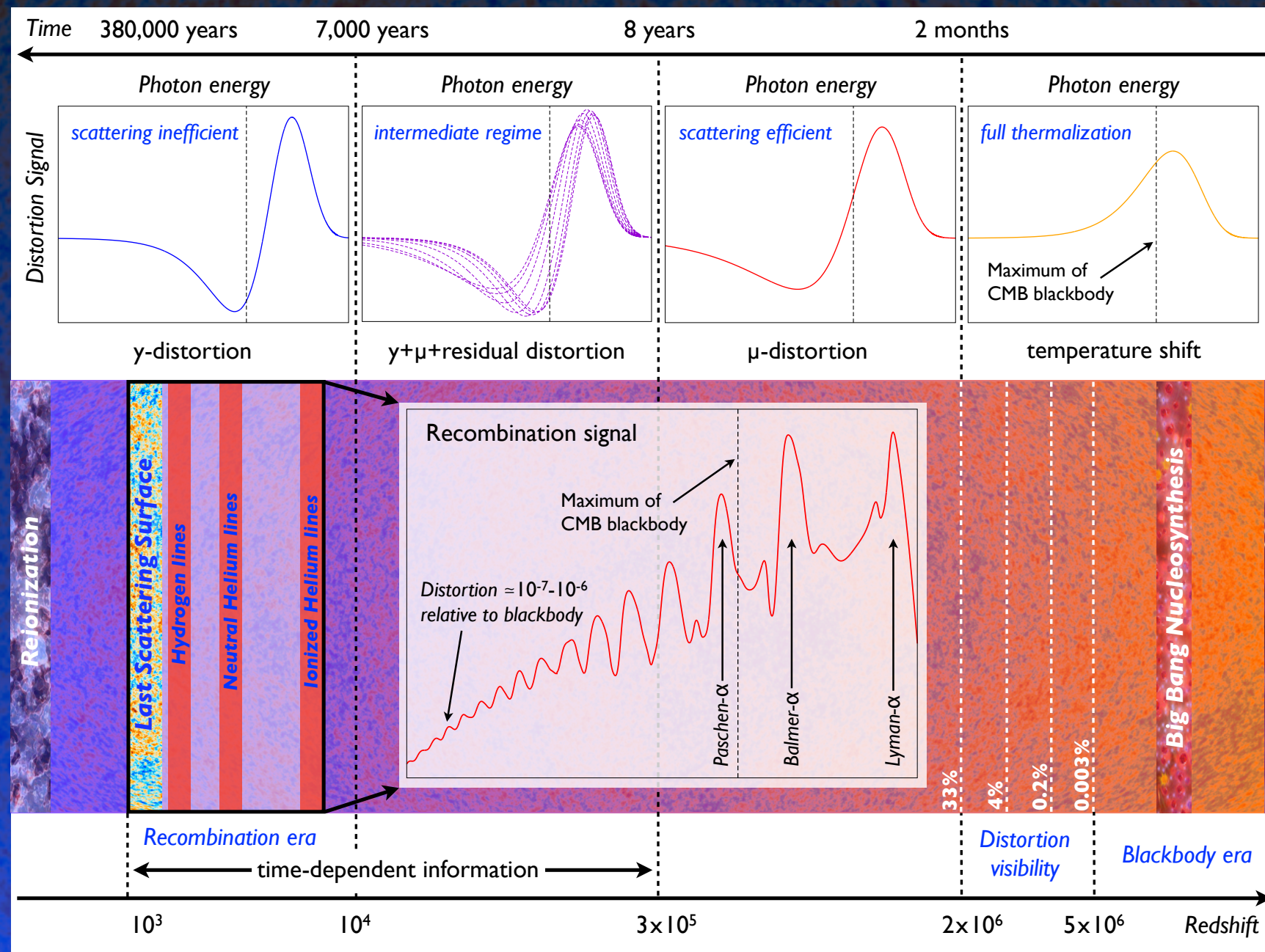


Next Frontiers in Cosmology with CMB* Spectral Distortions



MANCHESTER
1824

The University of Manchester

Jens Chluba

Sixth Zeldovich meeting, Pescara, Italy

13th -17th of July 2026



* CMB $\triangleq$ Cosmic Microwave Background

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

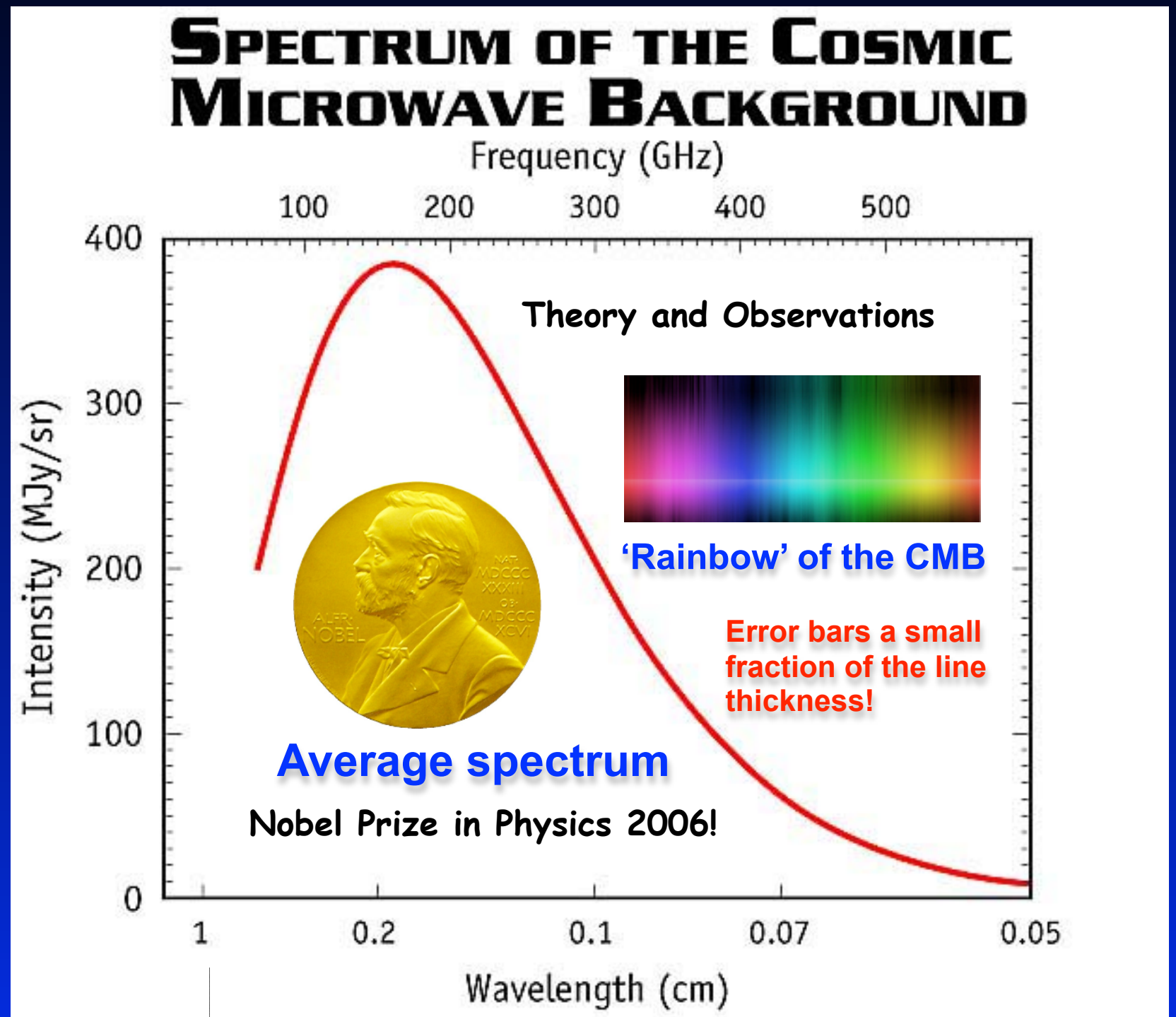


$$T_0 = 2.725 \pm 0.001 \text{ K}$$

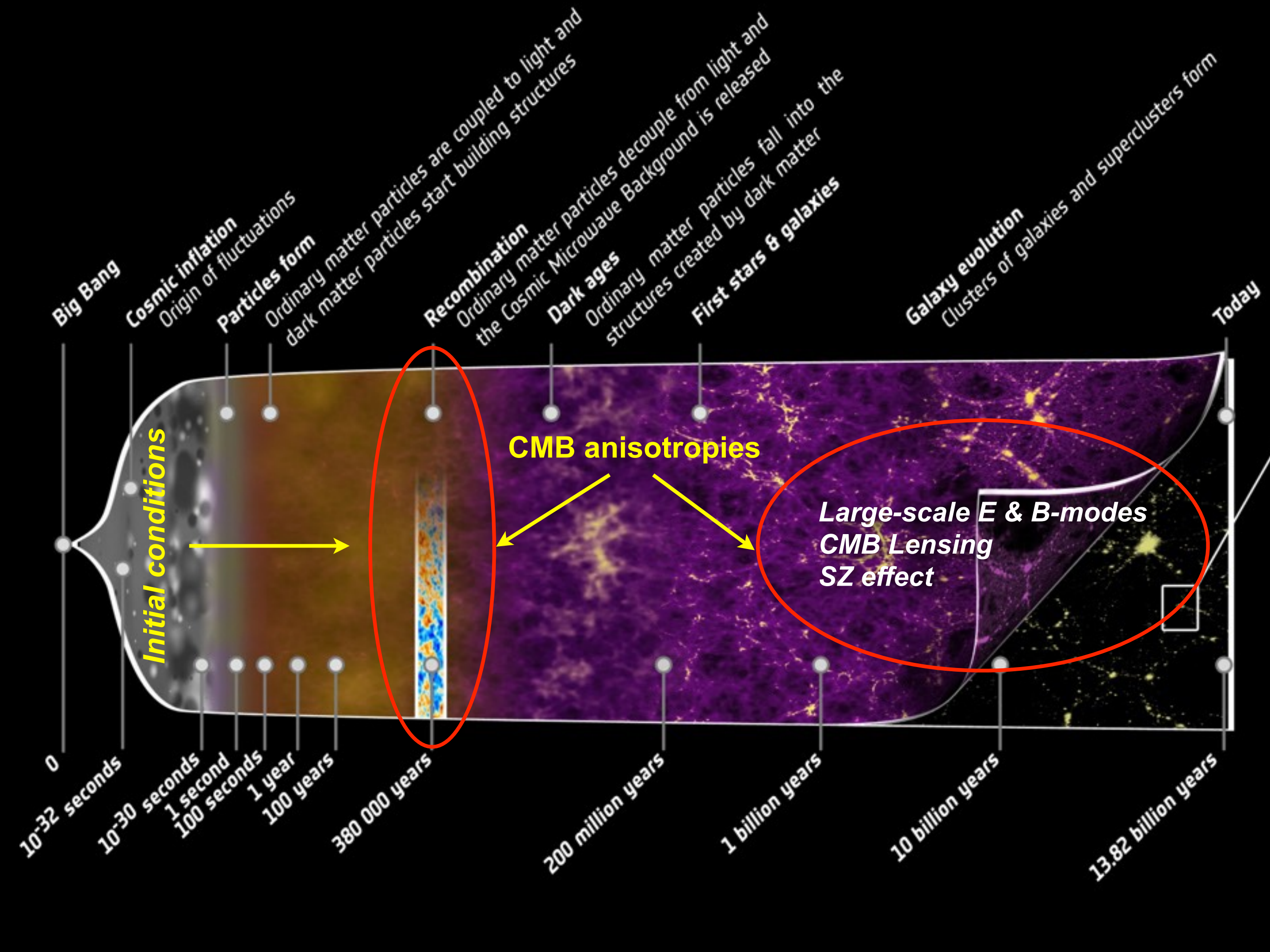
$$|y| \leq 1.5 \times 10^{-5}$$

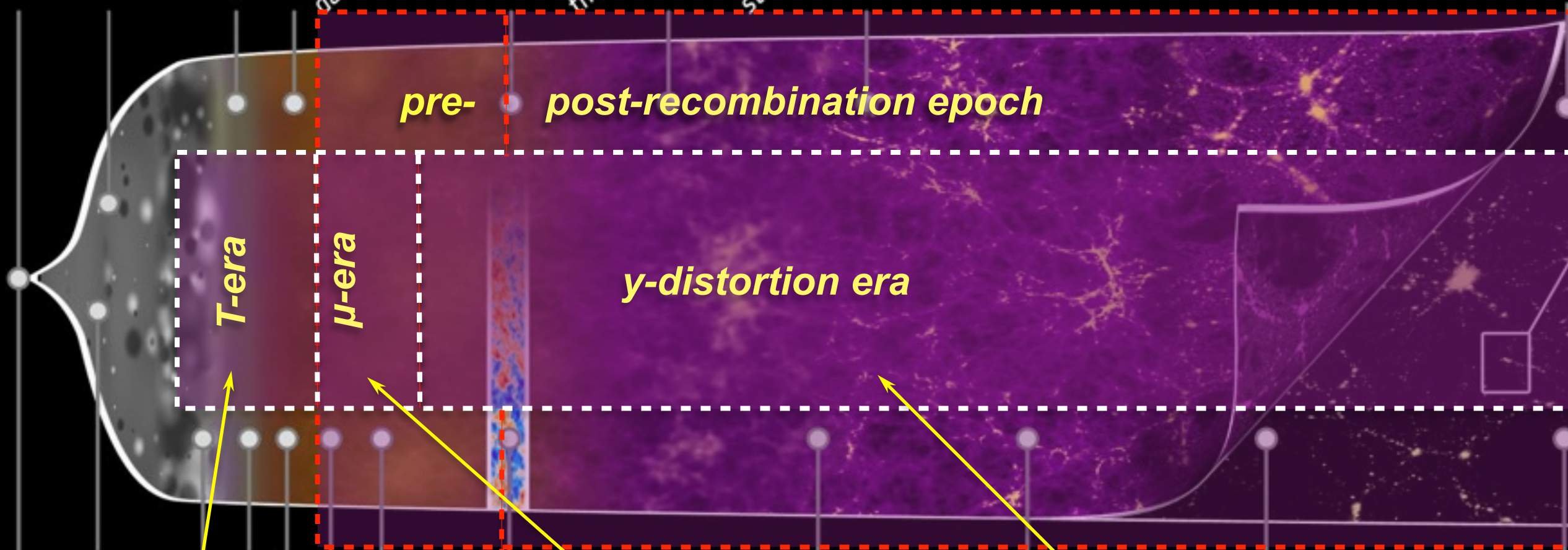
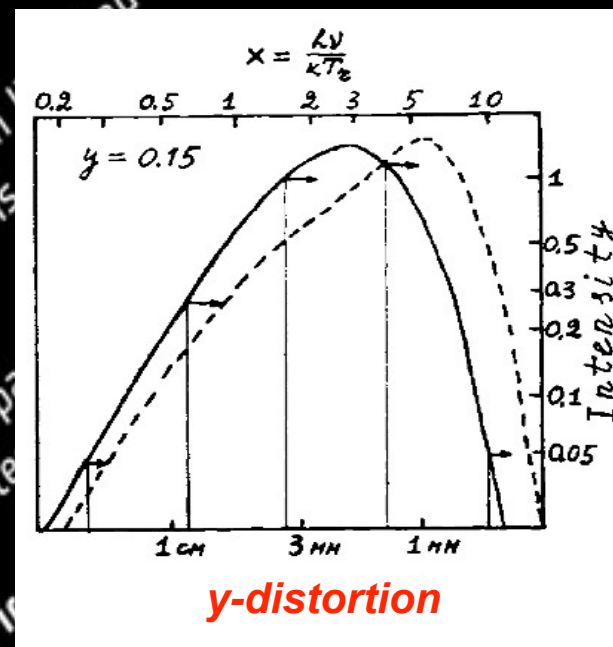
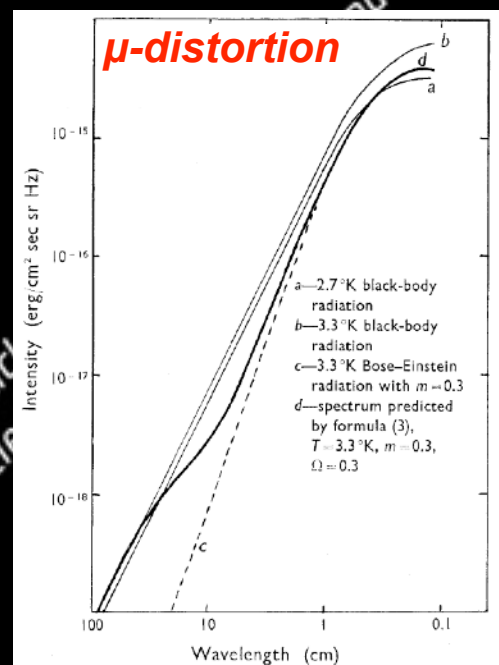
$$|\mu| \leq 9 \times 10^{-5}$$

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

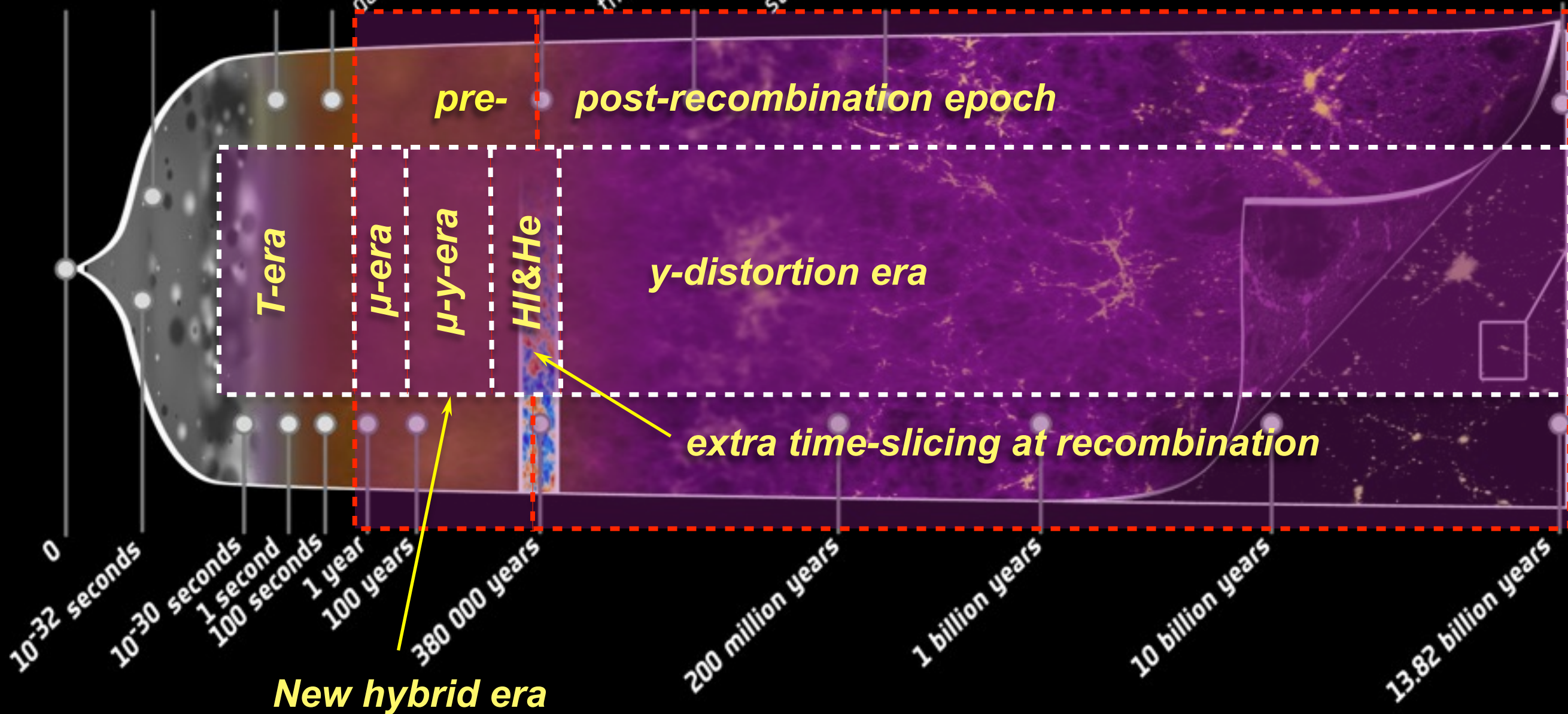
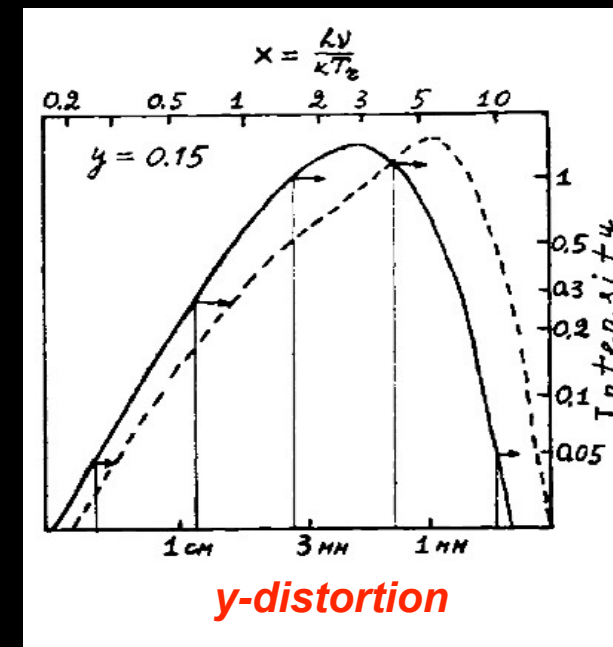
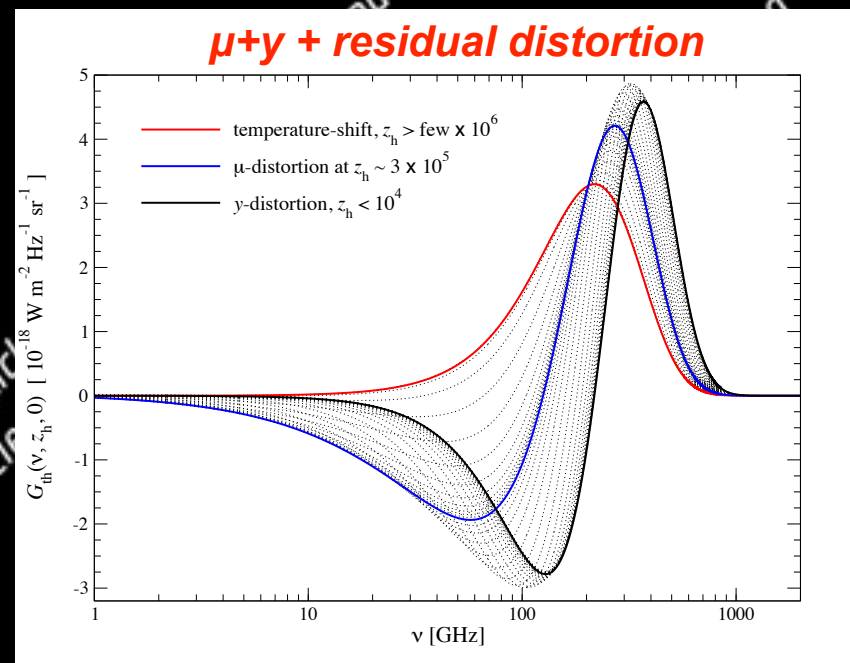
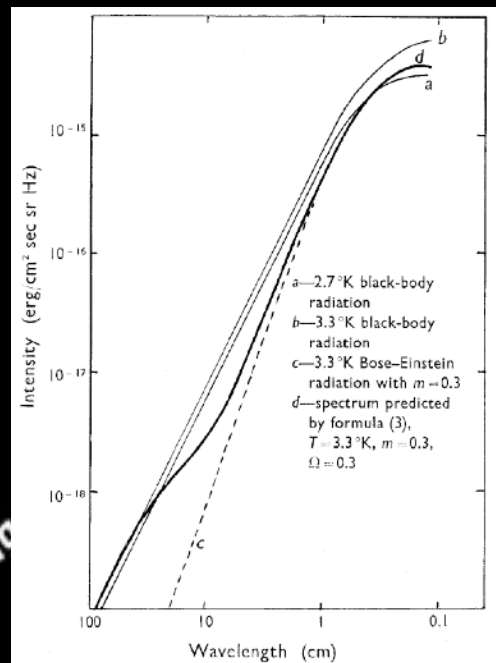




$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left. \frac{\Delta \rho_\gamma}{\rho_\gamma} \right|_T$$

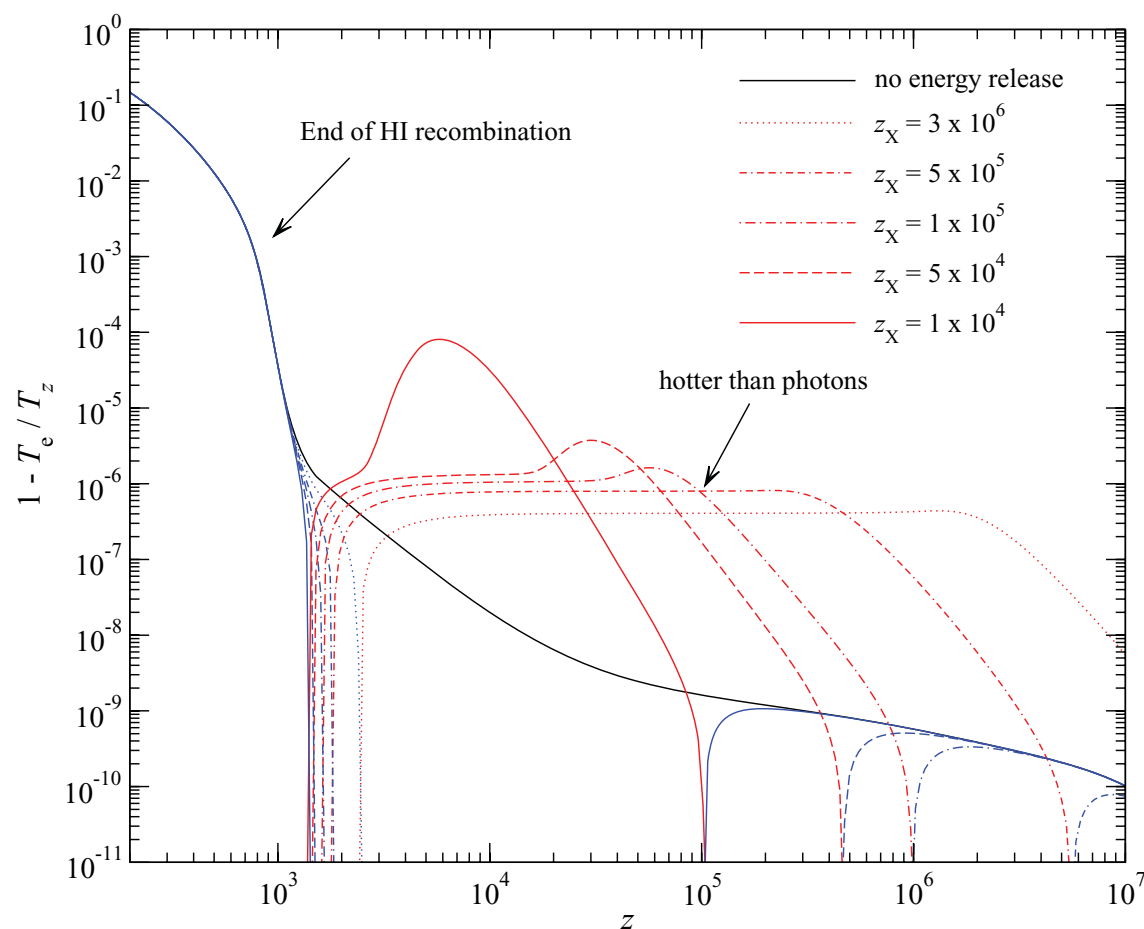
$$\mu \simeq 1.4 \left. \frac{\Delta \rho_\gamma}{\rho_\gamma} \right|_\mu$$

$$y \simeq \frac{1}{4} \left. \frac{\Delta \rho_\gamma}{\rho_\gamma} \right|_y$$

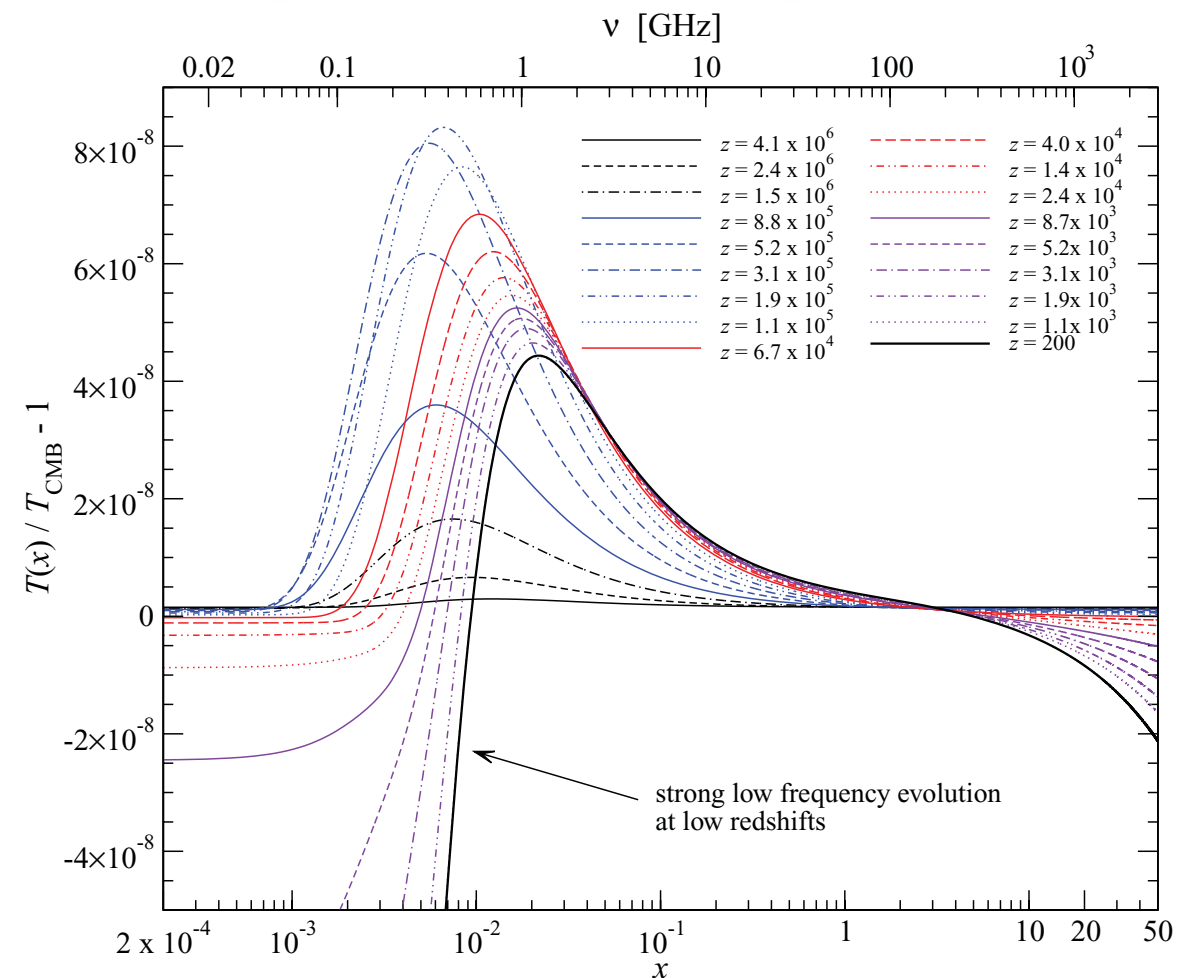


CosmoTherm: a (new) flexible thermalization code

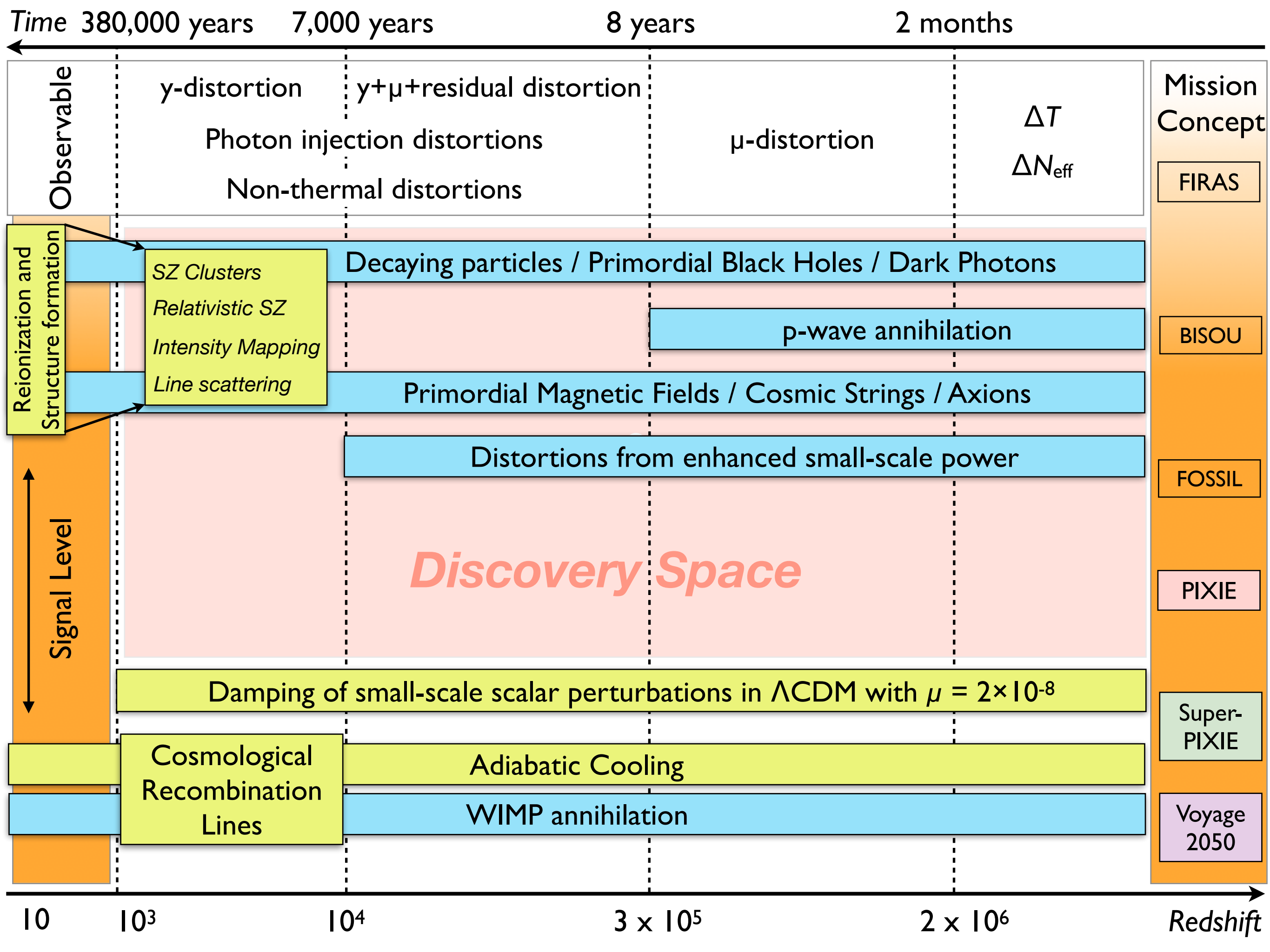
- Solve the thermalization problem for a *wide range* of energy release histories
- several scenarios already implemented (*decaying particles, damping of acoustic modes*)
- first *explicit* solution of time-dependent energy release scenarios
- open source code
 - will *soon* be available at www.Chluba.de/CosmoTherm/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



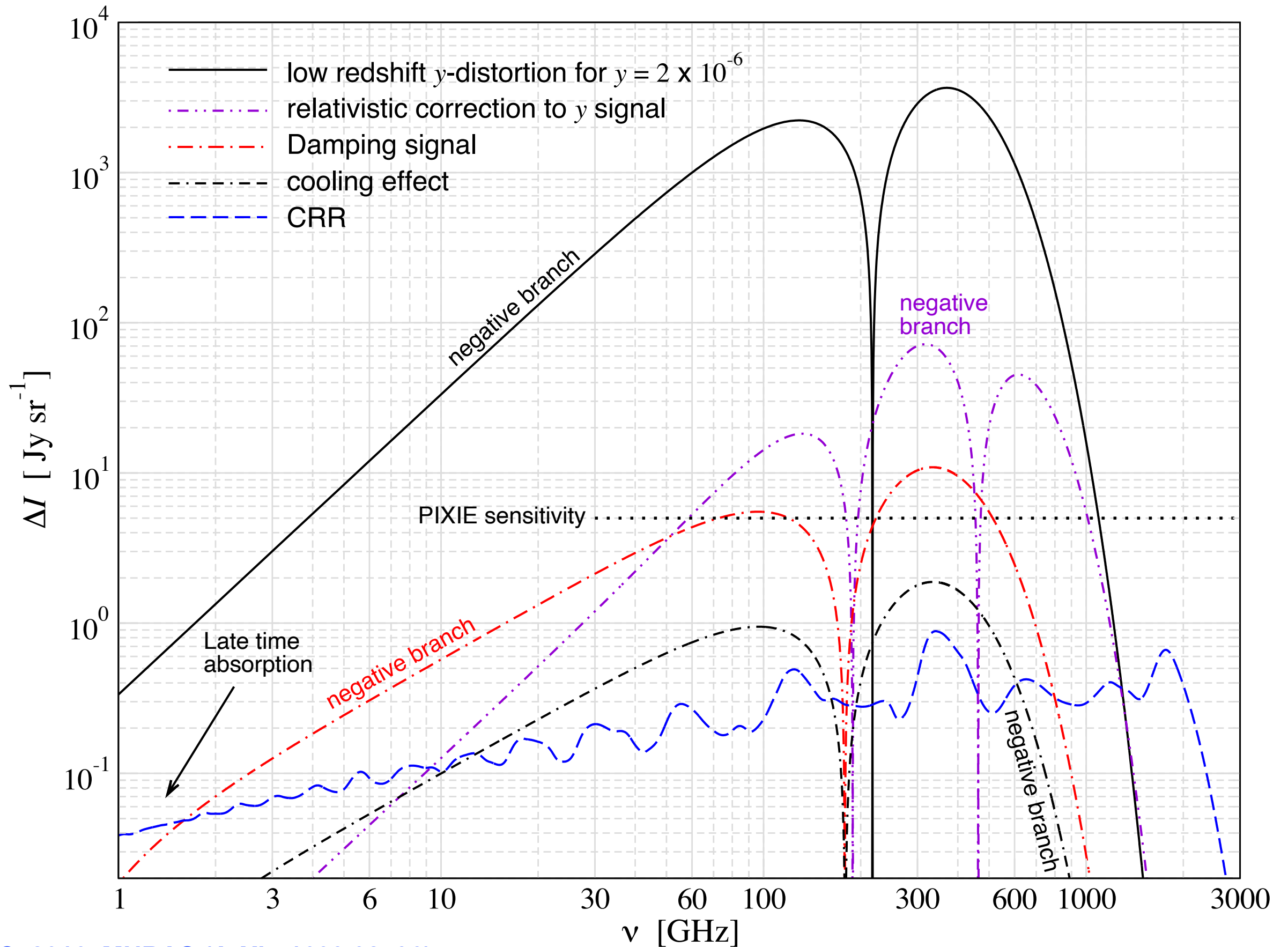
Electron temperature evolution



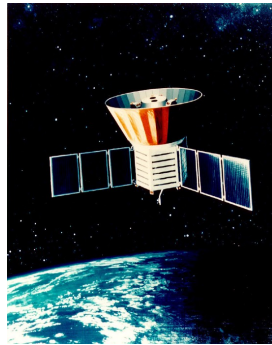
Evolution of distortion



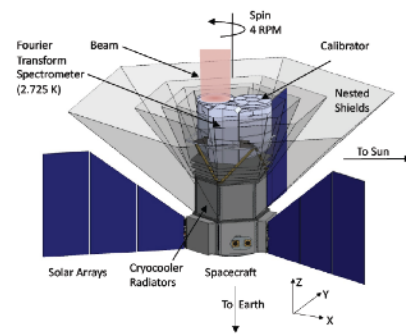
Average Λ CDM spectral distortions



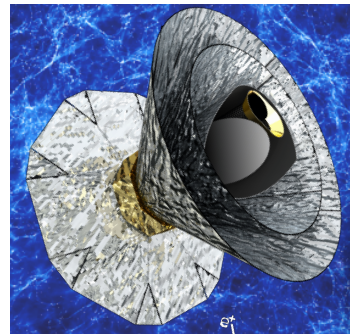
History of distortion experiments and proposals



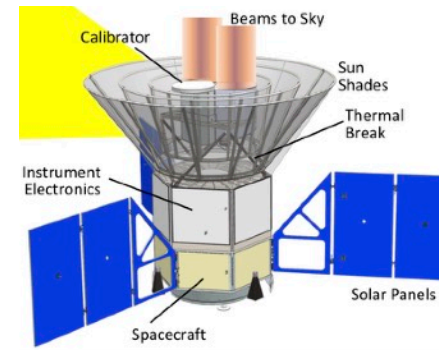
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



PRISM
De Bernardis



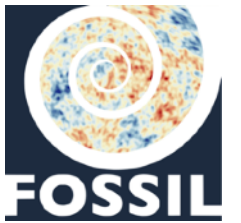
PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE



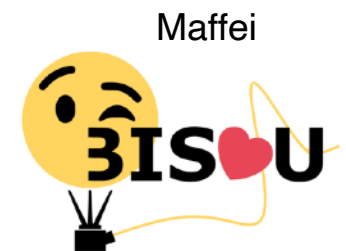
Aghanim



Aghanim



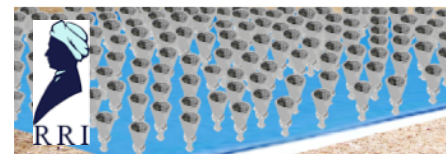
ARCADE 2
Kogut & Fixsen



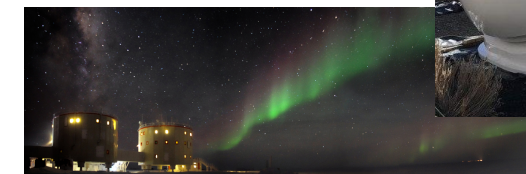
Maffei



Gervasi, Zannoni & Tartari



APSERa
Subrahmanyam & Rao



COSMO
De Bernardis, Masi & Battistelli



TMS
Rubiño-Martin

1989

2008

2011

2013

2015

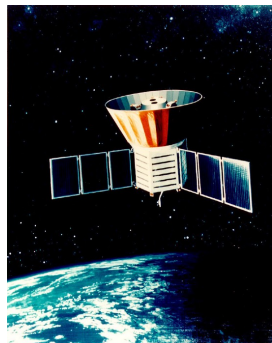
2016

2018

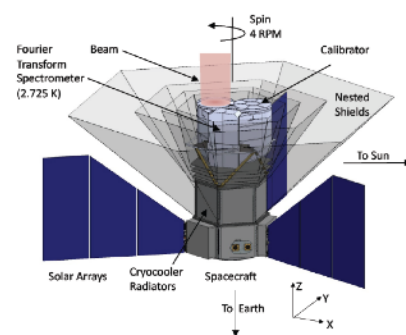
2022



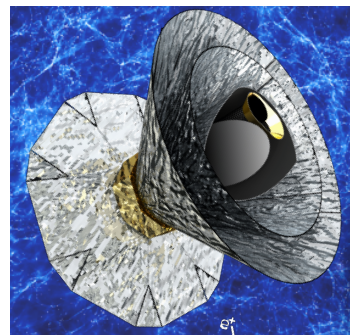
History of distortion experiments and proposals



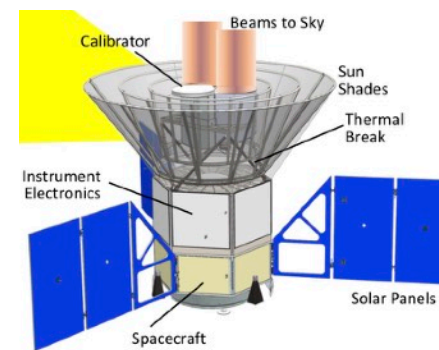
COBE/FIRAS
Mather & Fixsen



PIXIE
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PRISM
De Bernardis



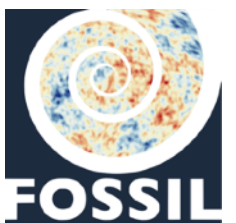
PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE



Aghanim

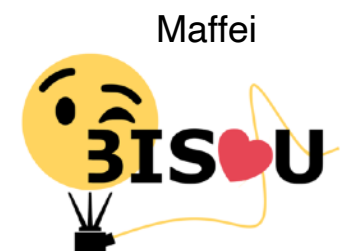
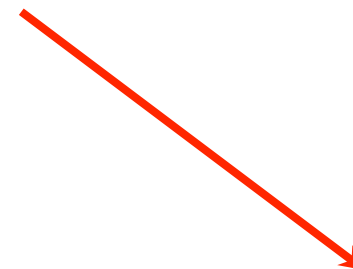


Aghanim



ARCADE 2
Kogut & Fixsen

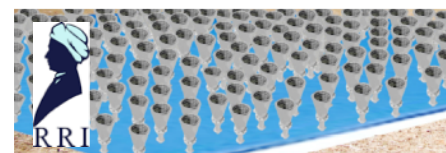
Not just fiction
anymore!



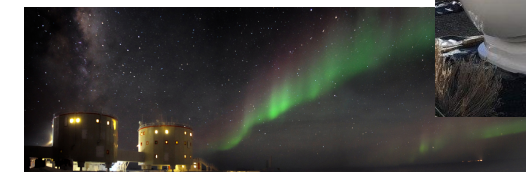
Maffei



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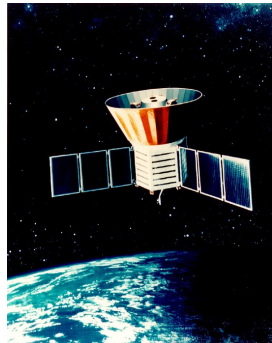
2016

2018

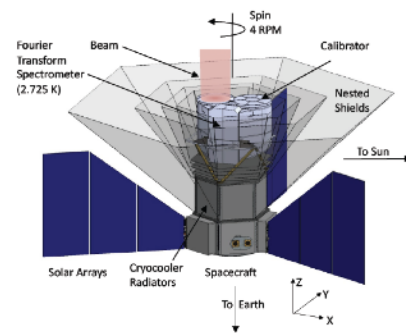
2022



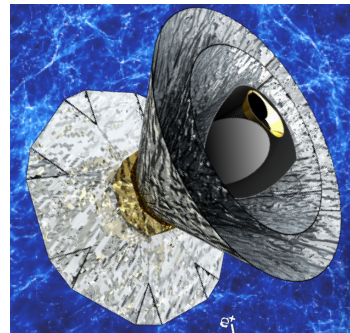
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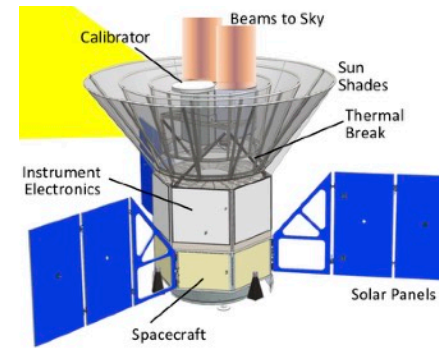
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



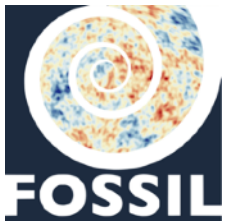
PRISM
De Bernardis



PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE



FOSSIL
Aghanim



TMS and COSMO in construction!
BISOU officially in Phase A!
FOSSIL in step 2 of M8 selection!

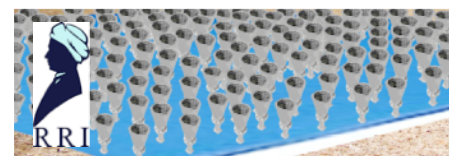
Maffei



ARCADE 2
Kogut & Fixsen



TRIS
Gervasi, Zannoni & Tartari



APSERa
Subrahmanyam & Rao



COSMO
De Bernardis, Masi & Battistelli



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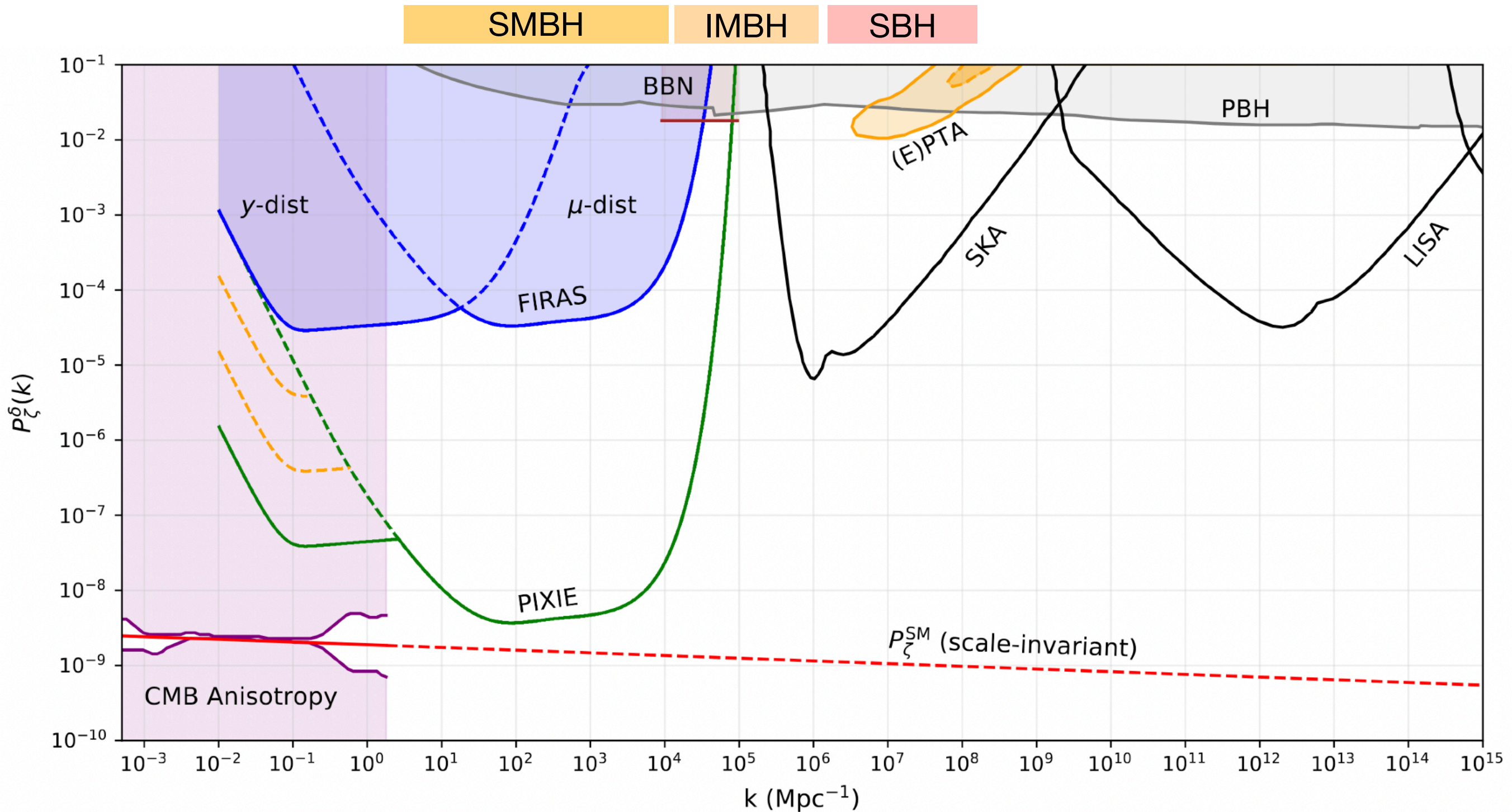
2018

2022



New Probe of the Early Universe

Small-scale power constraints and PBH formation

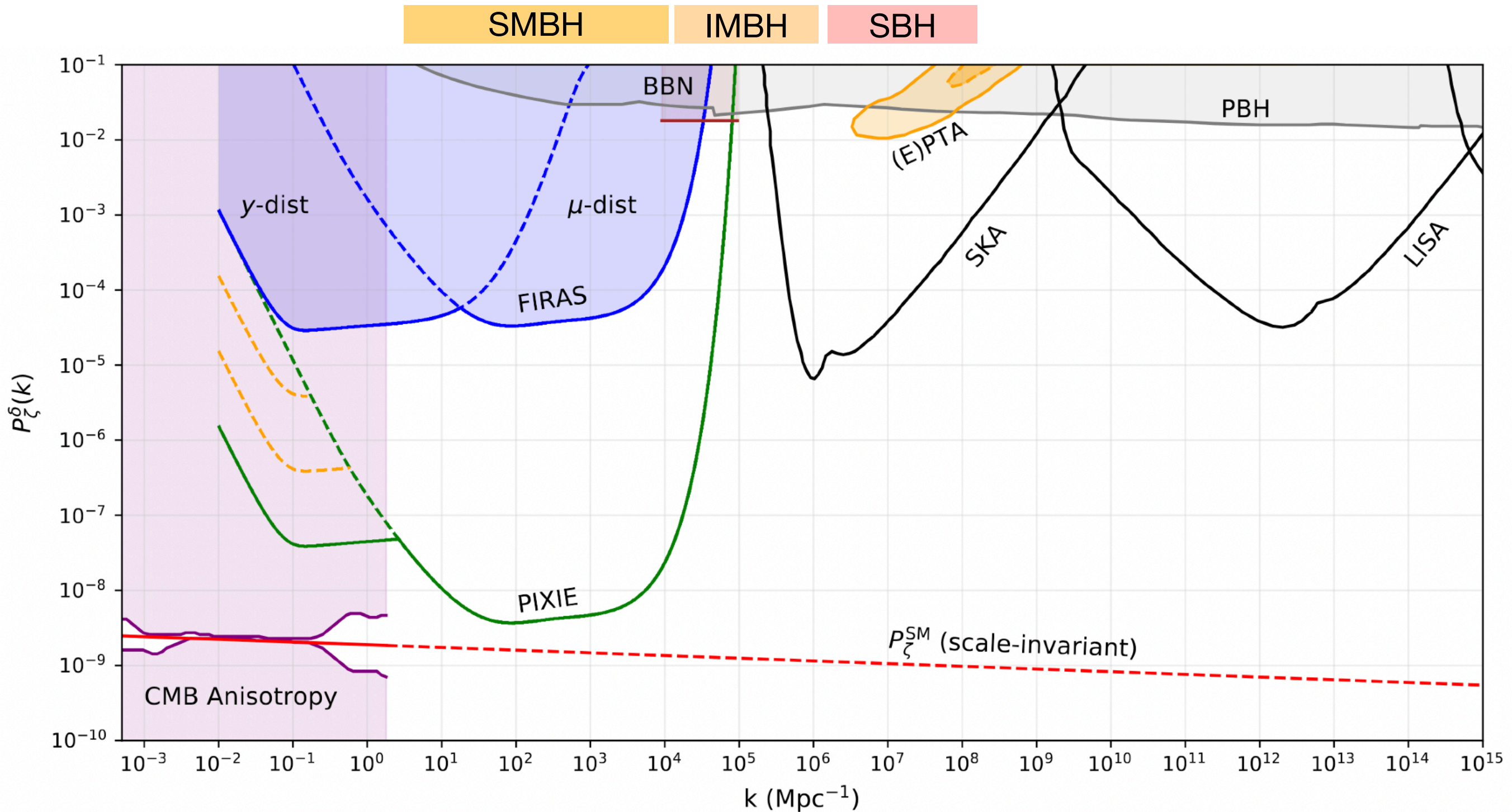


JC, Khatri & Sunyaev, 2012

JC, Erickcek & Ben-Dayan, 2012

Cyr et al., 2023, ArXiv:2309.02366

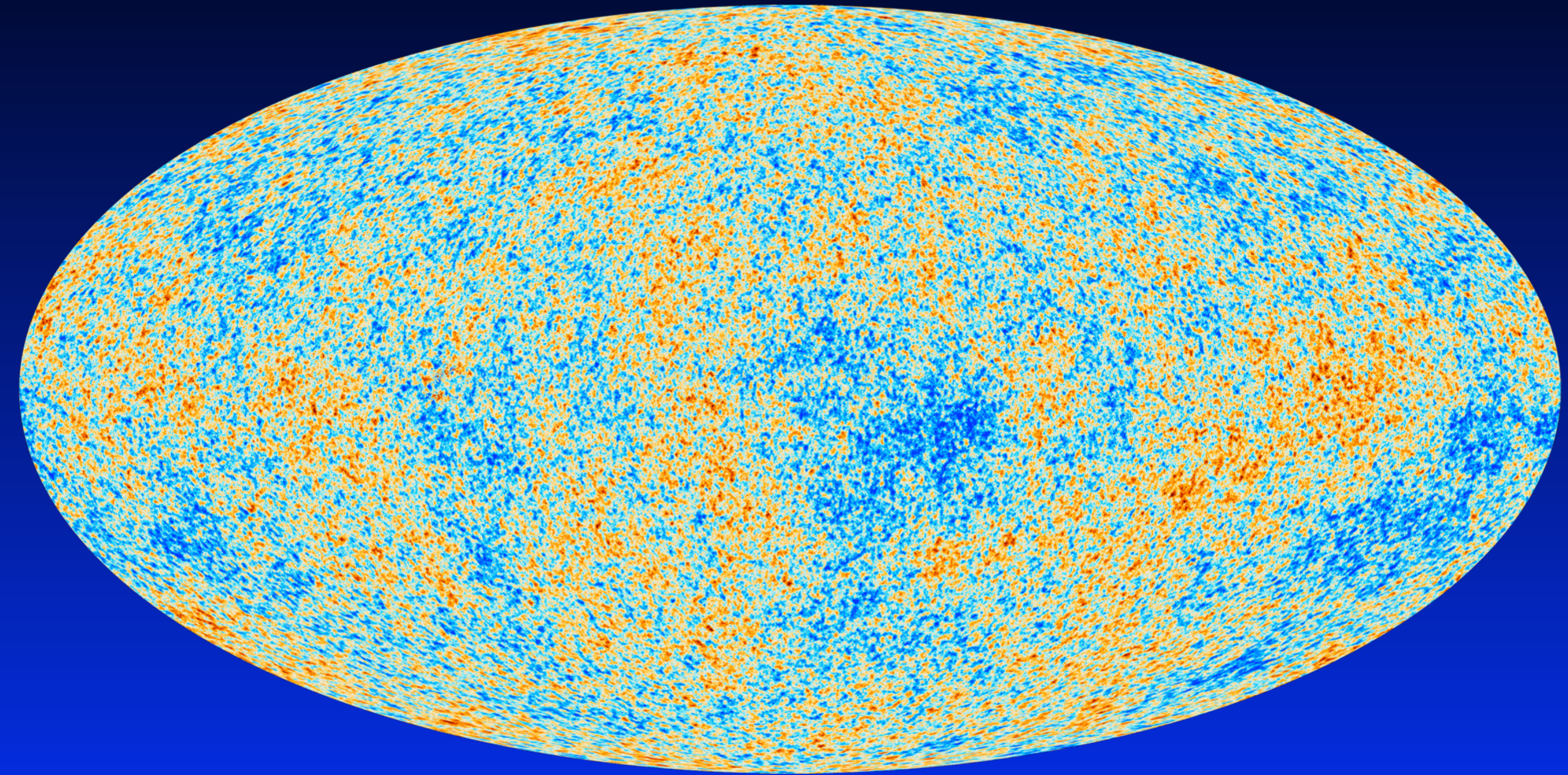
Small-scale power constraints and PBH formation



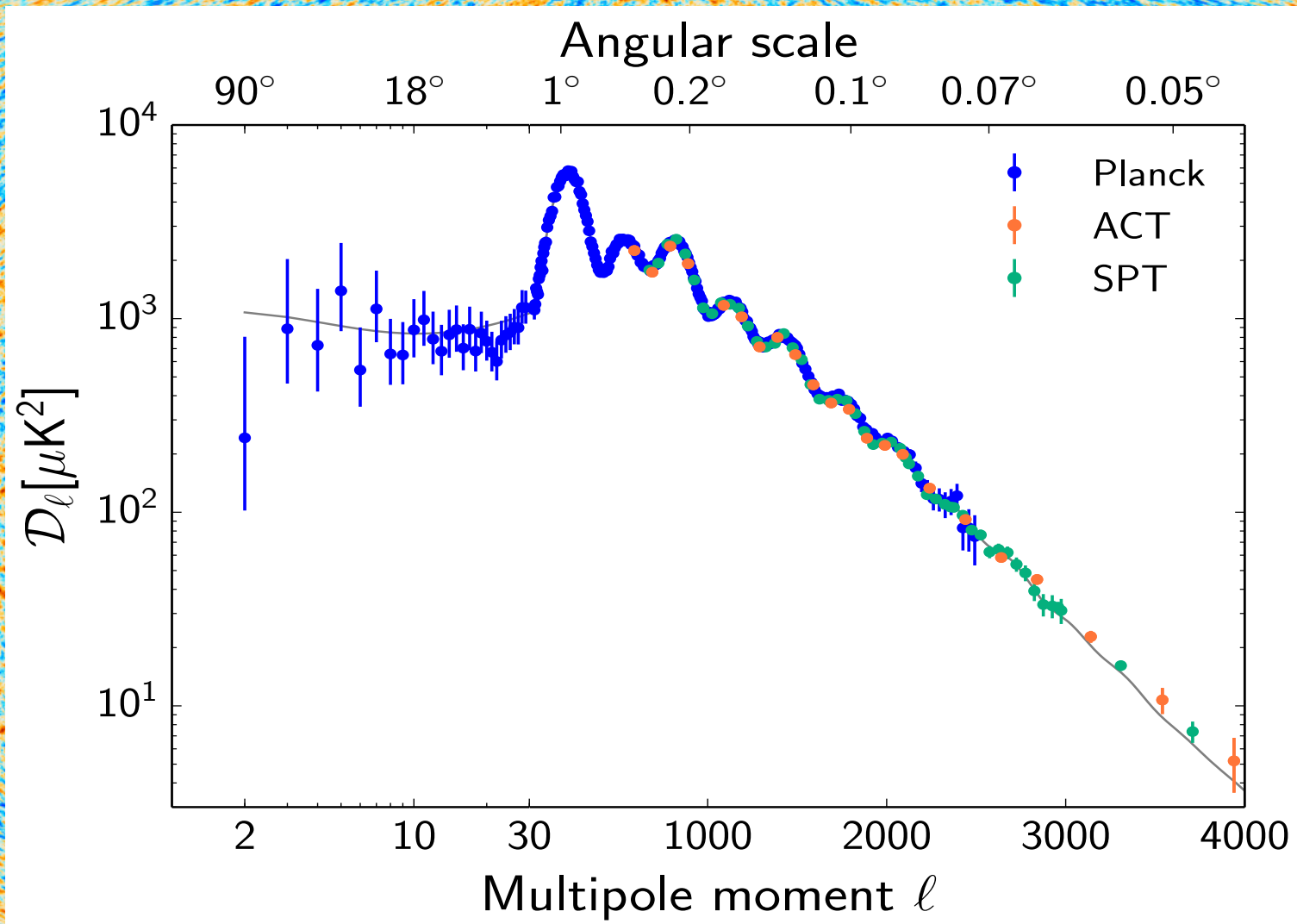
JC, Khatri & Sunyaev, 2012
JC, Erickcek & Ben-Dayan, 2012
Cyr et al., 2023, ArXiv:2309.02366

A CMB spectrometer could shed light on
primordial black hole formation

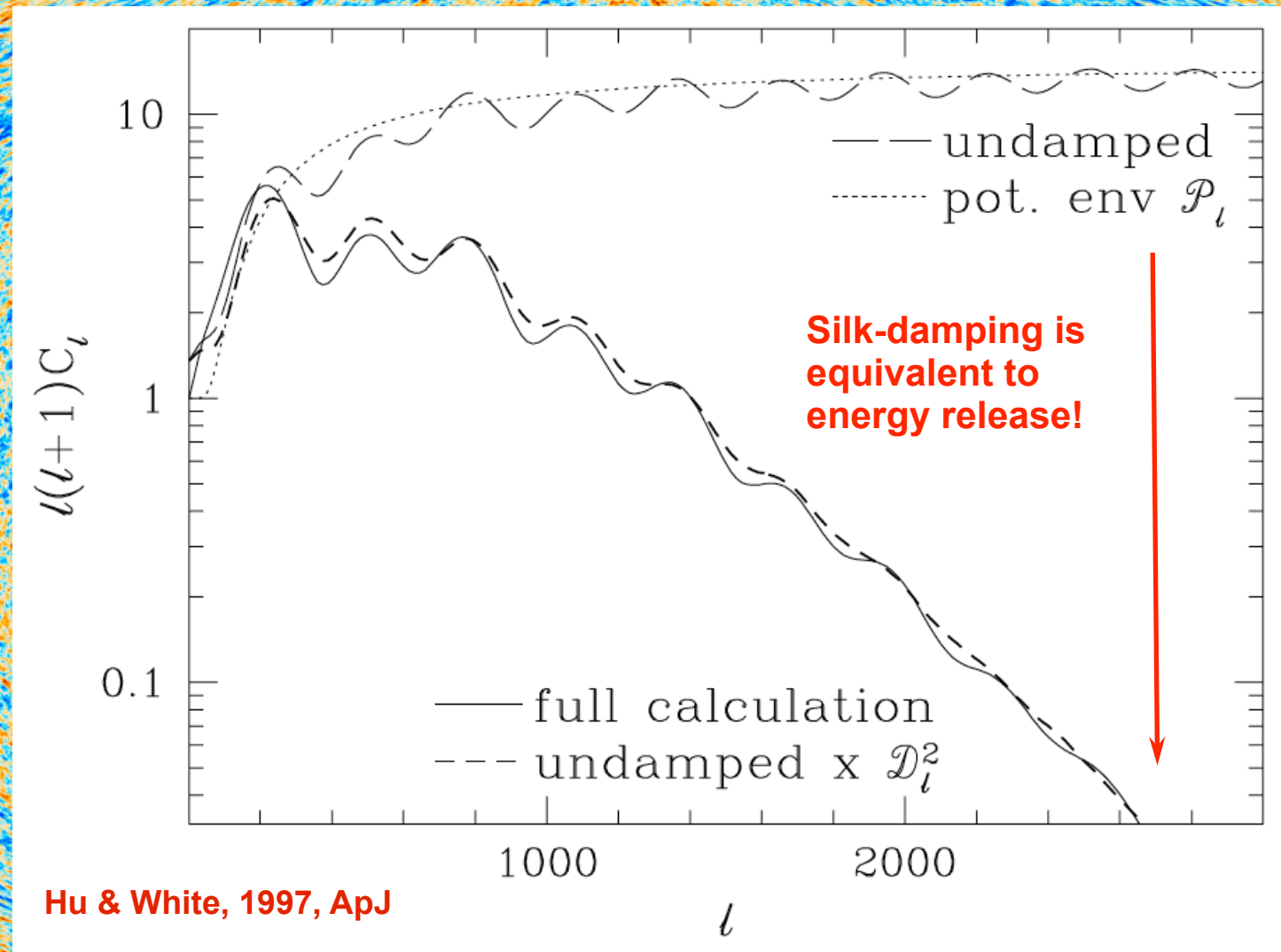
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



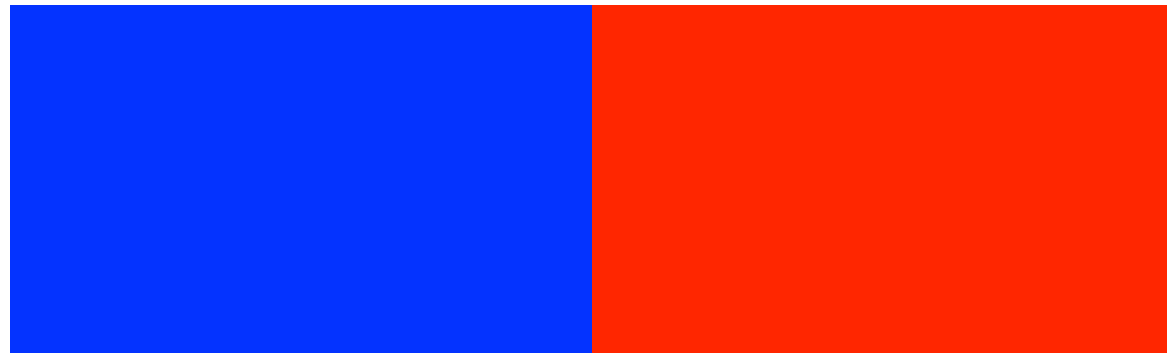
Dissipation of small-scale acoustic modes



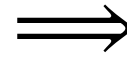
Ideas go back to Sunyaev & Zeldovich, 1970

Distortion due to mixing of blackbodies

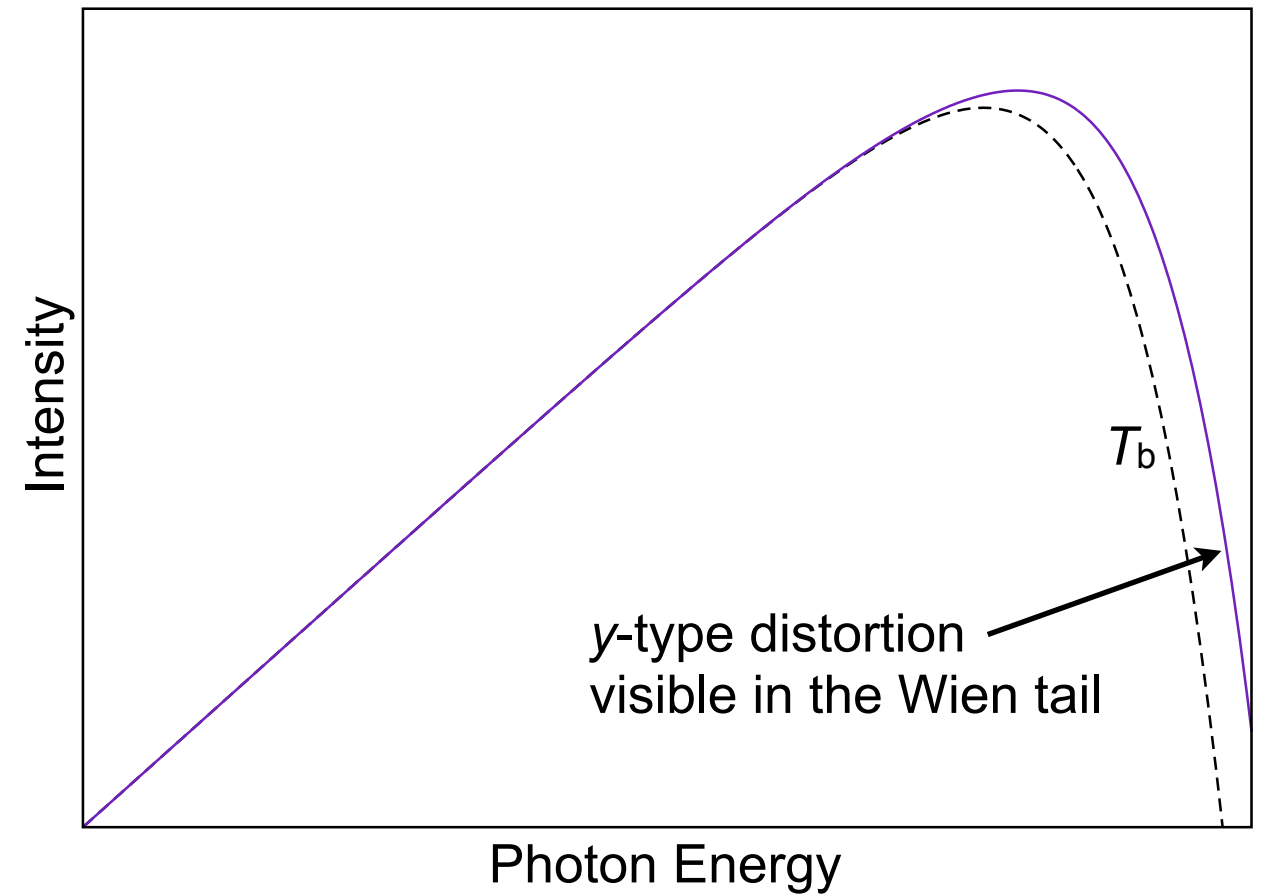
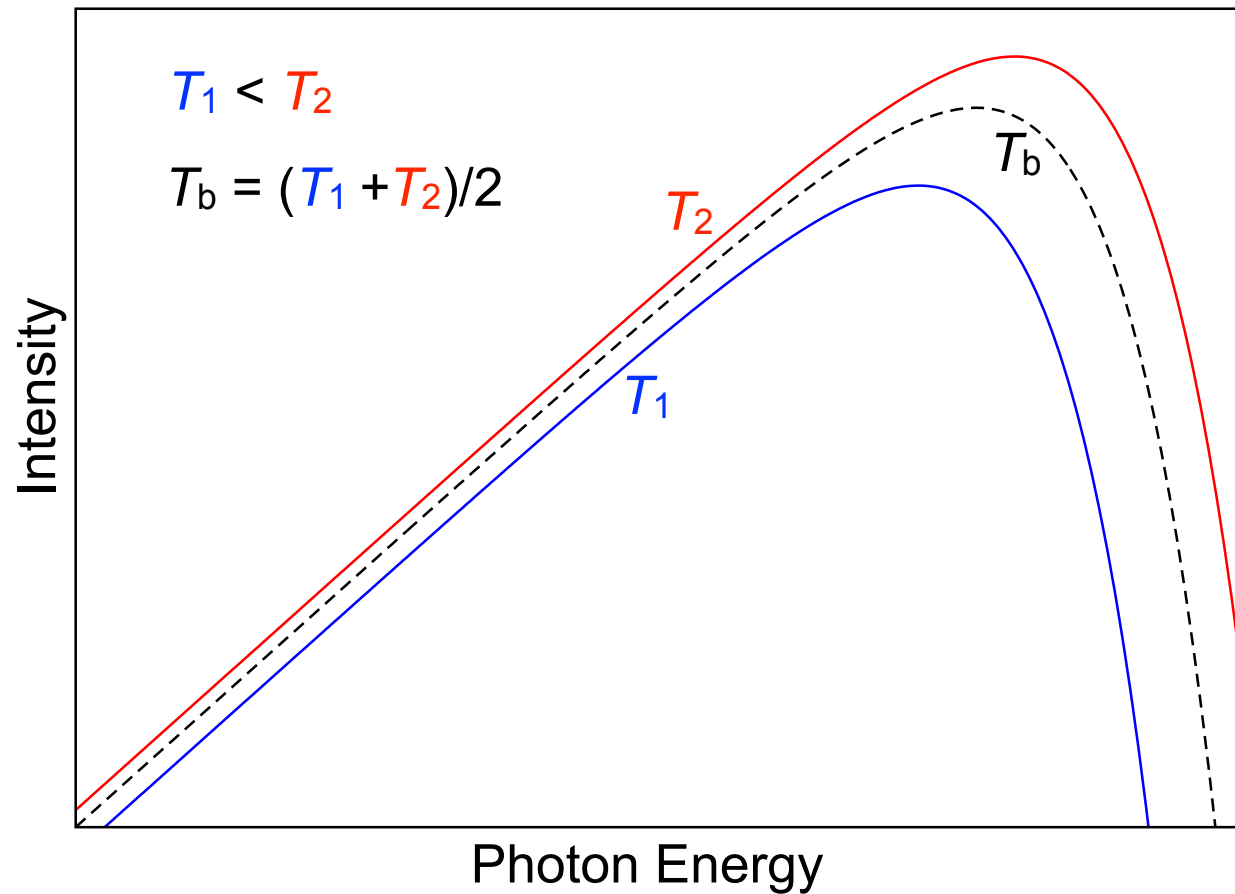
Blackbody spectra



Photon mixing



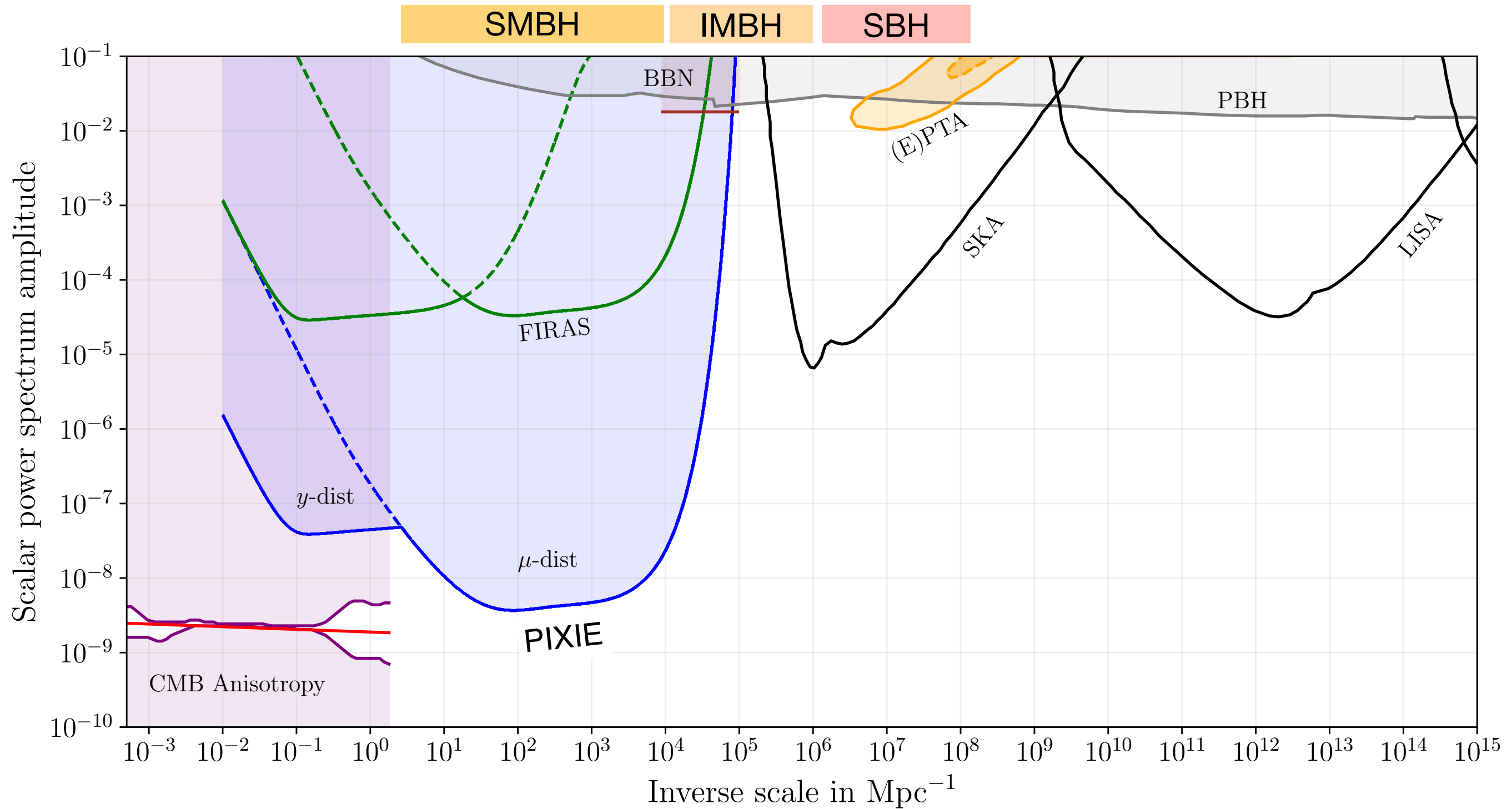
Blackbody + y -distortion



JC, Hamann & Patil, 2015

Mixing is mediated by Thomson scattering $\Rightarrow$ Silk damping

Exploring the small-scale Universe



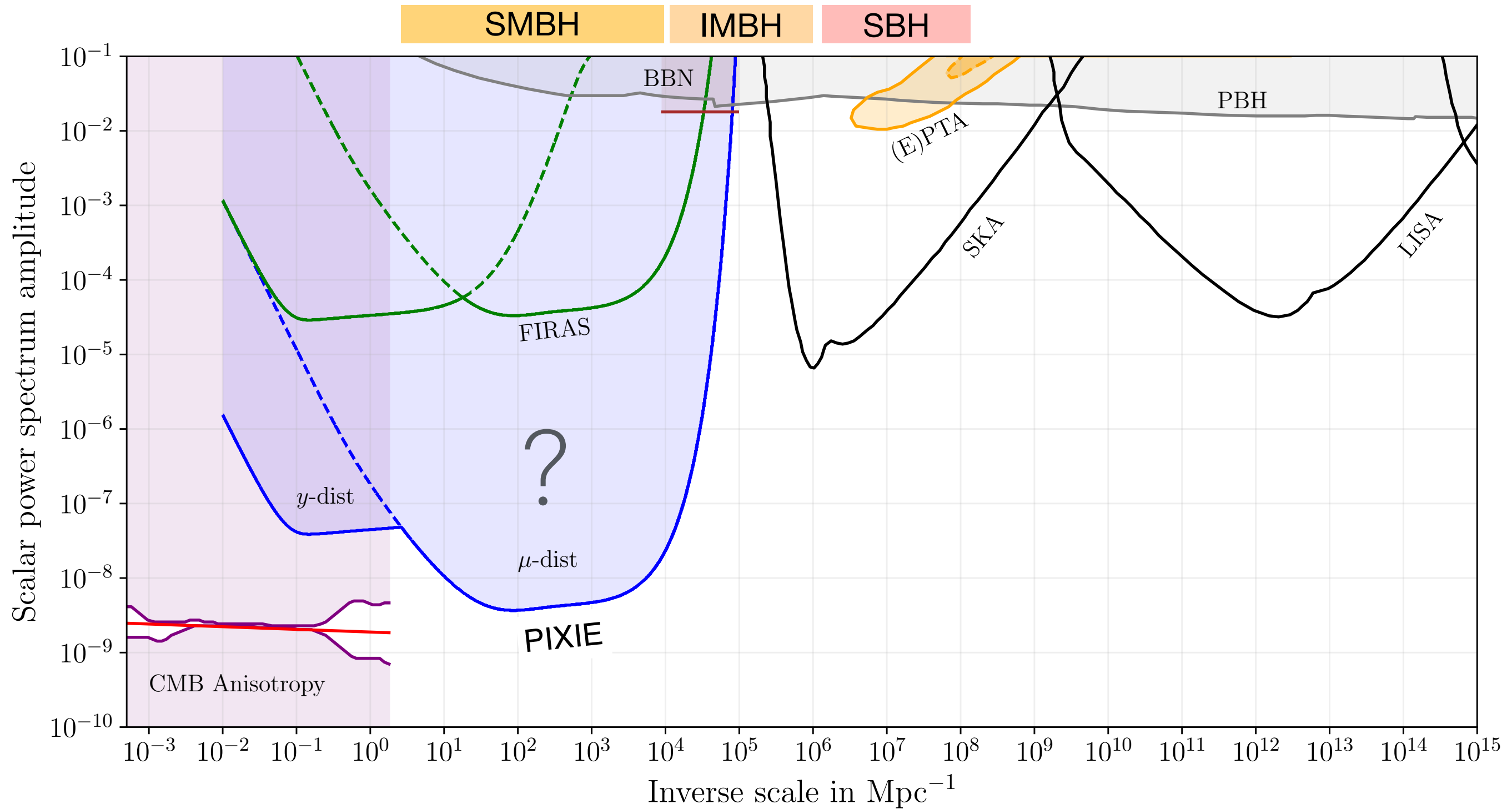
JC, Khatri & Sunyaev, 2012

JC, Erickcek & Ben-Dayan, 2012

Jeong et al., 2014

Cyr et al., 2023, ArXiv:2309.02366

Exploring the small-scale Universe



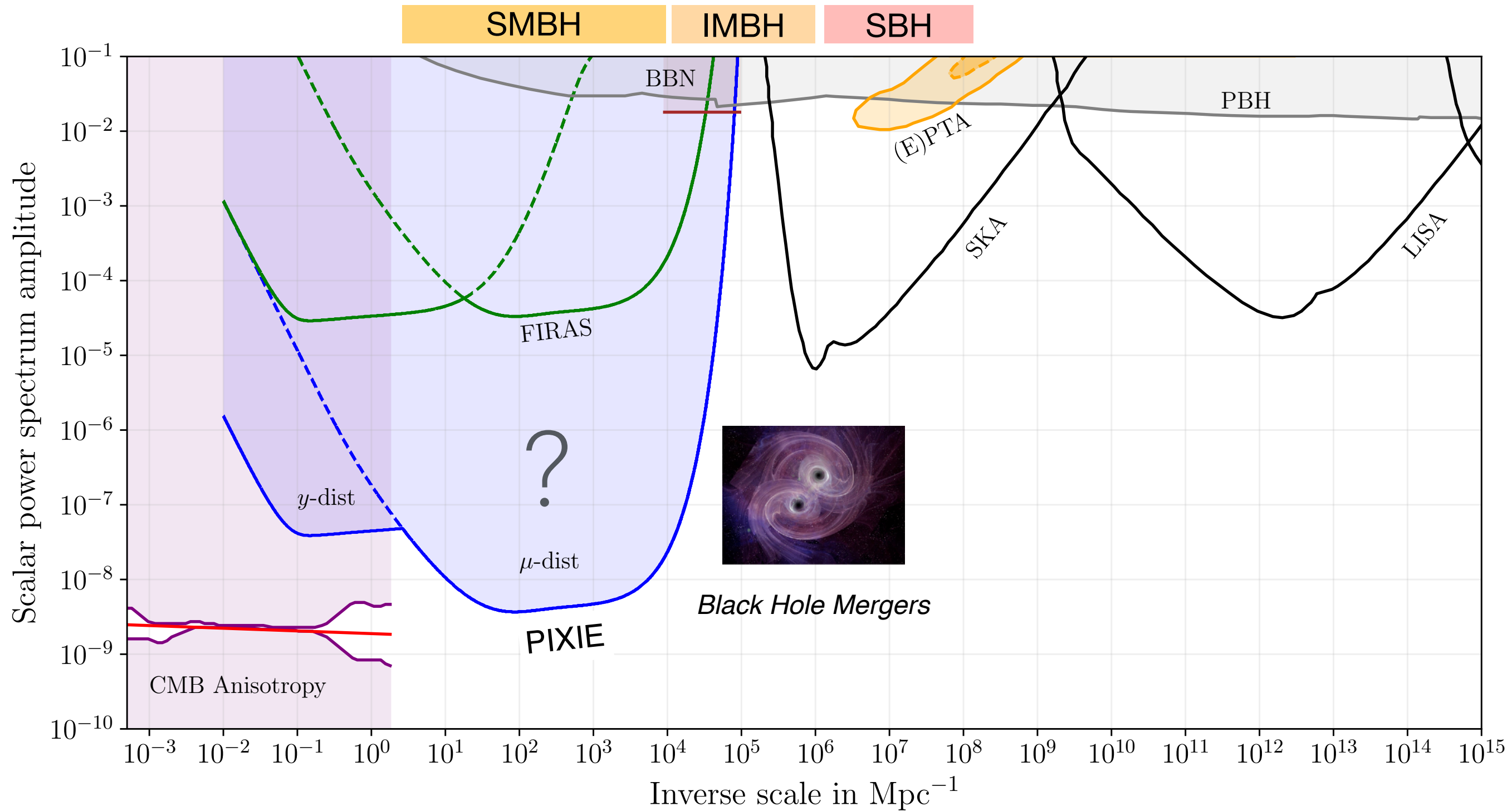
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Exploring the small-scale Universe



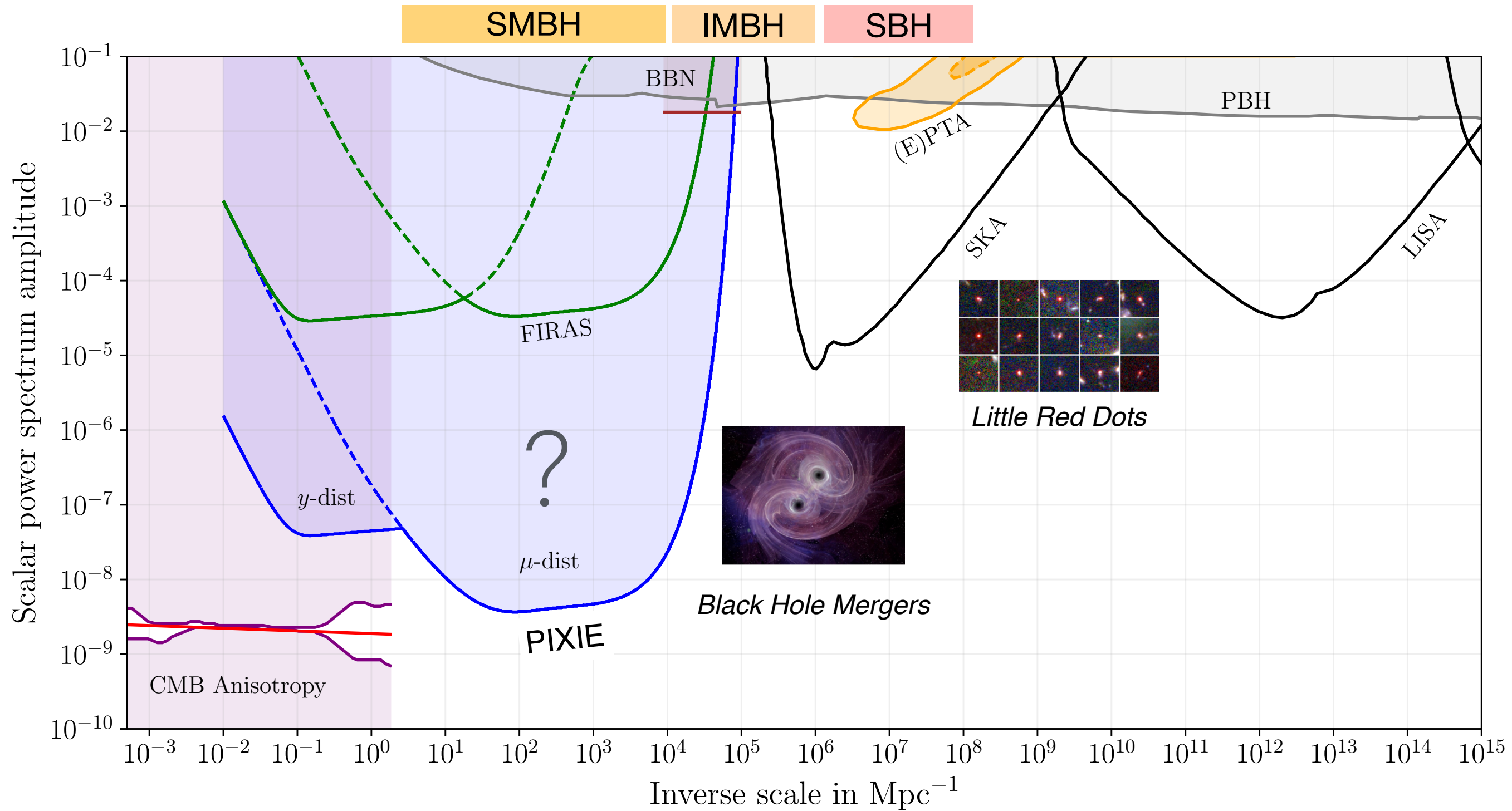
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Exploring the small-scale Universe



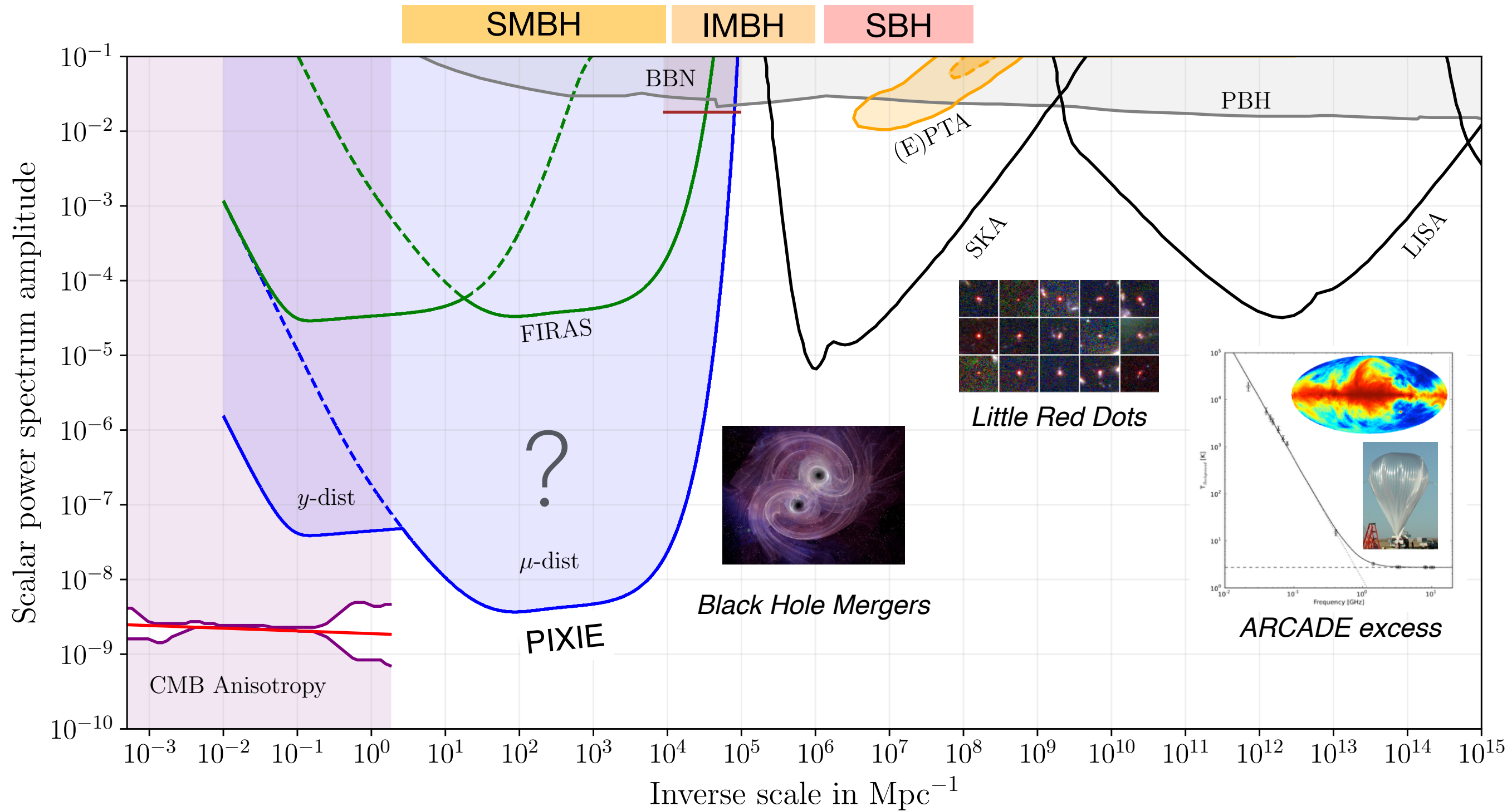
JC, Khatri & Sunyaev, 2012

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Exploring the small-scale Universe



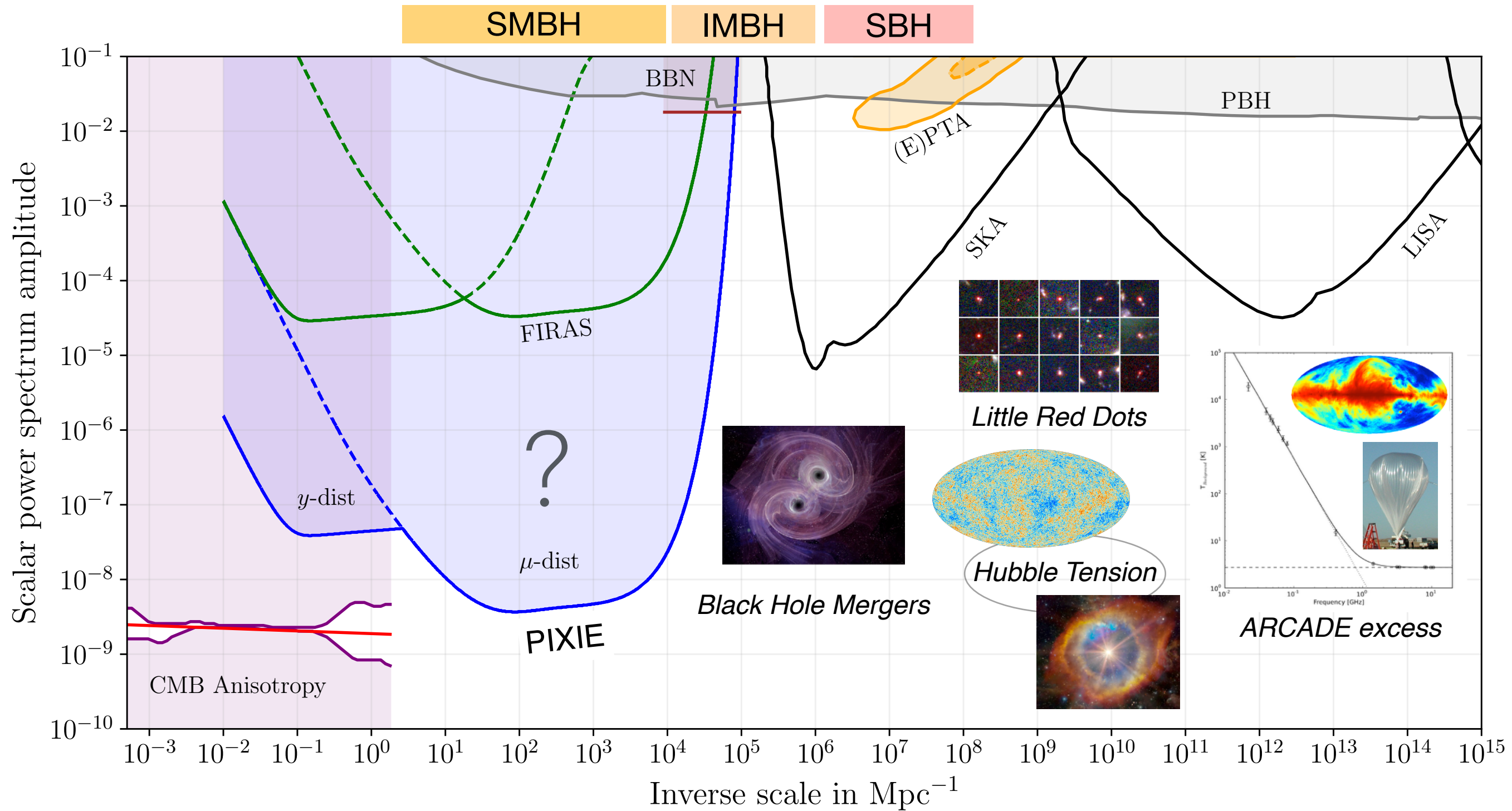
JC, Khatri & Sunyaev, 2012

JC, Erickcek & Ben-Dayan, 2012

Jeong et al., 2014

Cyr et al., 2023, ArXiv:2309.02366

Exploring the small-scale Universe



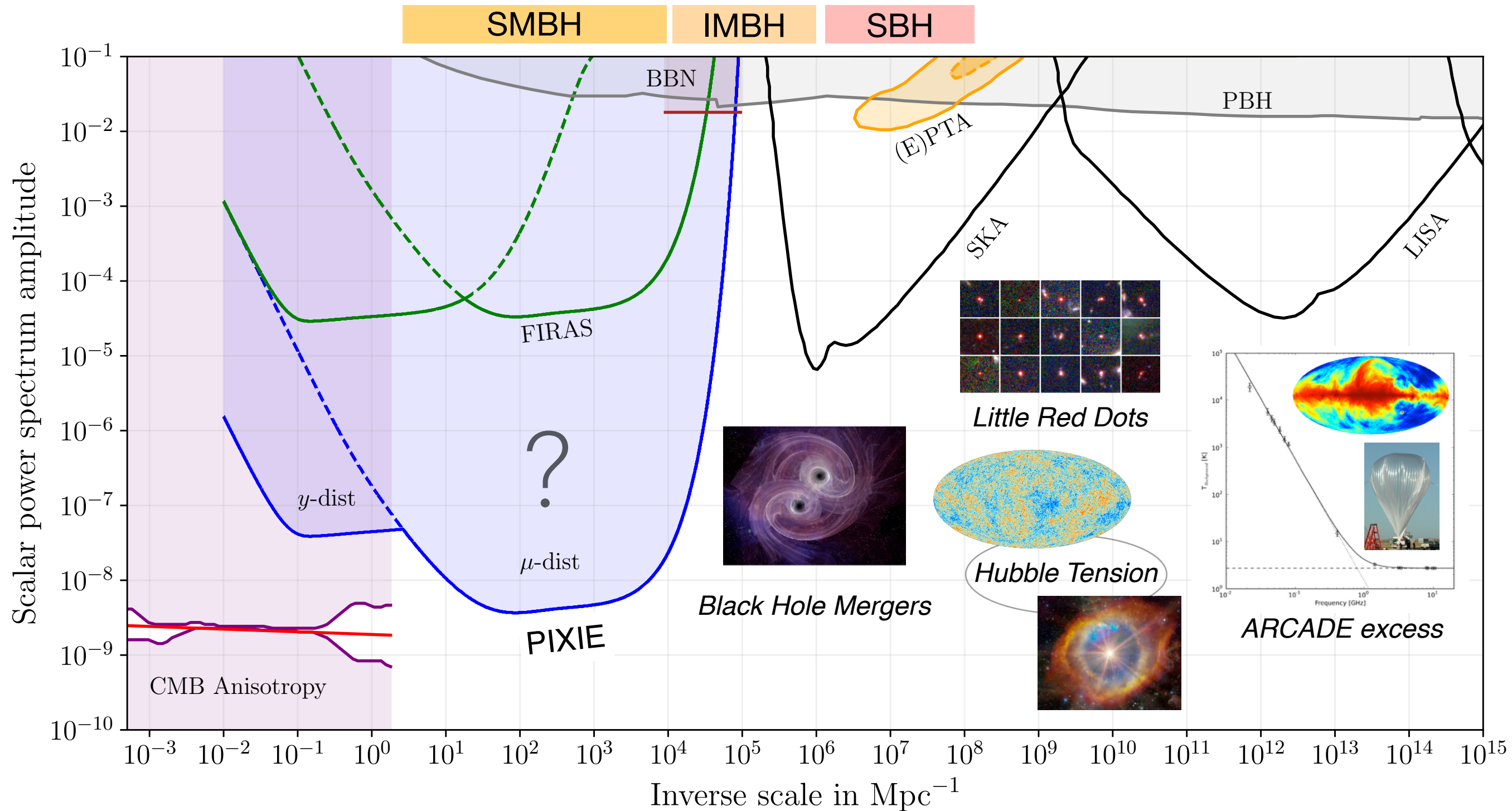
JC, Khatri & Sunyaev, 2012

JC, Erickcek & Ben-Dayan, 2012

Jeong et al., 2014

Cyr et al., 2023, ArXiv:2309.02366

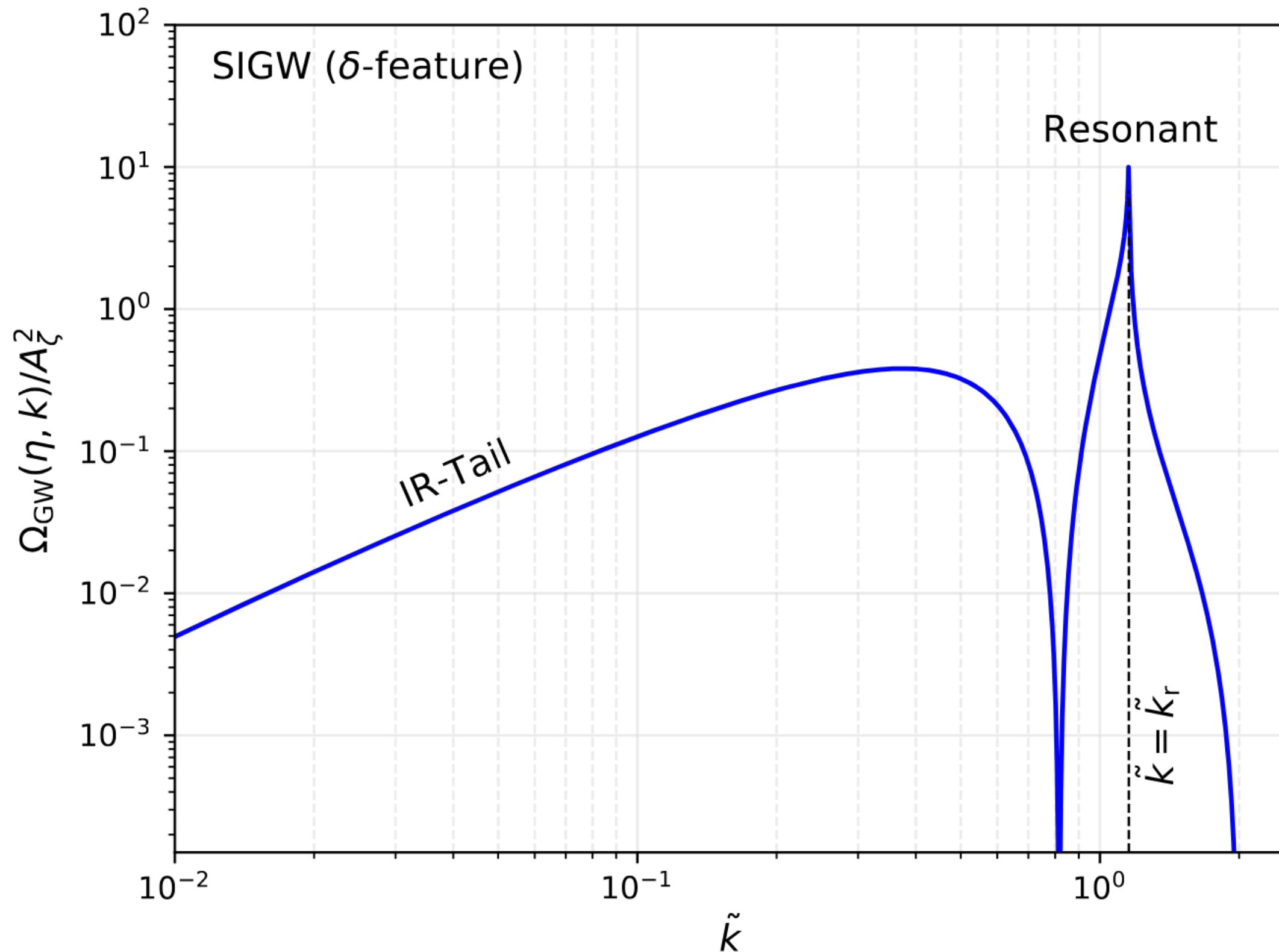
Exploring the small-scale Universe



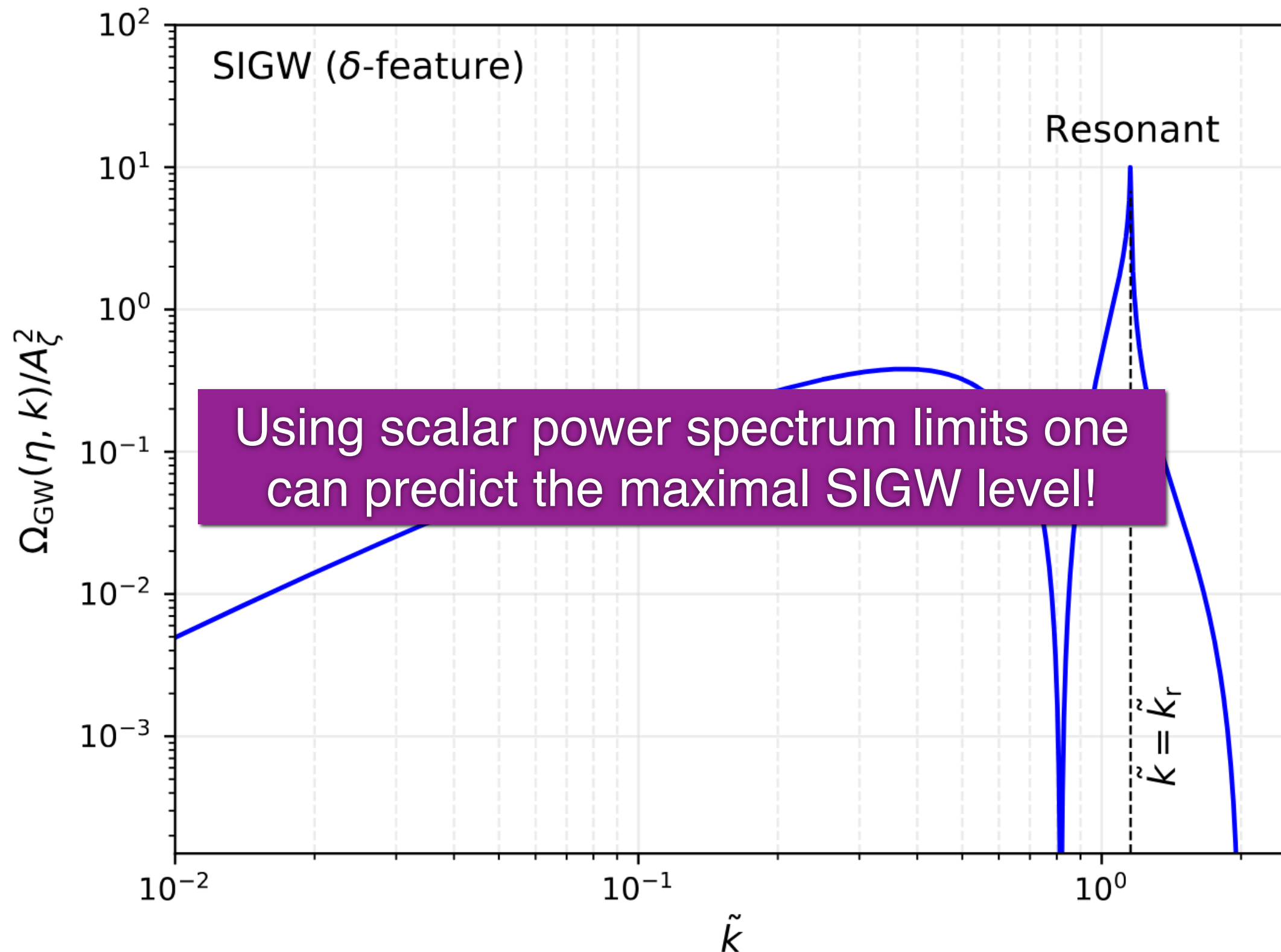
JC, Khatri & Sunyaev, 2012
 JC, Erickcek & Ben-Dayan, 2012
 Jeong et al., 2014
 Cyr et al., 2023, ArXiv:2309.02366

A CMB spectrometer could will be crucial
 in exploring these questions!

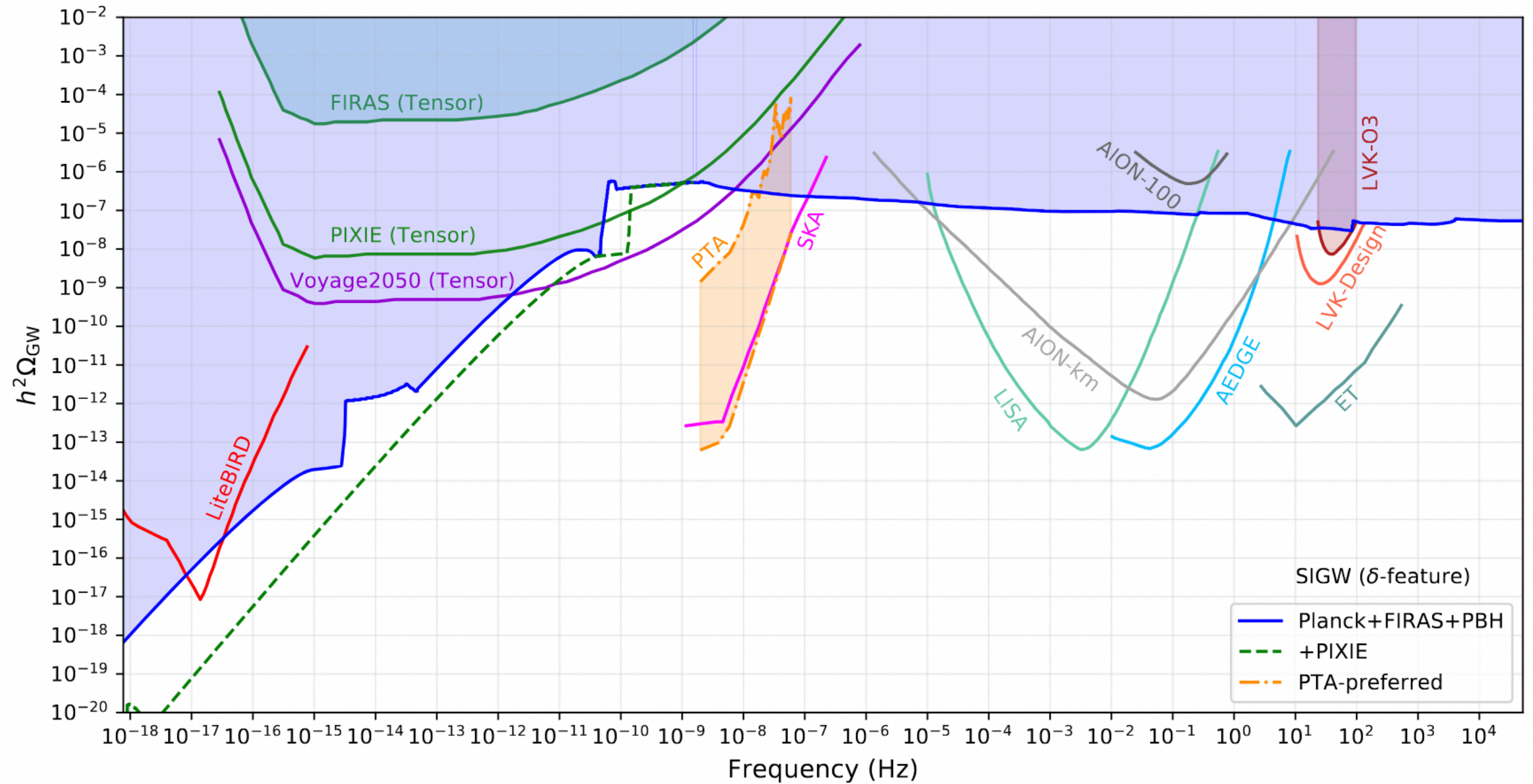
Scalar Induced Gravitational Waves



Scalar Induced Gravitational Waves



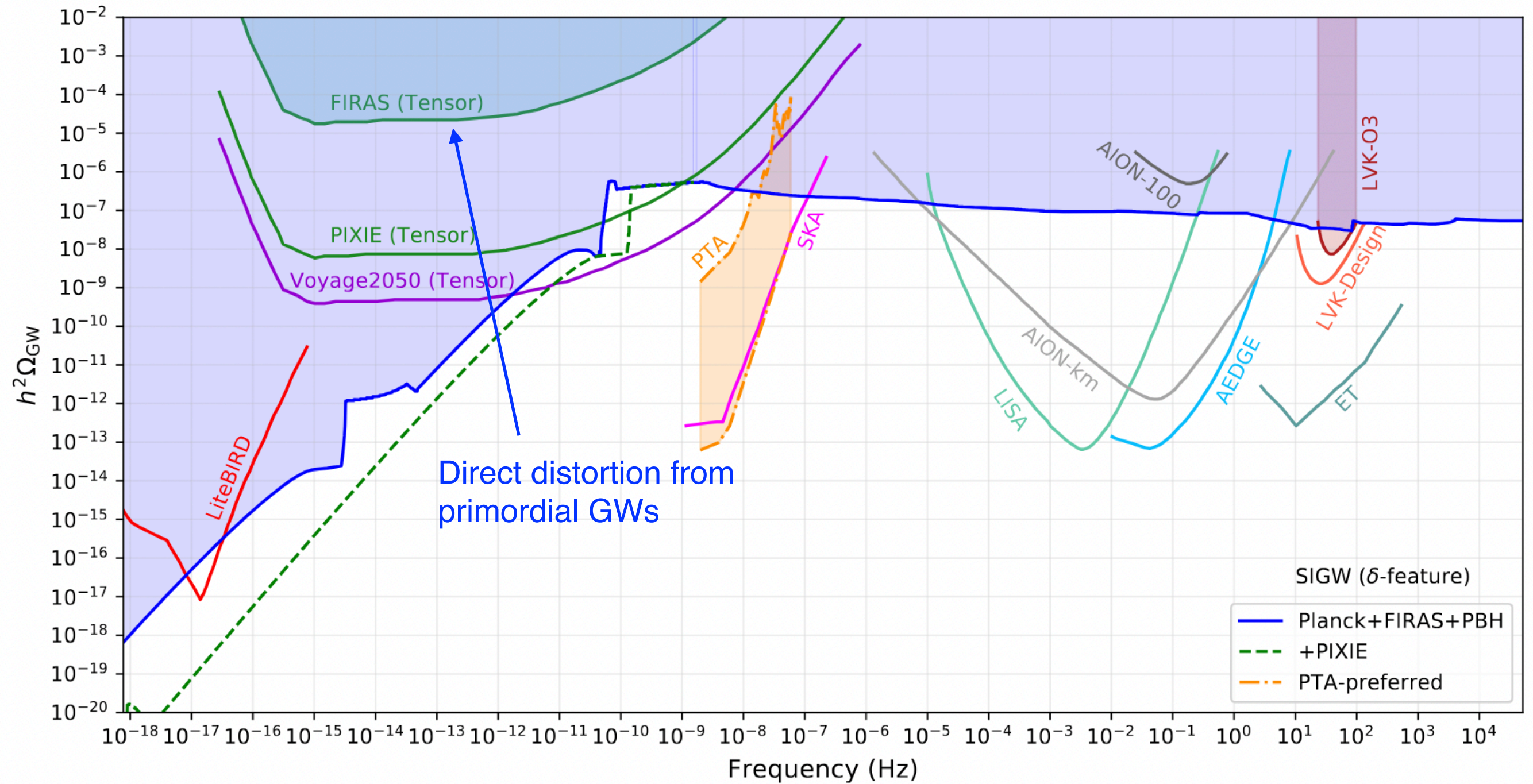
Spectral distortion link to GW backgrounds



Kite et al., 2020, ArXiv:2010.00040

Cyr et al., 2023, ArXiv:2309.02366

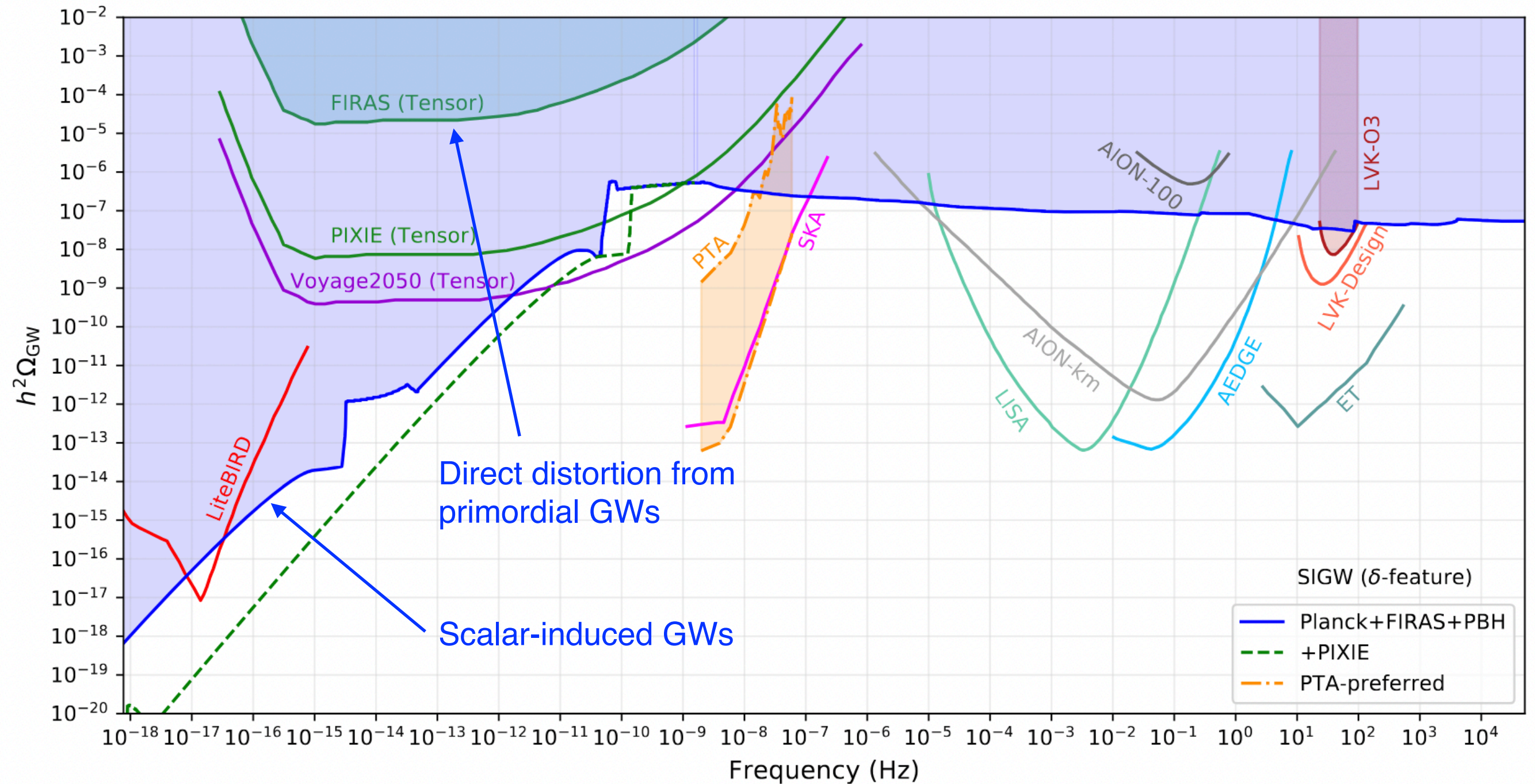
Spectral distortion link to GW backgrounds



Kite et al., 2020, ArXiv:2010.00040

Cyr et al., 2023, ArXiv:2309.02366

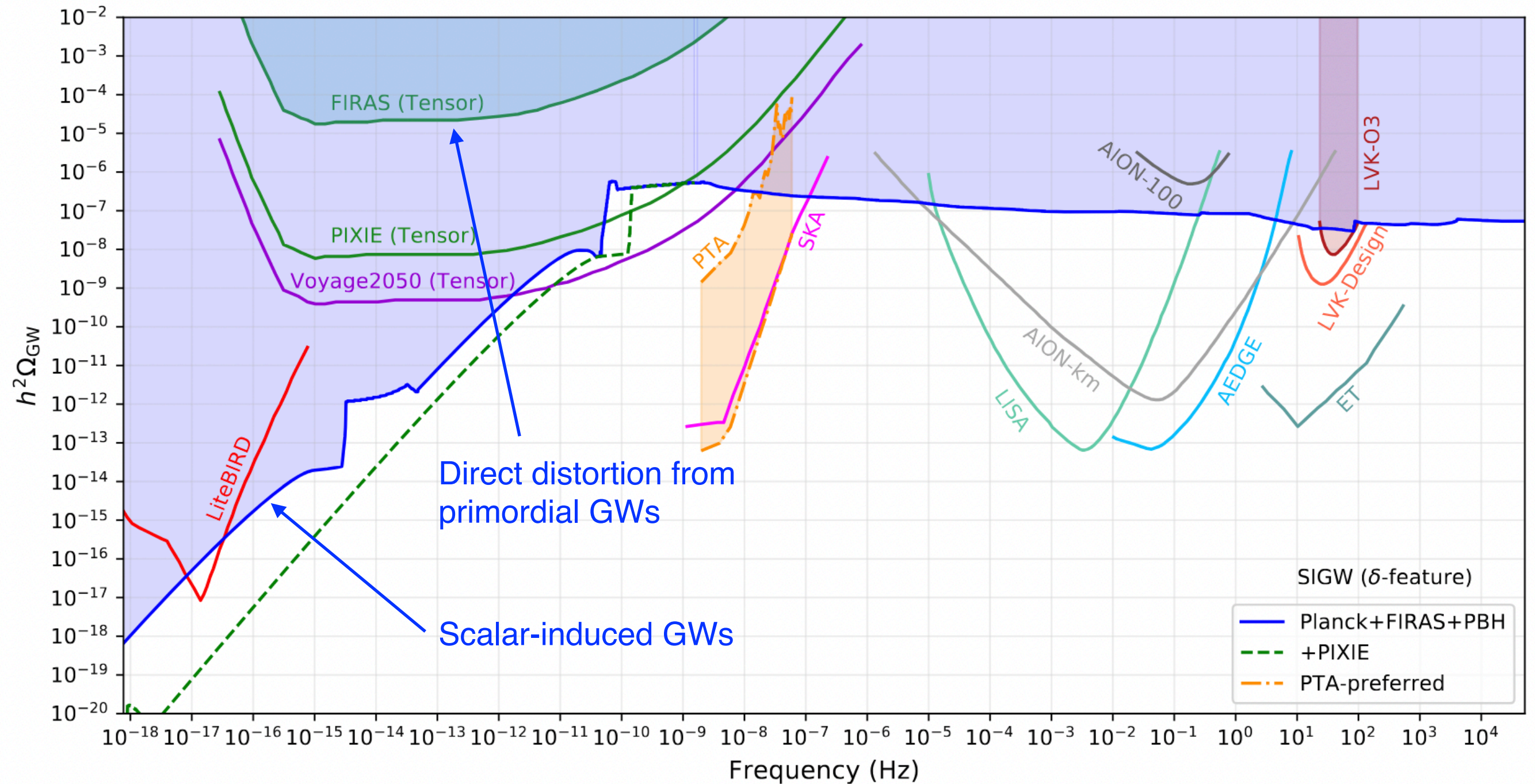
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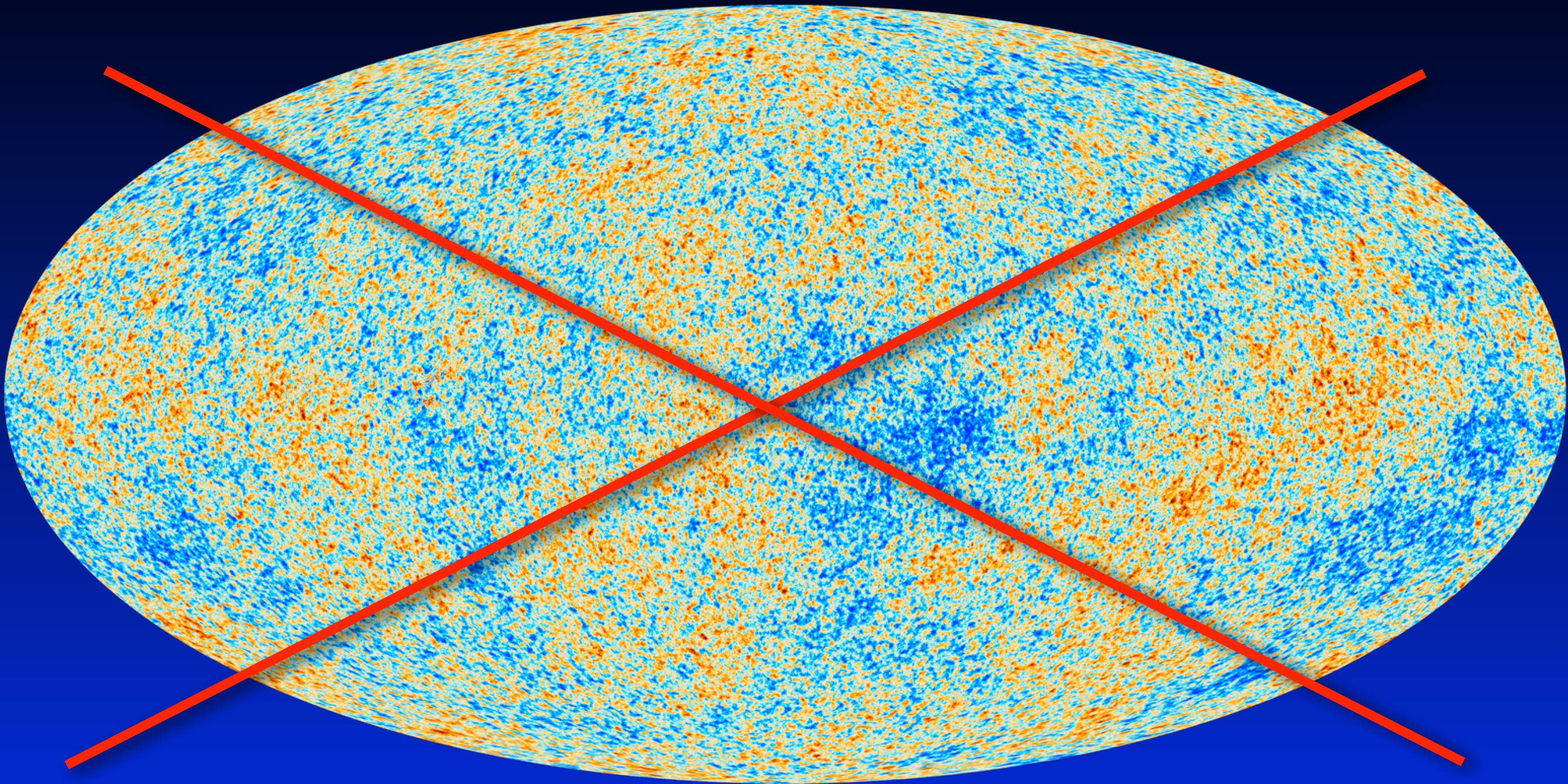
Spectral distortion link to GW backgrounds



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

Spectral distortion anisotropies

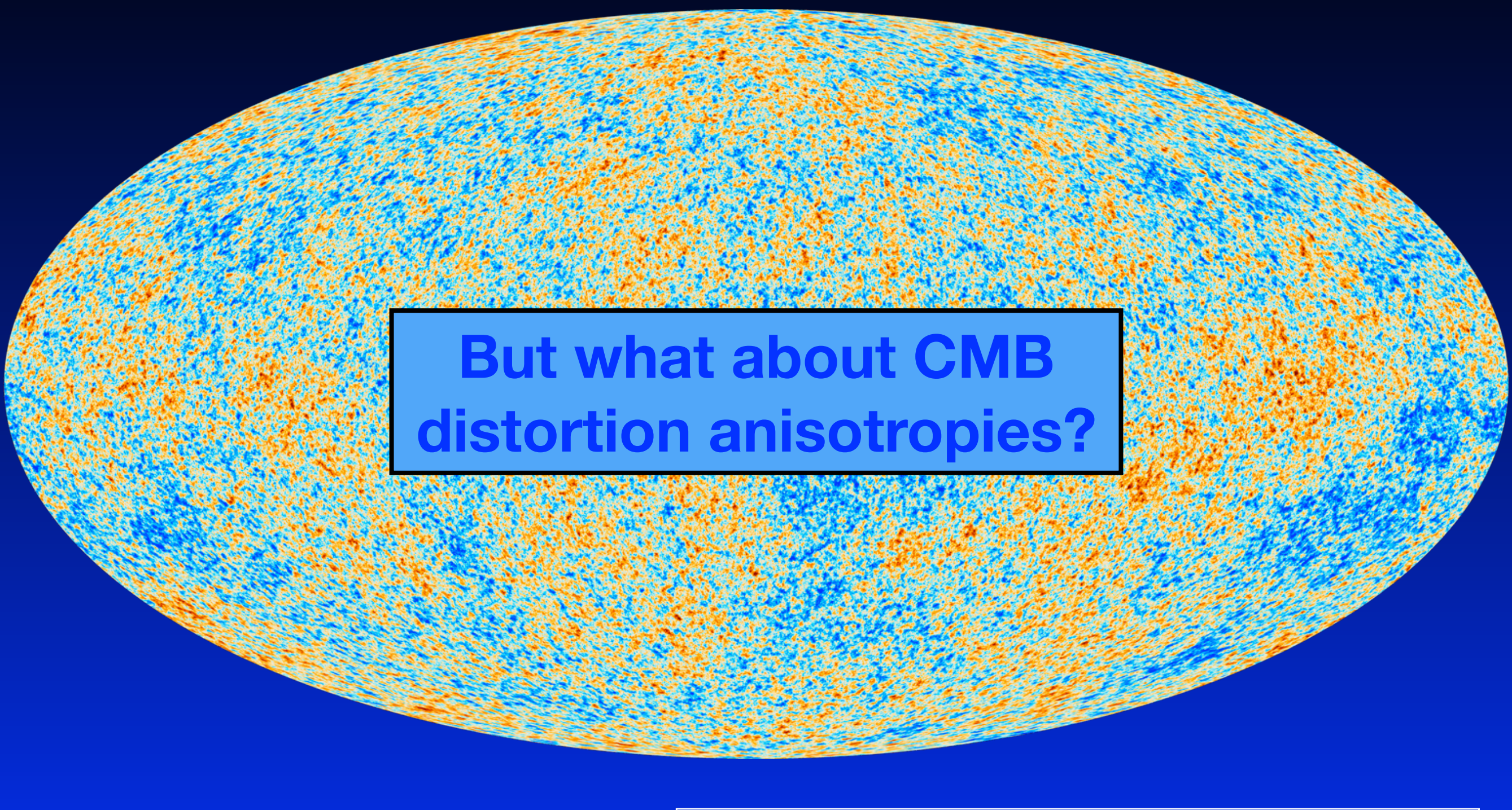
Cosmic Microwave Background Anisotropies



Planck all-sky
temperature map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

Cosmic Microwave Background Anisotropies

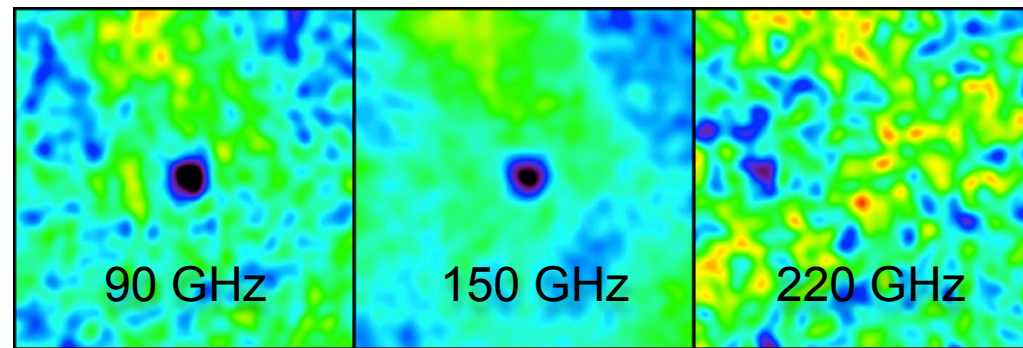
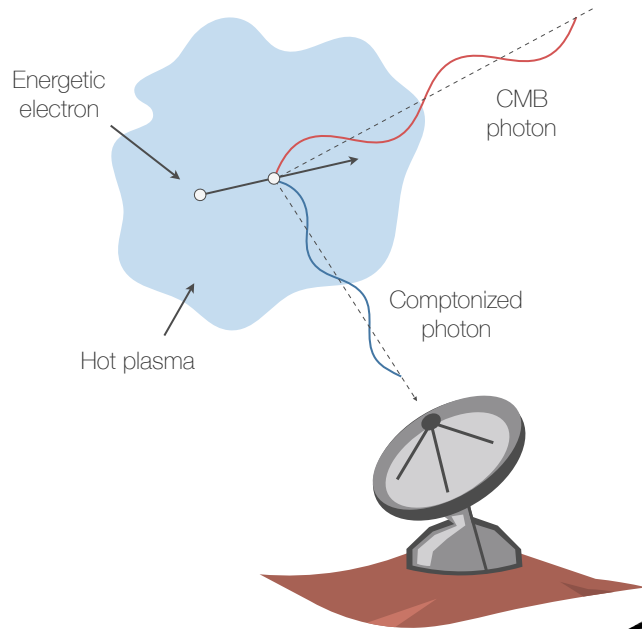
A large, oval-shaped map of the Cosmic Microwave Background (CMB) temperature anisotropies. The map is filled with a dense, noisy pattern of blue and orange colors, representing temperature variations across the sky. The colors are more concentrated in the center, with some darker blue and lighter orange areas towards the edges.

**But what about CMB
distortion anisotropies?**

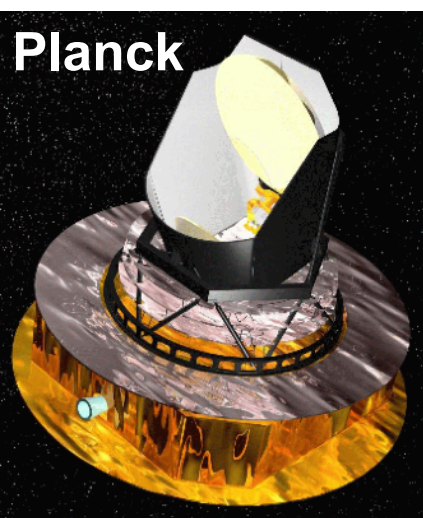
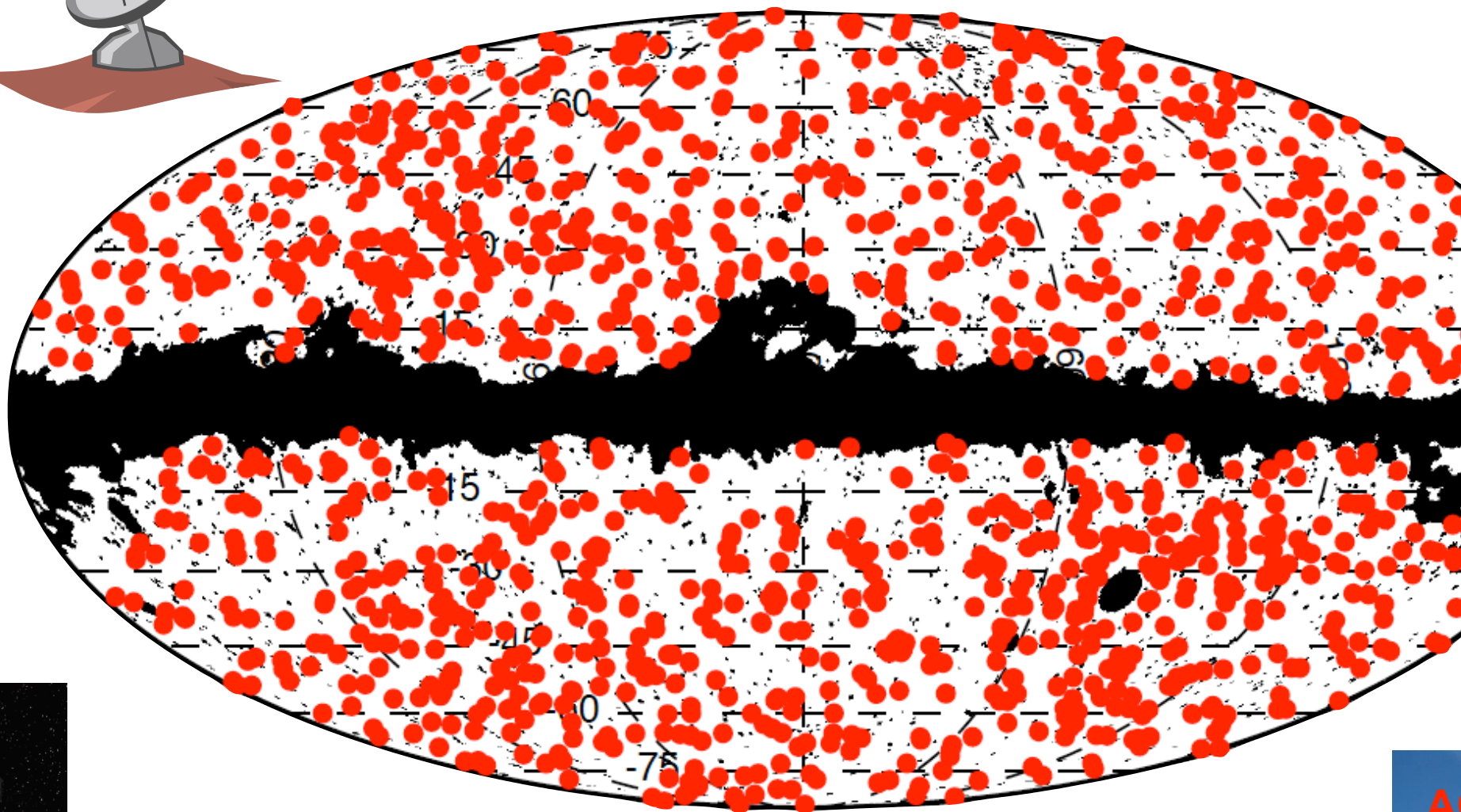
Planck all-sky
temperature map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

Thermal SZ effect is now routinely observed!



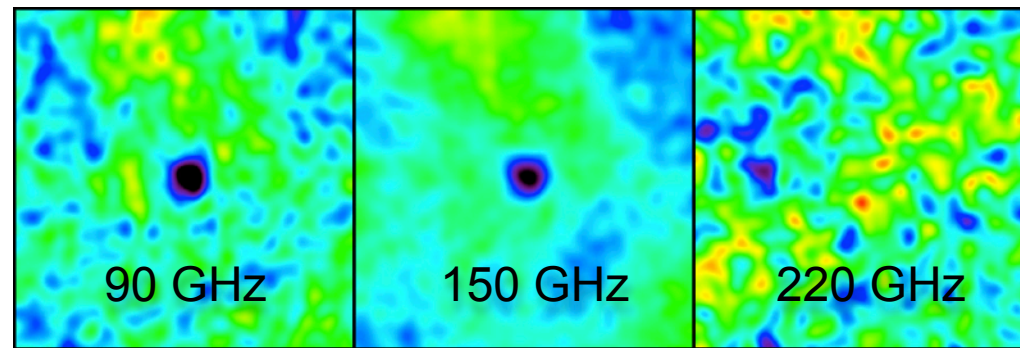
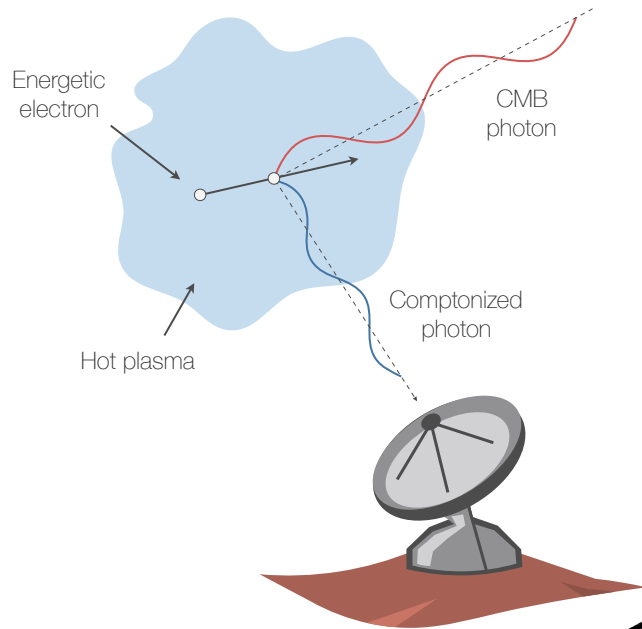
~ 1230 objects



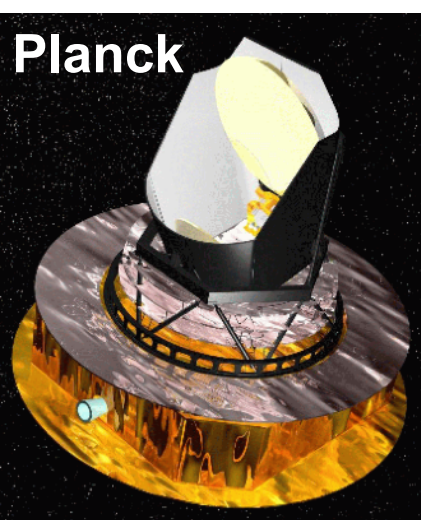
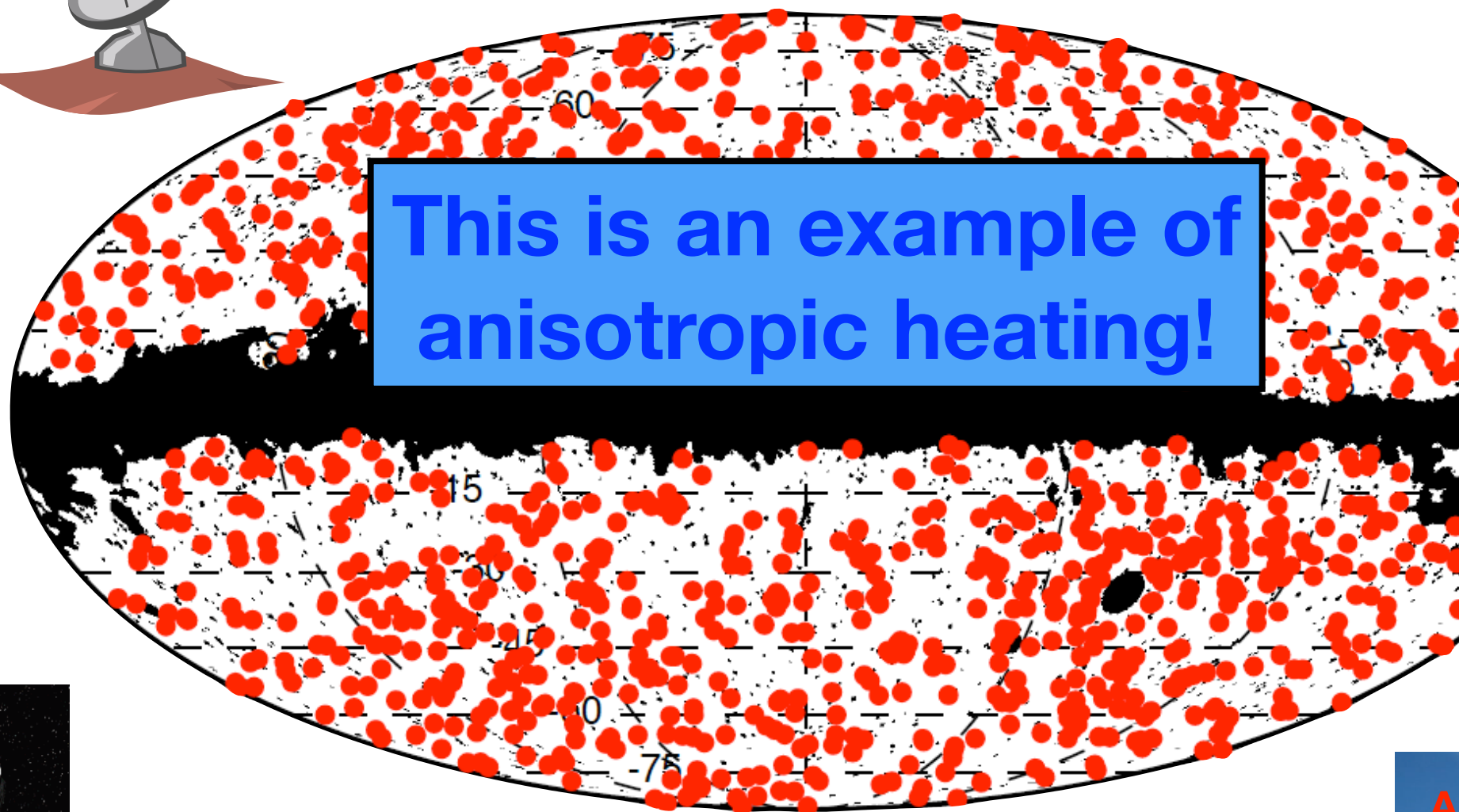
Planck Collaboration, 2013, paper XXIX



Thermal SZ effect is now routinely observed!

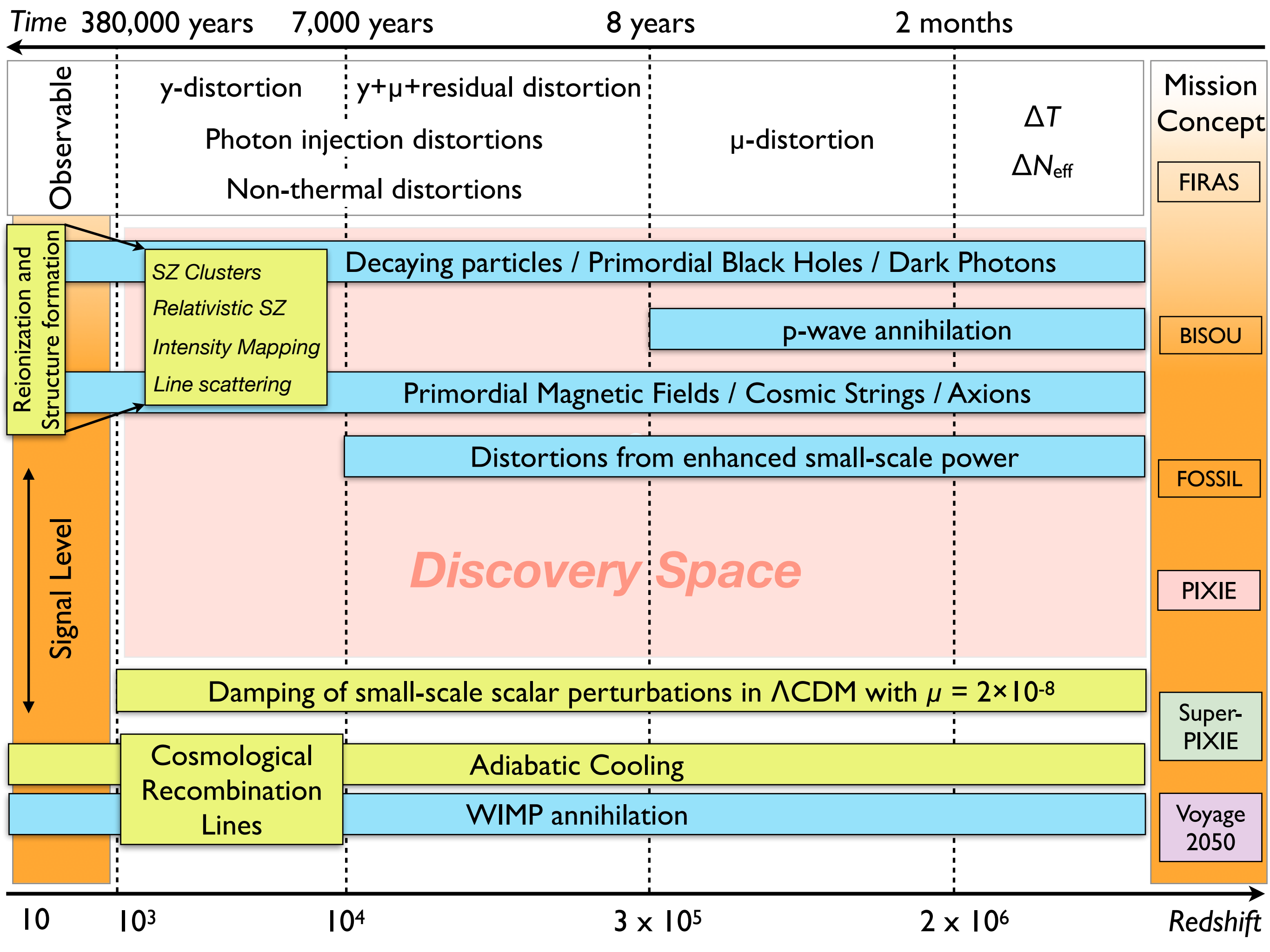


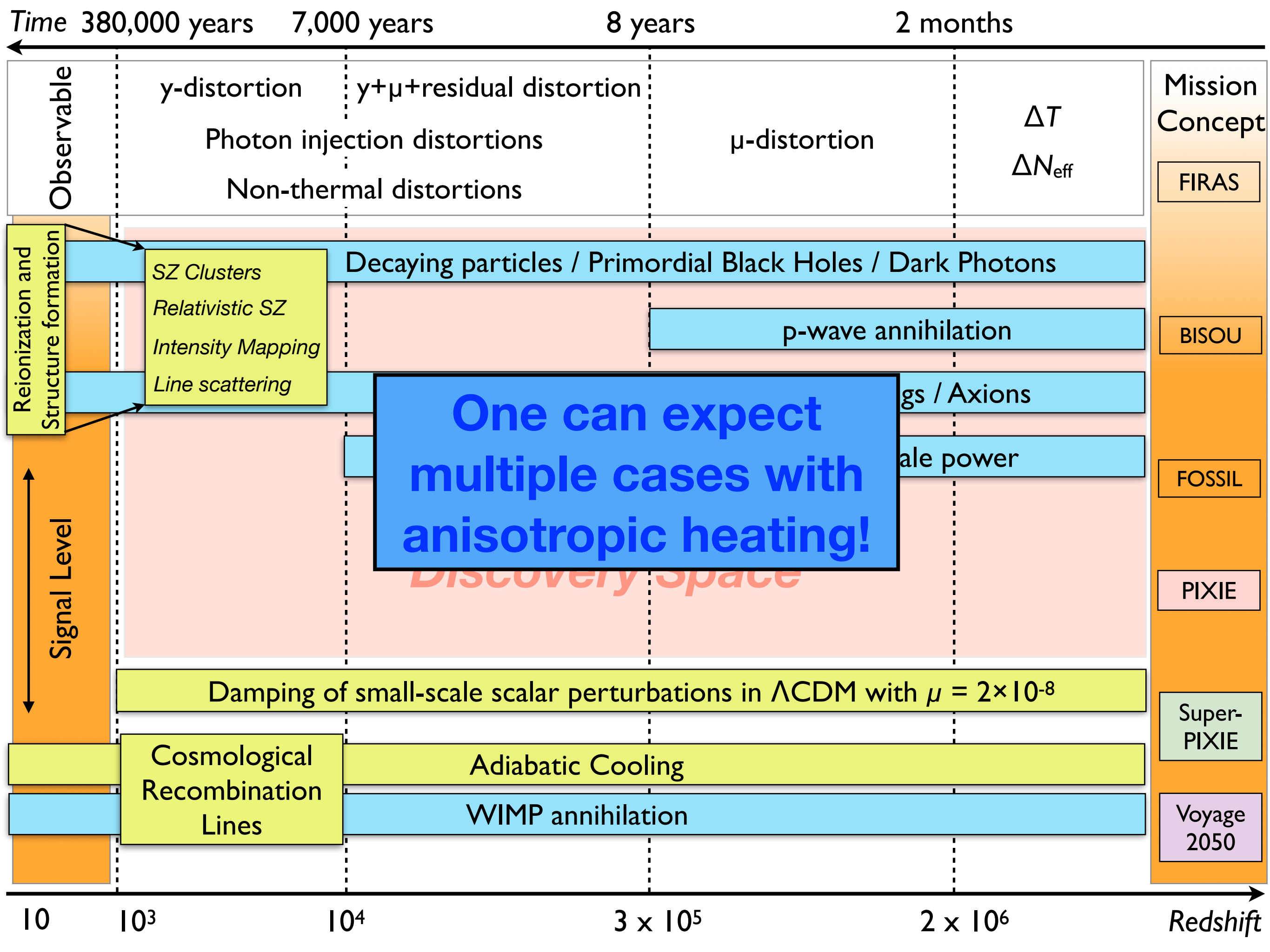
~ 1230 objects



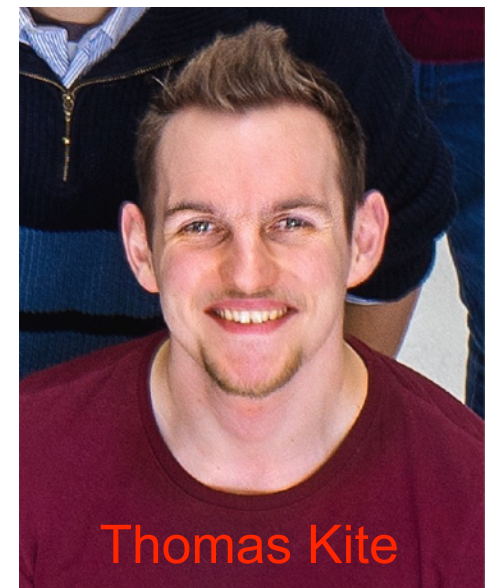
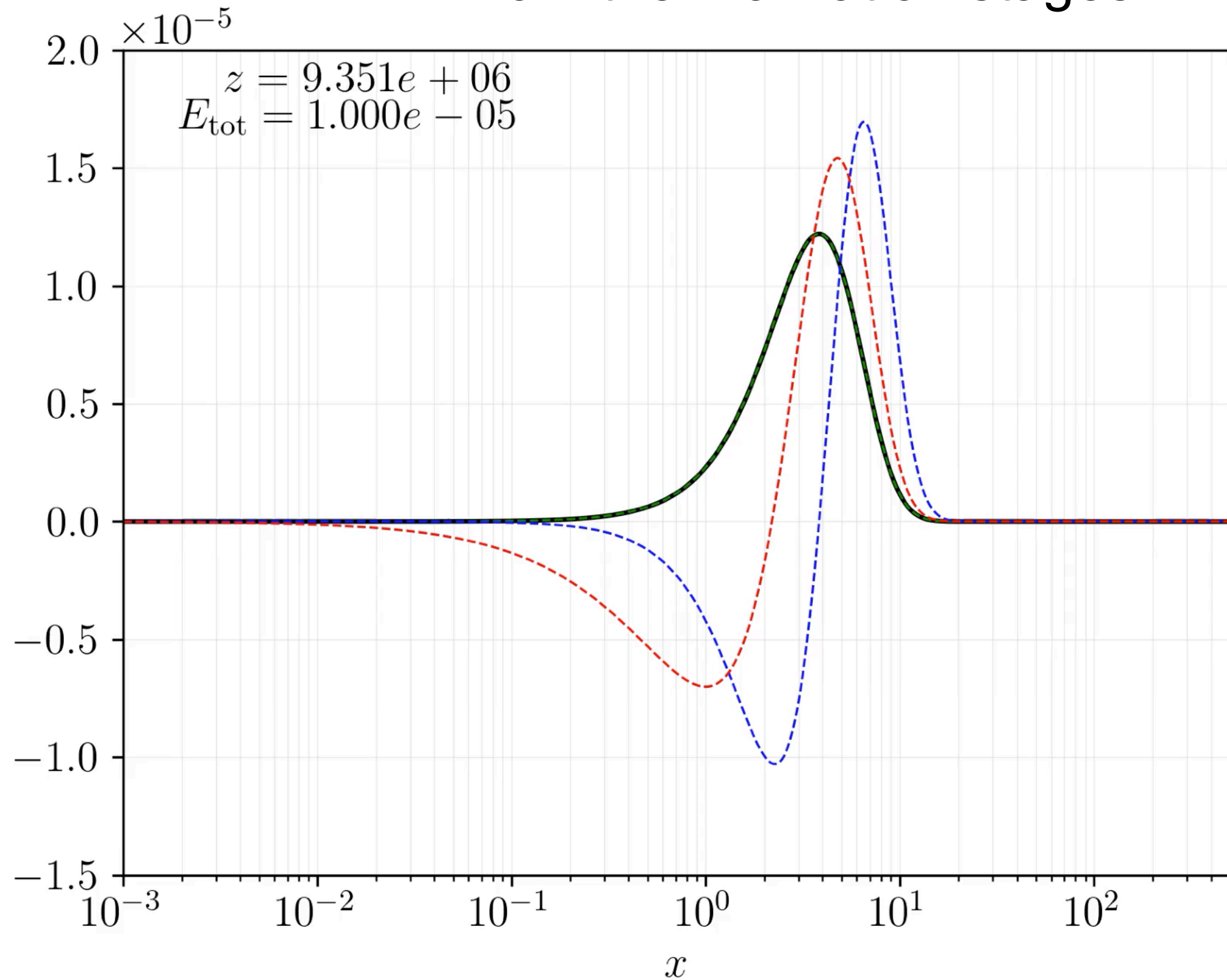
Planck Collaboration, 2013, paper XXIX







Main thermalization stages



JC, ArXiv:1304.6120

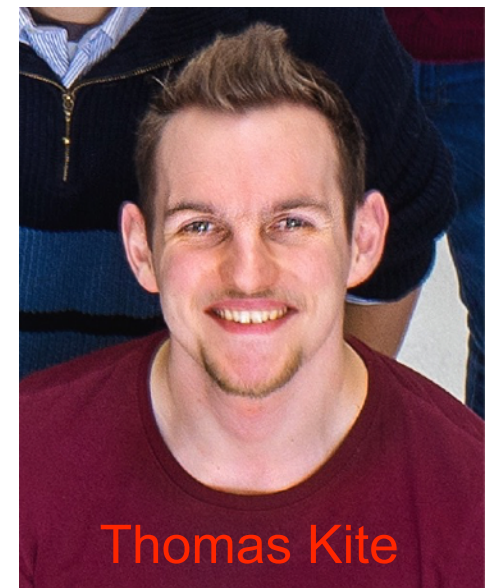
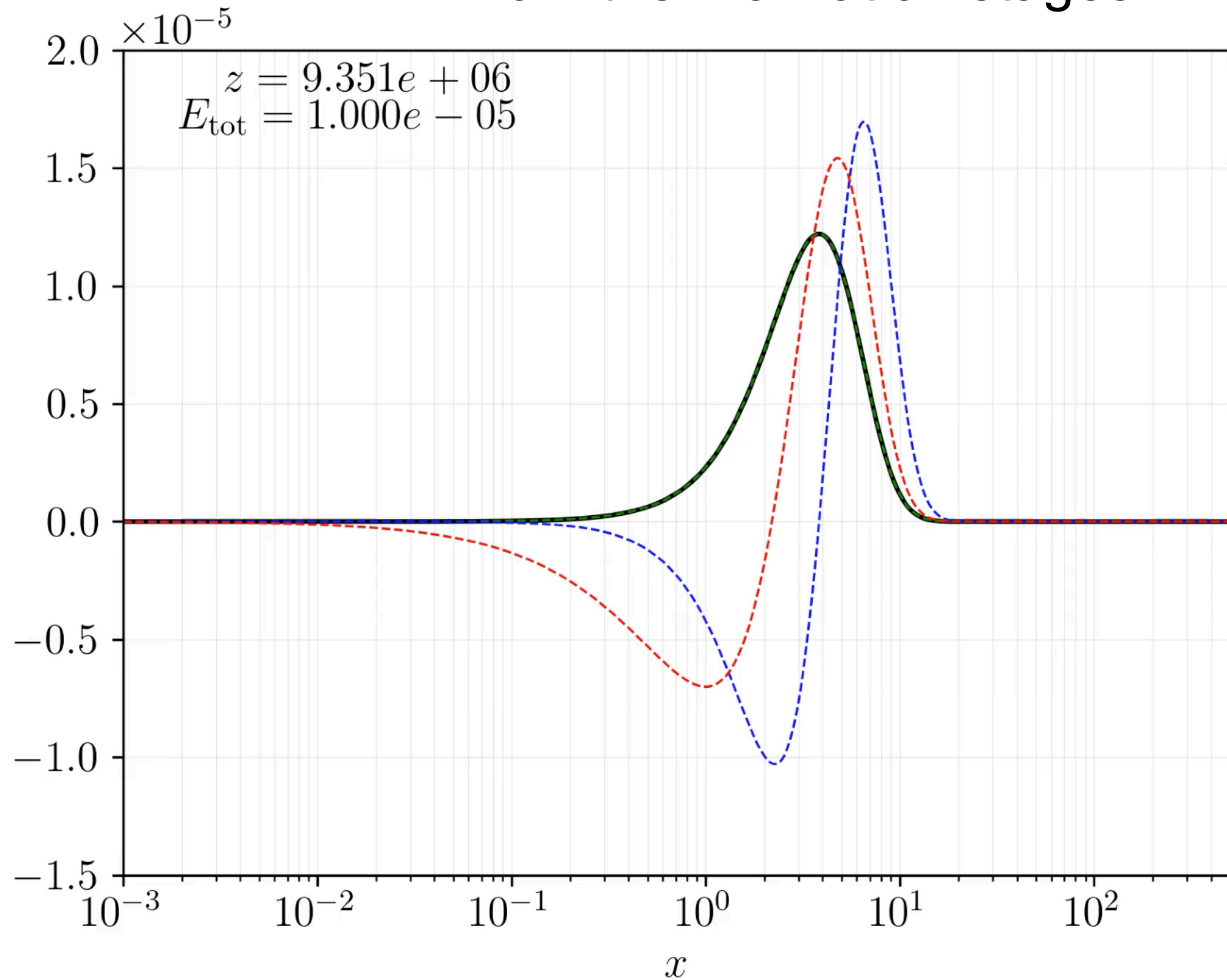
JC, Kite & Ravenni, 2022, papers I

JC, Ravenni & Kite, 2022, papers II

Kite, Ravenni & JC, 2022, papers III

New discretization of the Greens function

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New discretization of the Greens function

Final photon Boltzmann hierarchy with thermalization effects

$$\frac{\partial \mathbf{y}_0^{(1)}}{\partial \eta} = -k_B \mathbf{y}_1^{(1)} - \frac{\partial \Phi^{(1)}}{\partial \eta} \mathbf{b}_0^{(0)} + \frac{\mathbf{Q}'^{(1)}}{4} + \Theta_0^{(1)} \mathbf{C}_0^{(0)} + \mathbf{S}_0'^{(1)} \\ + \tau' \theta_z \left\{ M_T \mathbf{y}_0^{(1)} + \left[(\delta_b^{(1)} + \Theta_0^{(1)} + \Psi^{(1)}) M_T + \Theta_0^{(1)} M_{BK} \right] \mathbf{y}_0^{(0)} \right\}$$

$$\frac{\partial \mathbf{y}_1^{(1)}}{\partial \eta} = k \left(\frac{1}{3} \mathbf{y}_0^{(1)} - \frac{2}{3} \mathbf{y}_2^{(1)} \right) + \frac{k}{3} \Psi^{(1)} \mathbf{b}_0^{(0)} - \tau' \left[\mathbf{y}_1^{(1)} - \frac{\beta^{(1)}}{3} \mathbf{b}_0^{(0)} \right] + \mathbf{S}_1'^{(1)} \\ - \frac{\beta^{(1)}}{3} (1 - M_B) \left[\tau' \theta_z M_T \mathbf{y}_0^{(0)} + \frac{\mathbf{Q}'^{(0)}}{4} + \mathbf{S}_0'^{(0)} \right],$$

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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
JC, Evangelista, Daman & Vasil, ArXiv:2602.14963

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

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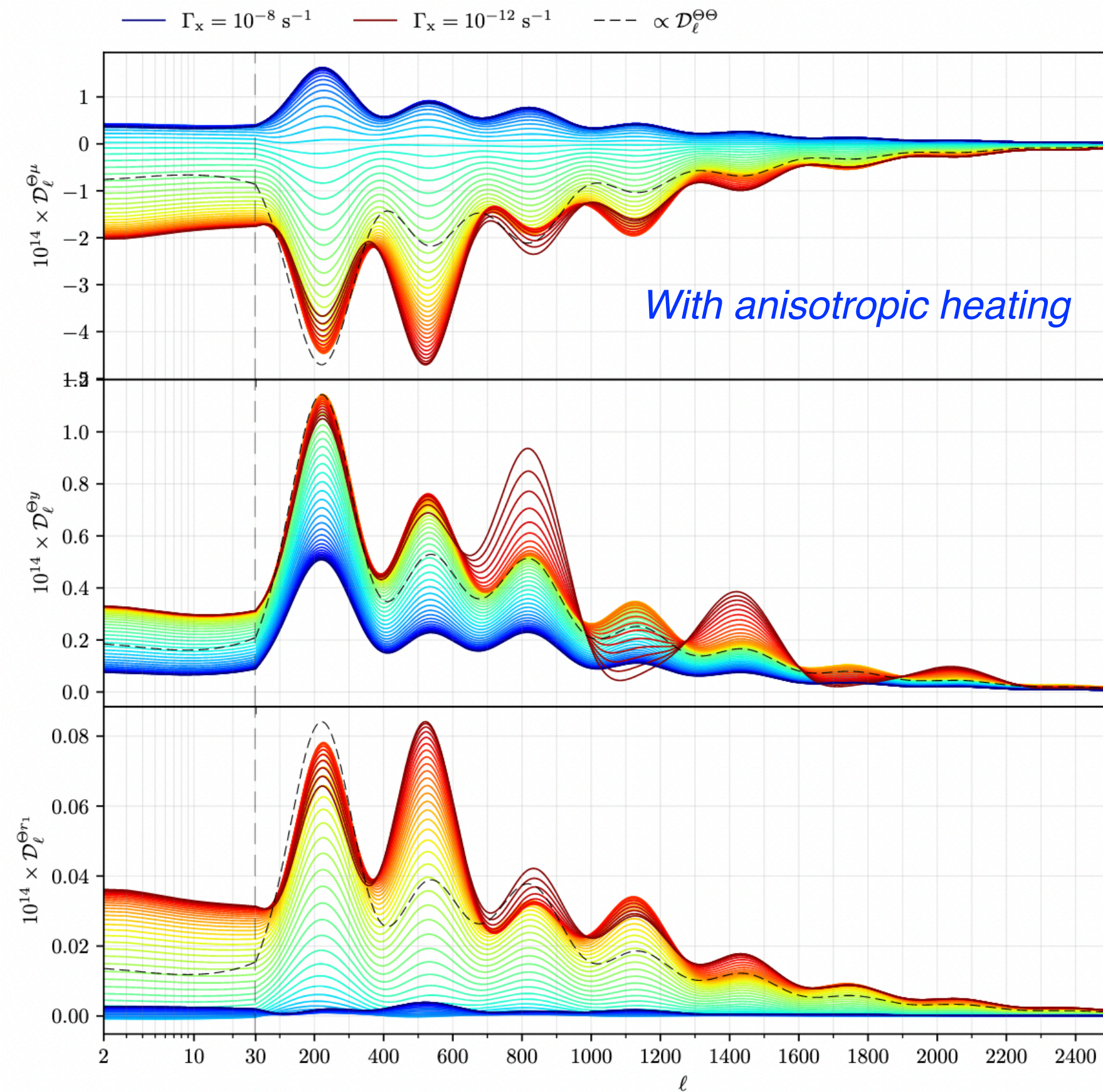
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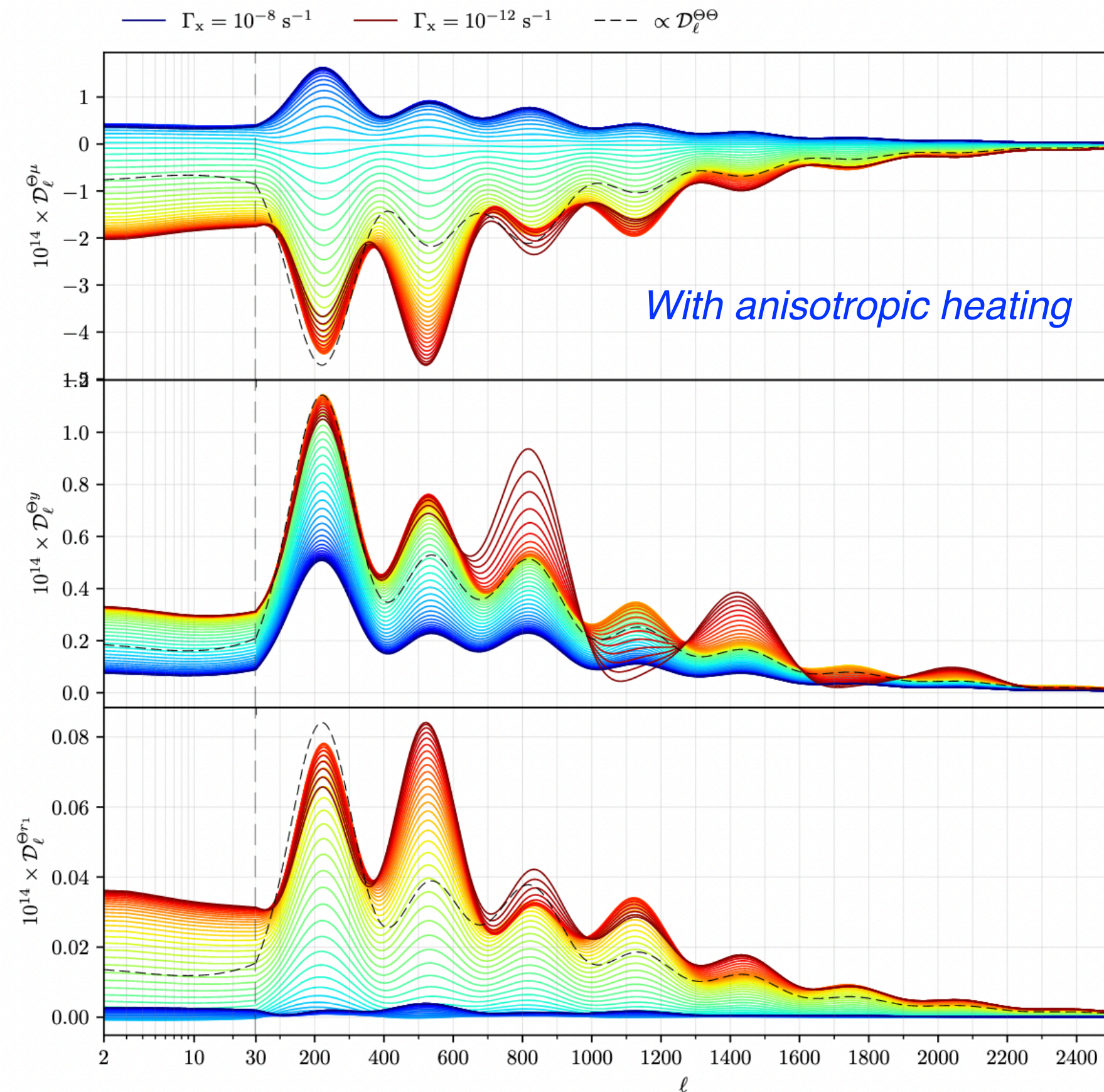
Now implemented in CosmoTherm but can be done with any Boltzmann code (e.g., CAMB or CLASS)

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

CMB power spectra for decaying particles



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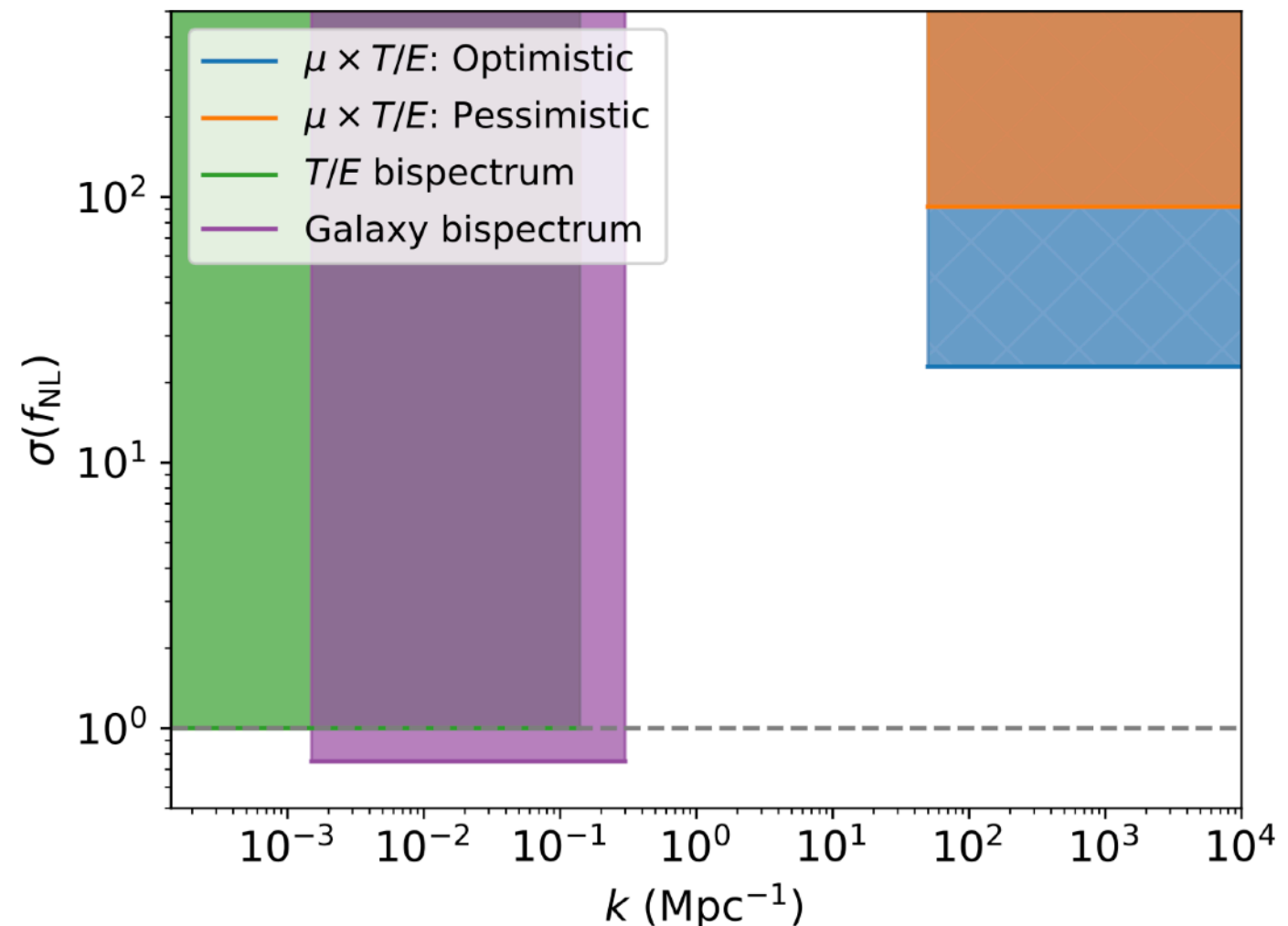
Can be constrained with CMB imagers like Planck, ACT, SPT, Litebird, SO & PICO!

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...*



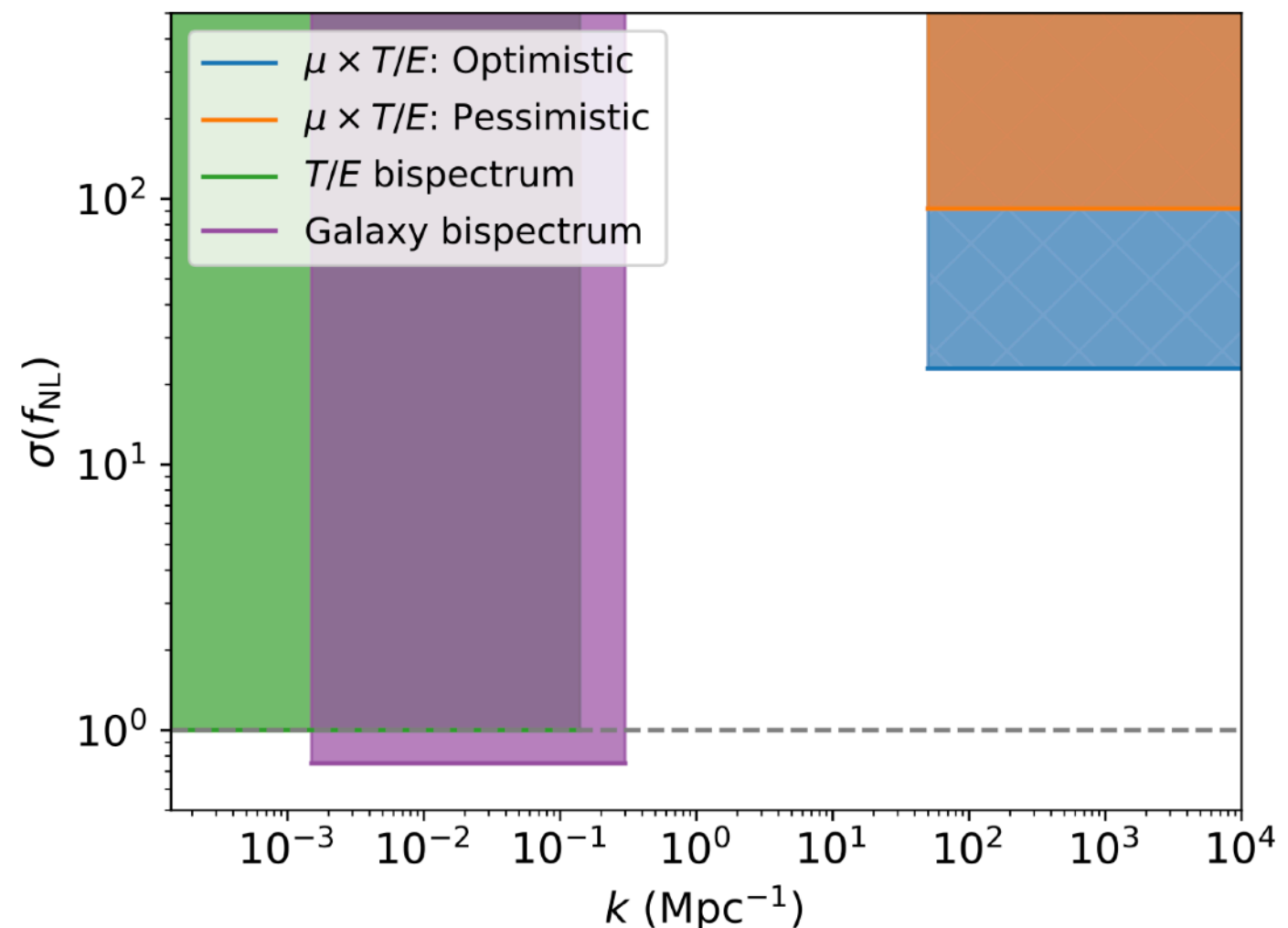
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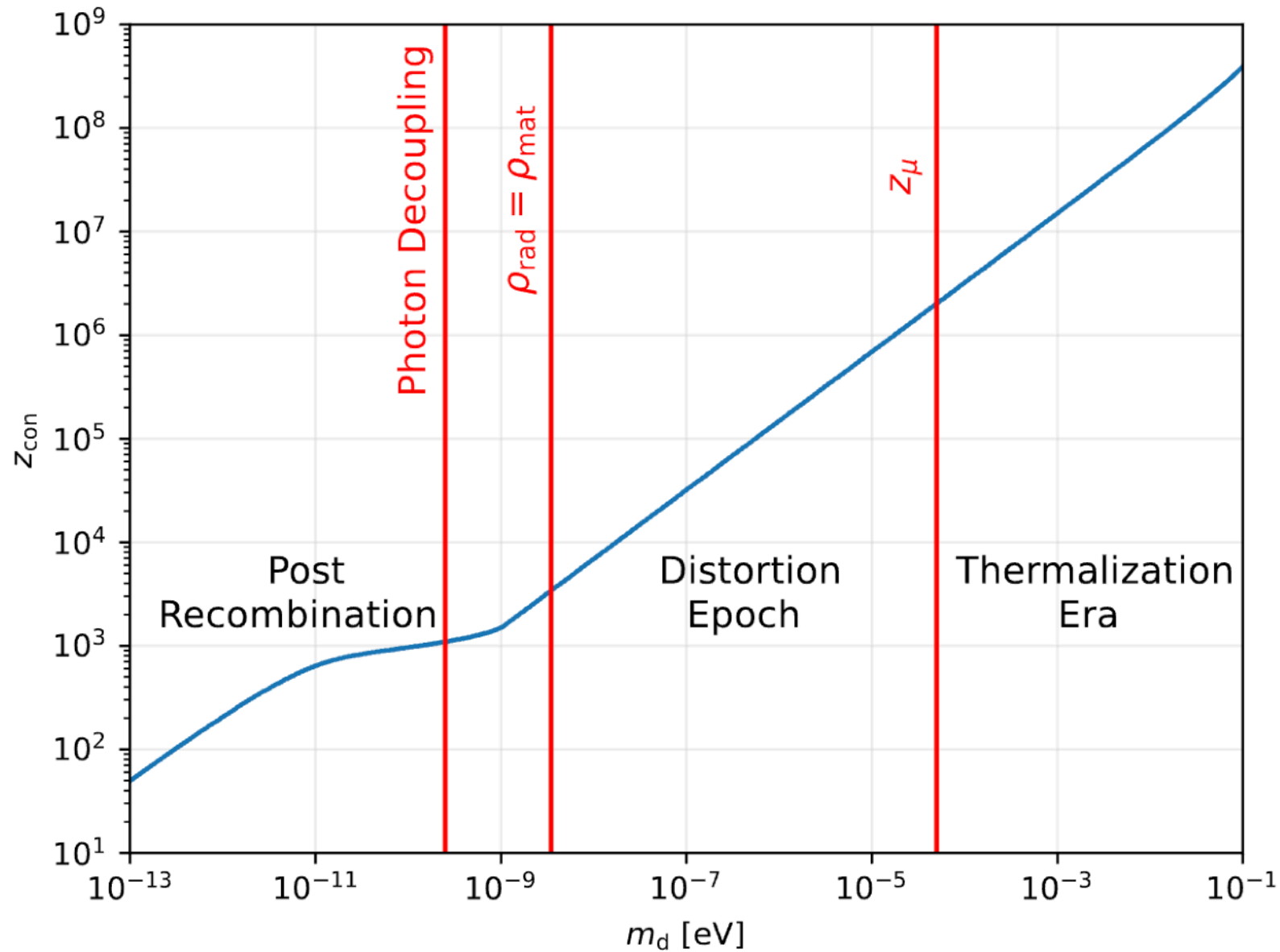
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Detailed study with realistic foregrounds and systematics is required!



Worked example: dark photon constraints

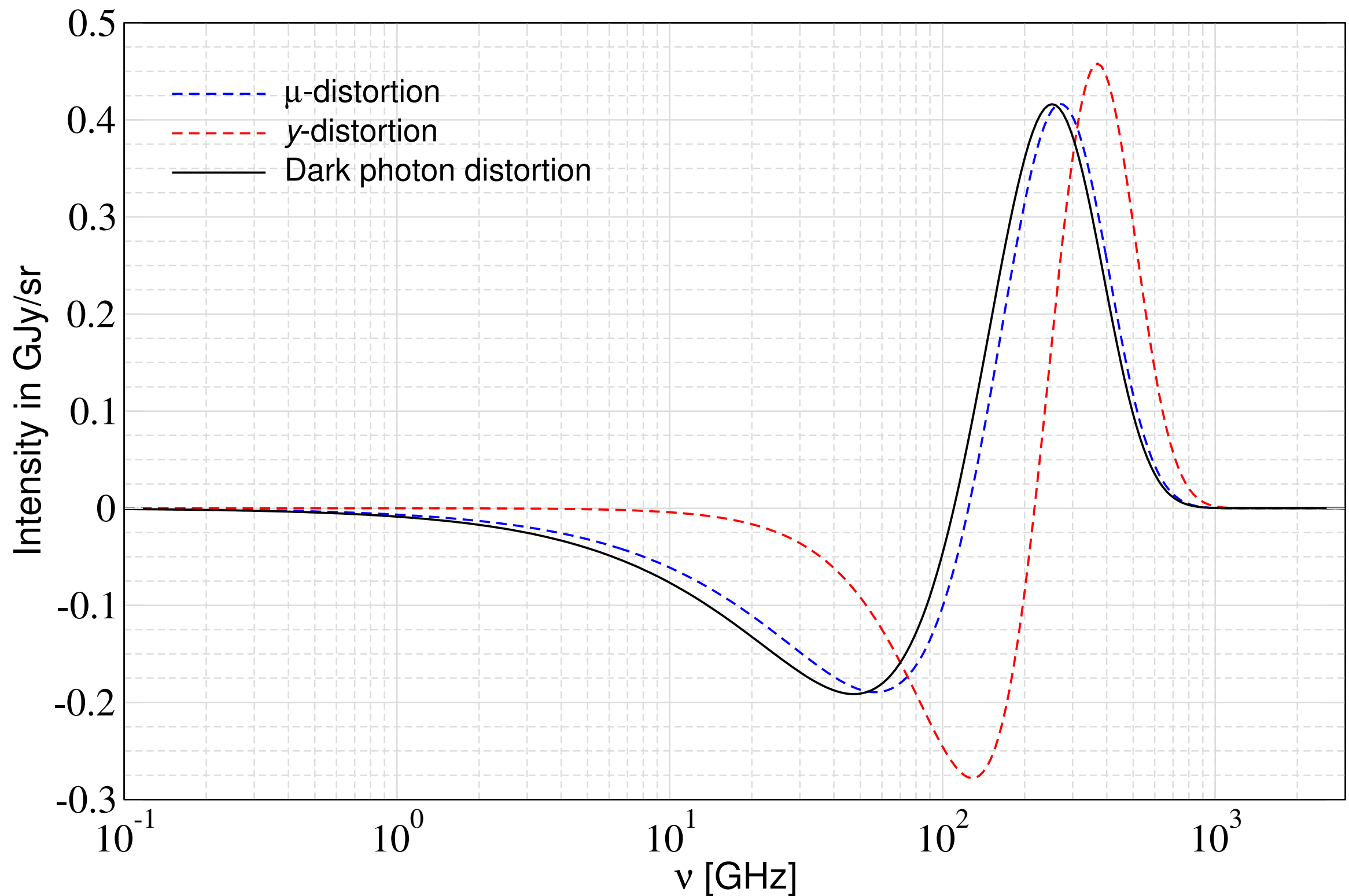
Distortions from dark photon conversion



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

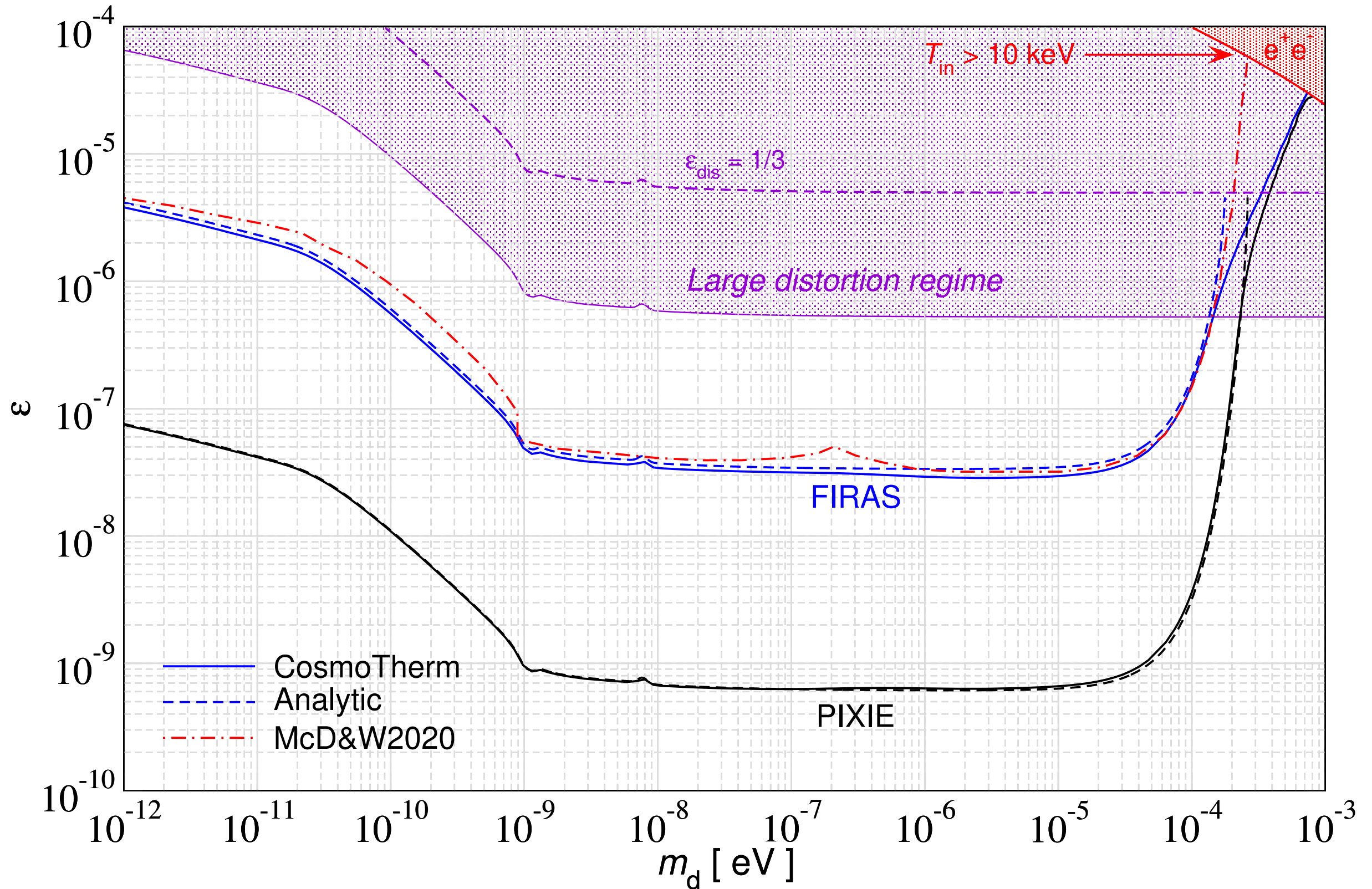
This leads to removal of CMB photons which causes a distortion

Distortions from dark photon conversion

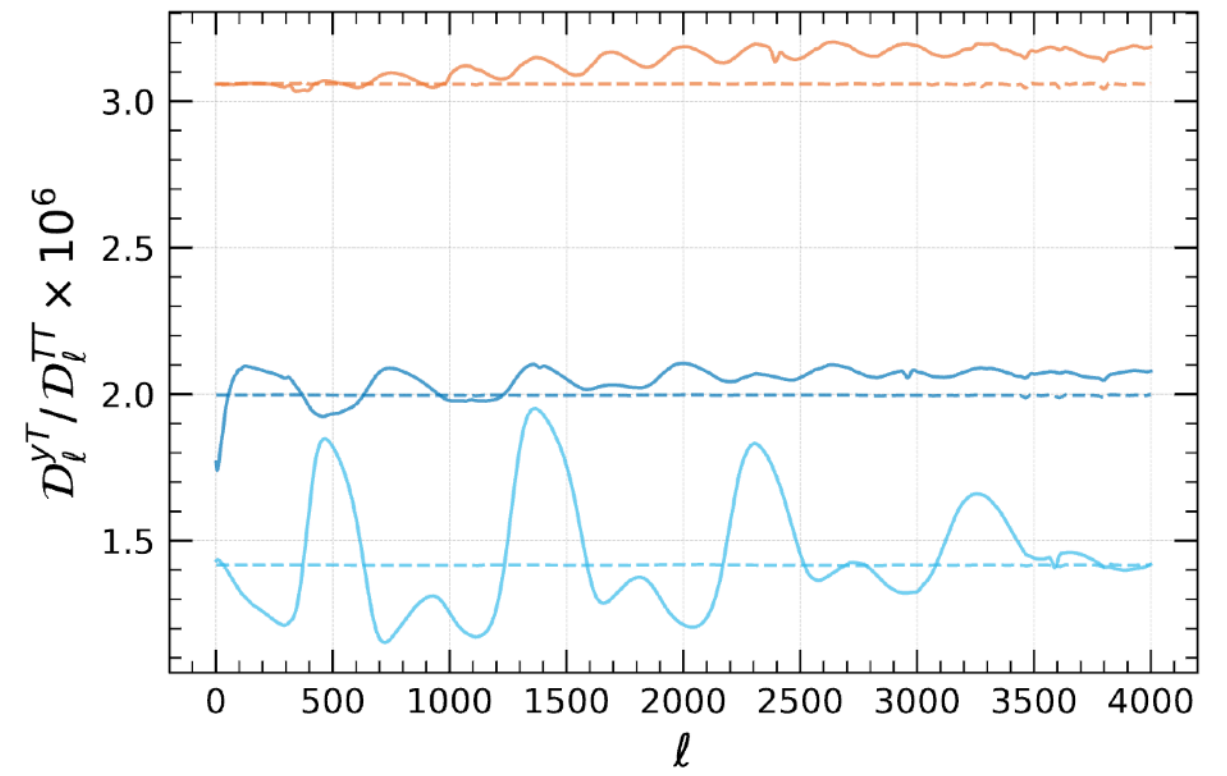
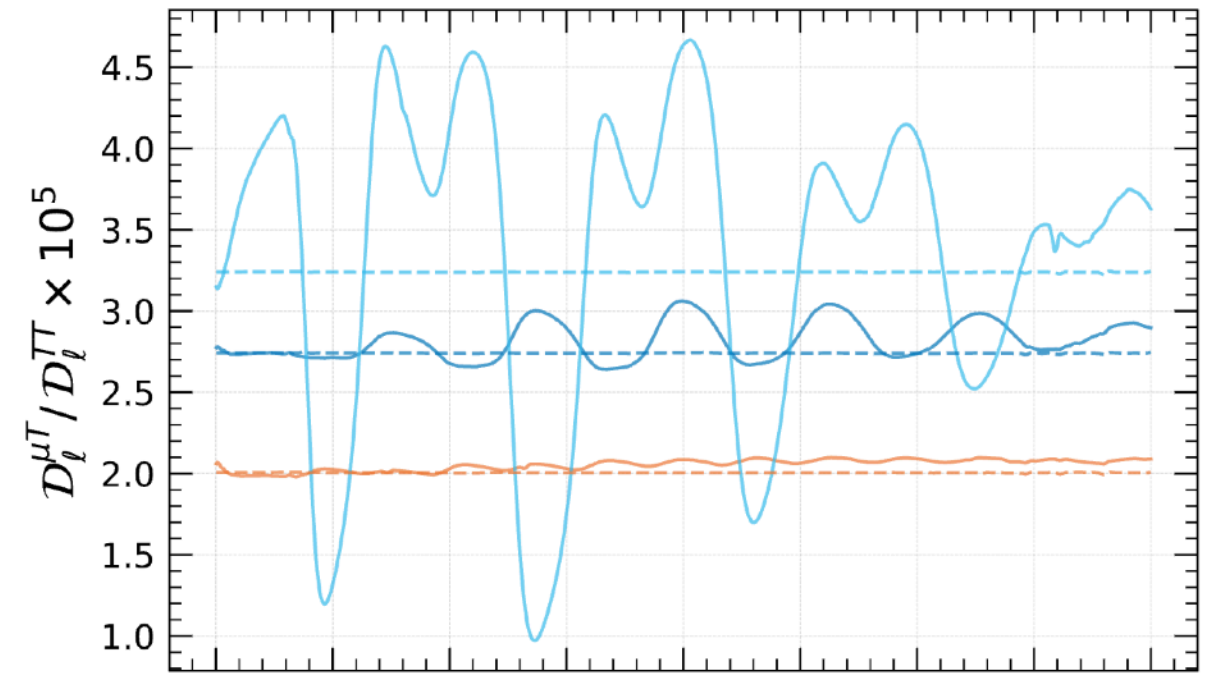
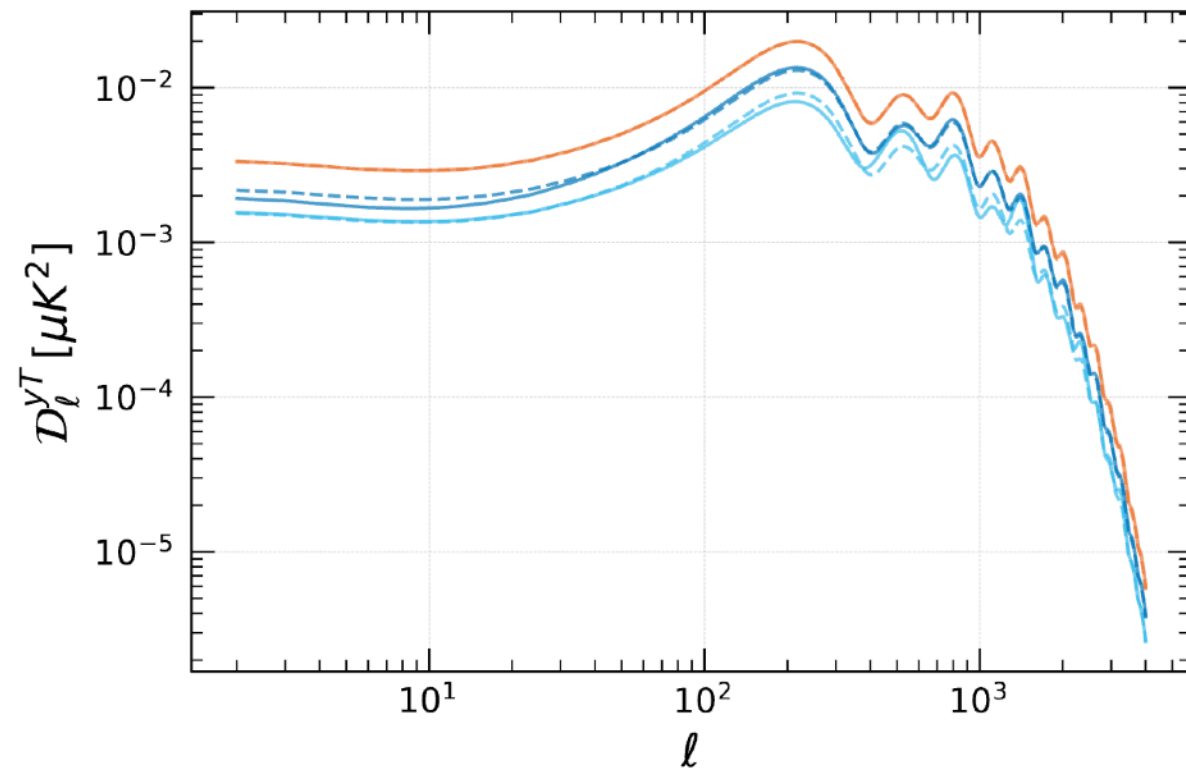
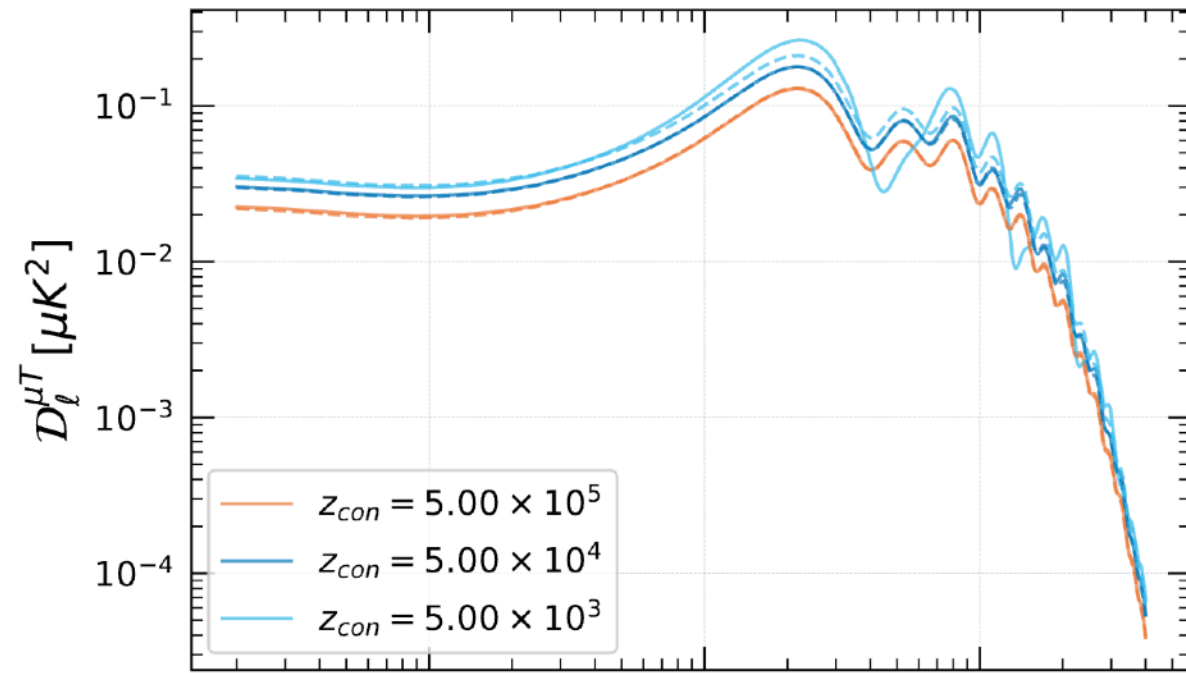


Distortion very close to a μ distortion!

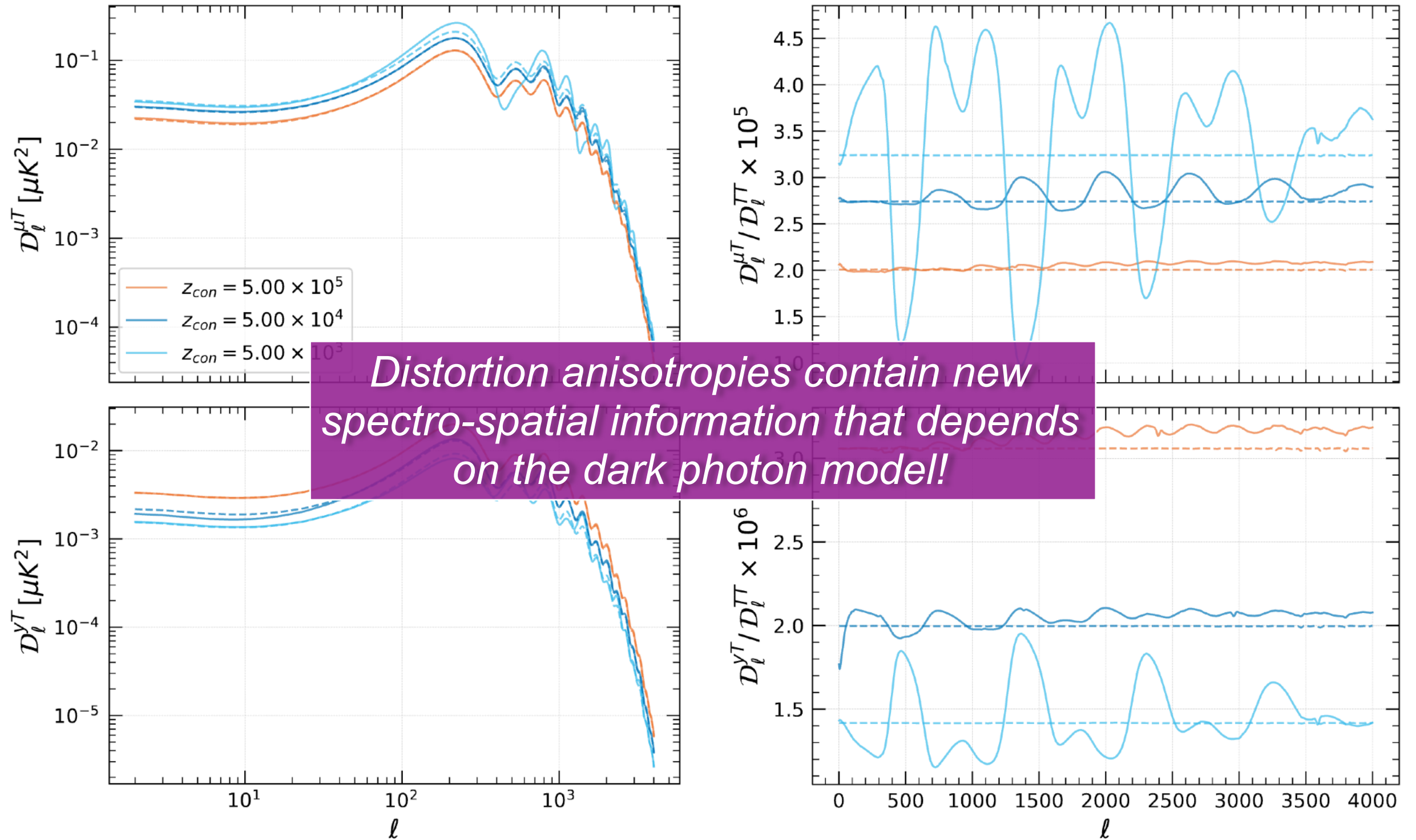
Revised Constraints on Dark Photons - *monopole*



Anisotropies from dark photon conversion!

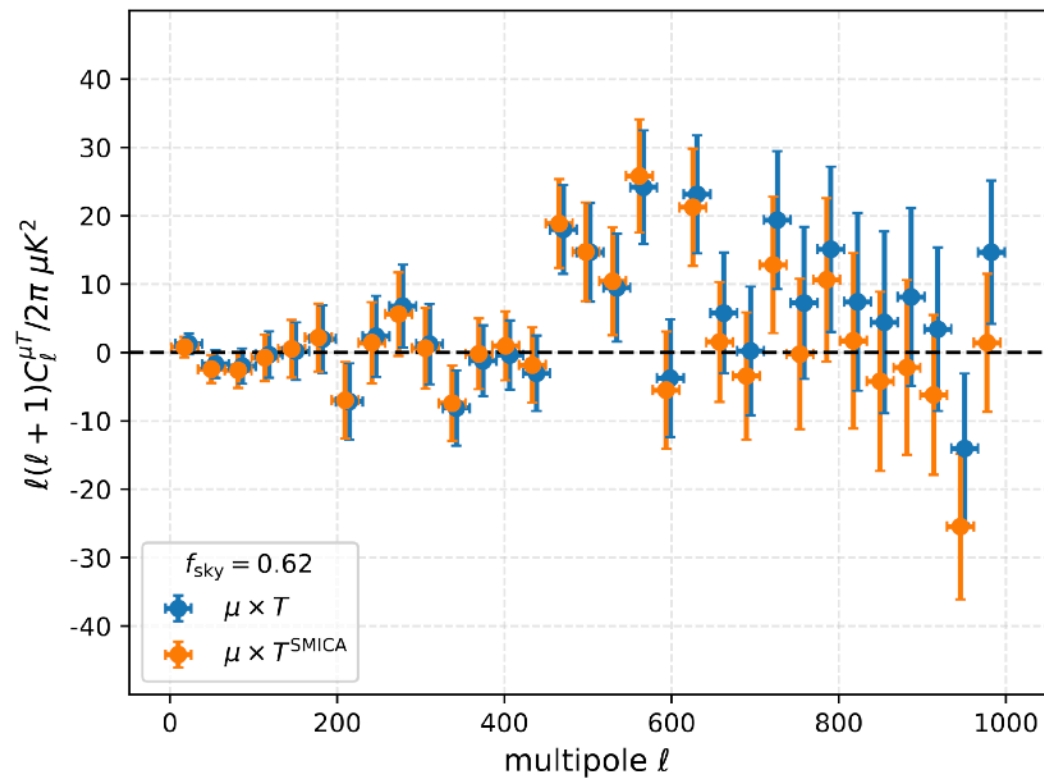


Anisotropies from dark photon conversion!



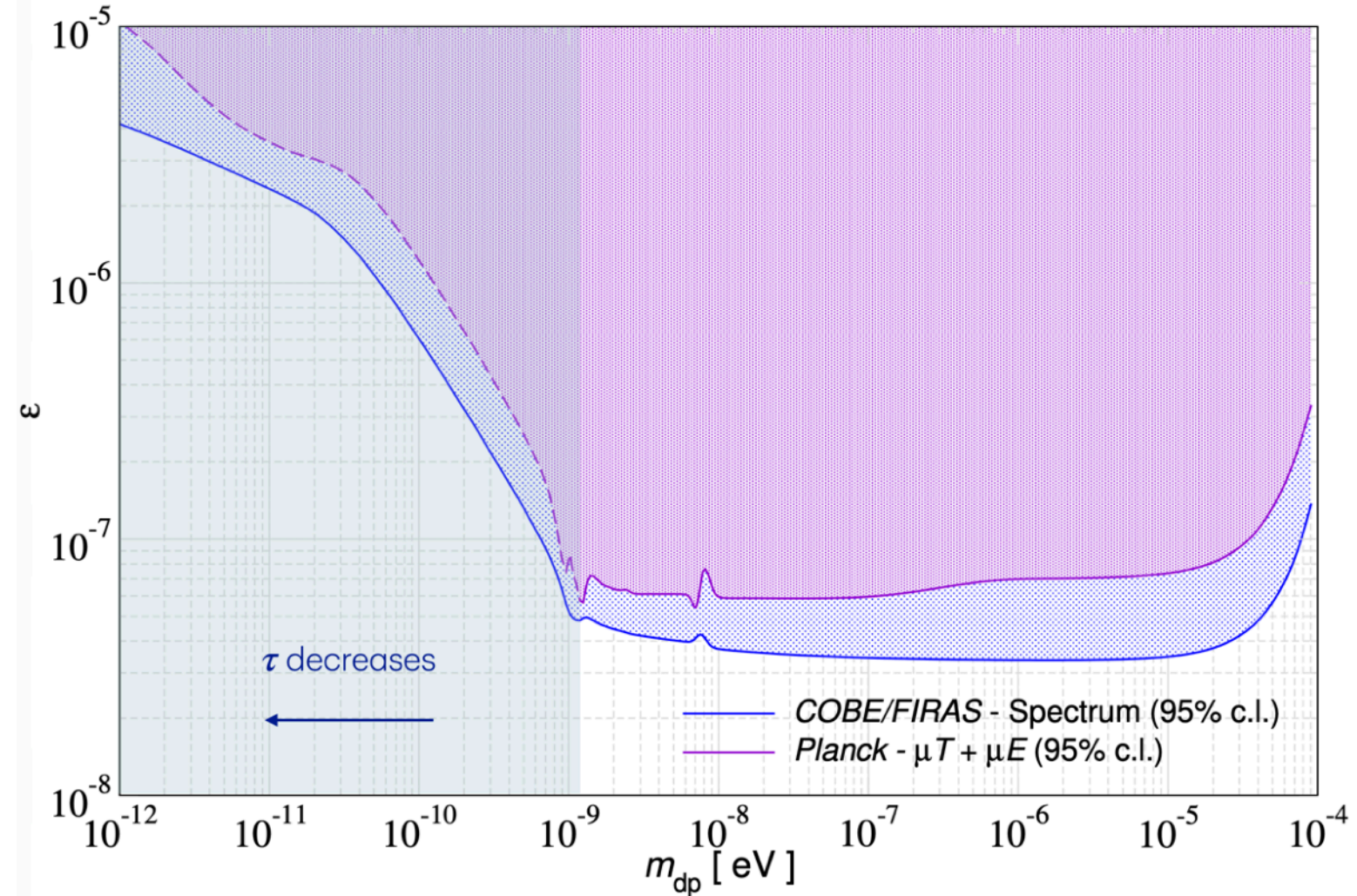
Novel dark photon constraints from *Planck*

Constraints on μT from *Planck*



Rotti, Ravenni & JC, ArXiv:2205.15971

Constraints on dark photon models

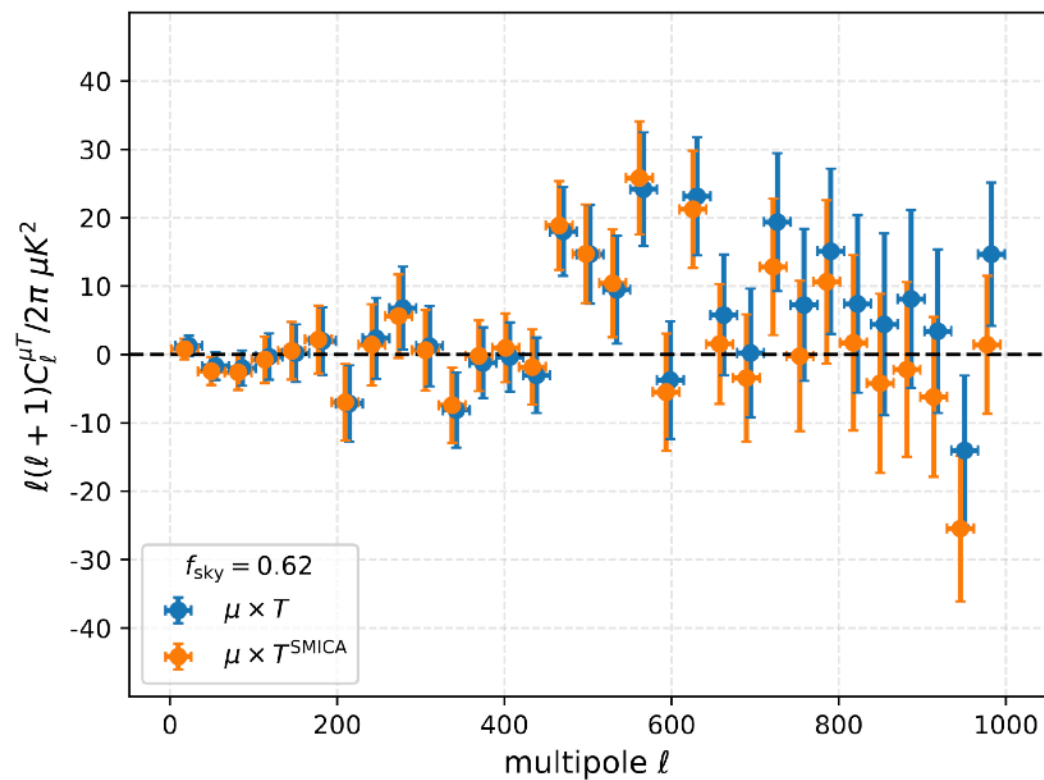


- New independent constraint using *existing* data
- In some regions comparable to monopole constraint
→ *combined constraint could be improved*
- Addition of ACT & SPT data might provide further leverage!
- Improvements from modelling still possible!

Evangelista, JC & Cyr, ArXiv:2606.09491

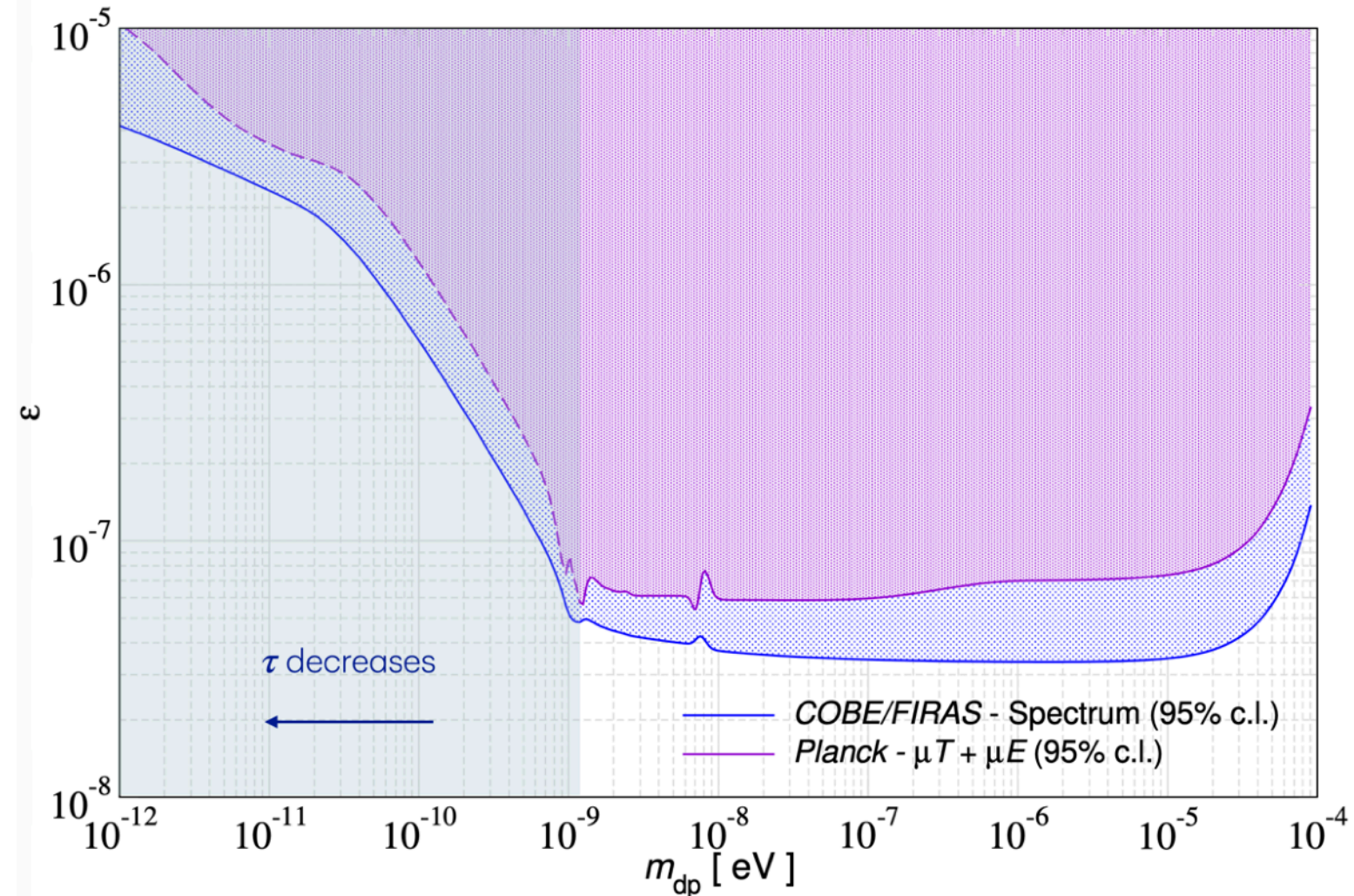
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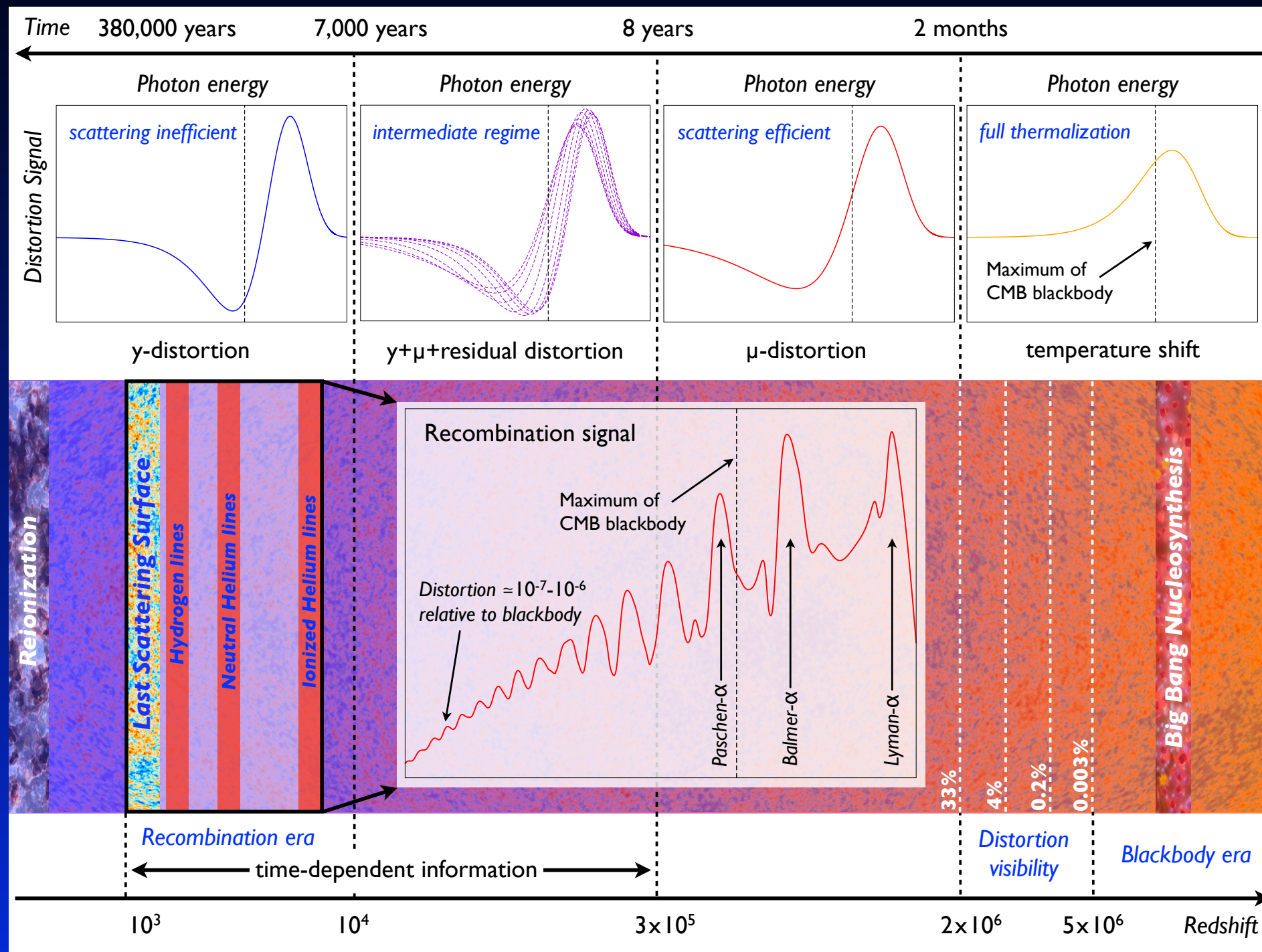
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*Many new results
can be expected!*

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in Λ CDM

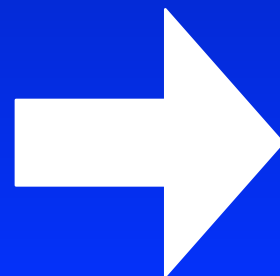
New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

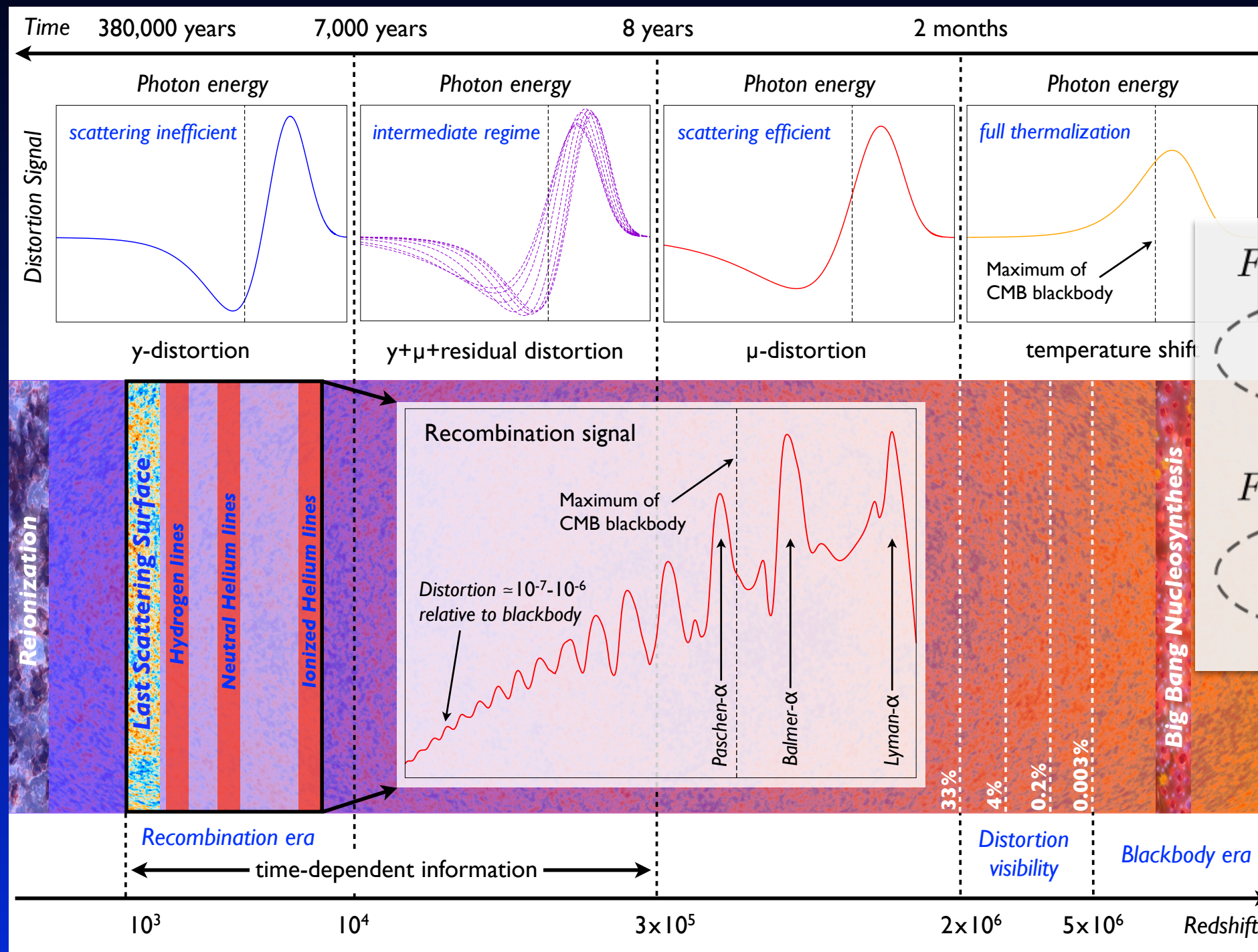
Complementarity and synergy with CMB anisotropy studies

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

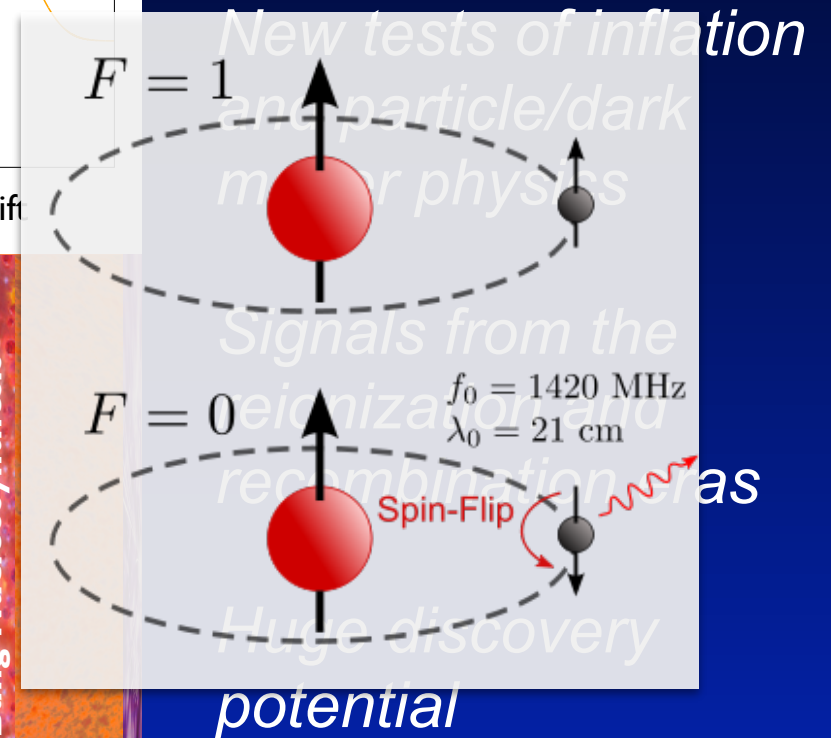


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 FOSSIL**

Uniqueness of CMB Spectral Distortion Science

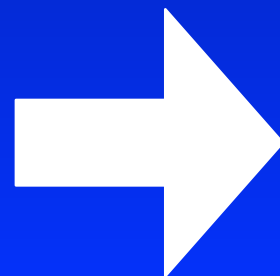


Guaranteed distortion signals in Λ CDM



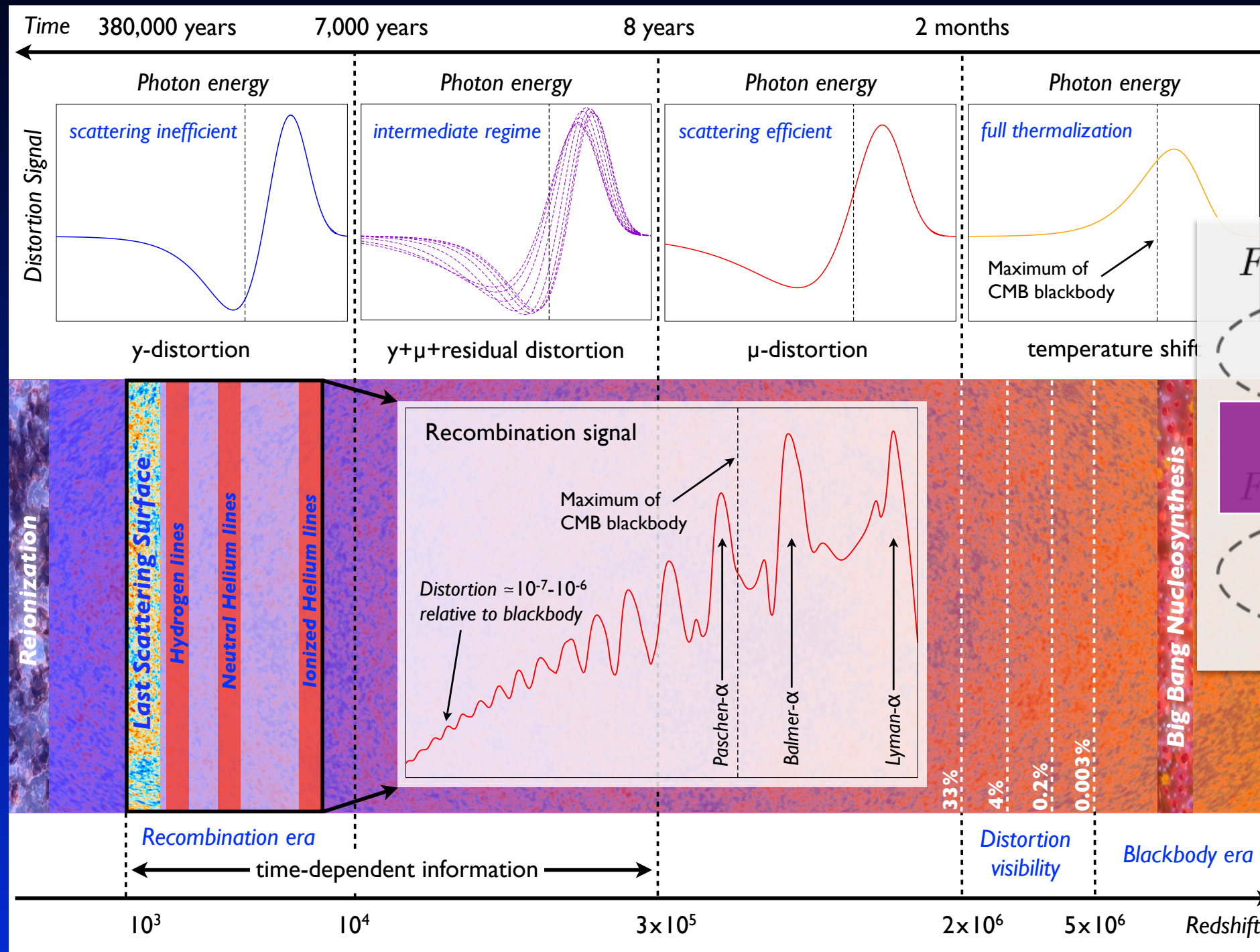
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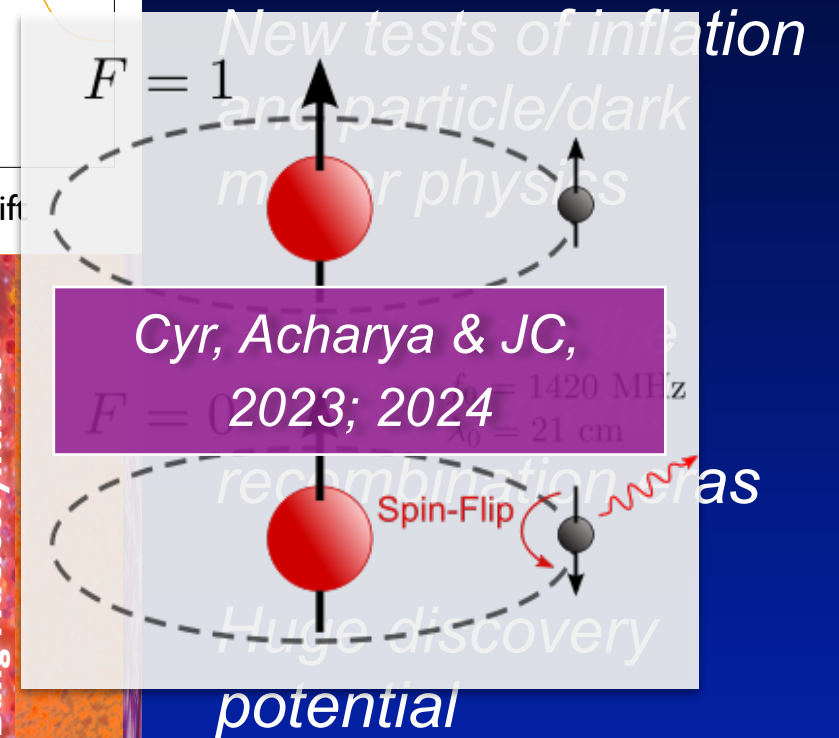


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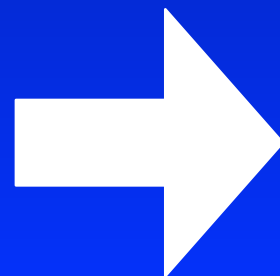


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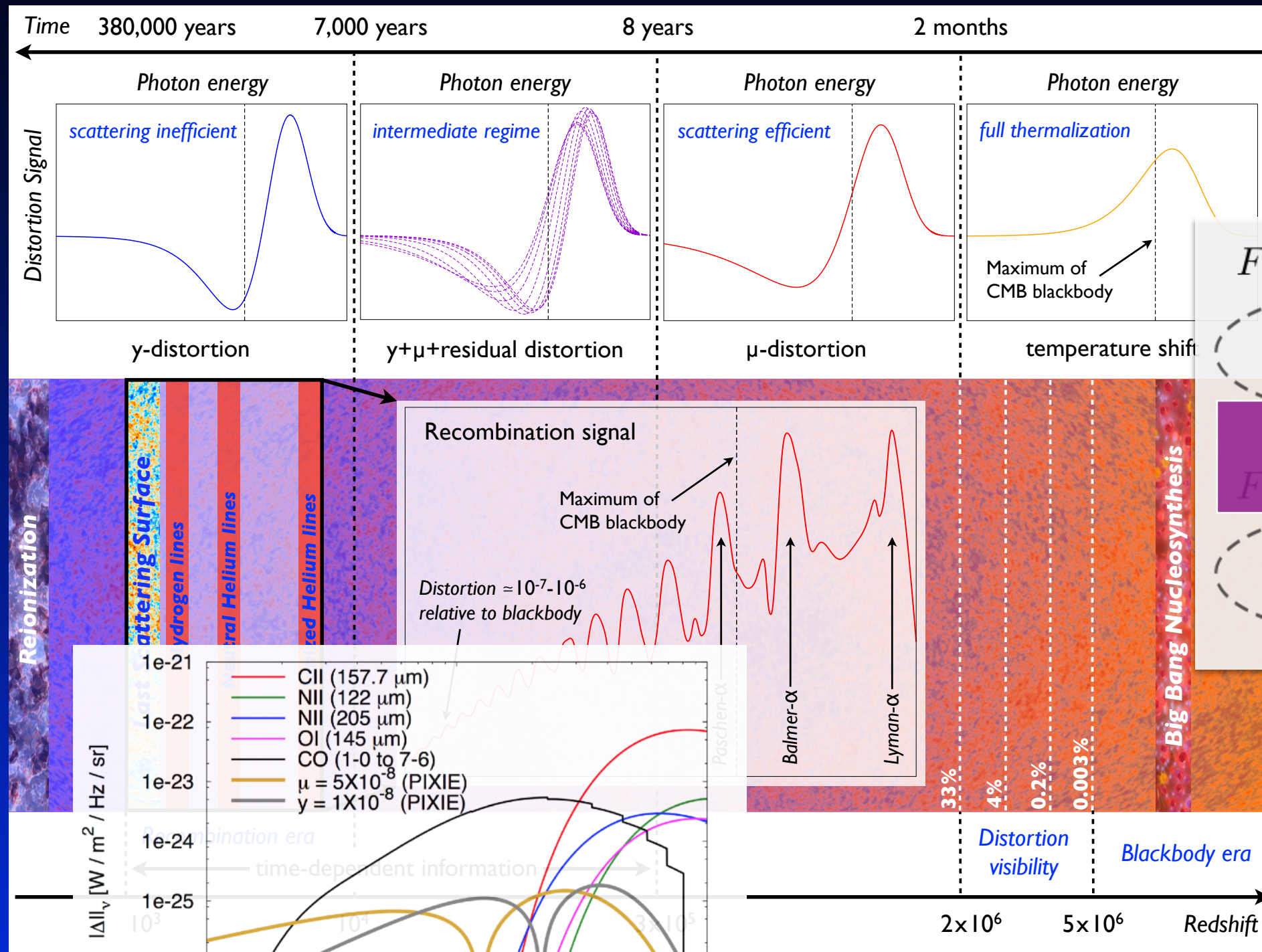
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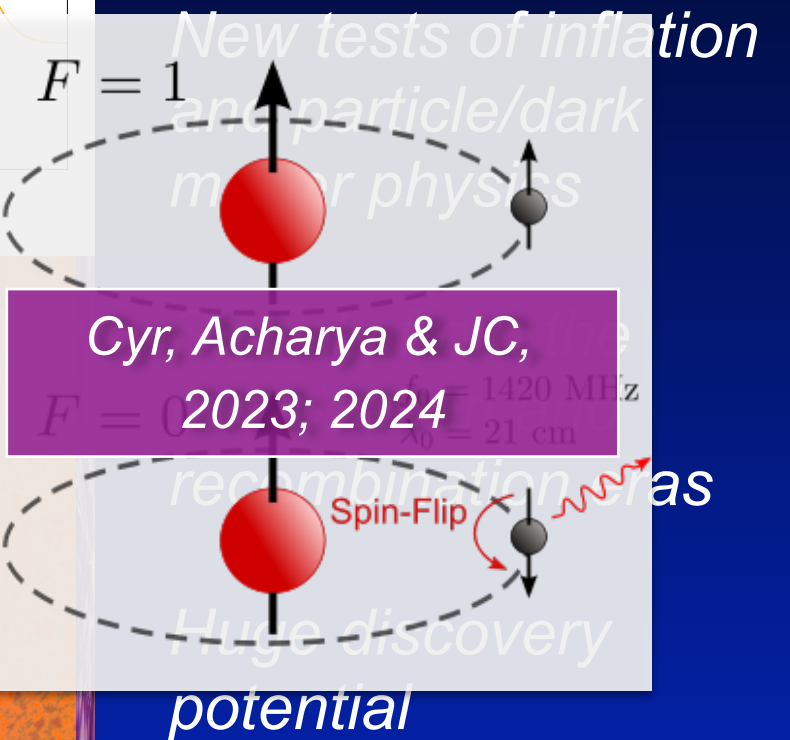


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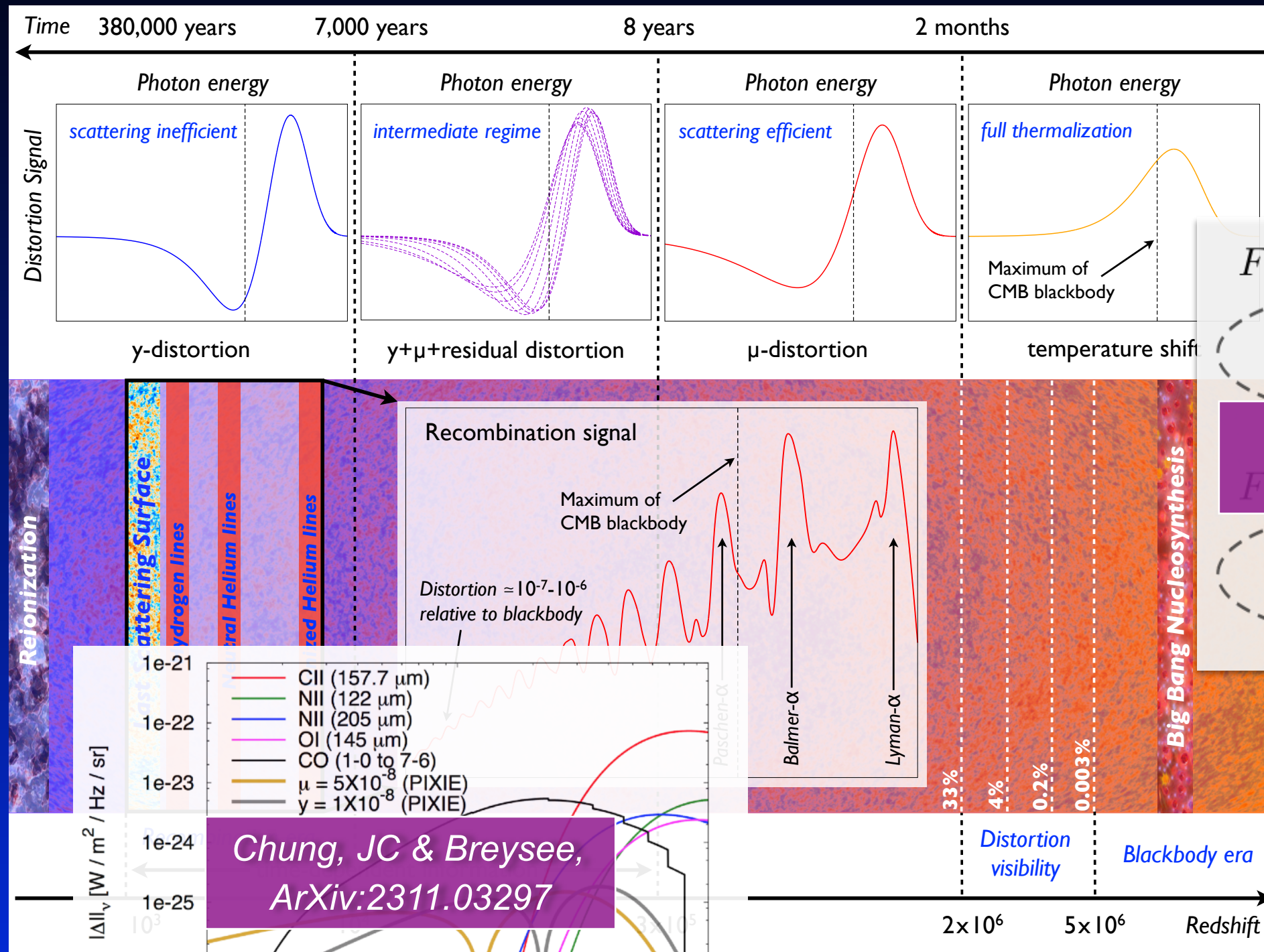
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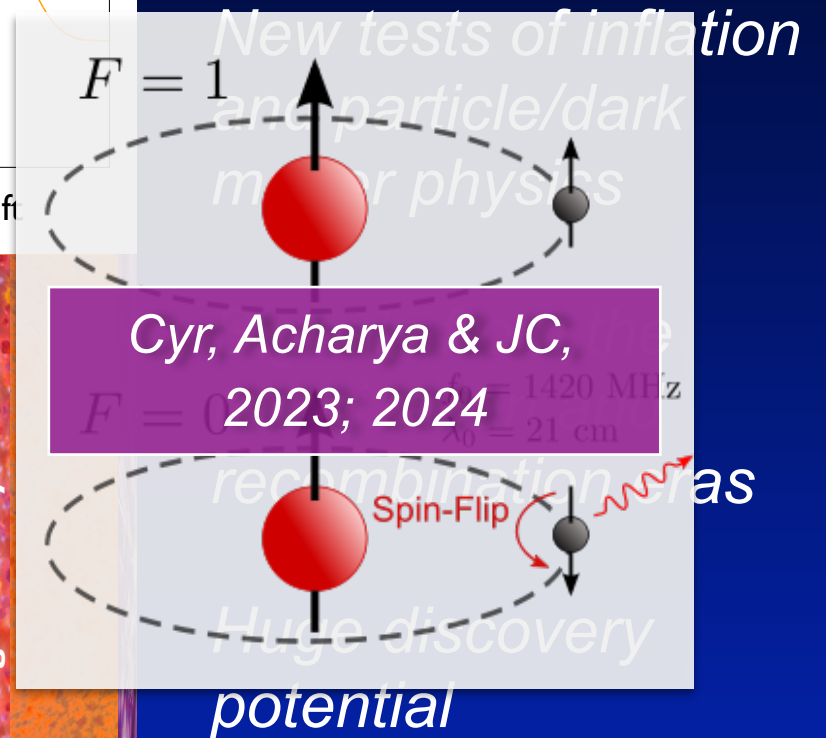
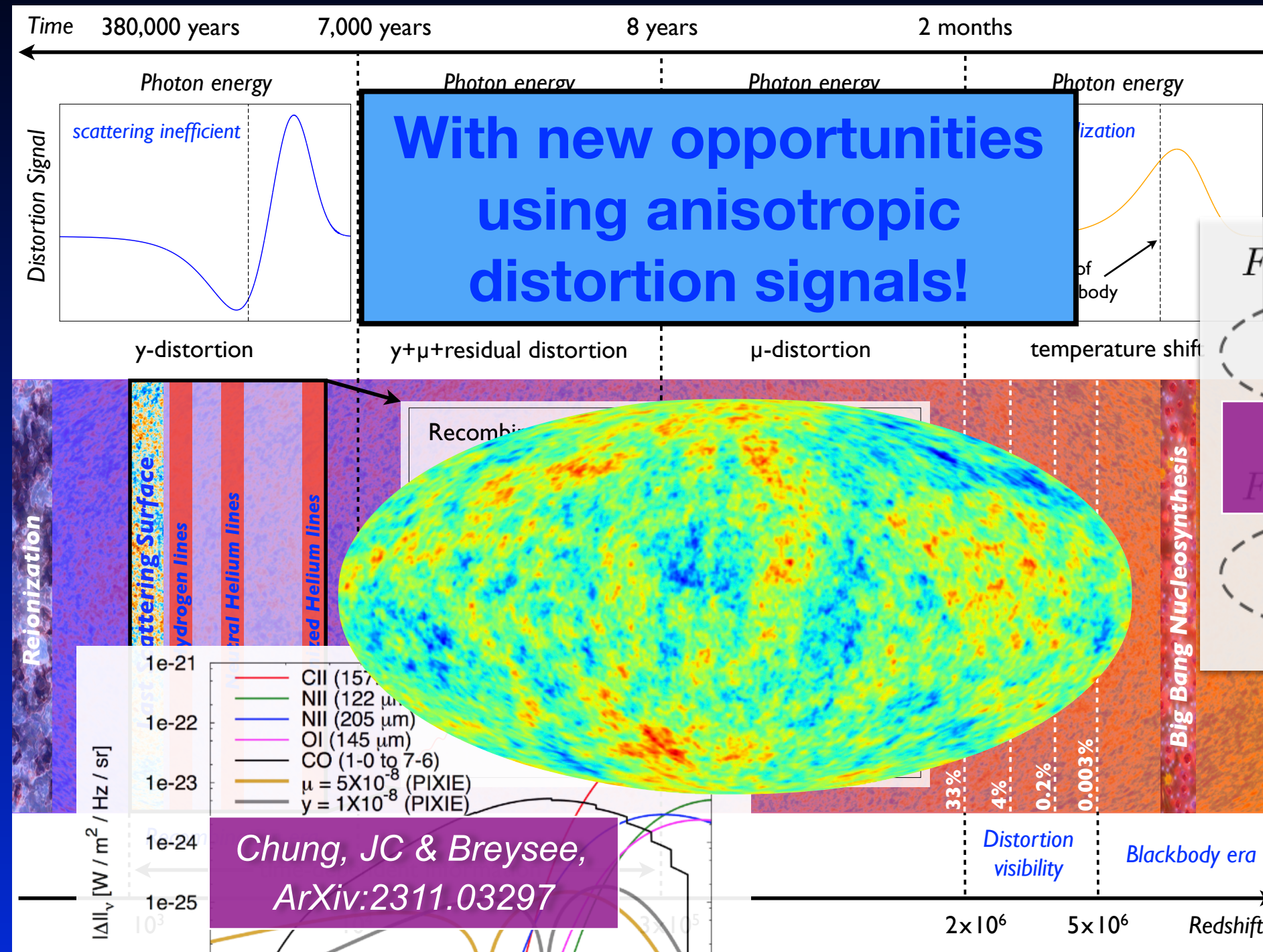
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