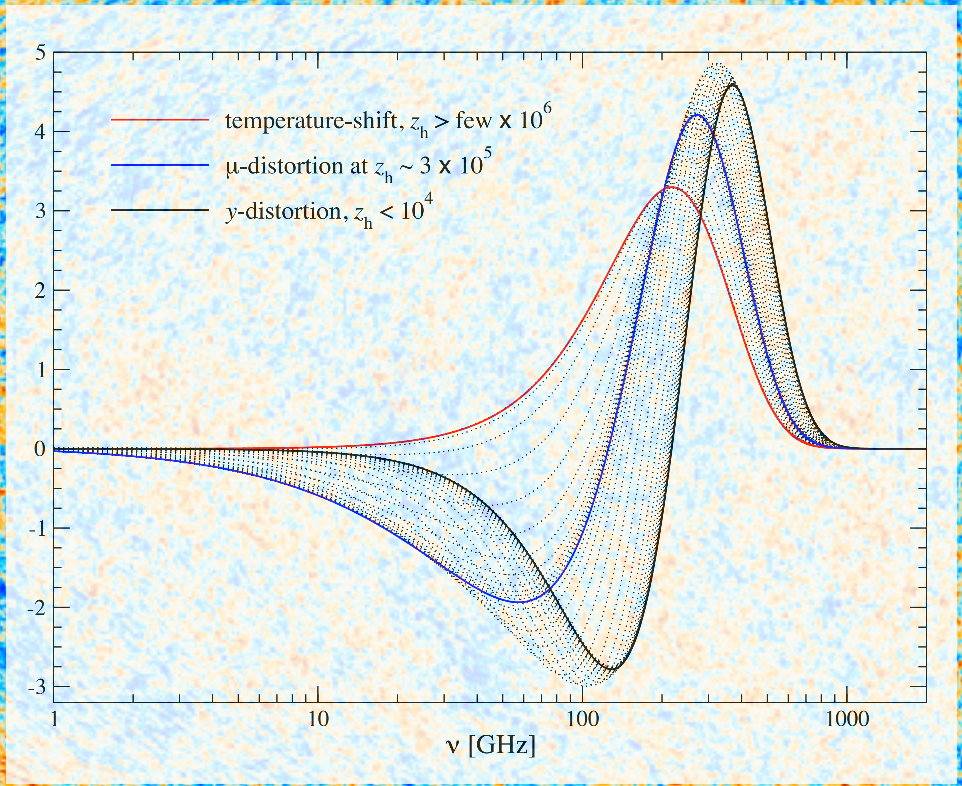
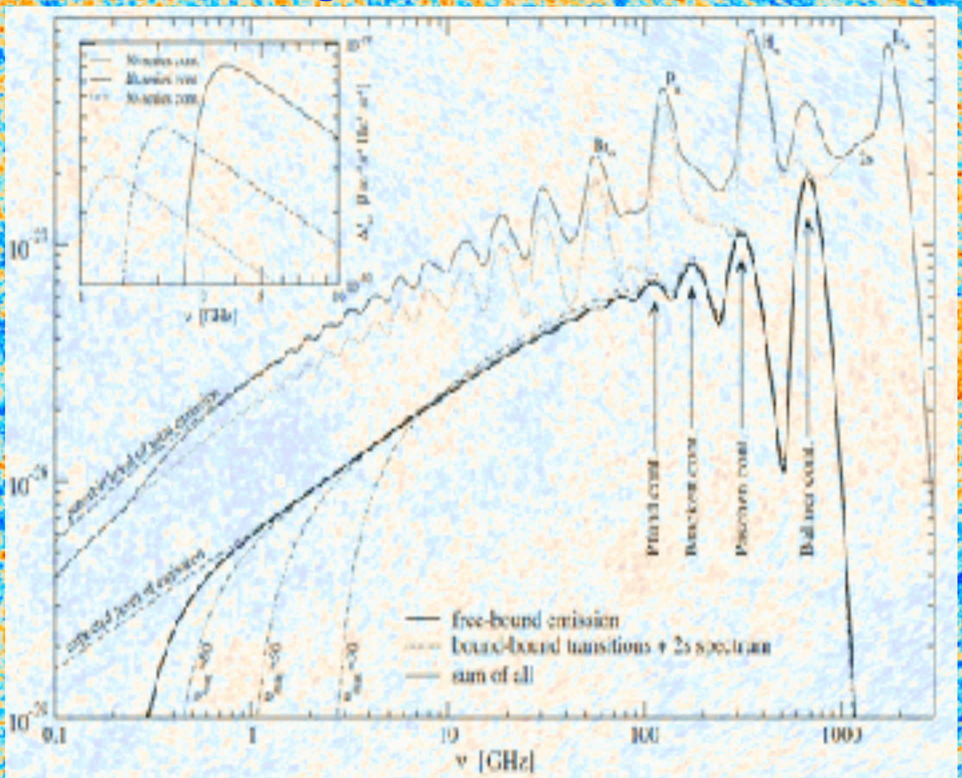
New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background

Primordial Distortions



Cosmological Recombination lines



MANCHESTER 1824
The University of Manchester

Jens Chluba

B-modes from Space

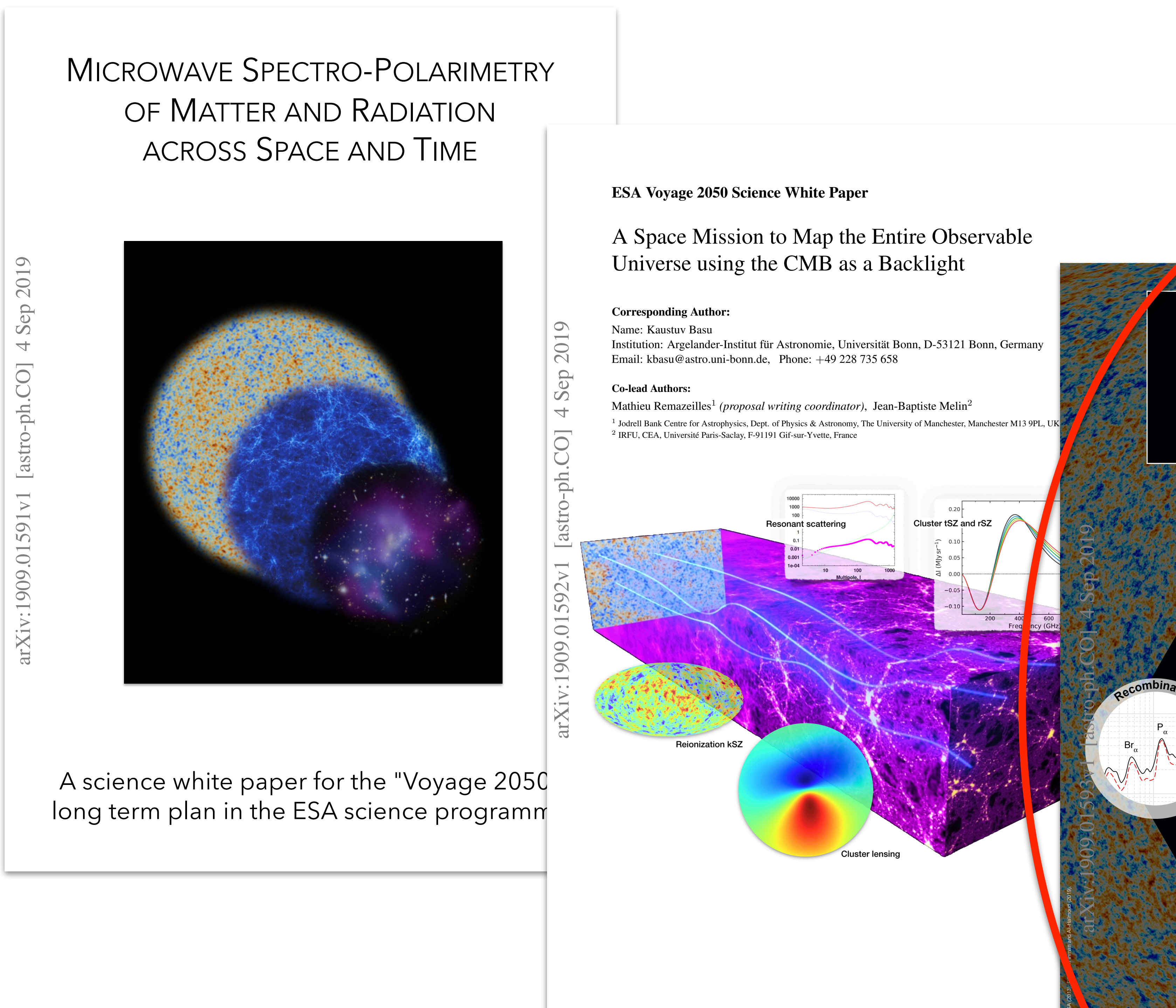
MPA, Garching, Dec 16th-19th, 2019

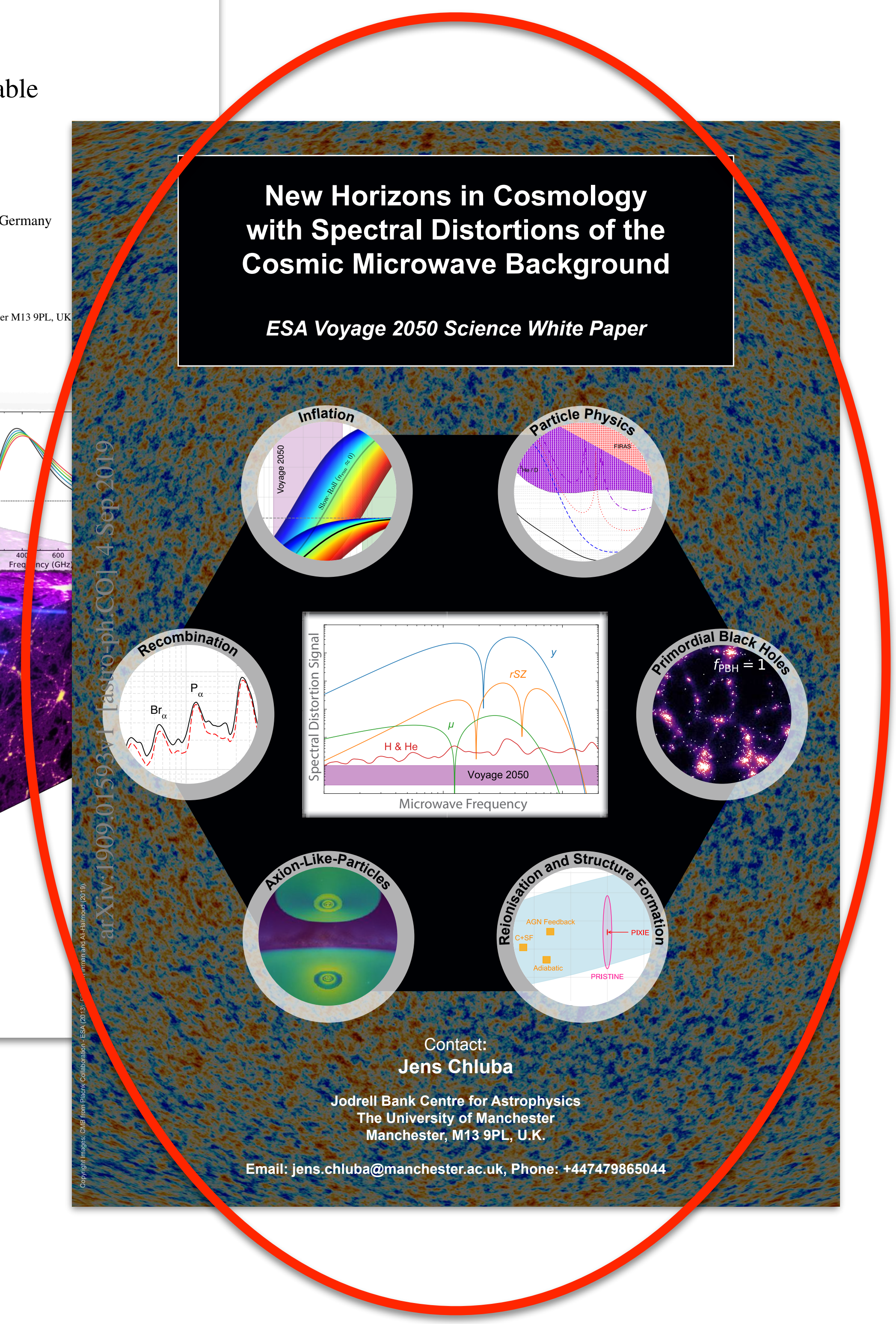
erc

THE ROYAL SOCIETY

** CMB ≙ Cosmic Microwave Background*

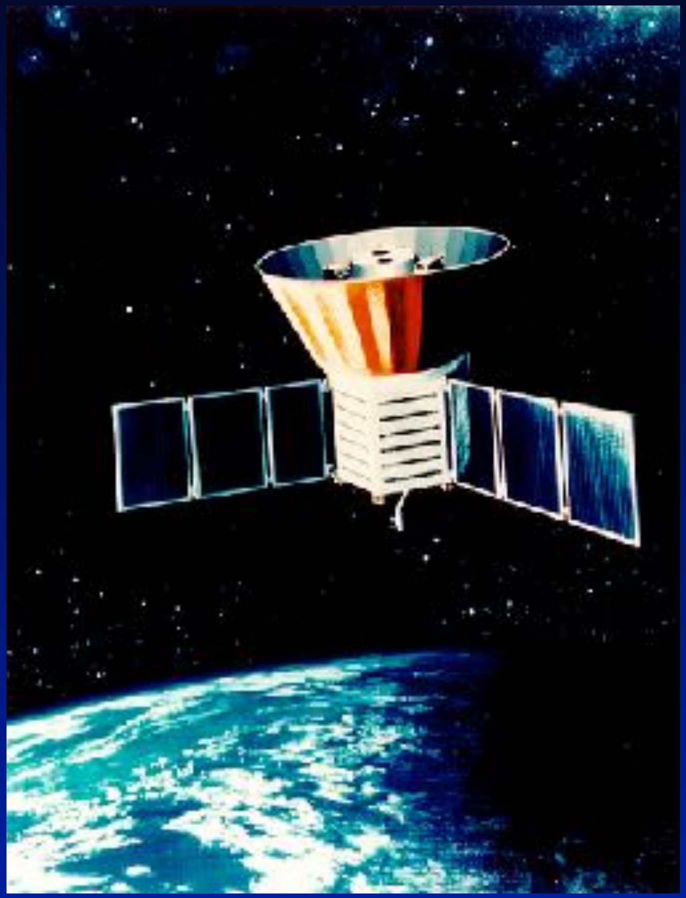
ESA Voyage 2050 White Papers

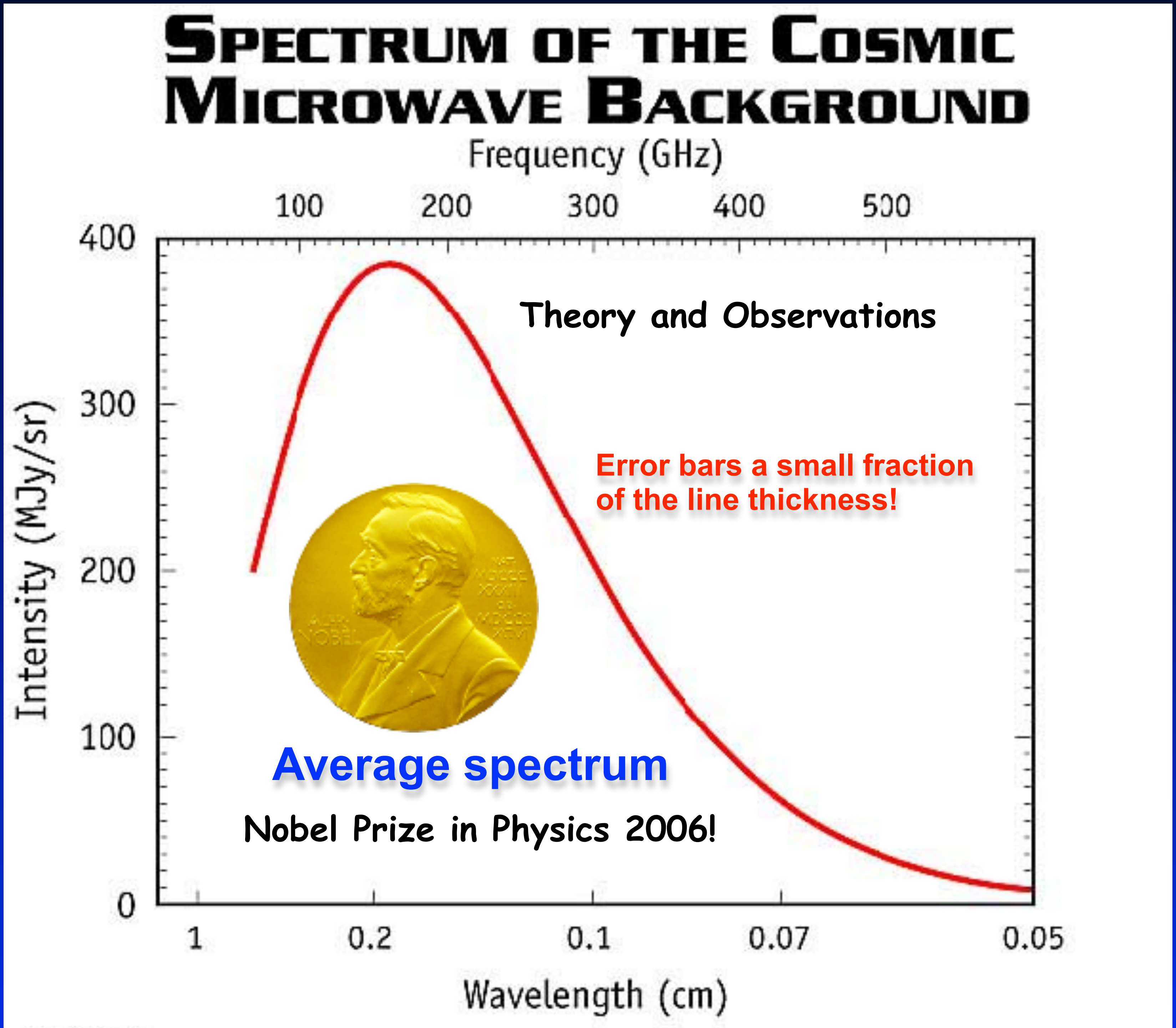




http://arxiv.org/abs/1909.01591
http://arxiv.org/abs/1909.01592
http://arxiv.org/abs/1909.01593

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





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

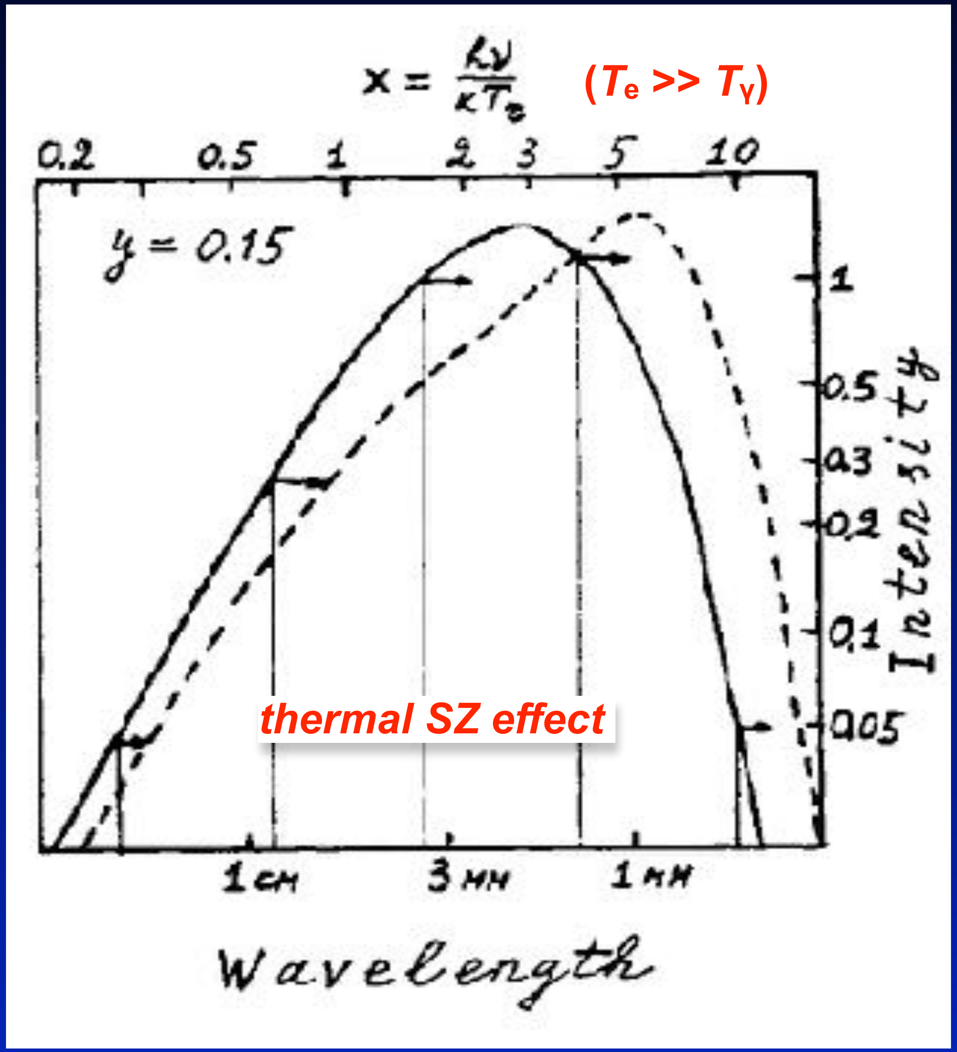
$$|y| \leq 1.5\times10^{-5}$$

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

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

Classical types of primordial CMB distortions

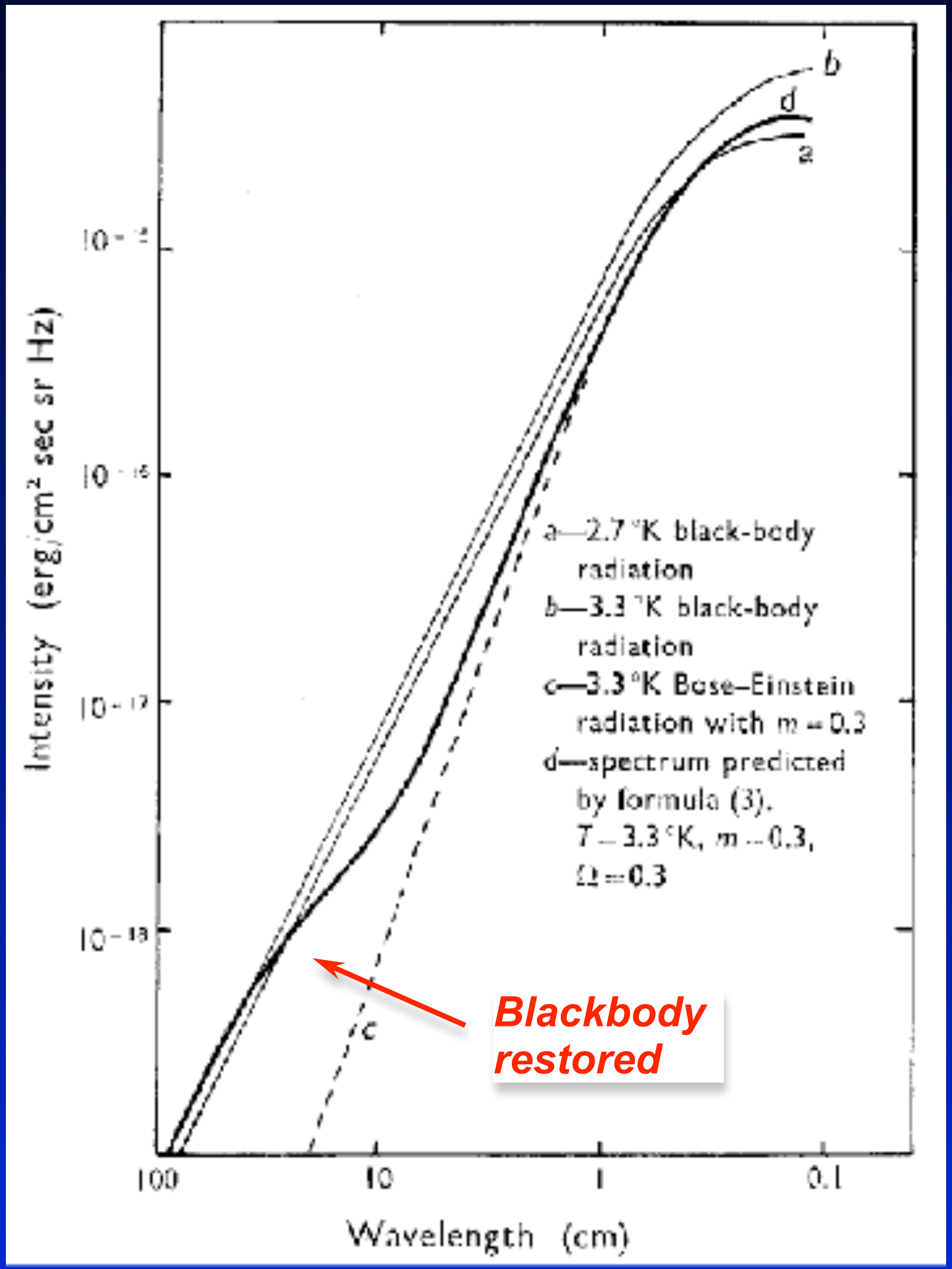
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

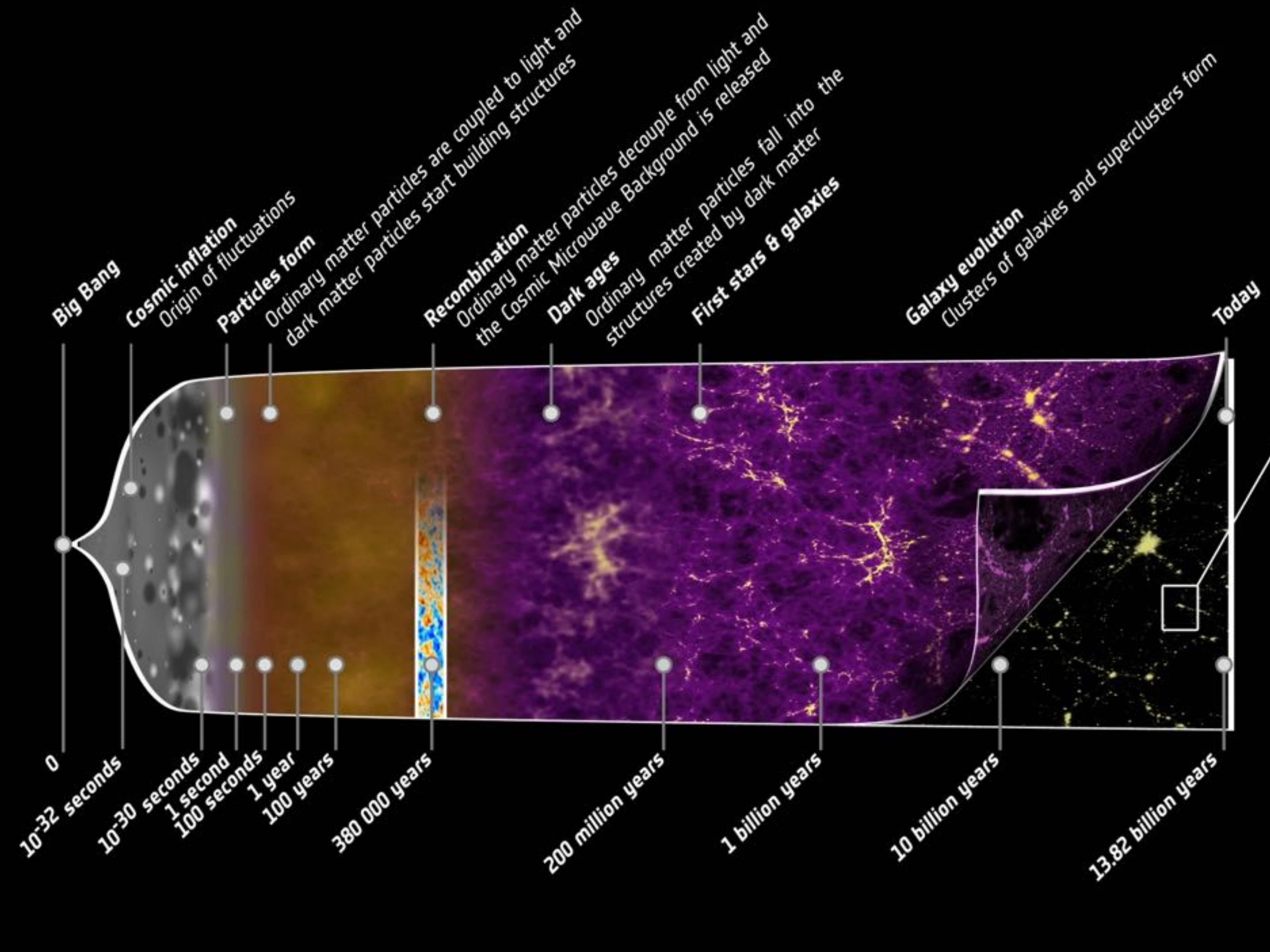
- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering `inefficient'

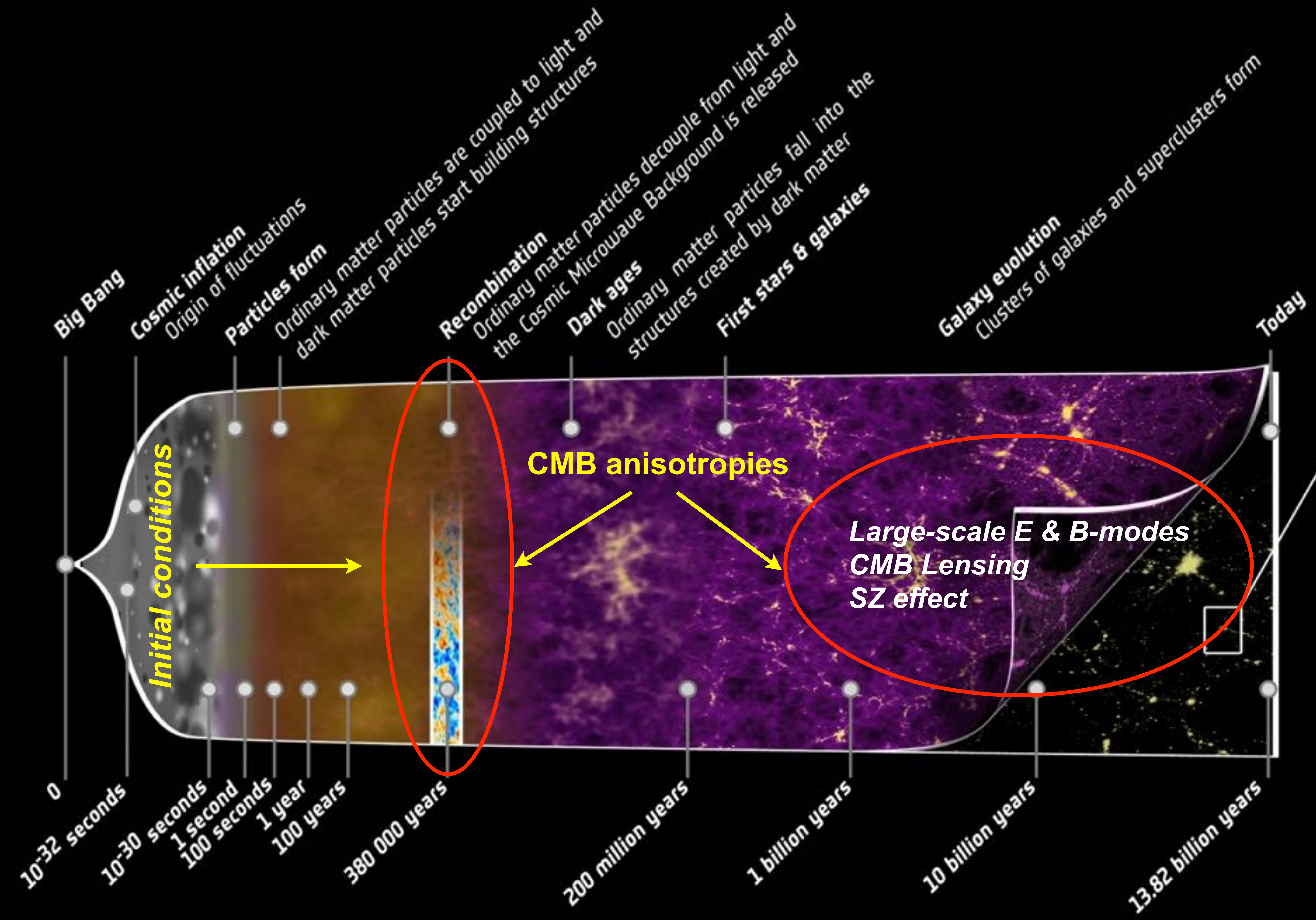
Chemical potential μ-distortion



Sunyaev & Zeldovich, 1970, ApSS, 2, 66

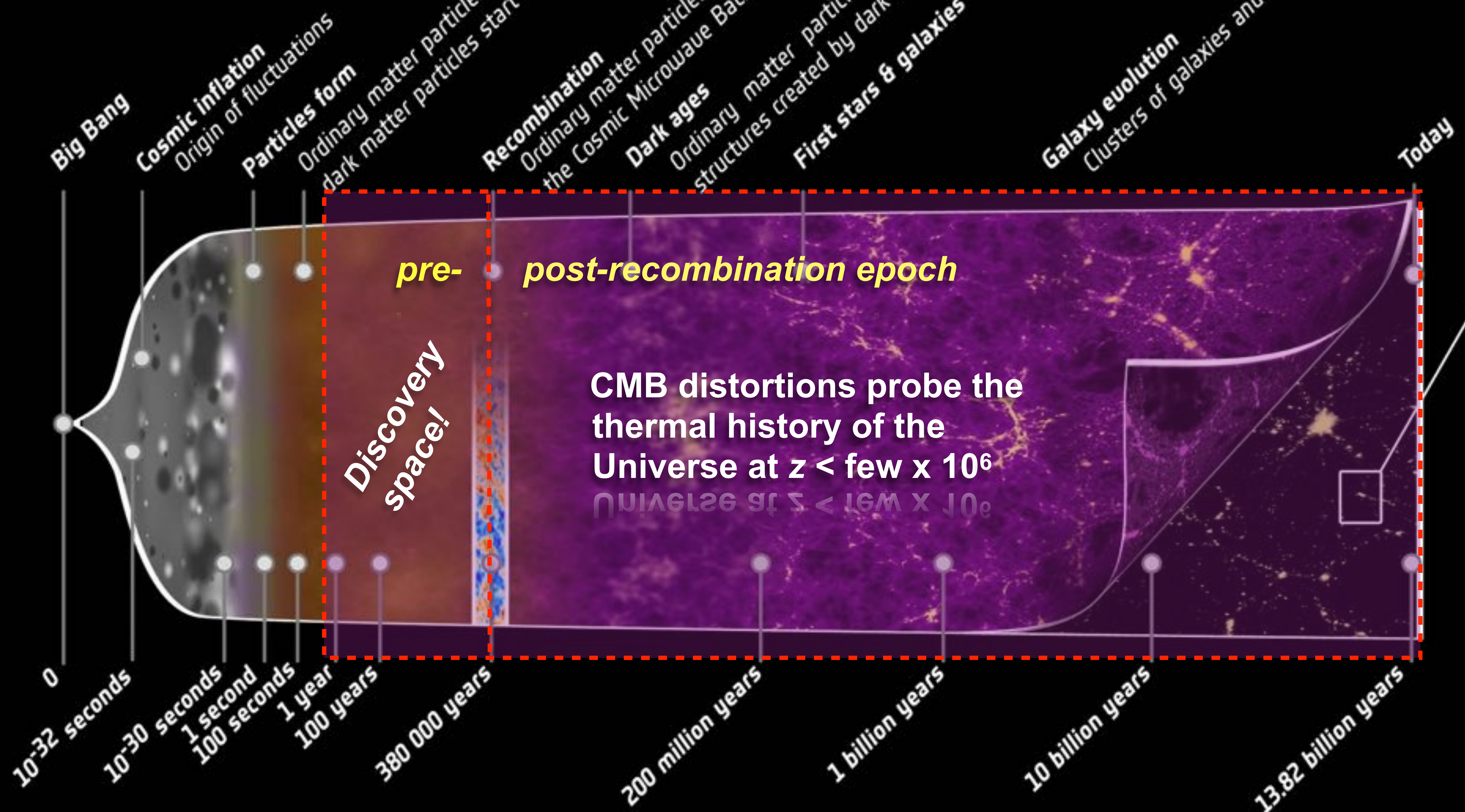
- important at very times (z>50000)
- scattering `very efficient'

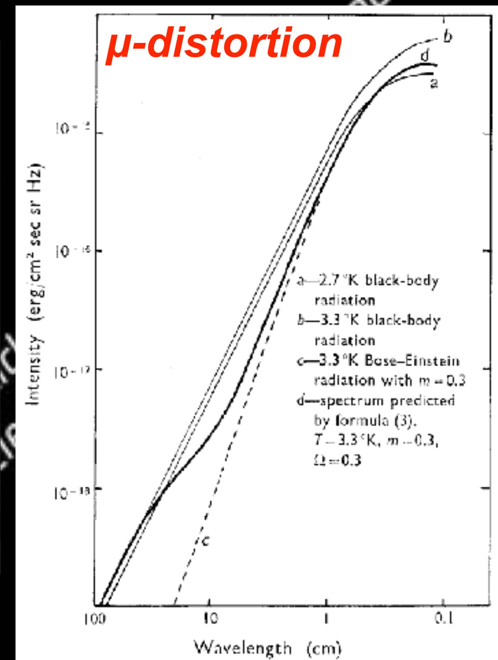

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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

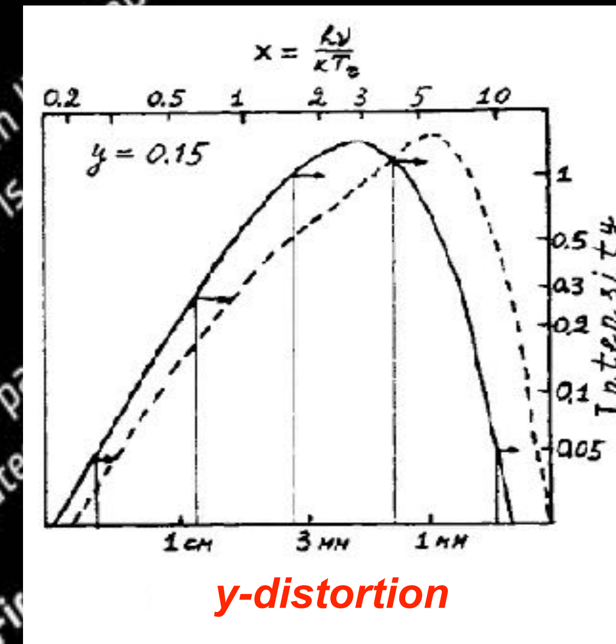


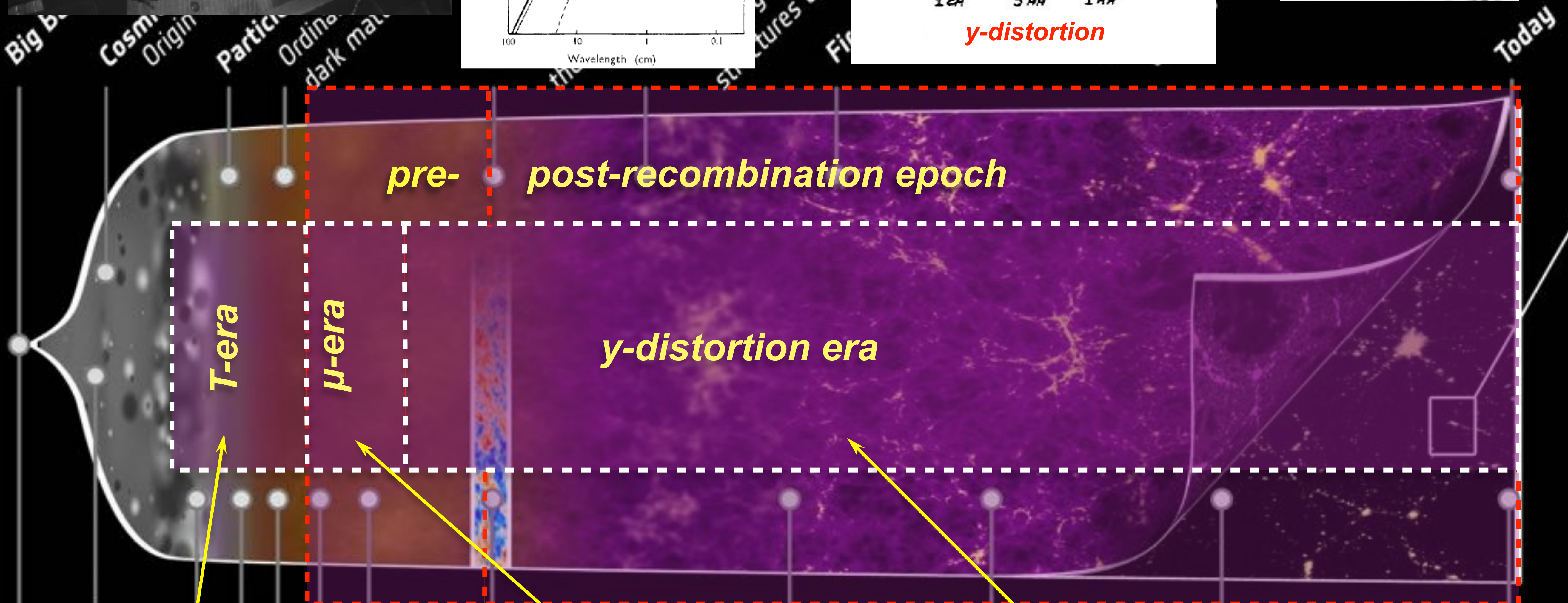
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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

Measurements of CMB spectrum will open a new unexplored window to the early Universe!

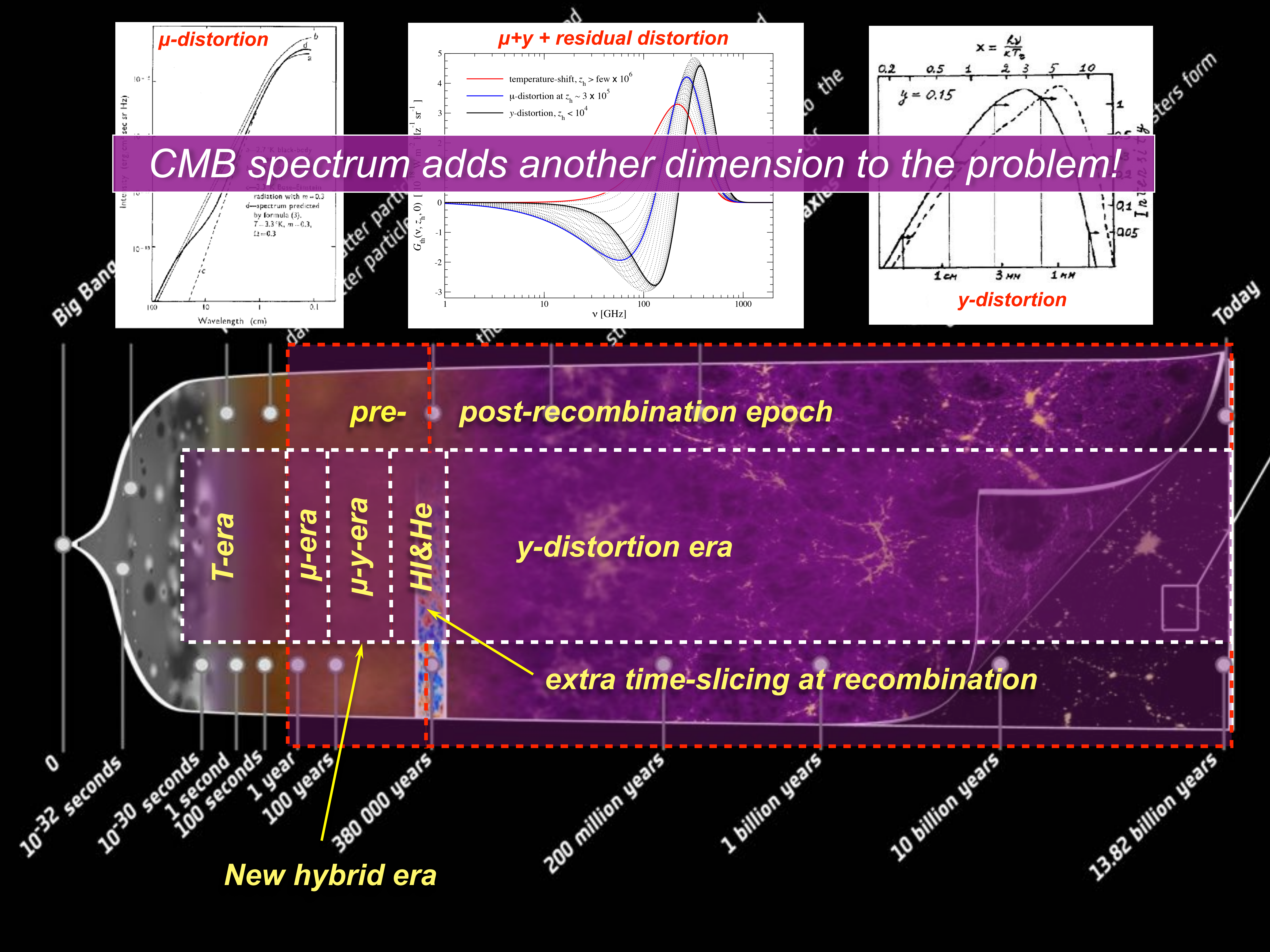








$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T \qquad \mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \qquad y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$


μ-distortion
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at z_h ~ 3 x 10^5
y-distortion, z_h < 10^4
ν [GHz]
y-distortion
CMB spectrum adds another dimension to the problem!
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
New hybrid era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
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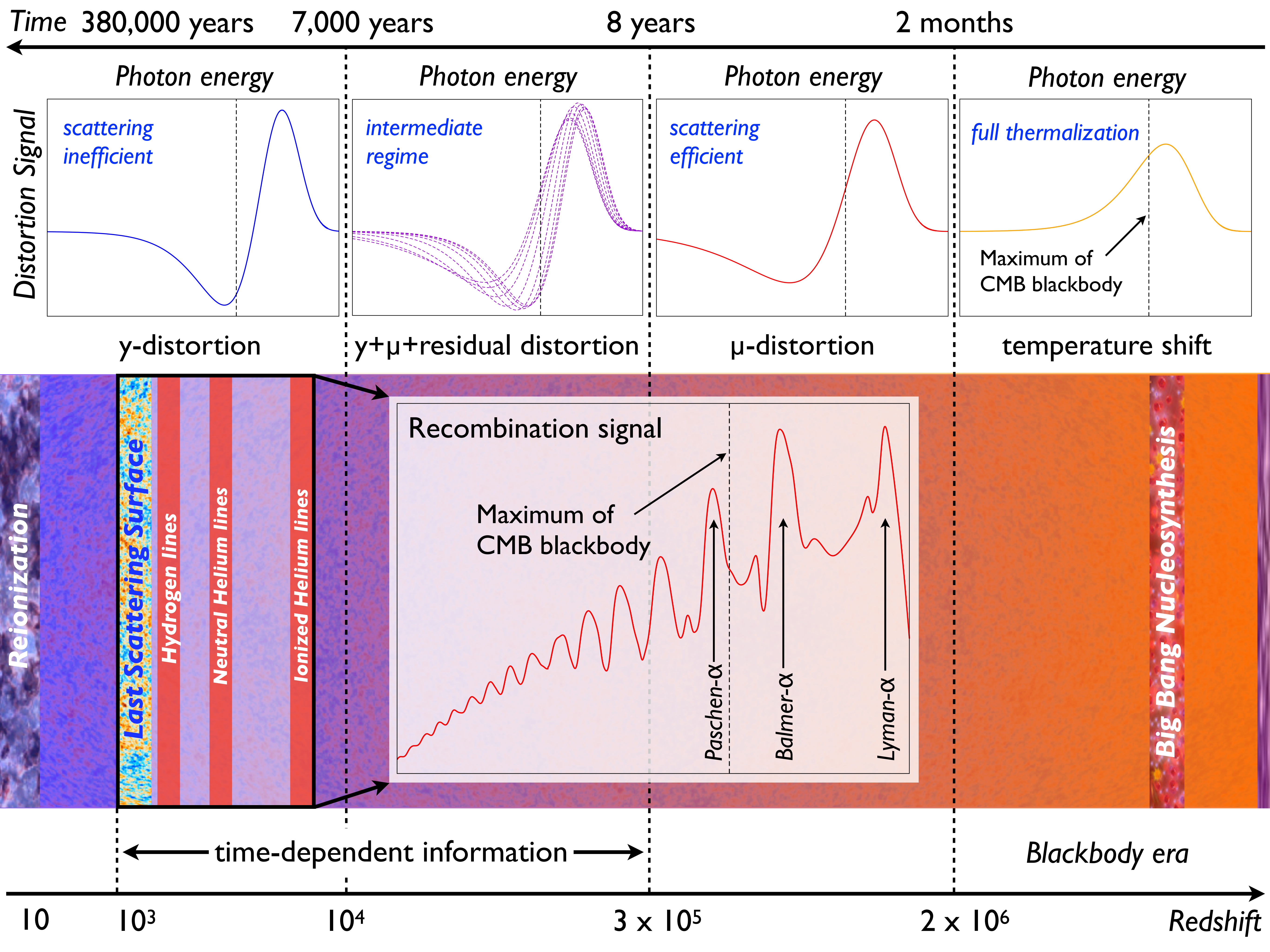
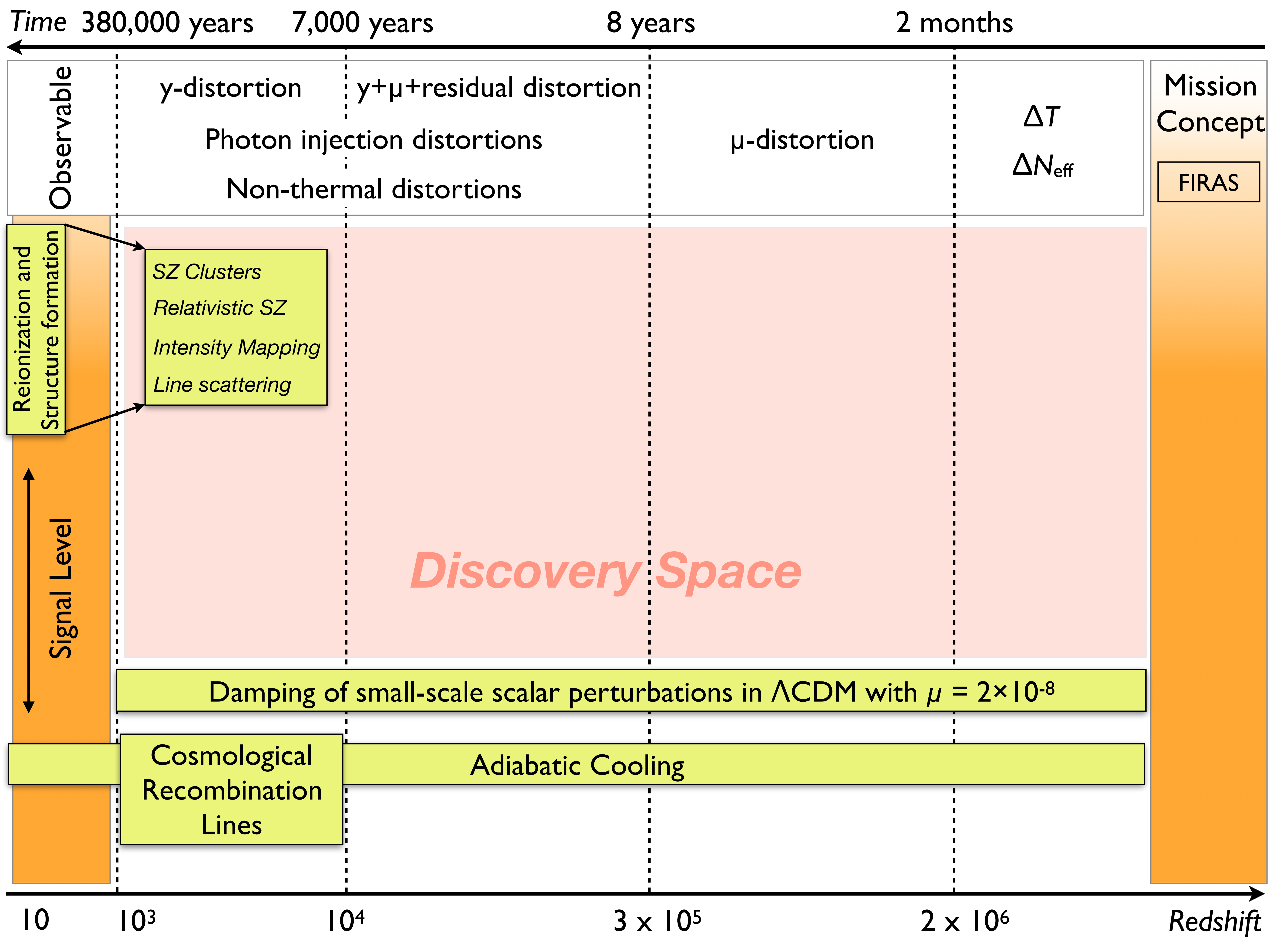
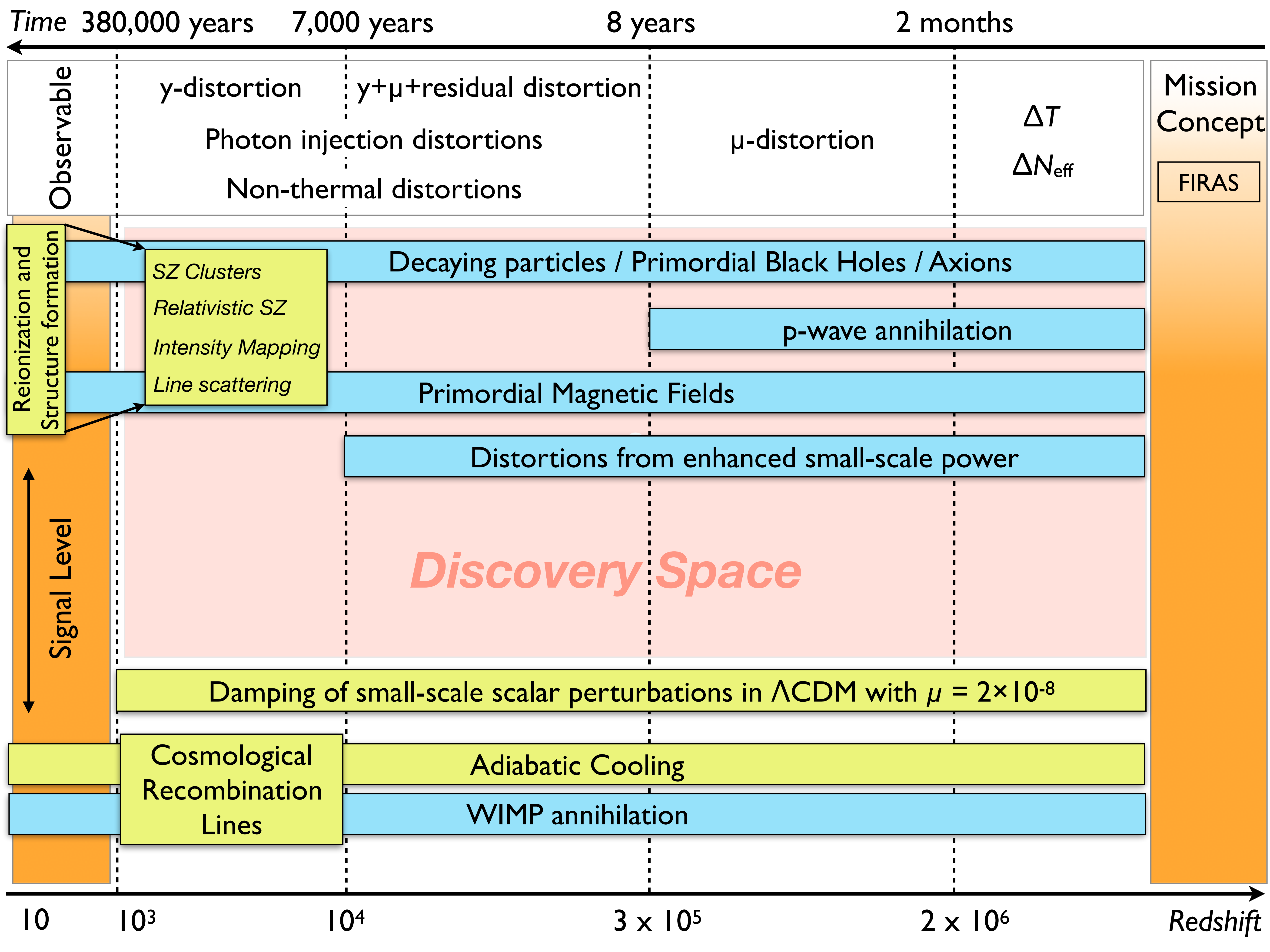


Time 380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
intermediate regime
scattering efficient
full thermalization
Maximum of CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Reionization
Last Scattering Surface
Hydrogen lines
Neutral Helium lines
Ionized Helium lines
Recombination signal
Maximum of CMB blackbody
Paschen-α
Balmer-α
Lyman-α
Big Bang Nucleosynthesis
time-dependent information
Blackbody era
10
10³
10⁴
3 x 10⁵
2 x 10⁶
Redshift


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
Reionization and Structure formation
SZ Clusters
Relativistic SZ
Intensity Mapping
Line scattering
Discovery Space
Signal Level
Damping of small-scale scalar perturbations in ΛCDM with μ = 2×10^-8
Cosmological Recombination Lines
Adiabatic Cooling
10
10^3
10^4
3 x 10^5
2 x 10^6
Redshift



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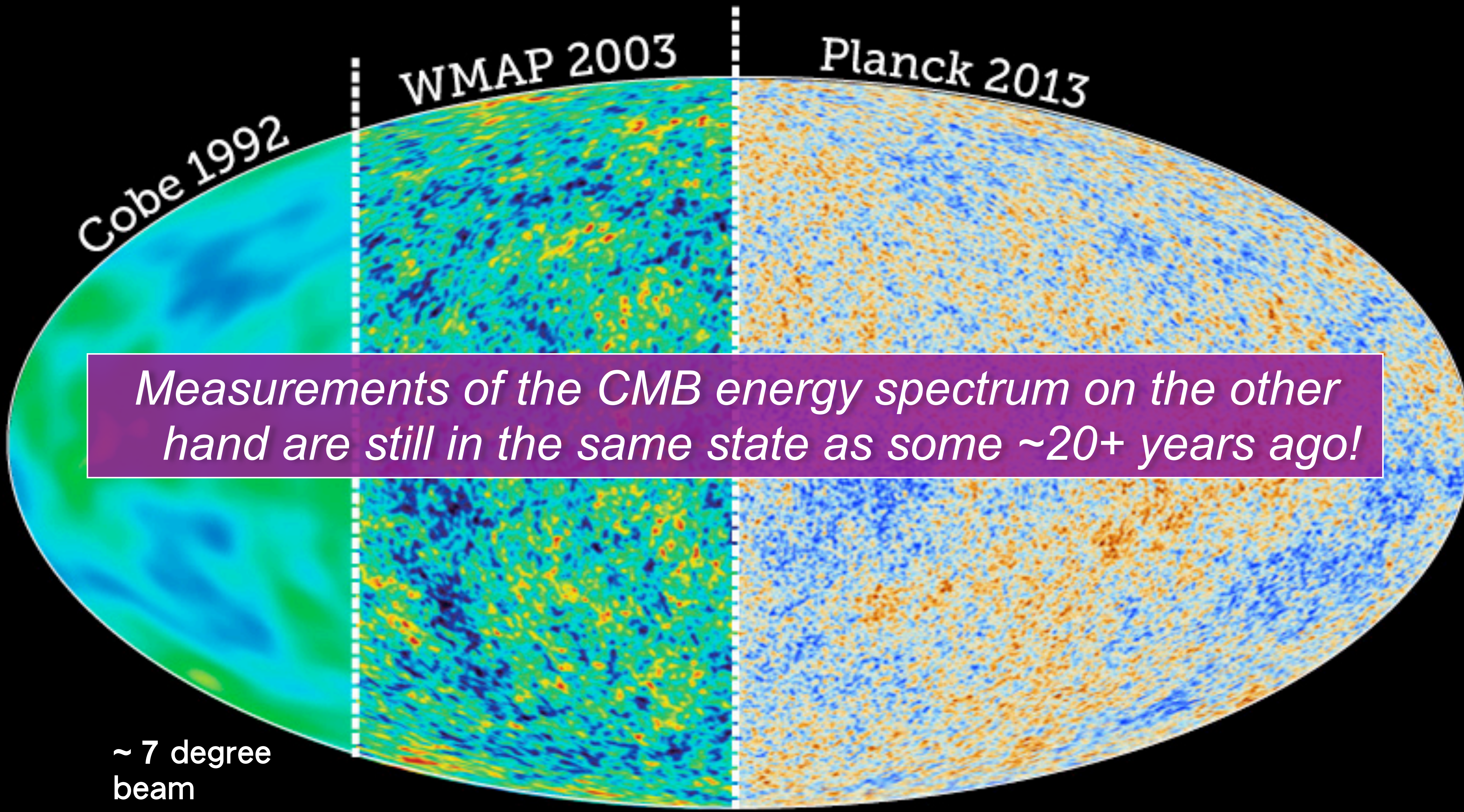
Primordial Magnetic Fields
Distortions from enhanced small-scale power
Discovery Space
Signal Level
Damping of small-scale scalar perturbations in ΛCDM with μ = 2×10-8
Cosmological Recombination Lines
Adiabatic Cooling
WIMP annihilation
10 10³ 10⁴ 3 x 10⁵ 2 x 10⁶ Redshift

Dramatic improvements in angular resolution and sensitivity over the past decades!



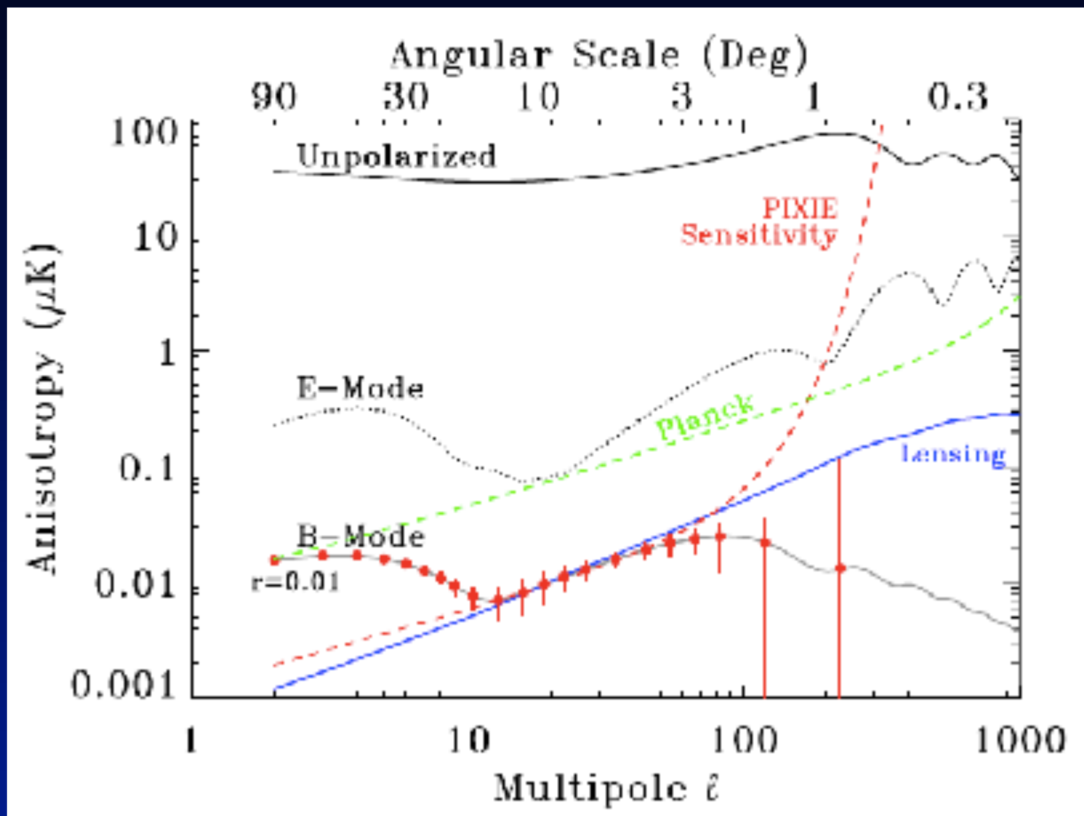
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

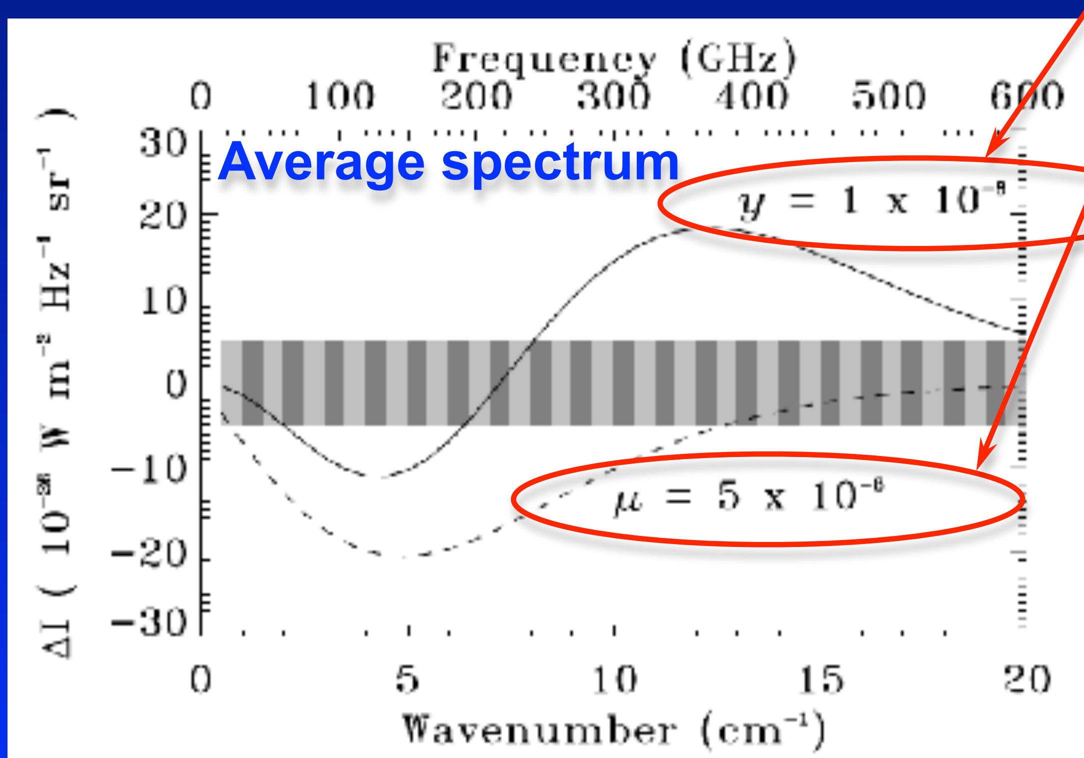
~ 0.3 degree beam

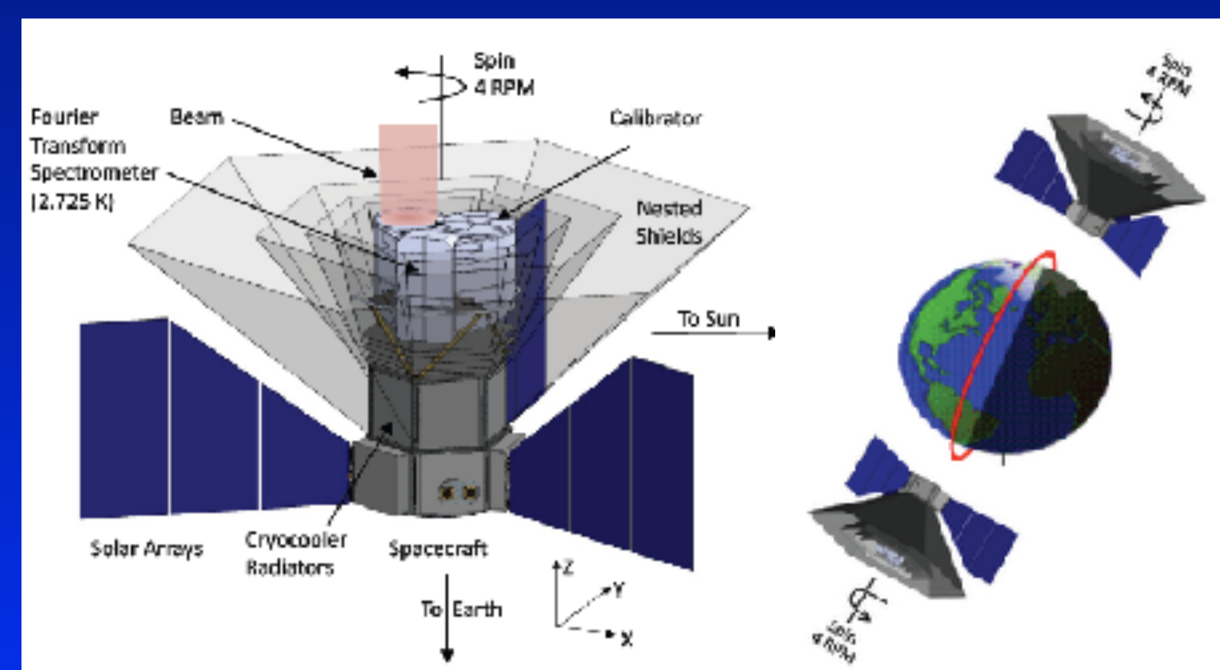
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer



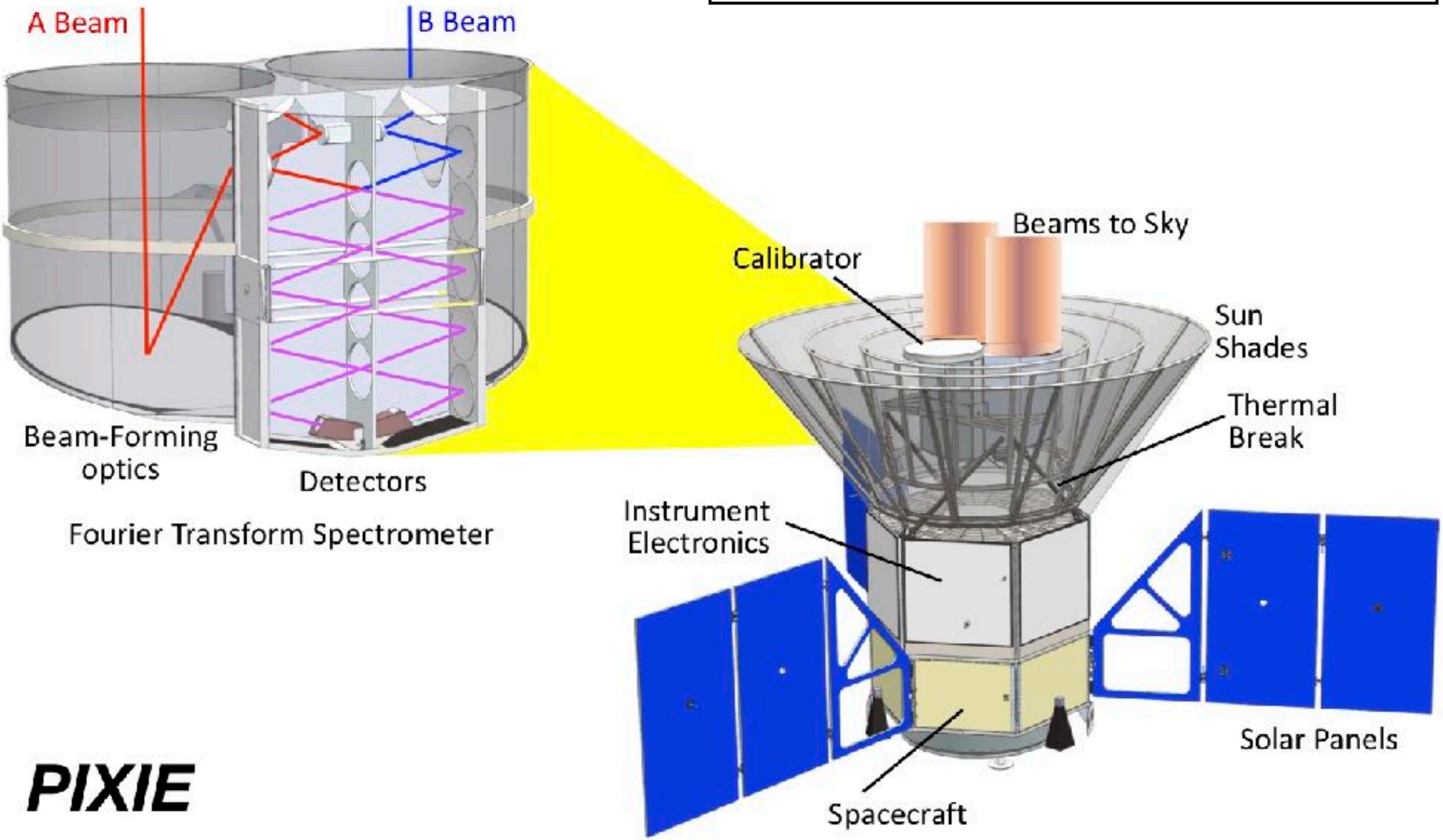
- 400 spectral channel in the frequency range 30 GHz and 6THz (Δν ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 and 2016 as NASA EX mission (i.e. cost ~ 250 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044

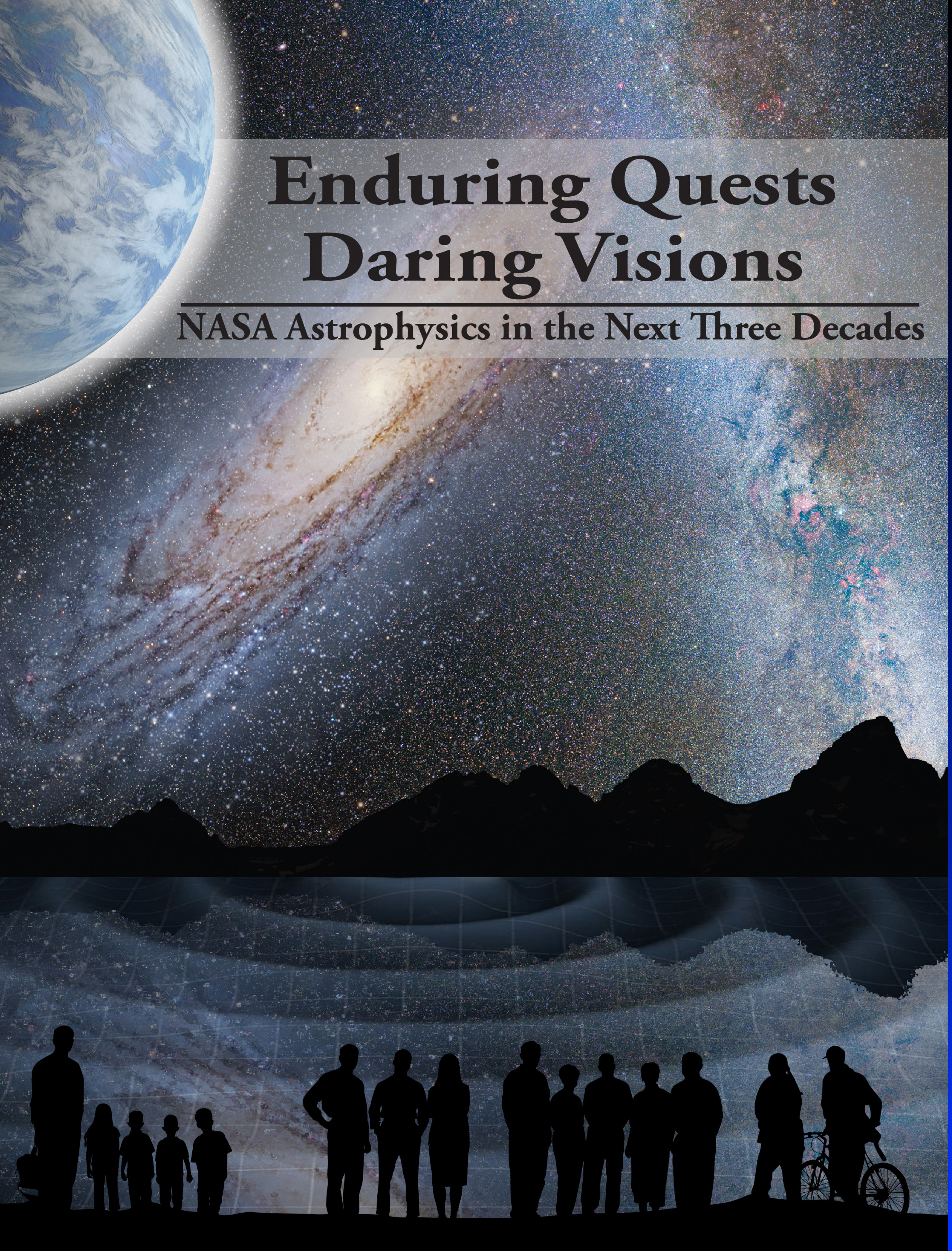
Built on the heritage of FIRAS



PIXIE

Kogut et al, BAAS, 2019, 2019, arXiv:190713195

Courtesy Al Kogut & Dale Fixsen



NASA 30-yr Roadmap Study

(published Dec 2013)

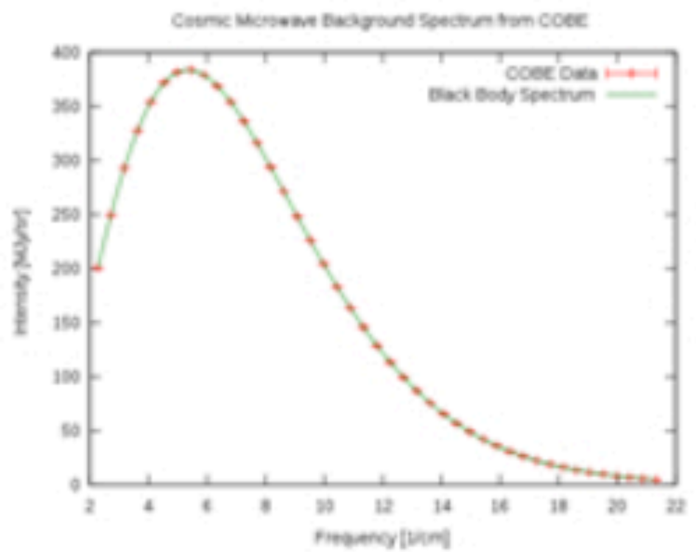
How does the Universe work?

"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

➡ *Ongoing NASA Decadal Review*

Super-PIXIE

Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion



About APSERa

The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval plasma in the early Universe adds broad spectral lines to the relic Cosmic Radiation. The lines are extremely wide because recombination is stalled and extended over redshift space. The spectral features are expected to be isotropic over the whole sky.

The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby radio-quiet locations and relocated to a remote site for long duration exposures to detect the subtle features in the cosmic radio background arising from recombination. The observing site would be appropriately chosen to minimize RFI from geostationary satellites and to be able to observe towards sky regions relatively low in foreground brightness.

COSMO at Dome C

COSmological Monopole Observer

SAPIENZA
UNIVERSITÀ DI ROMA

Taken from a talk by Elia Battistelli

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

CNR IFN Istituto di Fotonica e Nanotecnologie

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

ASU ARIZONA STATE UNIVERSITY

PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE — ITALIANTARTIDE

Probing fundamental physics with CMB spectral distortions

12 Mar 2018, 00:30 → 16 Mar 2018, 19:00 Europe/Zurich

503-1-001 - Council Chamber (CERN)

Most recent activities

Decadal science WP submitted in Feb

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[56], 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]

cnes

PRISTINE

PI: Nabila Aghanim

F-class: Spectrometer

VOYAGE 2050
LONG-TERM PLANNING OF THE ESA SCIENCE PROGRAMME

SCHEDULE FOR THIS CALL AND IMPORTANT DATES

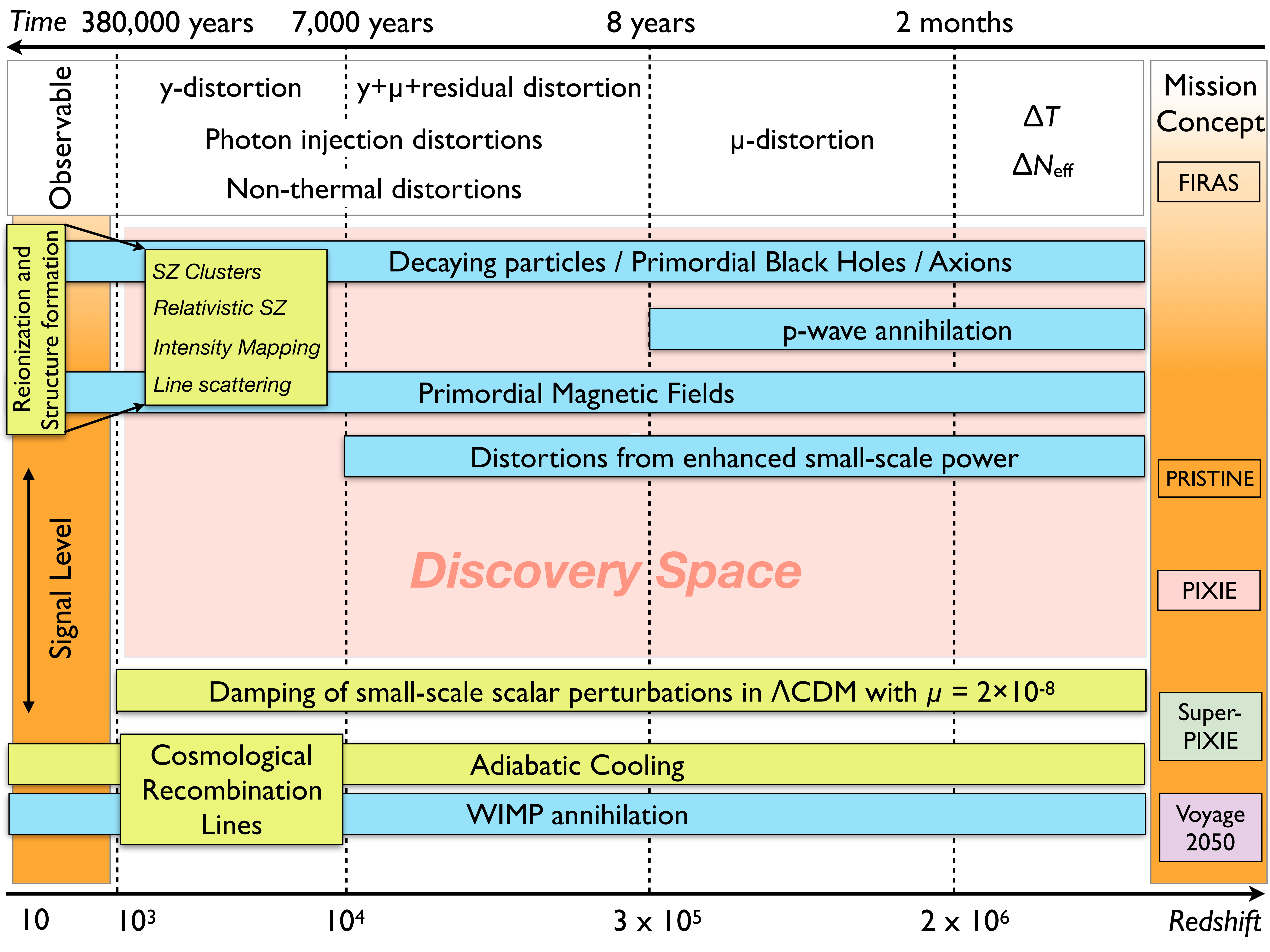
Activity	Date
Senior Committee appointed	December 2018
Call for Membership of Topical Teams issued	4 March 2019
Call for White Papers issued	4 March 2019
Deadline for receipt of applications for Topical Team membership	6 May 2019, 12:00 (noon) CEST
Topical Team members appointed	July 2019
Deadline for 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

cnes

BISOU

a Balloon Interferometer for Spectral Observations of the primordial Universe

PI: Bruno Maffei



Time 380,000 years 7,000 years 8 years 2 months
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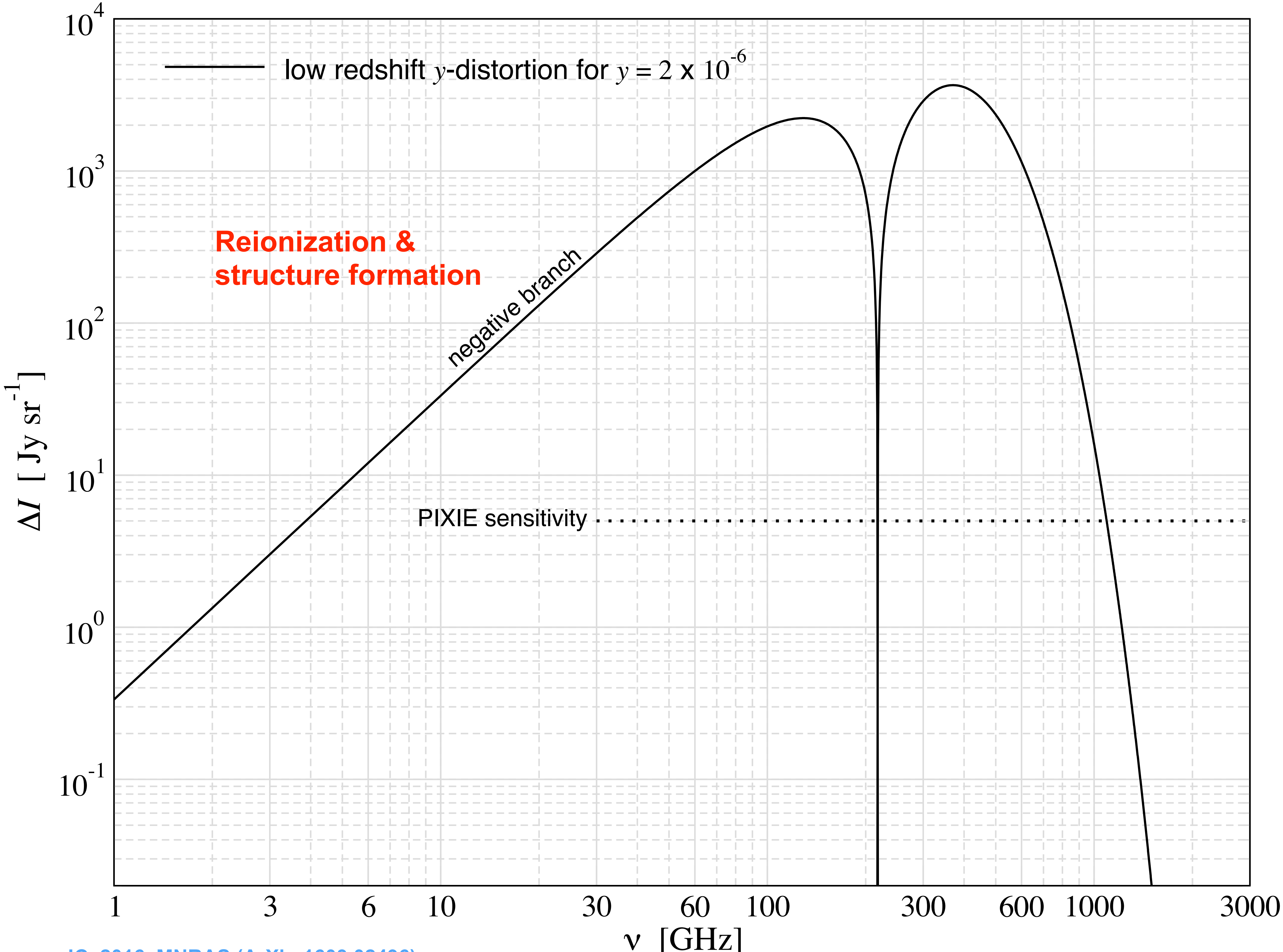
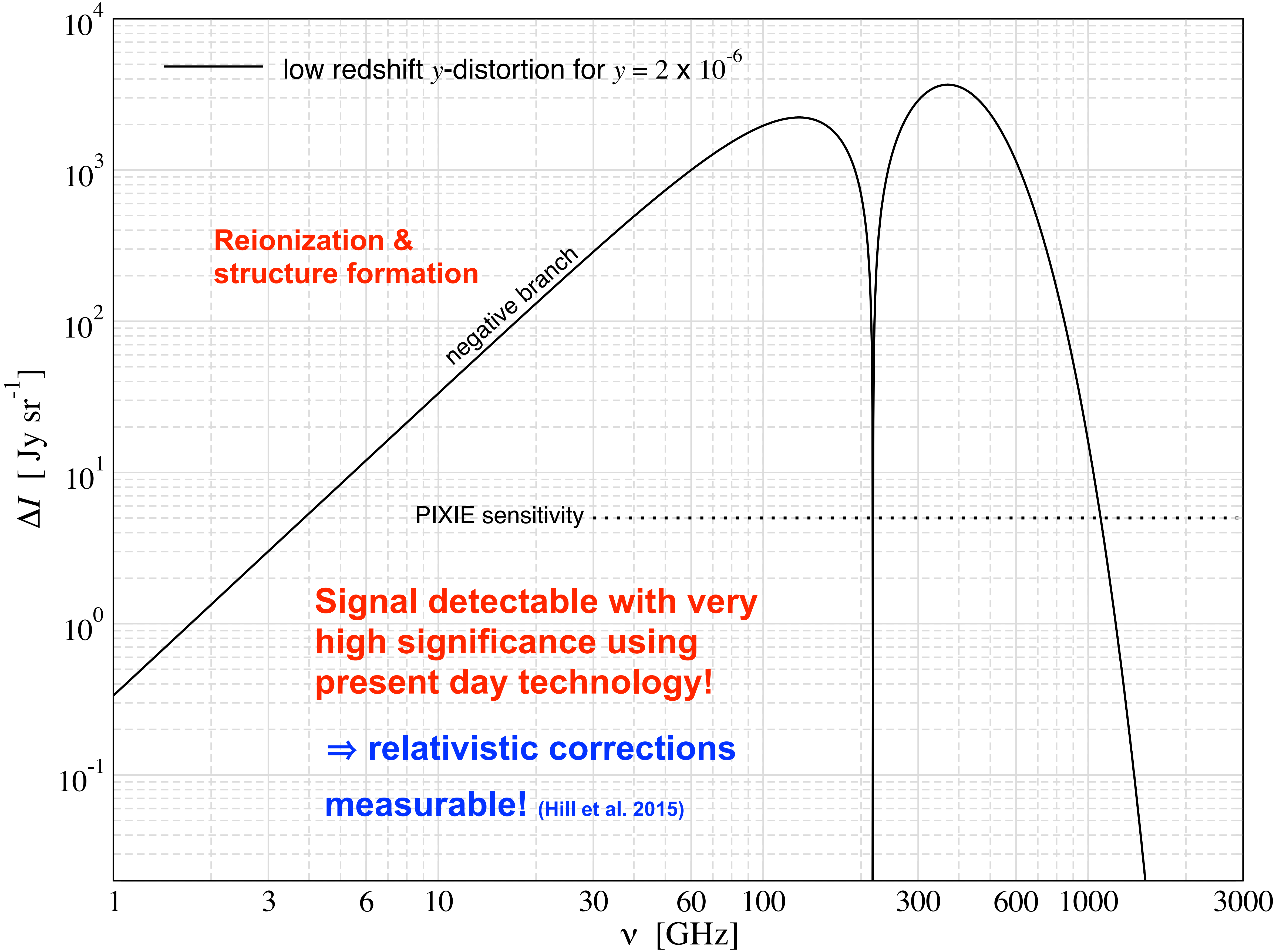
Adiabatic Cooling
WIMP annihilation
Voyage 2050
10 10³ 10⁴ 3 x 10⁵ 2 x 10⁶ Redshift

Average CMB spectral distortions

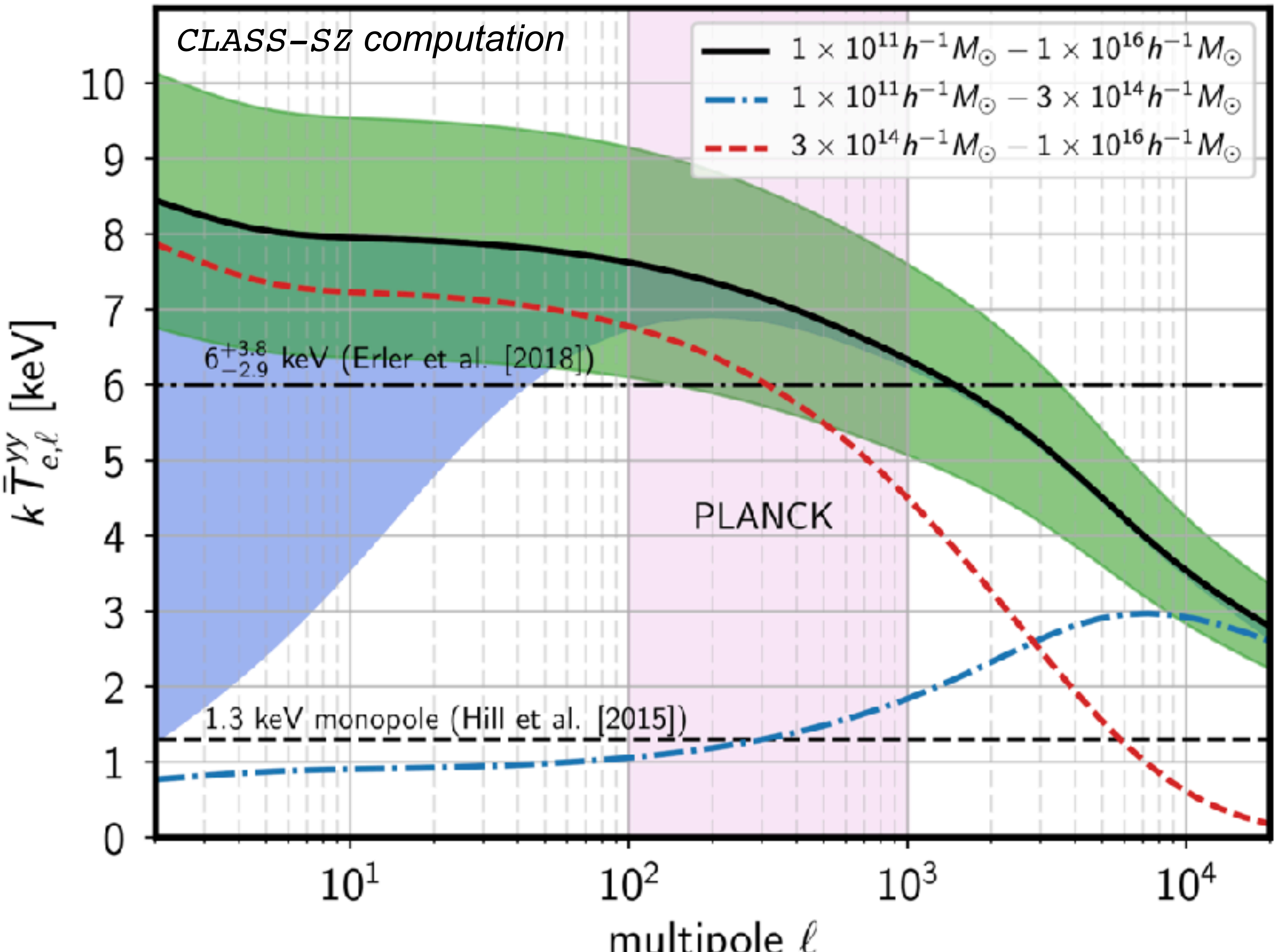


JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



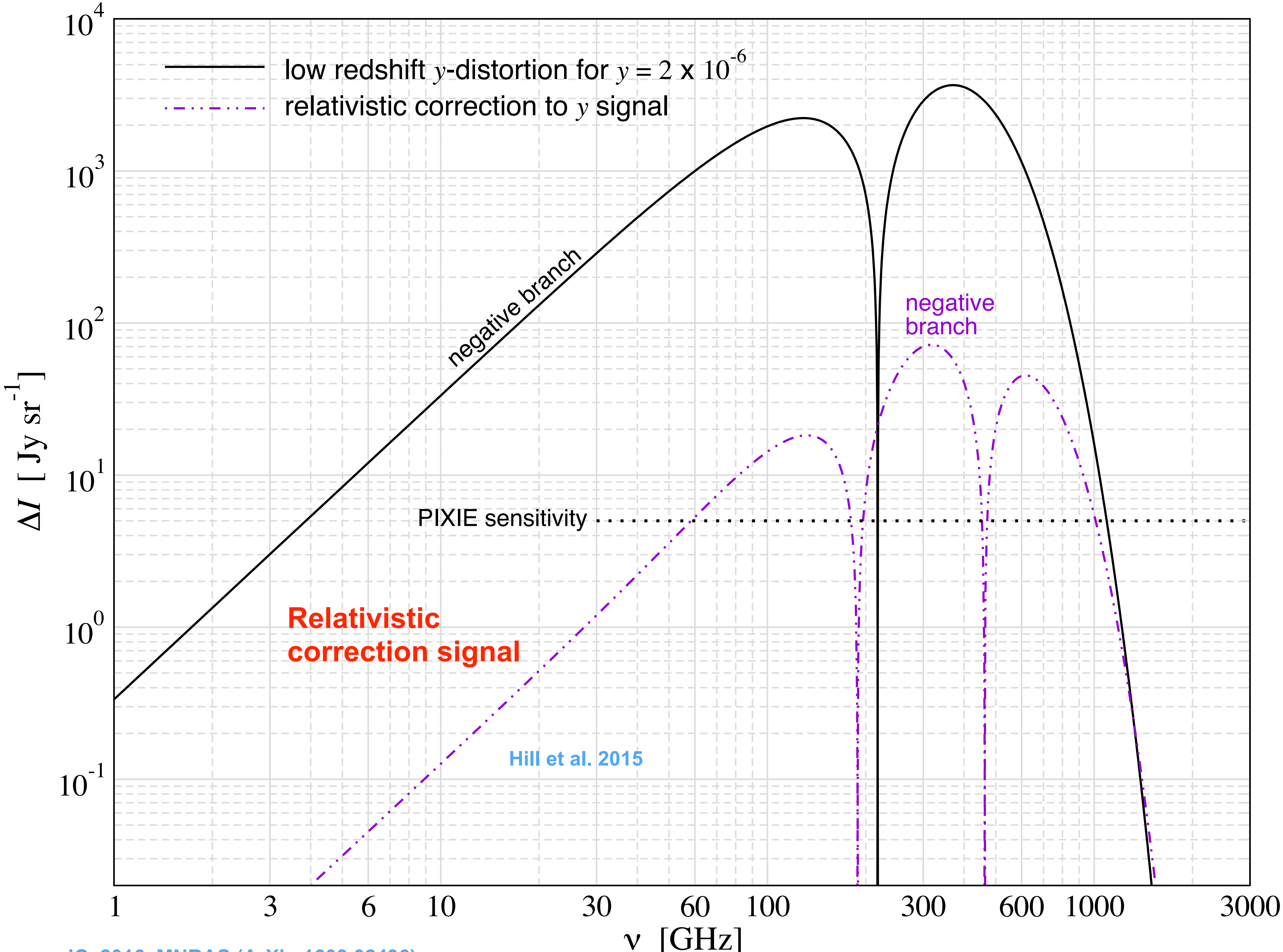
Theoretical estimate for the y^2-weighted temperature



Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

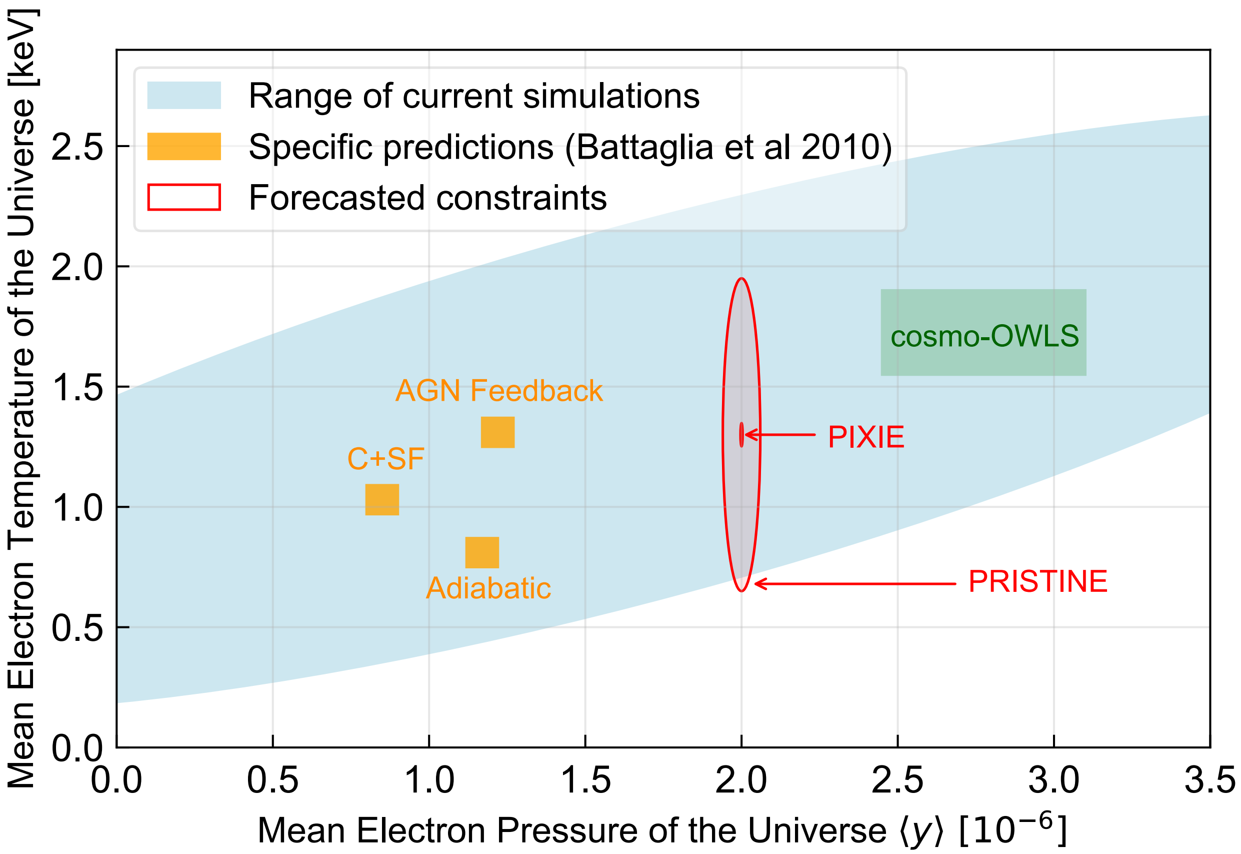
Talk by Mathieu Remazeilles

Average CMB spectral distortions

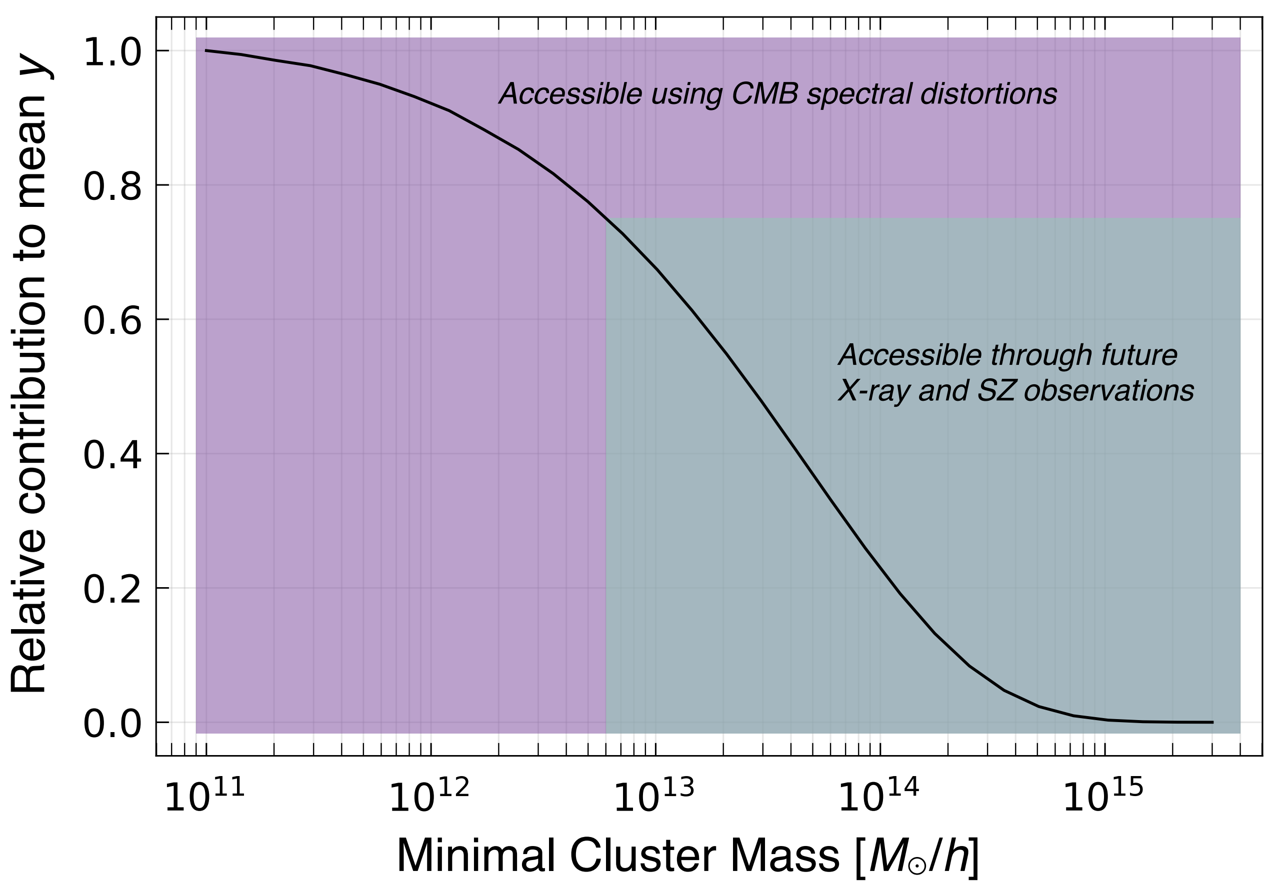


JC, 2016, MNRAS (ArXiv:1603.02496)

Learning about feedback processes using average rSZ



- Models highly uncertain
- Tight constraints from spectral distortions
- *Census* of all the hot gas in the Universe from *y* parameter

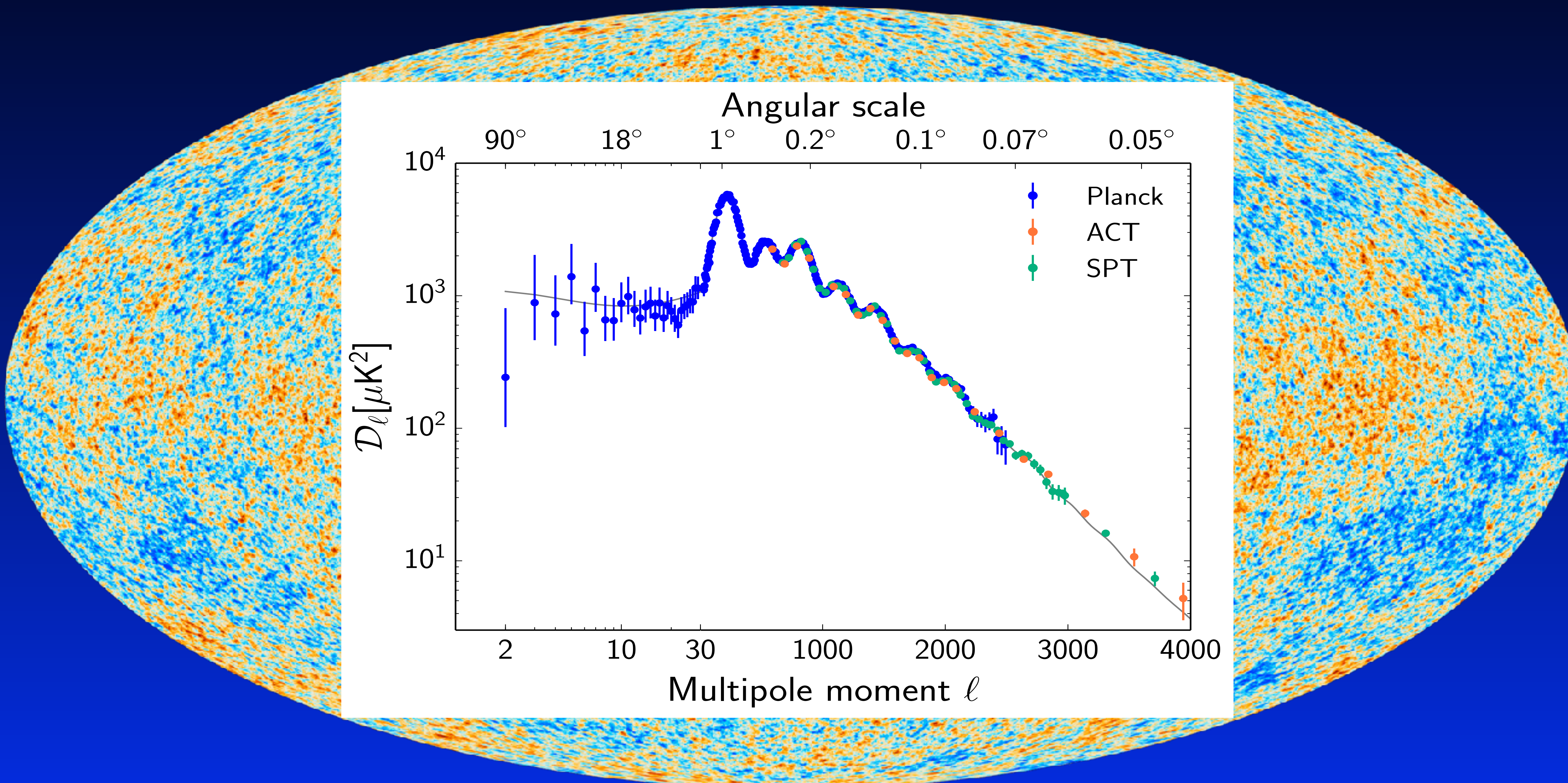


Bolliet et al., in prep

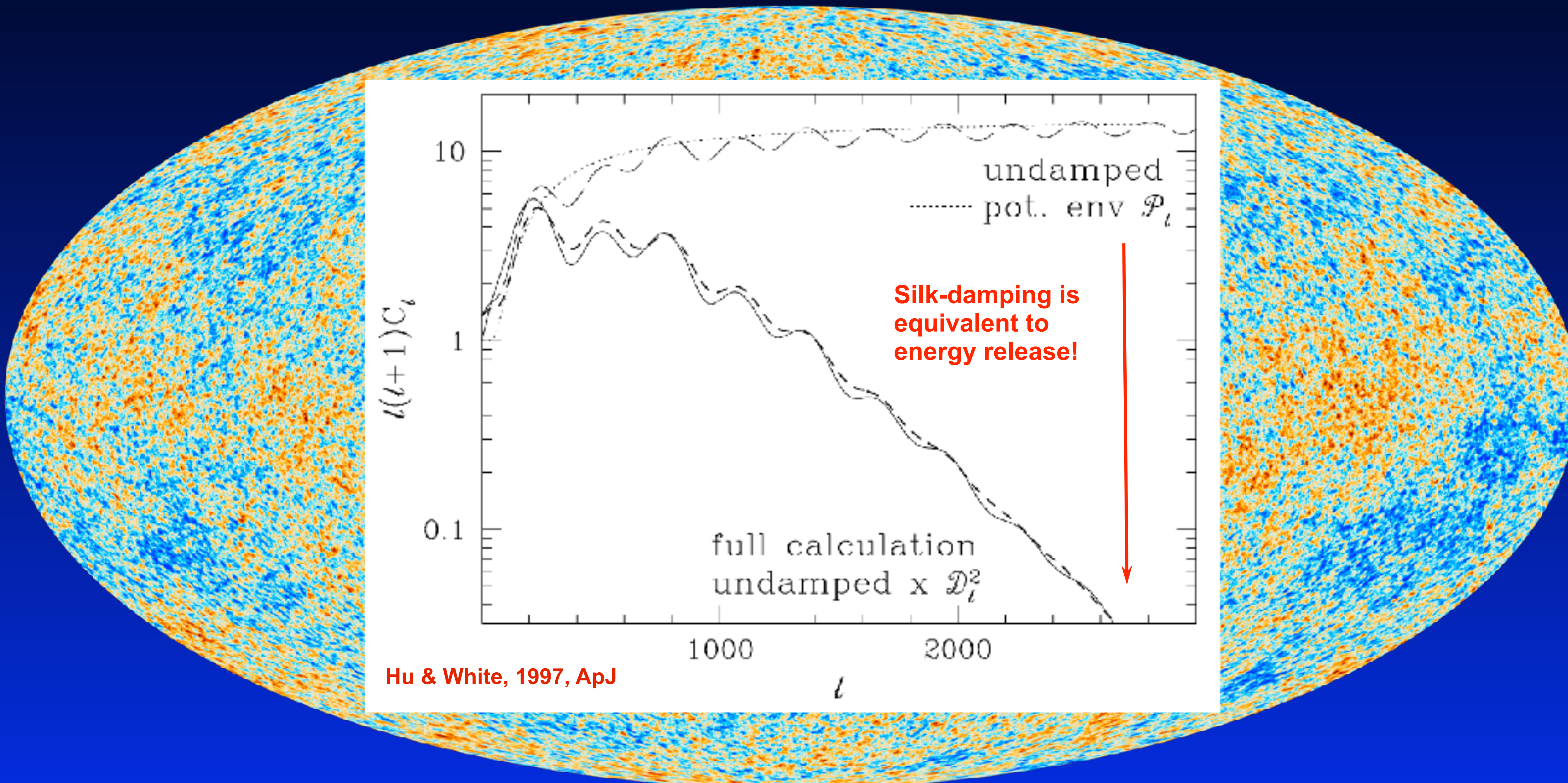
http://arxiv.org/abs/1909.01593

The dissipation of small-scale acoustic modes

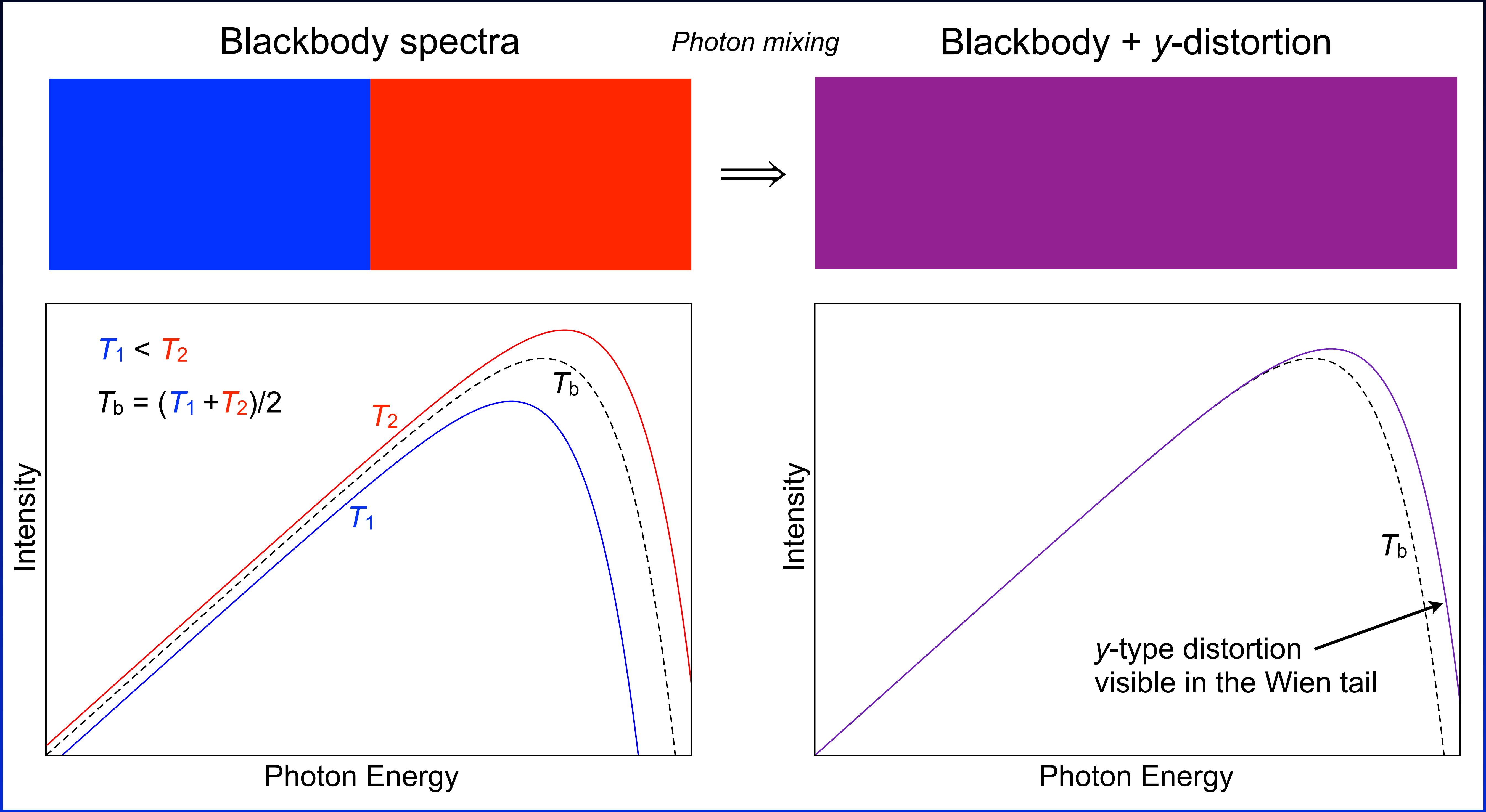
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



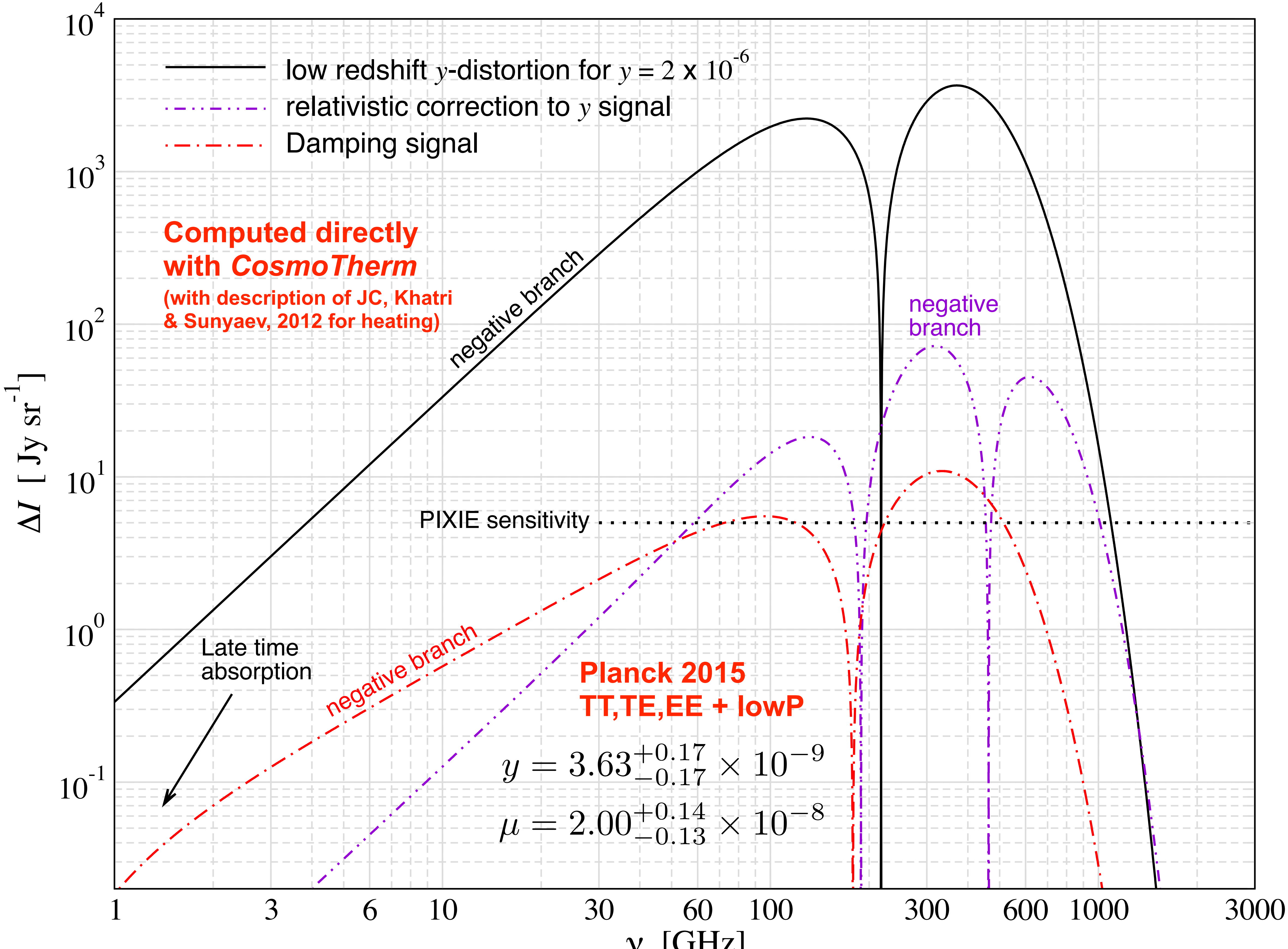
Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

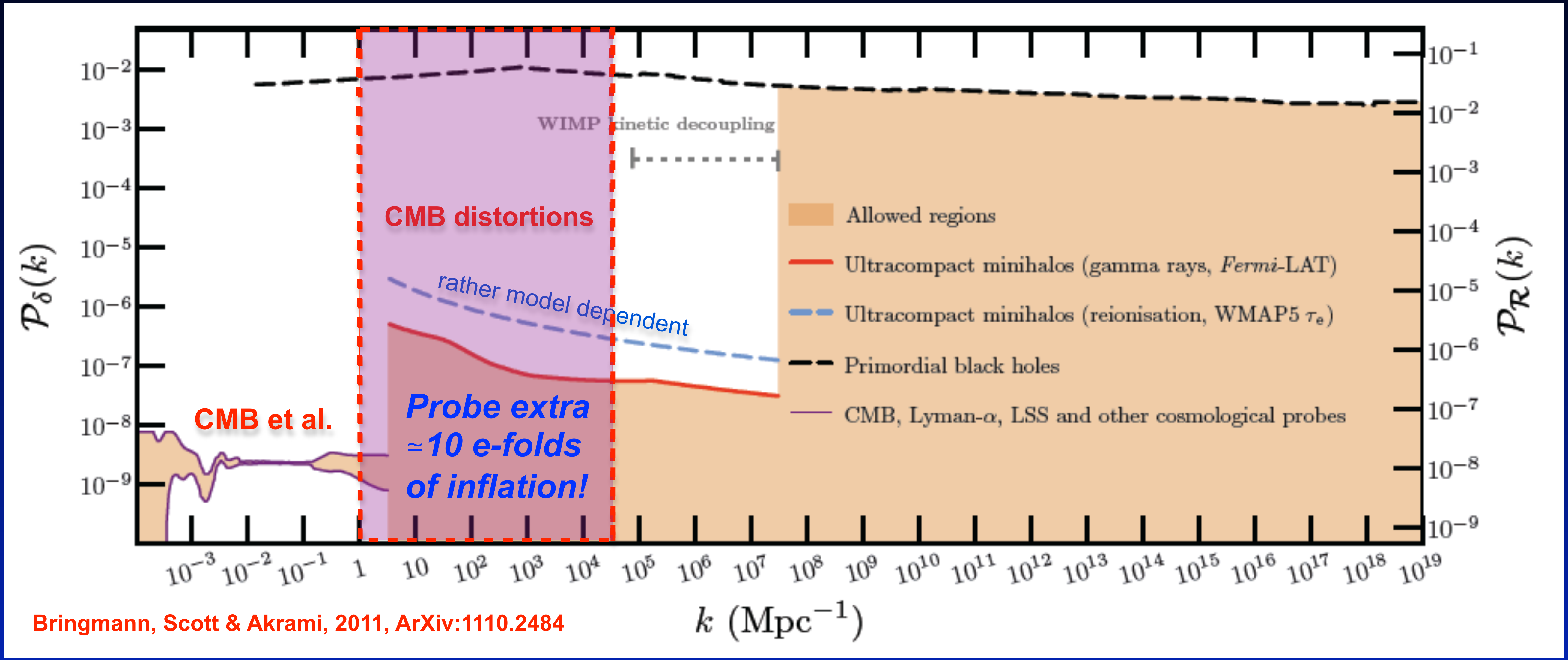
Mixing is mediated by Thomson scattering ⇒ Silk damping

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

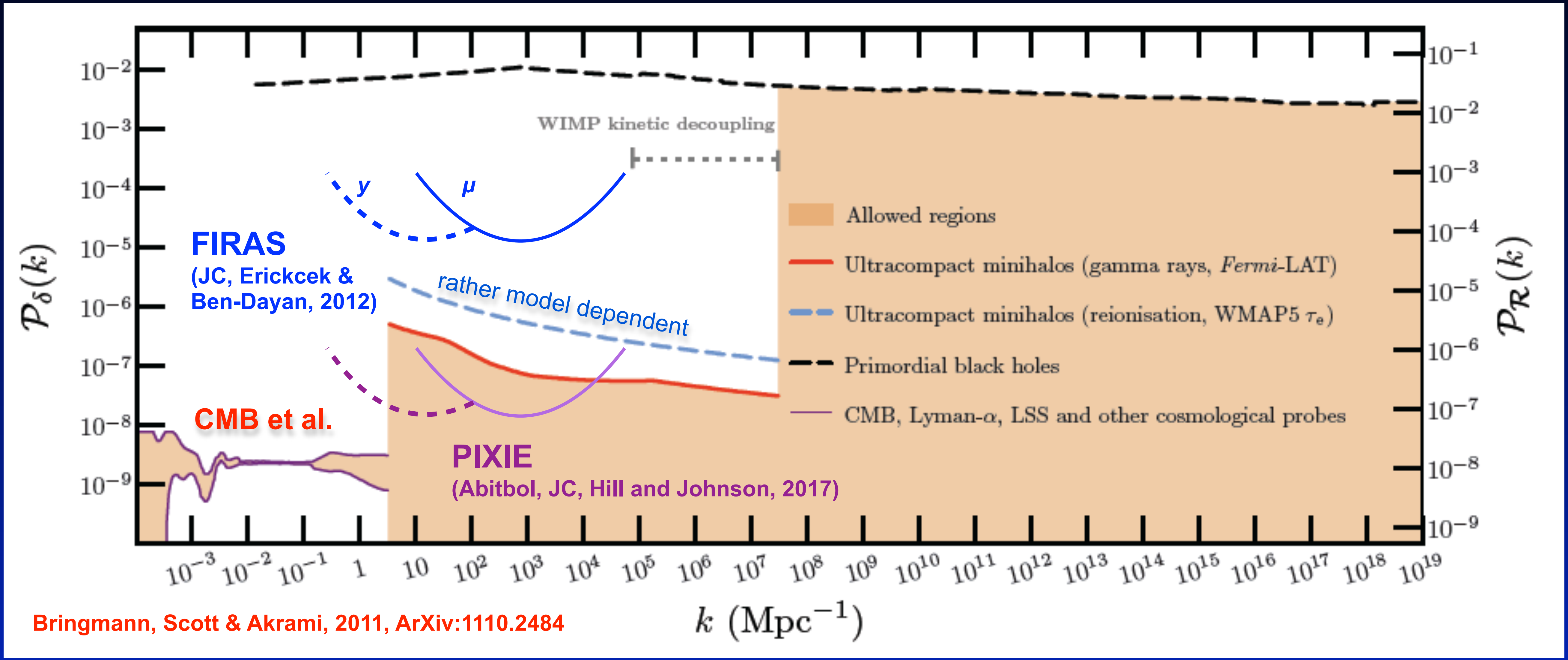
Distortions provide new power spectrum constraints!



- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about early-universe physics

e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

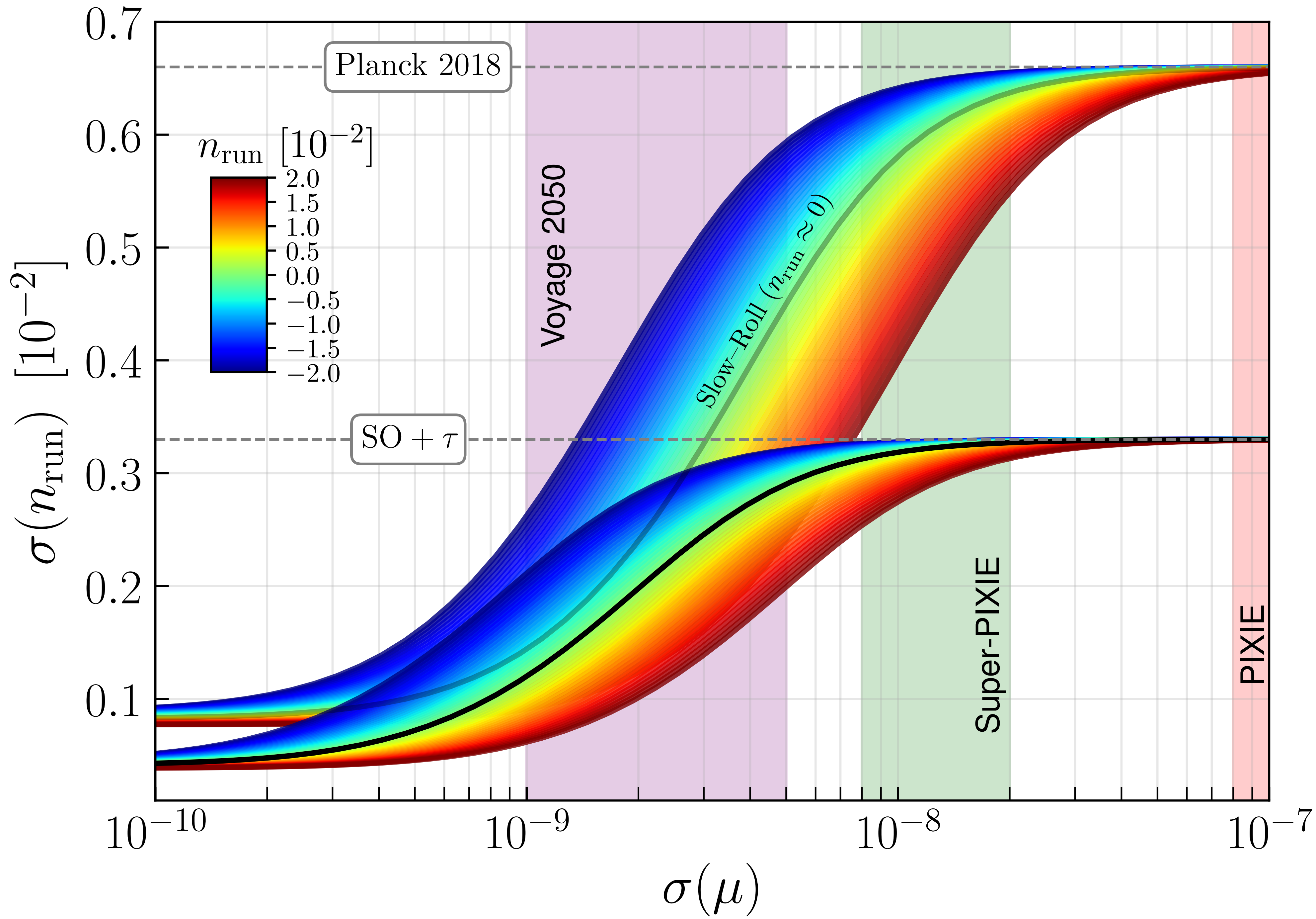
Distortions provide new power spectrum constraints!



- Amplitude of power spectrum rather uncertain at k > 3 Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about early-universe physics

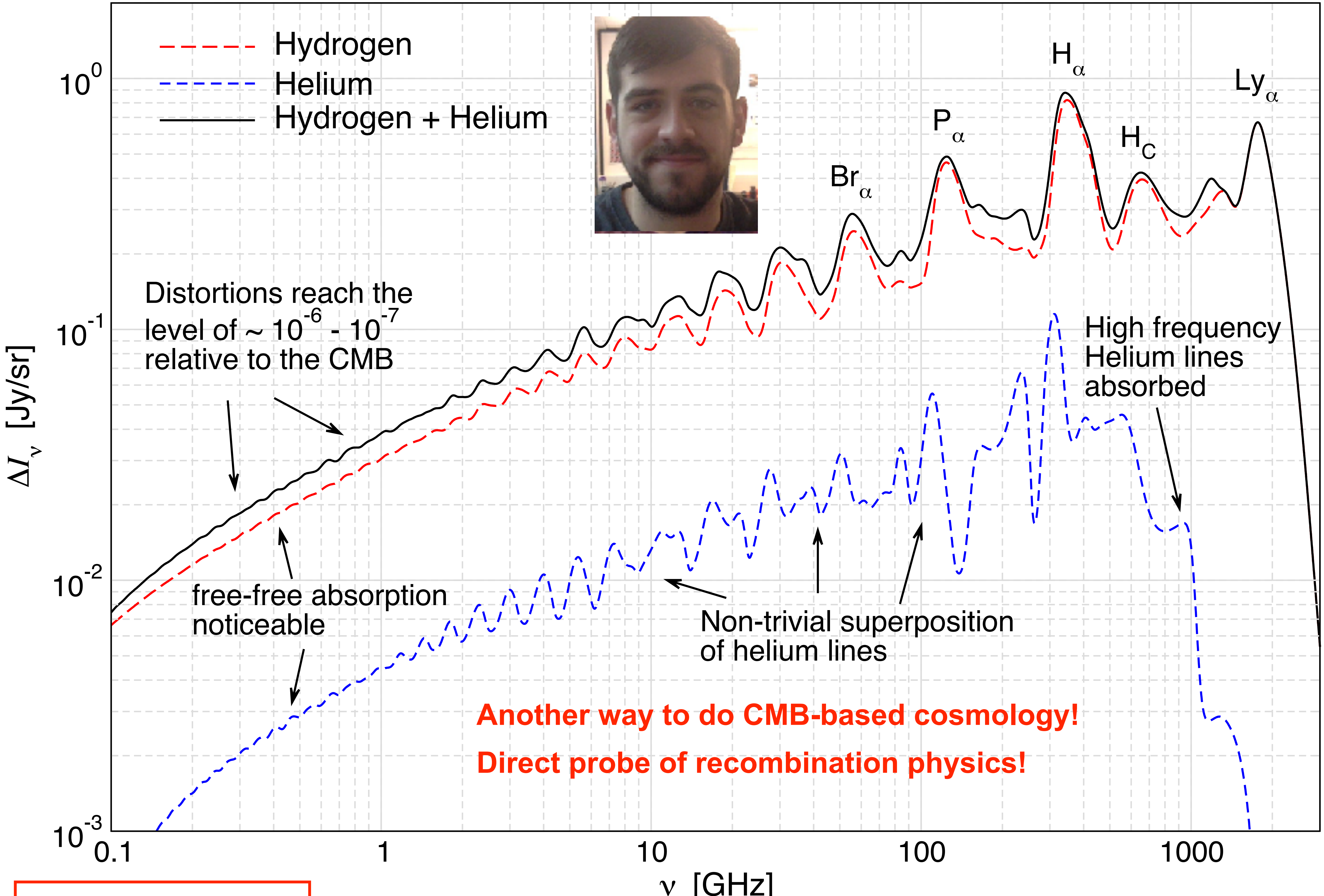
e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

Constraints on running of the scalar spectral index



http://arxiv.org/abs/1909.01593

Cosmological Recombination Radiation

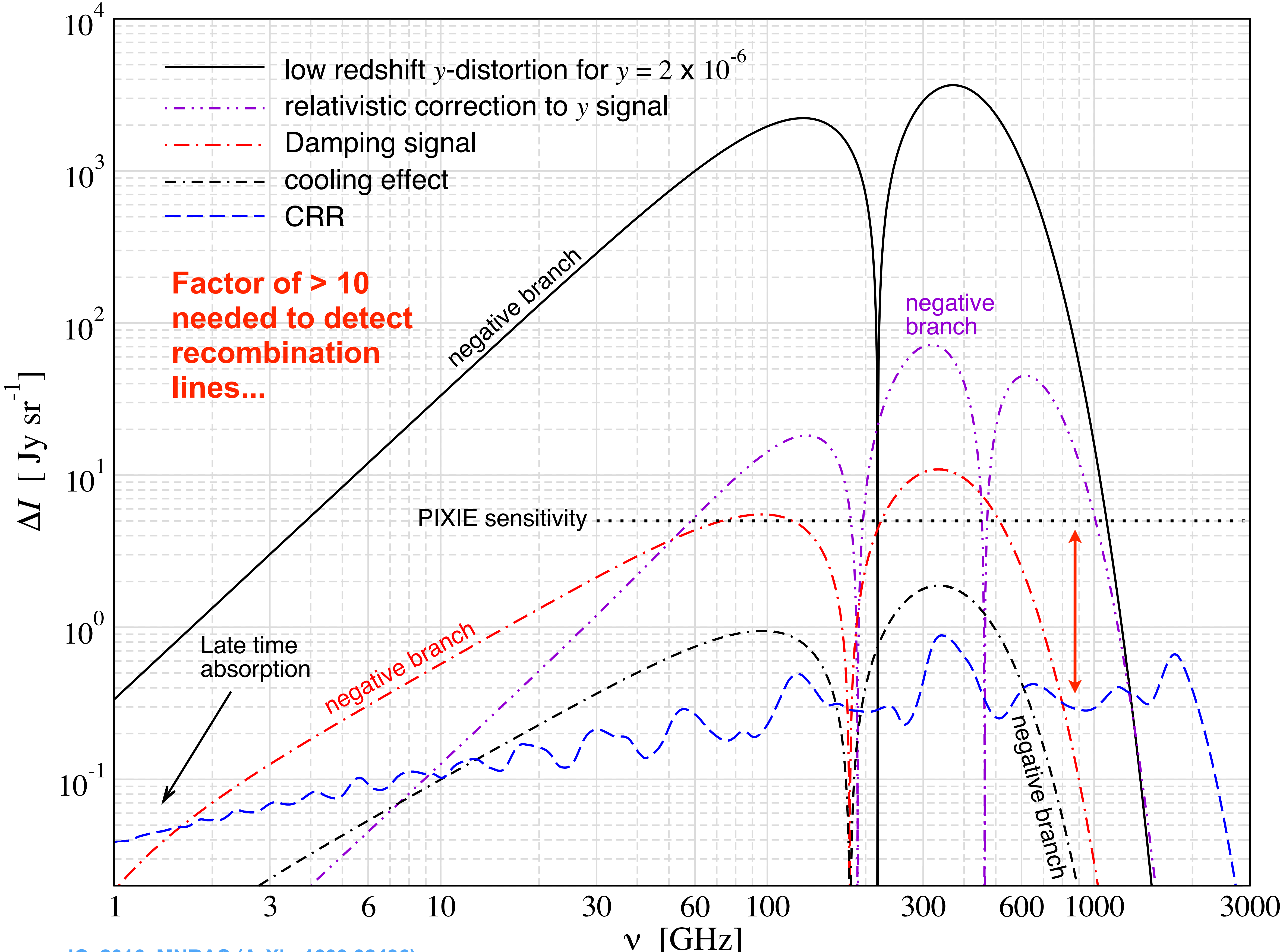


Courtesy Luke Hart

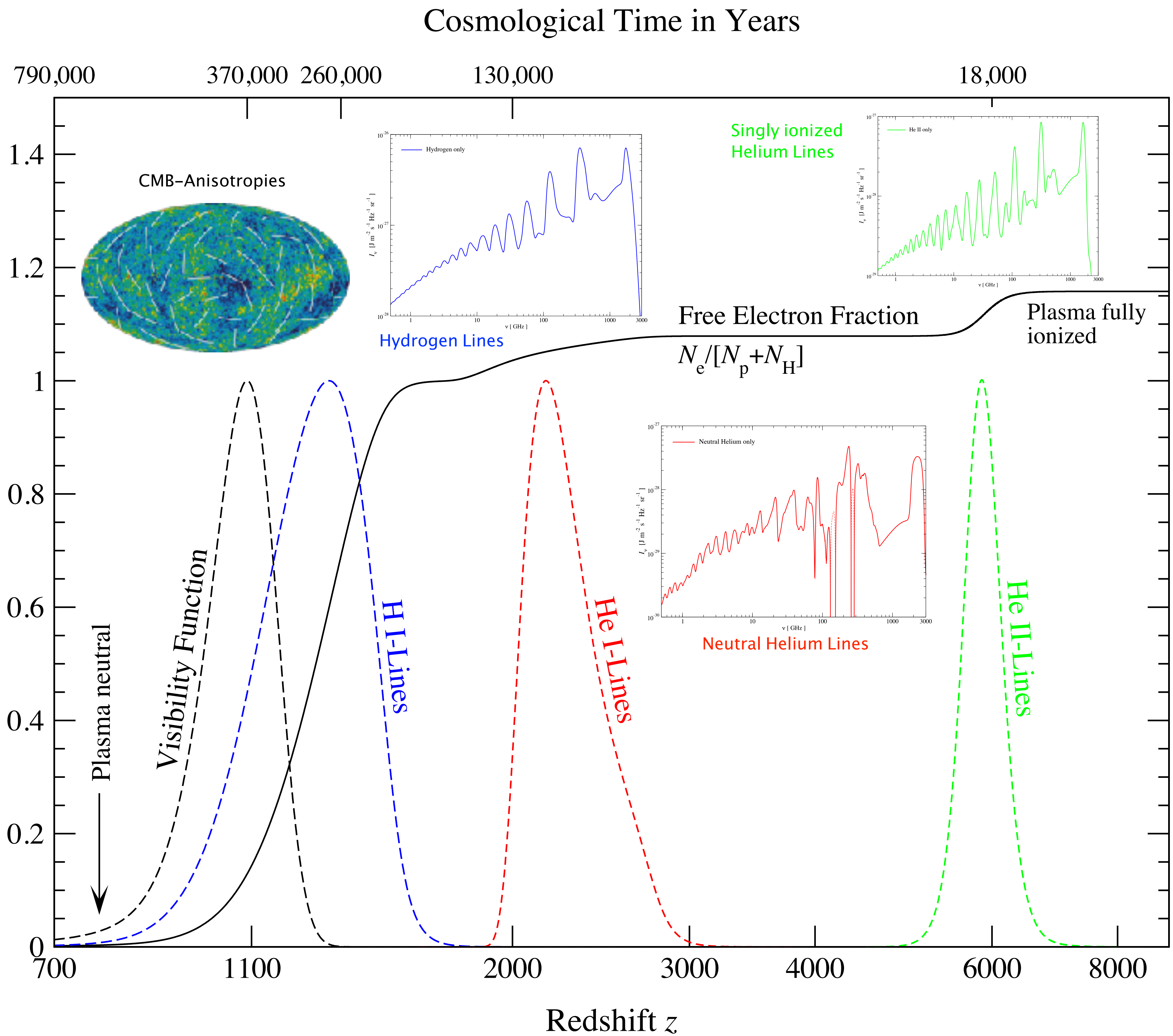
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009, JC & Ali-Haimoud, arXiv:1510.03877

http://arxiv.org/abs/1909.01593

Average CMB spectral distortions

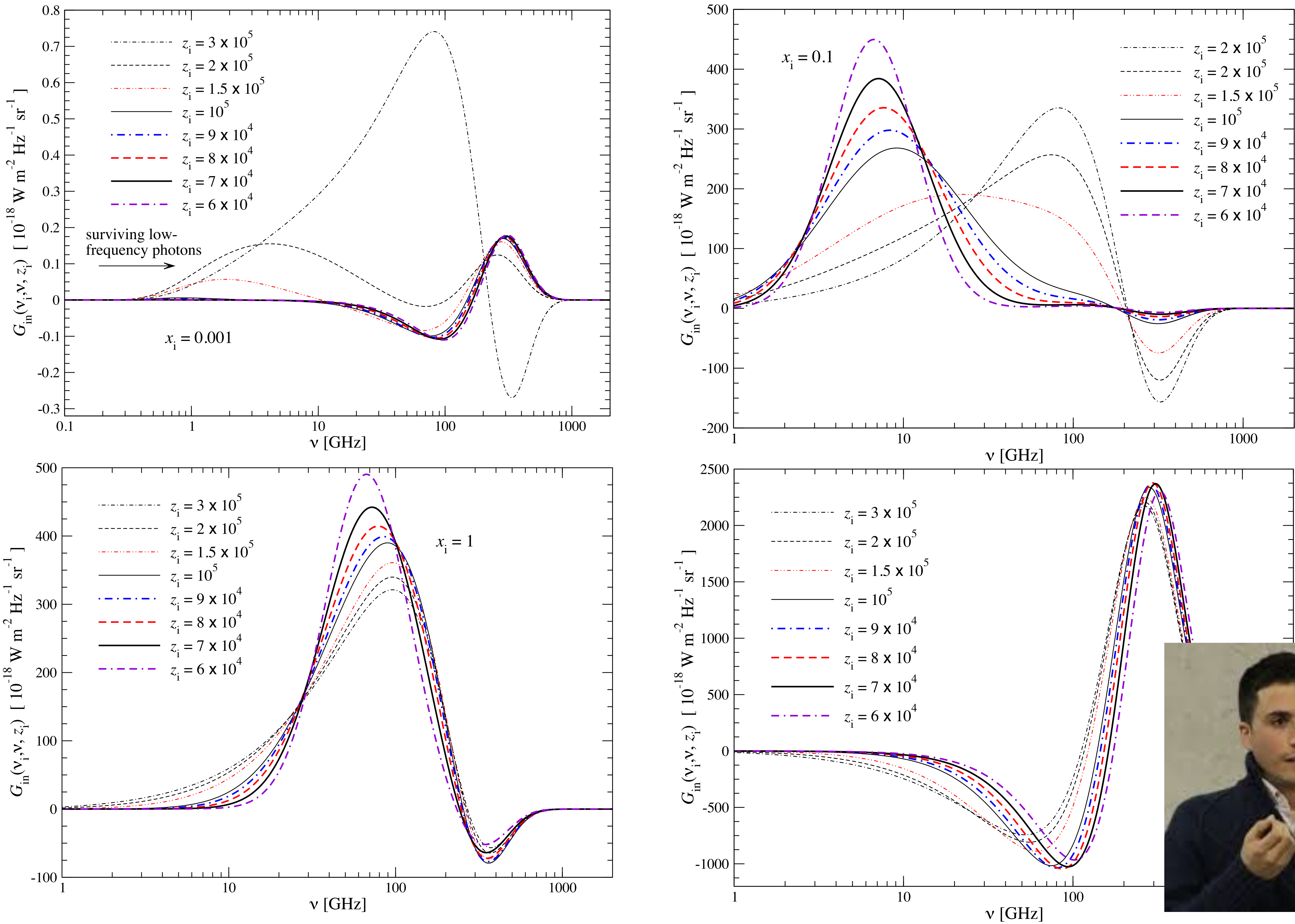


JC, 2016, MNRAS (ArXiv:1603.02496)



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

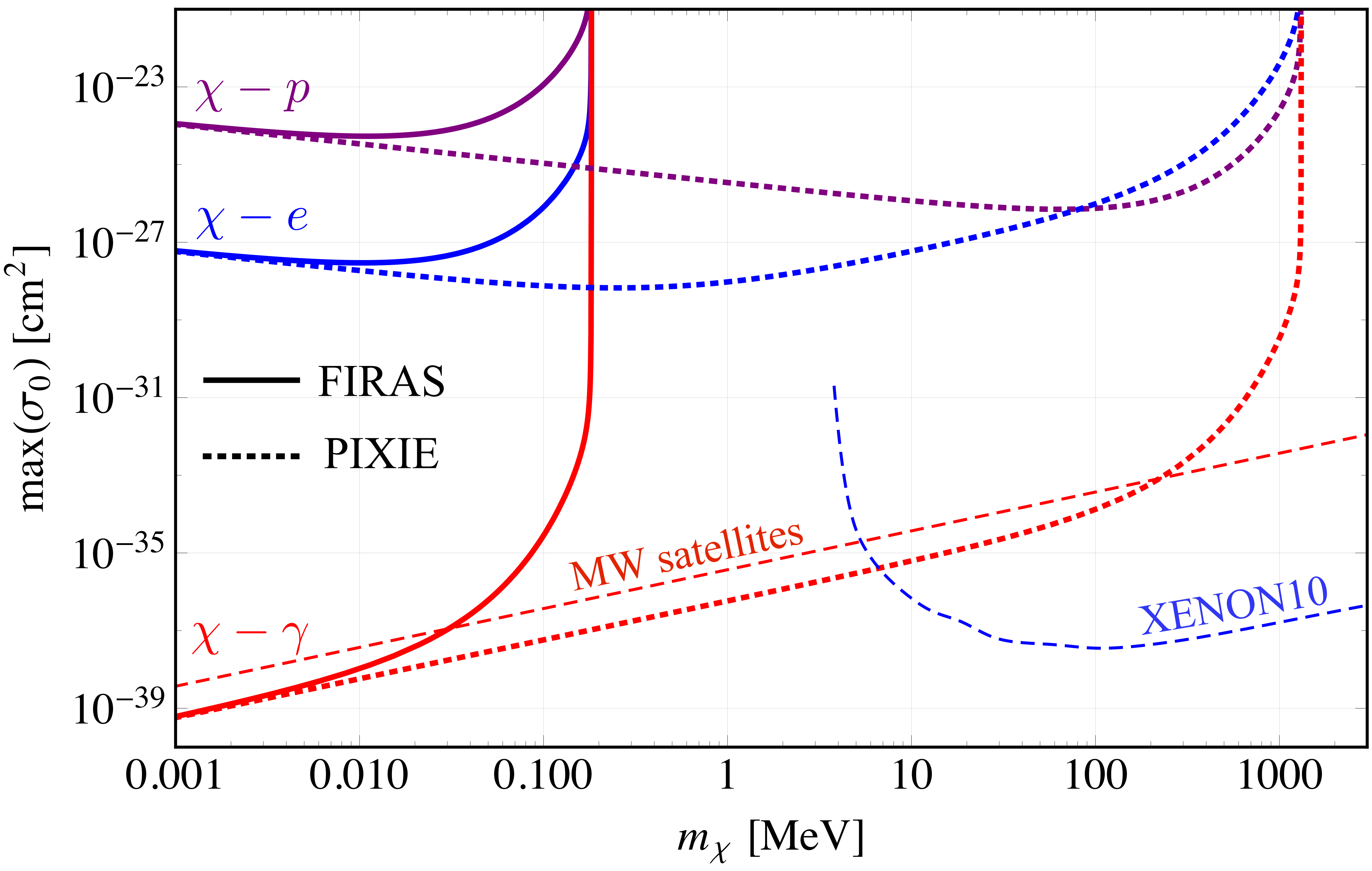
Rich phenomenology of photon injection distortions



JC 2015, ArXiv:1506.06582

Bolliet et al., in prep

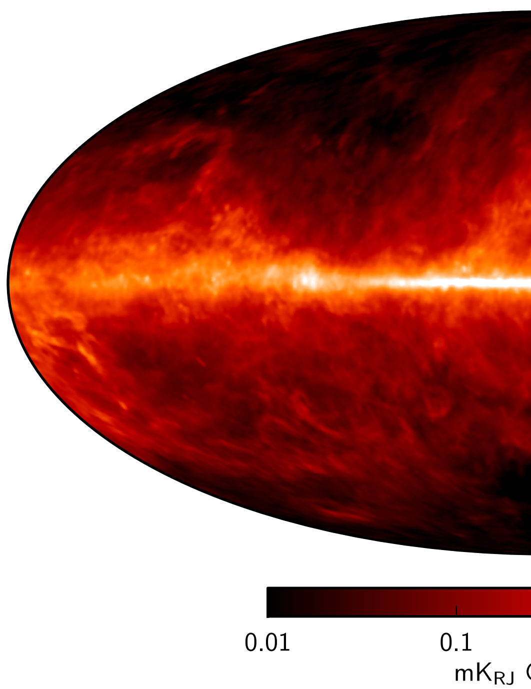
Distortion constraints on DM interactions through adiabatic cooling effect



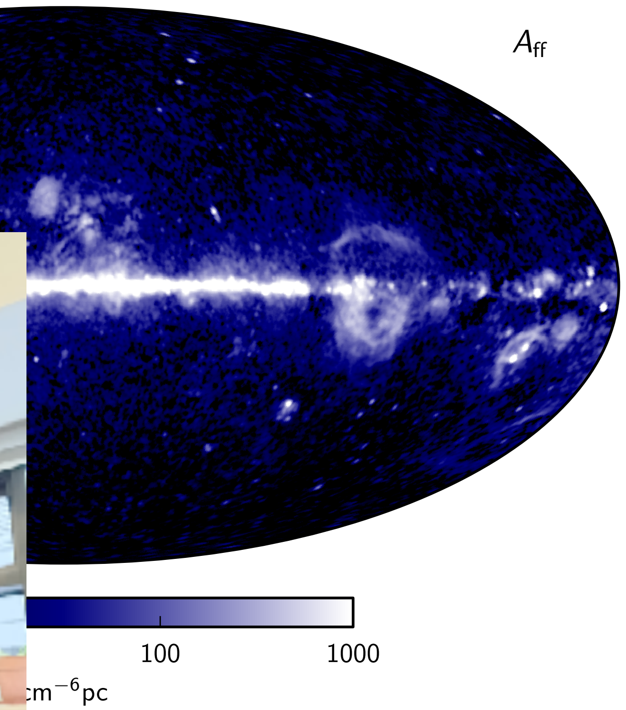
Ali-Haimoud, JC & Kamionkowski, 2015

Some of the foregrounds and their spatial variation

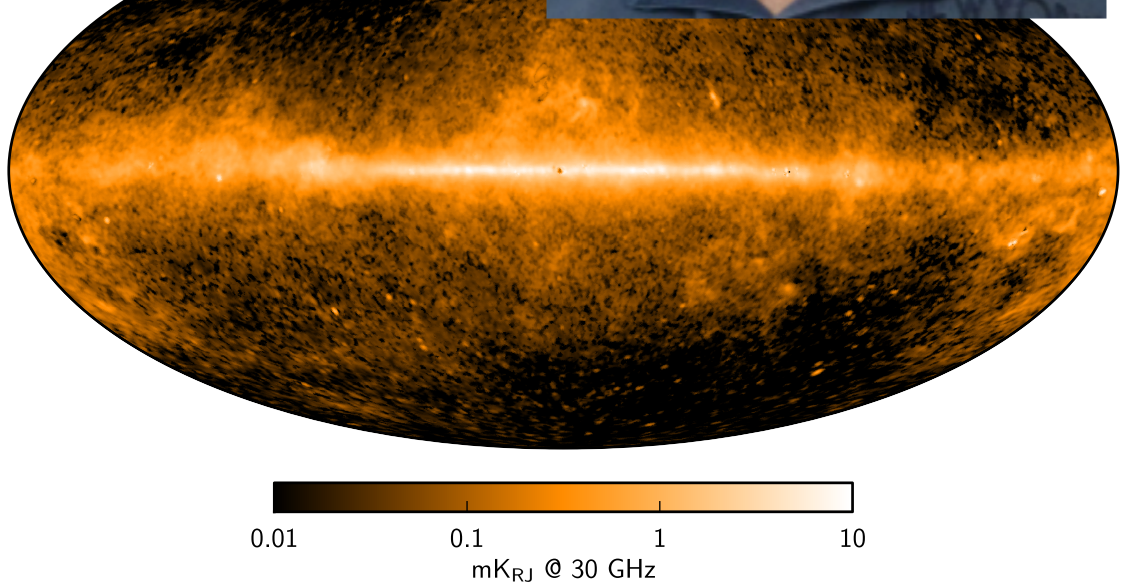
Thermal dust



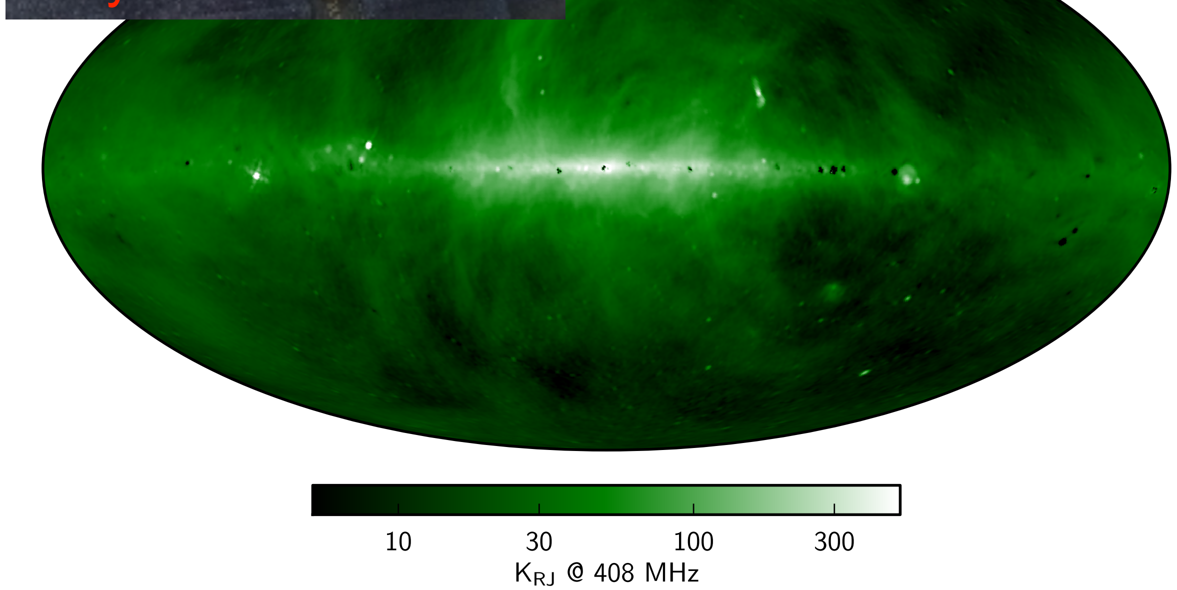
free-free emission



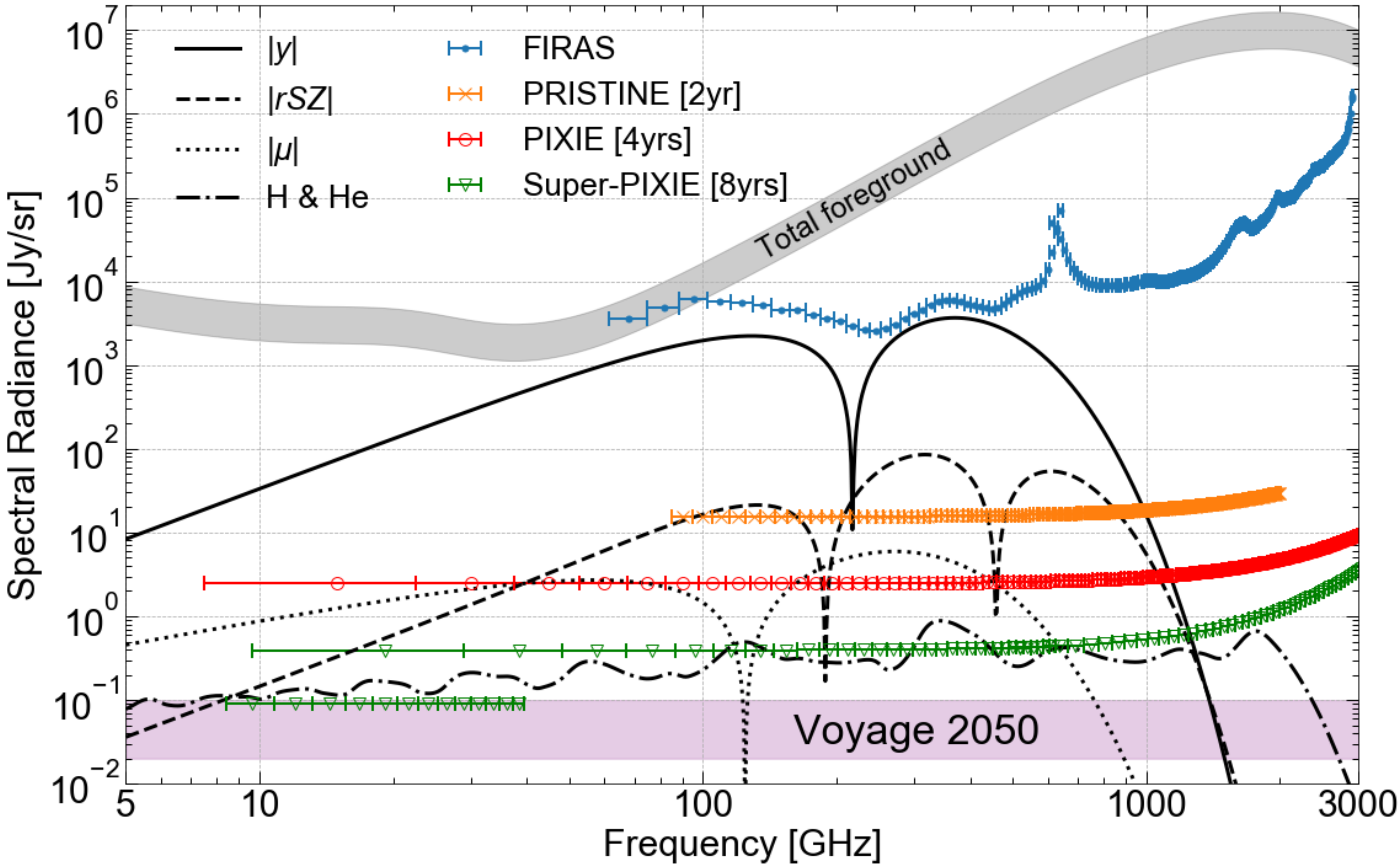
Spinni



chrotron



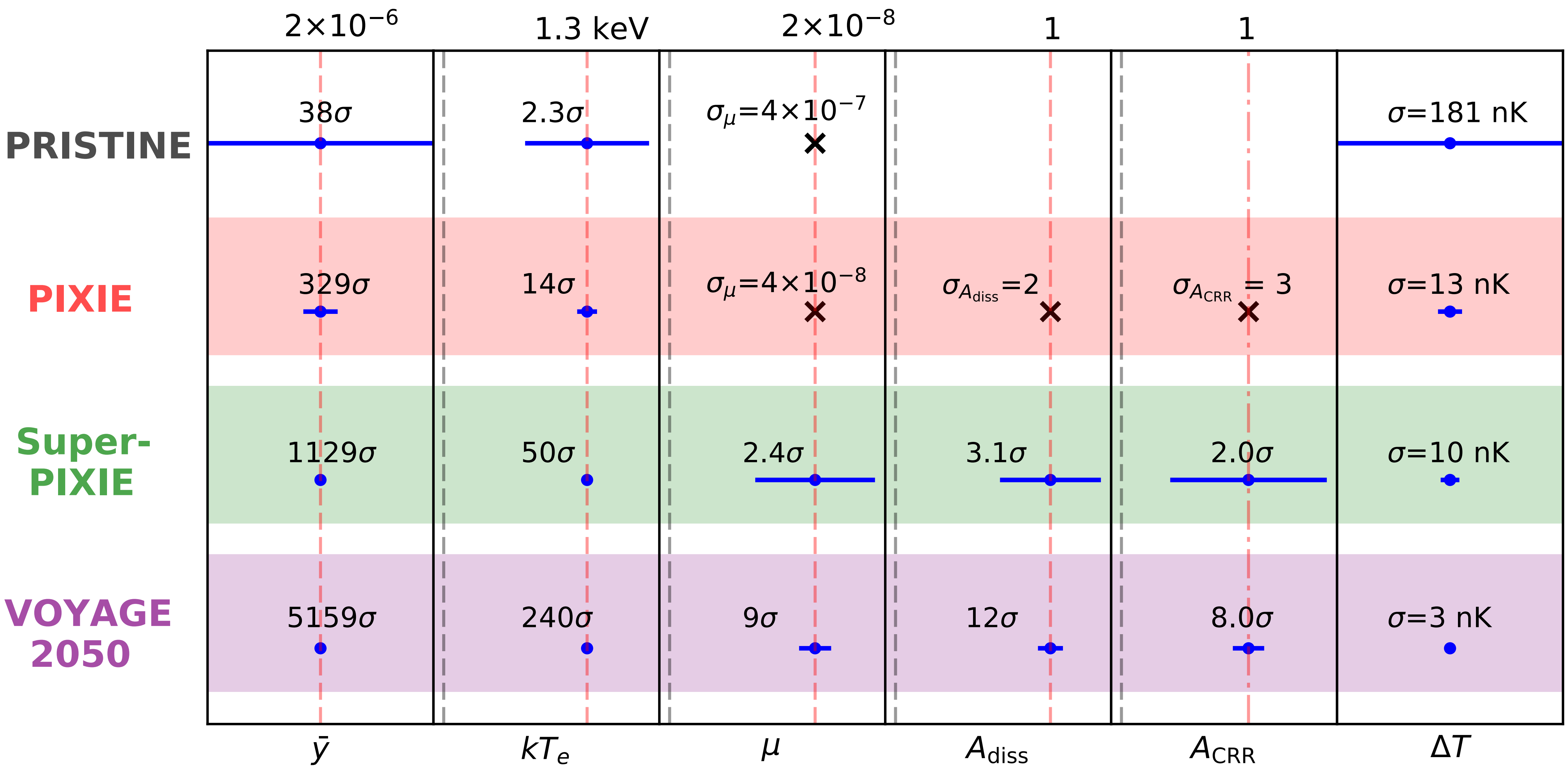
Comparison of distortion signals with foregrounds



http://arxiv.org/abs/1909.01593

Forecasts based on Abitbol, JC & Hill, 1705.01534

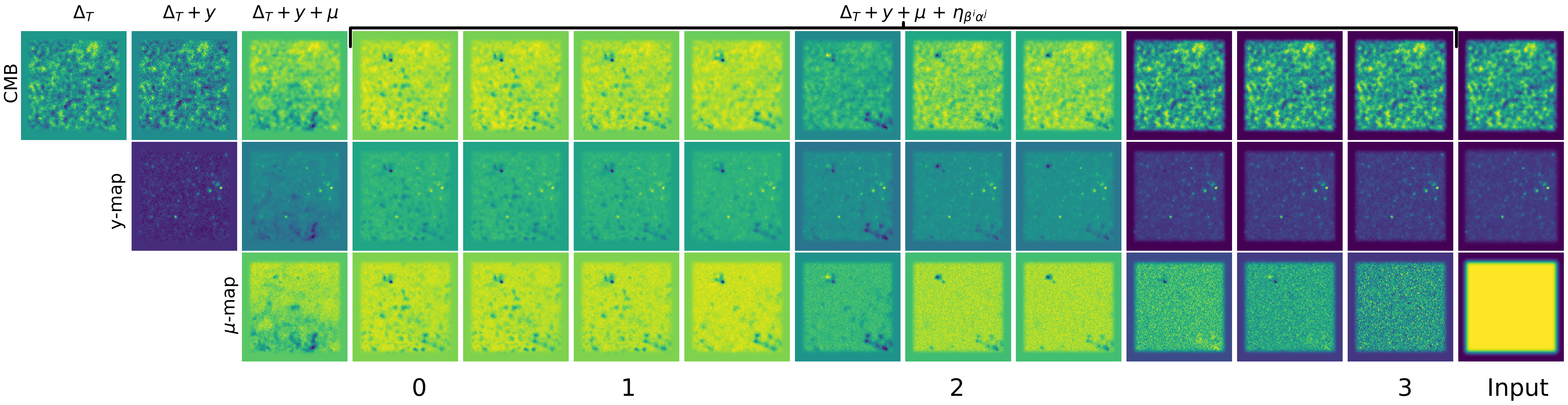
Forecasted sensitivities of different spectrometer concepts

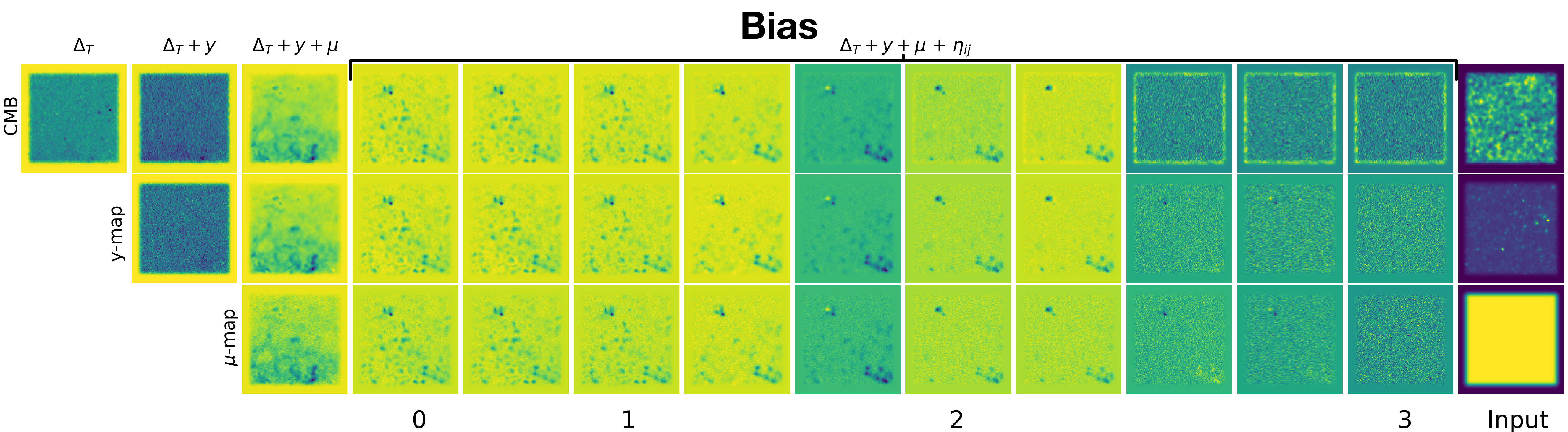


- Greatly improved limit on μ ‘easy’, but a detection of ΛCDM value will be hard
- Measurement of relativistic correction signal very robust even with foregrounds
- Low-frequency measurements from the ground are required

Courtesy Aditya Rotti

Recovering cosmological observables



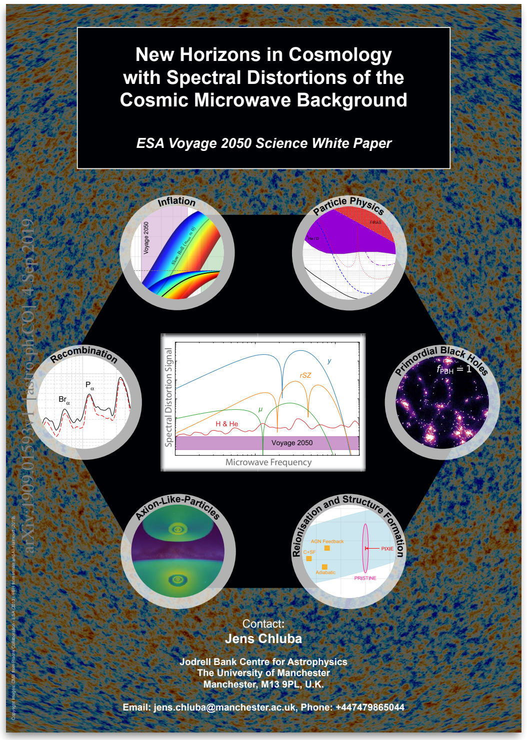


Talk by Aditya Rotti

Noise RMS : 50 Jy/px

Voyage 2050 Roadmaps towards distortion measurements

- *Option 1*: combination of CMB imager + spectrometer
  - Synergistic approach (*e.g., channel cross calibrations*)
  - Ultimate distortion measurement likely beyond



ArXiv:1909.01593

Voyage 2050 Roadmaps towards distortion measurements

- *Option 1*: combination of CMB imager + spectrometer
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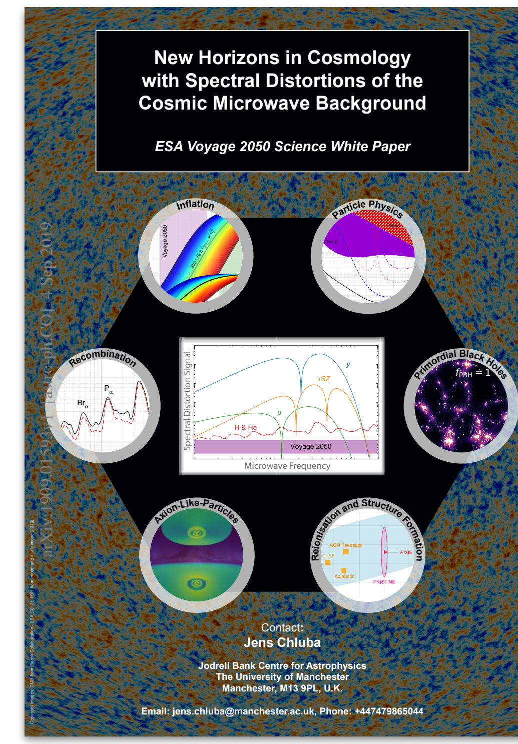
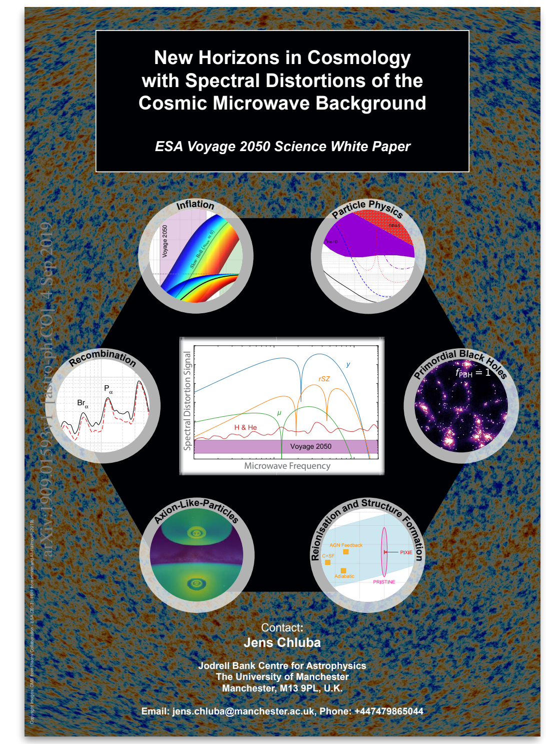
- *Option 2*: M-class CMB spectrometer
  - Ultimate distortion mission beyond 2050 timescale



ArXiv:1909.01593

Voyage 2050 Roadmaps towards distortion measurements

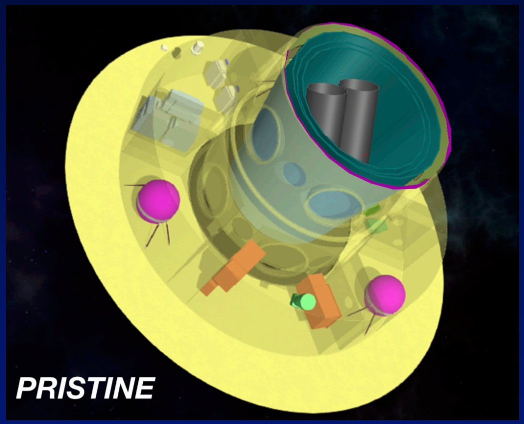
- *Option 1*: combination of CMB imager + spectrometer
  - Synergistic approach (*e.g., channel cross calibrations*)
  - Ultimate distortion measurement likely beyond
- *Option 2*: M-class CMB spectrometer
  - Ultimate distortion mission beyond 2050 timescale
- *Option 3*: L-class CMB spectrometer + pathfinder
  - Pathfinder will be able to see average y and rSZ!
  - Risk mitigation by learning about foreground challenge
  - Pathfinder could be balloon or small satellite

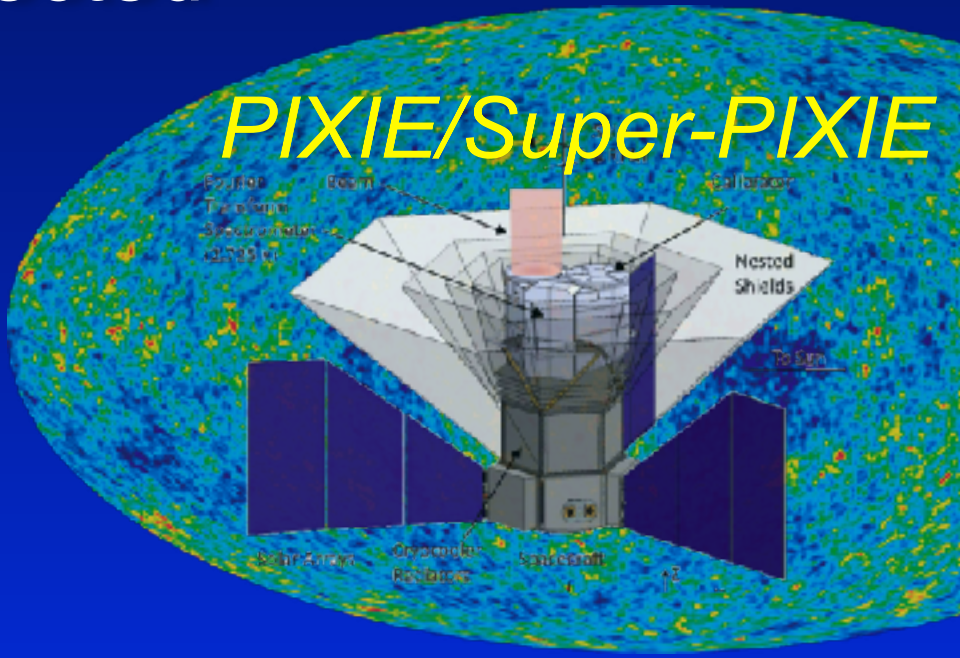


ArXiv:1909.01593

What can CMB spectral distortions add?

- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected
  - y-distortion from low redshifts
  - damping signal & recombination radiation
- Test various *inflation* models
  - damping of the small-scale power spectrum
- *Discovery* potential
  - decaying particles and other exotic sources of distortions





Unique science opportunities for the next decades!