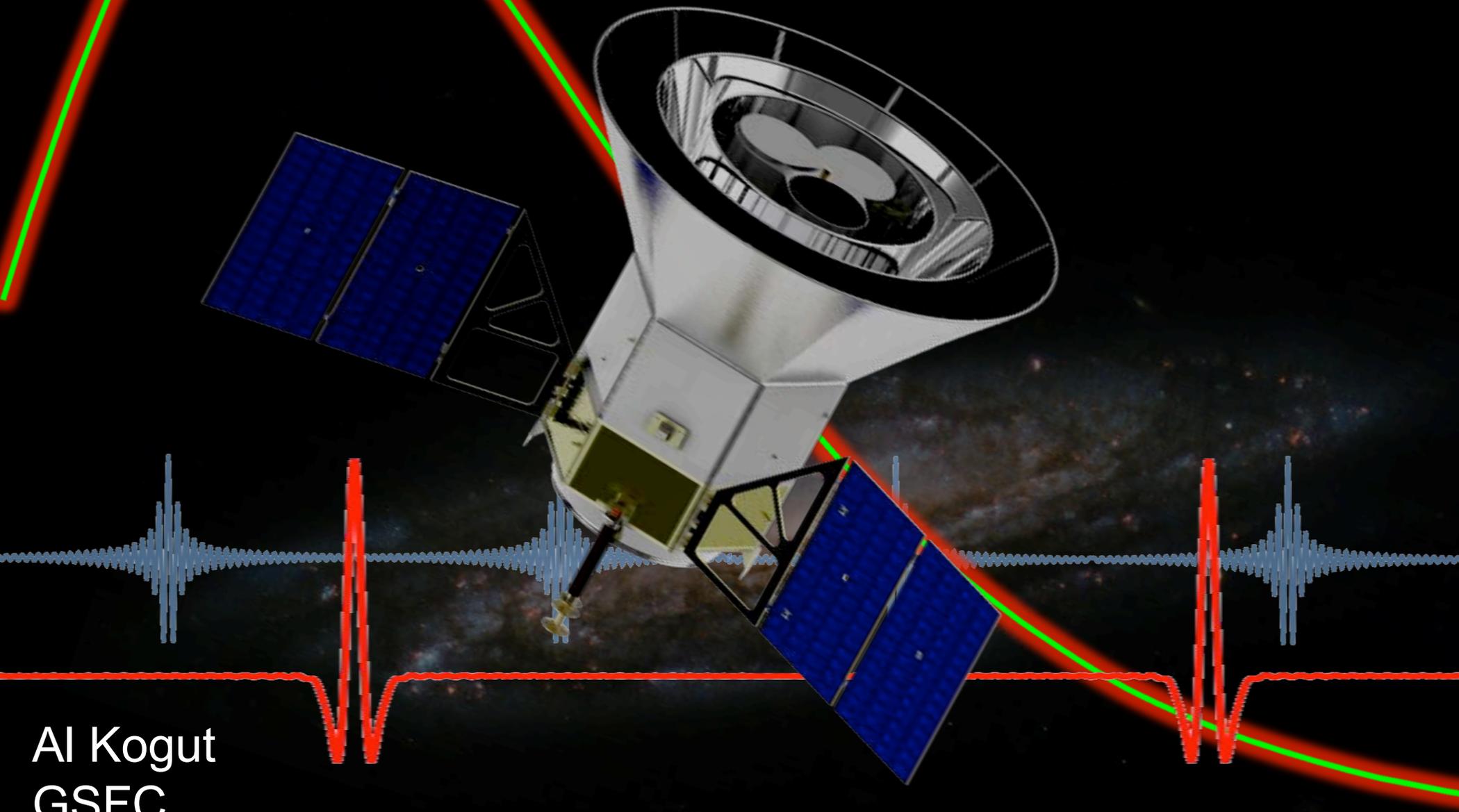


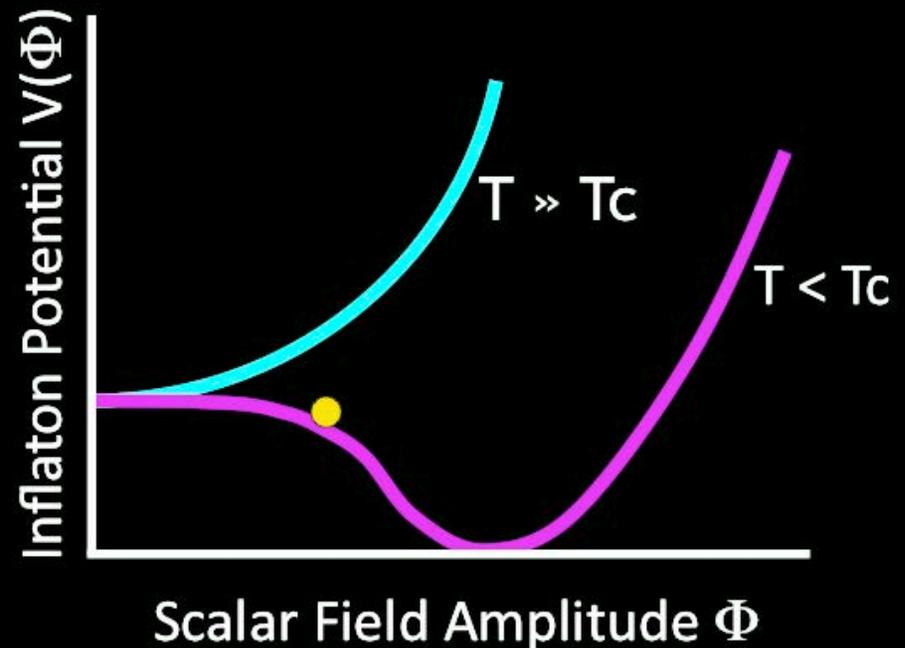
The Primordial Polarization Explorer



AI Kogut
GSFC

Science from CMB Polarization

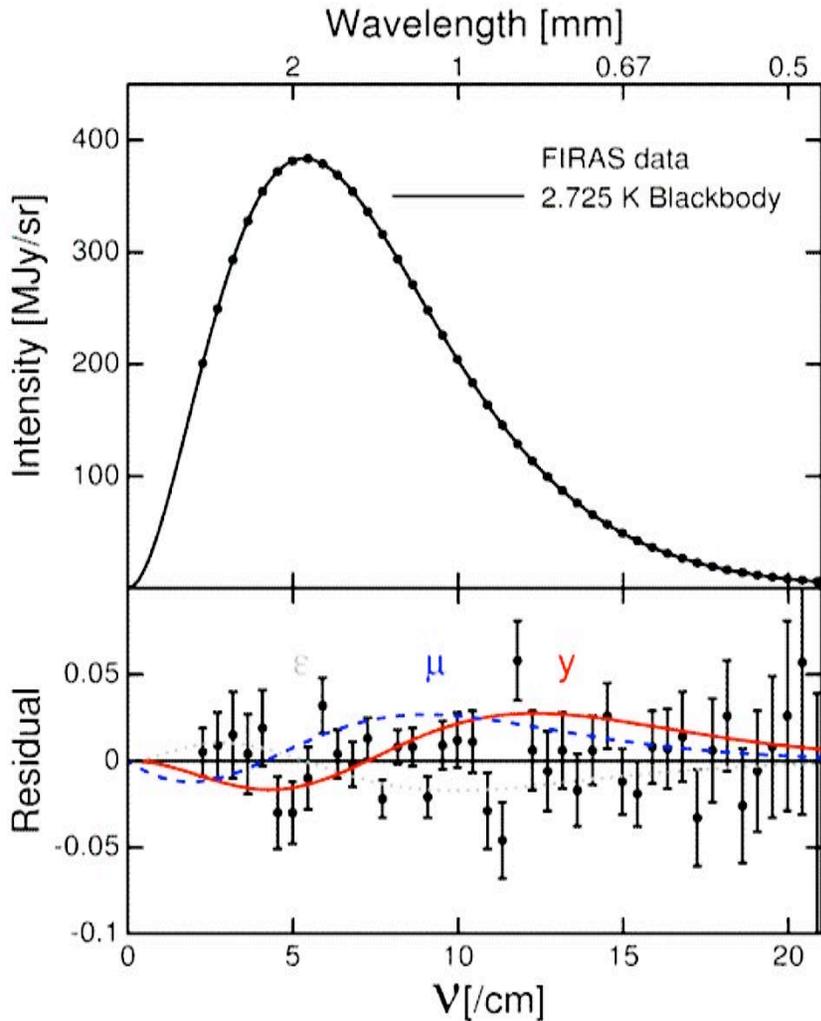
- **Search for primordial inflation**
Trace evolution back to single quantum system
Oldest information in the universe
- **Test physics at Grand Unification energies**
 10^{16} GeV : Grand Unification theory
Trillion (!) times higher energy than Higgs boson
- **Observational evidence of quantum gravity**
LIGO: Classical gravitational radiation
CMB: Gravity obeys quantum mechanics



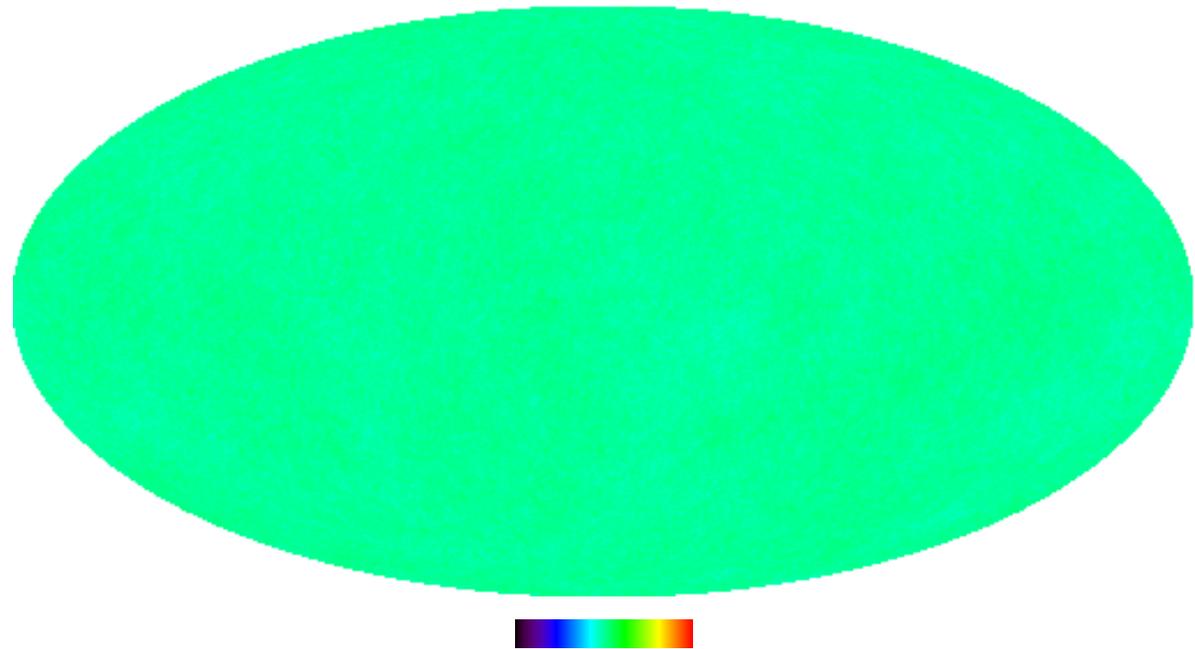


Blackbody Spectrum

COBE limits distortions to 50 ppm – Is that enough?



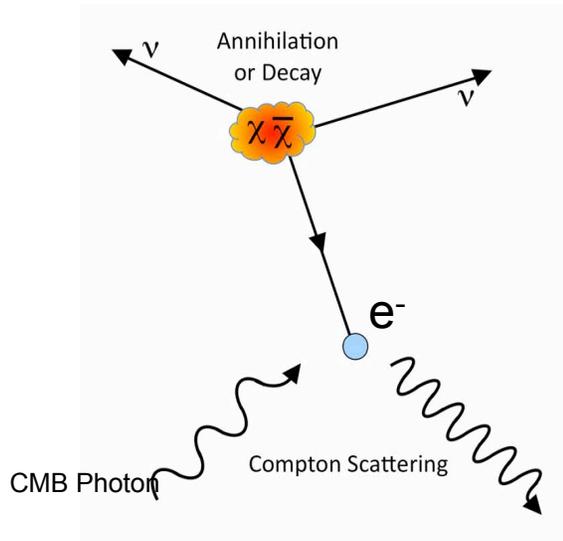
FIRAS spectrum: Blackbody at 50 ppm



Planck sky map: Isotropic at 50 ppm

PIXIE 1000x deeper than COBE – Sky cannot be black at this level

CMB Spectral Distortions



Optically thin case: Compton y distortion

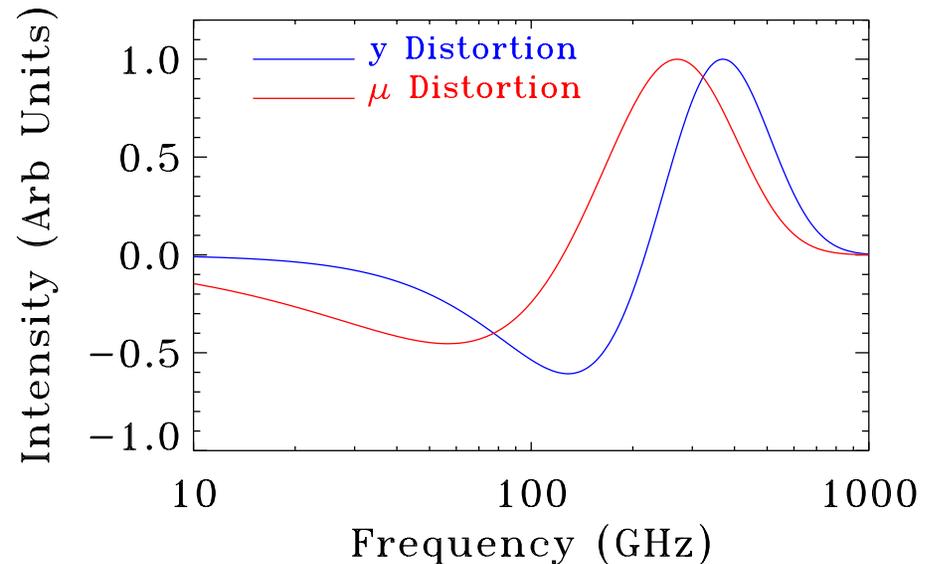
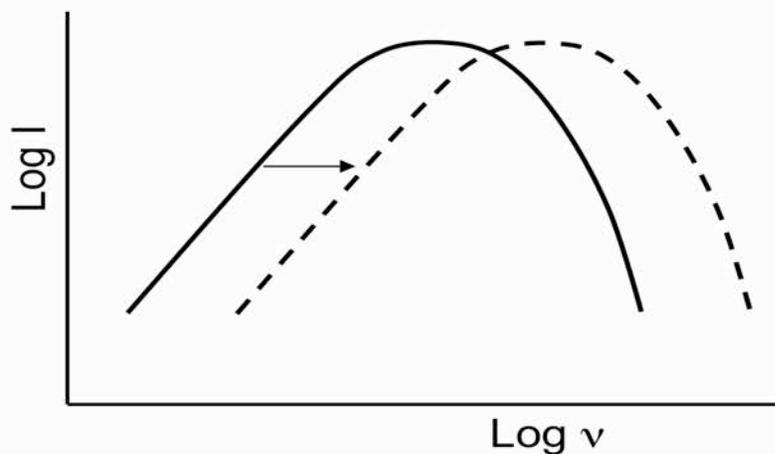
$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(x) - 1} \left[1 + \frac{y x \exp(x)}{\exp(x) - 1} \left(\frac{x}{\tanh(x/2)} - 4 \right) \right]$$

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

Optically thick case: Chemical potential distortion

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

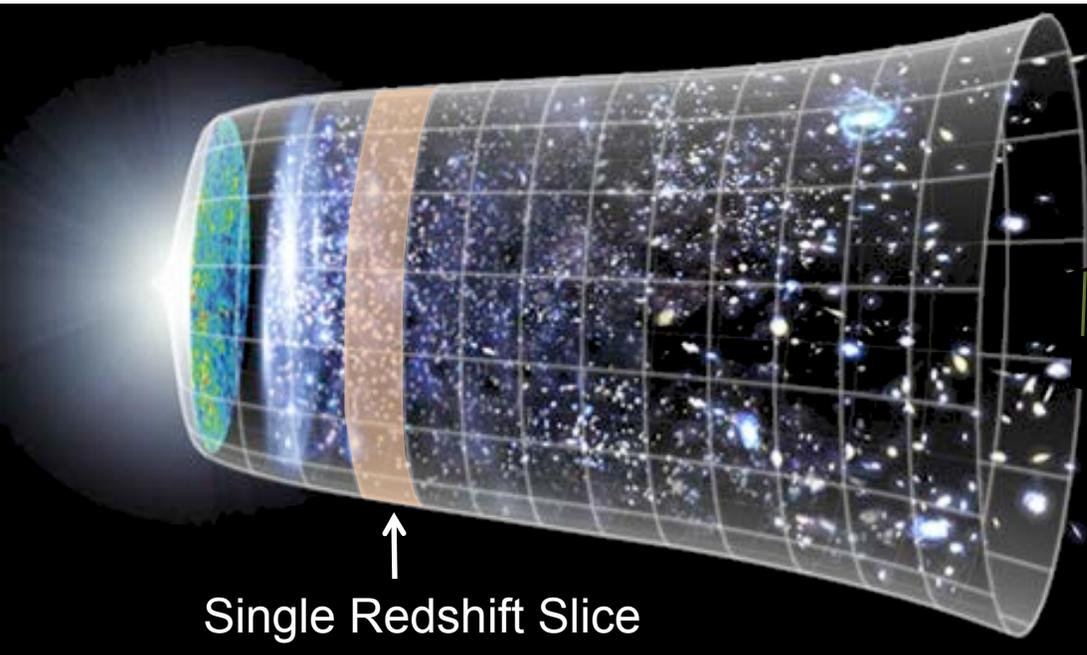
$$\mu = 1.4 \frac{\Delta E}{E}$$



Distortion to blackbody spectrum proportional to integrated energy release

Far-IR Tomography

Intensity Mapping with C+, N+, CO lines



Low spatial resolution

Integrated emission from many sources

Multiple frequency bins

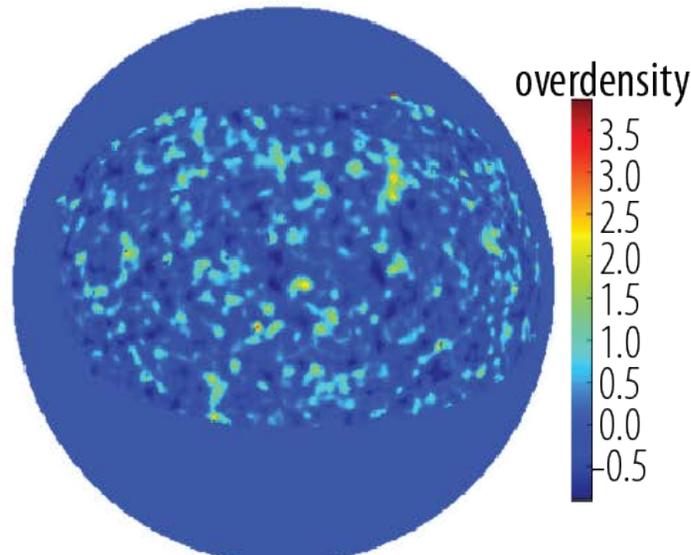
Multiple redshift slices

Red-shifted far-IR lines

C+ 158 μm \rightarrow Star formation rate

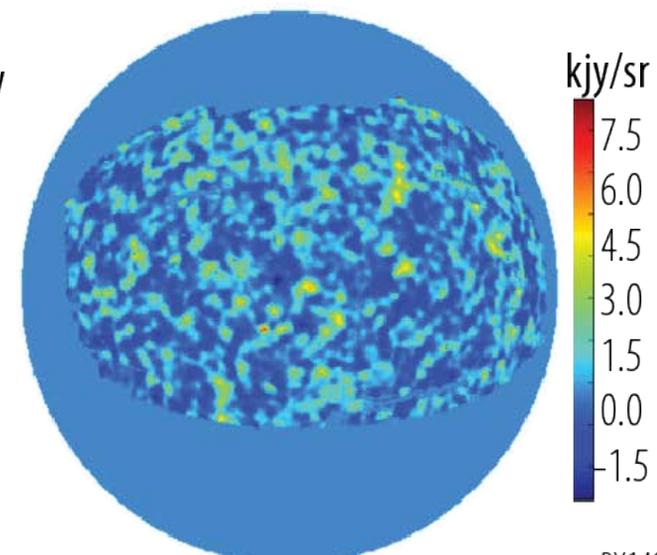
CO ladder \rightarrow Cold gas reservoir

BOSS



$0.51 < z < 0.53$

PIXIE



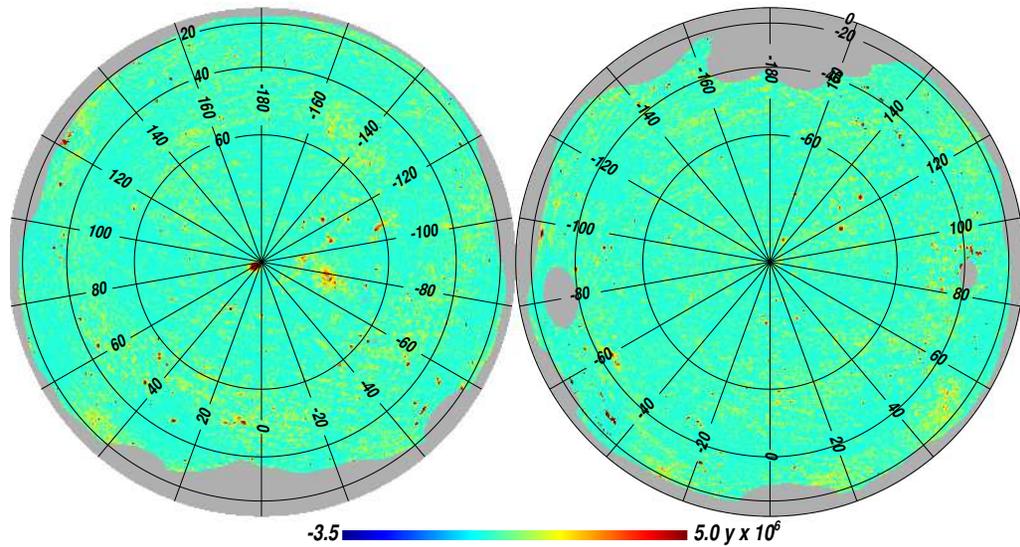
Single Channel 1245 GHz

PX140

Cross-correlate PIXIE with redshift-tagged galaxy surveys

- Track star formation vs redshift
- 5—10% redshift bins at $z=2-3$
- Compare to continuum CIB

y Distortion: Structure Formation



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

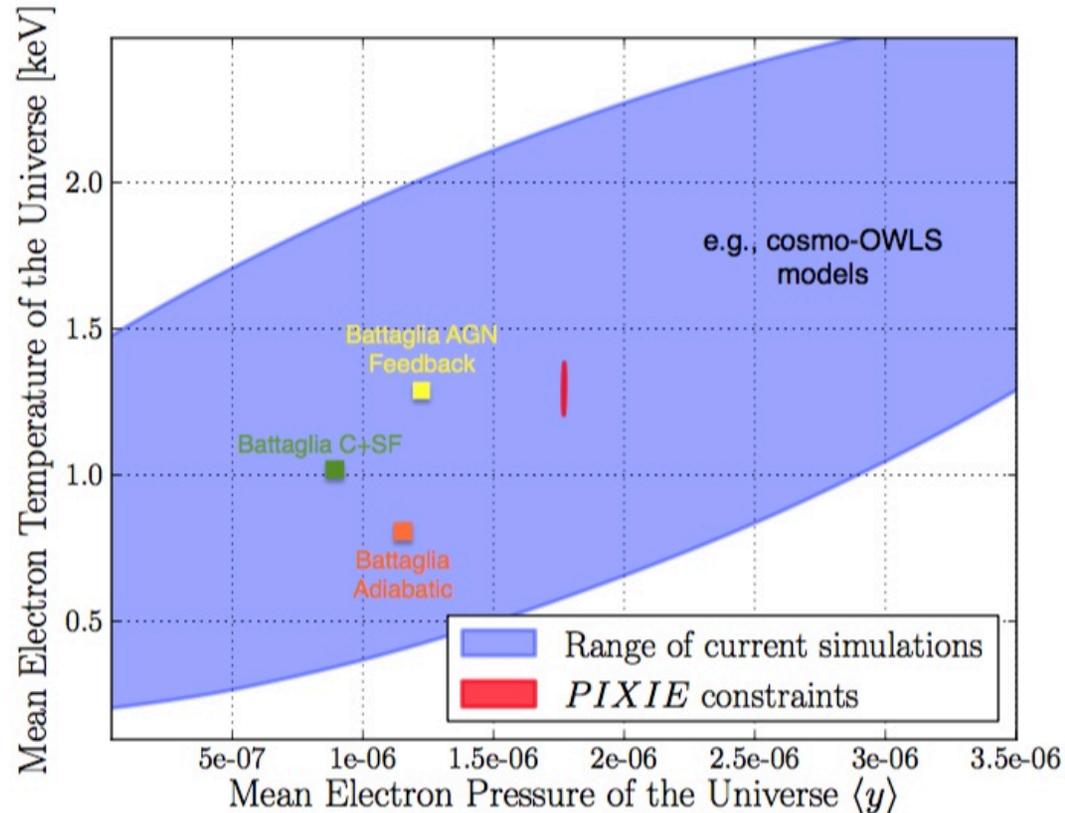
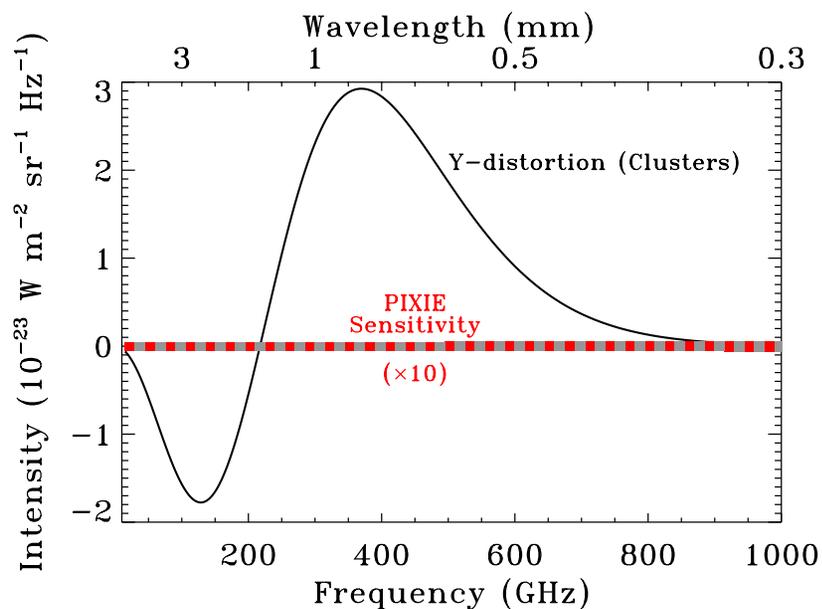
PIXIE 15-sigma detection

Total monopole: $y = 1.6 \times 10^{-6}$

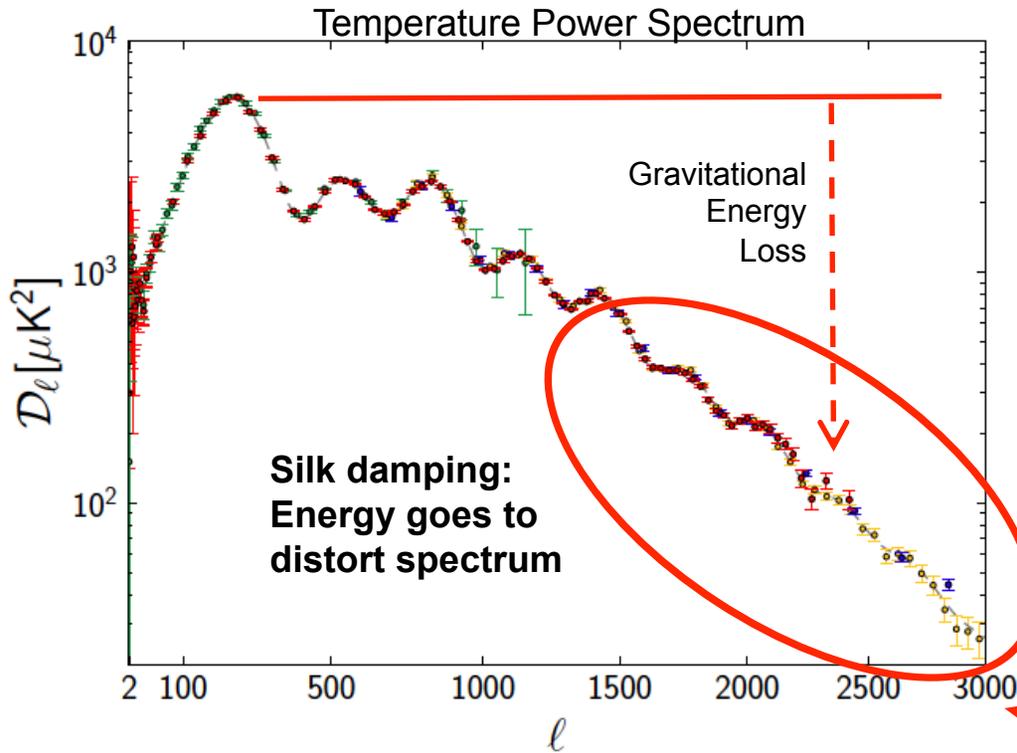
PIXIE 450-sigma detection

Relativistic correction (feedback)

PIXIE 15-sigma detection



Mu Distortions: Inflation



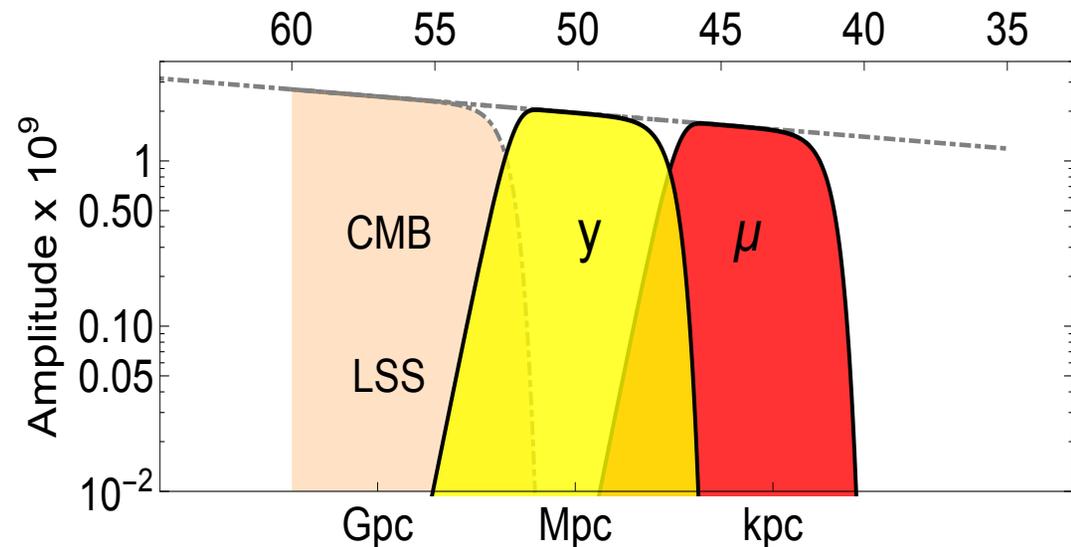
Energy release at $10^4 < z < 10^6$

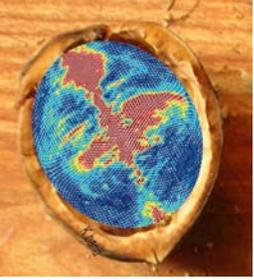
$$\text{Chemical potential } \mu = 1.4 \frac{\Delta E}{E}$$

Trace primordial power spectrum
to 5 decades smaller scales
regardless of what created it!

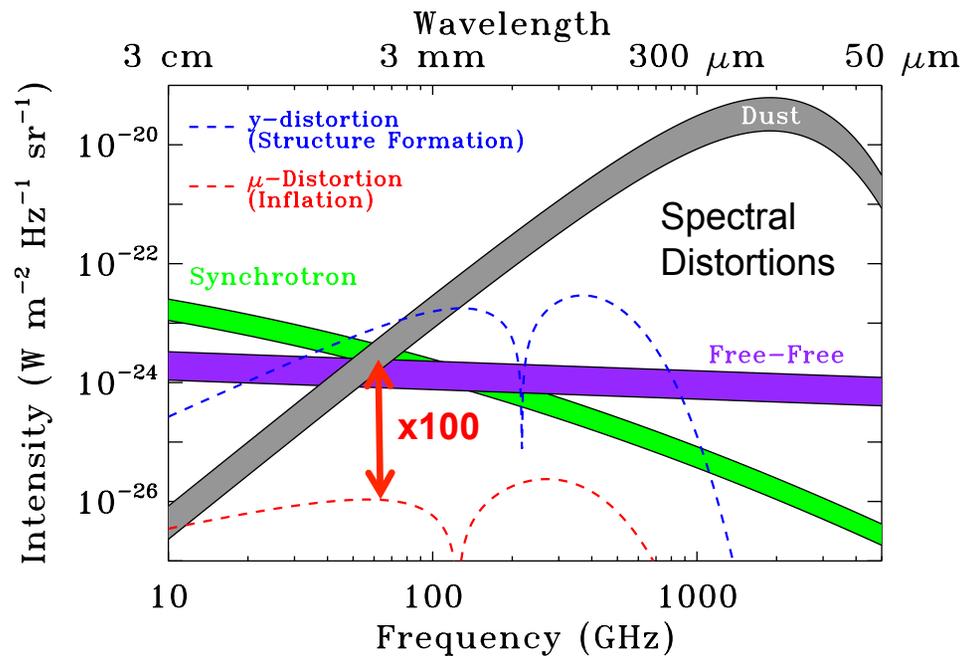
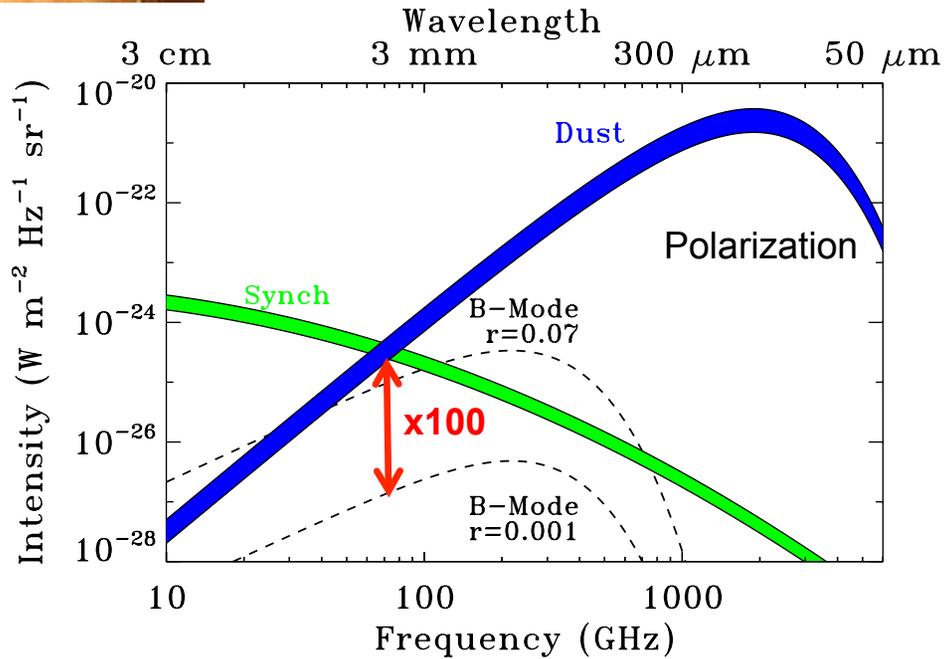
Spectral distortions extend tests of inflation
by 5 orders of magnitude in physical scale

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



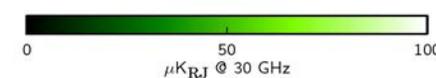
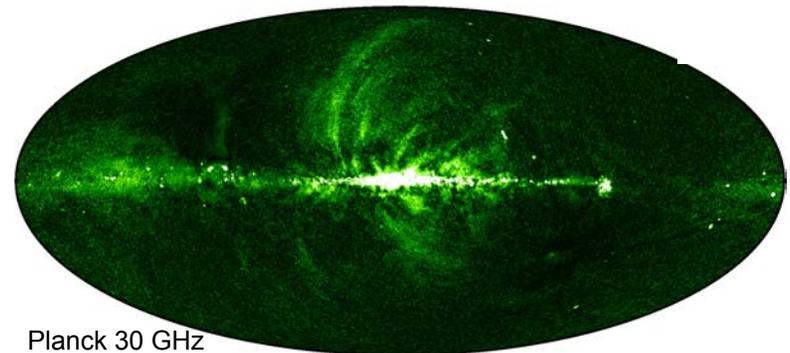
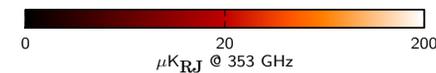
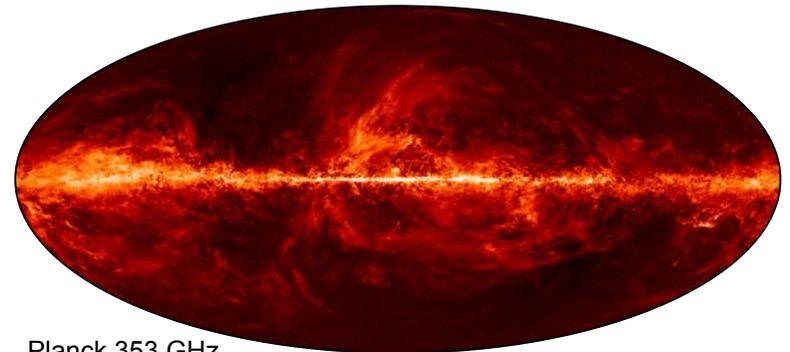


CMB in a Nutshell

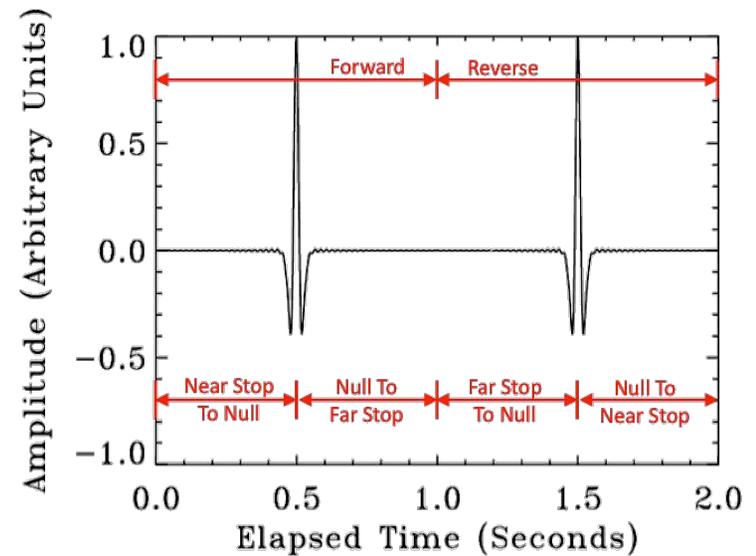
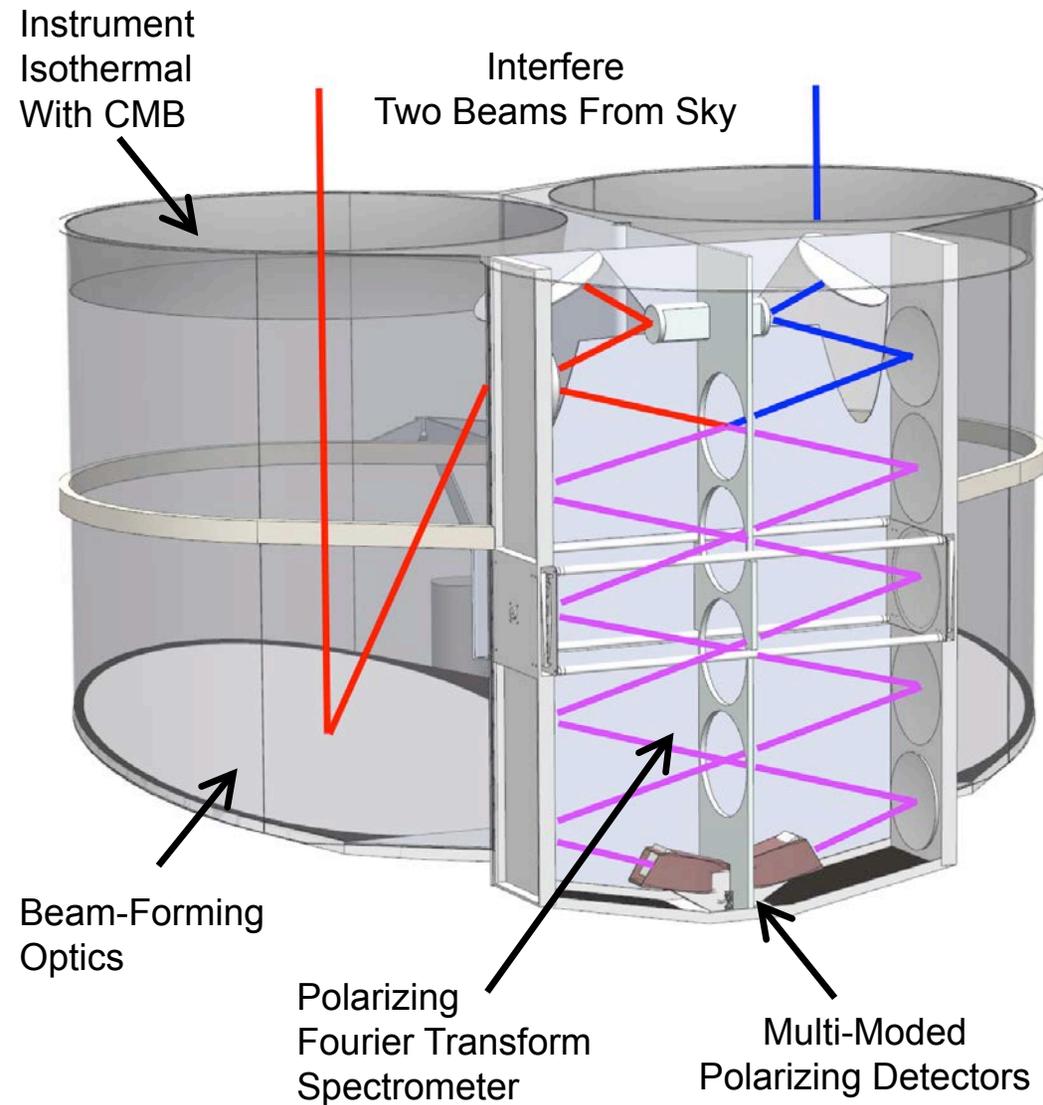


Cosmic Coincidence: Similar Requirements for B-modes and Distortions

- Sensitivity
- Foreground Discrimination
- Systematic Error Rejection



PIXIE Nulling Polarimeter



**Measured Fringe Pattern
Samples Frequency Spectrum
of Polarized Sky Emission**

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

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

Stokes Q

Zero means zero: No fringes if sky is not polarized

Blackbody Calibrator Tests Blackbody Distortions

**Calibrator stowed:
Polarization only**

$$P_{Lx} = \frac{1}{2} \int (E_{Ay}^2 + E_{Bx}^2) + \underbrace{(E_{Bx}^2 - E_{Ay}^2)}_{\text{Sky Stokes Q}} \cos(\omega/c) d\omega$$

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

Sky Stokes Q



Partially-assembled
blackbody calibrator

**Calibrator deployed:
Spectral distortions!**

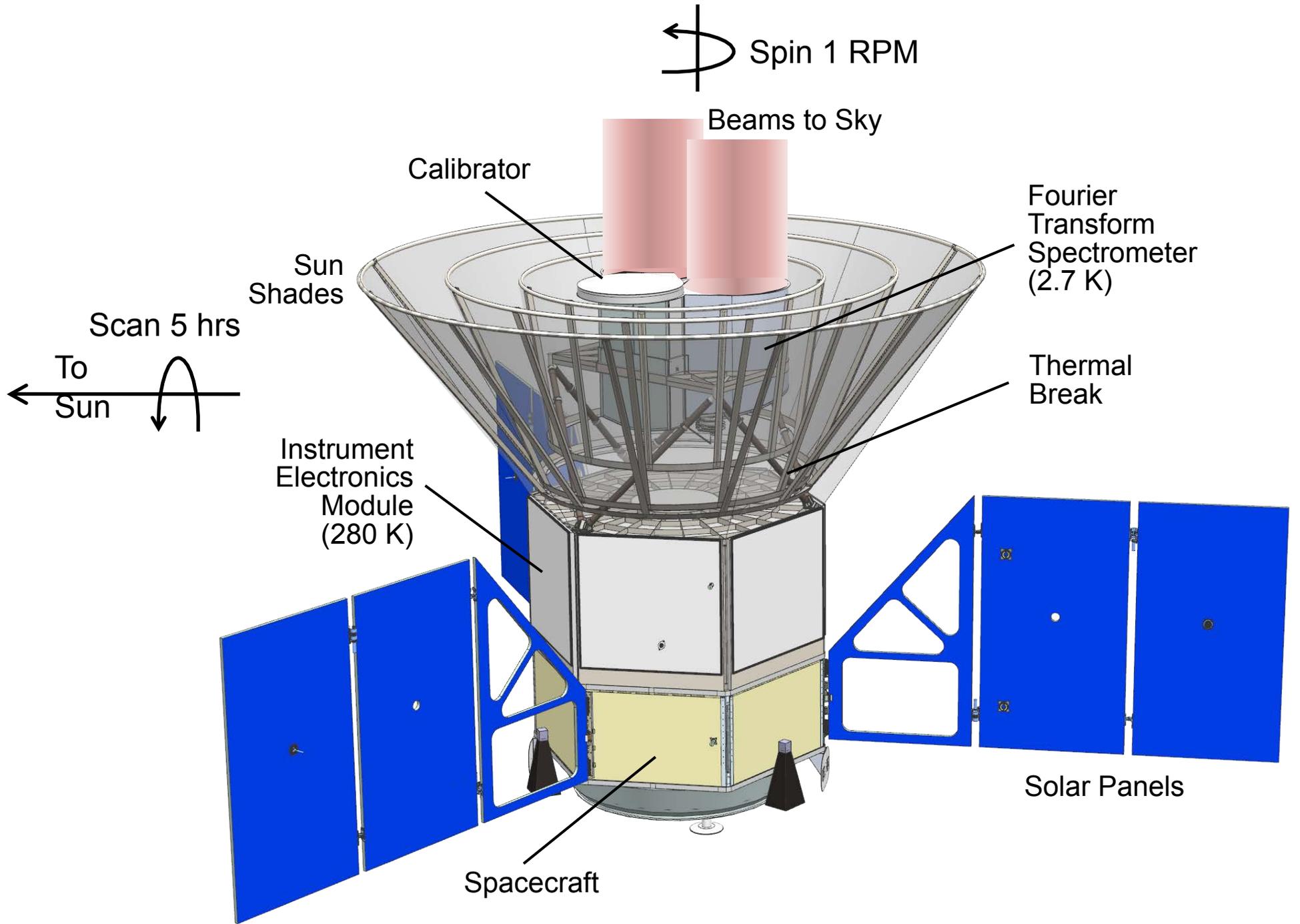
$$P_{Lx} = \frac{1}{2} \int (E_{Cal,y}^2 + E_{Sky,x}^2) + \underbrace{(E_{Sky,x}^2 - E_{Cal,y}^2)}_{\text{[Calibrator-Sky]}} \cos(\omega/c) d\omega$$

$$P_{Ly} = \frac{1}{2} \int (E_{Cal,x}^2 + E_{Sky,y}^2) + \underbrace{(E_{Sky,y}^2 - E_{Cal,x}^2)}_{\text{[Calibrator-Sky]}} \cos(\omega/c) d\omega$$

[Calibrator-Sky]
Spectral Difference

Like FIRAS,
But 1000x
More Sensitive!

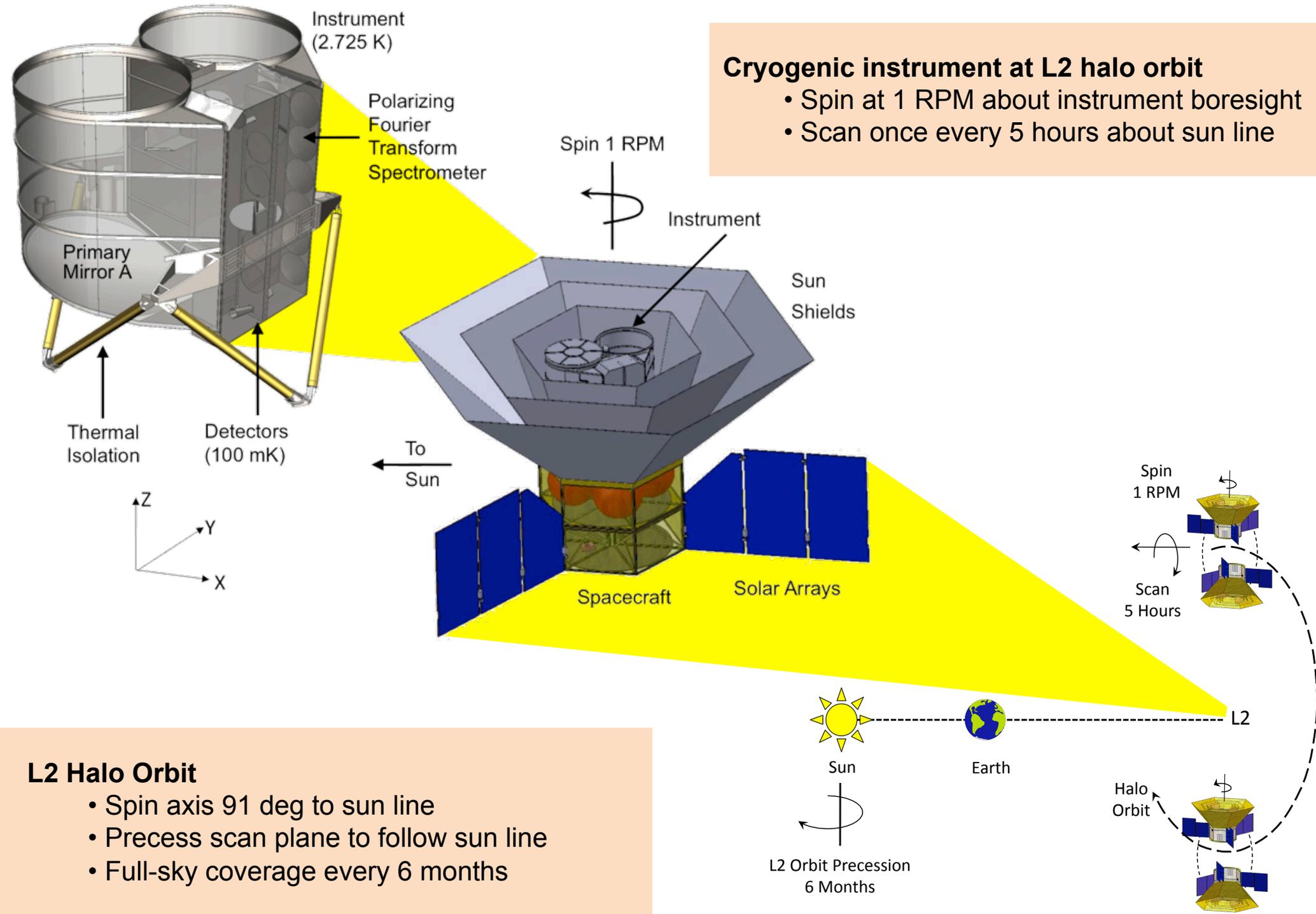
PIXIE Observatory



Instrument and Observatory

Cryogenic instrument at L2 halo orbit

- Spin at 1 RPM about instrument boresight
- Scan once every 5 hours about sun line

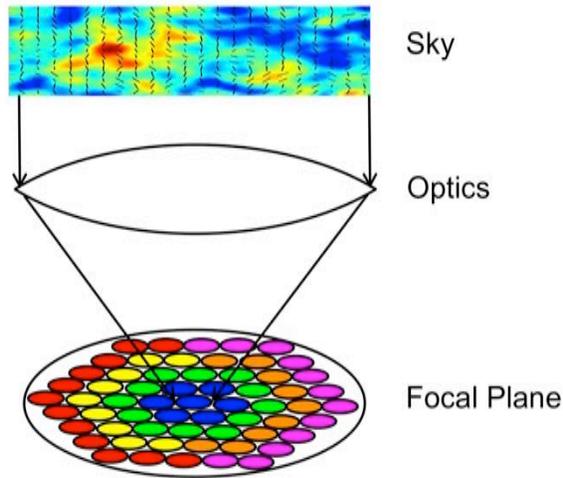


L2 Halo Orbit

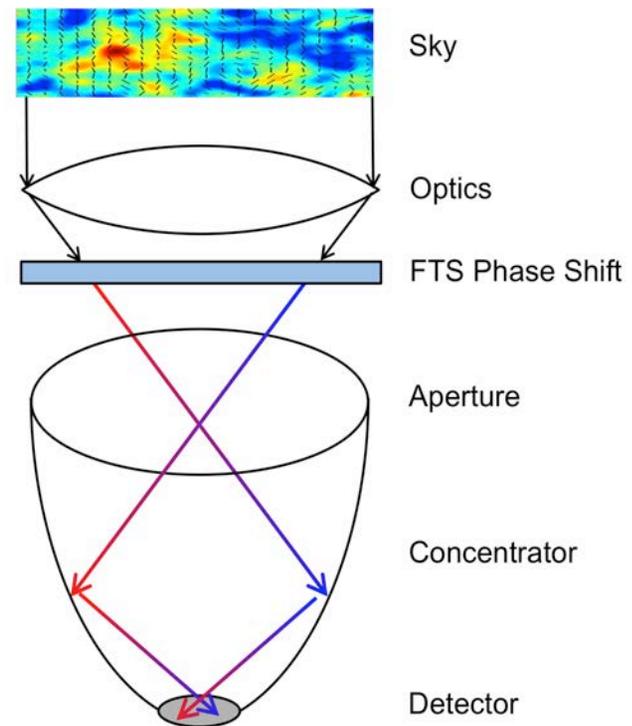
- Spin axis 91 deg to sun line
- Precess scan plane to follow sun line
- Full-sky coverage every 6 months

Sensitivity the Easy Way

Single-Moded Optics



Multi-Moded Optics

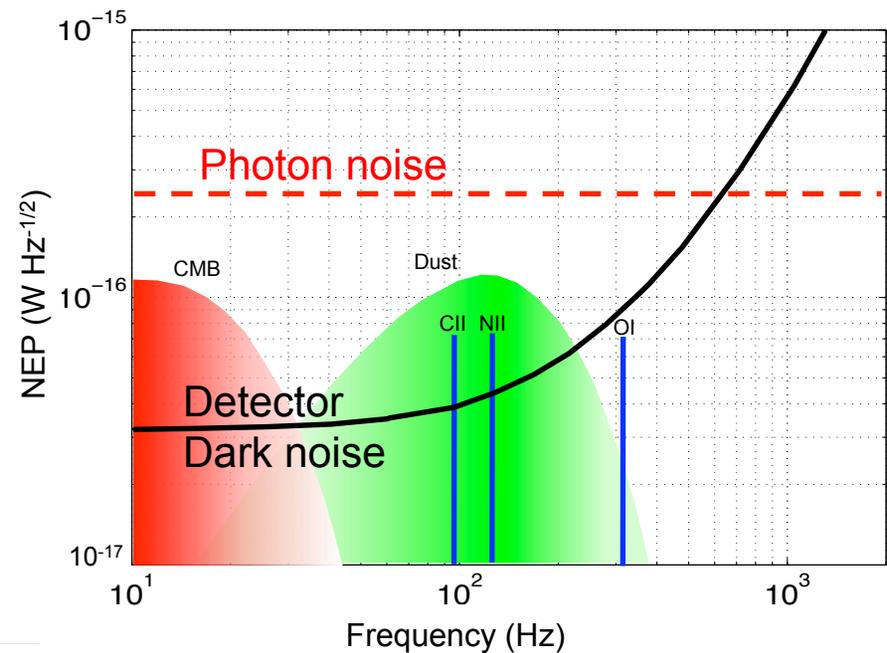
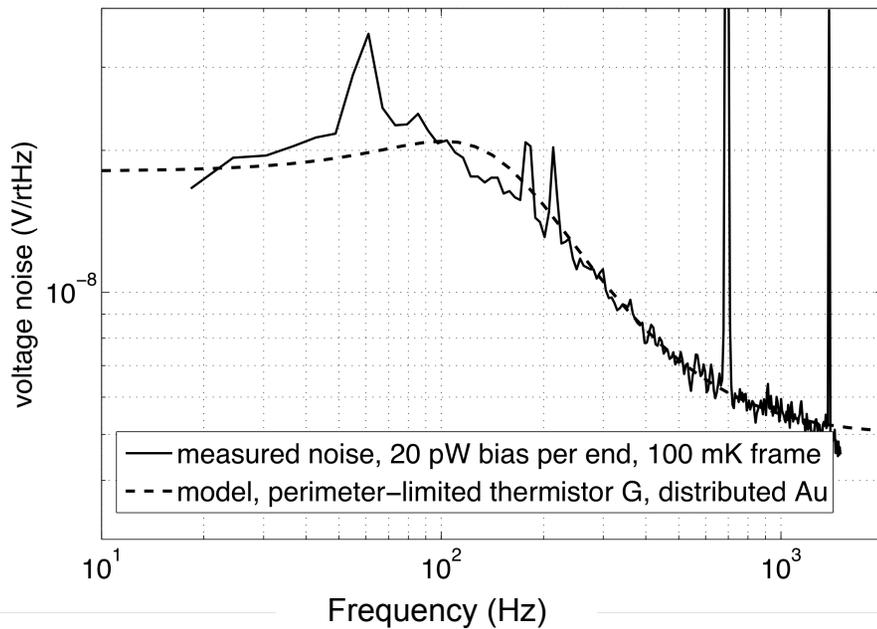
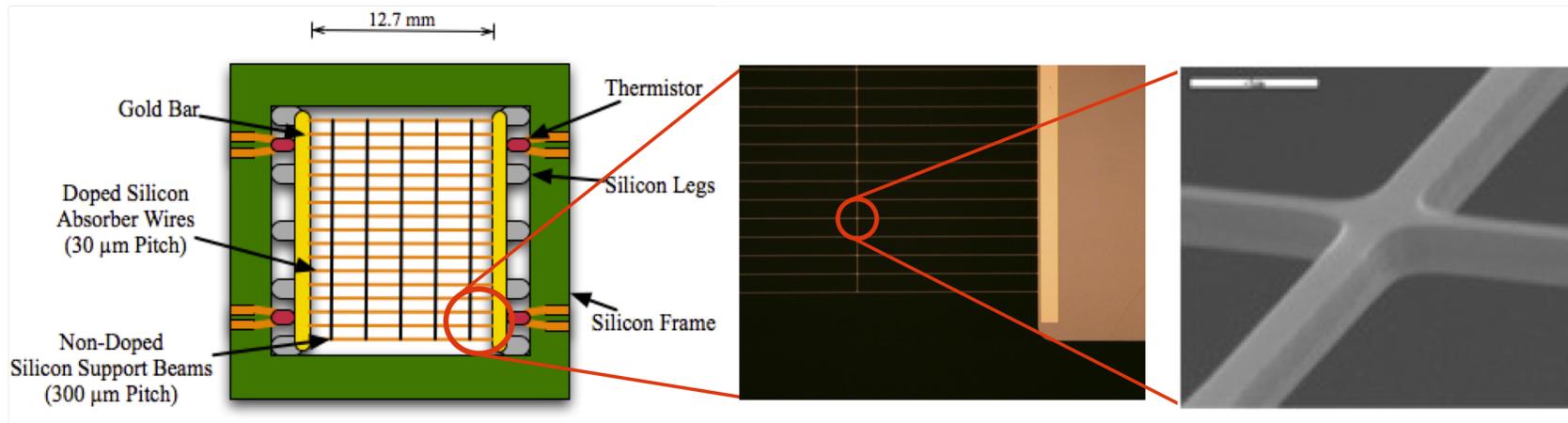


Diffraction Limit: $A\Omega = \lambda^2$
Single mode on each of 10,000 detectors

Conserve etendu: $N_{\text{mode}} = A\Omega / \lambda^2$
10,000 modes on each single detector

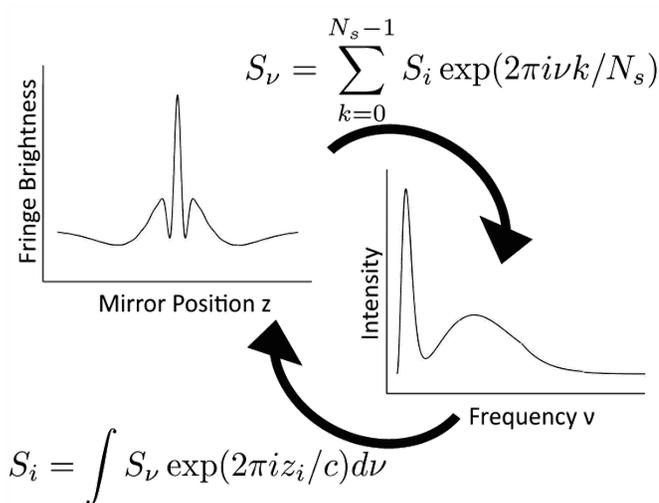
Trade angular resolution for frequency coverage

PIXIE Detectors



Demonstrate multi-moded single-polarization photon-limited detectors

Foregrounds the Easy Way



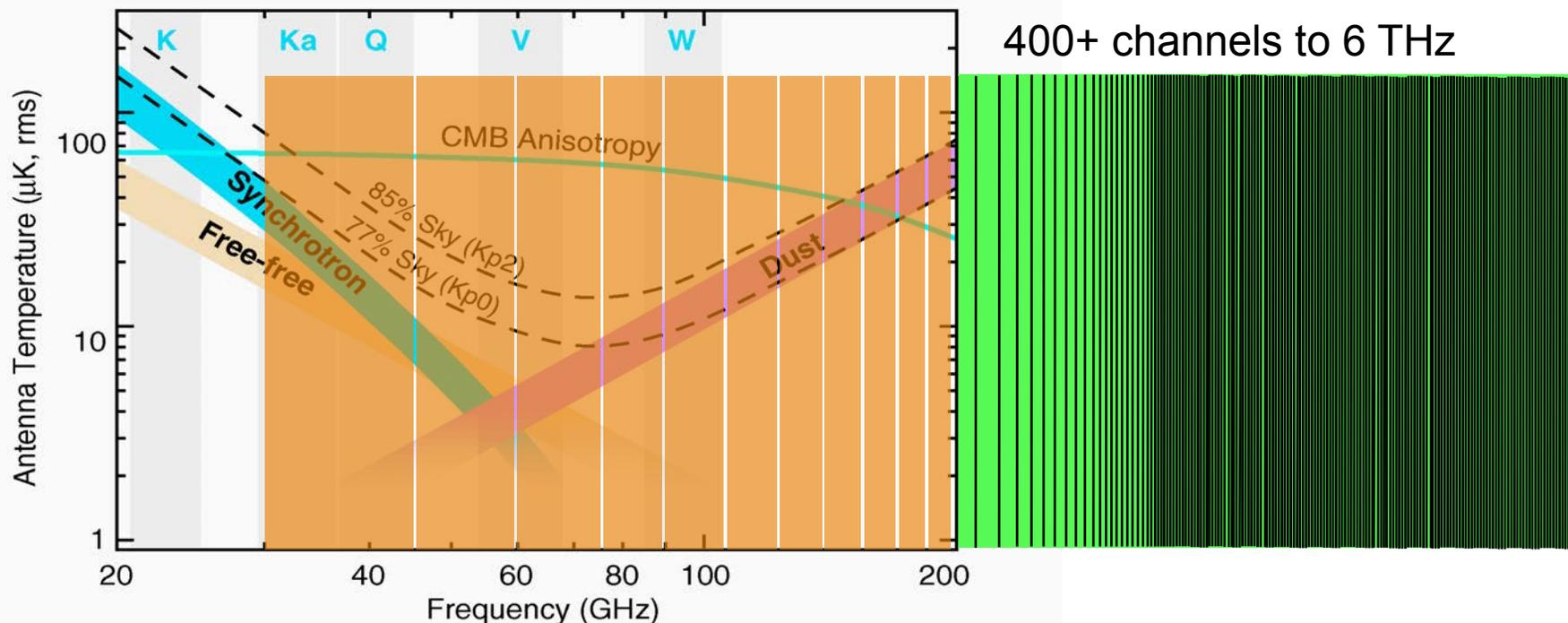
Phase delay L sets channel width

$$\Delta\nu = c/L = 14.41 \text{ GHz}$$

Number of samples sets frequency range

$$\nu_i = [1, 2, 3 \dots N/2] * \Delta\nu$$

**Lowpass filter on optics
limits response to zodiacal light**

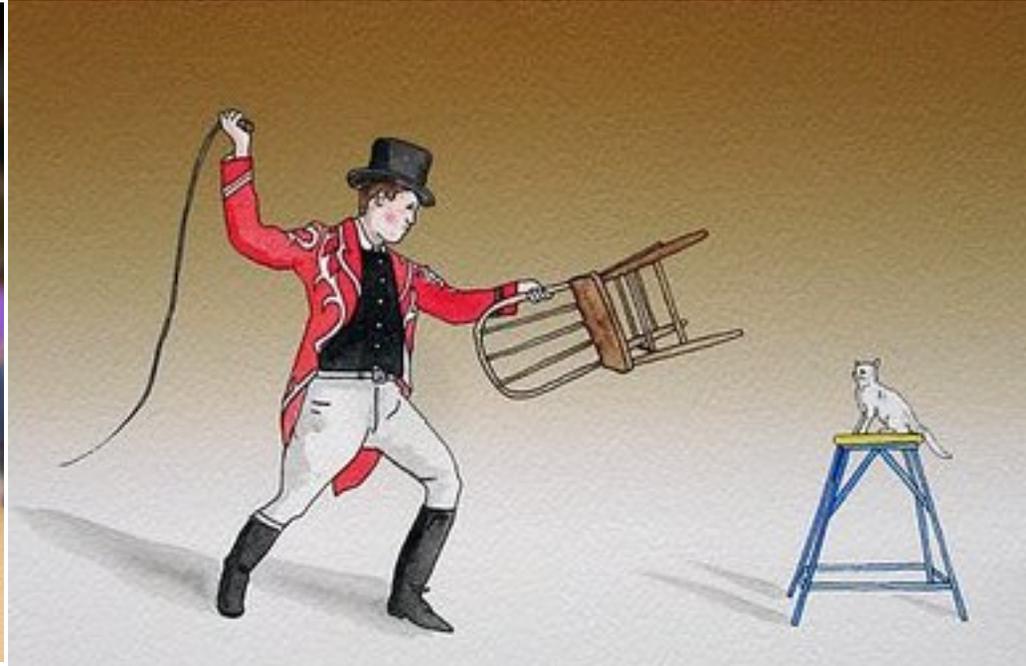


Many samples per mirror stroke = Many frequency bins

Systematic Error Control

Would you rather tame a lion ...

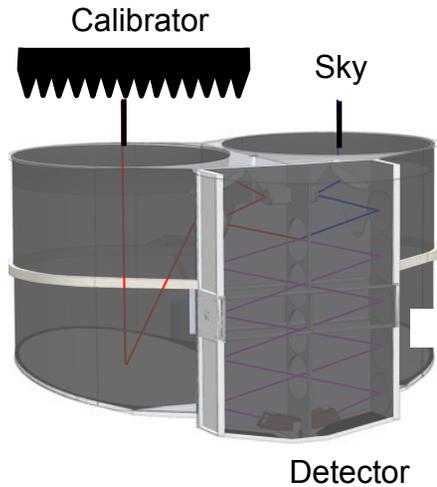
... Or a kitten?



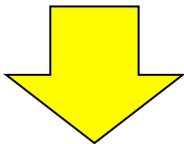
Multiple paths to minimize systematic errors

Taming the Beast: A Menagerie of Methods

Null Operation

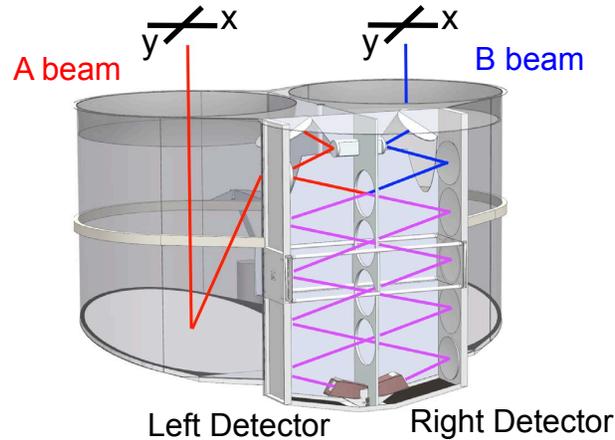


Instrument isothermal with CMB
Minimize syserr source term

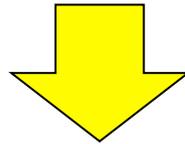


Minimize offsets
Offsets < 1 mK

Differential Operation

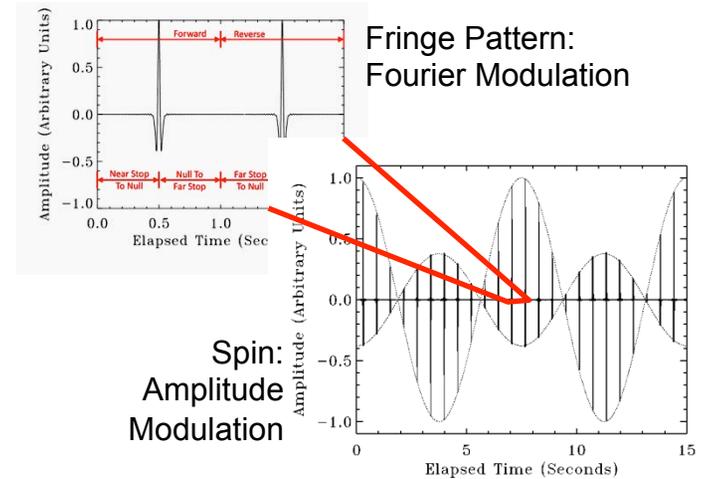


Signal cancellation prior to detection
Only 2nd order residual in sky signal!

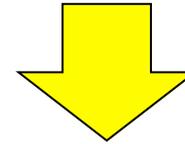


Double-difference
Residuals < 1 nK

Signal Modulation



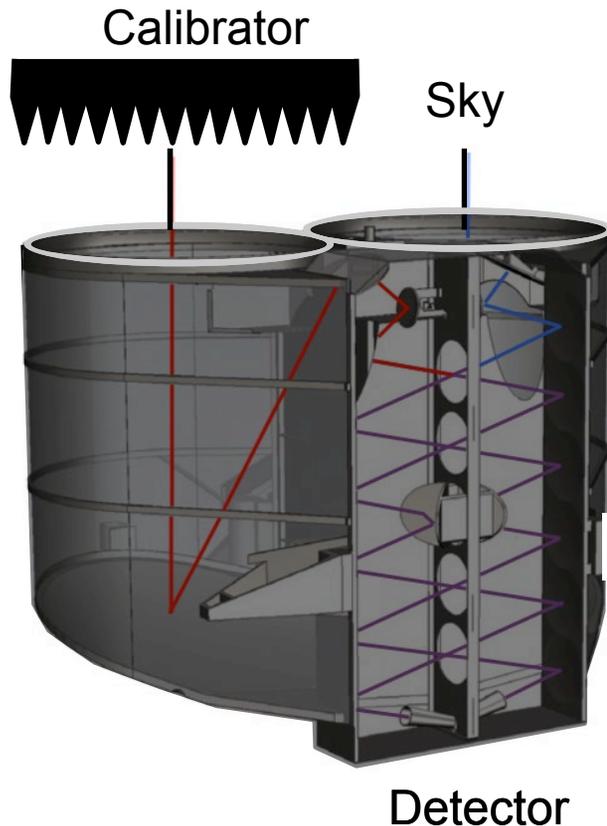
FTS / spin / scan create complex time series
Slow drifts, etc, transform out of signal band



Immunity to slow drifts
Clean ID for syserr

Example: Instrument Emission

Chain Multiple Nulls Together



Maximum ΔT few mK

Mirror Emissivity x 0.01 → tens of μK

Left/Right Asymmetry x 0.01 → few hundred nK

Swap hot vs cold x 0.01 → few nK

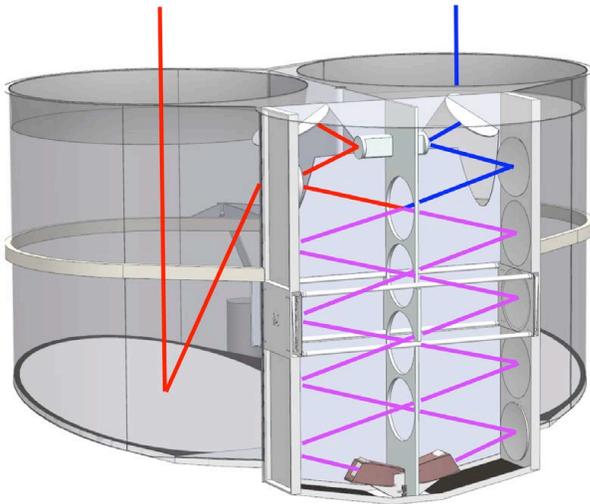
Uncorrected Error few nK (with blue-ish tinge)

Corrected Error $\ll 1$ nK

Multiple levels of nulling reduce systematics to negligible levels without relying on any single null

Example: Beam Patterns

First ...



Difference 2 beams prior to detection to cancel common-mode effects

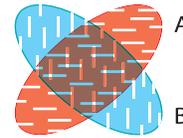


Beam A



Beam B

Common Mode



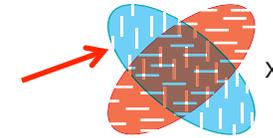
Differential Ellipticity
Single Detector

$$P_{Lx} \propto F_{Ax} E_x^2 - F_{By} E_y^2$$

$$P_{Ly} \propto F_{Ay} E_y^2 - F_{Bx} E_x^2$$

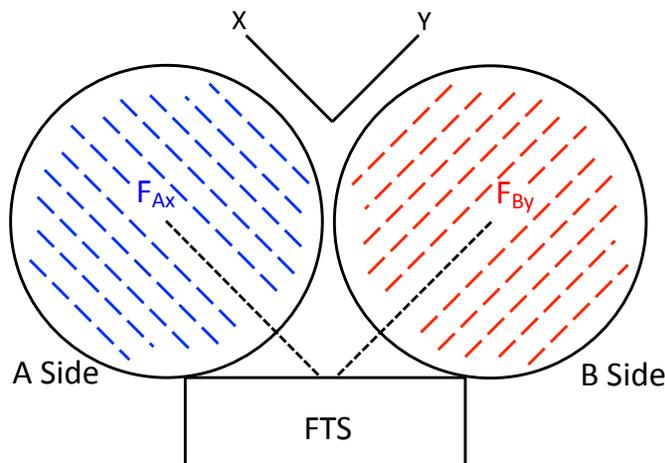
$$P_{Rx} \propto F_{Bx} E_x^2 - F_{Ay} E_y^2$$

$$P_{Ry} \propto F_{By} E_y^2 - F_{Ax} E_x^2$$



Second Order Cancelling
Compare Detectors

Then ...



Instrument A/B symmetry:
X polarization in **A** beam (blue)
is mirror image of
Y polarization in **B** beam (red)

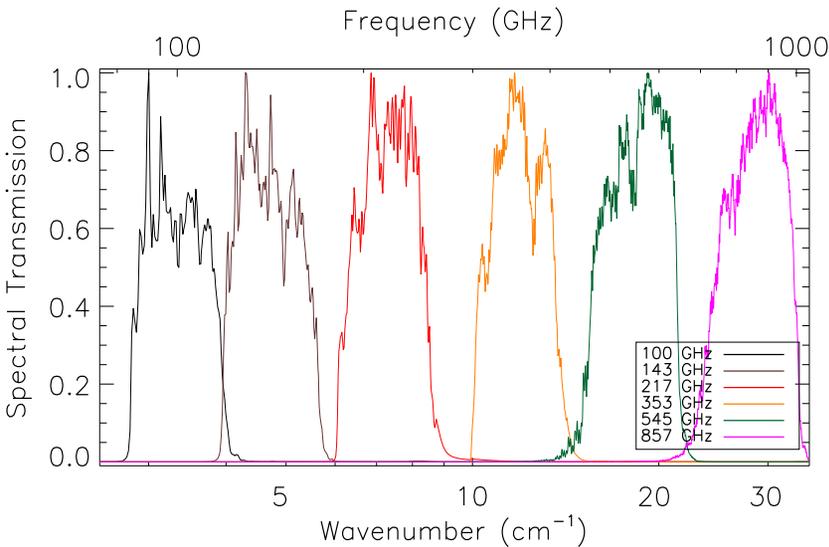
Anti-symmetric beam difference
forces beam effects
to **odd** spin harmonics
($m = 1, 3, 5 \dots$)

Sky signals only at $m=0$ (distortions)
or $m=2$ (polarization)

Multiple levels of cancellation & symmetry

Example: Bandpass Calibration

Math is Fun

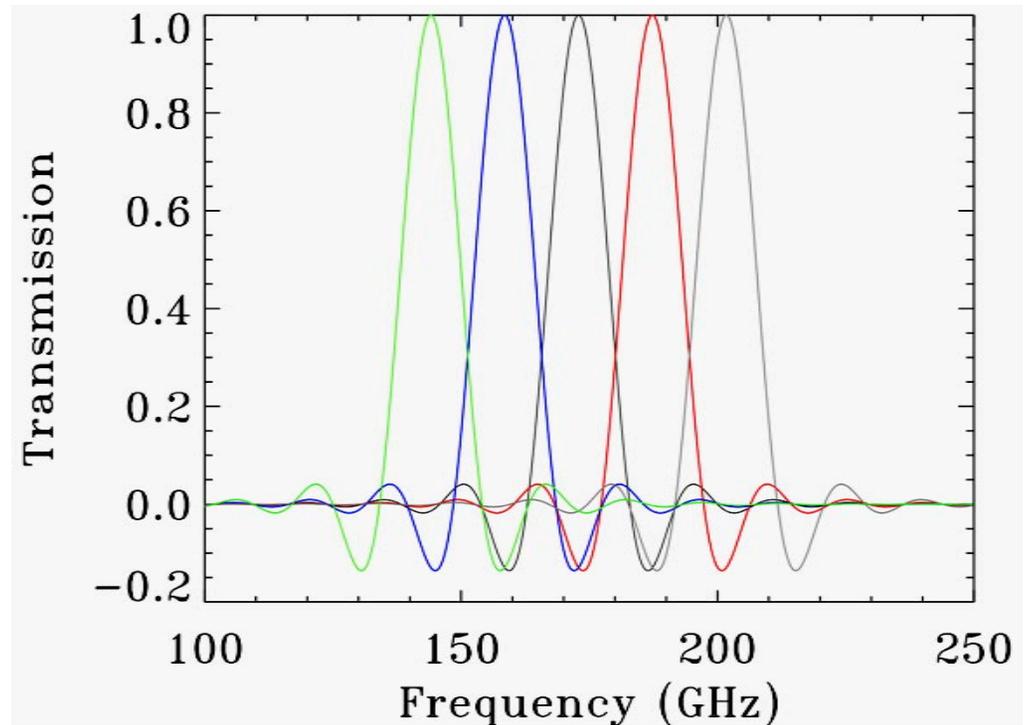


Bandpass mismatch + foregrounds = T → B error
Analog filters difficult to model at nK precision

FTS synthesized bands determined by sampling and apodization **only**

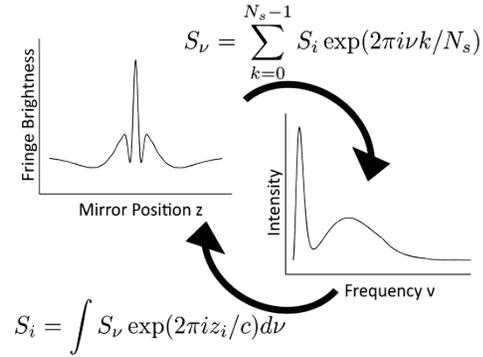
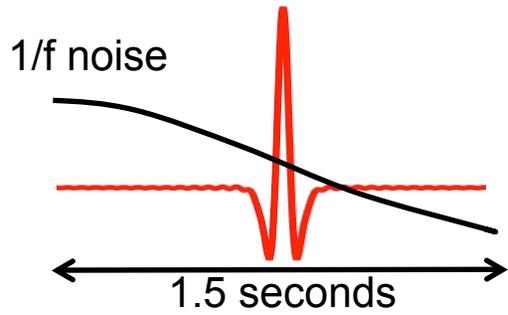
$$\nu_i = [1, 2, 3 \dots N/2] * \Delta\nu$$

Pick maximum stroke so $\Delta\nu = \nu_{CO} / M$
Every M^{th} channel centered on a CO line!

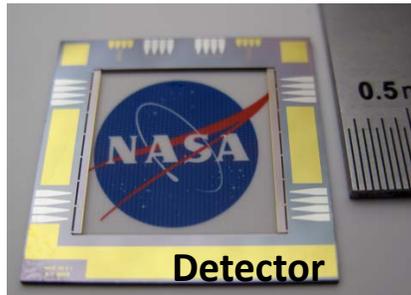
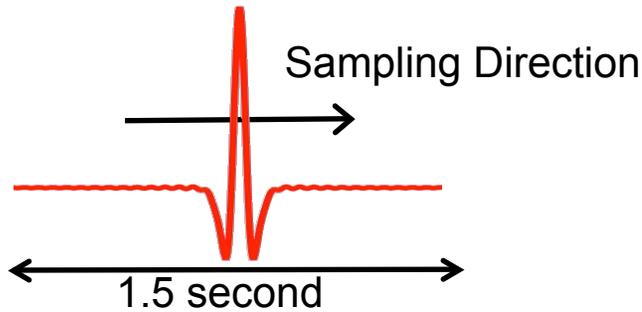


Mathematically deterministic frequency decomposition on a single detector

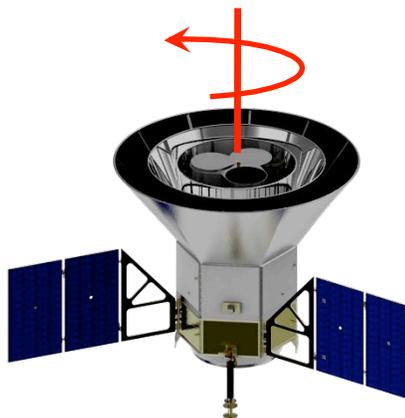
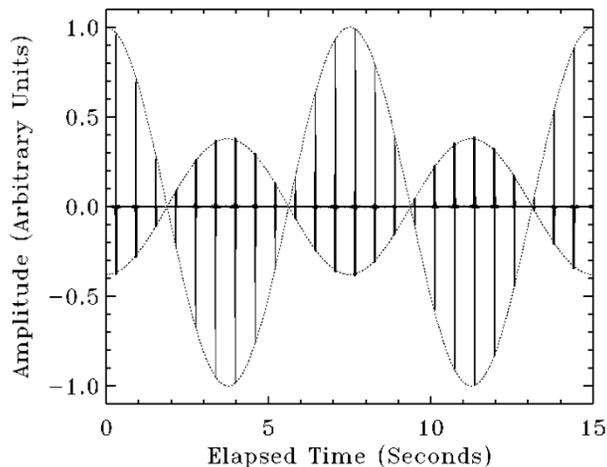
Example: Signal Modulation



1/f noise gets Fourier-transformed into lowest bins of synthesized spectra
No striping in CMB maps

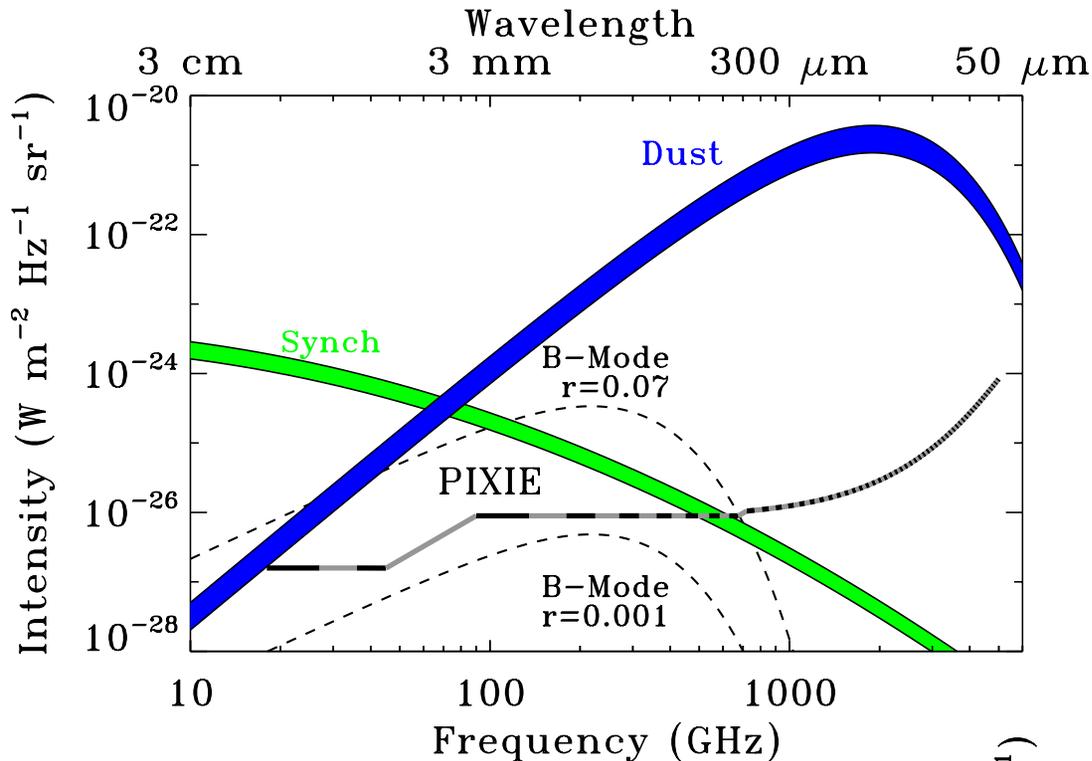


Peak at zero phase delay provides before-and-after reference for detector time constants
126,000,000 times per detector



Spacecraft spin creates amplitude modulation of entire fringe pattern
Immunity to simple spin harmonics

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 $0.9^\circ \times 0.9^\circ$
- Pixel sensitivity $6 \times 10^{-26} \text{ W m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$
- CMB sensitivity 70 nk RMS per pixel

Legacy Archive for far-IR Astrophysics

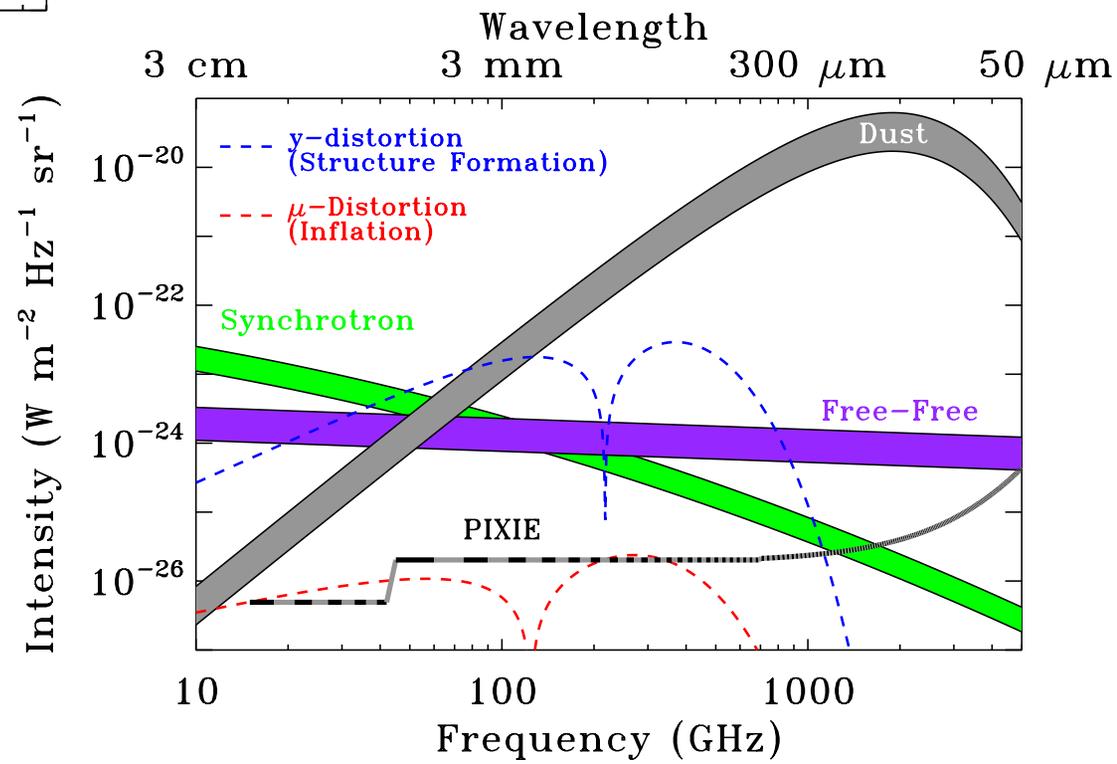
Multiple Science Goals

- Polarization / inflation
- Tau / neutrino mass
- Spectral distortions / growth of structure
- ISM and Dust Cirrus

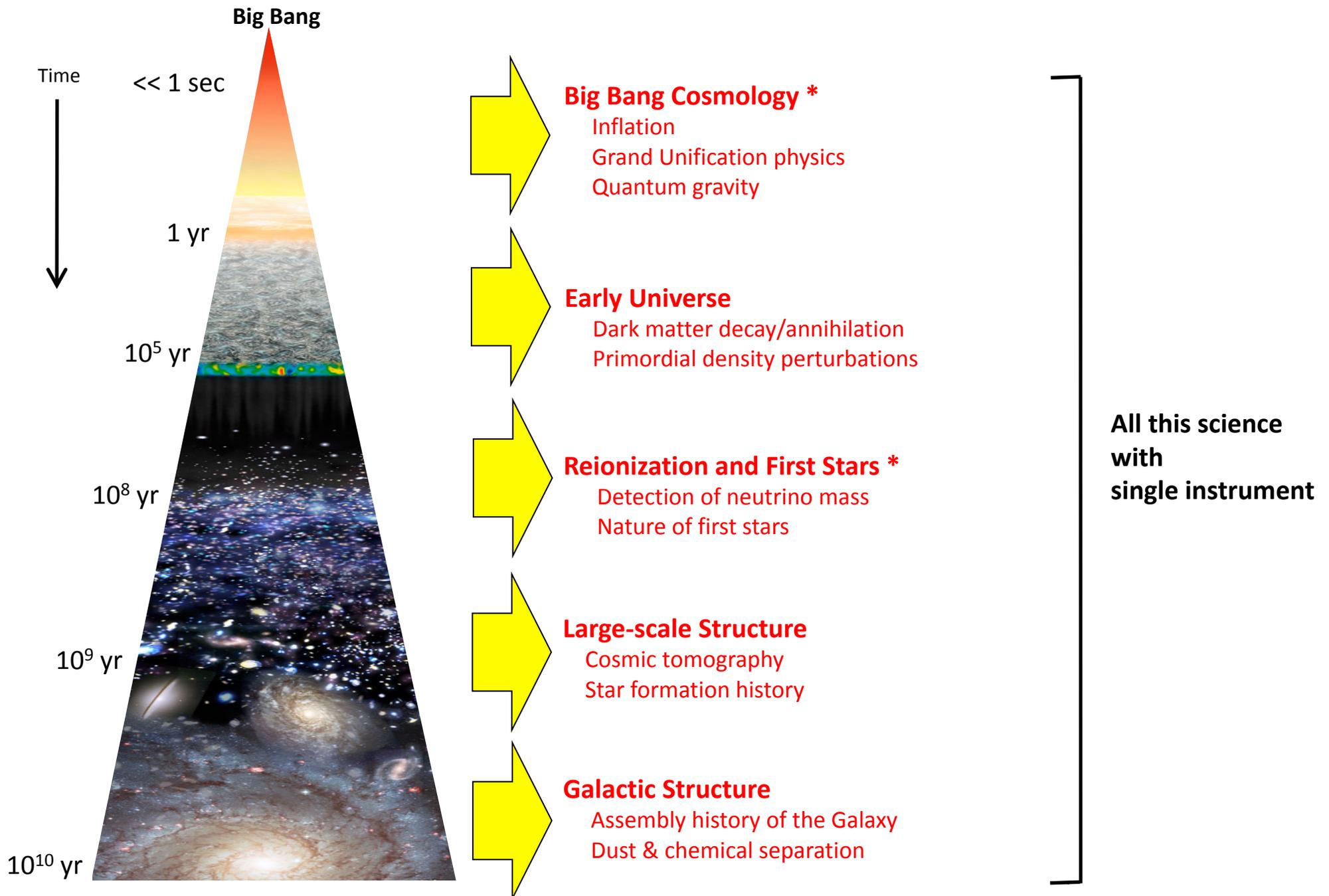
95% CL Limits:

B-mode: $r < 4 \times 10^{-4}$

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



Multiple Decadal Goals in One MIDEX Mission



* Specifically called out in Astro-2010 Decadal Survey

PIXIE Status

Conceived as NASA MIDEX mission

- \$250M Cost Cap + launch vehicle
- 4—5 years from selection to launch

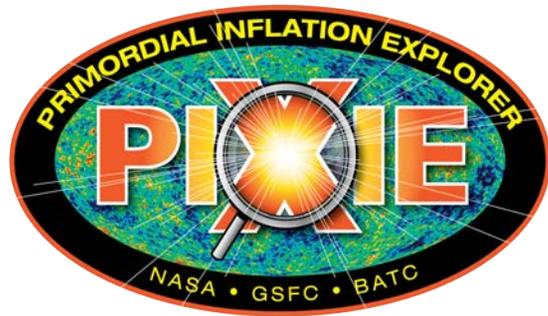
But ... PIXIE not selected

Continue to develop mission concept

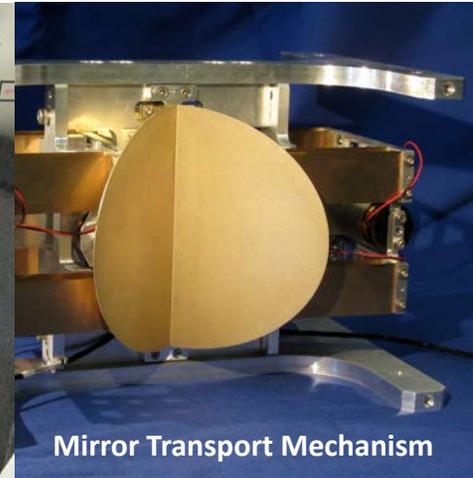
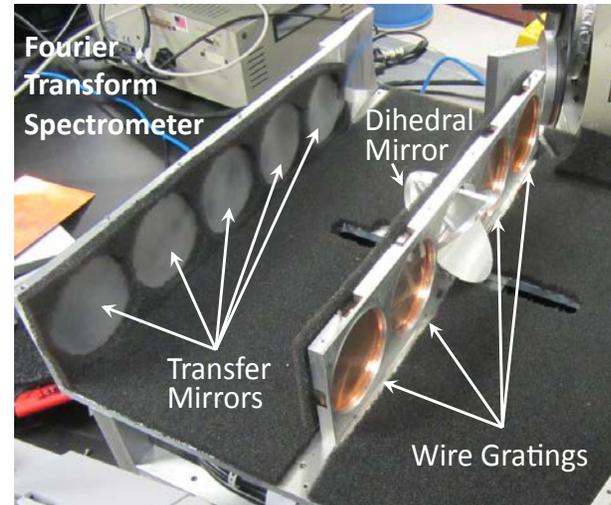
- Dust Buster balloon to measure dust
- 2019 Mission of Opportunity
- 2022 MIDEX AO

Complementary to planned CMB missions

- LiteBIRD / PICO / CMB-S4
- High-frequency dust foreground
- Unique spectral distortion science

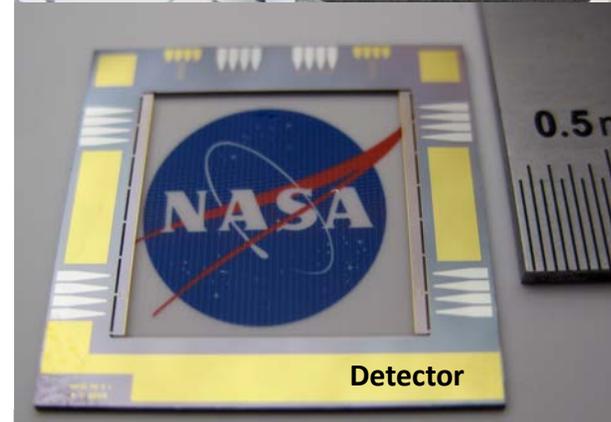


"PIXIE's spectral measurements alone justify the program"
-- NASA review panel

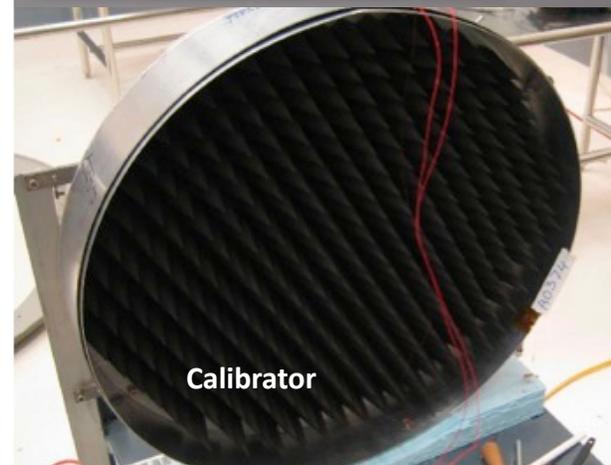


Mirror Transport Mechanism

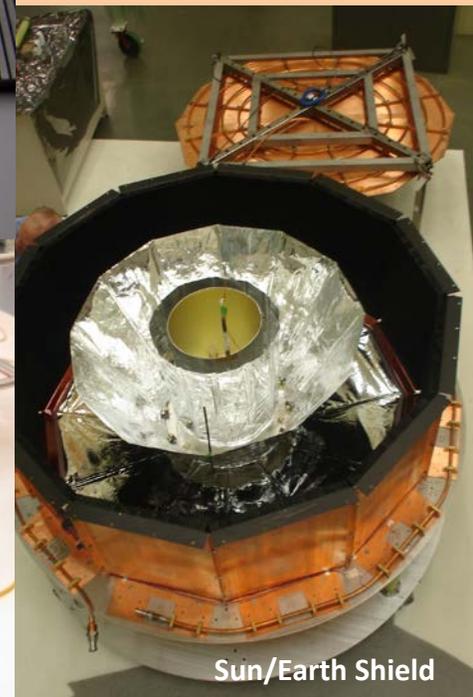
**Mature
technology**



Detector



Calibrator



Sun/Earth Shield