BISOU and the path towards a CMB spectrometer mission.

Balloon Interferometer for Spectral Observation of the primordial Universe

B. Maffei
for the BISOU and FOSSIL collaborations

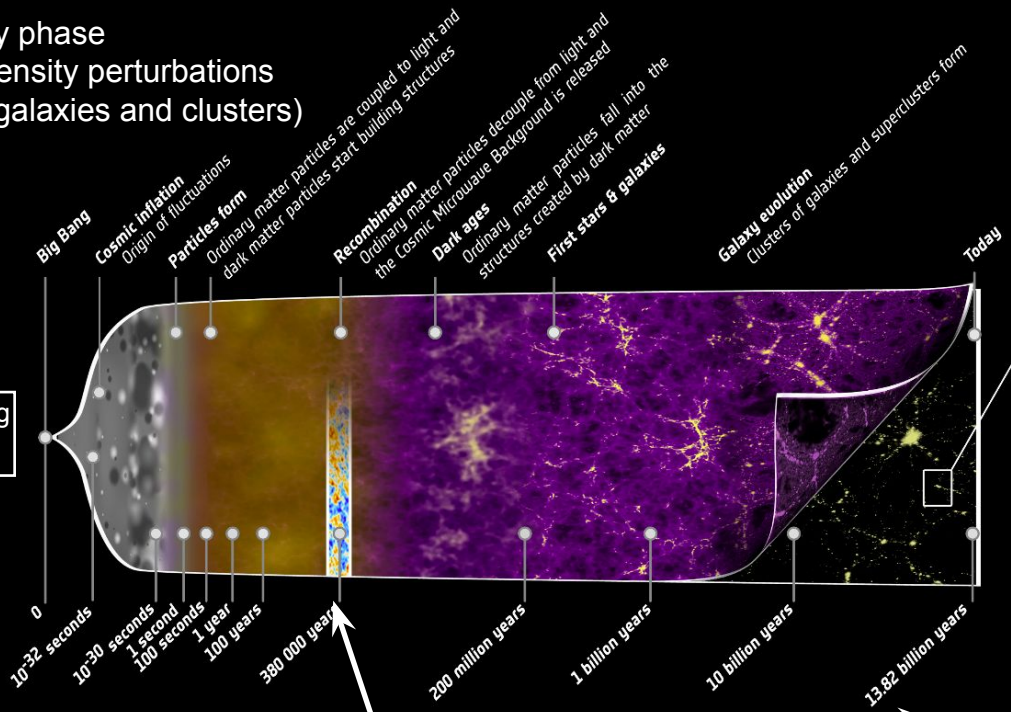
Future Role of FIR-Submm Space Observations
Leiden 2-4 April 2025

A (very) short history of our Universe

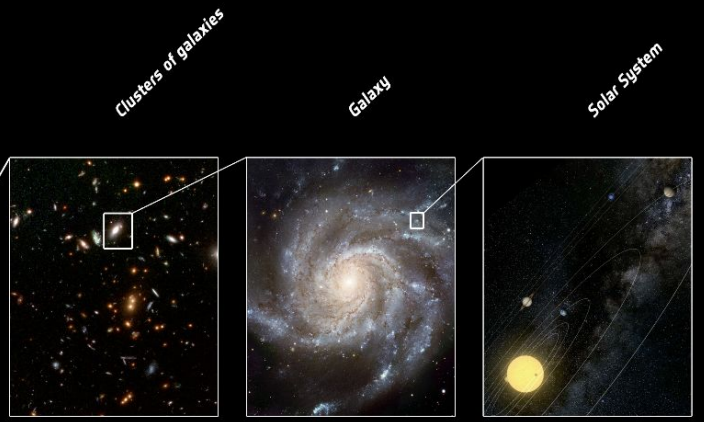
~ 13.8 Gyrs

- Growth of perturbations via **gravitational collapse** → Formation of the first stars & galaxies
- **Dynamics** and evolution of the Universe → Composition of the Universe (ordinary matter, dark matter, dark energy

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



Hot Big Bang
Initial time



ESA - C. Carreau

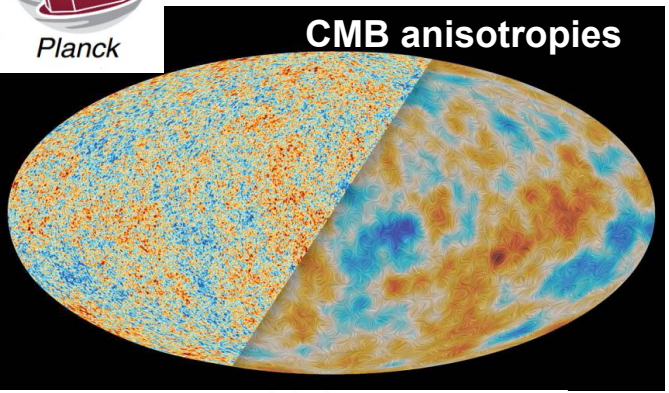
Very hot opaque plasma
(T> 3000K)

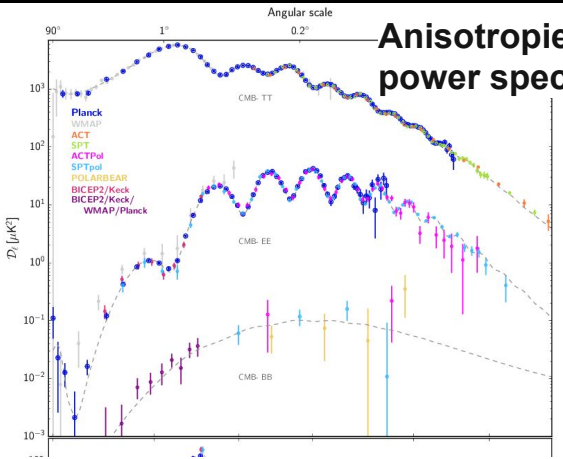
T ~ 3000K , Recombination,
Universe becomes transparent
Last scattering surface → CMB

CMB seen today as a near-perfect blackbody at T = 2.725K

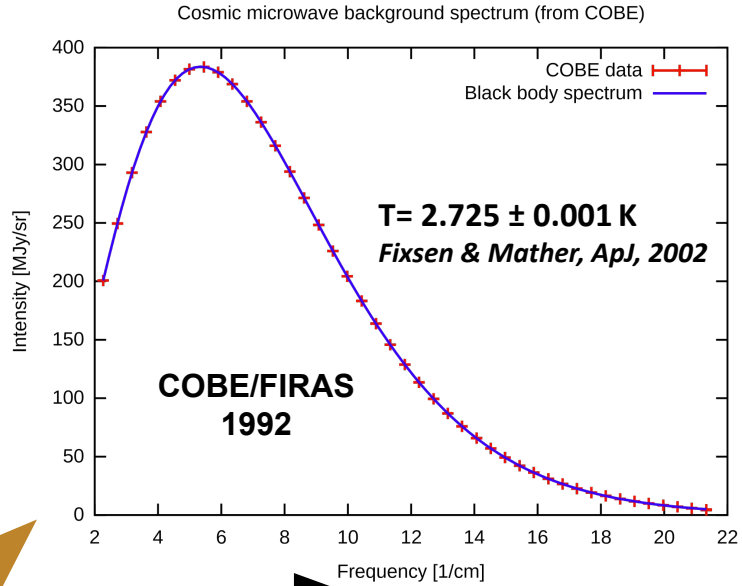
The Cosmic Microwave Background

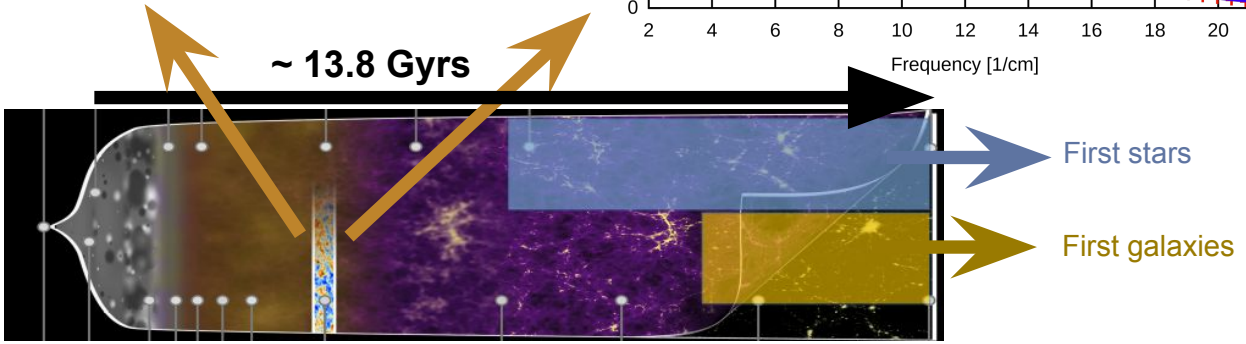
Hot Big Bang scenario → CMB with **blackbody spectrum**





Anisotropies angular power spectrum



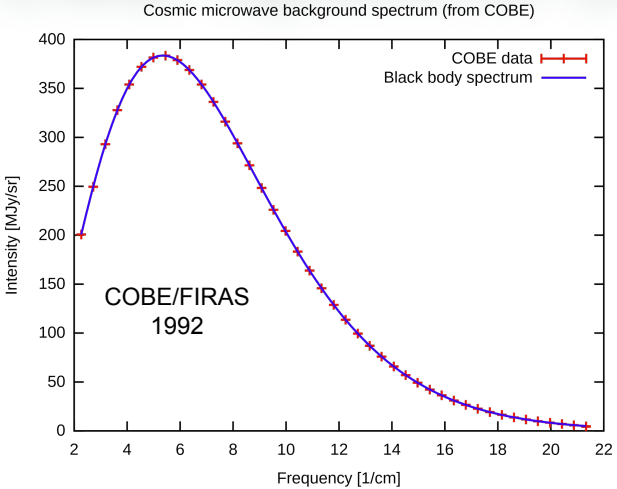


ESA - C. Carreau

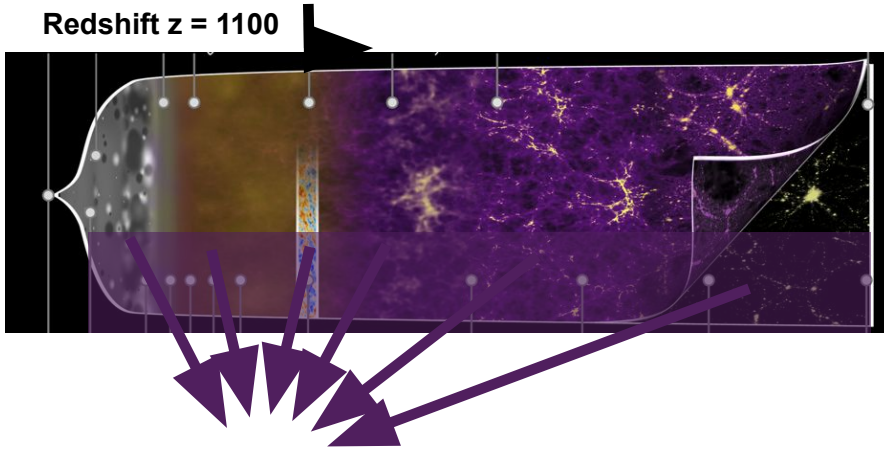
CMB Spectral Distortions

*Chluba et al., **Experimental Astronomy, 2021***

"New horizons in cosmology with spectral distortions of the cosmic microwave background"



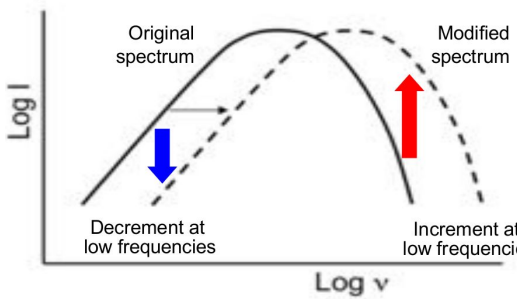
Energy input from inflation to the formation of first stars & galaxies

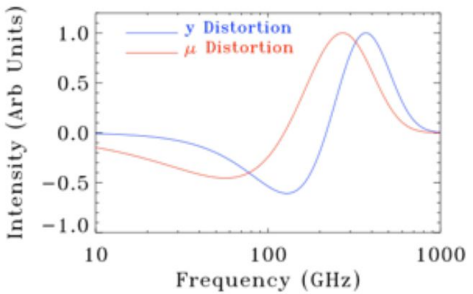


CMB spectral distortions

Blackbody distortions proportional to energy release

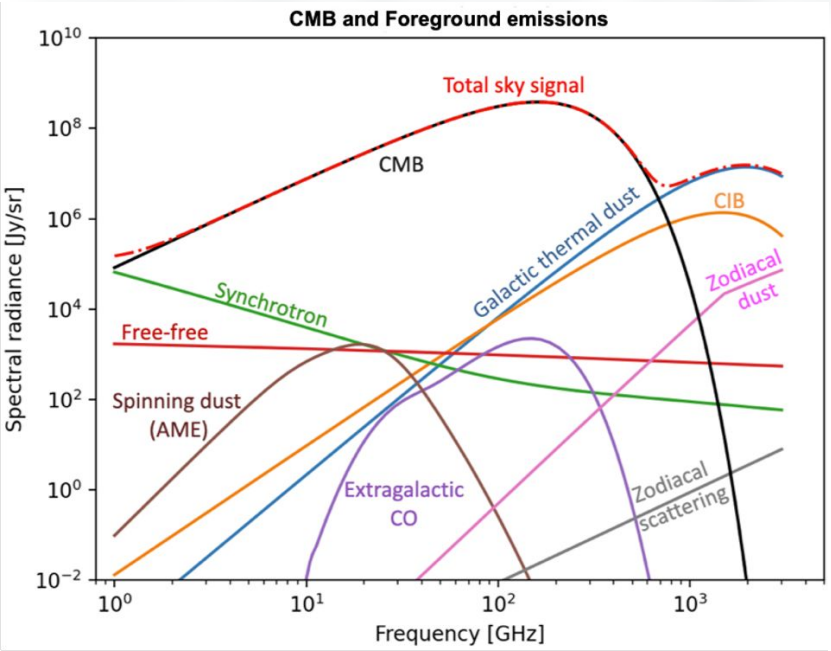
- Inverse Compton scattering ***y* distortion** (Optically thin regime)
- Chemical potential ***μ* distortion** (Optically thick regime)

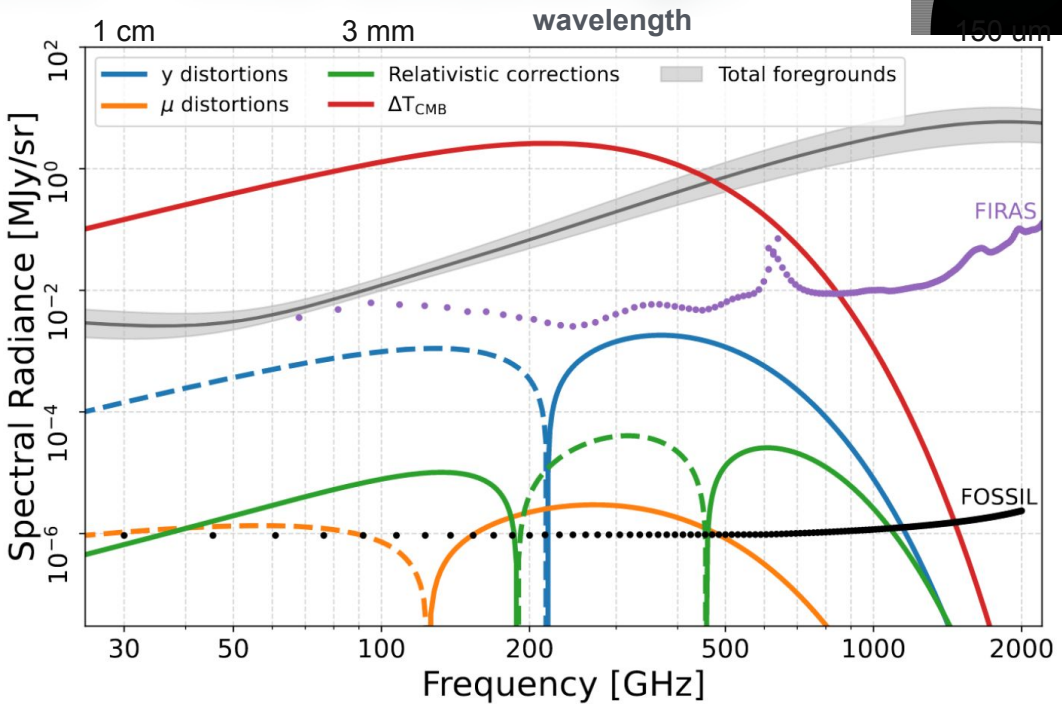




Courtesy A. Kogut

Astrophysical Signals - The challenge





- **PIXIE (2016)**: NASA MIDEx proposal (A. Kogut)
- **PRISTINE (2018)**: answer to ESA F1 call (N. Aghanim)
- **FOSSIL (2022)**: answer to ESA M7-call (N. Aghanim & B. Maffei)

Blackbody component:
$\Delta I_\upsilon / I_\upsilon \sim 10^{-5}$

y-distortion:
$\Delta I_\upsilon^y / I_\upsilon \sim 10^{-6}$

μ-distortion:
$\Delta I_\upsilon^\mu / I_\upsilon \sim 10^{-8}$

Strategy / Purposes / Goals

ESA Voyage 2050:

"New physical probes of the early Universe and **high precision spectroscopy of CMB**" is one of the 3 selected themes for the large missions (L3 horizon 2054…)

- **Strategy**
  - Bridge between 1992 and L6 @2055+ (or hopefully earlier?), i.e. >**63 ans**
  - Consolidate the community and concept for a future space mission
  - Prepare the younger generation for a future mission → **M8 ?**

- **Science: 3 primary goals**
  - Improve by 1 order magnitude CMB monopole brightness measurement (average temperature)
  - Measure for the first time y-distortion monopole
  - Improve the measure of cosmic infrared background absolute intensity
- **Technology**
  - Increase TRL of the instrument concept
  - Enable technological developments & increase TRL of subsystems
  - Acquire knowledge on key subsystems
  - Study of systematics

Need for a pathfinder !

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

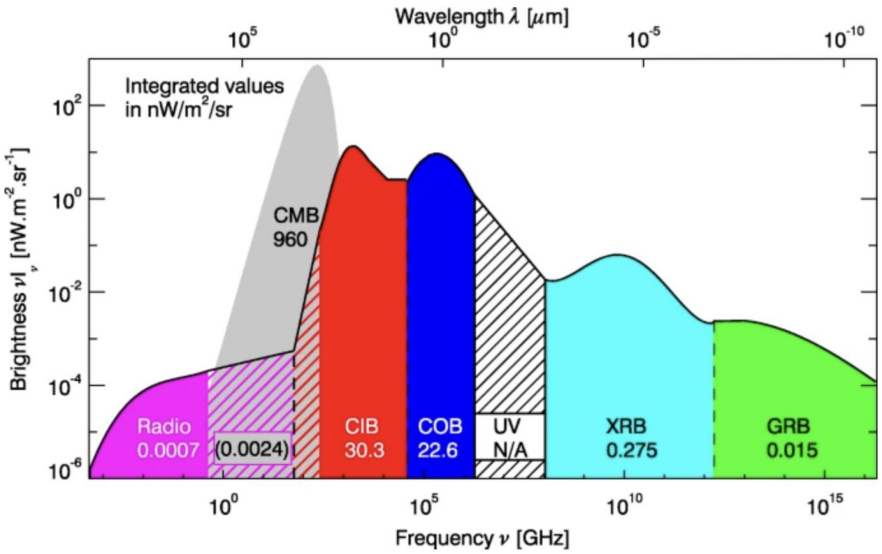
Phase A

2nd Goal: Cosmic Infrared Background

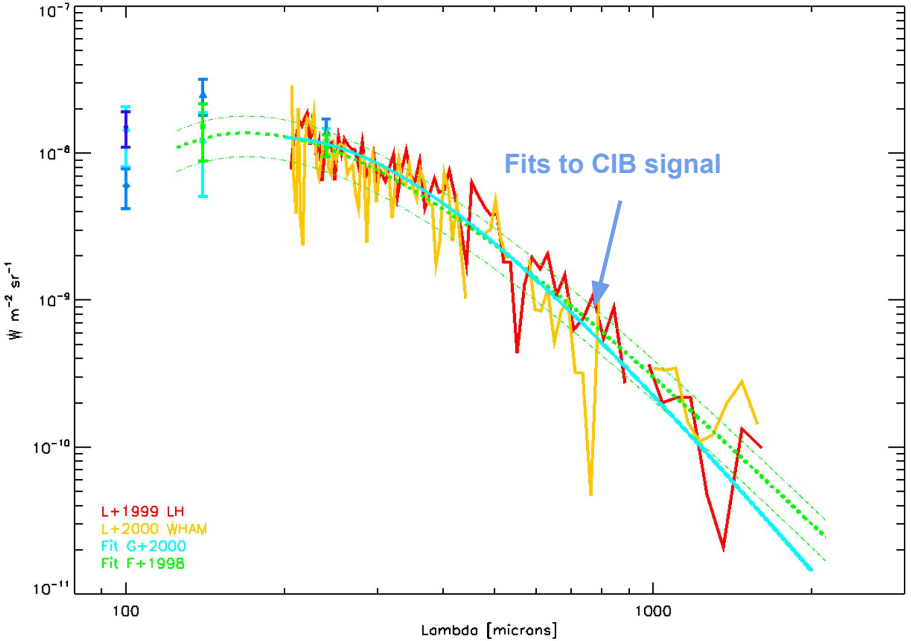
CIB = second brightest background after CMB = tracer of star formation across time

Absolute intensity of CIB (z=2–3) @percent level → **Cosmic star-formation history**

Second brightest after CMB



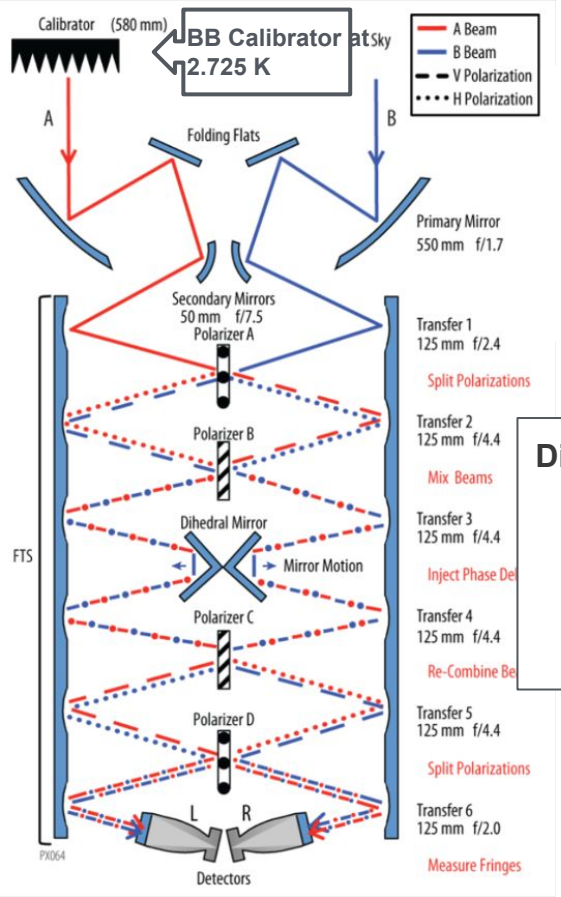
Status of CIB intensity measurement



Courtesy G. Lagache

Instrument concept

PIXIE original concept (*A. Kogut et al. 2011)*



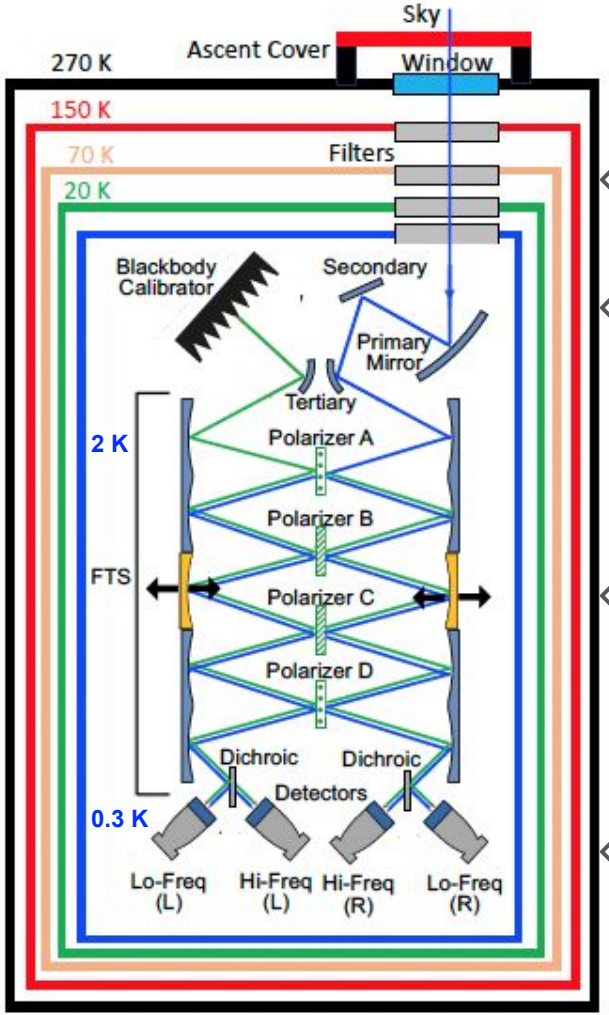
Concept evolution

- FOSSIL
- PIXIE (latest)
- Balloon constraints
- Gondola constraints

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

2 outputs
Multi-moded optics



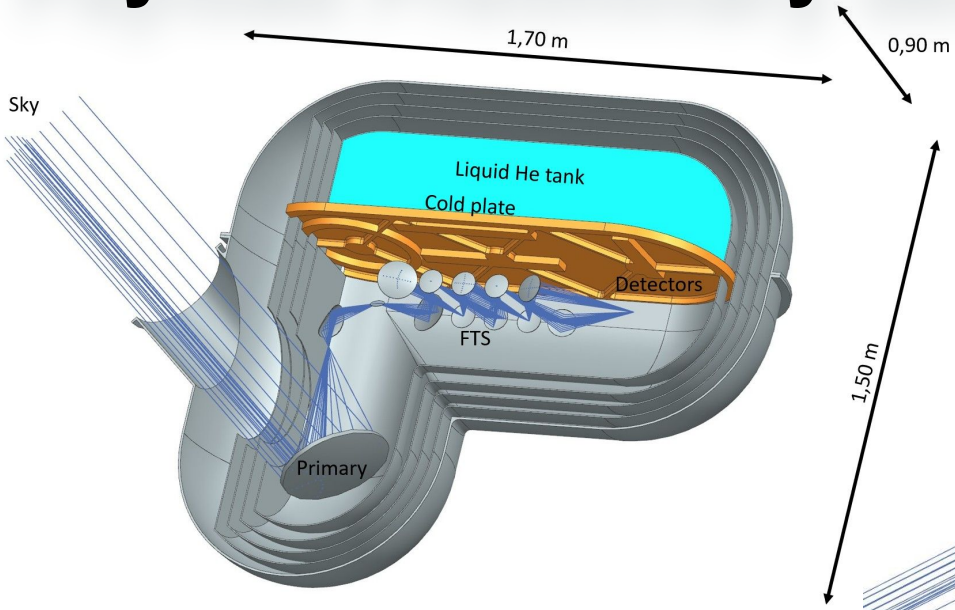
warmer components

Optics Asymmetry

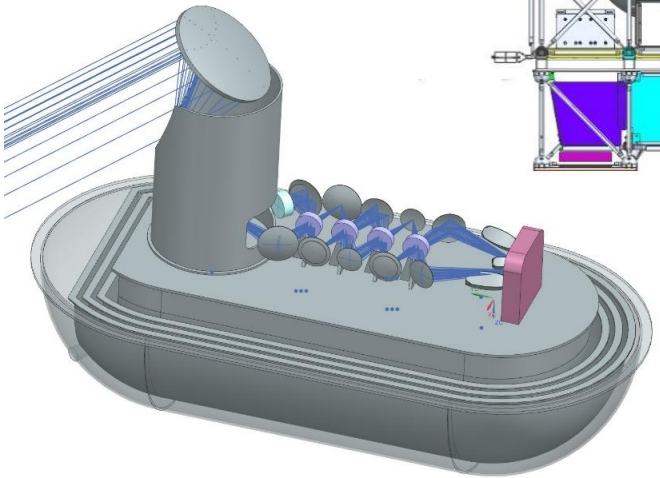
More compact FTS

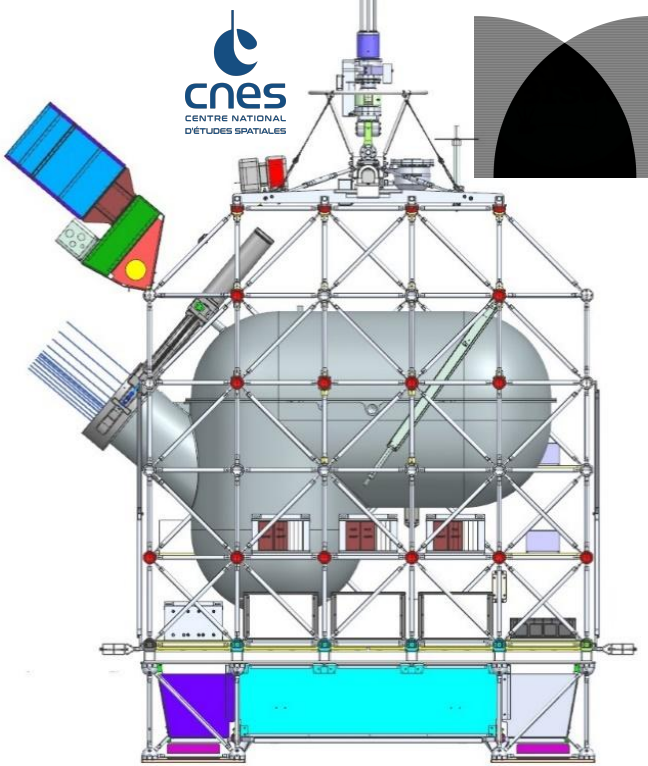
Sub-bands Dichroics

Payload Preliminary design



Estimated mass about 600 kg



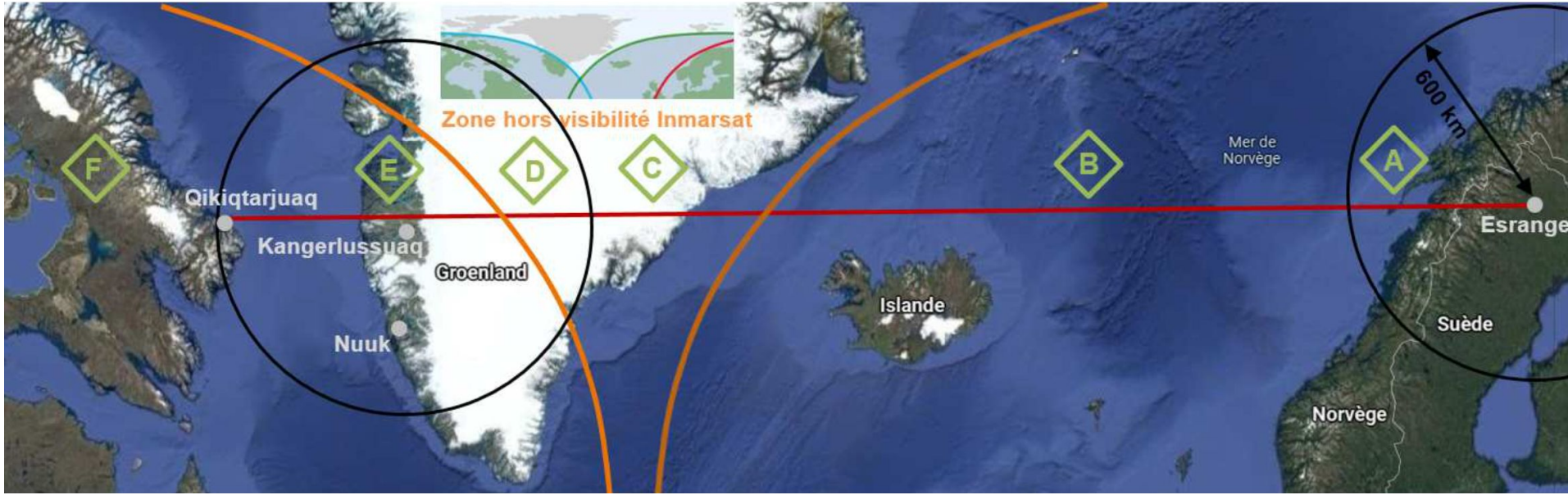


BISOU payload within CNES CARMEN gondola

Balloon flight target

Potential 5-day flight

800 000 m^3 He balloon or maybe 900 000 m^3



First CNES transatlantic demonstration flight in June 2024

Observation strategy: No survey but integration over targeted low foreground regions of the sky

Sensitivity estimates

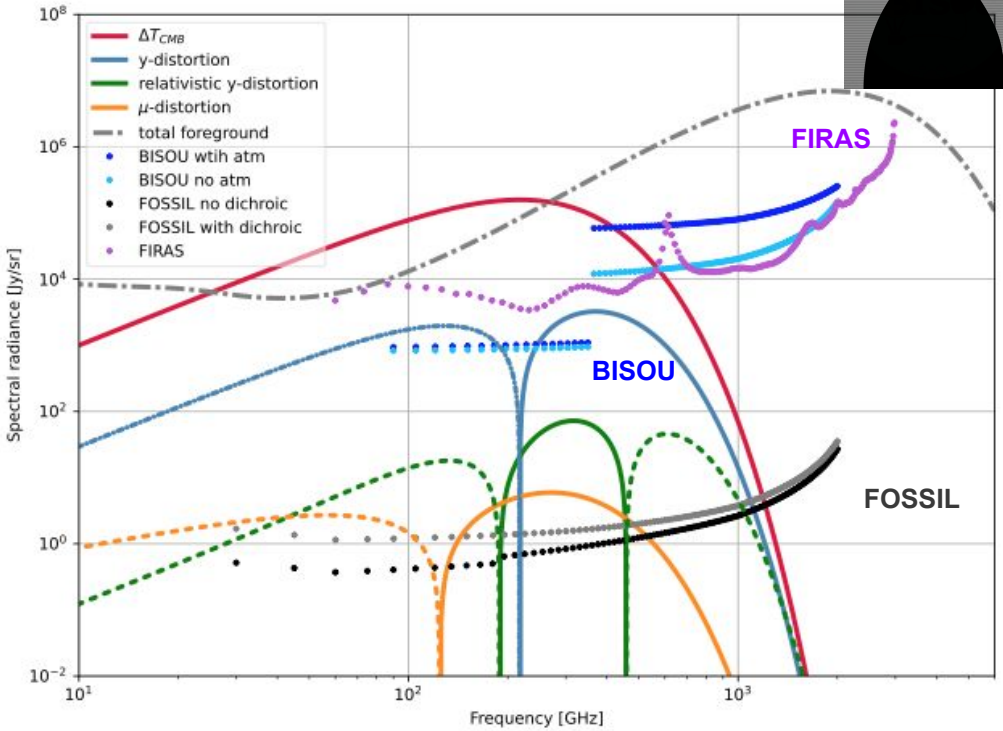
sky emission model + sensitivity estimate

- **Instrument baseline**
  - Based on 1 detector only
  - f_{max}= 2 THz, f_{min}= 90 GHz,
  - Dichroic frequency split at 350 GHz,
  - Transatlantic flight: 5 days with 75% observation efficiency
  - Atmosphere not taken into account

Model using Fisher formalism assuming Gaussian posteriors

- **Model baseline**
  - Marginalization over all (non-shown) astrophysical parameters
  - 10% prior on synchrotron parameters
  - AME and μ-distortion neglected

Parameters uncertainties

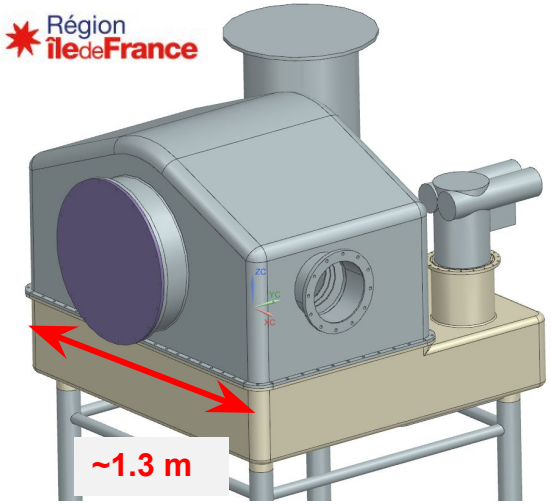


	y	A_{CIB}
SNR (σ)	5.6	2.3
Improvement factor over FIRAS	25	2

X. Coulon et al, in preparation

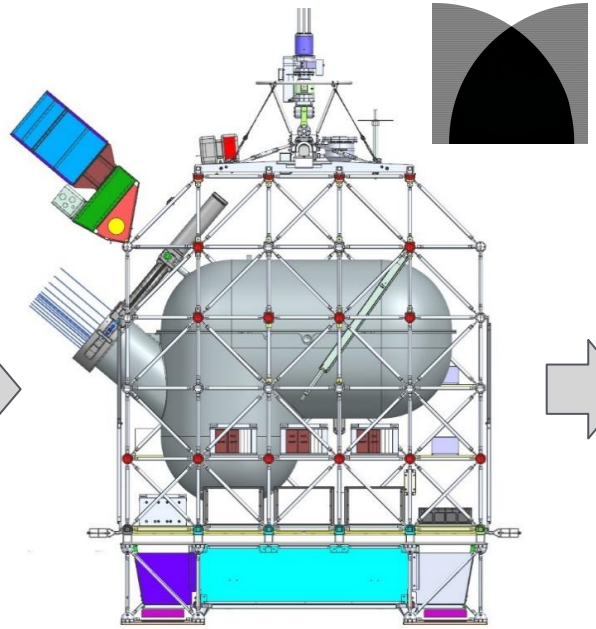
Overall strategy towards a future space mission

BISOU Cryogenic Laboratory BreadBoard (2023 - 2028)



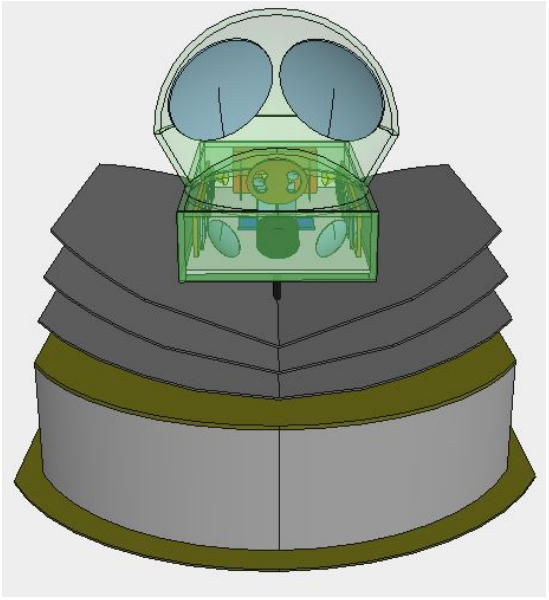
- Detector R&D programme
- Sub-systems prototypes

BISOU balloon experiment pathfinder (2020 - 2031)



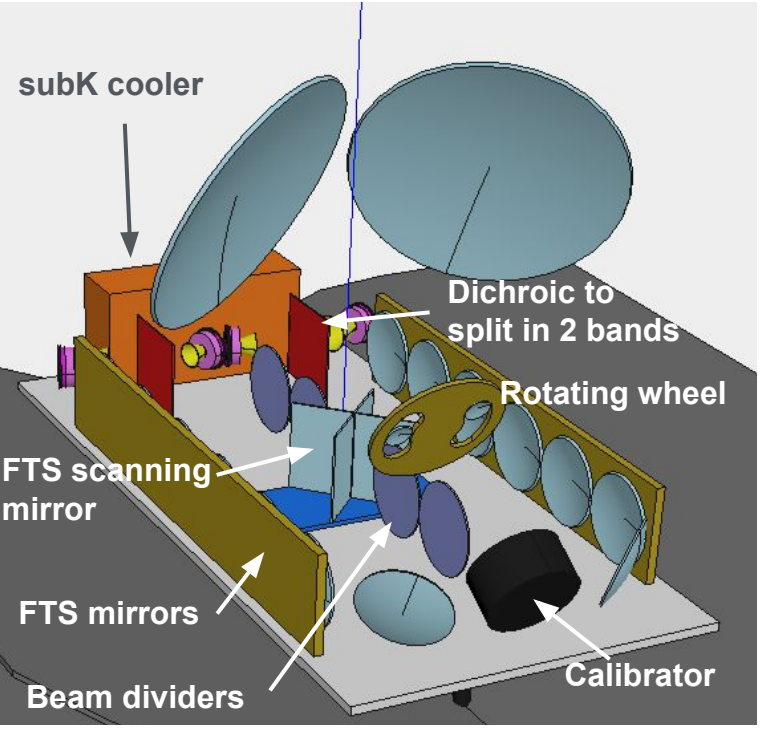
Evolution for subsequent flights?

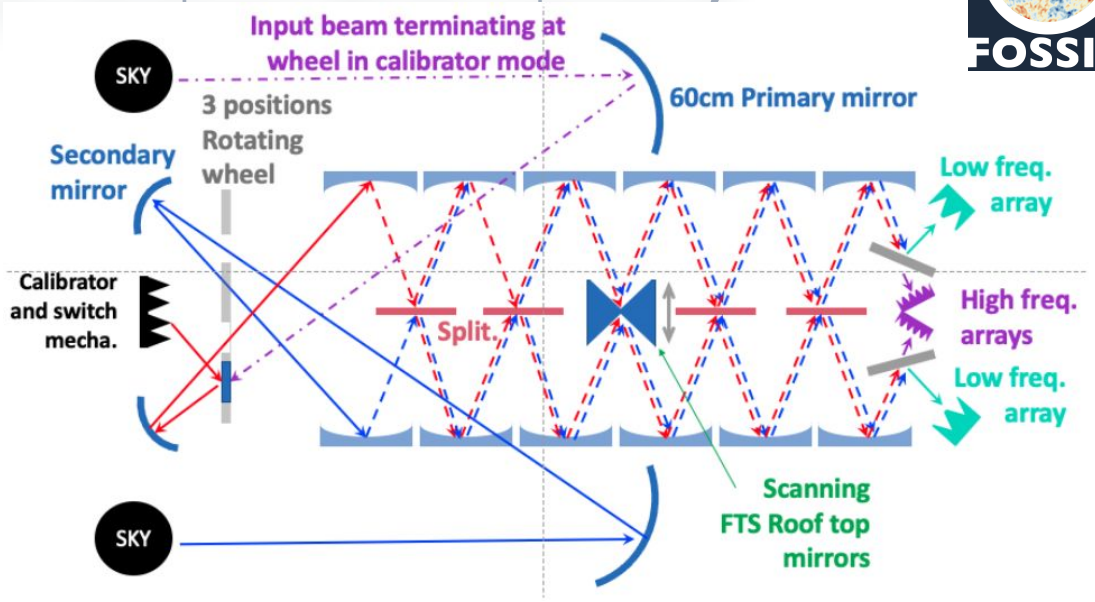
Future space mission (--> M 2041? or L 2055+?)



FOSSIL

M7 Proposal to ESA (FTS fOr CMB Spectral diStortIon expLoration)





- 3 operation modes → commutation via rotating wheel
  - **Modes 1 & 2 (one input from sky second from calibrator) for science observation**
  - **Mode 3 (2 inputs from sky) for control of optical systematics**
- Beam from sky goes through primary
- Beam dividers combine the 2 inputs
- 2 outputs at the exit of the last beam divider
- Identical dichroics at each output split in 2 spectral bands directed towards the 4 FPUs

FOSSIL 2022

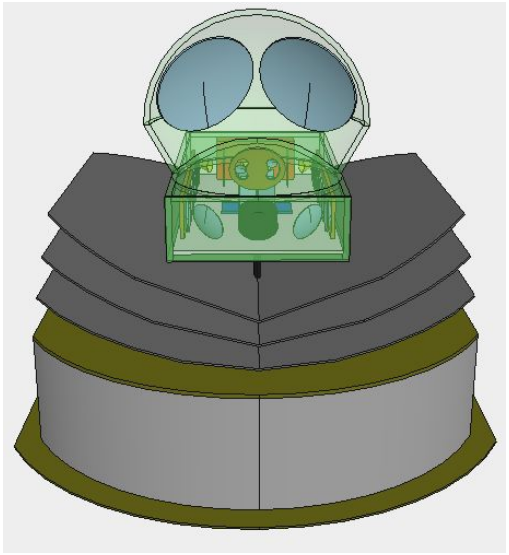
First **full-sky low resolution absolute spectrometric survey** after COBE/FIRAS

Expected performance

- 30 to 2000 GHz (2 bands split ~200 GHz)
- Δv=15GHz (R from about 2 → 130)
- Angular Resolution ~1.4 deg equivalent Gaussian beam
- Sensitivity ~1 Jy/sr @[30 GHz, 3yrs, **1 detector**]

Instrument

- Whole instrument in an enclosure at 2.7 K
- 2 telescopes: 60 cm primary aperture
- FTS: 2 inputs (Sky & Calibrator) & 2 outputs
- Internal calibrator @ 2.5 - 2.9 K
- 4 FPUs (2 spectral bands for each FTS outputs)
- Multimoded detectors @ **100 to 300mK**
- Intensity measured with respect to known BlackBody calibrator



SVM similar to ARIEL

M8 forecast for 1 single detector

- **Foregrounds:** CIB, dust, extragal CO, AME, synch (5% prior), free-free → 12 parameters
- **Signals:** CMB temp., y, μ → 4 parameters

- 70% clean sky
- 3 years of observation
- 75% effective obs. time

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

Most optimistic (TBC)

Most pessimistic (TBC)

Marginalization over parameters other than (columns)

	CMB (only)	Dust	Sync, FF, AME	Dust, CIB, CO	Sync, FF, Dust, CIB	Sync, FF, AME, Dust, CIB, CO
$y_{tot} = 1.77\times10^{-6}$ (σ)	17 292	10 194	2 645	463	390	331
Δy_{tot} ($\times10^{-9}$) (95% c.l.)	0.20	0.35	1.3	7.7	9.1	11
y_{tot} (n×FIRAS)	73 271	43 194	11 207	1 962	1 653	1 403
$kT_{eSZ} = 1.245$ keV (σ)	486	241	220	52	43	30
ΔkT_{eSZ} (keV) (95% c.l.)	5.1	10	11	48	58	83
$\mu = 2\times10^{-8}$ (σ)	16	16	1.3	2.7	0.30	0.29
$\Delta\mu$ ($\times10^{-8}$) (95% c.l.)	0.24	0.25	3.1	1.5	13	14
μ (n×FIRAS)	36 450	35 775	2 924	6 975	677	646

M8 Proposal to ESA

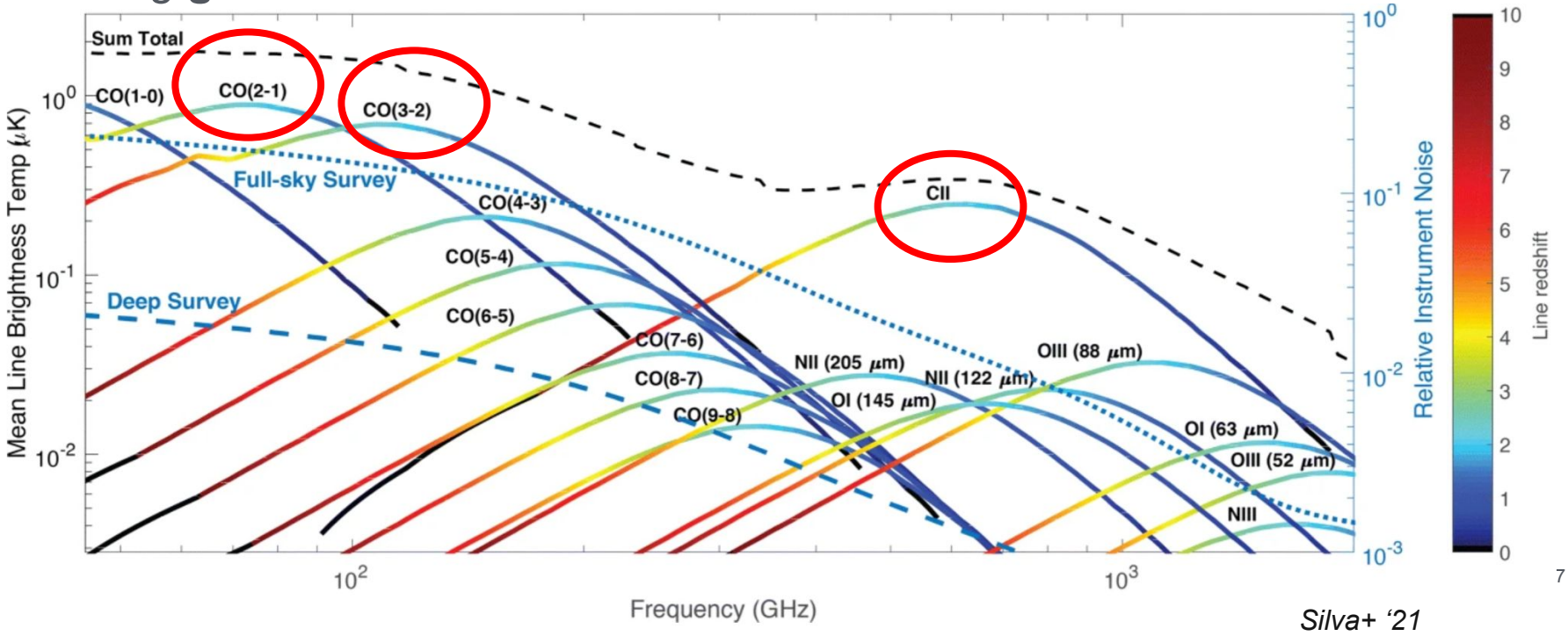
Evolution of M7 FOSSIL proposal

See full M7 proposal at
https://www.ias.universite-paris-saclay.fr/en/content/fossil

M8 Proposal to ESA: additional science case ?

What about emission lines in the Large Scale Structure ?

Monopole emission and low-resolution intensity maps of **far-IR lines** (CII & CO) in star-forming **galaxies at the cosmic noon**



Silva+ '21