Complementarity and synergy with CMB projects

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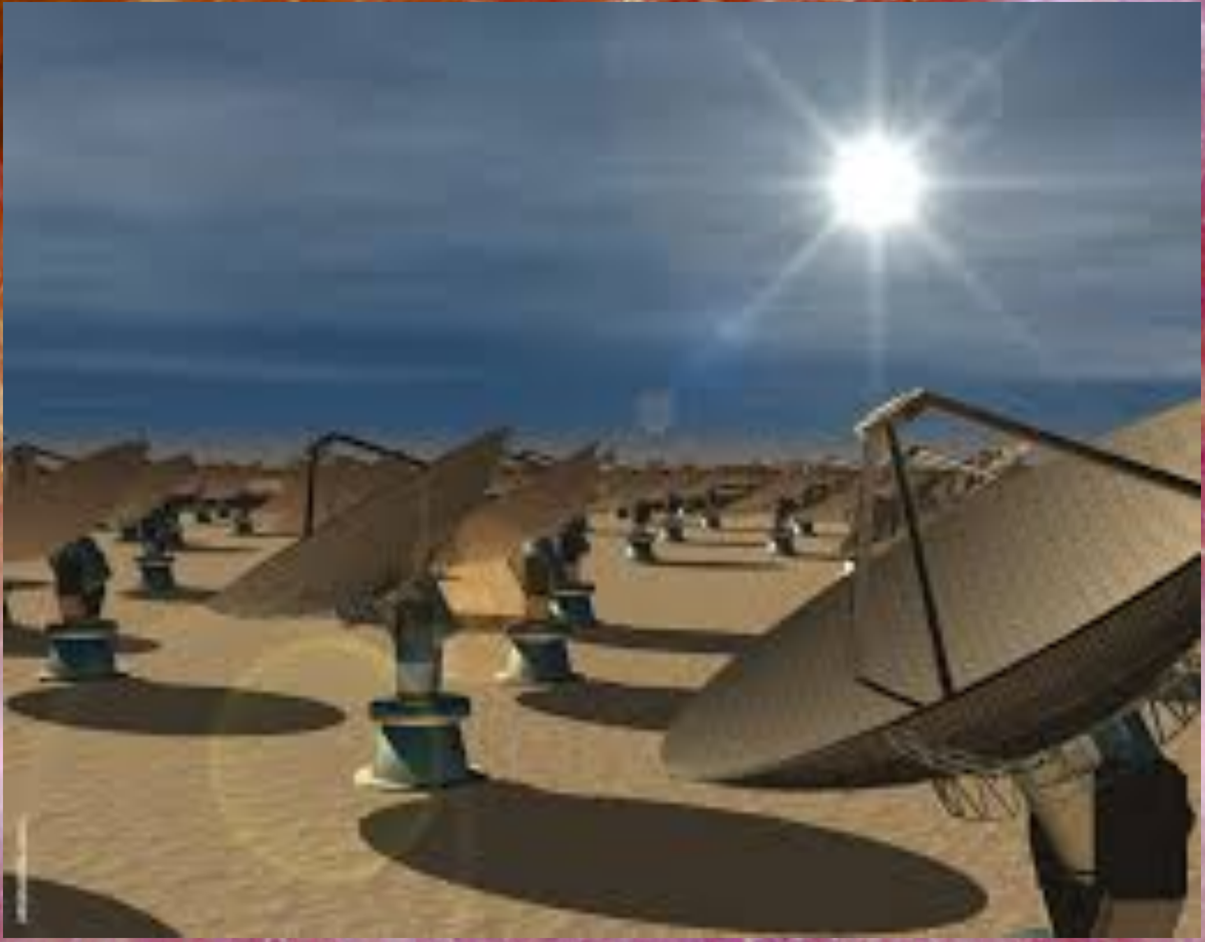


The II National Workshop of SKA science and technology

Bologna
(Area della Ricerca - CNR)
3-5 December 2018

Outline

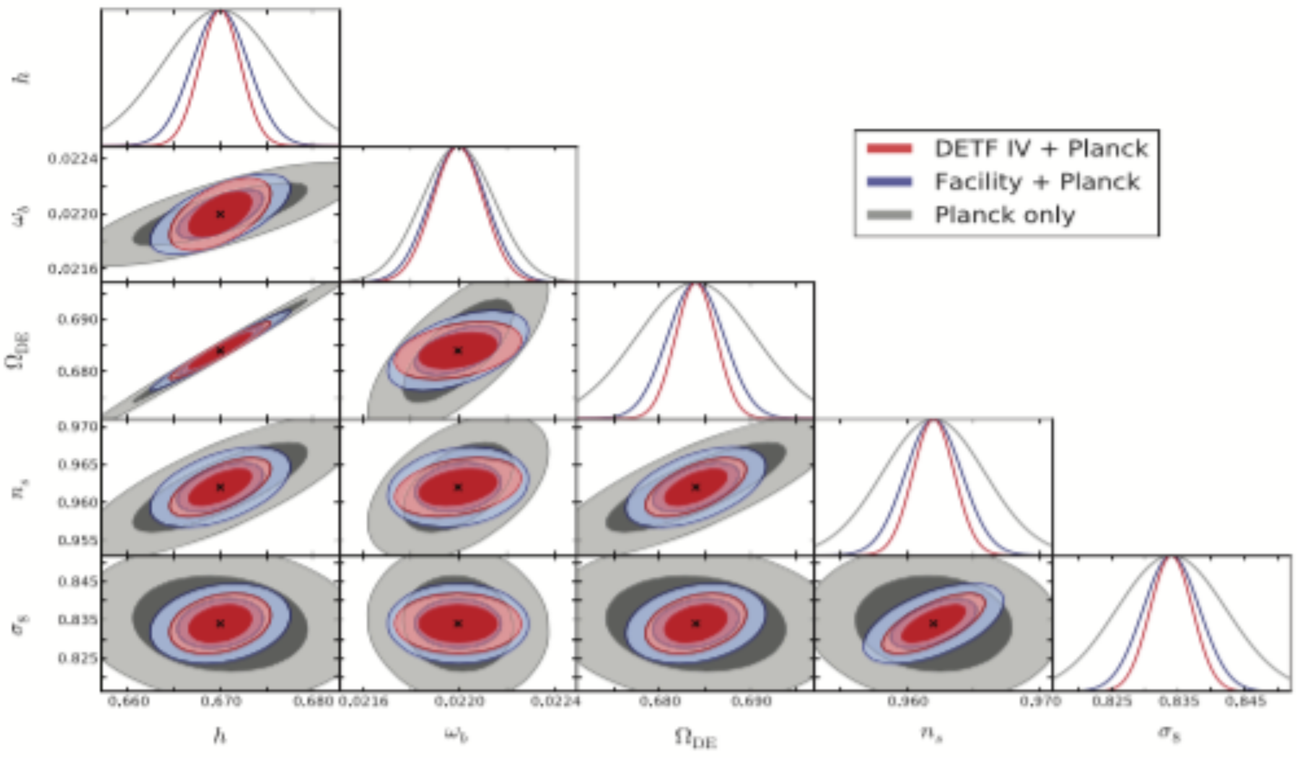
- **Cosmological parameter improvements**
- **Cross-correlation between CMB & galaxy surveys**
  - **ISW**
  - **Non-Gaussianities**
- **Primordial magnetic fields through APS with SKA**
- **SKA contributions to future CMB spectrum studies**
  - **extragalactic foreground by faint point (radio)sources**
  - **free-free, Bose-Einstein, (Comptonization) distortions**
- **Complementary approaches to cosmological reionization**

- Other topics (no time to discuss here)
  - SZ effects from galaxy clusters
  - SZ effects at galactic scales
  - Galactic diffuse radio emission

Cosmological parameters with SKA - I

Complementarity and Synergy in Cosmology

From K. Takahashi et al. 2014



"Facility" survey: representative of SKA1 in combined mode

"DETF IV" survey: representative of Euclid redshift survey

Figure 2: Compared constraints from a Fisher matrix analysis on ΛCDM parameters using different probe combinations Bull et al. (2014). "Facility" is representative of the SKA1 survey in combined (single dish plus interferometric) mode, and "DETF IV" is representative of e.g. the Euclid redshift survey. Both SKA1 and Euclid should come on similar time frames (around 2020) and have similar power on this model.

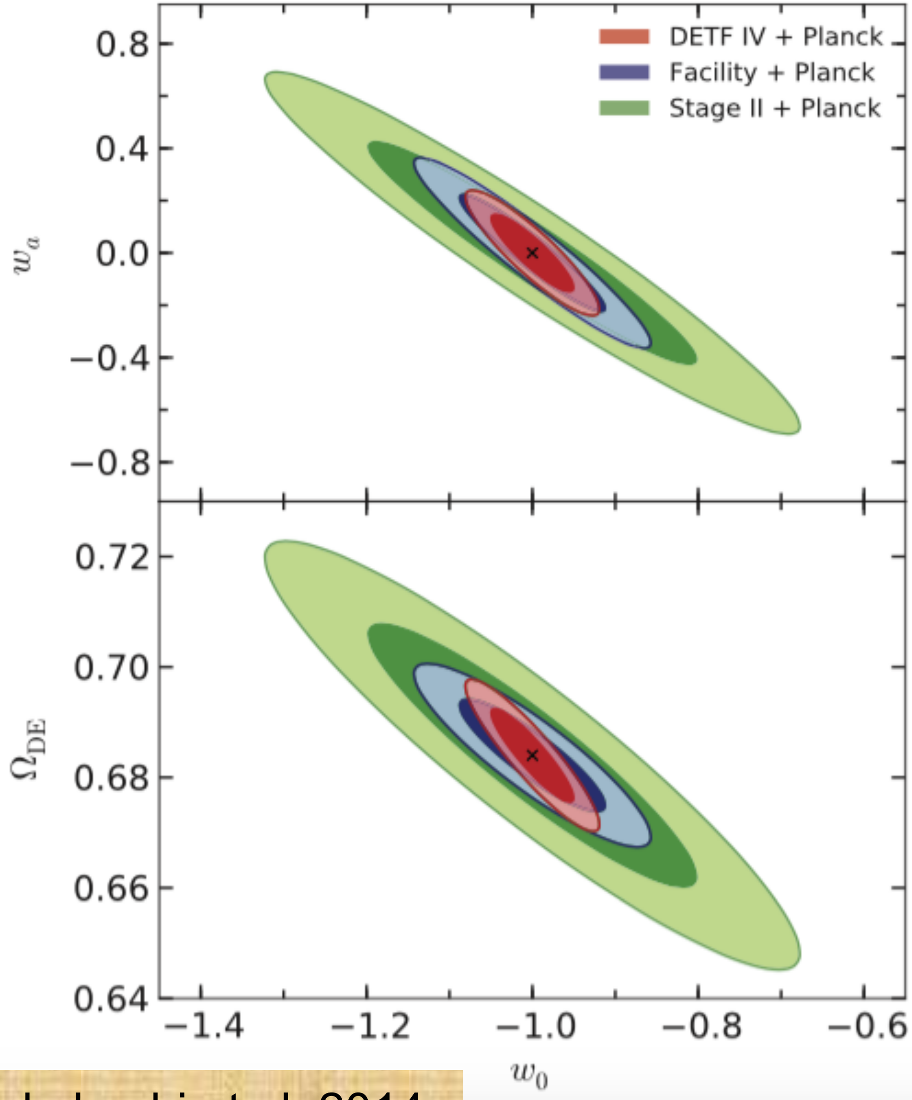
Cosmological parameters with SKA - II

Constrains from a Fisher matrix analysis of different combinations of *Planck* CMB data with either the "Facility" of "DETF IV" surveys.

Again, we see that both combinations have comparable constraining power.

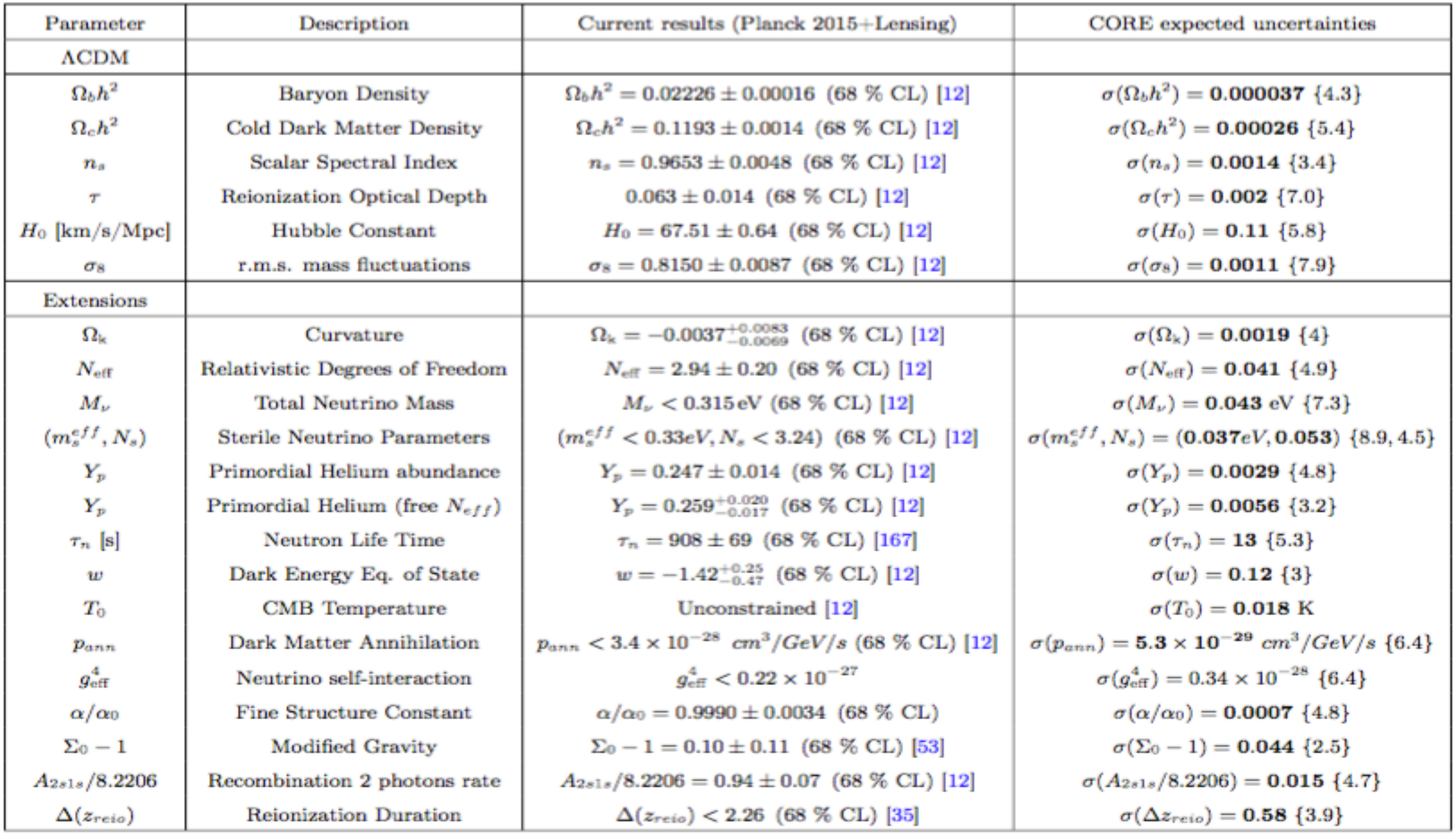
Here the dark energy equation of state is parametrised as $w(a) \simeq w_0 + (1 - a)w_a$, where a is the scale factor.

"Facility" survey: representative of SKA1 in combined mode
"DETF IV" survey: representative of Euclid redshift survey



From K. Takahashi et al. 2014

Future CMB - Ex: cosmological parameters with CORE



Parameter	Description	Current results (Planck 2015+Lensing)	CORE expected uncertainties
ΛCDM			
$\Omega_b h^2$	Baryon Density	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL) [12]	$\sigma(\Omega_b h^2) = \mathbf{0.000037}$ {4.3}
$\Omega_c h^2$	Cold Dark Matter Density	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL) [12]	$\sigma(\Omega_c h^2) = \mathbf{0.00026}$ {5.4}
n_s	Scalar Spectral Index	$n_s = 0.9653 \pm 0.0048$ (68 % CL) [12]	$\sigma(n_s) = \mathbf{0.0014}$ {3.4}
τ	Reionization Optical Depth	0.063 ± 0.014 (68 % CL) [12]	$\sigma(\tau) = \mathbf{0.002}$ {7.0}
H_0 [km/s/Mpc]	Hubble Constant	$H_0 = 67.51 \pm 0.64$ (68 % CL) [12]	$\sigma(H_0) = \mathbf{0.11}$ {5.8}
σ_8	r.m.s. mass fluctuations	$\sigma_8 = 0.8150 \pm 0.0087$ (68 % CL) [12]	$\sigma(\sigma_8) = \mathbf{0.0011}$ {7.9}
Extensions			
Ω_k	Curvature	$\Omega_k = -0.0037^{+0.0083}_{-0.0069}$ (68 % CL) [12]	$\sigma(\Omega_k) = \mathbf{0.0019}$ {4}
$N_{\rm eff}$	Relativistic Degrees of Freedom	$N_{\rm eff} = 2.94 \pm 0.20$ (68 % CL) [12]	$\sigma(N_{\rm eff}) = \mathbf{0.041}$ {4.9}
M_ν	Total Neutrino Mass	$M_\nu < 0.315\,{\rm eV}$ (68 % CL) [12]	$\sigma(M_\nu) = \mathbf{0.043}$ eV {7.3}
(m_s^{eff}, N_s)	Sterile Neutrino Parameters	$(m_s^{eff} < 0.33eV, N_s < 3.24)$ (68 % CL) [12]	$\sigma(m_s^{eff}, N_s) = (\mathbf{0.037}eV, \mathbf{0.053})$ {8.9, 4.5}
Y_p	Primordial Helium abundance	$Y_p = 0.247 \pm 0.014$ (68 % CL) [12]	$\sigma(Y_p) = \mathbf{0.0029}$ {4.8}
Y_p	Primordial Helium (free N_{eff})	$Y_p = 0.259^{+0.020}_{-0.017}$ (68 % CL) [12]	$\sigma(Y_p) = \mathbf{0.0056}$ {3.2}
τ_n [s]	Neutron Life Time	$\tau_n = 908 \pm 69$ (68 % CL) [167]	$\sigma(\tau_n) = \mathbf{13}$ {5.3}
w	Dark Energy Eq. of State	$w = -1.42^{+0.25}_{-0.47}$ (68 % CL) [12]	$\sigma(w) = \mathbf{0.12}$ {3}
T_0	CMB Temperature	Unconstrained [12]	$\sigma(T_0) = \mathbf{0.018}$ K
p_{ann}	Dark Matter Annihilation	$p_{ann} < 3.4 \times 10^{-28}\ cm^3/GeV/s$ (68 % CL) [12]	$\sigma(p_{ann}) = \mathbf{5.3 \times 10^{-29}}\ cm^3/GeV/s$ {6.4}
$g^4_{\rm eff}$	Neutrino self-interaction	$g^4_{\rm eff} < 0.22 \times 10^{-27}$	$\sigma(g^4_{\rm eff}) = 0.34 \times 10^{-28}$ {6.4}
α/α_0	Fine Structure Constant	$\alpha/\alpha_0 = 0.9990 \pm 0.0034$ (68 % CL)	$\sigma(\alpha/\alpha_0) = \mathbf{0.0007}$ {4.8}
$\Sigma_0 - 1$	Modified Gravity	$\Sigma_0 - 1 = 0.10 \pm 0.11$ (68 % CL) [53]	$\sigma(\Sigma_0 - 1) = \mathbf{0.044}$ {2.5}
$A_{2s1s}/8.2206$	Recombination 2 photons rate	$A_{2s1s}/8.2206 = 0.94 \pm 0.07$ (68 % CL) [12]	$\sigma(A_{2s1s}/8.2206) = \mathbf{0.015}$ {4.7}
$\Delta(z_{reio})$	Reionization Duration	$\Delta(z_{reio}) < 2.26$ (68 % CL) [35]	$\sigma(\Delta z_{reio}) = \mathbf{0.58}$ {3.9}

From E. Di Valentino et al. 2018, JCAP

Table 34. Current limits from Planck 2015 and forecasted CORE-M5 uncertainties. The first 6 rows assume a ΛCDM scenario while the following rows give the constraints on single parameter extensions. In the fourth column, numbers in curly brackets {...} give the improvement in the parameter constraint when moving from Planck 2015 to CORE-M5, defined as the ratio of the uncertainties $\sigma^{Planck}/\sigma^{CORE}$.

Cross-correlations between (radio source) catalogs & CMB maps

✧ The sensitivity of the SKA (SKA2_mid_dish in particular, but also SKA precursors) is so high on typical FoVs of ~ degree side at frequencies around one GHz, that it is reasonable to think to cover a significant sky fraction (thousands of square degrees) with unprecedented sensitivity accumulating some months of integration.

✧ A 1-yr SKA survey will contain > $10^9(f_{sky}/0.5)$ HI galaxies in at redshifts $0 < z < 1.5$

✧ This makes the combination of *Planck* and SKA a powerful tool for improved cross-correlation analyses between CMB and radio data, that can be generalized to surveys in other frequency bands

Cross-correlations between (radio source) catalogs & CMB maps

Cross-correlation & angular power spectrum

Given a CMB map in temperature and a galaxy survey x = (T, G) (vector in pixel space), the Quadratic Maximum Likelihood (QML) (Tegmark '97) provides an estimator of the angular power spectrum $C_\ell X$, with X being one of TT, TG, GG

The QML estimator is well suited for such analysis for several reasons:

- ✓ it is optimal (i.e. unbiased and minimum variance);
- ✓ it is a computationally demanding method and can be currently applied only at modest resolution but this is not a problem for studying effects present at large angular scales for which where the computation is affordable on a supercomputer;
- ✓ it is pixel based, making trivial the masking process necessary because of foreground emission or incomplete sky coverage.

Applications to ISW effect – I

✧ The Integrated Sachs Wolf (ISW) effect results from the line of sight integral in the Sachs-Wolfe ‘67 equation

✧ It arises when CMB photons streaming across the Universe interact with the time evolving gravitational potential wells associated with the foreground large scale structure

✧ Potential evolution → net change of the photon energies as they pass through them

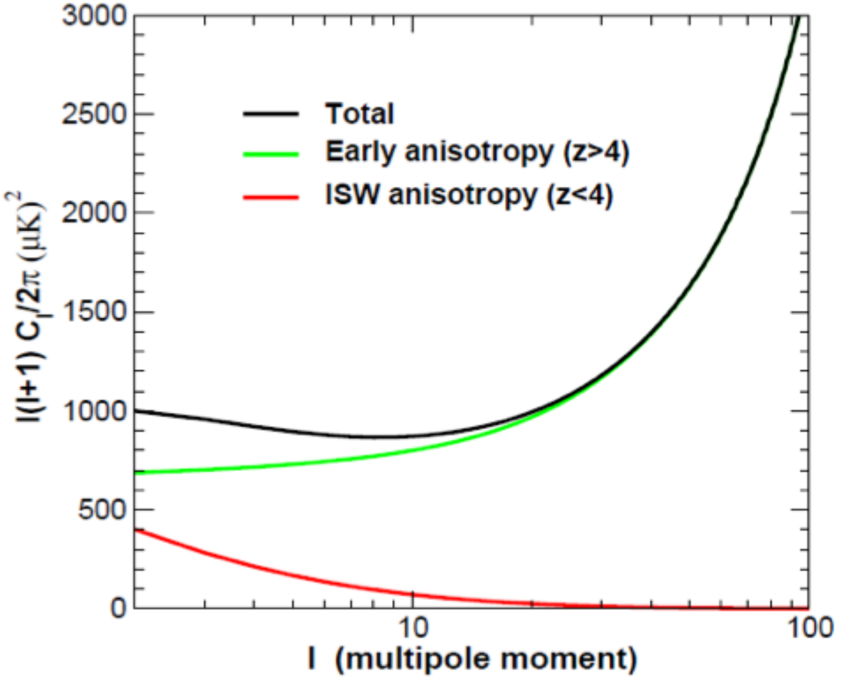
✧ ISW is a linear effect depending on the cosmological model, since it requires a change in equation of state of the cosmic fluid

✧ Evolution/variation of gravitational potential related to the linear density perturbations of matter. Change is important at:

- early times, when the universe goes from being radiation dominated to matter dominated (early ISW)
- at late times, as the dark energy (or curvature) takes over from the matter (late ISW)

Unlike the early ISW, the late ISW is virtually uncorrelated with the CMB anisotropies generated at last scattering

Applications to ISW effect – II



← Typical auto-correlation function for the ISW for a ΛCDM model (Crittenden et al. '96)

➢ Advantageous to isolate the late ISW generated at low z with the cross-correlation of the CMB maps with LSS surveys:

✓ CMB photons cross a time-varying potential and become slightly hotter or colder

➢ Statistically, we expect a tiny correlation of hot spots in the CMB with LSS, an effect which expected to be less than 1 μK

➢ Interesting results have been already achieved from cross-correlating WMAP & SDSS and WMAP & NVSS (Raccanelli et al. '08, Schiavon et al. '12), opening the road for *Planck* & SKA analyses

Applications to non-Gaussianities

- Primordial perturbations at the origin of the LSS may leave their imprint in the form of small deviations from a Gaussian distribution
- Different kinds of configurations, such as the so-called local type, equilateral, enfolded, orthogonal, have been predicted
- Profound implications for inflationary mechanisms
- Extragalactic radio sources are particularly interesting as tracers of the LSS, since they span large volumes up to high redshifts. Ex.: Radio sources from NVSS, quasars from SDSS DR6 and DR7, LRG from SDSS II have been analyzed by Xia et al. ’11 also in combination with WMAP map:
  - f_{NL} = 48±20, 50±265, 183±95 at 68% CL for local, equilateral, enfolded configurations

- Camera et al. (2014) find that with SKA2 (in its full configuration) it will possible to constrain f_{NL}^{loc} down to

$$\sigma(f_{NL}^{loc}) \simeq 1.54$$

- Thanks to the large number of HI galaxies that will be detected up to high z
- These works indicate the possibility to improve with SKA the constraints on f_{NL}^{loc} of a factor ~ 3 with respect to *Planck* results

Primordial magnetic fields (PMF)

✧ If lower bounds for PMF from *Fermi* will be confirmed, SKA can perform crucial measurements towards the probe of the generation mechanism.

  ✧ SKA measurement of very high-ℓ multipoles can improve these bounds on PMF as well as the characterization of foreground and secondary anisotropies beyond the Silk damping tail.

  ✧ The smoking gun of the Faraday rotation of CMB polarization anisotropies from intervening magnetic fields from a stochastic background of PMF is a B-polarization signal at very high-ℓ multipoles, $\ell \sim 10^4$.

✧ SKA observations can target such signal.

SKA synergy with Microwave Background studies

From C. Burigana et al. 2014

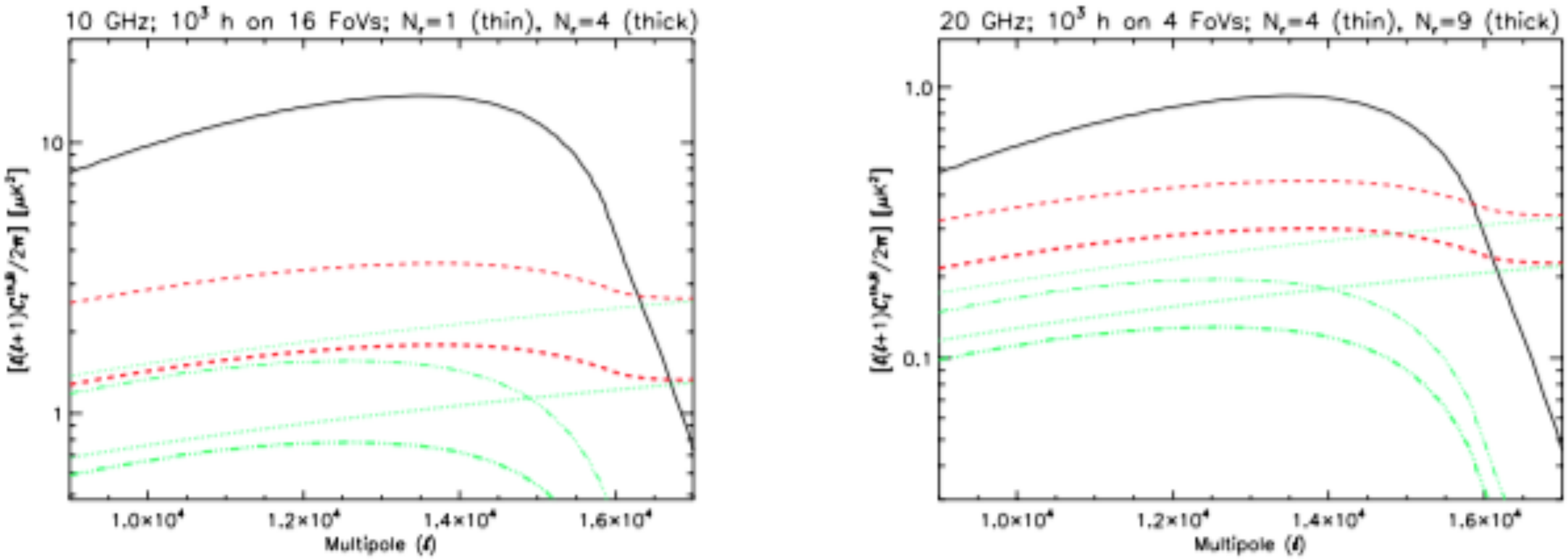
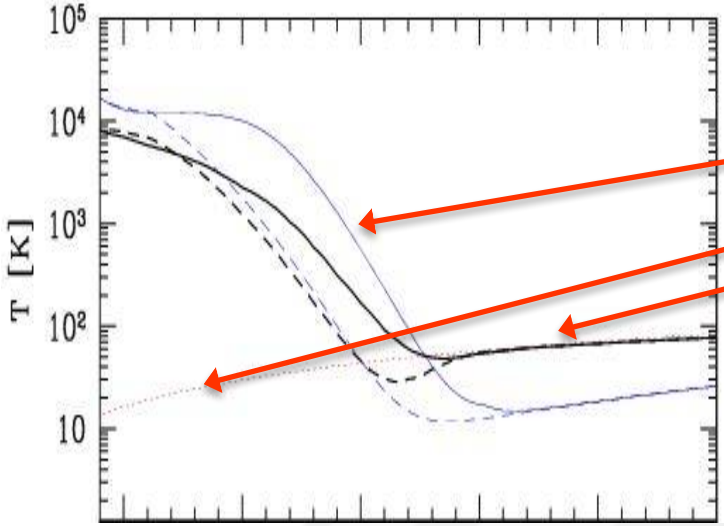


Figure 3: B-mode APS of the CMB at 10 GHz and 20 GHz induced by the Faraday rotation field with PMF normalization comoving scale $\lambda = 1$ Mpc and $n_B = 0$ (solid black line – adapted from Fig. 2 in Kosowsky et al. 2005) compared with SKA2 sensitivity (red dashes) achieved in $\sim 10^3$ hours of integration on a suitable number of FoVs, each of area $\simeq 0.49 \times (1.67\,\mathrm{GHz}/\nu)^2$ deg^2. Cosmic+sampling variance from this signal (green three-dots) and instrumental noise limitation (green dots) are also separately displayed. A 10% binning in ℓ is assumed. With relatively short baselines exploited here, the sharing of the same integration time on a number of FoVs may be more advantageous in terms of trade-off between the minimization of sampling and noise variances. The use of a focal-plane array with a number of receivers, N_r, allowing to observe a correspondingly larger sky area in the same time, will imply a better signal-to-noise ratio. See also the text.

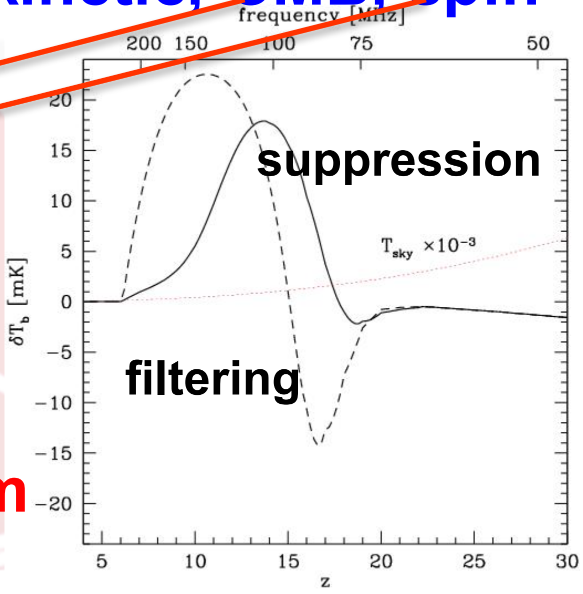
Theoretical model adapted from Kosowsky et al. 2005

Temperatures:[kinetic, CMB, spin (21 cm)]



Schneider et al. 2008
MNRAS, 384, 1525

Reionization: synergy CMB-21cm



suppression

filtering

Planck Collaboration: Planck constraints on reionization history

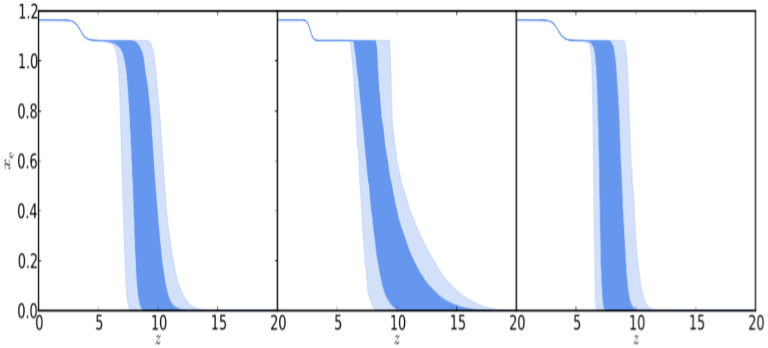
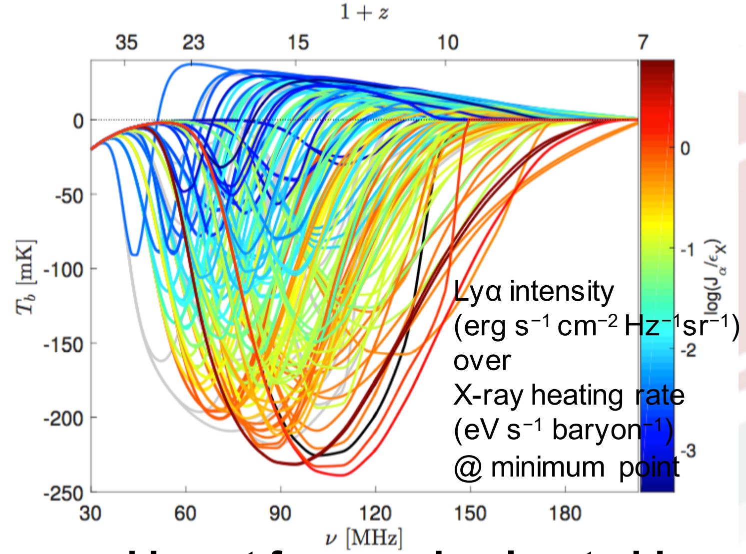


Fig. 18. Constraints on ionization fraction during reionization. The allowed models, in terms of z_{re} and Δz, translate into an allowed region in $x_e(z)$ (68 % and 95 % in dark blue and light blue, respectively), including the z_{end} > 6 prior here. *Left*: Constraints from CMB data using a redshift-symmetric function ($x_e(z)$ as a hyperbolic tangent with δz = 0.5). *Centre*: Constraints from CMB data using a redshift-asymmetric parameterization ($x_e(z)$ as a power law). *Right*: Constraints from CMB data using a redshift-symmetric parameterization with additional constraints from the kSZ effect.

PIP XLVII, 2016



Lyα intensity
(erg s^{-1} cm^{-2} Hz^{-1}sr^{-1})
over
X-ray heating rate
(eV s^{-1} baryon^{-1})
@ minimum point

Cohen et al. 2016

Envelope of 193 possible models

- ✓ **negative signals up to ~ −250mK**
- ✓ **positive signals up to ~ 50mK**

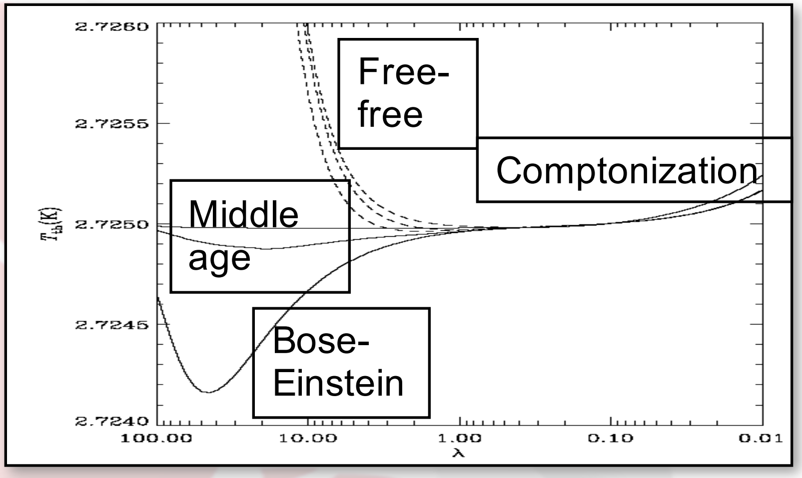
peaking at frequencies located in a wide range between ~ 50 and 150 MHz corresponding to z ~ 30 to 10

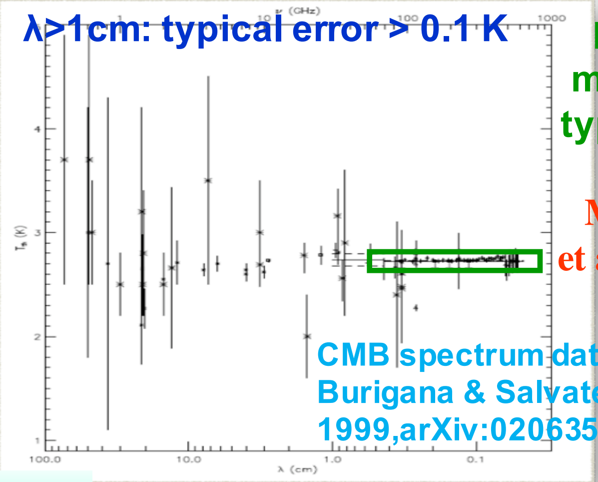
21cm require removal of foreground at a few x 10^{-3} level

… but EDGES ☺

SKA contribution to future CMB spectrum projects

- Current limits on CMB spectral distortions and energy dissipation processes in the plasma, $|\Delta\varepsilon/\varepsilon_i| \lesssim 10^{-4}$ ← **NASA COBE/FIRAS**
- "Early" space mission proposals:
  DIMES at λ ≥ 1 cm; **FIRAS II** at λ ≤ 1 cm
  → probing energy exchanges 10–100 times smaller than the FIRAS
- **PIXIE** (NASA): spectrum measures in polarization dedicated CMB space mission, degree resolution
- **PRISM** (ESA): high(est) sensitivity, arcmin resolution, wide(est) frequency coverage
- **Differential (dipole) approaches:** work also for pure anisotropy experiments, e.g. **CORE (ESA)**, **PICO (NASA)** – possibly also absolute measures –, **LiteBIRD (JAXA)**

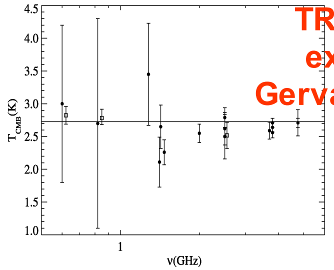




λ>1cm: typical error > 0.1 K

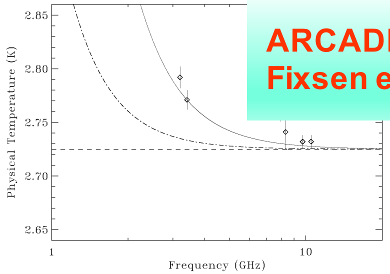
FIRAS measures: typical error ±0.0001 K
Mather, et al., 1999,

CMB spectrum data collection; Burigana & Salvaterra, 1999,arXiv:0206350



TRIS, ground experiment Gervasi et al 2008

Fig. 5.—CMB thermodynamic temperature measured at low frequencies (see Table 1). For easier comparison with previous measurements (*filled circles*), TRIS data points (*open squares*) have been slightly shifted in frequency. The horizontal solid line is the CMB temperature obtained by FIRAS at higher frequencies.



ARCADE 2, balloon Fixsen et al. 2011

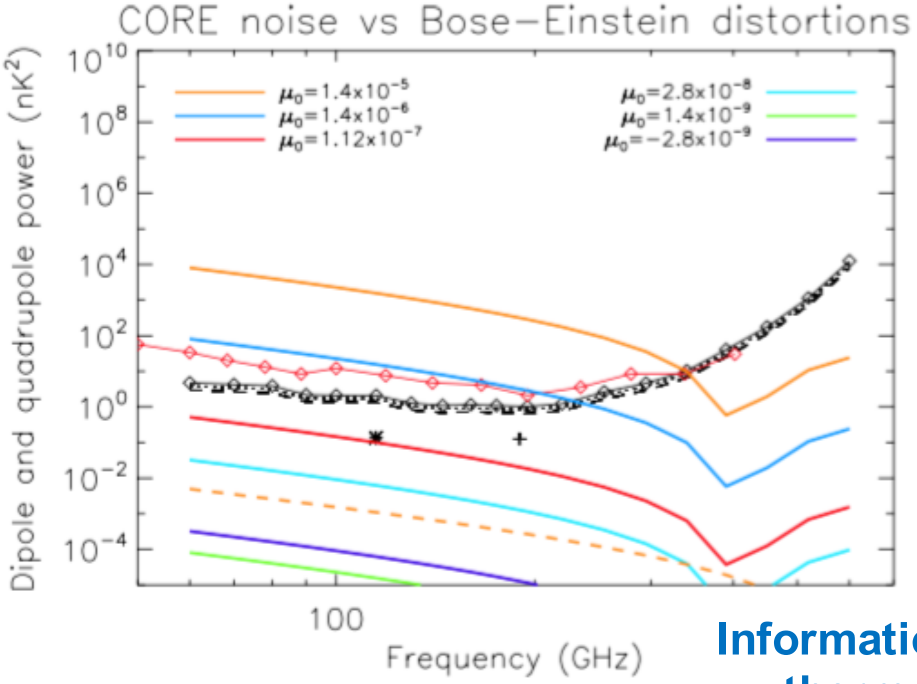
Low ν: crucial for free-free distortions, where Bose-Einstein like distortions are also more prominent

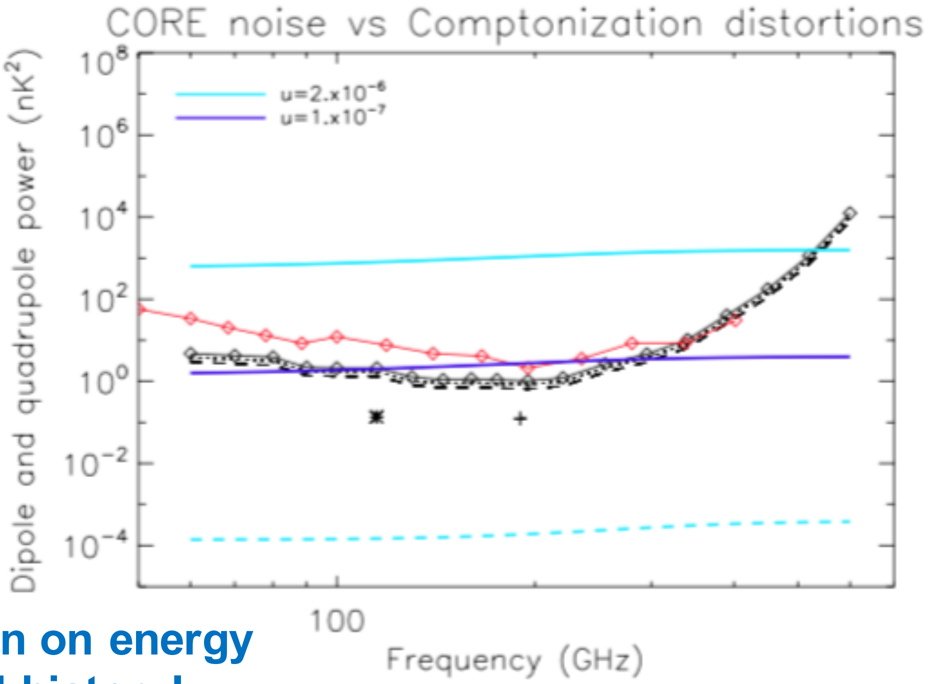
Great hopes from PIXIE absolute spectrum measurements (Kogut et al. 2011) to constrain (or detect) energy exchanges 1000 times smaller than the FIRAS upper limits

Differential (dipole) approaches

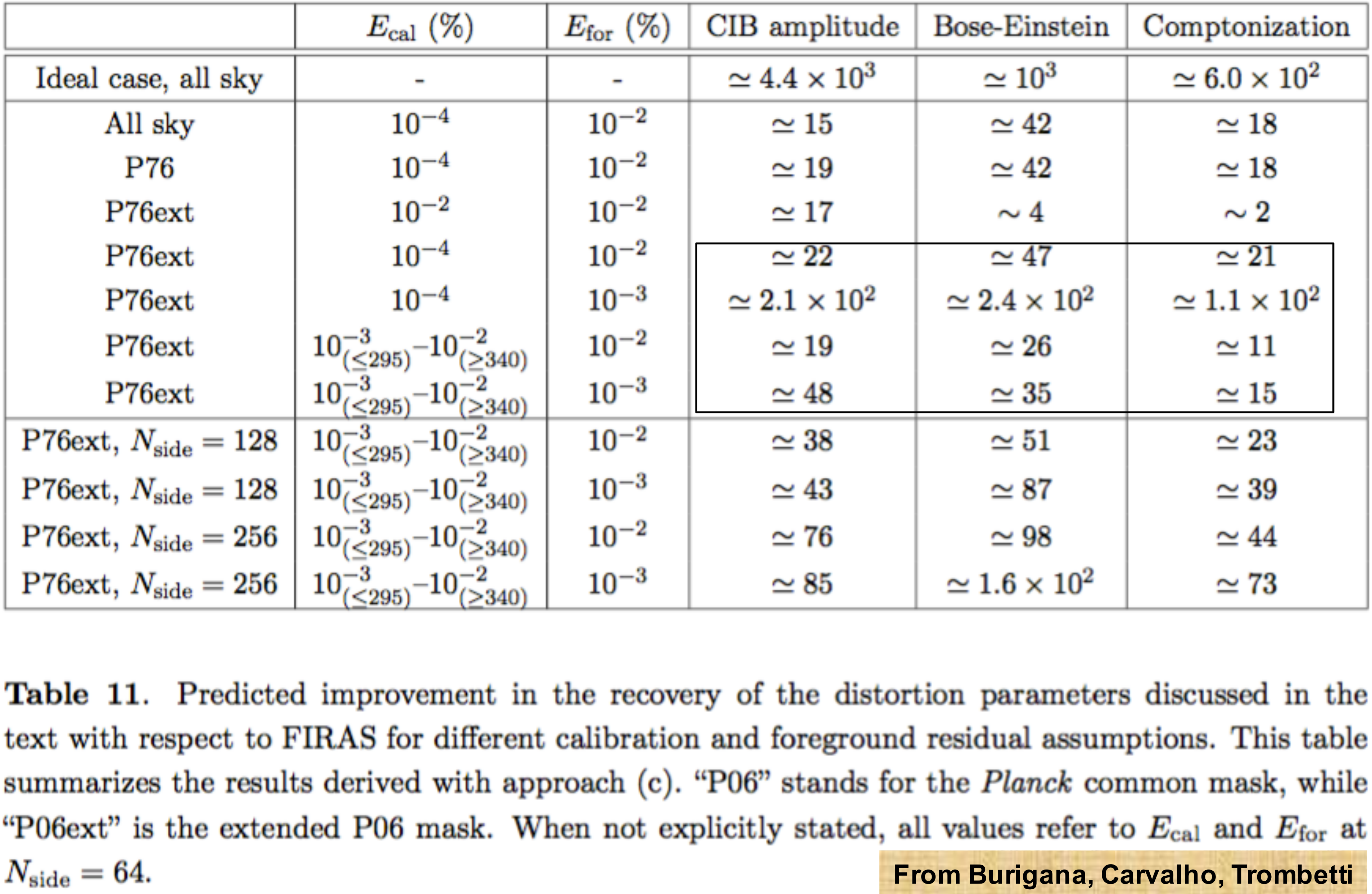
Angular power spectrum of the dipole map difference between distorted spectra and current blackbody spectrum vs CORE (black) & LiteBIRD (red) white noise power spectrum

From Burigana, Carvalho, Trombetti et al. 2018, JCAP





Information on energy thermal history!

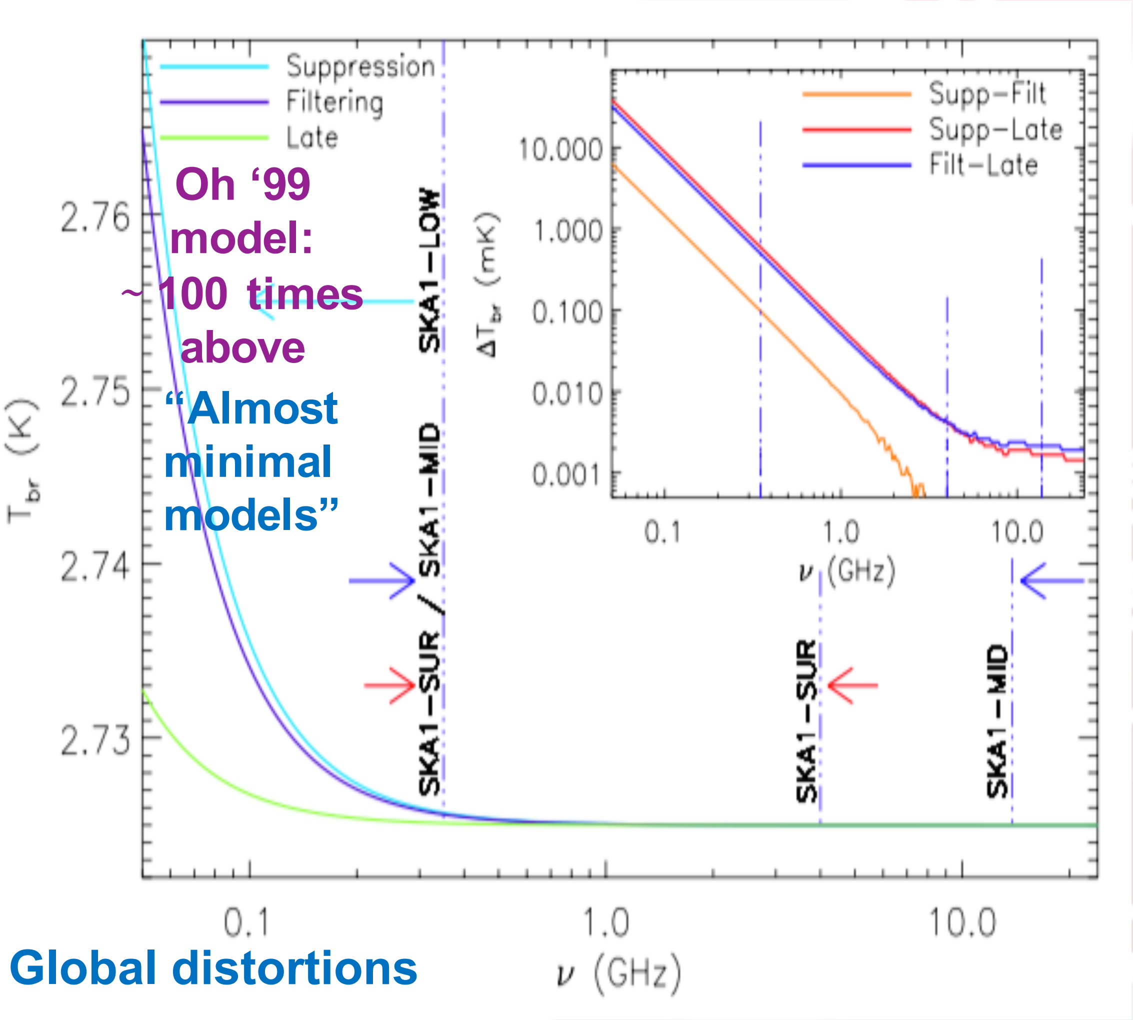


	$E_{\rm cal}$ (%)	$E_{\rm for}$ (%)	CIB amplitude	Bose-Einstein	Comptonization
Ideal case, all sky	-	-	$\simeq 4.4 \times 10^3$	$\simeq 10^3$	$\simeq 6.0 \times 10^2$
All sky	10^{-4}	10^{-2}	$\simeq 15$	$\simeq 42$	$\simeq 18$
P76	10^{-4}	10^{-2}	$\simeq 19$	$\simeq 42$	$\simeq 18$
P76ext	10^{-2}	10^{-2}	$\simeq 17$	~ 4	~ 2
P76ext	10^{-4}	10^{-2}	$\simeq 22$	$\simeq 47$	$\simeq 21$
P76ext	10^{-4}	10^{-3}	$\simeq 2.1 \times 10^2$	$\simeq 2.4 \times 10^2$	$\simeq 1.1 \times 10^2$
P76ext	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-2}	$\simeq 19$	$\simeq 26$	$\simeq 11$
P76ext	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-3}	$\simeq 48$	$\simeq 35$	$\simeq 15$
P76ext, $N_{\rm side} = 128$	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-2}	$\simeq 38$	$\simeq 51$	$\simeq 23$
P76ext, $N_{\rm side} = 128$	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-3}	$\simeq 43$	$\simeq 87$	$\simeq 39$
P76ext, $N_{\rm side} = 256$	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-2}	$\simeq 76$	$\simeq 98$	$\simeq 44$
P76ext, $N_{\rm side} = 256$	$10^{-3}_{(\le 295)}$–$10^{-2}_{(\ge 340)}$	10^{-3}	$\simeq 85$	$\simeq 1.6 \times 10^2$	$\simeq 73$

Table 11. Predicted improvement in the recovery of the distortion parameters discussed in the text with respect to FIRAS for different calibration and foreground residual assumptions. This table summarizes the results derived with approach (c). "P06" stands for the *Planck* common mask, while "P06ext" is the extended P06 mask. When not explicitly stated, all values refer to $E_{\rm cal}$ and $E_{\rm for}$ at $N_{\rm side} = 64$.

From Burigana, Carvalho, Trombetti et al. 2018, JCAP

Free-free distortions from cosmological reionization vs SKA & vs extragalactic foregrounds



Oh '99 model: ~100 times above

"Almost minimal models"

Global distortions

Courtesy T. Trombetti 2015

FF radio emission induces both global and localized distortions

$$\frac{T_{br}(x)}{T_r} \simeq \frac{y_B(x)}{x^2} - 2u\phi_i + \phi_i$$

$$u \simeq 1/4(\Delta\varepsilon/\varepsilon_i)$$

Even for minimal models @ frequencies around <u>few GHz</u>
FF signal above

- ✓ (1) radiosource background
- ✓ (2) confusion noise

Removing sources above few tens of nJy → Source back:
< 1mK @ ν > 1 GHz
< 10mK @ ν < 0.3 GHz

Condon et al. 2012 $5\,\sigma_{\rm conf} \sim 5 \times 1.2\,(\nu/3\rm GHz)^{-0.7}\,(\theta/8'')^{10/3}\ \mu Jy$

From I. Prandoni & N. Seymour 2014

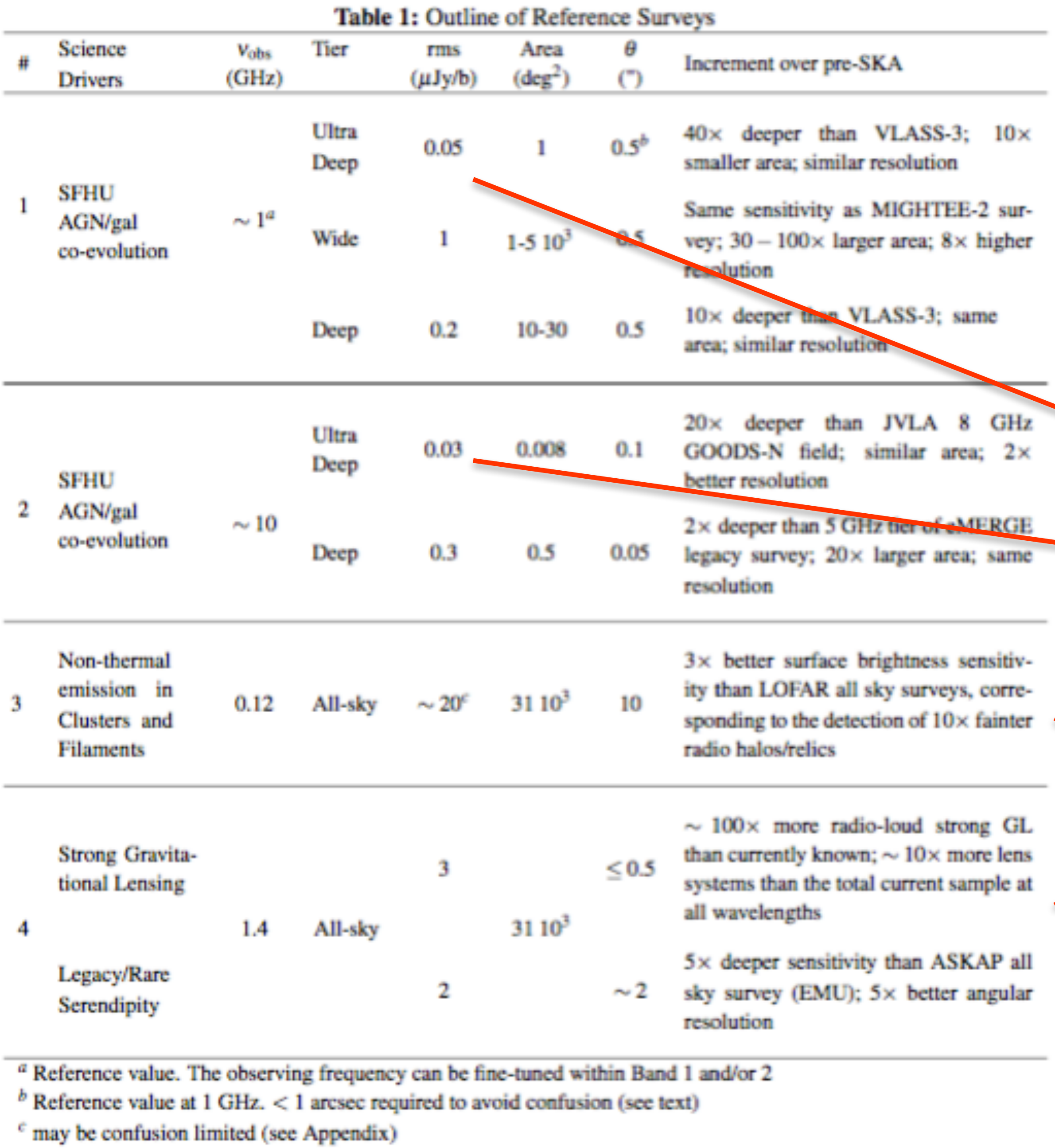


Table 1: Outline of Reference Surveys

#	Science Drivers	ν_{obs} (GHz)	Tier	rms (μJy/b)	Area (deg^2)	θ (″)	Increment over pre-SKA
1	SFHU AGN/gal co-evolution	$\sim 1^a$	Ultra Deep	0.05	1	0.5^b	40× deeper than VLASS-3; 10× smaller area; similar resolution
			Wide	1	1-5 10^3	0.5	Same sensitivity as MIGHTEE-2 survey; 30 – 100× larger area; 8× higher resolution
			Deep	0.2	10-30	0.5	10× deeper than VLASS-3; same area; similar resolution
2	SFHU AGN/gal co-evolution	~ 10	Ultra Deep	0.03	0.008	0.1	20× deeper than JVLA 8 GHz GOODS-N field; similar area; 2× better resolution
			Deep	0.3	0.5	0.05	2× deeper than 5 GHz tier of eMERGE legacy survey; 20× larger area; same resolution
3	Non-thermal emission in Clusters and Filaments	0.12	All-sky	$\sim 20^c$	31 10^3	10	3× better surface brightness sensitivity than LOFAR all sky surveys, corresponding to the detection of 10× fainter radio halos/relics
4	Strong Gravitational Lensing	1.4	All-sky	3	31 10^3	≤ 0.5	~ 100× more radio-loud strong GL than currently known; ~ 10× more lens systems than the total current sample at all wavelengths
	Legacy/Rare Serendipity			2		~ 2	5× deeper sensitivity than ASKAP all sky survey (EMU); 5× better angular resolution

[a] Reference value. The observing frequency can be fine-tuned within Band 1 and/or 2

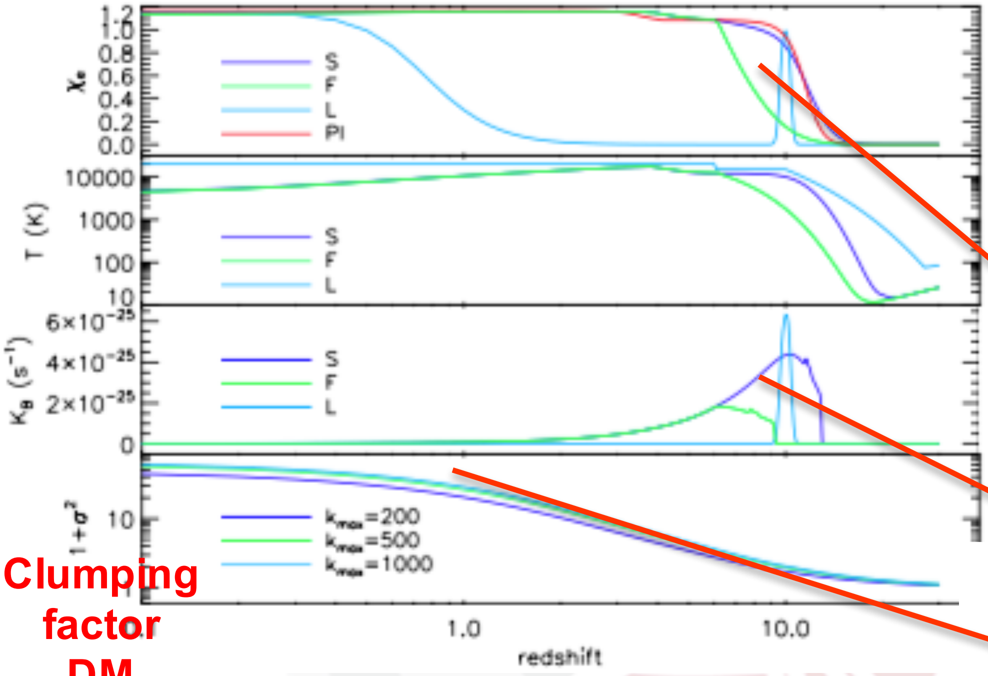
[b] Reference value at 1 GHz. < 1 arcsec required to avoid confusion (see text)

[c] may be confusion limited (see Appendix)

Ultra-deep source number counts (useful also for intermediate/ small scale foregrounds vs 21cm & FF & E/B modes)

All-sky surveys (useful also for Galactic foregrounds for all above topics)

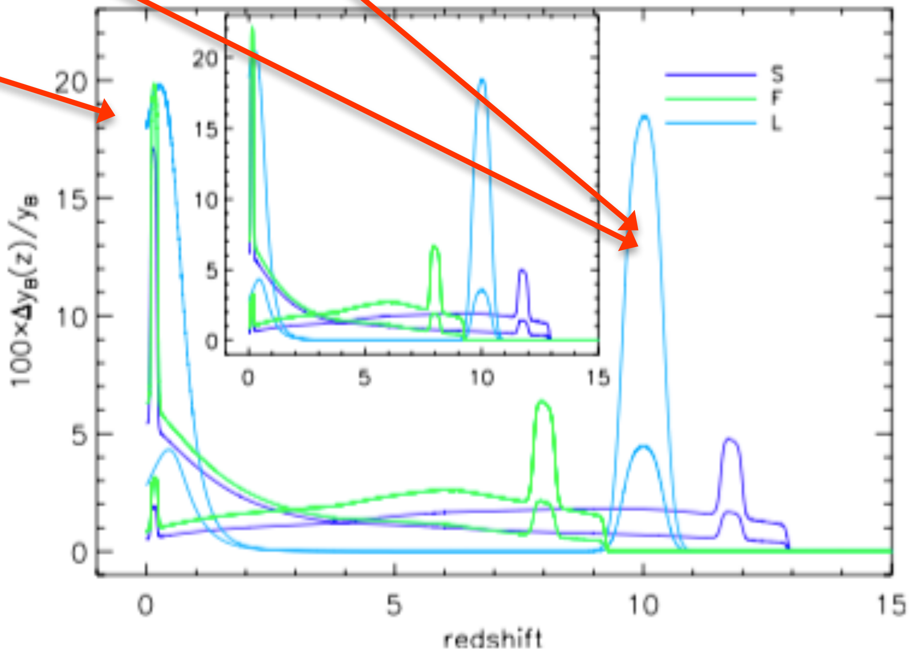
Not only integrated information - I (free-free)



Clumping factor DM

redshift dependence of "free-free main terms"

T. Trombetti & C. Burigana, 2014, MNRAS

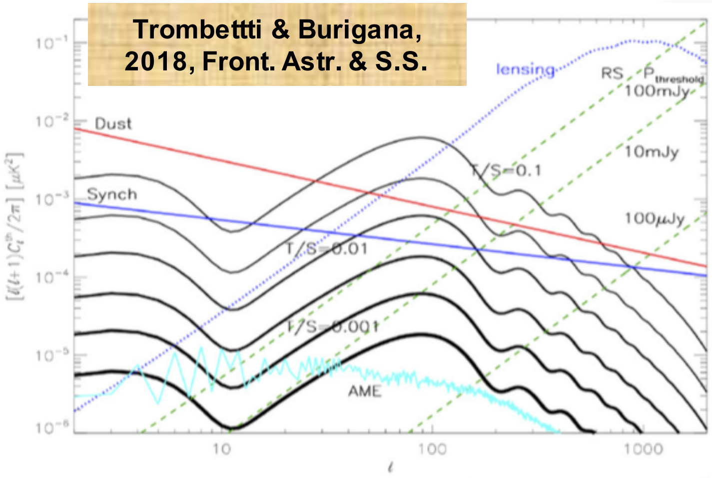


Relative contributions of different redshifts →

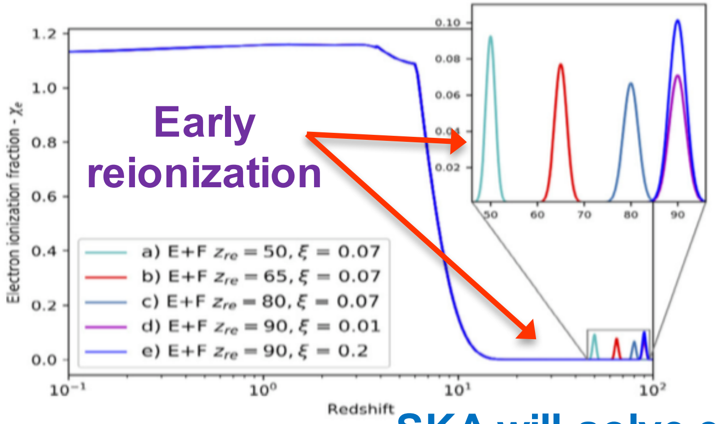
Two main epochs:

- **when reionization starts (earlier epochs)**
- **when clumping >> 1 (later epochs) → implications also for thermal properties of DM**

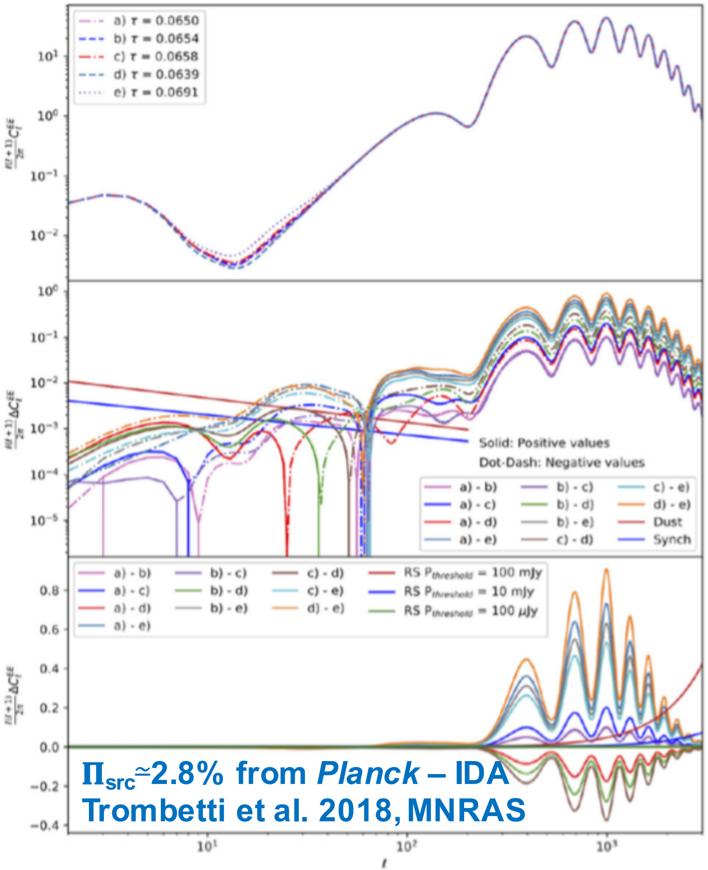
CMB B & E modes from reionization vs foreground residuals Not only integrated information - II (reionization E-modes)



Trombettti & Burigana, 2018, Front. Astr. & S.S.



Early reionization



Π_{src}≃2.8% from *Planck* – IDA
Trombetti et al. 2018, MNRAS

Low & intermediate multipoles

Galactic dust: from 353 GHz assuming an error of 0.01 in the grain spectral index

Galactic synchrotron: from 30 GHz assuming an error of 0.02 in the emission spectral index

SKA will solve extragal. source contamination problem
→ delensing in B-modes
→ early reionization E-modes

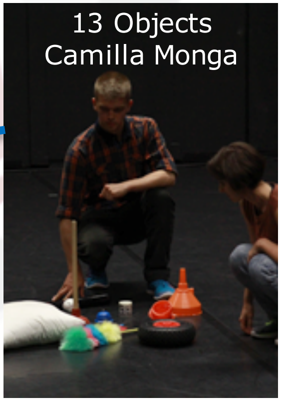
Source thresholds:

- ✓ **100 mJy current CMB experiments**
- ✓ **10 mJy future CMB experiments**
- ✓ **100 μJy representative of SKA (generously including frequency extrapolation uncertainties)**

Intermediate & high multipoles

Conclusions

- **Huge progress in HI galaxy surveys with SKA and their cosmological implications**
- **Optimizing surveys for scientific aims is critical**
- ***Planck (for many background parameters) (+ Euclid)* + SKA will provide strong constraints on cosmological parameters, NG, and DE nature, possibly ultimately answering to a set of fundamental questions**
- **Important cosmological topics will be jointly studied with radio and microwave surveys (i.e. SKA + *Planck* + hopefully CORE, LiteBIRD, PIXIE, ground based S4-S5, e.g. CLASS), including**
  - **PMF**
  - **spectral distortions / energy dissipations**
  - **cosmological (re)ionization through 21cm, FF, EE/TE/BB**



13 Objects
Camilla Monga

- **Space and ground will be more and more complementary**
- **Reducing foreground signals and systematics is a critical and fundamental issue in practically all contexts**

Thanks for the attention!

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