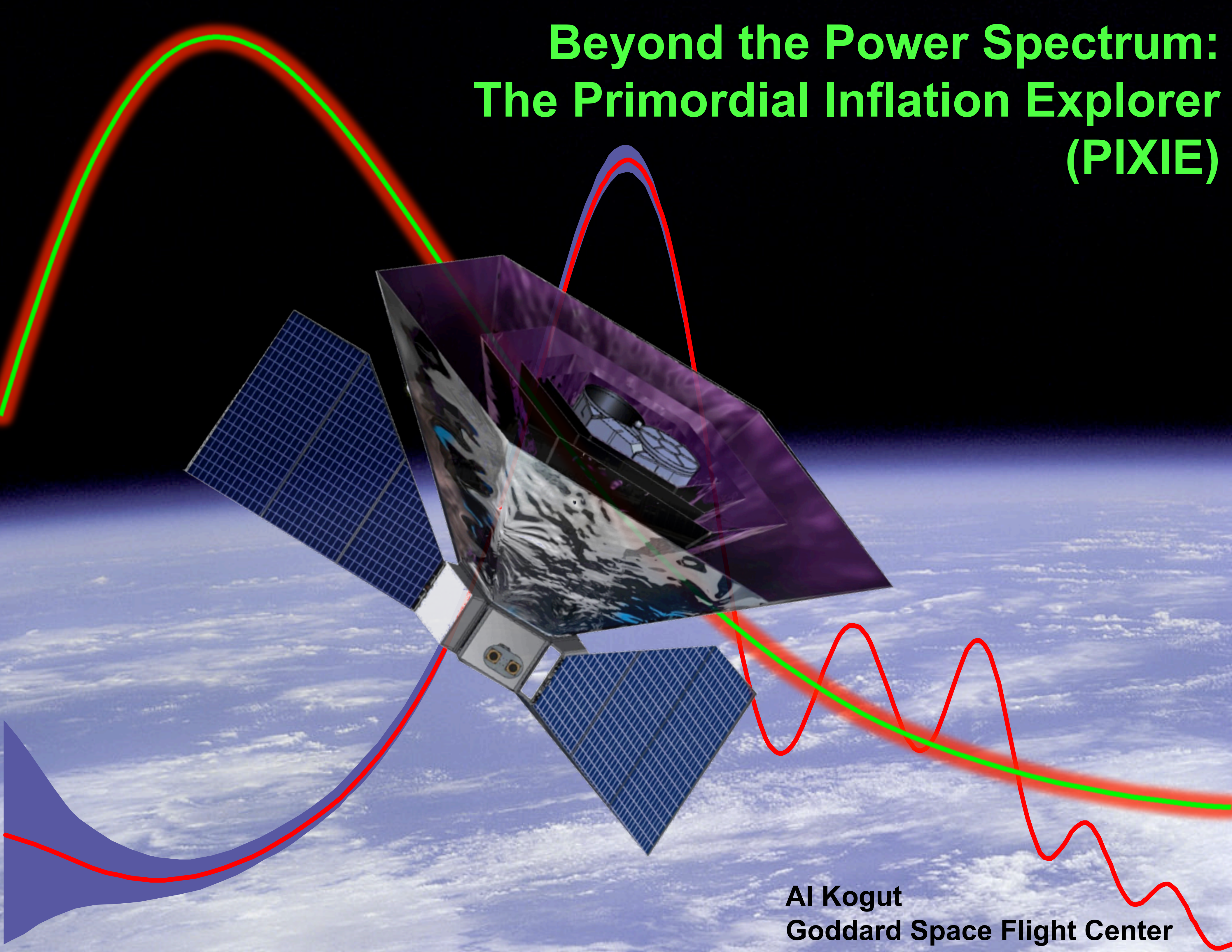
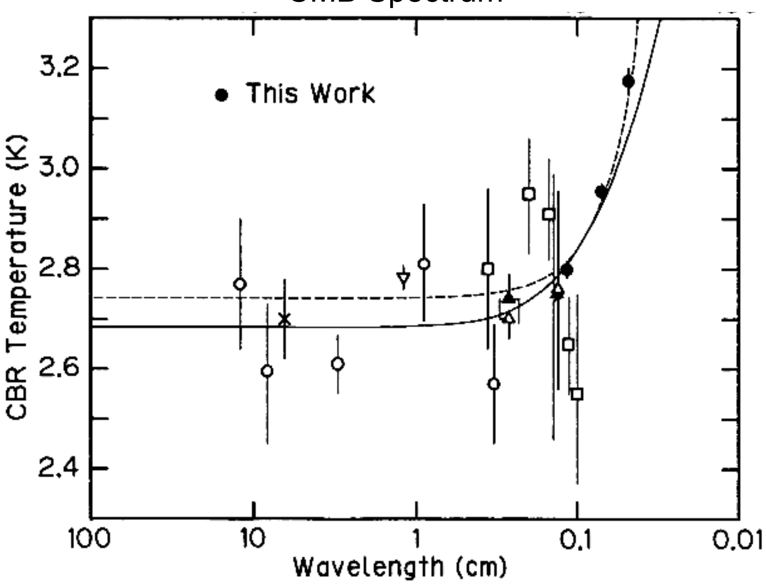
Beyond the Power Spectrum: The Primordial Inflation Explorer (PIXIE)



Al Kogut
Goddard Space Flight Center

Cosmology at the Dawn of the Chalonge School

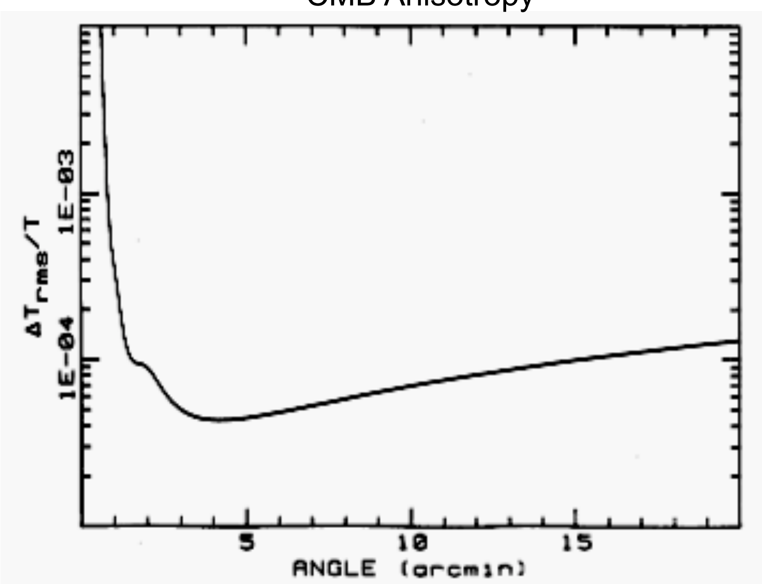
CMB Spectrum

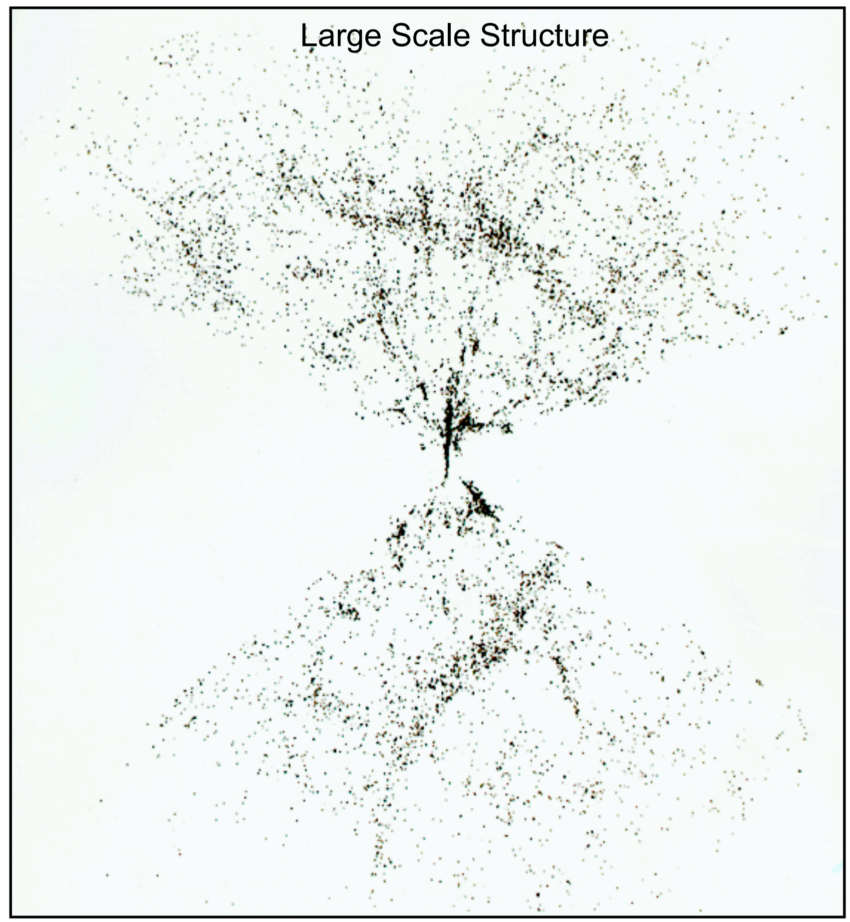


More Questions Than Answers (or data!)

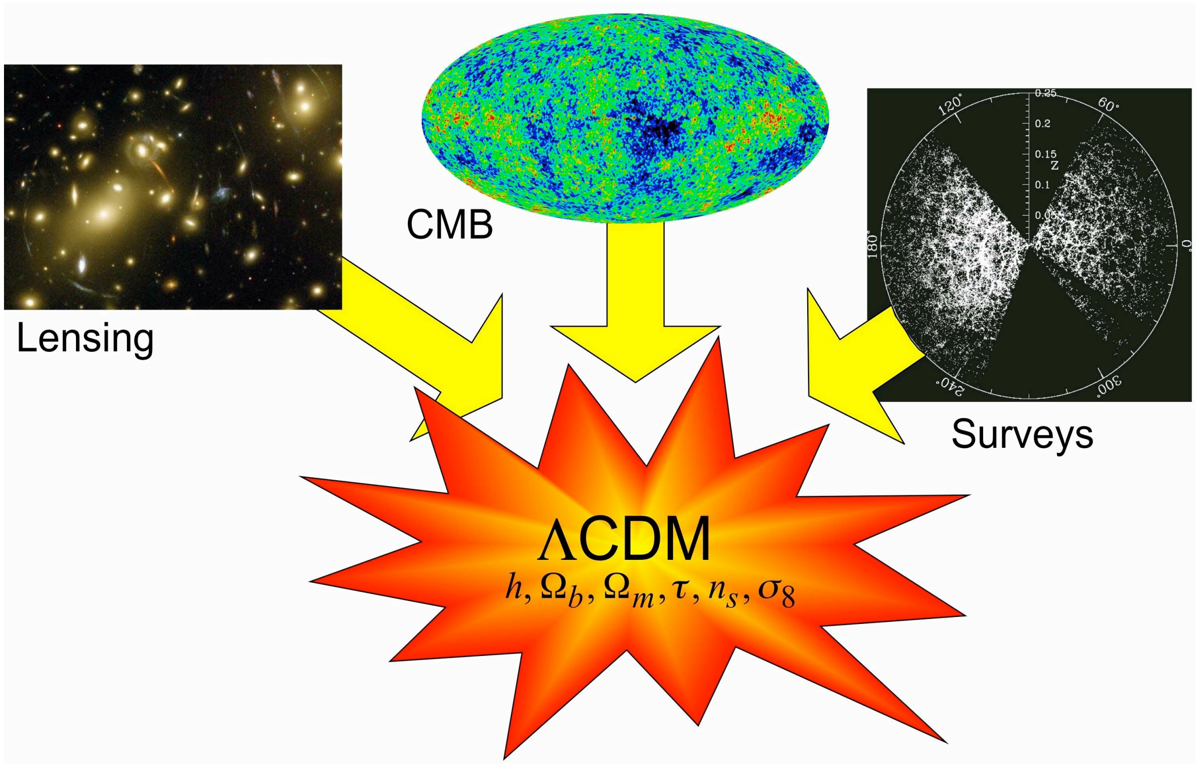
- CMB spectrum: Blackbody (maybe)
- CMB anisotropy: A moving target?
- Large Scale Structure: Open universe?
- Rotation Curves: Dark matter?

CMB Anisotropy



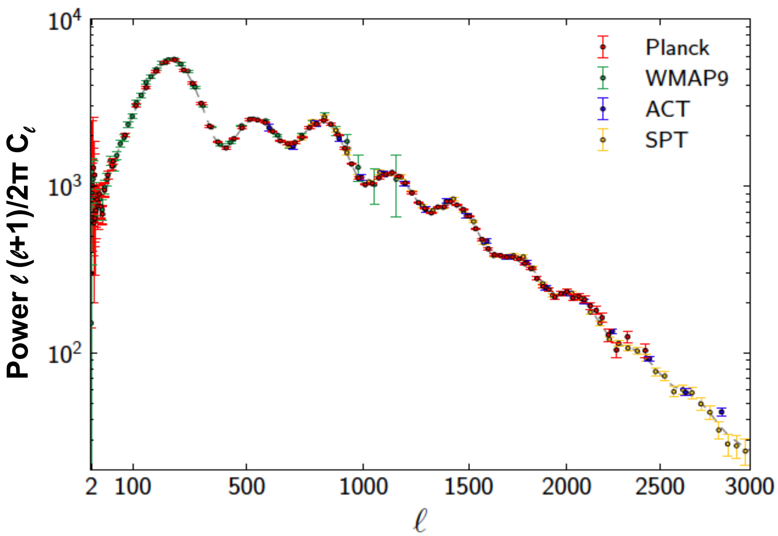


CMB and Precision Cosmology

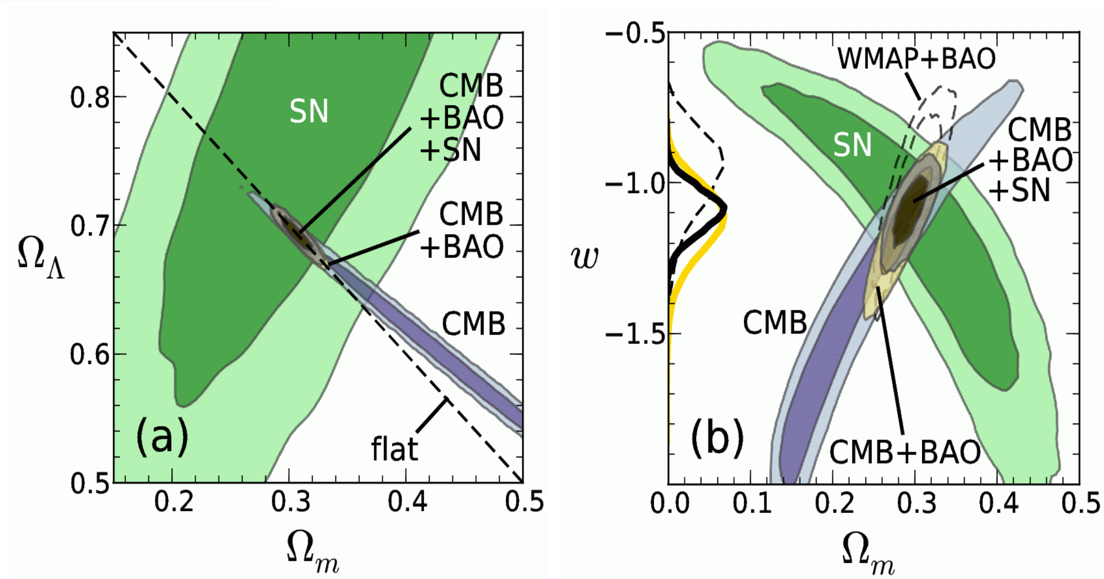


"Standard Model"for cosmology

$\Omega_b h^2 = 0.02214 \pm 0.00024$
$\Omega_c h^2 = 0.1187 \pm 0.0017$
$\Omega_\Lambda h^2 = 0.692 \pm 0.010$
$n_s = 0.9608 \pm 0.0054$
$\tau = 0.092 \pm 0.013$
$\sigma_8 = 0.826 \pm 0.012$



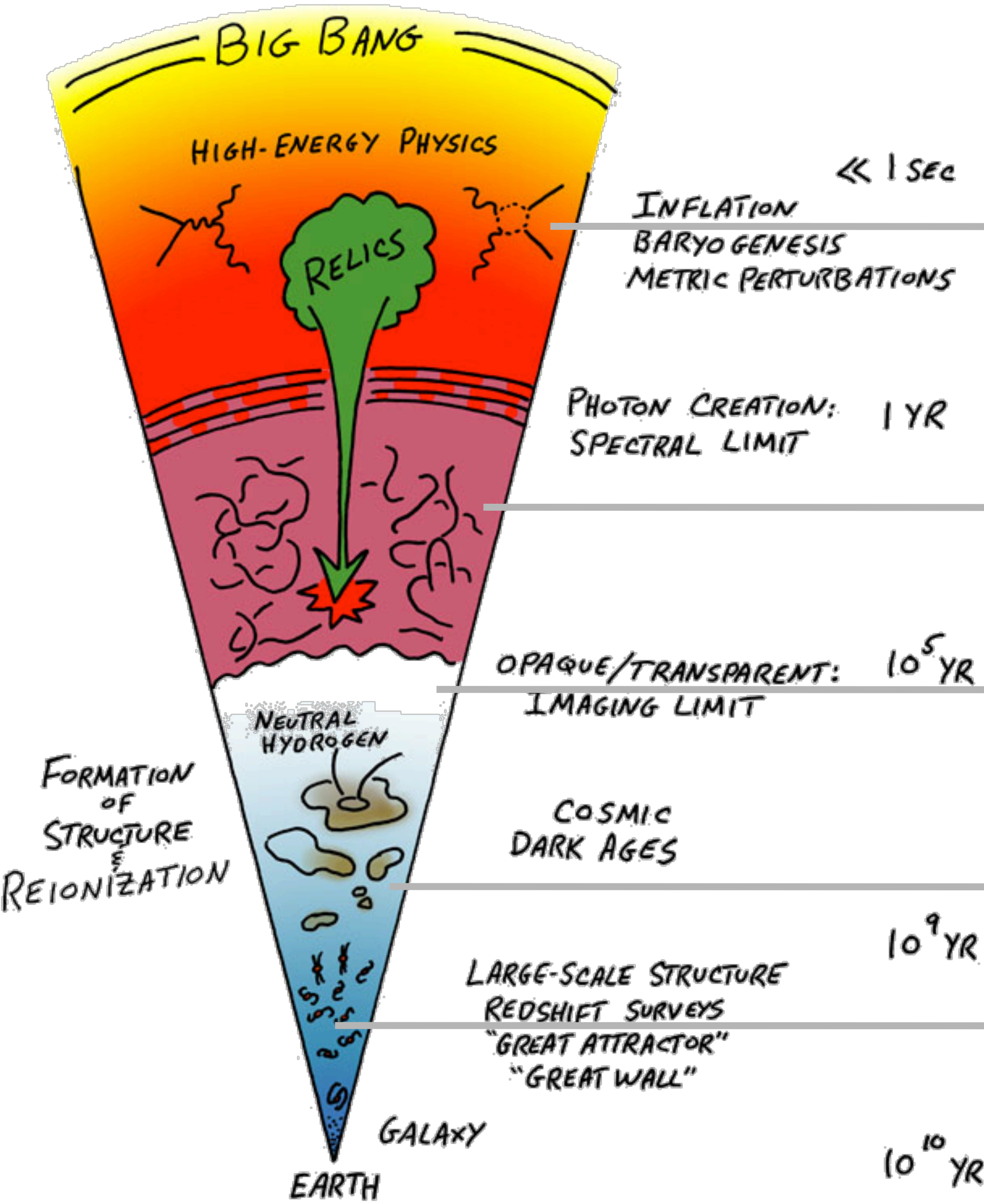
Consistency between CMB missions



Consistency between multiple tests

The End of Cosmology?

CMB: Backlight for the Universe



Inflation
Primordial perturbations
GUT Physics

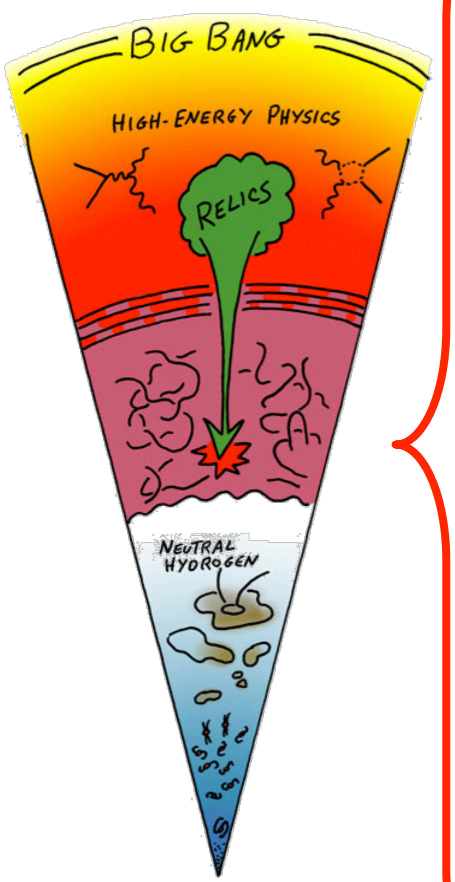
Silk damping
Dark matter decay / annihilation
Number of neutrino species

Primordial helium abundance
Primary CMB anisotropy

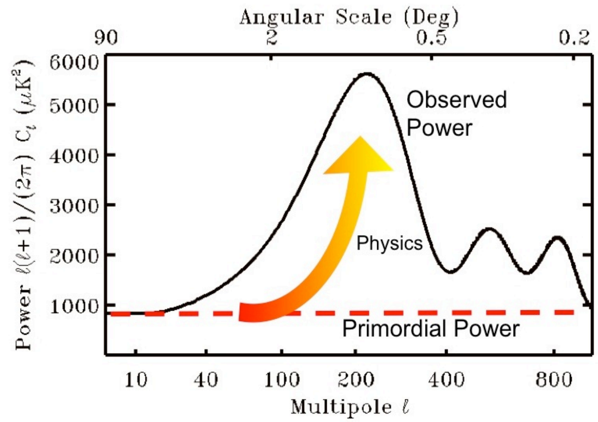
Reionization

Lensing & large-scale structure
SZ signals and cluster growth

A Sampler of CMB Signals

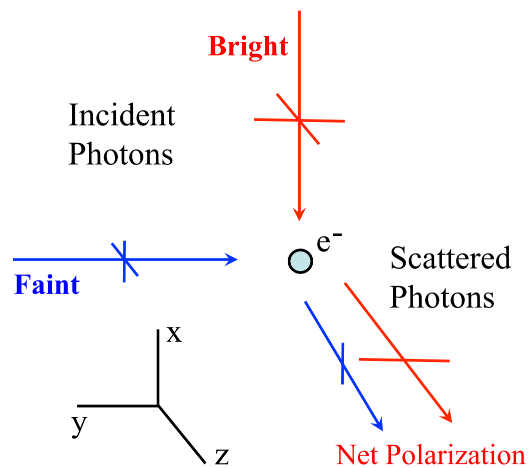


Temperature Anisotropy



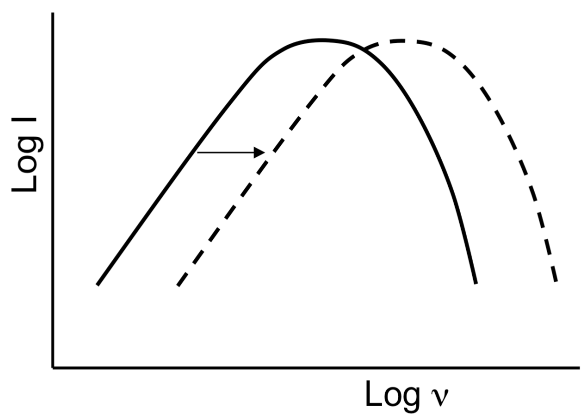
"Background" cosmology
Inflation (tensor + non-Gaussian)
Topology
Large-scale structure

Polarization



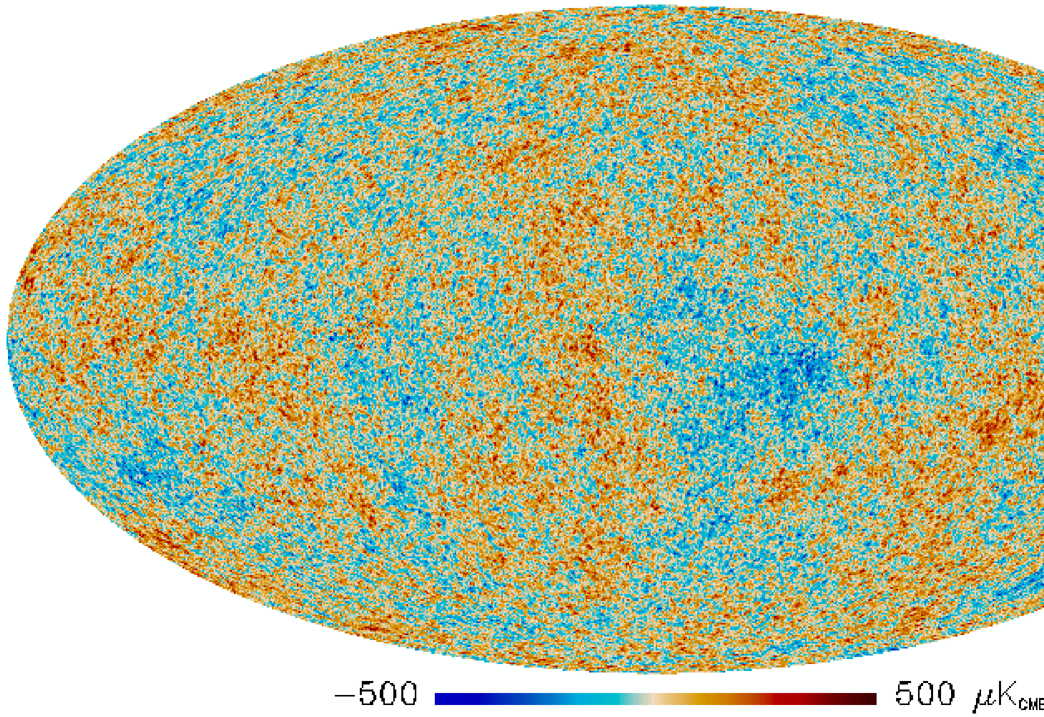
Inflation (B-modes)
"Background" cosmology (E-modes)
Neutrino physics
Reionization

Spectral Distortions

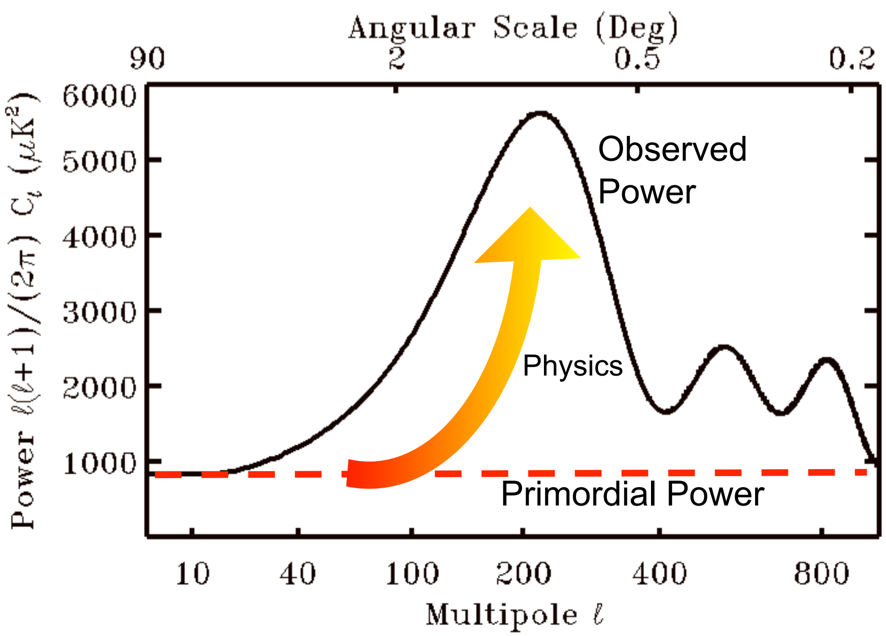


Inflation / Silk damping
Dark matter decay / annihilation
Primordial helium abundance
Reionization

CMB and Precision Cosmology



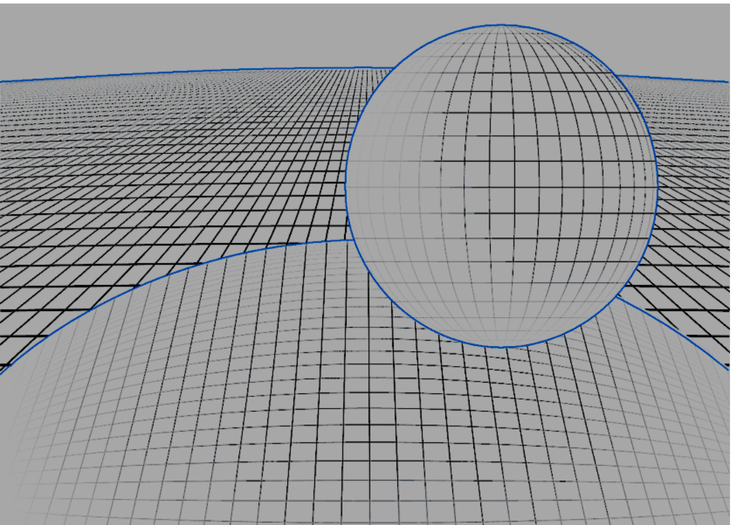
Planck fulll-sky map
of CMB anisotropy



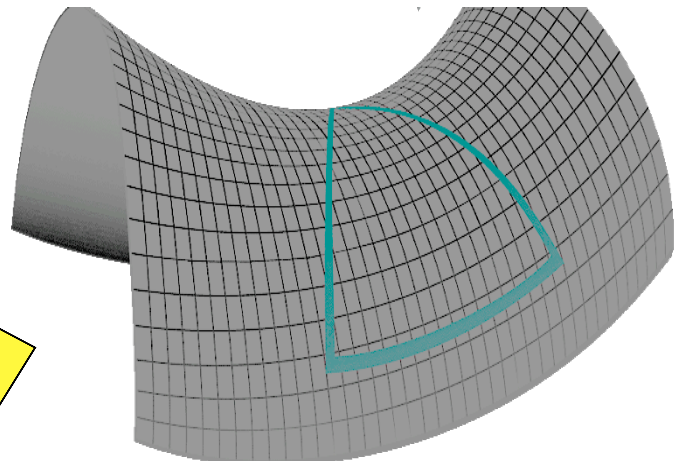
Planck-only ΛCDM Parameters

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057
Ω_Λ	0.6964	0.693 ± 0.019
σ_8	0.8285	0.823 ± 0.018
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$
H_0	68.14	67.9 ± 1.5
Age/Gyr	13.784	13.796 ± 0.058
$100\theta_*$	1.04164	1.04156 ± 0.00066
r_{drag}	147.74	147.70 ± 0.63
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011

Inflation and CMB Polarization

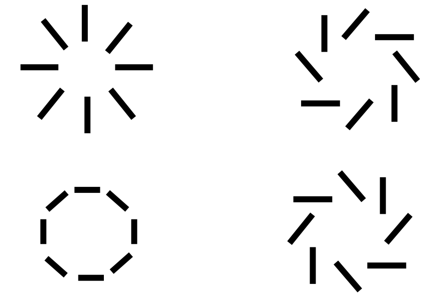


Inflating Space-Time ...



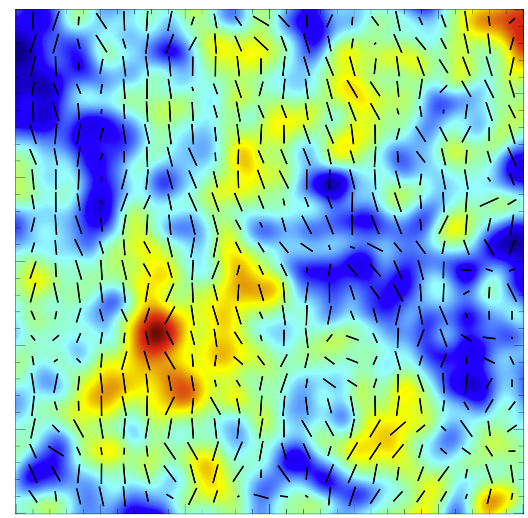
Creates Gravitational-Wave Background ...

$$V^{1/4} = 10^{16}\ \mathrm{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$



E Modes
Even Parity

B Modes
Odd Parity

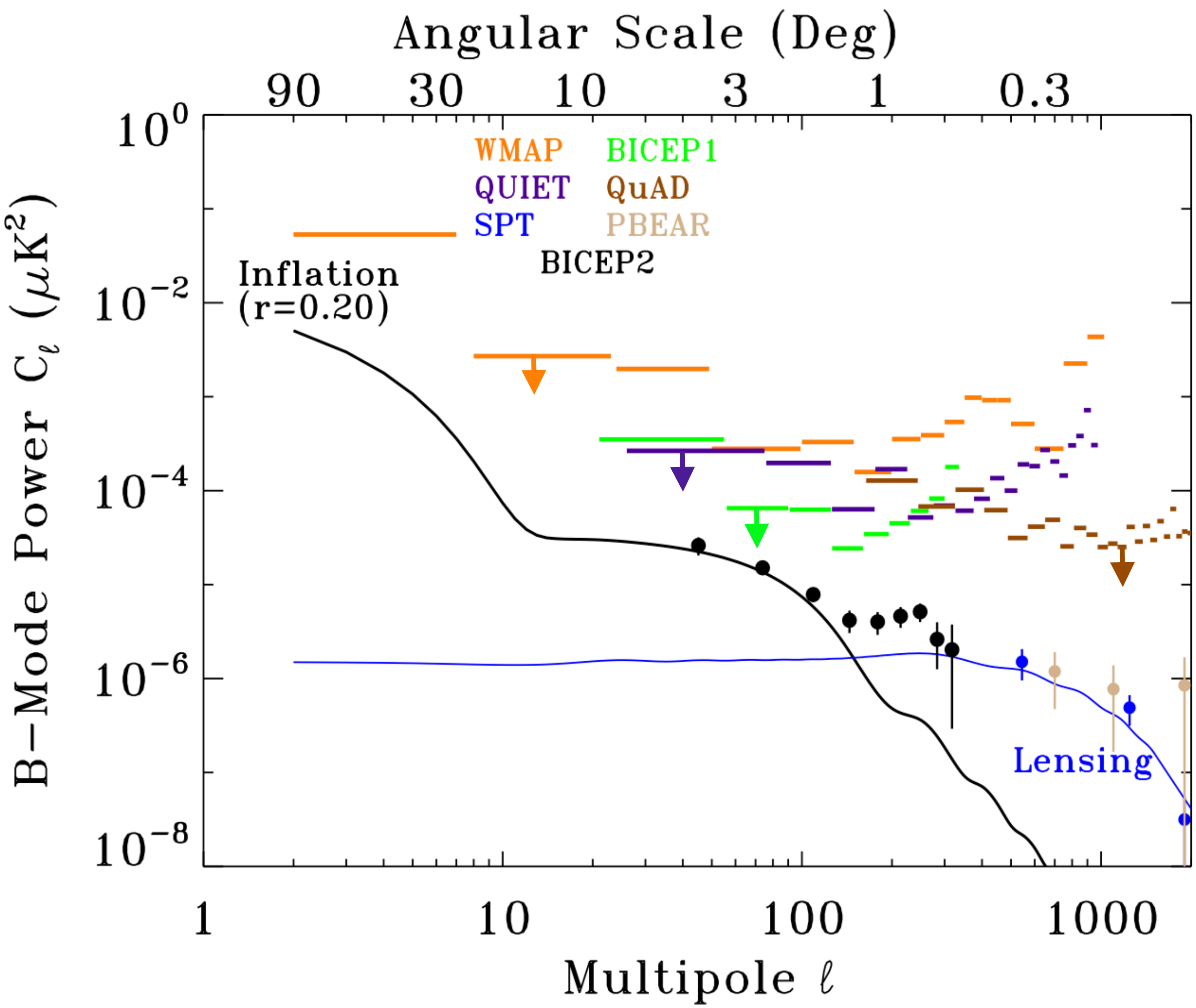


Which Sources CMB Polarization

B-Mode Polarization:
“Smoking Gun” Signature of Inflation

Polarization Status 2014

Parameter r = ratio of tensor (B-mode) to scalar (unpolarized) power



Generally consistent with lensing at small scales
+
inflation at degree scales

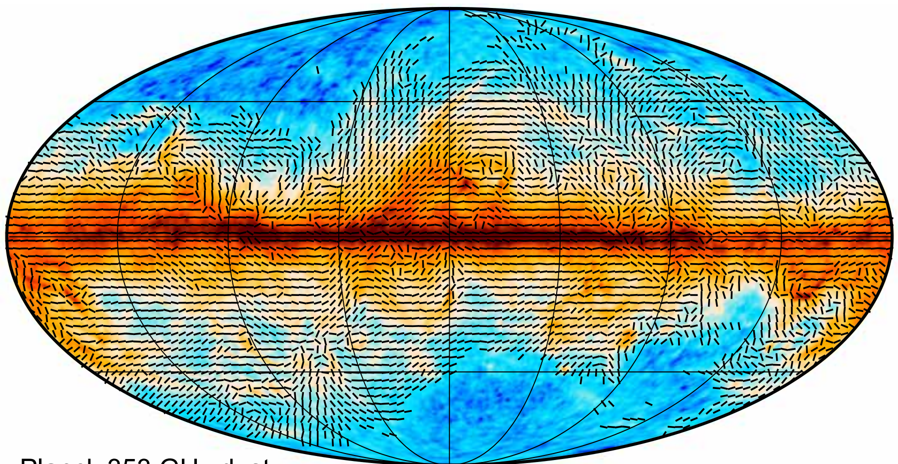
BUT ...

B-mode amplitude r=0.2 conflicts with upper limits r<0.11 from unpolarized data

Possible contribution from Galactic dust foreground?

BICEP2 collaboration 2014, PRL, 112, 24, 241101

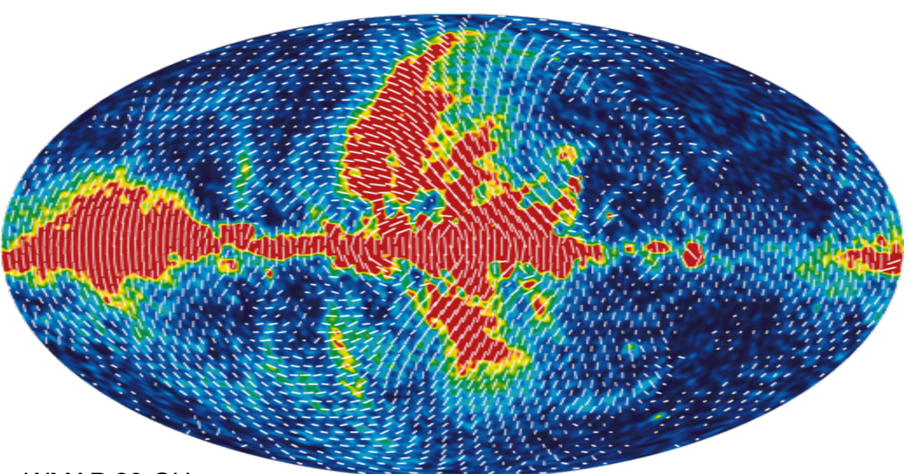
Polarized Foregrounds



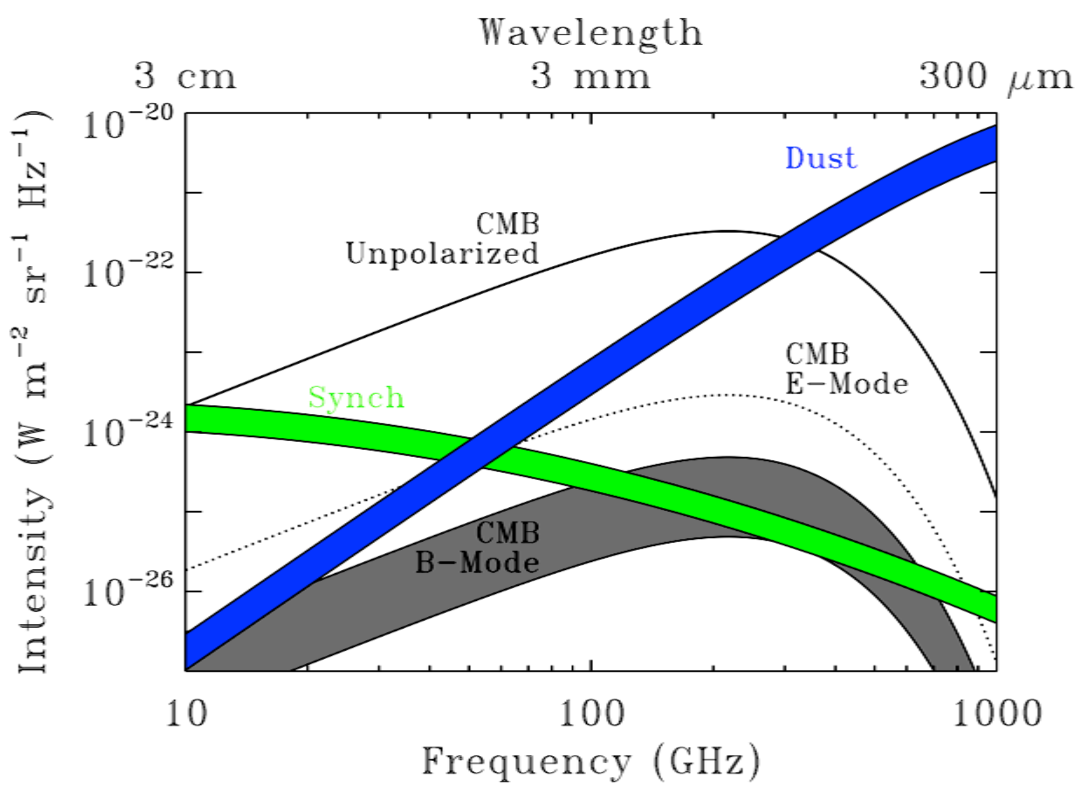
Planck 353 GHz dust

Separate CMB from foreground emission

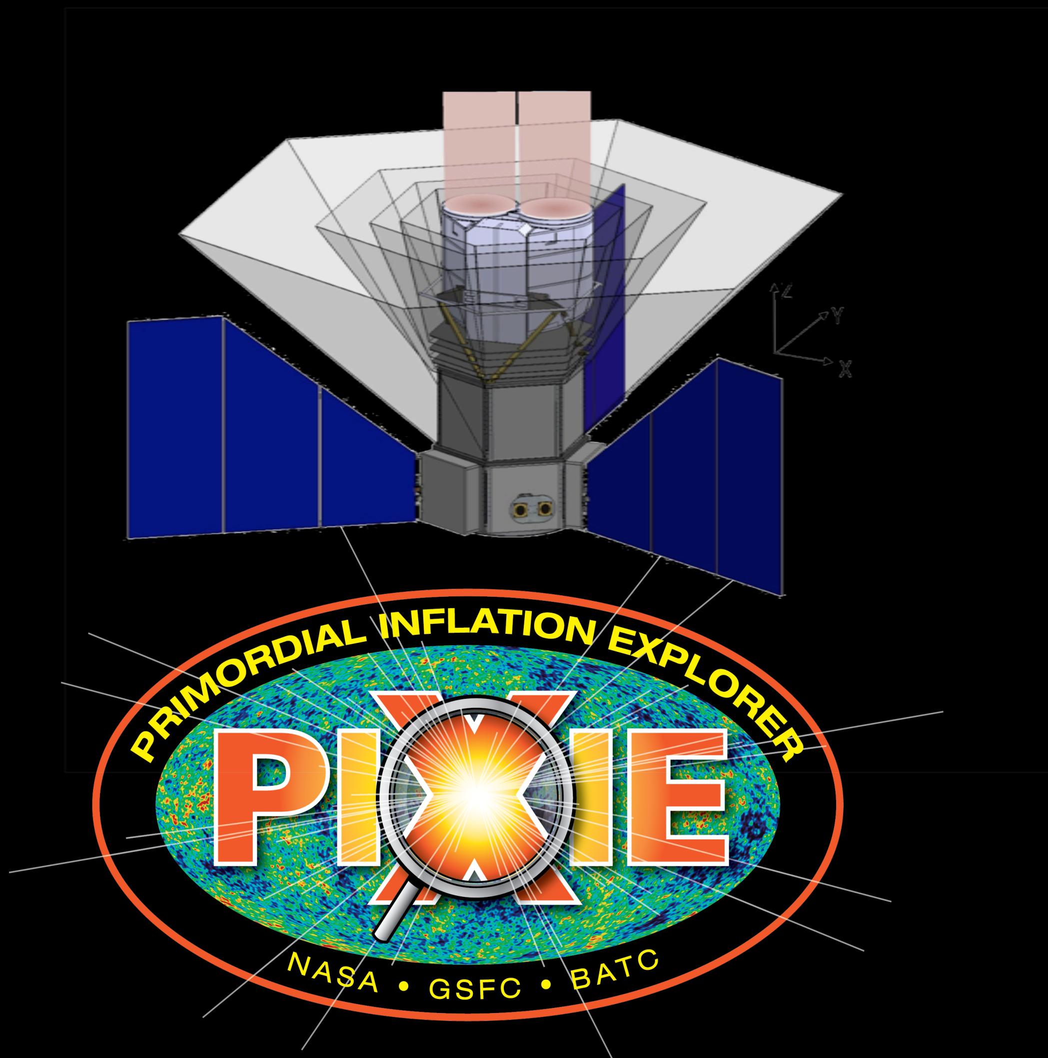
- Multiple frequency channels
- High sensitivity
- Control instrumental signature



WMAP 23 GHz
synchrotron



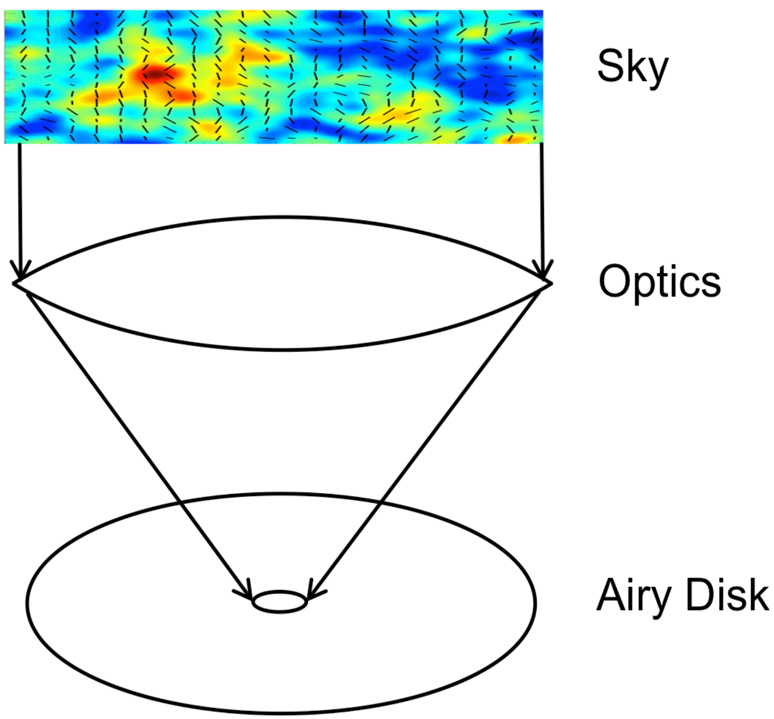
Primordial Inflation Explorer



Name	Role	Institution
A. Kogut	PI	GSFC
D. Fixsen	IS	UMD
D. Chuss	Co-I	GSFC
J. Dotson	Co-I	ARC
E. Dwek	Co-I	GSFC
M. Halpern	Co-I	UBC
G. Hinshaw	Co-I	UBC
S. Meyer	Co-I	U. Chicago
H. Moseley	Co-I	GSFC
M. Seiffert	Co-I	JPL
D. Spergel	Co-I	Princeton
E. Wollack	Co-I	GSFC

Characterize B-Mode Power Spectrum (and More!)

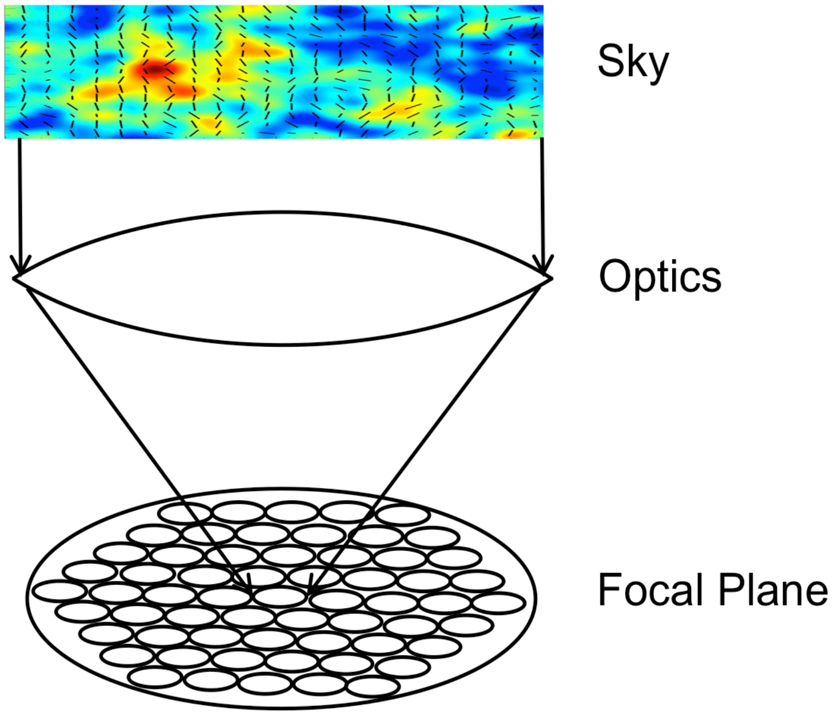
Optical Design for CMB



Conventional
Focal Plane

Single-Moded Pixel

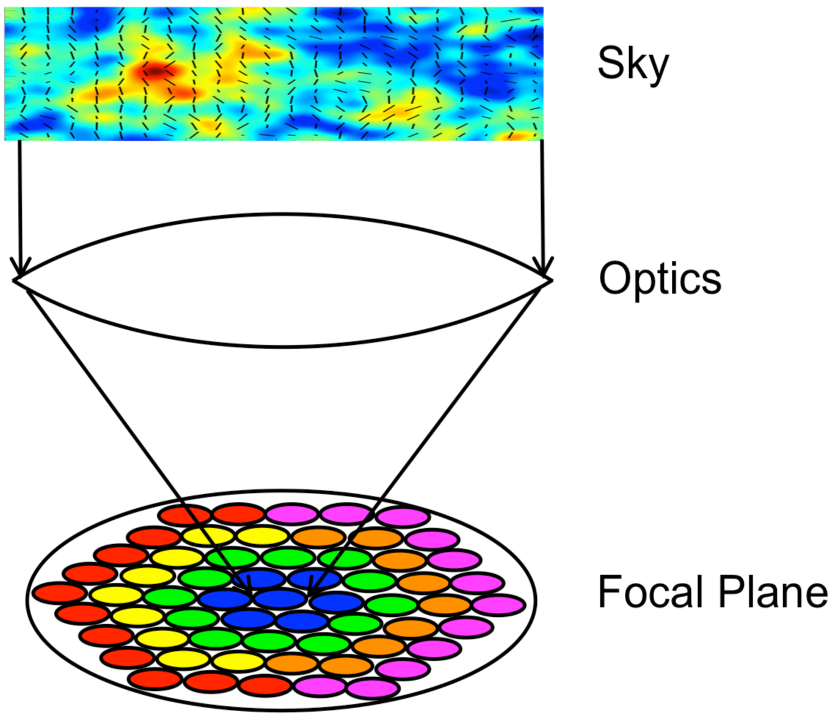
Optical Design for CMB



Conventional Focal Plane

Photon Limit: Add Detectors

Optical Design for CMB

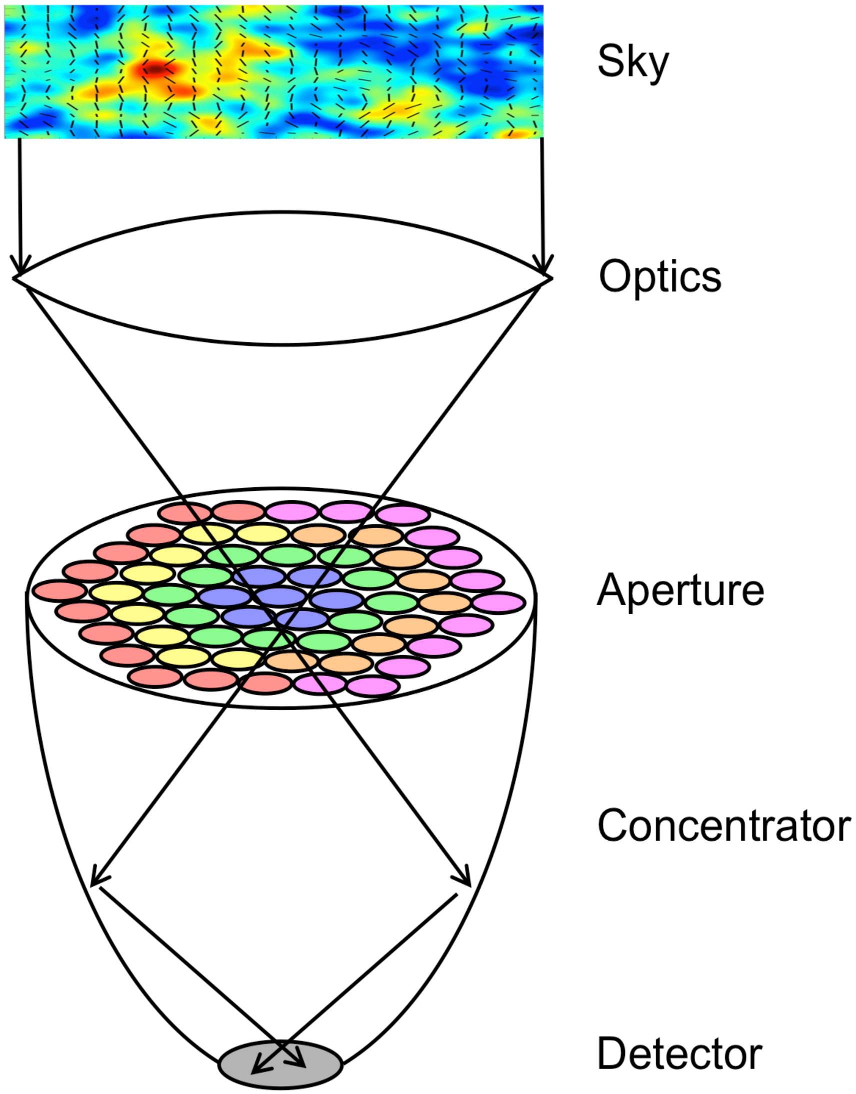


Conventional Focal Plane

Foregrounds: Separate Bands

Problem: Getting enough sensitivity in enough frequency bands requires ~10,000 background-limited detectors!

PIXIE Optical Solution

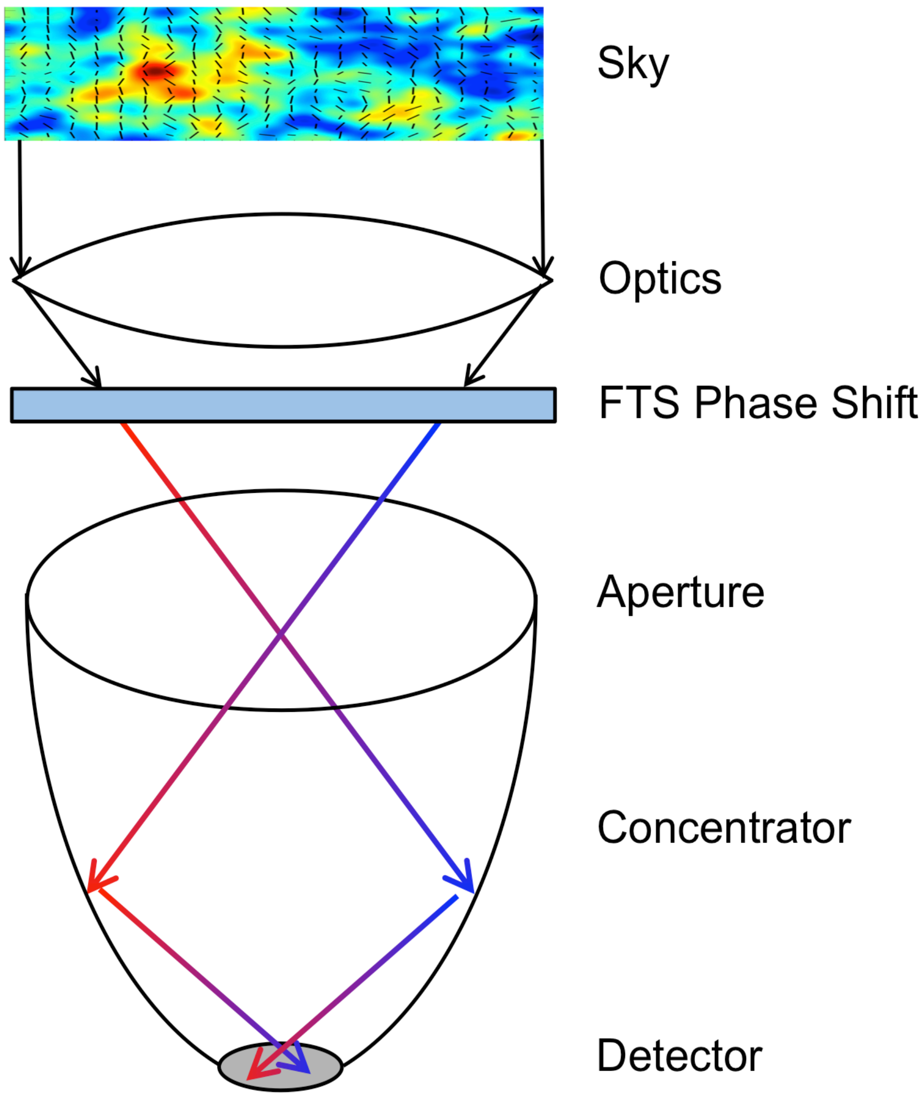


PIXIE

Need more photons, not more detectors!

Replace tiled focal plane
with
multi-moded concentrator

PIXIE Optical Solution



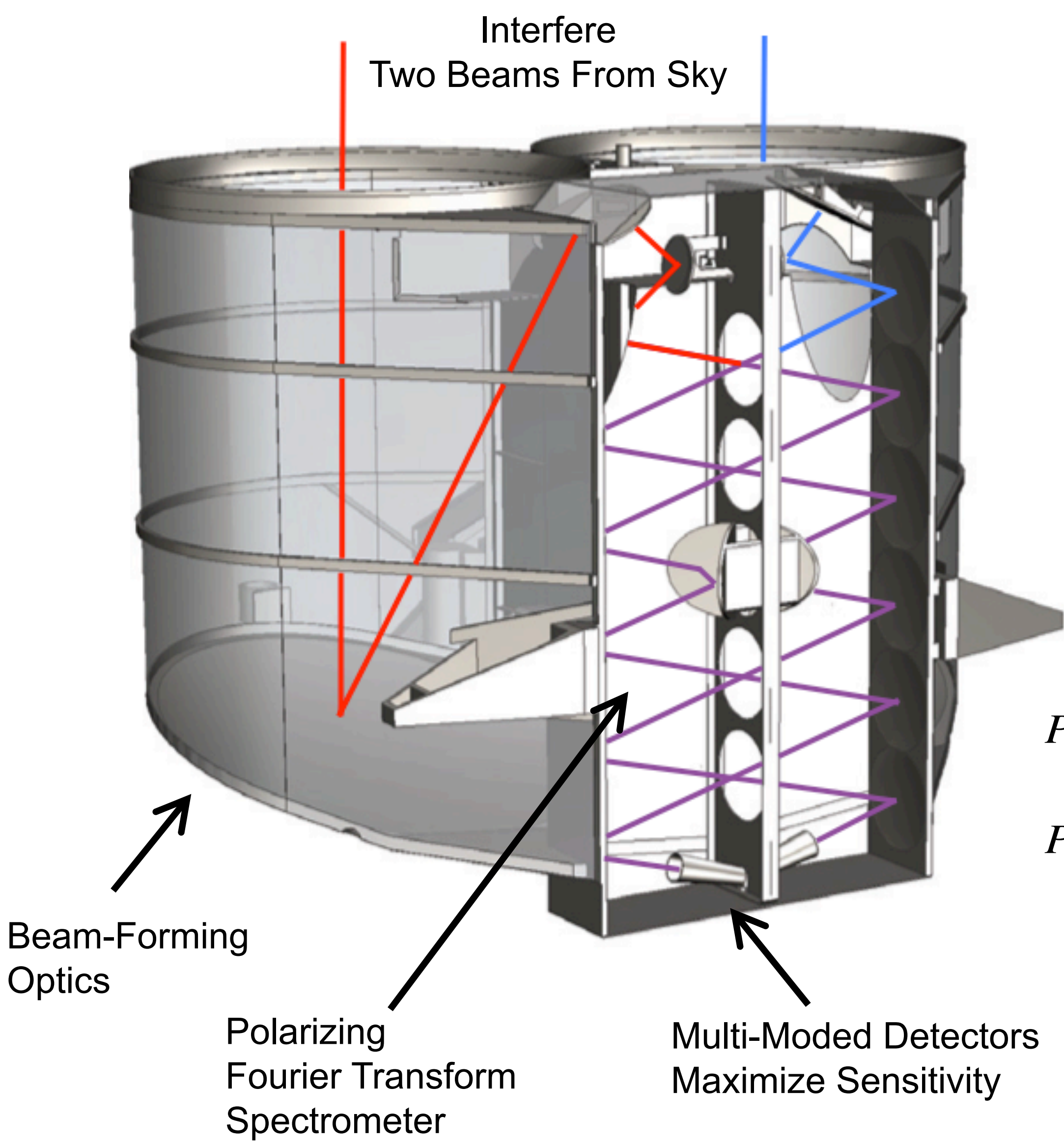
PIXIE

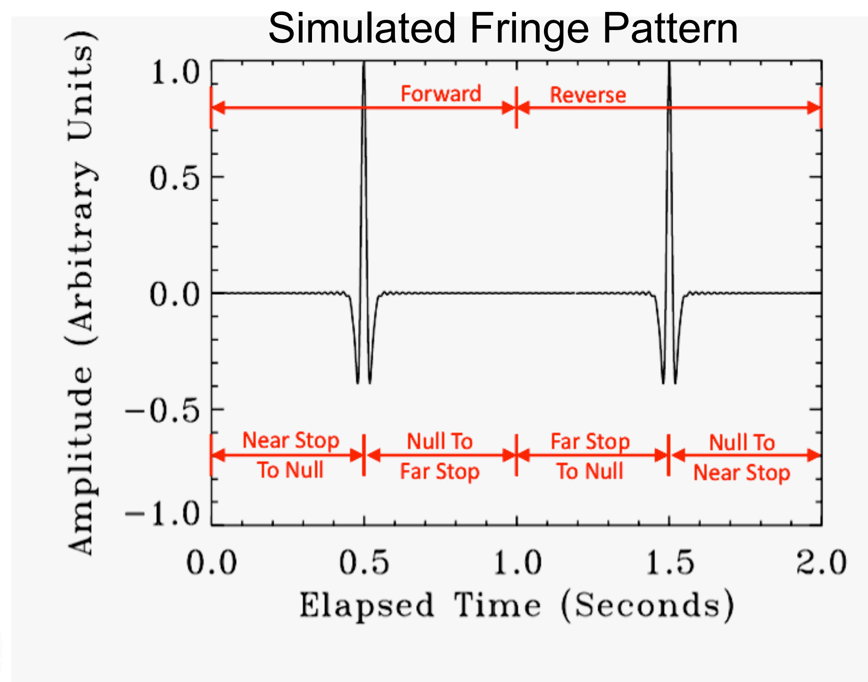
Replace multi-color detectors
with
Fourier transform spectrometer

Replace tiled focal plane
with
multi-moded concentrator

Win-Win: Sensitivity and spectra from a single detector

PIXIE Nulling Polarimeter





$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

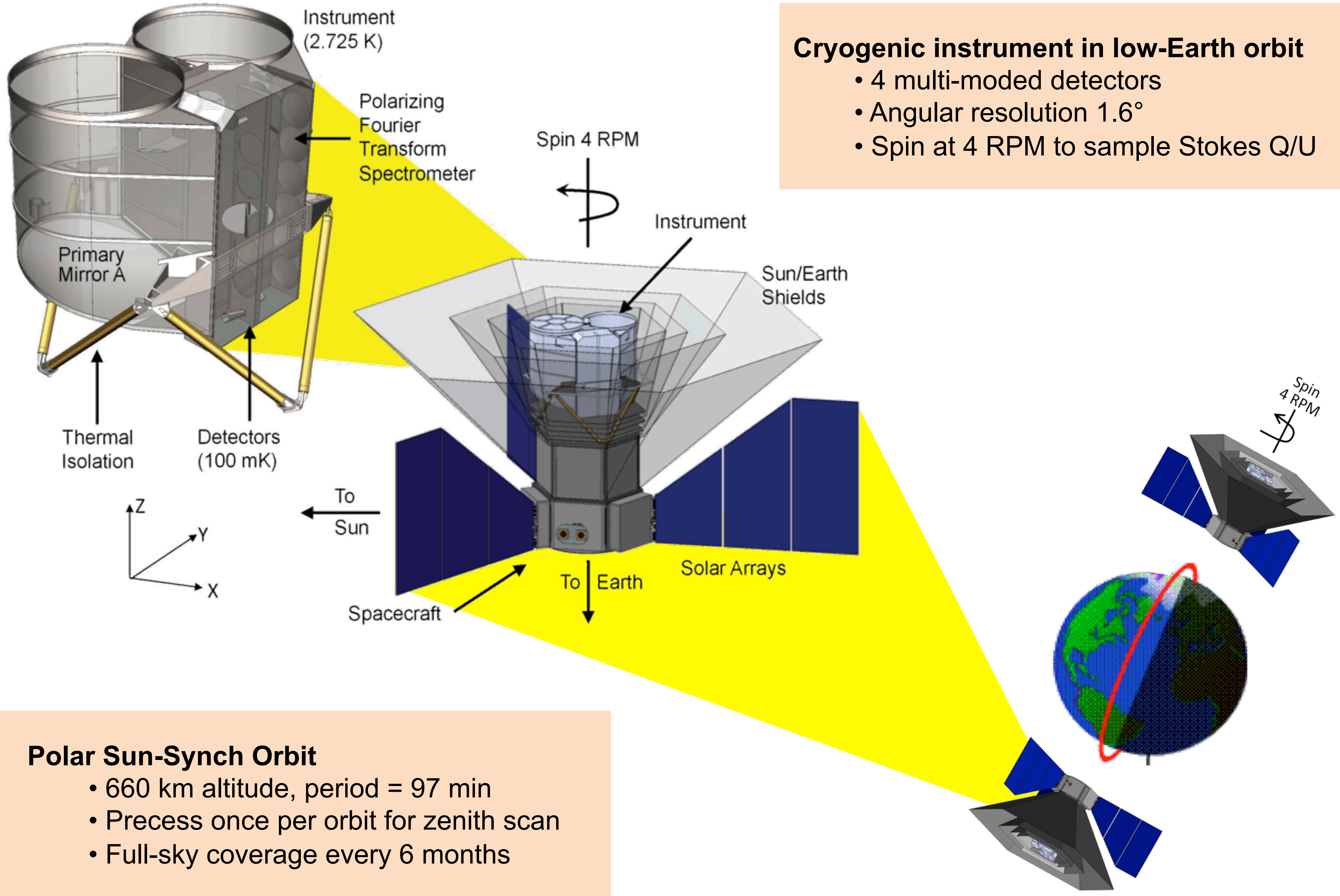
$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \underbrace{\left(E_{By}^2 - E_{Ax}^2\right)}_{\text{Stokes Q}}\cos(z\omega/c)\, d\omega$$

Measured Fringes Sample Frequency Spectrum of Polarized Sky

Instrument and Observatory

Cryogenic instrument in low-Earth orbit

- 4 multi-moded detectors
- Angular resolution 1.6°
- Spin at 4 RPM to sample Stokes Q/U

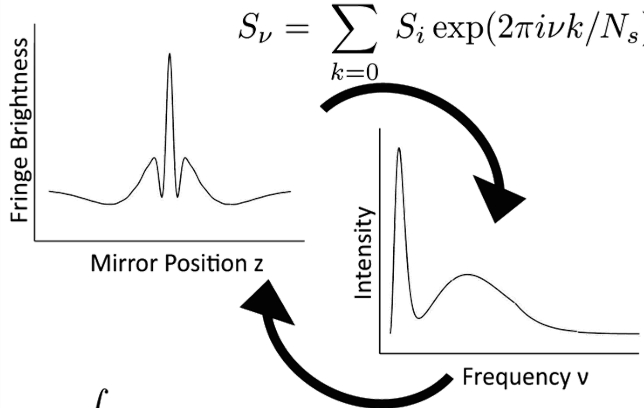


Polar Sun-Synch Orbit

- 660 km altitude, period = 97 min
- Precess once per orbit for zenith scan
- Full-sky coverage every 6 months

Solving the Foreground Puzzle

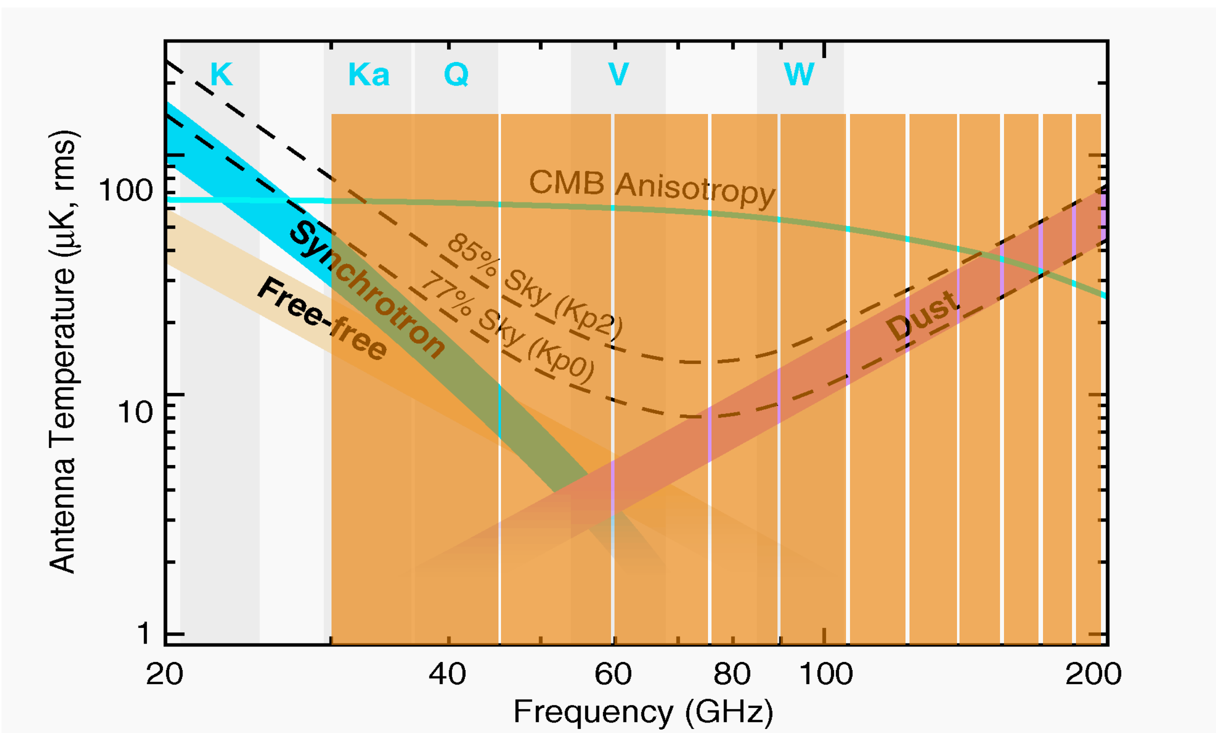
$$S_\nu = \sum_{k=0}^{N_s-1} S_i \exp(2\pi i \nu k/N_s)$$



$$S_i = \int S_\nu \exp(2\pi i z_i/c) d\nu$$

Phase delay L sets channel width
$\Delta\nu = c/L = 15$ GHz

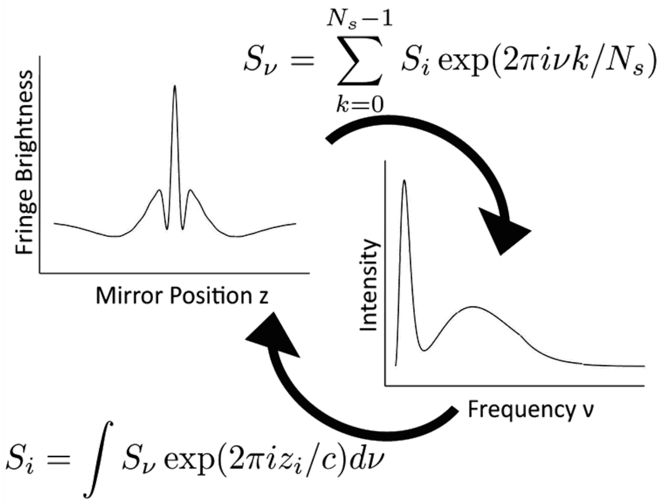
Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)^*\Delta\nu$



Example:
24 samples during fringe sweep
12 channels 15 GHz to 180 GHz

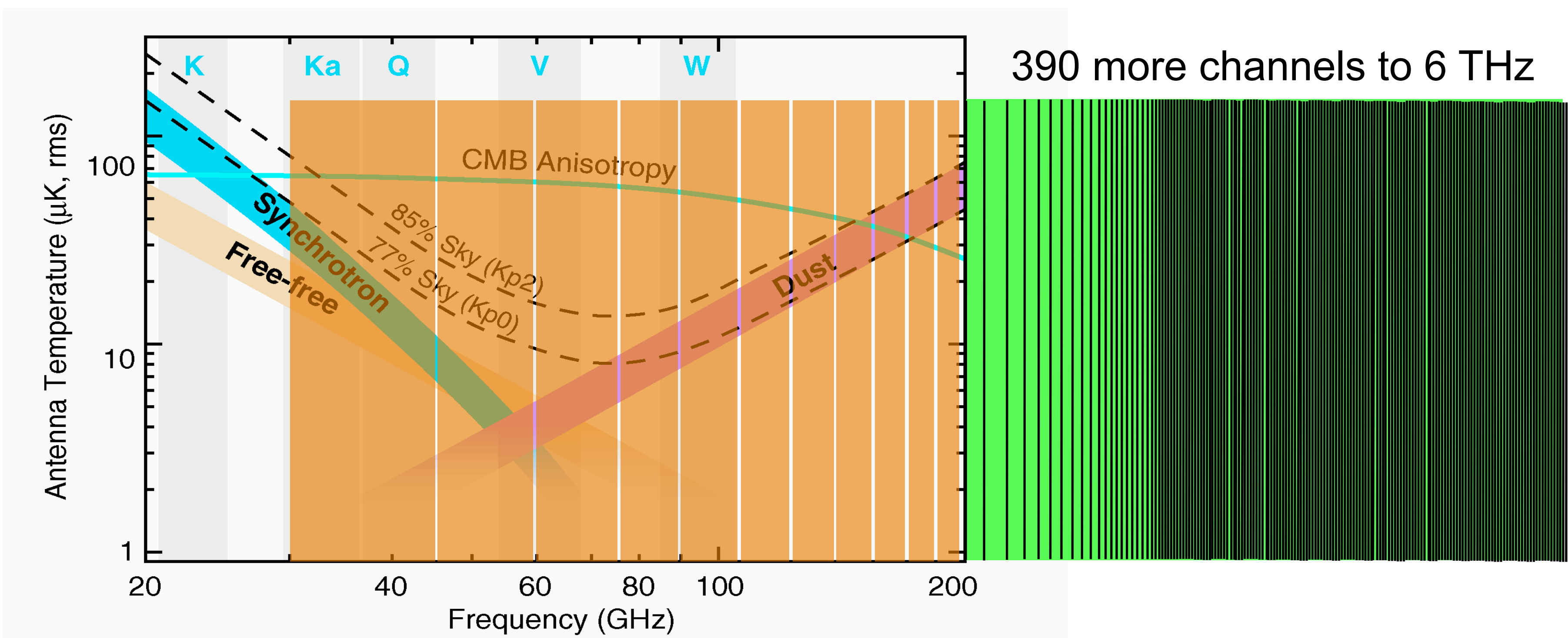
But why stop there?

Solving the Foreground Puzzle



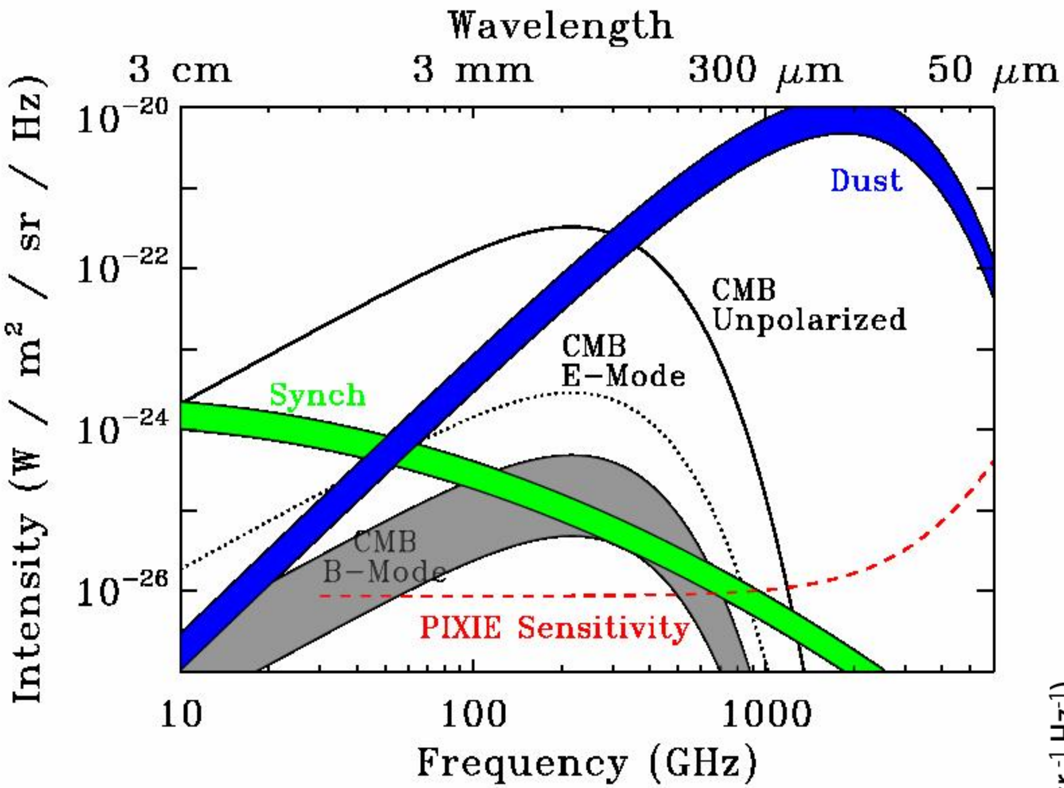
Phase delay L sets channel width
$\Delta\nu = c/L = 15$ GHz

Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)*\Delta\nu$



Sample more often: Get more frequency channels!

PIXIE "Foreground Machine"



Spectral coverage spanning 7+ octaves

Polarized spectra from 30 GHz to 6 THz

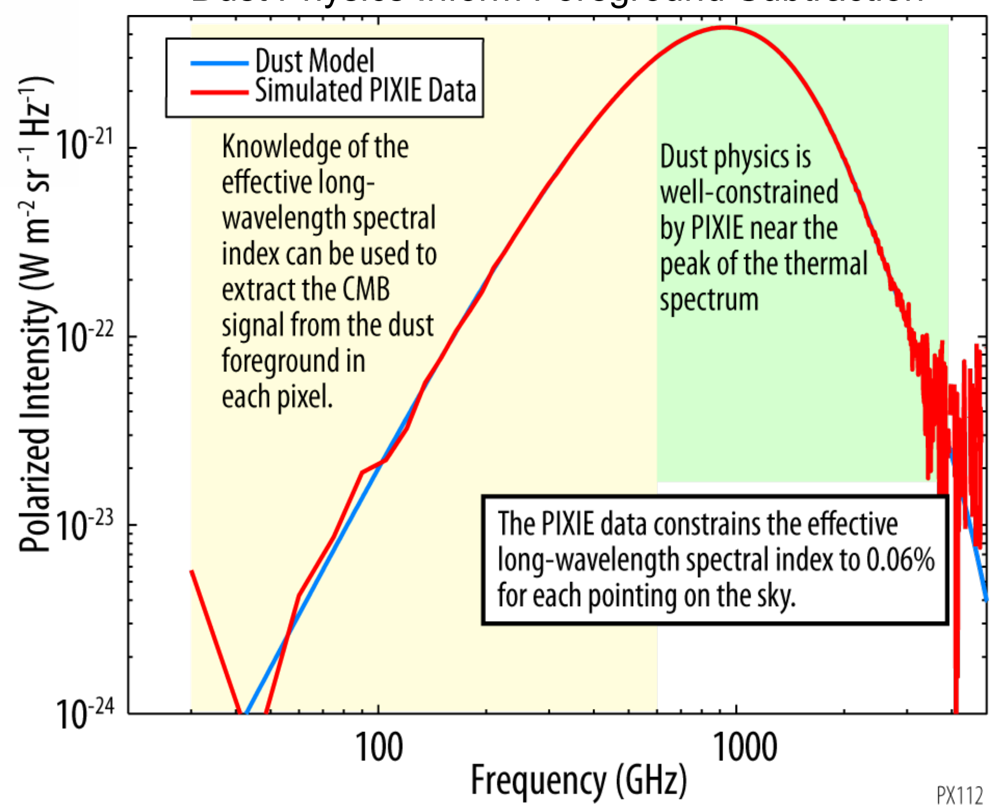
400 channels with mJy sensitivity per channel

Sensitivity plus broad frequency coverage

Foreground S/N > 100 in each pixel and freq bin

Spectral index uncertainty ±0.001 in each pixel

Dust Physics Inform Foreground Subtraction



If PIXIE can't figure out the foregrounds, it probably can't be done!

PX112

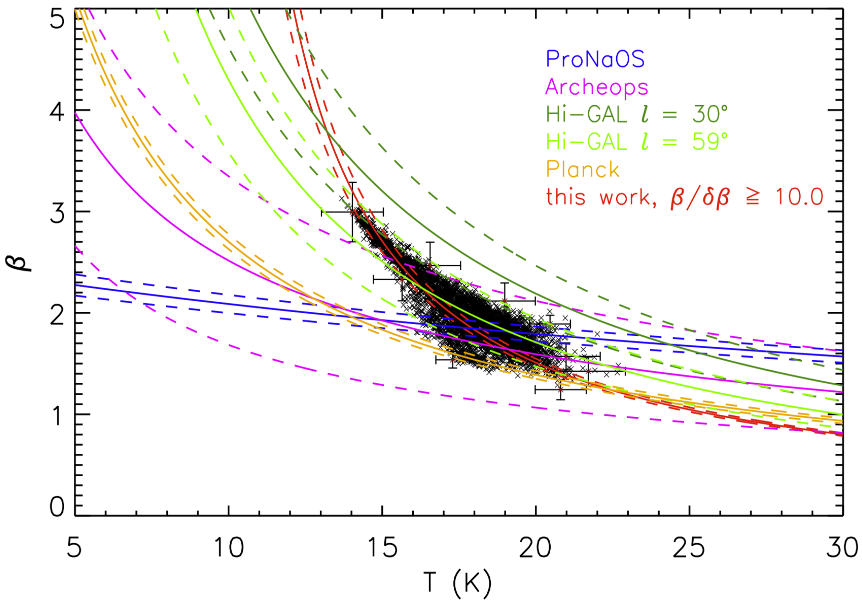
The Problem With Foregrounds

With seven free parameters,
you can fit a charging rhino.

What if the universe
uses a different model
than the one you're fitting?

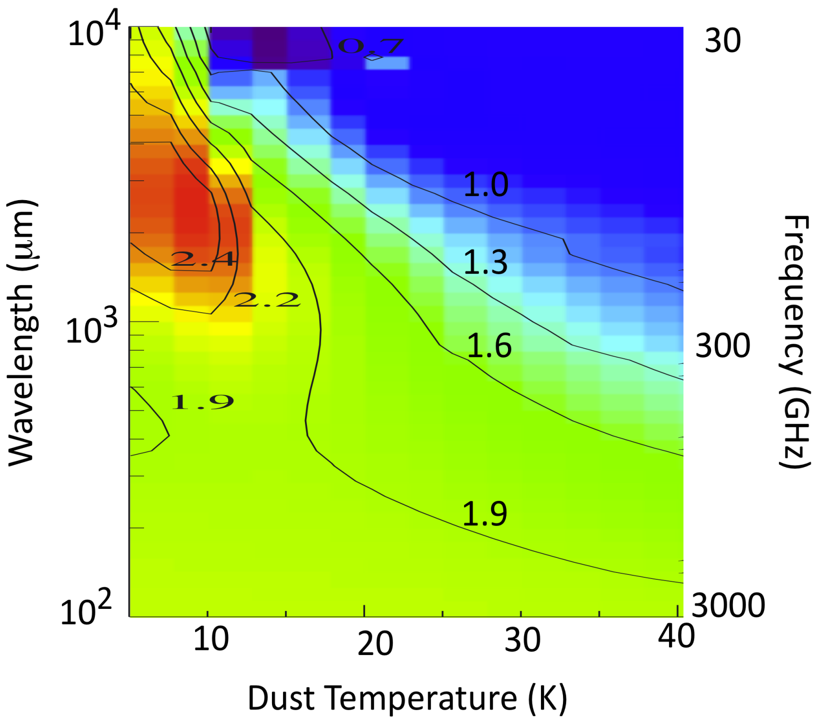
Parametric Dust Models

A Cautionary Tale



Empirical fits show correlation between T and β
Greybody model, pixel-to-pixel variation

Liang et al. 2012, arXiv:1201.0060



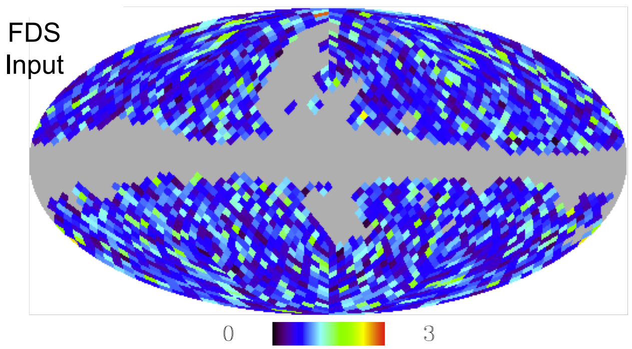
Solid-state model of disordered medium
Two-level system predicts variation in β

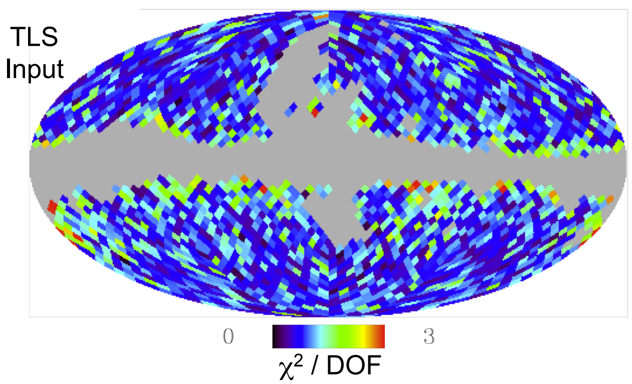
- Steeper β for colder T at fixed frequency
- Flatter β for lower freq at fixed temperature

Meny et al. 2007, A&A, 468, 171
Paradis et al. 2011, A&A, 534, A118
Paradis et al. 2012, A&A, 537, A113

Is either model the correct description?
How can we tell?

A Tale Of Two Models





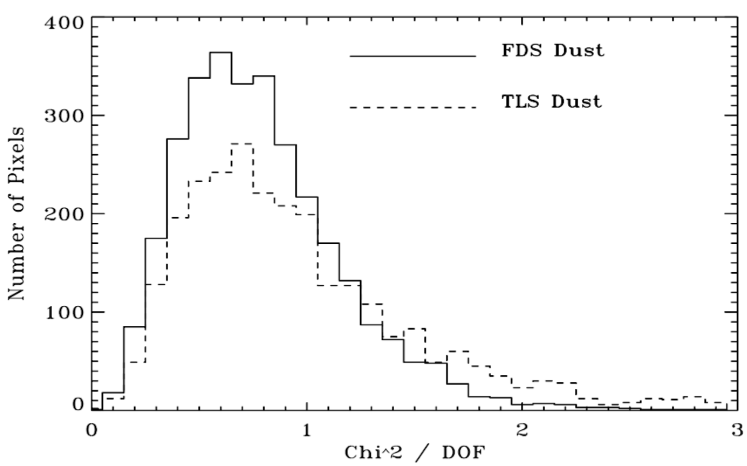
Input Sky: CMB + Dust (either greybody or two-level system) + noise

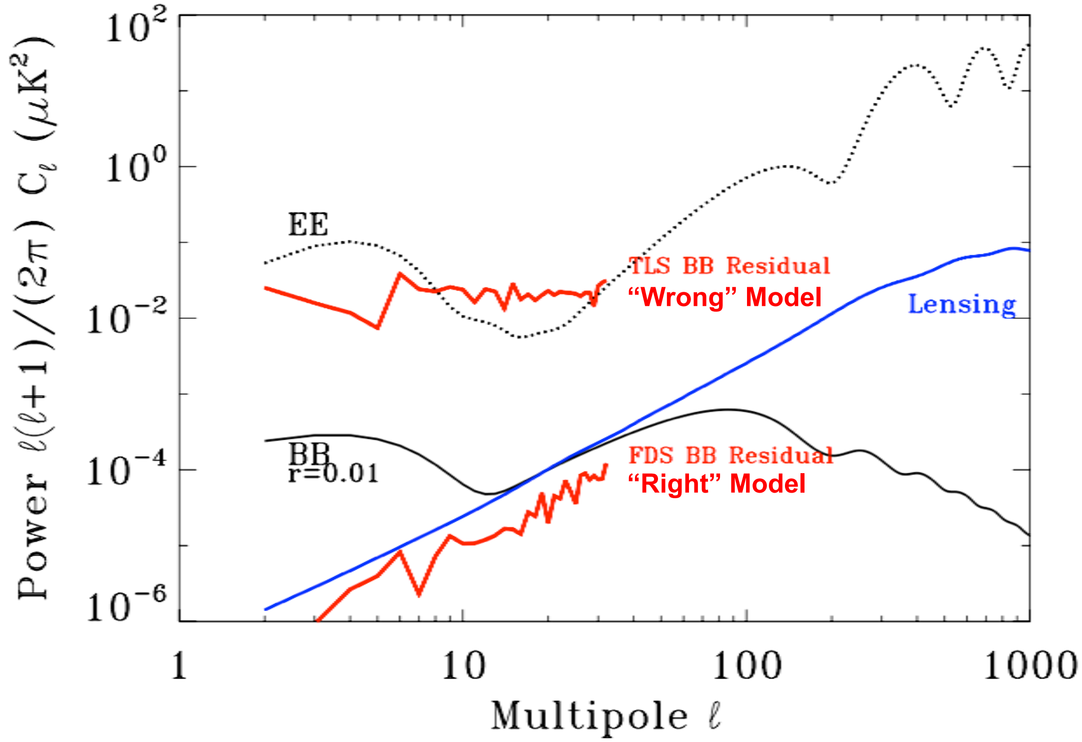
9 EPIC Channels (30, 45, 70, 100, 150, 220, 340, 500, 850 GHz)

Fit 8 parameters to 18 maps assuming dust follows greybody spectrum

- CMB amplitude (Q and U)
- Cold dust amplitude (Q and U) and spectral index
- Warm dust amplitude (Q and U) and spectral index

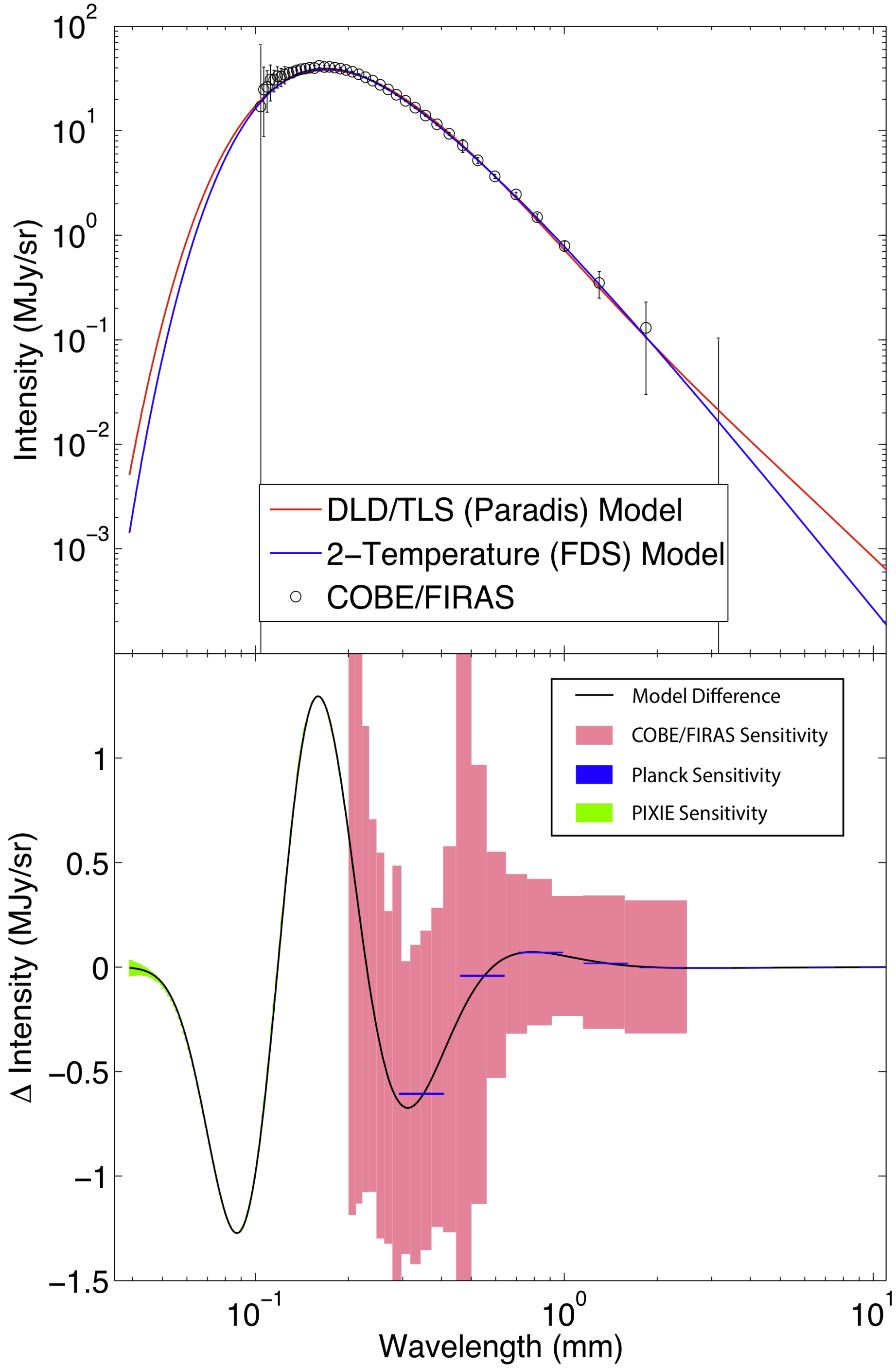
Compare Output to Input CMB Maps





Same χ^2 But Different C_l: Worst-Case Scenario!

PIXIE vs Dust Models

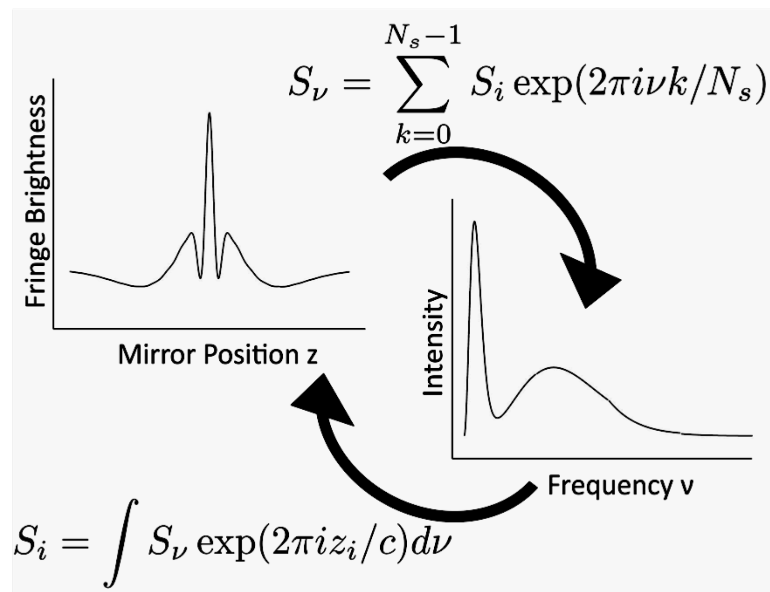


400 frequency channels from 30 GHz to 6 THz

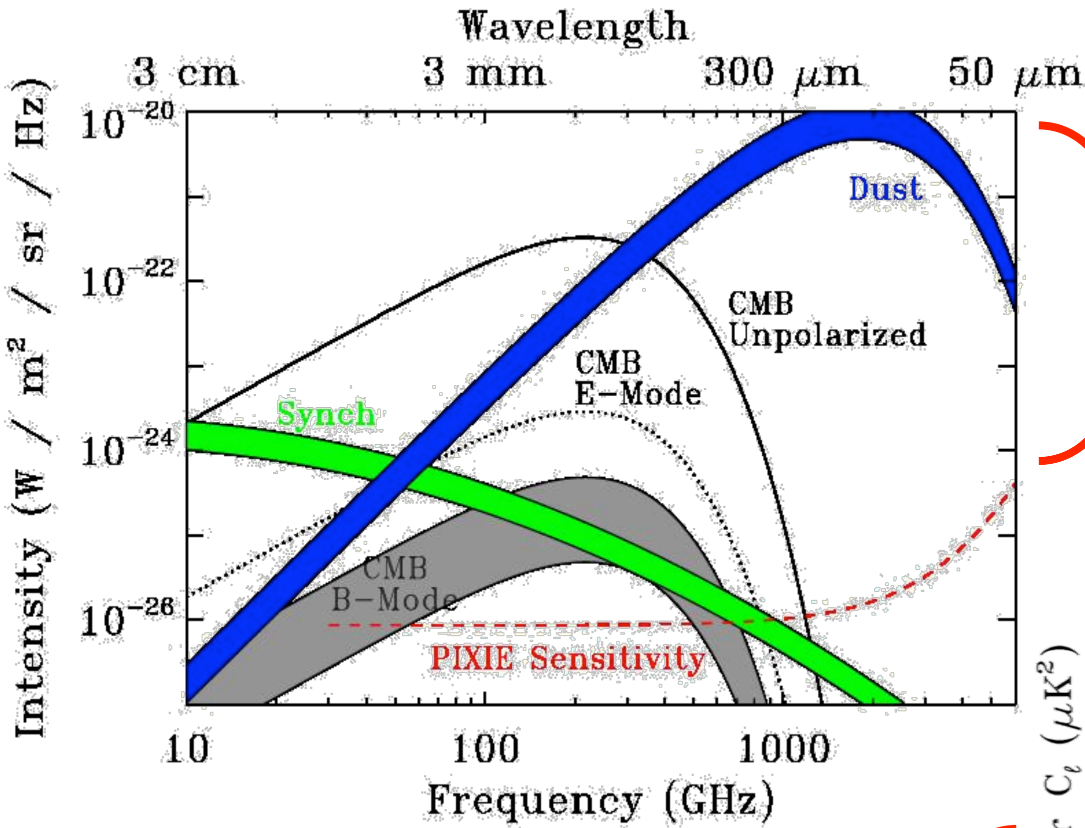
- Distinguish FDS from TLS emission model
- Determine correct parametric model
- Use THz data to inform low-freq CMB fit

Get channels almost for free

- Longest mirror stroke sets channel width
- Sampling rate sets number of channels
- No messy focal plane allocations

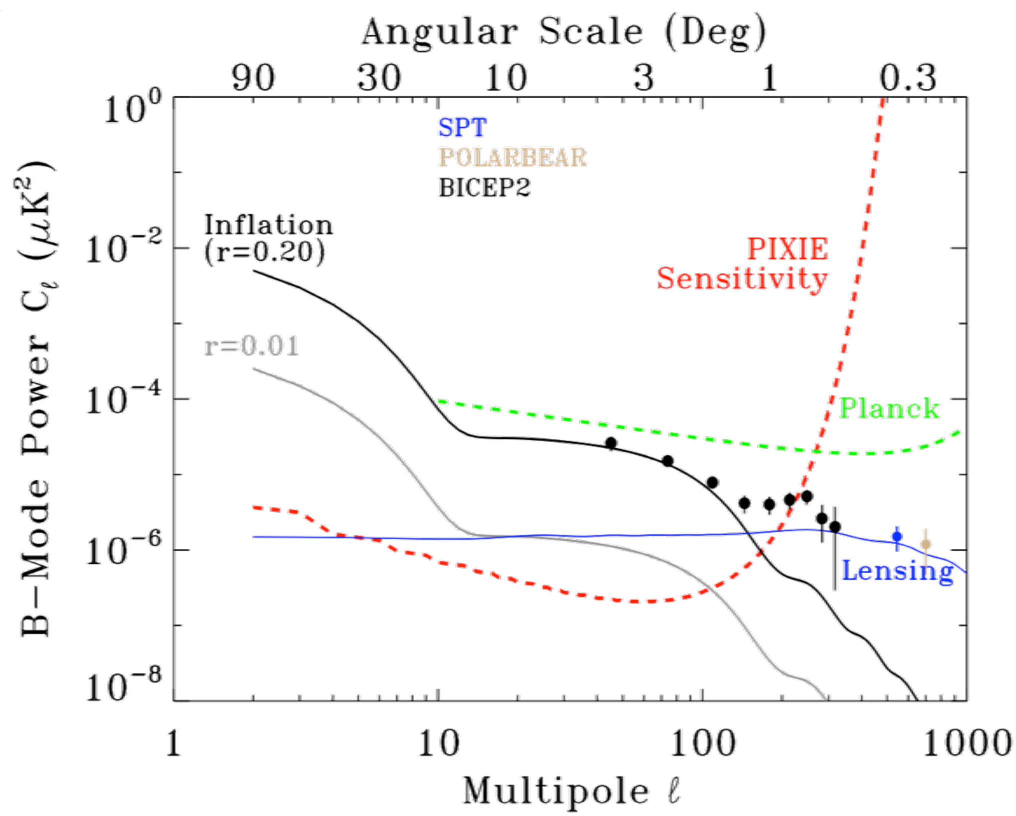


PIXIE Polarization Goals



400-Channel "Foreground Machine"

Less than 1% noise penalty
for foreground subtraction



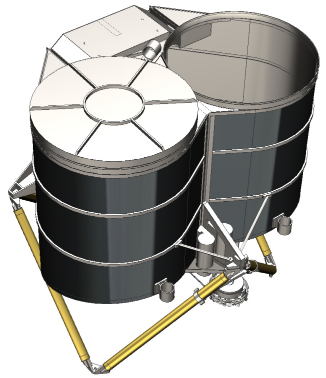
Sensitivity r < 2 x 10^{-4} (95% CL)

CMB sensitivity 70 nK per 1° pixel
Measure r to 1% even for minimal r ~ 0.02

Measure Inflationary Signal to Limits of Astrophysical Foregrounds


BUT WAIT,
there's more!

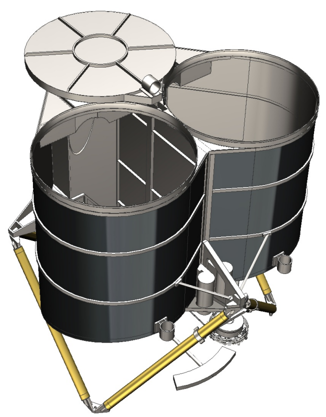
Blackbody Calibrator Adds Spectrum Science



Calibrator blocks "A" beam: Fringes measure ΔI + [Q,U]

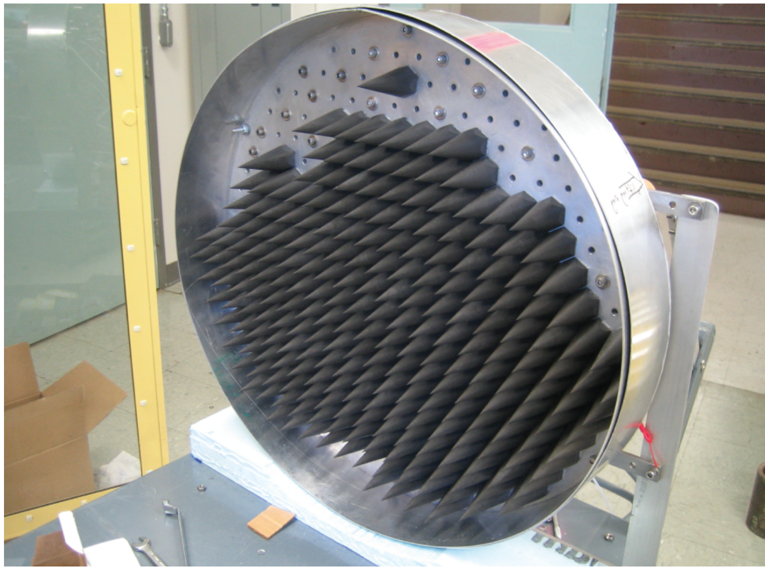
$$\begin{aligned}
S(\nu)_{Lx} &= 1/4\,[\,I(\nu)_{\rm sky} - I(\nu)_{\rm cal} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/4\,[\,I(\nu)_{\rm sky} - I(\nu)_{\rm cal} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Rx} &= 1/4\,[\,I(\nu)_{\rm cal} - I(\nu)_{\rm sky} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/4\,[\,I(\nu)_{\rm cal} - I(\nu)_{\rm sky} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,]
\end{aligned}$$

Flip sign:
Hot vs cold calibrator

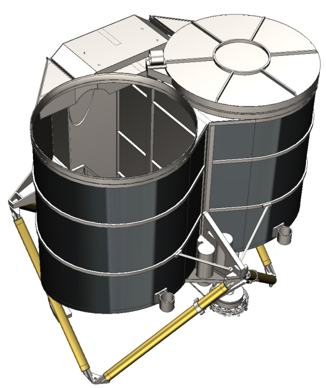


Calibrator stowed: Fringes measure [Q,U] only

$$\begin{aligned}
S(\nu)_{Lx} &= 1/2\,[+Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/2\,[-Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Rx} &= 1/2\,[+Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/2\,[-Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,]
\end{aligned}$$



Partially-assembled blackbody calibrator



Calibrator blocks "B" beam: Fringes measure -ΔI - [Q,U]

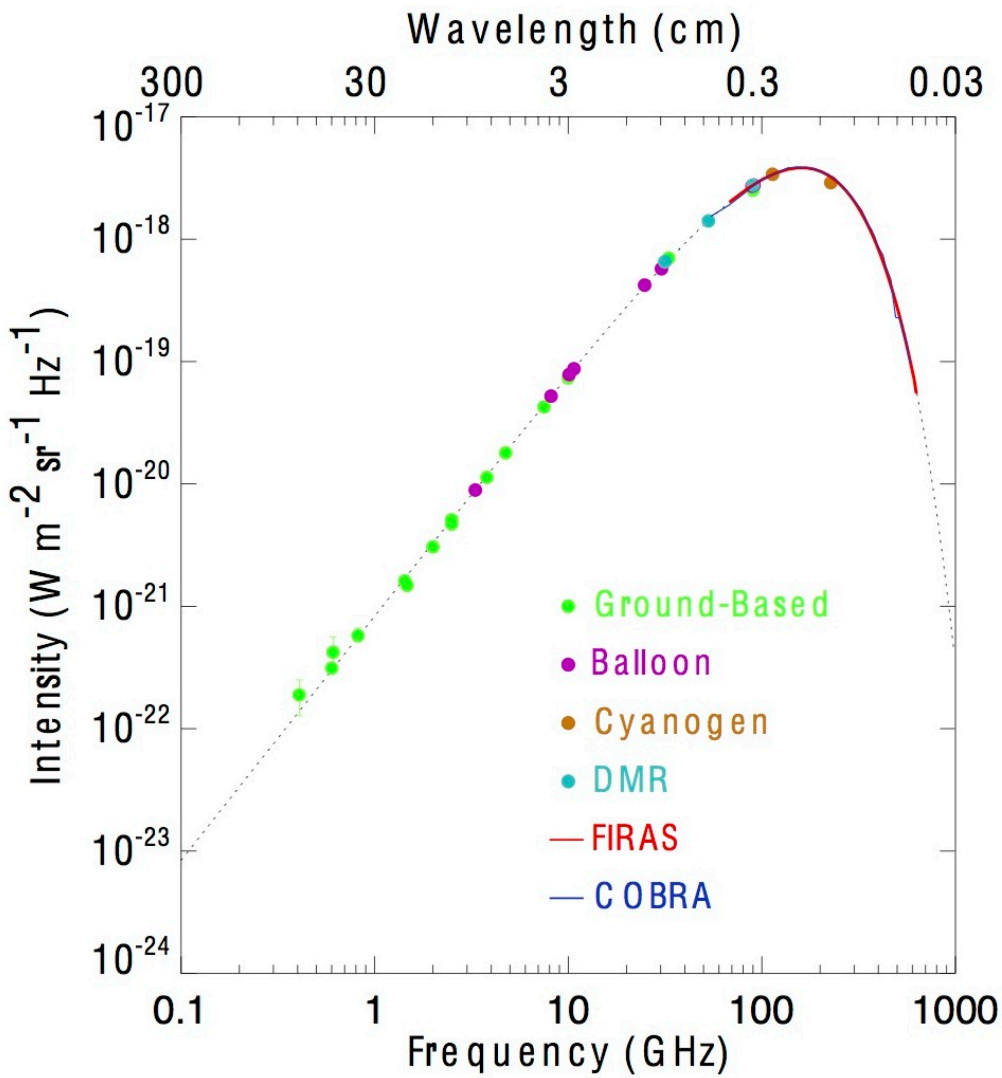
$$\begin{aligned}
S(\nu)_{Lx} &= 1/4\,[\,I(\nu)_{\rm cal} - I(\nu)_{\rm sky} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/4\,[\,I(\nu)_{\rm cal} - I(\nu)_{\rm sky} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Rx} &= 1/4\,[\,I(\nu)_{\rm sky} - I(\nu)_{\rm cal} + Q(\nu)_{\rm sky}\cos 2\gamma + U(\nu)_{\rm sky}\sin 2\gamma\,] \\
S(\nu)_{Ly} &= 1/4\,[\,I(\nu)_{\rm sky} - I(\nu)_{\rm cal} - Q(\nu)_{\rm sky}\cos 2\gamma - U(\nu)_{\rm sky}\sin 2\gamma\,]
\end{aligned}$$

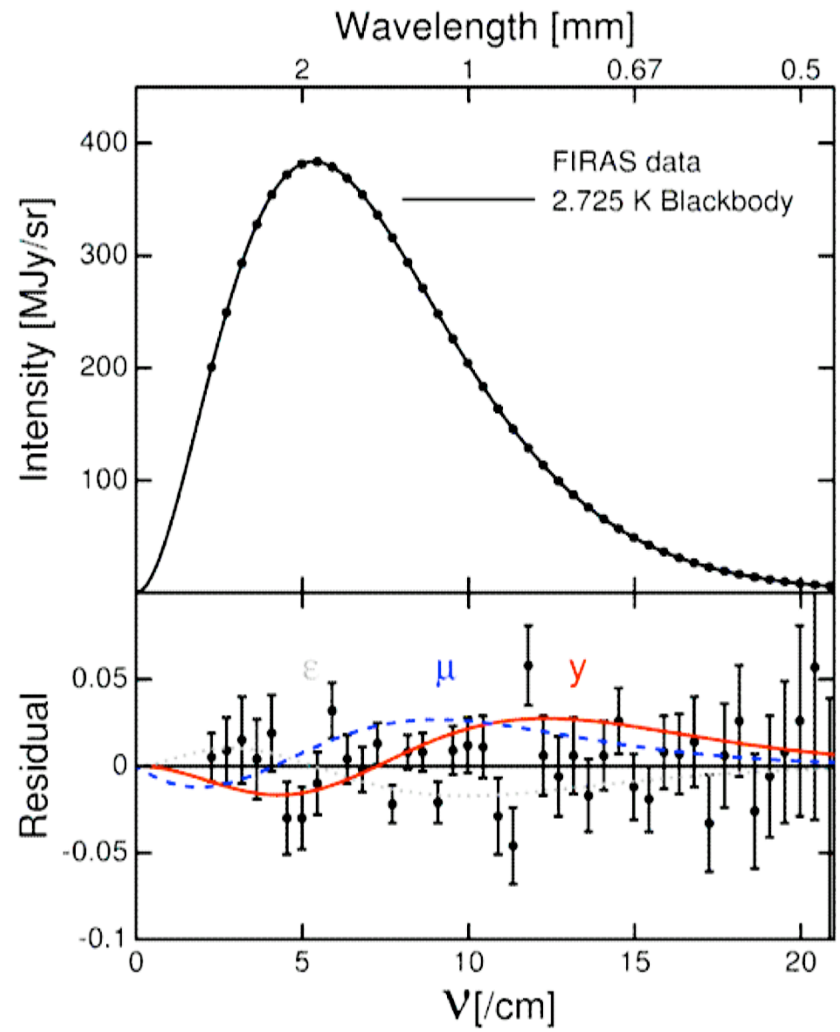
Flip sign:
A vs B beam

Blackbody Spectral Distortion!
1000 Times More Sensitive Than COBE/FIRAS

Blackbody Spectrum

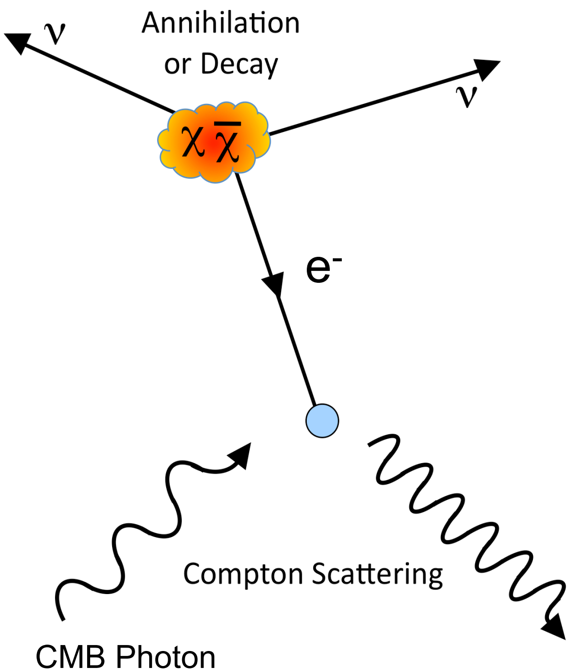
COBE: Sky is blackbody within 50 ppm





PIXIE: Improve COBE limits by factor 1000. Sky can not be black at this level!

Spectral Distortion from Energy Release



Optically thin case: Compton y distortion

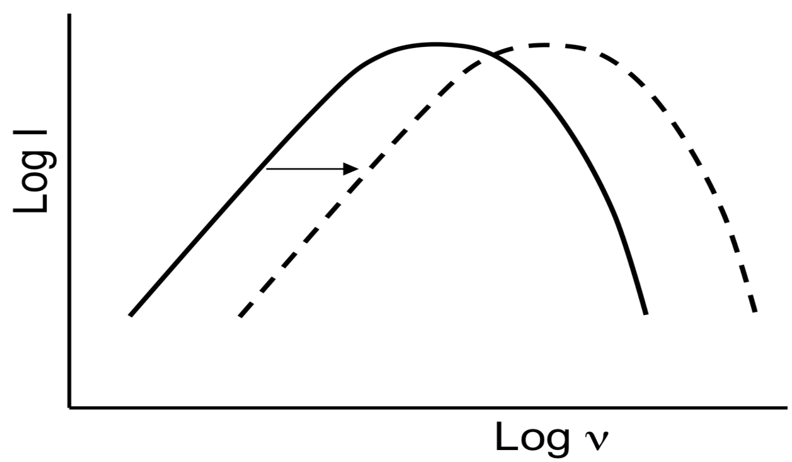
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(x)-1}\left[1+\frac{y\,x\,\exp(x)}{\exp(x)-1}\left(\frac{x}{\tanh(x/2)}-4\right)\right]$$

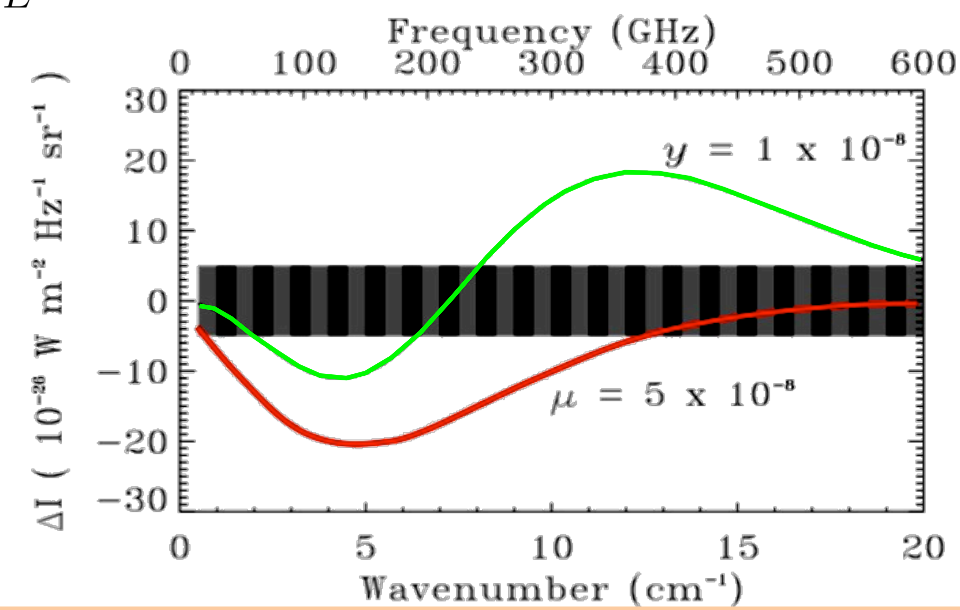
$$y = \int \frac{kT_e}{mc^2}\, nc\sigma_T\, dt$$

Optically thick case: Chemical potential distortion

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

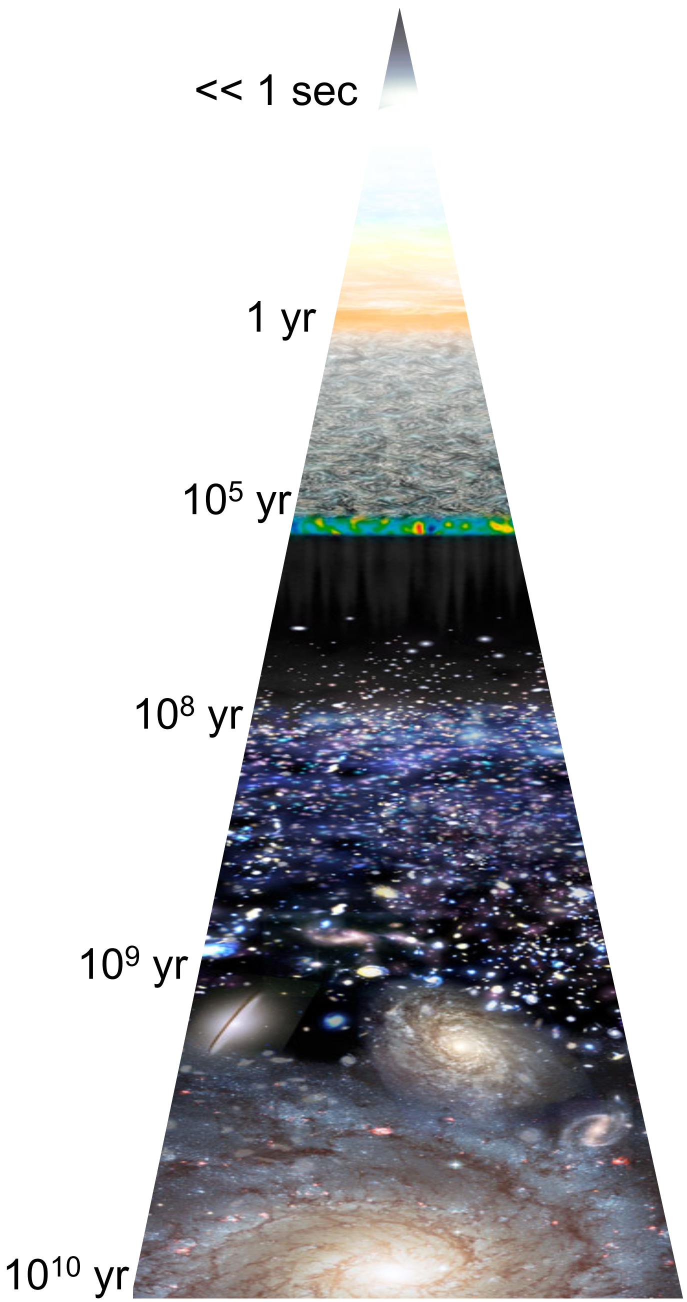
$$\mu = 1.4\,\frac{\Delta E}{E}$$





Distortion to blackbody spectrum proportional to integrated energy release

PIXIE: Testing The Standard Model



Big Bang Cosmology *
- Inflation
- GUT physics
- Quantum gravity

Early Universe
- Dark matter decay/annihilation
- Primordial density perturbations

Reionization and First Stars *
- Ionization history at end of Dark Ages
- Nature of first stars

Large-scale Structure
- Galaxy bias vs dark matter density
- Star formation at redshift 2--3

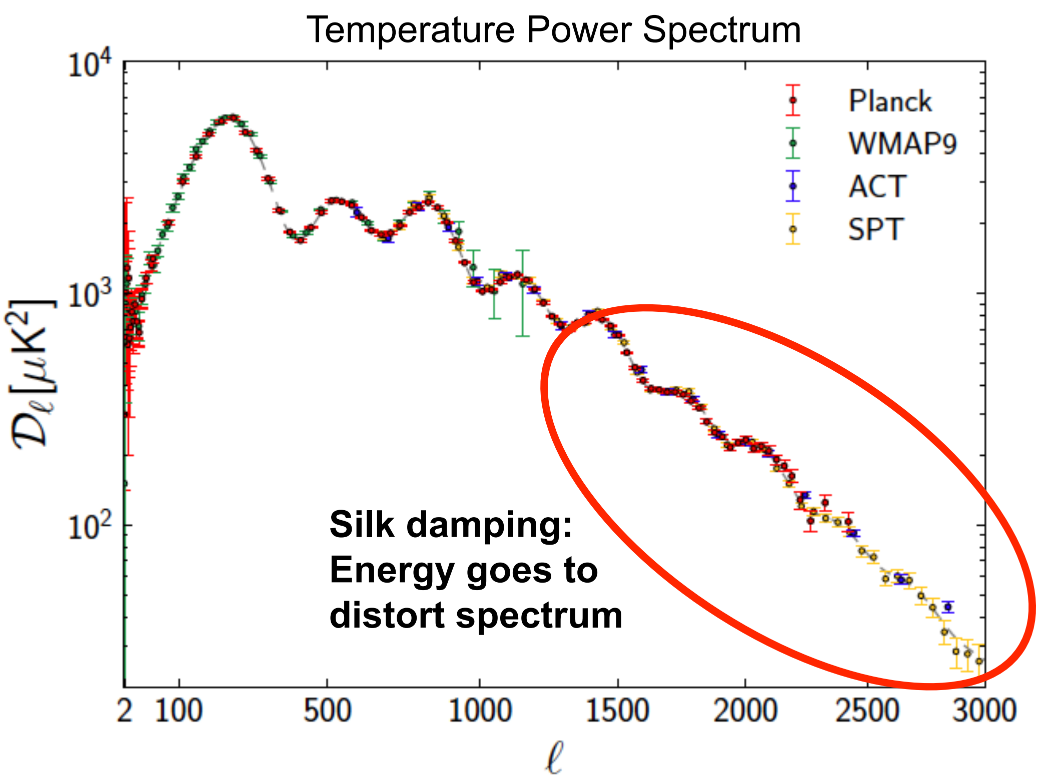
Galactic Structure
- Assembly history of the Galaxy
- Dust & chemical separation

Primary Science: Big Bang Cosmology

Secondary Science: Early Universe; Reionization and First Stars; Large-scale Structure; Galactic Structure

* Specifically called out in Astro-2010 Decadal Survey

Spectral Distortions: Inflation

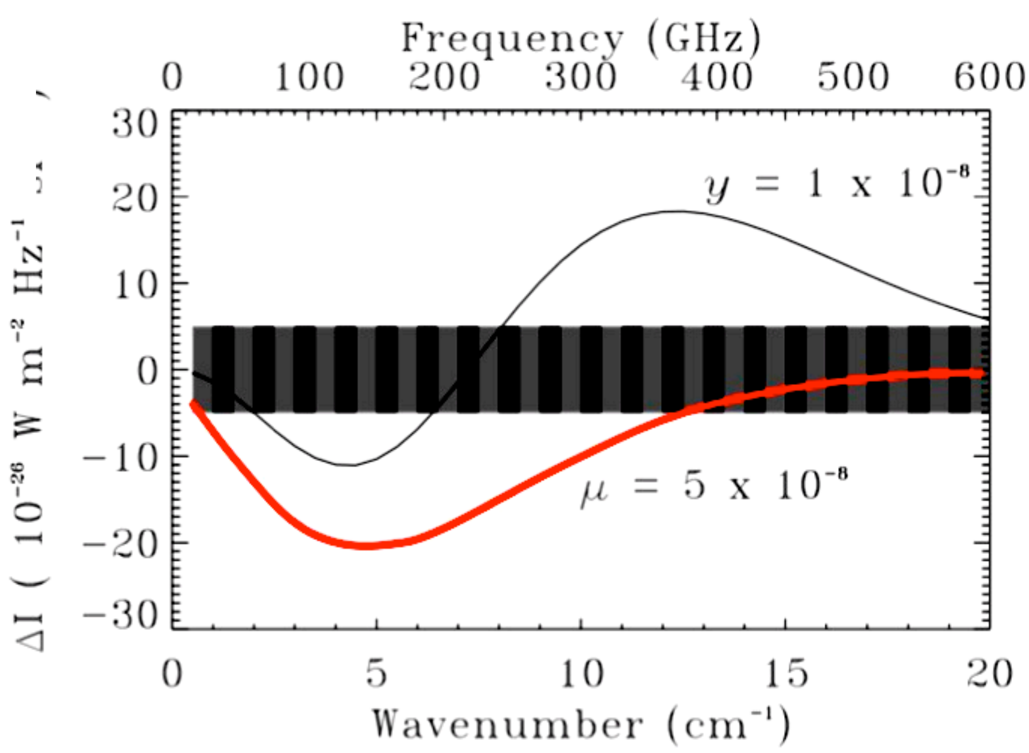


Energy release at $10^4 < z < 10^6$

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

PIXIE limit $\mu < 10^{-8}$

Distort CMB from blackbody spectrum

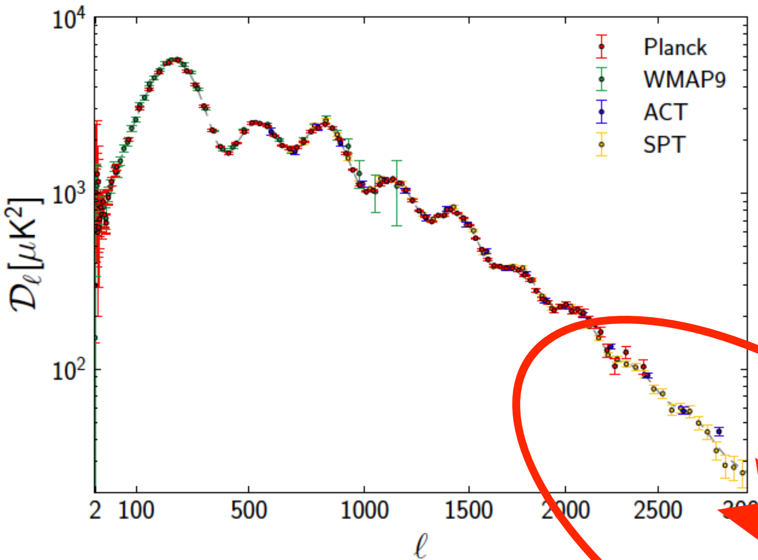


Silk damping of primordial perturbations

- Scalar index n_s and running dln n_s/dln k
- Physical scale ~1 kpc ($1M_\odot$)

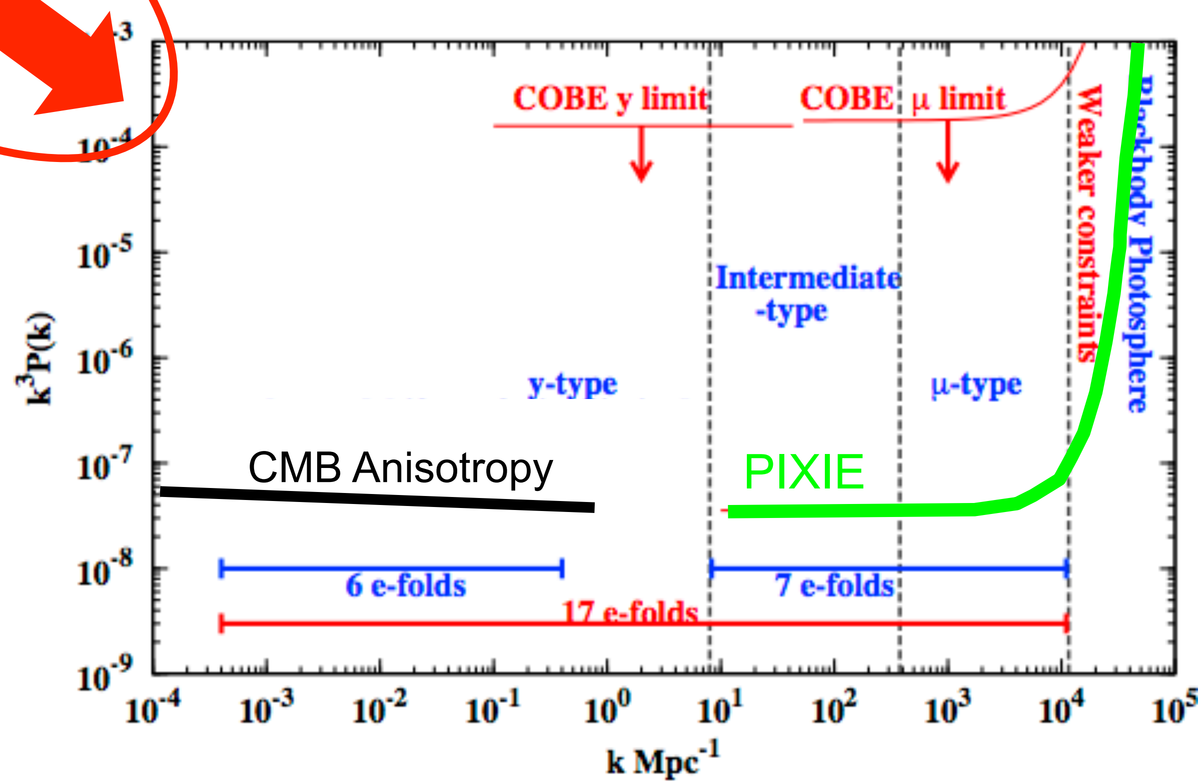
Daly 1991
Hu, Scott, & Silk 1994
Chluba, Erickcek, & Ben-Dayan 2012

Beyond the Power Spectrum



Spectral distortions extend tests of inflation by 4 orders of magnitude in physical scale

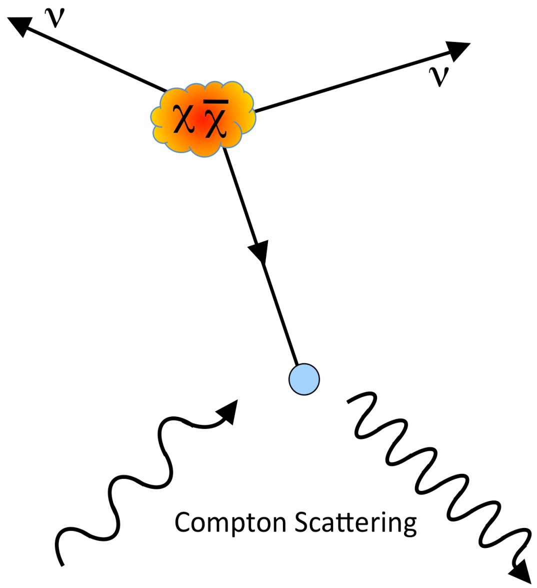
- Scalar index and running
- Non-Gaussian f_{NL}
- Tensor index and running



Complementary to both CMB anisotropy and polarization

Sunyaev & Khatri 2013

Spectral Distortions: Dark Matter Annihilation



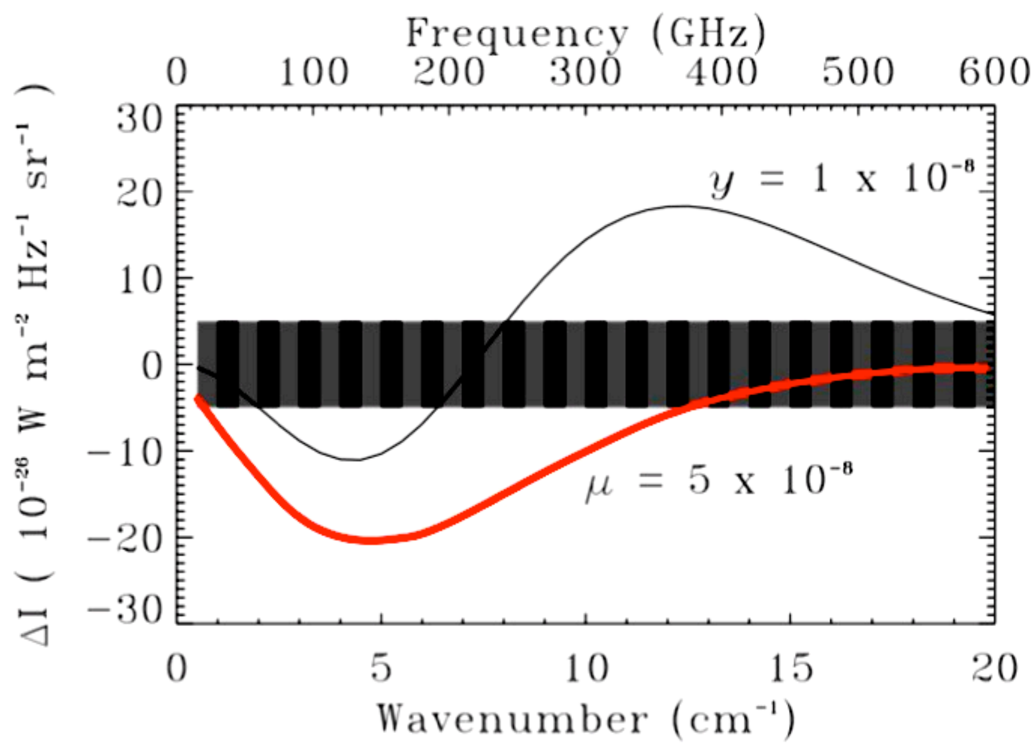
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(\frac{h\nu}{kT}+\mu)-1}$$

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

Annihilation rate ~ n^2 ~ z^6

Number density n ~ m^{-1}

$$m_\chi > 80\ \mathrm{keV}\left[f\left(\frac{\mu}{5\times10^{-8}}\right)\left(\frac{\sigma v}{6\times10^{-27}\ \mathrm{cm^3\ s^{-1}}}\right)\left(\frac{\Omega_\chi}{0.112}\right)^2\right]^{1/2}$$



Dark matter annihilation

PIXIE limit $\mu < 10^{-8}$

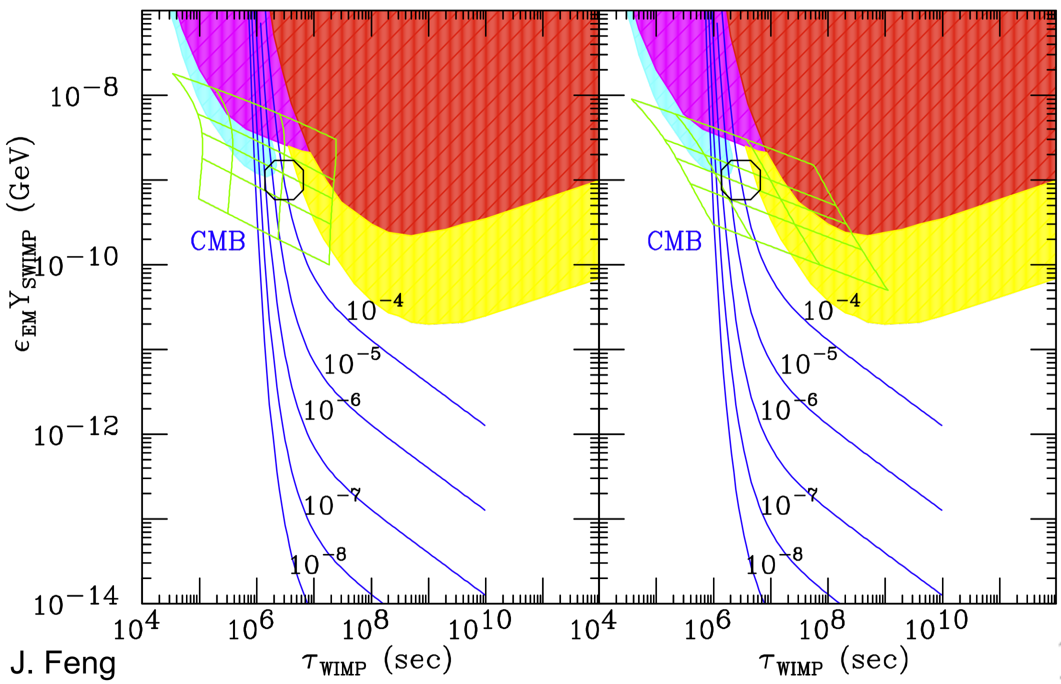
Neutralino mass limit $m_\chi > 80$ keV

Definitive test for warm dark matter

McDonald et al 2001
de Vega & Sanchez 2010

Spectral Distortions: Dark Matter Decay

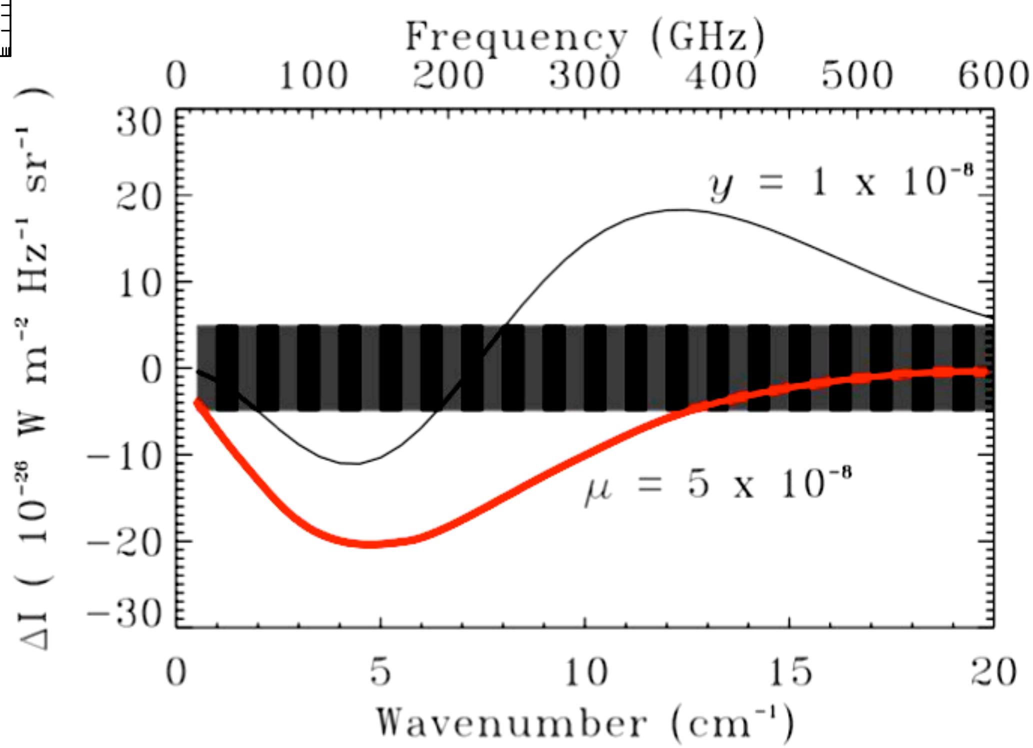
slepton decay



J. Feng

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

Energy release $\Delta E \sim \Omega_{DM}\, \Gamma\, \Delta m$



Dark matter decay

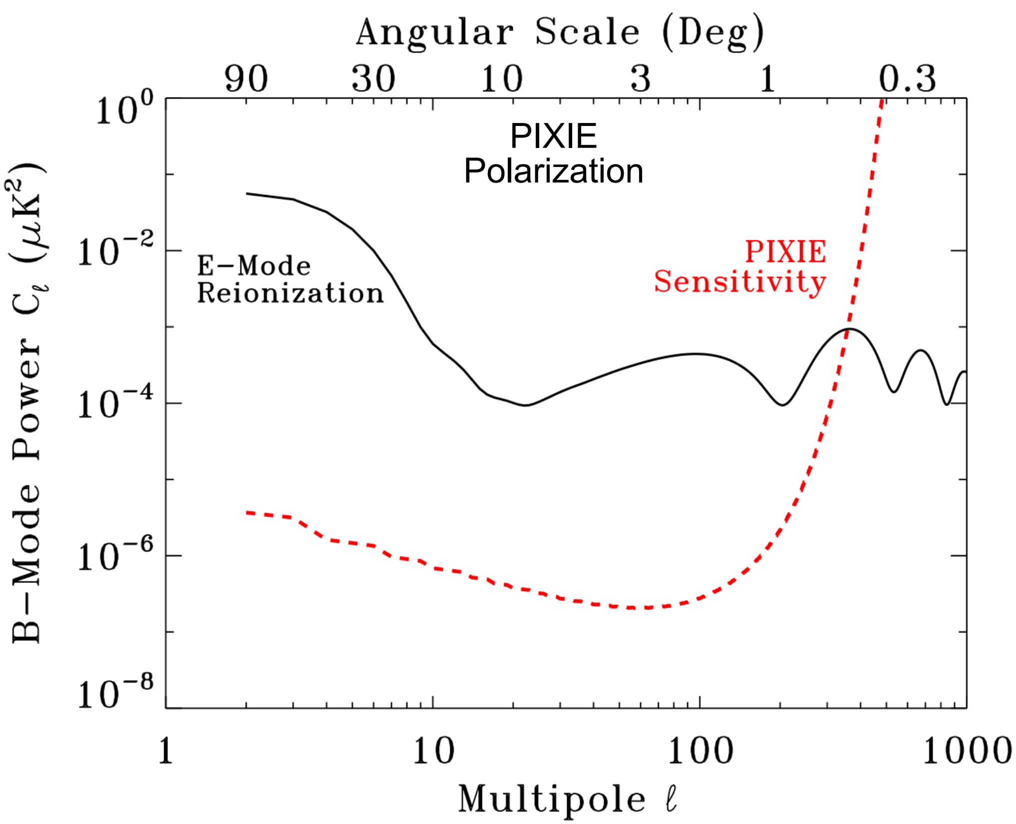
PIXIE limit $\mu < 10^{-8}$

Reach cosmological limit $\tau < 3 \times 10^6$ sec

Test for gravitino dark matter

McDonald et al 2001
de Vega & Sanchez 2010

Spectral Distortions: Reionization

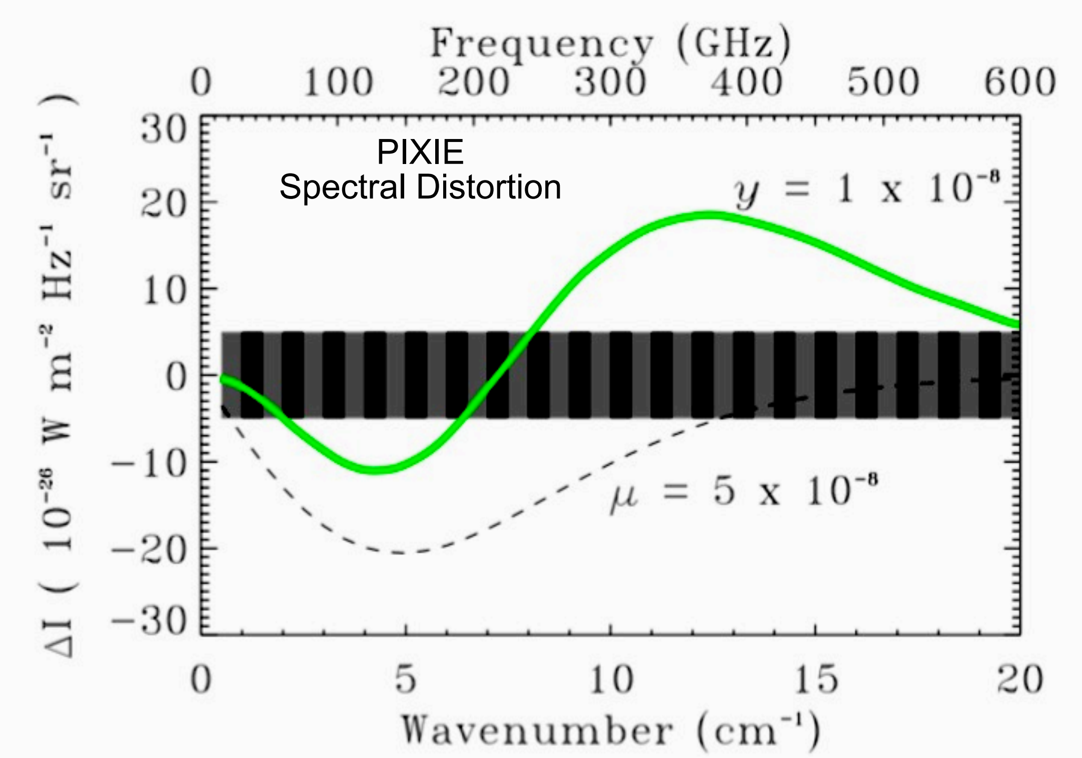


Spectrum: y distortion ~ Electron pressure $\int nkT_e$

- PIXIE limit $y < 5 \times 10^{-9}$
- Distortion must be present at $y \sim 10^{-7}$

Polarization: Optical depth ~ Electron density n

Same scattering for both signals

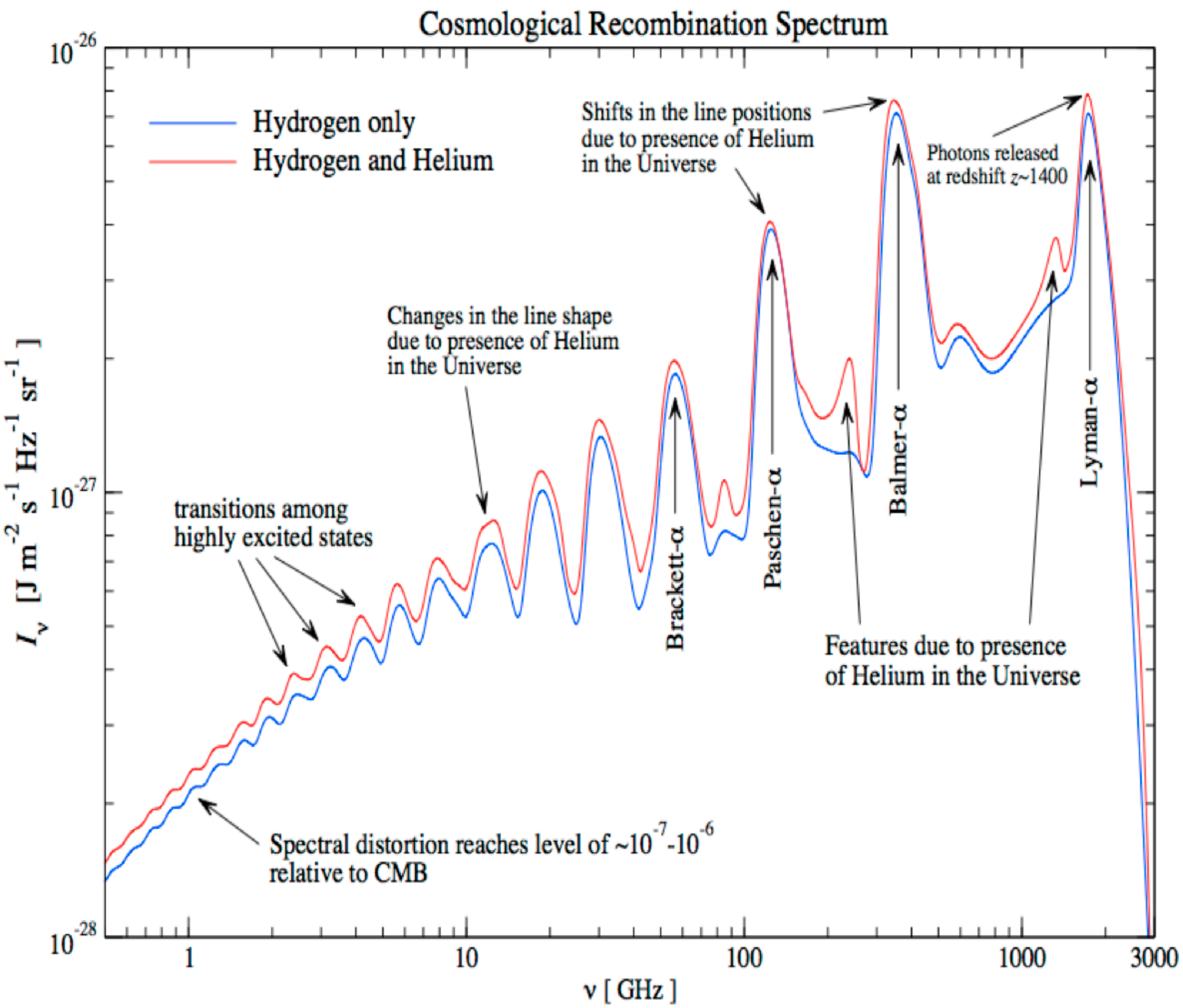


Combine to get n and T_e

- T_e probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects

Spectral Distortions: Recombination



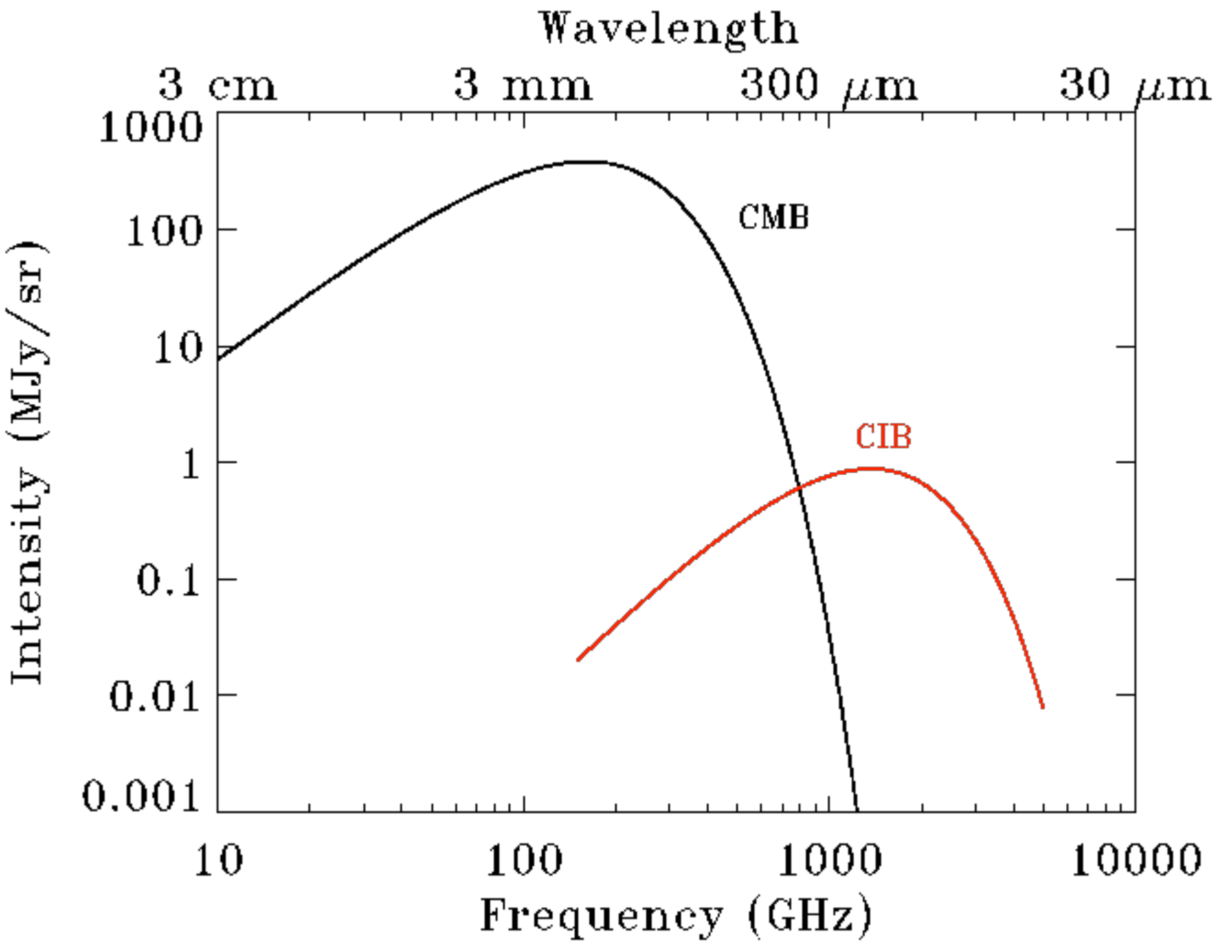
Line emission at recombination yields complex spectral features

- Physics at recombination
- Primordial He abundance

Baseline PIXIE mission: 2σ detection of modified spectrum

Sunyaev & Khatri 2013

Cosmic Infrared Background



Thermal Dust Emission from z ~ 1--3

- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

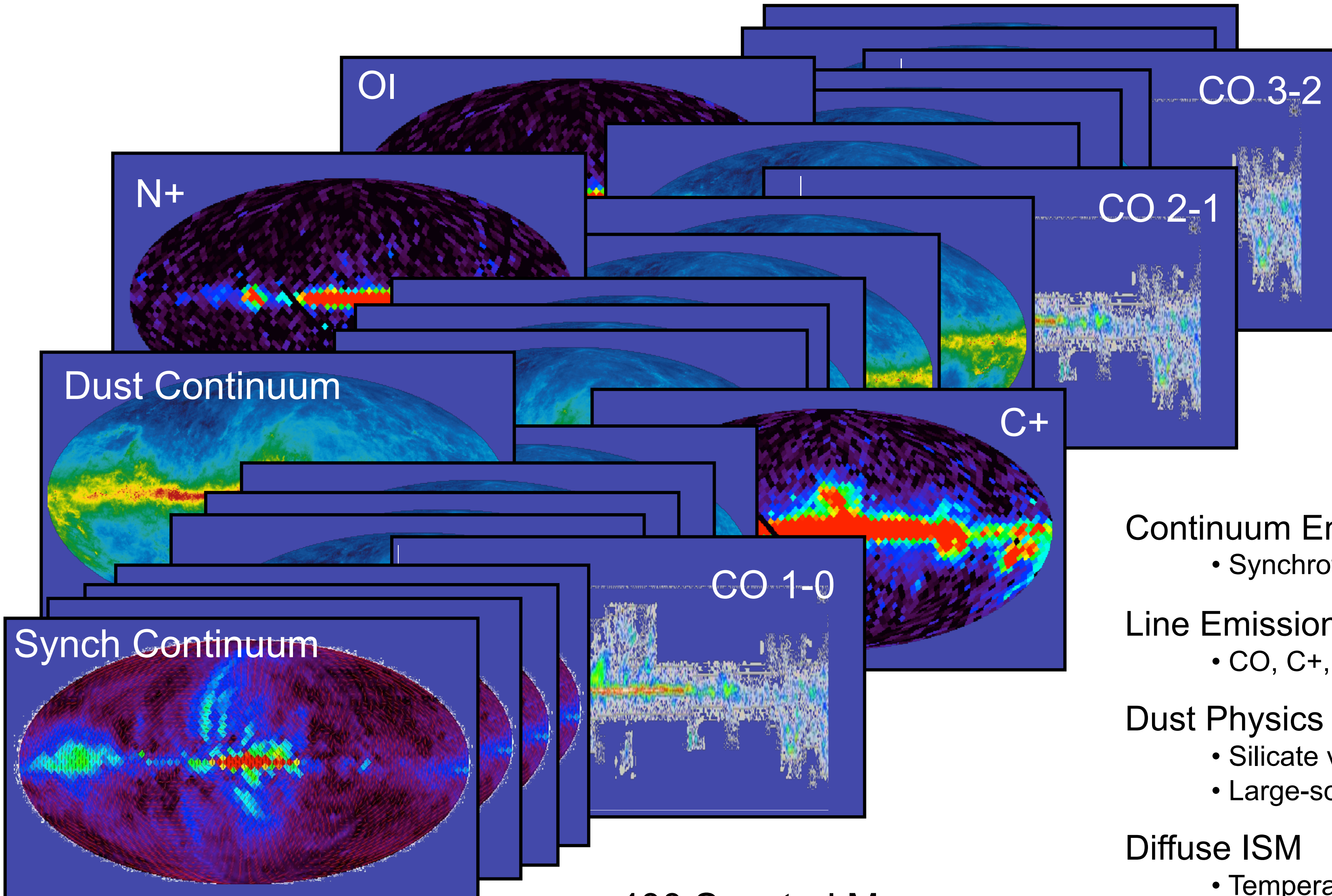
Frequency coverage over CIB peak

- Complement Herschel, Planck

PIXIE noise is down here!

Knox et al. 2001
Fixsen & Kashlinsky 2011

Spectral Line Emission



Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

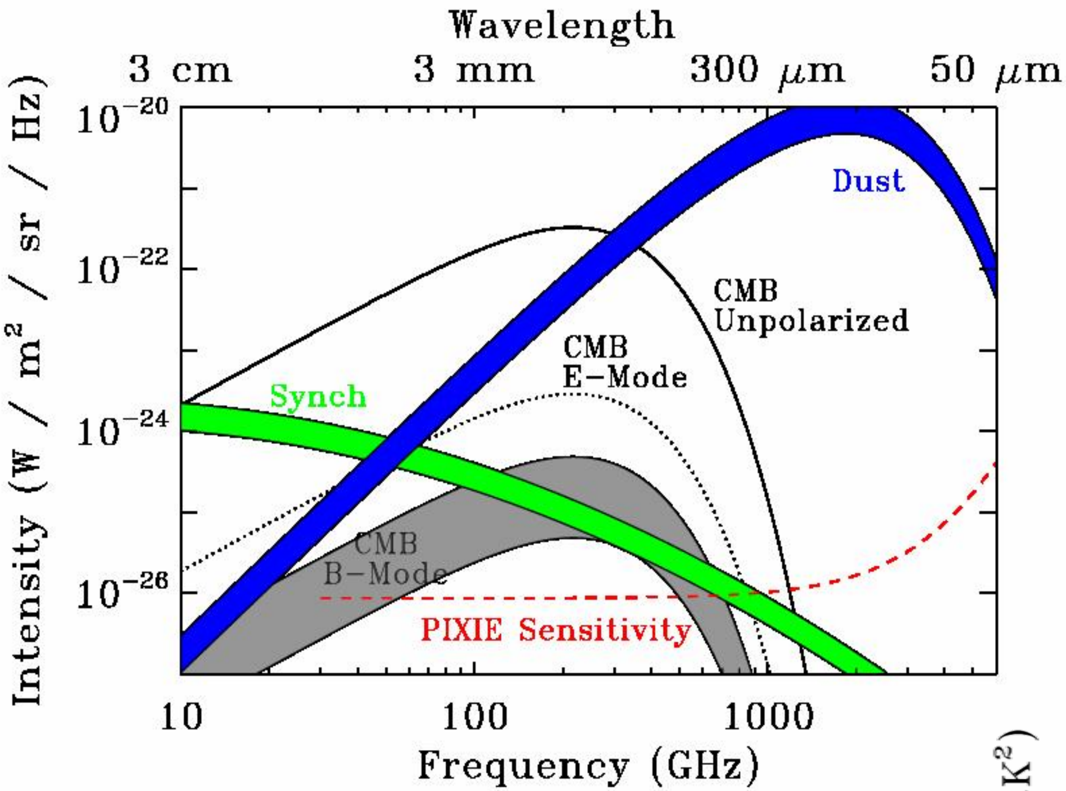
Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metalicity

400 Spectral Maps
Stokes I, Q, U
$\Delta\nu$ = 15 GHz

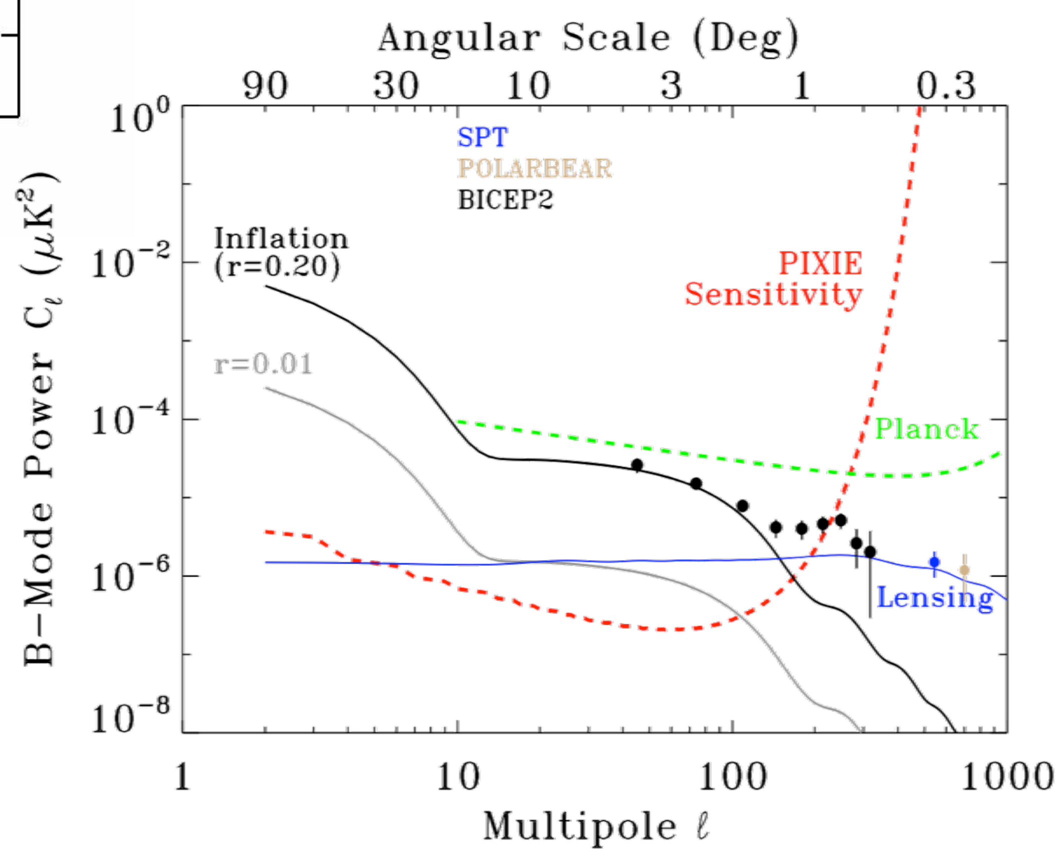
Extremely Rich Data Set!

Unique Science Capability



Full-Sky Spectro-Polarimetric Survey

- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6×10^{-26} W m^{-2} sr^{-1} Hz^{-1}
- CMB sensitivity 70 nk RMS per pixel



Multiple Science Goals

- Inflation/GUT Physics
- Dark Matter
- Reionization/First Stars
- ISM and Dust Cirrus

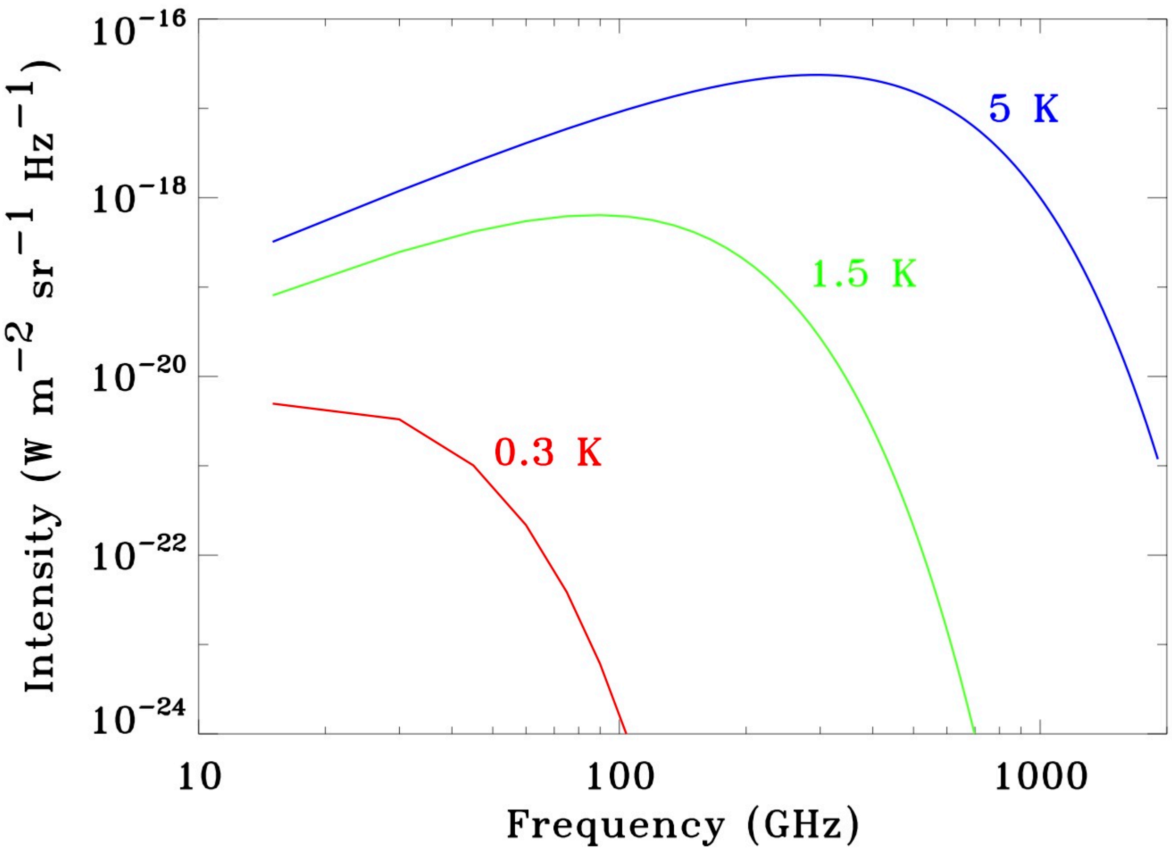
B-mode: $r < 2 \times 10^{-4}$ (2σ)

Distortion $|\mu| < 10^{-8}$, $|y| < 5 \times 10^{-9}$


BUT WAIT,
there's more!

Planck Radiation Law

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

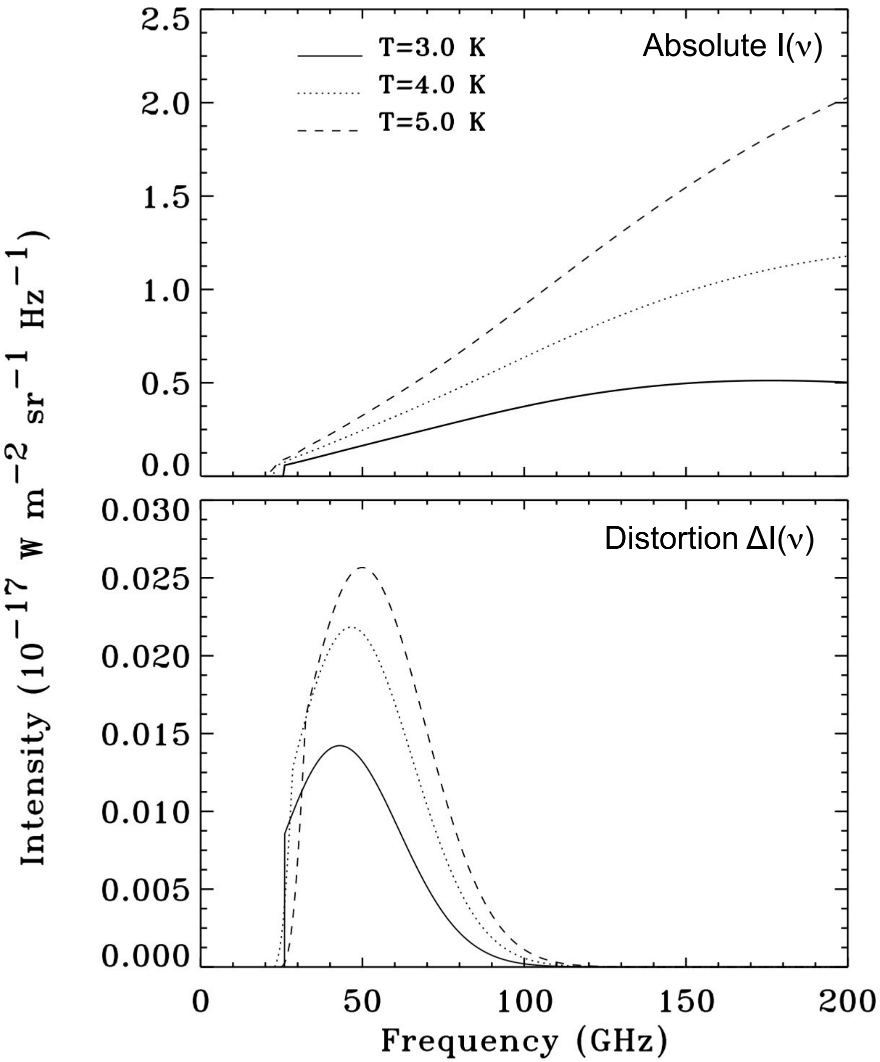


- Foundation of quantum physics
- Derived from few simple assumptions
  - Quantization of energy
  - No barrier to photon creation

Finest 1928 technology

Direct measurements limited to few percent precision
Last serious efforts date to late 1920's

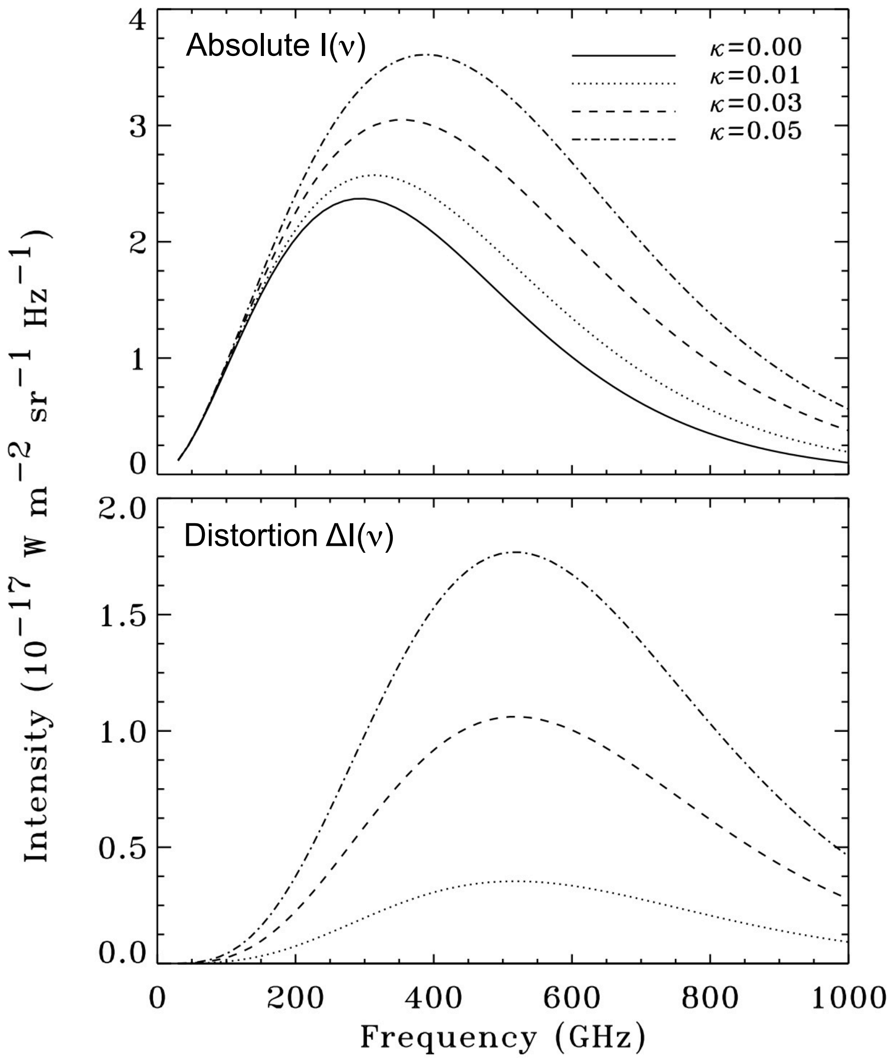
Sample Distortions from Planck Law



U(1) Spontaneous symmetry breaking

$$I(\nu, T) = B(\nu, T)\,(1 - G(T, \nu))$$

Limit G < 9 x 10^{-6}



Single-loop quantum gravity

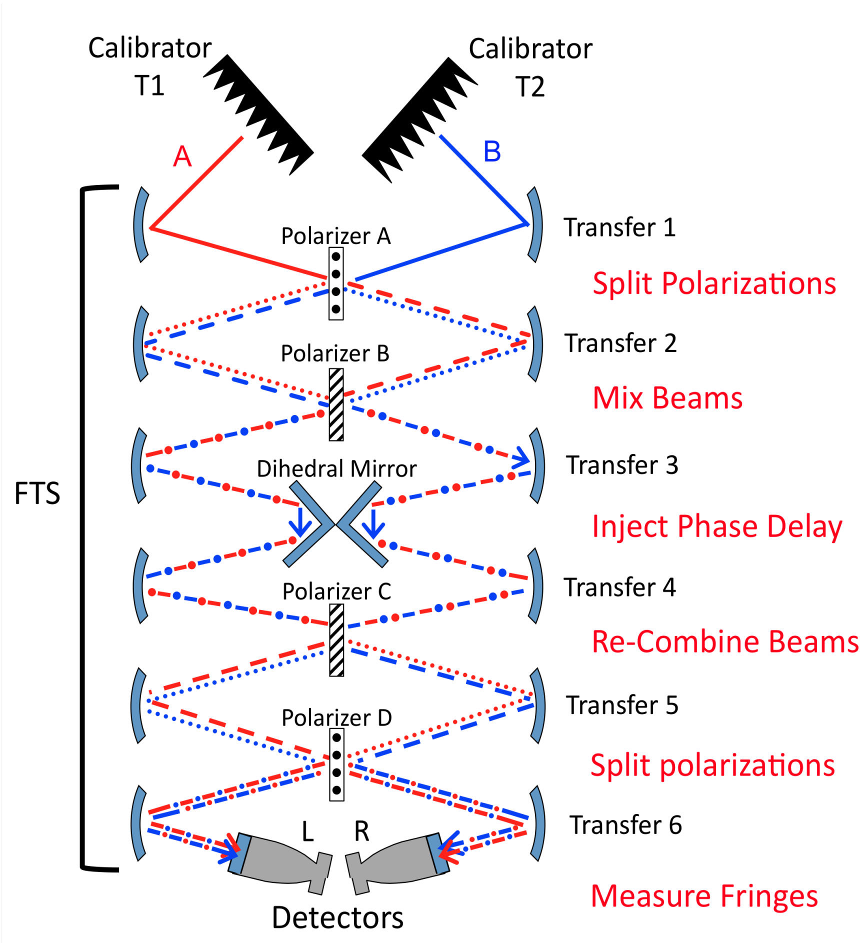
$$I(\nu, T) = B(\nu, T)\left(1 + \kappa(T)x^2\right)$$

Limit κ < 6 x 10^{-9}

Primack & Sher 1980; Ludescher & Hofmann 2009

Yepez, Romero, & Zapora 2004

Precision Test of Planck Law



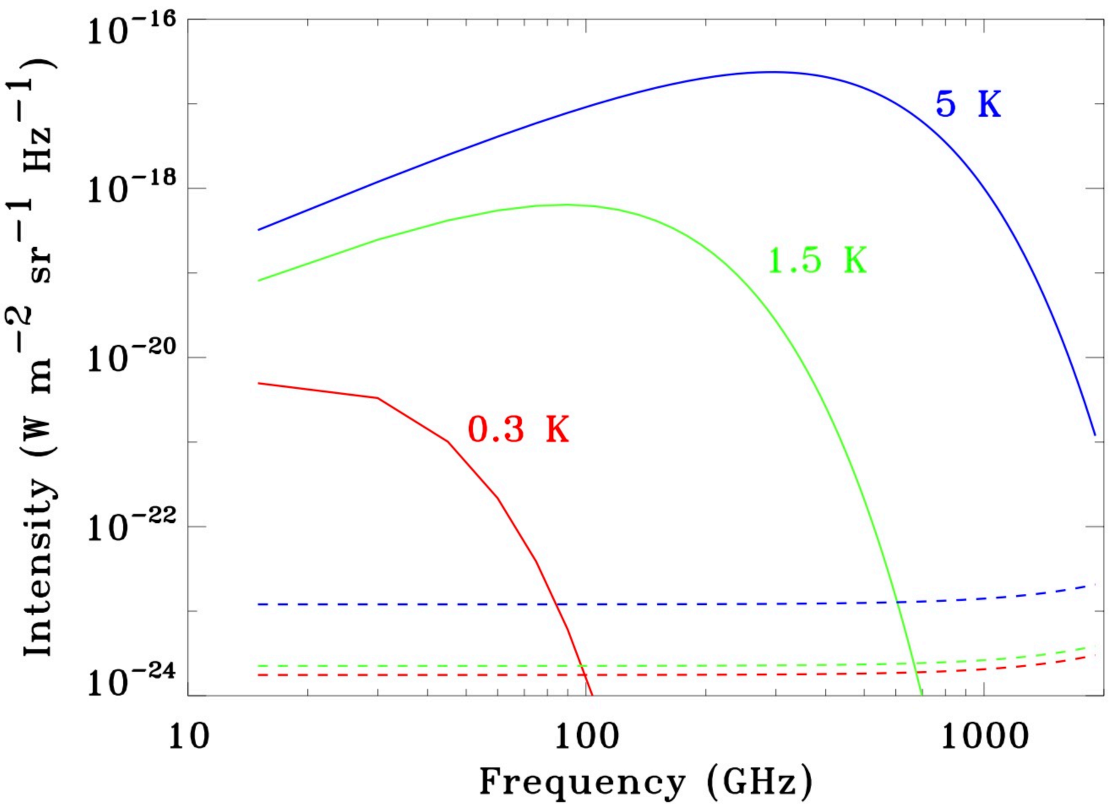
PIXIE FTS with two blackbody calibrators

S/N ratio > 10^6 per bin in 1 hour

Limiting factor is systematics

10^{-5} precision from lab measurement

10^{-7} precision with Galactic CO calibration



Interesting science at 10^{-6} level

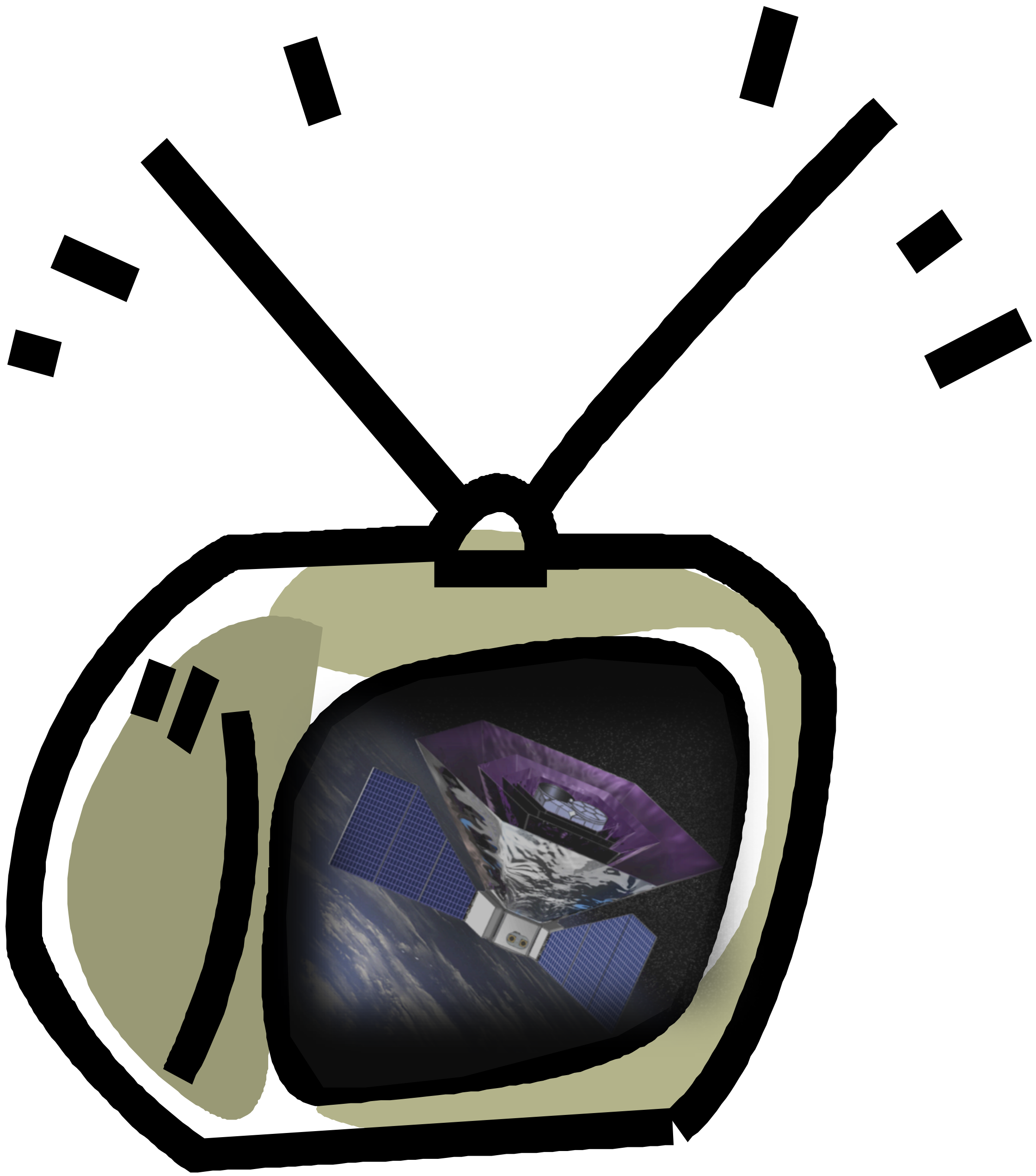
U(1) spontaneous symmetry breaking

CPT violation, quantum gravity

Photon mass / chemical potential

New measurement of Boltzmann constant

Now how much would you pay?



A Non-Cosmological Problem

Will a future Congress fund a $1B Inflation Probe?

Low-cost alternative within existing NASA budget line

NASA Explorer Program

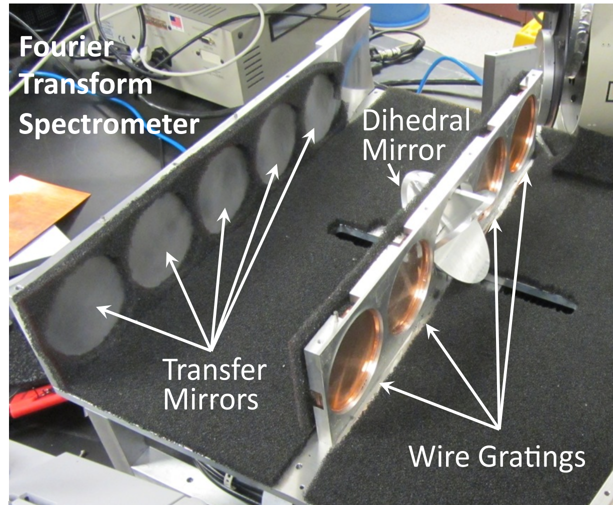
Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

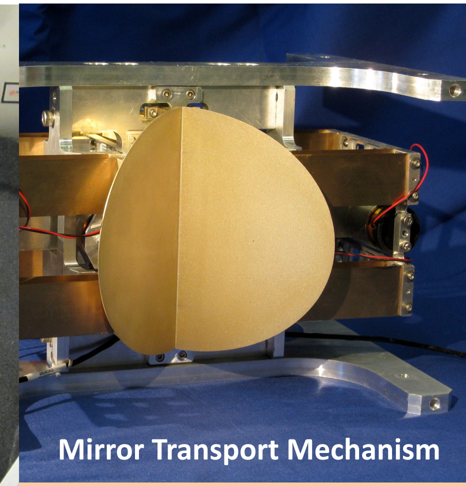
PIXIE not selected; urged to re-propose
- Category I Science rating
- Broad recognition of science appeal

Re-propose to next MIDEX AO (2017)
- Technology is mature
- Launch early next decade

"PIXIE's spectral measurements alone justify the program"

-- NASA review panel





Mature technology