The SZ effect as a Cosmic Thermometer

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On behalf of F. Melchiorri and

The *GEMINI-SZ* collaboration

International Workshop "Cosmology with SZ and X-Ray Observatories"

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Outline

- Cosmological framework, basic foundations
- Feasibility
- A sample approach on available data
- The GEMINI-SZ project

Cosmological framework

- "Relativistic" cosmology:
  - Find an exact solution to Einstein's equations for the universe as a whole ("model of the universe")
  - Classify all possible models (accurately choose reference frame to represent the solutions)
  - How do photons behave? (Compute geodesics sometimes nontrivial)
  - Define a set of observables to verify each model
- "Observational" cosmology:
  - Choose the "most likely" model from the above (e.g. FRW) and define its parameters (Omega, H, equation of state…)
  - Measure parameters from observations
  - Feed in model refinements to fit the data
  - Get the best set of parameters fitting the widest sample of experimental data → **Concordance Model**

Caveats

Warning: "Precise" does not mean "accurate"

Objection 1: need to feed new parameters into model to achieve better concordance with the data (e.g. omega=0.3 from clustering, need Lambda to get concordance with Omega=1 from CMB)

Objection 2: some so-called "concordance" parameters live in really odd and dangerous domains (e.g. w < -1…)

Message: Never give up in searching alternate solutions, i.e. never forget the questions

"Is precision cosmology really accurate?"

"Are the current 10+ cosmological parameters the modern epicycles?"

"How can we manage to test the modern paradigm of precision cosmology?"

Distance duality

- Assume gen. Rel. is valid
- Then, all distances are unique. In particular, the so-called distance duality relation (based on photon conservation+photons motion on null geodesics) holds ("standard candles are also standard rulers"):

$$\frac{d_L(z)}{d_A(z)(1+z)^2} = 1$$

- Trying to test this duality (cfr. e.g. Kunz, Basset, 2004) is a difficult task because distance measurements are generally bound to the physics of very different astrophysical objects (SNIa, galaxies, clusters of galaxies) and mechanisms of local non-conservation of photons may be a significant source of biasing.

Other tests

- X-Ray and SZE measurements on galaxy clusters (lower biasing due to object modeling) to measure

$$D_A^{obs}(z) = D_A(z)\eta^2(z), \qquad \eta(z) = \frac{D_A}{D_L}(1+z)^2 \neq 1!!!!$$

Cfr. Uzan, Aghanim, Mellier, 2004

- Test Tolman's relationship for galaxy surface brightness:

$$B_S \propto (1+z)^{-n}, n \neq 4!!!!$$

Cfr. Lubin, Sandage, 2001 *(4 companion papers)*

- Measure the CMB temperature scaling as a function of redshift (strictly bound to photon propagation through cosmic distances) and check against alternate scenarios (and possible nonlocal anisotropy of the universe):

$$T_{CMB}(z) = T_0 f(z), \qquad f(z) \neq 1+z$$

T(z) from SZ: basics

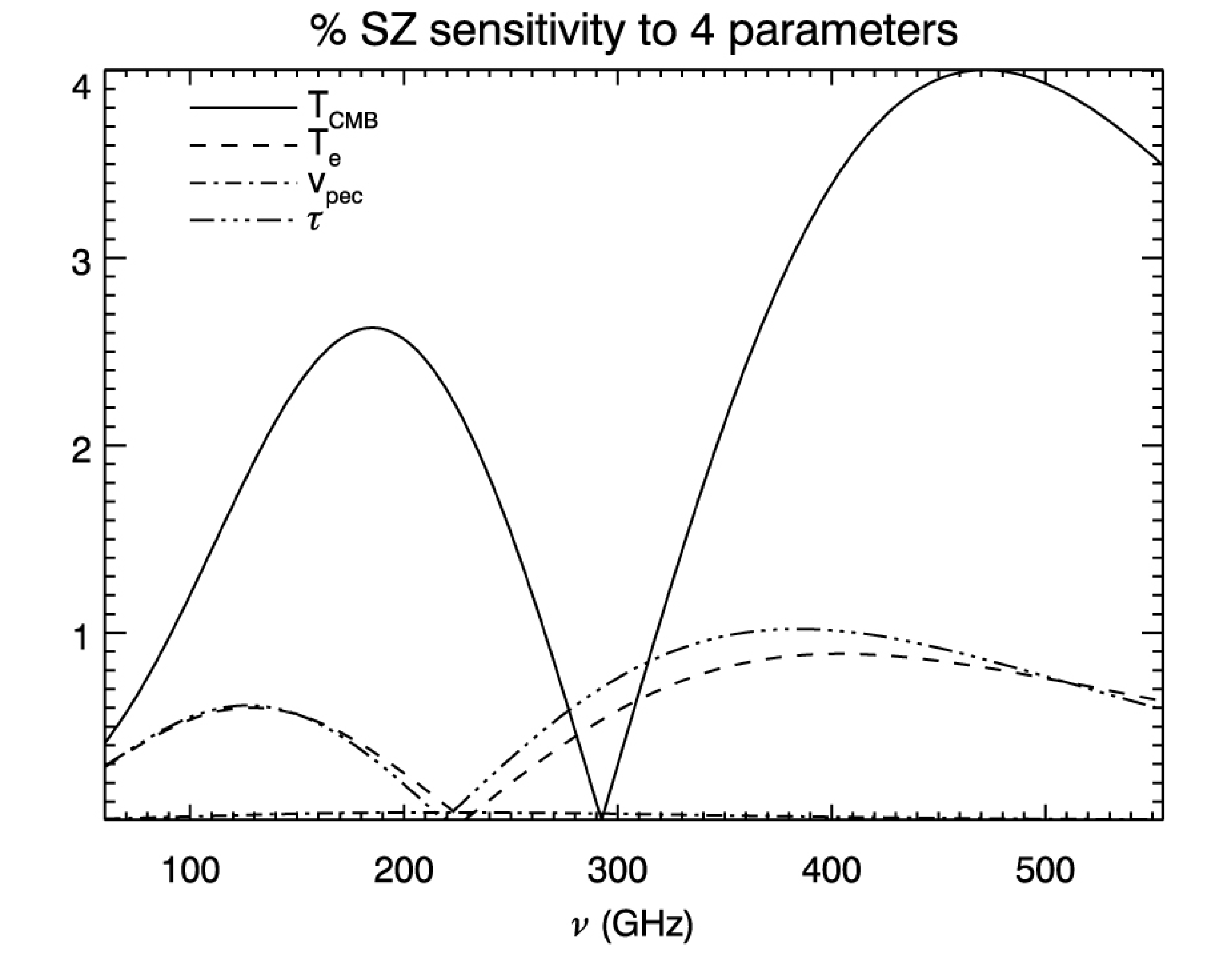
Sz spectrum depends on frequency through the nondimensional ratio $h\nu/kT$, which is redshift-invariant only for standard scaling of T(z), i.e. $\nu(z)/T(z)=\nu(0)/T(0)$

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.

Can we be sensitive to this effect?

T_{CMB} vs z –uncertainties

intrinsic SZ dependence on parameters



Relative variation of SZ signal, evaluated for a typical

10^{-4} comptonization parameter at a T_e=10keV, Vpec=300km/s along l.o.s.

Stronger dependence on T_{CMB} , but high uncertainties on electron temperatures and target sensitivity on T_{CMB} balance back the different contributions.

Assuming contribution from all uncertainties, one gets target sensitivity on exp. Data at the level of at least 10%.

T_{CMB} vs z –uncertainties instrument sensitivity

Typical sensitivity values for ground-based observations (e.g. MITO-SP):

Optical responsivity @ 140GHz: ~400μK/nV

Noise figure @ mod frequency (6Hz) $\approx 10 nV / \sqrt{Hz}$

⇒~4 mK/sqrt(Hz) @ mod freq.

Average over 26mHz ENBW of the DAQ filter chain to obtain rms noise in 1 sec:

$$4 \frac{mK}{\sqrt{Hz}} \cdot \sqrt{26 \cdot 10^{-3} Hz} \cong 650 \mu K_{rms}$$

Typical thermal S-Z from rich clusters are ~100μK:

$$T_{\text{int}} = \left(\frac{Sensitivity}{Signal} \right)^2 \approx 30s$$

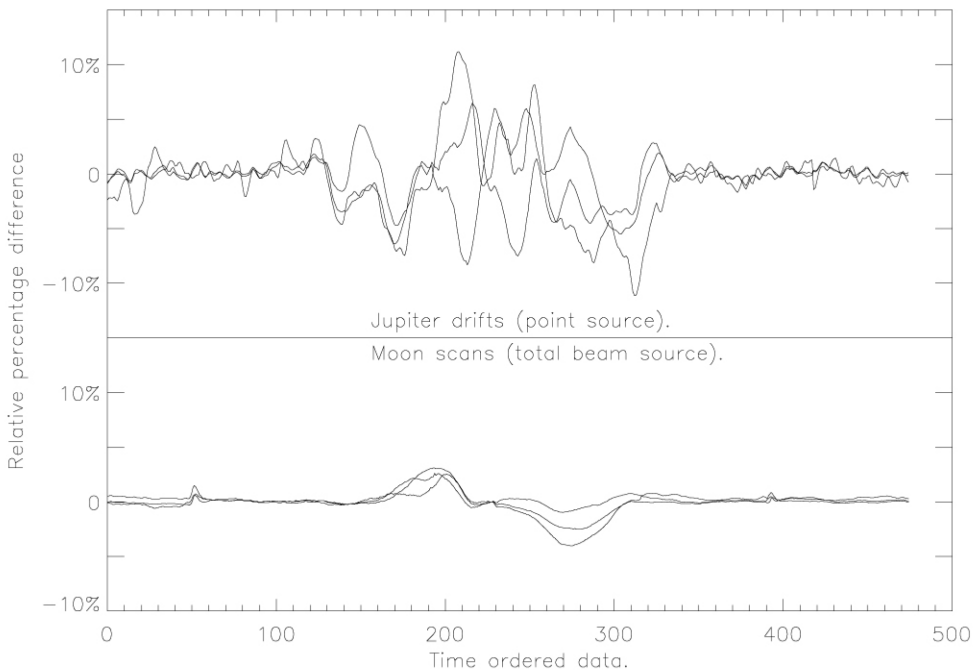
not a big deal for targeted, ground based (i.e. no pointing reconstruction needed and generally low targeting systematics). And things improve for balloon –borne instruments.

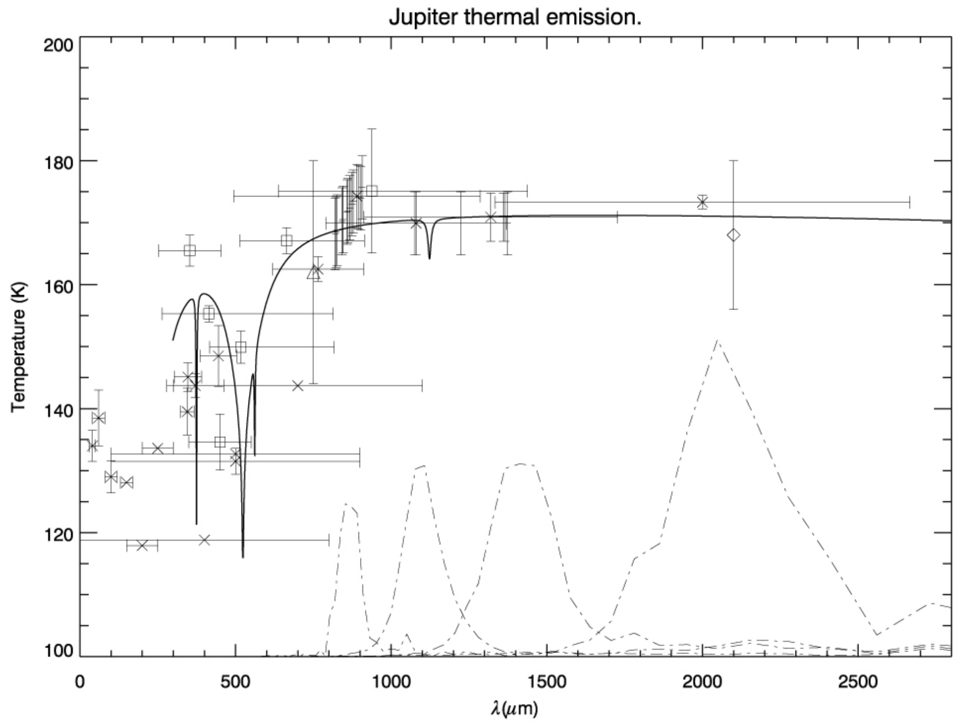
(NOTE: not including dilution and finite beam-throws)

Observational issues

- Operate at high frequencies with multifrequency capabilities (possibly operate with multicolor detectors to minimize observational biasing due to time lag between observations at different frequencies).
- Very accurate calibration is needed. Alternatively, evaluate the parameters from combination of signals that are most likely to be dominated by detector noise rather than calibration uncertainty.
- Real-life datasets need proper treatment to deal with instrumental systematics and proper removal of atmospheric contributions.

Calibration issues





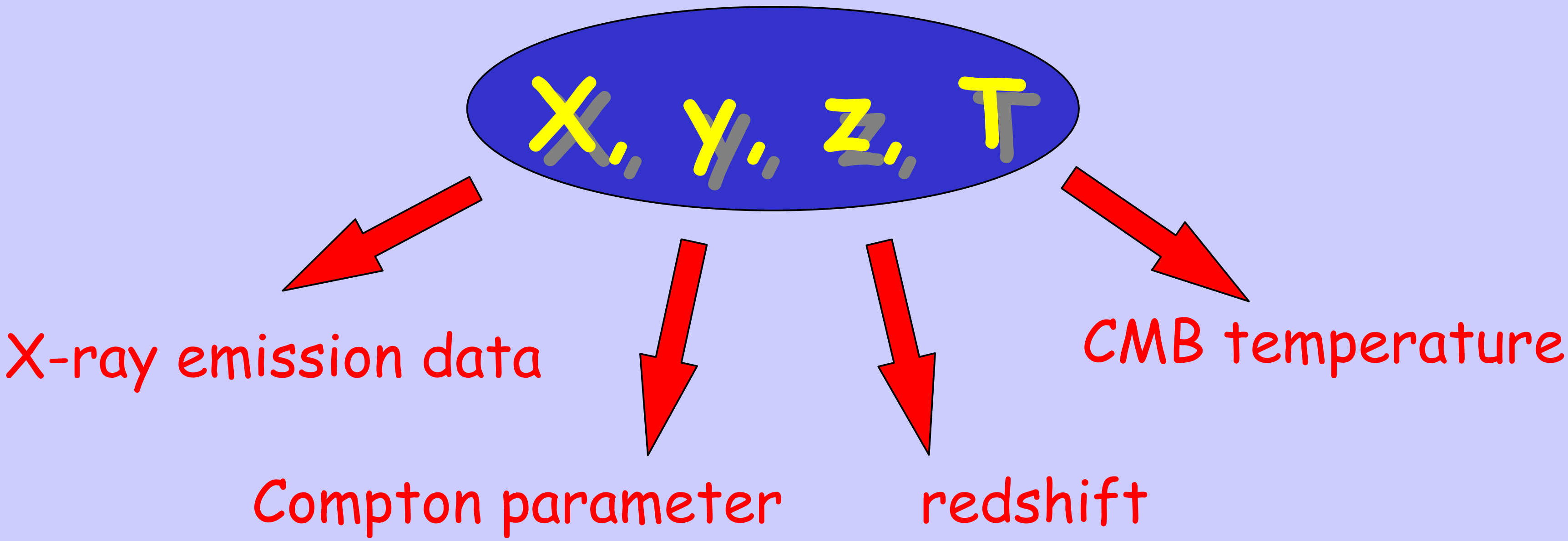
Potential impact on limit sensitivity of the measure.

Need careful data manipulation to get rid of this problem (discuss later)

A new observational reference frame

"The CMB temperature along the redshift should be estimated by SZ measurements"

- Fabbri R., Melchiorri F. & Natale V. Ap&SS, 59, 223, 1978
- Rephaeli Y., ApJ, 241, 858, 1980

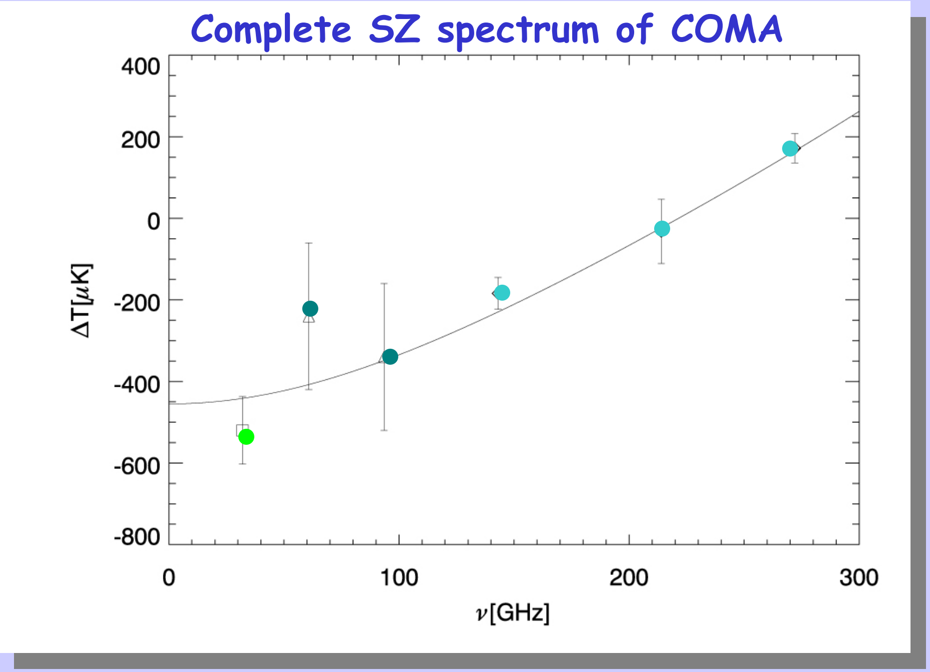


T_{CMB} *vs* z : A1656 by MITO, OVRO & WMAP

Observatory	Freq (GHz)	Δν (GHz)	fov (FWHM) (arcmin)	Sensitivity (mK $s^{1/2}$)	ΔT (μK)
OVRO	32.0	6.5	7.35	1.40	-520 ± 83
WMAP (V)	60.8	13.0	20	1.13	-240 ± 180
WMAP (W)	93.5	19.0	13	1.48	-340 ± 180
MITO (1)	143	30	16	1.21	-184 ± 39
MITO (2)	214	30	16	1.14	-32 ± 79
MITO (3)	272	32	16	0.89	172 ± 36

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

(De Petris M. et al. Ap.JL 574, 119-122, 200
& Savini G. et al. New Astr. 8, 7, 727-736, 2003)



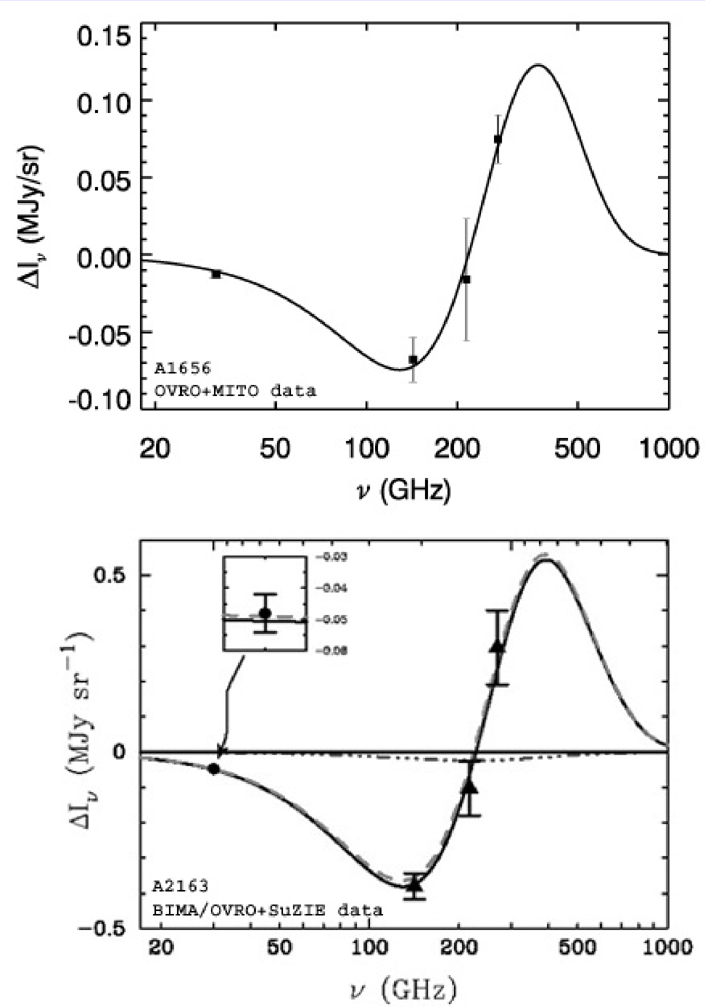
... including also WMAP data

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

(Bennet et al. Ap.J.Suppl. 148, 97, 2003 & Battistelli et al. Ap.JL 598, 75-78, 2003)

T_{CMB} vs z : A1656 & A2163

Observatory	Cluster	Freq.[GHz]	ΔI[MJsr^{-1}]	ΔT[μK]
OVRO	COMA/A1656	32 ±6.5	-0.0159 ±0.0028	-520 ±93
MITO	COMA/A1656	143 ±15	-0.068 ±0.014	-179.3 ±37.8
MITO	COMA/A1656	214 ±15	-0.016 ±0.039	-33.4 ±81.2
MITO	COMA/A1656	272 ±16	0.075 ±0.015	169.8 ±35.1
OVRO & BIMA	Abell2163	30 ±0.5	-0.048 ±0.006	-1777 ±222
SuZIE	Abell2163	141.59 ±6.34	-0.380 ±0.037	-1011.3 ±98.0
SuZIE	Abell2163	216.71 ±7.48	-0.103 ±0.077	-213.0 ±159.3
SuZIE	Abell2163	269 ±12.88	0.295 ±0.105	662.2 ±235.7



OVRO = Herbig et al, ApJ.L, 449, 5, 1995
MITO = De Petris et al. ApJ.L, 574, 119, 2002
OVRO&BIMA = LaRoque et al., astro-ph/0204134
SuZIE = Holzapfel et al., ApJ., 479, 17, 1997

T_{CMB} vs z : Method 1/2

Fit of measured SZ signals ratios with the expected values by changing T(z)/(1+z) as in the following:

$$\frac{\Delta S_i}{\Delta S_j} = \frac{G_i}{G_j}\frac{A\Omega|_i}{A\Omega|_j}\frac{\int_0^\infty \Delta I(x)\varepsilon_i(\nu)d\nu}{\int_0^\infty \Delta I(x)\varepsilon_j(\nu)d\nu}$$

ΔI : CMB intensity change due to SZ defined as

SZ_{THERM} + SZ_{KIN} + $SZ_{REL\ COR}$

$$\Delta I(x) = \frac{2k^3T^3}{h^2c^2}\frac{x^4e^x}{\left(e^x-1\right)^2}\left[\theta f_1(x) - \beta + R(x,\theta,\beta)\right]\tau$$

.. and for the i-channel

ΔS_i : Measured signal

G_i : Responsivity

$A\Omega_i$:Throughput

$\varepsilon_i(\nu)$:Transmission efficiency

$$x = h\nu / k\mathbf{T}$$
$$\theta = kT_e / mc^2$$
$$f_1(x) = \coth(x/2) - 4$$
$$\beta = V/c$$
$$R(x,\theta,\beta) \cong \theta^2[f_2(x) + \theta f_3(x) + \theta^2 f_4(x) + \theta^3 f_5(x)]$$
$$- \beta\theta[g_1(x) + \theta g_2(x)] + \beta^2[1 + \theta g_3(x)]$$

T_{CMB} vs z : Method 2/2

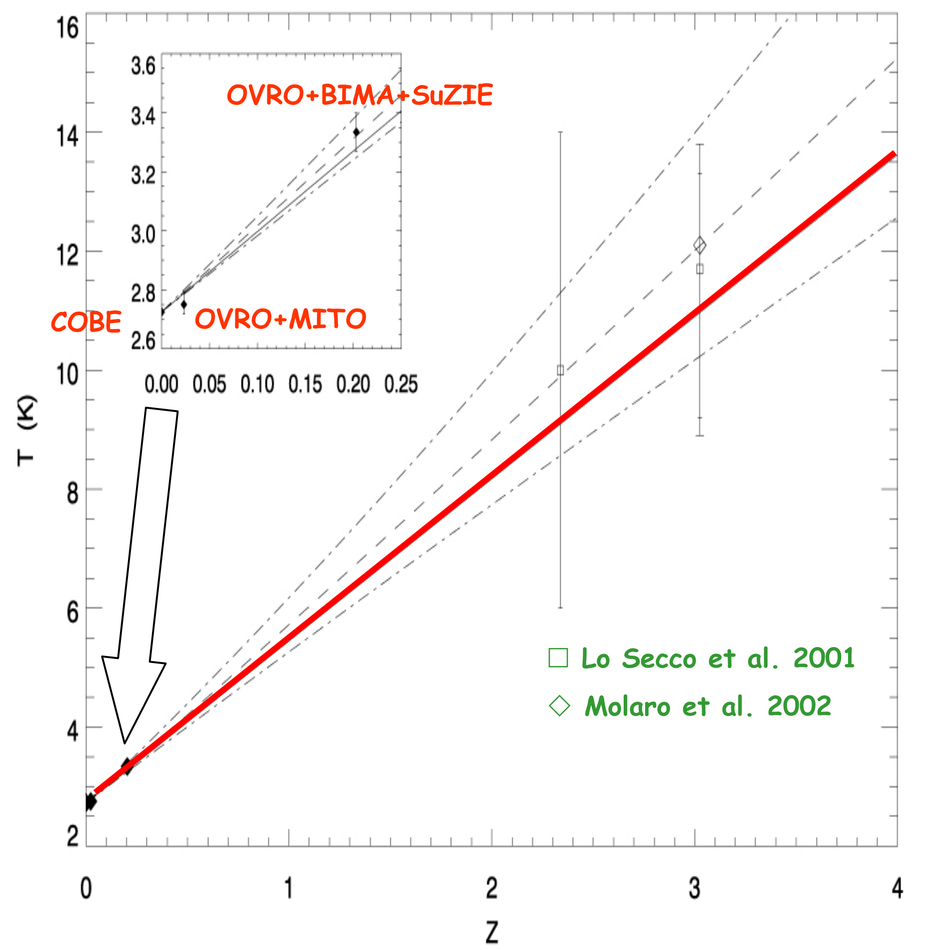
… by considering the ratios between channels we obtain a result that is:

☺ **independent of absolute calibration uncertainties (T_{planet});**

☺ **independent of τ, if KIN-SZ removed or β negligible;**

☹ **dependent on precise knowledge of $A\Omega_i$ (remember drift scans info) and $\varepsilon_i(\nu)$ (remember spectra measurements)**

T_{CMB} vs z : Results



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

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

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

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

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

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

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

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

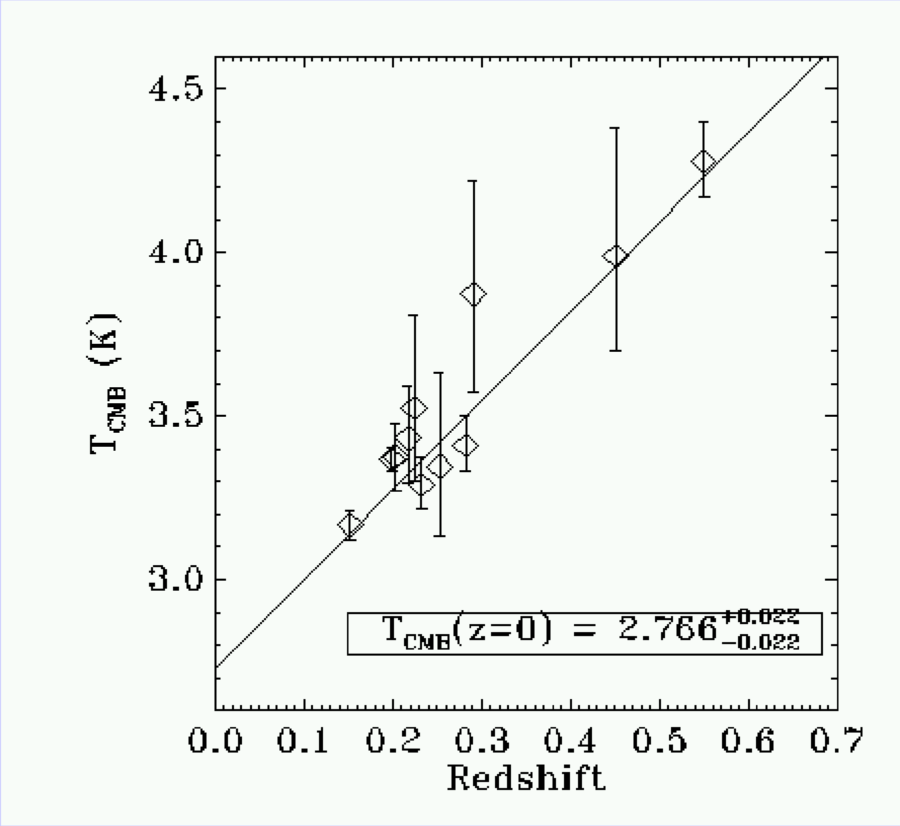
$$d = -0.17 \pm 0.36(95\%c.l.)$$

Molecular microwave transitions CONSISTENT

Standard Model CONSISTENT

T_{CMB} vs z : more data

A Preliminary measurement of the temperature of the CMB versus redshift derived from a set of 11 clusters measured with SuZIE. The line is the expected value based on the COBE FIRAS measurement.



Still very marginal: need targeted observations with dedicated instrumentation and good planning of observations (details later…)

Check Suzie web page

What you need

•(Not so) high sensitivity (order mKs$^{1/2}$ for rich nearby clusters), often strongly background limited even in dry and cold sites

•For GB observations, excellent site testing and accurate modeling of the atmosphere

•Check for instrumental systematics and take care of stability issues

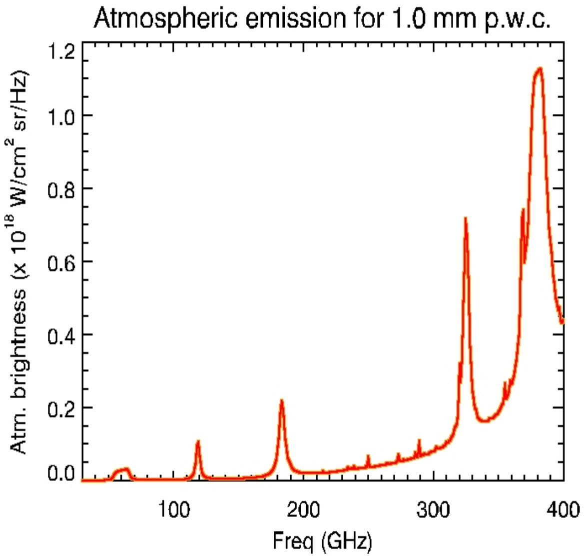
•Accurately choose your obs. strategy and its impact on observables: simulate, optimize, finalize, test.

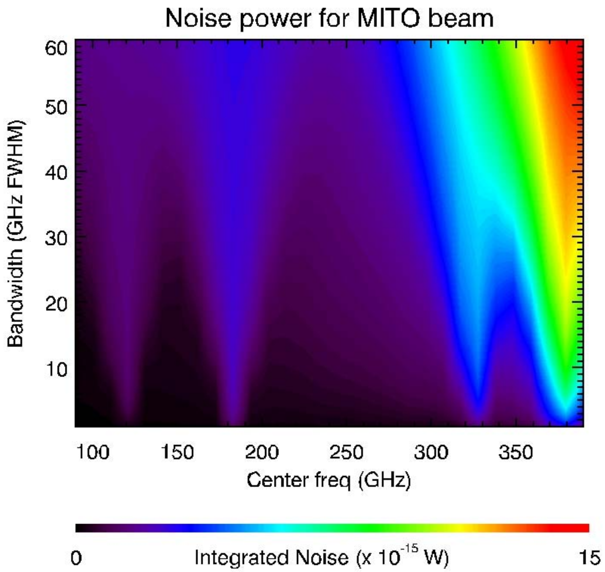
•No "brute force" approach is really needed

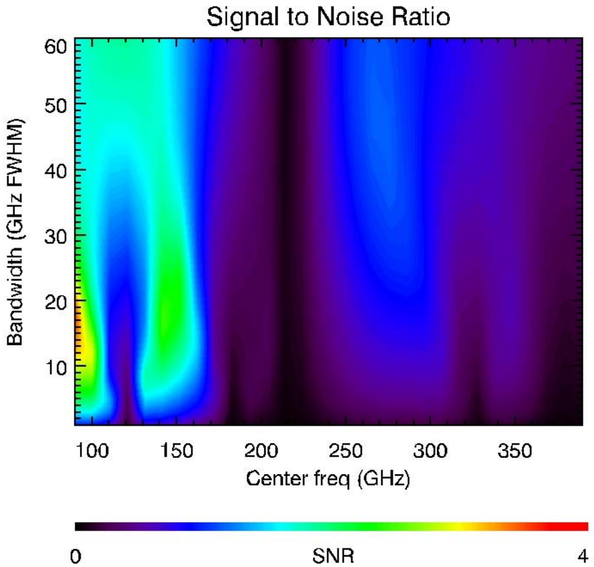
•You don't need to be "egalitarian" in choosing the obs. targets.

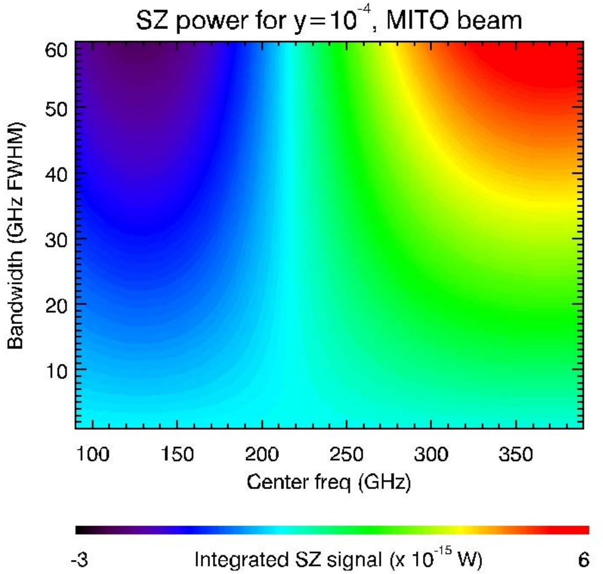
⇒An instrument designed around the observable

Choice of frequencies (preliminary)





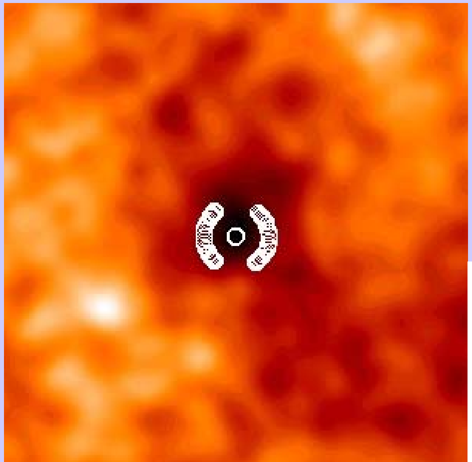


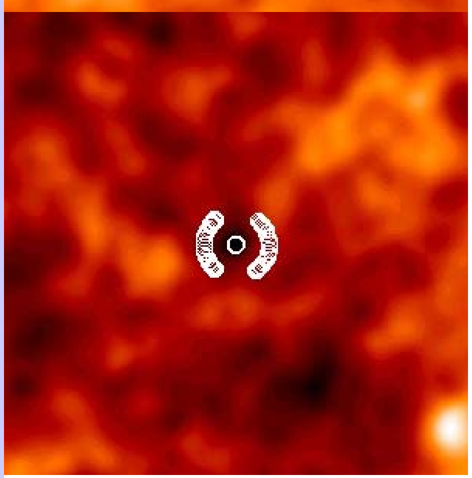


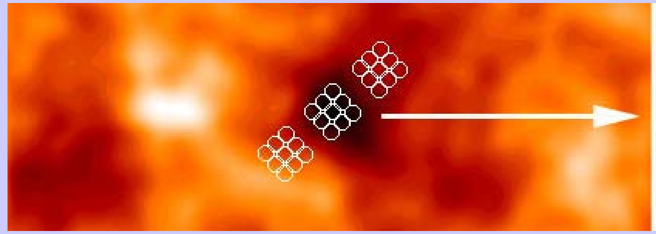
- Include realistic estimates for water vapour content
- Match bandpass shapes to realistic filter design
- Evaluate the impact on T_{cmb} measurements

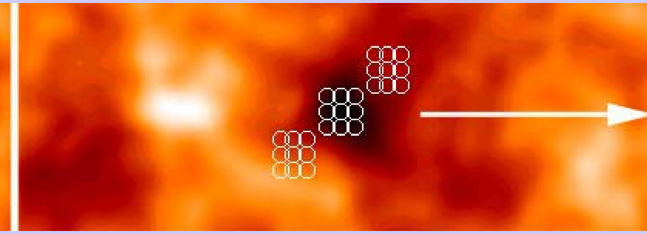
(Atm. Models by J Pardo, analysis by S. De Gregori)

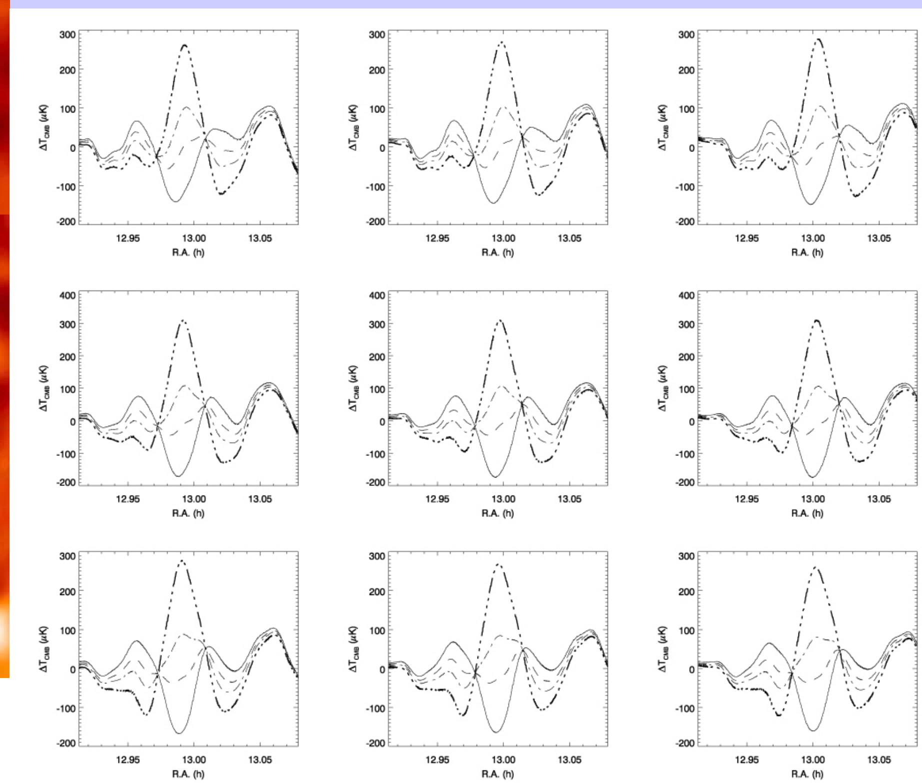
Simulating obs. Strategy

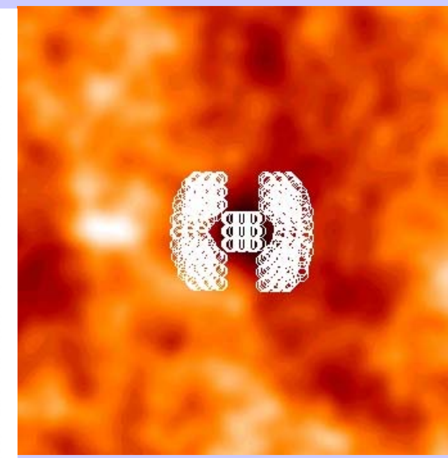


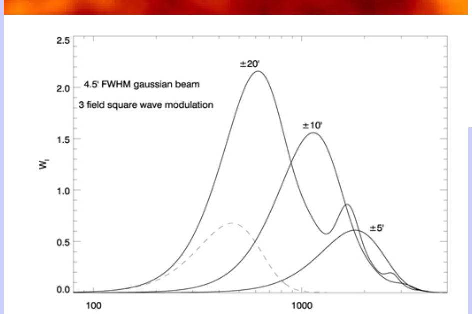






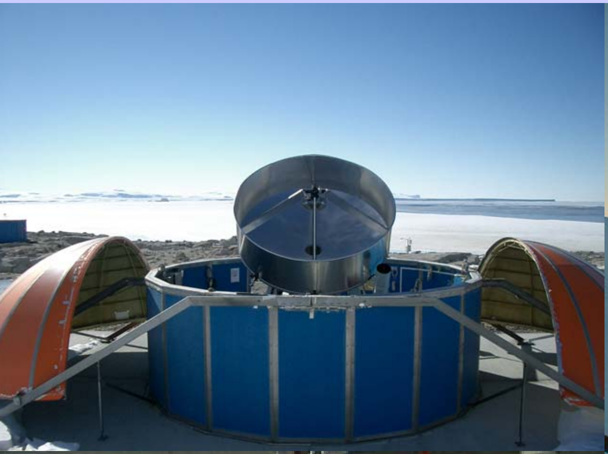


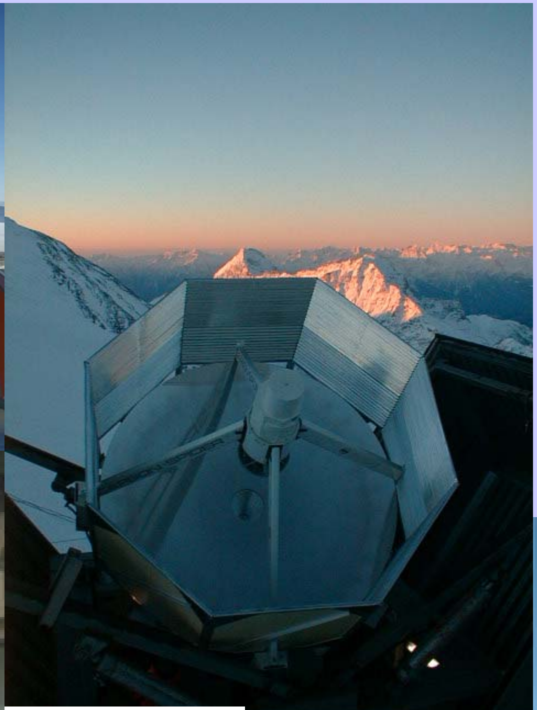




Work in progress…

GEMINI-SZ Project





"A joint effort

for SZ science"

http://oberon.roma1.infn.it/gemini

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CEA, Saclay

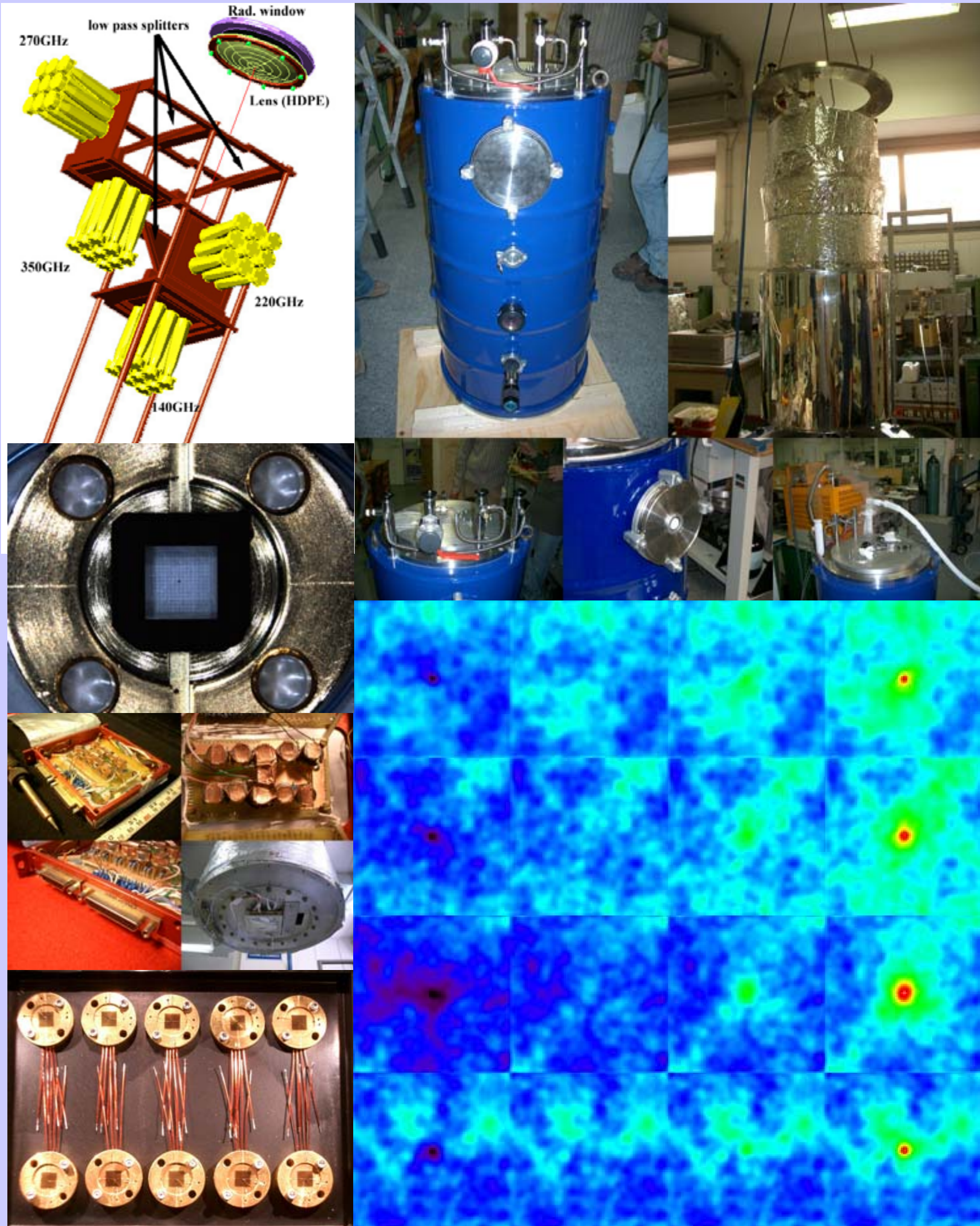
Obs. De Paris

Gemini-SZ
-facilities and plans-

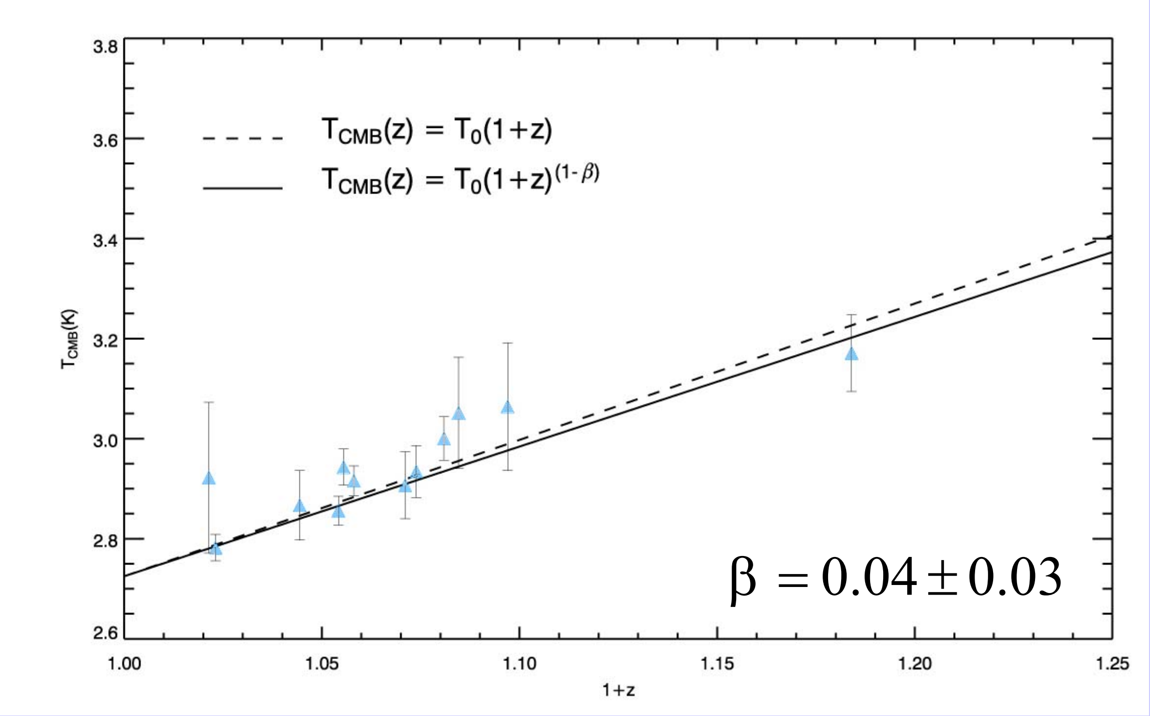
- 2 Ground based telescopes: MITO (N.H.) and OASI/COCHISE (S.H.) to perform routine observations of SZ effect in the mm/submm region
- The balloon-borne platform OLIMPO based on the best available detector technology, first dedicated balloon for SZ measurements
- 2 twin multipixel, multicolor photometers (MADs) under development for MITO+clone for S.H. measurements
- The MASTER radiometer, for line measurements in the submm region and atm. Line absorption monitoring
- The CASPER wideband atmospheric spectrometer

MAD status

- Cryostat delivered Jan 2004, testing and qualification completed in June 2004 (new 4.2K rad shield committed)
- Refrigerator qualification due Aug 2004. Integration will follow.
- Cryostat wiring 30% complete (140 x 2.5m wires…).
- Detector tests performed Dec 2003. Currently 40 pixels available, evenly distributed over the 4 bands. Waiting for SW detector delivery from Cardiff.
- Prototype cold JFET module and warm preamplifier box tested and charcterized.
- Cold bolometer to optics interface designed and committed
- DAQ and fast data preview beta version available (needs scaling to 40 channels)
- …work in progress!!



Planned observations



(Sims and fit by L.Lamagna, G. Luzzi)

Looks promising!

Need to select higher redshift clusters and

(not so) more precise X-Ray datasets to gain more statistical significance

Work in progress to achieve tighter connection with "realistic" scenarios

- 15 galaxy clusters (Mohr at al. '99) observed with 4' beam
- Sensitivity "on the field": 400 $\mu K\ s^{1/2}$
- 3 field modulation strategy
- Assumed atmosphere contribution controlled and removed at 90% c.l.
- "Blind" data treatment and signal extraction
- MCMC to fit on SZ parameters+CMB temp.
- Scaling discriminated at 3σ level

Final remarks

- Original tool to hunt down the modern epicycles and test isotropy of the Universe up to the redshift of galaxy clusters
- Information extracted *almost* for free from good SZ data
- Good results are obviously still bound to reliability of modern X-Ray measurements…now working on XMM data
- Work in progress to perform systematic mm/submm measurements of SZ.