CMB Spectral Distortion Science

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CMB Probe Executive Committee Telecon
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Outline

- Review:
  - Theory of spectral distortions
  - Current constraints
- Signals:
  - Compton-y (and more)
  - μ
  - Beyond y and μ

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Theory of Spectral Distortions

Thermal History of Universe — Key Epochs

- $z >> 10^6$: efficient Comptonization + production of low-frequency photons by double-Compton + brem.

→ injection only changes temperature-time relation — produces unobservable change in mean T_{CMB}

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- $5 \times 10^4 < z < 2 \times 10^6$: double-Compton not efficient, but (elastic) Compton scattering is; equilibrium can be achieved but with conserved photon number

→ injection produces μ-type distortion

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- $5 \times 10^4 < z < 2 \times 10^6$: double-Compton not efficient, but (elastic) Compton scattering is; equilibrium can be achieved but with conserved photon number

→ injection produces μ-type distortion

- $z < 5 \times 10^4$: Compton scattering not efficient; photons fall out of kinetic equilibrium with electrons

→ injection produces y-type distortion

Time 380,000 years 7,000 years 8 years 2 months

Photon energy

Distortion Signal

scattering inefficient

218 GHz

y ~ 1/4 Δρ/ρ

y-distortion

Photon energy

intermediate regime

y+μ+residual distortion

Photon energy

scattering efficient

125 GHz

μ ~ 1.4 Δρ/ρ

μ-distortion

Photon energy

full thermalization

Maximum of
CMB blackbody

temperature shift

Last Scattering Surface

Hydrogen lines

Neutral Helium lines

Ionized Helium lines

cold dilute

Recombination signal

Maximum of
CMB blackbody

Distortion ≃10^{-7}-10^{-6}
relative to blackbody

Paschen-α

Balmer-α

Lyman-α

33%

4%

0.2%

0.003%

hot dense

Recombination era

time-dependent information

Distortion visibility

Blackbody era

10^3 10^4 3×10^5 2×10^6 5×10^6 Redshift

Chluba+ (2012)

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Theory of Spectral Distortions

What processes can inject (or remove) energy?

- Electron-positron annihilation ($z \sim 10^8$ - 10^9): too early

- Adiabatically expanding ordinary matter
  - non-relativistic matter redshifts as $T_e \sim (1+z)^2$
  - since $T_{CMB} \sim (1+z)$, electrons "Compton cool" CMB until $z \sim 150$
  - due to large heat capacity of CMB, small effect: **$\mu \sim -2 \times 10^{-9}$**

- Heating by decaying/annihilating particles + exotic sources

Sunyaev, Zel'dovich, Danese, de Zotti, Hu, Silk,

Chluba, Daly, many others

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- Dissipation of primordial acoustic modes: **prediction of standard cosmological model (positive μ and y distortions)**

Sunyaev, Zel'dovich, Danese, de Zotti, Hu, Silk,

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- Dissipation of primordial acoustic modes: **prediction of standard cosmological model (positive μ and y distortions)**

- Thermal SZ Effect from groups+clusters, intergalactic medium, reionization: **prediction of standard cosmological model (positive y distortion)**

Sunyaev, Zel'dovich, Danese, de Zotti, Hu, Silk,

Chluba, Daly, many others

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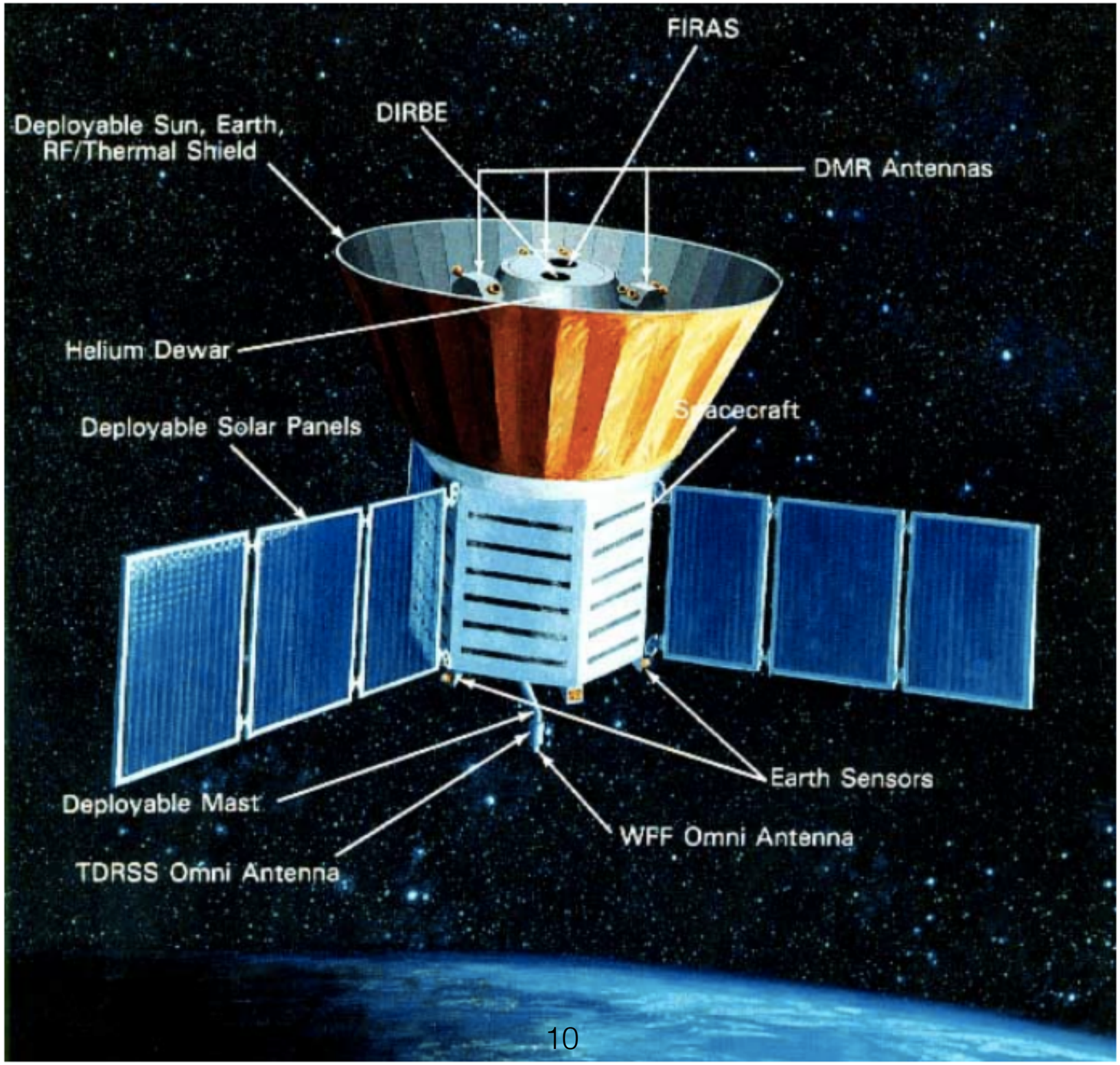
State of the Field

FIRAS

launched
1989



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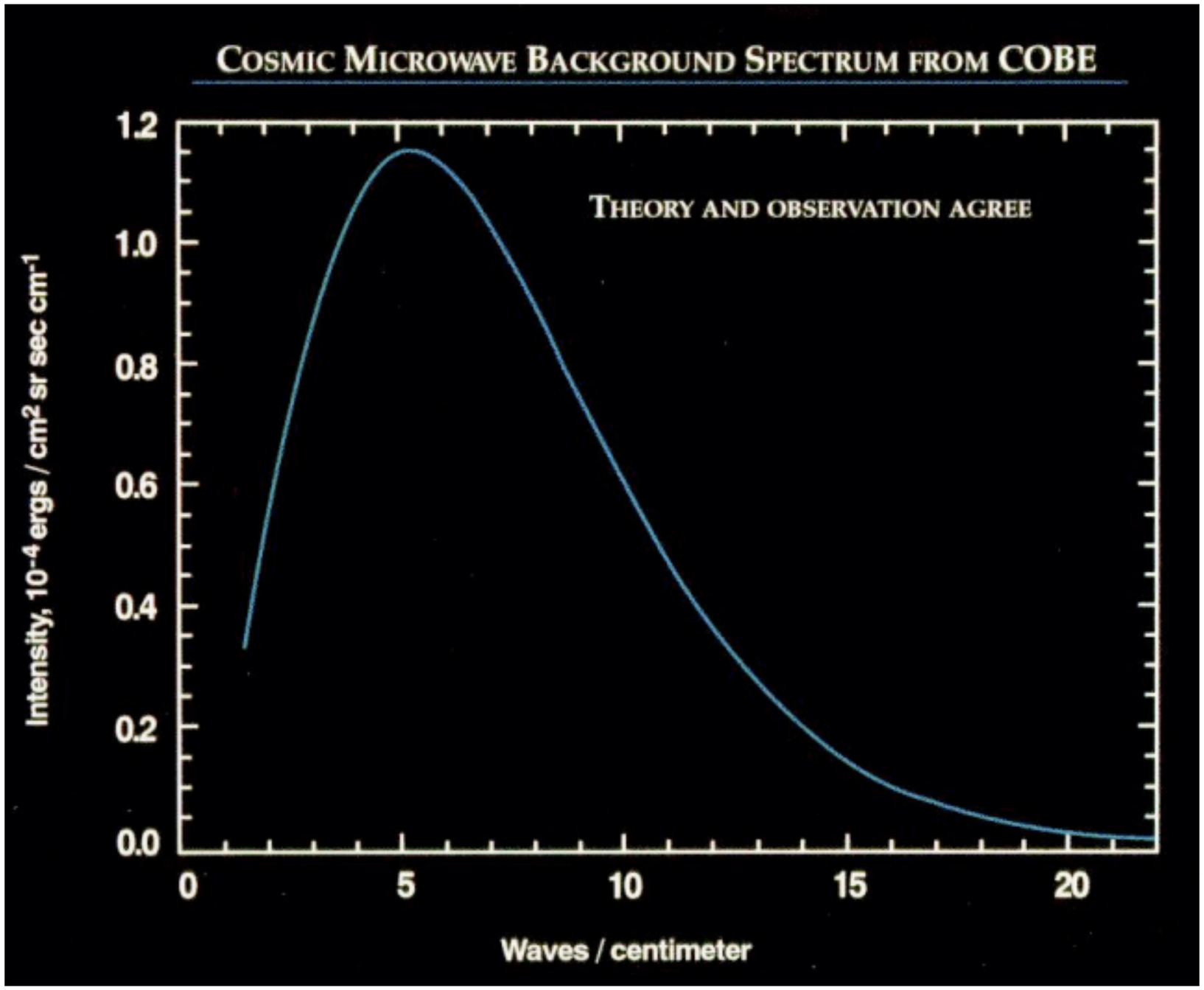
State of the Field

CMB spectrum is blackbody to 50 ppm precision

T = 2.72548 +/- 0.00057 K



Fixsen+ (1996); Fixsen (2009)

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State of the Field
FIRAS

- $|y| < 1.5 \times 10^{-5}$ at 95% CL
- $|\mu| < 9 \times 10^{-5}$ at 95% CL
- Dipole spectrum ~ dP/dT (also using FIRAS+WMAP)
- Absolute CIB spectrum
- Absolute Zodiacal light spectrum
- Map of major Galactic emission lines

Fixsen+ (1996) + more

Signals: Mean y Distortion

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Signals: Mean y Distortion

Groups and clusters dominate ("foreground"/signal!)

- **Groups and clusters: $y \sim 1.6 \times 10^{-6}$** [JCH+ 2015]
- IGM: $y \sim 10^{-7}$ [JCH+ 2015; Battaglia, JCH+ (to appear)]
- Reionization: $y \sim 10^{-7}$ [JCH+ 2015; Battaglia, JCH+ (to appear)]
- Small-scale CMB T fluctuations: $y \sim 8 \times 10^{-10}$ [Chluba & Sunyaev 2004]
- Damping of acoustic modes: $y \sim 4 \times 10^{-9}$ [Chluba+ 2012]
- Local Group: $y \sim 5 \times 10^{-9}$ [e.g. Khatri & Sunyaev 2015]

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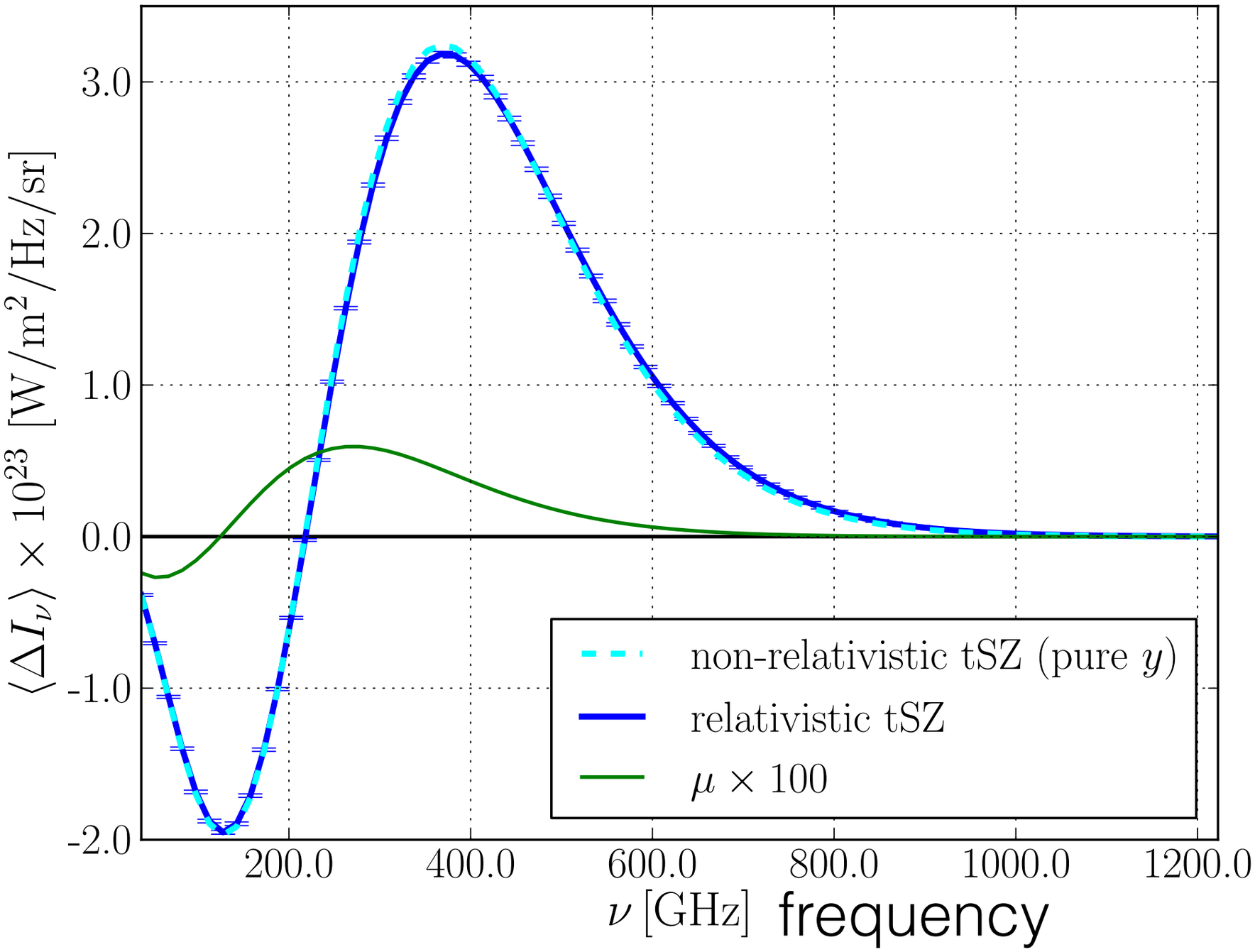
A guaranteed signal

PIXIE: ~1000σ detection of global tSZ signal (stat. err. only)



JCH+ (2015)

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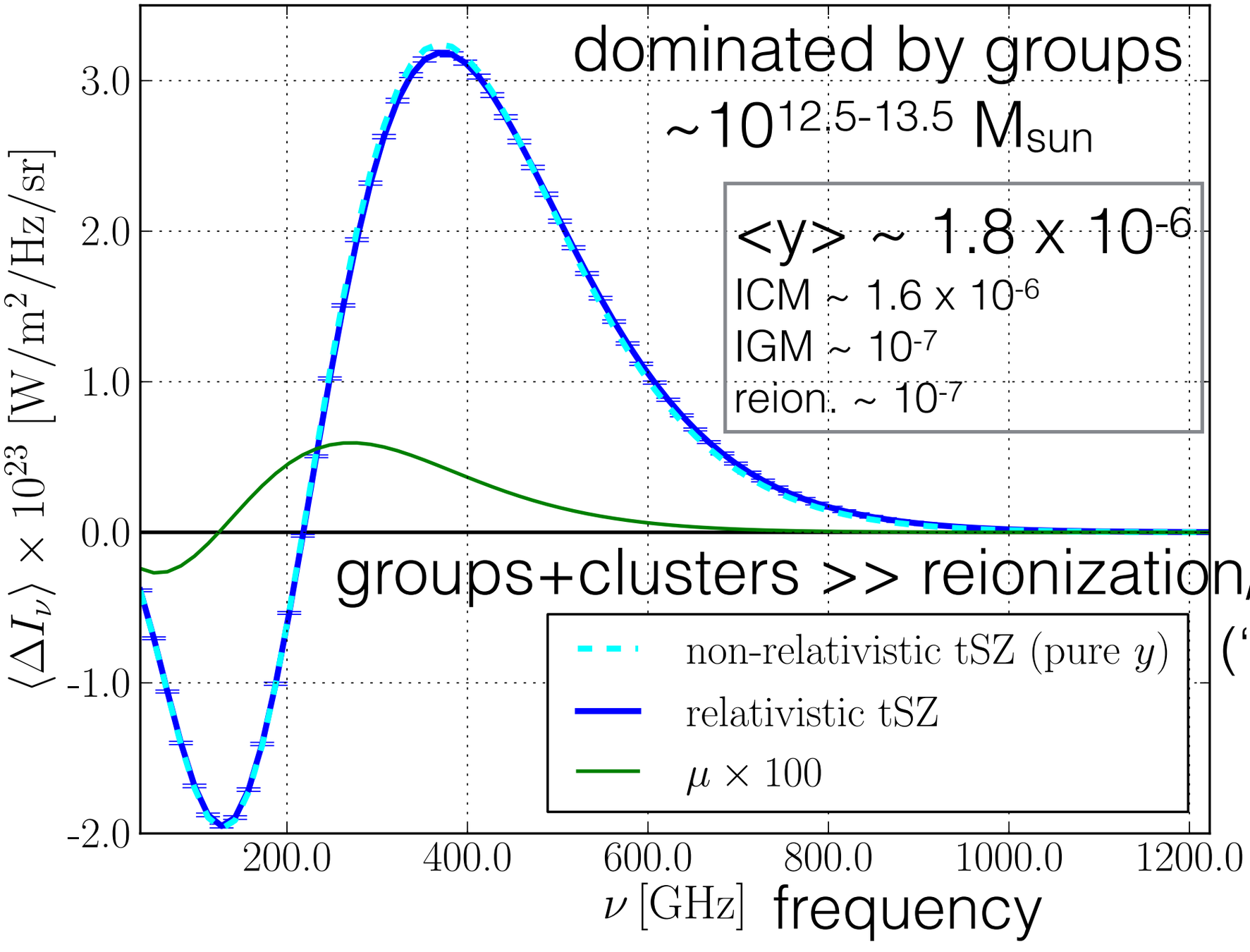
A guaranteed signal

PIXIE: ~1000σ detection of global tSZ signal (stat. err. only)

specific intensity



JCH+ (2015); see also Dolag+ (2015) & de Zotti+ 16 (2016)

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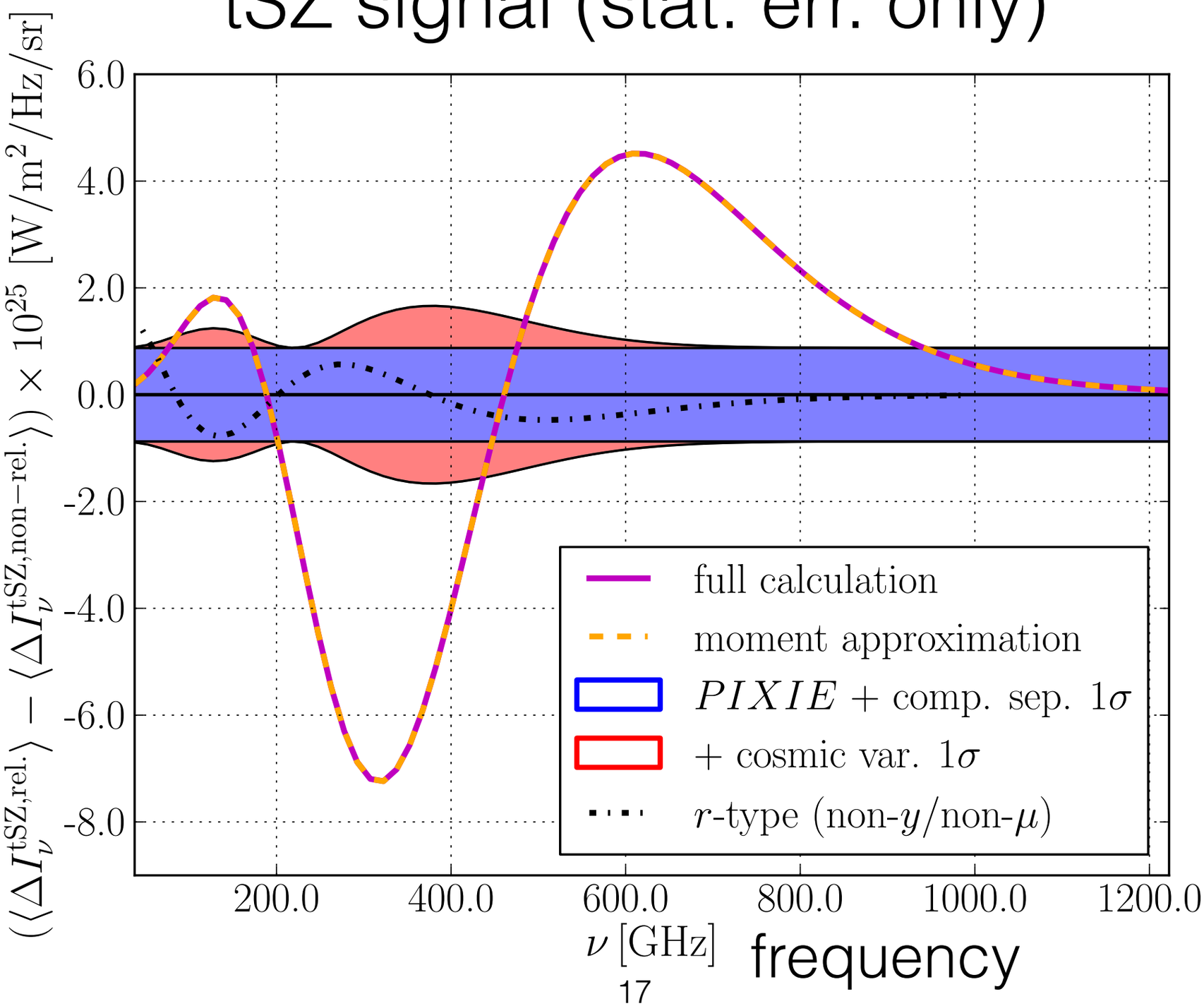
Guaranteed signalS

PIXIE: ~30σ detection of relativistic effects in global tSZ signal (stat. err. only)

specific intensity



JCH+ (2015)

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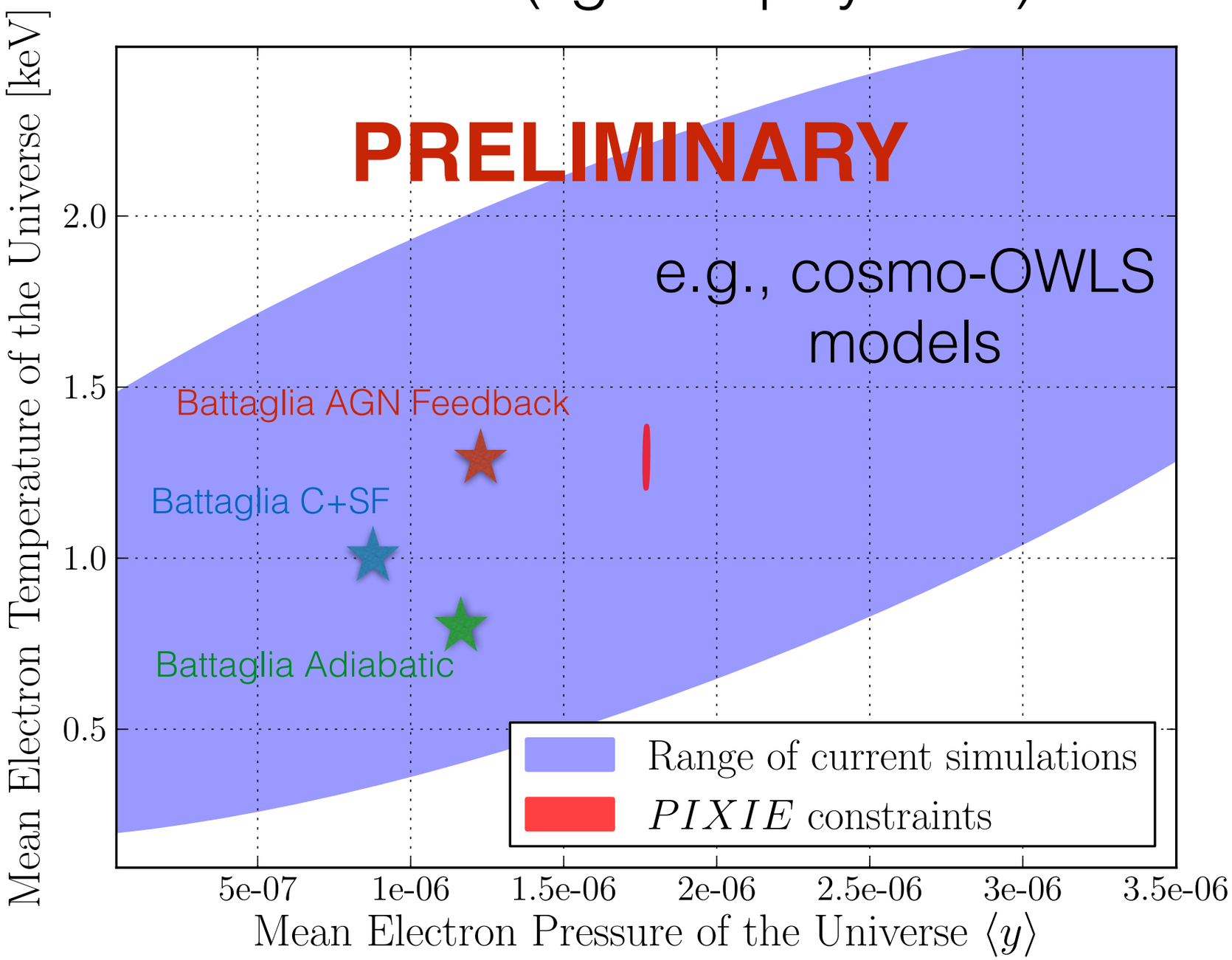
What will we learn?

sub-percent constraints on models of baryonic structure formation ("gastrophysics")

mean y-weighted electron temp. in the Universe



mean gas pressure in the Universe

Battaglia, JCH+ (in prep.)

What will we learn?

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- Measurement of total thermal energy in electrons

$$\langle y \rangle = \frac{\sigma_{\rm T}}{m_{\rm e}c^2} \int \frac{d^2\hat{\mathbf{n}}}{4\pi} \int dl P_{\rm e}(\hat{\mathbf{n}}, l) \propto E_{\rm e}^{\rm th,tot}$$

- "Integral constraint" on feedback energy injected over cosmic time (analogous to τ for reionization)

$$E_{\rm e}^{\rm th,tot} = E_{\rm e}^{\rm coll} - E_{\rm e}^{\rm cool} + E_{\rm e}^{\rm inj}$$

JCH+ (2015); Battaglia, JCH+ (to appear)

What will we learn?

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$$E_{\rm e}^{\rm th,tot} = E_{\rm e}^{\rm coll} - E_{\rm e}^{\rm cool} + E_{\rm e}^{\rm inj}$$

- Crucial ingredient for understanding baryonic effects on matter power spectrum (necessary for e.g. upcoming weak lensing surveys)

- Calibration of X-ray T—M relation with relativistic effects

- After low-z contributions are isolated via cross-correlations with tracer samples, new reionization constraints

JCH+ (2015); Battaglia, JCH+ (to appear)

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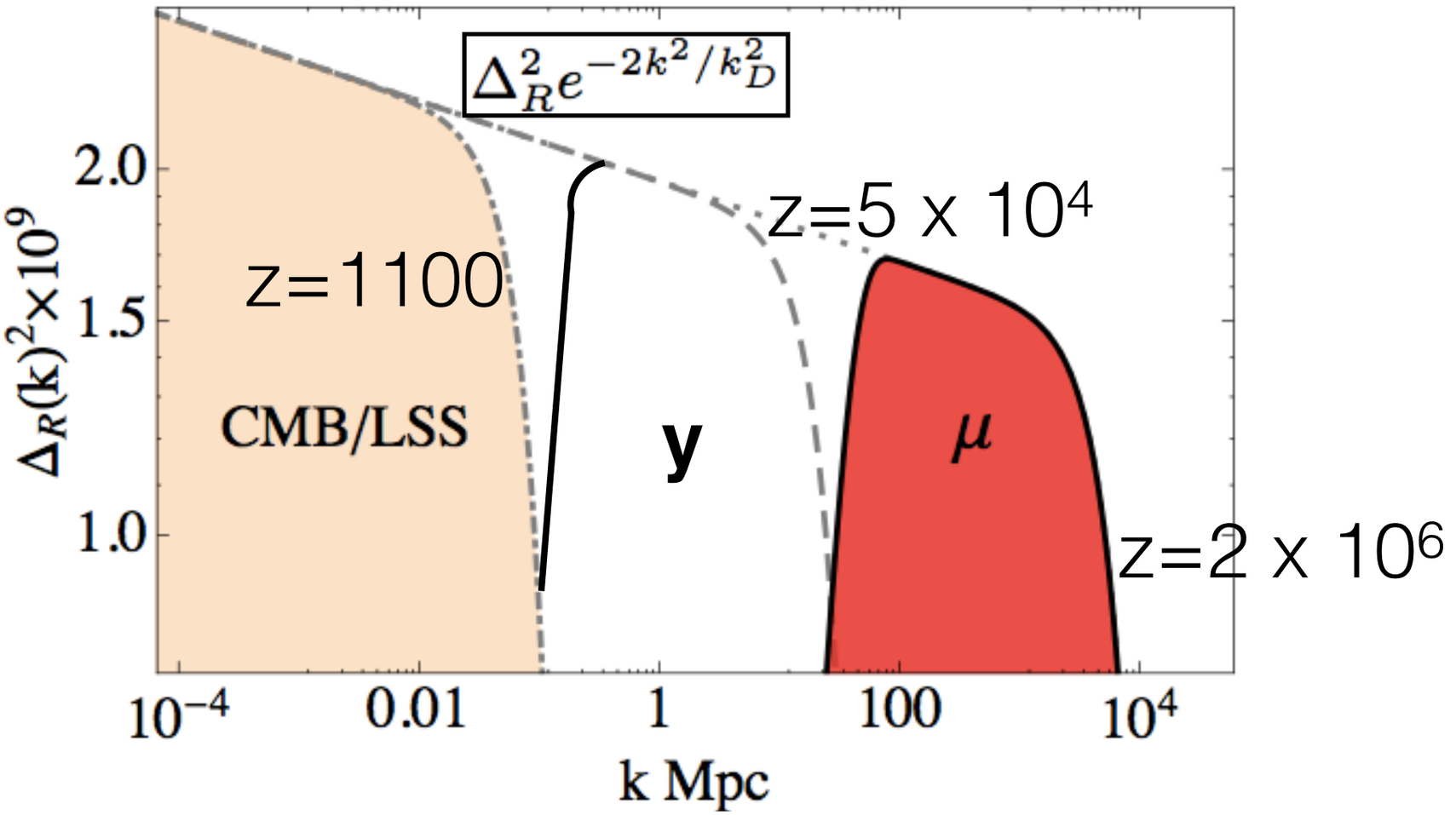
Signals: Dissipation of Acoustic Modes



$$\langle \mu \rangle \approx \int \mathrm{d}\log k\, \Delta^2_{\mathcal{R}}(k) W_\mu(k) \qquad \langle y \rangle \approx \int \mathrm{d}\log k\, \Delta^2_{\mathcal{R}}(k) W_y(k)$$

Probe of primordial power on extremely small scales
(50 h/Mpc < k < 10^4 h/Mpc)

Pajer & Zaldarriaga (2012); Chluba+ (2012); Emami+ (2015)

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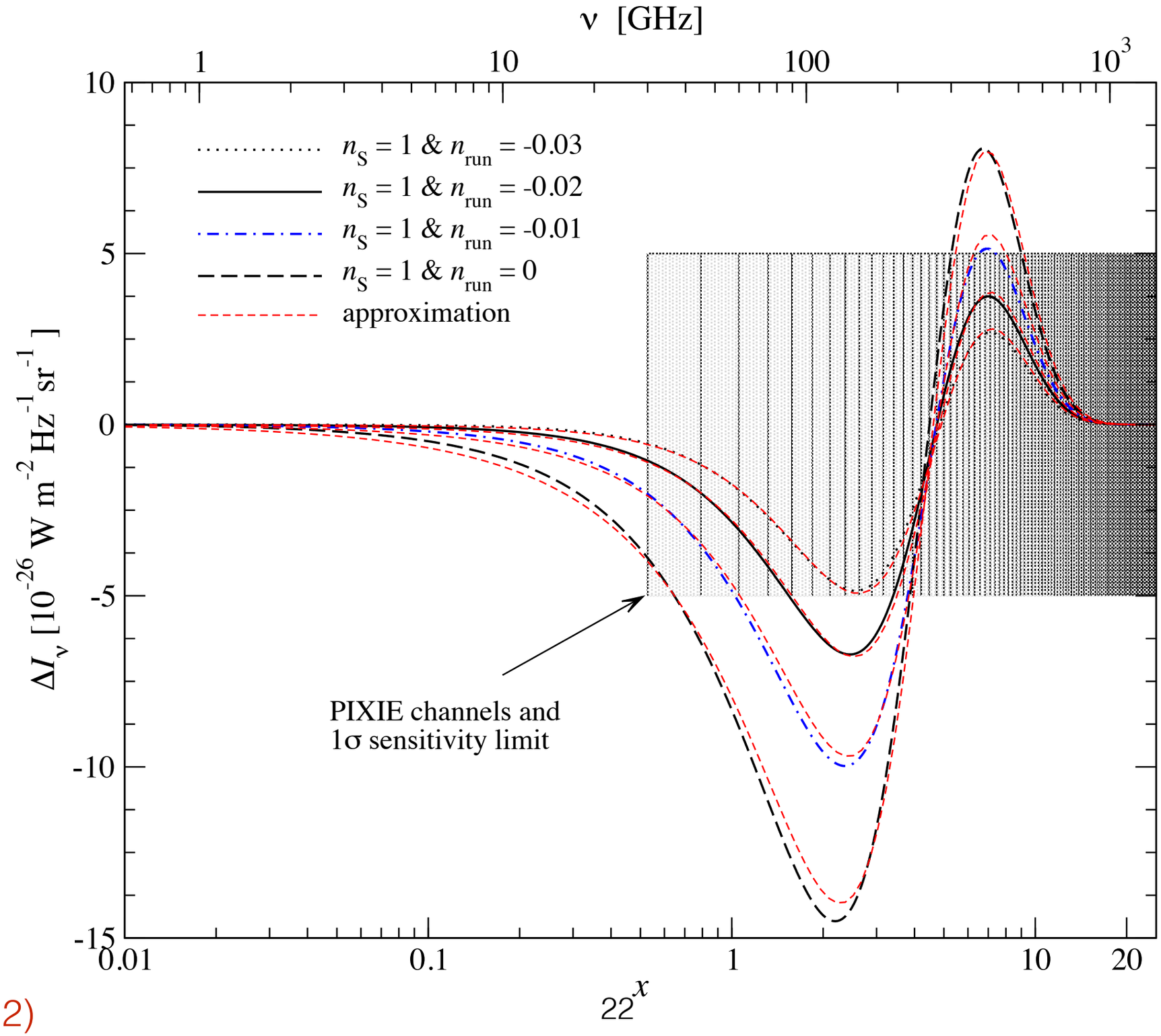
Dissipation of Acoustic Modes

Distortion signal depends on n_s, $n_{run}=dn_s/d\ln k$, …



Chluba+ (2012)

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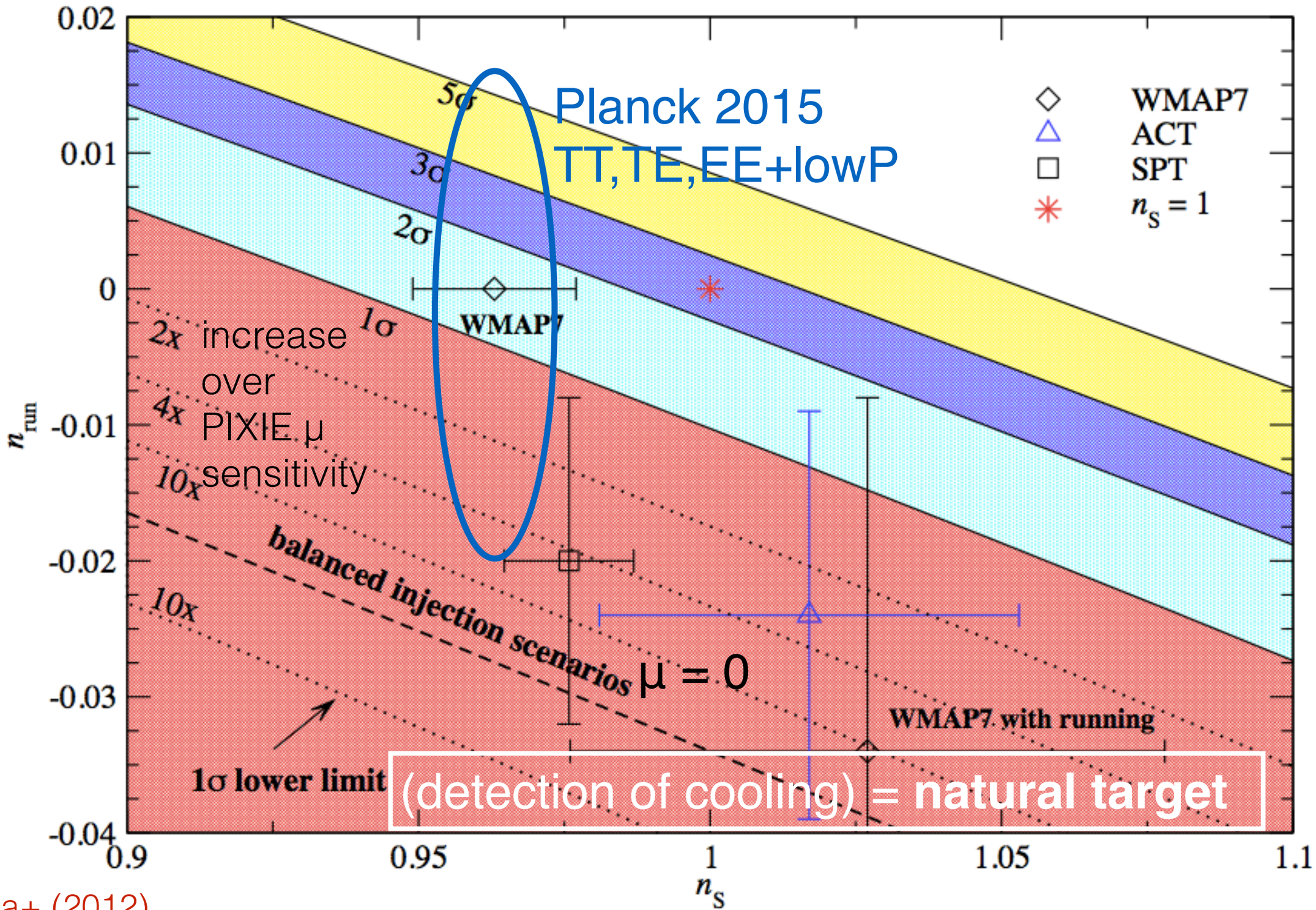
Dissipation of Acoustic Modes

PIXIE forecasted constraints from primordial μ



Chluba+ (2012)

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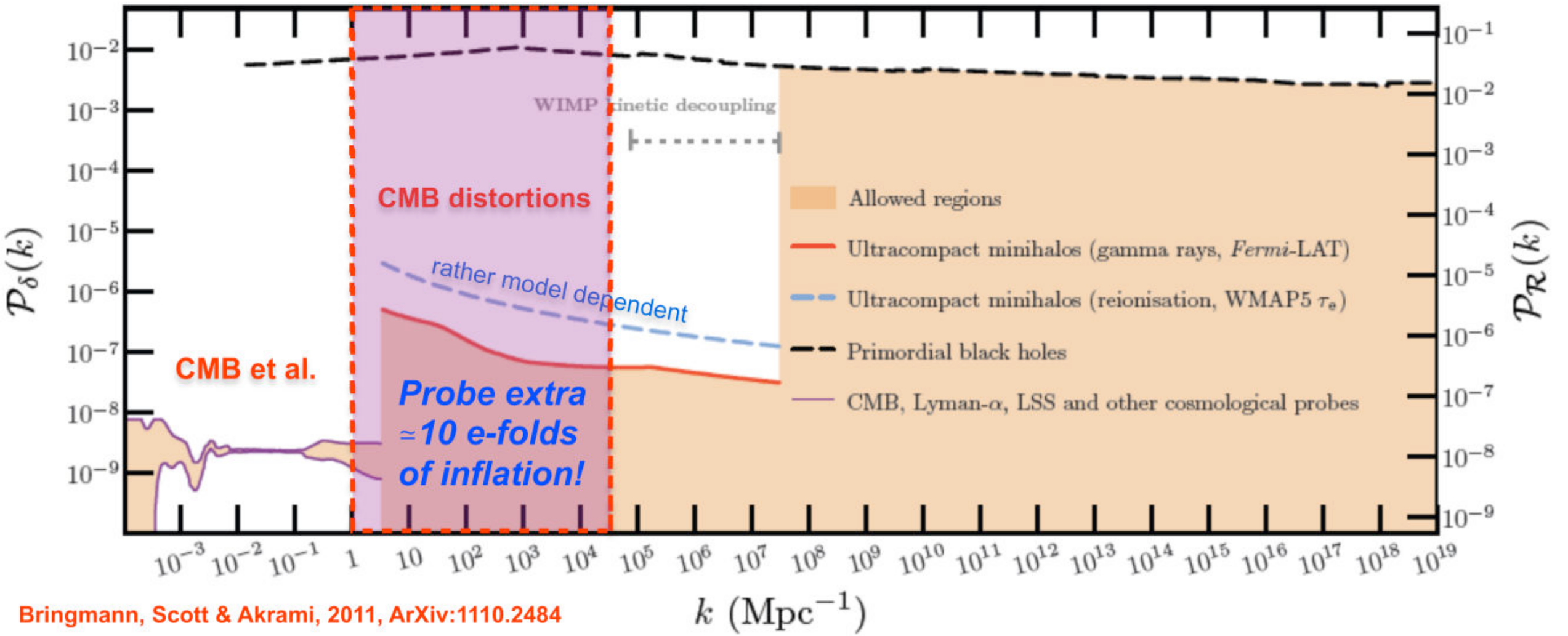
Dissipation of Acoustic Modes



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

Increase from ~7 to ~17 in number of inflationary e-foldings probed by cosmologists!
Probe power spectrum at M_{sun} scales!

+Chluba

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Dissipation of Acoustic Modes

Also a sensitive probe of small-scale non-Gaussianity

- μT correlation probes the very-squeezed limit of the primordial bispectrum (yT perhaps also possible)

- CV limit: $f_{NL} \sim 10^{-3}$ (compared to ~5 for TTT)

- For PIXIE, large f_{NL} on small scales would be necessary for a detection:

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

$$\downarrow$$

$$\sim 1$$

- But we are probing an entirely new regime!

Pajer & Zaldarriaga (2012)

Example: *PIXIE*

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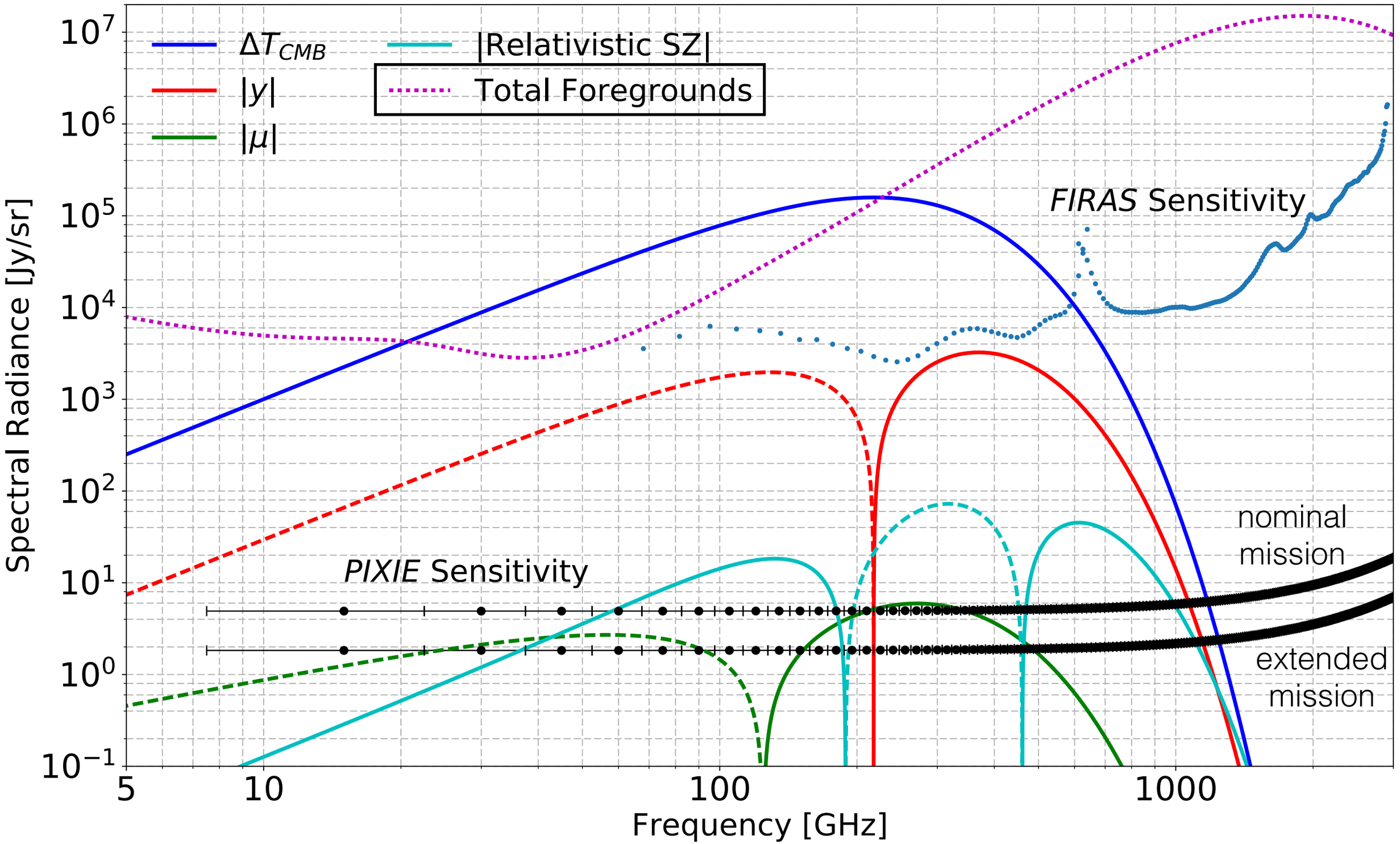

Abitbol, Chluba, **JCH**, and Johnson (2017)

Example: *PIXIE*

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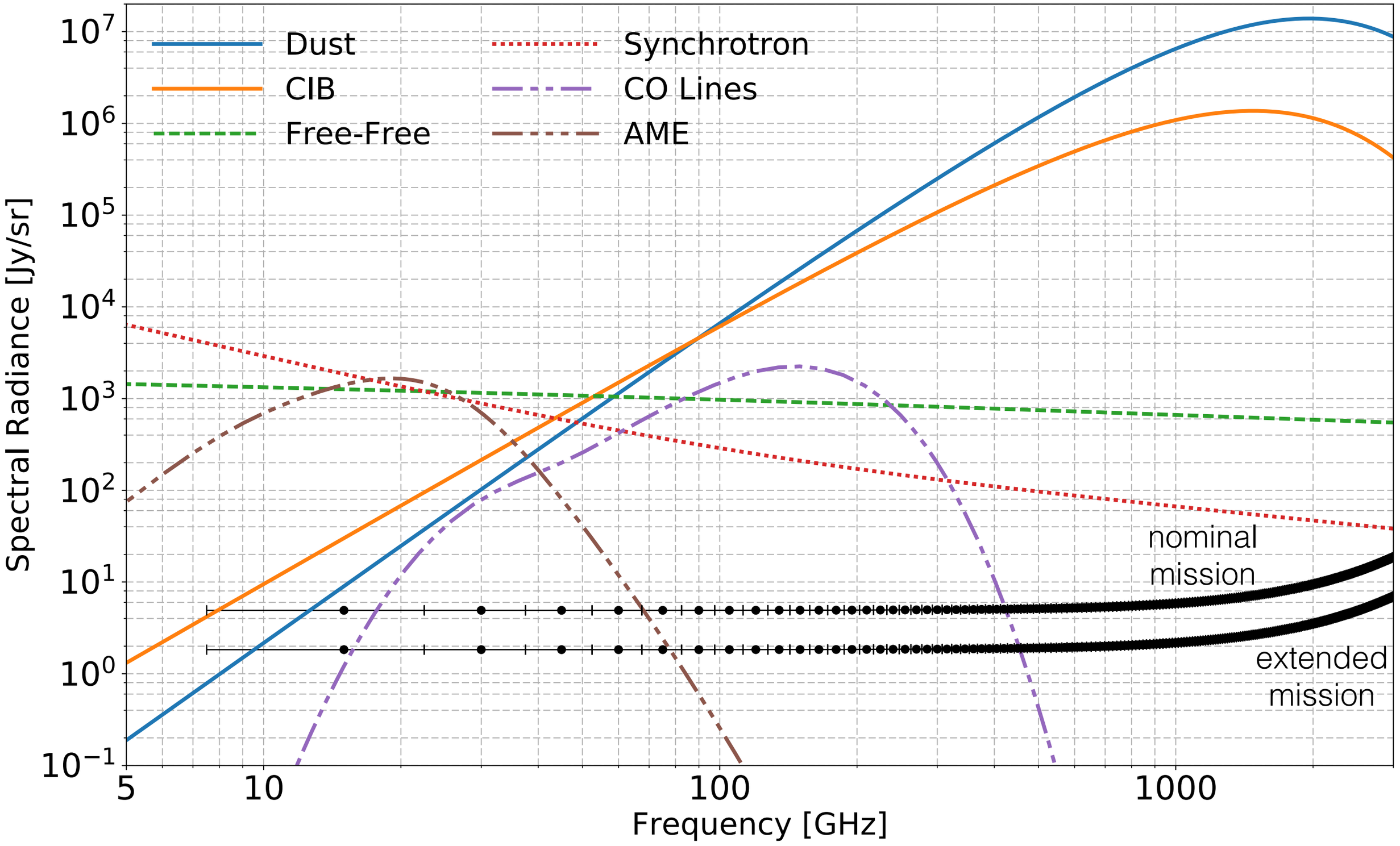

Abitbol, Chluba, **JCH**, and Johnson (2017)

PIXIE Forecasts

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first spectral distortion forecasts with full foreground model

Foreground	Spectral Radiance [Jy/sr]	Free Parameters and Values	Additional Information
Thermal Dust	$x = \frac{h\nu}{kT_{\rm D}}$ $\Delta I_{\rm D}(\nu) = A_{\rm D}\, x^{\beta_{\rm D}}\, \frac{x^3}{e^x-1}$	$A_{\rm D} = 1.36 \times 10^6$ Jy/sr $\beta_{\rm D} = 1.53$ $T_{\rm D} = 21$ K	$\Delta I_{\rm D}(\nu_r) = 6,608$ Jy/sr
CIB	$x = \frac{h\nu}{kT_{\rm CIB}}$ $\Delta I_{\rm CIB}(\nu) = A_{\rm CIB}\, x^{\beta_{\rm CIB}}\, \frac{x^3}{e^x-1}$	$A_{\rm CIB} = 3.46 \times 10^5$ Jy/sr $\beta_{\rm CIB} = 0.86$ $T_{\rm CIB} = 18.8$ K	$\Delta I_{\rm CIB}(\nu_r) = 6,117$ Jy/sr
Synchrotron	$\Delta I_{\rm S}(\nu) = A_{\rm S} \left(\frac{\nu}{\nu_0}\right)^{\alpha_{\rm S}} \left[1 + \frac{1}{2}\omega_{\rm S} \ln^2\left(\frac{\nu}{\nu_0}\right)\right]$	$A_{\rm S} = 288.0$ Jy/sr $\alpha_{\rm S} = -0.82$ $\omega_{\rm S} = 0.2$	$\Delta I_{\rm S}(\nu_r) = 288$ Jy/sr 10% prior assumed on $A_{\rm S}$ and $\alpha_{\rm S}$ $\nu_0 = 100$ GHz
Free-Free	$\nu_{\rm ff} = \nu_{\rm FF}\,(T_{\rm e}/10^3\ {\rm K})^{3/2}$ $\Delta I_{\rm FF}(\nu) = A_{\rm FF}\left(1 + \ln\left[1 + \left(\frac{\nu_{\rm ff}}{\nu}\right)^{\sqrt{3}/\pi}\right]\right)$	$A_{\rm FF} = 300$ Jy/sr	$\Delta I_{\rm FF}(\nu_r) = 972$ Jy/sr $\{T_{\rm e}, \nu_{\rm FF}\} = \{7000\ {\rm K}, 255.33\ {\rm GHz}\}$
Integrated CO	$\Theta_{\rm CO}(\nu) = {\rm CO\ template}(\nu)$ $\Delta I_{\rm CO}(\nu) = A_{\rm CO}\Theta_{\rm CO}(\nu)$	$A_{\rm CO} = 1$	$\Delta I_{\rm CO}(\nu_r) = 1,477$ Jy/sr Template in Jy/sr
Spinning Dust	$\Theta_{\rm SD}(\nu) = {\rm SD\ template}(\nu)$ $\Delta I_{\rm SD}(\nu) = A_{\rm SD}\Theta_{\rm SD}(\nu)$	$A_{\rm SD} = 1$	$\Delta I_{\rm SD}(\nu_r) = 0.25$ Jy/sr Template in Jy/sr

Abitbol, Chluba, **JCH**, and Johnson (2017) forecasts use only spectral information

PIXIE Forecasts

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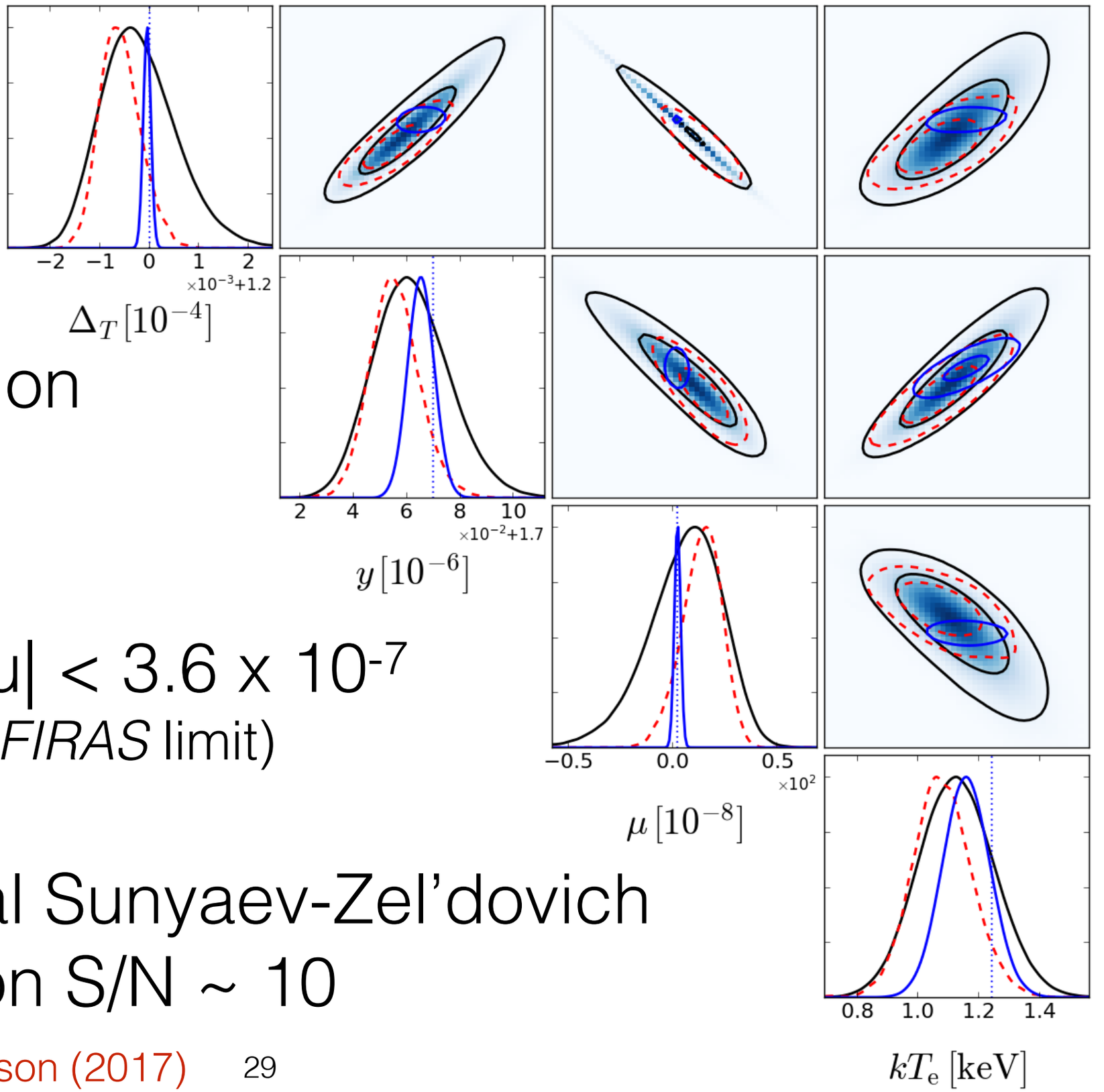
Dust+CIB+CO / Dust+CIB+Synch+FF / All fg

$\sigma(T_{CMB}) \sim 100$ nK
(S/N ~ 1.3 x 10^7)



Compton-y detection
S/N ~ 200

μ limit (95% CL): $|\mu| < 3.6 \times 10^{-7}$
(250x better than *FIRAS* limit)

Relativistic thermal Sunyaev-Zel'dovich
detection S/N ~ 10

Abitbol, Chluba, **JCH**, and Johnson (2017)

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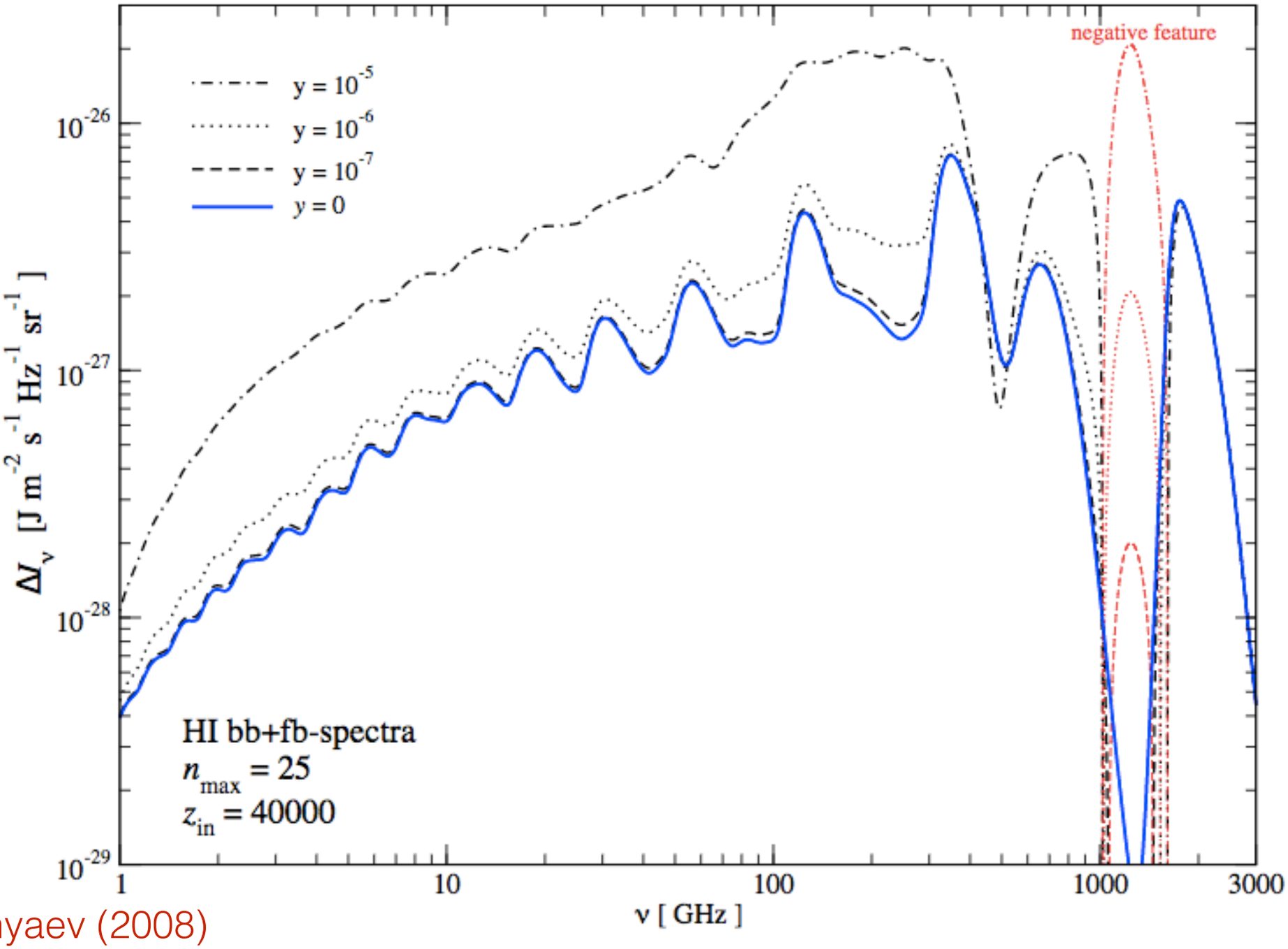
Primordial *y*: hope?

Is there any hope for primordial y? Subtle effects in recombination line spectrum



Chluba & Sunyaev (2008)

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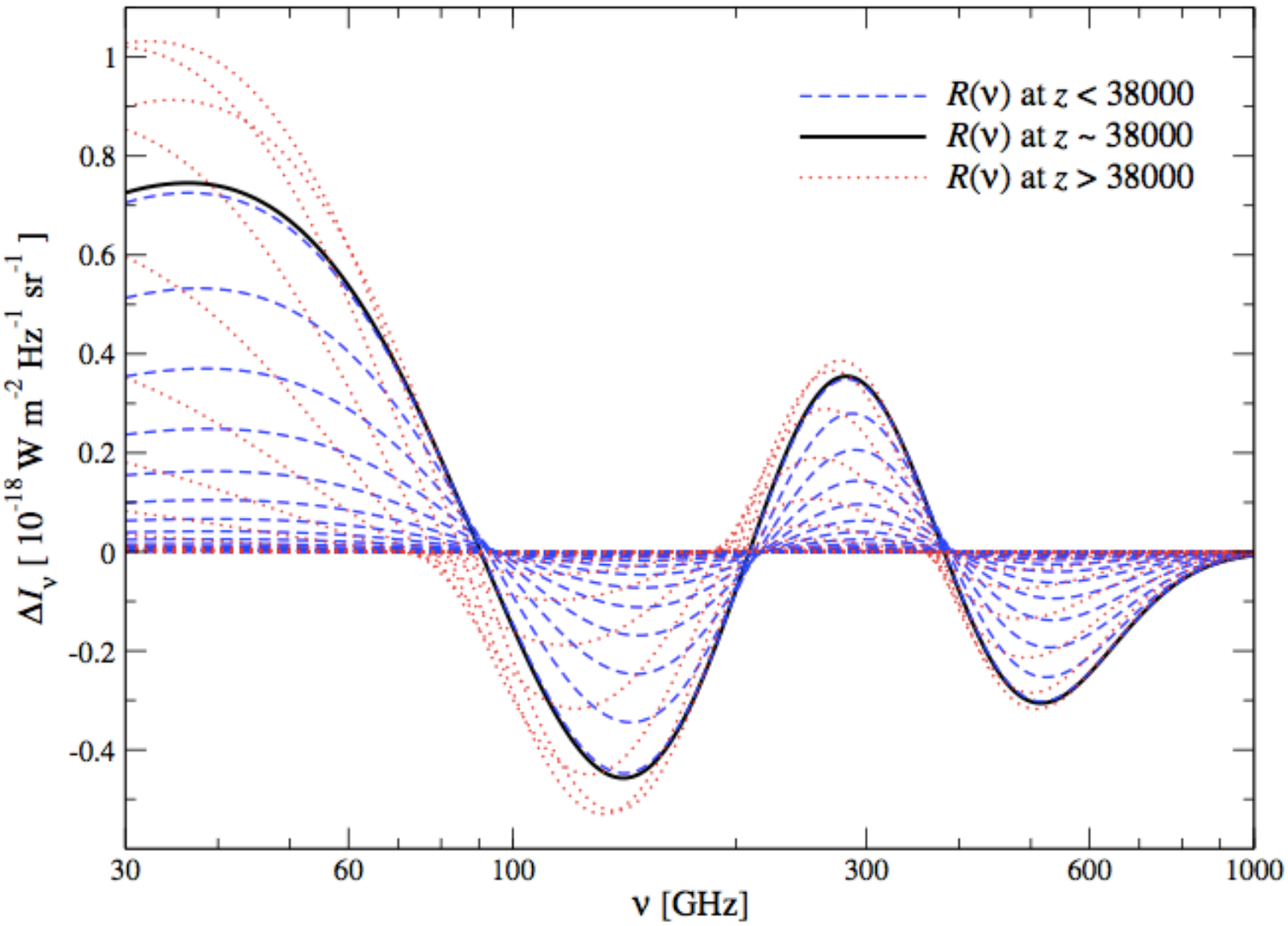
Beyond y and μ

residual ("r-type") distortions



- distortions can be decomposed in principal components
- new set of observables — key to origin of SD signal

Chluba & Jeong (2013)

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Outlook

- The global thermal SZ signal is the largest guaranteed CMB spectral distortion (<y>), including relativistic effects.

- Measurements with PIXIE or similar probes will provide unprecedented constraints on baryonic structure formation.

- Target for μ: LCDM Silk damping signal, $\mu \sim -2 \times 10^{-8}$
  - PIXIE: $\Delta\mu \sim$ few $\times 10^{-7}$ (w/ foregrounds)
  - Even new limits strongly constrain decaying particles, running of spectral index, primordial black holes, +++

- Many other possible signals:
  - Constraints on local-type primordial non-Gaussianity via <yT> and <yE> cross-correlations [Emami+ (2015)] or scale-dependent halo bias in <yy> power spectrum [JCH & Pajer (2013)]
  - Detection of higher-order moments of the electron temperature distribution (beyond $\langle T_e \rangle$)