

Intensity [MJy/sr]

400
300
200
100

FIRAS data with 400σ errorbars
— 2.725 K Blackbody

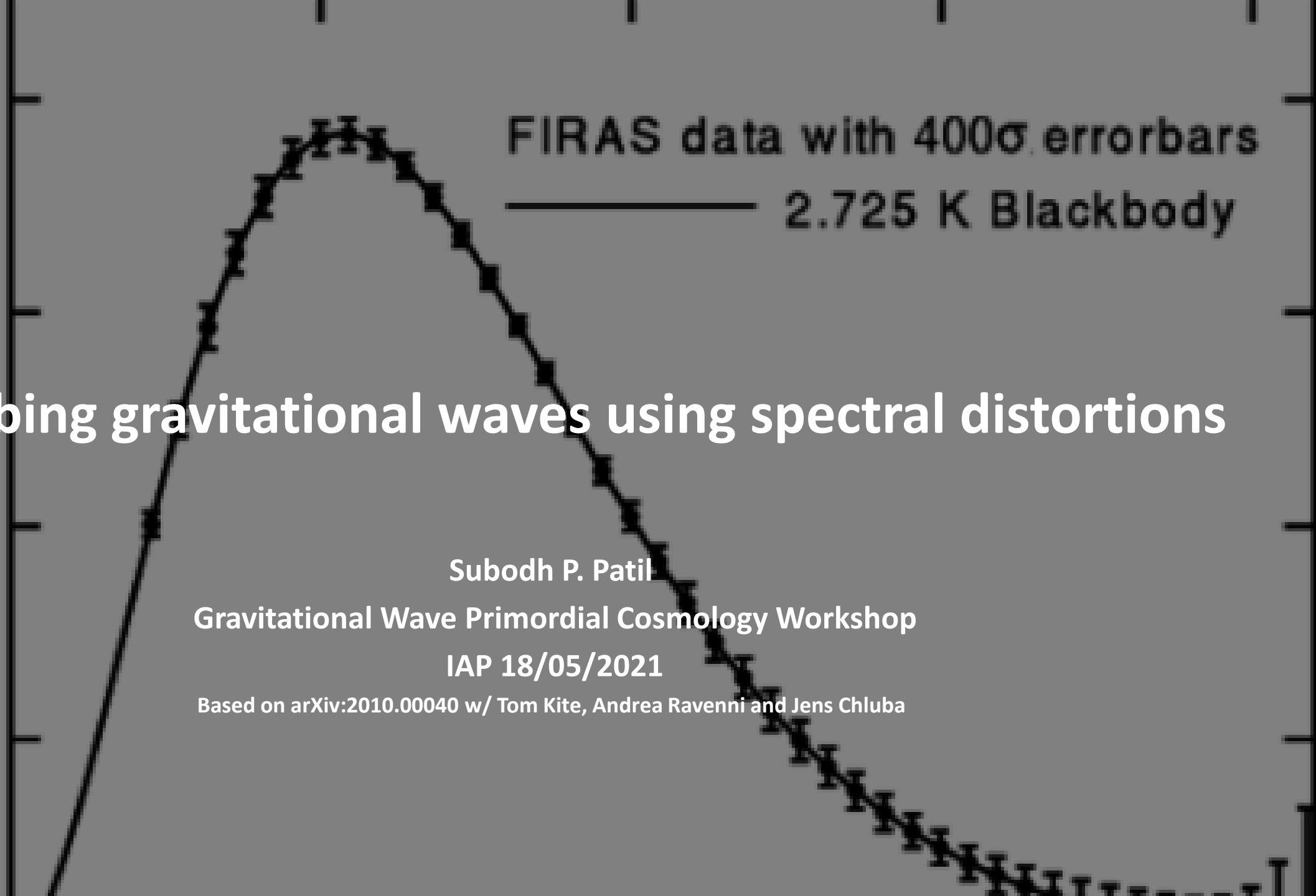
Probing gravitational waves using spectral distortions

Subodh P. Patil

Gravitational Wave Primordial Cosmology Workshop

IAP 18/05/2021

Based on arXiv:2010.00040 w/ Tom Kite, Andrea Ravenni and Jens Chluba





To date, our *cleanest* probe of fluctuations in the early universe has been the CMB

- Black body spectrum of 2.7 K with $\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$
- Angular anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$



What is the information content of the CMB?

- Temperature (T) and polarization (E,B) in each direction $\leftrightarrow 10^6$ 'pixels' in the sky.
- Spectrum of incident photons in a given direction (new information only w/ deviations from blackbody).

What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- Damping tail to be measured more precisely (SPTPol, ACTPol, CMB S4...)
- Forecast $\sum_{\nu} m_{\nu} \sim 0.05$ eV
- Cosmological measurement of a BSM parameter?

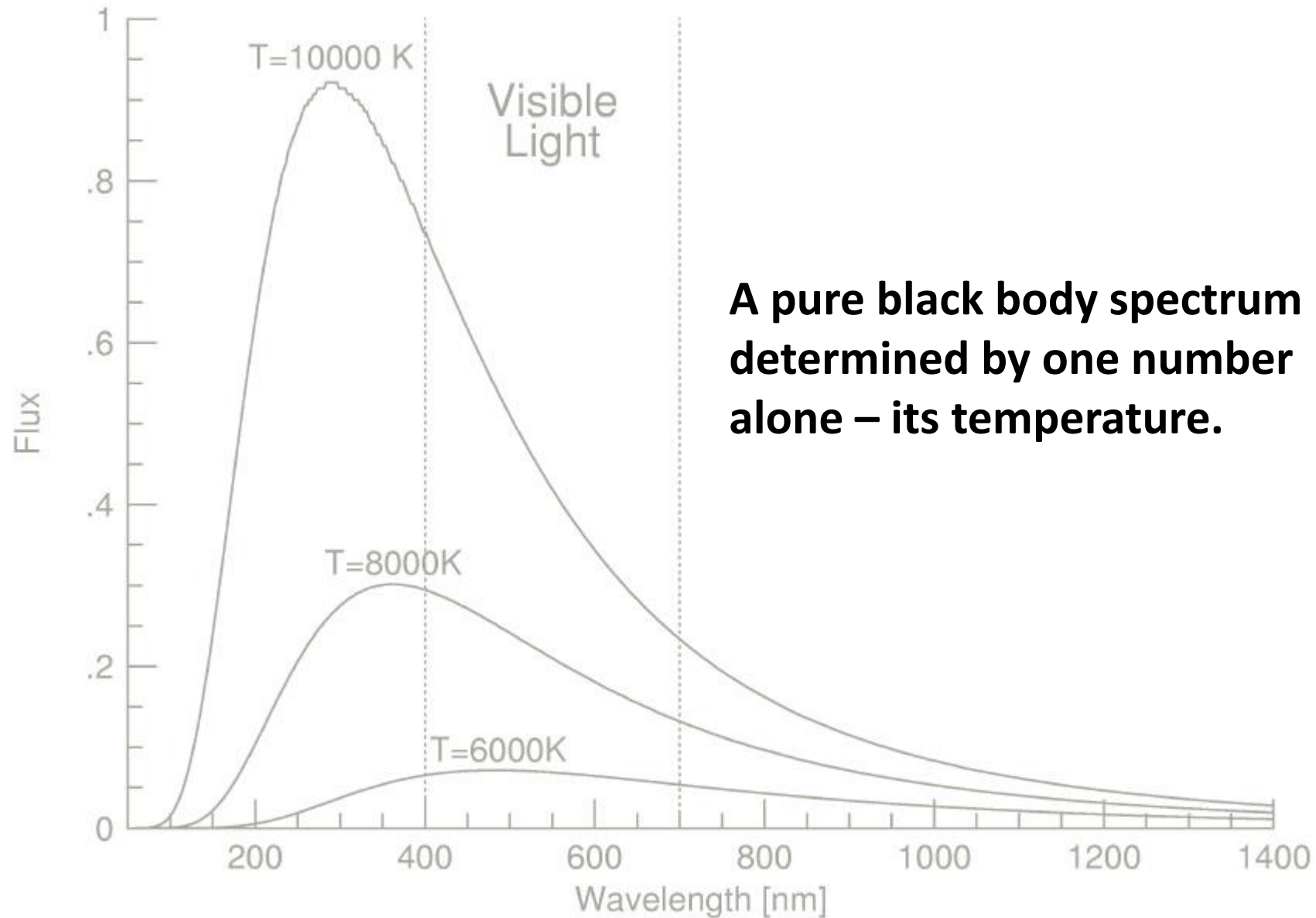
$$\mathcal{L} \supset \frac{H^\dagger H}{\Lambda} \bar{\psi} \psi; \quad \Lambda \sim 10^{16} \text{ GeV}$$

What is the information content of the CMB?

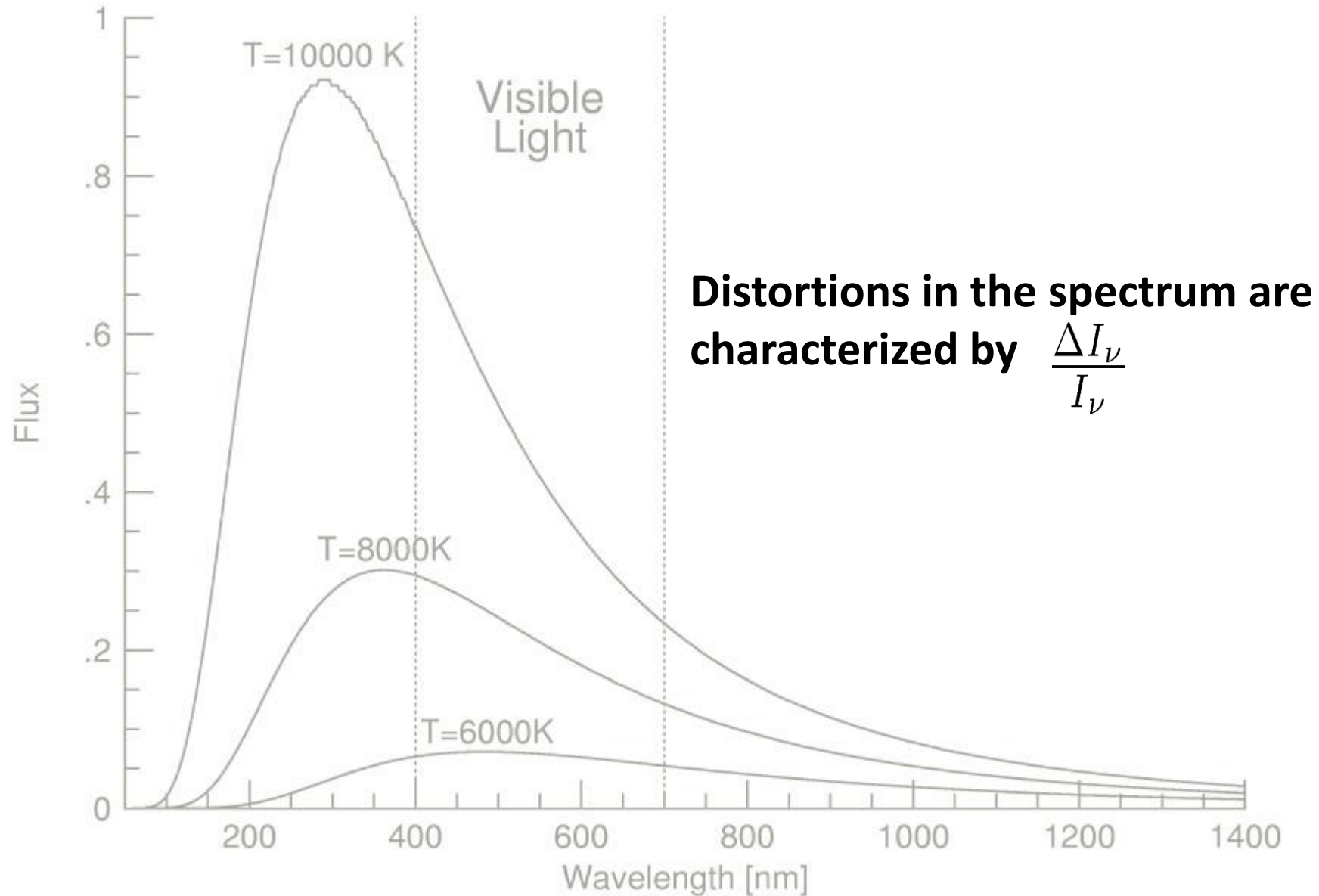
- The spectrum itself remains the last unexplored dimension of the CMB!
- Contains a wealth of information not obtainable by other means...

$$\frac{\Delta T}{T}(\nu) \gtrsim 10^{-7} \rightarrow 10^{-9}$$

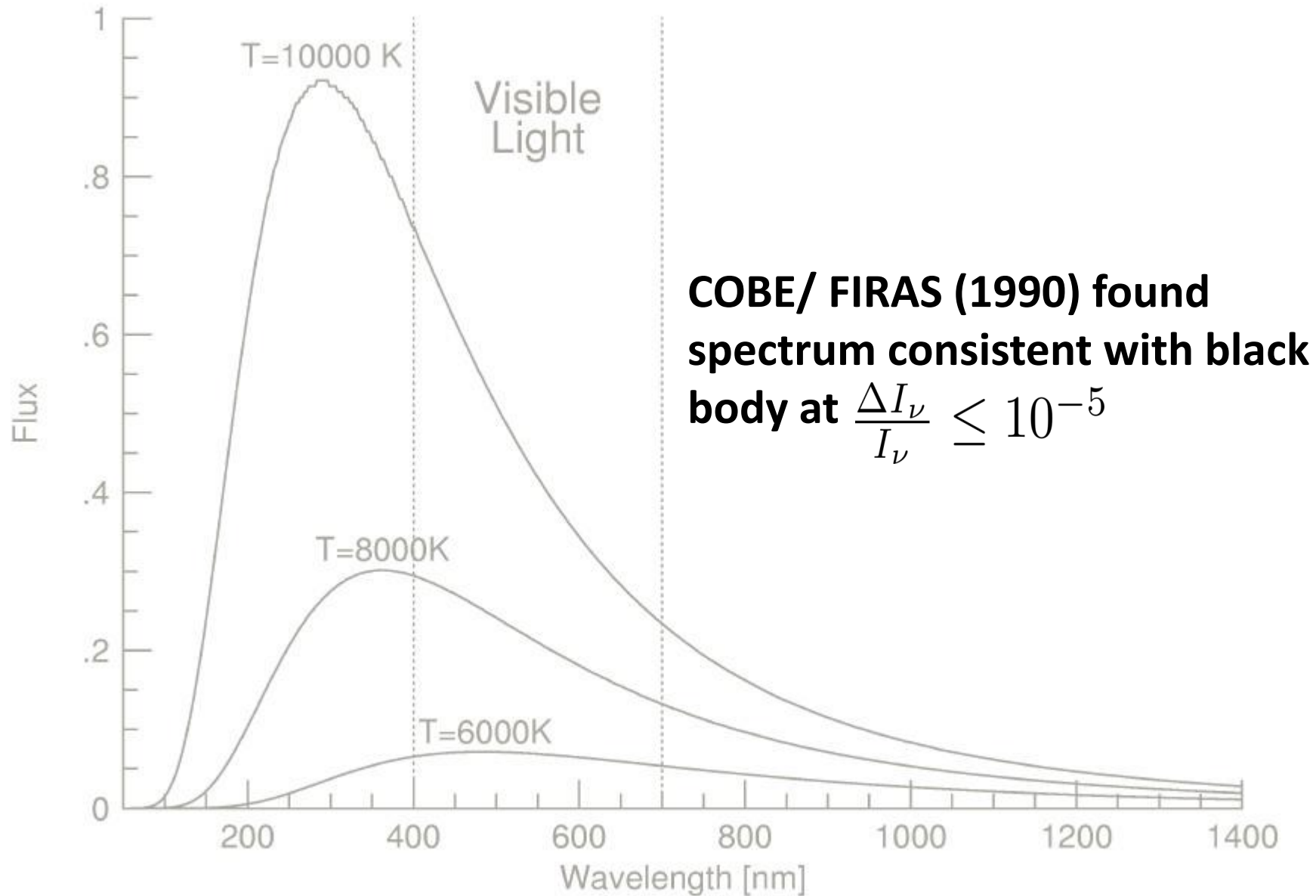
CMB spectral distortions



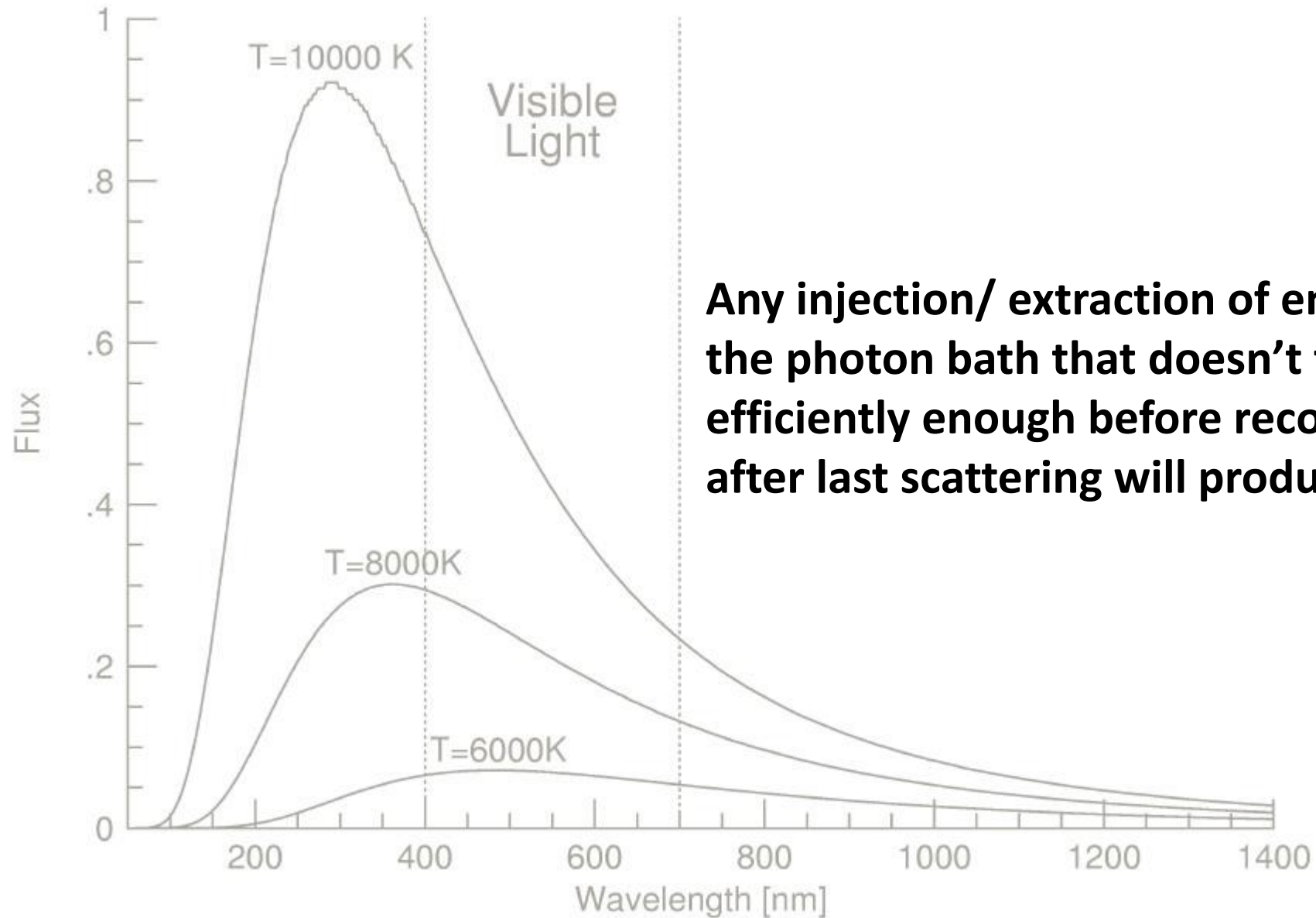
CMB spectral distortions



CMB spectral distortions

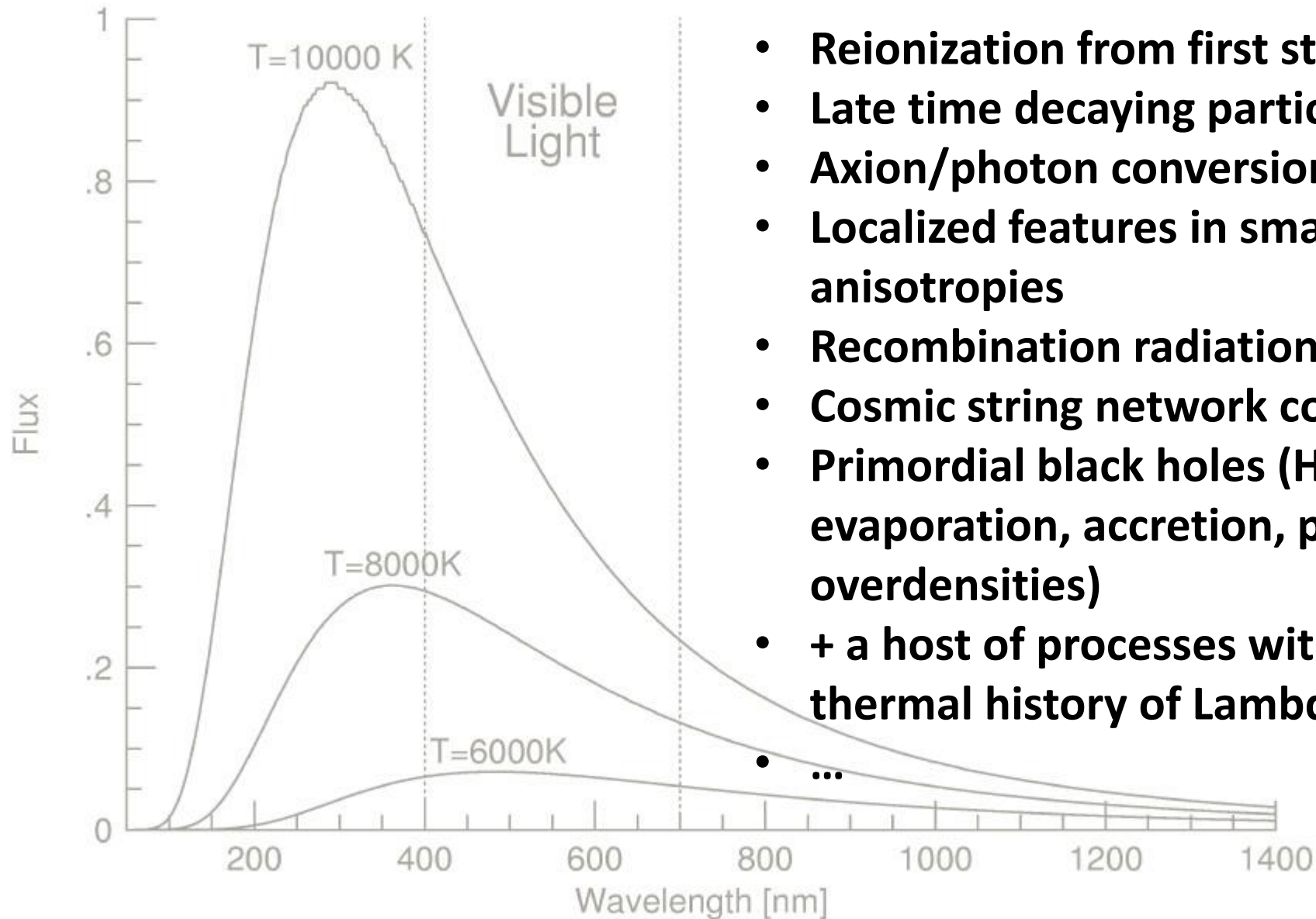


CMB spectral distortions



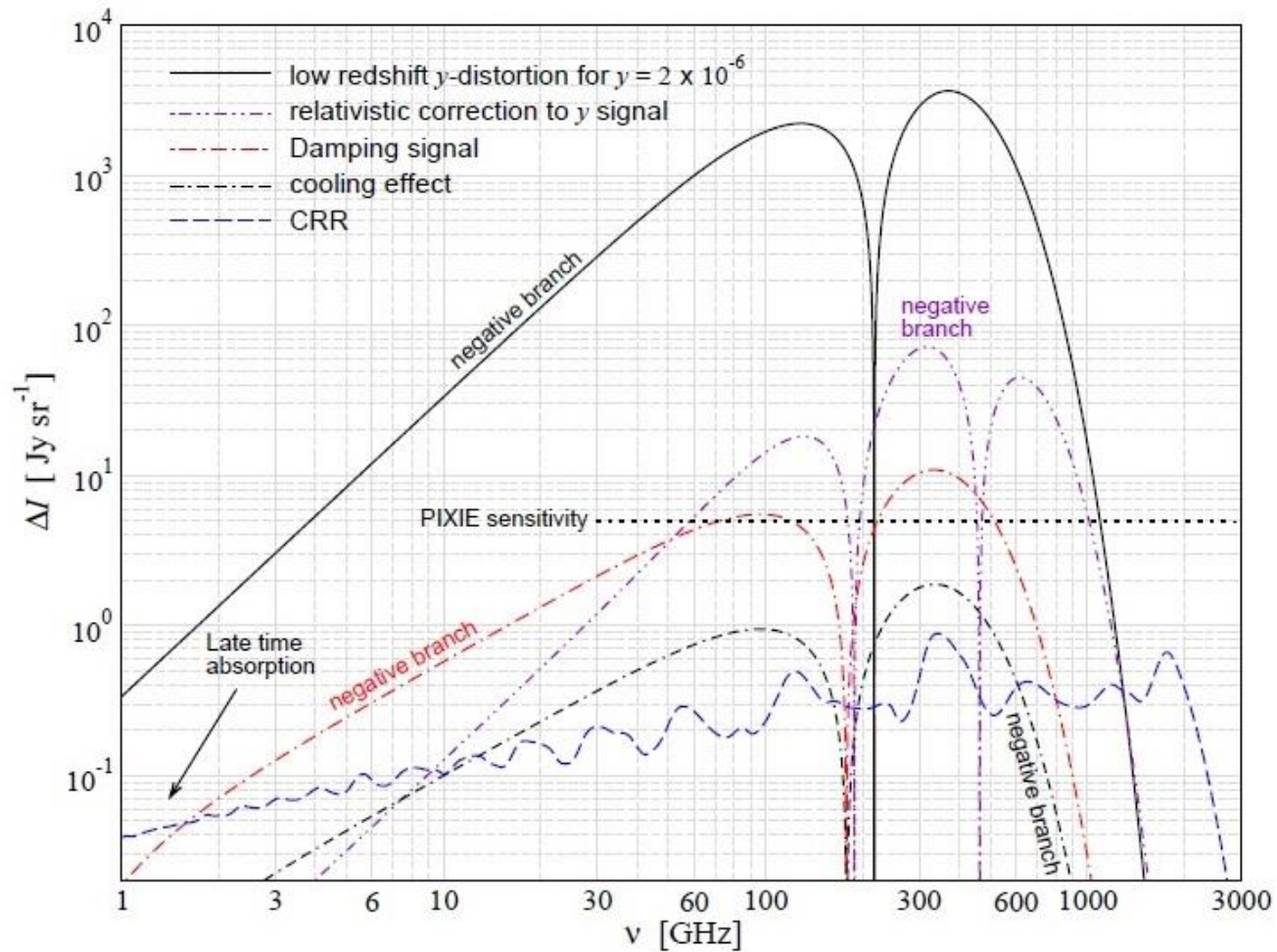
Any injection/ extraction of energy into/ from the photon bath that doesn't thermalize efficiently enough before recombination, or after last scattering will produce distortions...

CMB spectral distortions



- Reionization from first stars
- Late time decaying particles
- Axion/photon conversion
- Localized features in small scale anisotropies
- Recombination radiation of H, He
- Cosmic string network collapse
- Primordial black holes (Hawking evaporation, accretion, primordial overdensities)
- + a host of processes within the standard thermal history of Lambda CDM
- ...

CMB spectral distortions

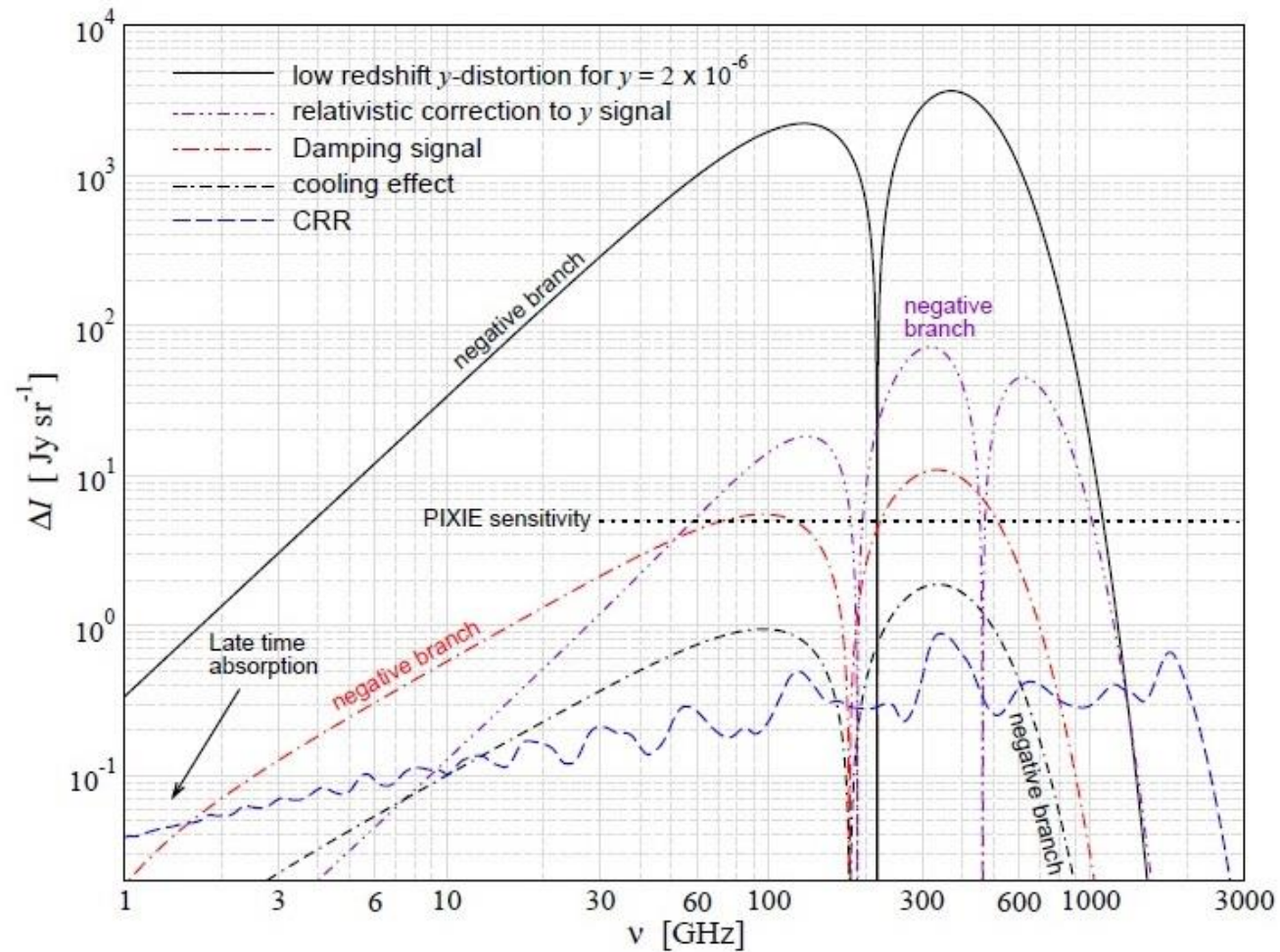


Reionization 'bump' at $\frac{\Delta I_\nu}{I_\nu} \sim 10^{-6} - 10^{-7}$
 Decaying particles/ small scale features at

$$\frac{\Delta I_\nu}{I_\nu} \sim 10^{-8} - 10^{-9}$$

(Fig. courtesy J. Chluba)

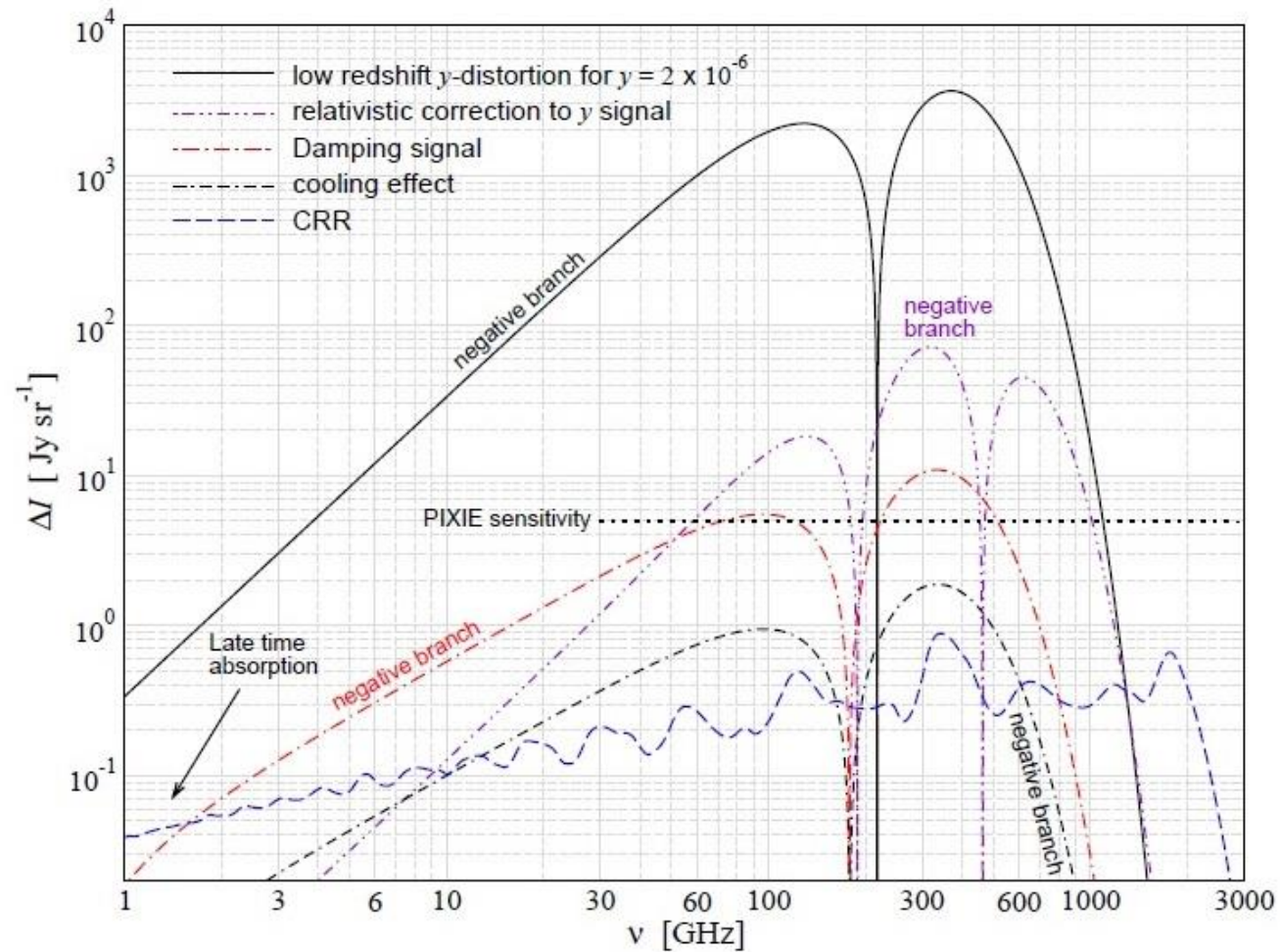
CMB spectral distortions



A low cost, quick off the ground mission could readily improve on FIRAS...

(Fig. courtesy J. Chluba)

CMB spectral distortions



[Recombination lines plausibly observable from the ground (cf. APSERA)]

(Fig. courtesy J. Chluba)

CMB spectral distortions and BSM physics I

[Or, a laundry list of projects for anyone with a string/ BSM phenomenological predisposition... if this is you **feel free to get in touch!**]

Any particles that decay within the window $10^7 < z < 10^3$
into charged particles or photons can result in SD.

i.e. for lifetimes $10^6 < \tau < 10^{14} s$

For gravitationally suppressed decays $\tau \sim \frac{M_{\text{Pl}}^2}{m^3}$

Gravitinos (already studied), moduli fields, dilatons, KK
resonances 100 GeV – 100 MeV

Constraining power on string/ beyond Standard Model
phenomenological scenarios

CMB spectral distortions and BSM physics I

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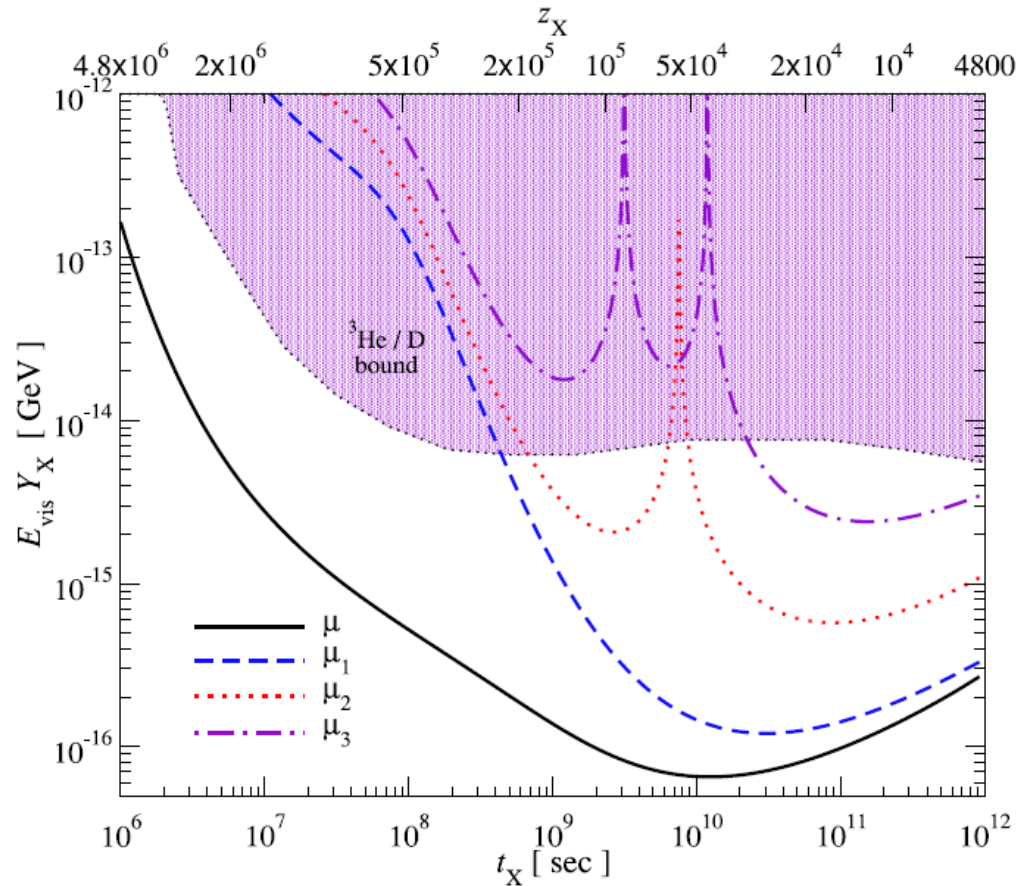


FIG. 1: $E_{\text{vis}} := \text{mass} \times \text{branching ratio into photons}$; $Y_X := n_X/S$ is the relic density of species X relative to the entropy density [6].

(Fig. courtesy J. Chluba and D. Jeong)

Outline

- **An overview of basic physics of spectral distortions**
- **The different types of spectral distortions**
- **Dissipation of scalar modes; $1 \lesssim k \lesssim 10^4 \text{ Mpc}^{-1}$**
- **Dissipation of tensor modes; $1 \lesssim k \lesssim 10^6 \text{ Mpc}^{-1}$**
- **SDs as a stochastic GW background detector in the sky**
- **Constraints on various phenomenological scenarios**

Spectral distortions primer

A black body spectrum is entirely characterized by one number, T :

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$$

Since $\rho_\gamma \propto T^4$ in thermal equilibrium, any injection of photons into the primordial plasma must be distributed according to $\simeq \frac{\partial B_\nu}{\partial T}$ in order to shift the temperature to $T \rightarrow T' = T + \frac{1}{4} \frac{\delta\rho_\gamma}{\rho_\gamma}$

If this is not true, distortions in the spectrum will result...

There are two `main' types of distortion: μ - distortions;

$$\tilde{B}_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{(h\nu - \mu)/(k_B T)} - 1}$$

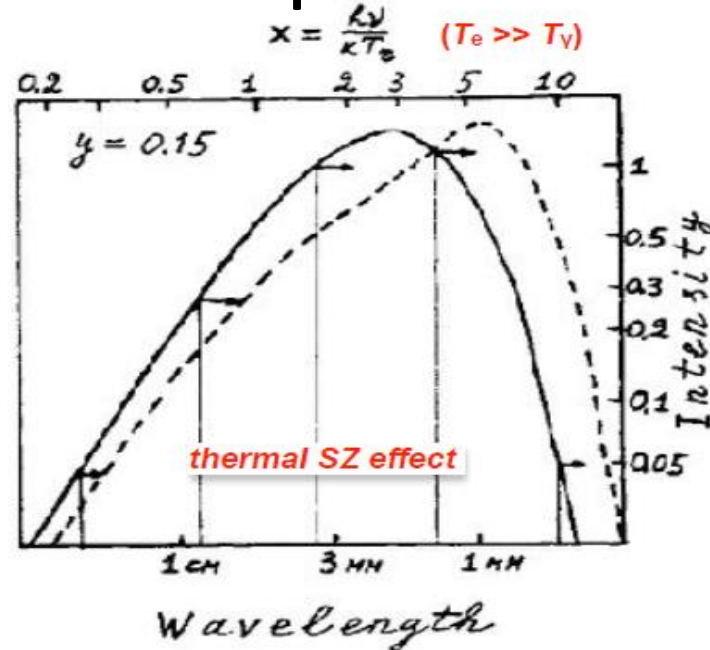
... important at $z > 50,000$, when Compton scattering is efficient

Spectral distortions primer

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... and y -distortions;
important at $z < 50,000$
(scattering is inefficient)

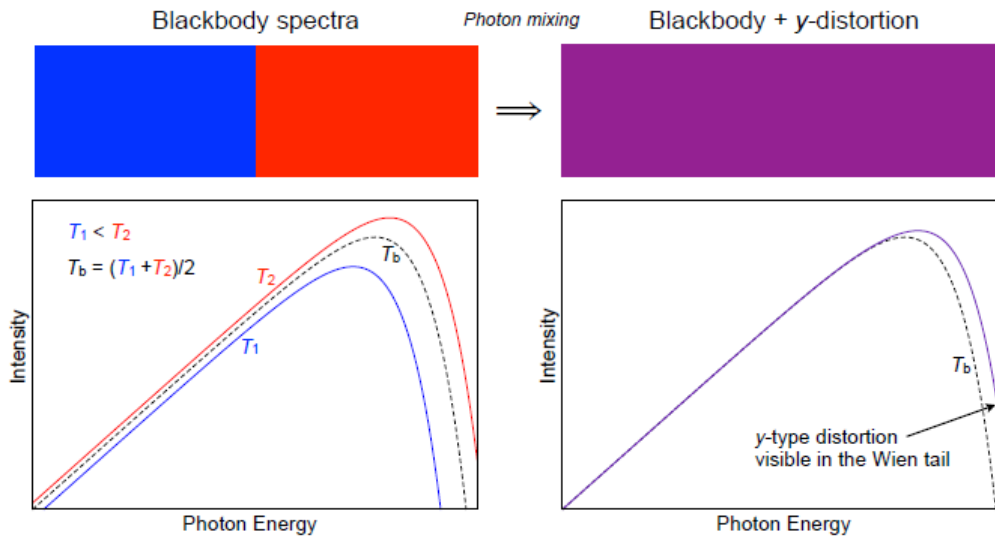
Fig. courtesy Sunyaev and Zeldovich

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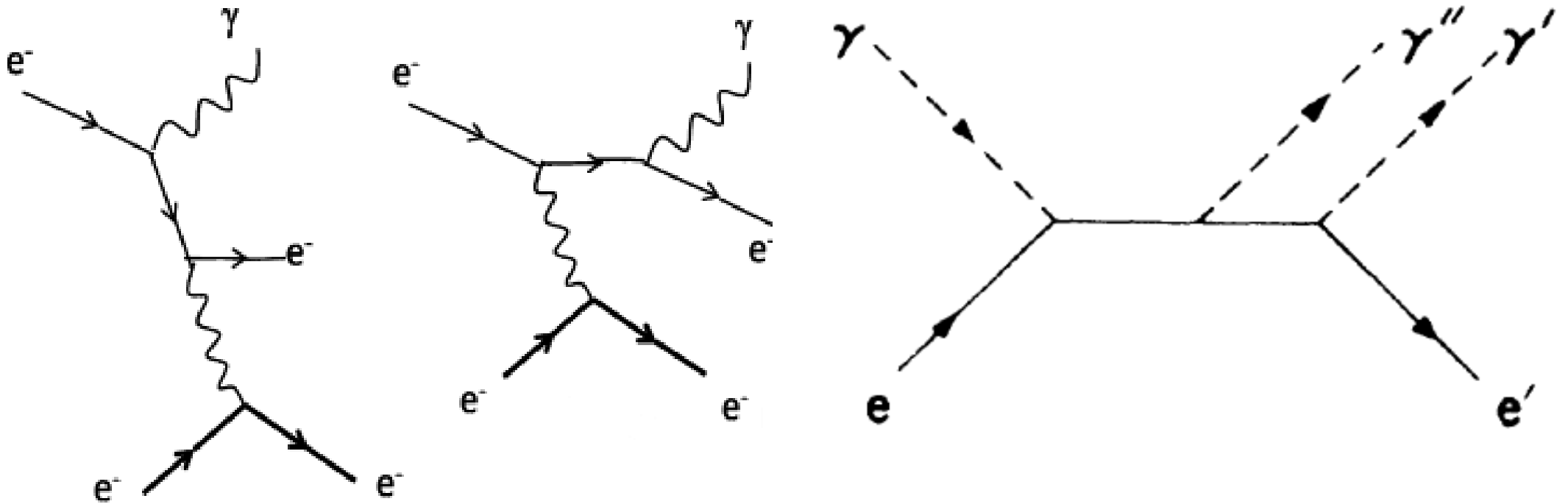
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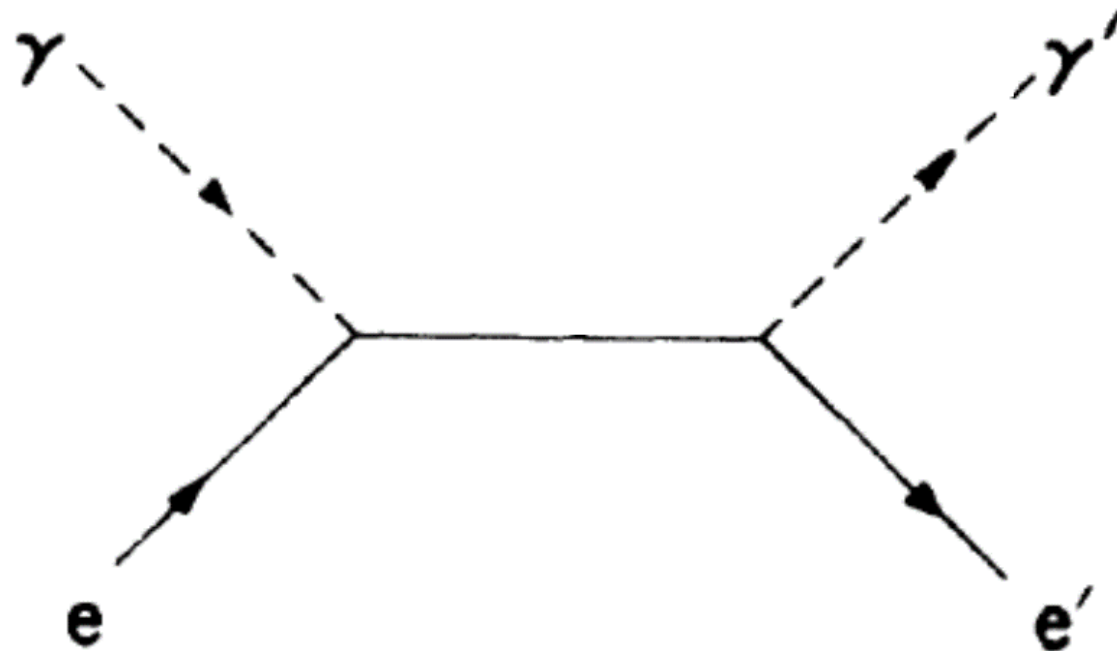
Spectral distortions primer

In the early universe, brehmsstrahlung and double Compton scattering affect the number of photons:



Spectral distortions primer

... whereas regular Compton scattering redistributes photons in phase space



For $z > 10^6$, Compton scattering is very efficient, thermalization is rapid.

Spectral distortions primer

Given an energy release history, can compute the distortion of the spectrum via a 'thermal' Green's function formalism

$$\Delta I_\nu \approx \int G_{\text{th}}(\nu, z') \frac{d(Q/\rho_\gamma)}{dz'} dz'$$

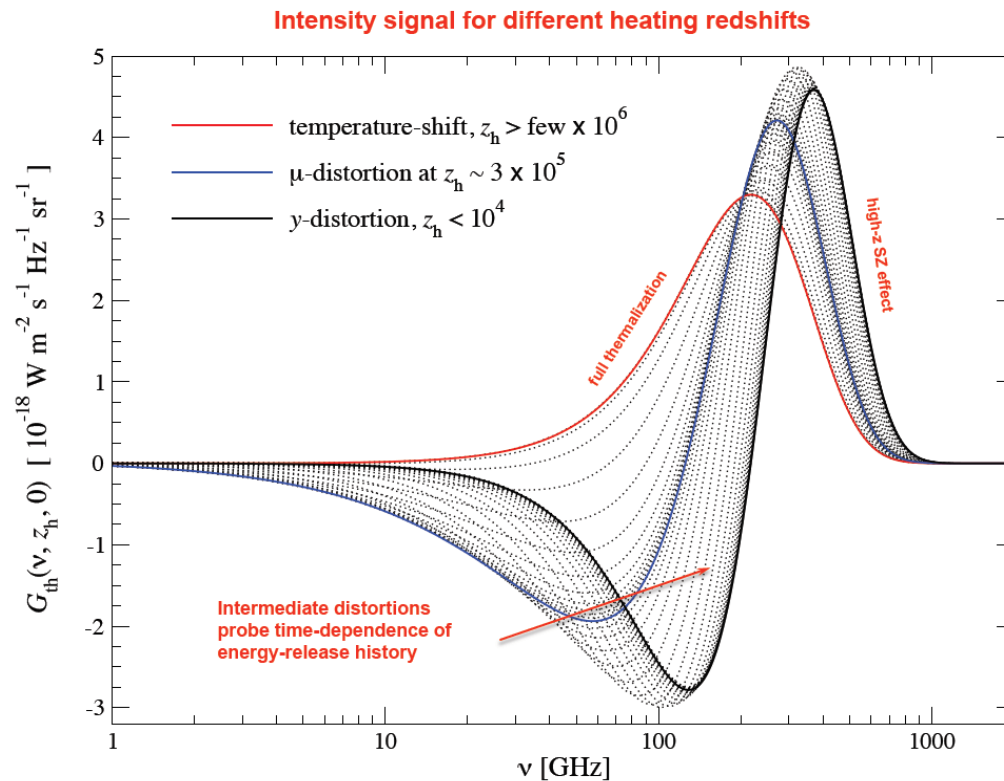
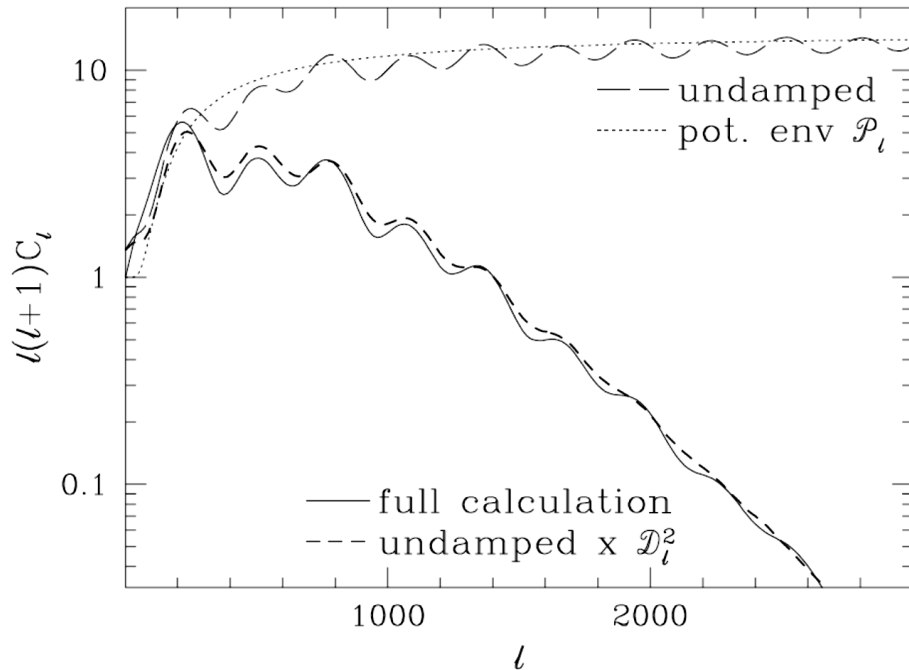


Fig. from Chluba, Hamann and Patil (2015)

Dissipation of scalar modes

Longitudinal perturbations in photon fluid dissipate due to free streaming and scattering (cf. the angular power spectrum if Silk damping didn't occur)



(Fig. courtesy W. Hu and M. White)

$$\mu_{\text{ac}} \approx \int_{k_{\text{min}}}^{\infty} \frac{k^2 dk}{2\pi^2} P_{\mathcal{R}}(k) W_{\mu}(k)$$

$$y_{\text{ac}} \approx \int_{k_{\text{min}}}^{\infty} \frac{k^2 dk}{2\pi^2} P_{\mathcal{R}}(k) W_y(k)$$

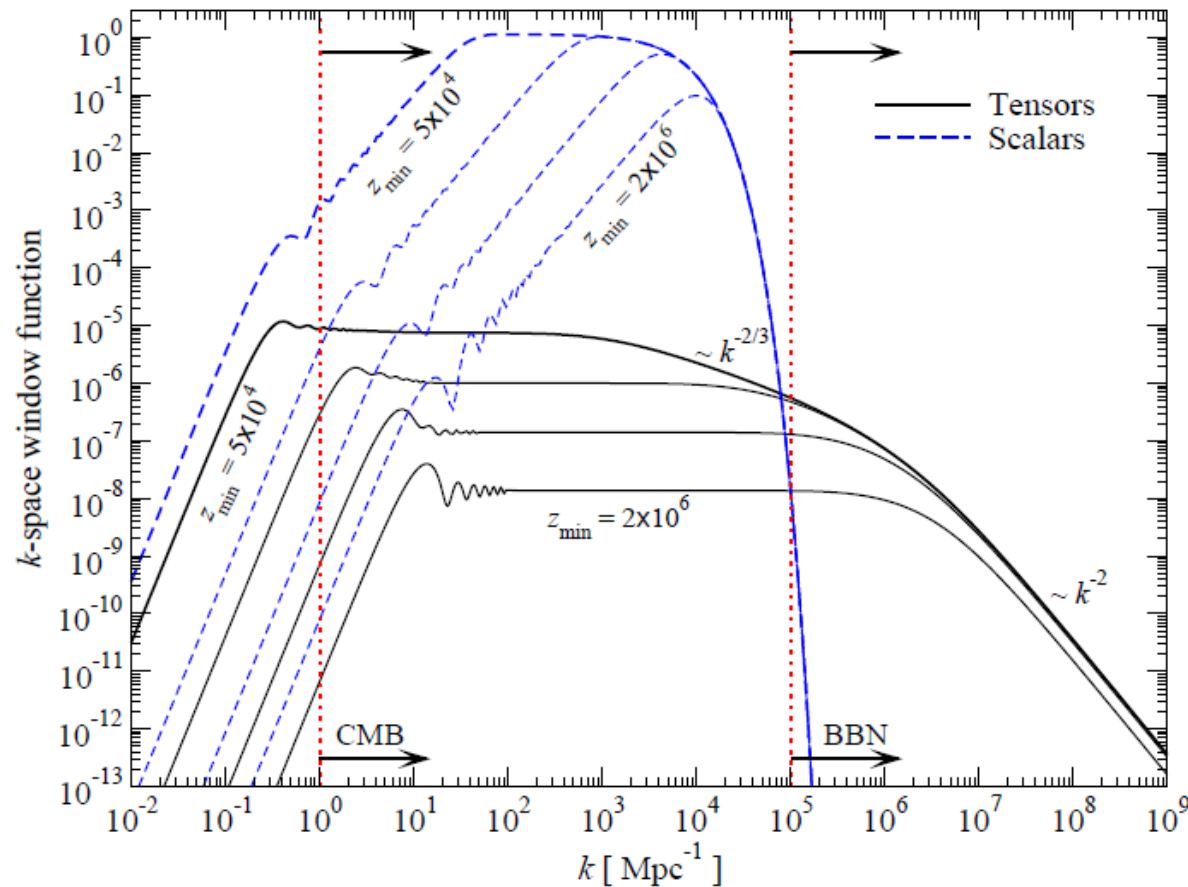
$$W_{\mu}(k) \approx 2.8A^2 \left[\exp \left(- \frac{\left[\frac{\hat{k}}{1360} \right]^2}{1 + \left[\frac{\hat{k}}{260} \right]^{0.3} + \frac{\hat{k}}{340}} \right) - \exp \left(- \left[\frac{\hat{k}}{32} \right]^2 \right) \right]$$

$$W_y(k) \approx \frac{A^2}{2} \exp \left(- \left[\frac{\hat{k}}{32} \right]^2 \right) \quad \hat{k} = k / [1\text{Mpc}^{-1}]$$

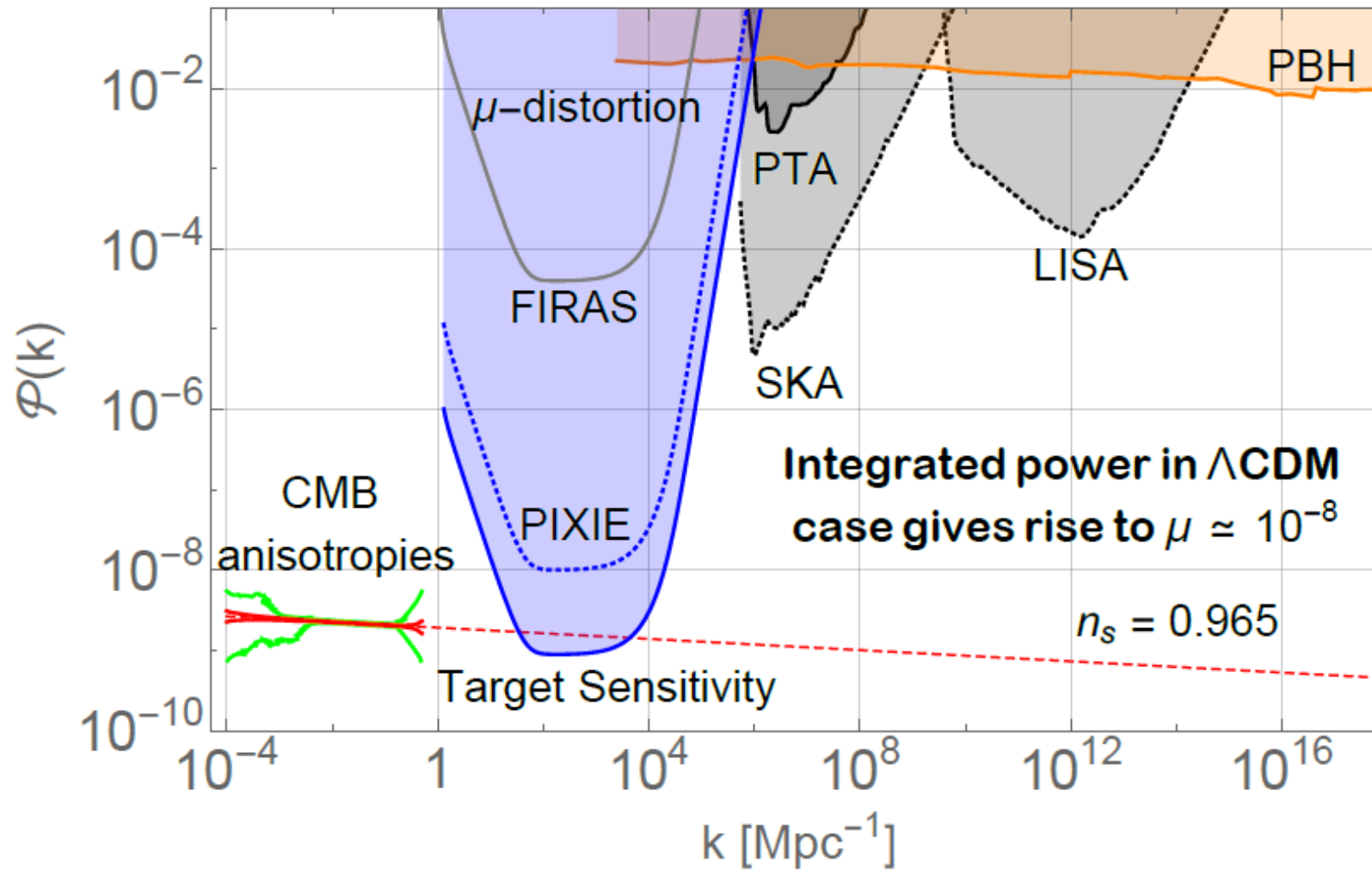
Dissipation of tensor modes

Whereas tensor perturbations dissipate mainly through just free streaming:

$$\mu_T \approx \int_0^\infty \frac{k^2 dk}{2\pi^2} P_T(k) W_T(k)$$

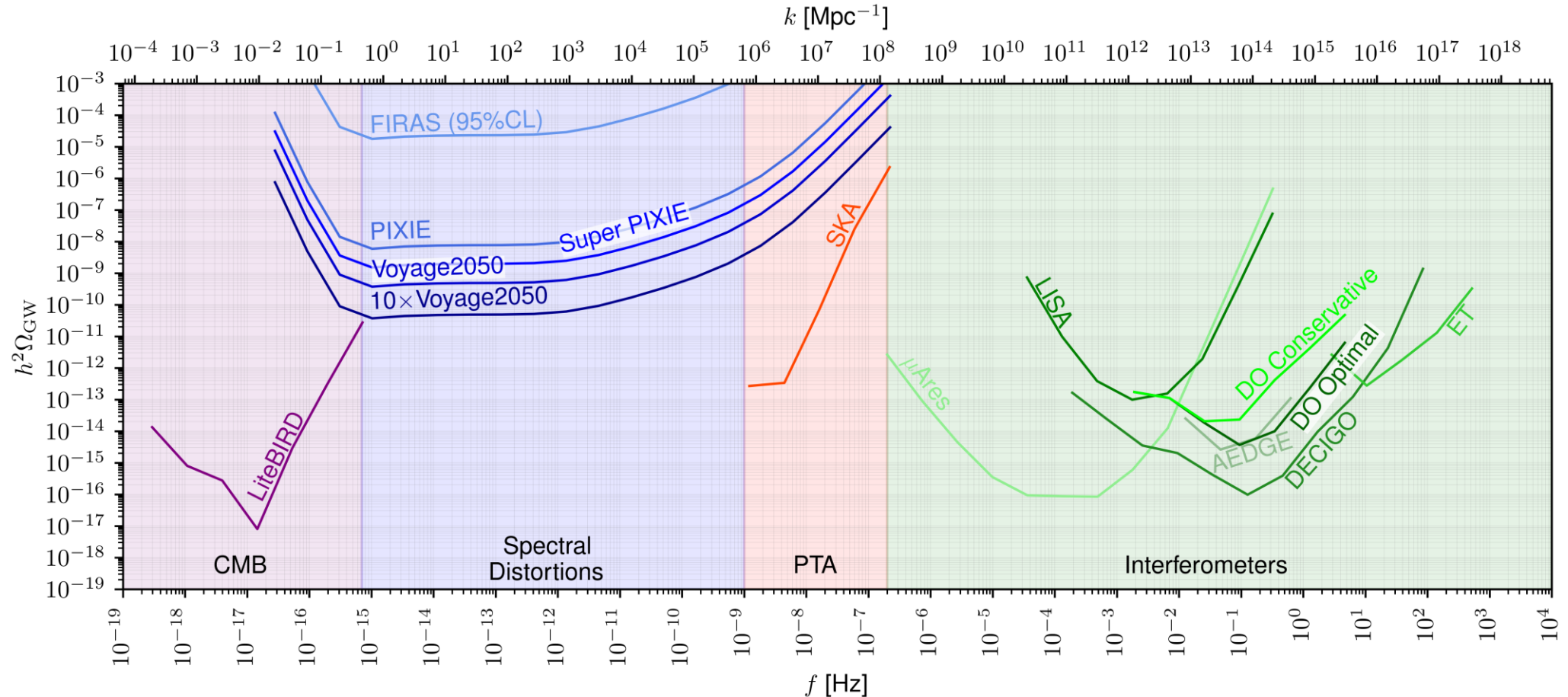


SDs probe small scale scalar power



SDs probe tensor power

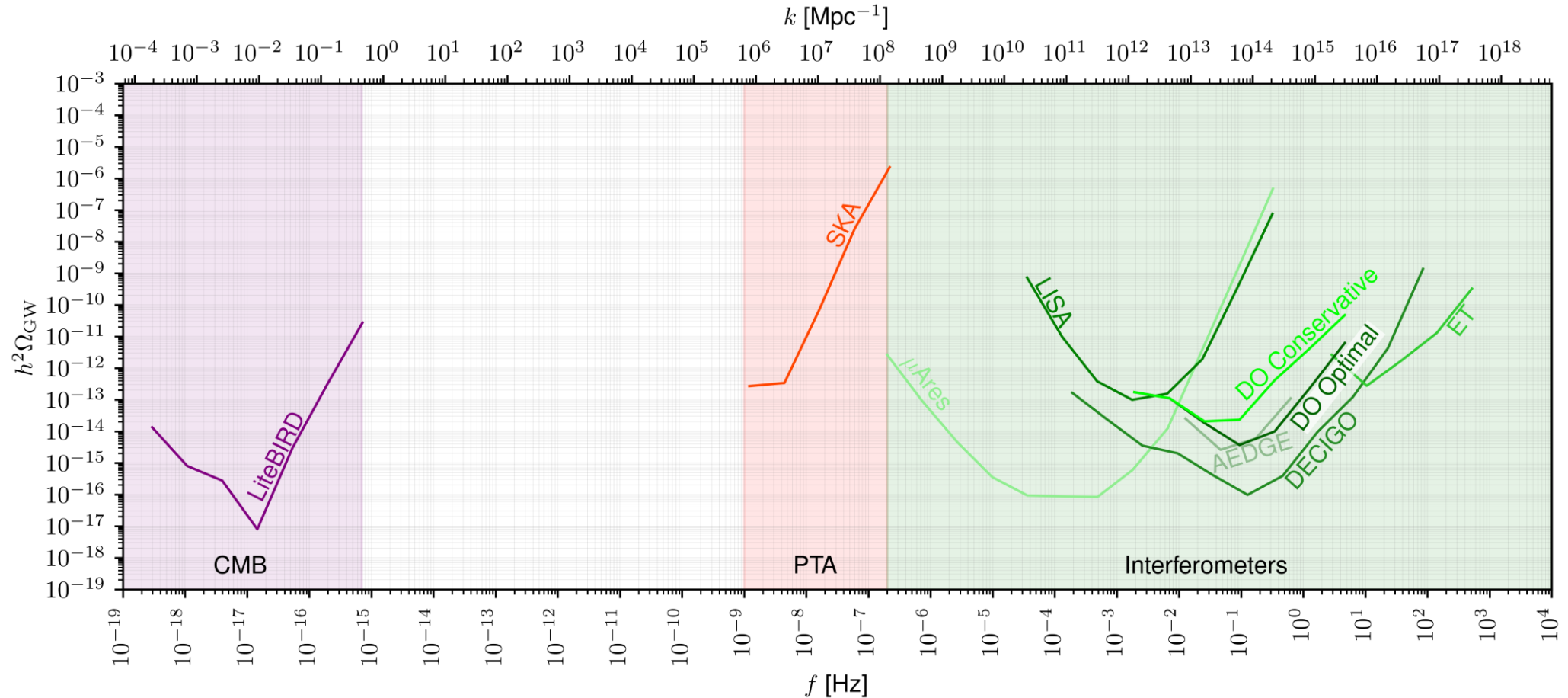
Spectral distortions can probe stochastic gravitational wave backgrounds at frequencies inaccessible to other probes (!)



(Fig. from Kite et al, 2010.00040)

SDs probe tensor power

Spectral distortions can probe stochastic gravitational wave backgrounds at frequencies inaccessible to other probes (!)

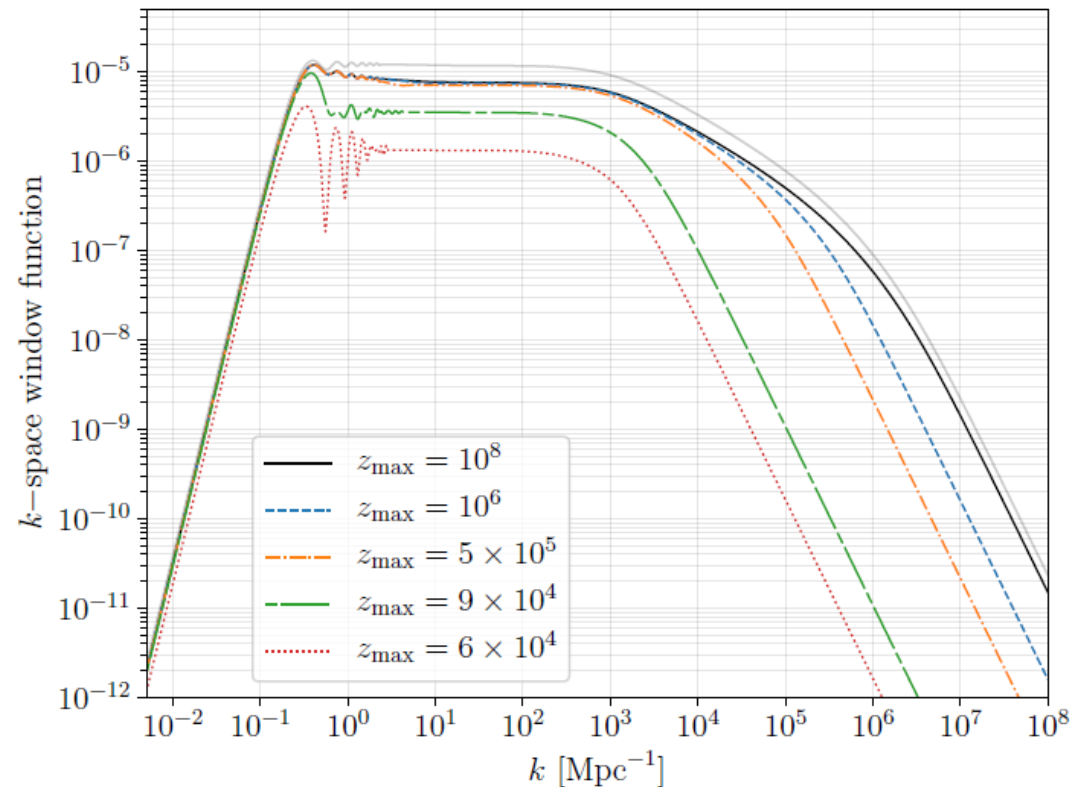


(Fig. from Kite *et al*, 2010.00040)

Spectral distortions and BSM physics II

Need to account that for some scenarios, GWs are produced on sub-horizon scales

$$\langle \mu_{\text{GW}} \rangle (z = 0) = \int_0^\infty d \ln k \int_0^\infty dz' W_\mu(k, z) \mathcal{P}_T(k, z)$$



(Kite *et al*, 2010.00040)

Spectral distortions and BSM physics II

Ultra-light “audible” axions Machado, Ratzinger, Machado, Stefanek; arXiv:1912.01007

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\alpha}{4f_\phi} \phi X_{\mu\nu} \tilde{X}^{\mu\nu} \right]$$

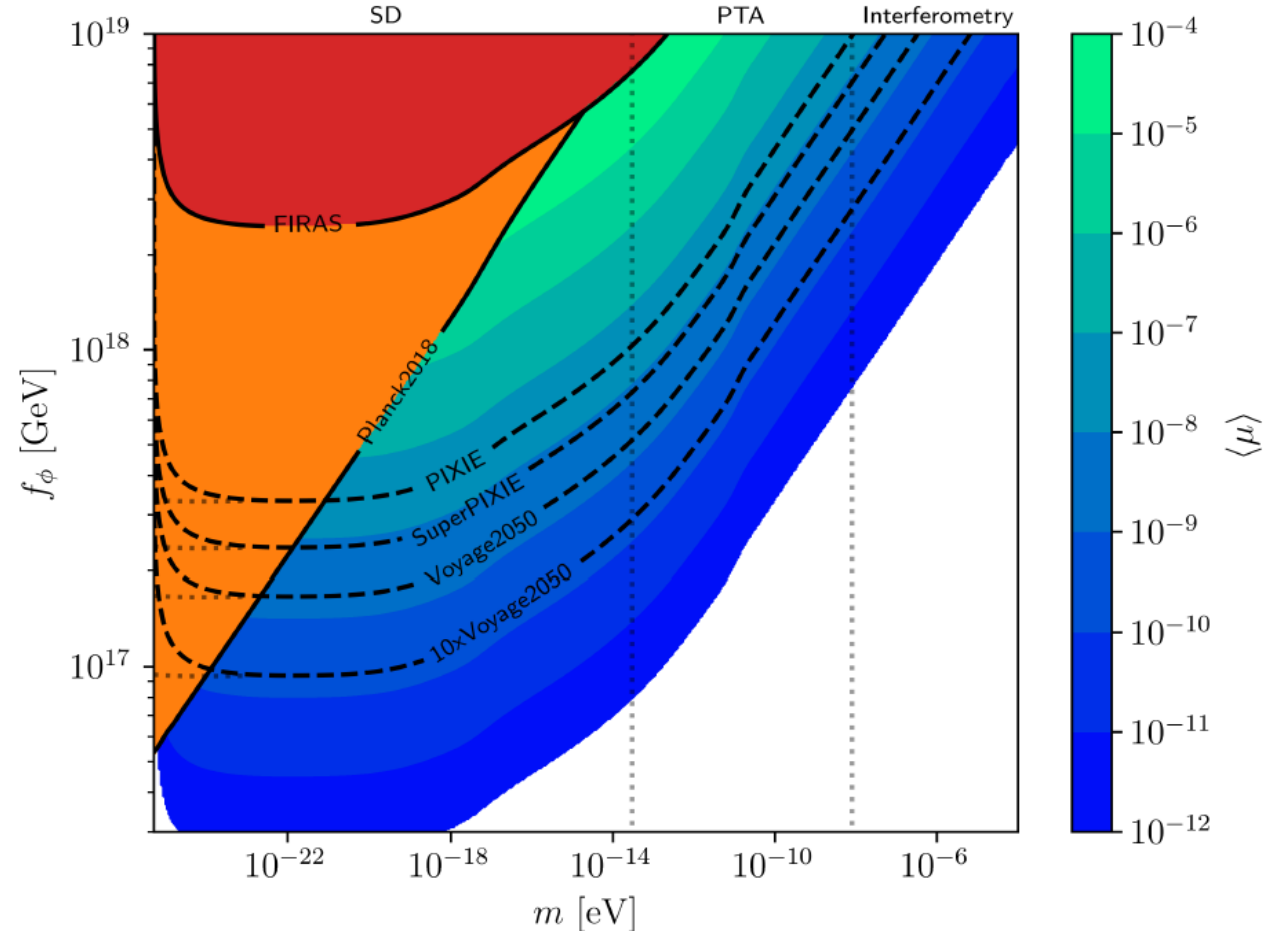
Global U(1) broken at $\Lambda \sim \sqrt{mf}$
When $H < m$ at $T_{\text{osc}} \approx \sqrt{mM_P}$
axion oscillations produce dark photons that source chiral GW's:

$$\Omega_{\text{GW}}^{\text{U}(1)}(k) = \frac{6.3 \Omega_{\text{GW}}^{\text{U}(1)}(f_{\text{AA}}) (k/\tilde{k})^{1.5}}{1 + (k/\tilde{k})^{1.5} \exp[12.9(k/\tilde{k} + 1)]}$$

$$\tilde{k} = 1.3 \times 10^{15} [f_{\text{AA}}/\text{Hz}] \text{Mpc}^{-1}$$

$$f_{\text{AA}} \approx 6 \times 10^{-4} \text{Hz} \left[\frac{\alpha\theta}{66} \right]^{2/3} \left[\frac{m}{10 \text{meV}} \right]^{1/2}$$

$$\Omega_{\text{GW}}^{\text{U}(1)}(f_{\text{AA}}) \approx 1.67 \times 10^{-4} g_{\rho,*}^{-1/3} \left[\frac{f_\phi}{M_{\text{pl}}} \right]^4 \left[\frac{\theta^2}{\alpha} \right]^{4/3}$$



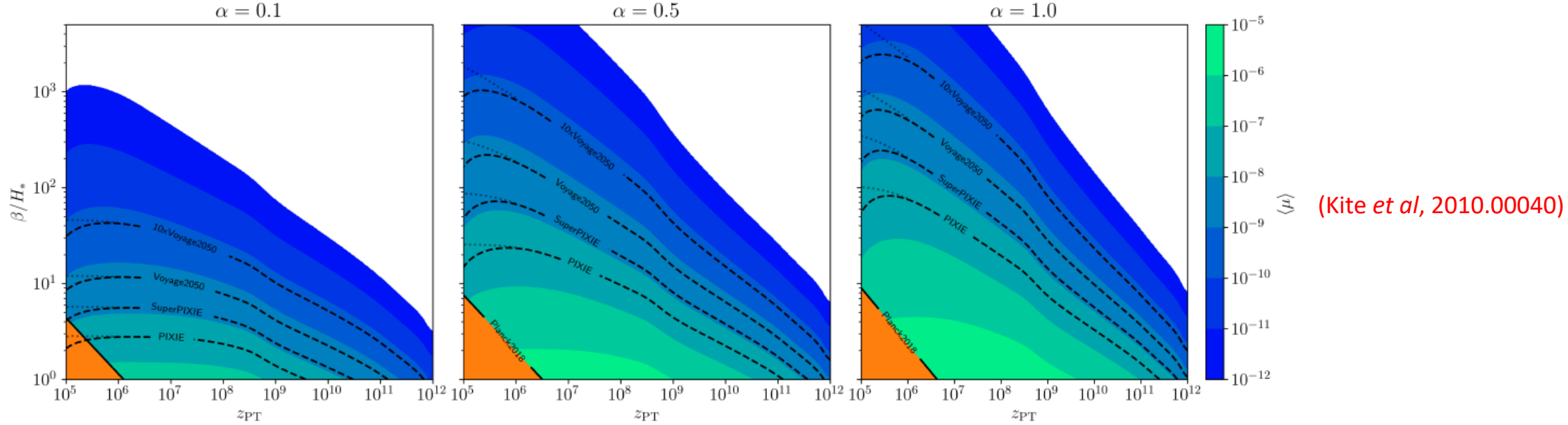
(Kite et al, 2010.00040)

Spectral distortions and BSM physics II

First order phase transitions beyond the SM

Cf. review by Caprini and Figueroa; arXiv:1801.04268

Three sources of GWs: bubble wall collisions, MHD turbulence and sound waves



$$h^2 \Omega_{\text{GW}}^{\text{BC}}(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta} \right)^2 \left(\frac{\kappa_{\text{BC}} \alpha}{1 + \alpha} \right)^2 \left(\frac{100}{g_*(T_*)} \right)^{\frac{1}{3}} \times \left(\frac{0.11 v_w^3}{0.42 + v_w^2} \right) \frac{3.8 (f/f_{\text{BC}})^{2.8}}{1 + 2.8 (f/f_{\text{BC}})^{3.8}}$$

$$f_{\text{BC}} = 1.65 \times 10^{-5} \text{Hz} \left(\frac{0.62}{1.8 - 0.1 v_w + v_w^2} \right) \chi_0$$

$$\chi_0 = \left[\frac{\beta}{H_*} \right] \left[\frac{T_*}{100 \text{GeV}} \right] \left[\frac{g_*(T_*)}{100} \right]^{\frac{1}{6}}$$

$$h^2 \Omega_{\text{GW}}^{\text{SW}}(f) = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta} \right) \left(\frac{\kappa_v \alpha}{1 + \alpha} \right) \left(\frac{100}{g_*(T_*)} \right)^{\frac{1}{3}} \times v_w \left(\frac{f}{f_{\text{SW}}} \right)^3 \left(\frac{7}{4 + 3 (f/f_{\text{SW}})^2} \right)^{\frac{7}{2}}$$

$$f_{\text{SW}} = 1.9 \times 10^{-5} \text{Hz} v_w^{-1} \chi_0$$

$$h^2 \Omega_{\text{GW}}^{\text{MHD}}(f) = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta} \right) \left(\frac{\kappa_{\text{MHD}} \alpha}{1 + \alpha} \right)^{\frac{3}{2}} \left(\frac{100}{g_*(T_*)} \right)^{\frac{1}{3}} \times v_w \frac{(f/f_{\text{MHD}})^3}{[1 + (f/f_{\text{MHD}})]^{\frac{1}{3}} (1 + 8\pi f/h_*)}$$

$$f_{\text{MHD}} = 2.7 \times 10^{-5} \text{Hz} v_w^{-1} \chi_0$$

Spectral distortions and BSM physics II

Cosmic string network collapse:

Leptogenesis via a $B-L$ $U(1)$ phase transition in an $SO(10)$ GUT theory.

GWs produced by the subsequent collapse of the string network.

$$h^2\Omega_{\text{GW}}^{\text{CS}} = h^2\Omega_{\text{GW}}^{\text{plateau}} \min \left[(f/f_*)^{3/2}, 1 \right]$$

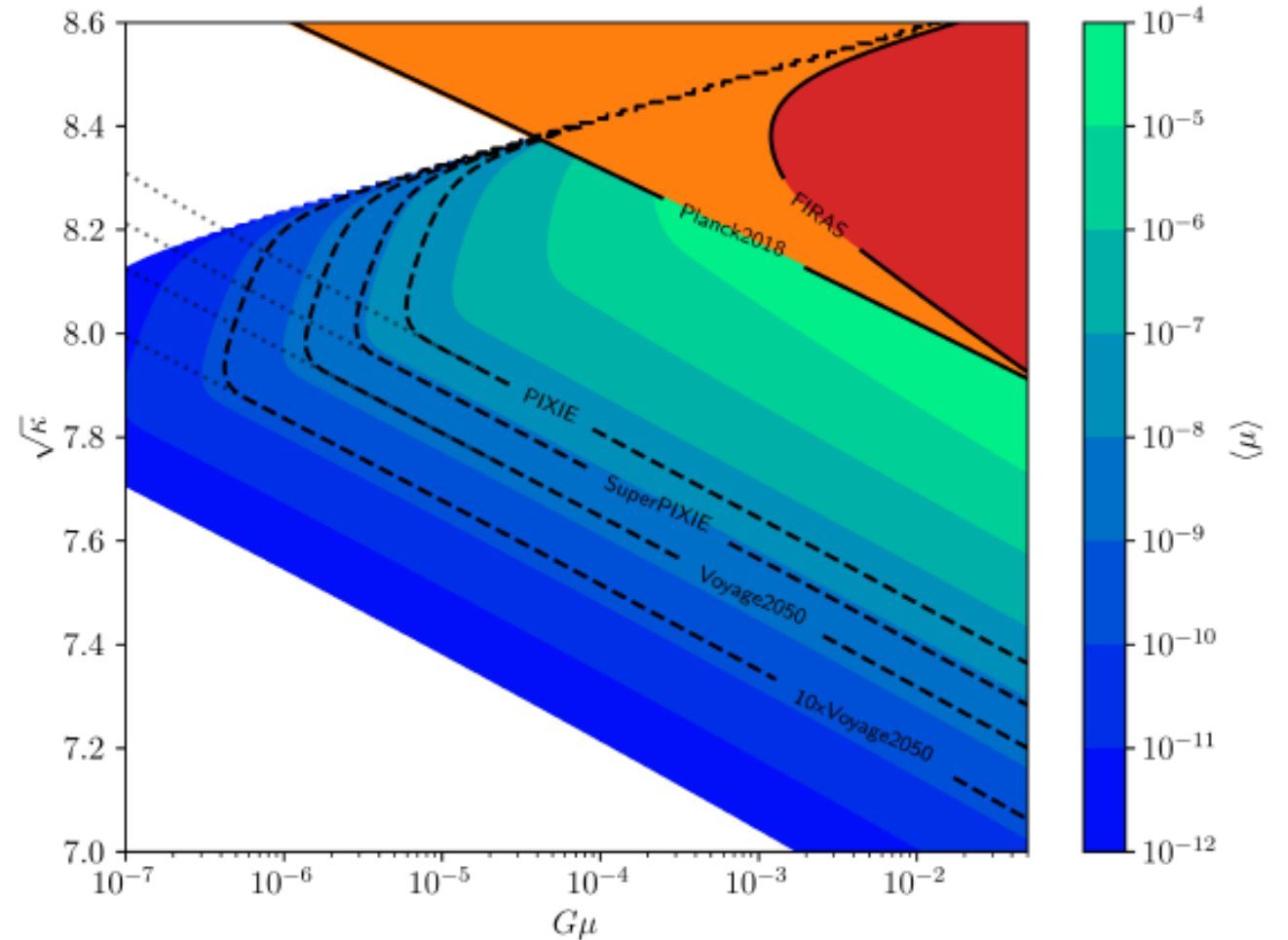
$$f_* = 3 \times 10^{14} \text{ Hz} e^{-\pi\kappa/4} \left[\frac{G\mu}{10^{-7}} \right]^{-1/2}$$

$$h^2\Omega_{\text{GW}}^{\text{plateau}} = 8.04\Omega_r h^2 \left[\frac{G\mu}{\Gamma} \right]^{1/2}$$

$$z_{\text{collapse}} = \left(\frac{70}{H_0} \right)^{1/2} \left(\Gamma \frac{(G\mu)^2}{2\pi G} e^{-\pi x} \right)^{1/4}$$

$$\Omega_\Gamma h^2 = 2.5 \times 10^{-5}, \Gamma \approx 50$$

arXiv:1801.04268; Buchmuller, Domcke, Murayama and Schmitz



(Kite et al, 2010.00040)

Concluding remarks ^{1]}

- Spectral distortions can probe both scalar and tensor (and vector) perturbation dissipation in the primordial plasma.
- Sensitivity to residual 'r'-type distortions can probe energy release history.
- A complimentary probe of physical processes at scales inaccessible by other means.
- A new portal for GW cosmology
- Many BSM scenarios can be further (already?) constrained by SD!

