Chicago Spectral Distortion Workshop

# What do we learn from Spectral Distortions? Theory for Experimentalists

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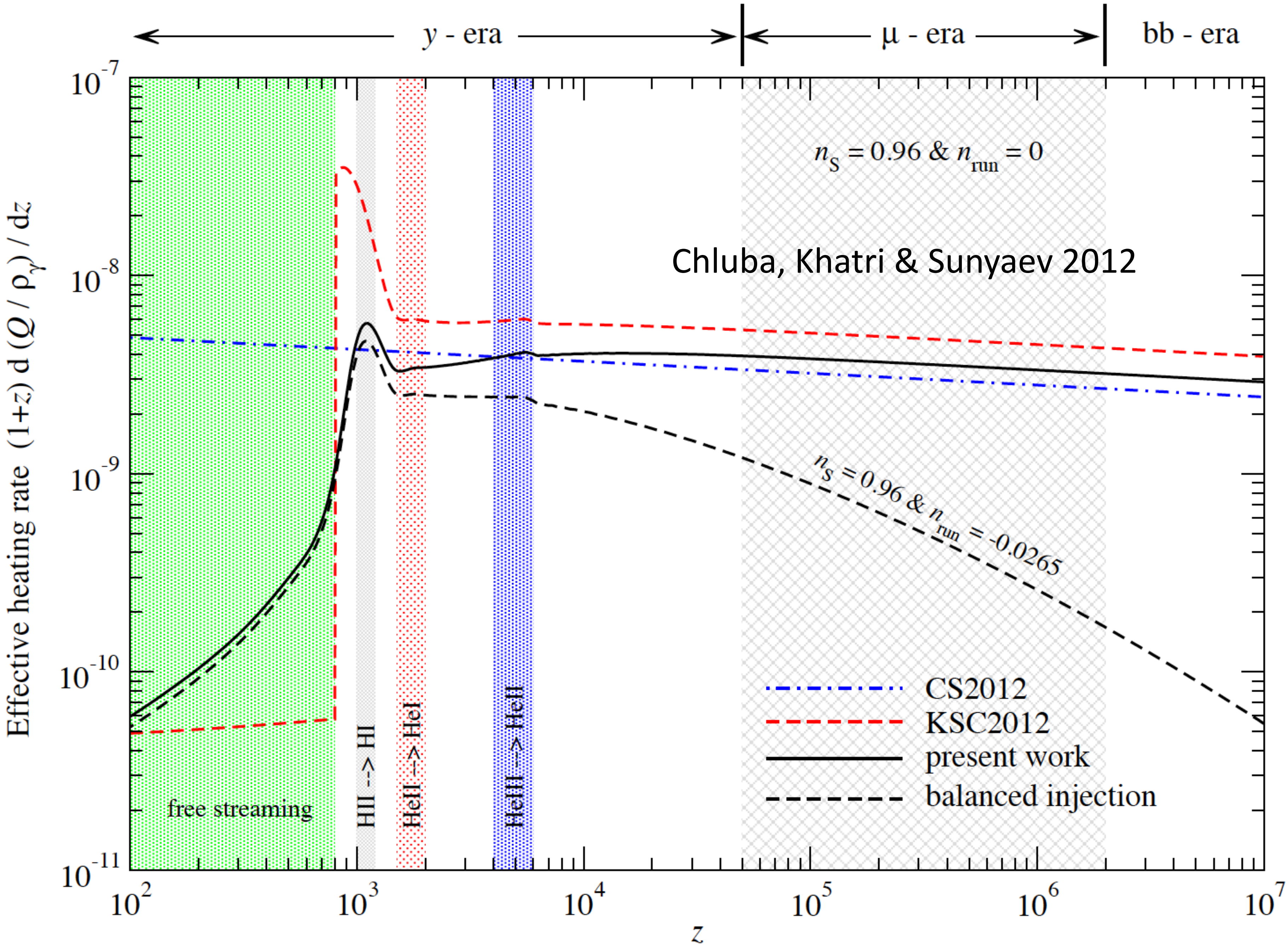
# Thermal History of Universe

- Energy injection at $z >> 10^6$ changes temperature-time relation
- During $4 \times 10^4 < z < 2 \times 10^6$ energy injection produces $+\mu$ distortions (adiabatic cooling produce $-\mu$ distortions
- Energy injection after recombination produces y distortions



y - era
μ - era
bb - era
$n_S = 0.96$ & $n_{run} = 0$
Chluba, Khatri & Sunyaev 2012
$n_S = 0.96$ & $n_{run} = -0.0265$
Effective heating rate $(1+z)\, d(Q/\rho_\gamma)/dz$
free streaming
HII --> HI
HeII --> HeI
HeIII --> HeII
CS2012
KSC2012
present work
balanced injection
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
$10^{6}$
$10^{7}$
$z$

# Energy Injection in the first month

- $z >> 2 \times 10^6$, double Compton and Bremstralhung interactions of photons with electron-ion plasma was very efficient.
- Changes temperature-time relation

# Energy injection in the μ era

- Adiabatic cooling produce a negative mu distortion $\mu = -2.2 \times 10^{-9}$ (Chluba and Sunyaev 2012)
  - NR matter redshifts as $(1+z)^2$
  - Electrons “cool” CMB
- Damping of acoustic waves heats the universe and produce a positive μ distortion

Pajer and Zaldarriaga 2012

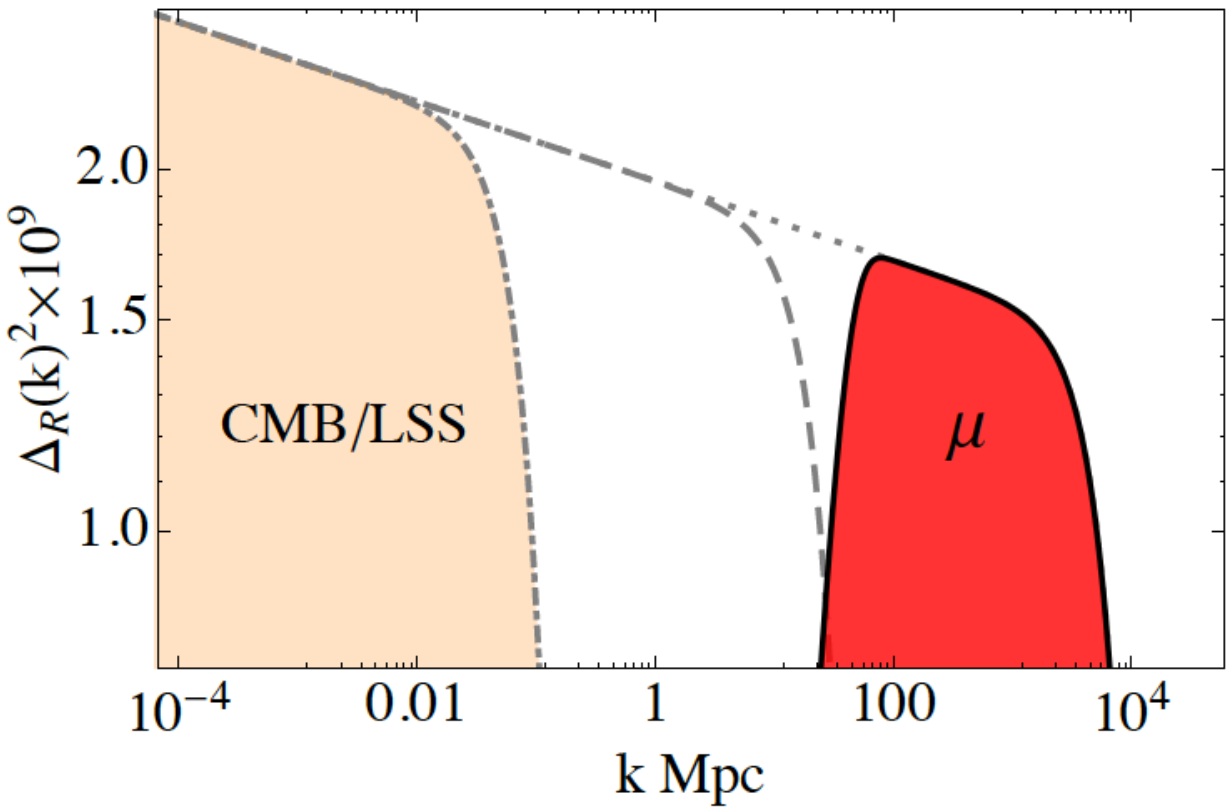



Figure 1: The figure shows the power spectrum with Silk damping as function of $\log k$. The dotted, dashed and dot-dashed lines are $\Delta_R^2 e^{-2k^2/k_D^2}$ at $z_{\mu,i} = 2 \times 10^6$, $z_{\mu,f} = 5 \times 10^4$ and $z_L = 1100$ respectively. The red area on the right indicated by $\mu$ is the difference of the power spectrum between $z_{\mu,i}$ and $z_{\mu,f}$. Once integrated over $\log k$ this gives the $\mu$-distortion. For comparison on the left we have highlighted the scales probed by LSS and CMB anisotropies.

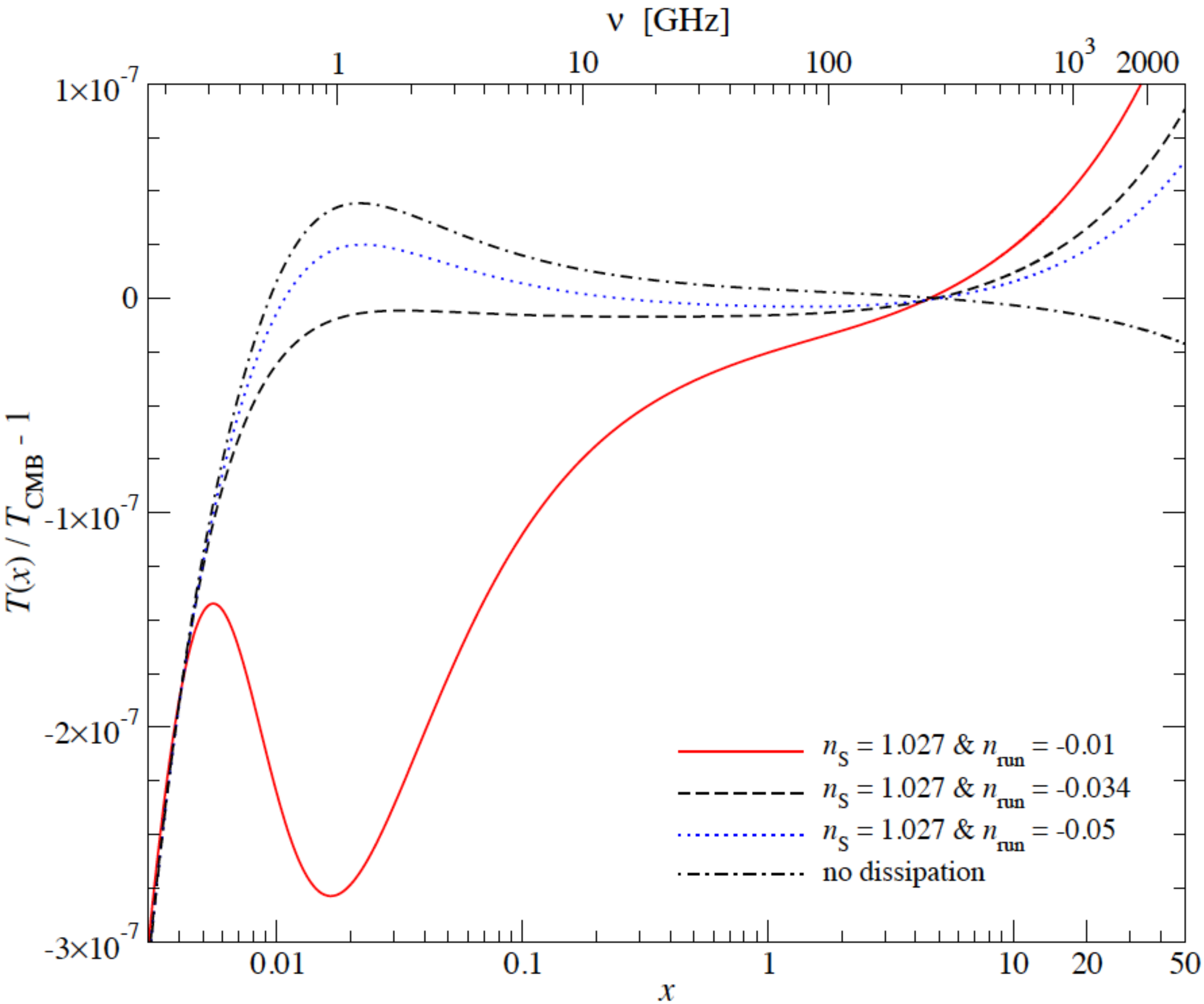
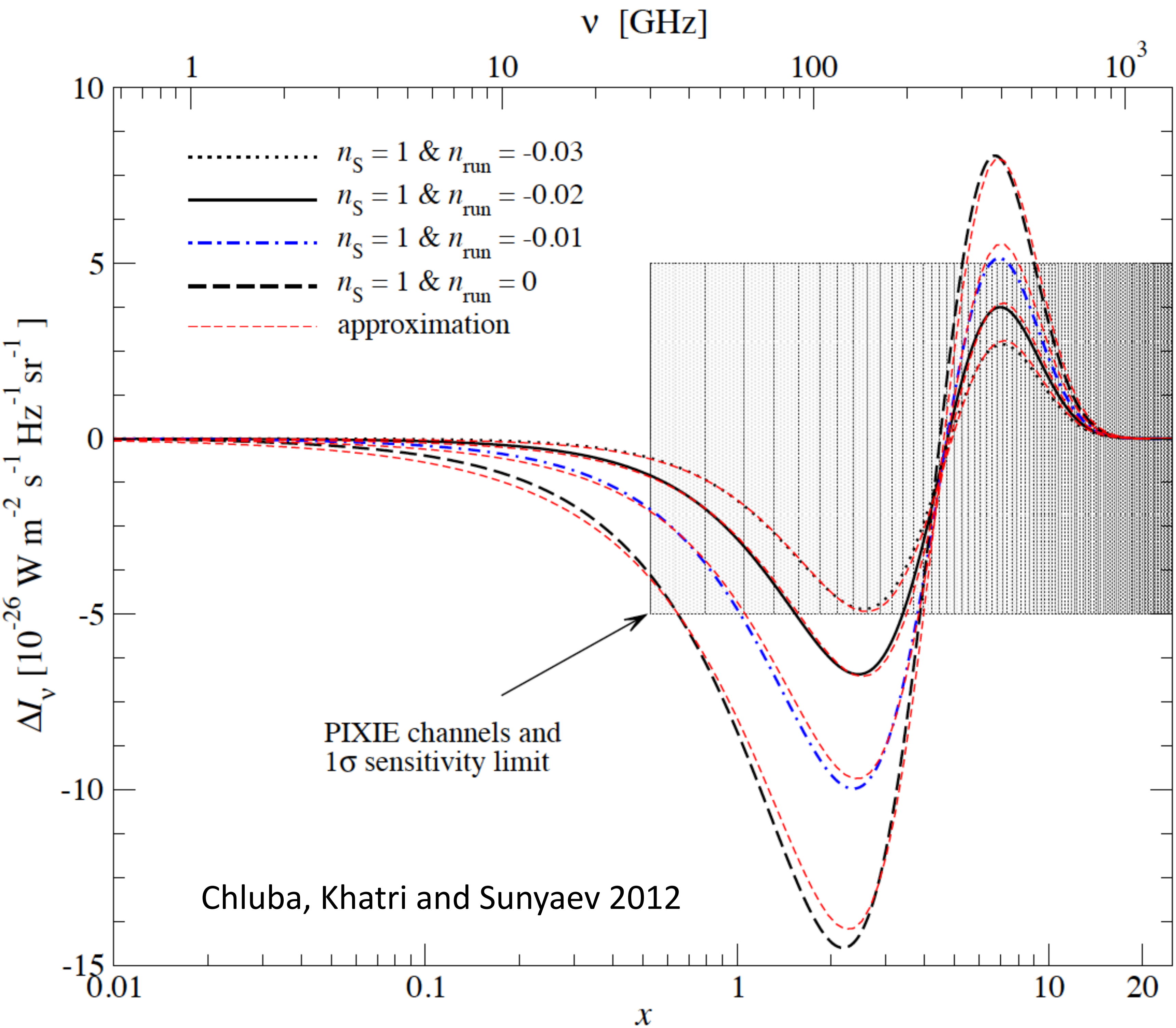
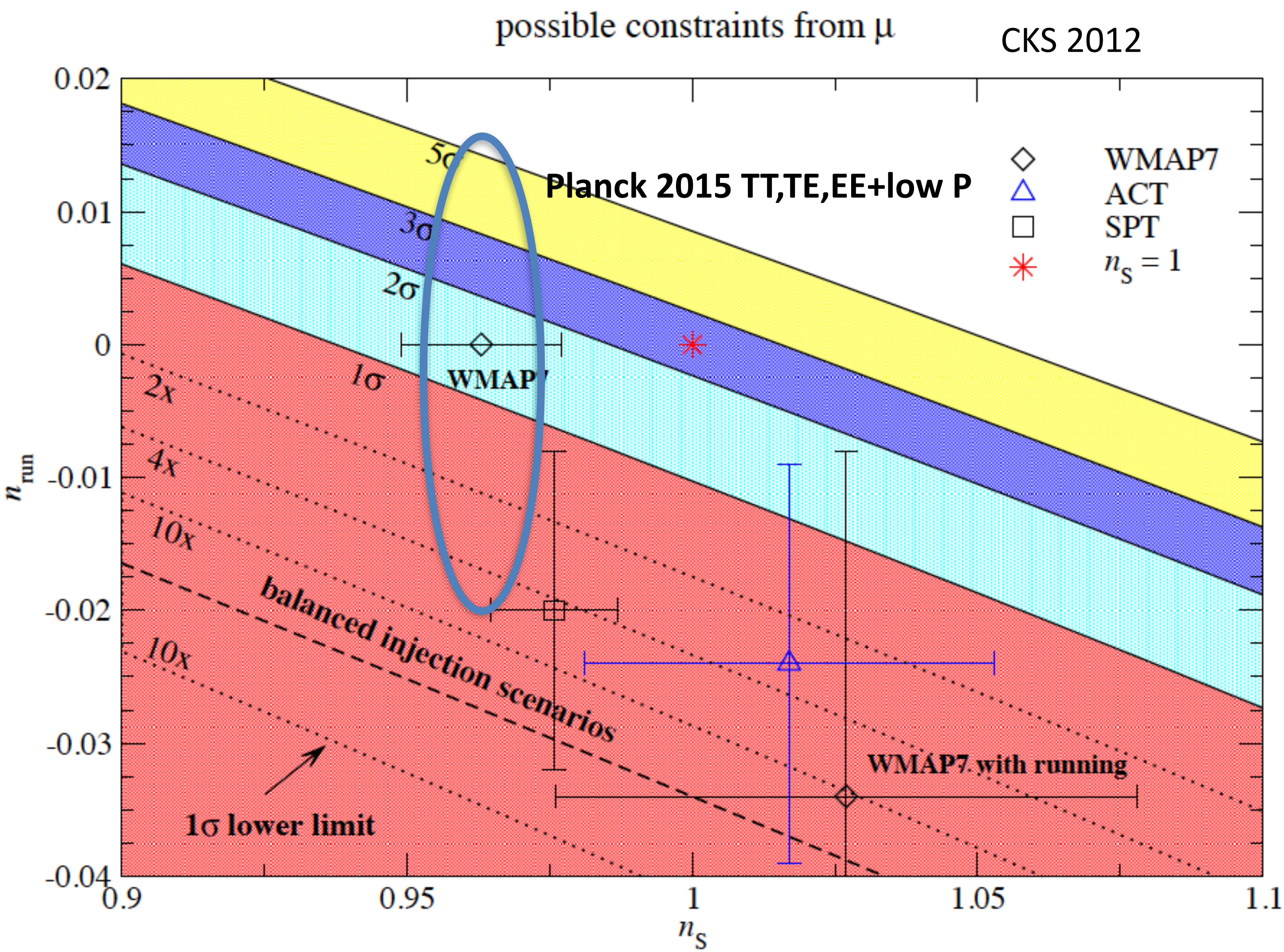



**Figure 11.** Spectral distortion from acoustic damping and BE condensation for $n_S = 1.027$ and $n_{run} = -0.01, -0.034, -0.05$. The balanced scenario is very close to $n_{run} = -0.034$. For comparison we also show the case without any dissipation.



ν [GHz]
1
10
100
$10^3$
10
5
0
-5
-10
-15
$n_S = 1$ & $n_{run} = -0.03$
$n_S = 1$ & $n_{run} = -0.02$
$n_S = 1$ & $n_{run} = -0.01$
$n_S = 1$ & $n_{run} = 0$
approximation
$\Delta I_\nu$ [$10^{-26}$ W m$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$]
PIXIE channels and
1σ sensitivity limit
Chluba, Khatri and Sunyaev 2012
0.01
0.1
1
10
20
$x$


possible constraints from μ
CKS 2012
Planck 2015 TT,TE,EE+low P
WMAP7
ACT
SPT
$n_S = 1$
5σ
3σ
2σ
1σ
WMAP7
2x
4x
10x
10x
balanced injection scenarios
1σ lower limit
WMAP7 with running
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0.9
0.95
1
1.05
1.1
$n_{run}$
$n_S$

# Non-Gaussianities and μ distortions

- Potential ability to probe very small values of $f_{NL}$
- Harder to see than μ distortions. Detection requires large NG signal on small scales

$$\frac{S}{N} \simeq 0.7 \times 10^{-3}\, b\, f_{NL} \left( \frac{\sqrt{4\pi} \times 10^{-8}}{w_\mu^{-1/2}} \right) .$$

Pajer and Zaldarriaga 2012

# Y distortions: Groups Win!

- Small scale CMB fluctuations (8 x $10^{-10}$ [Chluba and Sunyaev 2004))
- Acoustic waves 4 x $10^{-9}$ (CKS 2012)
- Reionization $10^{-7}$ (Hill et al. 2015)
- IGM $10^{-7}$
- ***Clusters + Groups $10^{-6}$*** (KS 2015: > 5.4 x$10^{-8}$)

$$\left\langle \tau_e \frac{kT_e}{m_e c^2} \right\rangle$$

Hill et al. 2015

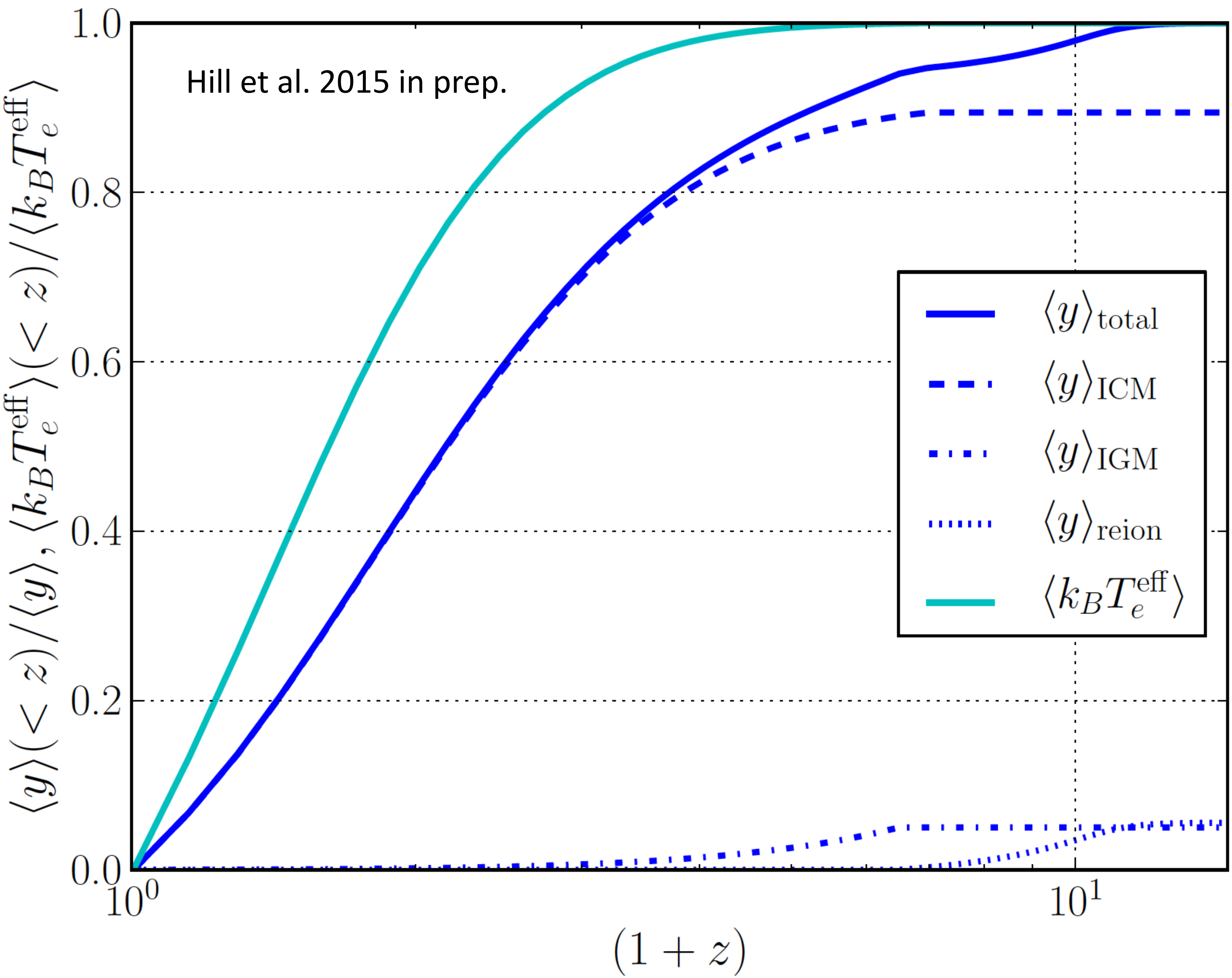
$$1.6 \times 10^{-6} \left(\frac{\sigma_8}{0.80}\right)^5$$

# Group and Clusters

- From $10^{13}$ - $10^{14}$ solar mass clusters at z~1
- Calibrated with stacking analyses on Planck
  - (Greco et al. 2015; Planck 2013 XI)
- Dominates even if CMB-S4 is used to remove contribution of known clusters
- Because clusters are hot (kT ~ keV), the relativistic TSZ correction is detected in PIXIE
- PIXIE should be able to make > 100 sigma detection of both mean y and characteristic temperature
- Sensitive to energy injection history

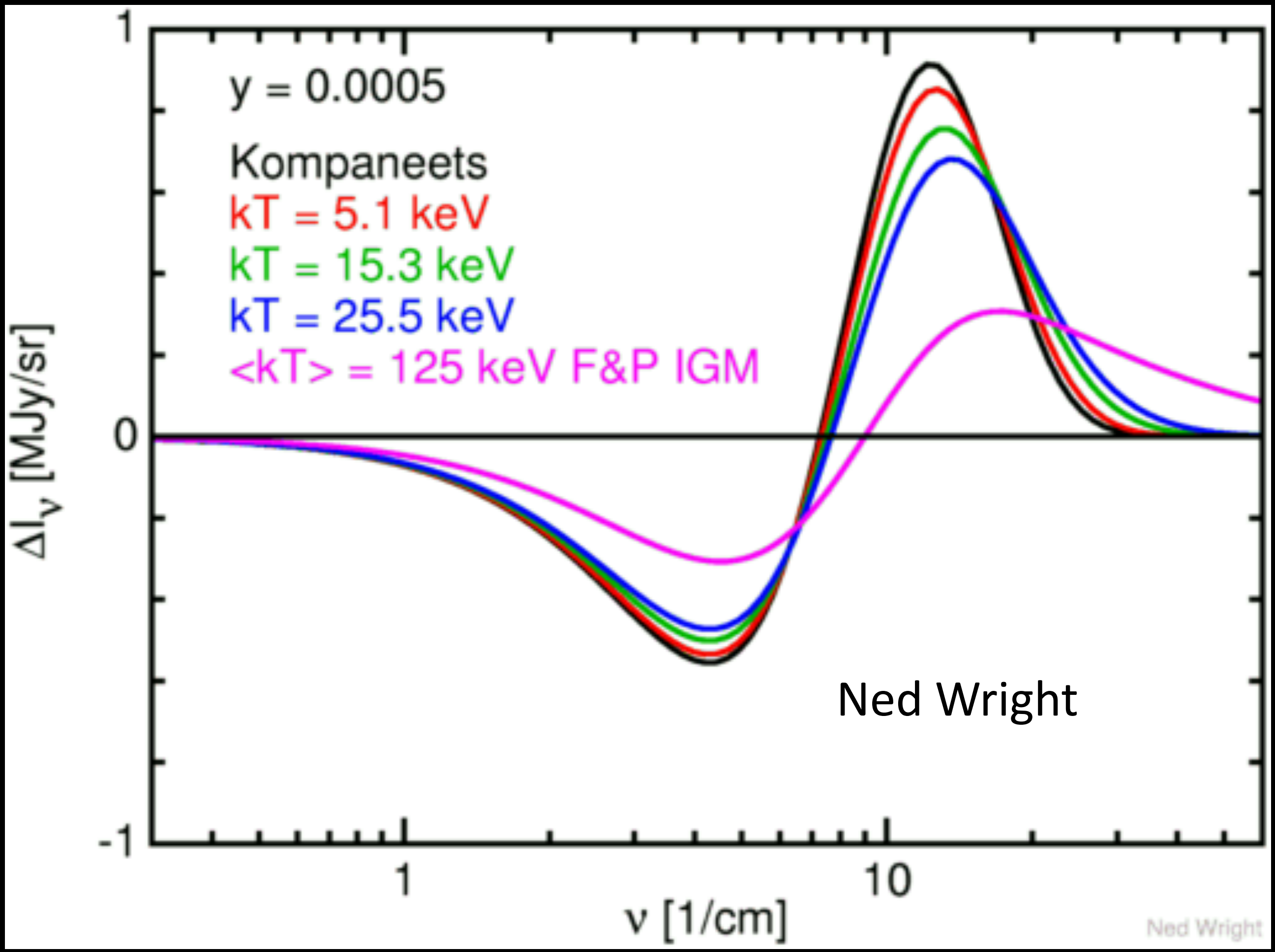





Hill et al. 2015 in prep.
$\langle y \rangle (< z)/\langle y \rangle, \langle k_B T_e^{\rm eff} \rangle (< z)/\langle k_B T_e^{\rm eff} \rangle$
$(1+z)$
$10^0$
$10^1$
0.0
0.2
0.4
0.6
0.8
1.0
$\langle y \rangle_{\rm total}$
$\langle y \rangle_{\rm ICM}$
$\langle y \rangle_{\rm IGM}$
$\langle y \rangle_{\rm reion}$
$\langle k_B T_e^{\rm eff} \rangle$

# Relativistic Correction

- Clusters are hot enough that the relativistic correction changes the shape of the spectrum

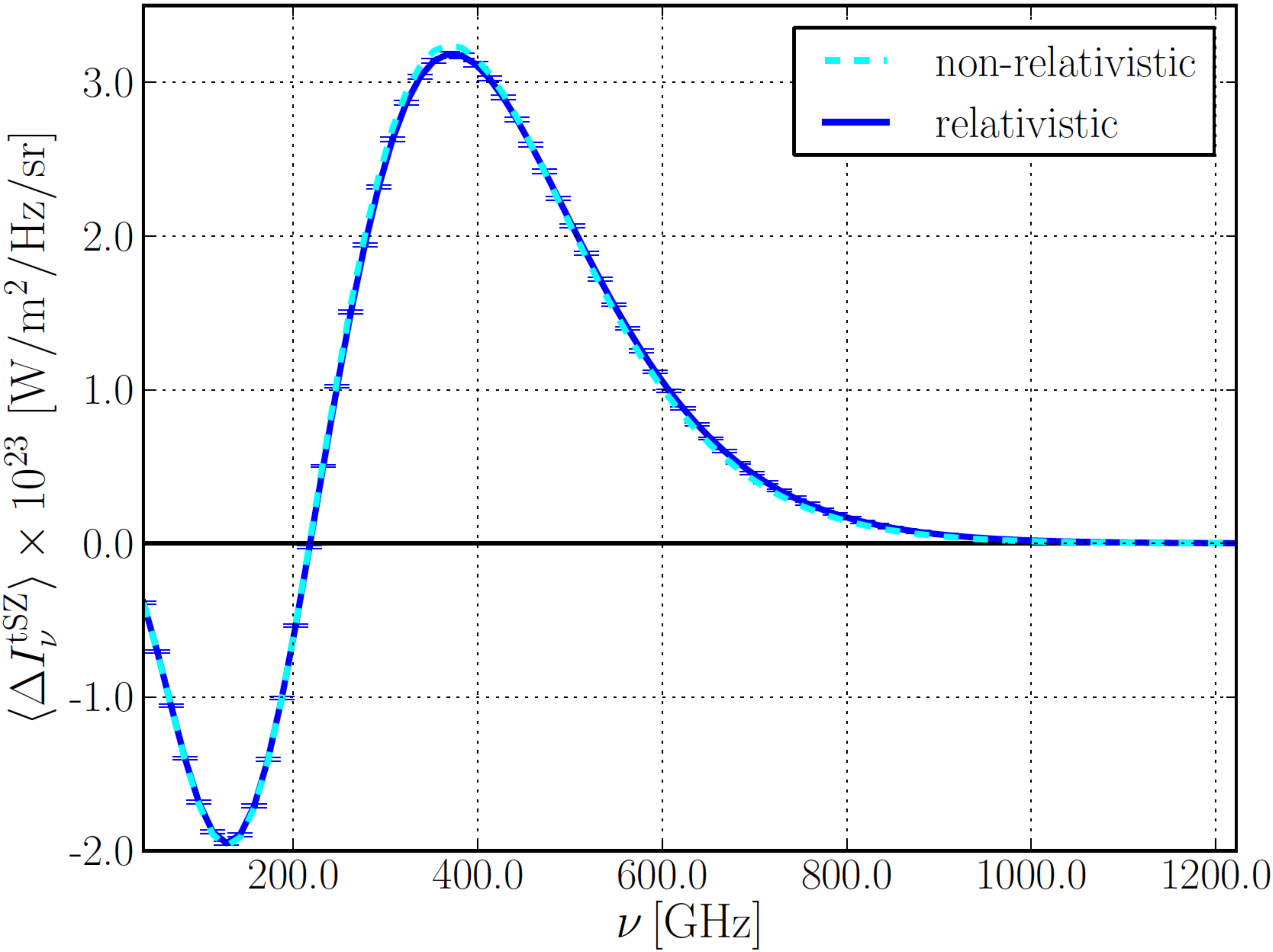


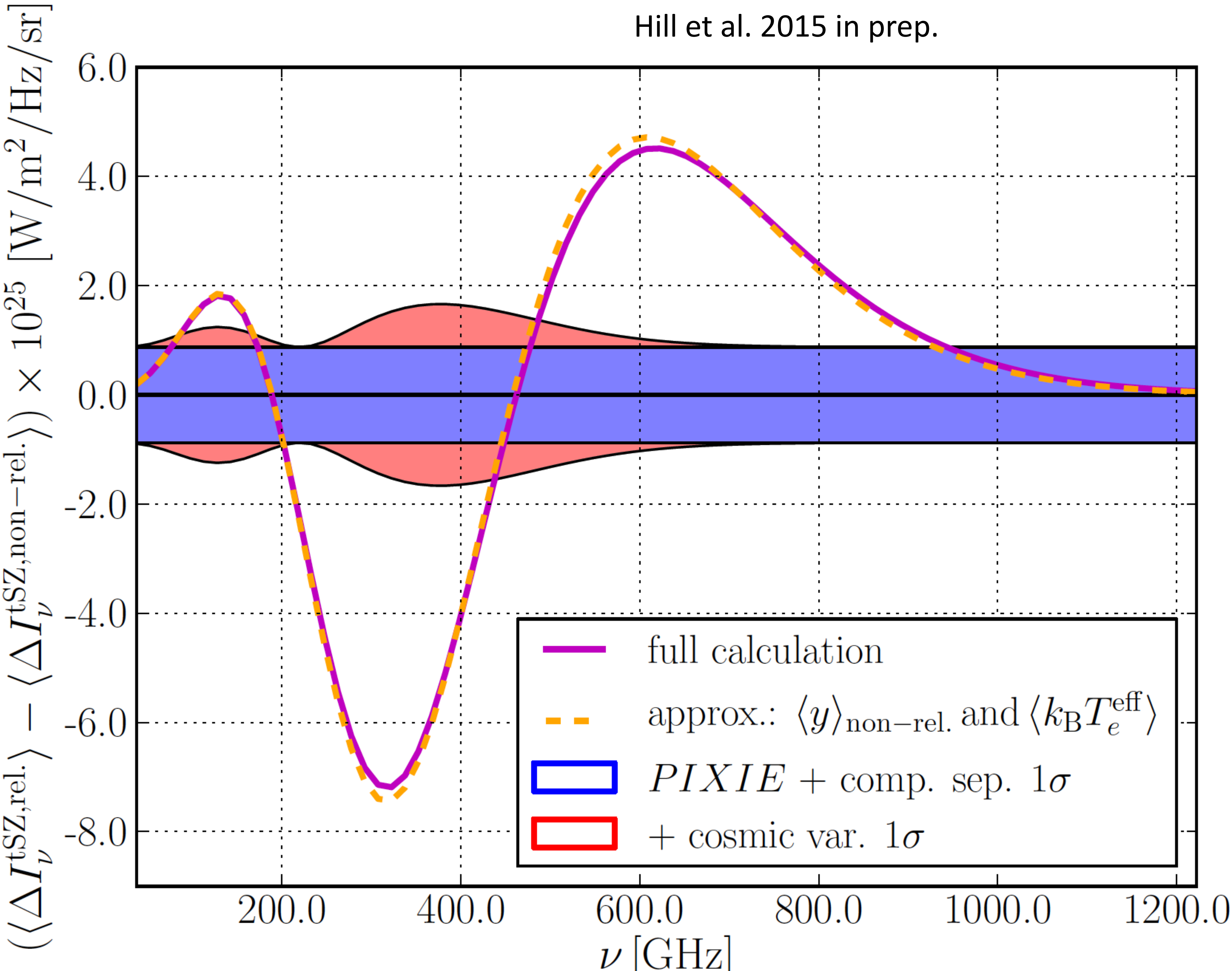
# Contribution to Y from Clusters

$$\langle \Delta I_\nu^{\rm tSZ} \rangle = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} \int d^2\hat{\mathbf{n}}\, \Delta I_\nu^{\rm tSZ}(\hat{\mathbf{n}}, M, z)\,, \tag{4}$$

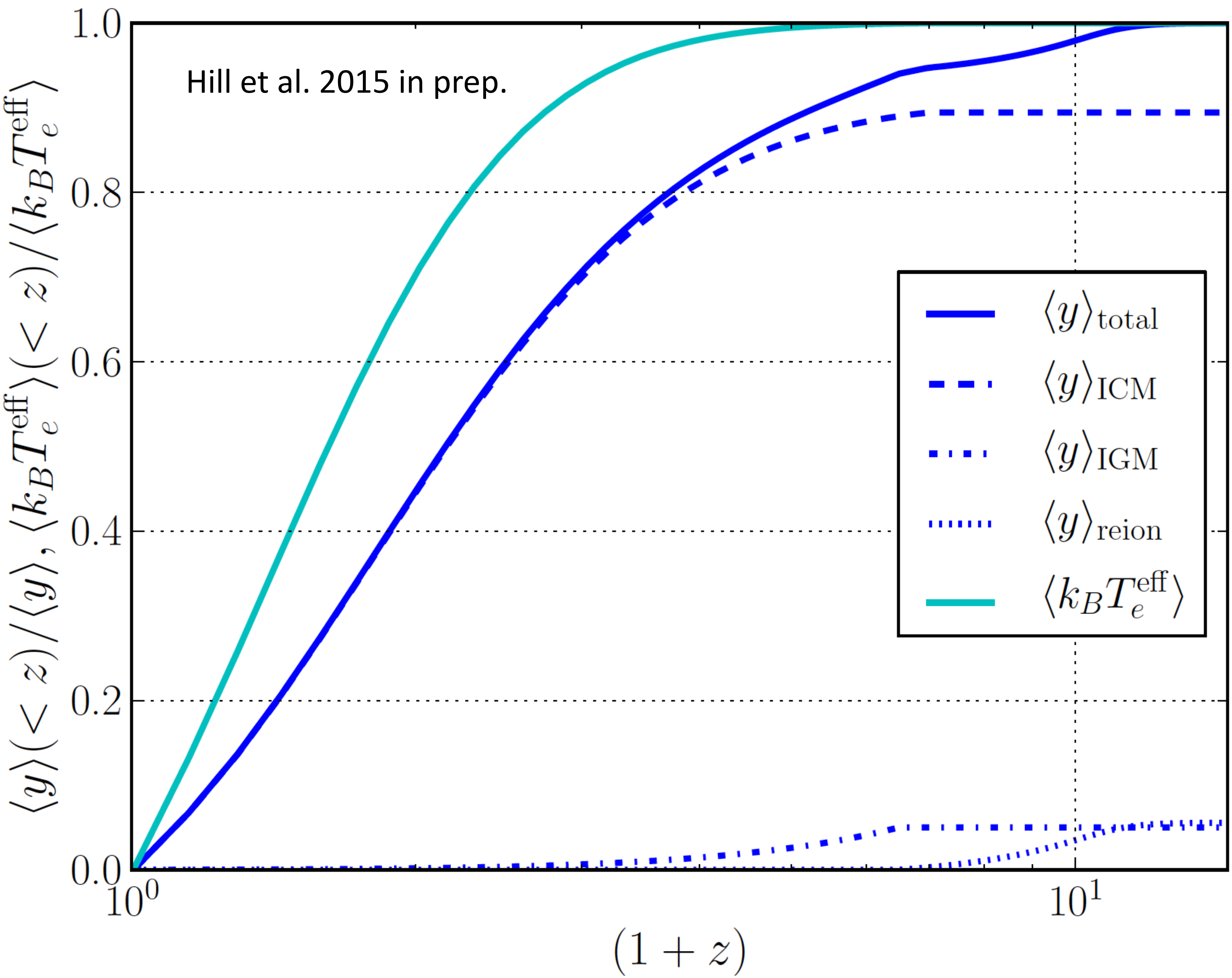
$$\langle k_B T_e^{\rm eff} \rangle \;=\; \frac{1}{\langle y \rangle} \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} \times \int d^2\hat{\mathbf{n}}\, k_B T_e(\hat{\mathbf{n}}, M, z) y(\hat{\mathbf{n}}, M, z)\,,$$

Hill et al. 2015 in prep





Hill et al. 2015 in prep.
$(\langle \Delta I_\nu^{\mathrm{tSZ,rel.}} \rangle - \langle \Delta I_\nu^{\mathrm{tSZ,non-rel.}} \rangle) \times 10^{25}$ [W/m$^2$/Hz/sr]
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
200.0
400.0
600.0
800.0
1000.0
1200.0
$\nu$ [GHz]
full calculation
approx.: $\langle y \rangle_{\mathrm{non-rel.}}$ and $\langle k_B T_e^{\mathrm{eff}} \rangle$
$PIXIE$ + comp. sep. 1$\sigma$
+ cosmic var. 1$\sigma$


Hill et al. 2015 in prep.
$\langle y \rangle(<z)/\langle y \rangle, \langle k_B T_e^{\rm eff} \rangle(<z)/\langle k_B T_e^{\rm eff} \rangle$
$(1+z)$
$10^0$
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0.0
0.2
0.4
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$\langle y \rangle_{\rm total}$
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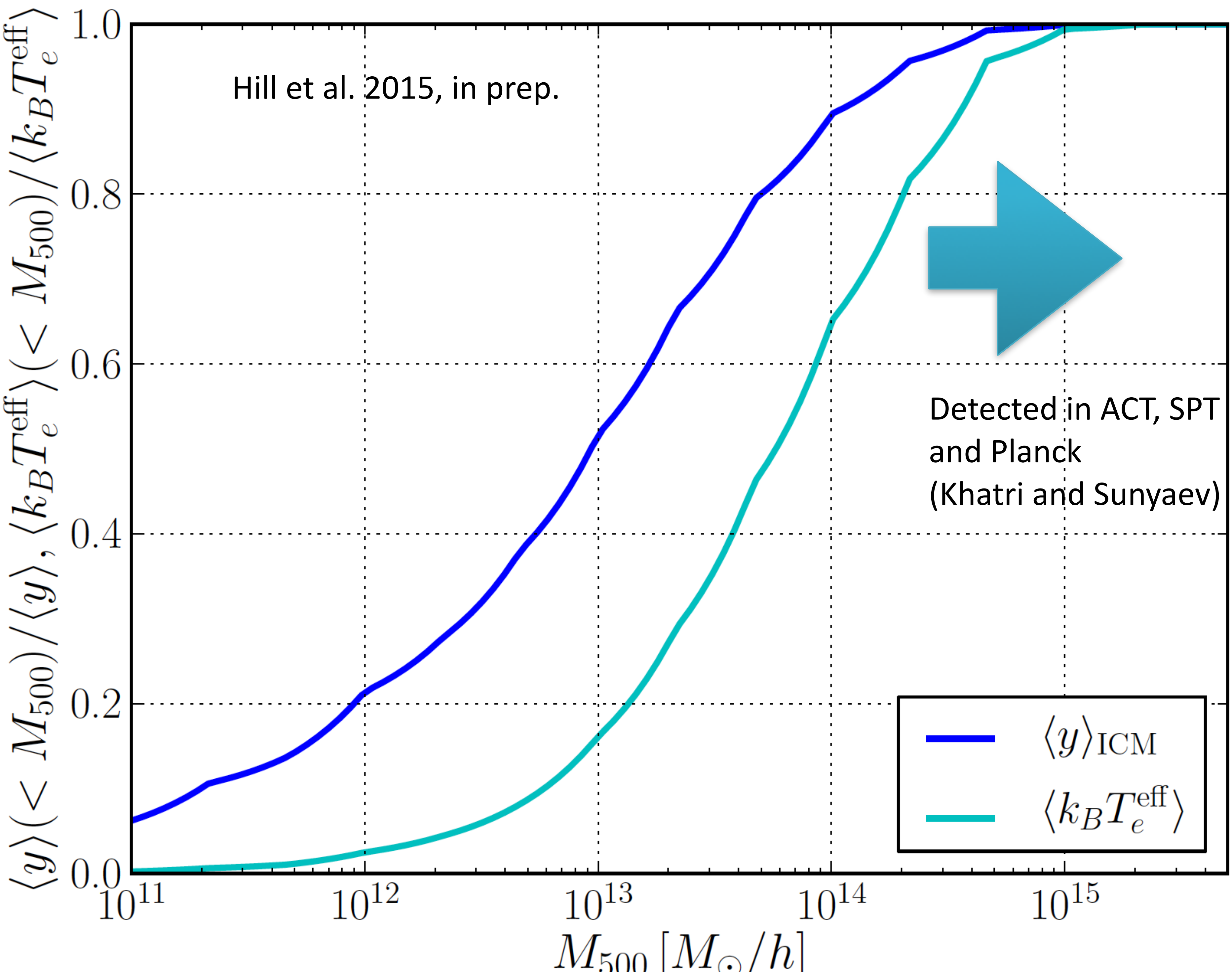
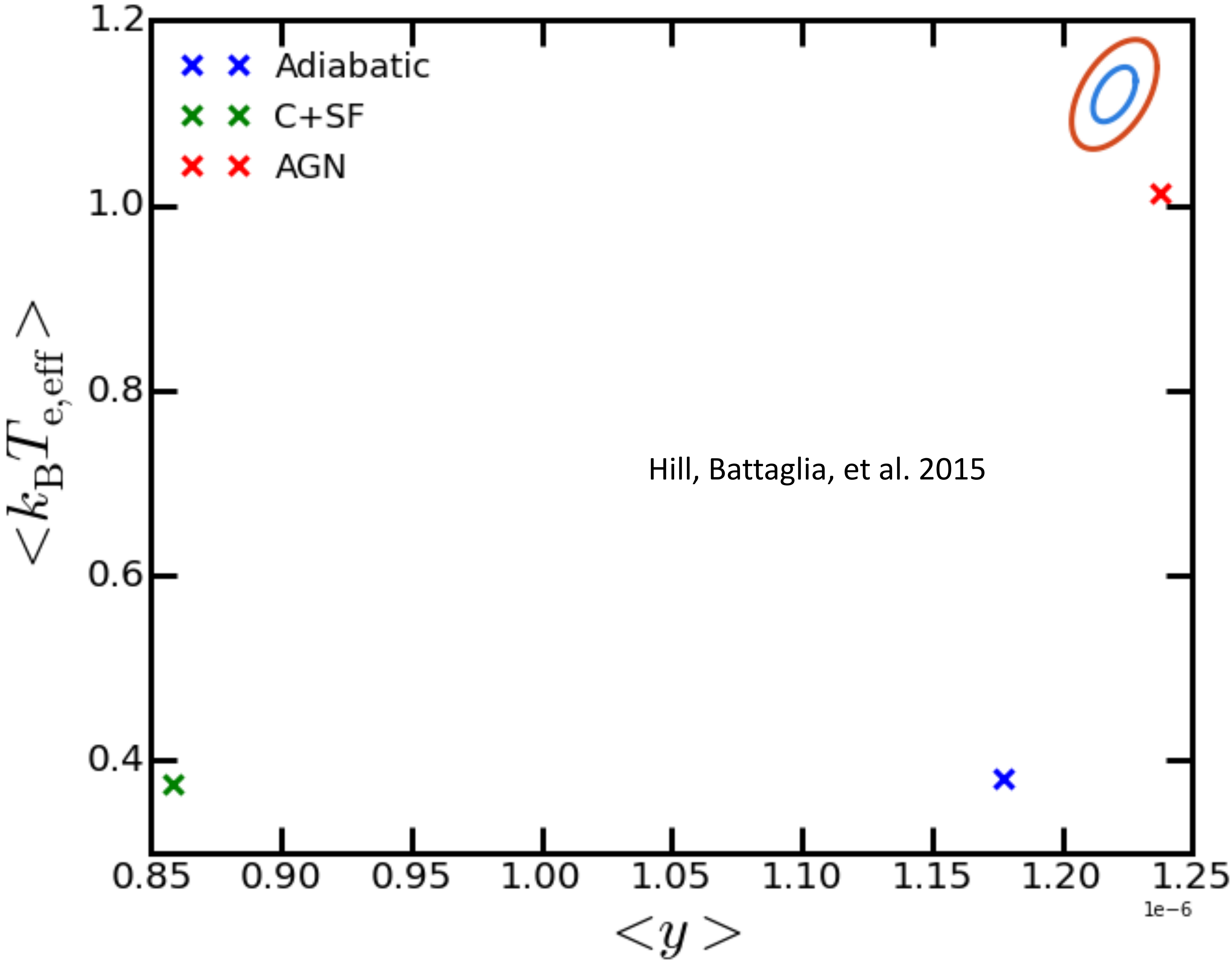
$\langle y \rangle_{\rm IGM}$
$\langle y \rangle_{\rm reion}$
$\langle k_B T_e^{\rm eff} \rangle$

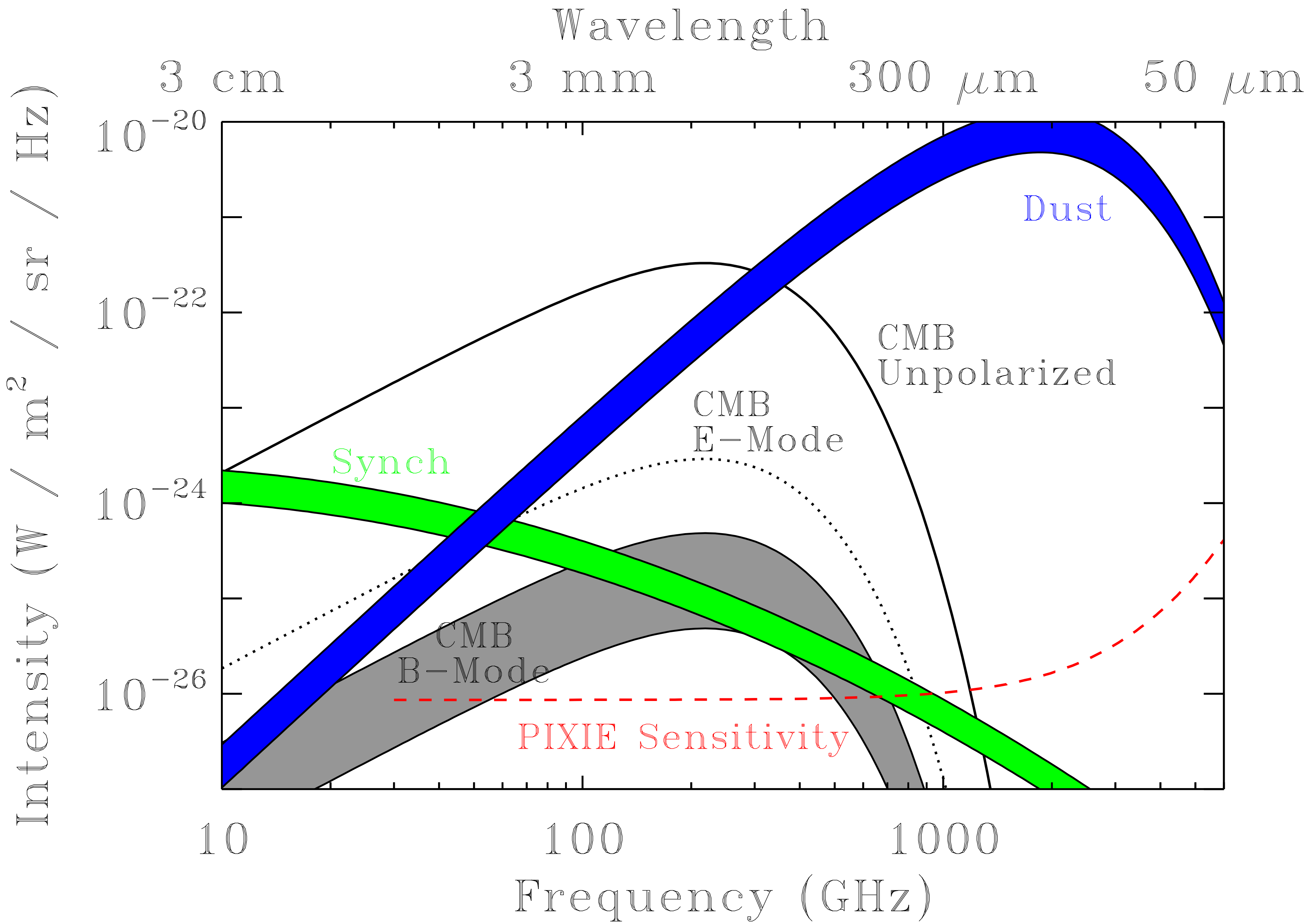


Hill et al. 2015, in prep.
Detected in ACT, SPT
and Planck
(Khatri and Sunyaev)
$\langle y \rangle_{\mathrm{ICM}}$
$\langle k_B T_e^{\mathrm{eff}} \rangle$
$\langle y \rangle (< M_{500}) / \langle y \rangle, \langle k_B T_e^{\mathrm{eff}} \rangle (< M_{500}) / \langle k_B T_e^{\mathrm{eff}} \rangle$
$M_{500} \, [M_{\odot}/h]$
0.0
0.2
0.4
0.6
0.8
1.0
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$
$10^{15}$



Adiabatic
C+SF
AGN
Hill, Battaglia, et al. 2015
1.2
1.0
0.8
0.6
0.4
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
1e−6
$< k_B T_{e,\mathrm{eff}} >$
$< y >$

# Foregrounds scare me!

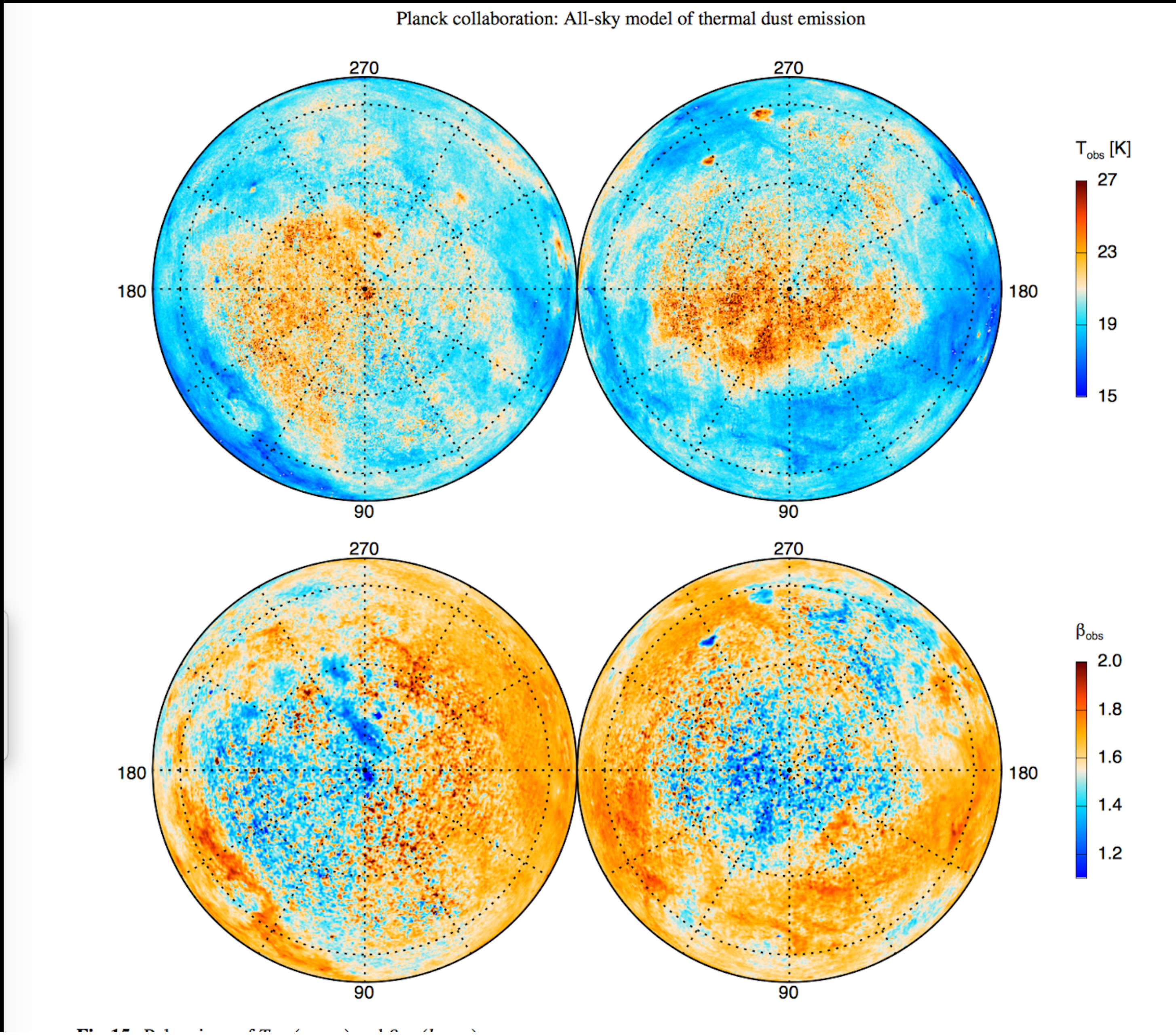


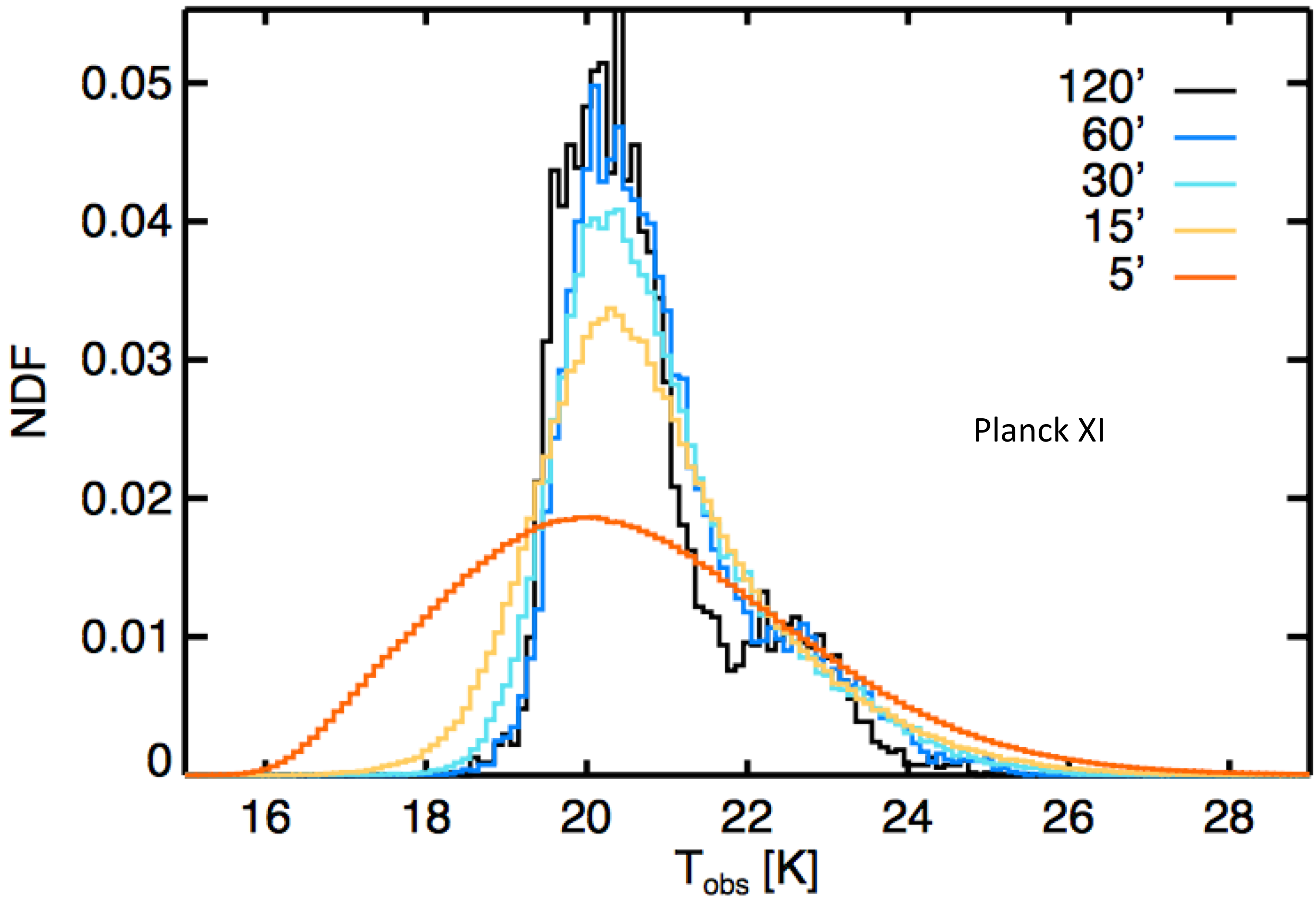
# Dust properties are varying

- Galactic dust temperature is slowly varying as a function of position
- Multiple temperatures along different lines of sight
- CIB amplitude and spectrum are also spatially varying
- Need to fit for $\boldsymbol{\tau}(T_{dust})$ at each position, possibly $\boldsymbol{\tau}(T_{dust,}\beta)$

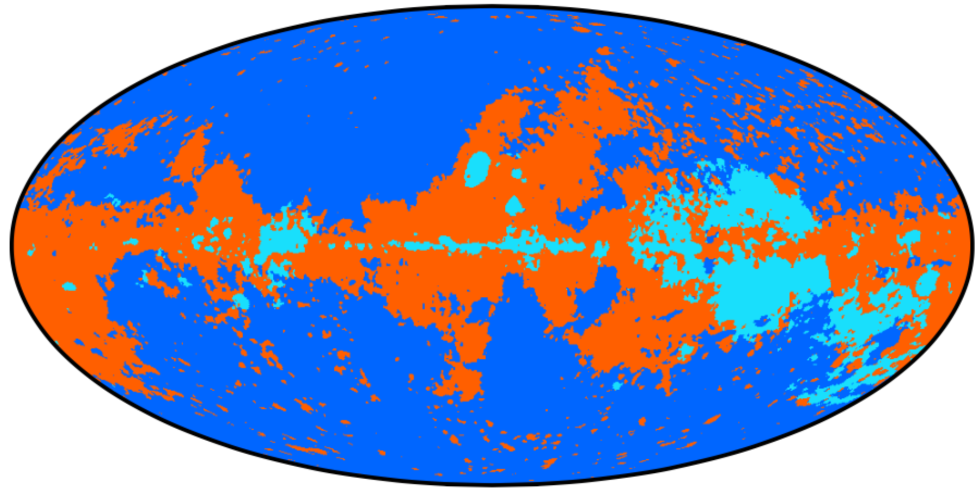
$$I(\nu, \hat{n}) = \int dT_{dust} \tau(T_{dust}, \hat{n}) B_\nu(T_{dust})$$

# Planck dust temperature map

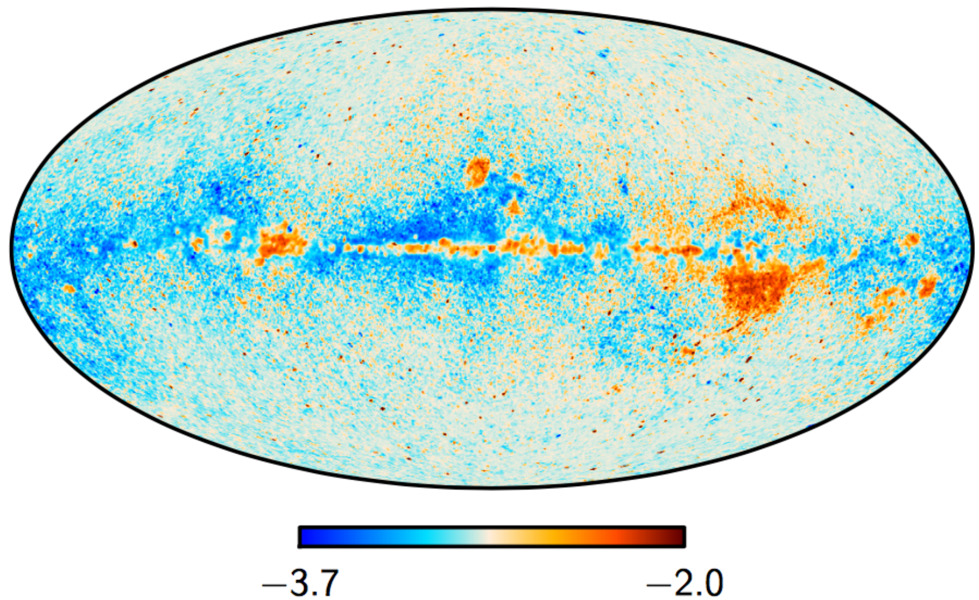



0.05
0.04
0.03
0.02
0.01
0
NDF
16
18
20
22
24
26
28
$T_{obs}$ [K]
120'
60'
30'
15'
5'
Planck XI

# Synch + Spinning Dust



(a) Dominant low-frequency component map



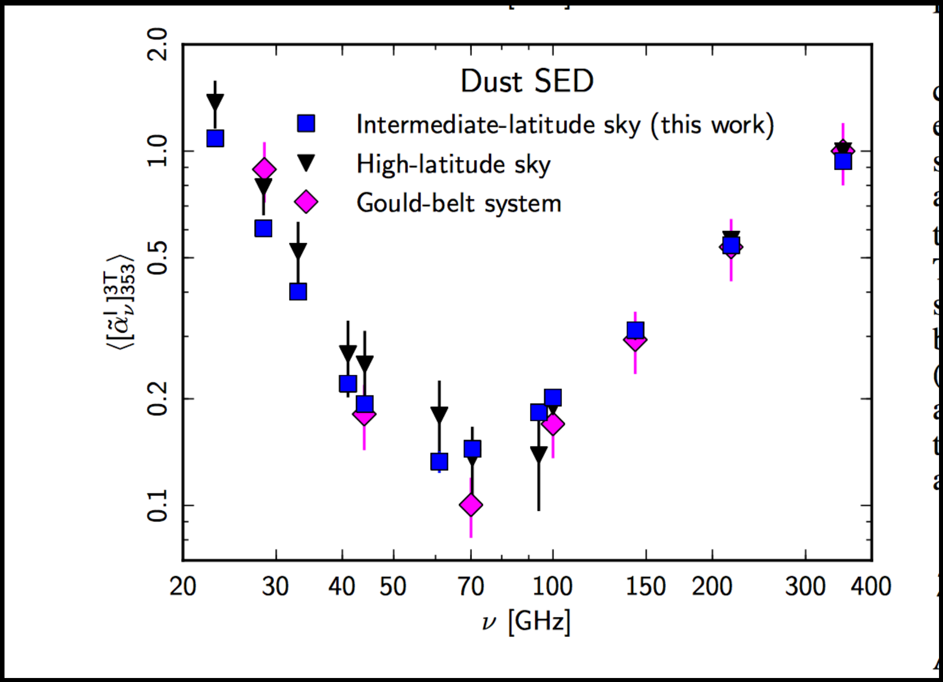

(b) Low-frequency component power-law index

**Fig. 23.** *Top*: dominant foreground component per pixel at 30 GHz in the FFP6 simulation. Dark blue indicates that synchrotron emission is the strongest component at 30 GHz, light blue indicates that free-free dominates, and orange indicates that spinning dust (AME) is the strongest component. *Bottom*: the recovered low-frequency power-law index derived from the same simulation.

Planck 2013 X

# More worries

- Spatial variations in synch. spectral index
- Spatial variations in synch-dust cross-correlations
- Spinning dust, magnetized dust
- Spatial variations in extragalactic line emission
- Need more study!




Planck XXII

# Conclusions

- Photon spectrum records the energy input history of the universe since z ~2,000,000
- mu distortions probe the power spectrum on scales far below CMB
- z< 2 groups and clusters will likely be the dominant source of y distortions
- PIXIE measurements of relativistic distortion should be very sensitive to energy input to clusters and baryon feedback
- Foregrounds are hard