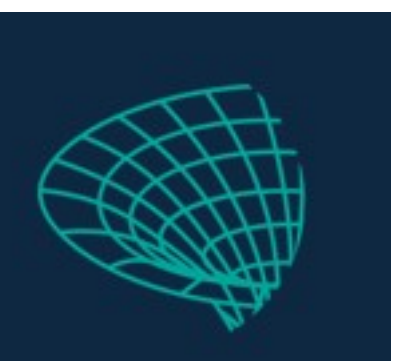




Stress-Testing the Universe With CMB Spectral Distortions

Bryce Cyr

Based on arxiv: 2610.xxxx 2606.09491, 2409.12115, 2406.12985



Tensions in Cosmology
GGI



July 22nd, 2026



Outline

The WHAT: Distortion Science 101

- Current state of the art

The HOW:

- How are spectral distortions generated?
- BSM case study: Resonant dark photon conversions

The WHEN: Experimental Timelines

- Tenerife Microwave Spectrometer (TMS)
- COSMO
- BISOU
- FOSSIL

WHAT: is a CMB spectral distortion?

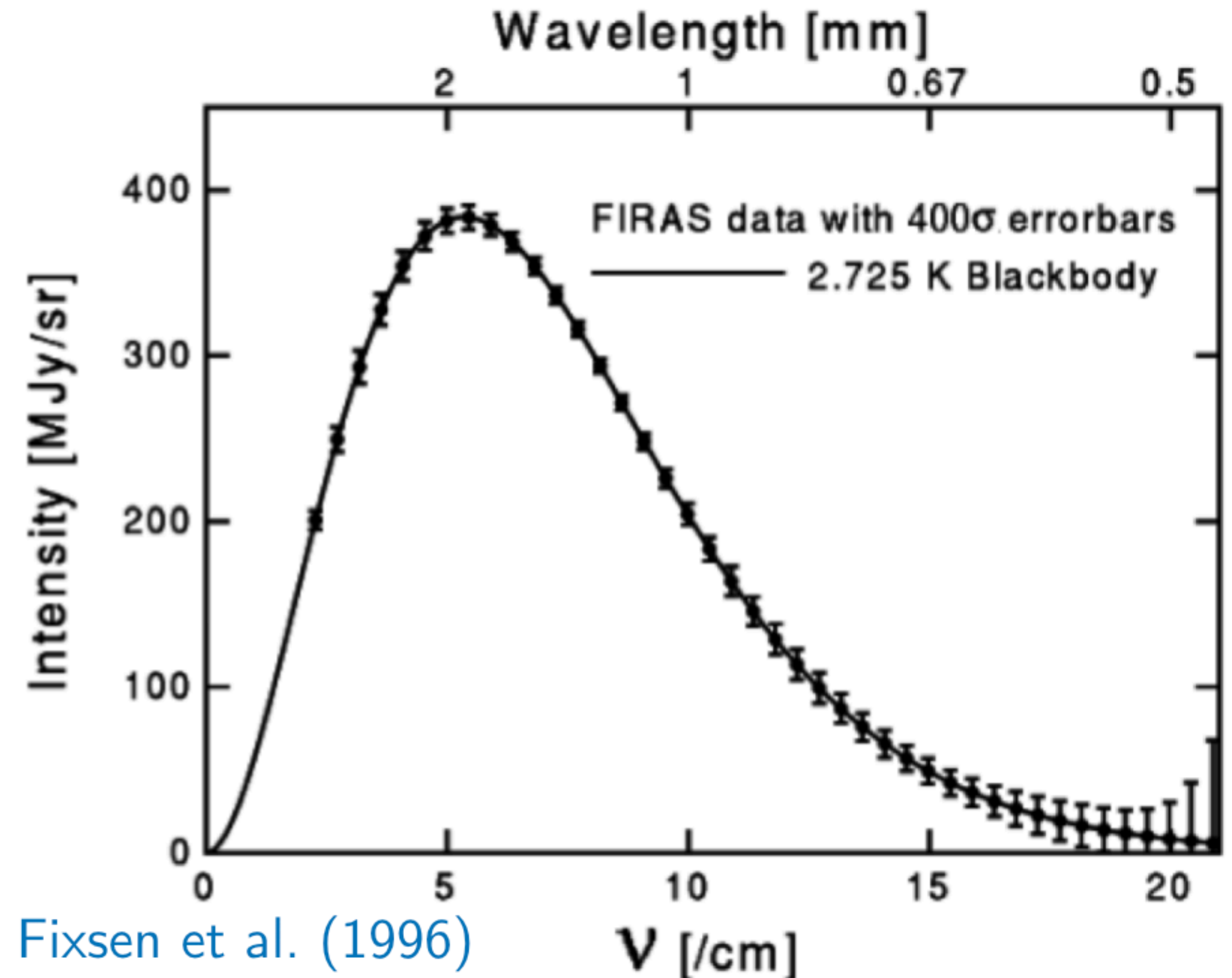
COBE/FIRAS measured nearly perfect blackbody of the CMB.

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

COBE/FIRAS

$$|\mu| \lesssim 10^{-4}$$

$$|y| \lesssim 10^{-5}$$



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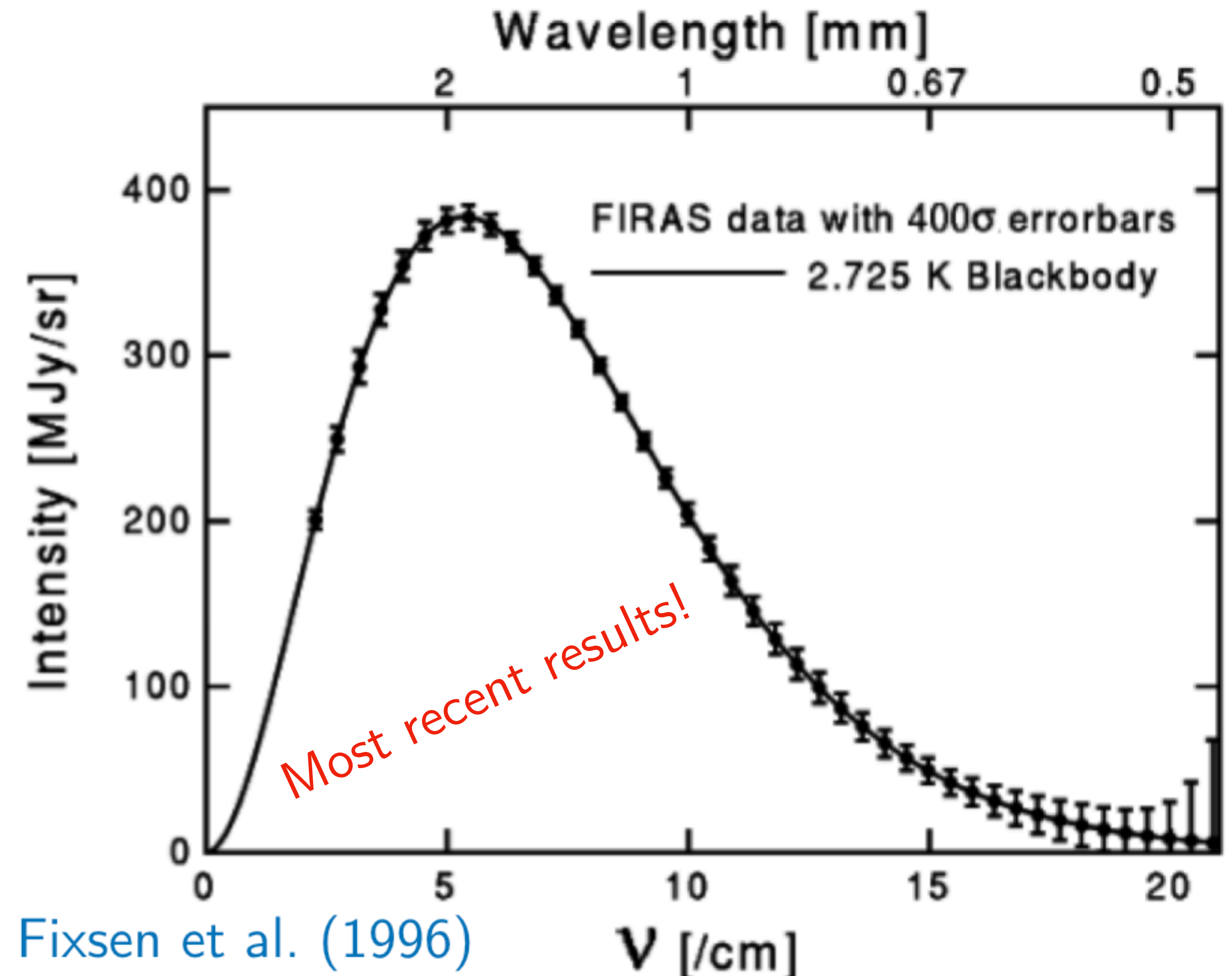
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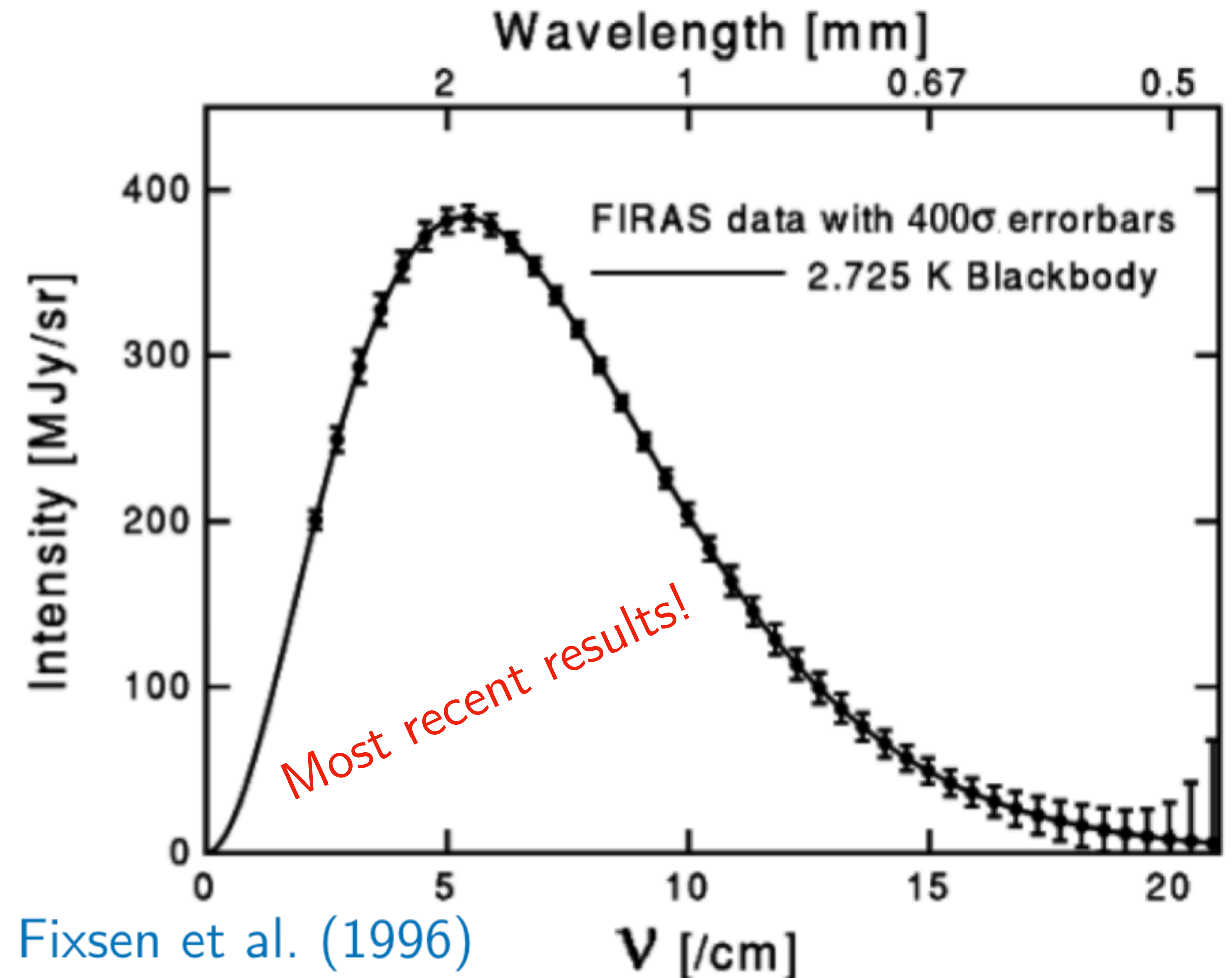
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FOSSIL/PIXIE

$$|\mu| \lesssim 10^{-8}$$

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



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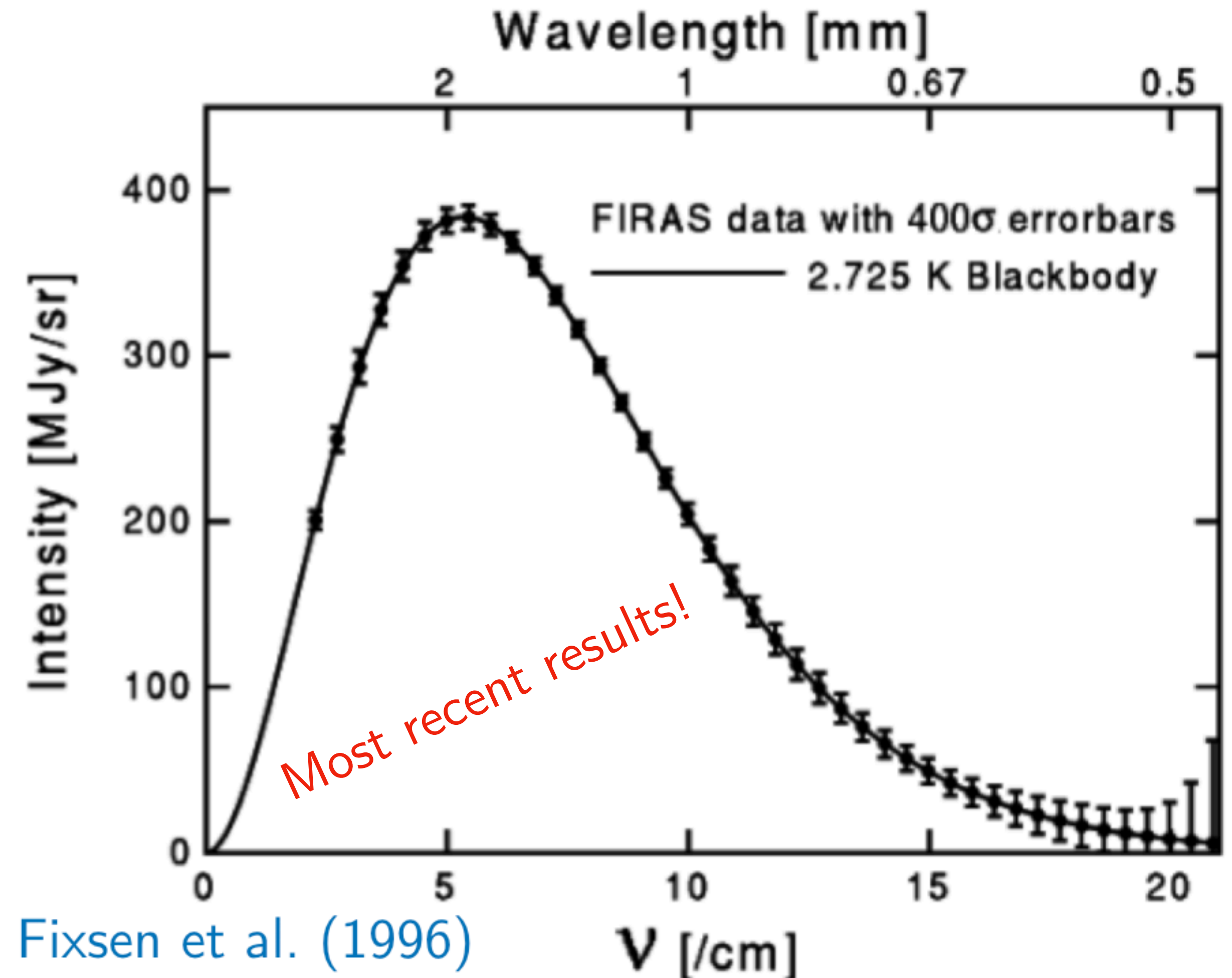
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A distorted spectrum implies the non-thermal injection and/or extraction of energy/entropy.



Fixsen et al. (1996)

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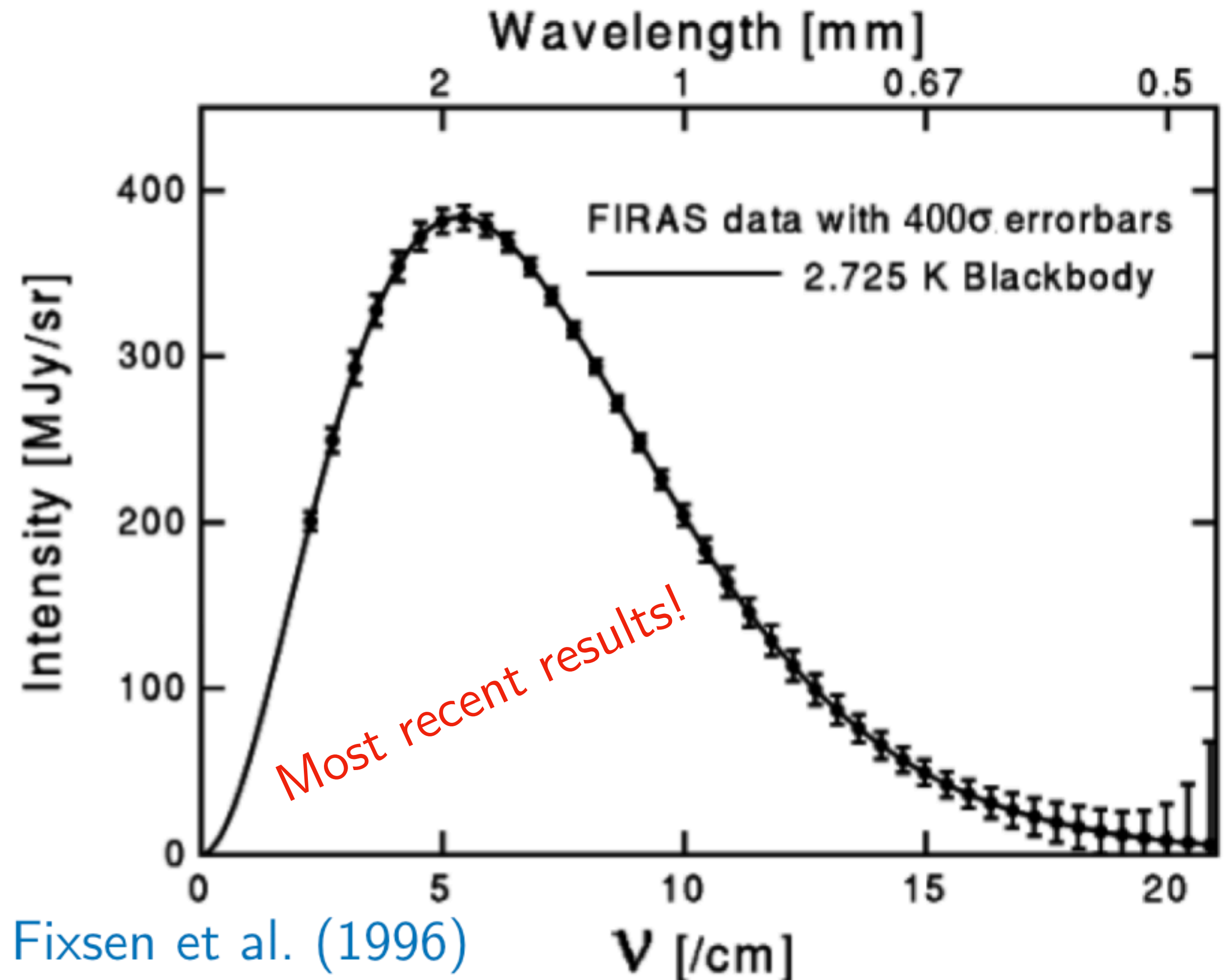
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Fixsen et al. (1996)

SM signal at $\mu \simeq 2 \times 10^{-8}$

No shortage of possible BSM distortions!

HOW: are distortions thermalized?

How does one thermalize a distorted spectrum?

- Energy redistribution
- Photon creation/destruction

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

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$$z \gtrsim 10^6$$

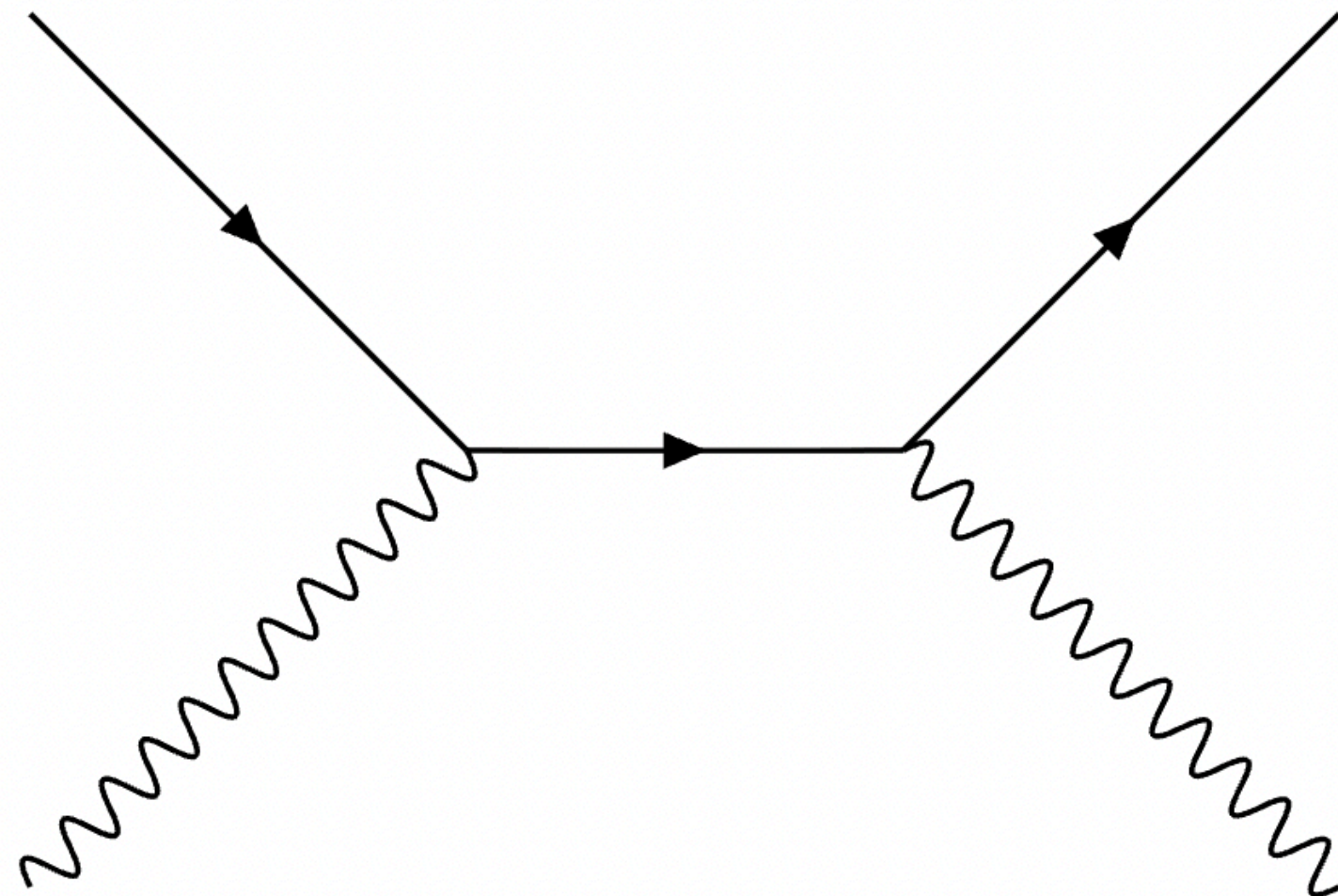
T-shift

Compton

(energy changing)

$$z_C \simeq 5 \times 10^4$$

$$(T_C \simeq 12 \text{ eV})$$

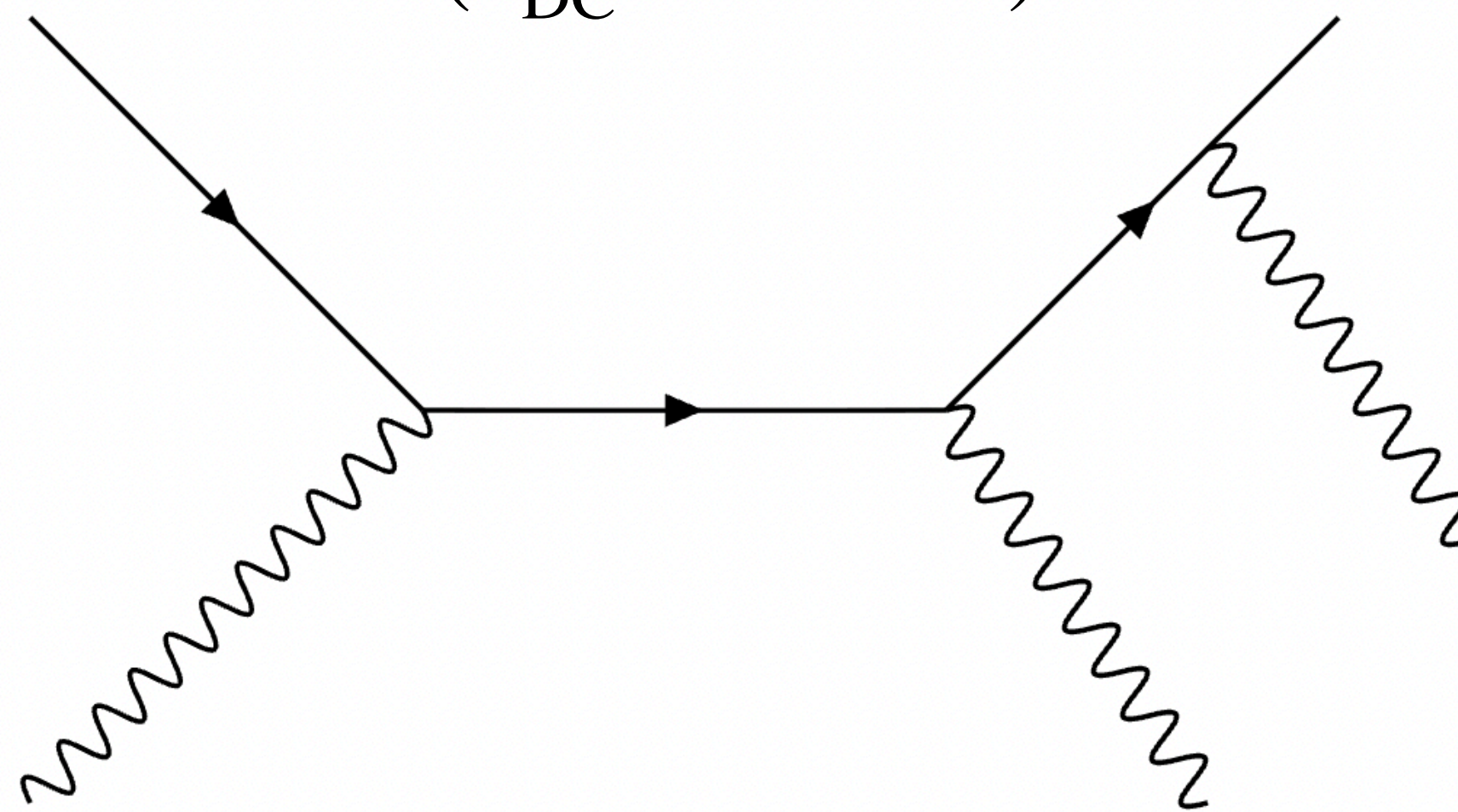


Double Compton

(number changing)

$$z_{DC} \simeq 2 \times 10^6$$

$$(T_{DC} \simeq 470 \text{ eV})$$

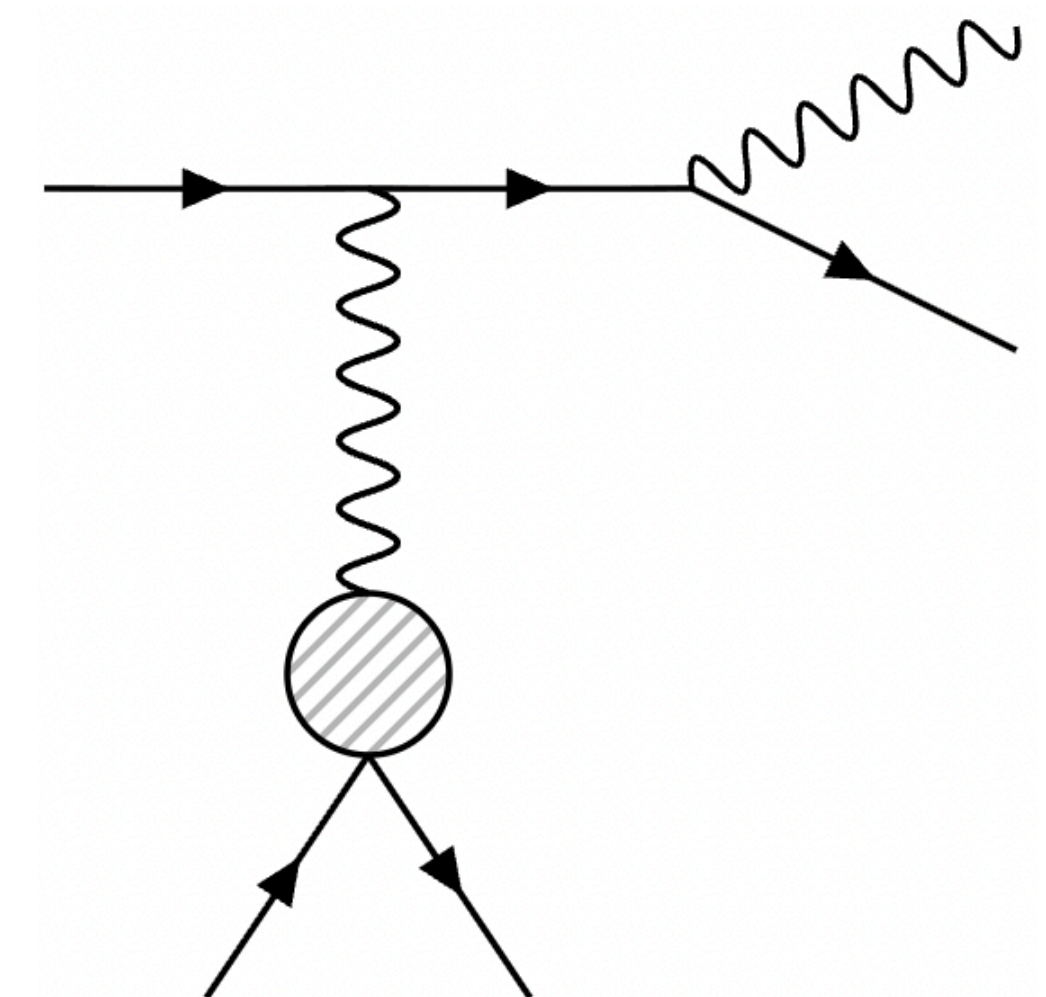


Bremsstrahlung

(number changing)

$$z_{BR} \simeq 5 \times 10^6$$

$$(T_{BR} \simeq 1.2 \text{ keV})$$



HOW: are distortions thermalized?

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$$5 \times 10^4 \lesssim z \lesssim 10^6$$

μ -distortion

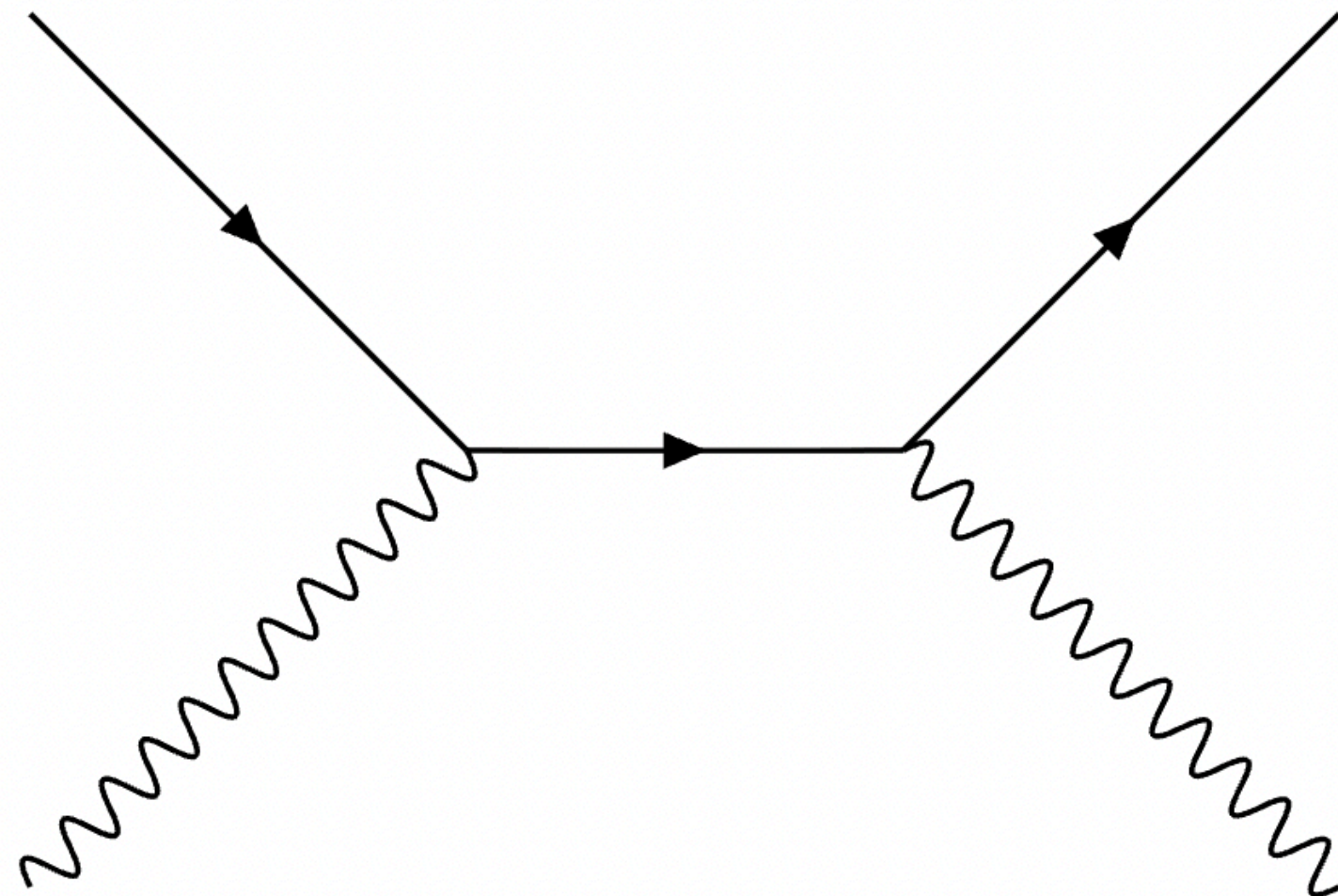
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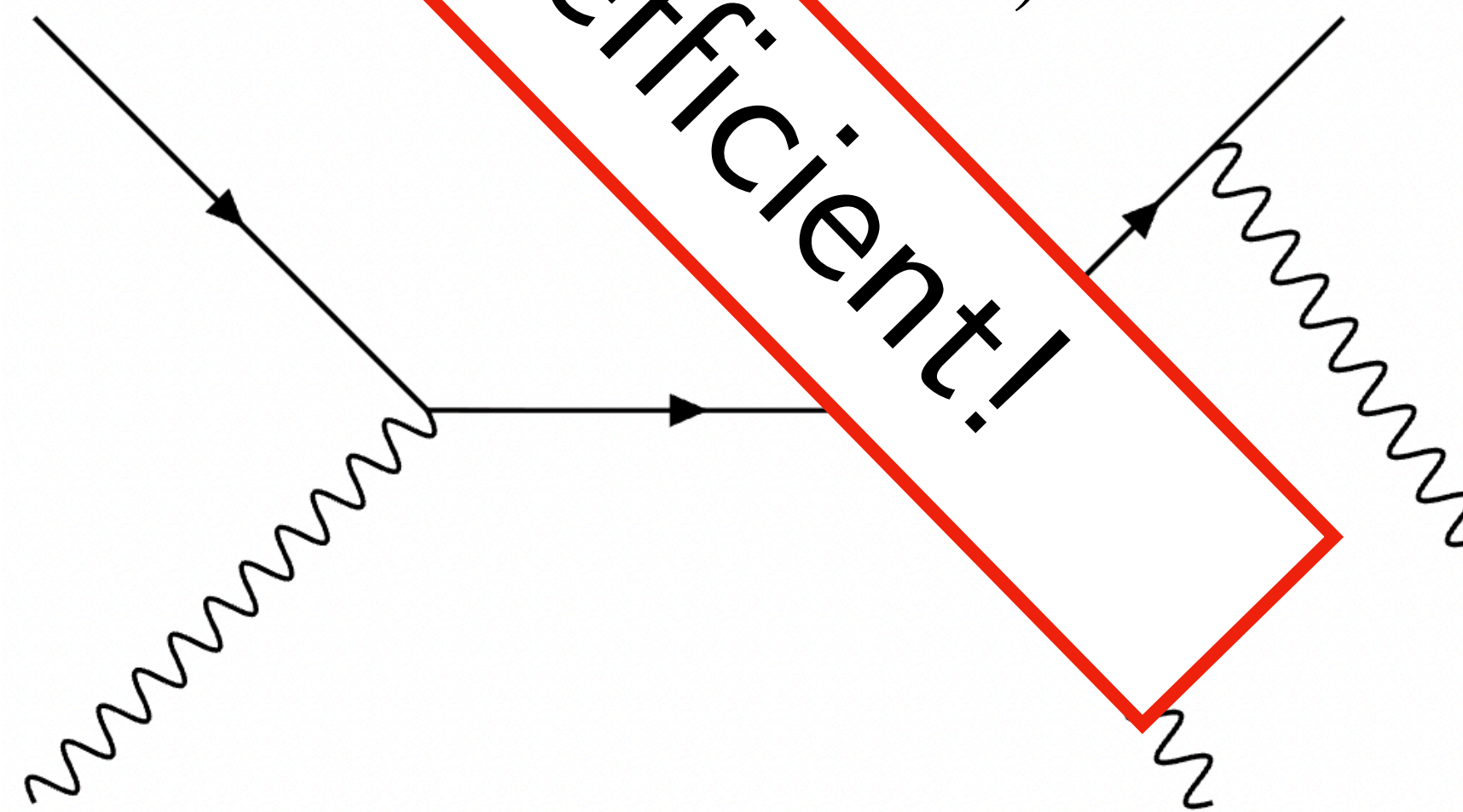


Double Compton

(number changing)

$$z_{DC} \simeq 2 \times 10^6$$

$$(T_{DC} \simeq 170 \text{ eV})$$

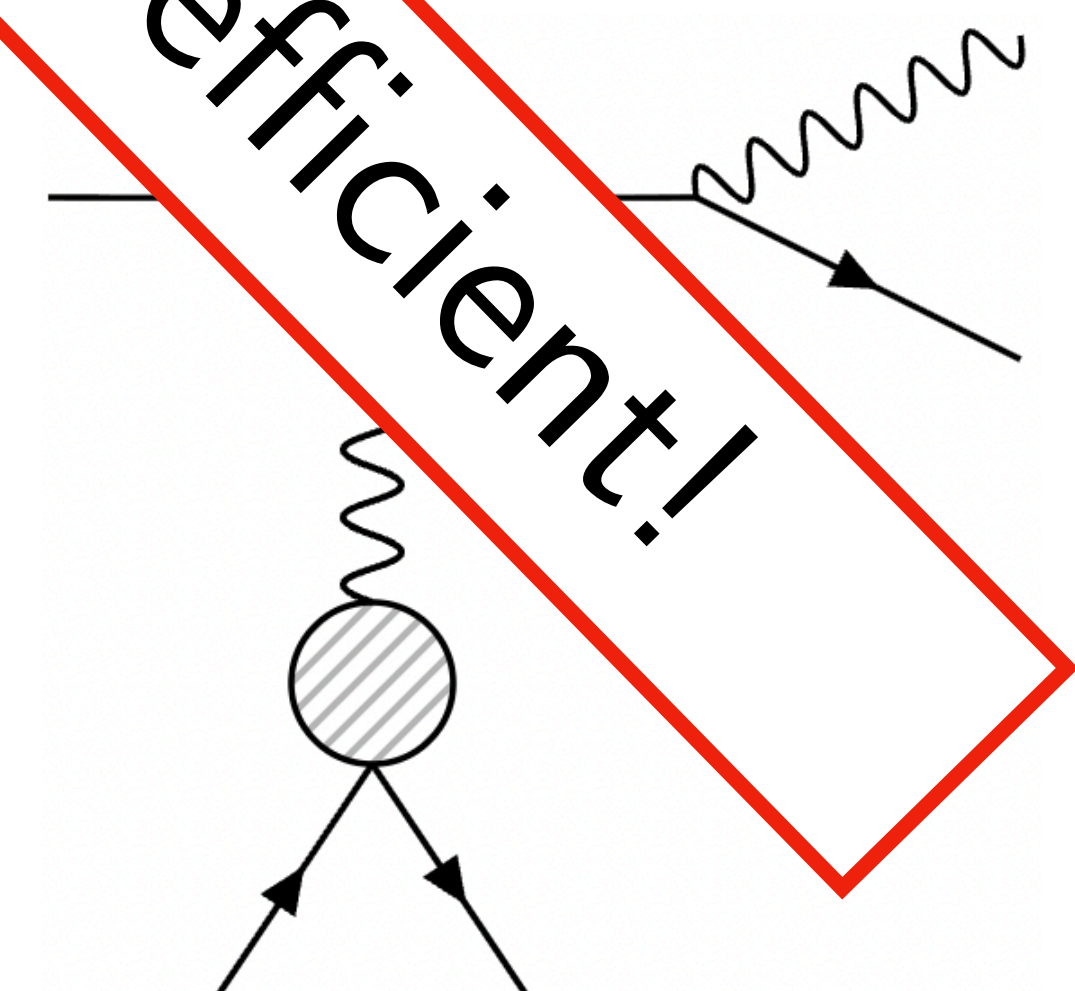


Bremsstrahlung

(number changing)

$$z_B \simeq 5 \times 10^6$$

$$(T_B \simeq 1.2 \text{ keV})$$



HOW: are distortions thermalized?

How does one thermalize a distorted spectrum?

- Energy redistribution
- Photon creation/destruction

$$\begin{array}{l} z \lesssim 5 \times 10^4 \\ \gamma\text{-distortion} \end{array}$$

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

Compton

(energy changing)

$$n \simeq 5 \times 10^4$$

$$(12 \text{ eV})$$

Inefficient!

Double Compton

(number changing)

$$n \simeq 2 \times 10^6$$

$$(170 \text{ eV})$$

Inefficient!

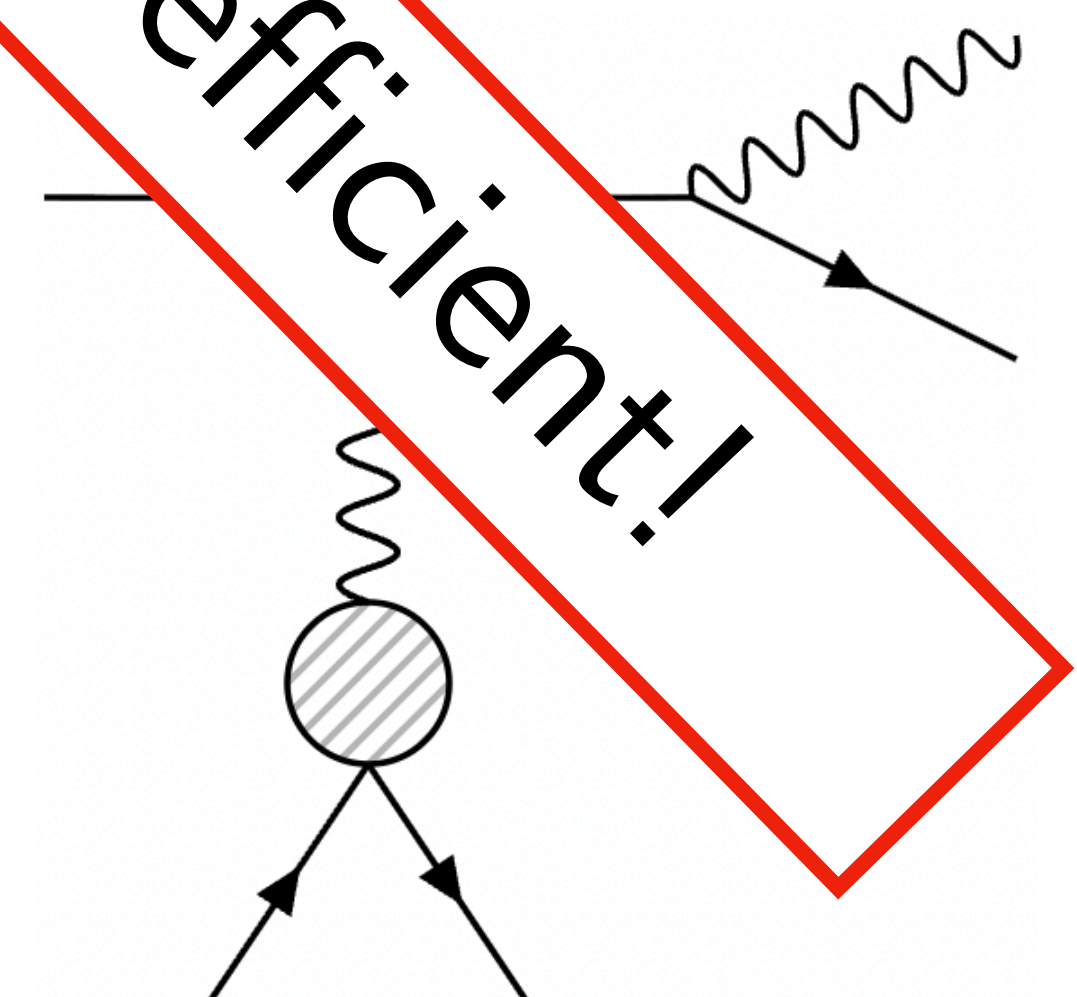
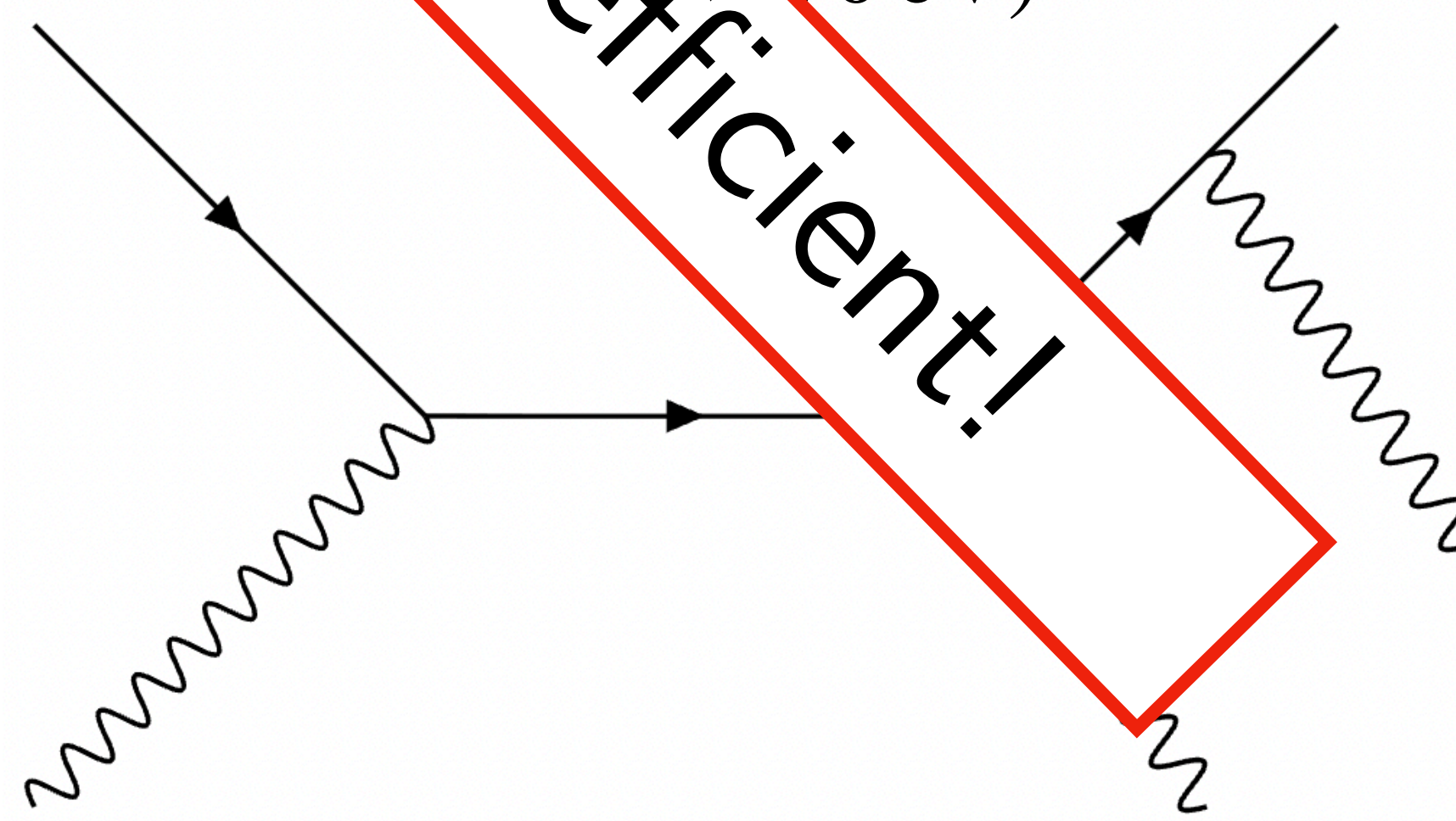
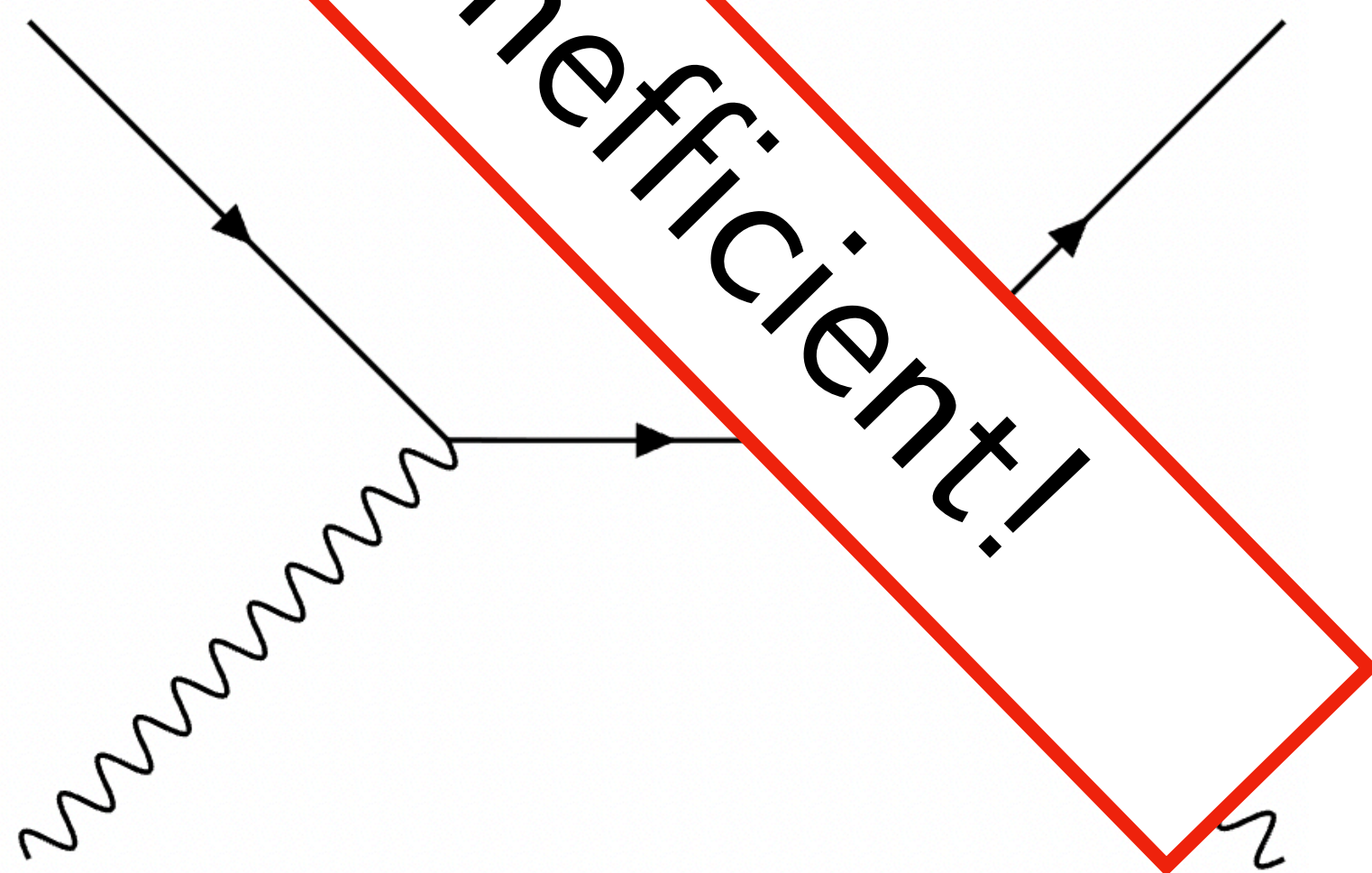
Bremsstrahlung

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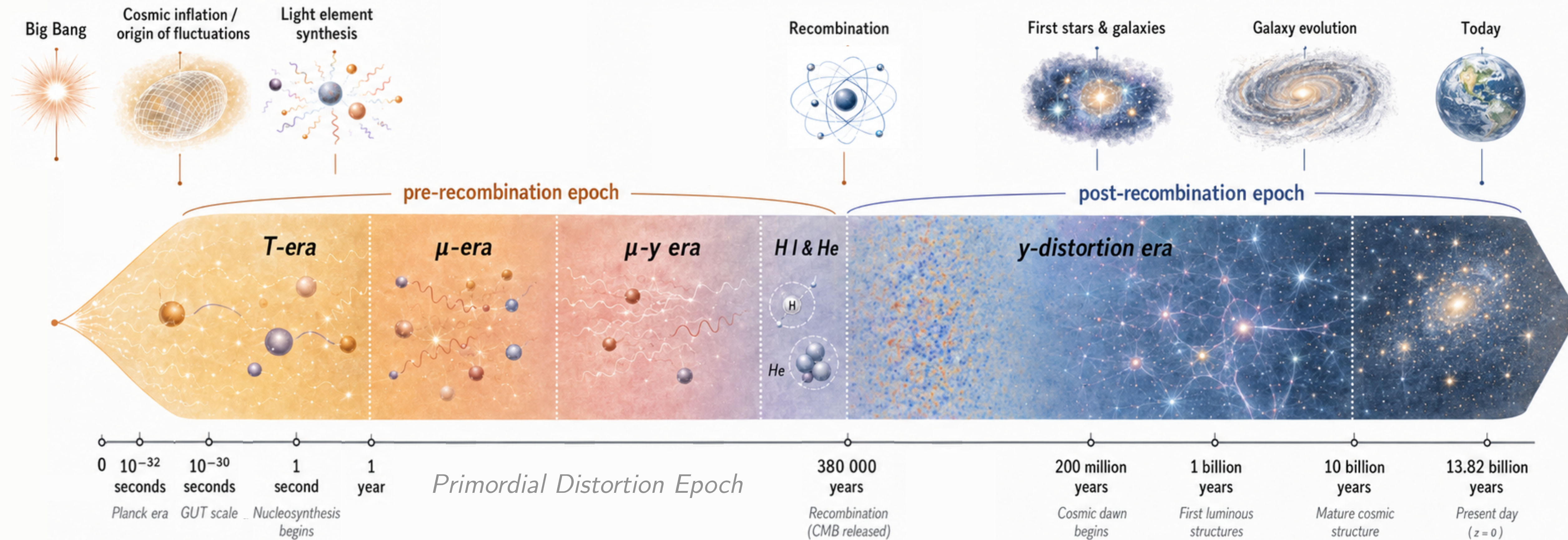
$$n \simeq 5 \times 10^6$$

$$(1.2 \text{ keV})$$

Inefficient!



The chronology of spectral distortions



HOW: are distortions thermalized?

Green's function approach effective at high z .

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

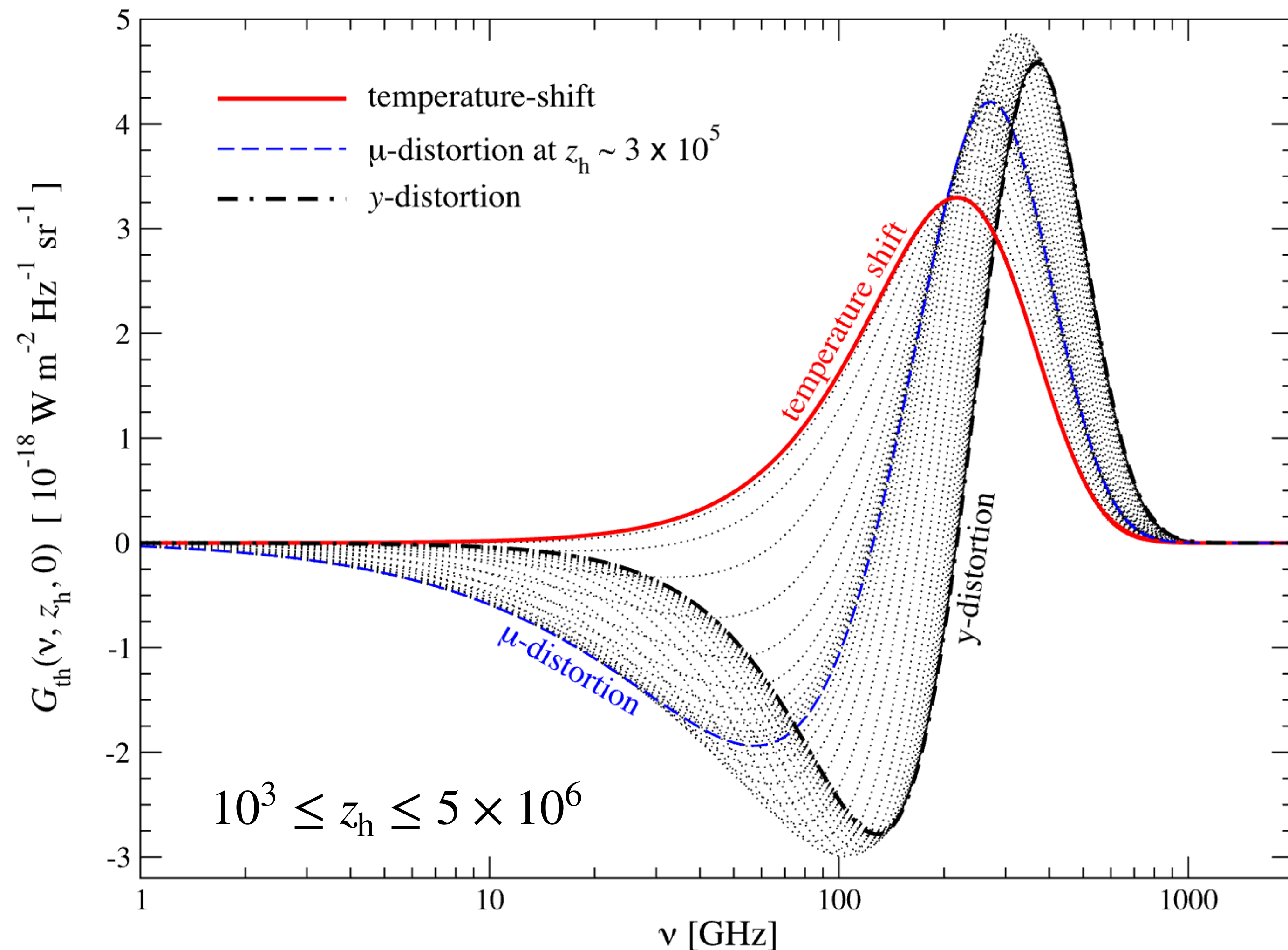
At $10^4 \lesssim z \lesssim 10^5$ distortion is not just a pure $\mu + y$ spectrum, residuals contain valuable information on time-dependence of injection source.

Chluba and Jeong (2014)

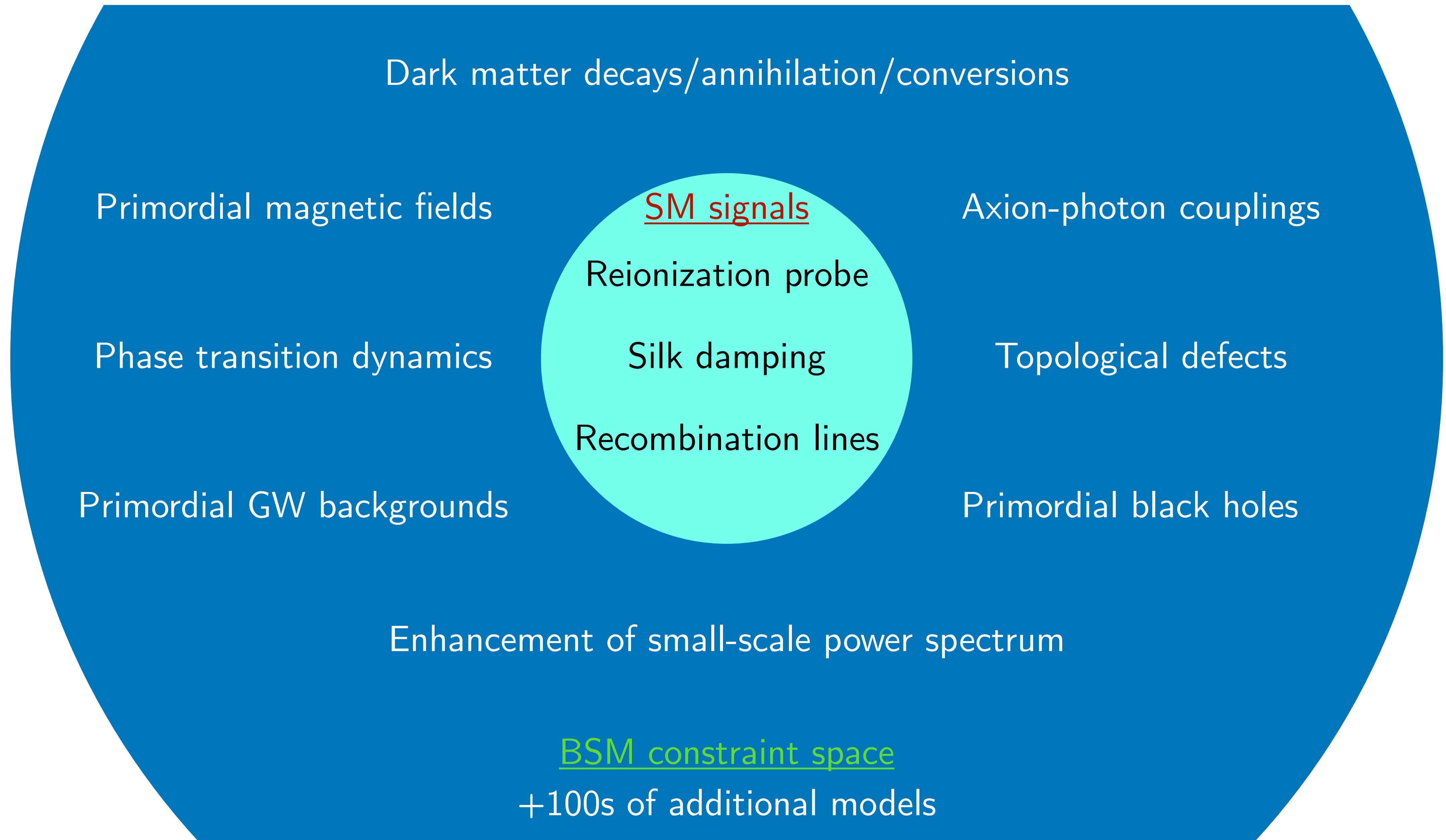
Can be characterized by either:

- PCA decomposition.
- OPE polynomial basis coefficients.

Barenboim et al (2025)

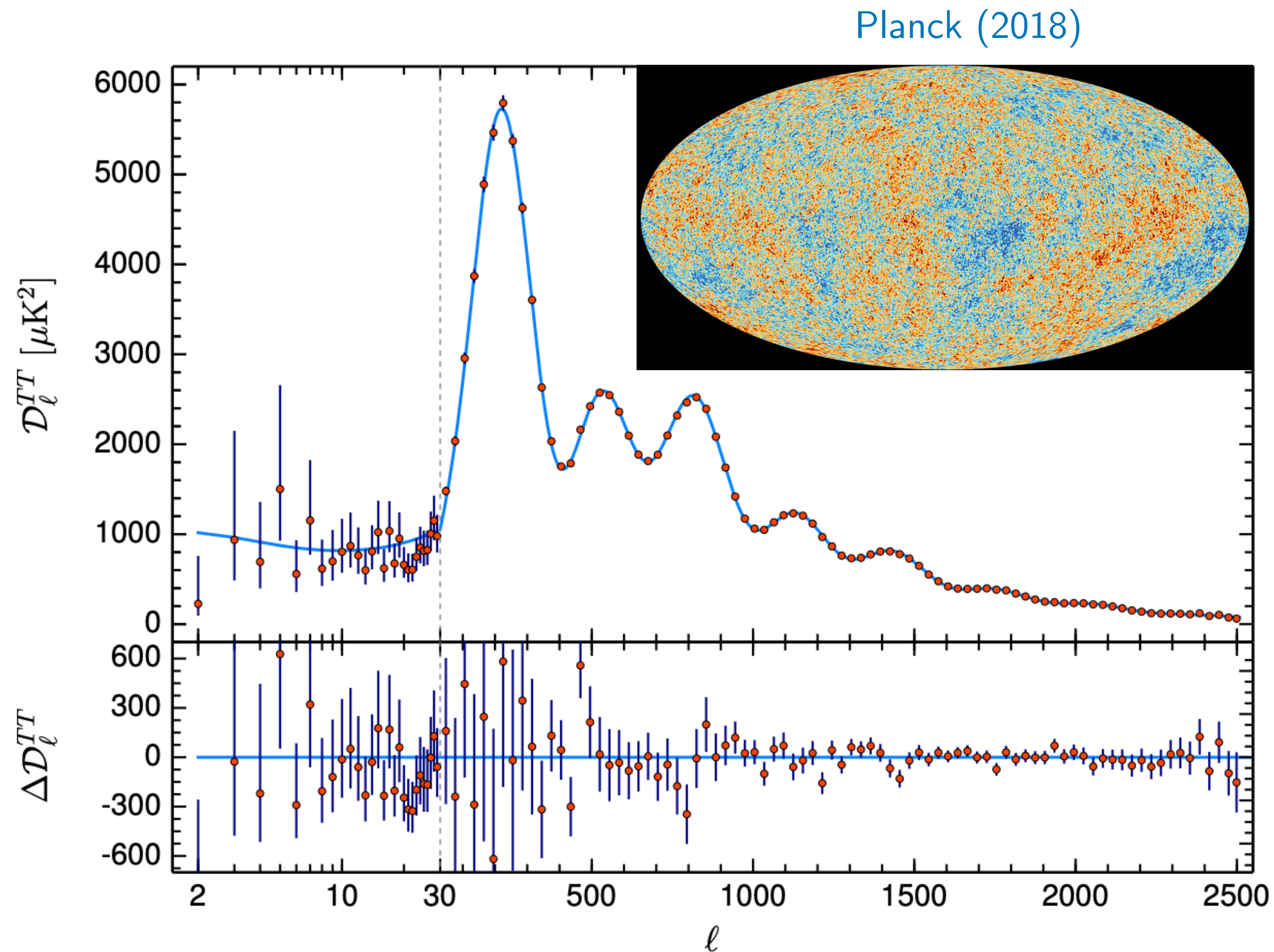


A powerful probe of exotic physics



Silk damping: A standard model signal

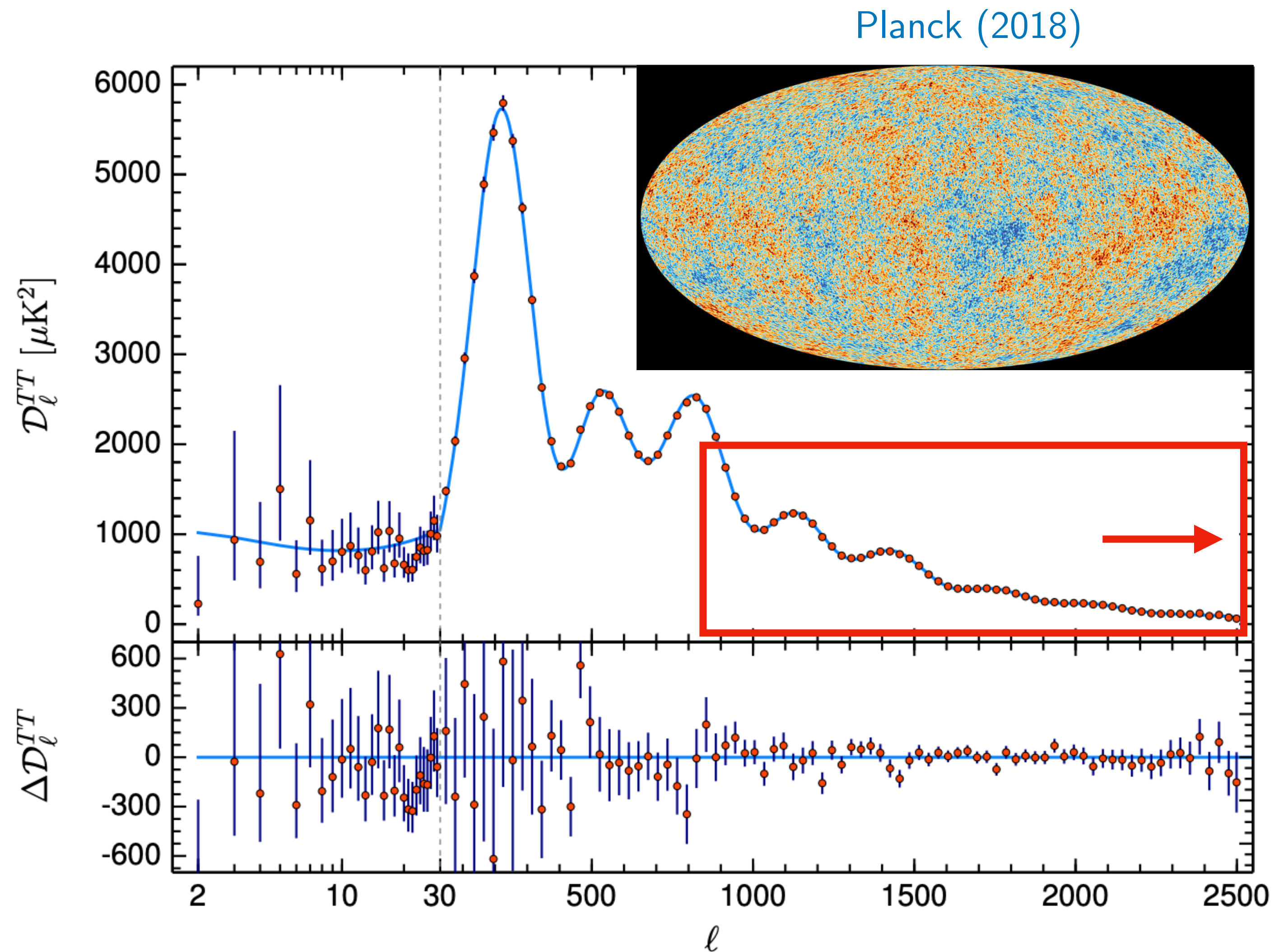
Modes enter the horizon, begin to oscillate, and suffer diffusion (Silk) damping as electrons and photons of different temperatures mix.



Silk damping: A standard model signal

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Measured amplitude of small scale modes are greatly suppressed.

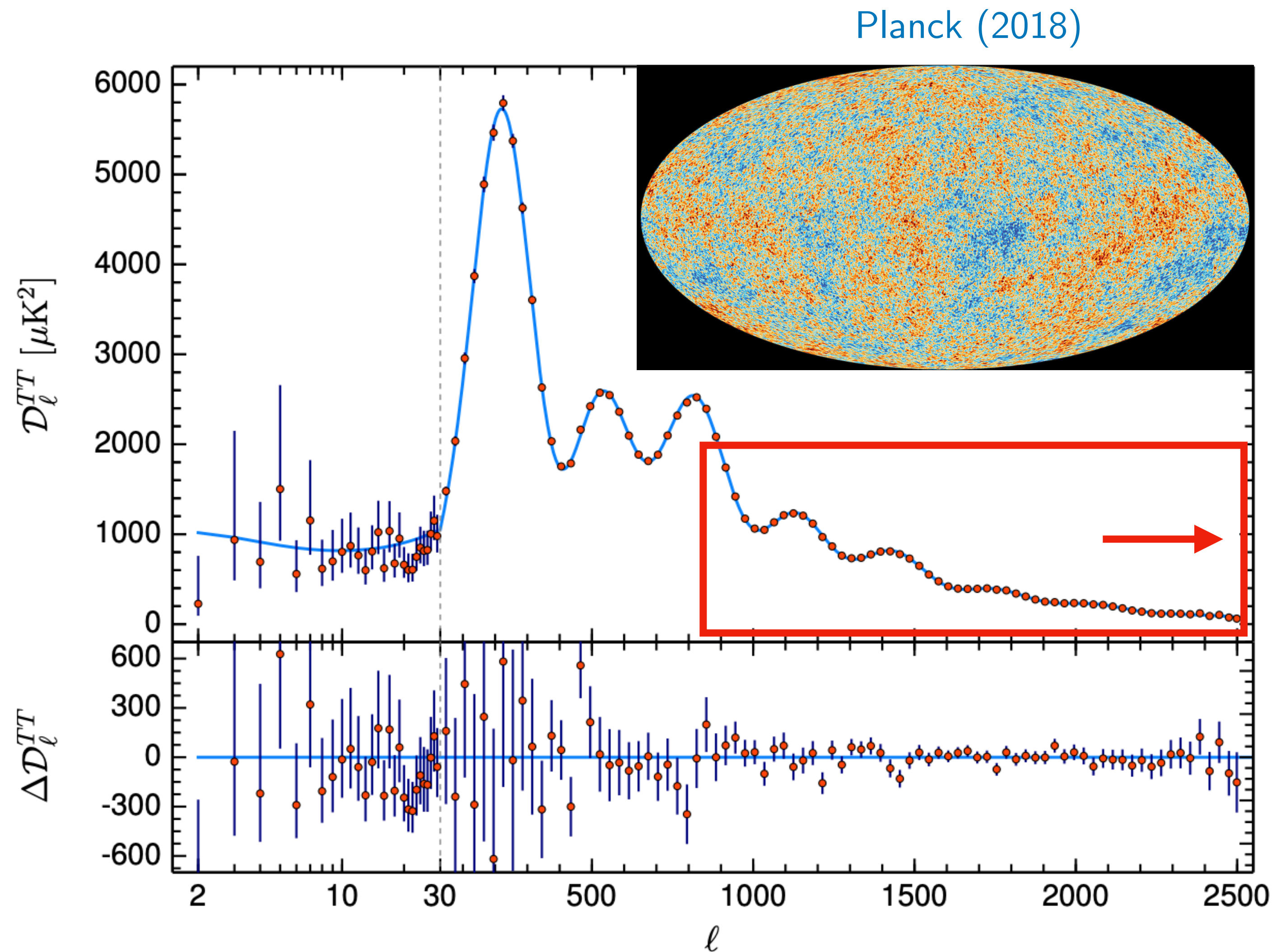


Silk damping: A standard model signal

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 Silk (1994)

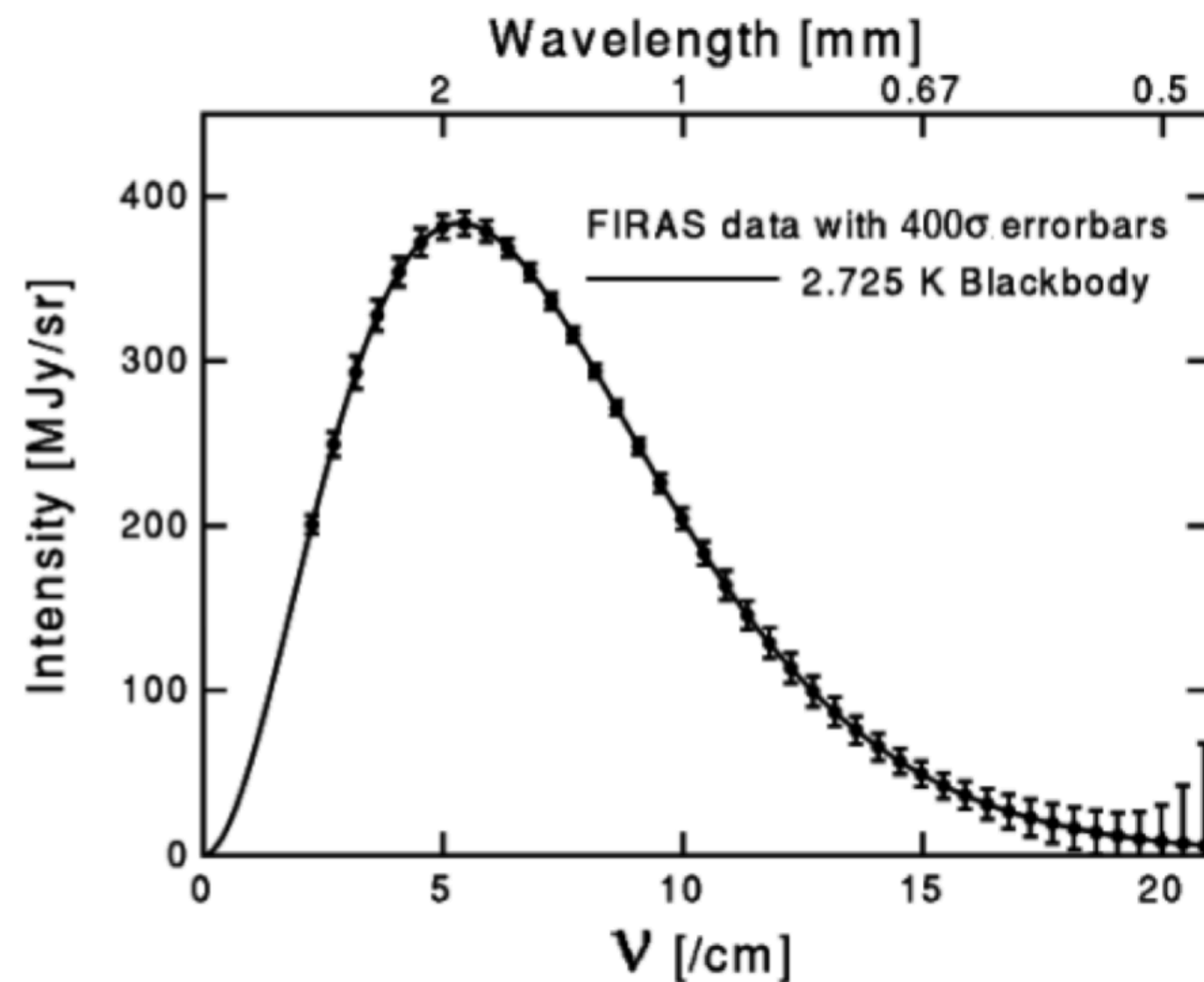
Chluba, Khatri, Sunyaev (2012)

BC et al. (2023a)

The sum of unequal temperature BBs will:

$$T - \delta T$$

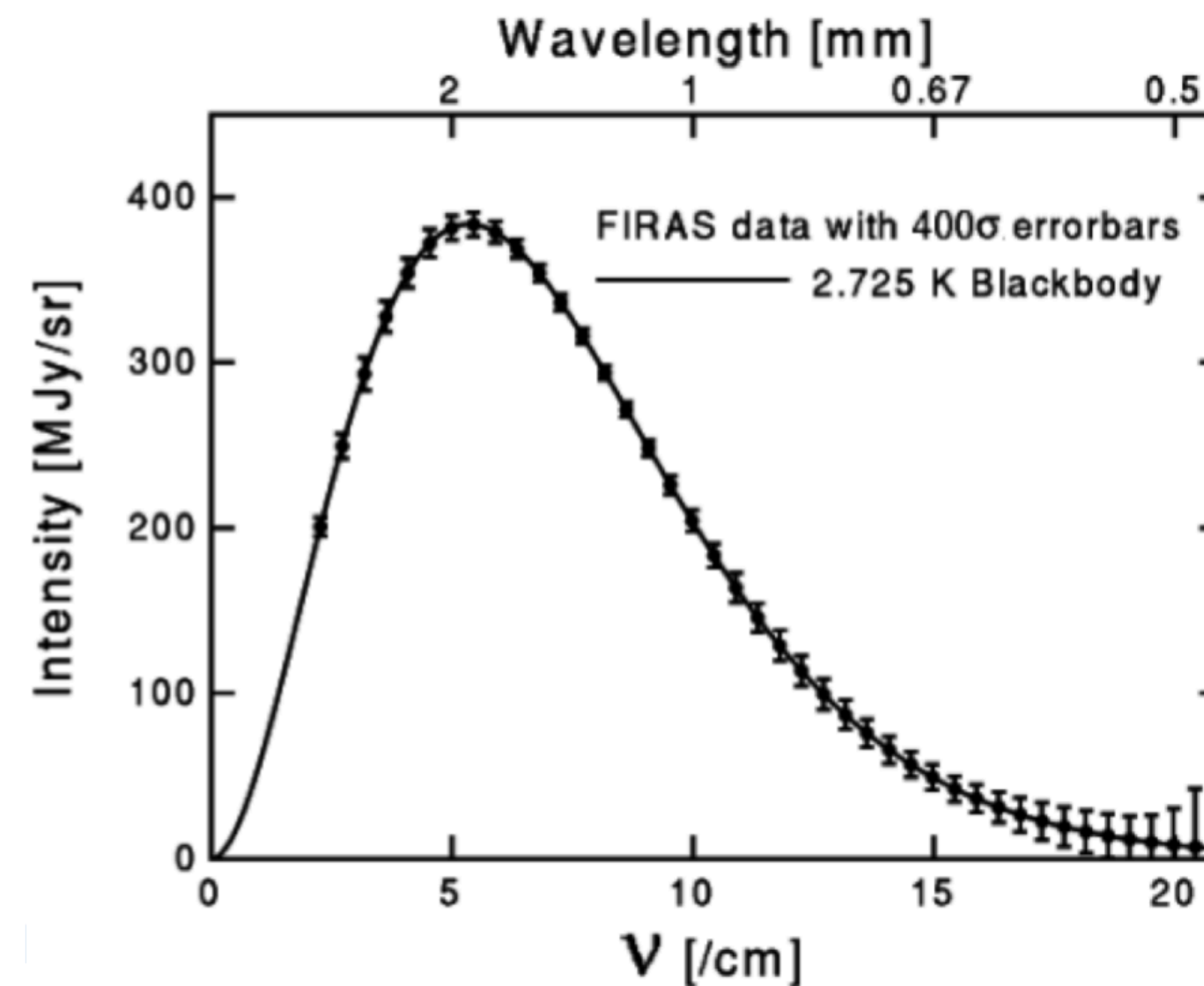
$$\mu, y = 0$$



+

$$T + \delta T$$

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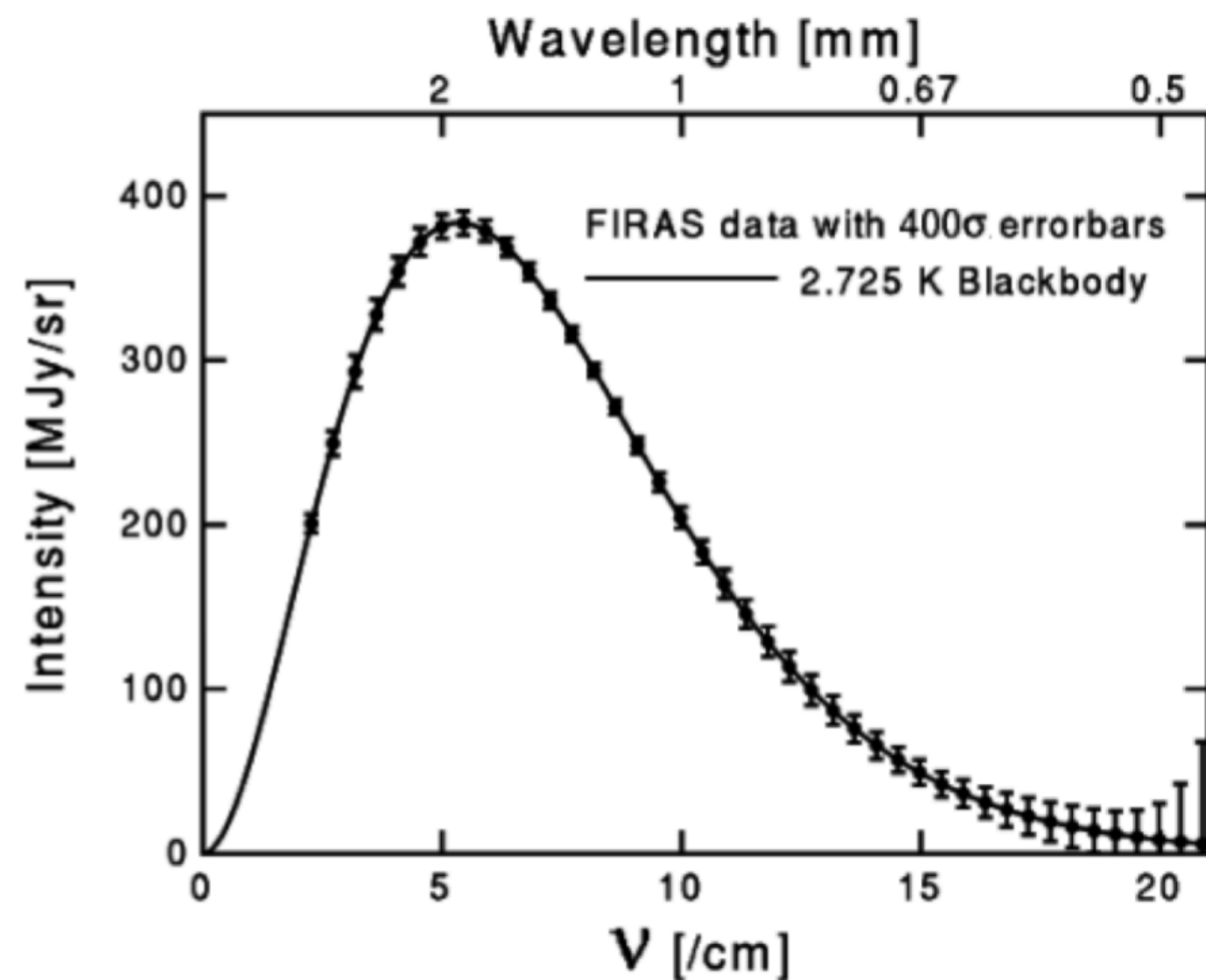
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The sum of unequal temperature BBs will **not** produce a thermal spectrum.

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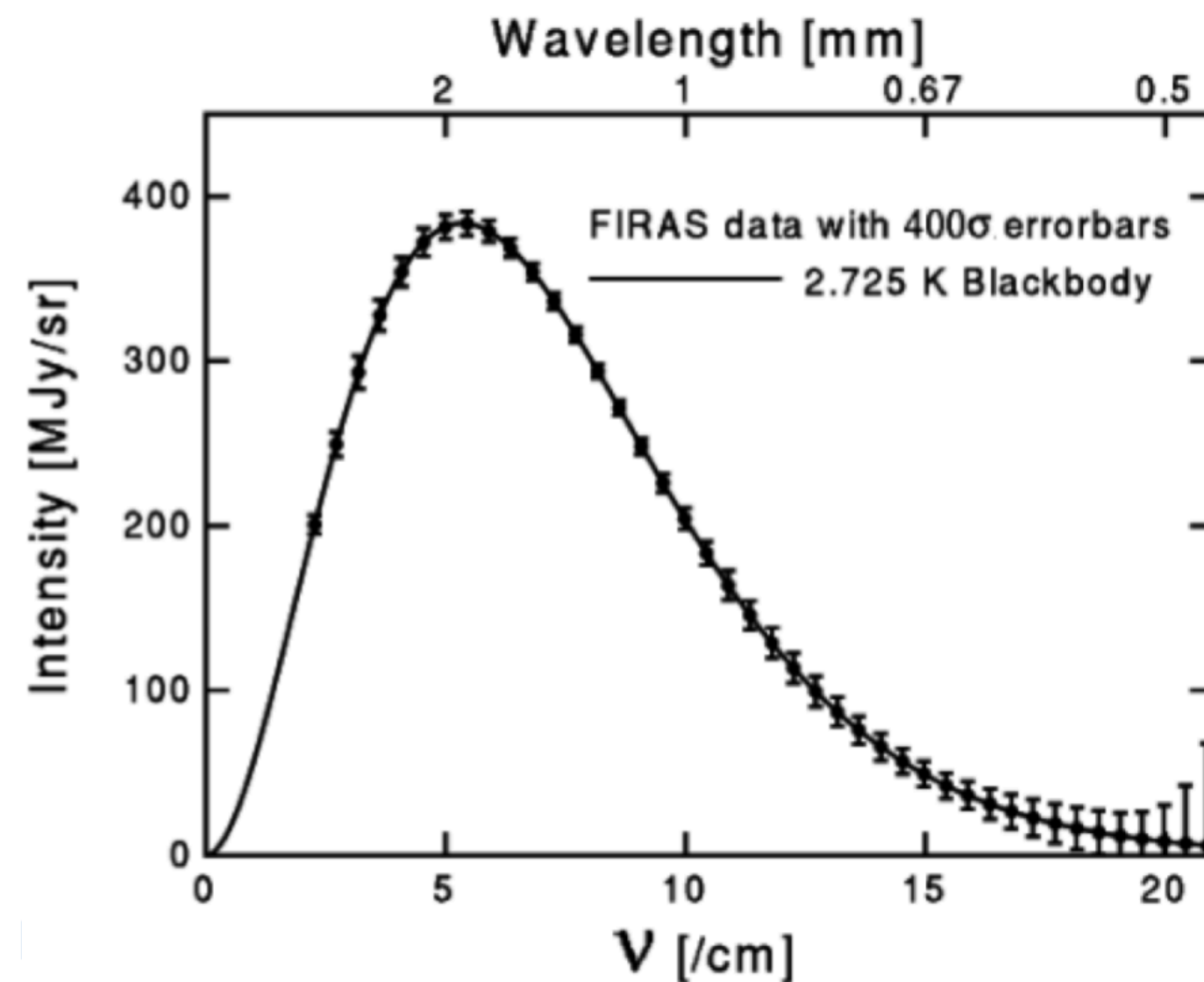
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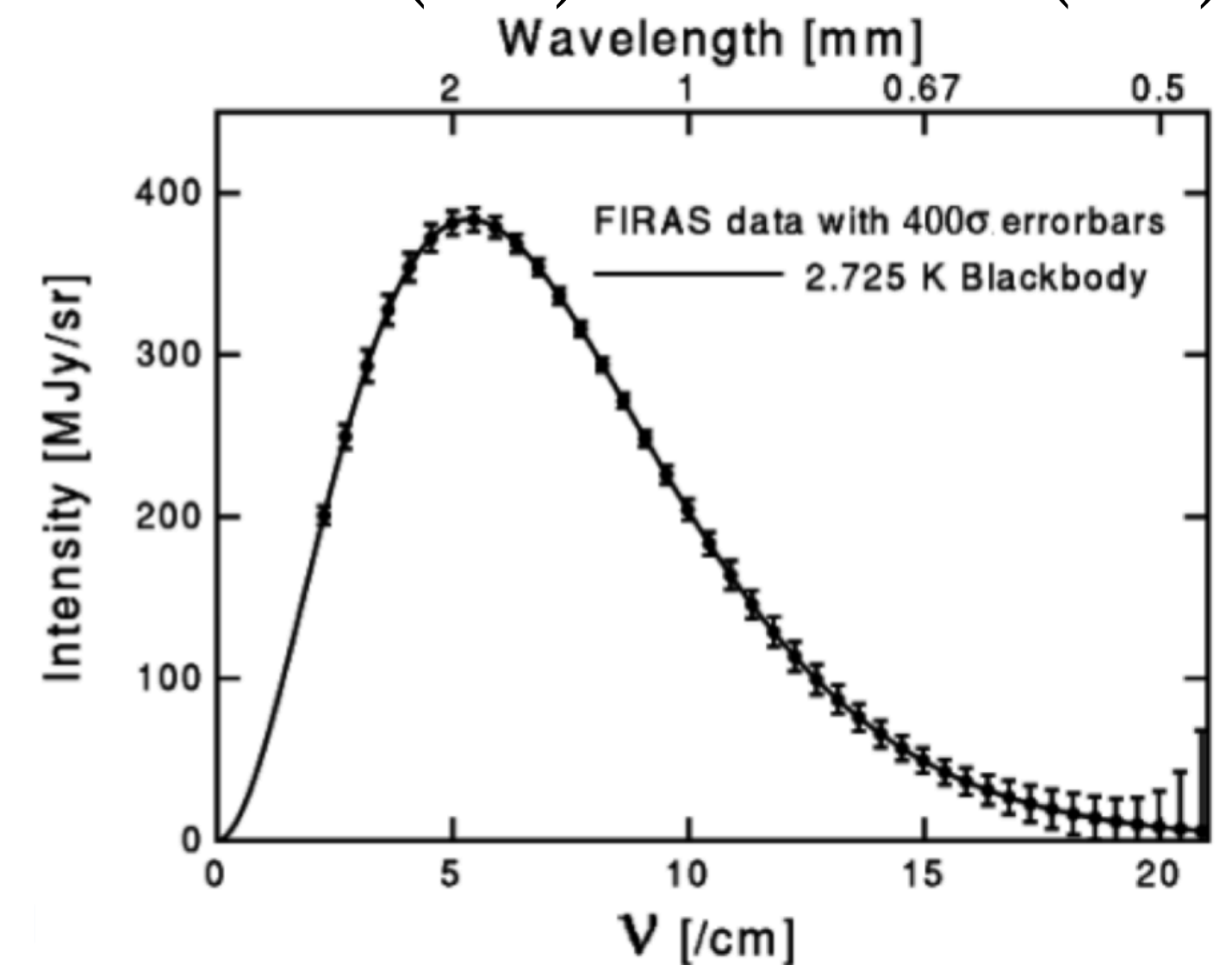
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≠

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

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



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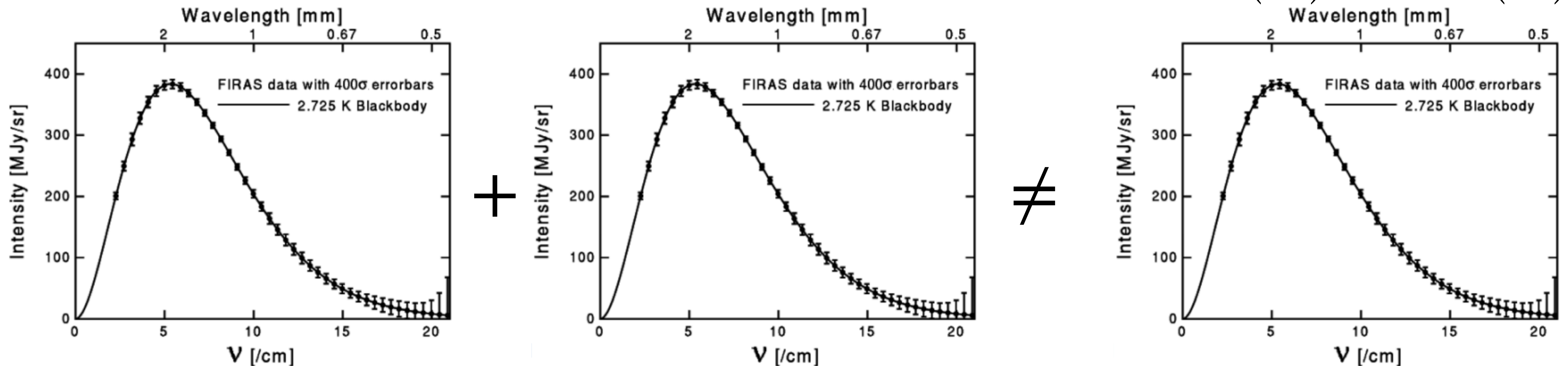
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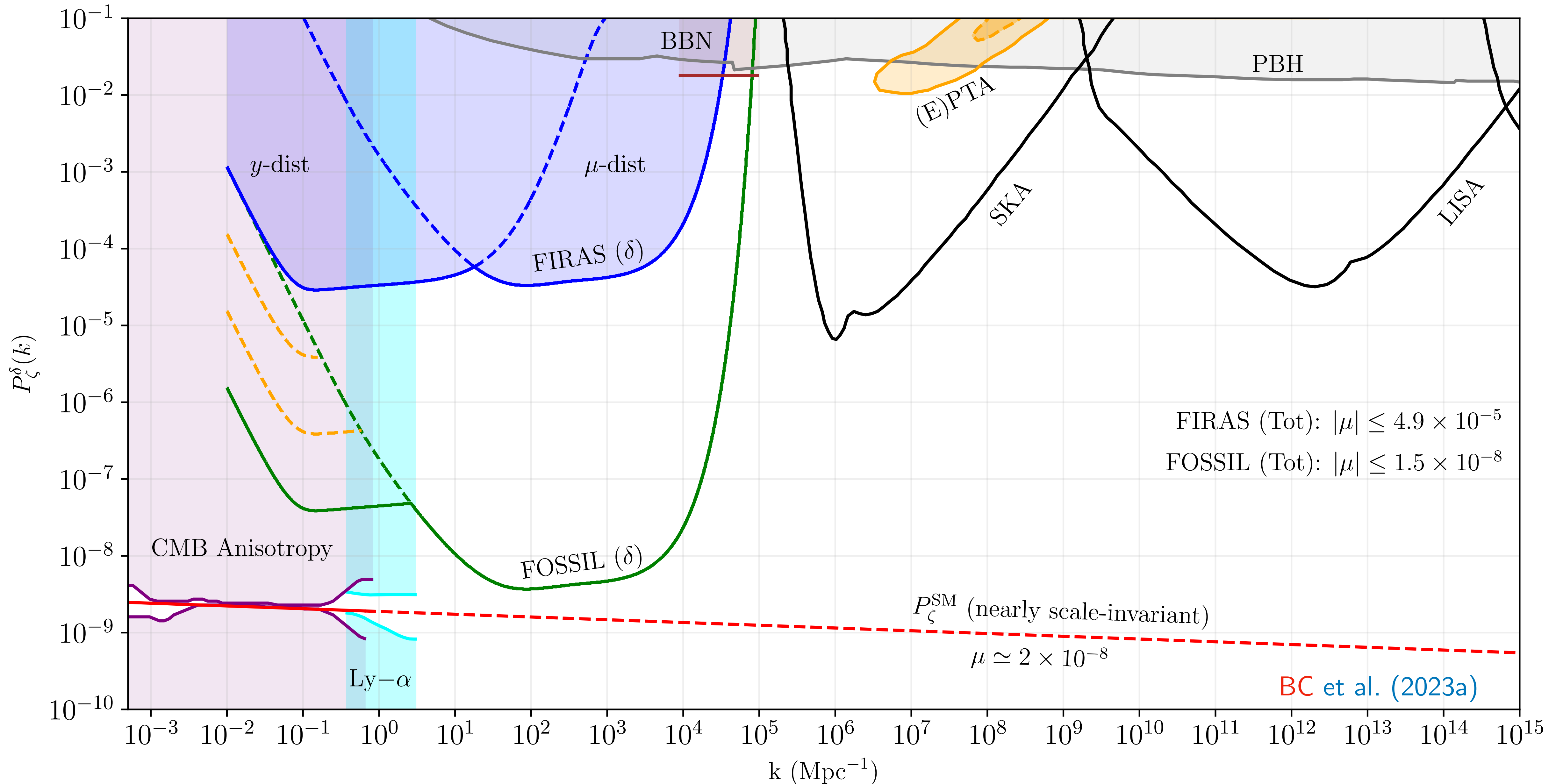
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SDs sensitive to A_s at $50 \text{ Mpc}^{-1} \lesssim k \lesssim 10^4 \text{ Mpc}^{-1}$

Silk damping prediction: $\mu \simeq 2 \times 10^{-8}$

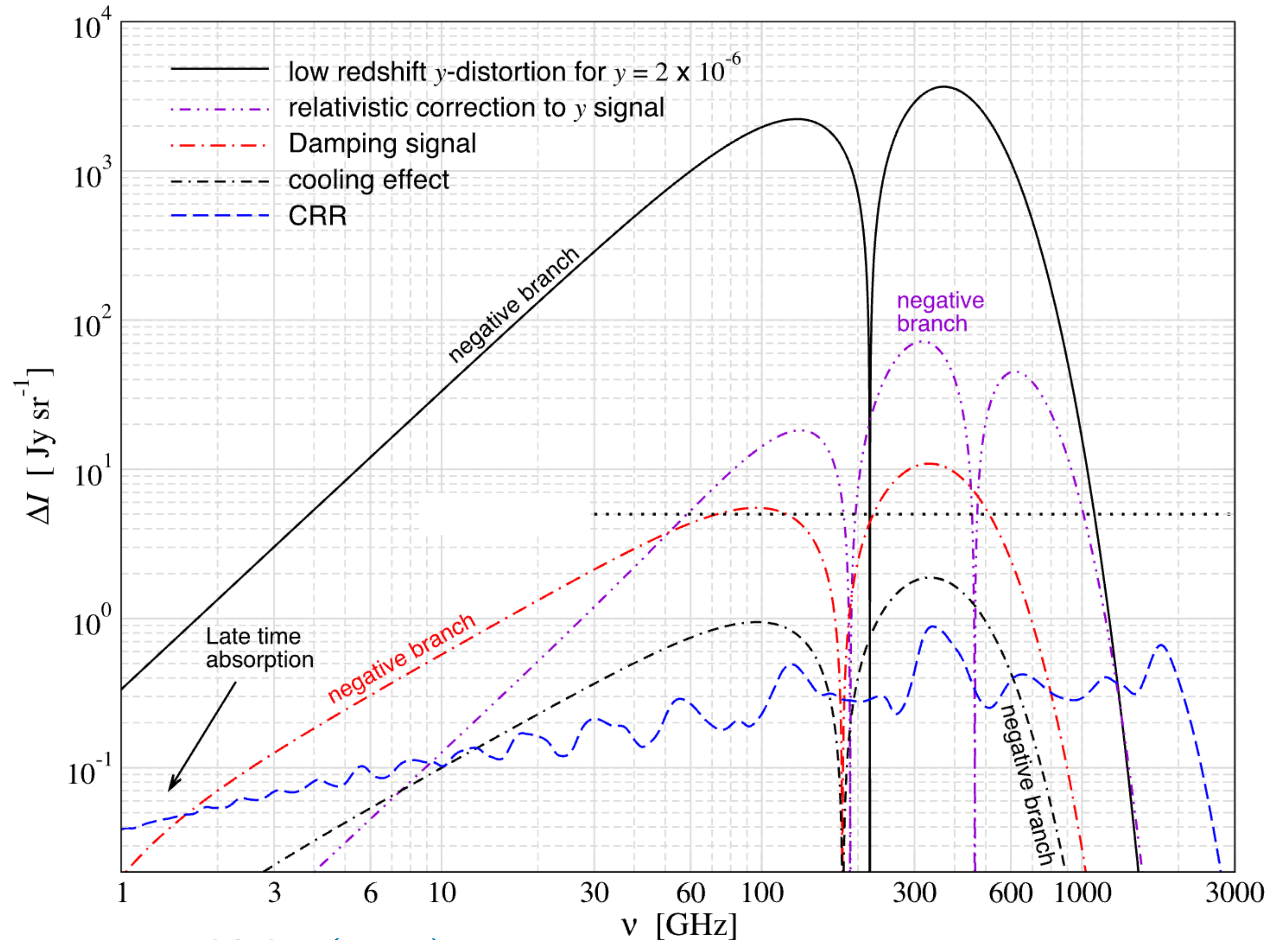
The scalar primordial power spectrum (PPS)



The Zoo of SM distortions

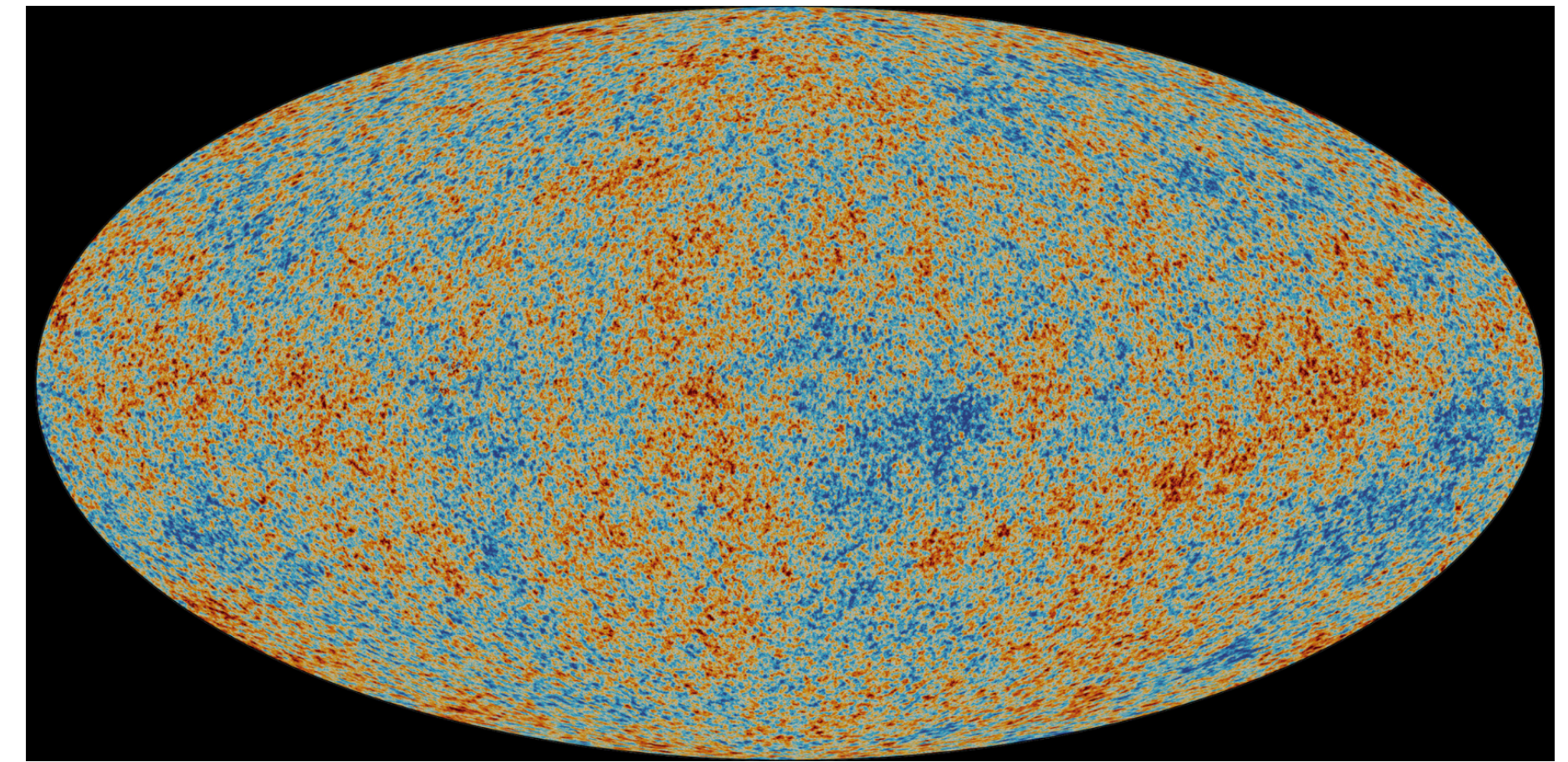
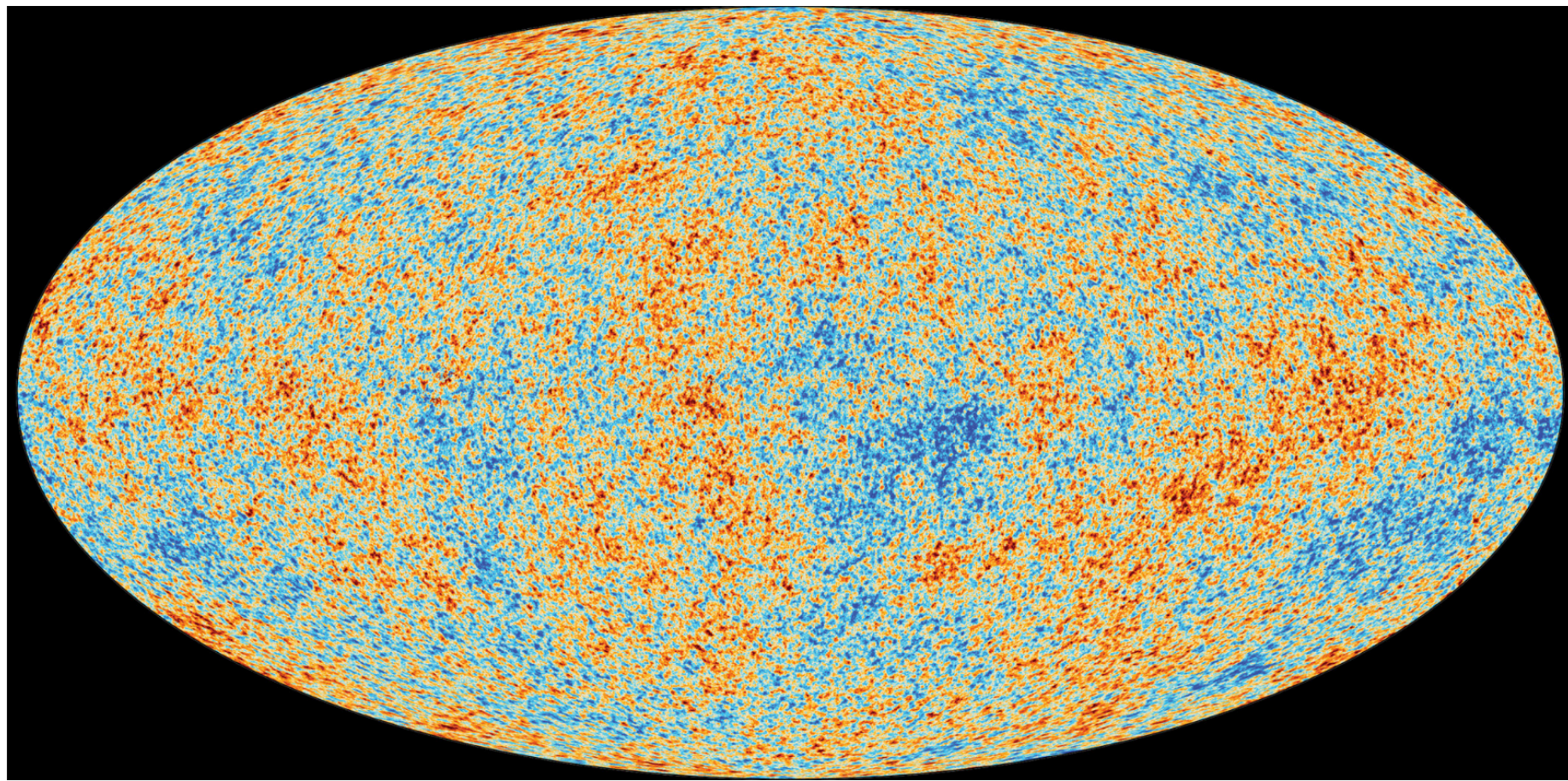
- Global SZ distortion
 $y \simeq 10^{-6}$
- Relativistic SZ and reionization heating
 $y \simeq 10^{-8} - 10^{-7}$
- Dissipation of small scale modes (Silk damping)
 $|\mu| \simeq 2 \times 10^{-8}$
- Recombination lines

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



Chluba (2016)

Spectral Distortions from Dark Photons



Dark Photon (not) Dark Matter

BC et al. (2024a)

Simple extension to the SM, invoke a new (local) $U(1)$ symmetry.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_d^2}{2}A'_\mu A'^\mu + A_\mu j_{\text{em}}^\mu$$

Field redefinitions can get rid of kinetic mixing - at the expense of having a non-diagonal mass matrix.

This gives rise to conversions $\gamma_{\text{CMB}} \leftrightarrow \gamma'$ occurring in analogy to neutrino oscillations, though their signatures in the CMB are tiny.

McDermott and Witte (2020)

Is it possible to boost the conversion rate?

[See also Arsenadze et al. (2024)]

Resonant Mixing

The photon is not in vacuum! Interactions with the plasma induce a thermal mass.

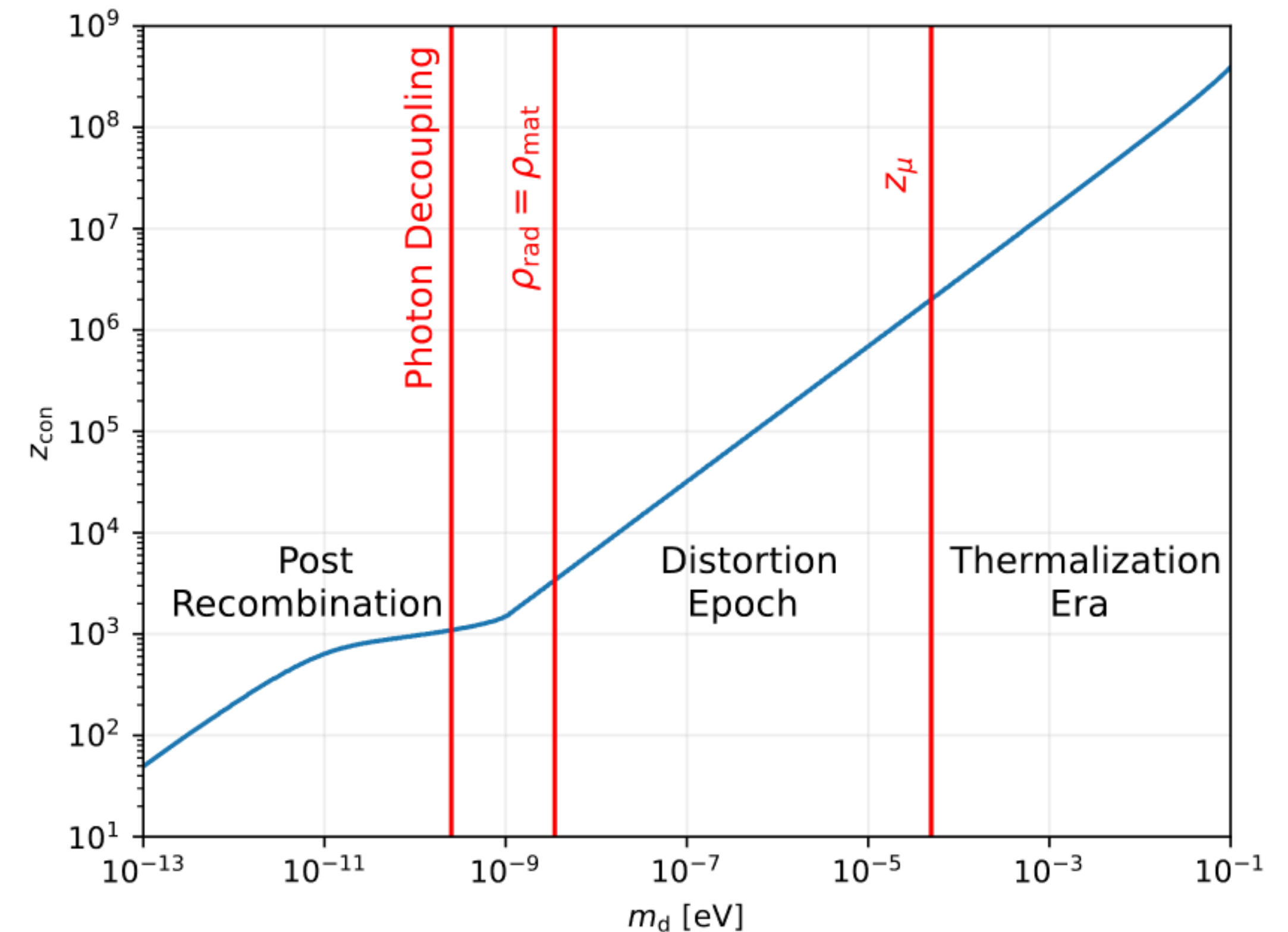
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Resonance when $m_\gamma(z) \simeq m_d!$



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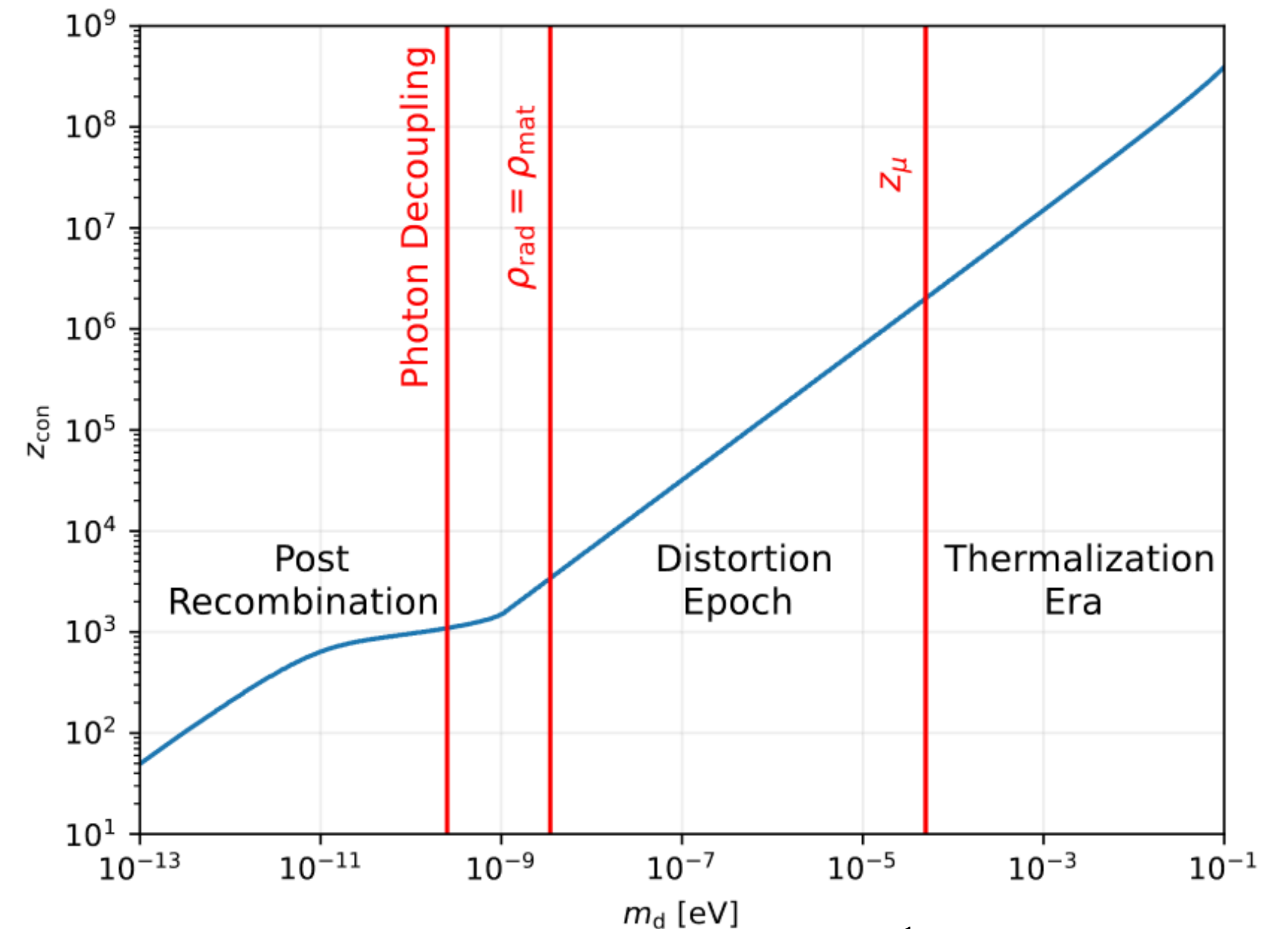
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Conversion probability determined by the Landau-Zener formalism

$$P_{\gamma \leftrightarrow \gamma_d} \simeq 1 - \exp\left(-\frac{\gamma_{\text{con}}}{x}\right) \quad \gamma_{\text{con}}(\epsilon, m_d) = \frac{\pi m_d^2 \epsilon^2}{T_0 H(z)(1+z)^2} \left| \frac{d \ln m_\gamma^2}{dz} \right|_{z=z_{\text{con}}}^{-1}$$

$x = \omega/T$
 $x_{\text{peak}} \simeq 2.82$



Analytic Distortion Estimates (Assume $\rho_{\text{DP}} \simeq 0$ initially)

The amplitude of a spectral distortion can be readily estimated using a Green's function approach:

Chluba (2015)

$$\mu \simeq 1.4 \int dz \left(\frac{1}{\rho_{\text{CMB}}} \frac{d\rho}{dz} - \frac{4}{3n_{\text{CMB}}} \frac{dn}{dz} \right) J_{\mu}(z)$$

Bianchini and Fabbian (2022)

$$|\mu| \lesssim 4.7 \times 10^{-5}$$

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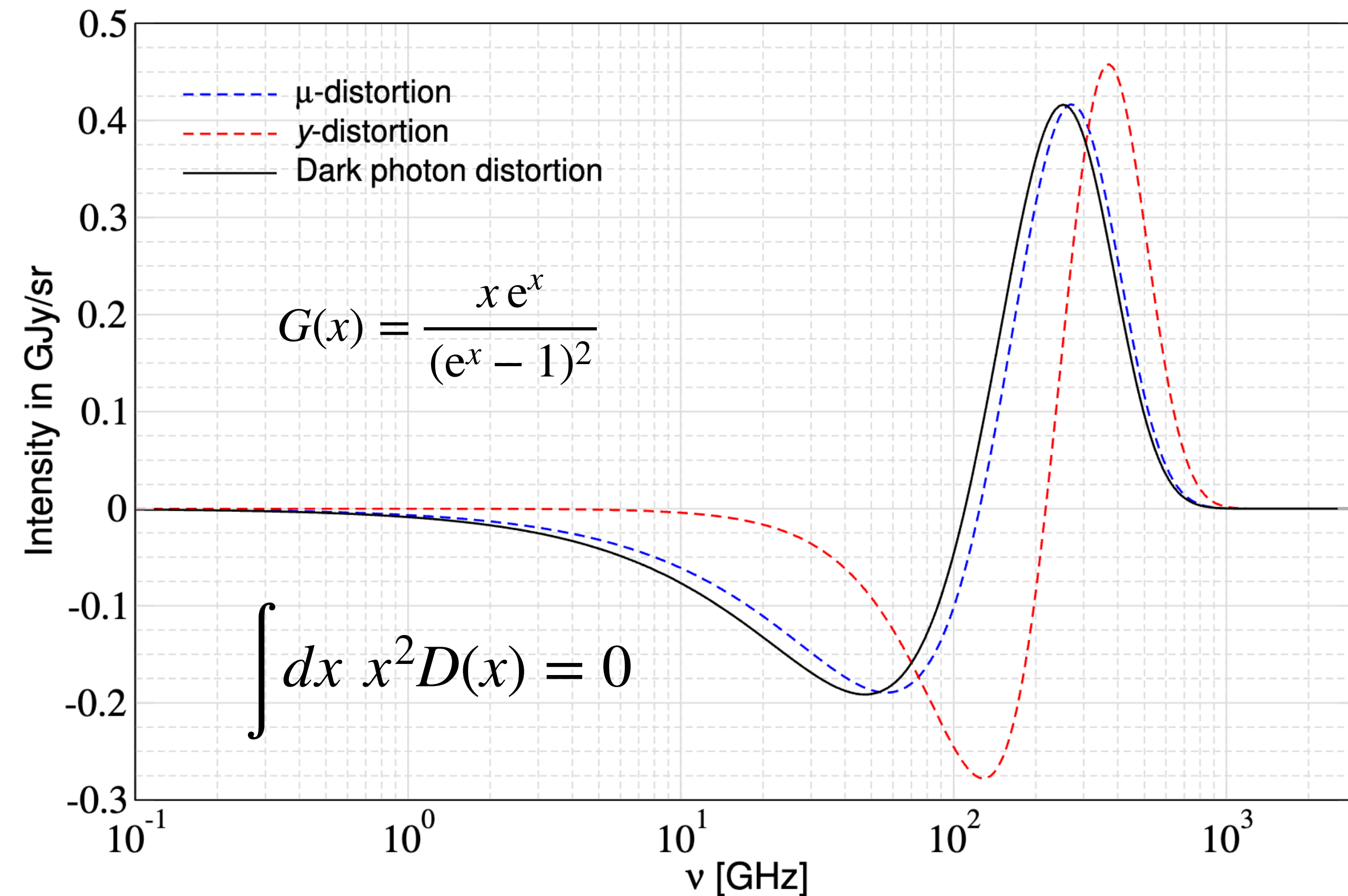
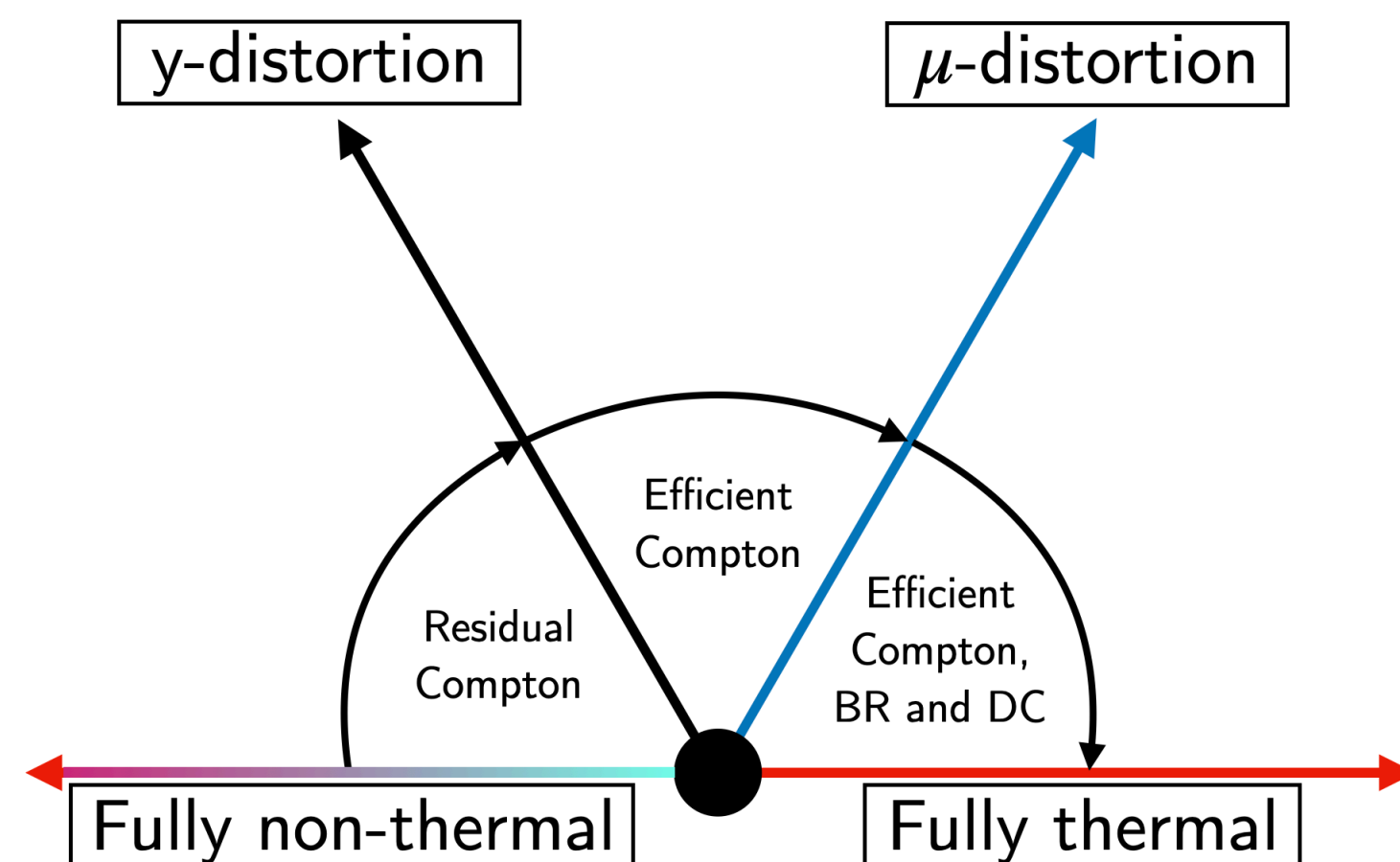
A blackbody spectrum is a delicate balance between photon energies and number densities. When photons are directly extracted or injected in RJ tail, this **entropy term** MUST be considered.

Shape of the dark photon distortion

Exact shape of distortion induced by a single conversion is calculable.

Small ΔT jump at conversion time.

Dark photon distortion: Very close to a μ -distortion, even at late times.



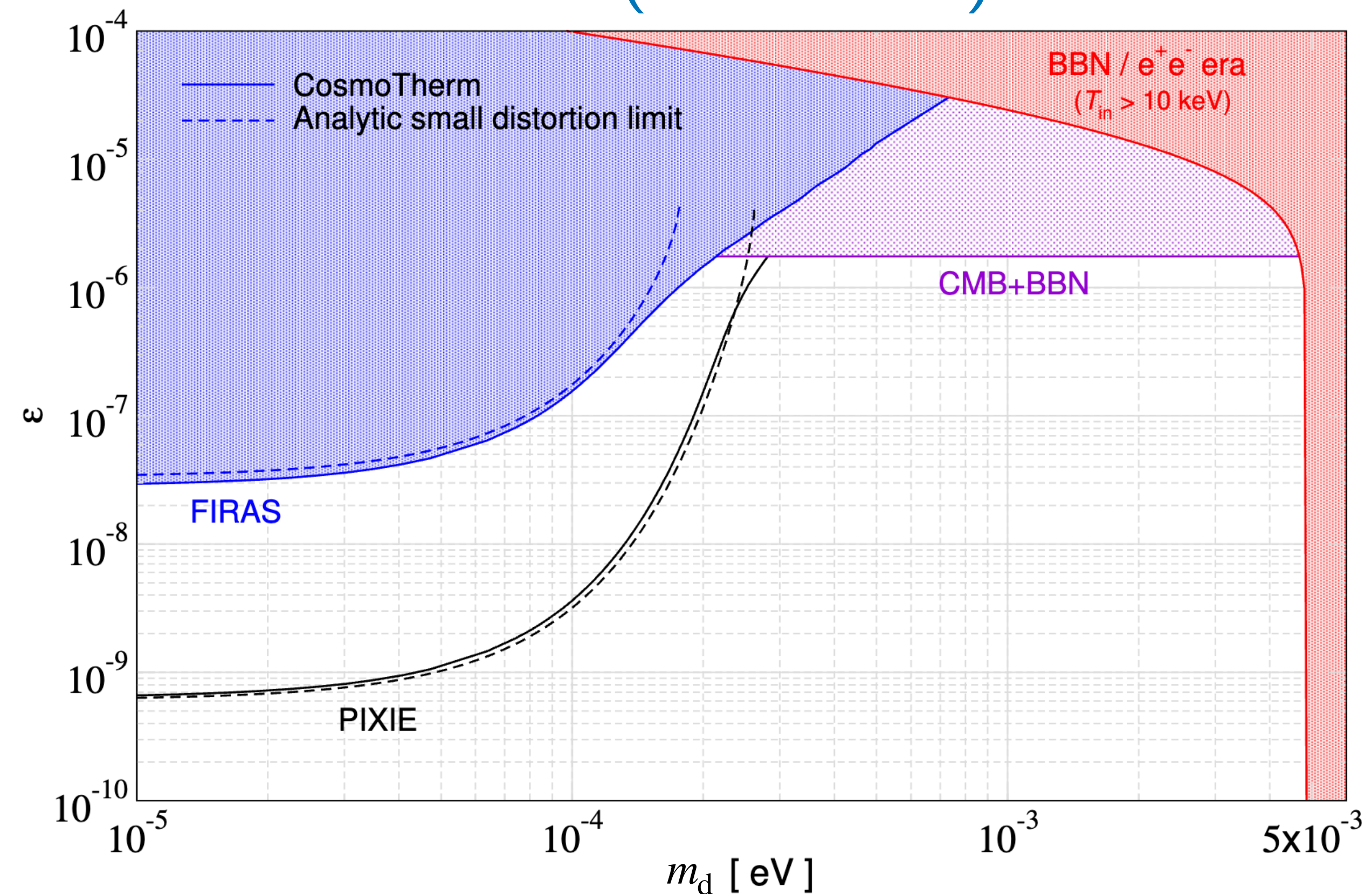
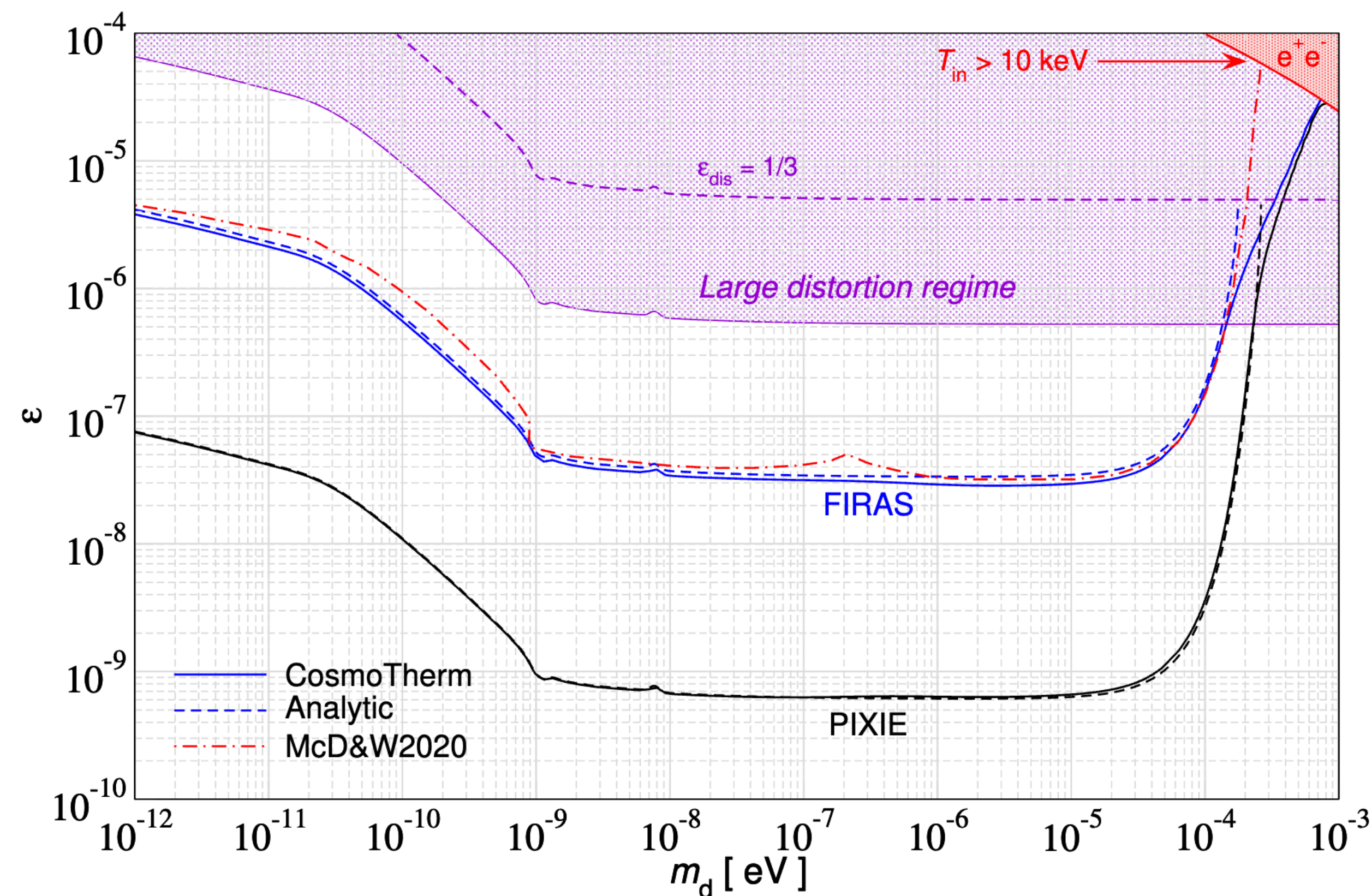
$$\Delta n = \left[\underbrace{\left(\frac{G_2}{4G_3} - \frac{G_1}{3G_2} \right)}_{\text{Temp shift}} G(x) + \underbrace{\left(\frac{G_1}{3G_2} G(x) - \frac{n_{\text{bb}}(x)}{x} \right)}_{\text{Dark photon dist}} \right] \gamma_{\text{con}}$$

Dark photon (not) dark matter

$$\mu \simeq 1.4 \int dz \left(\frac{1}{\rho_{\text{CMB}}} \frac{d\rho}{dz} - \frac{4}{3n_{\text{CMB}}} \frac{dn}{dz} \right) J_\mu(z)$$

Energy extraction

Entropy extraction
(dominant)

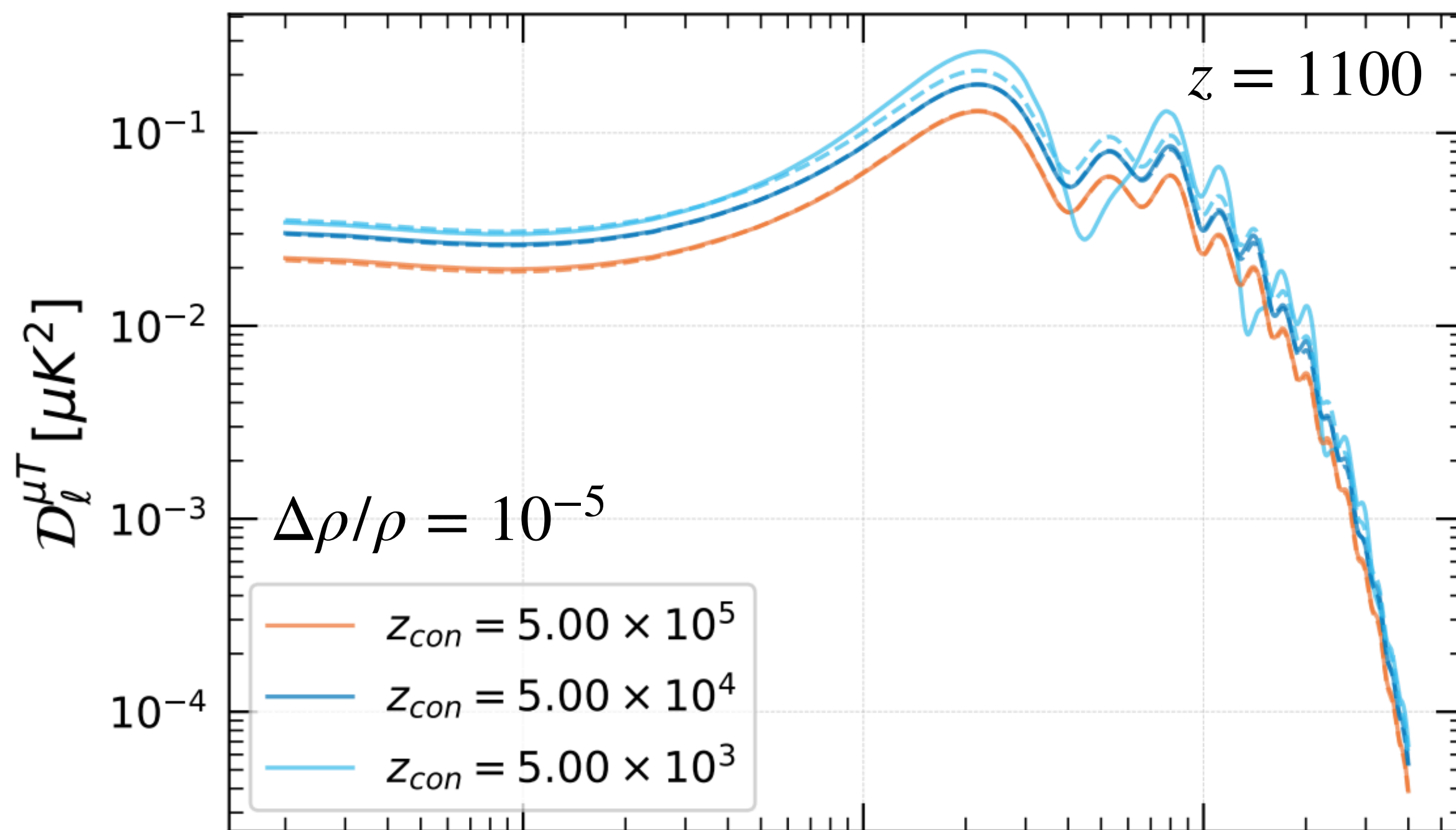


Anisotropic spectral distortions

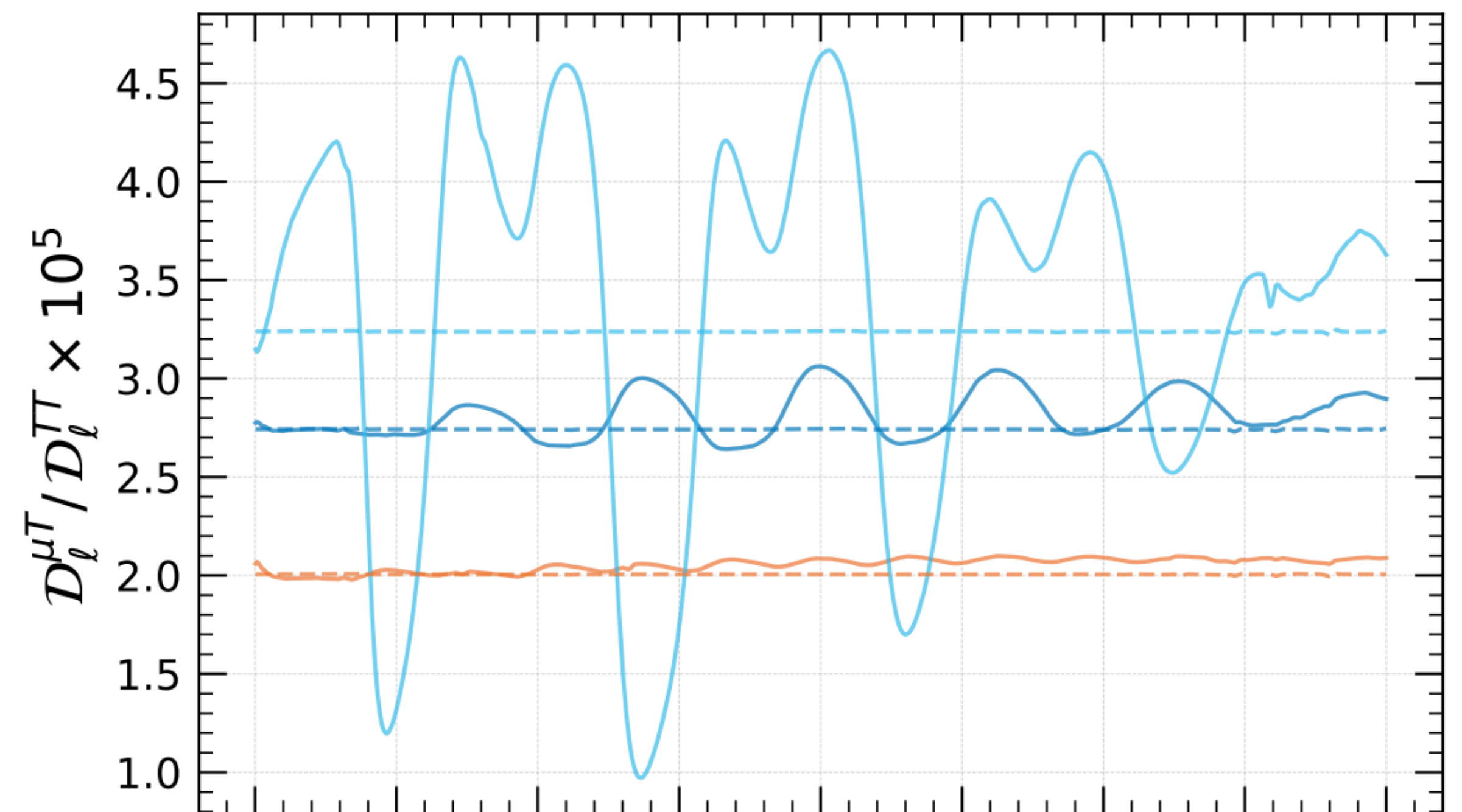
Background quantities are anisotropic, so resonant conversions are too!

Oscillations out of phase with temp anisotropies most prevalent near recombination.

Evangelista, Chluba and BC (2026)



Dashed: $\mu_\ell^{(1)}(\eta, k) \approx b_0^{(0)}(\eta) \Theta_\ell^{(1)}(\eta, k)$,



Solid: Full anisotropic sourcing of DP distortion

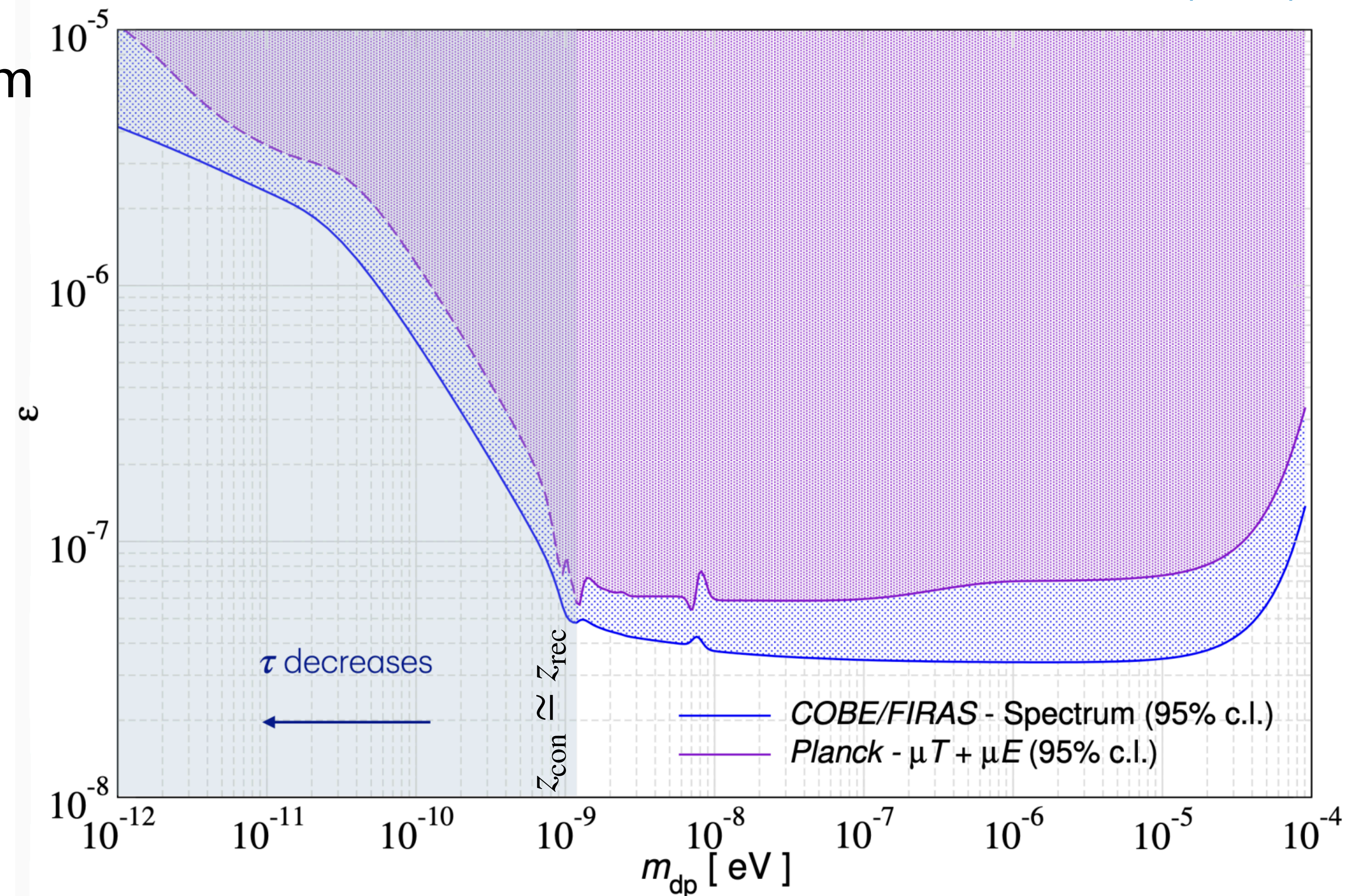
Anisotropic spectral distortions

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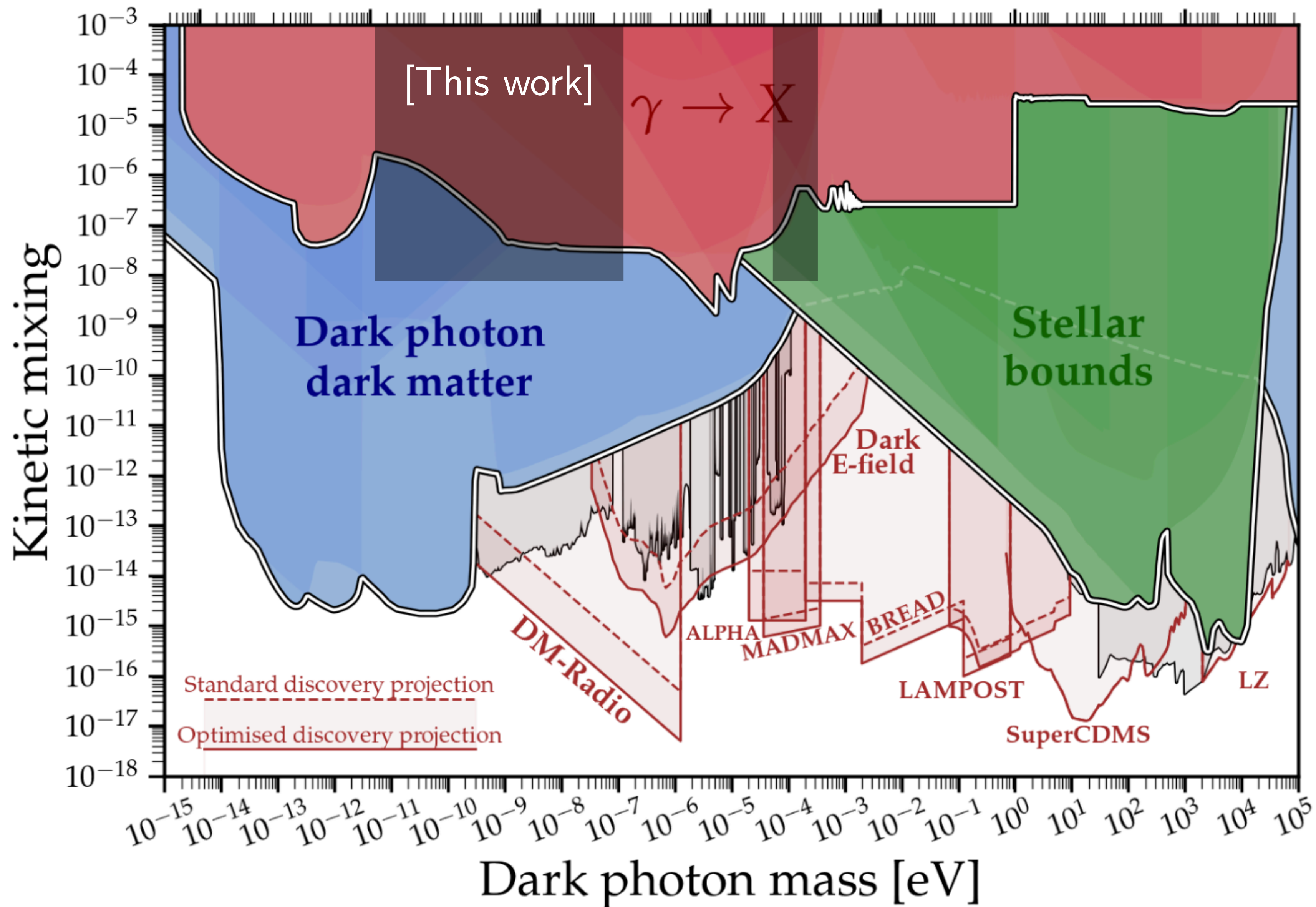
Constraints come mainly from large scales ($\ell \gtrsim 400$)

Marginal improvements with ACT/SPT expected

More substantial improvements with future Litebird and SKA data!



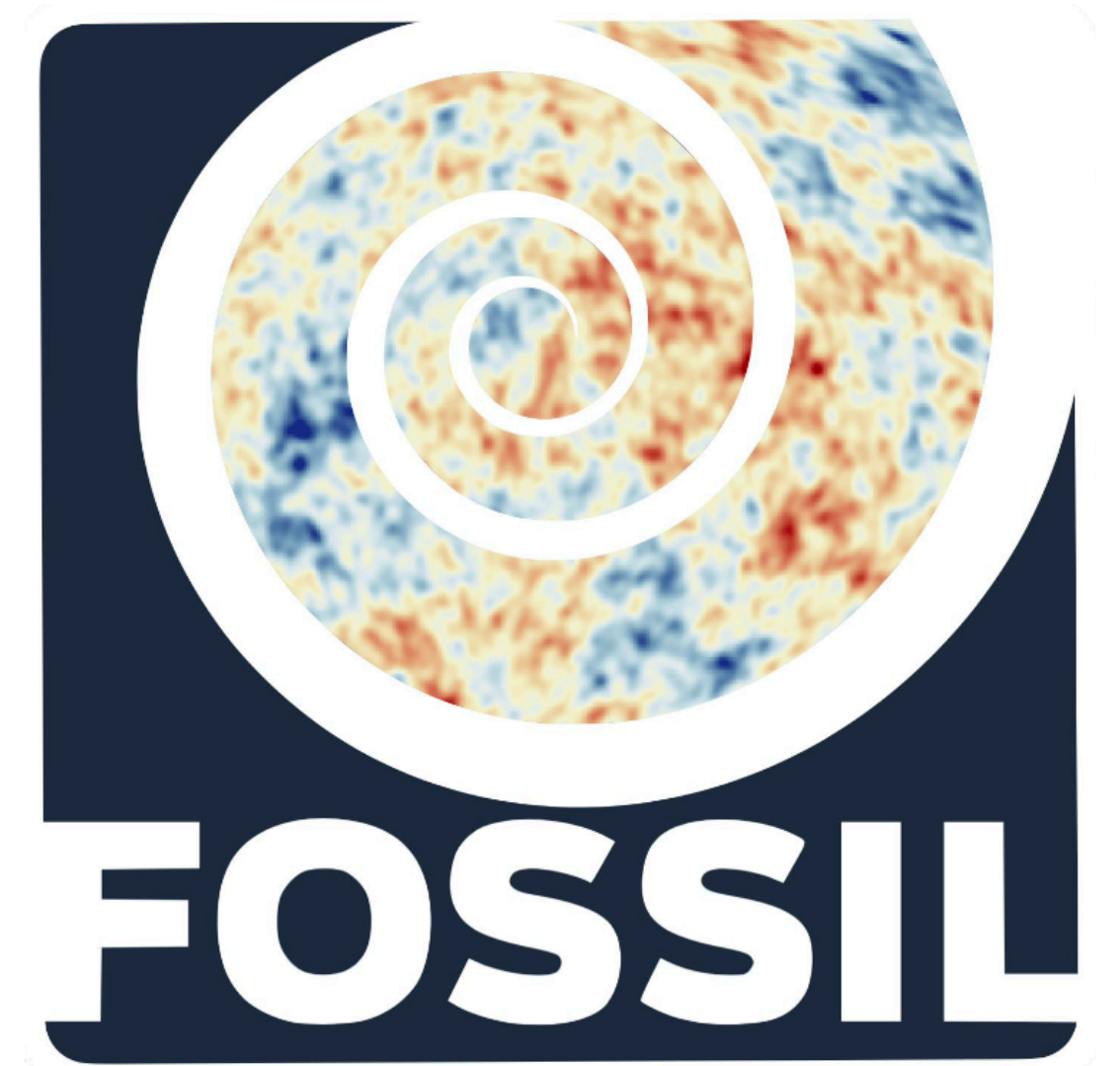
Comparison to other probes





Experimental Prospects

Censored!



From the ground: TMS and COSMO

Ground based observations targeting of CMB spectrum.

Tenerife Microwave Spectrometer (TMS): *Soon!*

- Observe from Canaries at 10-20 GHz (RJ tail).
- Provides much needed follow-up on radio synchrotron background.



PI: Jose-Alberto



PI: Paolo

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PI: Jose-Alberto

COSmic Monopole Observer (COSMO):

Late '20s!

- Two observing windows (110-170 and 200-300 GHz) in the Antarctic.
- Targeting sky-averaged global SZ y-distortion.
- Alongside TMS, provide important pathfinders for both BISOU and FOSSIL.



PI: Paolo

From the atmosphere: BISOU



From the atmosphere: BISOU



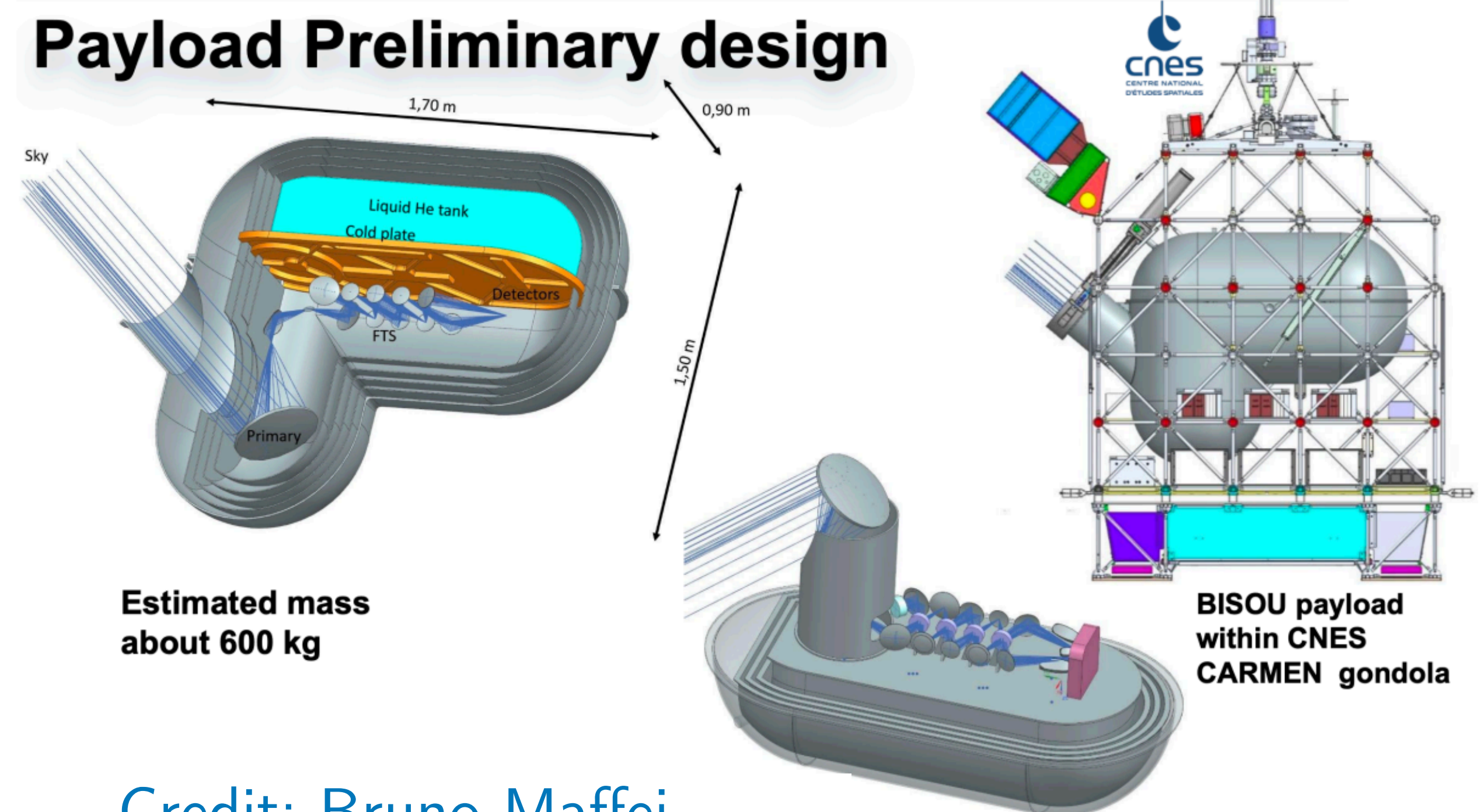
From the atmosphere: BISOU

Balloon experiment set for 5 day flight over Atlantic.

- Roughly a 5σ detection of global (SZ) γ -distortion.
- $\simeq 3\sigma$ detection on the CIB monopole amplitude.



PI: Maffei



Credit: Bruno Maffei

From the atmosphere: BISOU

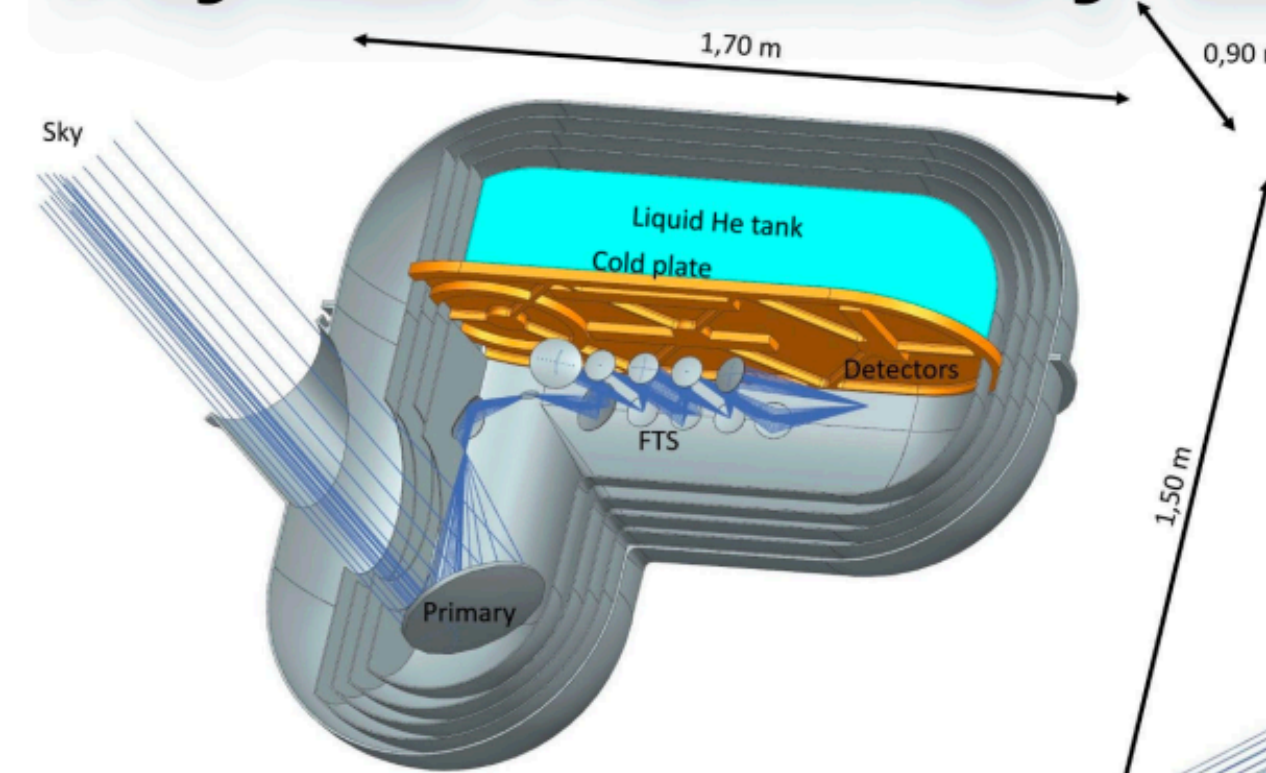
Balloon experiment set for 5 day flight over Atlantic.

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- $\simeq 3\sigma$ detection on the CIB monopole amplitude.
- 90 to 2000 GHz (split @ $\simeq 250$ GHz).
- $\Delta\nu = 15$ GHz.
- $\simeq 3$ deg. eq. Gaussian beam.
- $\simeq 300$ sq. degrees covered.
- Marginalization over all parameters.
- 10% prior on synchrotron parameters.
- AME and μ -distortion neglected.

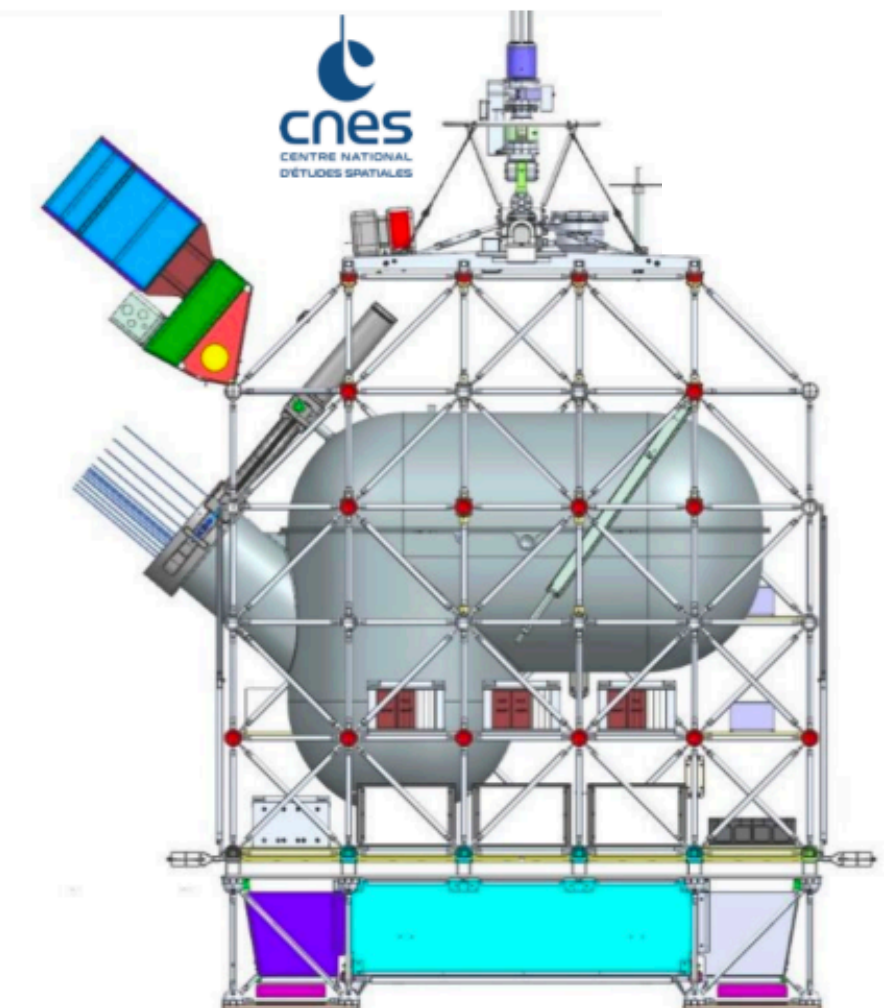


PI: Maffei

Payload Preliminary design



Estimated mass
about 600 kg



BISOU payload
within CNES
CARMEN gondola

Credit: Bruno Maffei

From the atmosphere: BISOU

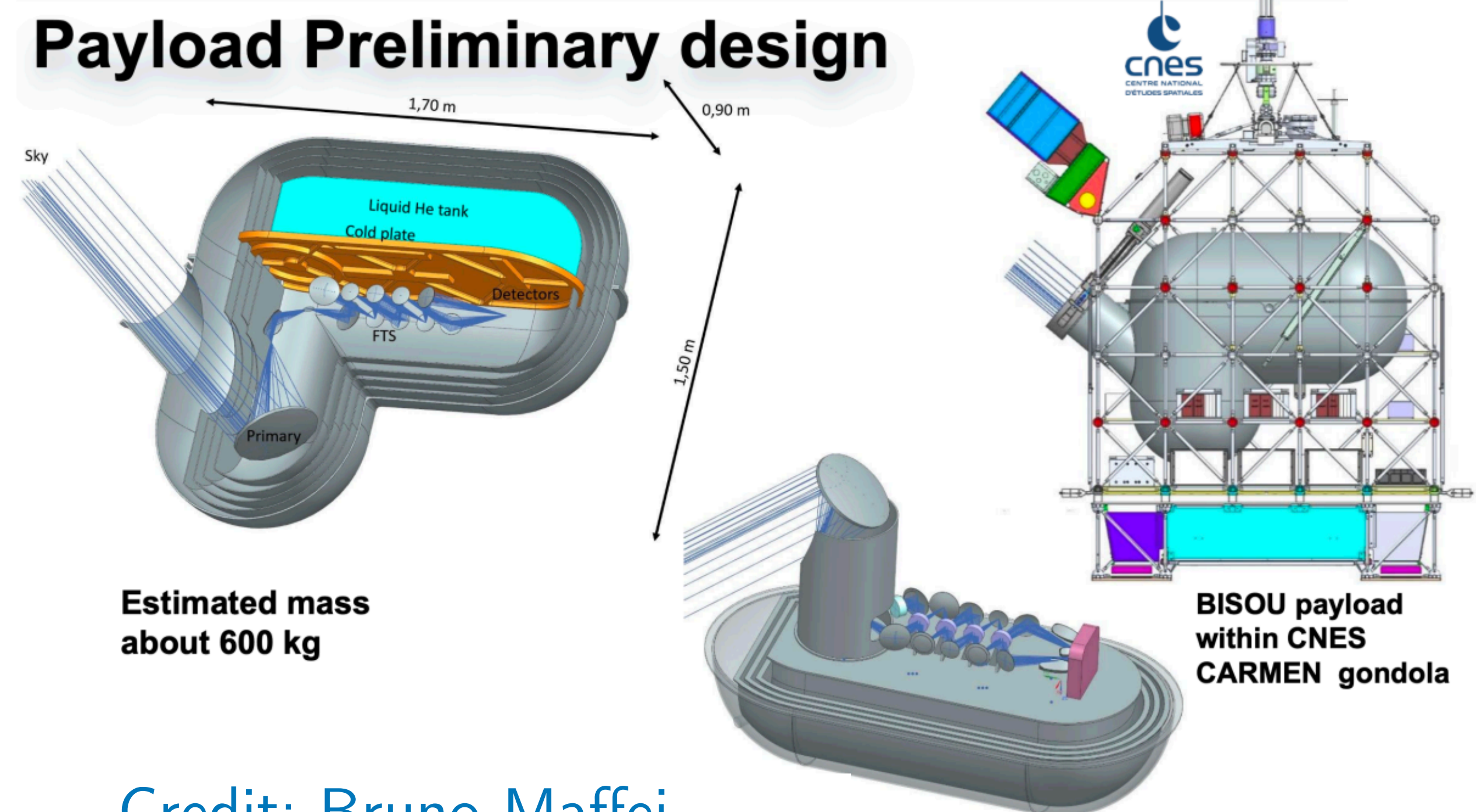
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Tech flight 2029-2030
Science run expected 2031



PI: Maffei

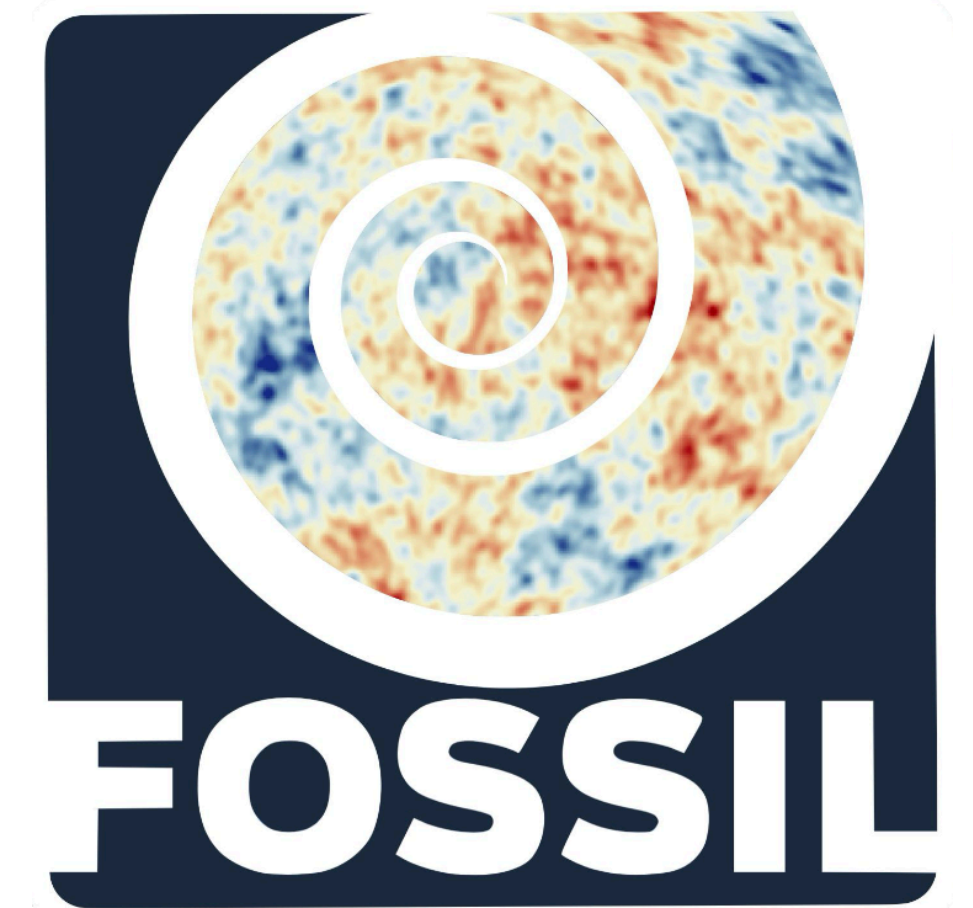


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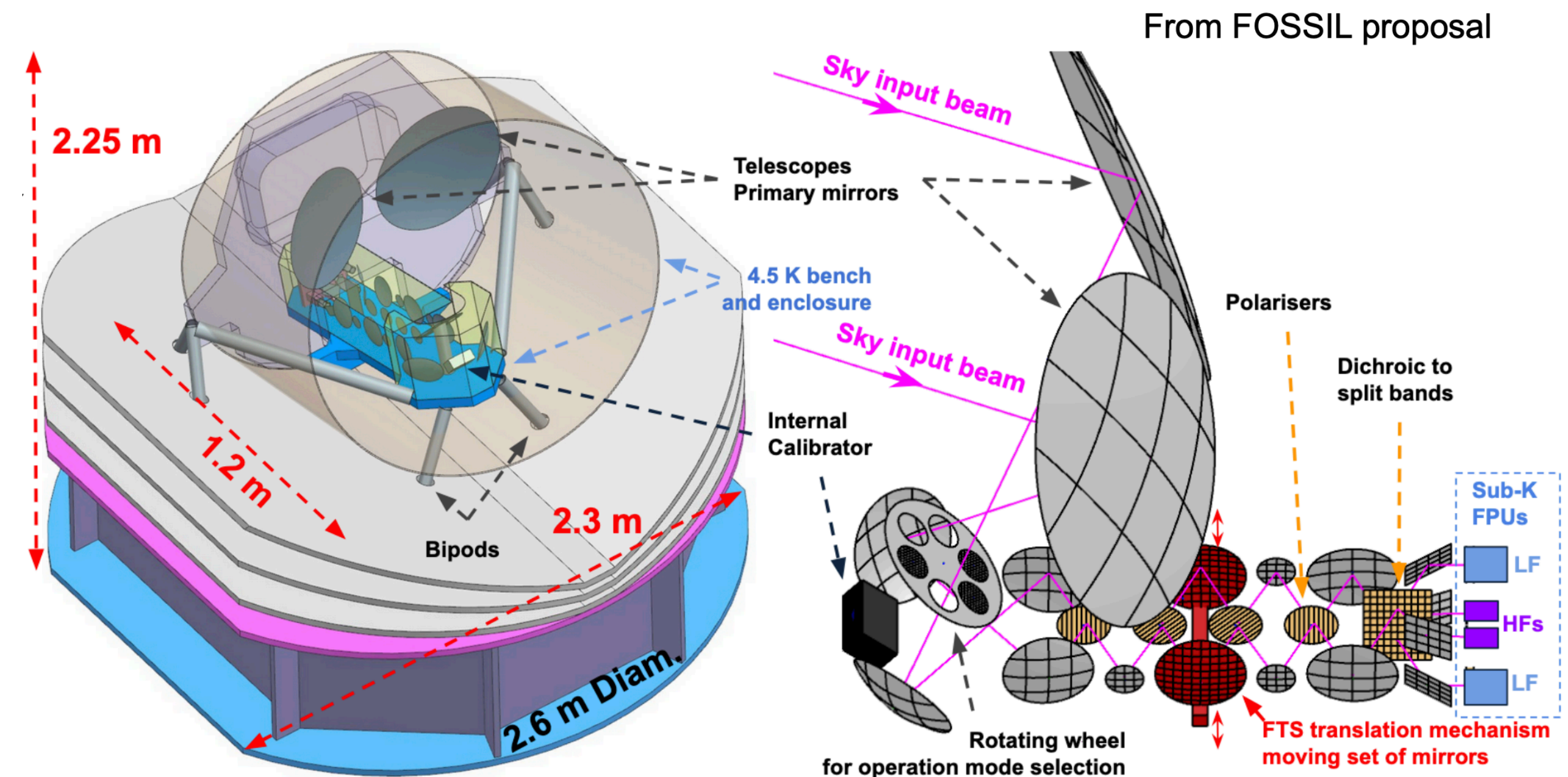
From space: FOSSIL

Mission proposed as part of the M8 call from ESA.

- A detection of the primordial μ at $\simeq (2 - 4)\sigma$.
- Global y -distortion at $\mathcal{O}(100\sigma)$.
- Distortions from relativistic SZ corrections at $\mathcal{O}(10\sigma)$.



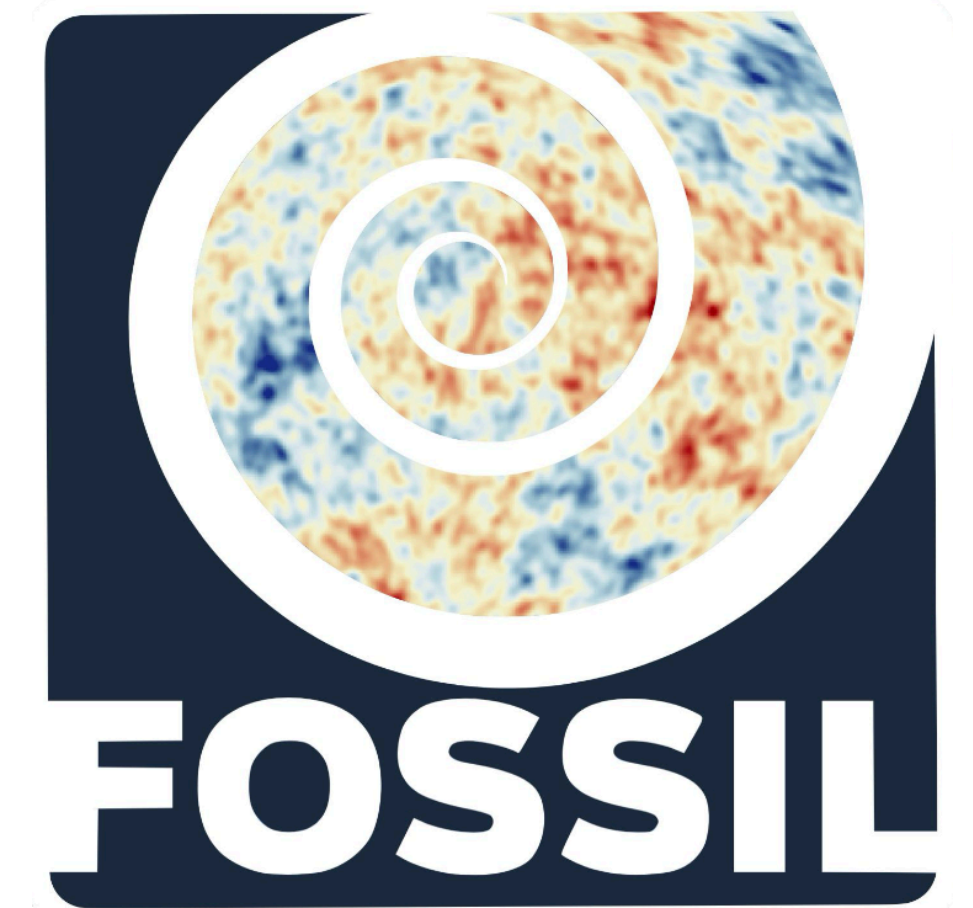
PI: Aghanim



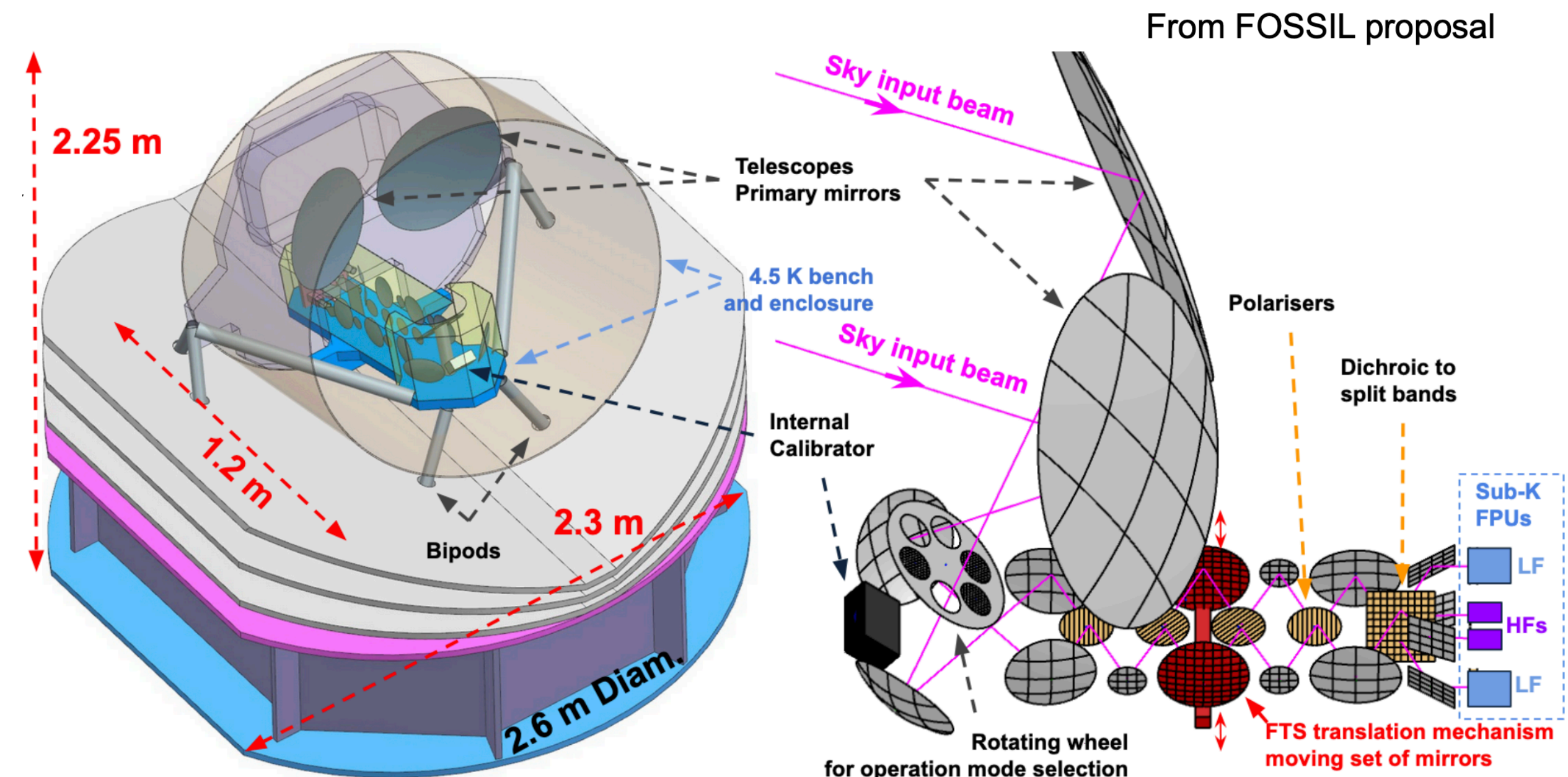
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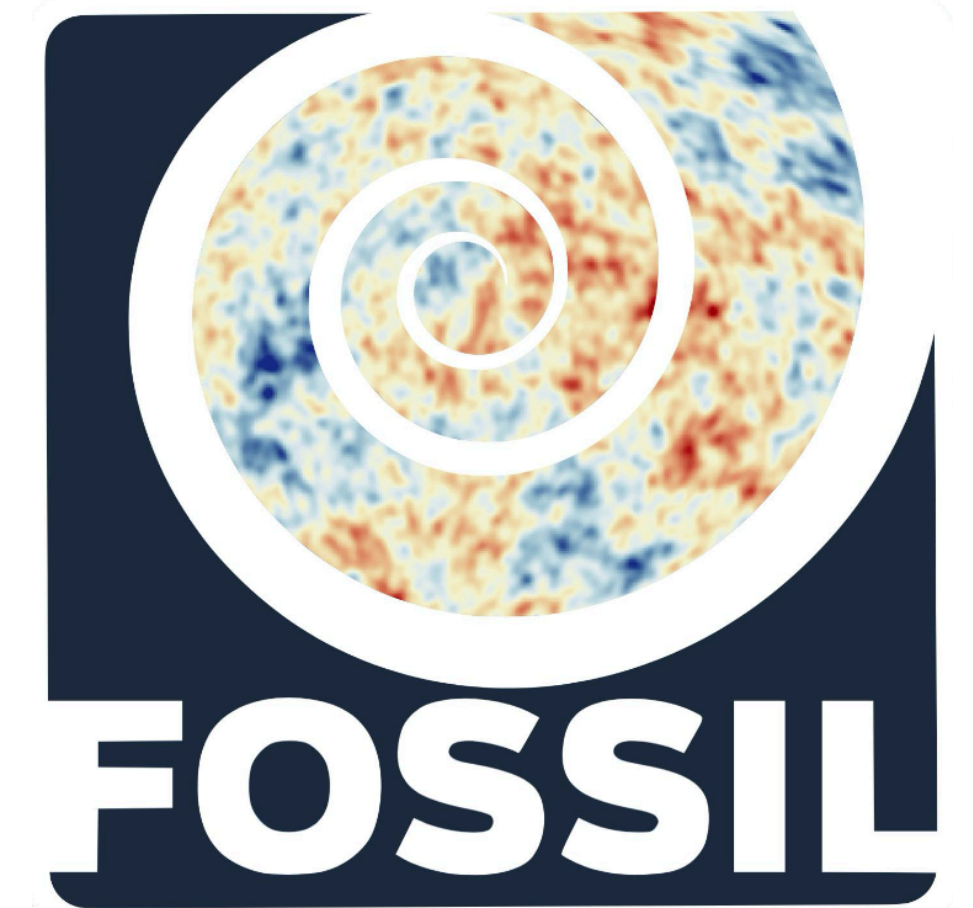


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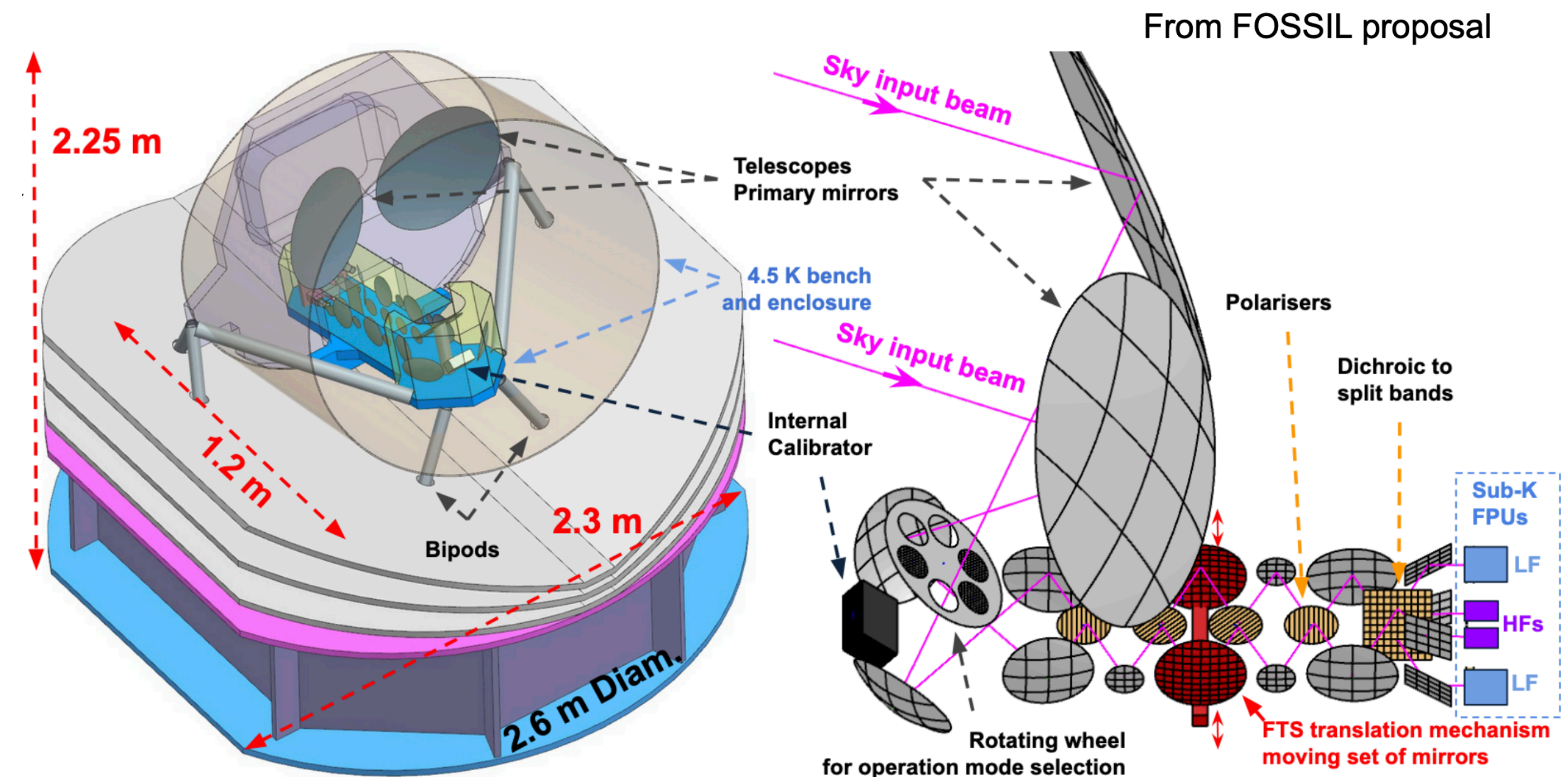
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Phase-0 selection: Fall 2026
Phase-A selection: Fall 2027
ESA final selection: 2030
Launch: 2041



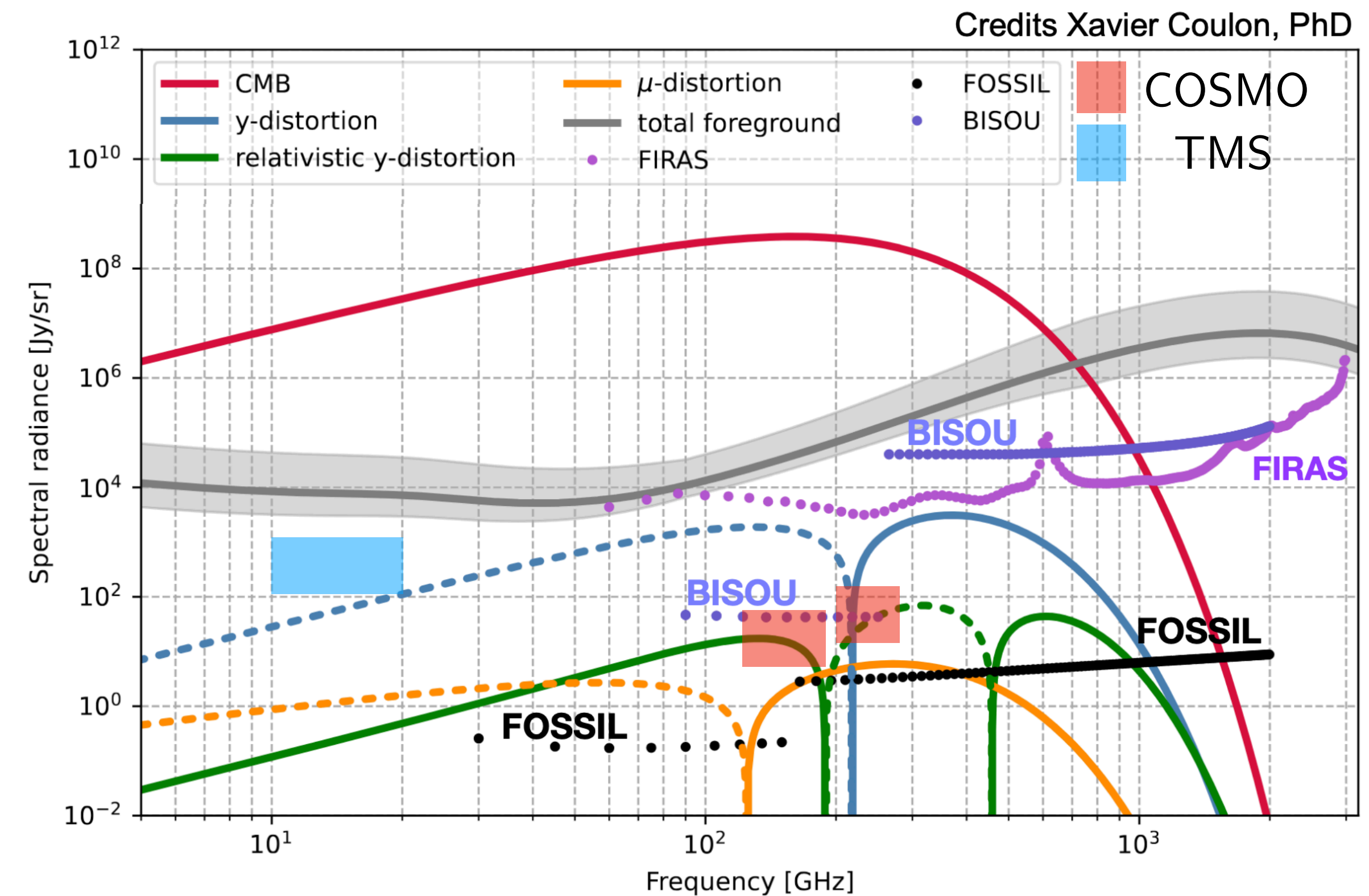
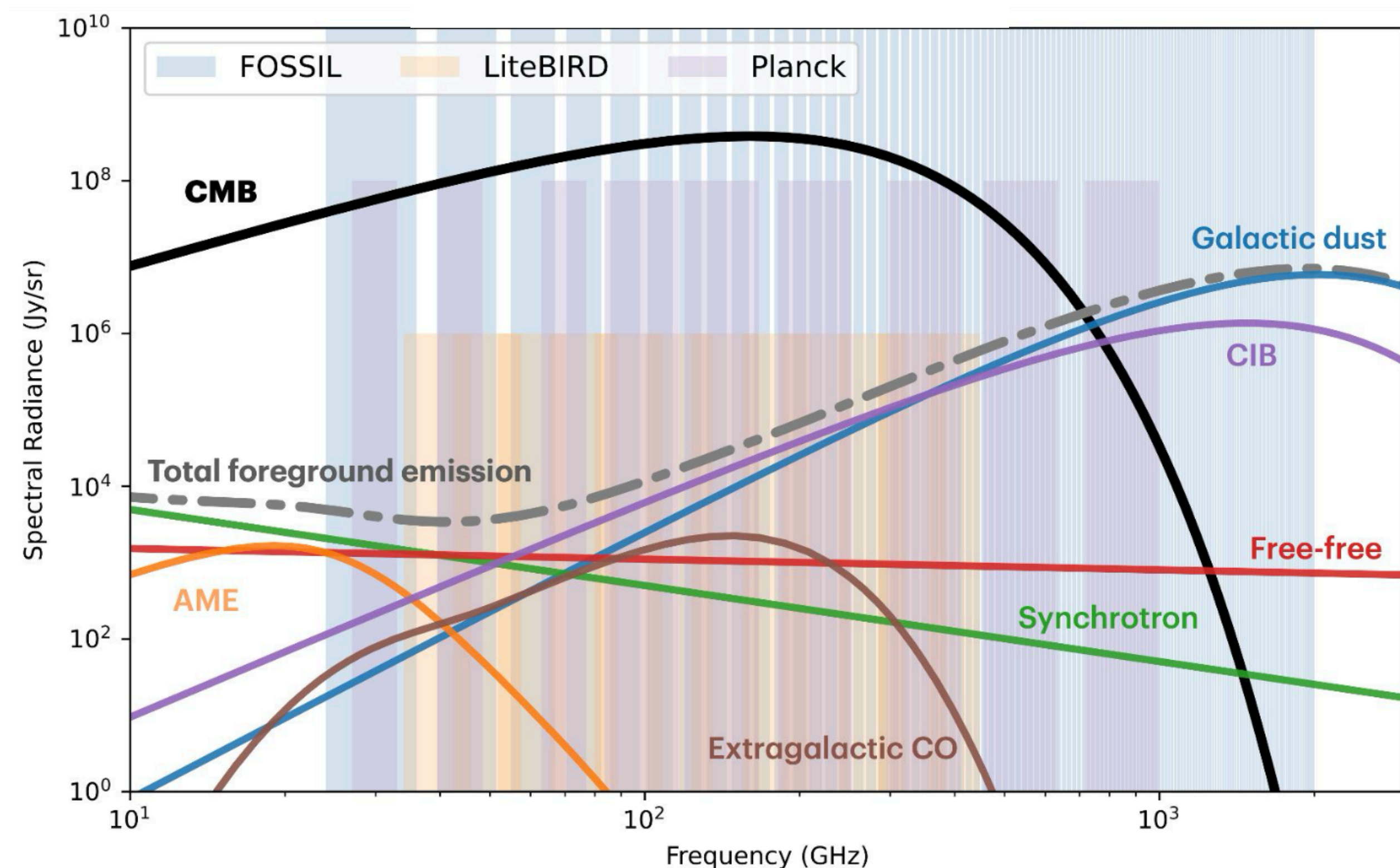
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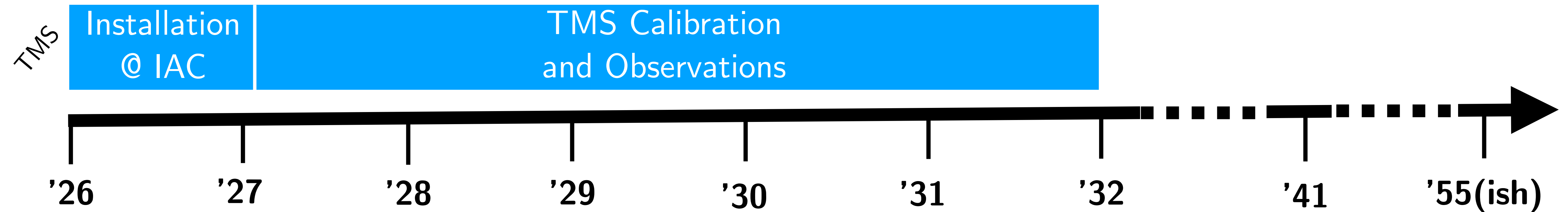
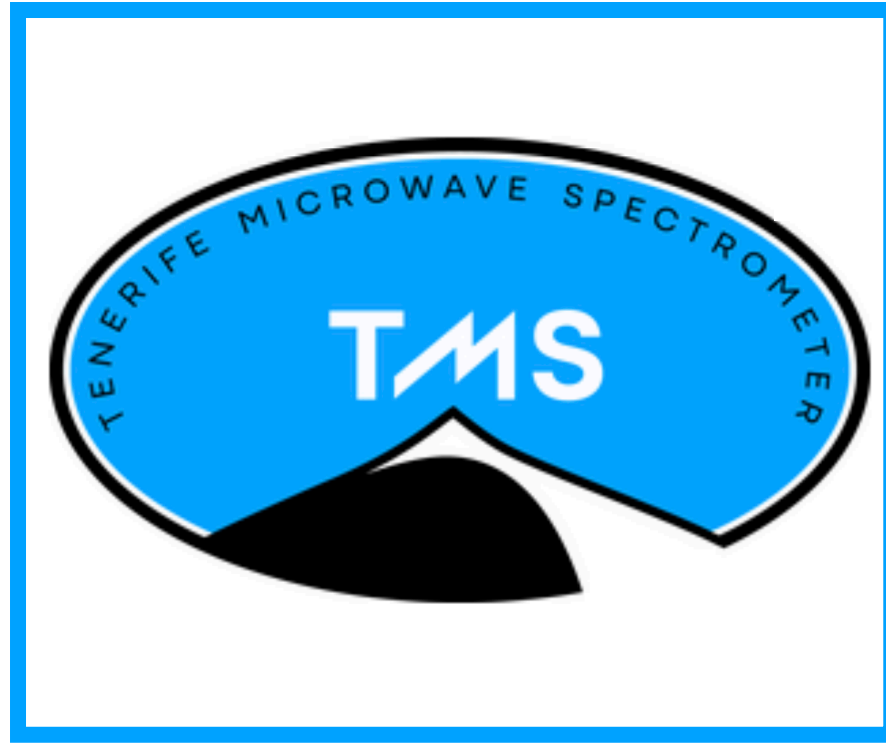
Sensitivities (and challenges)

The foregrounds are bright, but not insurmountable given >100 frequency channels from FOSSIL.

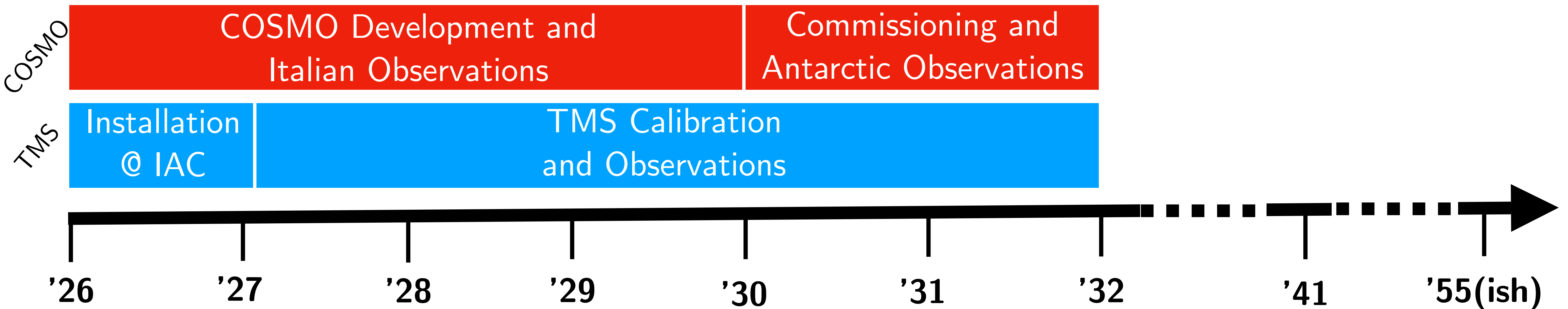
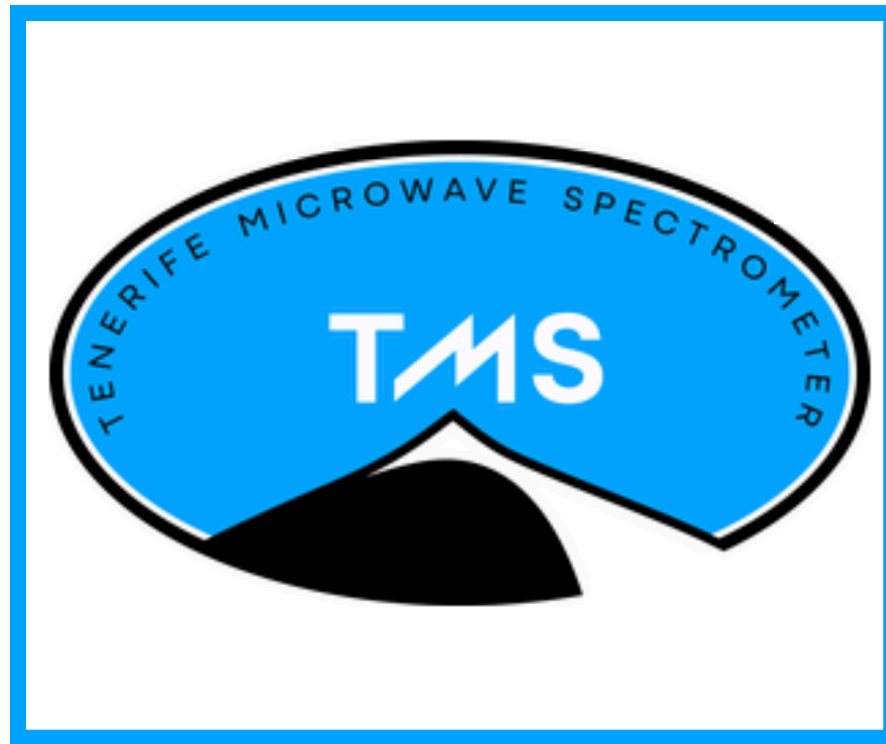
A detection of μ (and possibly also the $H\alpha$ recombination line) is possible!



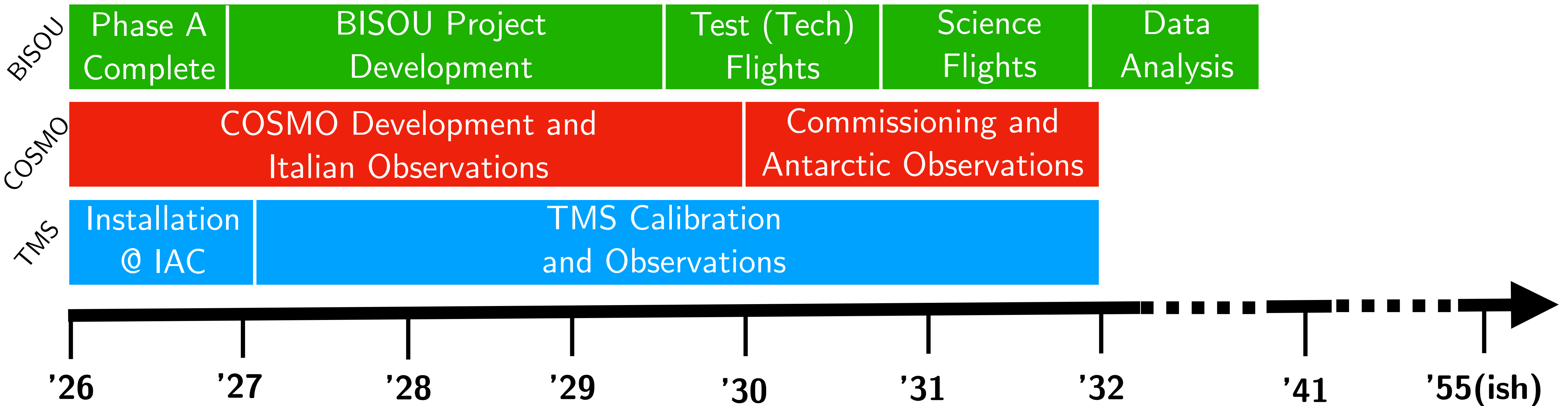
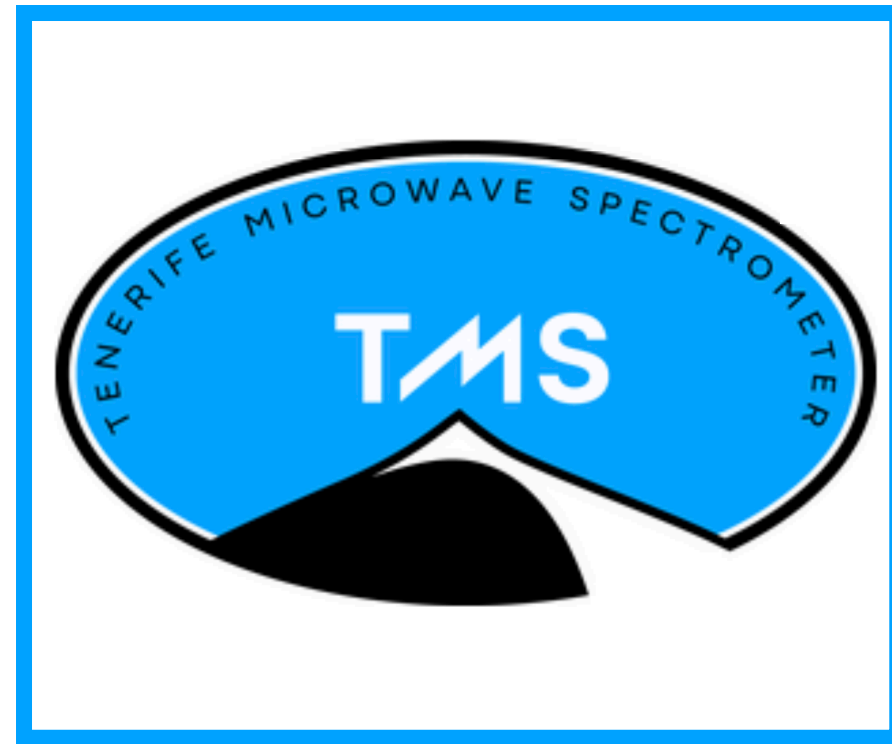
Roadmap at a Glance



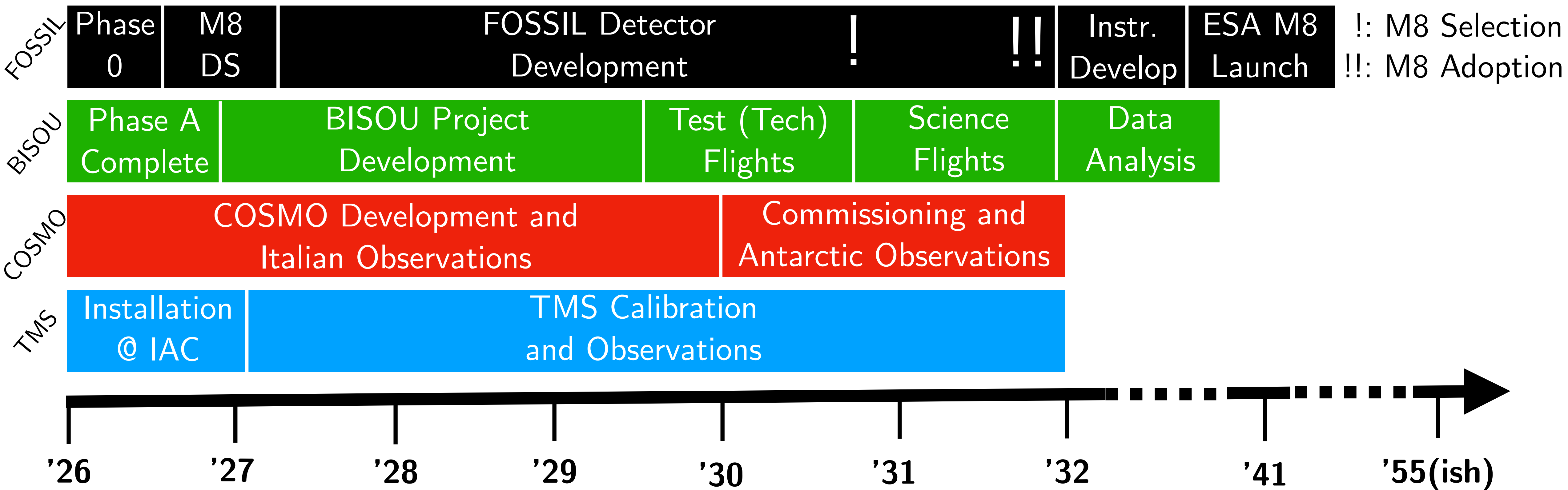
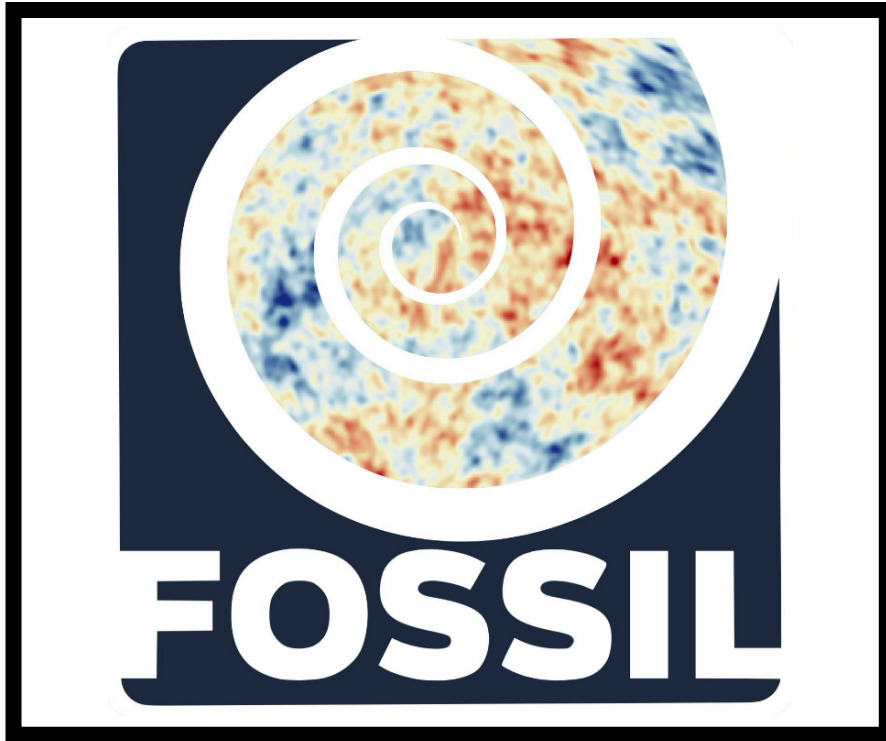
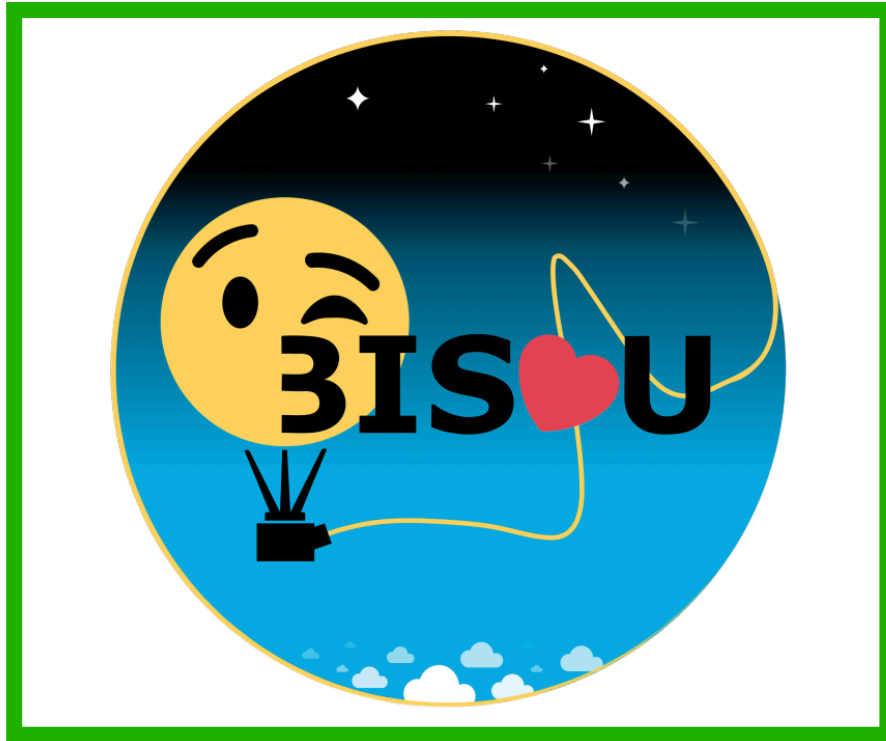
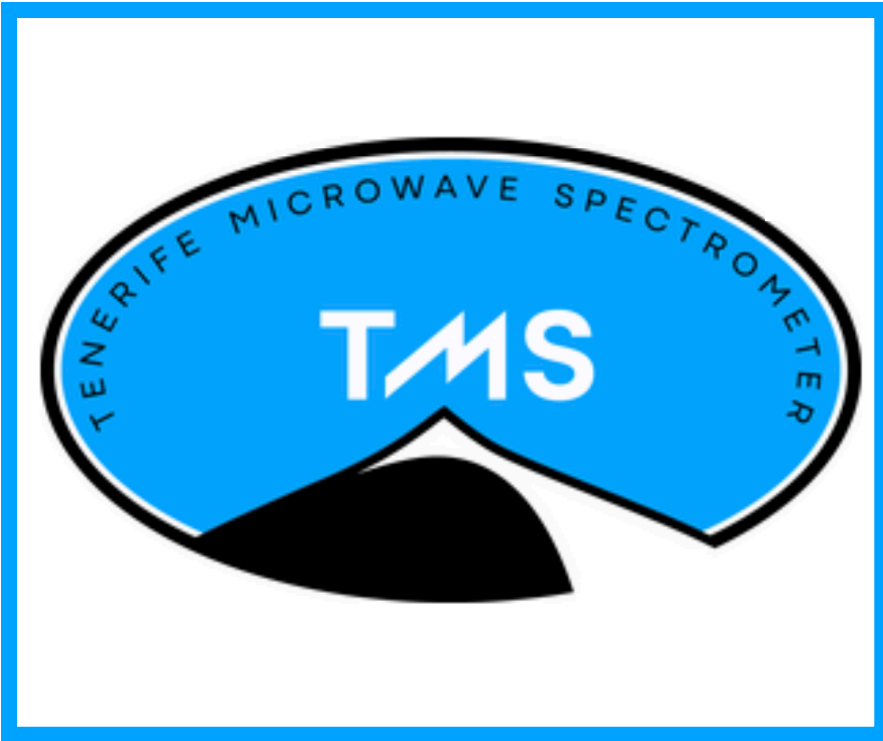
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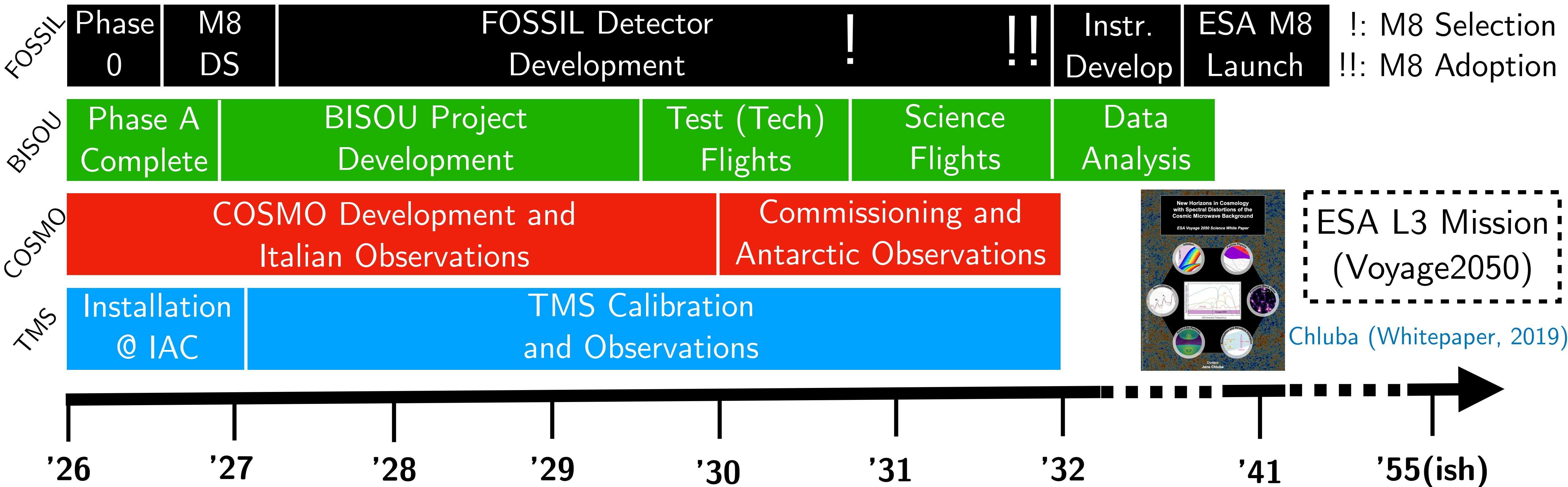
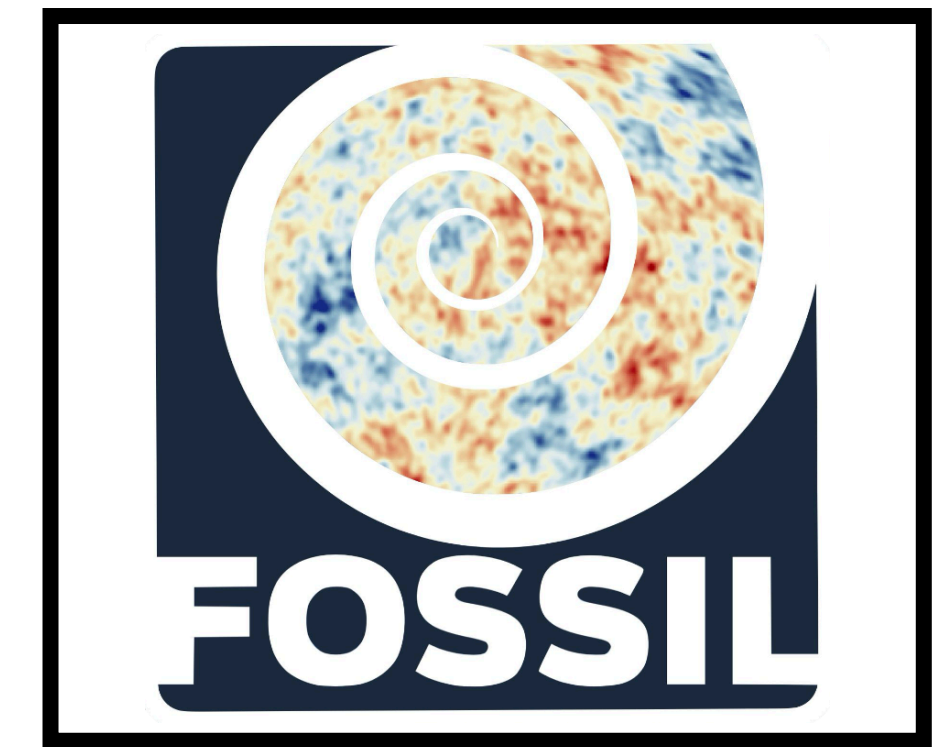
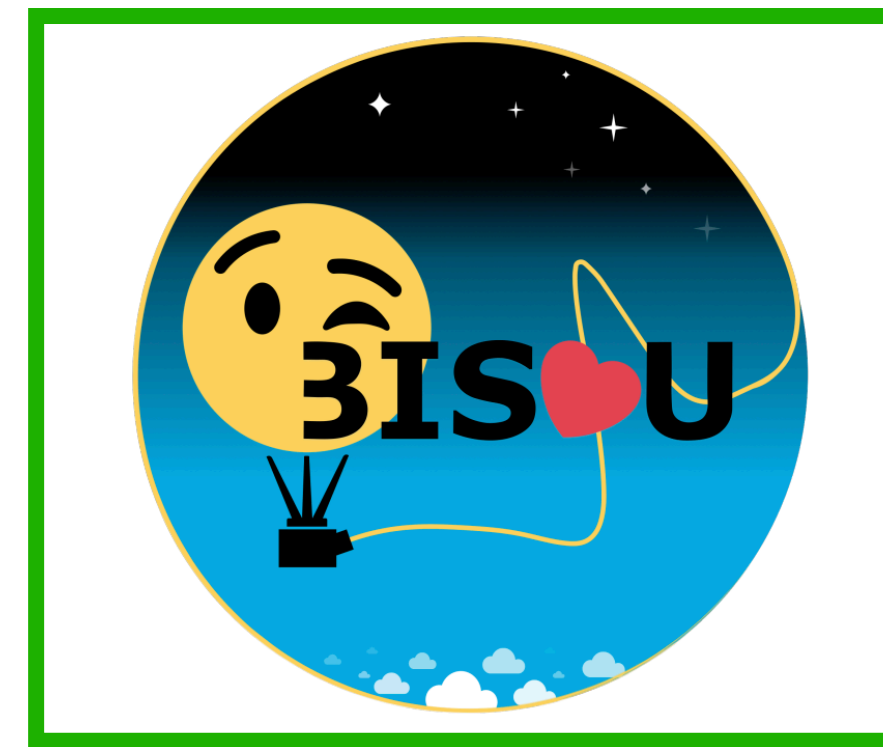
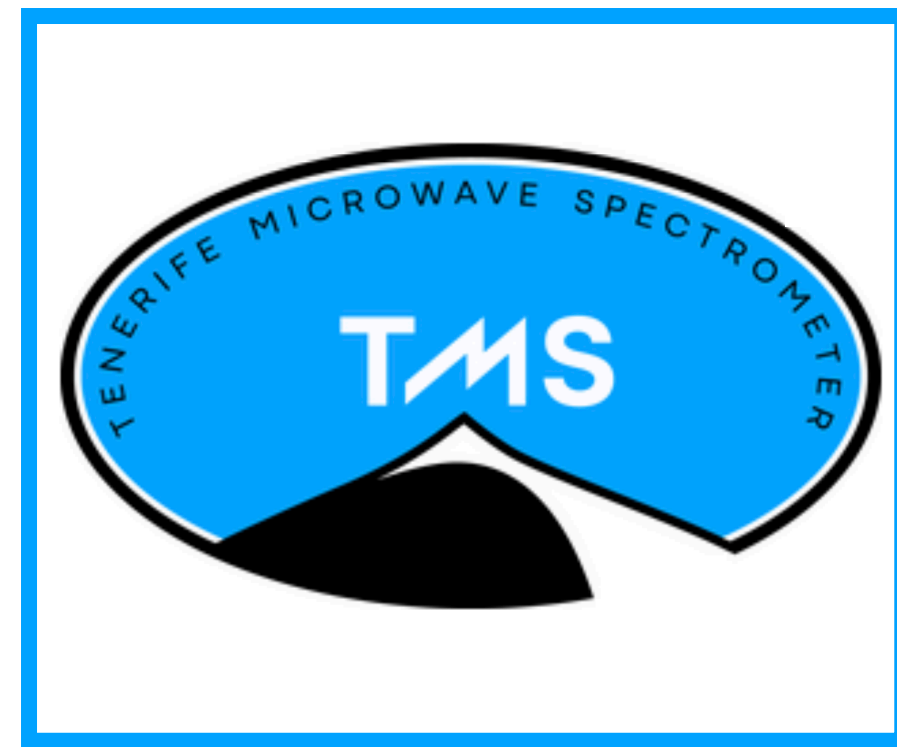
Roadmap at a Glance



Roadmap at a Glance



Roadmap at a Glance



Conclusions

CMB spectral distortions provide a unique and highly sensitive way to probe the thermal history of our Universe.

Cosmological and astrophysical signals within Λ CDM are within reach of current technology. Plethora of BSM signals to also hunt for.

First ever monopole spectral (y-)distortion detection is coming in 5-10 years, through combined efforts of TMS, COSMO, and BISOU.

From space (FOSSIL, Voyage2050), primordial μ provides a robust and highly sensitive test of primordial perturbations on small scales.

Thank you!

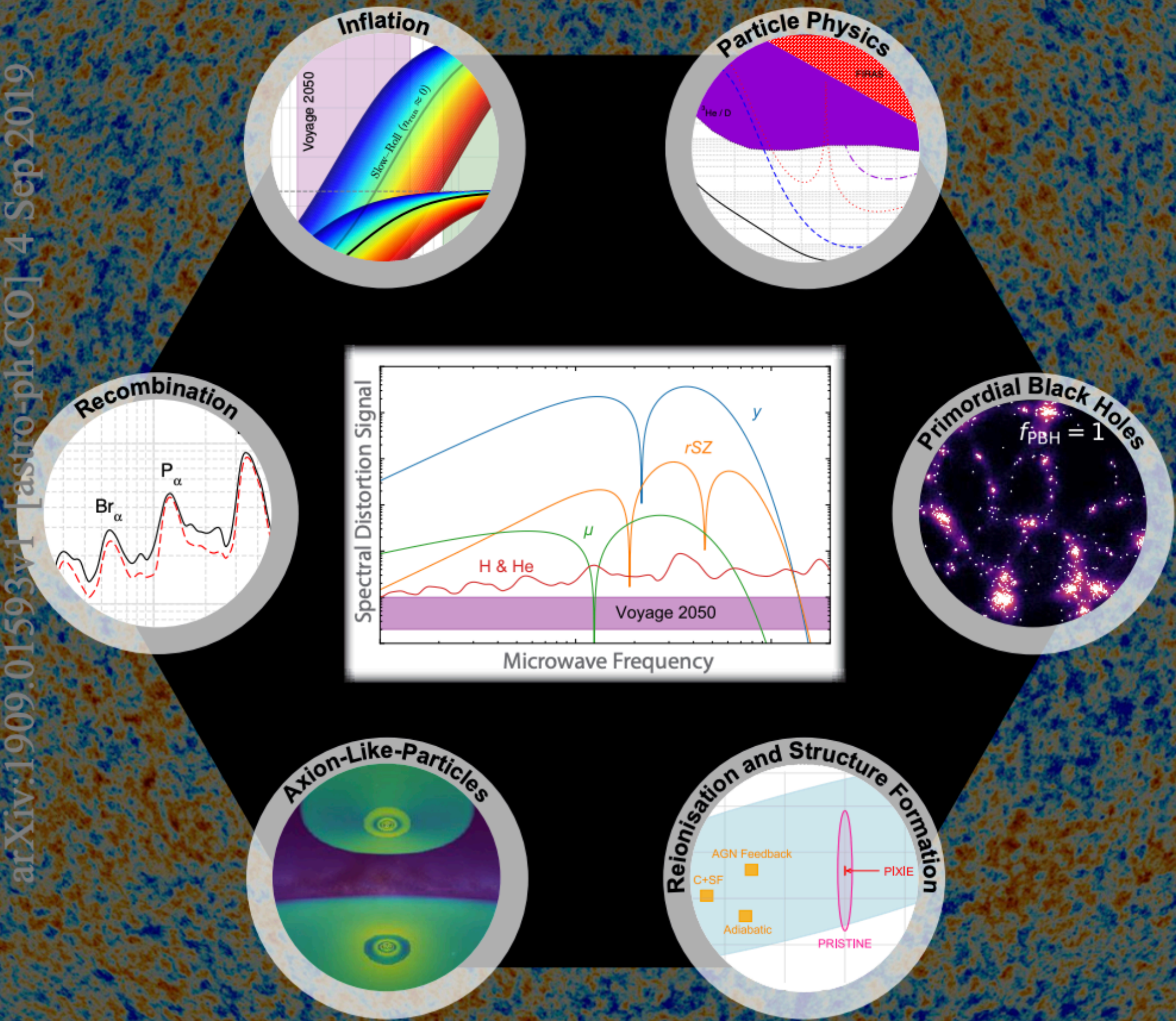
The Voyage2050 program

- 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

arXiv:1909.01593v1 [astro-ph.CO] 4 Sep 2019



Contact:
Jens Chluba

Energy injection rate

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

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

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

Chluba and Grin (2013)

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

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

