Staniszewski et al. 1st tSZ discovered cluster (SPT)

2013: tSZ surveys → thousands of tSZ detected clusters

Planck *[Planck Early Results VIII, Planck 2013 results XXIX]*

SPT *[Staniszewski et al. 2009, Williamson et al. 2010, Reichardt et al. 2013]*

ACT *[Marriage et al. 2011, Menanteau et al. 2010, Hasselfield et al. 2013]*

it is only very recently that SZ-selected samples have reached a significant size

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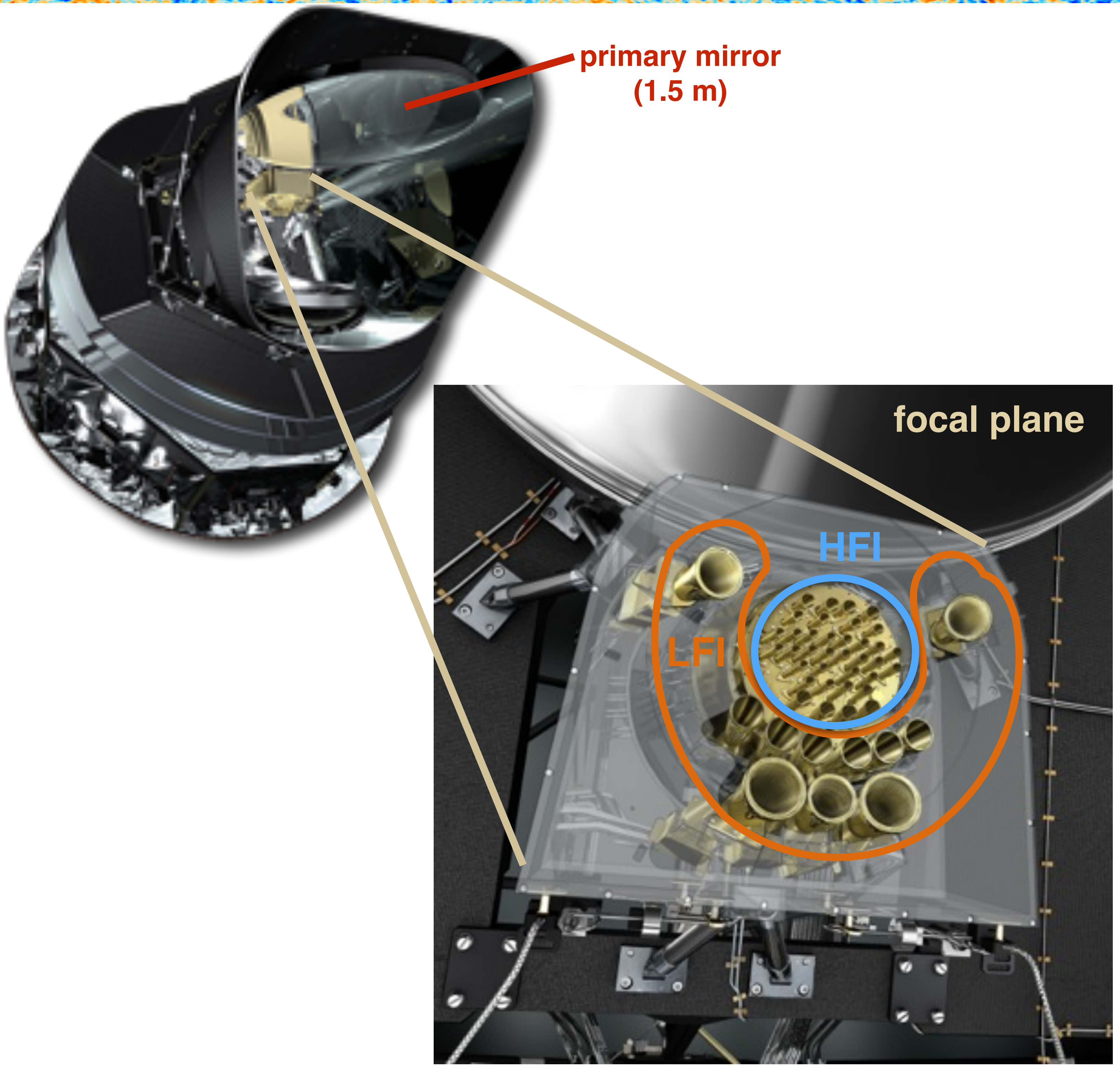
ESA's **Planck** observatory:

- launched in May 2009
- the **3rd mission dedicated to CMB temperature anisotropies**
- 2 instruments:
  LFI 20K radiometers
  (30 → 70 GHz)
  HFI 100 mK bolometers
  (100 → 857 GHz)
- 29 months of operation at L2 (5 HFI sky surveys, 8 LFI surveys)



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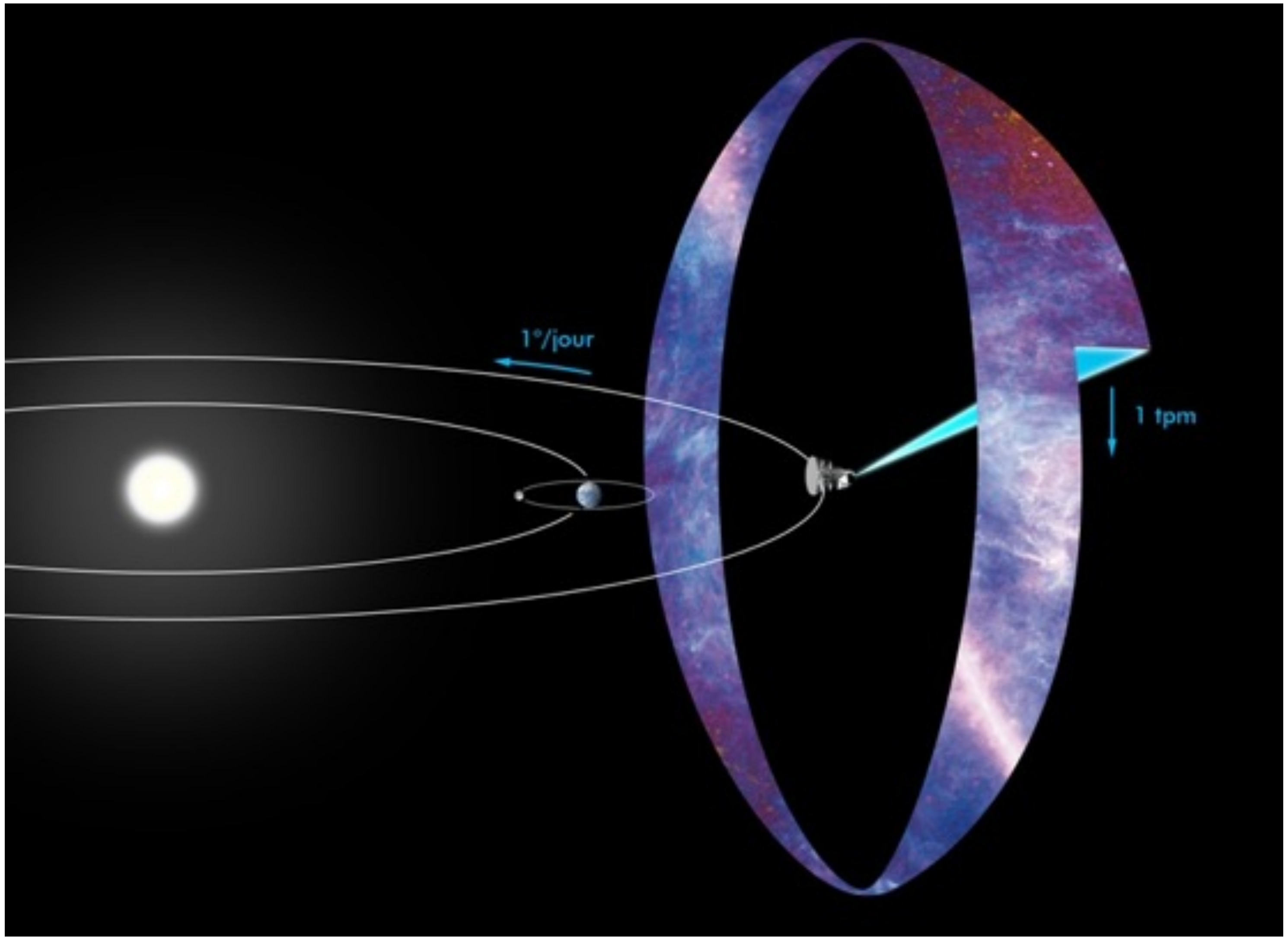
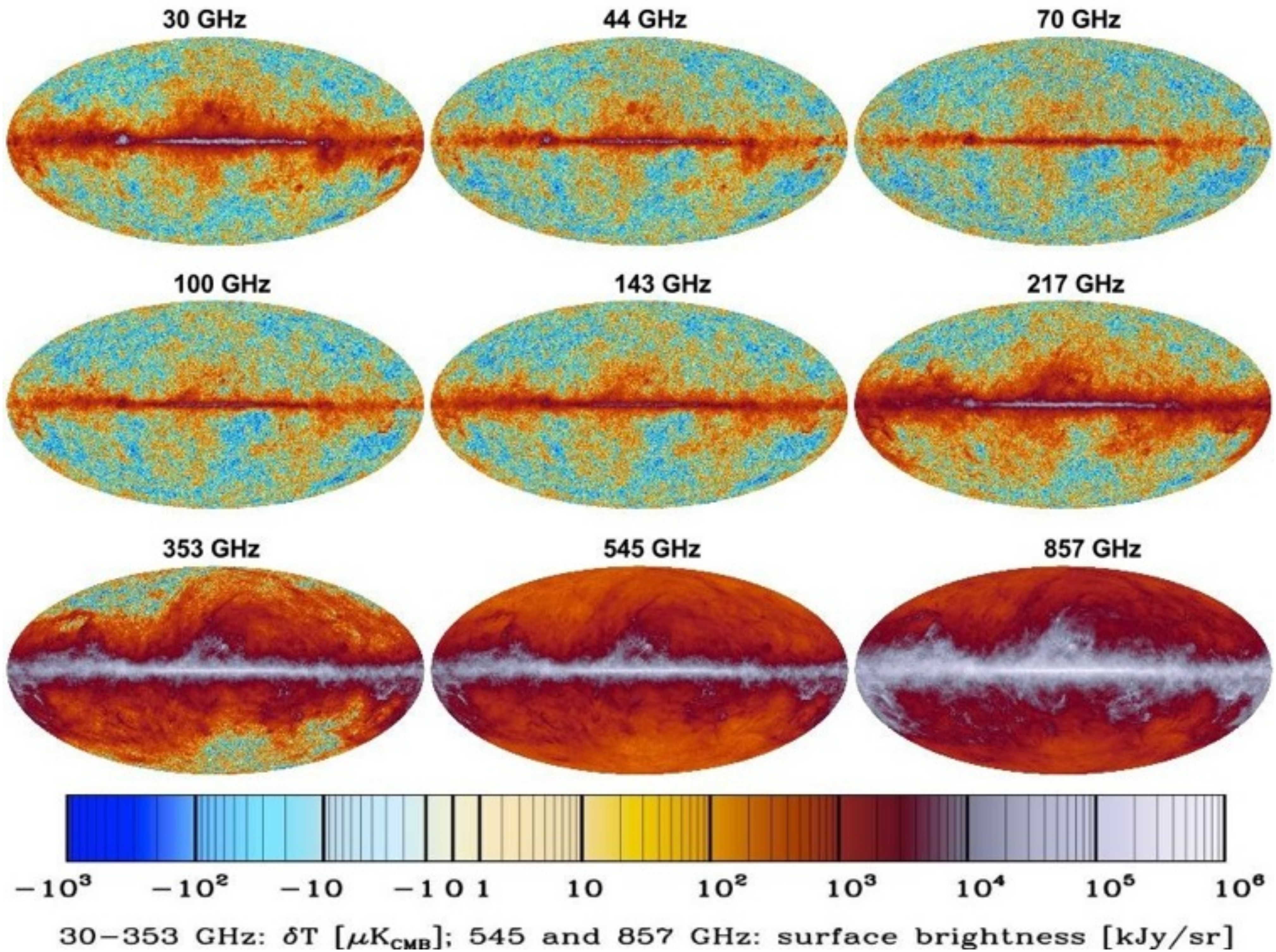


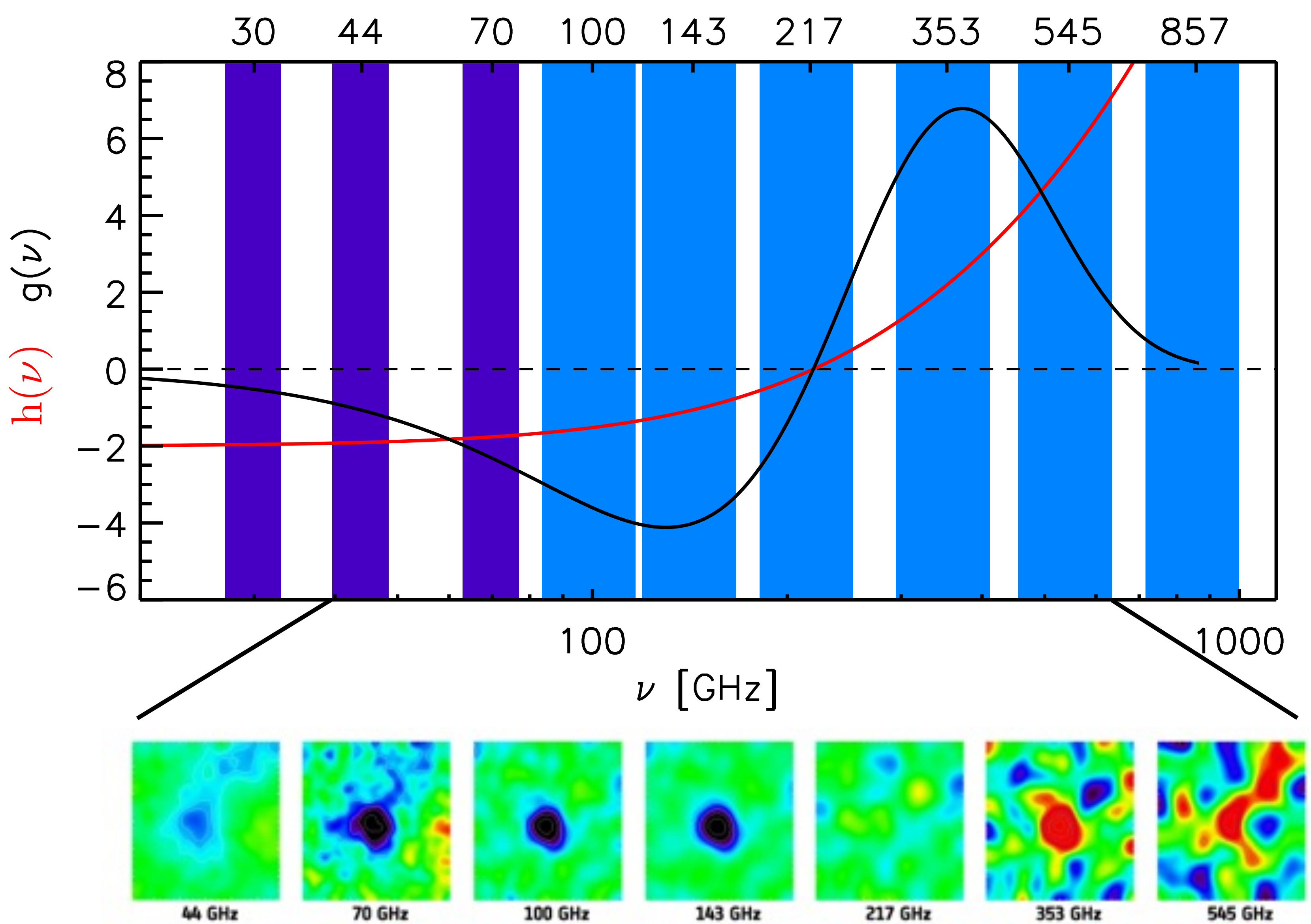
Planck frequency maps

LFI

HFI



Planck: first all-sky SZ survey



$$\frac{\Delta T_{CMB}}{T_{CMB}} = h(\nu)y$$

$$y \sim 10^{-5}$$

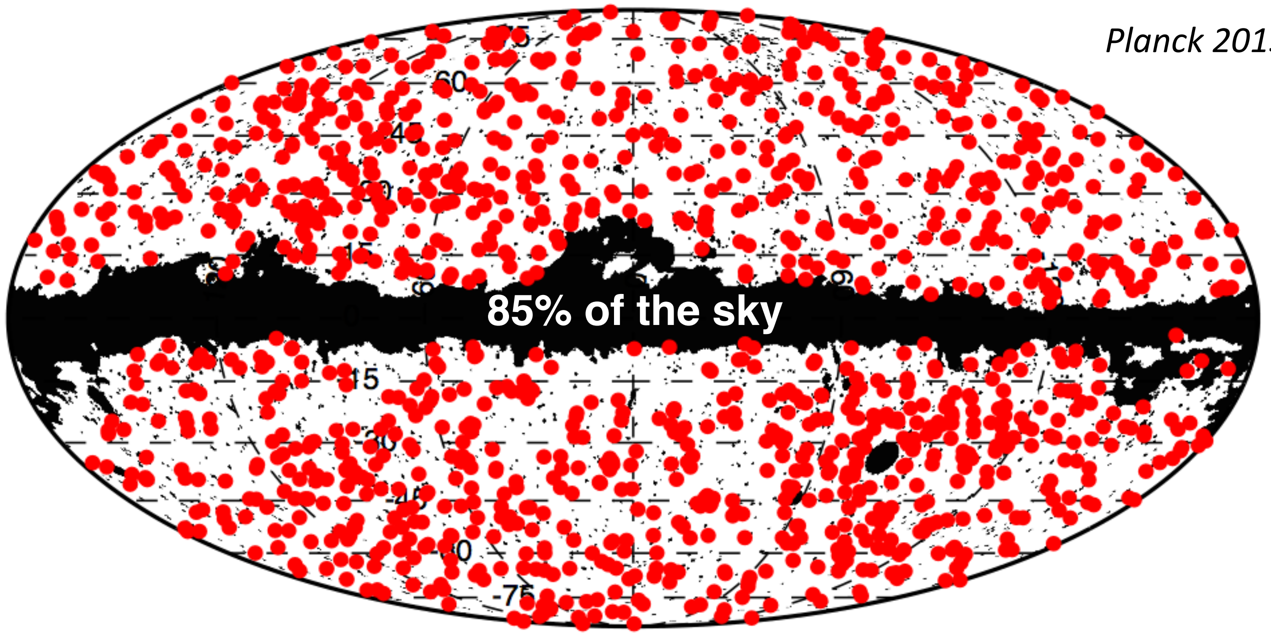
⇨ **blind detection of cluster through their SZ signature**

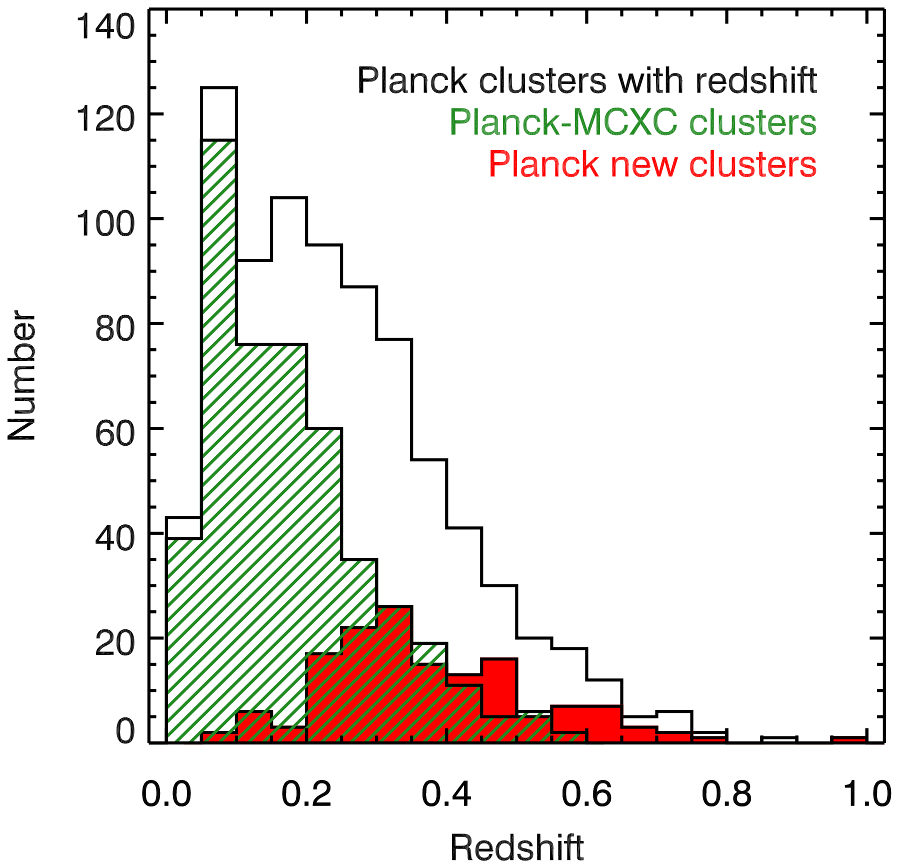
full-sky reconstruction of the SZ emission

Planck SZ catalogue

All-sky catalogue of 1227 SZ sources *

Planck 2013 results XXIX



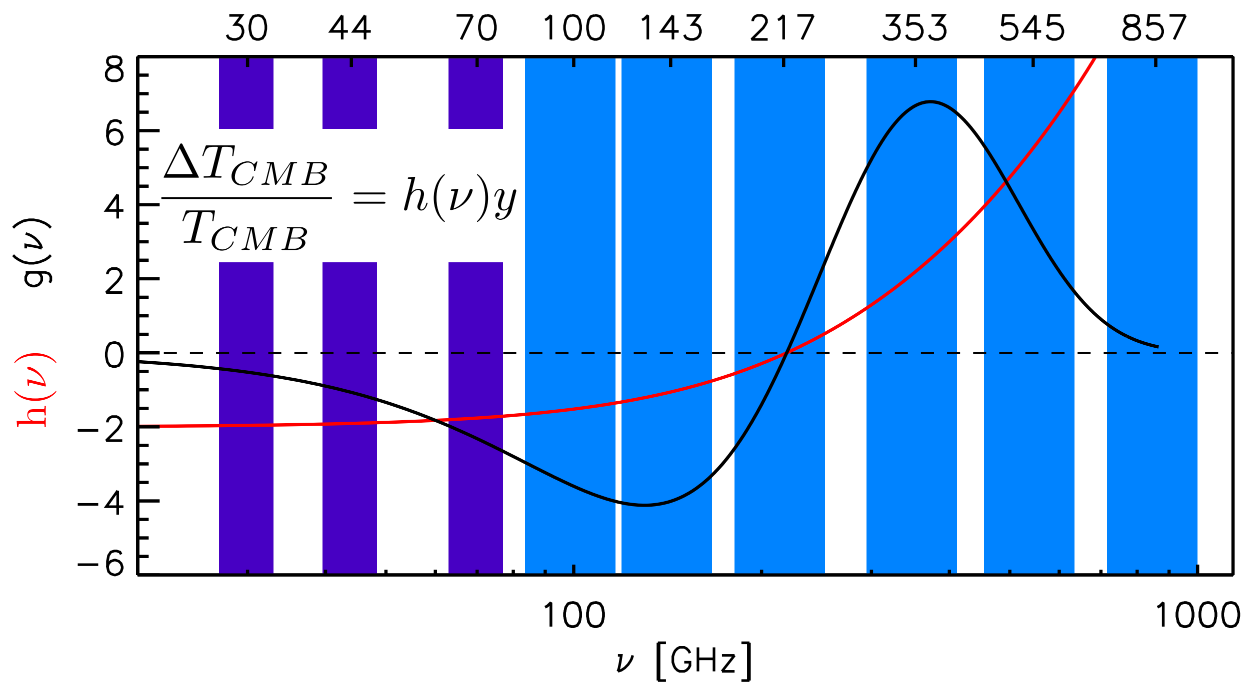


**based on nominal mission data*

- built with an adapted extraction technique (Matched Multi-Filter)
- 861 confirmed galaxy clusters (178 new, mass and redshift estimates for 813)
- Search for counterparts in existing surveys (RASS, WISE, SDSS, DSS) and cluster catalogues (X, optical, SZ)
- Follow-up programs: X-rays (XMM), optical (several telescopes), and SZ (AMI)

[Planck intermediate results. XXVI (2014), Perrott et al., (2014)]

Planck full-sky SZ map



Adapted component separation algorithms:

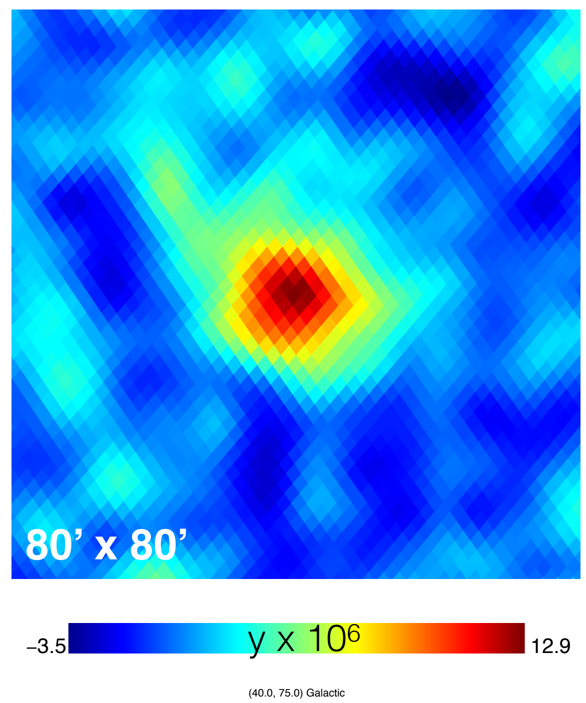
- N**ILC** (Needlet Iindependent Linear Combination, *Remazeilles et al. 2011*)
- M**ILC**A (Modified Internal Linear Combination Algorithm, *Hurier et al. 2013*)

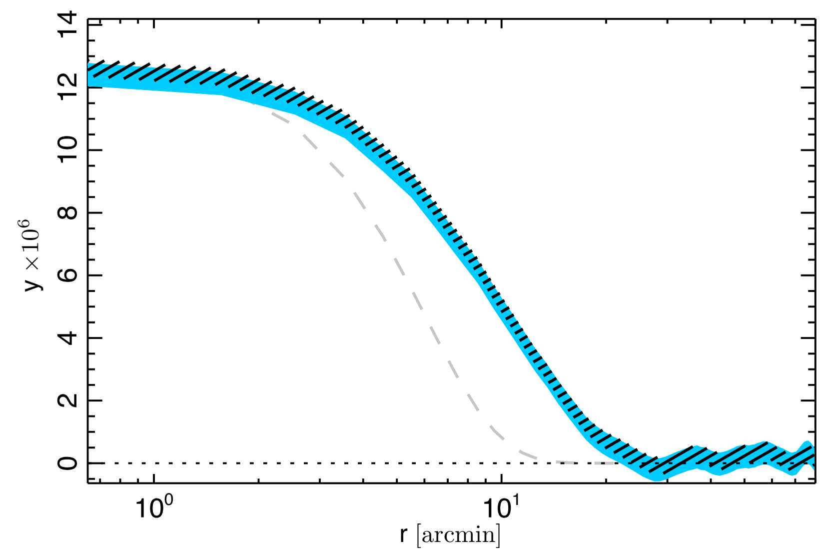
constraints on electromagnetic spectra: preserve tSZ effect and remove CMB

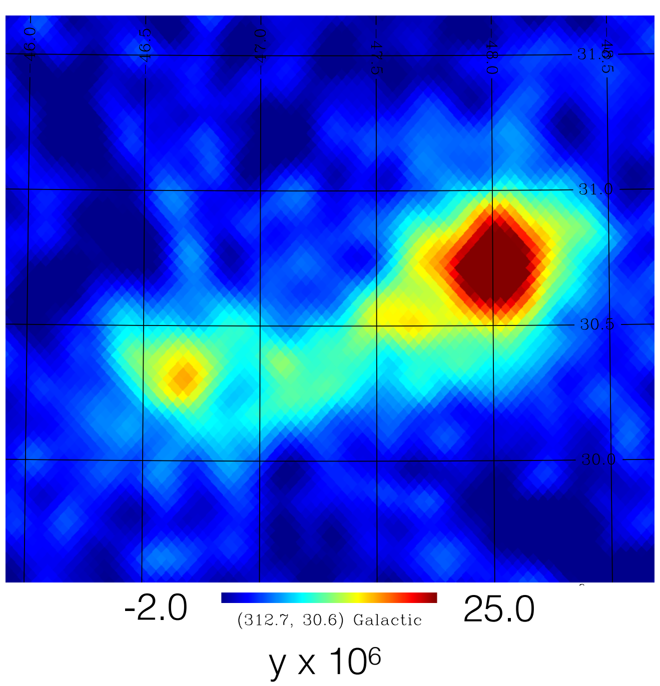
We reconstruct the tSZ amplitude

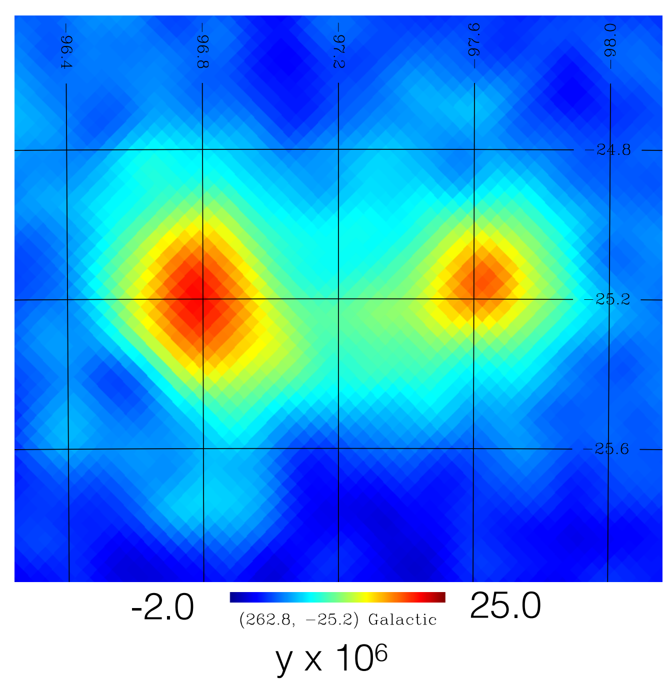
$$y = \Sigma_i \Sigma_\alpha w_i^\alpha B^\alpha T_i$$

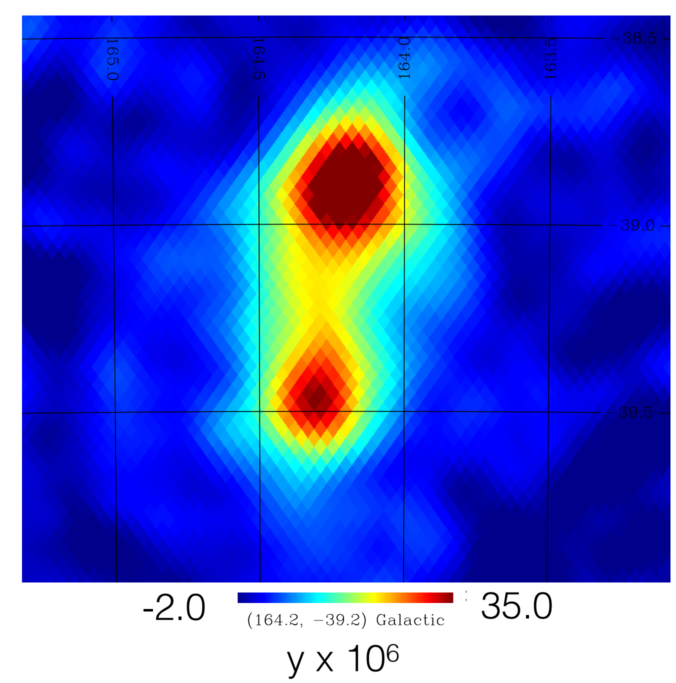
reconstructed SZ maps



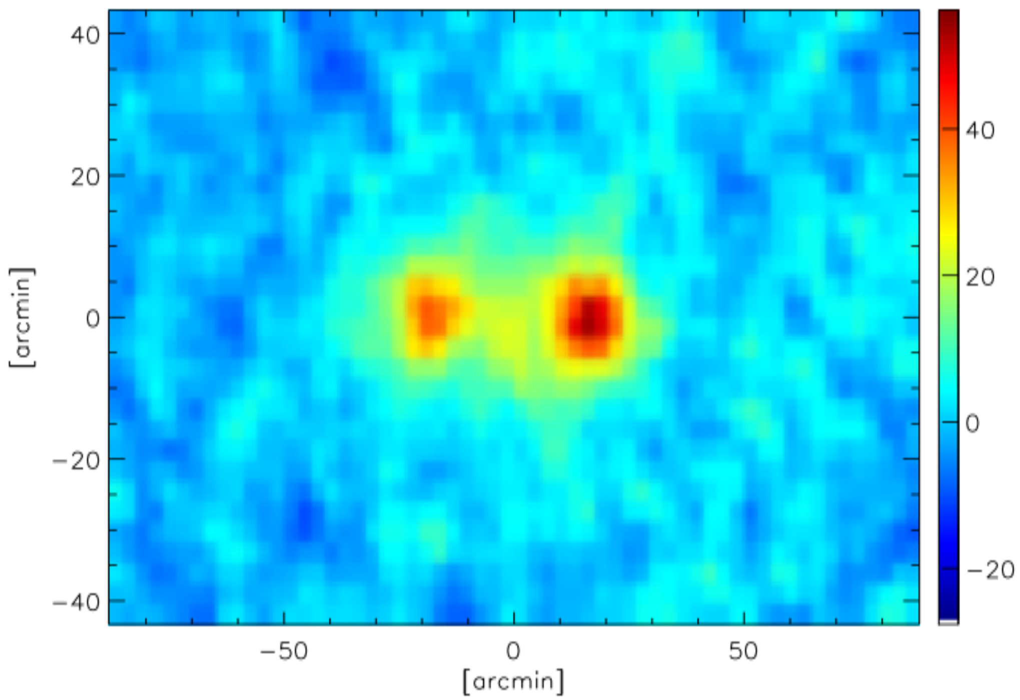




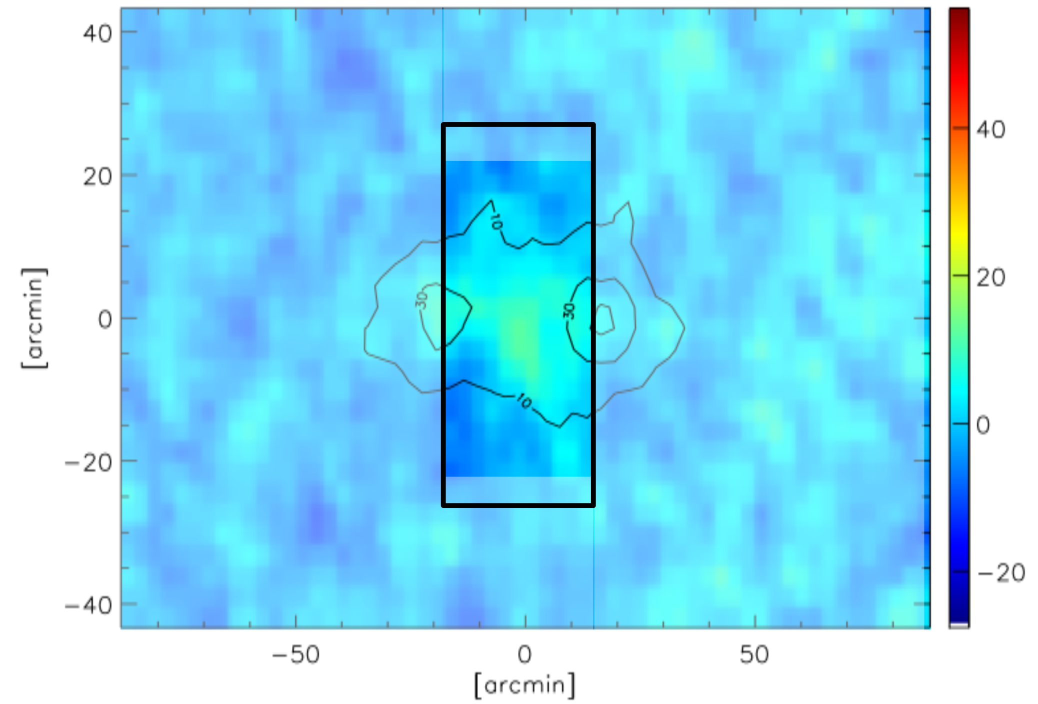




SZ from inter-cluster regions



1^{st} detection of SZ diffuse emission



2D-fit: X + SZ (ROSAT+Planck)

Isothermal filament

$$n_e(r) = \frac{n_e(0)}{\left(1 + (\frac{r}{r_c})^2\right)^{\frac{3}{2}\beta}}$$

$$n_{e,0} = (3.72 \pm 0.17) \times 10^{-4} cm^{-3}$$

$$T_e = (7.08 \pm 0.85)\, keV$$

[Planck intermediate results. VIII (2013)]

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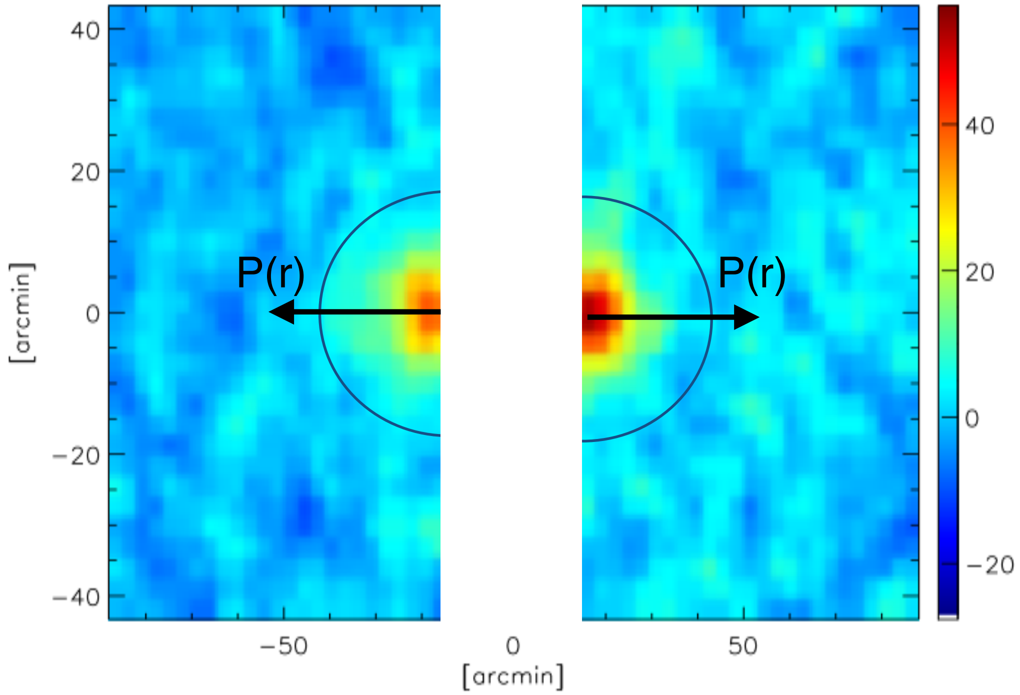

$$P(r) = \frac{P_0}{(\frac{r}{r_s})^{\gamma}[1+(\frac{r}{r_s})^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

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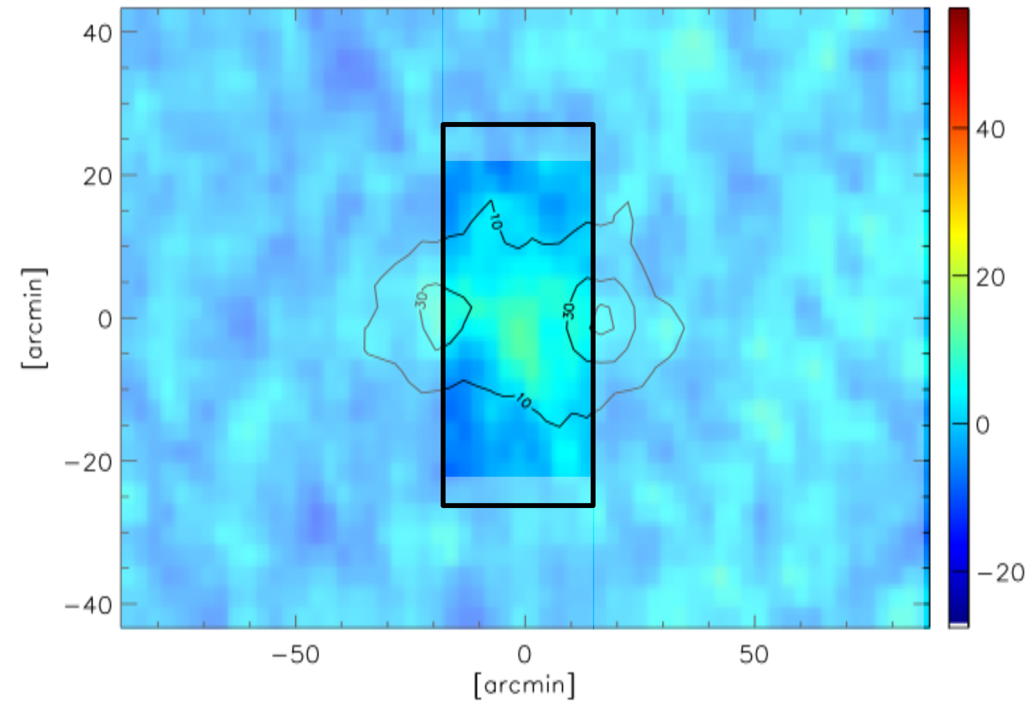

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Universal pressure profile

hydrostatic equilibrium

$$y \propto \int P_e dl \quad \Longleftrightarrow \quad \frac{dP_e(r)}{dr} = -\mu m_p G \frac{M_{tot}(<r)}{r^2} n_e(r)$$

generalized NFW *[Nagai et al. (2007)]*

$$P(r) = \frac{P_0}{(\frac{r}{r_s})^\gamma [1 + (\frac{r}{r_s})^\alpha]^{(\beta-\gamma)/\alpha}}$$

$$YD_A^2 \propto f_{gas} M_{tot}^{5/3} E(z)^{2/3}$$

$$\Rightarrow \quad P(r) = P_{500} p\left(\frac{r}{r_{500}}\right)$$ *[Arnaud et al. (2010)]*

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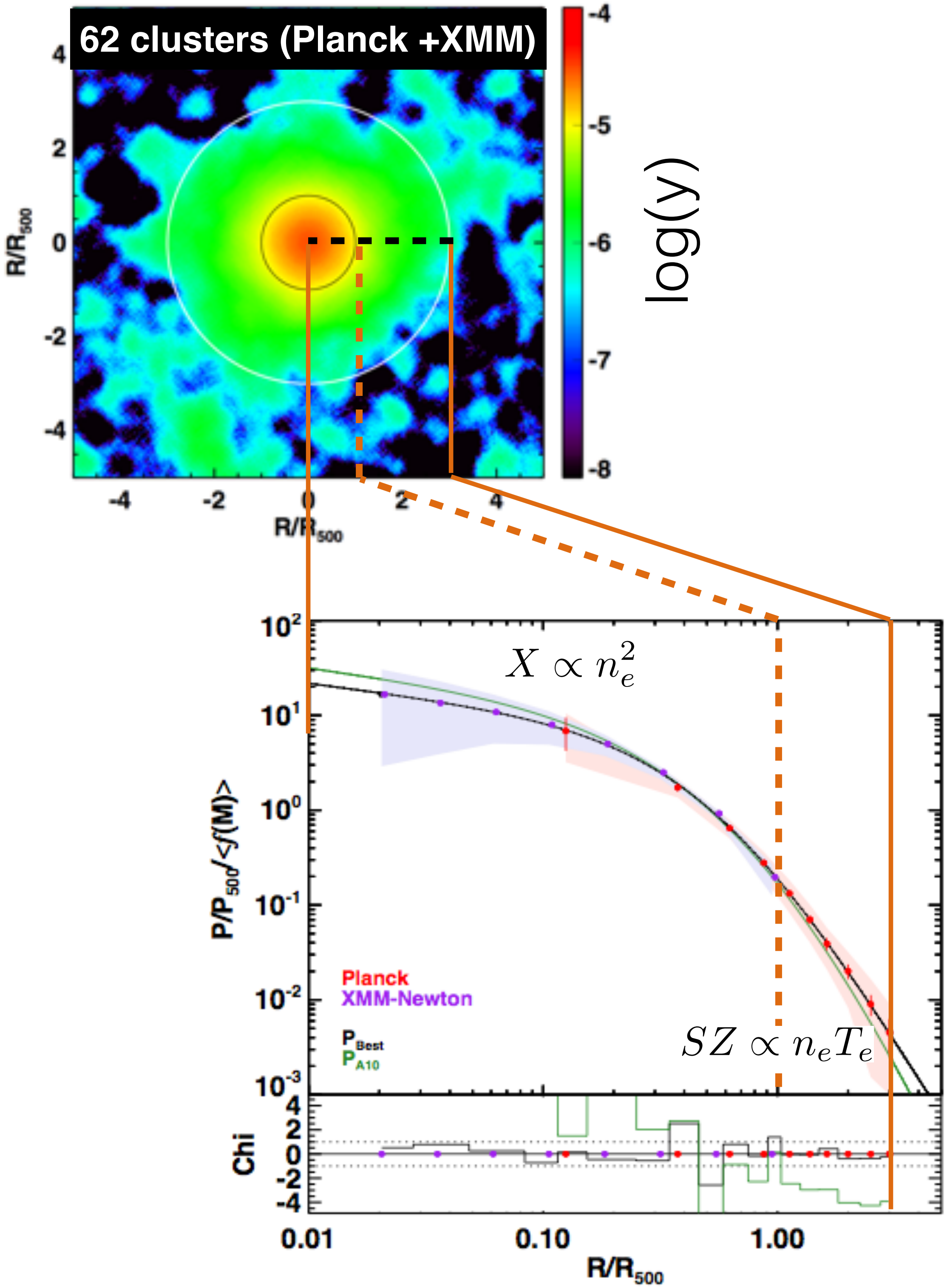
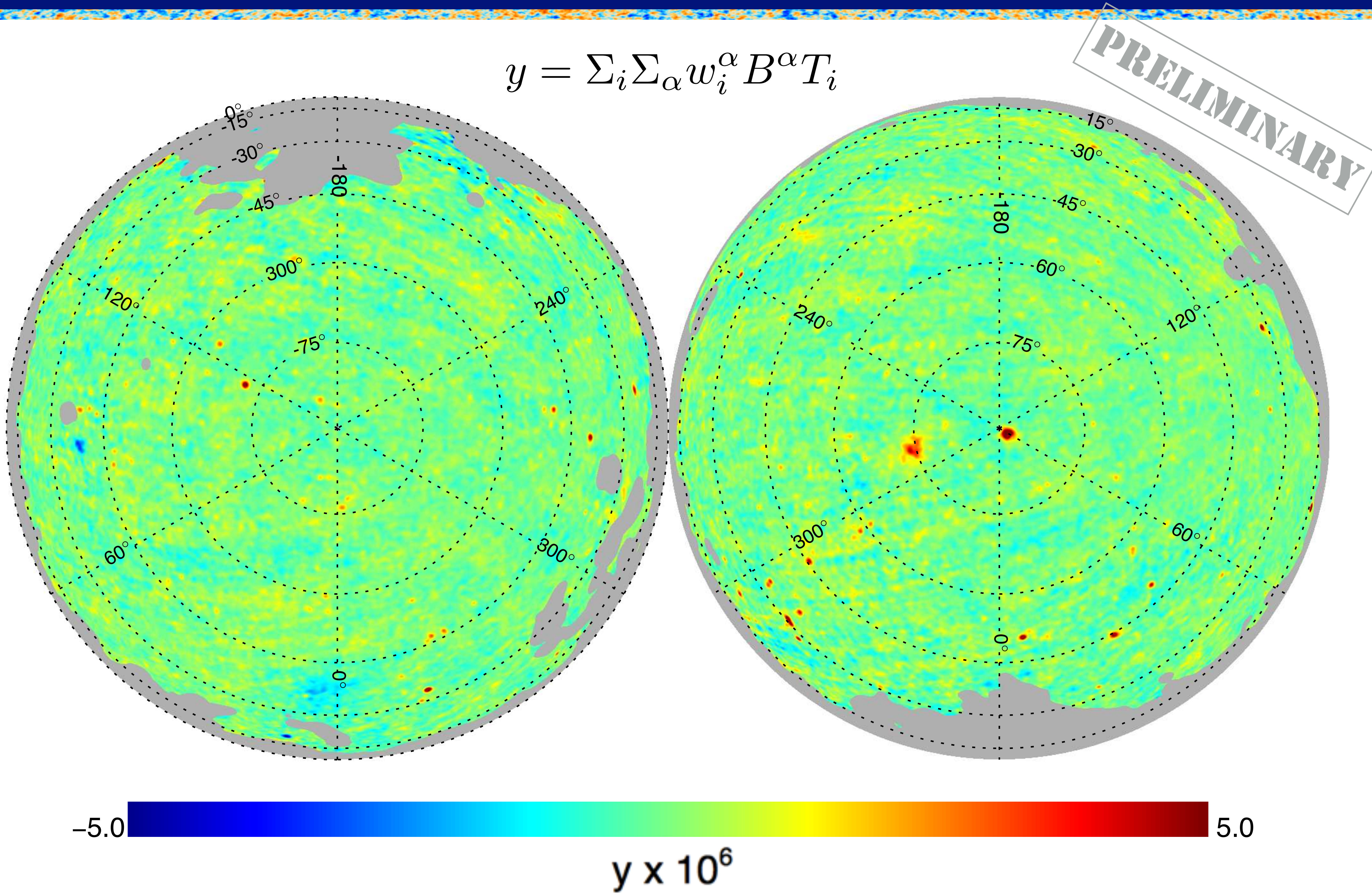


[Planck intermediate results. V (2013)]

full-sky y-map

$$y = \Sigma_i \Sigma_\alpha w_i^\alpha B^\alpha T_i$$



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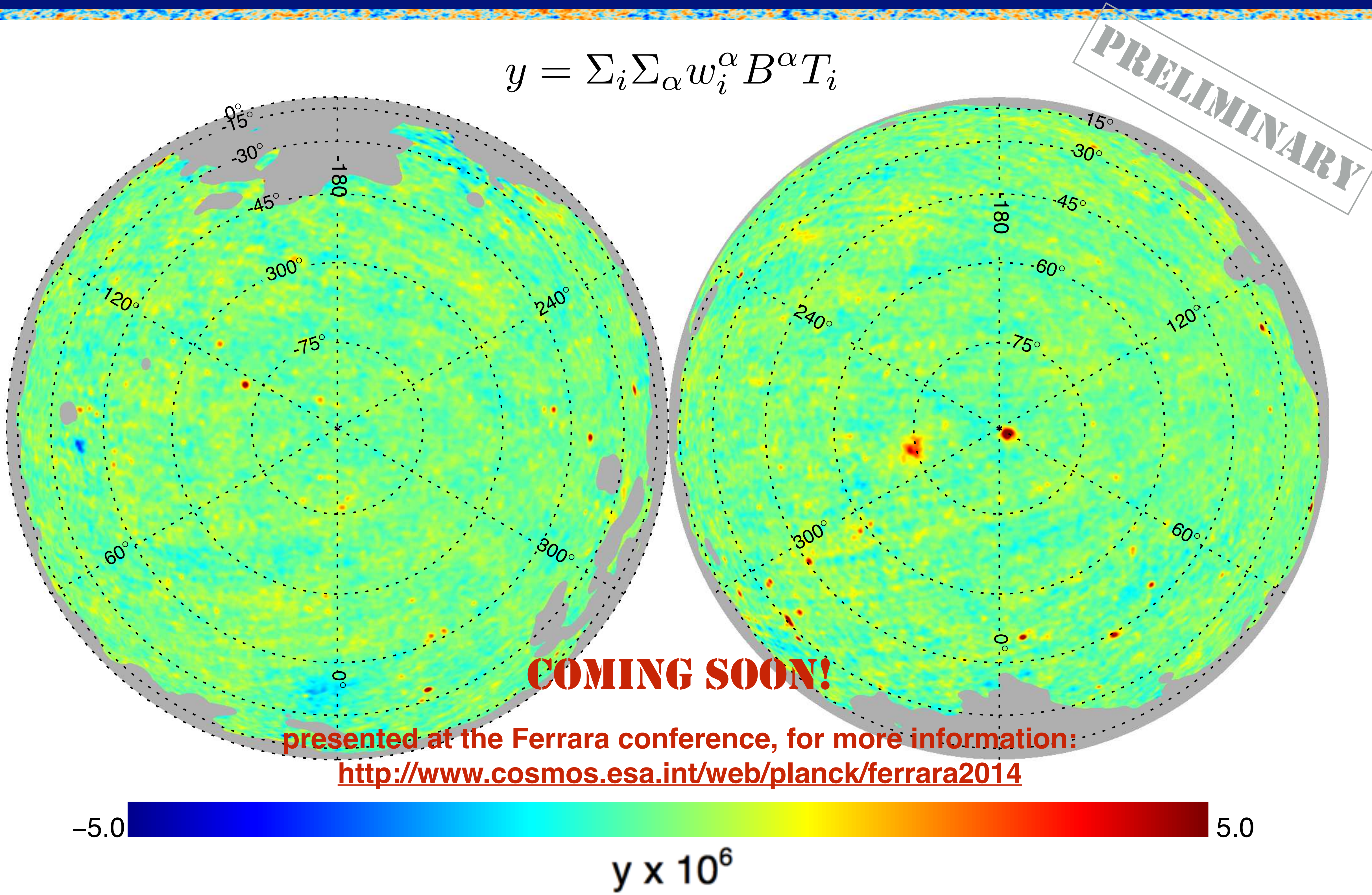
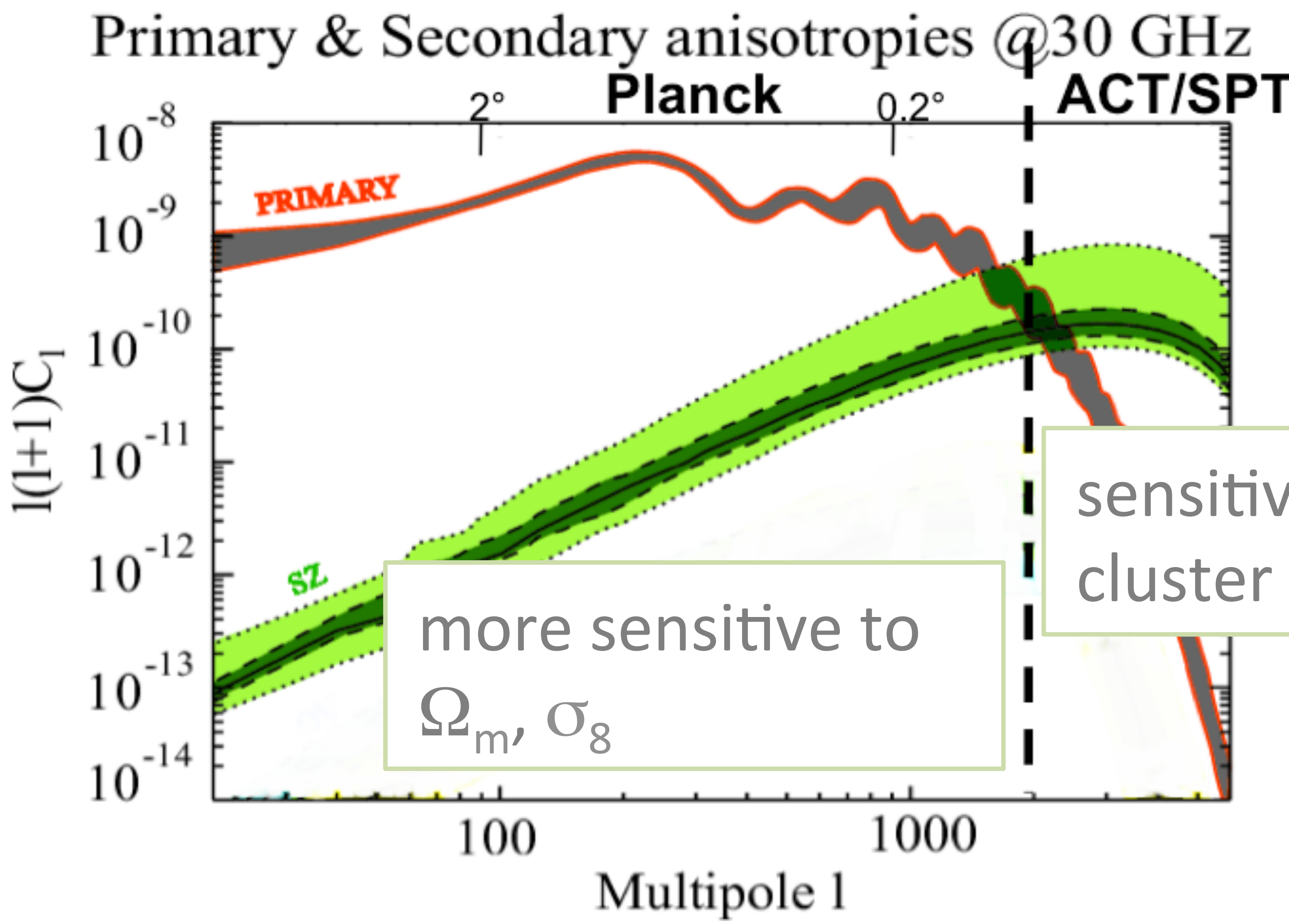


presented at the Ferrara conference, for more information:
http://www.cosmos.esa.int/web/planck/ferrara2014

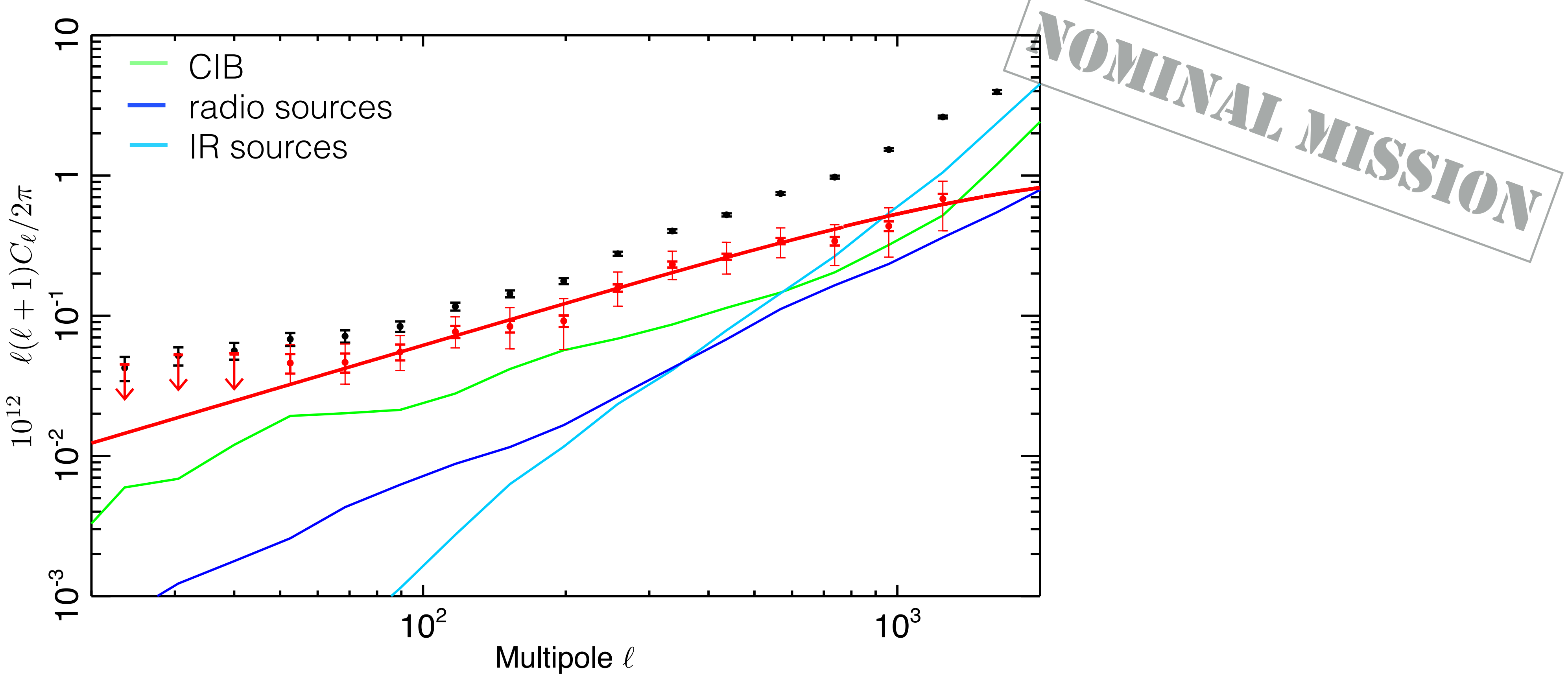
SZ power spectrum



more sensitive to Ω_m, σ_8

sensitive to the details of cluster astrophysics

SZ power spectrum



$$C_\ell = C_\ell^{tSZ}(\Omega_m, \sigma_8) + A_{CIB} C_\ell^{CIB} + A_{PS}(C_\ell^{IR} + C_\ell^{Rad})$$

modelling of residual foregrounds

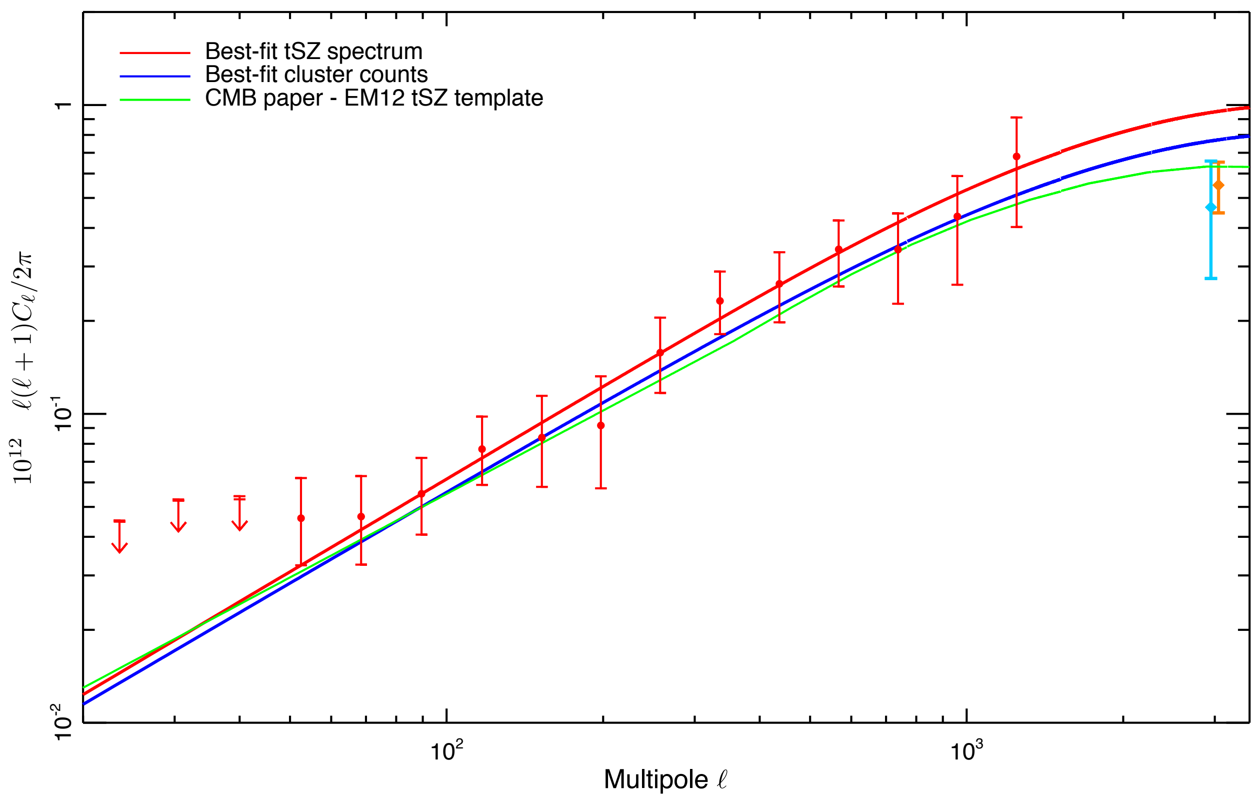
analytic model of the signal

$$\frac{dn(\sigma_8, \Omega_m)}{dM} + \begin{cases} Y_\Delta = A M_\Delta^\alpha \\ M_{tot}^{HE} = (1-b) M_{tot} \\ P_e(r) \end{cases}$$

Planck 2013 results. XXI (2013)

SZ power spectrum

NOMINAL MISSION



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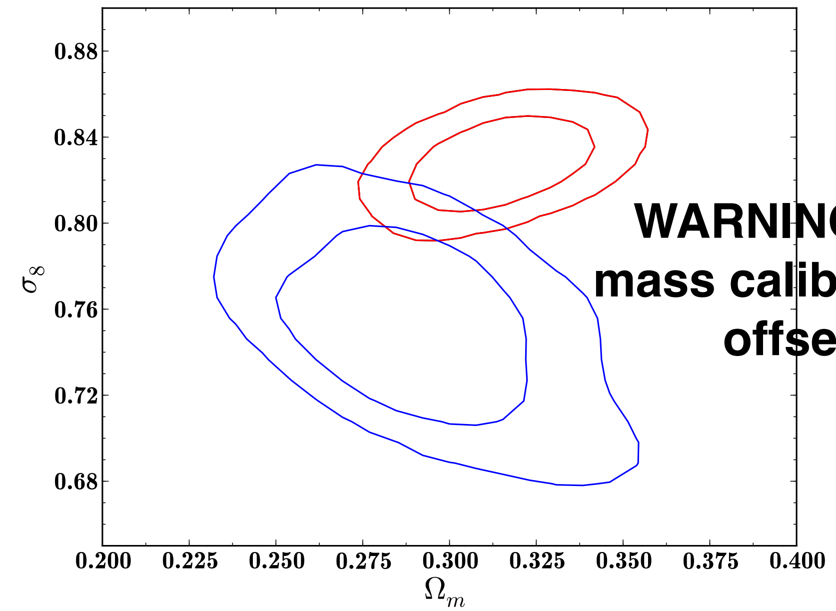


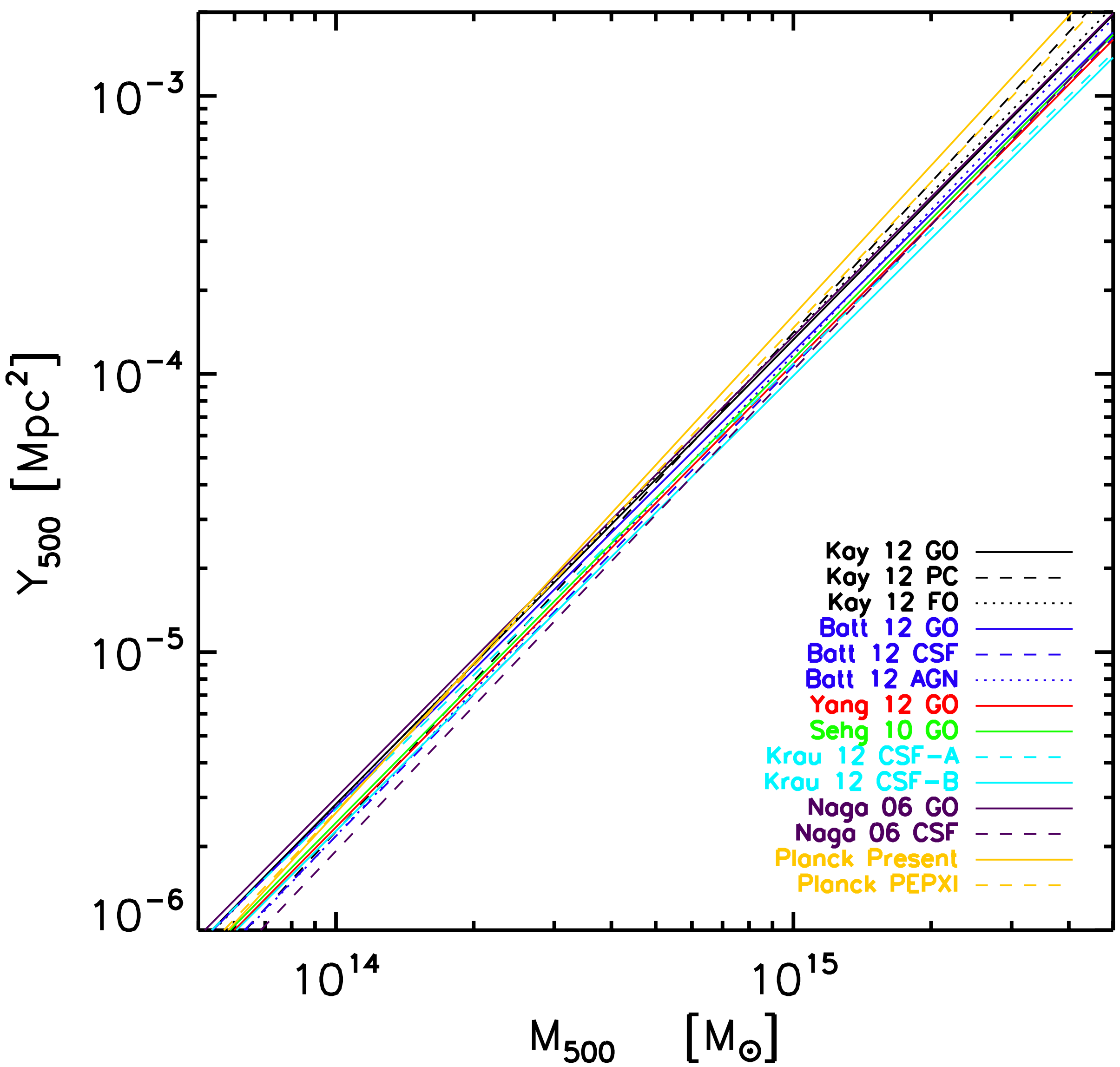
WARNING: different mass calibrations drive offsets in σ_8

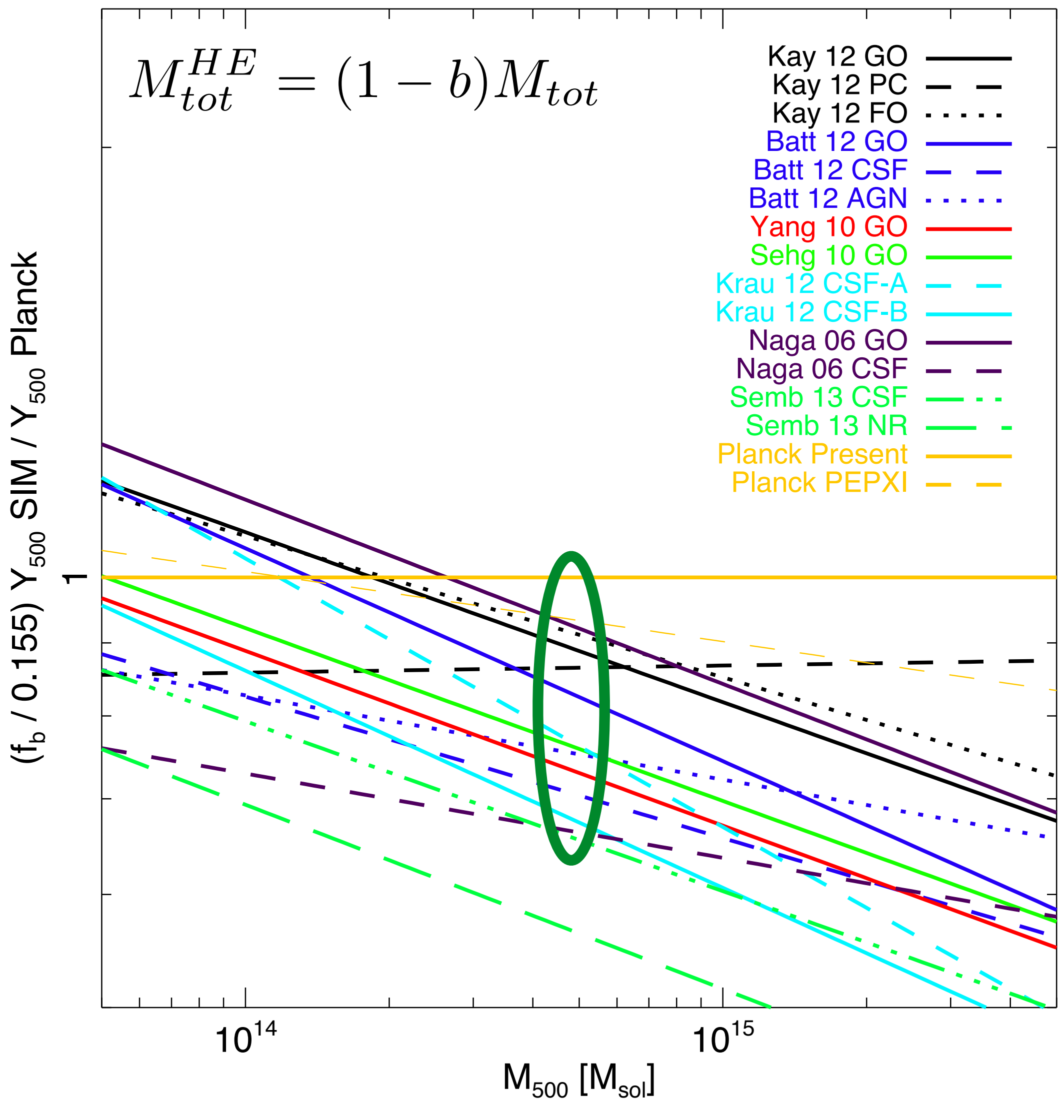
Planck 2013 results. XX, XXI (2013)

mass bias

$$\Delta I_{SZ} \propto Y_\Delta = \int_{r_\Delta} P_e(r)dV$$

$$YD_A^2 \propto f_{gas} M_{tot}^{5/3} E(z)^{2/3}$$ self-similar evolution





Need for accurate cluster masses

Weak lensing mass calibration

A very active field!

Weak lensing can provide a direct (complementary) absolute mass normalization of such scaling relations

CCCP *(Hoekstra+2012, Mahdavi+2013),* ***Weighing the Giants*** *(von der Linden+2014; Applegate+2014),* ***400d WL*** *(Israel+2014),* ***CFHTLenS*** *(Ford +2014),* ***SPT WL*** *(High+2012),* ***LoCuSS*** *(Okabe+2010; Marrone+2013),* ***WISCy*** *(Gruen+2014),* ***CLASH*** *(Umetsu+2014)*

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

~ 2020: Euclid + LSST

surveys from which it will be possible to extract cluster samples **(large number of z>1 clusters)** with high completeness and purity, large sky coverage and well known selection function

SPT-3G (2016 - 2019)
2,500 deg2 (10 times deeper then SPT)

Advanced ACTPol
20,000 deg2 over 3 years, complete overlap with LSST

Future SZ goals

ACT, **SPT** and **Planck**: **tSZ-selected cluster catalogues** containing hundreds, thousands of candidates with **arcmin resolution**

Clusters and their **tSZ** (ICM) signal are becoming a valuable cosmological tool

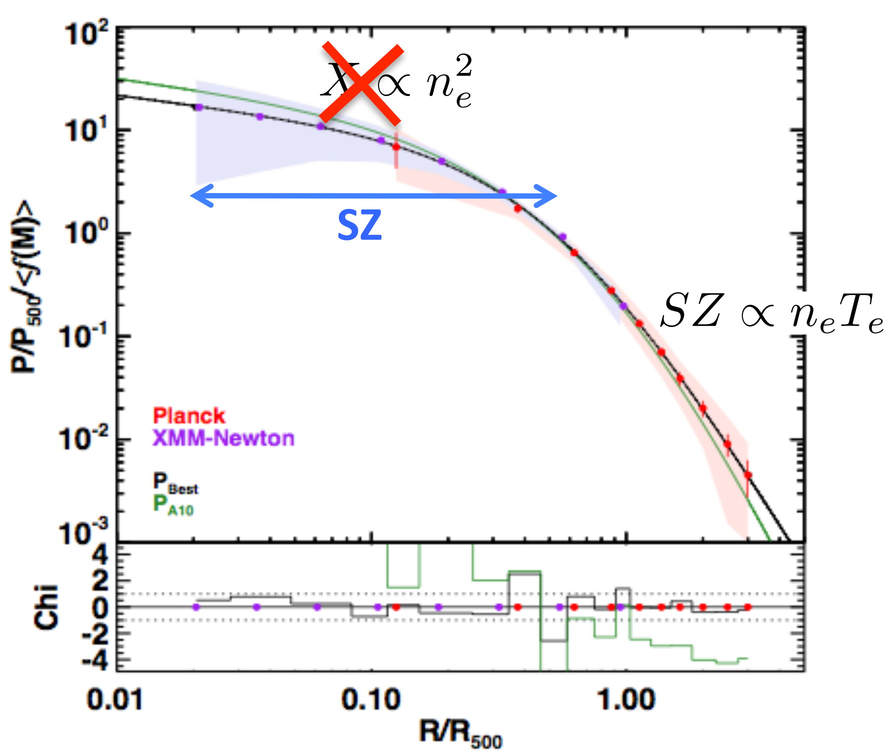
[e.g. Planck 2013 Results. XX]

→ $\boxed{M_{Hyd} = (1-b)M_{tot}}$

$$YD_A^2 \propto f_{gas} M_{tot}^{5/3} E(z)^{2/3}$$

well known for the local Universe

$$\frac{P(r)}{P_{500}} = \frac{P_0}{(\frac{r}{r_s})^{\gamma}[1+(\frac{r}{r_s})^{\alpha}]^{(\beta-\gamma)/\alpha}}$$



→ @ high-z ?

→ not yet directly explored with SZ at r ≈ 0.1 r_{500}
[e.g. Planck Intermediate Results. V (XMM+Planck), *McDonald et al. 2014* (Chandra+SPT)*]*

→ deviation from the average behavior as a function of *z*, dynamics, M_{tot} etc.

High angular resolution tSZ observations and follow-ups are now necessary to deeply explore the cluster internal structure and to better address the physics at play, especially when dealing with intermediate and high z objects.

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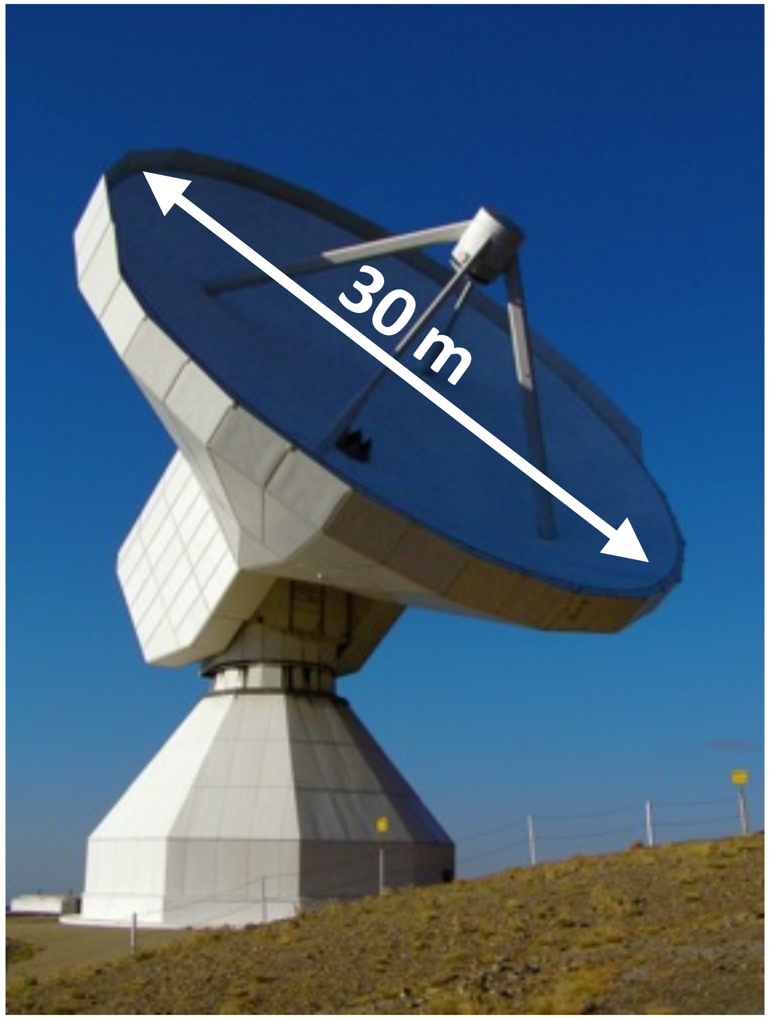
New IRAM KID Array: the telescope

The **New IRAM KID Array** is a dual-band **KIDs camera** developed in Grenoble to work at the **IRAM 30m telescope**



- Located at **2850 m a.s.l.** (Pico Veleta, Sierra Nevada)
- One of today's largest and most sensitive radio telescopes for tracing millimeter waves
- $\varnothing$ = 30 m
- f.o.v. = 6.5 arcmin

→ FWHM = 17 arcsec @2mm
FWHM = 12 arcsec @1mm

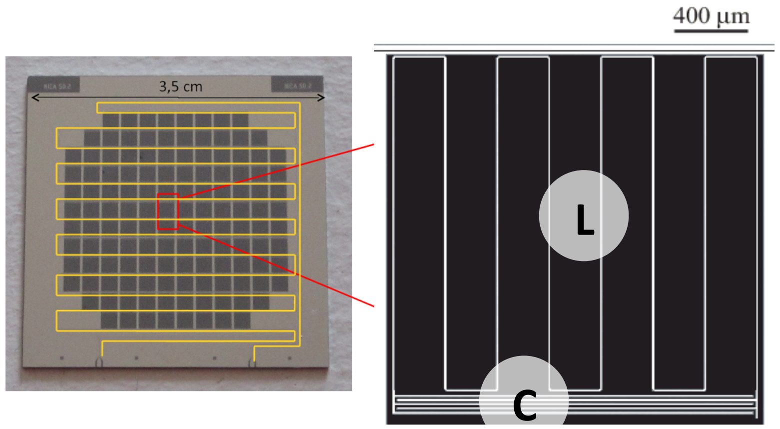
NIKA	260 GHz	150 GHz
beam (FWHM)	12.5"	18.5"
# of det	224	132
fov eff. diameter	1.8'	2.0'
sensitivity	35 mJy*s$^{1/2}$	14 mJy*s$^{1/2}$

we need large matrix of detectors !

Catalano, A., Ponthieu, N., Calvo M., & NIKA Collaboration, 2014
Calvo, M., Roesh, M., Désert, F.-X., et al, 2013

New IRAM KID Array: the detectors

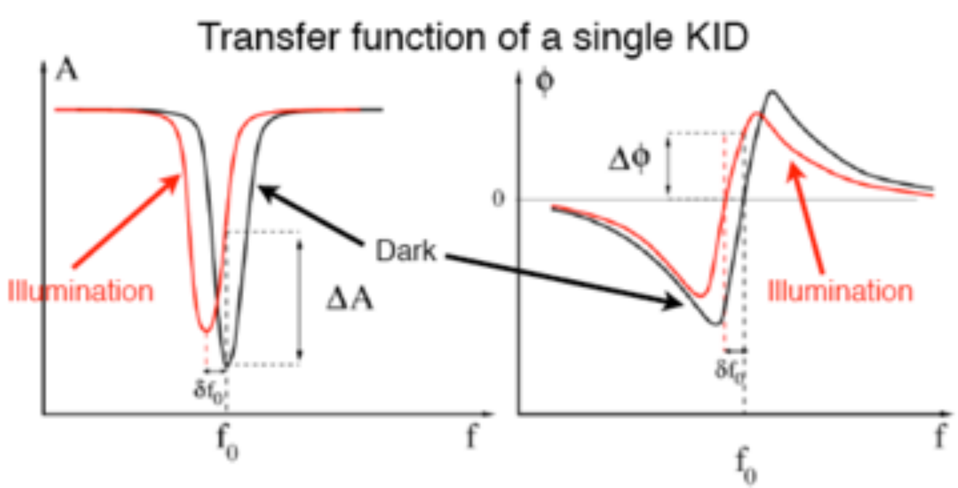
Interesting alternative to bolometers:



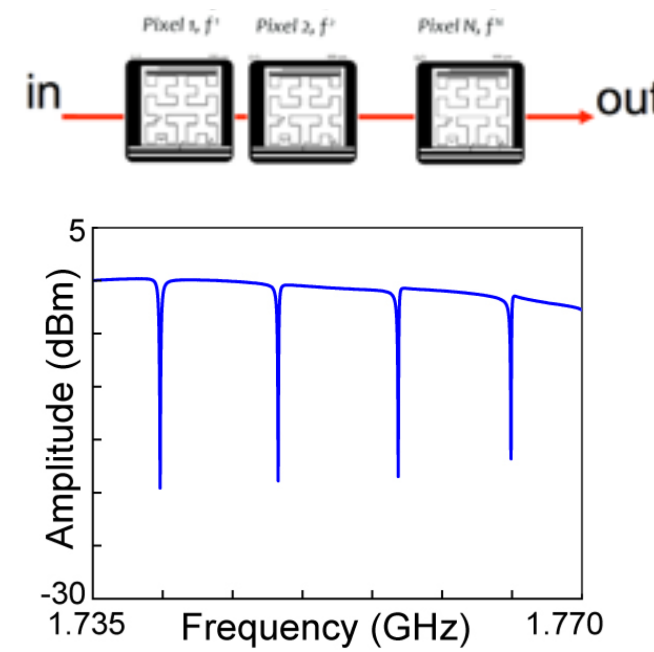
Kinetic Inductance Detectors (**KIDs**) are **superconducting RLC resonators** @ T ≈ 100 mK << T_c ≅ 1.2K

Incoming radiation changes the kinetic inductance by breaking Cooper pairs

$$\delta f_0 \propto \delta L_k \propto P_{opt}$$



pixels connected to a single transmission line, **naturally multiplexable**

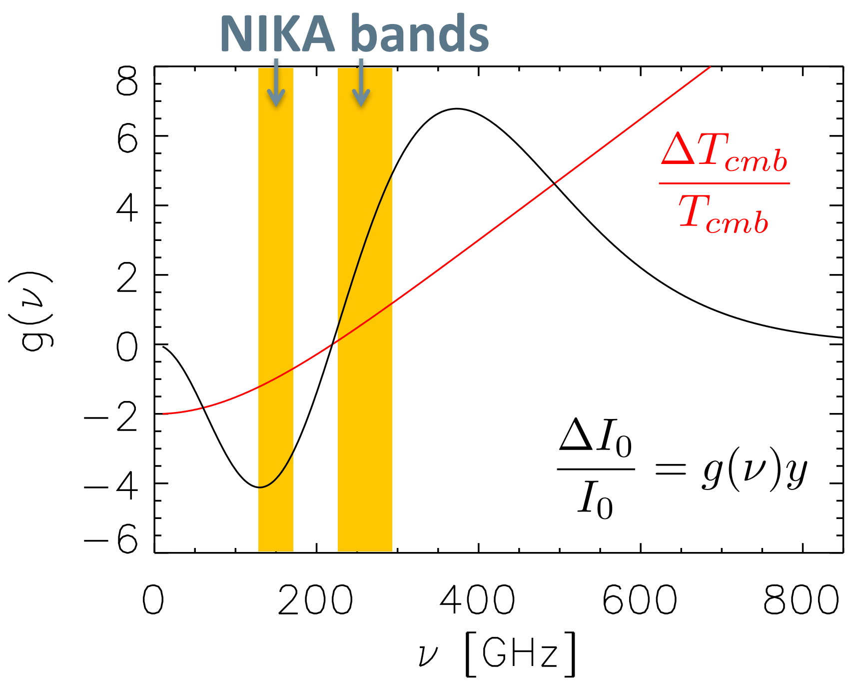


Monfardini, Benoit, Bideaud et al. 2011

matrix of hundreds (NIKA) or thousands (NIKA2, the final instrument) of pixels can be realized

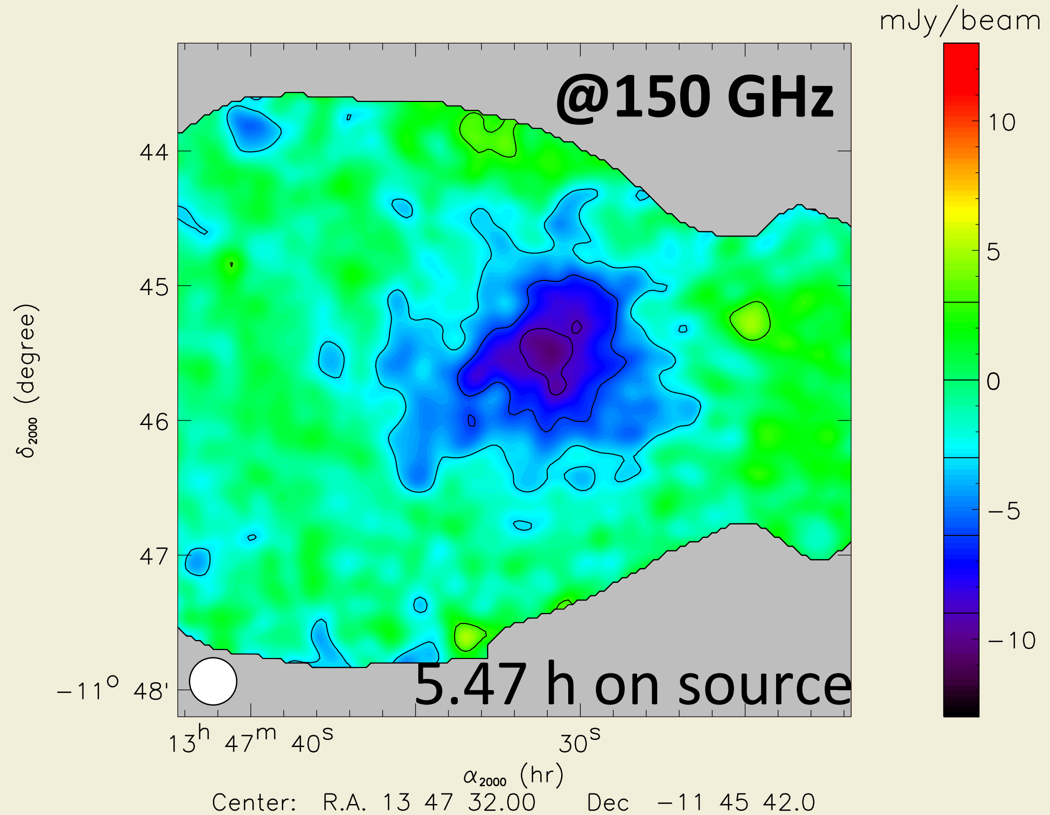
SZ with NIKA

In November 2012 NIKA has produced the first SZ map ever achieved with KIDs



intermediate redshift (z = 0.451), compact, strong and well known

RXJ1347.5-1145:



[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration 2014]

SZ with NIKA

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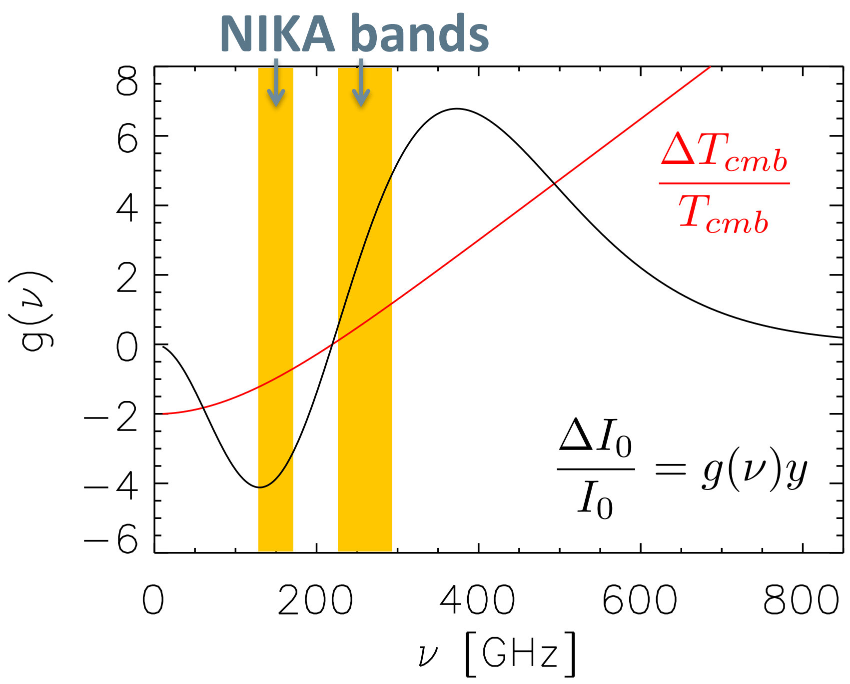

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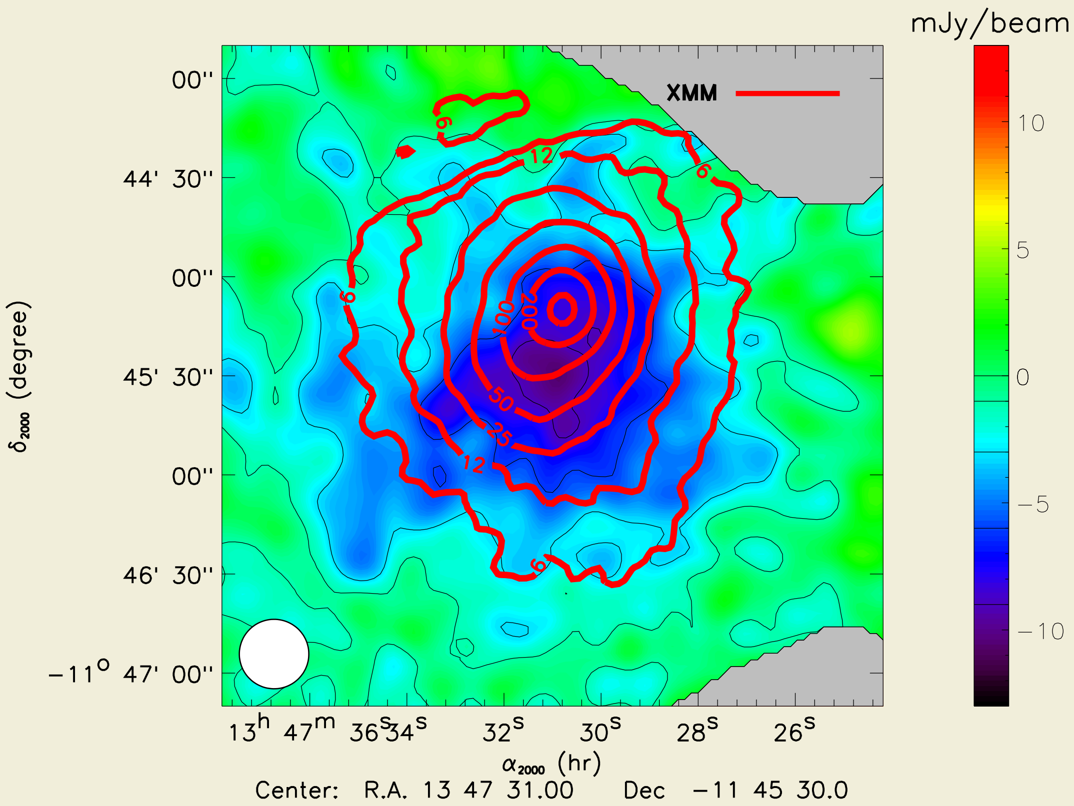
RXJ1347.5-1145:



[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration 2014]

SZ with NIKA

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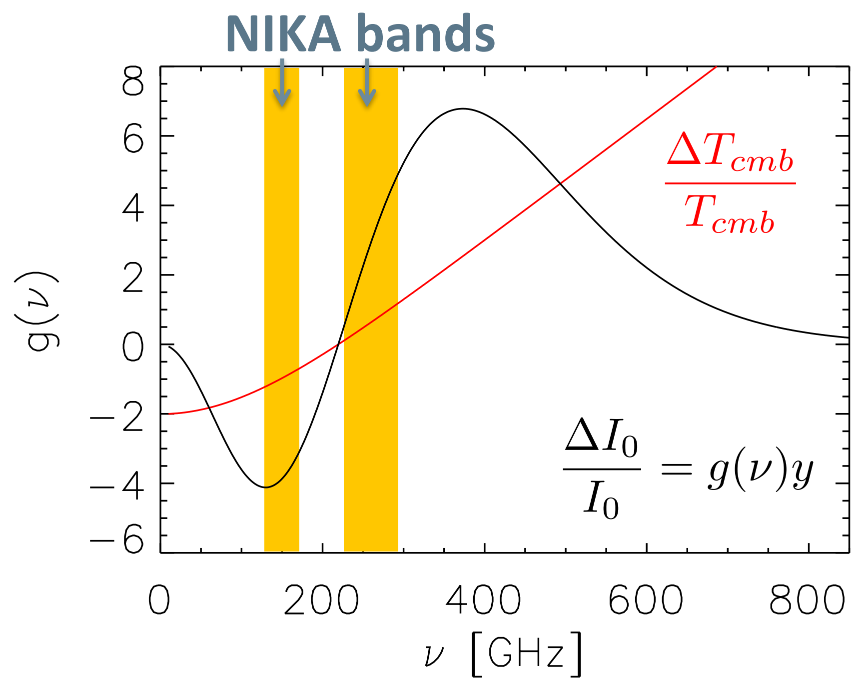
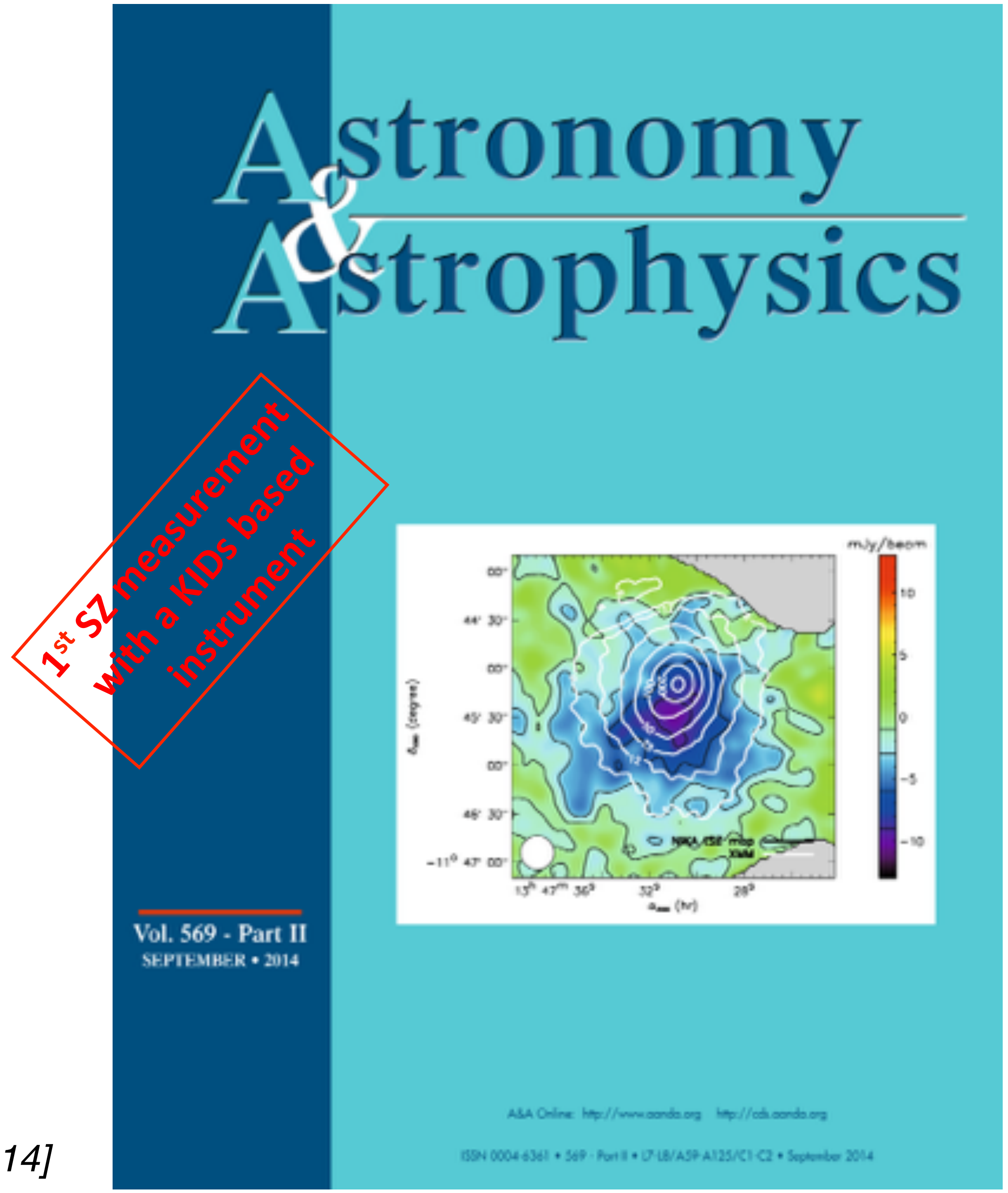
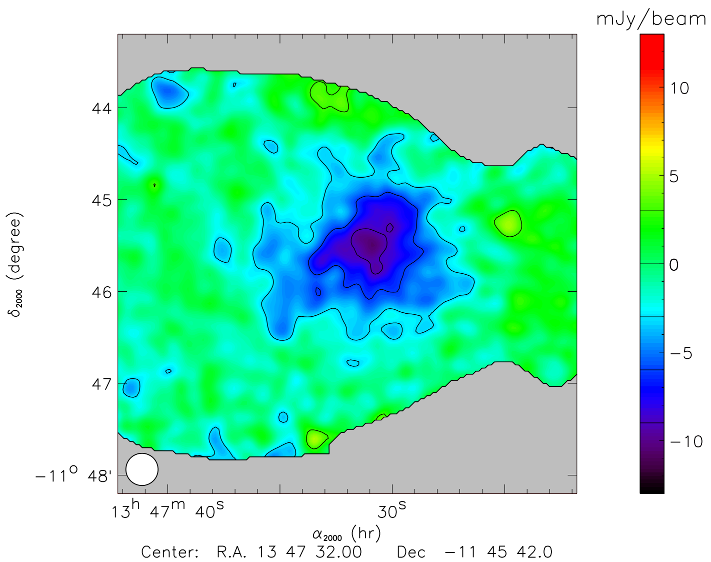




[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration 2014]

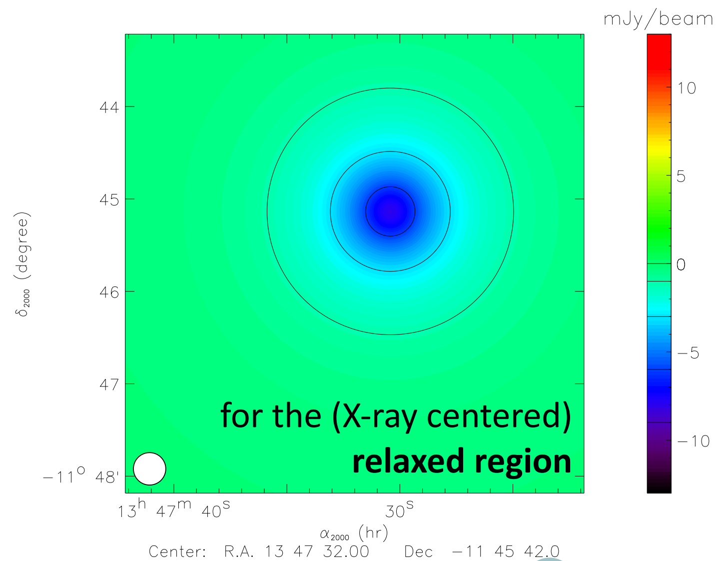
SZ with NIKA

Data



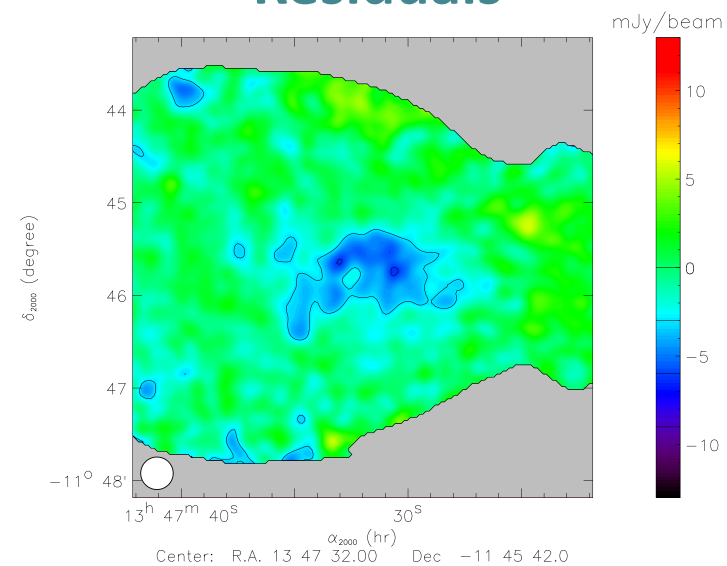
=

Best-fit model



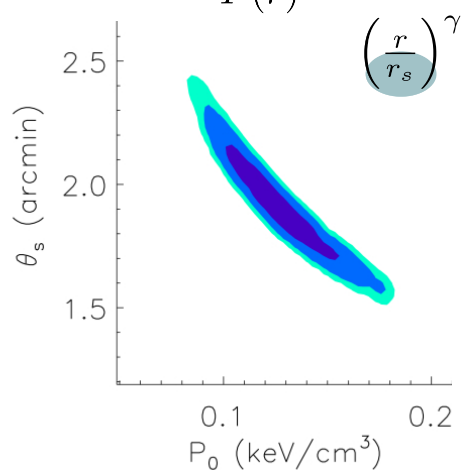
+

Residuals



- Observations performed in November 2012
- Dual-band common-mode decorrelation using the 240 GHz
  ⟶ large scales are recovered

$$P(r) = \frac{P_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$



$\alpha = 1.2223$
$\beta = 5.4905$
$\gamma = 0.7736$

excess of signal corresponding to a shock from a merging event

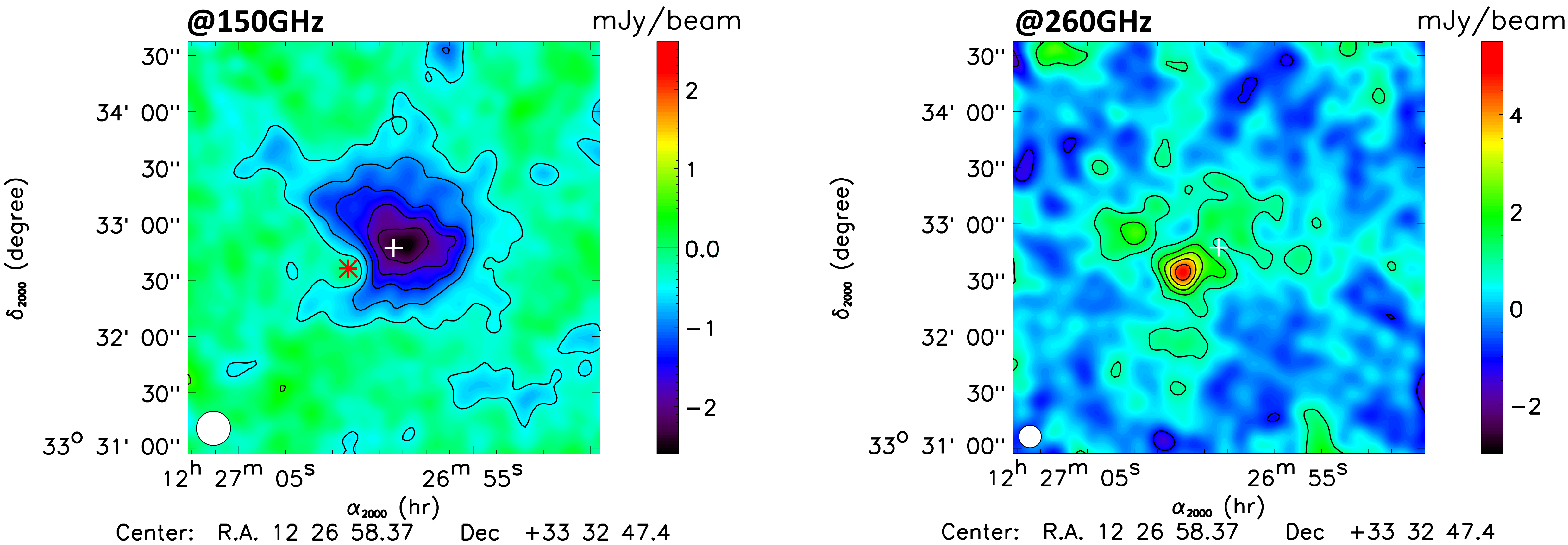
Using only NIKA data we have been able to show that RXJ1347.5-1145 is well described by a relaxed cool-core subject to a merging on its South-East part

[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration 2014]

SZ pilot study: high-z cluster

NIKA: open to external observers since the 2013/2014 winter campaign

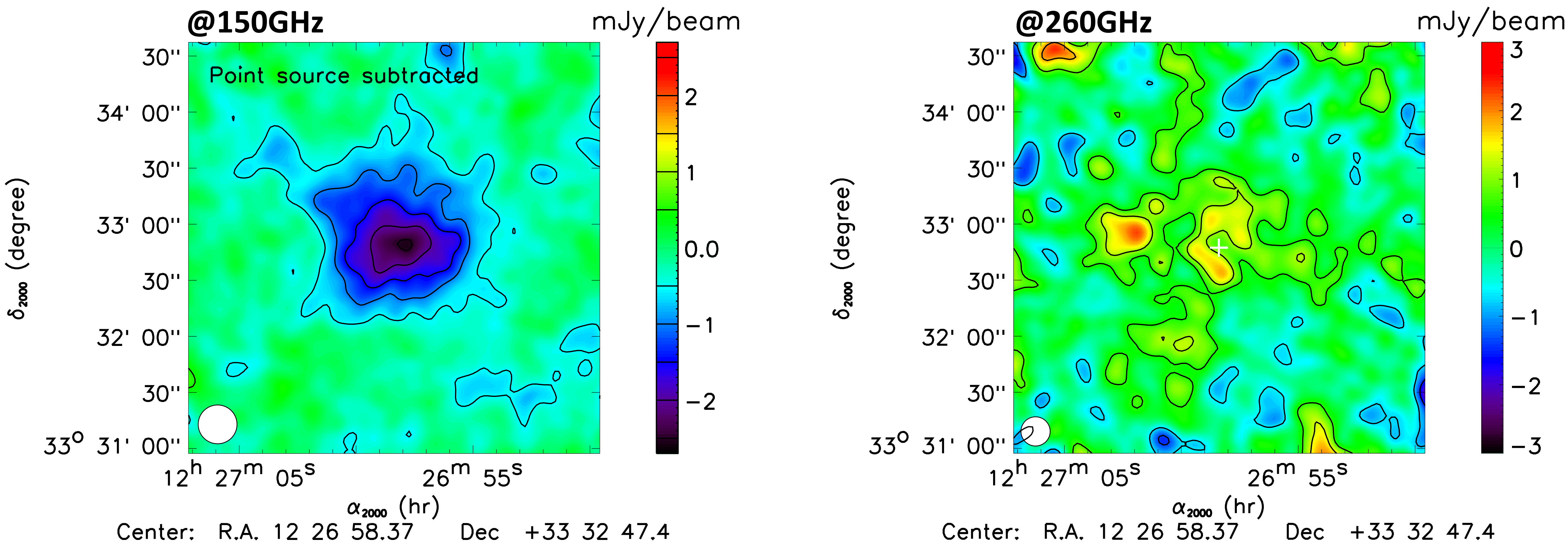
February 2014 - 1st open pool: **CL J1226.9+3332 (z=0.89)**



[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration arXiv:1410.2808]

SZ pilot study: high-z cluster

February 2014 - 1st open pool: CL J1226.9+3332 (z=0.89)



measure angular scales structures from 20'' up to 3' (r ≈ 0.1 - 1 r_{500})

- **NIKA**: pressure profile → **M_{tot} & Y**
- **NIKA + X-ray:** Mass, temperature and entropy radial profiles

[R. Adam, B. Comis, J. F. Macias-Perez & NIKA Collaboration arXiv:1410.2808]

SZ pilot study

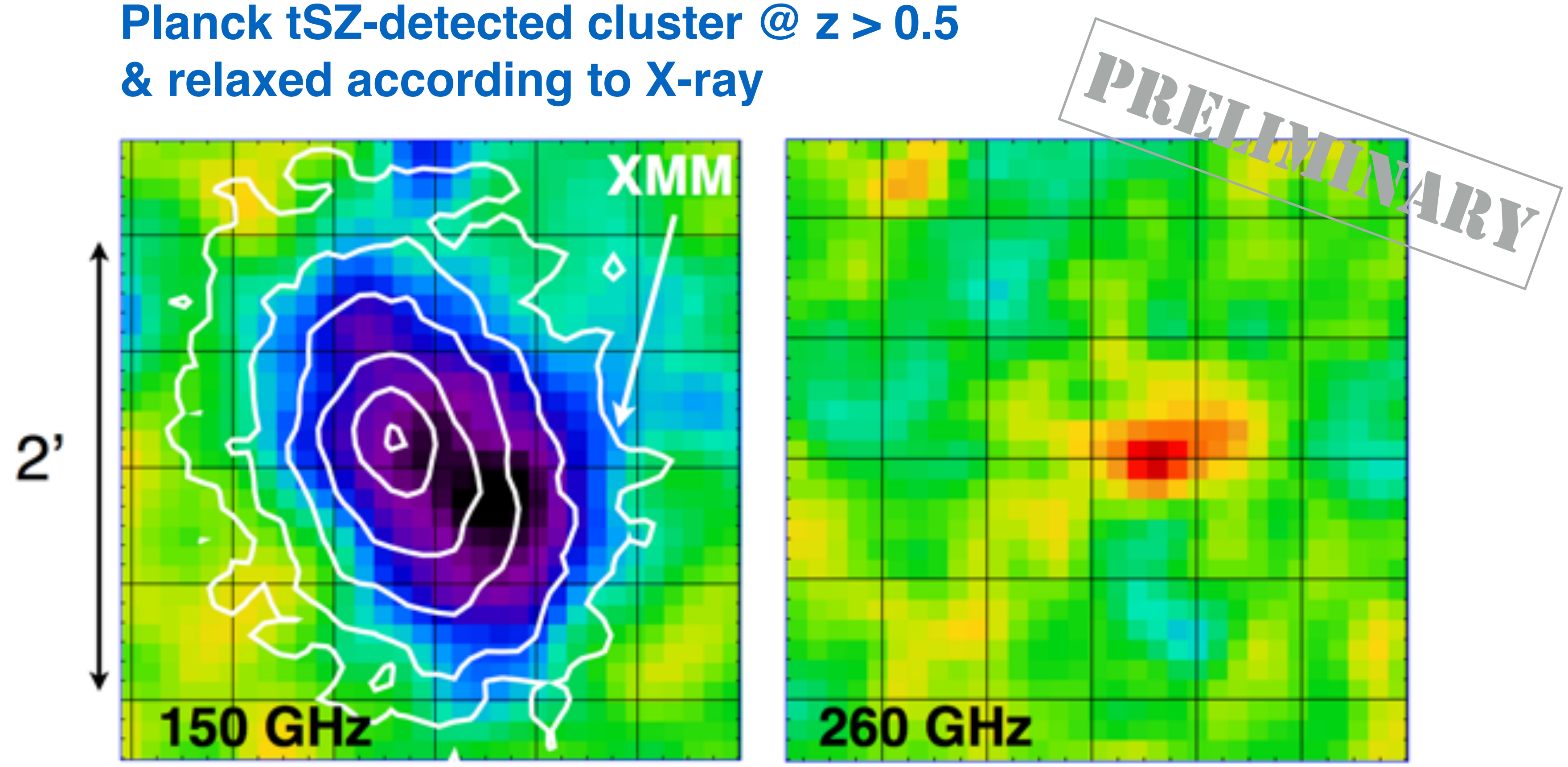
- KID arrays are competitive detectors for millimeter wave astronomy and in particular for the observation of galaxy clusters via the tSZ effect
- **NIKA is capable of producing high-quality cluster maps with excellent angular resolution (~ 20”), enabling detailed examination of cluster morphology through the tSZ effect.**
- NIKA2 could be well-suited for in-depth studies of the ICM from local to distant clusters (e.g. follow up of PLANCK’s clusters at high redshift)

November 2014 - 2nd open pool

→ **sample a representative range of cluster X-ray morphologies**

→ **test NIKA detection at lower tSZ signals** and Planck detection significance $Y_{500} \approx 0.4 - 0.6\ Y_{500}^{RXJ1347}$

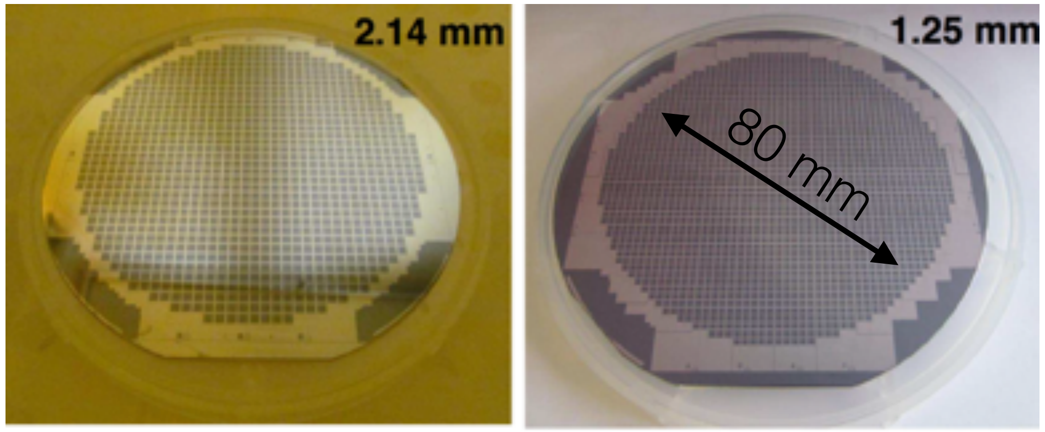
Planck tSZ-detected cluster @ z > 0.5 & relaxed according to X-ray



NIKA2

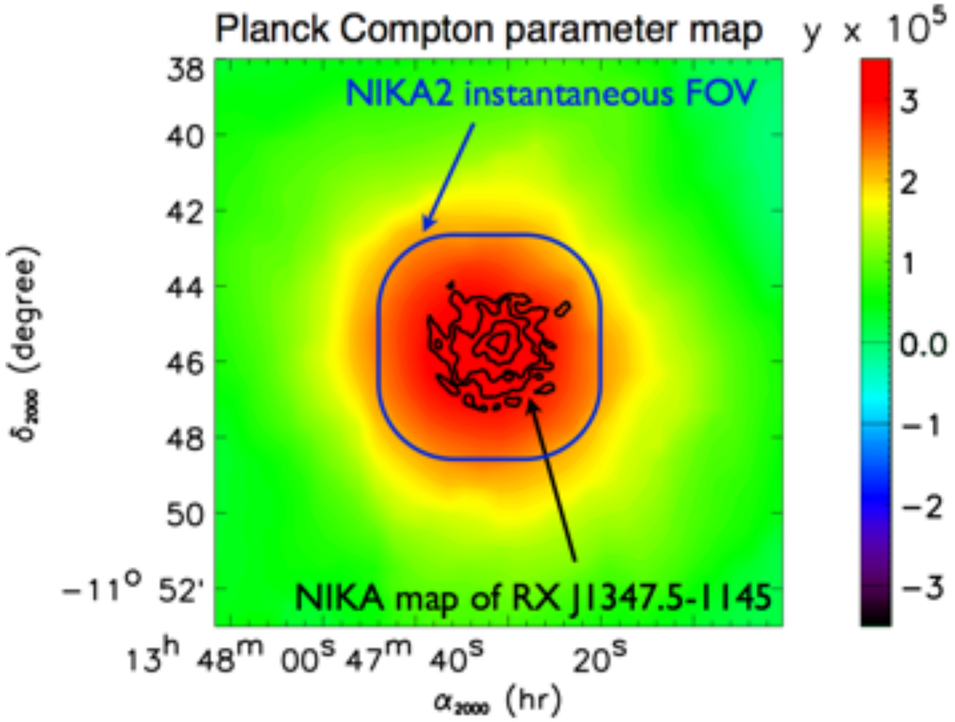
NIKA is the prototype of NIKA2, which will be permanently installed at the IRAM 30-meter telescope at the end of 2015.

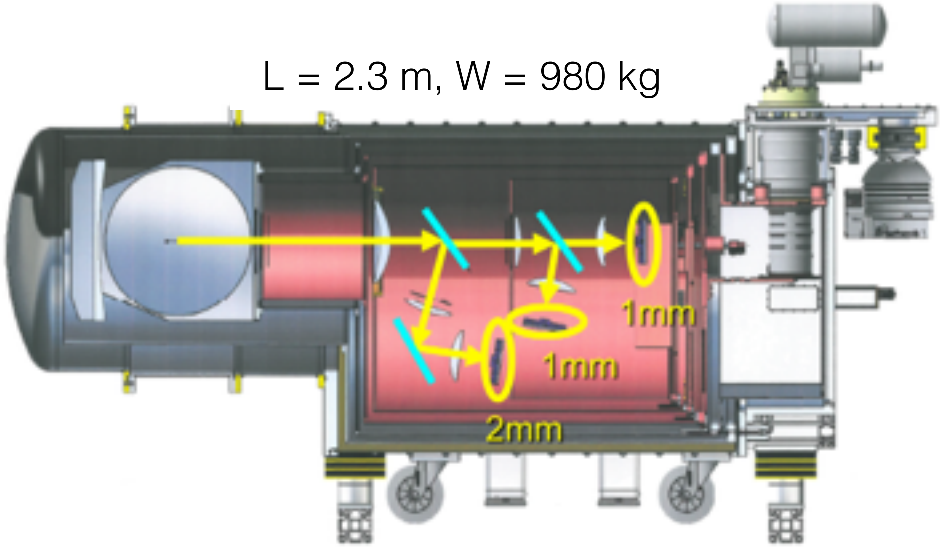
- **Large KID arrays**: 2x2000 KIDs at 260 GHz; 1000 KIDs at 150 GHz



1020 KIDs array for 2mm band

1932 KIDs array for 1.2mm band





- **A dilution cryostat** (3He-4He, 100 mK) **+ 2 cryo-refrigerators** (pulse-tube, intermediate temperature stage)
- **dedicated re-imaging optics** (warm and cold)
- **dedicated readout electronics** (**NIKEL** *[O. Bourrion et al. 2012]*, 20 boxes, warm)

NIKA2

NIKA	260 GHz	150 GHz
beam (FWHM)	12.5”	18.5”
# of det	224	132
fov eff. diameter	1.8’	2.0’
sensitivity	35 mJy*$s^{1/2}$	14 mJy*$s^{1/2}$

NIKA2	260 GHz	150 GHz
beam (FWHM)	12.5”	18.5”
# of det	2x2000	1000
fov eff. diameter	6.5’ (5’)	6.5’ (5’)
Sensitivity	30 mJy*$s^{1/2}$ (15 mJy*$s^{1/2}$)	20 mJy*$s^{1/2}$ (10 mJy*$s^{1/2}$)

NIKA2 has been selected as the IRAM next generation continuum (and polarisation) instrument at the 30m telescope.

It will be installed for commissioning at the end of 2015

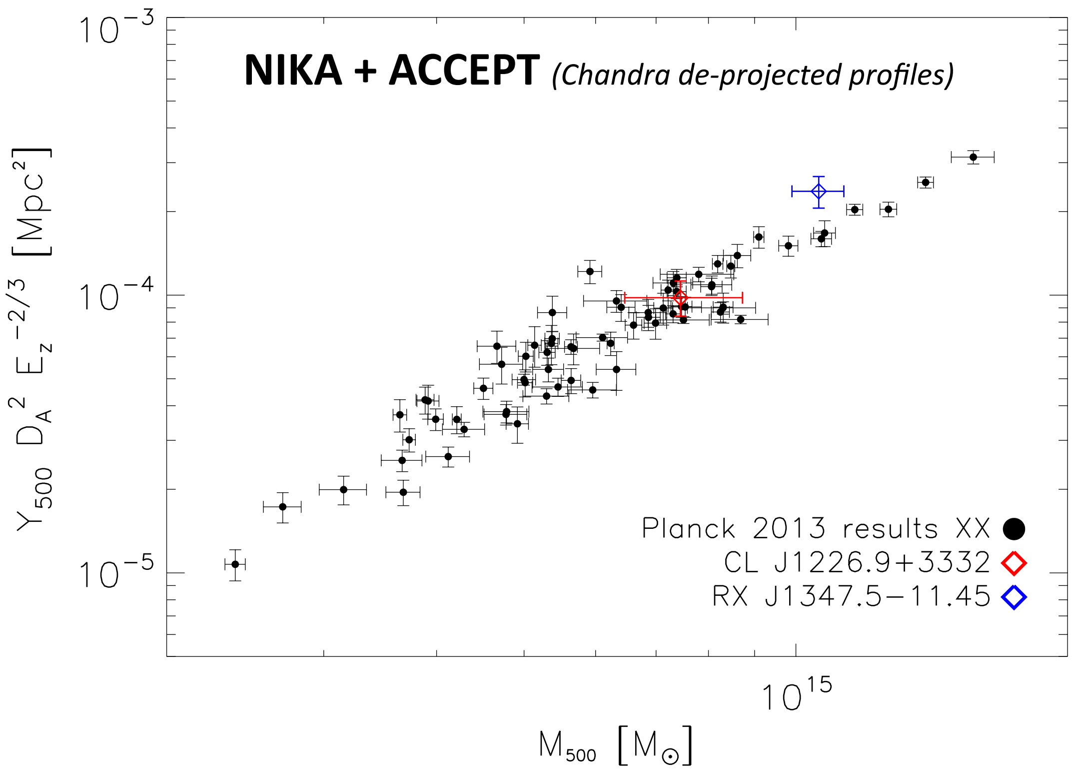
dual-band imaging capabilities (150 GHz and 260 GHz), it will be able to measure the linear polarization of the targeted sources at 260 GHz

NIKA2

NIKA2 will be well-suited for in-depth studies of the ICM from local to distant clusters

10' x 10' region	sensitivity	rms	rms @
1mm	18 mJy √s /beam	0.13 mJy/beam	0.1 mJy/beam
2mm	12 mJy √s /beam	0.09 mJy/beam	0.06 mJy/beam

2h - 10h per cluster !



Statistically significant, representative **NIKA sample of ≈ 50 clusters @ z > 0.5**

- study of the calibration of the **SZ flux as a mass proxy, its evolution with redshift and cluster dynamics**
- **redshift evolution** of the universal cluster pressure profiles, as well as deviations from its mean behavior due to cluster complex astrophysics and thermodynamical history

Outline

Cosmology and cosmology with galaxy clusters

The thermal Sunyaev-Zel'dovich effect

SZ (cosmological) results from the Planck satellite

Future goals for SZ observation (with NIKA)

Conclusions

Conclusions & Perspectives

tSZ surveys have proved to be competitive and complementary with respect to traditional methods of cluster detection (e.g. X-ray, optical)

⇨ **are now providing a reliable tool to push cluster detection and characterization to higher redshifts, A USEFUL COSMOLOGICAL TOOL**

High angular resolution tSZ observations and follow-ups are mandatory to deeply explore the cluster internal structure and to better address the physics at play, especially when dealing with intermediate and high z objects: SZ observations are at the core of the NIKA and NIKA2 projects

Cluster derived cosmological constraints are now limited by **systematics associated with the use of direct observables as proxies for mass**

the new generation SPT and ACT experiments
LSST, Euclid, and WFIRST in the optical/IR
eRosita in the X-rays

complementary, to address systematics