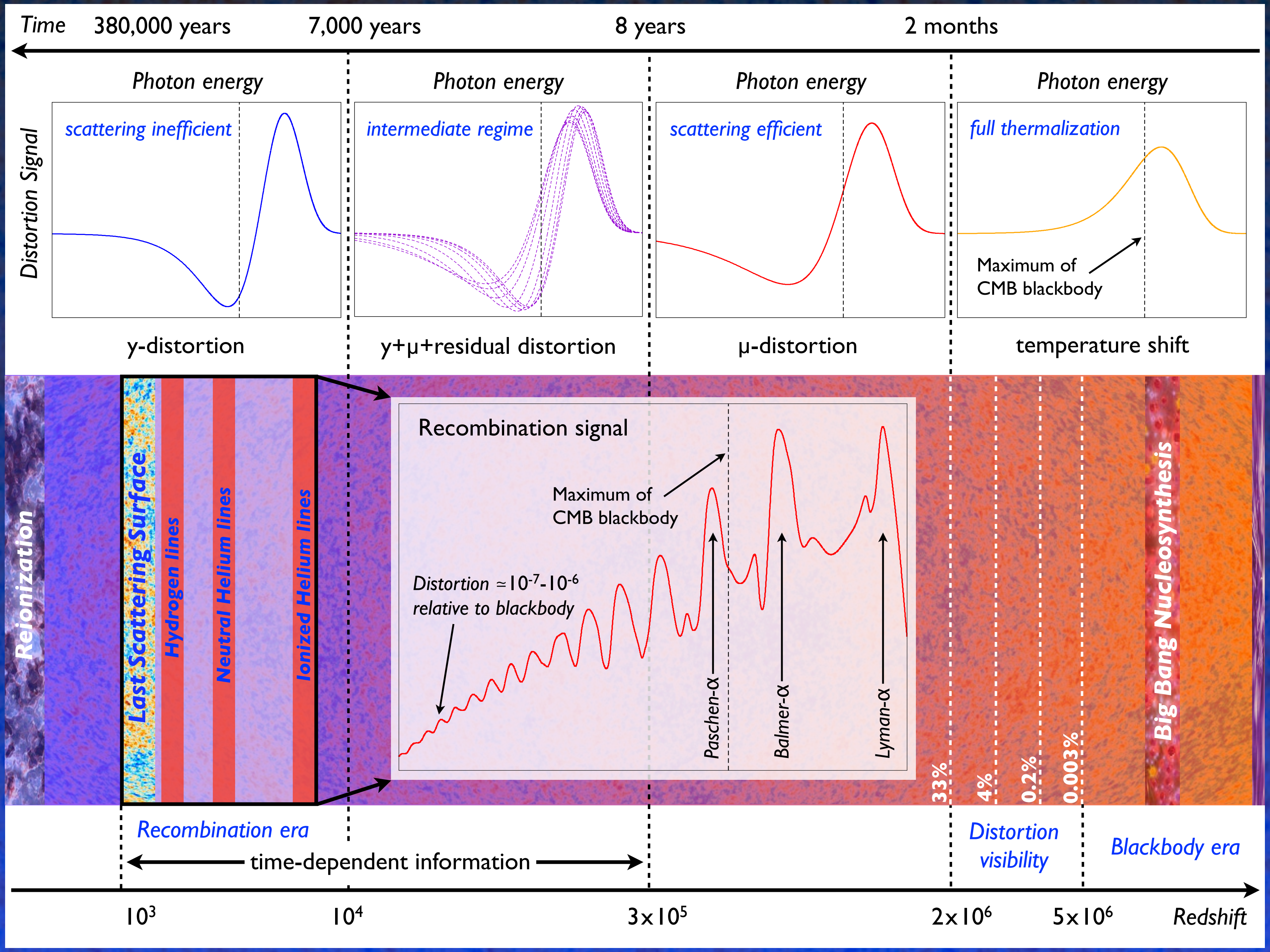
Exploring new horizons with CMB* spectral distortions



MANCHESTER
1824
The University of Manchester

Jens Chluba

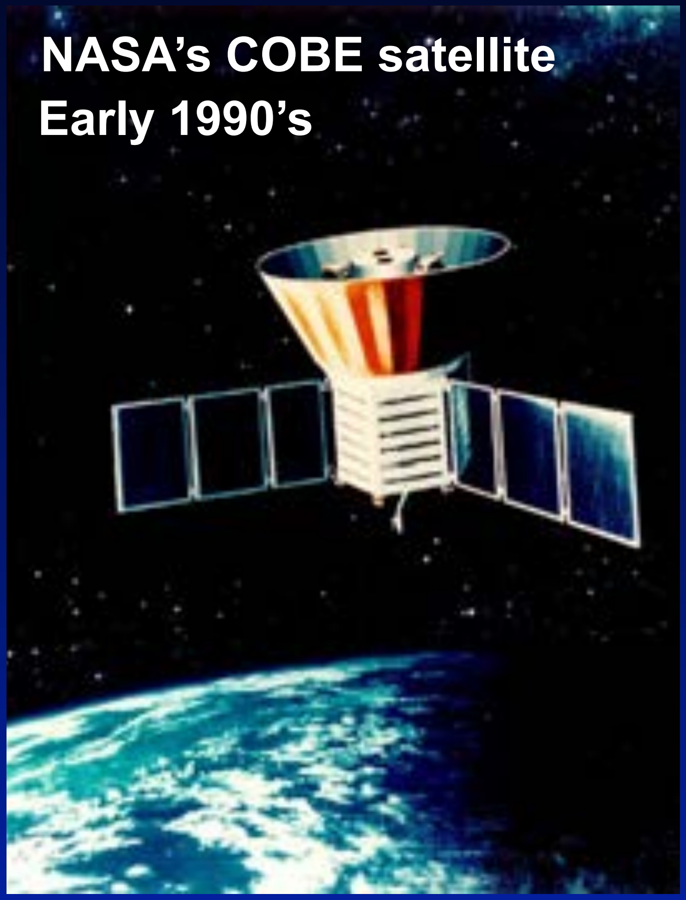
CMB@60

May 30th 2025

erc
THE ROYAL SOCIETY

* CMB ≙ Cosmic Microwave Background

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

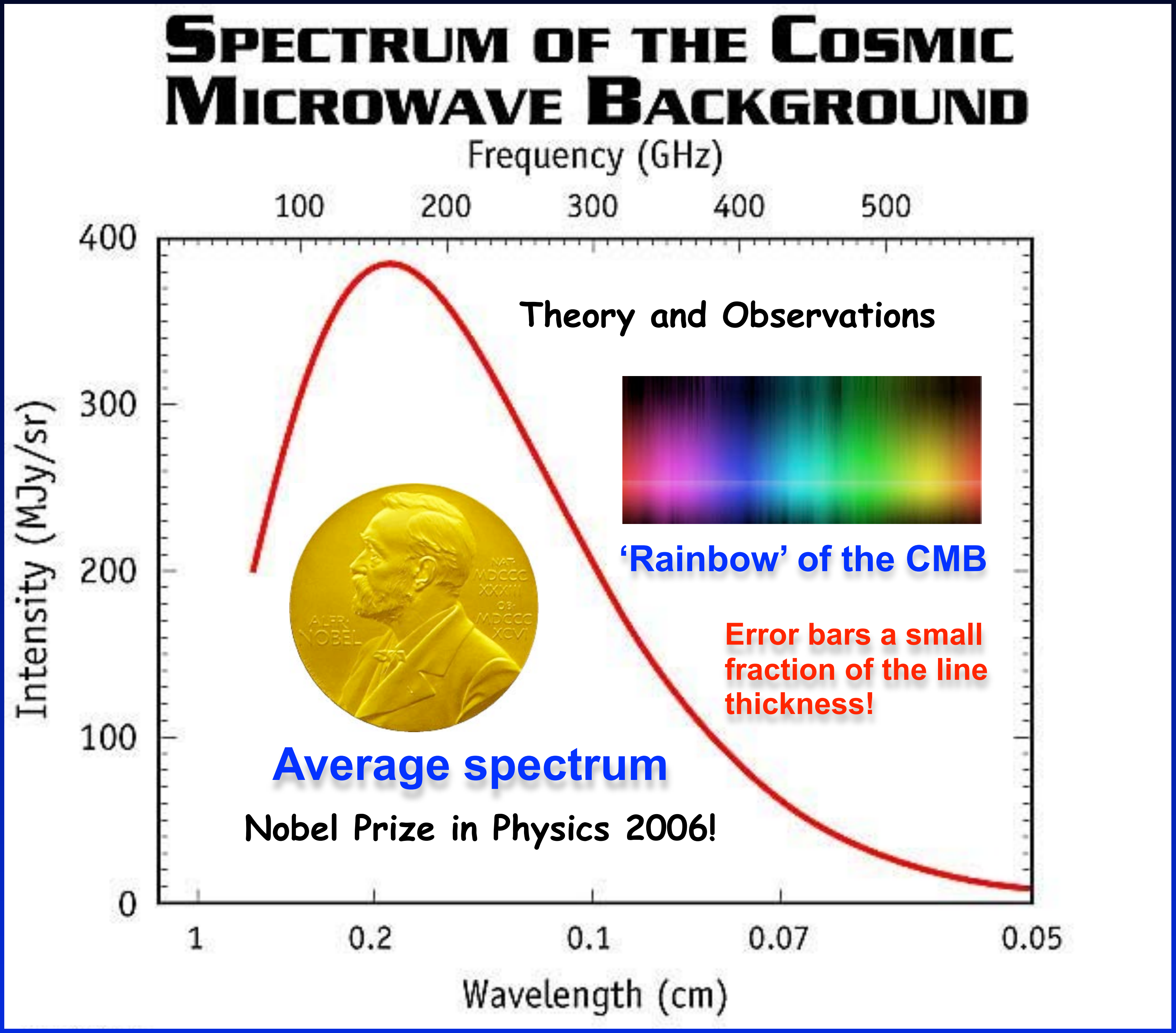


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \le 1.5\times10^{-5}$$

$$|\mu| \le 9\times10^{-5}$$

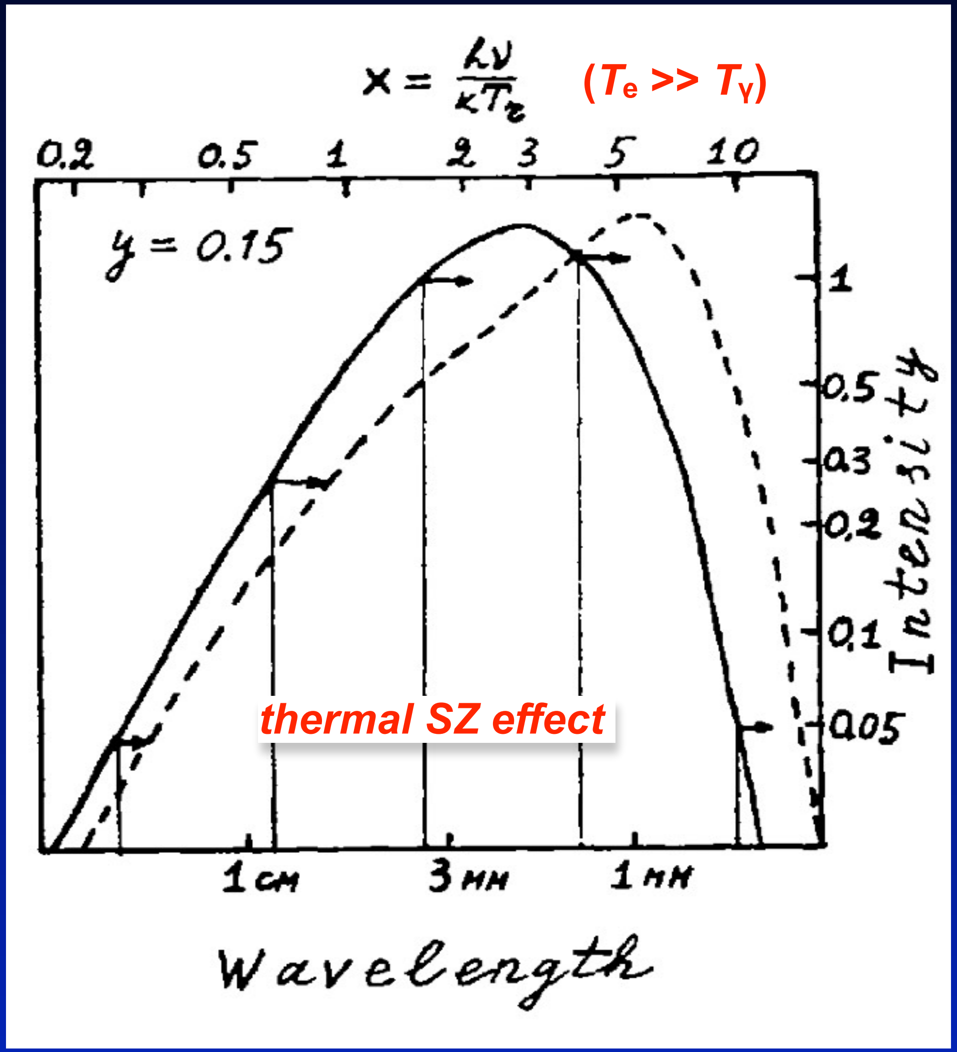
Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen, 2003, ApJ, 594, 67
Fixsen, 2009, ApJ, 707, 916



Blackbody spectrum to very high precision

Standard types of primordial CMB distortions

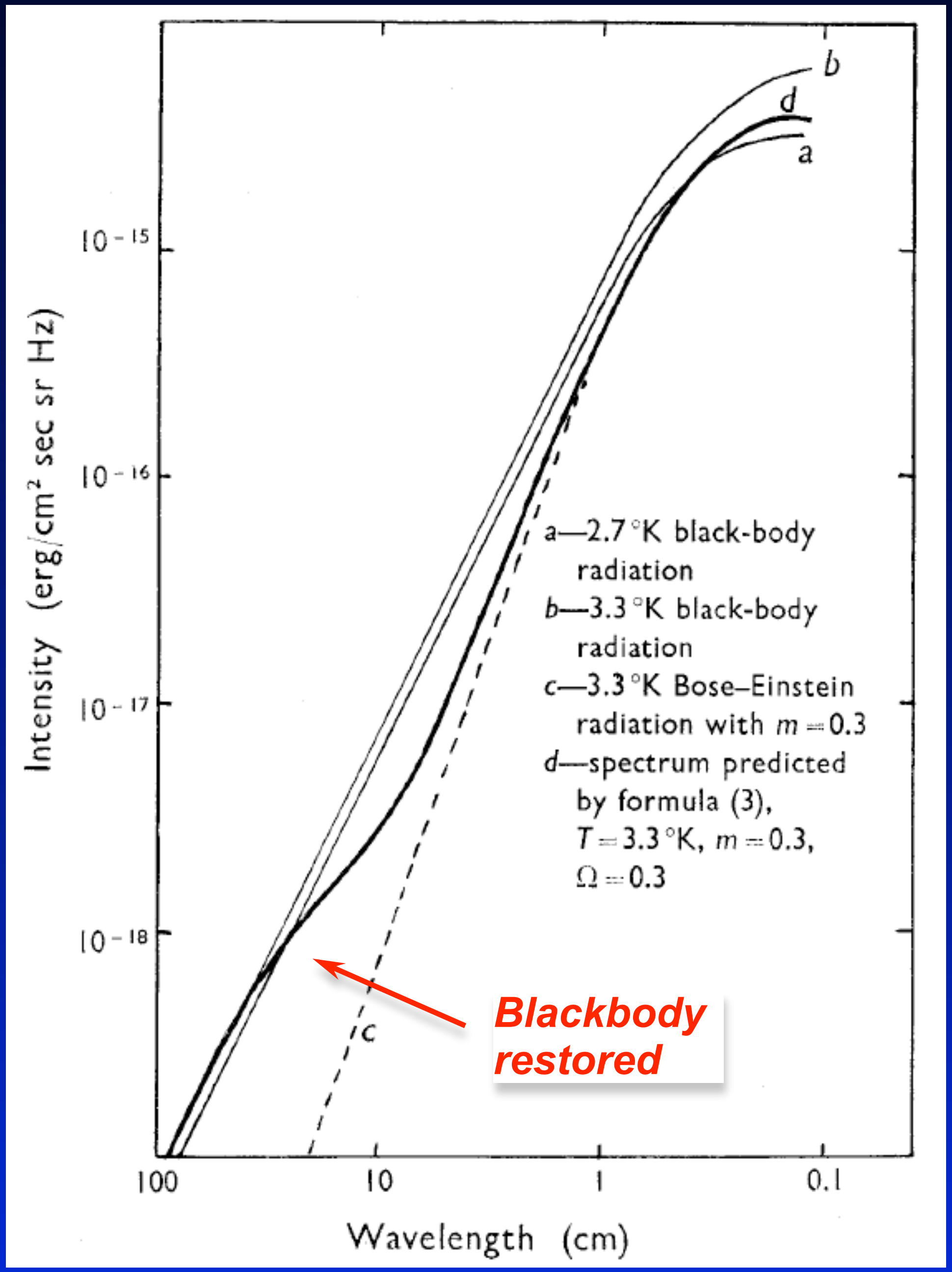
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering \`inefficient'

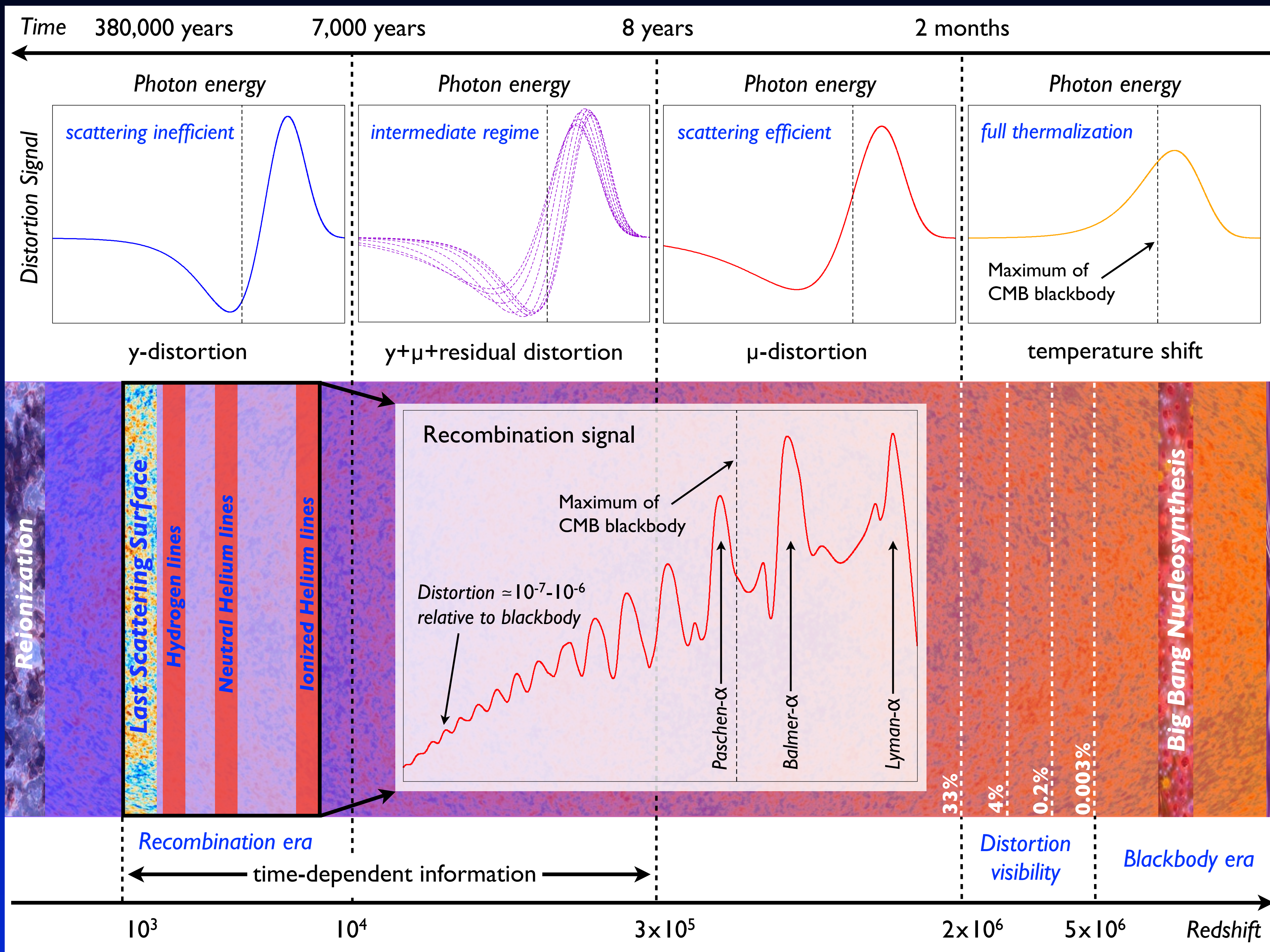
Chemical potential μ-distortion



Sunyaev & Zeldovich, 1970, ApSS, 2, 66

- important at early times (z>50000)
- scattering \`very efficient'

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

Zeldovich & Sunyaev, 1969
Sunyaev & Zeldovich, 1970
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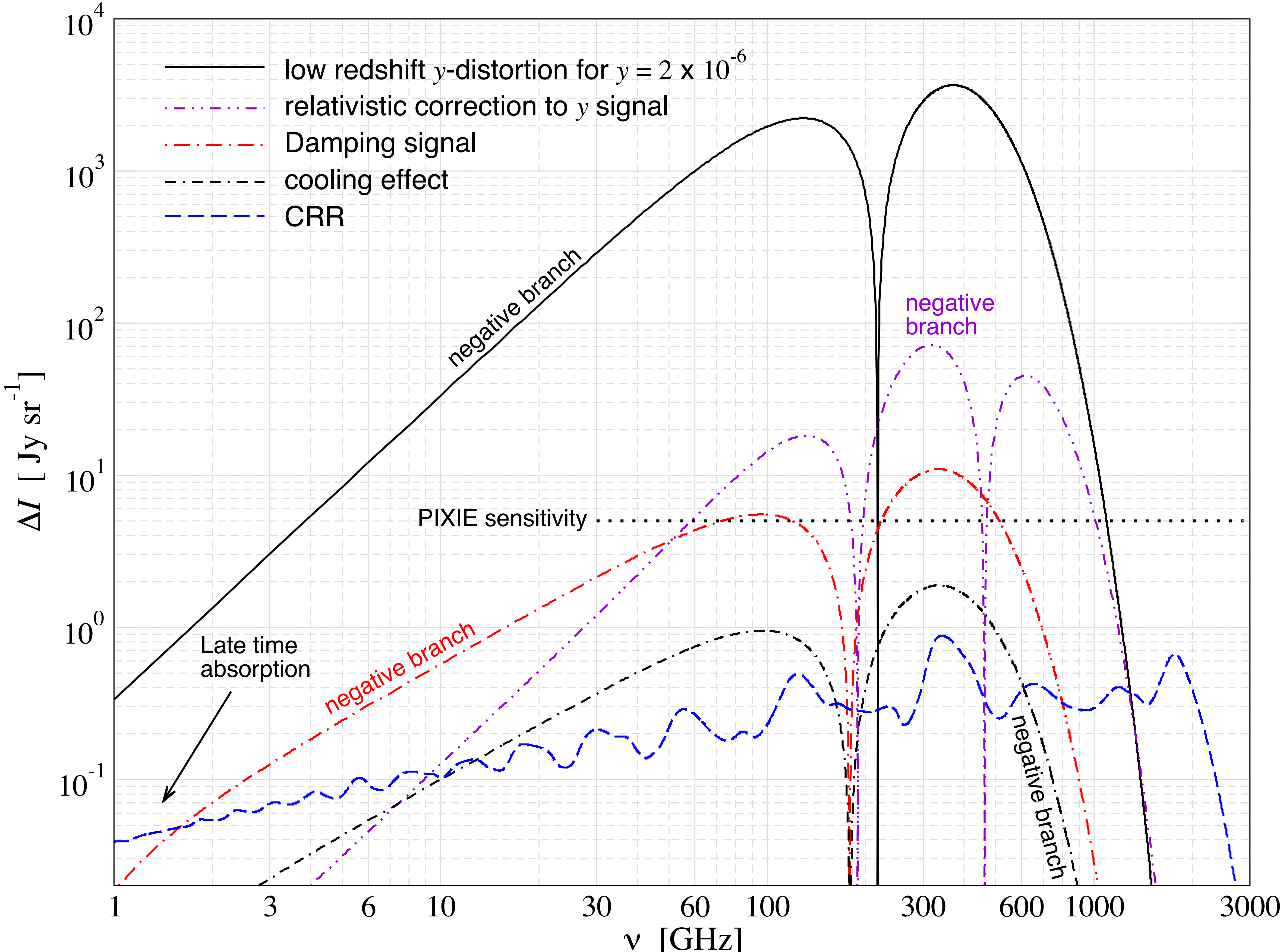
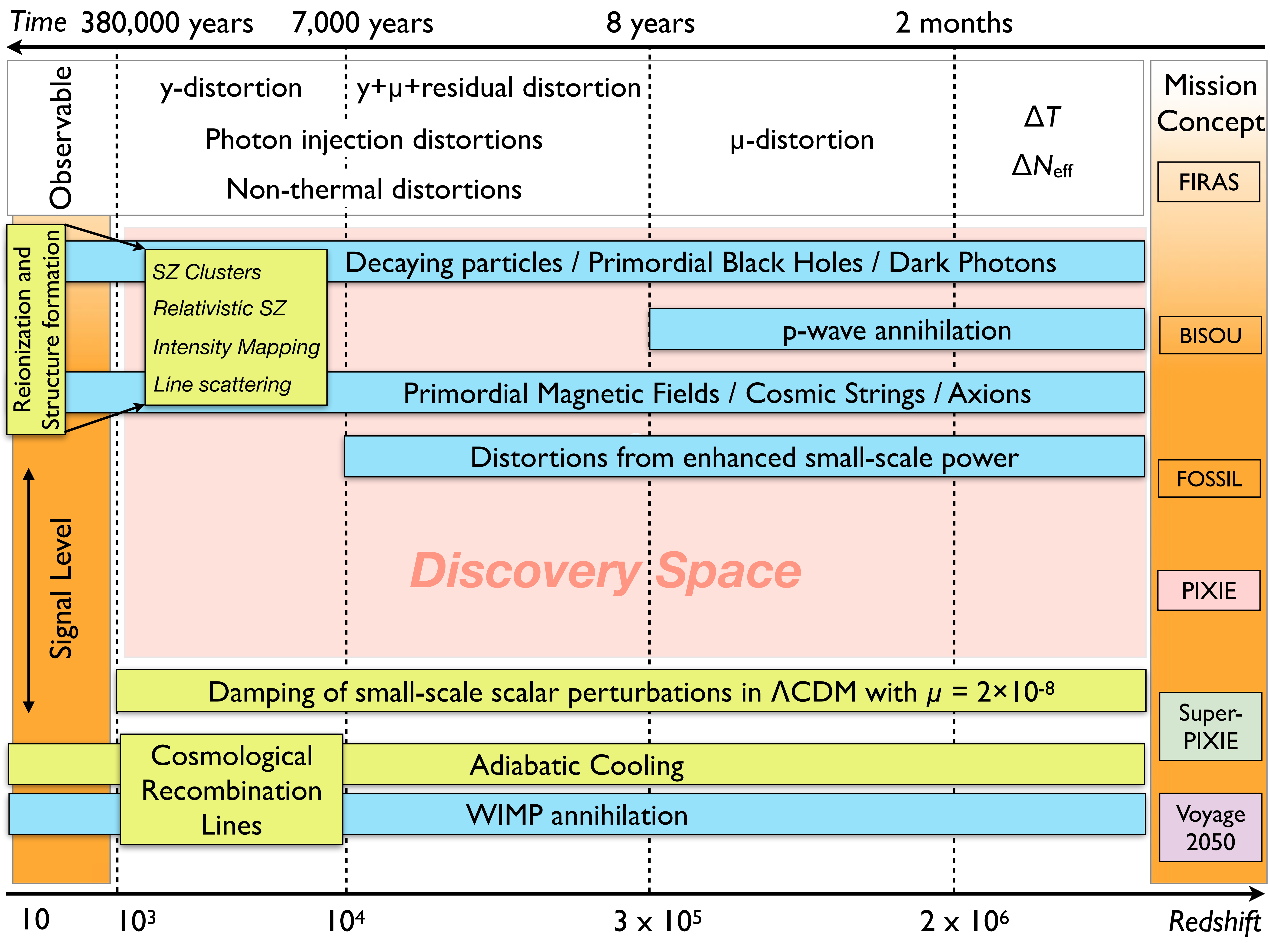
Hu & Silk, 1993; JC et al. 1909.01593

COSMO
TMS
BISOU
Voyage 2050

Average ΛCDM spectral distortions

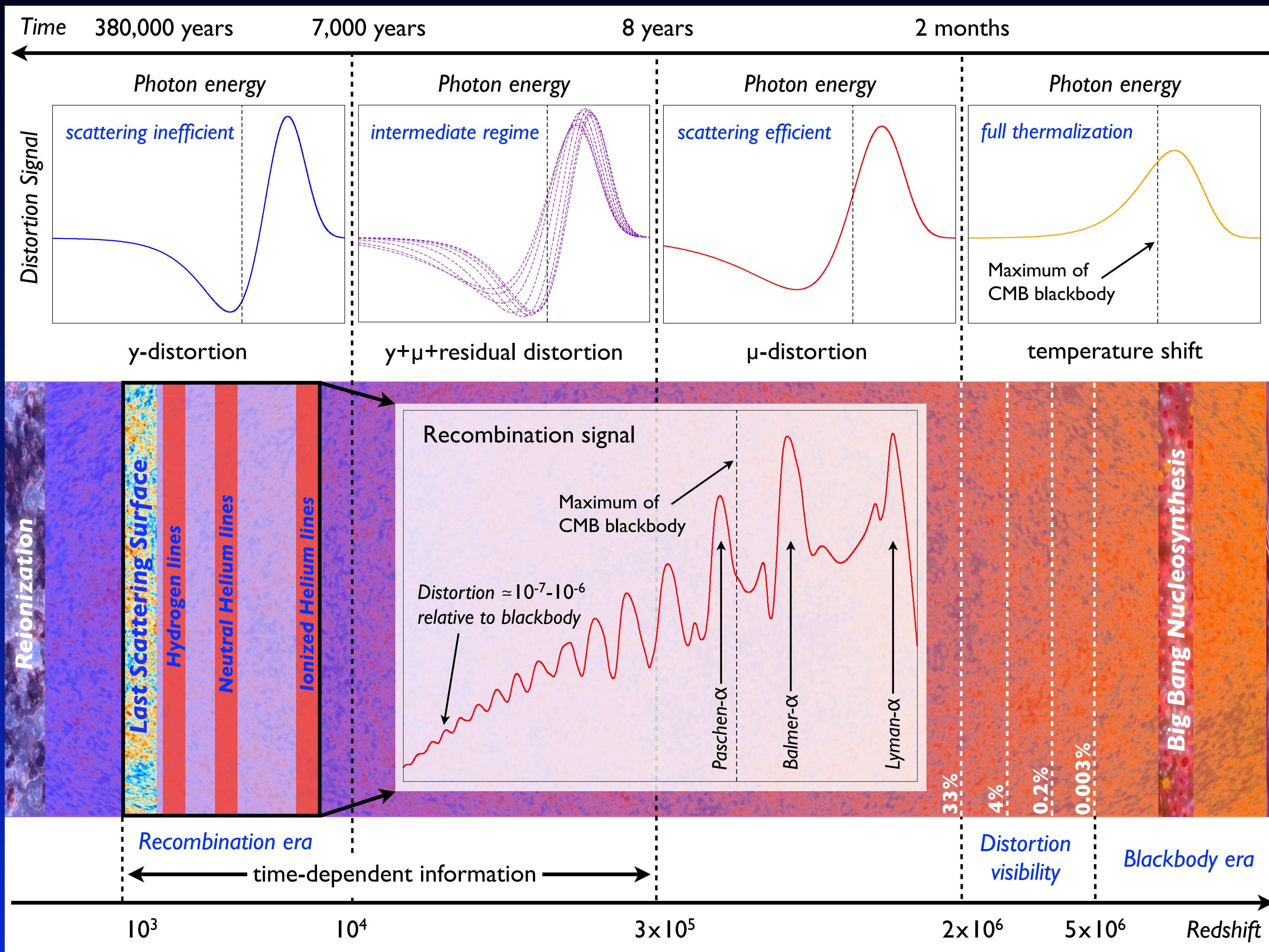


JC, 2016, MNRAS (ArXiv:1603.02496)



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
Intensity Mapping
Line scattering
Decaying particles / Primordial Black Holes / Dark Photons
p-wave annihilation
Primordial Magnetic Fields / Cosmic Strings / Axions
Distortions from enhanced small-scale power
Signal Level
Discovery Space
Damping of small-scale scalar perturbations in ΛCDM with μ = 2×10-8
Cosmological Recombination Lines
Adiabatic Cooling
WIMP annihilation
10
10³
10⁴
3 x 10⁵
2 x 10⁶
Redshift

Uniqueness of CMB Spectral Distortion Science



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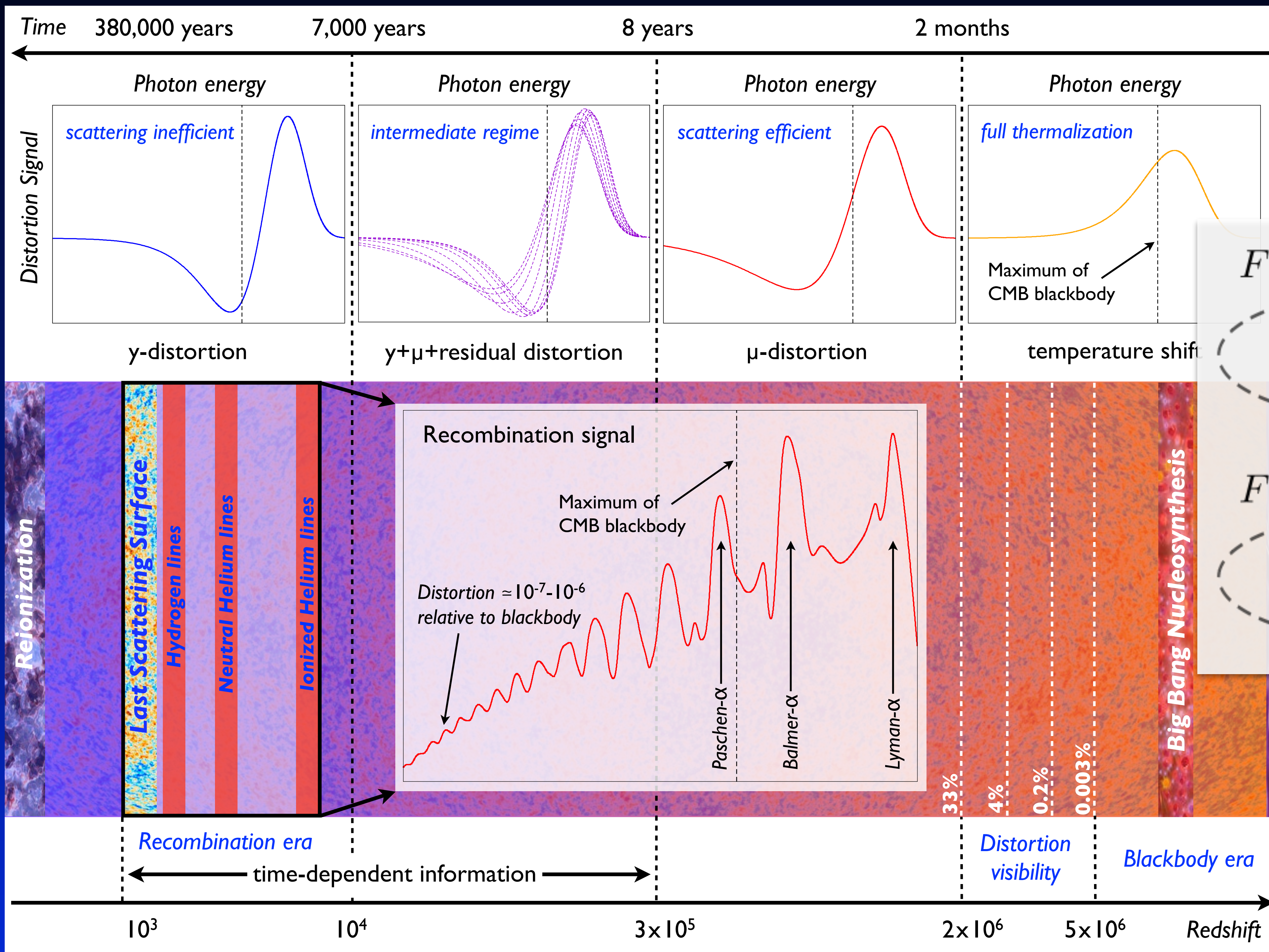

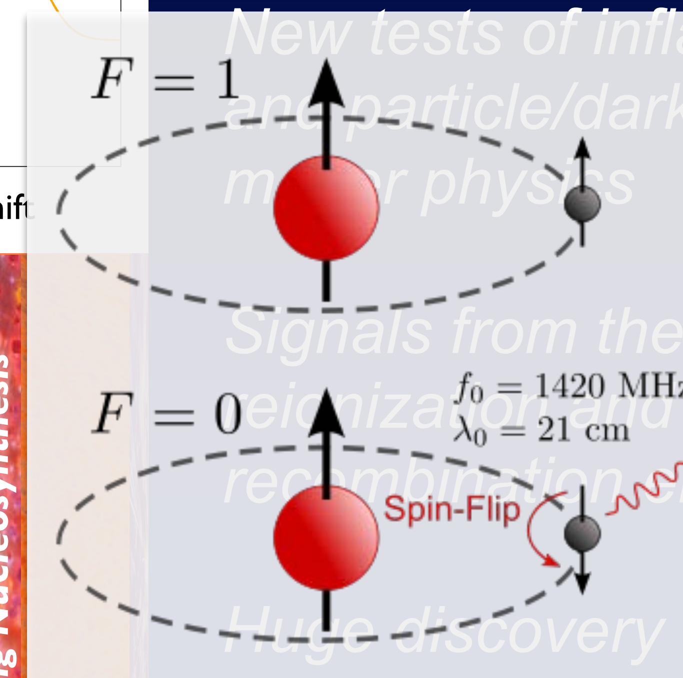

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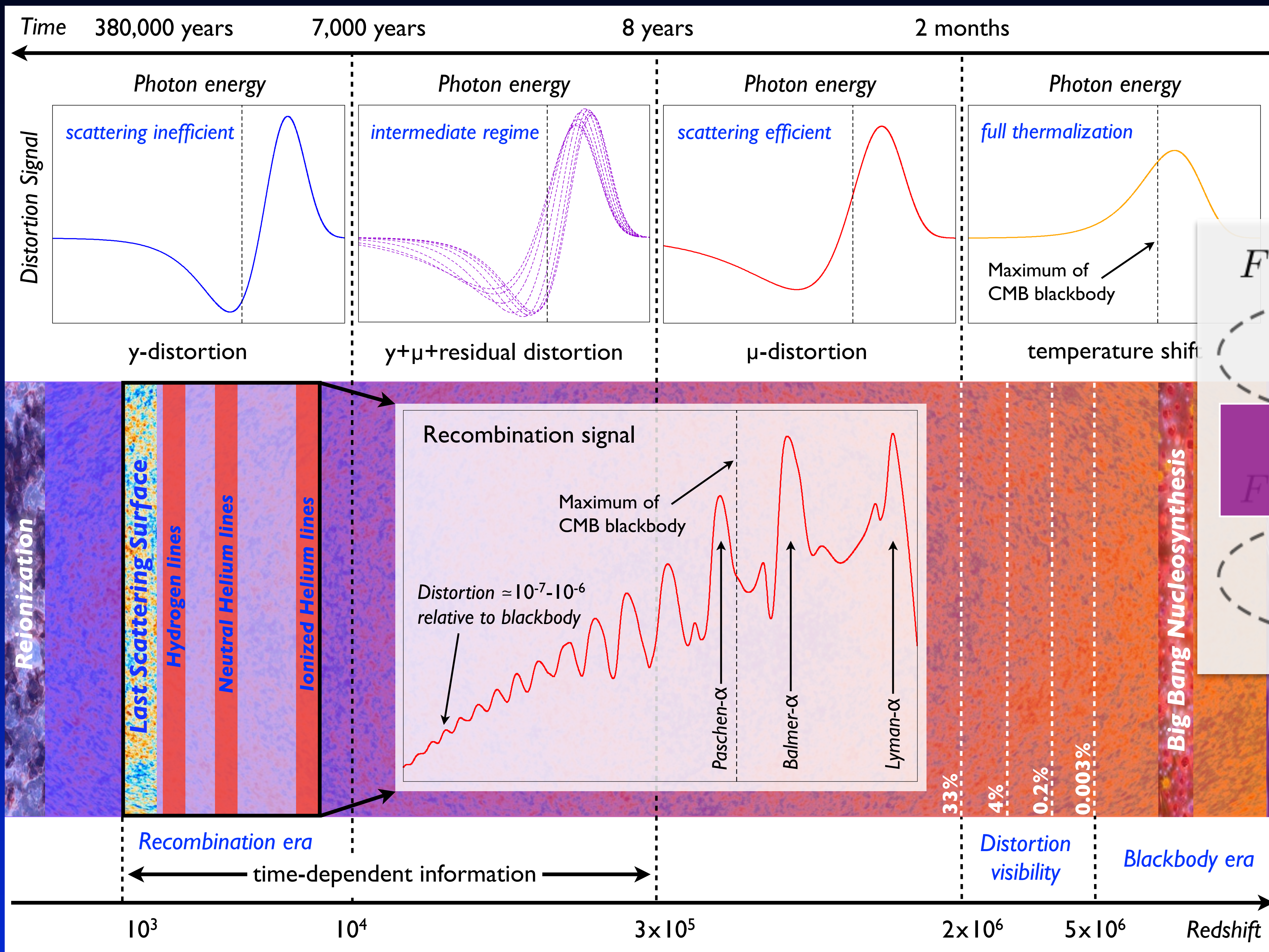

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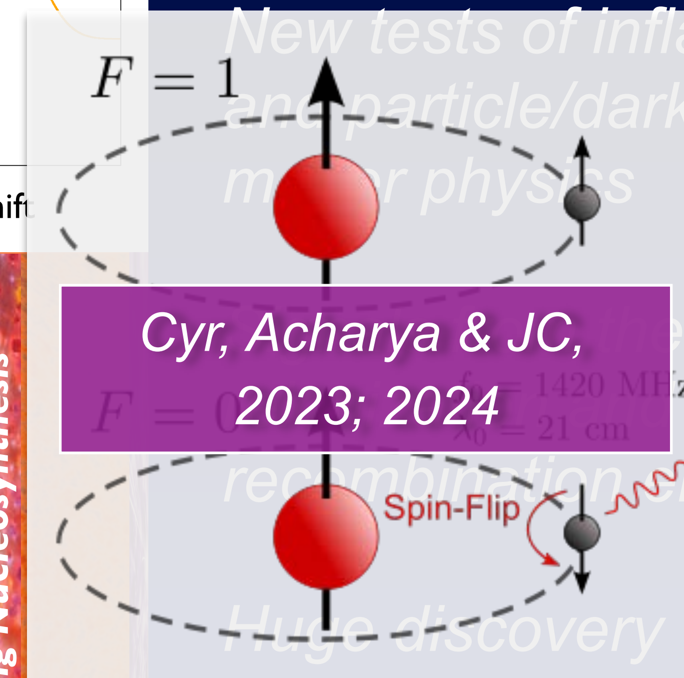

recombination eras

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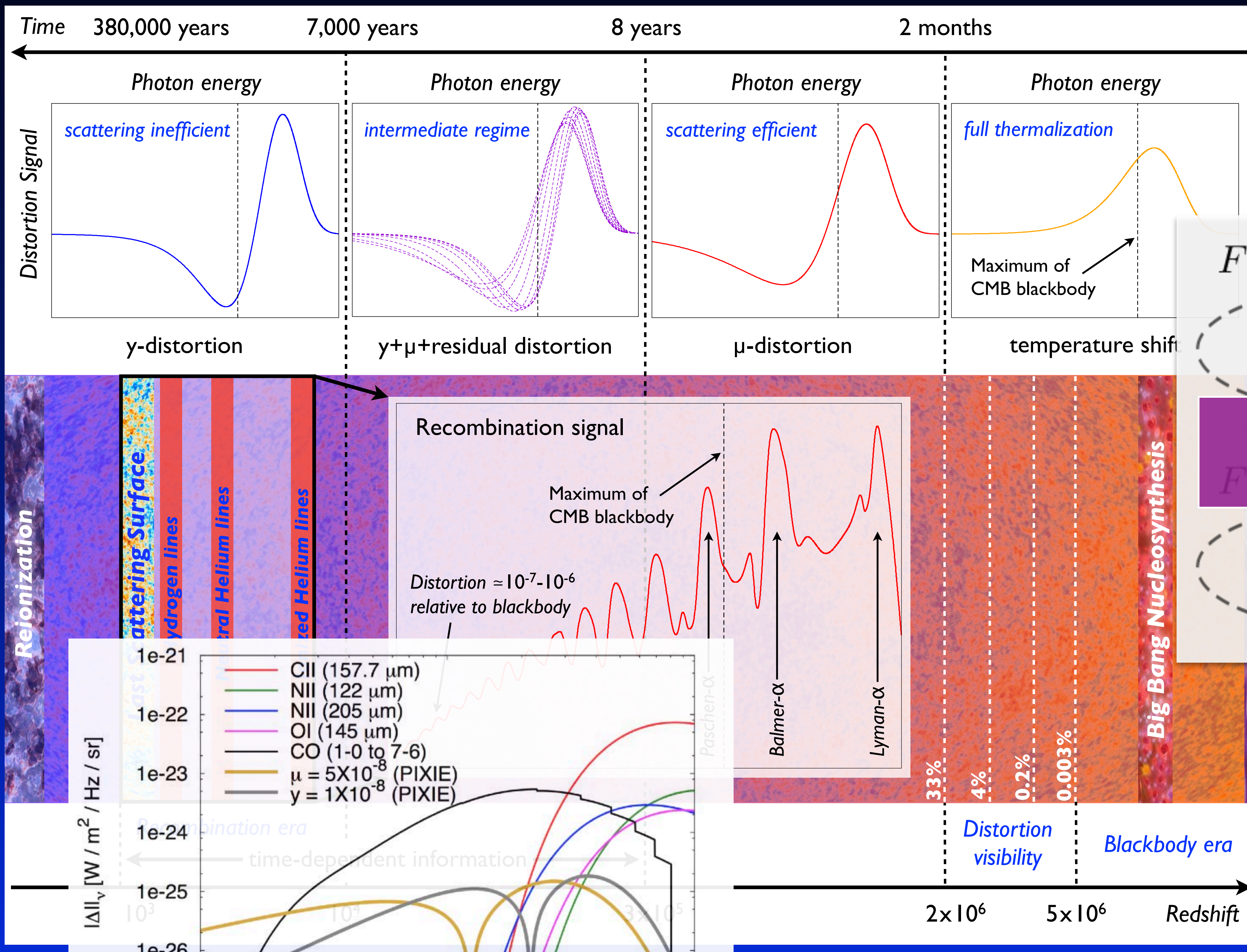

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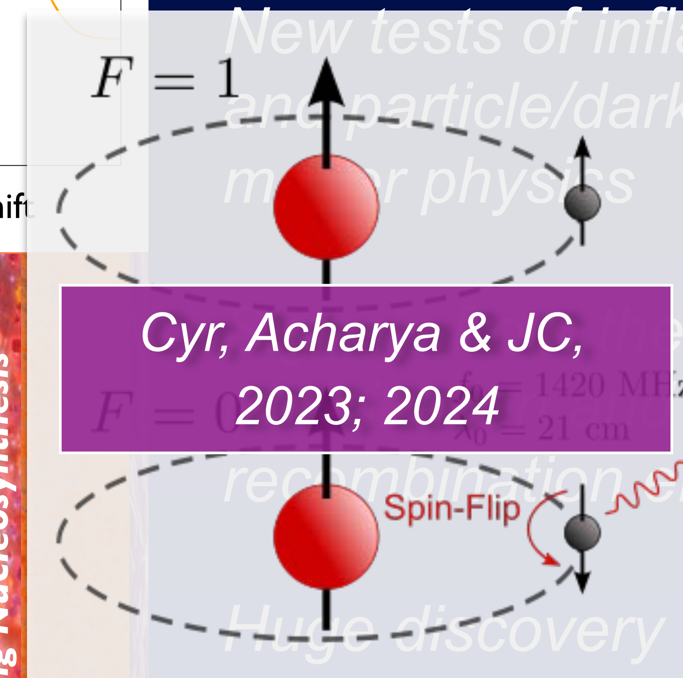

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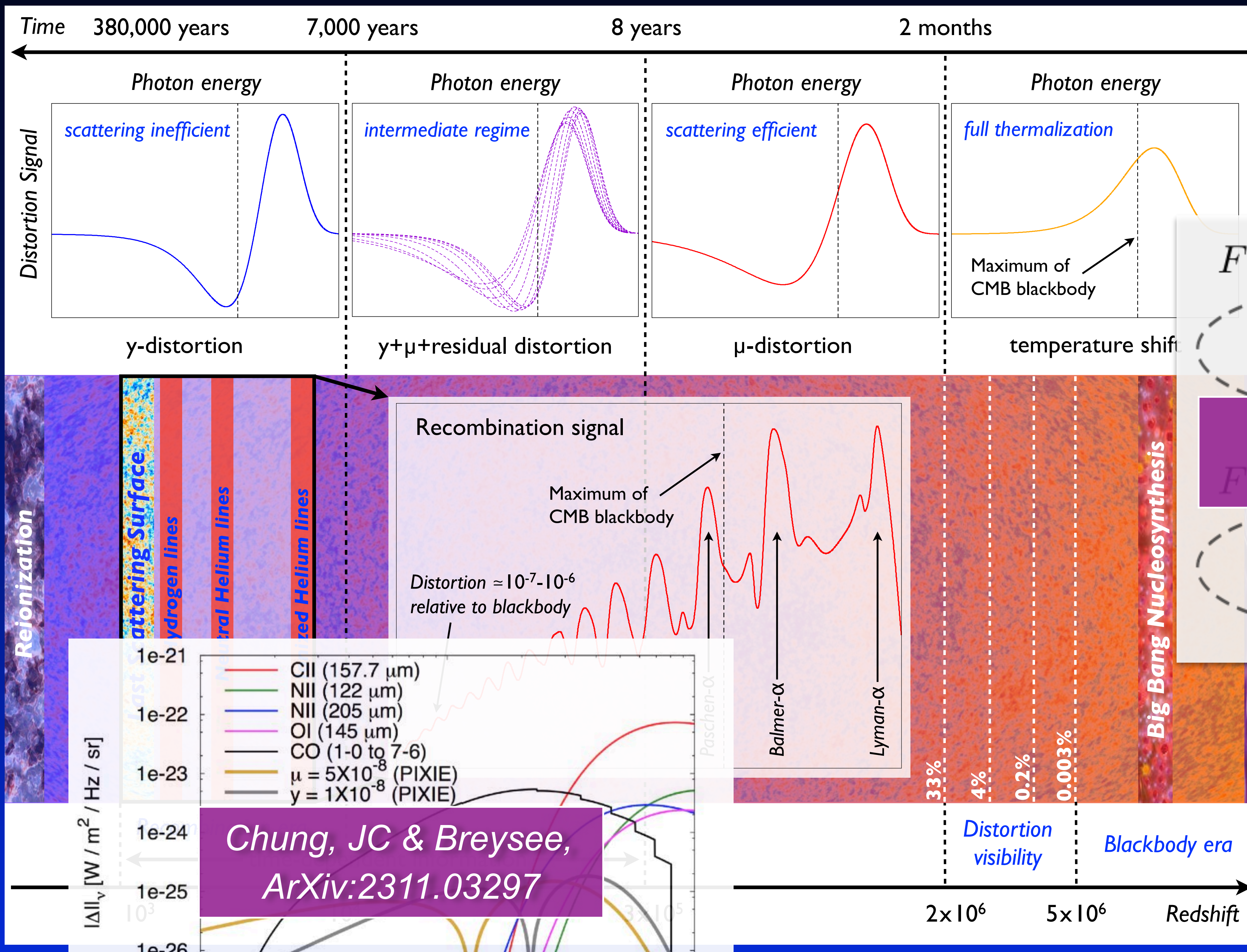

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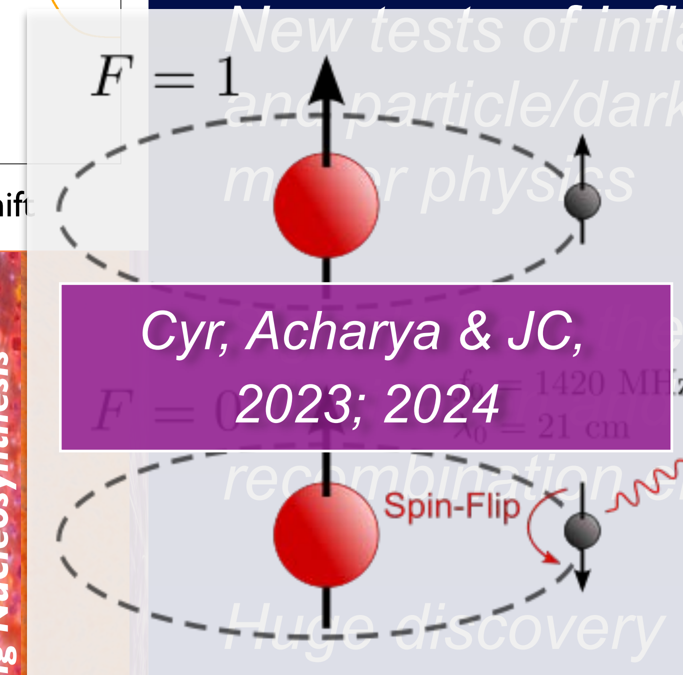

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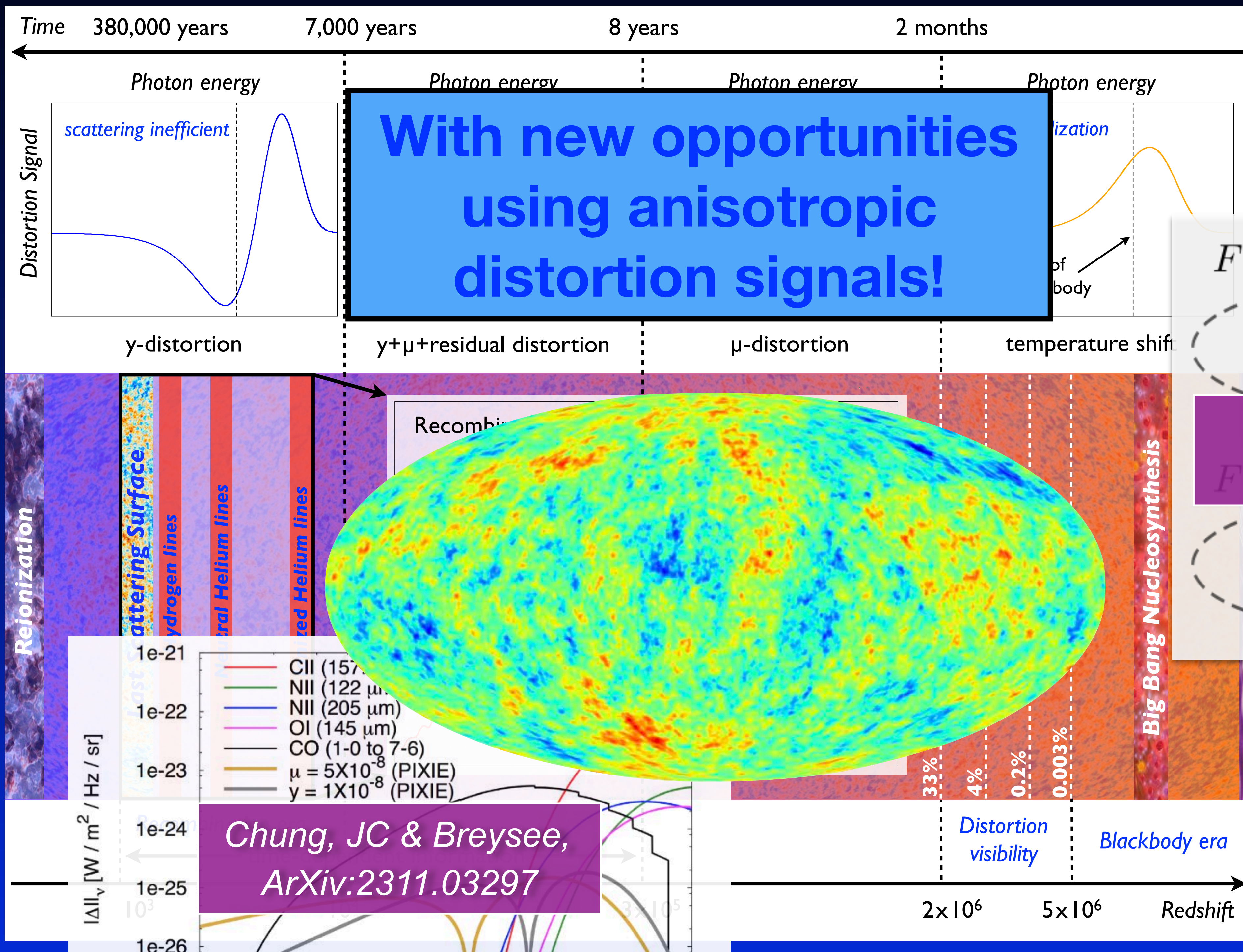
Uniqueness of CMB Spectral Distortion Science

Planck, Litebird, SKA, CMB-S4 & PICO



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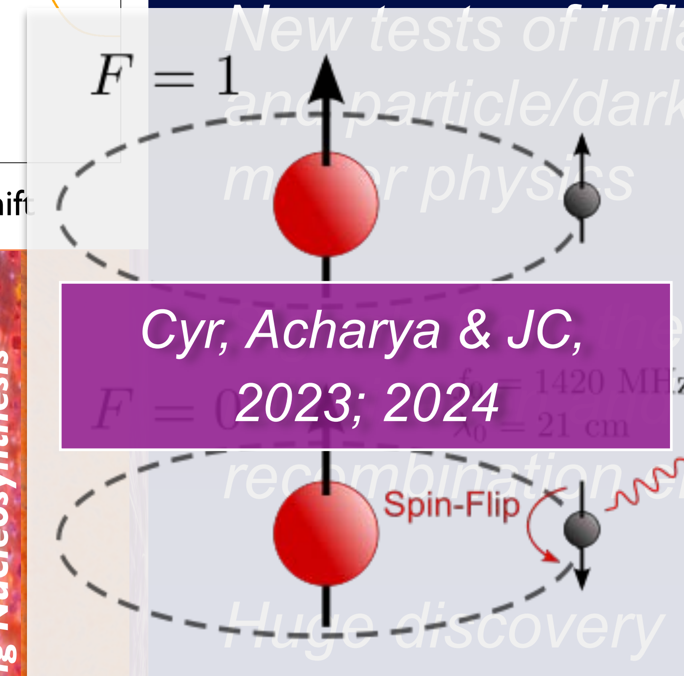

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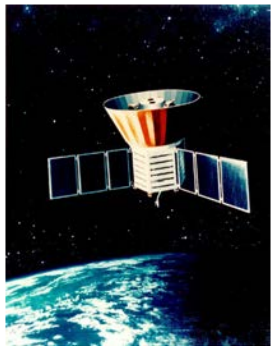
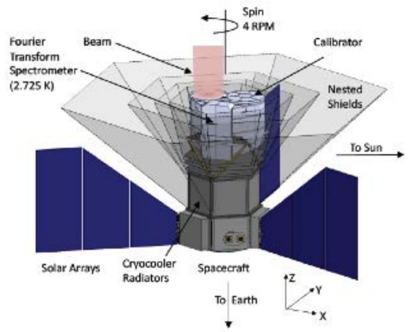
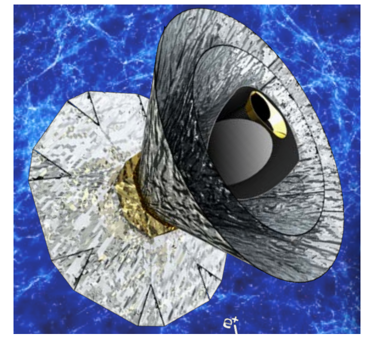
History of distortion experiments and proposals



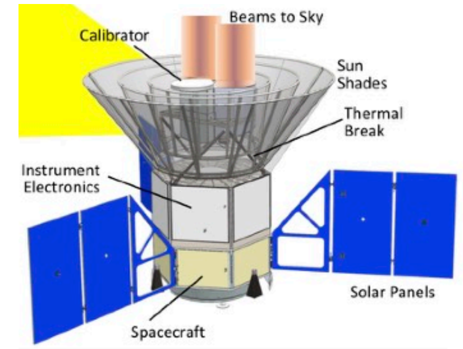
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



PRISM
De Bernardis



PIXIE
Kogut & Fixsen

Super-PIXIE

(PIXIE)

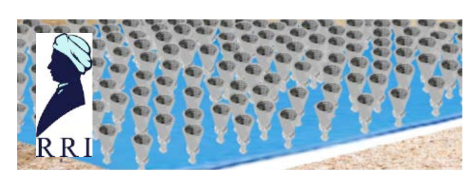
FOSSIL
Aghanim

PRISTINE
Aghanim

ARCADE 2
Kogut & Fixsen

Maffei
BISOU

TRIS
Gervasi, Zannoni & Tartari



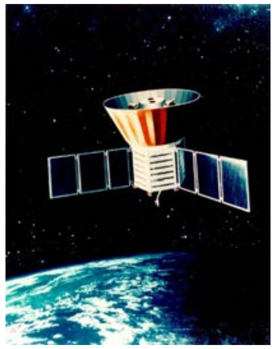
APSERa
Subrahmanyan & Rao

COSMO
De Bernardis, Masi & Battistelli

TMS
Rubiño-Martin

1989 — 2008 — 2011 — 2013 — 2015 — 2016 — 2018 — 2022

History of distortion experiments and proposals



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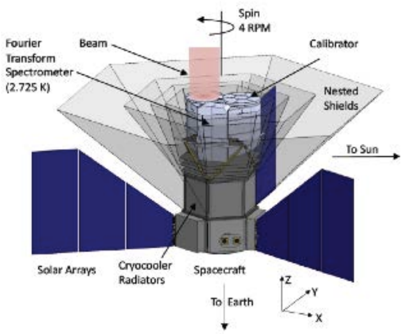

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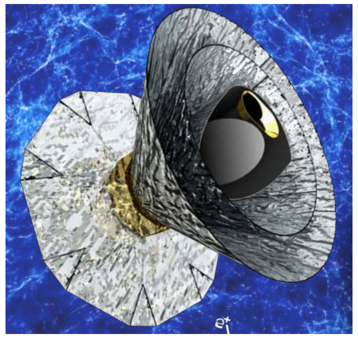
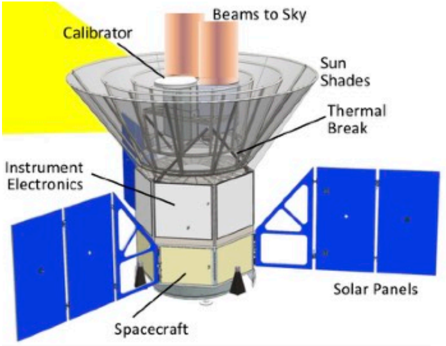


PRISM
De Bernardis



PIXIE
Kogut & Fixsen

Super-PIXIE

PRISTINE
Aghanim

(PIXIE)

FOSSIL
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ARCADE 2
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1989 ≀≀ 2008 2011 2013 2015 2016 2018 ~~2022~~ 2025

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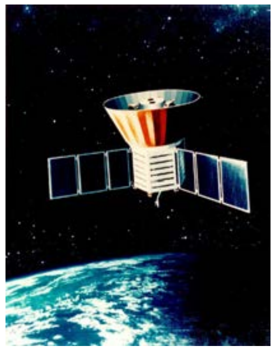

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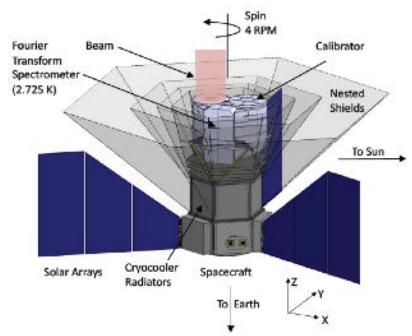
Mather & Fixsen



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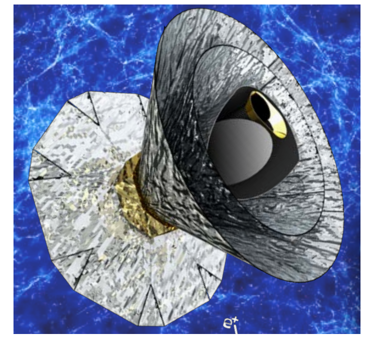

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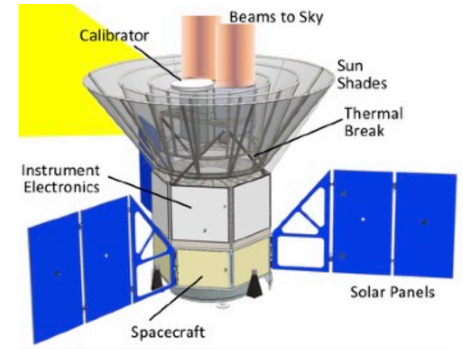
De Bernardis



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Super-PIXIE

(PIXIE)

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Not just fiction anymore!

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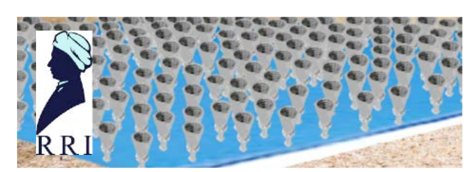

APSERa
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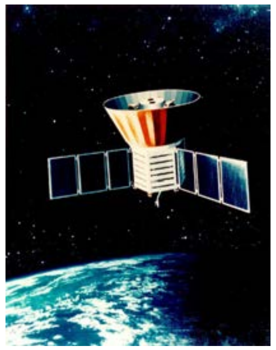
1989 | 2008 | 2011 | 2013 | 2015 | 2016 | 2018 | ~~2022~~ 2025

History of distortion experiments and proposals



COBE/FIRAS

Mather & Fixsen

(PIXIE)

XIE

FOSSIL

Aghanim

ei

TMS

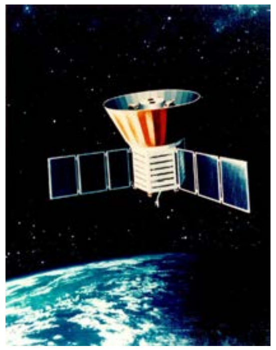
Rubiño-Martin

tistelli

1989 ~~2022~~ 2025

Browne & Wilkinson

History of distortion experiments and proposals



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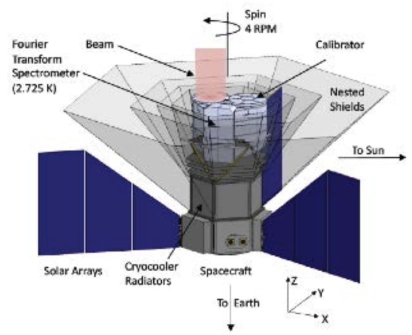
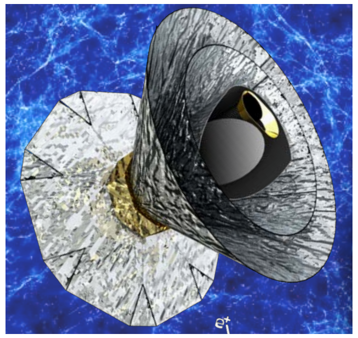


PIXIE

Kogut & Fixsen



PRISM

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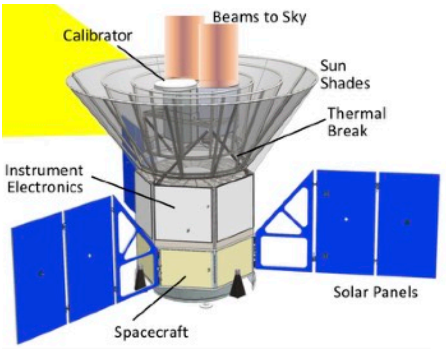

PIXIE

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FOSSIL M8

(PIXIE)

FOSSIL

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TRIS

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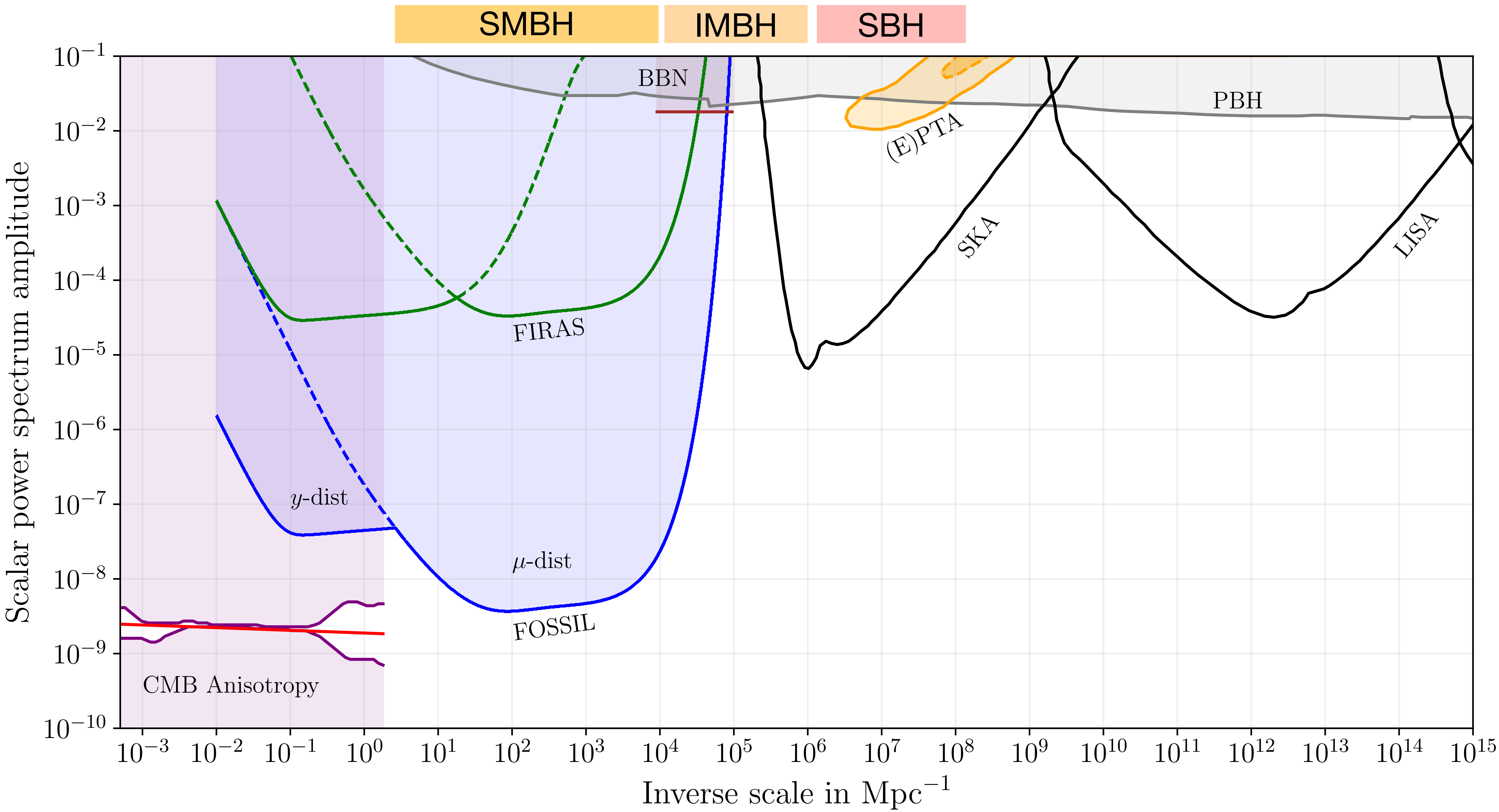
1989 2008 2011 2013 2015 2016 2018 ~~2022~~ 2025

Exploring the small-scale Universe



Cyr et al, 2024, MNRAS (ArXiv:2309.02366)

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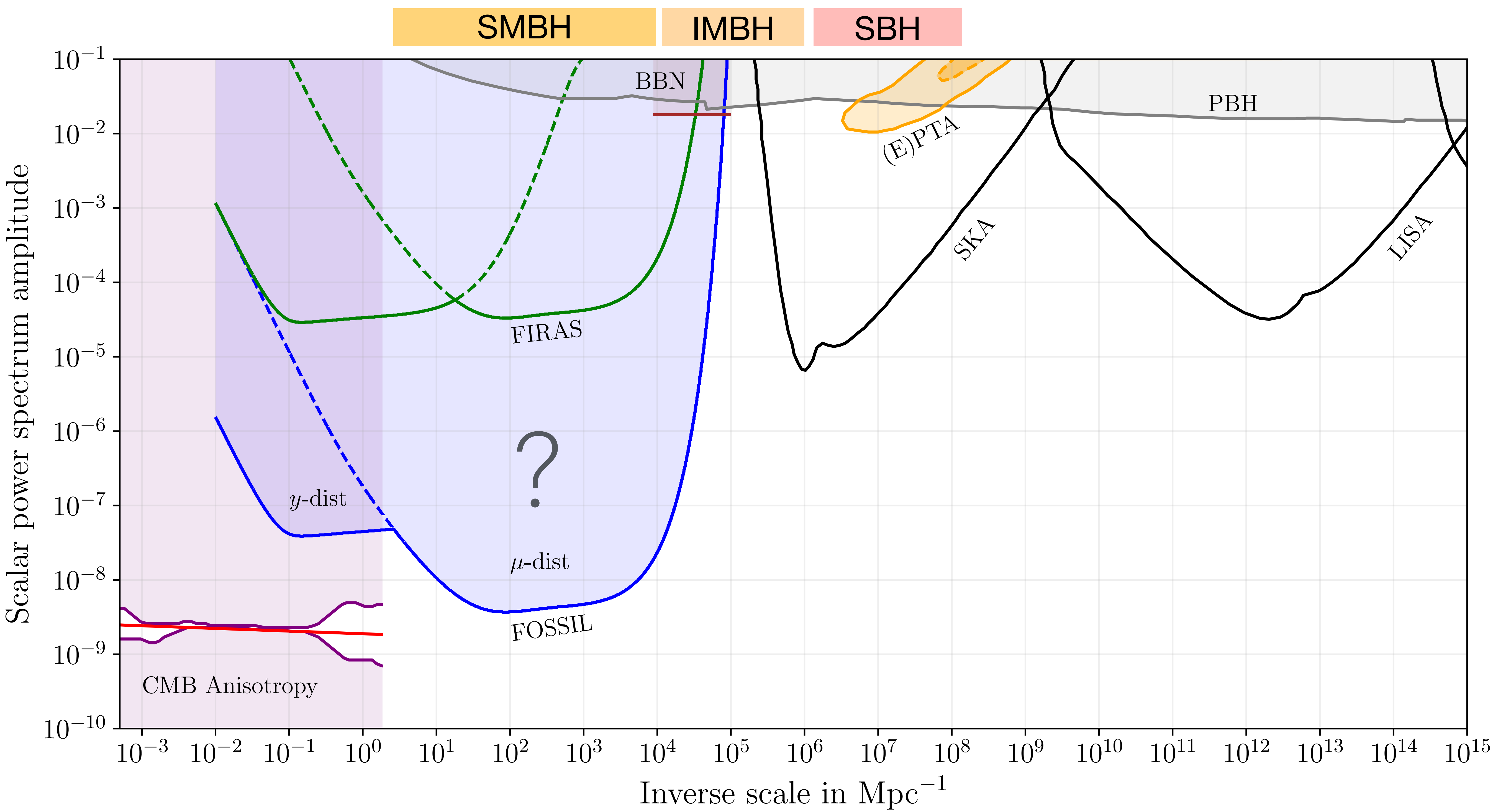

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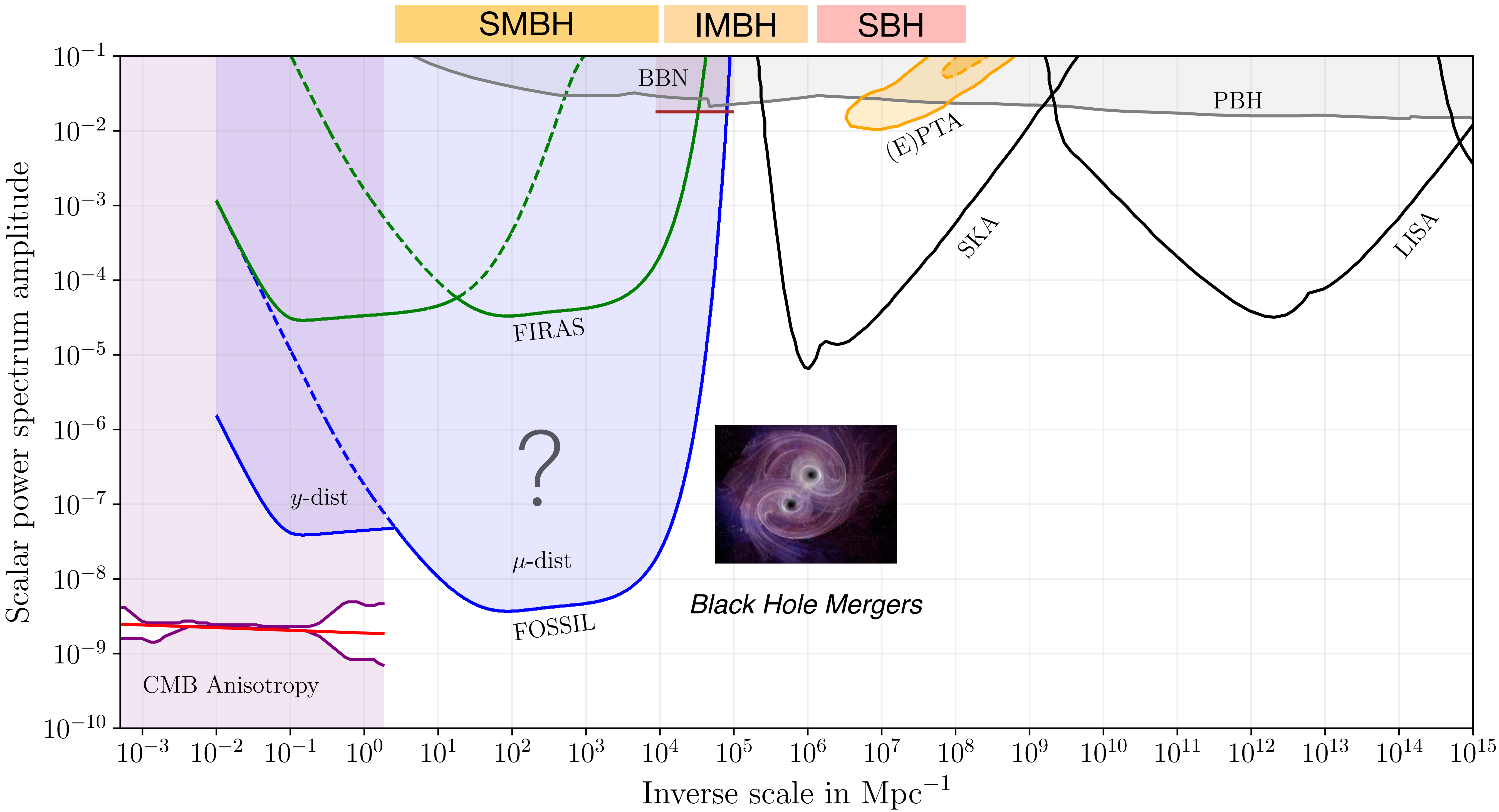

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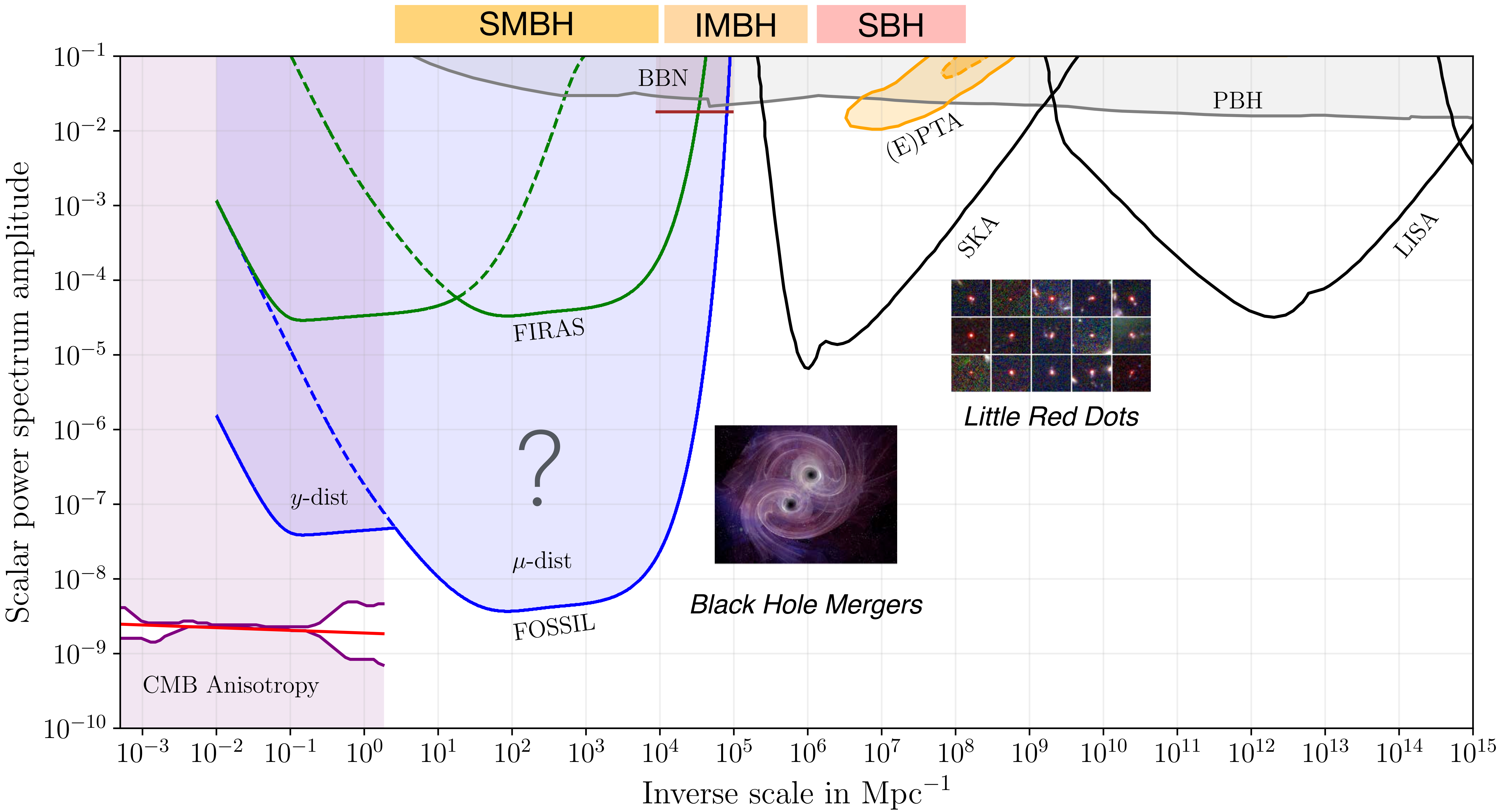

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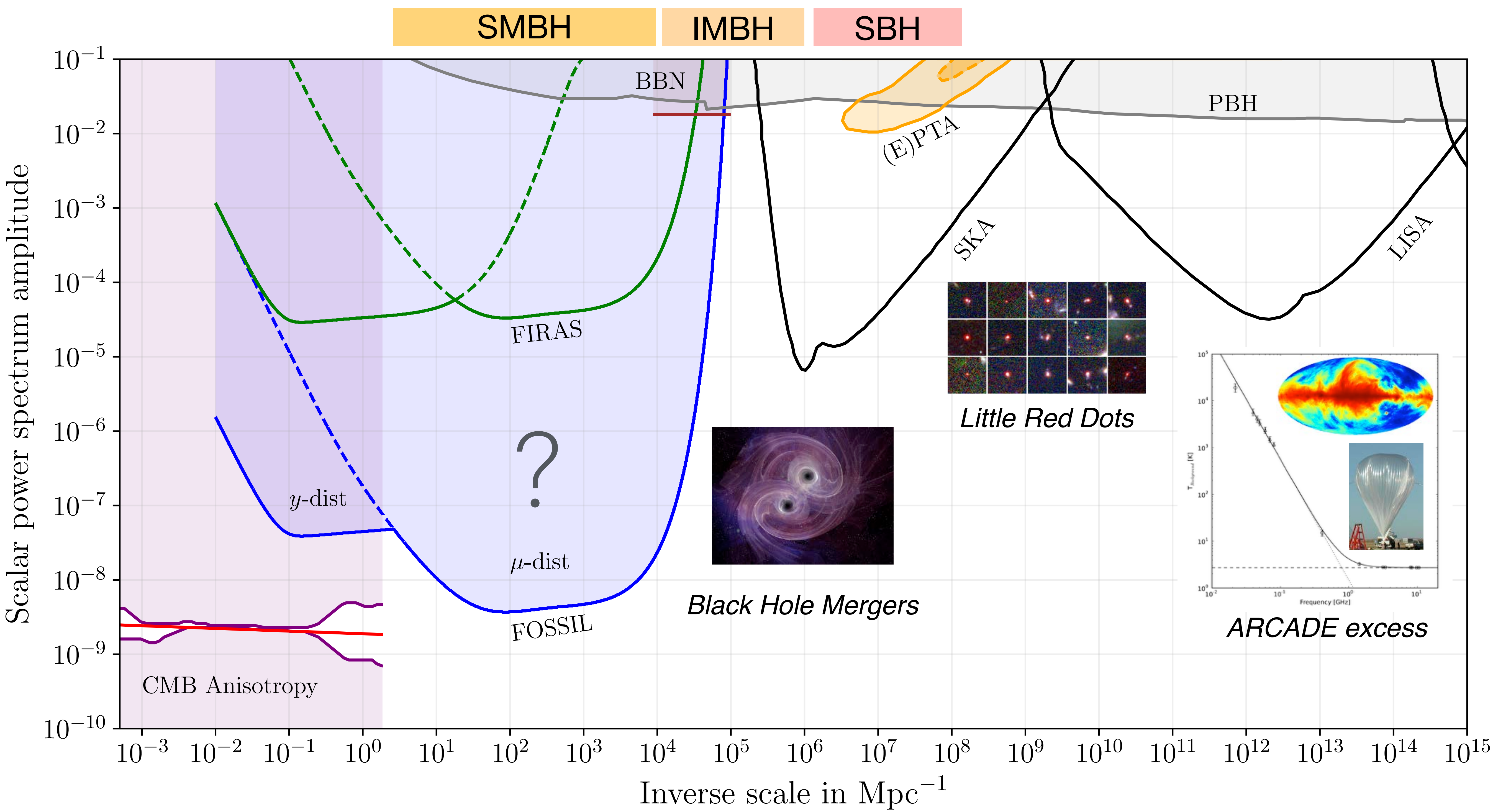

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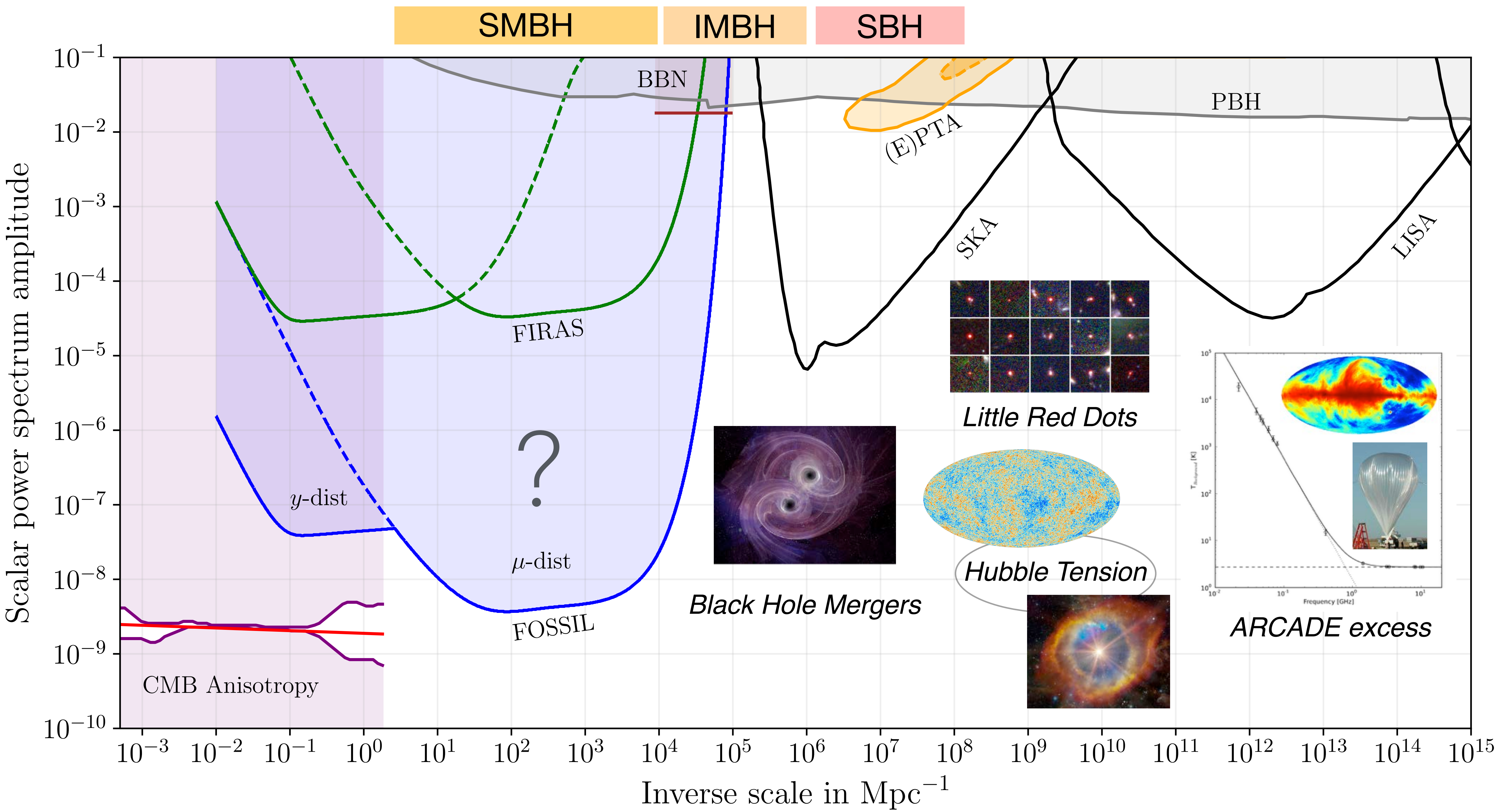
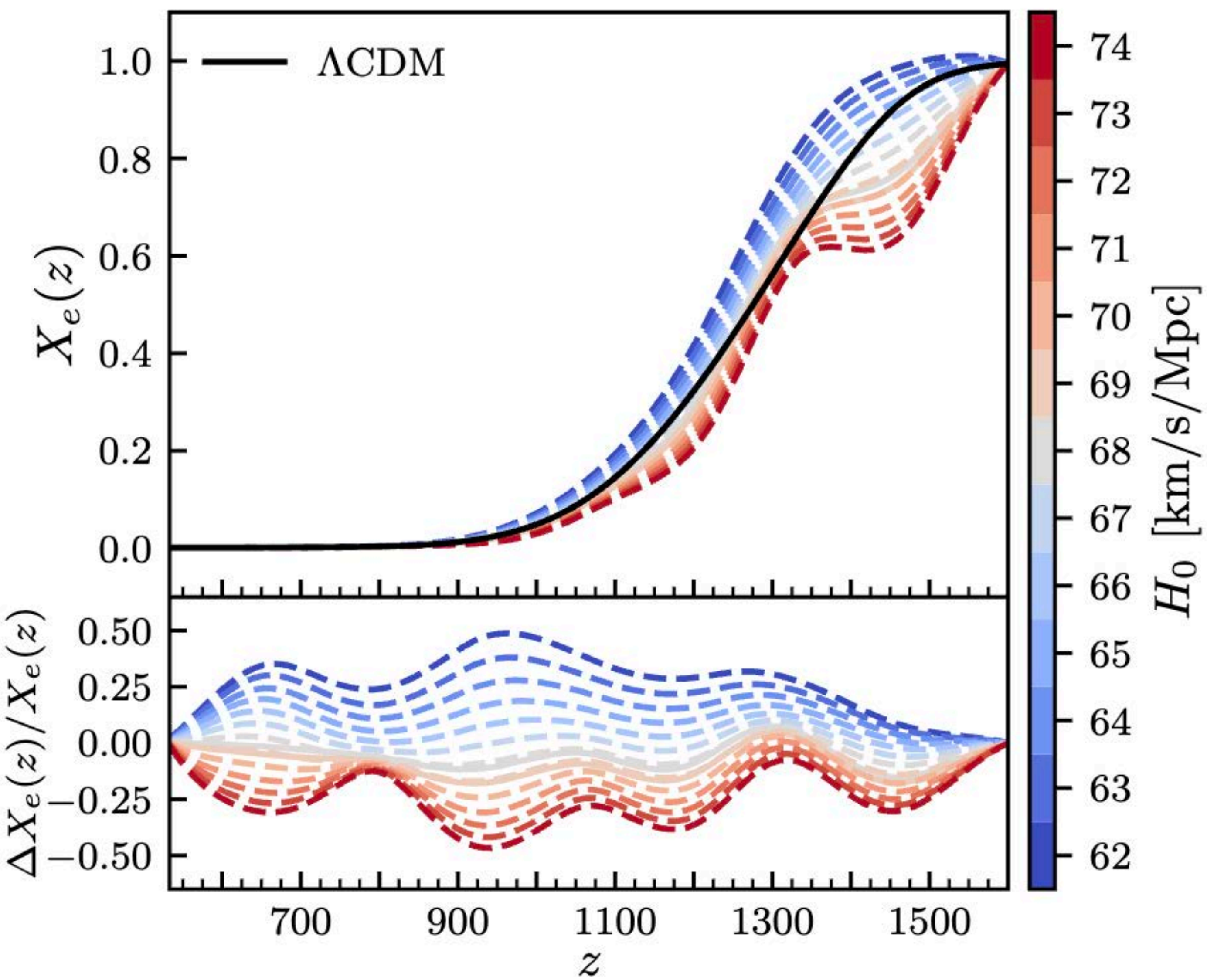
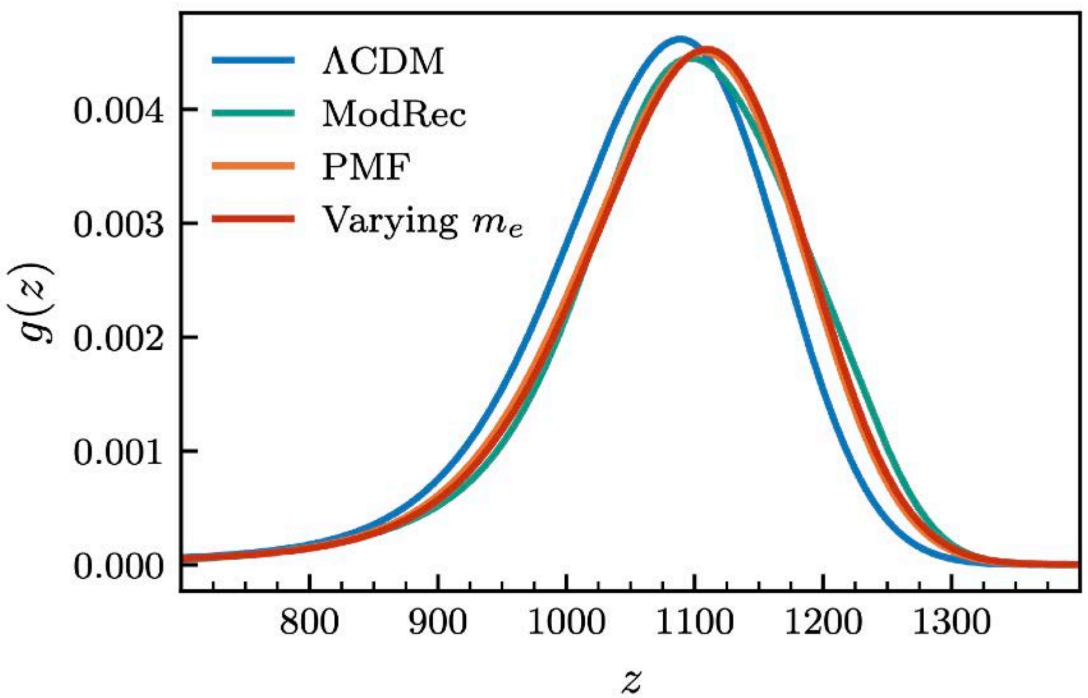
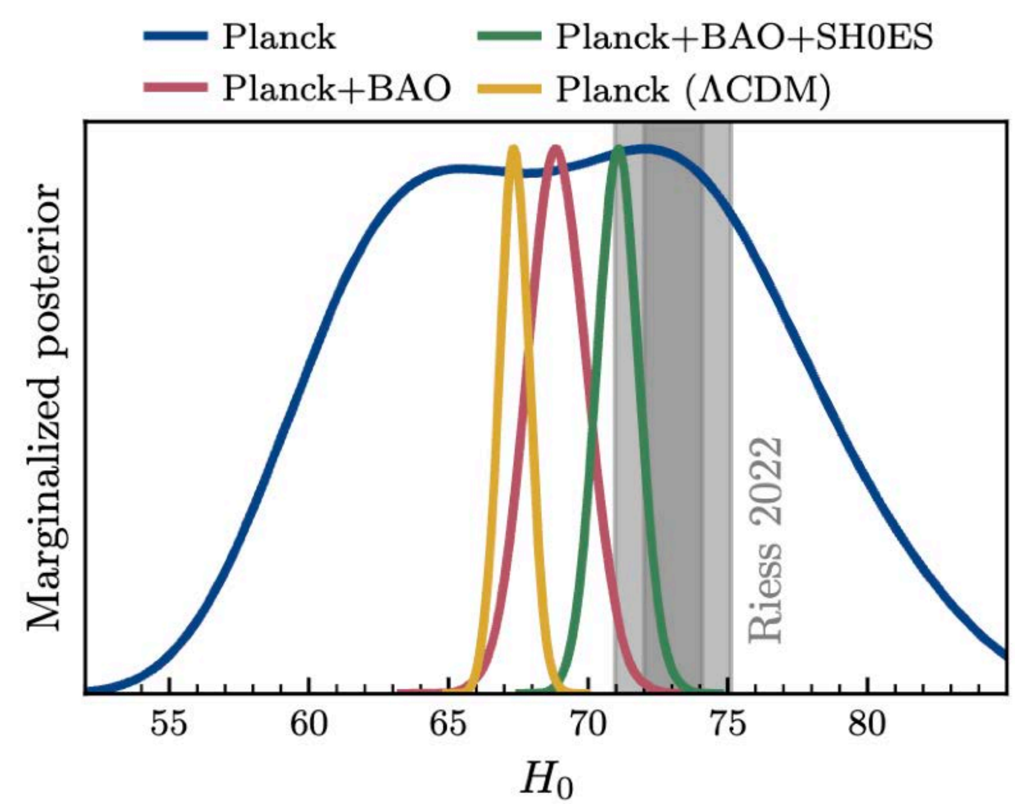


Cyr et al, 2024, MNRAS (ArXiv:2309.02366)

Cosmological data seems to be preferring early recombination scenarios!



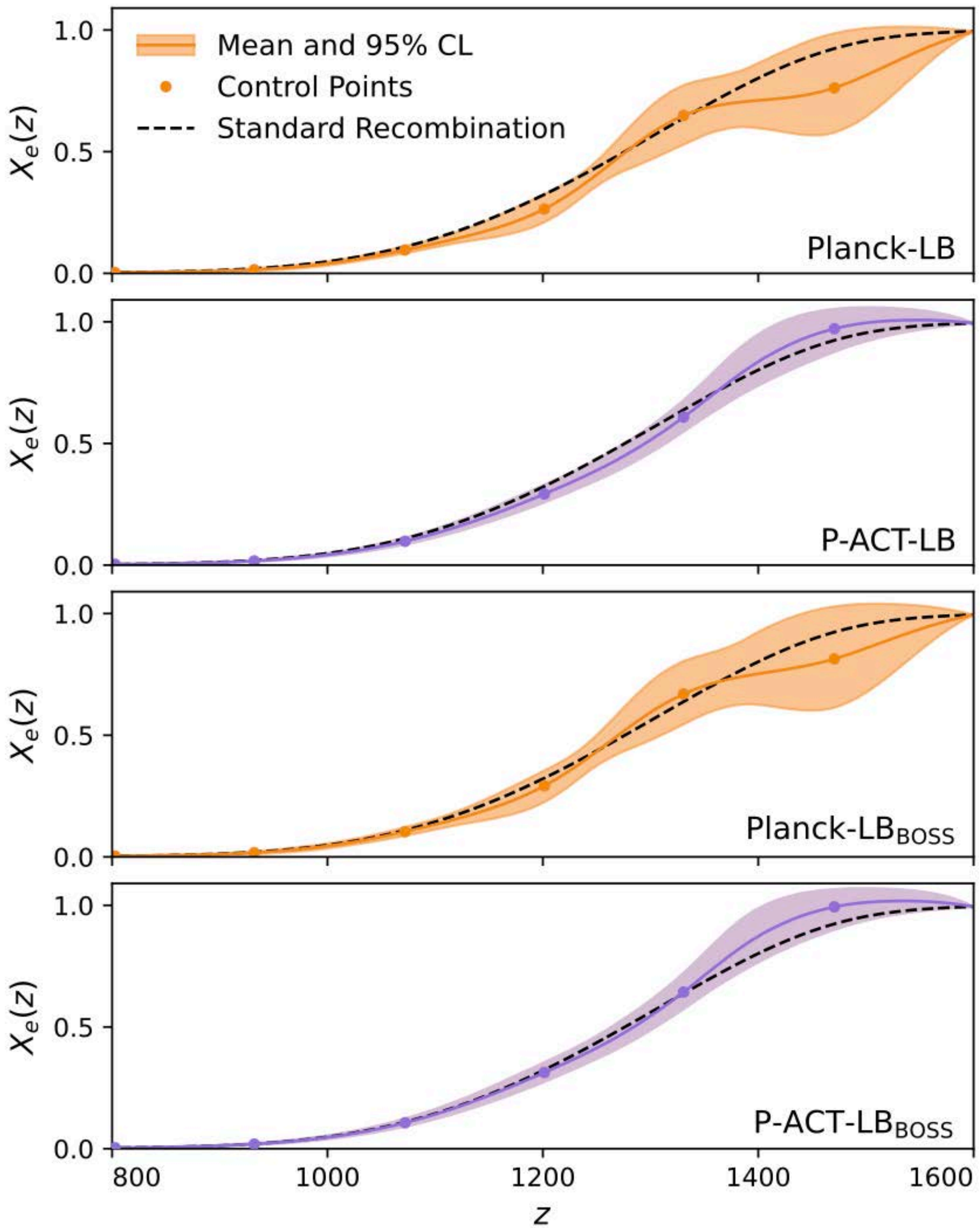


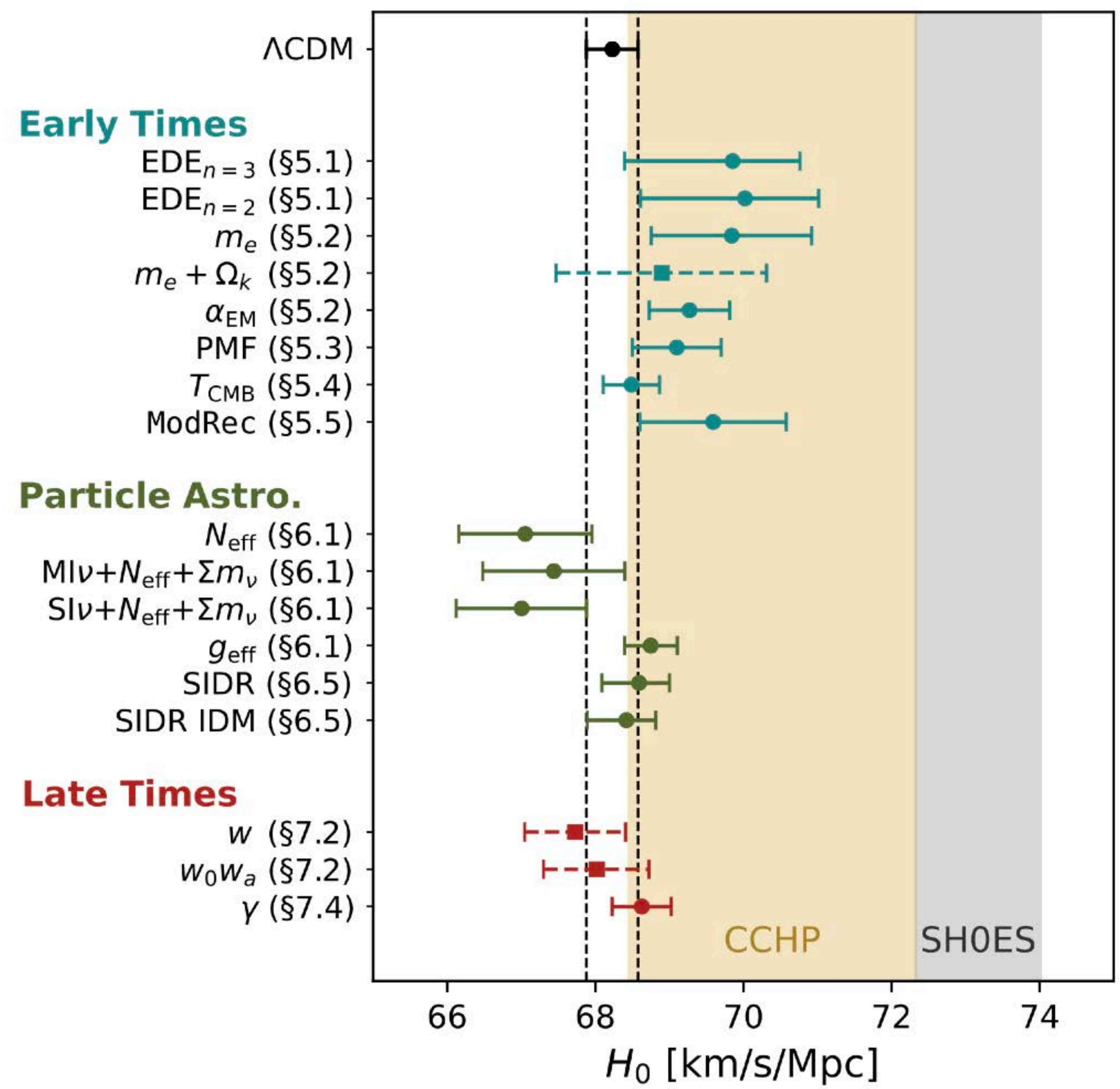


Model-independent reconstruction of free electron fraction using Emulators

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

ACT Study of Extended Cosmological Models

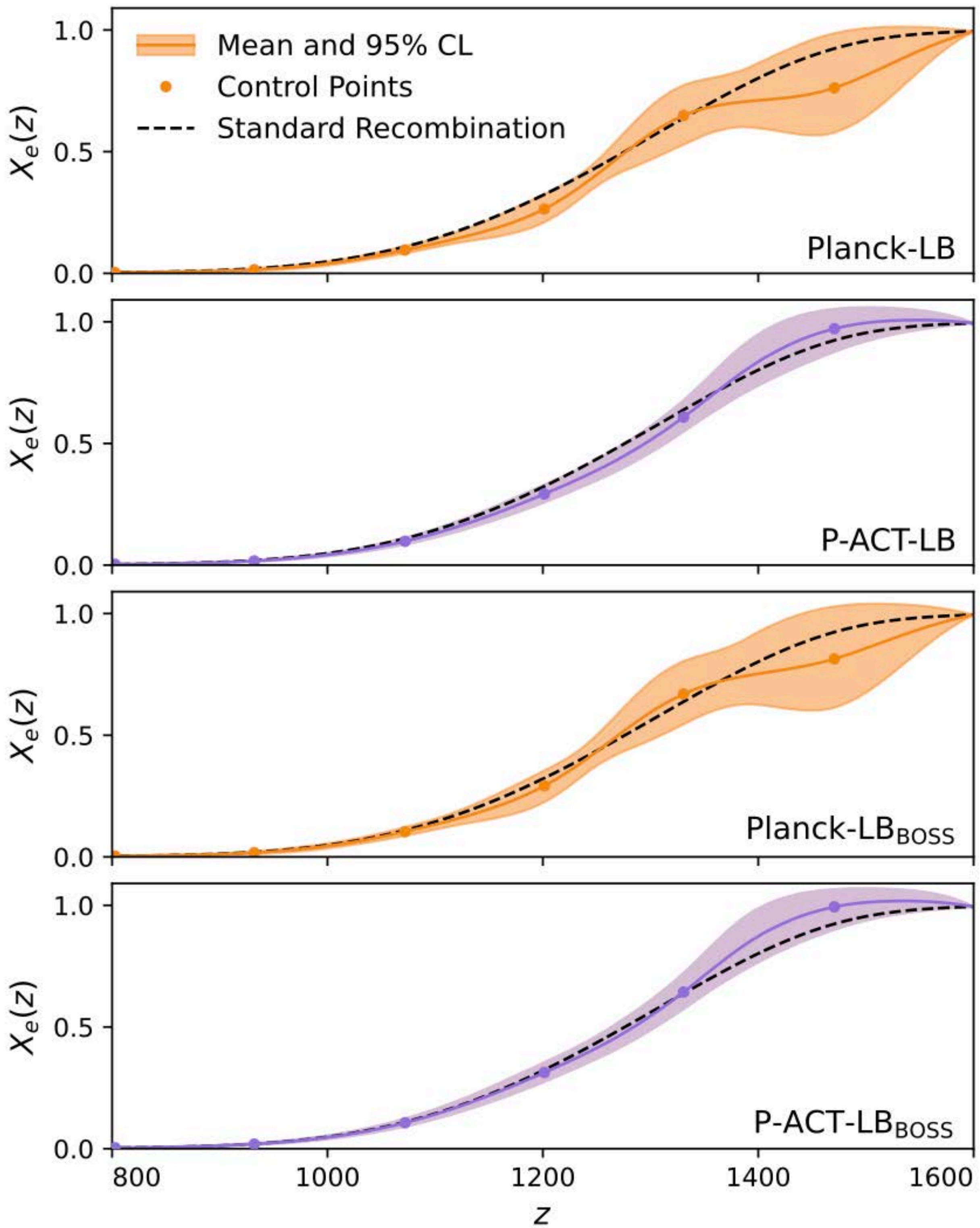


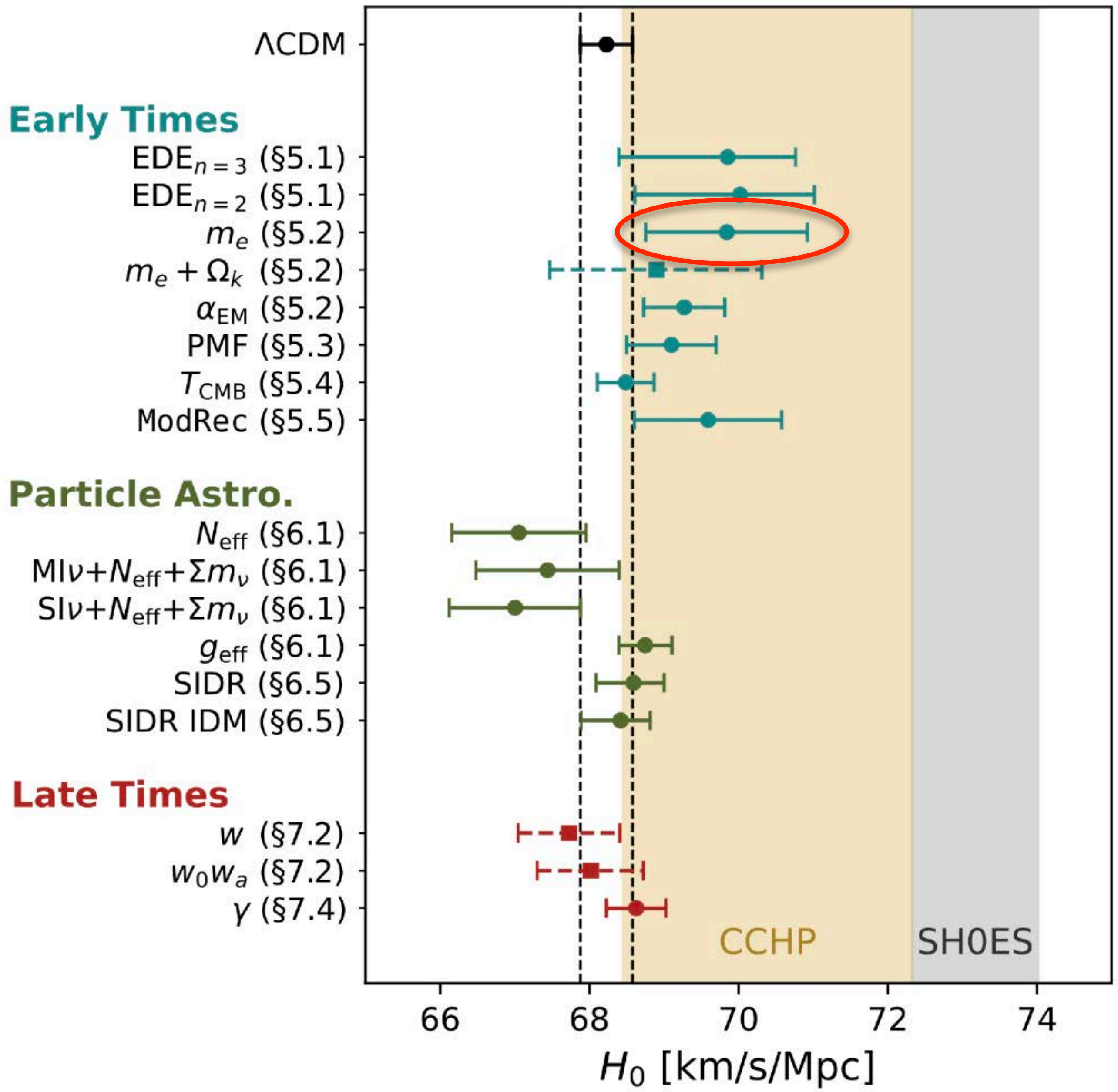


Modified recombination scenarios do quite well in comparison to other HT solutions!

Calabrese et al., ArXiv:2503.14454

ACT Study of Extended Cosmological Models





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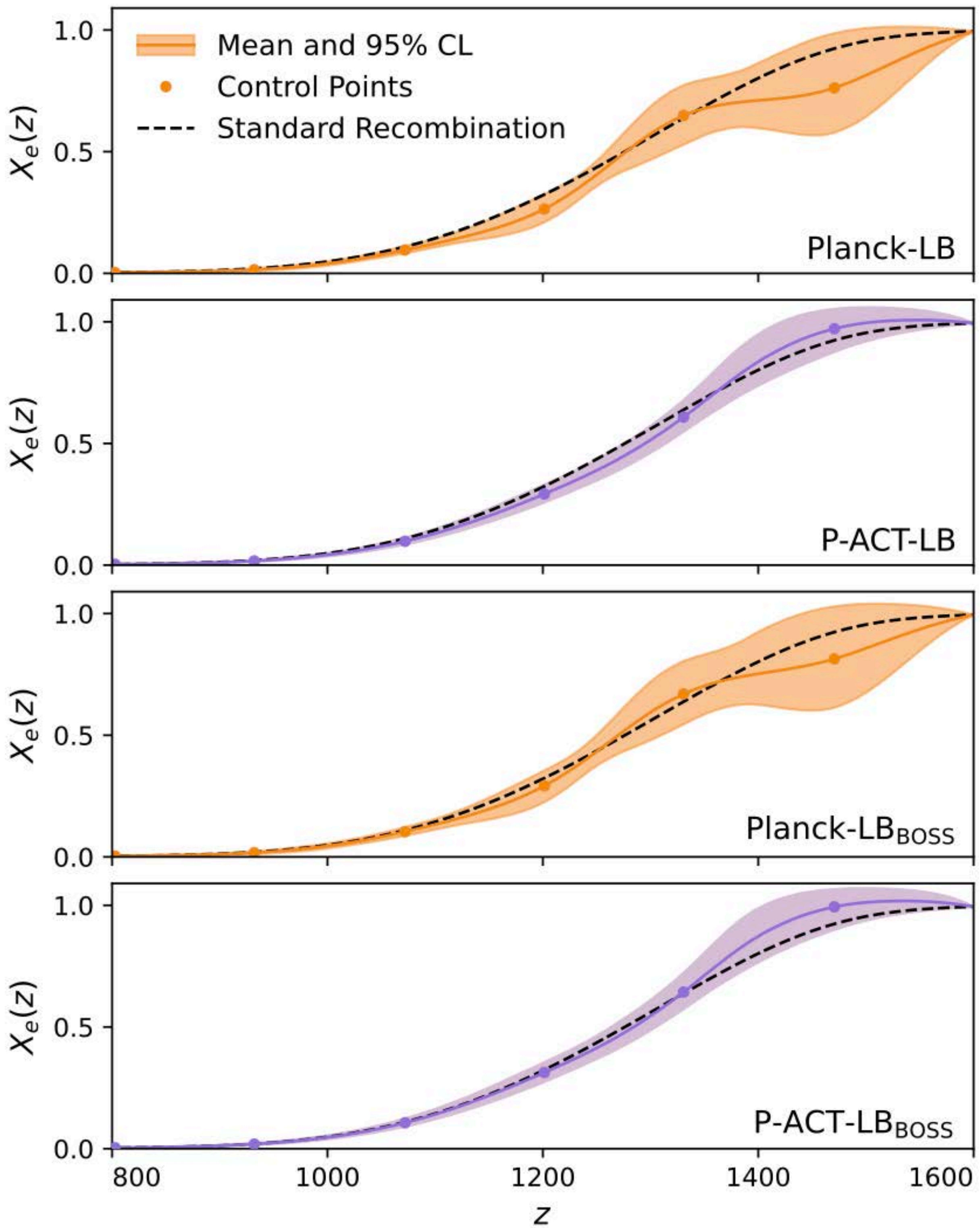
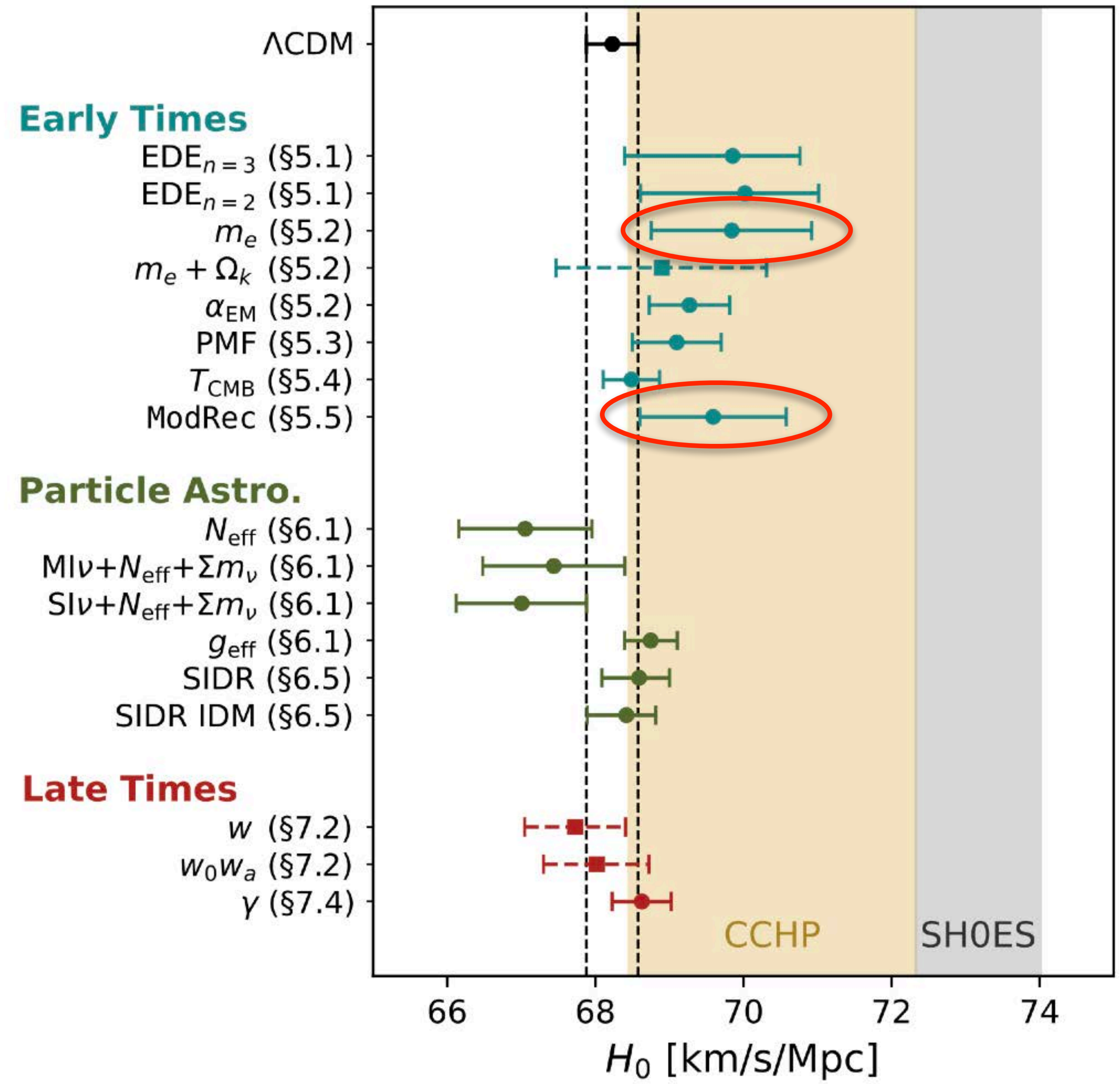
Calabrese et al., ArXiv:2503.14454

ACT Study of Extended Cosmological Models





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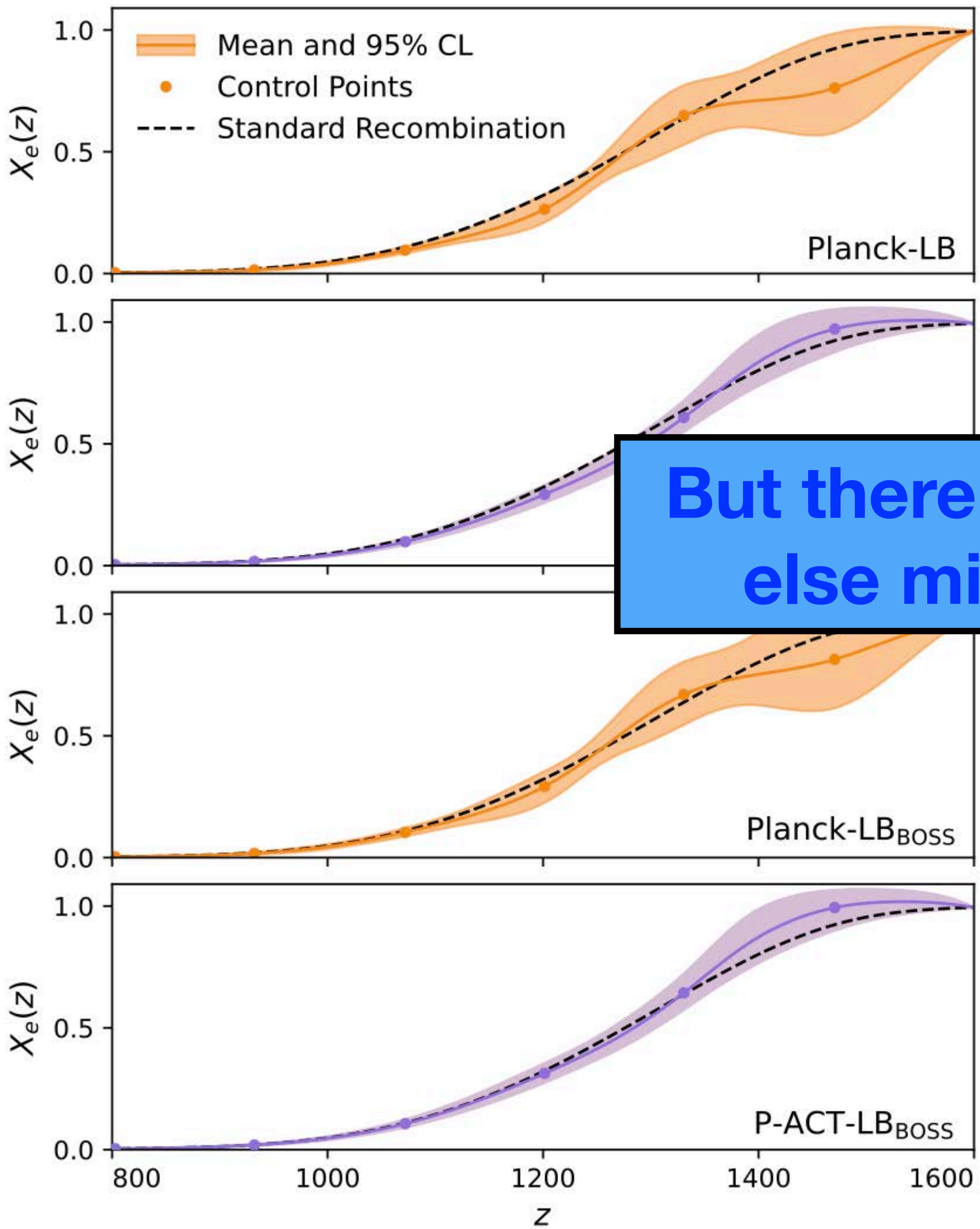
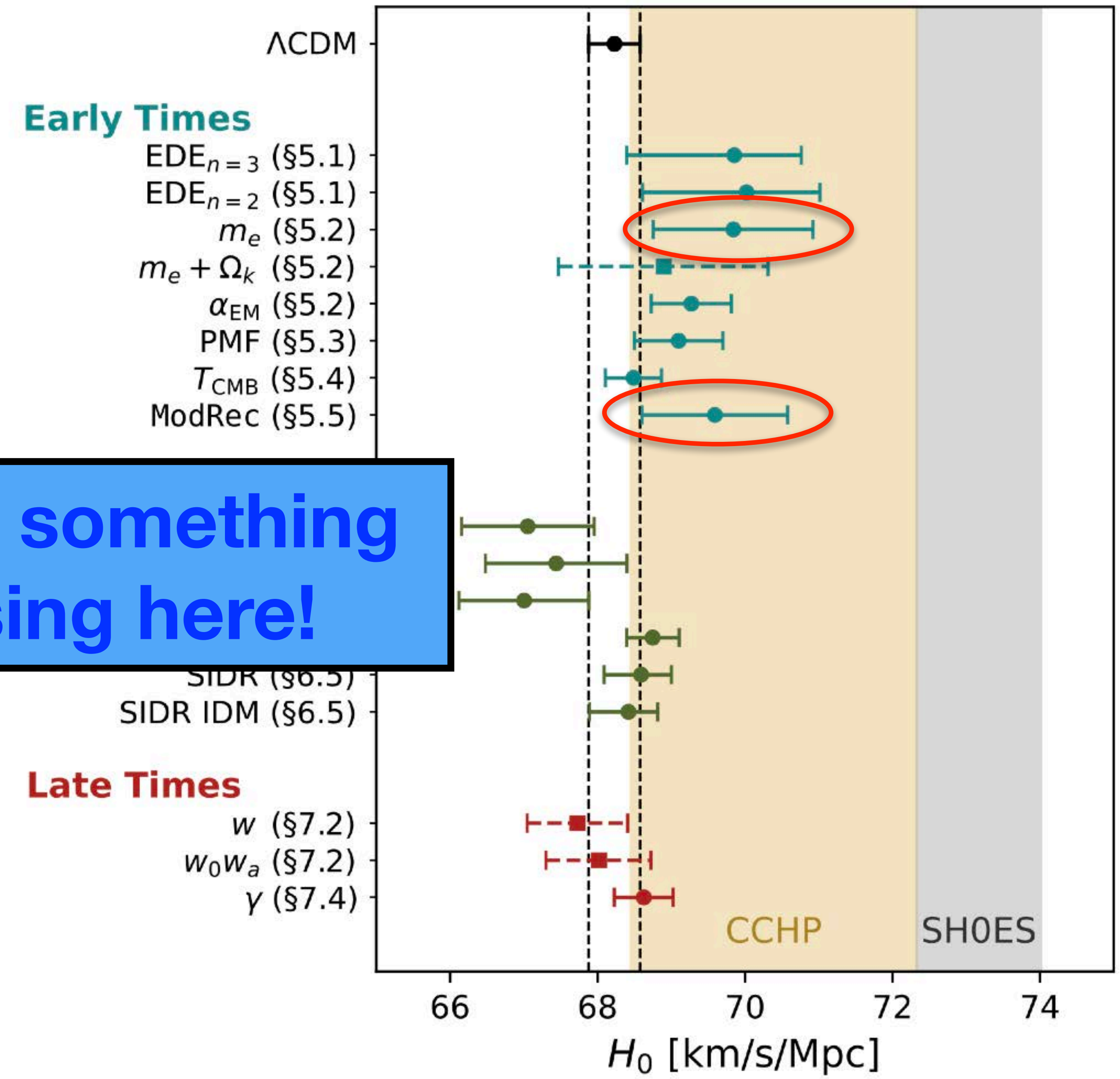




But there is something else missing here!

Modified recombination scenarios do quite well in comparison to other HT solutions!

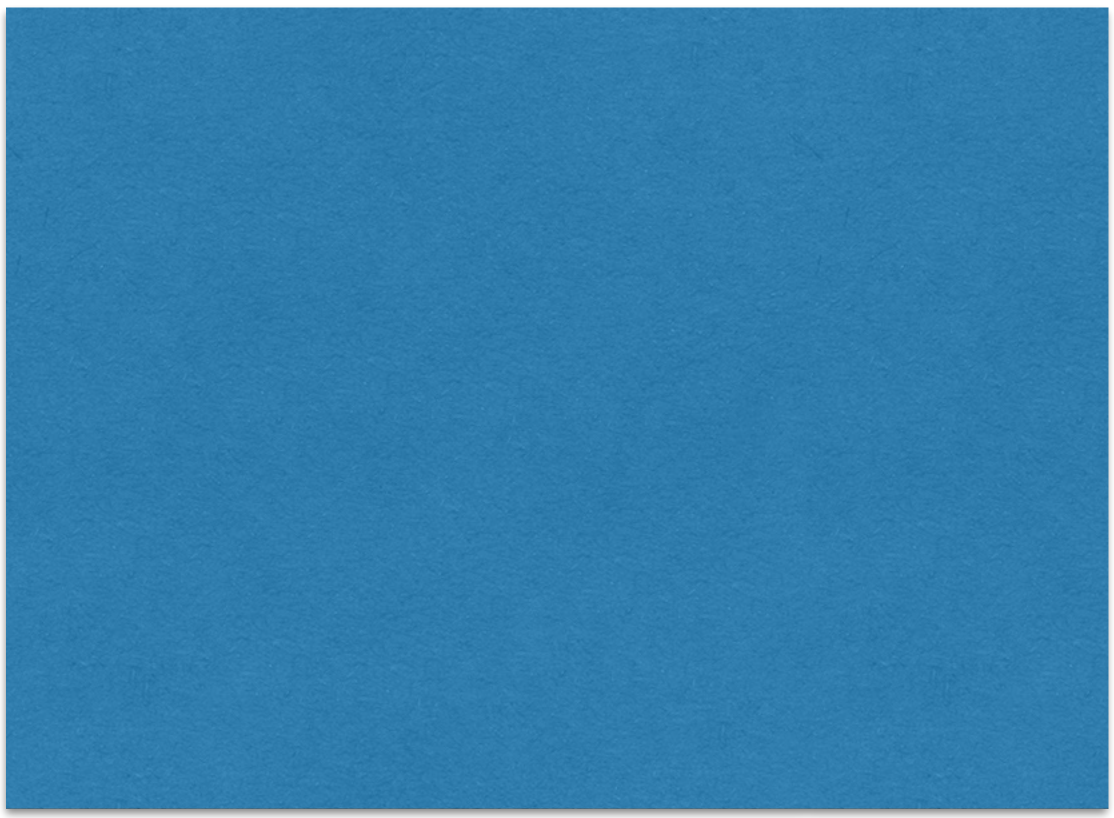
Calabrese et al., ArXiv:2503.14454

The two main effects of baryon clumping at very small scales

JC, Vasil & Battye, ArXiv:2505.22242

The two main effects of baryon clumping at very small scales

Uniform medium



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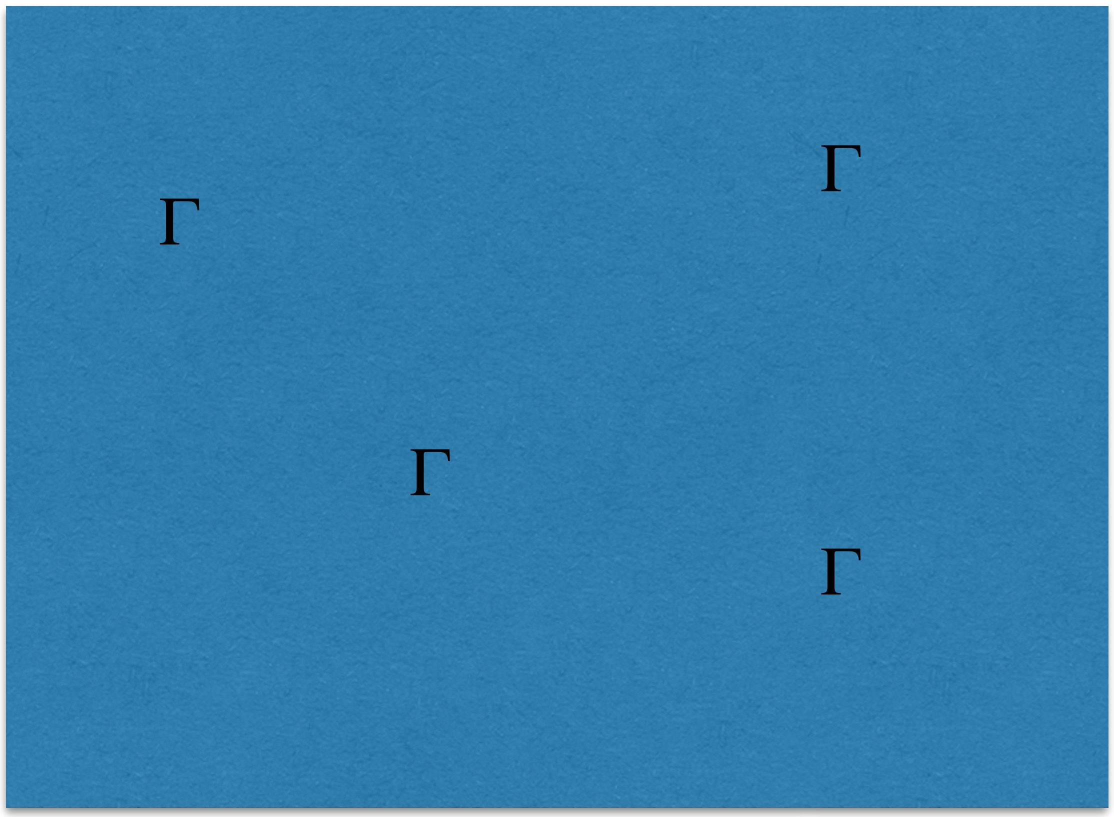

$$\Gamma = \sigma_{\rm T} N_{\rm e} a$$

JC, Vasil & Battye, ArXiv:2505.22242

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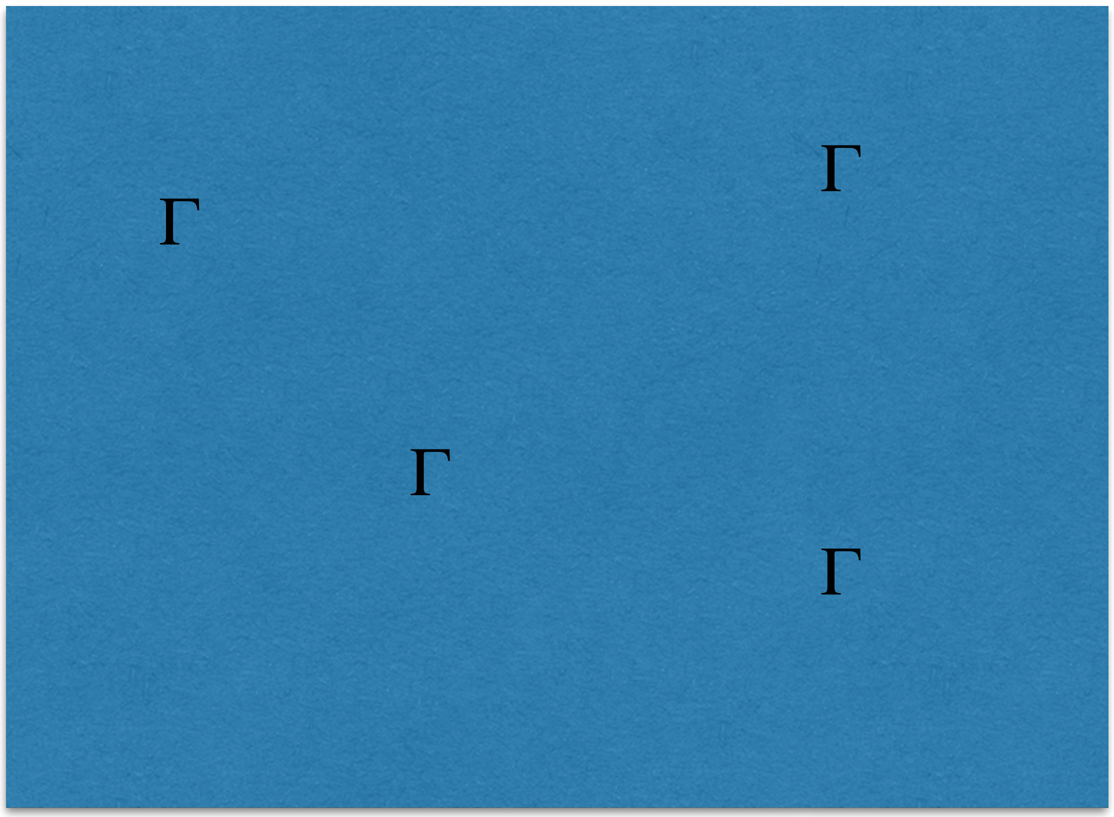
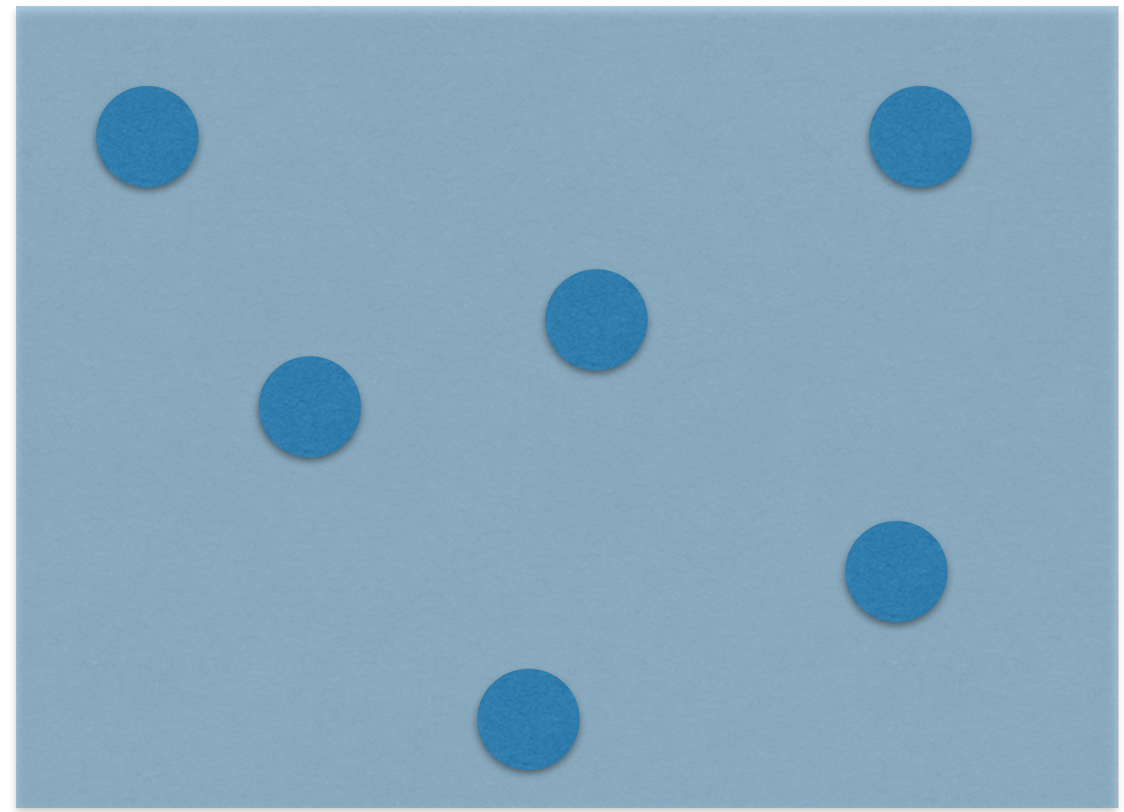


Clumpy medium



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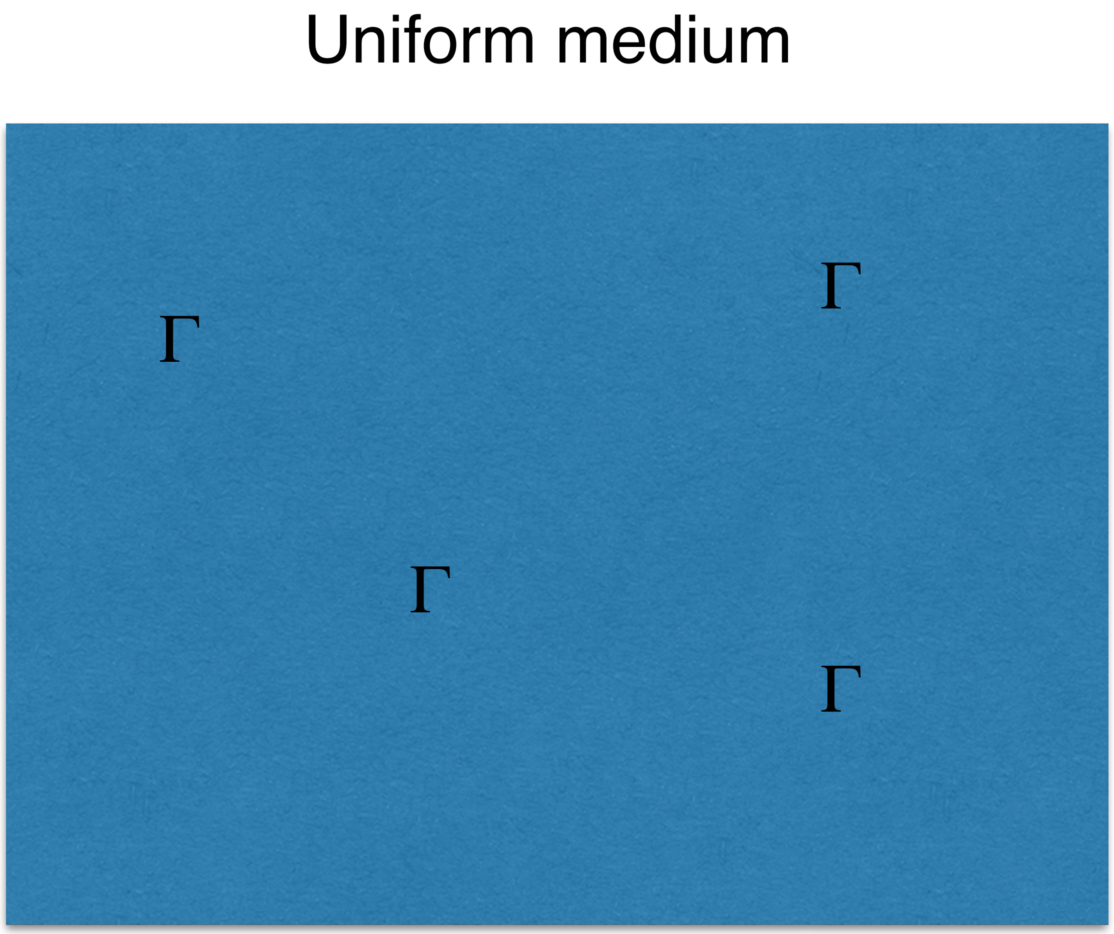

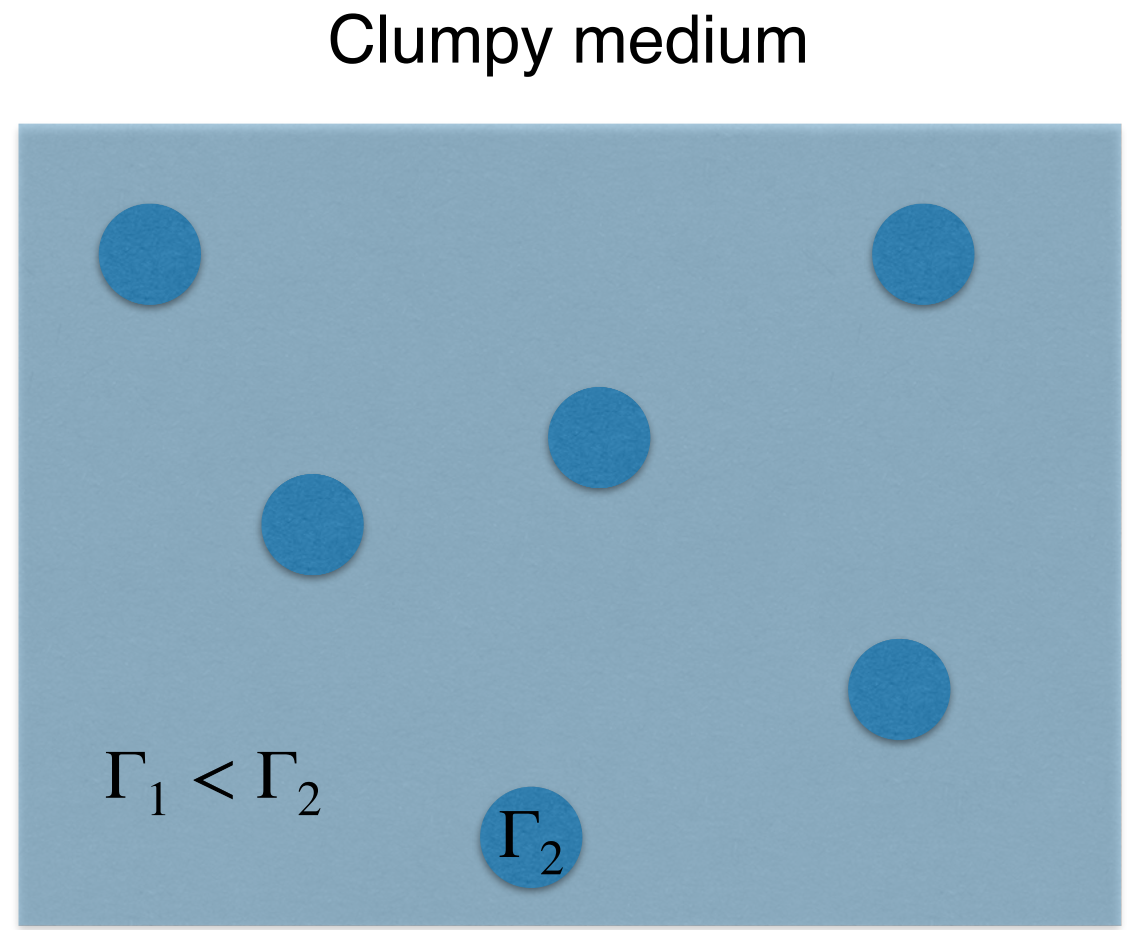

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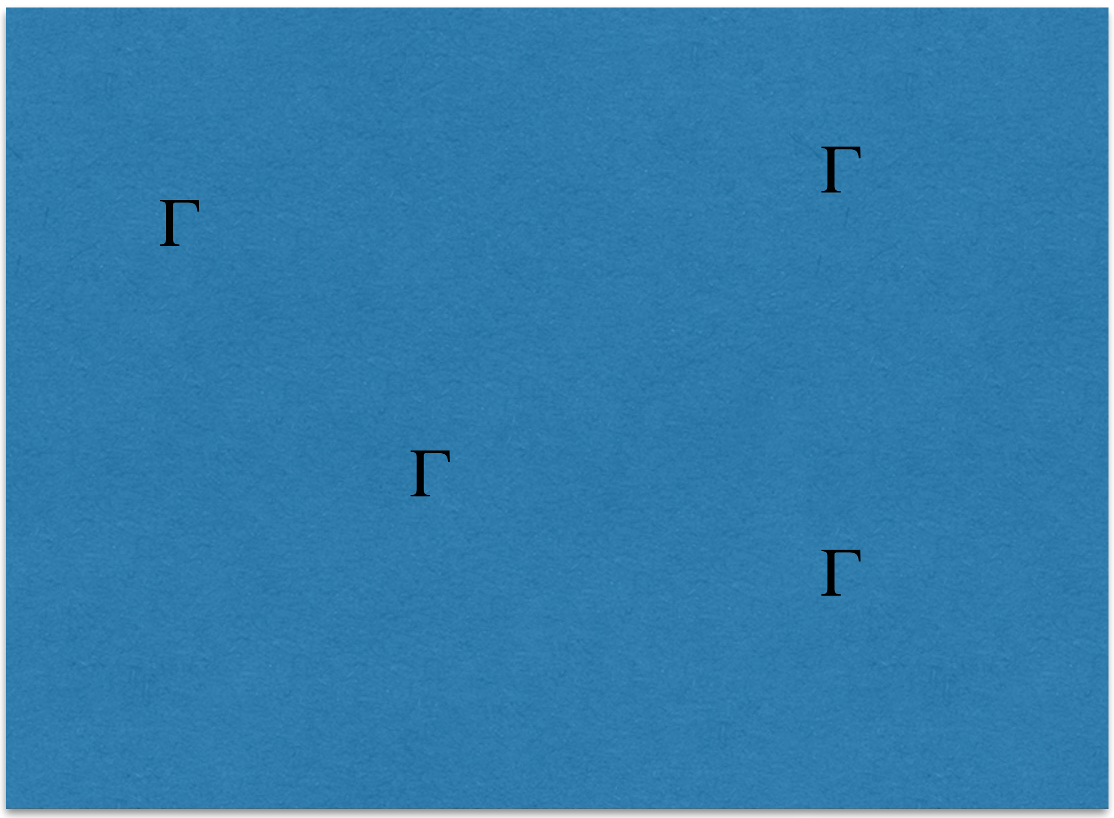

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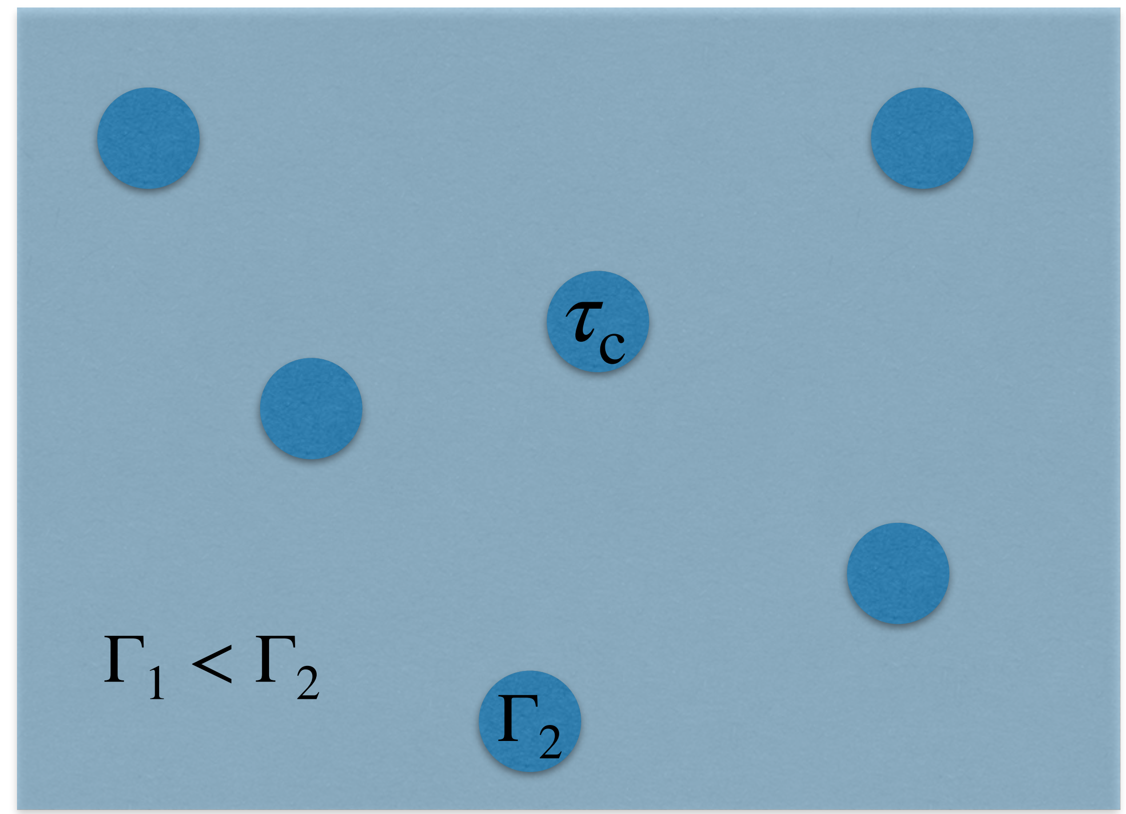

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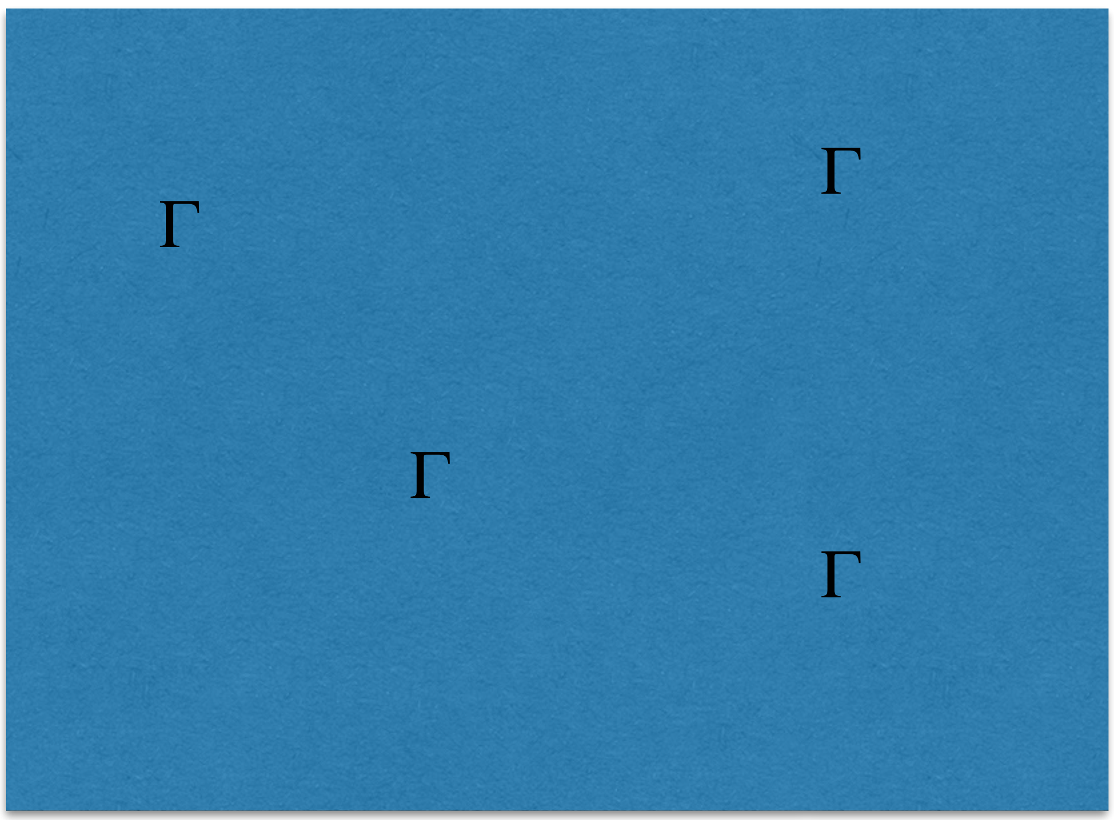

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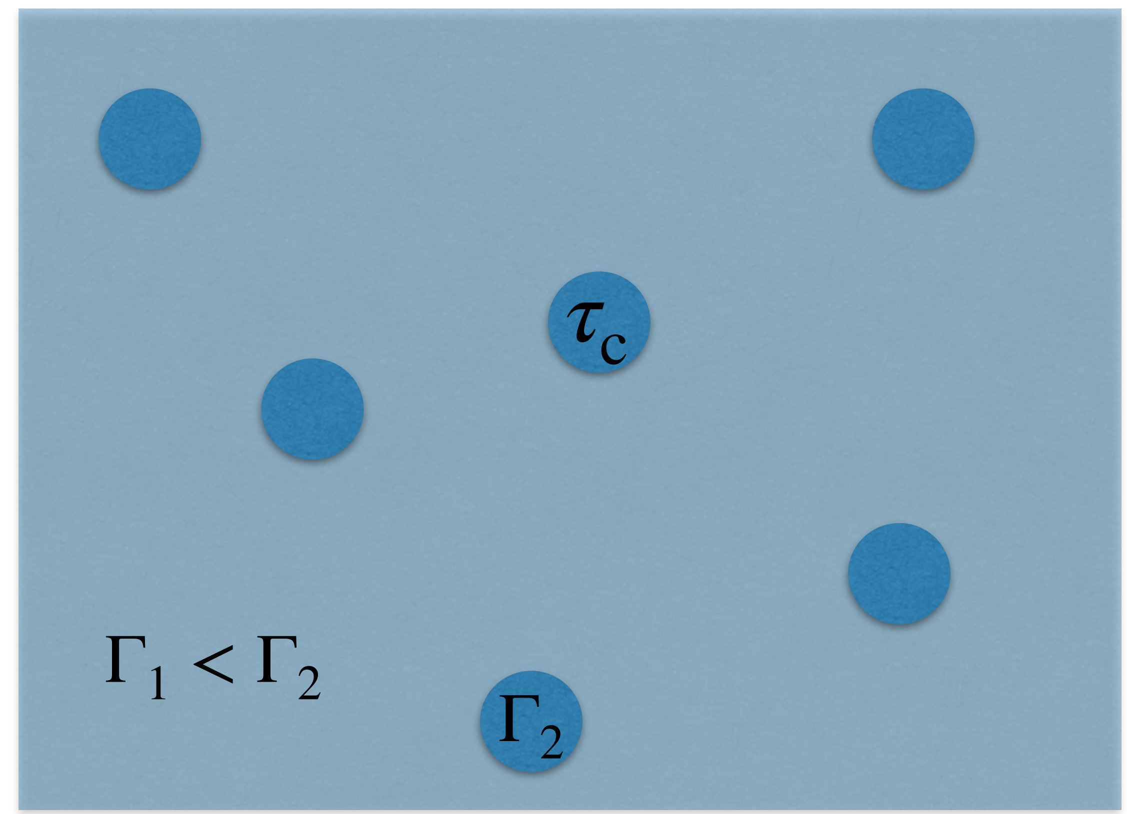

$$\Gamma = \sigma_{\rm T} N_{\rm e} a$$

$$\Gamma \approx \sigma_{\rm T} \bar{N}_{\rm e} a [1 - \zeta_{\rm e}]$$

$$\zeta_{\rm e} = \tau_{\rm c} \sigma_{\rm e}^2$$

JC, Vasil & Battye, ArXiv:2505.22242

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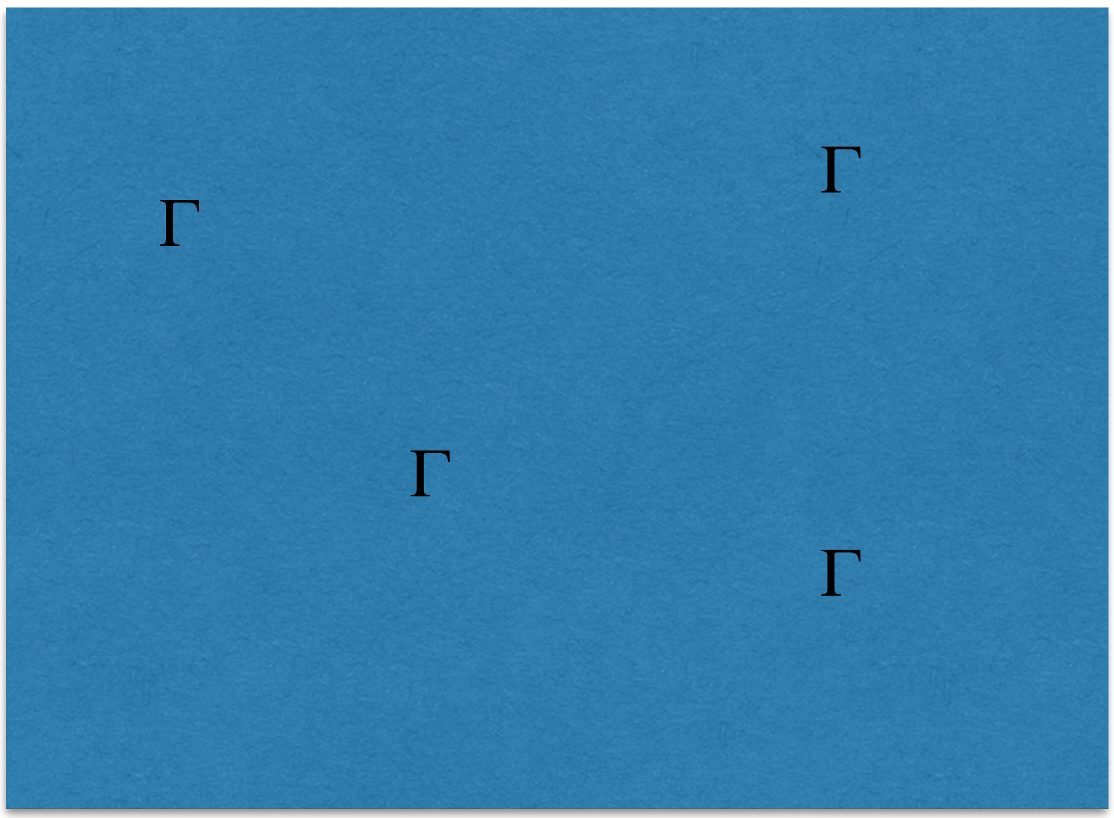

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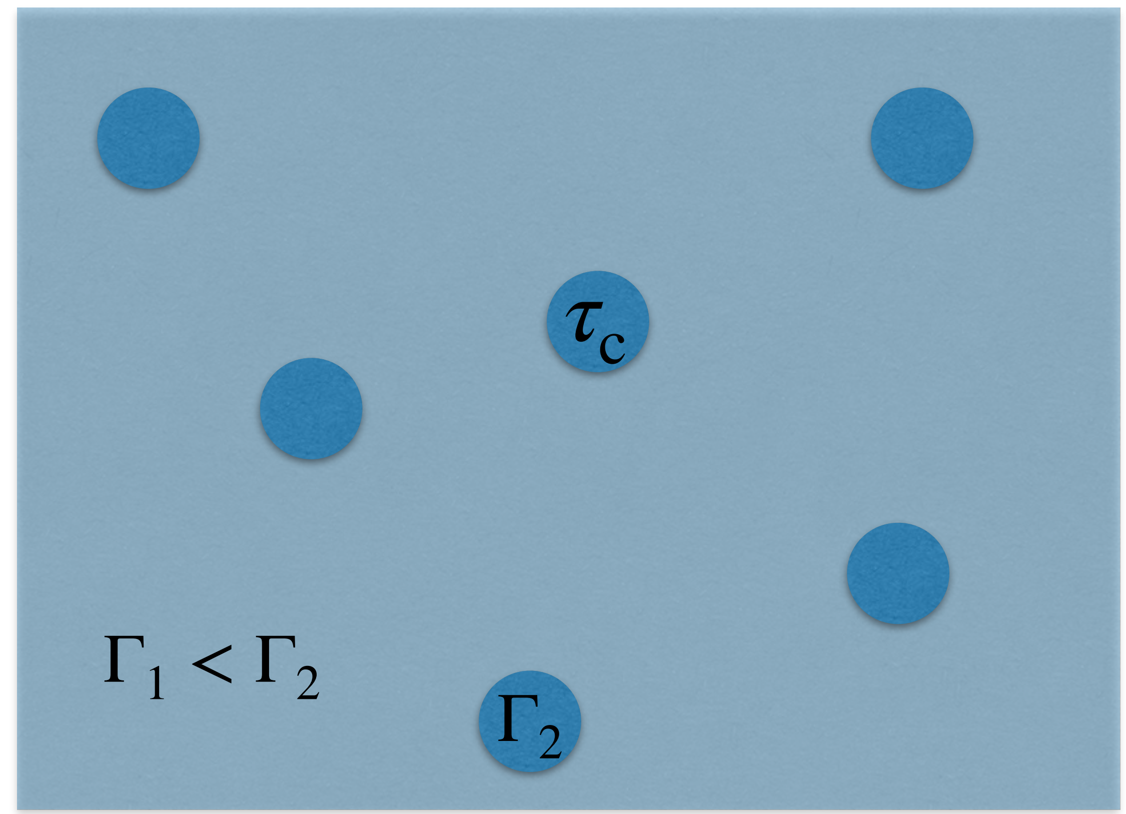

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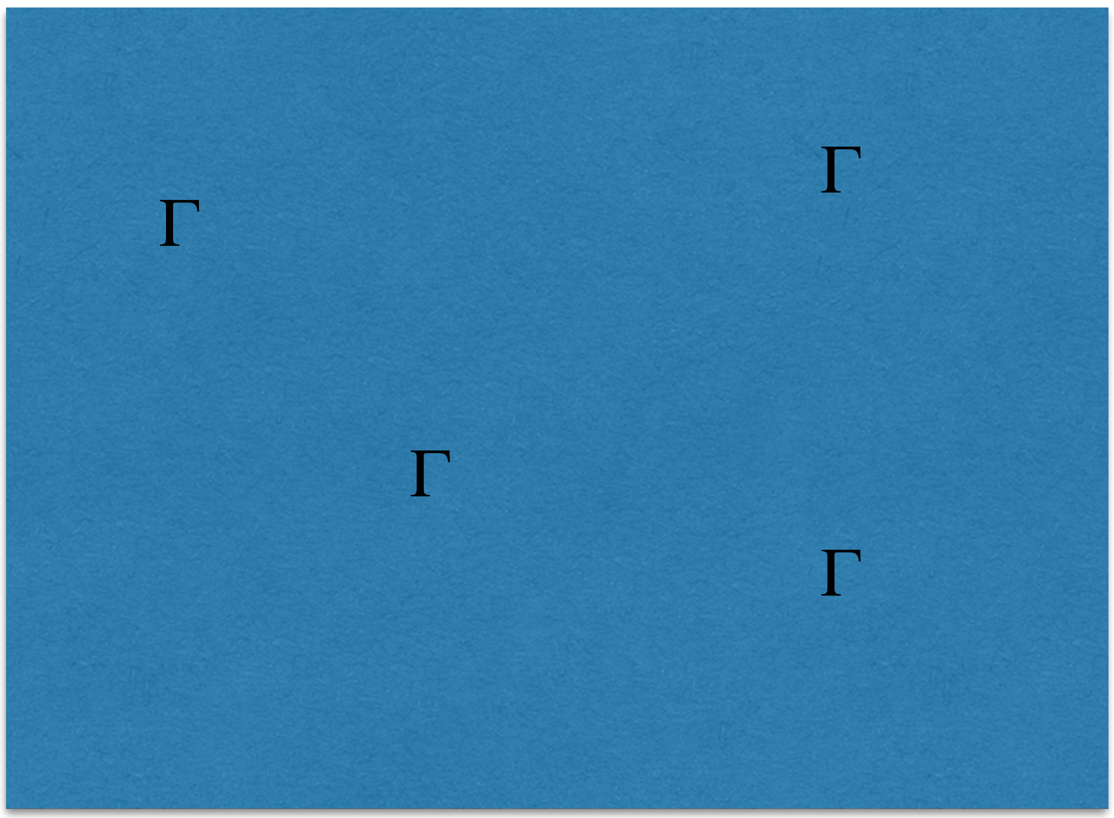

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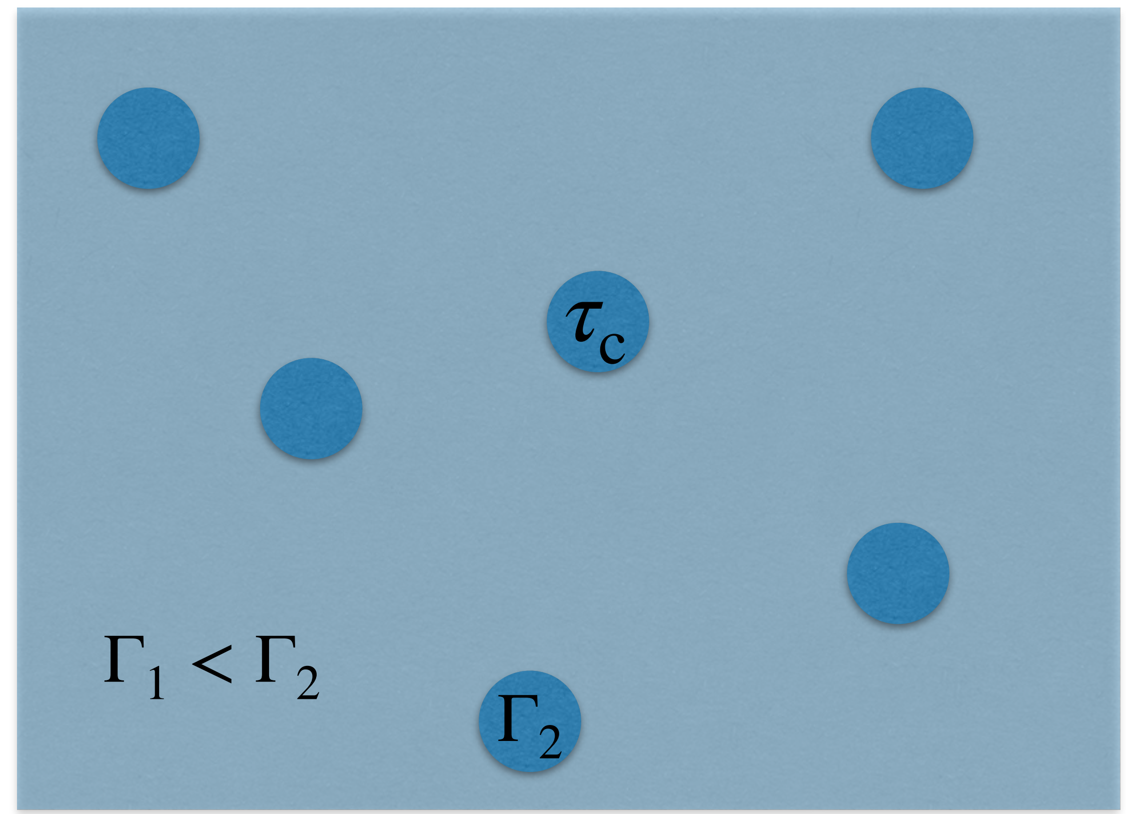

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Optical depth across coherence length

JC, Vasil & Battye, ArXiv:2505.22242

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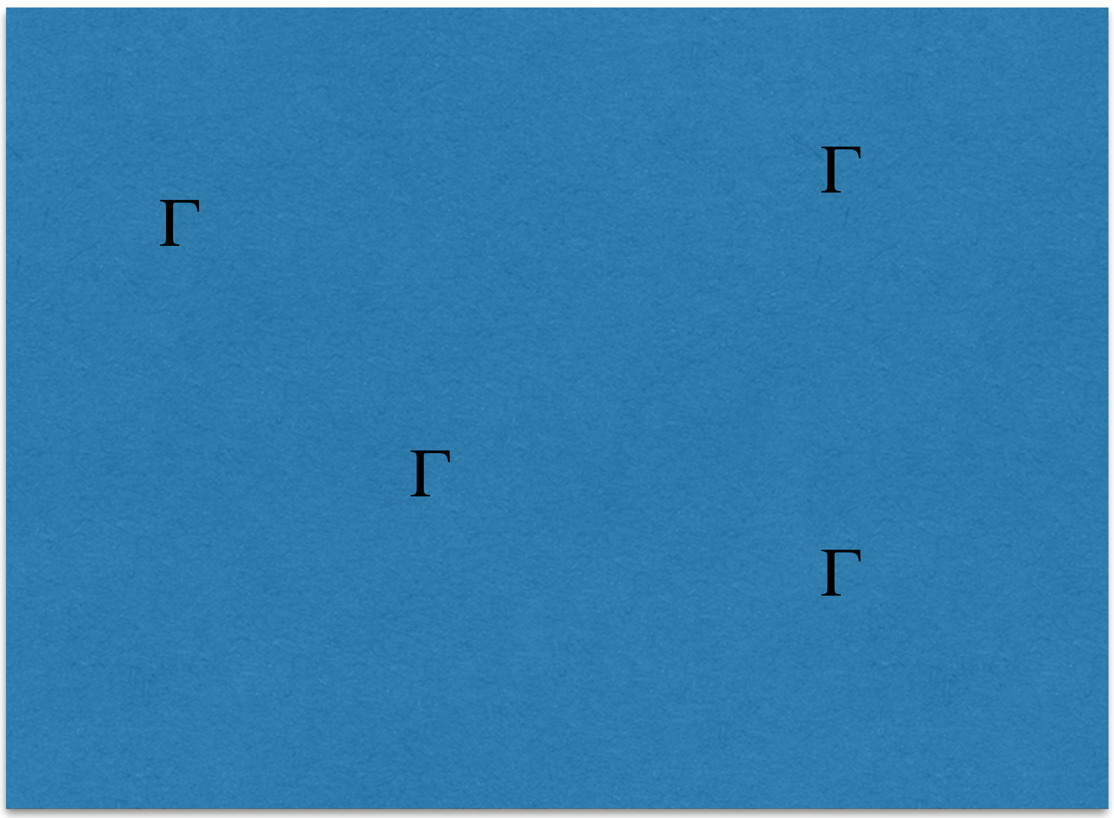

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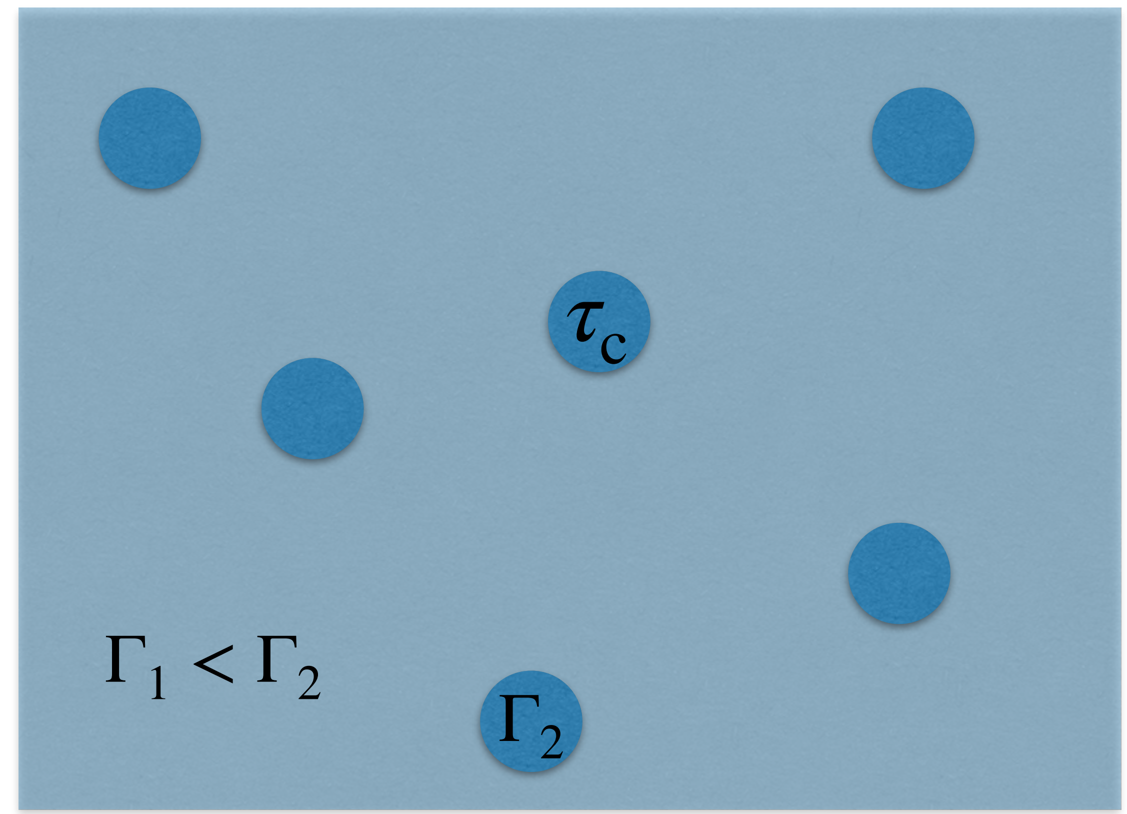

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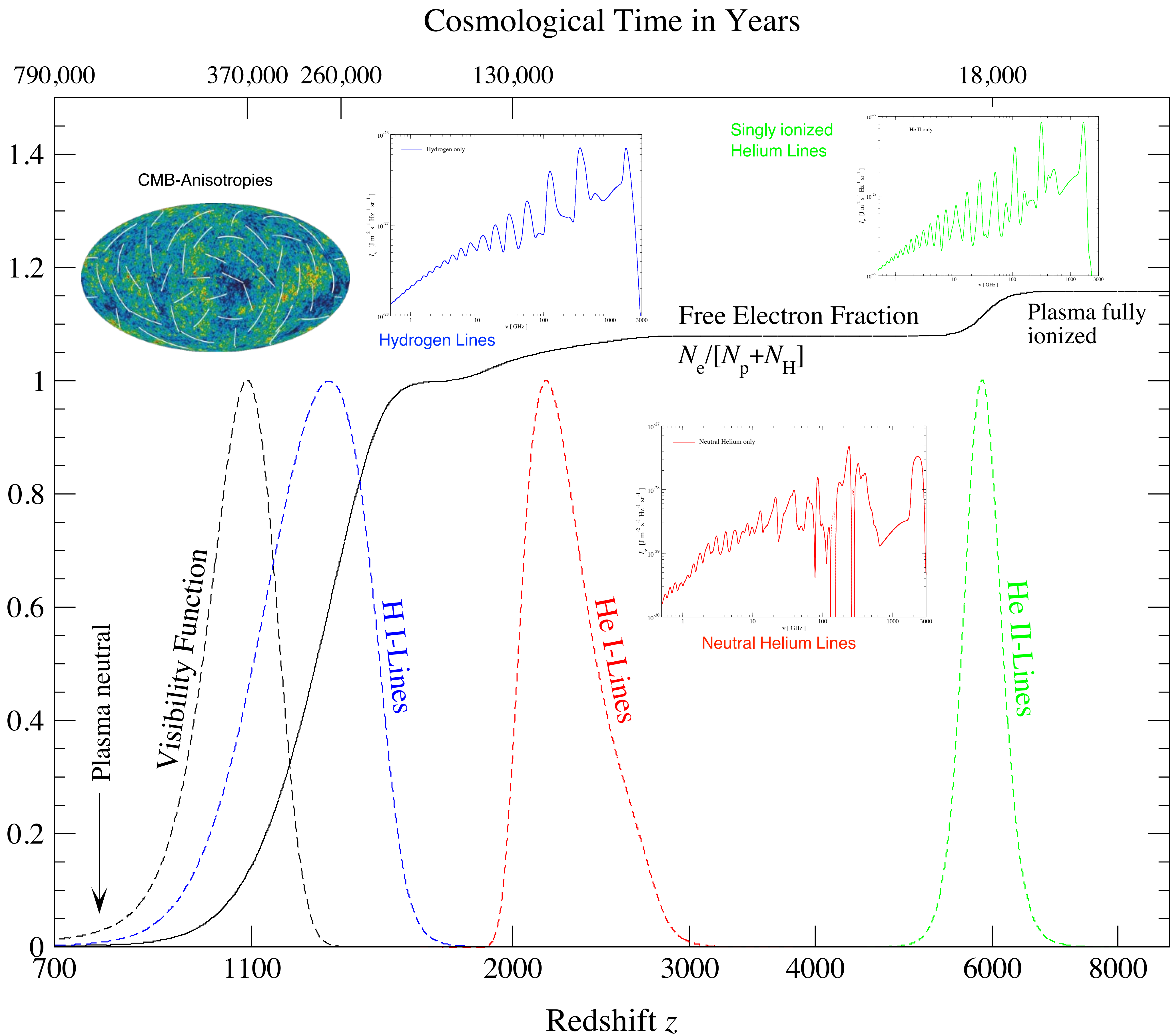
Optical depth across coherence length

Electron variance

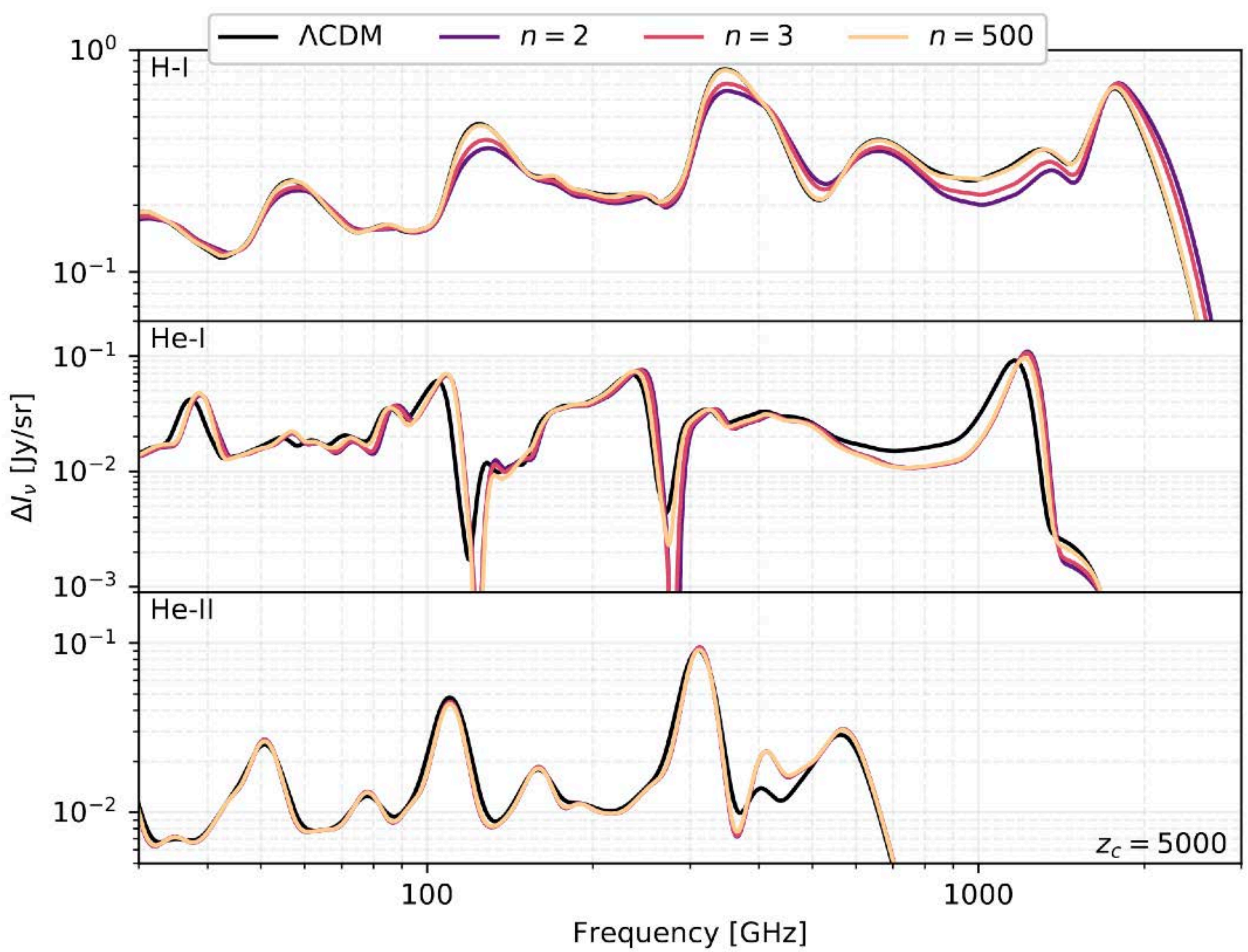
JC, Vasil & Battye, ArXiv:2505.22242

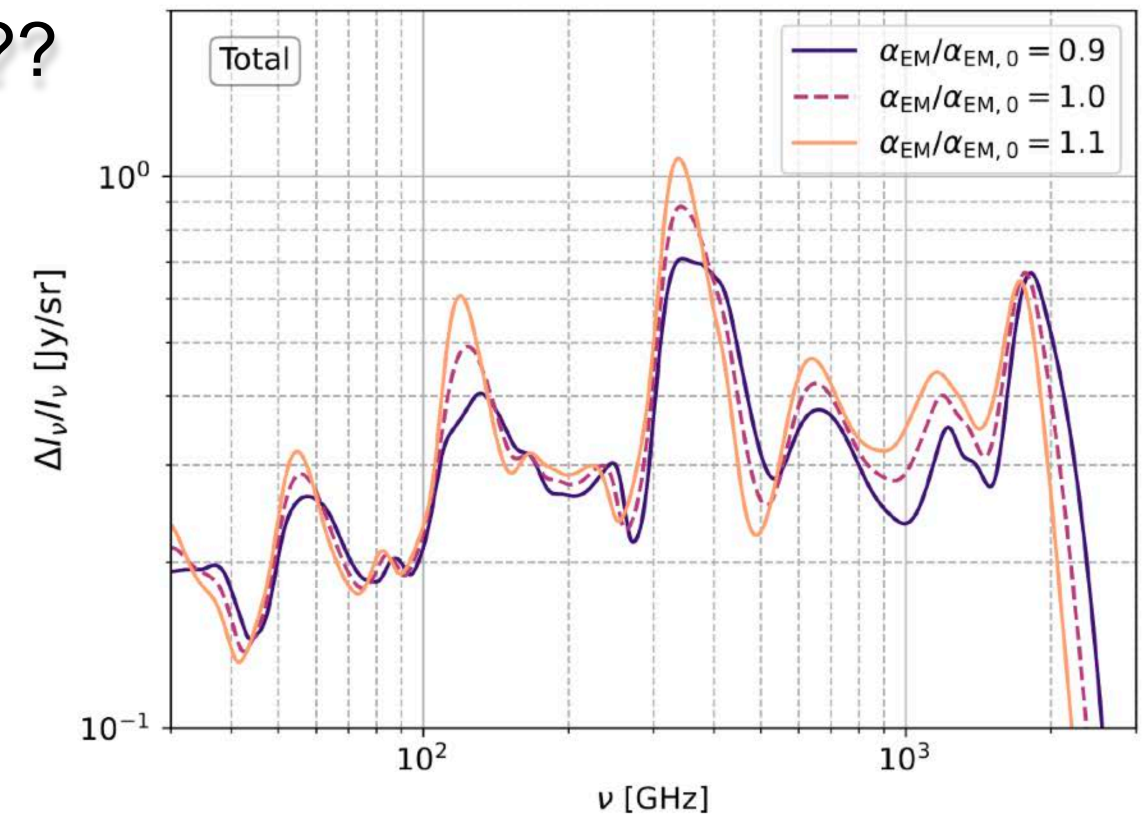


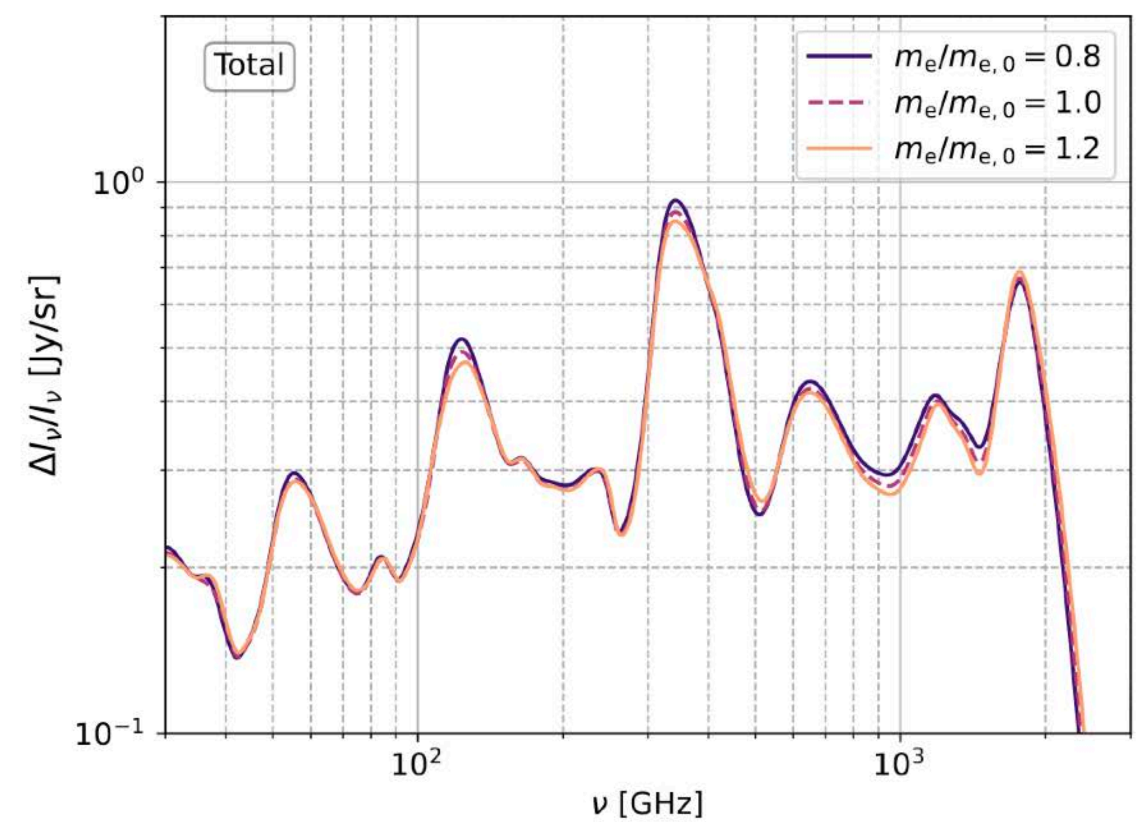
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen Lines
Singly ionized Helium Lines
Neutral Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
Hydrogen only
Neutral Helium only
He II only
ν [GHz]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
700
1100
2000
3000
4000
6000
8000
Redshift z

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!





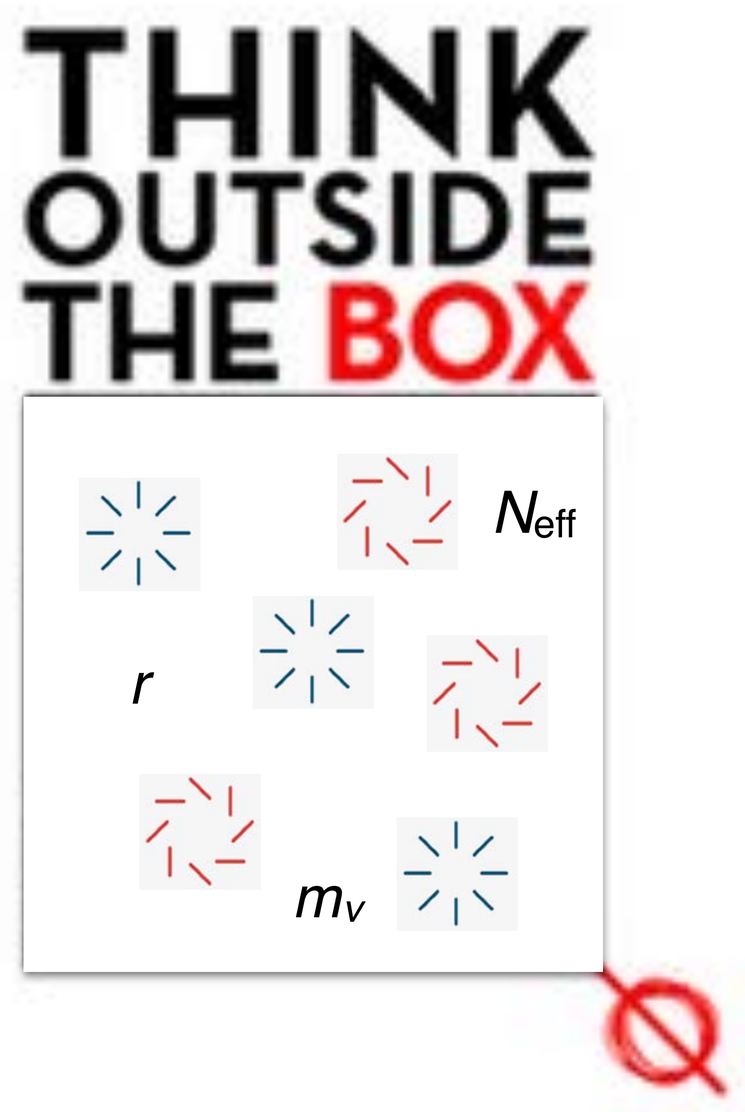


Hart & JC, 2022, ArXiv:2209.12290

‘From Planck to the future’ - Ferrara 2022

Courtesy: Reno Mandolesi

‘From Planck to the future’ - Ferrara 2022



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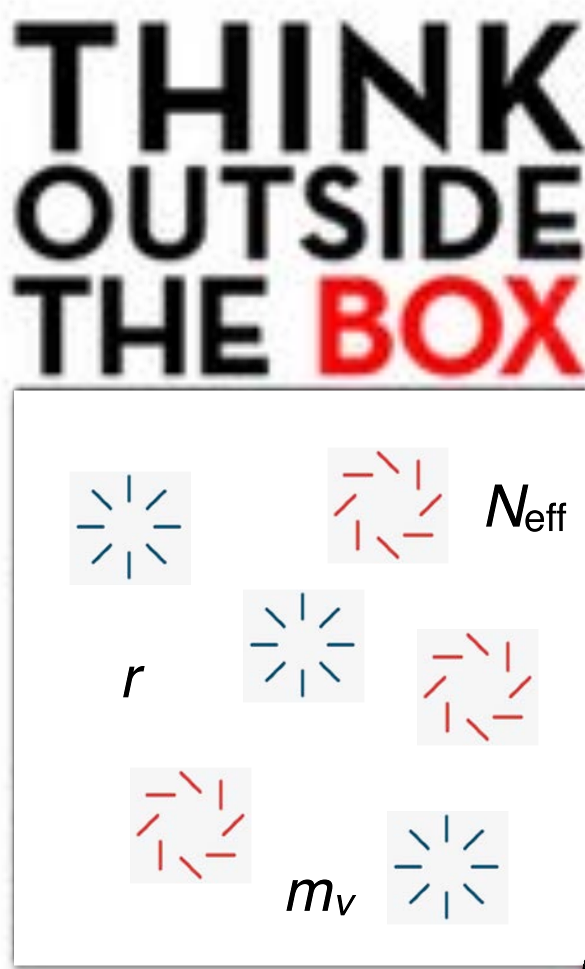

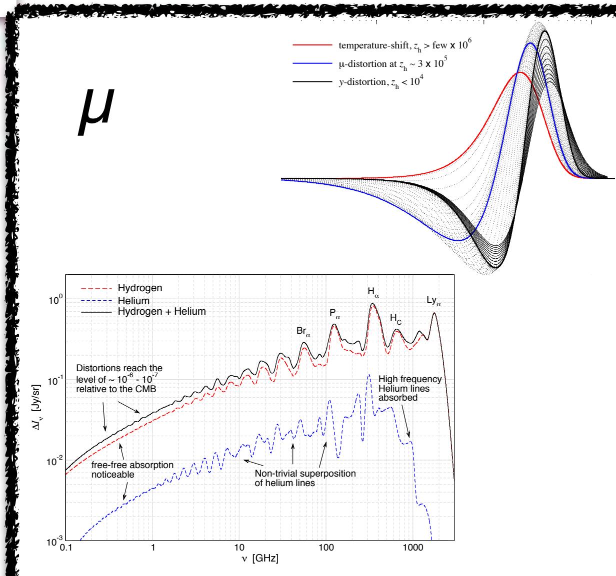

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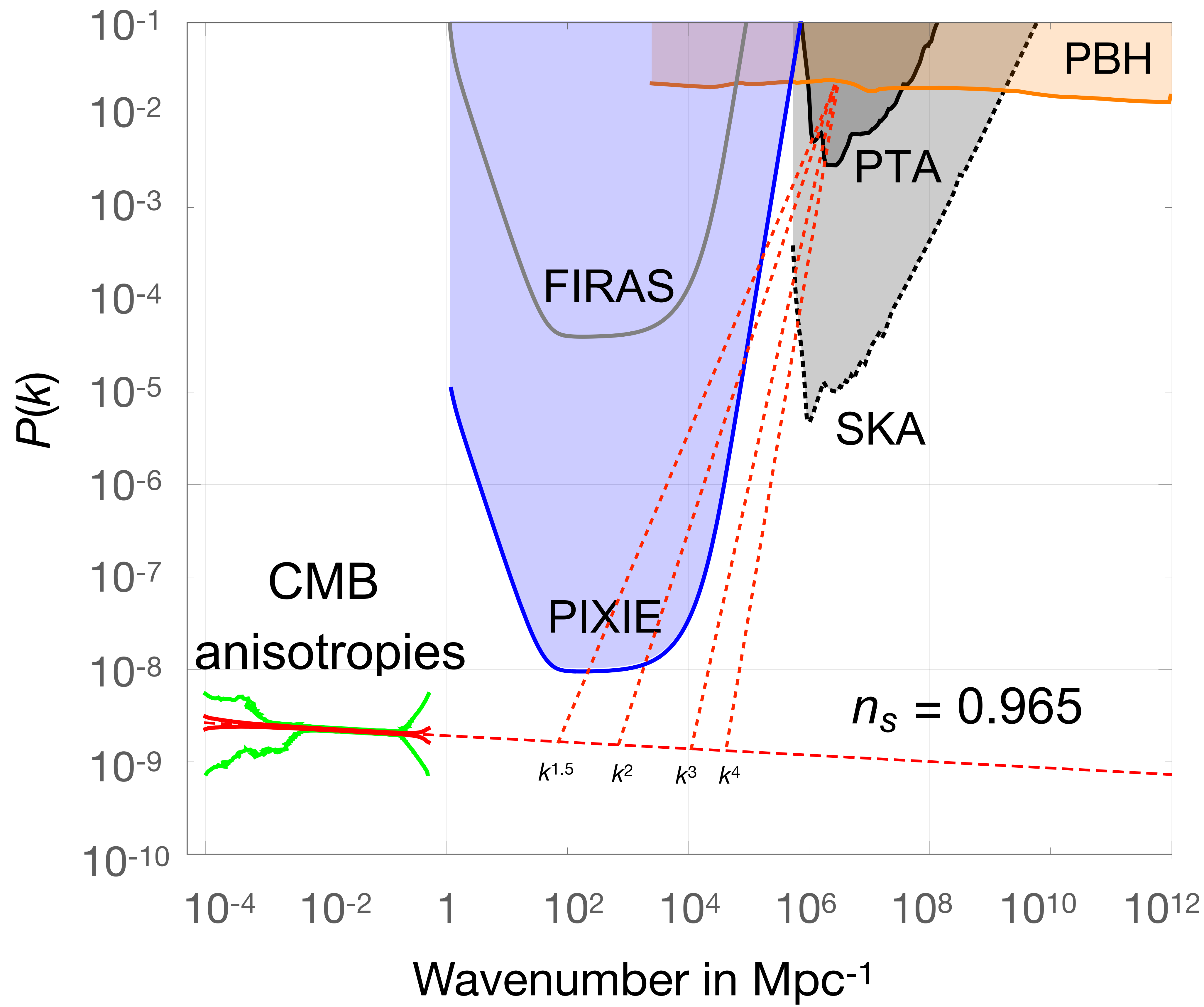
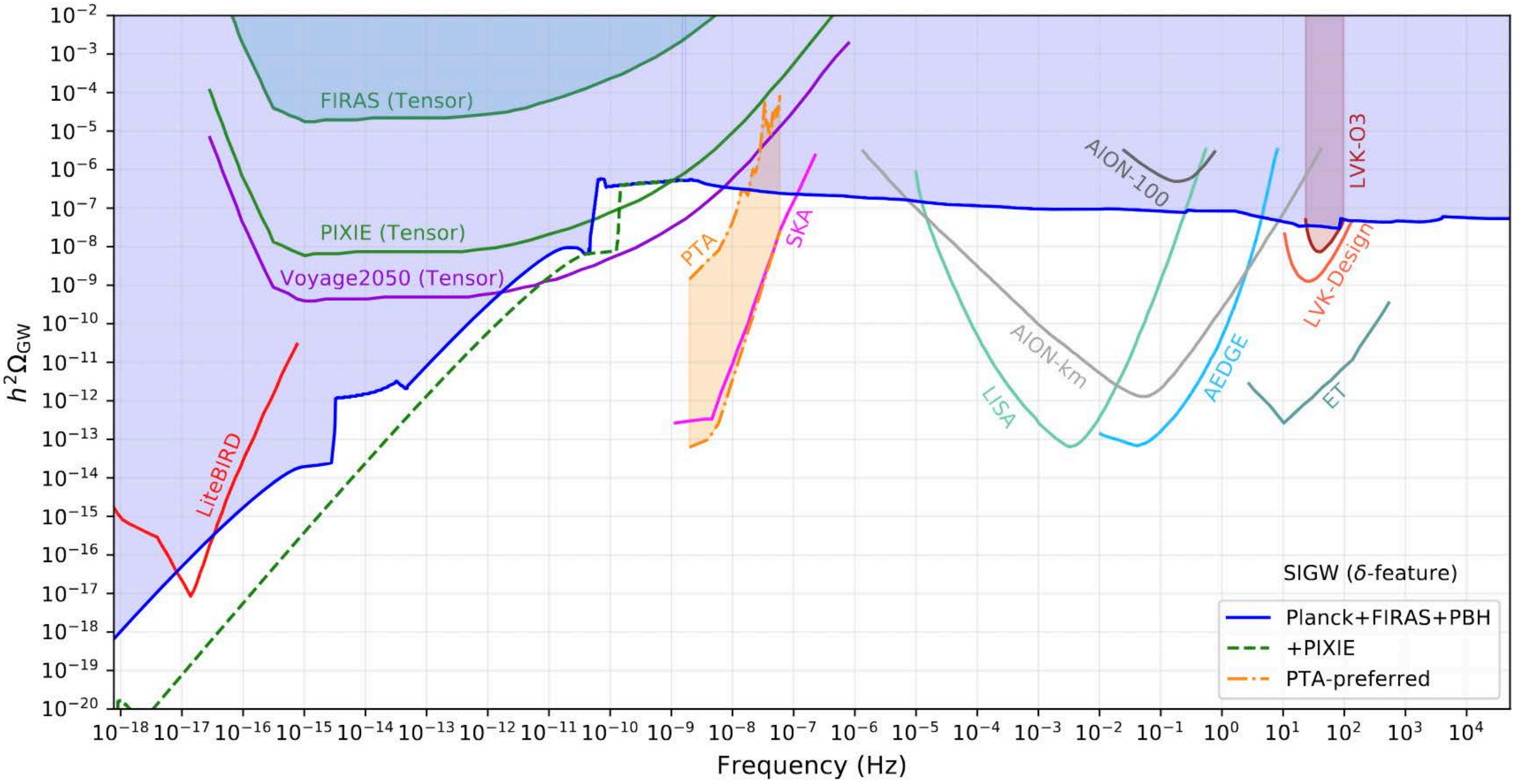
AKADEMIA KOPERNIKAŃSKA
ŚWIATOWY KONGRES KOPERNIKAŃSKI
Panel discussion:
Exploration of the Cosmic Microwave Background – the Future
Prof. John Carlstrom (University of Chicago)
Prof. Masashi Hazumi (High Energy Accelerator Research Organization - KEK, and Kavli IPMU, Tokyo University)
Prof. Lyman Page (Princeton University)
Dr. Charles Lawrence (Jet Propulsion Laboratory, Pasadena)
rof. Rafael Rebolo (Institute
strophysics of the Canary Islands)
f. Jens Chluba (Universit
anchester)
NICOLAUS COPERNICUS WORLD CONGRESS

Small-scale power and PBH link



Spectral distortion link to GW backgrounds



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

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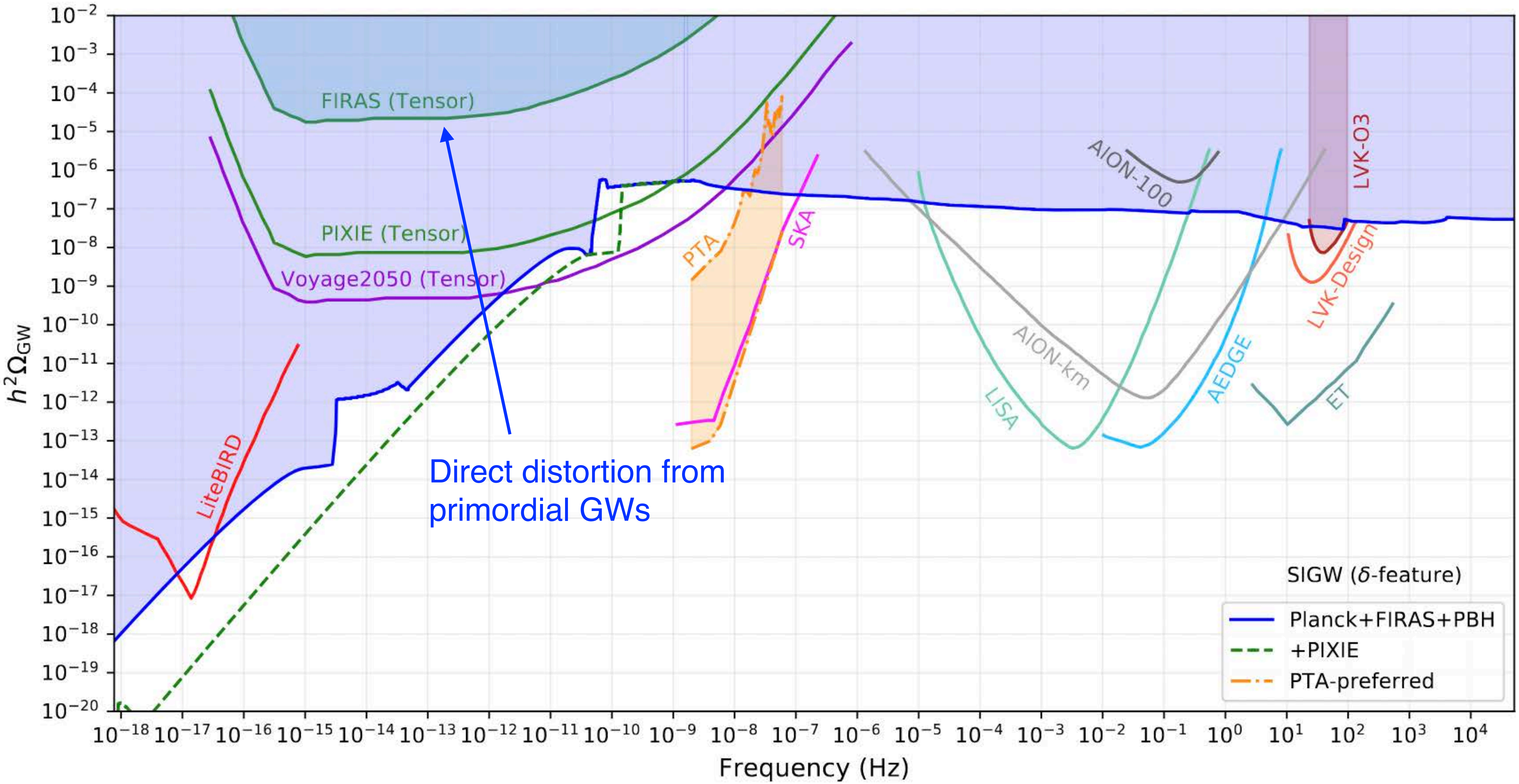

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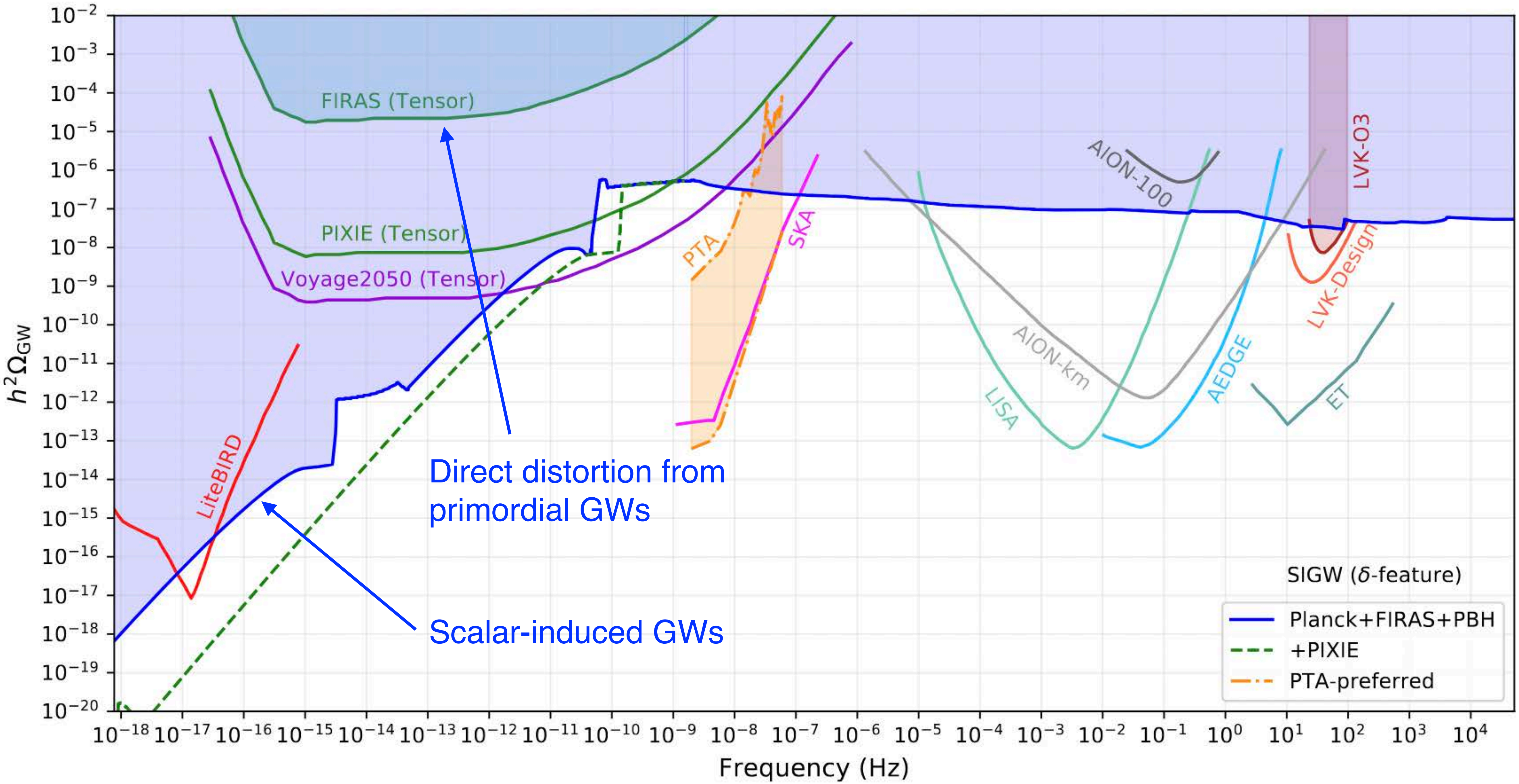

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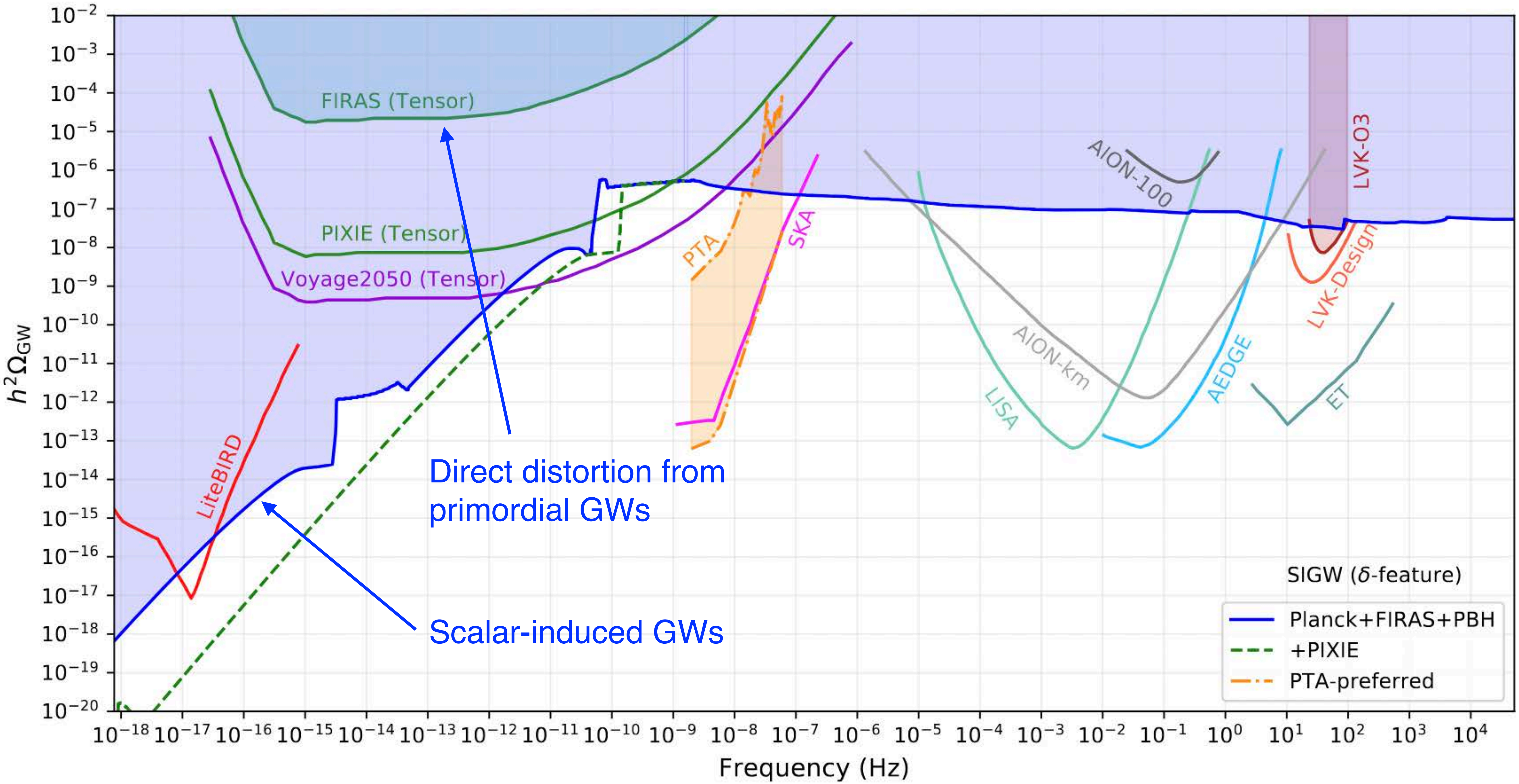
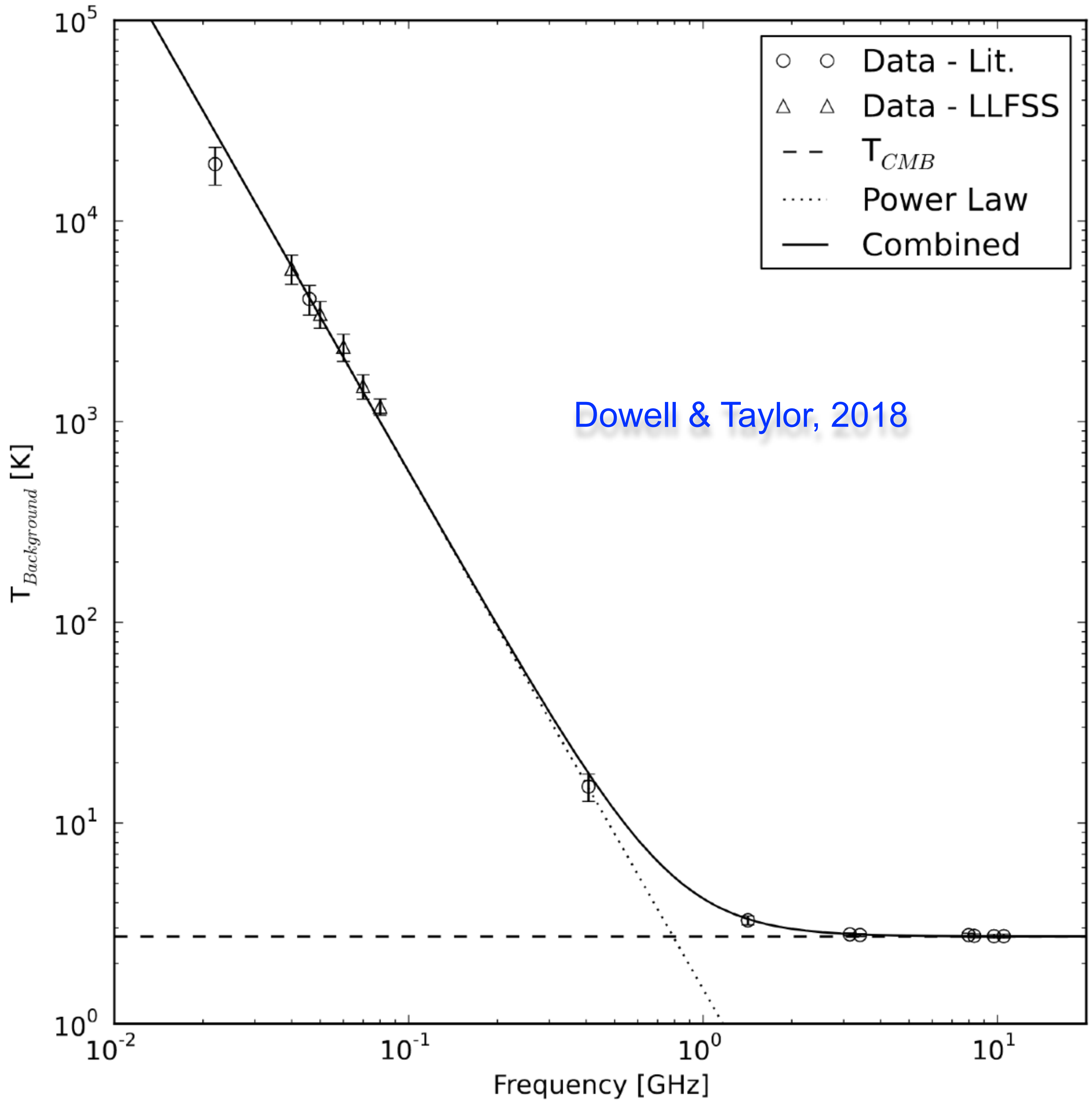


A CMB spectrometer could rule out SIGWs as cause for large-scale *B*-modes

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

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)

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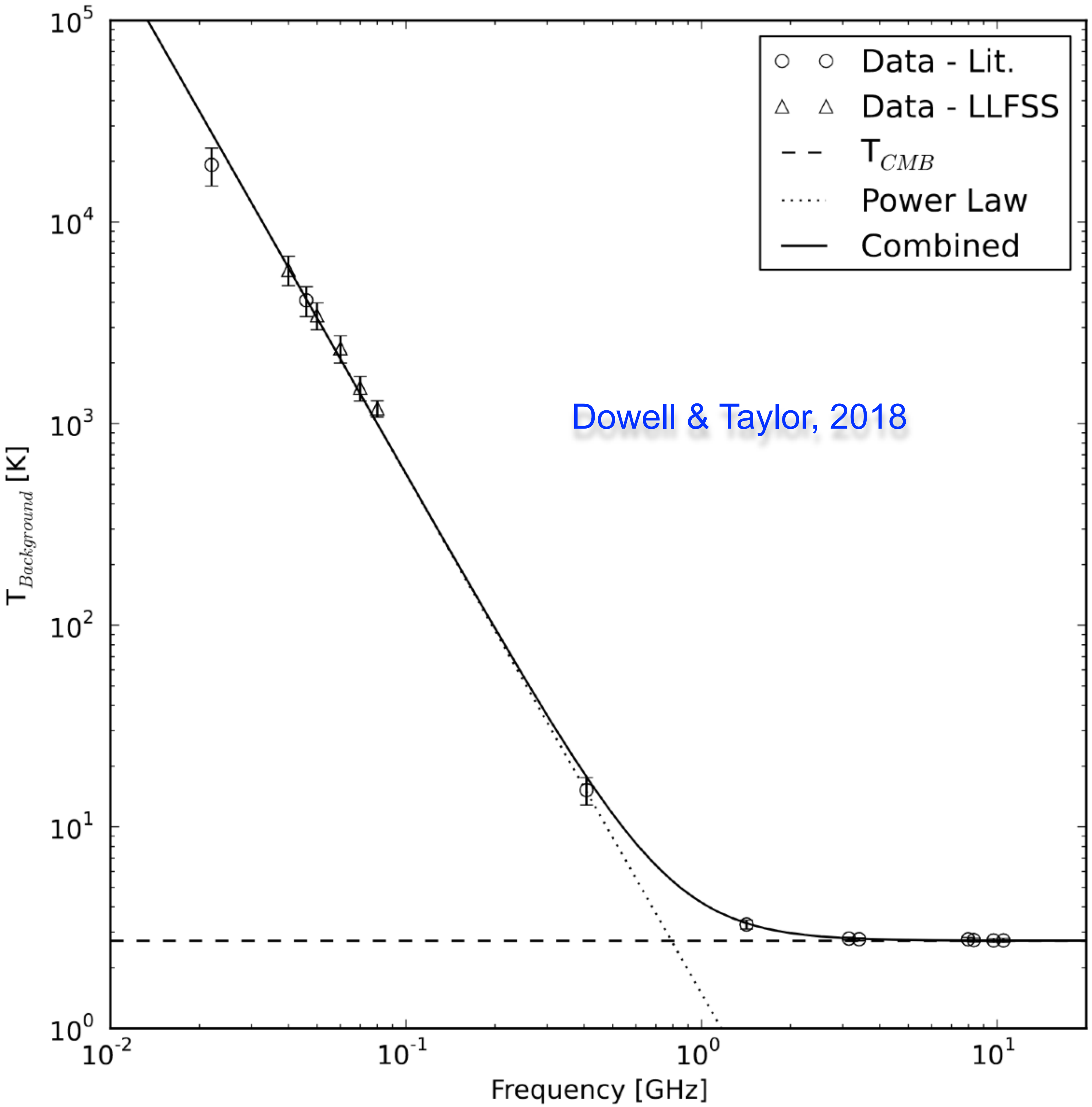

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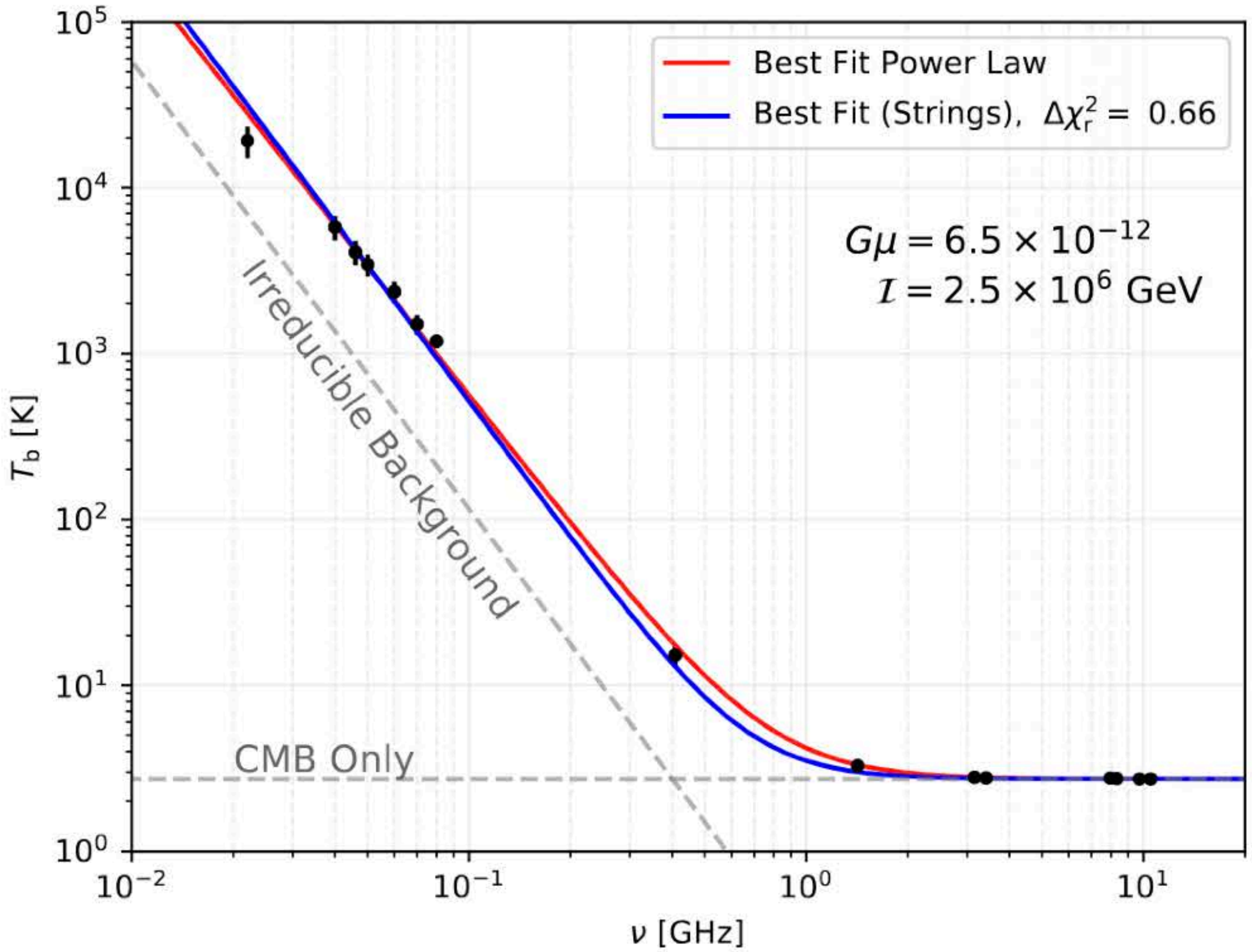
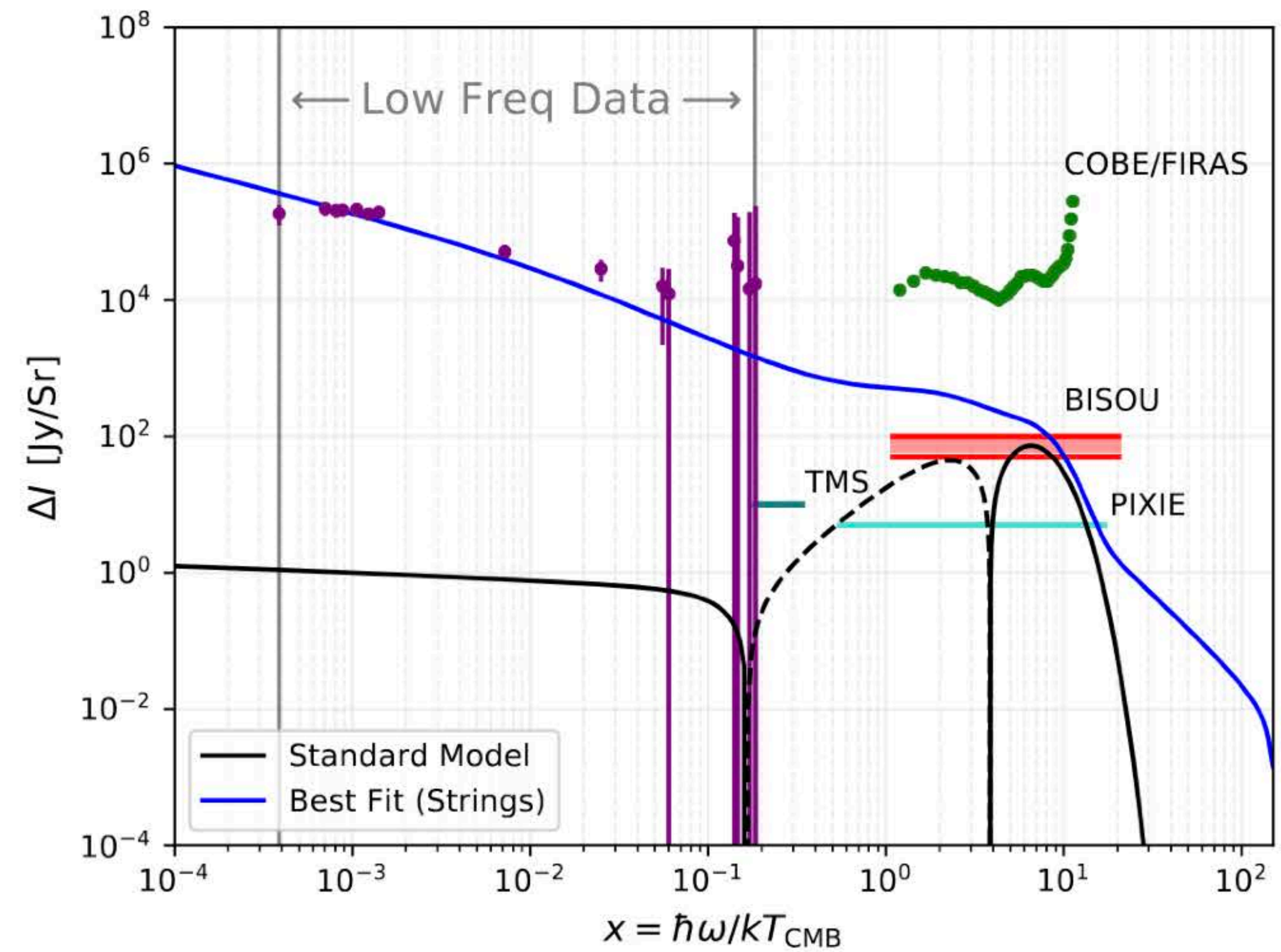
Is this an early (z>10?) radio background possibly from accreting black holes or new physics?

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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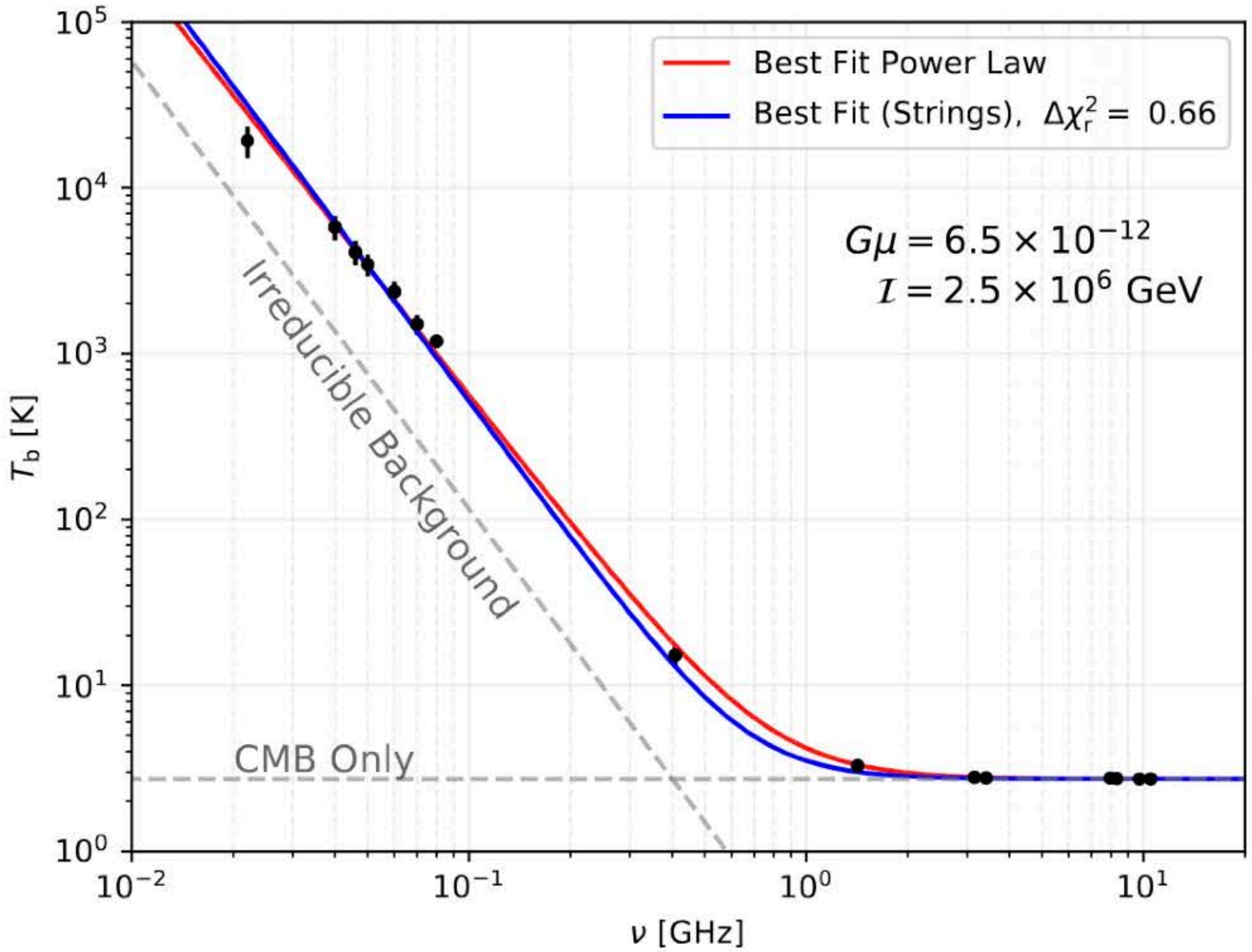

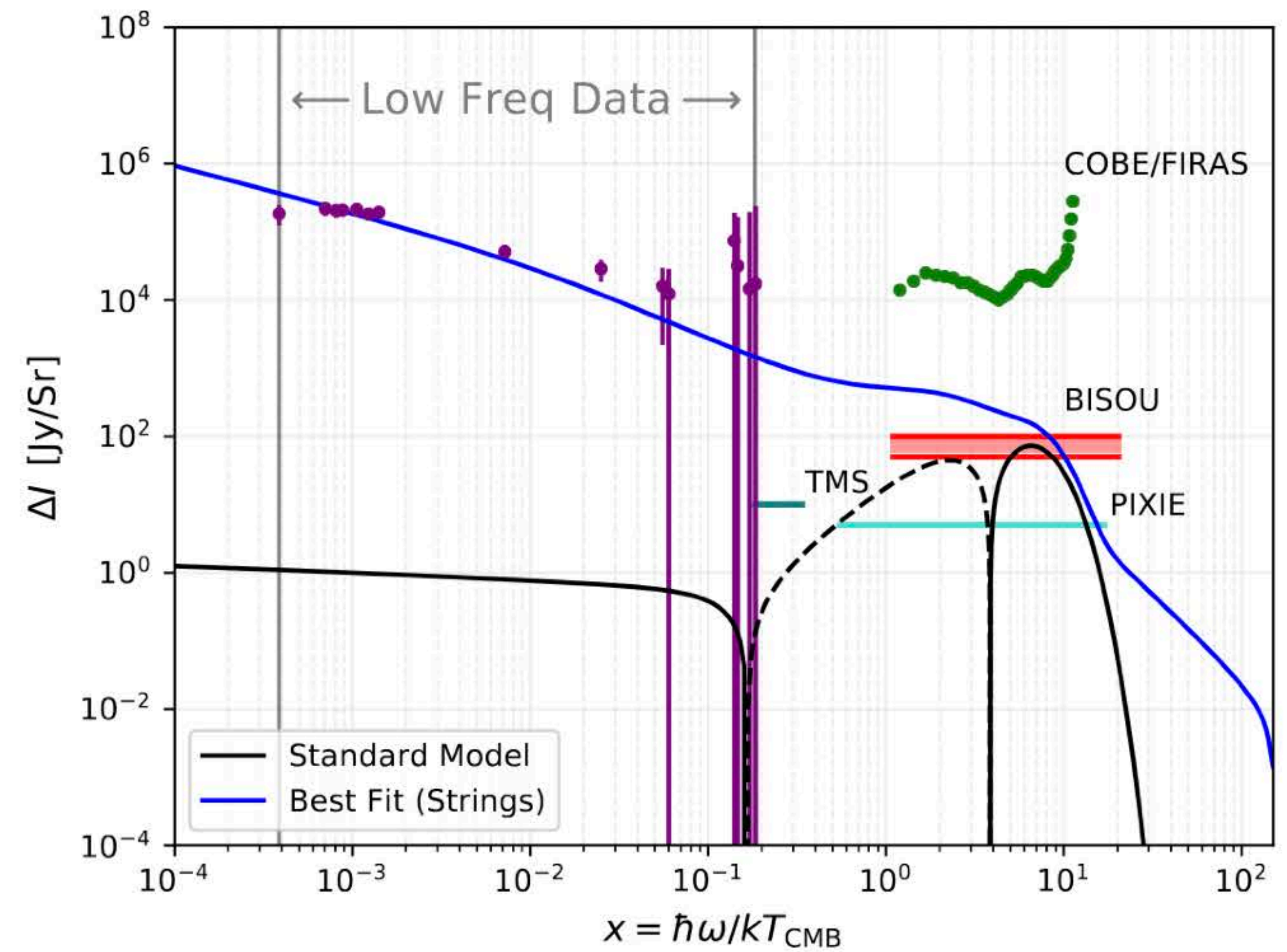

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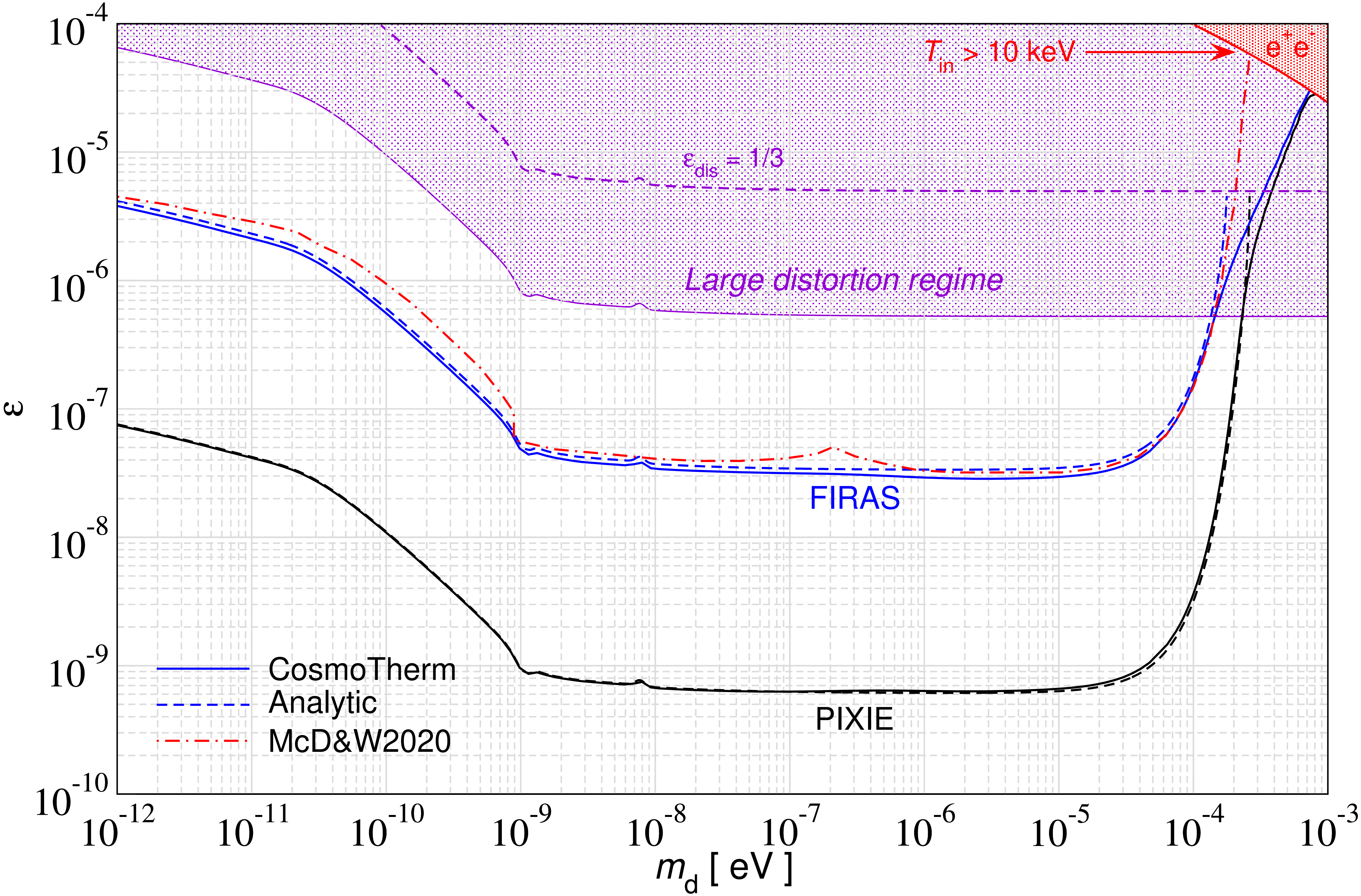
Cyr, JC & Acharya, 2023, ArXiv:2308.03512

CMB spectrometers could test the origin of the RSB!

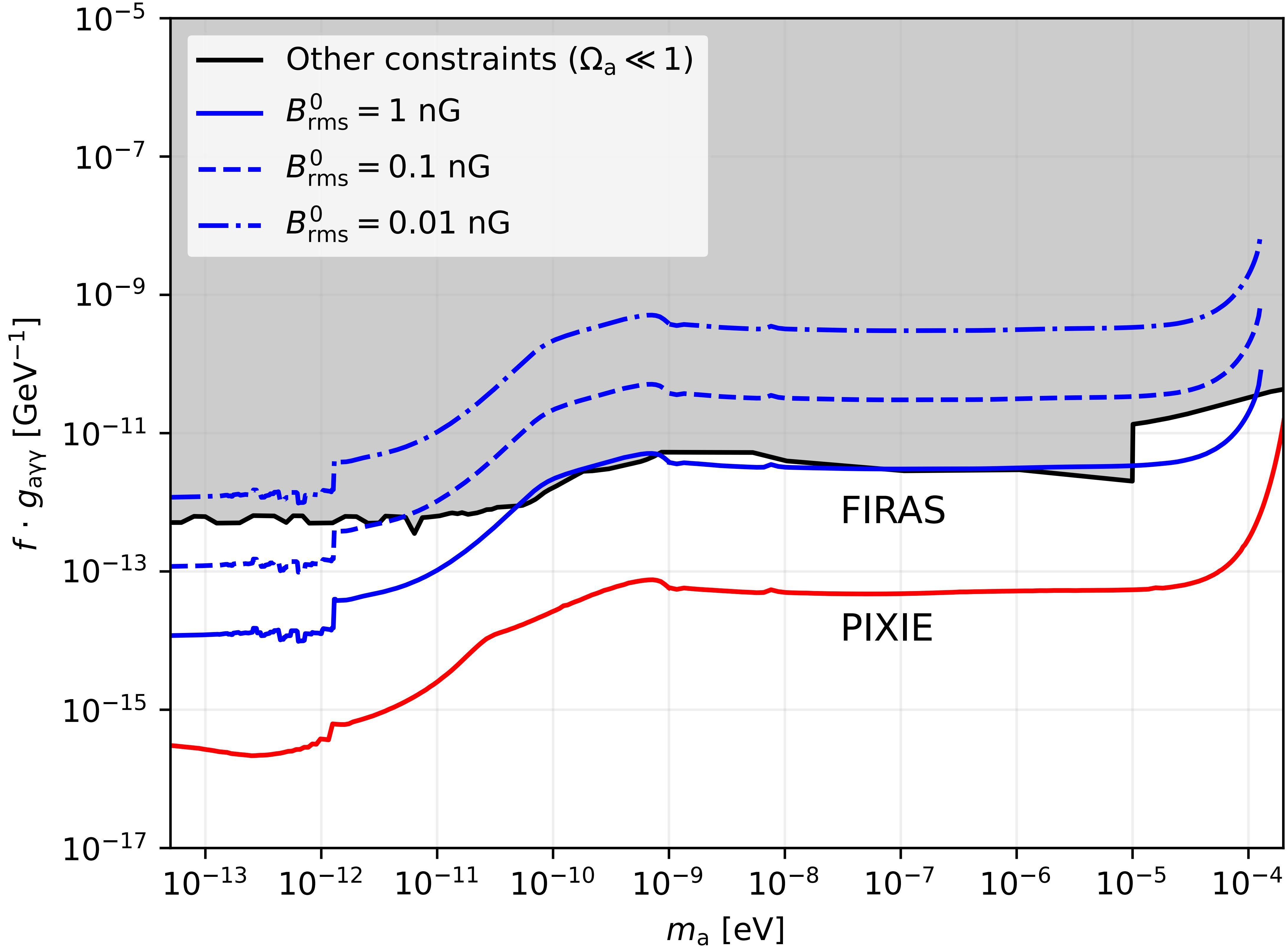
Revised Constraints on Dark Photons



JC, Cyr & Johnson ArXiv:2409.12115

COBE/FIRAS constraints still competitive

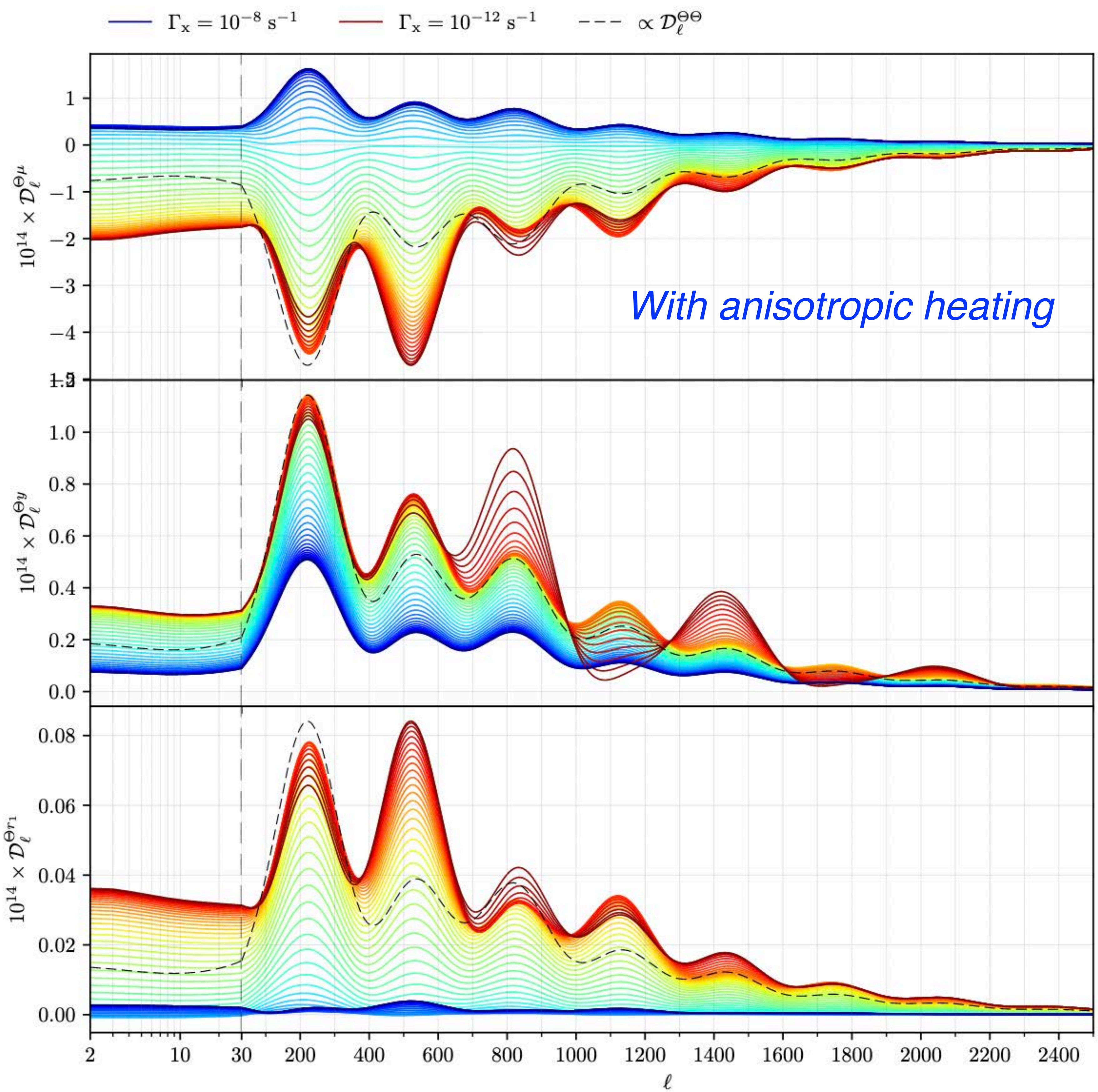
Revised Constraints on Axions



Cyr, JC & Manoj ArXiv:2411.13701

Significant uncertainties from B field modelling

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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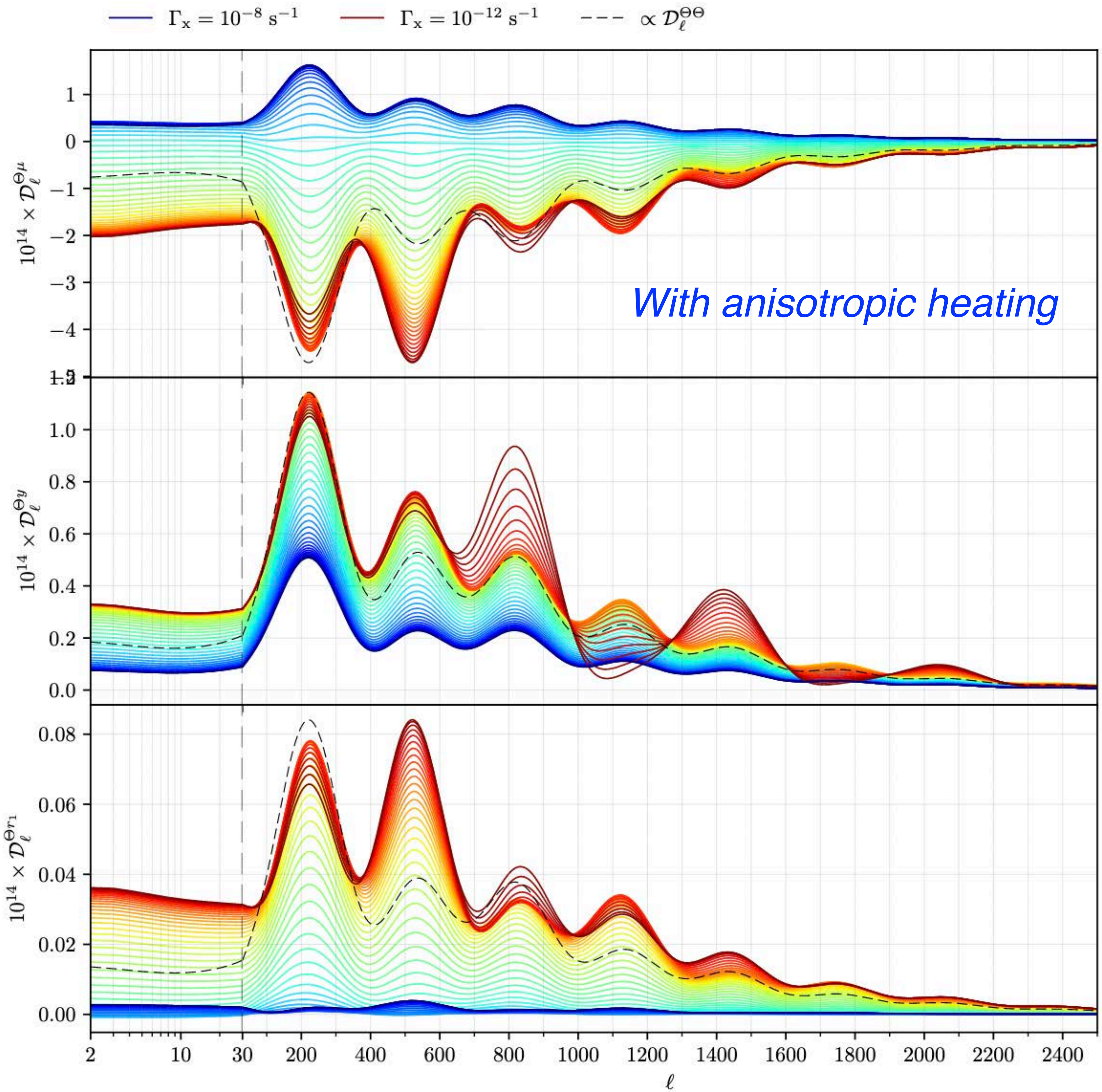

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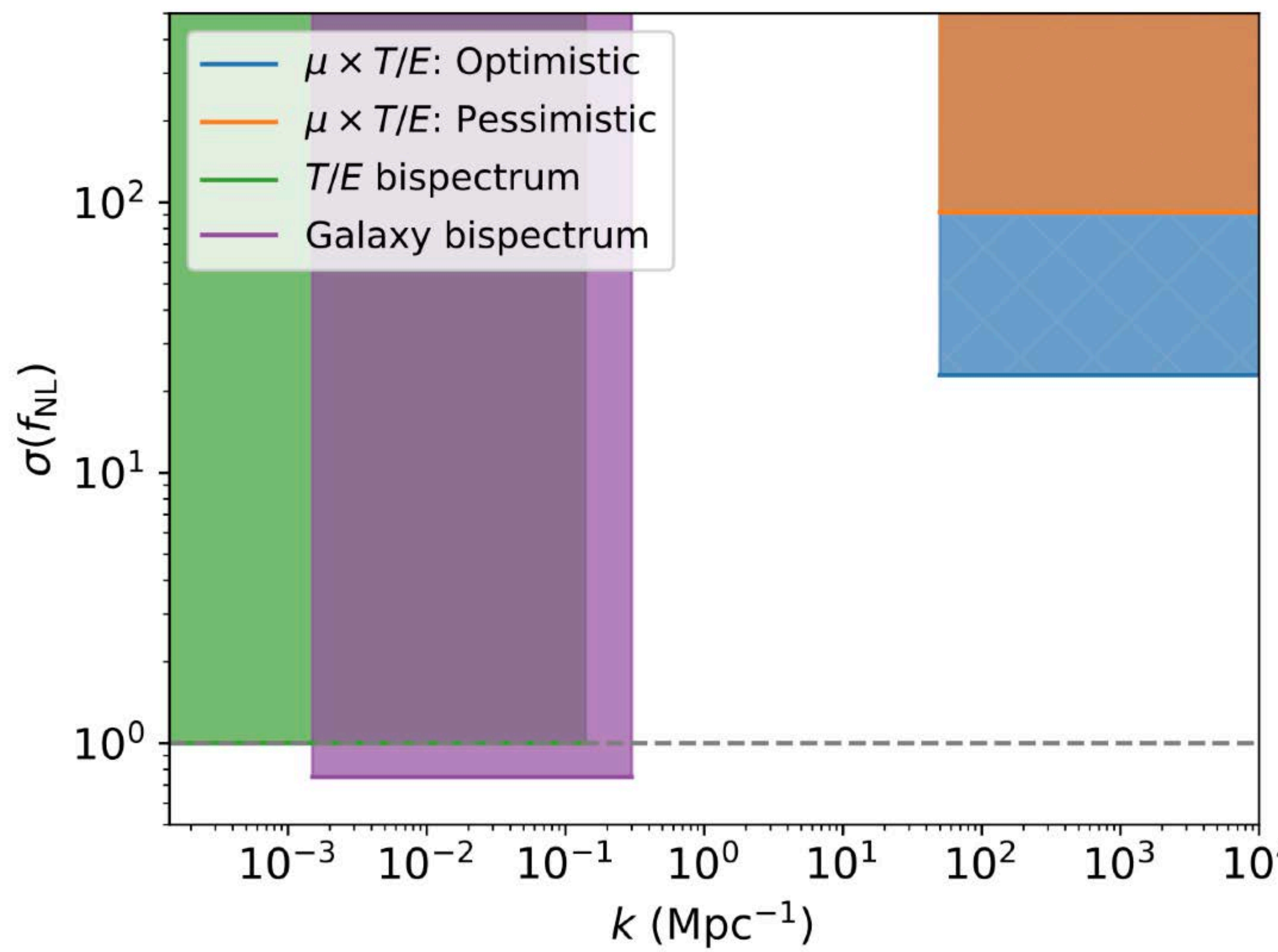
Can be constrainted with CMB imagers like Planck, Litebird, SO, CMB-S4 & PICO!

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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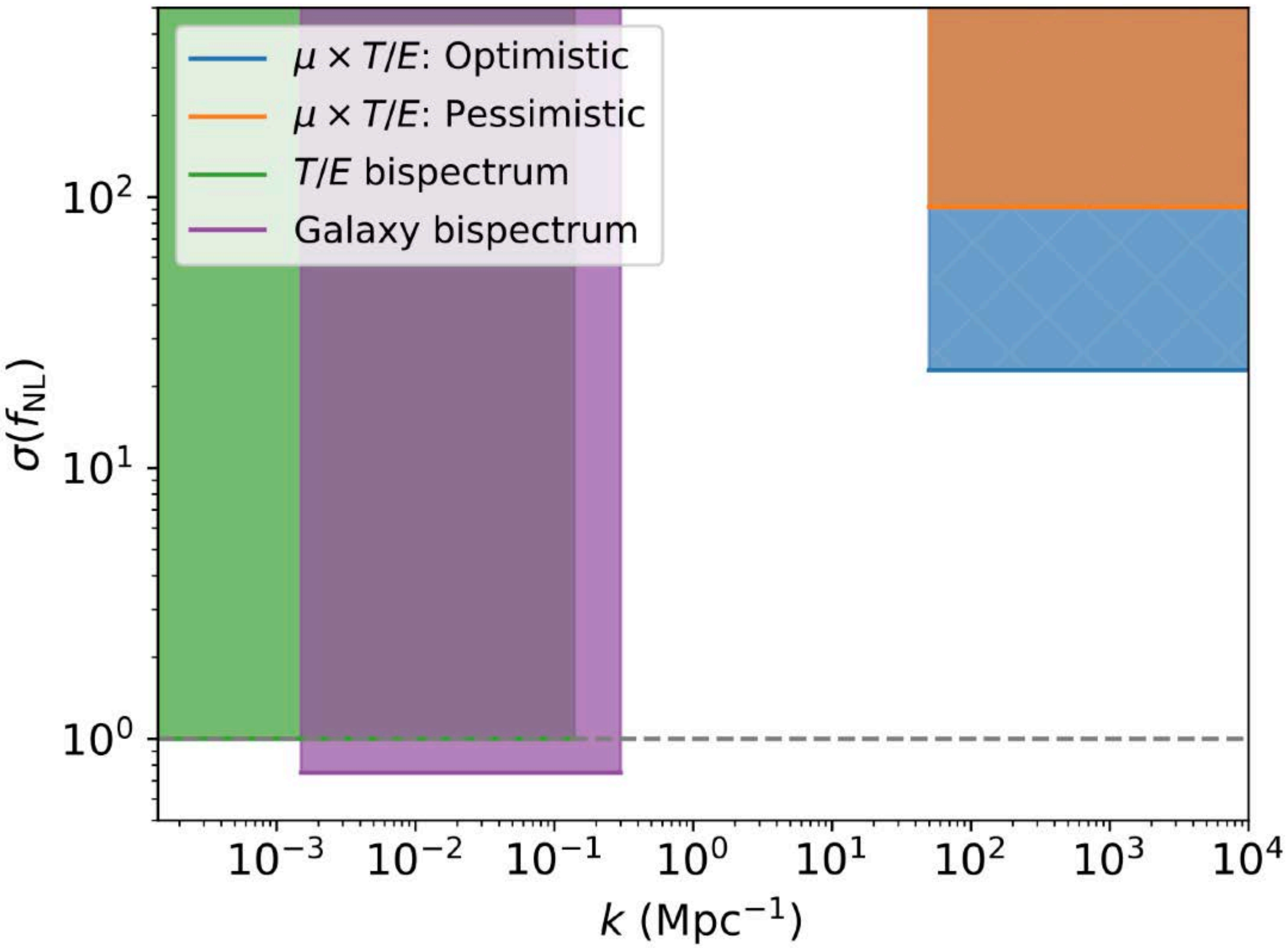

- Constraints on small scales
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Detailed study with realistic foregrounds and systematics is required!

Zegeye et al., ArXiv:2406.04326