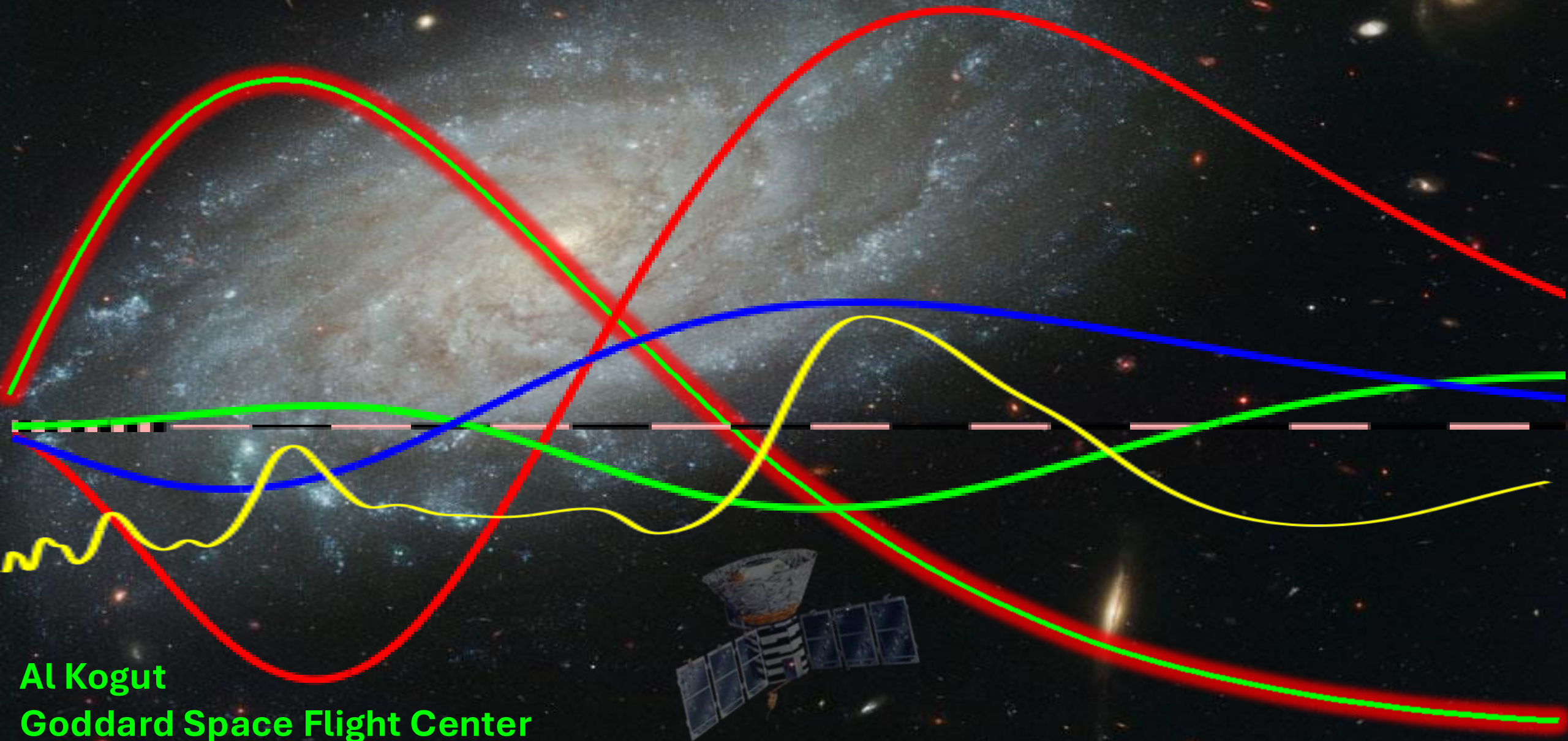


CMB Spectral Distortions: The New Frontier

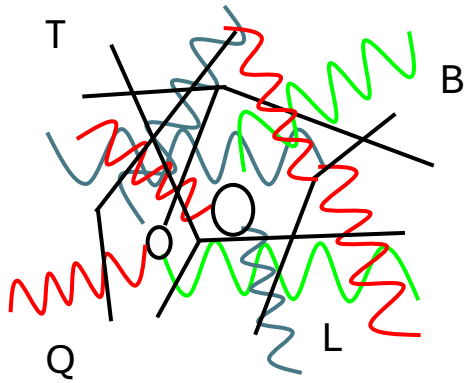
CMB Probe+: A full sky millimeter/submillimeter-wave polarimetric imager and spectrometer



Al Kogut

Goddard Space Flight Center

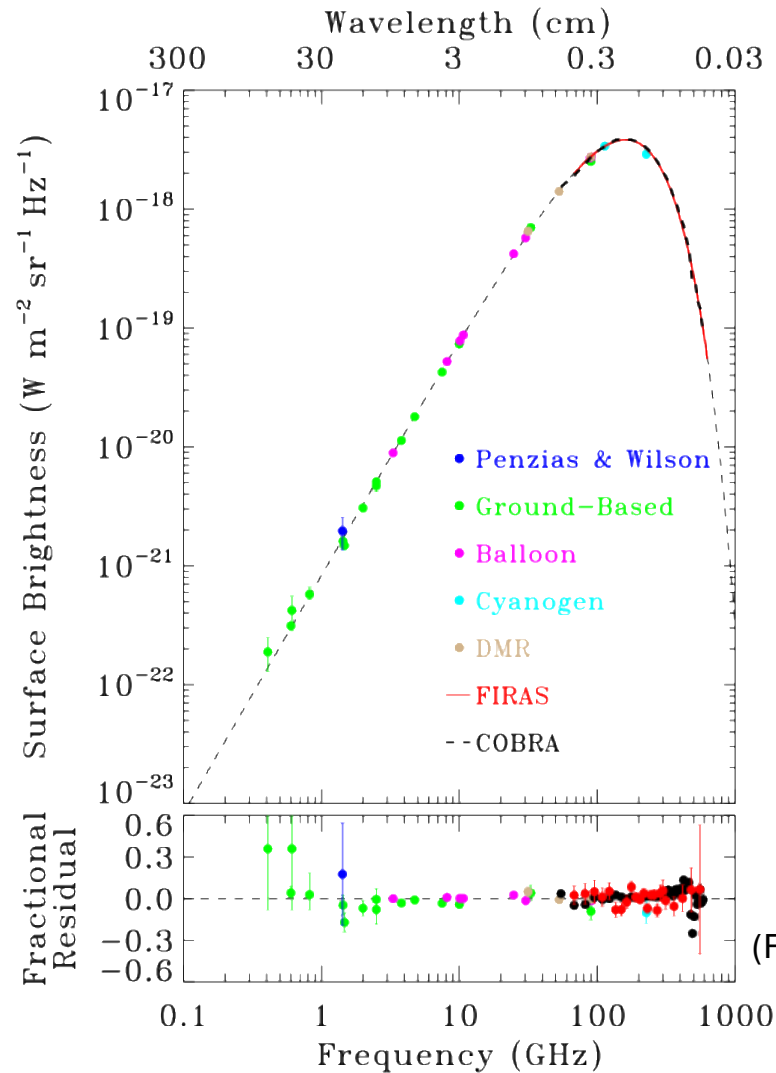
Cosmology from Thermodynamics



Thermal Equilibrium:

- Interaction rates $\gg$ Hubble Expansion
- Fully characterized by temperature plus list of conserved quantum numbers

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$



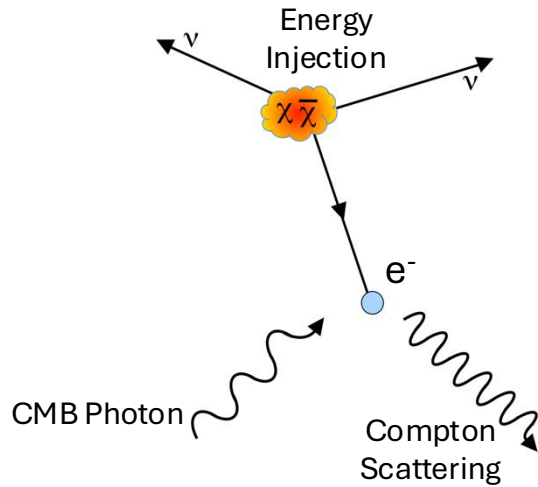
CMB spectrum consistent with a
single blackbody
across
3 decades in frequency
and
5 orders of magnitude in intensity

But ...

Exciting science lurking
just below current limits

Blackbody = Hot, dense phase in early universe
Temperature = Photon number

CMB Spectral Distortions



Optically thin case: Compton y distortion

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(x) - 1} \left[1 + \frac{y x \exp(x)}{\exp(x) - 1} \left(\frac{x}{\tanh(x/2)} - 4 \right) \right]$$

$$y = \int \frac{kT_e}{mc^2} n c \sigma_T dt$$

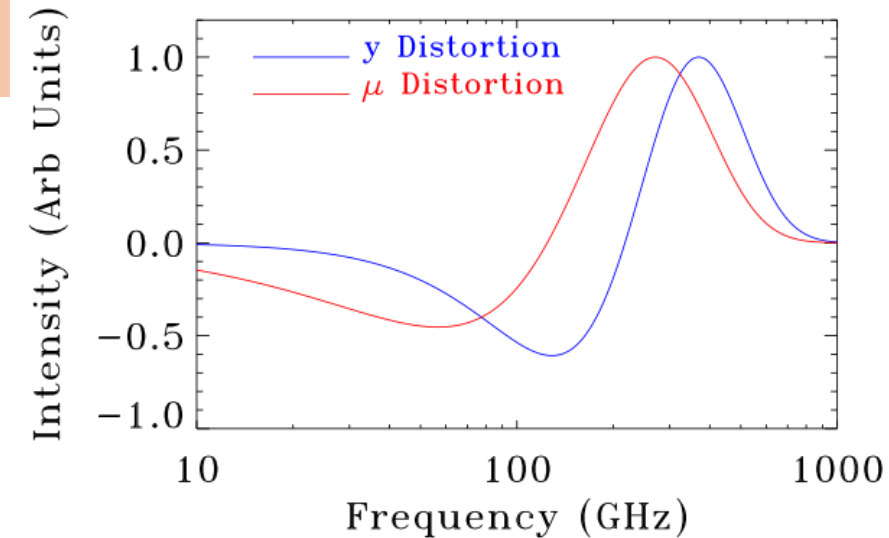
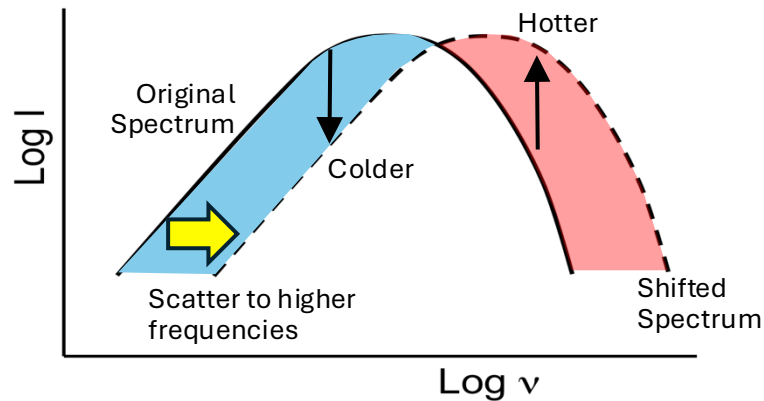
**Electron pressure
Electron temperature**

Optically thick case: Chemical potential distortion

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT} + \mu) - 1}$$

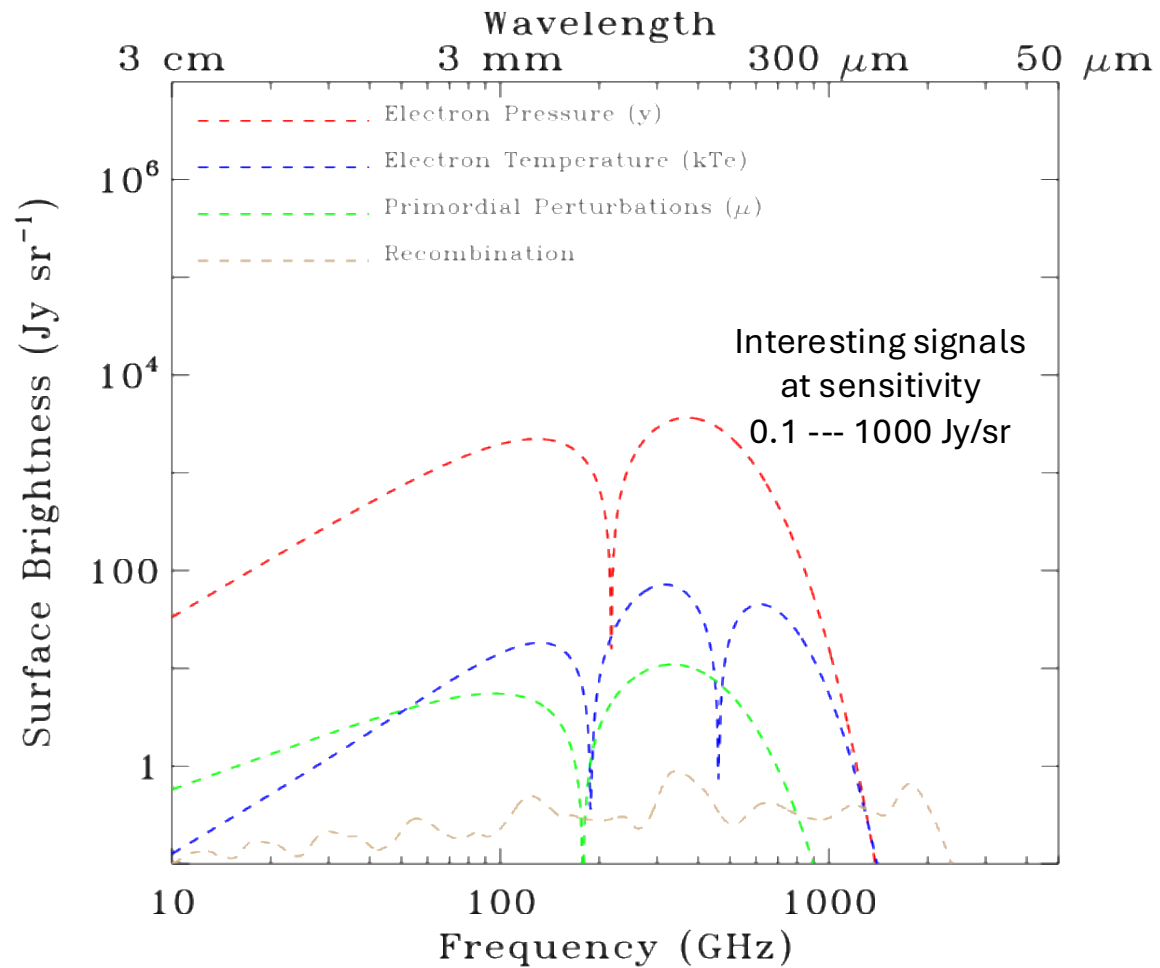
$$\mu = 1.4 \frac{\Delta E}{E}$$

Total energy release

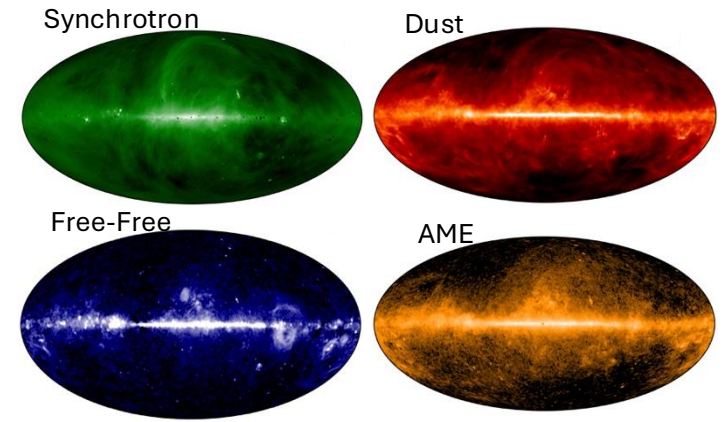


Distortions track fundamental property of universe: its energy budget

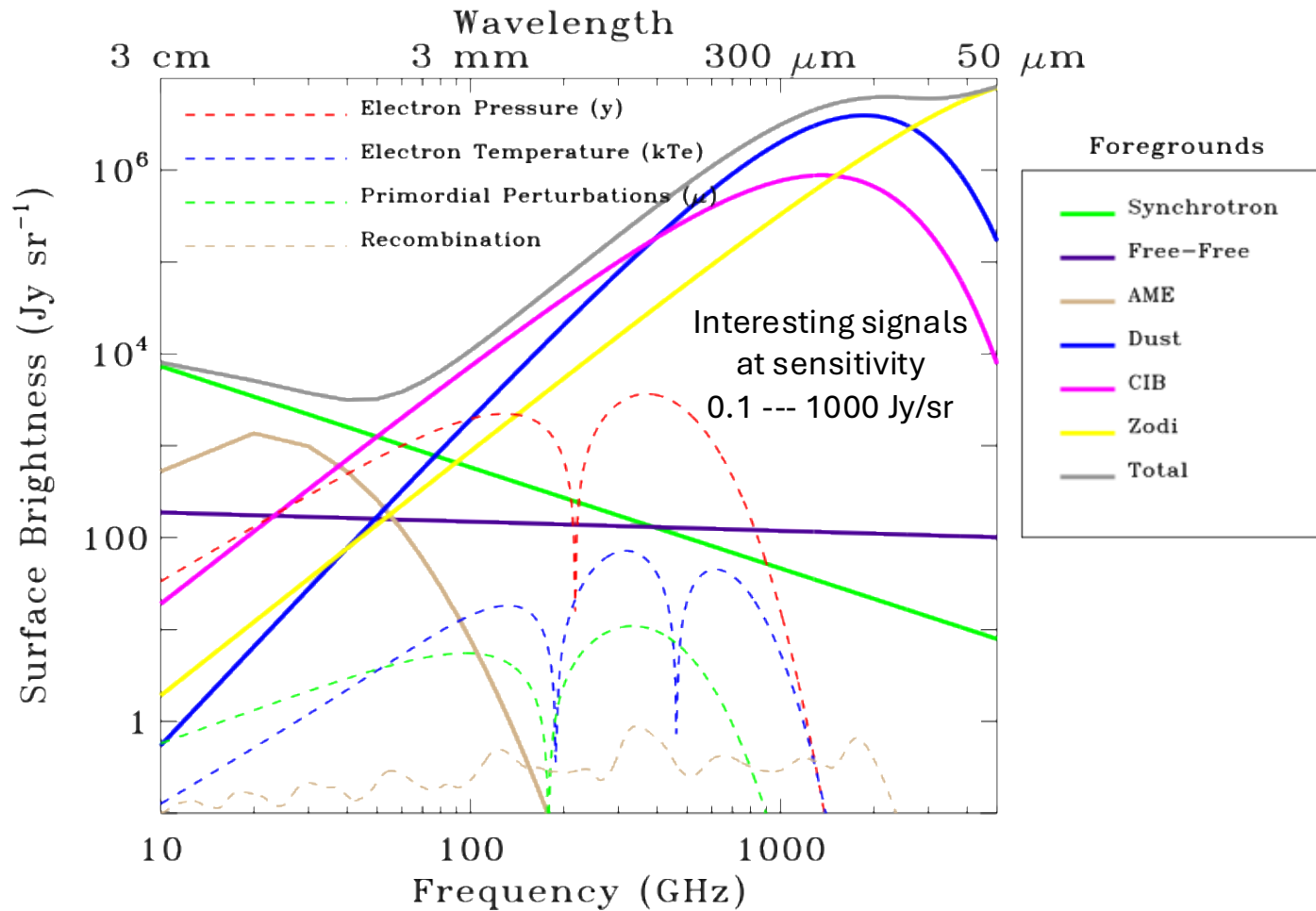
Spectral Distortions vs Everything Else



Problem:
The CMB ain't the only source on the sky

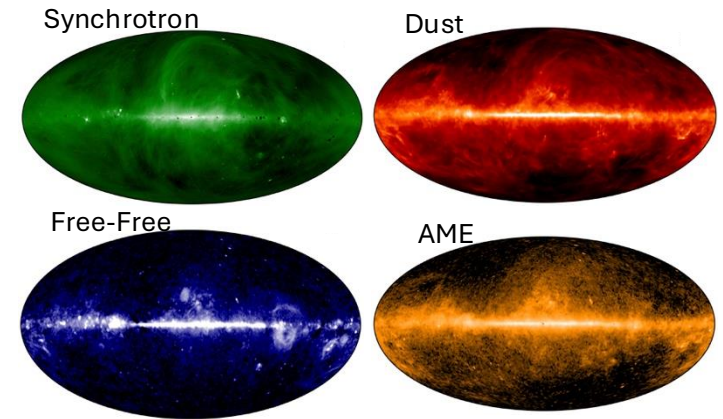


Spectral Distortions vs Everything Else

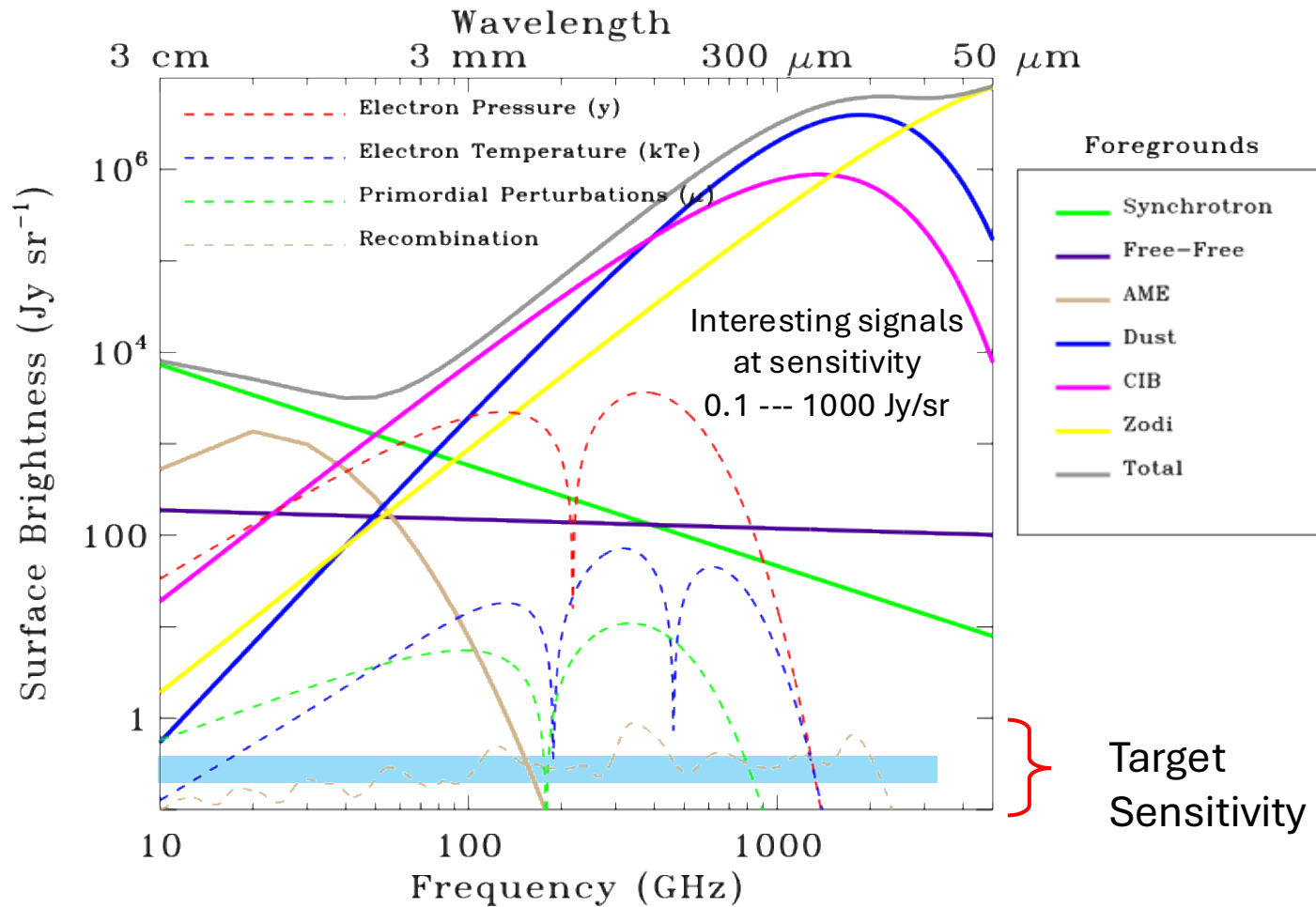


Problem:

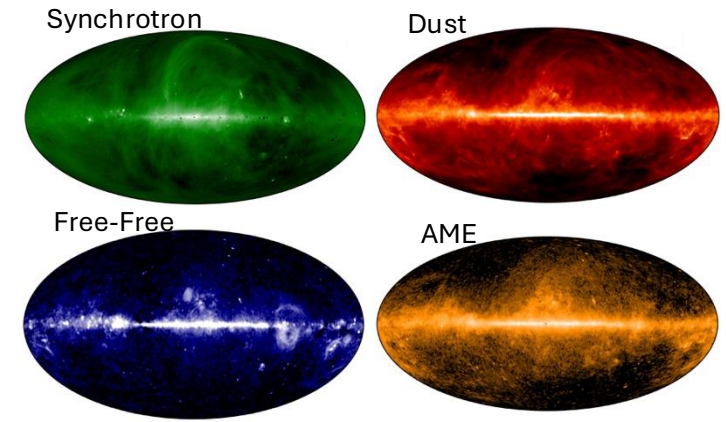
The CMB ain't the only source on the sky



Spectral Distortions vs Everything Else



Problem:
The CMB ain't the only source on the sky



Spectral distortion detection requires

Absolute spectra

with

Broad frequency coverage

2 decades 15—1500 GHz

at

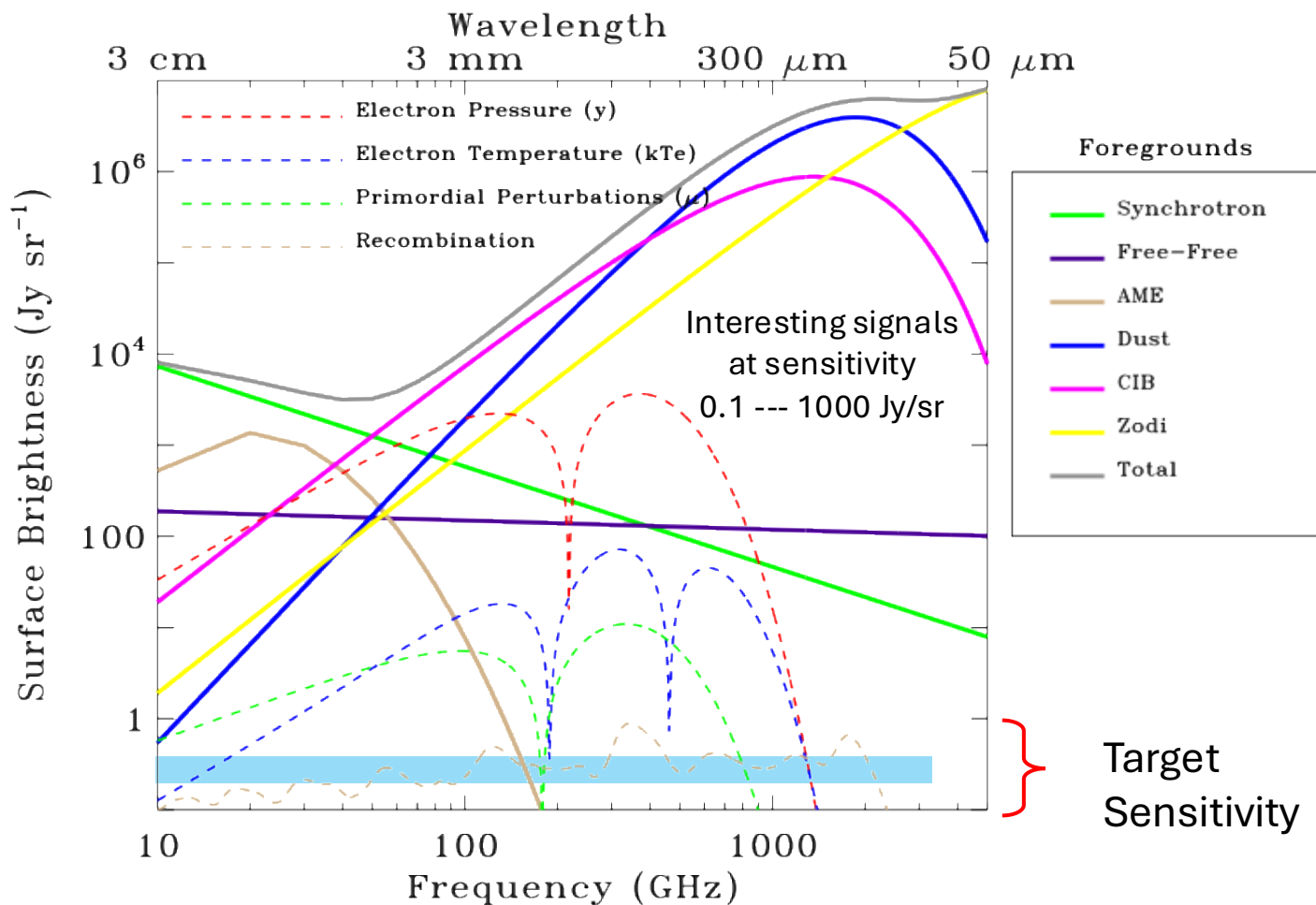
Sensitivities

100 Jy/sr (γ distortion)

1 Jy/sr (μ distortion)

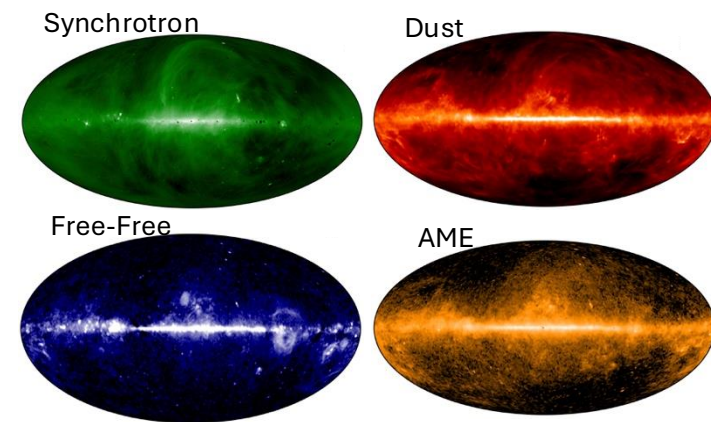
0.1 Jy/sr (recombination lines)

Spectral Distortions vs Everything Else



What you don't need: High angular resolution
 Few degree angular resolution $\longleftrightarrow$ Small instrument!

Problem:
 The CMB ain't the only source on the sky



Spectral distortion detection requires

Absolute spectra

with

Broad frequency coverage

2 decades 15—1500 GHz

at

Sensitivities

100 Jy/sr (γ distortion)

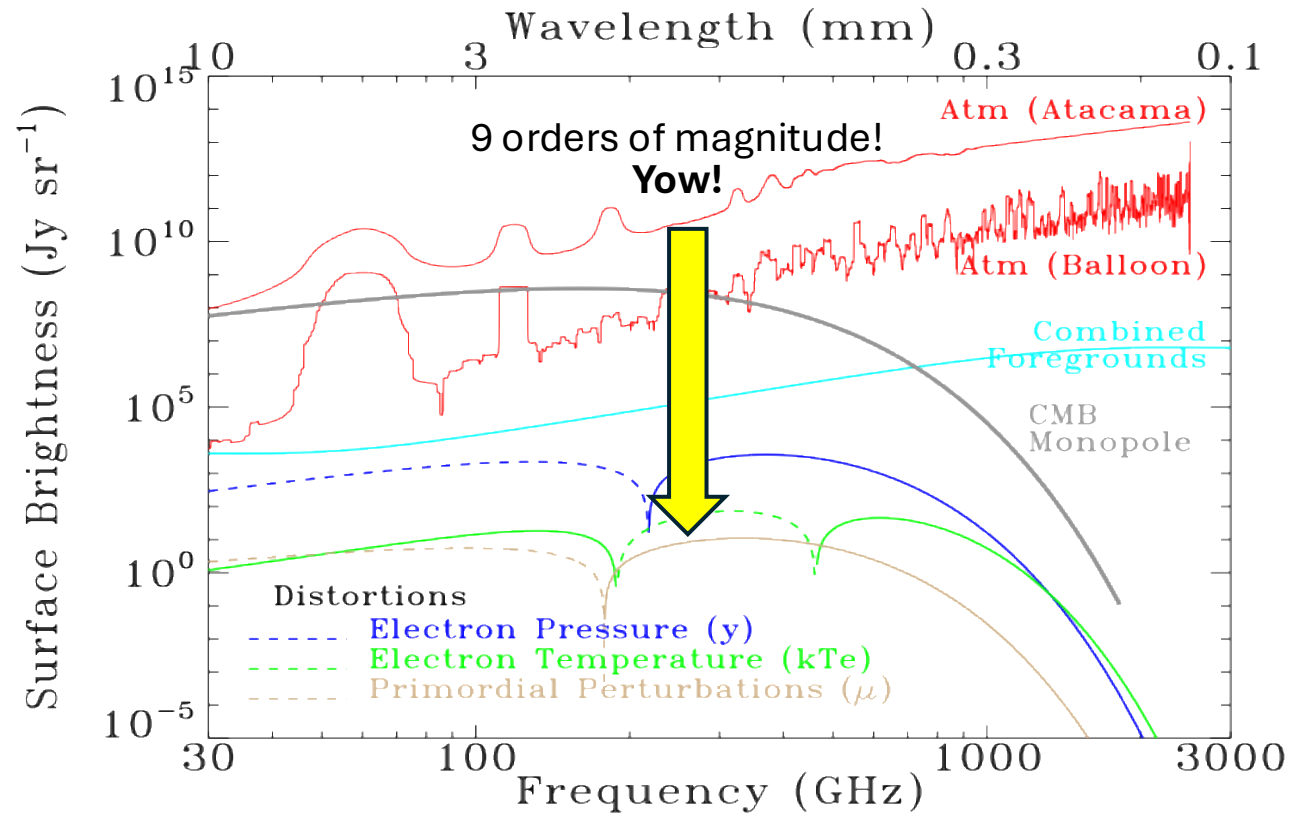
1 Jy/sr (μ distortion)

0.1 Jy/sr (recombination lines)

Why Space?



The Problem With Ground-Based Cosmology



Atm is orders of magnitude brighter than CMB distortions
Low transmission further attenuates CMB signals
Operating within atm requires (warm emissive) windows

Space: Unimpeded access across entire spectrum
Ideal environment for cryogenic instrument

Current Limits: Best of 1980's technology

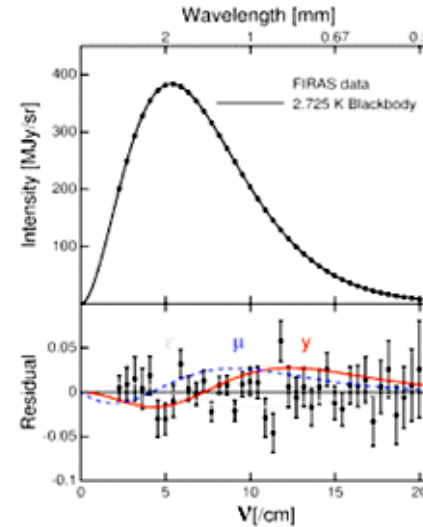


FIRAS cosmology

Blackbody spectrum confirmed

Energy Budget: $\Delta E/E < 4 \times 10^{-5}$ for $10^3 < z < 10^7$

- No “Little Bangs” after the Big Bang
- Steady State cosmology ruled out
- X-ray background from discrete sources
- Heavy neutrino decay limits



COBE/FIRAS

- CMB blackbody spectrum
- Limit distortions below 50 ppm
- Map CMB primary anisotropy
- dB/dT Spectrum of CMB anisotropy

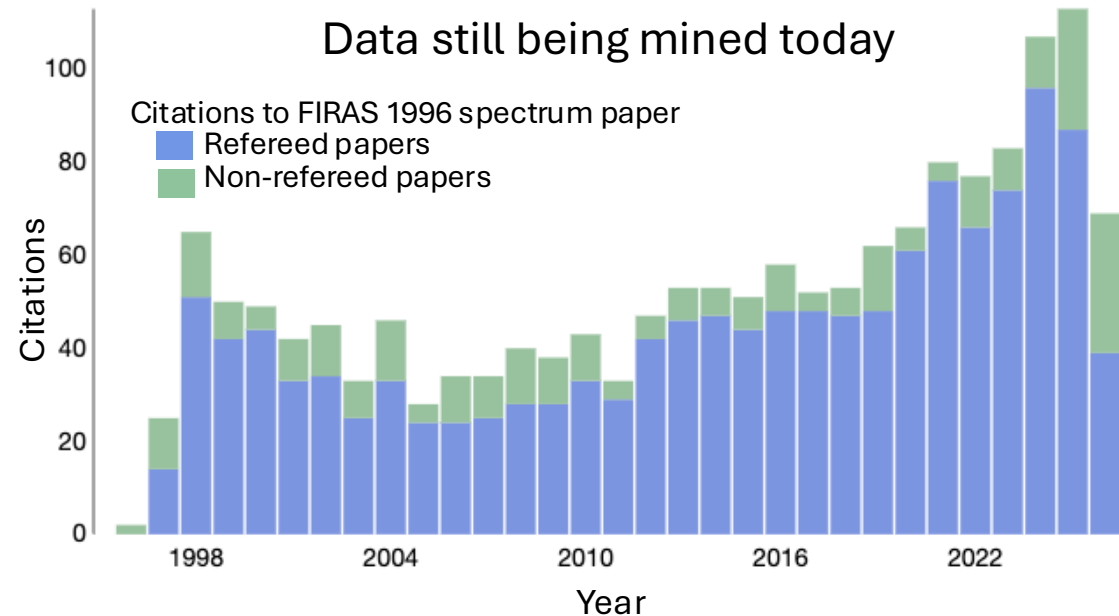
95% CL Upper Limits

$$|y| < 5 \times 10^{-6}$$

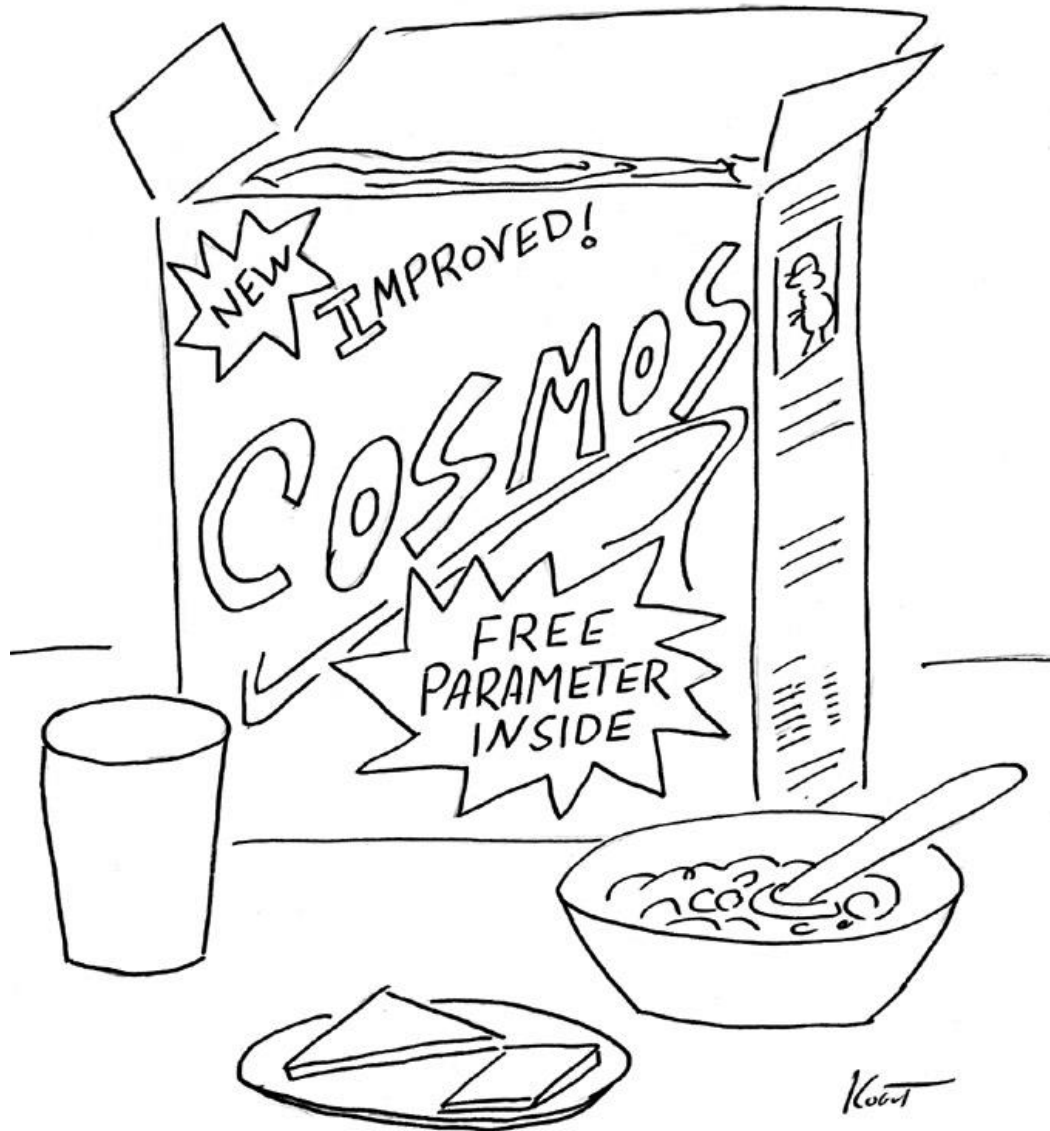
$$|\mu| < 5 \times 10^{-5}$$

Fixsen+ 1996, Bianchini & Fabbian 2022, Fabbian+ 2025

Data still being mined today



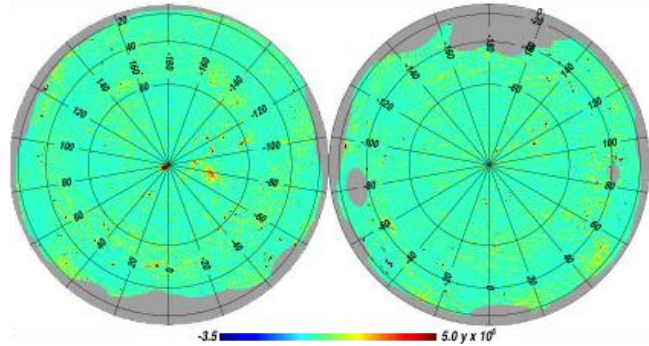
Science From Spectral Distortions



COBE launched 37 years ago
What might we see with a modern instrument?

y Distortion: Structure Formation

Electron Pressure & Temperature From Structure Formation



Planck floor: $y > 5.4 \times 10^{-8}$

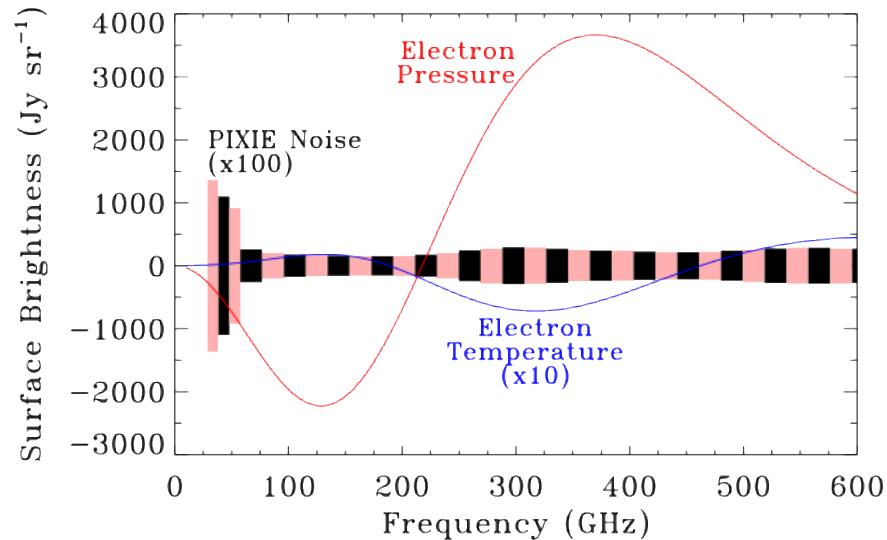
Total monopole: $y = 2 \times 10^{-6}$

Relativistic correction $kT_e = 1.2 \text{ keV}$

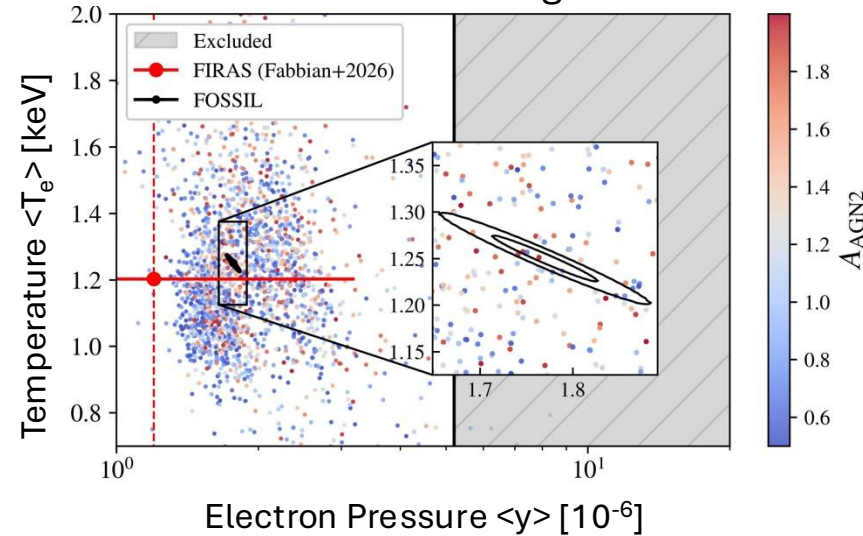
Electron Pressure

Electron Temperature

$$y = \int \frac{kT_e}{mc^2} nc\sigma_T dt$$



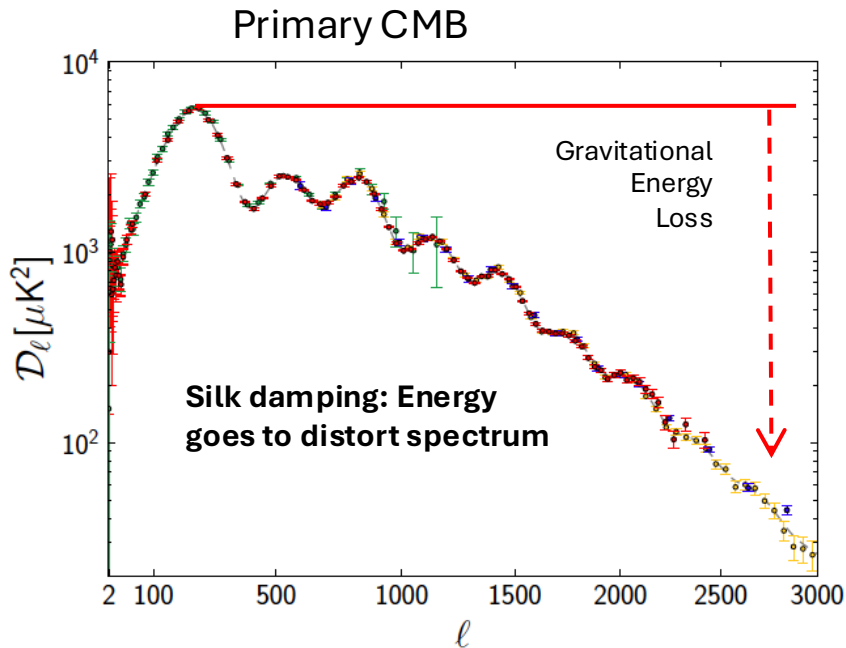
FOSSIL vs IllustrisTNG: 20-sigma detections



Mean electron number density:
Percent-level census of
“missing” baryons

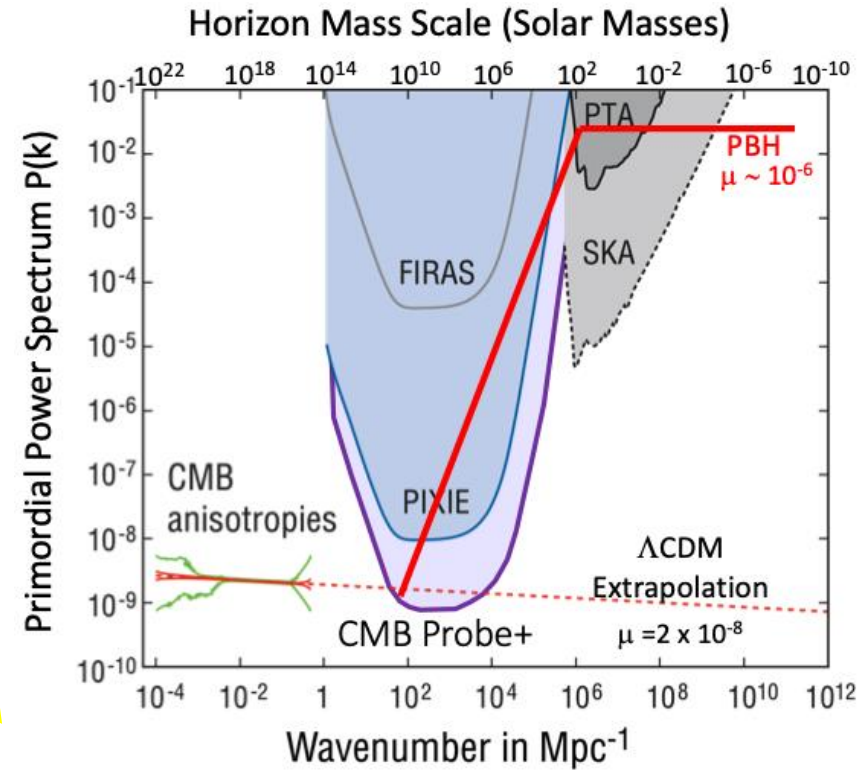
Calibrate Baryonic Feedback for Structure Formation

μ Distortion: Primordial Density Perturbations



Inflation may or may not be the correct description of the early universe, but density perturbations definitely exist!

Energy transfer to $\ell \sim 10^8$



Determine amplitude of density perturbations on scales 3--5 orders of magnitude beyond primary CMB

Slow-Roll Inflation

- Tilt n_s
- Running of the tilt
- Non-Gaussian coupling
- Inflationary potential

Complicated Inflation

- Waterfall transitions
- Multi-field inflation
- Iso-curvature

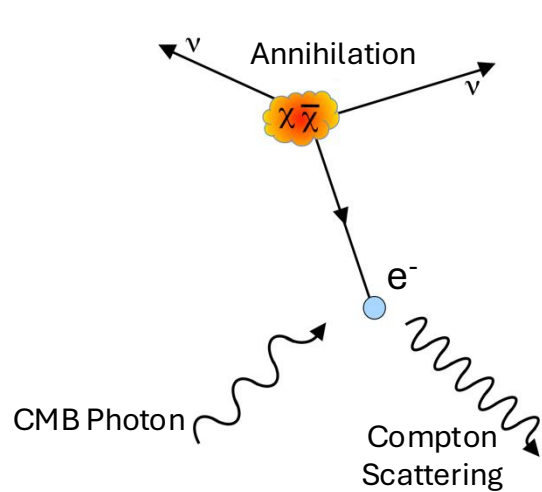
New Physics

- Axions
- Primordial black holes
- ???

Unique Probe of Physics on These Scales!

Spectral Distortions: Dark Matter

Discovery Space for New Physics



$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT} + \mu) - 1}$$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

Annihilation rate $\sim n^2 \sim z^6$

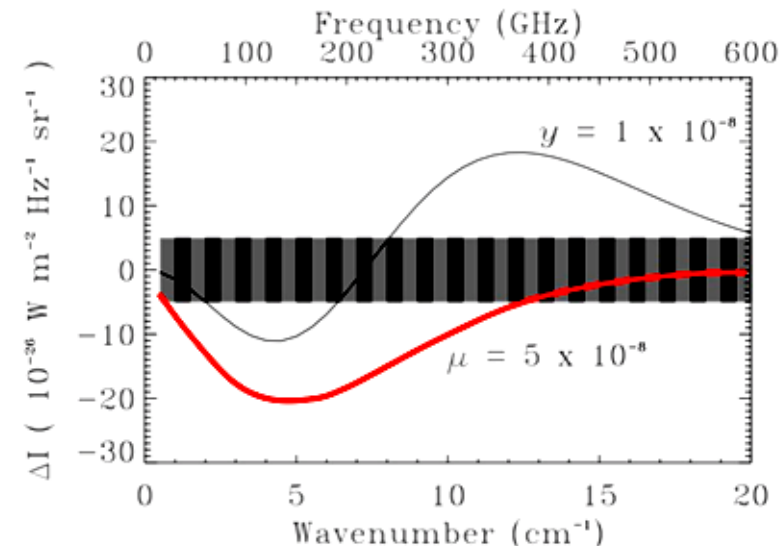
Number density $n \sim m^{-1}$

$$m_\chi > 80 \text{ keV} \left[f \left(\frac{\mu}{5 \times 10^{-8}} \right) \left(\frac{\sigma v}{6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}} \right) \left(\frac{\Omega_\chi}{0.112} \right)^2 \right]^{1/2}$$

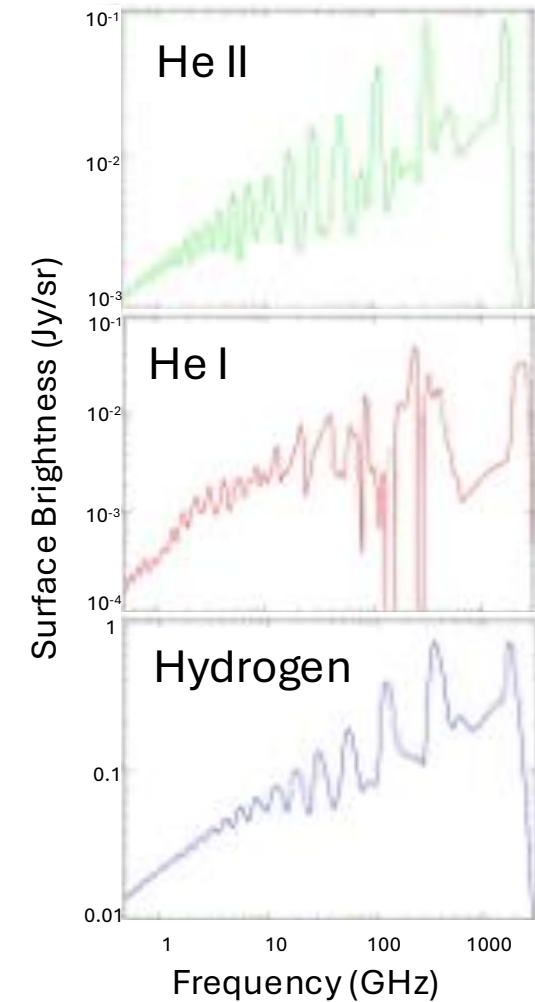
Dark matter annihilation

Neutralino mass limit $m_\chi > 80 \text{ keV}$

Definitive test for warm dark matter
Complement gamma-ray searches



Spectral Distortions: Cosmological Recombination



3 Recombination Epochs

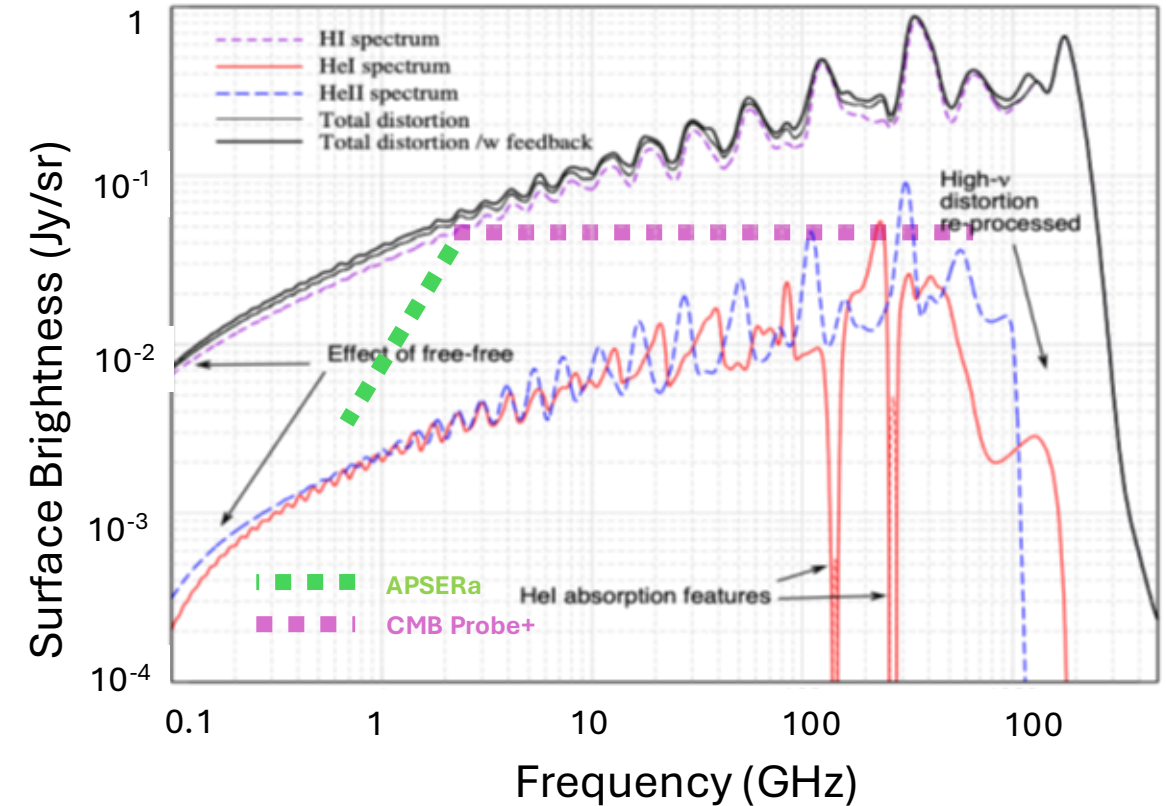
He II $z \sim 6000$

He I $z \sim 2500$

H I $z \sim 1300$

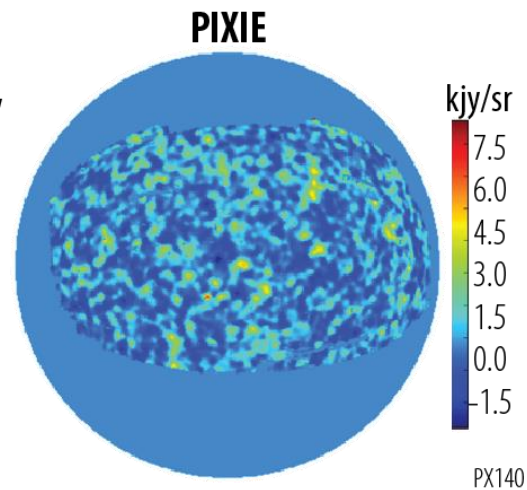
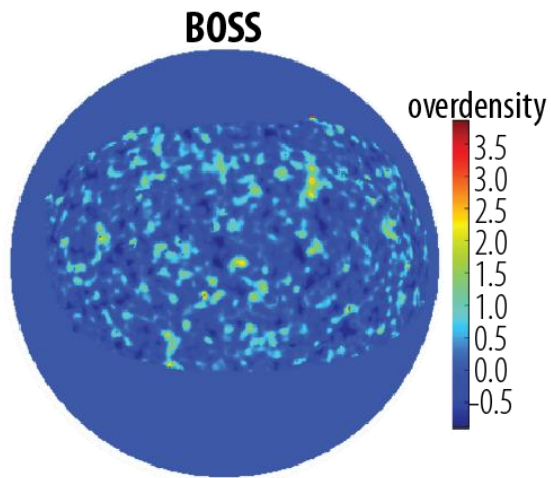
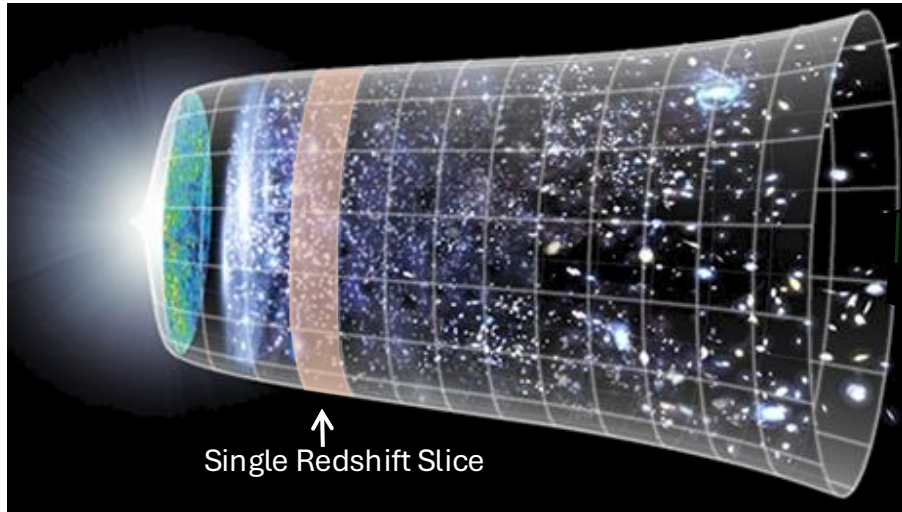
Independent test vs CMB anisotropy

Direct determinations of
Baryon density
Primordial helium density



Complex set of lines: Less confusion with continuum foregrounds

Spectral Distortions: Line Intensity Mapping



Modest spatial resolution

Integrated emission from all sources

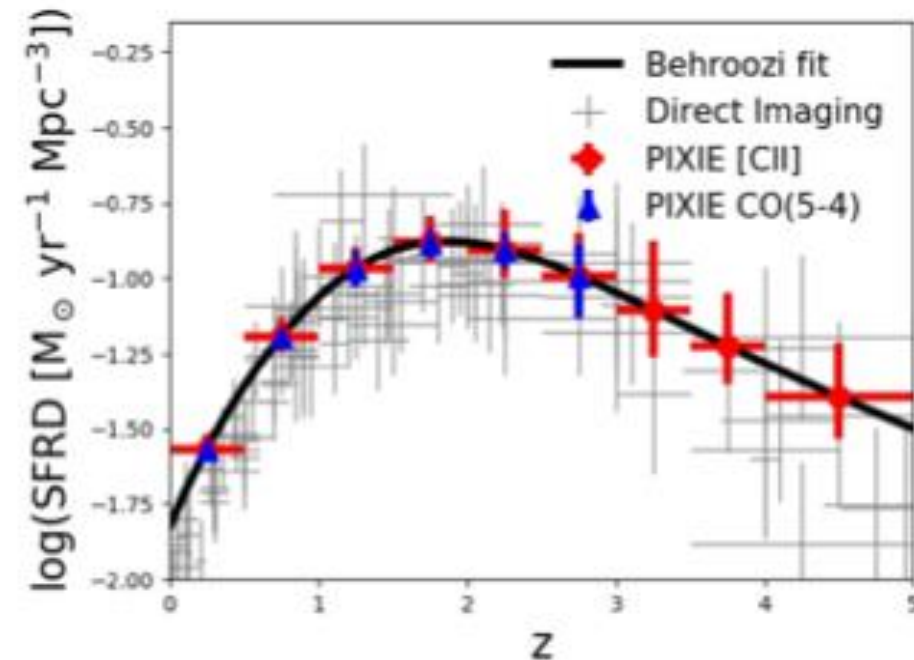
Multiple frequency bins

Multiple redshift slices

Red-shifted far-IR lines

C+ 158 μm $\rightarrow$ Star formation rate

CO ladder $\rightarrow$ Cold gas reservoir



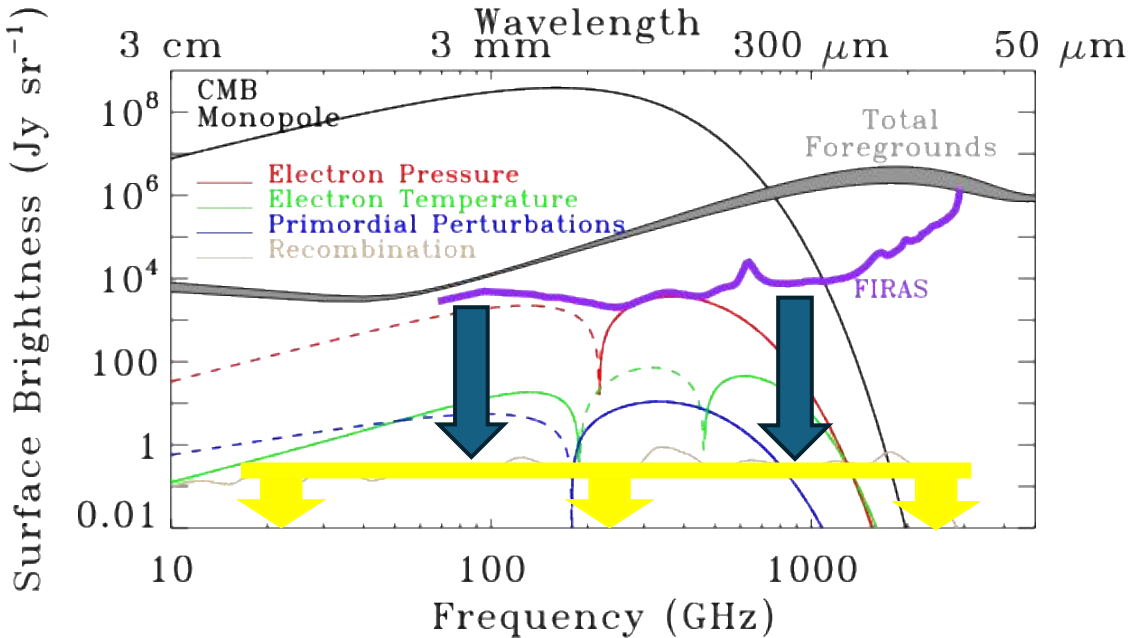
Get this free from CMB spectral survey

The Best Is Yet To Come?



Plenty of room for improvement!

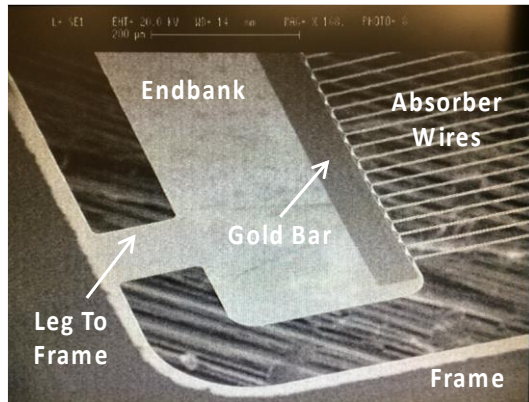
Design Feature	FIRAS	Today	Improvement
Detector Temperature	1.4 K	0.1 K	x 15
Etendue	1.5 cm ² sr	112 cm ² sr	x 9
Integration Time	1 month	5 years	x 8
Optical Efficiency	0.1	0.6	x 2.5
Observing Modes	1 of 4	Single Mode	x 2
Sky vs Calibrator	Separate Obs	Continuous	x 1.4
Data Acquisition	Single Direction	Both Directions	x 1.4
Total			x 11,000



Huge Discovery Space

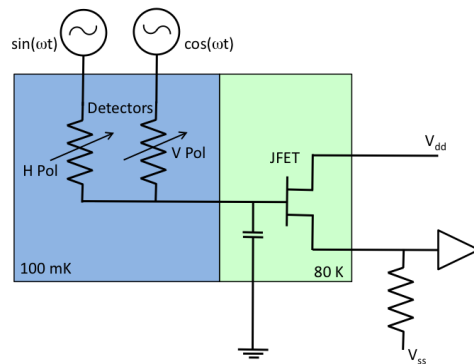
y Distortion	Electron Pressure	Recombination	Primordial Baryon Density
	Electron Temperature		Primordial Helium Abundance
	"Missing" Baryons		
	Primordial Non-Gaussianity		
μ Distortion	Primordial Density Perturbations	Foregrounds	Star Formation History
	Primordial Black Holes		Growth of Metals
	Dark Matter		Radio Synchrotron Background
	Cosmic Strings & Defects		Cosmic Infrared Background
	Primordial Non-Gaussianity		Dust Composition

Getting There: Technology Development



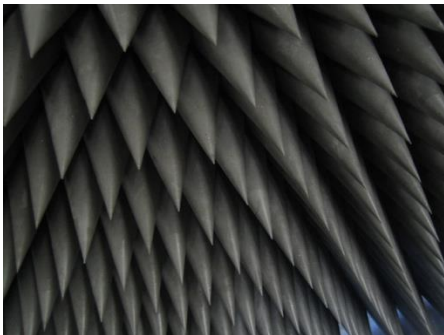
Detectors: Doped semiconductor bolometers

- 30x larger than Planck spiderweb bolometers
- Modest NEP ($10^{-16} \text{ W Hz}^{-1/2}$), not 10^{-19} !)
- Control of time constants



Readout:

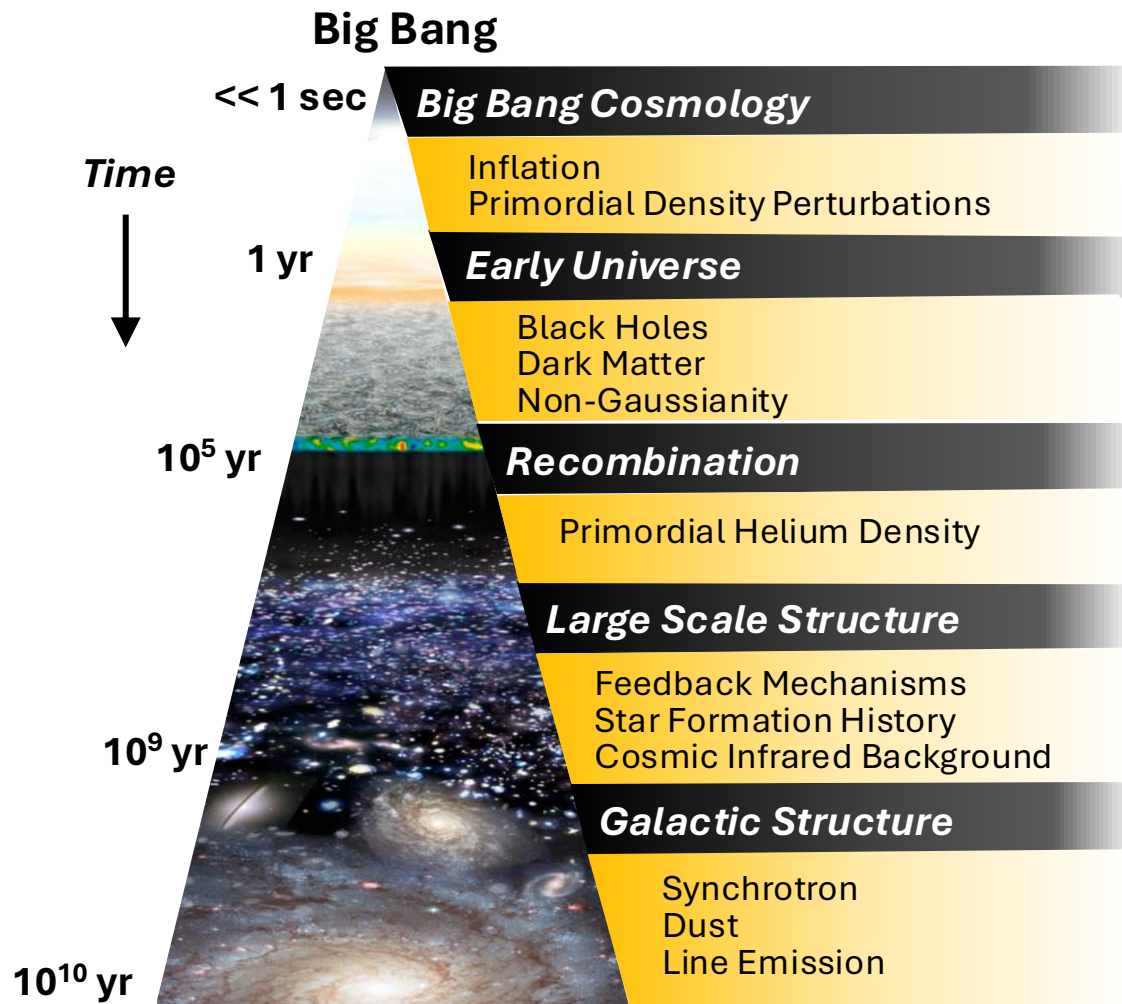
- High-impedance cryogenic sensor
- Tens (not thousands) of channels
- Like Hitomi/XRISM
but less susceptible to microphonics



Blackbody Calibrator:

- Reflection $< -65 \text{ dB}$
- Modest improvement over ARCADE-2
- Need to supply a few high-frequency photons

Science Across Cosmic Time



A small spectrometer on CMB Probe+ will

- ... Survey the full sky in 100+ spectral channels
- ... From 15 GHz to few THz (2 cm to ~100 μm)
- ... With absolute calibration and sensitivity < 1 Jy/sr

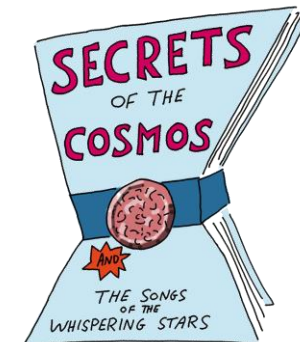
to provide key science including

- ... New tests of inflation and primordial power spectrum
- ... Feedback mechanisms for galaxy formation
- ... Star formation history on both sides of cosmic noon

opening huge discovery space for

- ... New physics (inflation, dark matter)
- ... Black hole, axions, primordial magnetic fields

and leaving a Decadal archive for astrophysics



Coming Soon To a Probe Near You!