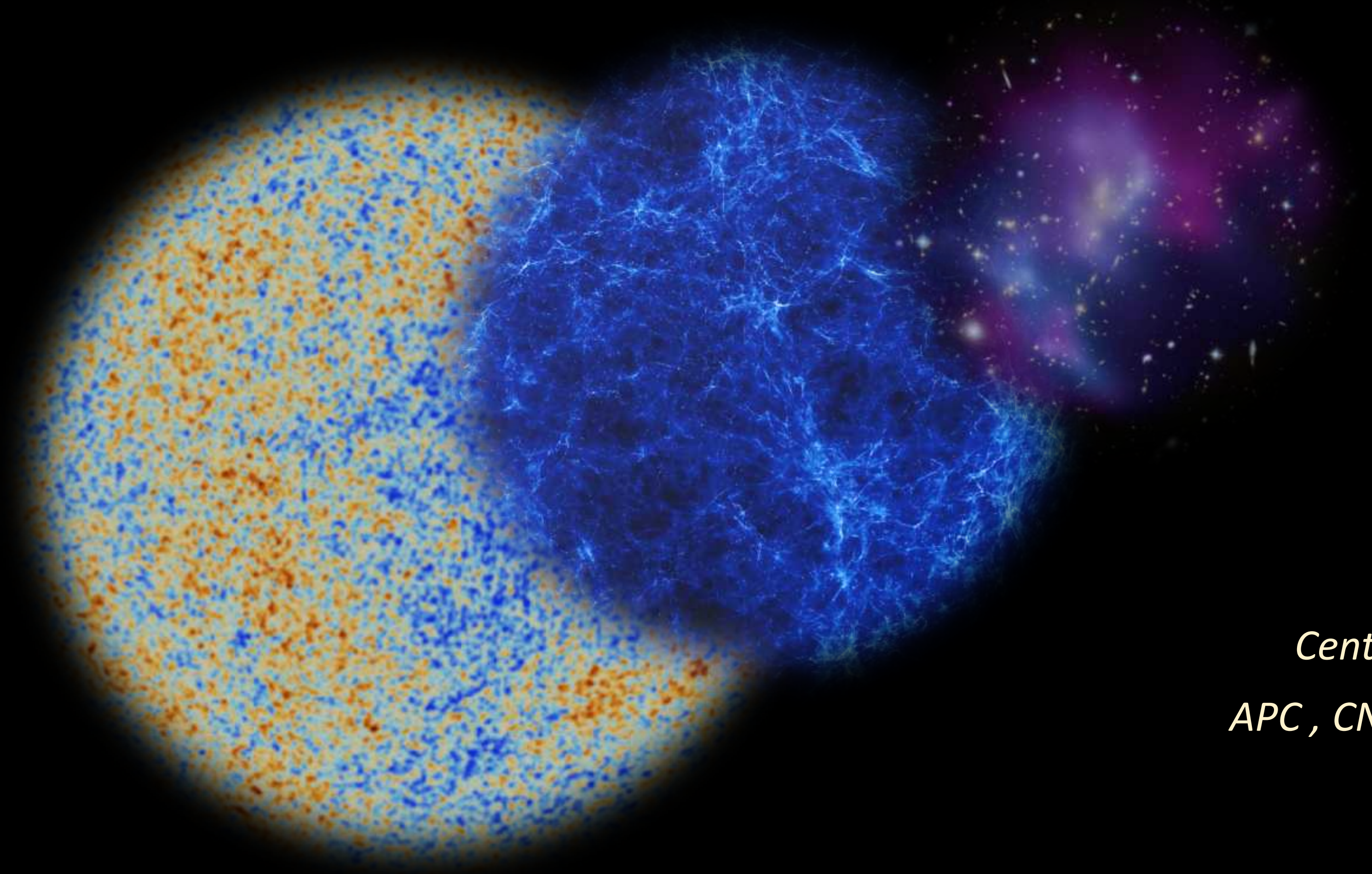
Options for an L-class Microwave Spectroscopy Space Mission



Jacques Delabrouille

Centre Pierre Binétruy, CNRS/IN2P3, Berkeley

APC , CNRS/IN2P3, Paris & IRFU/DAP, CEA-Saclay

Rationale for yet another CMB space mission

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The most sensitive CMB space mission to date, *PLANCK*, has been extraordinarily successful. It is hard to find a cosmology paper which does not, in a way or another, use *PLANCK* results!

But *PLANCK* is still far from having fully exploited the richness of the microwave sky !

There has been no progress on the CMB frequency spectrum since COBE-FIRAS (1990s)

PLANCK is not sensitive enough to fully exploit CMB polarization. We still have to

- reach cosmic variance limit on tau and hence Σm_ν (including constraints from B-modes !?)
- detect / map B-modes with high significance (high S/N ratio)
- map the (dark) mass with CMB lensing to cosmic variance limit
- test further extensions to standard 6+1 parameter ΛCDM

The number of frequency channels in current observations is insufficient to separate and fully characterize foreground emissions (say, with S/N >1 over the full sky)

Map the entire Universe in the Microwave

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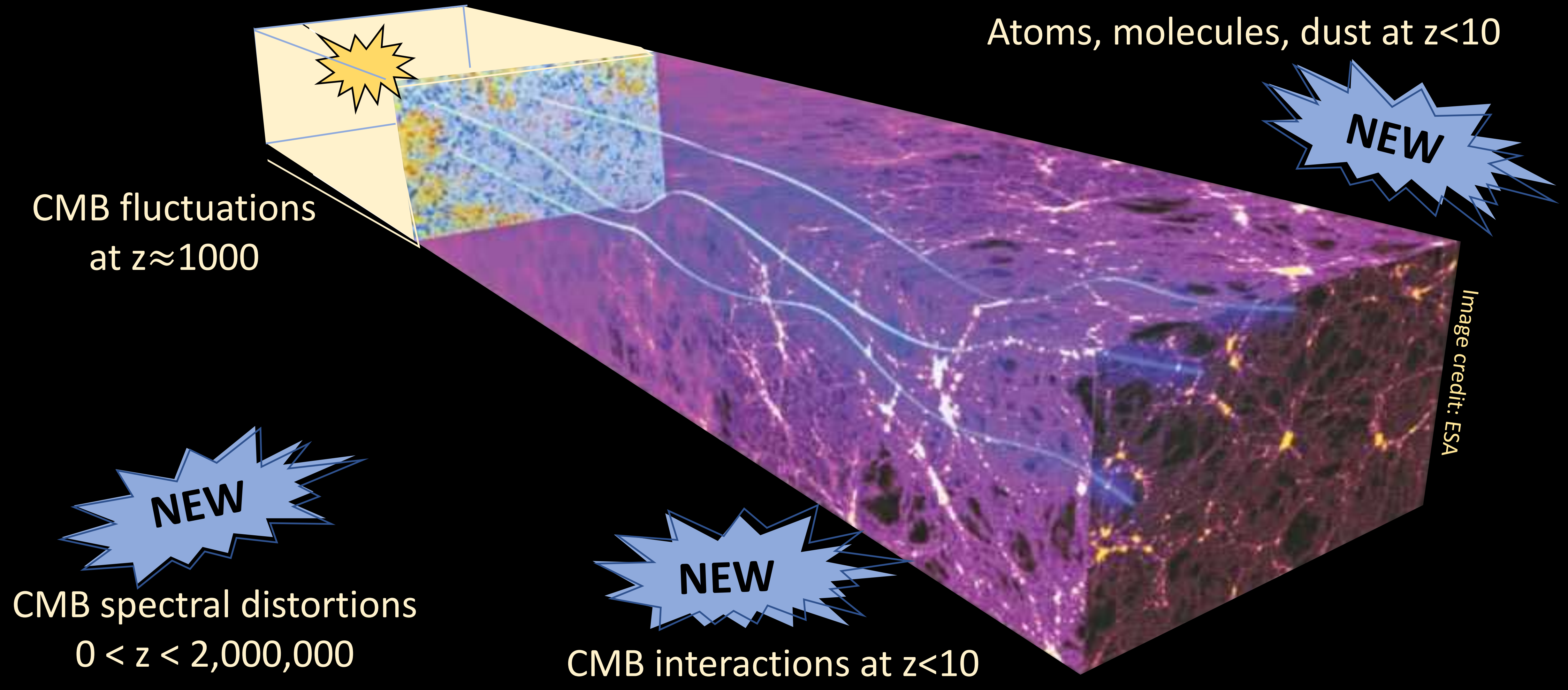
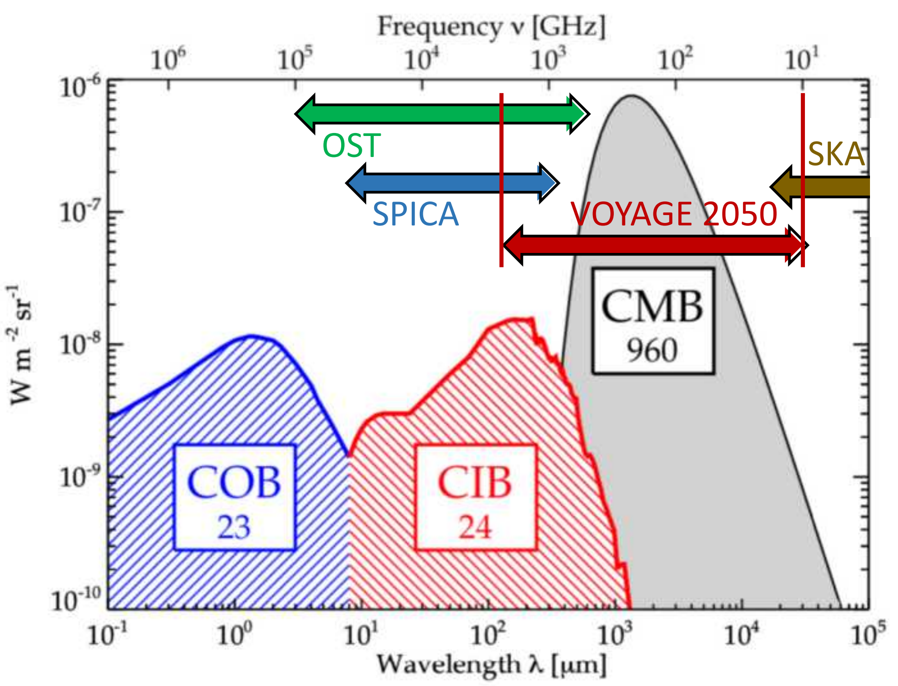


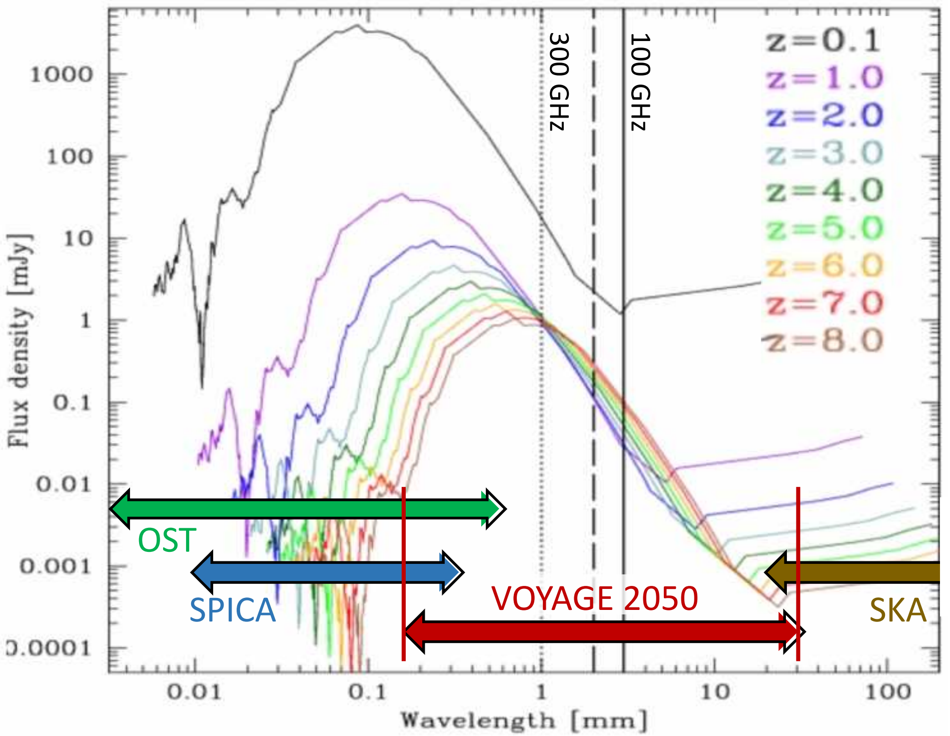
Why microwaves?

1- Most of the radiation in the Universe is in the microwaves!



(figure from H. Dole et al. 2006)

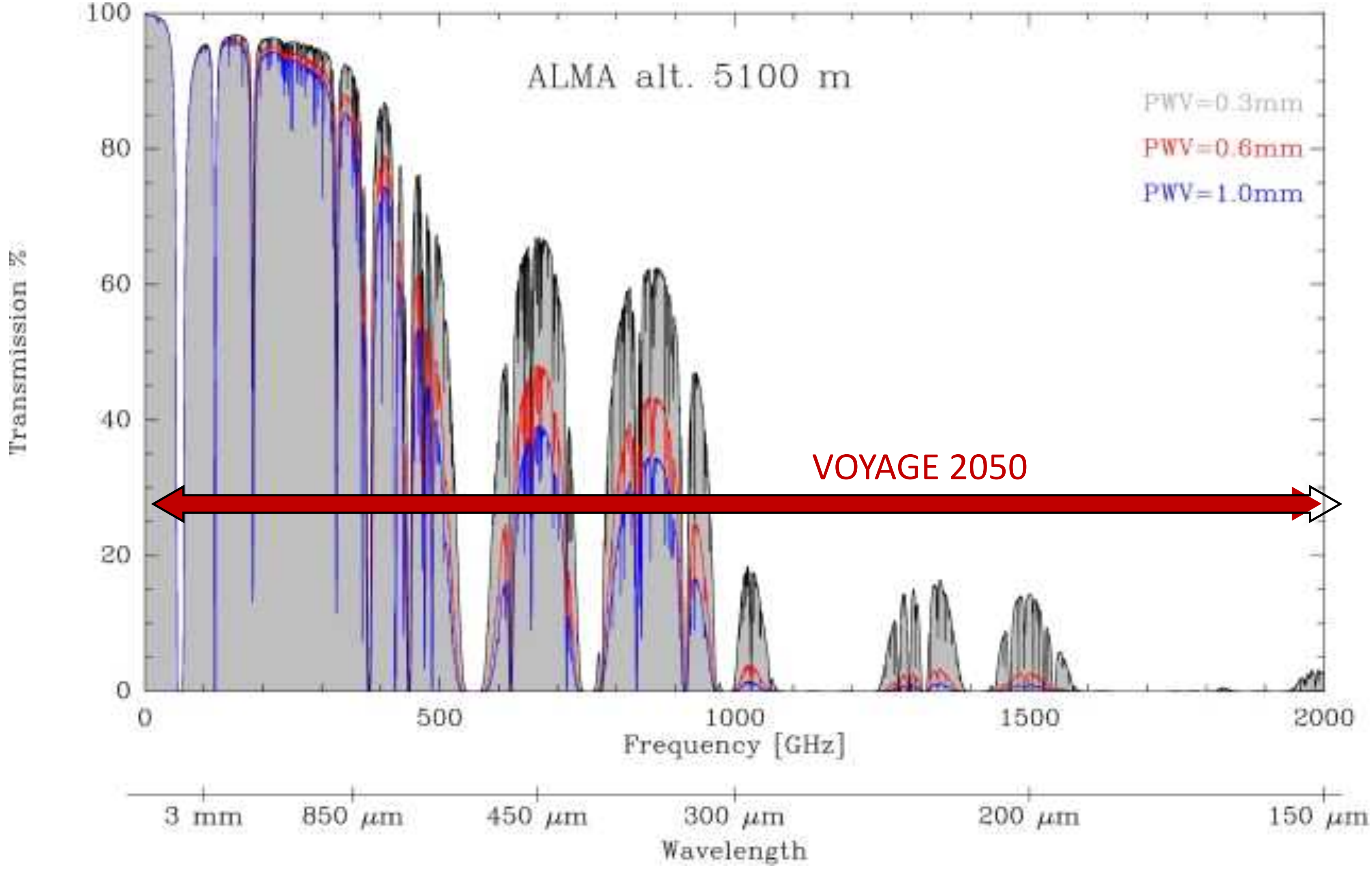
2- The most distant objects emit in the microwaves



(figure from R. Decarli website)

3- Complement planned observations in the 2030+ time frame

Why from space?



Atmospheric Transmission and Emission !

A coordinated microwave observation programme

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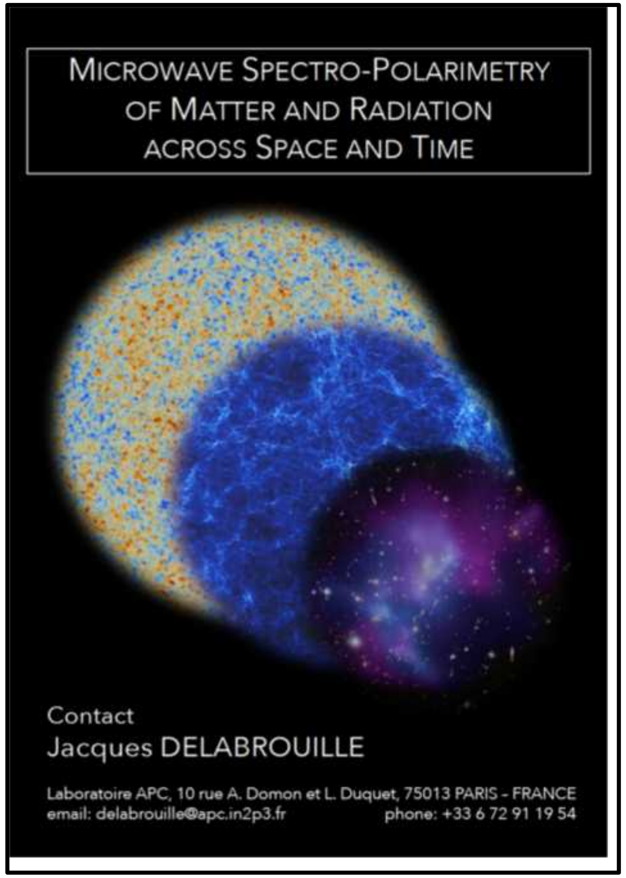
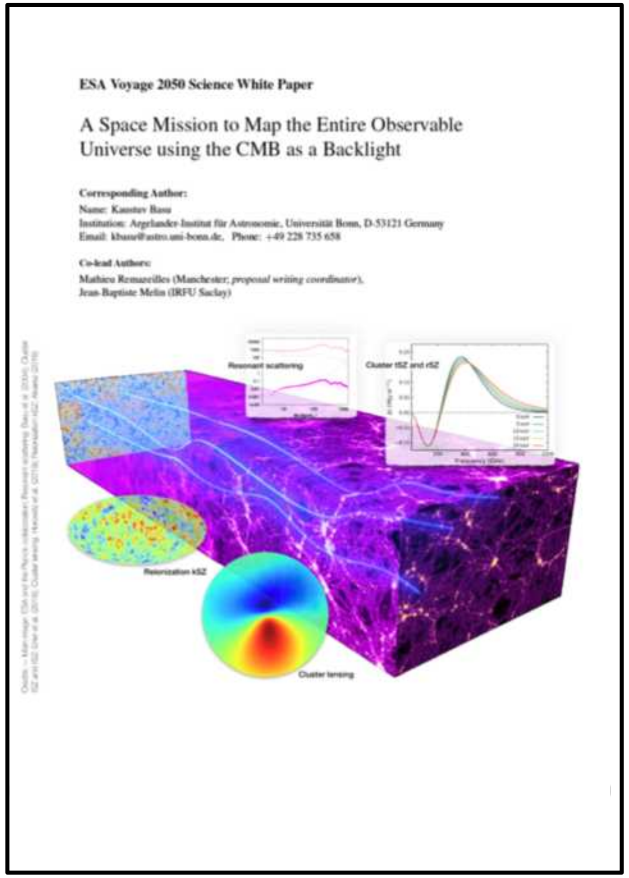
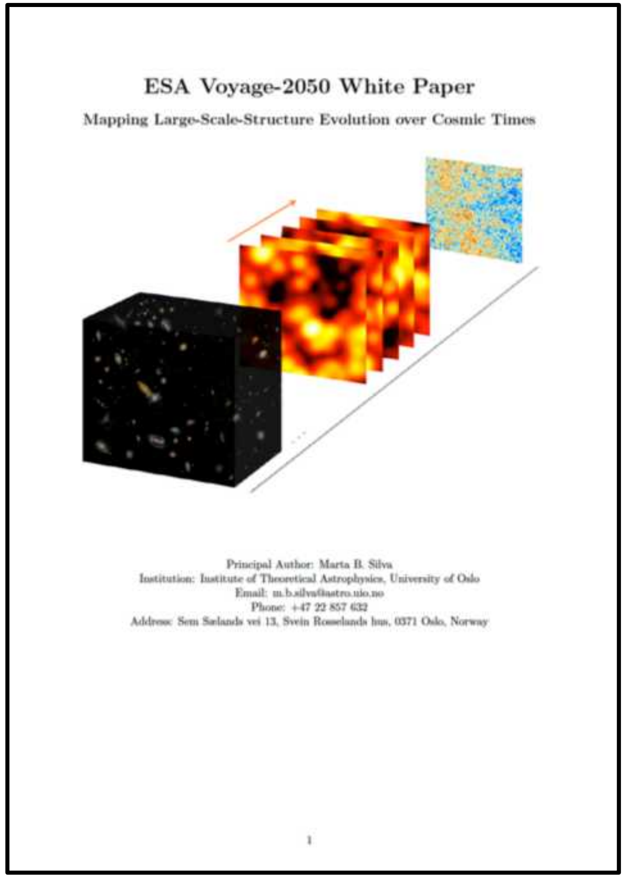


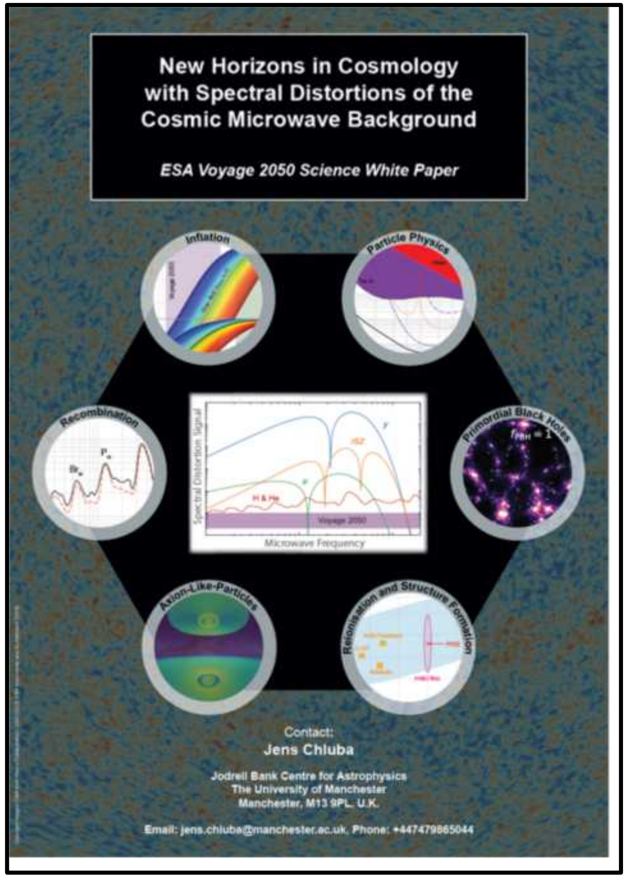
Microwave survey
Jacques Delabrouille et al.



CMB Backlight
Kaustuv Basu et al.



High redshift structures
Marta Silva et al.



Spectral distortions
Jens Chluba et al.

L-CLASS MISSION

3 SYNERGISTIC DESIGN-DRIVING SCIENCE CASES

White papers submitted by...

Jacques Delabrouille[1,2], Maximilian H. Abitbol[3], Nabila Aghanim[4], Yacine Ali-Haïmoud[5], David Alonso[3,6], Marcelo Alvarez[7,8], Anthony J. Banday[9], James G. Bartlett[1,10], Jochem Baselmans[11,12], Kaustuv Basu[13], Nicholas Battaglia[14], José Ramón Bermejo Climent[15], José L. Bernal[16], Matthieu Béthermin[17], Boris Bolliet[18], Matteo Bonato[19,20], François R. Bouchet[21], Patrick C. Breysse[22], Carlo Burigana[19], Zhen-Yi Cai[23,24], Jens Chluba[18], Eugene Churazov[25,26], Helmut Dannerbauer[27], Paolo De Bernardis[28,29], Gianfranco De Zotti[20], Eleonora Di Valentino[18], Emanuela Dimastrogiovanni[30], Akira Endo[11,31], Jens Erler[13], Simone Ferraro[8,7], Fabio Finelli[15], Dale Fixsen[32], Shaul Hanany[33], Luke Hart[18], Carlos Hernández-Monteagudo[34], J. Colin Hill[35,36], Selim C. Hotinli[37], Kenichi Karatsu[11,12], Kirit Karkare[38], Garrett K. Keating[39], Ildar Khabibullin[25,26], Alan Kogut[40], Kazunori Kohri[41], Ely D. Kovetz[42], Guilaine Lagache[17], Julien Lesgourgues[43], Mathew Madhavacheril[44], Bruno Maffei[4], Nazzareno Mandolesi[45,46], Carlos Martins[47,48], Silvia Masi[28,29], John Mather[40], Jean-Baptiste Melin[2], Azadeh Moradinezhad Dizgah[49,50], Tony Mroczkowski[51], Suvodip Mukherjee[21], Daisuke Nagai[52], Mattia Negrello[6], Nathalie Palanque-Delabrouille[2], Daniela Paoletti[15], Subodh P. Patil[53], Francesco Piacentini[28,29], Srinivasan Raghunathan[54], Andrea Ravenni[18], Mathieu Remazeilles[18], Vincent Revéret[2], Louis Rodriguez[2], Aditya Rotti[18], Jose-Alberto Rubiño Martin[27,55], Jack Sayers[56], Douglas Scott[57], Joseph Silk[58,21,59], Marta Silva[60], Tarun Souradeep[61], Naonori Sugiyama[62], Rashid Sunyaev[25,26,35], Eric R. Switzer[40], Andrea Tartari[63], Tiziana Trombetti[19], Íñigo Zubeldia[64,65].

(Long-term community effort, join any time)

A large space mission with three instruments ?

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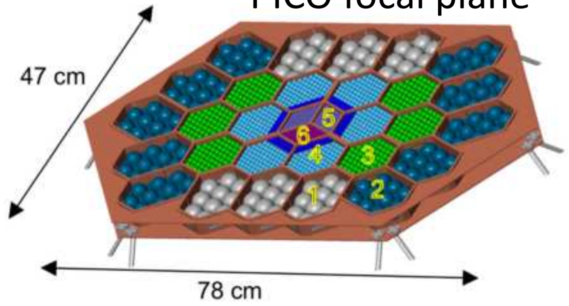
(This is what was originally proposed, and must now be revisited and developed)

1. A broad-band, multi-frequency polarised imager
   - Reference model: PICO instrument at the focus of 3.5m cold telescope
   - 21 bands from ~20 to ~800 GHz

CONTINUUM POLARIZED EMISSION

PICO focal plane

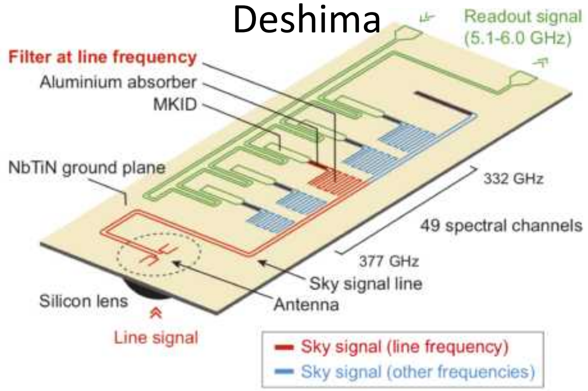


(S. Hanany et al. 2019)

2. A sensitive spectrometer with R ≈ 300
   - Reference model: Extended Deshima at the focus of the same telescope
   - Frequency range ~100-1000 GHz (goal 50-2000 GHz)

LINE EMISSION

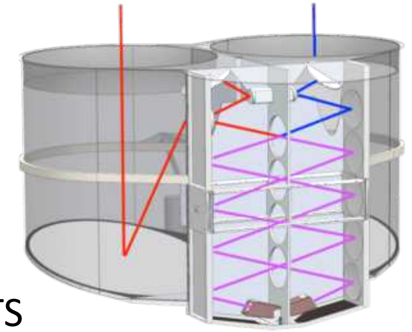
Deshima



(A. Endo et al. 2019)

3. An absolutely calibrated FTS
   - Reference model: a three-module version of PIXIE / PRISTINE
   - Frequency range ~10-2000 GHz

INTEGRATED EMISSION



PIXIE FTS

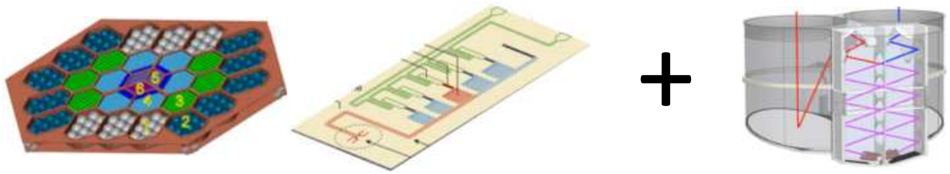
(A. Kogut et al. 2019)

A large space mission with three instruments ?

(This is what was originally proposed, and must now be revisited and developed)

- Large cold telescope (req. 2.8m, baseline 3.5m, ~8 Kelvin) ⟺ L-class mission

- Three cryogenic instruments
  - Two at the focus of the large telescope
  - One separate (could be on another platform)



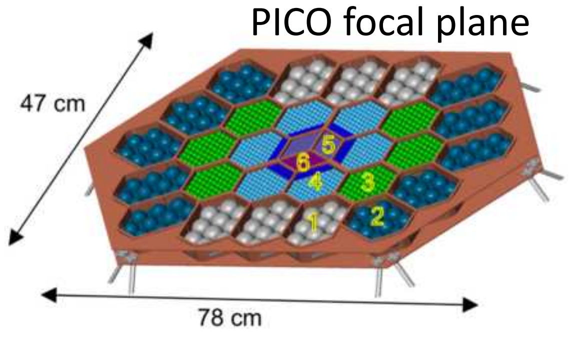
- Three possible modes of observation for a ~6-year mission
  - Survey 1 – full sky, ~2 years — **Go Broad !**
  - Survey 2 – deep patches, ~2 years — **Go Deep !**
  - Observatory – open time, ~2 years — **Be Flexible !**

A large space mission with three instruments ?

1. A broad-band, multi-frequency polarised imager

- Reference model: PICO instrument at the focus of 3.5m cold telescope
- 21 bands from ~20 to ~800 GHz

CONTINUUM POLARIZED EMISSION



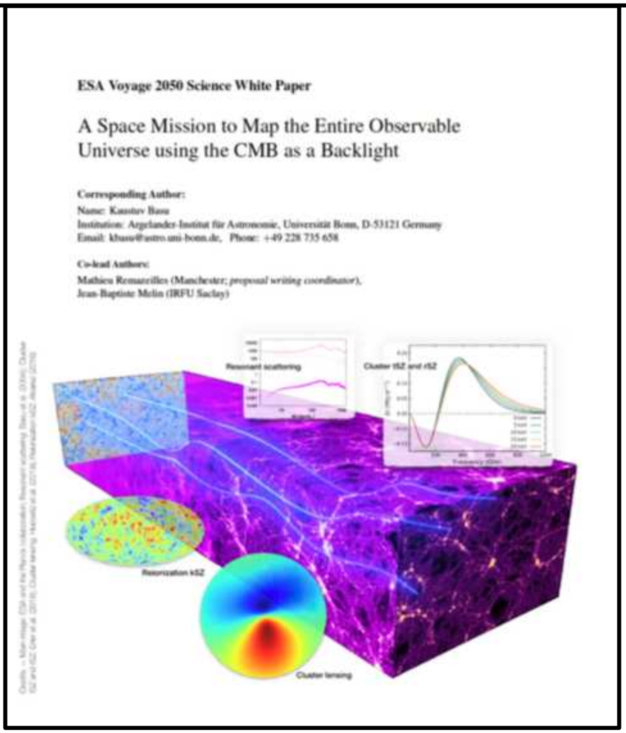
(S. Hanany et al. 2019)

CMB polarization science, Inflation

- (lensing potential; primordial GW; probing extensions of the ΛCDM model)
- Reionization optical depth, lift degeneracies for Σm_ν

Cluster science and Cosmology

- Thermal, kinematic SZ effects; relativistic corrections
- ~1 million clusters detected (complete census)
- Cluster masses from lensing (with polarization)
- Polarized SZ effect (transverse motion)


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 Germany

Co-lead Authors:
Mathieu Remazeilles (Manchester; *proposal writing coordinator*),
Jean-Baptiste Melin (IRFU Saclay)

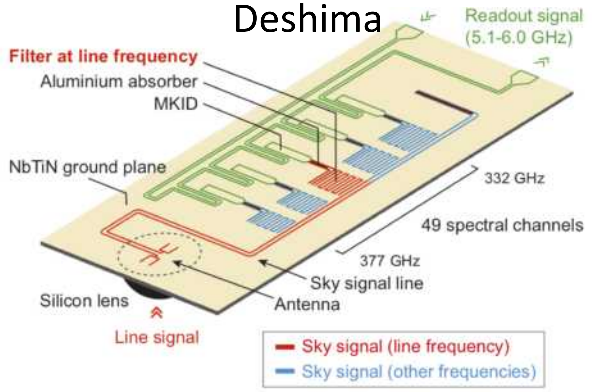
A large space mission with three instruments ?

2. A sensitive spectrometer with R ≈ 300

- Reference model: Extended Deshima at the focus of the same telescope
- Frequency range ~100-1000 GHz (goal 50-2000 GHz)

LINE EMISSION

Deshima



(A. Endo et al. 2019)

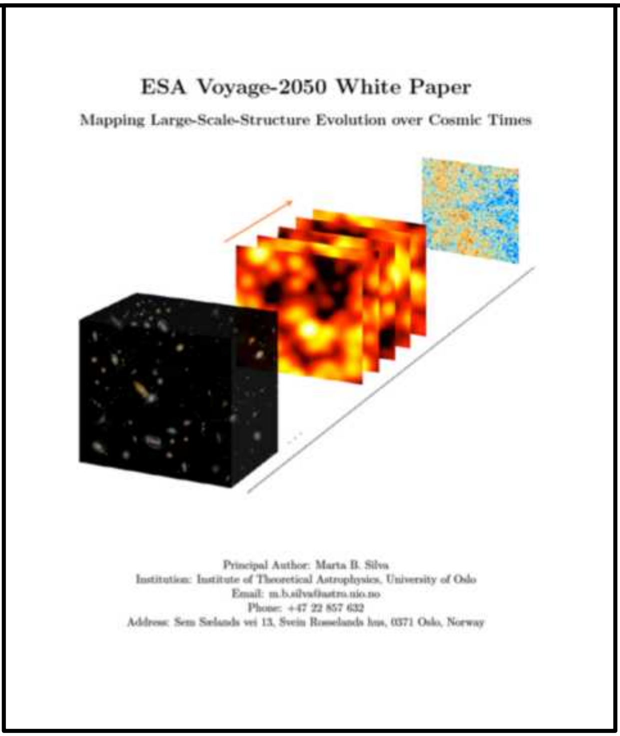
Line intensity mapping

- Map the 3D distribution of metals in the Hubble volume (CO, C+, …)
- CIB tomography

High redshift sources

- High redshift protoclucters
- Strongly lensed sources
- More than 1 million sources at z>4

Negrello et al., 2020



ESA Voyage-2050 White Paper

Mapping Large-Scale-Structure Evolution over Cosmic Times

Principal Author: Marta B. Silva
Institution: Institute of Theoretical Astrophysics, University of Oslo
Email: m.b.silva@astro.uio.no
Phone: +47 22 857 632
Address: Sem Sælands vei 13, Svein Rosselands hus, 0371 Oslo, Norway

Requirements

1. **Probing the EoR with [CII] line tomography (Reionization, protoclusters, metal and dust enrichment at high-z).** Requires sensitive [CII] observations in the 6 to 8 redshift range plus removal of interloping lines in map space. Survey requirements: spectral coverage over the 200 - 400 GHz frequency range; spectral resolution of R=300 (or higher); angular resolution of 1′ (ideal) to 6′ (minimum); sky coverage of 100 deg^2.

2. **Cosmology with statistical tomography of [CII] and FIR lines.** Survey requirements: minimum sky coverage of 1000 deg^2 but ideally 10000 deg^2; spectral resolution of R=300 (minimum); spectral coverage over the 200 - 2000 GHz frequency range; sky survey sensitivity (minimum). Going even higher in frequency would make it possible to detect more FIR lines.

3. **Tracing the SFRD history and CIB tomography with [CII].** Survey requirements: spectral resolution of R=200-400; spectral coverage over the 200 - 2000 GHz frequency range; sky coverage of minimum 100 deg^2; sky survey sensitivity.

4. **Measuring the molecular gas content up to high-z with CO.** Also, includes constraining the CO SLED up to z∼ 8 and probing the redshift evolution of galaxies ISM. Survey requirements: spectral coverage over the 50(minimum 100) - 400 GHz frequency range; spectral resolution of R=300 (minimum); sky coverage of 100 deg^2; deep survey sensitivity; angular resolution of 1′ (ideal) to 6′ (minimum).

5. **ISM and CGM of galaxies at z=2 with FIR lines plus AGN at high-z.** FIR lines can probe the ISM in galaxies and the CGM during the peak of star formation activity. The [OIII] line is a powerful tool to quantify the number density and distribution of AGN. Survey requirements: spectral resolution of R=200-400, spectral coverage over the 300 - 2000(3000) GHz frequency range; minimum sky coverage of 100 deg^2, deep survey sensitivity or higher.

6. **Cross-correlation and synergies with other surveys.** Survey requirements: wide frequency coverage, spectral resolution of R=200-400 (minimum); deep survey location should overlap with at least one HI 21-cm line field and preferably with several other galaxy/LIM surveys.

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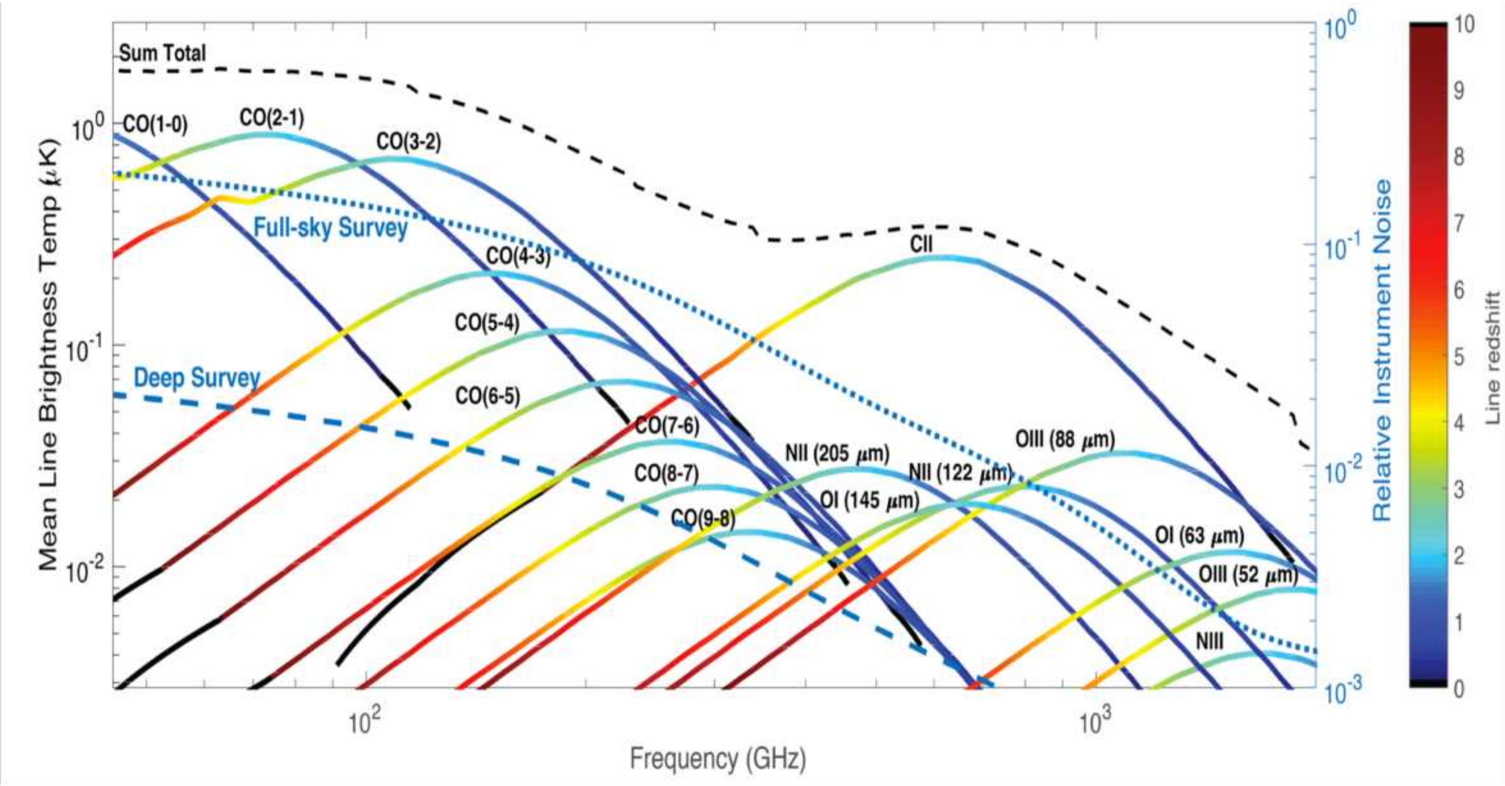
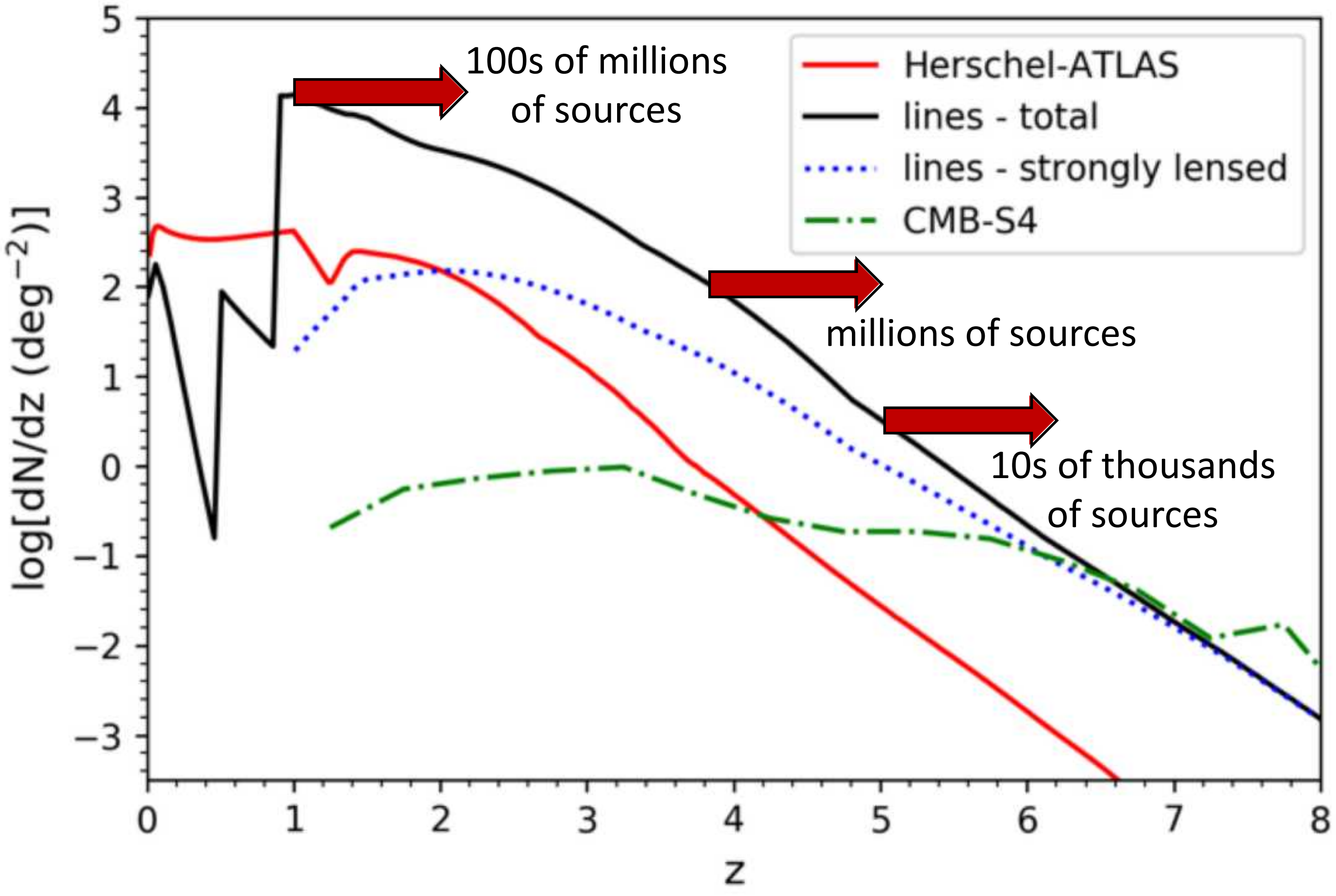
Sensitivity for mapping lines



- Model emission for main atomic and molecular lines.
- Instrumental sensitivity for an instrument of 64 spectrometers with photon-noise limited performance in bands $\nu/d\nu = 300$ and with 30% efficiency. We assumed an 8K telescope with Planck-type emissivity.
- *About 70,000 channels total*

High redshift sources



(figure from Matteo Bonato)

Spectroscopy offers the means to de-blend even with a 3-4m class telescope

Mostly un-blended !!

Individual sources / halos
with redshift information!

A large space mission with three instruments ?

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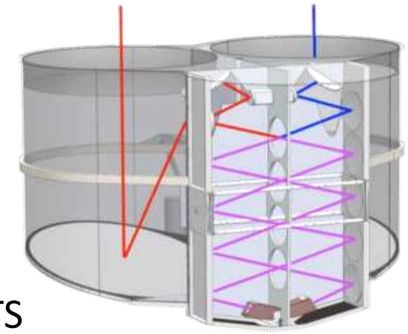
3. An absolutely calibrated FTS

- Reference model: a three-module version of PIXIE / PRISTINE
- Frequency range ~10-2000 GHz

INTEGRATED EMISSION



PIXIE FTS

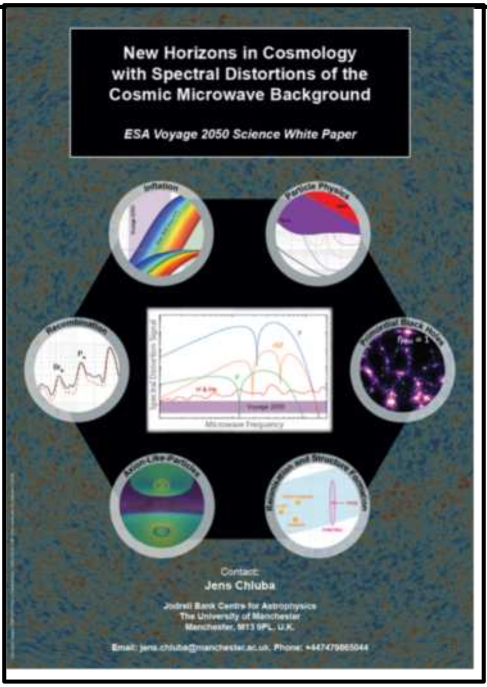
(A. Kogut et al. 2019)

CMB spectral distortions

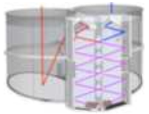
- Inflation; Universe at hugh redshift
- Dark matter
- Intensity mapping

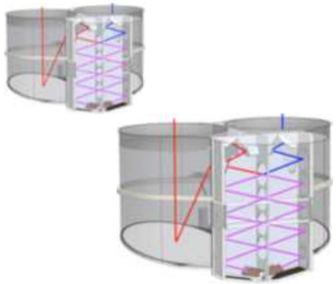
Foreground science

- Galactic (Thermal dust and other ISM emissions …)
- Extra-galactic (CIB, LIM, …)



Absolute spectrometry : instrument(s)





One or more small Fourier Transform Spectrometers modules

- For zero-level of intensity maps and CMB spectral distortions
- The multi-module options allows for better sensitivity at low and high frequency, and for different band widths in the three instruments…
- Is it the best solution?

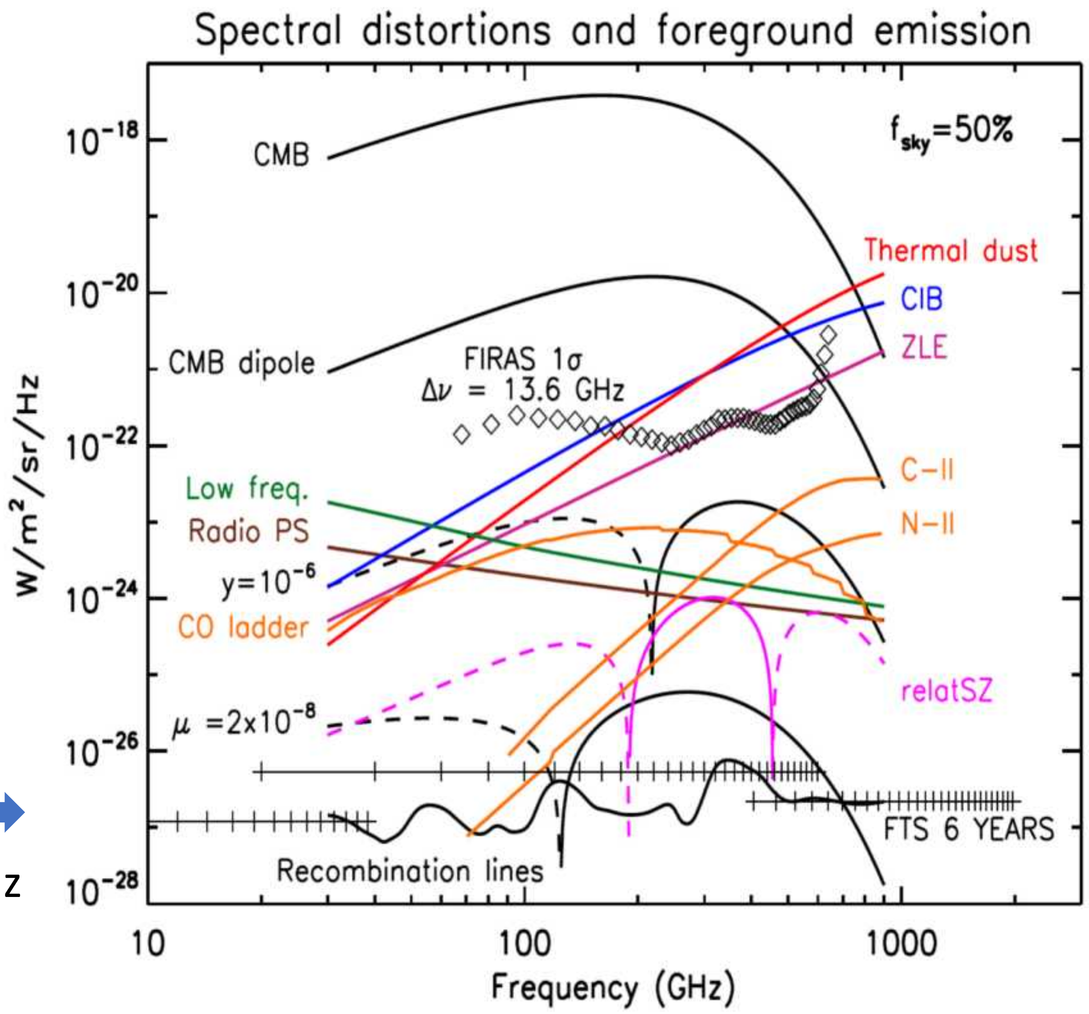
Table II: Multi-module absolute spectrometer; The mission sensitivity in the last column assumes 70% useful data and a 6-year mission.

Module	$\nu_{\rm min}$ (GHz)	$\nu_{\rm max}$ (GHz)	$\Delta\nu$ (GHz)	Sensitivity (Jy.$\sqrt{\rm s}$)	Mission sens. (Jy sr^{-1})
LFM	9.6	38.4	2.4	1435	0.12
MFM	20	600	20	6200	0.54
HFM	406	2000	58	2520	0.22

Sensitivity

The sensitivity target to reach the most interesting cosmological signals is of the order of 0.1 to 1 Jy/sr (integrated)

1 Jy/sr = 2.5 nK_{CMB} at 150 GHz



Sensitivity

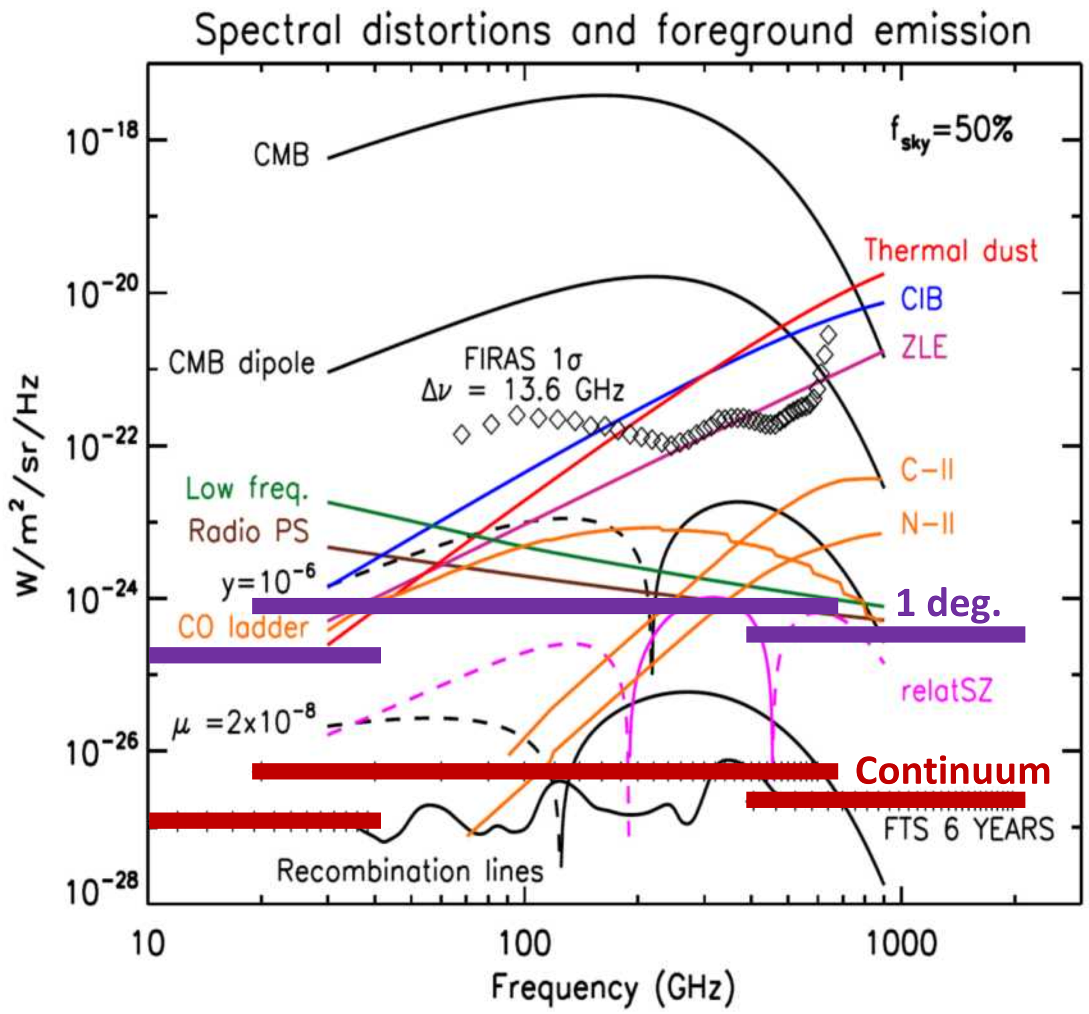
The sensitivity target to reach the most interesting cosmological signals is of the order of 0.1 to 1 Jy/sr (integrated)

Corresponding sensitivity of 20 to 200 Jy/sr per degree-size pixel

Can be reached with three PIXIE-type FTS spectrometers observing for 6 years

Foregrounds will be a big challenge at the level of sensitivity that is envisioned!

It might be the foregrounds that will set the angular resolution requirement…



-- Can we do absolute spectroscopy at the focus of a large telescope? --

ESA report

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ESA report

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2.3.1 New Opportunities for Exploring the Early Universe

Missions exploiting new probes, such as measuring the detailed spectrum of the CMB or observing GWs with high precision or in a new spectral window, can each answer many of these questions. Considerable advances have been, and are being, made in microwave instrumentation, enabling Fourier Transform Spectroscopy (FTS) to probe any injection of energy in the early Universe at $z > 10^3$, up to 100 000 times better than the FIRAS spectrograph on board NASA's *COBE* satellite. The improvement by such a large factor promises a huge space for discovery. This science requires absolutely calibrated spectrographs, and cannot be done by the relatively calibrated radiometers of NASA's *WMAP* or bolometers of ESA's *Planck* satellite. Such a mission would not only detect the guaranteed signals of the standard paradigm of cosmology (thus providing an important test for our current understanding), but would also offer a discovery space for evidence of axion-like particles, annihilating dark matter particles, primordial magnetic fields as the origin of magnetic fields in the Universe, and primordial black holes. Considerable advances have also been made in GW laser interferometry and in gravity reference sensors. On the ground, this is attested to by the remarkable precision achieved by the *LIGO* and *Virgo* detectors in the deca-to-kilohertz GW bands, and in

ESA report

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2.3.4 Recommendation

The Senior Committee recommend that ESA should develop a Large mission capable of deploying new instrumental techniques such as gravitational wave detectors or precision microwave spectrometers to explore the early Universe (say $z > 8$). Such a mission would shed light on outstanding questions in fundamental physics and astrophysics, such as how inflation occurred and the Universe became hot and then transparent, how the initial cosmic structures grew, how the first black holes formed and how supermassive black holes came to exist less than a billion years after the Big Bang.

While the focus of this Large mission is on the early Universe and the exciting new insights into the physics and astrophysics of that era, it is expected that the space observatories proposed to meet these objectives will also accomplish significant science at lower redshifts by the nature of their survey and new spectroscopic capabilities.

Decadal survey report

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CMB-S4 strongly endorsed

- Opens the path for NSF participation

Space missions

- Large Flagship in IR/O/UV ("small" version of LUVOIR, budget 11 B$)
- Smaller Flagship (3-5 B$) and Probe-class (1.5 B$) in FIR (SPICA mentioned explicitly) or X-rays
- Possible next probe-class for CMB polarization explicitly mentioned for the next decade
- No mention of LiteBIRD, not even in the list of related missions operating or in development

CMB mentioned 234 times, CMB-S4 65 times, PICO 1 time

J

Report of the Panel on Electromagnetic Observations from Space 2

EXECUTIVE SUMMARY

3. *Early Universe Cosmology:* A mission designed to provide high-precision measurements of the polarization of the cosmic microwave background at a range of frequencies. This would complement major ground-based facilities in exploring several of the greatest mysteries of fundamental physics—inflation, dark matter, dark energy, and neutrino mass, as well as the growth of structure with cosmic time.

The history of the CMB field is that of continuously improving ground and sub-orbital experiments, punctuated by comprehensive measurements from satellite missions (COBE, WMAP, and Planck). This trend will continue into the next decade. CMB observations will ultimately be limited by the accuracy with which emission from all other astronomical sources in the universe can be separated out, and by systematic errors. Ground and space measurements are complementary. From the ground, CMB polarization observations offer better angular resolution, using large aperture telescopes that would be expensive to fly in space, combined with excellent performance in a handful of atmospheric windows. Space, with its unrestricted access to all frequencies over the whole sky, its capability for uniquely accurate absolute calibration using the orbital motion of the spacecraft around the barycenter of the Solar system, and its freedom from atmospheric and other interfering signals, offers the lowest systematic errors and foreground residuals. Important progress in the next decade can be made by ambitious observations from the ground on angular scales of roughly ten degrees and smaller. Space observations will unquestionably be needed for the best foreground separation and lowest systematic errors on all angular scales, and especially on angular scales of greater than about ten degrees.

A future dedicated CMB space mission, with a goal of measuring the polarized signal to the fundamental limits set by foregrounds, would realize these goals. This will require substantial early work to (1) improve all aspects of the detector systems (e.g., mm-wave filtering and coupling, CMB-noise limited detectors, low-noise stable readouts, low-noise cryogenics); (2) enhance the ability to simulate and separate foreground emission from the CMB; (3) simulate and mitigate the effects of systematic errors; and (4) use this knowledge to optimize the design of a flight system. This preparatory work could begin immediately, eventually resulting in a Probe-class mission, with a final design based on a targeted competition, selected near the end of the decade. The appropriate investment in technology development in advance of that selection is estimated by the panel to be ~$100 million, spent over the decade.

Decadal survey report

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7.5.3.5 An Early Universe Cosmology and Fundamental Physics Probe

As detailed in the report of the Panel on Cosmology, studies of the cosmic microwave background continue to provide data that address profound and fundamental questions about the universe on the largest scales and during its earliest moments. As noted by the EOS-2 panel report, "space observations will unquestionably be needed for the best foreground separation and the lowest systematic errors on all angular scales, and especially on angular scales of greater than about ten degrees." With investment in technologies this decade, combined with ground-measurements, cosmic microwave background (CMB) probe mission could potentially be a compelling candidate for the future probe call in the 2030's, complementing the survey's ground-based CMB-S4 recommendation.

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A large space mission with ~~three~~ instruments ?

two (?)

1. ~~A broad-band, multi-frequency polarised imager~~
   - ~~Reference model: PICO instrument at the focus of 3.5m cold telescope~~
   - ~~21 bands from ~20 to ~800 GHz~~

Other options?

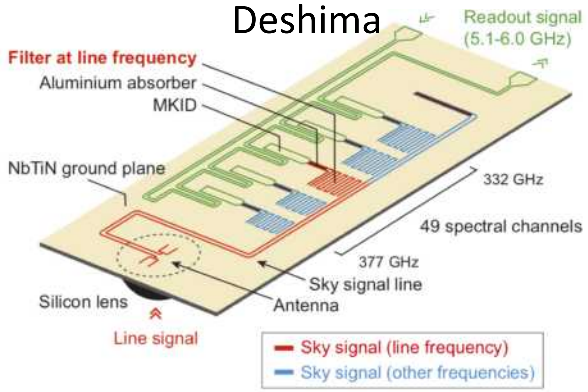
2. A sensitive spectrometer with R ≈ 300
   - Reference model: Extended Deshima at the focus of the same telescope
   - Frequency range ~100-1000 GHz (goal 50-2000 GHz)
   - ***Could also do some of the cluster science***

LINE EMISSION

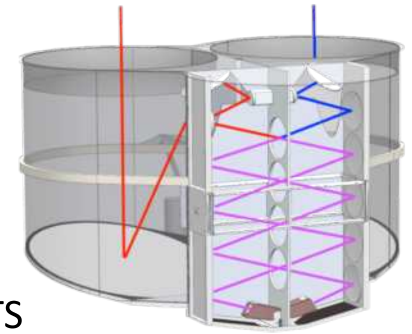
3. An absolutely calibrated FTS
   - Reference model: a three-module version of PIXIE / PRISTINE
   - Frequency range ~10-2000 GHz

INTEGRATED EMISSION

Deshima



(A. Endo et al. 2019)



PIXIE FTS

(A. Kogut et al. 2019)

Summary

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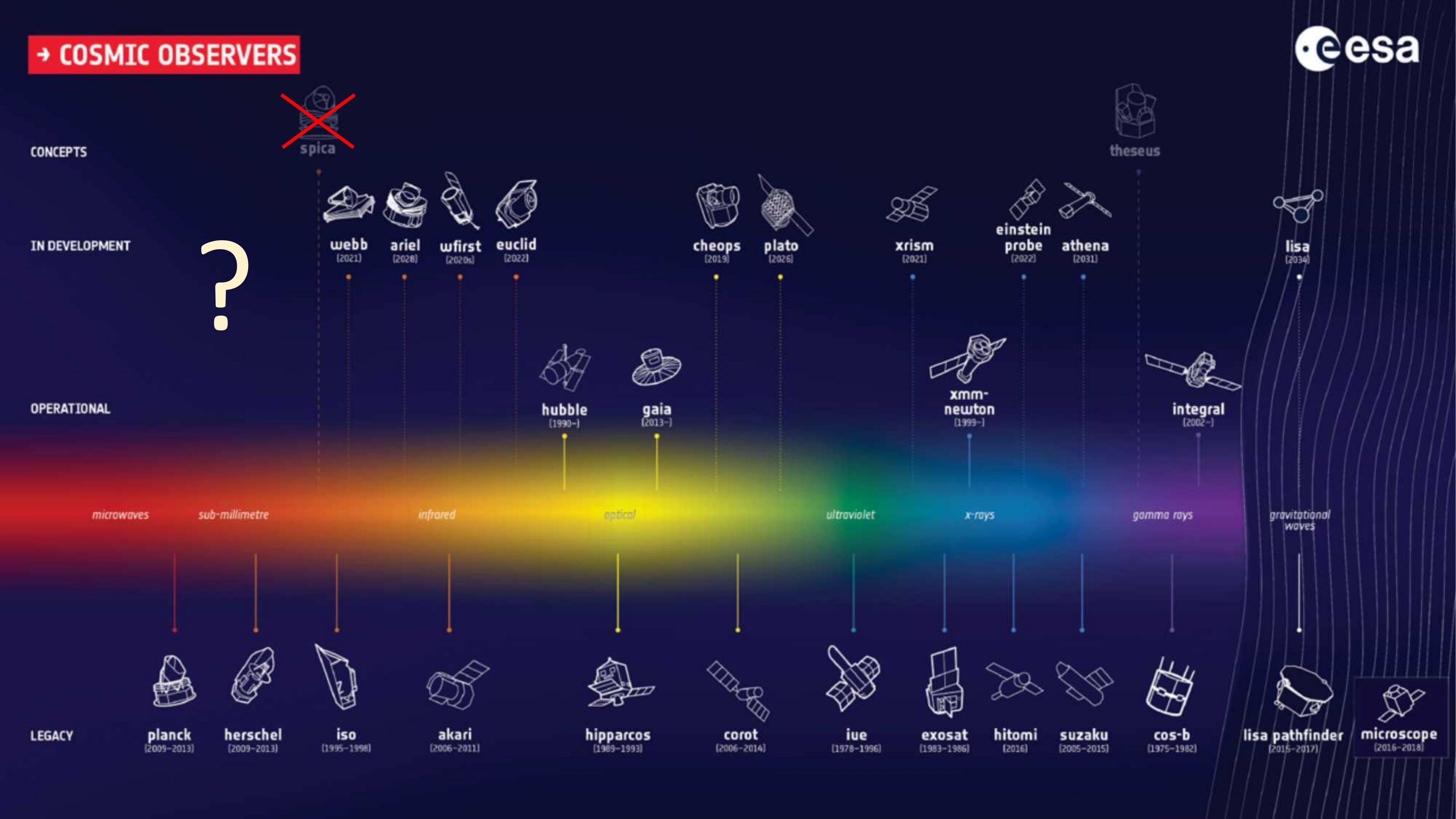
There will be opportunities for CMB space missions in Europe and in the US

- At ESA / in Europe
  - From Voyage 2050, better perspectives for microwave spectroscopy than for polarization.
  - Prepare for proposing a ***feasible*** L-class mission capable of detecting μ spectral distortions and CMB recombination lines.
  - Time frame: 2035-2050…
  - Foreground separation will set angular resolution requirements for CMB science. Opportunity for great foreground science (ISM, extragalactic astrophysics and cosmology)
  - 2 instruments? Can we do absolute spectroscopy at the focus of a large telescope?

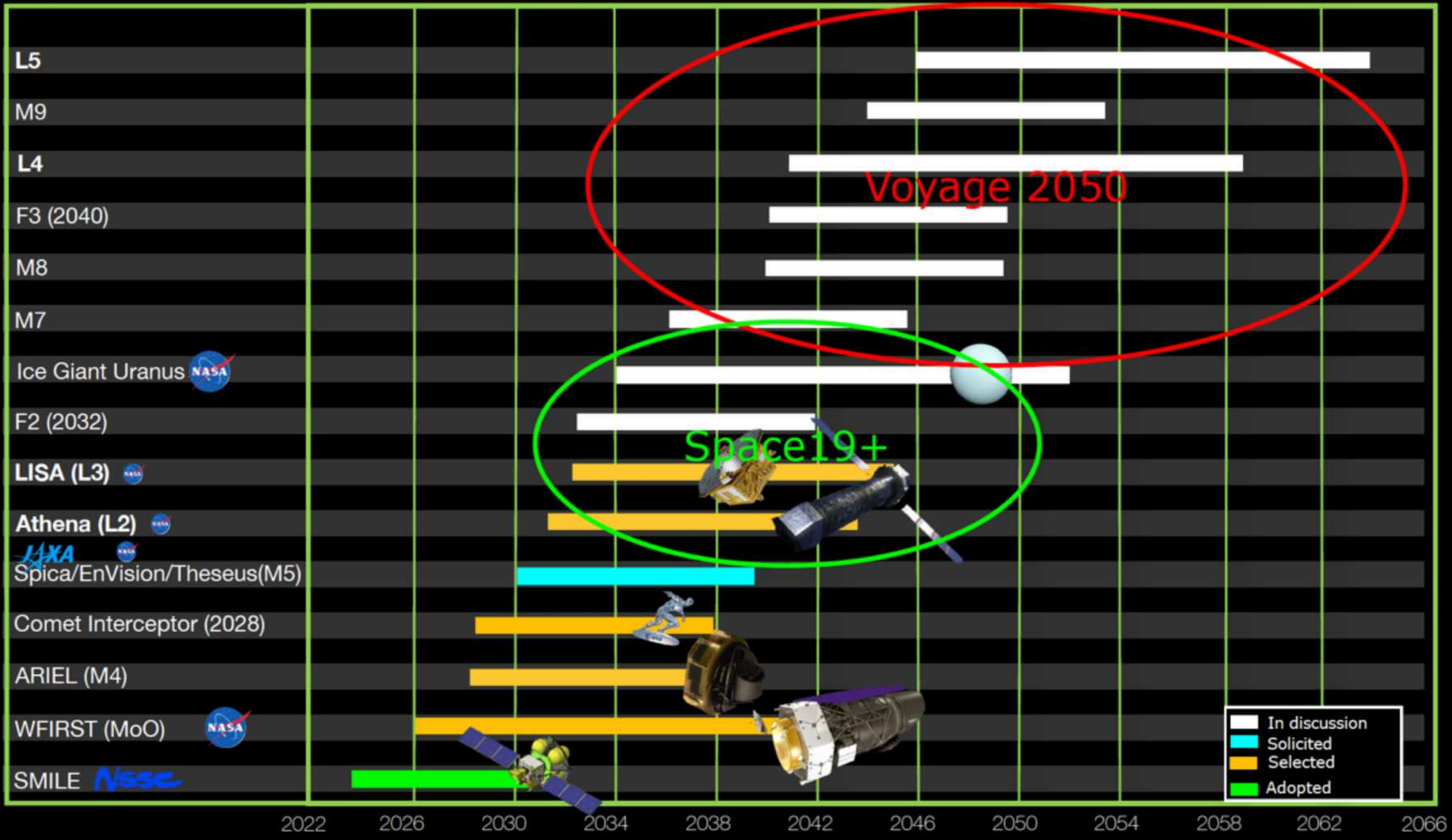
- At NASA / in the US
  - Possible next probe-class (<1.5 B$) for CMB polarization post 2030 (next decade)
  - Preparatory work could begin immediately (with a budget of 100 M$ over 10 years)

Thank you
for your attention


→ COSMIC OBSERVERS
esa
CONCEPTS
spica
theseus
IN DEVELOPMENT
?
webb (2021)
ariel (2028)
wfirst (2020s)
euclid (2022)
cheops (2019)
plato (2026)
xrism (2021)
einstein probe (2022)
athena (2031)
lisa (2034)
OPERATIONAL
hubble (1990–)
gaia (2013–)
xmm-newton (1999–)
integral (2002–)
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
gravitational waves
LEGACY
planck (2009–2013)
herschel (2009–2013)
iso (1995–1998)
akari (2006–2011)
hipparcos (1989–1993)
corot (2006–2014)
iue (1978–1996)
exosat (1983–1986)
hitomi (2016)
suzaku (2005–2015)
cos-b (1975–1982)
lisa pathfinder (2015–2017)
microscope (2016–2018)

Future ESA Space Science Missions

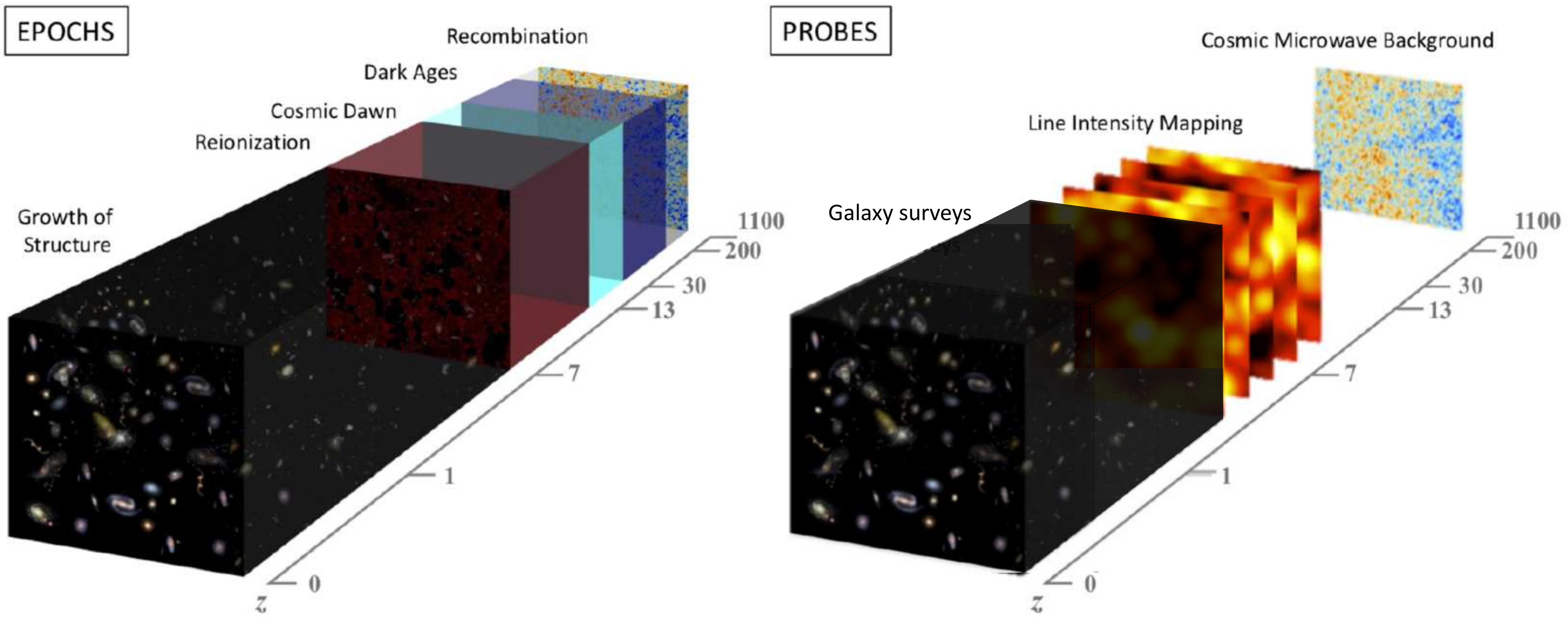
Slide G. Hasinger



ESA report

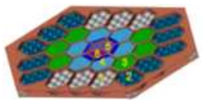
CNRS • Berkeley
Centre
Pierre
Binétruy

Structure tomography



- **Matter power spectra;**
- **Knots in the cosmic web, from protoclusters to clusters;**
- **Different gas phases in structures;**
- **History of star formation, molecular gas, dust in structures**

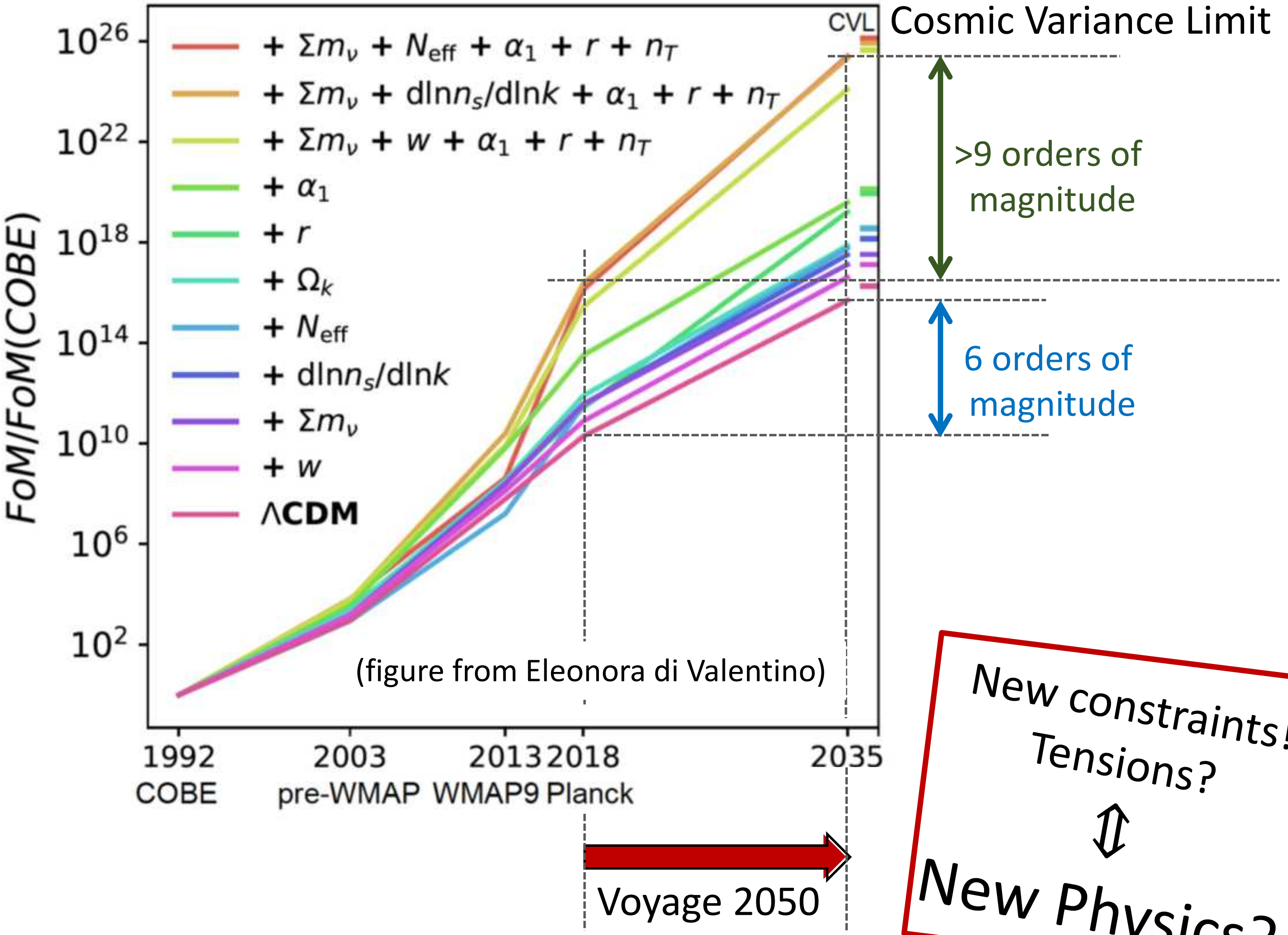
ΛCDM under scrutiny



- ΔT & ΔP CMB sensitivity
  ≈ 5000 × Planck
  ≈ 10 × CMB-S4 (polar.)
- Impressive constraints (with CMB alone!)

$\sigma(\Sigma m_\nu) \sim 10^{-2}$
$\sigma(N_{\rm eff}) \sim 0.016$ } Neutrinos

$\sigma(r) \sim 10^{-4}$
$\sigma(n_s) \sim 0.0015$ } Inflation



New constraints! Tensions?
⇕
New Physics?