Measuring spectral distortions with FOSSIL and BISOU

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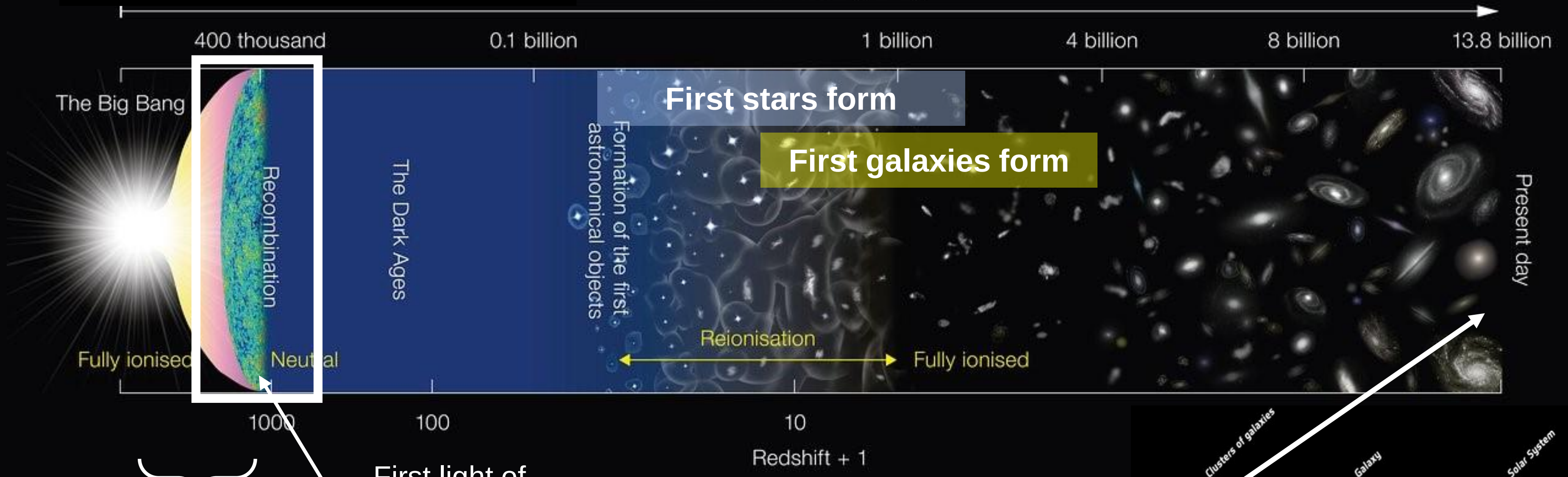
on behalf of the **FOSSIL** and **BISOU** collaborations

Challenges at the CMB Frontier, Suwa University, 29th June - 3rd July 2026

A (very) short history of our Universe

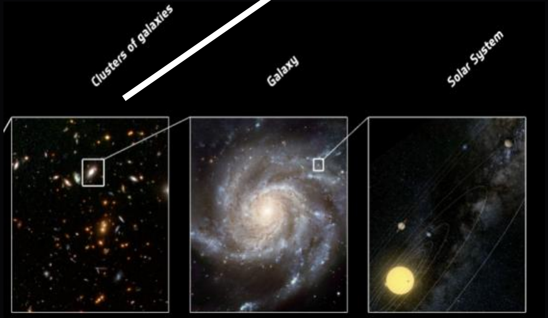
Inflationary phase → Initial density perturbations (seeds of galaxies and clusters)



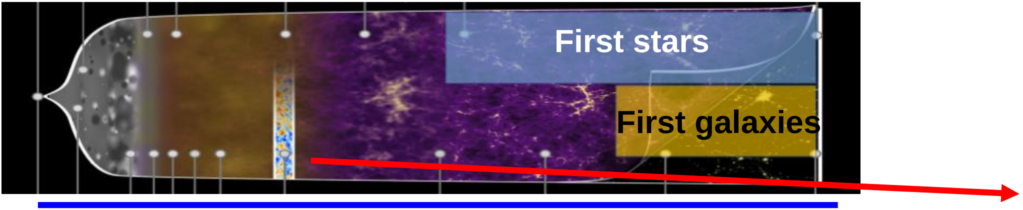
Very hot universe
T > 3000 K
Opaque Plasma

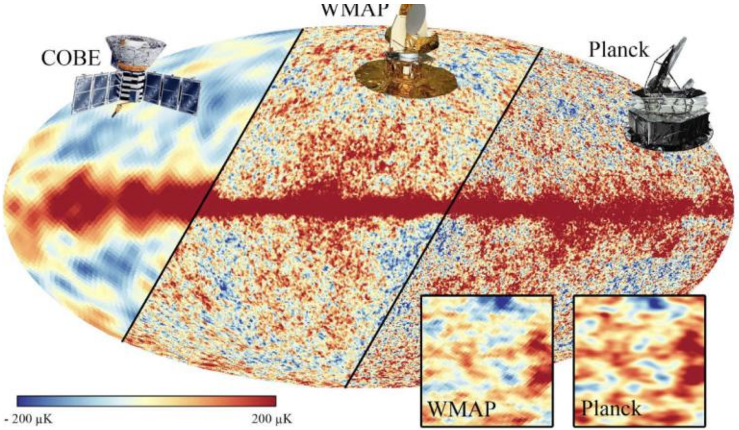
First light of the Universe

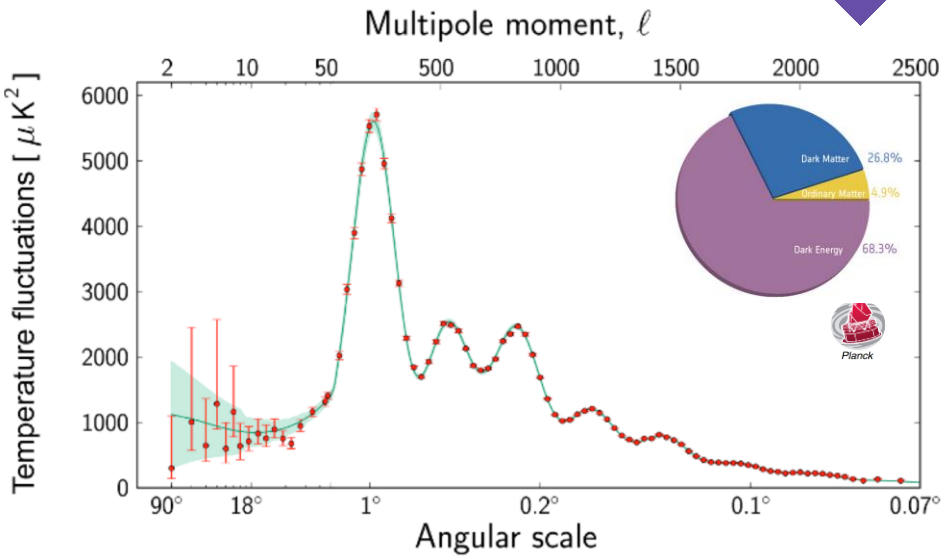
T~ 3000 K. Recombination
Universe becomes transparent.
Last scattering surface → CMB



Cosmic Microwave Background (CMB) - Anisotropies



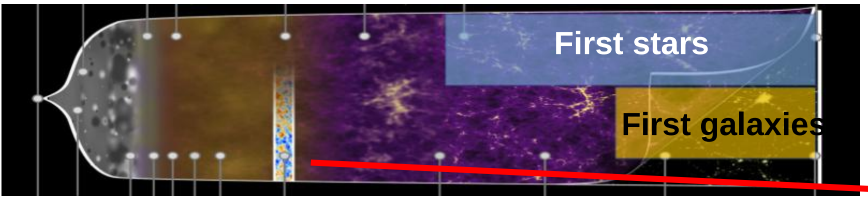




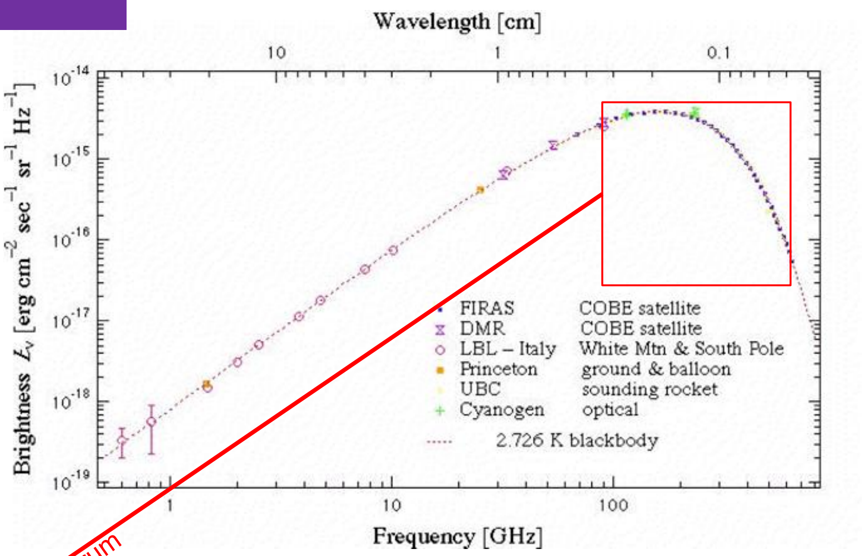
Next step: primordial B-modes

- LiteBIRD
- Several ground-based and balloon-borne projects

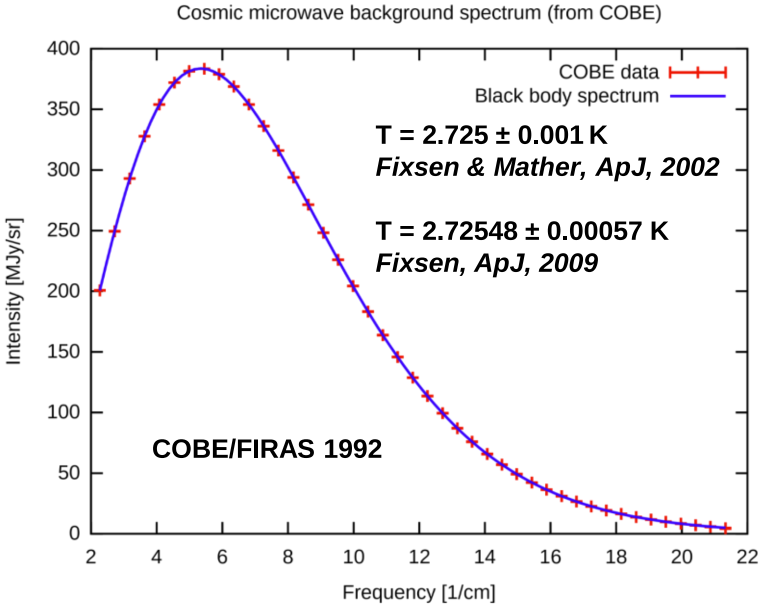
Cosmic Microwave Background : Spectrum



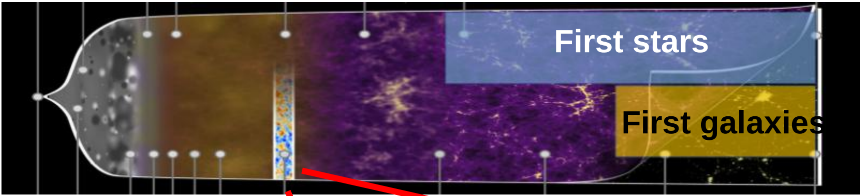
13.8 Gyrs

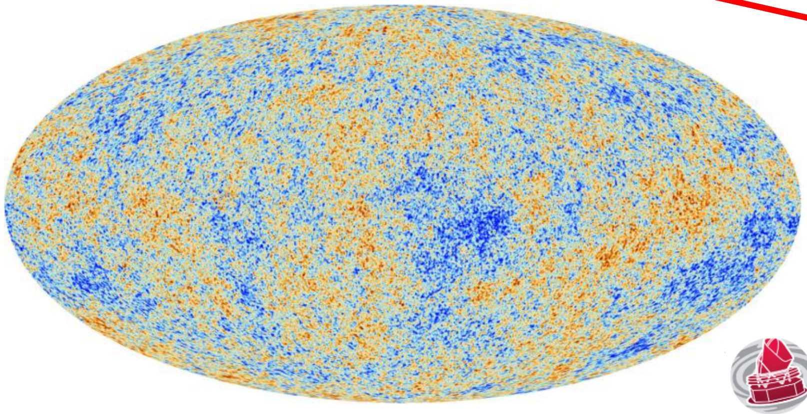


Hot **big-bang** →
CMB with blackbody spectrum

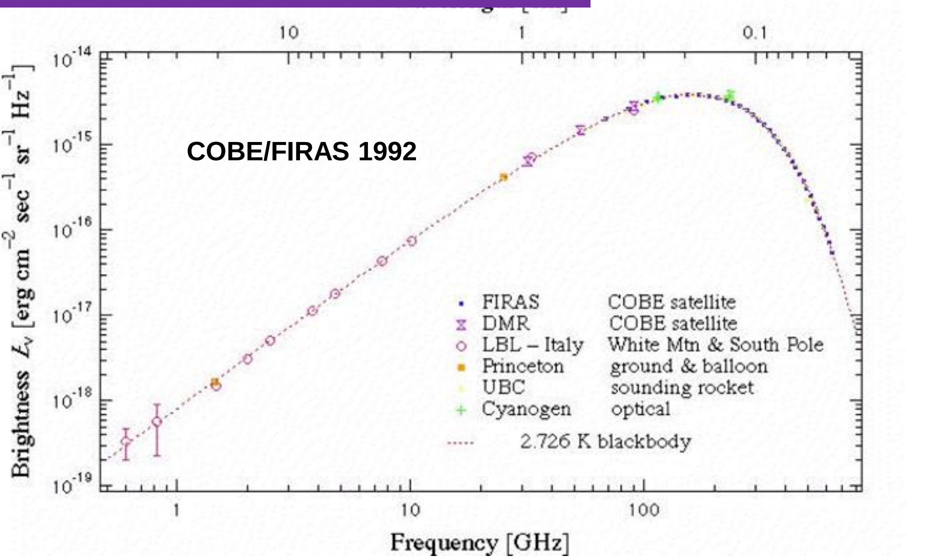


Cosmic Microwave Background : Spectrum + Anisotropies



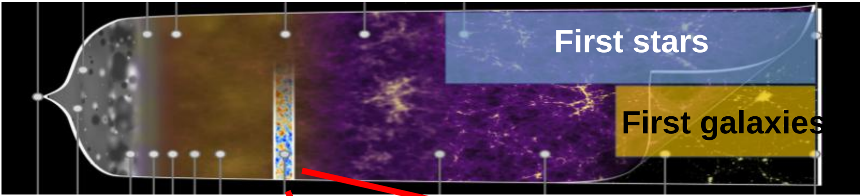


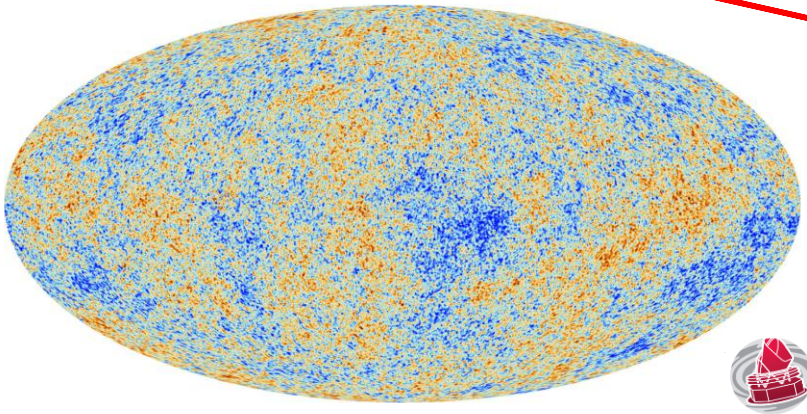
Planck



- Establishing the hot **big-bang** scenario / ΛCDM
- Establishing the existence of **initial density perturbations** seeding galaxies and clusters
- Showing the growth of perturbations into large-scale structure through **gravitational instability**
- Determining the **geometry** & **energy density composition** of the Universe

Cosmic Microwave Background : Spectrum + Anisotropies





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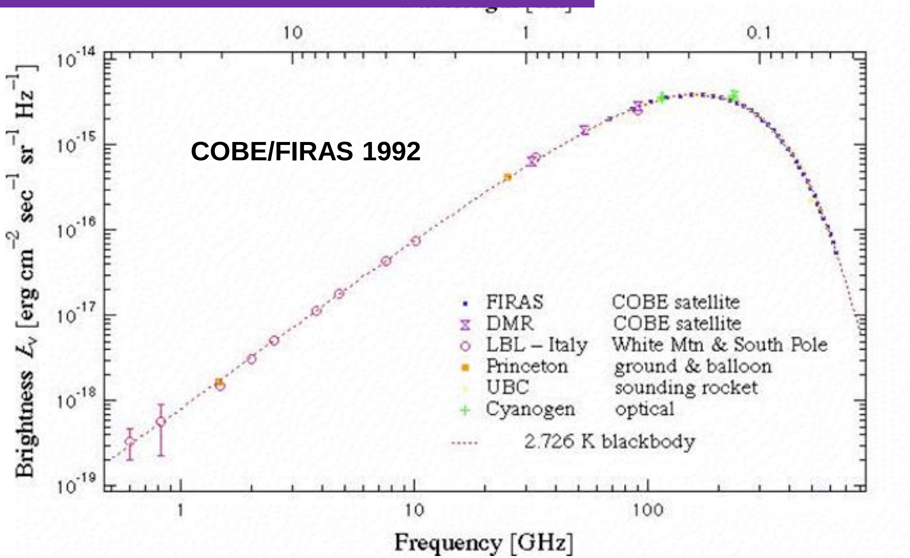

… However …

Key open questions in cosmology

- Establishing the hot **big-bang** scenario / ΛCDM
- Establishing the existence of **initial density perturbations** seeding galaxies and clusters
- Showing the growth of perturbations into large-scale structure through **gravitational instability**
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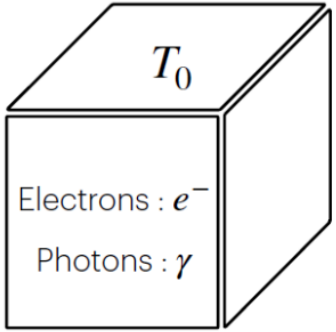
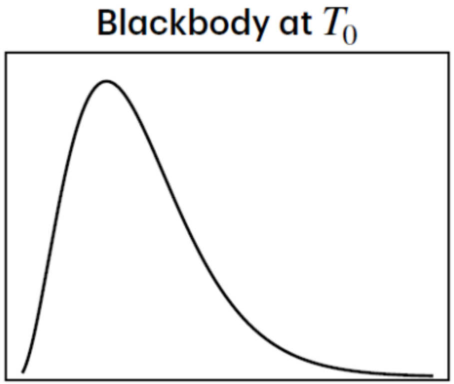
CMB Spectral Distortions : Thermalisation

Credits: X. Coulon, PhD thesis 2026
Adapted from Lucca, PhD thesis 2023





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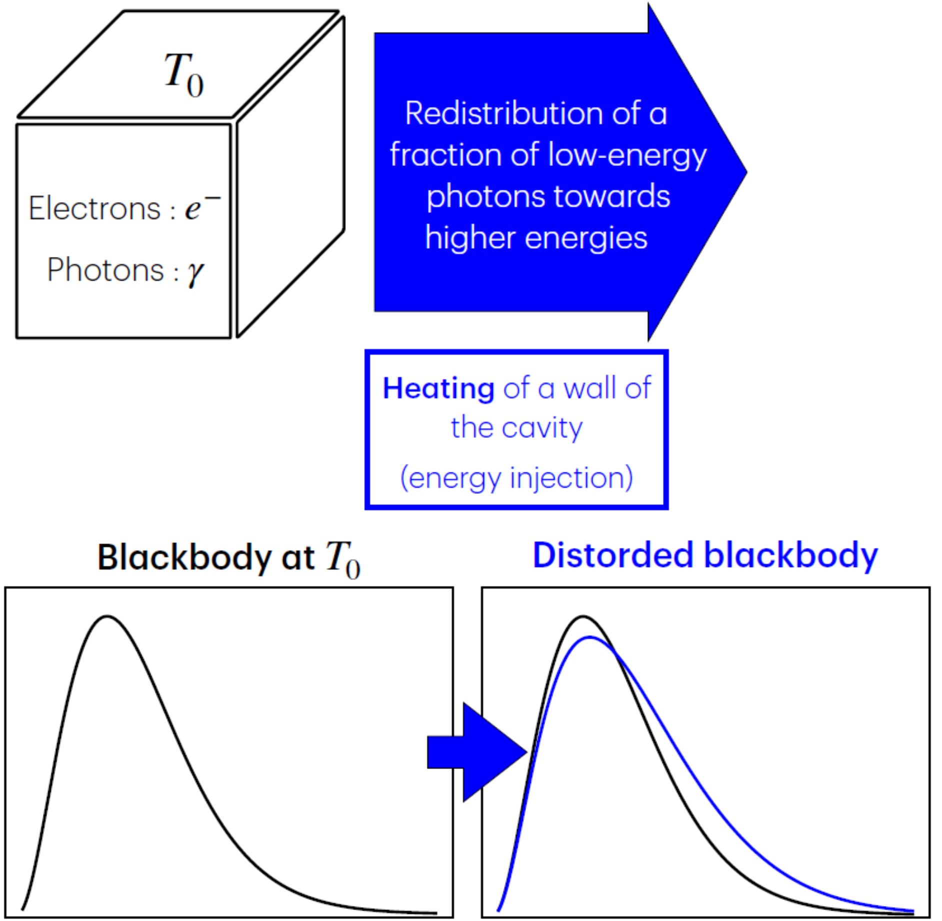

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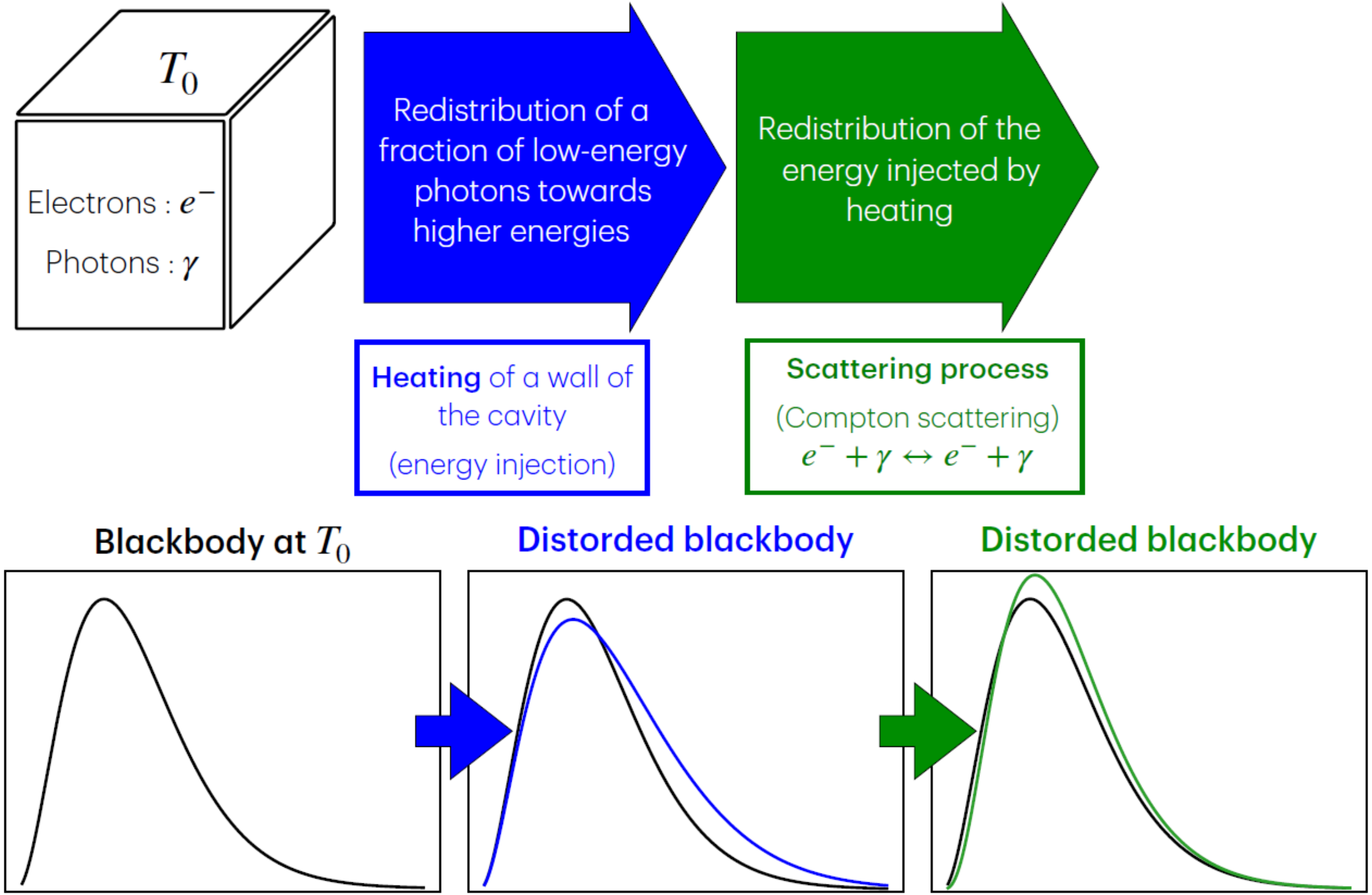

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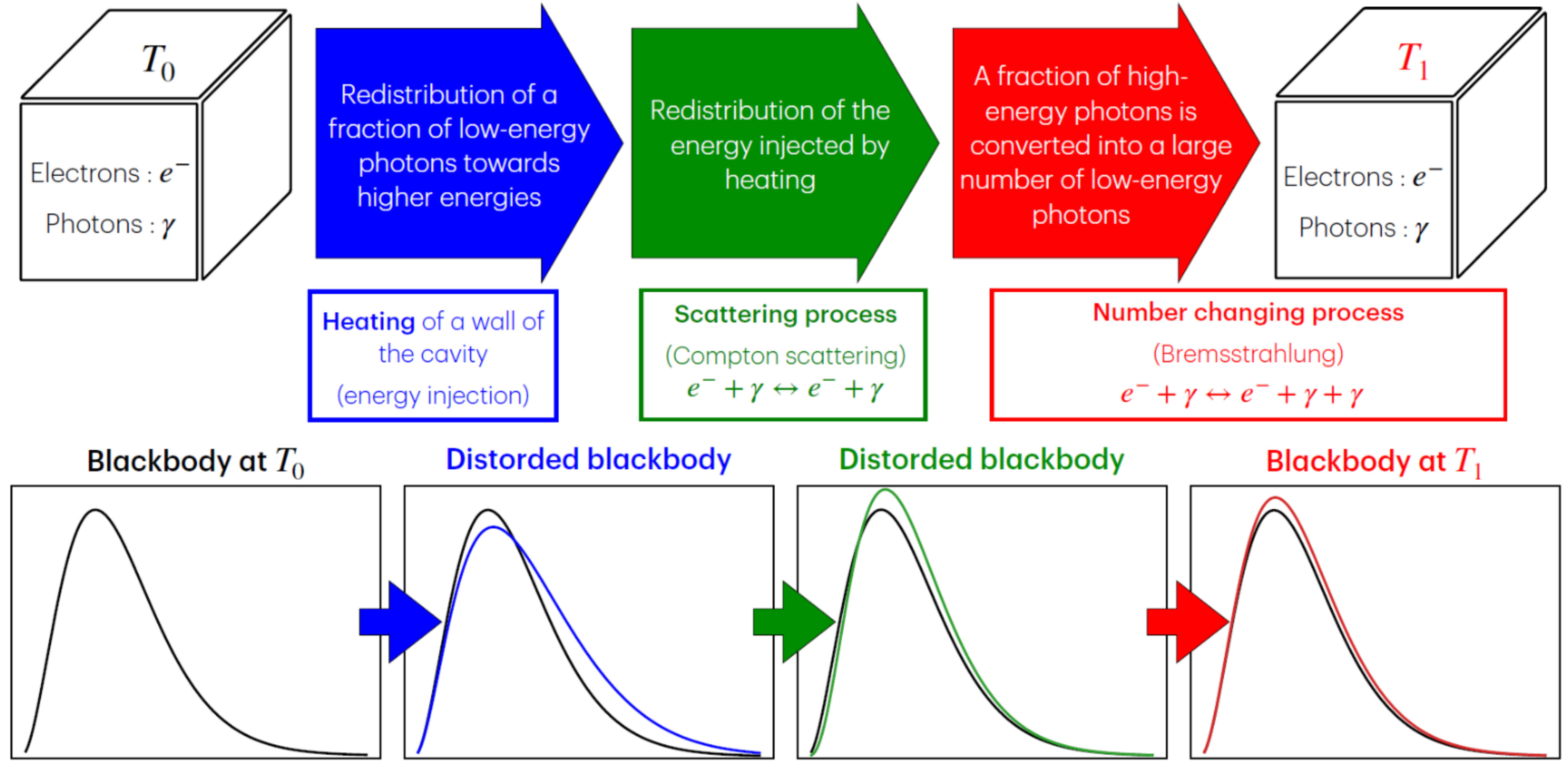
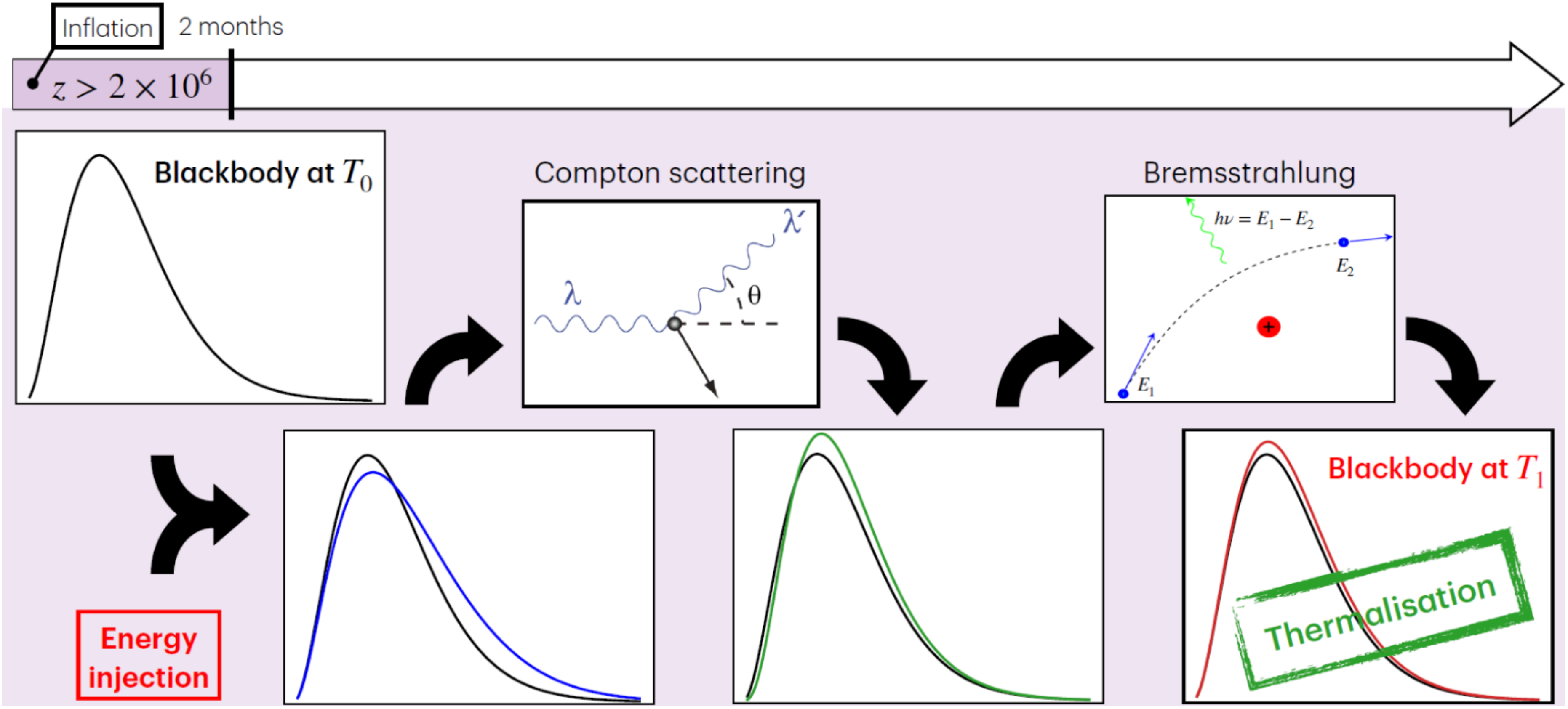


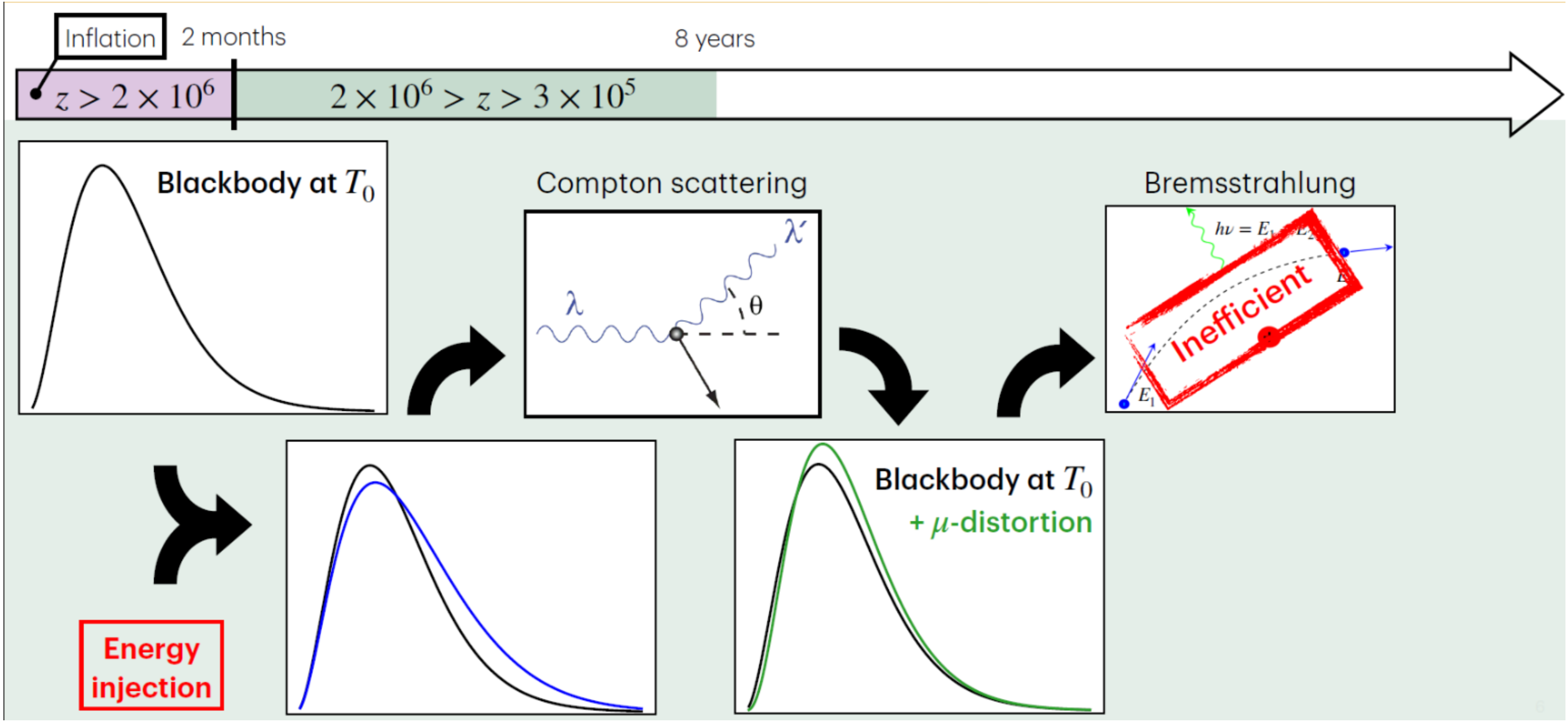
CMB Spectral Distortions : Thermalisation summary

Credits: X. Coulon



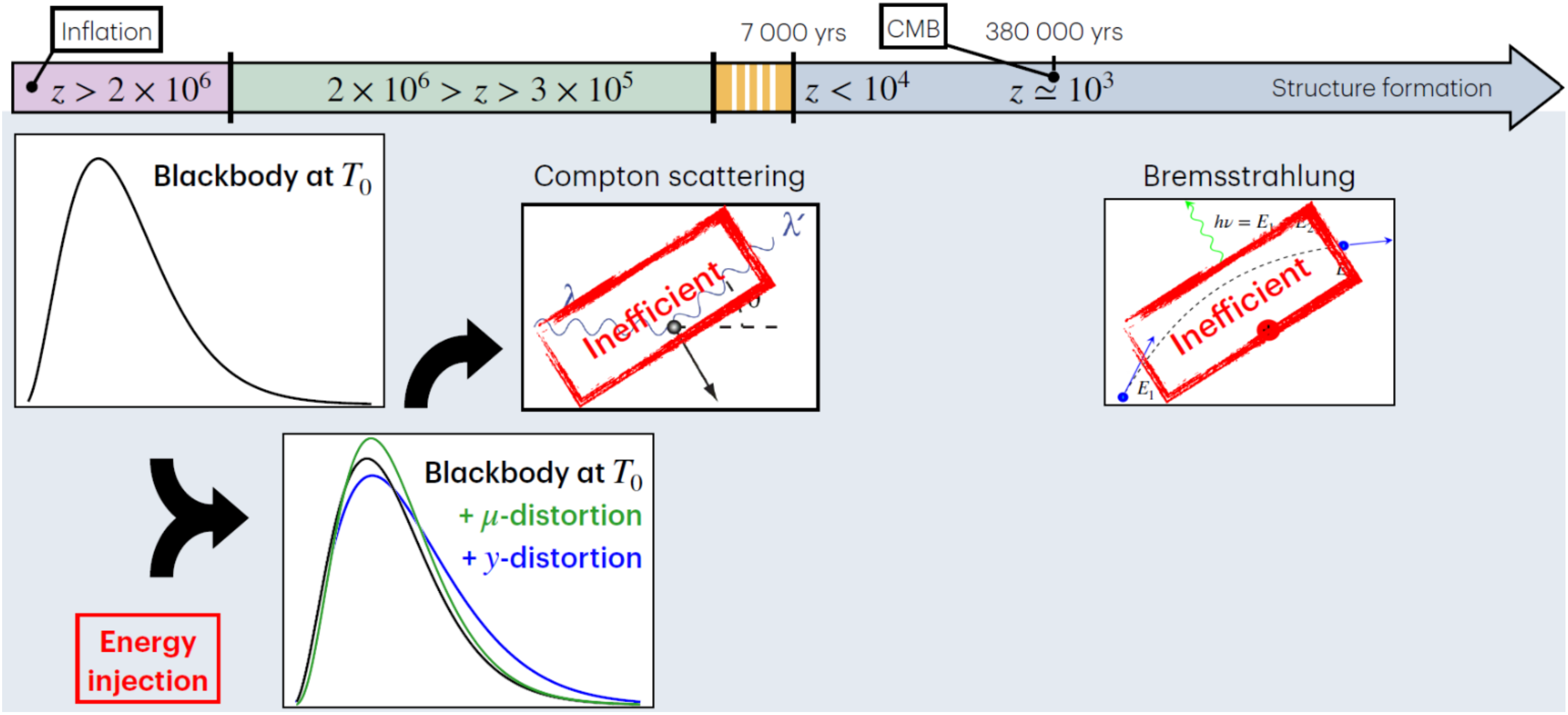
CMB Spectral Distortions : μ-distortion

Credits: X. Coulon



CMB Spectral Distortions : μ and y distortions

Credits: X. Coulon



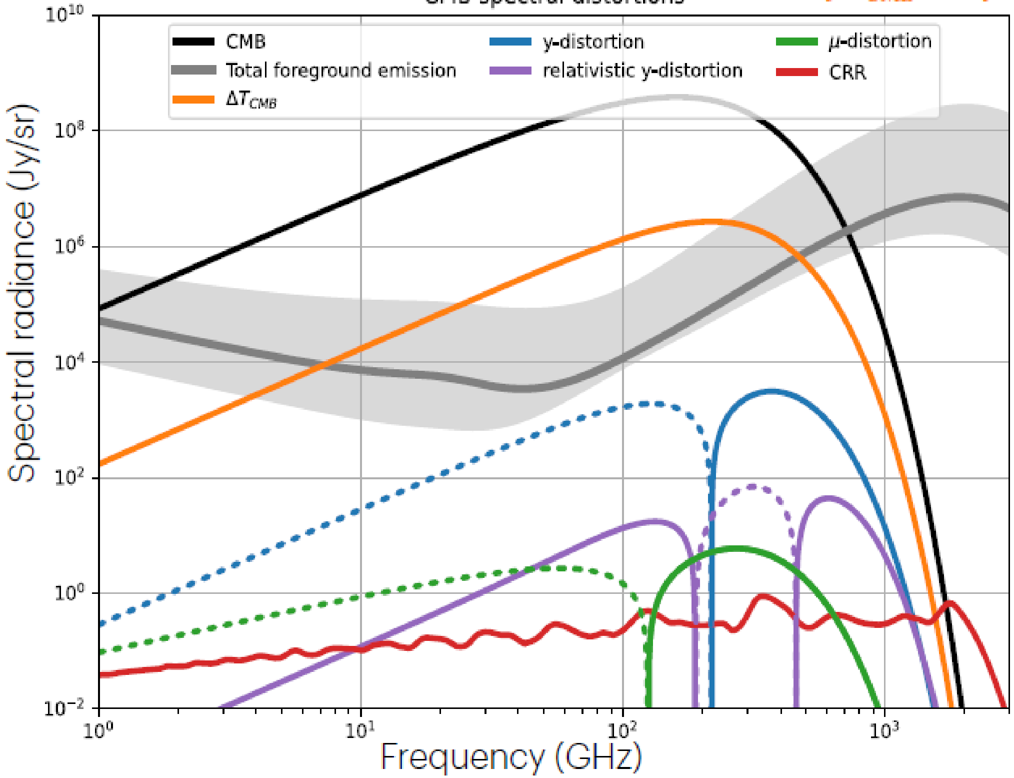
CMB Spectral Distortion signatures

Credits: X. Coulon

$$I_\nu^{\rm CMB} = B_\nu(T_0) + \Delta I_\nu^{\rm CMB} = B_\nu(T_0) + \underbrace{\Delta B_\nu}_{= B_\nu(T_{\rm CMB}) - B_\nu(T_0)} + \Delta I_\nu^{y} + \Delta I_\nu^{rel-y} + \Delta I_\nu^{\mu} + \ldots$$

with $B_\nu(T)$: blackbody emission at T

Chluba & Jeong 2014



Moment expansion:

CMB	Parameters
Temperature shift	$\Delta T_{\rm CMB}$
y-distortion	y
Relativistic correction	T_e
μ-distortion	μ

Chluba+2014, Abitbol+2017, Hill+2015, Chluba+2016, Chluba+2017

- $\Delta I_\nu^y / \Delta I_\nu^{\rm CMB} \simeq 10^{-6}$
- $\Delta I_\nu^{rel-y} / \Delta I_\nu^{\rm CMB} \simeq 10^{-7}$
- $\Delta I_\nu^{\mu} / \Delta I_\nu^{\rm CMB} \simeq 10^{-8}$

Cosmological Concordance & Key open questions

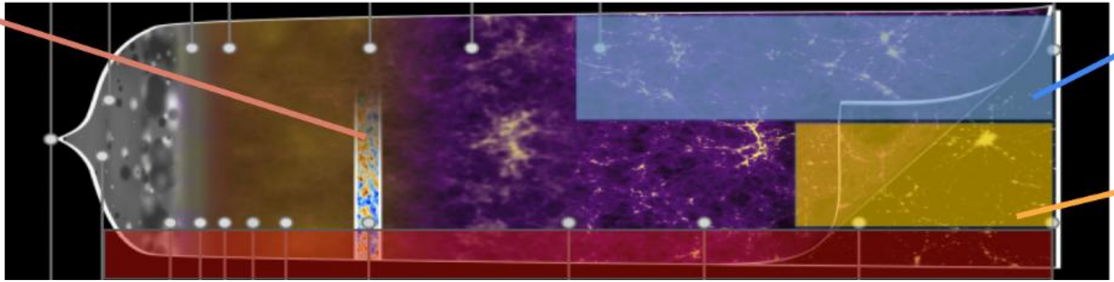
How did the Universe begin & What is it made of?

- What powered inflation?
- What is dark matter made of?
- Are there primordial BHs, how did they form?

How did the Universe evolve?

- What is the thermal energy in the LSS?
- What is the energy injected by SMBH?
- Why did star formation peak ~10 billion years ago?

Density perturbations @inflation → CMB temp./polar. anisotropies



Structure form via Gravitational collapse

Cosmic web of sheets, filaments, nodes, voids

Energy release & photon injection → Distort the CMB Blackbody spectrum

(**y:** Inverse Compton scattering & **μ:** Chemical potential)

Test the cosmological model across the history of Universe

Towards CMB spectral distortions measurements

Several attempts

- PIXIE mission proposals (A. Kogut et al)
  - NASA MidEx - 2011 & 2016
- PRISTINE (N. Aghanim et al)
  - ESA F1 - 2018
- FOSSIL (N. Aghanim et al.)
  - ESA M7 - 2022

Feedback from Agencies

- CNES
  - One of the top priorities together with CMB polarisation
  - Prospectives 2019 and 2024
- ASTRONET 2022 - 2035
  - report identifies **spectral distortions as a new CMB probe**
- ESA Voyage 2050
  - ***New physical probes of the early Universe and high precision spectroscopy of CMB*** is one of the 3 themes for large missions (horizon >2055!)
  - White paper (Chluba et al, 2021)

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FOSSIL
FTS fOr CMB Spectral diStortIon expLoration

ESA M8 phase 2 proposal submitted in march 2026 (N. Aghanim et al.)

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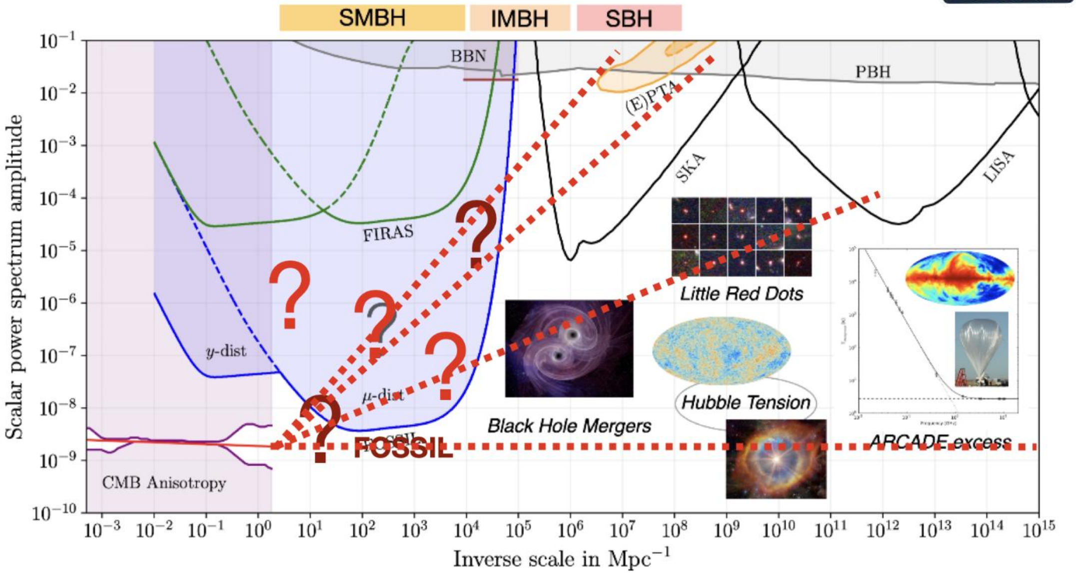
How did the Universe begin ? What is its content ?

Primary goal:

Probing density perturbations

Dissipation of evolving initial perturbation from standard inflation → Spectral distortions **μ = 2. 10^{-8}**

- ❖ **Constrain & test inflation**
  - ➢ Departures from the prediction would out single-field slow-roll inflation
- ❖ **Probe primordial perturbations**
  - ➢ Open a unique window at unexplored scales down to a few tens pc
- ❖ **Constrain origin of BHs**
  - ➢ Probe formation of primordial & intermediate-mass BHs



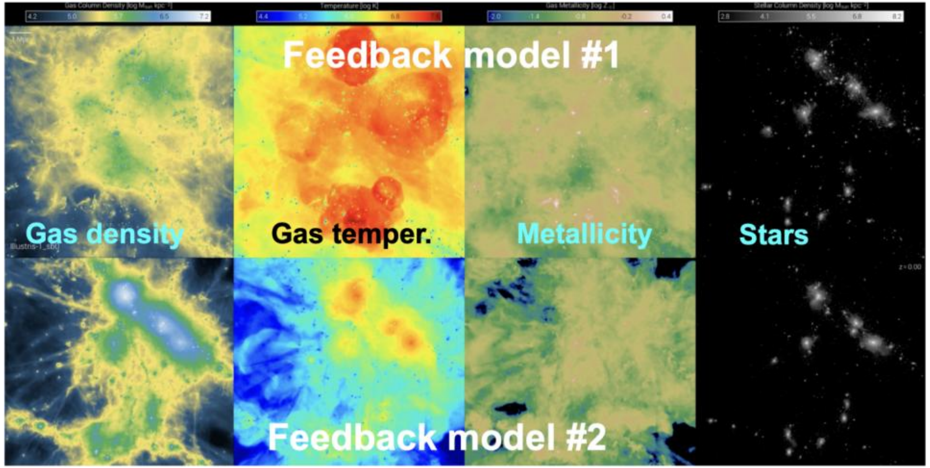
Primary goal: **Probing the dark sector**

Dark matter decay, annihilation and scattering with standard model particles → Spectral distortions

- **Constrain the nature of DM** by probing its interaction cross section with baryons & photons
- **Constrain photon to dark-photon conversion** kinetic mixing parameter

How did the Universe evolve?

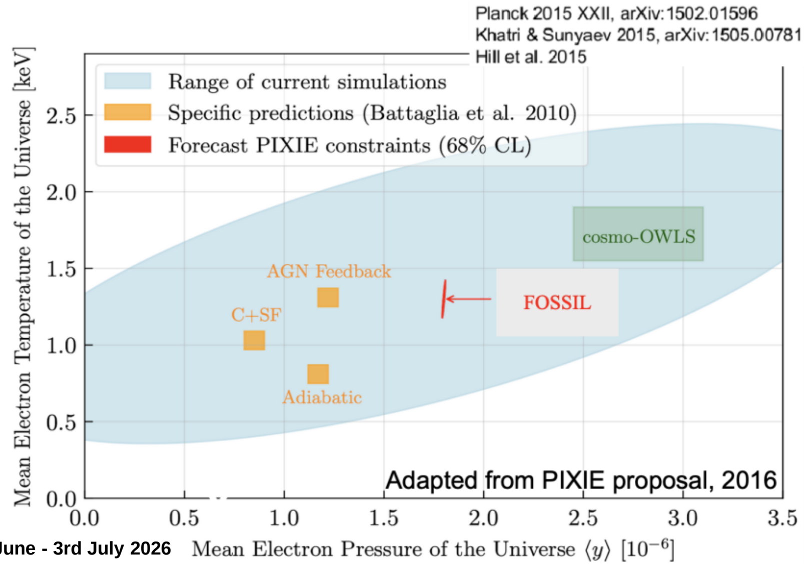
Credits. TNG-project.org



Primary goal: Probing the formation & evolution of the large-scale structure (LSS)

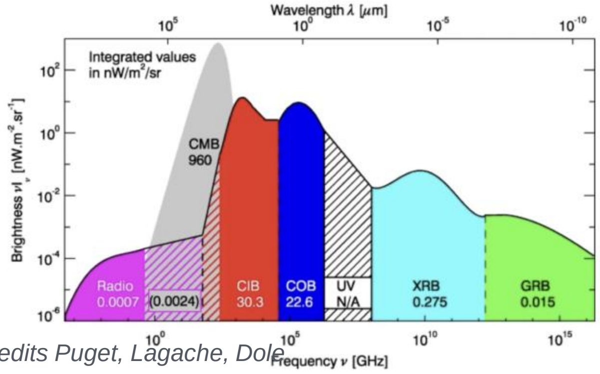
Energy release from collapse of baryons & feedback processes & reionisation
→ **y distortions** in relativistic & non-relativistic regimes

- Provide a **complete census of the thermal energy** from structure formation & reionisation
- Measure **temperature of hot gas** down to $kT_{eSZ} \simeq 1.3$ keV
- Stringent constraints on total energy injected by **feedback from SuperMassive BHs**



Enabled Goals & Synergies

- **Star-formation history & Metal enrichment at cosmic noon**
  - Absolute intensity of CIB @percent level
  - Monopole emission and low-resolution intensity maps of far-IR lines (CII & CO)
- **Dust properties & Physical conditions of ISM phases**
  - Spatially variable foreground models & SED
  - Emission lines from molecular gas (CO, CS, H2O), PDRs,...



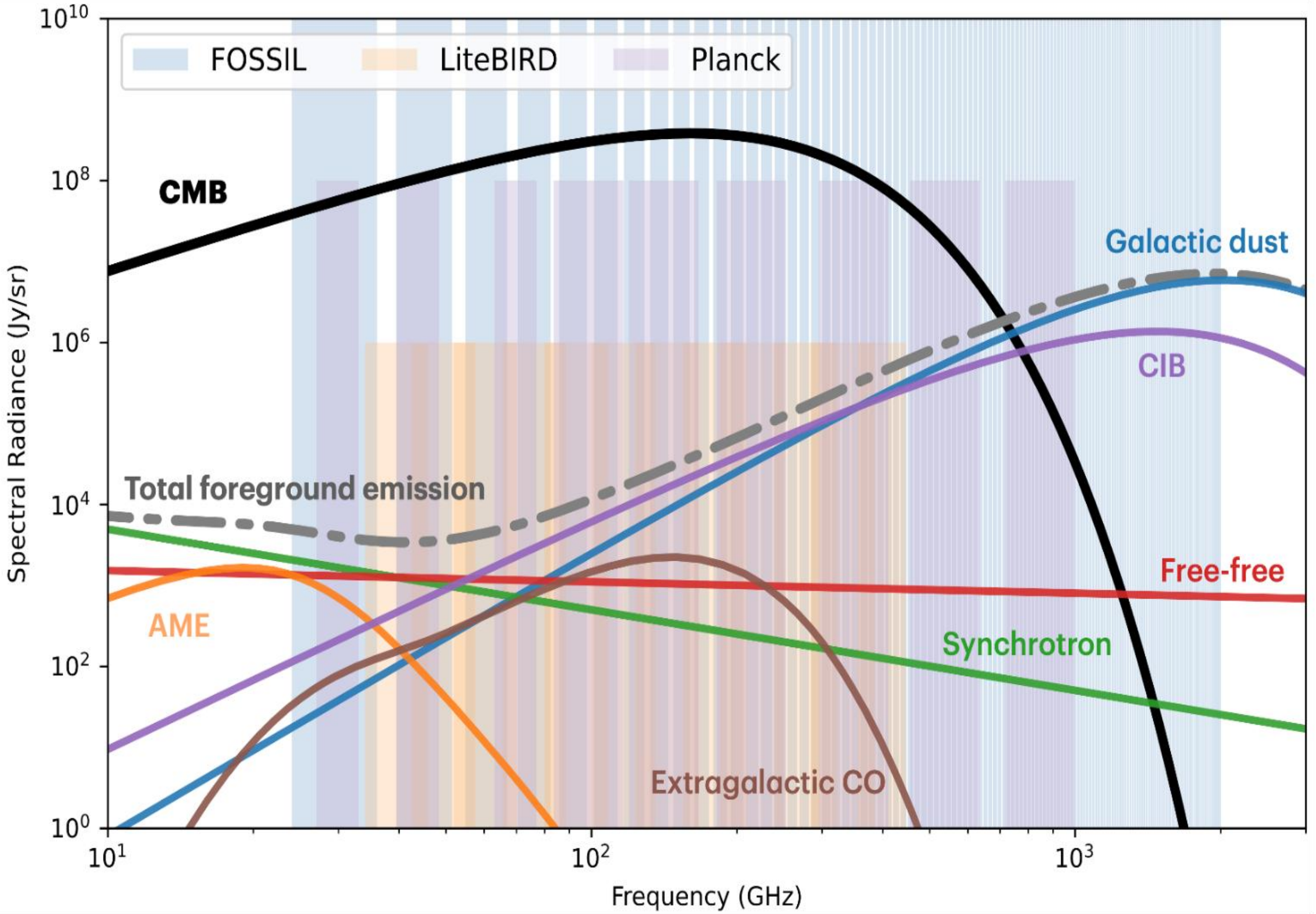
Credits Puget, Lagache, Dole

Synergies

- Control foreground models with FOSSIL for **B-mode CMB polarisation measurements**
- Cross-correlation analyses with FOSSIL
  - Probe the first stages of galaxy formation in combination with **LIM experiments**
  - Provide absolutely-calibrated measurements of the y distortions from galaxy groups and clusters inaccessible from **CMB imagers**

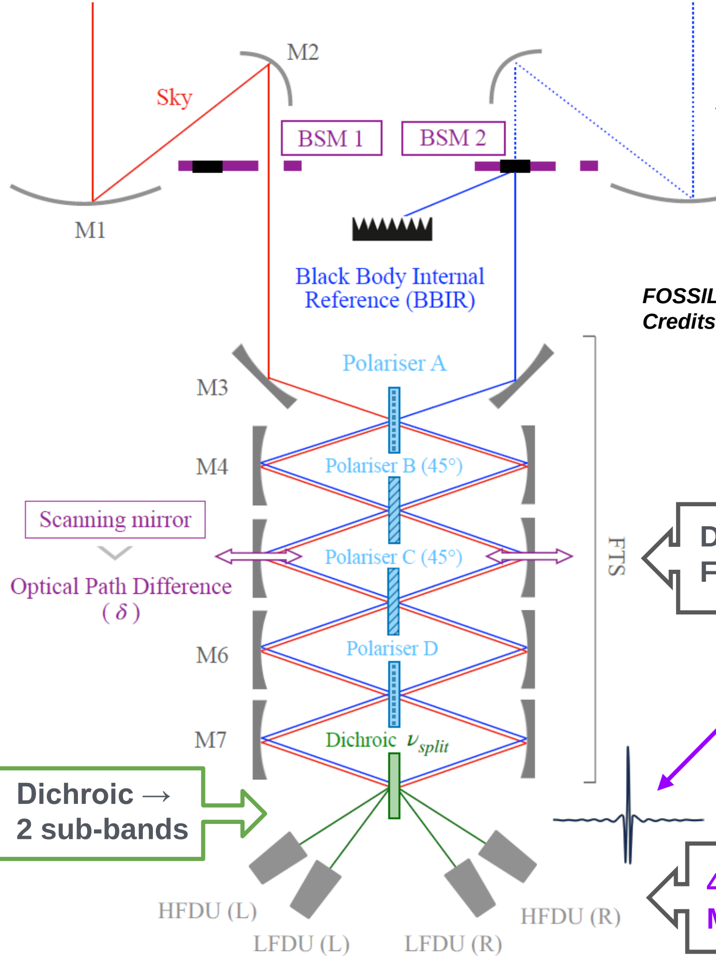
Measurement requires a very large spectral range

Credits: Xavier Coulon, PhD & in prep.
FOSSIL proposal 2026



Measurement concept

Absolute Spectrometer:
Differential FTS with respect to a known internal reference



2 inputs with matched optics

FOSSIL concept from PIXIE
Credits: M. Loquet Le Gall & X. Coulon

Differential FTS

Interferogram

Dichroic → 2 sub-bands

4 outputs
Multi-moded optics

Measurement concept

Absolute Spectrometer:
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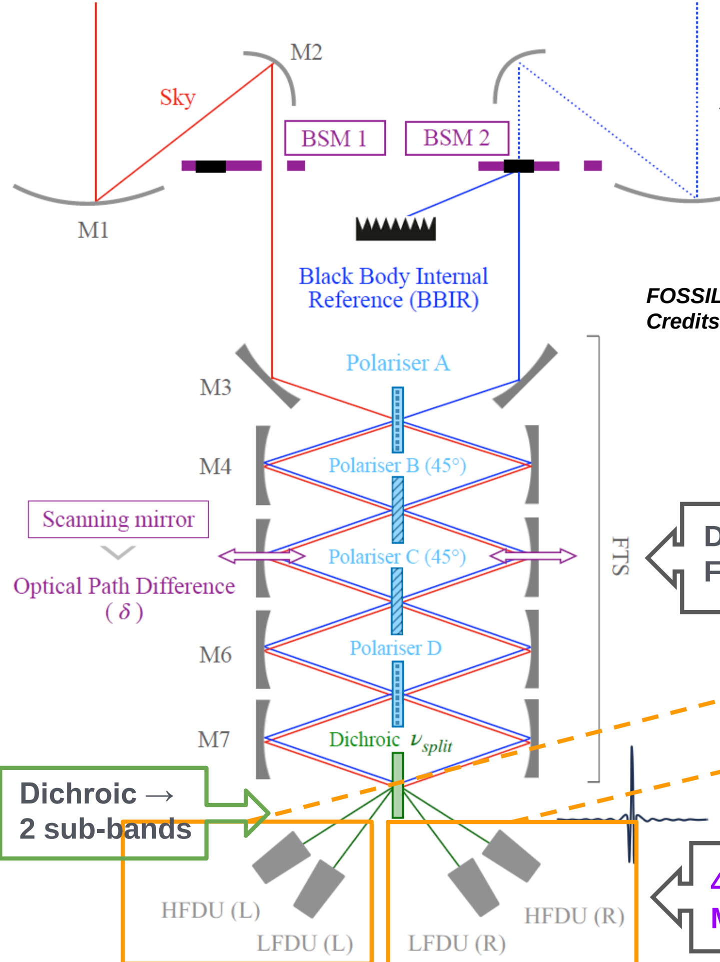

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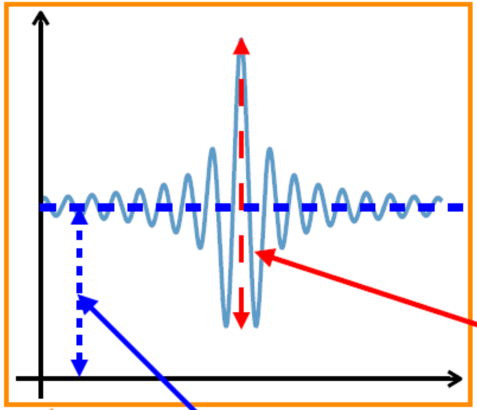

FFT

Difference between the emission spectrum of the sky and that of the reference

$\propto I_{sky} - I_{ref}$

$\propto I_{sky} + I_{ref}$

$$P_L = C + \frac{1}{4}\int \left(I_{sky} - I_{ref}\right) \cos\left(\frac{4\delta\omega}{c}\right) d\omega$$

$$P_R = C + \frac{1}{4}\int \left(I_{ref} - I_{sky}\right) \cos\left(\frac{4\delta\omega}{c}\right) d\omega$$

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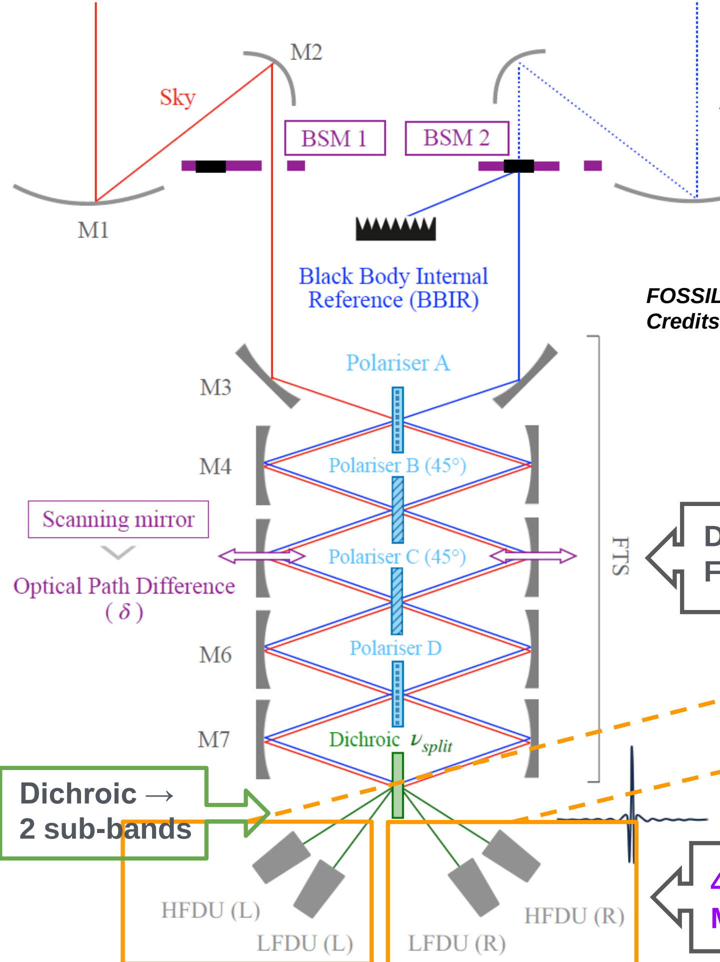

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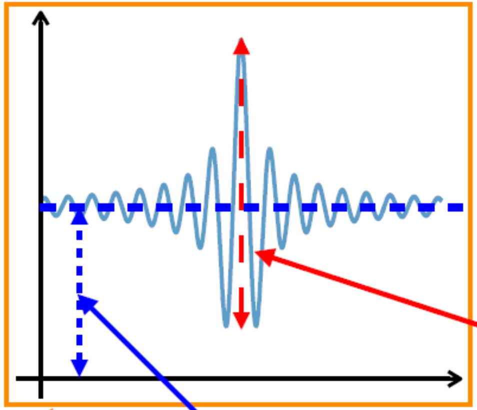

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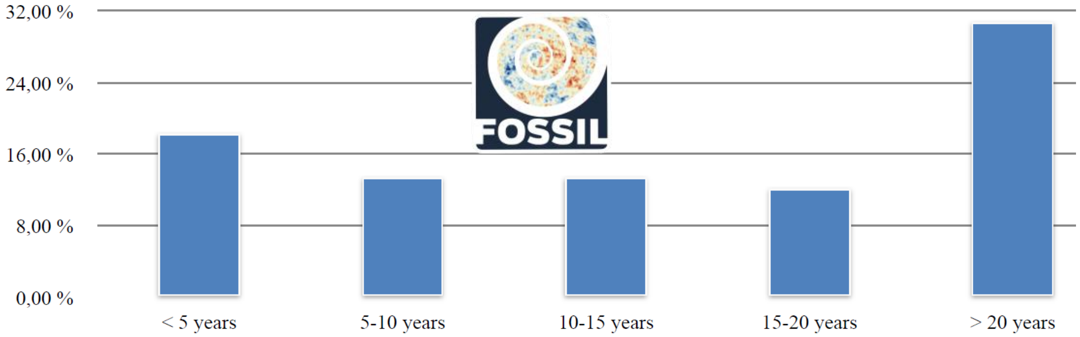
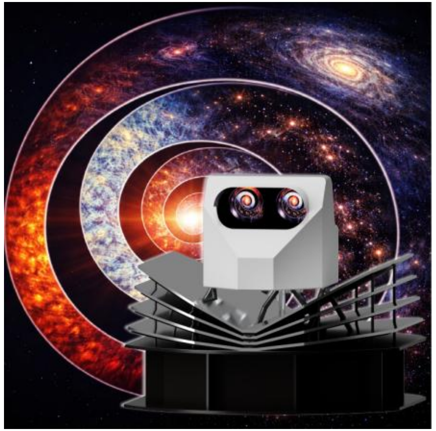
- Full instrument needs to be at about T_{CMB}
- The Black Body Internal Reference is set at the temperature of the CMB 2.725 K
- The detectors need to be cooled at sub-K temperature : about 0.1 K

FOSSIL (FTS fOr CMB Spectral diStortIon expLoration) ESA M8 proposal

FOSSIL consortium
- Nabila Aghanim et al
- 265 members
  - 22% female
  - 45% under 15 years experience
- 20 countries
- over 92 institutes





Credits: V. Sauvage

Milestones
- Spring 2025: Step 1 M8 proposal submitted to ESA
- Autumn 2025: invitation for Step 2 proposal
- March 2026: Step 2 proposal submitted

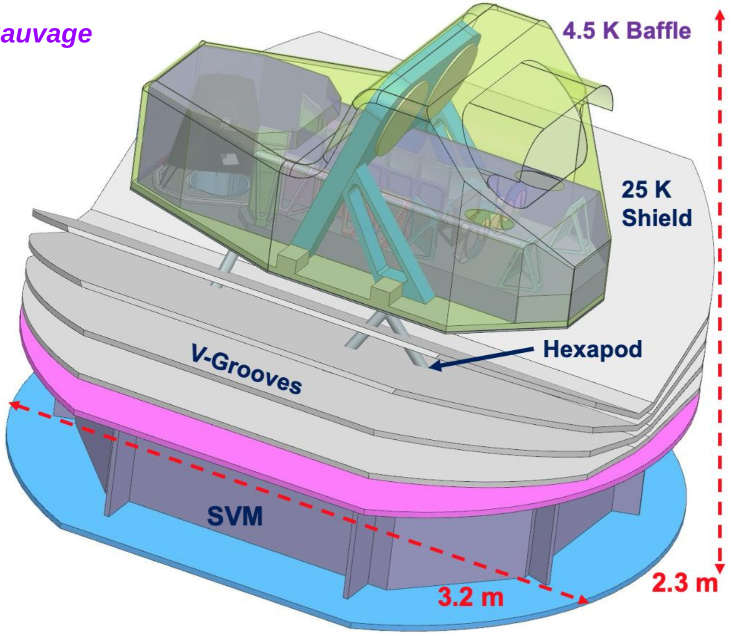
- Autumn 2026: Selection for phase 0 study (1-year) ?
- ….
- Launch in 2041

FOSSIL Payload

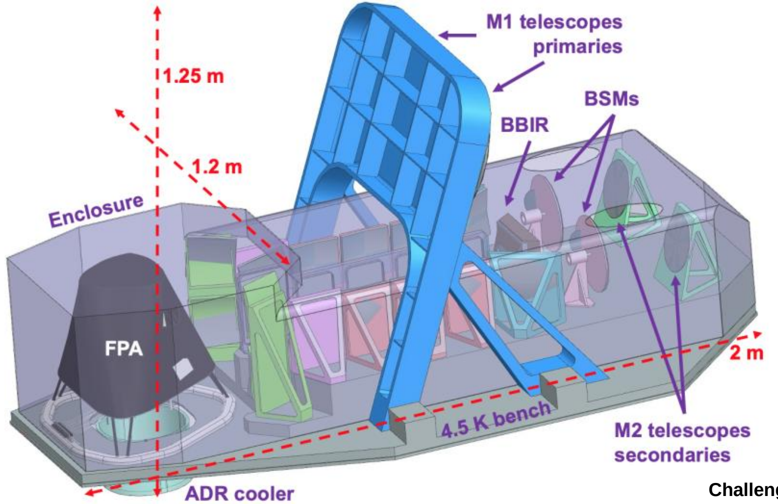
For more details see talks from V. Sauvage and M. Loquet Le Gall

Sky intensity measured w.r.t. B-B reference

- Full sky coverage from L2
- 50 to 2000 GHz (split @~300 GHz)
  - Goal to go down to 30 GHz
- $\Delta\nu$=15 GHz → about 130 bands
- Spatial Resolution
  - ~1.6 deg eq Gaussian beam
- Sensitivity ~1 Jy/sr @50 GHz



Credits: B. Borgo & FOSSIL



- Instrument & telescopes cooled at ~4.5 K
- 2 telescopes: 40 cm primary aperture
- BB Internal Reference @ 2.5 - 2.9 K
- 4 FPUs
  - each with multimoded feedhorn coupled detectors
  - operating @~50mK
  - Kinetic Inductance Detectors

Path towards a future space mission

Tenerife Microwave Spectrometer (*José Alberto Rubiño-Martin et al*)
Ground based spectrometer at Teide observatory covering 10-20 GHz

COSmic Monopole Observer (*Silvia Masi et al*)
Ground based spectrometer at Dome C - Antarctica
110-170 GHz and 200-300 GHz. → ***See L. Lamagna’s talk***

Balloon Interferometer for Spectral Observation of the early Universe (*Bruno Maffei et al*)
Balloon-borne spectrometer covering 90 - 1500 GHz

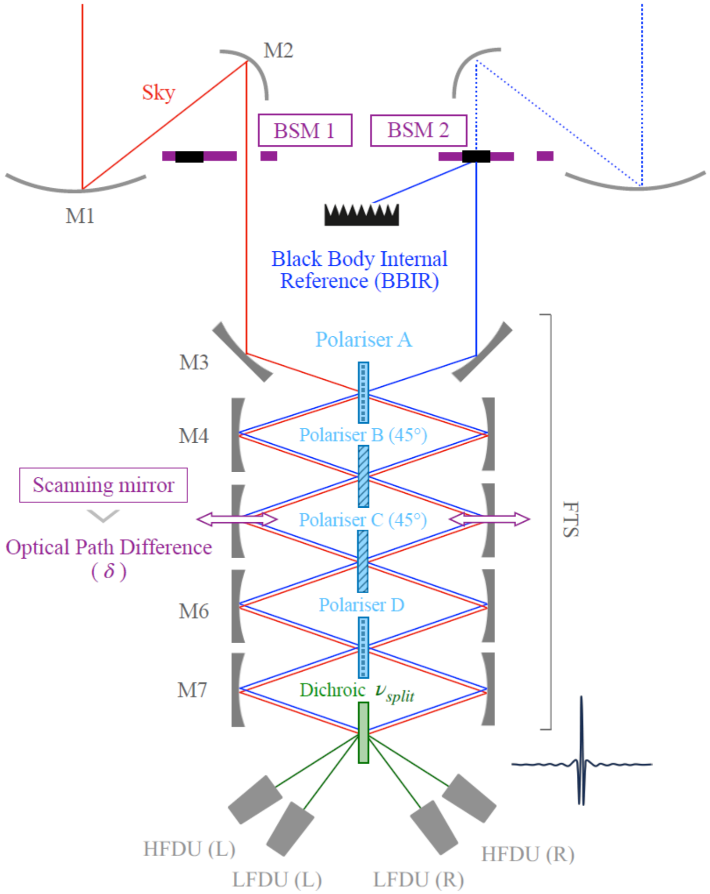
+ Laboratory breadboard in development

BISOU BALLOON pathfinder

Balloon **I**nterferometer for **S**pectral **O**bservation of the primordial **U**niverse

Measurement concept

Adaptation for stratospheric balloon project



FOSSIL concept from PIXIE
Credits: M. Loquet Le Gall

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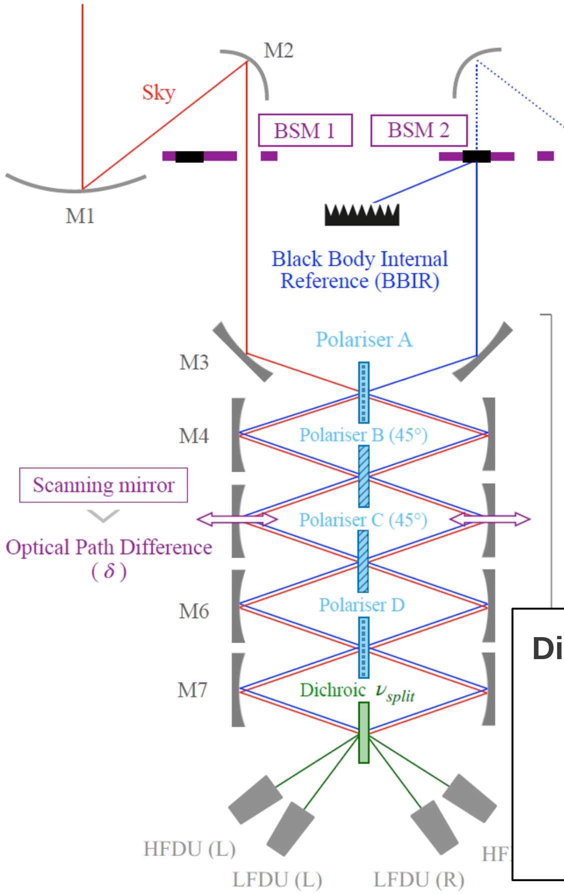


FOSSIL concept from PIXIE
Credits: M. Loquet Le Gall

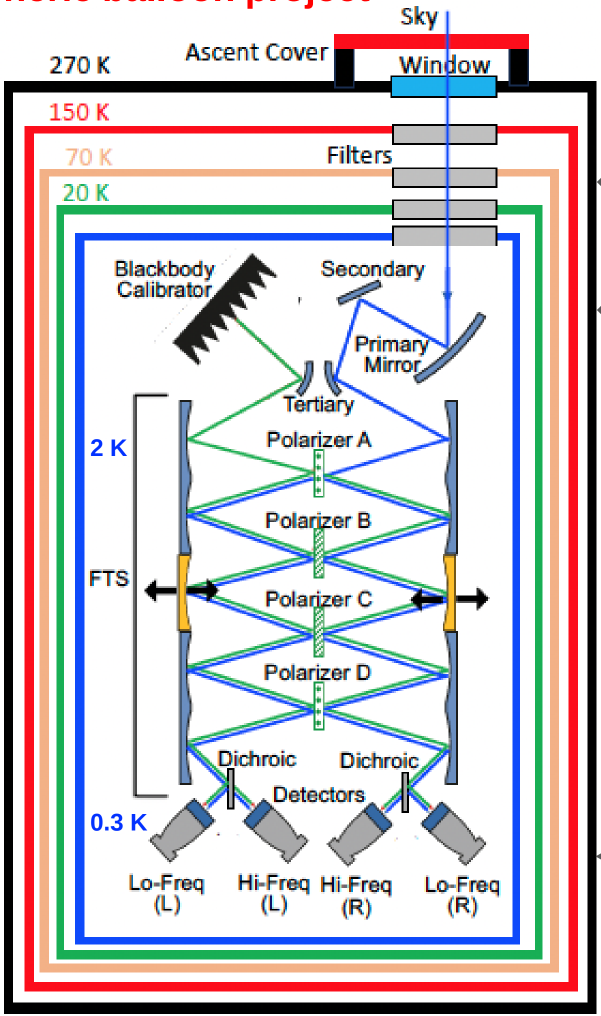
Concept evolution

- Balloon constraints
- Gondola constraints

- Limited mass and volume
- Access to sky
- Residual atm

Differential (Sky-Calibrator) FTS

- 90 GHz – 2 THz band
- 15 GHz spec. resolution
- About 3 deg beam
- NEP_{det} < few 10^{-16} $W.Hz^{-0.5}$ enough



warmer components

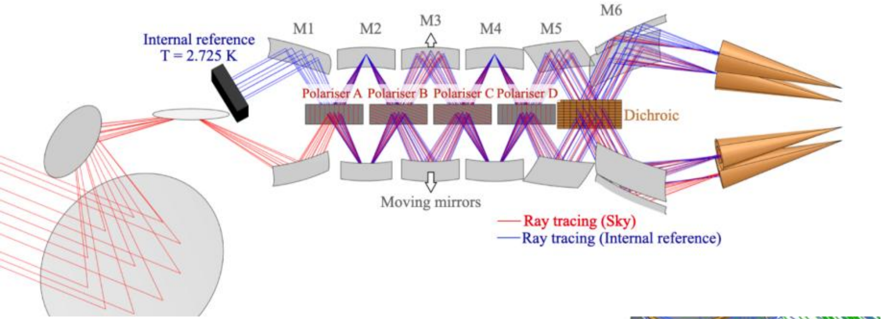
Optics Asymmetry

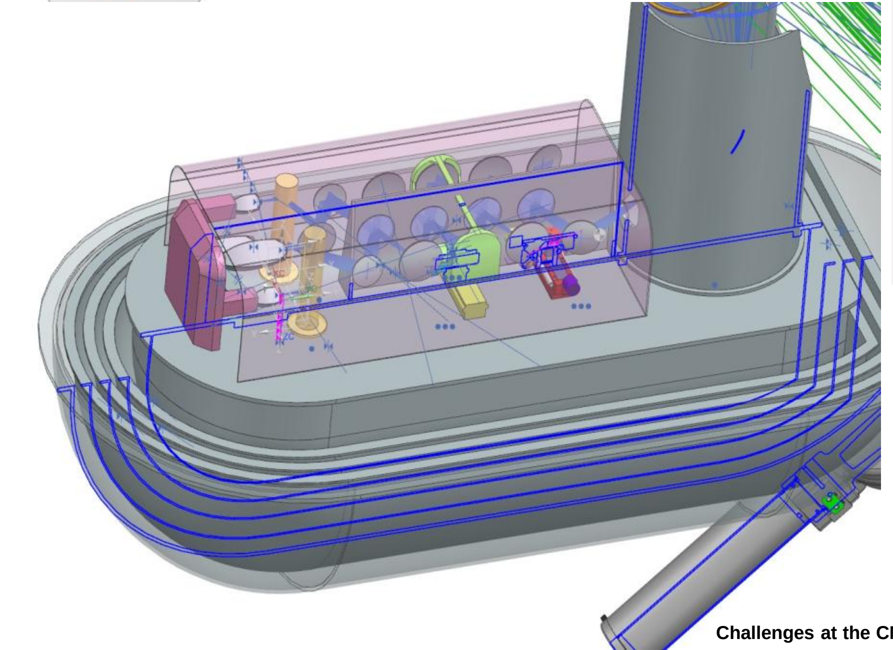
Needs to be within a dewar (extra mass)

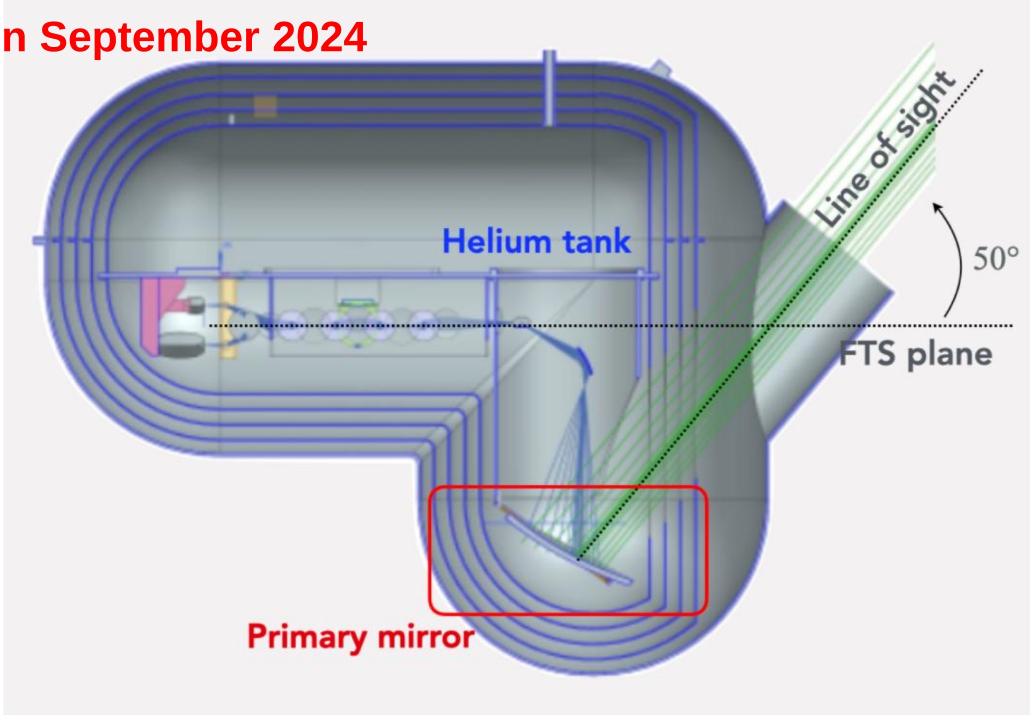
BISOU

CNES Phase A study started in September 2024

see M. Loquet Le Gall's talk

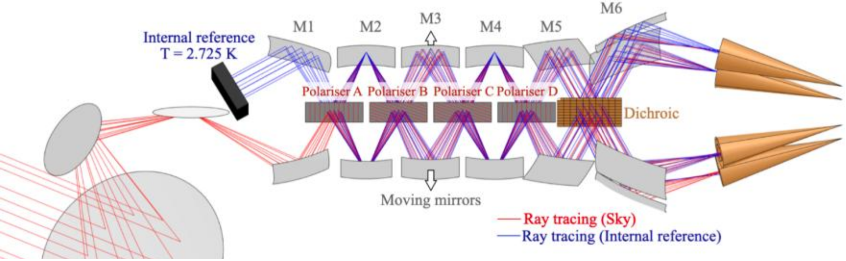


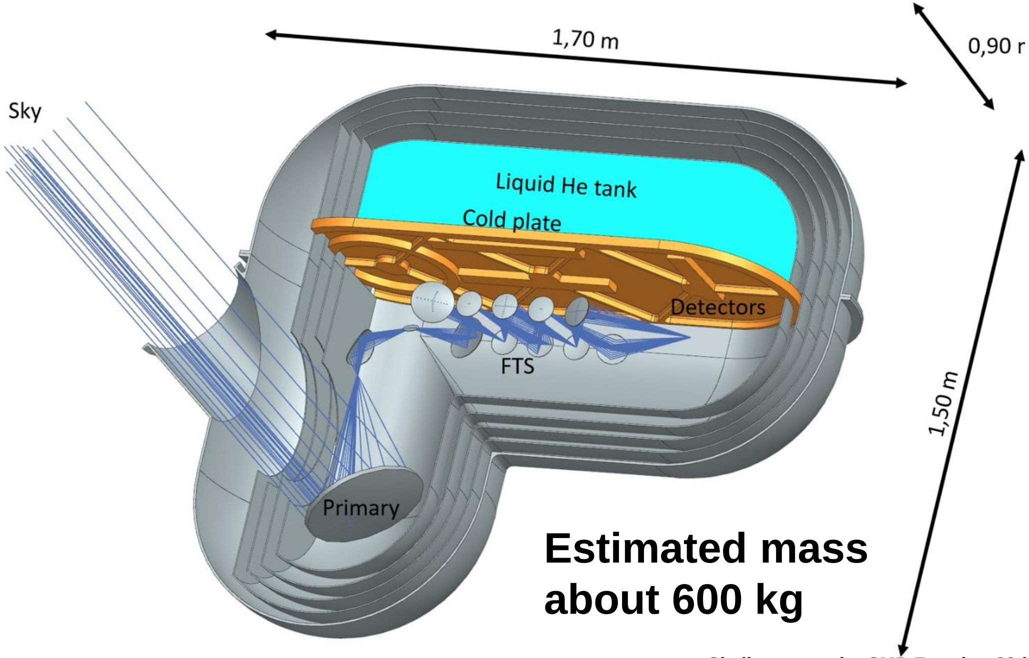




BISOU CAD model.
Credits: B.Borgo

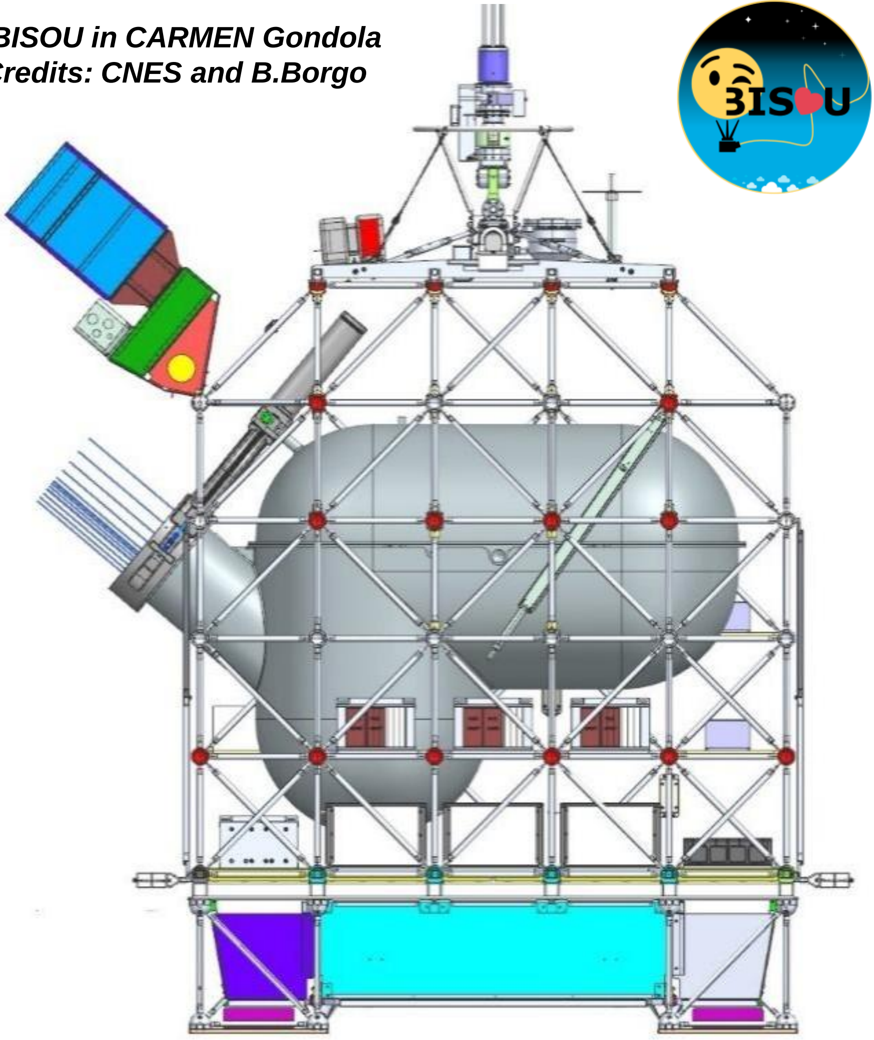
BISOU



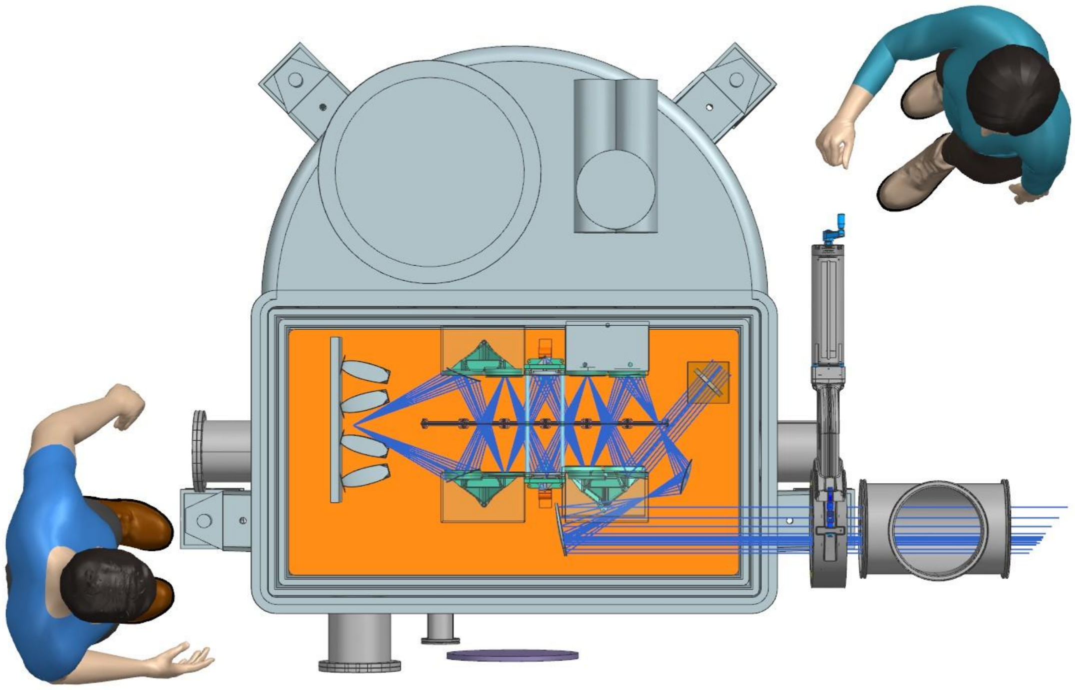


Estimated mass about 600 kg

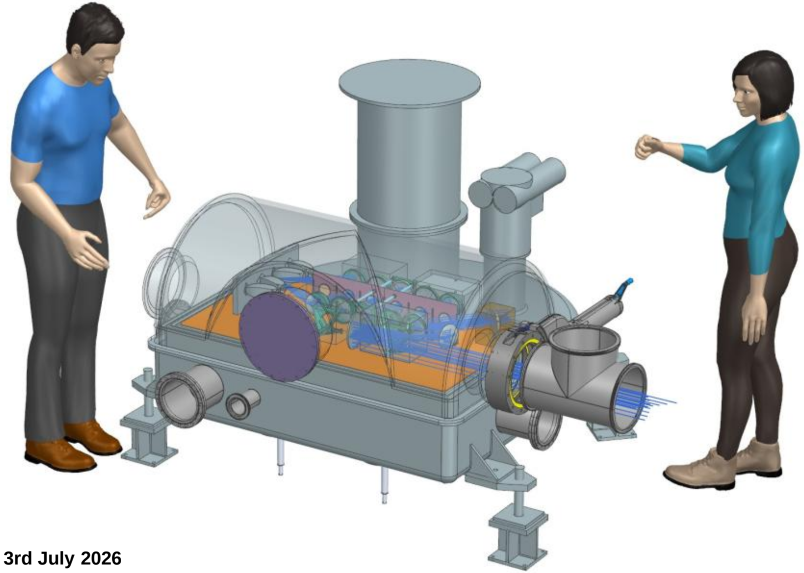
BISOU in CARMEN Gondola
Credits: CNES and B.Borgo



BISOU BreadBoard Model (BBM)



BISOU-BBM
Credits: IAS team



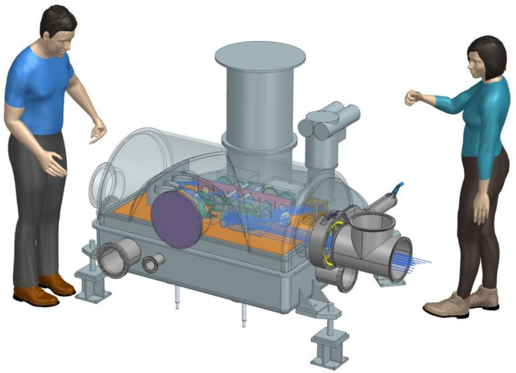
- Laboratory fully representative model of BISOU instrument
- Most of the design performed
- Several parts ordered, to be delivered during summer 2026

Summary of overall strategy towards CMB SD measurements

Voyage 2050 ESA program : ***Spectral distortions of the CMB are listed among the key scientific priorities***

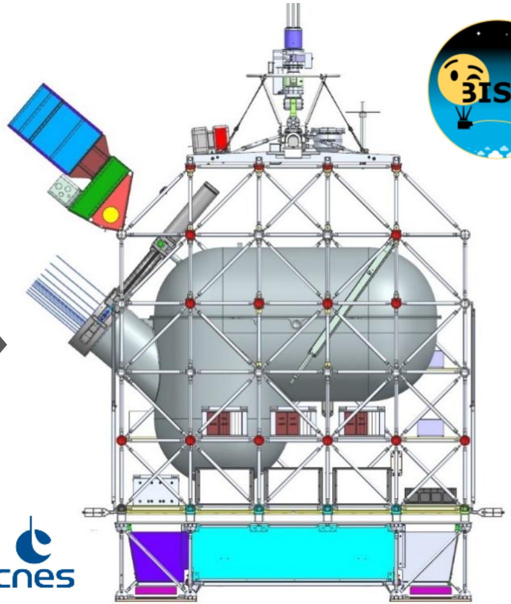
BISOU Laboratory Cryogenic BreadBoard Model

learn, consolidate & de-risk BISOU and prepare technology for a future space mission



BISOU stratospheric balloon pathfinder

CNES Phase A, to measure the y-distortion monopole, more accurate measurement of the CIB & study systematic effects

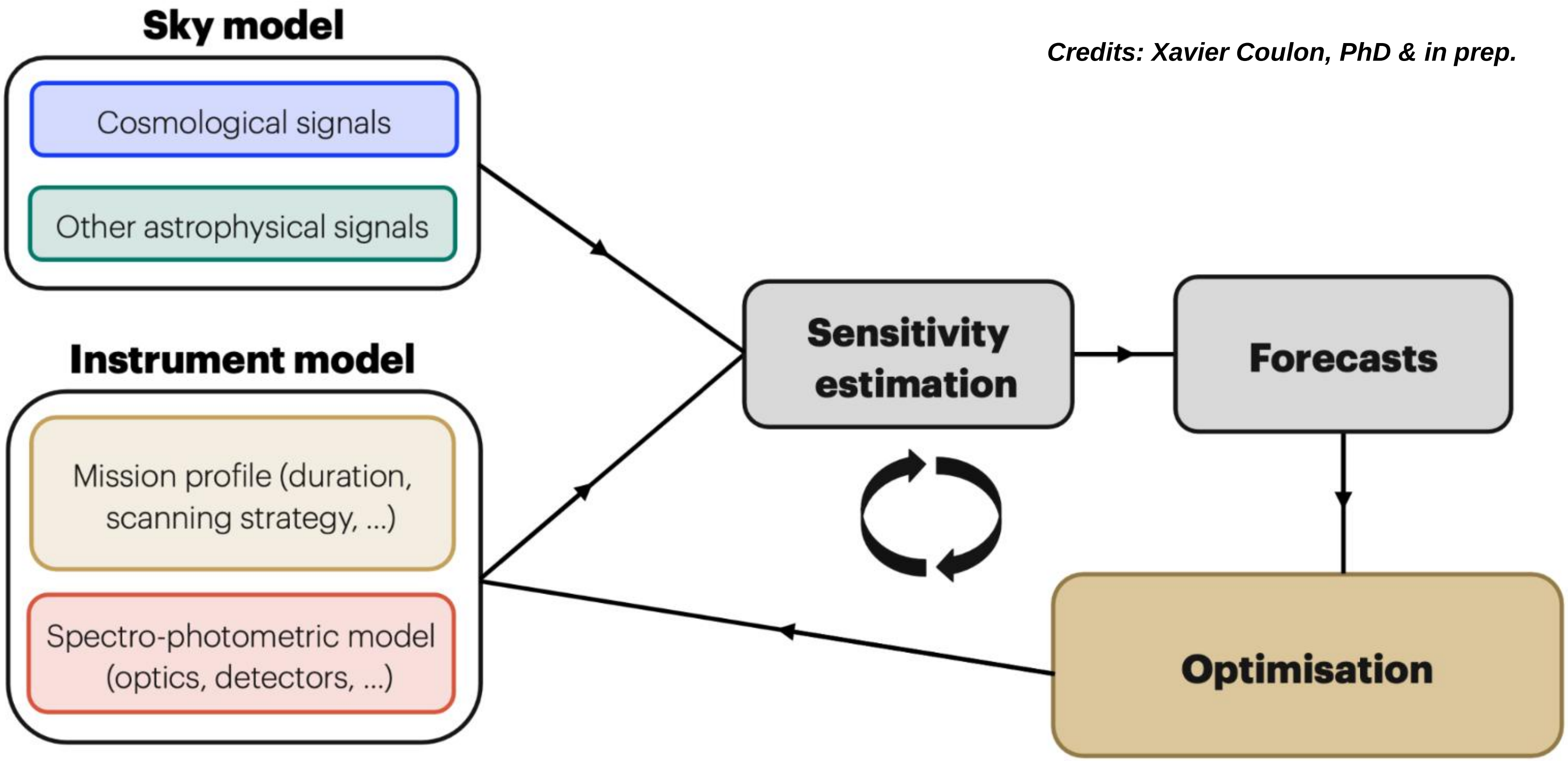


Future space mission FOSSIL ? (--> 2041)

M8 ESA proposal **FOSSIL** (N. Aghanim et al)
step 2 proposal submitted on 19/04/2026
Selection for ESA Phase 0 Nov 2026

Instrument Optimisation and Forecasts

Credits: Xavier Coulon, PhD & in prep.



Sky & Instrument model parameters

Credits: Xavier Coulon, PhD & in prep.

Foregrounds	Parameters
Galctic dust	A_d, T_d, β_d
Synchrotron	A_s, β_s, C_s
Free-free	$A_{ff}, \beta_{ff}, C_{ff}$
AME	$A_1^{ame}, \nu_1, A_2^{ame}$
CIB	$A_{cib}, T_{cib}, \beta_{cib}$
Extragalactic CO lines	A_{CO}
Zodiacal dust	$\epsilon_{th}(\nu), T_{th}, \beta_{th}$
Zodiacal scattering	$\epsilon_{sc}, T_{sc}, \beta_{sc}$

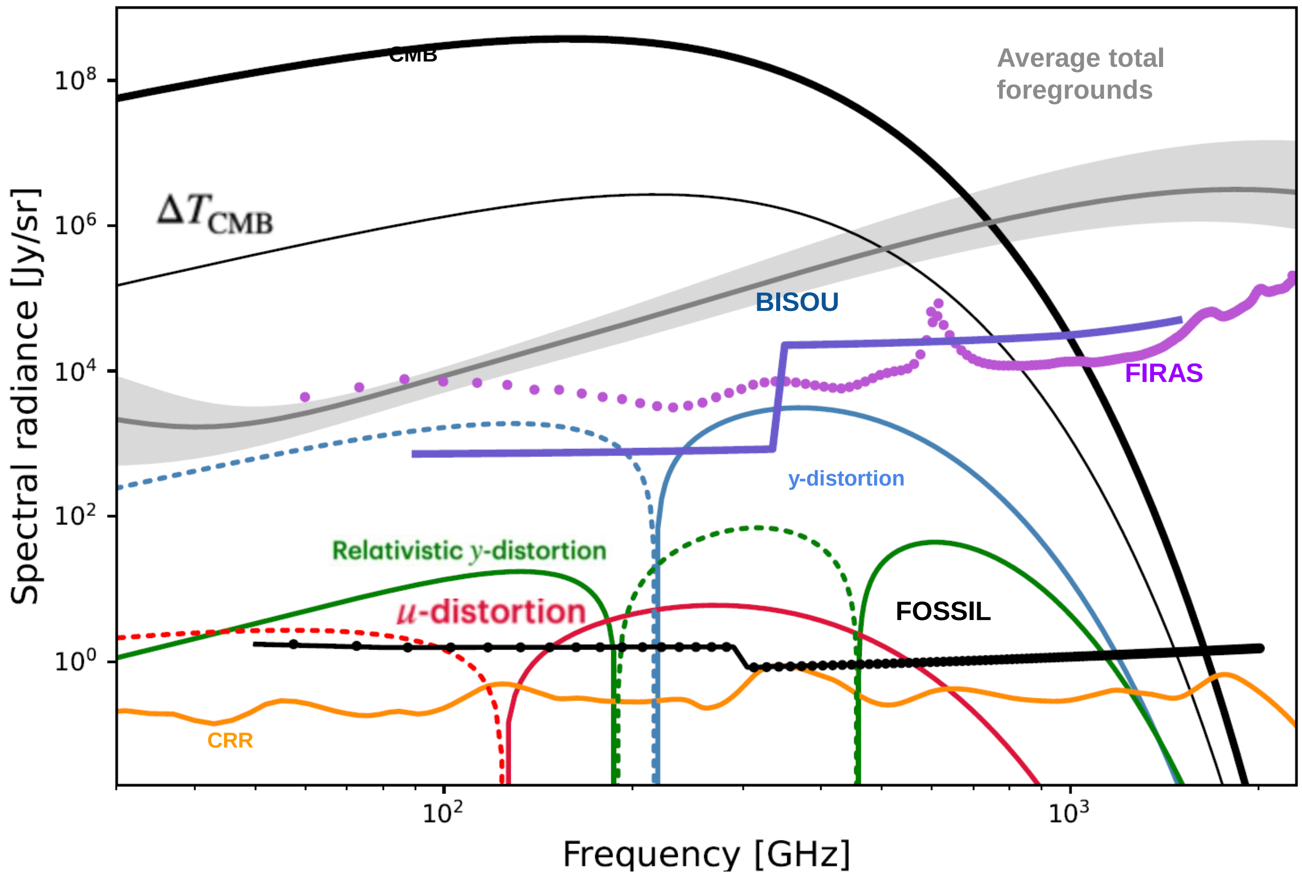
CMB	Parameters
CMB	
CMB temperature correction	ΔT_{CMB}
y-distorsion	y
Relativistic y-distortion	T_e
-distortion	μ

Instrument & mission	Parameters
Minimal frequency	ν_{min}
Maximal frequency	ν_{max}
Splitting frequency	ν_{split}
Spectral resolution	$\Delta\nu$
Detector efficiency	eff_{det}
Number of detectors per FPA	N_{det}
Effective observational time	τ
Number of optical element	K
Transmission of each optical element	$(t_k)_{1\leq k\leq K}$
Temperature and emissivity of optical element	$(\epsilon_k(\nu), T_k)_{1\leq k\leq K}$
Number of mode at the minimal frrequecy	N
Primary mirror diameter	A
Line of sight	$\vec{p}$

New observational window and targets

Credits: Xavier Coulon, PhD & in prep. FOSSIL proposal 2026

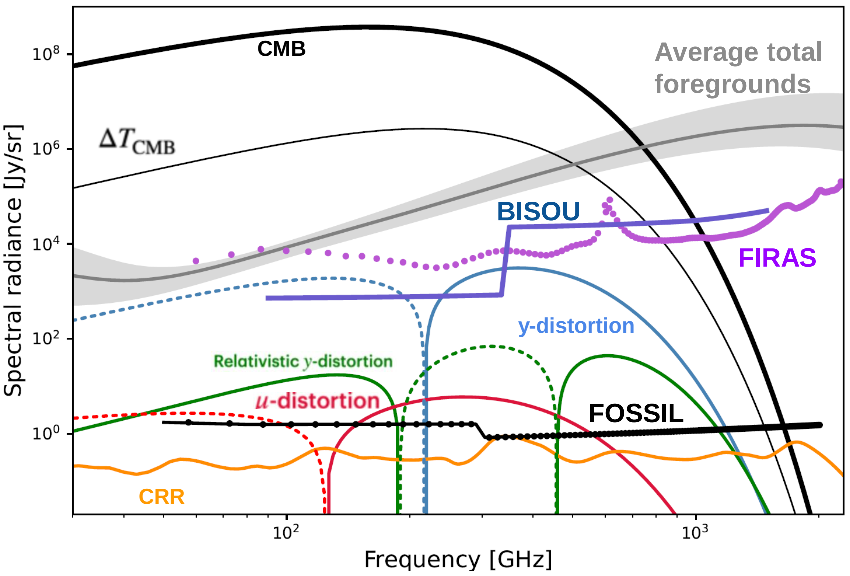
CMB spectral distortions



New observational window and targets

Credits: Xavier Coulon, PhD & in prep.
FOSSIL proposal 2026

CMB spectral distortions



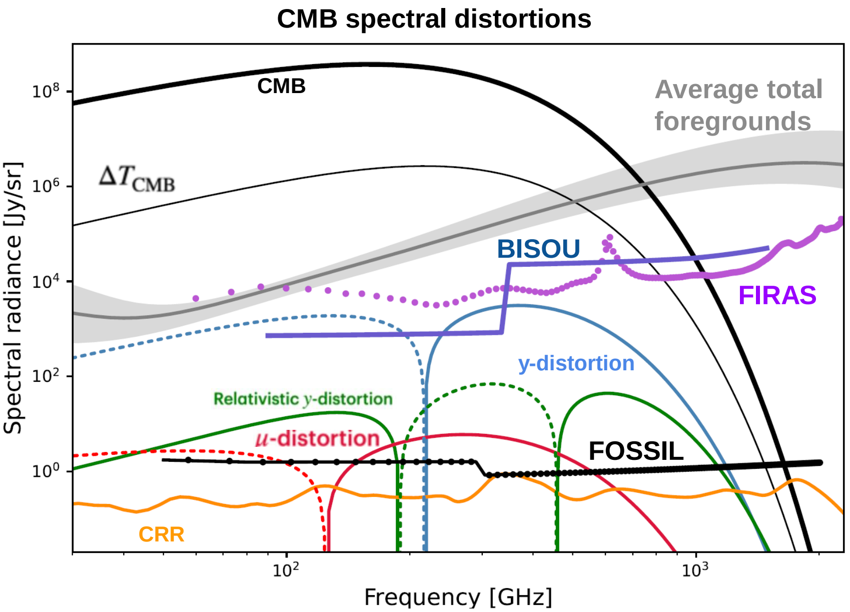
35+ years after FIRAS, a **full-sky absolute spectrometric survey is needed**

BISOU

- Frequency span 90 GHz – 1.5 THz → Ideal for the foreground challenge
- Monopole **y distortion >1 order magnitude better** than FIRAS → at **about 5 σ**
- Consolidate new measurement concept → FOSSIL

New observational window and targets

Credits: Xavier Coulon, PhD & in prep.
FOSSIL proposal 2026



35+ years after FIRAS, a **full-sky absolute spectrometric survey is needed**

BISOU

- Frequency span 90 GHz – 1.5 THz → Ideal for the foreground challenge
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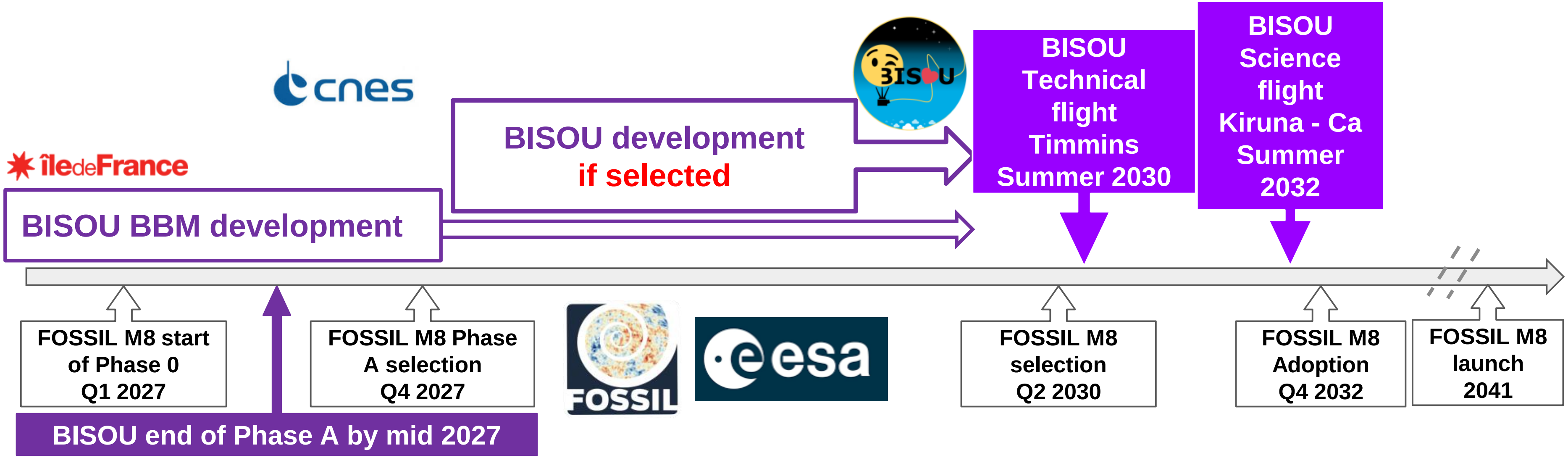
- Consolidate new measurement concept → FOSSIL

FOSSIL : 50 years after FIRAS

- ~130 frequency bands covering 50 GHz - 2 THz → Ideal for the challenge of foreground
- Monopole **y distortion >3 orders magnitude better** than FIRAS → at **hundreds σ**
- Average temperature of hot gas from relativistic SZ down to **$kT_{eSZ} \simeq$ 1.3 keV at tens σ**
- μ distortions **~ a thousand times better** than FIRAS → **μ=2. 10^{-8} at ~σ(μ)=1.5. 10^{-8}**
- **σ(μ)=5. 10^{-9}** when using spatial information (see F. Bianchini and G. Fabbian)

Timeline and Conclusion



CMB spectral distortions is unique probe to understand the history of our Universe

It is scientifically timely and we are ready for it !