T_{CMB} vs redshift and the Hubble diagram from the Sunyaev–Zel'dovich effect

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Outline

- CMB
- SZE
- $T_{CMB}(z)$
- Cluster parameter recovery with Planck HFI and SAGACE
- Hubble diagram from SZE: case of Planck HFI

Cosmic Microwave Background (CMB)

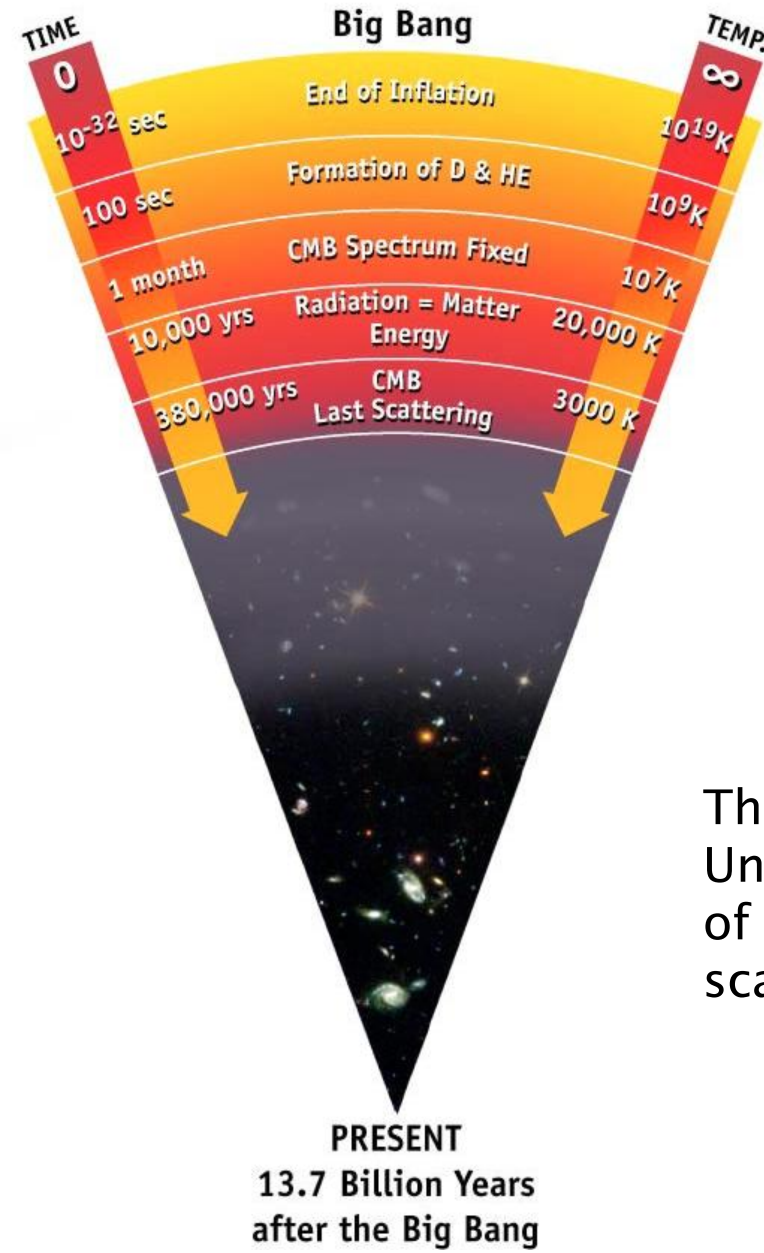
The Big Bang theory (Gamov 1948) foresees a primordial Universe which expands while cooling down.

The early Universe can be described as a plasma, in which ionized matter is coupled to radiation through Thomson scattering.

When the temperature falls below 3000K (at z~1000) electrons and protons recombine forming neutral hydrogen. Thomson scattering is no longer effective, therefore matter and radiation decouple.

The mean free path of photons becomes larger than the causal horizon: photons can travel freely to us.

Cosmic Microwave Background (CMB)



The CMB is the dominant radiation field in the Universe.

Discovered in 1965 by Penzias and Wilson. One of the most powerful pieces of informations in support of Big Bang theory.

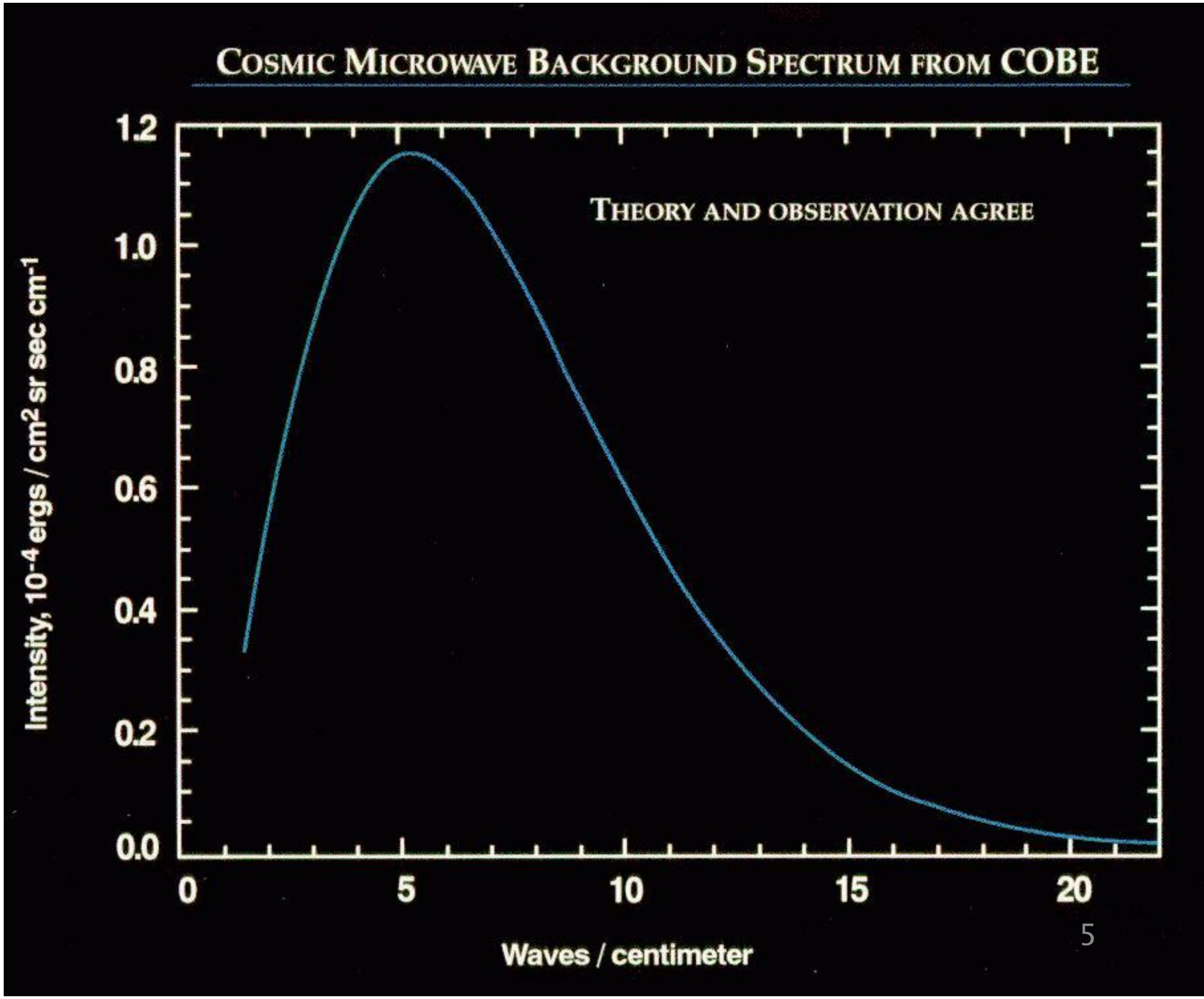
The CMB is interpreted as an image of the Universe at decoupling, that is the image of the surface from which photons were scattered by electrons for the last time.

CMB: BB spectrum

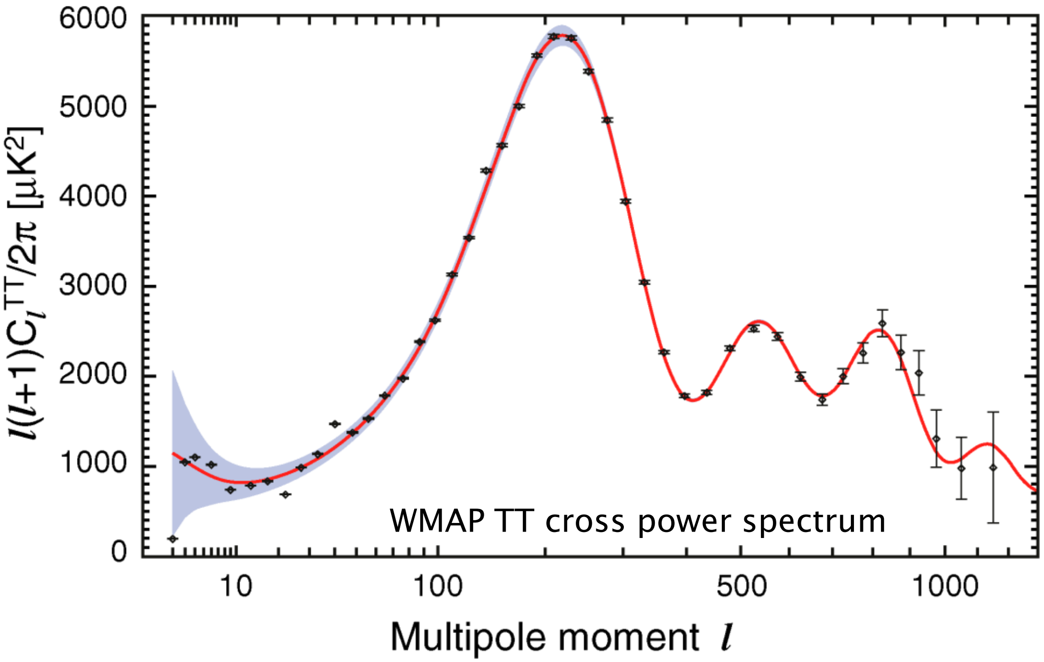
Being the CMB generated in a thermal equilibrium state, we expect a blackbody spectrum.

Observations by FIRAS on board COBE satellite have confirmed that the radiation is extremely close to the black body form at a temperature

$T_0 = (2.725 \pm 0.002)K$



CMB: power spectrum



The inhomogeneities in the matter distribution at z=1000 produced intensity fluctuations of the radiation field:

Primary Anisotropies

Predicted anisotropies are very sensitive to a wide range of cosmological parameters: accurate measurements of them provide excellent constraints on cosmological models.

Secondary anisotropies from galaxy clusters

There are a number of structures in the Universe that can affect the propagation of radiation between the decoupling epoch and the present, which lead to secondary anysotropies.

Clusters of galaxies, which are the most massive well differentiated structures in the Universe, introduce secondary anisotropies: both metric perturbations (Rees-Sciama) and due to comptonization of the CMB (Sunyaev Zel'dovich effect).

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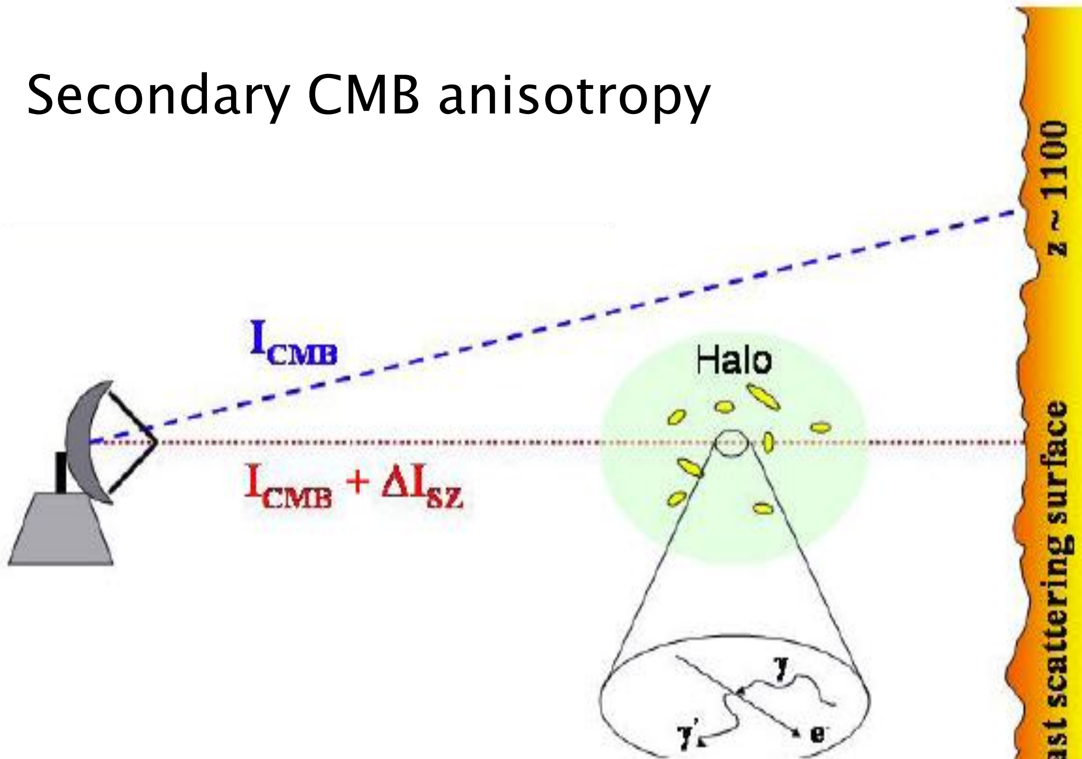
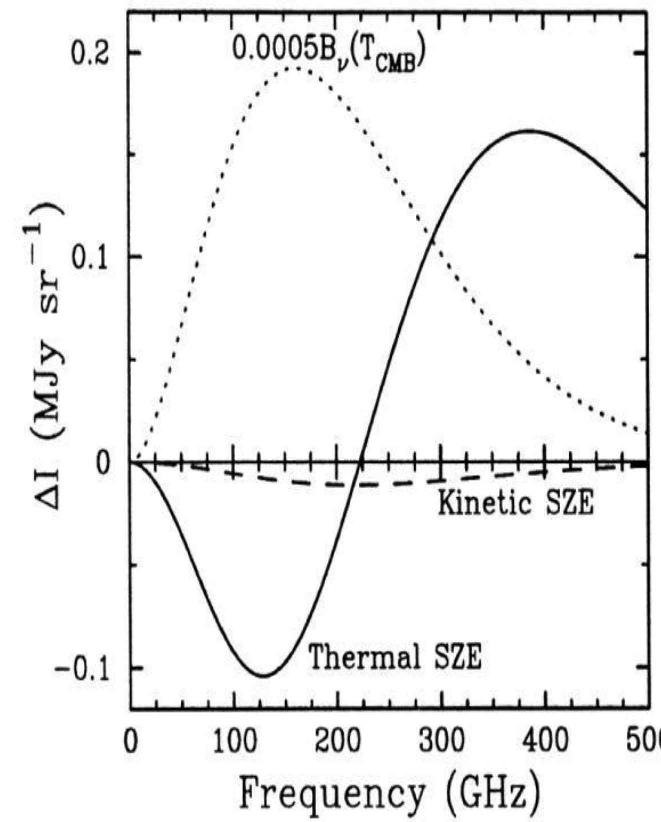
The Sunyaev Zel'dovich Effect (SZE) (I)

Secondary CMB anisotropy



Comptonization of the CMB by electrons in the hot gas of galaxy clusters.

$$\Delta I_{SZ} = SZ_{TERM} + SZ_{CIN} + SZ_{COR\ REL}$$



Spectral distorsion of the CMB due to the SZE

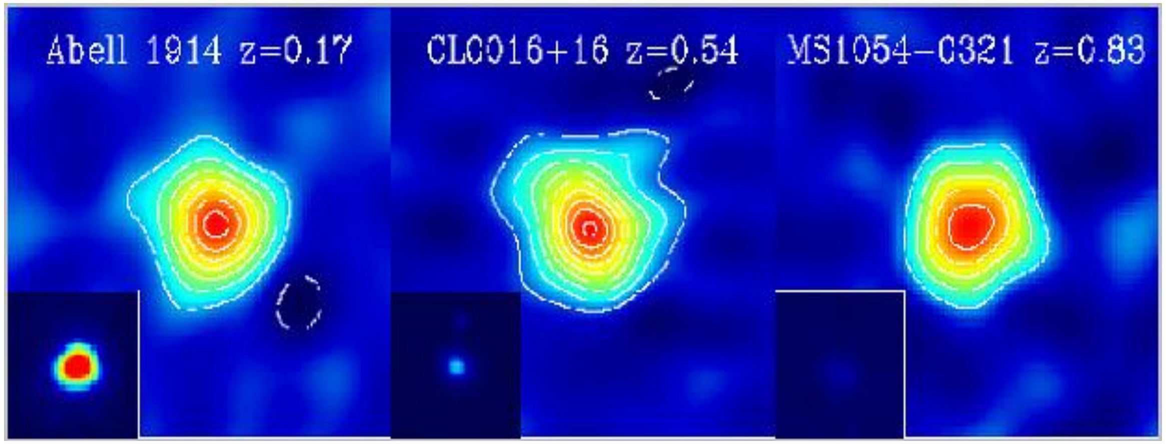
(Carlstrom JE A&A , 40, 643,2002)

The Sunyaev Zel'dovich Effect (SZE) (II)

Properties:
- unique spectral shape
- Redshift independent
- $\propto$ electron pressure in cluster atmospheres

$$\Delta I_{SZ} \propto \int n_e dl$$

$$S_X \propto \int n_e^2 dl$$



Xrays Xrays Xrays

- **Galaxy clusters Physics:**
  - τ optical depth
  - T_e electronic temperature
  - v_{pec} peculiar velocity
- **Cosmology:**
  - $T_{CMB}(z)$
  - H_0
  - Ω_B
  - evolution of abundance of clusters

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$T_{CMB}(z)$: why measure it?

- Observational test of the standard model: $T_{CMB}(z)=T_0(1+z)$
  $T_0 = (2.725 \pm 0.002)$K solar system value measured by COBE/FIRAS (Mather et al.1999)

- Test of the nature of redshift
  (test of the Tolman's law (Tolman. R. C., 1930, Proc. Nat. Acad, Sci., 16, 511)) ; Sandage 1988; Lubin & Sandage 2001)

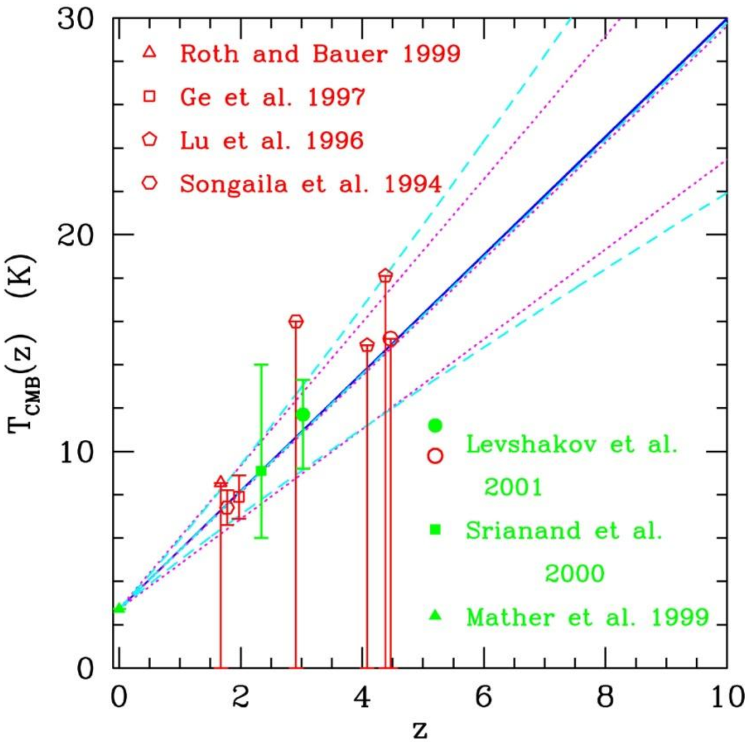
- Constraints on alternative cosmological models (which rely on the physics of the matter and radiation content of the Universe):
  - Λ-decaying models
    (Overduin and Cooperstock, Phys.Rev.D, 58 (1998)); (Puy,A&A,2004); (Lima et al., MNRAS, 312 (2000))
  - Decaying scalar field cosmologies

- Possible constraints on the variation of fundamental constants over cosmological time

$T_{CMB}(z)$: measurements

Measurements of CMB temperature traditionally through the study of excitation temperatures in high redshift molecular clouds.
First attempt pionered by (Bahcall and Wolf, 1968)

- Many high redshift estimates of T_{CMB} at redshift of absorbers
  (Songaila et al 1994; Lu et al. 1996; Ge et al 1997; Roth and Bauer, 1999; Srianand et al 2000; loSecco et al. 2001; Levshakov et al. 2002; Molaro et al. 2002; Cui et al. 2005)
- Systematics:
  - CMB is not the only radiation field populating the energy levels, from which transitions occur.
  - detailed knowledge of the physical conditions in the absorbing clouds is necessary (Combes and Wiklind, 1999; Combes ,2007)



(LoSecco et al. Phys. Rev. D, 64, 123, 2002)

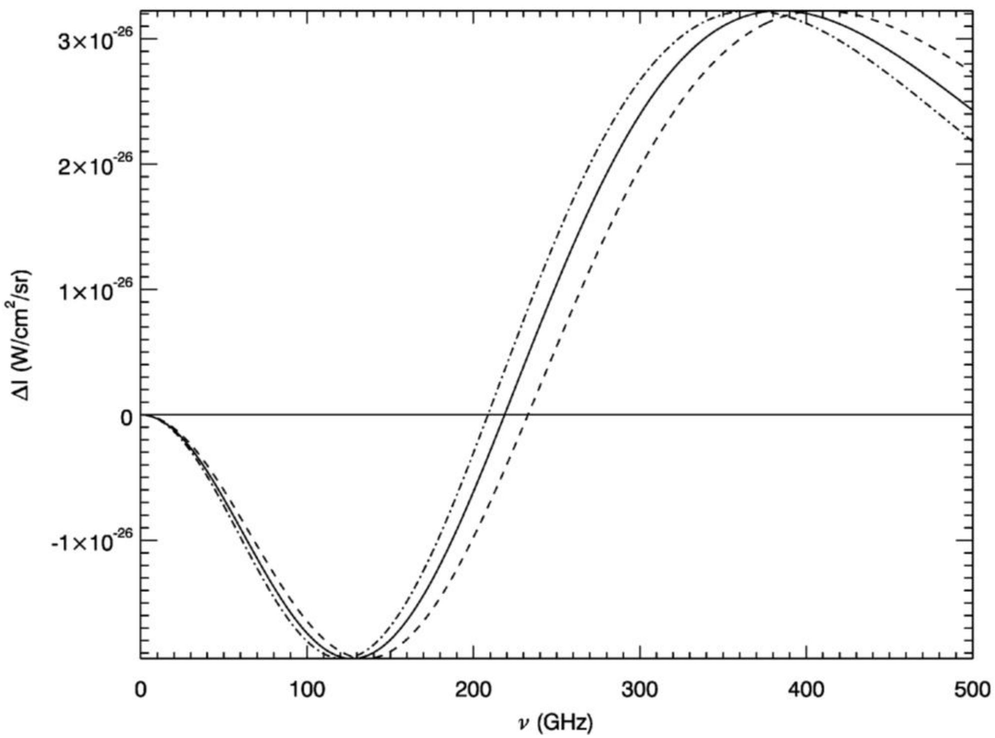
$T_{CMB}(z)$ from SZE (I)

(Fabbri R., F. Melchiorri & V. Natale. Ap&SS **59**, 223, 1978; Rephaeli Y. Ap.J. **241**, 858, 1980)

ΔI_{SZ} depends on frequency ν through the nondimensional ratio $h\nu/kT$:

$$x = \frac{h\nu(z)}{kT_{CMB}(z)} = \frac{h\nu_0(1+z)}{kT_0(1+z)} = \frac{h\nu_0}{kT_0}$$

redshift-invariant only for standard scaling of T(z)



In all other non standard scenarios, the “almost” universal (remember rel. corrections!) dependence of thermal SZ on frequency becomes z-dependent, resulting in a small dilation/contraction of the SZ spectrum on the frequency axis.

Ex: $T_{CMB}(z) = T_{CMB}(0)(1+z)^{1-a}$

(Lima et al. 2000)

$$x' = \frac{h\nu_0(1+z)}{kT_0(1+z)^{(1-a)}} = \frac{h\nu_0}{kT_{CMB}{}^*}$$

where $T^*_{CMB} = T_{CMB}(0)(1+z)^{-a}$

COMA observations

SZ on A1656 by MITO

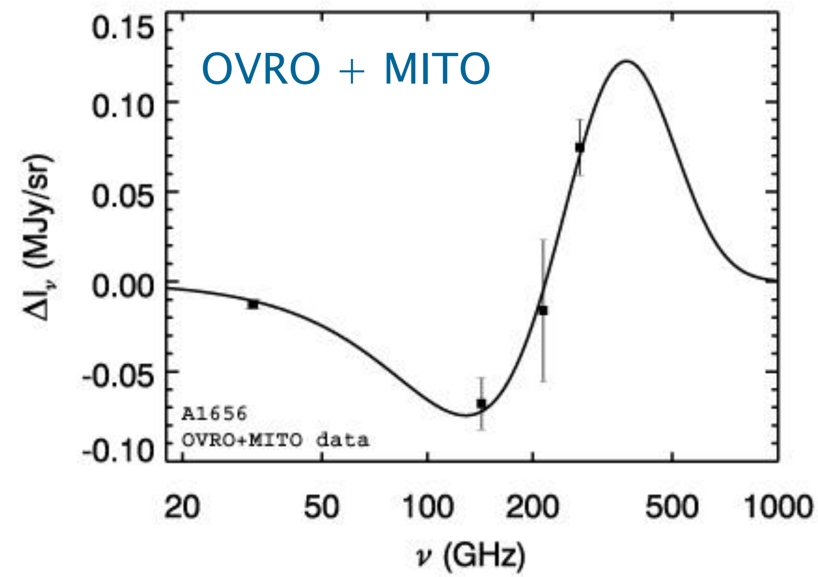
$$\Delta T_0(143\text{GHz}) = (-184 \pm 39)\ \mu\text{K}$$

$$\Delta T_0(214\text{GHz}) = (-32 \pm 79)\ \mu\text{K}$$

$$\Delta T_0(272\text{GHz}) = (+172 \pm 36)\ \mu\text{K}$$

$$\Rightarrow \tau_0 = (5.05 \pm 0.84) \cdot 10^{-3}$$

(De Petris M. et al. Ap.JL **574**, 119–122, 2002 & Savini G., ..L.G. et al. New Astr. **8**, 7, 727–736, 2003)



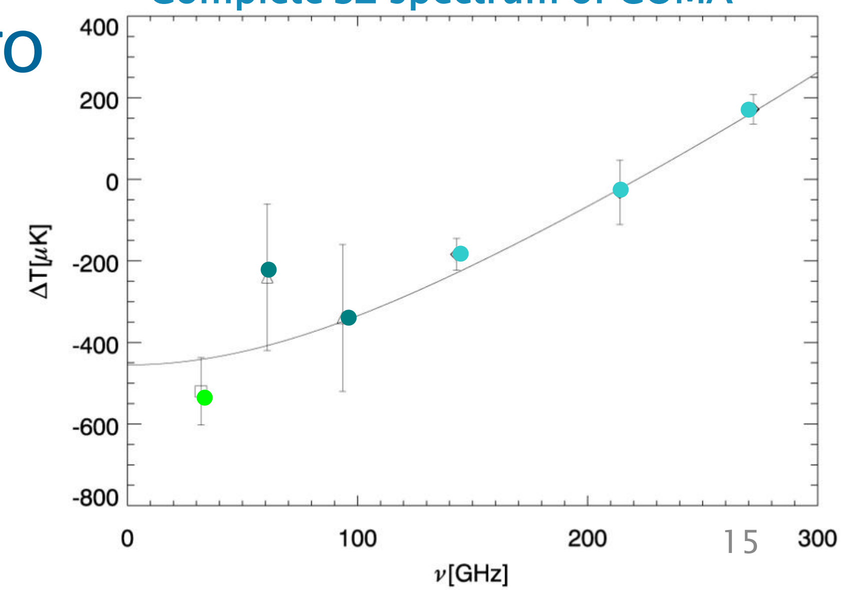
SZ on A1656 by OVRO+WMAP+MITO

First SZ spectrum with 6 frequencies

$$\Rightarrow \tau_0 = (5.35 \pm 0.67) \cdot 10^{-3}$$

(Battistelli,..L.G. et al. ApJ, 598:L75, 2003)

Complete SZ spectrum of COMA



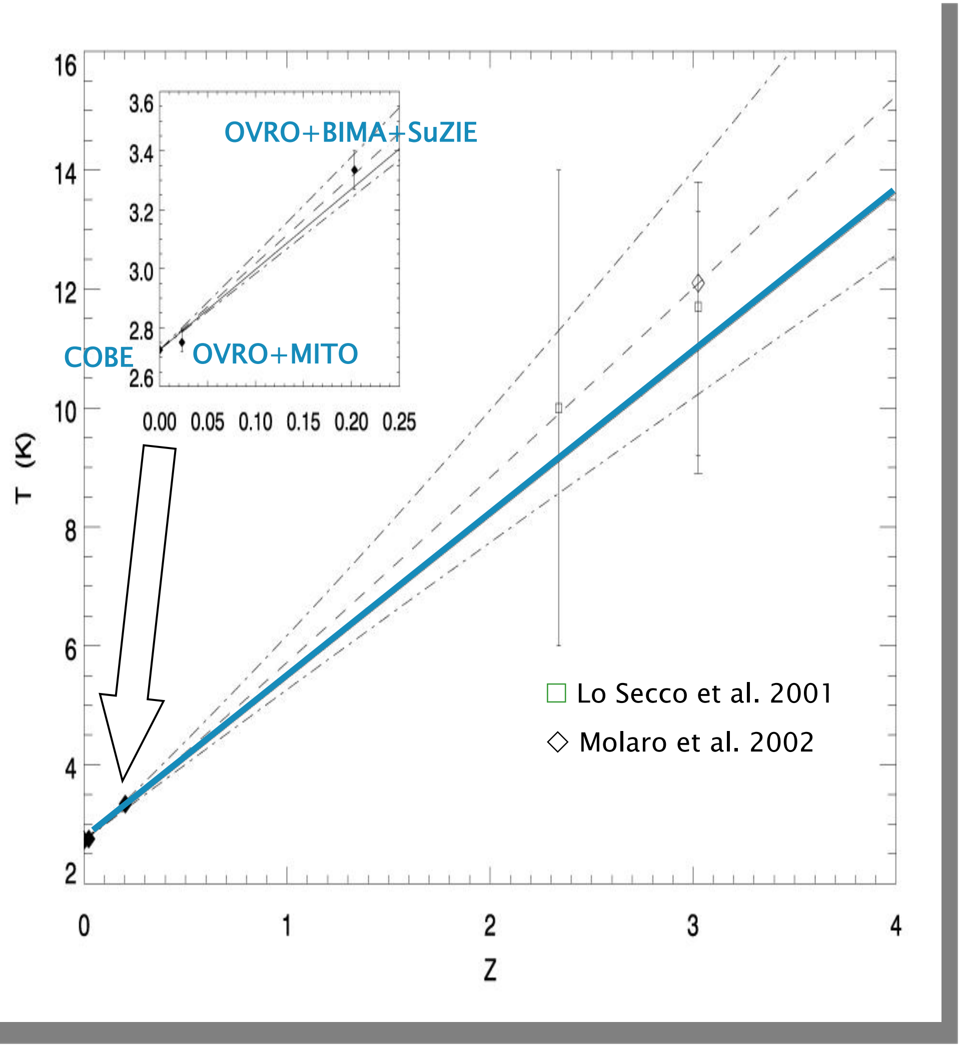
$T_{CMB}(z)$ from SZE: first application

Fit of measured SZ signals ratios ($\Delta I_{SZ}(\nu_1)/\Delta I_{SZ}(\nu_2)$) with the expected values by changing $T(z)/(1+z)$

- independent of absolute calibration uncertainties (T_{planet});
- independent of τ, if KIN–SZ removed or β negligible;
- dependent on precise knowledge of $A\Omega_i$ and $\varepsilon_i(\nu)$
- Ratios have non gaussian distributions and introduce correlations

$T_{CMB}(z)$ from SZE: first results

COMA+A2163



(Battistelli et al., ApJL 580, 101, 2002)

$$T_{CMB}(z=0) = 2.725^{+0.02}_{-0.02}\mathrm{K}$$

$$T_{A1656}(z=0.0231) = 2.789^{+0.080}_{-0.065}\mathrm{K}$$

$$T_{A2163}(z=0.203) = 3.377^{+0.101}_{-0.102}\mathrm{K}$$

$$T(z) = T_0(1+z)$$

$$T(z) = T_0(1+z)^{1-a}$$

$$T(z) = T_0[1+(1+\gamma)z]$$

$$a = -0.16^{+0.34}_{-0.32}(95\%\mathrm{c.l.})$$

$$d = -0.17 \pm 0.36(95\%\mathrm{c.l.})$$

Molecular microwave transitions CONSISTENT

Standard Model CONSISTENT

$T_{CMB}(z)$ from SZE: extended dataset

SZ measurements of 14 clusters by different experiments expressed in central thermodynamic temperature

	OVRO+BIMA[a]	SuZIE II[b]				SCUBA[c]
Cluster	$\Delta T_{30\mathrm{GHz}}$ (mK)	$\Delta T_{145\mathrm{GHz}}$ (mK)	$\Delta T_{221\mathrm{GHz}}$ (mK)	$\Delta T_{273\mathrm{GHz}}$ (mK)	$\Delta T_{355\mathrm{GHz}}$ (mK)	$\Delta T_{353\mathrm{GHz}}$ (mK)
A520	-0.66 ± 0.09[d]	-0.44 ± 0.13	0.14 ± 0.14	-	1.78 ± 0.41	2.60 ± 0.57
A697	-1.22 ± 0.12	-0.93 ± 0.13	0.41 ± 0.16	-	2.80 ± 0.62	-
A773	-1.08 ± 0.11	-0.91 ± 0.16	0.04 ± 0.25	-	2.40 ± 0.89	2.7 ± 2.0
A1689	-2.06 ± 0.17	-	-	-	-	2.93 ± 0.40
A1835	-2.90 ± 0.21	-1.74 ± 0.26	0.14 ± 0.41	1.73 ± 0.59	-	-
A2204	-3.22 ± 0.32	-0.65 ± 0.10	0.21 ± 0.10		1.85 ± 0.44	-
A2261	-1.36 ± 0.14	-1.56 ± 0.18	0.21 ± 0.50	-	5.1 ± 1.5	-
A2390	-	-0.91 ± 0.10	-0.10 ± 0.17	-	1.23 ± 0.34	2.40 ± 0.44
CL0016+16	-1.44 ± 0.09	-0.57 ± 0.23	0.66 ± 0.46	1.82 ± 0.68	-	1.96 ± 0.64
MS0451-03	-1.48 ± 0.09	-0.779 ± 0.065	-0.21 ± 0.10	0.91 ± 0.66	1.16 ± 0.34	-
RXJ1347	-5.15 ± 0.60	-3.22 ± 0.39	-0.10 ± 0.39	-	6.2 ± 1.5	5.36 ± 0.54
ZW3146	-2.02 ± 0.25	-1.56 ± 0.39	-0.25 ± 0.48	-	3.1 ± 1.3	-

	OVRO[d]	MITO[e]			SCUBA[c]
Cluster	$\Delta T_{32\mathrm{GHz}}$ (mK)	$\Delta T_{143\mathrm{GHz}}$ (mK)	$\Delta T_{214\mathrm{GHz}}$ (mK)	$\Delta T_{272\mathrm{GHz}}$ (mK)	$\Delta T_{353\mathrm{GHz}}$ (mK)
A1656	-0.520 ± 0.093	-0.179 ± 0.037	0.033 ± 0.080	0.170 ± 0.034	-

	OVRO+BIMA[a]	SuZIE I[f]			SCUBA[c]
Cluster	$\Delta T_{30\mathrm{GHz}}$ (mK)	$\Delta T_{142\mathrm{GHz}}$ (mK)	$\Delta T_{217\mathrm{GHz}}$ (mK)	$\Delta T_{268\mathrm{GHz}}$ (mK)	$\Delta T_{353\mathrm{GHz}}$ (mK)
A2163	-1.89 ± 0.17	-1.011 ± 0.098	-0.21 ± 0.16	0.66 ± 0.24	

[a](Bonamente *et al.* 2006); [b](Benson *et al.* 2003; Benson *et al.* 2004);
[c](Zemcov *et al.* 2007); [d](Herbig *et al.* 1995; Mason *et al.* 2001);
[e](De Petris *et al.* 2002; Savini *et al.* 2003);[f](Holzapfel *et al.* 1997a).

X-ray data
(Bonamente et al., APJ,647,25,2006)

(De Gregori, ..L.G. et al., Nuovo Cimento B, 122, 2008)

$T_{CMB}(z)$ from SZE: Ratios approach (RI)

Ratios of SZ intensity change (RI): $\Delta I_{SZ}(\nu_1)/\Delta I_{SZ}(\nu_2)$

Joint likelihood to extract the universal parameter "a" of the Lima model: Marginalization over T_e, v_p, C.

- weakly dependent on IC gas properties if β negligible

(no marginalization on τ)

- not considered measurements at the crossover frequency

(Cauchy tail)

- bias due to arbitrariness in selecting the intensity change used in denominator of ratios

- more precise SZ measurements or larger dataset $\longrightarrow$ bias removed

$T_{CMB}(z)$ from SZE: Direct approach (I)

Directly ΔI_{SZ} measurements (DI):

- easier control of systematics
- more complex structure in the parameter space

Joint likelihood to extract the universal parameter "a" of the Lima model: marginalization (numerical+analytical) over τ, T_e, v_p, C

Priors: $P(T_{ei}) = N(E(T_{ei}), \sigma(T_{ei}))$

$P(v_p) = N(0\ \mathrm{km/s}, 1000\ \mathrm{km/s})$

$P(T_{CMB}) = \mathrm{flat}$

$P(\tau) = \mathrm{flat}$ (only for DI)

$P(C) = N(1, 0.1)$

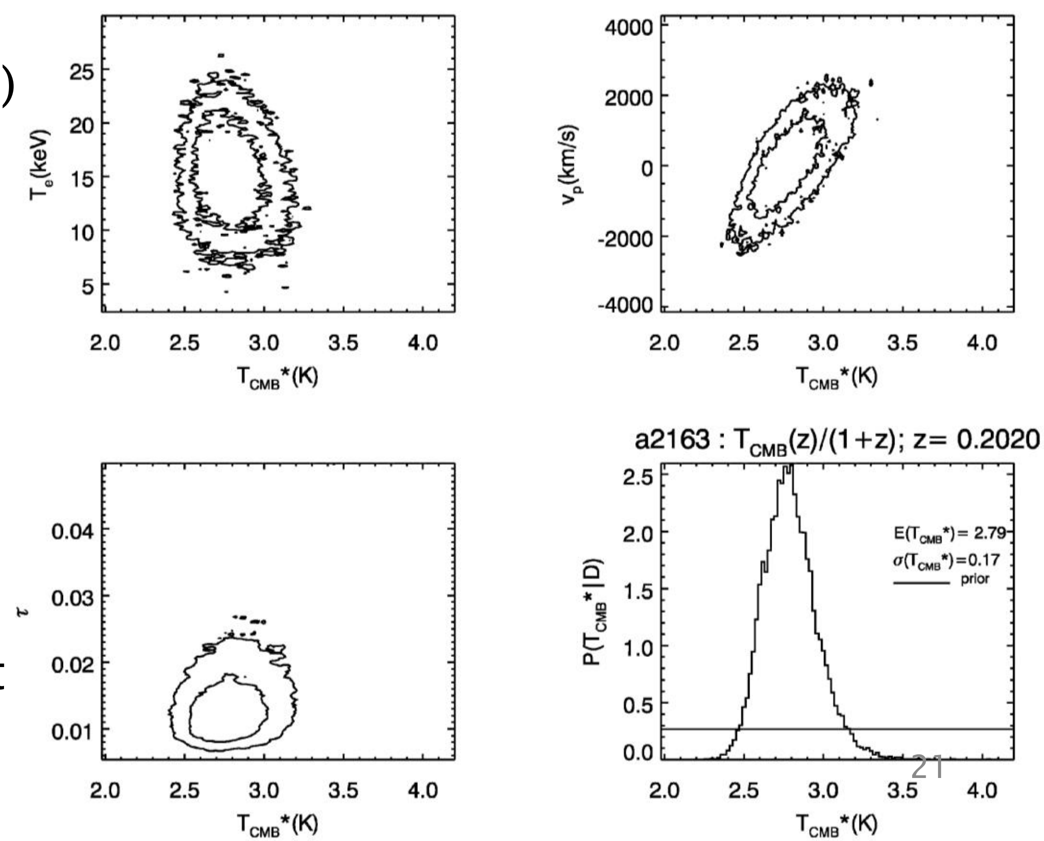
$T_{CMB}(z)$ from SZE: Direct approach (II)

Directly ΔI_{SZ} measurements (DI):

Single likelihoods for each cluster to provide individual determinations of $T_{CMB}(z)$ at z of each cluster

- independent from the particular scaling assumed for the temperature (i.e. the Lima model)
- only assumption $\nu(z)=\nu_0(1+z)$

- MCMC algorithm
- Posteriors for all parameters
- Study of correlations
- Main degeneracies:
    - T(z) vs τ
    - T(z) vs v_p always evident



$T_{CMB}(z)$ from SZE: Results

Cluster	$T(z)$ (K)
A1656	2.72 ± 0.10
A2204	2.90 ± 0.17
A1689	2.95 ± 0.27
A520	2.74 ± 0.28
a2163	3.36 ± 0.20
A773	3.85 ± 0.64
A2390	3.51 ± 0.25
a1835	3.39 ± 0.26
A697	3.22 ± 0.26
ZW3146	4.05 ± 0.66
RXJ1347	3.97 ± 0.19
CL0016+16	3.69 ± 0.37
MS0451	4.59 ± 0.36

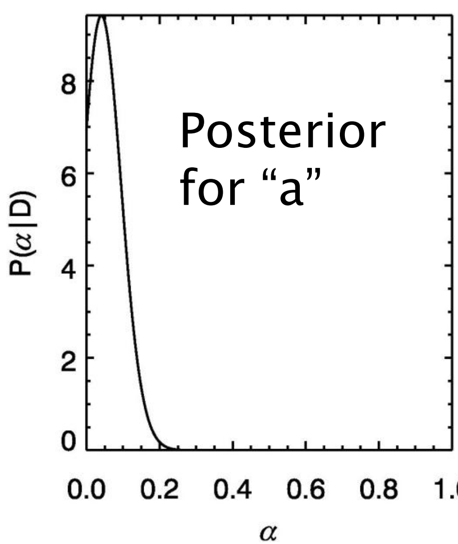
Flat prior $a \in [0,1]$ (theoretical motivation)
(Lima et al 2000)

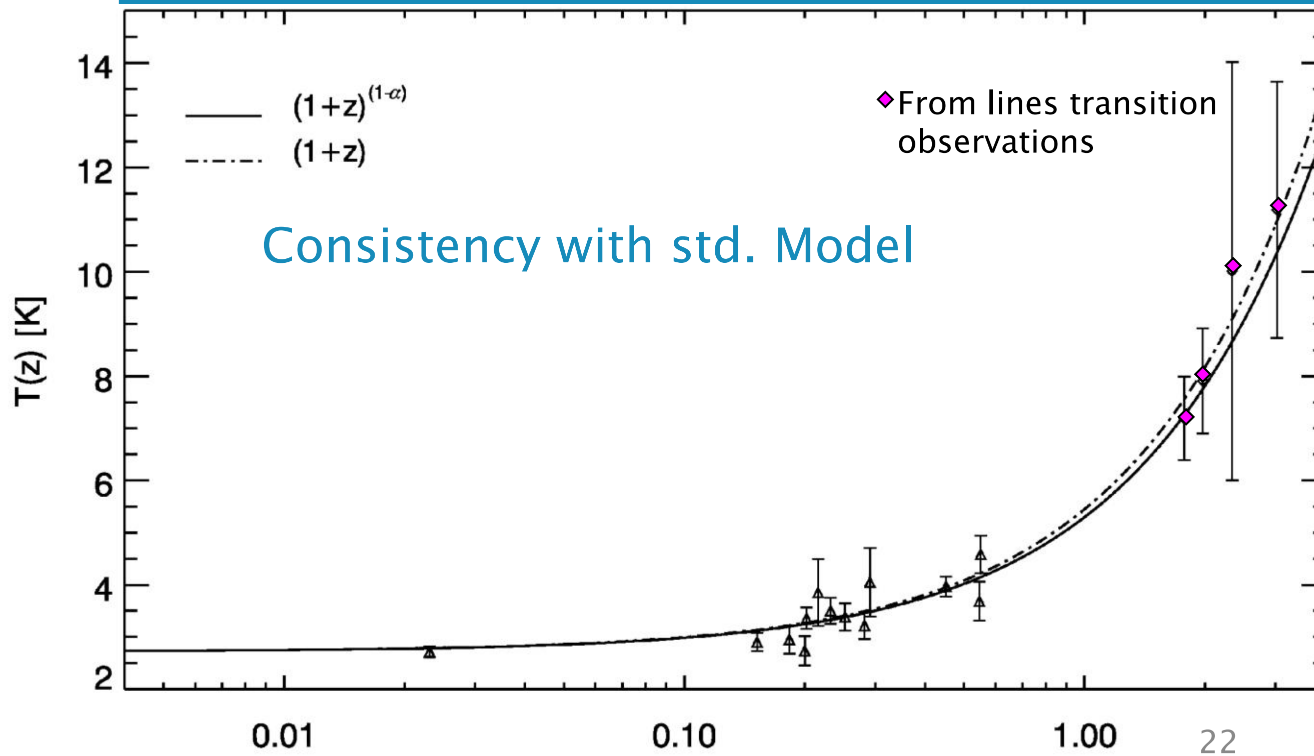
All limits are at 68% probability level

RI $a \leq 0.092$

DI (JL) $a \leq 0.059$

DI (SL-MCMC) $a \leq 0.12$ (including lines $a \leq 0.079$)





(Luzzi et al., ApJ 705, 1122, 2009)

$T_{CMB}(z)$ from SZE: simulations

Simulated observations of 50 well known clusters

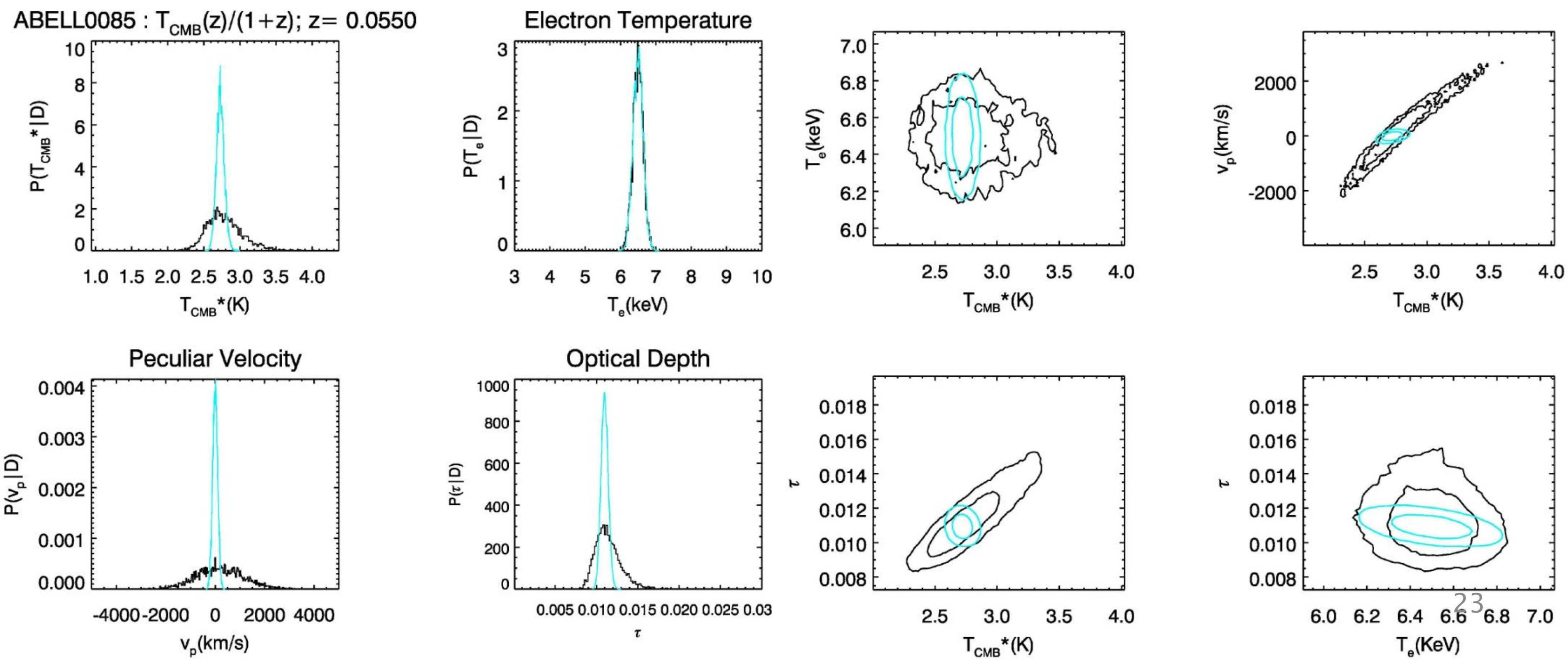
mock dataset analyzed to recover input parameters of the cluster

Analysis: MCMC

$P(v_p) = N(0\ km/s, 1000\ km/s)$

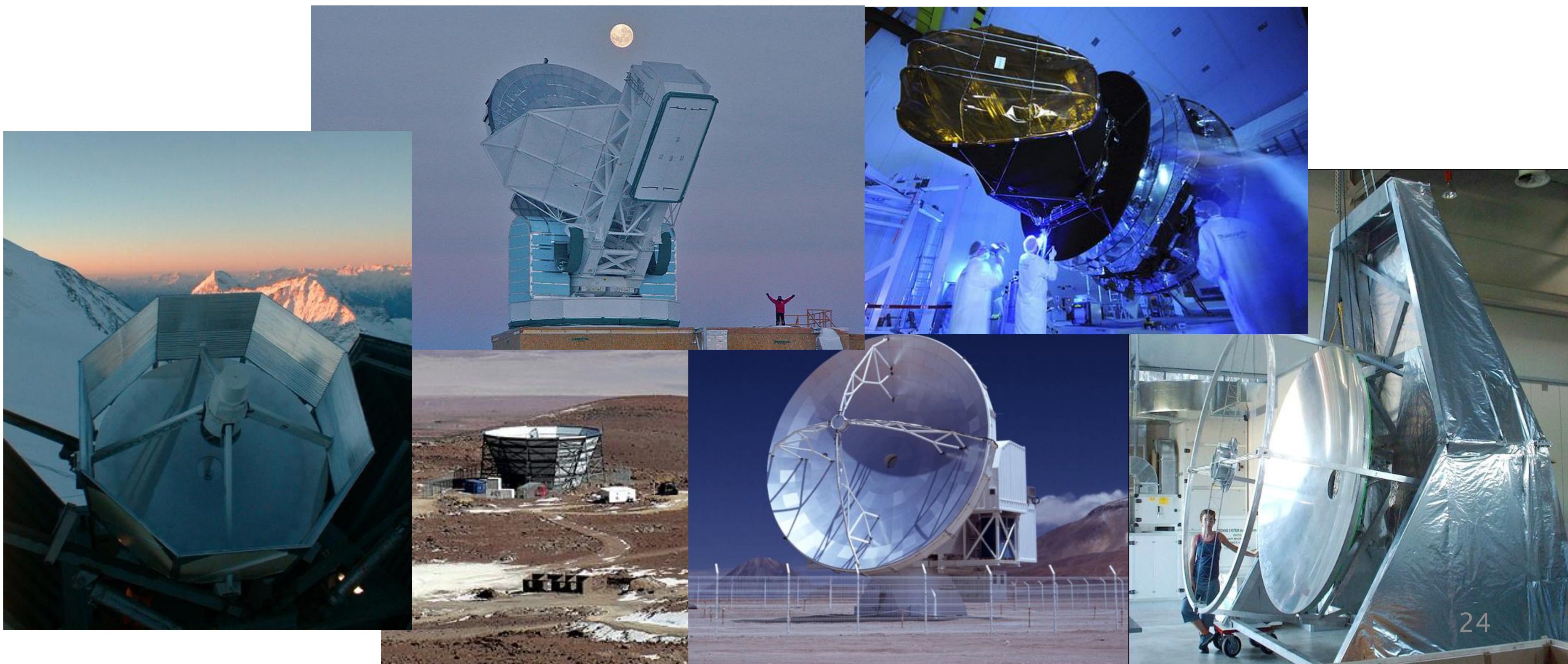
$P(v_p) = N(0\ km/s, 100\ km/s)$

$P(T_e) = N(6.50KeV, 0.14KeV)$



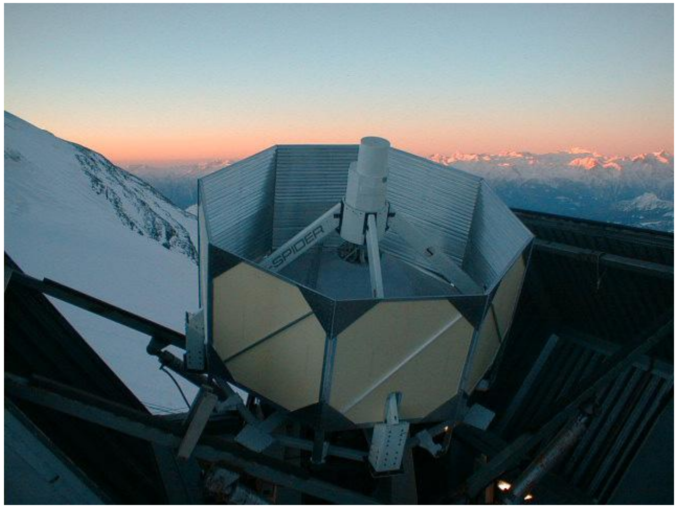
SZE experiments

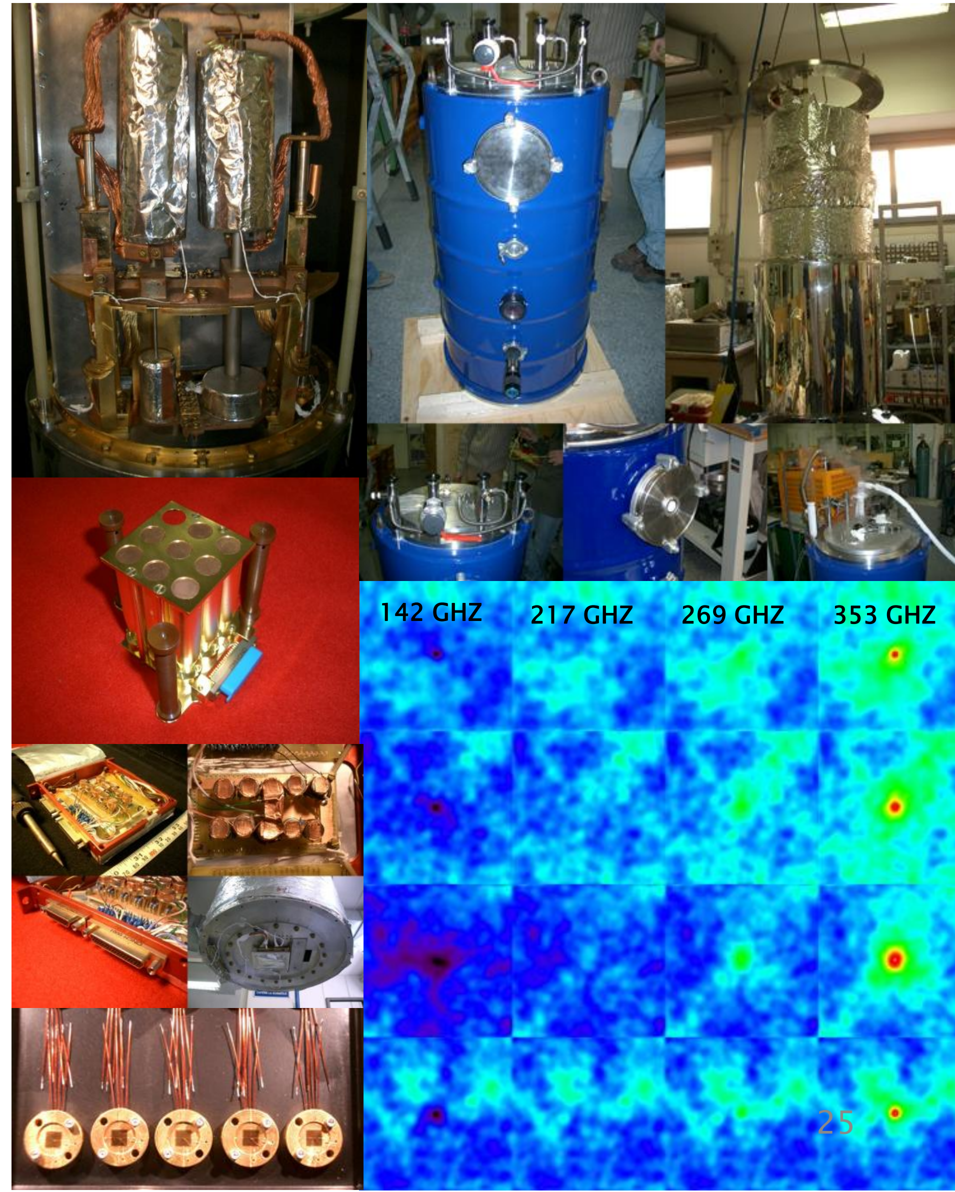
- Ongoing and near future surveys with ACT, APEX-SZ, SPT, Planck and detailed mapping of a sample of nearby clusters with MAD and OLIMPO experiments will provide much more precise and uniform datasets:
    - bias in the ratio approach largely removed
    - reduced skeweness in τ and $T_{cmb}(z)$ distributions (DI)



MAD

MITO (Millimeter and Infrared Testagrigia Observatory)



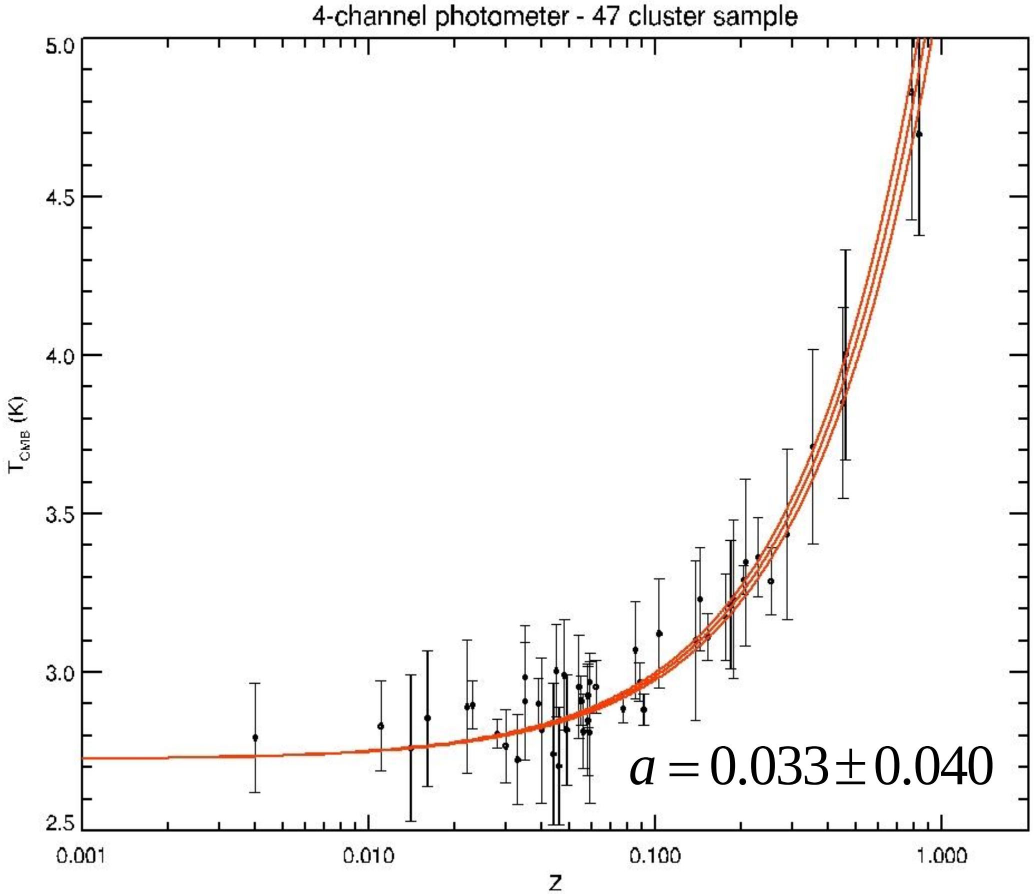


MAD (Multi Array of detectors)

photometer upgrades MITO with a multi-pixel configuration based on bolometer array consisting of 3x3 pixels operating at four frequency bands (142, 217, 269, 353 GHz) and with beamsizes down to 4.5’.

(Lamagna, ..L.G. et al., 2004 Proc of Enrico Fermi School, CLIX. SIF, 2005)

Planned observations

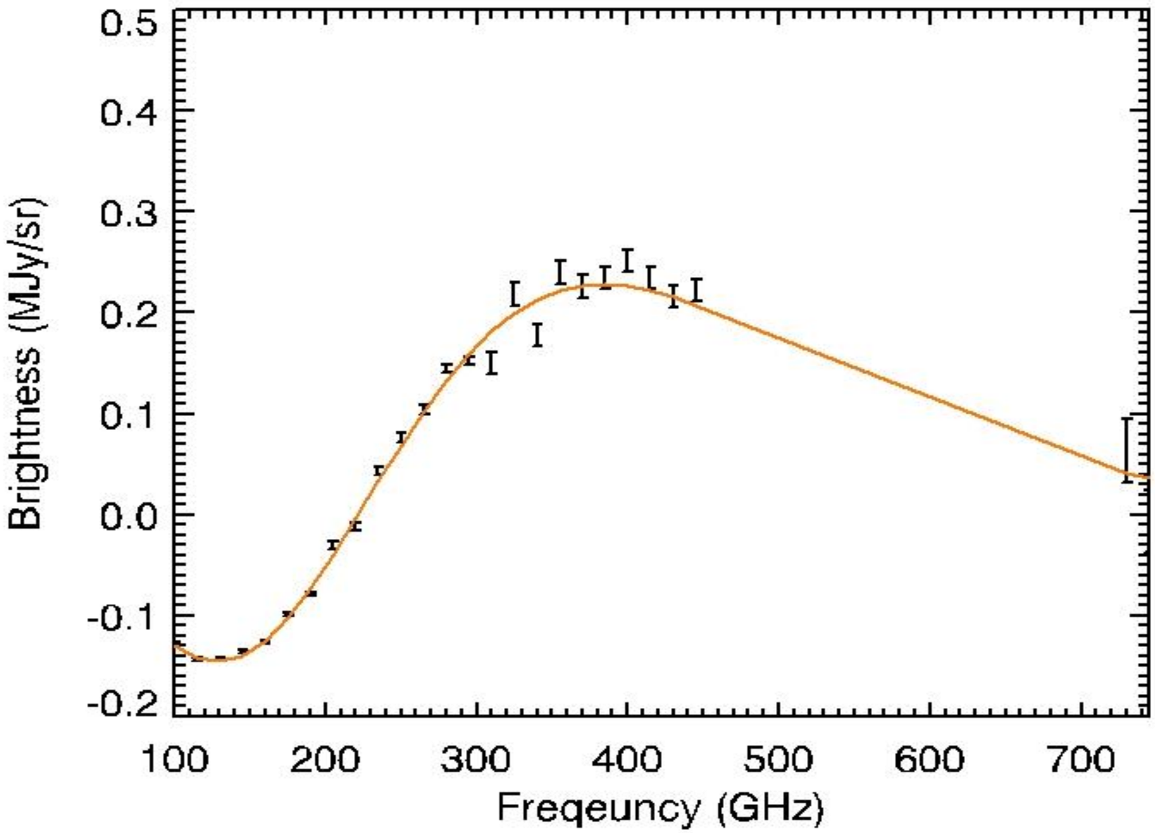


(Sims and fit by L. Lamagna)

- 47 simulated well known galaxy clusters (from BAX catalog) observed in 4 frequency bands with angular resolution ranging from 4.7 and 1.9 arcmin.
- Assumed atmosphere noise with 90% transparency.
- "Blind" data treatment and signal extraction
- MCMC to fit on SZ parameters+CMB temp.

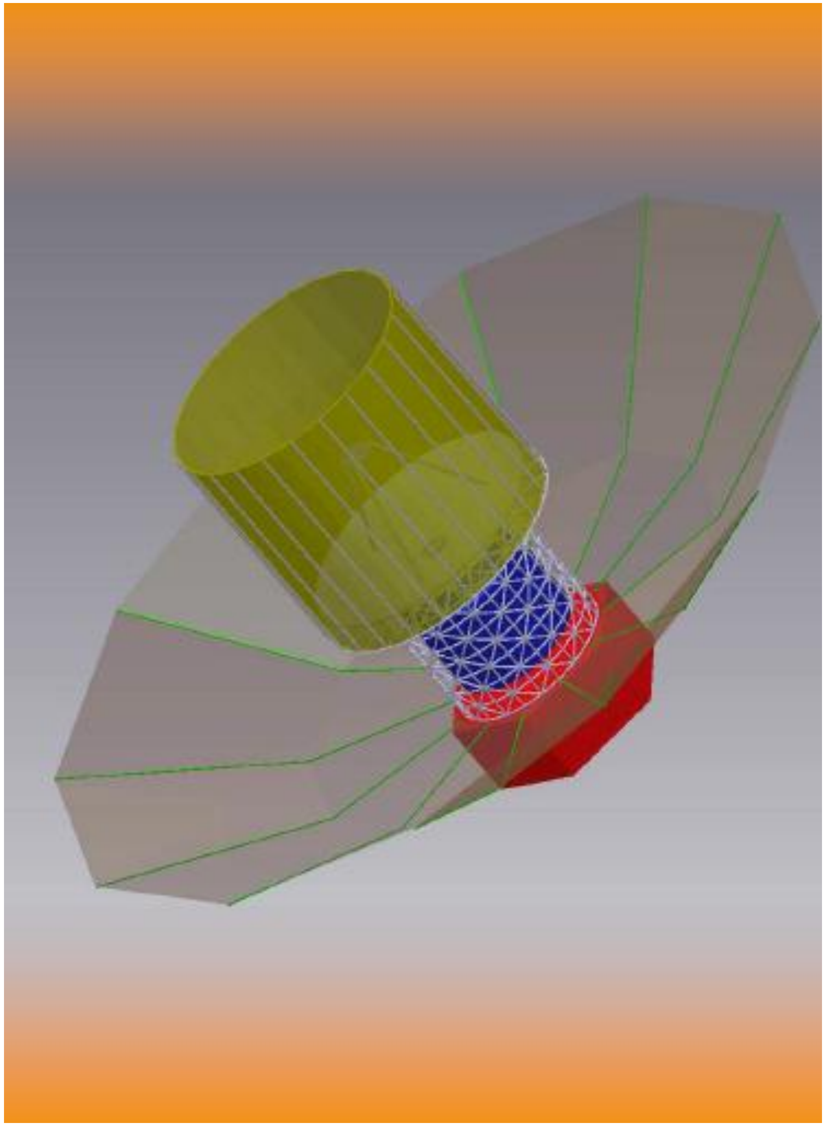
Future SZE experiments

- Accurate spectroscopic observations from space towards a limited number of clusters (like the proposed SAGACE satellite) would allow to control a large part of the degeneracies between $T_{CMB}(z)$ and cluster parameters.



SAGACE project

SAGACE (Spectroscopy Active Galaxies and Clusters Explorer)



Space borne spectrometer, coupled to a 3m telescope:

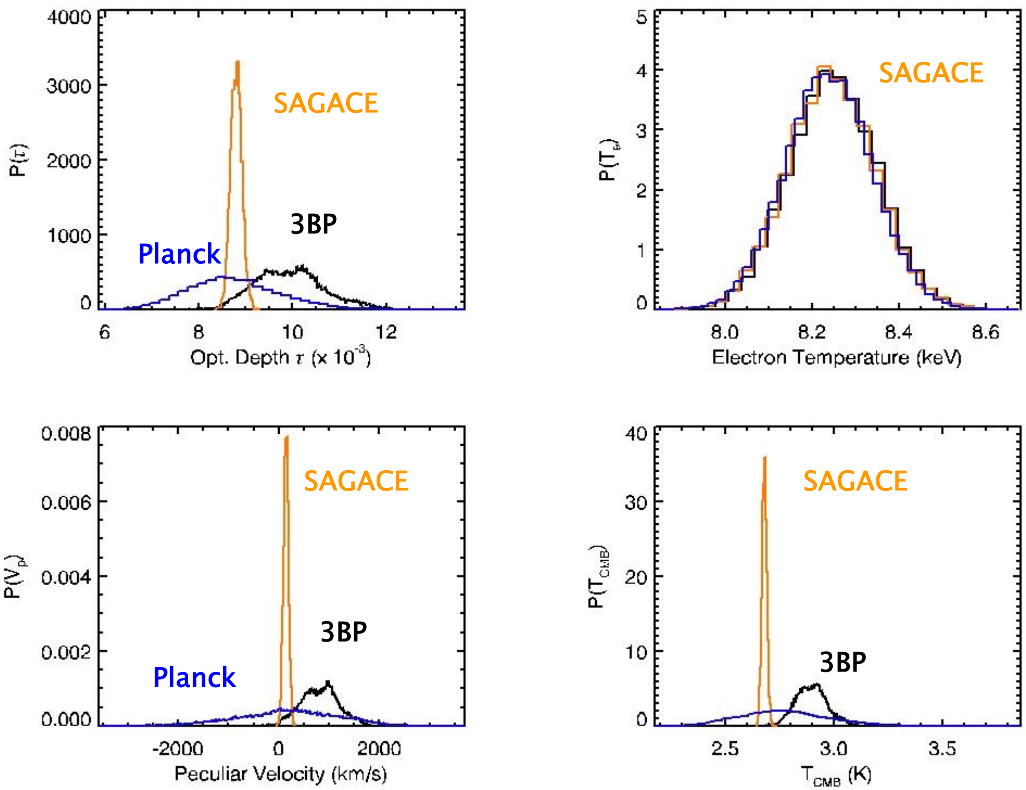
- able to cover frequency ranges 100-450 and 720-760 GHz,
- With angular resolution ranging from 4.2 to 0.7 arcmin
- with photon noise limited sensitivity

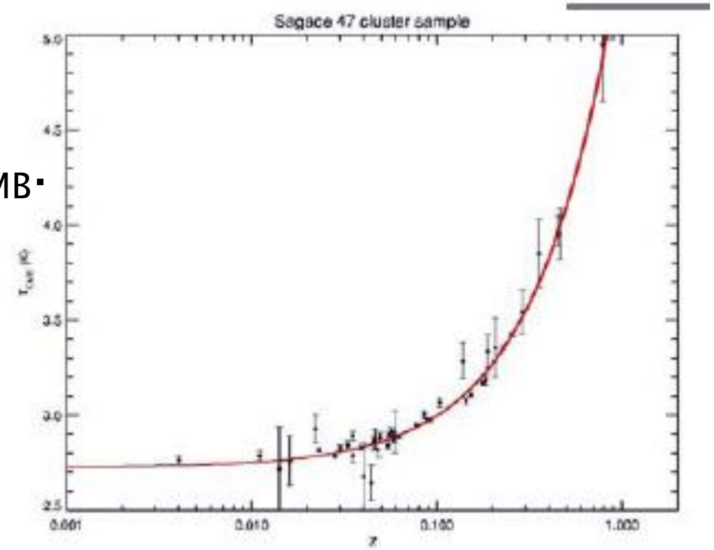
- The SAGACE observational program aims at performing a millimetric and submillimetric spectroscopy study from space of cosmic structures in the Universe.

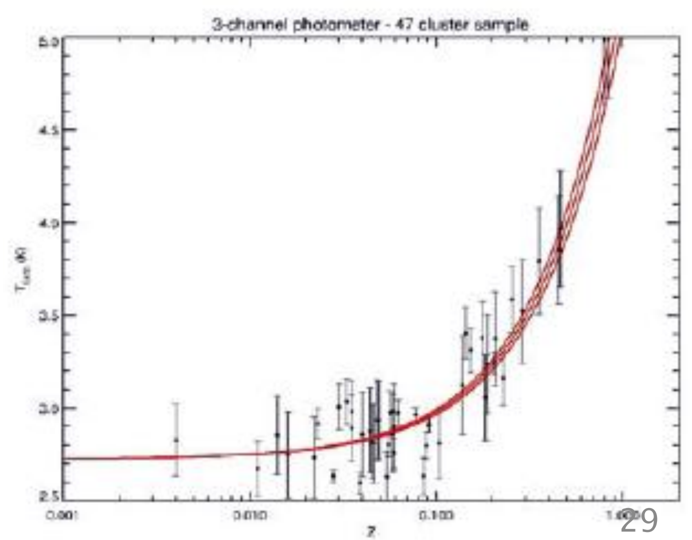
- SAGACE will provide spatially resolved spectroscopic observations of clusters with exquisite precision and accuracy.

Scientific impact of SAGACE

The high accuracy of the spectral measurements allows to control a large part of the existing degeneracies between the cluster parameters and T_{CMB}.







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Cosmological parameters from a survey of well known X-ray and optical clusters with Planck HFI

- Planck HFI ideal to study SZE in galaxy clusters
  - spectral coverage: positive and negative part of the spectral distorsion
  - angular resolution: nearby clusters resolved and confusion reduced at large depth
  - full sky survey : thousand of clusters

- Survey dedicated to a sample of well knonw clusters in the X-ray and optic

  subsample of the complete catalog

  selection of the subsample:
  - nearby clusters: H_0 (Hubble diagram- SZ-X method)
  - high redshift clusters: feasibility test to extract Ω_M from the Hubble diagram

Method SZ-X to determine distances

Method SZ-X (Cavaliere et al, 1977)
Advantages of the techinque:
- Completely independent of other techinques
- Measures distances at high z directly, without any intervening chain of distances estimantors (as in the usual distance ladder).

- Constraints complementary to those set by the number density of clusters in redshift space.

- Agreement of different techinques for measuring the cosmological parameters provides cross-check of our understanding of the underlying processes and a control against systematic errors.

- A sample of ~100 high redshift clusters: traces the expansion history of the Universe, valuable independent check respect to SNIa.

- SZ-X method is a physical method, based on relatively simple gravitational virialization of clusters, as opposed to complicated physics and chemistry involved in galaxy formation and supernovae explosion.

Catalogue (I)

- 166 clusters using X-Rays Clusters Databased (BAX)

Cluster name	
RA (J2000)	
DEC (J2000)	
z	Redshift
F_X	X flux in the ROSAT band (0.1–2.4 KeV) (10^{-12} erg/s/cm^2)
Reference F_X	
L_X	X Luminosity in the ROSAT band (0.1–2.4 KeV) (10^{44} erg/s)
Reference –L_X	
Bande –Inf (KeV)	
Bande –Sup (KeV)	
T_X	X-ray Gas temperature (KeV)
σ_{Tx}	
Reference T_X	
Instrument	
R_{core}	Core radius (arcsec)
σ_{Rcore}	
Reference–R_{core}	
β	Slope of the gas density profile (isothermal beta model)
σ_β	

Catalogue (II)

Derived parameters

n_{e0}	Central electronic density (isothermal beta model+ Furuzawa et al,, 1998)
y_{th}	Central comptonization parameter
T_{th}	Optical depth
Y_{int}	Comptonization parameter integrated over the cluster extent
D_{ASZX}	Angular distance

Simulation

Planck HFI instrumental characteristics (Bluebook 2005) :

- Frequency bands: 100, 143, 217, 353 GHz
  (545, 857 GHZ not included: ideal for removing foregrounds)

- CMB and foregrounds assumed previously removed

- NET: 50, 62, 91, 277 $\mu K\sqrt{s}$

- Number of detectors: 8,12,12,12

- Angular resolution: 9.5, 7.1, 5.0, 5.0 arcmin

- Integration time: 10 s/cluster (uniform sky coverage and 2 years of observation)

- Integration time multiplied for the number of detectors

- Error estimates on the SZ signal takes into account beam dilution

Forecasts for SZ signal assume Isothermal beta model

Data analysis

- Mock dataset analyzed to recover the original input cluster parameters.

- MCMC algorithm: allows to explore the full space of the cluster parameters (τ, v_p, T_e) (including calibration uncertainty: scale factor).

- MCMC: generates random sequences of parameters, which simulate posterior distributions for all parameters (Lewis and Bridle 2002)

Priors: $P(T_{ei}) = N(E(T_{ei}), \sigma(T_{ei}))$

$P(v_p) = N(0\ \mathrm{km/s}, 1000\ \mathrm{km/s})$

$P(\tau) = \text{flat (con } \tau \in [0, 6\ \tau_{th}])$

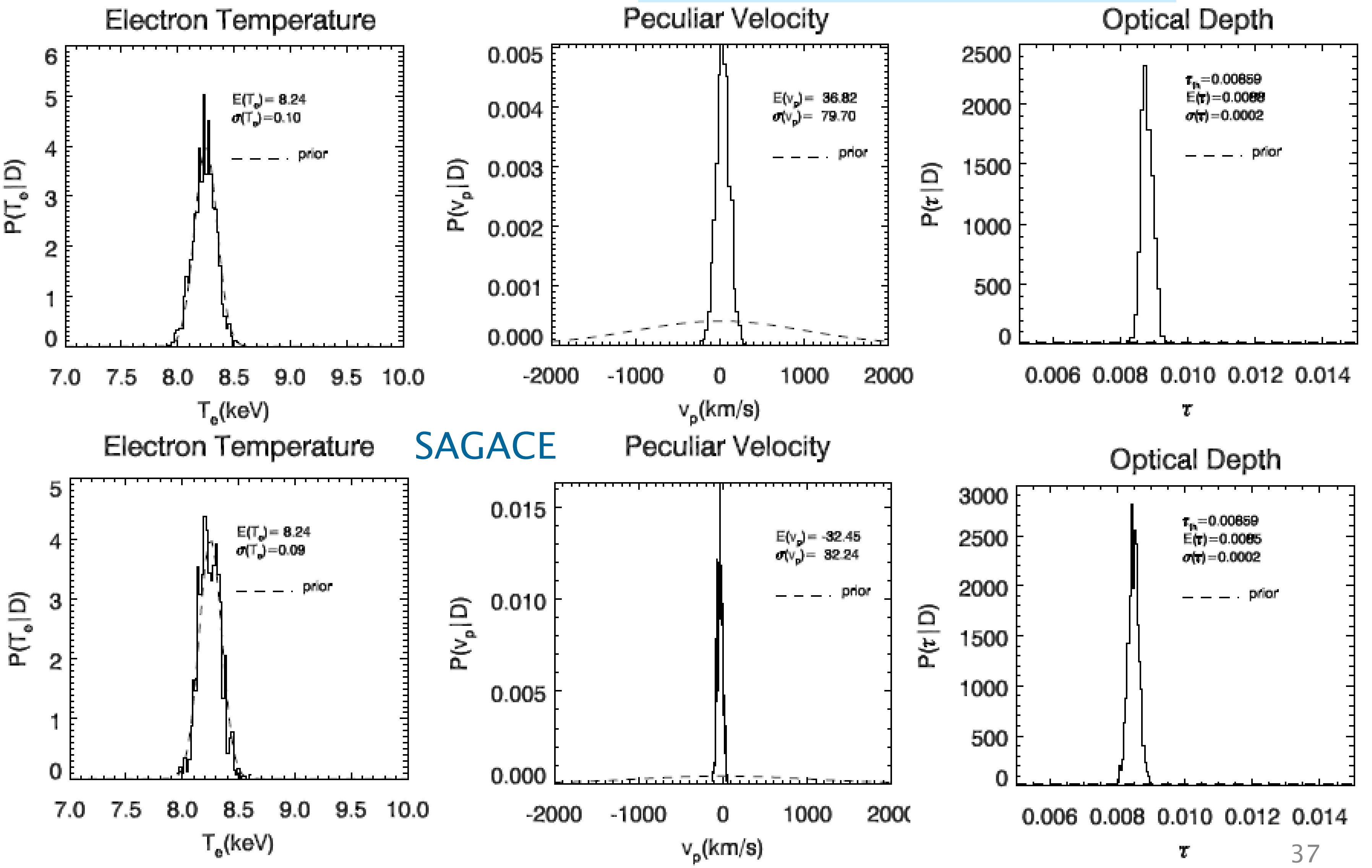
$P(C) = N(1, 0.01)$

Cluster parameters: Planck HFI vs SAGACE (I)

Planck HFI

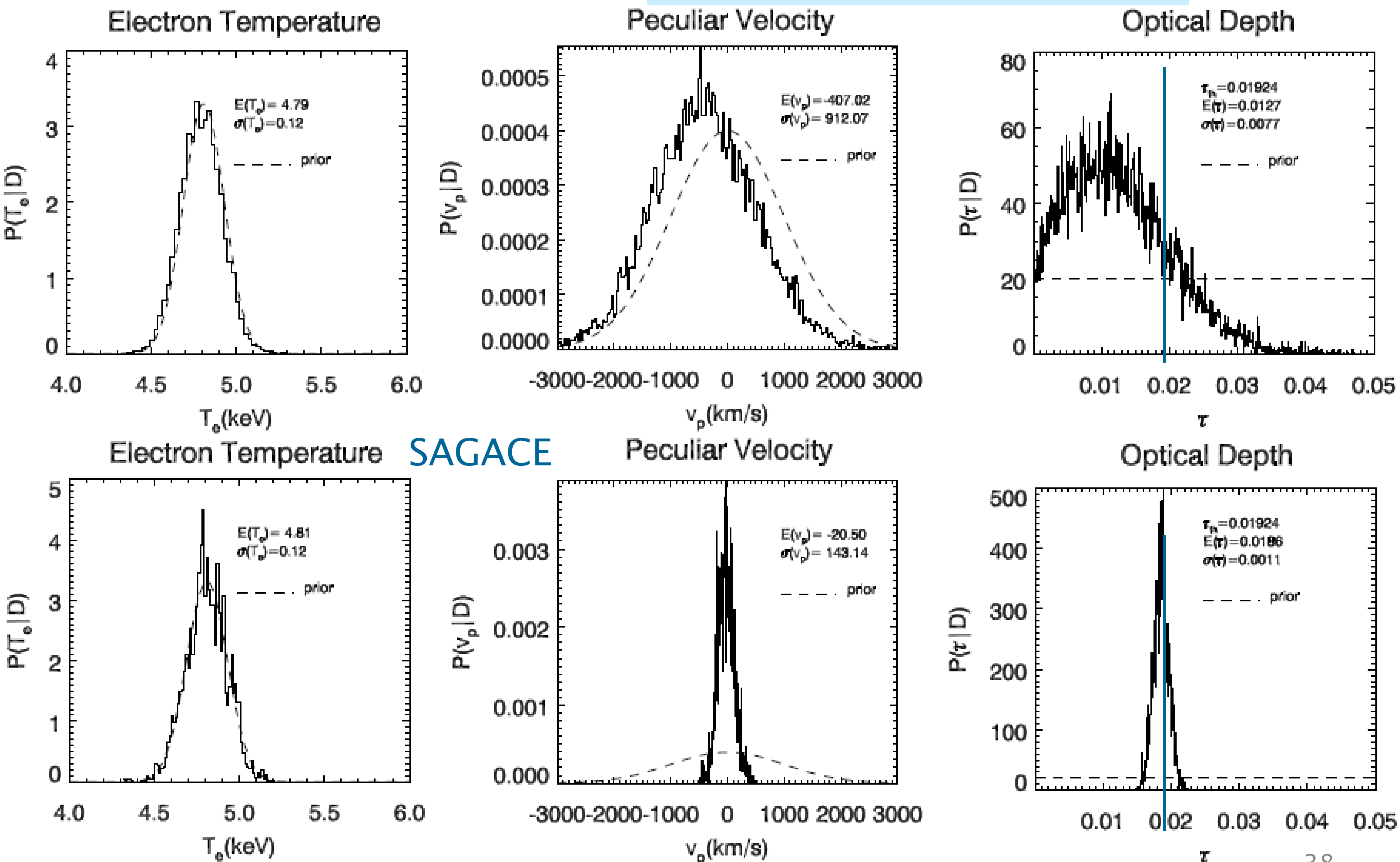
ABELL1656 z= 0.0230 Θ_c=10.5’

SAGACE



Cluster parameters: Planck HFI vs SAGACE (II)

Planck HFI ABELL0383 z= 0.1870 Θ_c=0.39'



(De Bernardis, ..L.G. et al., Proc. of the 12th Marcel Grossman Meeting, 2010)

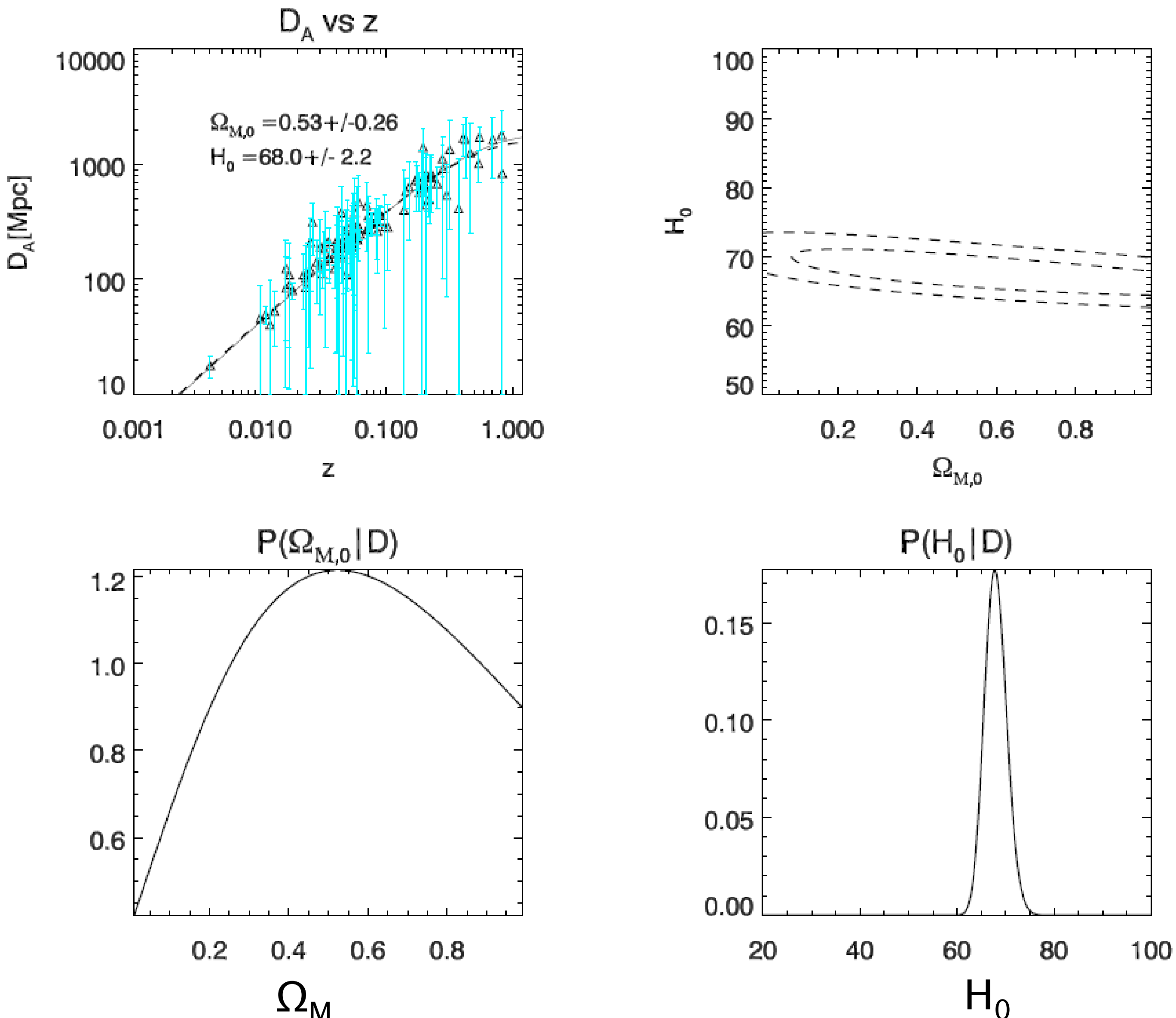
Outline

- CMB
- SZE
- $T_{CMB}(z)$
- Cluster parameter recovery with Planck HFI and SAGACE
- Hubble diagram from SZE–X: case of Planck HFI

Hubble diagram for Planck HFI: data analysis

- Posteriors for all parameters
- Clusters with almost flat τ posterior excluded from the sample
- Recovered parameters are combined with X fluxes to exctract distances
- Sample (108 clusters) used to produce the Hubble diagram

Results (I)



D_A vs z
$\Omega_{M,0}$ =0.53+/-0.26
H_0 =68.0+/- 2.2
D_A[Mpc]
10000
1000
100
10
0.001
0.010
0.100
1.000
z
100
90
80
70
60
50
H_0
0.2
0.4
0.6
0.8
$\Omega_{M,0}$
$P(\Omega_{M,0}|D)$
1.2
1.0
0.8
0.6
0.2
0.4
0.6
0.8
Ω_M
$P(H_0|D)$
0.15
0.10
0.05
0.00
20
40
60
80
100
H_0

Results (II)

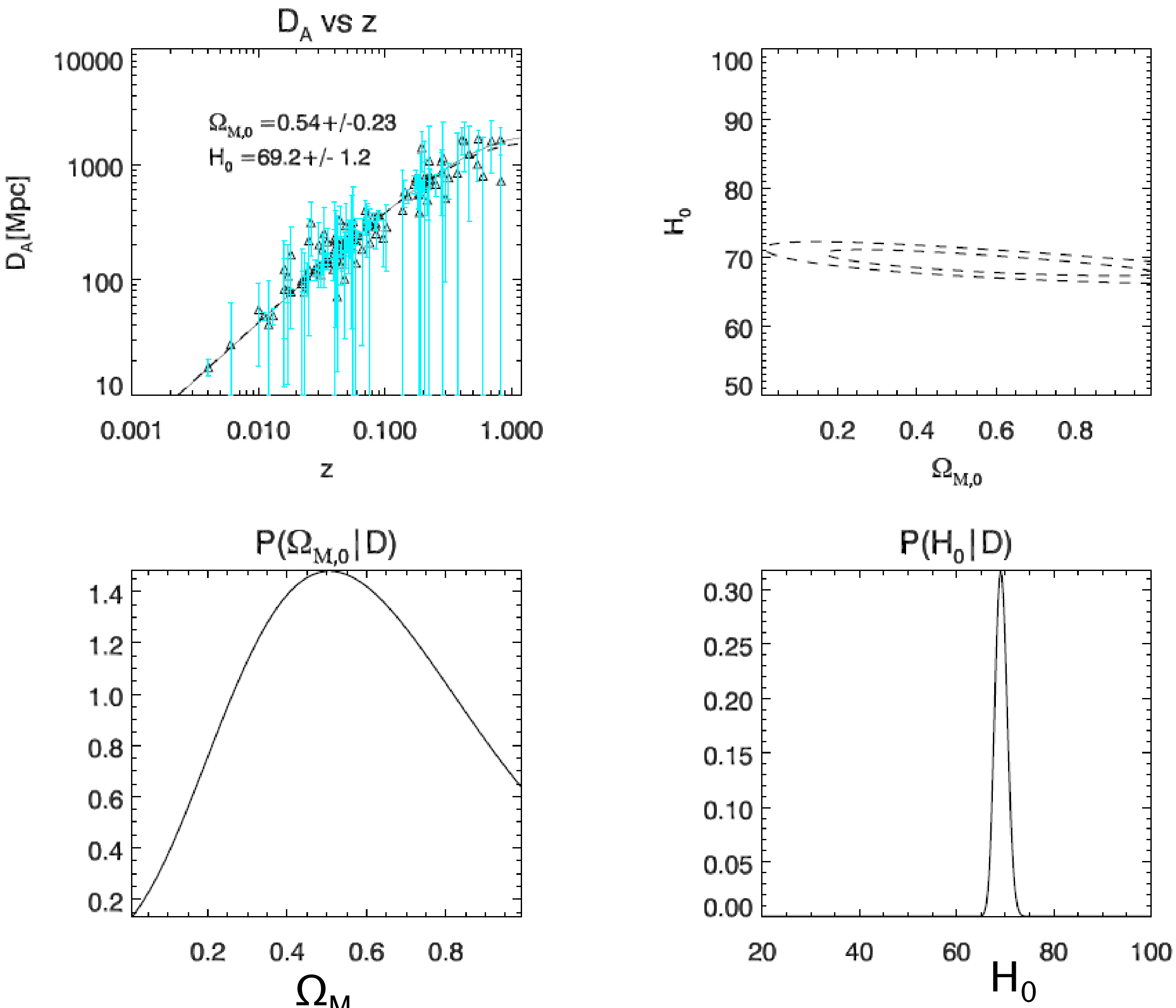
- Exctraction of H_0 and Ω_M assuming ΛCDM:
  priors: $P(\mathbf{H_0})$ = flat ($\mathbf{H} \in [20,100]$ Km/s),
  $P(\Omega_M)$ = flat ($\Omega_M \in [0;1]$)

- 3% sensitivity on the Hubble constant

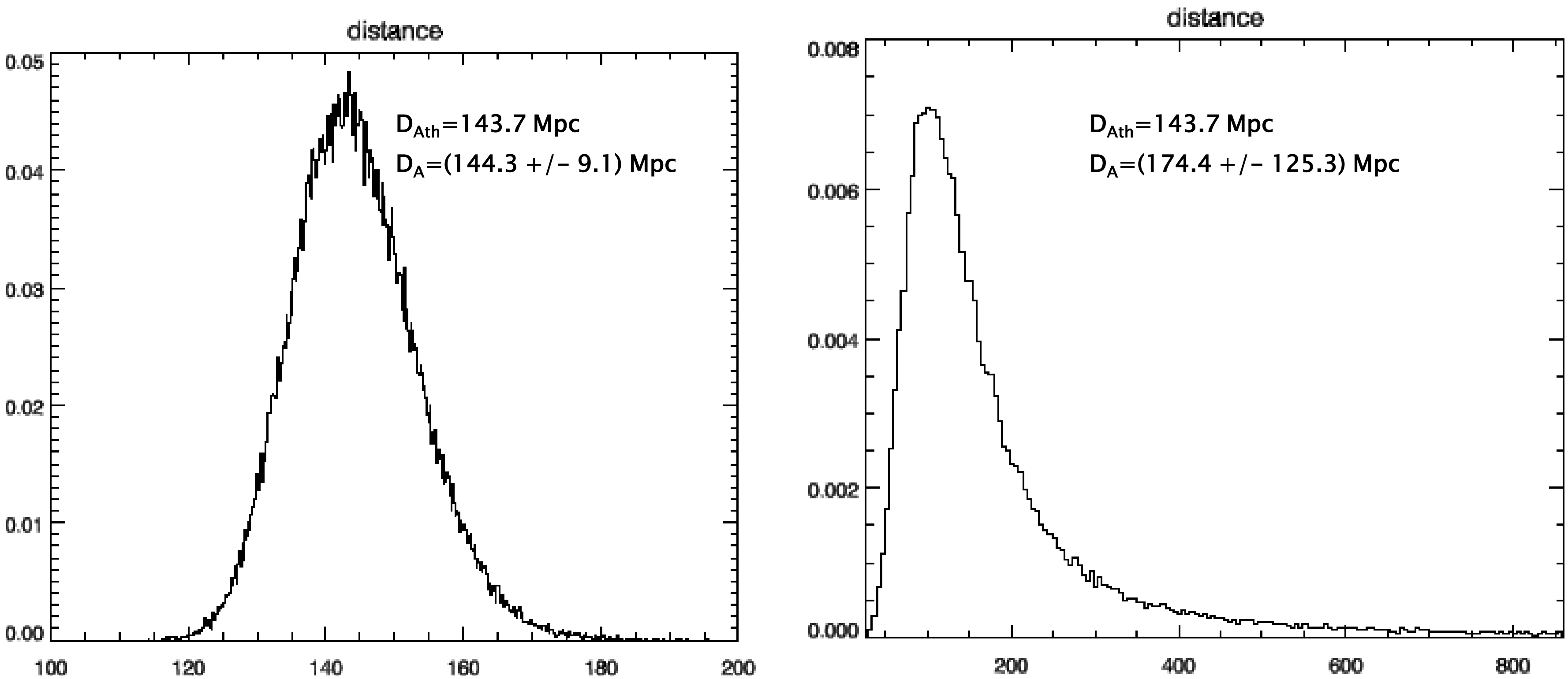
- Ω_M not costrained. Need for complementary constraints from other dataset and/or larger redshift exploration.

Results (III)

"Ideal" X- ray catalogue with 2% uncertainties on θ_c, β, T_e



Bias in the determination of H_0



Angular distance for the cluster 2A0335+096. Left: histogram of angular distance as obtained by Montecarlo using the expression of Furuzawa et al. (1998) and assuming all parameters SZ and X-ray known with errors at 1%. Right: as above but with all parameters known with gaussian distribution and errors at 10%.

H(z)

$$H(z) = \left[\frac{d}{dz} (d_A (1+z)) \right]^{-1}$$

Direct determination of the expansion history of the Universe from the distance data by making no assumptions about the underlying cosmological model.

This approach is model independent but at cost of being highly sensitive to the amount and quality of the available data. “Reconstruction program”: (Starobinsky, JEPT Lett 68, 757, 1998); (Daly and Djorgovski ApJ 597, 9, 2005) ; (Shafieloo et al 2005).

Conclusions

- SZE is an original tool to observationally test the standard scaling of T_{CMB} and its isotropy up to the redshift of galaxy clusters and to put constraints on alternative cosmological models.

- With near future SZE experiments more precise measurements of the $T_{CMB}(z)$ scaling law could set constraints on the variation of fundamental constants over cosmological time.

- Clusters parameters optimally recovered by experiments with spectroscopic capabilities (SAGACE project).

- SZ-X technique for measuring distances: H_0 with a method completely independent of others (with Planck HFI 3% sensitivity on H_0)

- Clusters of galaxies alone can be used to constrain cosmological parameters independently from other methods.