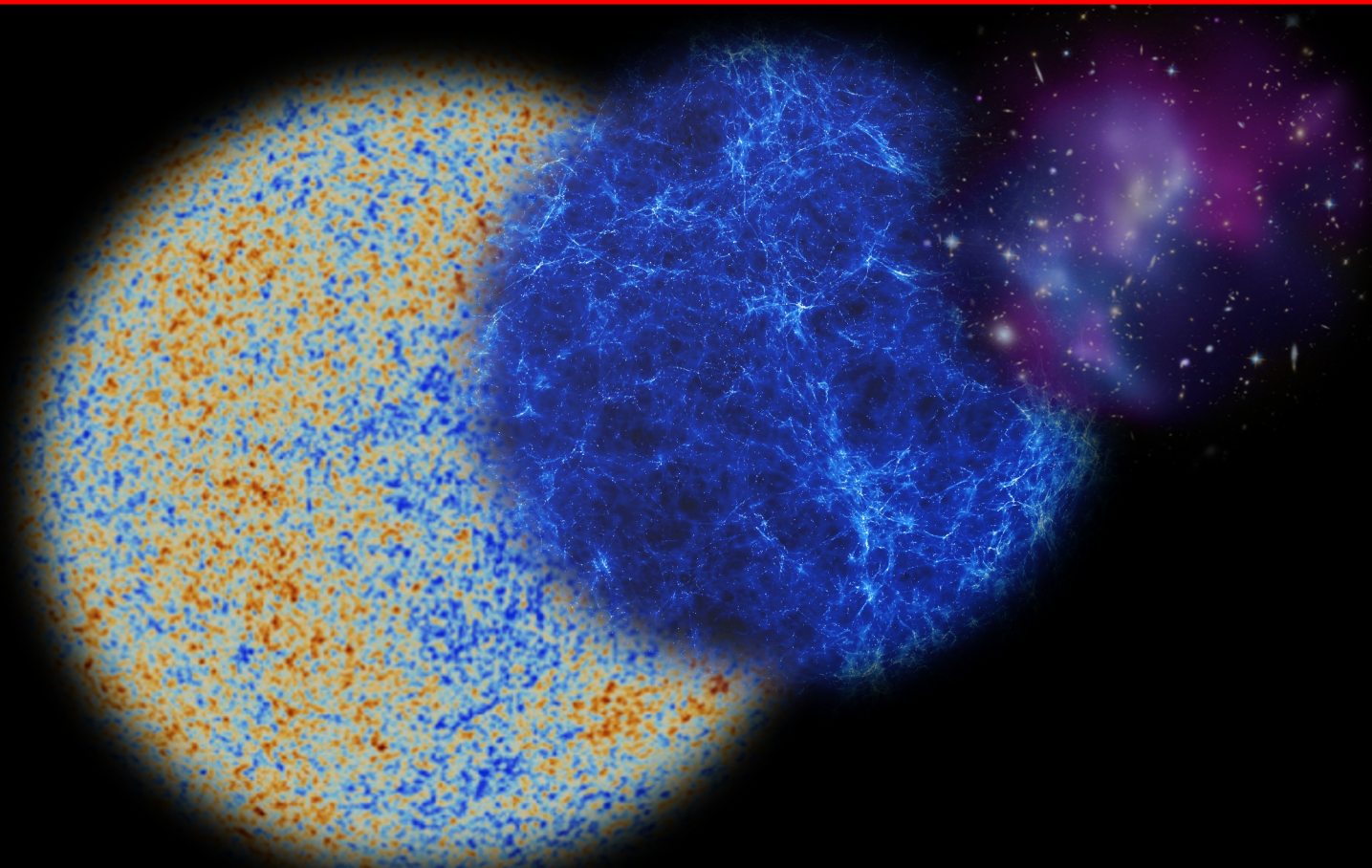


Future CMB observations from space

CORE, PRISM and "Voyage 2050"



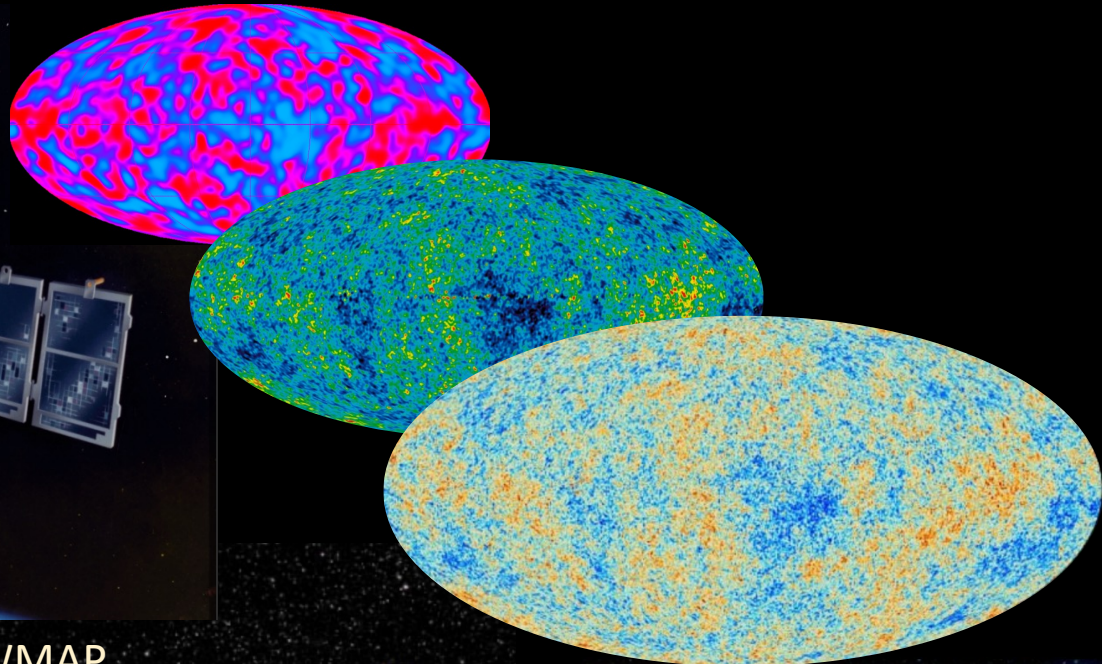
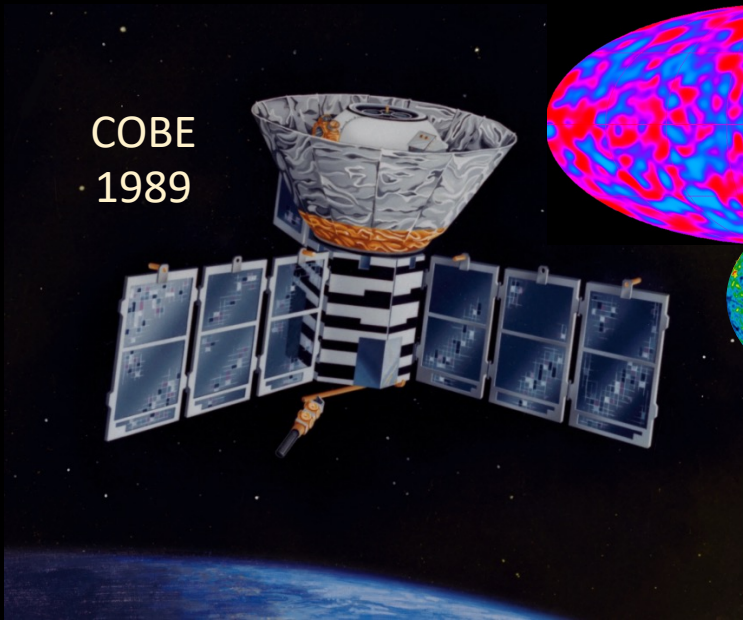
Jacques Delabrouille

Centre Pierre Binétruy CNRS-Berkeley

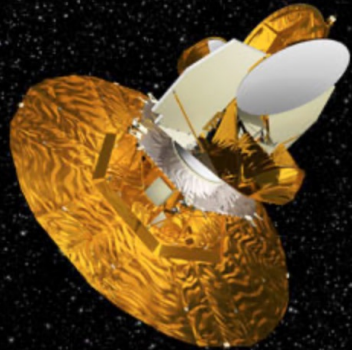
and LBNL, Berkeley

(Glorious) Past of microwave observations from space

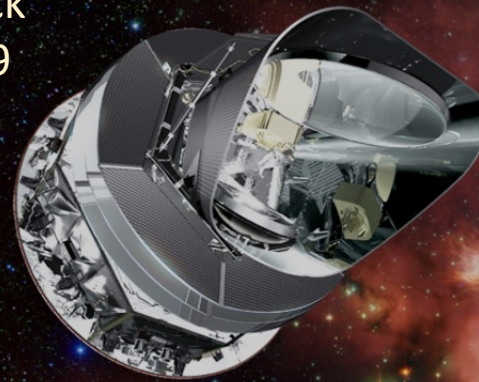
COBE
1989



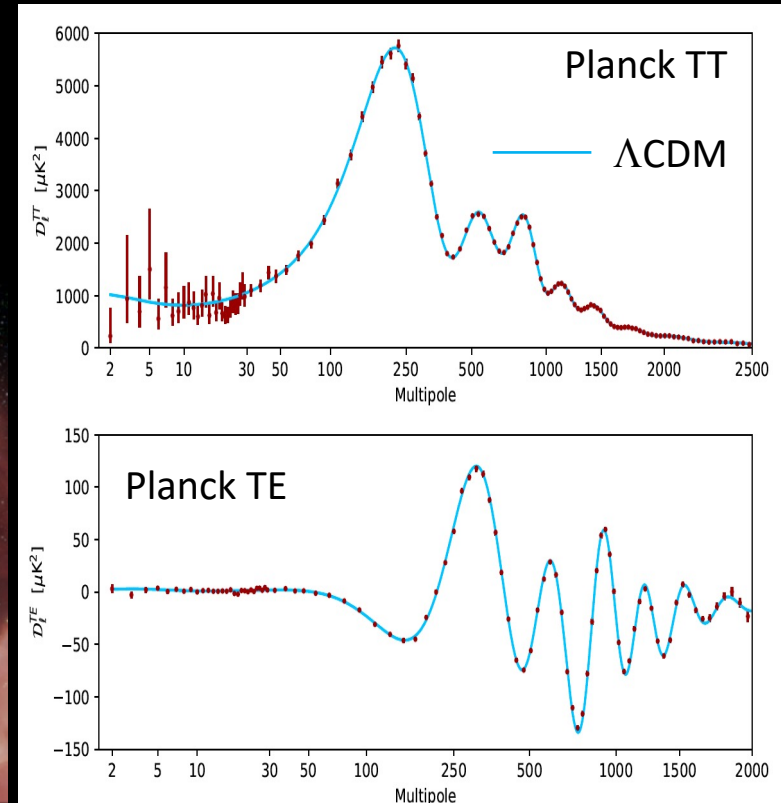
WMAP
2001



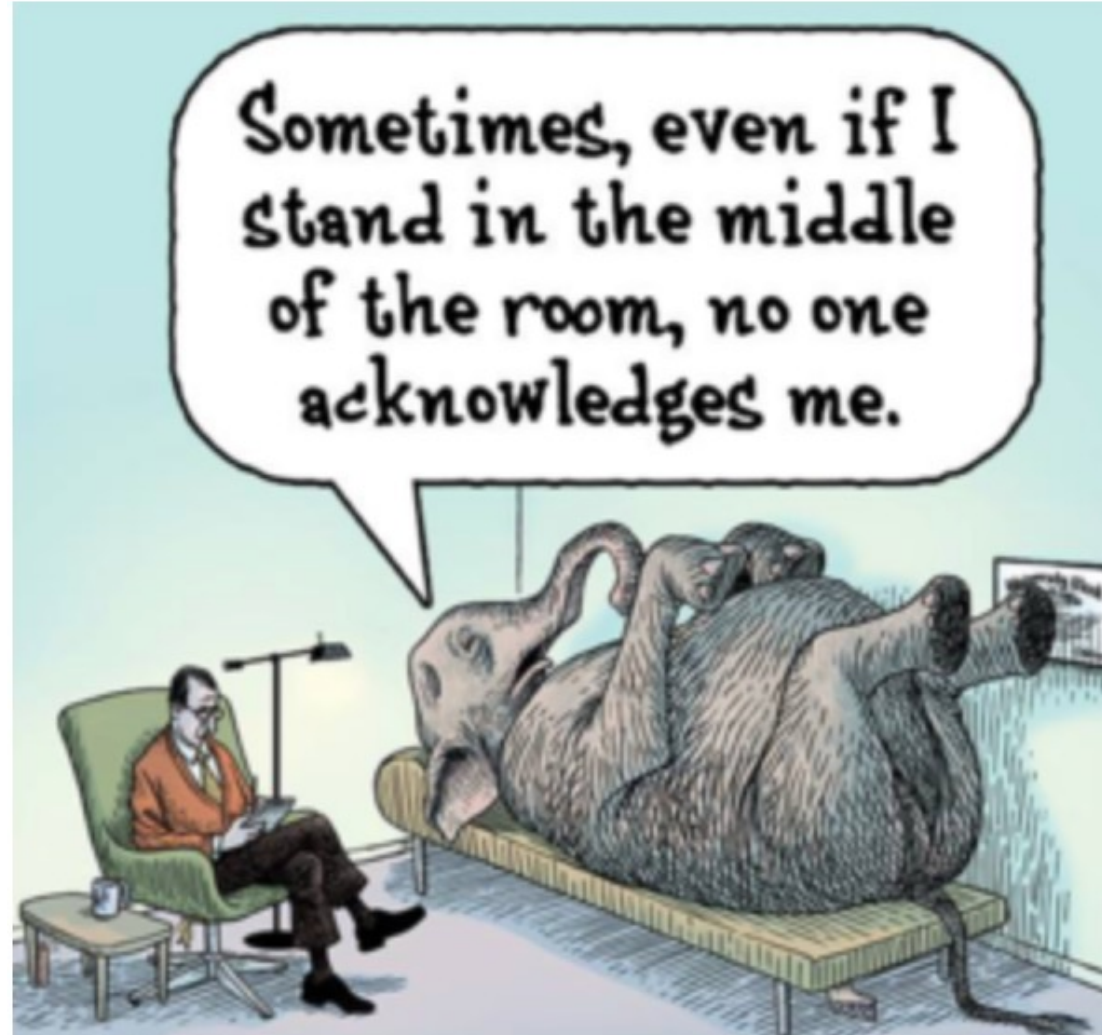
Planck
2009



Planck 2018 results



Are we done?



Are we done?

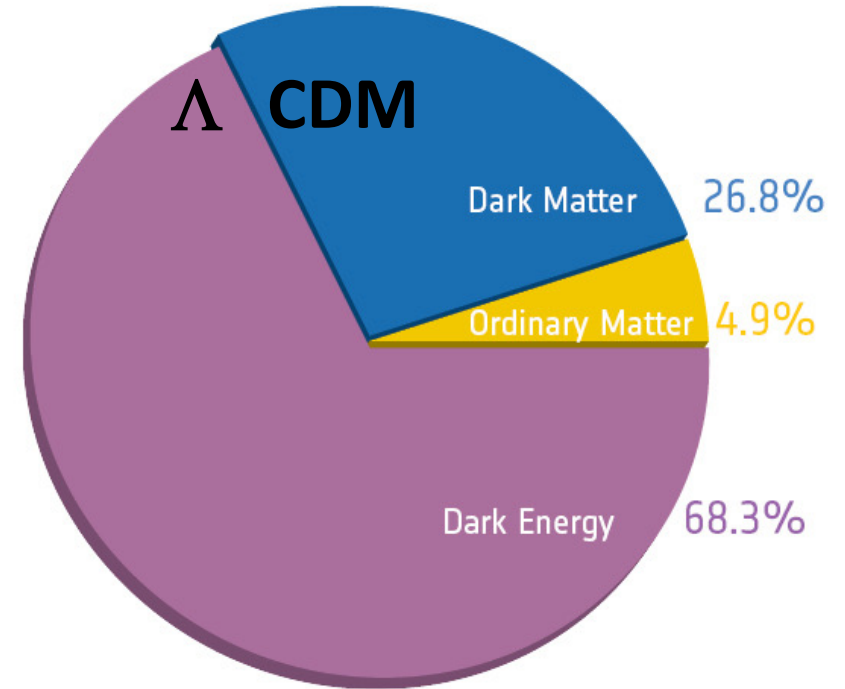
- Inflationary Λ CDM

- *impressively successful*

But

- **incomplete** theoretical foundation
- **anomalies and tensions** \Rightarrow cracks in the model?
- **fundamental questions** remain unanswered

1. *Dark sector?*
2. *Inflation?*
3. *Gravitation?*



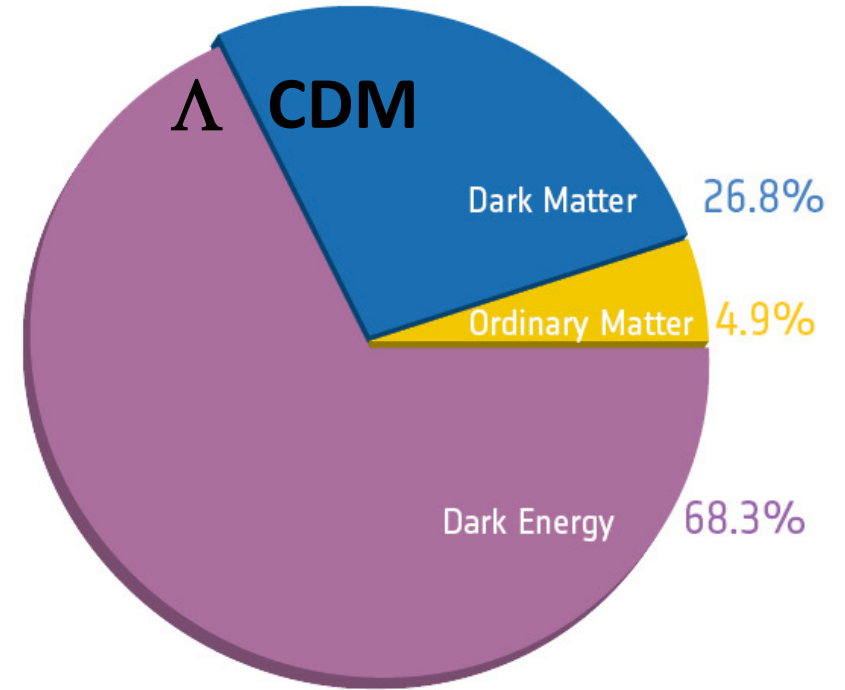
Are we done?

- Inflationary Λ CDM

- *impressively successful*

But

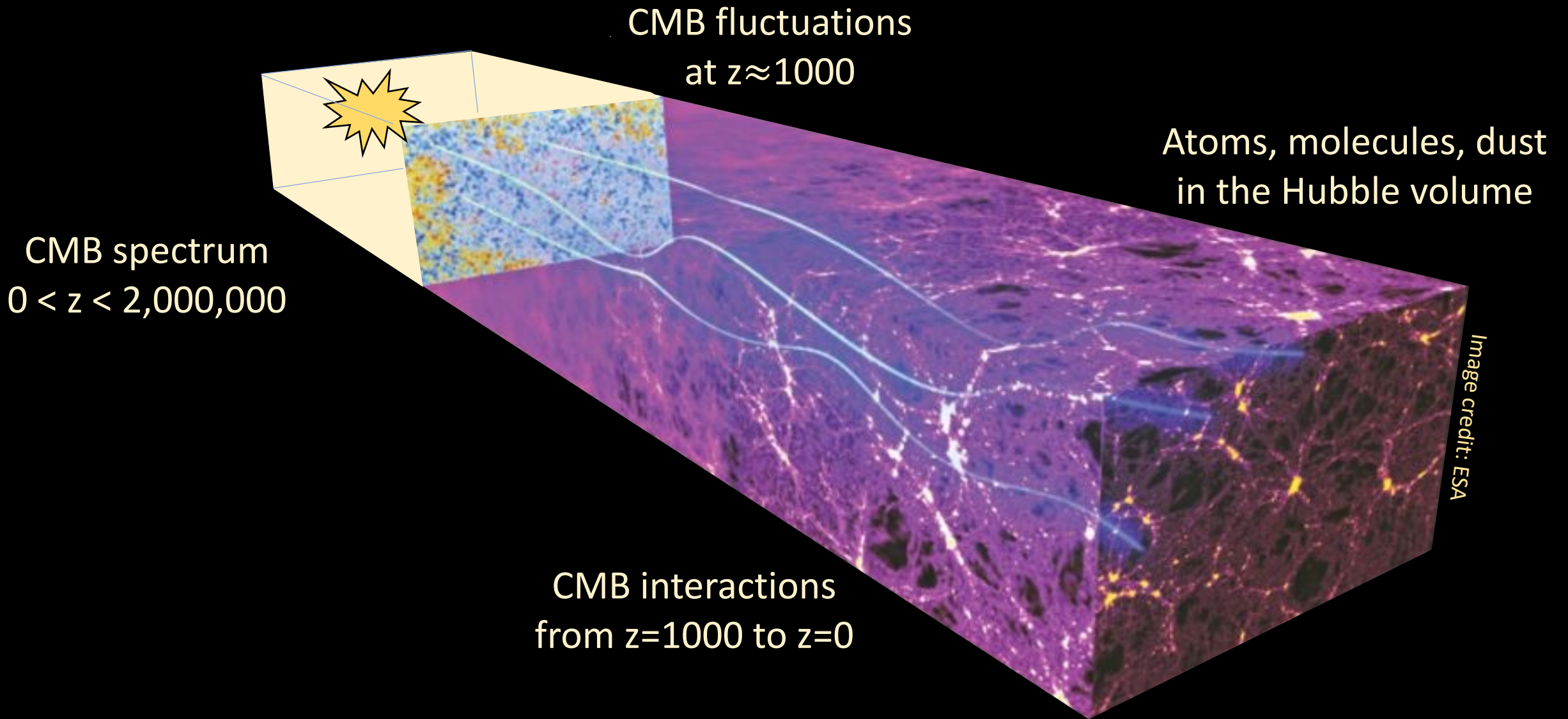
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1. *Dark sector?*
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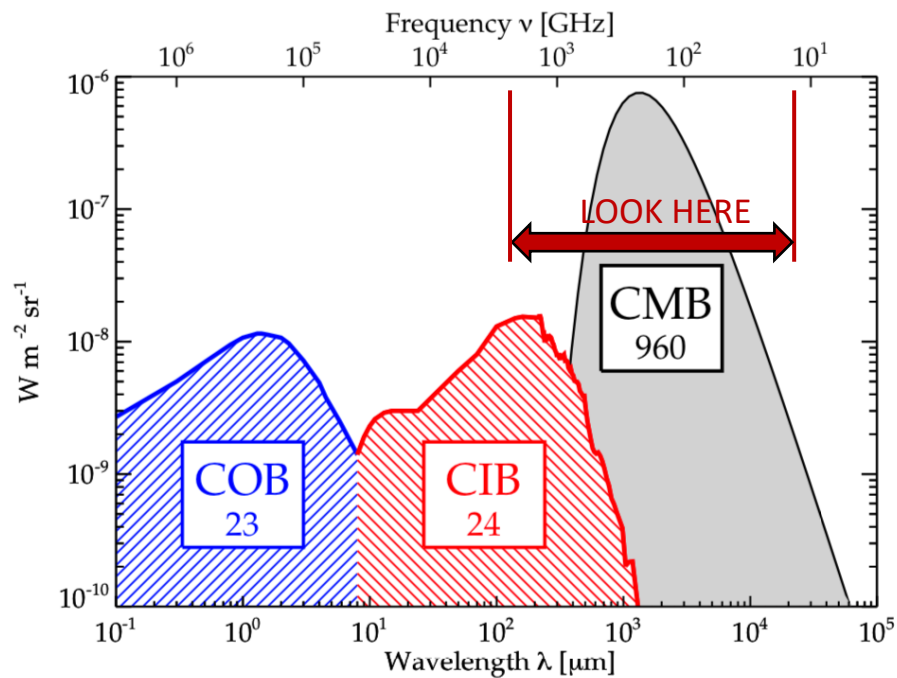
The distribution of matter and energy across space, time and scales encodes answers to these questions

Map the entire observable Universe in the microwave



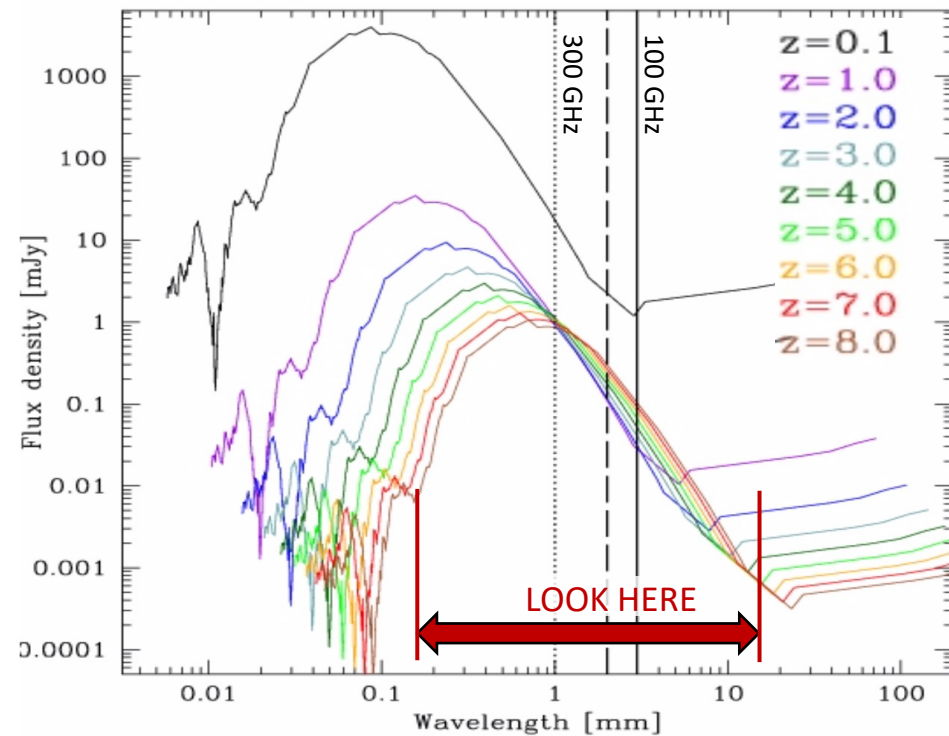
Why microwaves ?

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)

Three paths in microwave observations

- Broad-band polarized imaging
15-20 bands



*CMB anisotropies
(inflation? Λ CDM?)*

- Absolute spectroscopy
 $R \approx 20+$ (≈ 100 frequency bands)



*CMB spectrum
(energy exchange?)*

- Moderate resolution spectroscopy
 $R \approx 500-1000$



*Atoms and molecules
(3D structure tomography)*

Most useful frequency range
 $\approx 20-2000$ GHz

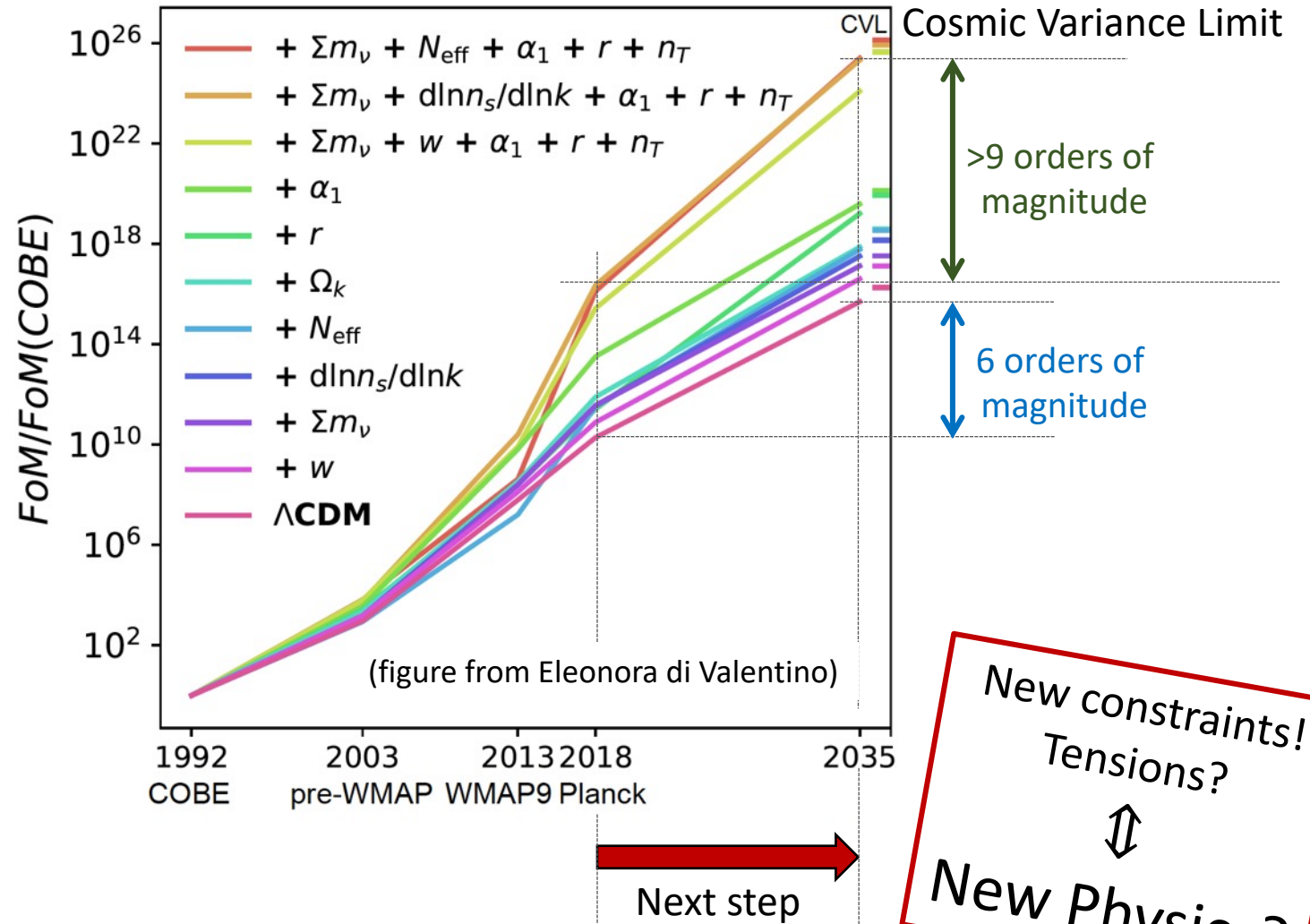
Broad-band polarized imaging: Λ CDM under scrutiny...

The ultimate CMB space mission

- ΔT & ΔP CMB sensitivity
 $\approx 10000 \times$ Planck
 $\approx 10 \times$ CMB-S4 (polarization)

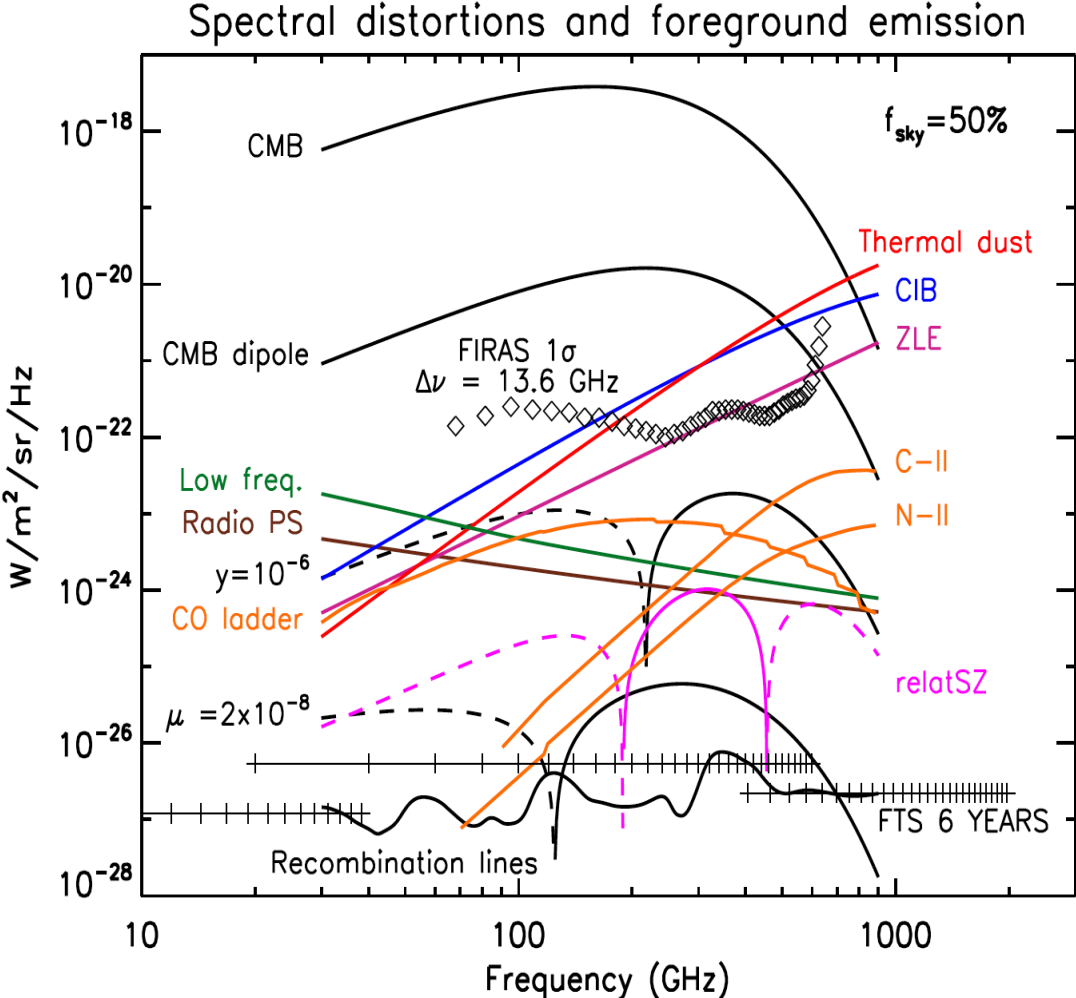
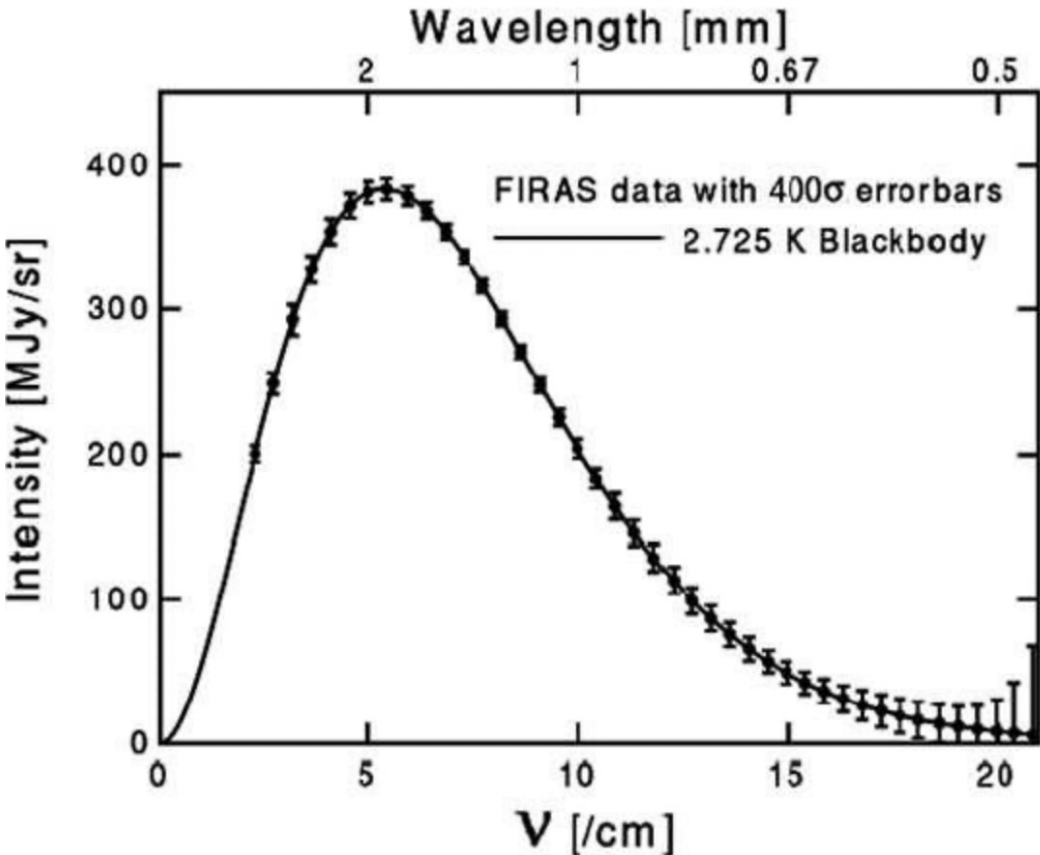
$$\left. \begin{aligned} \sigma(\Sigma m_\nu) &\sim 10^{-2} \\ \sigma(N_{\text{eff}}) &\sim 0.016 \end{aligned} \right\} \text{Neutrinos}$$

$$\left. \begin{aligned} \sigma(r) &\sim 10^{-4} \\ \sigma(n_s) &\sim 0.0015 \end{aligned} \right\} \text{Inflation}$$

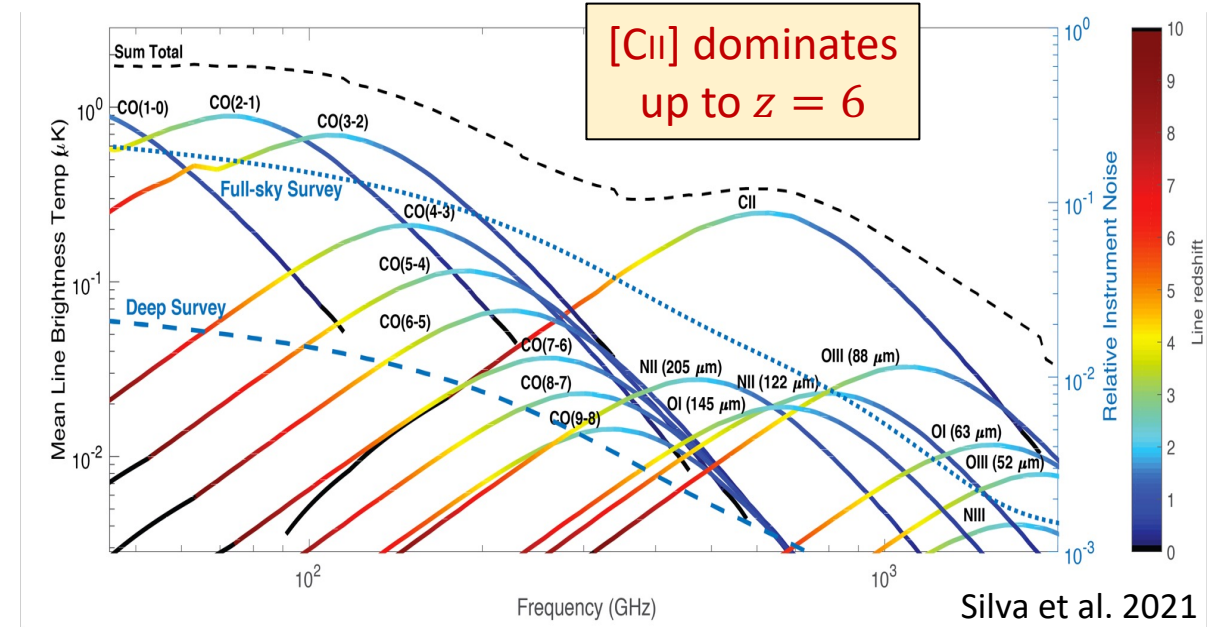
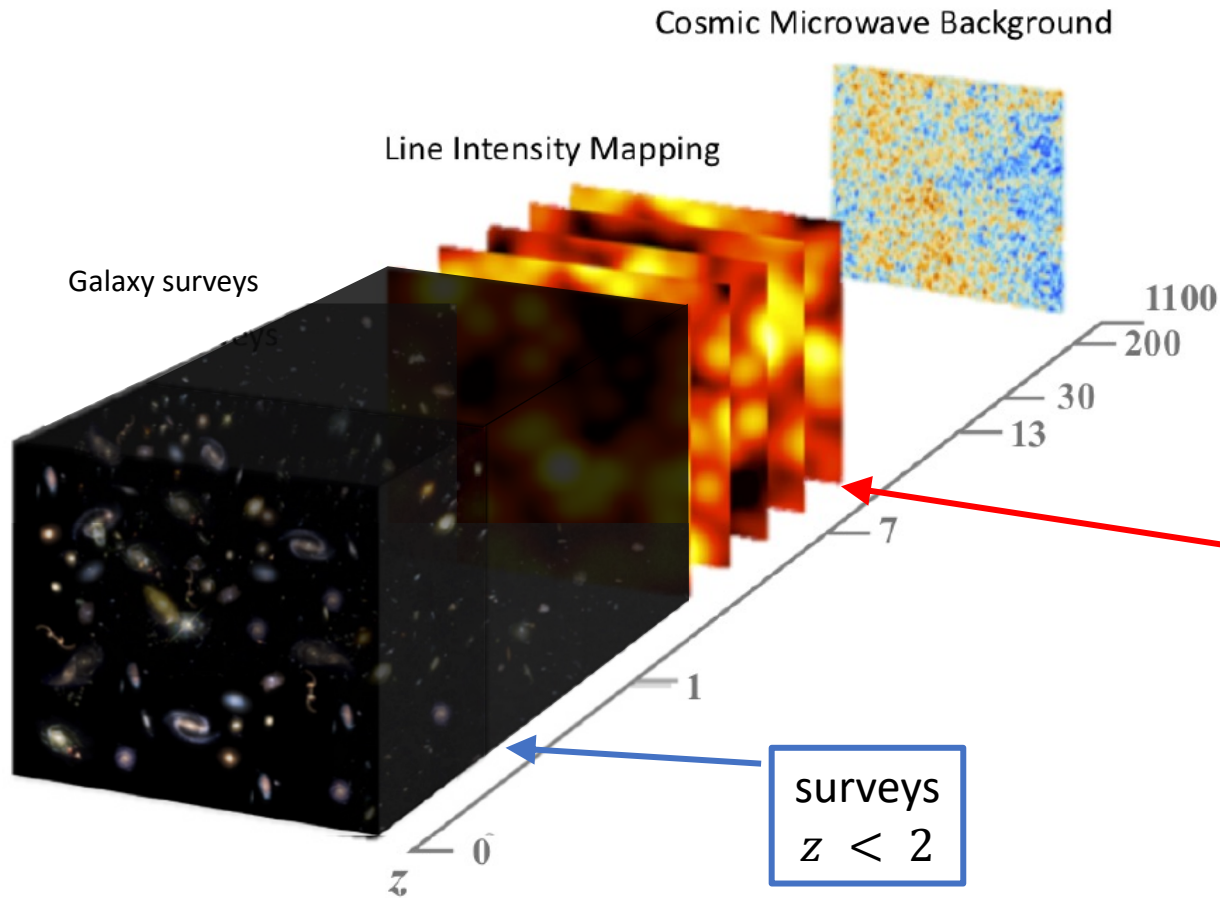


New constraints!
Tensions?
↕
New Physics?

Absolute spectroscopy: Energy exchange with the CMB



Moderate resolution spectroscopy: LIM



**Line Intensity Mapping:
the high-redshift Universe
in 3D**

- **CORE (Cosmic ORigins Experiment)**

- The "ultimate" M-class CMB space mission
- Submitted several times at ESA (M3: 2011; M4: 2015; M5: 2018)

No success, in spite of strong community and national agency support.

10 publications in a special issue of JCAP: JCAP Volume 2018, Number 4

- **PRISM (Primordial Radiation Imaging and Spectroscopy Mission)**

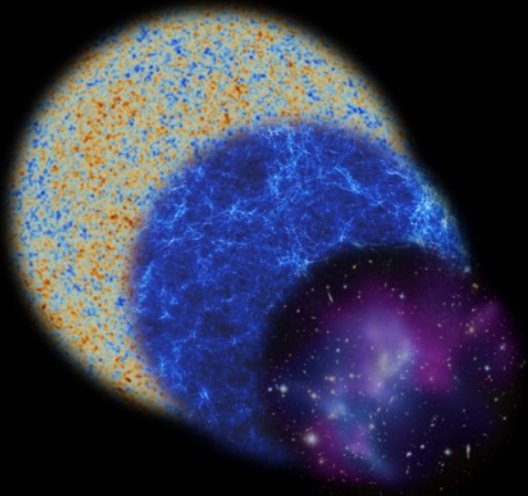
- More capable than CORE: larger dish, imaging + spectroscopy
- Submitted as an L-class ESA mission (L2-L3: 2013)

Made it to the top-5, but lost competition to LISA and Athena.

PRISM white paper, André et al., JCAP, 2014 (arXiv:1310.2554)

Voyage 2050: Four coordinated science topics

MICROWAVE SPECTRO-POLARIMETRY OF MATTER AND RADIATION ACROSS SPACE AND TIME



Contact
Jacques DELABROUILLE

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ESA Voyage 2050 Science White Paper

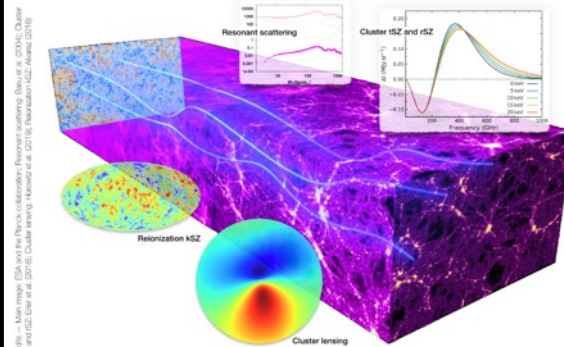
A Space Mission to Map the Entire Observable
Universe using the CMB as a Backlight

Corresponding Author:

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

Colead Authors:

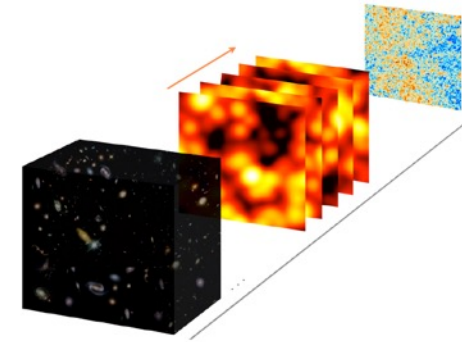
Mathieu Remazeilles (Manchester, proposal writing coordinator),
Jean-Baptiste Melin (IRFU Saclay)



Credits: - Main image: ESA and the Planck collaboration, Resonant scattering: Basu et al. (2016), Cluster tSZ and rSZ: Ewer et al. (2016), Cluster lensing: Mandel et al. (2016), Reionization tSZ: Alvarez (2018)

ESA Voyage-2050 White Paper

Mapping Large-Scale-Structure Evolution over Cosmic Times

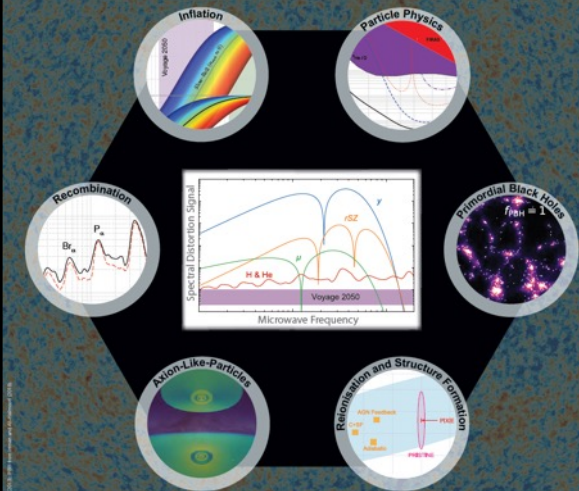


Principal Author: Marta B. Silva
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Phone: +47 22 857 632
Address: Sen Sælands vei 13, Svein Rosselands hus, 0371 Oslo, Norway

High redshift structures
Marta Silva et al.

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

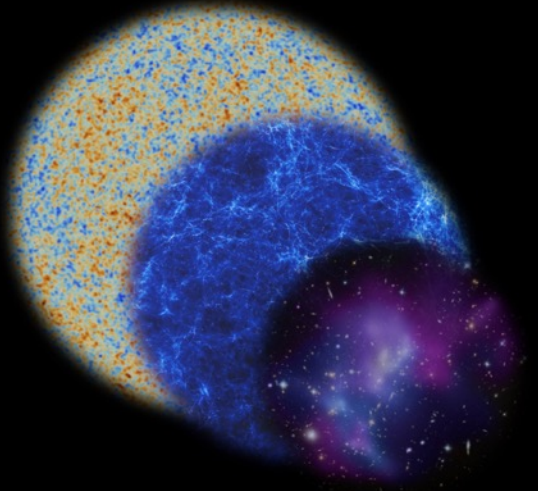
Spectral distortions
Jens Chluba et al.

Microwave survey
Jacques Delabrouille et al.

CMB Backlight
Kaustav Basu et al.

Voyage 2050: Four coordinated science topics

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OF MATTER AND RADIATION
ACROSS SPACE AND TIME



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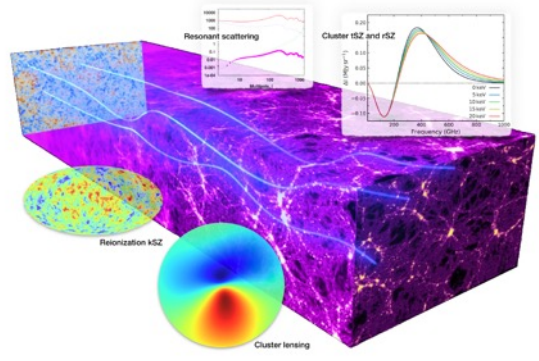
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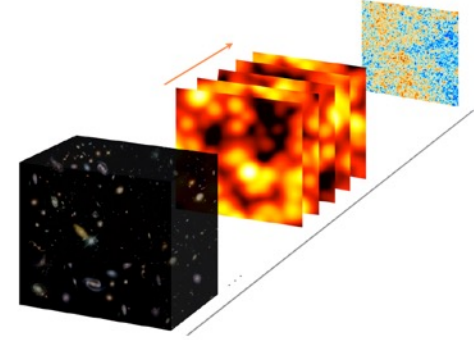


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CMB Backlight
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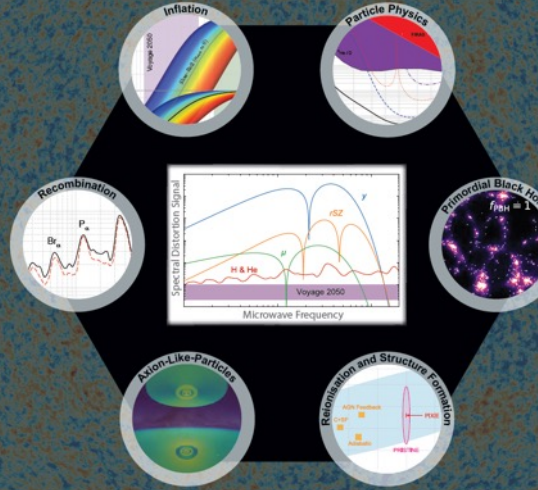


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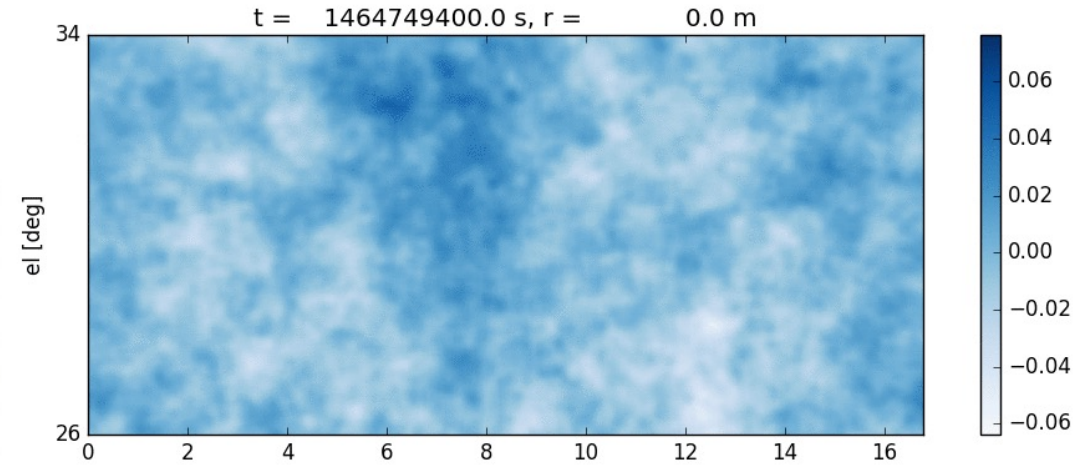
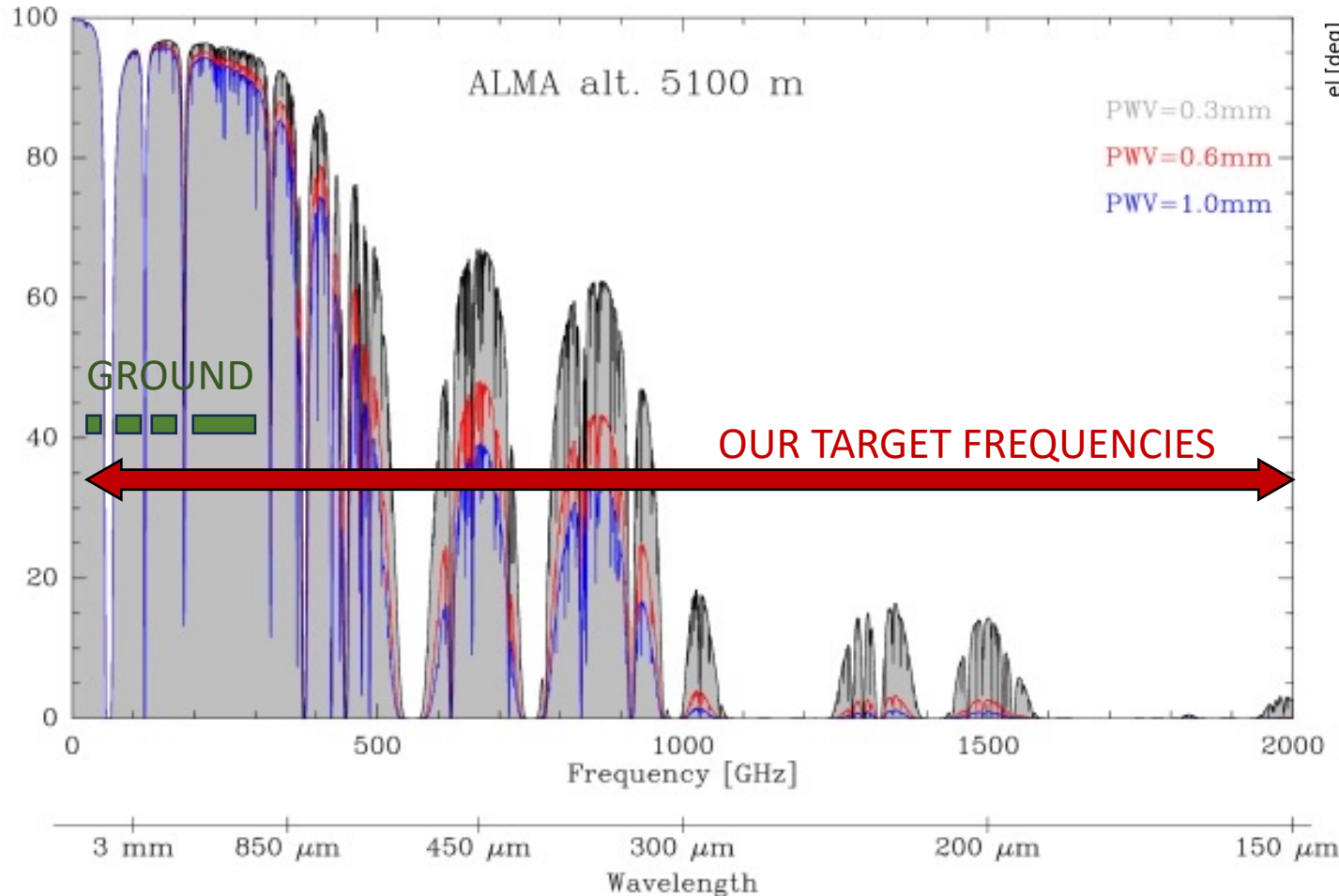
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Potential science themes for an
M-CLASS MISSION

Candidate for an
L-CLASS MISSION

Why from space ?

Chile (Atacama)



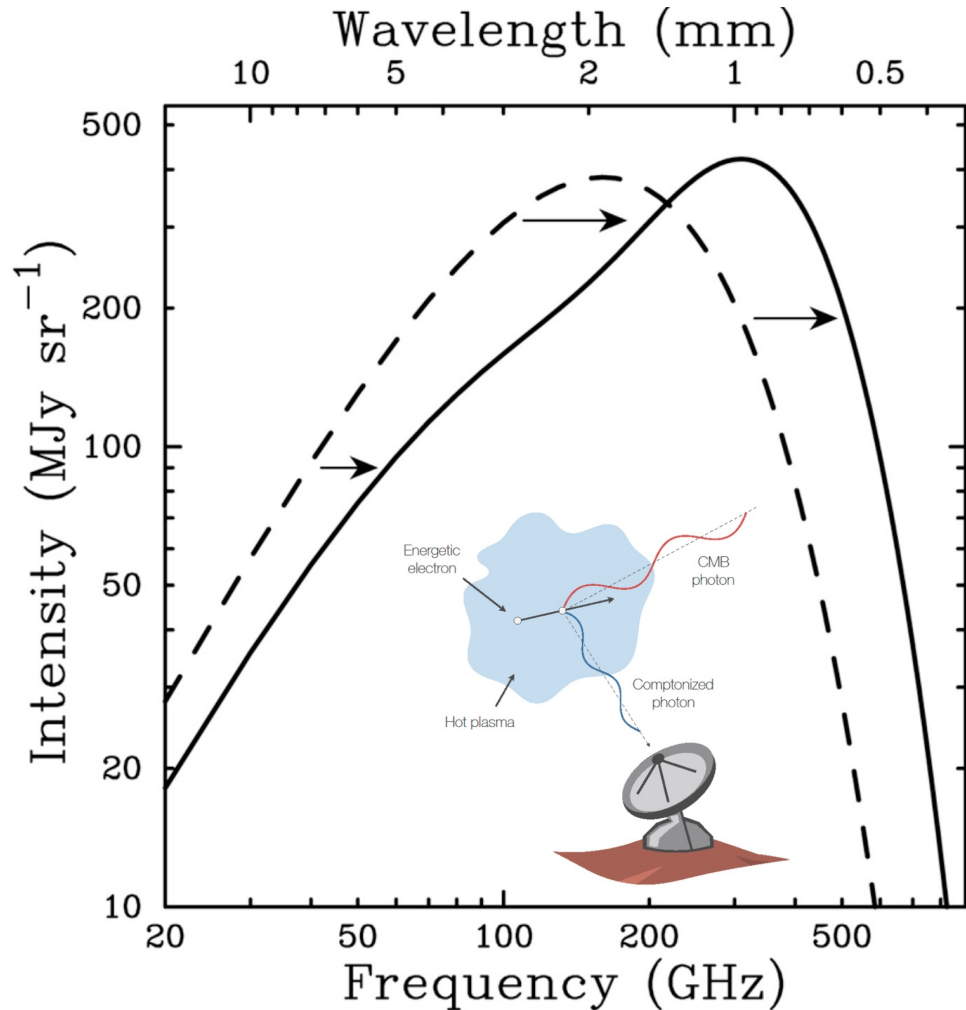
Atmospheric
Transmission and Emission !

1 detector in space
=
100-1000+ ground-based detectors

- **Very rich science case for microwave polarimetric spectro-imaging**
 - From space for full science return
 - Ultimate CMB science
 - Unique opportunity to explore the universe on the largest scales
- **An option at ESA for a future L-Class mission**
 - Prepare for a CMB spectroscopy L-class mission bid in 2030-2040
 - TRL increase is key: balloons, other missions
 - Science: build on upcoming ground-based observations (CMB-S4, CCAT/FYST)
- **In the US**
 - Prepare for a probe-class mission bid in the next decade

Thank you for your attention

Map the entire Universe using CMB as a backlight



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

