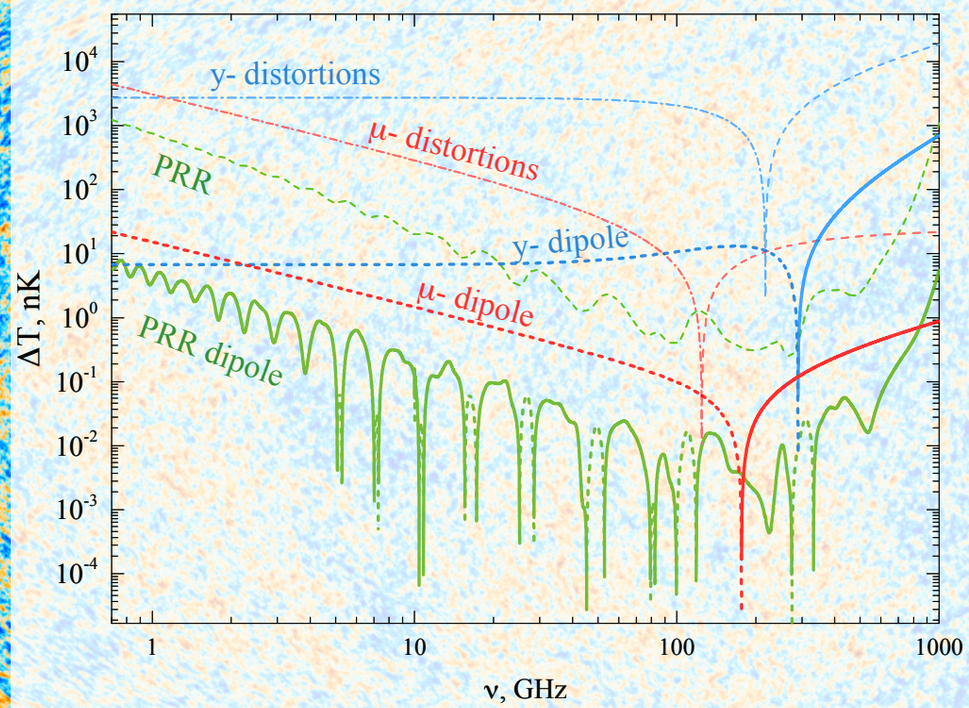
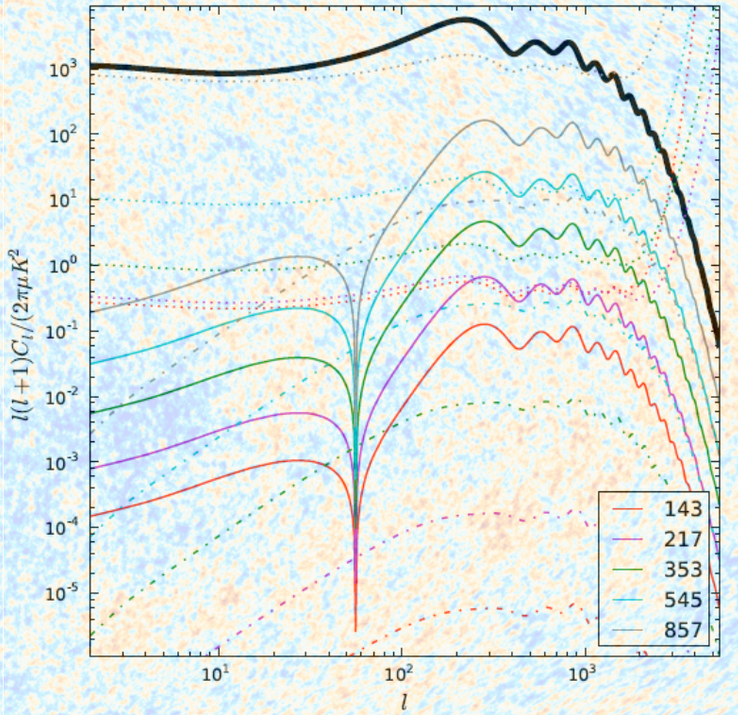
Spectral-Spatial distortions of the CMB





Jens Chluba

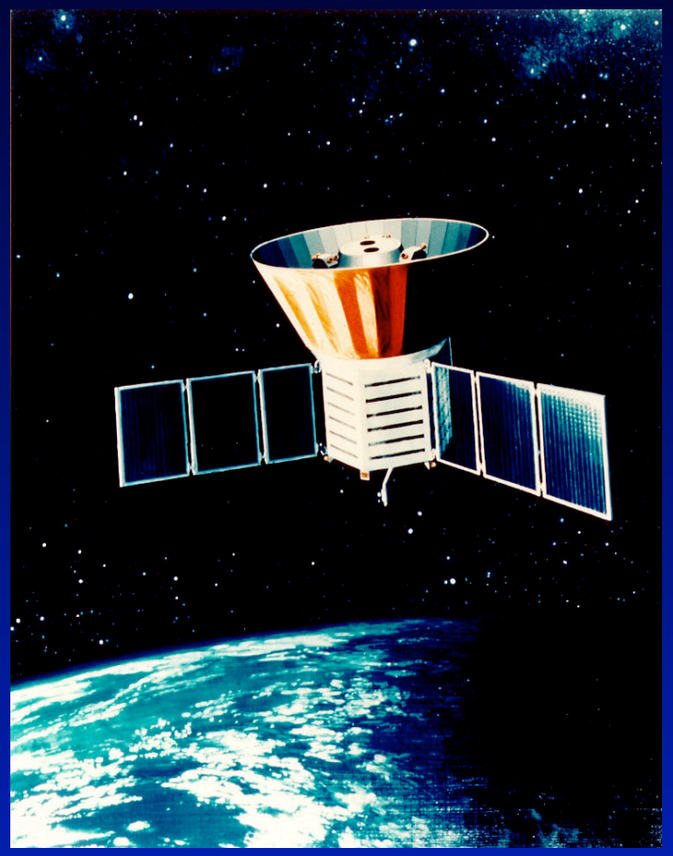
MANCHESTER 1824
The University of Manchester

COrE+ Meeting @ CERN

CERN, Geneva, May 17th, 2016

THE ROYAL SOCIETY

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

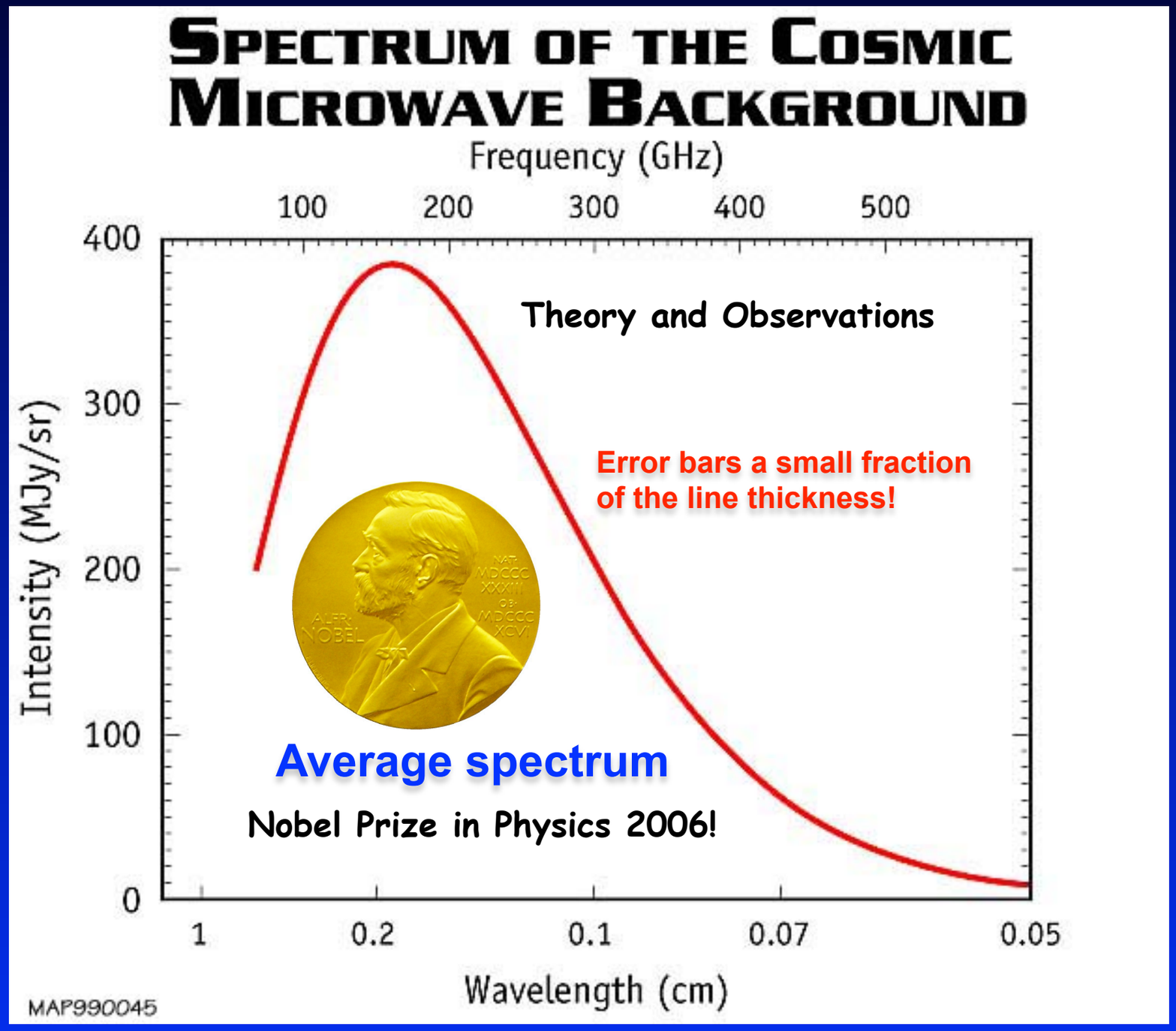


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \le 1.5\times10^{-5}$$

$$|\mu| \le 9\times10^{-5}$$

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67



Only very small distortions of CMB spectrum are still allowed!

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

„high“ redshifts

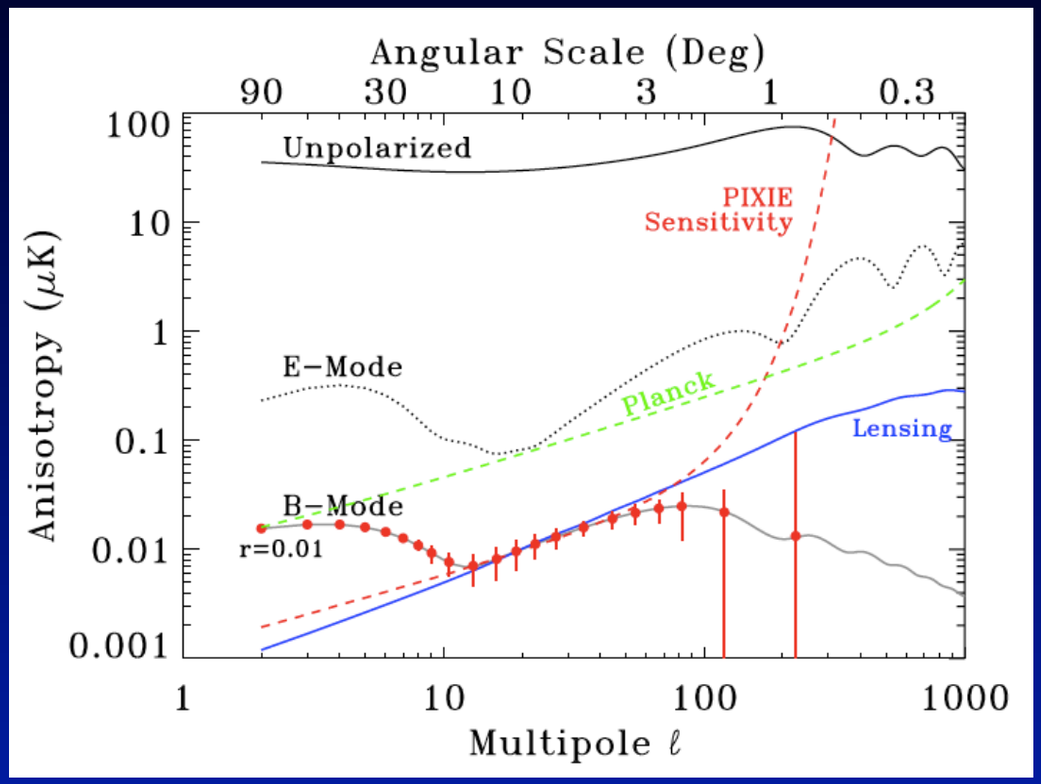
„low“ redshifts

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- more exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

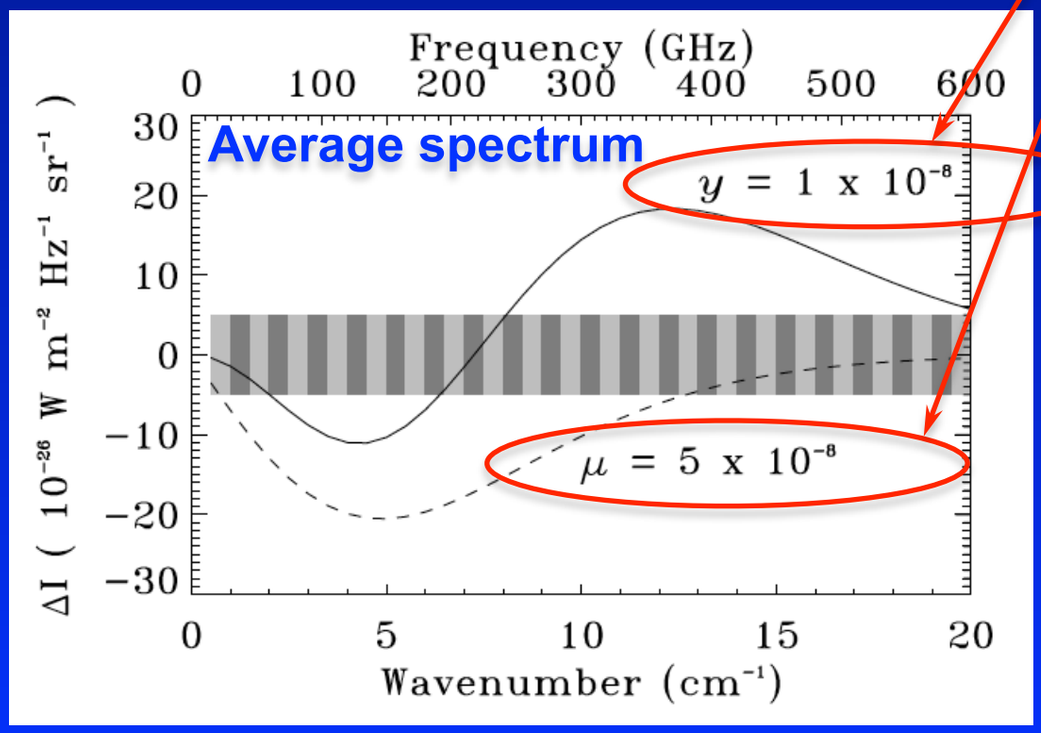
pre-recombination epoch

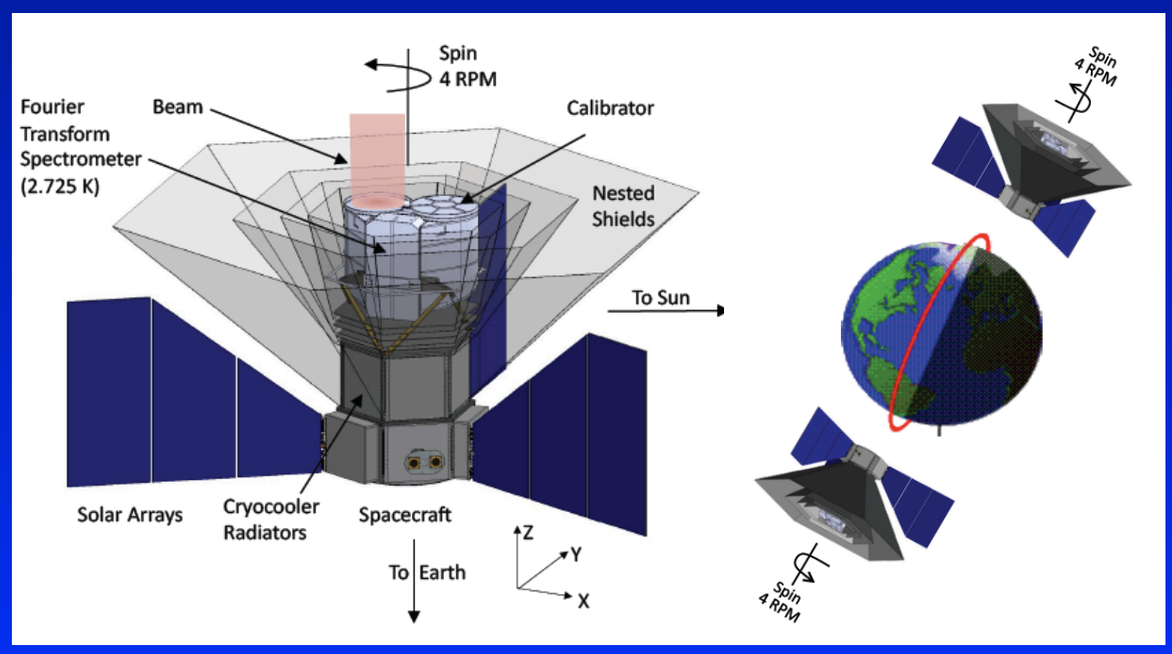
post-recombination

PIXIE: Primordial Inflation Explorer



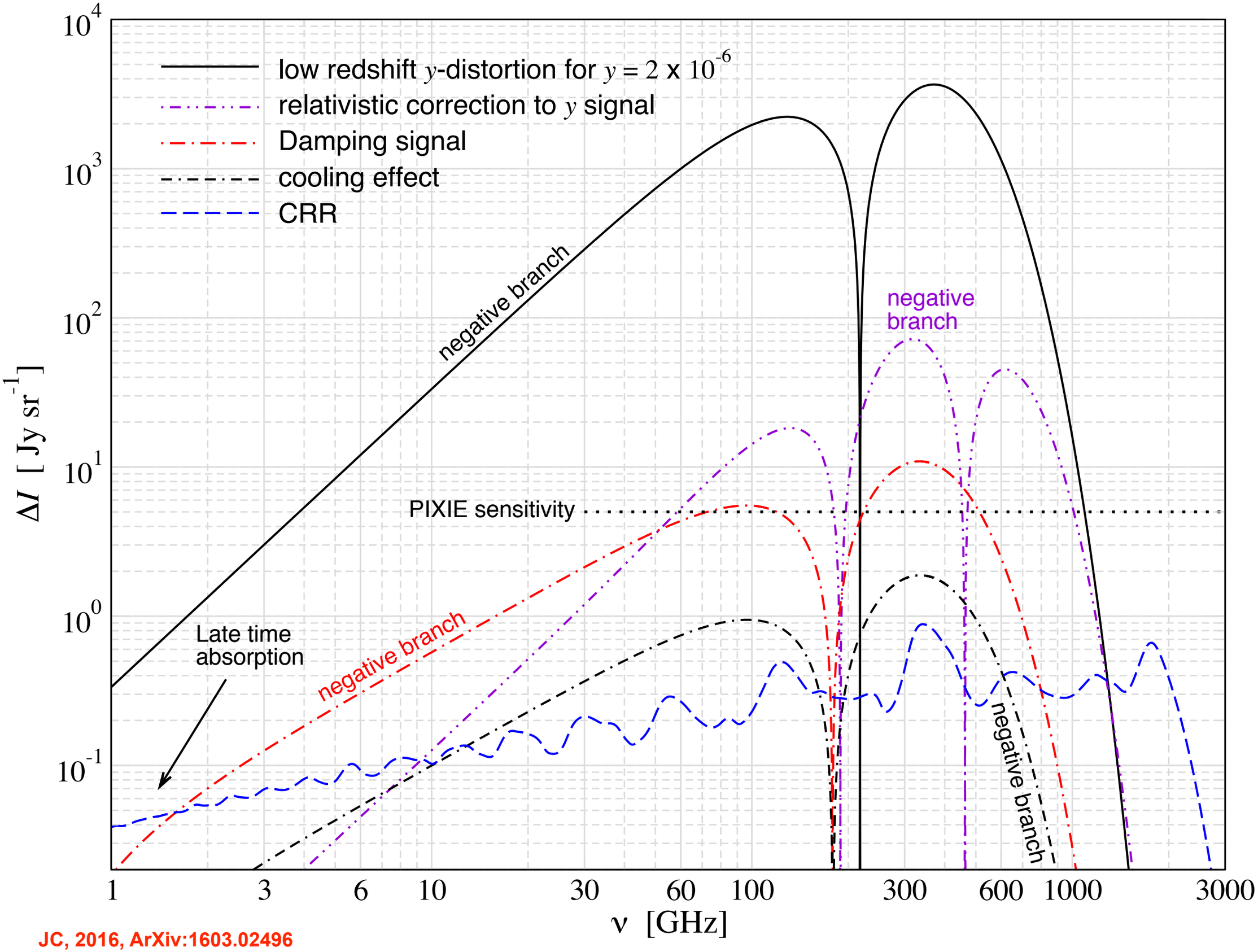
- 400 spectral channel in the frequency range 30 GHz and 6THz (Δν ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y *monopole*
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044

Average CMB spectral distortions



JC, 2016, ArXiv:1603.02496

What about anisotropies in the CMB spectrum?

What is required to produce spectral-spatial anisotropies?

- Anisotropic heating or photon injection mechanisms
  - usually *tiny* in ΛCDM (perturbations on a quite small signal)
  - *clusters of galaxies* and *warm hot intergalactic medium*
  - μ and y distortions due to *primordial non-Gaussianity*
  - *isocurvature perturbations* / *anisotropic BBN* / *cosmic bubble collisions*
  - possible link to *CMB anomalies* (test stationarity of spectrum...)?
- Scattering signals
  - generation similar to CMB anisotropies
  - strong frequency dependence
  - *dark ages* and *recombination epoch*
- Motion-induced signals (see talk by Carlo Burigana)
  - distortion of the CMB dipole due to monopole distortions
  - distortions due to *mixing of blackbodies* of varying temperatures

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ΛCDM

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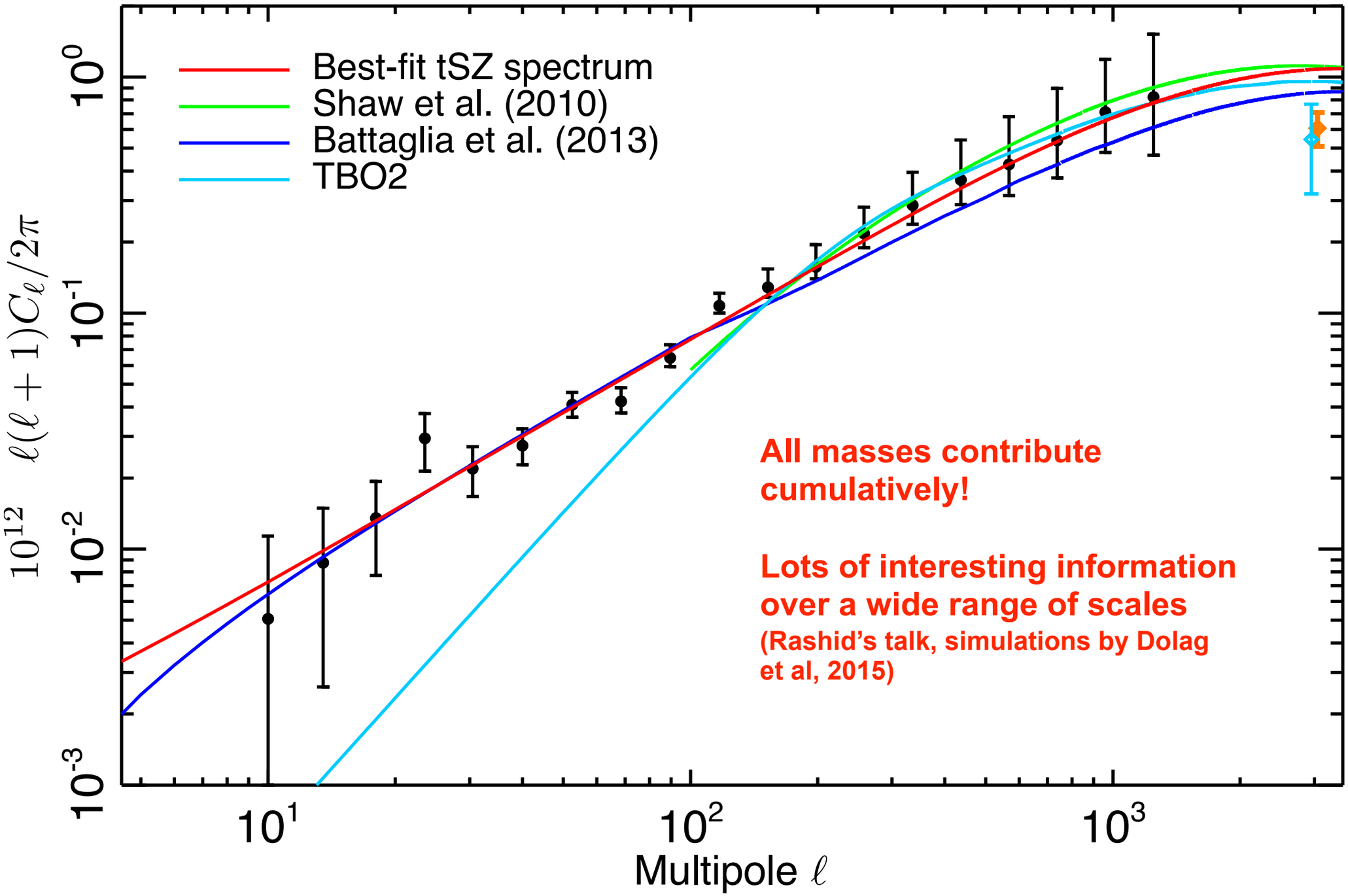
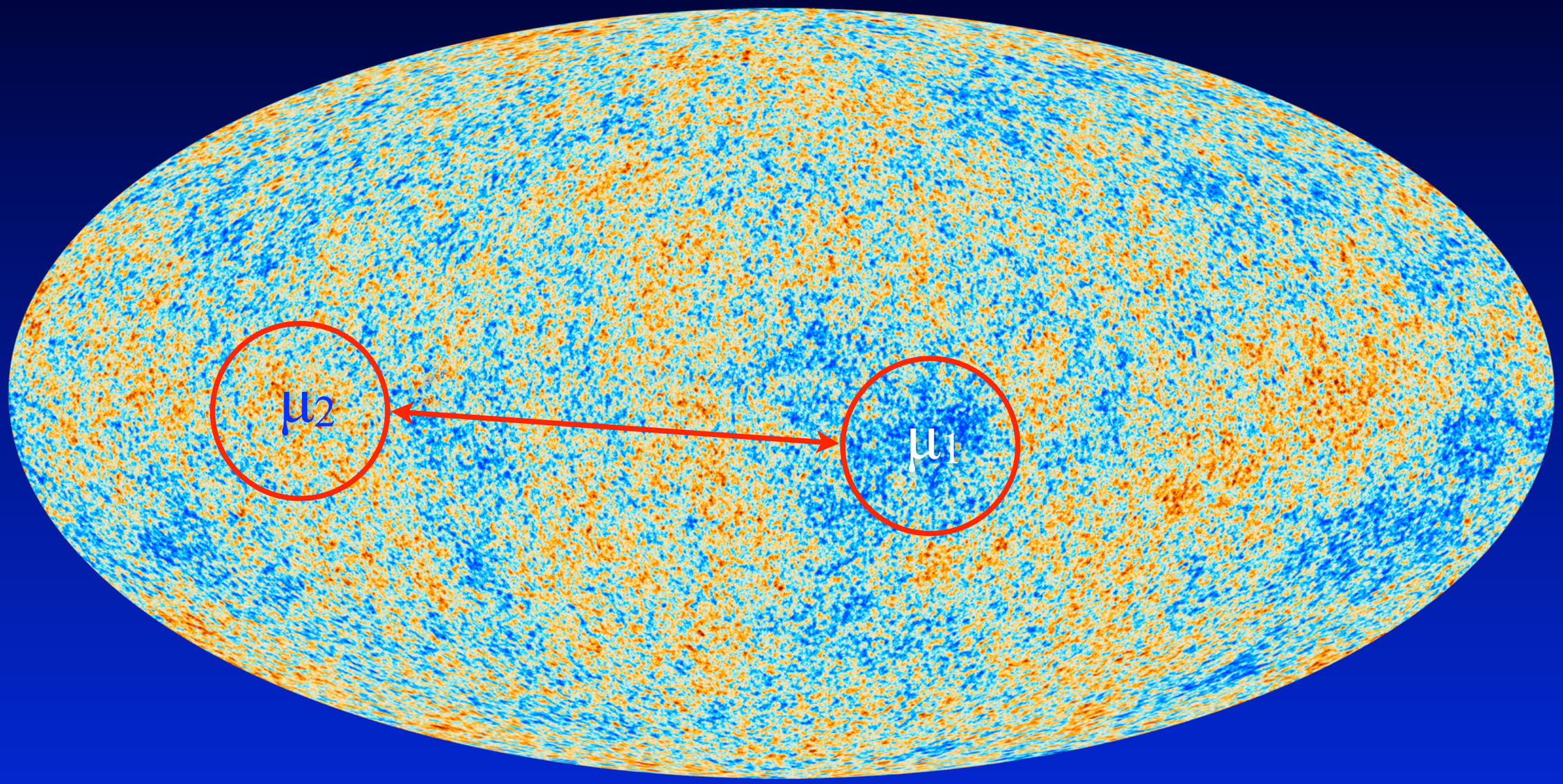
Measured power spectrum for y-parameter



Planck Collaboration, 2015, XXII

Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- Uniform heating (e.g., dissipation in Gaussian case or quasi-uniform energy release)

  → distortion practically the same in different directions

- Spatially varying heating rate (e.g., due to *ultra-squeezed limit non-Gaussianity* or *cosmic bubble collisions*)

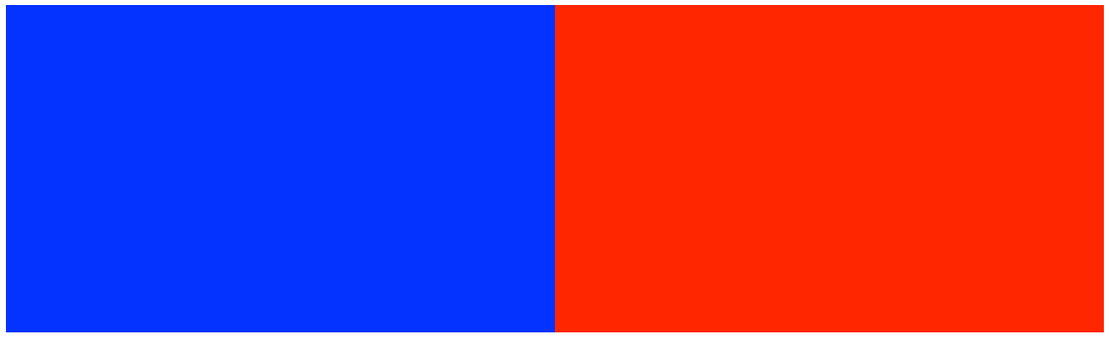
  → distortion varies in different directions

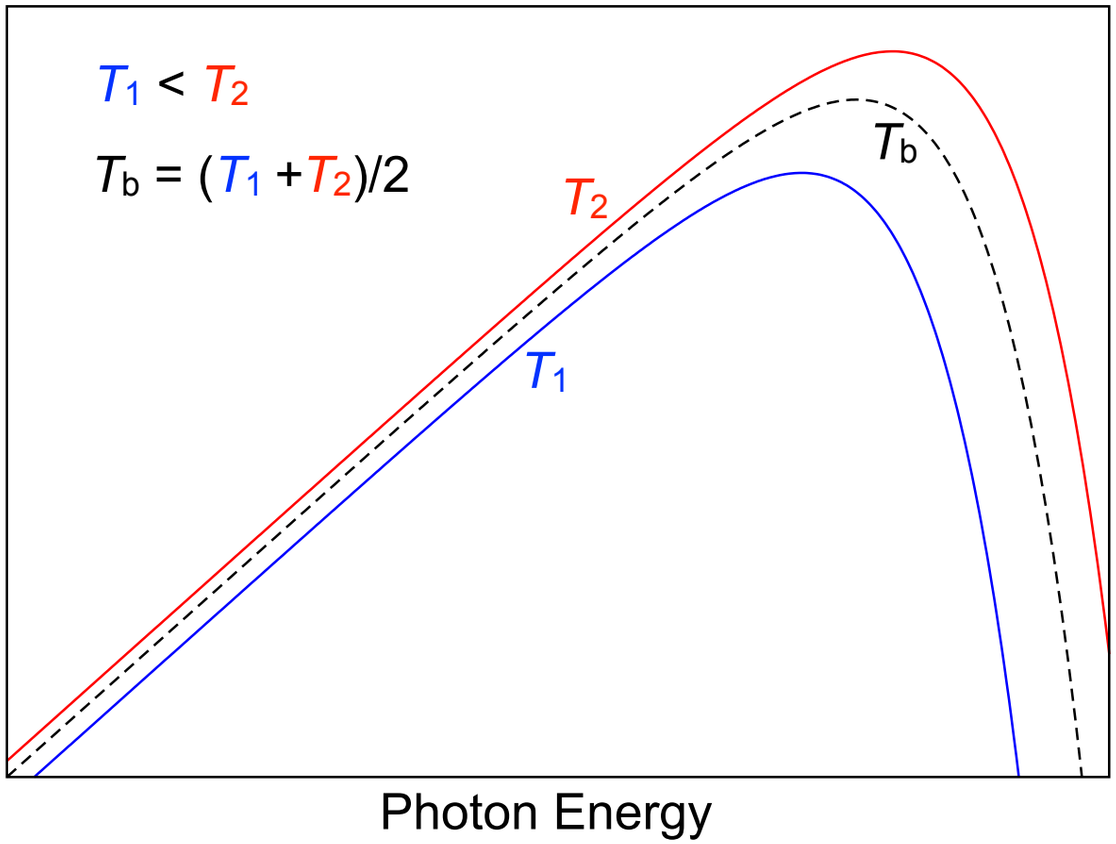
Distortion due to mixing of blackbodies

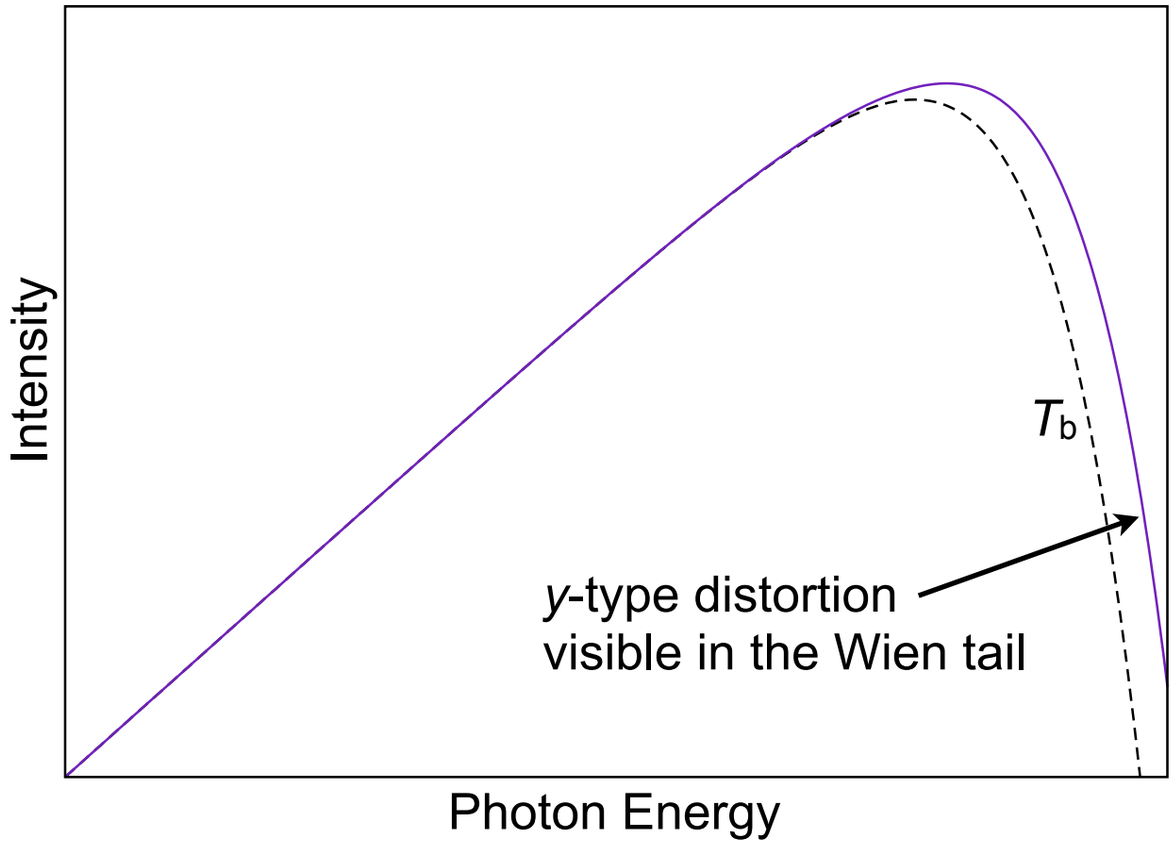
Blackbody spectra

Photon mixing

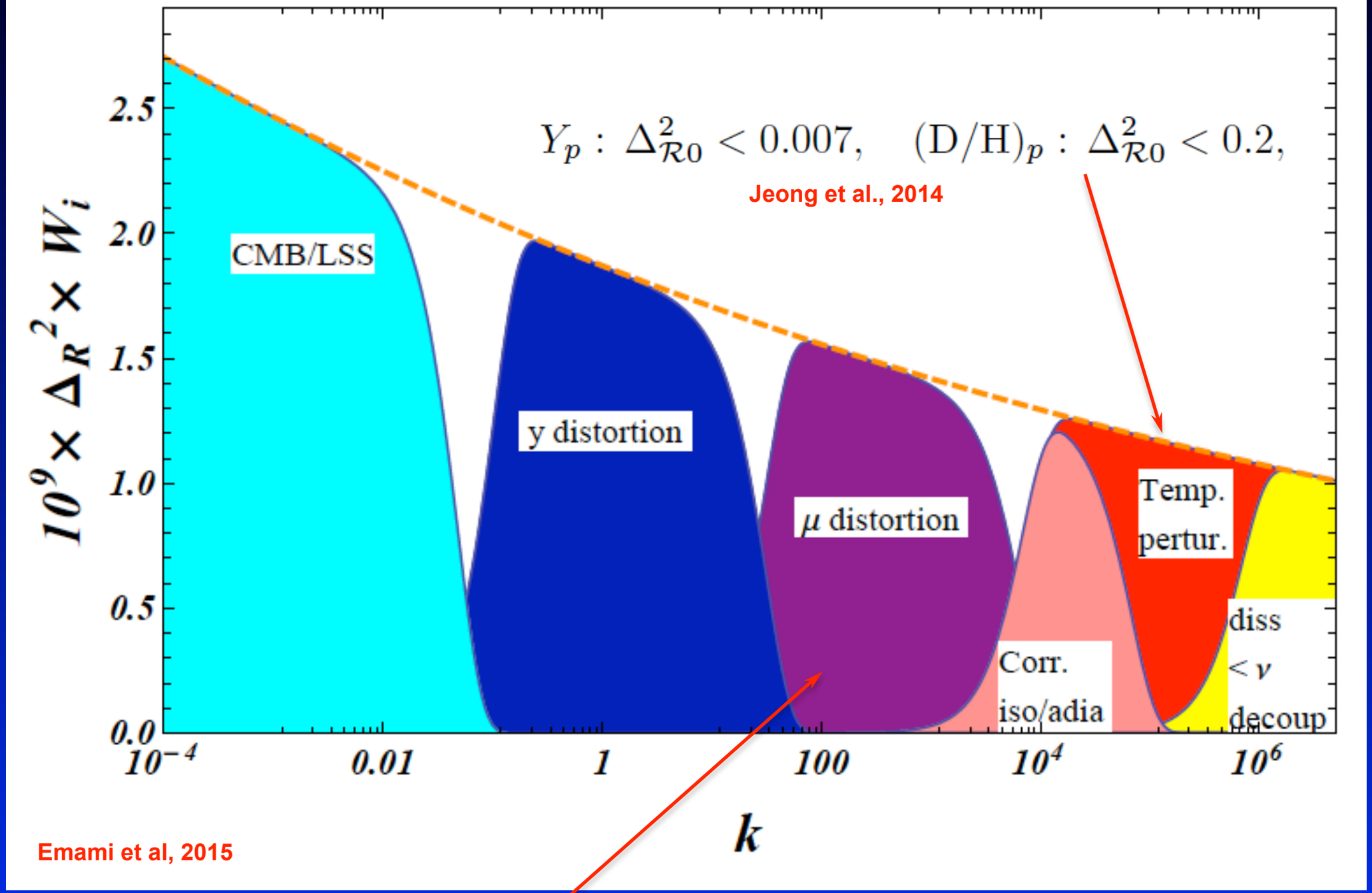
Blackbody + *y*-distortion







JC, Hamann & Patil, 2015



- *μ for ultra-squeezed limit non-Gaussianity*
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013)

Signals for ultra-squeezed non-Gaussianity

- Different correlation signals (see Emami et al, 2015)

$$C_\ell^{\mu T} \simeq 12 f_{\rm nl}^{\mu}\, C_\ell^{TT}$$
$$C_\ell^{yT} \simeq 12 f_{\rm nl}^{y}\, C_\ell^{TT}$$

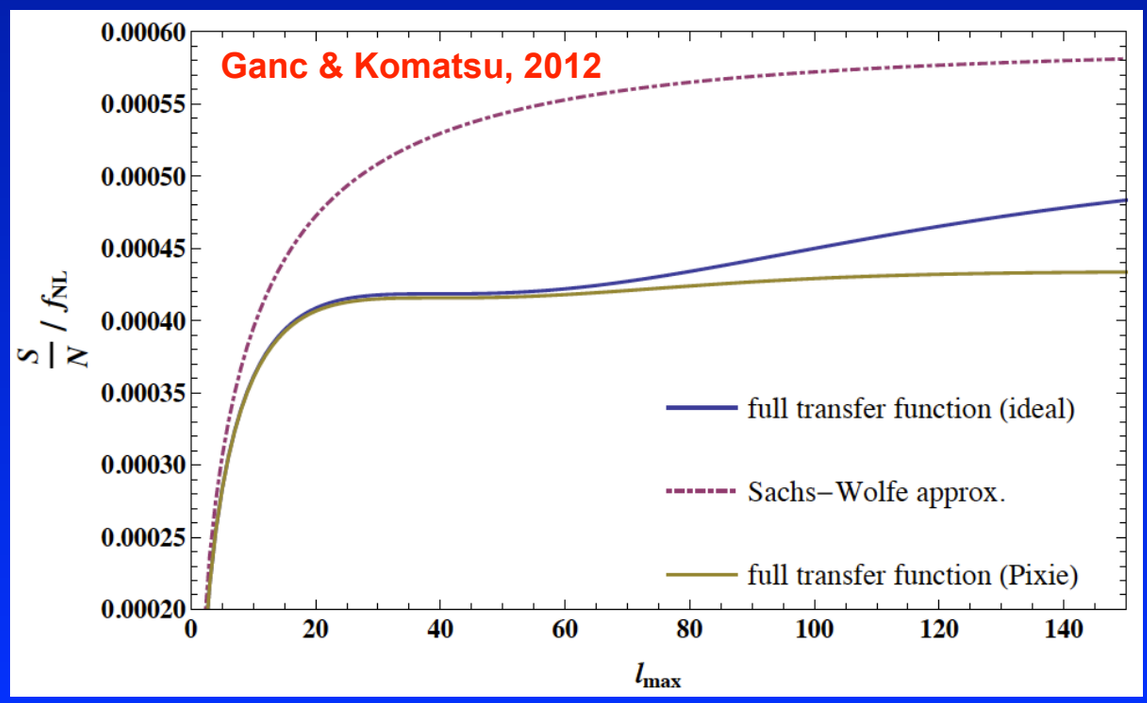
$$\Leftrightarrow$$

$$f_{\rm nl}^{\mu} \simeq f_{\rm nl}(740\,{\rm Mpc}^{-1}) \simeq 220 \left(\frac{\mu_{\rm min}}{10^{-9}}\right)\left(\frac{\langle\mu\rangle}{2\times10^{-8}}\right)^{-1}$$
$$f_{\rm nl}^{y} \simeq f_{\rm nl}(7\,{\rm Mpc}^{-1}) \simeq 220 \left(\frac{y_{\rm min}}{2\times10^{-10}}\right)\left(\frac{\langle y\rangle}{4\times10^{-9}}\right)^{-1}$$

- achievable sensitivity depends on *monopole* distortion!
- μT "*cleanest*" signal since it can only be created at early times
- yT also created by ISW but *scale-dependence* could help distinguishing it from the high-*z* signal
- possible link to *CMB anomalies?*

Requirements

- *precise cross-calibration of frequency channels*
- higher angular resolution does not improve cumulative S/N much
  (→ *PIXIE-like experiment may be enough*)



Spectral Anisotropies in CMB Cold Spots

1.8 deg Pixels with SNR>5 Excess at 143 GHz and low ISM emission

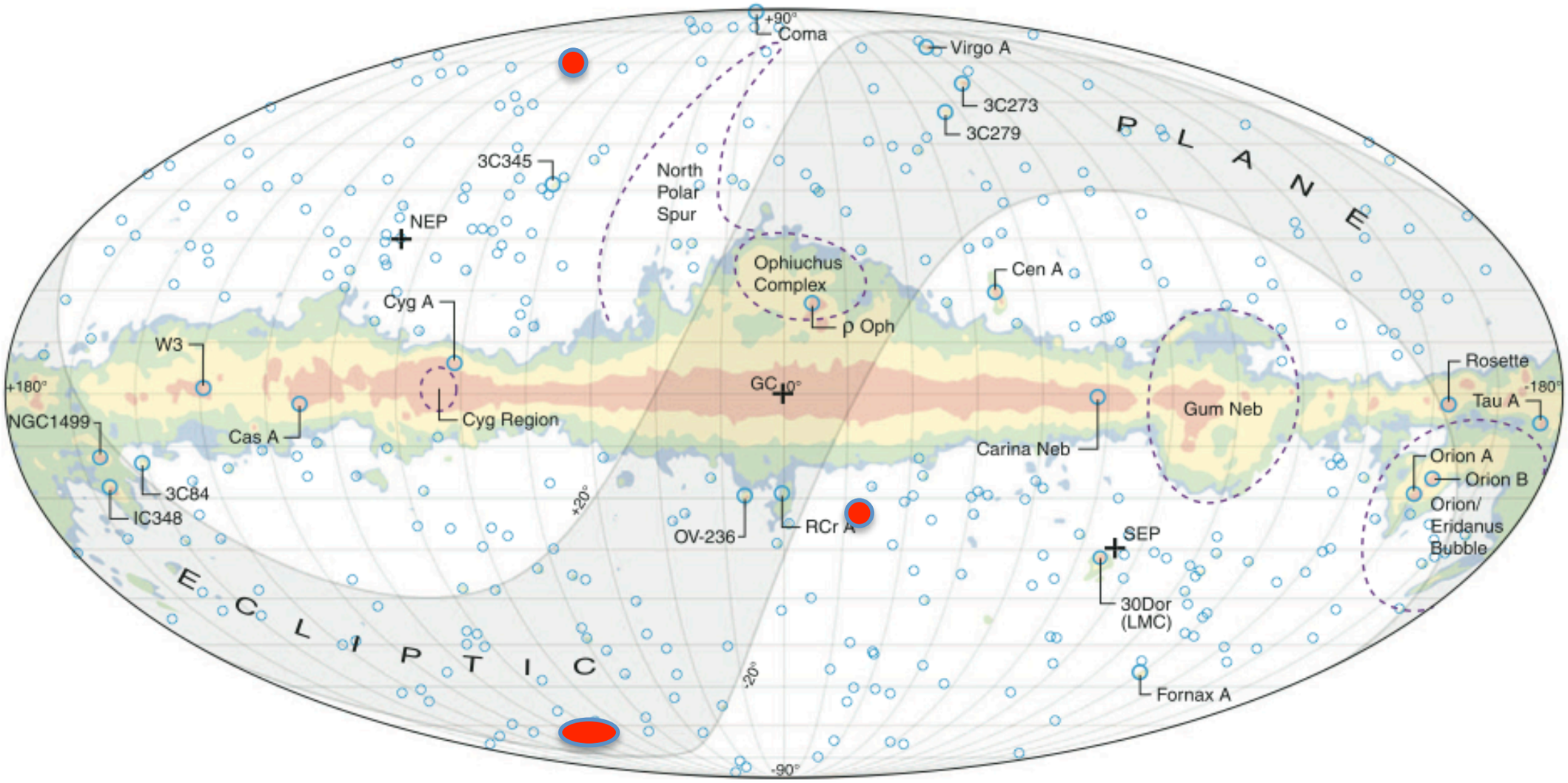
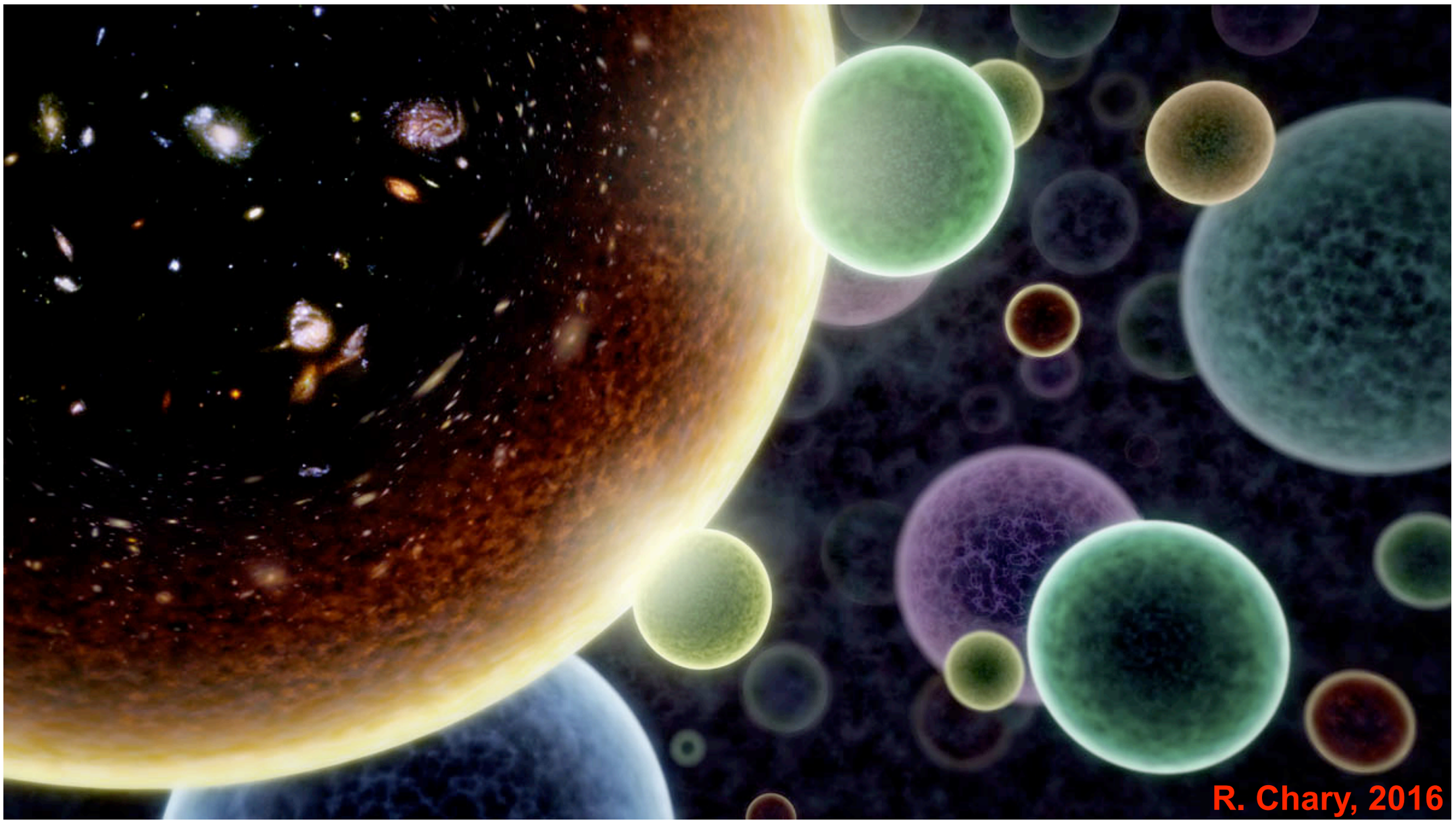


Figure 12. Microwave emission near the Galactic plane is traced by a *K*-band minus *W*-band difference map, which eliminates CMB anisotropy. A log scale is used for the color region and blue circles represent the positions of the brightest point sources, as seen by *WMAP*.

R. Chary 2016, ApJ, 817, 33

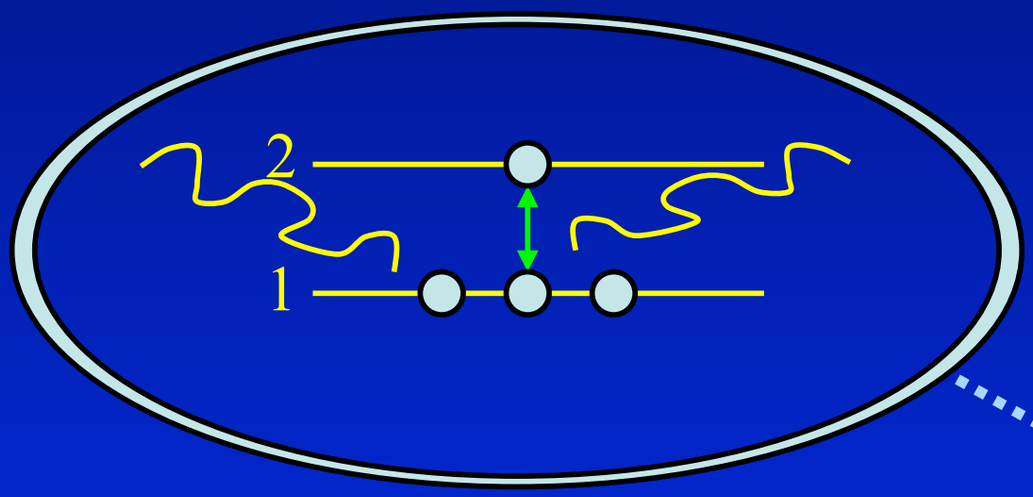
Signature of the Multiverse ????



- Multi-frequency observations will certainly help to understand the origin of these deviant patches and may furthermore discover new regions

Coherent scattering of the CMB photons

(RHS05)



λ_{12} : Rest frame wavelength

CMB photon

z=0

Hydrogen atom at redshift z

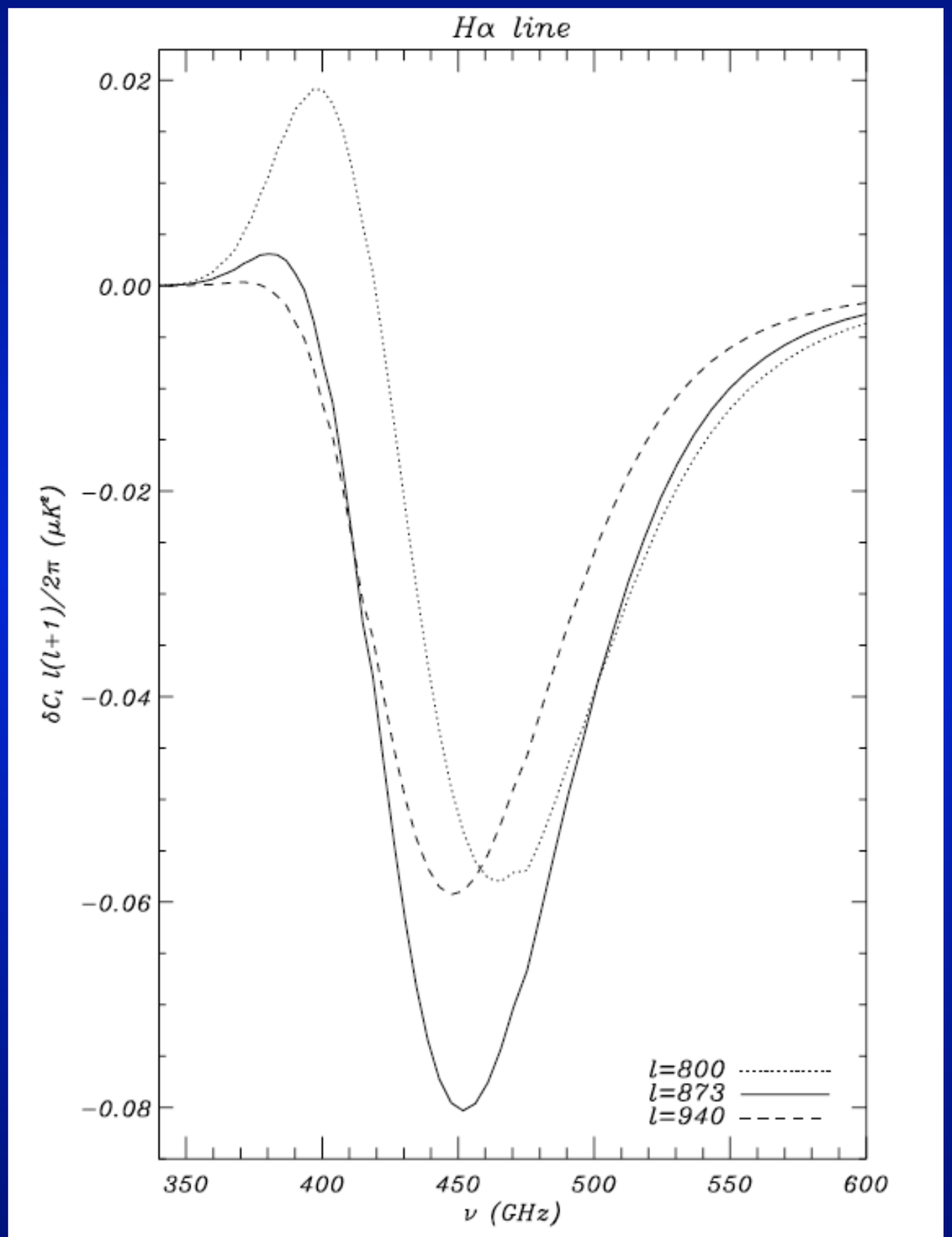
z=1000

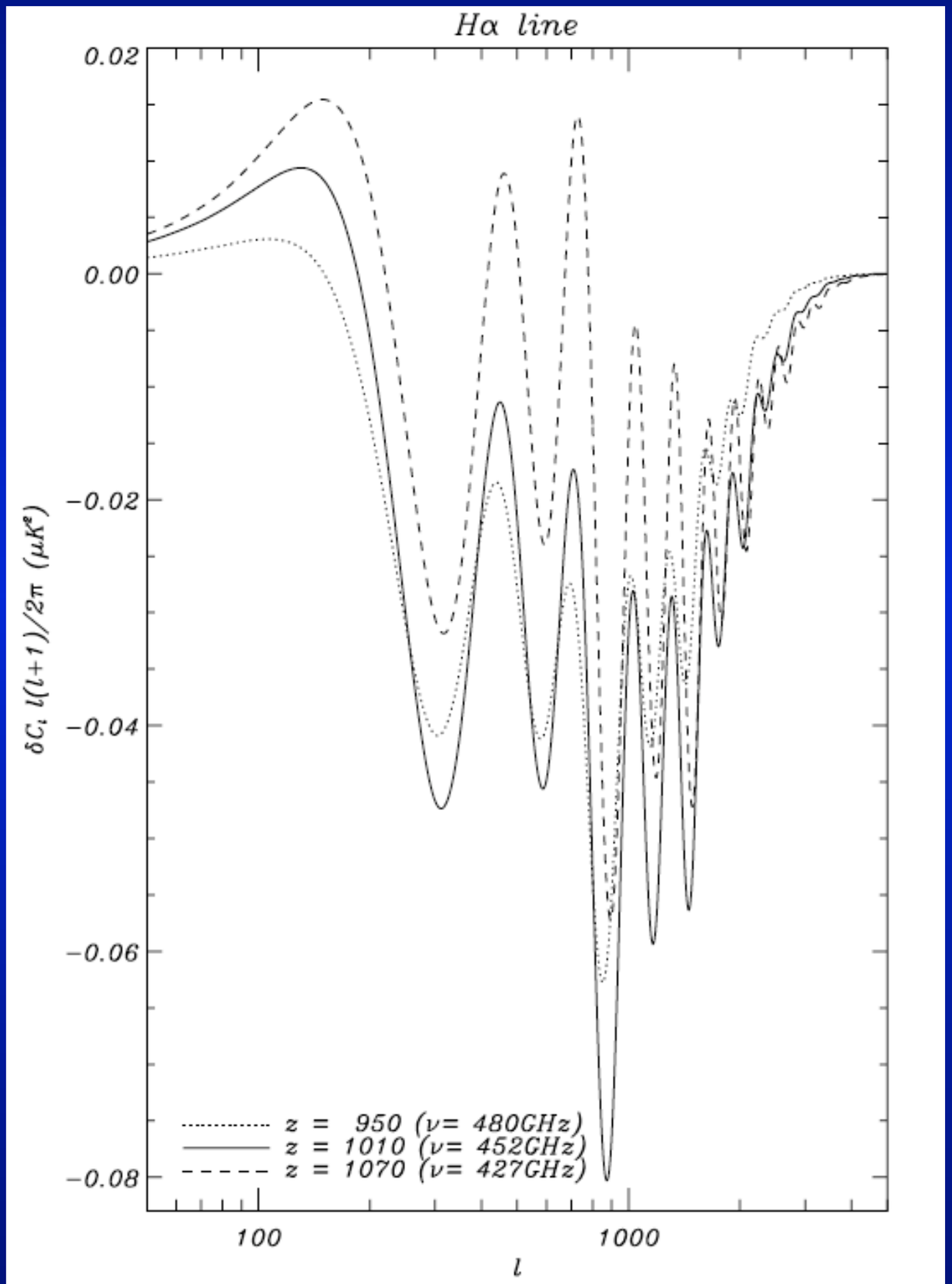
$$\frac{\Delta T}{T_0}(\theta) = e^{-\tau_\nu} \left.\frac{\Delta T}{T_0}(\theta)\right|_{orig.} + \left.\frac{\Delta T}{T_0}(\theta)\right|_{new}$$

λ_{12} $\longleftarrow$ $\lambda_{12}\,(1+z)$

Courtesy J.A. Rubino-Martin

The Hα line (III)

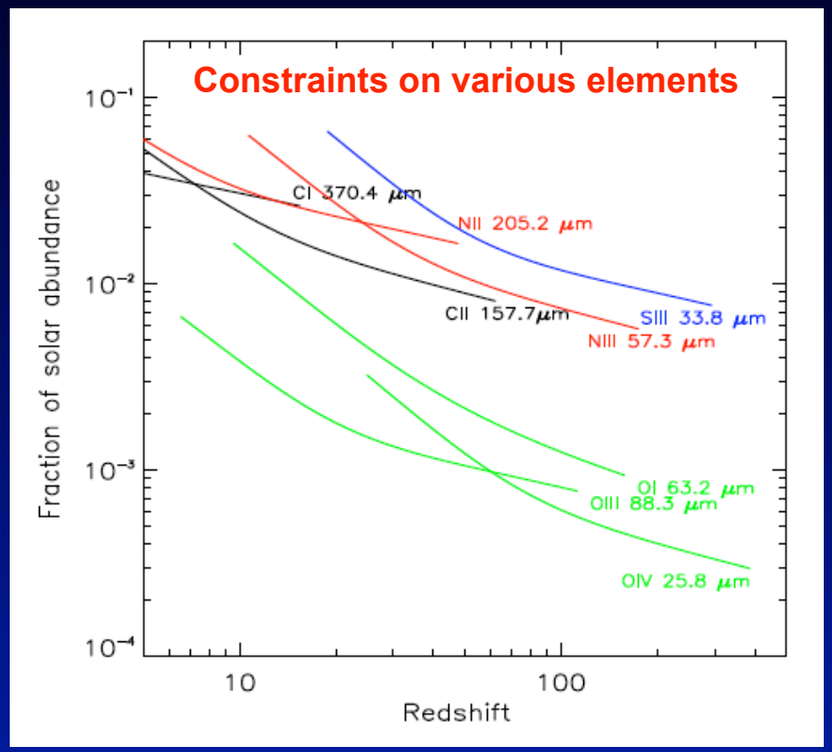


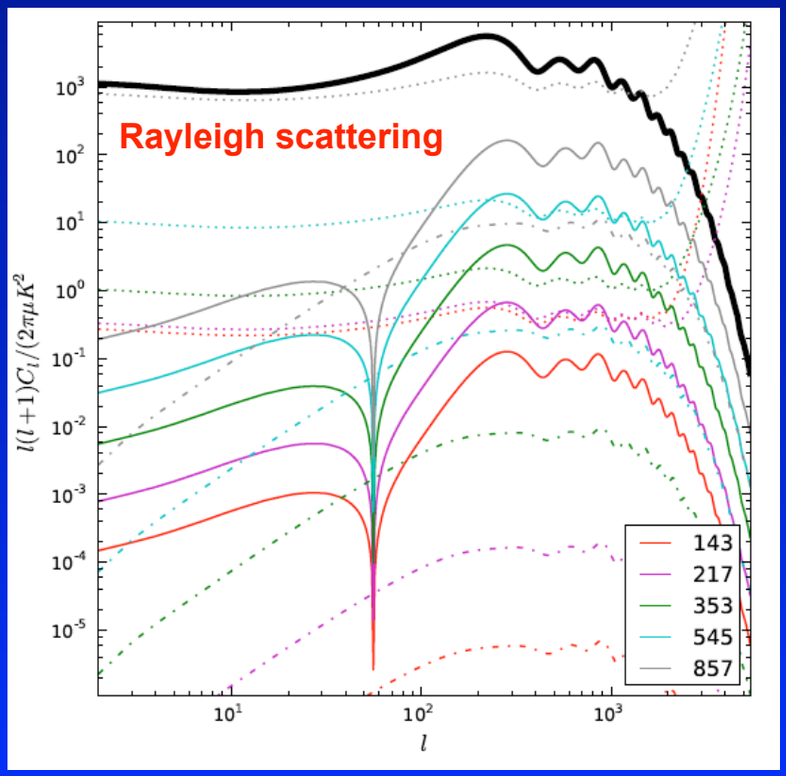


Courtesy J.A. Rubino-Martin

Other extremely interesting new signals

- Scattering signals from the dark ages
  (e.g., Basu et al., 2004; Hernandez-Monteagudo et al., 2007; Schleicher et al., 2009)
  - constrain abundances of chemical elements at high redshift
  - learn about star formation history
- Rayleigh / HI scattering signals
  (e.g., Yu et al., 2001; Rubino-Martin et al., 2005; Lewis 2013)
  - provides way to constrain recombination history
  - important when asking questions about $N_{\rm eff}$ and $Y_{\rm p}$
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium
  - need low frequency measurements...





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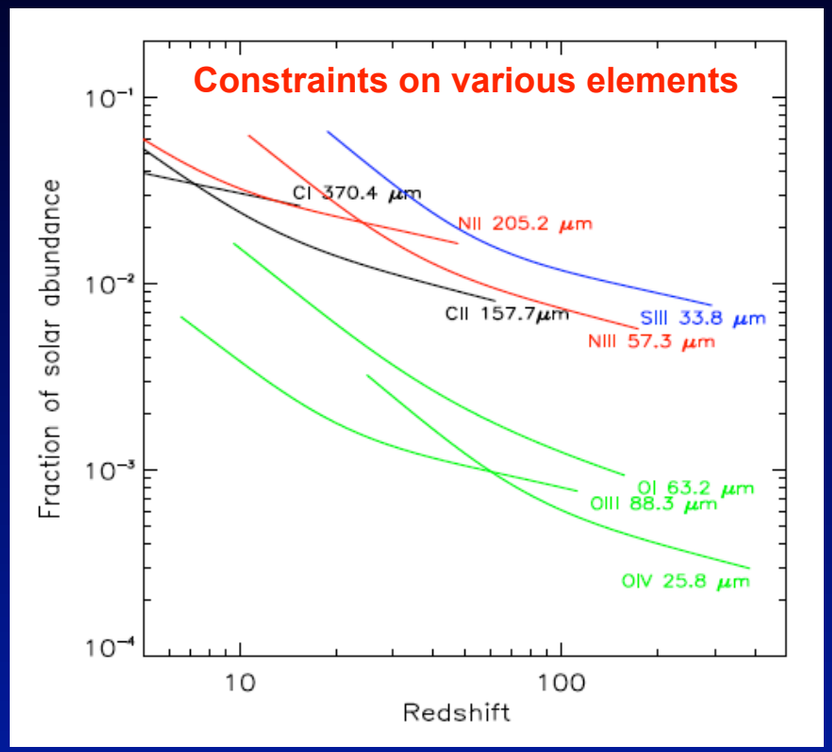
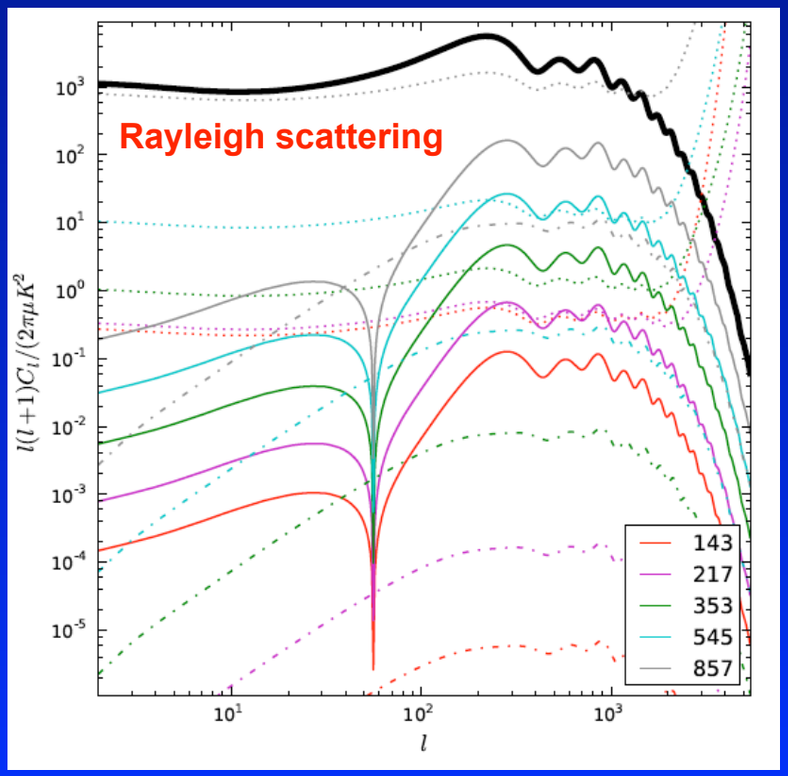
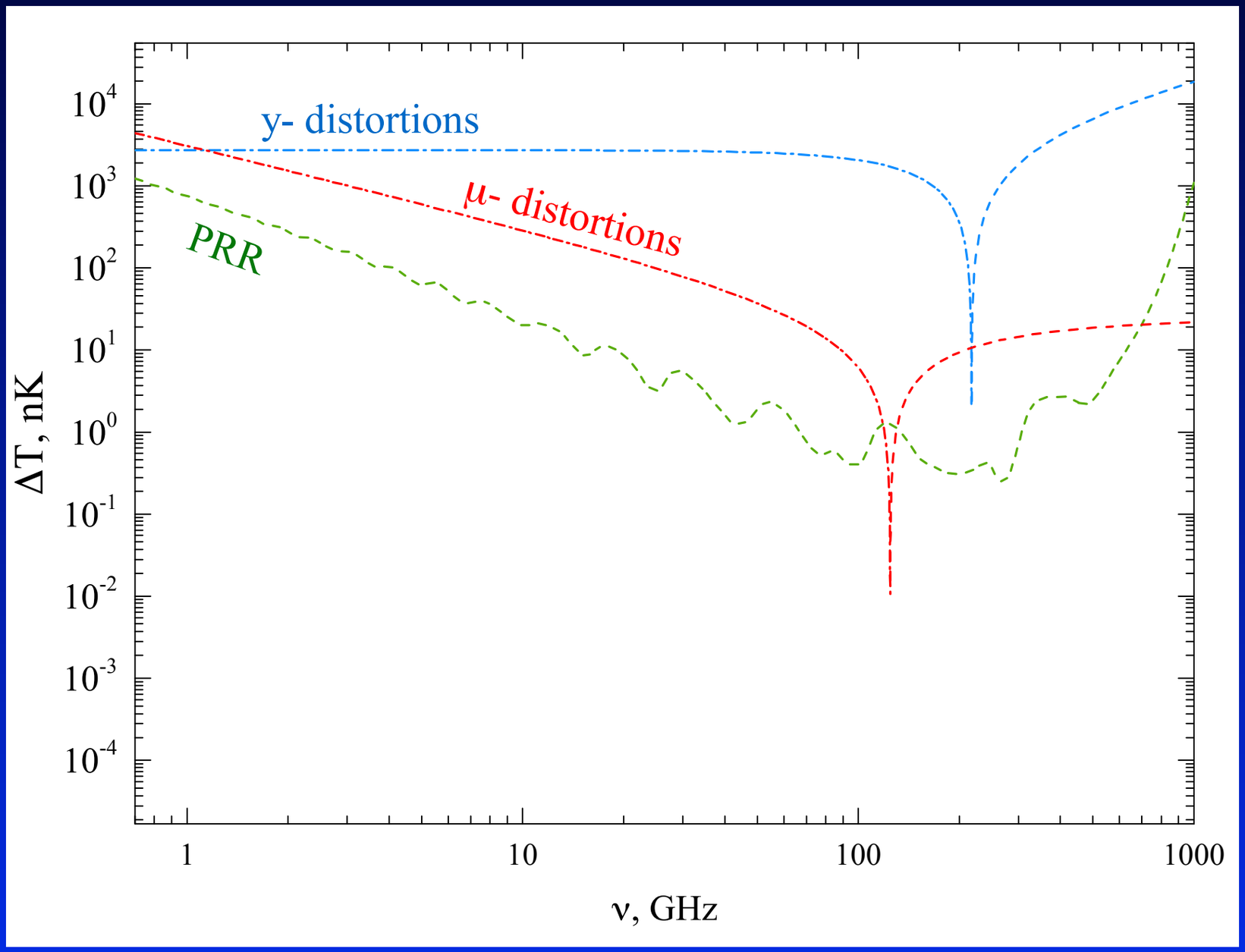
All these effects give spectral-spatial signals and require precise channel cross calibration ↔ synergy with PIXIE!





Spectral distortions of the CMB dipole



- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

- including primordial distortions of the CMB

⇒ *CMB dipole is distorted*

$$\eta_{\rm d}(\nu,\mathbf{n}) \approx -\nu\partial_\nu\eta_{\rm m}(\nu)\,\beta\cos\Theta$$

- spectrum of the dipole is sensitive to the *derivative* of the monopole spectrum
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- foregrounds will also *leak* into the dipole in this way → obtain foreground *monopole*

Danese & de Zotti, 1981
Balashev, Kholupenko, JC, Ivanchik & Varshalovich, ArXiv:1505.06028

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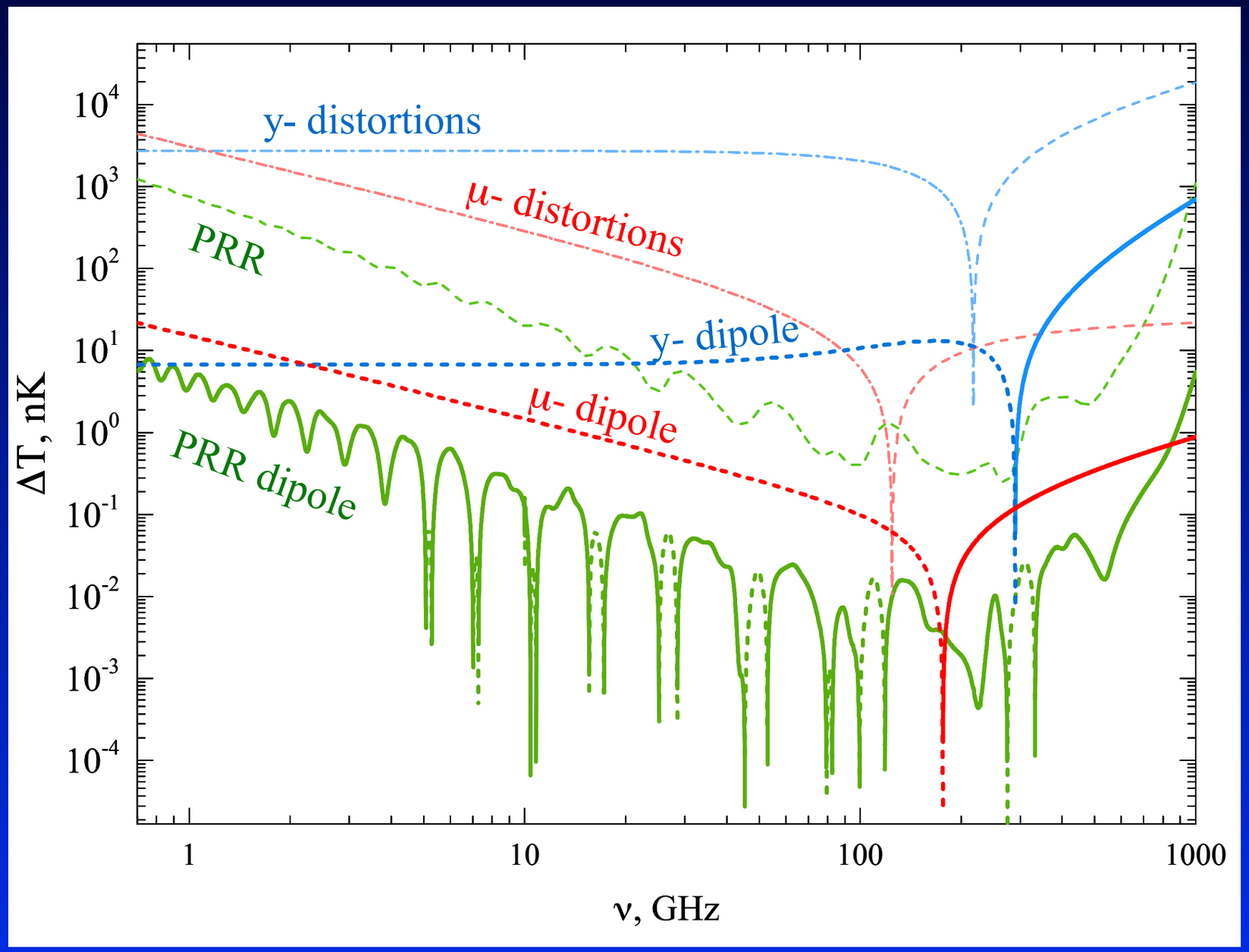

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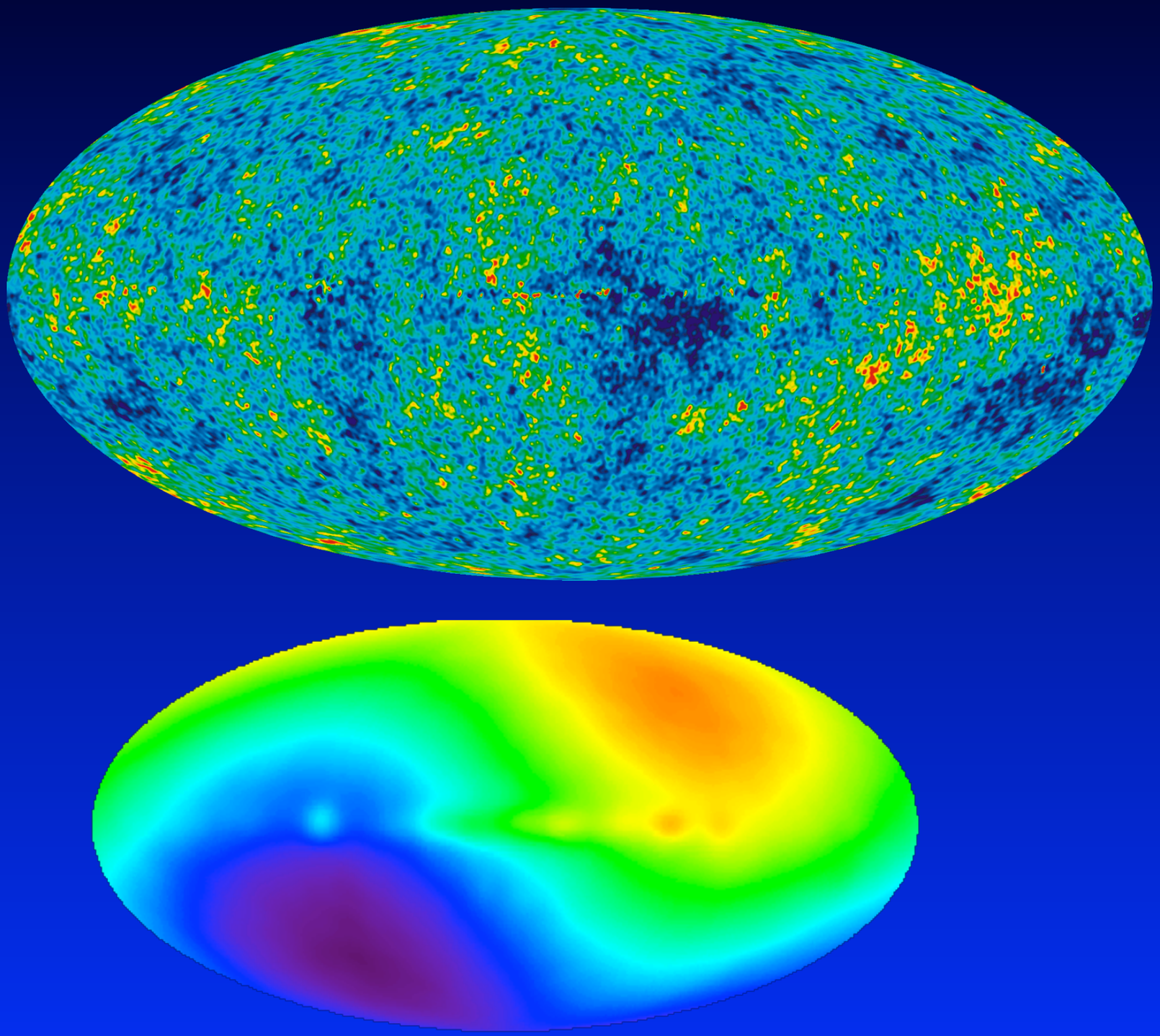
Distortions caused by superposition of blackbodies



- average spectrum

$$\Rightarrow\ y \simeq \frac{1}{2}\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 8\times 10^{-10}$$

$$\Delta T_{\rm sup} \simeq T\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 4.4{\rm nK}$$

- known with very high precision

- *CMB dipole* ($\beta \sim 1.23\text{x}10^{-3}$)

$$\Rightarrow\ y = \frac{\beta^2}{6} \approx (2.525\pm 0.012)\times 10^{-7}$$

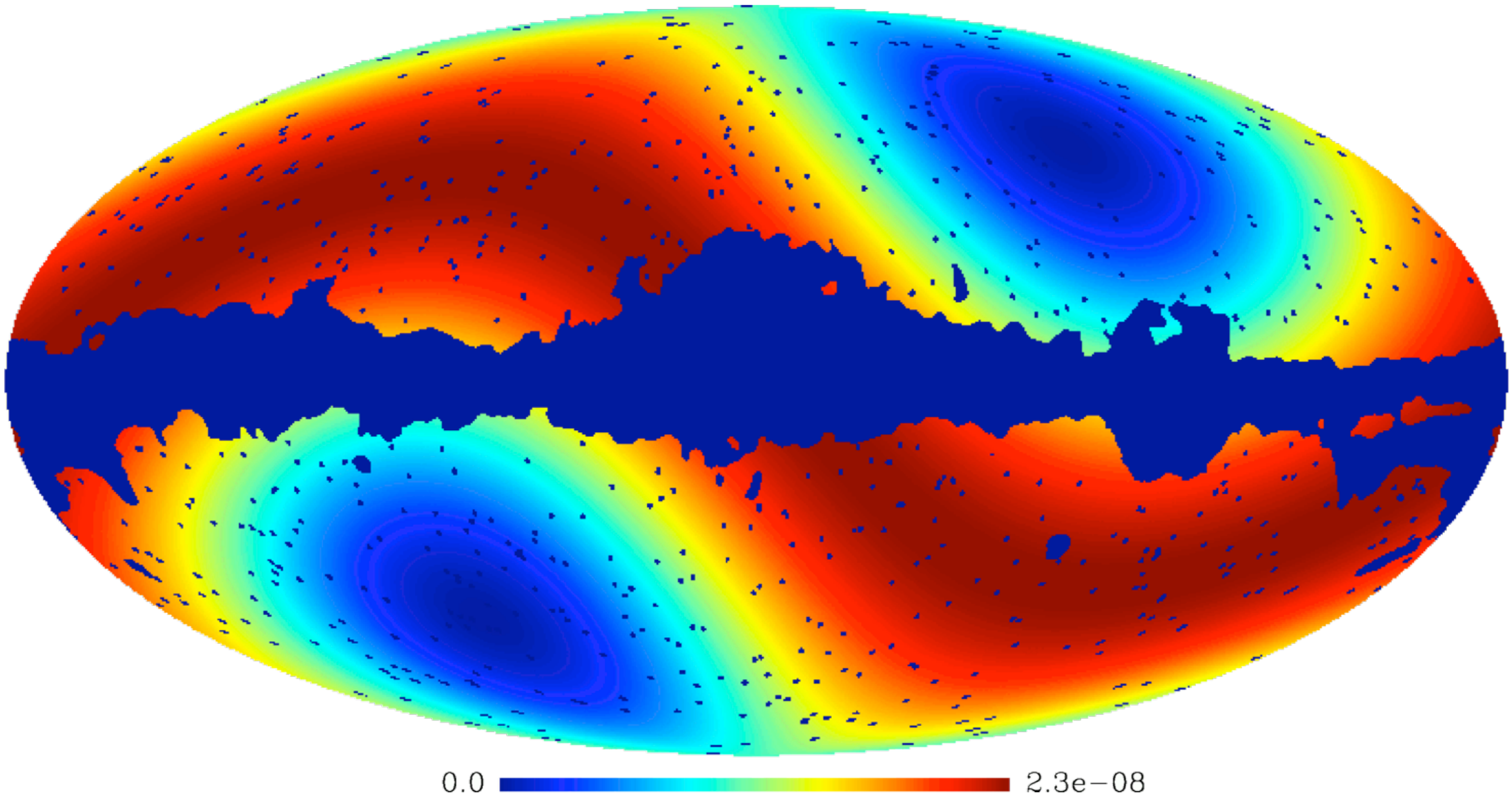
$$\Delta T_{\rm sup} \simeq T\,\frac{\beta_{\rm c}^2}{3} \approx 1.4\mu{\rm K}$$

- electrons are up-scattered
- can (and should) be taken out down to the level of y ~ 10^{-9}

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012
JC, 2016, ArXiv:1603.02496

COBE/DMR: ΔT = 3.353 mK

Motion-induced distortion of quadrupole



- *y*-type quadrupole ~ 10^{-6} due to Doppler dipole
- `Artifact' of the spherical harmonic expansion
- Similar effects for higher multipoles (*aberration*)

Kamionkowski & Knox, 2003
JC & Sunyaev, 2004

Thank you!