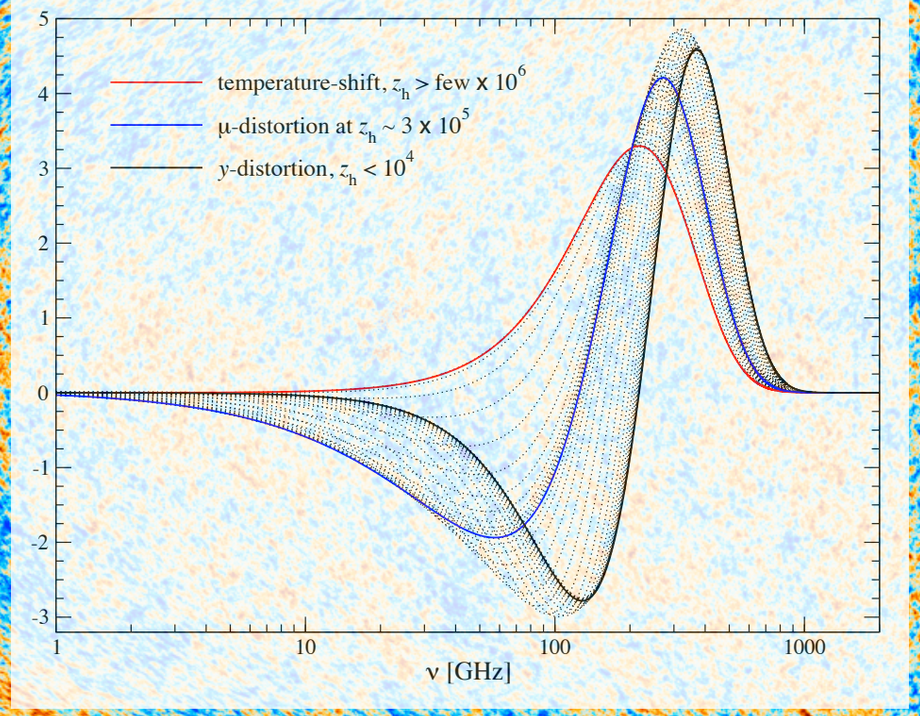
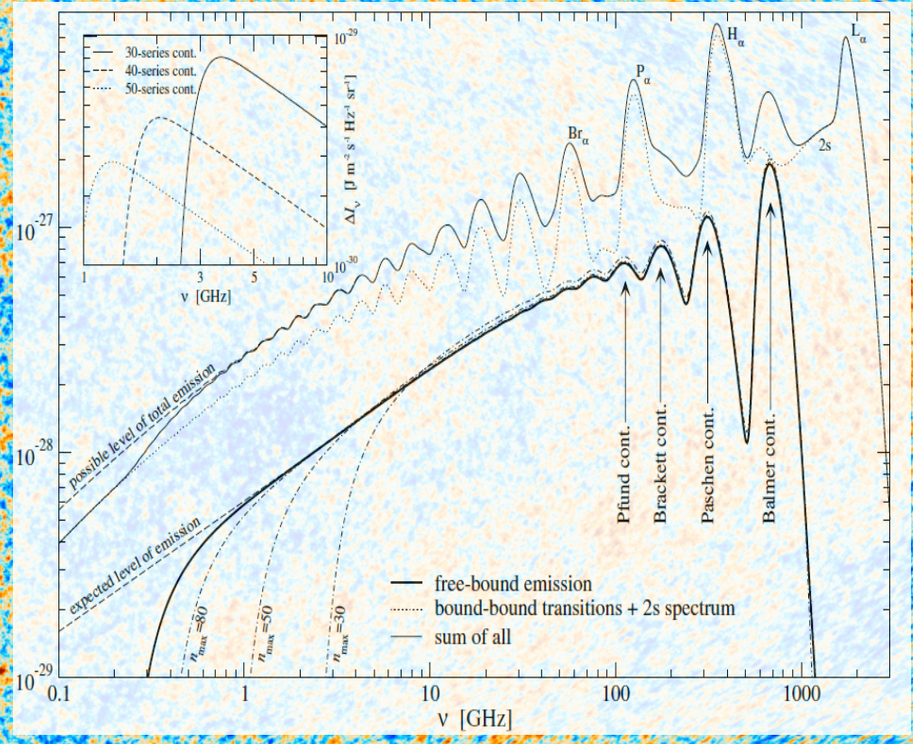
CMB Spectroscopy: What Spectral Distortions Could Add

(PIXIE, COSMO, APSERa and PRISTINE)

Primordial Distortions



Cosmological Recombination lines



MANCHESTER 1824
The University of Manchester

Jens Chluba

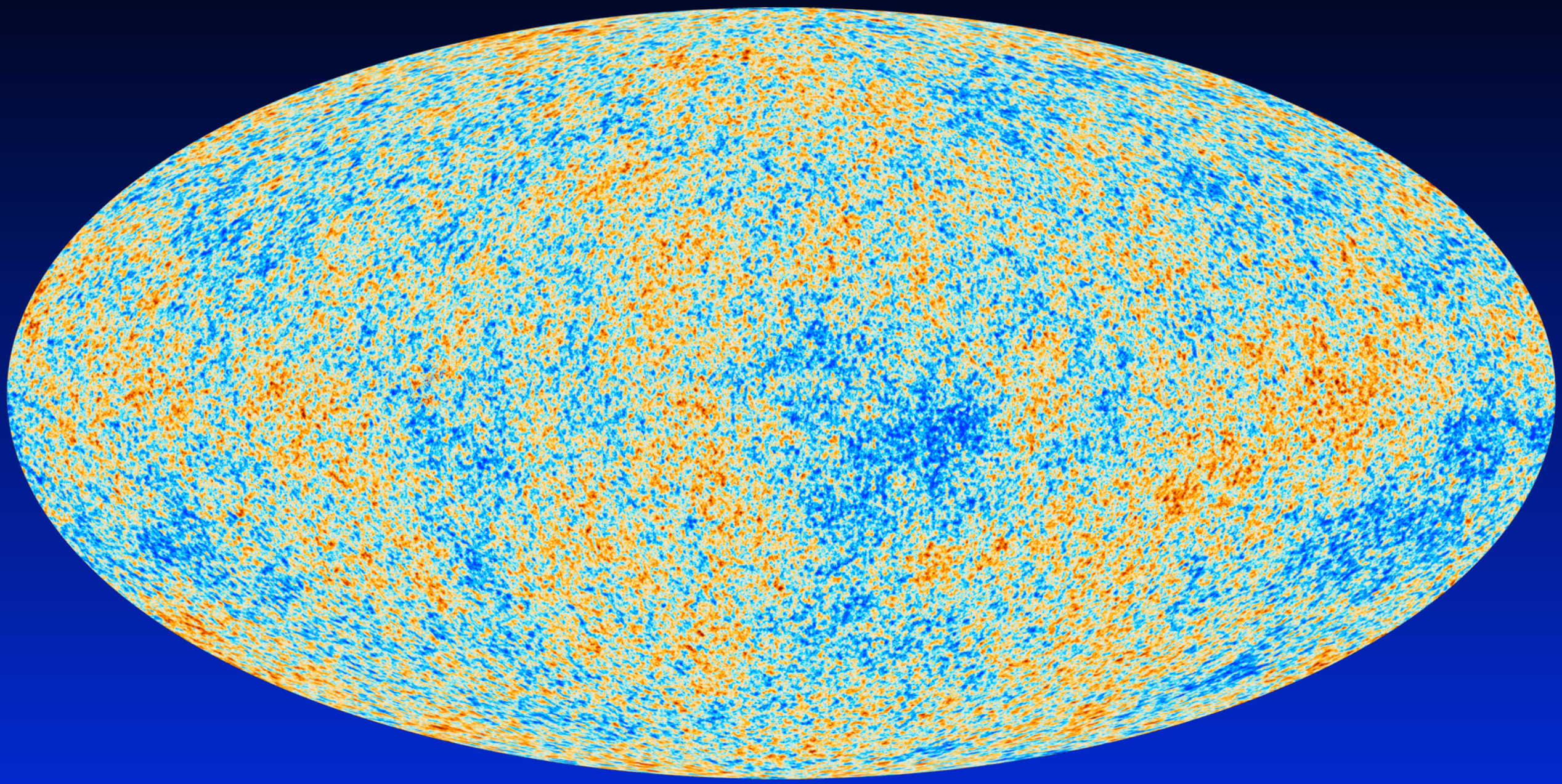
CMB Foregrounds for B-mode Studies

Tenerife, 15-18th October 2018

erc

THE ROYAL SOCIETY

Cosmic Microwave Background Anisotropies

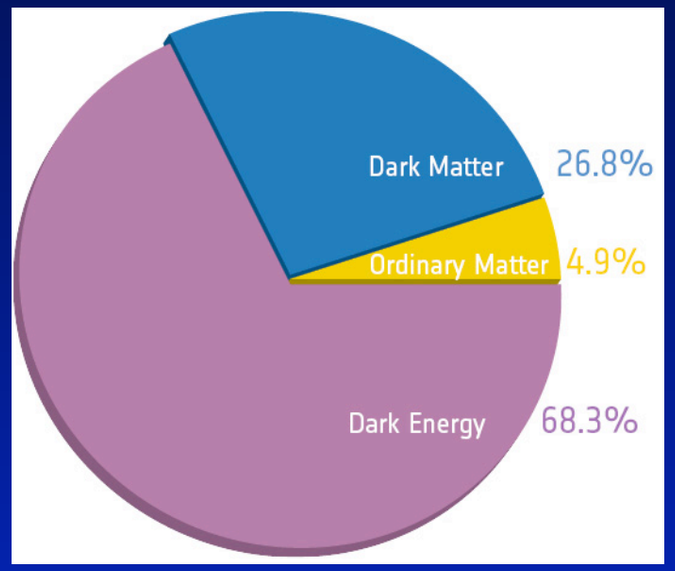


Planck all-sky temperature map

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

CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!

- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter (“CDM”)
- accelerated expansion today (“Λ”)
- Standard BBN scenario → N_{eff} and Y_p
- Standard ionization history → $N_e(z)$



Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck Collaboration, 2015, paper XIII

What are the *main* next targets for CMB anisotropies?

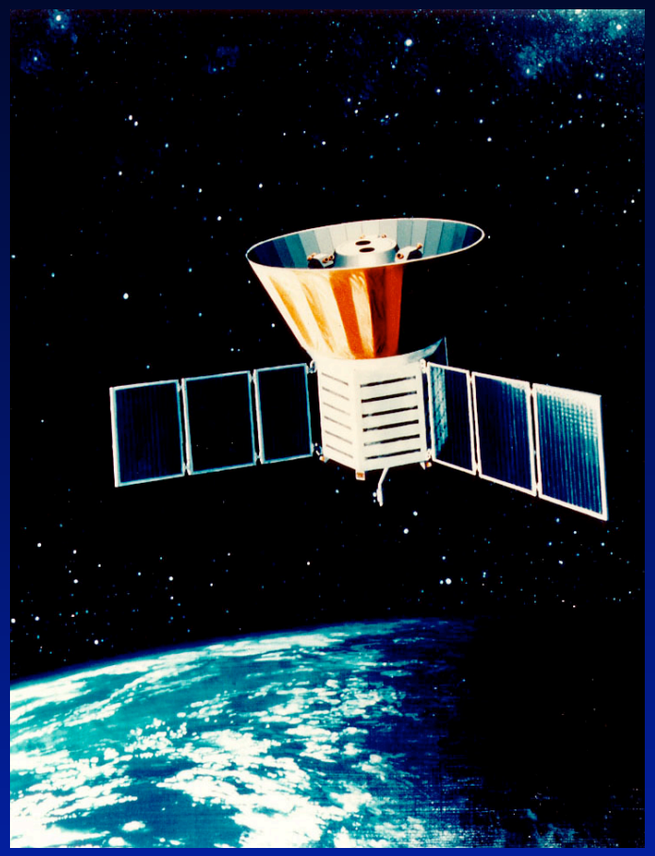
- *Primary* CMB temperature kind of finished...
- E modes cosmic variance limited to high-*l*
  - CVL-limit on Thomson optical depth from large-scale E modes
  - refined *CMB damping tail science* from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional 'proof of inflation'
- CMB anomalies
  - stationarity of E and B-modes, lensing potential, etc across the sky
- SZ cluster science
  - large cluster samples and (individual) high-res cluster measurements

➡ *CORE*
➡ *PIXIE*
➡ *Litebird*
➡ *CMB S4*
➡ *Simons Observatory*
➡ *PICO*

A bright and exciting future with lots of activity!

CMB provides another independent piece of information!

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



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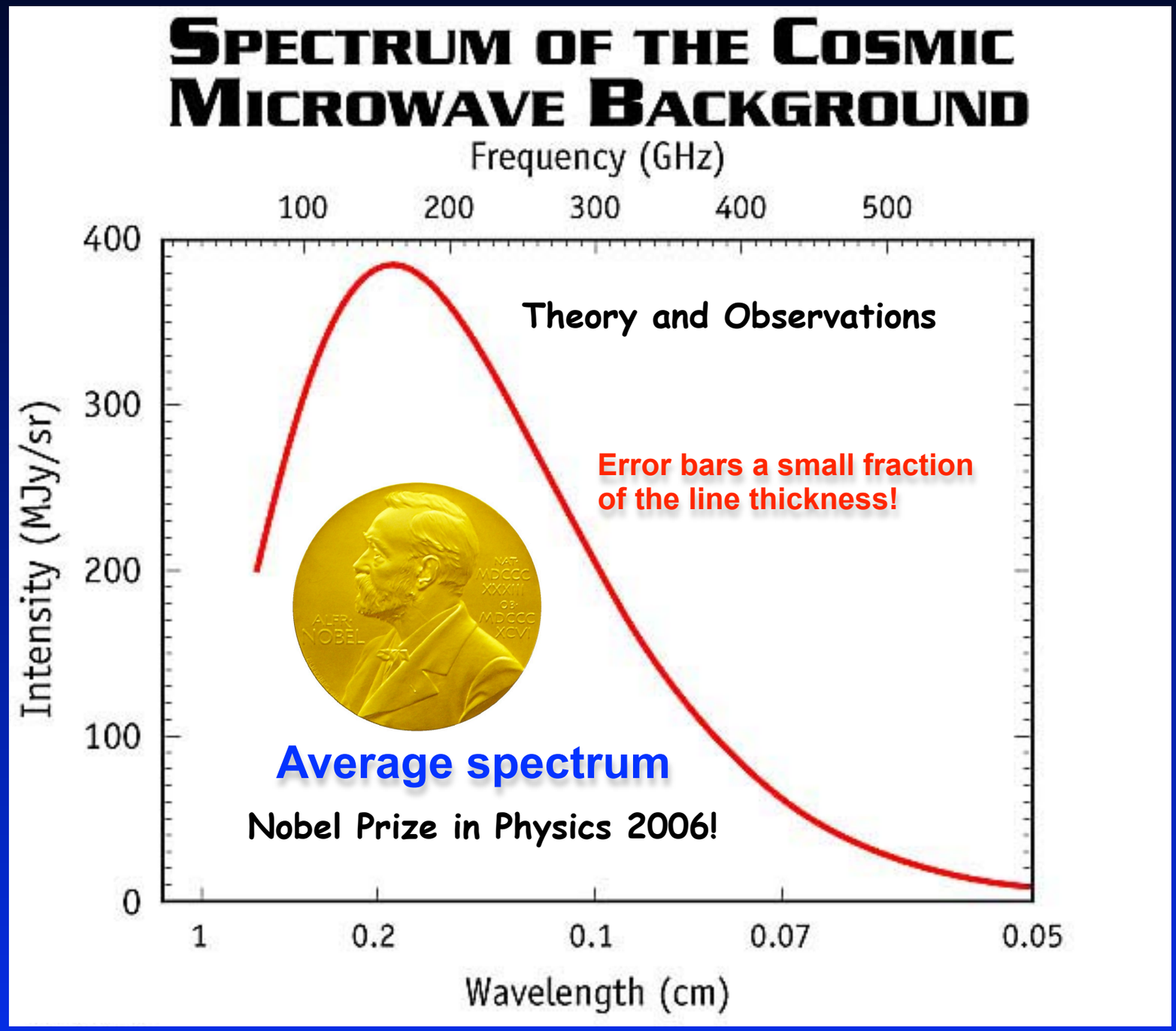
$$|y| \leq 1.5\times10^{-5}$$

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



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

Big Bang
0

Cosmic inflation
Origin of fluctuations
10^{-32} seconds

Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10^{-30} seconds
1 second
100 seconds

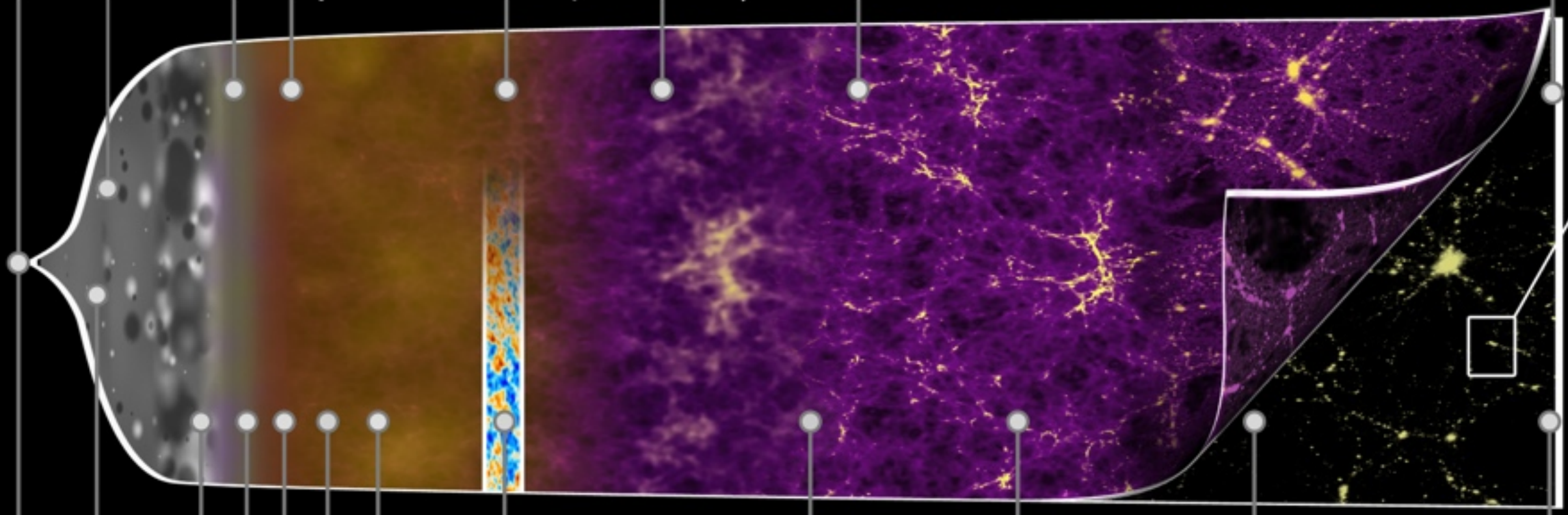
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
1 year

Dark ages
Ordinary matter particles fall into the structures created by dark matter
100 years
380 000 years

First stars & galaxies
200 million years

Galaxy evolution
Clusters of galaxies and superclusters form
1 billion years
10 billion years

Today
13.82 billion years



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Dark ages
Ordinary matter particles fall into the structures created by dark matter

First stars & galaxies

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Clusters of galaxies and superclusters form

Today

Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect

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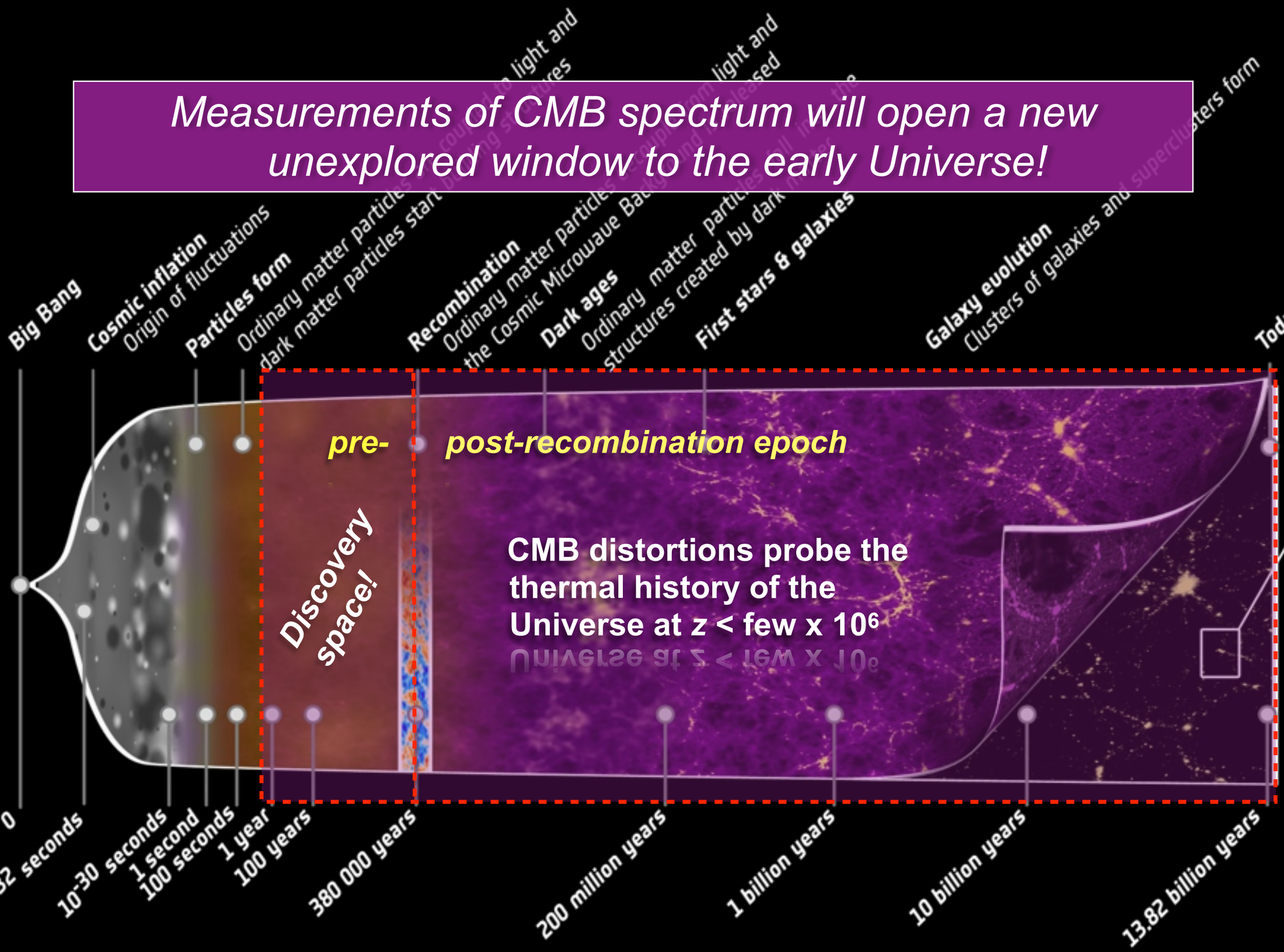
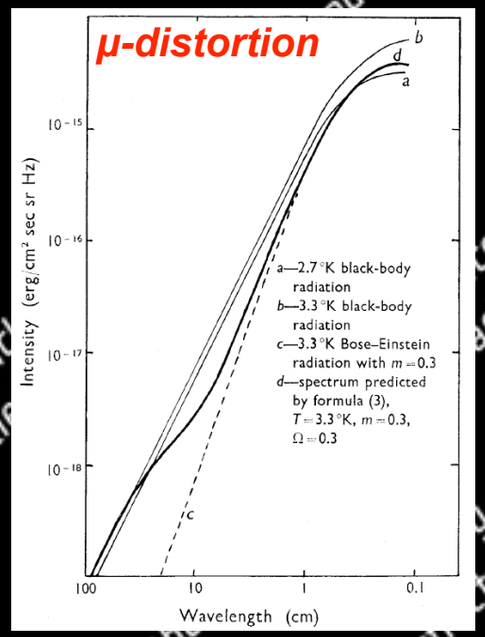
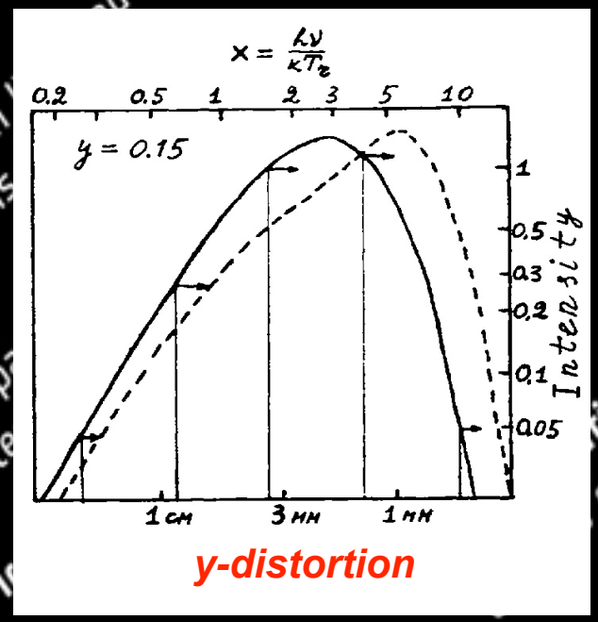
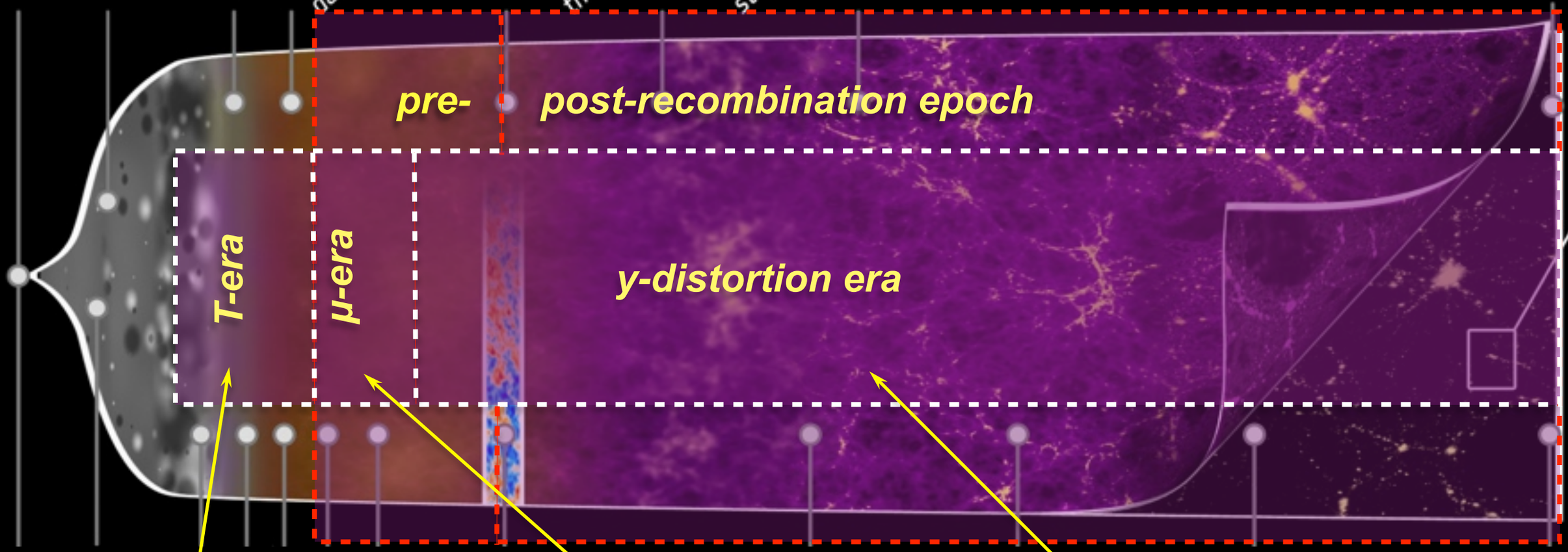
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

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

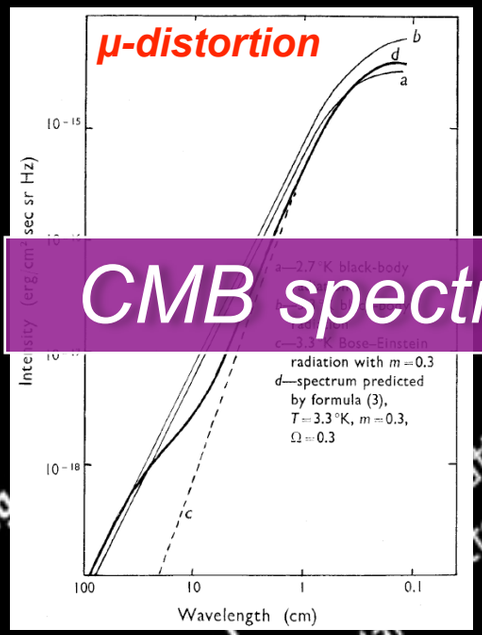


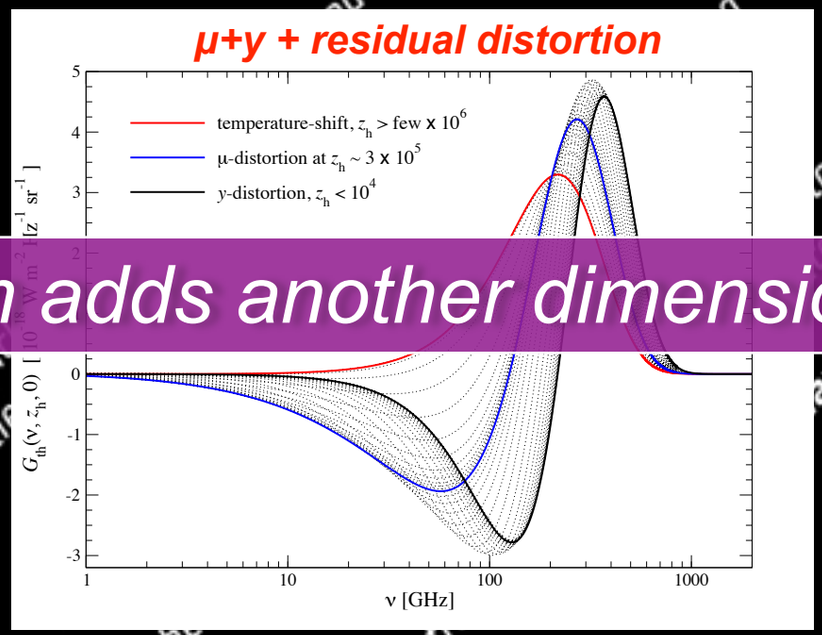


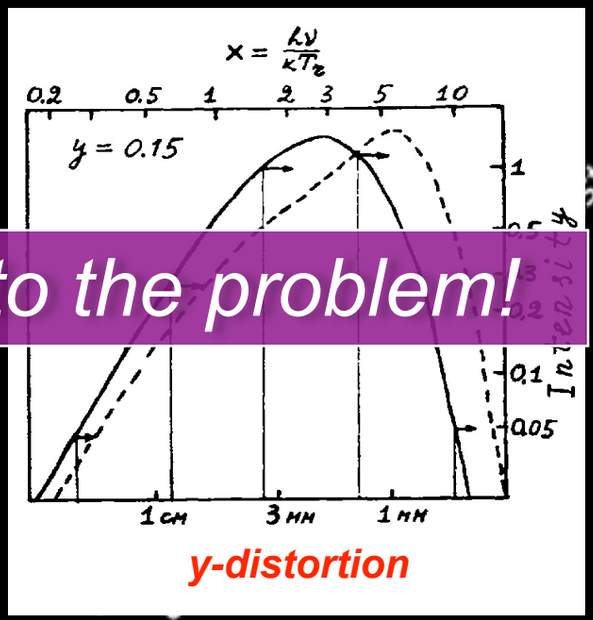




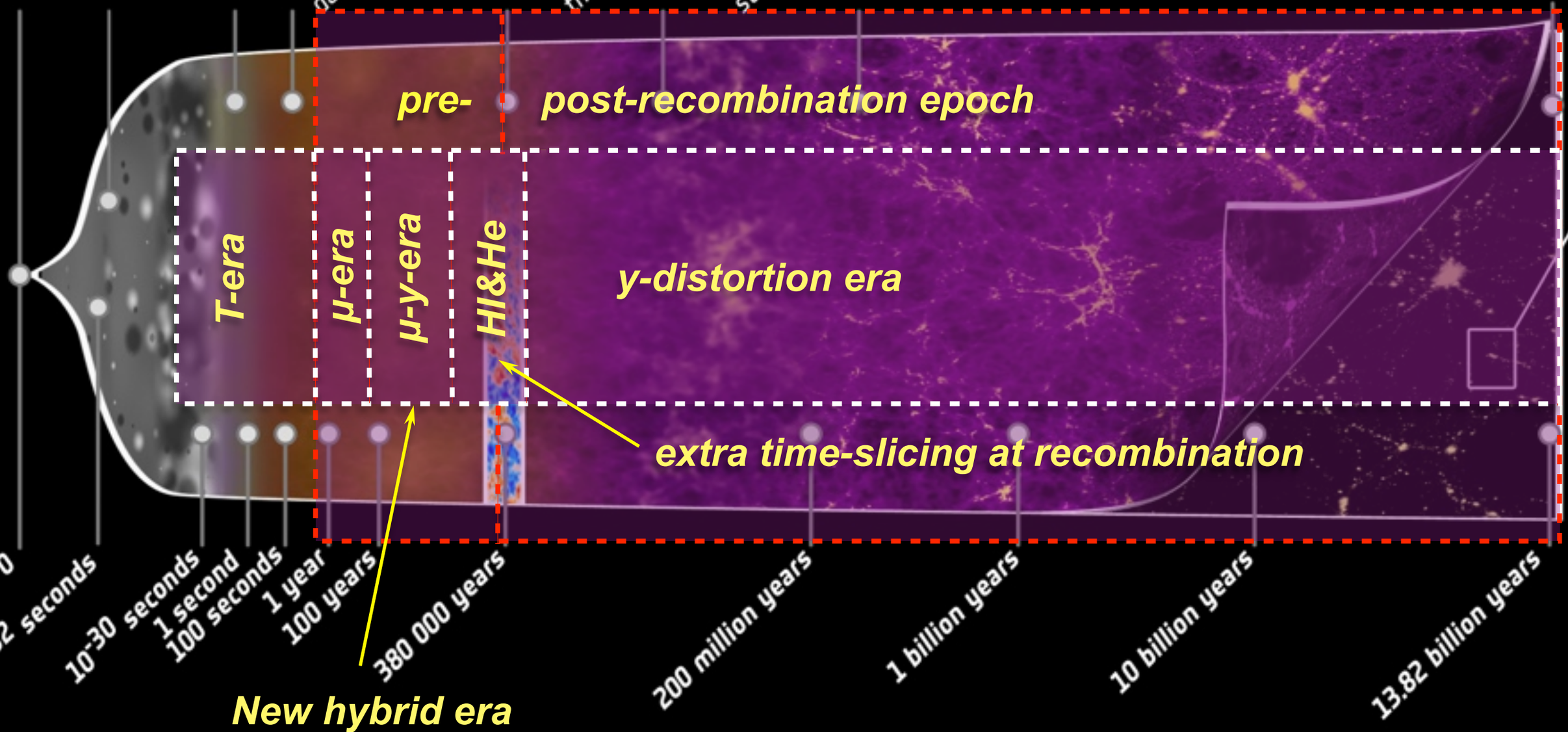
$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T \qquad \mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \qquad y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$



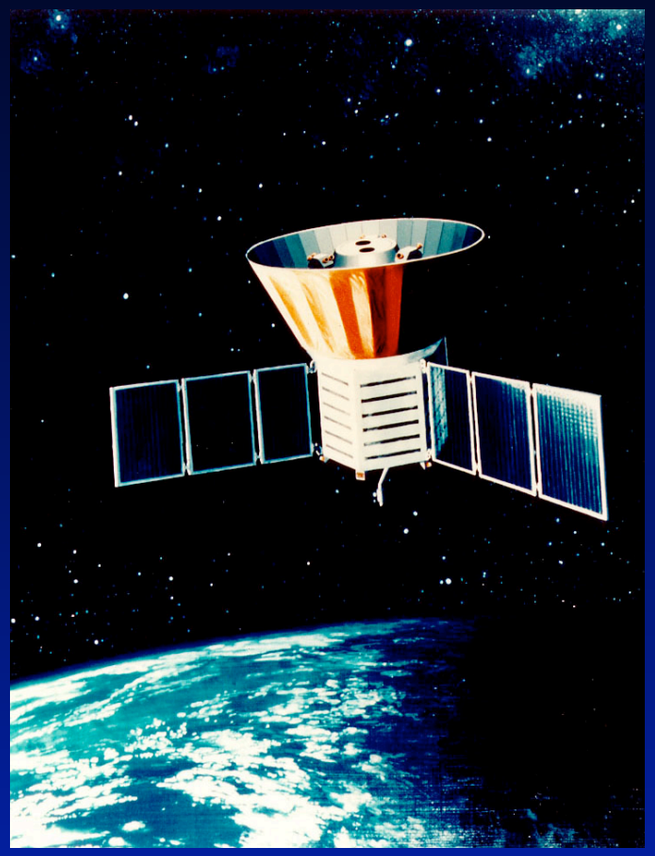




CMB spectrum adds another dimension to the problem!



COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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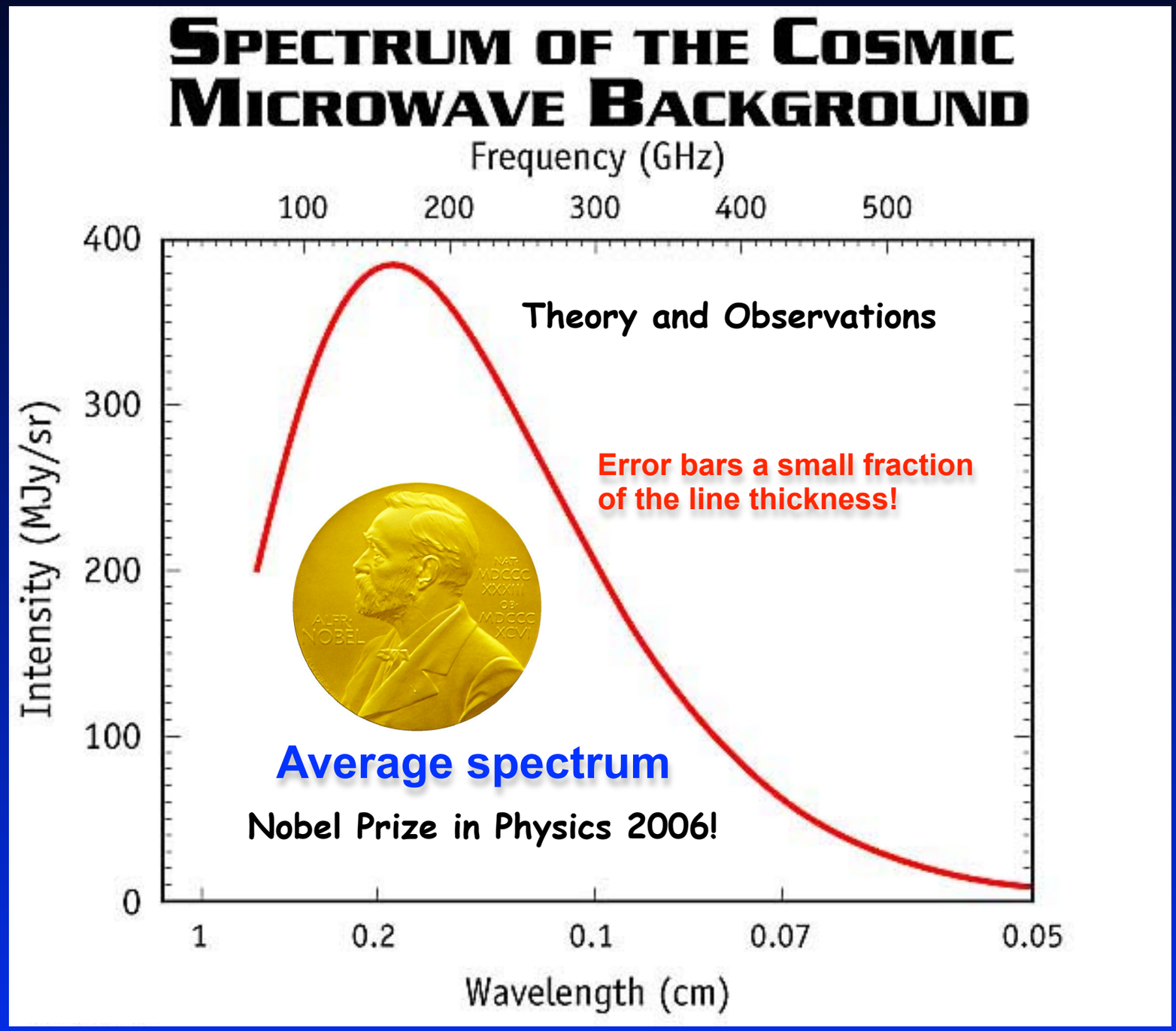

Only very small distortions of CMB spectrum are still allowed!

Physical mechanisms that lead 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
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„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
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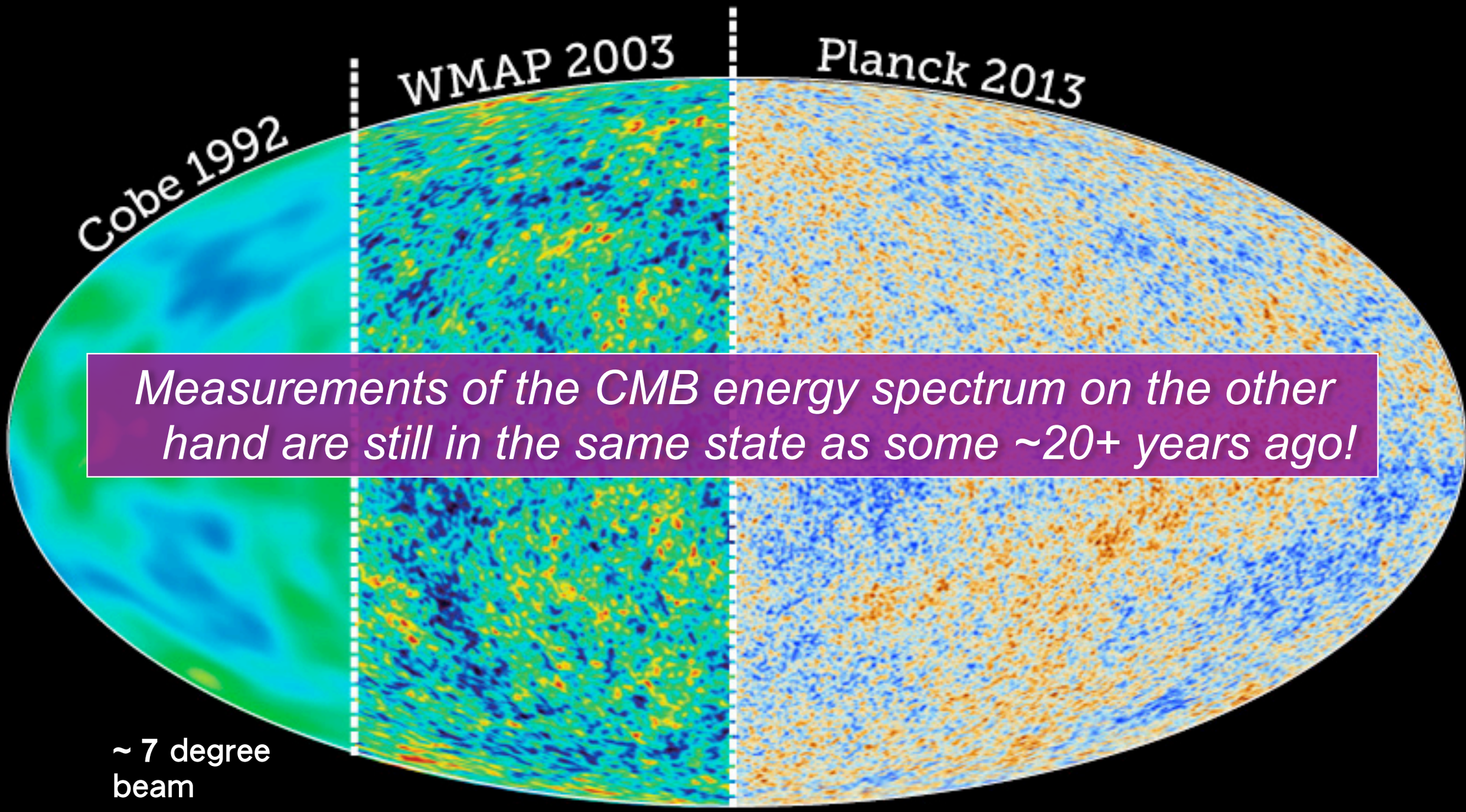
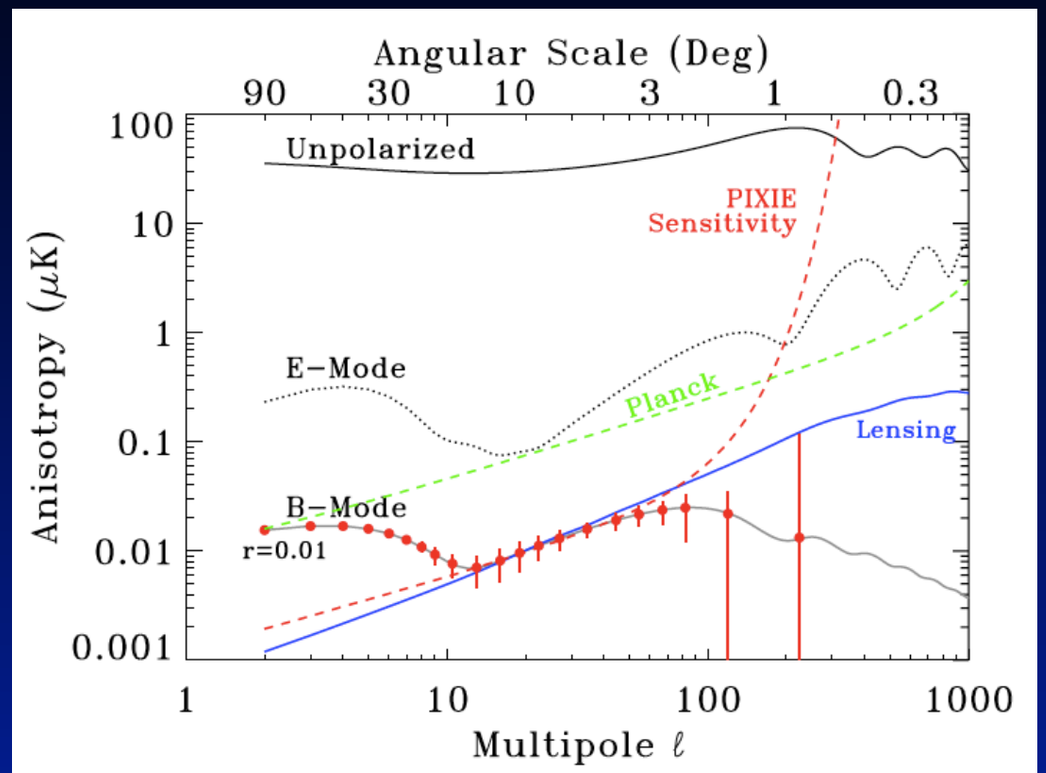
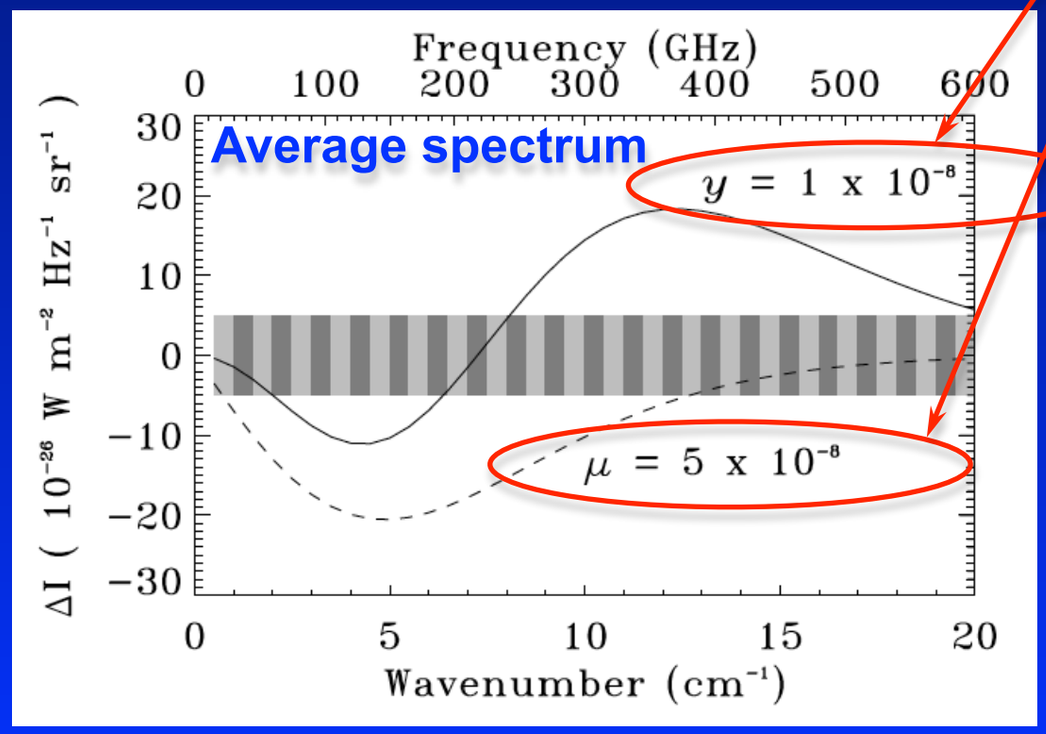
Dramatic improvements in angular resolution and sensitivity over the past decades!



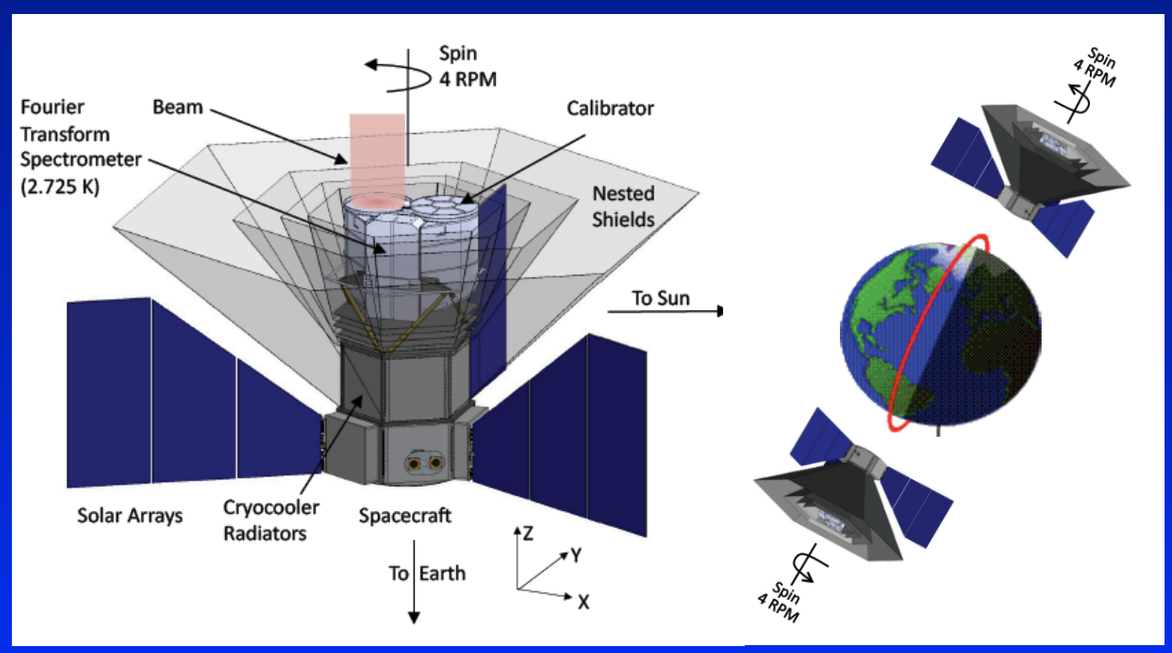
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

PIXIE: Primordial Inflation Explorer

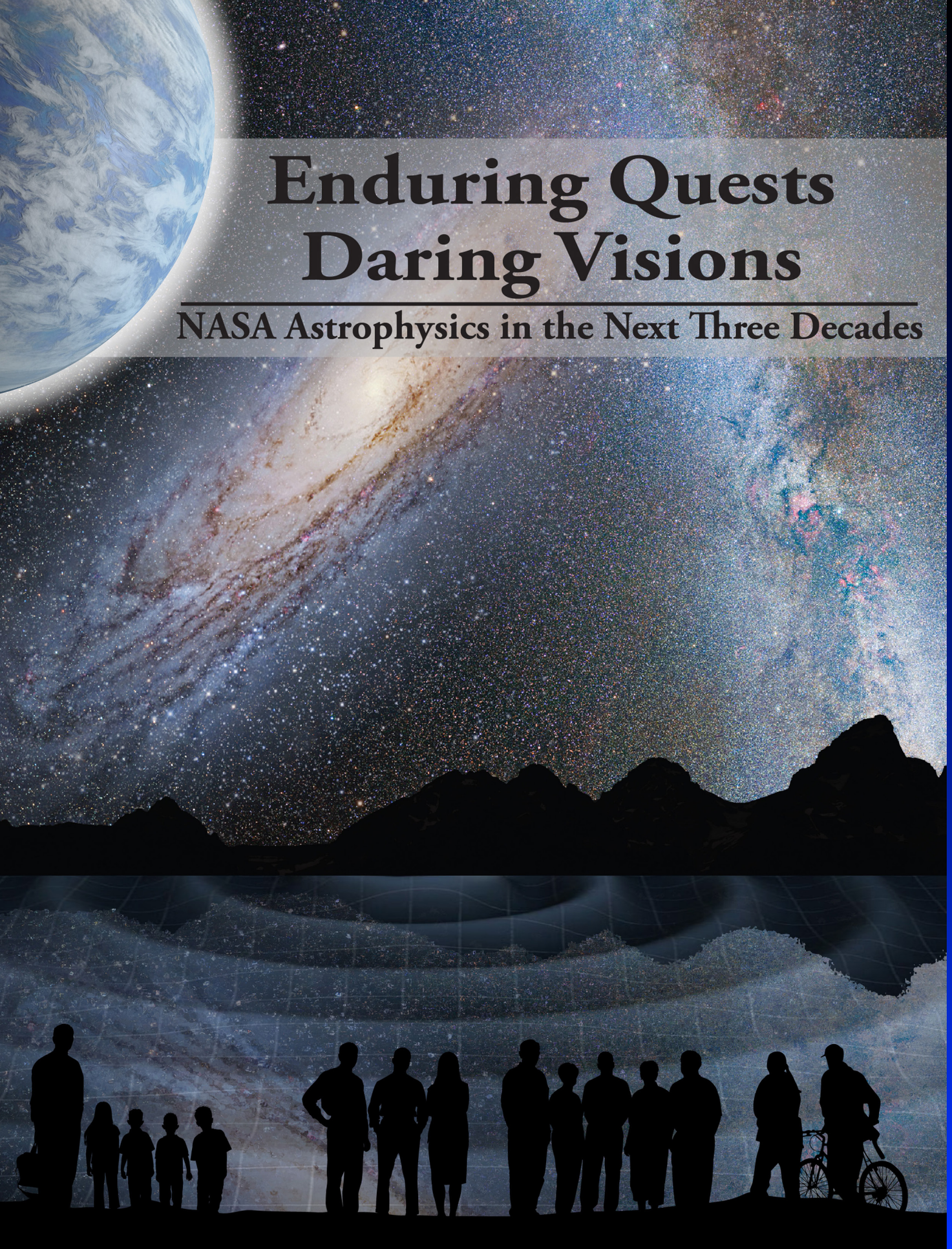




- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 & 2016 as NASA EX mission (i.e. cost ~ 200-250 M$)



Kogut et al, JCAP, 2011, arXiv:1105.2044



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."

New mission concepts:

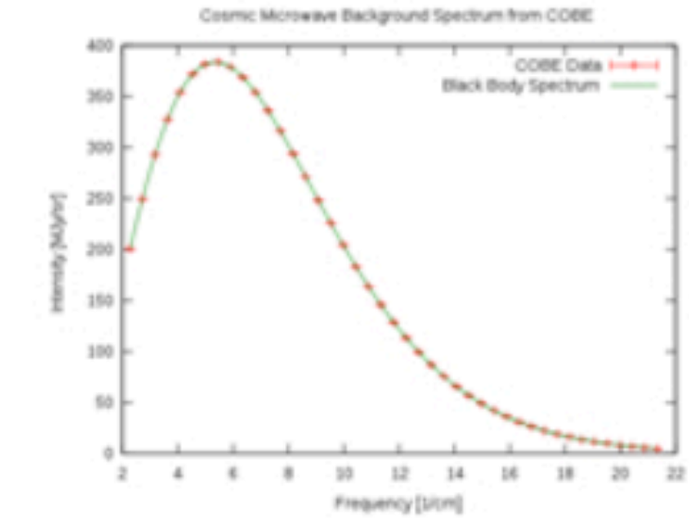
PRISTINE (France)
CMB-Bharat (India)

Decadal Survey

White papers for Jan 2019

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

HOME PEOPLE



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.

Details in Rao et al., ArXiv:1501.07191

COSMO at Dome C

COSmological Monopole Observer

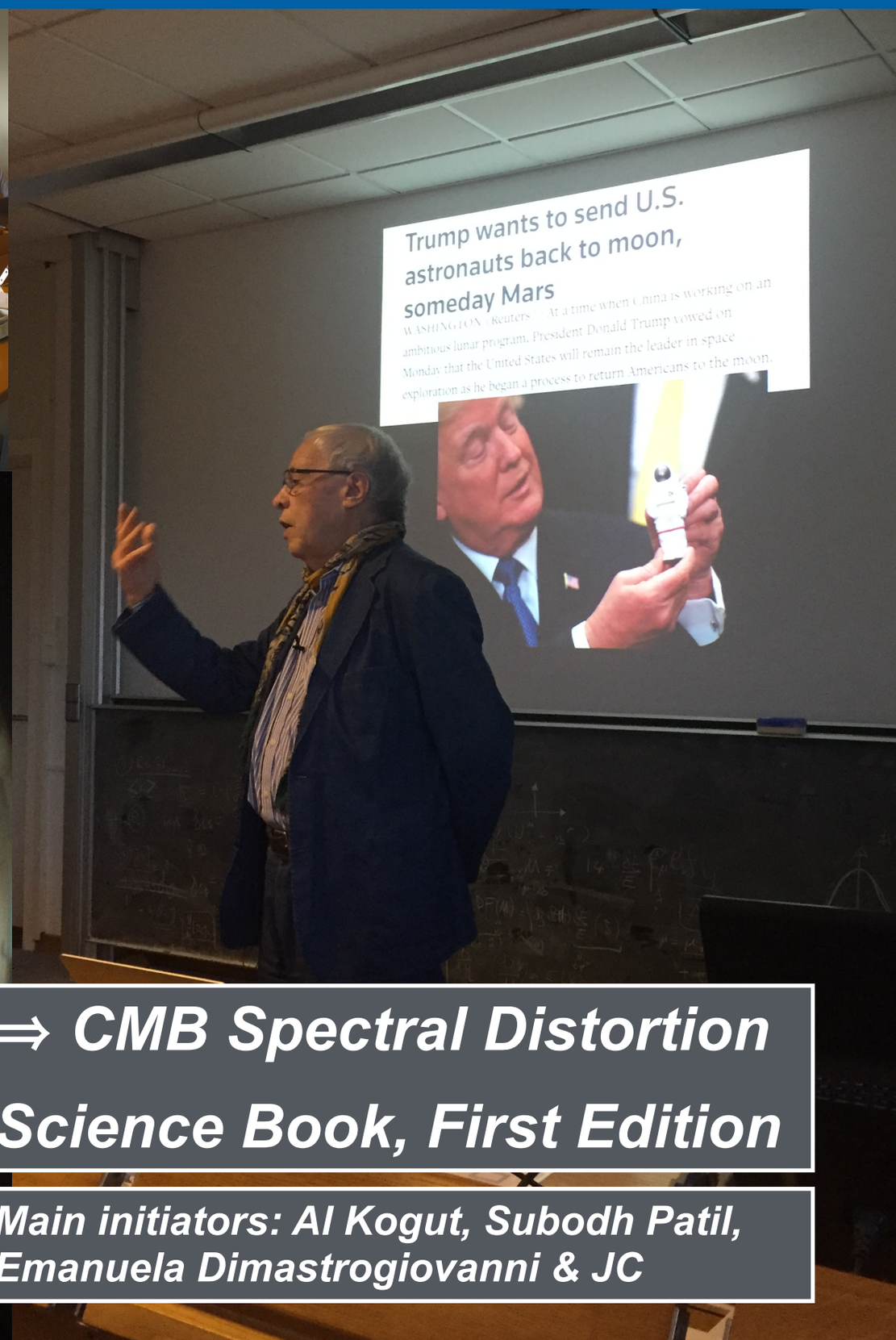

Concordia station at Dome-C

Taken from a talk by Elia Battistelli

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)



⇒ CMB Spectral Distortion Science Book, First Edition

Main initiators: Al Kogut, Subodh Patil, Emanuela Dimastrogiovanni & JC

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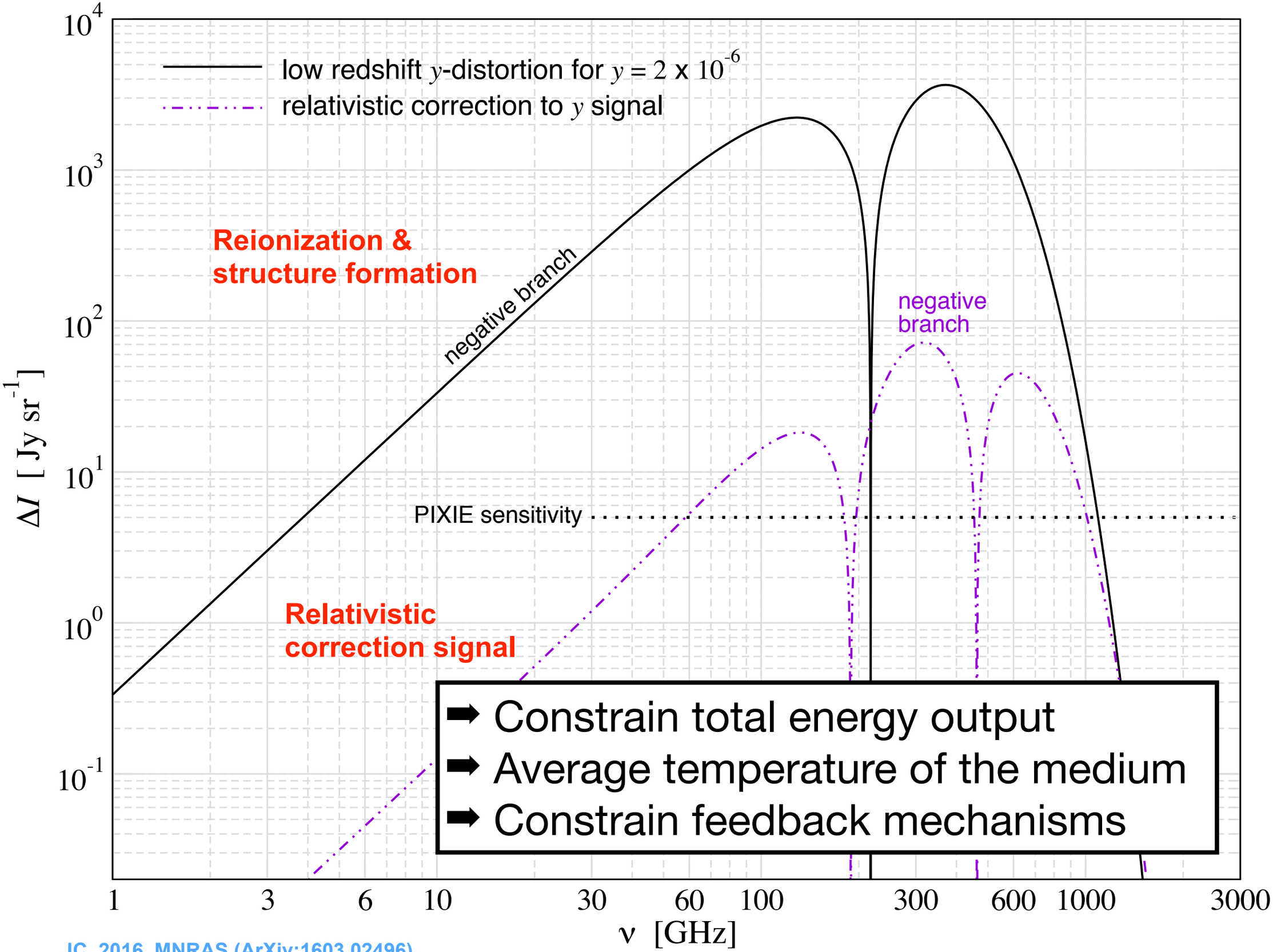
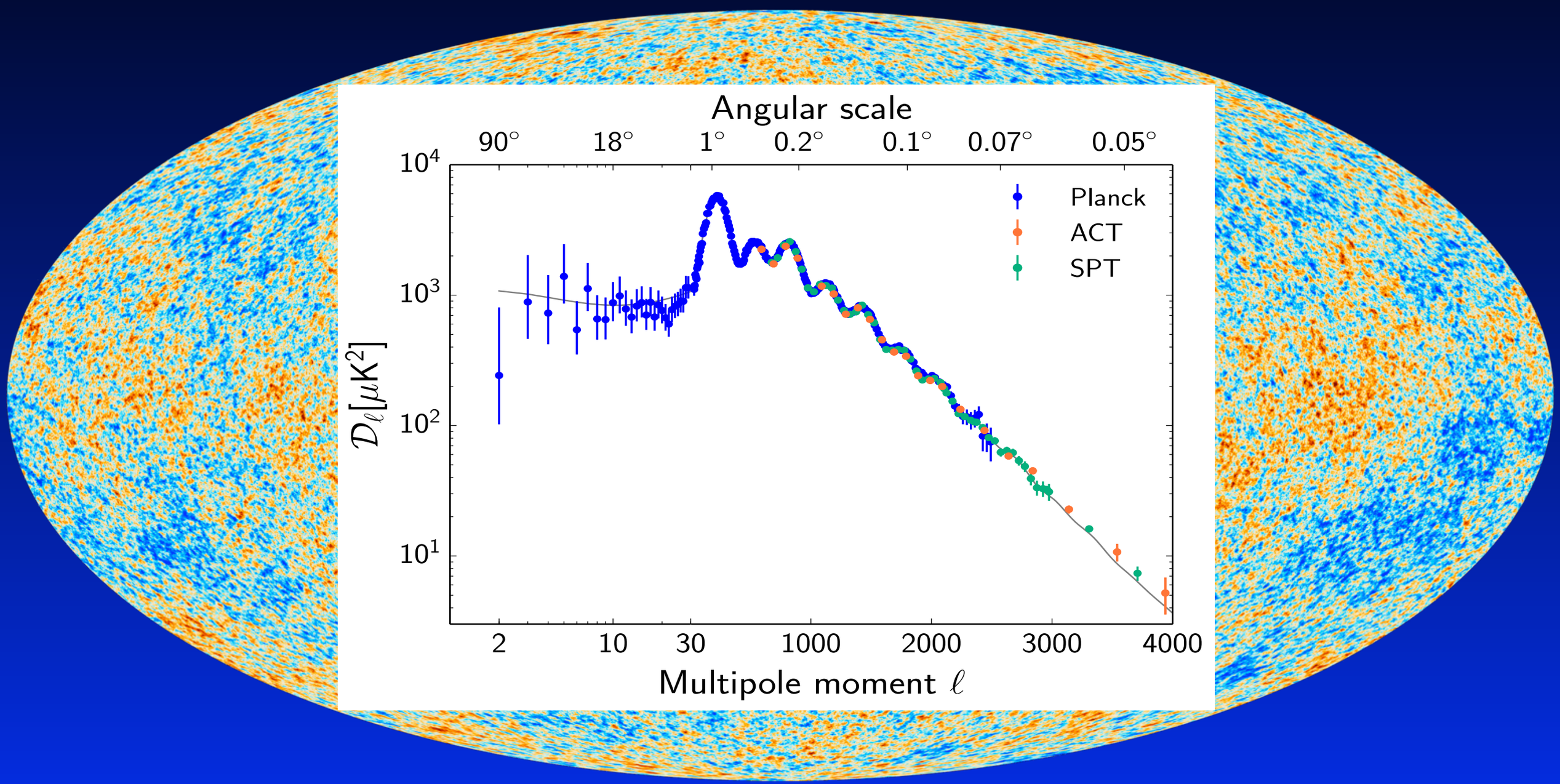
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Dissipation of small-scale acoustic modes



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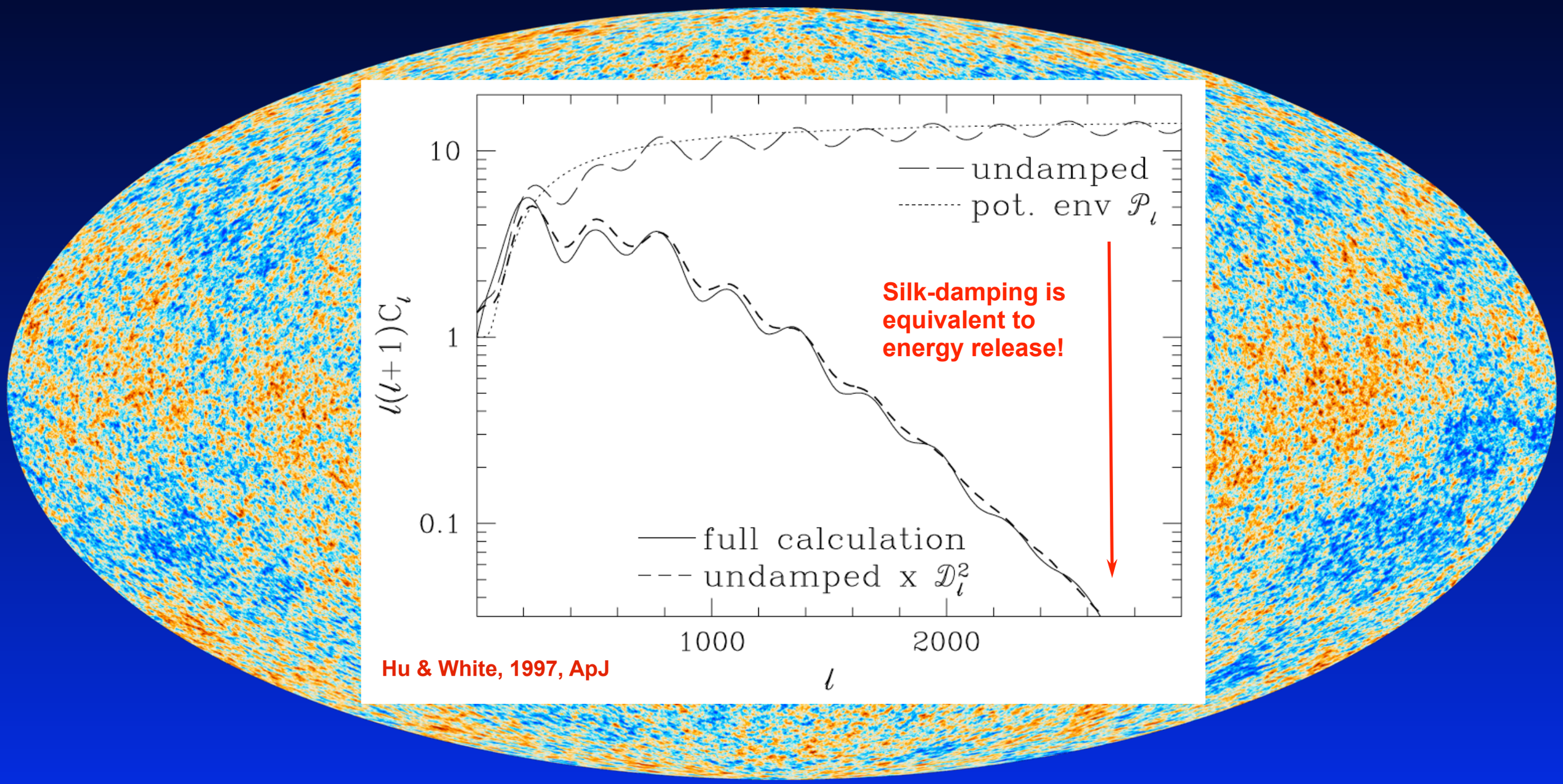


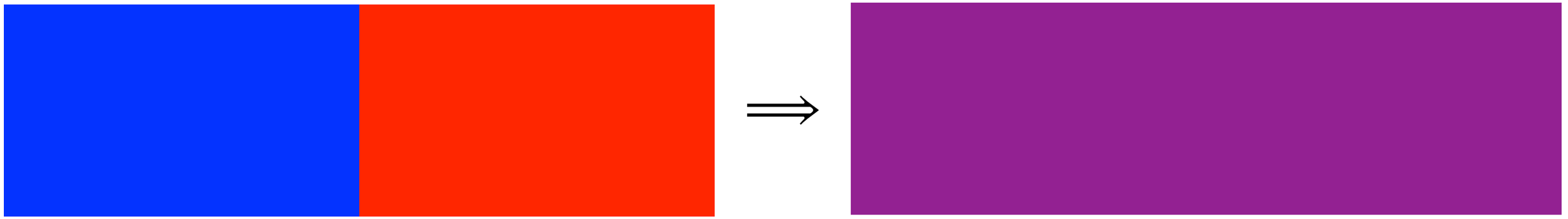
Hu & White, 1997, ApJ

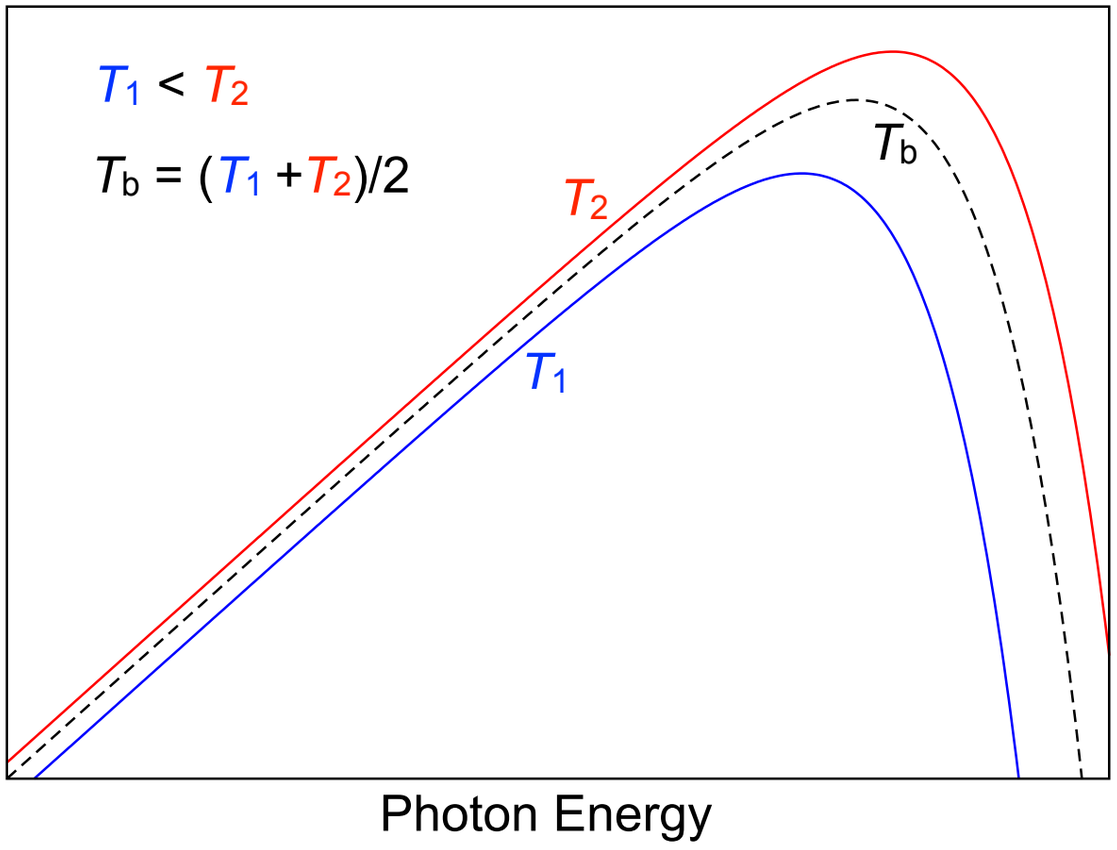
Distortion due to mixing of blackbodies

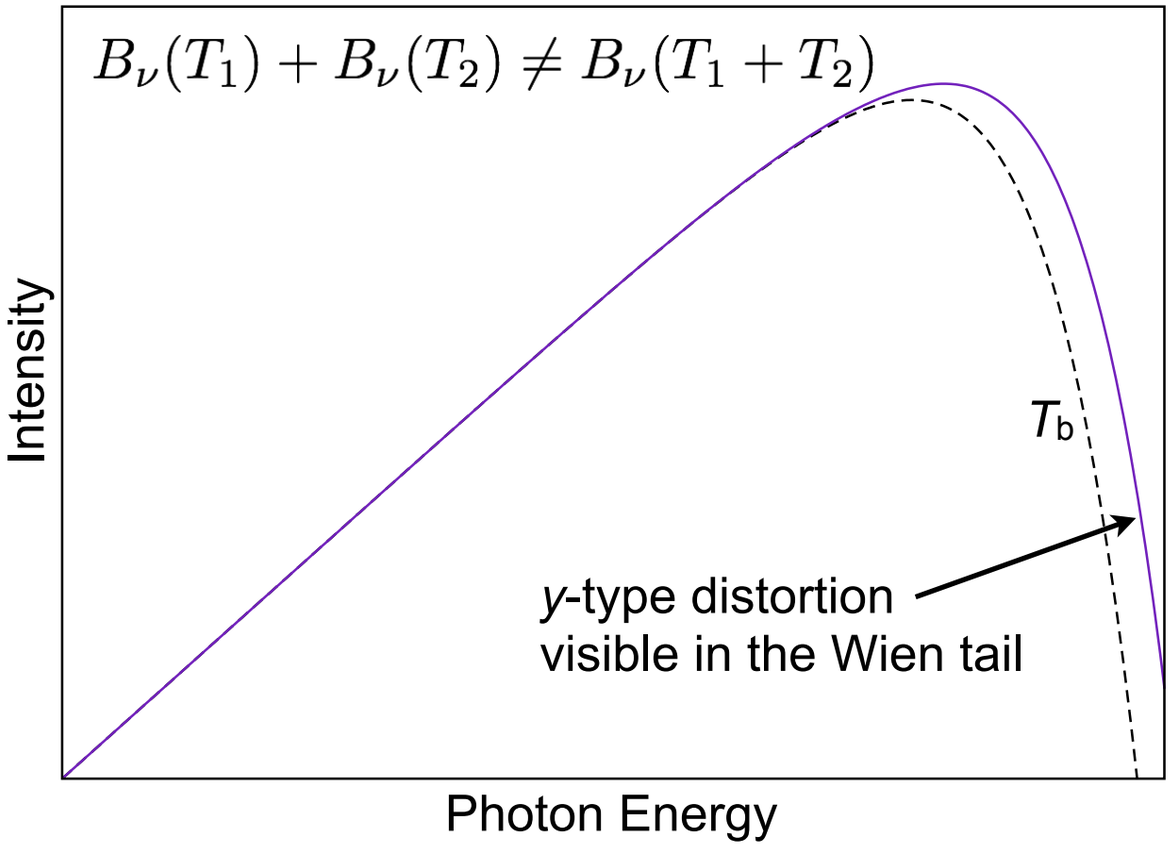
Blackbody spectra

Photon mixing

Blackbody + *y*-distortion







JC, Hamann & Patil, 2015

Mixing is mediated by Thomson scattering ⇒ Silk damping

Early power spectrum constraints from FIRAS

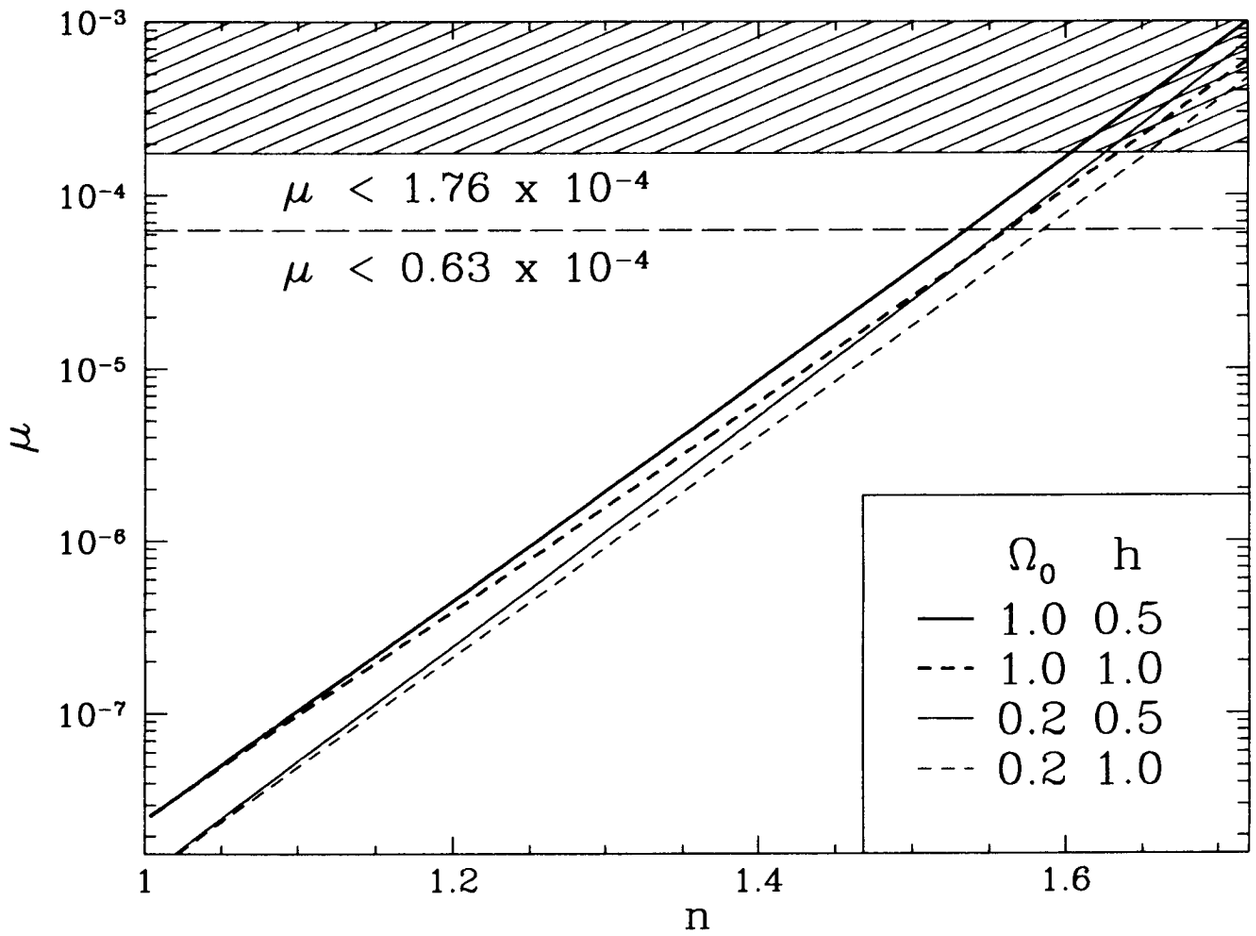
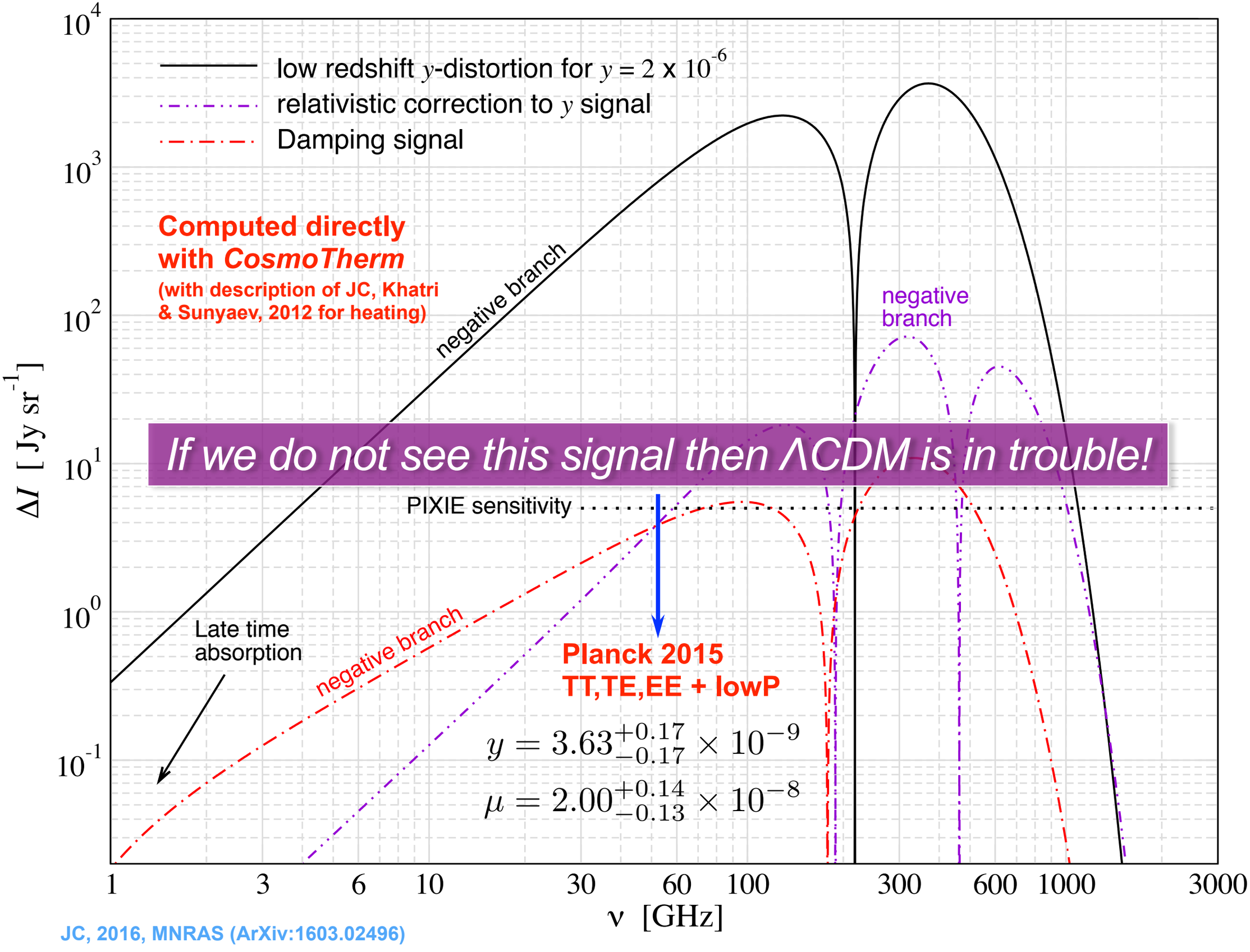


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper limit is effectively $\mu < 1.76 \times 10^{-4}$ (see text). The corresponding constraint on n is relatively weakly dependent on cosmological parameters: $n < 1.60$ $(h = 0.5)$ and $n < 1.63$ $(h = 1.0)$ for $\Omega_0 = 1$ and quite similar for $0.2 < \Omega_0 = 1 - \Omega_\Lambda < 1$ universes. These limits are nearly independent of Ω_B. We have also plotted the optimistic 95% upper limit on $\mu < 0.63 \times 10^{-4}$ for comparison as discussed in the text.

- based on classical estimate for heating rate
- Tightest / cleanest constraint at that point!
- simple power-law spectrum assumed
- *μ~10^{-8} for scale-invariant power spectrum*
- $n_S \lesssim 1.6$

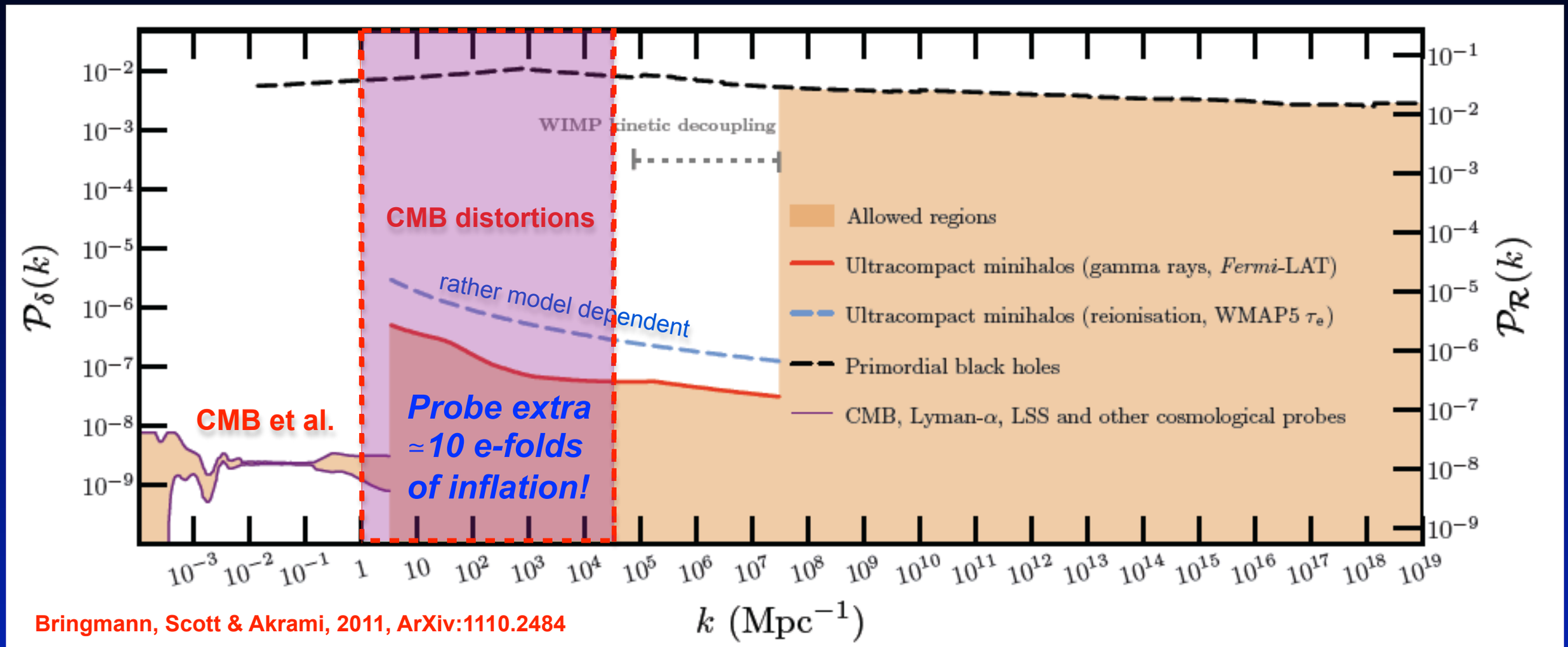
Hu, Scott & Silk, 1994

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Distortions provide new power spectrum constraints!



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- 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}
- *complementary* piece of information about early-universe physics

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

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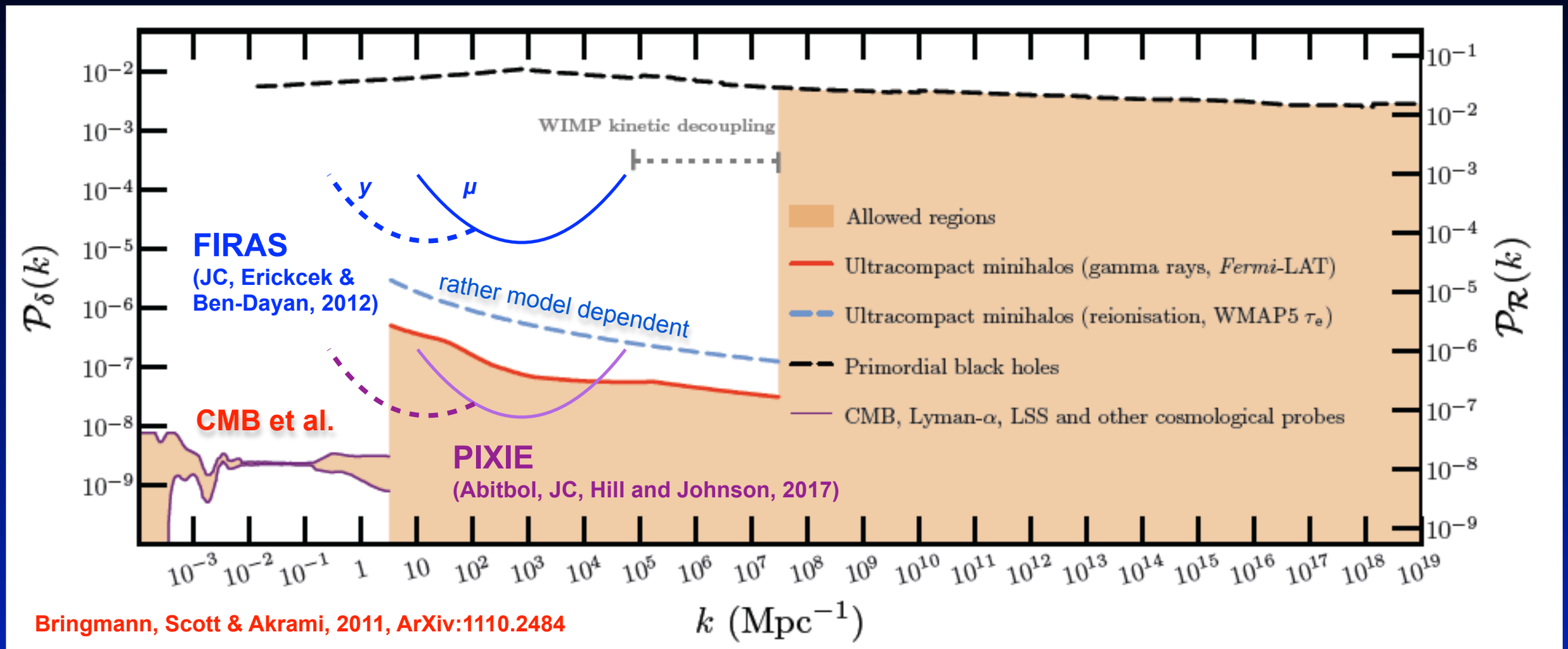

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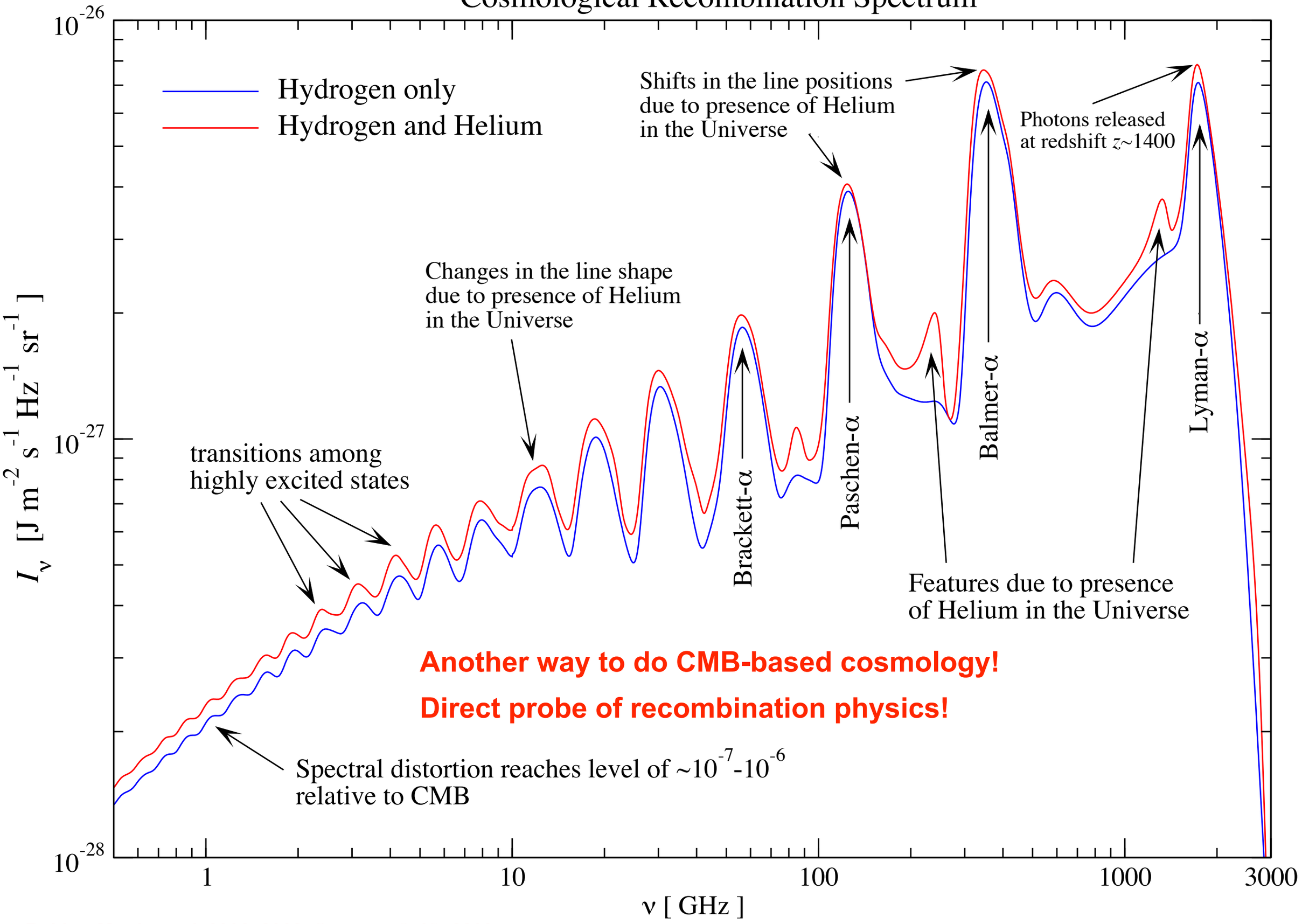
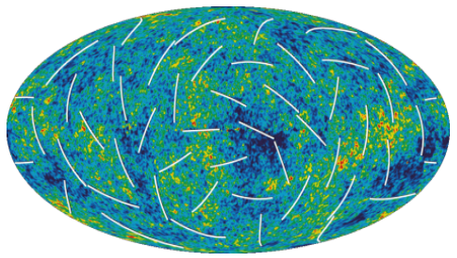


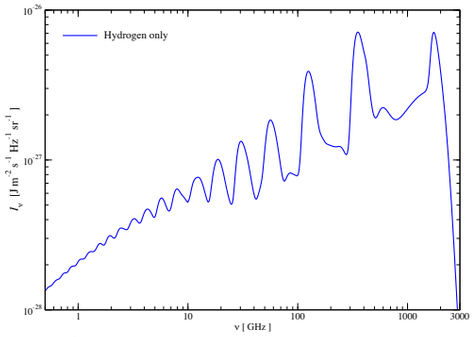
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

Cosmological Time in Years

790,000 370,000 260,000 130,000 18,000

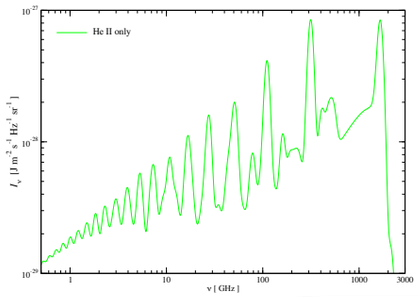
CMB-Anisotropies





Hydrogen Lines

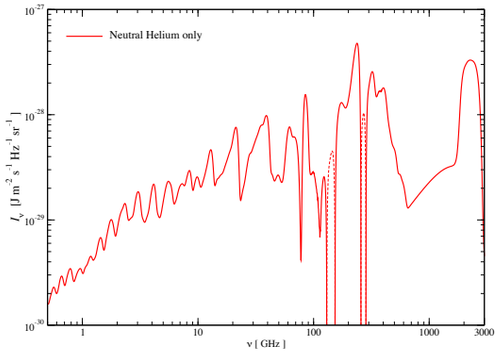
Singly ionized Helium Lines



Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized



Neutral Helium Lines

Visibility Function

Plasma neutral

H I-Lines

He I-Lines

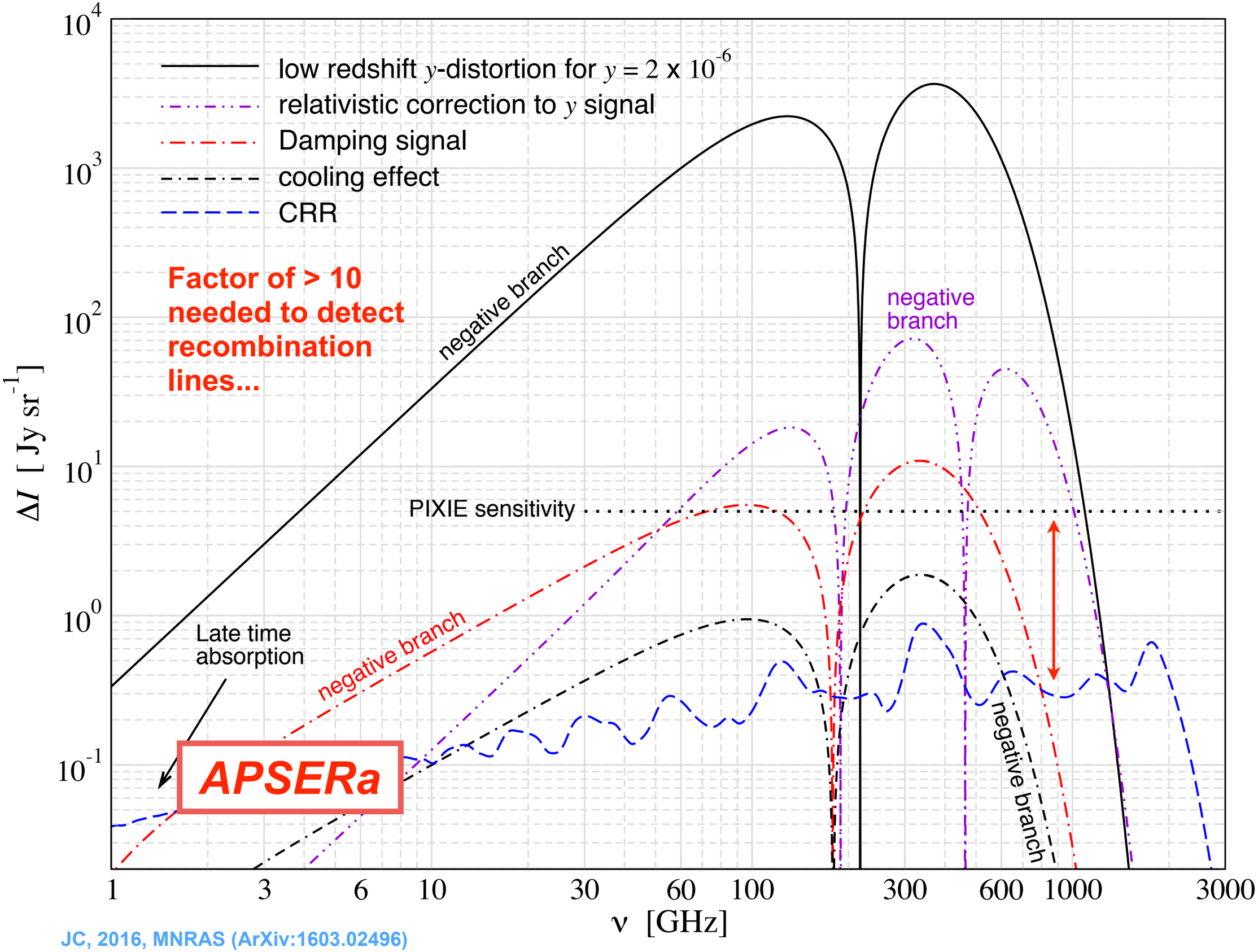
He II-Lines

1.4 1.2 1 0.8 0.6 0.4 0.2 0

700 1100 2000 3000 4000 6000 8000

Redshift z

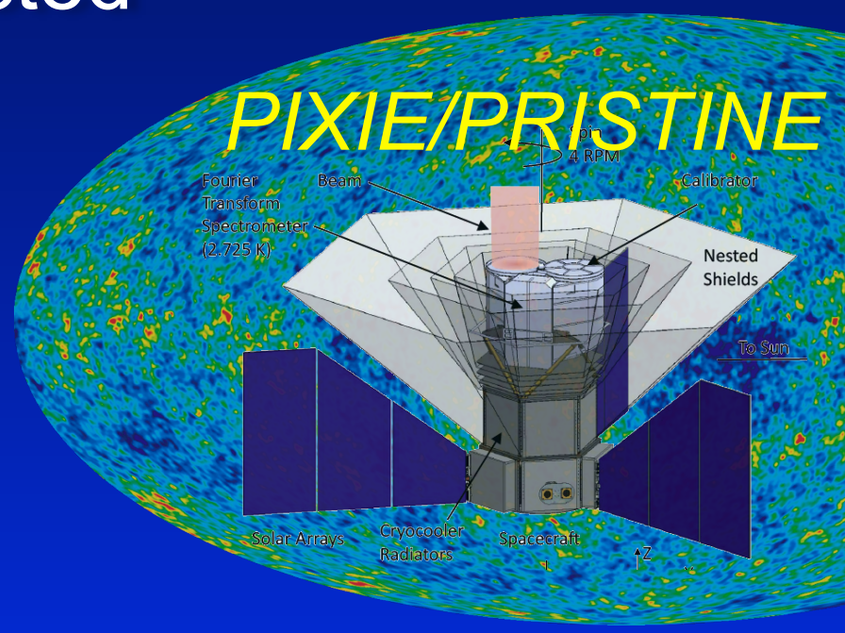
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

What can CMB spectral distortions teach us?

- 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 CMB 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



We should really make use of this information!

Steps forward on CMB spectral distortions

- *Pioneering* work from the ground
  - Improved constraints on μ and *y*
  - Possible detection of average late-time *y*-distortion
  - Discovery potential (e.g., ARCADE excess, EDGES)

  ➡ COSMO at Dome-C and APSERa

- *Low-frequency foregrounds*
  - One of the main problems for distortions (Abitbol, JC, Hill and Johnson, 2017)
  - Capitalize on *existing experience* (e.g., C-Bass, Quijote)
  - One of the *important inputs* for B-mode searches

- Advancing the frontier from *space*
  - Probe of *inflation* and early-Universe physics
  - Complementary science to B-modes + *guaranteed* signals
  - Absolutely calibrated multi-frequency maps incredibly valuable (e.g., calibration issues, foreground separation)

  ➡ PRISTINE, PIXIE-prime, CMB-Bharat

What is PRISTINE?

Polarized Radiation Interferometer for Spectral disTorsions and INflation Exploration

Aims, boundary conditions and collaboration

- Measure both CMB polarisation and distortions
- From design of COBE/FIRAS and PIXIE optimise and adapt the science case and instrument deign for a small mission
  - y-type distortions
  - Do from space what can *best* be done from space
  - Complementarity with other missions and ground based projects
  - Do not have the ambition of a definitive CMB mission

European and US Consortium

PI: Nabila Aghanim

Max Abitbol
Jonathan Aumont
François Bouchet
Jens Chluba
Hervé Dole
Marian Douspis
Josquin Errard
Ken Ganga
Julien Grain
Vincent Guillet
Ariel Haziot
Guilaine Lagache
Mathieu Langer
Juan Macias-Perez
Bruno Maffei
Jean-Pierre Maillard
Anna Mangilli
Luca Pagano
Etienne Pointecouteau
Jean-Loup Puget
Mathieu Remazeilles
Louis Rodriguez
Gérard Rouillé
Abdellah Roussafi
Giorgio Savini
Jean-Luc Starck
Valentin Sauvage
Andrea Tartari
Neil Trappe
Sébastien Triqueneaux
Gérard Vermeulen
Al Kogut
Dale Fixsen

Courtesy: Bruno Maffei

Instrument Philosophy

Optimised imaging polarised FT Spectro. based on PIXIE concept

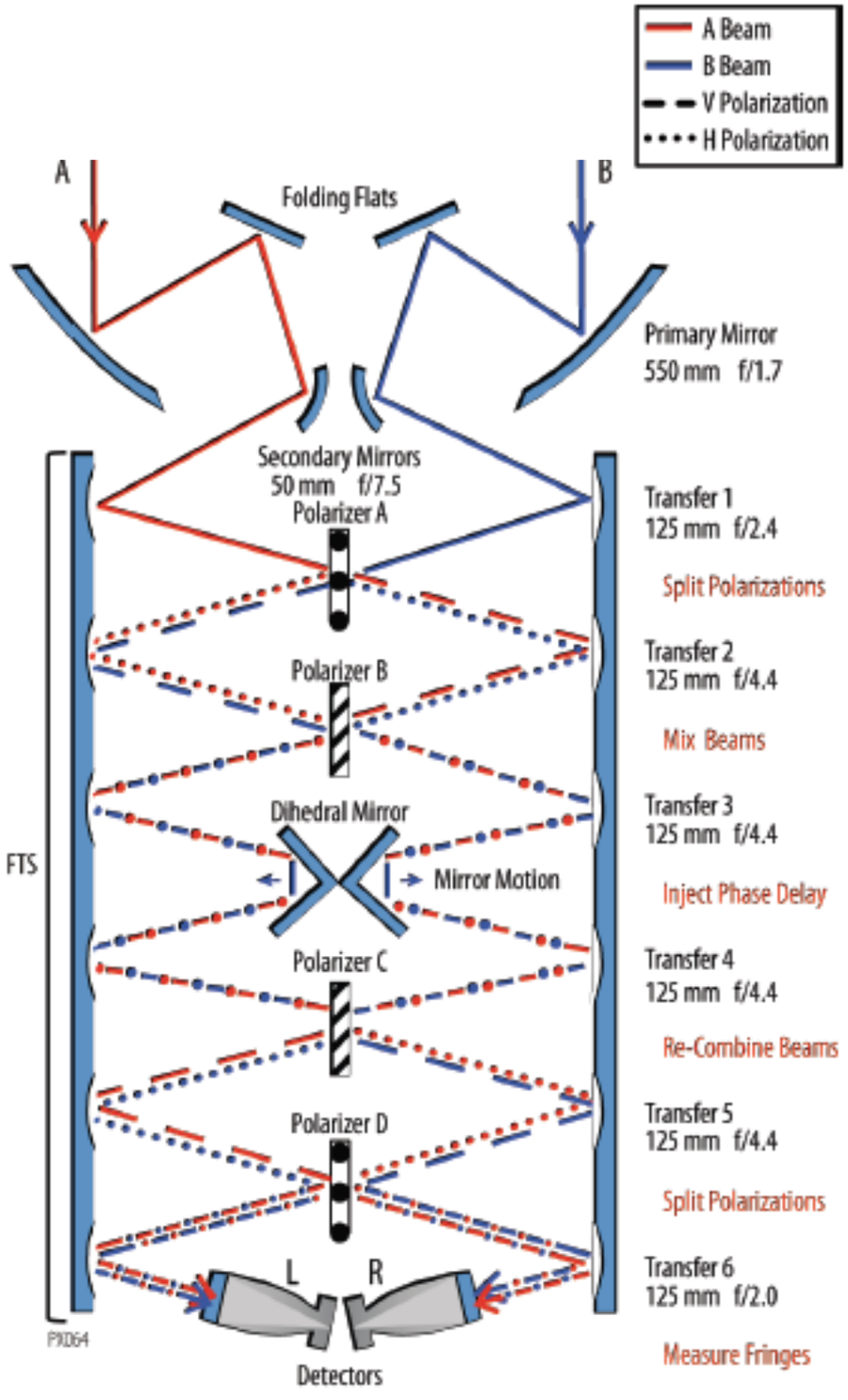
- Two telescopes of 36 cm each
- Frequency range 90 to 2000 GHz
  - 2 THz decreases largely the noise contribution from dust and mitigates degeneracy with CIB, and correlation with synchrotron
  - 90 GHz improves spatial resolution and constraints size of optical elements
- Spectral resolution of 5 GHz
  - Mitigates contamination from lines and optimises legacy ISM & galaxies
- Spatial resolution 0.75 deg equivalent Gaussian
- Array of 7 dual polarised pixels (x 2, one for each output port)
- Sensitivity similar to PIXIE /10
- Internal absolute photometric calibrator
- Try to reduce risks and have high TRL

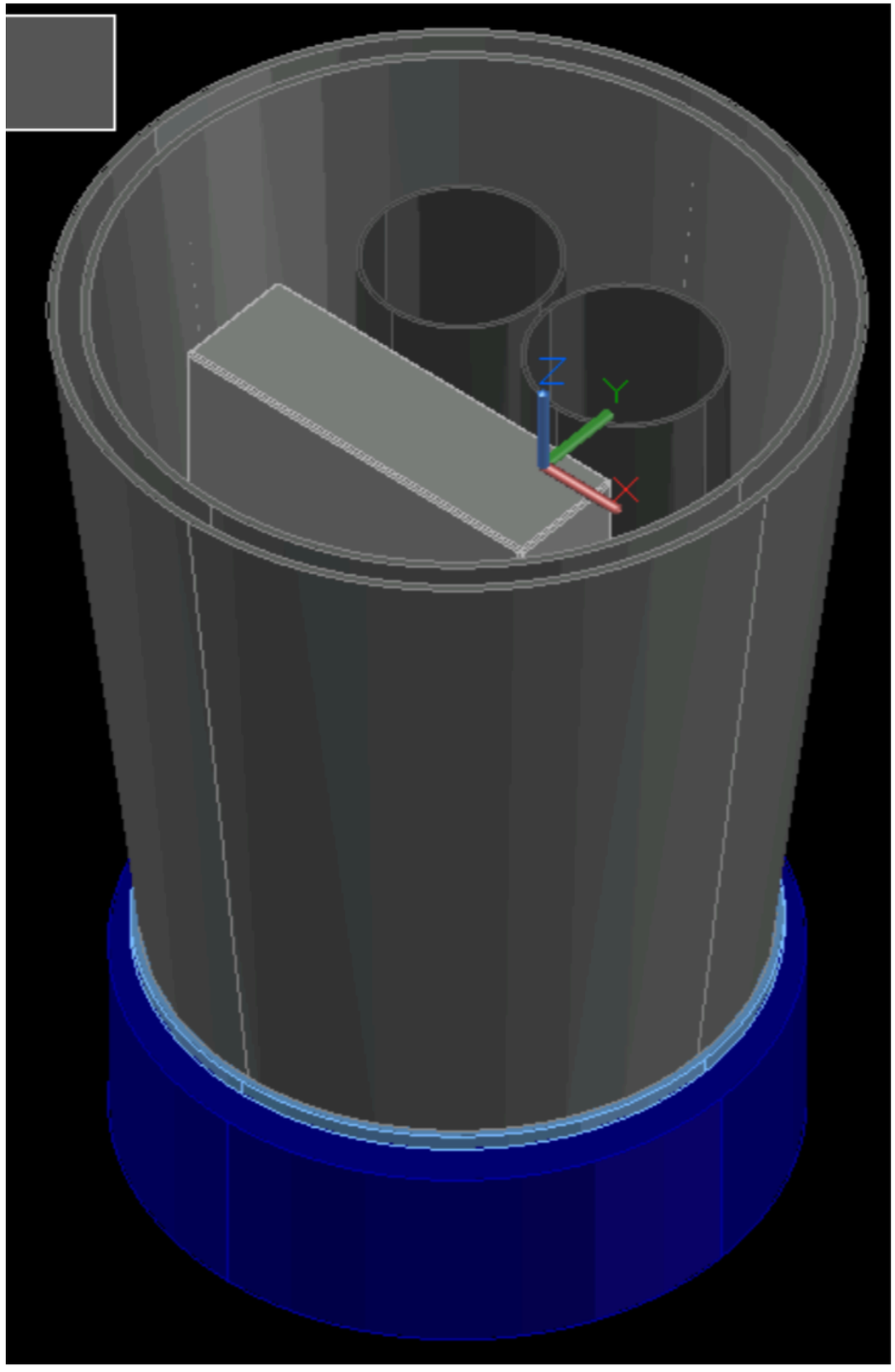
- Slow spinning

Proposal to be submitted to ESA (F-class)

Courtesy: Bruno Maffei

Instrument concept

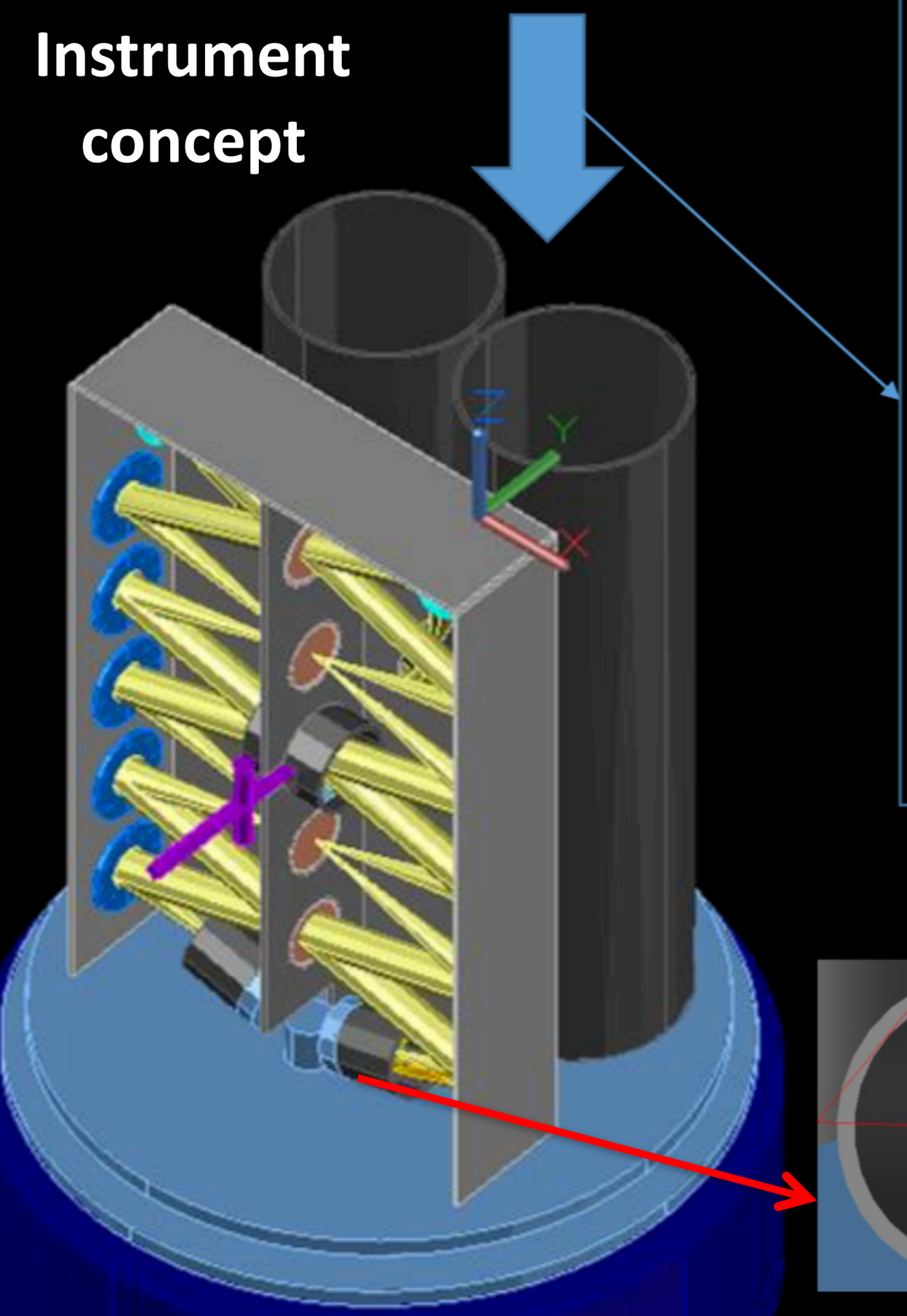


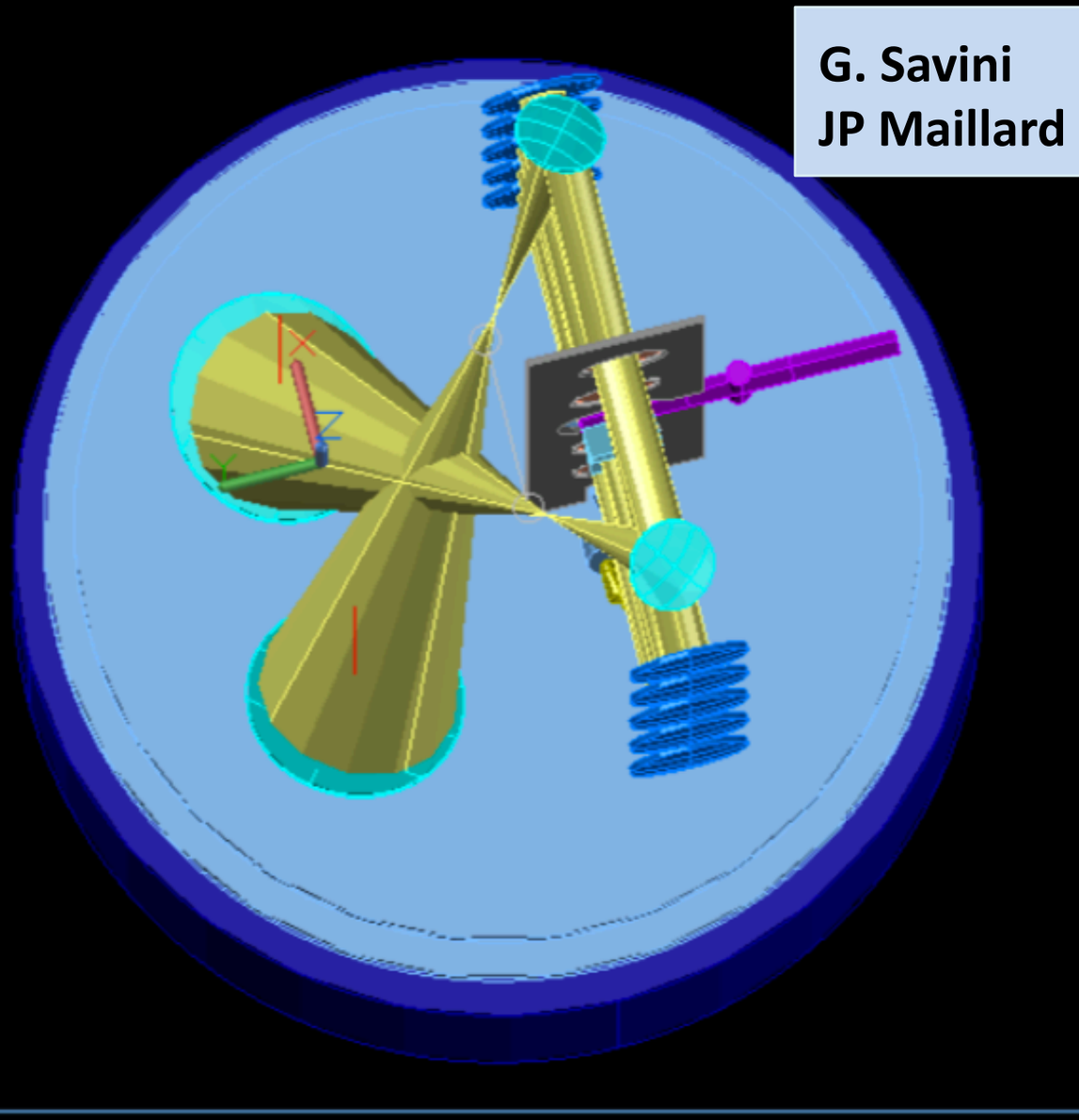


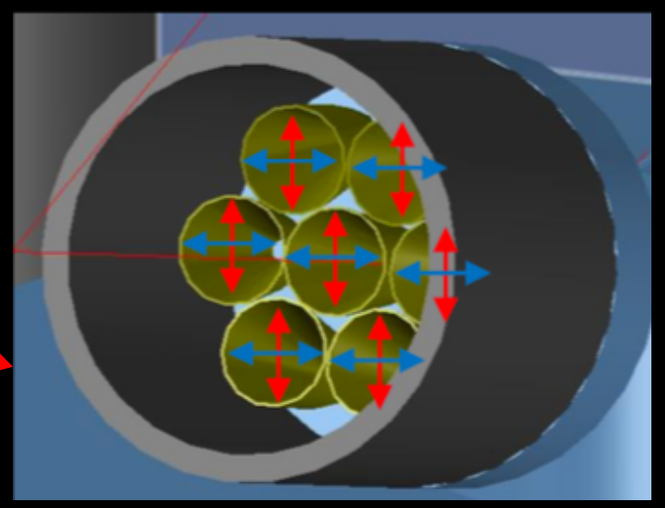
Courtesy: Bruno Maffei

Instrument concept

G. Savini
JP Maillard



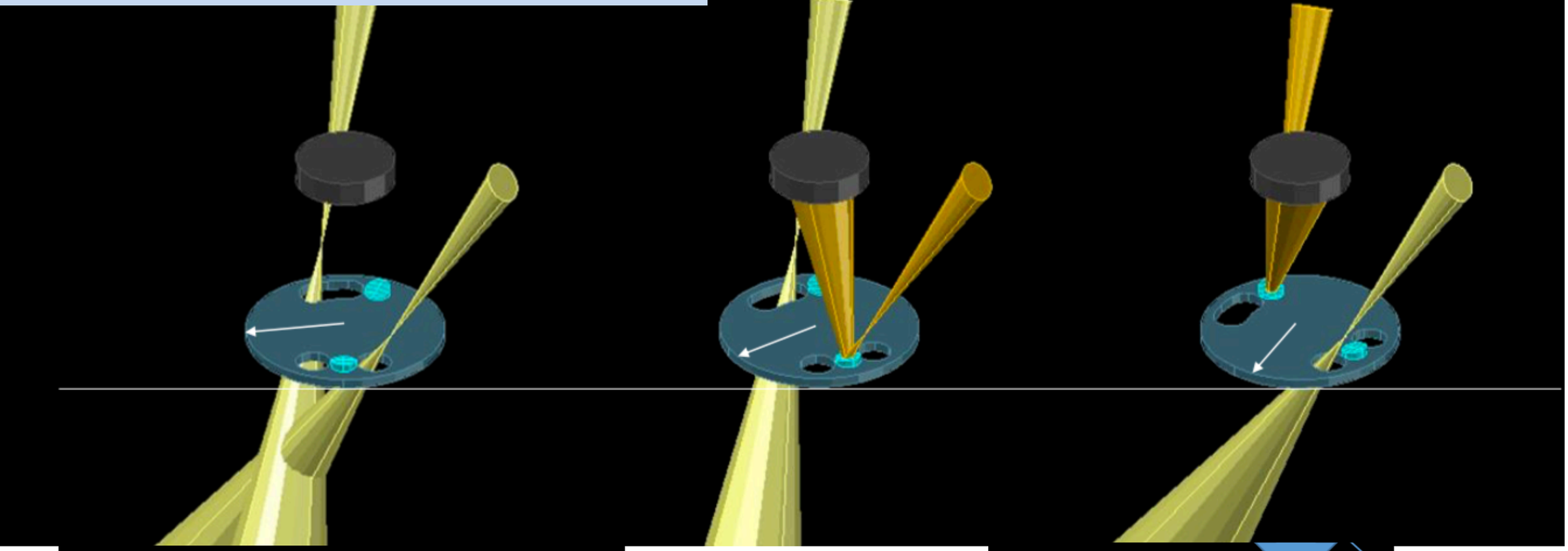


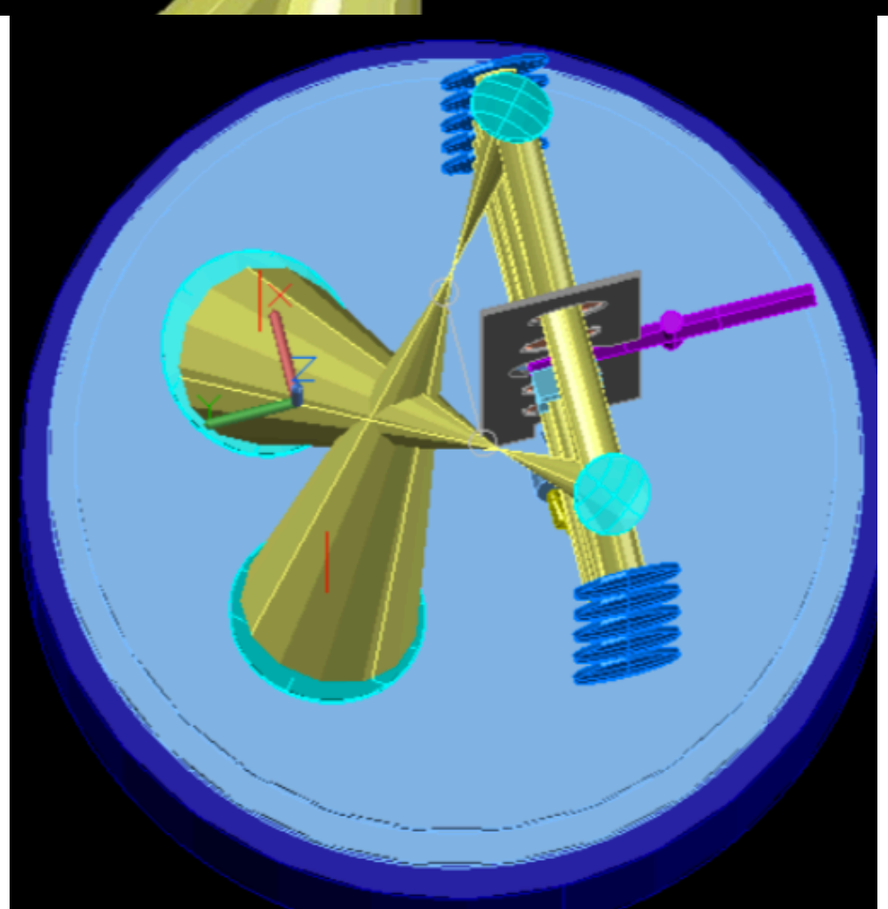


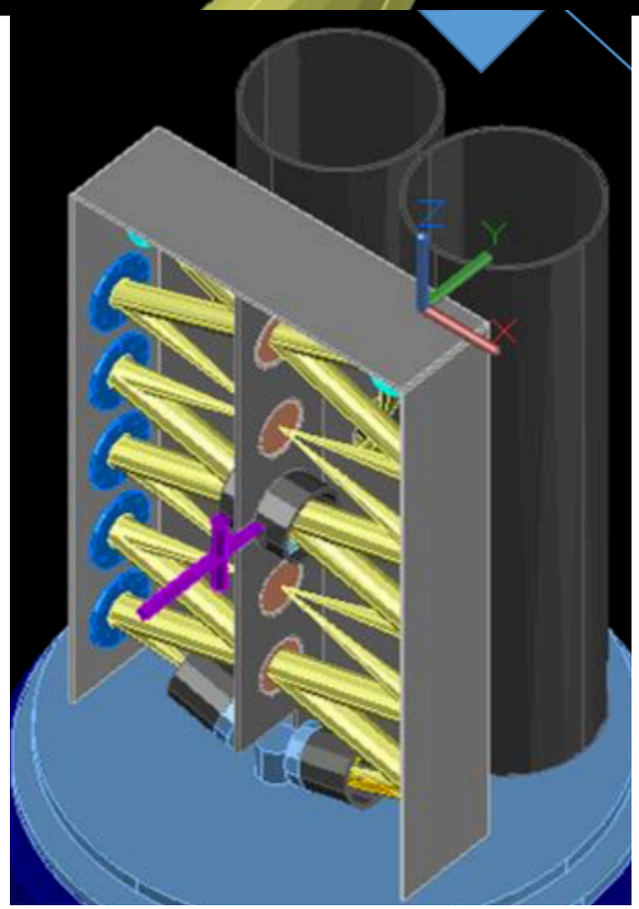
Detector array at ~ 100mK
7 horn-coupled dual-polarisation bolometers on curved focal surface

Potential internal calibration mechanism

G. Savini
JP Maillard







Science with PRISTINE

Spectral distortion forecasts by Max Abitbol:

- ➡ Significant detection of y (>10 σ)
- ➡ Close to detecting average rel. thSZ
- ➡ Improved limit on μ

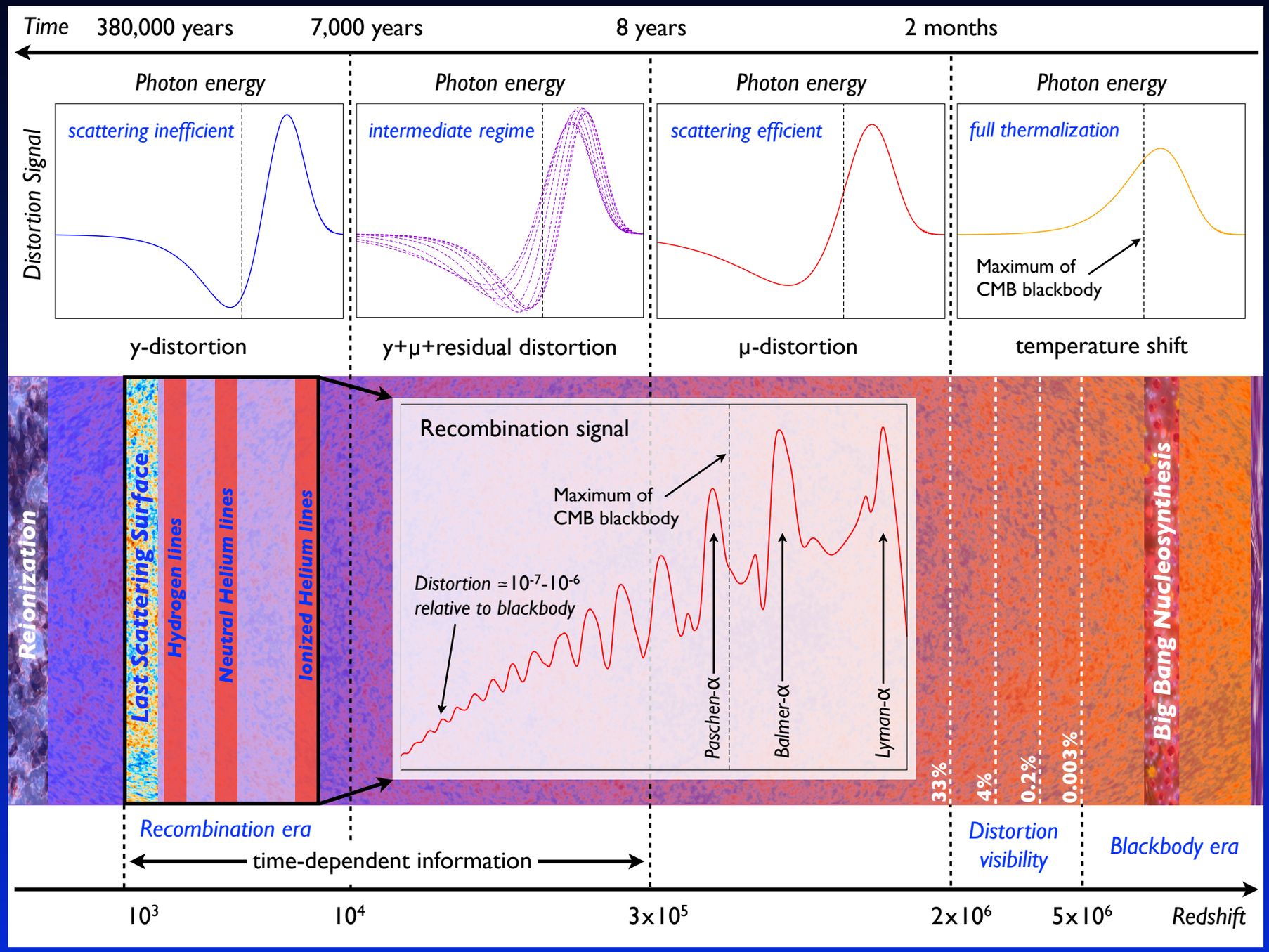
B-mode forecasts by Mathieu Remazeilles and Josquin Errard:

- ➡ 20 σ detection of τ and E-mode reconstruction at $2 \leq l \leq 50$
- ➡ 5 σ detection of $r = 10^{-2}$

Additional science and Foregrounds

- ➡ Large-angle CIB and CO intensity mapping
- ➡ Absolutely calibrated maps of the sky at *many* frequencies
- ➡ Goldmine for foreground studies
- ➡ Could be crucial for B-mode searches

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

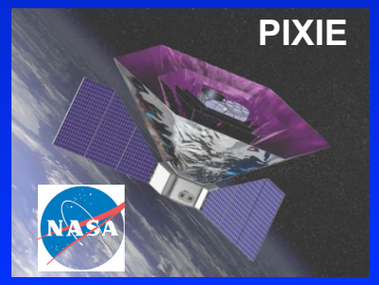
New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

Chluba & Sunyaev, MNRAS, 419, 2012
Chluba et al., MNRAS, 425, 2012
Silk & Chluba, Science, 2014
Chluba, MNRAS, 2016



PRISTINE COSMO

CMB-Bharat