Reionization

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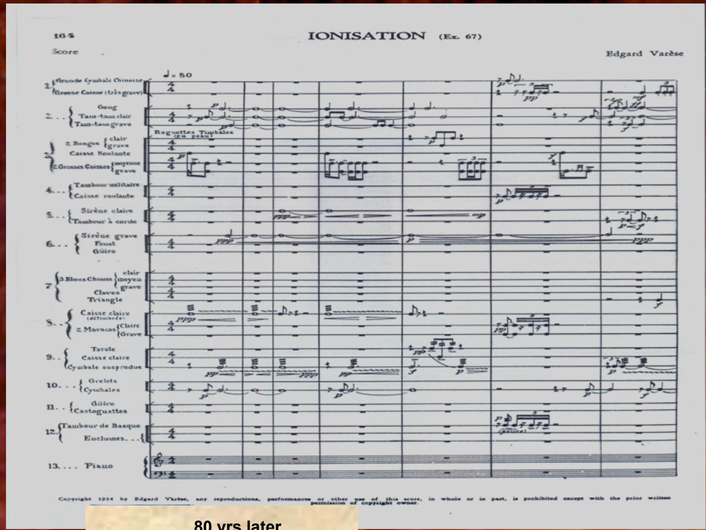
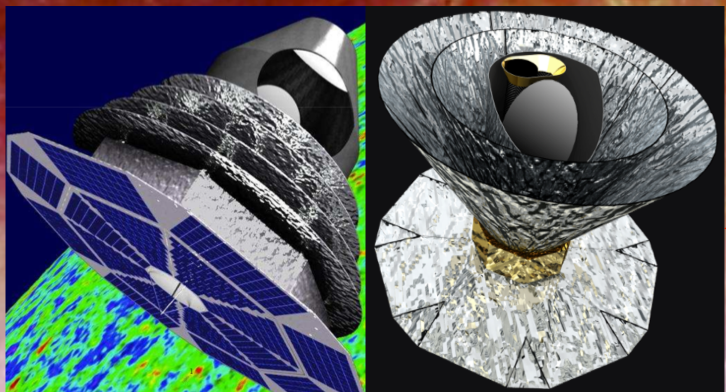
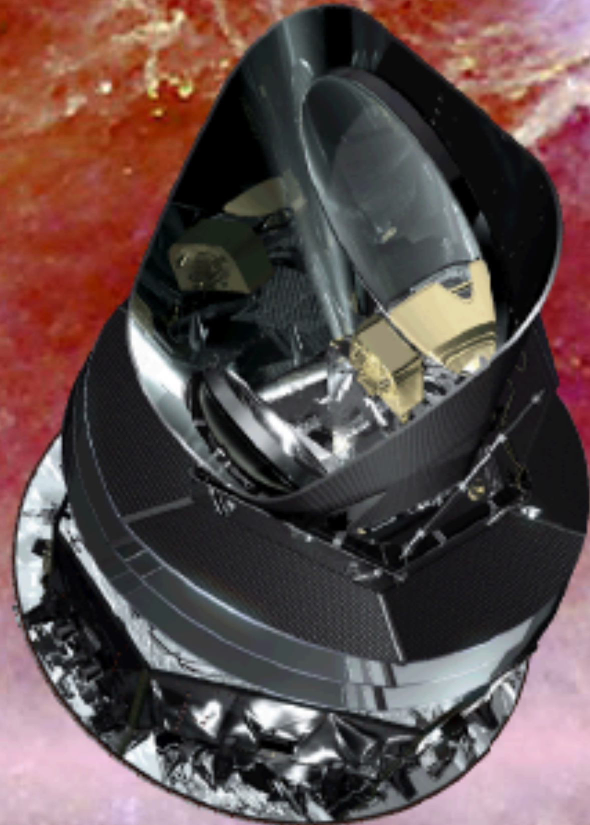
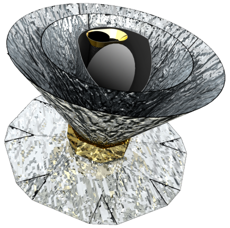


80 yrs later
1934 → 2014





COrE/PRISM Workshop
for an M4 ESA Mission
Paris, February 10-11, 2014



Scientific themes for future microwaves to far-IR missions

- Primordial <u>CMB B-modes</u>, high precision CMB T (absolute!) and <u>E</u>
- CMB spectral distortions
  - <u>thermal history</u>, energy exchanges between CMB and matter
  - <u>reionisation</u>, decaying dark-matter particles, small scale primordial P(k)
- All crucial/unique for → early Universe & fundamental physics

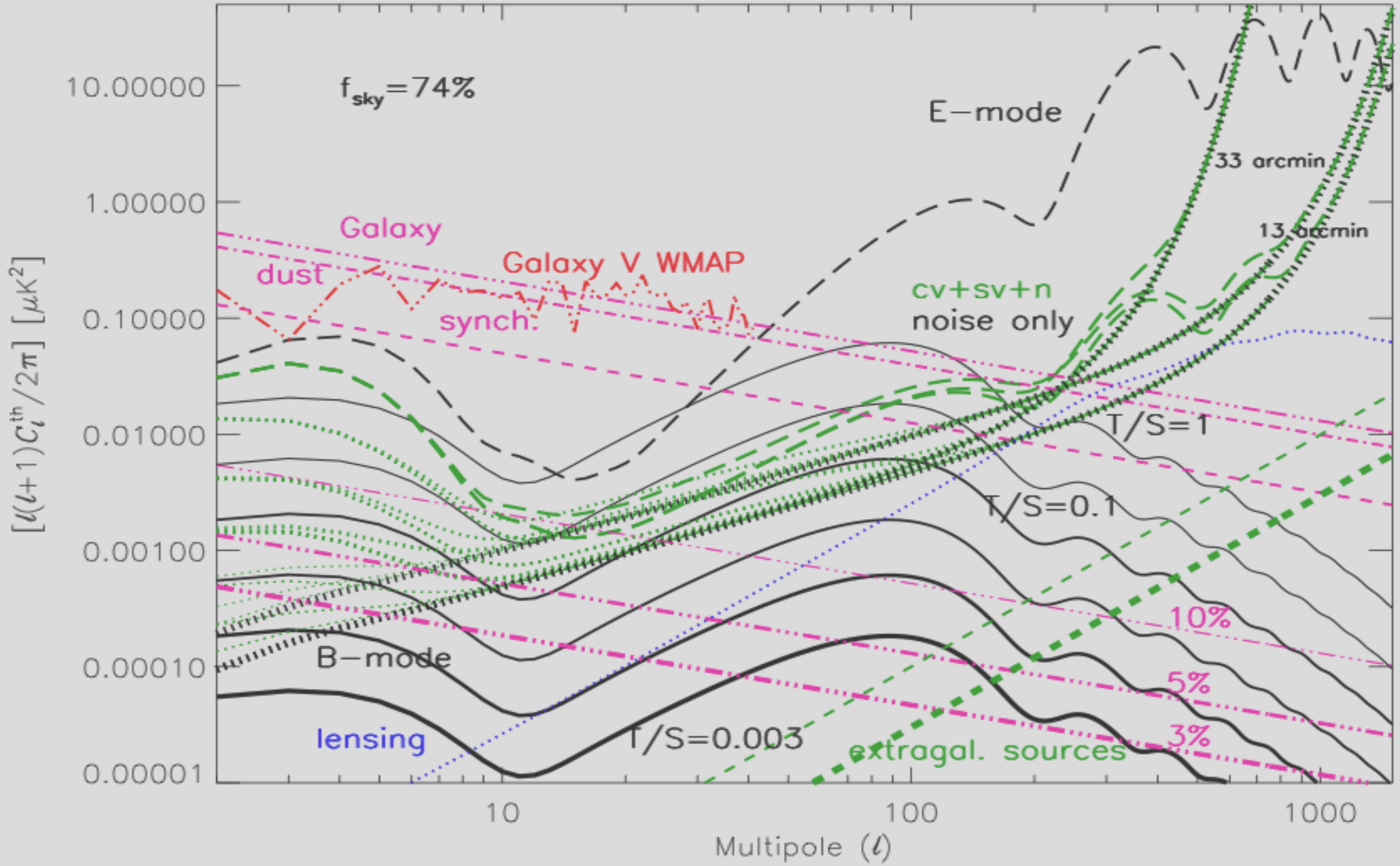
- 3D cosmic structures:
  - A complete census of galaxy clusters (hot baryons and mass up to z>3)
  - CMB lensing (projected mass)
  - The CIB and dusty galaxies (up to z>6) – dust, AGNs and interplay, P(k) in shells
- 3D cosmic velocity flows
- All phases of the galactic interstellar medium:
  - Dust (thermal, spinning, size and chemical composition)
  - Cosmic rays (synchrotron components)
  - Gas (neutral and ionised), free-free, atoms and molecules, molecular clouds,
  - Magnetic field via polarisation of dust (and synchrotron)

Observables vs physical mechanisms

- Thomson scattering
  - Anisotropies, mainly
    - EE, BB, TE modes
  - Comptonization distortions

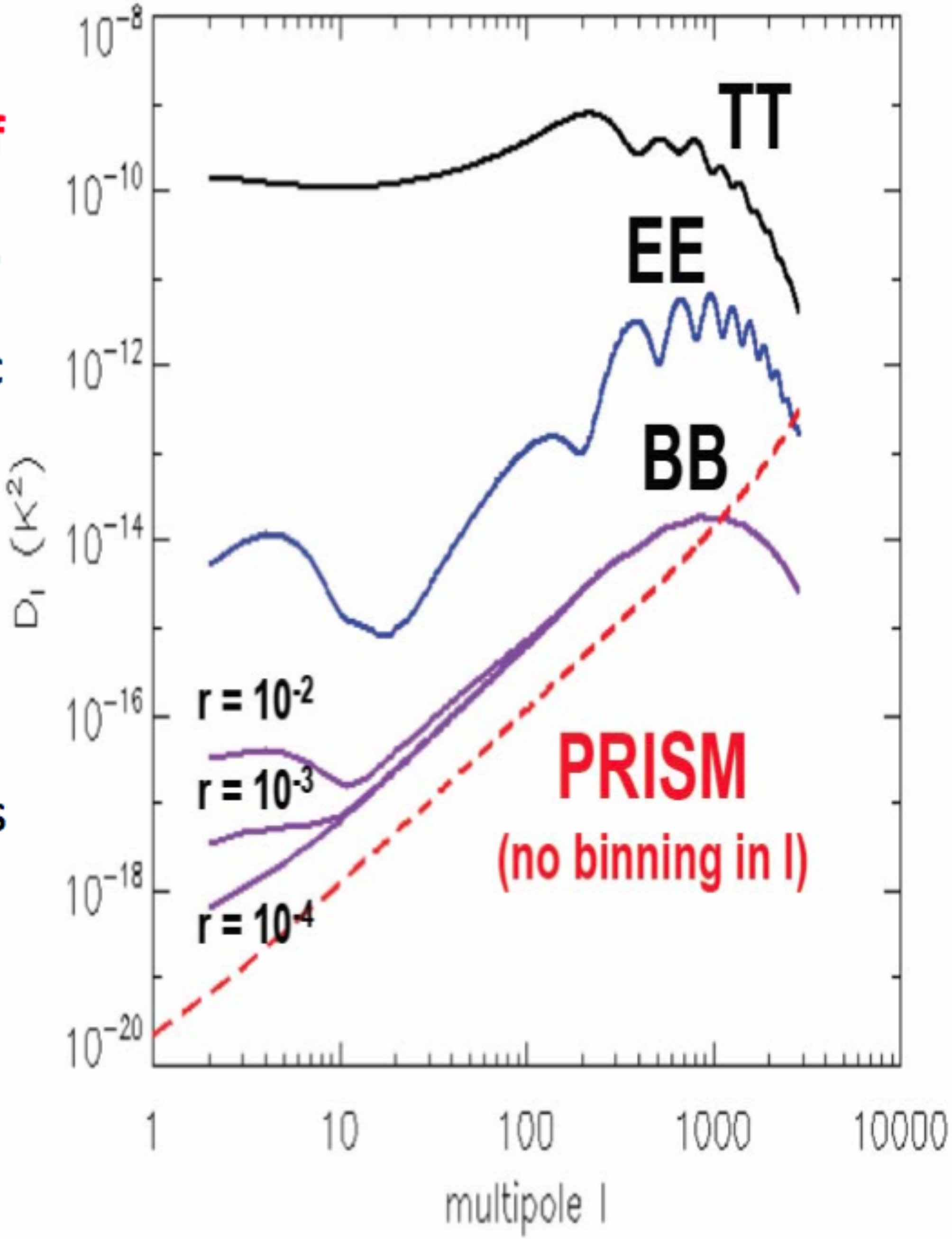
- Free-free
  - Distortions (intermediate/long wavelengths)
  - Link with clumping

CMB polarization with *Planck*
E & B – 30% binning, f_{sky}=74%



Measuring B-modes

- Measuring B-modes to r=0.001 will require **exquisite control of polarized foregrounds**.
- Current extrapolations with the simplest allowed foreground models predict that the galactic foreground will outshine the r=0.001 primordial by about x100 in all frequency channels, and emission properties are likely to be more complicated than many of the optimistic foreground forecasts suggest
- While forthcoming experiments could find hints of cosmological B modes, **only a large mission with wide frequency coverage and high angular resolution can provide a reliable and convincing detection.**



Reionizaton: beyond τ approximation

- The so-called τ or z_{RE} ”approximation” in CAMB code for CMB APS computation through numerical solution of Boltzmann equation “implies” a given simple analytical recipe for χ evolution

- More realistic models assume χ evolution based on
  - phenomenological approaches mimicking classes of (astro)physical processes
  - astrophysical models
  - detailed physical processes

Astrophysical reionization models

Inhomogeneous reionization: lognorm overdensity distribution.

Sources of reionization:

- PopIII stars: Salpeter IMF but metal free (Schaerer 06)
- PopII stars: Salpeter IMF, Bruzual & Charlot
- Quasars: important for $z<6$

Chemical feedback governs the transition from PopIII to PopII stars ($Z_{crit}=10^{-5+/-1}$ Z_{sun}): the two populations are coeval and PopIII stars can form also at relatively low-z.

Radiative feedback: temperature increase in ionized region → huge suppression of low-mass galaxies formation.

✓**Suppression model (Choudhury & Ferrara '06, MNRAS, 371, L55):** radiative feedback is effective in DM haloes with circular velocity below a critical value $v_{crit} \sim (2k_B T/\mu m_p)^{1/2}$ where T is the average temperature of ionizing regions [~ 30 km/s for $T=3\times10^4$ K]

✓**Filtering model (Gnedin 2000 ApJ, 542, 535):** the average baryonic mass within haloes in photoionized regions is a fraction of the universal value:

$$\frac{M_b}{M} = \frac{\Omega_b / \Omega_m}{[1+(2^{1/3}-1)M_C / M]^3}$$

where M_C is the mass of haloes that retain 50% of their gas mass.

Phenomenological models

(Naselsky & Chiang 04, MNRAS 347, 795)

$$\varepsilon_i(z) = \varepsilon_0 \exp\left[-\frac{(z - z^{(1)}_{\rm reion})^2}{(\Delta z_1)^2}\right] + \varepsilon_1 (1+z)^{-m} \Theta(z^{(1)}_{\rm reion} - z)$$

here ε_0, $z^{(1)}_{\rm reion}$, and $\Delta z_1 \ll z^{(1)}_{\rm reion}$ are free parameters describing the history of the first epoch of reionization which significantly decreases at $z > z^{(1)}_{\rm reion}$; ε_1, m, and (again) $z^{(1)}_{\rm reion}$ are free parameters describing the history o P. Naselsky and L.-Y. Chiang, 2004, MNRAS, 347, 795:reasing of $\varepsilon_i(z)$ with the time, being $\Theta(x)$ the step function.

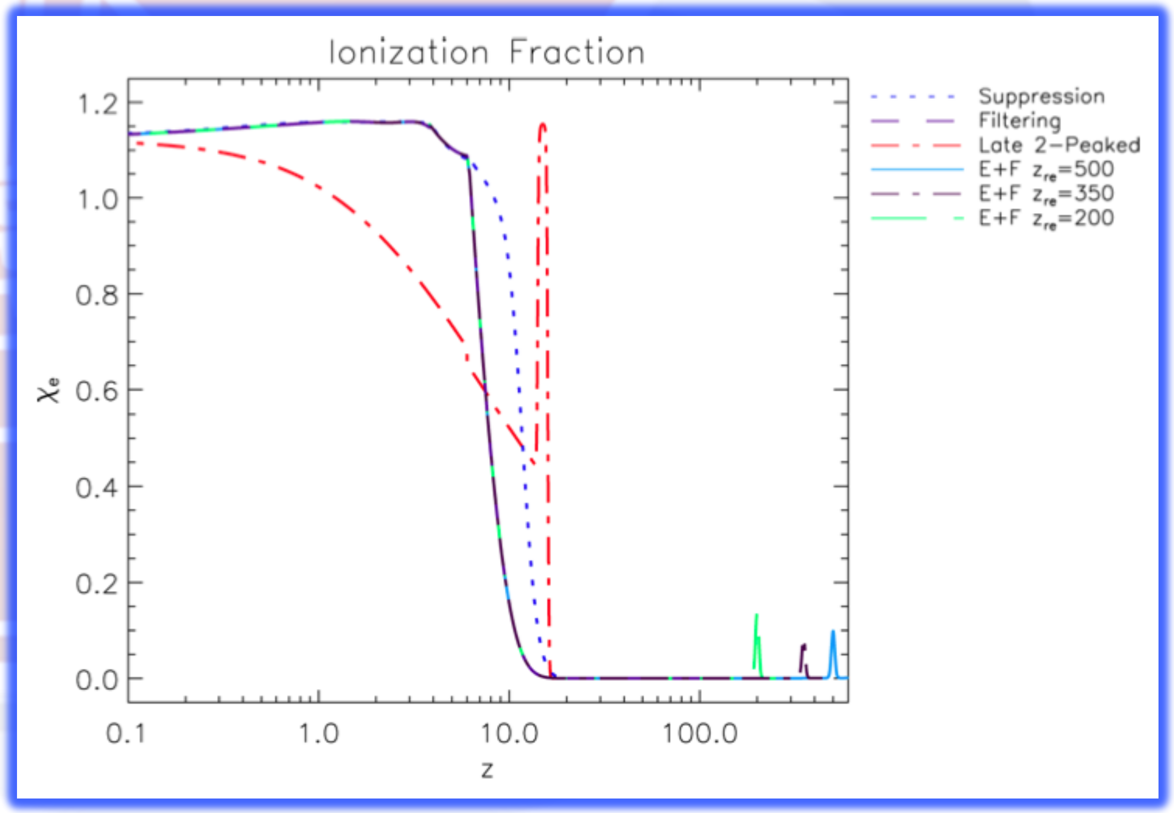
$$\varepsilon_i(z) = \xi \exp\left[-\frac{(z - z_{\rm reion})^2}{(\Delta z)^2}\right]$$

quite similar to that assumed to describe the first reionization epoch for late processes, can be exploited in this context [37]; again ξ, $z_{\rm reion}$, and Δz are free parameters describing the history of this high redshift reionization scenario. Assuming $\Delta z \ll z_{\rm reion}$ implies the choice of a peak-like model.

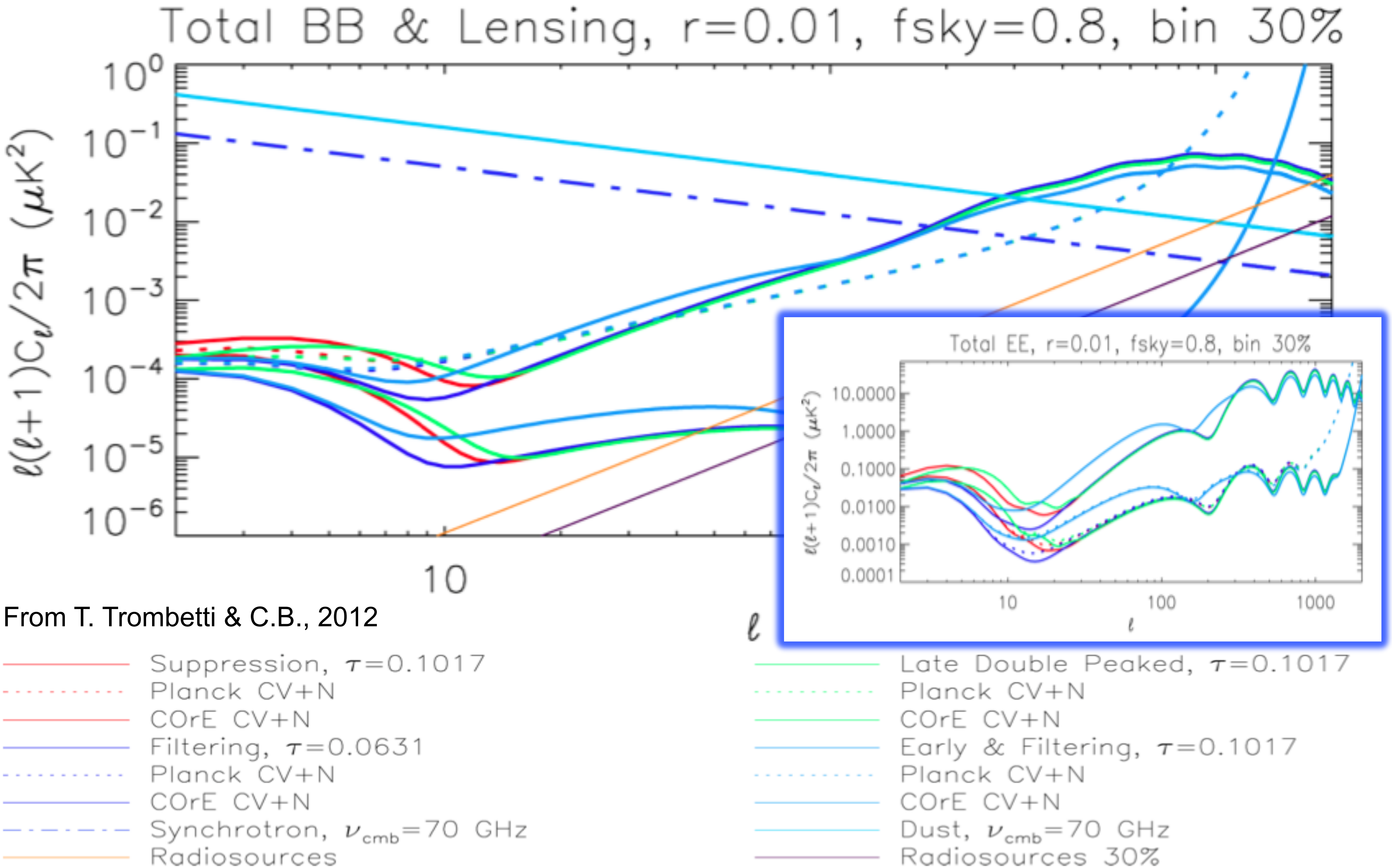
Extension to all modes
B-modes & reionization beyond simple tau-approximation

- Future of CMB polarization anisotropies:
  - towards B-modes & full exploitation of all modes
- Implementation of reionization models in CAMB code considering all modes & in particular B-modes (T. Trombetti & C.B., 2012, JMP, 3, 1918)
- Inclusion of
  - Phenomenological models (high/low z)
  - Astrophysical models
  - Mix of models

Typical cases →

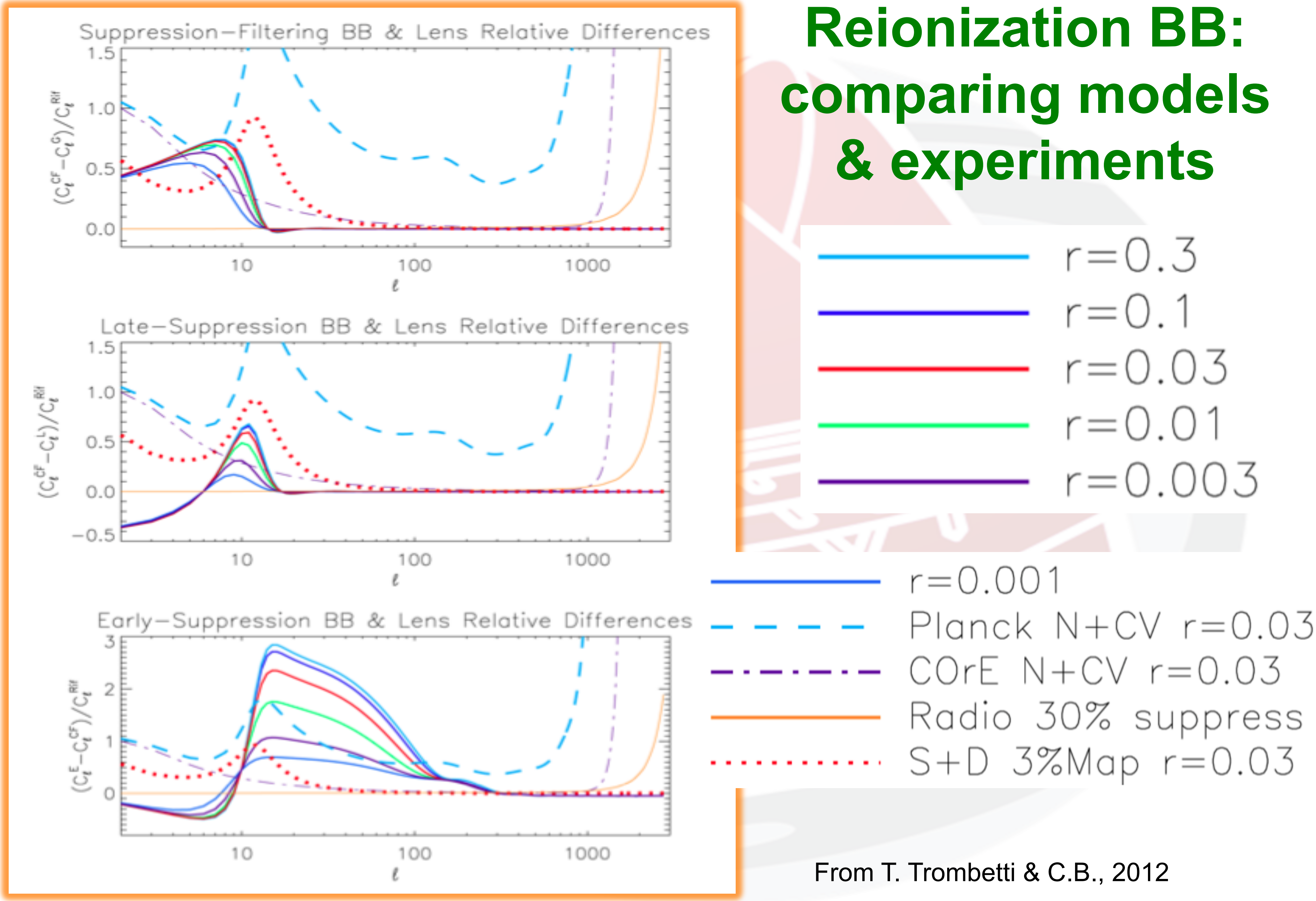


EE & BB predictions



From T. Trombetti & C.B., 2012

Reionization BB: comparing models & experiments



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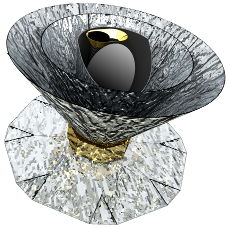


CMB spectral distortions

❖ Current observations *consistent with Blackbody & Standard Big-Bang Model* **… but:**

- **Very small distortions** in continuum spectrum are
  - ❖ **strongly predicted** to be generated during ***late epochs*** ($z < 10^4$), as Comptonization, free-free distortions associated to **reionization / structure formation**, hot galaxy clusters: **clearly detectable by PRISM (≳100σ!)**
  - ❖ **or may be produced or have to be produced** at ***earlier epochs*** (Bose-Einstein distortions, intermediate shapes, "exotic shapes") by "exotic" processes, as decays, annihilation, cooling/Bose condensation, damping of primordial perturbations probing the *power spectrum on very small scales (inflation)*: **detectable by PRISM → New physics!**
- **→ "Direct" reconstruction** of thermal history & thermodyn. processes **up to $z \cong 10^7$**
- ➢ N.B.: fully analogy with CMB anisotropy before COBE/DMR:
  Standard model would be untenable if no distortion were detected

➢ **H & He recombination lines from $z \simeq 10^3$**

- ➢ *HI Balmer & Paschen-α lines detectable with* ***PRISM***
- ➢ ***additional anisotropic signal detectable with PRISM***

➢ **Resonant scattering signals of metals during the *dark ages***

Astrophysical models:
CMB Comptonization distortions

	Suppression	Filtering
u	1.69×10^{-7}	9.65×10^{-8}
$u(z\geq6)$	7.98×10^{-8}	1.05×10^{-8}

(C.B. et al. 2008, MNRAS, 385, 404)

Compatible with FIRAS limits → call for next generation CMB experiments (FIRAS II, DIMES, Moon Based ideas,

PIXIE – Kogut et al. 2011, JCAP, 7, 25,

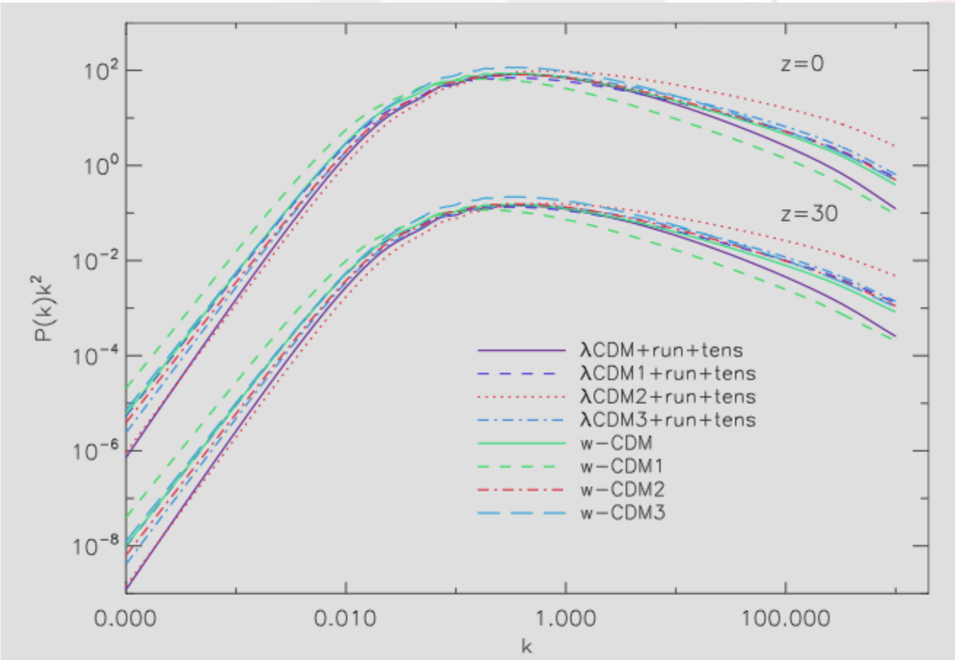
PRISM Coll. 2013, 2014)

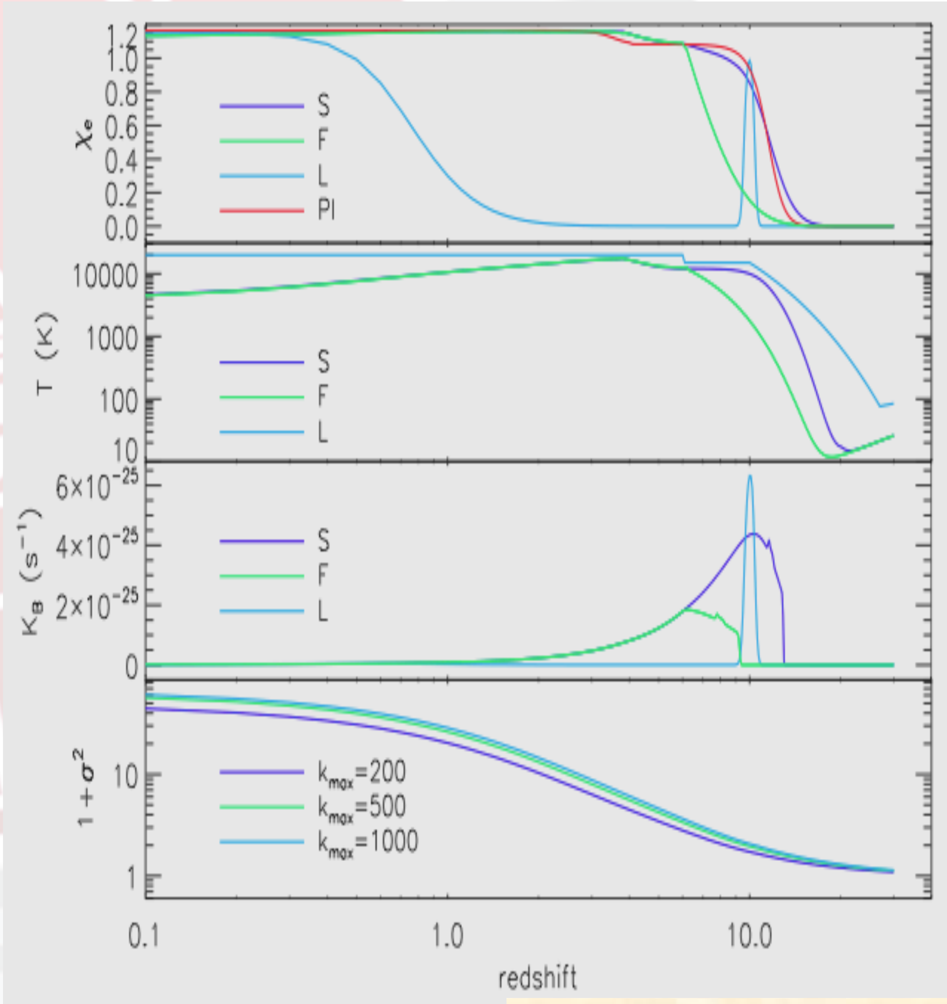
IASF INAF asi agenzia spaziale italiana

Free-free distortions: effect of clumping

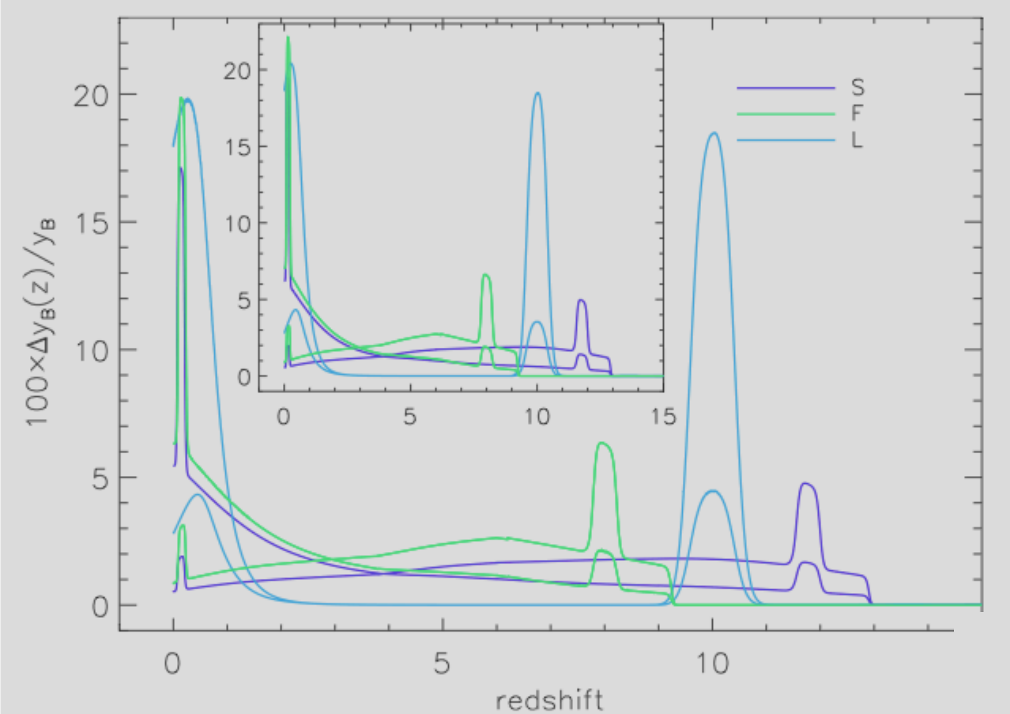
- **The homogeneous approximation is a rough lower limit approximation for free-free, because of the $(\Omega_b)^2$ dependence implying an amplification factor, related to P(k) (and DM particle properties)**

$$\frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} = 1 + \frac{\langle(\delta\rho)^2\rangle}{\langle\rho\rangle^2} = 1 + \sigma^2 > 1$$





T. Trombetti & C.B. 2014, MNRAS 437, 2507

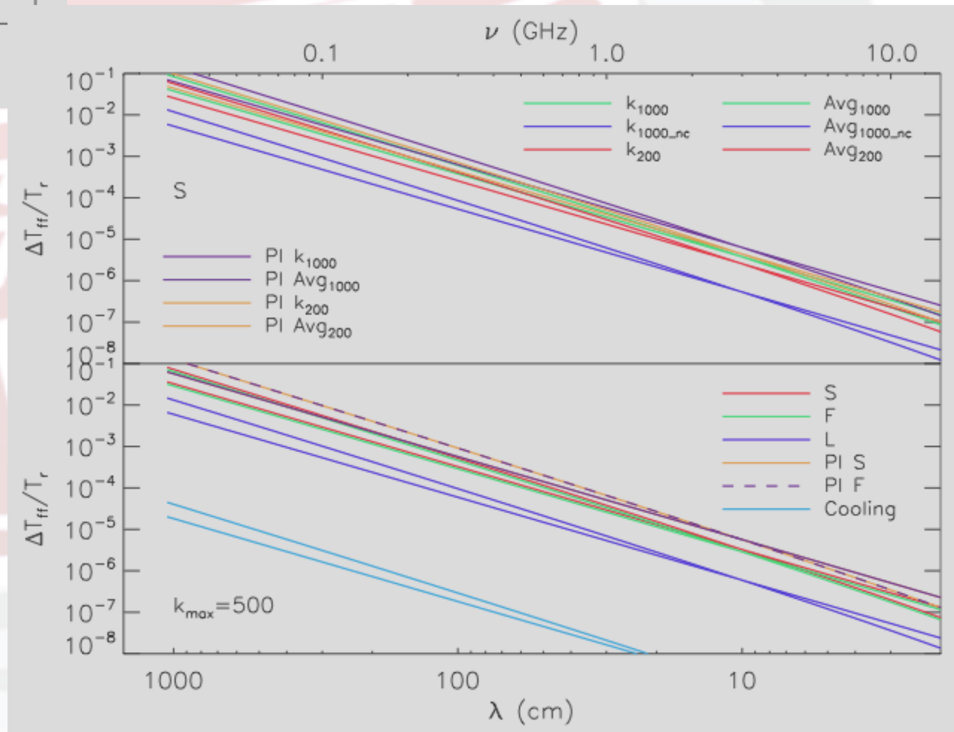


Relative contribution peaks when the process starts and at low z

✓**Spectral shape sligthy steeper than λ^2 (because of Gaunt factor)**

✓**Note the amplification by clumping, increasing for increasing k_{max}**

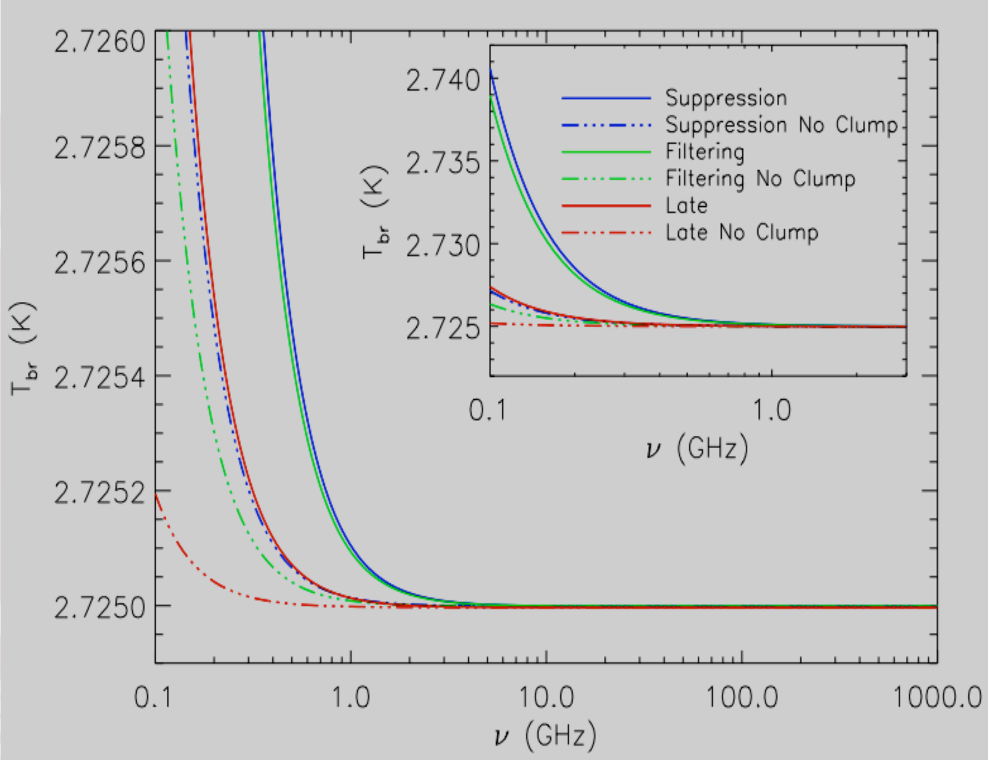
✓**(Negative) FF by cooling largely subdominant**



❖Without any particular assumption about complex haloes physics, **a robust lower limit to the global averaged free-free distortion signal expected from the diffuse ionized IGM** in a given cosmological reionization scenario can be derived from fundamental arguments based only on density contrast evolution on cosmological models and well-known radiative emission mechanisms (T. Trombetti & C.B. 2014, MNRAS 437, 2507):

✓ Boltzmann codes for the matter variance evaluation;

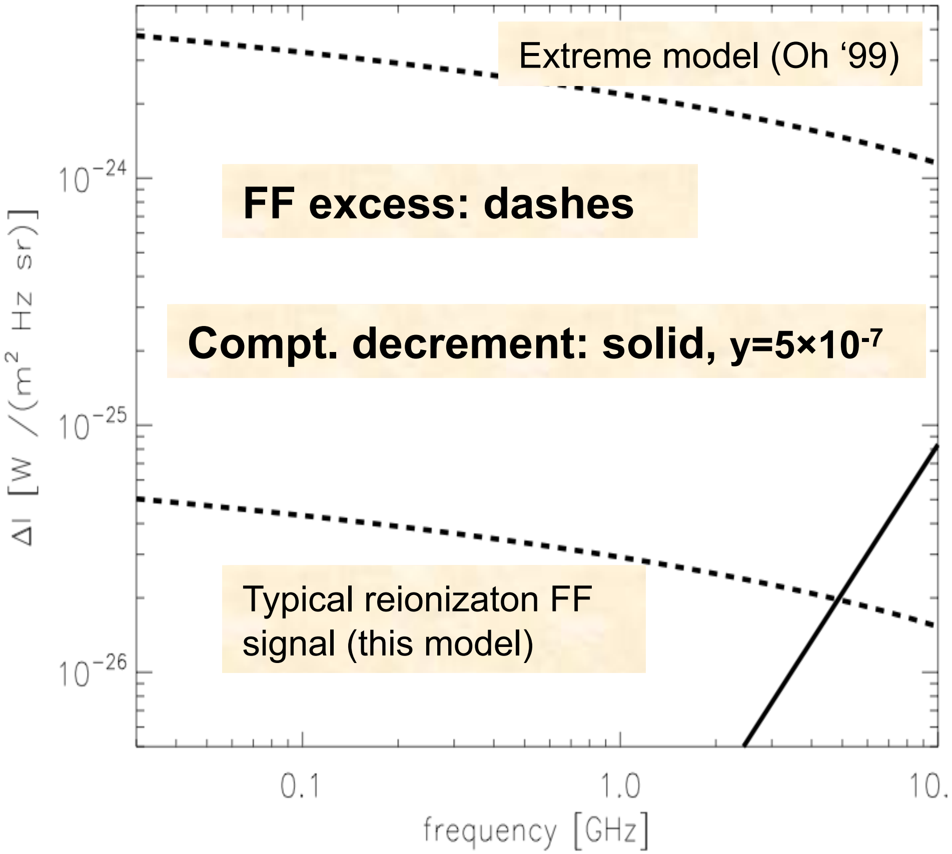
✓ a dedicated code for the free-free distortion including the correct time and frequency dependence of Gaunt factor.

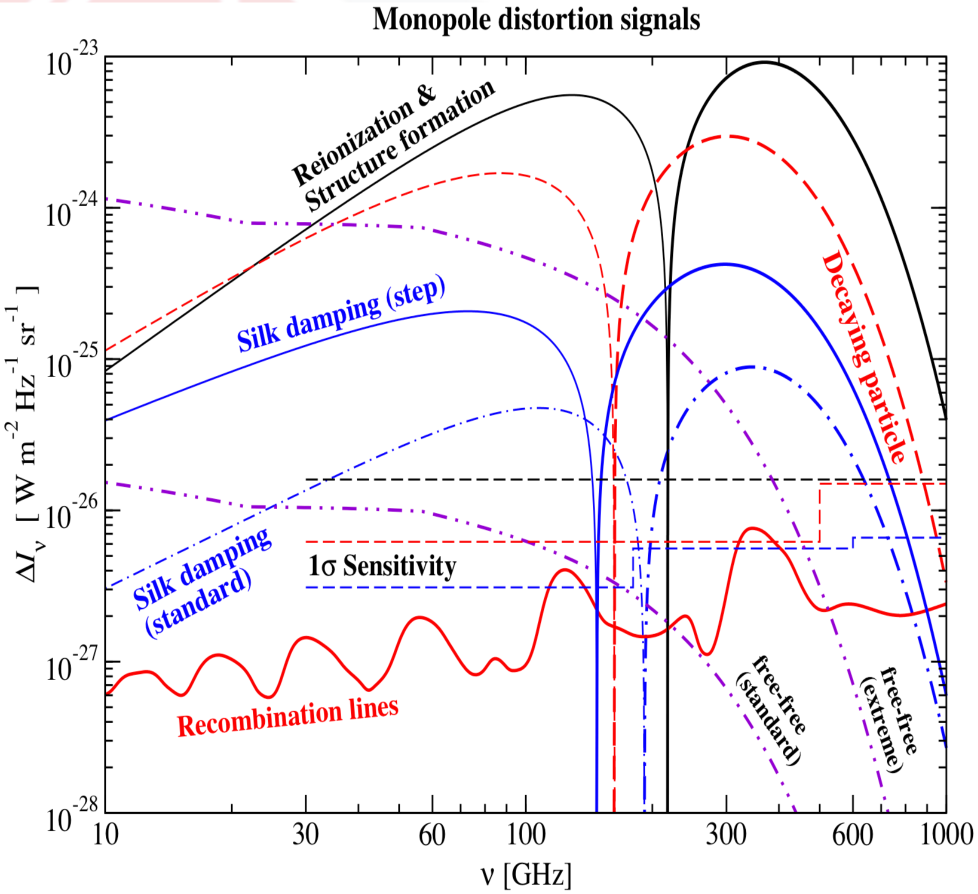


As shown in the figure, where signals from both free-free distortion and Comptonization decrement are included, the expected excess is at ~ mK level at decimeter wavelengths & a few % of Comptonization decrement expected in these models at λ < 1 cm.

Modest but not negligible impact for CMB space missions, main target for ground-based observations.

Summary of CMB spectral distortions in intensity





Low freqs.

Ground experiments, DIMES, ARCADE 2, SKA & its precursors

High freqs.

FIRAS II, Pixie, PRISM

From PRISM studies