Teasing new cosmological observables out of CMB spectral distortions

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The University of Manchester

The early universe picture

✓ **BIG BANG ("beginning of time"):**

Universe started as very hot and dense. It expands and cools down since then.

✓ **INFLATION ($t \simeq 10^{-35}$ sec):**

Universe underwent ultra-rapid accelerated exponential expansion (60 efolds!)

Intrinsic quantum fluctuations of the vacuum are amplified to macroscopic scales, giving rise to primordial density perturbations and primordial gravitational waves

Primordial density perturbations = initial seeds of cosmic structures formed later by gravitational instability: stars, galaxies, clusters of galaxies

✓ **RECOMBINATION ($t \simeq 380,000$ years):**

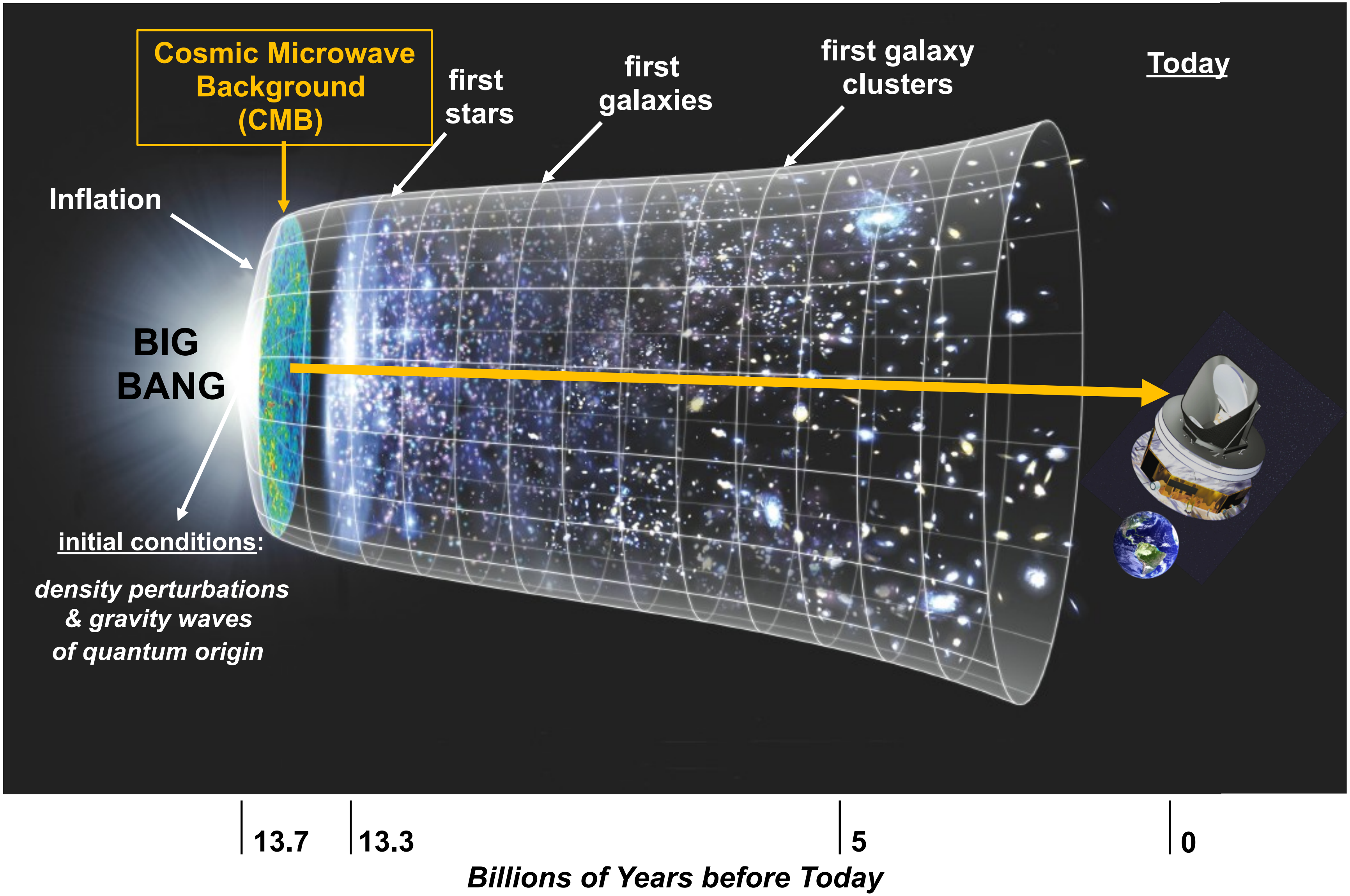
Photons stop being scattered by free electrons through the recombination of hydrogen and helium atoms (last scattering surface)

$\Downarrow$

The first light is released in the universe: Cosmic Microwave Background (CMB) radiation

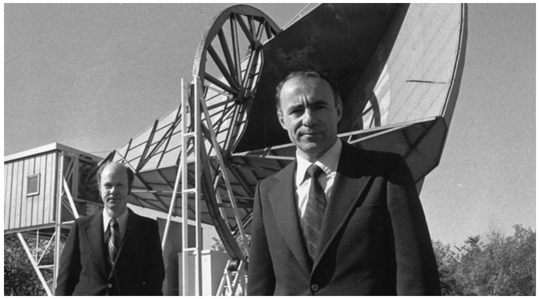
CMB radiation carries unique information on the initial conditions of the universe

The early universe picture



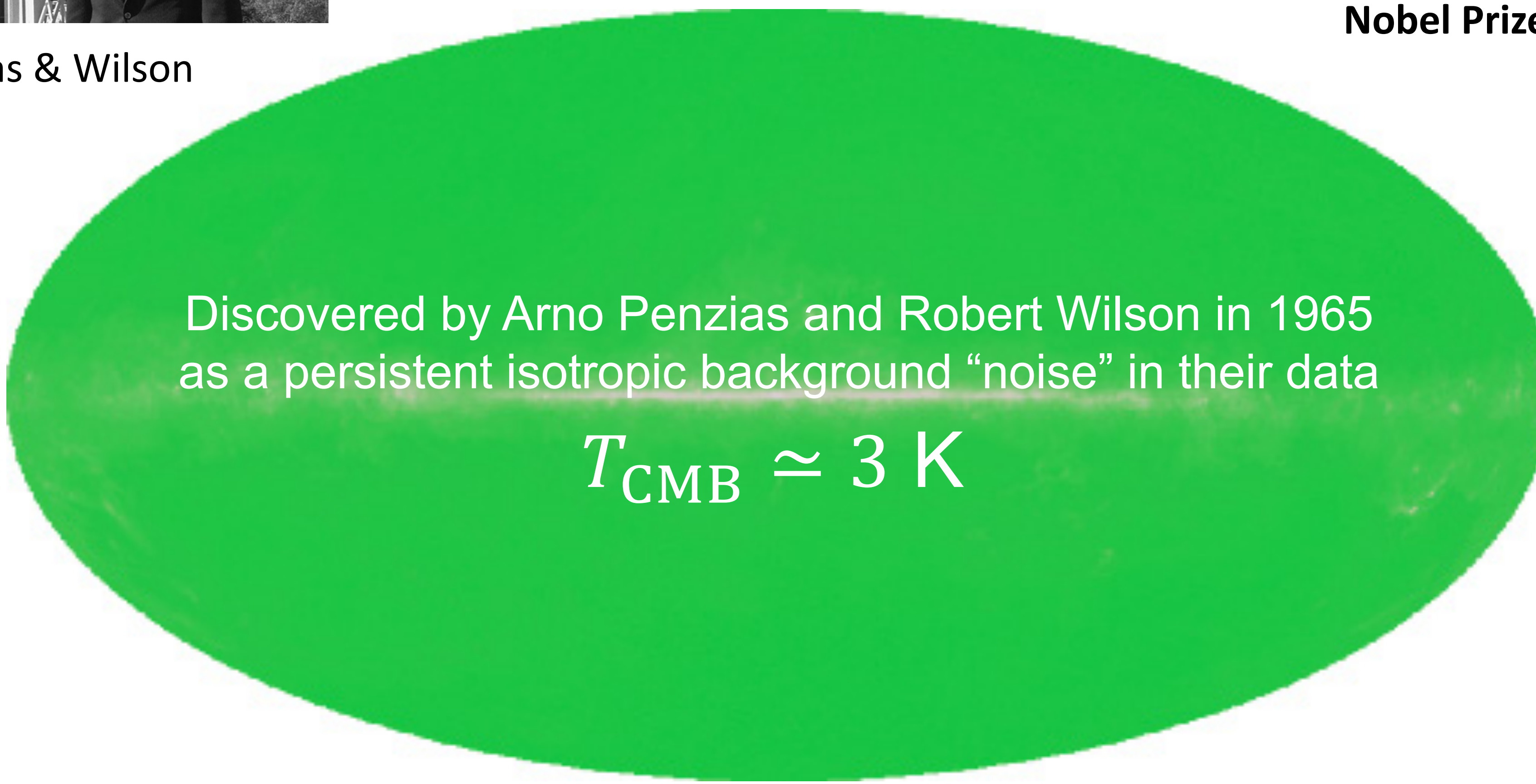
CMB radiation carries unique information on the initial conditions of the universe

Cosmic Microwave Background (CMB)



Penzias & Wilson

Nobel Prize 1978

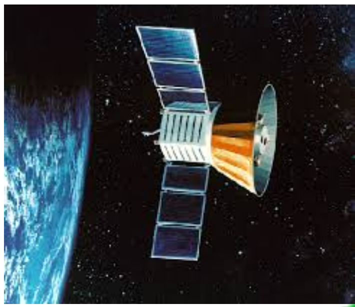


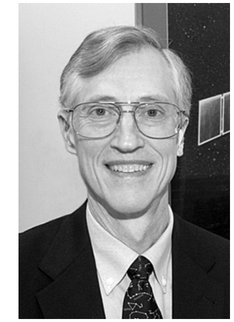
Discovered by Arno Penzias and Robert Wilson in 1965
as a persistent isotropic background "noise" in their data

$$T_{\mathrm{CMB}} \simeq 3\ \mathrm{K}$$

Energy spectrum: Blackbody

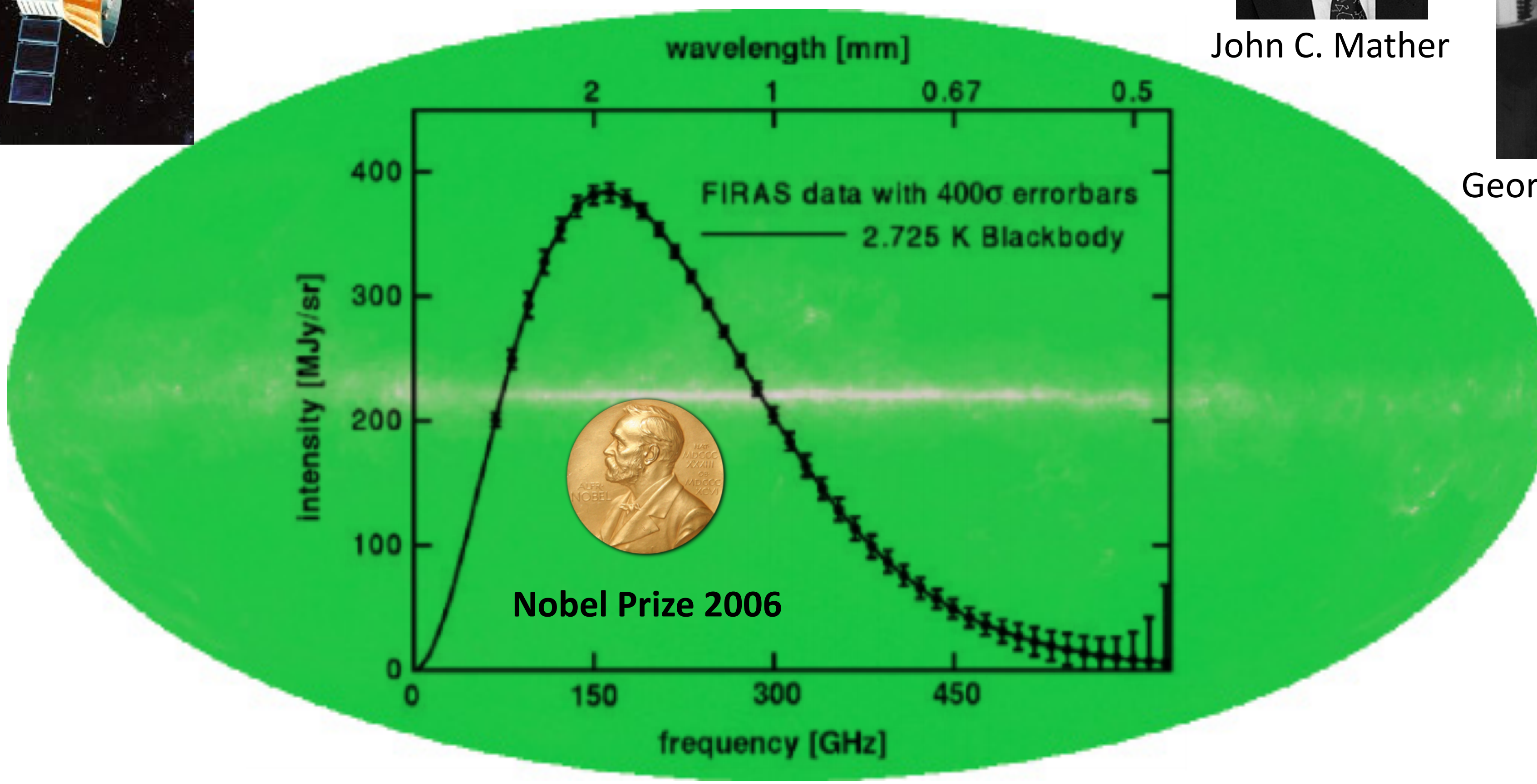
FIRAS spectrophotometer of COBE satellite (1992)





John C. Mather

George F. Smoot

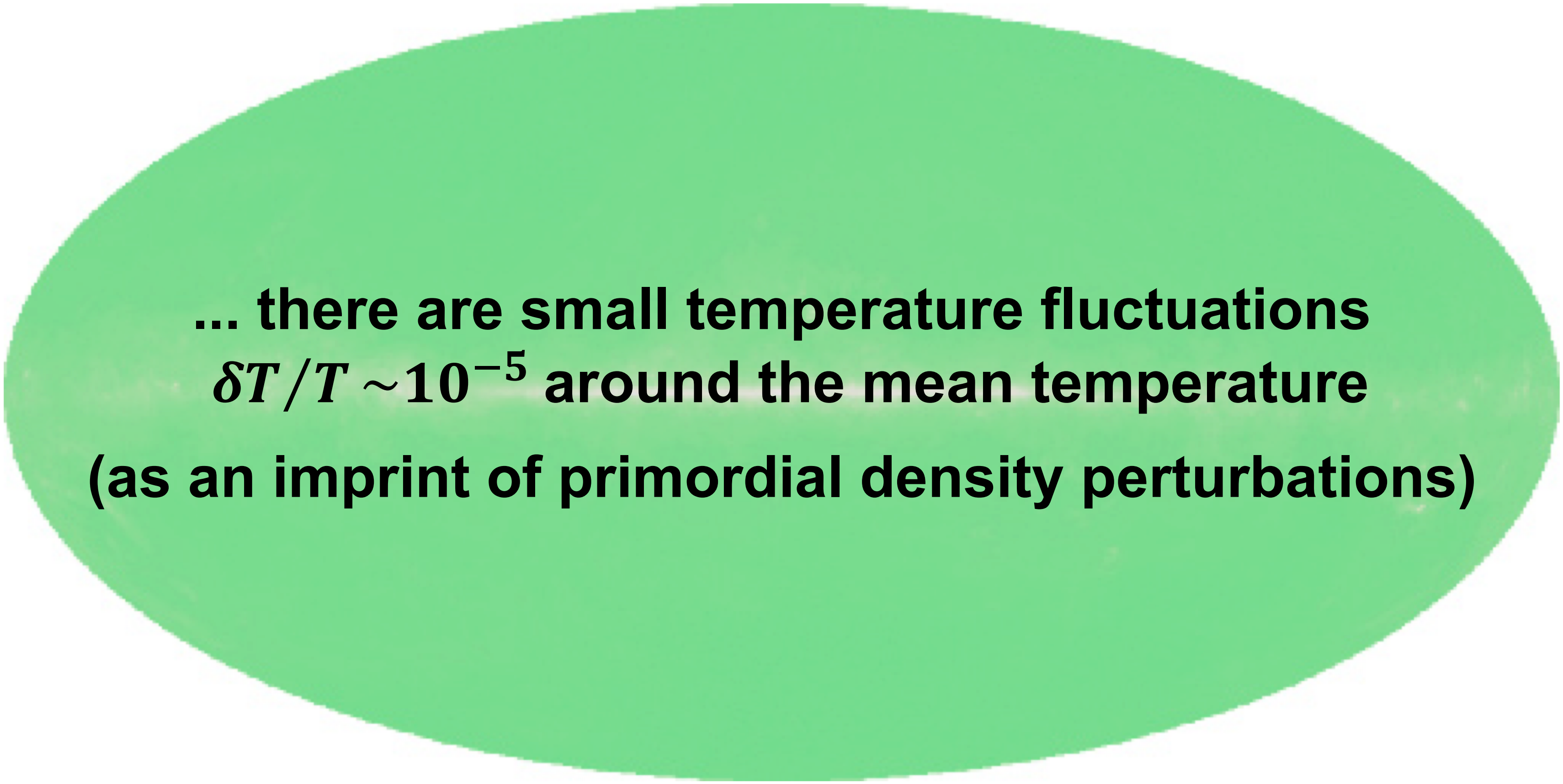


Precise blackbody spectrum at ≃0.01%

$$T_{\mathrm{CMB}} = 2.725\ \mathrm{K}$$

Mather et al, ApJ 1994
Fixsen et al, ApJ 1996

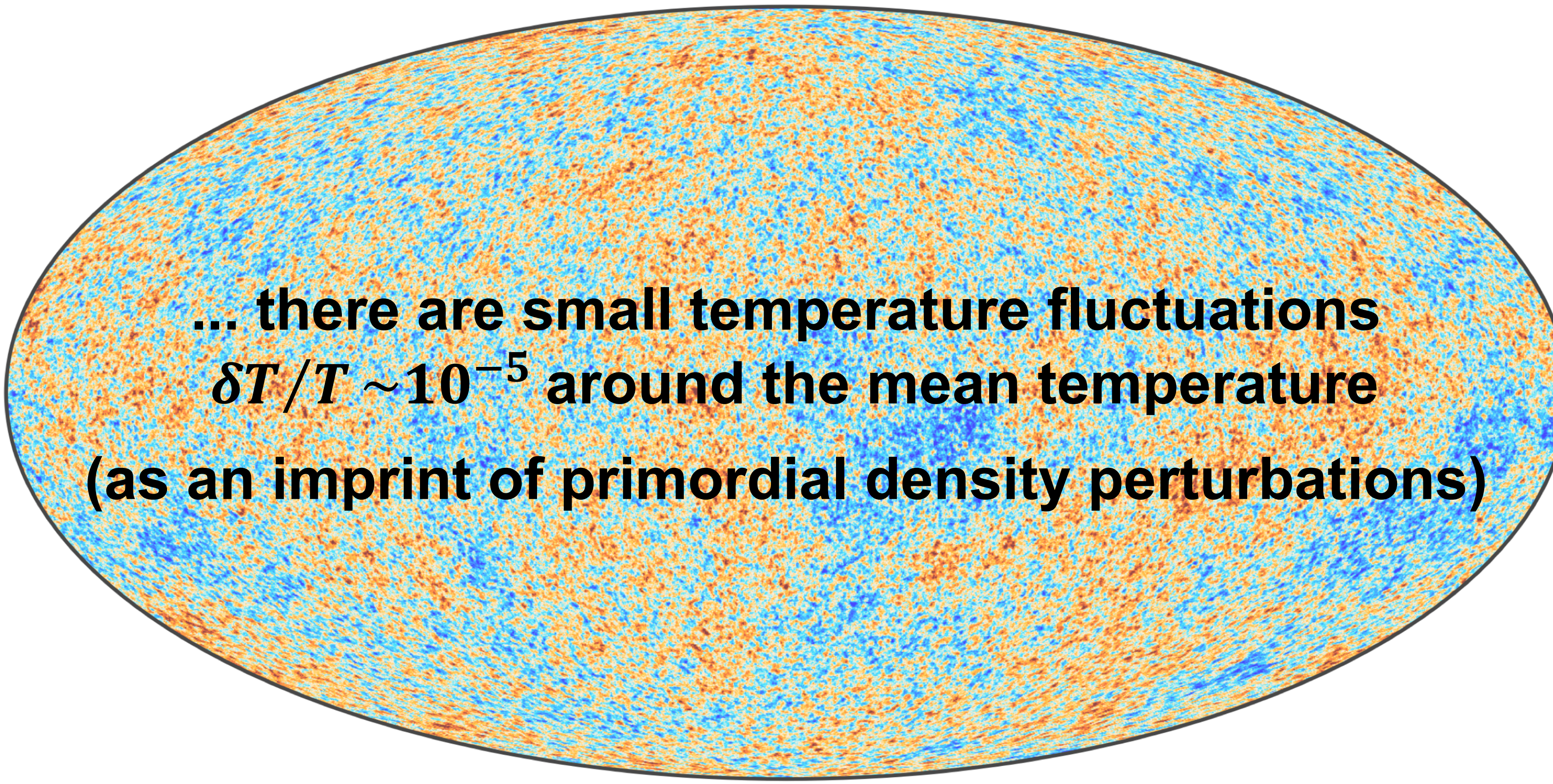
Aside from the average CMB radiation …



... there are small temperature fluctuations
$\delta T/T \sim 10^{-5}$ around the mean temperature

(as an imprint of primordial density perturbations)

CMB temperature anisotropies

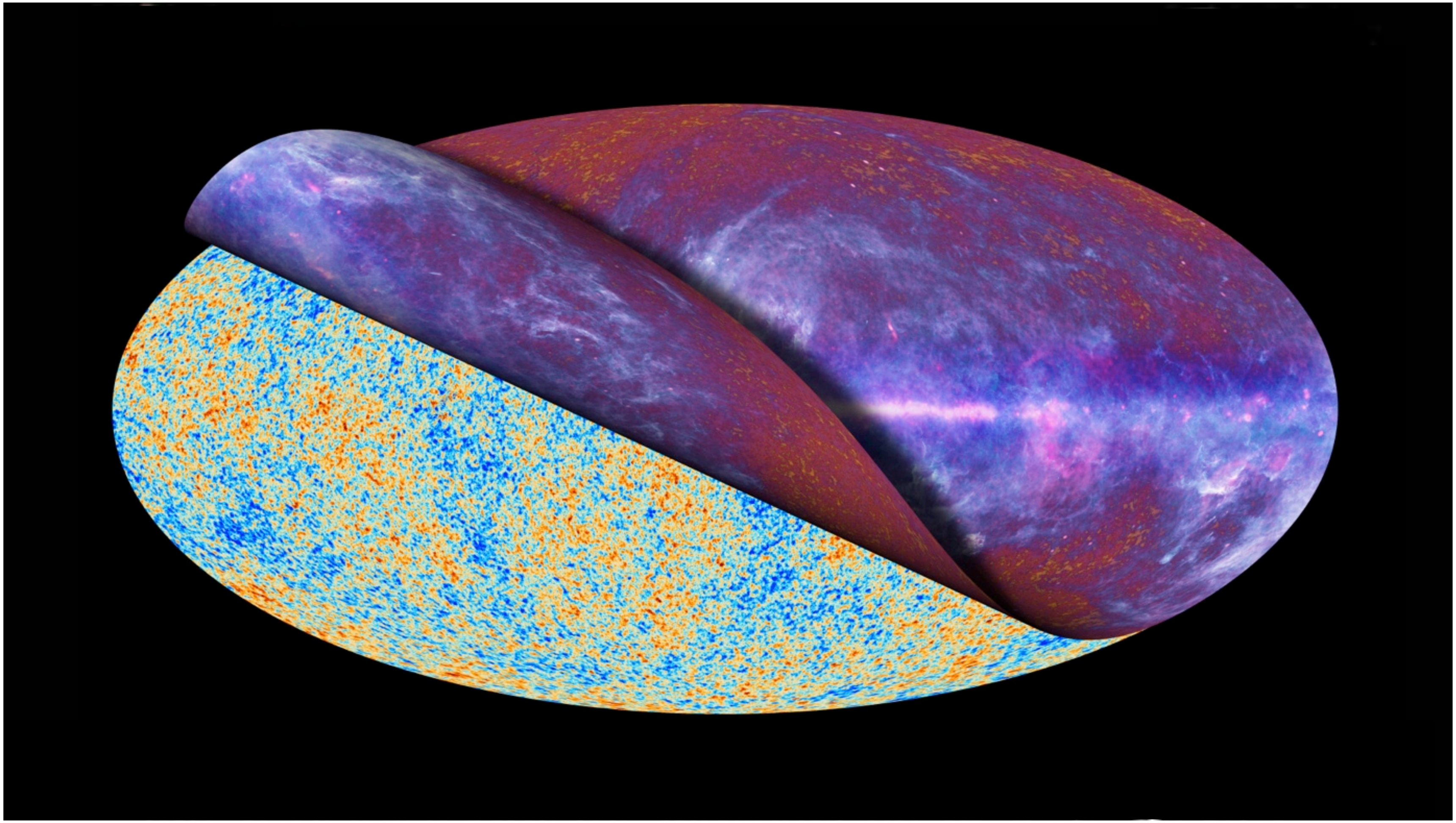


After subtracting the mean CMB radiation (monopole)

The Planck satellite scans the entire sky

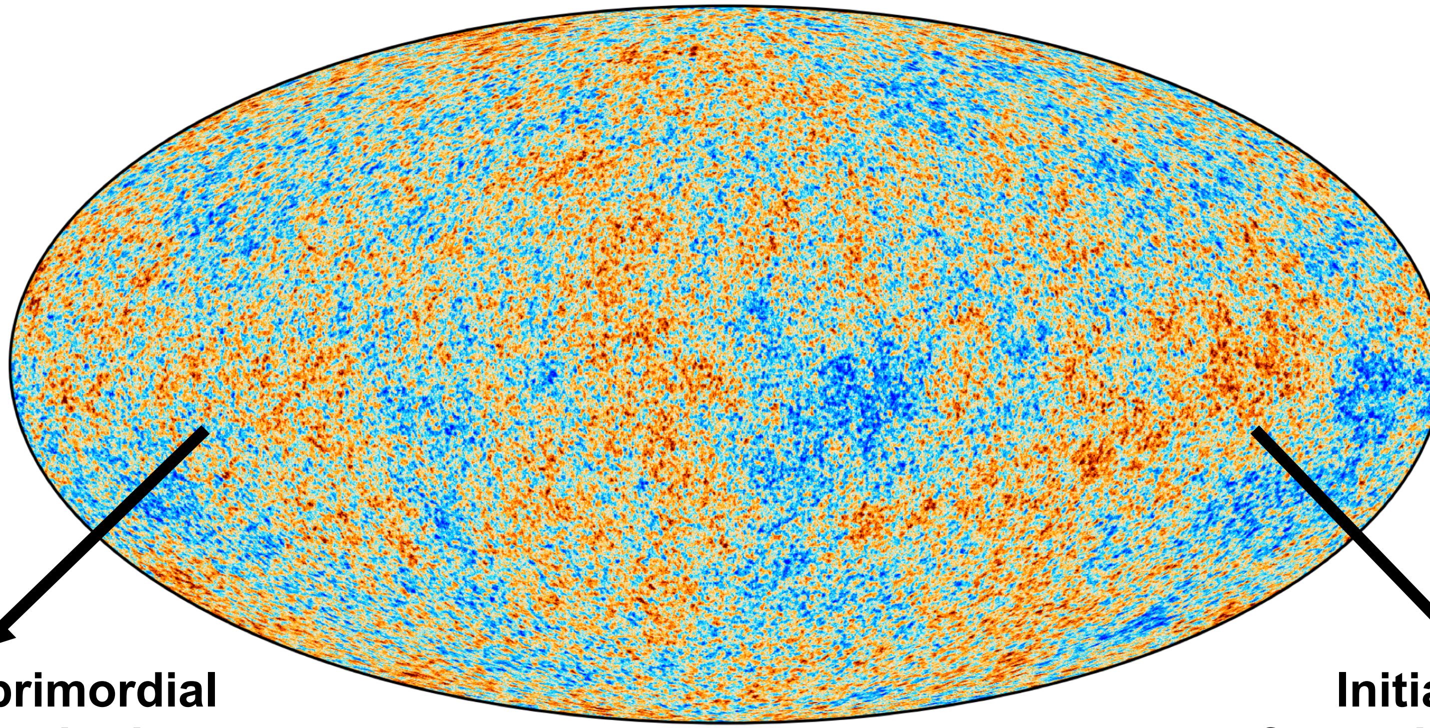
Credit: ESA

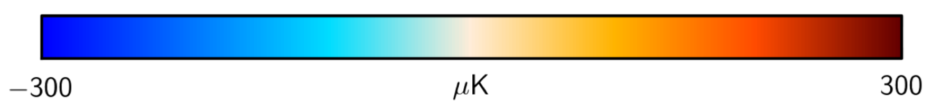
CMB radiation = background signal



Credit: ESA

The *Planck* CMB all-sky map: temperature fluctuations around 2.725 K





Imprint of primordial density perturbations in the early universe

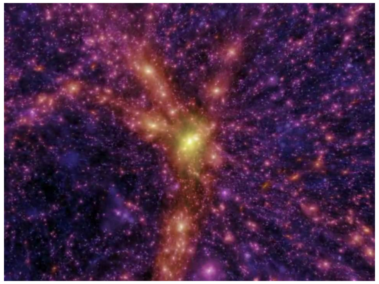
$$\frac{\delta T}{T} \simeq -\frac{1}{3}\Phi$$

$$\Delta\Phi = 4\pi G\ \delta\rho$$

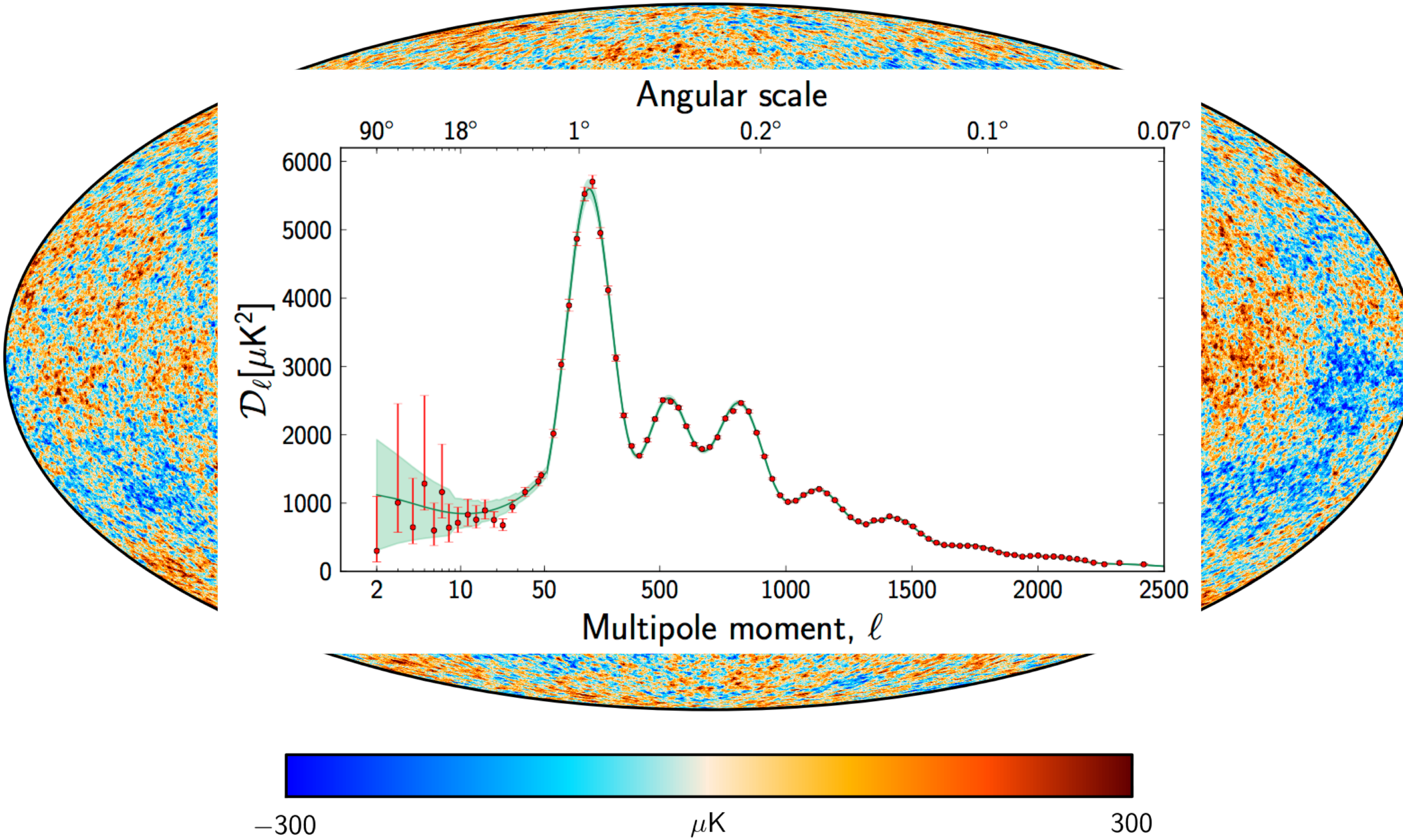
Oldest picture of our universe

380,000 years after the Big Bang

Initial seeds of cosmic structures: *stars, galaxies, clusters*

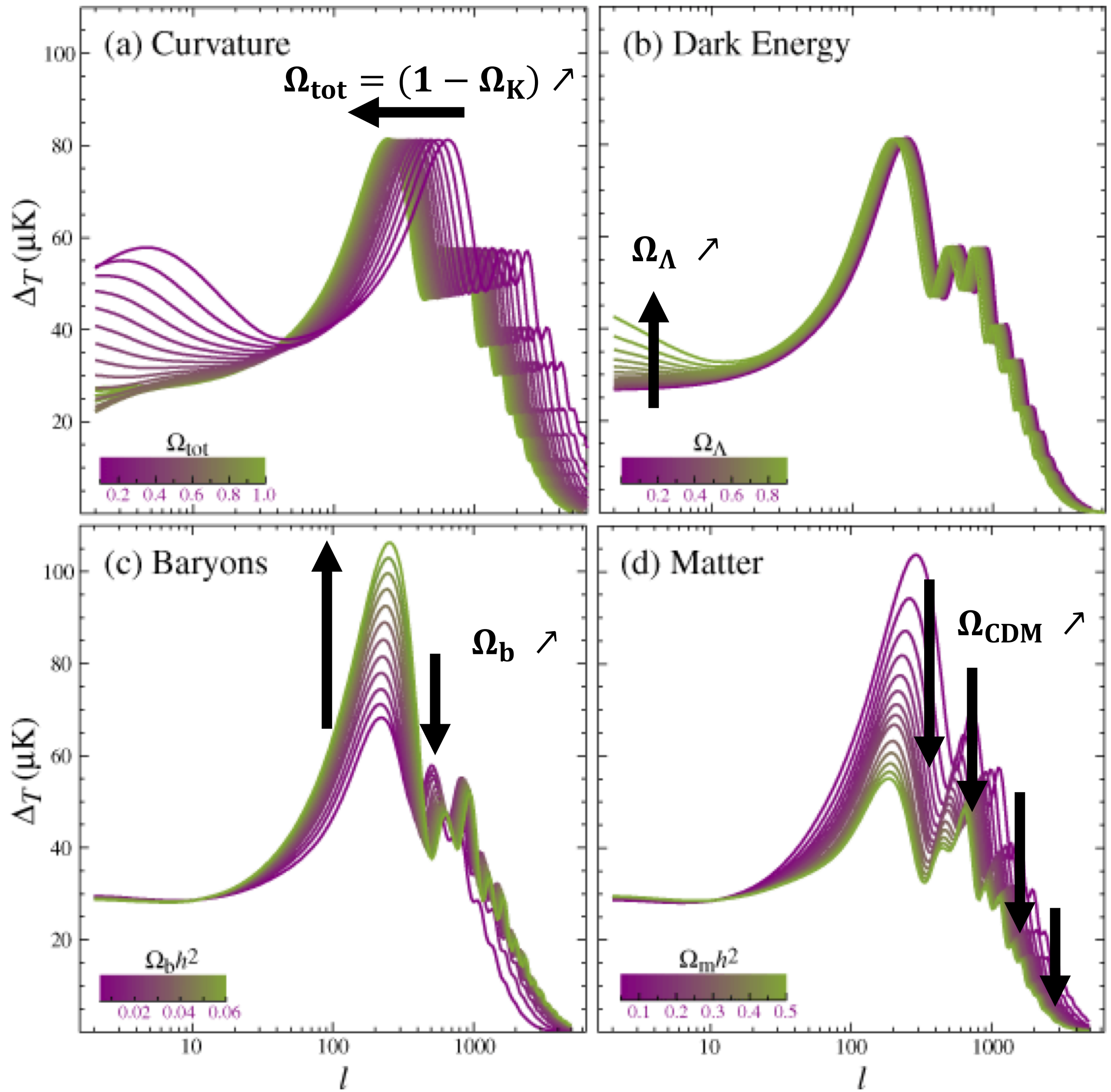


Power spectrum of CMB anisotropies

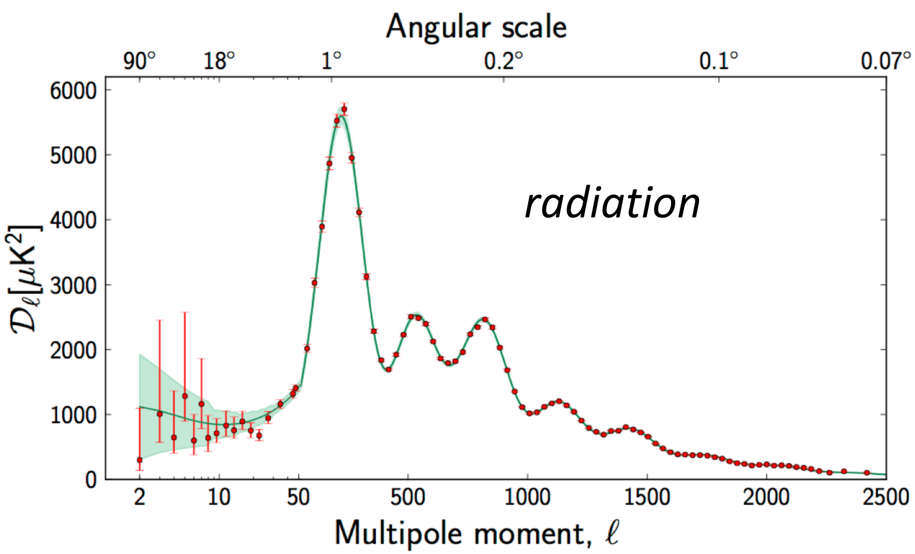


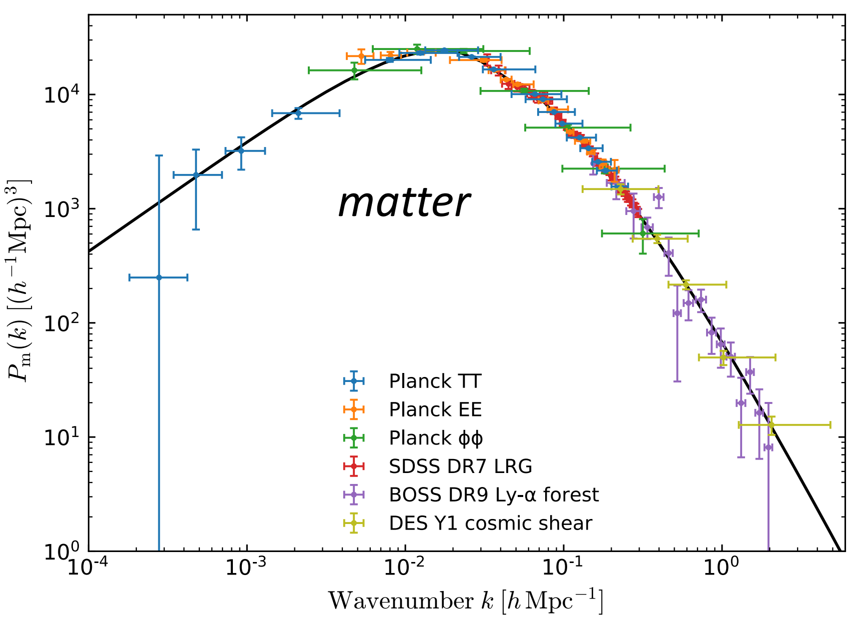
The exact shape of the CMB power spectrum is driven by cosmological parameters

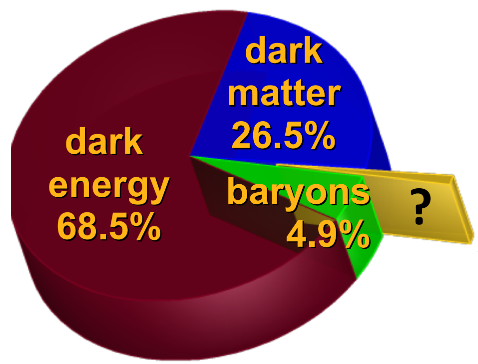
Hu & Dodelson ARAA (2002)



CMB anisotropies, LSS, and SNe taught us a lot about our universe



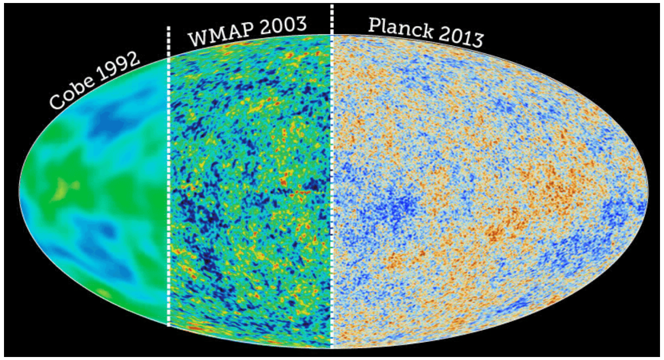


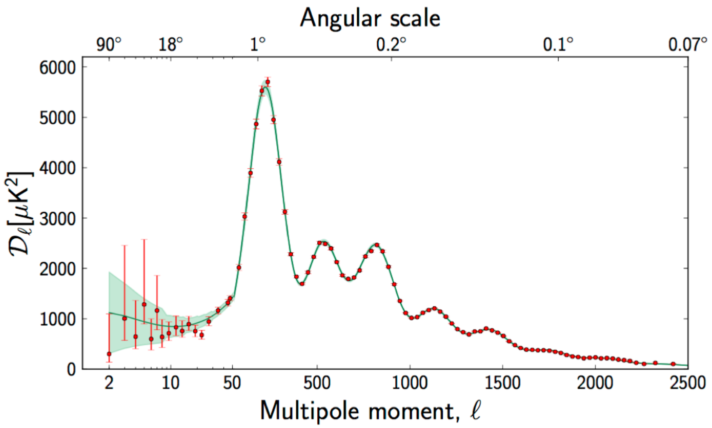


Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

Two independent observables for the CMB

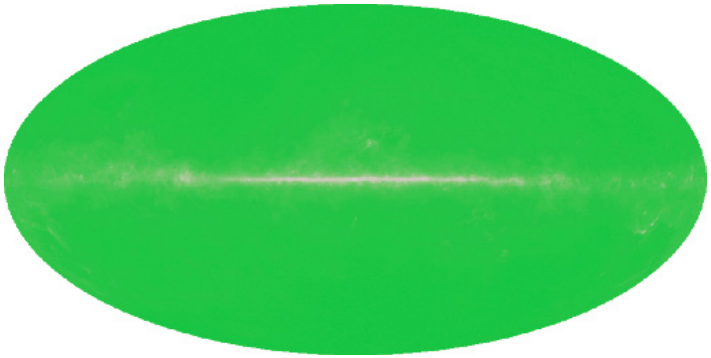
✓ **Power spectrum** (spatial information)

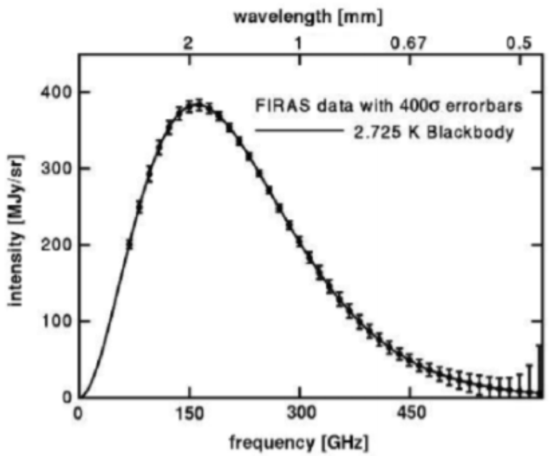




Intensity of CMB anisotropies across angular scales/multipoles

✓ **Energy spectrum** (spectral information)





Intensity of mean CMB radiation across frequencies

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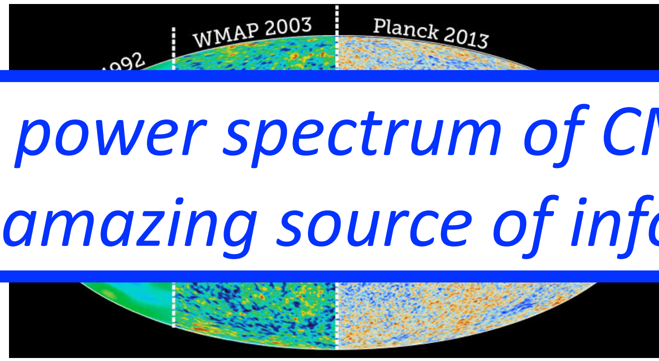

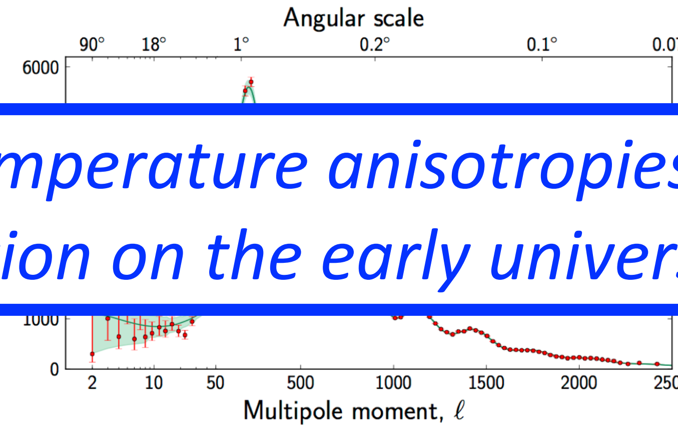

The power spectrum of CMB temperature anisotropies is an amazing source of information on the early universe

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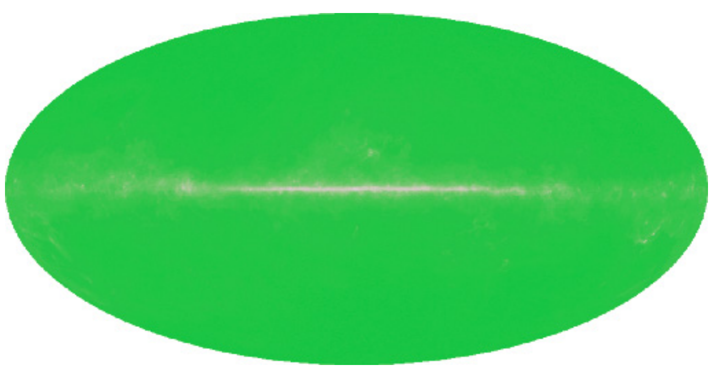

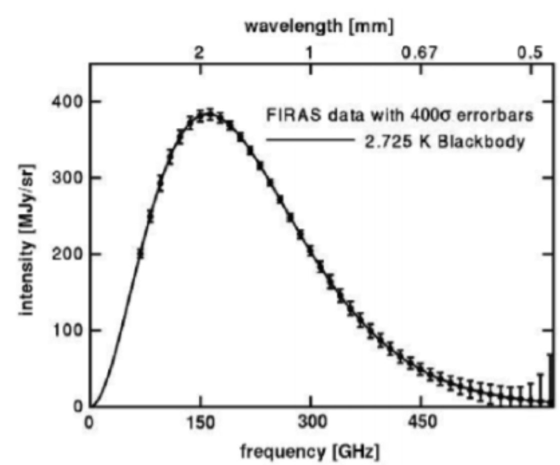

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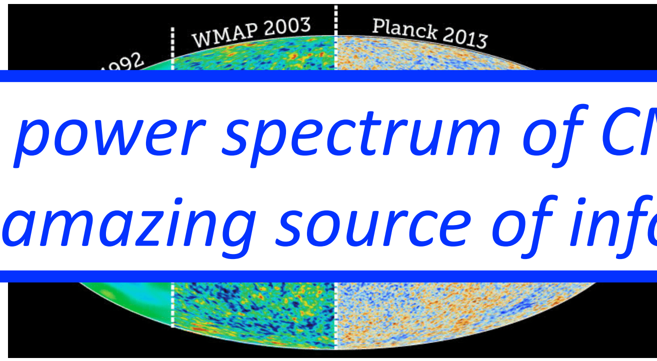

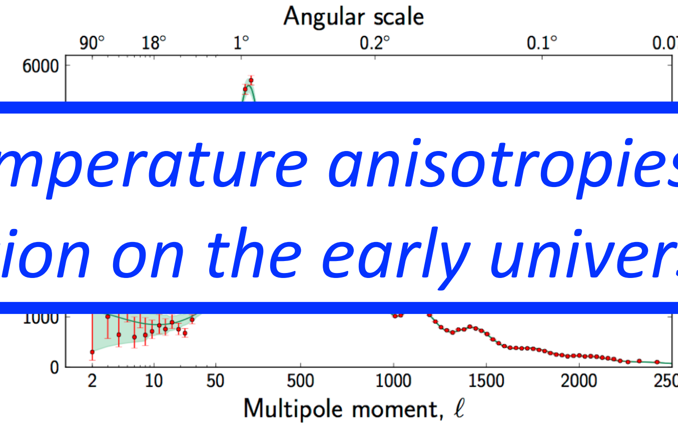

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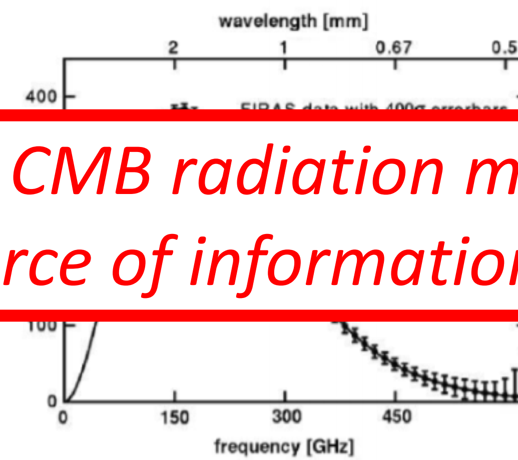

The energy spectrum of the mean CMB radiation may provide another independent source of information!

Intensity of mean CMB radiation across frequencies

Two independent observables for the CMB

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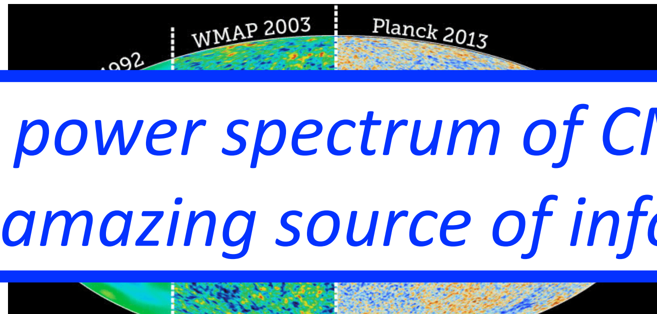

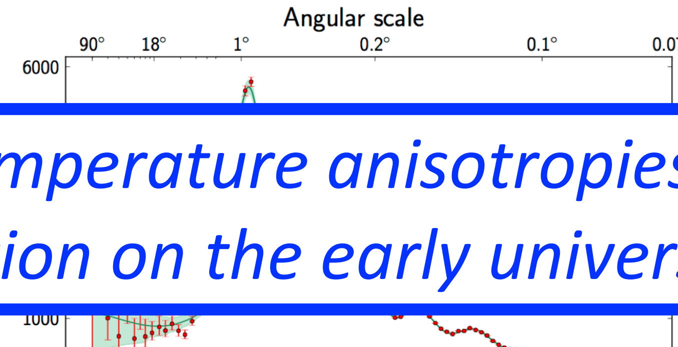

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Amazing progress in sensitivity over the past decades:
COBE, WMAP, Planck, ACT, SPT, BICEP, + several others

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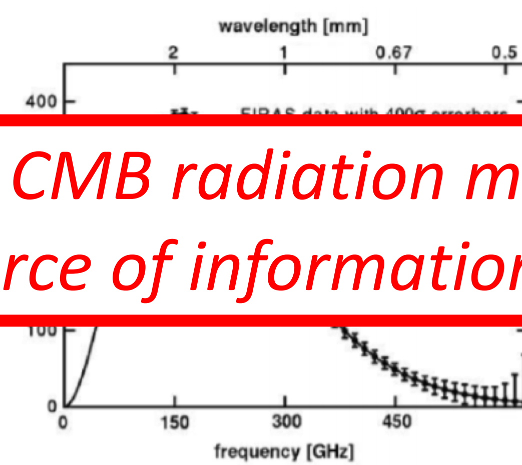

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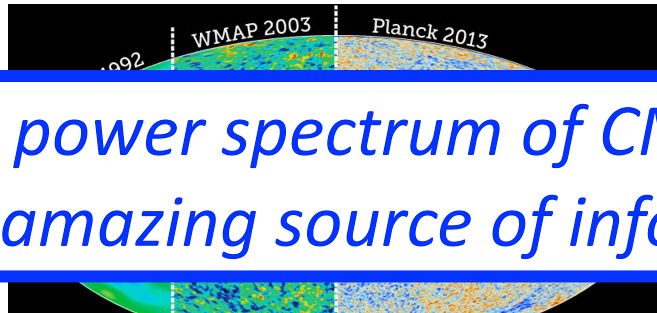

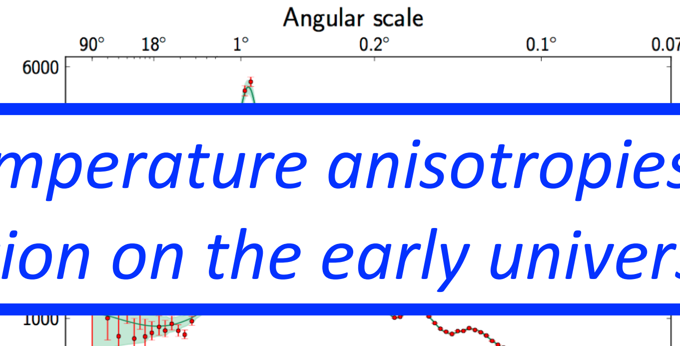

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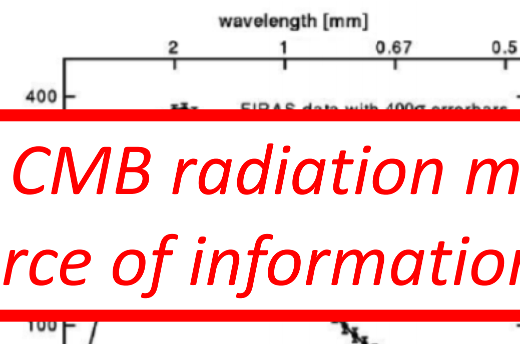
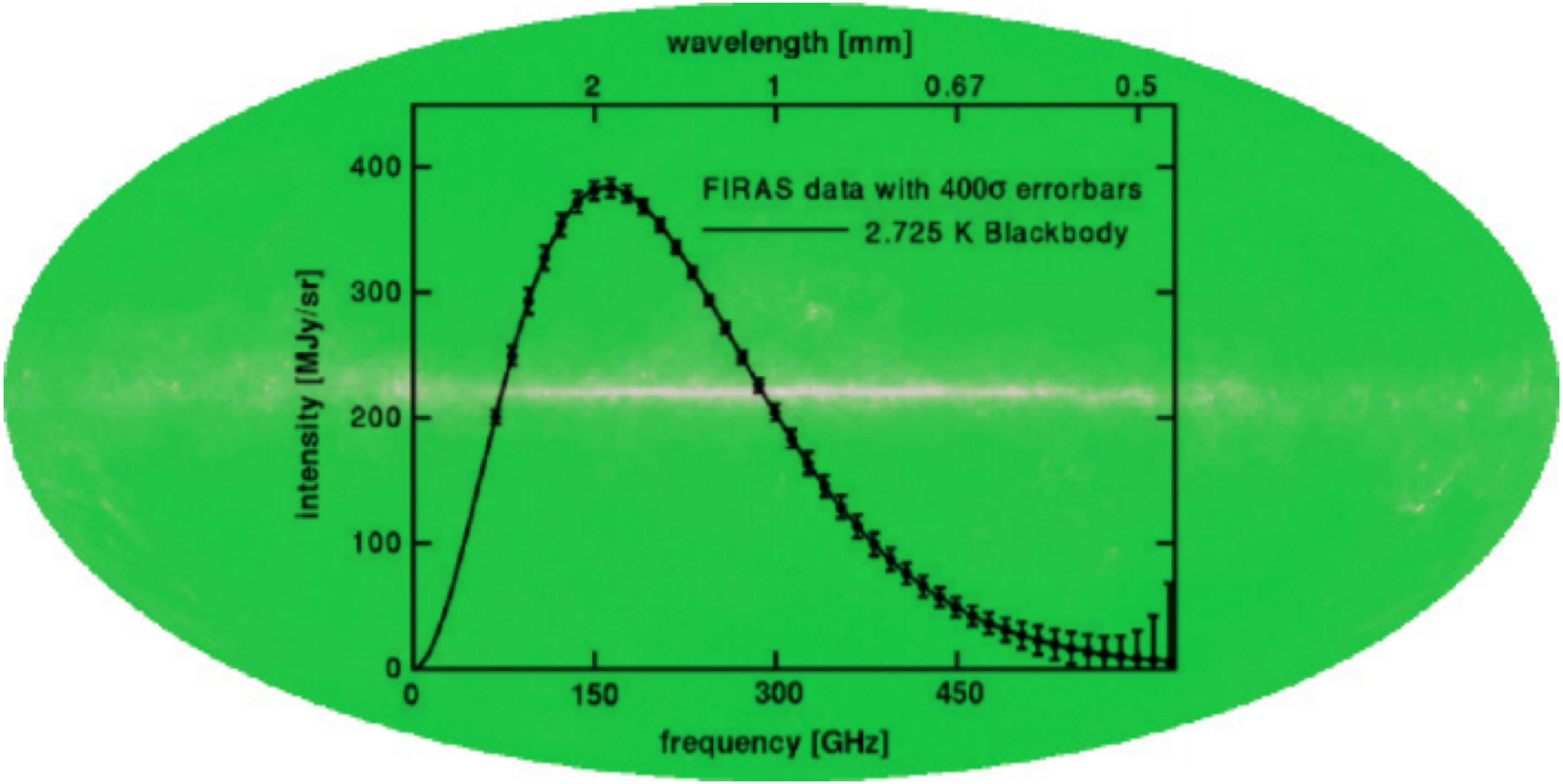


The energy spectrum of the mean CMB radiation may provide another independent source of information!

No further sensitive measurement since the 90s!
COBE/FIRAS

Is the average CMB energy spectrum a perfect blackbody?



Can we detect tiny departures from a perfect blackbody, also known as <u>CMB spectral distortions</u>?

Physical mechanisms leading to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

„high“ redshifts

pre-recombination epoch

„low“ redshifts

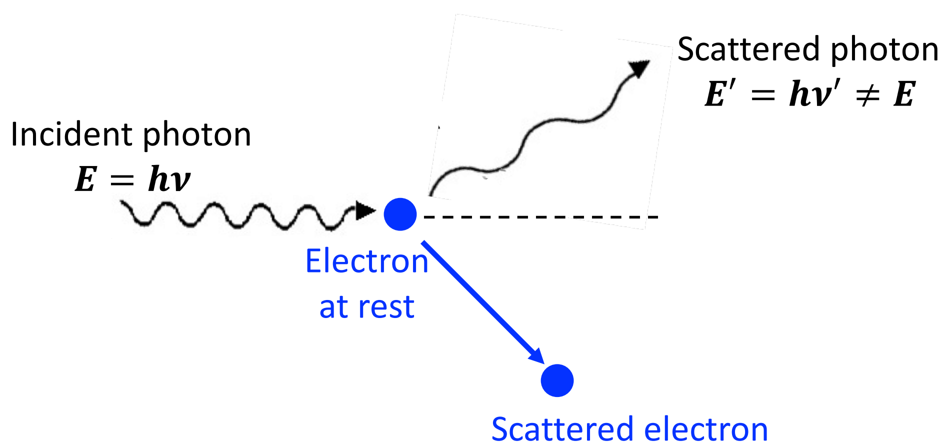
post-recombination

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Why CMB spectral distortions?

- ✓ Spectral distortions arise from interactions between matter and radiation
- ✓ Below a redshift of $z \lesssim 2\times10^6$, thermalization becomes inefficient, hence several processes drive matter and radiation out of thermal equilibrium
- ✓ Perturbations to thermal equilibrium cause energy exchanges between matter and radiation (heating of baryonic matter, injection of photons or other particles), leading to spectral distortions of the CMB blackbody radiation
- ✓ Classical types of CMB spectral distortions:
  y-type distortions and **μ-type distortions** due to **Compton scattering** between photons and free electrons causing an energy release

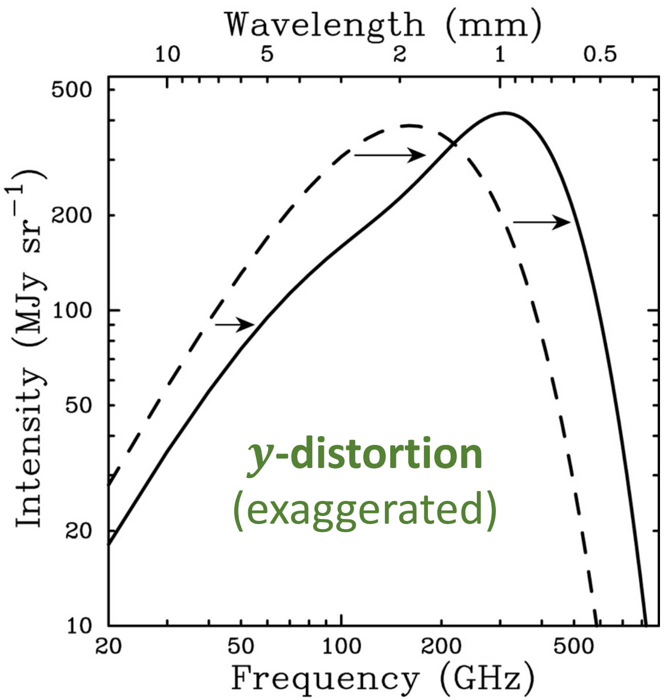
$$\boldsymbol{\gamma + e \longrightarrow e' + \gamma'}$$



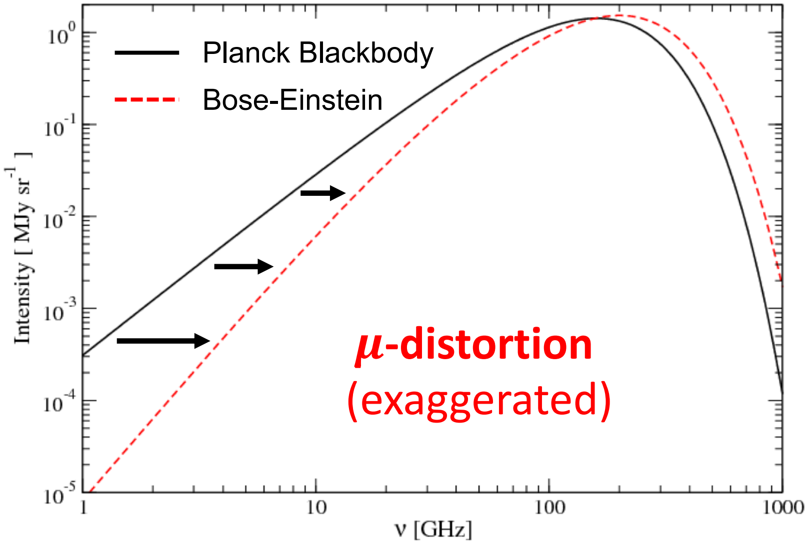
Blackbody distortions by Compton scattering

$$\gamma + e \longrightarrow \gamma' + e'$$

Sunyaev & Zeldovich, ApSS (1970)
Sunyaev & Zeldovich, ARAA (1980)



Important at late and early times
$0 < z < 5\times10^4$

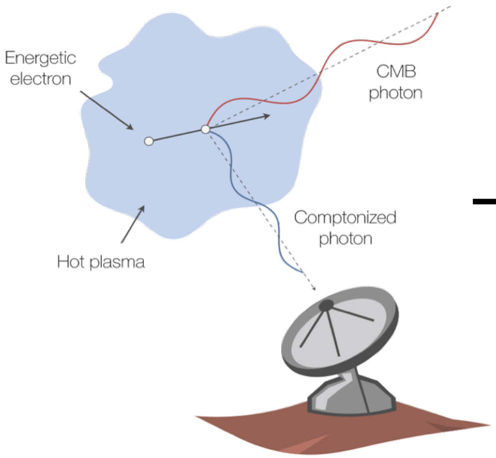


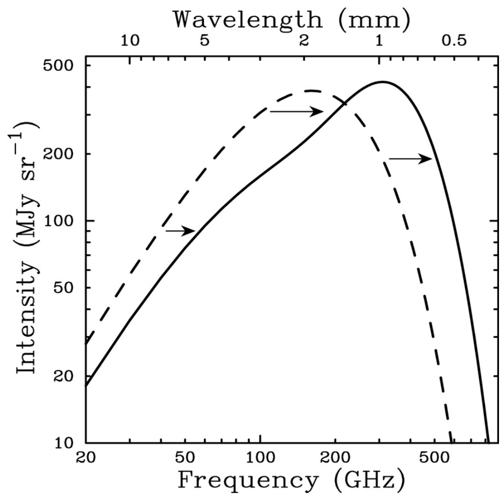
Important at very early times
$10^4 < z < 2\times10^6$

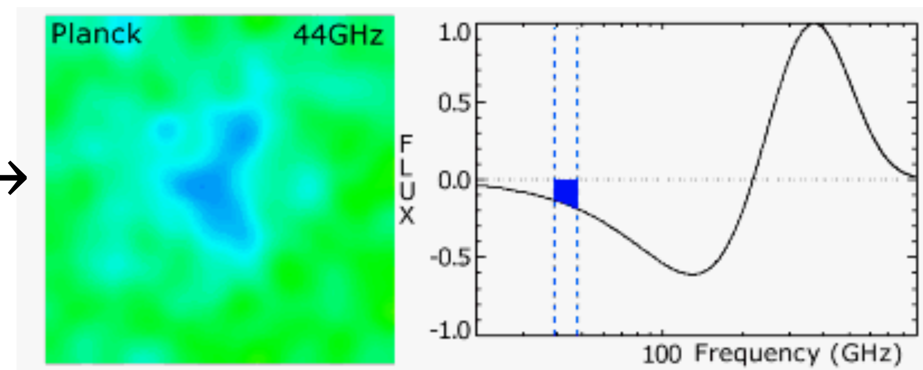
Compton scattering redistribute the energy of photons across frequencies

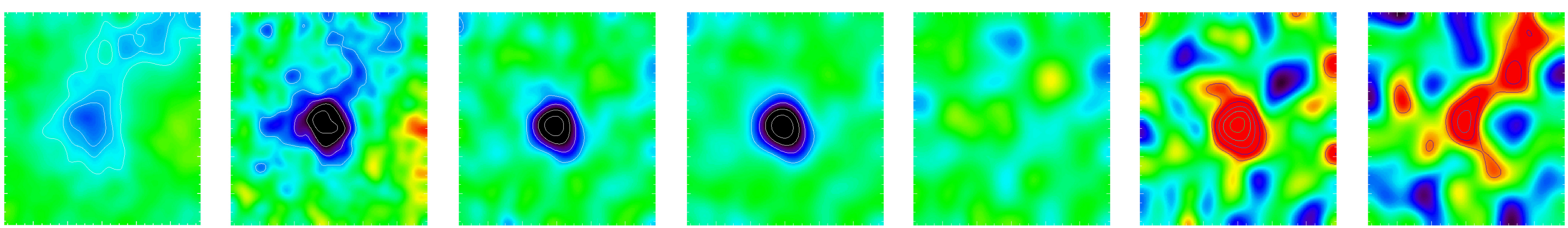
y-type distortion in the late universe: Thermal SZ effect

galaxy cluster







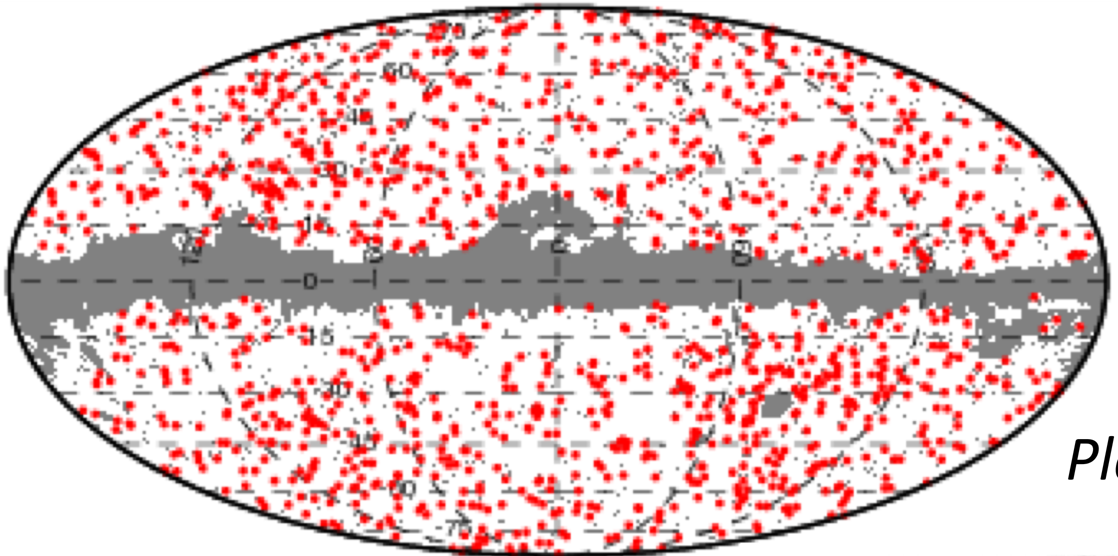


44 GHz **70 GHz** **100 GHz** **143 GHz** **217 GHz** **353 GHz** **545 GHz**

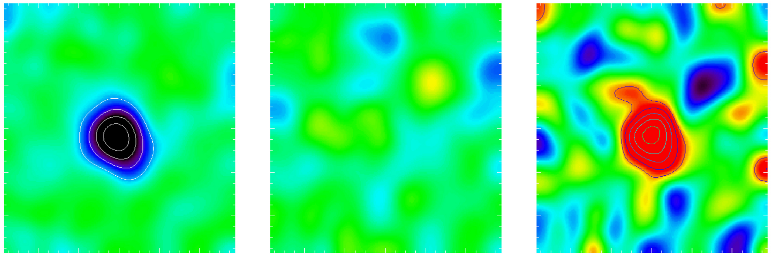
Credit: ESA/Planck Collaboration

Thermal SZ effect is now routinely observed

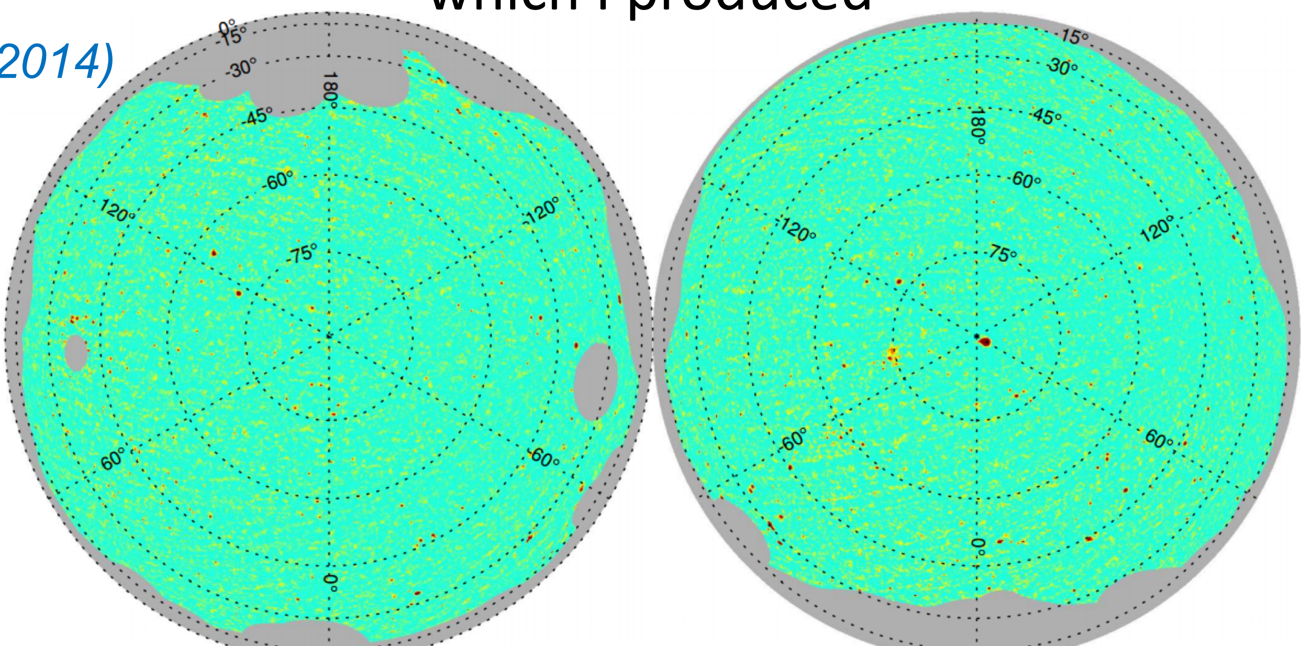
Planck SZ cluster catalog



Planck 2013 results XXIX A&A (2014)

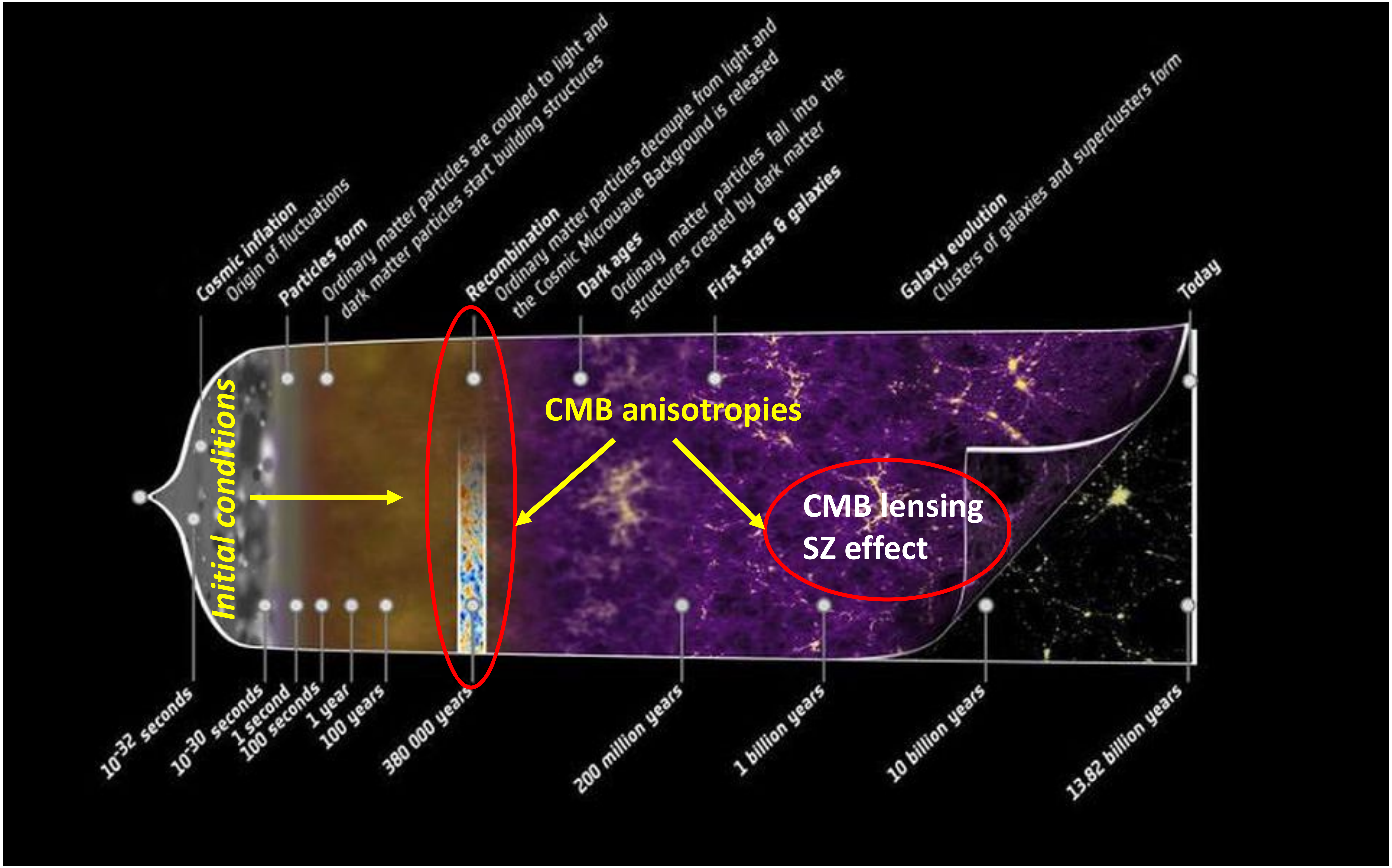


Planck SZ Compton y-map which I produced



Planck 2015 results XXII, A&A (2016)

When do spectral distortions happen?



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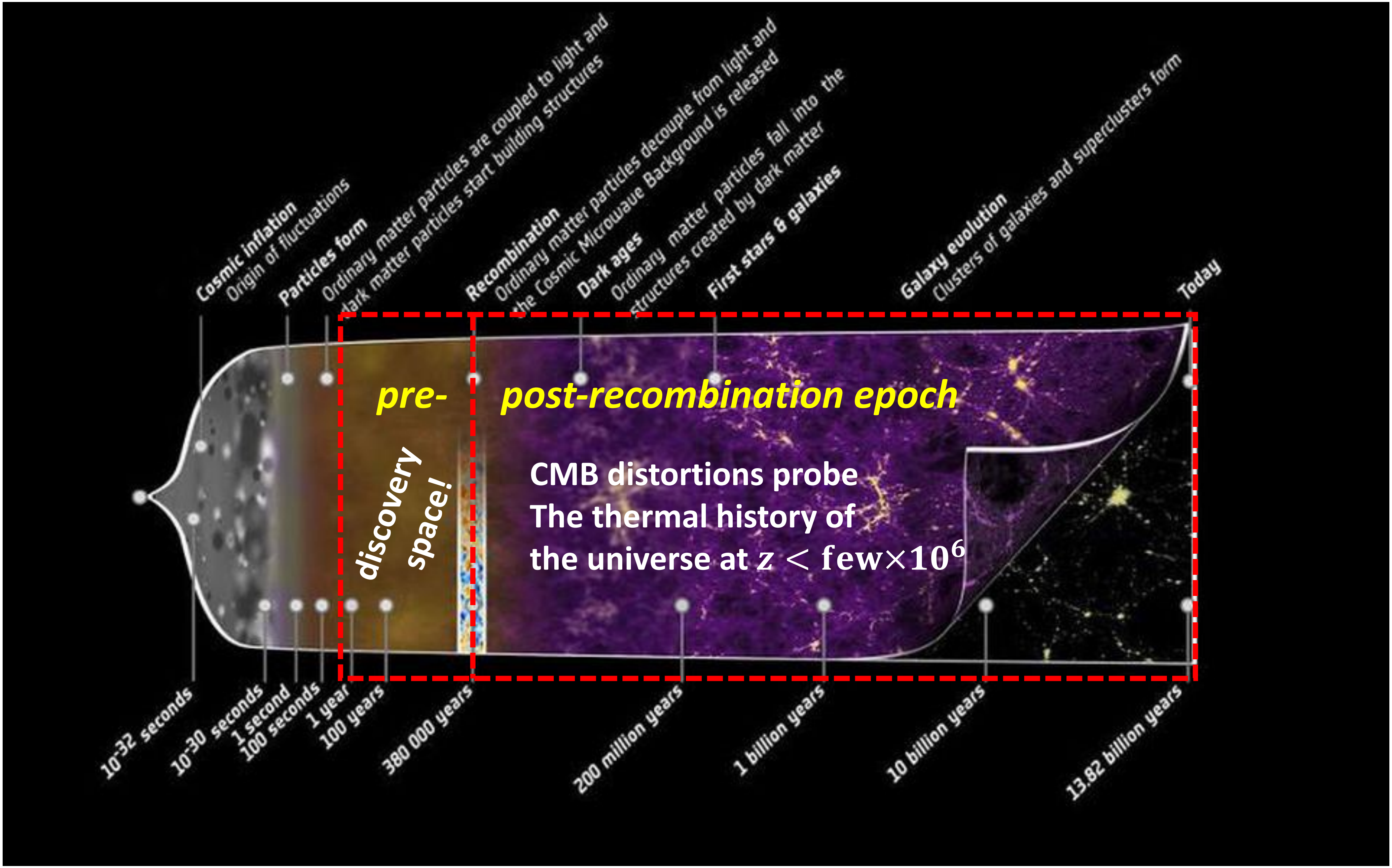

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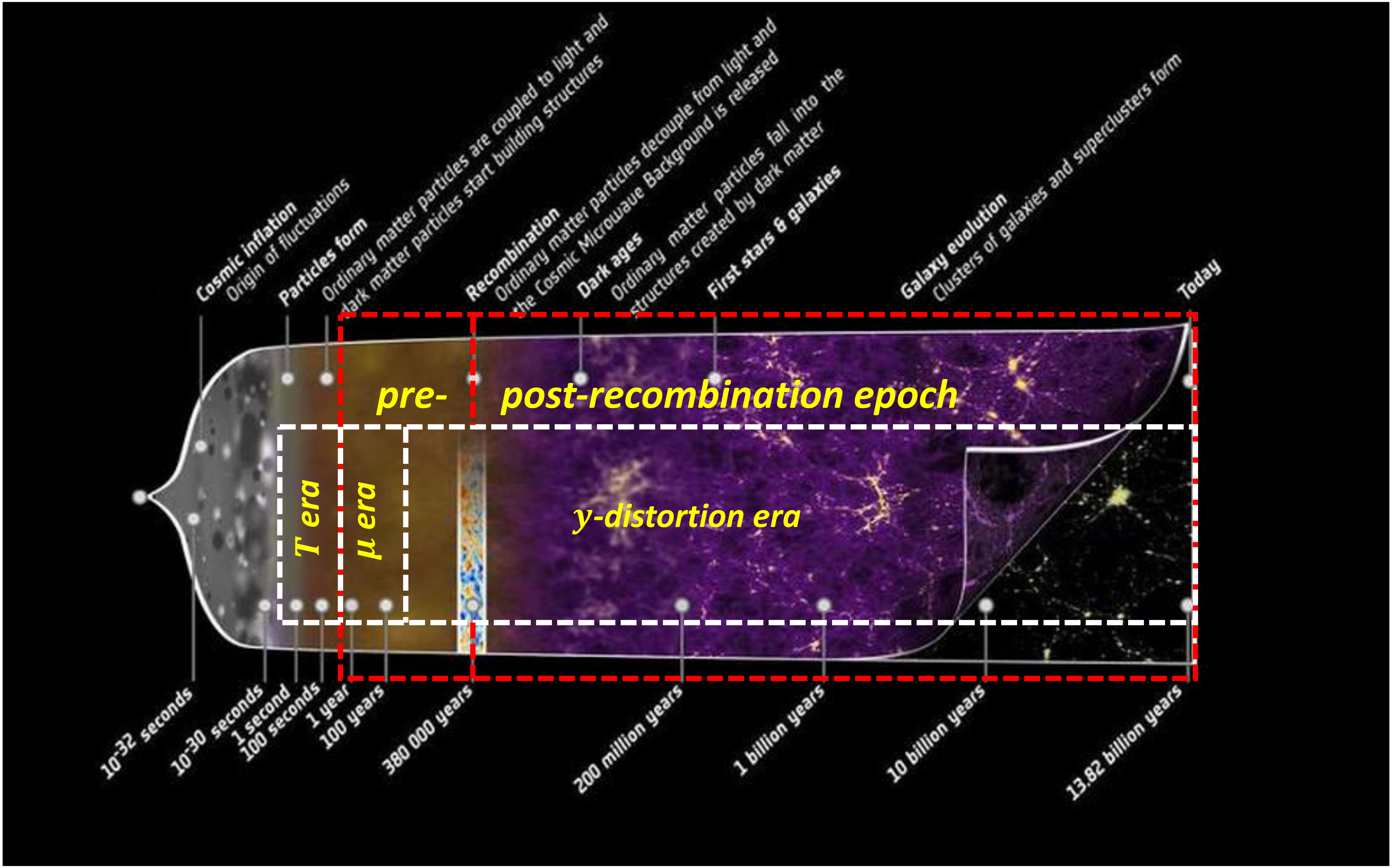

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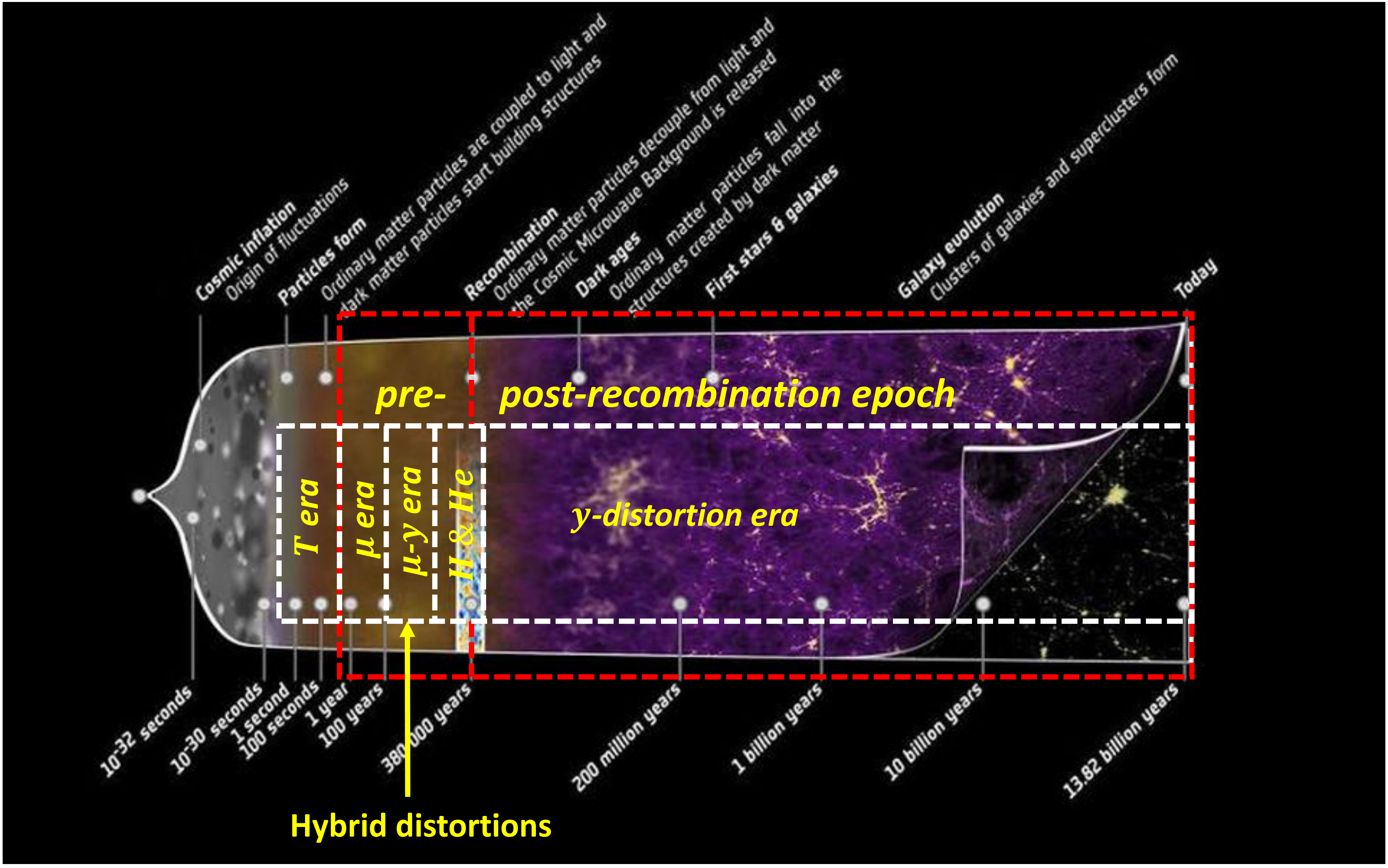


Boltzmann equation for the photons

$$\frac{dn_\nu}{dt} \equiv \frac{\partial n_\nu}{\partial t} + \frac{\partial n_\nu}{\partial x_i}\frac{dx_i}{dt} + \frac{\partial n_\nu}{\partial E}\frac{dE}{dt} + \frac{\partial n_\nu}{\partial p_i}\frac{dp_i}{dt} = \mathcal{C}[n]$$

$n_\nu(x^\mu, p^\mu)$: *photon occupation number*
$p^\mu = \left(\frac{E}{c}, p^i\right)$: *four-momentum*
$E = h\nu$: *photon energy*

- Isotropy & Homogeneity:

$$\Longrightarrow \boxed{\frac{\partial n_\nu}{\partial t} - H\nu\frac{\partial n_\nu}{\partial \nu} = \mathcal{C}[n]}$$

- Collision term (interaction with matter):

$$\mathcal{C}[n] = \left.\frac{dn_\nu}{dt}\right|_{CS} + \left.\frac{dn_\nu}{dt}\right|_{BR} + \left.\frac{dn_\nu}{dt}\right|_{DCS} + \left.\frac{dn_\nu}{dt}\right|_{S}$$

$\left.\frac{dn_\nu}{dt}\right|_{S}$ → **Other sources,** e.g. decaying particles

Compton scattering $e + \gamma \rightarrow e' + \gamma'$

Bremsstrahlung $e + p \rightarrow e' + p + \gamma$

Double Compton scattering $e + \gamma \rightarrow e' + \gamma' + \gamma''$

- Full thermal equilibrium: $\mathcal{C}[n] \equiv 0 \Longrightarrow$ blackbody conserved

- Energy release: $\mathcal{C}[n] \neq 0 \Longrightarrow$ spectral distortions

Thermal history of energy release

- **At redshifts $z > 2\times10^6$ → full thermal equilibrium**
  - ✓ *Compton scattering*, *Double Compton scattering*, and *Bremsstrahlung* are "efficient"
  - ✓ *Compton scattering* redistribute the energy of photon across frequencies
  - ✓ But *Double Compton scattering* and *Bremsstrahlung* create photons, thus restoring the **blackbody spectrum** and Planck's thermal equilibrium
- **At redshifts $5\times10^4 < z < 2\times10^6$ → spectral distortions**
  - ✓ *Double Compton scattering* and *Bremsstrahlung* become "inefficient", thus preventing to create photons to maintain full thermal equilibrium
  - ✓ Compton scattering is very "efficient" $\Longrightarrow$ **μ-distortion**
- **At redshifts $z < 5\times10^4$ → spectral distortions**
  - ✓ Compton scattering becomes "inefficient" $\Longrightarrow$ **y-distortion**

Compton scattering: $e + \gamma \rightarrow e' + \gamma'$

Kompaneets equation

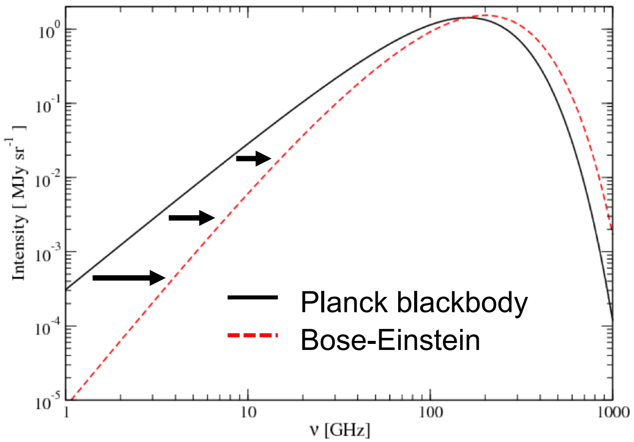
$$\left.\frac{dn}{dt}\right|_{CS} = \sigma_T n_e c \frac{kT_e}{m_e c^2} \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left[\frac{\partial n}{\partial x} + \frac{T_\gamma}{T_e} n(1+n)\right] \qquad x \equiv \frac{h\nu}{kT_\gamma}$$

$2\times10^6 > z > 5\times10^4$: "efficient" scattering $\Longrightarrow$ kinetic equilibrium

$$\frac{dn}{dt} \simeq 0 \Longrightarrow \frac{\partial n_\nu}{\partial x} \simeq -\frac{T_\gamma}{T_e} n\_(1+n)$$

$\Longrightarrow$ Bose-Einstein solution: ***μ*-type distortion**

$$n_{\rm BE}(x) \simeq n_{\rm Pl}(x) + \mu \frac{x e^x}{(e^x - 1)^2} \left[\frac{\pi^2}{18\zeta(3)} - \frac{1}{x}\right]$$



Compton scattering: $e + \gamma \to e' + \gamma'$

Kompaneets equation

$$\left.\frac{dn}{dt}\right|_{CS} = \sigma_T n_e c \frac{kT_e}{m_e c^2} \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left[\frac{\partial n}{\partial x} + \frac{T_\gamma}{T_e} n(1+n)\right] \qquad x \equiv \frac{h\nu}{kT_\gamma}$$

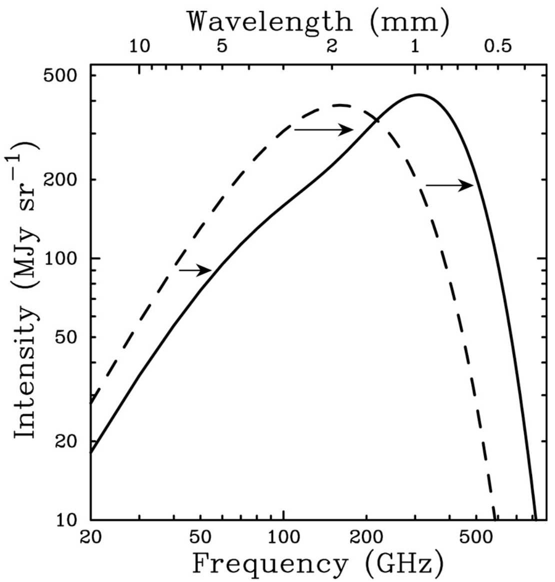
$5\times10^4 > z > 0$: "inefficient" scattering

$$T_e \gg T_\gamma \Longrightarrow \frac{dn}{dt} \simeq \sigma_T n_e c \frac{kT_e}{m_e c^2} \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \frac{\partial n}{\partial x}$$

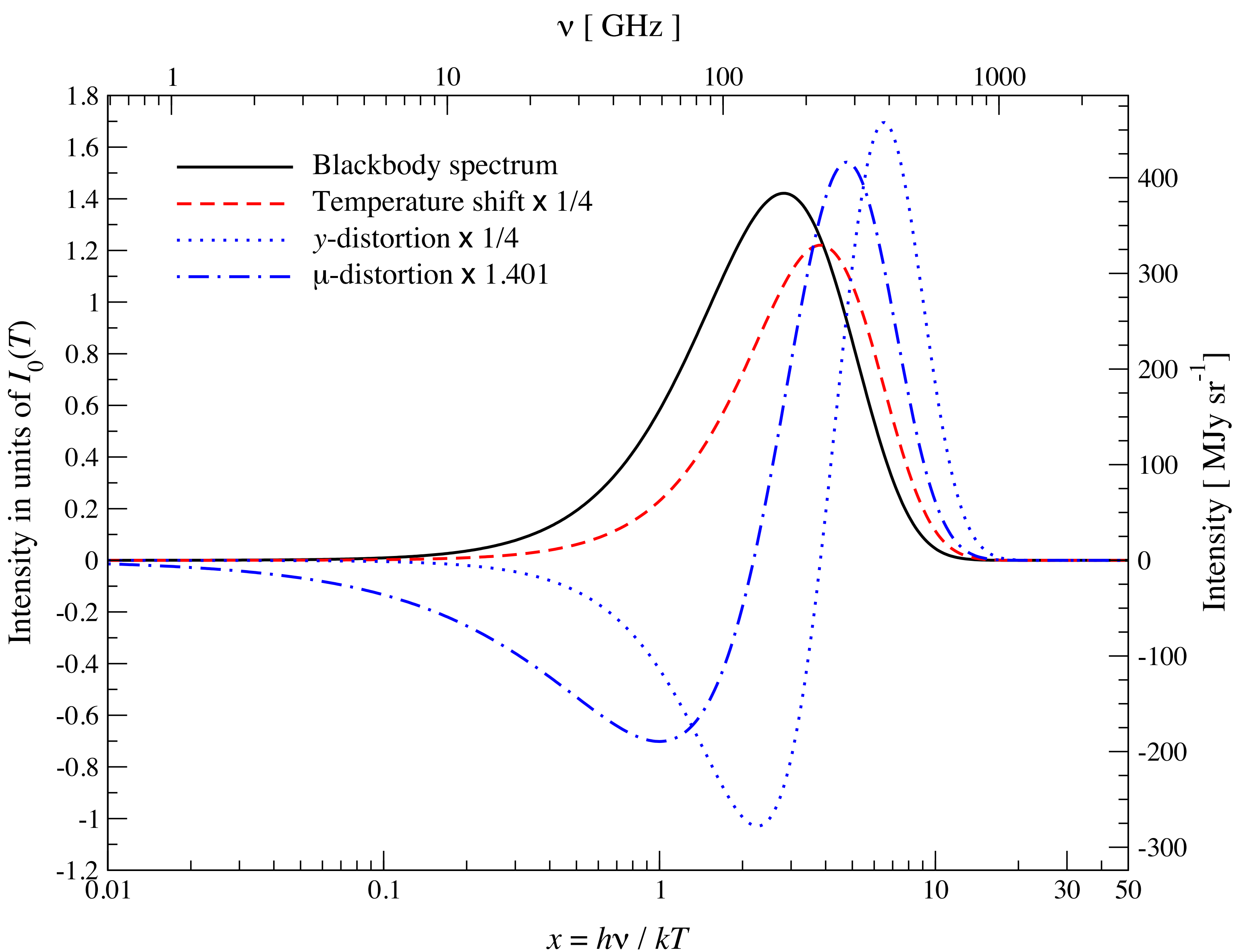
$\Longrightarrow$ ***y*-type distortion** (including thermal SZ effect)

$$n(x) \simeq n_{\rm Pl}(x) + y \frac{x e^x}{(e^x - 1)^2}\left[x \coth\frac{x}{2} - 4\right]$$

$$y = \int \frac{kT_e}{m_e c^2} \sigma_T n_e c dt$$

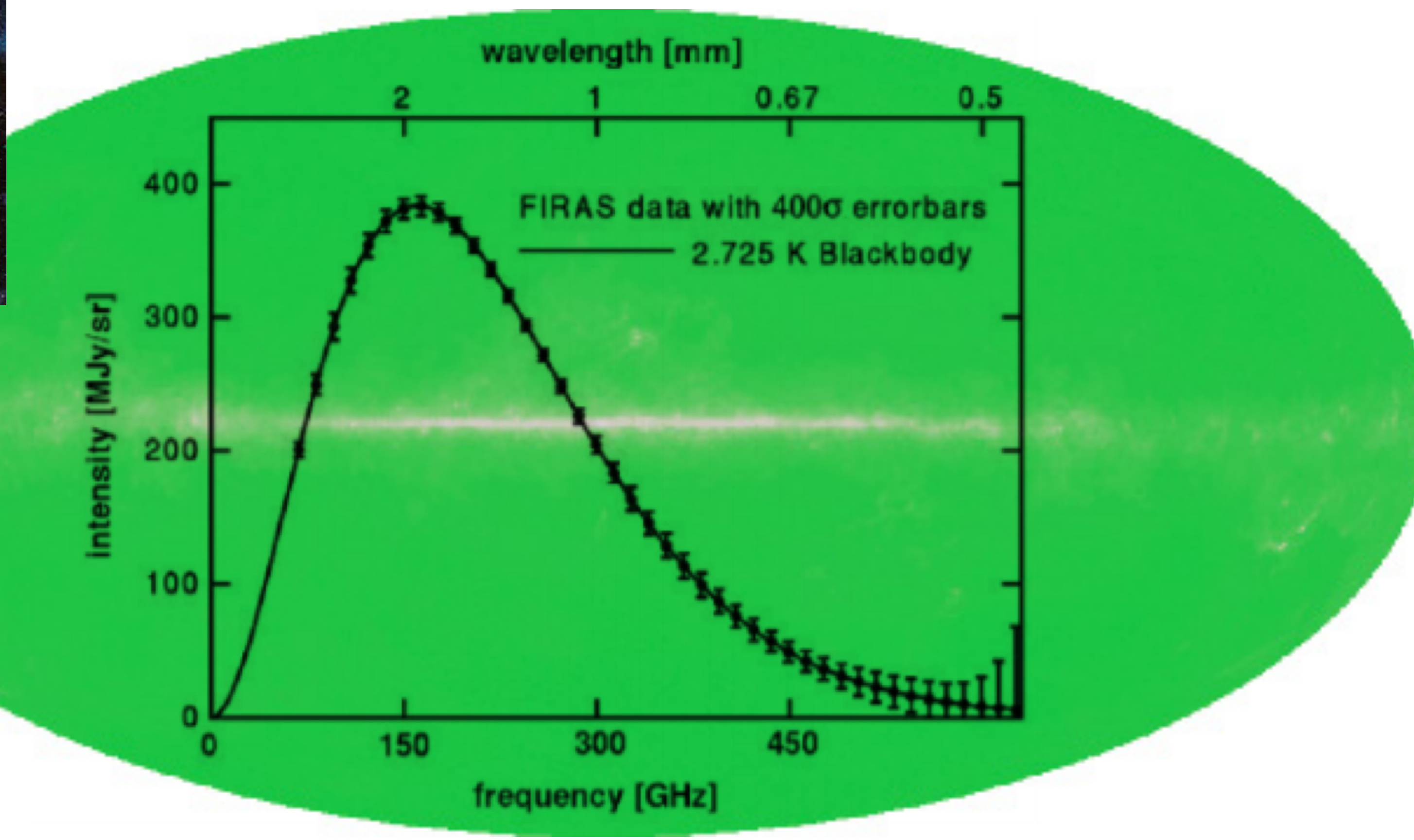


Typical distortions of the CMB spectrum after energy release by Compton scattering



Constraints from COBE/FIRAS (~ 90s)

(**F**ar **I**nfra**R**ed **A**bsolute **S**pectrophotometer)



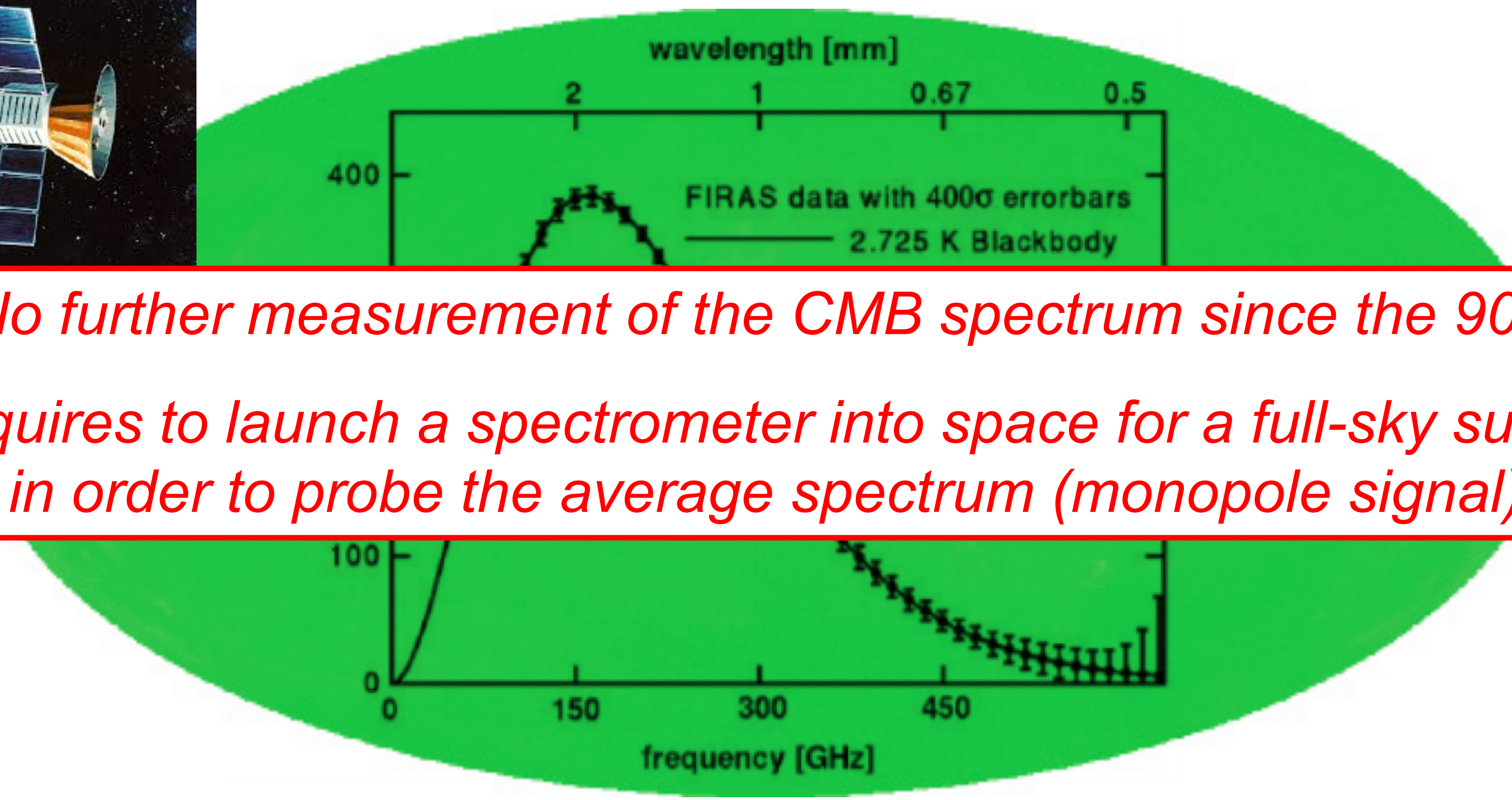
Mather et al, ApJ (1994)
Fixsen et al, ApJ (1996)
Fixsen et al, ApJ (2003)

- $T_{CMB} = 2.725 \pm 0.001$ K
- $|y| \leq 1.5\times10^{-5}$
- $|\mu| \leq 9\times10^{-5}$

Only tiny distortions of the CMB spectrum are still allowed (very faint signal!)

Constraints from COBE/FIRAS (~ 90s)

(**F**ar **I**nfra**R**ed **A**bsolute **S**pectrophotometer)



No further measurement of the CMB spectrum since the 90s!

Requires to launch a spectrometer into space for a full-sky survey in order to probe the average spectrum (monopole signal)

Mather et al, ApJ (1994)
Fixsen et al, ApJ (1996)
Fixsen et al, ApJ (2003)

- $T_{CMB} = 2.725 \pm 0.001$ K
- $|y| \leq 1.5 \times 10^{-5}$
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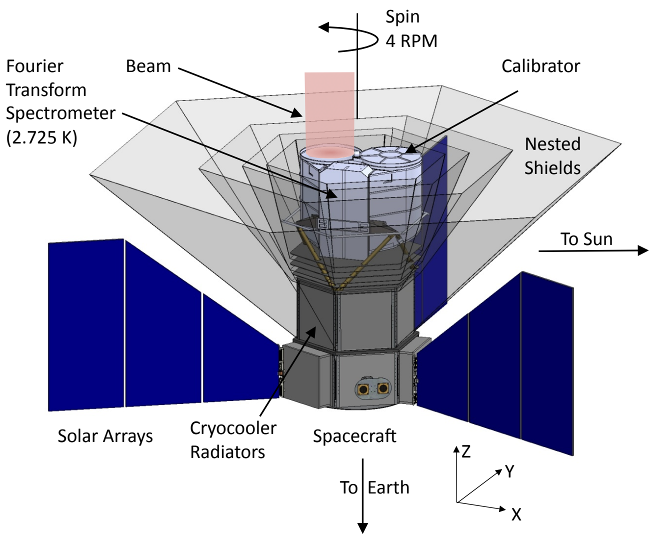
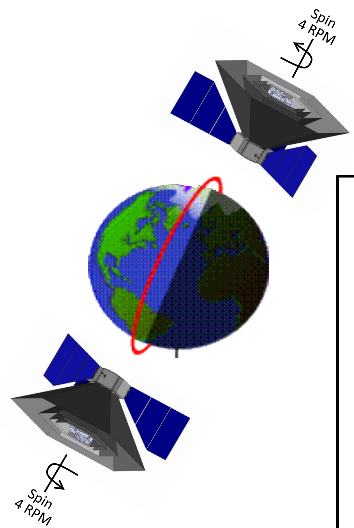
Only tiny distortions of the CMB spectrum are still allowed (very faint signal!)

PIXIE: Primordial Inflation Explorer

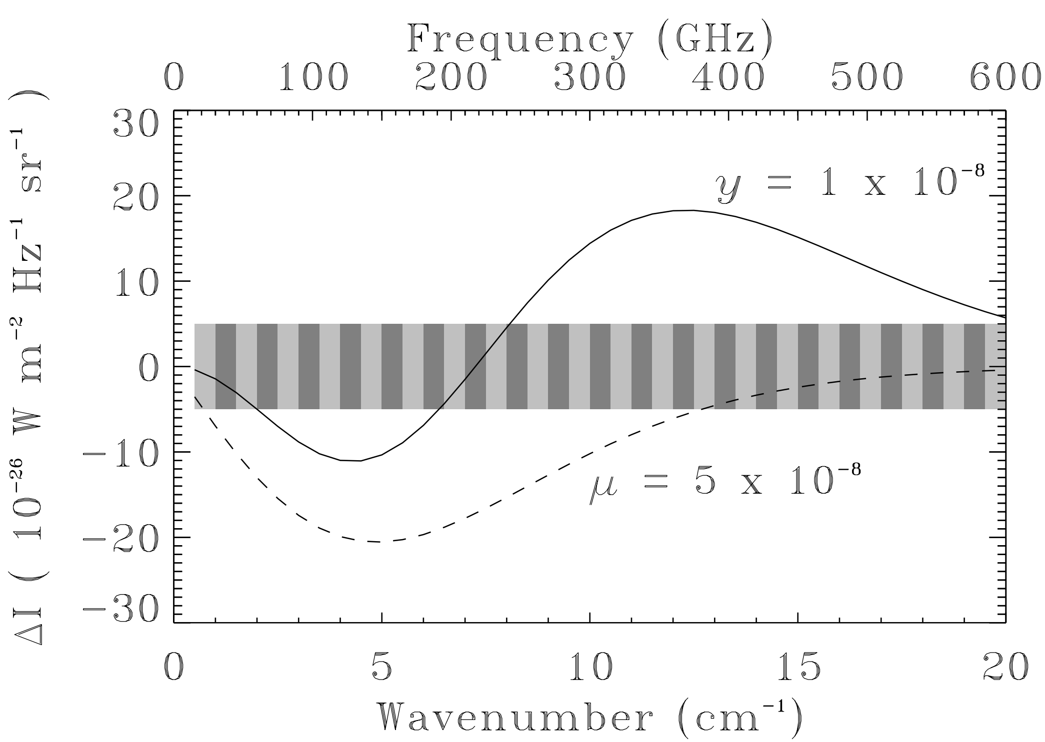




- ✓ 1000 times more sensitive than COBE/FIRAS
- ✓ 400 spectral bands between 30 GHz and 6000 GHz !
- ✓ Expected new limits on μ and y:

$$\mu \lesssim 5\times10^{-8}$$
$$y \leq 1\times10^{-8}$$

- ✓ Proposed to NASA in 2011 and 2016, but rejected



Kogut et al, JCAP 2011

Most recent activities

Astro2020 Science White Paper

Spectral Distortions of the CMB as a Probe of Inflation, Recombination, Structure Formation and Particle Physics

Primary thematic area: Cosmology and Fundamental Physics
Secondary thematic area: Galaxy Evolution
Corresponding author email: Jens.Chluba@Manchester.ac.uk

J. Chluba[1], A. Kogut[2], S. P. Patil[3], M. H. Abitbol[4], N. Aghanim[5], Y. Ali-Haïmoud[6], M. A. Amin[7], J. Aumont[8], N. Bartolo[9,10,11], K. Basu[12], E. S. Battistelli[13], R. Battye[1], D. Baumann[14], I. Ben-Dayan[15], B. Bolliet[1], J. R. Bond[16], F. R. Bouchet[17], C. P. Burgess[18,19], C. Burigana[20,21,22], C. T. Byrnes[23], G. Cabass[24], D. T. Chuss[25], S. Clesse[26,27], P. S. Cole[23], L. Dai[28], P. de Bernardis[13,29], J. Delabrouille[30,31], V. Desjacques[32], G. de Zotti[11], J. A. D. Diacoumis[33], E. Dimastrogiovanni[34,35], E. Di Valentino[1], J. Dunkley[36], R. Durrer[37], C. Dvorkin[38], J. Ellis[39], H. K. Eriksen[40], M. Fasiello[41], D. Fixsen[42], F. Finelli[43], R. Flauger[44], S. Galli[45], J. Garcia-Bellido[46], M. Gervasi[47], V. Gluscevic[36,48], D. Grin[49], L. Hart[1], C. Hernández-Monteagudo[50], J. C. Hill[28,51], D. Jeong[52,53], B. R. Johnson[54], G. Lagache[55], E. Lee[1], A. Lewis[23], M. Liguori[9,10,11], M. Kamionkowski[57], R. Khatri[58], K. Kohri[59], E. Komatsu[24], K. E. Kunze[59], A. Mangilli[60], S. Masi[13,29], J. Mather[2], S. Matarrese[9,10,11,61], M. A. Miville-Deschênes[62], T. Montaruli[63], M. Münchmeyer[19], S. Mukherjee[45,64], T. Nakama[65], F. Nati[47], A. Ota[66], L. A. Page[36], E. Pajer[67], V. Poulin[56,68], A. Ravenni[1], C. Reichardt[69], M. Remazeilles[1], A. Rotti[1], J. A. Rubiño-Martin[70,71], A. Sarkar[1], S. Sarkar[72], G. Savini[73], D. Scott[74], P. D. Serpico[75], J. Silk[56,76], T. Souradeep[77], D. N. Spergel[51,78], A. A. Starobinsky[79], R. Subrahmanyan[80], R. A. Sunyaev[24], E. Switzer[2], A. Tartari[81], H. Tashiro[82], R. Basu Thakur[83], T. Trombetti[20], B. Wallisch[28,44], B. D. Wandelt[45], I. K. Wehus[40], E.J. Wollack[2], M. Zaldarriaga[28], M. Zannoni[47]

PRISTINE

F-class spectrometer satellite proposed to ESA

PI: Nabila Aghanim

BISOU

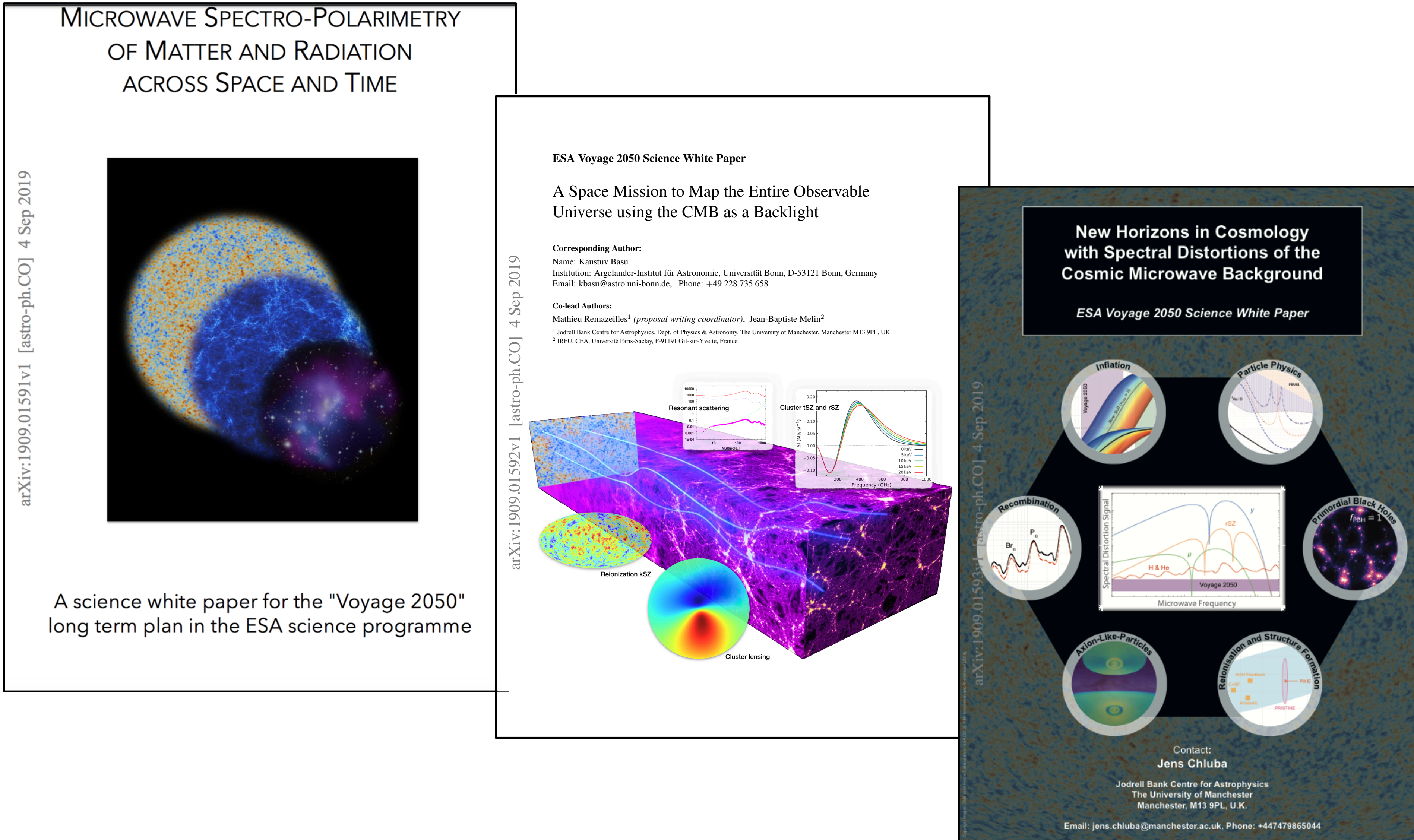
a Balloon Interferometer for Spectral Observations of the primordial Universe

PI: Bruno Maffei

VOYAGE 2050
LONG-TERM PLANNING OF THE ESA SCIENCE PROGRAMME

Activity	Date
Senior Committee appointed	December 2018
Call for Membership of Topical Teams issued	4 March 2019
Call for White Papers issued	4 March 2019
Deadline for receipt of applications for Topical Team membership	6 May 2019, 12:00 (noon) CEST
Topical Team members appointed	July 2019
Deadline for receipt of White Papers	5 August 2019, 12:00 (noon) CEST
Workshop to present White Papers	29 - 31 October 2019
Topical Teams report to Senior Committee	February 2020
Senior Committee recommendations to Director of Science	Mid-2020

ESA Voyage 2050 White Papers



https://arxiv.org/abs/1909.01591
https://arxiv.org/abs/1909.01592
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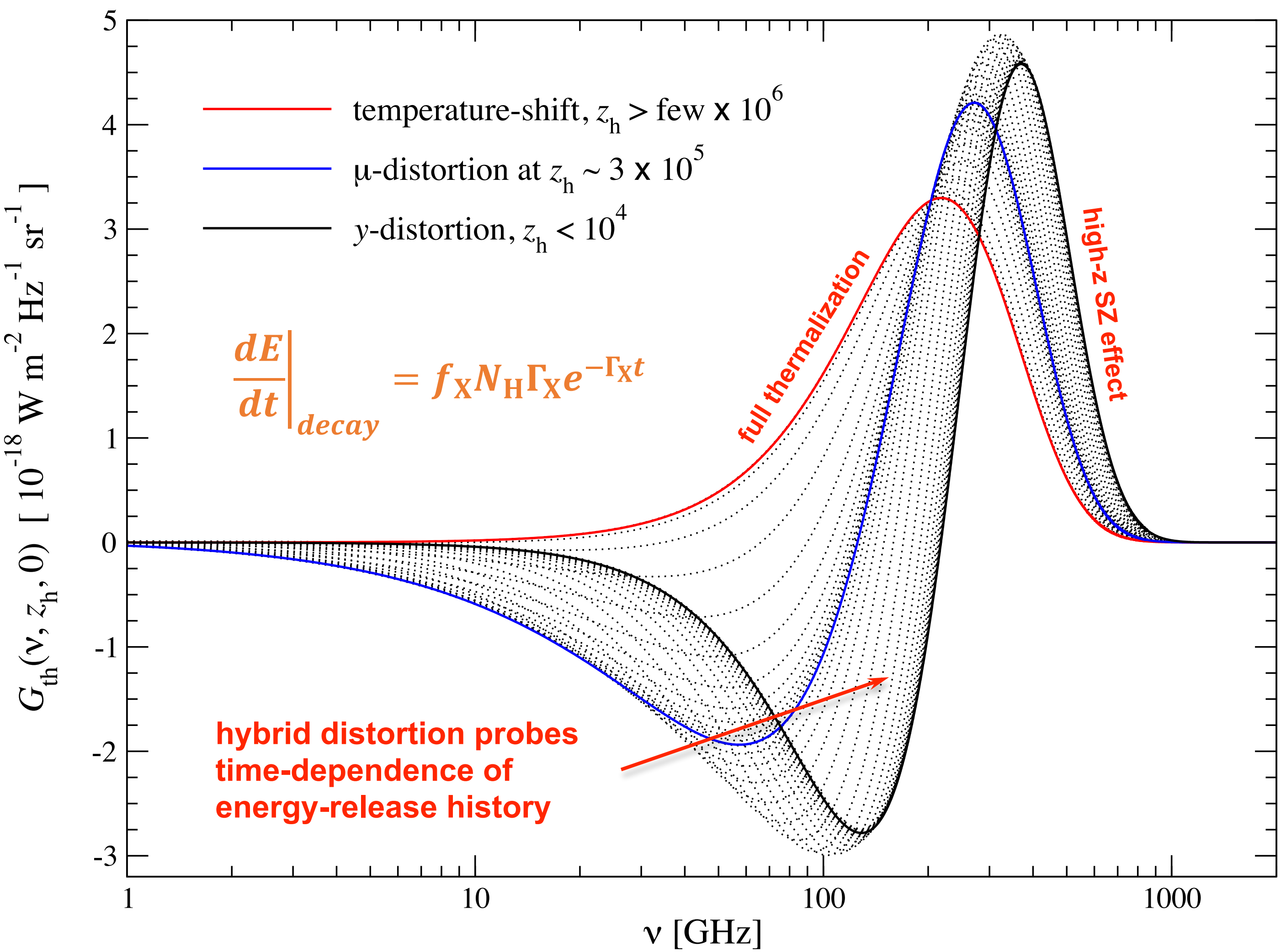
Hybrid spectral distortions from particle decay

Intensity signal for different heating redshifts

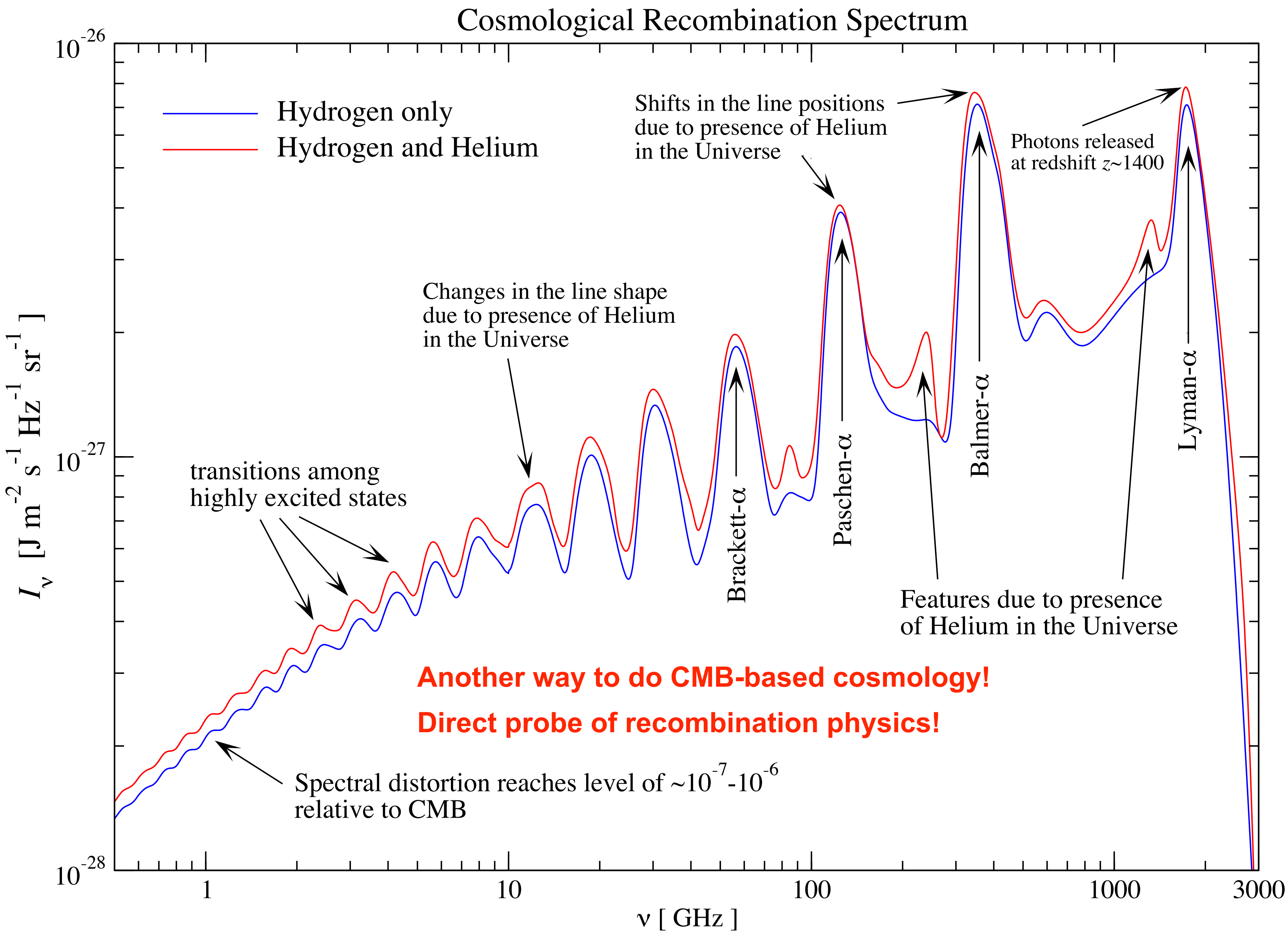


The intermediate shape of hybrid spectral distortions at redshifts $3\times10^5 > z_X > 10^4$ would allow to constrain the lifetime $t_X = \Gamma_X^{-1}$ of decaying relic particles!

Chluba & Jeong, MNRAS 2014

Other distortions: H & He recombination lines

$(10^4 > z > 10^3)$



Rubino-Martin et al, MNRAS (2006)

Sunyaev & Chluba, Astron. Nachr. (2009)

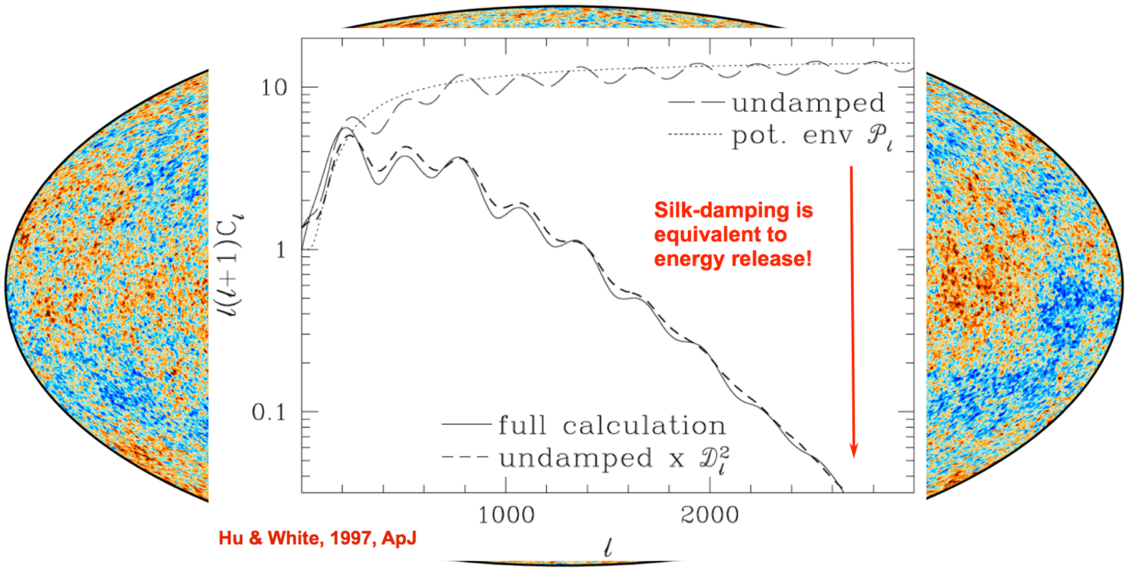
Spectral distortions from the dissipation of small-scale acoustic modes

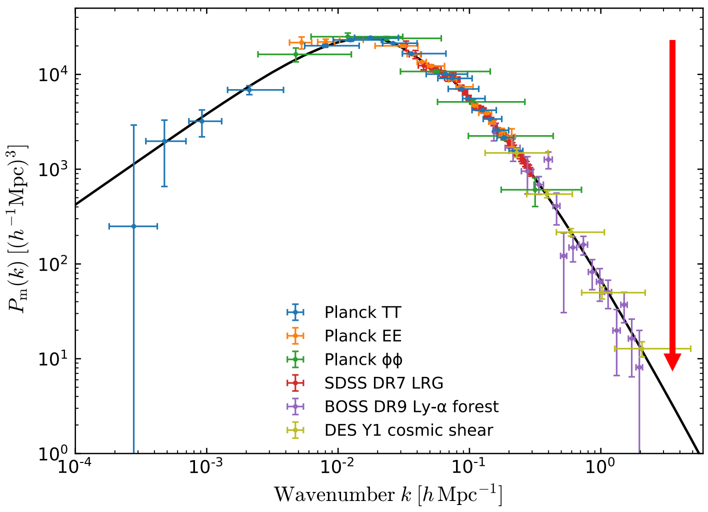
<u>Silk damping</u>: dissipation of small-scale acoustic modes

Caused by photons random-walking out of overdense/hot regions towards underdense/cold regions, thus uniformizing the temperature and density of small-scale regions foremost

⇒ Mixing of blackbodies with different temperatures

⇒ y- and μ-distortions to the average CMB spectrum

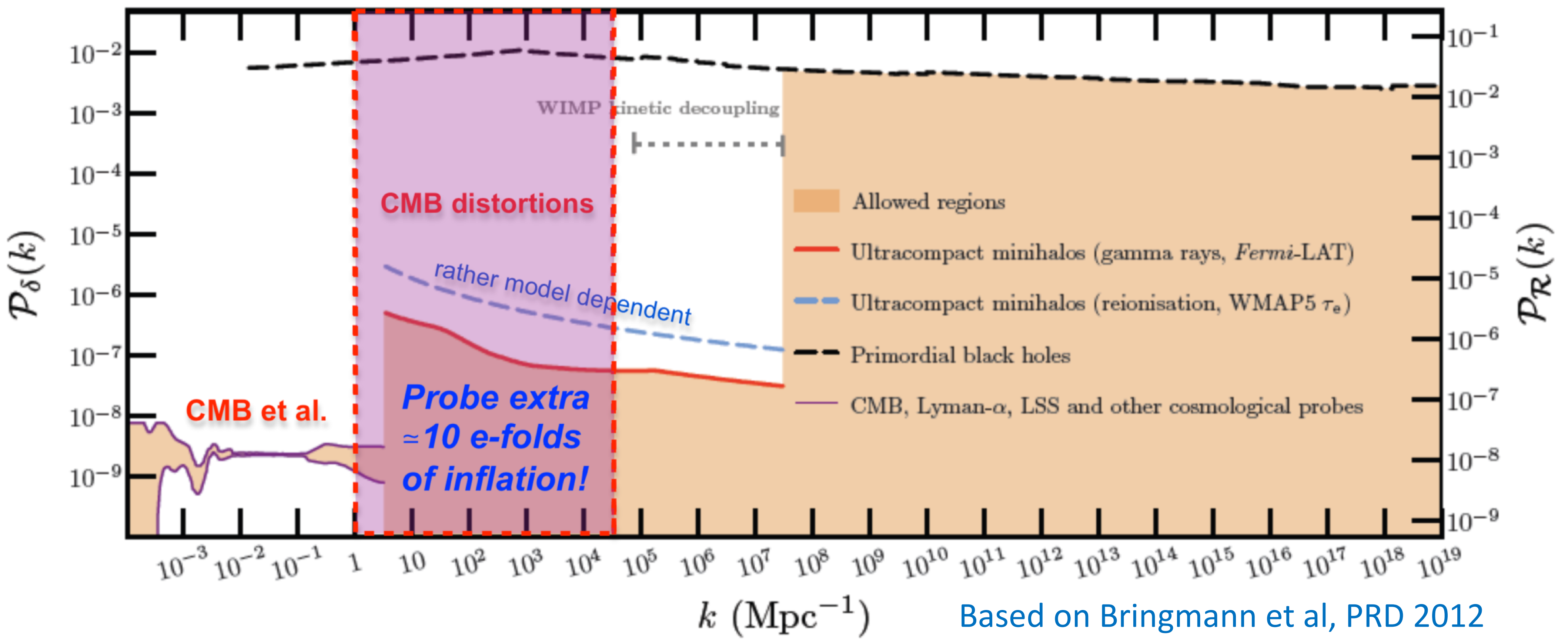




Small-scale modes $k > 3\ \mathrm{Mpc}^{-1}$ are inaccessible to CMB anisotropies and LSS !

But they are imprinted in CMB spectral distortions !

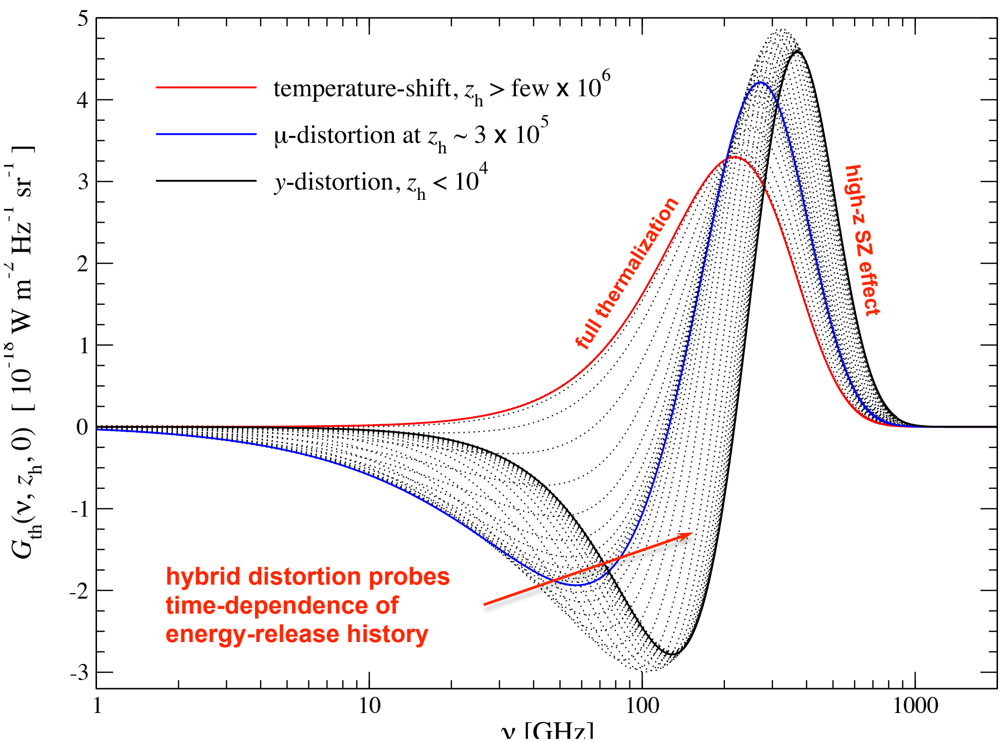
Distortions probe the primordial power spectrum at very small scales

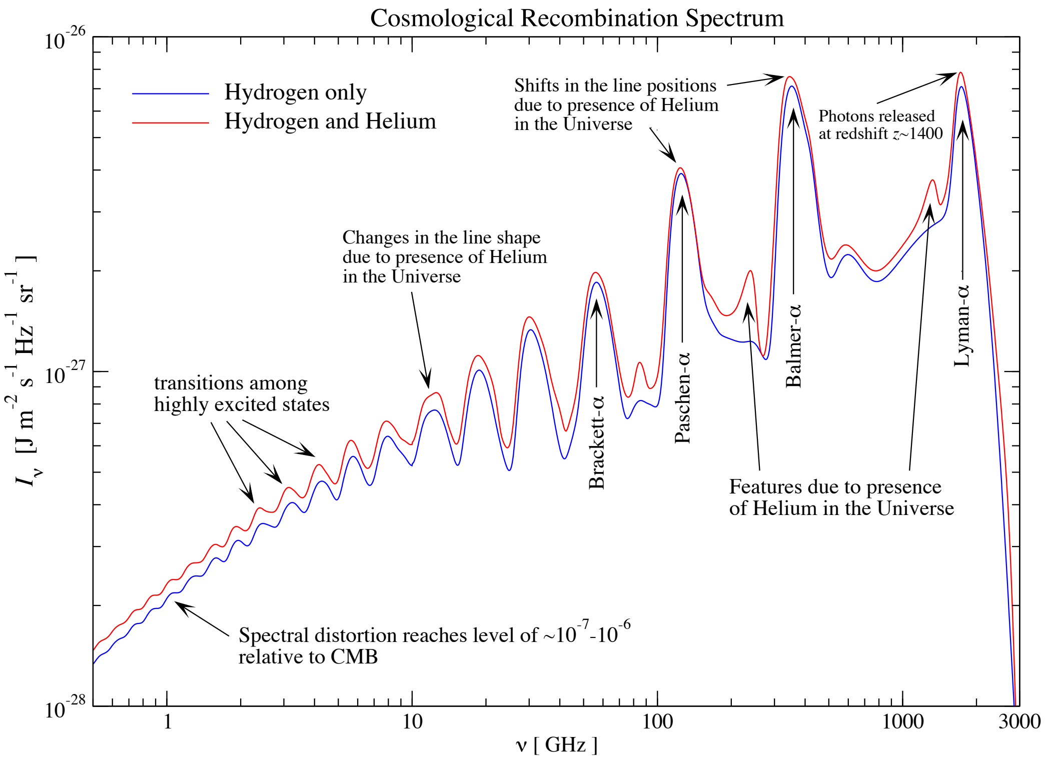


Based on Bringmann et al, PRD 2012

- ✓ Amplitude of power spectrum rather uncertain at $k > 3\ \mathrm{Mpc}^{-1}$
- ✓ CMB spectral distortions would extend our lever arm up to $k > 10^4\ \mathrm{Mpc}^{-1}$
- ✓ Improved limits at smaller scales can rule out many inflation models

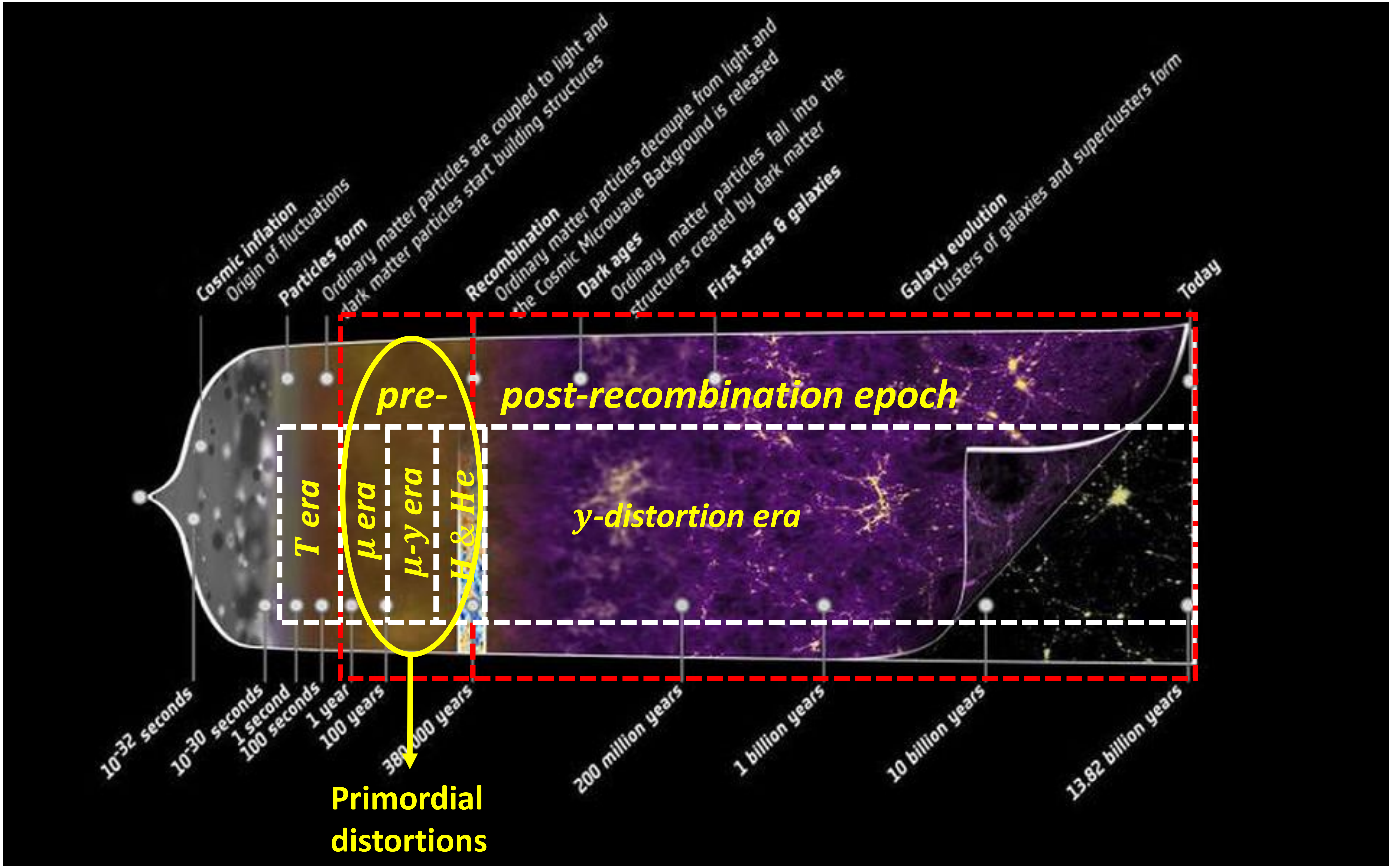
CMB blackbody distortions



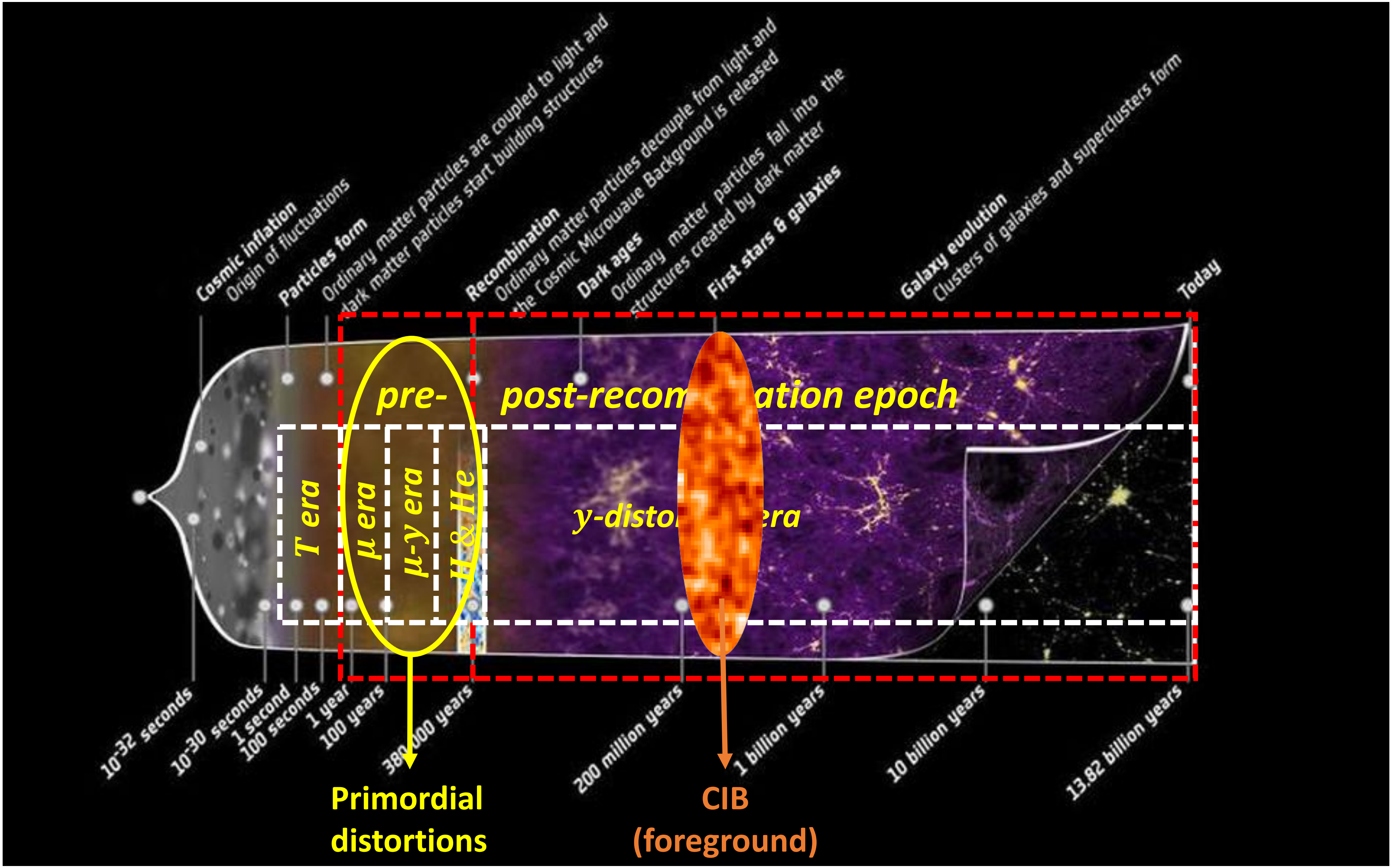


Scrutinizing the CMB energy spectrum through spectral distortions is the promise of new advances in cosmology !

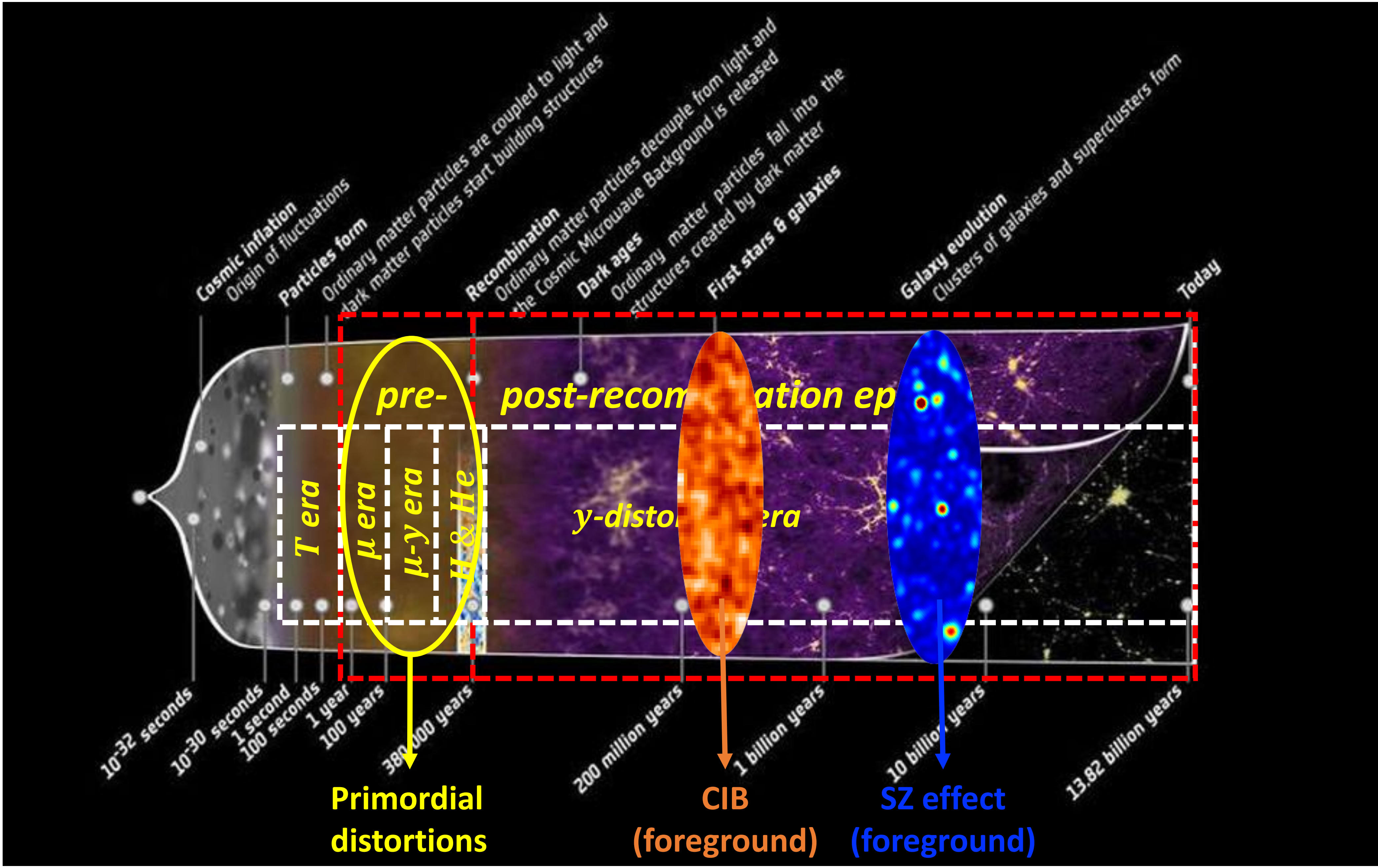
Foregrounds obscure spectral distortions



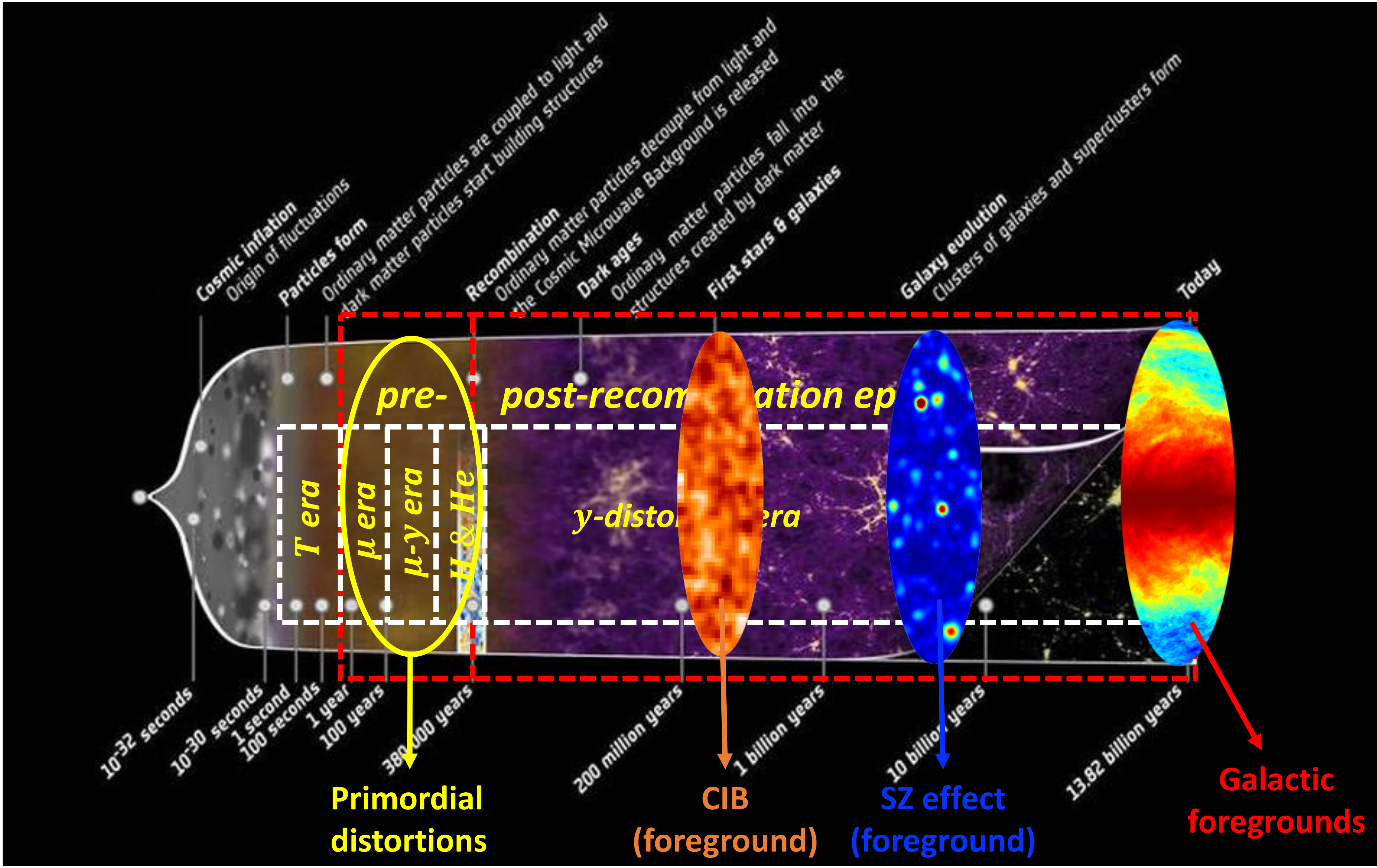
Foregrounds obscure spectral distortions



Foregrounds obscure spectral distortions

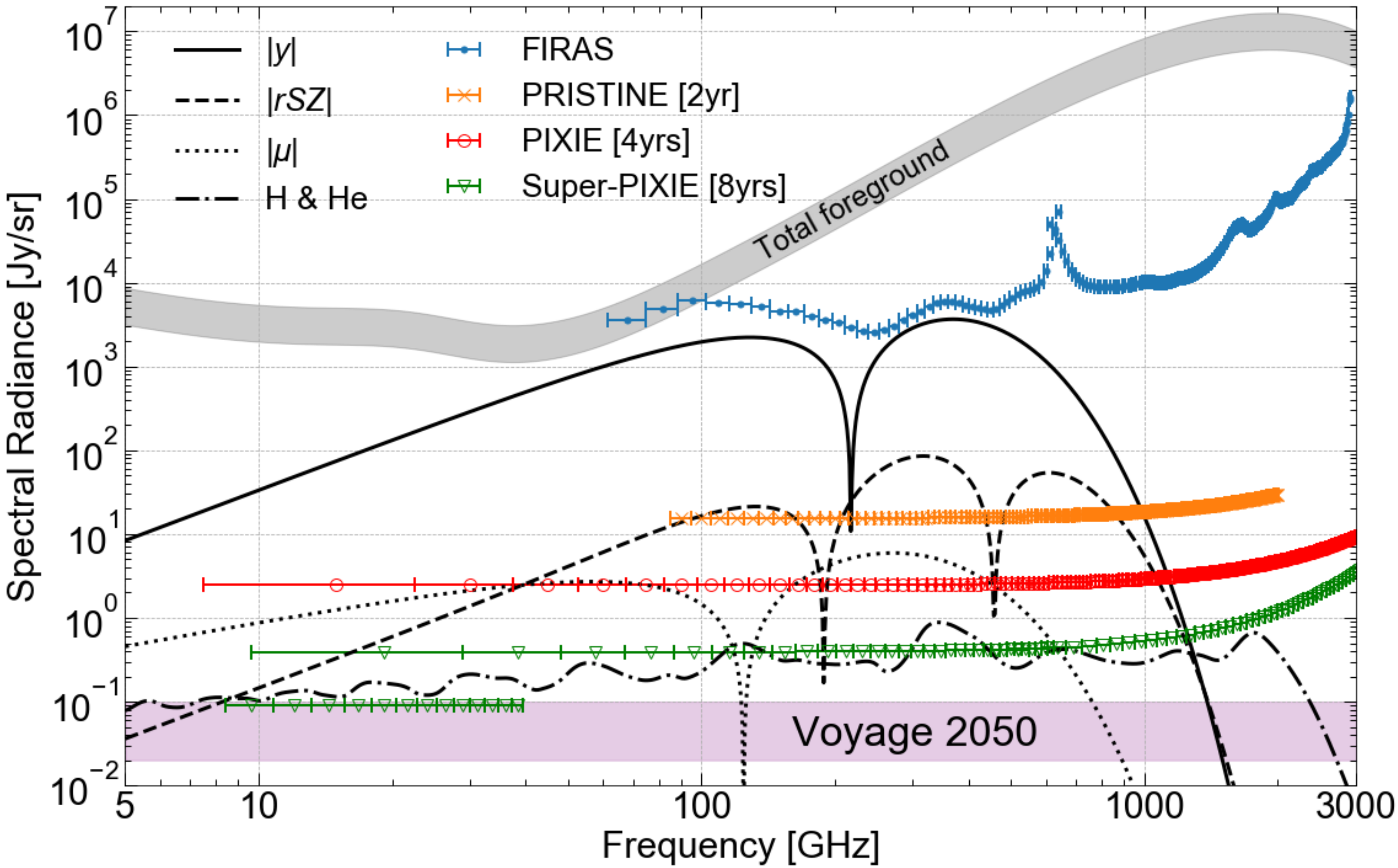


Foregrounds obscure spectral distortions



Spectral distortions versus Foregrounds

Chluba et al, arXiv:1909.01593



Subtracting huge foregrounds to unveil tiny CMB spectral distortions is extremely challenging!

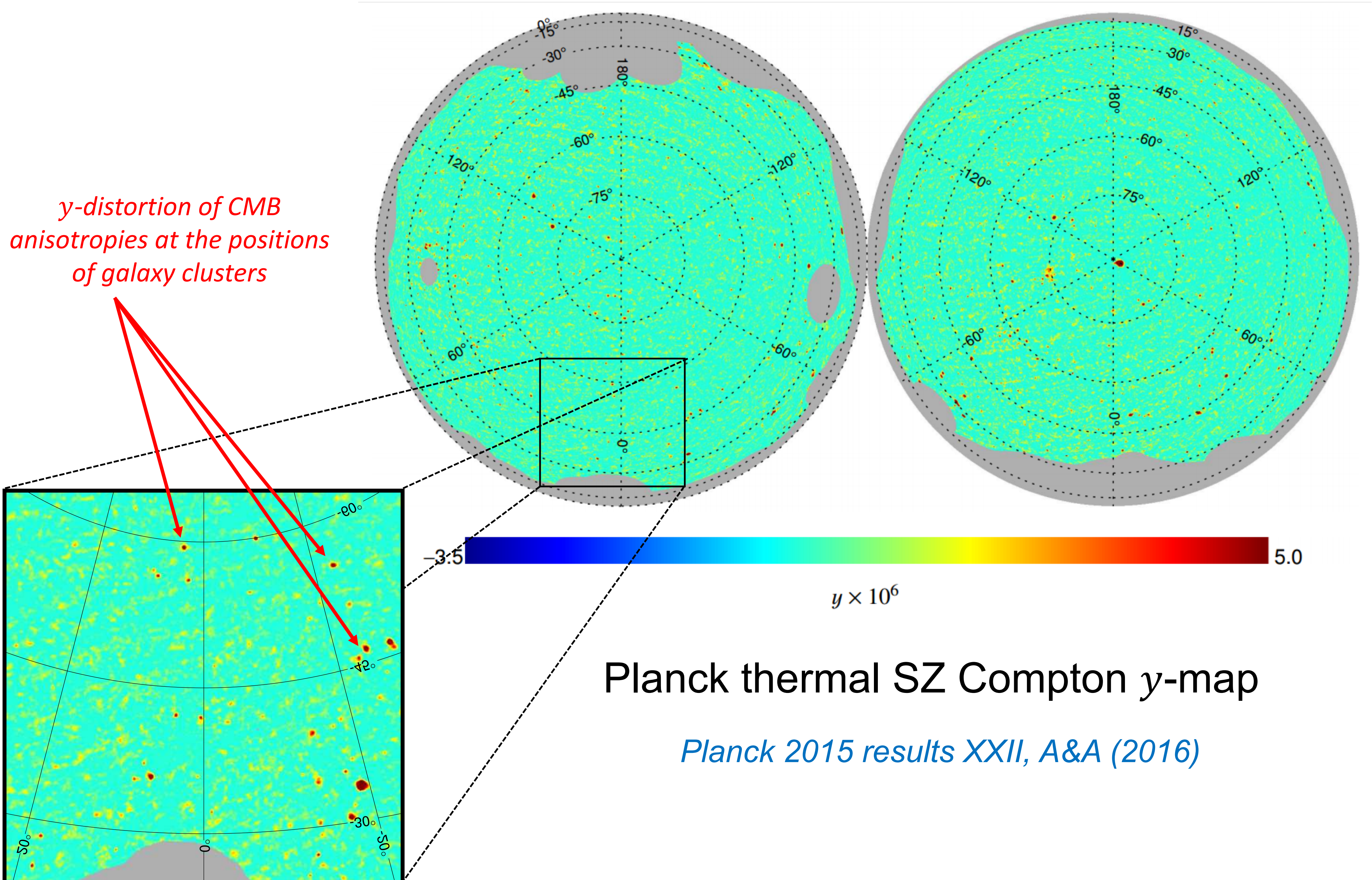
Spectral distortion anisotropies
(my recent work)

- ✓ Aside from average CMB spectral distortions, **anisotropic spectral distortions** (a.k.a. spatial-spectral distortions) arise from anisotropic heating mechanisms

- ✓ **y-distortion anisotropies** (thermal SZ effect) due to hot gas of electrons in galaxy clusters that scatter CMB photons

- ✓ **μ-distortion anisotropies?** due to anisotropic heating through the dissipation of small-scale acoustic modes if primordial perturbations are non-Gaussian (modes coupling)

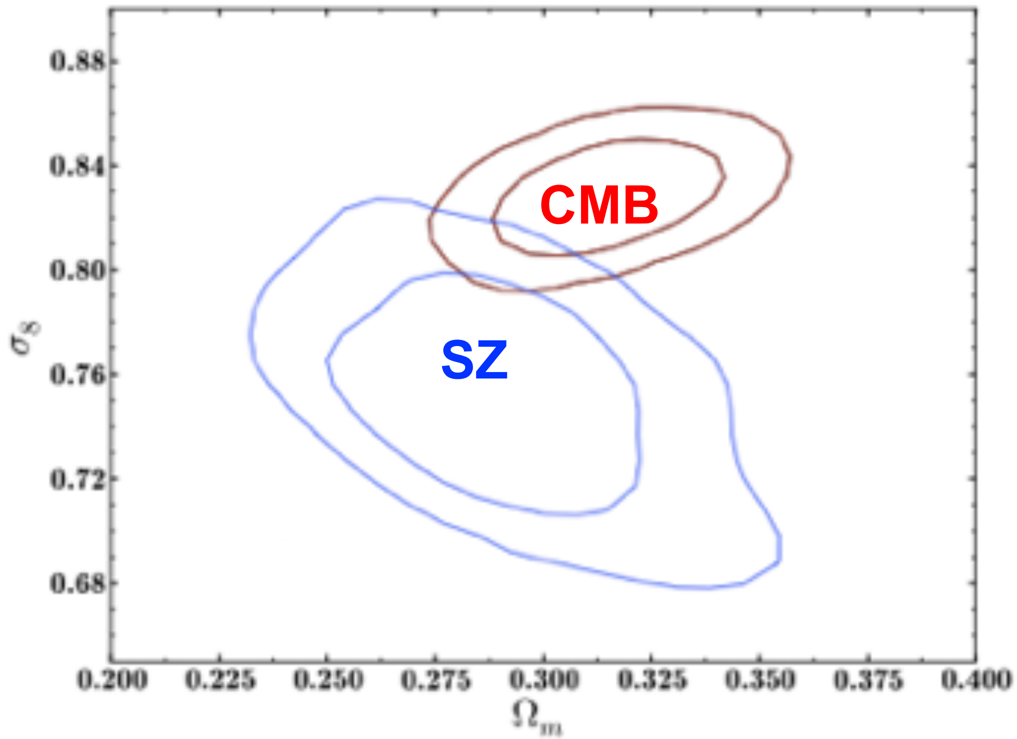
y-distortion anisotropies: thermal SZ effect



Planck thermal SZ Compton y-map

Planck 2015 results XXII, A&A (2016)

Planck tension on σ_8 between CMB and SZ



$\sigma_8 \simeq 0.82 \pm 0.02$

Planck 2013 results XVI

$\sigma_8 \simeq 0.77 \pm 0.02$

Planck 2013 results XX
Planck 2015 results XXII

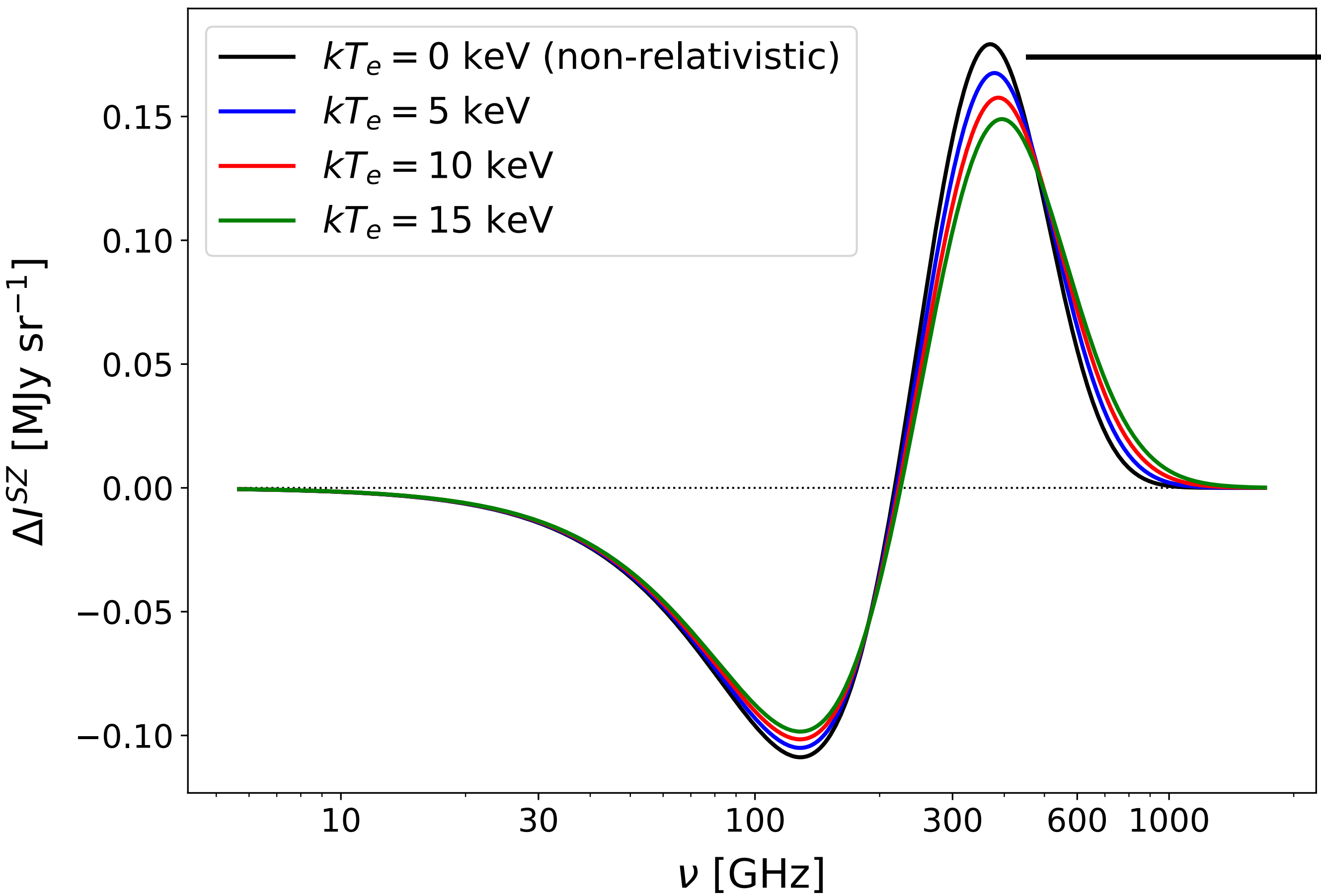
- Incompleteness of ΛCDM model?
  Evidence for massive neutrinos?

- Incorrect "mass-bias" between SZ gas and dark matter?
  Hydrodynamical simulations predict: $M_{\rm gas} \;/\; M_{\rm dark\,matter} = (1-b) = 0.8$

- **Miscalibrated SZ analysis by neglecting relativistic SZ corrections?**
  Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)

Relativistic SZ effect (rSZ)

$$I^{SZ}(\nu,\vec{n}) = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$

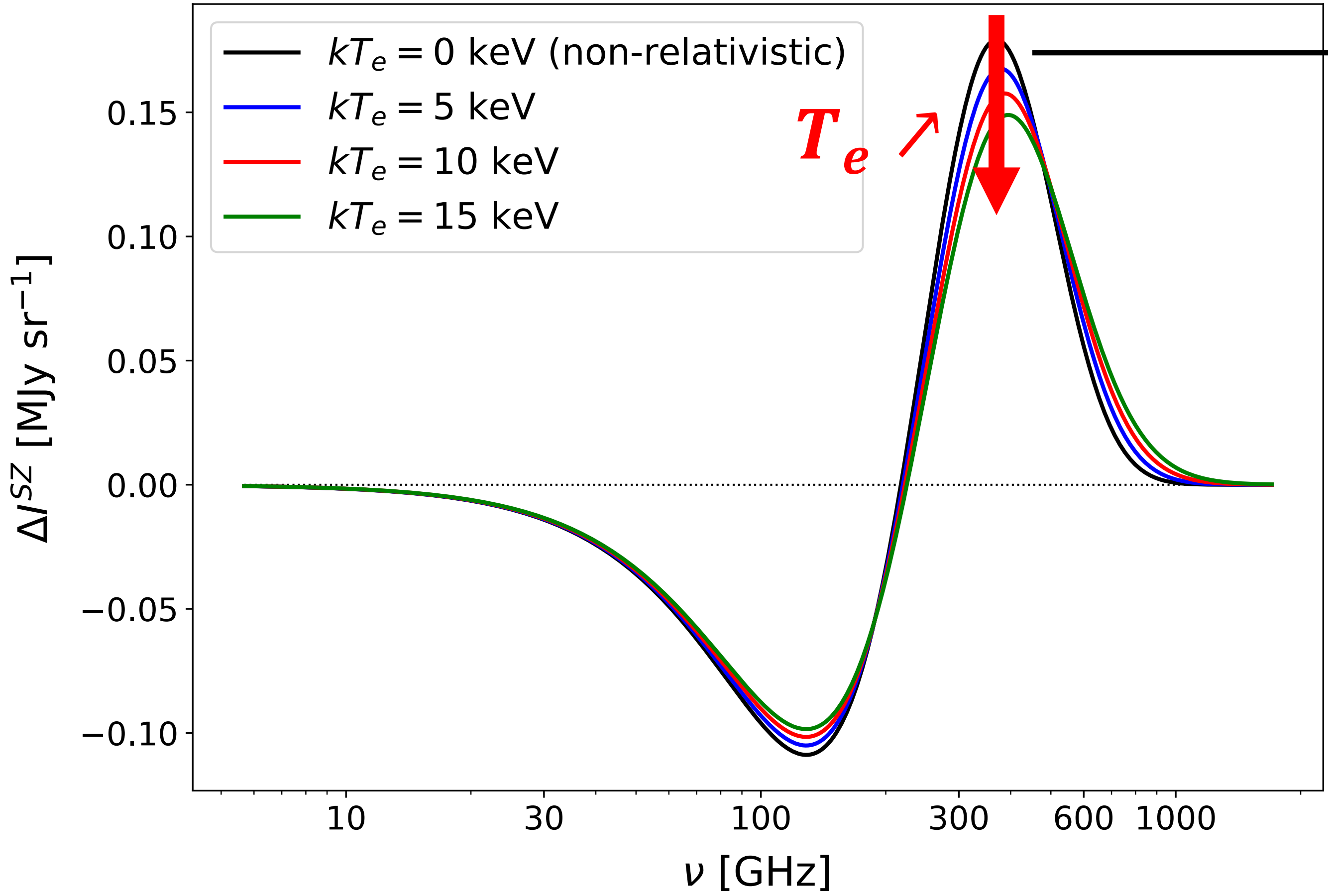


Planck's assumption: $T_e \simeq 0$ keV

Relativistic electron temperature corrections change the shape of the SZ distortion spectrum

Relativistic SZ effect (rSZ)

$$I^{SZ}(\nu, \vec{n}) = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$

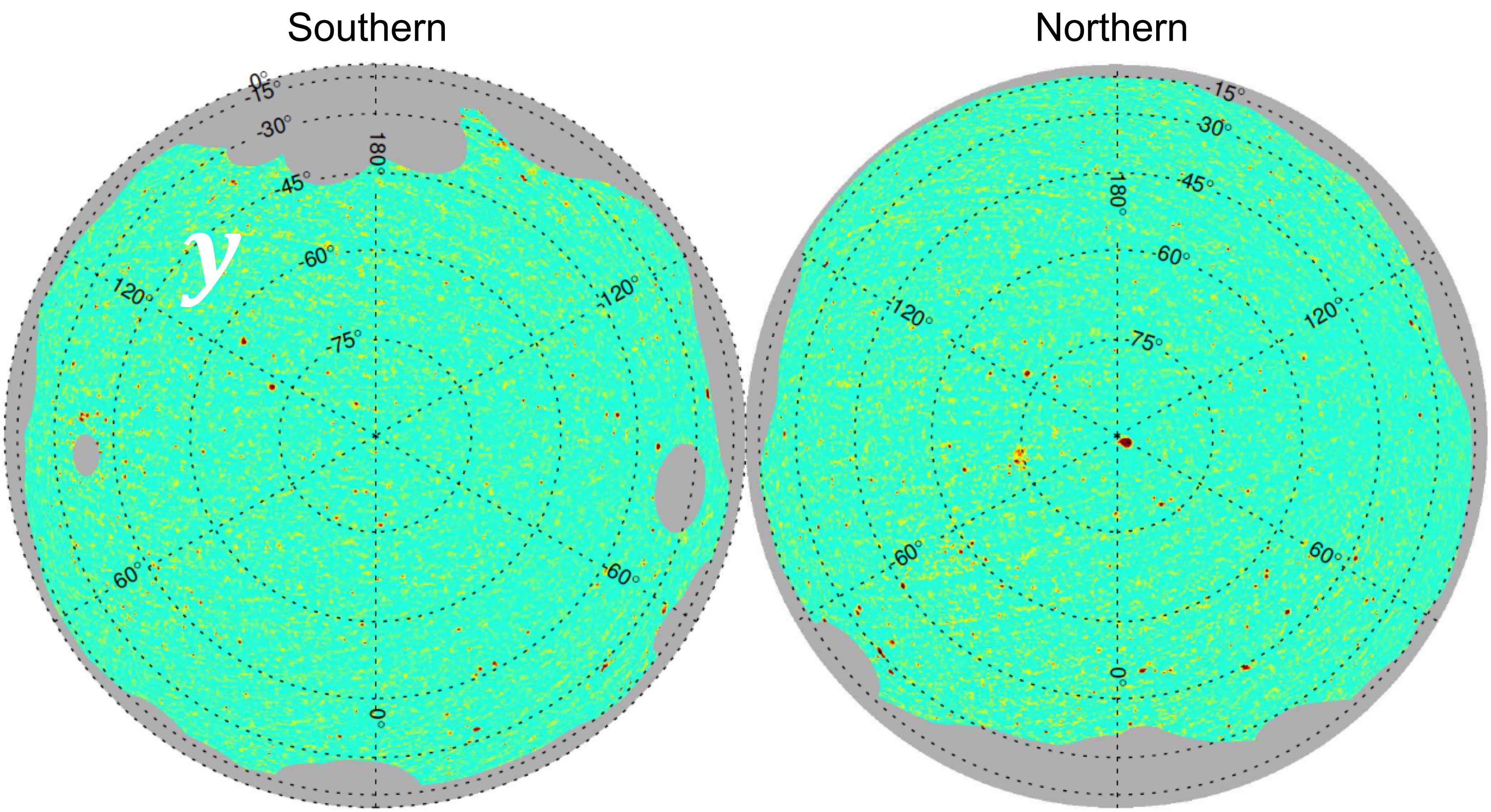


Planck's assumption: $T_e \simeq 0$ keV

- ✓ Relativistic temperature corrections reduce the overall SZ intensity at fixed Compton-y parameter
- ✓ Assuming non-relativistic spectrum $f(\nu, T_e = 0)$ for cosmological SZ analysis must lead to an underestimation of the Compton-y parameter

The *Planck* SZ Compton y-map

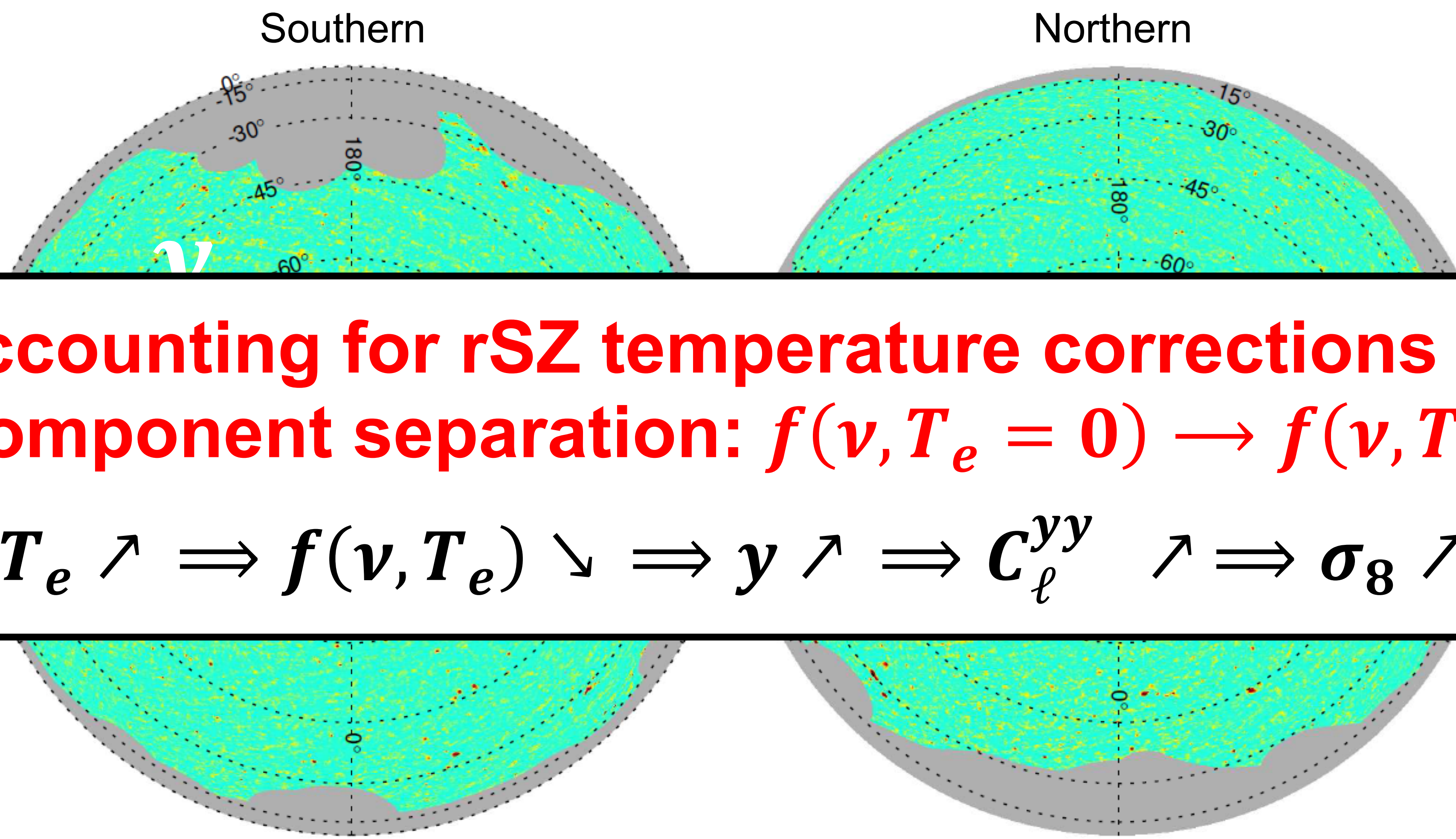
Non-relativistic assumption $\boldsymbol{f(\nu, T_e = 0)}$ for component separation



Planck 2015 results XXII, A&A (2016)

Revisiting the *Planck* SZ Compton y-map

Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)

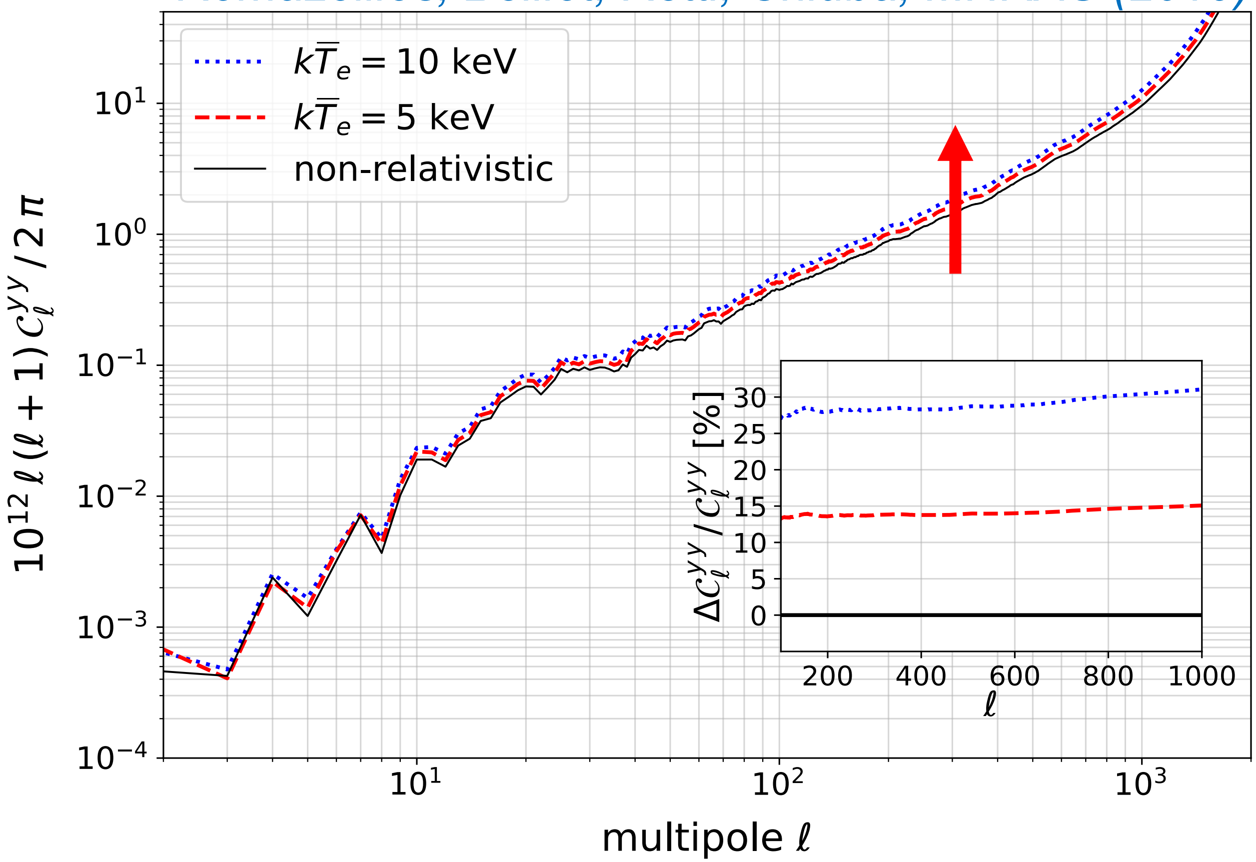


Accounting for rSZ temperature corrections in component separation: $f(\nu, T_e = 0) \longrightarrow f(\nu, T_e)$

$$T_e \nearrow \;\Longrightarrow\; f(\nu, T_e) \searrow \;\Longrightarrow\; y \nearrow \;\Longrightarrow\; C_\ell^{yy} \nearrow \;\Longrightarrow\; \sigma_8 \nearrow$$

Relativistic temperature corrections to *Planck* SZ power spectrum

Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)



C_ℓ^{yy} increases with the average temperature $\bar{T}_e$

$$C_\ell^{yy} \propto \sigma_8^{8.1} \implies \frac{\Delta\sigma_8}{\sigma_8} \simeq 0.019 \left(\frac{k\bar{T}_e}{5\ \mathrm{keV}}\right)$$

$k\bar{T}_e \simeq 5$ keV reduces Planck's tension by 1σ !

Mapping the electron temperature with rSZ

Remazeilles & Chluba, arXiv:1907.00916

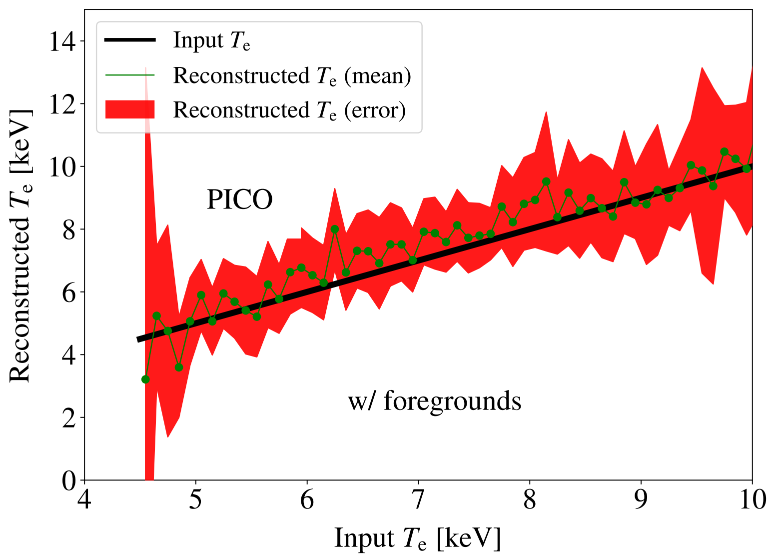
- Taylor expansion of the rSZ spectrum around pivot temperature $\overline{T}_e$:

$$I^{\mathrm{rSZ}}(\nu,\vec{n}) \simeq \underbrace{f(\nu,\overline{T}_e)}_{\text{Spectrum of } y}\ \underbrace{y(\vec{n})}_{y \text{ component}} + \underbrace{\frac{\partial f(\nu,\overline{T}_e)}{\partial T_e}}_{\text{Spectrum of } yT_e}\ \underbrace{\left(T_e(\vec{n}) - \overline{T}_e\right)y(\vec{n})}_{yT_e \text{ component}} + \mathcal{O}(T_e^2)$$

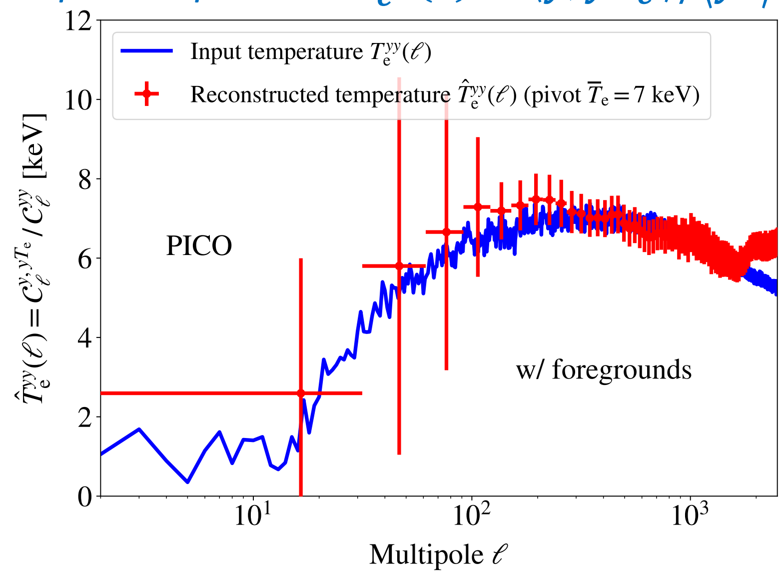
The y and yT_e components have distinct spectral signatures !

- Multi-frequency observations should allow us to disentangle the y and yT_e fields

Recovered electron temperatures T_e of clusters across the full sky: $\langle yT_e\rangle/\langle y\rangle$

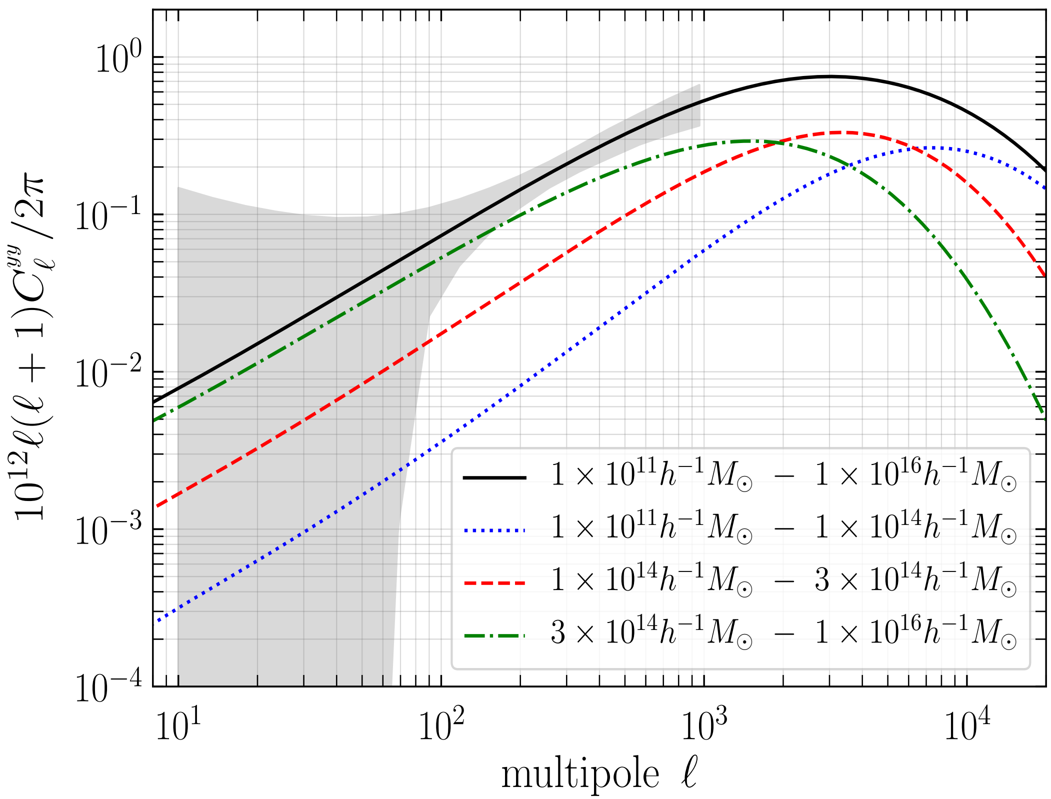


Reconstructed electron temperature power spectrum $T_e^{yy}(\ell) = \langle y, yT_e\rangle/\langle y^2\rangle$

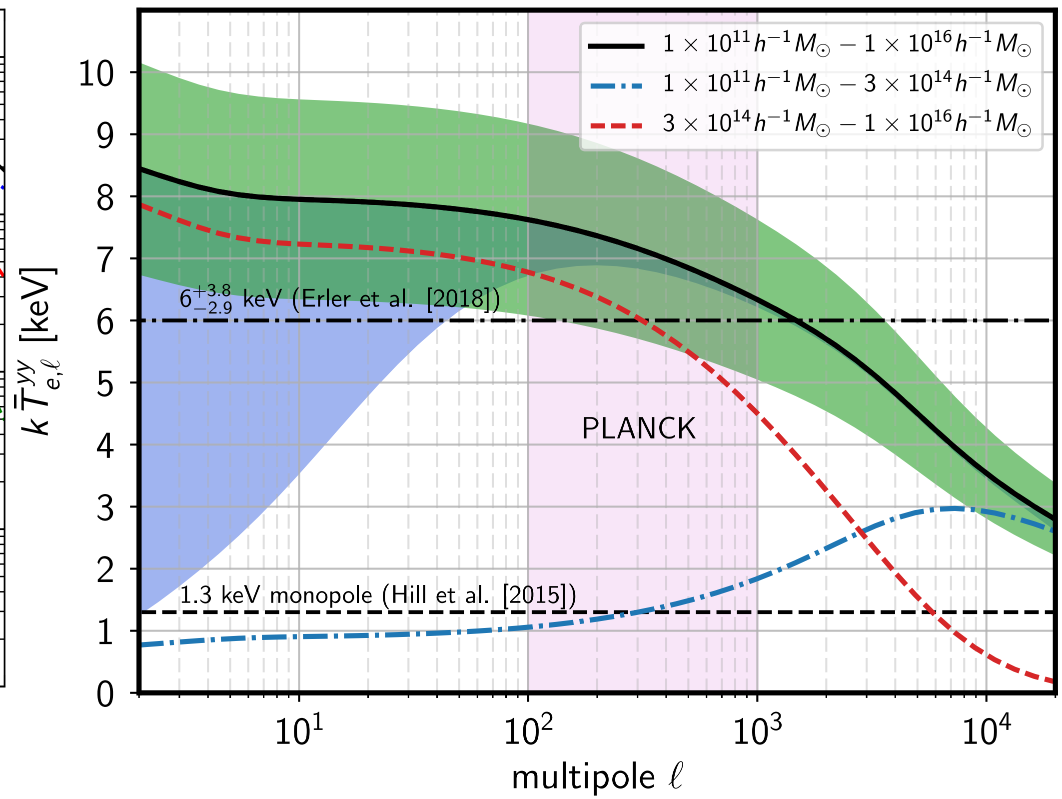


Two observables for future cluster cosmology !

$\boldsymbol{y}$-power spectrum: $\boldsymbol{C_\ell^{yy}}$



$\boldsymbol{T_e}$-power spectrum: $\boldsymbol{T_e^{yy}(\ell) = C_\ell^{T_e y,y} / C_\ell^{yy}}$



The shapes of power spectra $\boldsymbol{C_\ell^{yy}}$ and $\boldsymbol{T_e^{yy}}(\ell)$ have different scaling with cosmological parameters

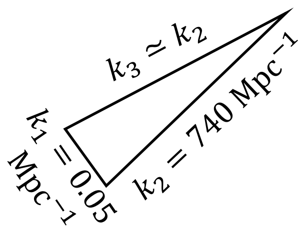
Remazeilles, Bolliet, Rotti, Chluba, MNRAS 2019

μ-distortion anisotropies

Aside from average (monopole) μ-distortions:

- **Physical mechanisms lead to μ-type distortion anisotropies:**
  - ✓ Silk damping of **non-Gaussian** primordial perturbations *– Pajer & Zaldarriaga, PRL (2012)*
  - ✓ Inflation with **non-standard** (i.e. not Bunch-Davies) vacuum *– Ganc & Komatsu, PRD (2012)*

- **Anisotropies of μ-type distortions (spectral-spatial anisotropies)** for non-Gaussian primordial perturbations in the ultra-squeezed limit



$$C_\ell^{\mu\mu} = 144\, C_\ell^{TT,\text{Sachs–Wolfe}}\, f_{\rm NL}^2(k_2)\, \langle\mu\rangle^2$$

- **Correlation of CMB temperature and μ-type distortion anisotropies** for non-Gaussian primordial perturbations in the ultra-squeezed limit

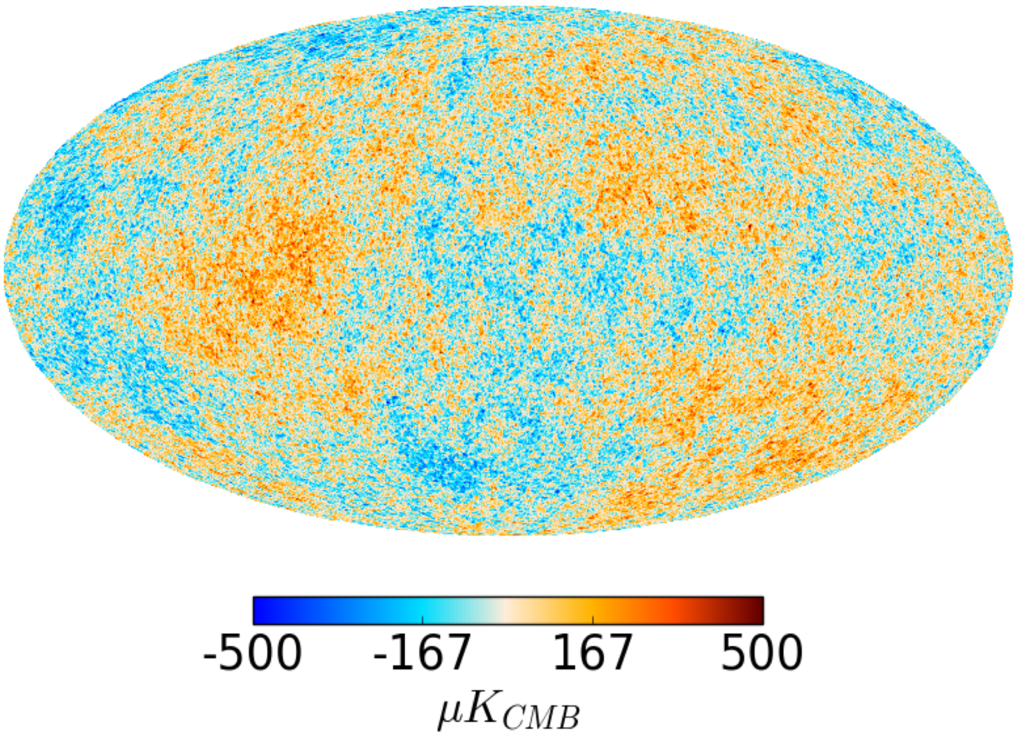
$$C_\ell^{\mu\times T} = 12\, C_\ell^{TT,\text{Sachs–Wolfe}}\, \rho(\ell)\, f_{\rm NL}(k_2)\, \langle\mu\rangle$$

Note: *scale-dependent non-Gaussianity* $f_{NL}(k) = f_{NL}(k_0)\left(\frac{k}{k_0}\right)^{n_{NL}}$ *with* $n_{NL} \simeq 1.6$ *would allow for*

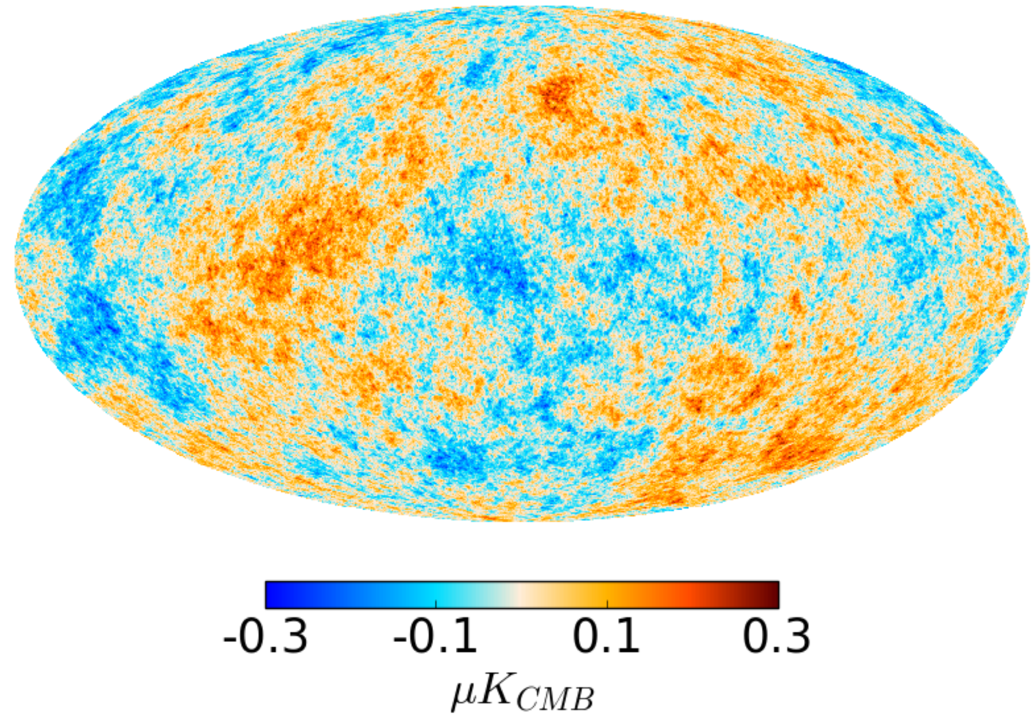
$$\begin{cases} f_{NL}(k_0 \simeq 740\ \text{Mpc}^{-1}) \simeq 4500 & (\mu\text{–distortion anisotropies scale}) \\ f_{NL}(k_0 = 0.05\ \text{Mpc}^{-1}) \simeq 5 & (\text{CMB temperature anisotropies scale}) \end{cases}$$

μ-distortion anisotropies

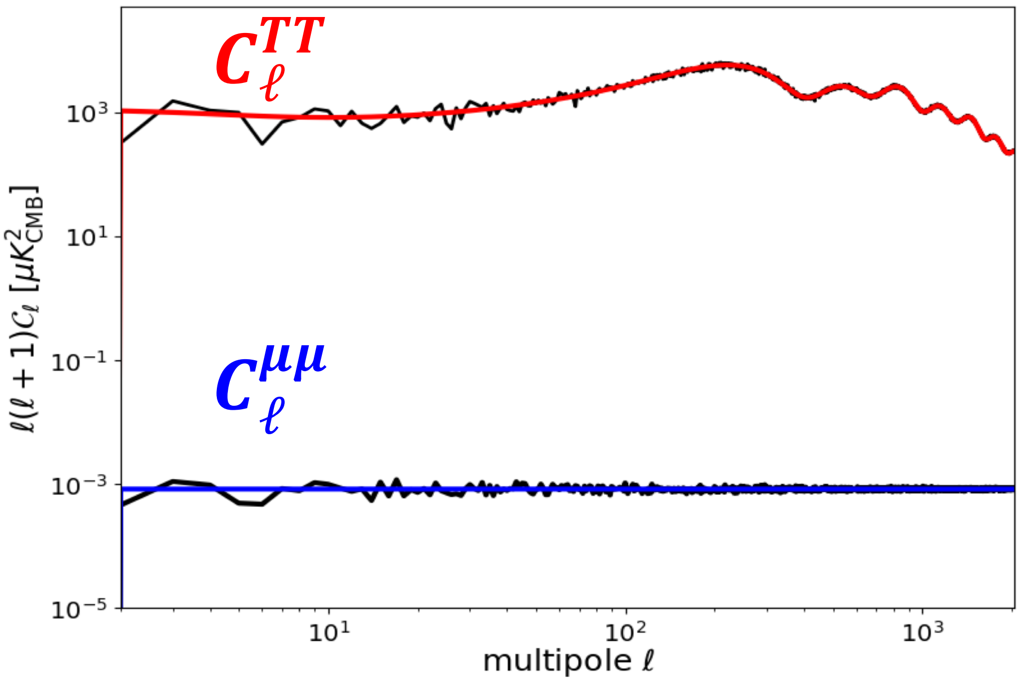
CMB T anisotropies

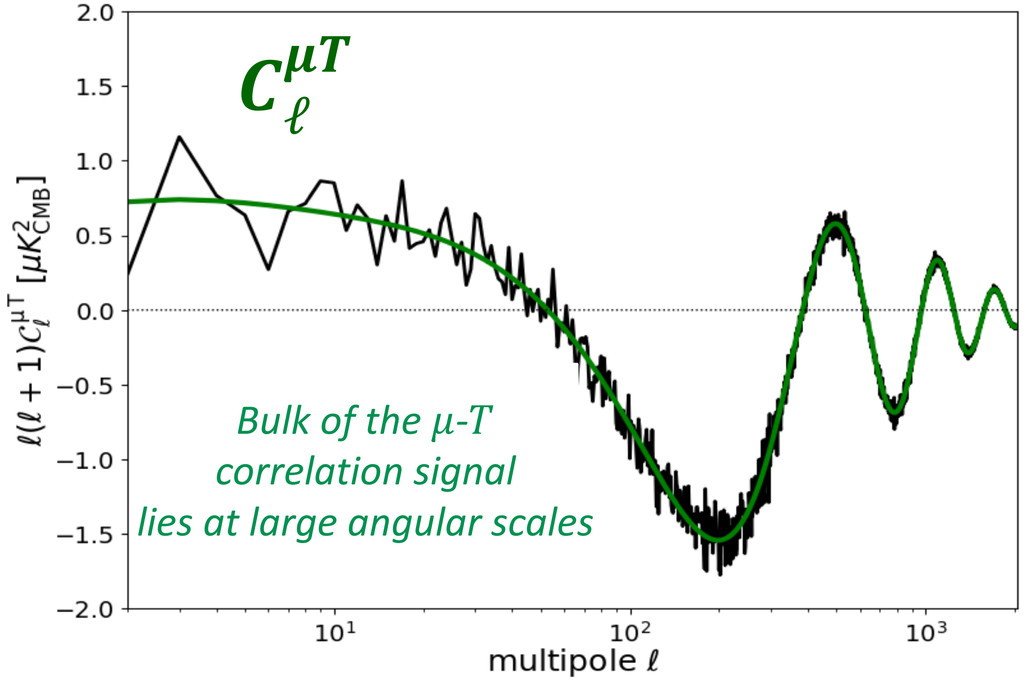


μ-distortion anisotropies?



Auto- and cross-power spectra of CMB temperature and μ-distortion anisotropies



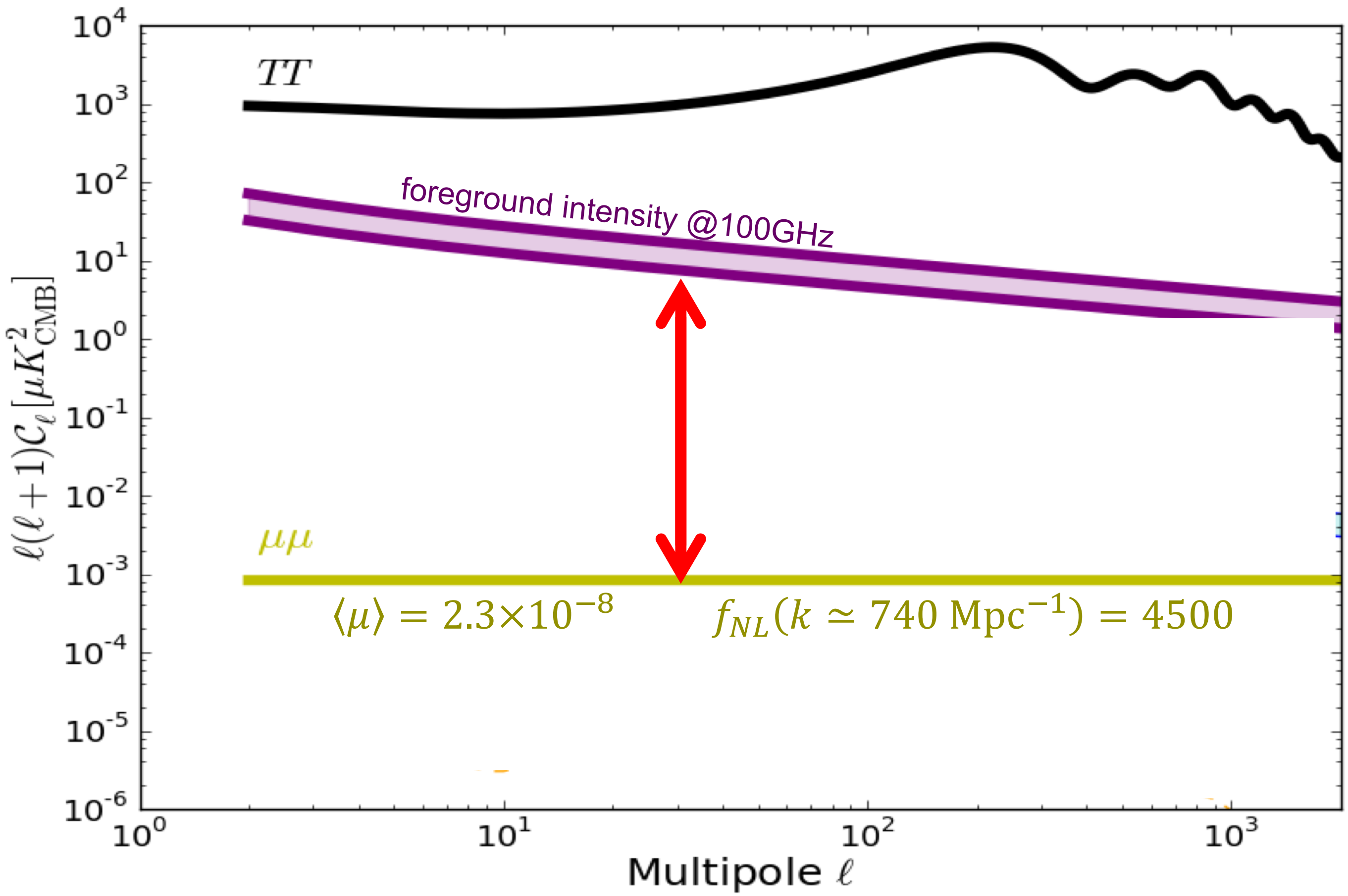


$\langle\mu\rangle = 2{\times}10^{-8}$ $\qquad f_{NL}(k \simeq 740\ \mathrm{Mpc}^{-1}) = 4500$

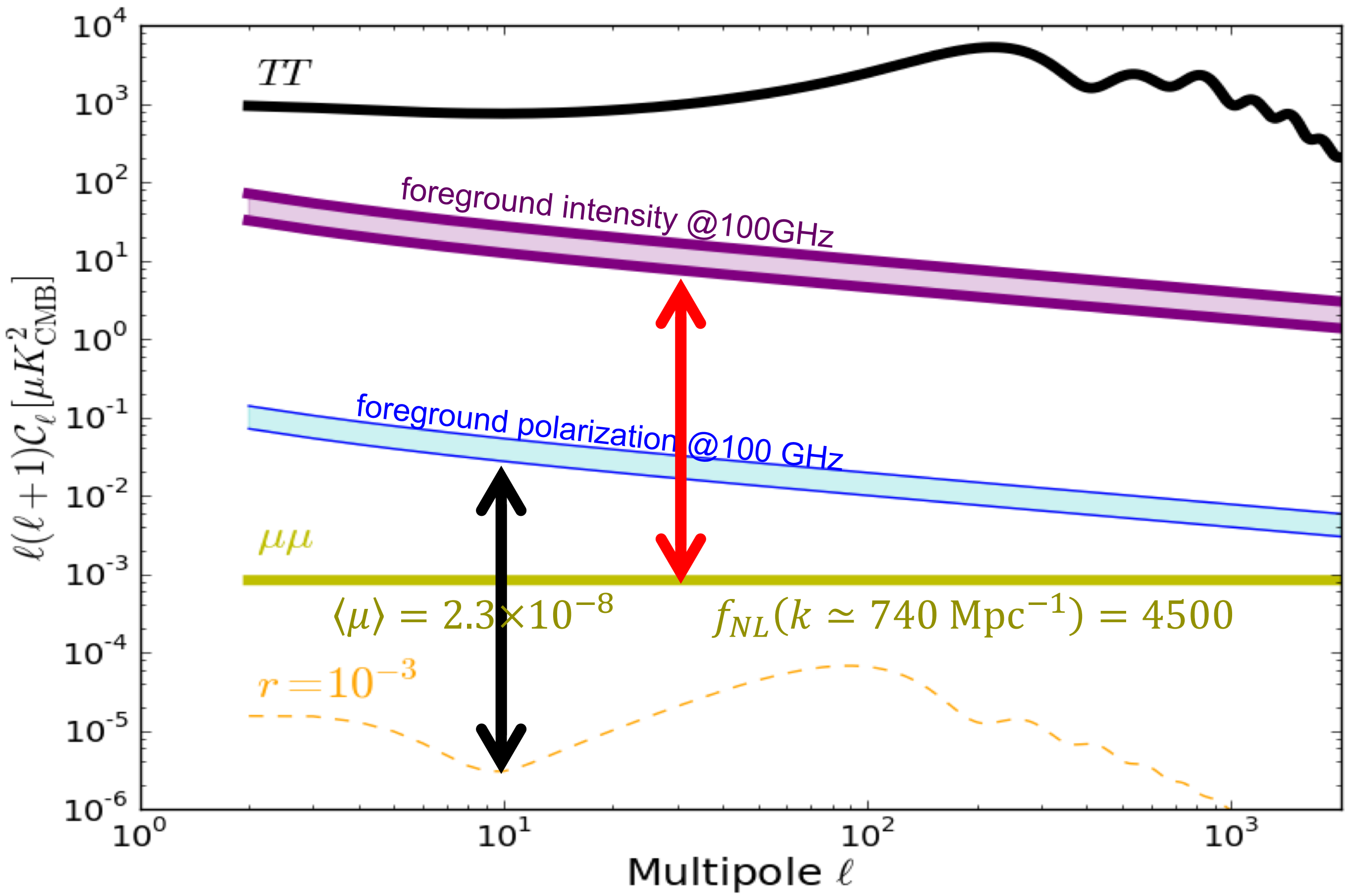
Ravenni et al, JCAP (2017)

Remazeilles & Chluba, MNRAS (2018)

μ-type distortion anisotropies



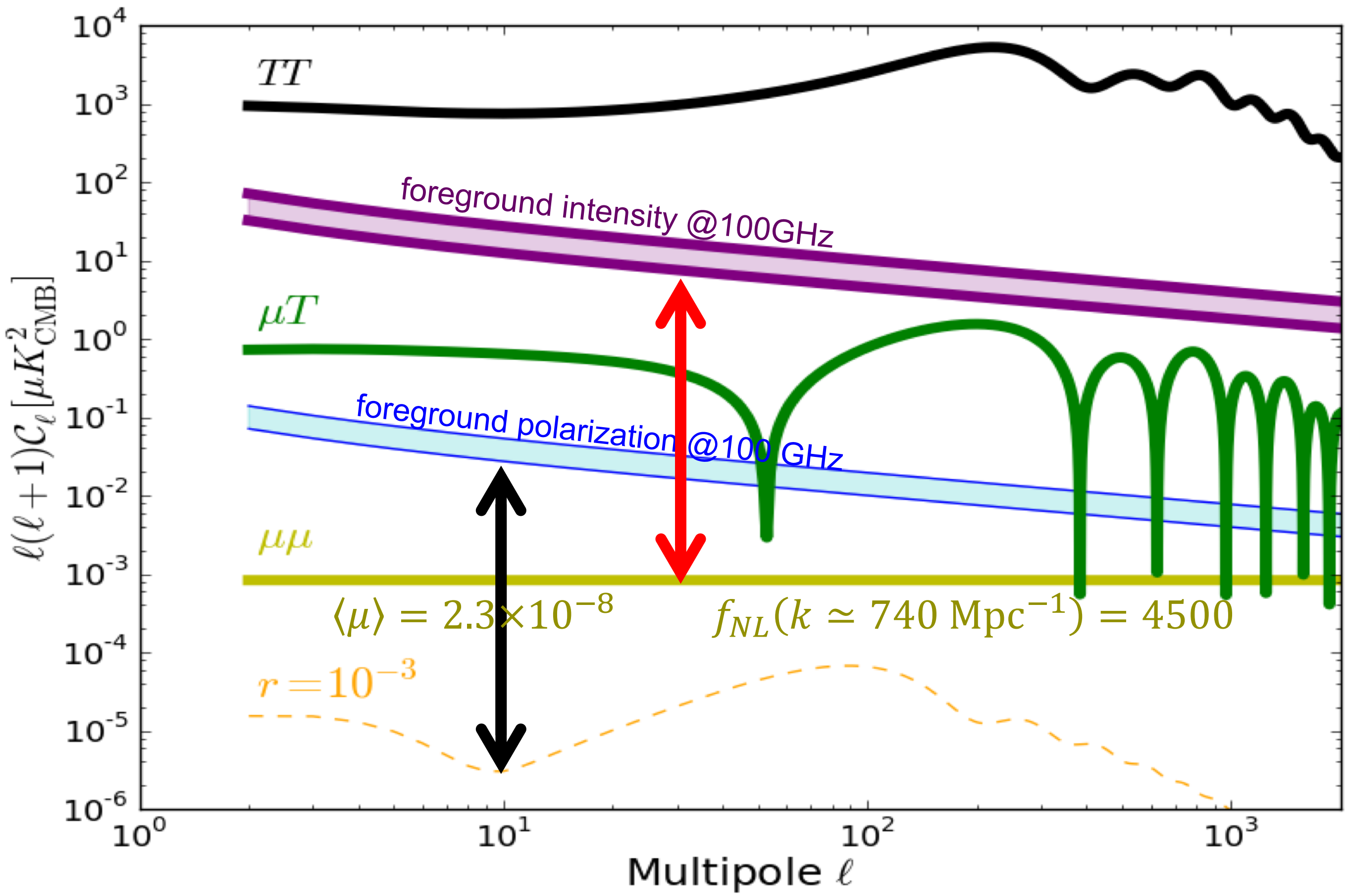
μ-type distortion anisotropies



Same dynamic range (signal-to-foregrounds ratio) than for primordial B-modes at $r = 10^{-3}$

→ ***A science case for future CMB imagers!***

μ-type distortion anisotropies



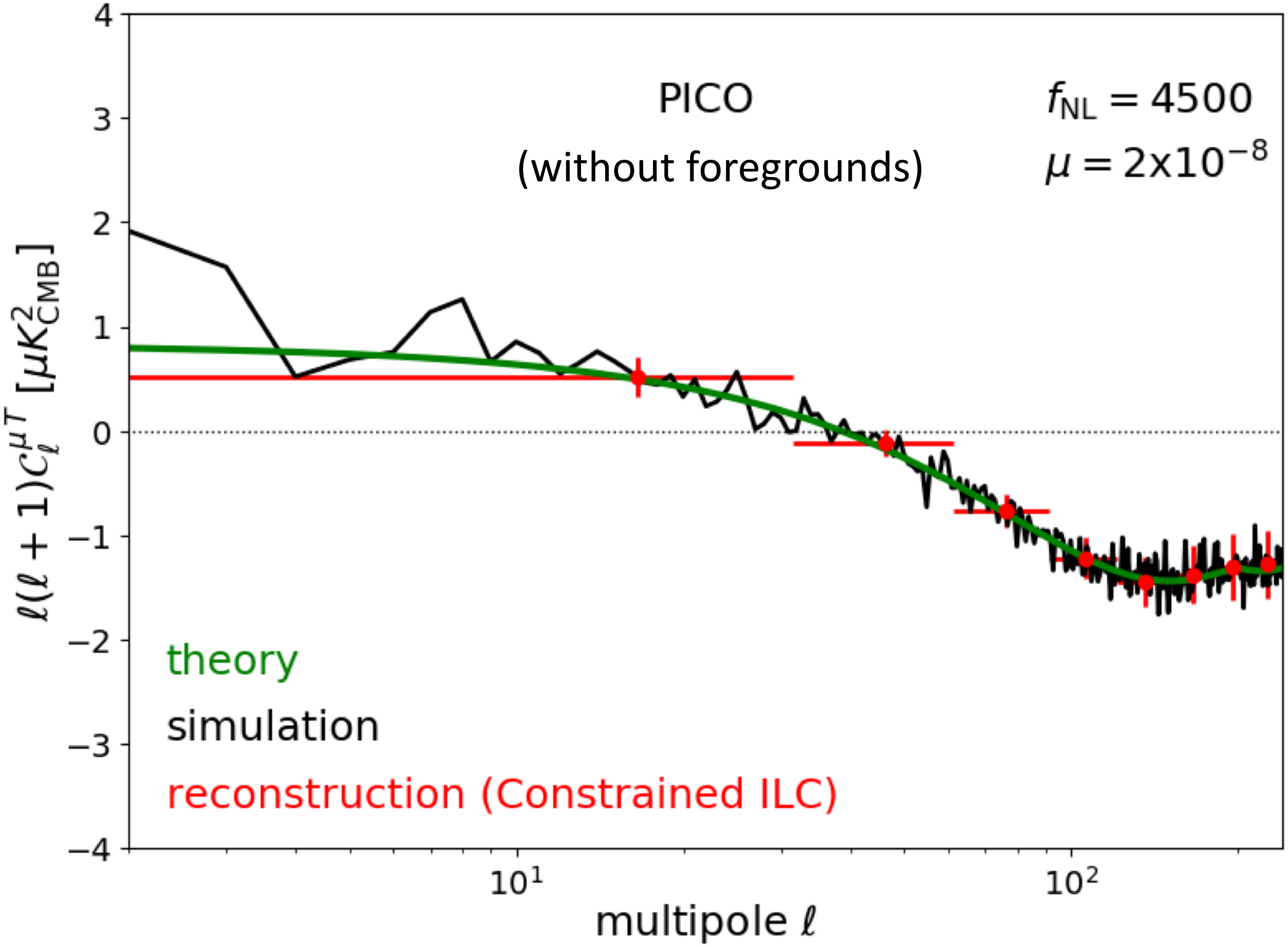
μ-T cross-power spectrum:

Enhanced μ-type distortion signal through correlation with CMB temperature anisotropies!

→ Accessible signal for future CMB imagers!

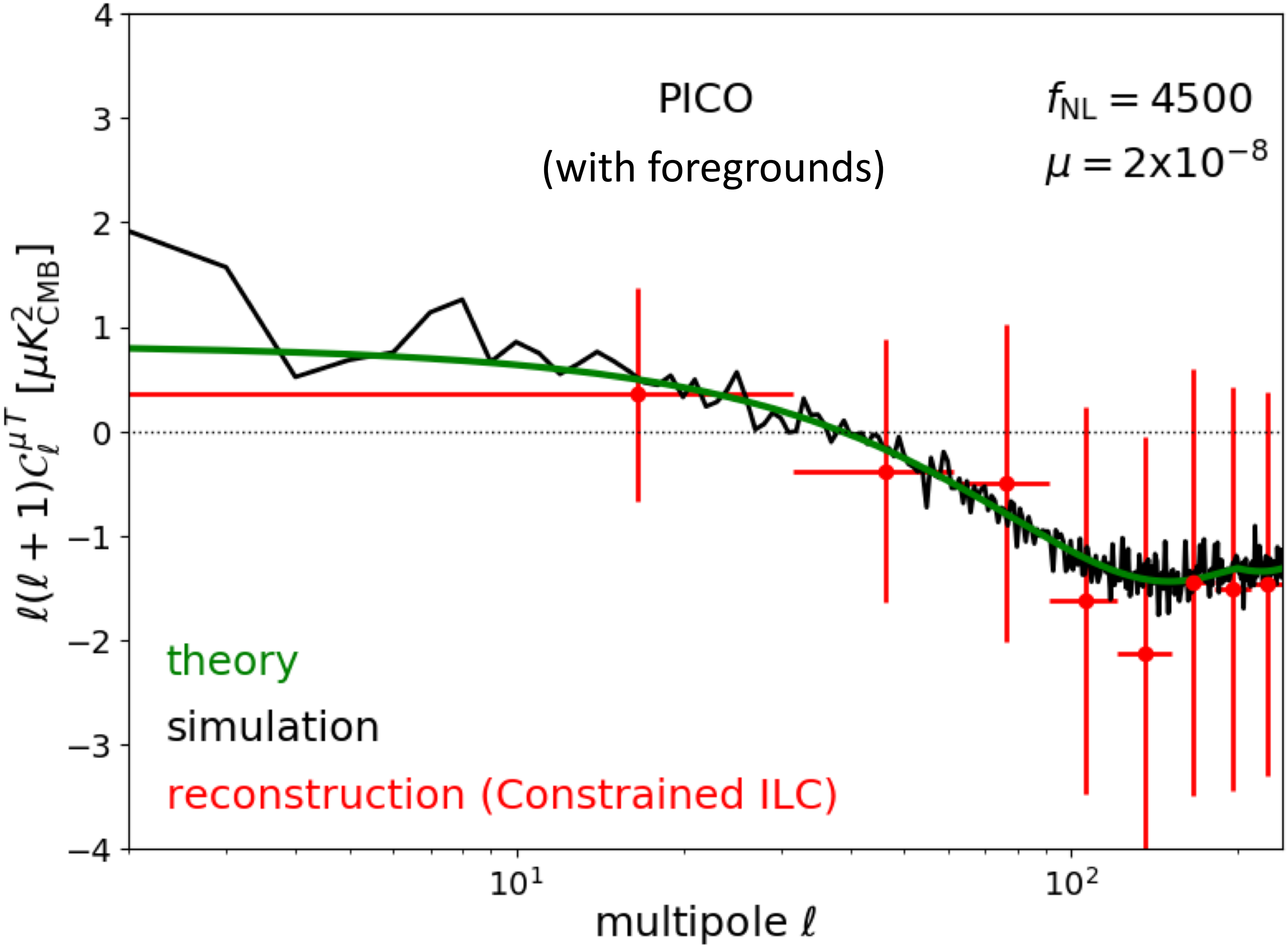
Detecting μ-distortions by reconstructing the enhanced μ-T cross-power spectrum

Remazeilles & Chluba, MNRAS (2018)



Detecting μ-distortions by reconstructing the enhanced μ-T cross-power spectrum

Remazeilles & Chluba, MNRAS (2018)



$> 2\sigma$ detection of $f_{\rm NL}[k \simeq 740\ \mathrm{Mpc}^{-1}]$ forecasted for PICO

A rich physics causes CMB spectral distortions!

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

„high" redshifts

pre-recombination epoch

„low" redshifts

post-recombination

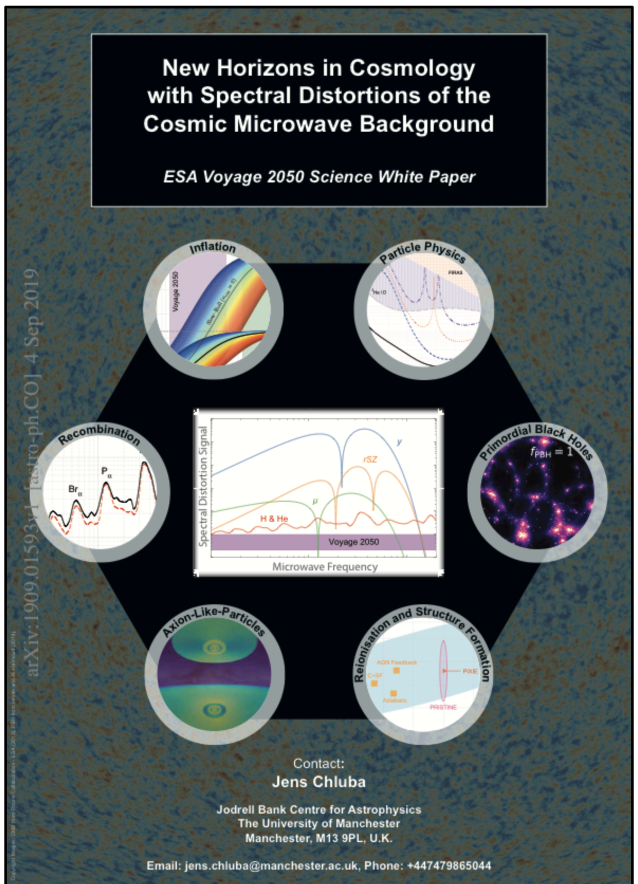
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Credit: Jens Chluba

ESA Voyage 2050 proposals

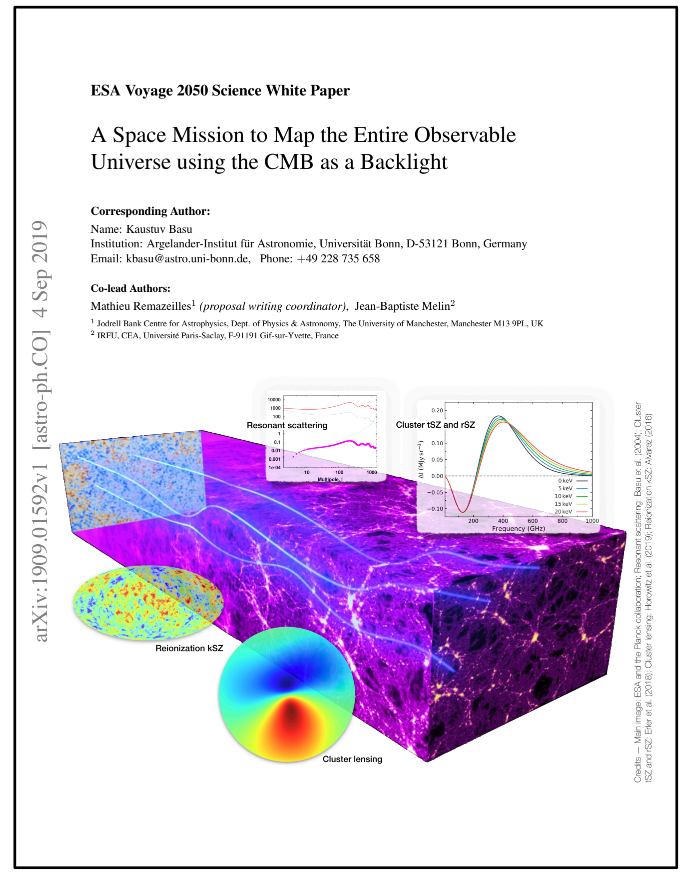
Science proposals in response to “ESA Voyage 2050” call for long-term space programme (next 3 decades)

Chluba, Abitbol, Aghanim, et al
1909.01593



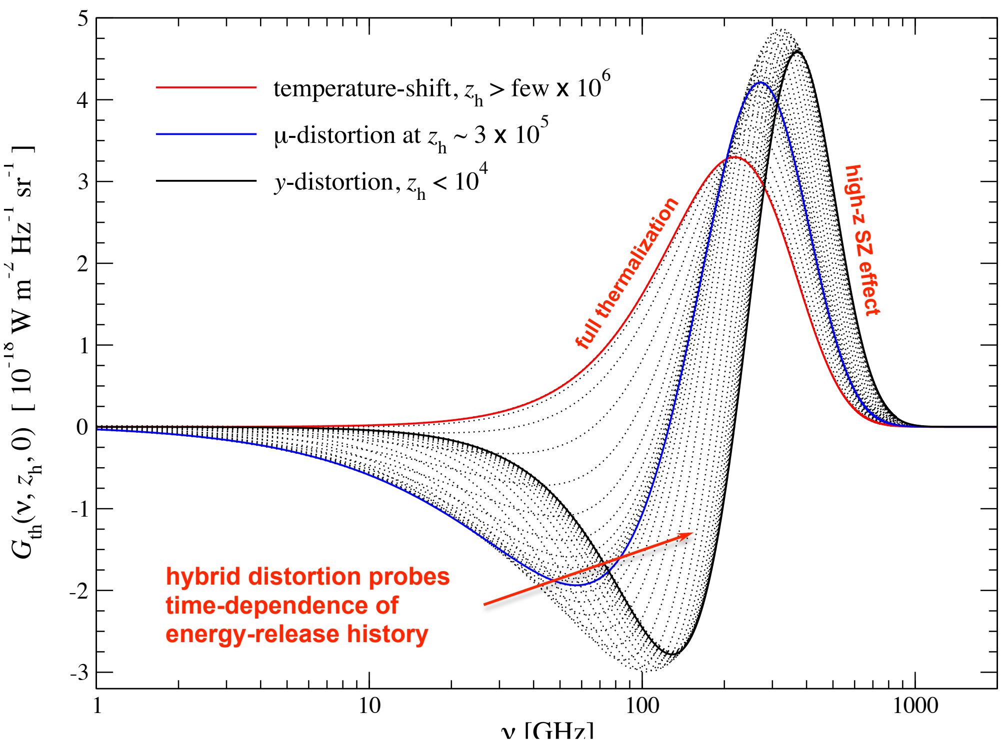
CMB spectral distortion science:
Probing the thermal history of the universe through interactions between matter and CMB radiation in early universe

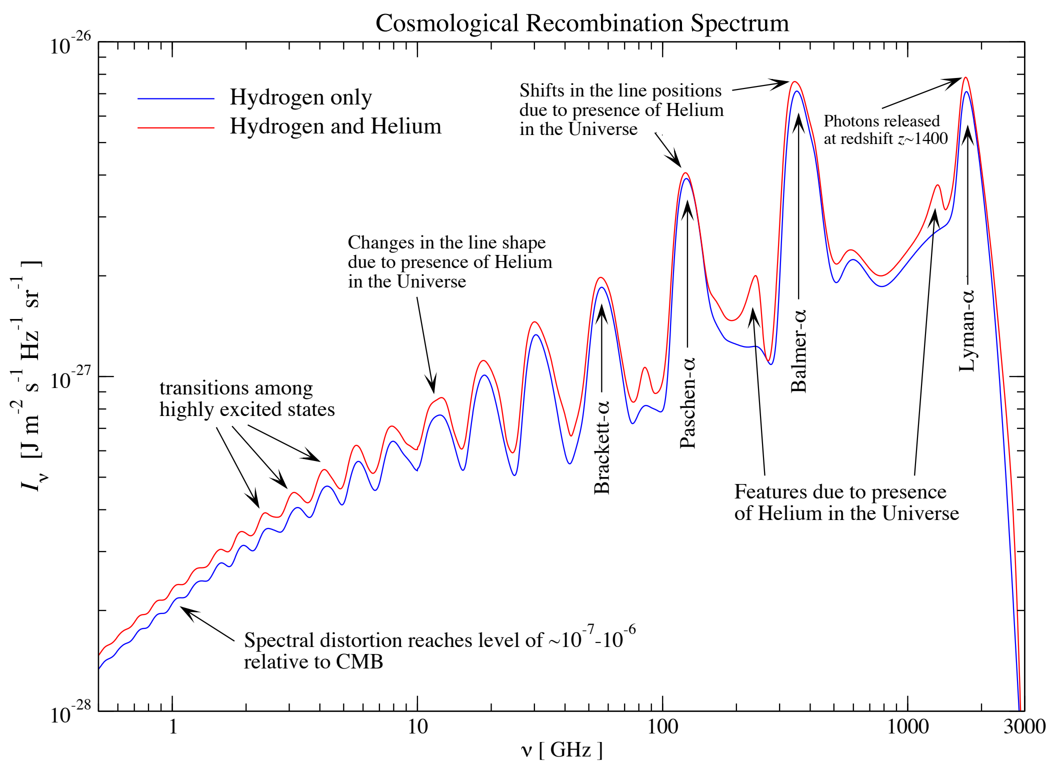
Basu, Remazeilles, Melin, et al
1909.01592



CMB “backlight” science:
Probing the cosmic web through interactions between matter and CMB radiation in late universe

Concluding word





CMB spectral distortions provide a new complementary probe of cosmology, inflation, and particle physics