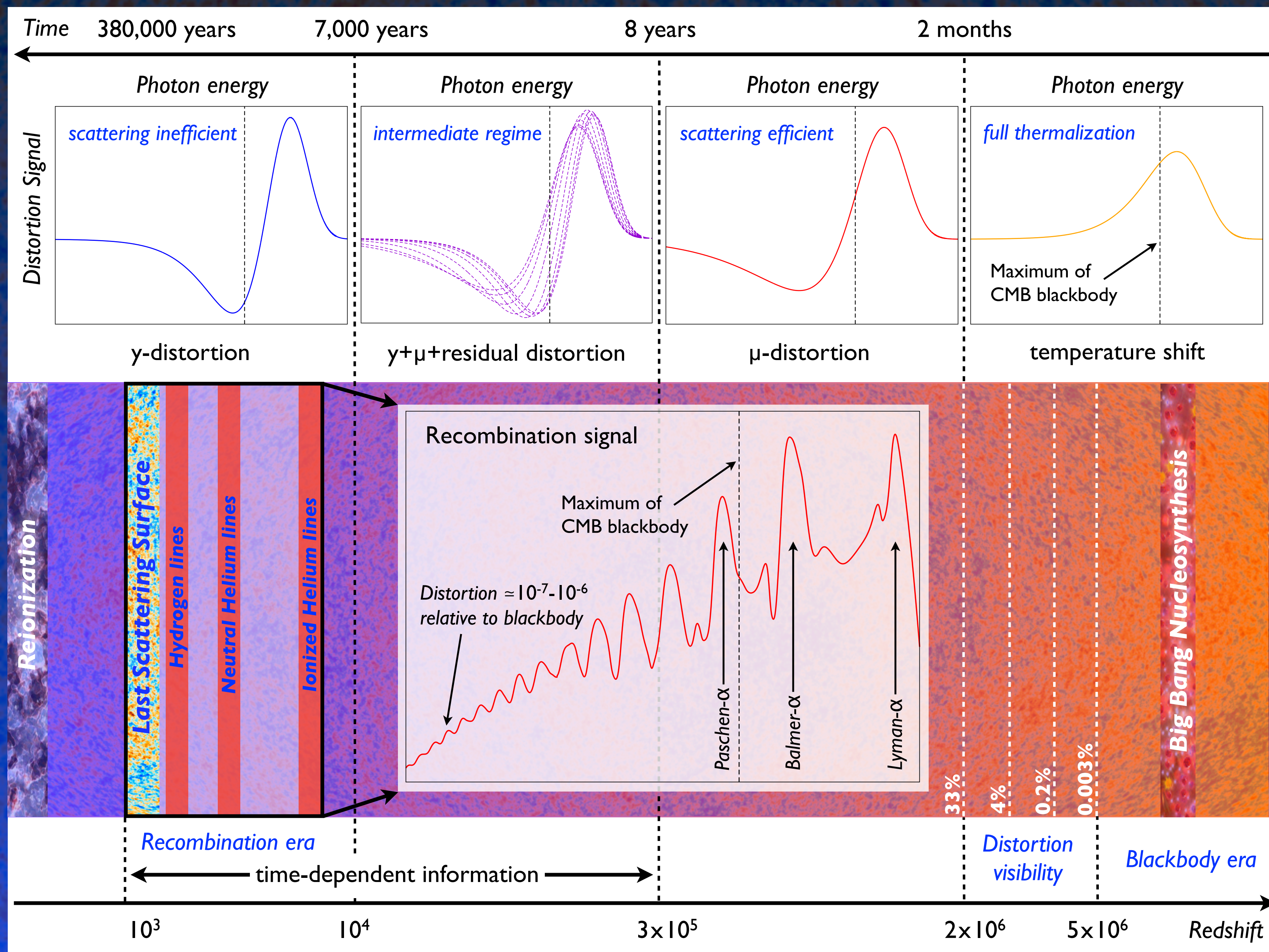
CMB* Spectral Distortions and Their Synergies



The University of Manchester

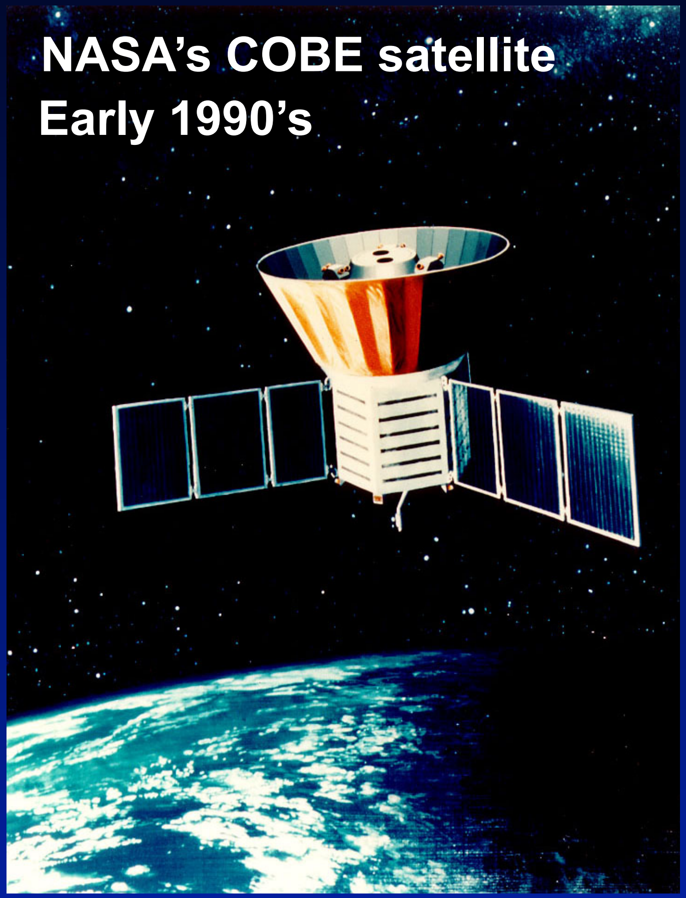
Jens Chluba

CMB-France # 6 @ IHP, Paris

December 18th 2024

* CMB ≙ Cosmic Microwave Background

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

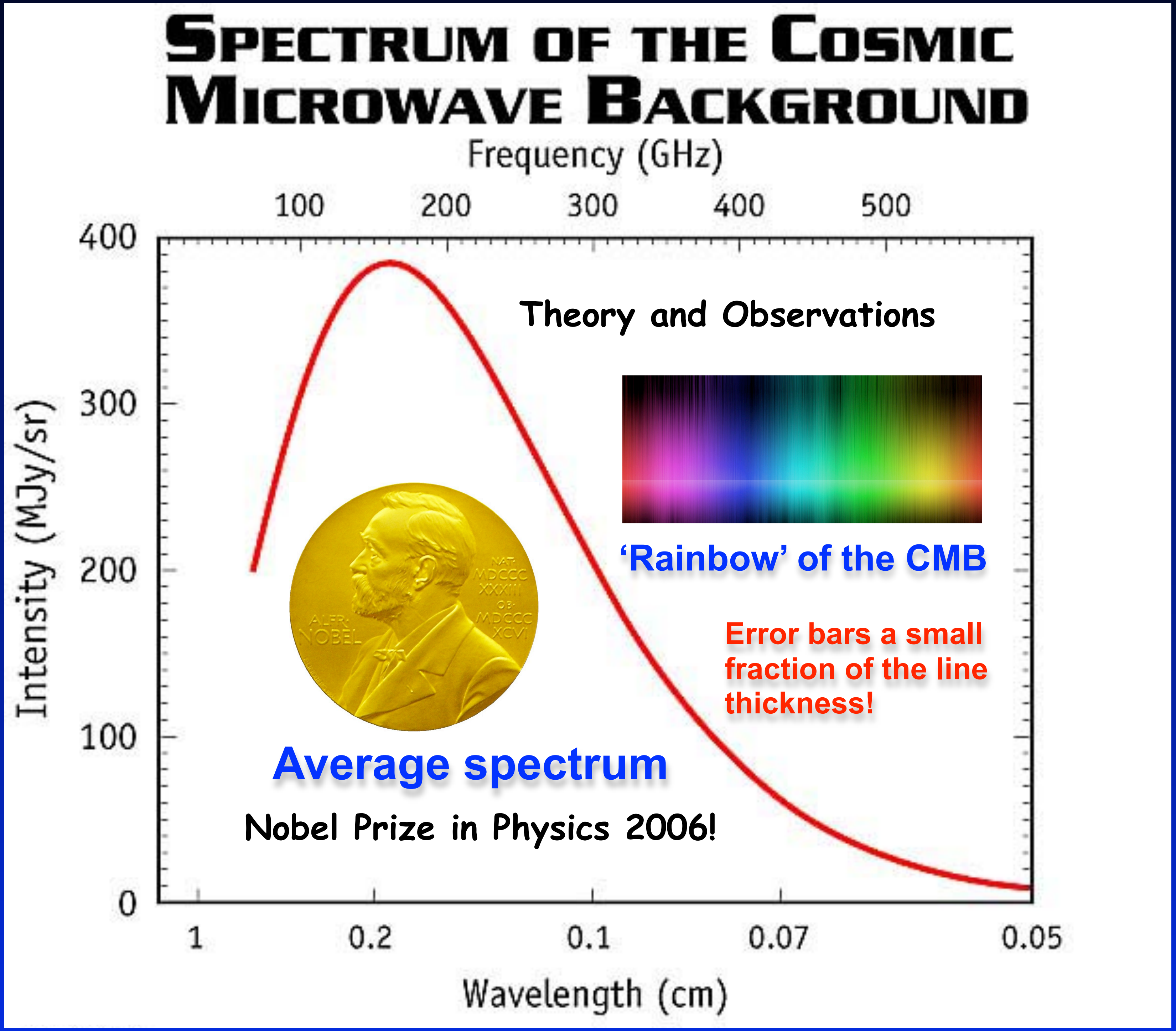


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

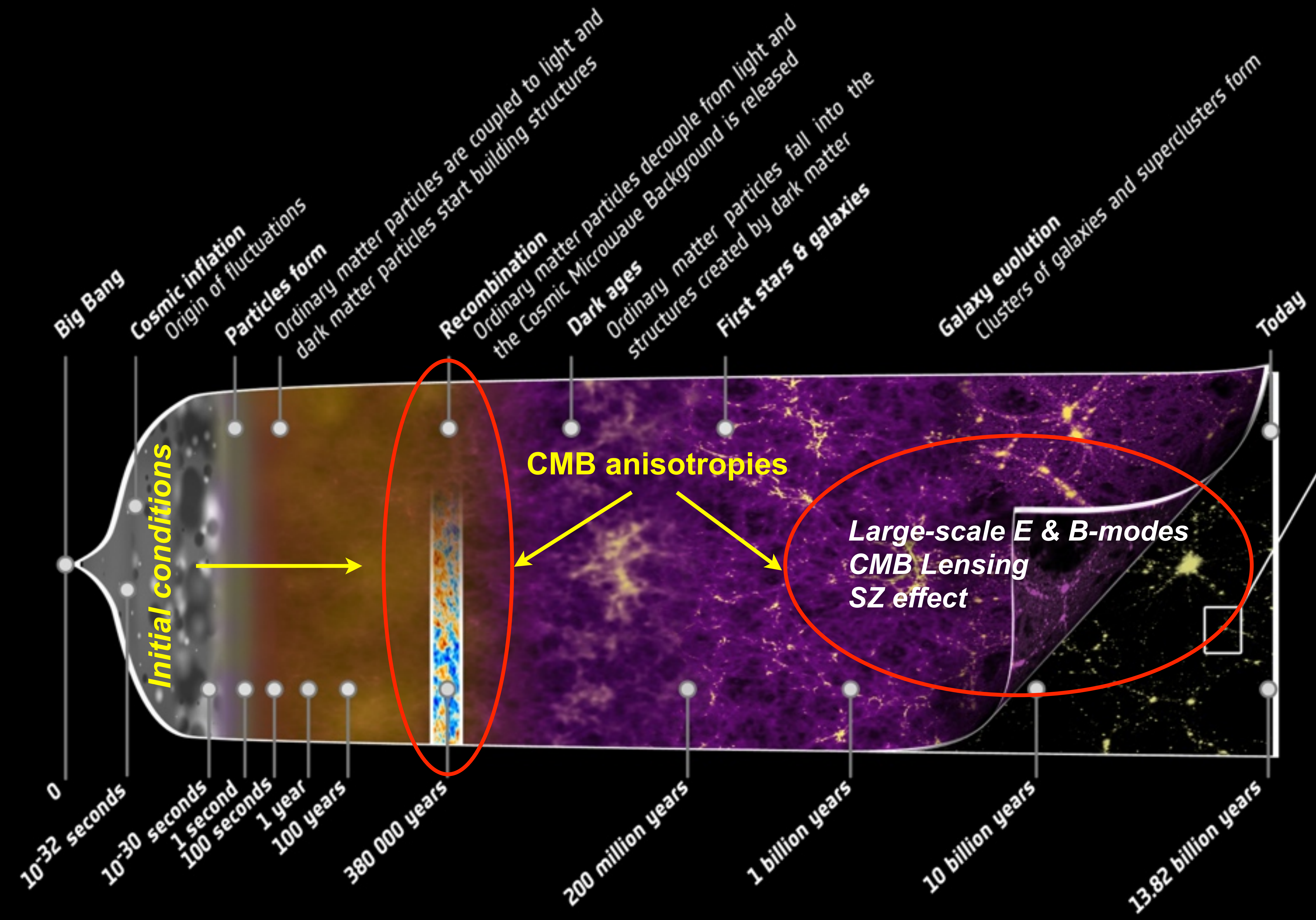
$$|y| \leq 1.5 \times 10^{-5}$$

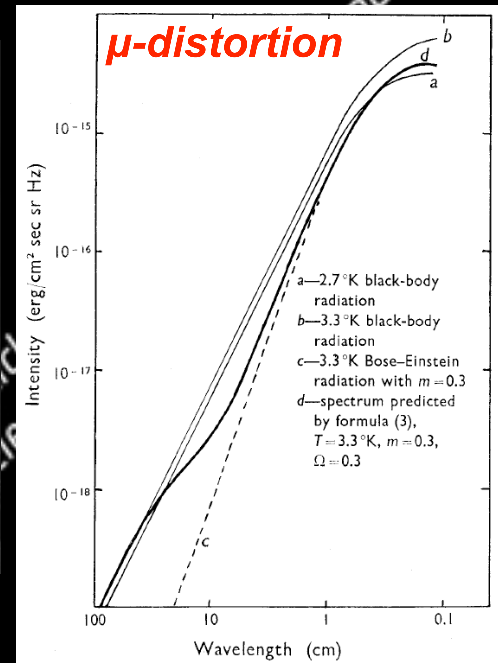
$$|\mu| \leq 9 \times 10^{-5}$$

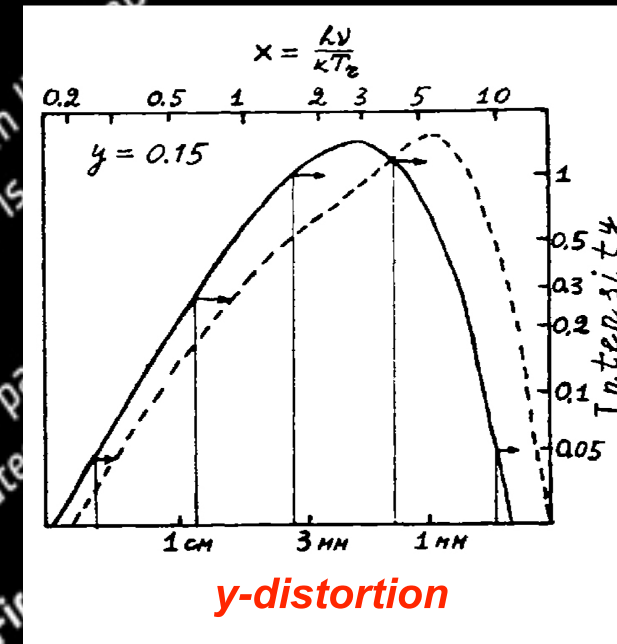
Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen, 2003, ApJ, 594, 67
Fixsen, 2009, ApJ, 707, 916

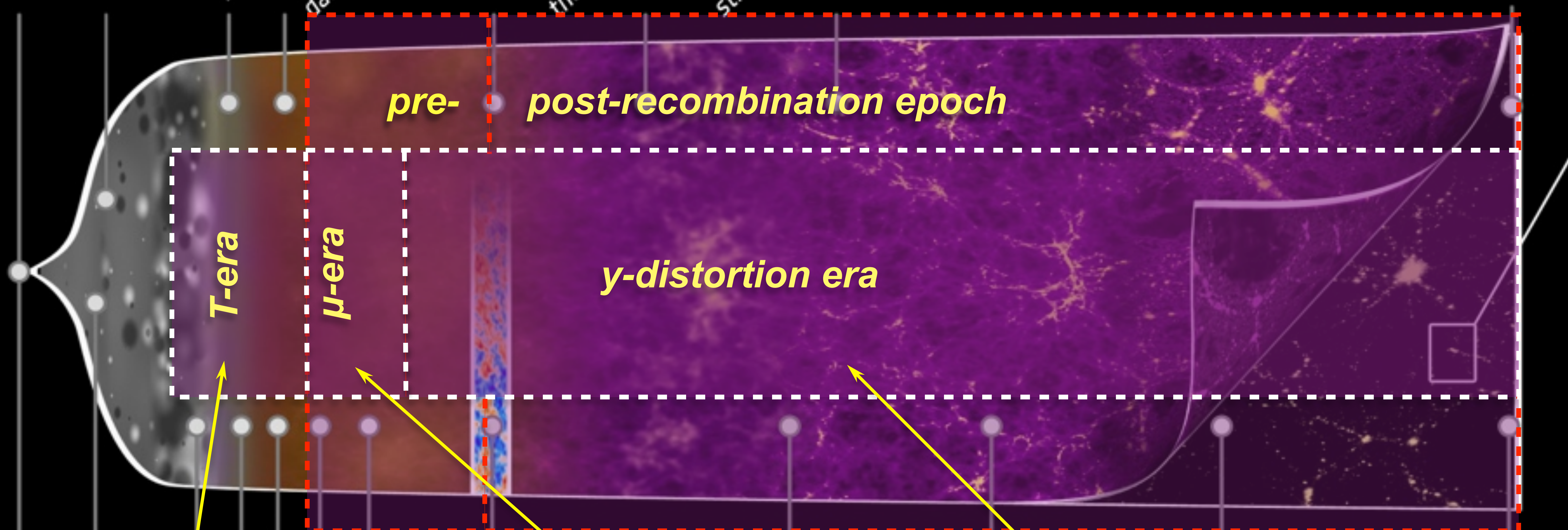


Blackbody spectrum to very high precision

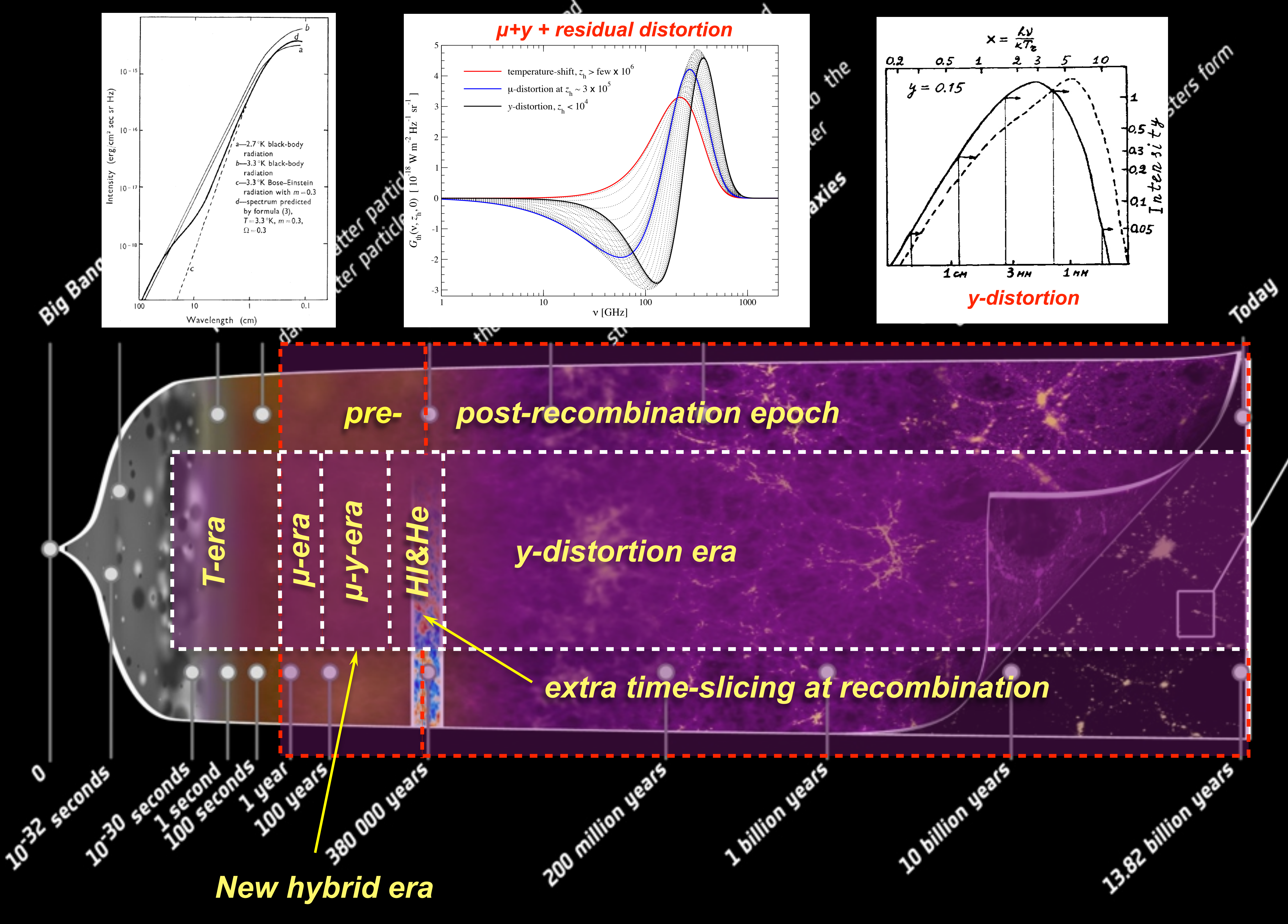

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Initial conditions
CMB anisotropies
Large-scale E & B-modes
CMB Lensing
SZ effect
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years







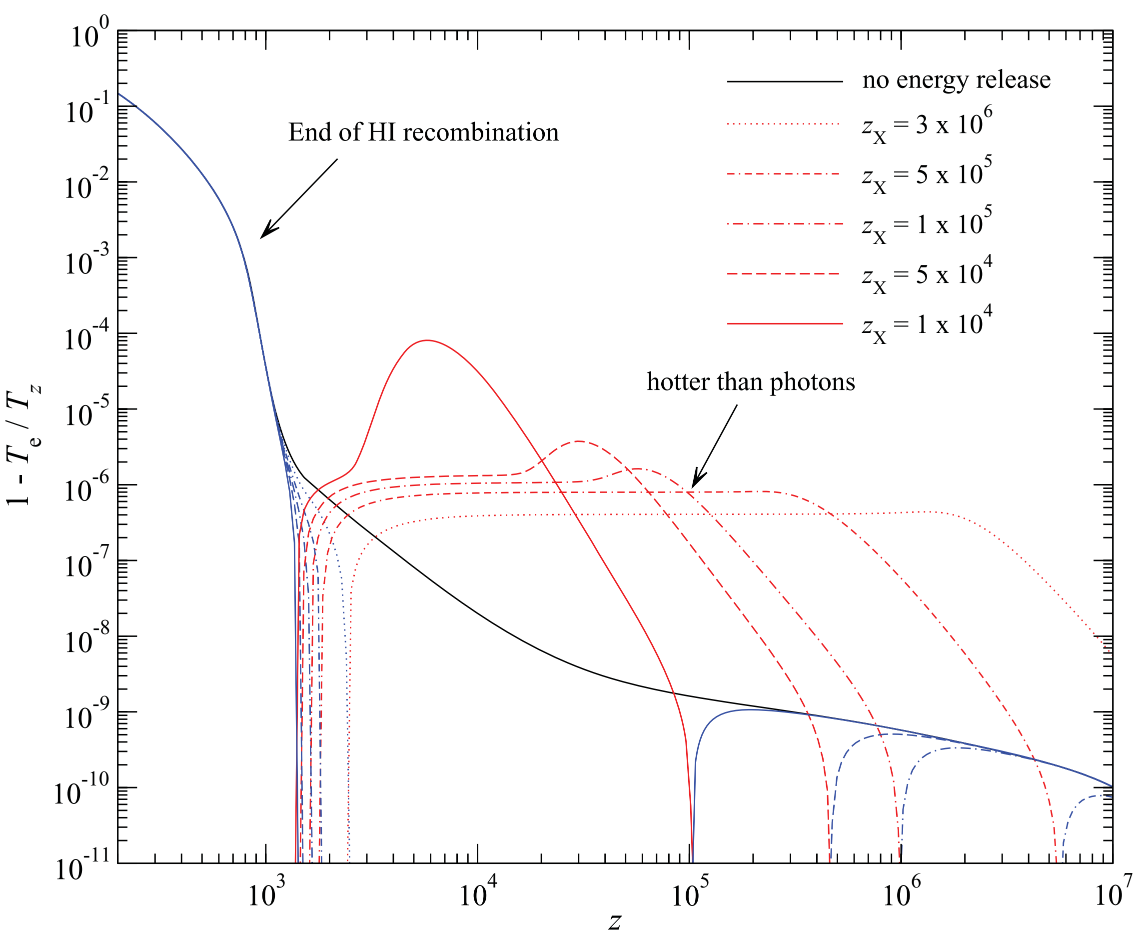
$$\frac{\Delta T}{T} \simeq \frac{1}{4}\,\frac{\Delta\rho_\gamma}{\rho_\gamma}\bigg|_T \qquad \mu \simeq 1.4\,\frac{\Delta\rho_\gamma}{\rho_\gamma}\bigg|_\mu \qquad y \simeq \frac{1}{4}\,\frac{\Delta\rho_\gamma}{\rho_\gamma}\bigg|_y$$



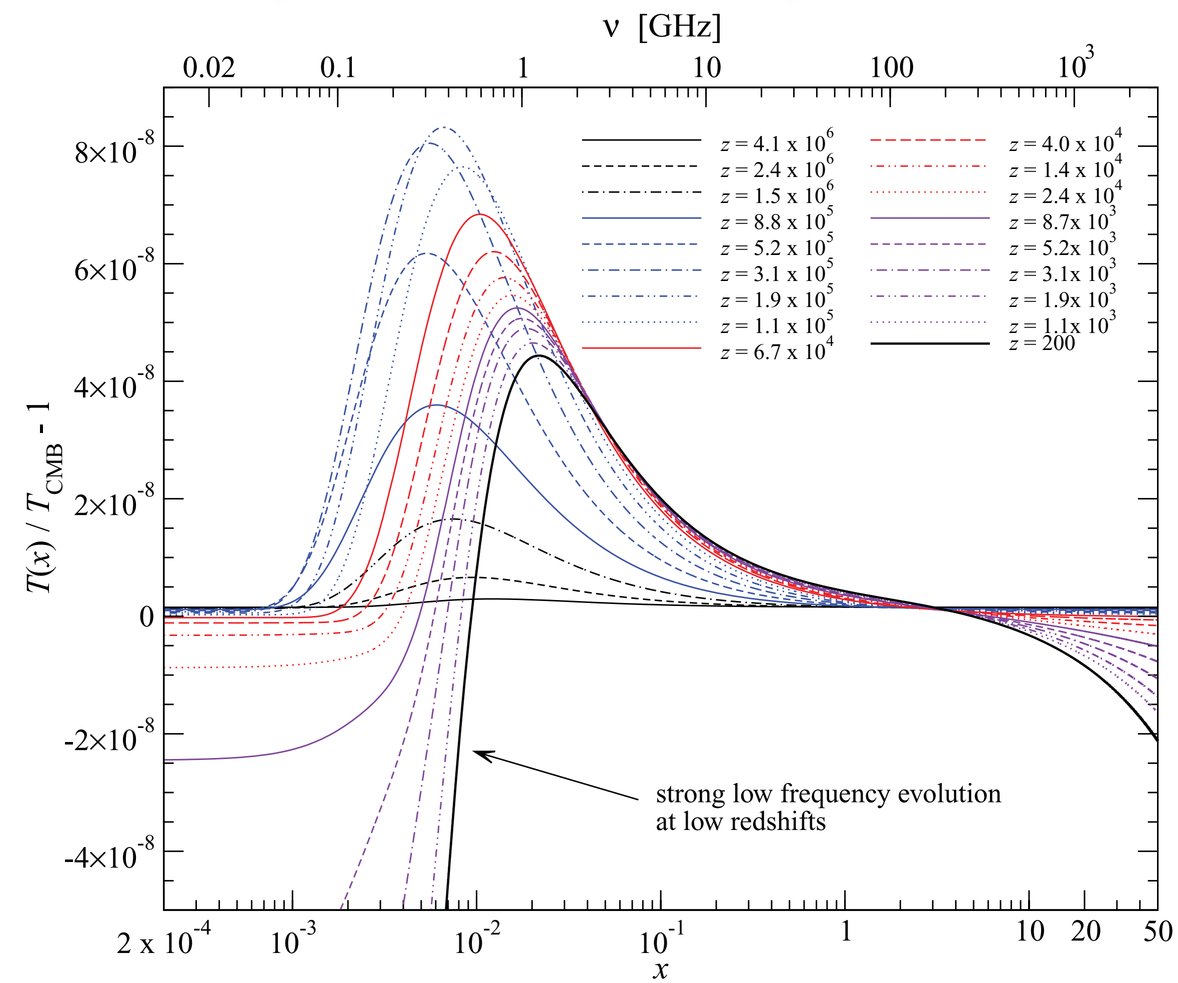
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at z_h ~ 3 x 10^5
y-distortion, z_h < 10^4
ν [GHz]
$G_{th}(\nu, z_h, 0)$ [10^{-18} W m^{-2} Hz^{-1} sr^{-1}]
a—2.7 °K black-body radiation
b—3.3 °K black-body radiation
c—3.3 °K Bose–Einstein radiation with m = 0.3
d—spectrum predicted by formula (3), T = 3.3 °K, m = 0.3, Ω = 0.3
Intensity (erg/cm² sec sr Hz)
Wavelength (cm)
y = 0.15
Intensity
y-distortion
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
New hybrid era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

CosmoTherm: a (new) flexible thermalization code

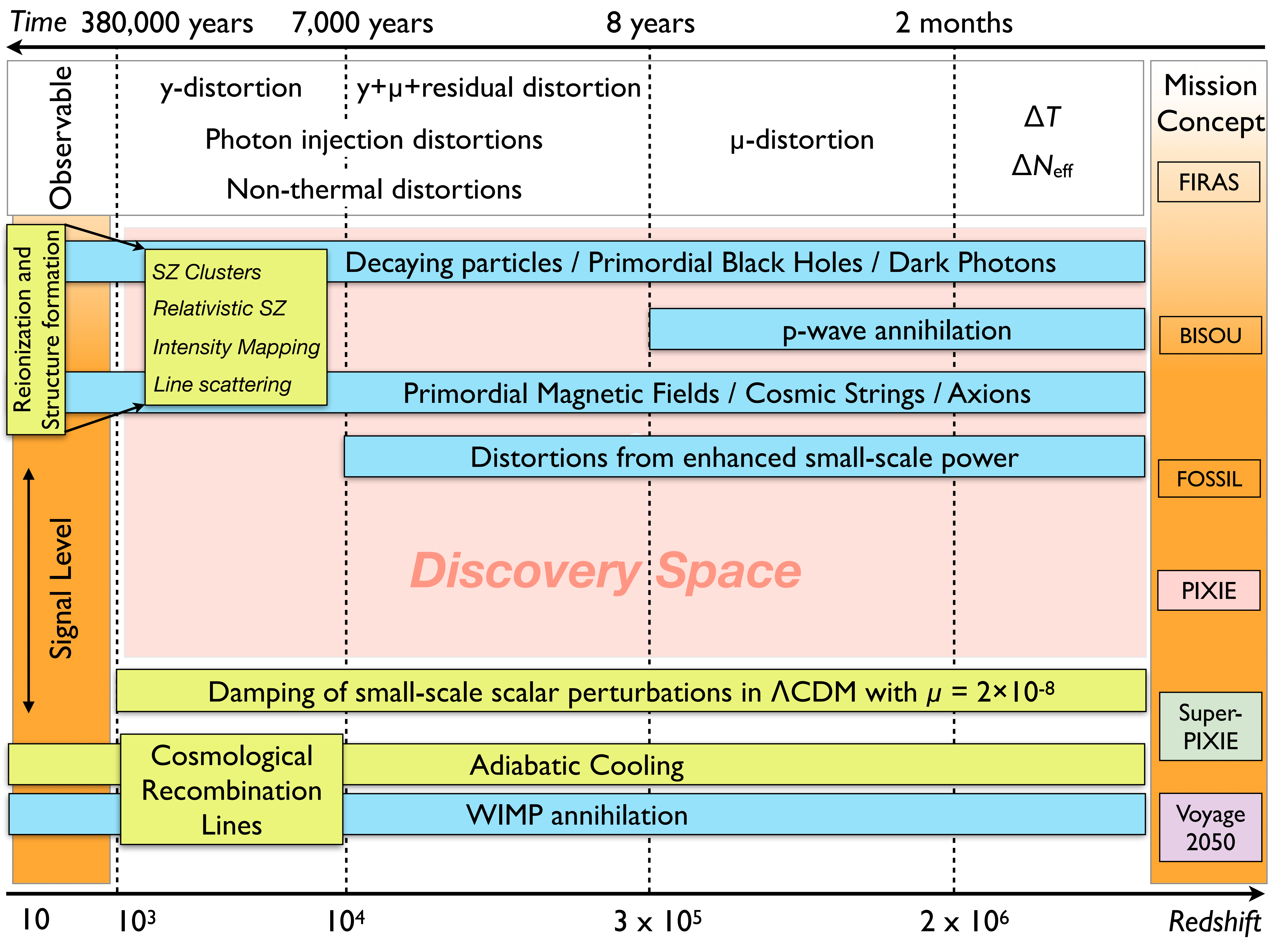
- Solve the thermalization problem for a *wide range* of energy release histories
- several scenarios already implemented *(decaying particles, damping of acoustic modes)*
- first *explicit* solution of time-dependent energy release scenarios
- open source code
  - will *soon* be available at `www.Chluba.de/CosmoTherm/`
- Main reference: JC & Sunyaev, MNRAS, 2012 (arXiv:1109.6552)



Electron temperature evolution



Evolution of distortion


Time 380,000 years
7,000 years
8 years
2 months
Observable
y-distortion
y+μ+residual distortion
Photon injection distortions
Non-thermal distortions
μ-distortion
ΔT
ΔN_eff
Mission Concept
FIRAS
BISOU
FOSSIL
PIXIE
Super-PIXIE
Voyage 2050
Reionization and Structure formation
SZ Clusters
Relativistic SZ
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Decaying particles / Primordial Black Holes / Dark Photons
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Distortions from enhanced small-scale power
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Signal Level
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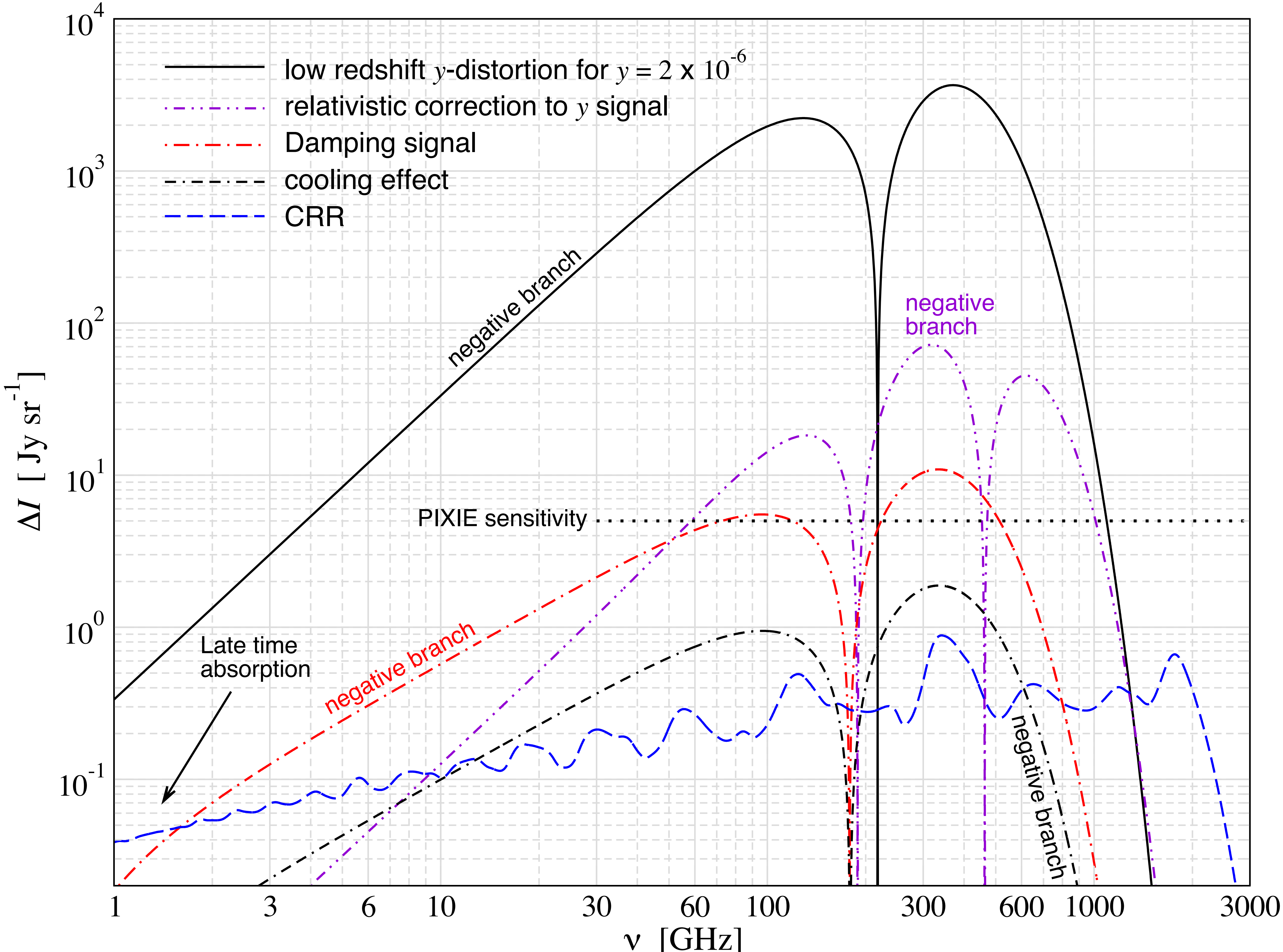
Cosmological Recombination Lines
Adiabatic Cooling
WIMP annihilation
10
10^3
10^4
3 x 10^5
2 x 10^6
Redshift

Average ΛCDM spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

- > 100 WP evaluated
- Identified three L-Class themes
  - Moons of the giant planets
  - From temperate Exoplanets to the Milky Way
  - New physical probes of the early Universe
- CMB Spectral distortions recognized as a possible '*New physical probe of the early Universe*'

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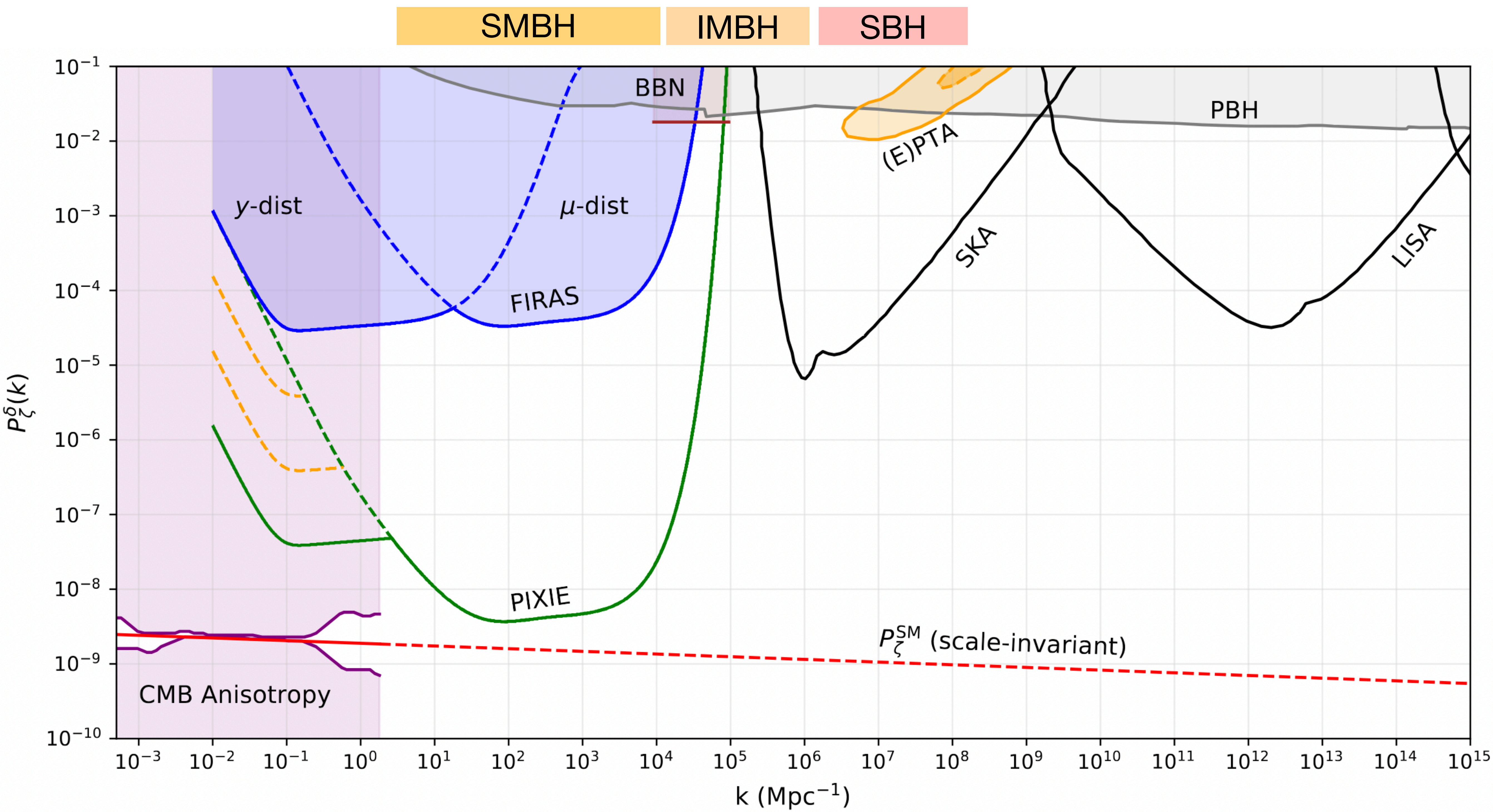
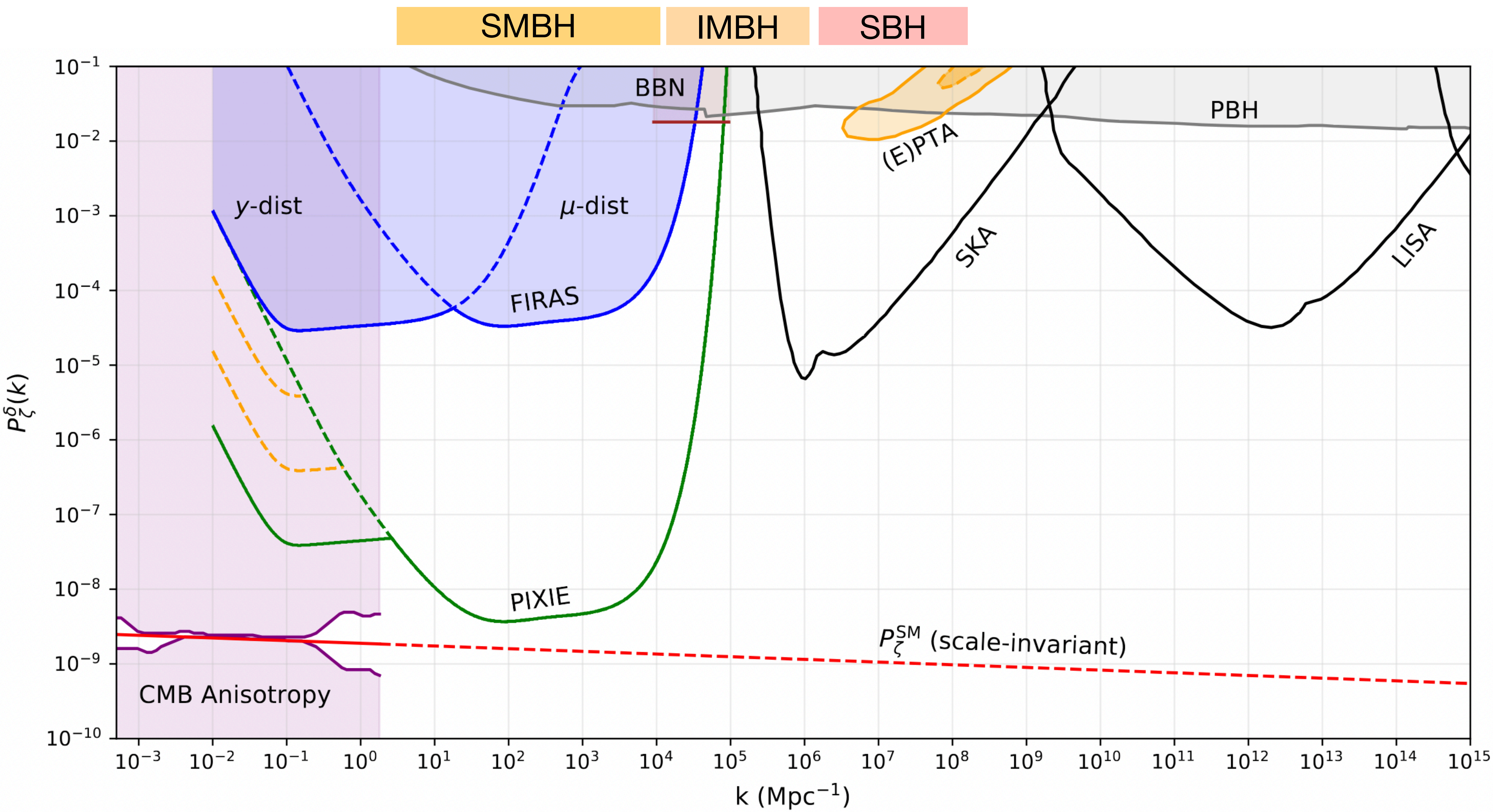
New Probe of the Early Universe

Small-scale power constraints and PBH formation



JC, Khatri & Sunyaev, 2012
JC, Erickcek & Ben-Dayan, 2012
Cyr et al., 2023, ArXiv:2309.02366

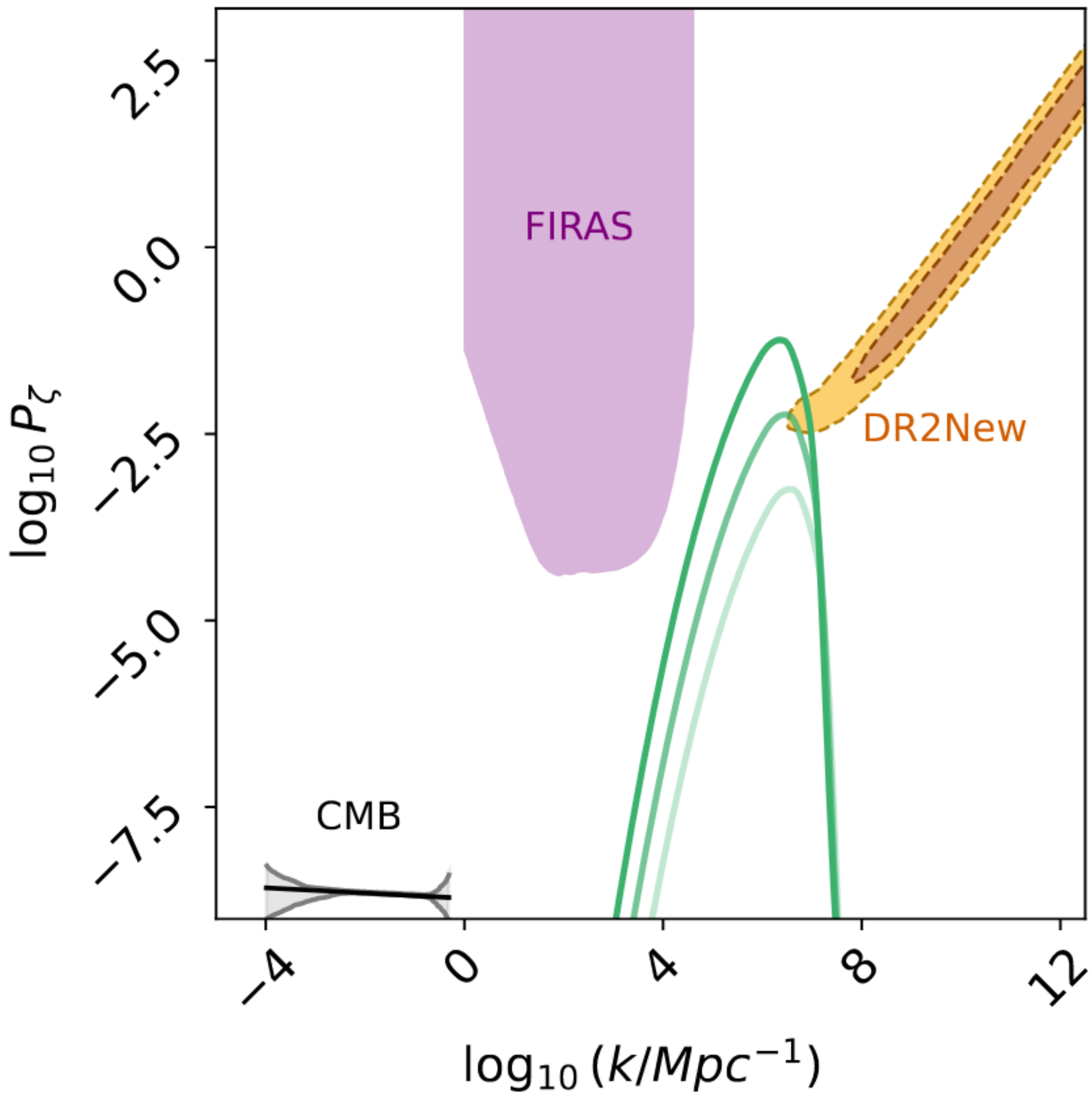
Small-scale power constraints and PBH formation



JC, Khatri & Sunyaev, 2012
JC, Erickcek & Ben-Dayan, 2012
Cyr et al., 2023, ArXiv:2309.02366

A CMB spectrometer could shed light on primordial black hole formation

Small-scale power and gravitational wave link



- Lots of excitement by recent NANOGrav detection of stochastic GW background
- GW sourced by primordial scalar perturbations also cause CMB distortions

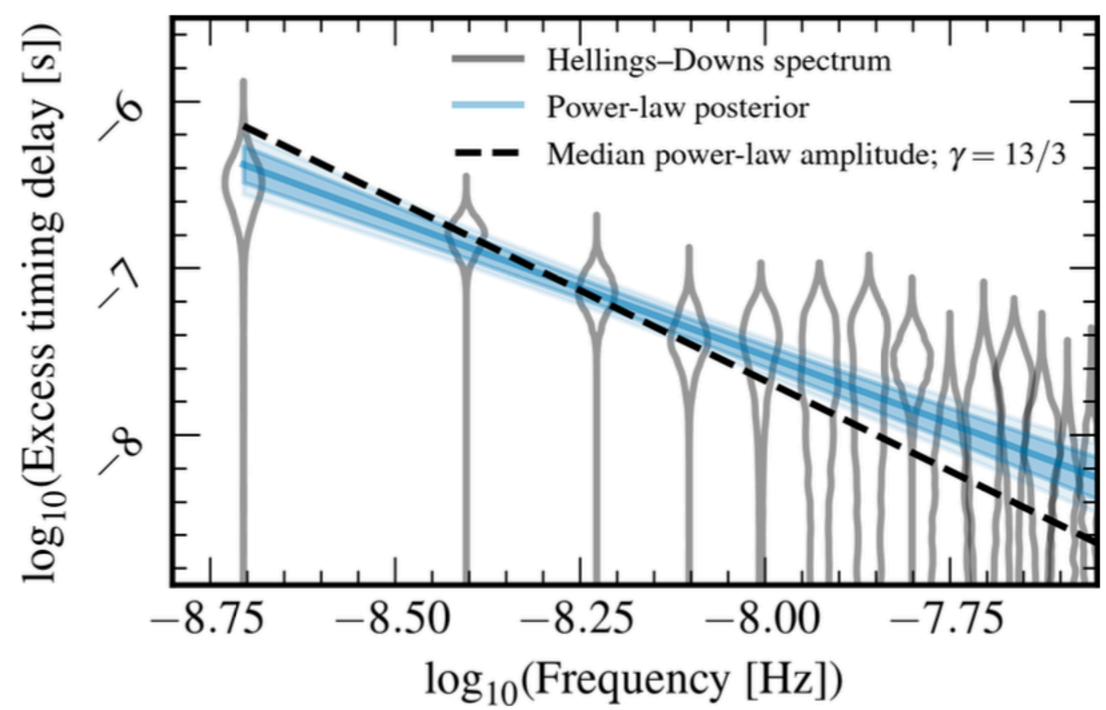


Figure from EPTA paper
https://arxiv.org/abs/2306.16227

Figure from NANOGrav paper
https://arxiv.org/abs/2306.16213

Origin of the GW background remains unclear

‘*Vanilla’* explanation: SMBH mergers

- Early SMBH population may be required
- Yet origin of these SMBH binaries unclear
- Could necessitate IMBH as seeds, maybe of *primordial* origin?

➡ Possible link to primordial small-scale scalar perturbations

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SIGWs, cosmic strings, phase transitions etc

- Modeling details still being debated
- These can leave imprints to the CMB spectrum!

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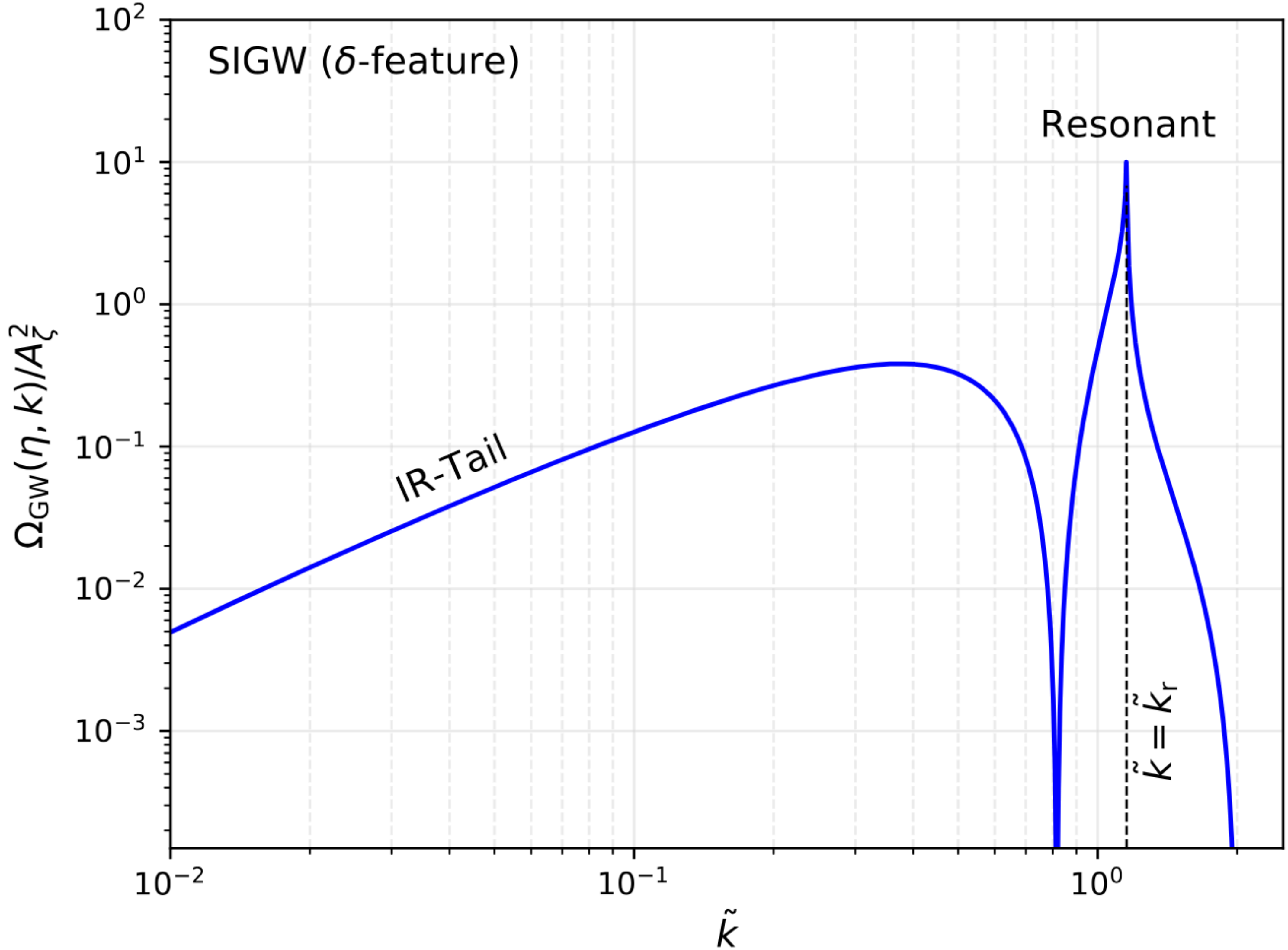
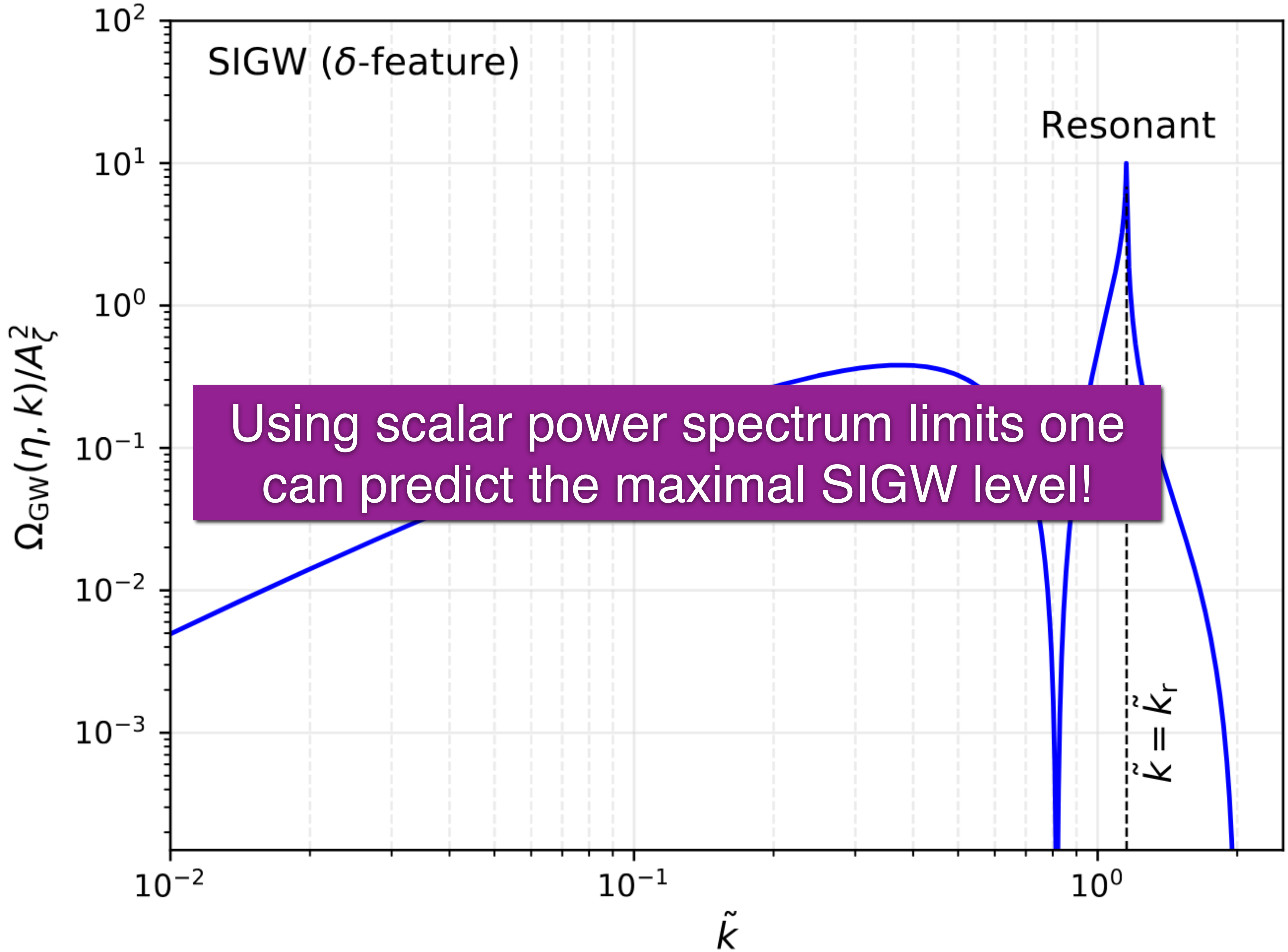
CMB spectral distortions provide one of the most primordial tracers one could hope for!

Scalar Induced Gravitational Waves



Ananda et al. 2007; Baumann et al. 2007

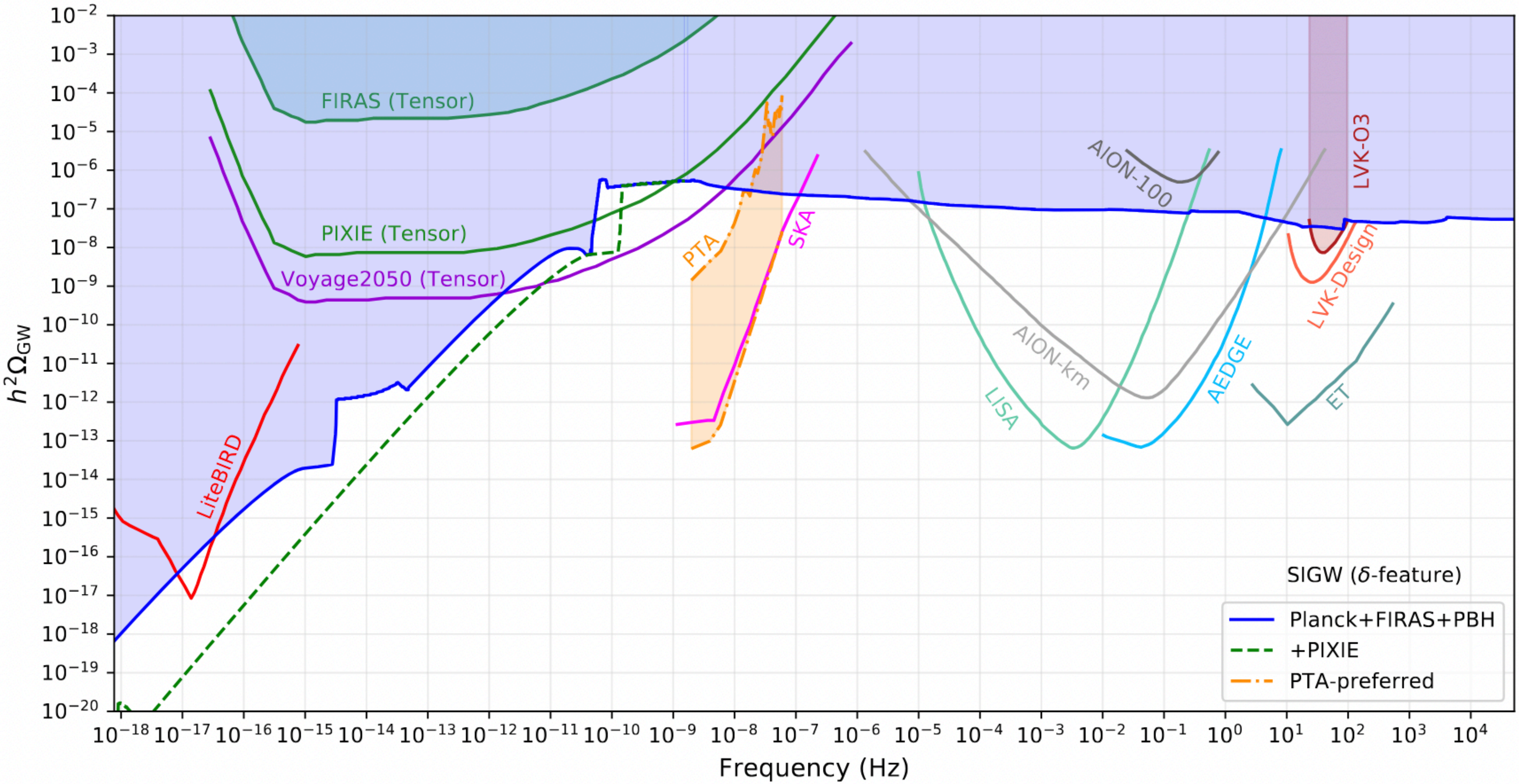
Scalar Induced Gravitational Waves



Using scalar power spectrum limits one can predict the maximal SIGW level!

Ananda et al. 2007; Baumann et al. 2007

Spectral distortion link to GW backgrounds



Kite et al., 2020, ArXiv:2010.00040
Cyr et al., 2023, ArXiv:2309.02366

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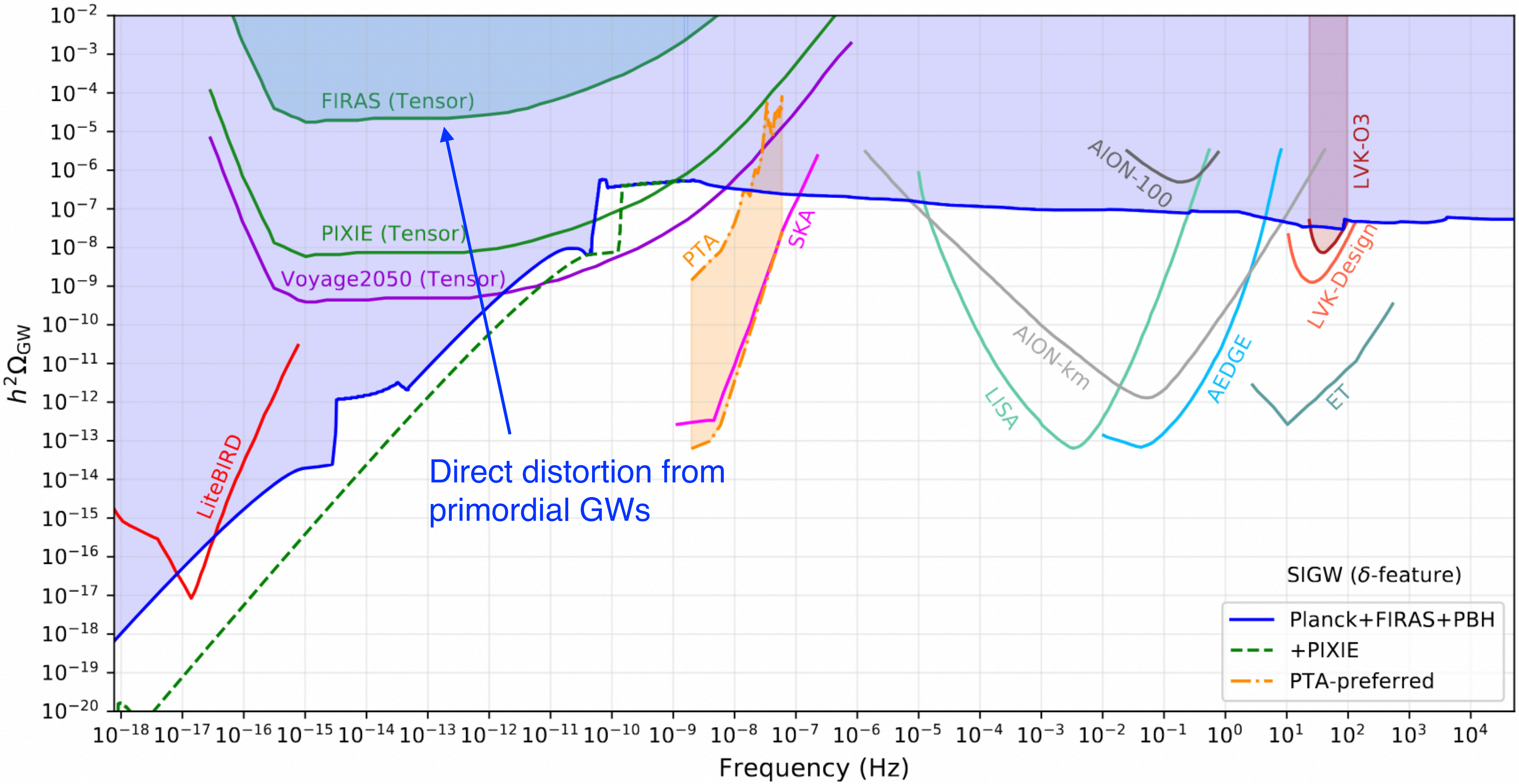

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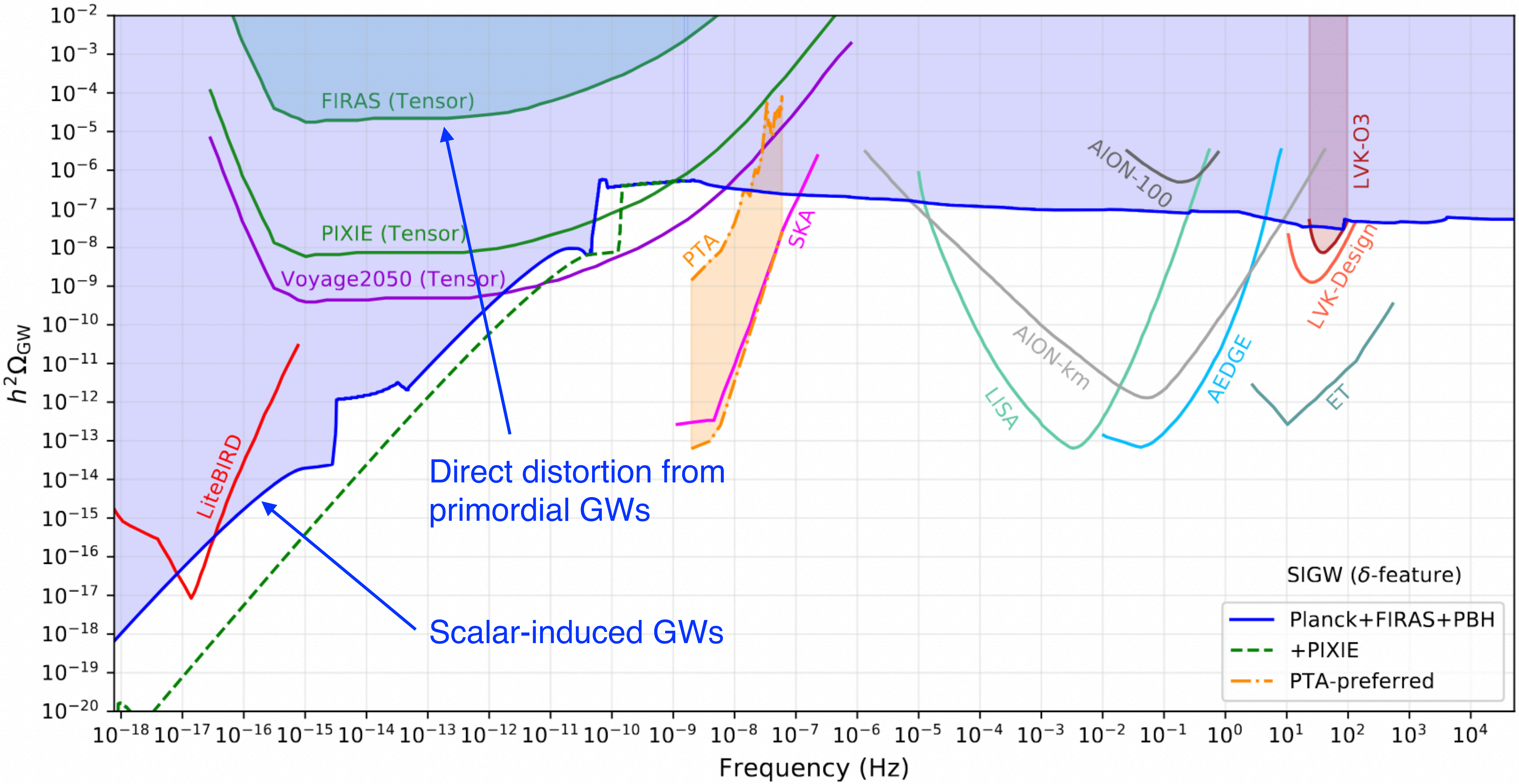

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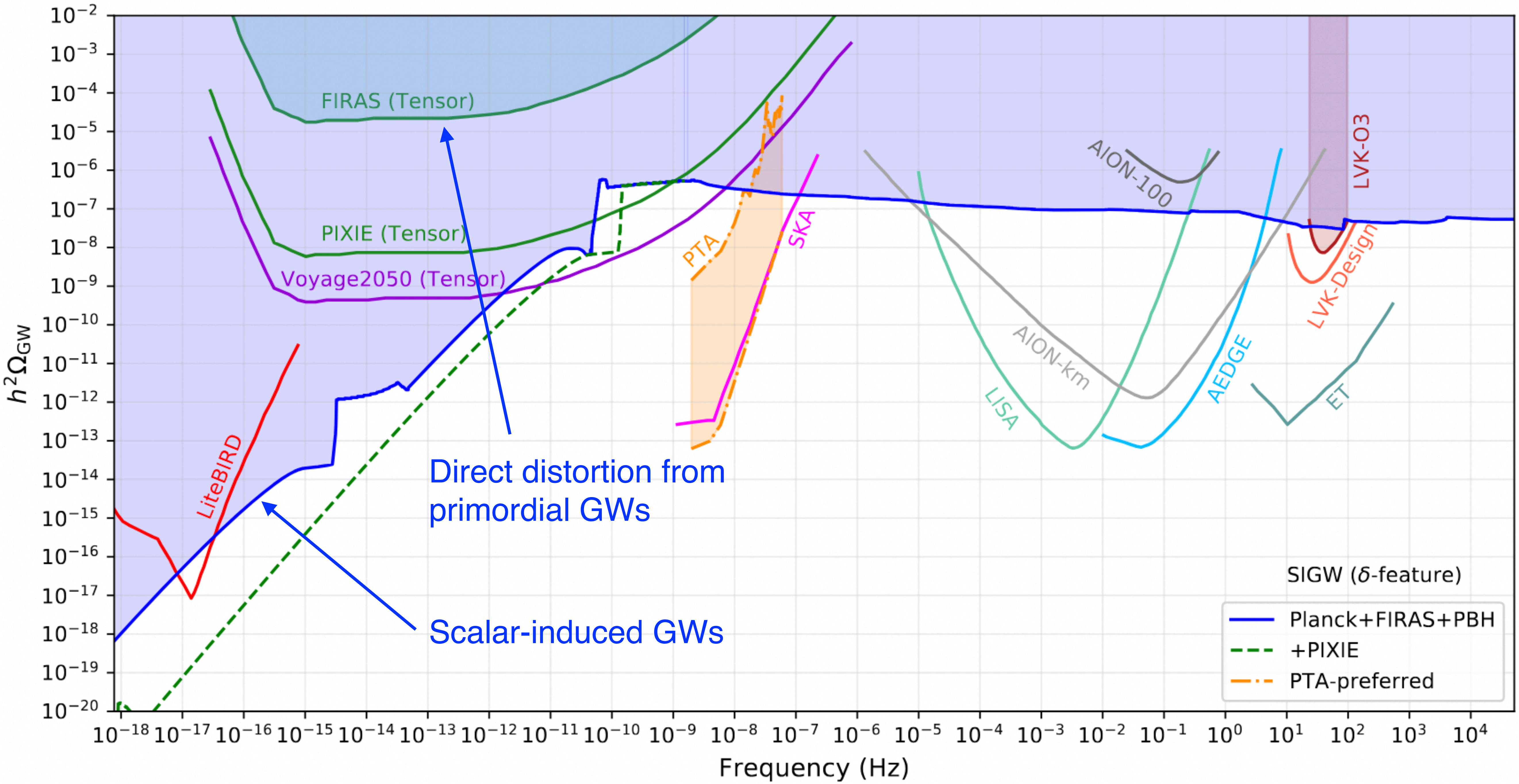
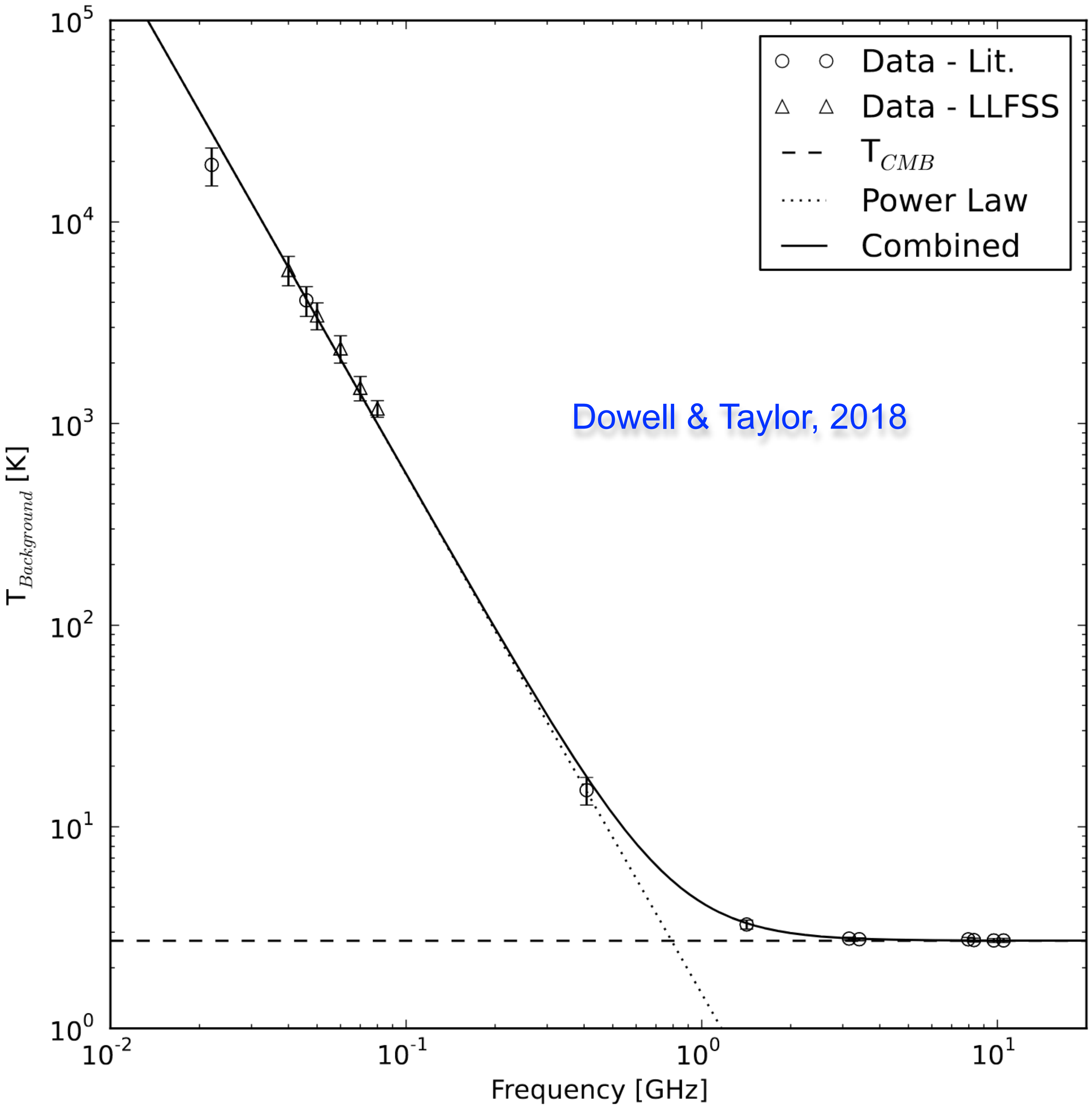


A CMB spectrometer could rule out SIGWs as cause for large-scale *B*-modes

Kite et al., 2020, ArXiv:2010.00040
Cyr et al., 2023, ArXiv:2309.02366

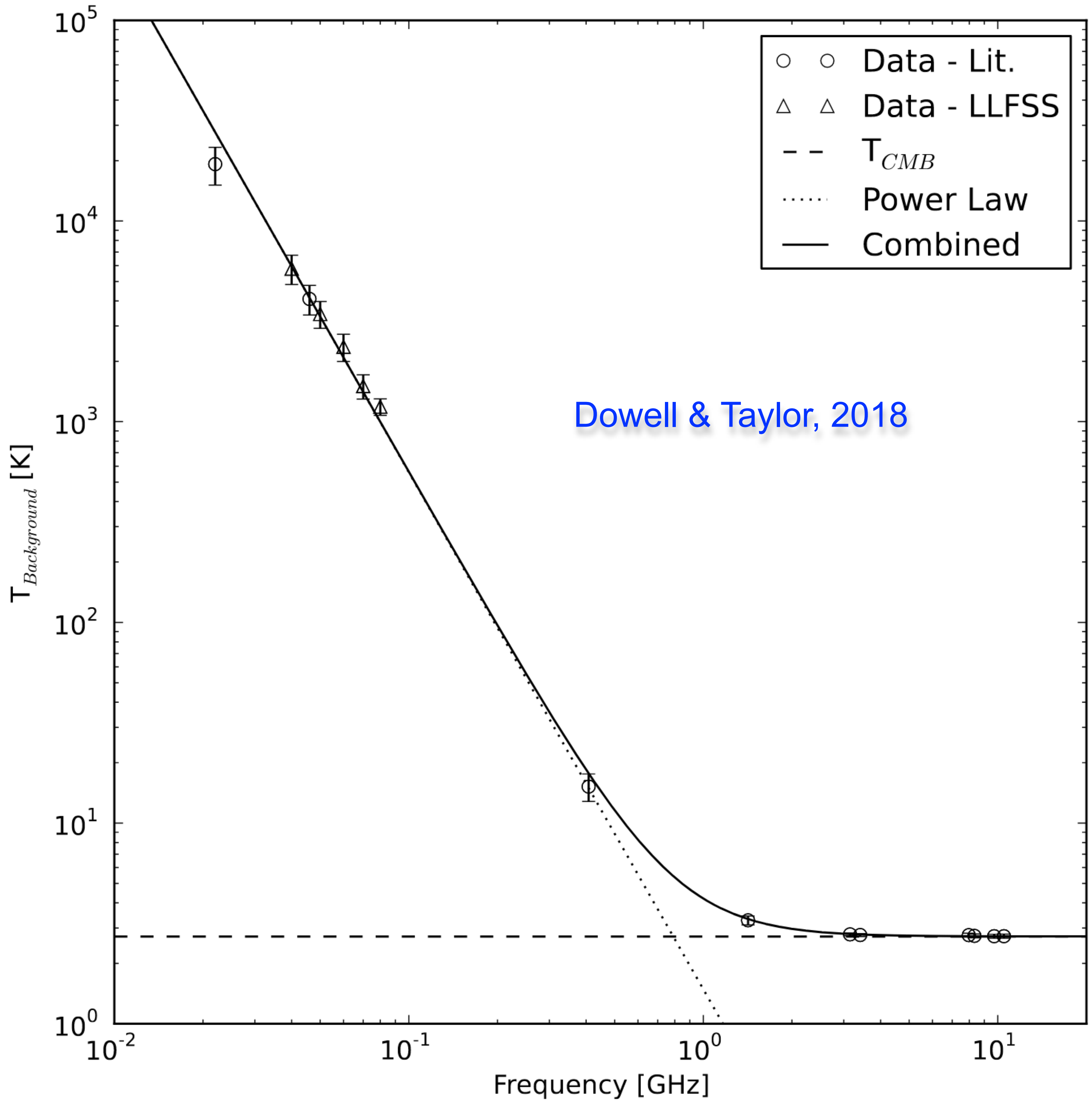
Is the ARCADE excess related to the GW signals?

The ARCADE radio excess



- Synchrotron-like signal first seen by ARCADE-2
  (Fixsen et al. 2011)
- Confirmed by LWA
  (Dowel & Taylor, 2018)
- *Isotropic* on the sky
- Still unexplained
  (discussions in Singal et al. 2018 & Singal et al. 2023)

The ARCADE radio excess



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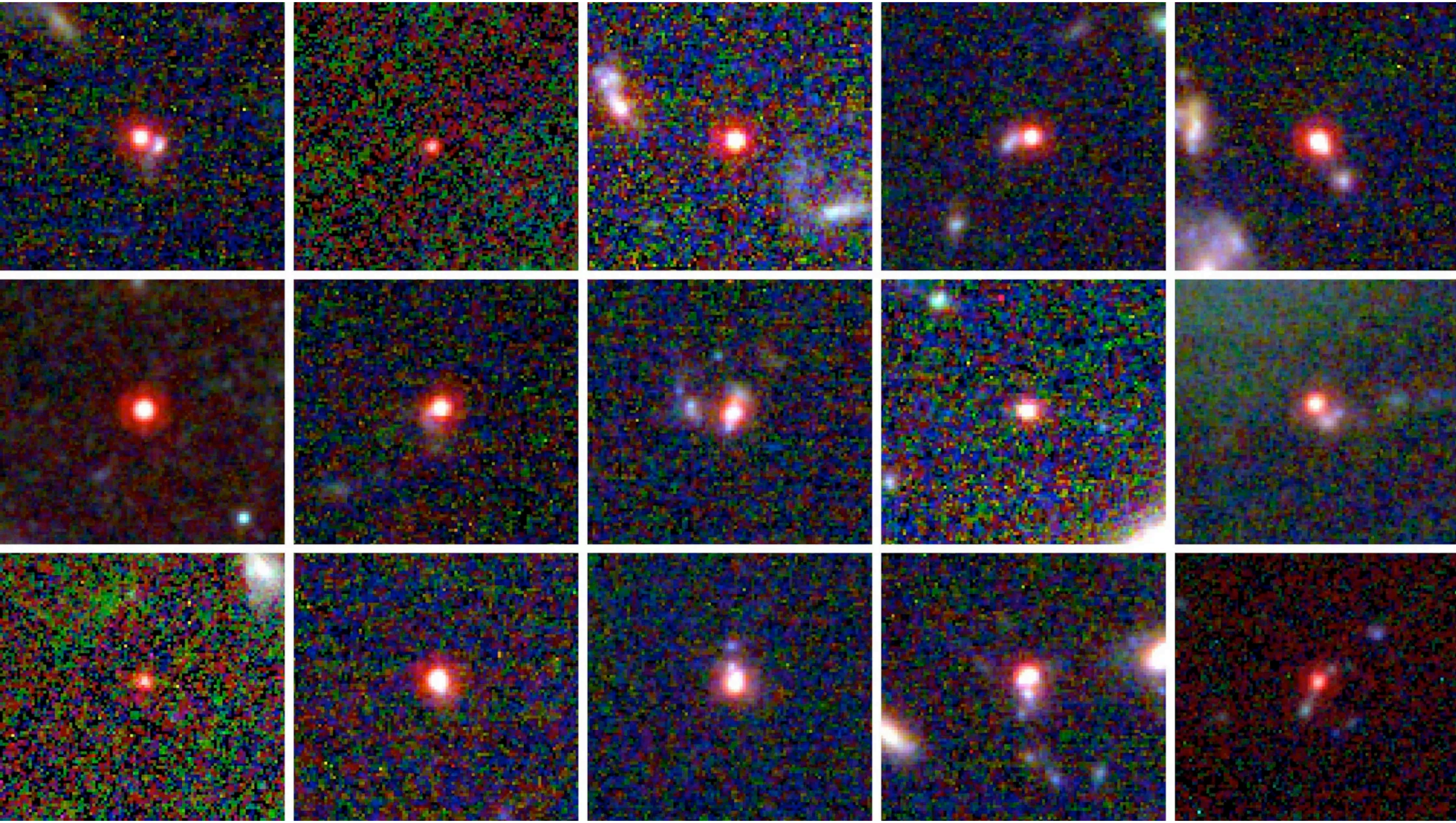
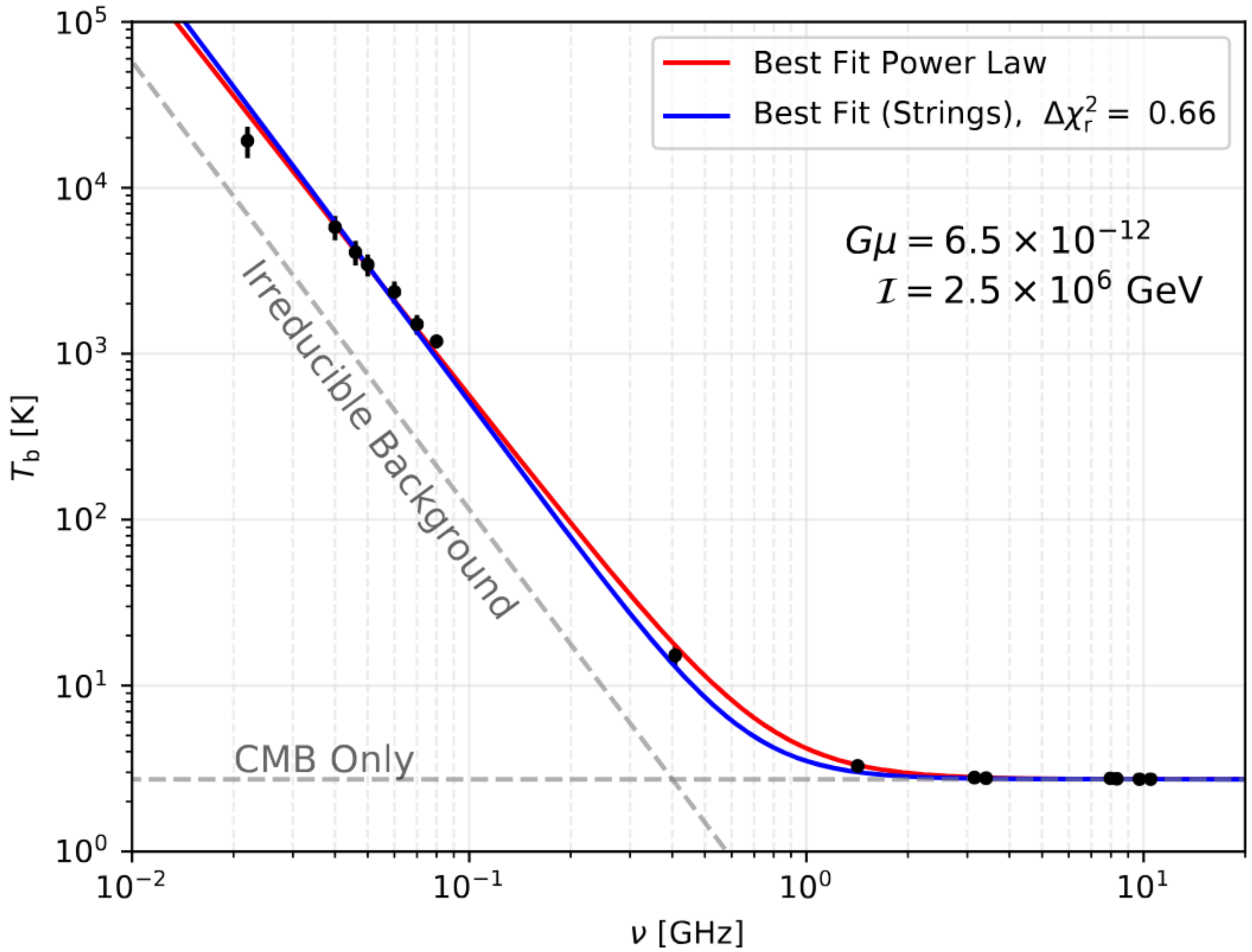
Is this an early (z>10?) radio background possibly from accreting black holes or new physics?

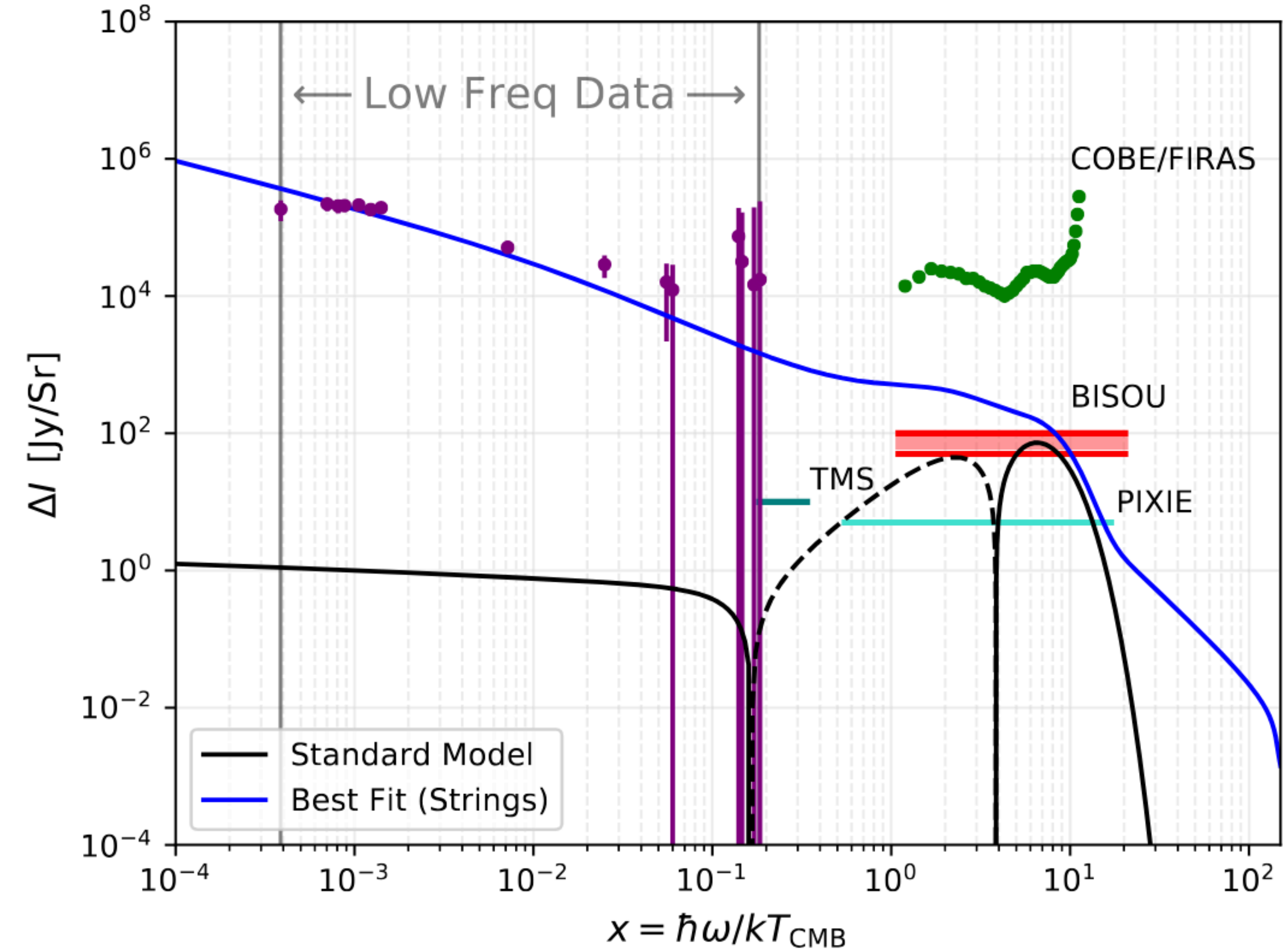
Little red dots linked to ARCADE excess?



Recent JWST observations

Cosmic String solution to ARCADE excess?





- Performed detailed modeling of distortions from Cosmic String network
- Tightly constrained by CMB anisotropies and low frequency radio data

- *Soft photon heating* highly relevant to 21 cm prediction (Acharya, Cyr & JC, 2022; Cyr, Acharya & JC, 2024)
- Intriguing solution to the RSB

Cyr, Acharya & JC, 2023, ArXiv:2305.09816

Cyr, JC & Acharya, 2023, ArXiv:2308.03512

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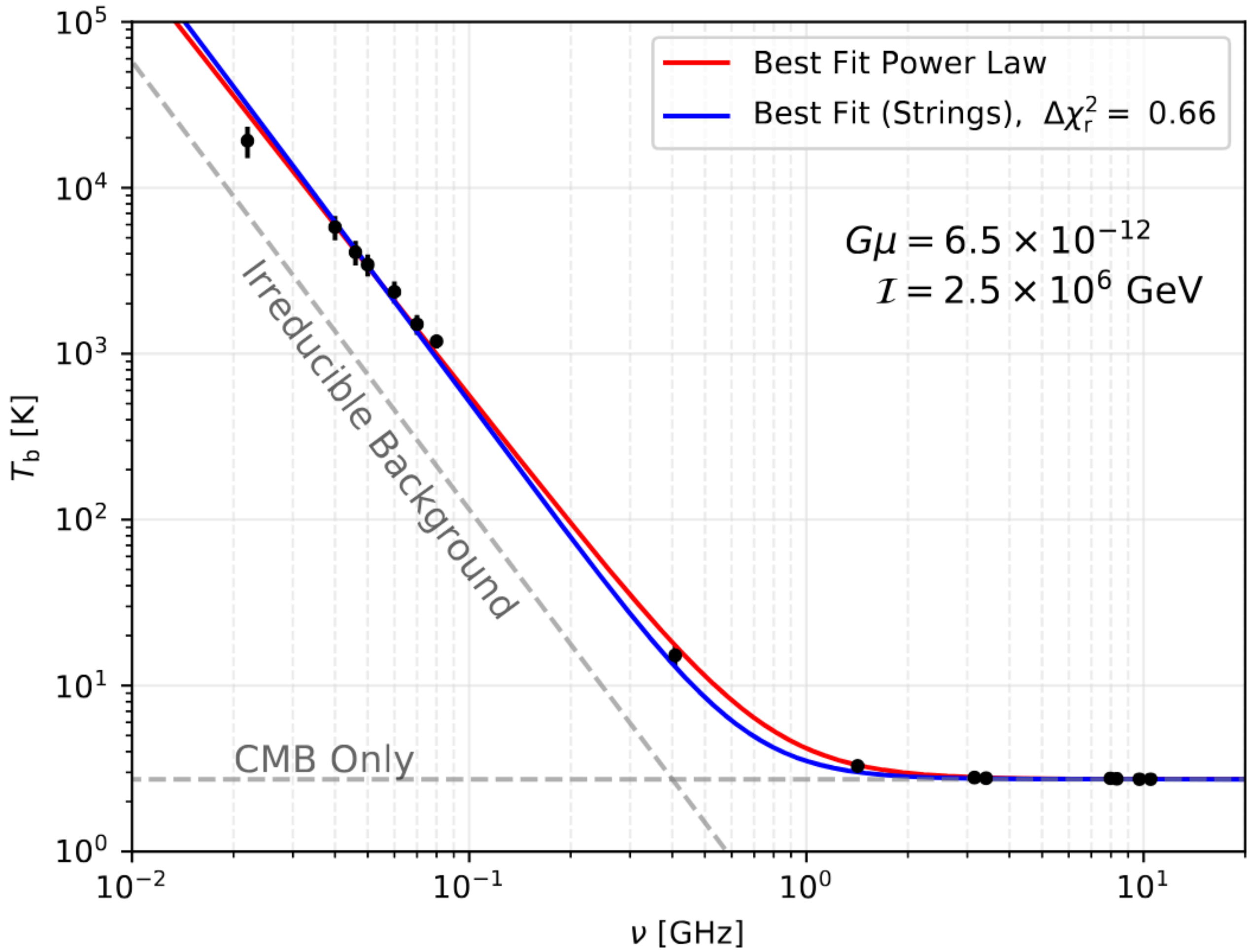

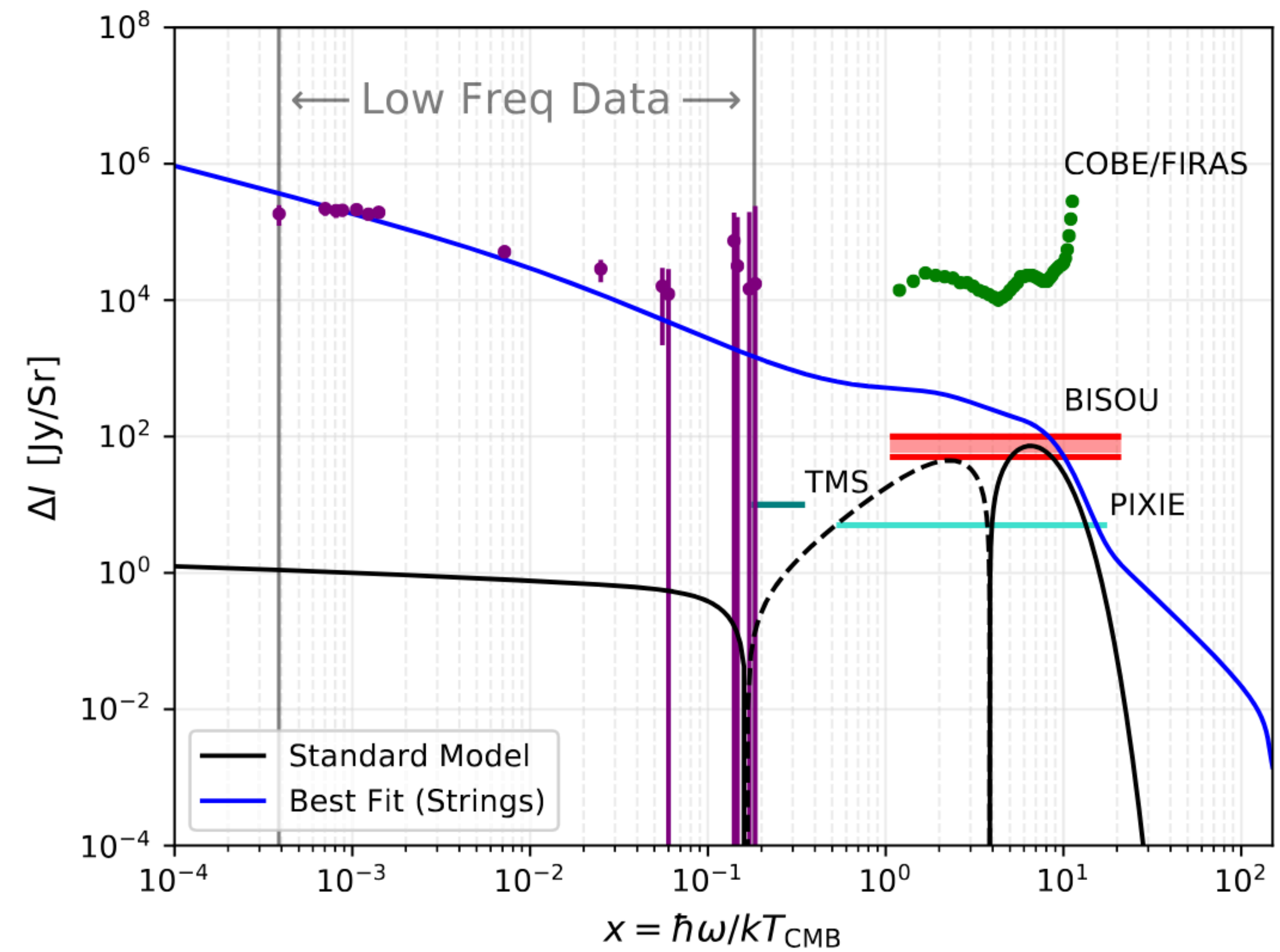

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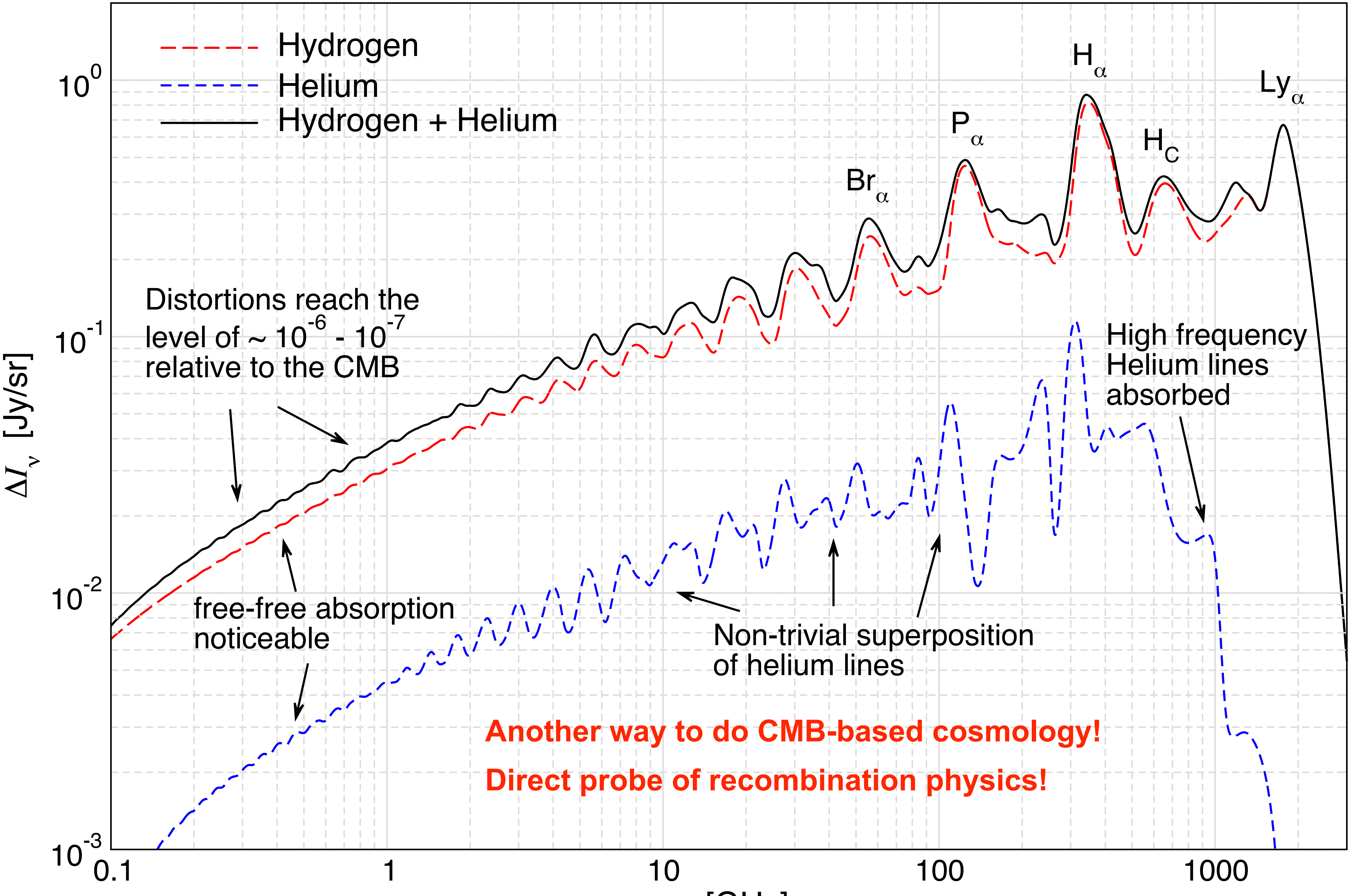
Cyr, Acharya & JC, 2023, ArXiv:2305.09816

Cyr, JC & Acharya, 2023, ArXiv:2308.03512

CMB spectrometers could test the origin of the RSB!

Link to the Hubble tension?

Cosmological Recombination Radiation



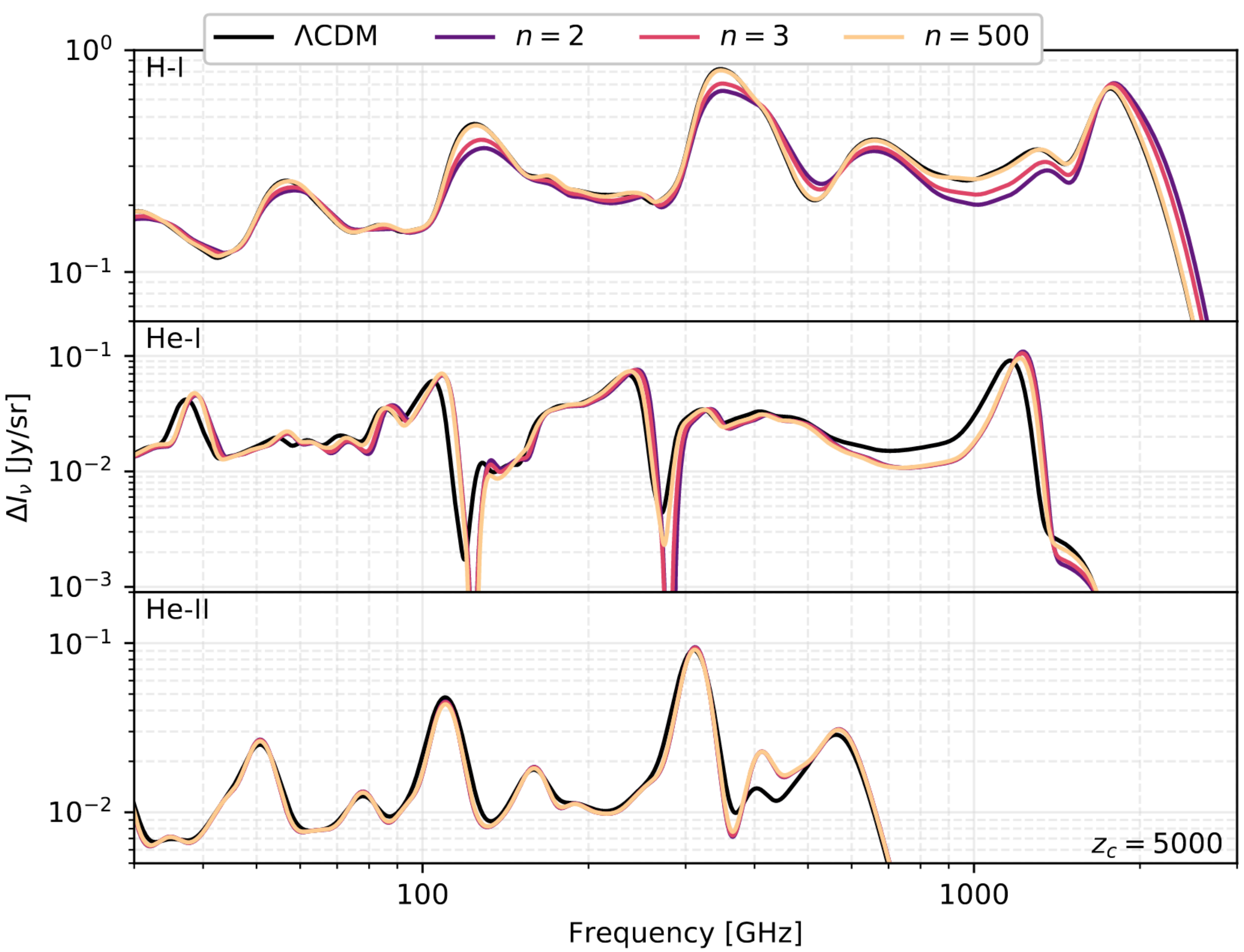
Courtesy Luke Hart

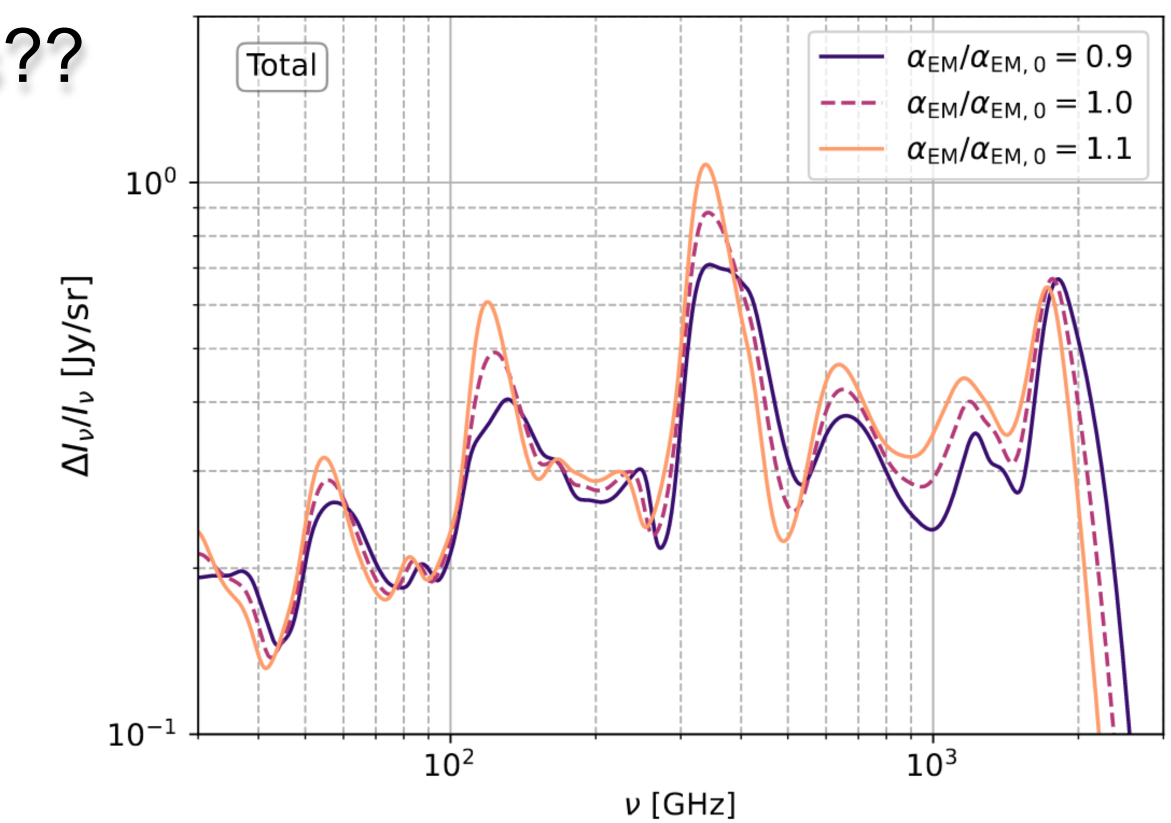
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009, JC & Ali-Haimoud, arXiv:1510.03877

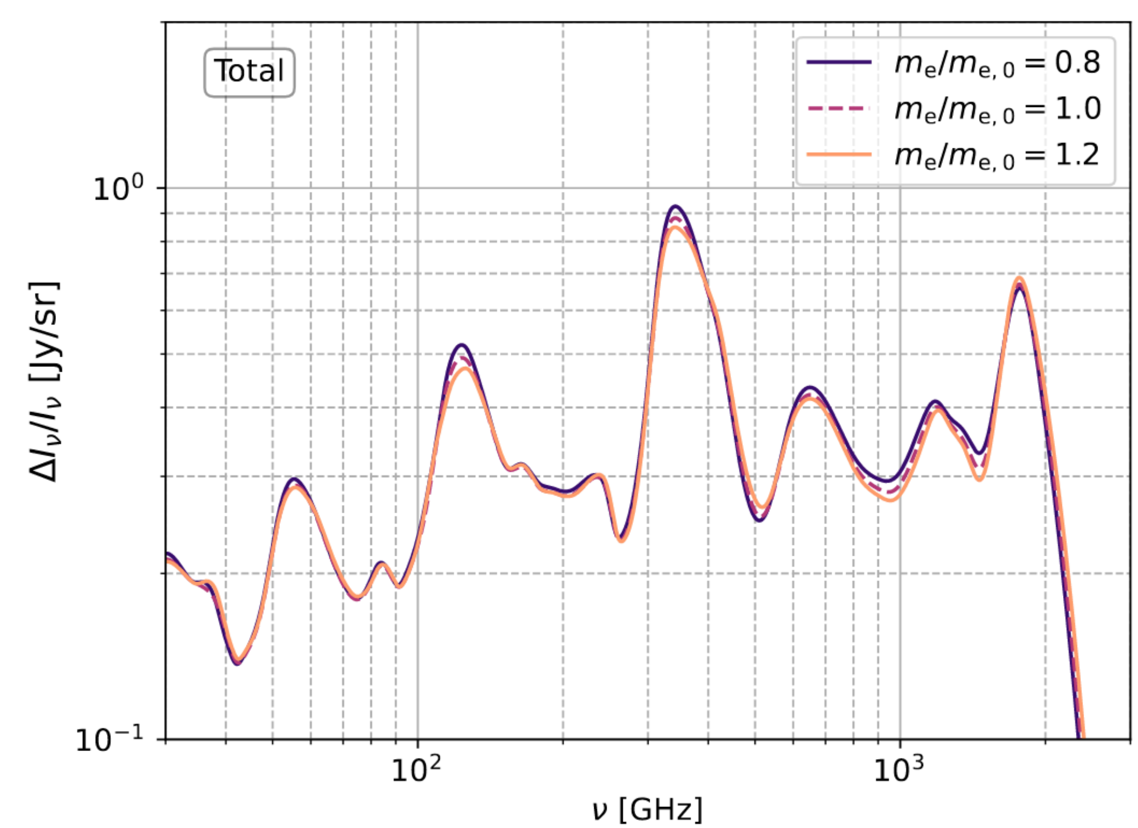
http://arxiv.org/abs/1909.01593

Testing the origin of the Hubble tension with the CRR

- Hubble tension persists… New Physics??
- H_0 Olympics identified EDE, Primordial Magnetic fields and varying m_e models as best solutions!
- These should affect the CRR!

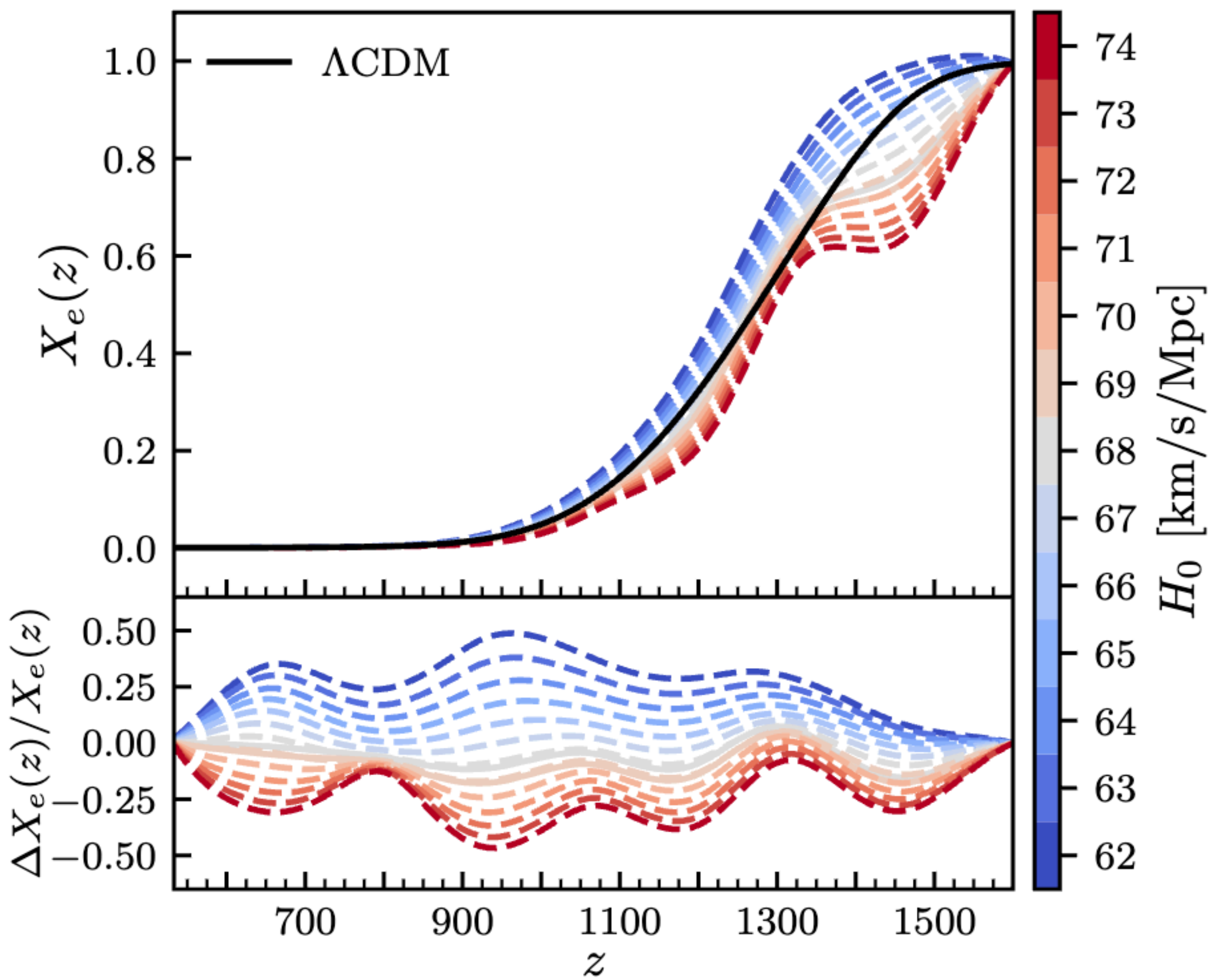


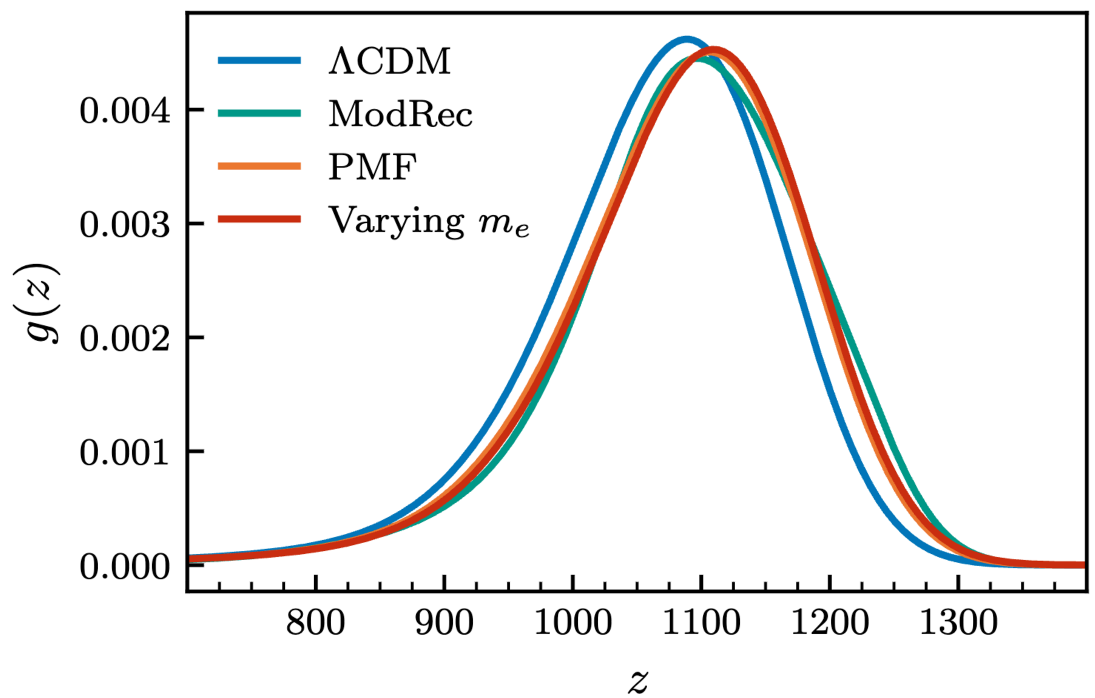


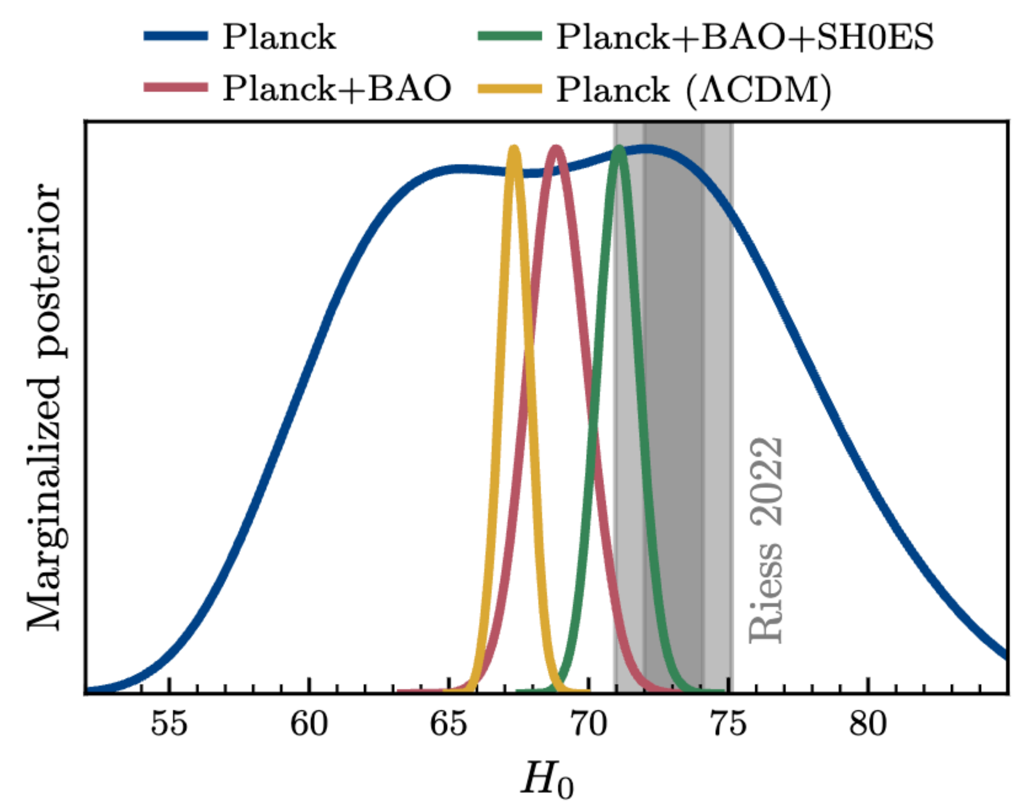


Hart & JC, 2022, ArXiv:2209.12290

Cosmological data seems to be preferring early recombination scenarios!





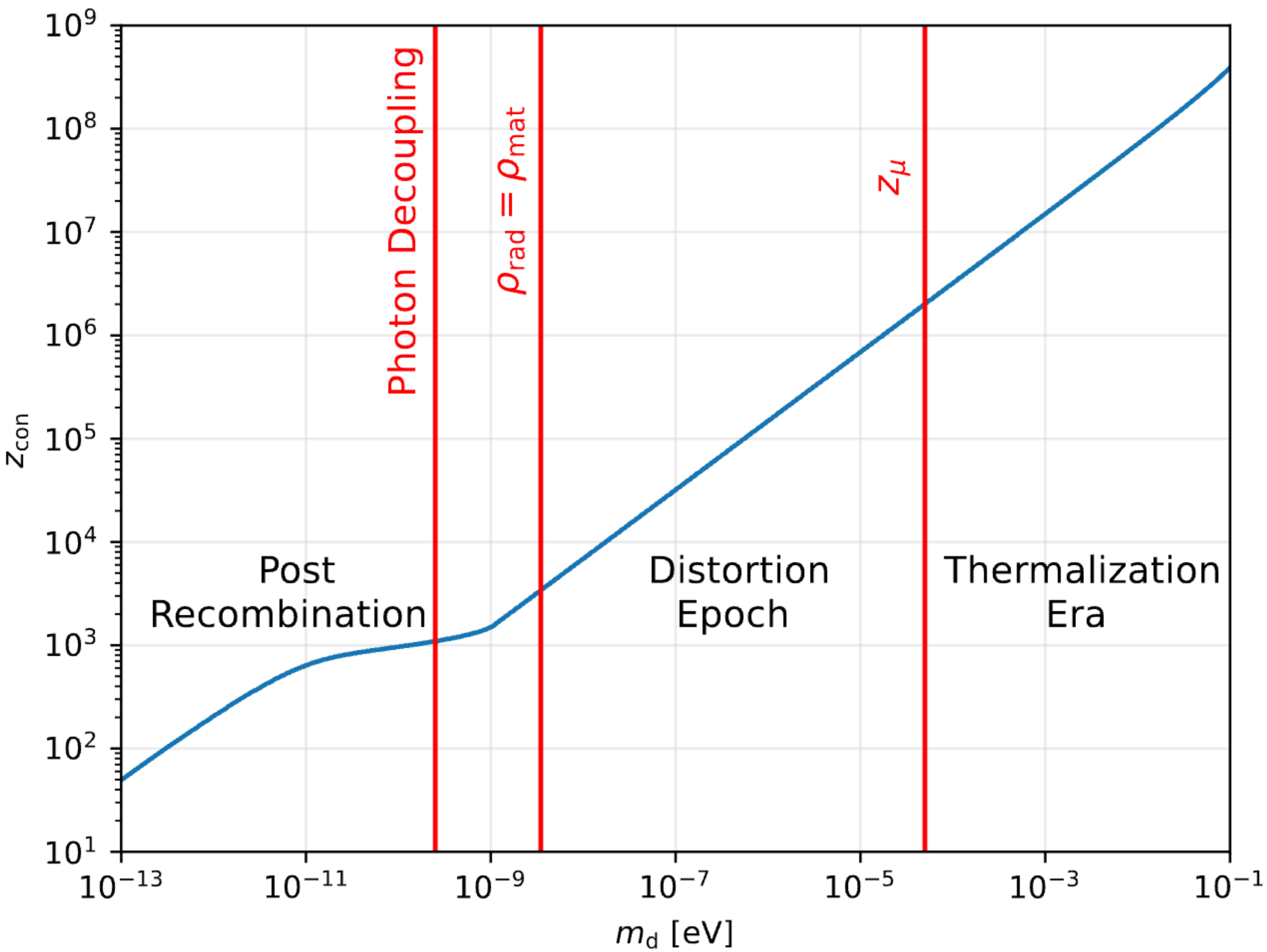


Model-independent reconstruction of free electron fraction using Emulators

Lynch, Knox & JC, ArXiv:2406.10202
Lynch, Knox & JC, ArXiv:2404.05715

Revised constraints on Axions and Dark Photons

Revised Constraints on Dark Photons - I

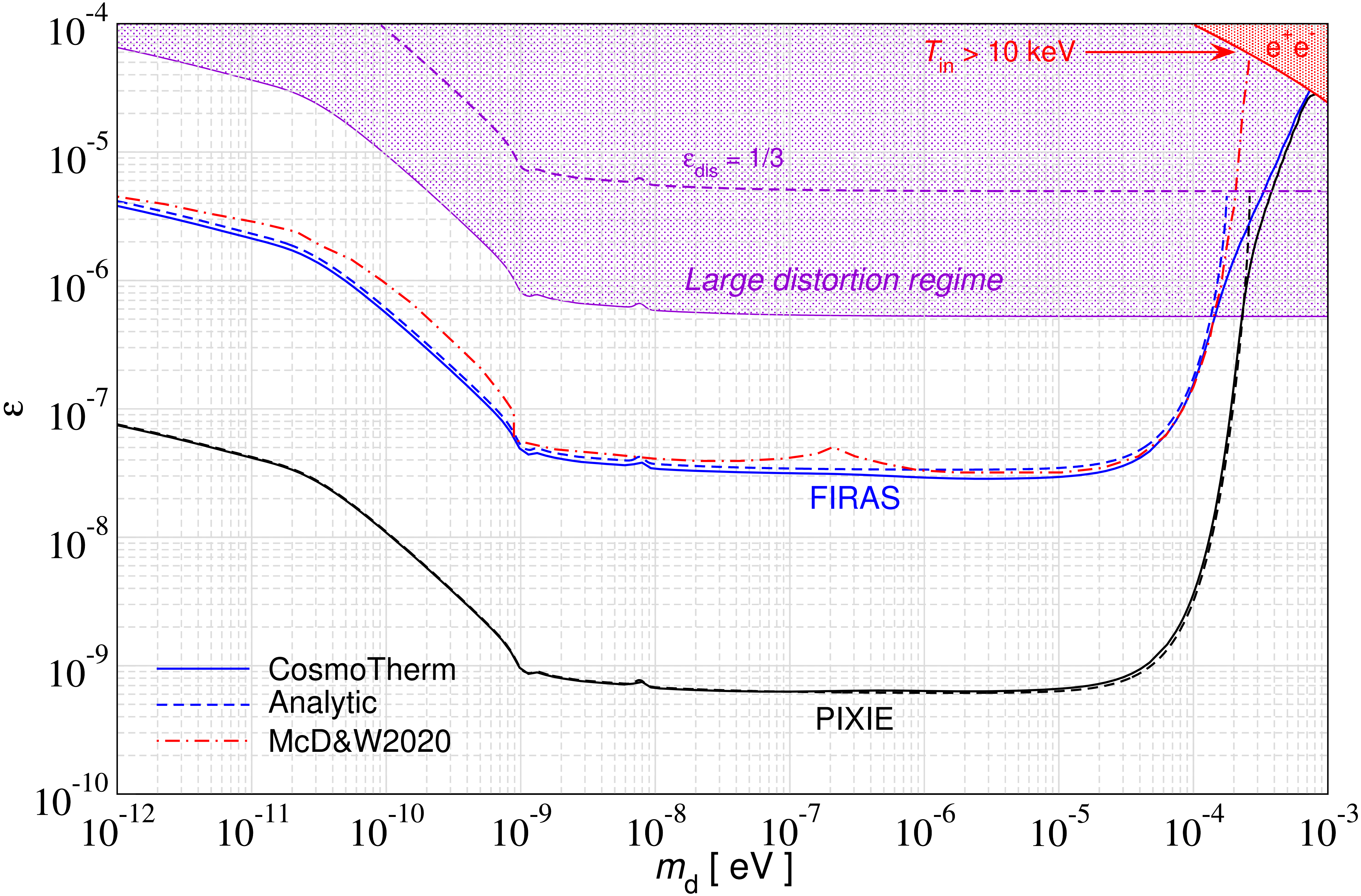


Dark photons can convert into normal photons when $m_d \simeq m_\gamma(z)$

This leads to removal of CMB photons which causes a distortion

JC, Cyr & Johnson ArXiv:2409.12115

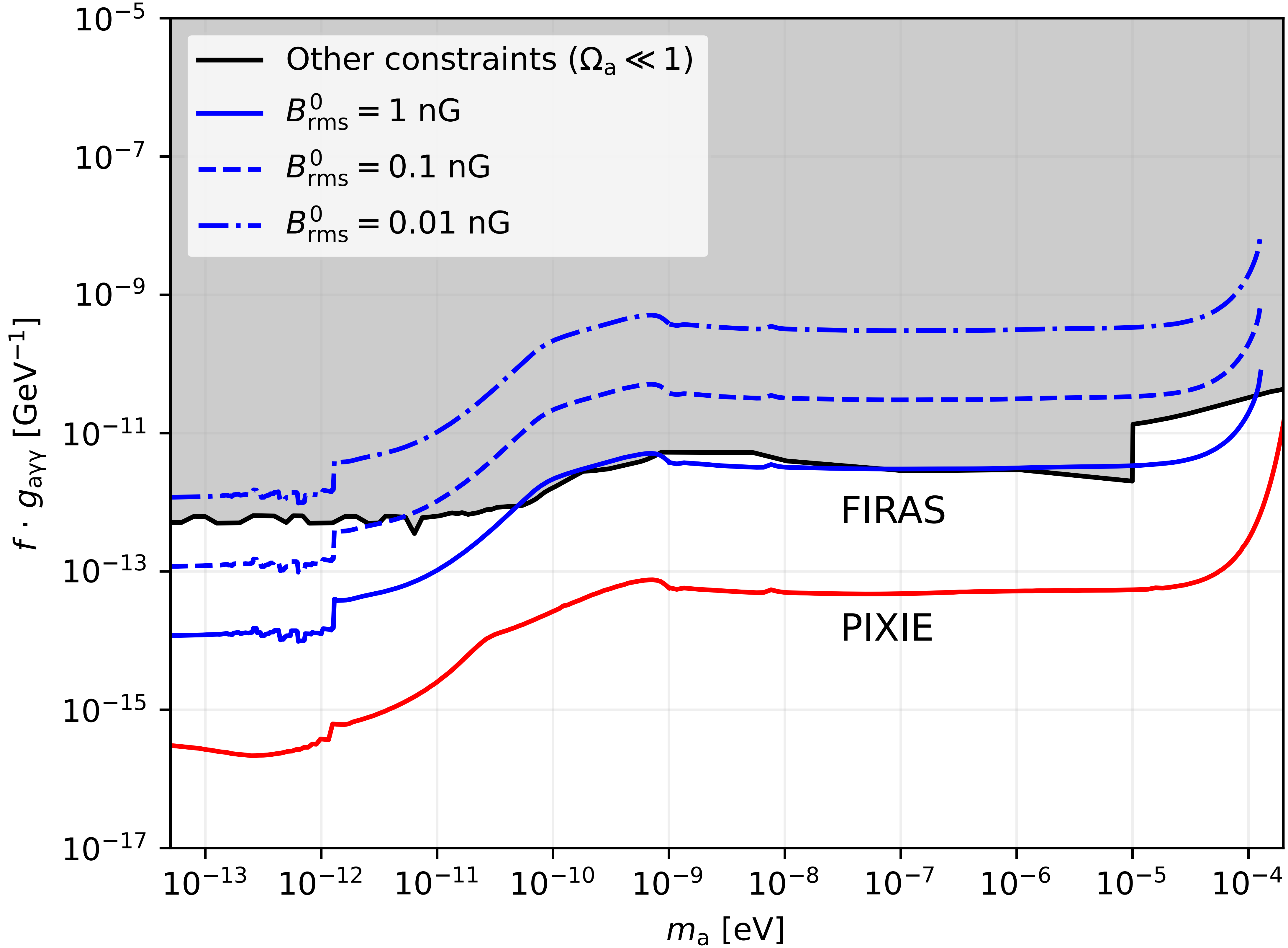
Revised Constraints on Dark Photons - IV



JC, Cyr & Johnson ArXiv:2409.12115

COBE/FIRAS constraints still competitive

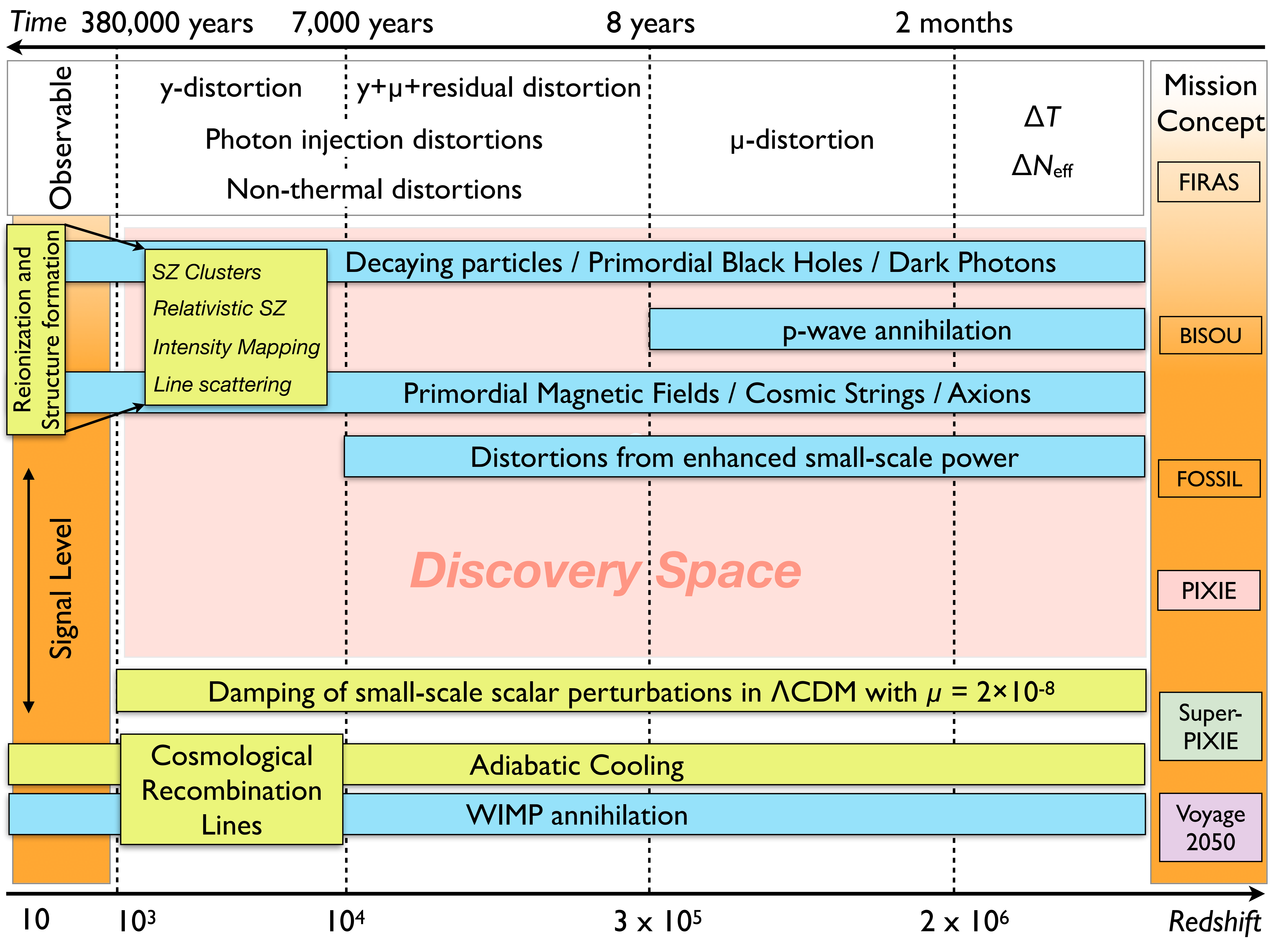
Revised Constraints on Axions - III



Cyr, JC & Manoj ArXiv:2411.13701

Significant uncertainties from B field modelling

Spectral distortion anisotropies



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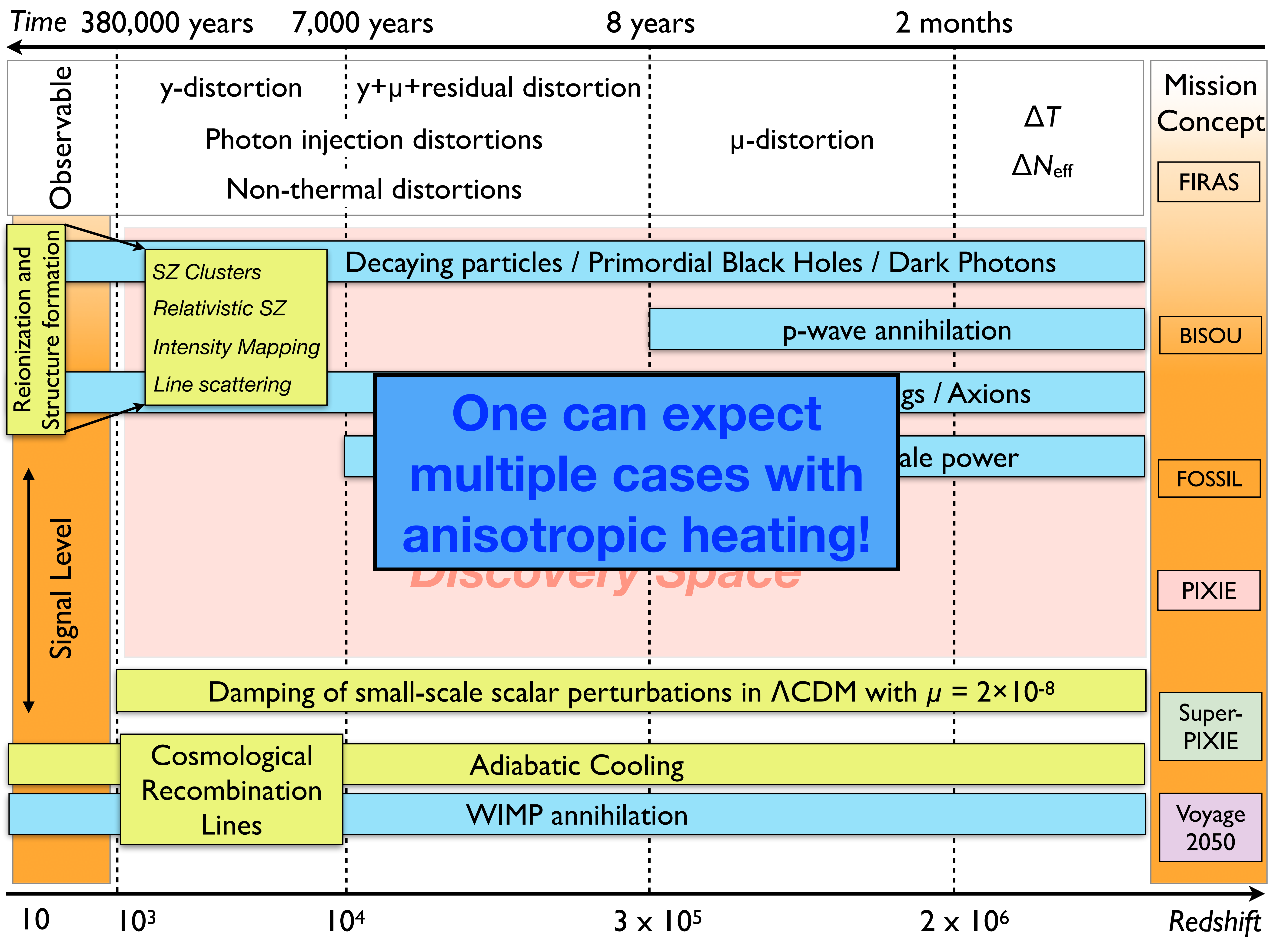

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ale power
One can expect multiple cases with anisotropic heating!
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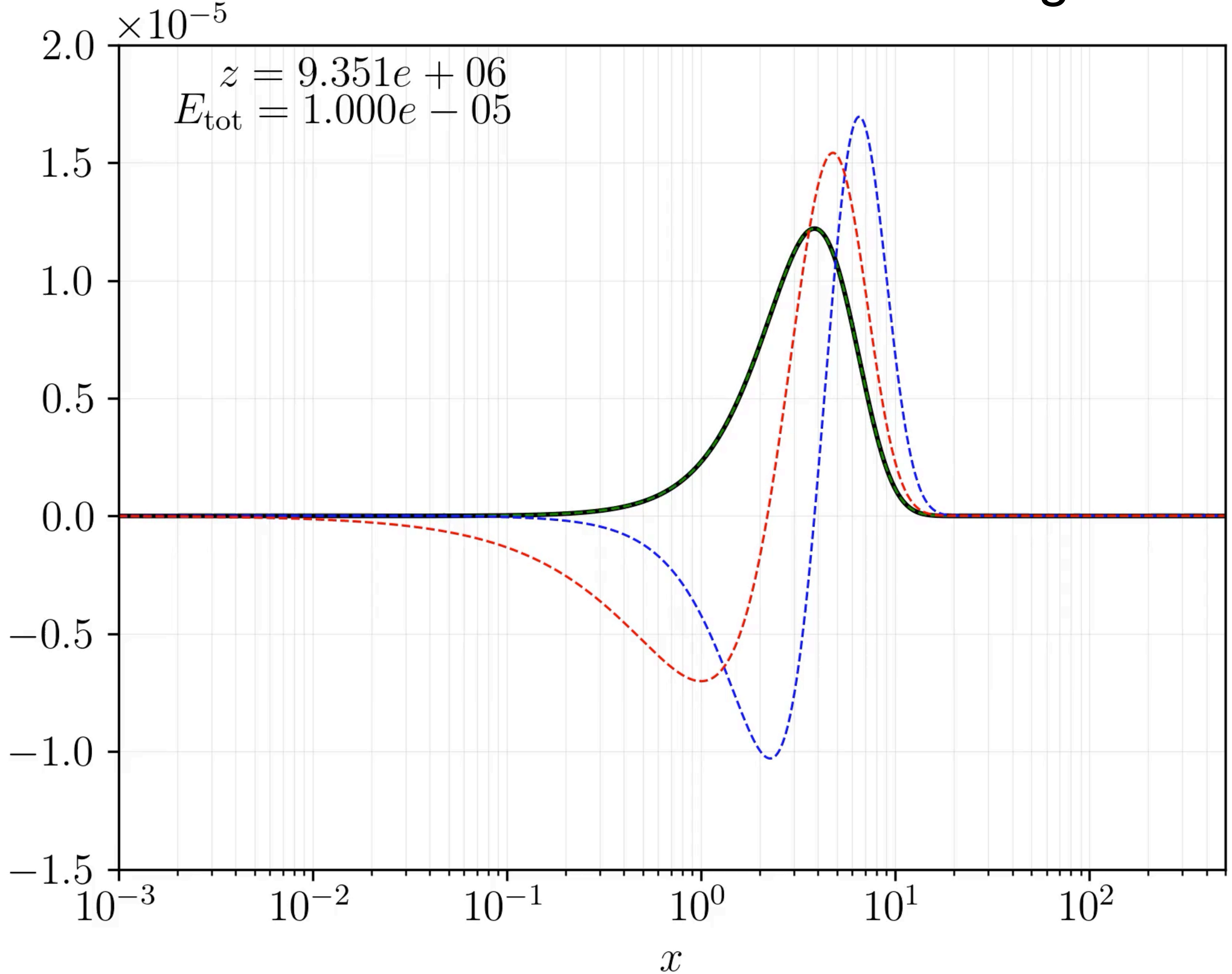
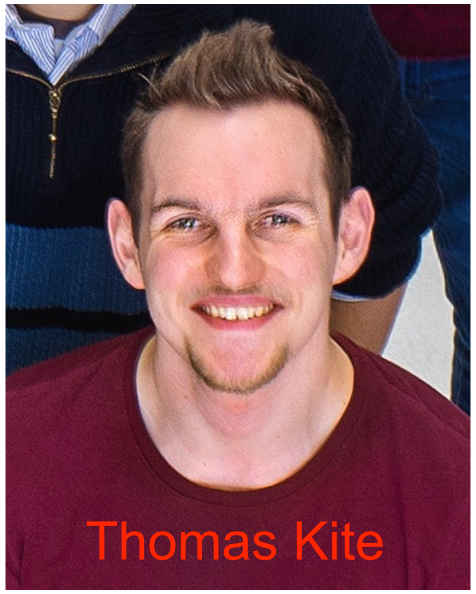
Redshift

Main thermalization stages

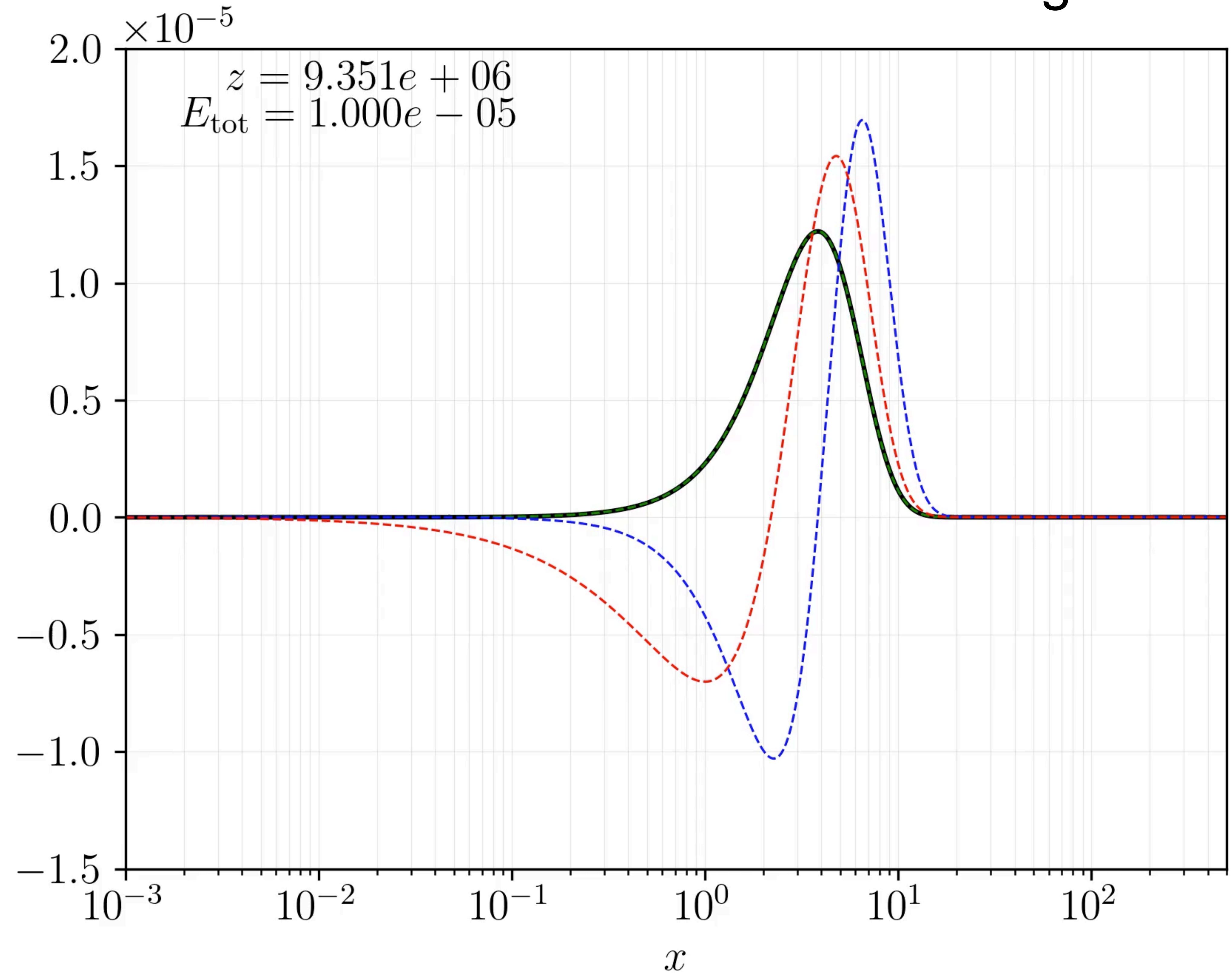


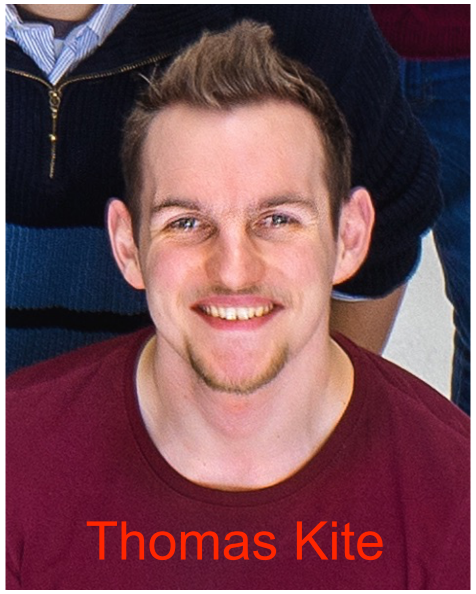


JC, ArXiv:1304.6120
JC, Kite & Ravenni, 2022, papers I
JC, Ravenni & Kite, 2022, papers II
Kite, Ravenni & JC, 2022, papers III

New discretization of the Greens function

Main thermalization stages





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New discretization of the Greens function

New photon Boltzmann hierarchy with thermalization effects

$$\frac{\partial \boldsymbol{y}_0^{(0)}}{\partial \eta} = \tau' \theta_z \left[M_{\rm K}\, \boldsymbol{y}_0^{(0)} + \boldsymbol{D}_0^{(0)} \right] + \frac{\boldsymbol{Q}'^{(0)}}{4},$$

$$\frac{\partial \tilde{\boldsymbol{y}}_0^{(1)}}{\partial \eta} = -k\, \tilde{\boldsymbol{y}}_1^{(1)} - \frac{\partial \tilde{\Phi}^{(1)}}{\partial \eta} \boldsymbol{b}_0^{(0)} + \frac{\boldsymbol{Q}'^{(1)}}{4}$$

$$+ \tau' \theta_z \left\{ M_{\rm K}\, \tilde{\boldsymbol{y}}_0^{(1)} + \boldsymbol{D}_0^{(1)} + \left[\tilde{\delta}_{\rm b}^{(1)} + \tilde{\Psi}^{(1)} \right] \left(M_{\rm K}\, \boldsymbol{y}_0^{(0)} + \boldsymbol{D}_0^{(0)} \right) + \tilde{\Theta}_0^{(1)} \left(\boldsymbol{D}_0^{(0)} + M_{\rm D}\, \boldsymbol{y}^{(0)} - \boldsymbol{S}^{(0)} \right) \right\},$$

$$\frac{\partial \tilde{\boldsymbol{y}}_1^{(1)}}{\partial \eta} = k \left(\frac{1}{3} \tilde{\boldsymbol{y}}_0 - \frac{2}{3} \tilde{\boldsymbol{y}}_2 \right) + \frac{k}{3} \tilde{\Psi}^{(1)} \boldsymbol{b}_0^{(0)} - \tau' \left[\tilde{\boldsymbol{y}}_1^{(1)} - \frac{\tilde{\beta}^{(1)}}{3} \boldsymbol{b}_0^{(0)} \right],$$

$$\frac{\partial \tilde{\boldsymbol{y}}_2^{(1)}}{\partial \eta} = k \left(\frac{2}{5} \tilde{\boldsymbol{y}}_1^{(1)} - \frac{3}{5} \tilde{\boldsymbol{y}}_3^{(1)} \right) - \frac{9}{10}\, \tau'\, \tilde{\boldsymbol{y}}_2^{(1)},$$

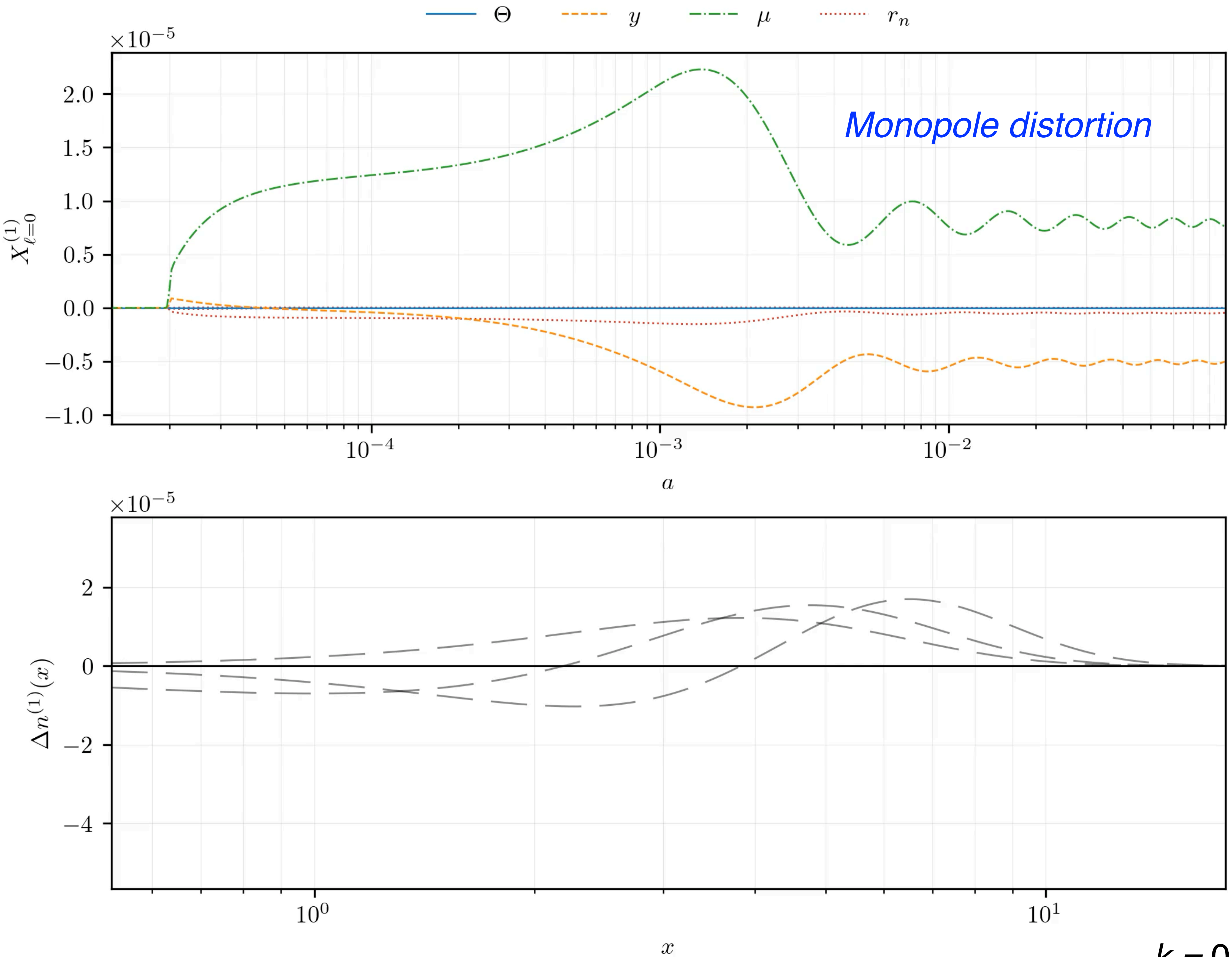
$$\frac{\partial \tilde{\boldsymbol{y}}_{\ell \geq 3}^{(1)}}{\partial \eta} = k \left(\frac{\ell}{2\ell+1} \tilde{\boldsymbol{y}}_{\ell-1} - \frac{\ell+1}{2\ell+1} \tilde{\boldsymbol{y}}_{\ell+1} \right) - \tau' \tilde{\boldsymbol{y}}_\ell^{(1)}.$$

These are the new thermalization and generalized source terms

JC, Kite & Ravenni, 2022, papers I, ArXiv:2210.09327
JC, Ravenni & Kite, 2022, papers II, ArXiv:2210.15308
Kite, Ravenni & JC, 2022, papers III, ArXiv:2212.02817

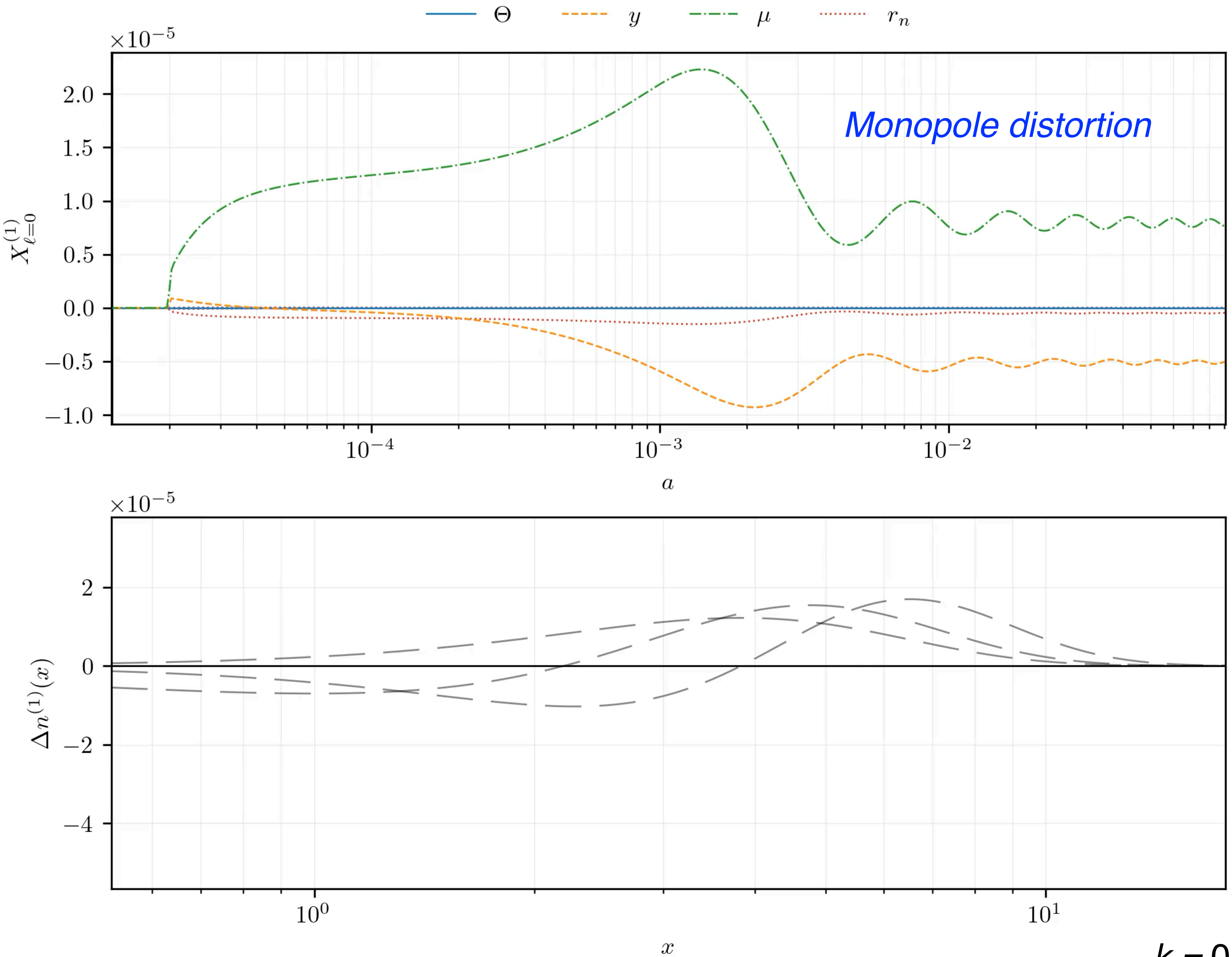
Now implemented in `CosmoTherm` but can be done with any Boltzmann code (e.g., `CAMB` or `CLASS`)

Evolution of modes for injection at z = 50,000



k = 0.01 Mpc^{-1}

Evolution of modes for injection at z = 50,000



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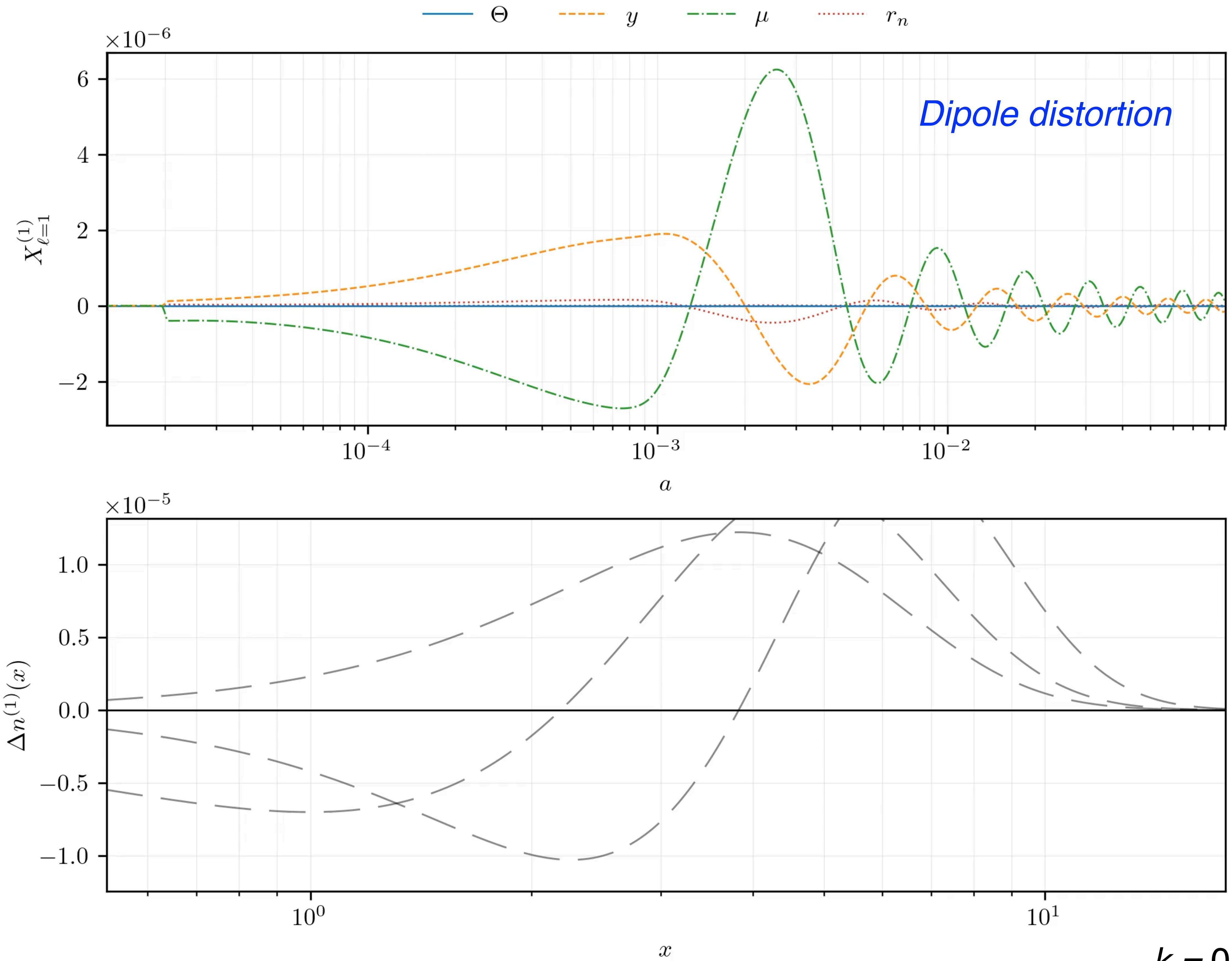

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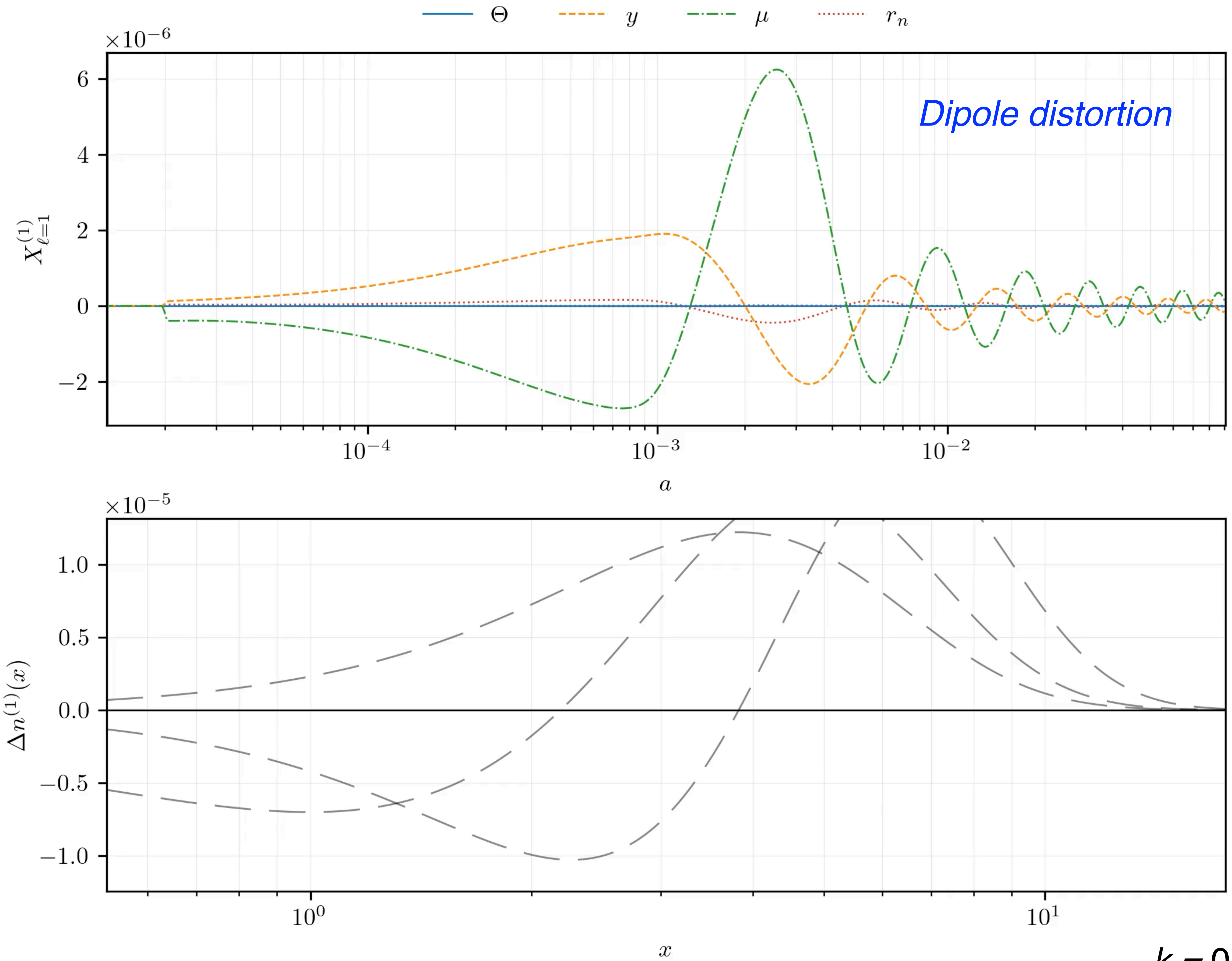

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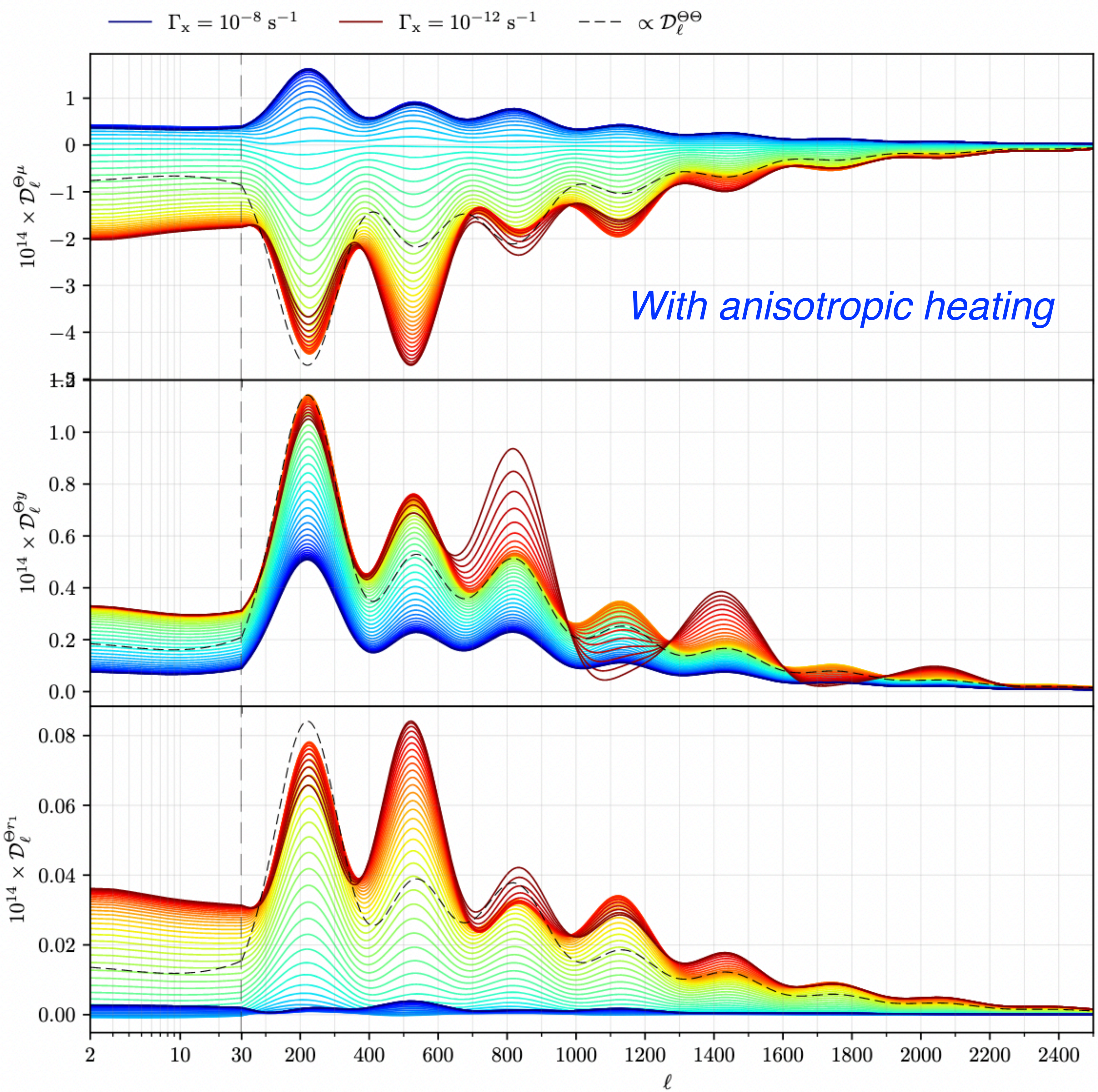
CMB power spectra for decaying particles



- New way to constrain these scenarios
- Anisotropic heating is important!
- Degeneracy between lifetime and abundance can in principle be broken by ℓ-dependence

Kite, Ravenni & JC, 2022, papers III, ArXiv:2212.02817

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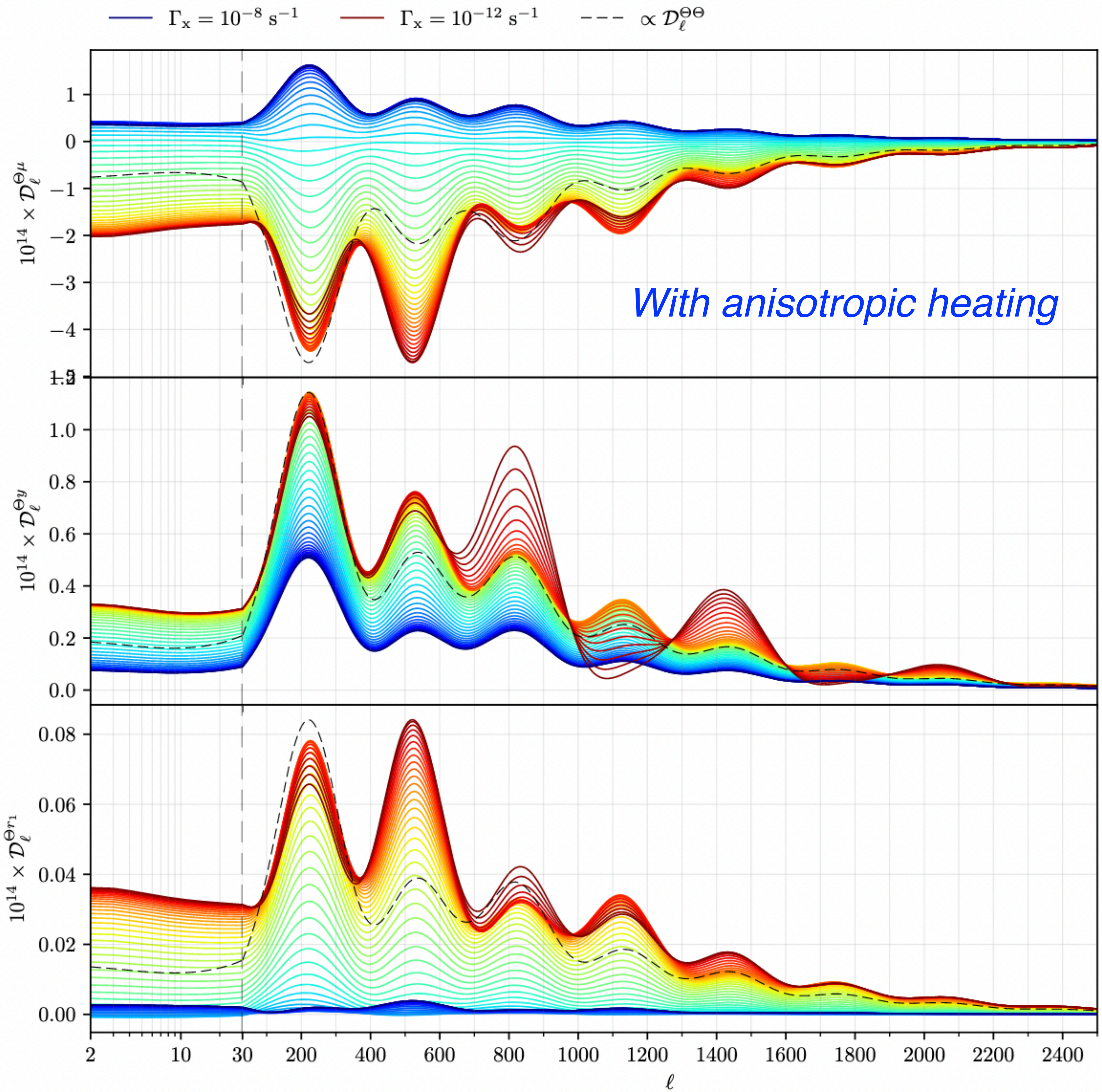


- New way to constrain these scenarios
- Anisotropic heating is important!
- Degeneracy between lifetime and abundance can in principle be broken by ℓ-dependence

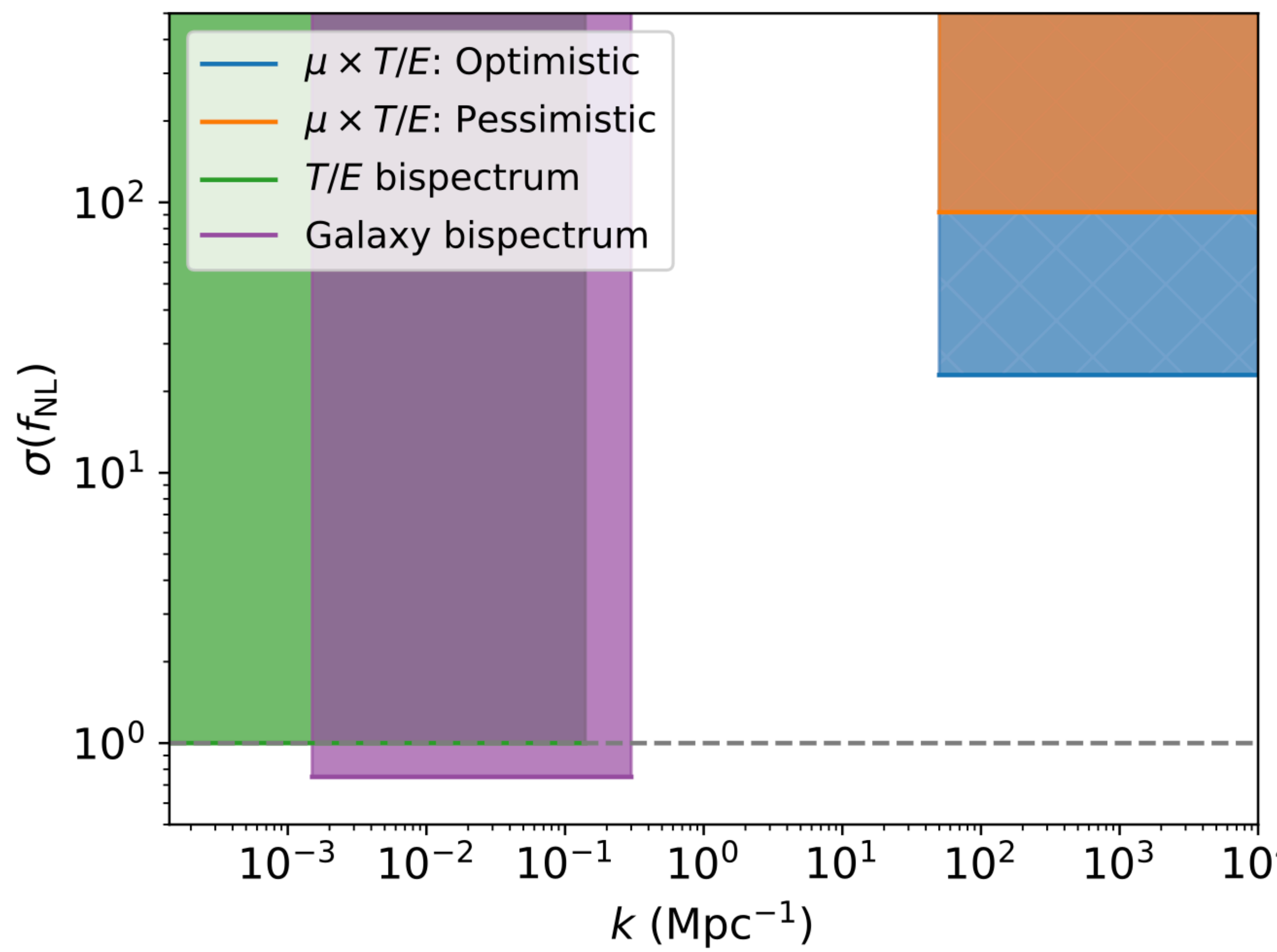
Can be constrainted with CMB imagers like Planck, Litebird, SO, CMB-S4 & PICO!

Kite, Ravenni & JC, 2022, papers III, ArXiv:2212.02817

SKA as a CMB experiment

- Single dish mode is enough for μ-T constraints
- Low frequency foreground monitor

- Constraints on small scales
- SKA+Litebird equivalent to PICO in terms of μ-T
- *SKA could even do B-modes…*



Zegeye et al., ArXiv:2406.04326

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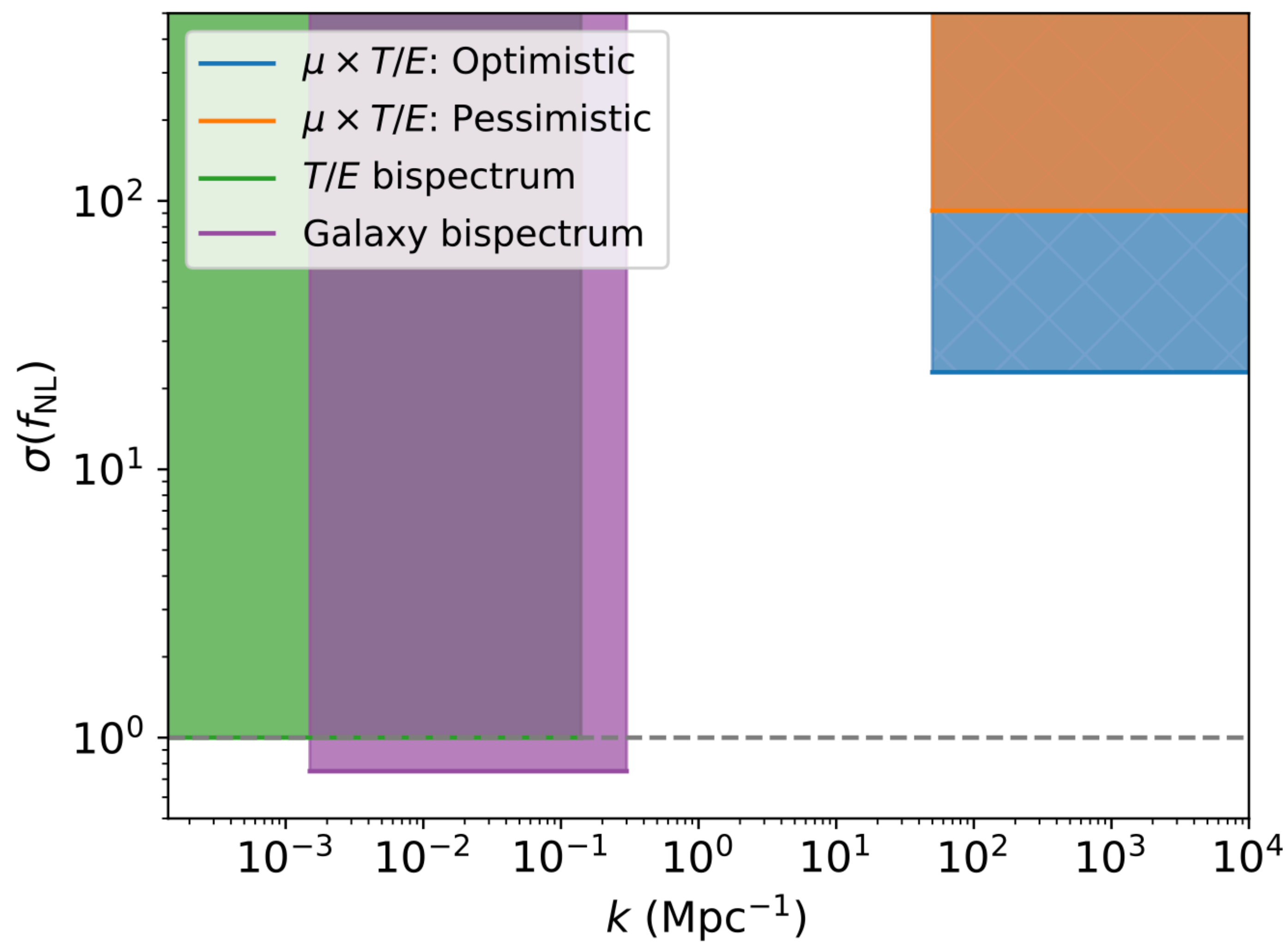
Detailed study with realistic foregrounds and systematics is required!



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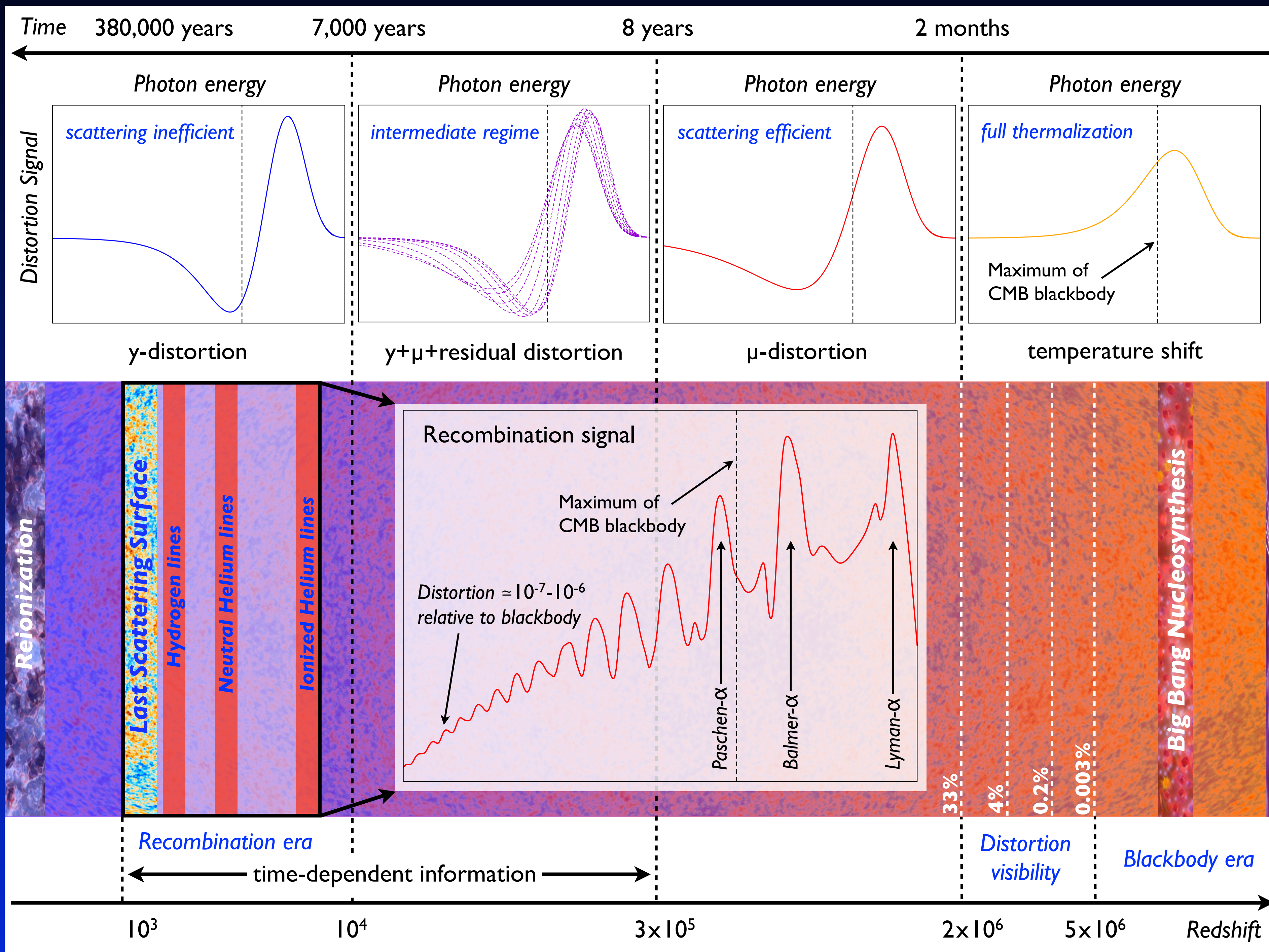
Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

JC & Sunyaev, MNRAS, 419, 2012
JC et al., MNRAS, 425, 2012
Silk & JC, Science, 2014
JC, MNRAS, 2016
JC et al., 2019, arXiv:1909.01593

COSMO
TMS
BISOU
Voyage 2050

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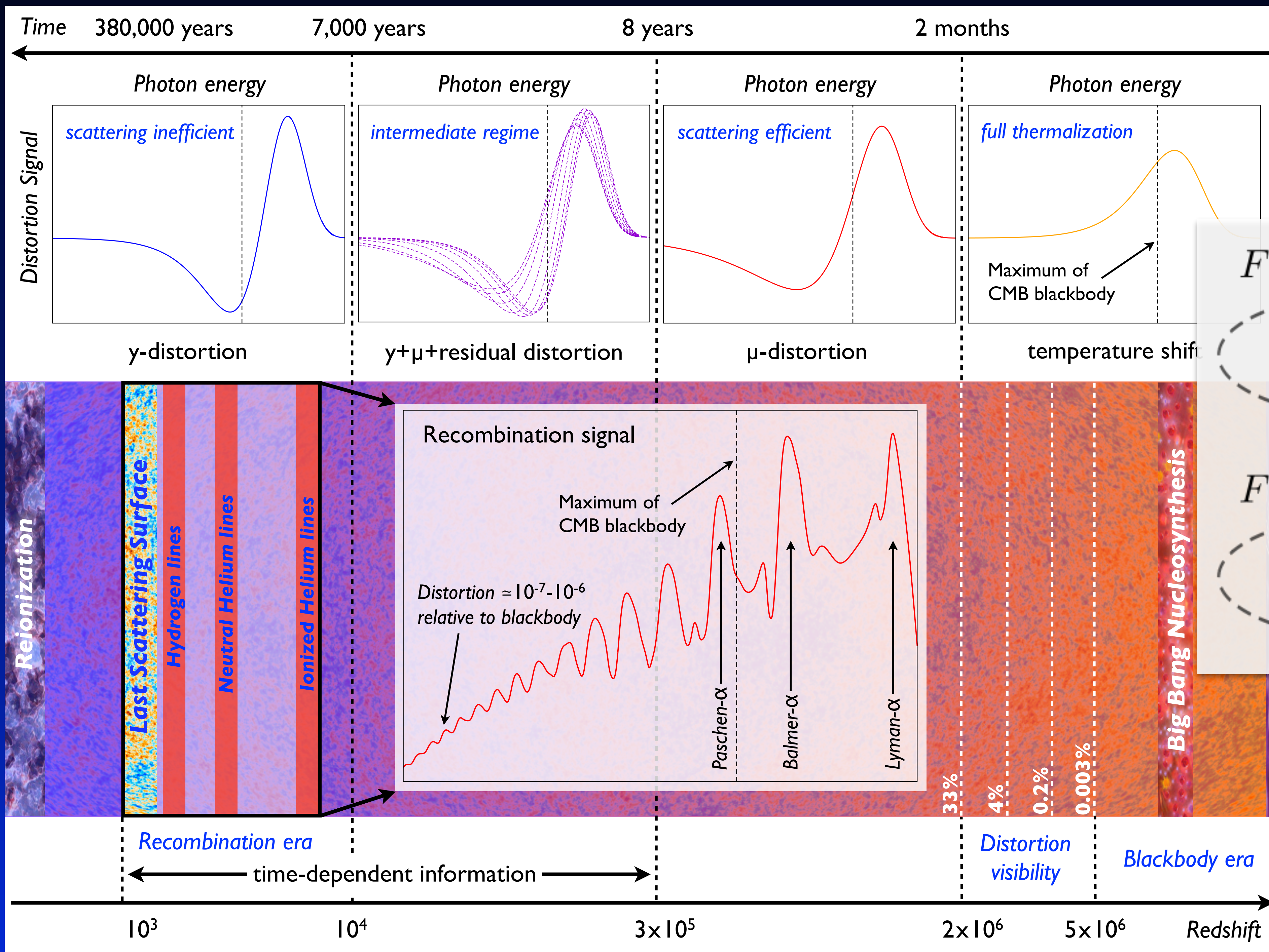

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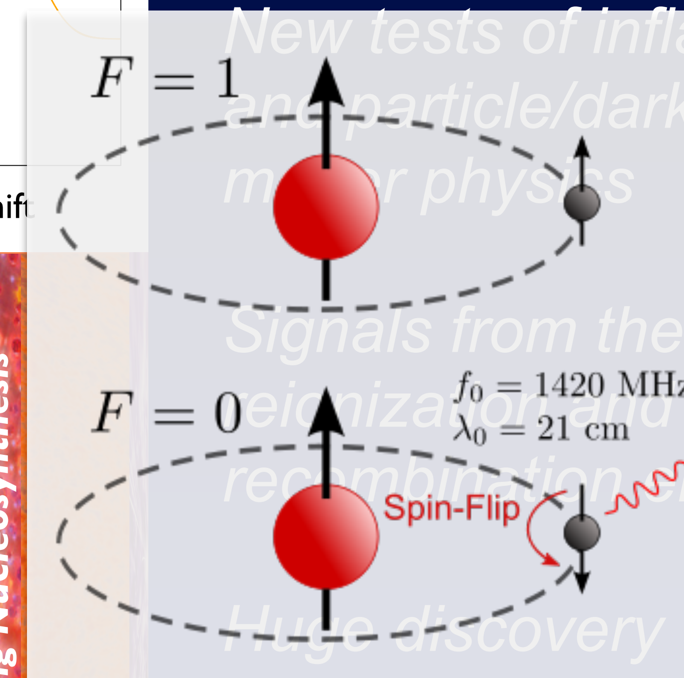

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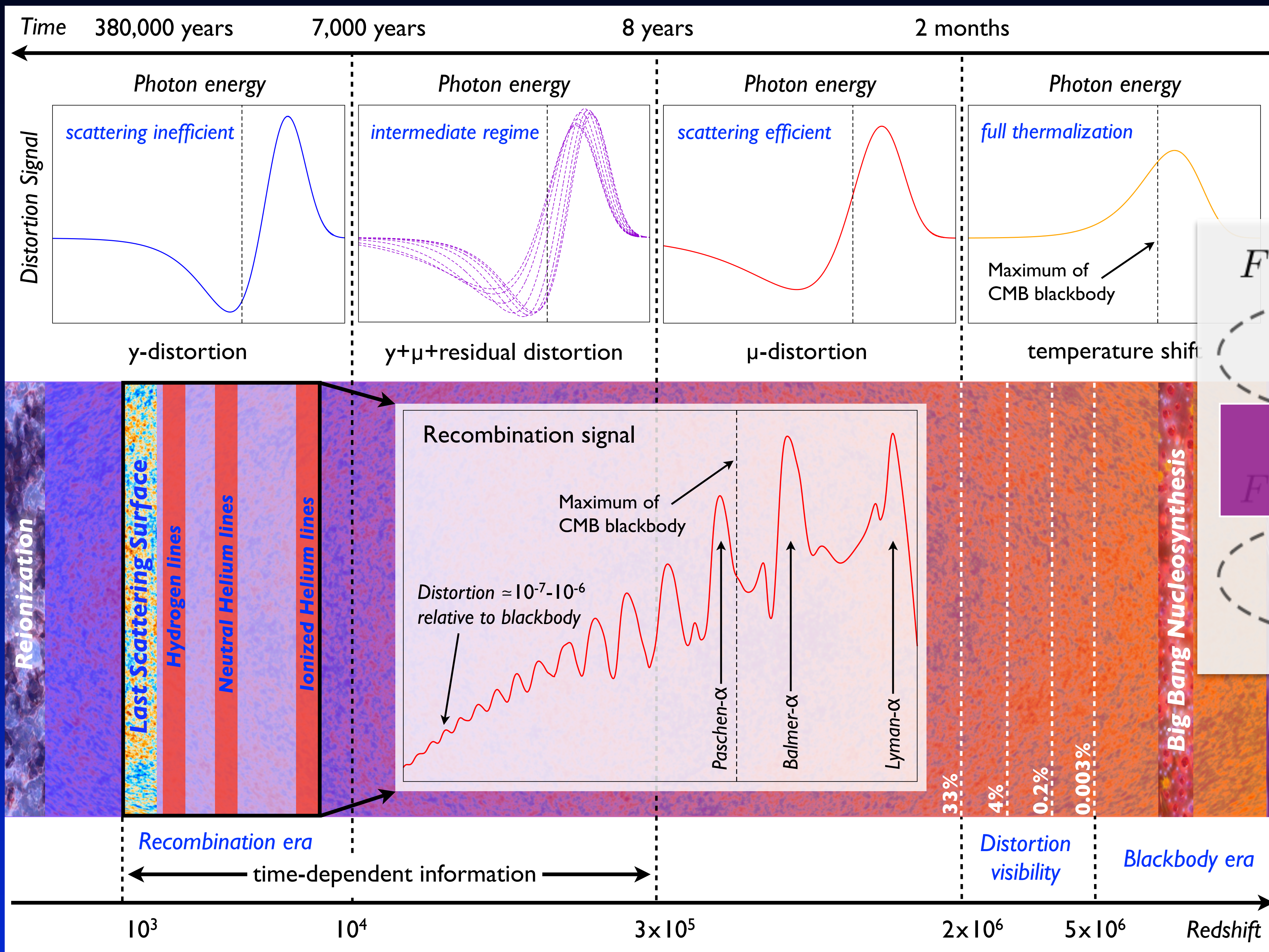

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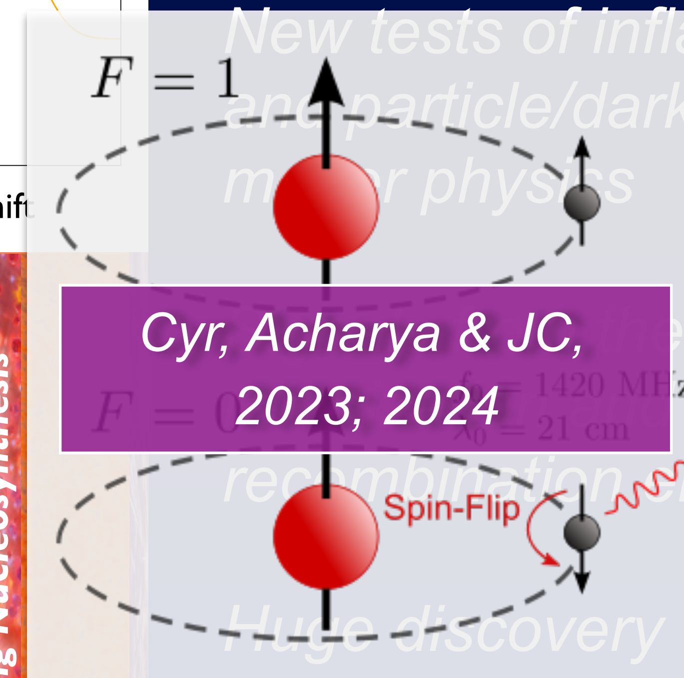

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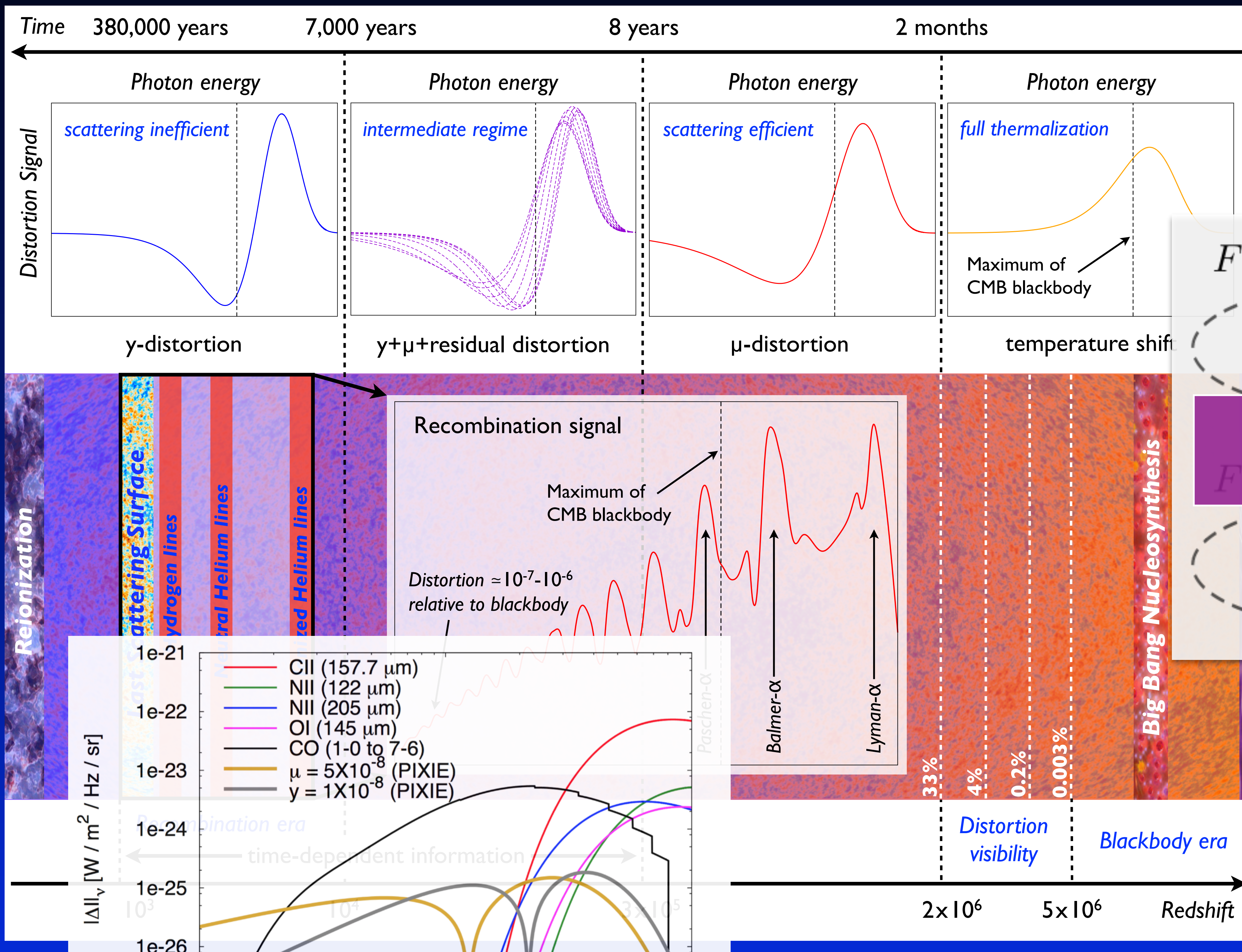

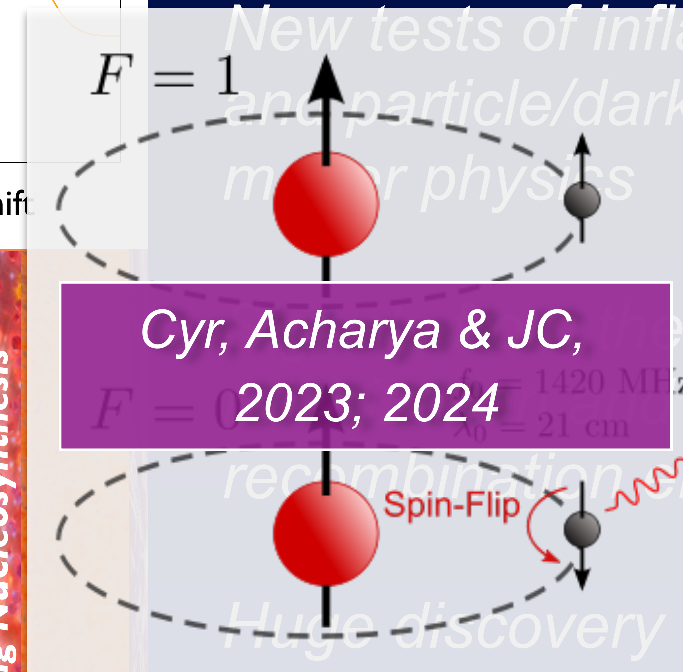

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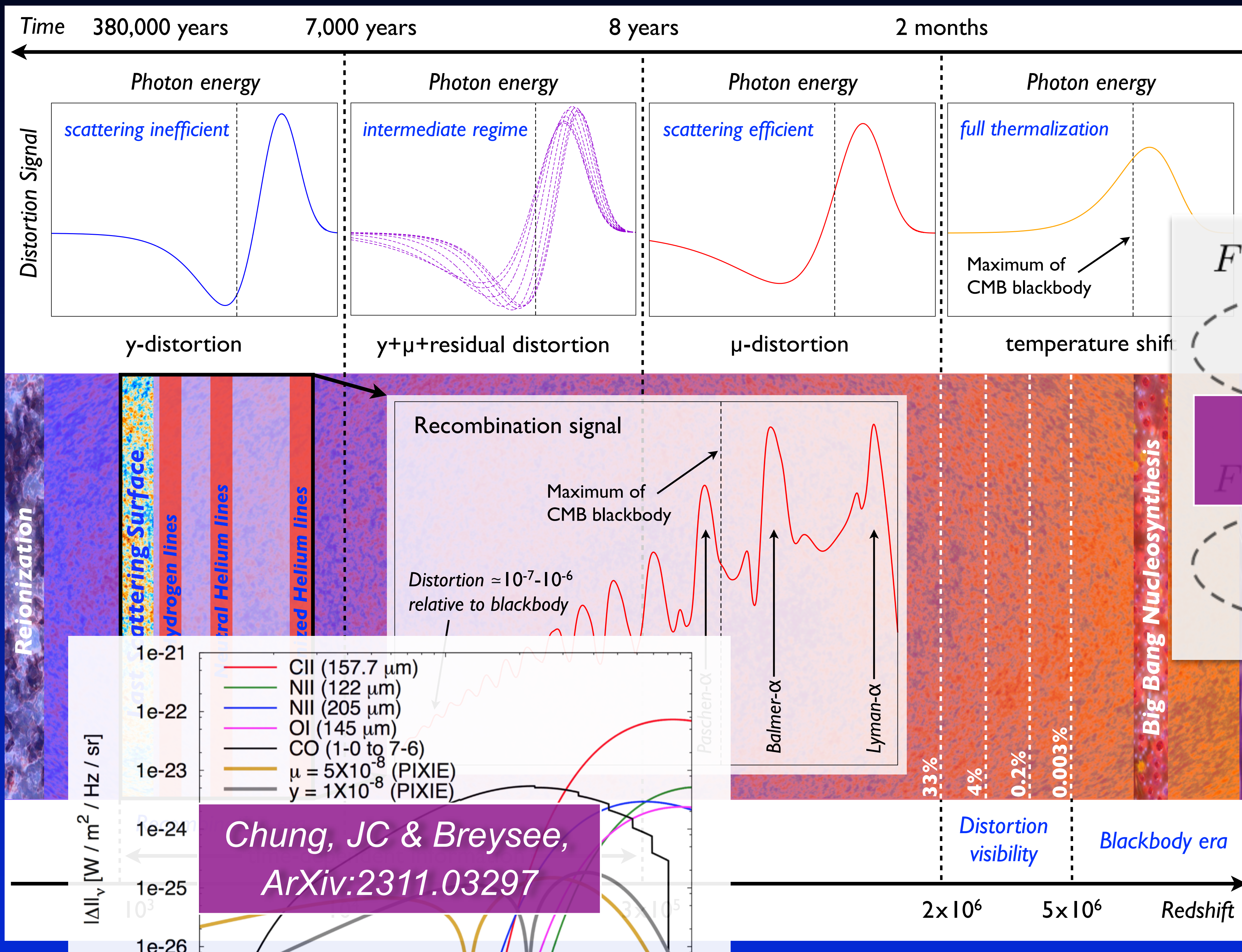

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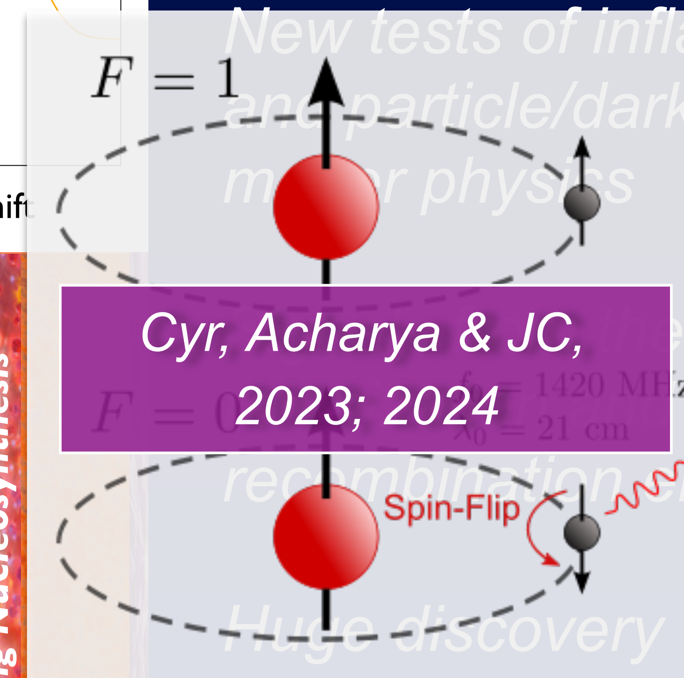

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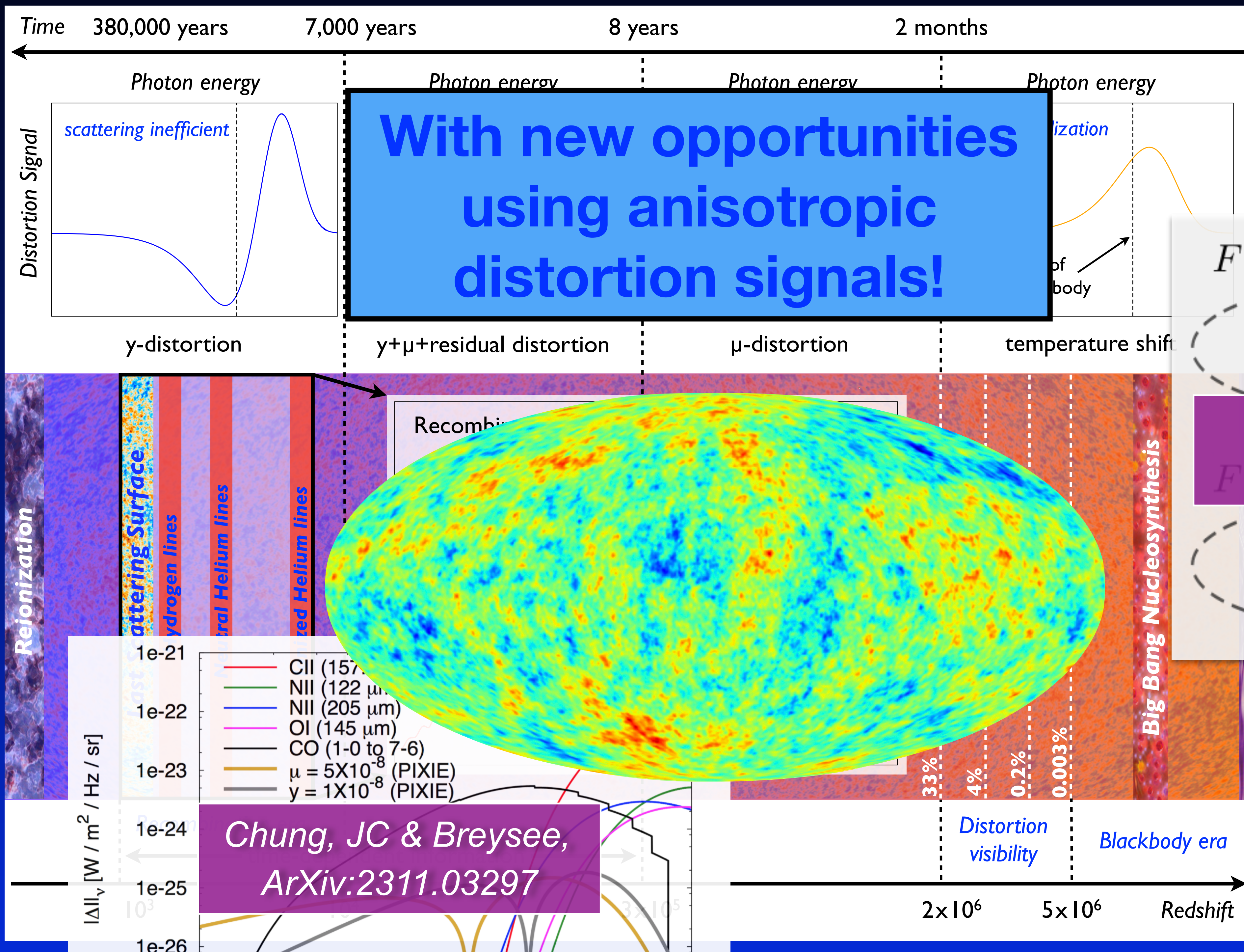
Uniqueness of CMB Spectral Distortion Science

Planck, Litebird, SKA, CMB-S4 & *PICO*

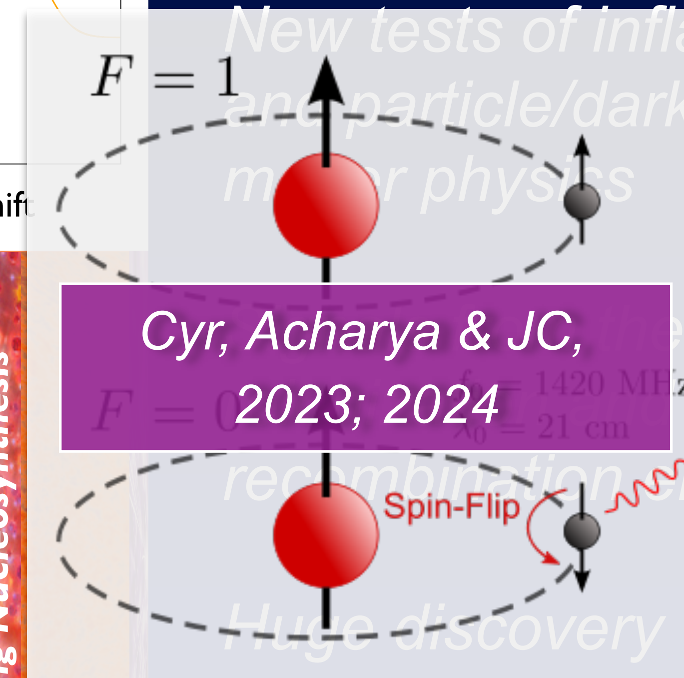


With new opportunities using anisotropic distortion signals!

Chung, JC & Breysee, ArXiv:2311.03297

Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics



Cyr, Acharya & JC, 2023; 2024

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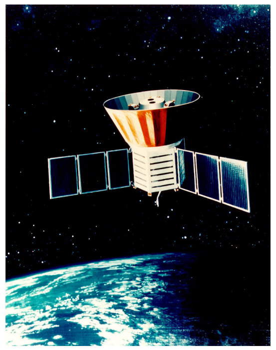
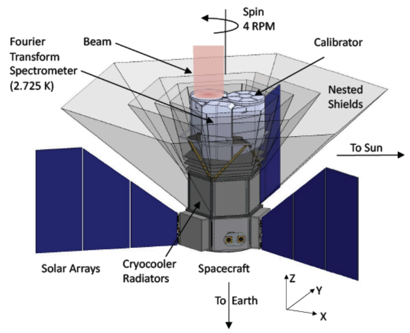
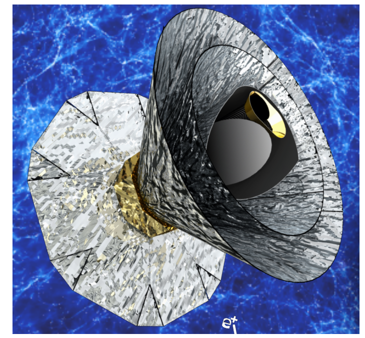
History of distortion experiments and proposals



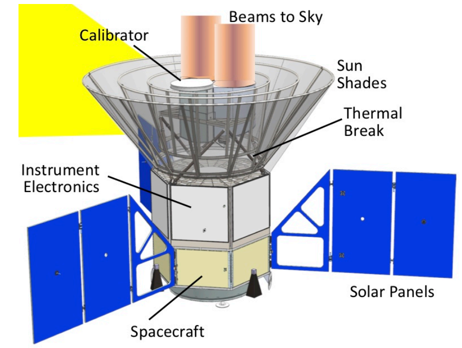
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



PRISM
De Bernardis



PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE

PRISTINE
Aghanim

FOSSIL
Aghanim

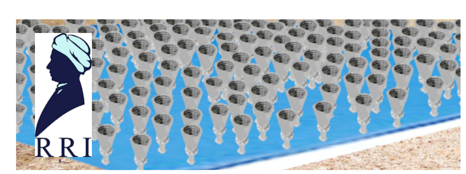
ARCADE 2
Kogut & Fixsen

Not just fiction anymore!

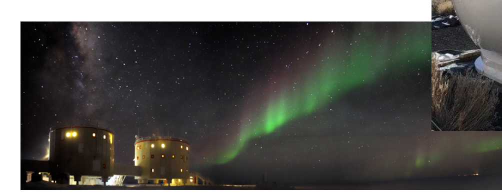
Maffei

BISOU

TRIS
Gervasi, Zannoni & Tartari



APSERa
Subrahmanyan & Rao



COSMO
De Bernardis, Masi & Battistelli

TMS
Rubiño-Martin

1989 ≈ 2008 2011 2013 2015 2016 2018 2022