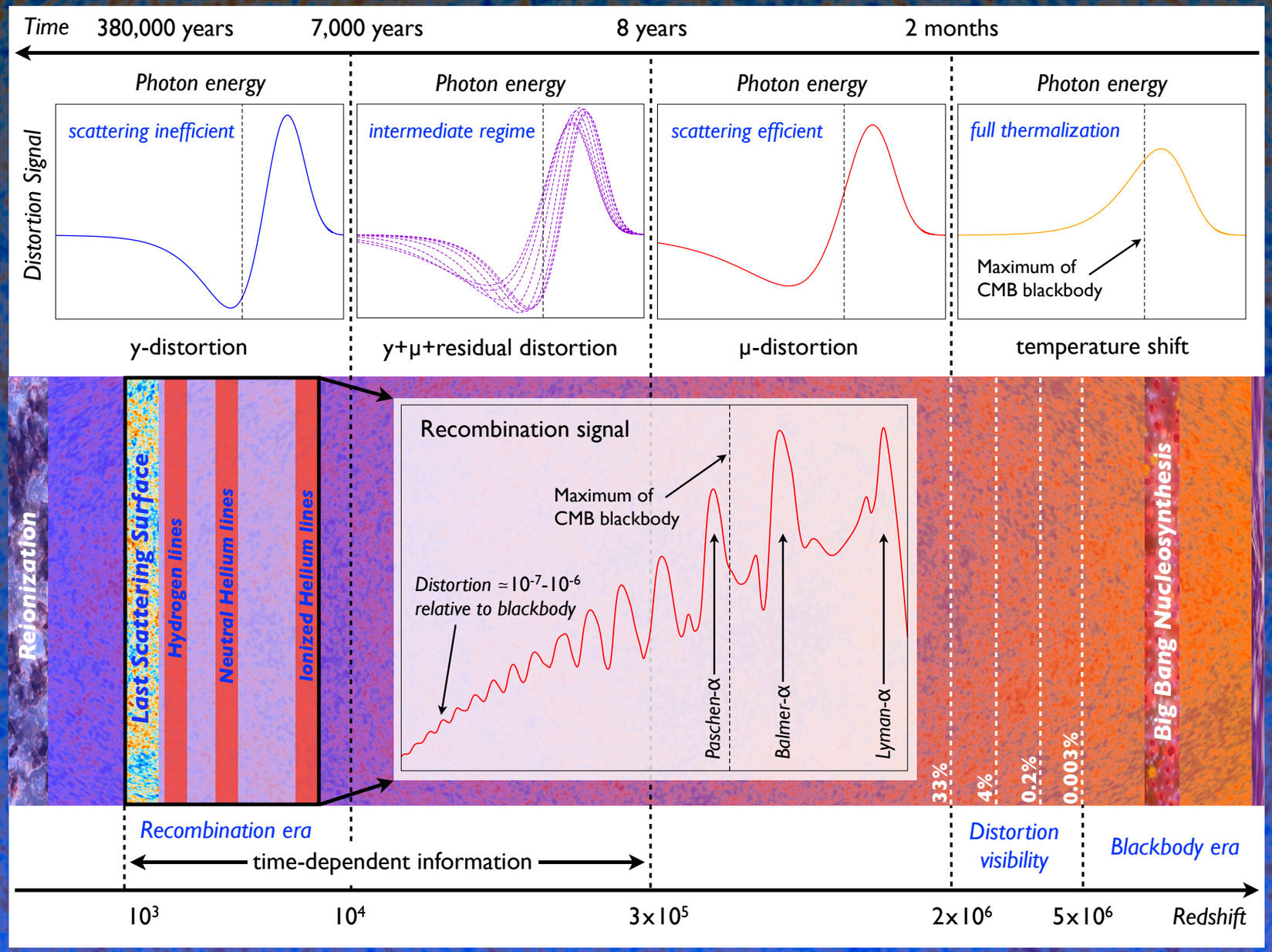
Status of CMB spectrometers and what we still need to make this happen



Jens Chluba

The University of Manchester

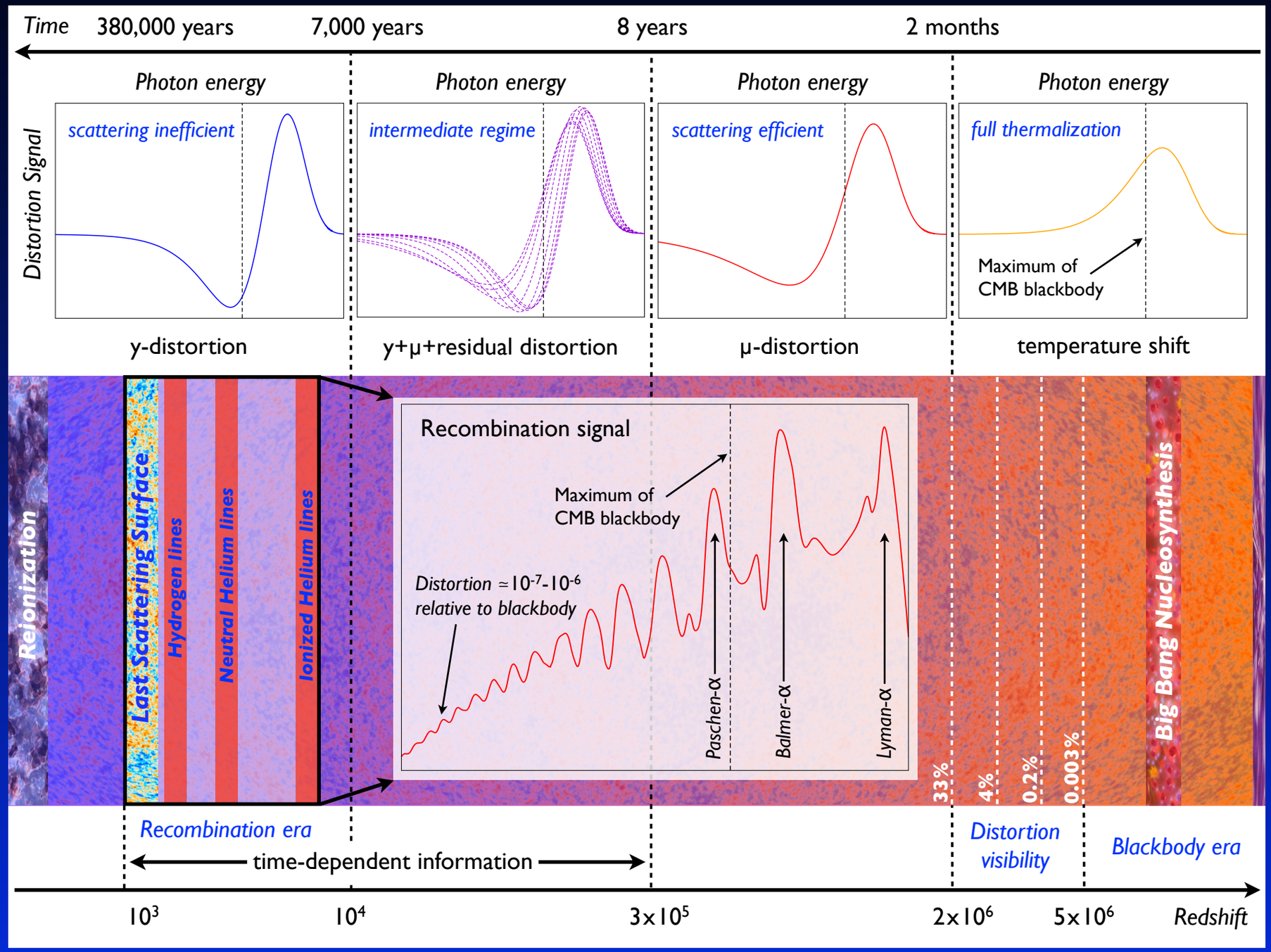
From Planck to the future of CMB, University of Ferrara

May 27th 2022

The Distortion Gang at Manchester

erc
THE ROYAL SOCIETY

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

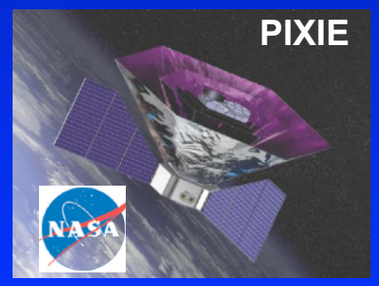
New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

JC & Sunyaev, MNRAS, 419, 2012
JC et al., MNRAS, 425, 2012
Silk & JC, Science, 2014
JC, MNRAS, 2016
JC et al., 2019, arXiv:1909.01593



PRISTINE
COSMO
SuperPIXIE
BISOU

Time 380,000 years 7,000 years 8 years 2 months

Observable

y-distortion

y+μ+residual distortion

Photon injection distortions

μ-distortion

ΔT

ΔN_{eff}

Non-thermal distortions

Mission Concept

FIRAS

Reionization and Structure formation

SZ Clusters

Relativistic SZ

Intensity Mapping

Line scattering

Decaying particles / Primordial Black Holes / Axions

p-wave annihilation

Primordial Magnetic Fields

Distortions from enhanced small-scale power

PRISTINE

Signal Level

Discovery Space

PIXIE

Damping of small-scale scalar perturbations in ΛCDM with $\mu = 2\times10^{-8}$

Super-PIXIE

Cosmological Recombination Lines

Adiabatic Cooling

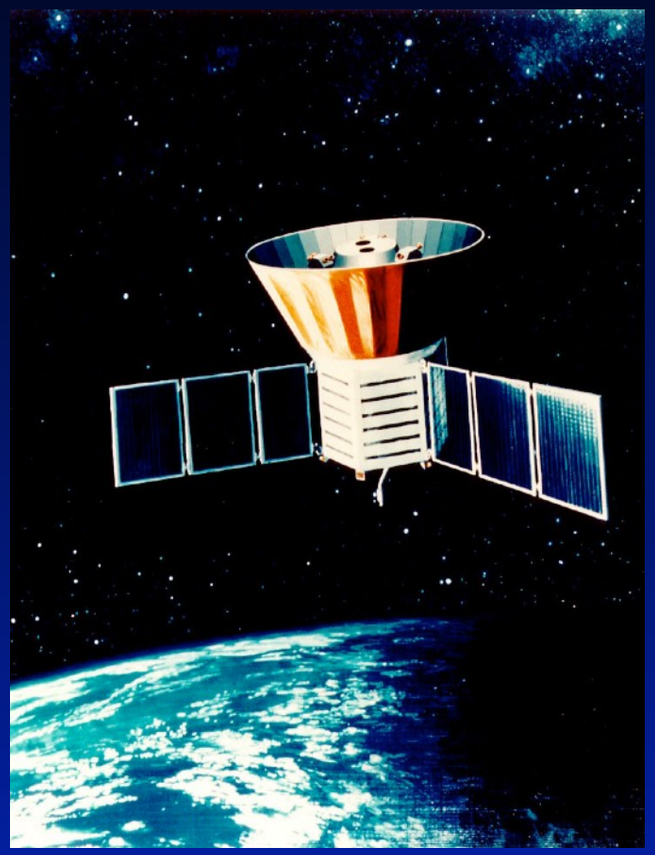
WIMP annihilation

Voyage 2050

10 10^3 10^4 3×10^5 2×10^6 *Redshift*

What is the status of CMB spectral distortions?

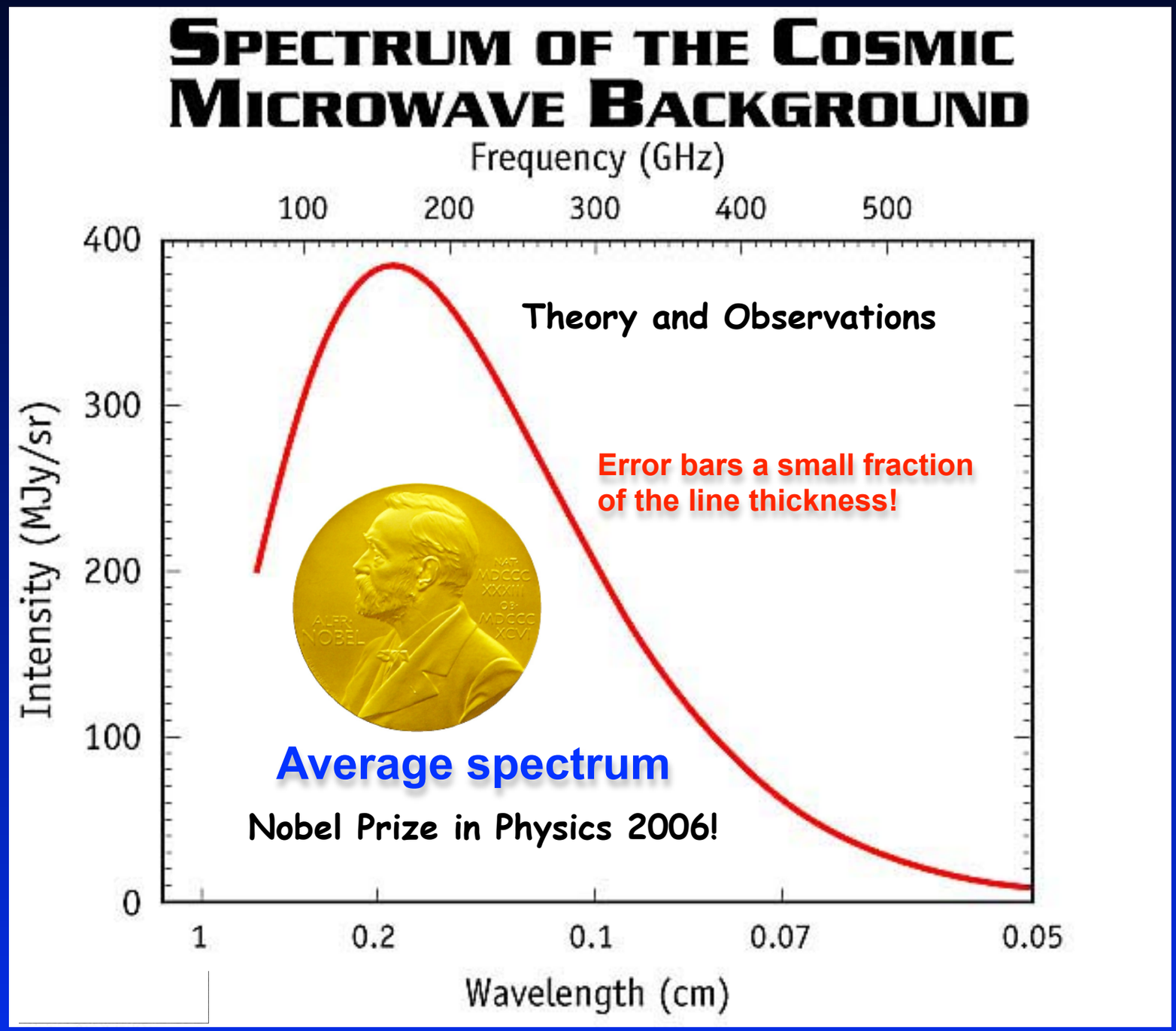
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

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

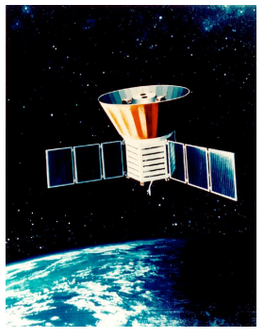
$$|\mu| \leq 9\times10^{-5}$$



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

Only very small distortions of CMB spectrum are still allowed!

History of distortion experiments and proposals



COBE/FIRAS

Mather & Fixsen

ARCADE 2

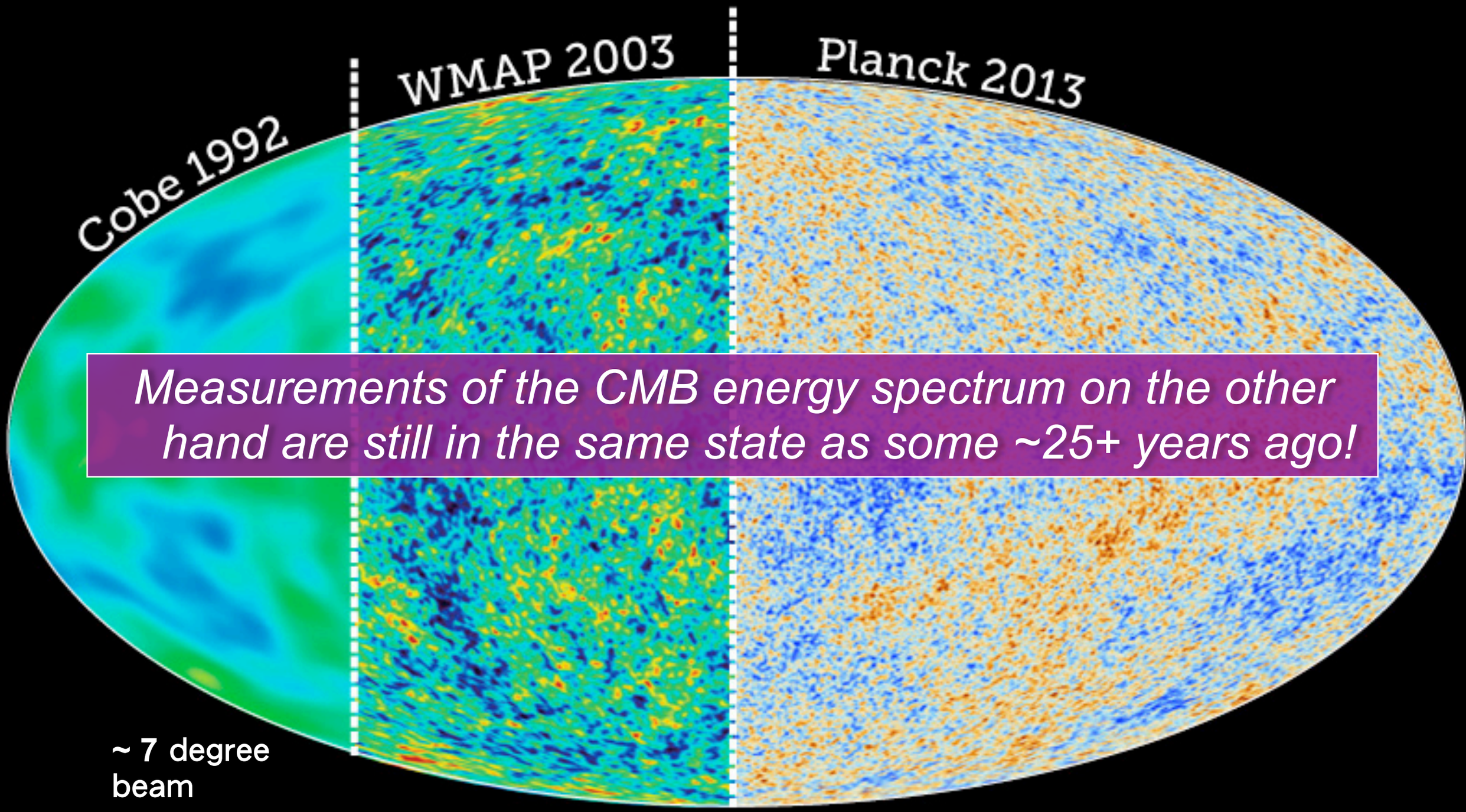
Kogut & Fixsen

TRIS

Gervasi, Zannoni & Tartari

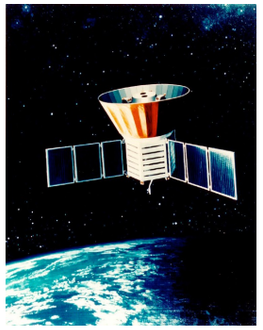
1989 2008 2011 2013 2015 2016 2018 2022

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



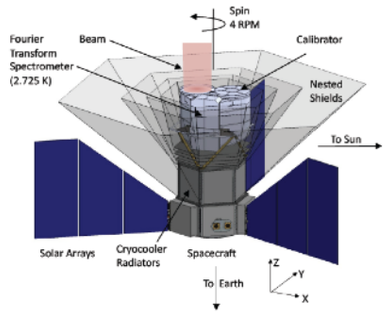
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~25+ years ago!

History of distortion experiments and proposals



COBE/FIRAS

Mather & Fixsen



PIXIE

Kogut & Fixsen

ARCADE 2

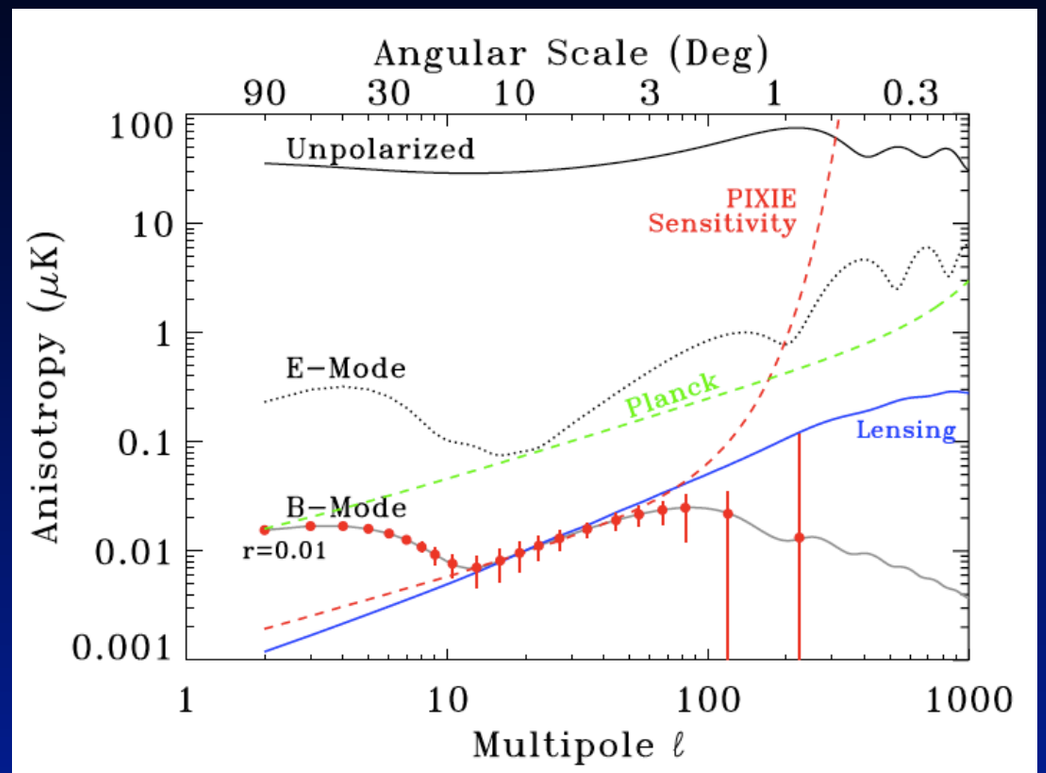
Kogut & Fixsen

TRIS

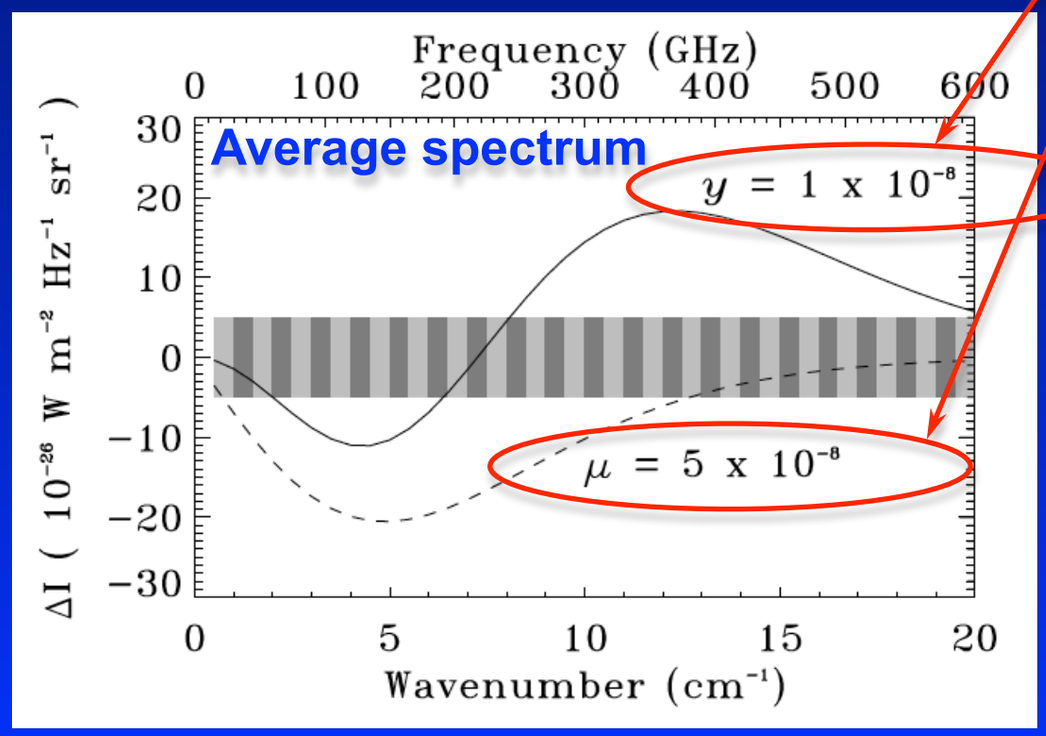
Gervasi, Zannoni & Tartari

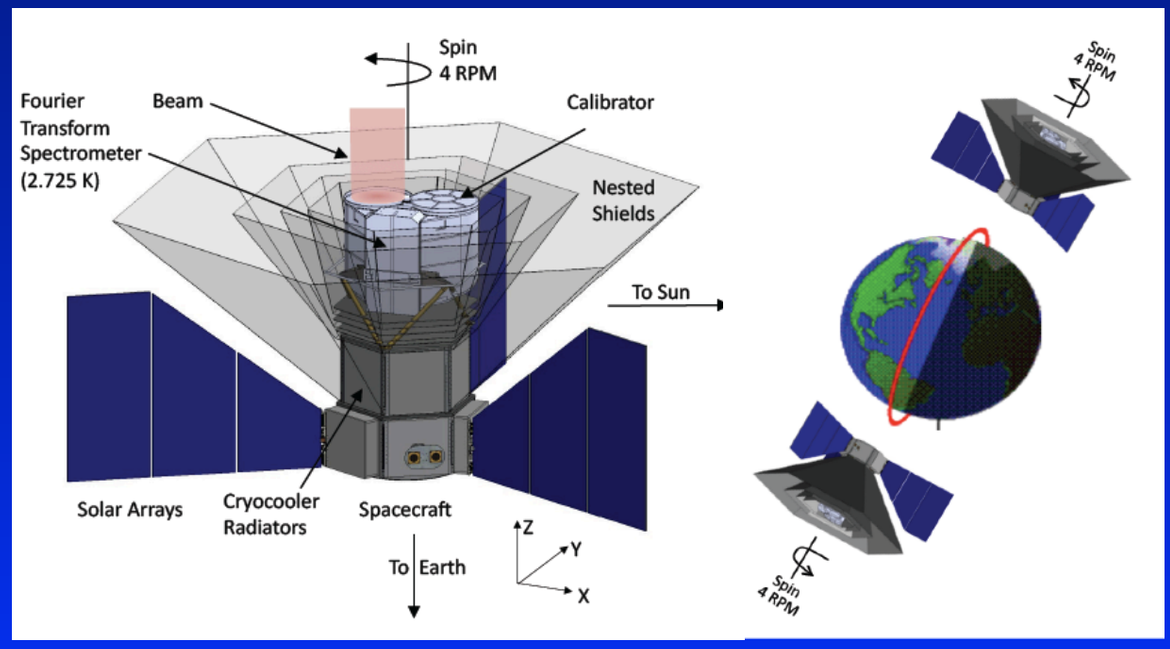
1989 2008 2011 2013 2015 2016 2018 2022

PIXIE: Primordial Inflation Explorer



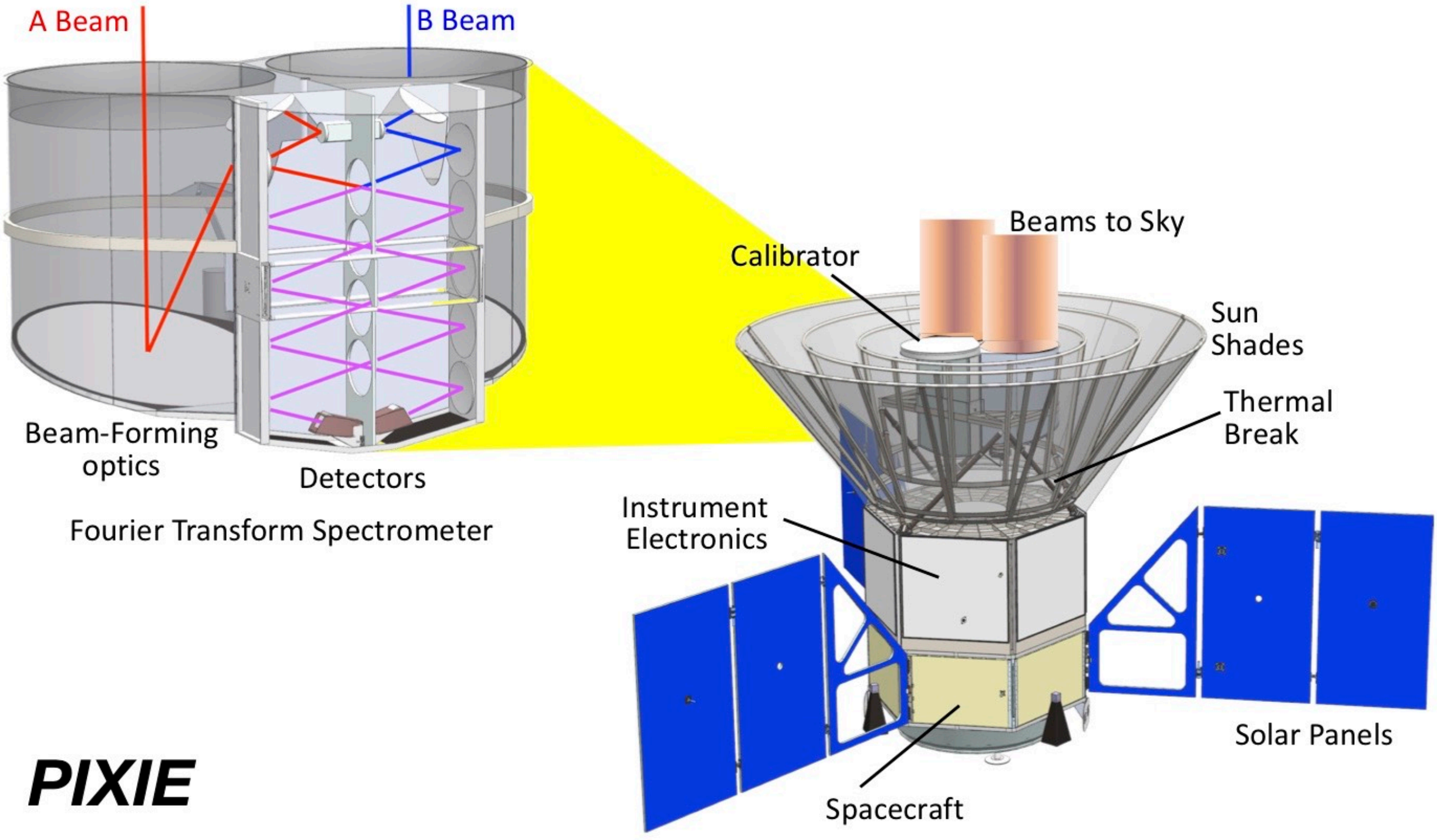
- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 and 2016 as NASA EX mission (i.e. cost ~ 300 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044

The main FTS concept

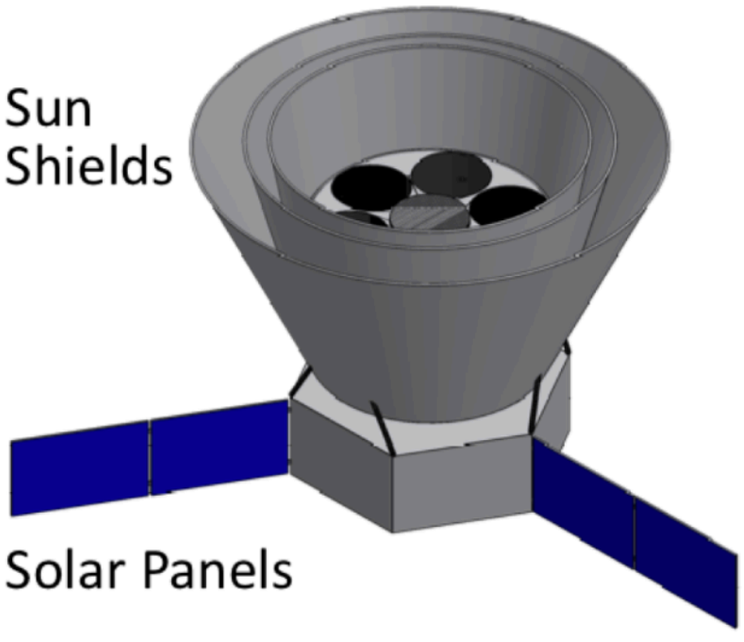


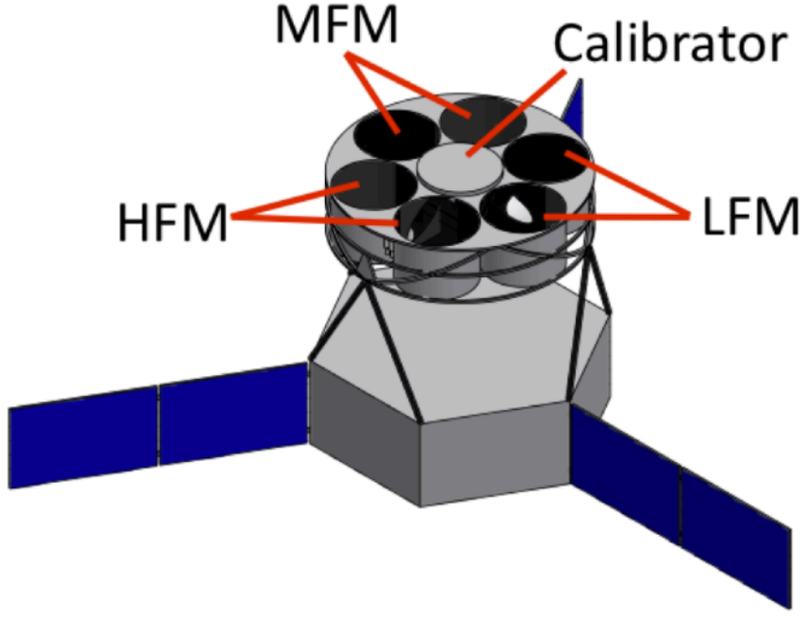
Kogut et al, BAAS, 2019, arXiv:190713195

Courtesy Al Kogut & Dale Fixsen

Other space spectrometers designs vary….

- Size of apertures or beam (to modify $A\,\Omega$)
- Observing time
- Mirror stroke → frequency resolution
- Multiple copies of ‘PIXIE’
- Dedicated FTS for different frequency-bands

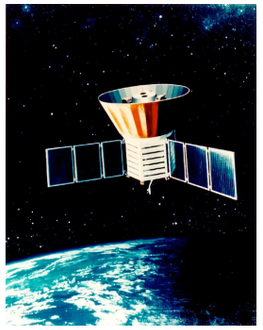




Super-PIXIE

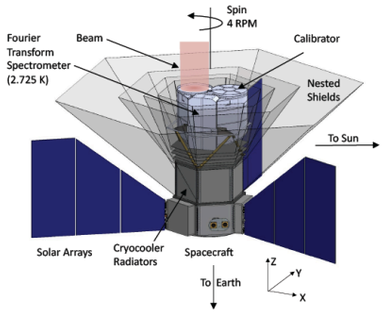
Kogut et al, BAAS, 2019, arXiv:190713195

History of distortion experiments and proposals



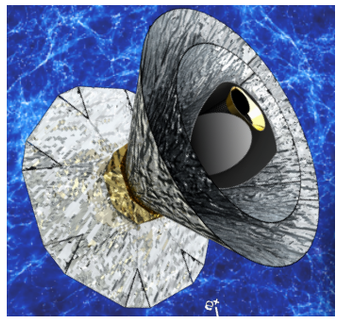
COBE/FIRAS

Mather & Fixsen



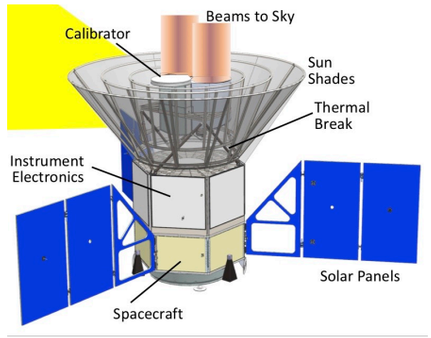
PIXIE

Kogut & Fixsen



PRISM

De Bernardis



PIXIE

Kogut & Fixsen

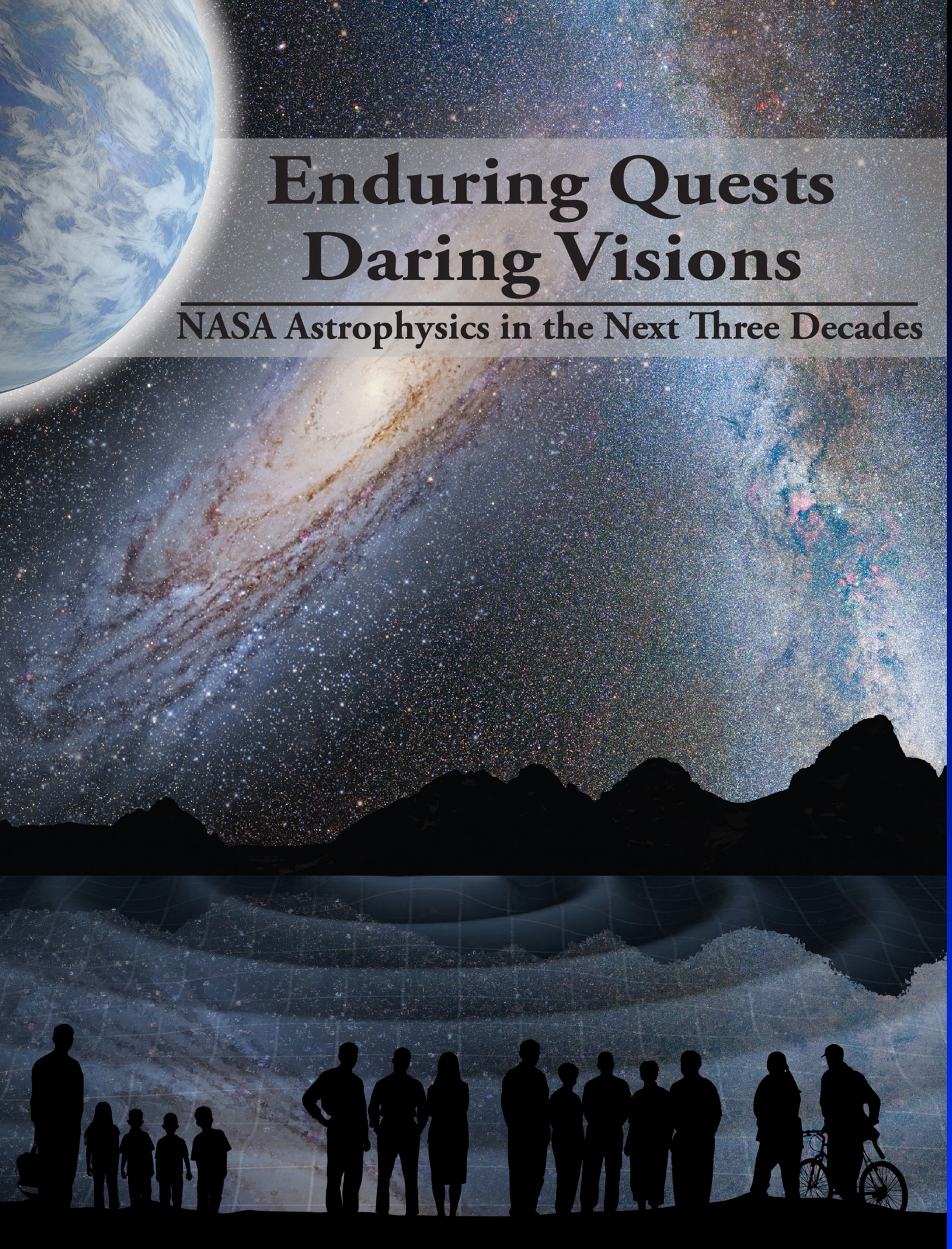
ARCADE 2

Kogut & Fixsen

TRIS

Gervasi, Zannoni & Tartari

1989 2008 2011 2013 2015 2016 2018 2022



NASA 30-yr Roadmap Study

(published Dec 2013)

How does the Universe work?

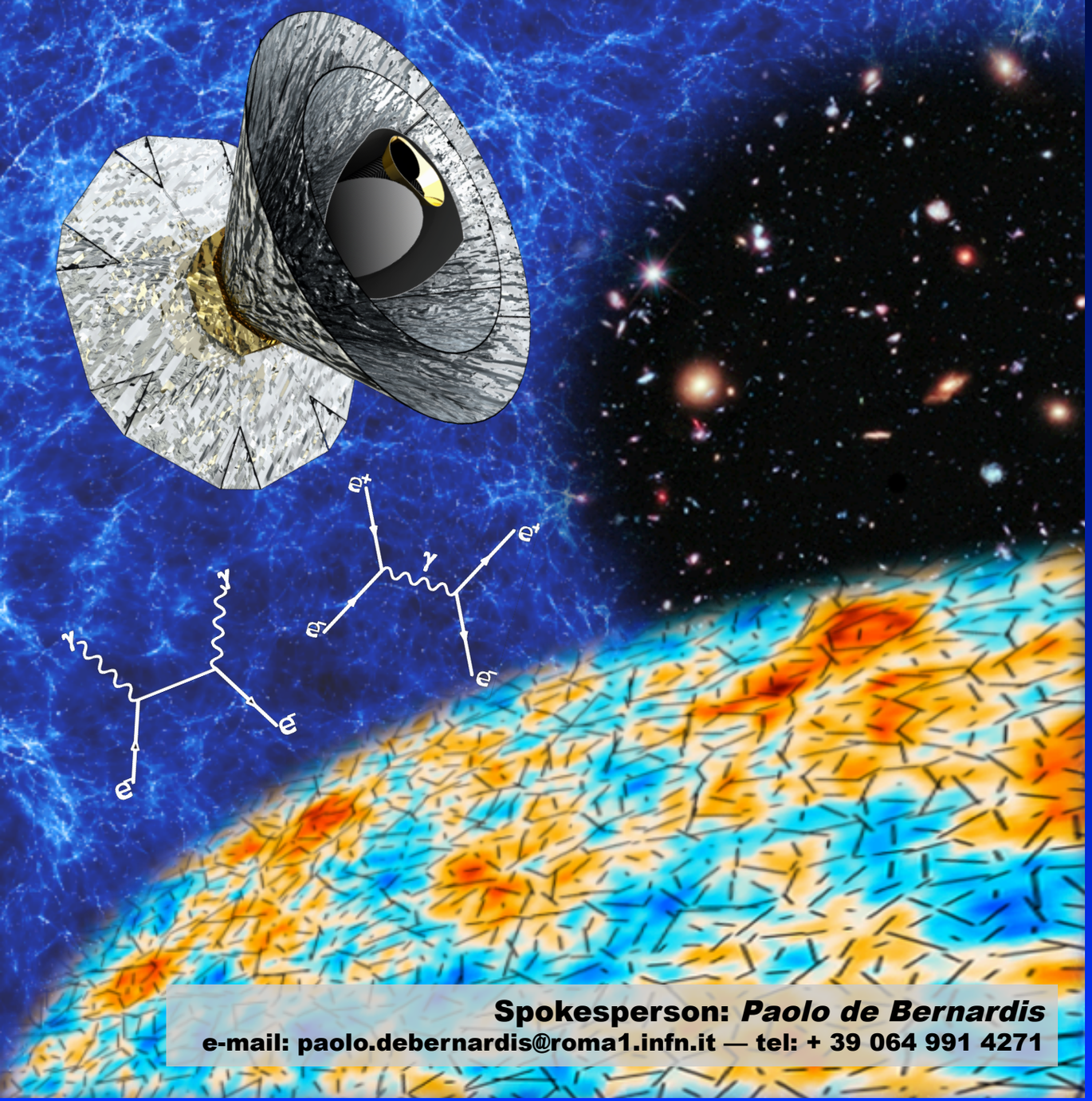
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

➡ *looked like positive prelude for NASA Decadal Review 2020*

Polarized Radiation Imaging and Spectroscopy Mission

PRISM

Probing cosmic structures and radiation with the ultimate polarimetric spectro-imaging of the microwave and far-infrared sky



Spokesperson: ***Paolo de Bernardis***
e-mail: paolo.debernardis@roma1.infn.it — tel: + 39 064 991 4271

Instruments:

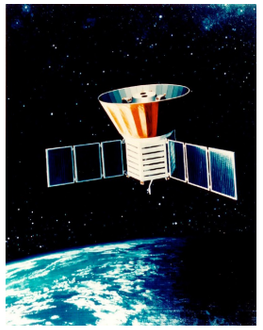
- L-class ESA mission
- White paper, May 24th, 2013
- Imager:
  - polarization sensitive
  - 3.5m telescope [arcmin resolution at highest frequencies]
  - 30GHz-6THz [30 broad ($\Delta\nu/\nu$~25%) and 300 narrow ($\Delta\nu/\nu$~2.5%) bands]
- Spectrometer:
  - FTS similar to PIXIE
  - 30GHz-6THz ($\Delta\nu$~15 & 0.5 GHz)

Some of the science goals:

- B-mode polarization from inflation ($r \approx 5\times10^{-4}$)
- count all SZ clusters >10^{14} M_{sun}
- CIB/large scale structure
- Galactic science
- *CMB spectral distortions*

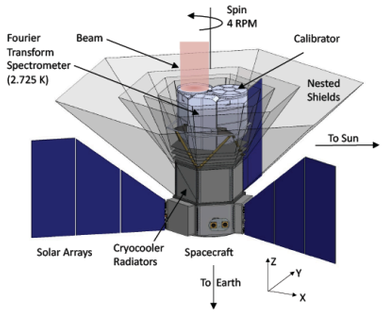
More info at: http://www.prism-mission.org/

History of distortion experiments and proposals



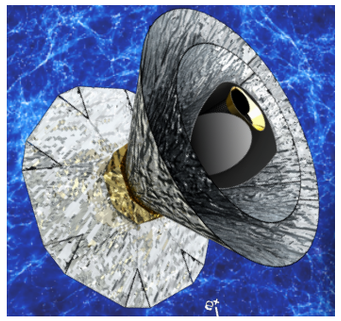
COBE/FIRAS

Mather & Fixsen



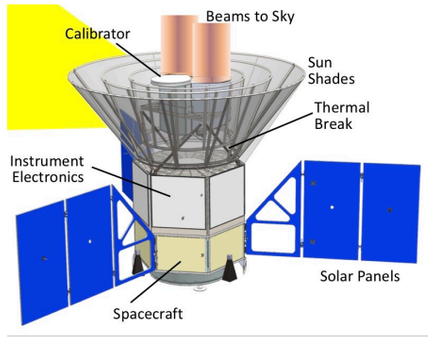
PIXIE

Kogut & Fixsen



PRISM

De Bernardis



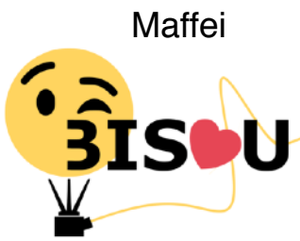
PIXIE

Kogut & Fixsen

ARCADE 2

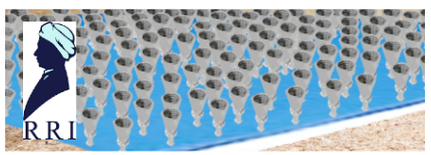
Kogut & Fixsen

Maffei



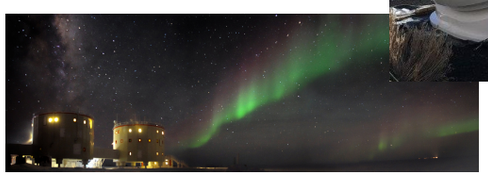
TRIS

Gervasi, Zannoni & Tartari



APSERa

Subrahmanyan & Rao



TMS

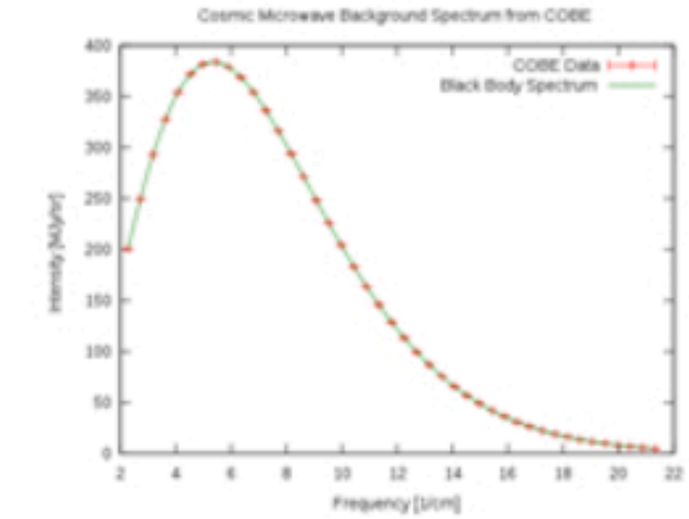
COSMO

De Bernardis, Masi & Battistelli

1989 2008 2011 2013 2015 2016 2018 2022

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.

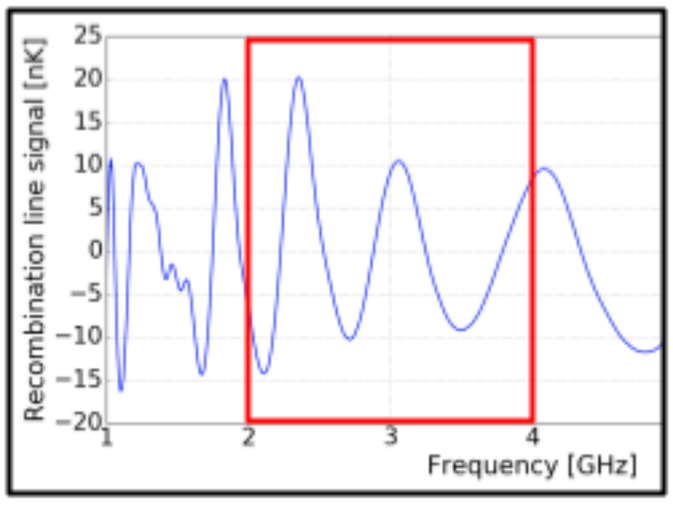
The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby 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.

Rao et al., ApJ, 2015, ArXiv:1501.07191

Array of Precision Spec… for detecting spectral r… the Epoch of RecombinAtio…

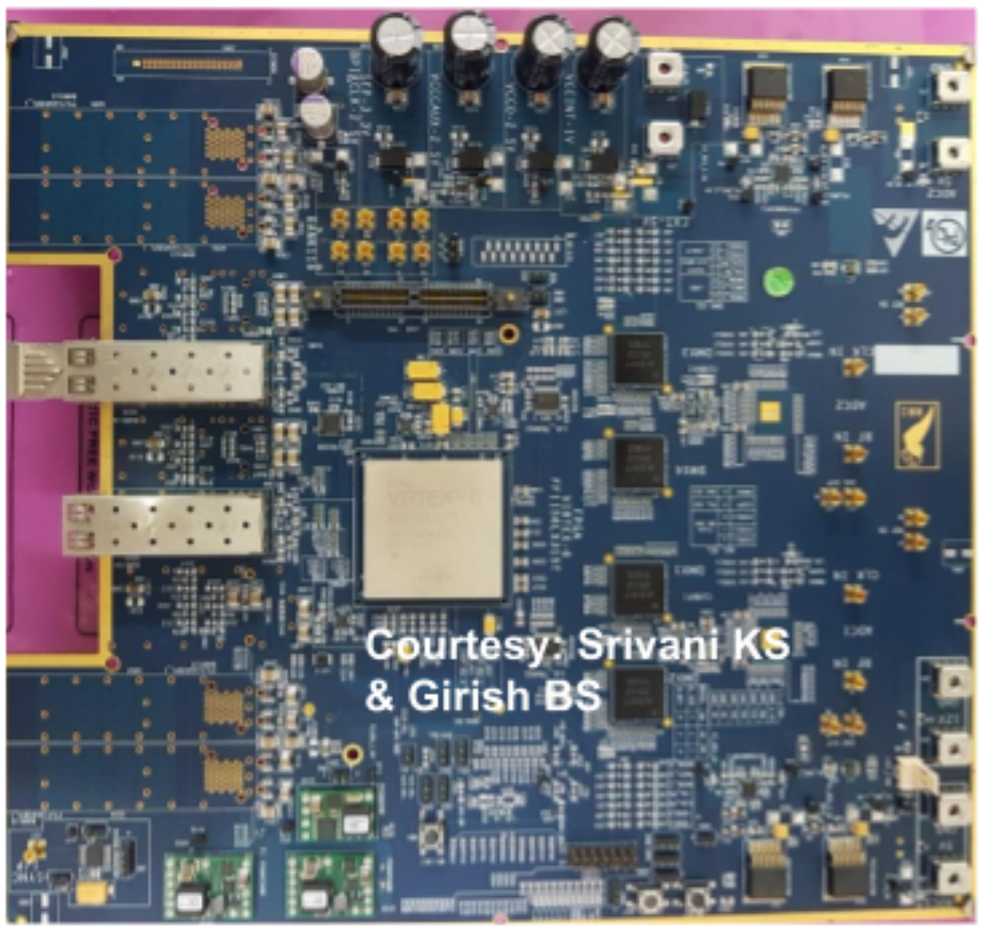
Mayuri Rao (RRI)

APSERa : Array of Precision Spectrometers for the Epoch of Recombination



Phase 1: Current status
1 element 2-4 GHz
Room temperature receiver
4 bit direct sampling board
One custom designed frequency independent antenna
Precision self-calibratable noise injection based receiver
System integration shortly

Phase 1.5
1 element 2-4 GHz
Cryogenic receiver
RFSoC direct sampling board
One custom designed frequency independent patch antenna
Precision self-calibratable noise injection based receiver
System integration shortly



Phase 2: Multi-element (final 128) array with patch antennas, cryogenic receiver, RFSoC boards, external and internal calibration

COSMO at Dome C

COSmological Monopole Observer

ArXiv:2110.12254

Taken from a talk by Elia Battistelli

SAPIENZA UNIVERSITÀ DI ROMA

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITAS STUDIORUM MEDIOLANENSIS

UNIVERSITA' 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

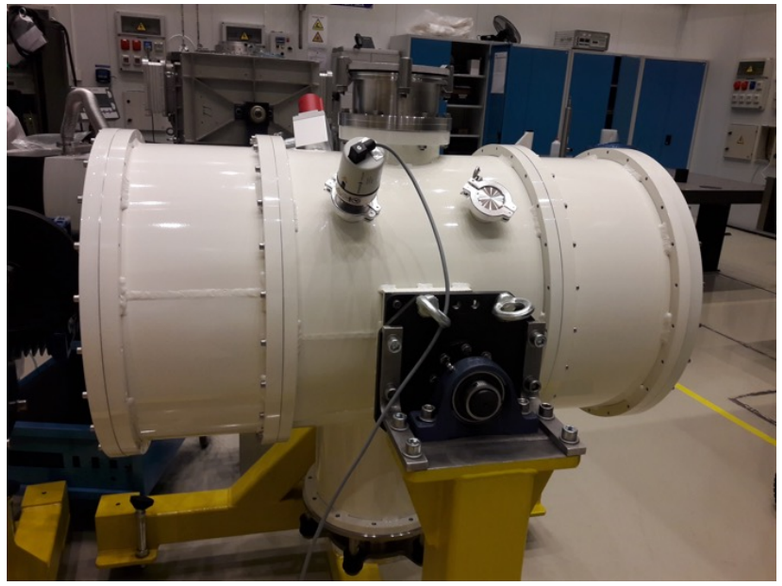
COSMO continuous cryogenics being built

Courtesy:
Paolo de Bernardis

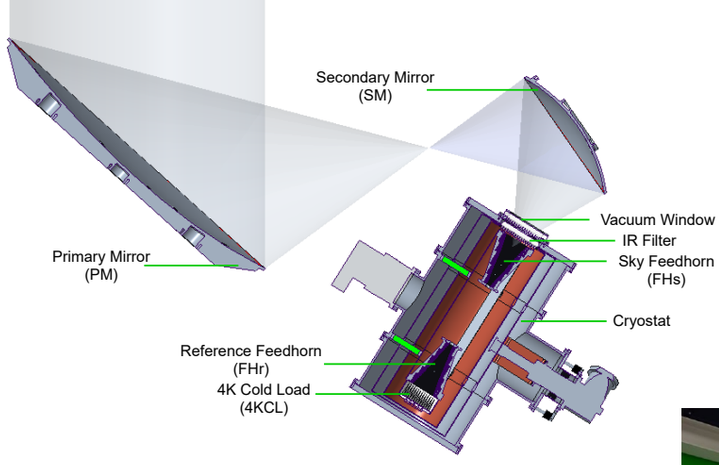
Tenerife Microwave Spectrometer (TMS), 10-20GHz

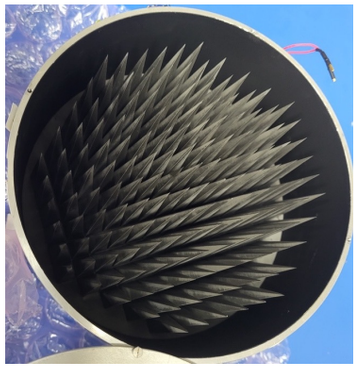
GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional "Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

- **IAC project. Instrumental participation:** INAF OAS BOLOGNA · Universidad Politécnica de Cartagena · UNIVERSITÀ DEGLI STUDI DI MILANO · idom



- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds (monopole signals; spectral dependence of monopole signals; ARCADE results) and CMB spectral distortions. Provides frequency intercalibration for QUIJOTE. (Rubino-Martin et al. 2020).
- **Location**: Teide Observatory (former VSA enclosure). Full sky dome.
- **Prototype for future instruments**. Also important **legacy value,** complementing future space missions.
- **Proposed instrument concept**:
  - FEM cooled to 4-10K (HEMTs).
  - Reference 4K load.
  - DAS based on FPGAs.
  - ~3deg beam, 0.25 GHz spectral resolution (40 bands).





- **Project Status**:
  - Enclosure and dome at the Teide Observatory. ✓
  - Platform fabricated. Installation summer 2022. ✓
  - Mirrors designed (Alonso-Arias et al 2022). To be fabricated (→ Fall 2022).
  - Cryostat at the IAC since July 2019. ✓
  - Optomechanics in final fabrication phase.
  - Reference load fabricated (Nov 2021). ✓
  - DAS based on FPGAs (→ end 2022).
  - Commissioning in 2023.

Courtesy: J.A. Rubiño-Martin

BISOU
A balloon project to measure the CMB spectral distortions

(currently in Phase 0)

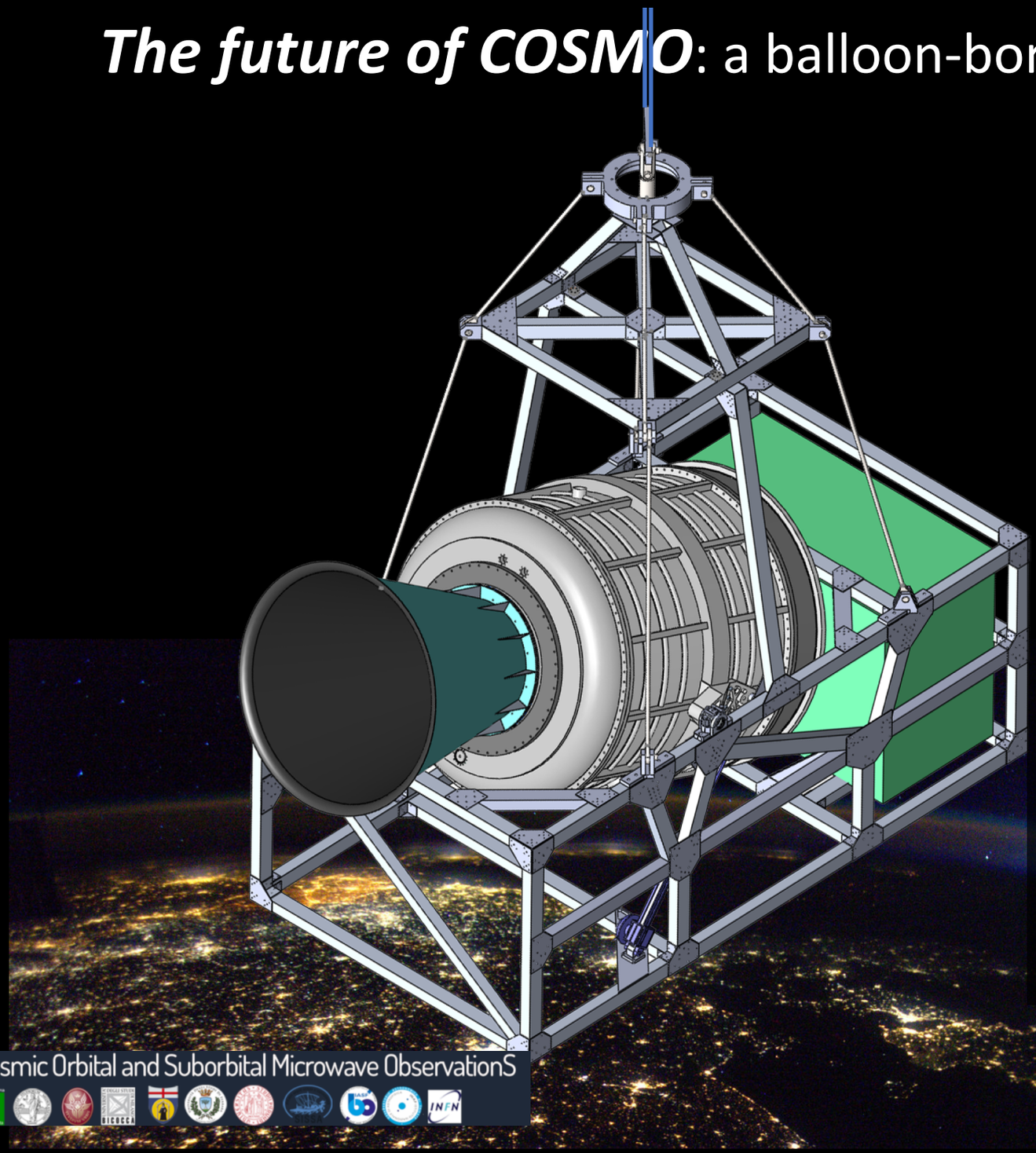
B. Maffei for the BISOU collaboration

CMB-France – Nov 2021

ArXiv:2111.00246

~ 90 GHz - 2THz

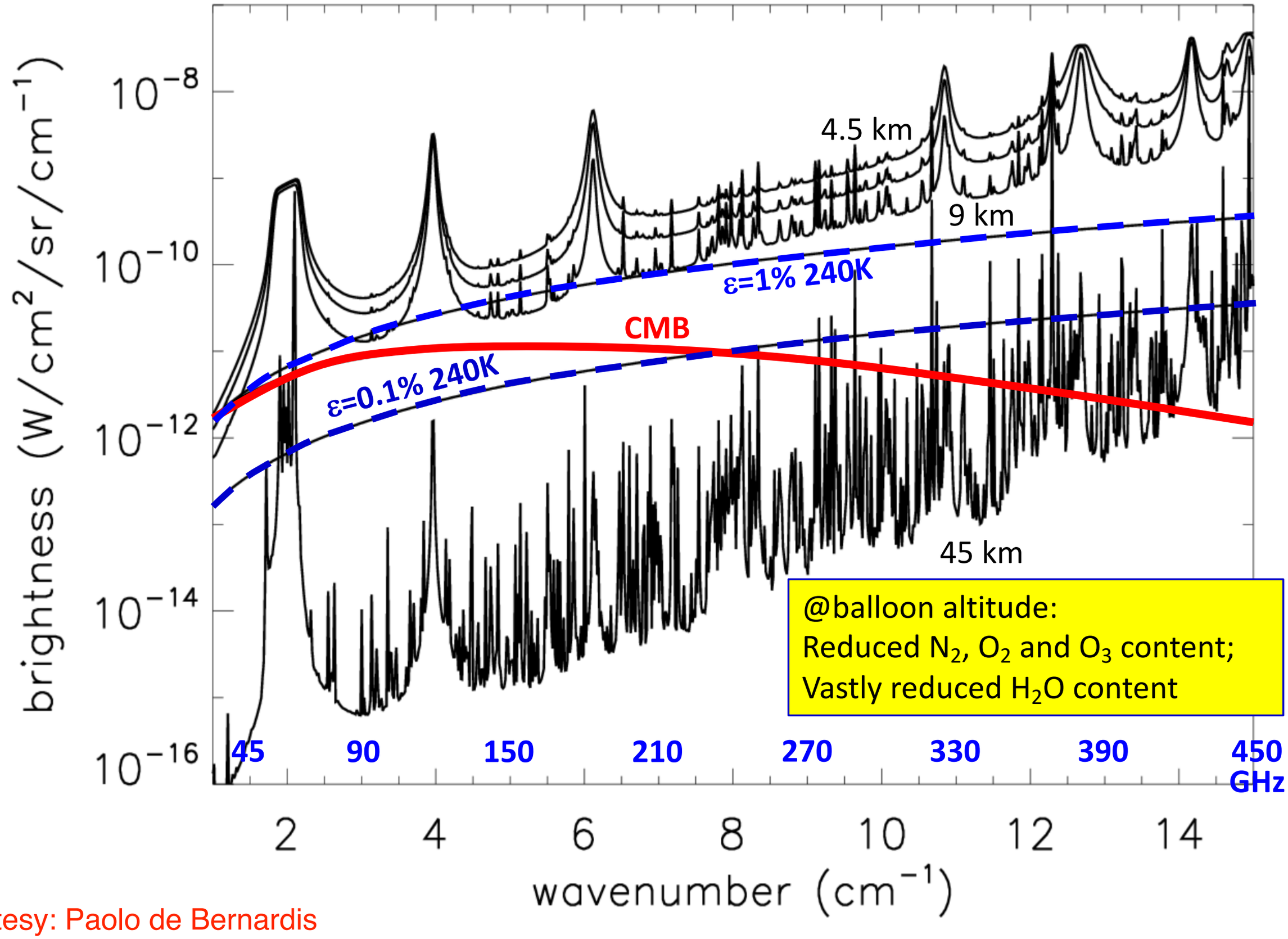
The future of COSMO: a balloon-borne instrument



- **Reuse of most of the LSPE** LDB gondola
  http://lspe.roma1.infn.it
- Suitable LHe cryogenic system
- Possible to add (slower) sky modulator
- Might gain a factor 10 wrt COSMO on the ground.
- We have the capacity to provide - in house:
  - Detectors (KIDs from OLIMPO)
  - Readout electronics (OLIMPO)
  - Cryogenic system (LSPE)
  - Cryogenic FTS (OLIMPO/COSMO)
  - Modulator (COSMO)
  - Gondola / ACS (LSPE)
  - Data processing / analysis
- French/UK/US collaborators interested to join and provide needed hardware.
- Might merge with French proposal BISOU (CNES study, modulator configuration TBD)
- **Long duration balloon** (14 days at float, NASA summer circumantarctic flight OK, polar night better)
- Might be ready to launch in **2027/28**.

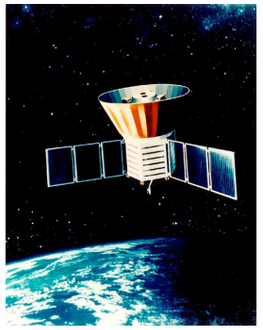
Courtesy: Paolo de Bernardis

Atmospheric Emission at different altitudes



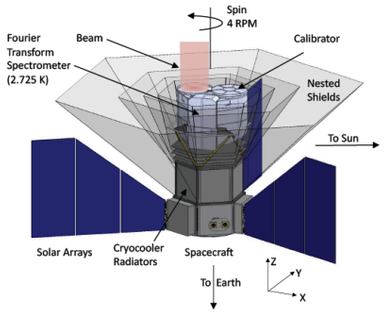
Courtesy: Paolo de Bernardis

History of distortion experiments and proposals



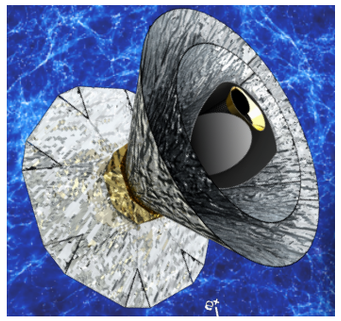
COBE/FIRAS

Mather & Fixsen



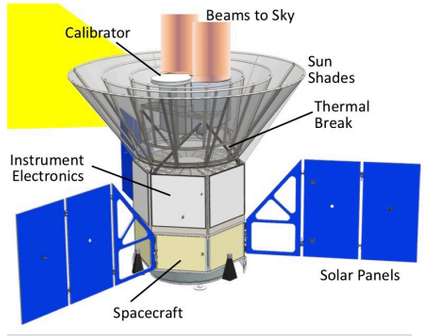
PIXIE

Kogut & Fixsen



PRISM

De Bernardis

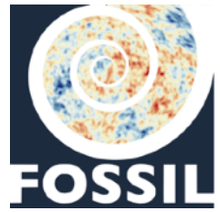


PIXIE

Kogut & Fixsen

(PIXIE)

Super-PIXIE



Aghanim

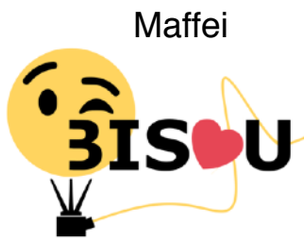
PRISTINE

Aghanim

ARCADE 2

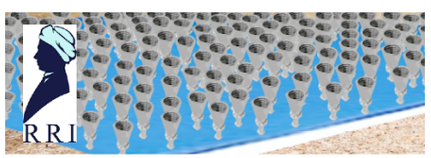
Kogut & Fixsen

Maffei



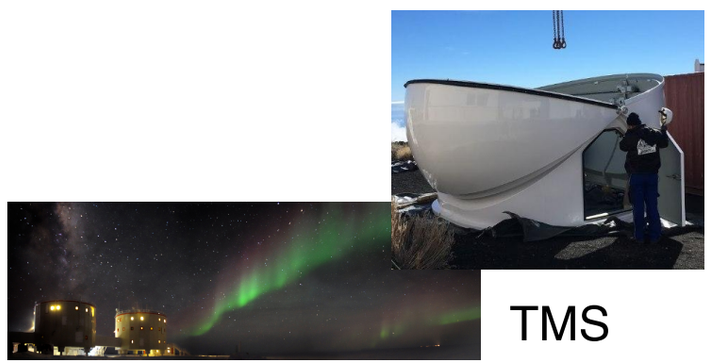
TRIS

Gervasi, Zannoni & Tartari



APSERa

Subrahmanyan & Rao



TMS

COSMO

De Bernardis, Masi & Battistelli

1989 2008 2011 2013 2015 2016 2018 2022

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 towards a space mission

Decadal science WP submitted Feb 2019

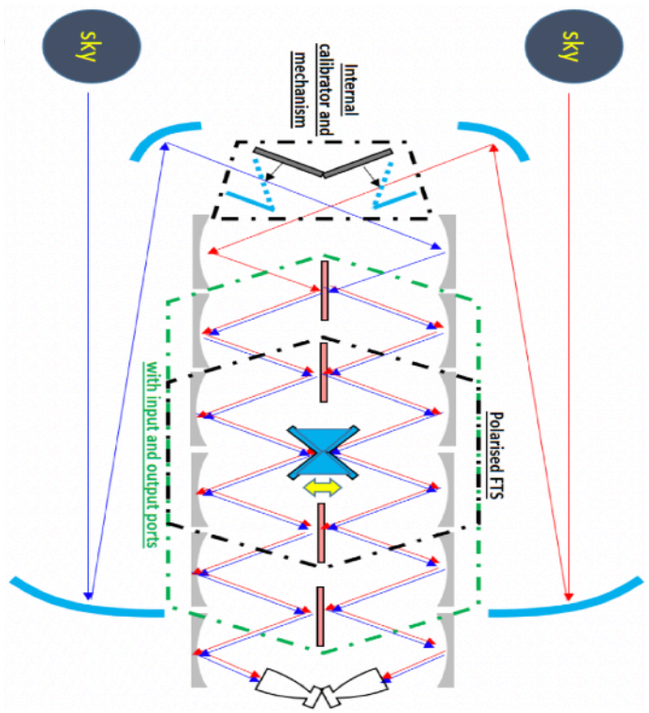
Astro2020 Science White Paper

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]

➡ *Sadly spectral distortions not mentioned in Decadal report that was published in Nov 2021*



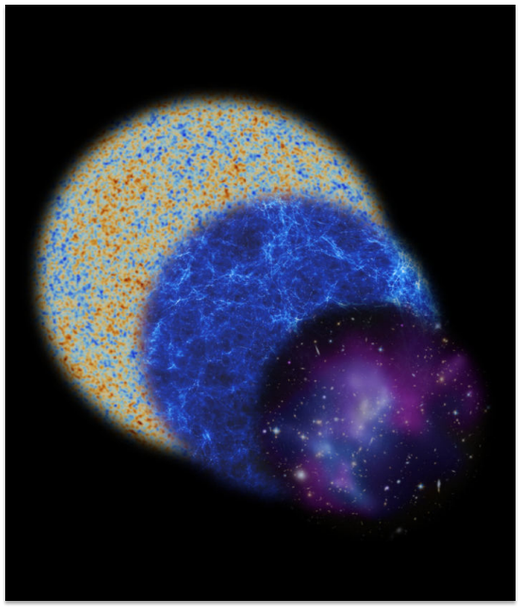
PI: Nabila Aghanim

F-class: Spectrometer

~ 90 GHz - 3THz

ESA Voyage 2050 White Papers

Microwave Spectro-Polarimetry of Matter and Radiation across Space and Time



A science white paper for the "Voyage 2050
long term plan in the ESA science programm

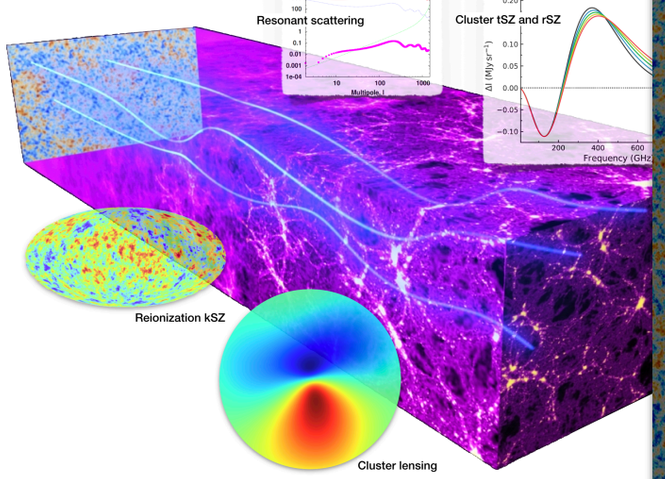
ESA Voyage 2050 Science White Paper

A Space Mission to Map the Entire Observable Universe using the CMB as a Backlight

Corresponding Author:
Name: Kaustuv Basu
Institution: Argelander-Institut für Astronomie, Universität Bonn, D-53121 Bonn, Germany
Email: kbasu@astro.uni-bonn.de, Phone: +49 228 735 658

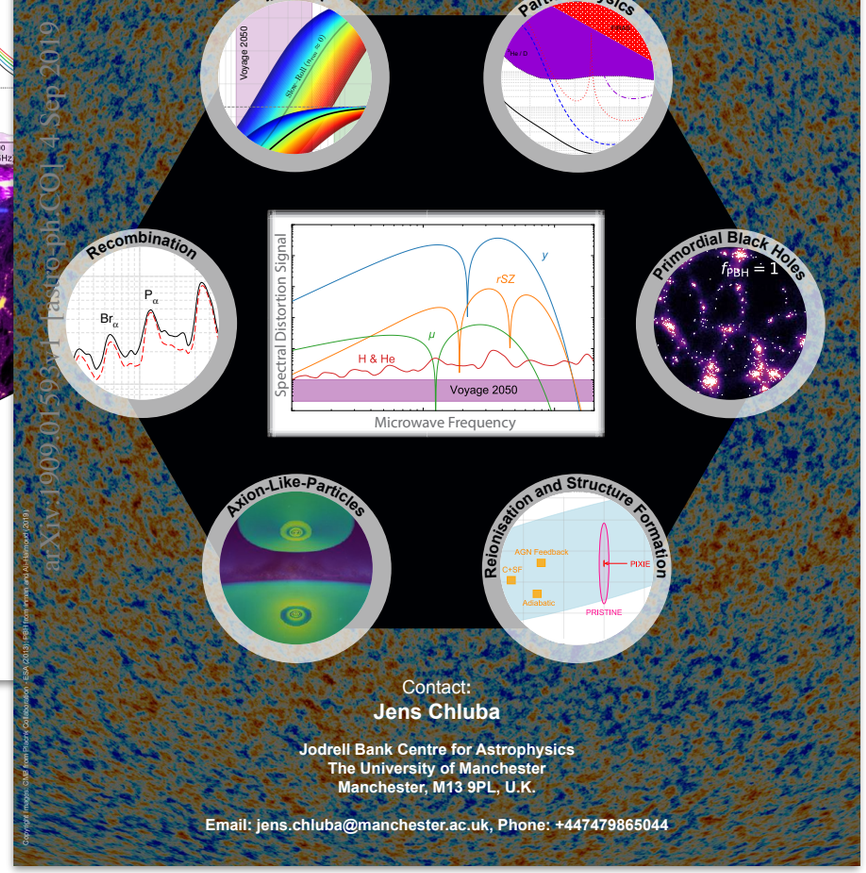
Co-lead Authors:
Mathieu Remazeilles[1] *(proposal writing coordinator)*, Jean-Baptiste Melin[2]

[1] Jodrell Bank Centre for Astrophysics, Dept. of Physics & Astronomy, The University of Manchester, Manchester M13 9PL, UK
[2] IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France



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

ESA Voyage 2050 Science White Paper

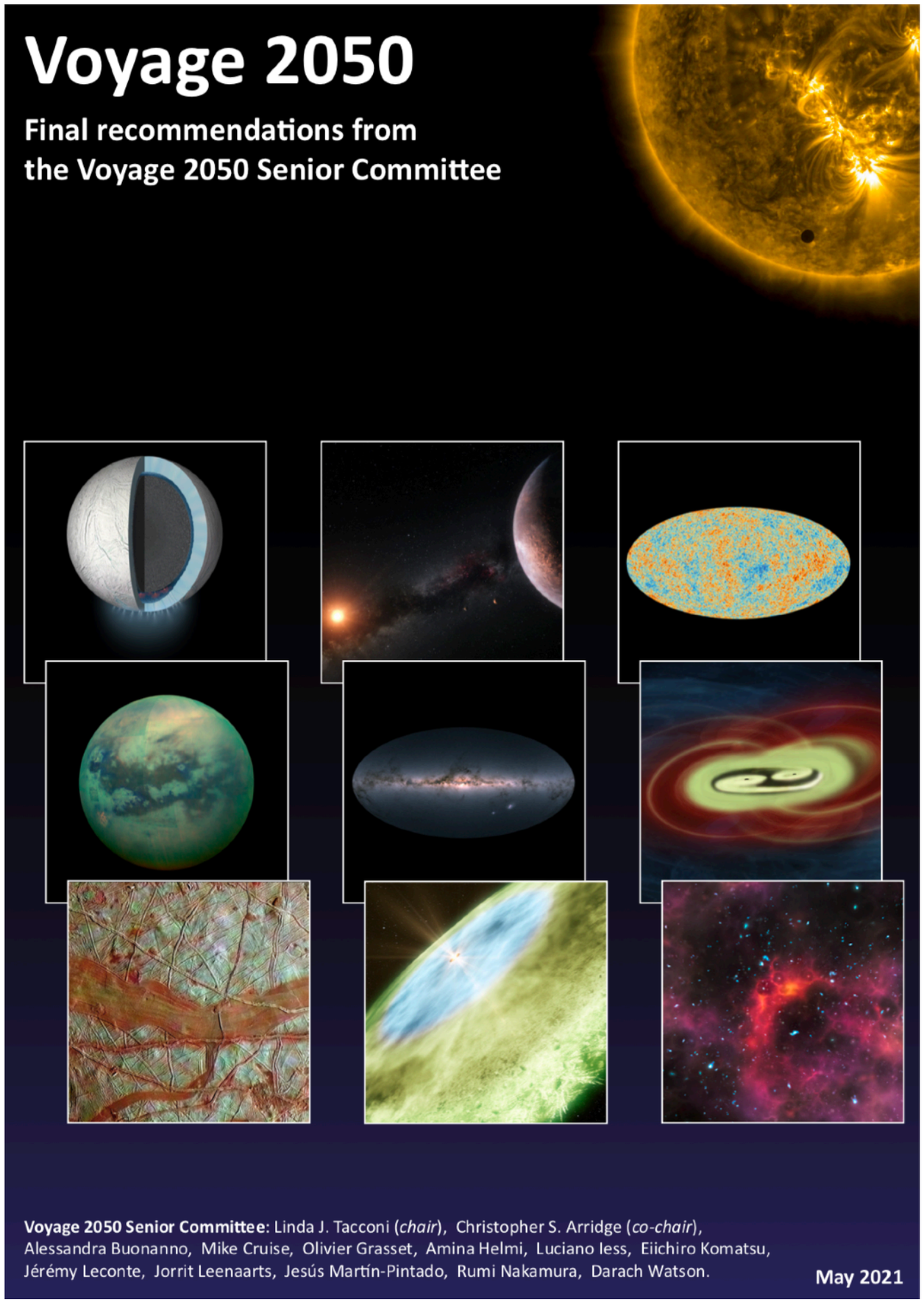


Contact:
Jens Chluba

Jodrell Bank Centre for Astrophysics
The University of Manchester
Manchester, M13 9PL, U.K.

Email: jens.chluba@manchester.ac.uk, Phone: +447479865044

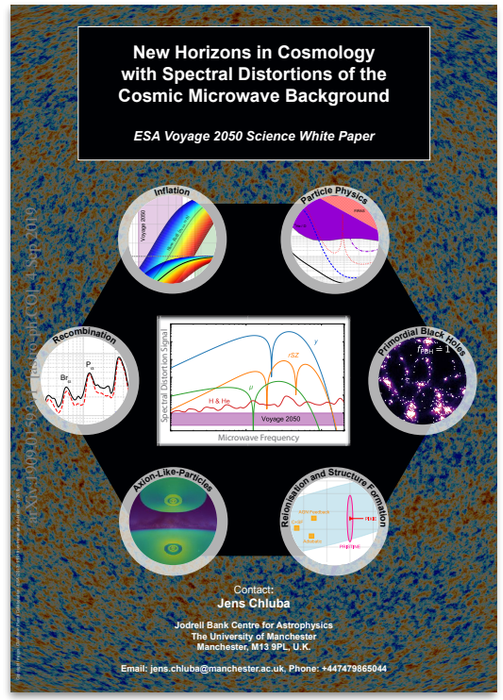
http://arxiv.org/abs/1909.01591
http://arxiv.org/abs/1909.01592
http://arxiv.org/abs/1909.01593



- > 100 WP evaluated
- Identified three L-Class themes
  - Moons of the giant planets
  - From temperate Exoplanets to the Milky Way
  - New physical probes of the early Universe
- CMB Spectral distortions recognized as a possible '*New physical probes of the early Universe*'

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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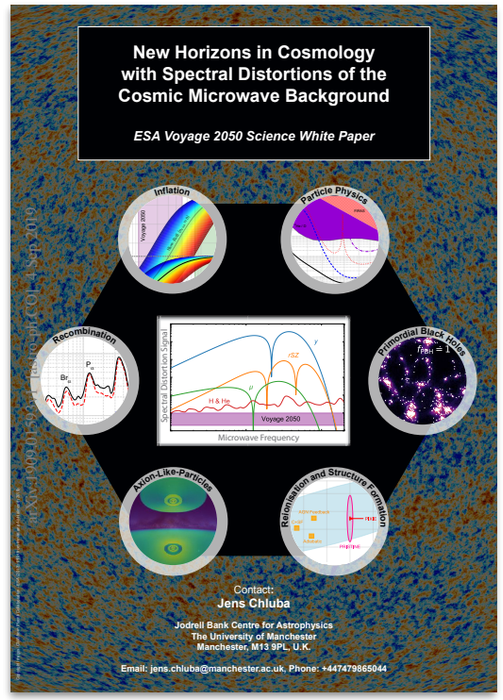
- *Option 2*: M-class CMB spectrometer

  - Ultimate distortion mission beyond 2050 timescale



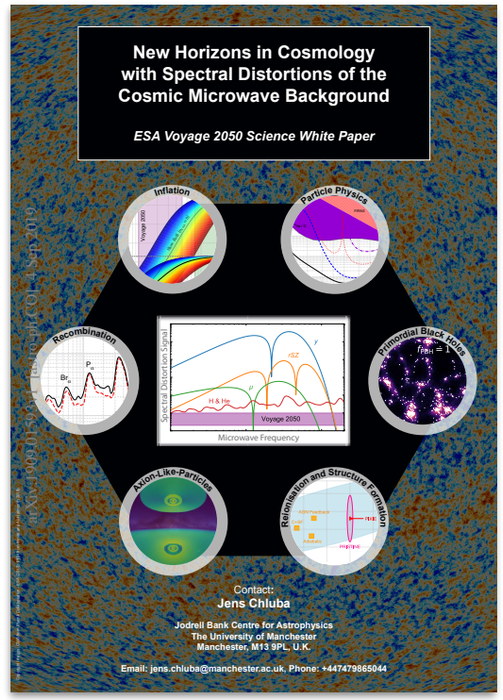
ArXiv:1909.01593

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 able to see average y and rSZ!
  - Risk mitigation by learning about foreground challenge
  - Pathfinder could be balloon or small satellite
  - Launch date ~ 2040's



ArXiv:1909.01593

PRISTINE

BISOU

FOSSIL

FTS fOr CMB Spectral diStortIon expLoration

A mission concept for the M-class ESA call

Nabila AGHANIM

Nabila.Aghanim@ias.u-psud.fr

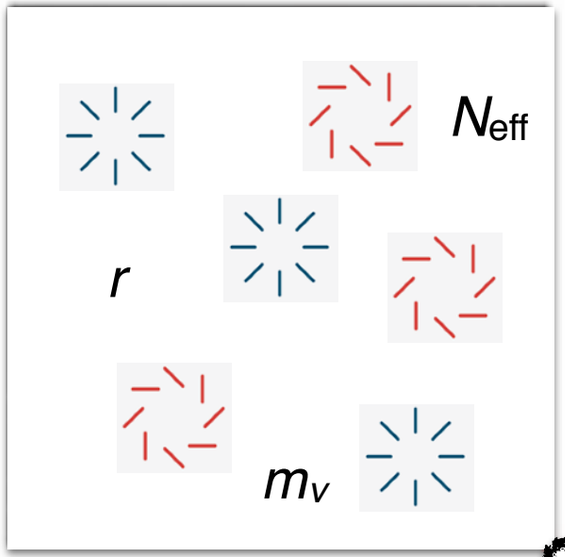
Institut d'Astrophysique Spatiale
Bâtiment 121, Rue Jean-Dominique Cassini,
F91440 Bures-sur-Yvette, France

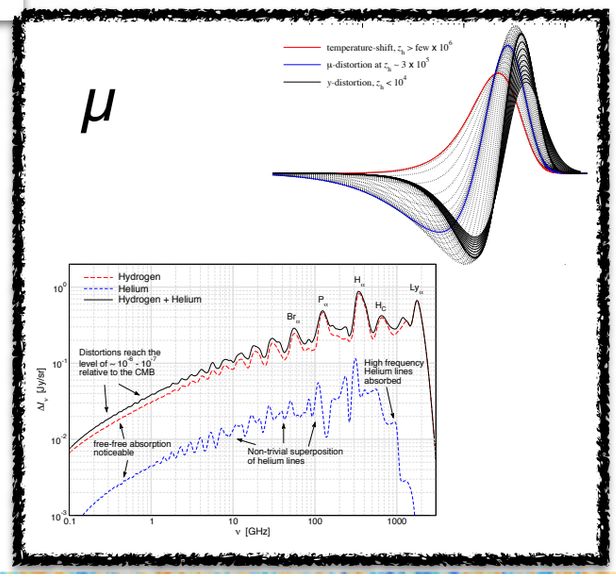
- Led by Nabila Aghanim (IAS/France)
- Cryogenic M-class mission
- Improved version of *PIXIE*
- Focused *only* on spectral distortions
- Launch 2037
- *Hoping to get more detailed feedback on this…*

How are we going to make this happen?

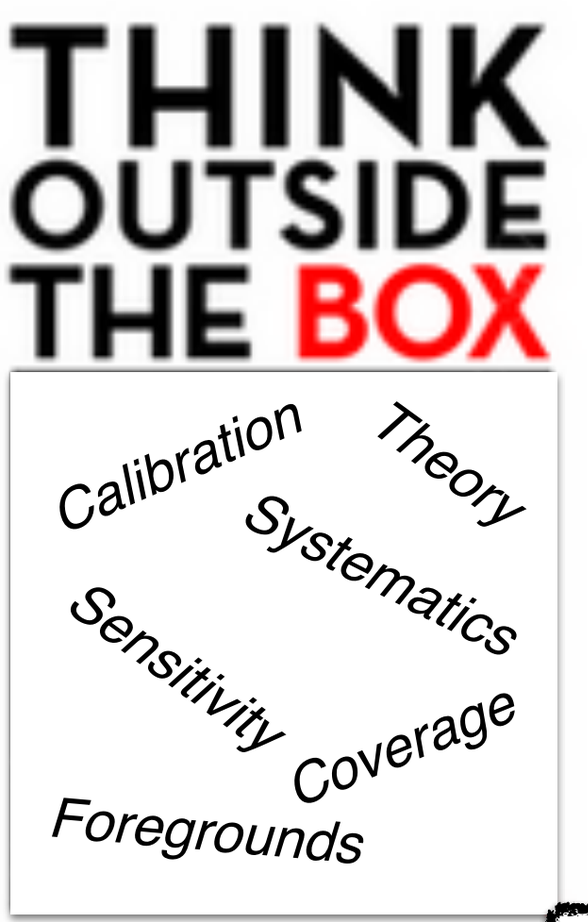
Courtesy: Reno Mandolesi

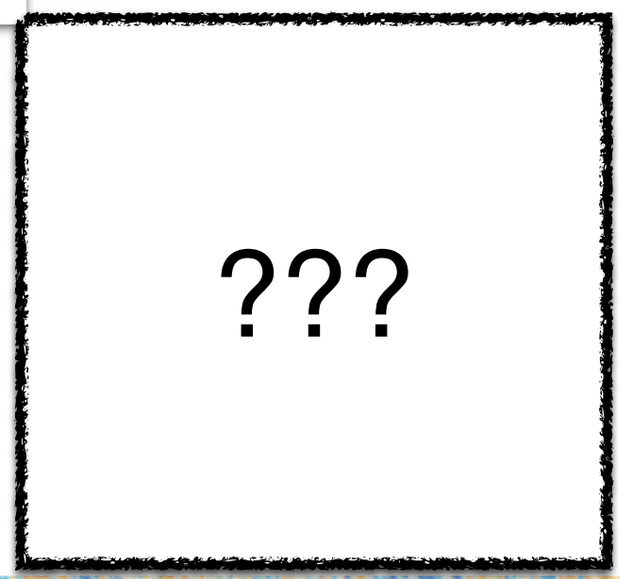
THINK OUTSIDE THE BOX





Courtesy: Reno Mandolesi





Courtesy: Reno Mandolesi

Open theory questions

- Theory has come a long way in the last 10 years
  - 2011 PIXIE proposal was still based on classical understanding of distortion theory
  - All subsequent proposals made strong link to inflationary μ-signal clear
  - Novel time-dependent information and residual distortion was understood!
  - Accurate predictions can now be made using various distortion codes

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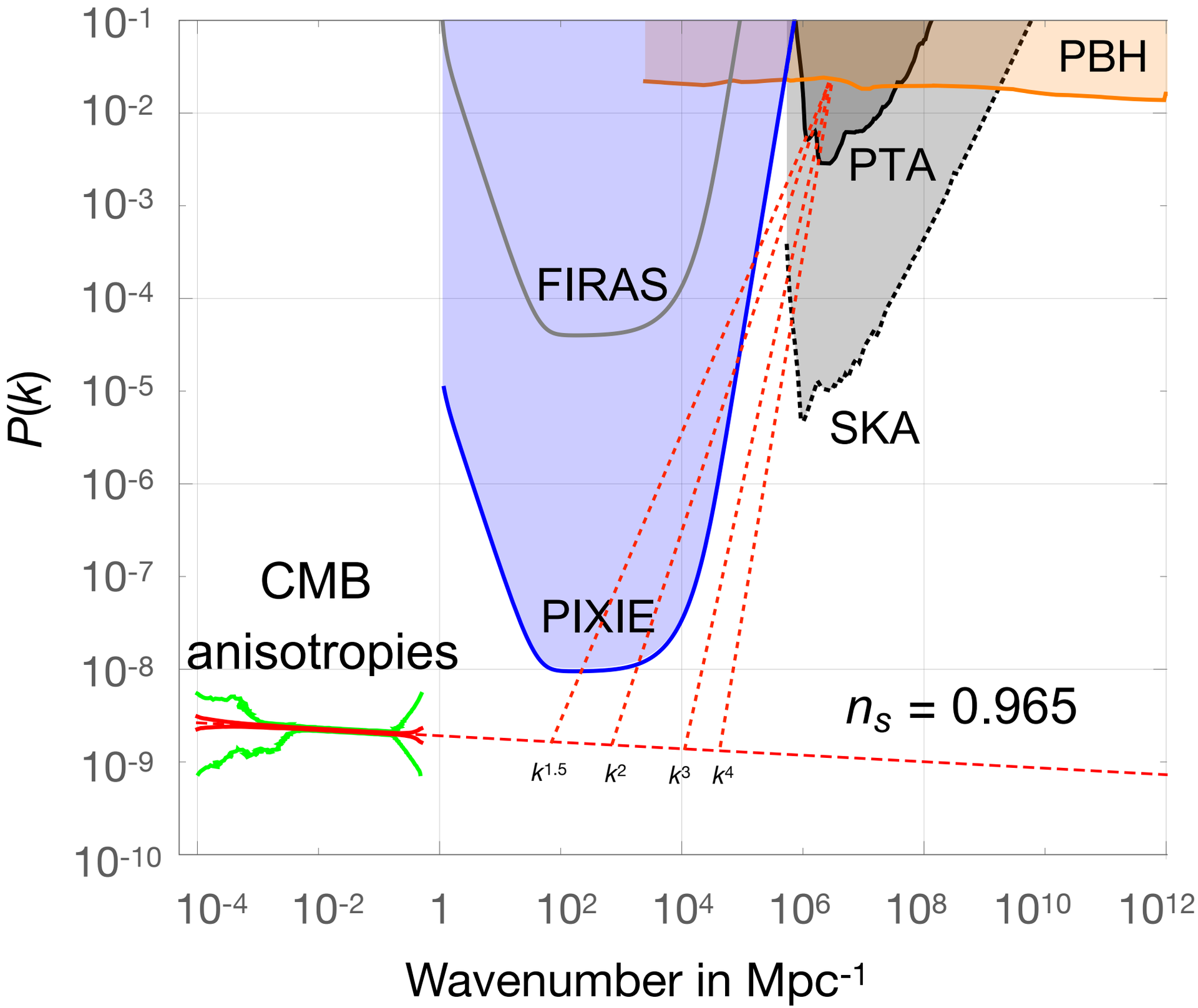
Small-scale power and PBH link



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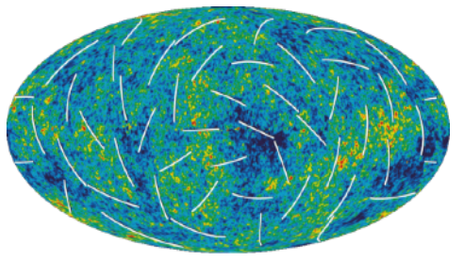
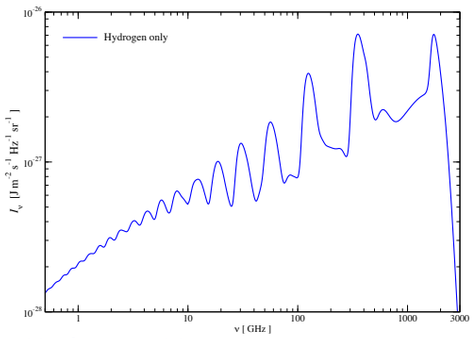
- Information from CRR on new physics
  - What about variation of fundamental constants?
  - Can we constrain early-dark energy and the expansion history?
  - Effect of pre-recombinational energy release?

Cosmological Time in Years

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

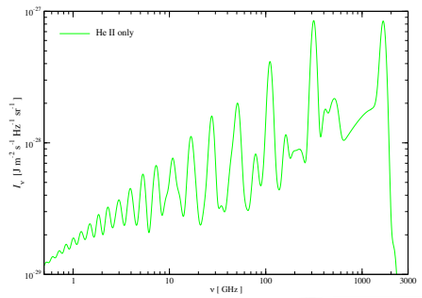
CMB-Anisotropies





Hydrogen Lines

Singly ionized Helium Lines



Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized

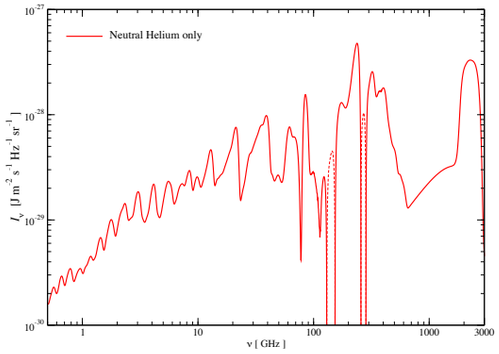
Visibility Function

Plasma neutral

H I-Lines

He I-Lines

He II-Lines



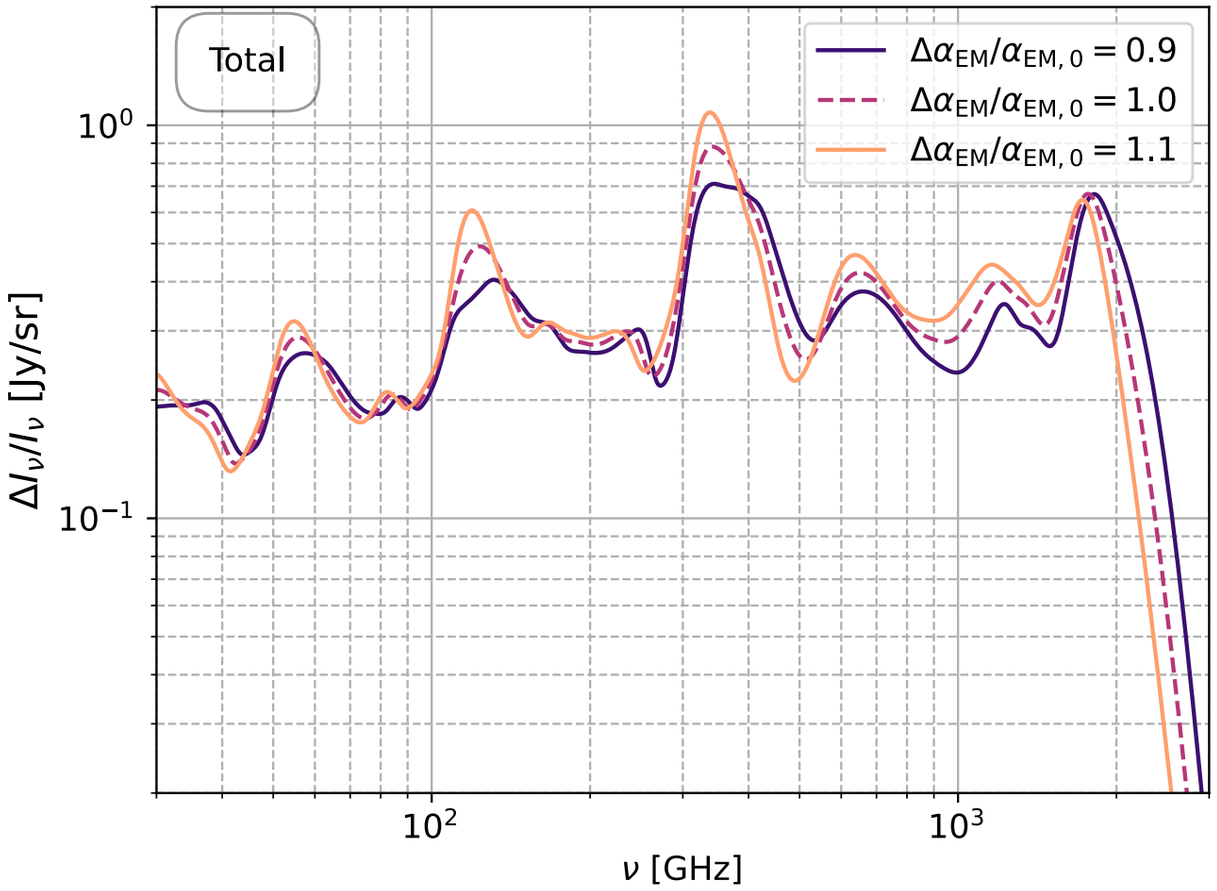
Neutral Helium Lines

1.4 1.2 1 0.8 0.6 0.4 0.2 0

700 1100 2000 3000 4000 6000 8000

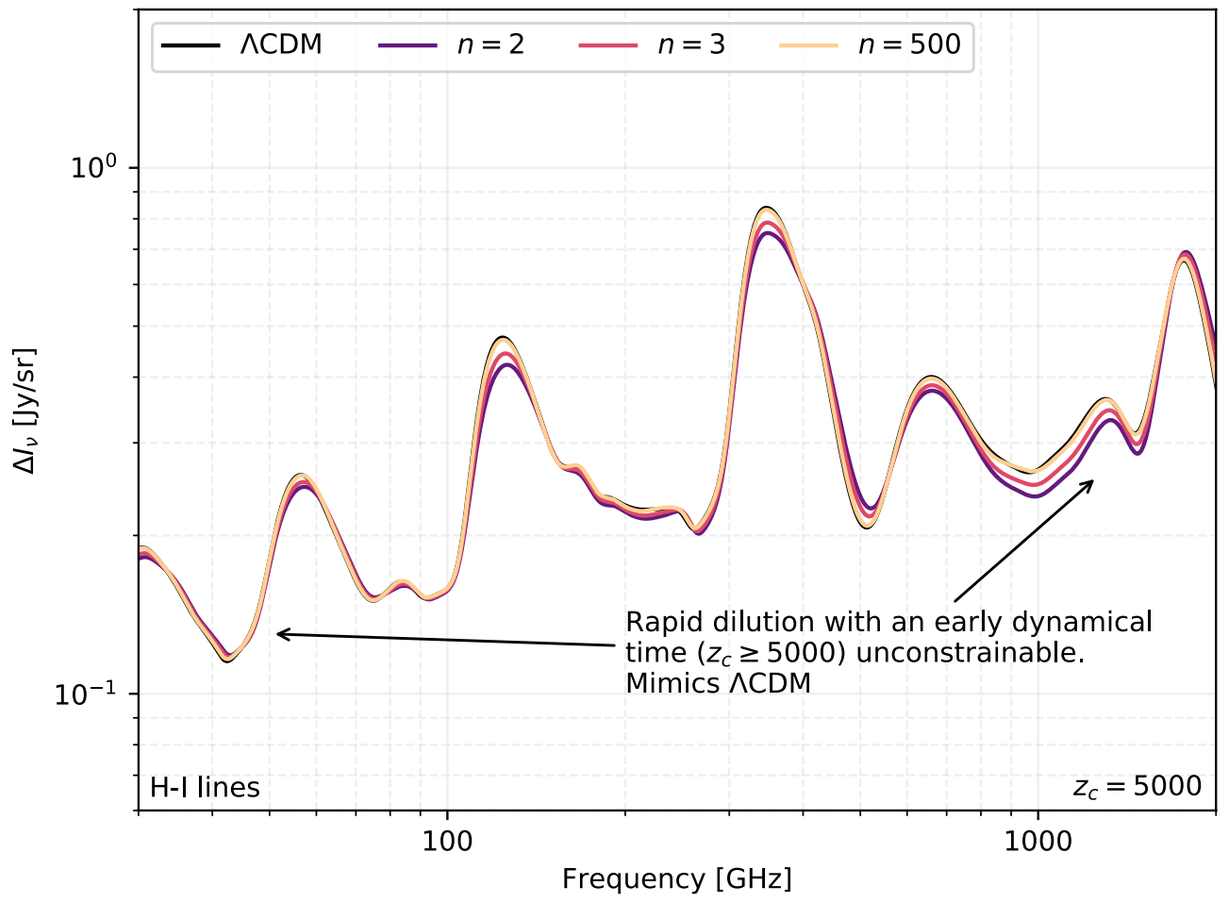
Redshift z

Novel information from the CRR



- Sensitivity of variations in before last scattering
- Another side of EDE?

- Sensitivity of CRR to expansion history
- EDE and Hubble tension?



Hart & JC, in preparation

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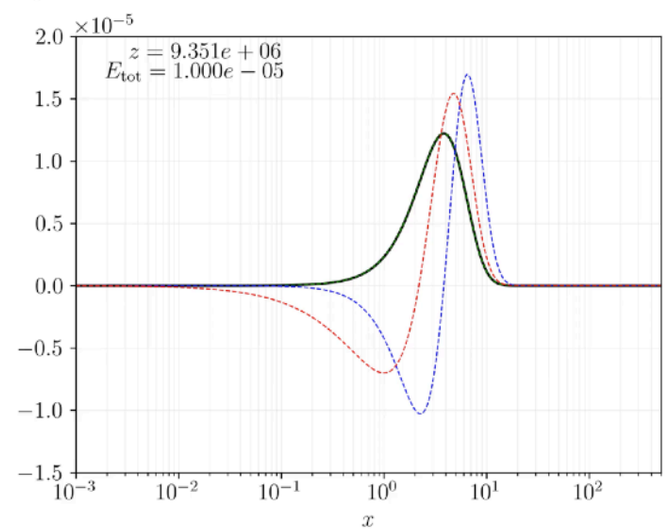
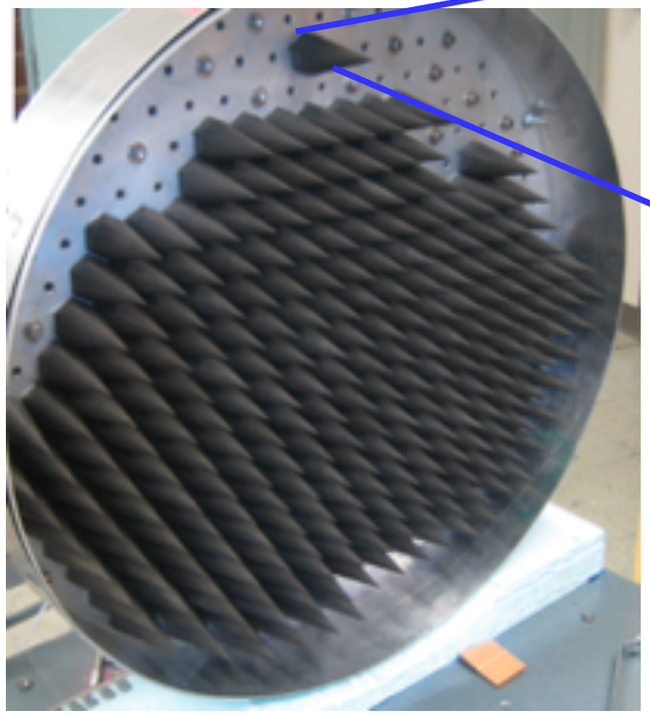
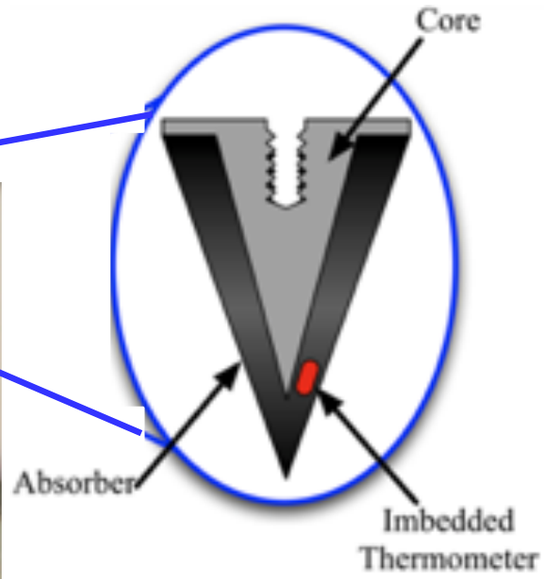
- Information from CRR on new physics
  - What about variation of fundamental constants?
  - Can we constrain early-dark energy and the expansion history?
  - Effect of pre-recombinational energy release?
- Understanding of anisotropic spectral distortions
  - The equivalent of `CAMB/CLASS` but for distortion…
  - How do photon ‘bombs’ look on the sky?



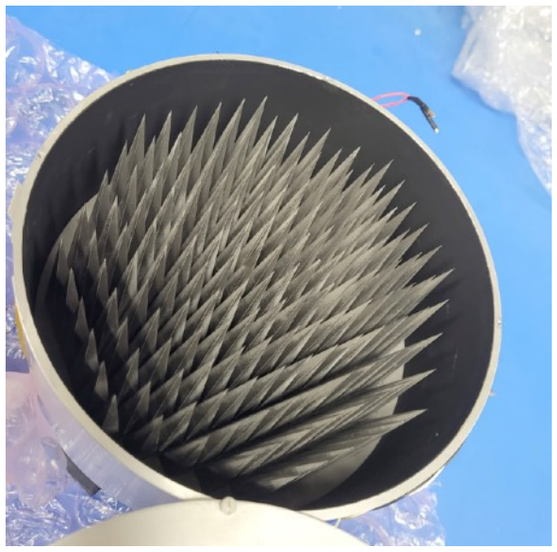
Calibrator demonstration





Large external calibrator developed for ***PIXIE*** over 30 to 6000 GHz
Kogut et al, PIXIE proposal 2016

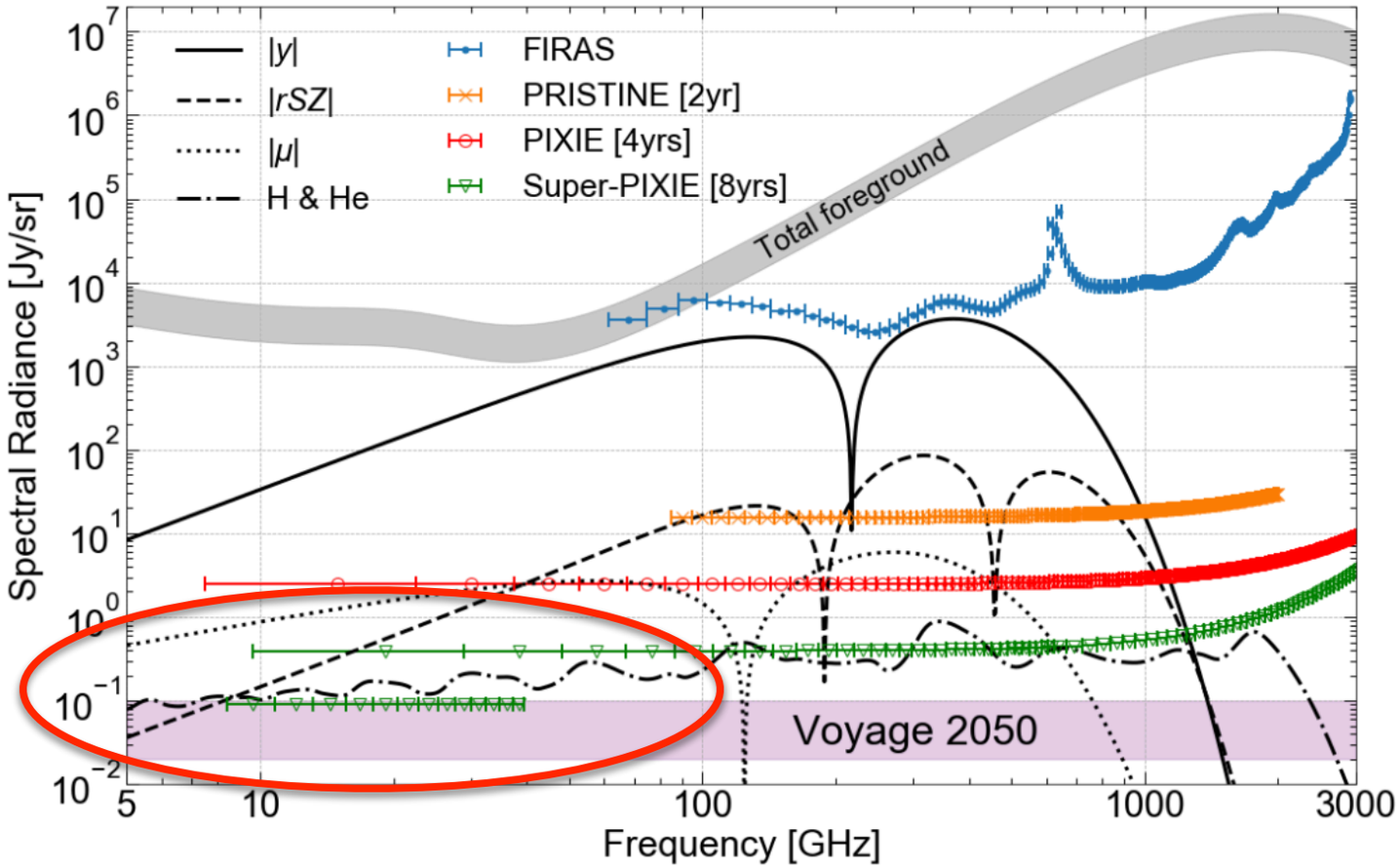
TMS calibrator

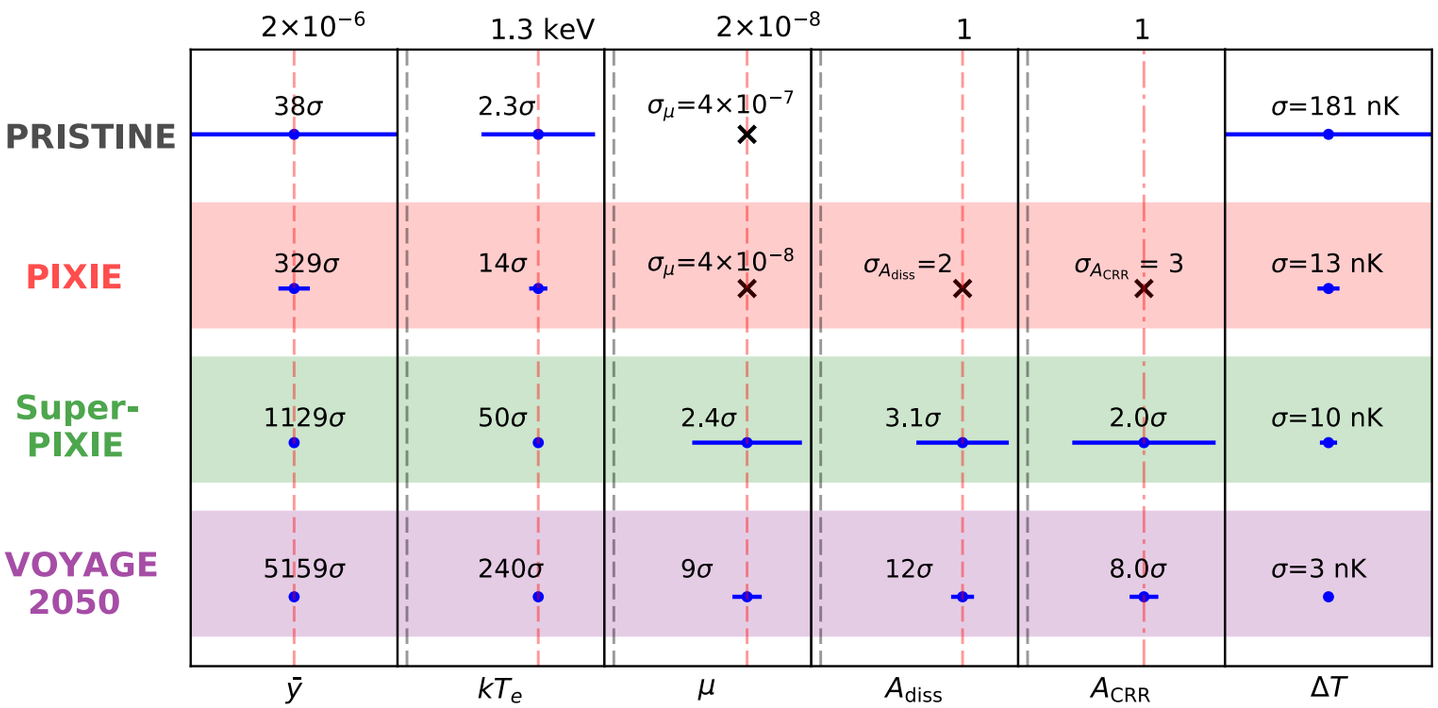


Courtesy: J.A. Rubiño-Martin

- Although deemed ‘easy’ to built, met with a lot of skepticism
- Demonstration of thermal stability and capabilities of monitoring temperature would be very helpful
- Misconceptions:
  - does not have to be a perfect blackbody itself
  - Relative calibration more accurate than absolute scale

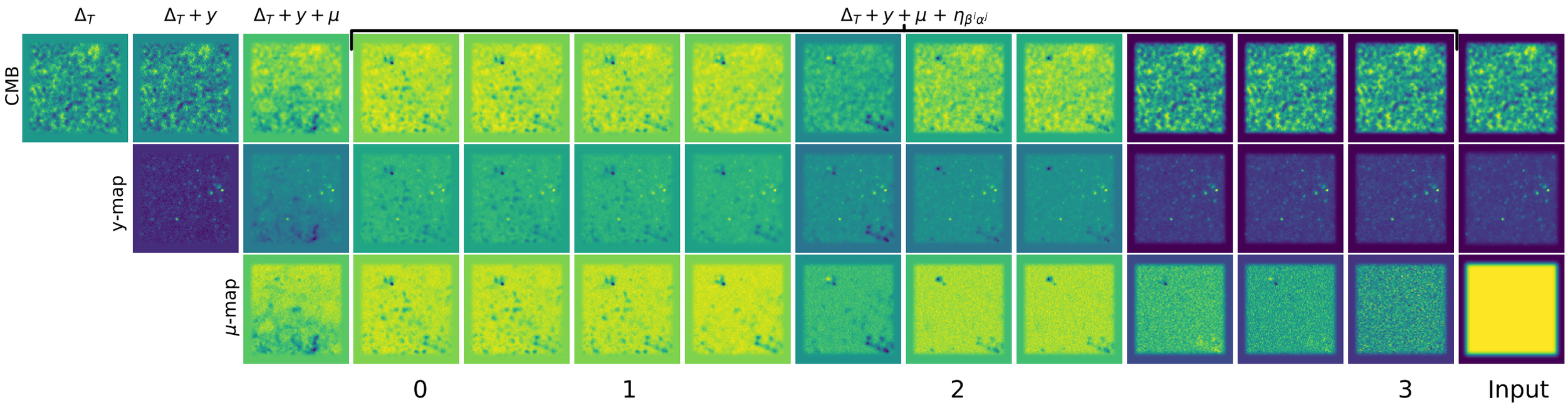
Improving low frequency coverage



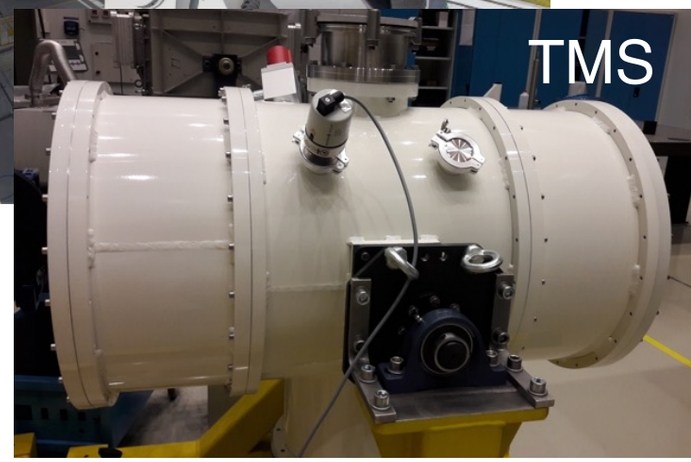


- Low frequency coverage is crucial for μ (Abitbol et al. 2017)
- Is a low frequency FTS really the best solution?
  - Few channels
  - Runs out of steam w.r.t. sensitivity
- Possible alternatives
  - radiometers?
  - Spectrometers on a chip?
  - FTS on chips (priv. conv. Kirit Karkare)?

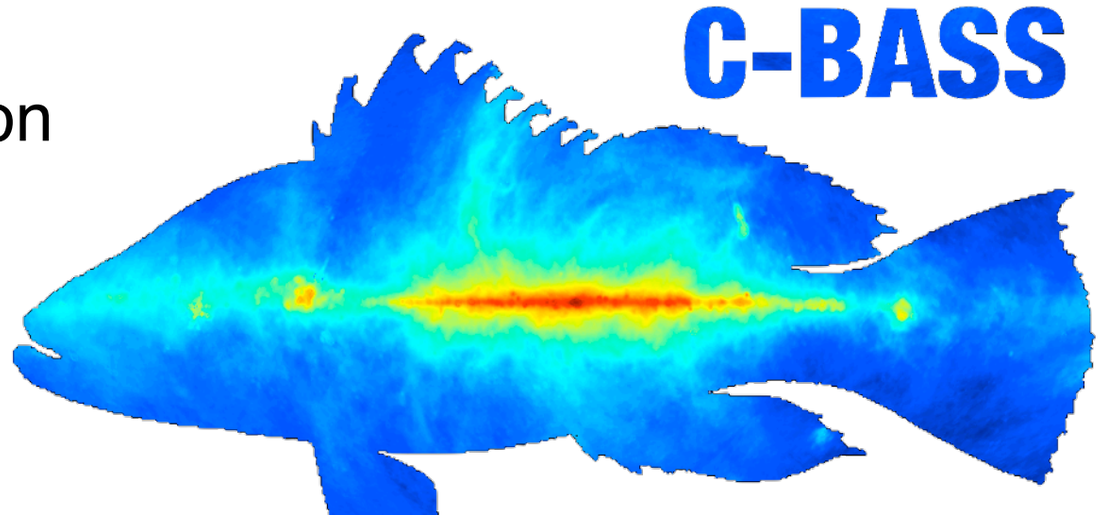
Spectral distortion foreground challenges



- How do we make the best use of spatial information?
- Do we need parametric methods or can one use semi-blind approaches?
- How to combine with external data sets?
- Synergies?
  - T_0 and calibration
  - Legacy value



Talk by J.A. Rubiño-Martin



Talk by Aditya Rotti

Talk by
Michael Jones

The distortion gang is getting organized!

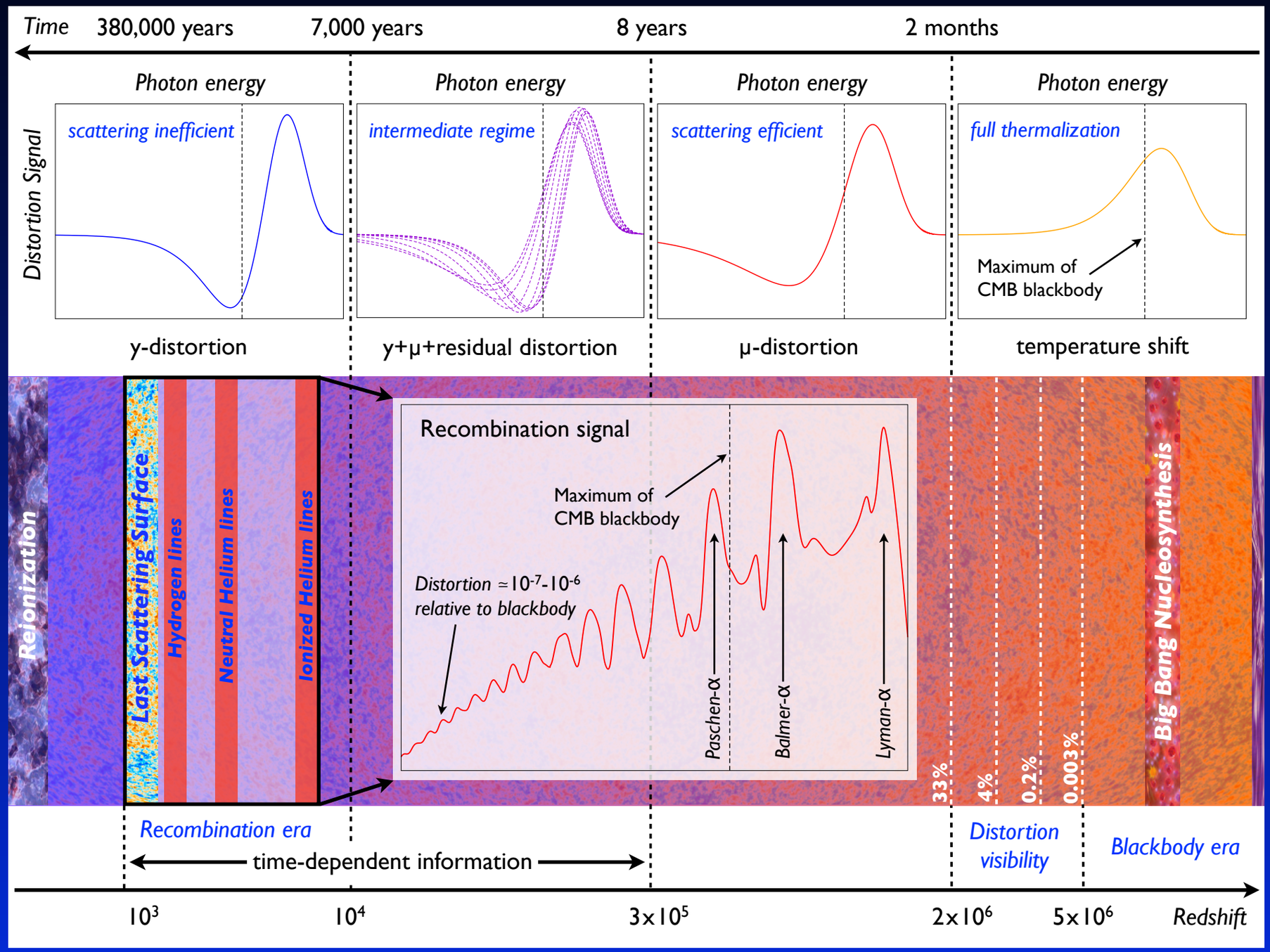
Distortion Workshop coming in October 2022!

Organizers: Subodh Patil, Ema Dimastrogiovanni, Daan Meerburg, Jacques Delabrouille and JC

- ***Main goals***:
  - start building a bigger community
  - bring experimentalists on board

- ***Guiding questions***:
  - What theory developments are still needed?
  - New component separation methods?
  - New technology ideas for low-frequency coverage

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

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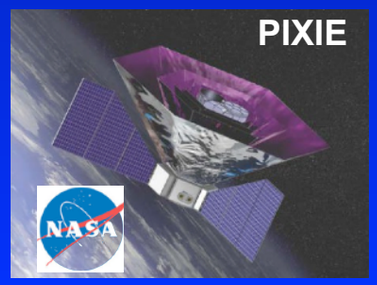

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