CMB spectral distortions as a probe of dark matter

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Outline

- CMB spectral distortion primer

- Analytic and numeric methods for distortions

- Wavy dark matter constraints
  - Dark photons
  - Axions (ALPs)
  - ALPs + dark photons

- Conclusions + future ideas

What is a CMB spectral distortion?

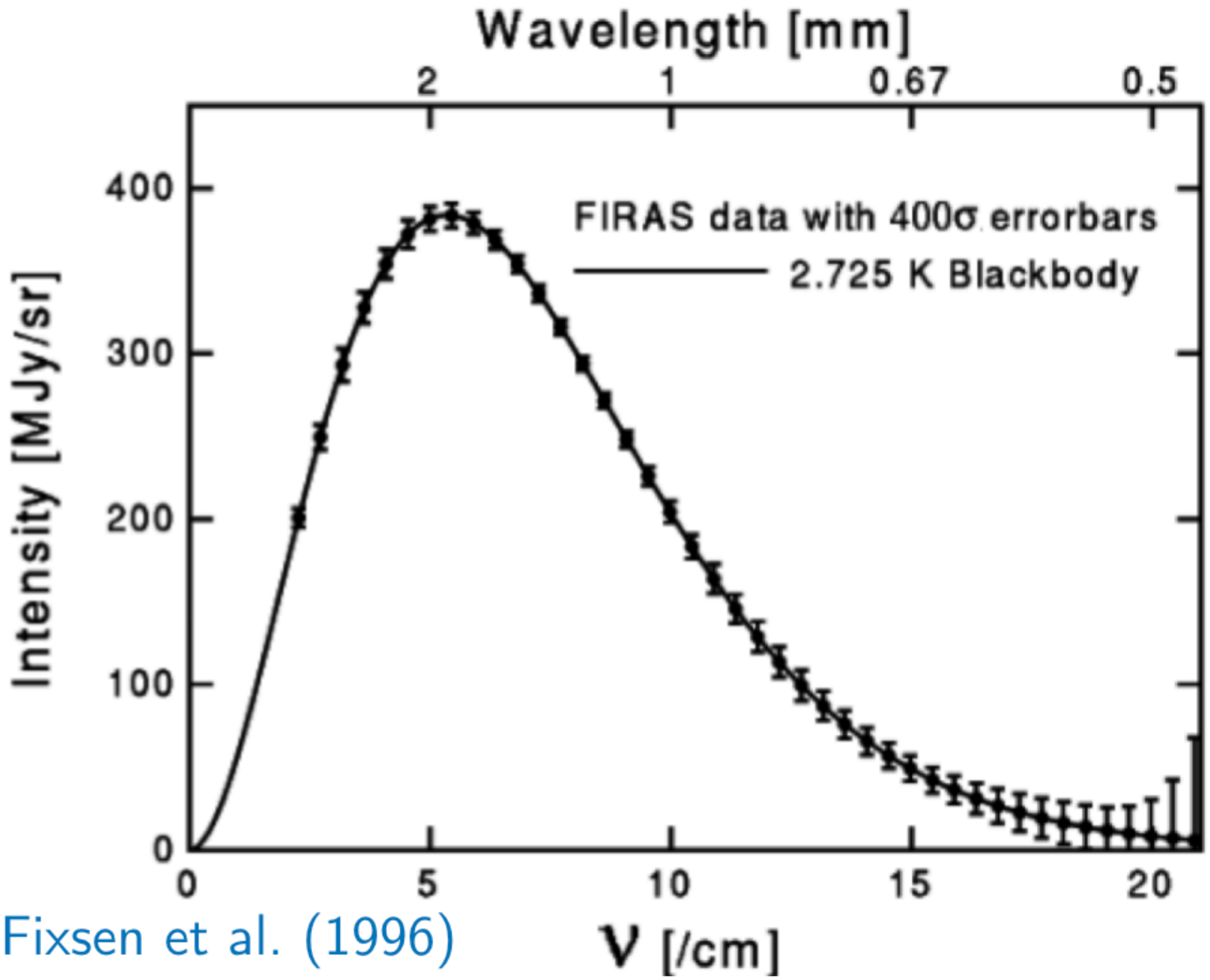
COBE/FIRAS measured nearly perfect blackbody of the CMB.

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

Nonthermal injections of energy and entropy can distort spectrum!

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

Exotic signals?



Fixsen et al. (1996)

COBE/FIRAS

$|\mu| \lesssim 10^{-4} \quad |y| \lesssim 10^{-5}$

PIXIE

$|\mu| \lesssim 10^{-8} \quad |y| \lesssim 2 \times 10^{-8}$

Generation of spectral distortions

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

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

How does one thermalize a distorted spectrum?

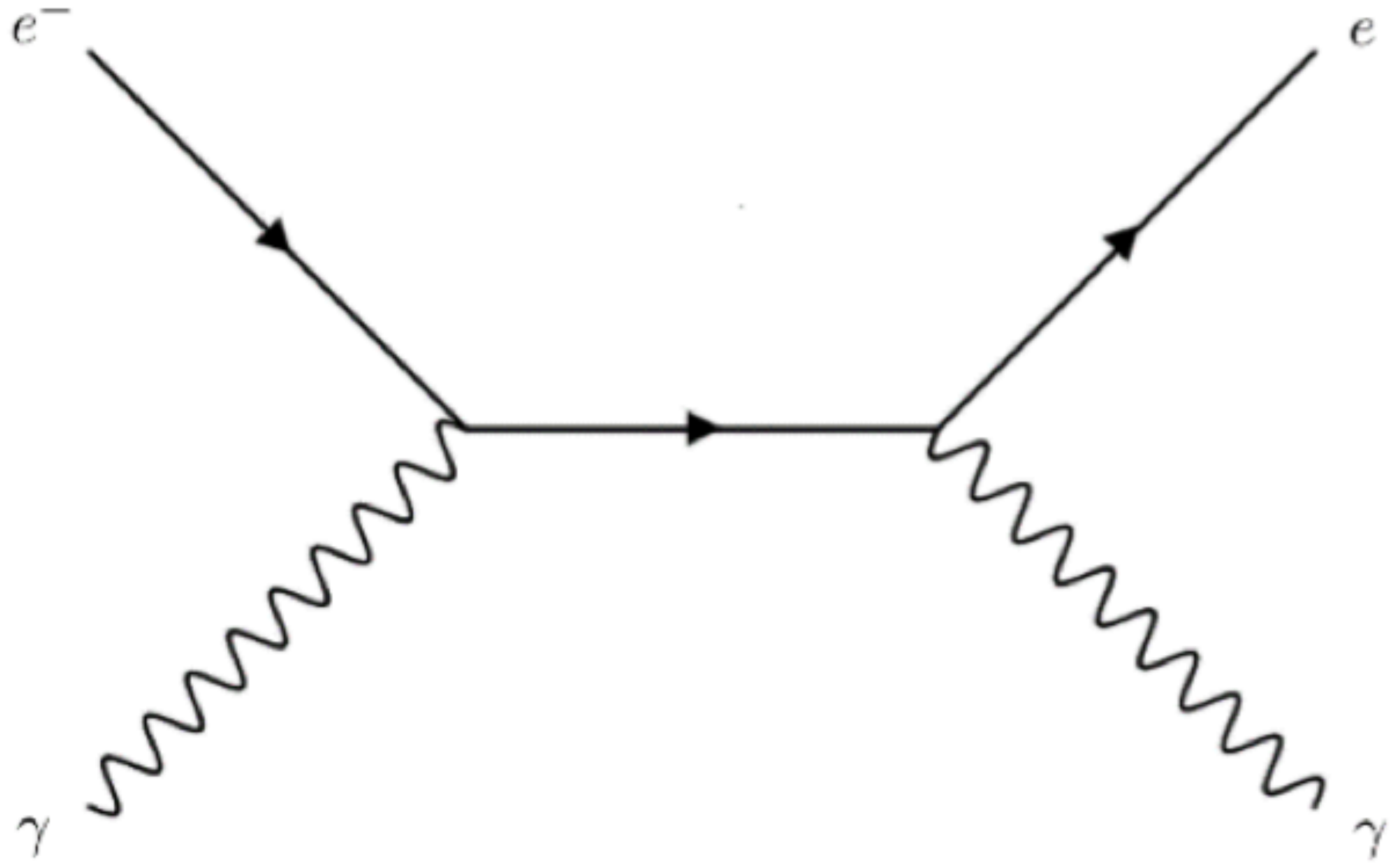
- Energy redistribution
- Photon creation/destruction

Freeze out redshift important! $\Gamma \simeq H$ $\Gamma = n\sigma v$

Compton

(energy changing)

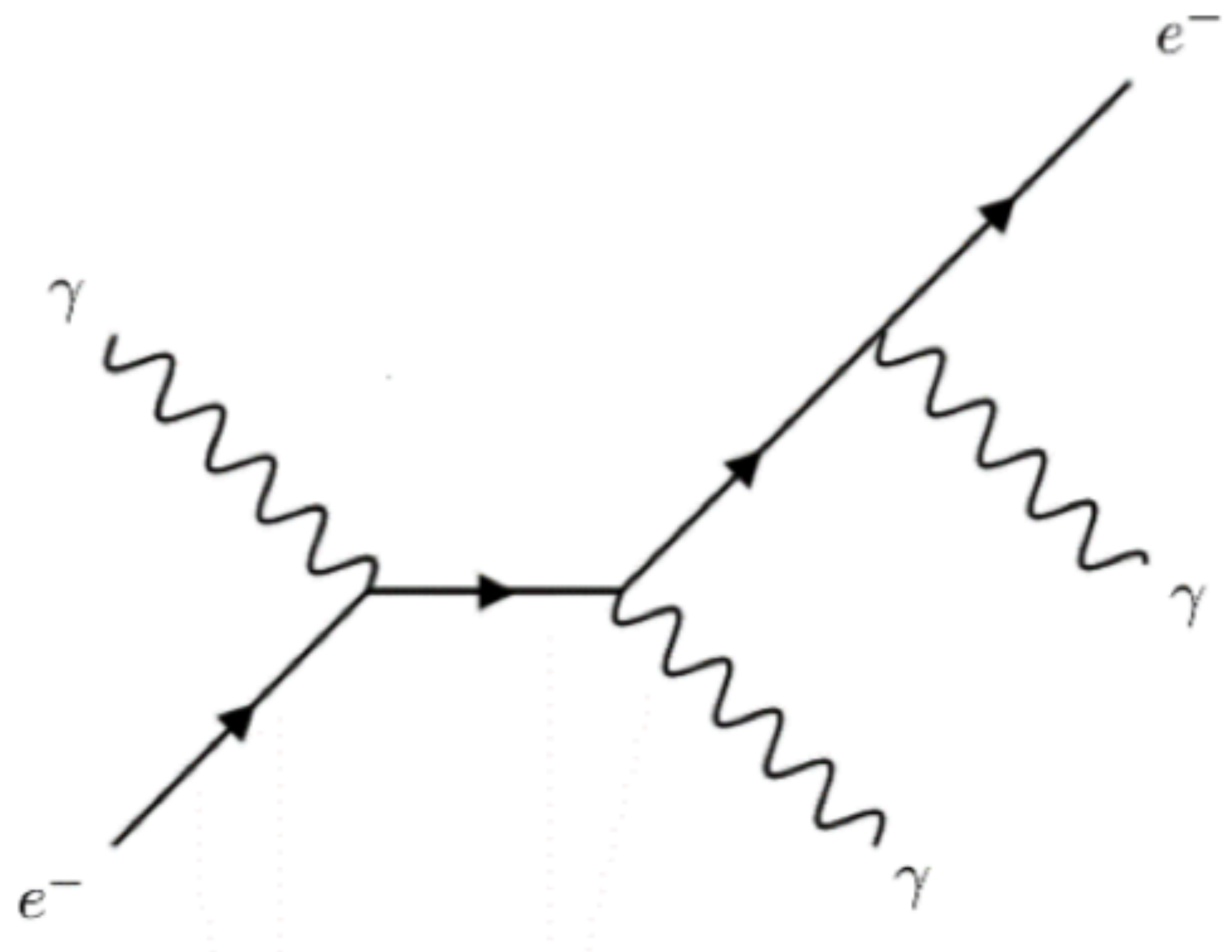
$z_{\mathrm{C}} \simeq 5 \times 10^4$
$(T_{\mathrm{C}} \simeq 12\,\mathrm{eV})$



Double Compton

(number changing)

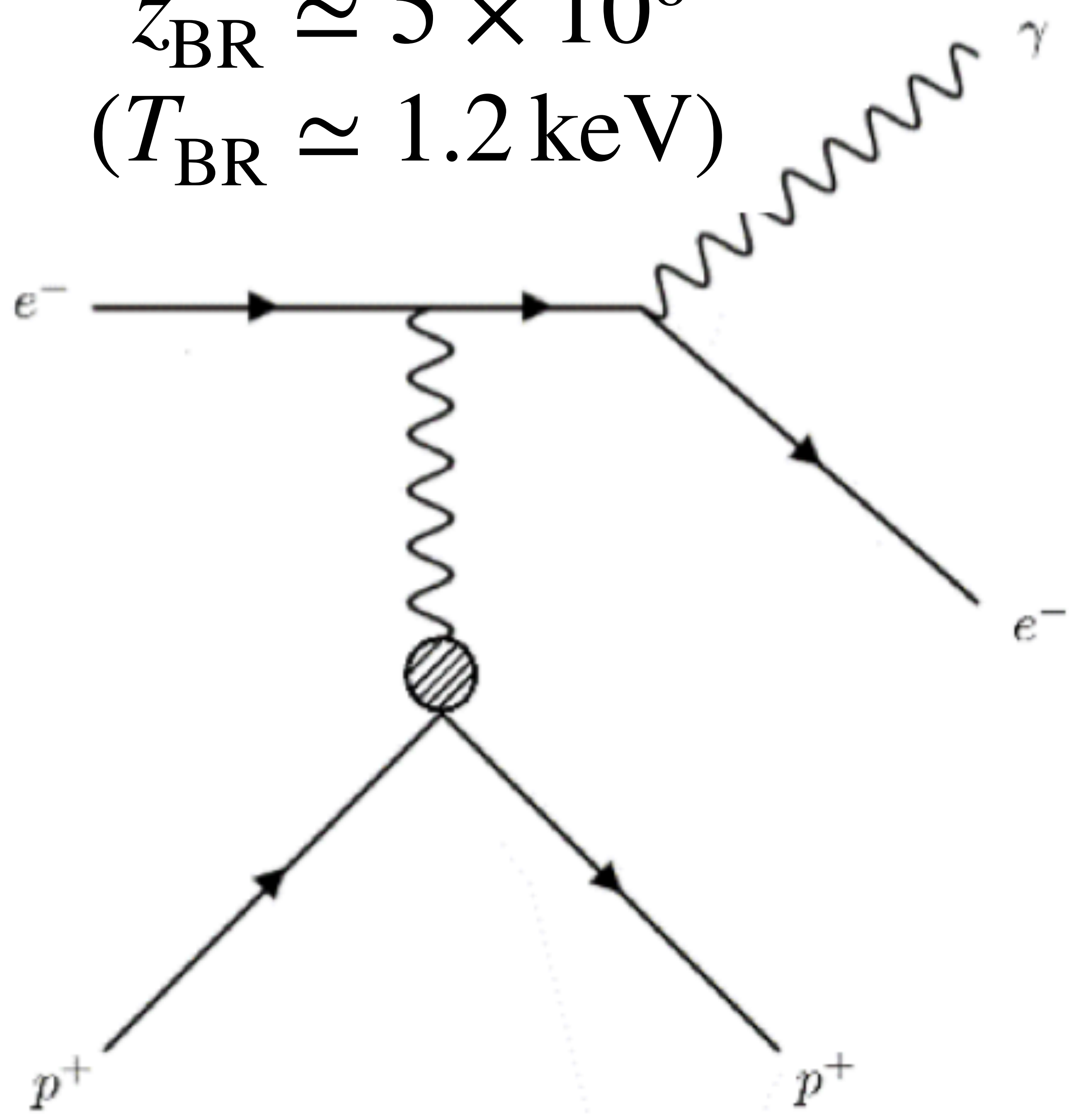
$z_{\mathrm{DC}} \simeq 2 \times 10^6$
$(T_{\mathrm{DC}} \simeq 470\,\mathrm{eV})$



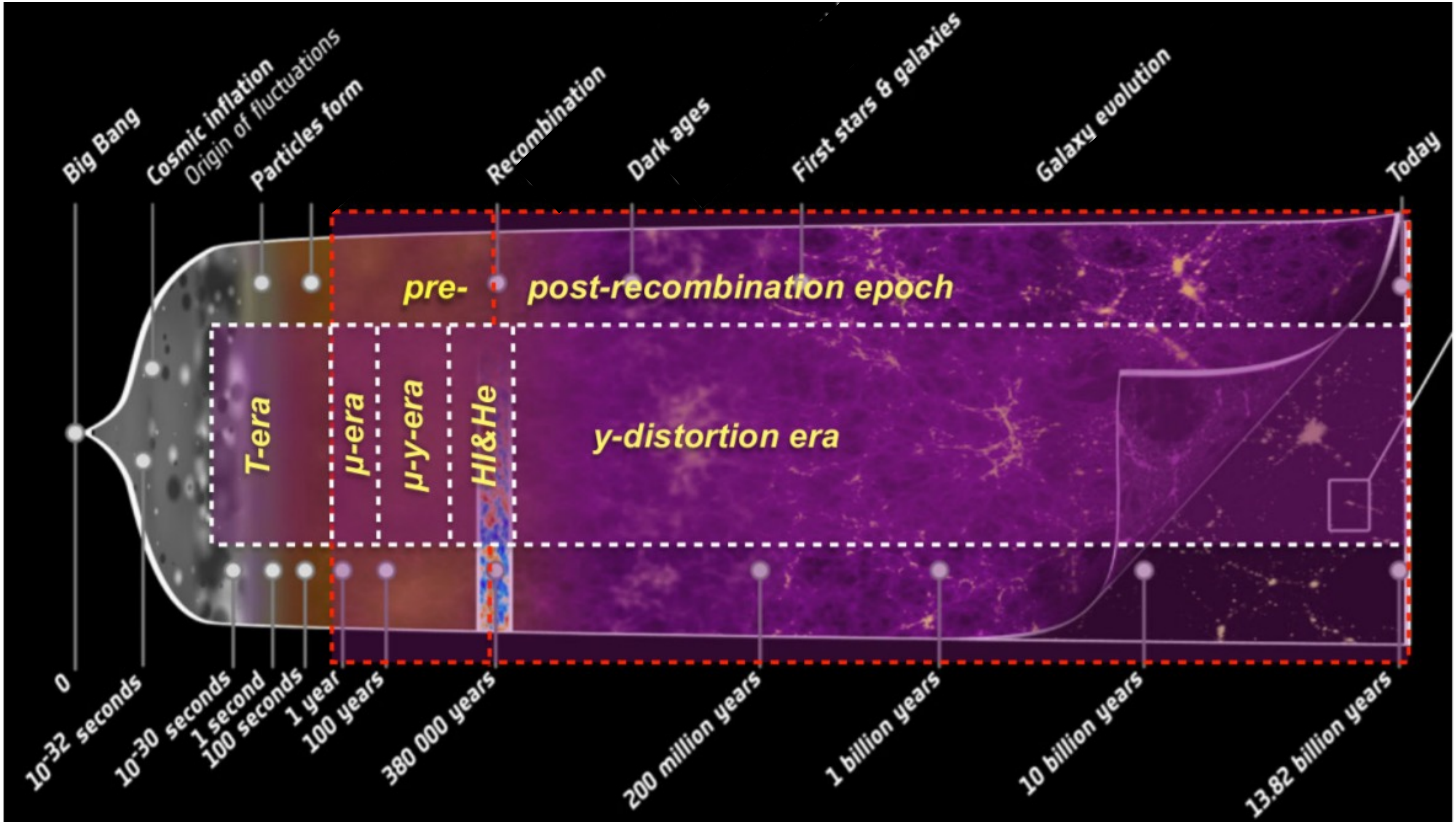
Bremsstrahlung

(number changing)

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



The distorted Universe



What distortions do we expect?

- Global SZ distortion

$$y \simeq 10^{-6}$$

- Relativistic SZ and reionization heating

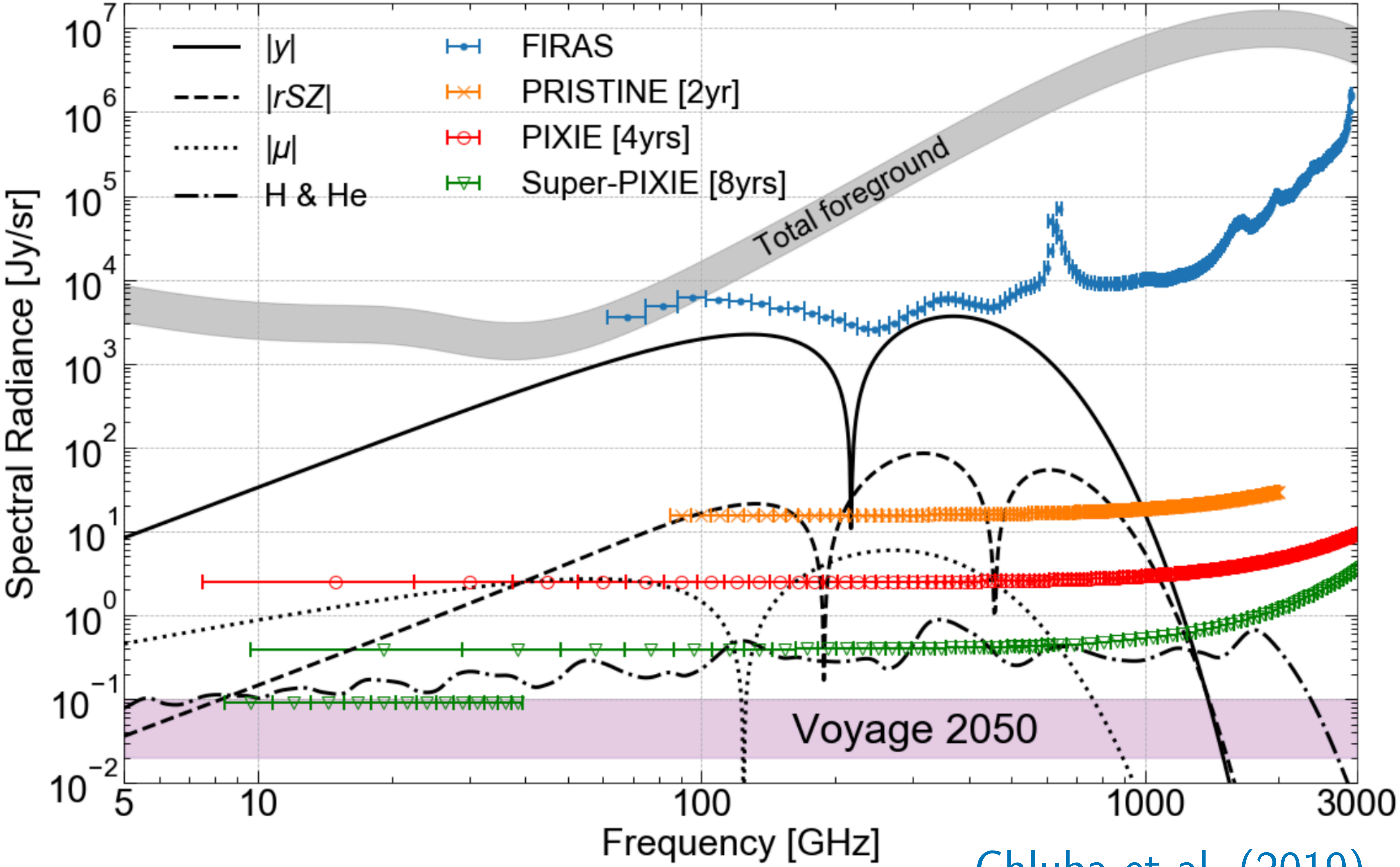
$$y \simeq 10^{-8} - 10^{-7}$$

- Dissipation of small scale modes (Silk damping)

$$|\mu| \simeq 2 \times 10^{-8}$$

- Recombination lines

$$\left|\frac{\Delta I}{I}\right| \simeq 10^{-9}$$



Chluba et al. (2019)

A powerful probe of exotic physics

Decaying/annihilating dark matter

Primordial magnetic fields

Phase transition dynamics

Primordial GW backgrounds

SM signals

Reionization probe

Silk damping

Recombination lines

Axion-photon couplings

Topological defects

Primordial black holes

Enhancement of small-scale power spectrum

BSM constraint space

+100s additional models

Experimental prospects

Ground-based:

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

Balloon-based:

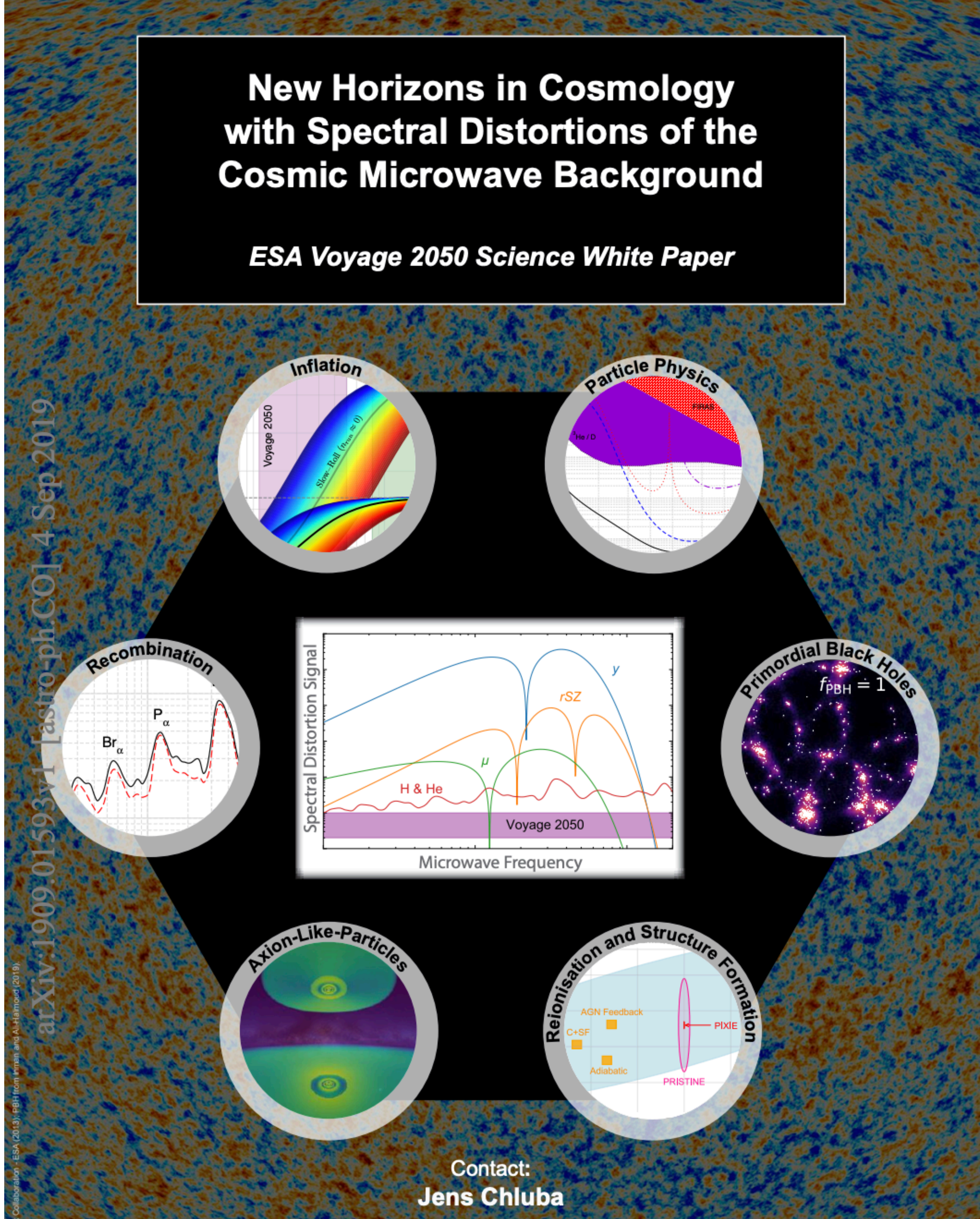
- BISOU - Balloon targeting global SZ distortion $(y \simeq 10^{-6})$. Early funding secured, measurement late 2020s.

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...

The Voyage2050 program

- Spectral distortions have been recognized by ESA as a high priority target for one of the three Voyage2050 L-class missions.
- Preparation has started for eventual call for proposals.
- Opportunities available for those interested in foreground science, synergies, experimental design, distortion theory.



New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background

ESA Voyage 2050 Science White Paper

Contact:
Jens Chluba

Distortion calculations: analytics

Chluba (2012. 2015)

Green's function method allows for simple estimates when non-thermal source terms can be computed (eg. $\mathrm{d}Q/\mathrm{d}z, \ \mathrm{d}N/\mathrm{d}z$).

μ-era:

$$\mu \simeq 1.401 \int_{z_{\mu/y}}^{\infty} \mathrm{d}z \left(\frac{1}{\rho_\gamma} \frac{\mathrm{d}Q}{\mathrm{d}z} - \frac{4}{3} \frac{1}{N_\gamma} \frac{\mathrm{d}N}{\mathrm{d}z} \right) \mathrm{e}^{-\left(\frac{z}{2\times 10^6}\right)^{5/2}}$$

$$z_{\mu/y} \simeq 5 \times 10^4$$

y-era:

$$y \simeq \frac{1}{4} \int_{z_{\rm rec}}^{z_{\mu/y}} \mathrm{d}z \, \frac{1}{\rho_\gamma} \frac{\mathrm{d}Q}{\mathrm{d}z} \qquad (\mathrm{d}N/\mathrm{d}z \ll 1)$$

Formalism breaks down for large entropy injection in y-era, and if dominant non-thermal injection happens near $z_{\mu/y}$.

Numerical methods: CosmoTherm

Chluba and Sunyaev (2012)

Code developed to solve the thermalization problem at all redshifts where generation of CMB spectral distortions is possible ($z \lesssim 2 \times 10^6$).

$$\frac{\partial n_\nu}{\partial \tau} - H t_{\rm C} \nu \frac{\partial n_\nu}{\partial \nu} = \left.\frac{dn_\nu}{d\tau}\right|_{\rm C} + \left.\frac{dn_\nu}{d\tau}\right|_{\rm DC} + \left.\frac{dn_\nu}{d\tau}\right|_{\rm BR} + \left.\frac{dn_\nu}{d\tau}\right|_{\rm Src}$$

- Possible to utilize full kernel expressions for high numerical accuracy.
- Interfaces with Recfast++ to compute recombination effects.

Chluba and Thomas (2011)

- Possesses a basic reionization module. Credit: Jiten Dhandha
- Functionality to incorporate a large variety of exotic injection scenarios (entropy and energy reprocessing).
- Simple likelihood analysis for easy comparison of models with various datasets (distortions, anisotropies, global 21-cm, radio backgrounds).

CosmoTherm: Energy injection scenarios

Flexible enough to handle and produce leading constraints on a variety of exotic injection scenarios:

- Decaying or annihilating dark matter. Chluba (2009) Bolliet et al. (2021)
- Modifications to the primordial scalar power spectrum. Chluba et al. (2015) Cyr et al. (2023c)
- Dissipation of primordial tensor modes. Kite et al. (2020) Cyr et al. (2023c)
- Decay of cosmic strings. Cyr et al. (2023a,b)
- Accretion and evaporation of primordial black holes. Acharya et al. (2022)

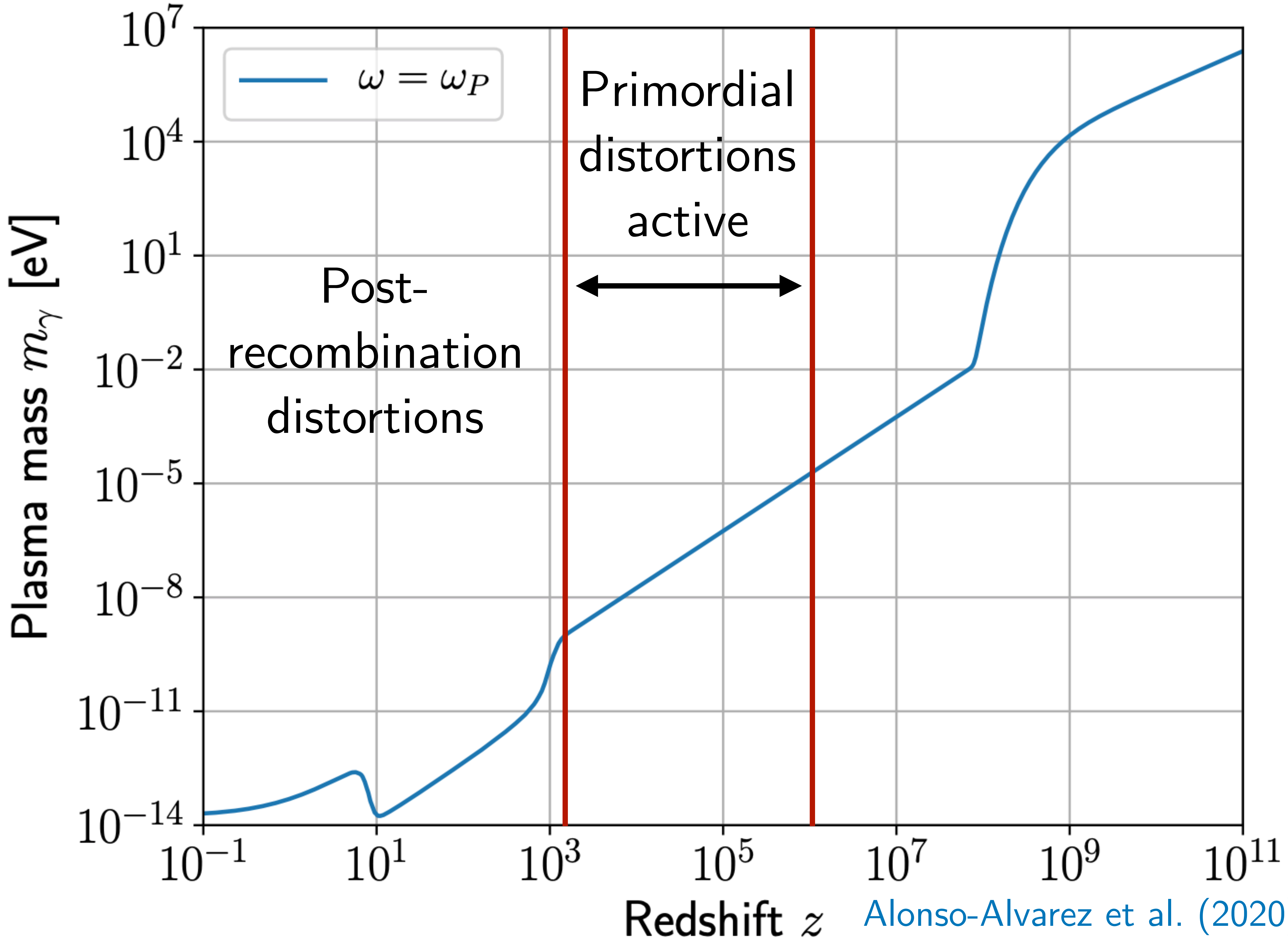
- + your favourite exotic model!

Wavy dark matter constraints

Thermal mass of photon sets firm lower bound on DM masses constrained by decays, conversions $m_{\rm dm} \gtrsim m_\gamma^{\rm therm}(z)$.

Some well studied models:

- Dark photon dark matter (resonant oscillations).
- Axion-photon couplings (perturbative decays).
- Axion-photon-dark photon models.



Alonso-Alvarez et al. (2020)

Dark photon dark matter

Mirizzi et al. (2009)

Kunze and Vazquez-Mozo (2015)

Hidden $U(1)$ sector will kinetically mix with the standard model photon:

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\sin\chi_0}{2}B_{\mu\nu}F^{\mu\nu} + \frac{\cos^2\chi_0}{2}m_{\gamma'}^2 B_\mu B^\mu + j_{\rm em}^\mu A_\mu$$

Interaction and propagation basis not aligned, analogous MSW effect ensures conversions between photon and dark photon.

Landau-Zener expression gives probability for (non-adiabatic) conversions.

$$P_{\gamma\to\gamma'} \simeq \frac{\pi m_{\gamma'}^2 \chi_0^2}{\omega} \left| \frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t} \right|_{t=t_{\rm res}}^{-1}$$

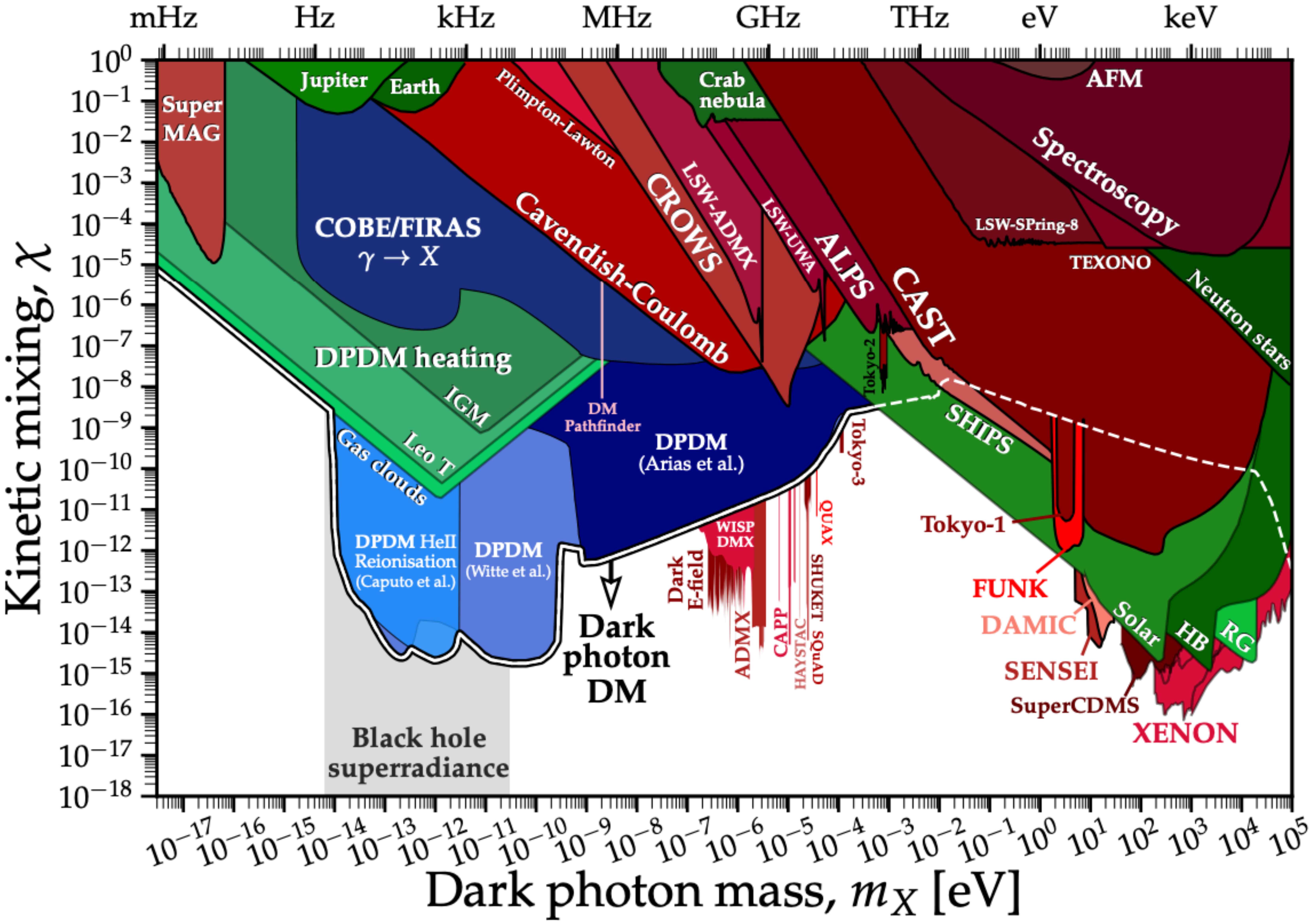
$$I_\omega(m_{\gamma'}, \chi_0) = B_\omega(1 - P_{\gamma\to\gamma'})$$

$$\Delta I_\omega / I_\omega \lesssim 10^{-4} \quad \text{(FIRAS)}$$

Dark photon dark matter

Constraints from pre- and post-recombination conversion.

COBE-FIRAS legacy value: Provided leading constraints until circa 2015.



Caputo et al. (2021)

ALP-photon couplings

Most generic ALPs possess a Chern-Simons coupling to the photon:

$$\mathscr{L}_{\mathrm{CS}} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Spontaneous decay rate very small...

$$\tau_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} \simeq 10^{43}\,\mathrm{s} \left(\frac{10^{-10}\,\mathrm{GeV}^{-1}}{g_{a\gamma\gamma}} \right)^2 \left(\frac{1\,\mu\mathrm{eV}}{m_a} \right)^3 \qquad (\Gamma = 1/\tau_a)$$

CMB background can help stimulate decays!

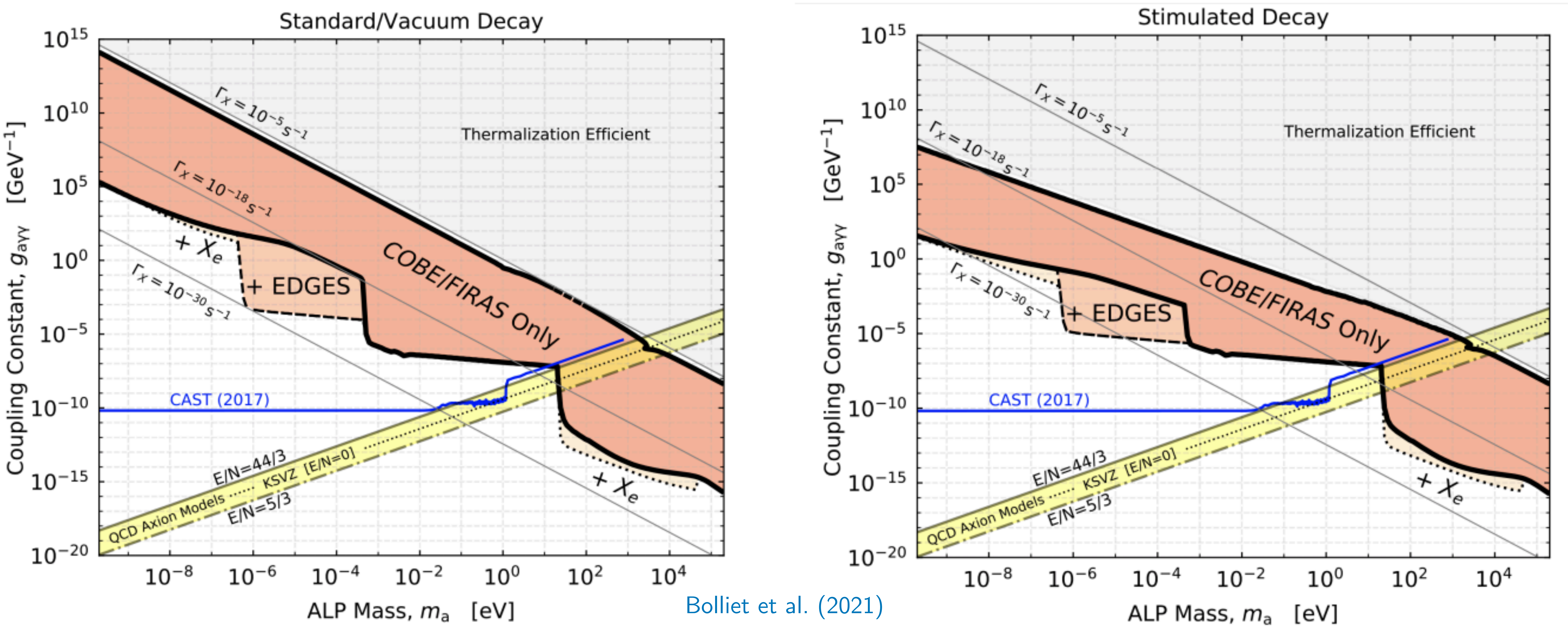
$$\Gamma_{\mathrm{stim}} \approx \Gamma_{\mathrm{pert}}(1 + 2n_\gamma) \qquad n_\gamma = (\mathrm{e}^x - 1)^{-1} \qquad (x = \hbar\omega / k_{\mathrm{b}} T)$$

For light axions, $\omega/T \ll 1$, strong boost to decay rate ($n_\gamma \gg 1$).

ALP-photon couplings

Low masses: Not competitive with CAST.

High masses: Near-leading constraints, PIXIE would probe much deeper.



Bolliet et al. (2021)

ALP-photon-dark photon models

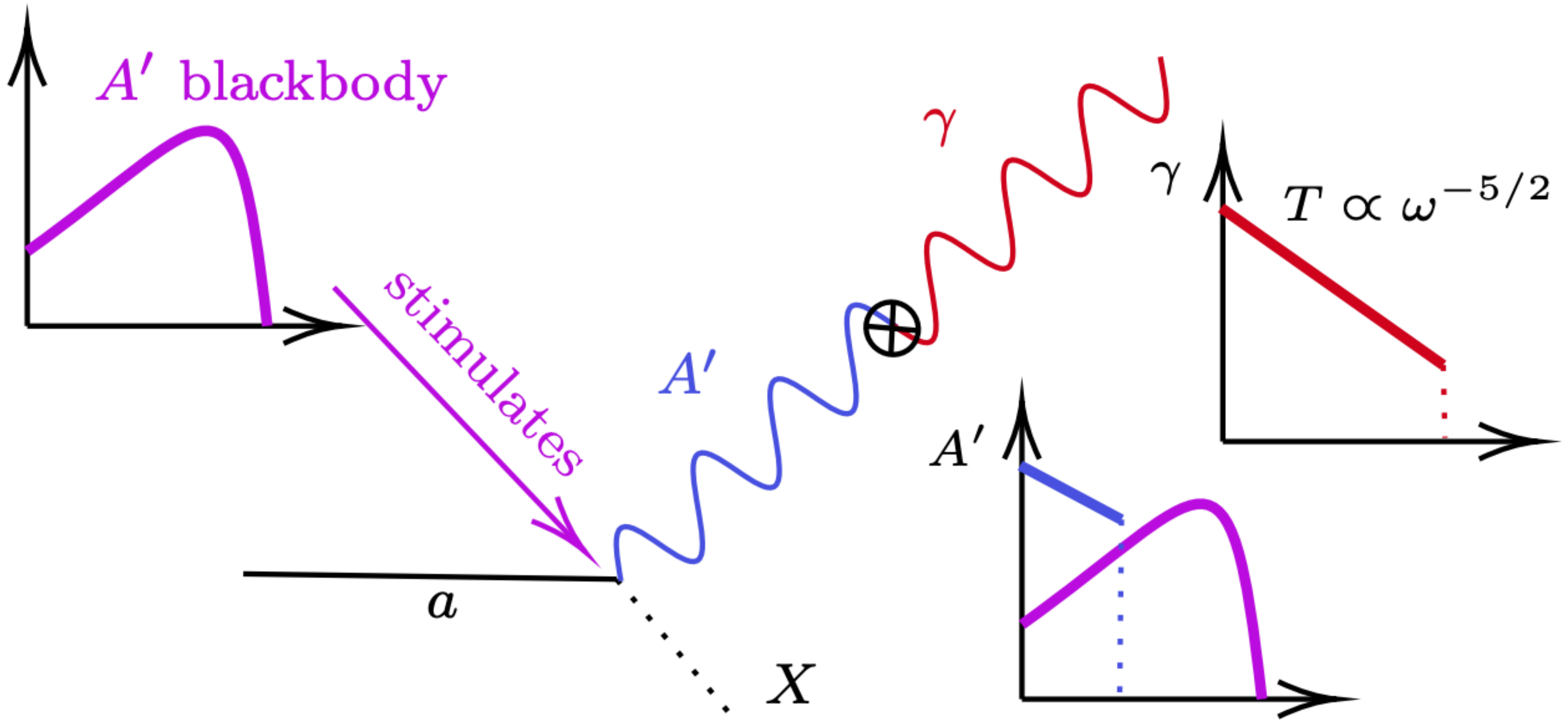
Ingredients: ALP (DM candidate), thermal dark photon bath ($T_{\gamma'} \approx 0.1\, T_\gamma$).

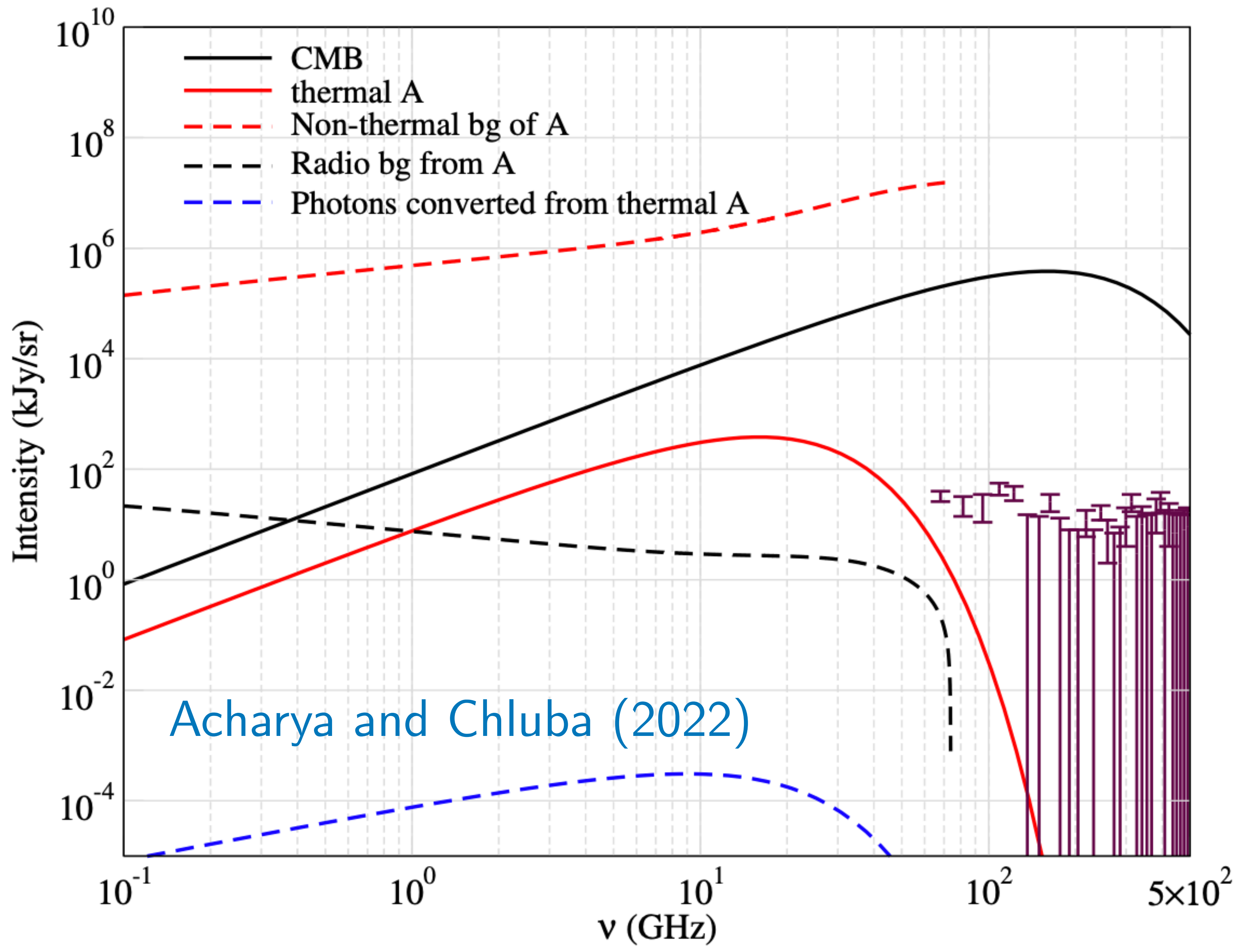
- DP bath stimulates decay of ALP.
- Resonant conversion to photons can potentially explain RSB.
- SDs constrainable by PIXIE.

Claims of RSB resolution disputed by Acharya and Chluba (2022).

- Improper EG BG modelling.
- Runaway self-stimulation expected with intense non-thermal DP BG.

Caputo et al. (2022)





Acharya and Chluba (2022)

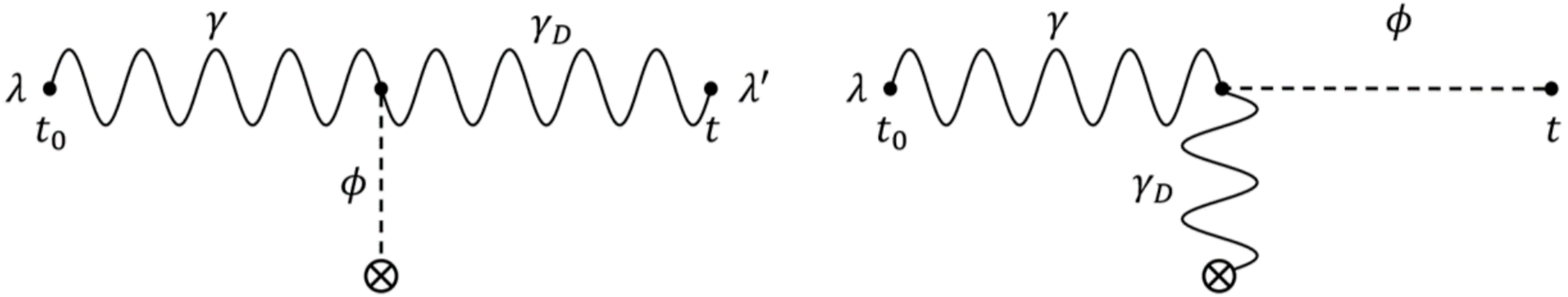
ALP-photon-dark photon models

Hook et al. (2023)

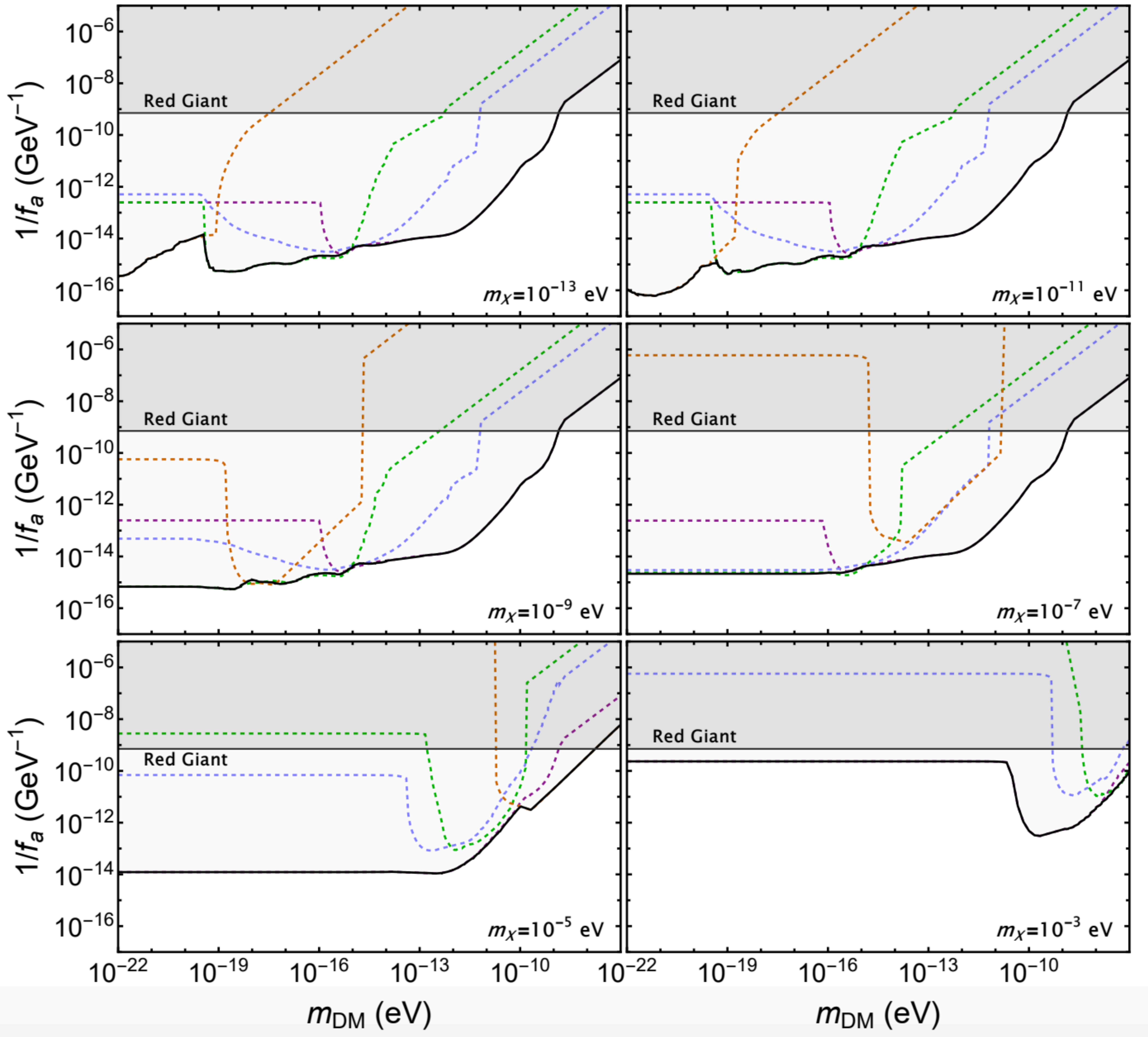
Consider presence of dark charge conjugation symmetry on ALP and DP, only unsuppressed operator is:

$$\mathscr{L}_{\mathrm{int}} = -\frac{g_{\mathrm{a}\gamma\gamma'}}{4} a B_{\mu\nu} \tilde{F}^{\mu\nu}$$

Interaction converts photons to dark photons in the presence of ALP DM background. Also works with ALP and DP roles reversed.



Hook et al. (2023)



ALP = DM

$\gamma \to \gamma'$

$(g_{a\gamma\gamma'} \sim 1/f_a)$

Possible project ideas

- Spectral distortions also have synergies with other observational probes (e.g. 21-cm Acharya, Cyr, Chluba (2023) and GW backgrounds Cyr, Chluba, Acharya (2023)), can induced signals in these channels also be probed using the CMB?

- Are there subtle signatures that can still be explored? Does wavy dark matter induce extra patch-mixing in the pre-recombination era, increasing the Silk-damping prediction on μ?

- How does the presence of a cutoff scale on small-scale structure alter the expected y-distortion from reionization?

Conclusions

- CMB spectral distortions can be used to probe a wide variety of exotic physics scenarios, including wavy dark matter.
- Constraints have been studied for dark photon dark matter and axion-photon interactions, but significant improvements to these calculations are now possible, both analytically and numerically.
- Models with more complicated dynamics and source terms can be studied in CosmoTherm to ensure robust predictions.
- Hints of possible explanation of extra-radio background from some models! Further studies necessary to better explore parameter space.

Thank you!

CosmoTherm: Reionization module

Credit: Jiten Dhandha (2021)

Solver models reionization following treatment of Furlanetto (2006)

- Inclusion of x_r which is solved iteratively alongside $T_{\rm spin}$.

Venumadhav et al. (2018)
Fialkov and Barkana (2019)
Mittal et al. (2022)

Ly-α background modelled by Hirata (2006), only stellar contributions.

Additionally

- Ionizing photons per baryon, $N_{\rm ion} = 4000$
- Star formation efficiency, $f_* = 0.1$
- Escape fraction, $f_{\rm esc} = 0.1$
- Ly-α background scaling factor, $f_\alpha = 1$
- X-ray heating scaling factor, $f_{\rm X} = 1$

See Acharya, Cyr, Chluba (2023) for more details

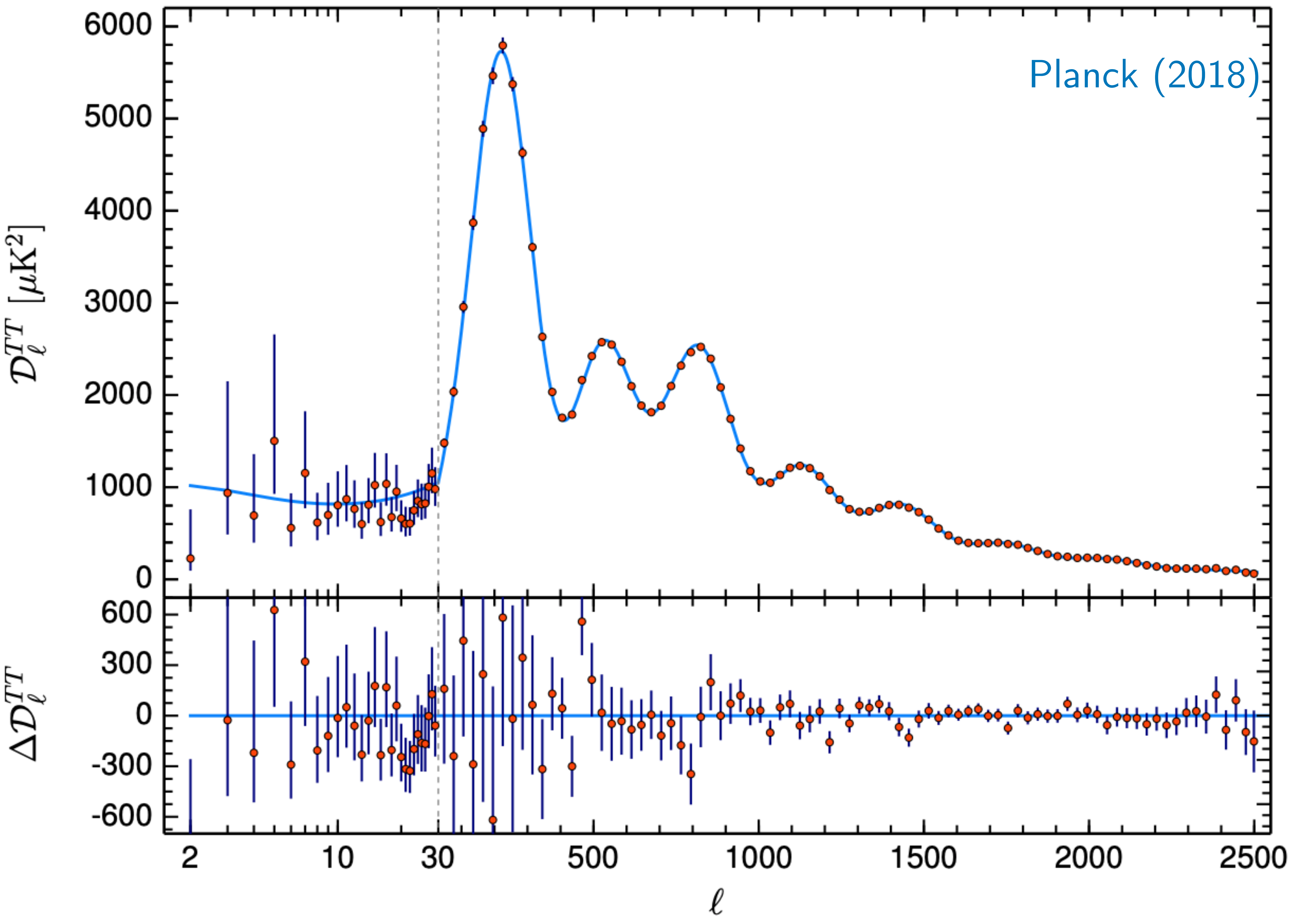
Silk damping - a standard model signal

Diffusion damping and free-streaming play significant role in the amplitude of small-scale modes.

Where does the energy initially present in those modes go?

Into the background plasma!

Doesn't necessarily imply a spectral distortion...



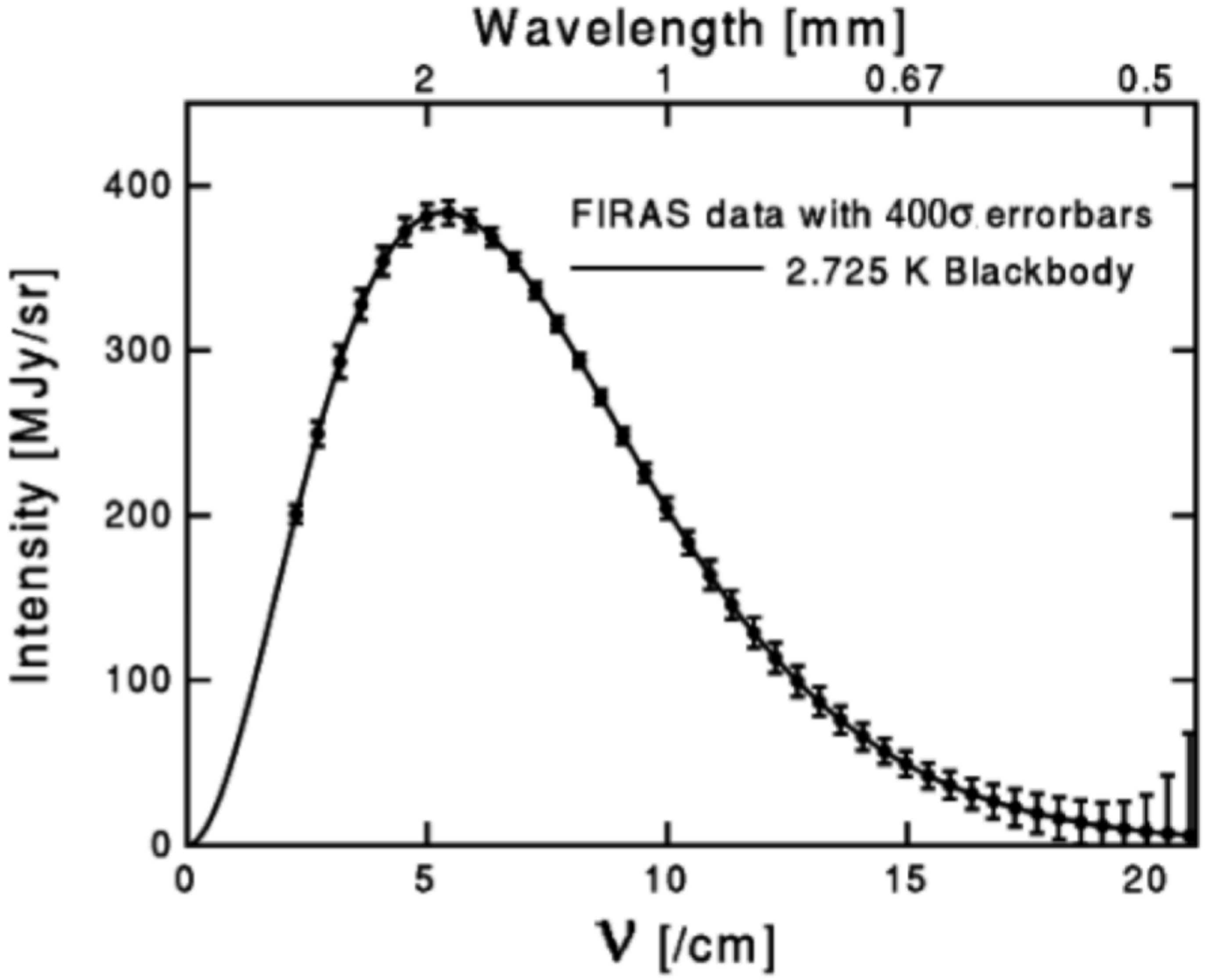
Mixing of blackbodies

Chluba, Khatri, Sunyaev (2012)

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

$$T - \delta T$$

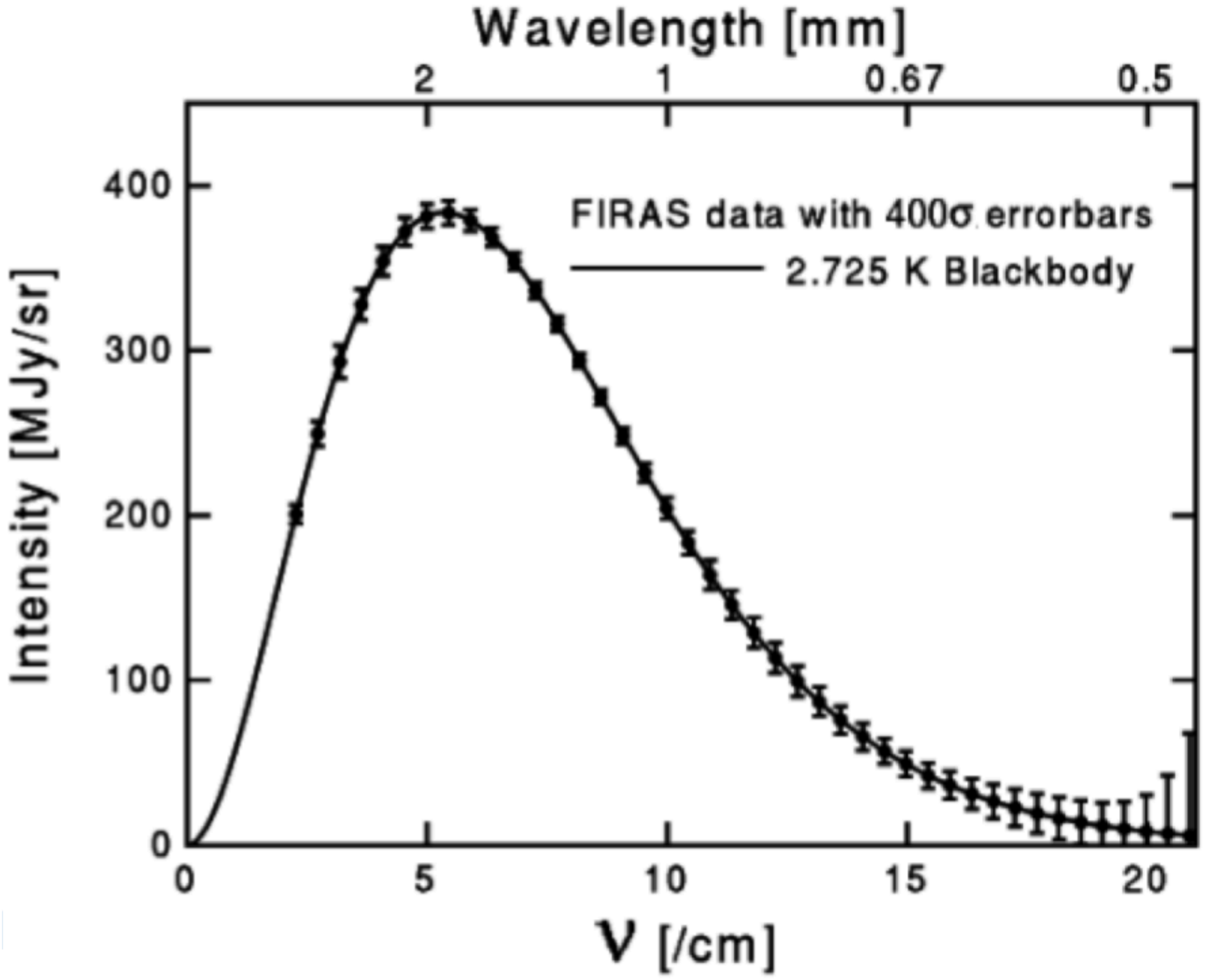
$$\mu, y = 0$$



$+$

$$T + \delta T$$

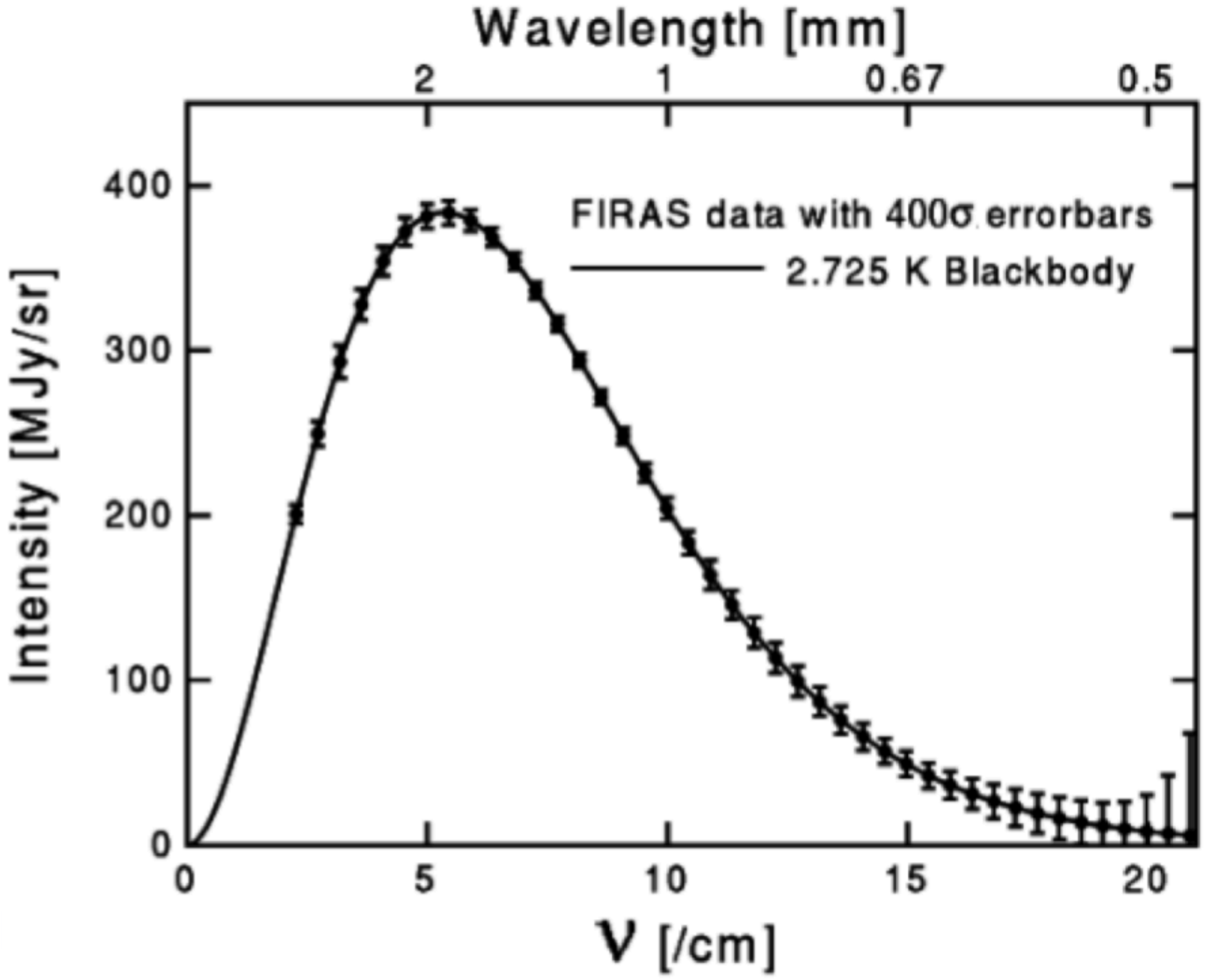
$$\mu, y = 0$$



$\neq$

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

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



Mixing generically produces a new spectrum which is approx. BB at a higher temperature, and a μ- or y-distortion depending on mixing redshift.

Energy injection rate

Physical picture: A given k-mode enters the horizon, oscillates, and dumps energy into the background when crossing the damping scale ($k_\mathrm{D}[z]$)

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

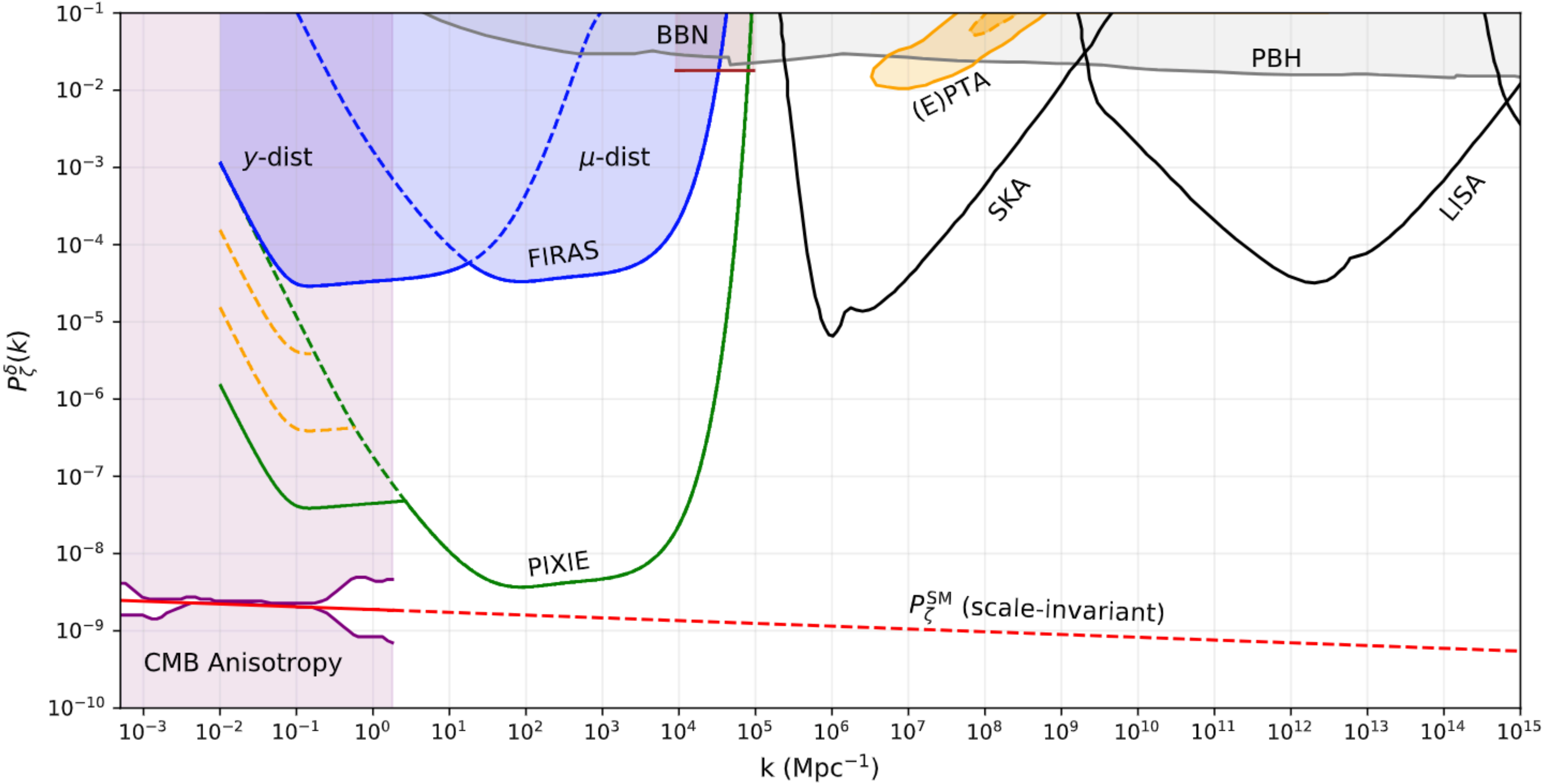
$$\frac{\mathrm{d}(Q_\mathrm{ac}/\rho_\gamma)}{\mathrm{d}z} \approx \frac{A^2}{Ha}\frac{32c^2}{45\dot{\tau}(z)}\int \mathrm{d}k \frac{k^4}{2\pi^2}P_\zeta(k)\mathrm{e}^{-k^2/k_\mathrm{D}^2(z)}$$

Chluba and Grin (2013)

- $A \approx 0.9$ for adiabatic fluctuations, suppressed for isocurvature.
- $\dot{\tau} = \sigma_\mathrm{T} N_\mathrm{e} c$ is rate of Thomson scattering.
- $\partial_t k_\mathrm{D}^{-2} \approx 8c^2/45a^2\dot{\tau}$ determines damping scale. Kosowsky and Turner (1995)

SDs sensitive to PPS at $50\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 10^4\,\mathrm{Mpc}^{-1}$
SM prediction: $\mu \simeq 2 \times 10^{-8}$

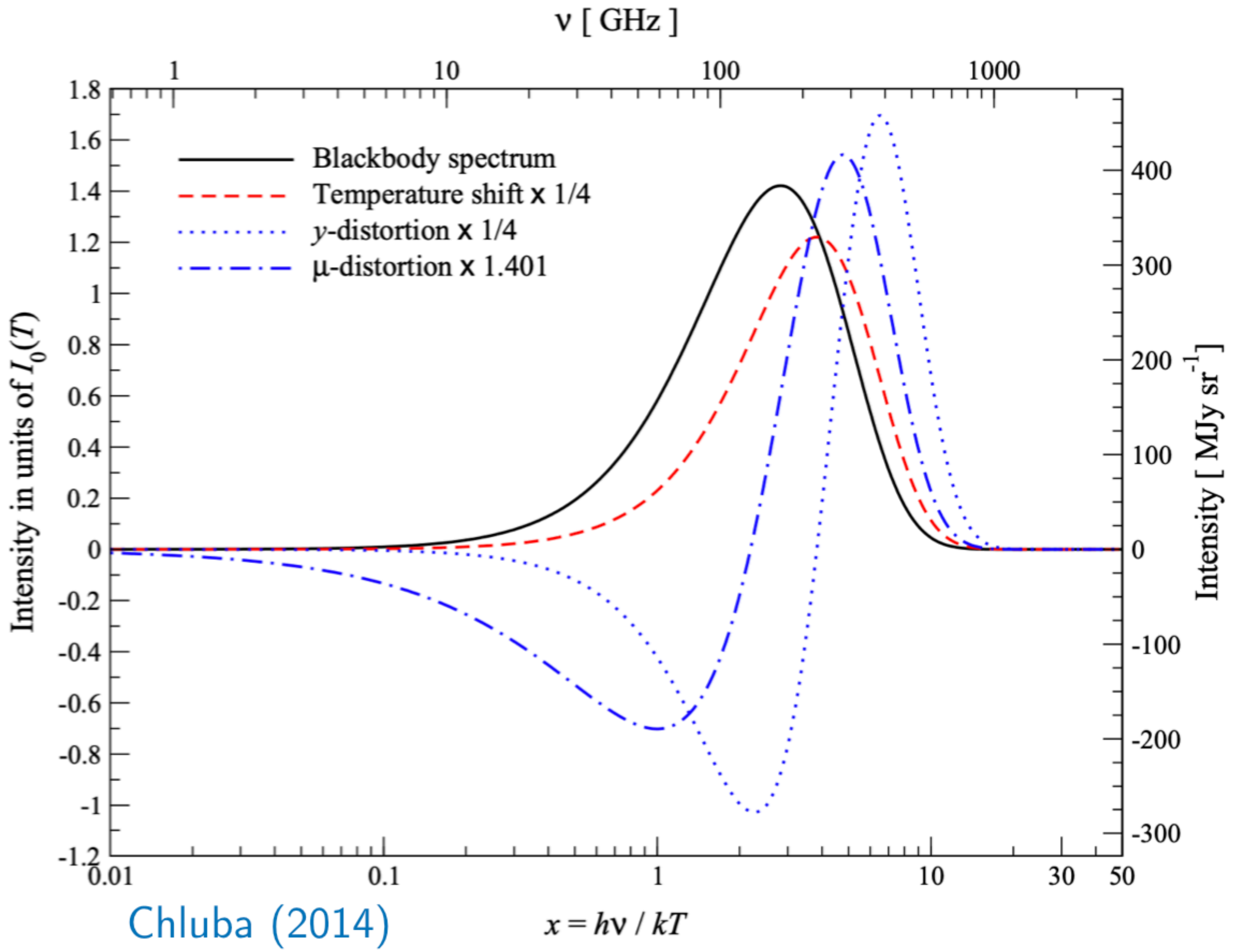
The scalar primordial power spectrum (PPS)



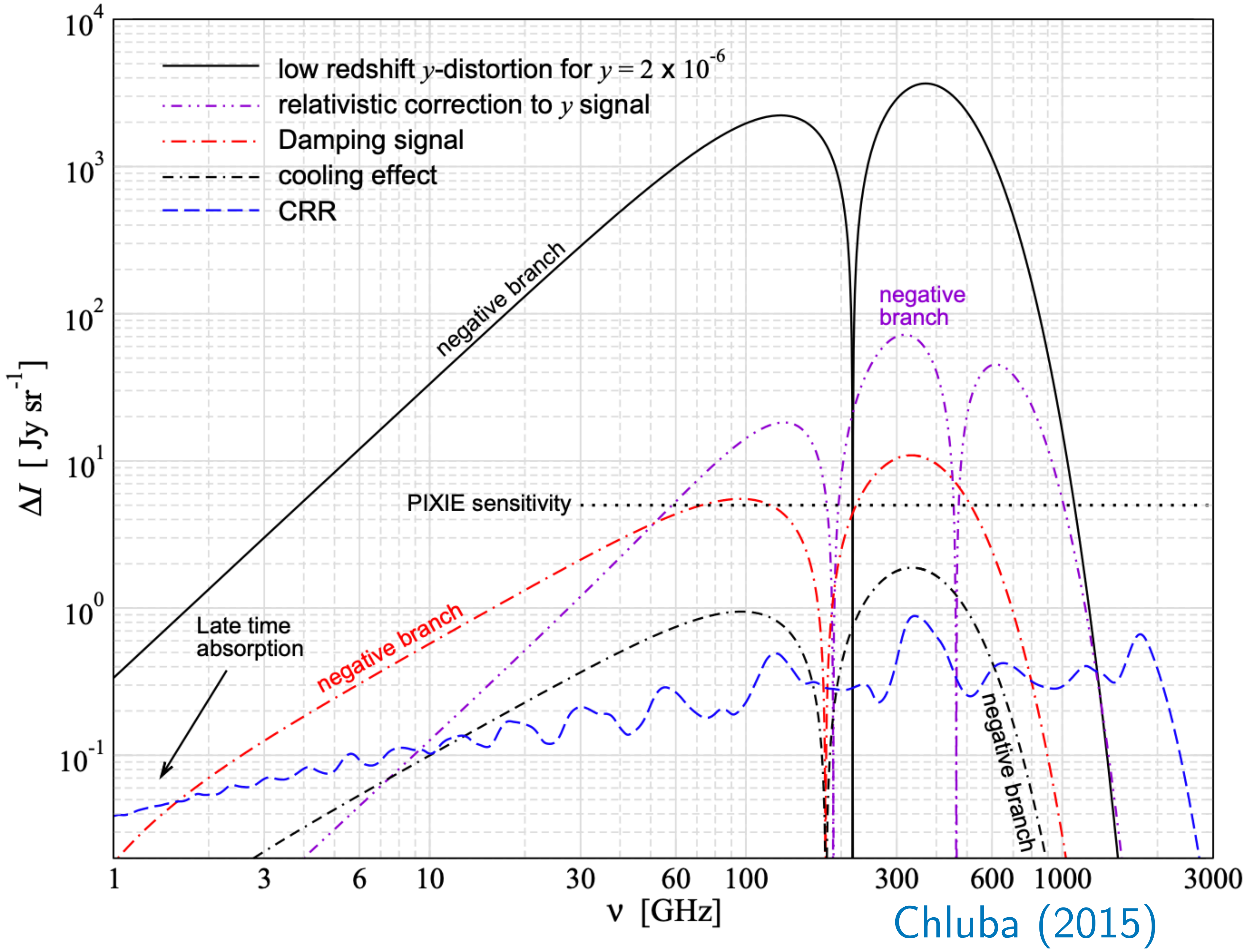
CosmoTherm: Photon processing

- Evolves photons in frequency range $10^{-5} \lesssim x \lesssim 200$ (CMB peak $x \simeq 3$).
- Adaptive time stepping from $z \lesssim 10^7$.
- Can utilize CSpack as well as BRpack for added precision.

Sarkar et al. (2019) Chluba et al. (2019)



Chluba (2014)



Chluba (2015)