CMB Spectral Distortions: A Multimessenger Probe of the Primordial Universe

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w/ Jens Chluba, Sandeep Acharya, +

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Bryce Cyr

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NSERC CRSNG

Outline

- CMB spectral distortions
  - Theory overview
  - Experimental update

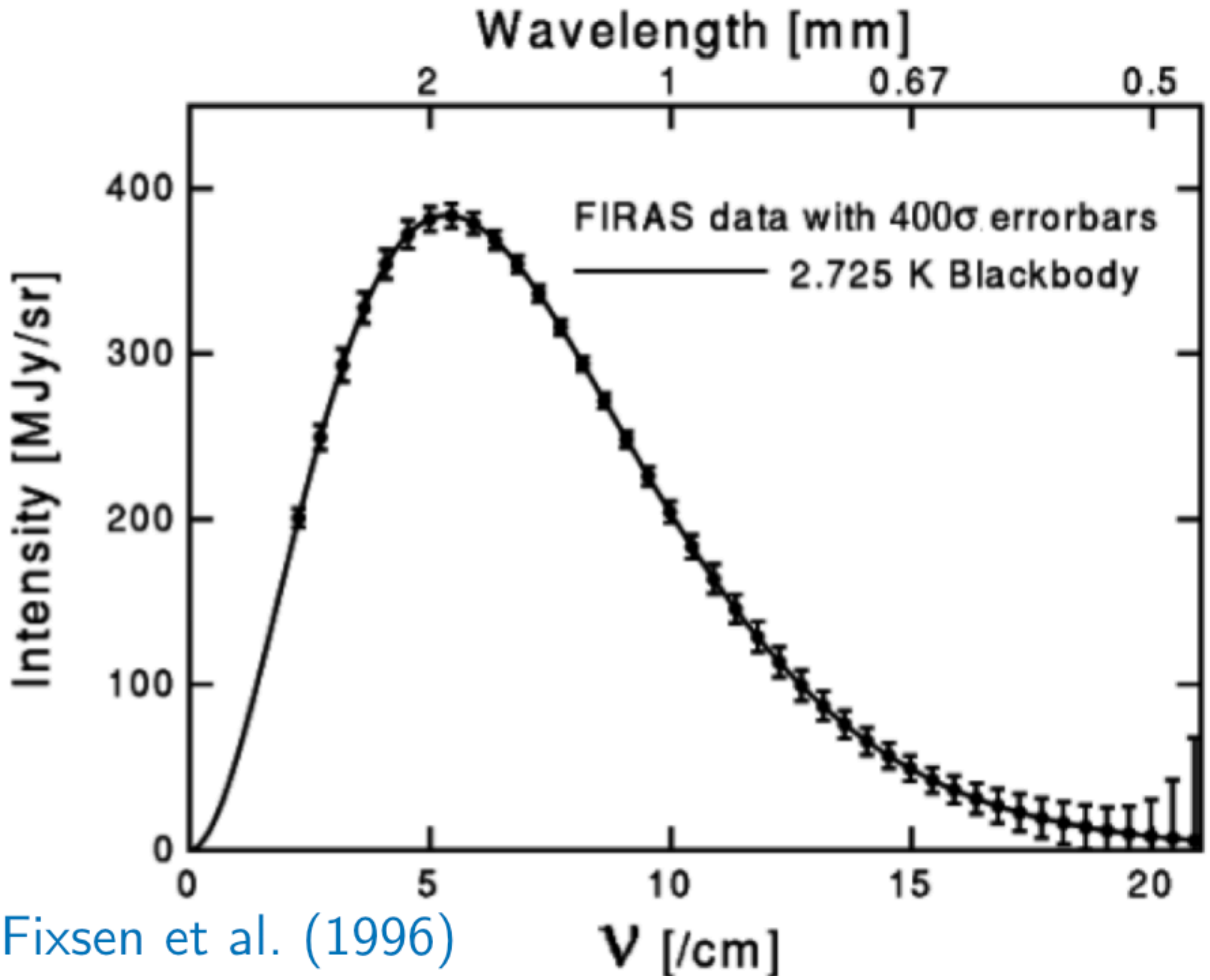
- Synergy: A probe of primordial gravitational waves
  - Progenitors of the PTA signal?
  - Imprints of GWs on CMB observables

- Synergy: 21cm Cosmology and low frequency spectral distortions
  - Detections, excesses, and mysteries?
  - Soft photon heating: The interplay between radio backgrounds and global 21cm observations

What is a CMB spectral distortion?

COBE/FIRAS measured nearly perfect blackbody of the CMB.

$$\frac{\Delta I_\nu}{I_\nu} \lesssim 10^{-5} \qquad I_\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1}$$



Fixsen et al. (1996)

COBE/FIRAS	PIXIE
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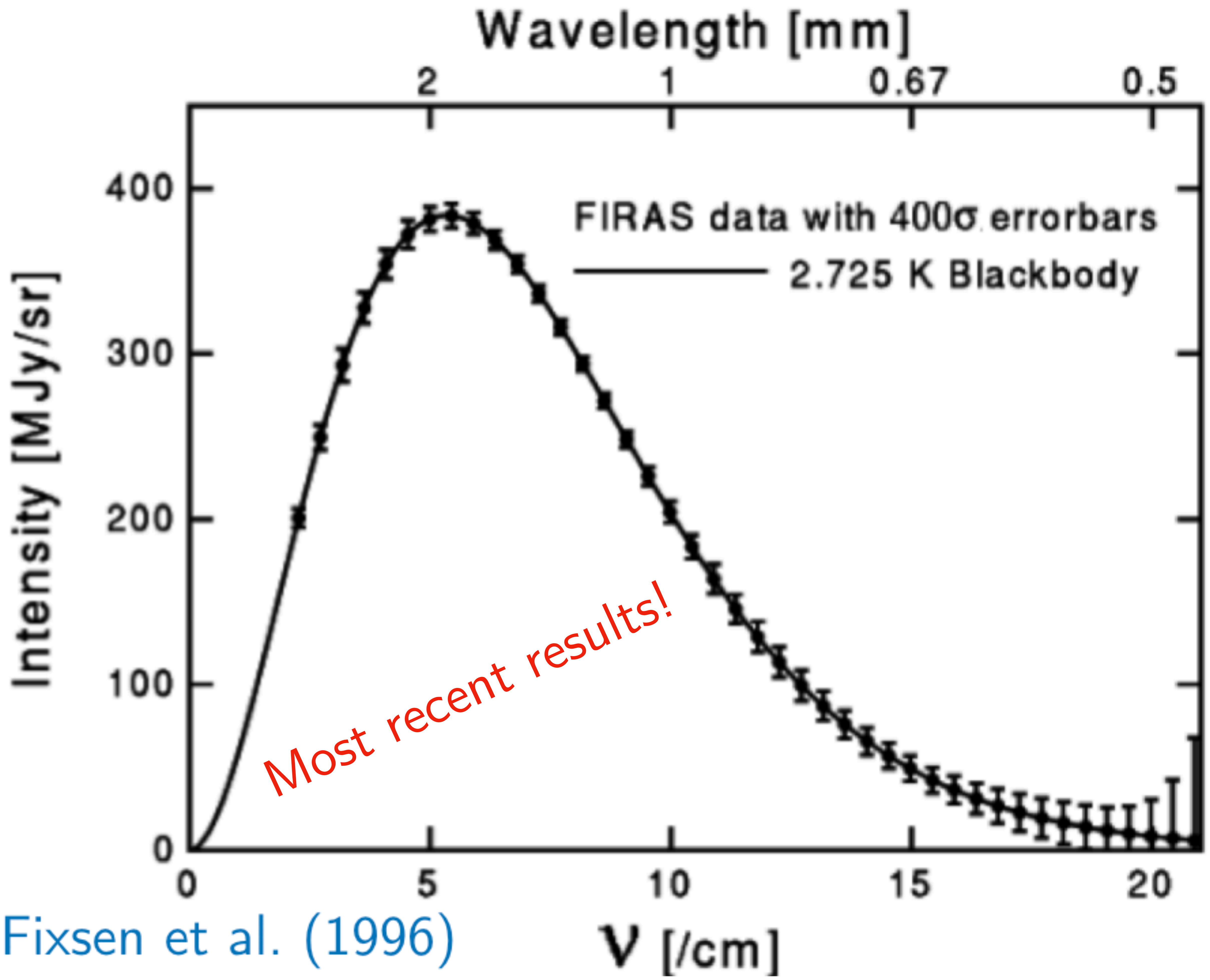

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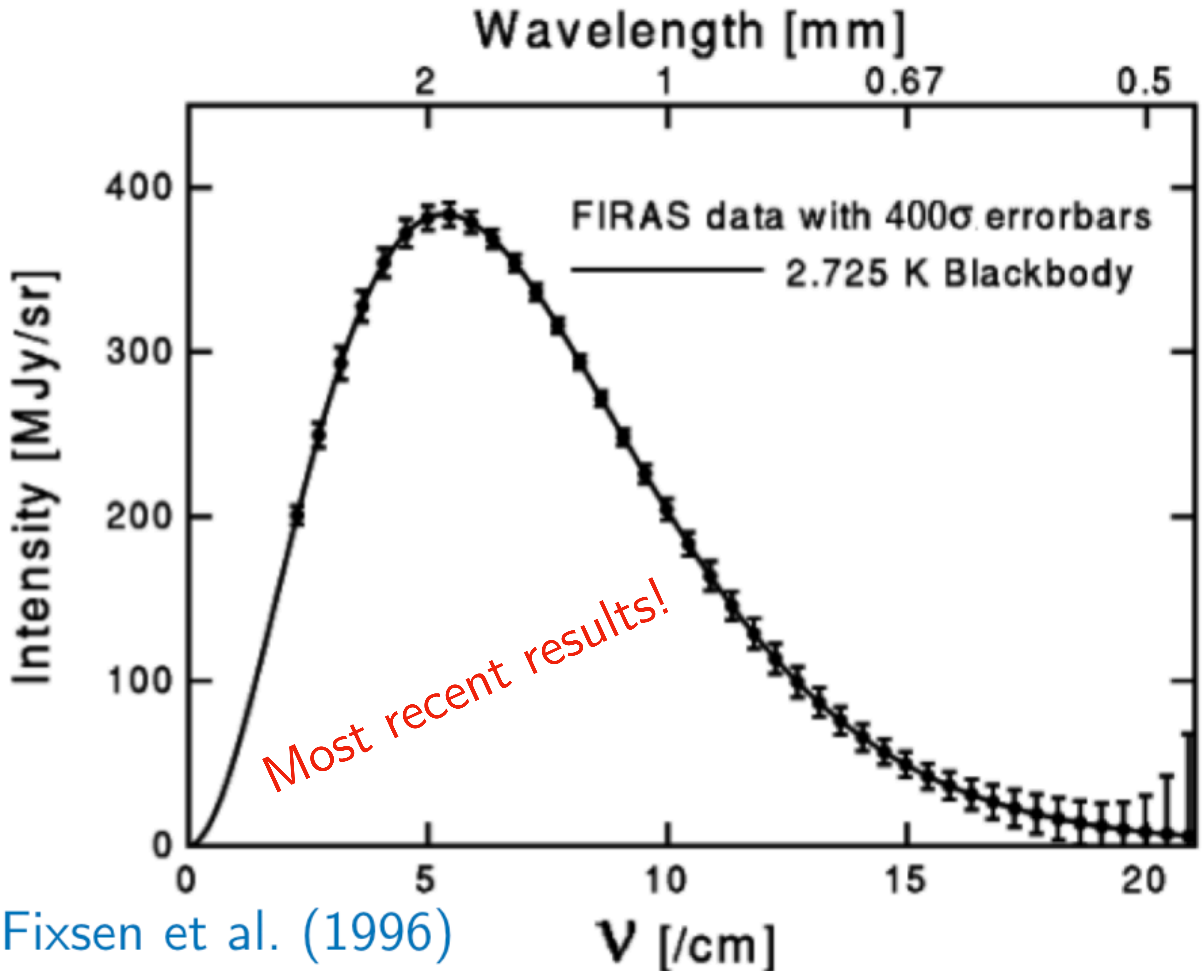

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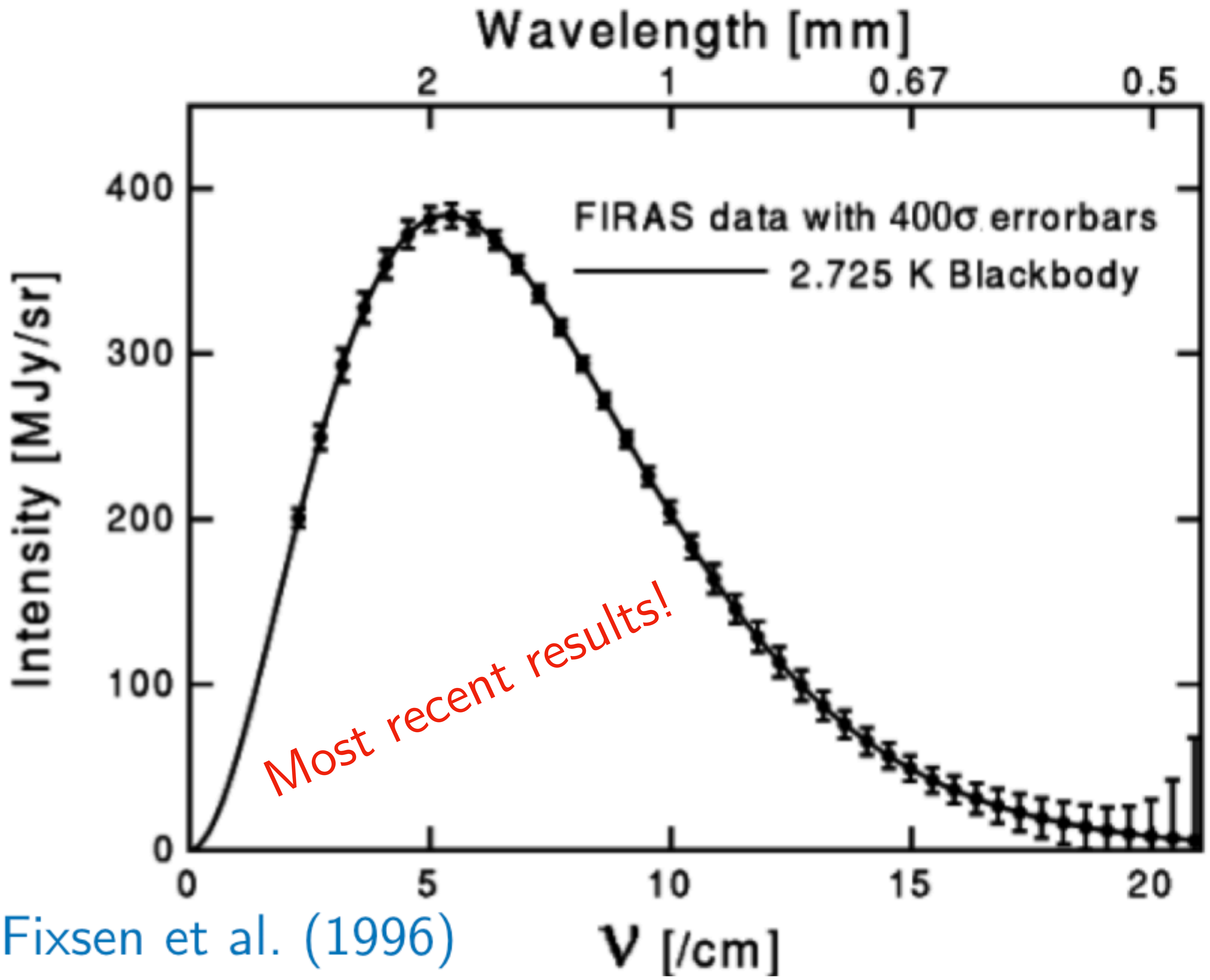

Fixsen et al. (1996)

SM signals at $\Delta I_\nu/I_\nu \simeq 10^{-8}$

Exotic signals?

Thermalization 101

How does one thermalize a distorted spectrum?

- Energy redistribution
- Photon creation/destruction

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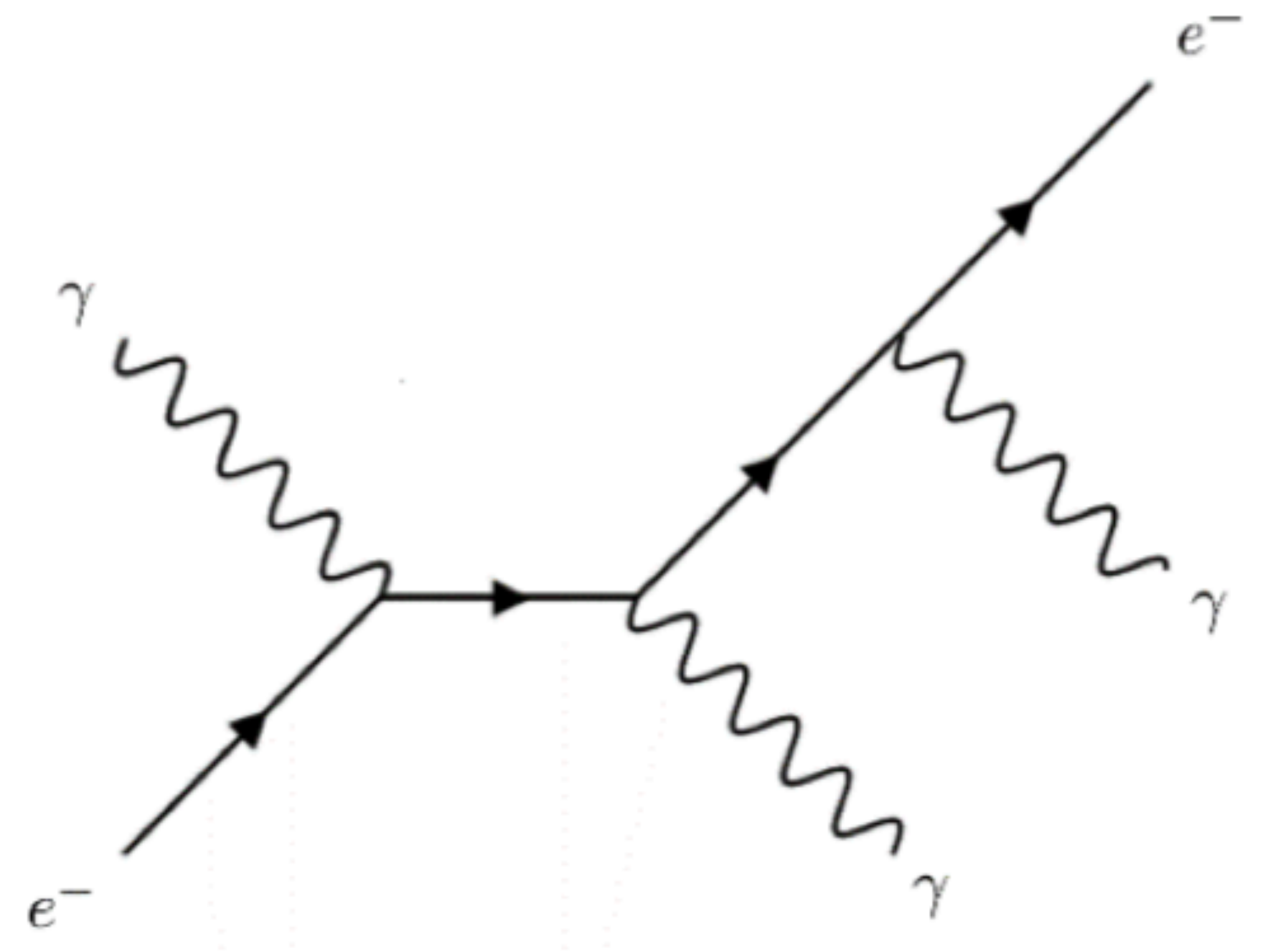
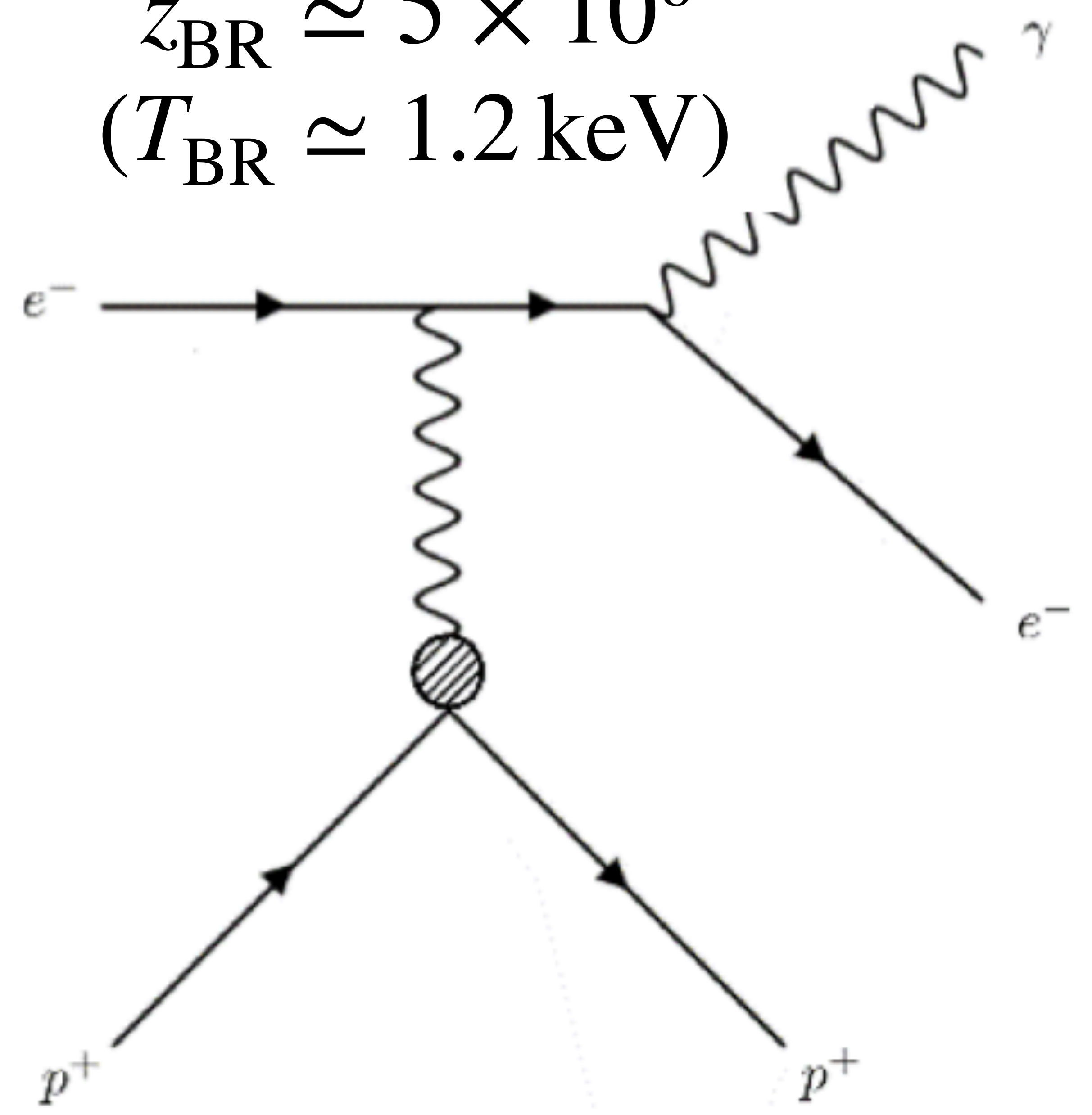
Double Compton
(number changing)

$z_{\mathrm{DC}} \simeq 2 \times 10^6$
$(T_{\mathrm{DC}} \simeq 470\,\mathrm{eV})$



Bremsstrahlung
(number changing)

$z_{\mathrm{BR}} \simeq 5 \times 10^6$
$(T_{\mathrm{BR}} \simeq 1.2\,\mathrm{keV})$



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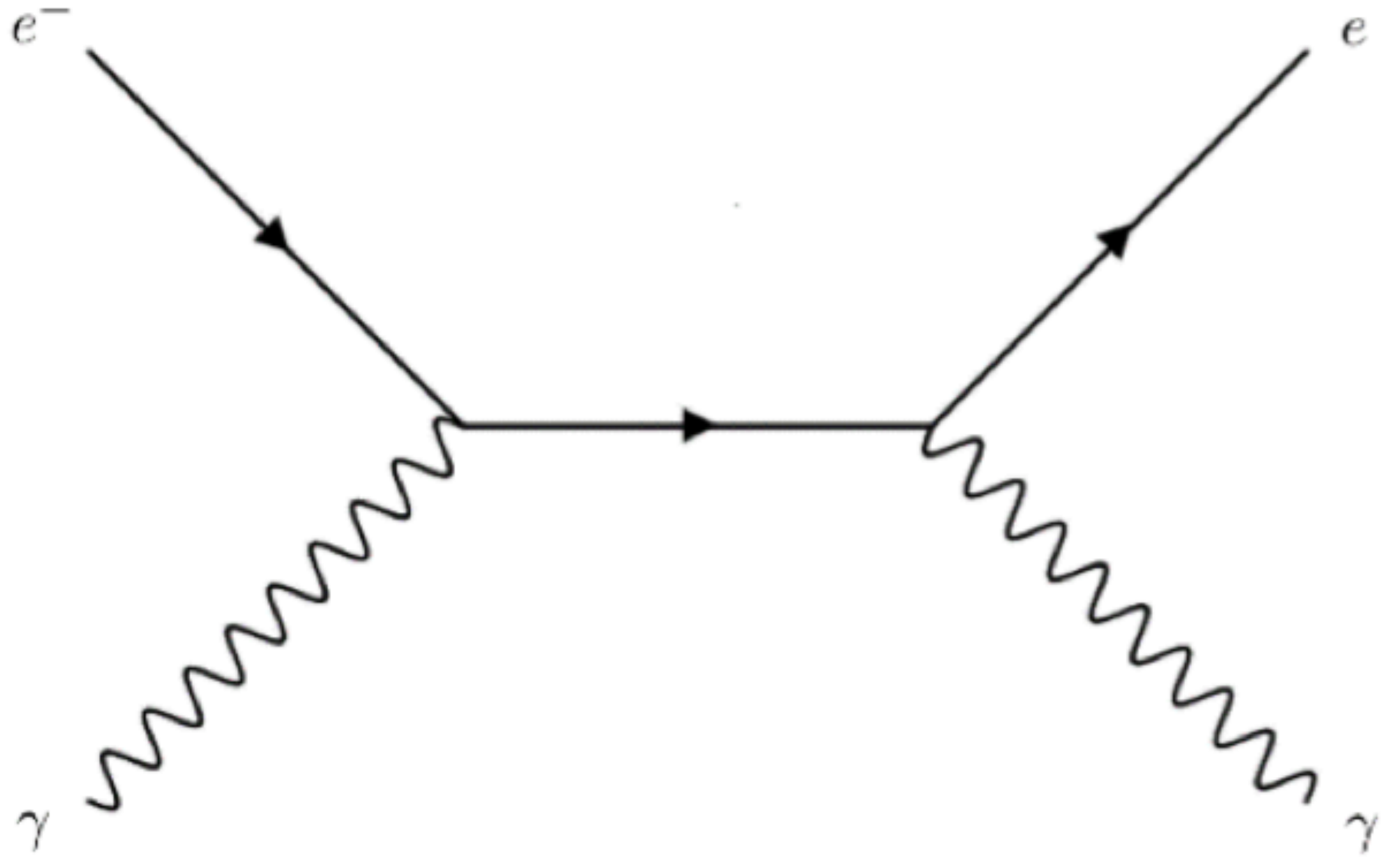

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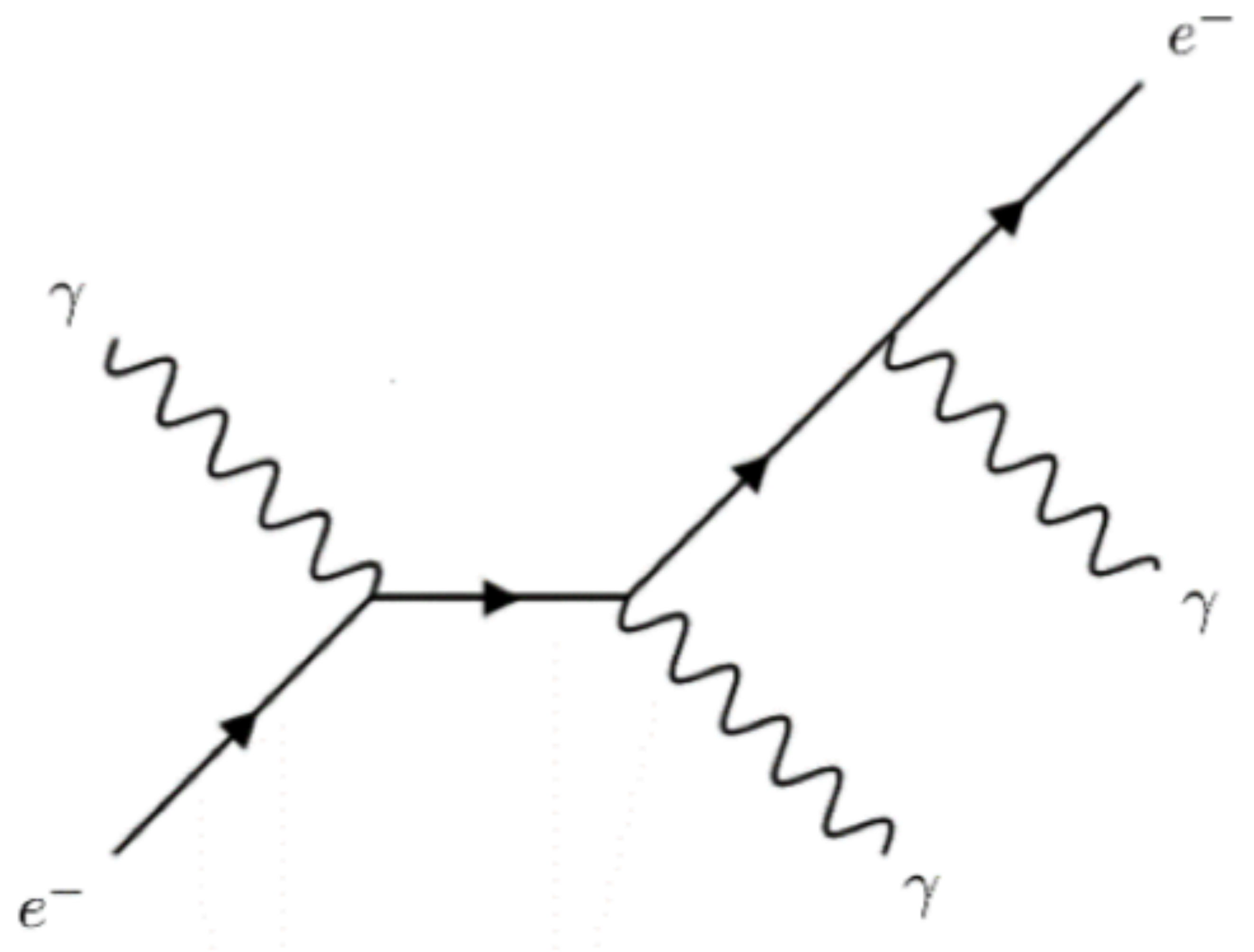

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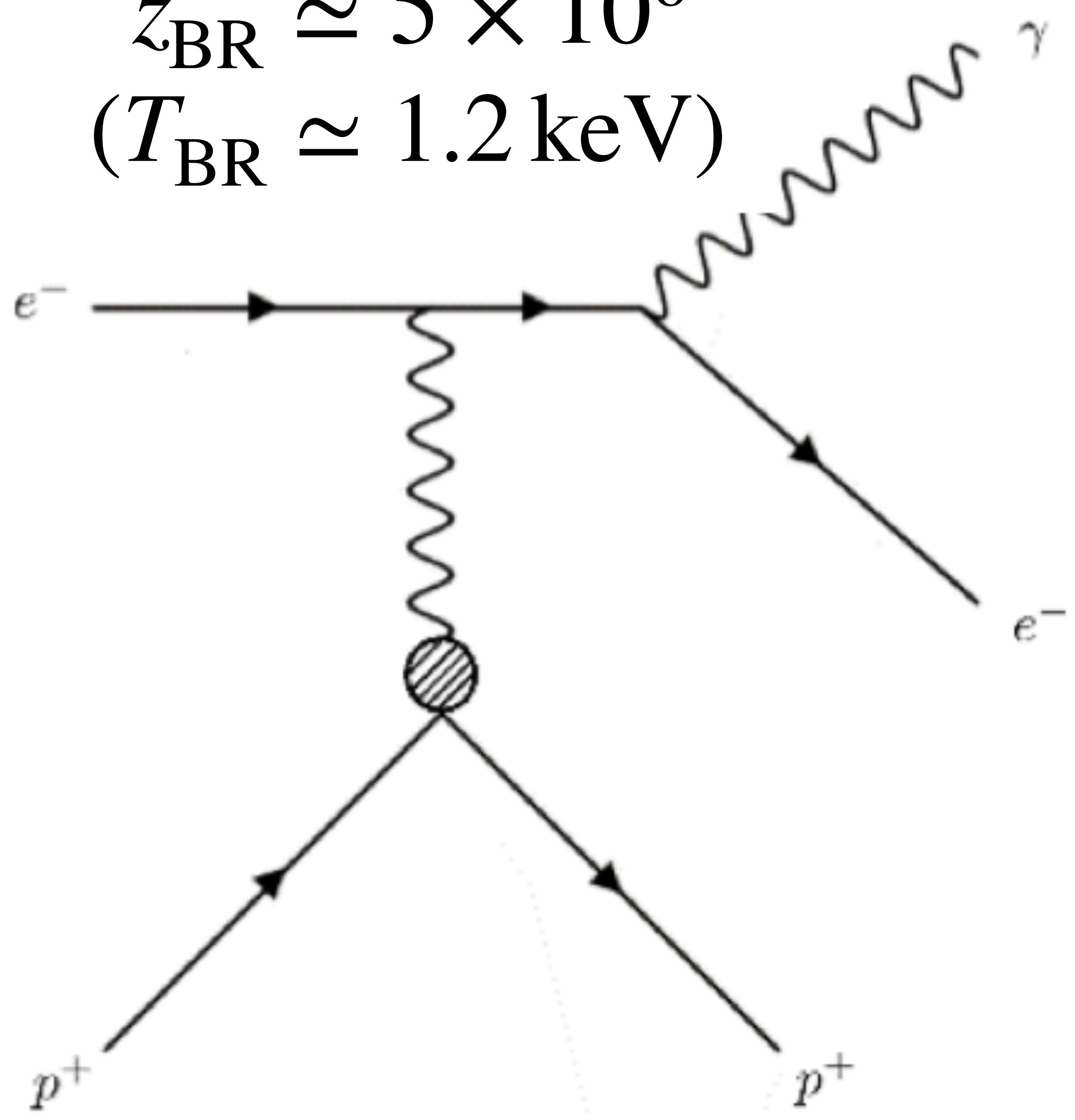

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μ-window: $5 \times 10^4 \lesssim z \lesssim 2 \times 10^6$

y-window: $z \lesssim 5 \times 10^4$

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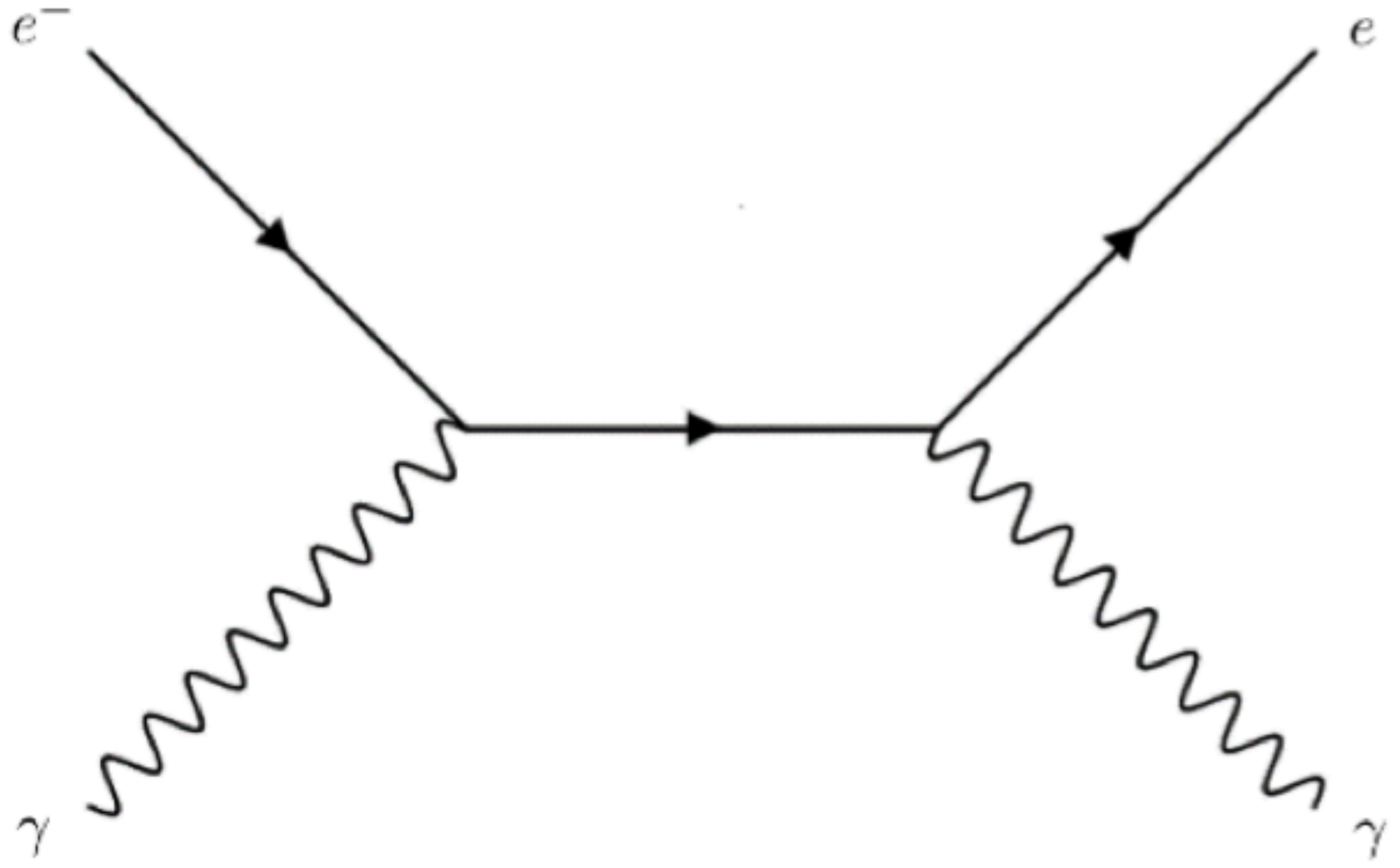

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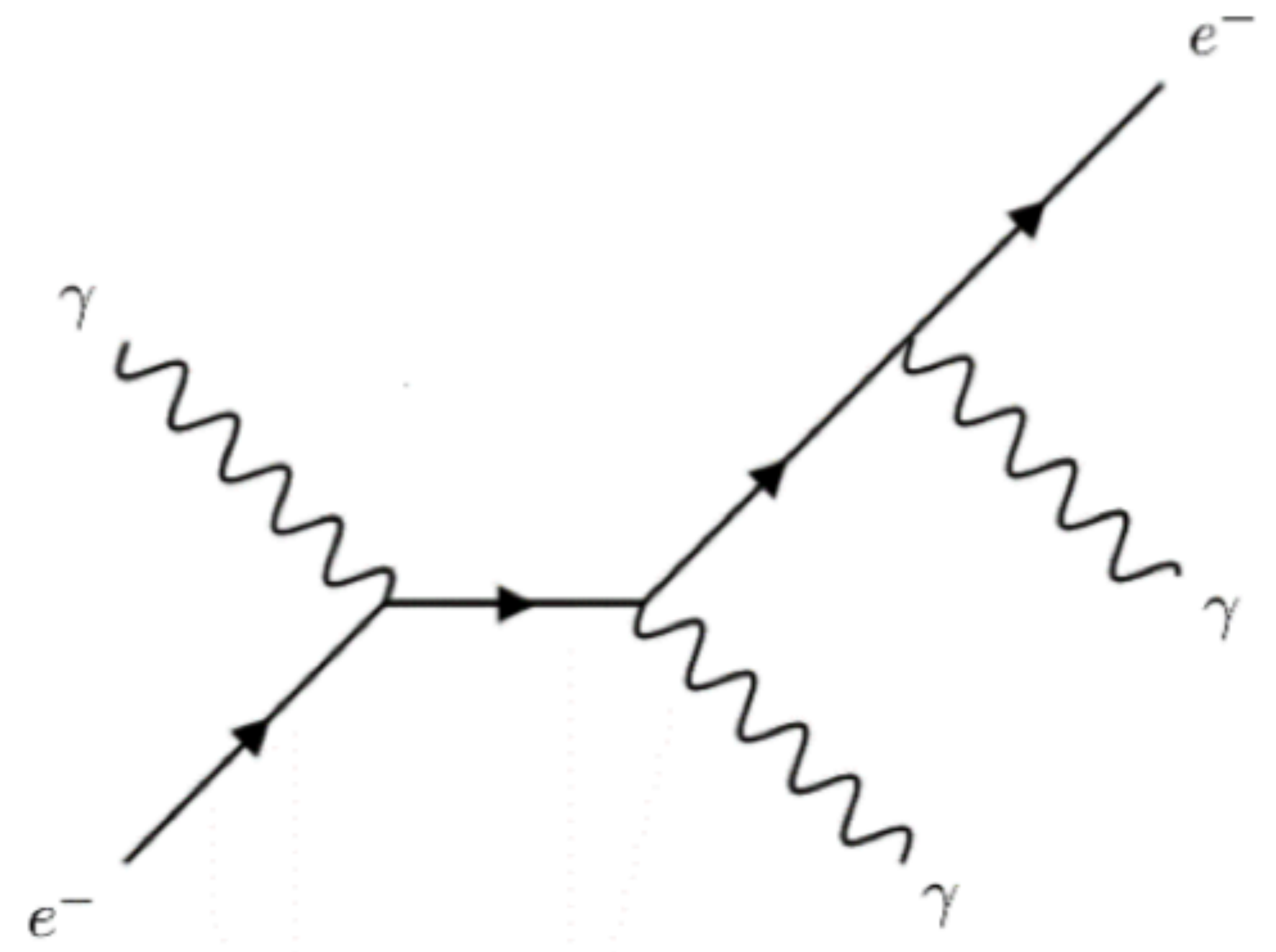

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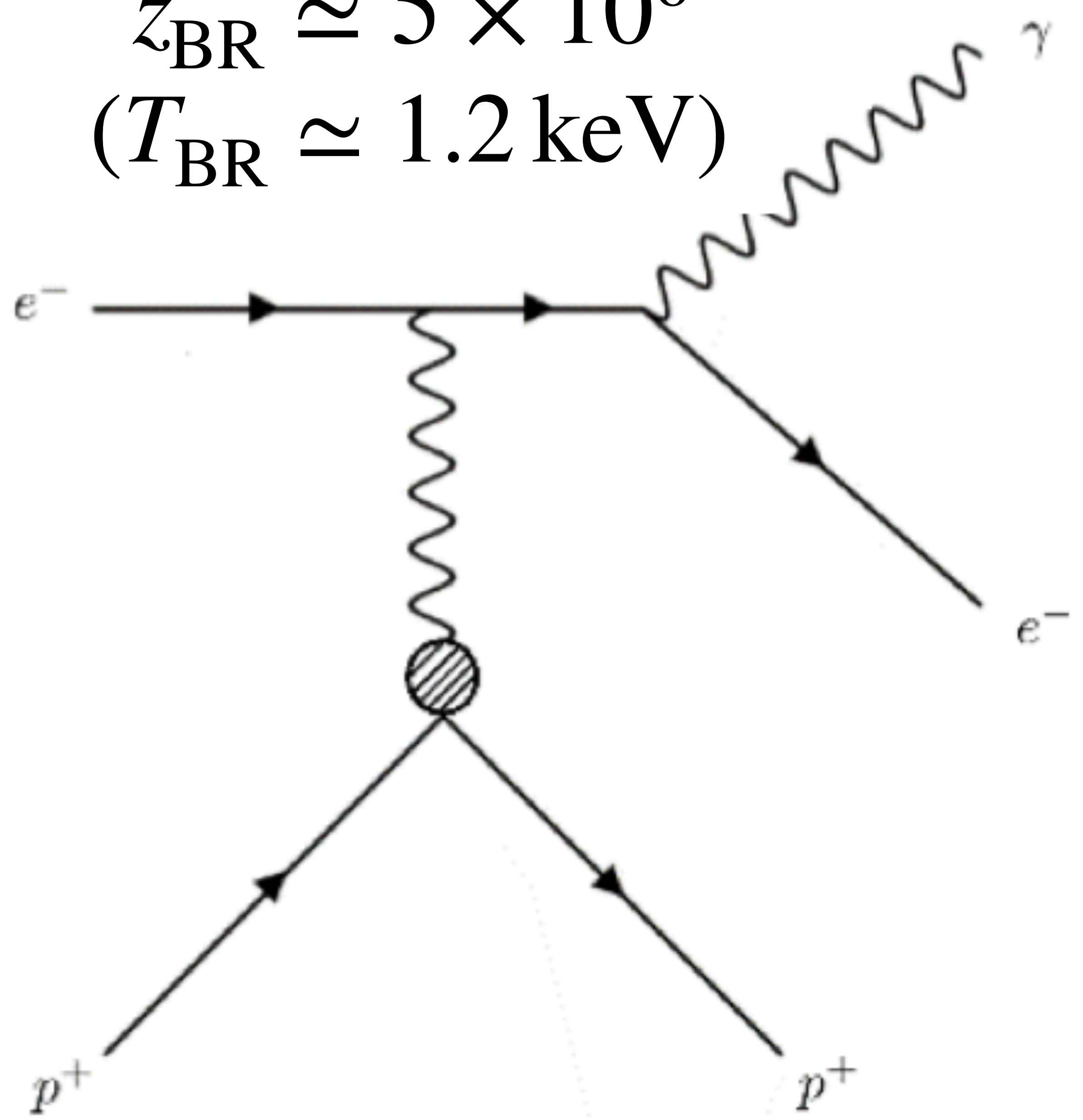
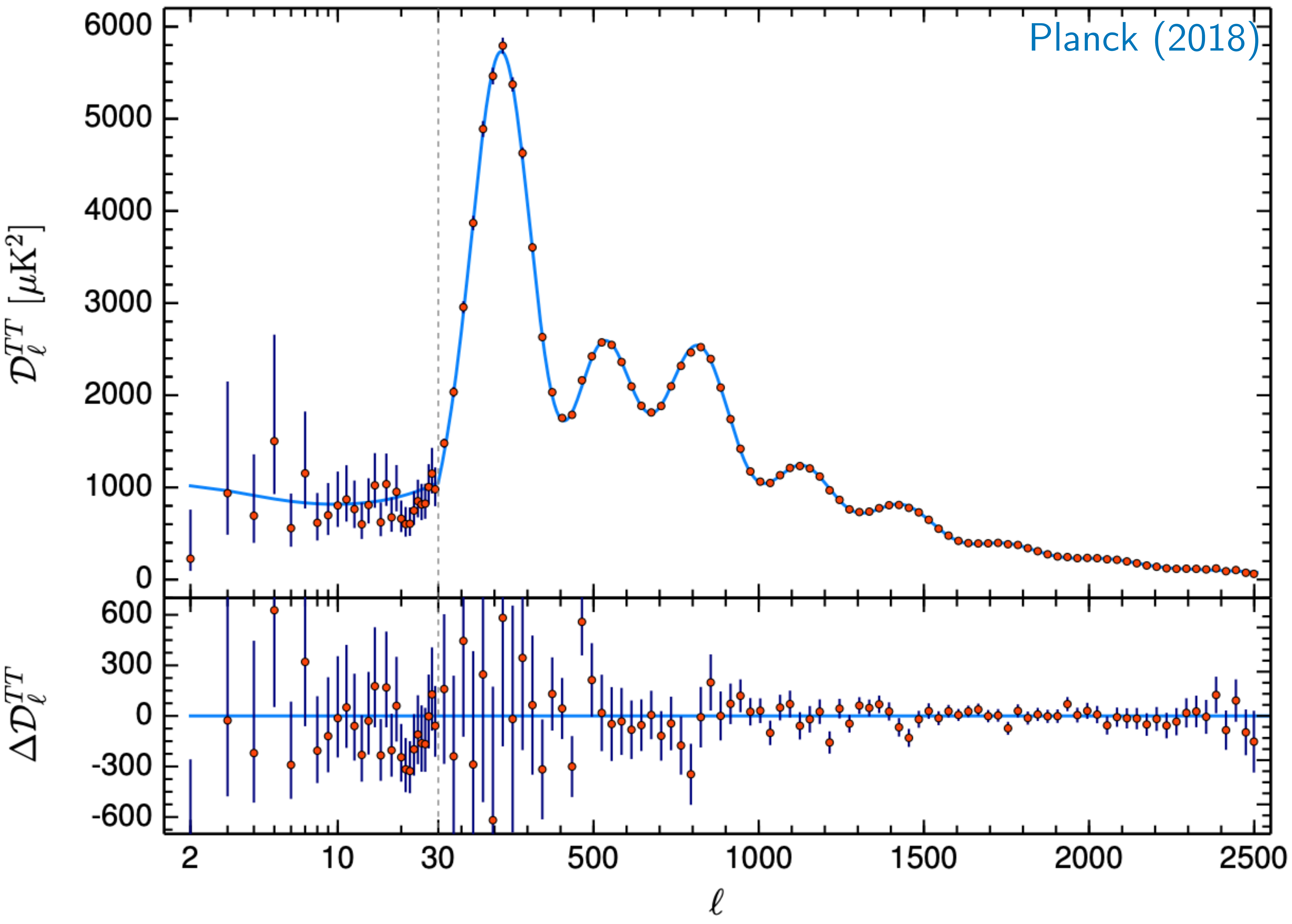


Silk damping: A standard model signal

Modes enter the horizon, begin to oscillate, and suffer diffusion (Silk) damping as electrons and photons of different temperatures mix.

Measured amplitude of small scale modes are greatly suppressed.

Where does that initial energy go? Into the plasma!



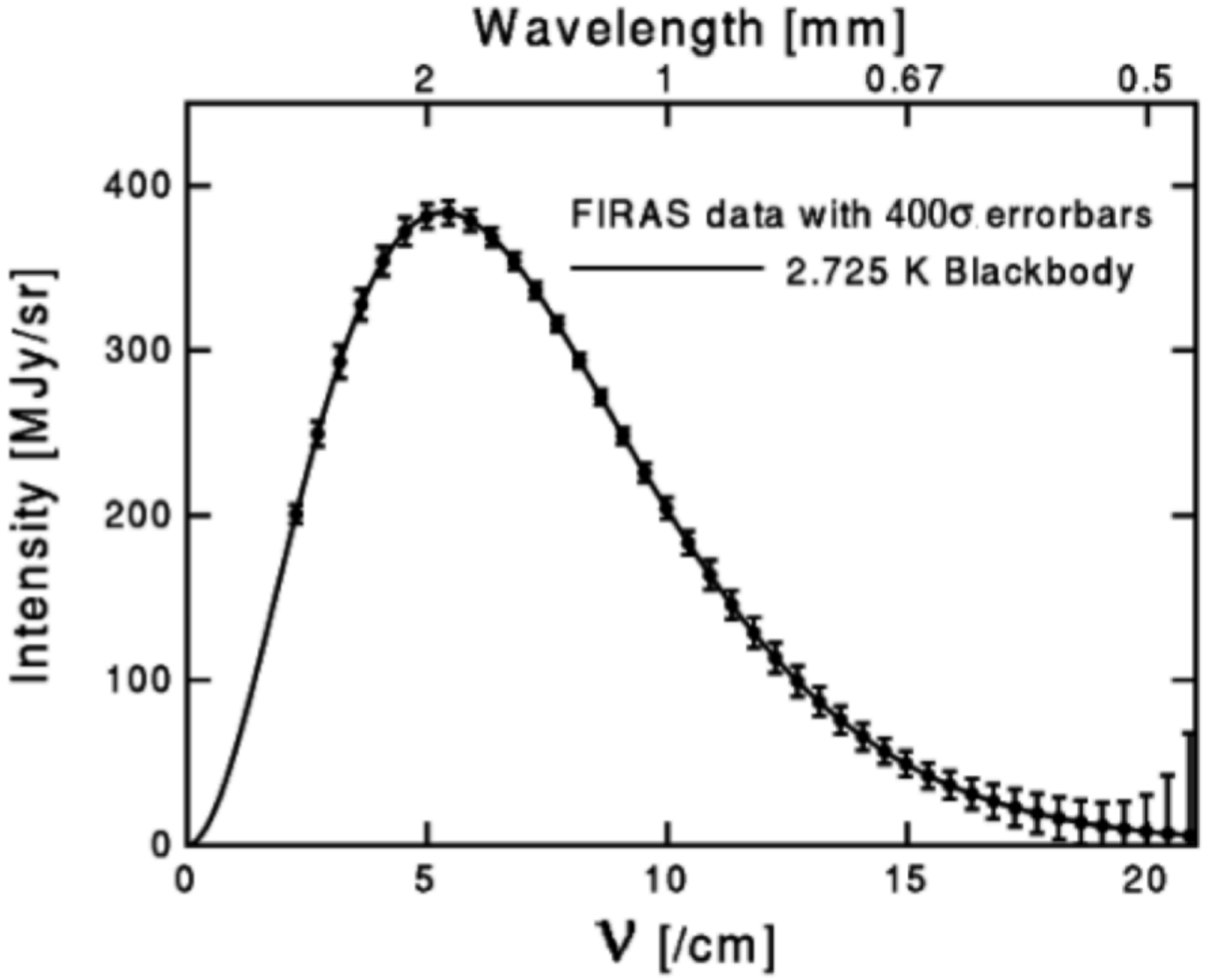
Mixing of blackbodies

Hu and Sugiyama (1995)
Chluba, Khatri, Sunyaev (2012)
BC et al. (2023a)

The sum of unequal temperature BBs will not produce a thermal spectrum.

$T - \delta T$ | $T + \delta T$ | $\rho_{\rm av} \propto T^4[1 + 6(\delta T/T)^2]$

$\mu, y = 0$ | $\mu, y = 0$ | $\mu = 2.8\left(\frac{\delta T}{T}\right)^2, \quad y = \frac{1}{2}\left(\frac{\delta T}{T}\right)^2$



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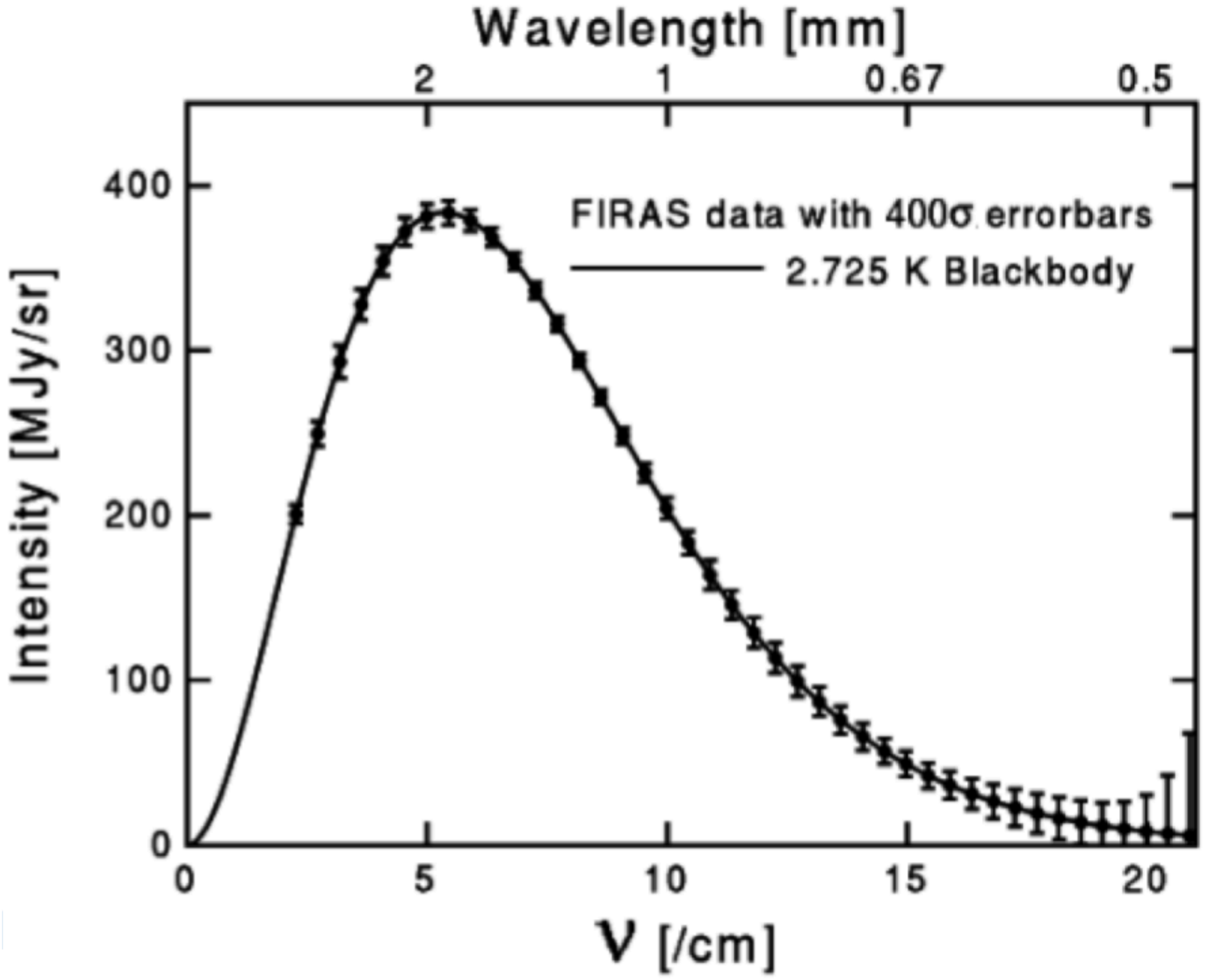

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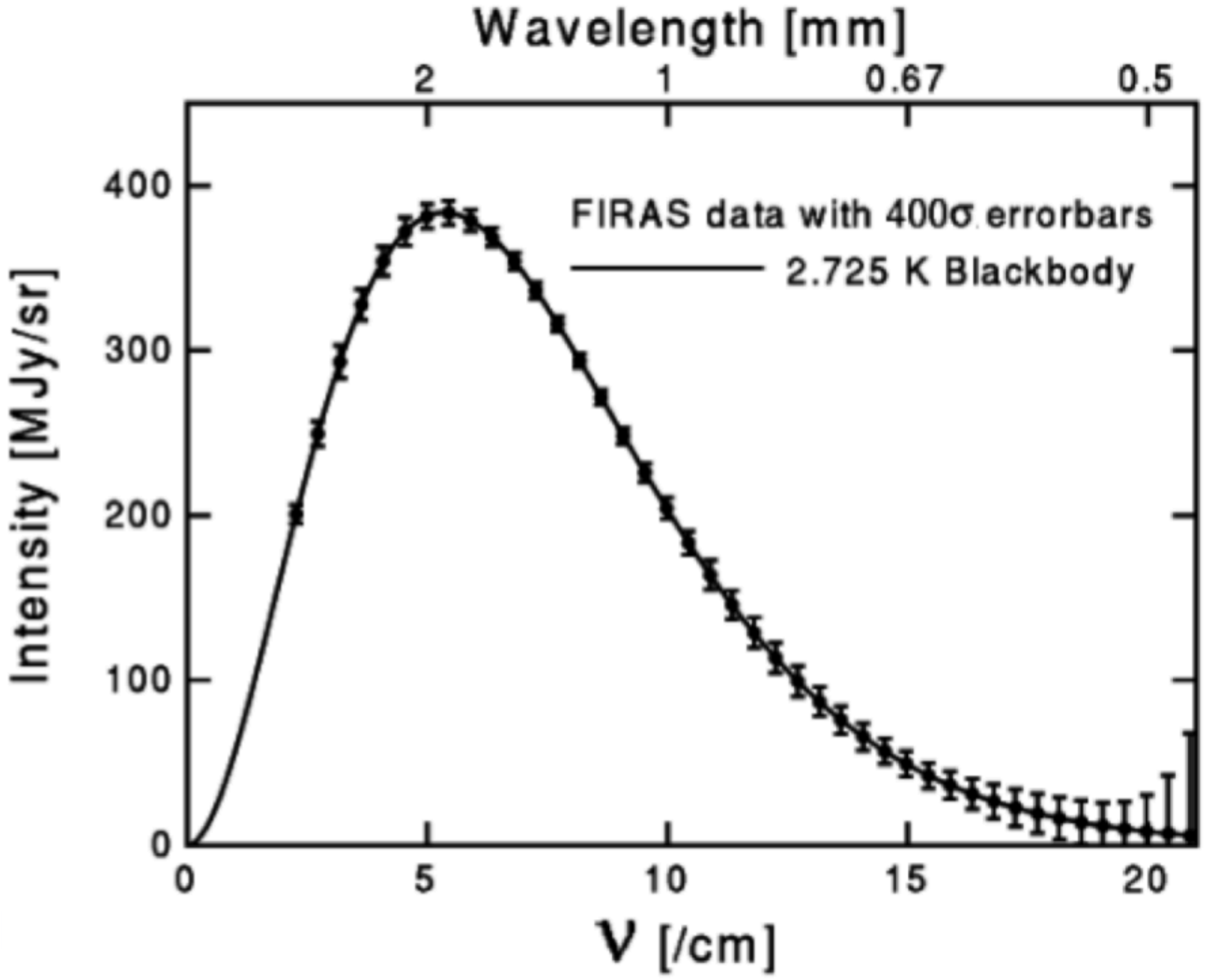

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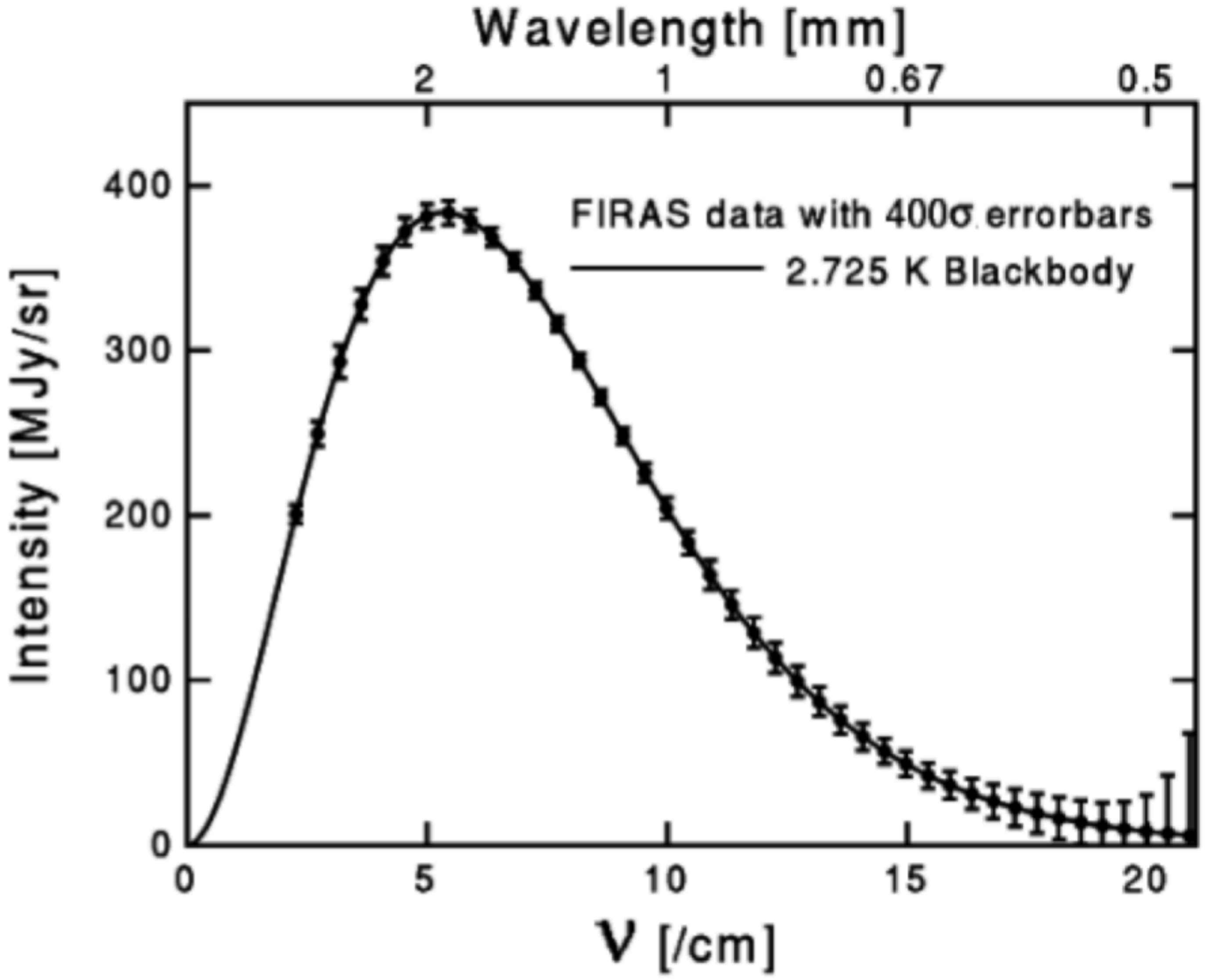

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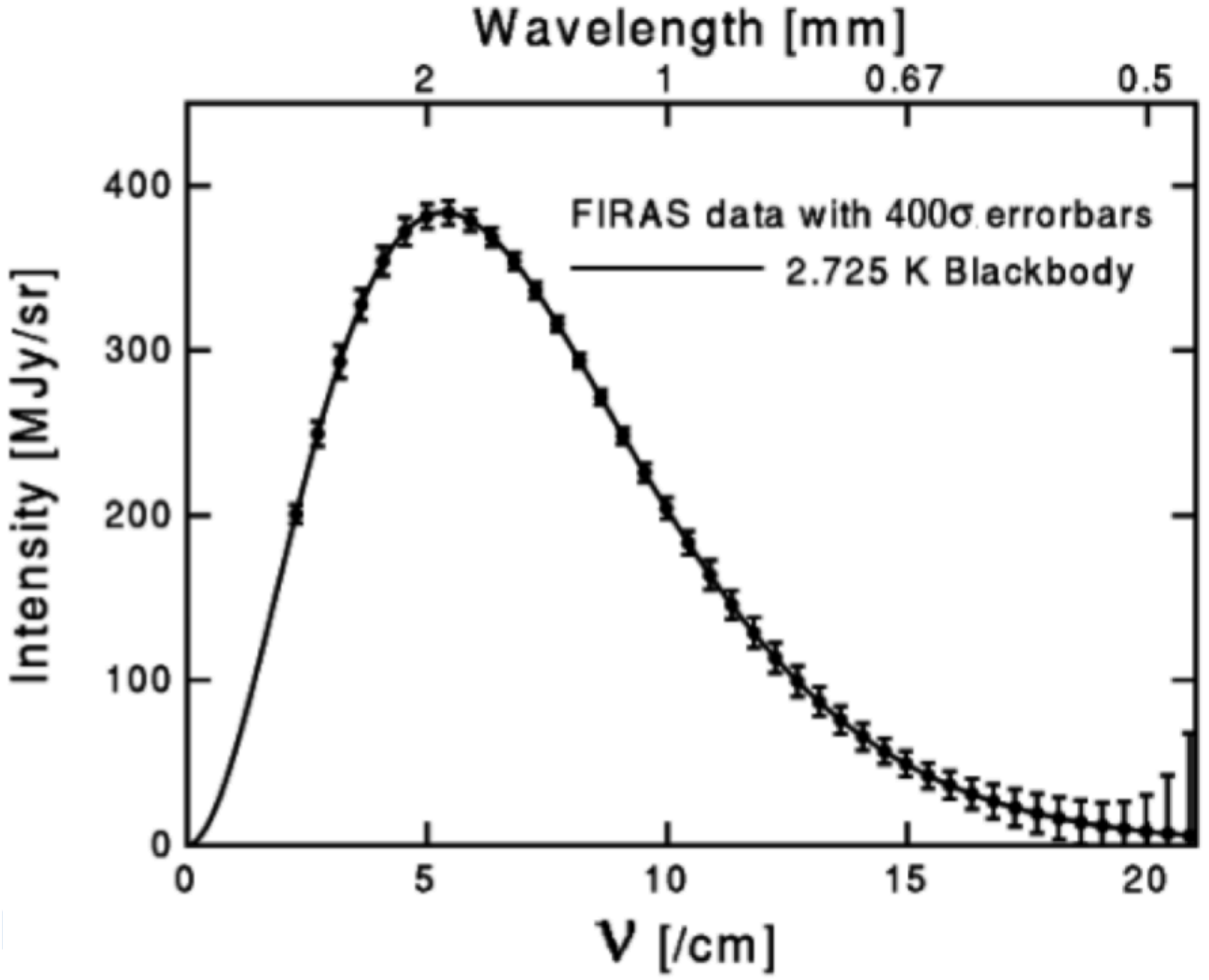

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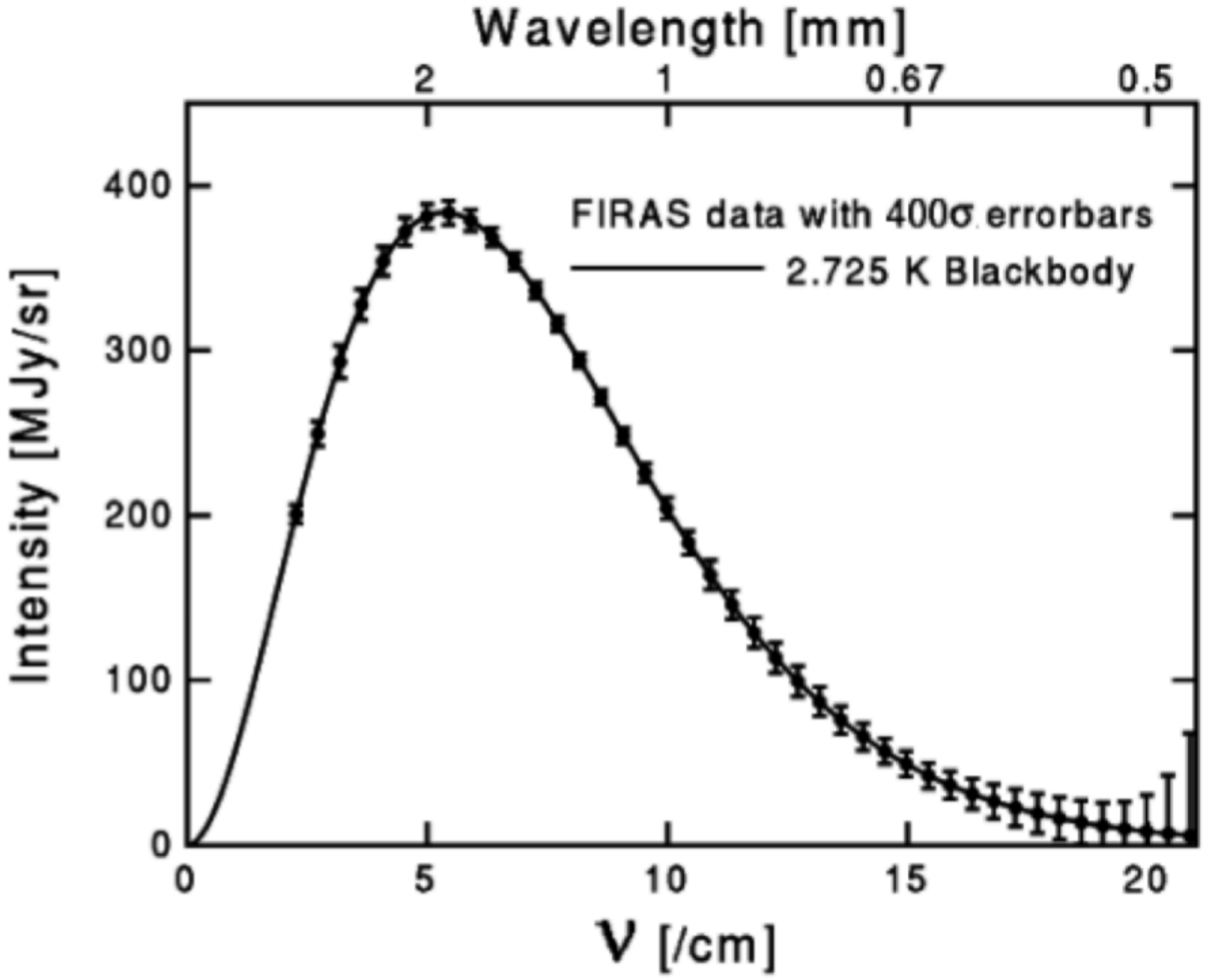
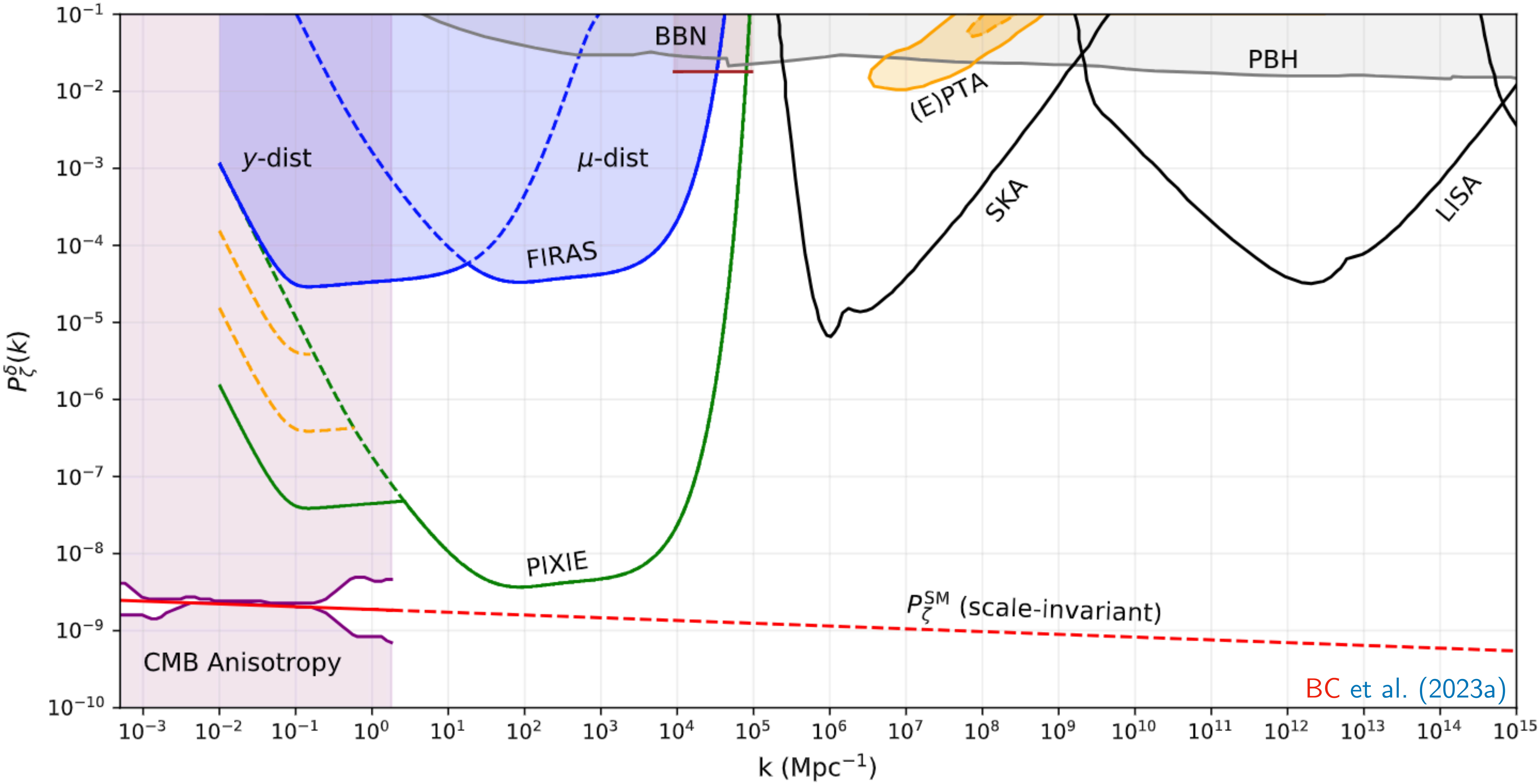


SDs sensitive to A_s at $50\,{\rm Mpc}^{-1} \lesssim k \lesssim 10^4\,{\rm Mpc}^{-1}$
Silk damping prediction: $\mu \simeq 2 \times 10^{-8}$

The scalar primordial power spectrum (PPS)



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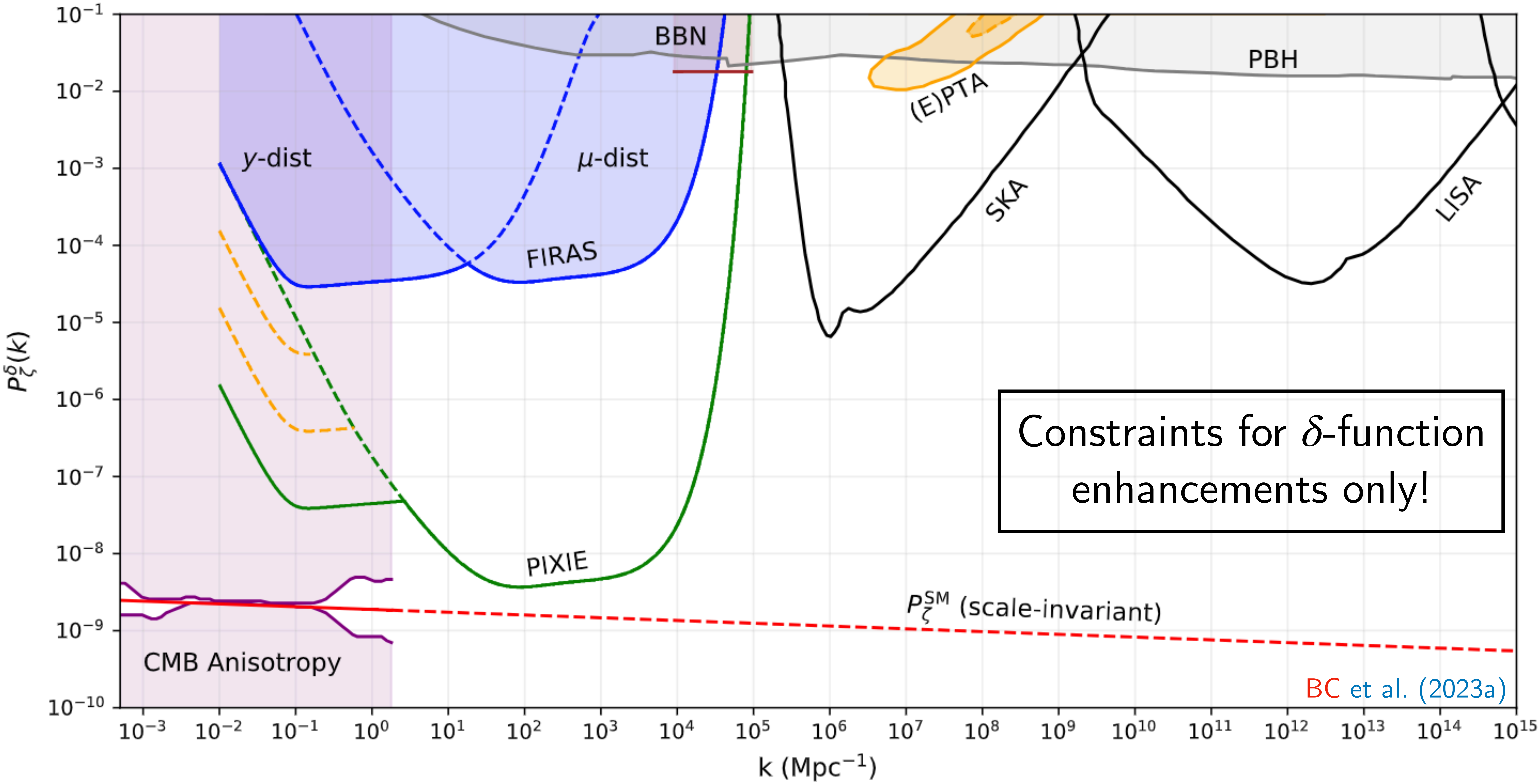
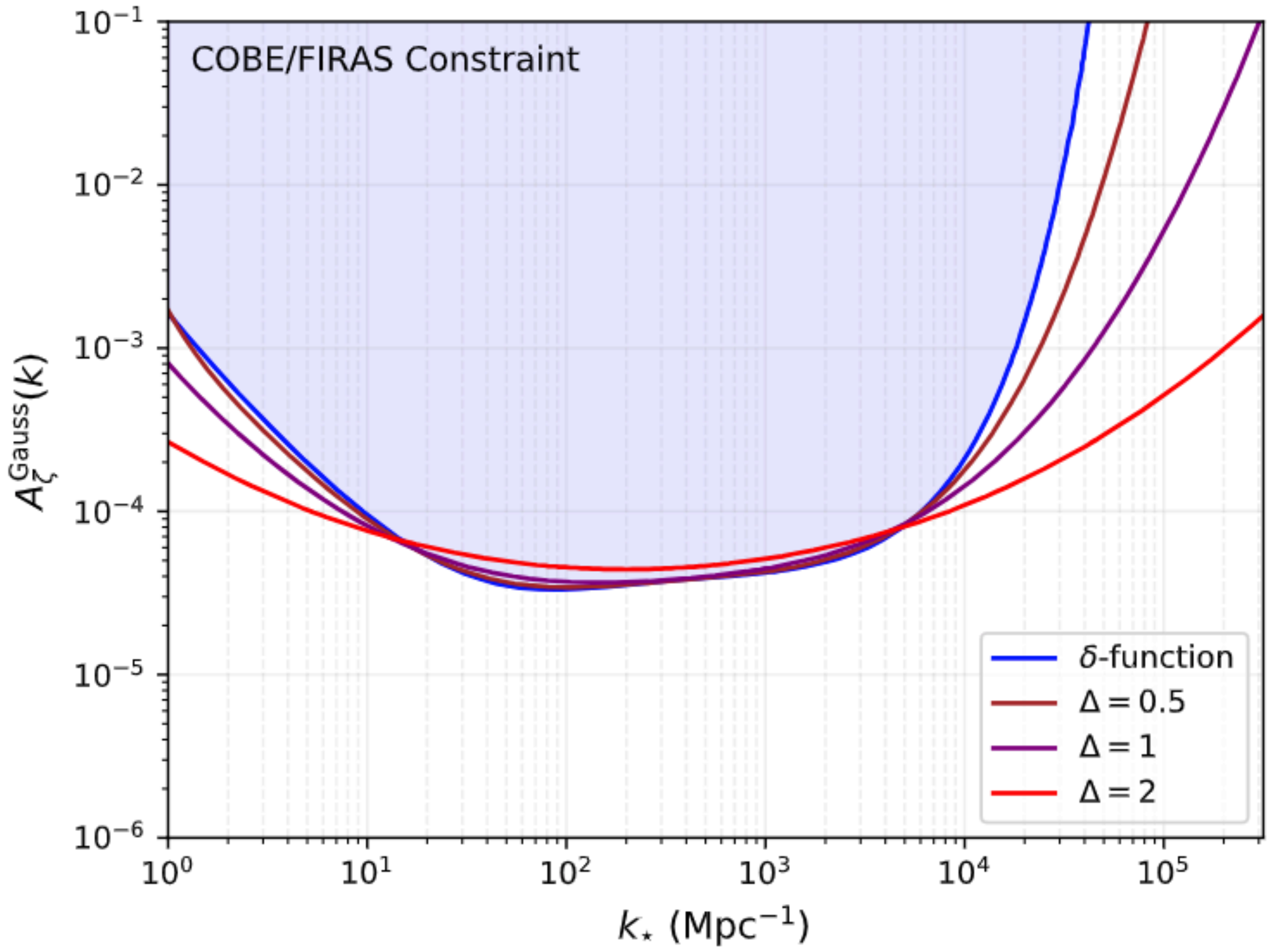


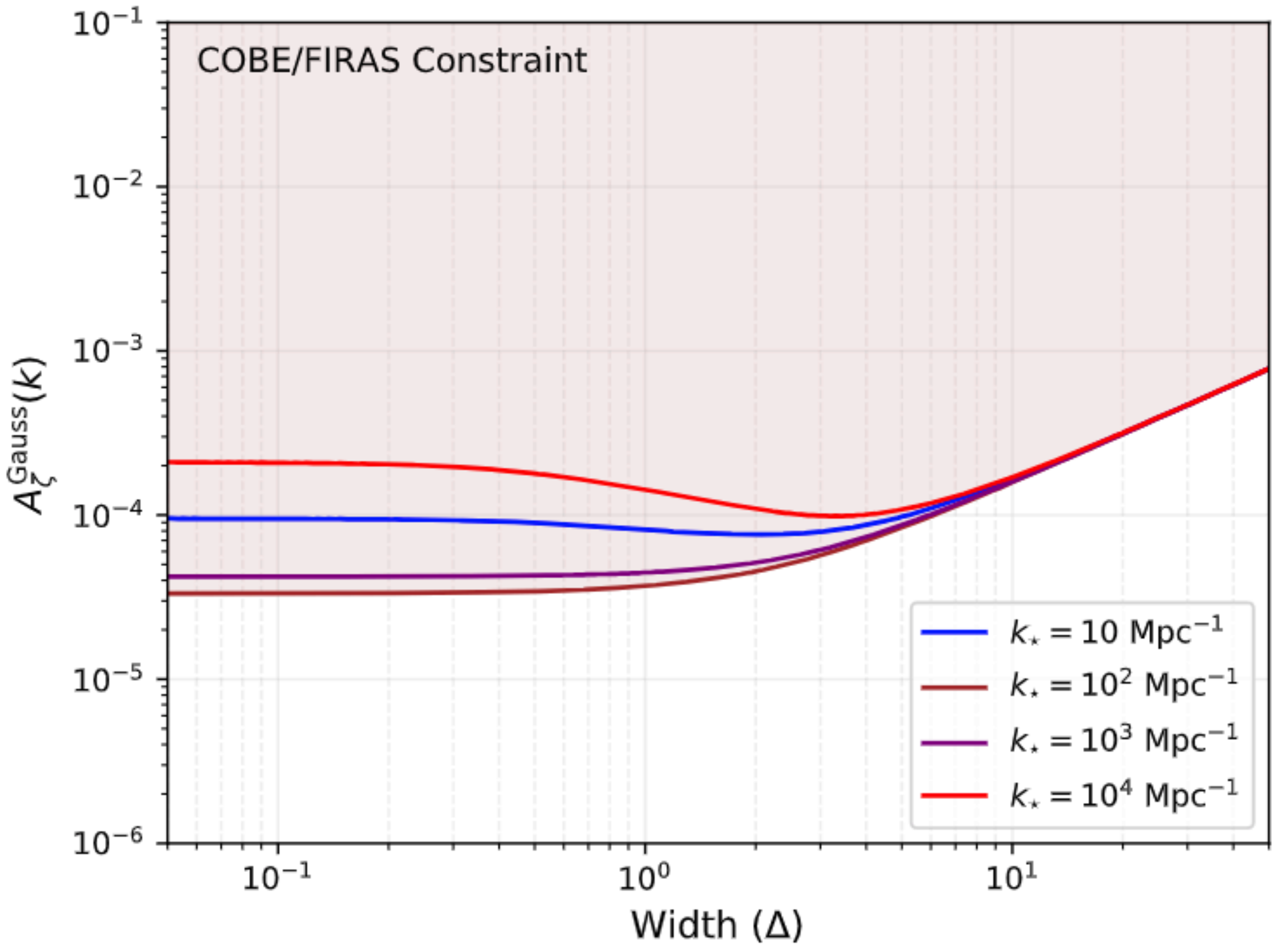
Constraints for δ-function enhancements only!

BC et al. (2023a)

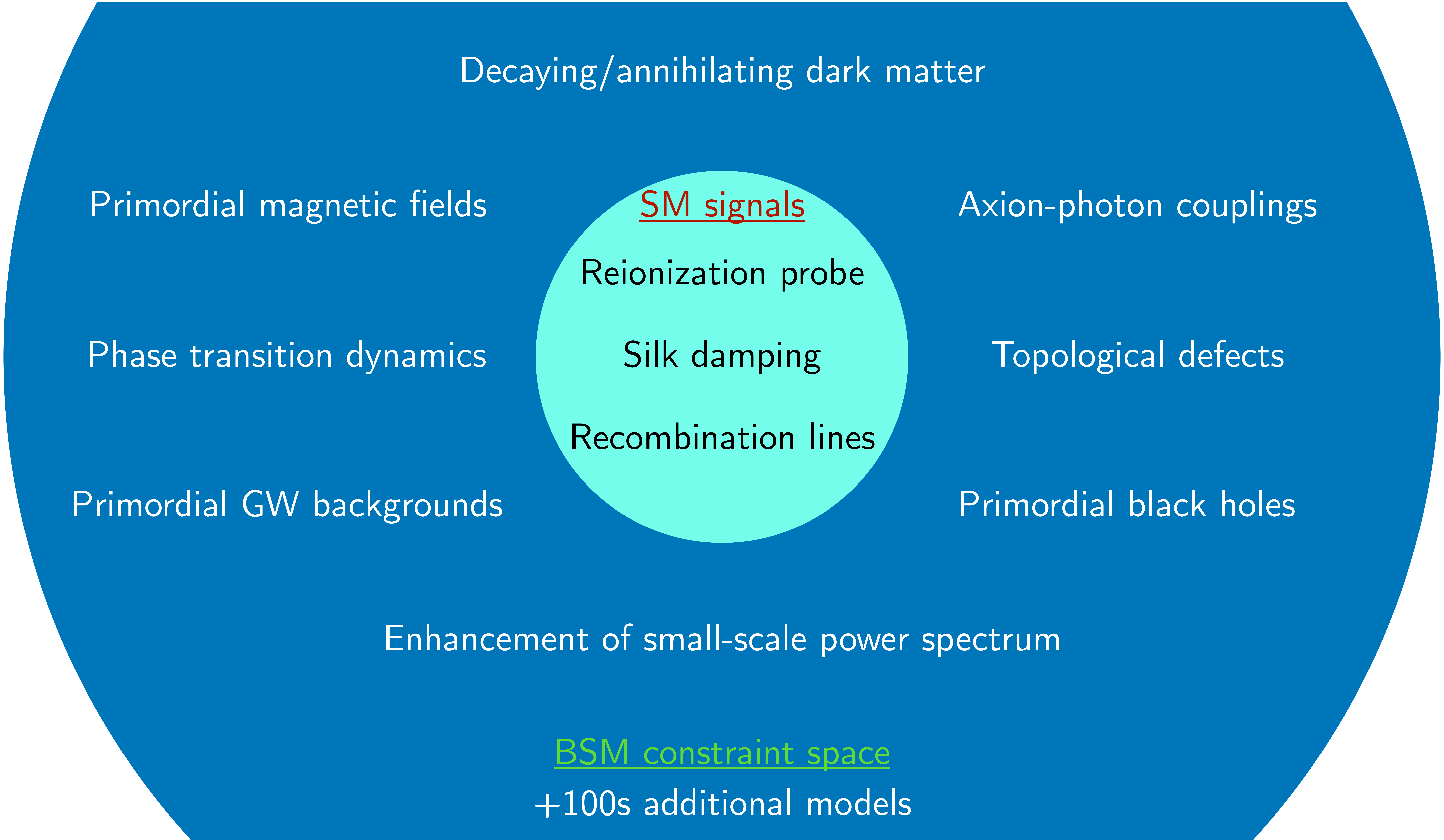
Different shapes: Gaussian peak

$$\mathscr{P}_\zeta^{\text{Gauss}} = \frac{A_\zeta^{\text{Gauss}}}{\sqrt{2\pi}\Delta}\exp\left[-\frac{1}{2}\left(\frac{\ln(k)-\ln(k_*)}{\Delta}\right)^2\right]$$





A powerful probe of exotic physics



Experimental prospects

Ground-based:

- TMS - Targeting 10-20 GHz region, ARCADE-2 coverage.
- COSMO - Measuring from Antarctica, target is global SZ signal.

Balloon-based:

- BISOU - Balloon targeting global SZ distortion $(y \simeq 10^{-6})$.
  Recently entered phase A, measurement late 2020s (!!!)

Space-based:

- COBE/FIRAS - Early 90s mission, measured $\Delta I_\nu / I_\nu \lesssim 10^{-5}$.
- PIXIE - Proposed and rejected multiple times, target $\Delta I_\nu / I_\nu \lesssim 10^{-8}$.
- ESA Voyage2050 - Stay tuned...

Gravitational wave backgrounds

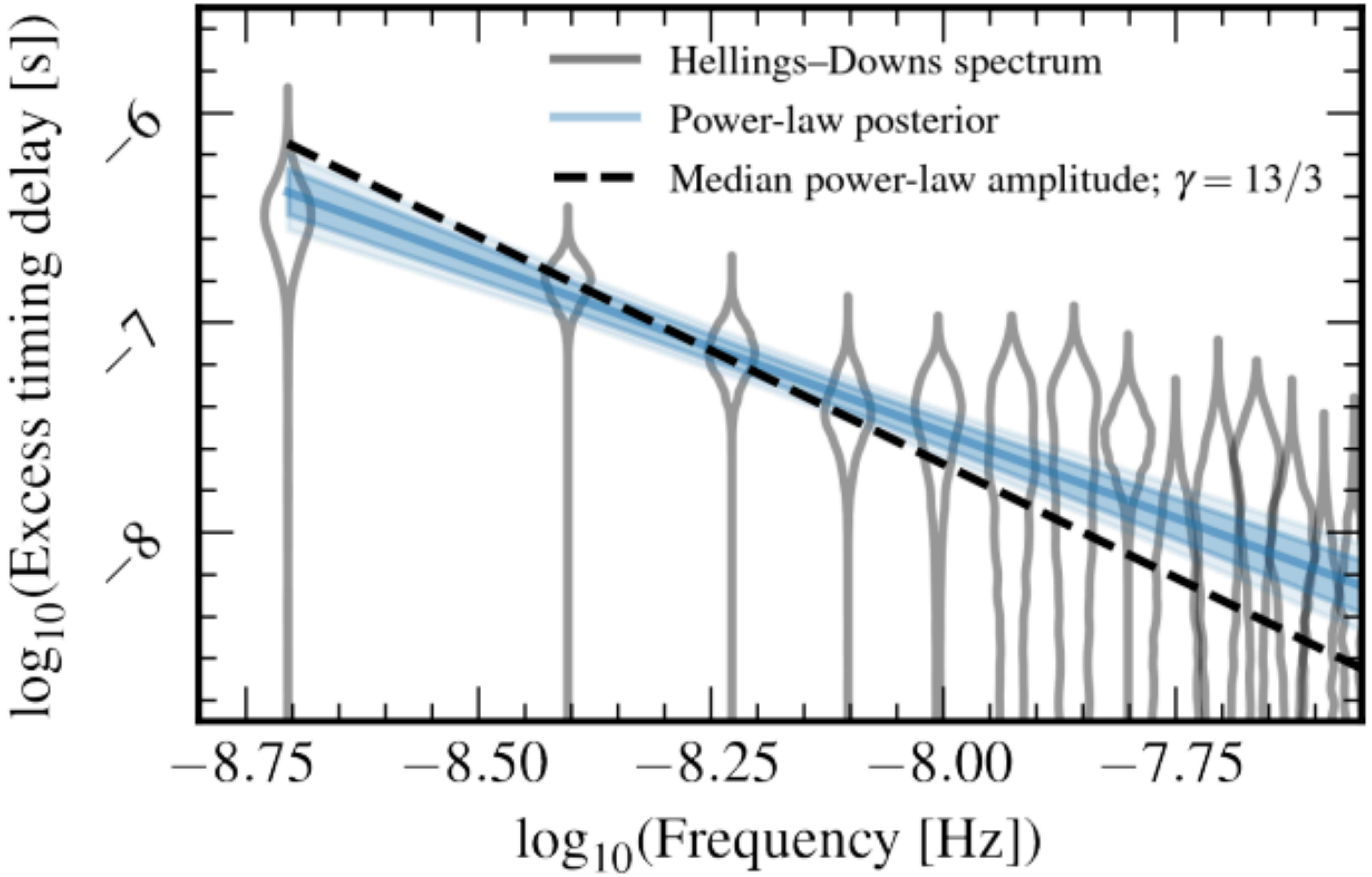
$+$

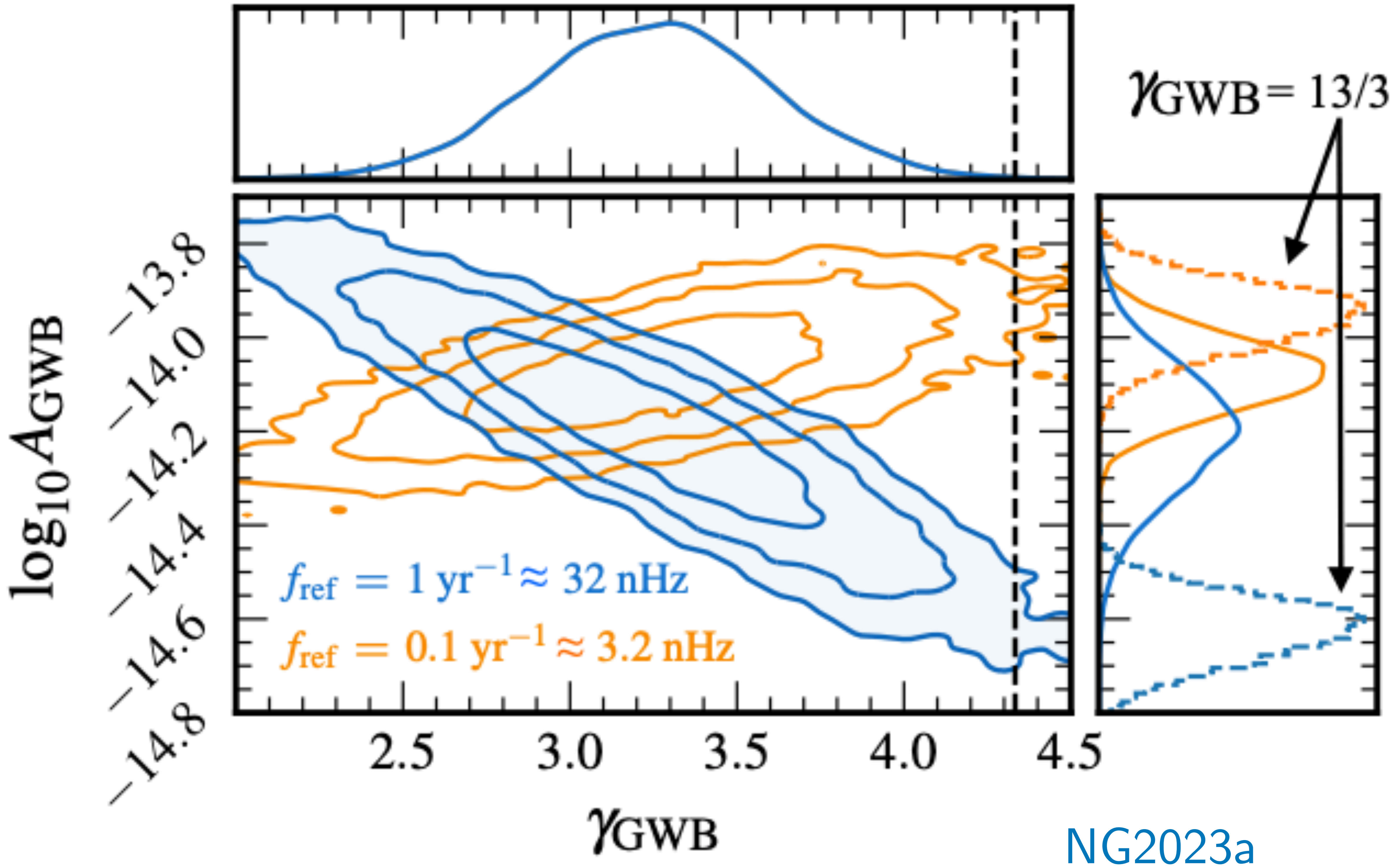
CMB spectral distortions

What exactly did the PTA consortium see?

Standard model expectation: SMBHBs, power law w/ index $\gamma = 13/3$.

Exotic models? Primordial or astrophysical? Can we disentangle?





NG2023a

Scalar Induced Gravitational Waves (SIGWs)

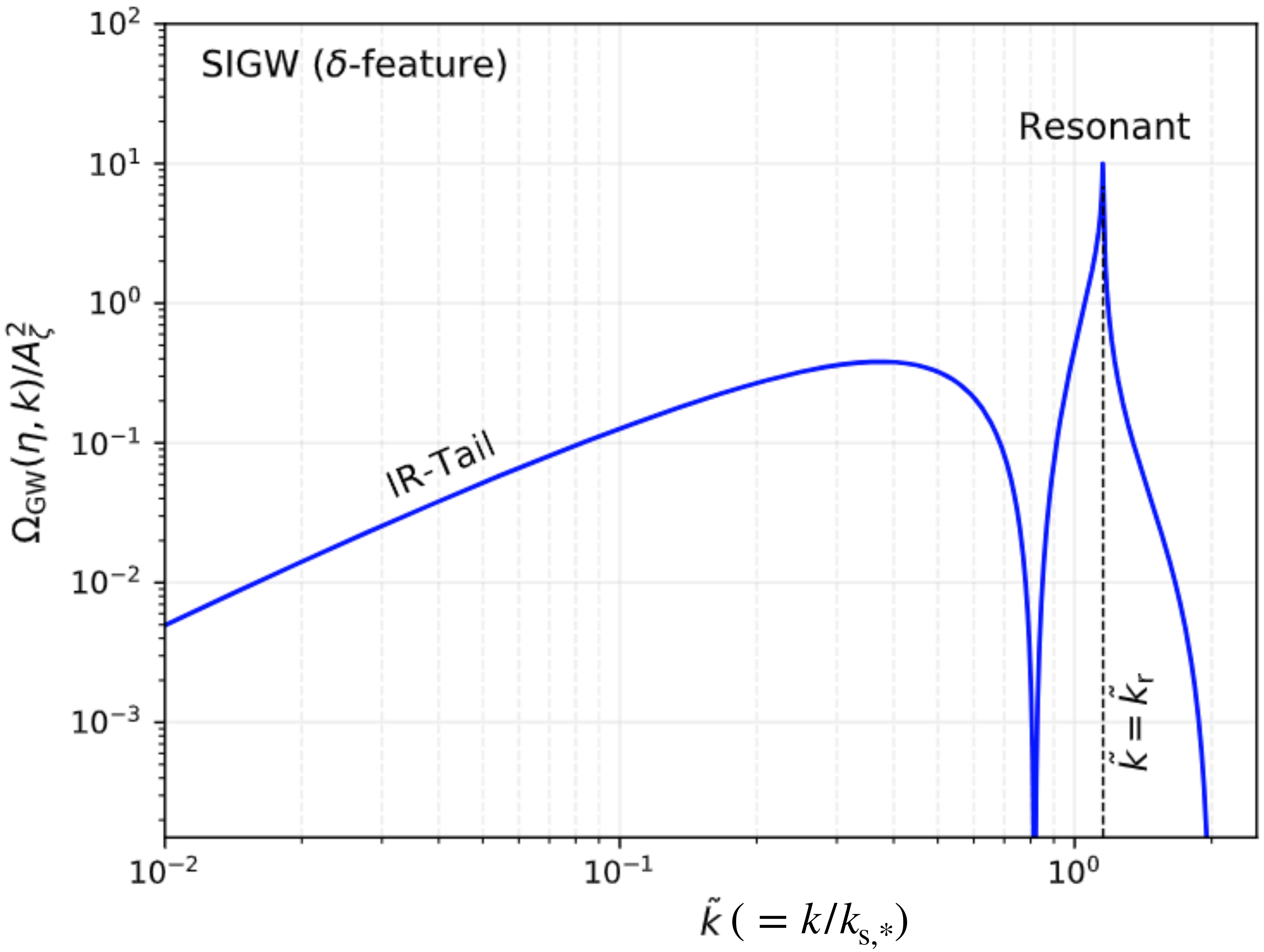
Second order in perturbation theory, scalar fluctuations source tensors!

Ananda et al. (2007) Baumann et al. (2007)

Amplification of PPS necessary to get appreciable effect ($\Omega_{\rm GW} \propto A_s^2$).

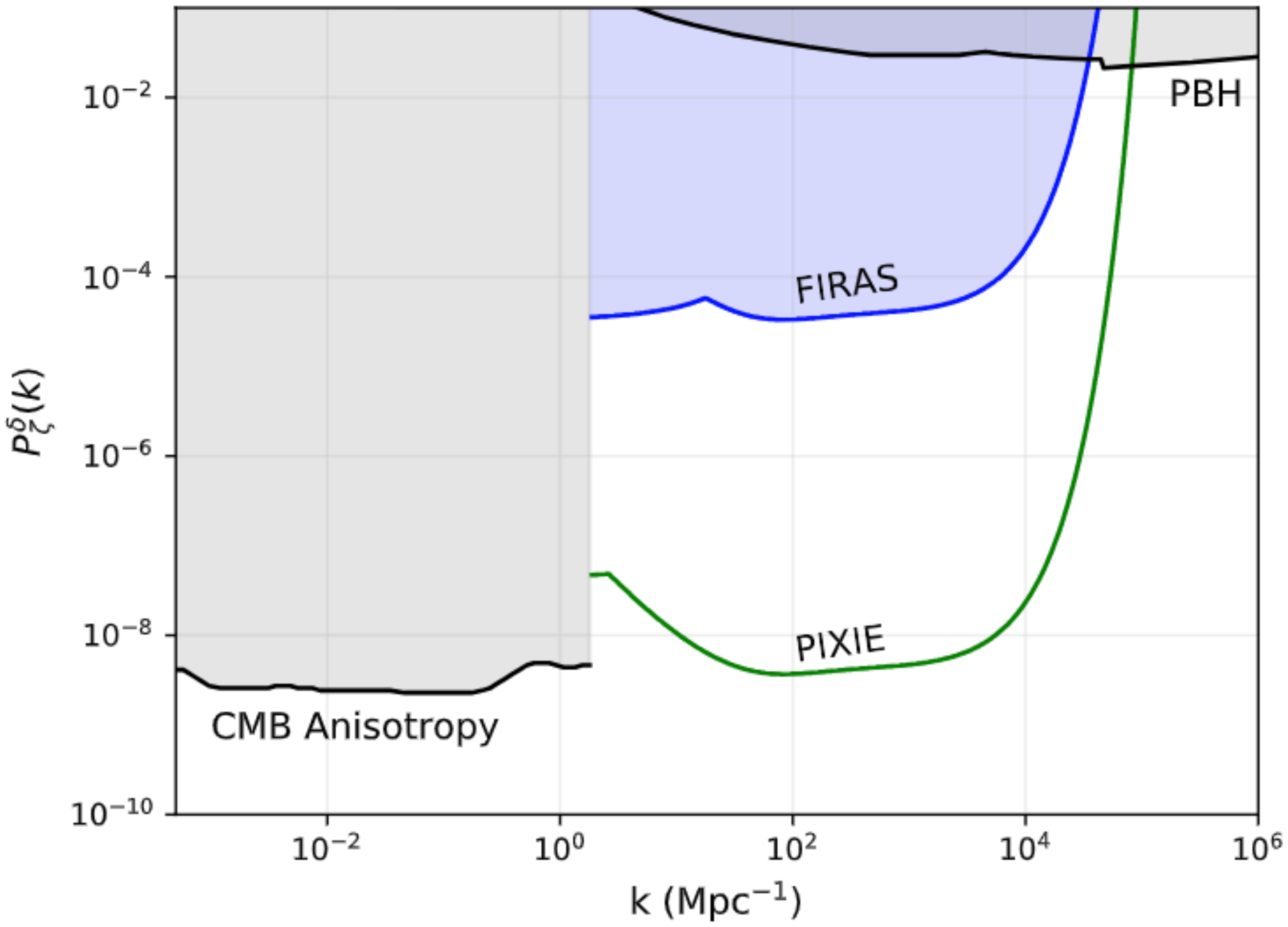
Highly shape dependent: Focus solely on δ-function enhancements.

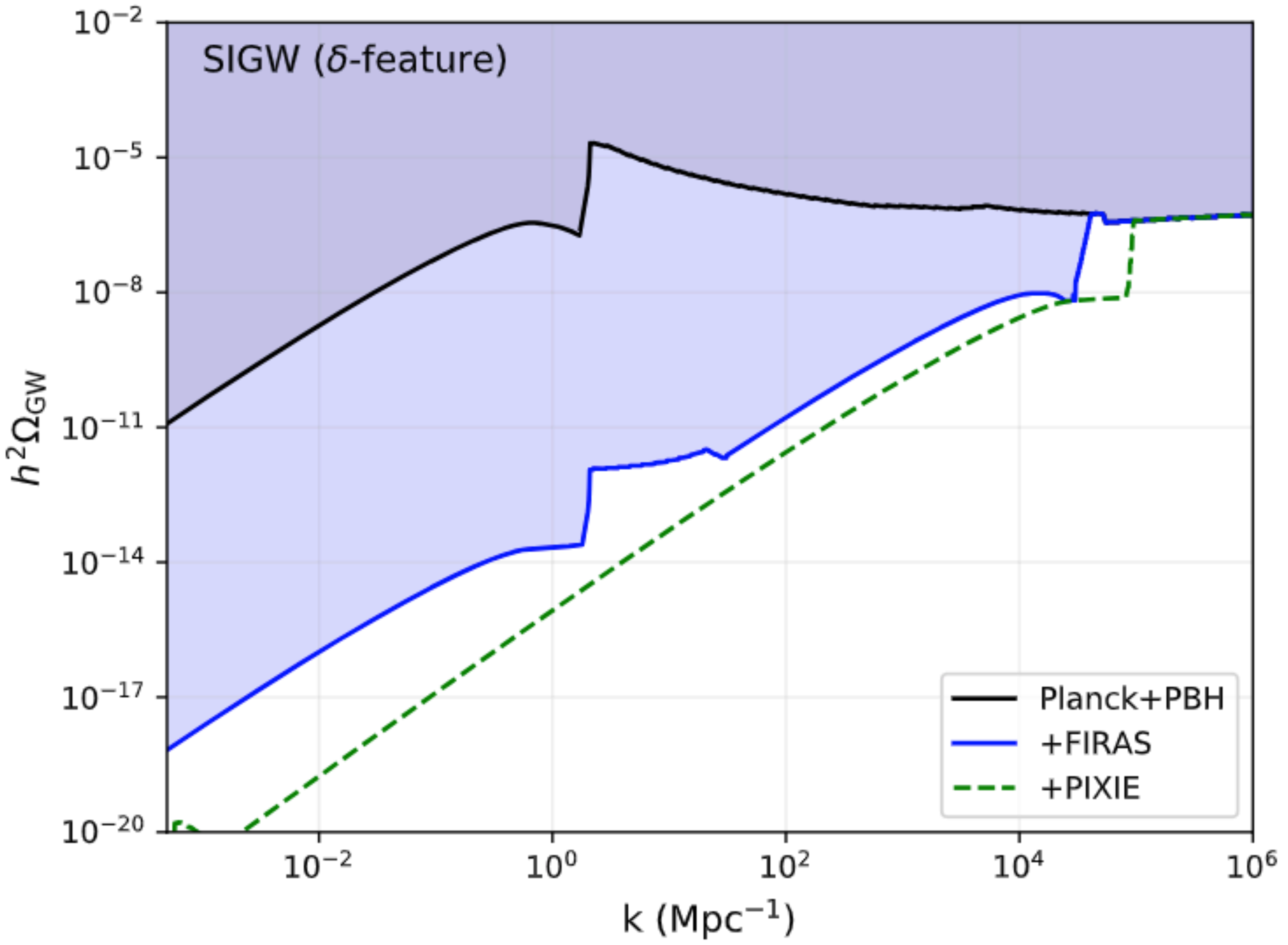
Two distinct features in GW response: IR tail and a resonant peak.



Mapping of PPS constraints

- One can translate constraints from the PPS into limits on the GW parameter space for specific shapes of scalar enhancements.
- Distortions provide a tool to help with primordial model discrimination!





Direct tensor dissipation

Gravitational waves generate CMB polarization fluctuations!

Ota et al. (2014)
Chluba et al. (2015)
Kite et al. (2021)

In contrast to scalar perturbations, GWs mix patches primarily through free-streaming effects (no diffusion through interactions with electrons).

Formalism analogous to scalar case, qualitative differences:

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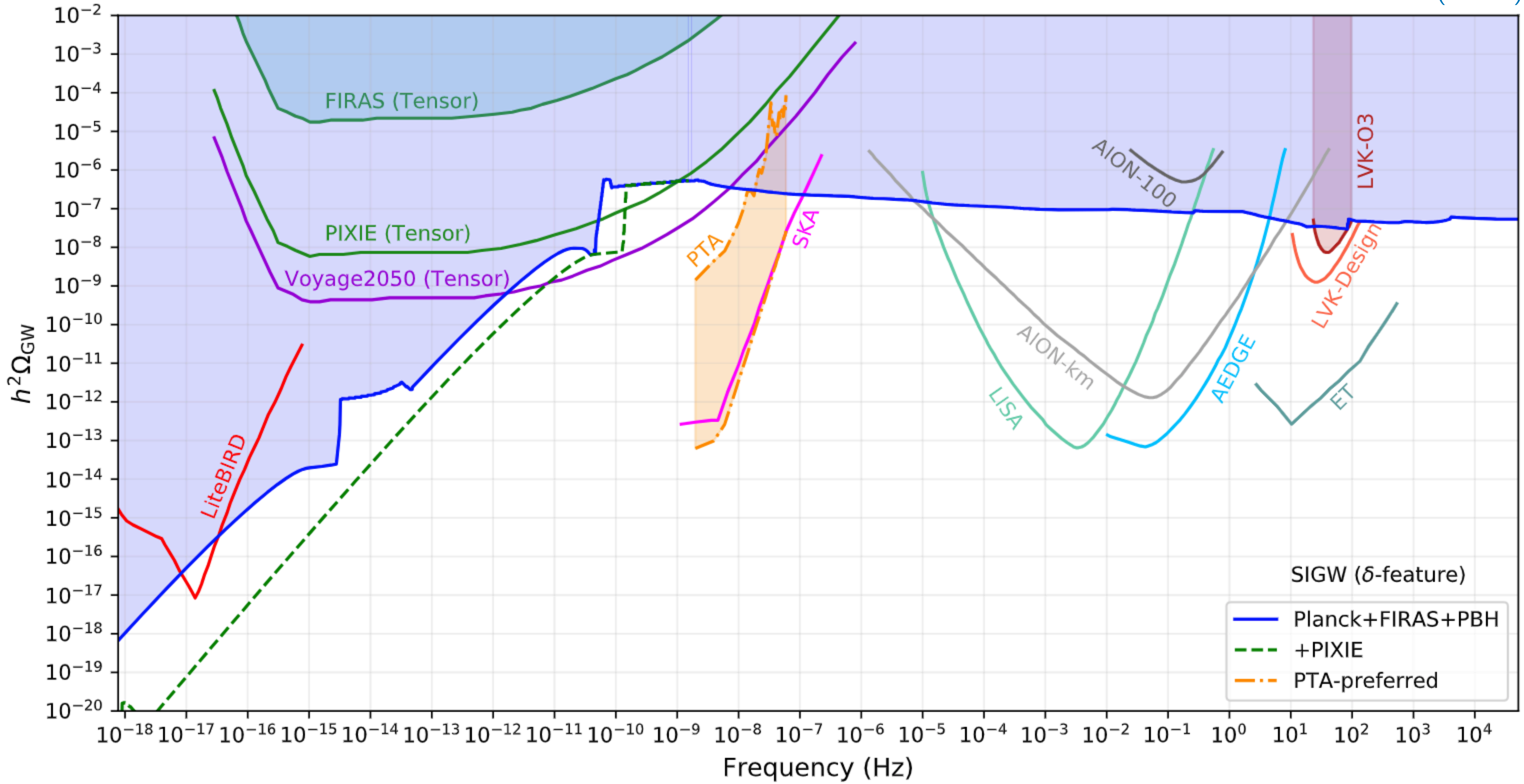
ANY tensor modes present at $z \gtrsim z_{\rm rec}$ will induce this distortion signature!

Mapping of PPS constraints

BC et al. (2023a)



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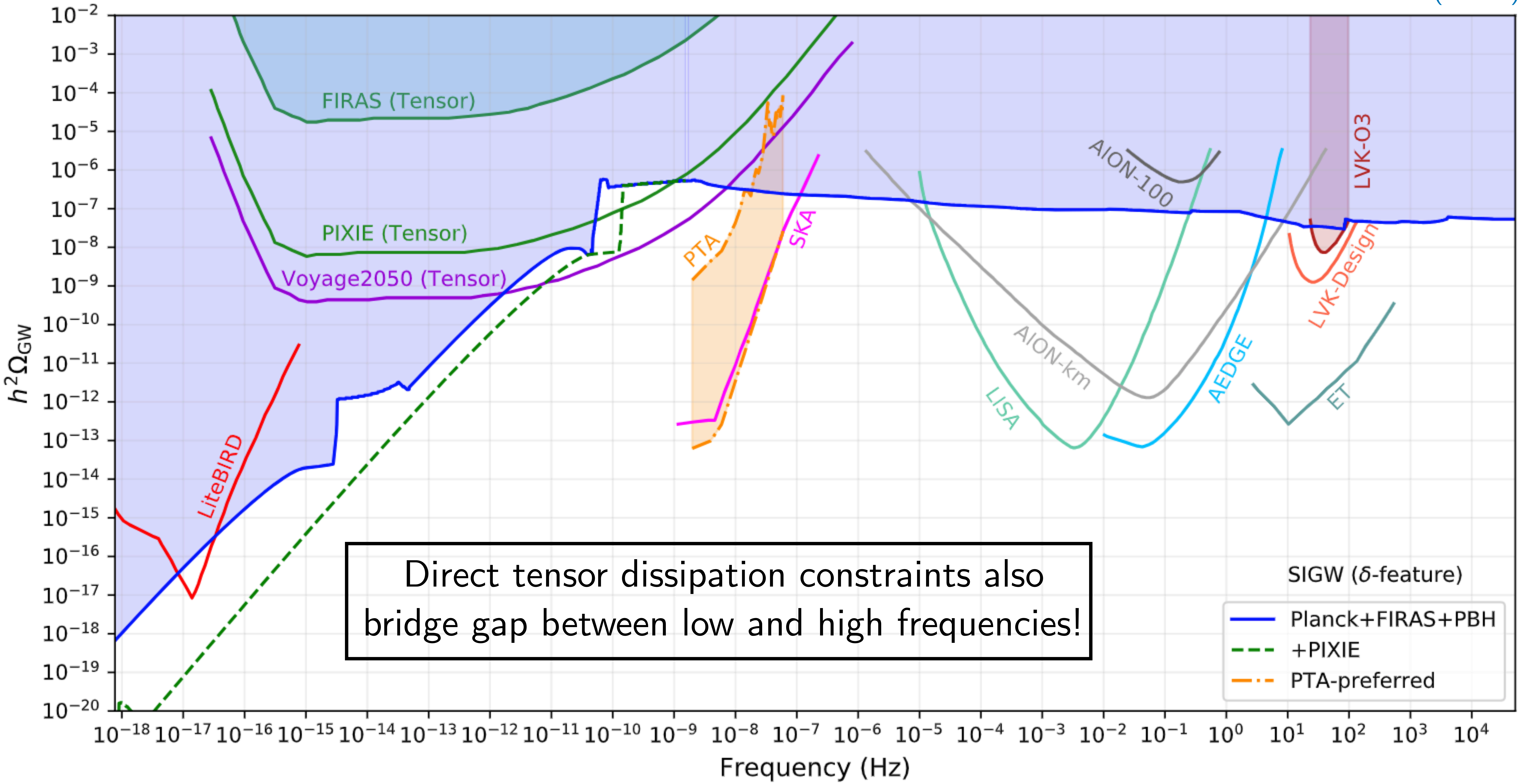


Direct tensor dissipation constraints also bridge gap between low and high frequencies!

21cm Cosmology
+
CMB spectral distortions

"How is 21cm cosmology impacted if the CMB spectrum contains a significant excess of photons deep in the Rayleigh-Jeans tail?"

“How is 21cm cosmology impacted if the CMB spectrum contains a significant excess of photons deep in the Rayleigh-Jeans tail?”

In other words… what happens in the presence of a primordial radio background?

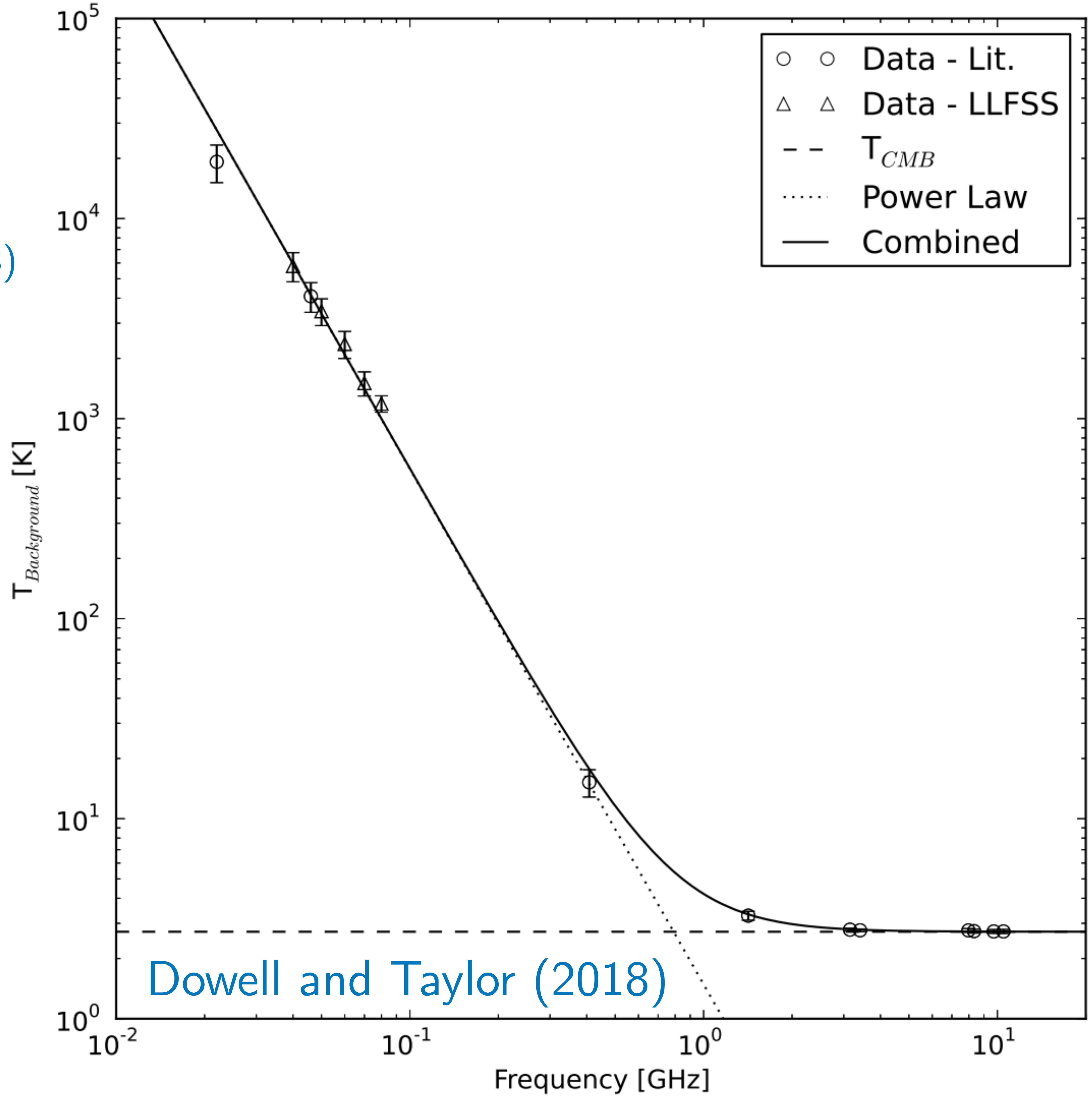
Mystery I: A radio synchrotron background?

Evidence for an unknown radio background from ARCADE-2 and LWA measurements. Fixsen et al. (2011) Dowell and Taylor (2018)

Power law fit (with extragalactic modelling) Gervasi et al. (2008) BC et al. (2023b,c)

$$T_{\rm RSB}(\nu) \simeq 1.230\,{\rm K}\left(\frac{\nu}{\rm GHz}\right)^{-2.555}$$

Is it primordial or astrophysical? How can we tell? Holder and Chluba (2021) Lee et al. (2022)

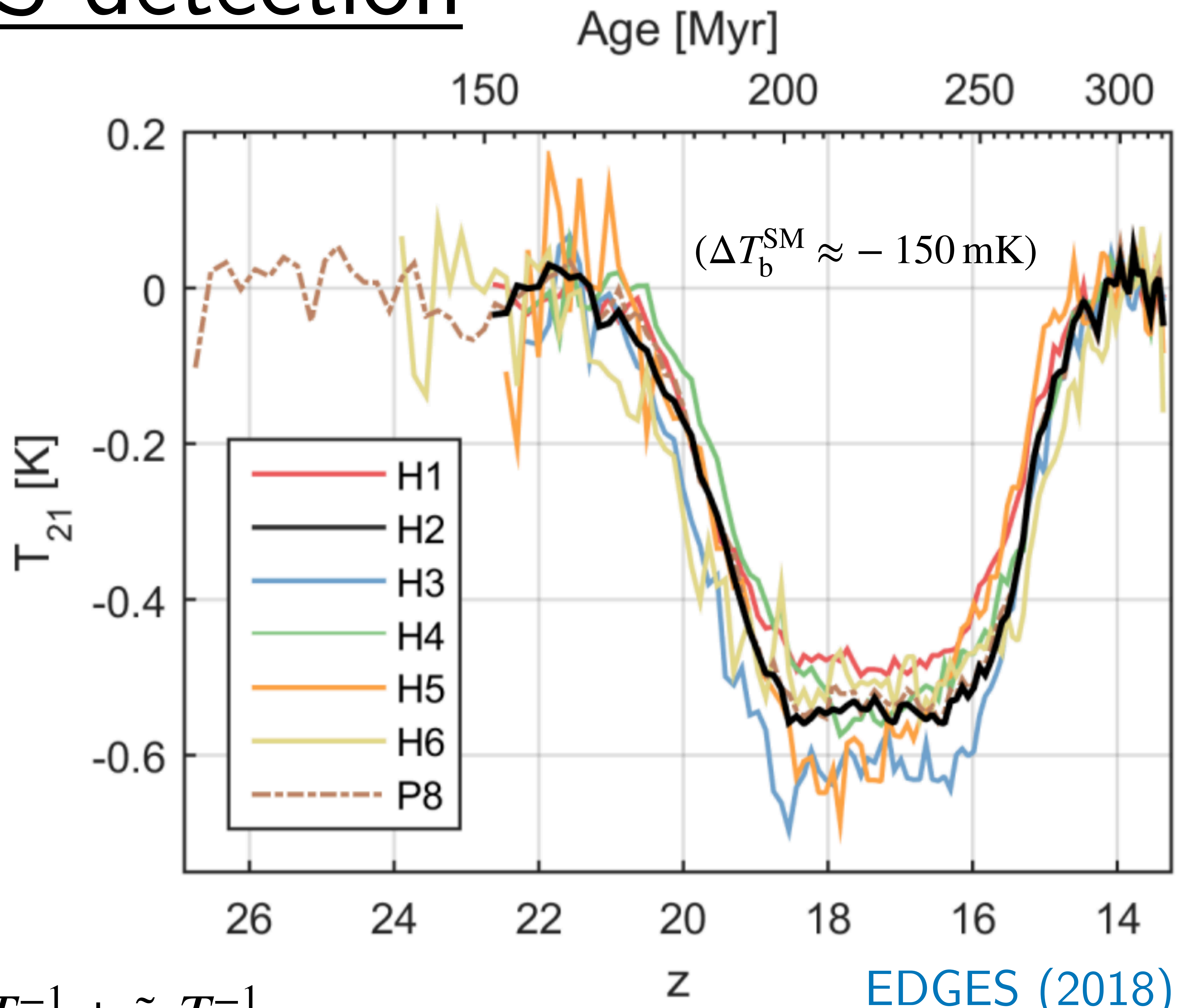


Mystery II: The EDGES detection

Discovery of a sky-averaged absorption signal at $z \approx 17$.

Flurry of exotic physics models:
- Milli-charged DM Kovetz et al. (2018)
- Cosmic strings Brandenberger, BC, Shi (2019)
- ...

SARAS 3 non-detection (2022).

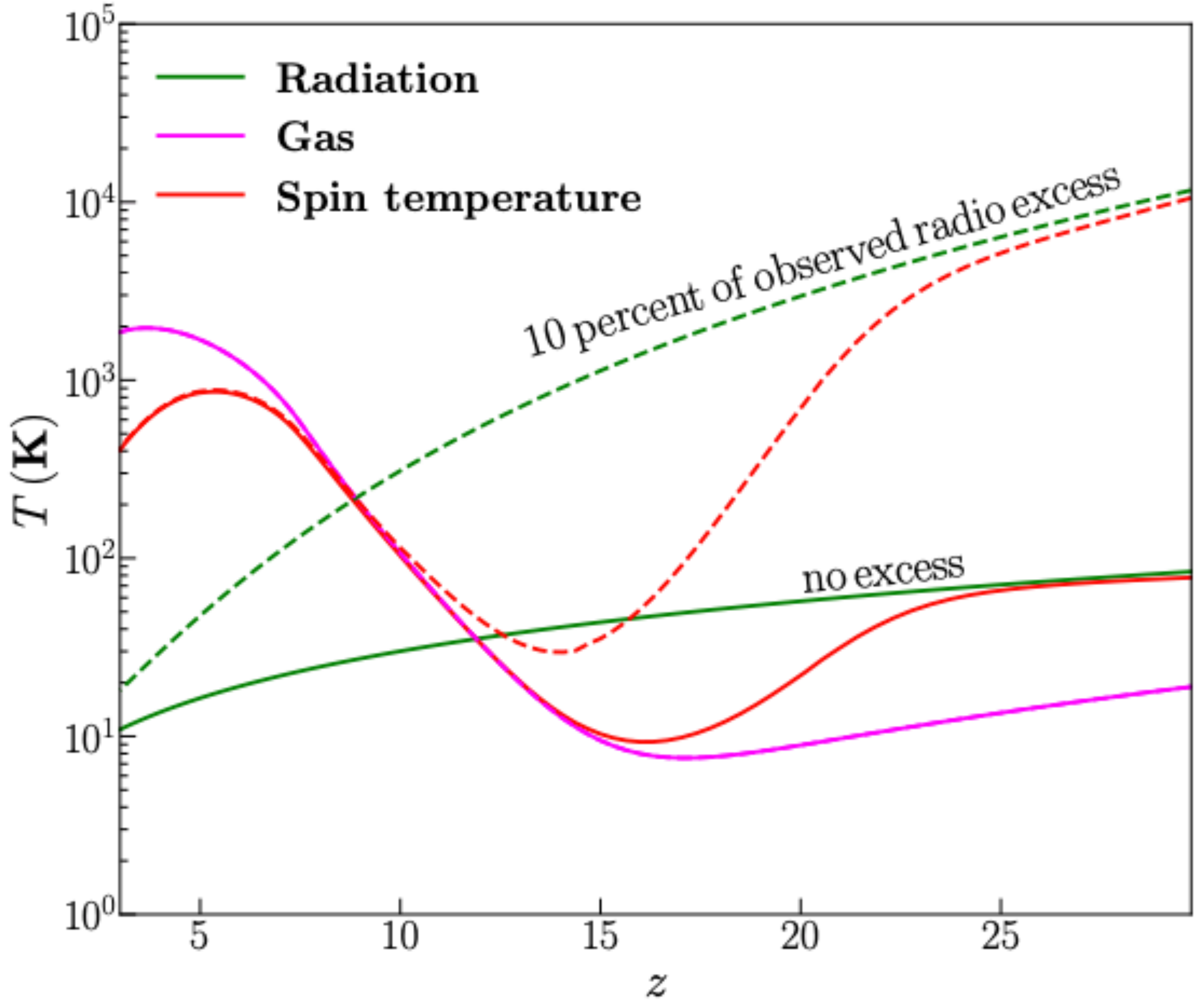


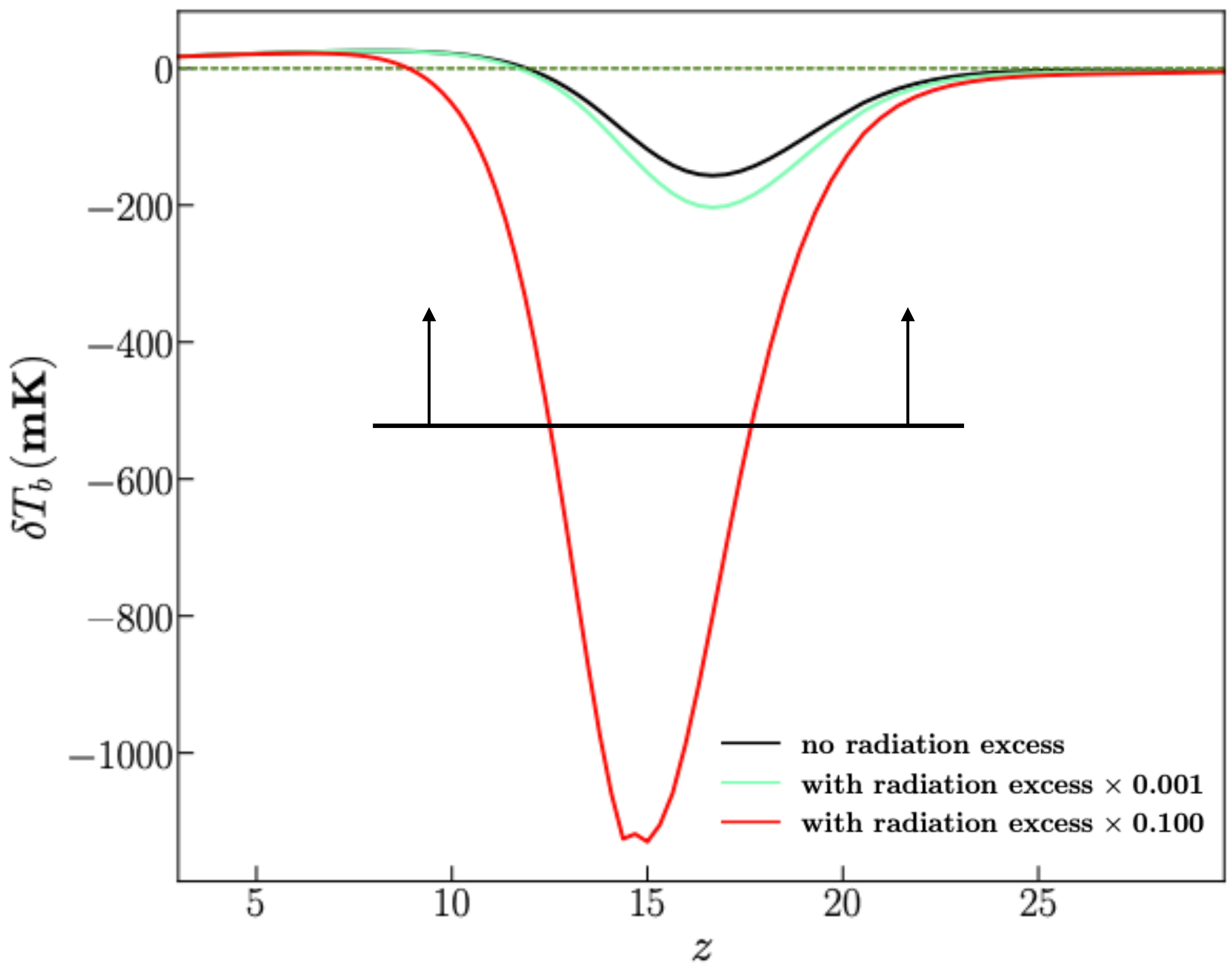
EDGES (2018)

$$\Delta T_b \propto x_{HI}(1 - T_R/T_{spin}) \qquad T_{spin}^{-1} = \frac{x_{rad}T_R^{-1} + x_c T_K^{-1} + \tilde{x}_\alpha T_\alpha^{-1}}{x_{rad} + x_c + \tilde{x}_\alpha}$$

Potential synergies

Feng and Holder (2018)





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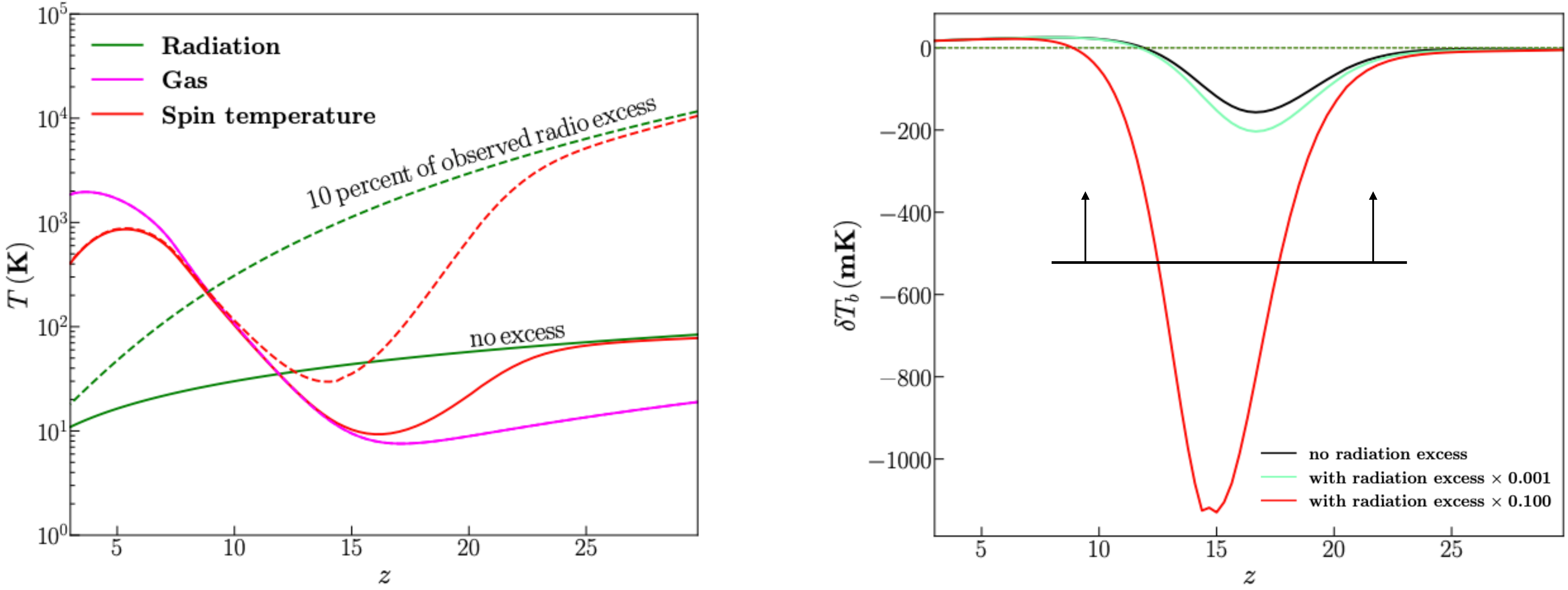

Conclusion: More than 5% of signal being primordial violates EDGES.

Implication: Strong constraints on exotic models which produce radio backgrounds.

Soft Photon Heating

Acharya, BC, Chluba (2023)
BC, Acharya, Chluba (2024)

Hard photons: Defined by $E_\gamma \gtrsim 10\,\mathrm{eV}$, can cause direct excitations and ionizations of the background, highly constrained by CMB anisotropy measurements.

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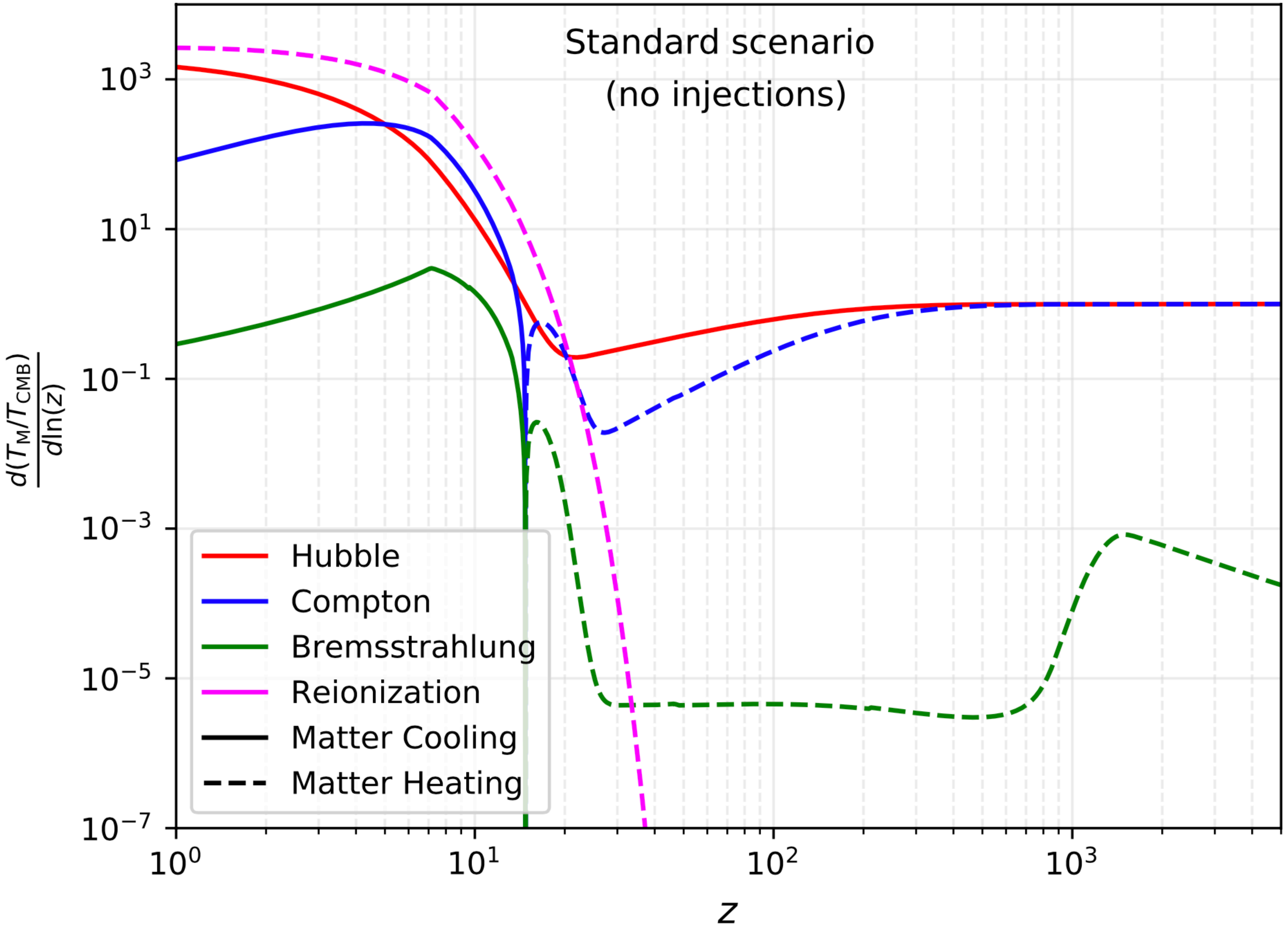
Soft photons: Lower energies ($E_{\rm ff,abs}(z) \lesssim E_\gamma \lesssim 10\,\mathrm{eV}$) will mostly free-stream. Photons with $E_\gamma \lesssim E_{\rm ff,abs}(z)$ be absorbed, heat the gas, and may induce some additional collisional ionizations.

Note: Definitions apply for post-recombination injections.

Matter Sector Heating Rates



$$\frac{\mathrm{d}T_\mathrm{M}}{\mathrm{d}z} = \frac{2T_\mathrm{M}}{1+z} + \frac{X_\mathrm{e}}{1+X_\mathrm{e}+f_\mathrm{He}} \frac{8\sigma_\mathrm{T}\rho_\mathrm{CMB}}{3m_\mathrm{e}c} \frac{T_\mathrm{M}-T_\mathrm{CMB}}{H(z)(1+z)} + \frac{\mathrm{d}T_\mathrm{ff}}{\mathrm{d}z}$$

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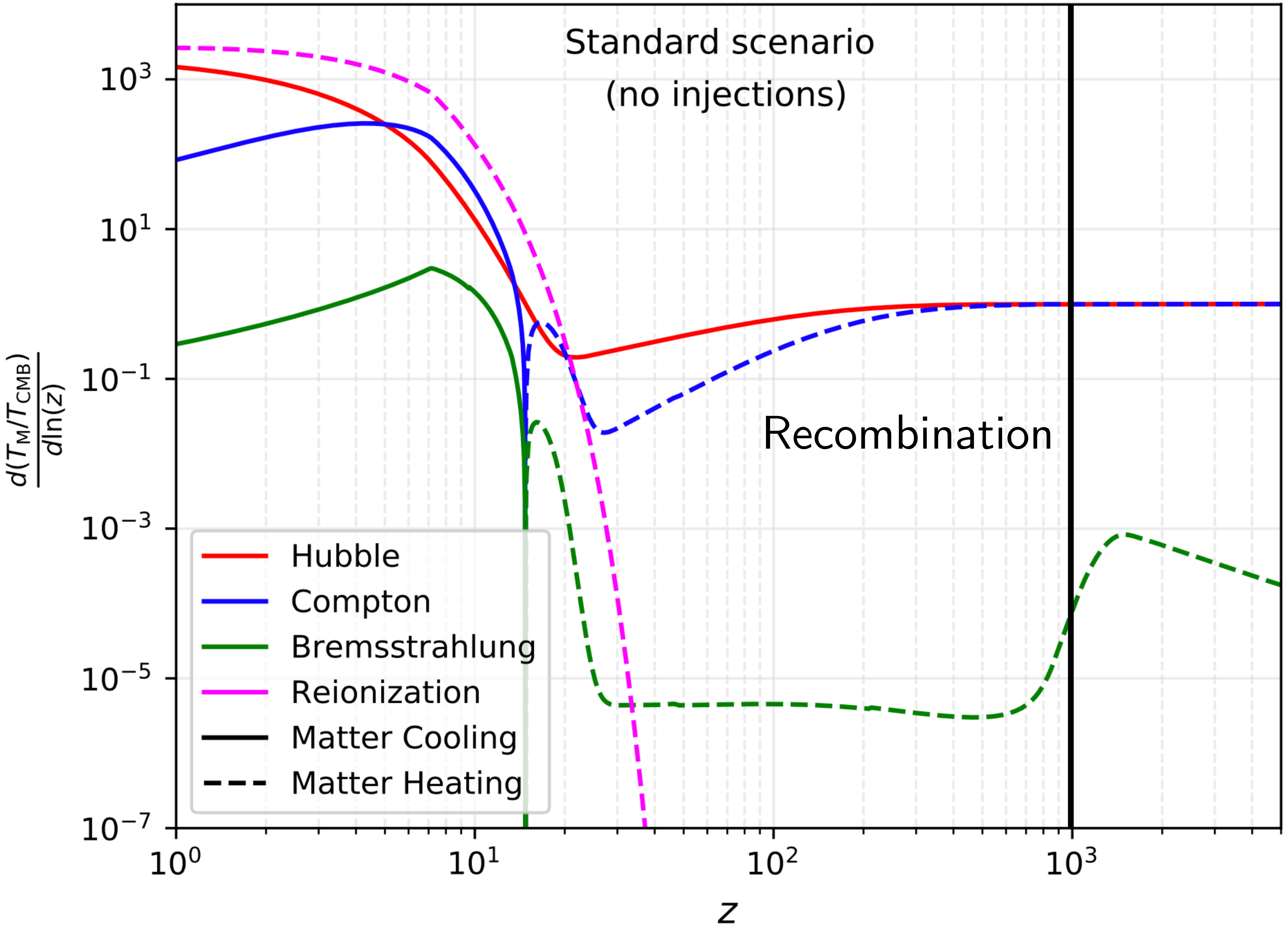

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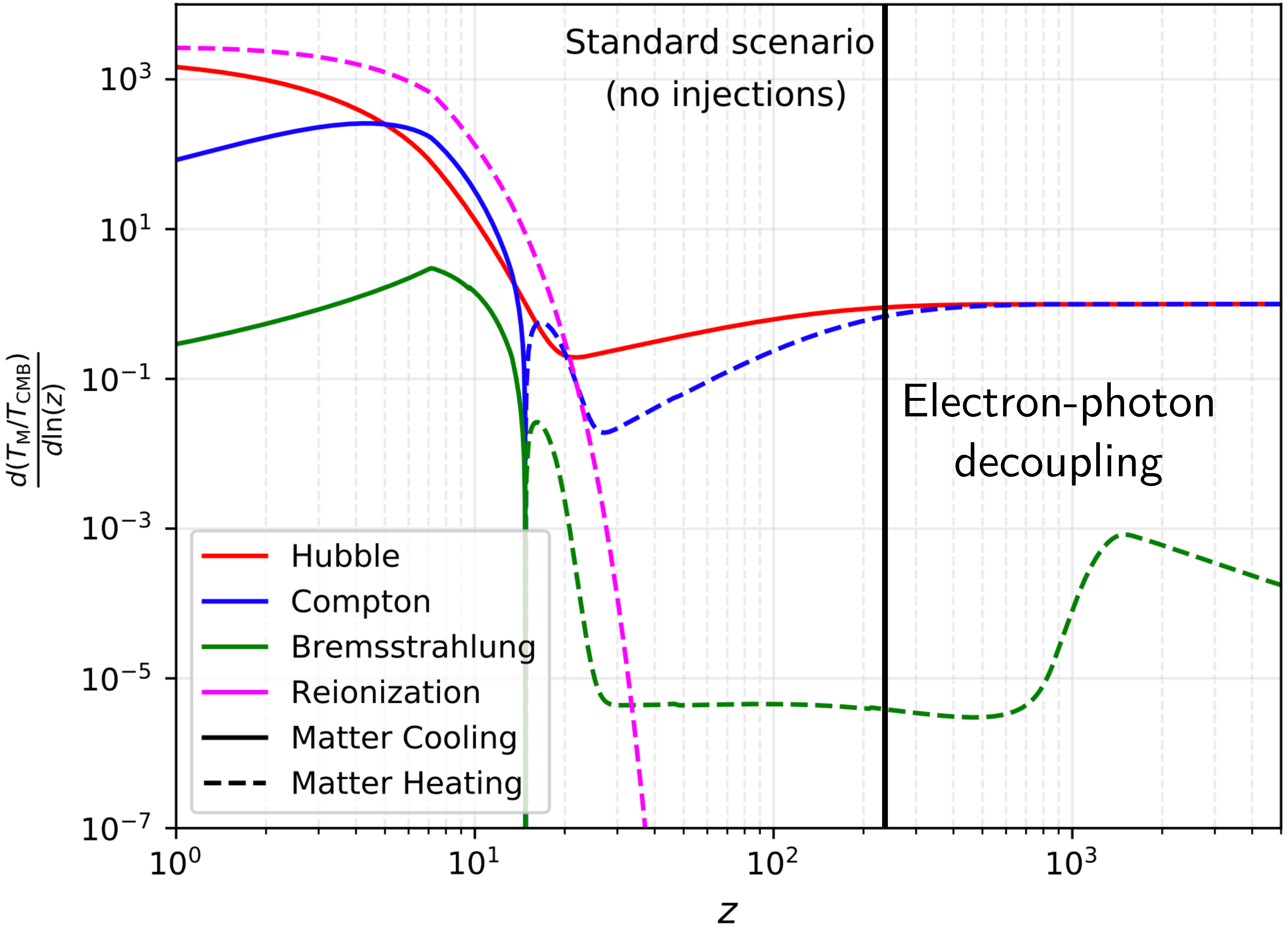
Matter Sector Heating Rates



$$\frac{\mathrm{d}T_\mathrm{M}}{\mathrm{d}z} = \frac{2T_\mathrm{M}}{1+z} + \frac{X_\mathrm{e}}{1+X_\mathrm{e}+f_\mathrm{He}} \frac{8\sigma_\mathrm{T}\rho_\mathrm{CMB}}{3m_\mathrm{e}c} \frac{T_\mathrm{M}-T_\mathrm{CMB}}{H(z)(1+z)} + \frac{\mathrm{d}T_\mathrm{ff}}{\mathrm{d}z}$$

High-z Synchrotron Injections

Consider quasi-instantaneous injections of a synchrotron background

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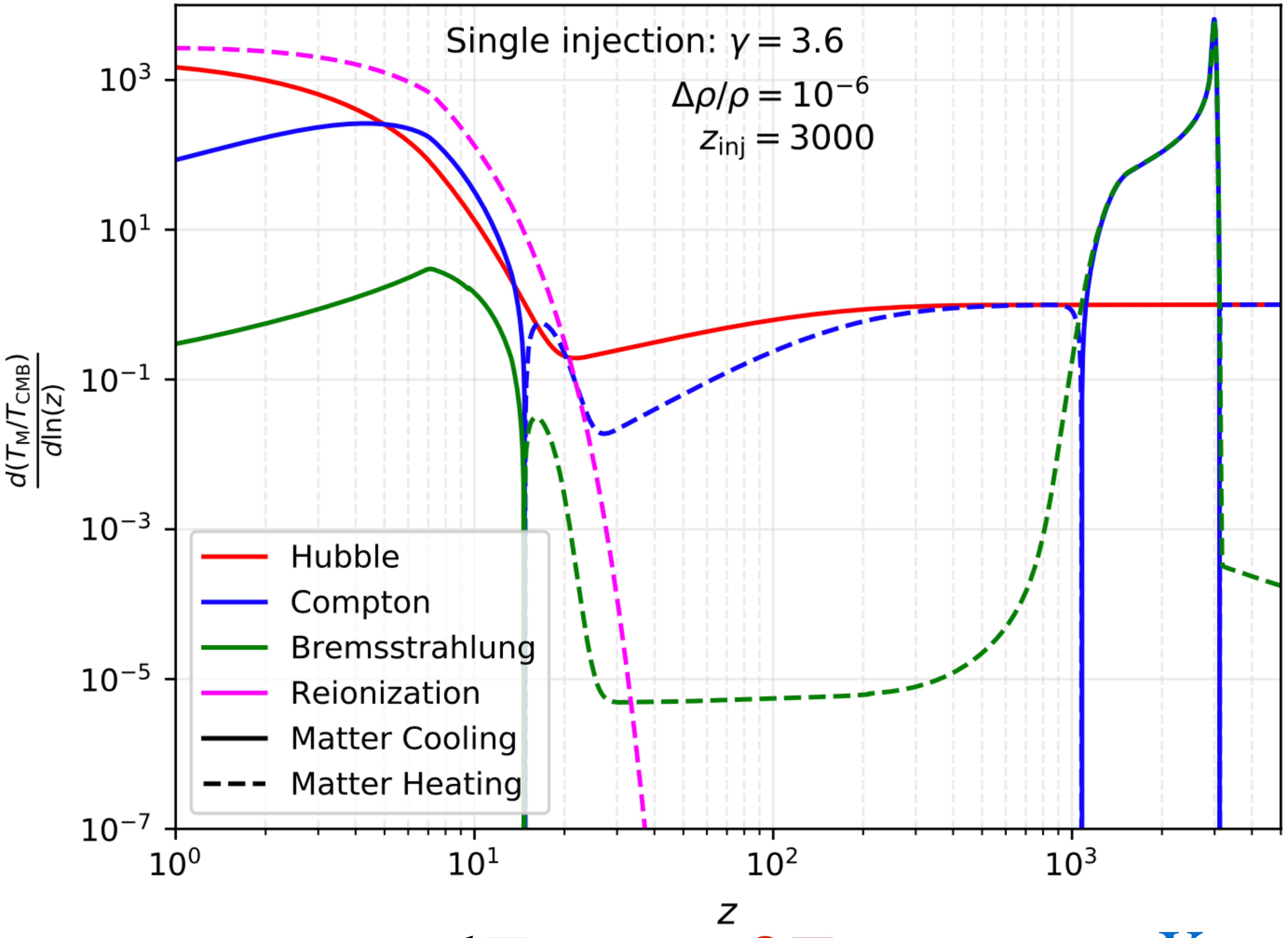

$$\frac{\mathrm{d}T_{\rm M}}{\mathrm{d}z} = \frac{2T_{\rm M}}{1+z} + \frac{X_{\rm e}}{1+X_{\rm e}+f_{\rm He}}\frac{8\sigma_{\rm T}\rho_{\rm CMB}}{3m_{\rm e}c}\frac{T_{\rm M}-T_{\rm CMB}}{H(z)(1+z)} + \frac{\mathrm{d}T_{\rm ff}}{\mathrm{d}z}$$

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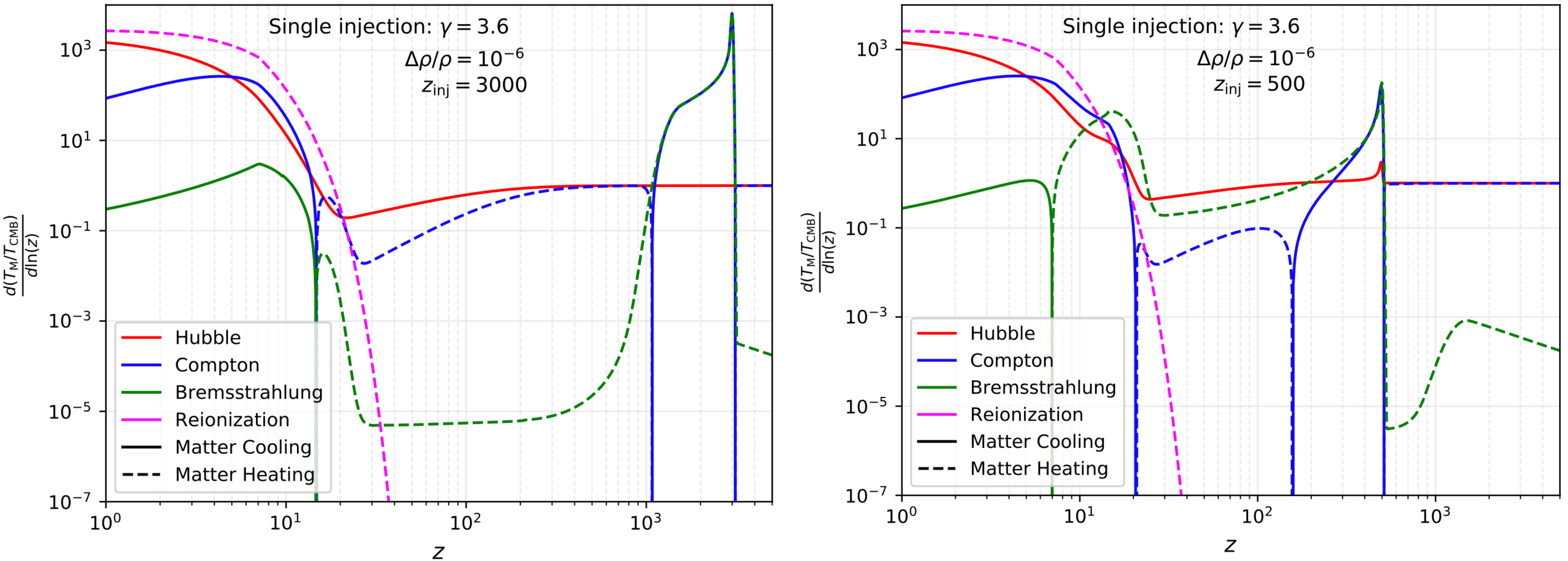

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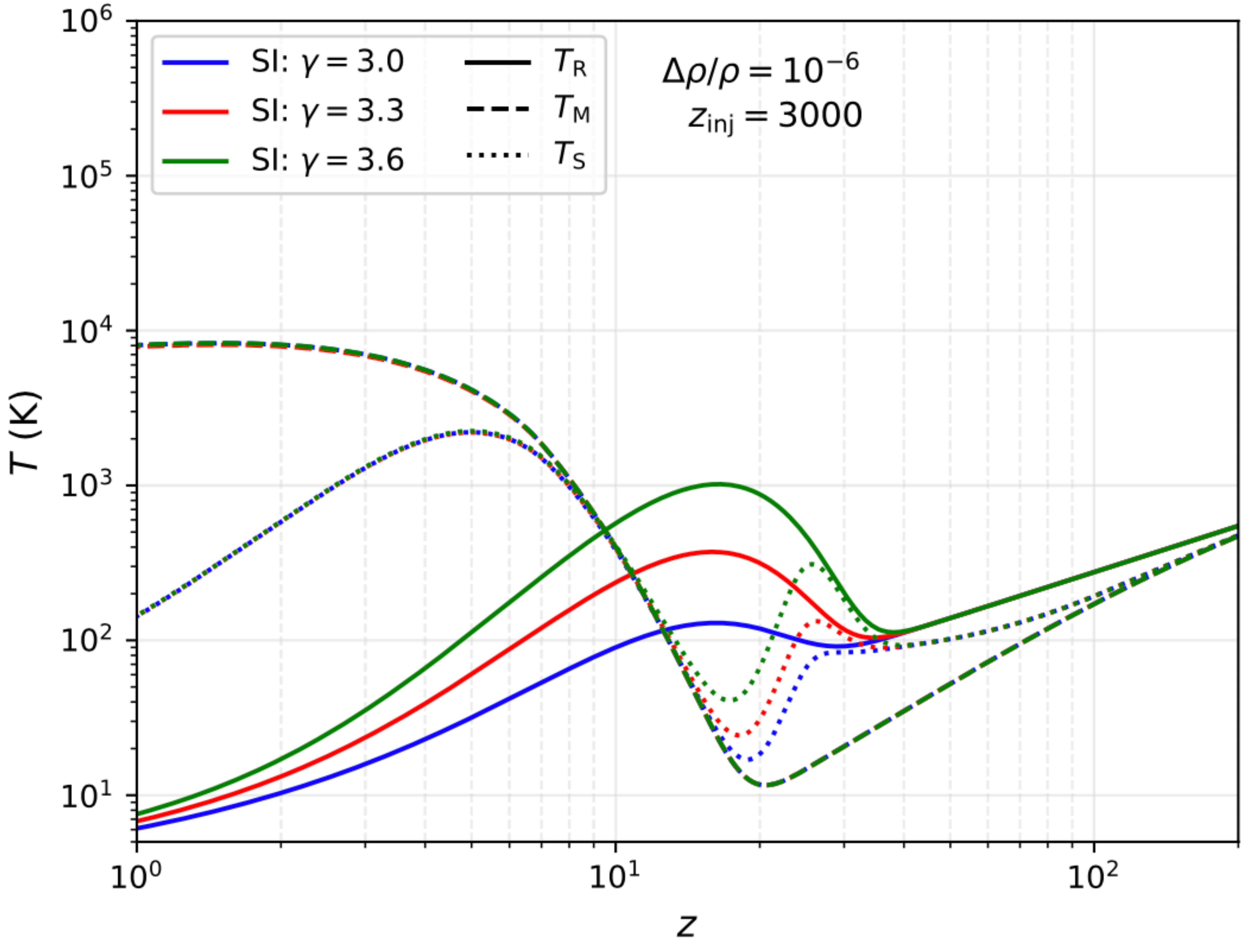
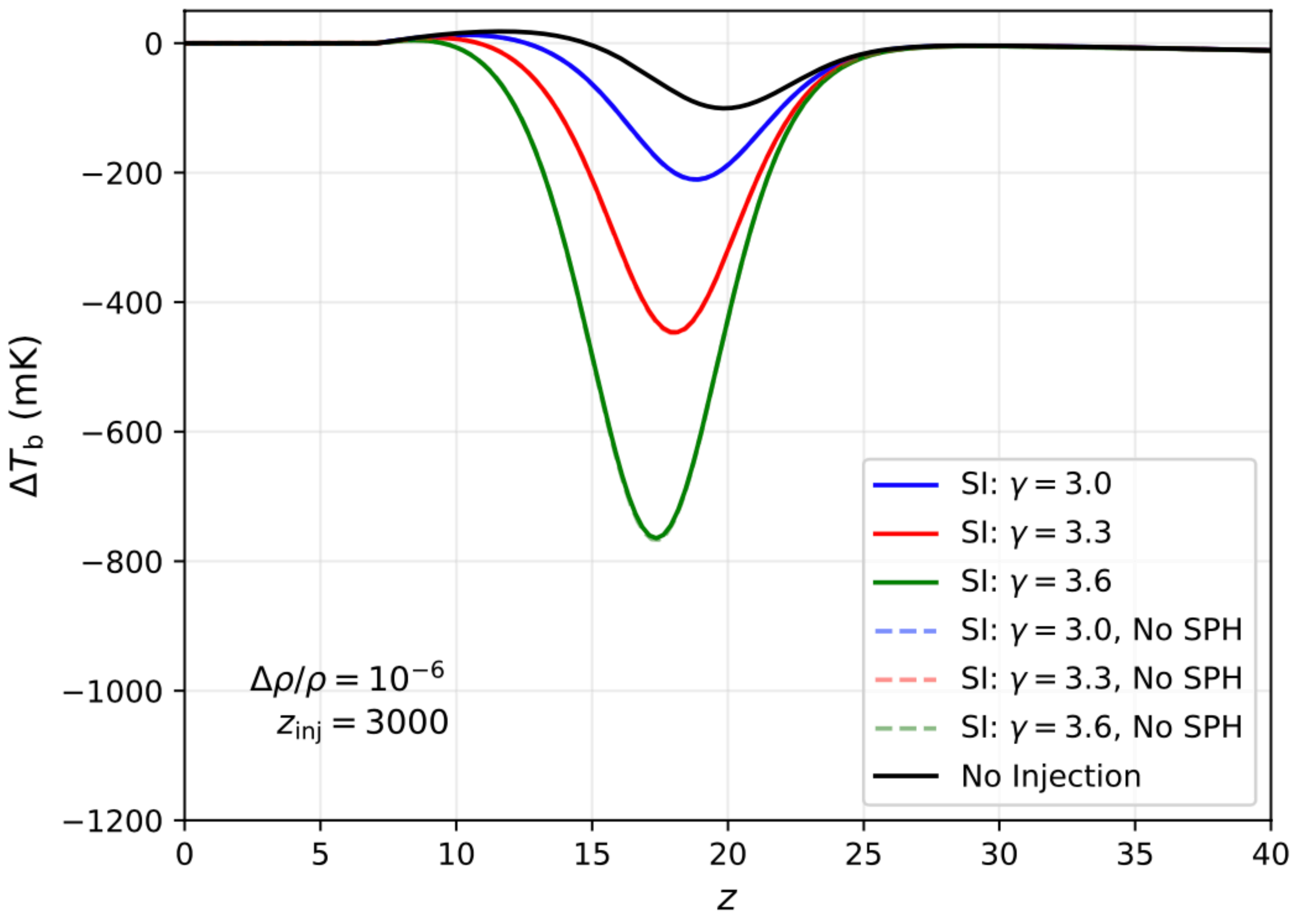
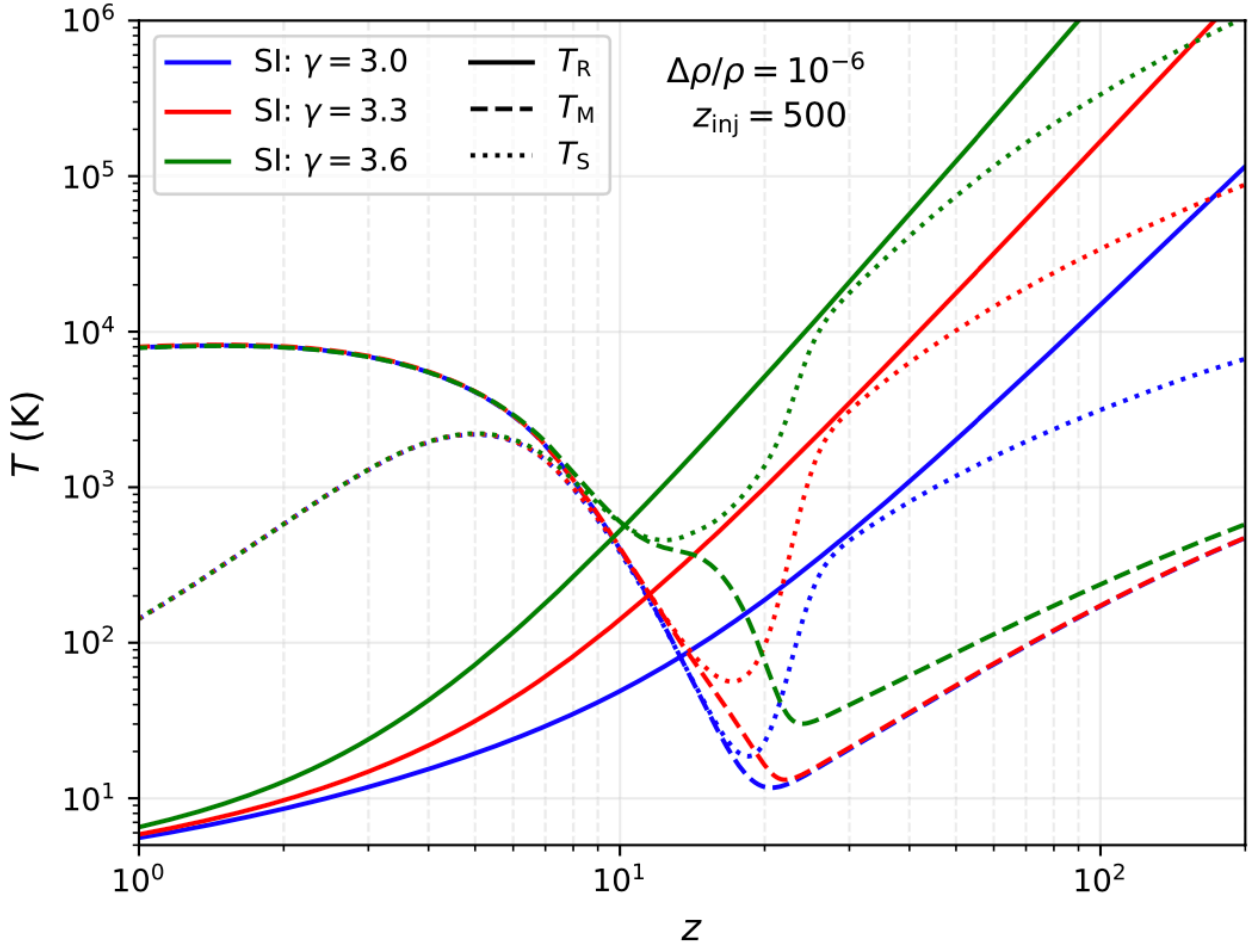
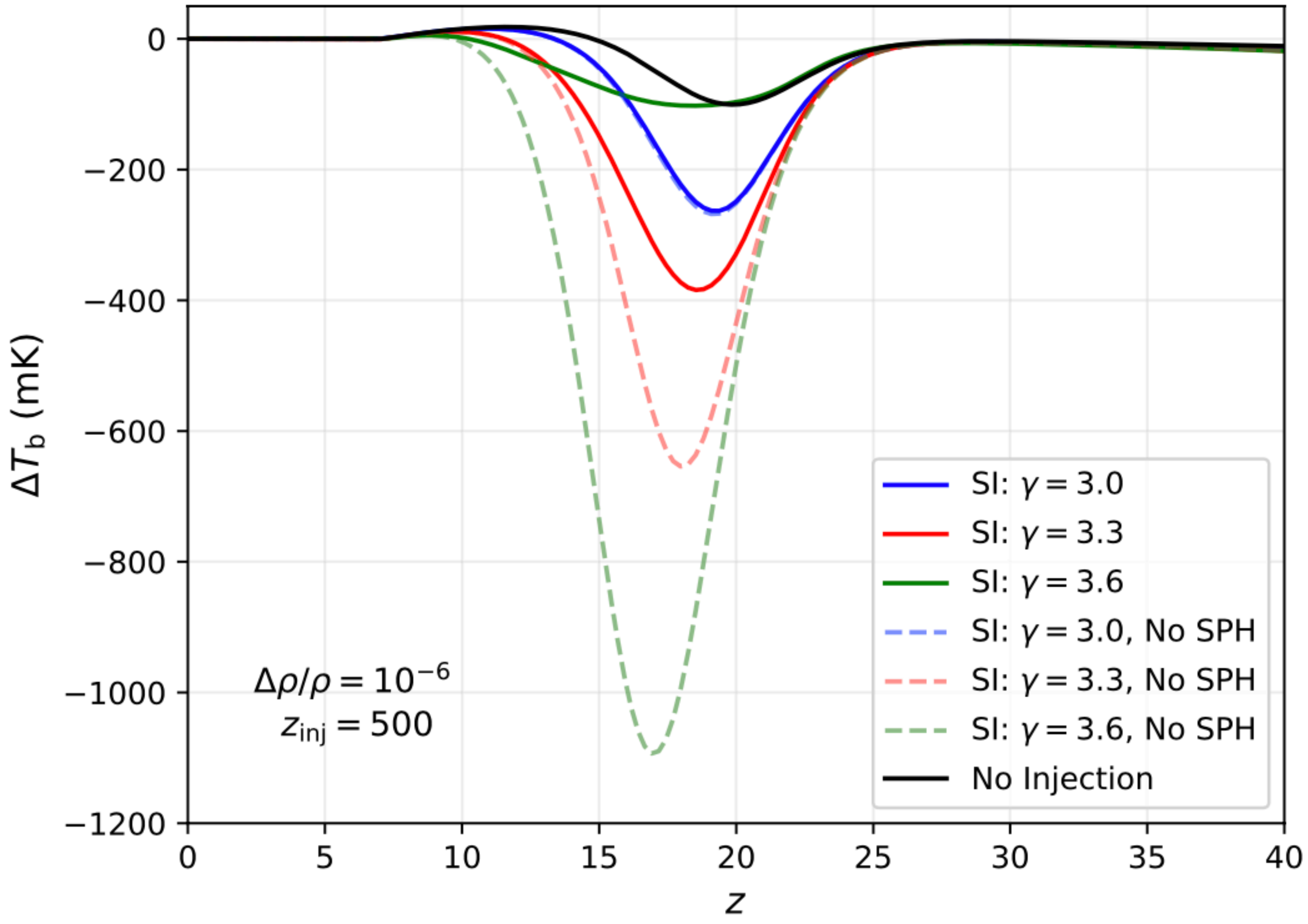
High-z Synchrotron Injections





High-z Synchrotron Injections





High-z Synchrotron Injections

Generation of a sufficiently steep radio background at $20 \lesssim z \lesssim z_{\rm rec}$ will induce dramatic changes to both the global 21cm signal + fluctuations.

Conclusions

The frequency spectrum of the CMB is rich with both standard model signals and the ability to produce stringent constraints on models of exotic energy injections.

Experimental activities beginning to ramp up - BISOU and Voyage2050.

Spectral distortion science highly synergistic to other (rapidly maturing) fields such as gravitational wave astronomy and 21cm cosmology.

Soft photon heating is a universal effect which dramatically modifies our understanding of 21cm physics in the presence of early radio backgrounds.

Thank you!