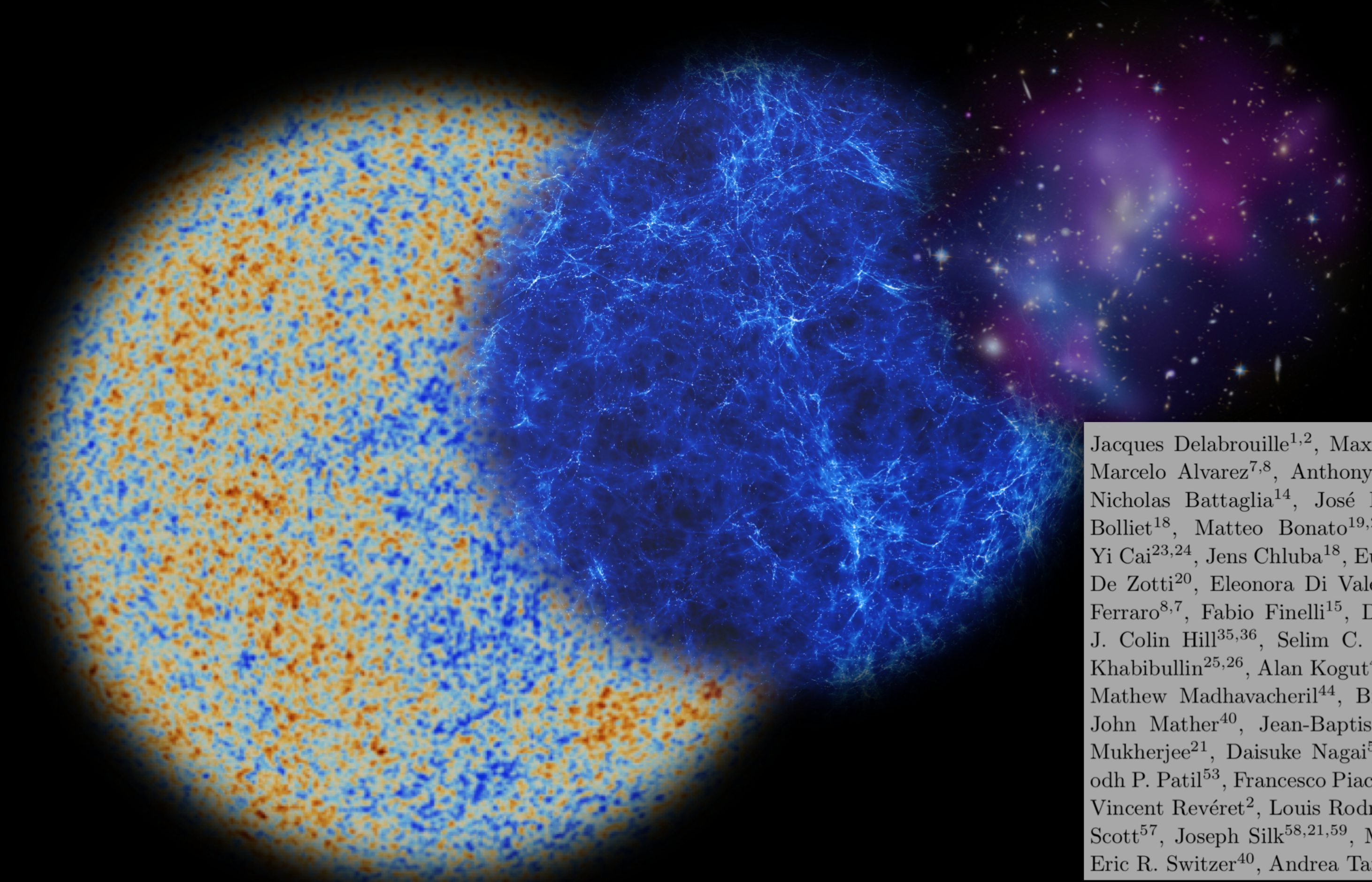
Microwave Spectro-Polarimetry of Matter and Radiation across Space and Time



Jacques Delabrouille

Laboratoire APC, CNRS/IN2P3, Paris

& IRFU, CEA-Saclay

on behalf of

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].

The context: ESA science in 2035-2050

SCIENCE MISSIONS | EUROPEAN SPACE AGENCY | SCIENCE &TECHNOLOGY | SIGN IN

voyage 2050

esa

Voyage 2050 » Ho...

- Home
- Workshop registration
- Workshop programme
- Workshop: second announcement
- White Papers
- Senior Committee
- Call for Membership of Topical Teams
- Call for White Papers

VOYAGE 2050
LONG-TERM PLANNING OF THE ESA SCIENCE PROGRAMME

***** Registration is open for the Workshop *****
***** See second announcement and registration form*****

4 March 2019

The Science Programme of the European Space Agency (ESA) relies on long-term planning of its scientific priorities. The first long-term plan, Horizon 2000, was the result of an exercise started in 1983, and it was followed by an extension, Horizon 2000 Plus, that resulted in the initiation of the Gaia and BepiColombo missions. The successive planning exercise, Cosmic Vision, was started in 2004 and is the current basis against which the content of the Science Programme is set.

Cosmic Vision is the result of a bottom-up process that began with a consultation of the broad scientific community. The plan, which comprises a variety of missions and extends up to 2035, defines the wide-ranging and ambitious scientific questions to be addressed by missions in the ESA Science Programme.

DOCUMENTATION

Letter of Invitation - White Papers (pdf)

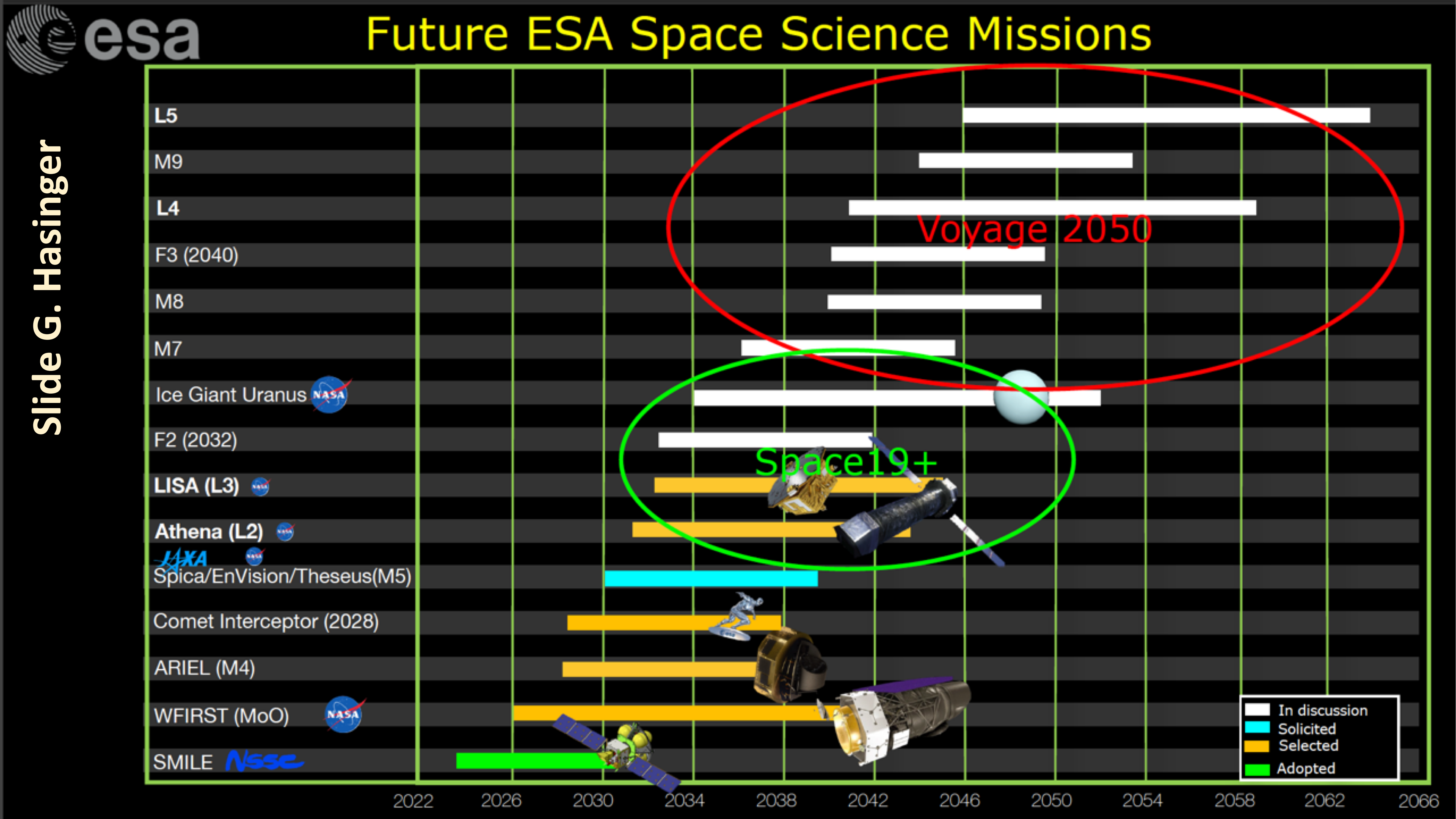
Letter of Invitation - Topical Team membership (pdf)

Call for White Papers (pdf)

Call for Membership of Topical Teams (pdf)

From Voyage 2050 web site

Future ESA Space Science Missions



Slide G. Hasinger

The context: ESA science in 2035-2050

This process will decide what science will be done by the three next L-class missions!

The Director of Science has appointed the Senior Committee to guide the Voyage 2050 process. This Committee, composed of scientists working in institutions in ESA Member States, is tasked to:

1. Recommend to the Director of Science the three science themes of the three L missions that will be part of the plan.

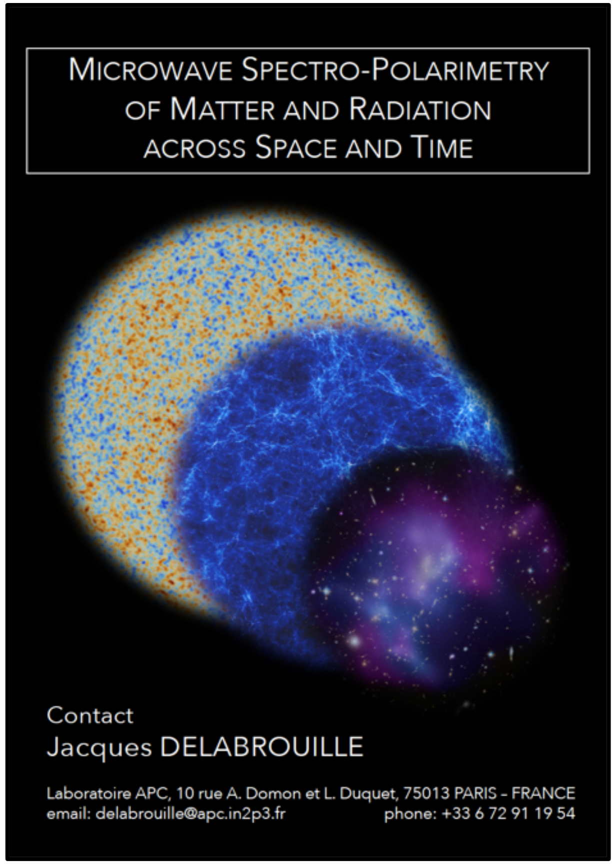
2. Identify a number of high-impact science themes that could be implemented through an M mission during the plan's time span. The actual M missions will be decided through open calls for missions issued in due time to retain flexibility in the Science Programme. However, the early identification of themes of interest will help the Agency in, e.g., developing key technologies.

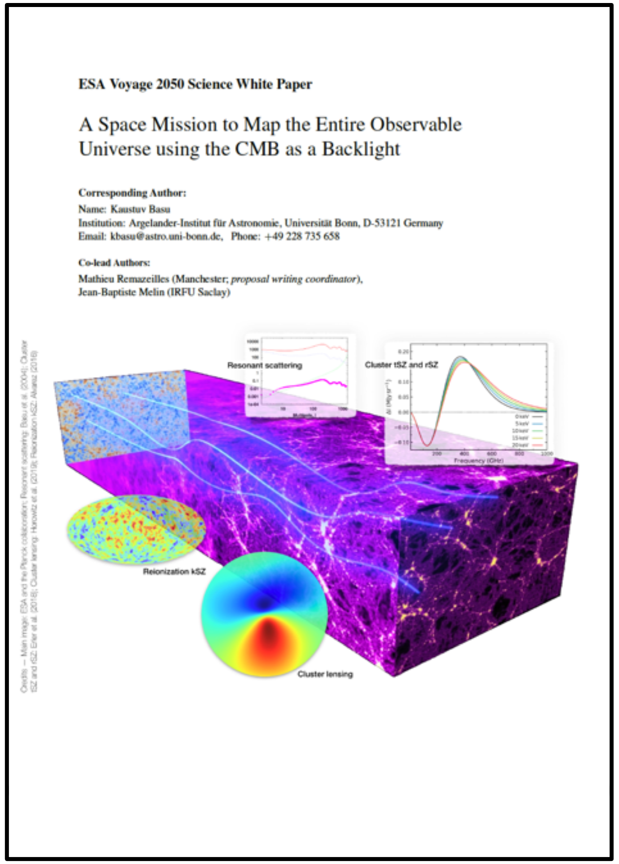
But we are not asked for mission proposals!

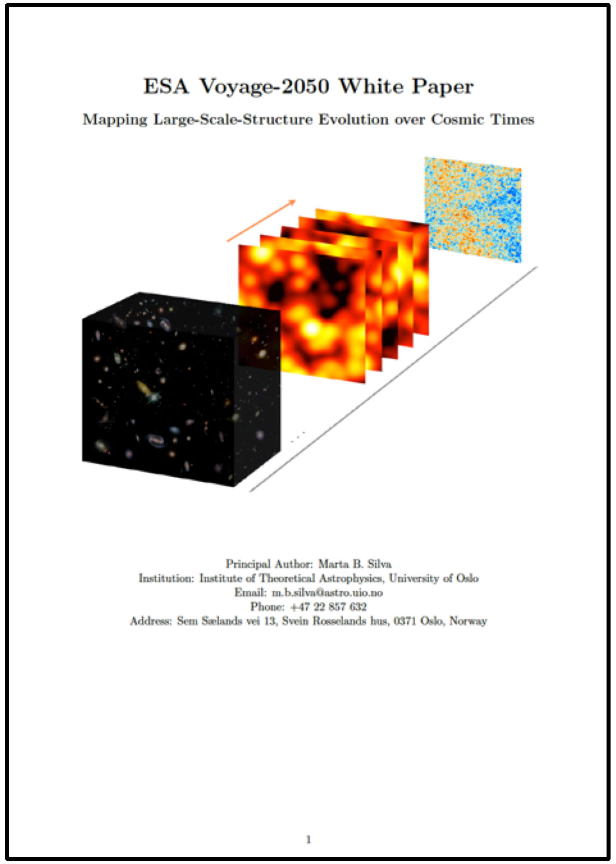
White Papers are not proposals for specific missions; they should rather argue why a specific scientific theme should have priority in the Voyage 2050 planning cycle. At the same time, and to ensure realism in the resulting Programme, applicants should briefly illustrate possible mission profiles.

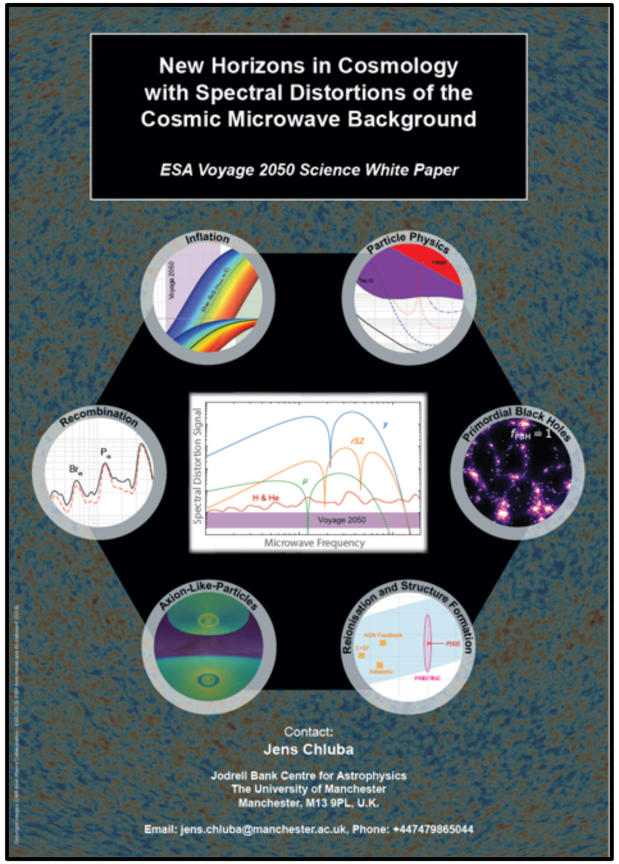
From Voyage 2050 call

A coordinated microwave observation programme









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

What science in 2035+ ?

Primordial B-modes?

2035

r	LiteBIRD / S4	PICO ?	Next ?
$r > 0.005$	detection	detection	map B-modes
$0.001 < r < 0.005$	hint?	detection	confirm
$0.0001 < r < 0.001$	-	hint?	push down?

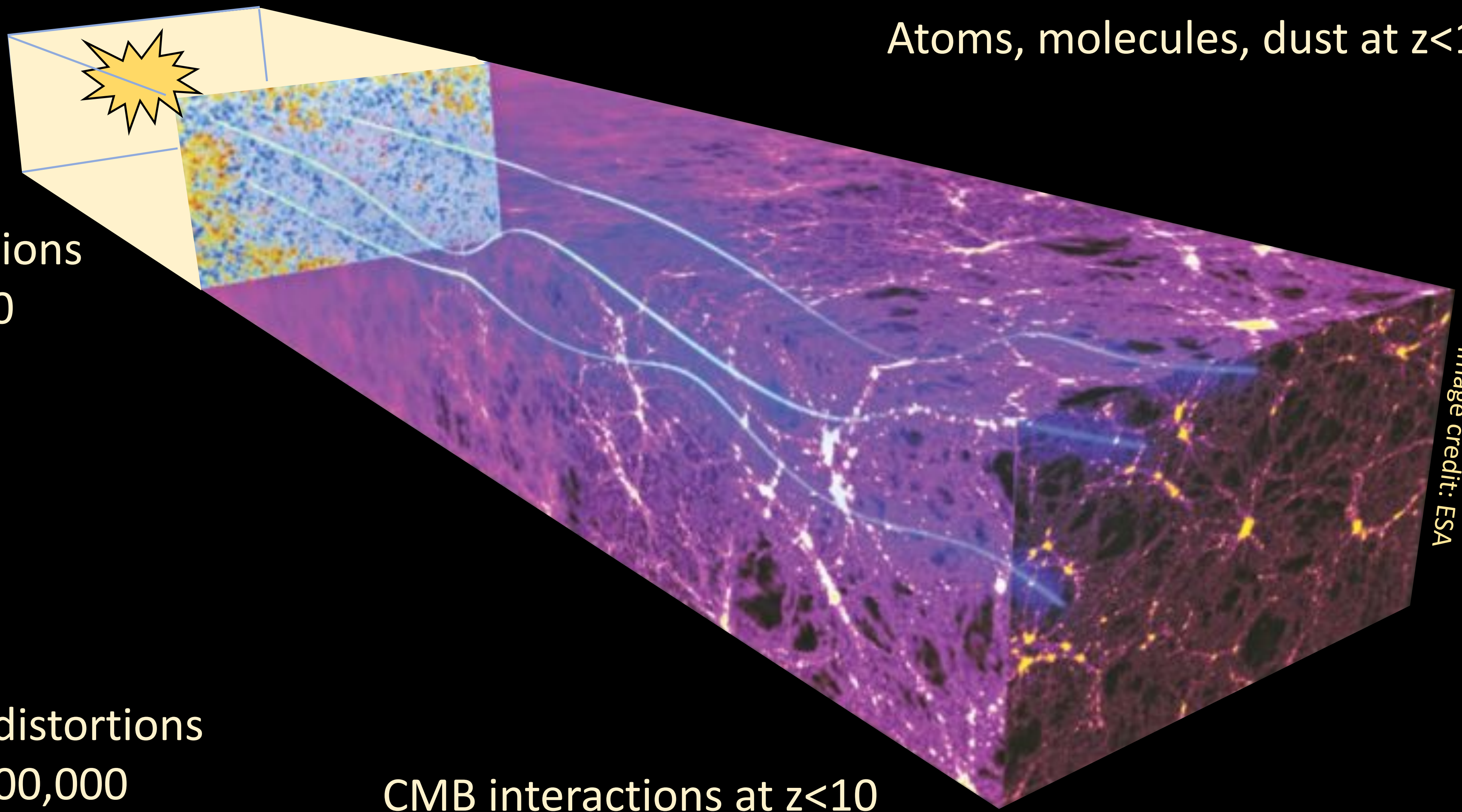
Or perhaps we hit a wall of foregrounds and lensing residuals?

- many more channels for full foreground understanding !
- much better delensing capability with CMB and with structures (CIB+LIM)

Map the entire Universe in the Microwave !!

Atoms, molecules, dust at z<10

CMB fluctuations
at z≈1000



CMB spectral distortions
0 < z < 2,000,000

CMB interactions at z<10

Map the entire Universe in the Microwave !!

Atoms, molecules, dust at z<10

NEW

CMB fluctuations
at z≈1000

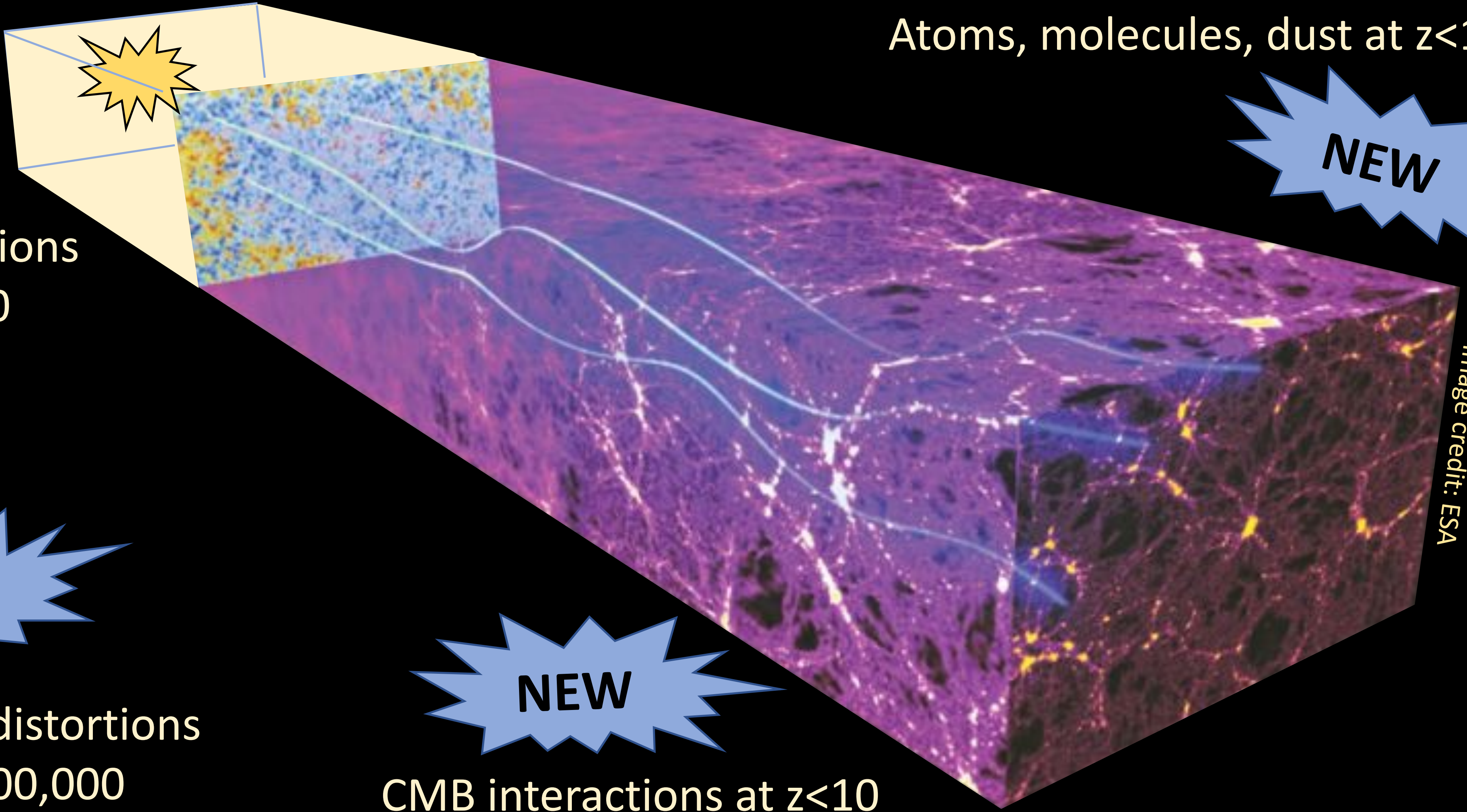


Image credit: ESA

NEW

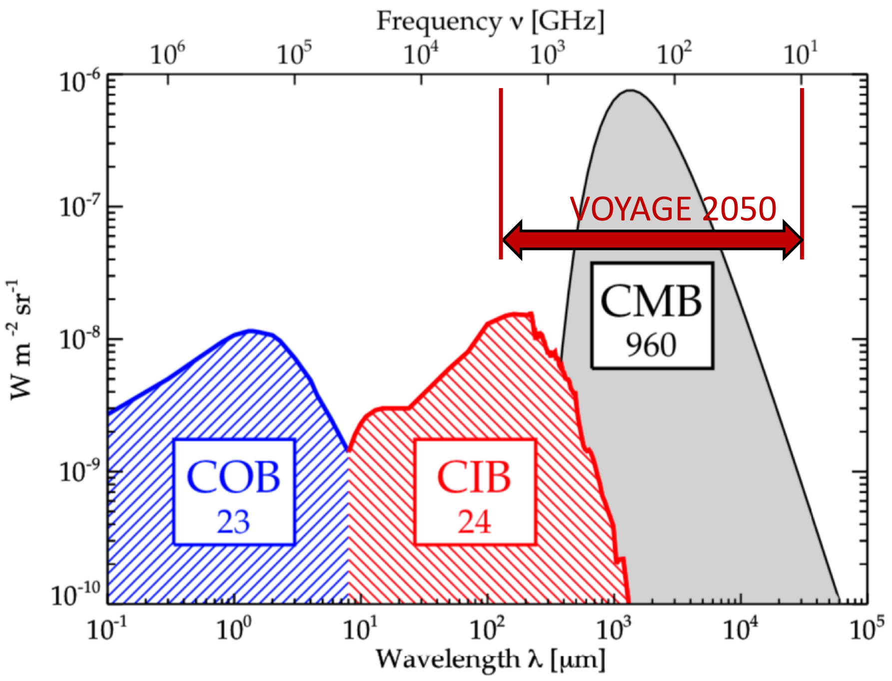
CMB spectral distortions
0 < z < 2,000,000

NEW

CMB interactions at z<10

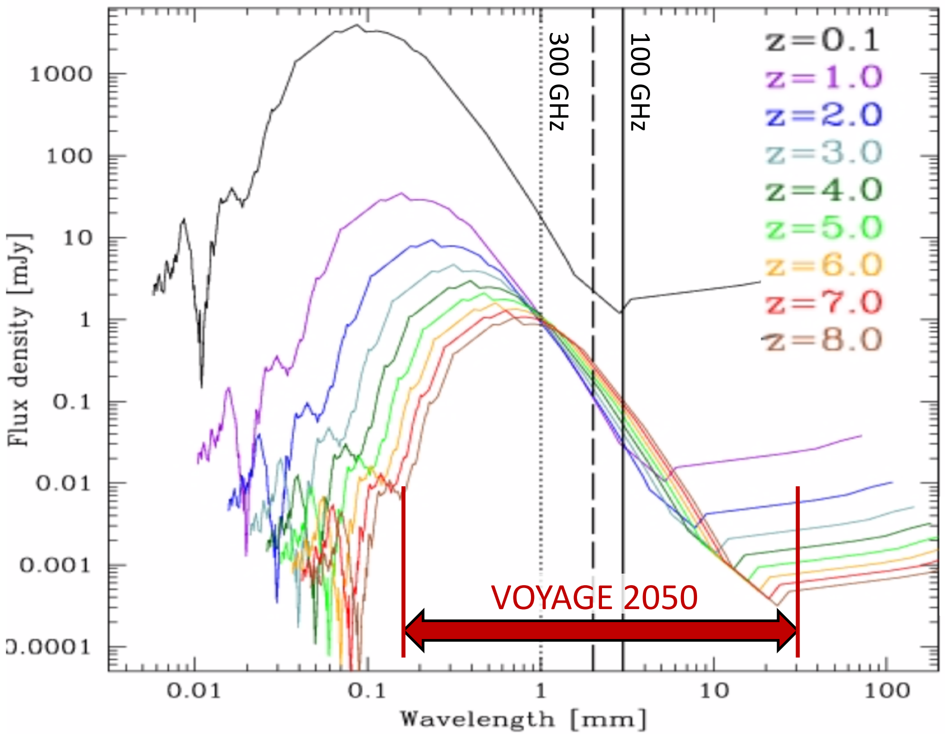
Why microwaves?

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)

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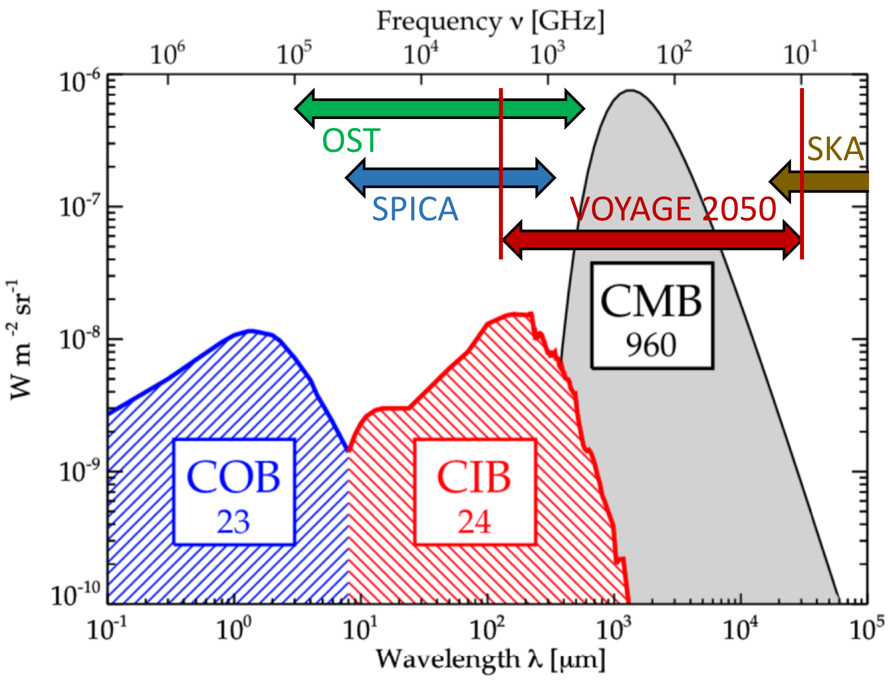

(figure from H. Dole et al. 2006)

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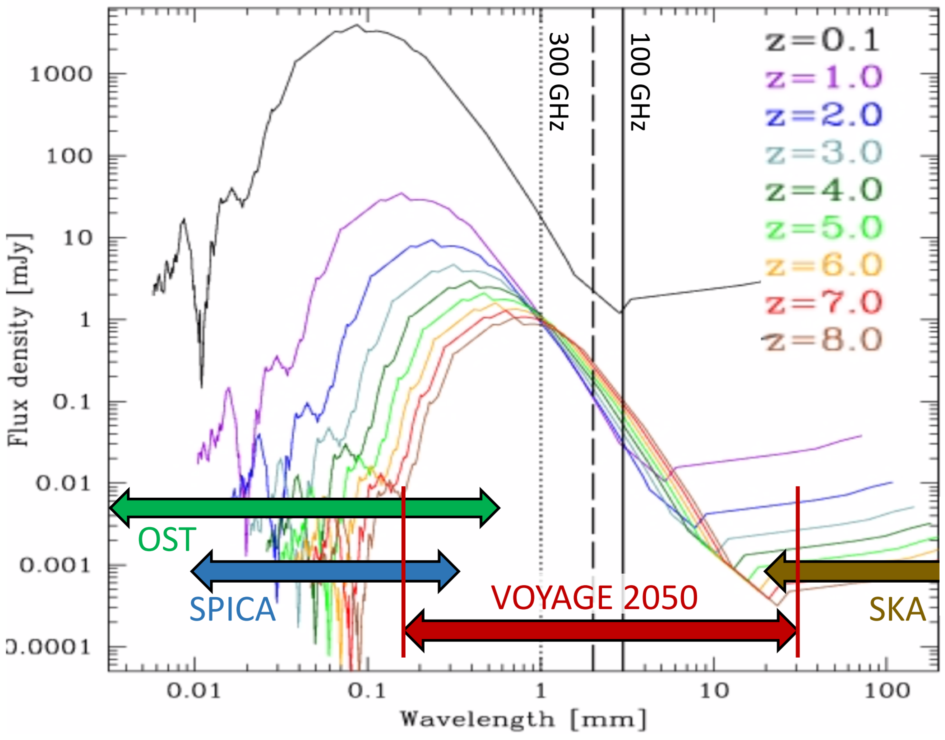
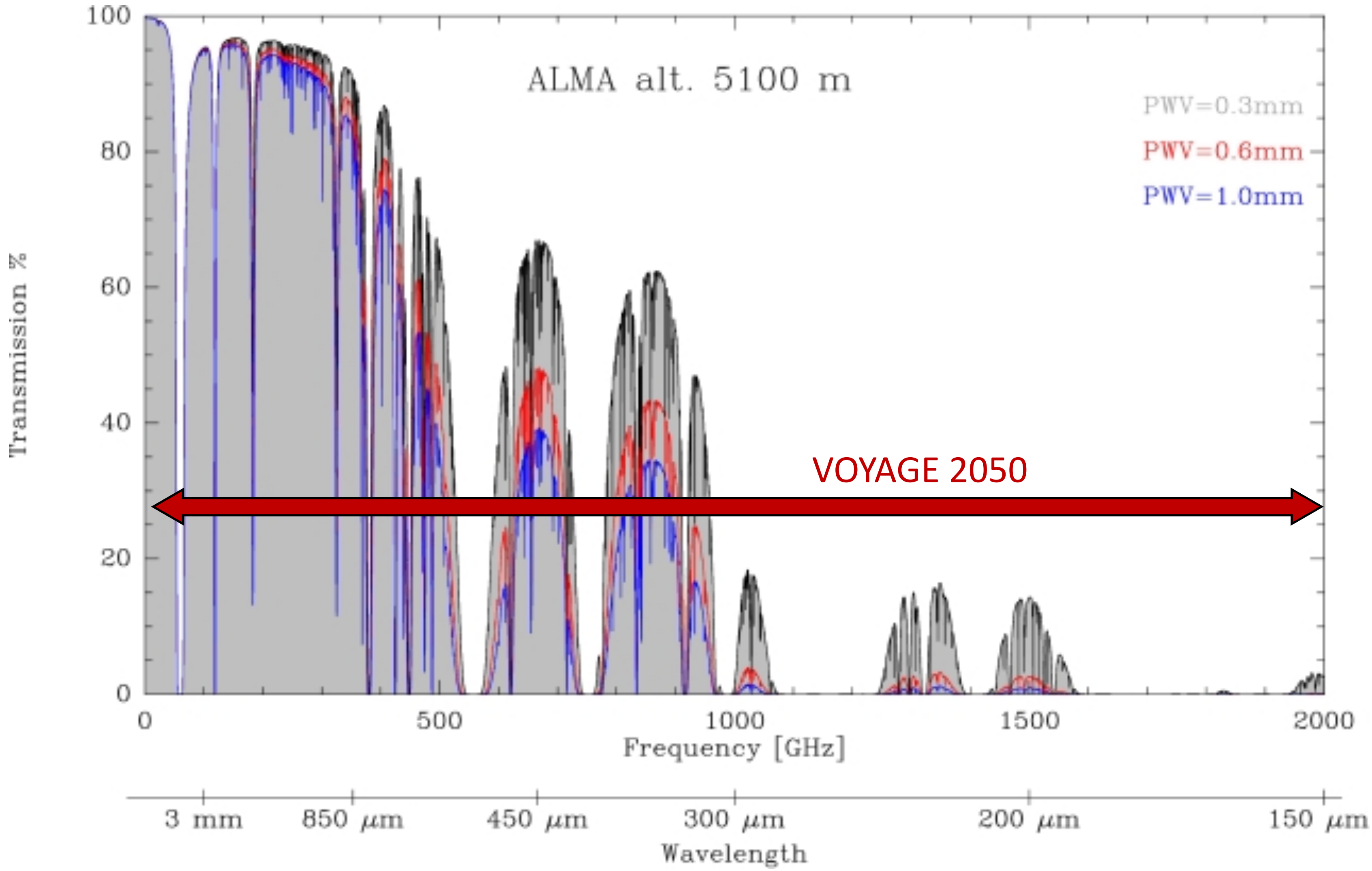


(figure from R. Decarli website)

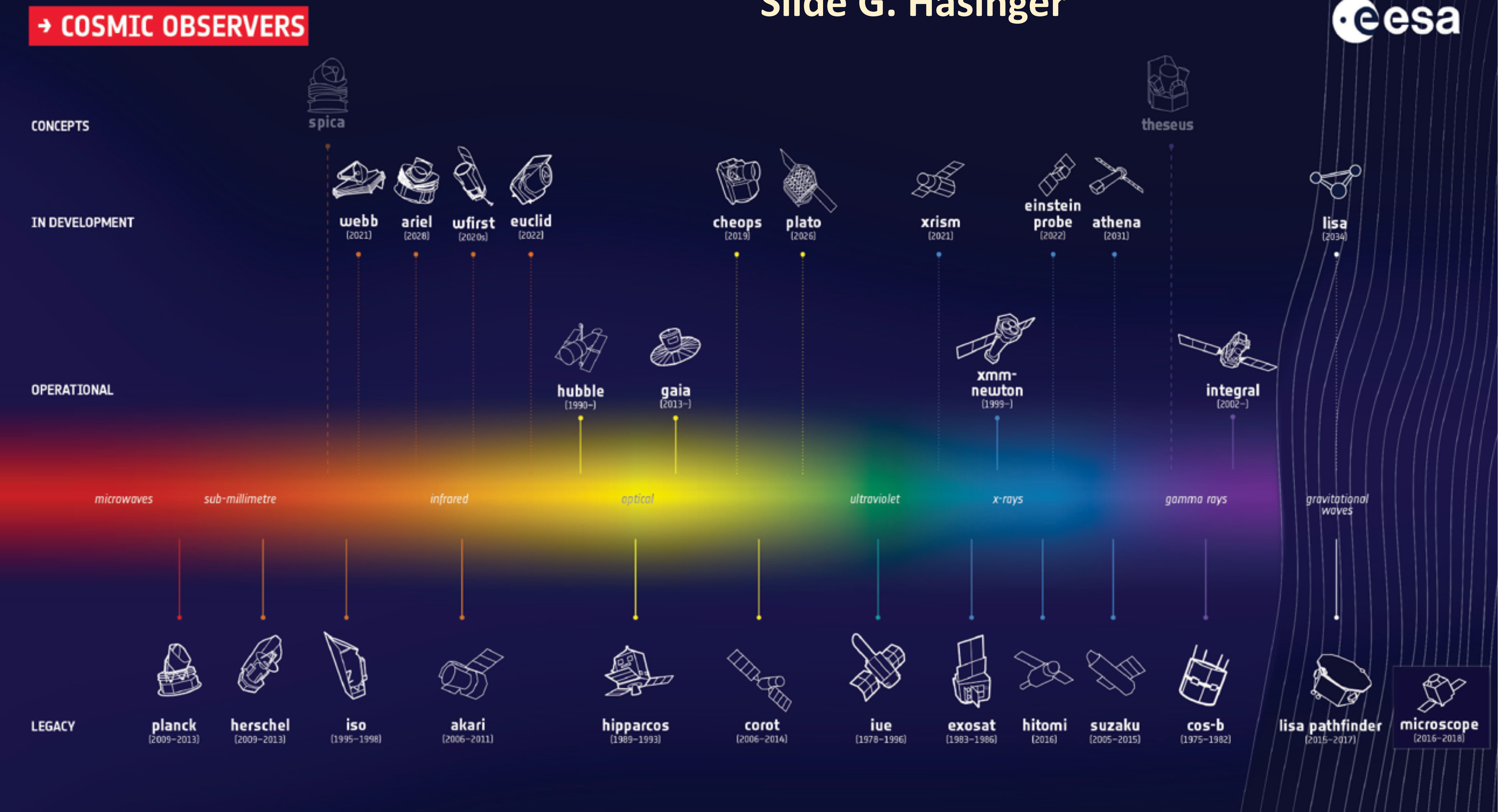
3- Complement planned observations in the 2030+ time frame

Why from space?

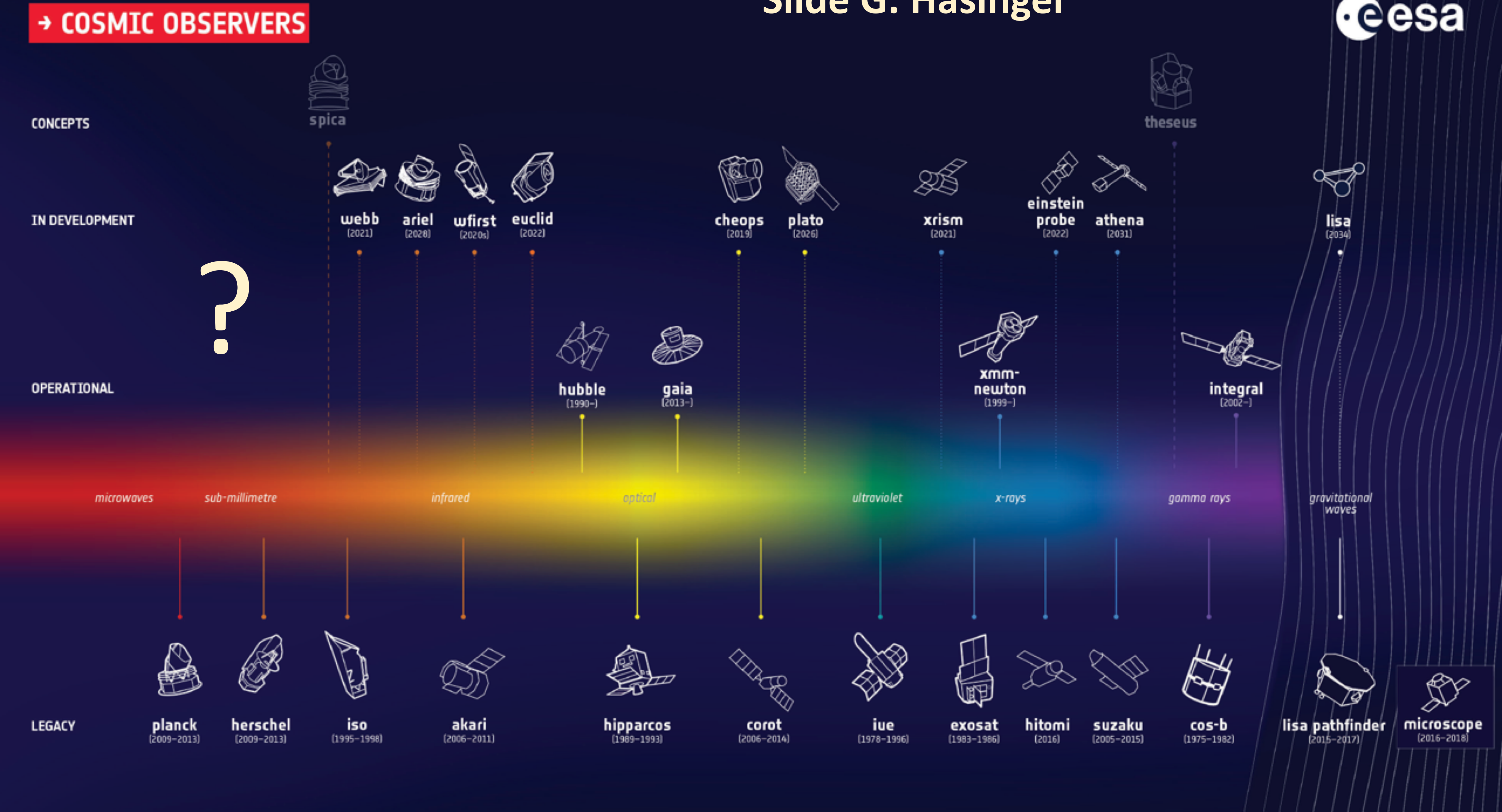


Atmospheric Transmission and Emission !

Slide G. Hasinger



Slide G. Hasinger



A space telescope / mission with 3 instruments

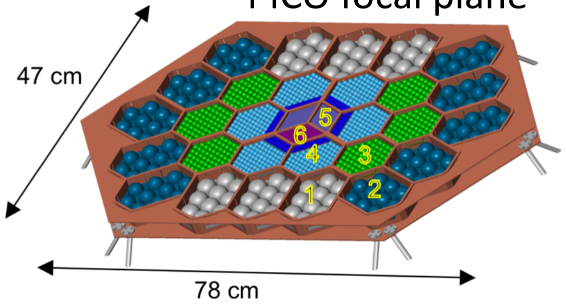
Microwave Imaging and Spectroscopy Telescope

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

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)

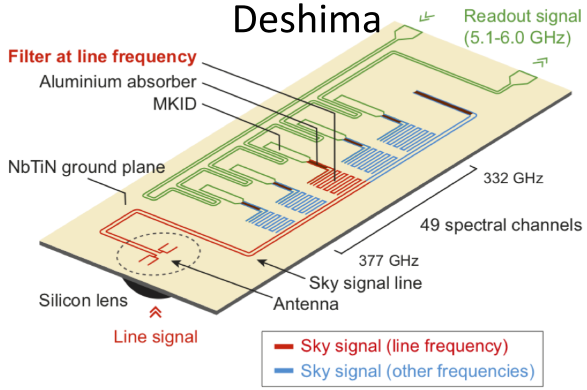
3. An absolutely calibrated FTS
    - Reference model: a three-module version of PIXIE / PRISTINE
    - Frequency range ~10-2000 GHz

PICO focal plane

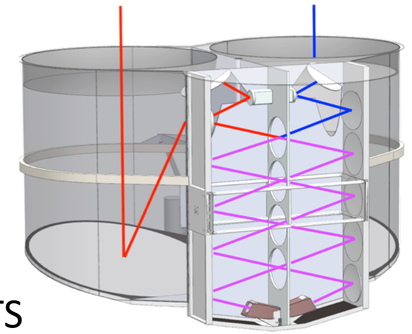


(S. Hanany et al. 2019)

Deshima



(A. Endo et al. 2019)



PIXIE FTS

(A. Kogut et al. 2019)

A space telescope / mission with 3 instruments

Microwave Imaging and Spectroscopy Telescope

1. A broad-band, multi-frequency polarised imager
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   - 21 bands from ~20 to ~800 GHz

CONTINUUM EMISSION

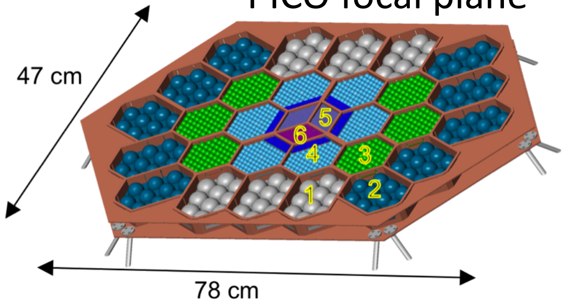
2. A sensitive spectrometer with R ≈ 300
   - Reference model: Extended Deshima at the focus of the same telescope
   - Frequency range ~100-1000 GHz (goal 50-2000 GHz)

LINE EMISSION

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

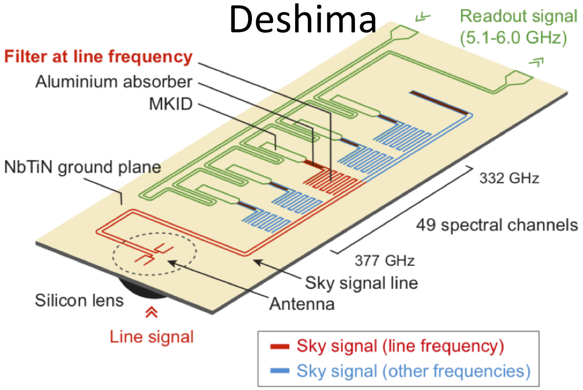
INTEGRATED EMISSION

PICO focal plane



(S. Hanany et al. 2019)

Deshima



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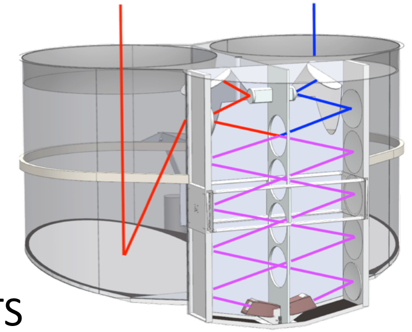


PIXIE FTS

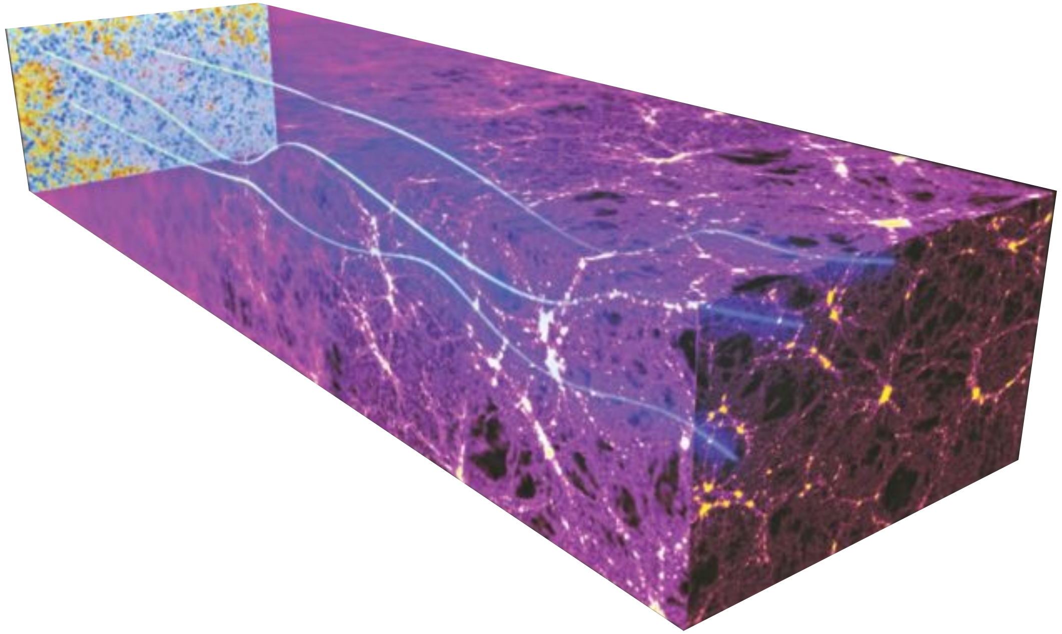
(A. Kogut et al. 2019)

Key scientific questions

1. Is ΛCDM the final word? Extensions?
2. Physics of the dark sector? Neutrino sector?
3. Structure formation?
4. Inflation?
5. Gravitation theory?

The distribution of matter and energy across space, time and scales encodes answers to these questions

Science highlight 1 : The build-up of structure



CMB "backlight" probes

- Hot gas with thermal Sunyaev-Zeldovich effect (>10^6 clusters)
- Gas temperature with relativistic corrections to SZ spectrum
- Velocity flows with kinematic and polarized SZ effects
- Dark matter and halo masses with CMB lensing
- Atoms with Rayleigh and resonant scattering

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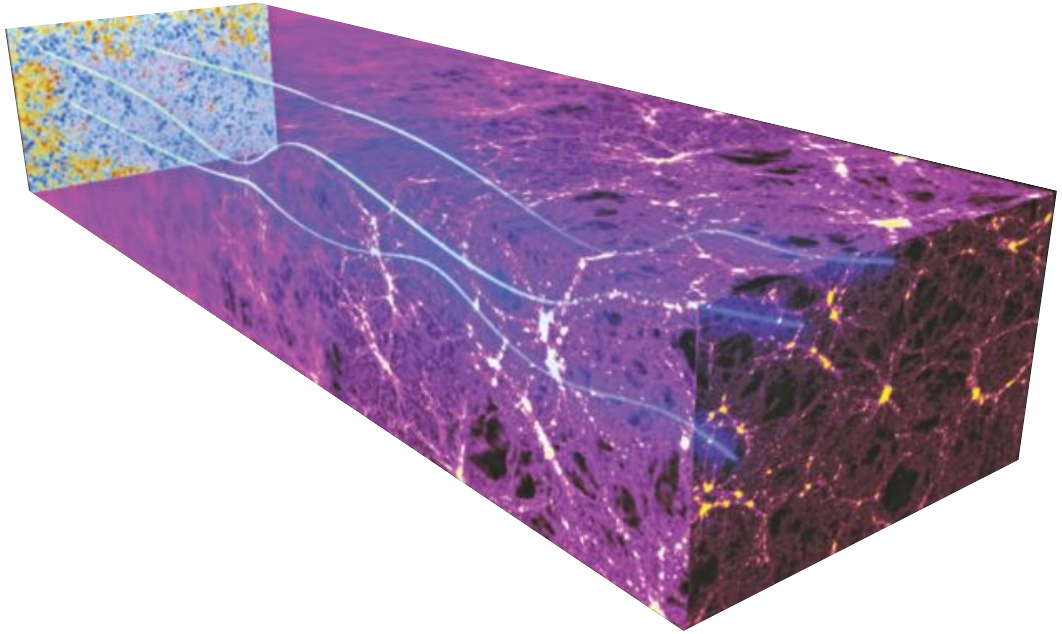

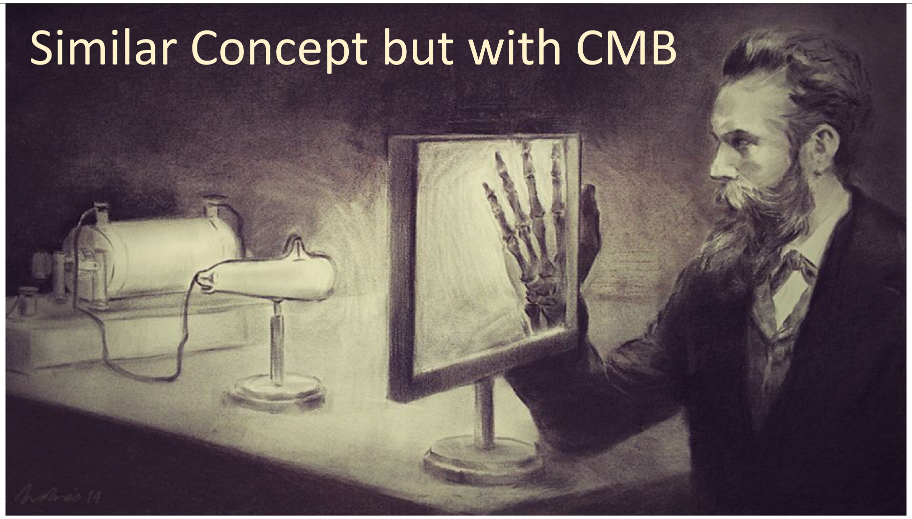

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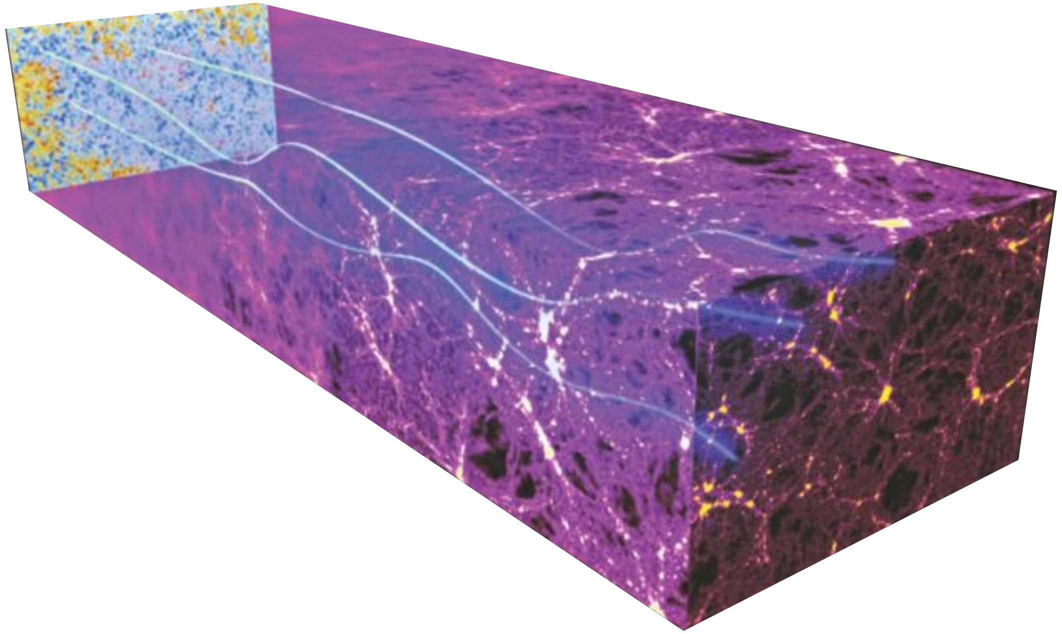

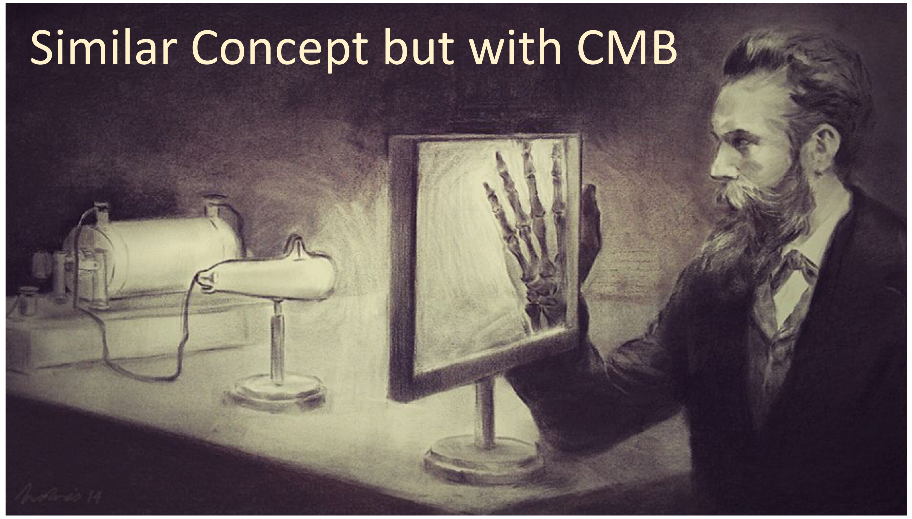

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- Atoms with Rayleigh and resonant scattering

- **Map entire cosmic web**

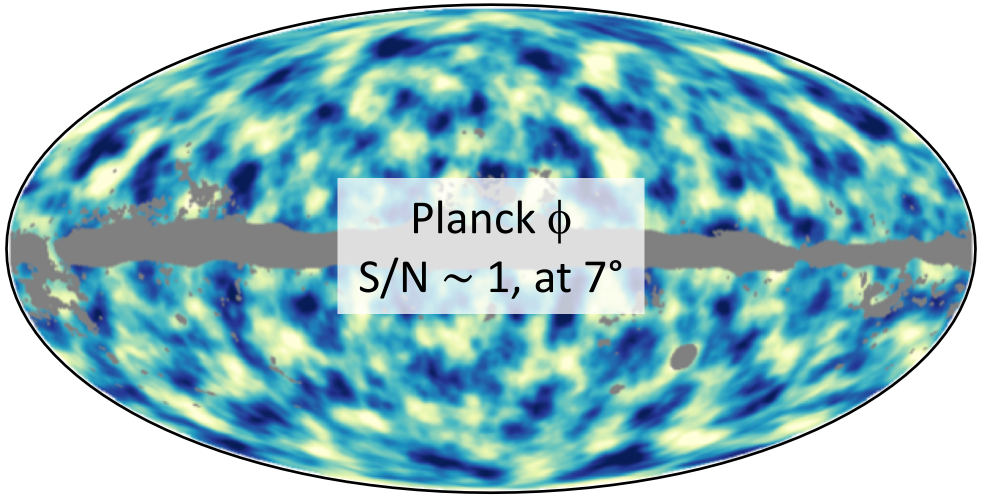
  ⇓

- **Dark Energy**
- **Modified gravity**
- **Distribution of early atoms**
- **Neutrino masses...**

Full sky Dark Matter maps

Transformative progress for DM mapping

Dark Matter distribution, z= a few



From Planck to Voyage 2050

Individual clusters +

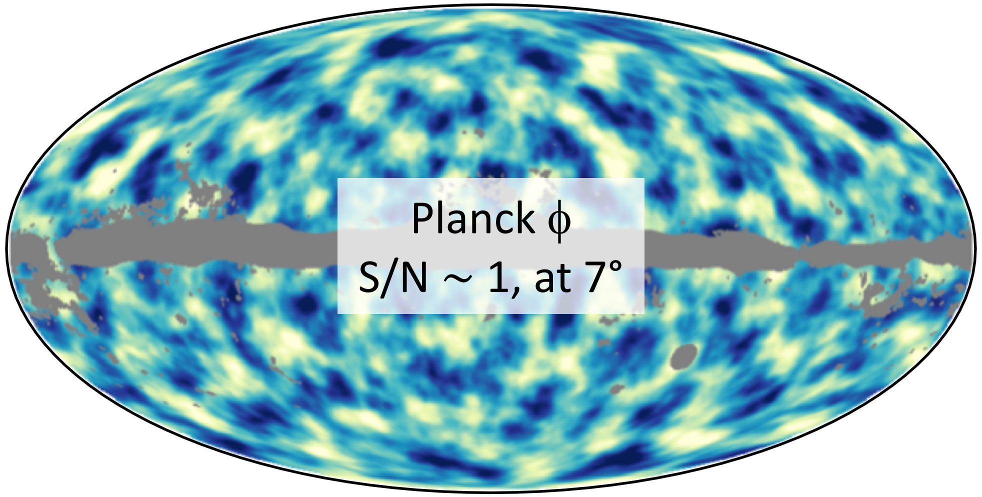
Future ϕ
S/N ≫ 1, at ~10'

High redshift weighted (z = 1-3)

Full sky Dark Matter maps

Transformative progress for DM mapping

Dark Matter distribution, z= a few



From Planck to Voyage 2050

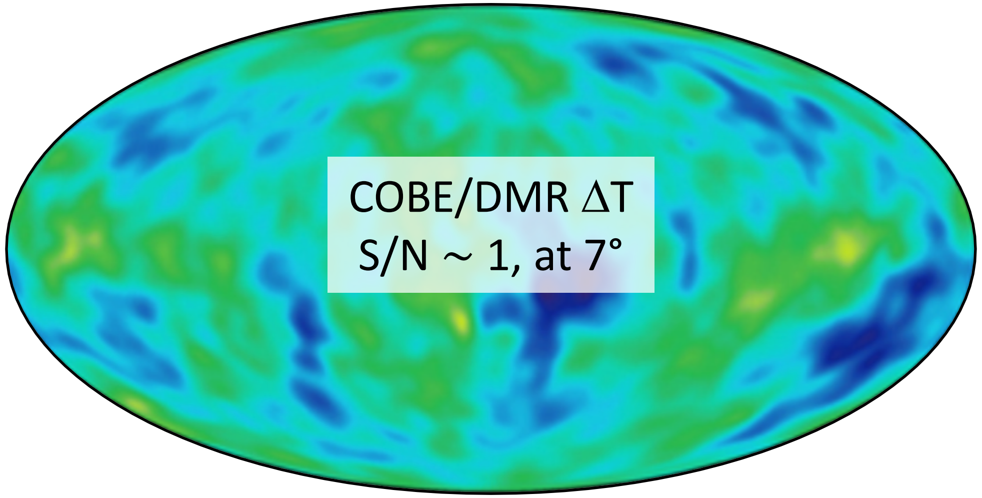
Individual clusters +

Future ϕ
S/N ≫ 1, at ~10'

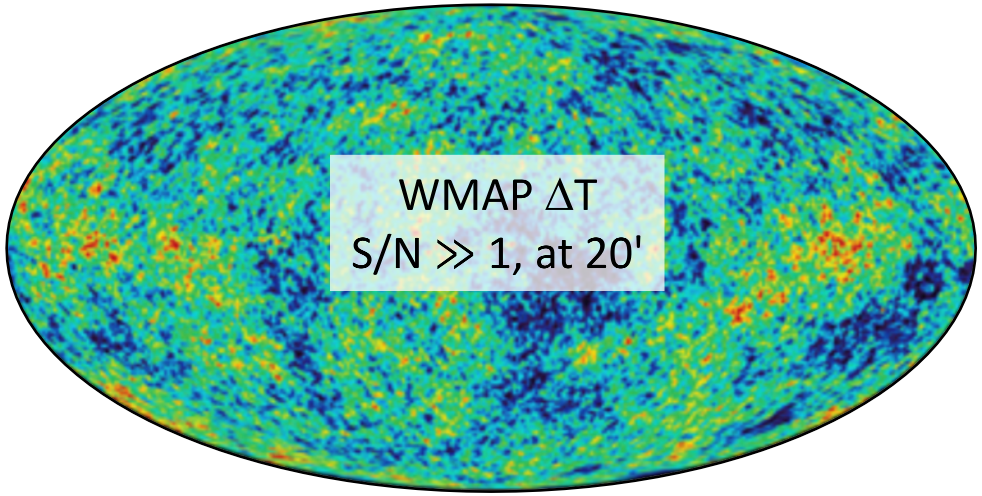
High redshift weighted
(z = 1-3)

Analogy

Temperature fluctuations, z=1000



From COBE/DMR to WMAP

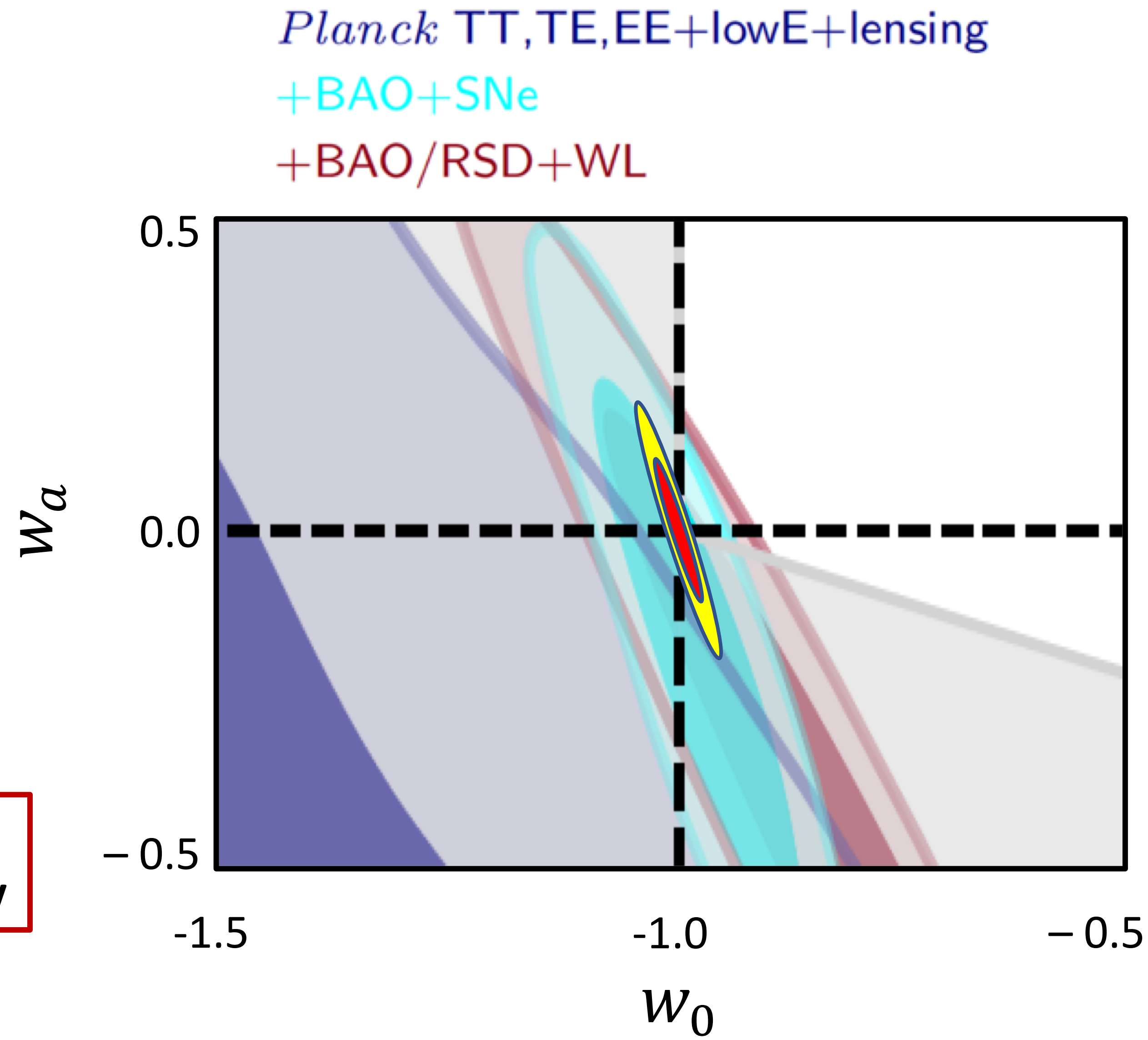


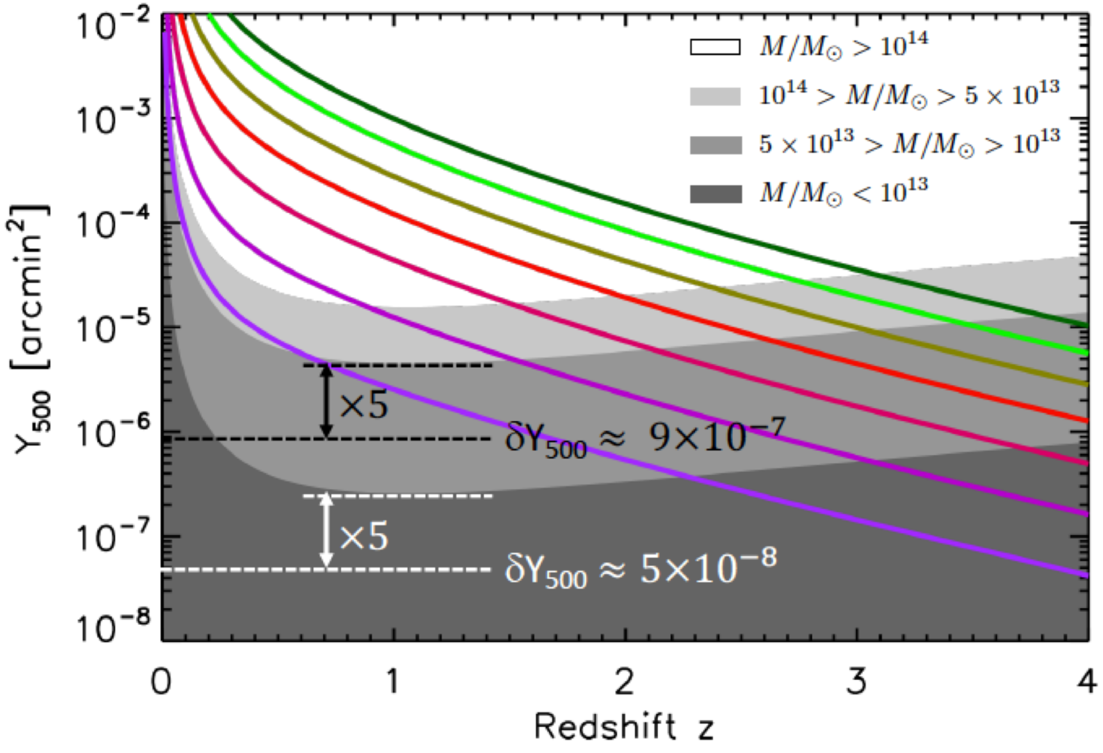
Dark Energy

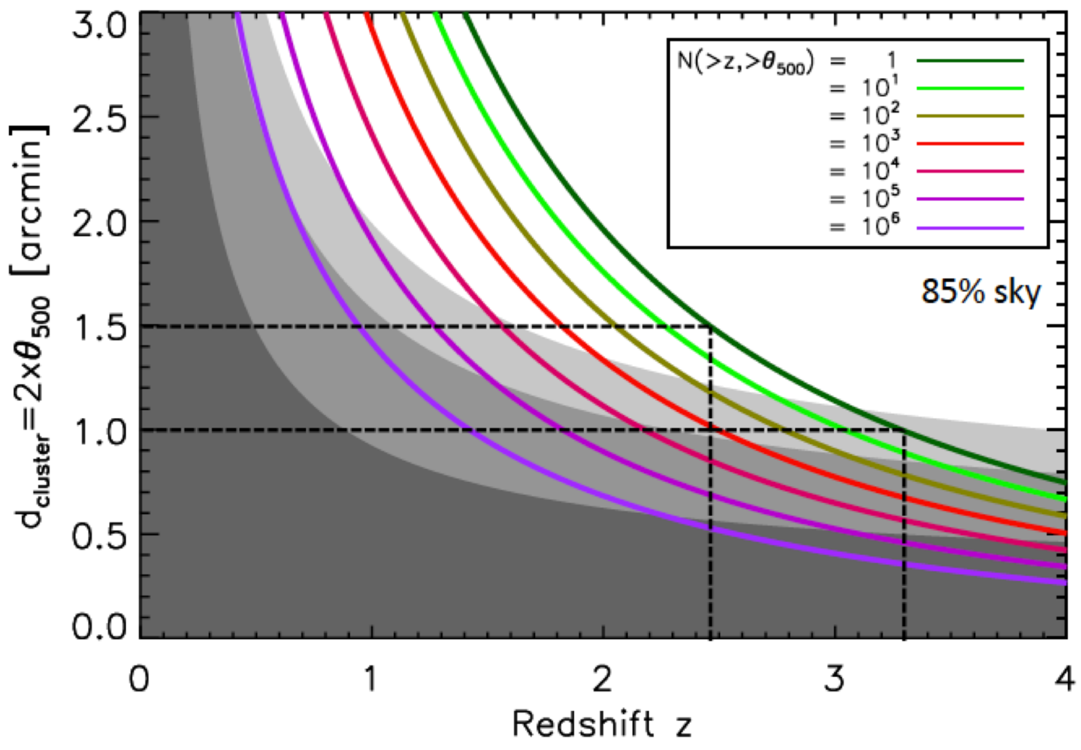
Cosmological exploitation of
10^6 galaxy clusters

Dark Energy Equation of state:
$w = w_0 + (1 - a)w_a$

Dark Energy parameters
Dark Energy homogeneity





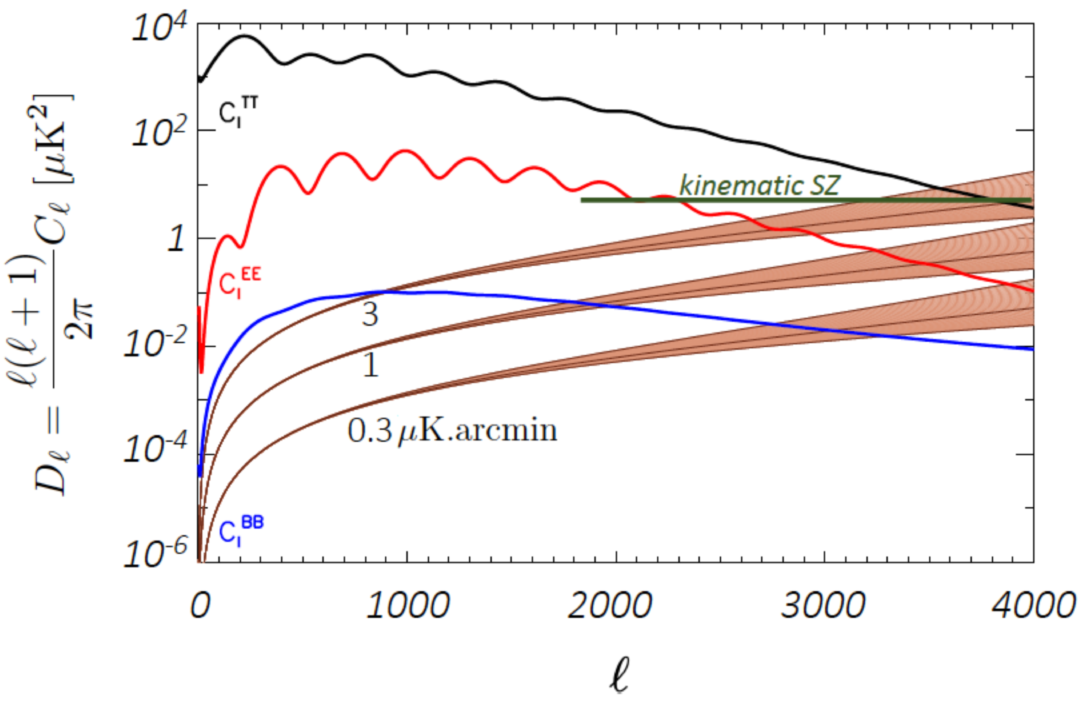


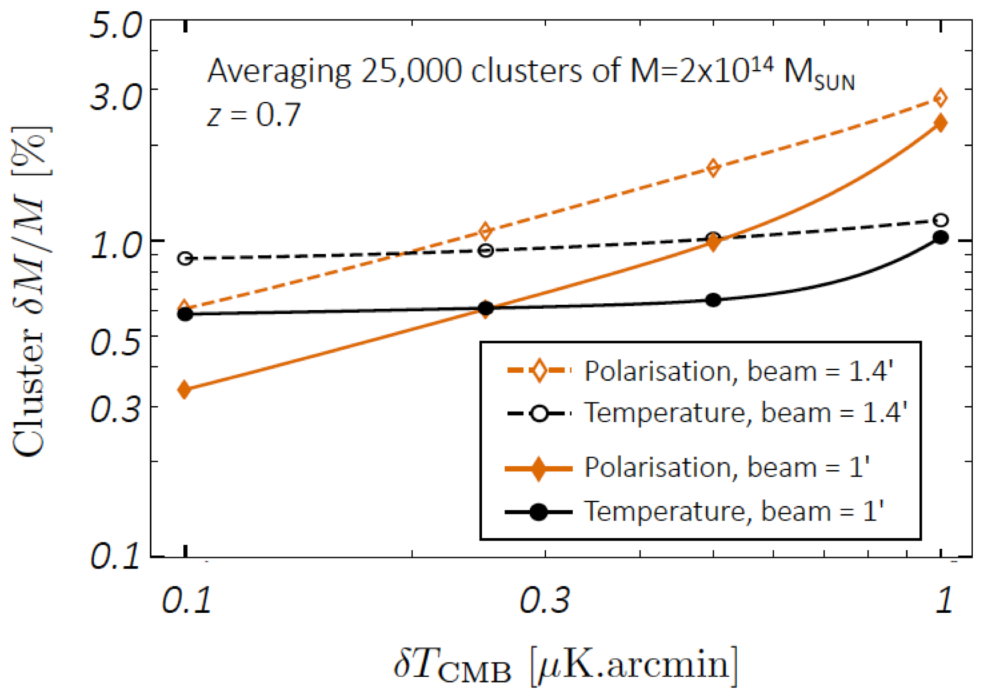
	SZ sensitivity (*y*.arcmin)
full-sky 2 years	1.7×10^{-7}
5% sky 6 months	7.7×10^{-8}

	Angular resolution
320 GHz	1 arcmin
220 GHz	1.4 arcmin

Ground complementarity for angular resolution <220 GHz

Measuring cluster velocities and masses



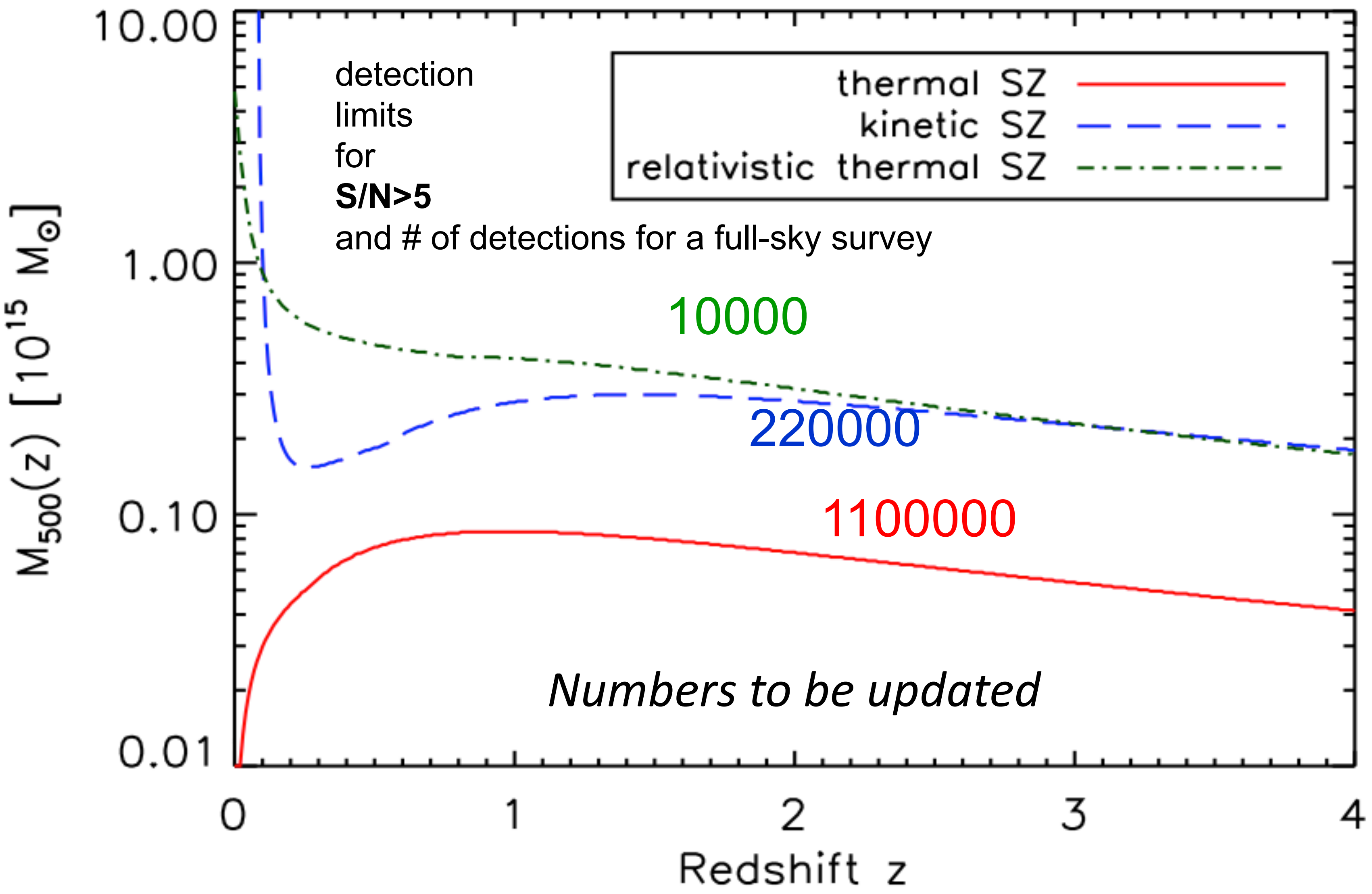


	CMB sensitivity (μK.arcmin)
full-sky 2 years	0.66
5% sky 6 months	0.29

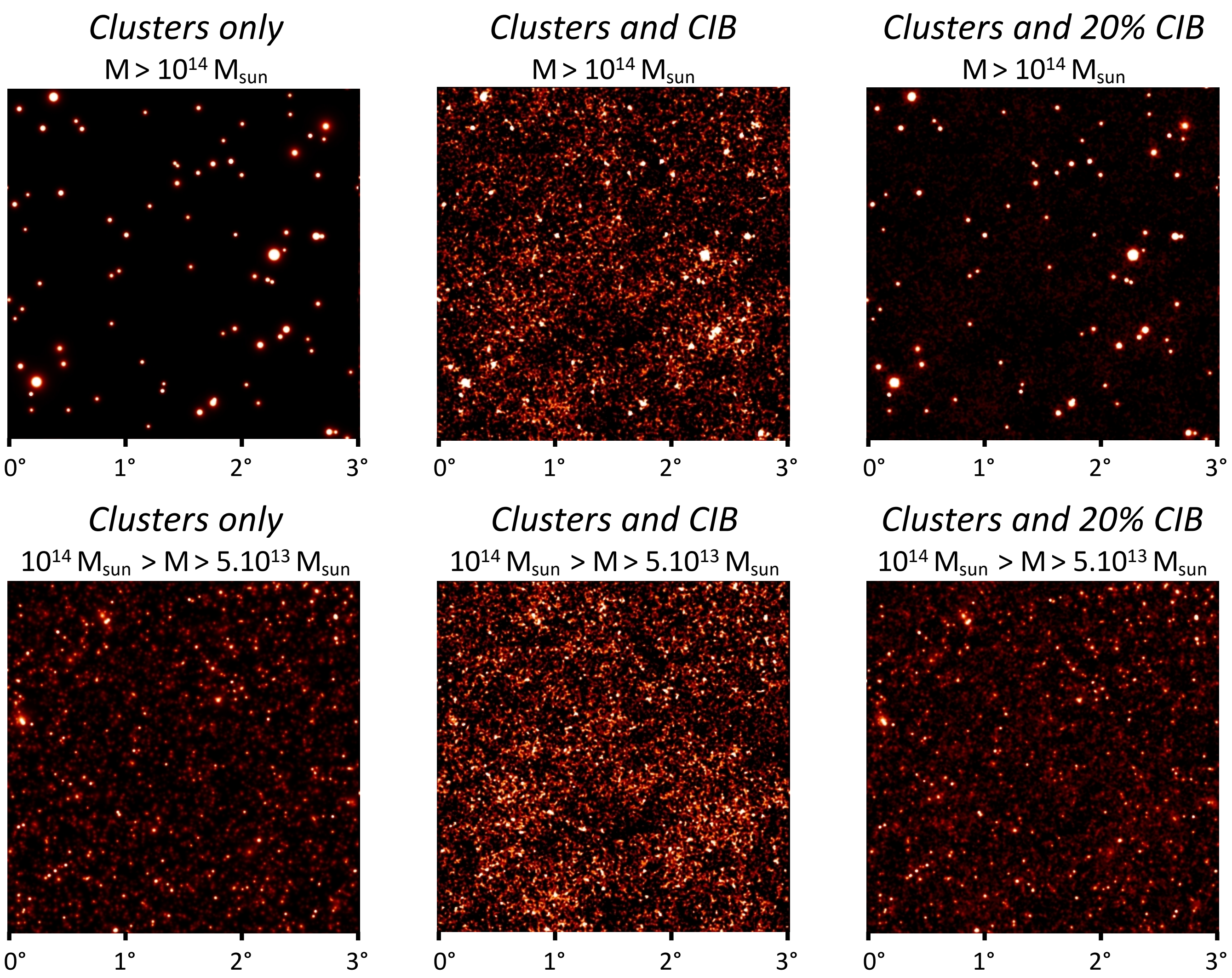
	Angular resolution
320 GHz	1 arcmin
220 GHz	1.4 arcmin

Ground complementarity for angular resolution <220 GHz

Numbers… (from PRISM 2013 – to be updated)

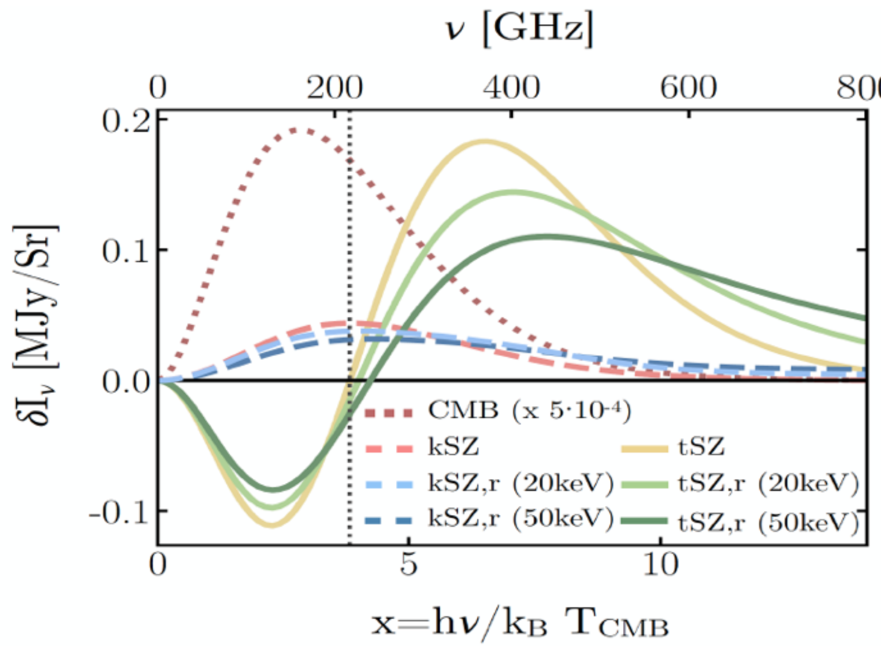


Confusion with CIB at 150 GHz…



Need to reduce the level of CIB contamination by a factor of 5 at least (better for kSZ and for rSZ)…

+ Multifrequency signals of interest



Mroczkowski et al. 2019

Basu et al., Astro2020 White Paper

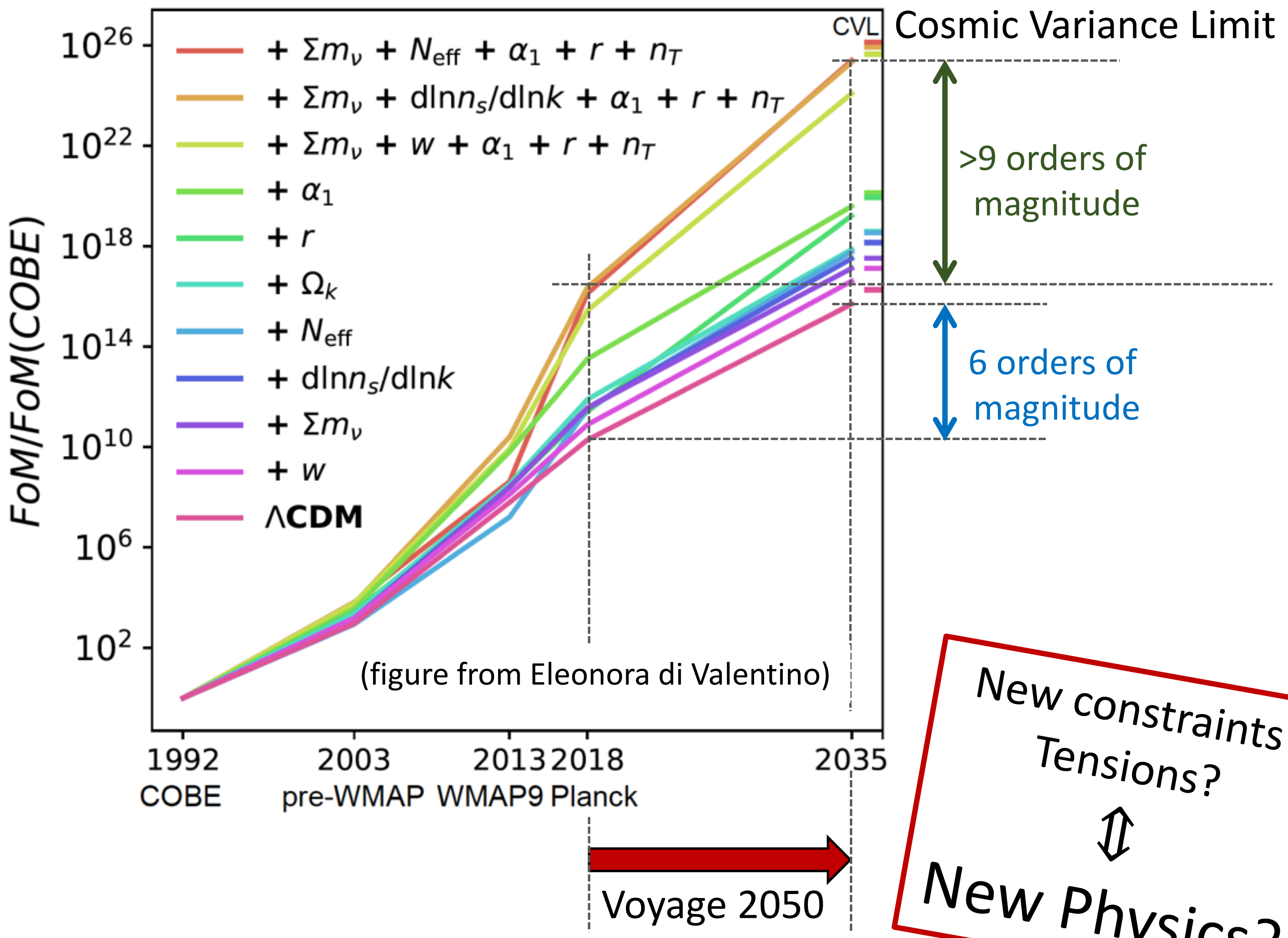
Science highlight 2: ΛCDM under scrutiny

- ΔT & ΔP CMB sensitivity
  ≈ 5000 × Planck
  ≈ 10 × CMB-S4 (polar.)

- Impressive constraints (with CMB alone!)

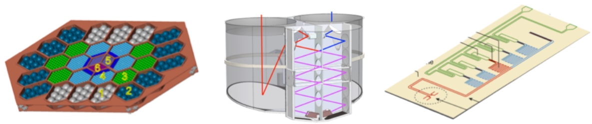
$\sigma(\Sigma m_\nu) \sim 10^{-2}$
$\sigma(N_{\rm eff}) \sim 0.016$ } Neutrinos

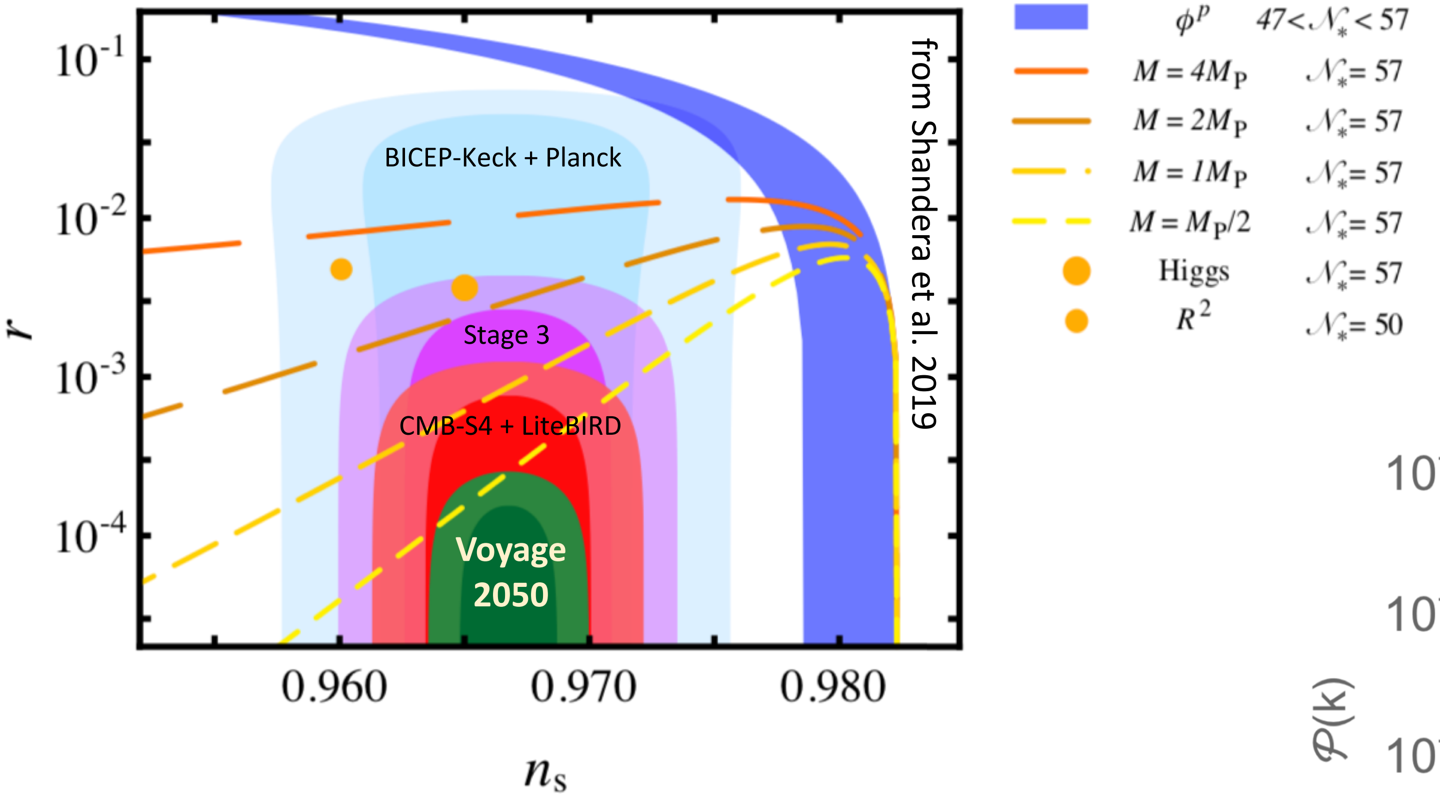
$\sigma(r) \sim 10^{-4}$
$\sigma(n_s) \sim 0.0015$ } Inflation



New constraints!
Tensions?
⇕
New Physics?

Science highlight 3 : Inflation

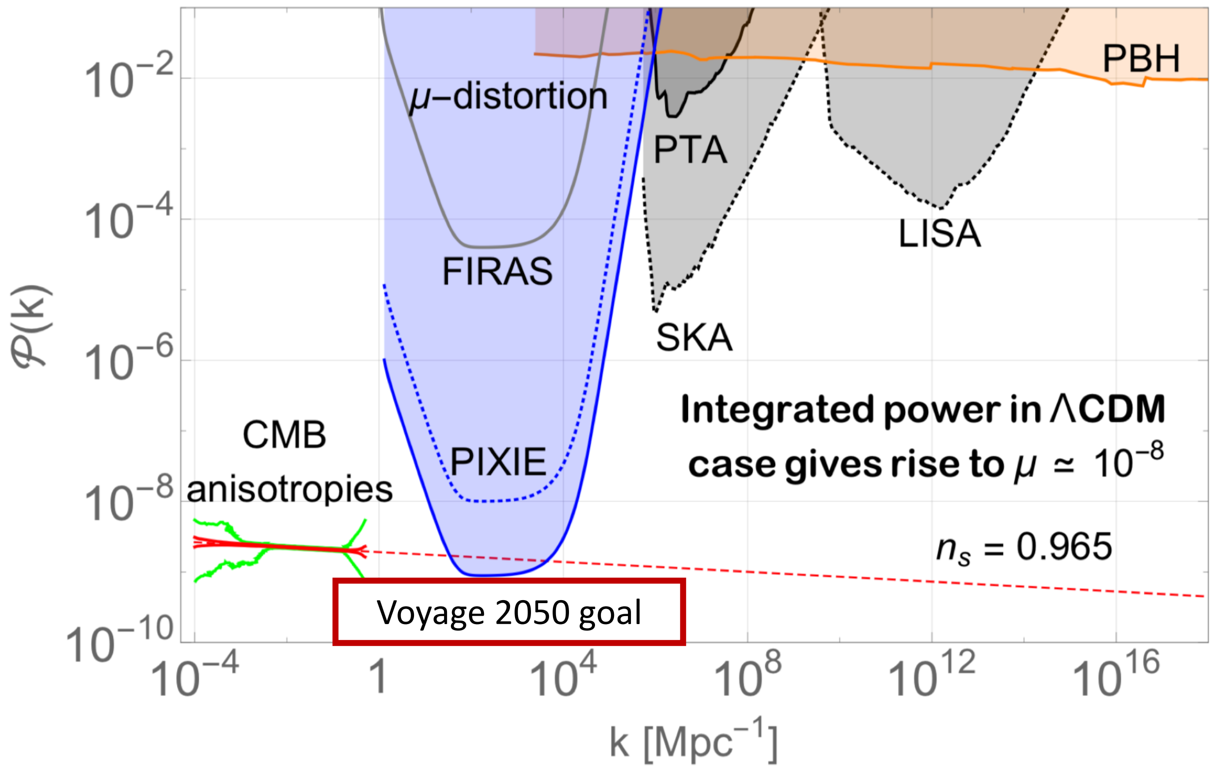




CMB Polarization

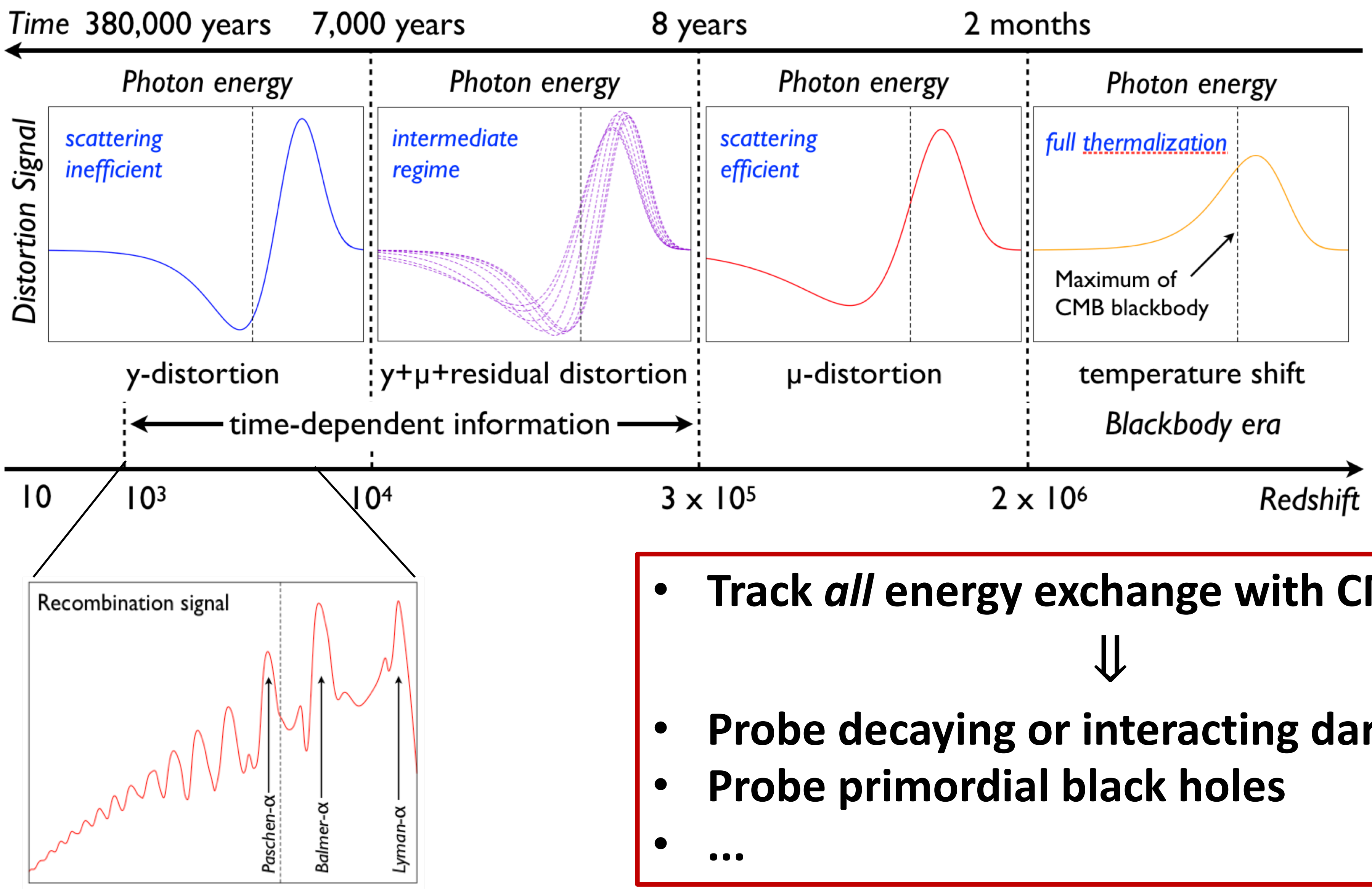
NG: f_{NL} local from CIB or correlations

CMB spectral distortions



- **Energy scale; Stationarity;**
- **Primordial spectra**
- **Non gaussianity ⟺ Multi field ?**

Science highlight 4: Cosmic thermal history

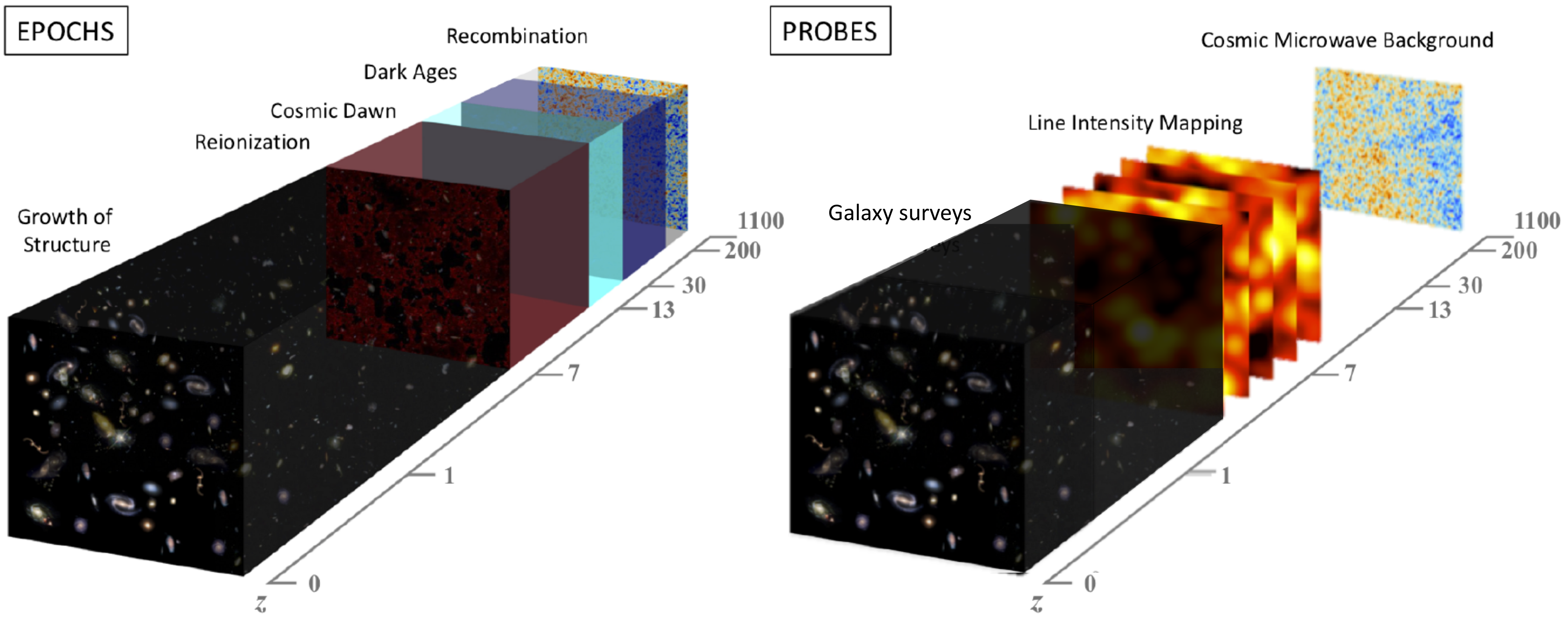


- **Track *all* energy exchange with CMB at z<2,000,000**

  ⇓

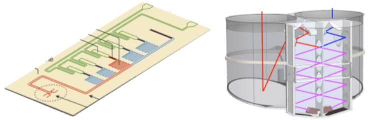
- **Probe decaying or interacting dark matter**
- **Probe primordial black holes**
- **...**

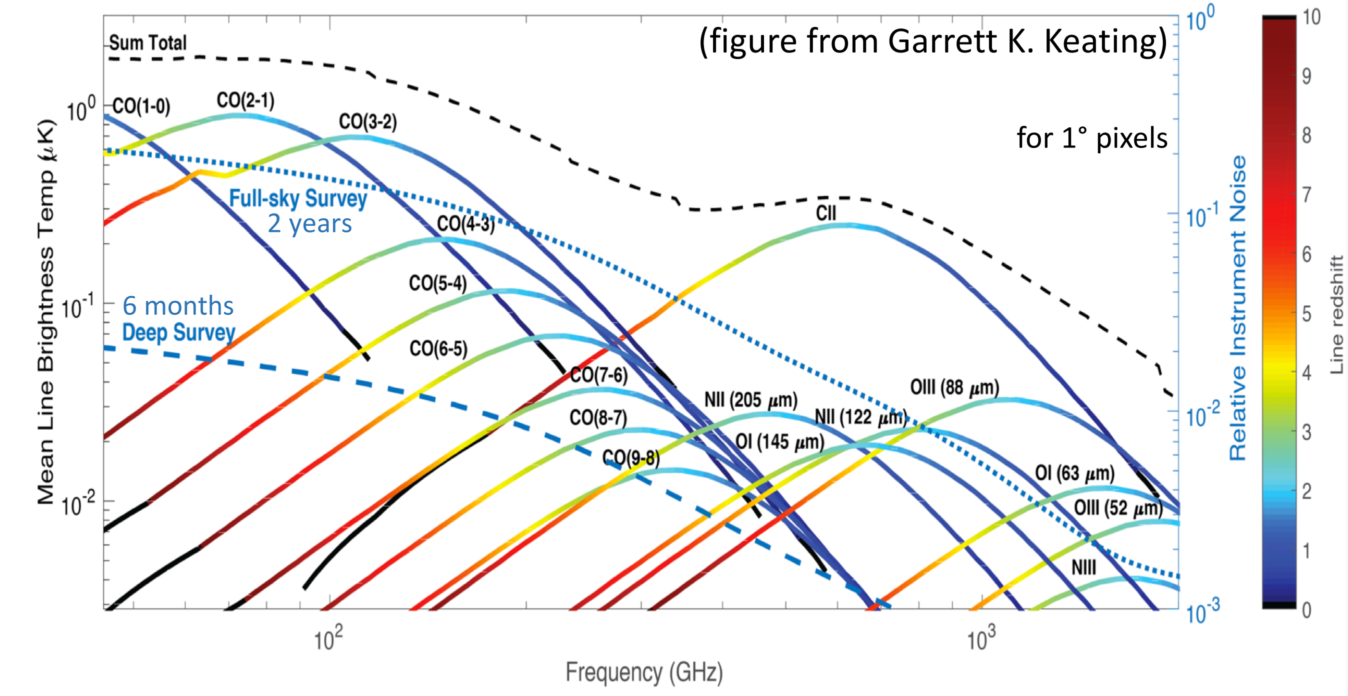
Science highlight 5: Structure tomography

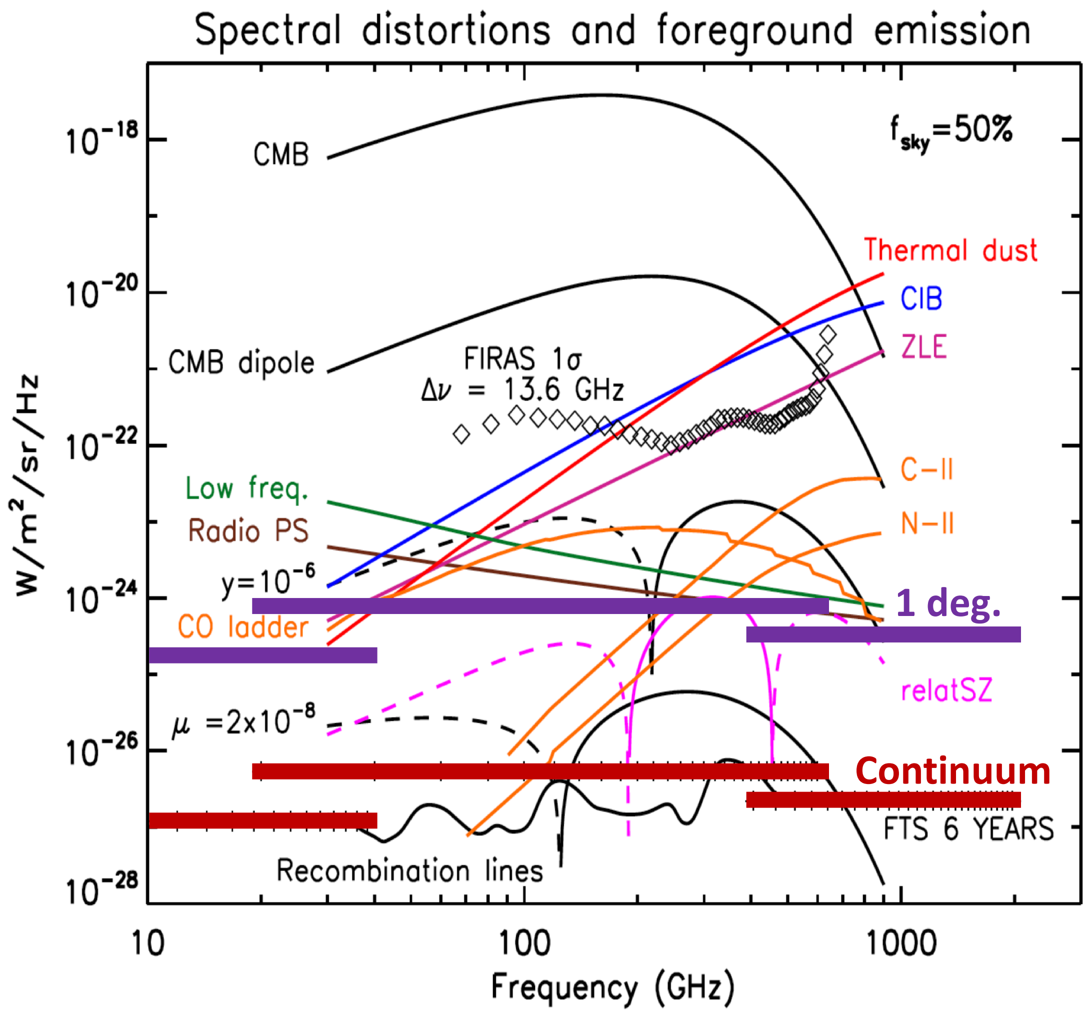


- **Matter power spectra;**
- **Knots in the cosmic web, from protoclusters to clusters;**
- **Different gas phases in structures;**
- **History of star formation, molecular gas, dust in structures**

Science highlight 5: Structure tomography



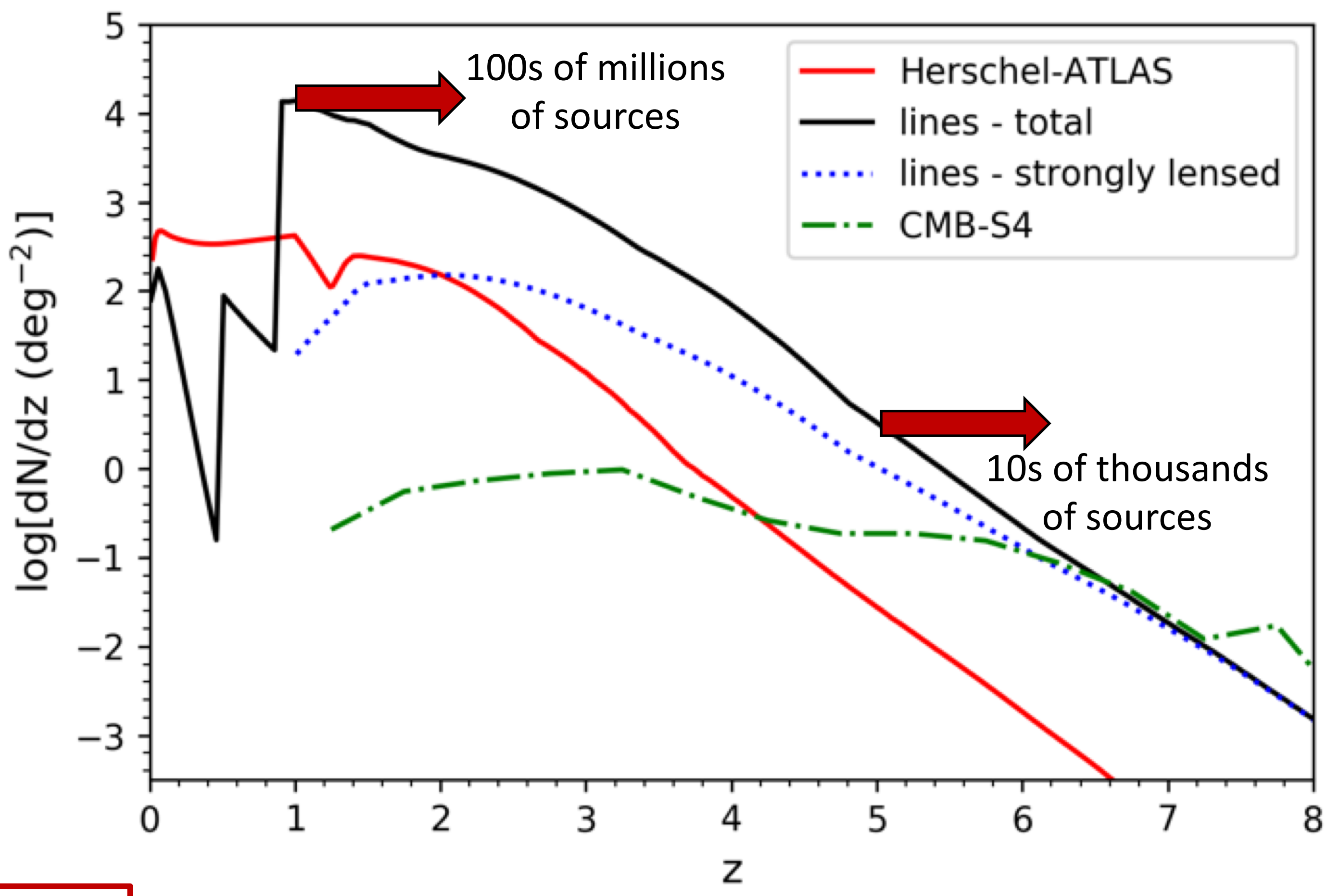




- **Integrated emission fluctuations**
- **Unimpeded frequency coverage**

Unique in this frequency range!

Science highlight 6 : High-z sources



(figure from Matteo Bonato)

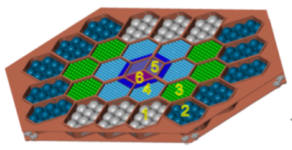
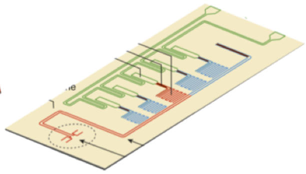
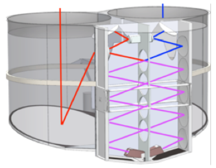
Mostly un-blended !!

Individual sources / halos
+ redshift information

Implementation?

- 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)

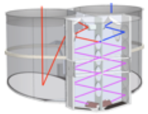
  + 

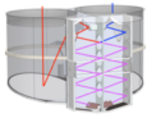
- Three modes of observation for a ~6-year mission
  - Survey 1 – full sky, ~2 years — **Go Broad !**
  - Survey 2 – deep patches, ~2 years — **Go Deep !**
  - Observatory – open time, ~2 years — **Be Flexible !**

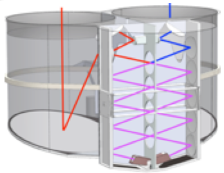
- Builds on previous proposals (with international collaborators)
  - PRISM White Paper for L2-L3
  - CORE proposal, PICO study (NASA)
  - PIXIE (NASA), PRISTINE
  - ECHO / CMB-Bharat (ISRO)

} **PIs are co-authors of the Voyage 2050 microwave spectro-polarimetry white paper**

Absolute spectrometry : instrument







One or more small Fourier Transform Spectrometers modules

- For zero-level of intensity maps and CMB spectral distortions
- Can be on a separate platform

- Can be an independent M-class mission, e.g. a revision of PIXIE / PRISTINE

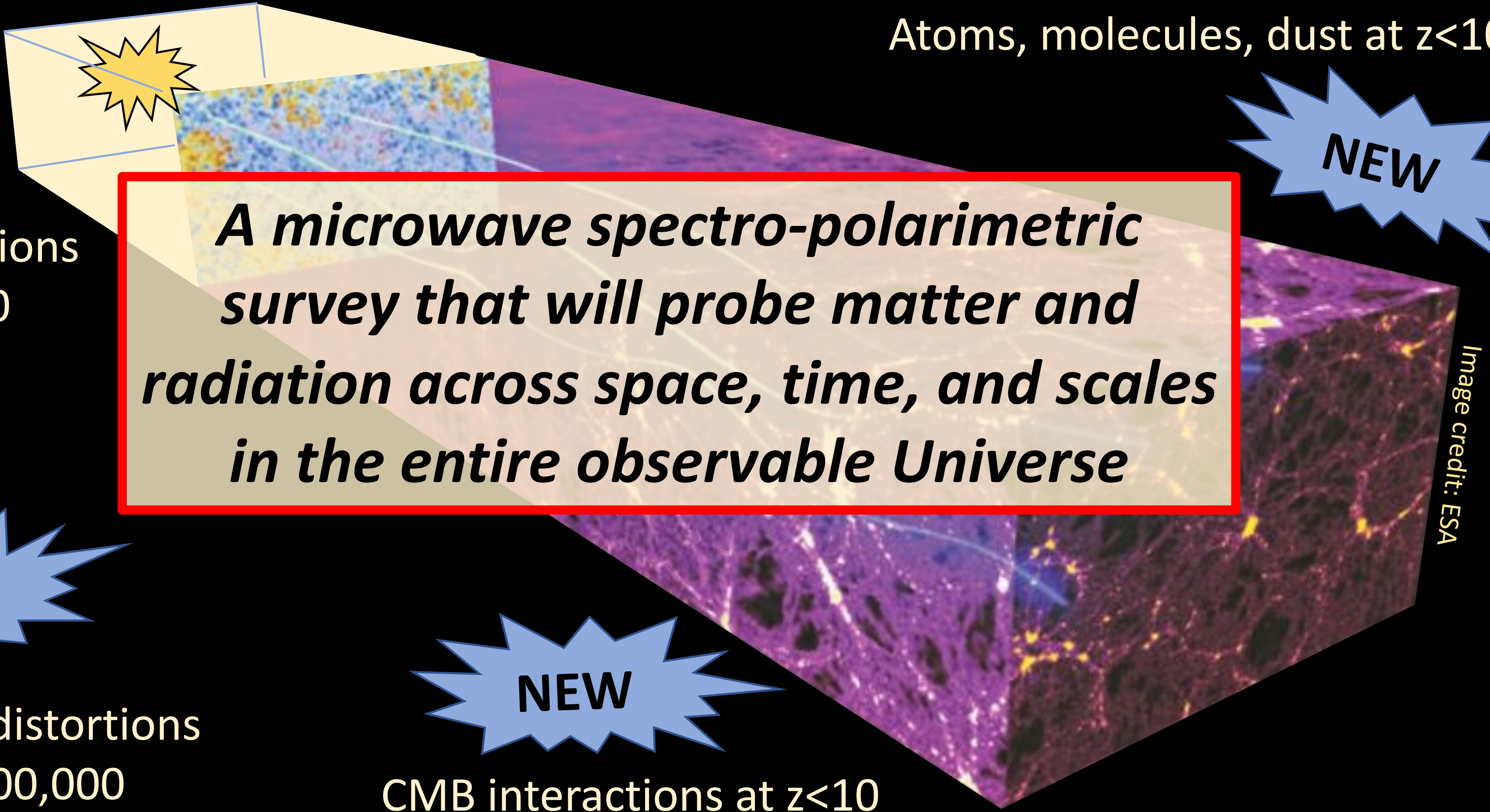
Table II: Multi-module absolute spectrometer; The mission sensitivity in the last column assumes 70% useful data and a 6-year mission.

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

Summary

- **Fundamental questions in Cosmology remain unanswered**
  - Tiny signatures in the microwave sky emission encode the answers
  - Their measurement requires an L-class space mission
- **Enormous science impact!**
  - Revolutionary for Cosmology
  - Huge discovery potential
  - High legacy value for many branches of astrophysics
- **A unique window on our Universe, available only from space**
  - All scales from Hubble-volume sizes to individual objects, all times
  - Spectroscopy with unimpeded frequency coverage from 10 to 2000 GHz
  - Comprehensive exploitation of the CMB: anisotropies, polarisation, spectrum, interactions

Map the entire Universe in the Microwave !!



Atoms, molecules, dust at z<10

NEW

CMB fluctuations at z≈1000

A microwave spectro-polarimetric survey that will probe matter and radiation across space, time, and scales in the entire observable Universe

NEW

CMB spectral distortions
0 < z < 2,000,000

NEW

CMB interactions at z<10