Towards CMB spectral distortions from Space

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on behalf of the BISOU and FOSSIL teams

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A new observational window

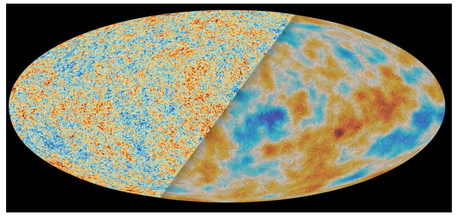
- What drives inflation?
- How did the Universe evolve?
- What is DM made of?
- How did black-holes form? What is the energy injected by SMBH?
- What is the thermal energy in the LSS?

From initial perturbations to formation/ evolution of stars, galaxies and clusters

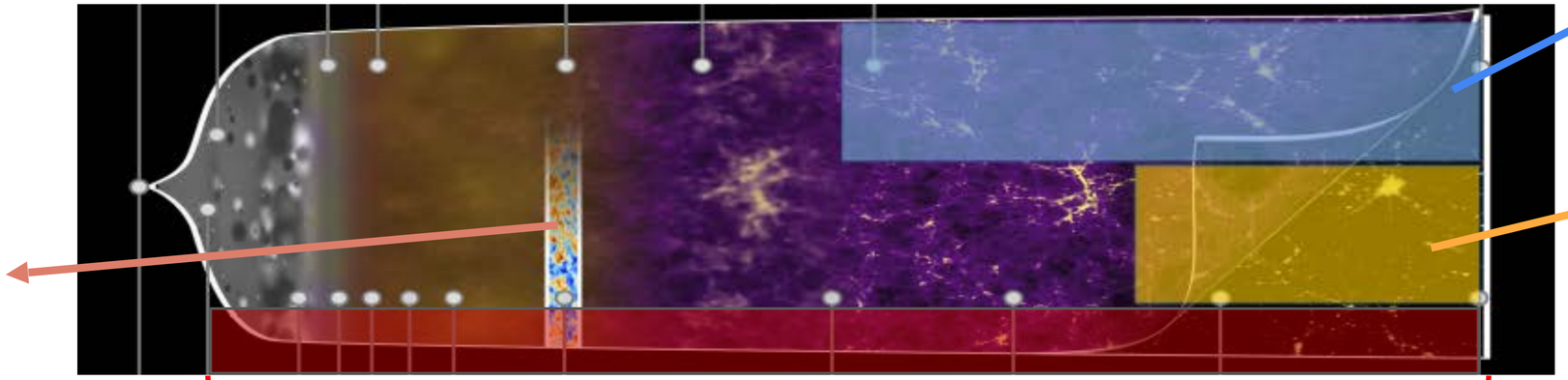
Blackbody distortions (energy release & epoch)

Cf. R. Sunyaev

CMB anisotropies



~13.7Gyrs



21cm (SKA)
First stars

Galaxy surveys
(e.g. Euclid)
First galaxies
(e.g. JWST)

ESA - C. Carreau

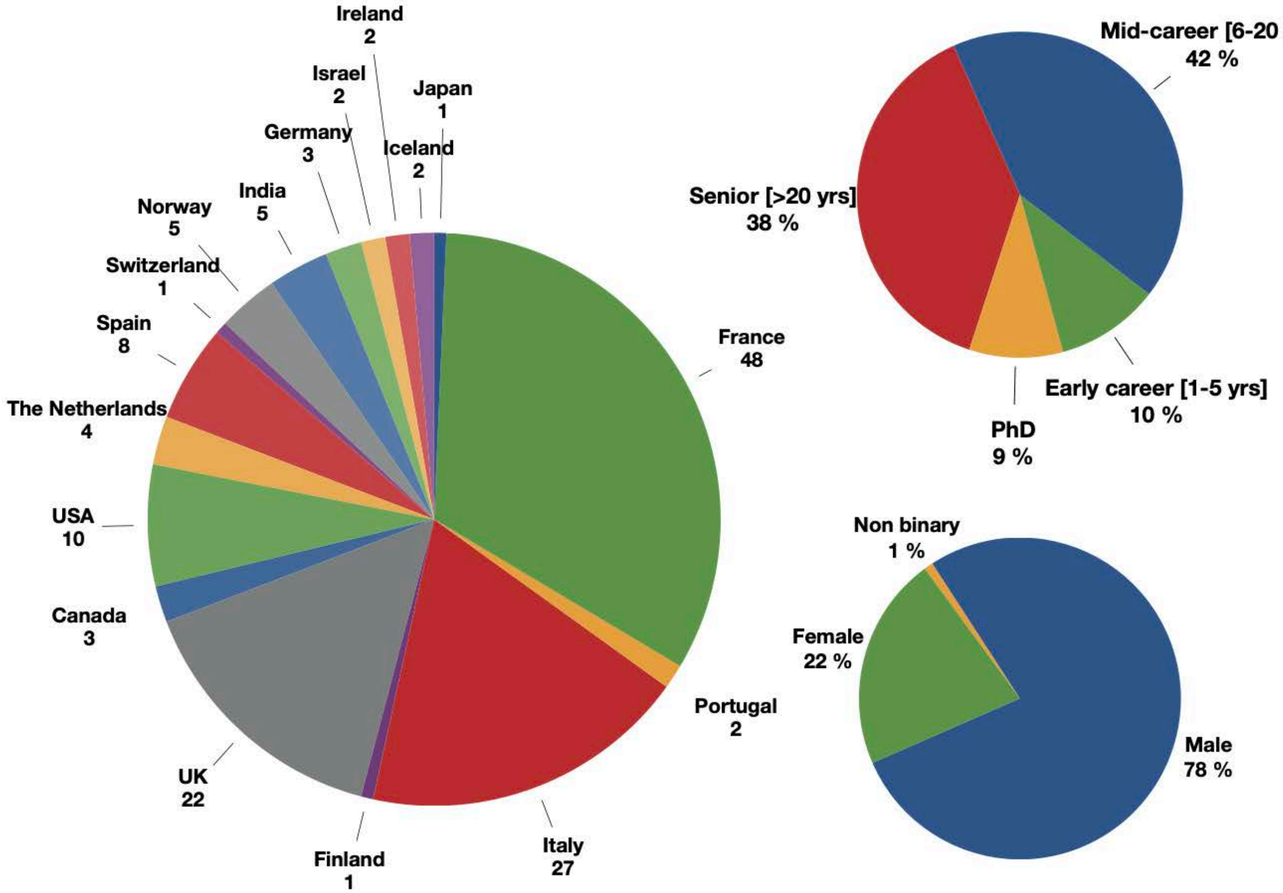
Testing the cosmological model across the history of Universe via Spectral Distortions

FOSSIL

FTS fOr CMB Spectral diStortIon expLoration

A mission concept for the M8 ESA call

A proposal submitted May 21st by ~150 members
(already beyond the WMAP small-team model!)



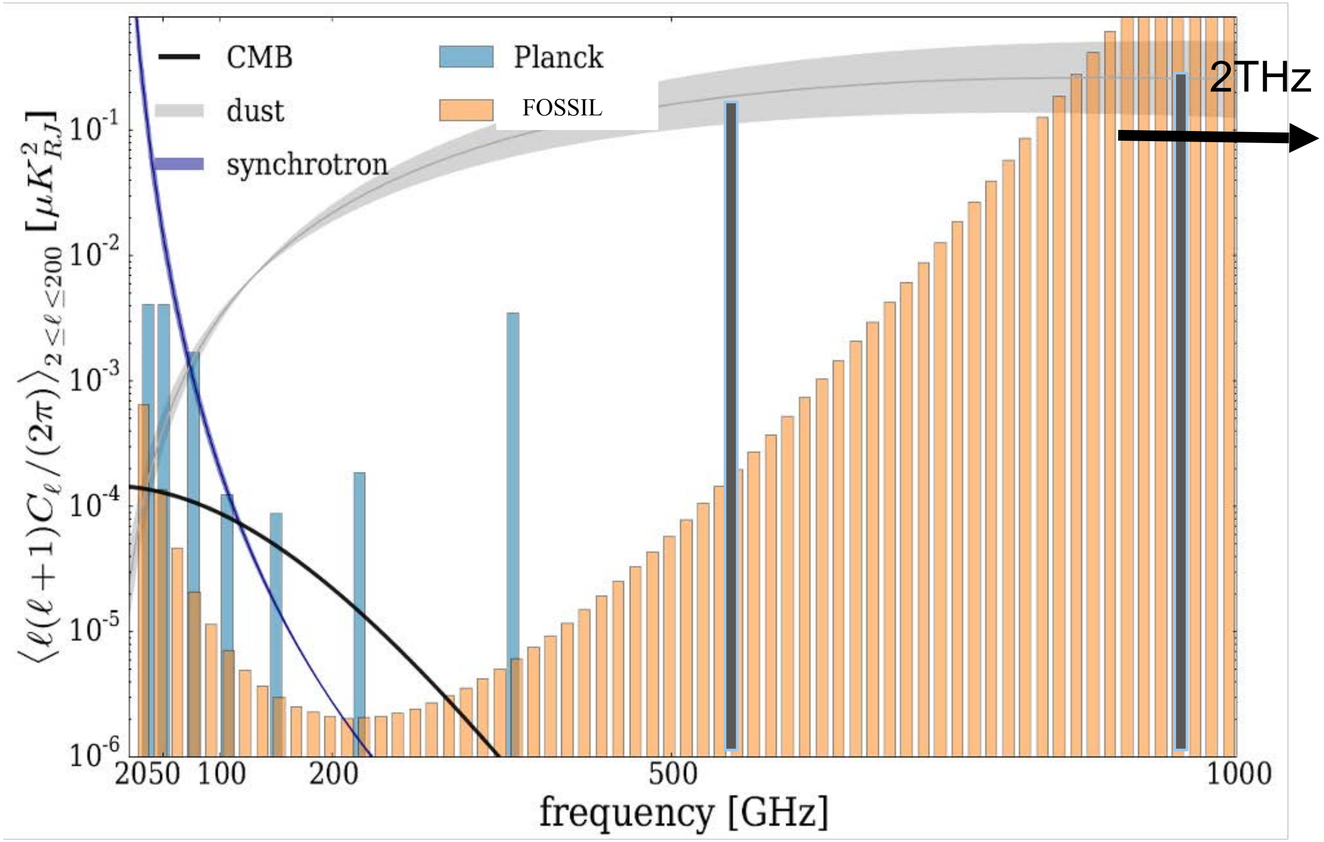
From FOSSIL proposal

FTS f**O**r CMB **S**pectral di**S**tort**I**on exp**L**oration

FOSSIL

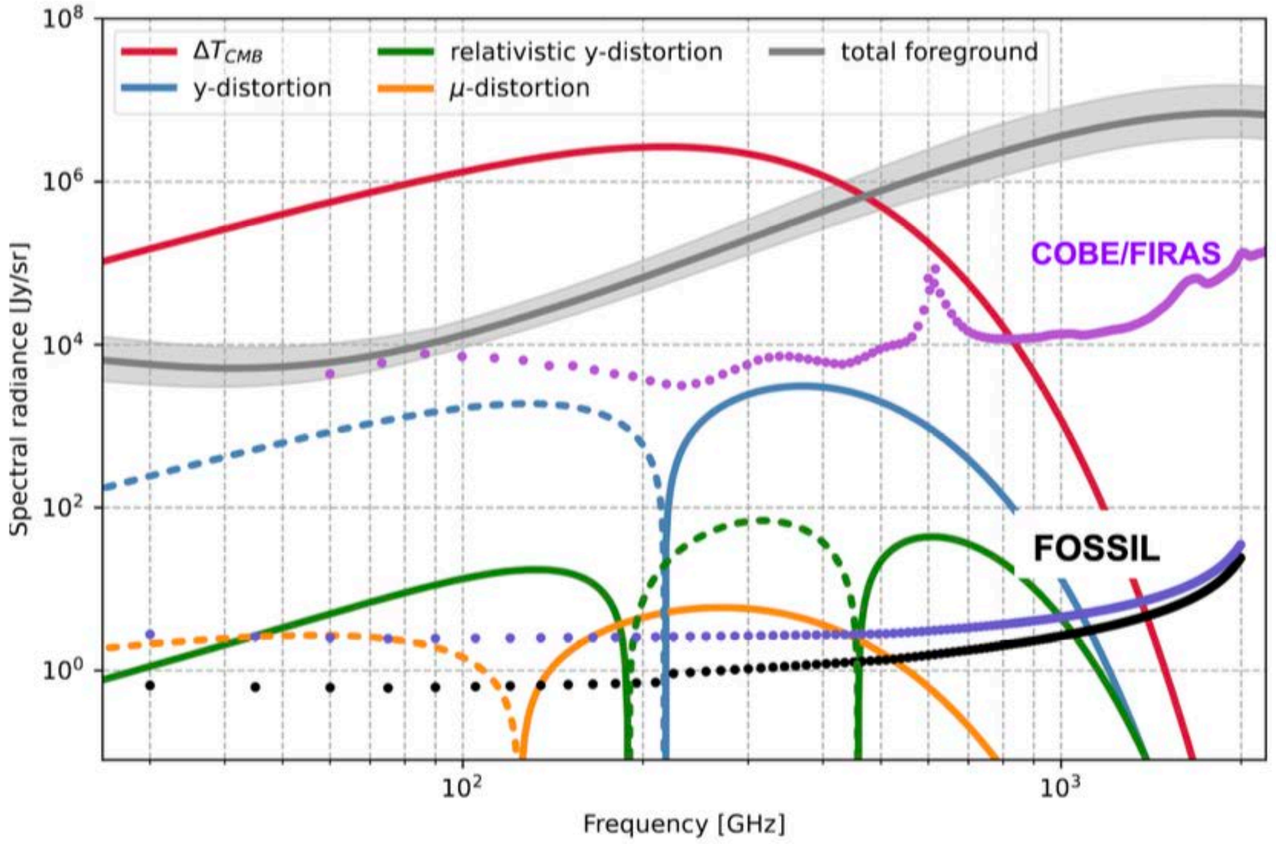
First **full-sky low resolution absolute spectrometric survey** after COBE/FIRAS

- ~ similar frequency coverage: 30GHz — 2THz
- ~130 frequency bands
- 4 years of observations (70% efficiency)
- 10 times better in angular resolution (~2deg)
- ~1000 better in sensitivity and hence many exciting challenges!



A new observational window & three main targets

- Monopole y distortion more than **3 orders magnitude better** than COBE/FIRAS allowing detection at tens of σ → **$y < 10^{-8}$**
- Average temperature of hot gas down to $kT_{sz} \simeq$ **1.3 keV at tens of σ** from measurement of relativistic SZ
- μ distortions **~thousand time better** than the COBE/FIRAS → **$\mu = 2.\ 10^{-8}$** at ~4σ
  [marginalising over high-frequency foregrounds & 20% prior on low frequency ones]

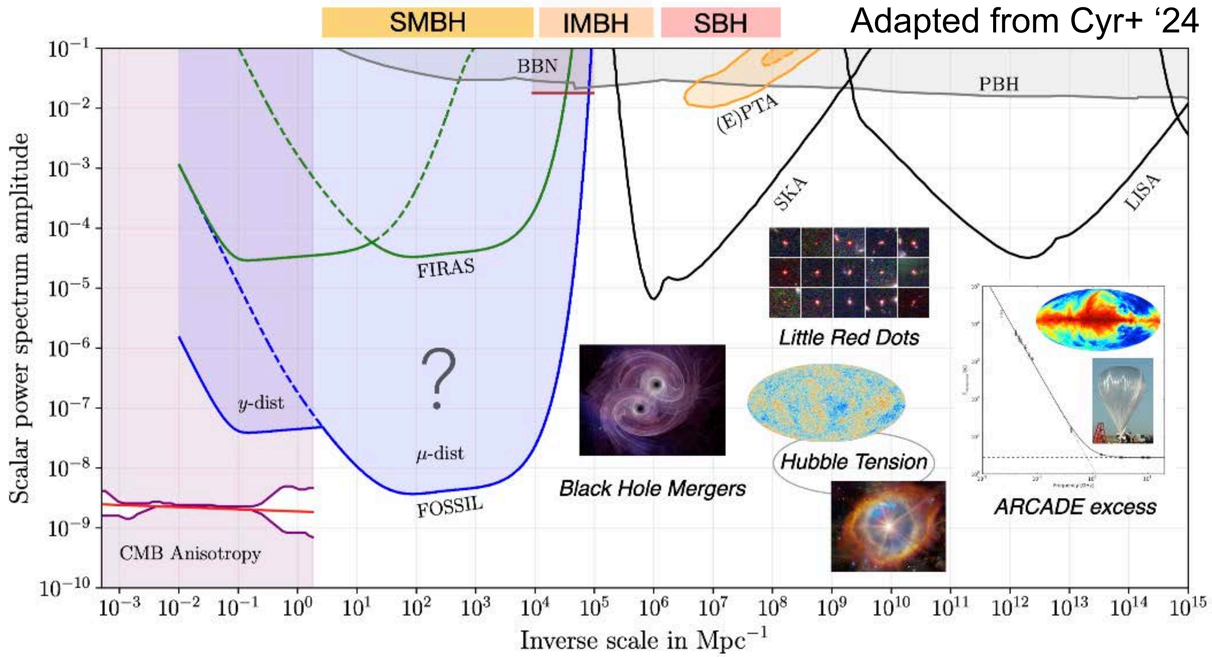


From FOSSIL proposal, Credits Xavier Coulon

Goal: Probing density perturbations

Cf Jens Chluba

- **Probe primordial power spectrum** → Open a **unique window to density perturbations** at unexplored small scales down to a few tens of pc
- Constrain the **origin of BHs** and the population of primordial BH intermediate-mass and stellar-mass
- **Constrain/detect effects of inflation**. Any departure from the standard model prediction of μ would rule out the single-field, slow-roll inflation

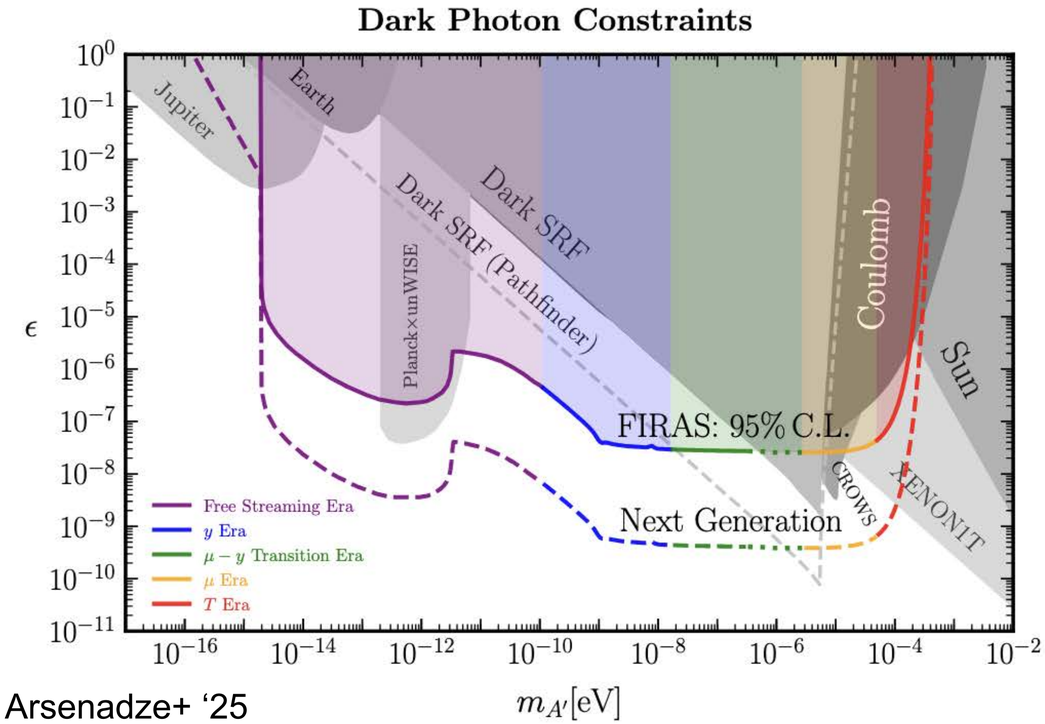


Also Daly 1991
Hu, Scott, & Silk 1994
Chluba, Erickcek, & Ben-Dayan 2012
Sunyaev & Khatri 2013

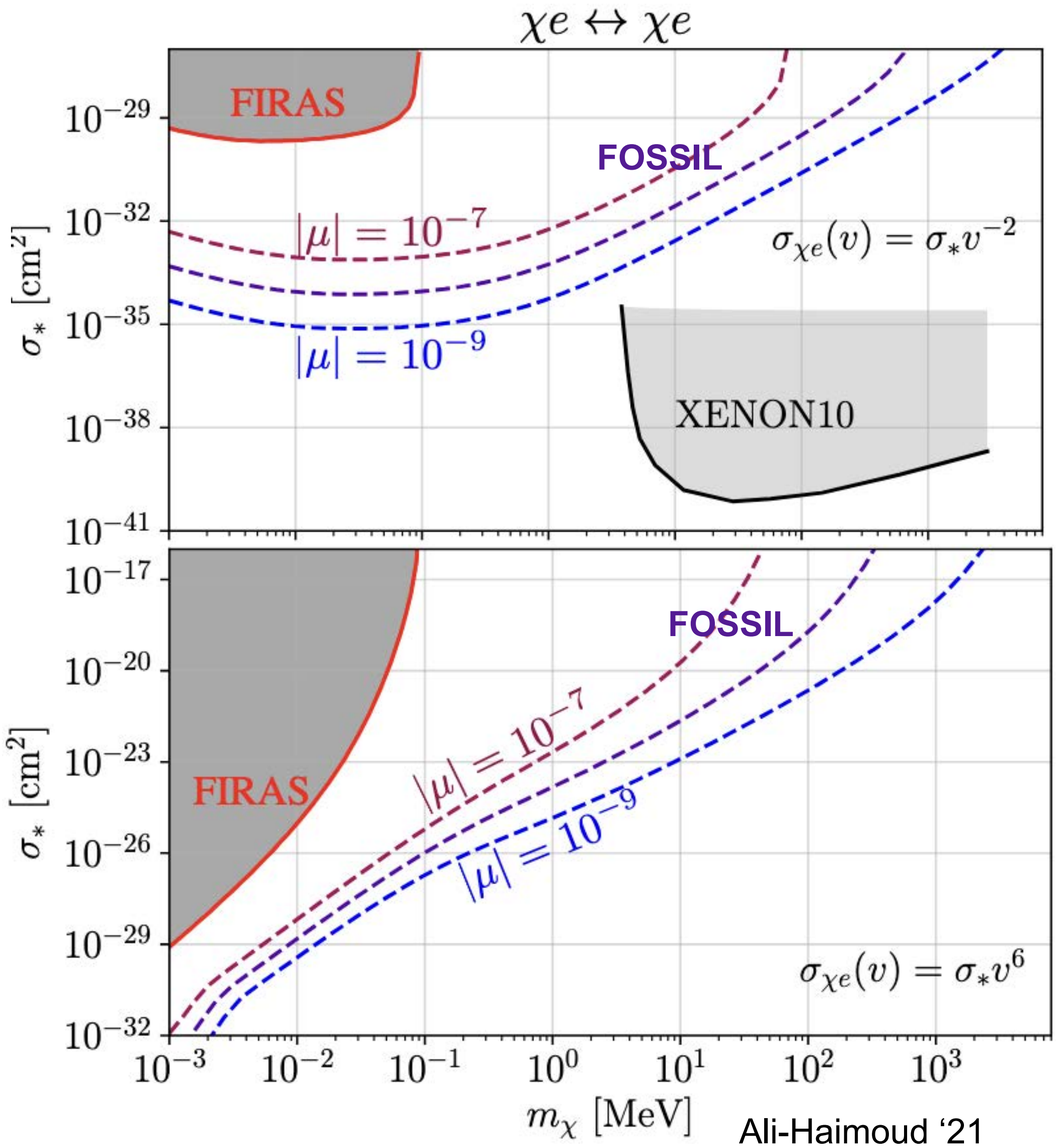
Goal: Probing the dark sector

Spectral distortions from DM decay, annihilation and scattering with standard model particles

- Constrain the **nature of DM** by probing its interactions with baryons & photons
- Signatures of **γ → dark-γ conversion**



Arsenadze+ ‘25



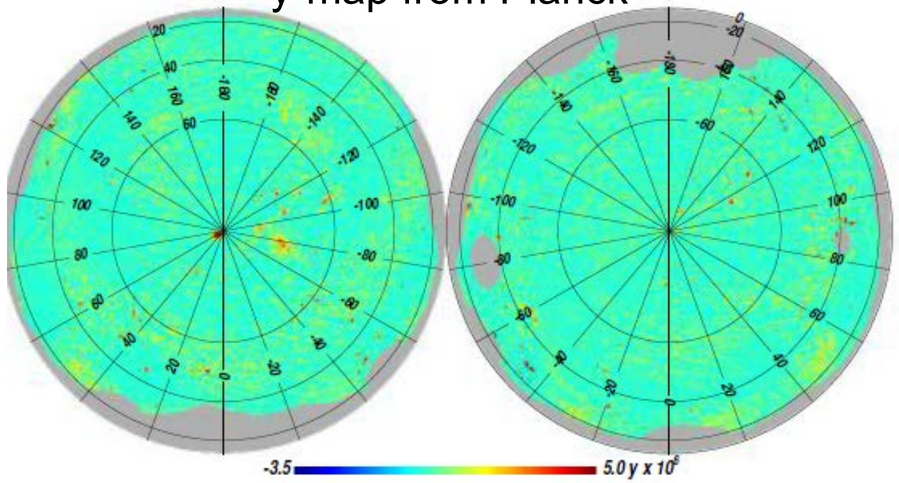
Ali-Haimoud ‘21

Goal: Probing LSS formation/evolution

Energy release at $z<10^3$ from collapse of baryons in clusters & cosmic web → y distortion traces Cosmic Web **hot gas content**

- **Thermal energy** in LSS
- **Temperature of hot gas** down to $T_{eSZ} \simeq 1.3$ keV
- Sub-percent level constraints on total **energy injected by SuperMassive BHs**

y-map from Planck

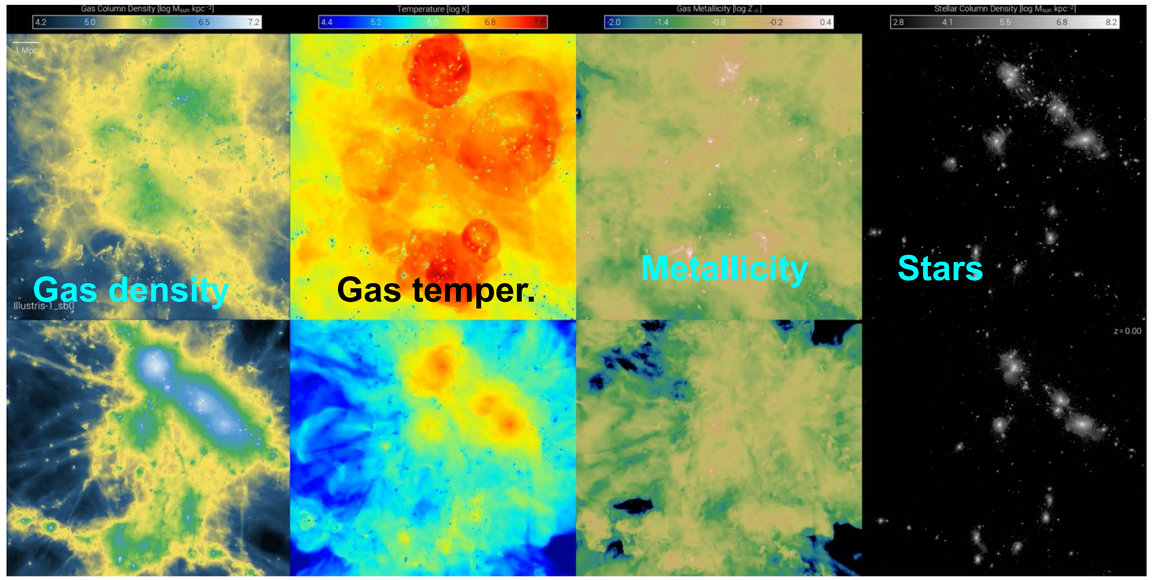


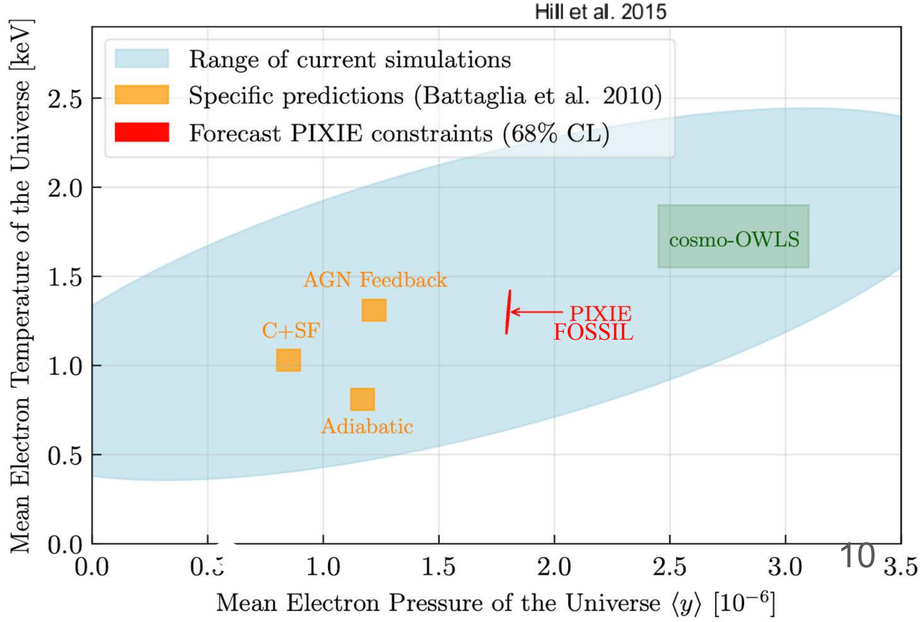
Planck 2015 XXII, arXiv:1502.01596
Khatri & Sunyaev 2015, arXiv:1505.00781
Hill et al. 2015

Credits. TNG-project.org

Feedback model1

Feedback model2



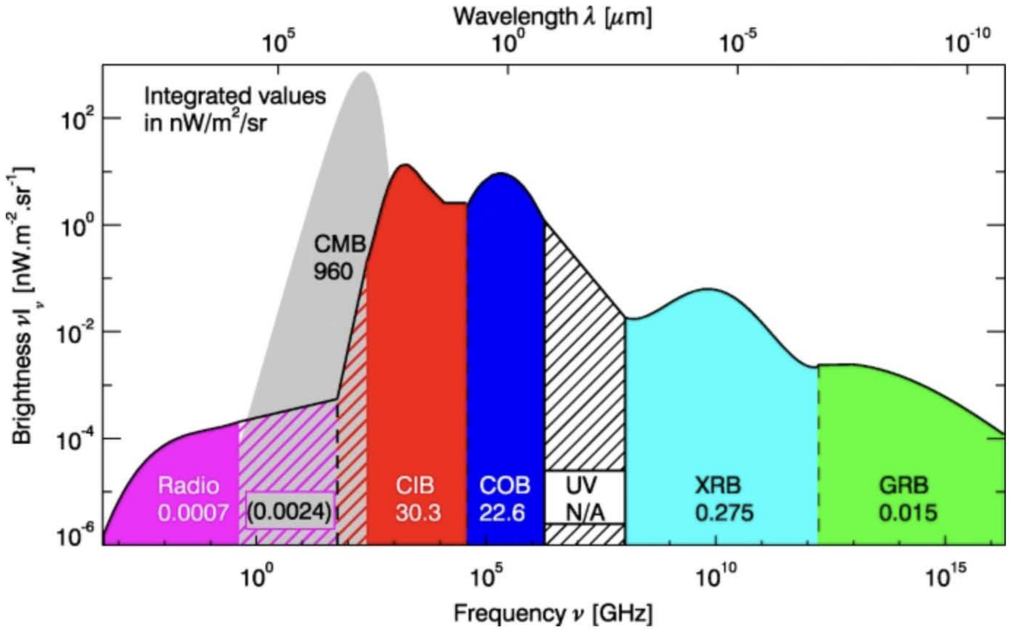


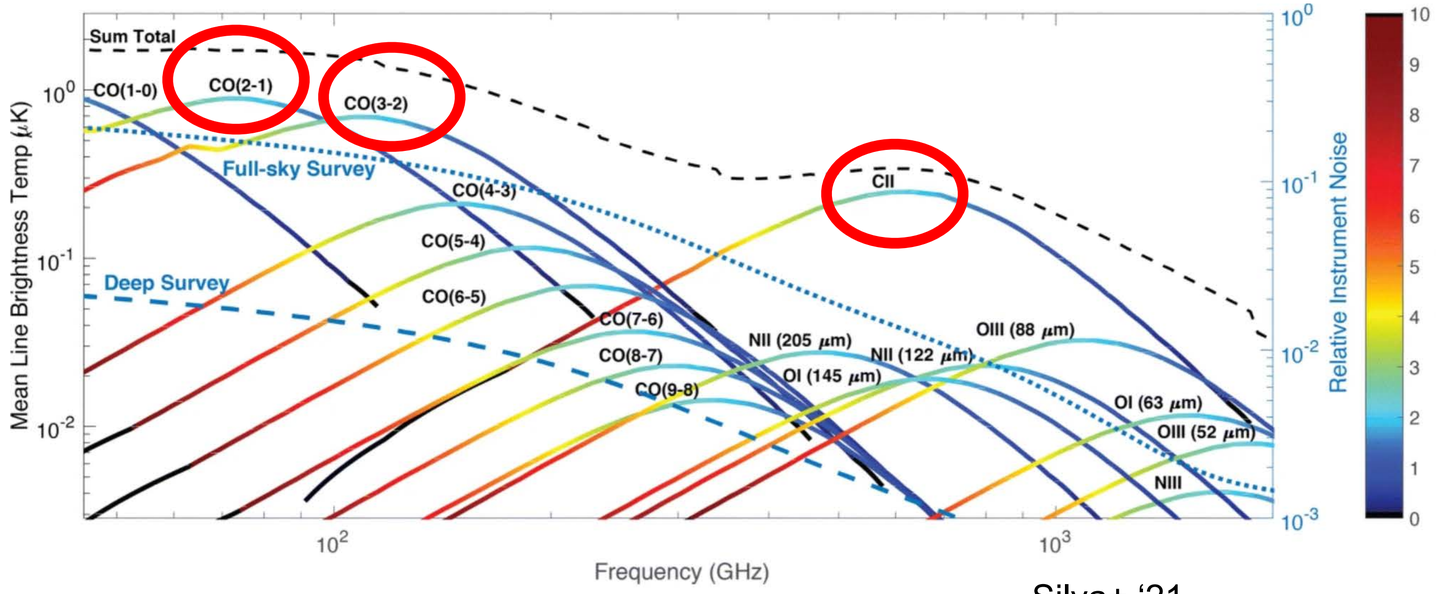
And: Probing cosmic star formation

Tracing star formation and metal enrichment across time

- **Absolute intensity of CIB** (z=2–3) @percent level → **Cosmic star-formation history**
- Monopole emission and low-resolution intensity maps of **far-IR lines** (CII & CO) in **star-forming galaxies at cosmic noon**

CIB = Second brightest after CMB

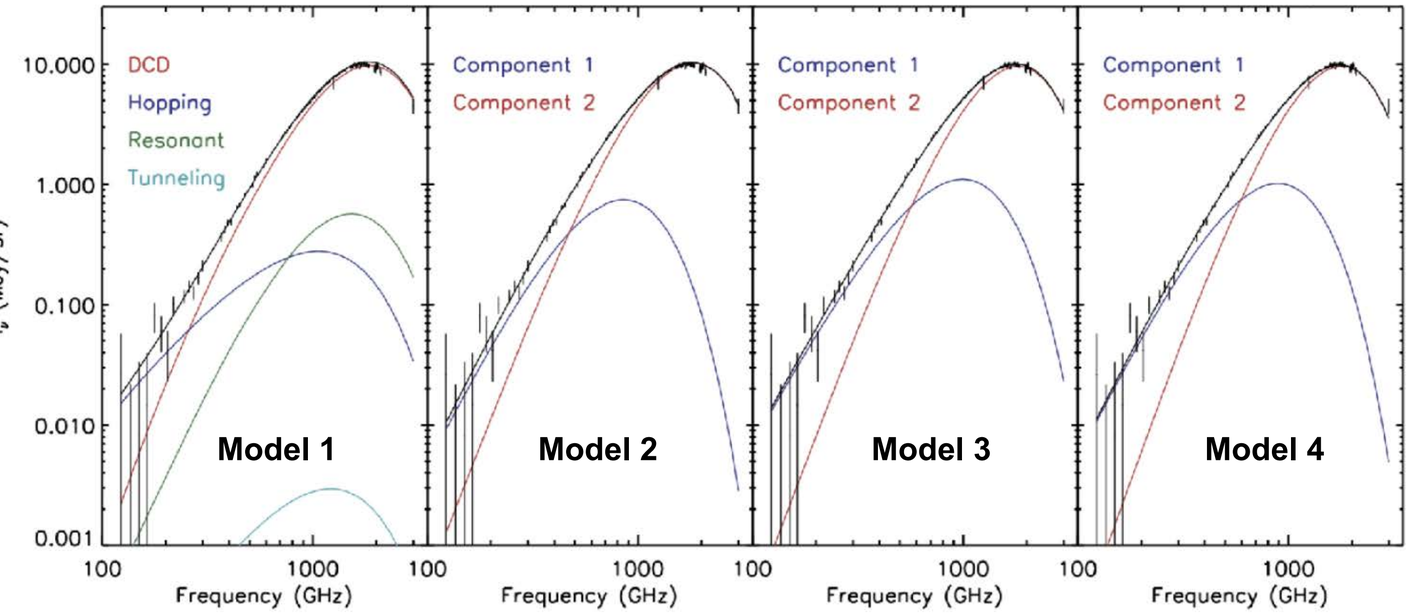




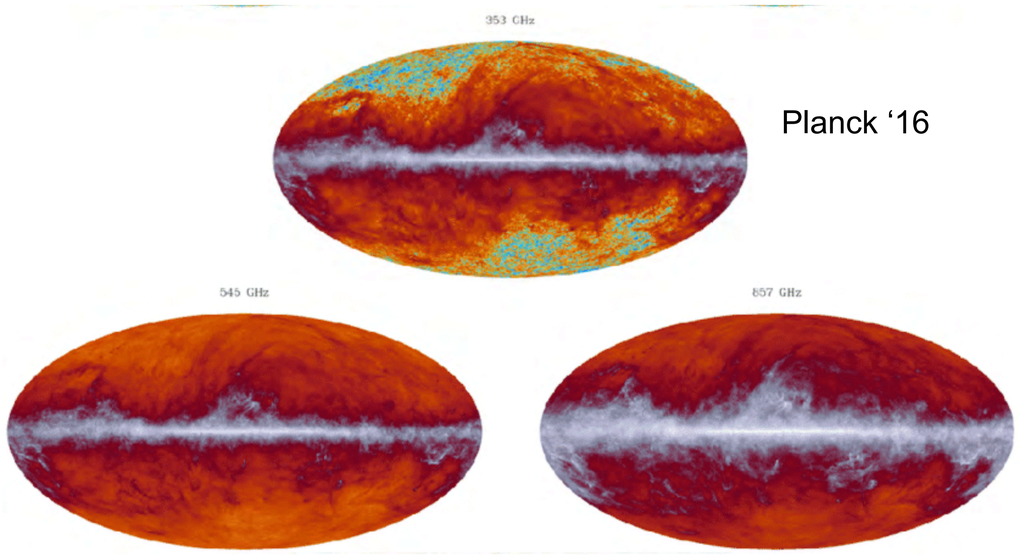
Silva+ ‘21

And: Milky way & foregrounds

Dust properties & SED → spatially variable foreground models for Bmodes, **Physical conditions of ISM phases** from emission lines, and many more

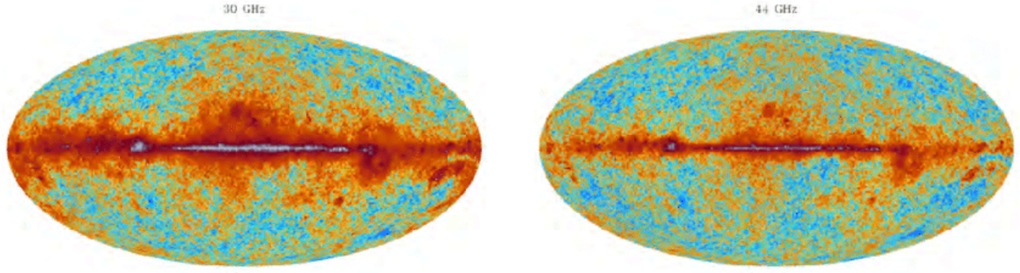


Odegard+ ‘16



Planck ‘16

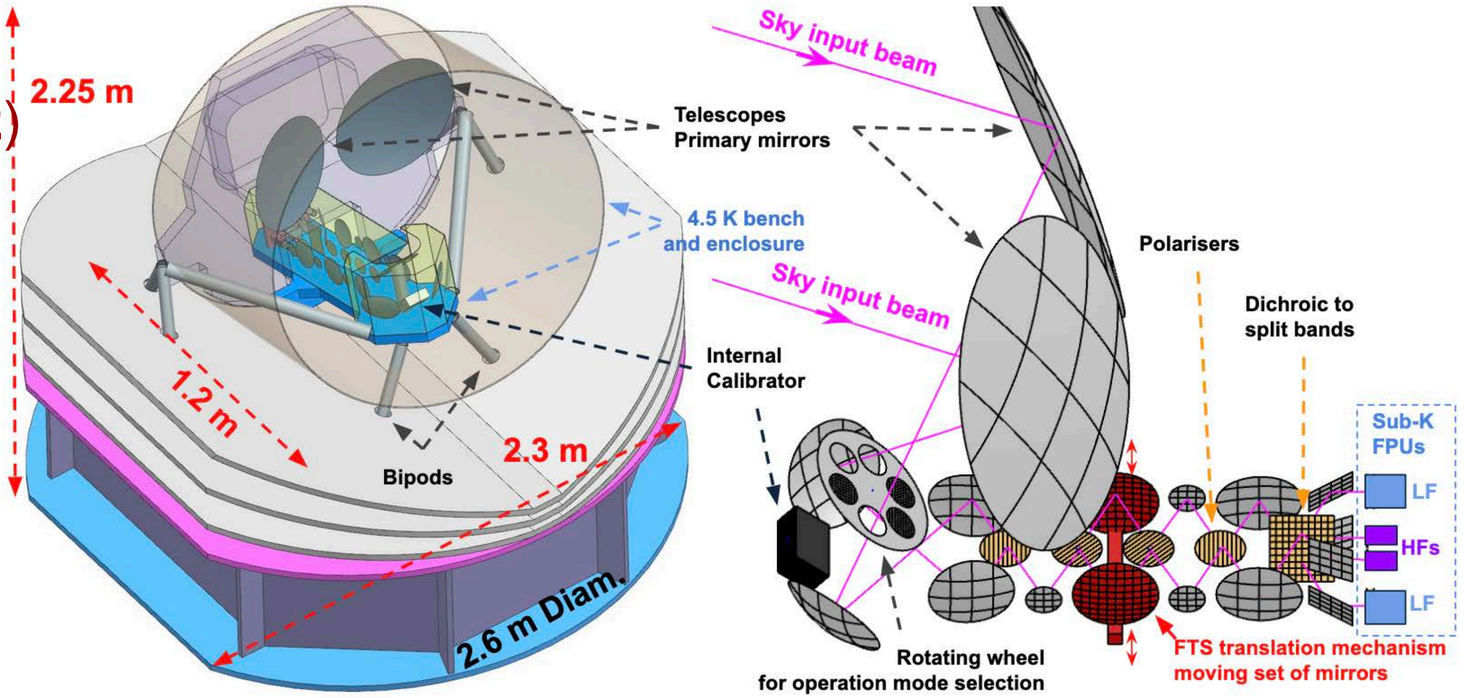
Kogut+ ‘11



Molecular Gas		Photodissociation Regions		HII Regions		Hot ($T > 10^5$ K) Gas	
CO $1 \rightarrow 0$	115 GHz	FeII	51.3, 87.4 μm	FeIII	51.7 μm	OIII	51.8 μm
CO $2 \rightarrow 1$	231 GHz	FeI	54.3, 111.2 μm	NIII	57.3 μm	NIII	57.3 μm
CO $30 \rightarrow 29$	3438 GHz	SI	56.3 μm	FeII	87.4 μm	FeV	70.4 μm
H_2O	22 GHz	OI	63.2 μm	FeIII	105.4 μm	OIII	88.4 μm
H_2O	183 GHz	SiII	68.5, 129.7 μm	NII	121.9 μm		
CS $1 \rightarrow 0$	49 GHz	OI	145.5 μm	SiII	129.7 μm		
CS $2 \rightarrow 1$	98 GHz	CII	157.7 μm	NII	205.2 μm		
CS $4 \rightarrow 3$	196 GHz	CI	370.4, 609.1 μm				

FOSSIL instrument concept

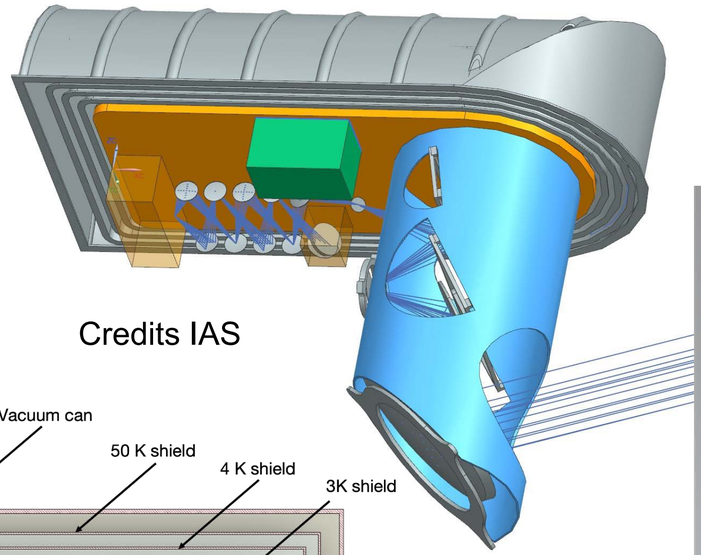
- **Heritage: PIXIE (2011,2016 NASA MidEx), PRISTINE (2018 ESA F1)**
  - 30 to 2000 GHz (**bands split ~200 GHz**)
  - Δv=15GHz
  - Resolution ~2 deg eq Gaussian beam
  - Sensitivity ~0.7 Jy/sr @[30 GHz]
  - Intensity measured wrt BB calibrator
- **Instrument**
  - Instrument in an enclosure at ~2.7 K
  - 2 telescopes: 50 cm primary aperture
  - FTS: 2 inputs (Sky & Calibrator) & 2 outputs
  - Internal calibrator @ 2.5 - 2.9 K
  - 4 FPUs (2 spectral bands per FTS output)
  - Very small number Multimoded detectors @ ~100mK
    - Resistive bolometers or KIDs or TES



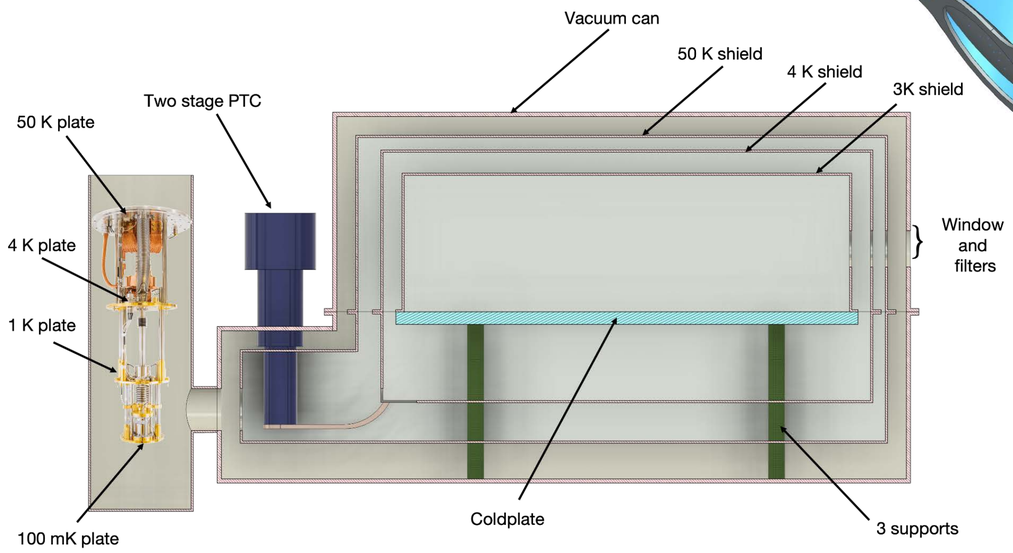
Instrument collaboration: ESA & France, Italy, UK, Spain, Ireland, Norway, Iceland, Netherlands, … & USA

Preparing for FOSSIL with BISOU

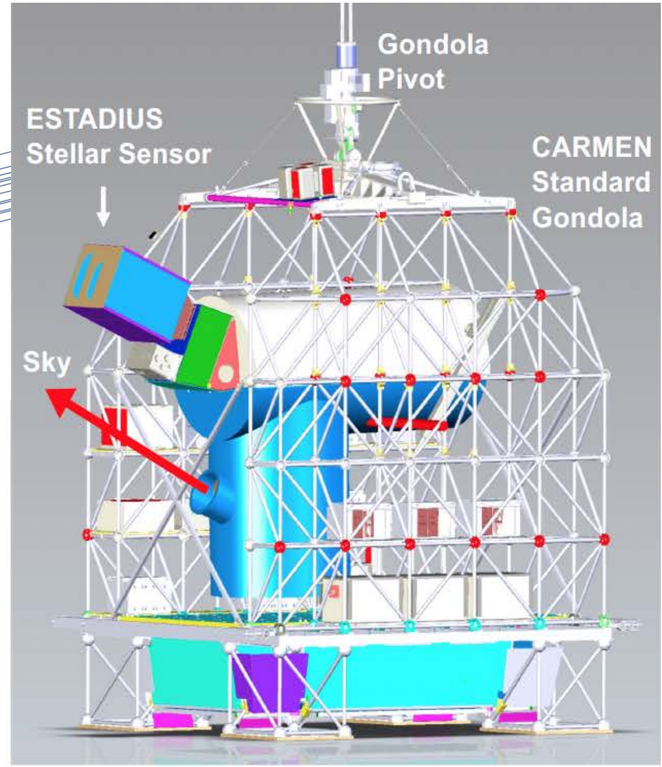
De-risking the concept & increasing TRL of subsystems via ongoing Phase A study, R&D and technical activities funded by CNES **pathfinder balloon (BISOU)** + ground-based experiment (**TMS @IAC**) + ground-based project (**COSMO, cf P. De Bernardis**), and many others



Credits IAS



Credits CNES



Why should we do it **NOW**?

A survey of the absolute intensity of the sky from 30 to 2000 GHz in hundreds of channels with an FTS in 2040s is timely

To probe the thermal history of the Universe across its evolution from inflation to the formation of LSS.

Factor ~1000 improvement allowing spectral distortion detection will:

- Constrain primordial density perturbations at scales unattainable otherwise
- Constrain formation of BHs
- Probe the nature of dark matter
- Constrain total energy injected by the formation and evolution of structures
- Probe diffuse galactic components across the Milky Way

➢ **Coherent with strategic plans** of ESA (Voyage 2050), Astronet,… & national agencies

➢ **Opens the future** & consolidates and **materialises community leadership** based on

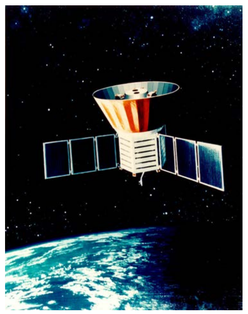
→ Key **instrumental developments** (concept & technology mature or clear paths for their maturation in time)

→ **Scientific leadership** in CMB and in the main (spectral distortions) & additional (LSS, Milky way) objectives

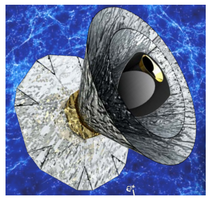
→ **Heritage** from CMB ground based, balloon & space missions

Towards CMB spectral distortions from Space

Sole observation from space —> CMB is a BB but not quite!

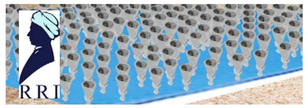


COBE/FIRAS



PRISM

ARCADE



APSERa

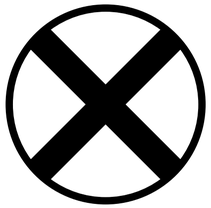
COSMO

ESA - M8

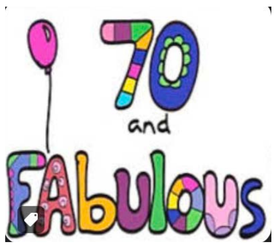
A unique opportunity

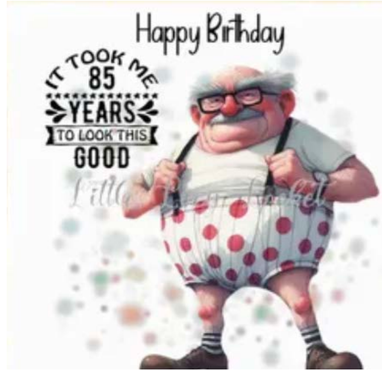
ESA - L6?

Too late if the only option!



~1970 ~1990 ~2010-2025 ~2040 ~2055





“We” **don’t want to do every thing, “we” want to do something** “(SD)” **and do it fast**

(Adapted from D. Wilkinson)

You’re welcome to help us shape the science case and instrument of FOSSIL

Contact N. Aghanim, J. Chluba, B. Maffei or other FOSSIL members