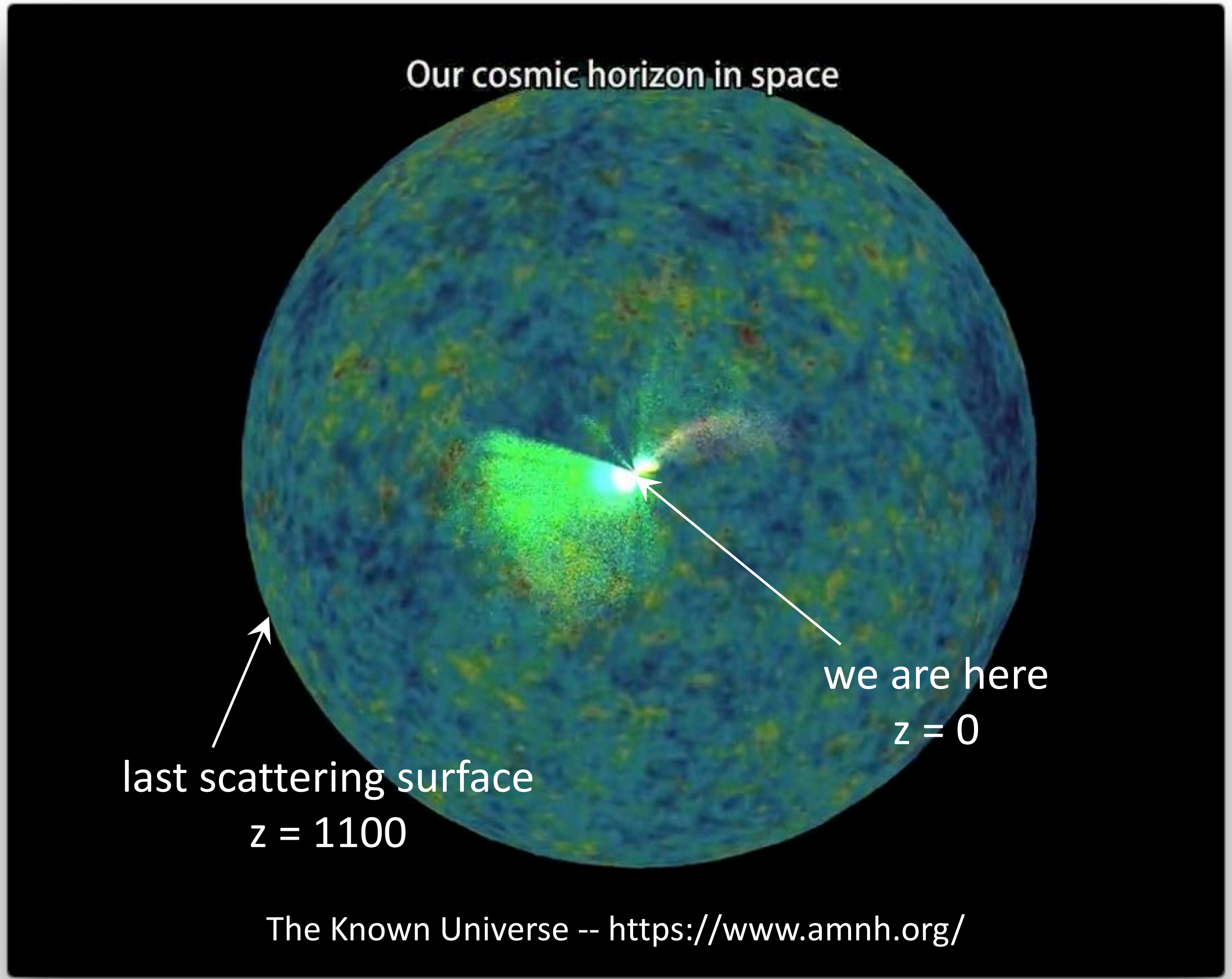
Discovering Signals
from the
Beginning of the Universe
with
Microwave and Millimeter-Wave Spectroscopy

Brad Johnson
Columbia University

Columbia University in the City of New York

How can we see beyond our cosmic horizon?



How can we see beyond our cosmic horizon?

1) B-mode polarization anisotropy produced by inflationary gravitational waves.

focus for this talk → 2) Spectral distortions in the CMB.

Outline of the Talk

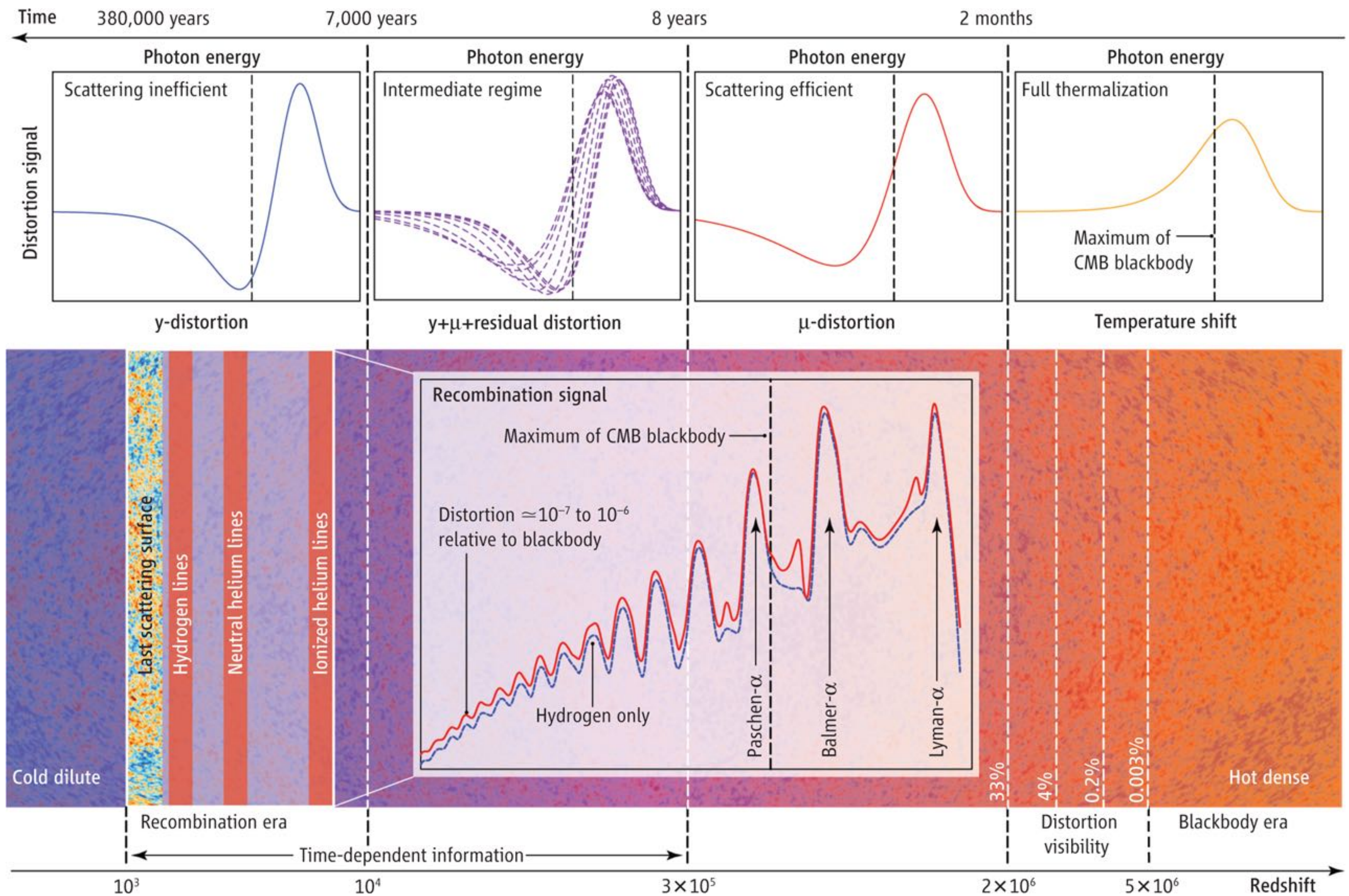
1) Overview of CMB Spectral Distortions
   y, μ, recombination lines

2) Prospects for Measuring CMB Spectral Distortions (Abitbol et al. (2017) *MNRAS*, 471, 1126-1140)

3) Investigating Anomalous Microwave Emission in the S140 Star-Forming Region (Abitbol et al. (2018) *ApJ, in prep*.)

4) A Novel Spectrometer for Discovering Signals from the Beginning of the Universe – RISE Funded

"Next Steps for Cosmology," Silk and Chluba (2014) *Science*, 344:586-588.



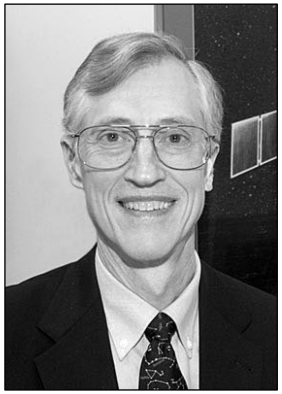
CMB Spectral Distortions

- ***μ*-type distortions** are the result of particles interacting with photons during the very early universe when photons were in equilibrium with matter ($z > 3 \times 10^5$).

- ***y*-type distortions** are produced later ($z < 3 \times 10^5$) when Compton scattering becomes an inefficient mechanism for energy exchange; this is the same mechanism that produces the thermal Sunyaev-Zel'dovich effect in galaxy clusters.

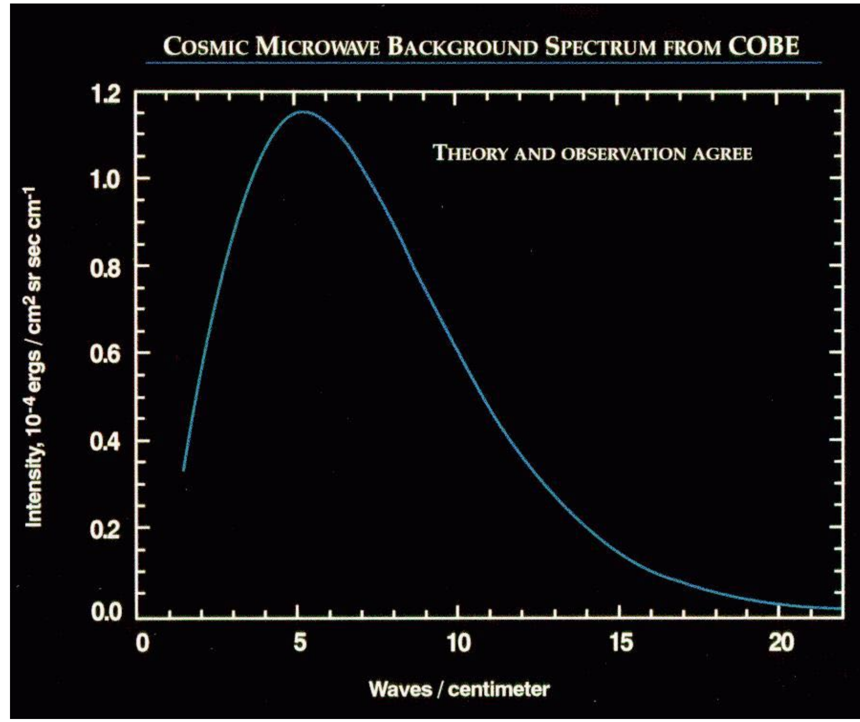
- A **recombination line spectrum** should have been produced when hydrogen and helium nuclei in the primordial plasma captured electrons during recombination, producing emission lines distinctly different from the usual CMB blackbody spectrum ($10^3 < z < 10^4$).

CMB Blackbody Spectrum & Anisotropy


Mather


Smoot

The **2006 Nobel Prize** in Physics was awarded jointly to John C. Mather and George F. Smoot *"for their **discovery of the blackbody form** and anisotropy of the cosmic microwave background radiation."*



THE ASTROPHYSICAL JOURNAL, 420:439–444, 1994 January 10

MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COBE*[1] FIRAS INSTRUMENT

J. C. MATHER,[2] E. S. CHENG,[2] D. A. COTTINGHAM,[3] R. E. EPLEE, JR.,[4] D. J. FIXSEN,[5] T. HEWAGAMA,[6] R. B. ISAACMAN,[4] K. A. JENSEN,[6] S. S. MEYER,[7] P. D. NOERDLINGER,[5] S. M. READ,[6] L. P. ROSEN,[6] R. A. SHAFER,[2] E. L. WRIGHT,[8] C. L. BENNETT,[2] N. W. BOGGESS,[2] M. G. HAUSER,[2] T. KELSALL,[2] S. H. MOSELEY, JR.,[2] R. F. SILVERBERG,[2] G. F. SMOOT,[9] R. WEISS,[7] AND D. T. WILKINSON[10]

Received 1993 February 5; accepted 1993 July 21

TABLE 1

ERRORS AND DEPENDENCE ON GALACTIC PLANE EXCLUSION ANGLE FROM 20° TO 40°

Parameter (unit)	Value	σ	Systemic Error	Galactic Range	95% CL
T_0 (K)	2.726	0.00001	0.005	±0.000012	0.010
$\mu\,(10^{-5})$......	−12	8		−1 to −21	33
$y\,(10^{-6})$......	3	8		−9 to +14	25

NOTE.—There is no known significant source of systematic error for y or μ besides the Galaxy. The quoted σ includes the effect of the simultaneous solution for a temperature shift and Galactic emission as well as y or μ.

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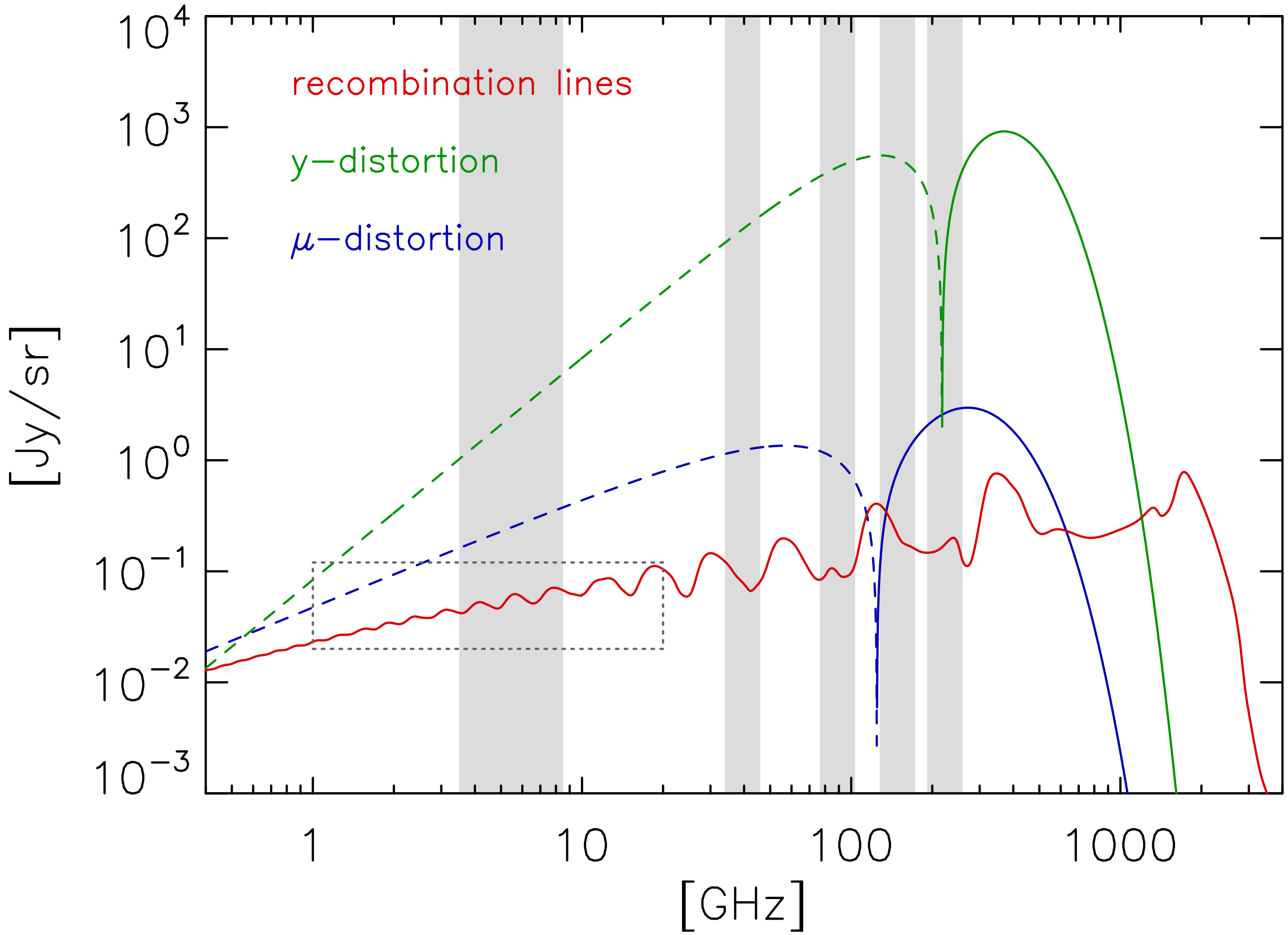
CMB Spectral Distortion Signals



← B-modes for comparison

2) Prospects for Measuring CMB Distortions

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **471,** 1126–1140 (2017)
Advance Access publication 2017 June 30

doi:10.1093/mnras/stx1653

Prospects for measuring cosmic microwave background spectral distortions in the presence of foregrounds

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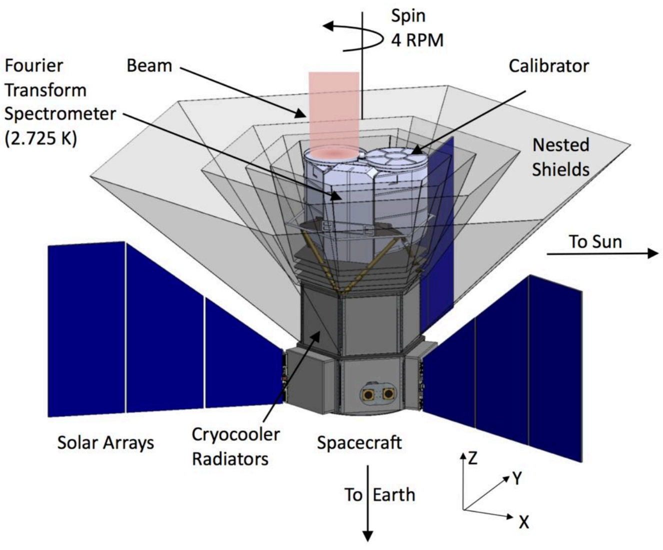
Accepted 2017 June 28. Received 2017 June 27; in original form 2017 May 3

We investigated the detectability of the μ and *y* spectral distortions using NASA's proposed PIXIE mission as the test case.



Kogut et al. (2011) *JCAP*, 07, 025.

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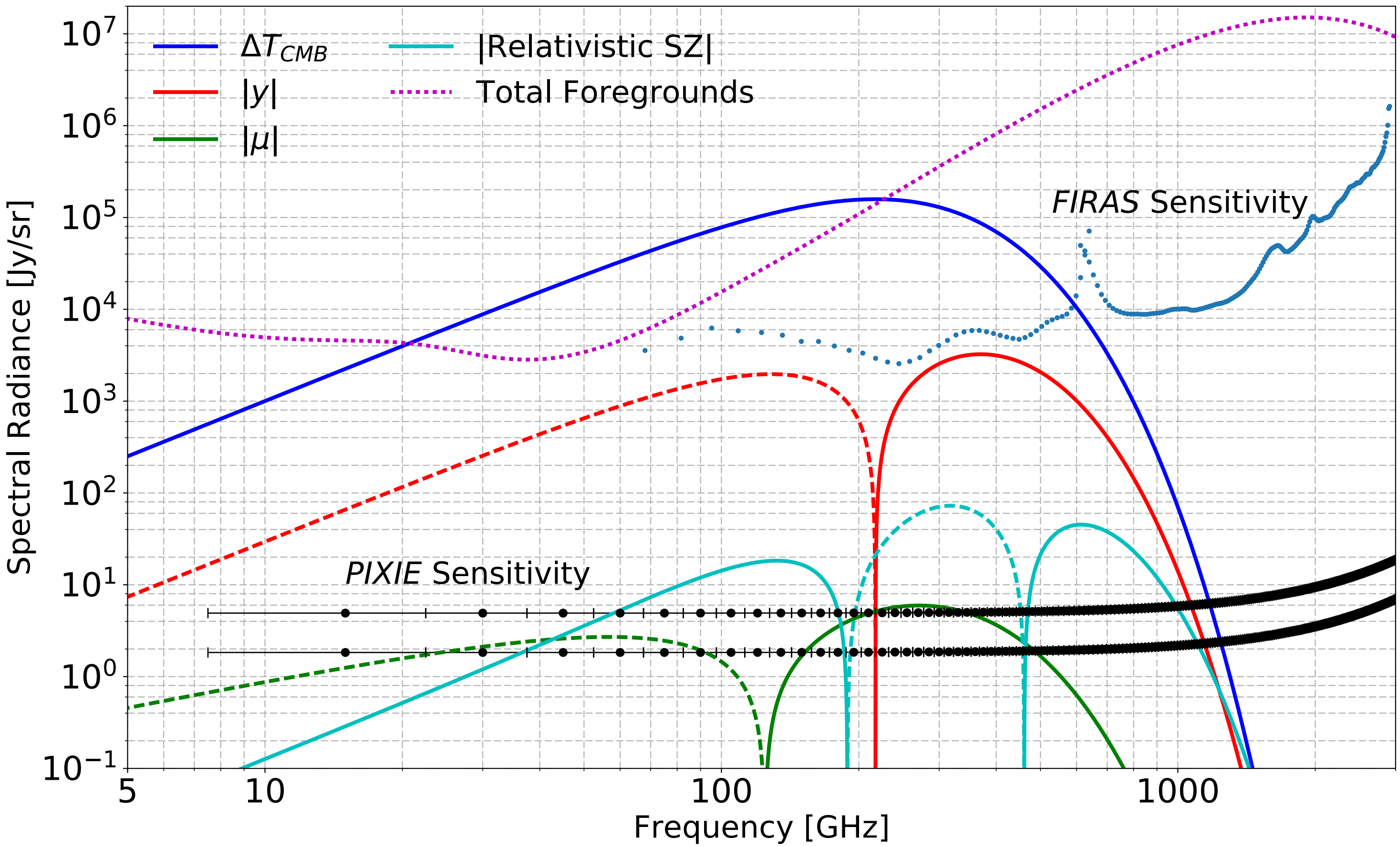
Could PIXIE measure *y* and μ?



Abitbol et al. (2017) *MNRAS*, 471, 1126-1140.

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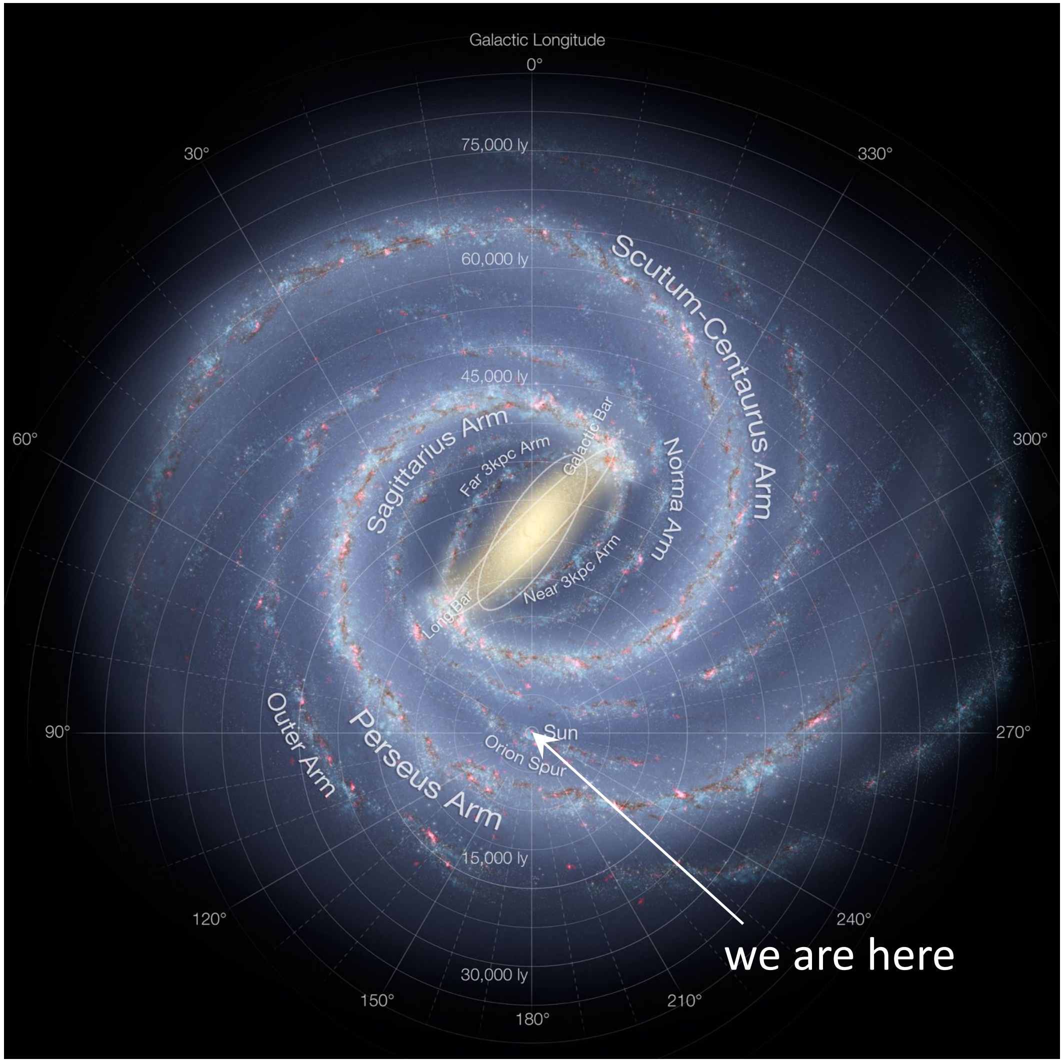
Problem: Galactic Signals



Credit: NASA/JPL-Caltech/ESO/R. Hurt

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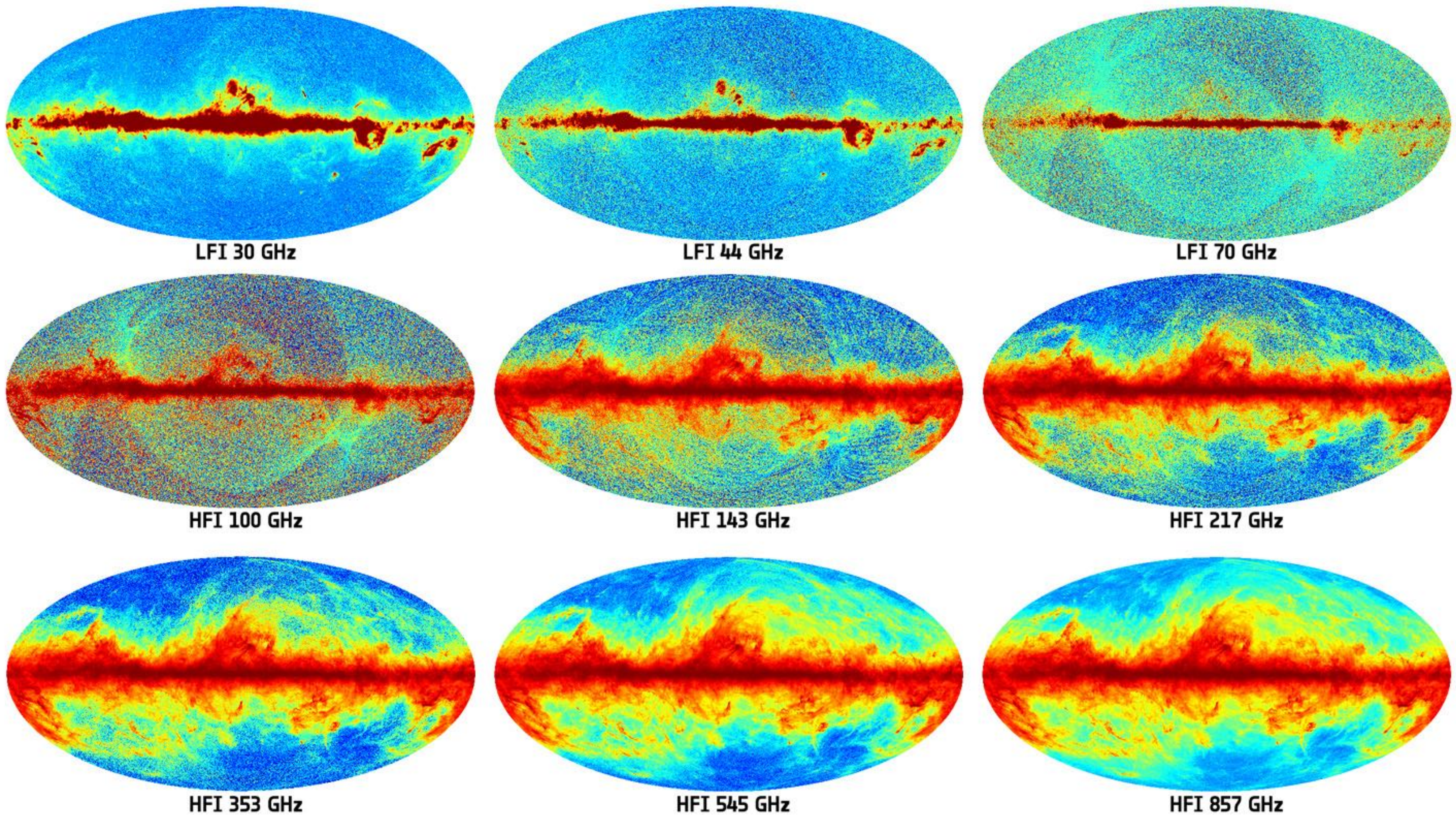
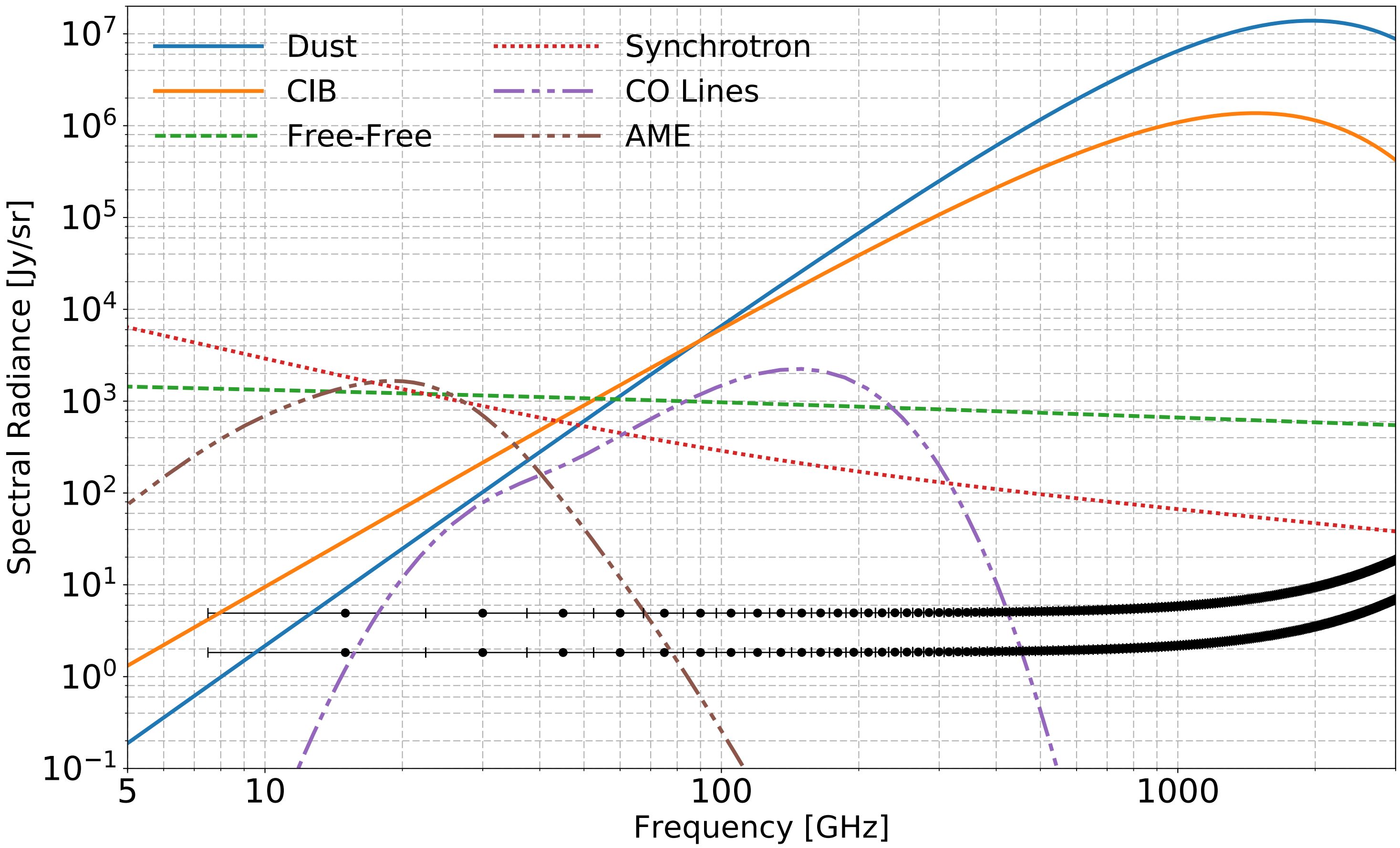
Planck all-sky foreground maps



Forecast Performance Including Galactic Signals



Abitbol et al. (2017) *MNRAS*, 471, 1126-1140.

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Galactic Signals

- **Free-free** or Bremsstrahlung emission is **unpolarized** radiation from electron-ion collisions. The free-free spectrum decreases as a power law $\beta = -2.15$, for electron temperatures between 500 and 20,000 K.

- **Synchrotron** radiation originates from cosmic ray electrons spiraling in Galactic magnetic fields. The synchrotron spectrum follows a power law with spectral index typically around $\beta = -3$, and it theoretically can be **up to 75% polarized**.

- **Thermal dust** emission comes from interstellar dust grains that are heated by ambient radiation from stars in the Galaxy. The emission obeys a modified blackbody spectrum at a temperature of 18 K and spectral index $\beta = 1.8$ up to 800 GHz (at even higher frequencies two component models are used). The dust has been measured to be approximately **5% polarized on average** over the sky but up to 20% polarized in regions of low optical depth.

- The **cosmic infrared background (CIB)** is the collective infrared radiation emitted by cosmic sources throughout the history of the Universe.

Anomalous Microwave Emission

- **Anomalous Microwave Emission (AME)** includes emission that does not correlate with dust, synchrotron, or free-free.
- The **physical mechanism behind the AME is not understood**, and we do not yet have reliable estimates of the degree to which it is polarized.
- The current prevailing theory for AME is that **small asymmetrical dust grains spin rapidly** and emit electric dipole radiation.
- **The polarization of spinning dust arises when grains align with the local magnetic field.**
- Other theories propose contributions from ferromagnetic dust grains and their associated magnetic dipole radiation.

Models Exist for Galactic Signals

Table 1. Foreground model motivated by *Planck* data. All SEDs, ΔI_X, are in units of Jy sr^{-1}. For each component, we also give the value of $\Delta I_X(\nu_r)$ at $\nu_r = 100$ GHz for reference.

Foreground	Spectral radiance (Jy sr^{-1})	Free parameters and values	Additional information
Thermal dust	$x = \frac{h\nu}{kT_D}$ $\Delta I_D(\nu) = A_D\, x^{\beta_D}\, \frac{x^3}{e^x - 1}$	$A_D = 1.36 \times 10^6$ Jy sr^{-1} $\beta_D = 1.53$ $T_D = 21$ K	$\Delta I_D(\nu_r) = 6608$ Jy sr^{-1}
CIB	$x = \frac{h\nu}{kT_{CIB}}$ $\Delta I_{CIB}(\nu) = A_{CIB}\, x^{\beta_{CIB}}\, \frac{x^3}{e^x - 1}$	$A_{CIB} = 3.46 \times 10^5$ Jy sr^{-1} $\beta_{CIB} = 0.86$ $T_{CIB} = 18.8$ K	$\Delta I_{CIB}(\nu_r) = 6117$ Jy sr^{-1}
Synchrotron	$\Delta I_S(\nu) = A_S \left(\frac{\nu}{\nu_0}\right)^{\alpha_S} \left[1 + \frac{1}{2}\omega_S \ln^2\left(\frac{\nu}{\nu_0}\right)\right]$	$A_S = 288.0$ Jy sr^{-1} $\alpha_S = -0.82$ $\omega_S = 0.2$	$\Delta I_S(\nu_r) = 288$ Jy sr^{-1} 10 per cent prior assumed on A_S and α_S $\nu_0 = 100$ GHz
Free–free	$\nu_{ff} = \nu_{FF}\,(T_e/10^3\text{ K})^{3/2}$ $\Delta I_{FF}(\nu) = A_{FF}\left(1 + \ln\left[1 + \left(\frac{\nu_{ff}}{\nu}\right)^{\sqrt{3}/\pi}\right]\right)$	$A_{FF} = 300$ Jy sr^{-1}	$\Delta I_{FF}(\nu_r) = 972$ Jy sr^{-1} $\{T_e, \nu_{FF}\} = \{7000\text{ K}, 255.33\text{ GHz}\}$
Integrated CO	$\Theta_{CO}(\nu) = \text{CO template}(\nu)$ $\Delta I_{CO}(\nu) = A_{CO}\Theta_{CO}(\nu)$	$A_{CO} = 1$	$\Delta I_{CO}(\nu_r) = 1477$ Jy sr^{-1} Template in Jy sr^{-1}
Spinning dust	$\Theta_{SD}(\nu) = \text{SD template}(\nu)$ $\Delta I_{SD}(\nu) = A_{SD}\Theta_{SD}(\nu)$	$A_{SD} = 1$	$\Delta I_{SD}(\nu_r) = 0.25$ Jy sr^{-1} Template in Jy sr^{-1}

Forecast PIXIE performance with Fischer/MCMC analysis.

Abitbol et al. (2017) *MNRAS*, 471, 1126-1140.

Conclusion from Abitbol et al. (2017)

Table 3. Forecasts with foregrounds, using MCMC. All results are for the extended mission (86.4 months), except for the first column (12 months). The given numbers represent the average of the two-sided 1σ marginalized uncertainty on each parameter. The models for the extended mission are sorted using the errors on y and kT_e. Values in parentheses are the detection significance (i.e. fiducial parameter value divided by 1σ error). We assume a 10 per cent prior on the synchrotron amplitude and spectral index, A_S and α_S, to represent external data sets. This only has a noticeable effect for the 14 and 16 parameter cases. No band average is included, but this is found to have only a small effect.

Sky model	CMB (baseline)	CMB	Dust, CO	Sync, FF, AME	Sync, FF, dust	Dust, CIB, CO	Sync, FF, dust, CIB	Sync, FF, AME dust, CIB, CO
# of parameters	4	4	8	9	11	11	14	16
σ_{Δ_T} [10^{-9}]	2.3	0.86	2.2	3.9	9.7	5.3	59	75
σ_y [10^{-9}]	1.2 (1500σ)	0.44 (4000σ)	0.65 (2700σ)	0.88 (2000σ)	2.7 (660σ)	4.8 (370σ)	12 (150σ)	14 (130σ)
$\sigma_{kT_{eSZ}}$ [10^{-2} keV]	2.9 (42σ)	1.1 (113σ)	1.8 (71σ)	1.3 (96σ)	4.1 (30σ)	7.8 (16σ)	11 (11σ)	12 (10σ)
σ_μ [10^{-8}]	1.4 (1.4σ)	0.53 (3.8σ)	0.55 (3.6σ)	1.7 (1.2σ)	2.6 (0.76σ)	0.75 (2.7σ)	14 (0.15σ)	18 (0.11σ)

PIXIE would not detect μ predicted by nucleosynthesis given expected effects from Galactic foreground signals.

Abitbol et al. (2017) *MNRAS*, 471, 1126-1140.

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3) Investigating Anomalous Microwave Emission in the S140 Star-Forming Region

Maximilian H. Abitbol[1], Glenn Jones[1], Bradley R. Johnson[1],
Clive Dickinson[2], Stuart Harper[2]

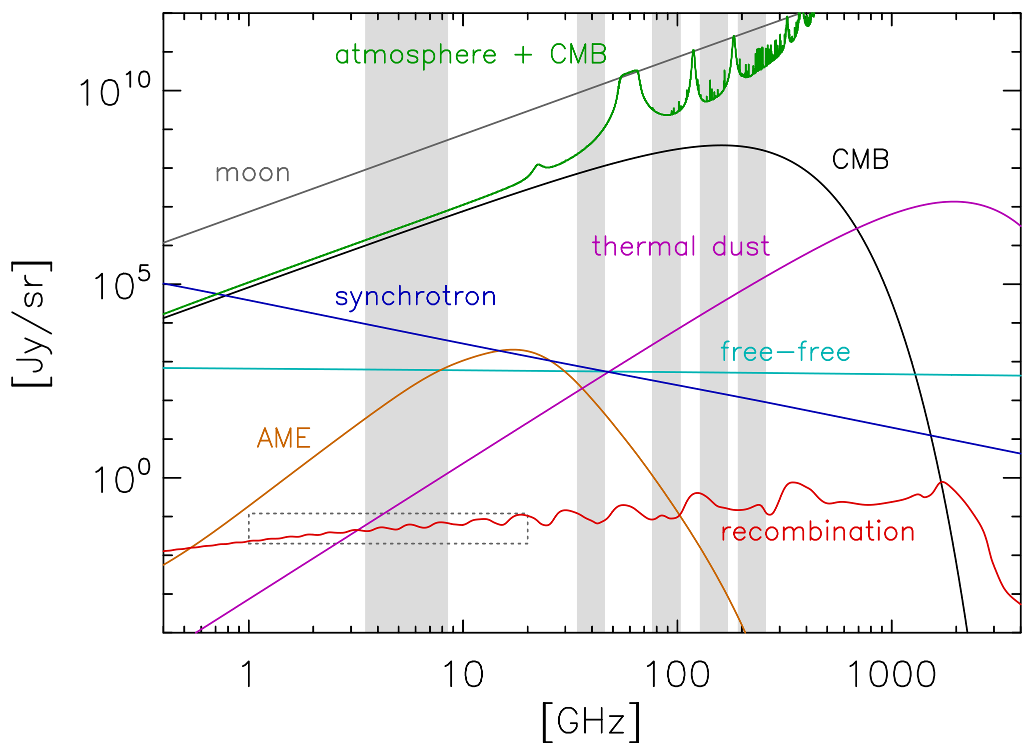
1) Department of Physics, Columbia University
2) Jodrell Bank, University of Manchester

3) Investigating Anomalous Microwave Emission in the S140 Star-Forming Region

Designed project in spring 2016.
Applied for observing time at Green Bank Telescope in summer 2016.
Awarded observing time at end of 2016 (GBT17A-259). ← 5th year review
Observations took place in spring 2017.
Analysis is done, first *ApJ* paper near submission.

Why study AME?

- Emission mechanism is not understood.
- Important foreground for B-mode studies if polarized.
- Foreground for future recombination line studies.
- Good entry-point project for my group.
- Following-up on Planck (2014) A&A 565, A103
- We're learning how to make spectropolarimetric observations and analyze data.



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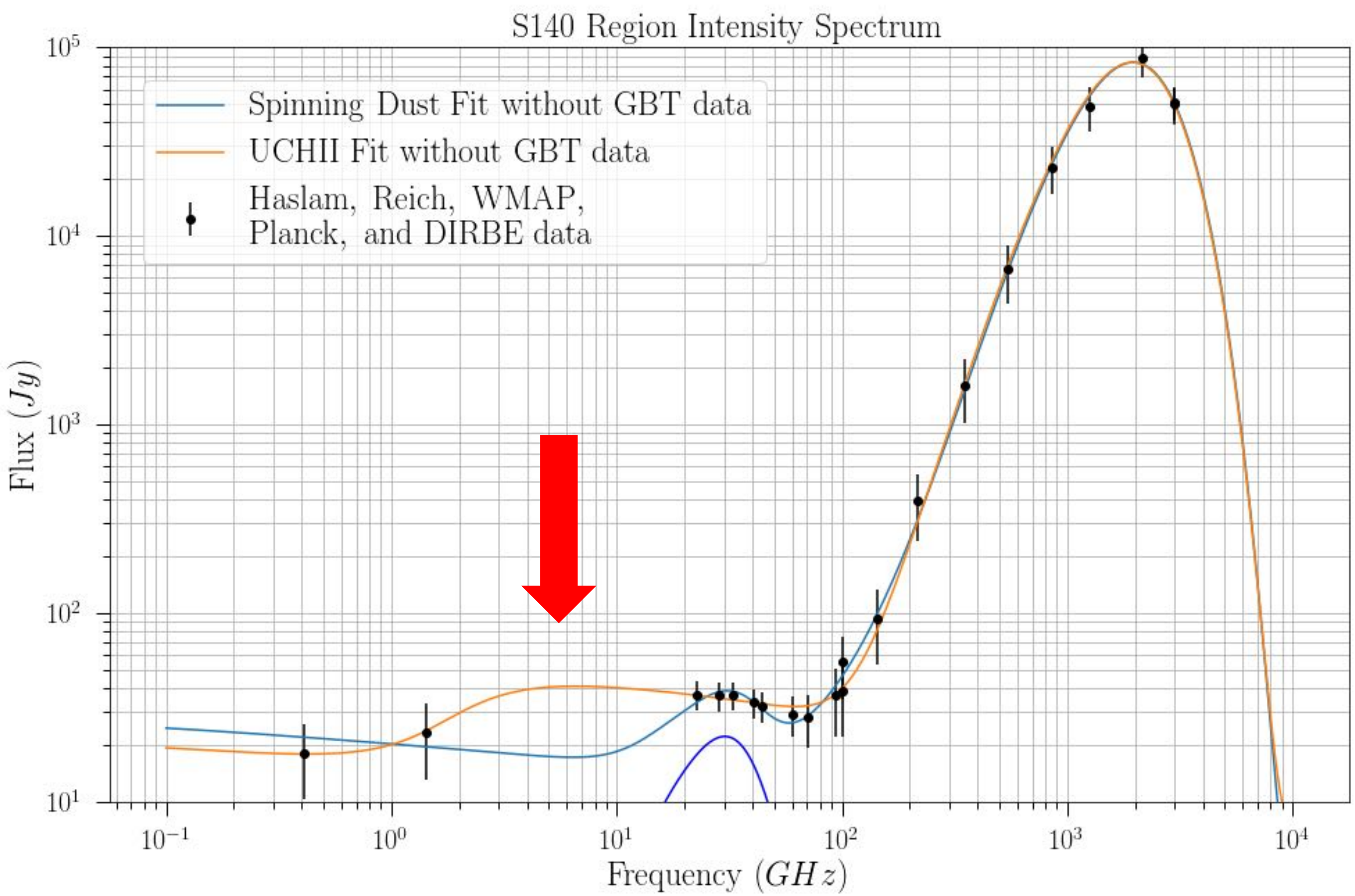
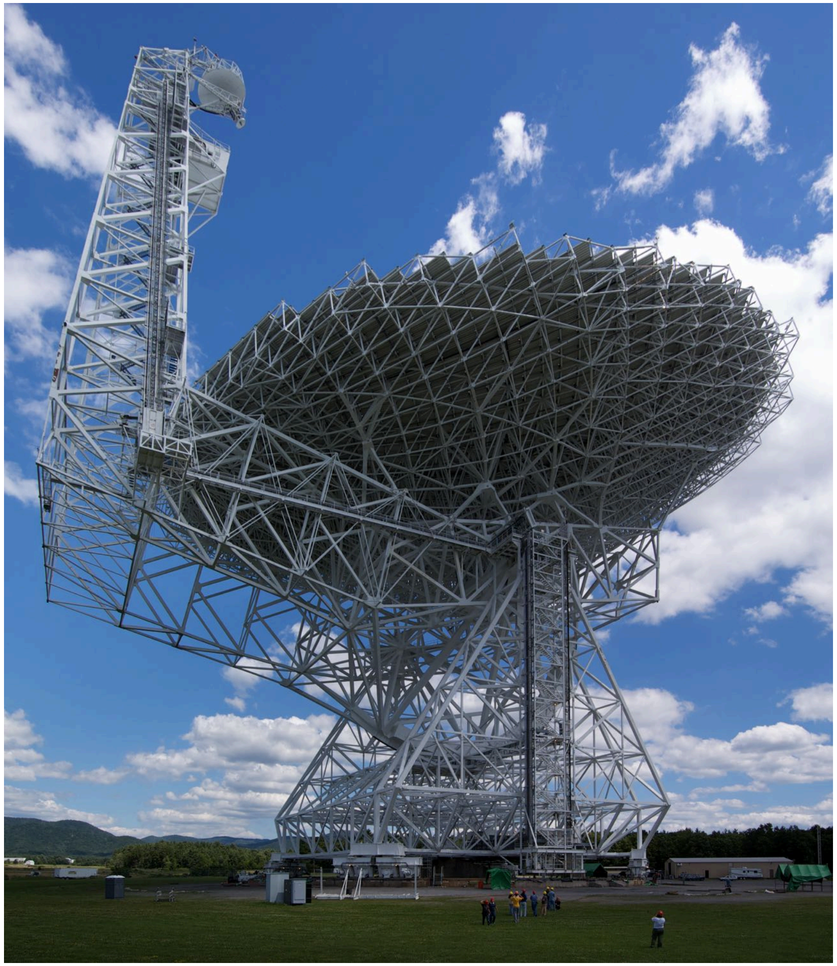
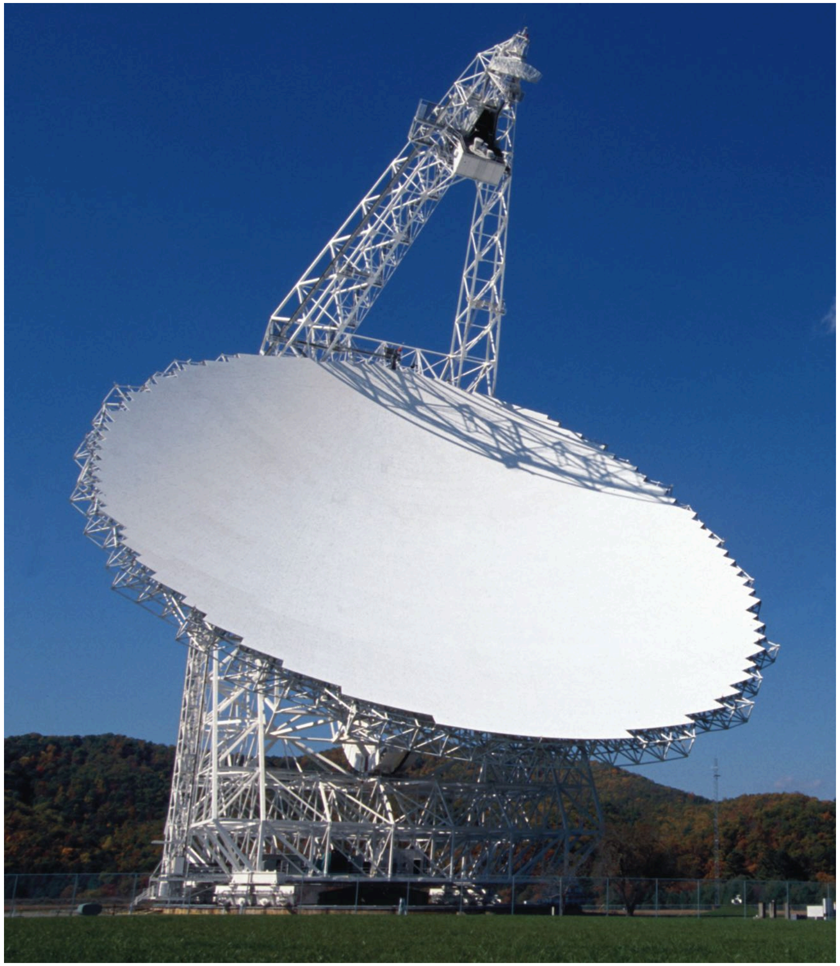
Result from Planck Collaboration



HII region = interstellar ionized hydrogen.

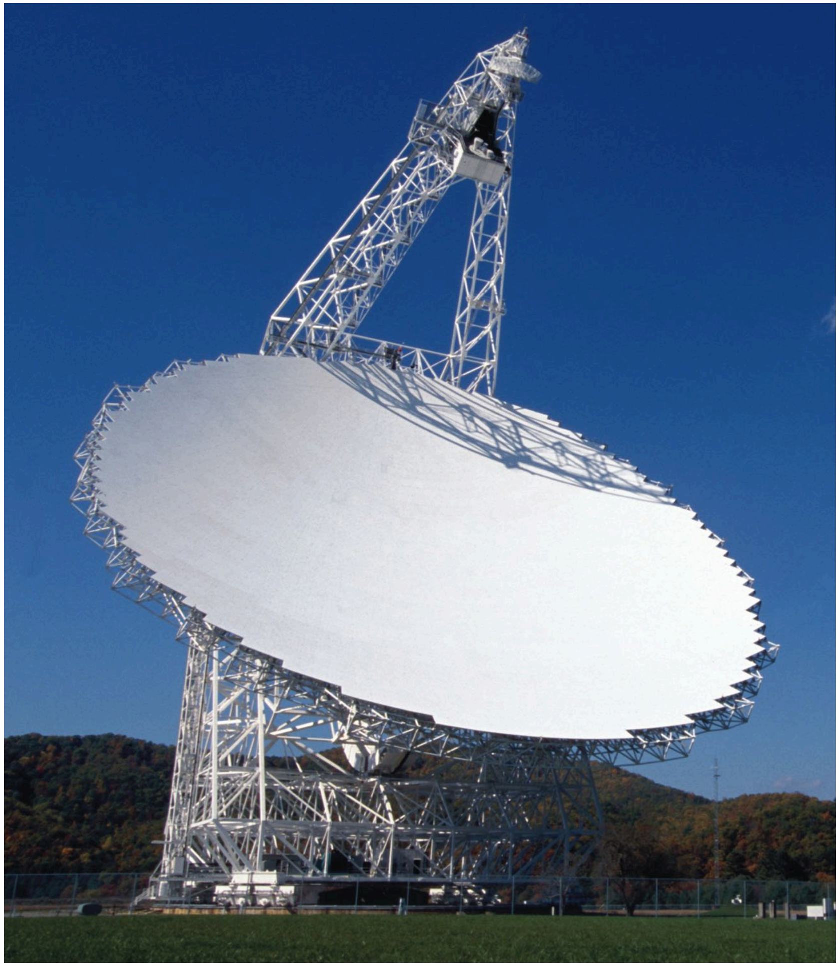
Green Bank Telescope (GBT)



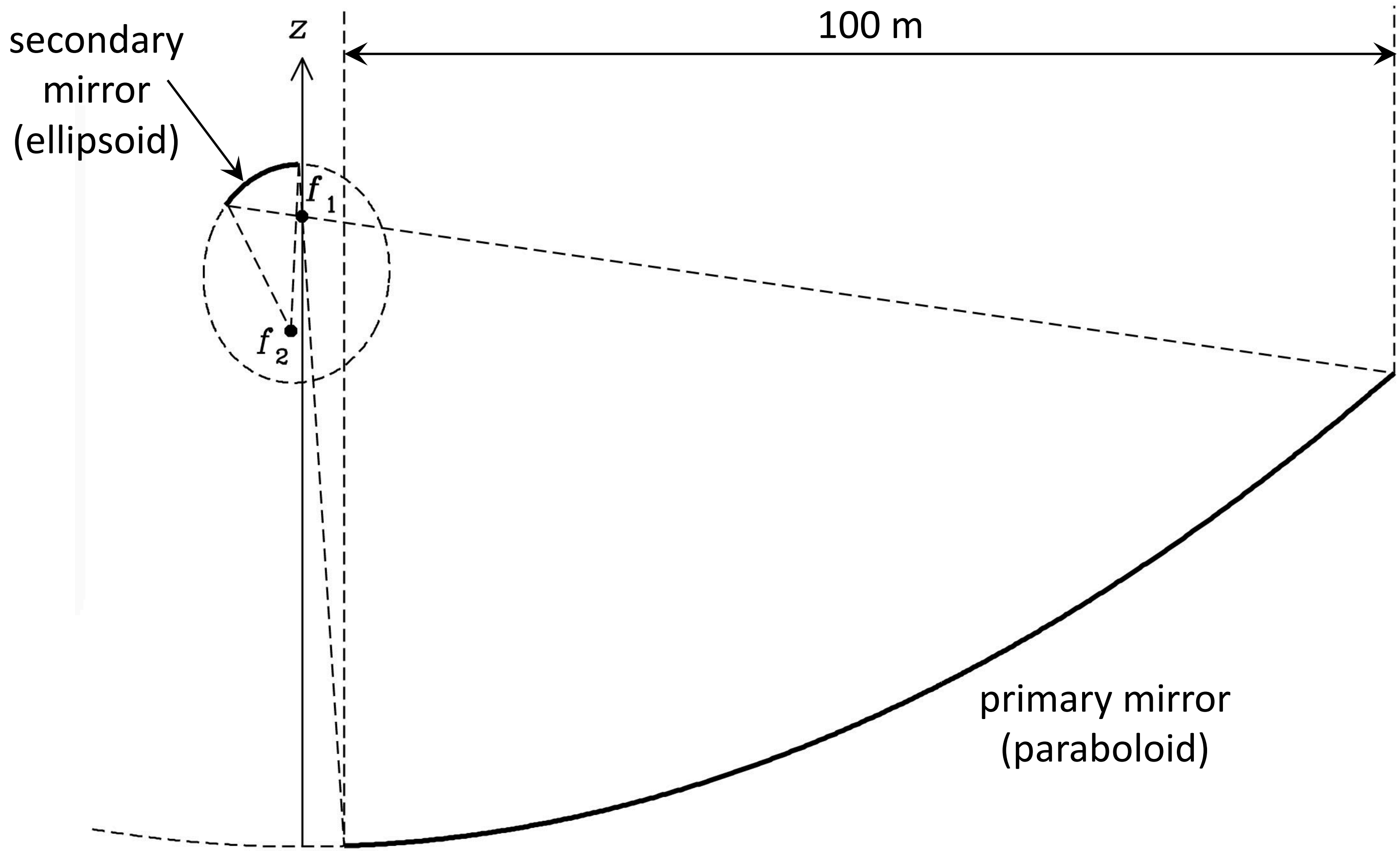


Green Bank Telescope (GBT)

- Sited in Green Bank, West Virginia
- Gregorian reflecting telescope
- diameter = 100 meters
- focal length = 60 meters
- observations possible between 0.1 and 116 GHz
- Our observations used the C-band receiver (4 to 8 GHz) and the VEGAS spectrometer.

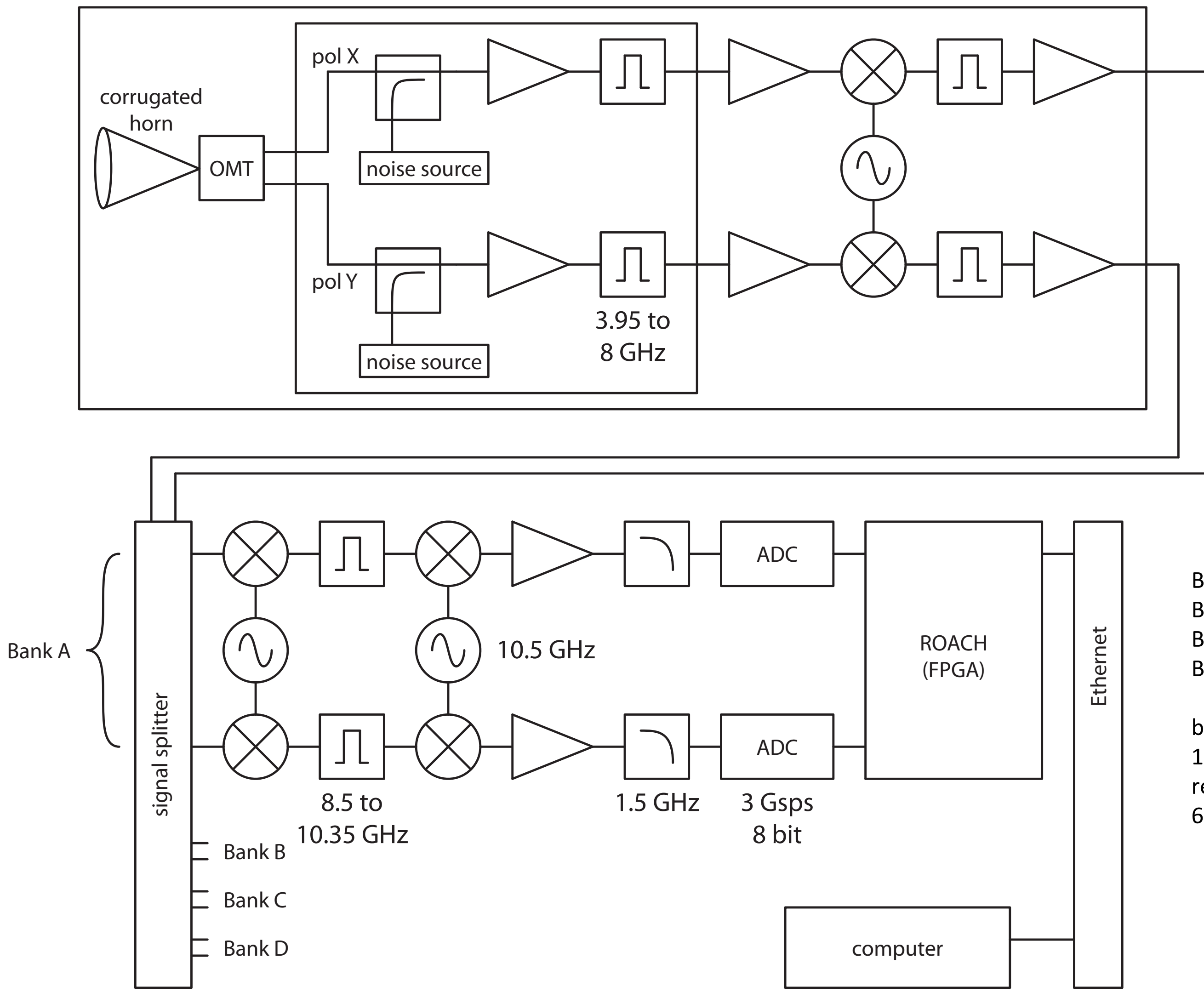


Green Bank Telescope (GBT)



GBT Receivers

VEGAS: Versatile GBT Astronomical Spectrometer

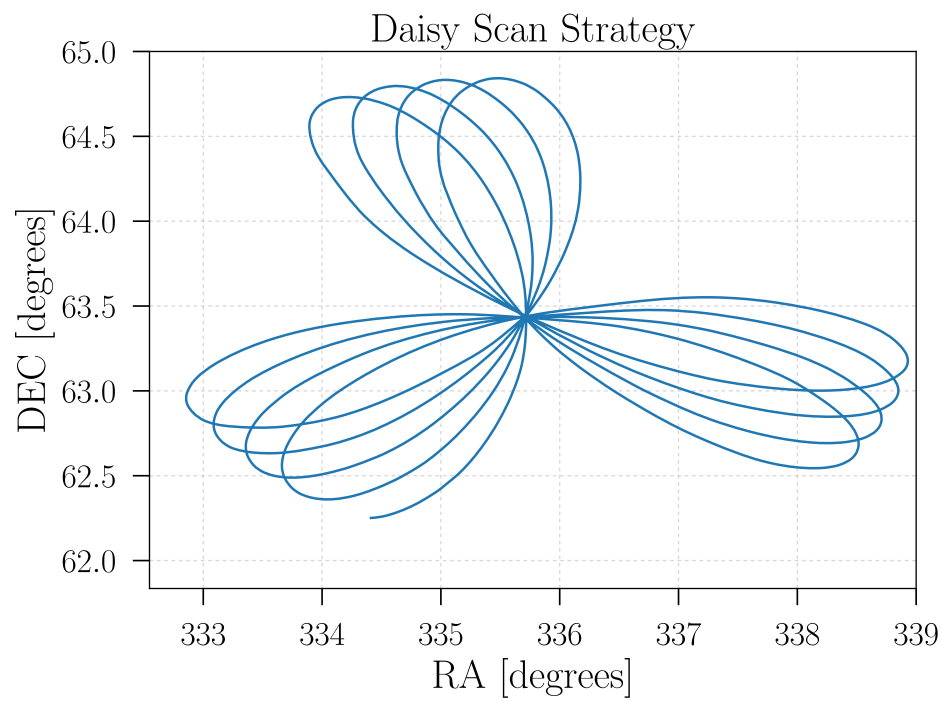


Bank A = 4.575 GHz
Bank B = 5.625 GHz
Bank C = 6.125 GHz
Bank D = 7.175 GHz

bandwidth = 1.25 GHz
16,384 channels per bank
resolution = 91.552 kHz
65,536 channels total

Observations

- Observations took place April 3, 5, 10; June 3, 4; July 31, 2017
- 18 hours of observations:
  10 hours mapping
  8 hours polarization calibration
- "daisy" scan strategy produces circular map (see right)
- absolute calibration:
  radio galaxy 3C 295 (z = 0.464)
- time dependent calibration:
  noise source switched at 25 Hz
- polarization calibration:
  3C 245, 3C 273, 3C 280



telescope pointing plotted

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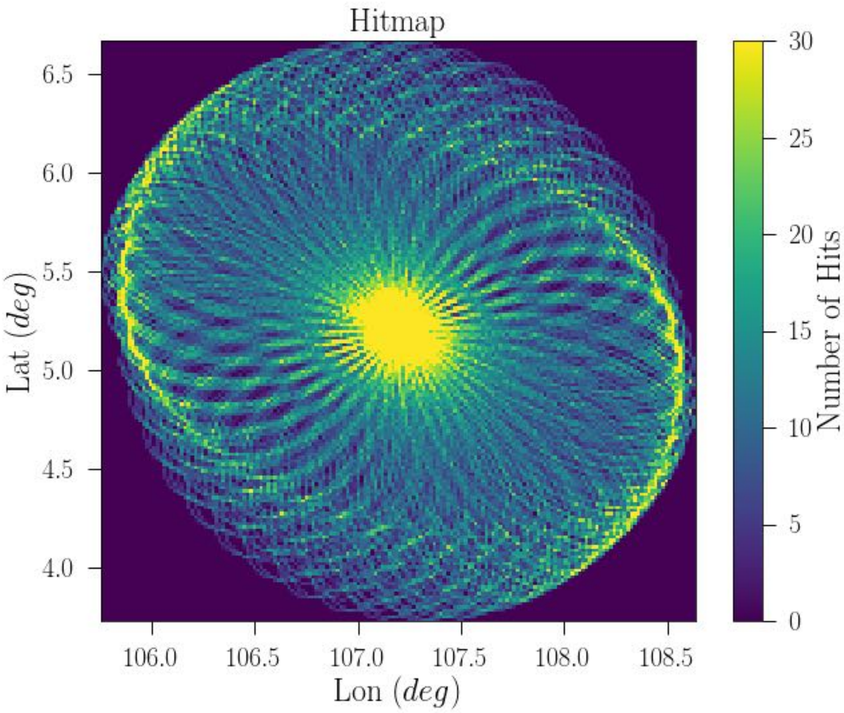

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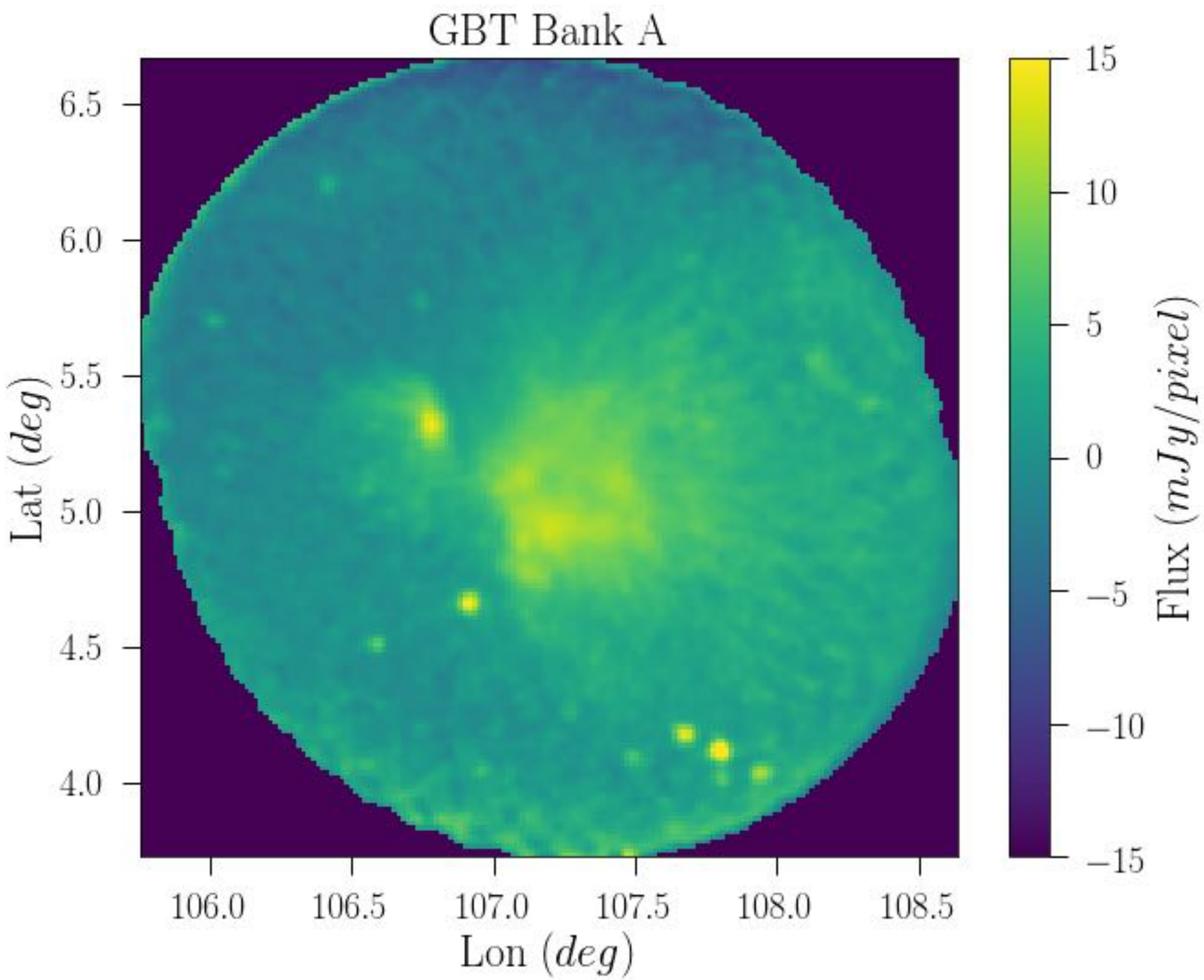
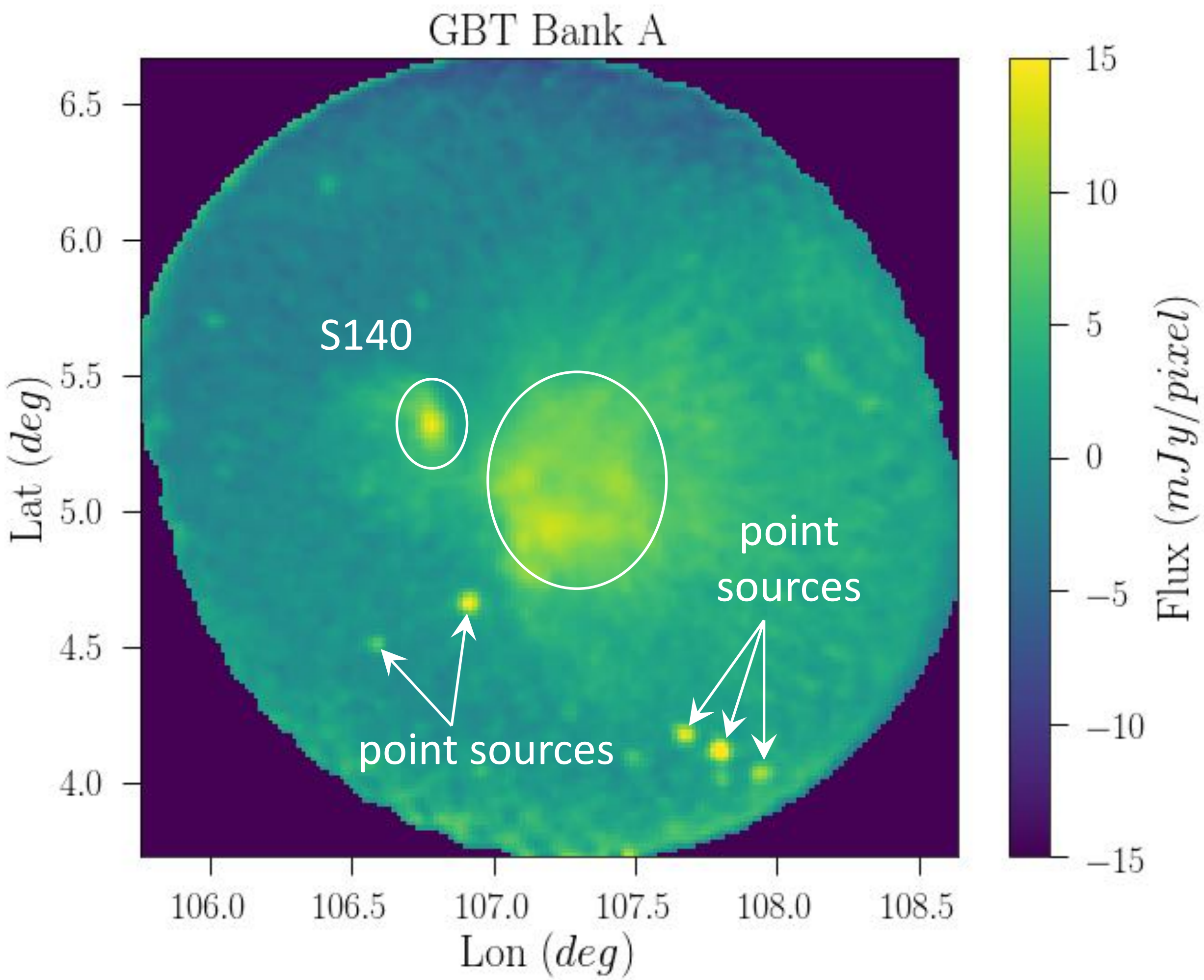
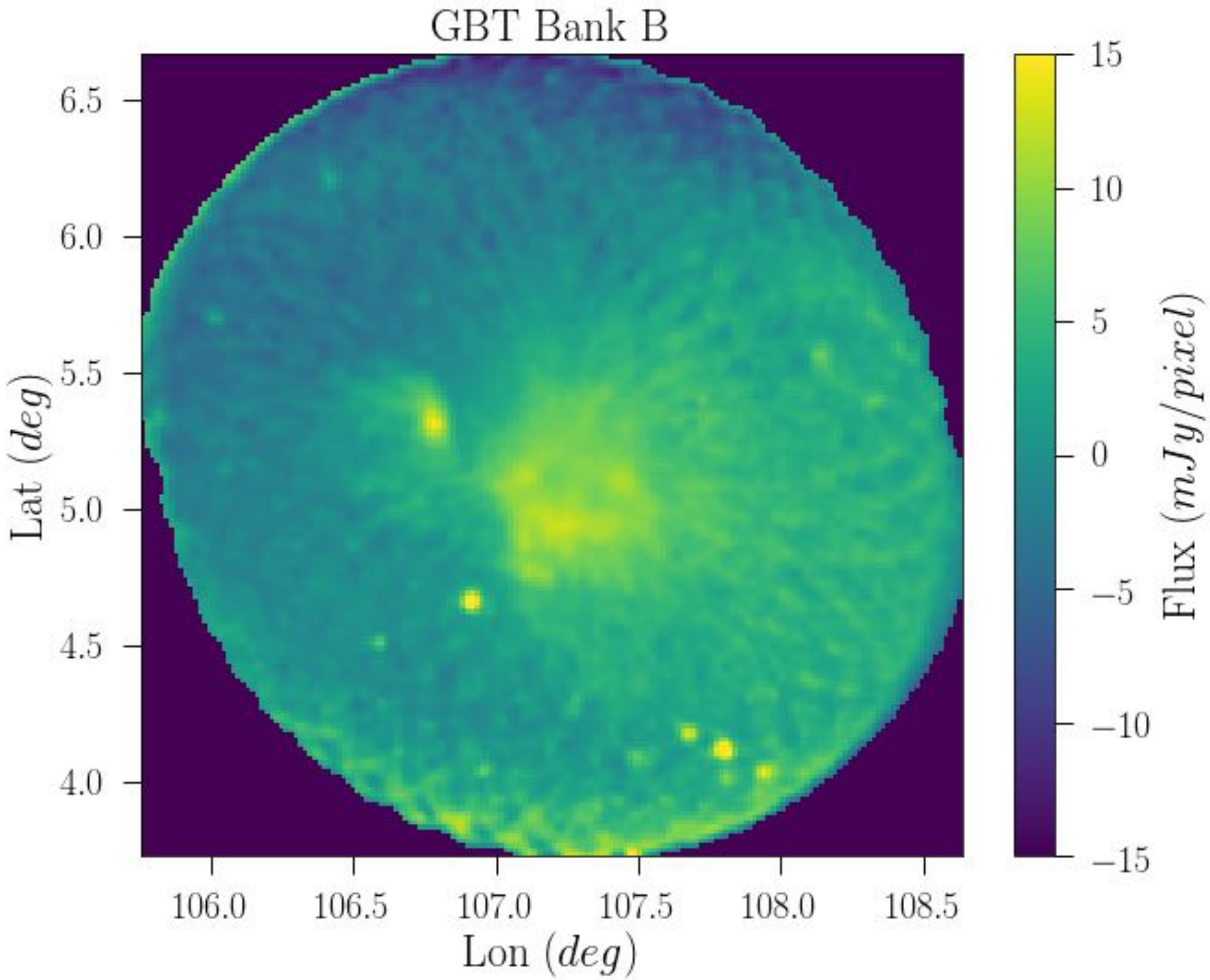
Results: Map from Bank A



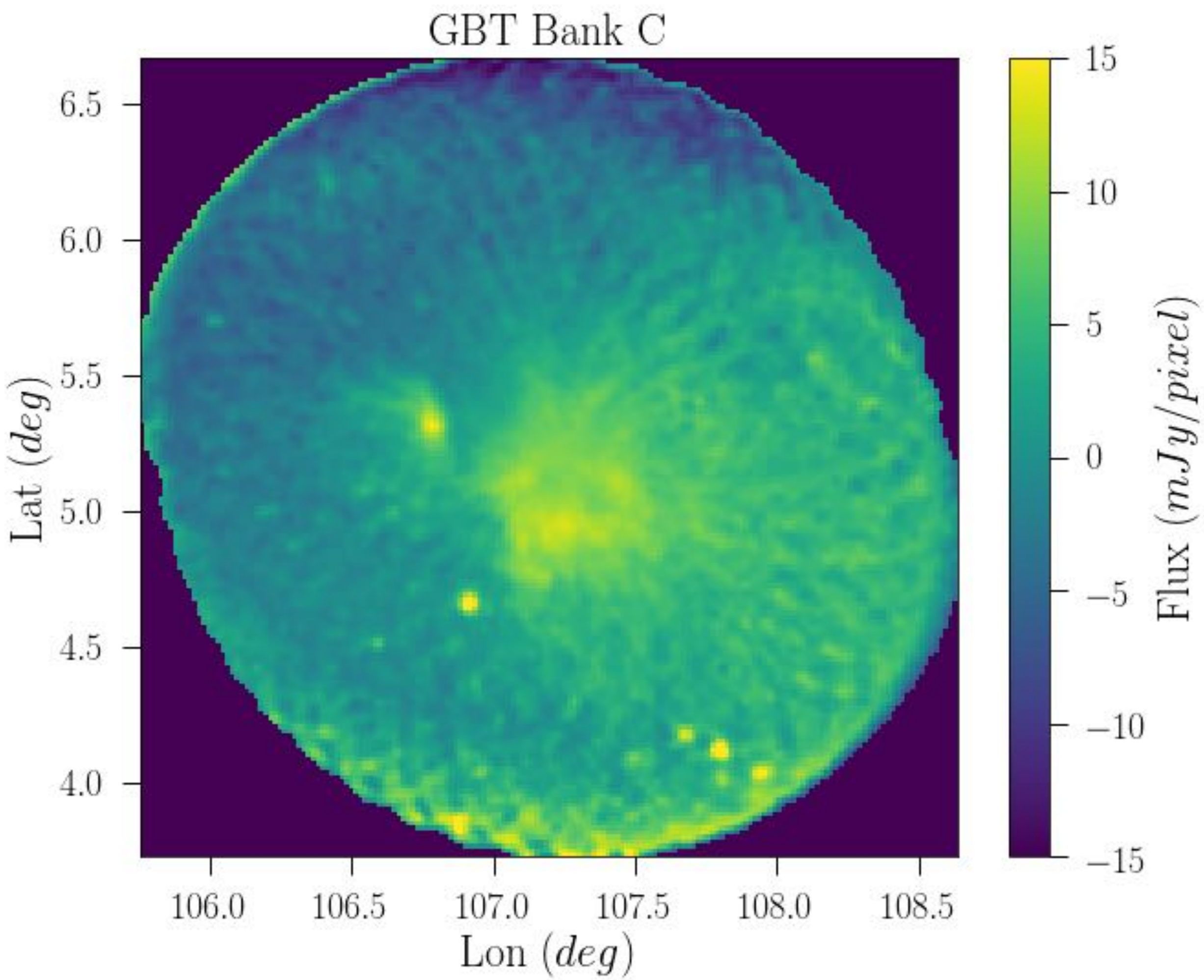
Results: Map from Bank A



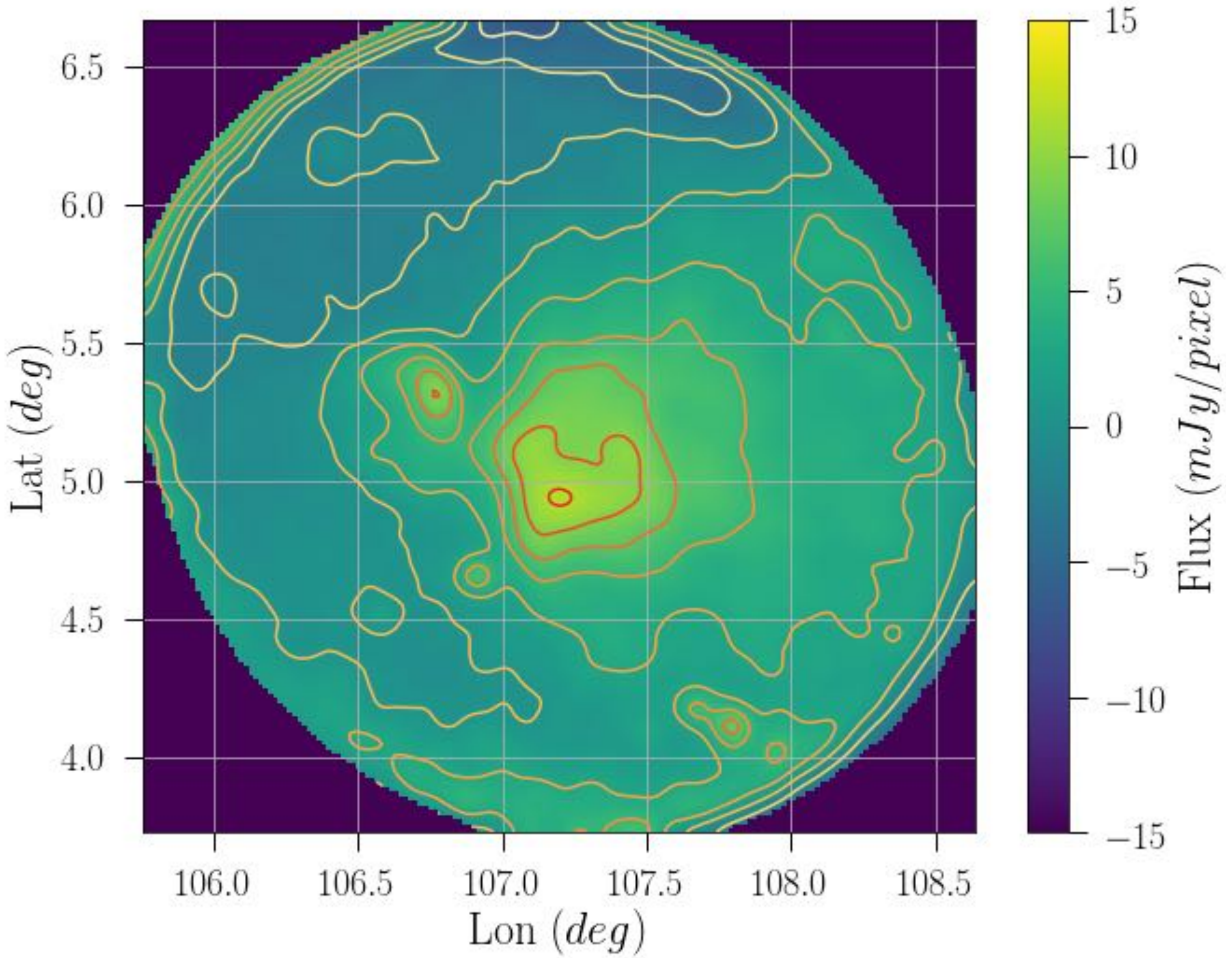
Results: Map from Bank B



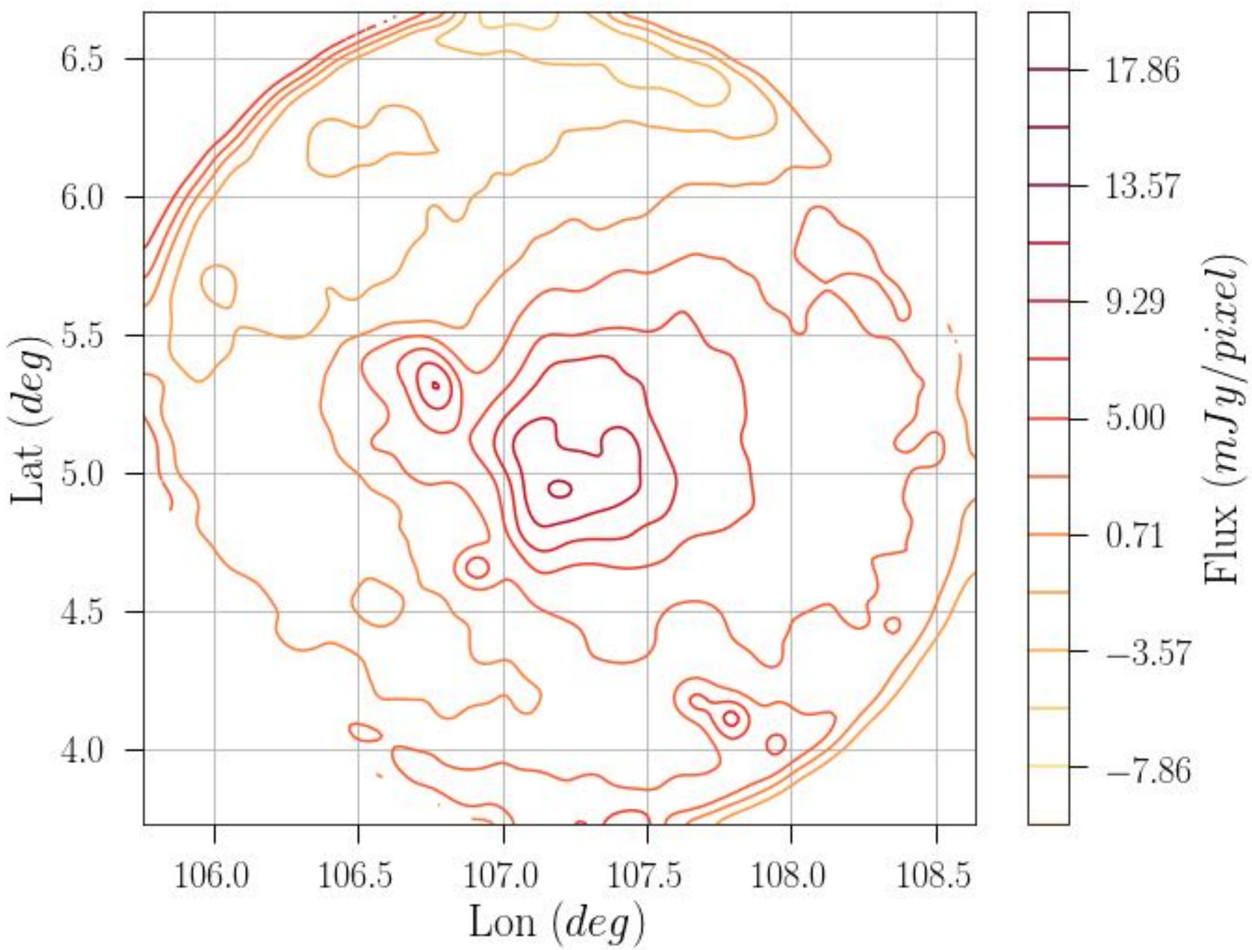
Results: Map from Bank C

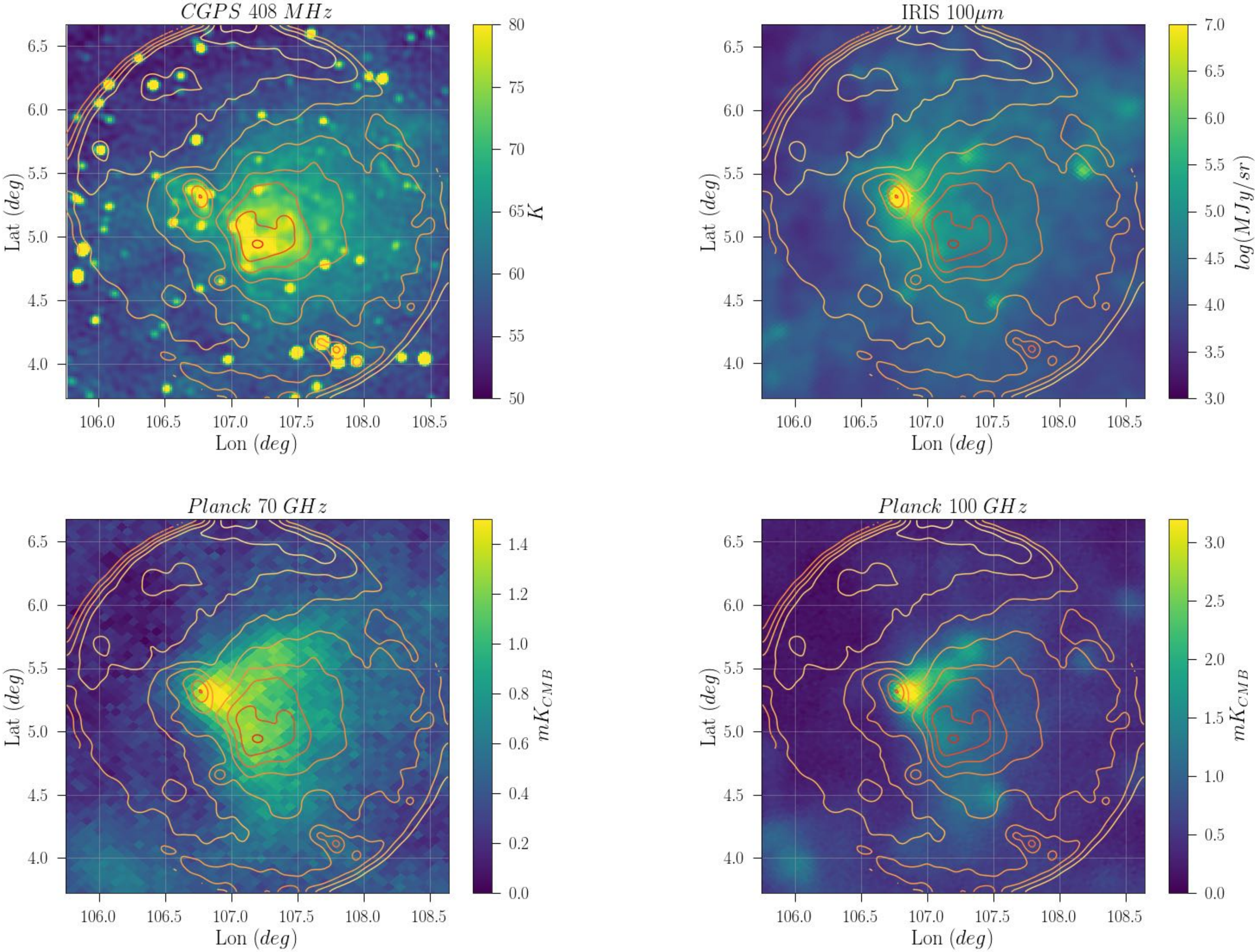


Smooth Maps for Combined Analysis

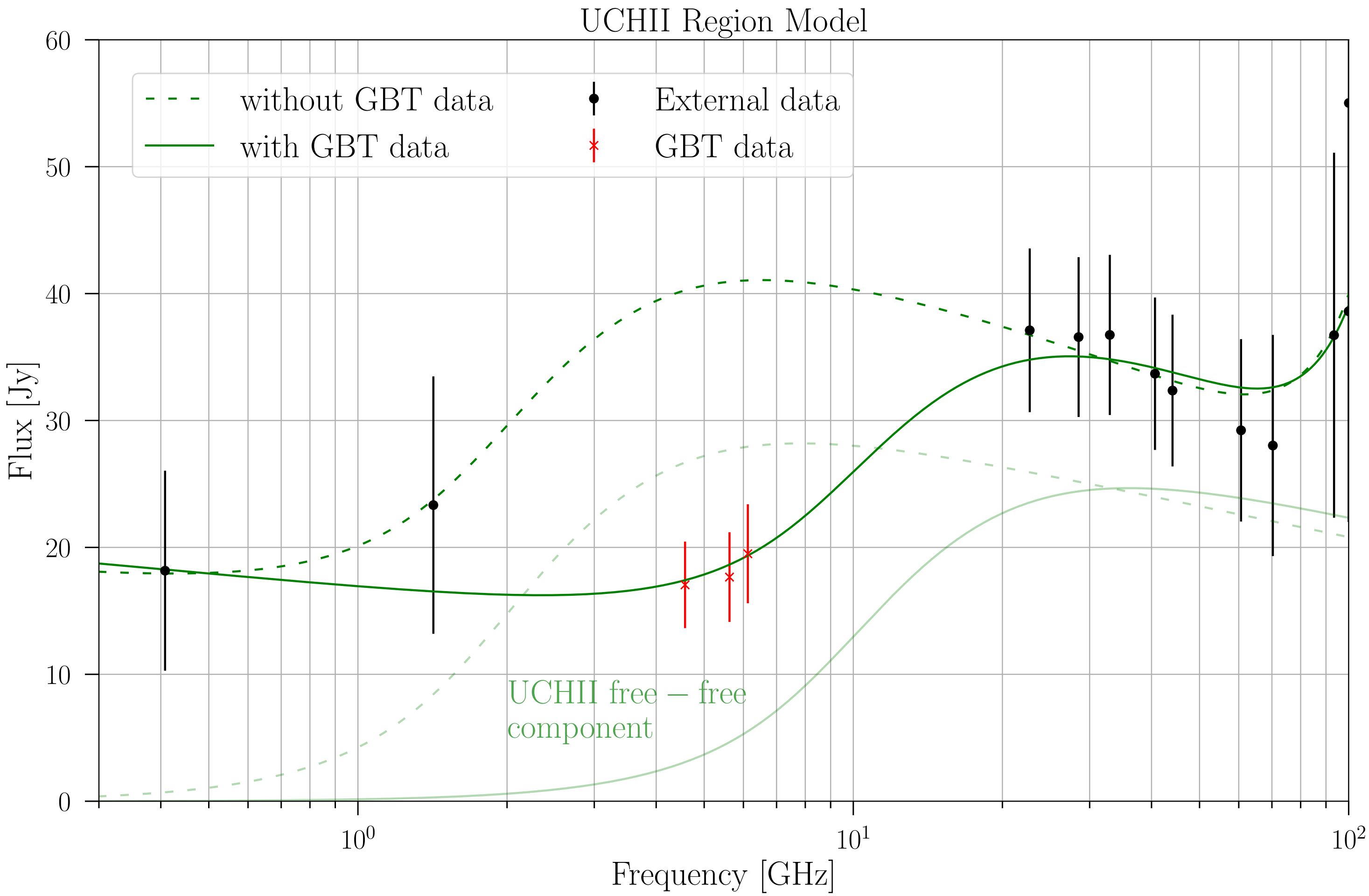


Smooth Maps for Combined Analysis

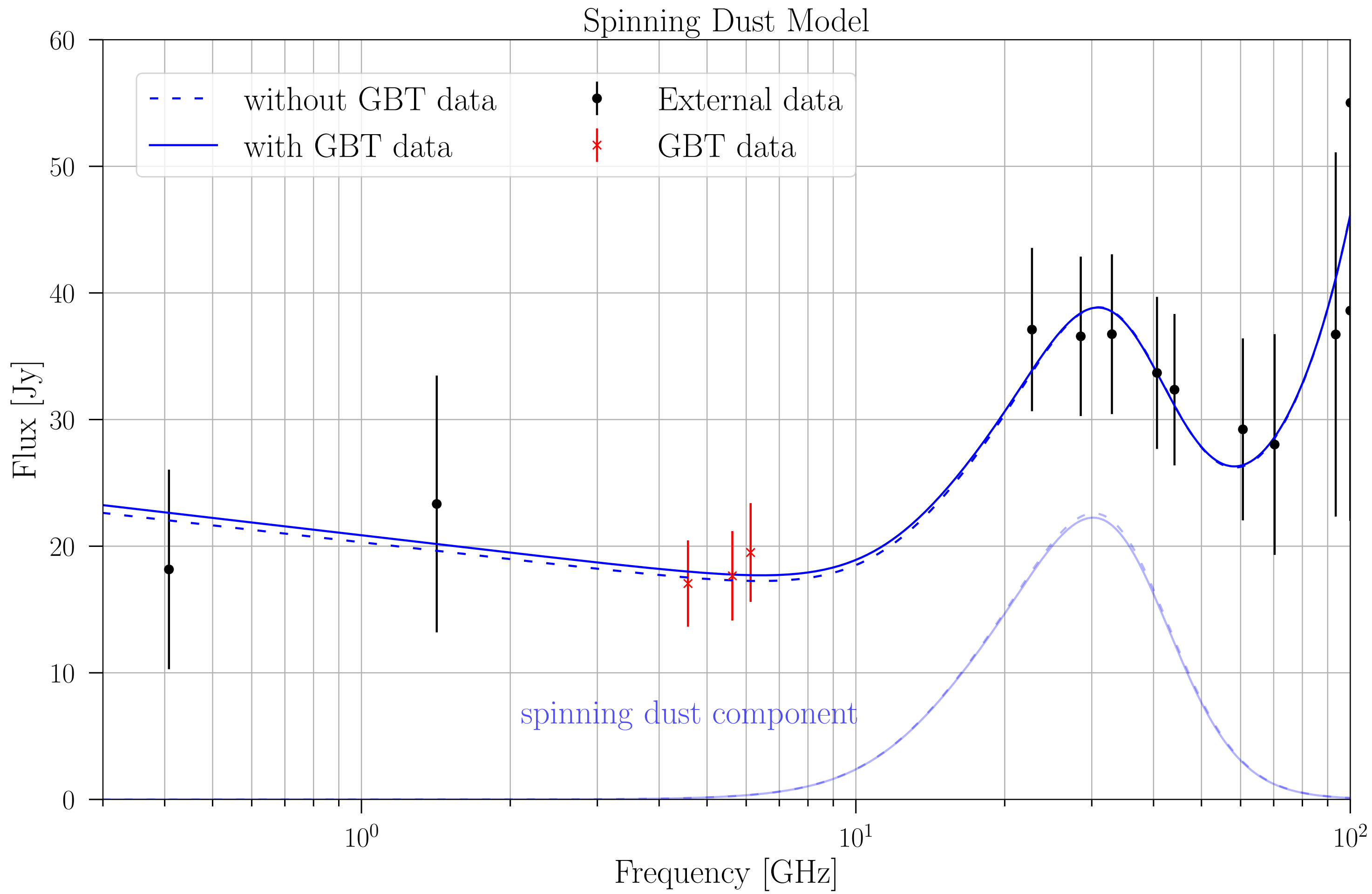



CGPS 408 MHz
IRIS 100μm
Planck 70 GHz
Planck 100 GHz
Lat (deg)
Lon (deg)
K
log(MJy/sr)
mK_CMB
106.0
106.5
107.0
107.5
108.0
108.5
4.0
4.5
5.0
5.5
6.0
6.5

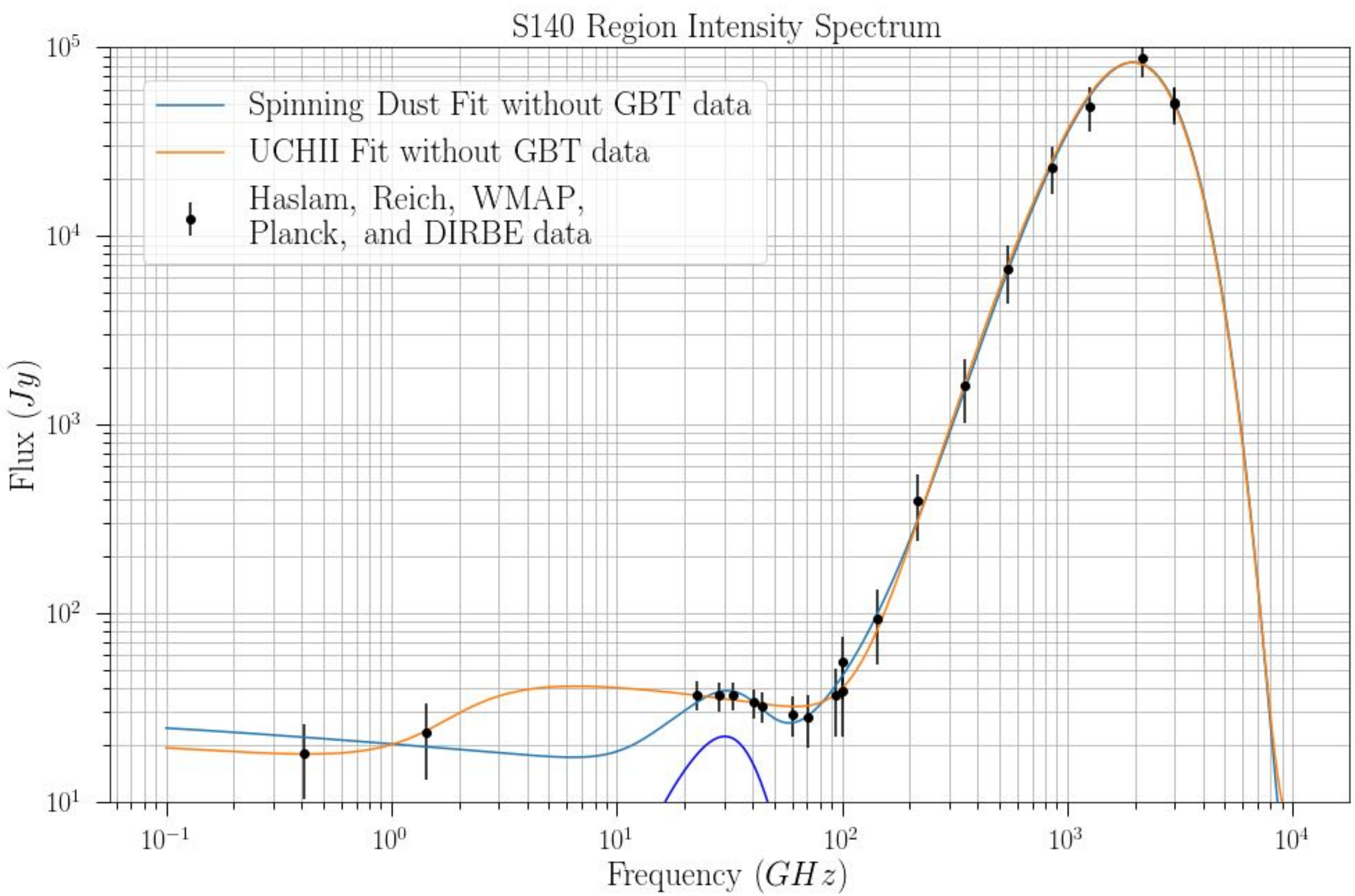
Results: Spectra



Results: Spectra

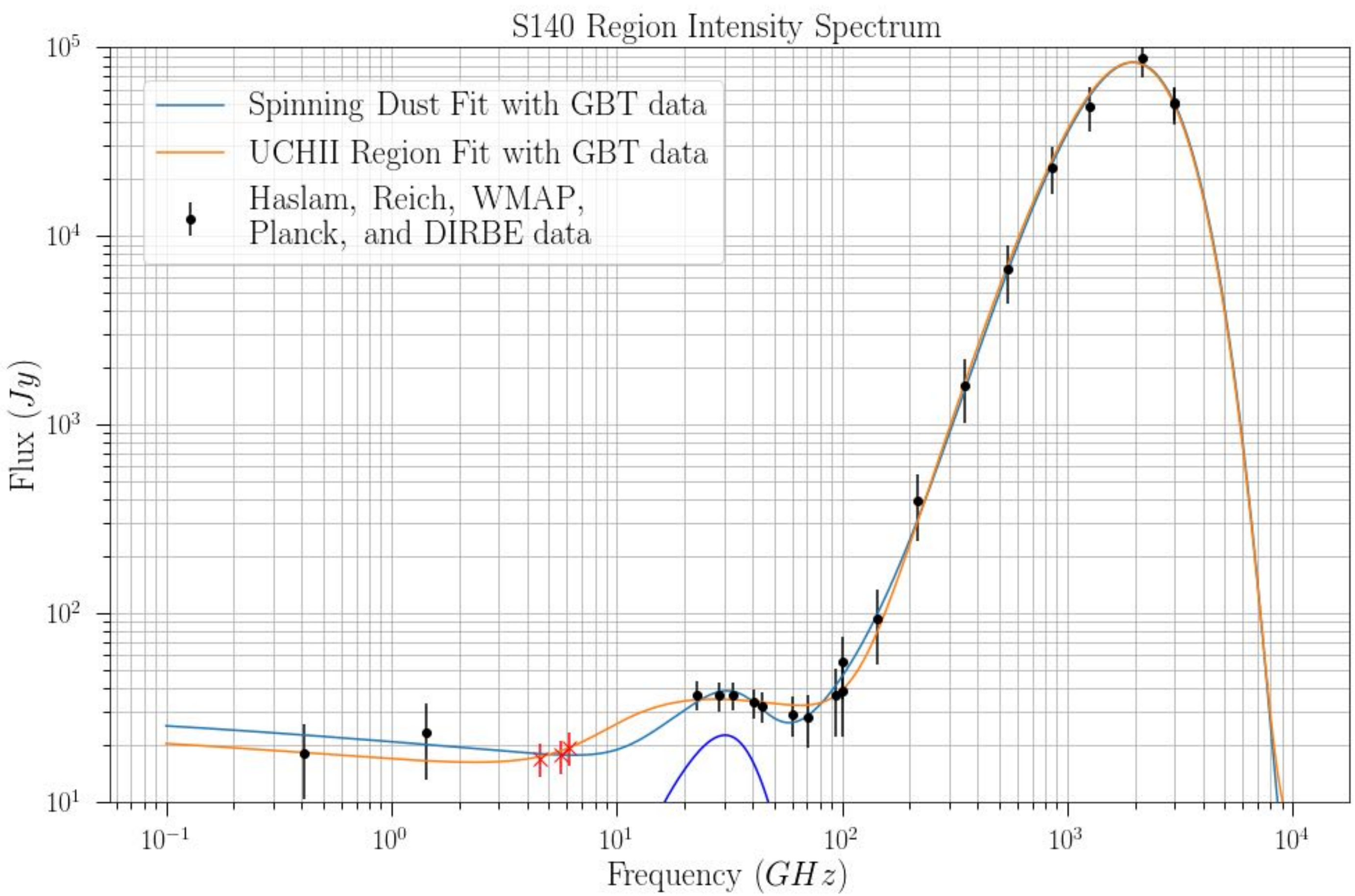


Spectra **Without** Our Measurements



HII region = interstellar ionized hydrogen.

Spectra **With** Our Measurements



HII region = interstellar ionized hydrogen.

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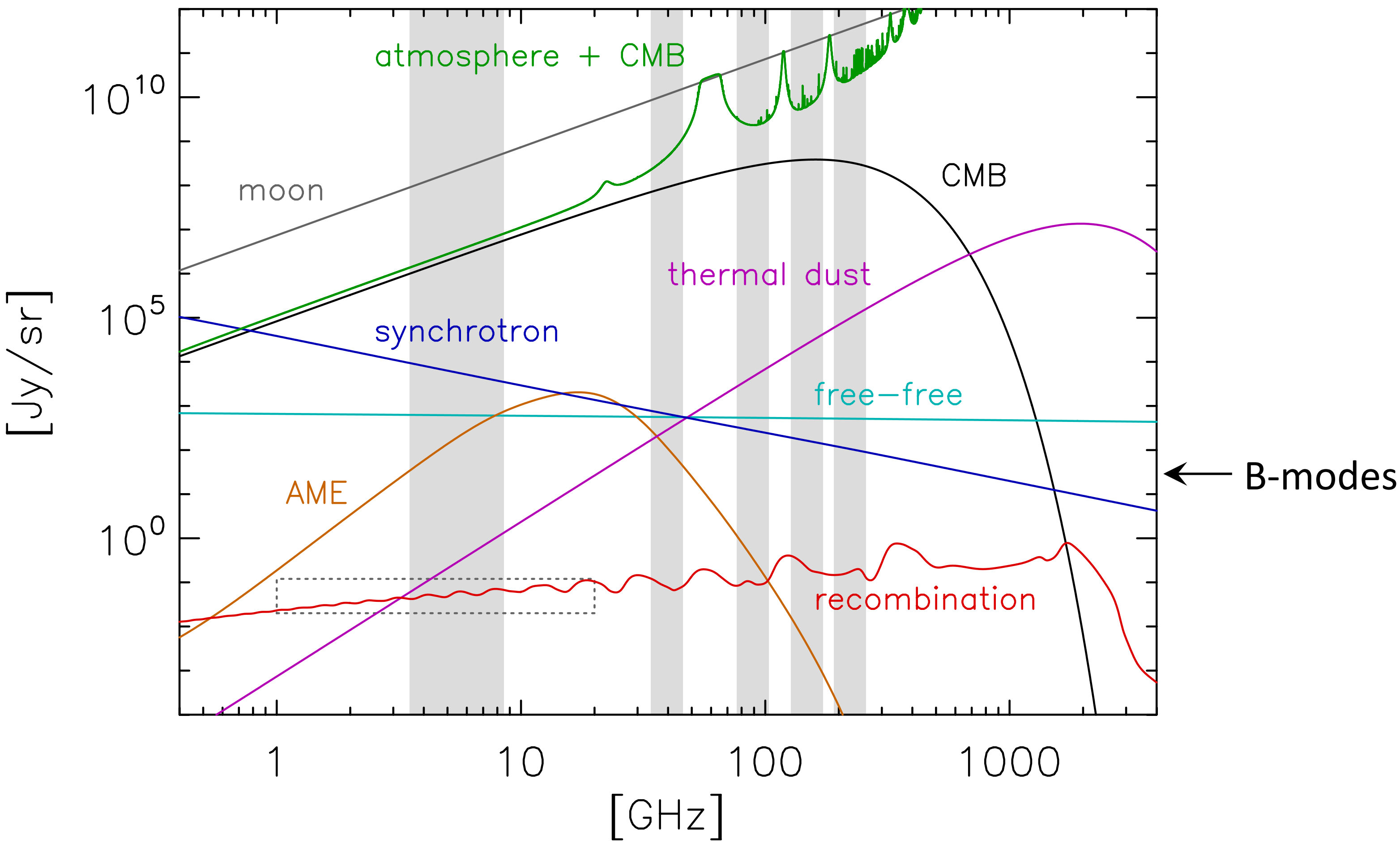
4) A Novel Spectrometer for Discovering Signals from the Beginning of the Universe

Bradley R. Johnson[1] & Harish Krishnaswamy[2]

1) Department of Physics, Columbia University
2) Department of Electrical Engineering, Columbia University

Spectra



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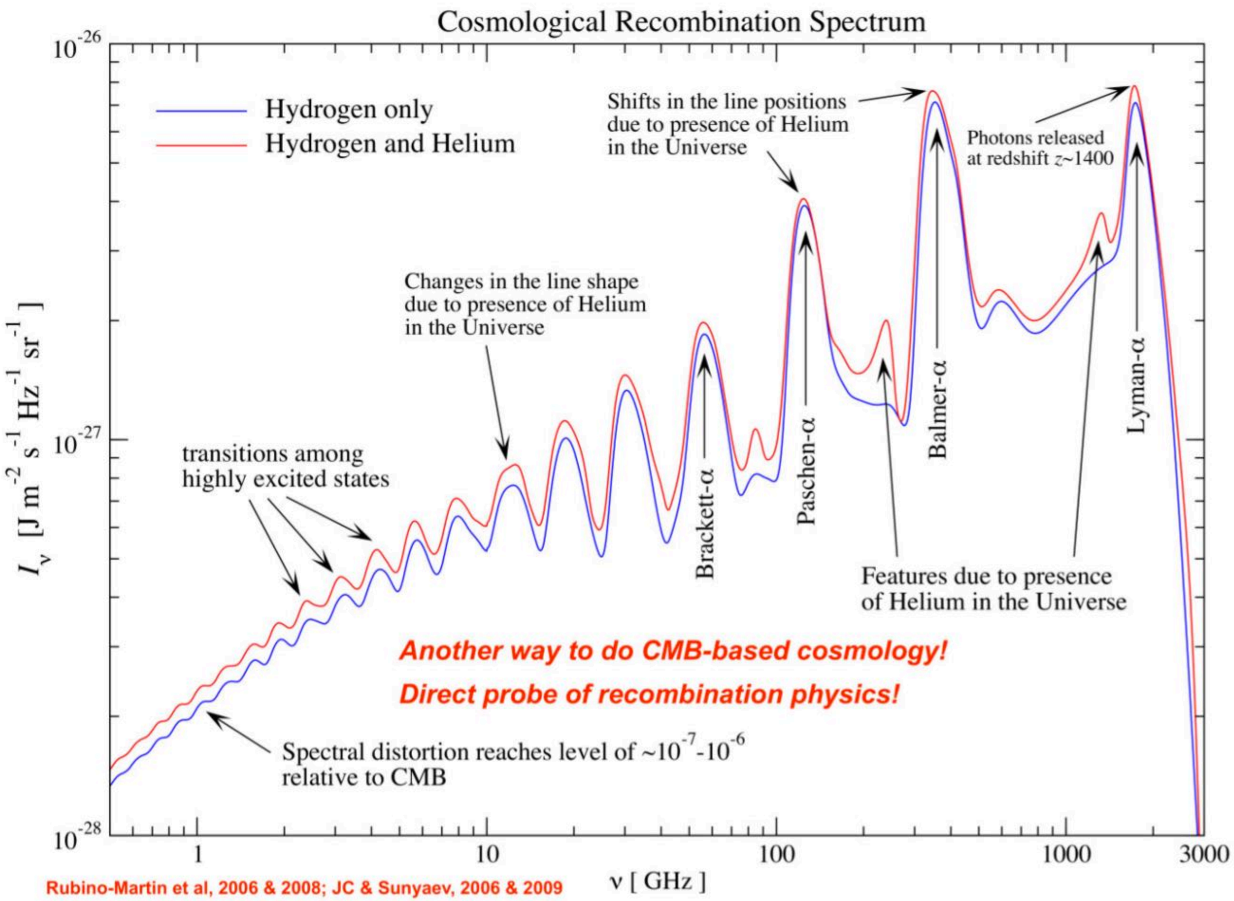
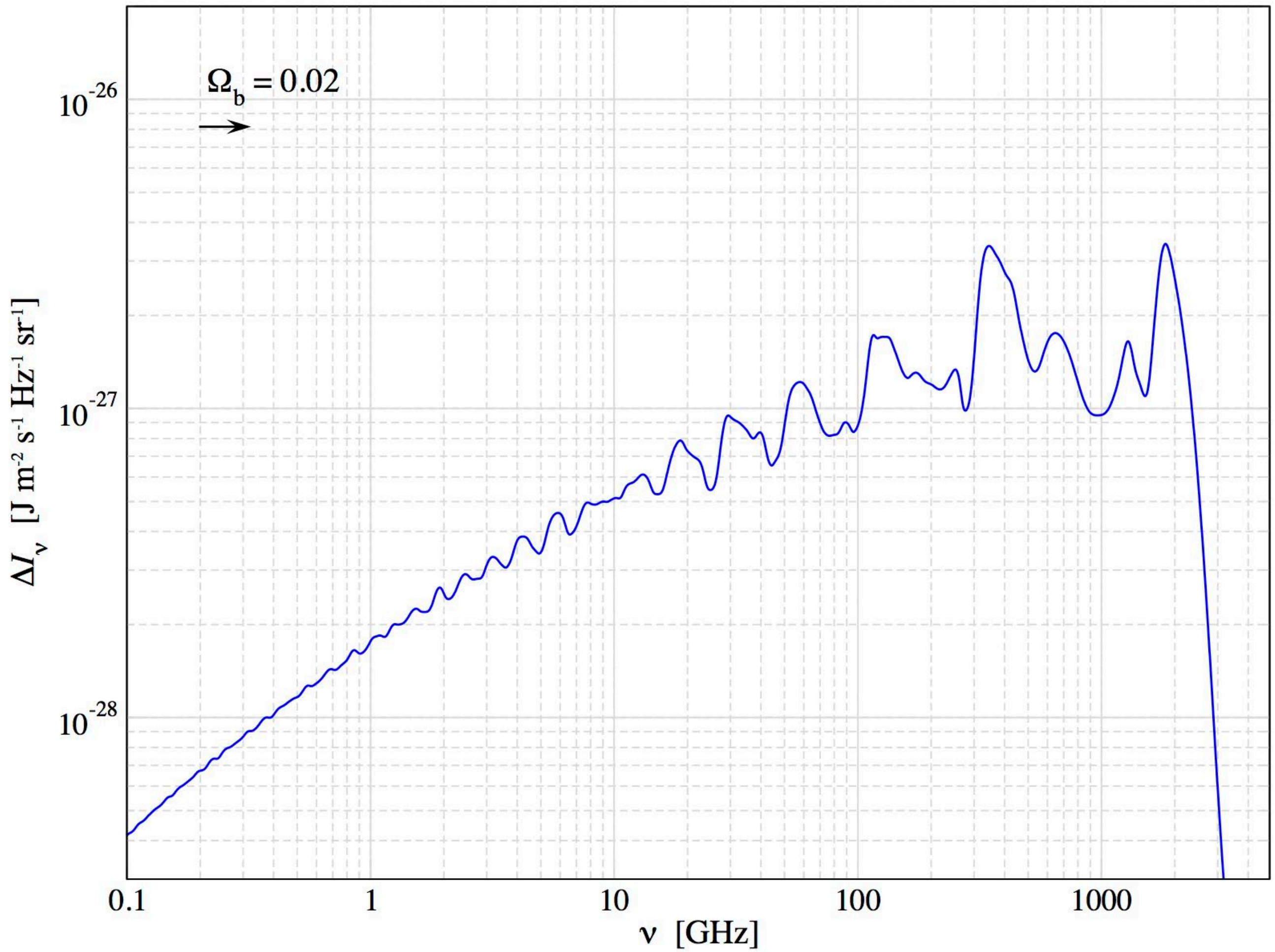


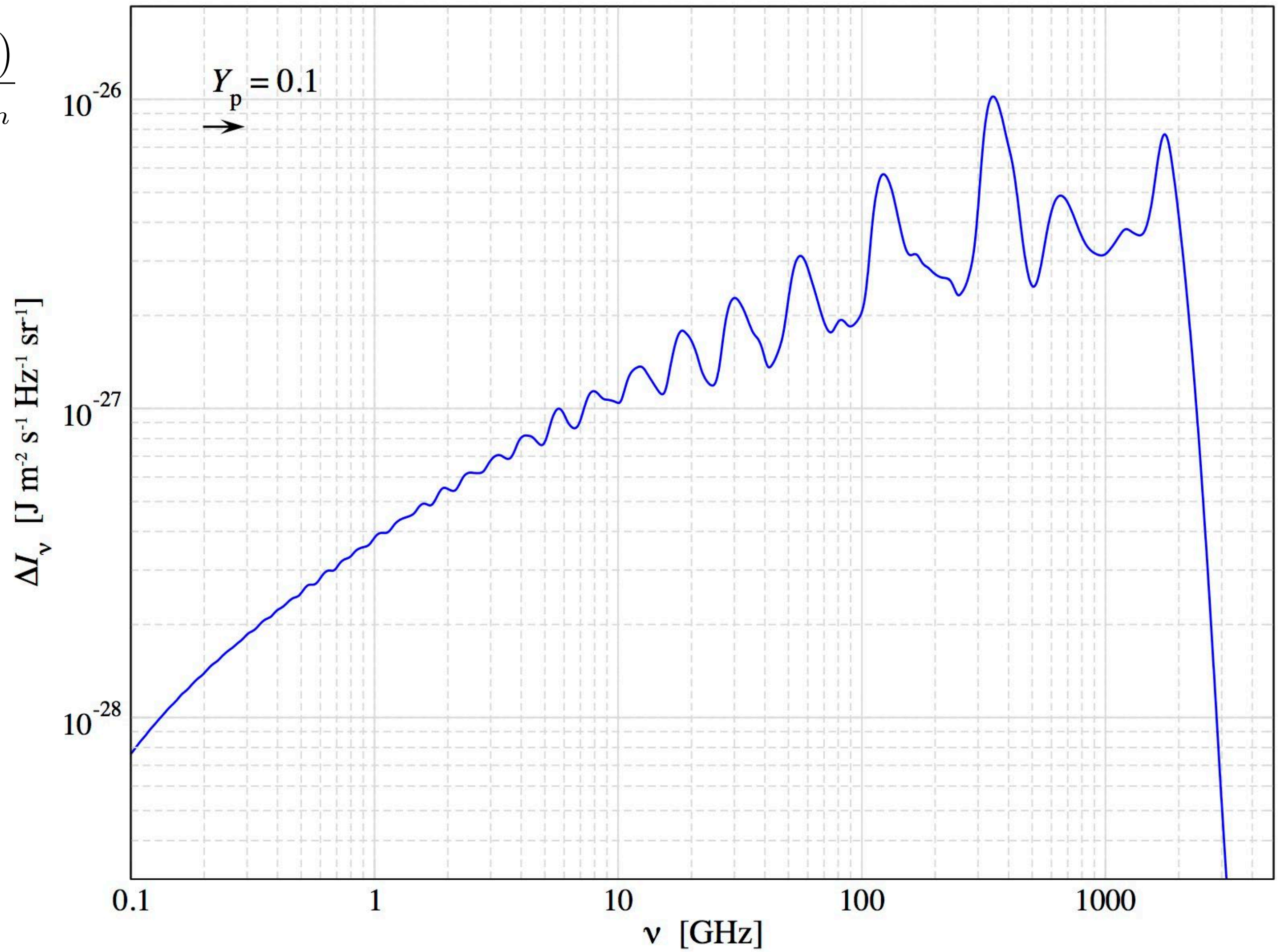
Figure 6 – The cosmological recombination radiation created in the redshift range $z \simeq 10^3 - 10^4$. The presence of helium in the Universe gives rise to unique features in the recombination spectrum. This *fingerprint* of the recombination era in principle allows us to test our understanding of the recombination history which is one on the fundamental ingredients for the computations of the CMB anisotropies.

Measuring Cosmological Parameters



Measuring Cosmological Parameters

$$Y_P = \frac{\rho\left({}^4\text{He}\right)}{\rho_{baryon}}$$



Pathfinder Spectrometer (PSPEC)

With RISE support, we will build a prototype instrument and use it as a test bed for learning how to:

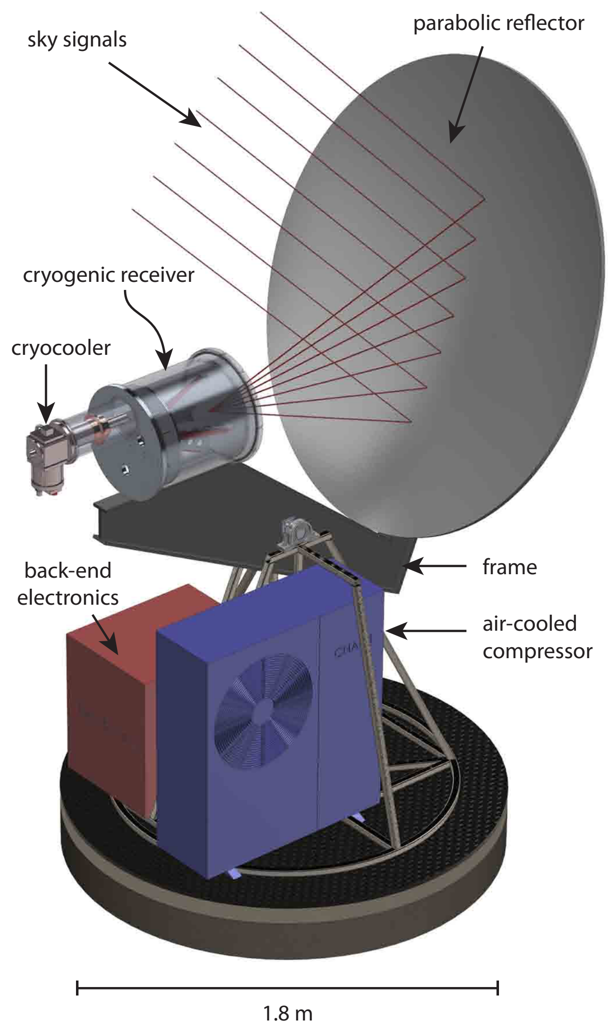
(i) perform the essential high-precision calibration measurements

(ii) manage radio frequency interference (RFI)

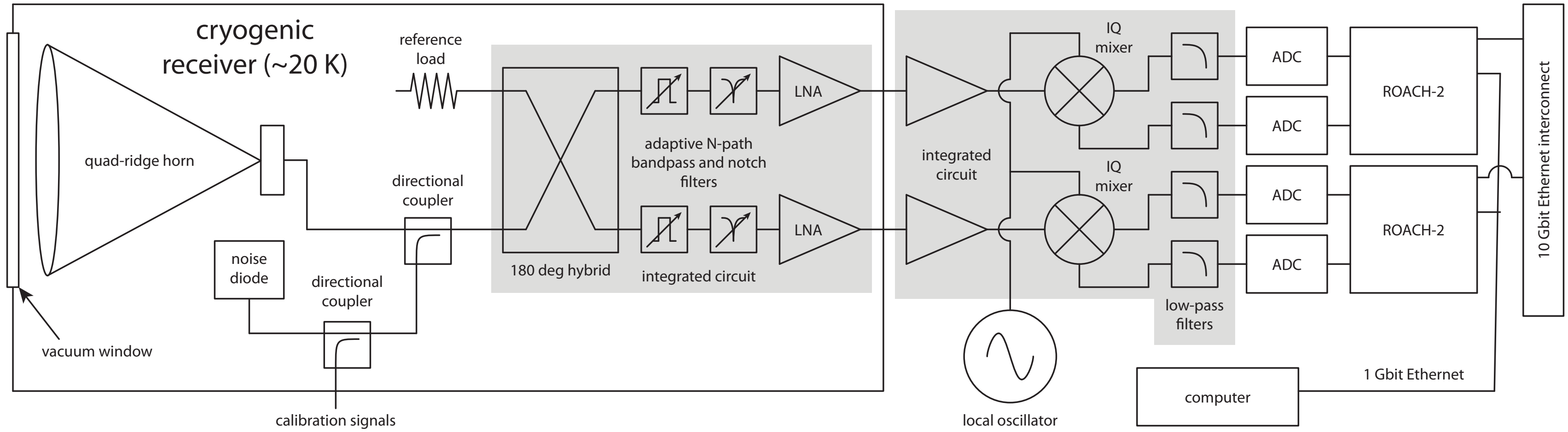
(iii) characterize the instrument beam

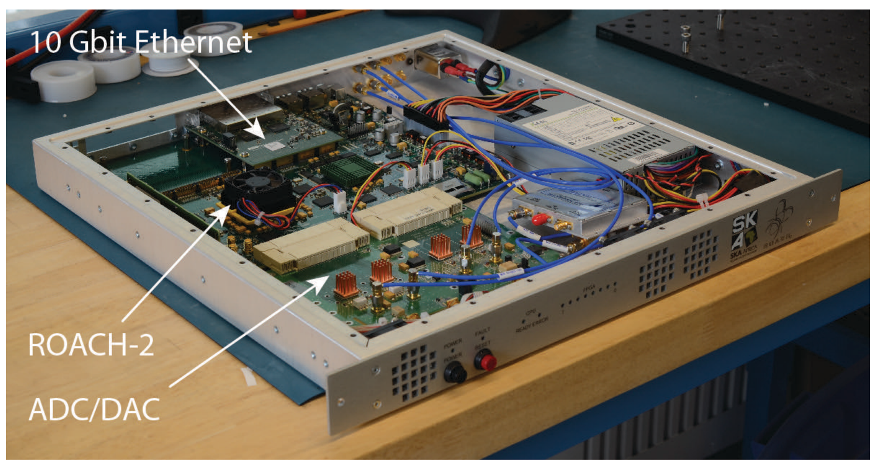
(iv) mitigate the effects of systematic errors

(v) characterize bright Galactic signals.



Pathfinder Spectrometer (PSPEC)





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Conclusions

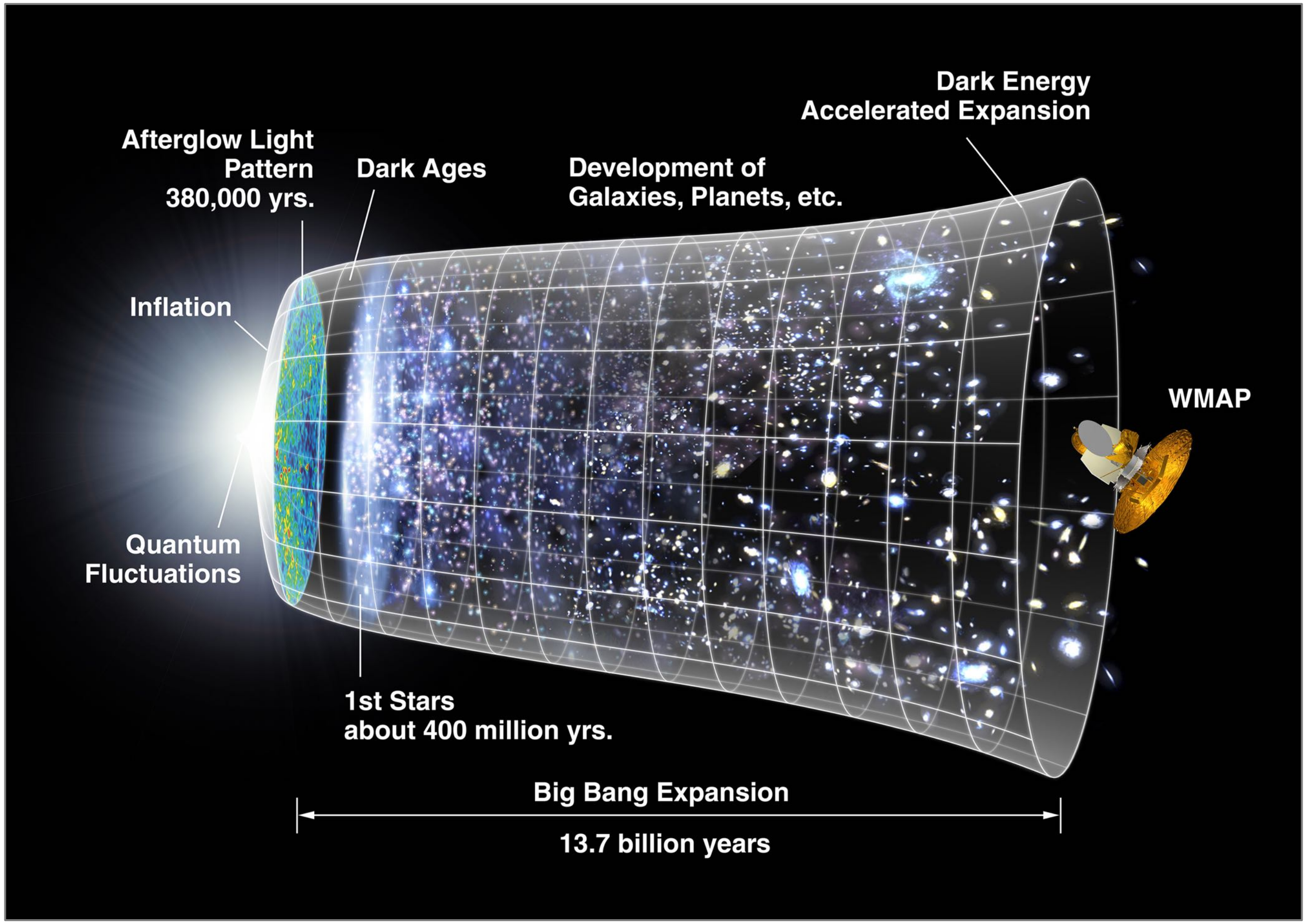
1) CMB Spectral Distortions provide a way to study the early Universe ($z > 1100$).

2) Measurements will be challenging.

3) Entry point -- we observed an AME region with GBT.

4) RISE Funded PSPEC project is just beginning.

Standard Model of Cosmology



http://map.gsfc.nasa.gov/media/060915/

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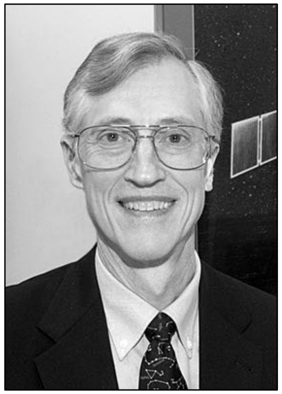
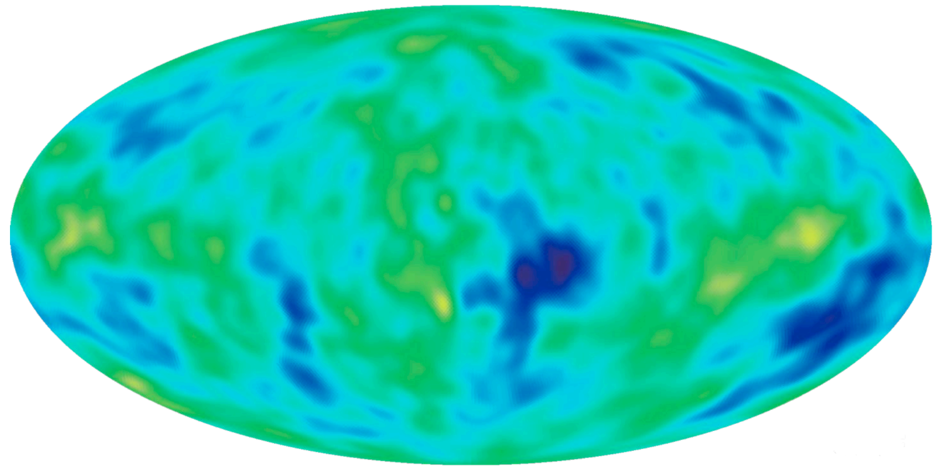
CMB Blackbody Spectrum & Anisotropy



Mather

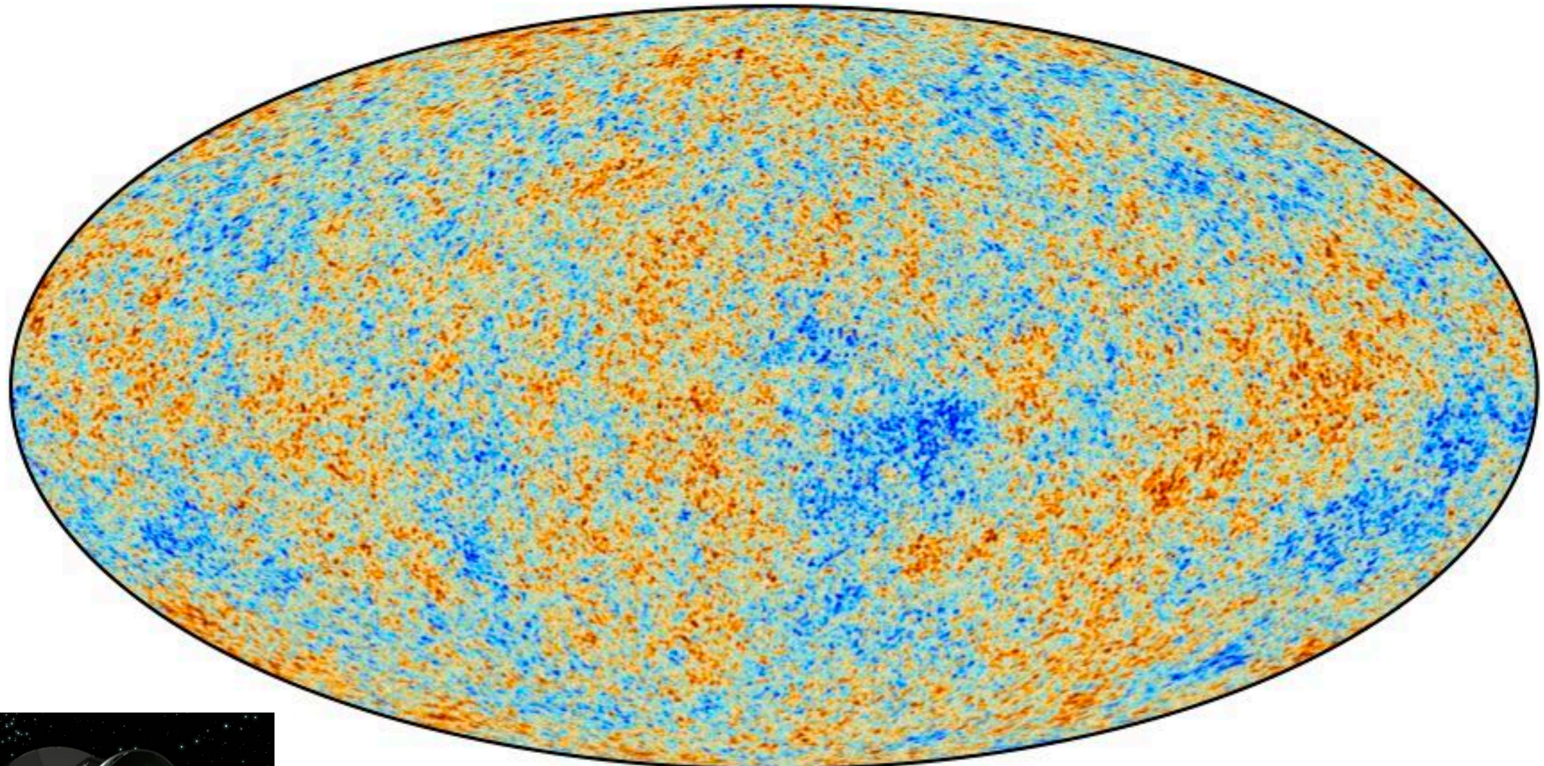
Smoot

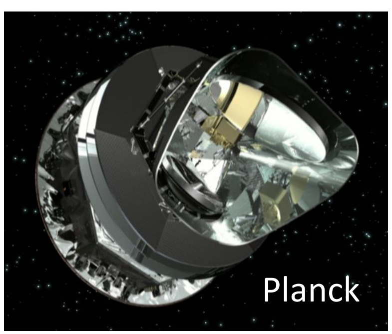
The **2006 Nobel Prize** in Physics was awarded jointly to John C. Mather and George F. Smoot *"for their **discovery of the blackbody form** and anisotropy of the cosmic microwave background radiation."*

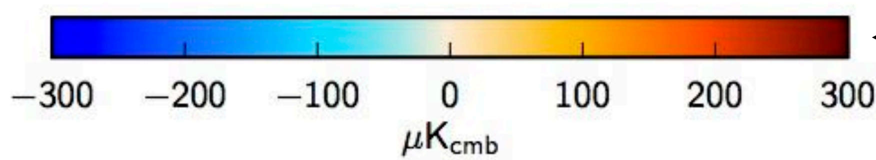


primordial anisotropy
(monopole, dipole, and Galactic signals removed)

What does this anisotropy image tell us?



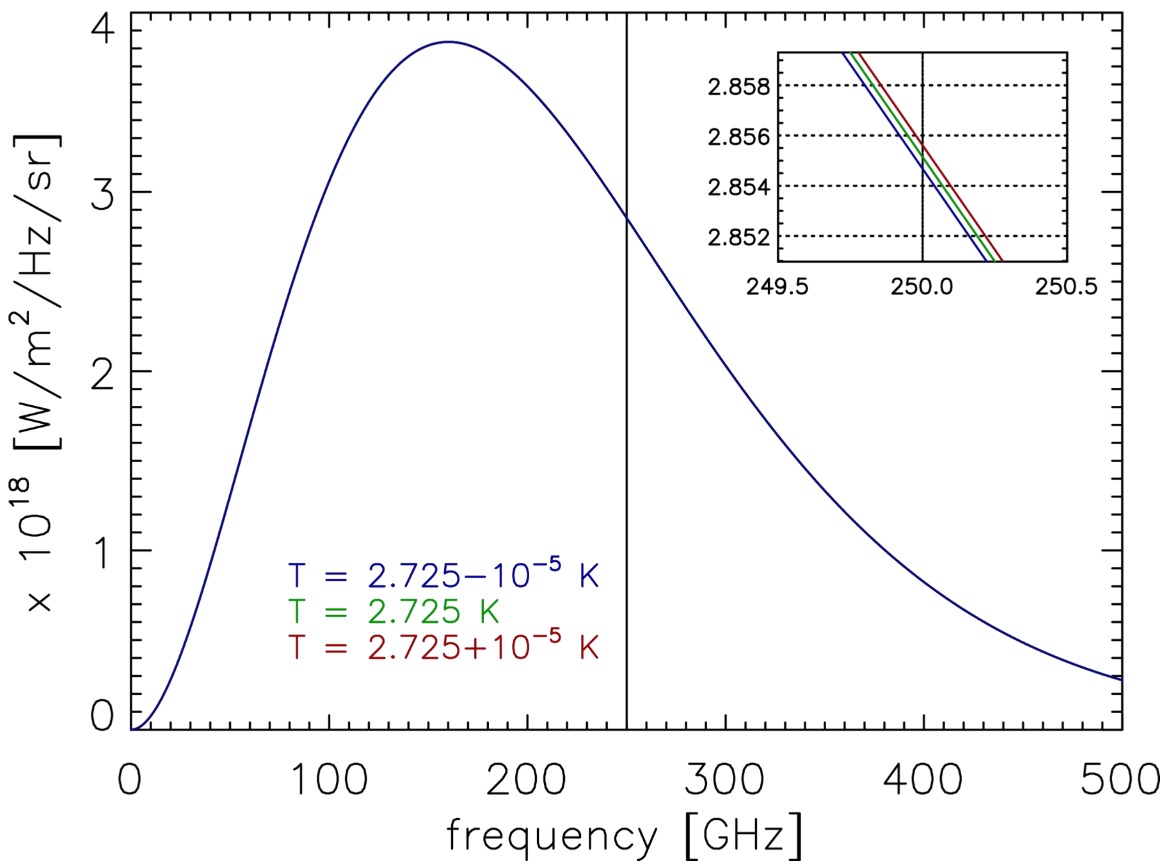




← zero = 2.73 K

Planck Collaboration (2016) A & A, 594, A1.

CMB Blackbody Spectrum



The image implicitly tells us this is true.

$$B_\nu = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT_o(1+z)}\right)-1\right]^{-1} \text{ where } \; T_o = 2.73 \; [\mathrm{K}]$$

Time Dependent Calibration