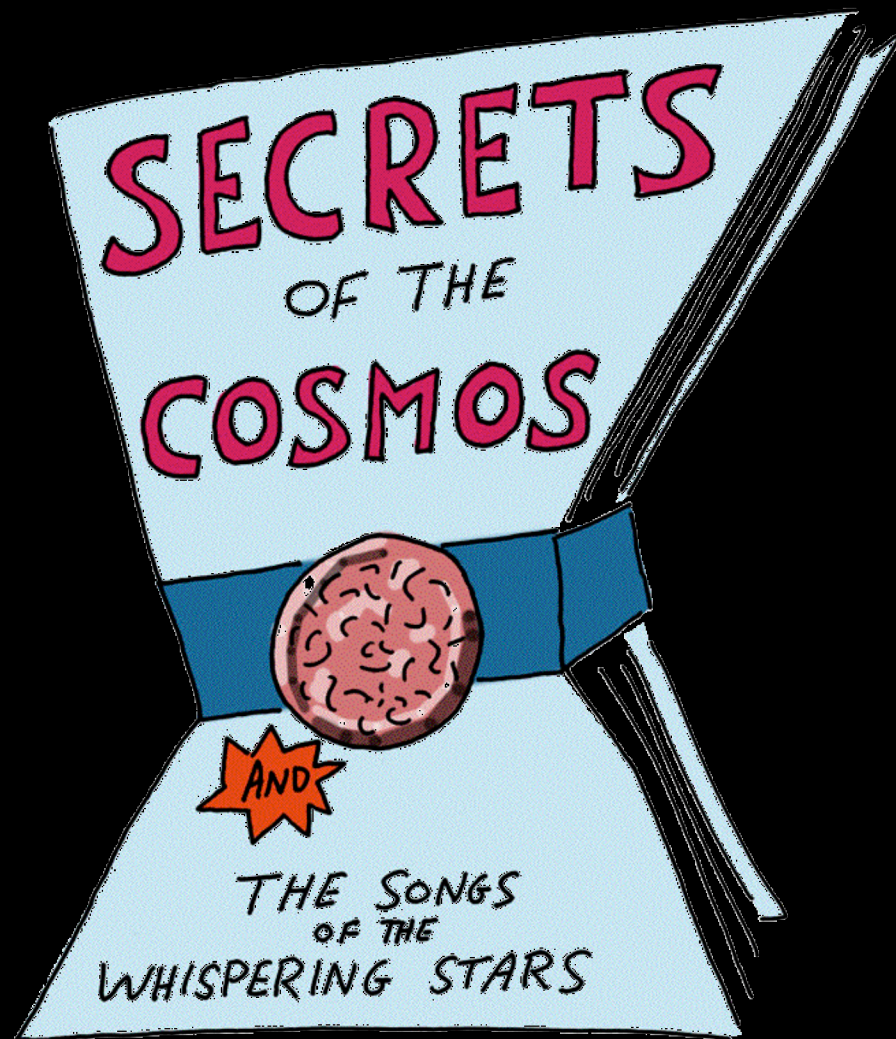
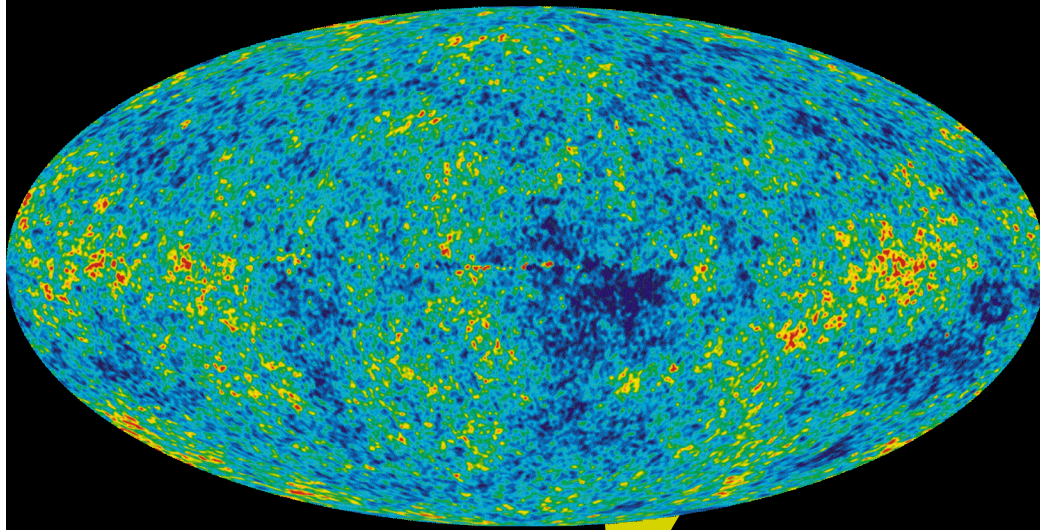


A New Look at Reionization



Al Kogut
Goddard Space Flight Center

Transition to The Modern Universe



How do you go
from this ...



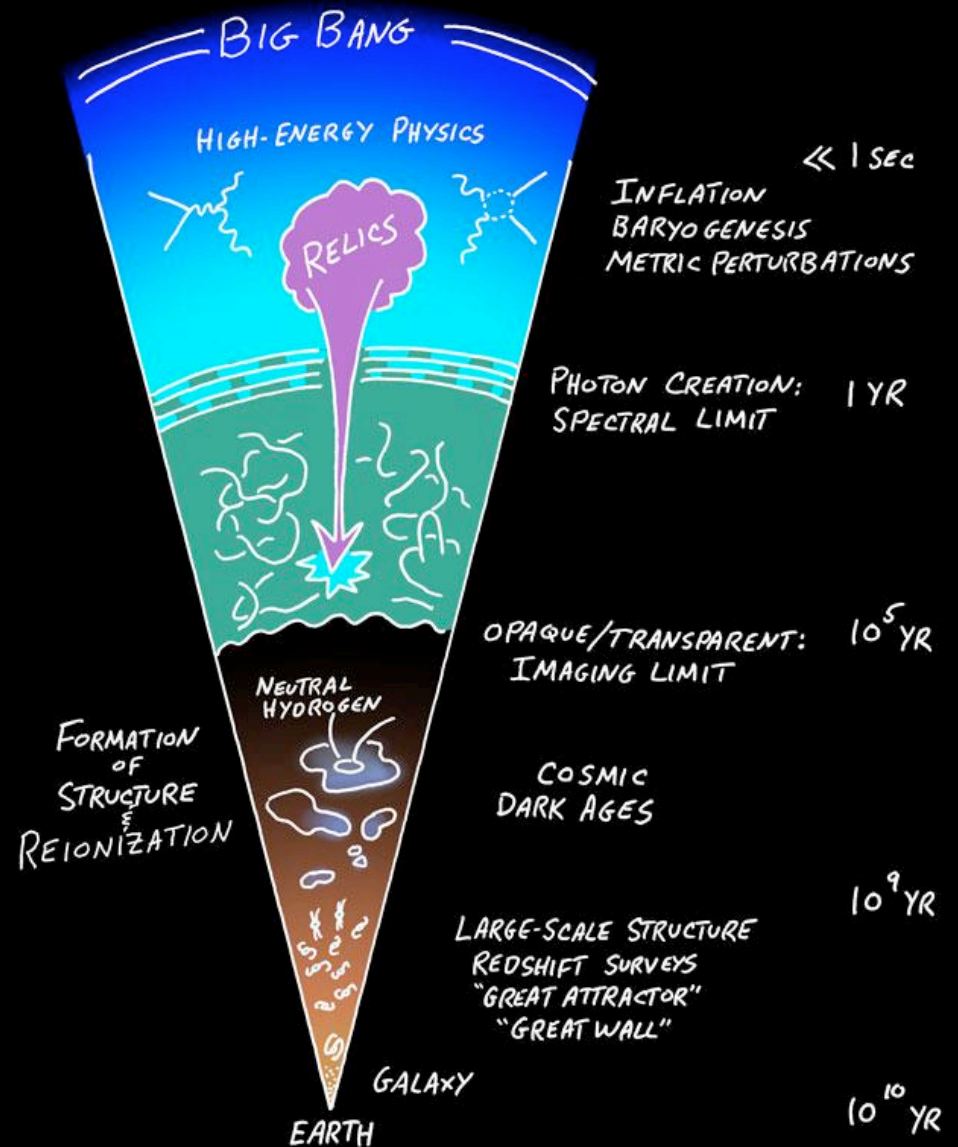
... To this?

Top Up? Top Down?
Pop III? Pop II?
UV Feedback?
Metal Pollution?

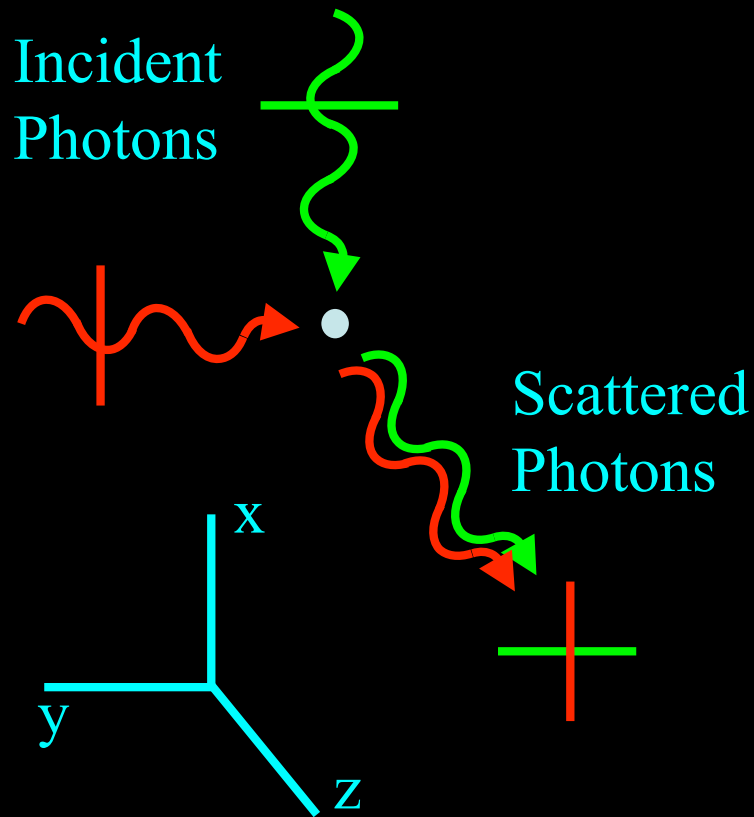
CMB: Backlight for Reionization

CMB predates collapsed structures

- Full Sky
- Fixed redshift
- Unbiased!

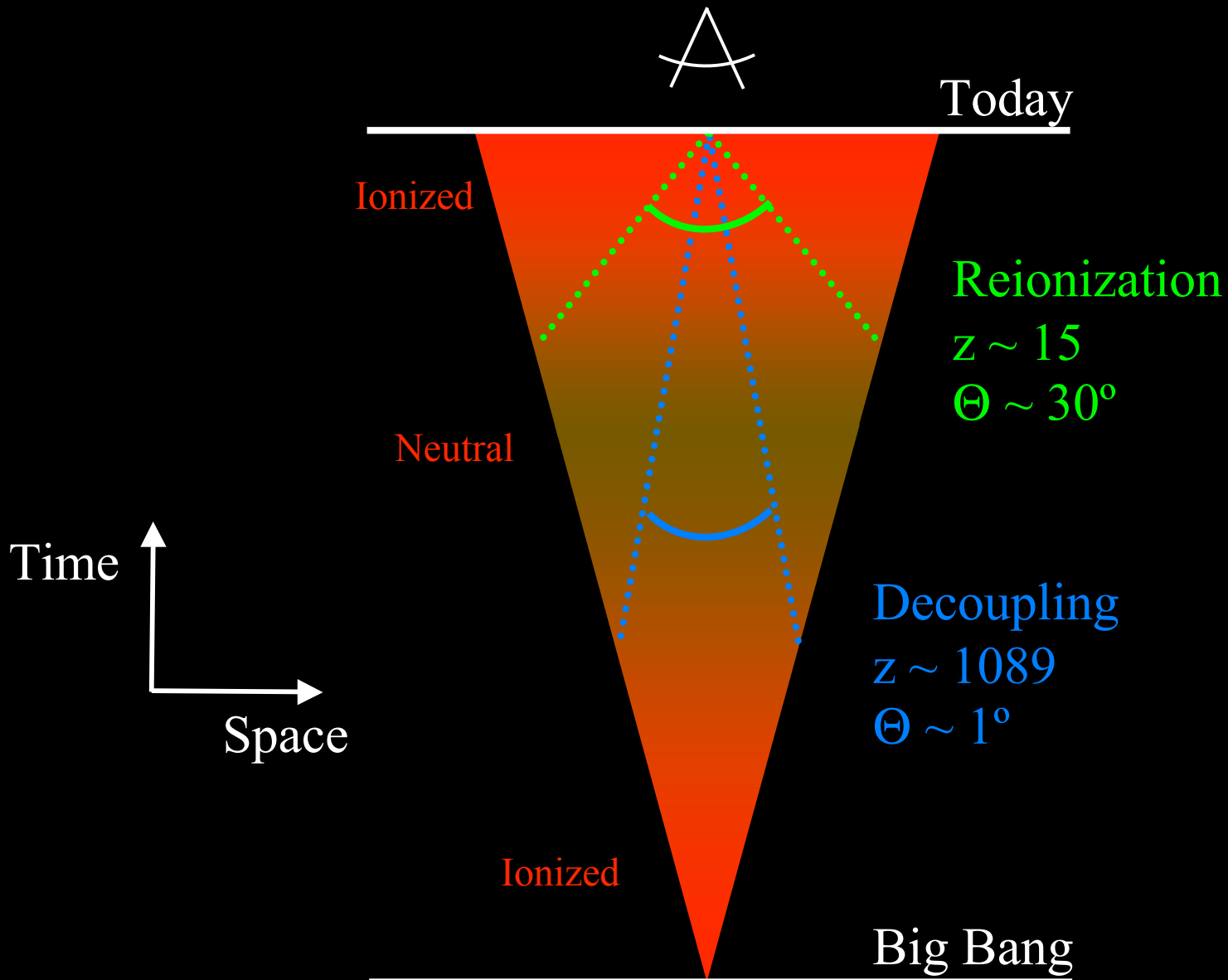


Reionization Part I: CMB Polarization



- Thomson scattering of anisotropic photon distribution by free electrons
- Quadropolar temperature anisotropy produces net linear polarization
- Expected amplitude \sim few percent of temperature anisotropy

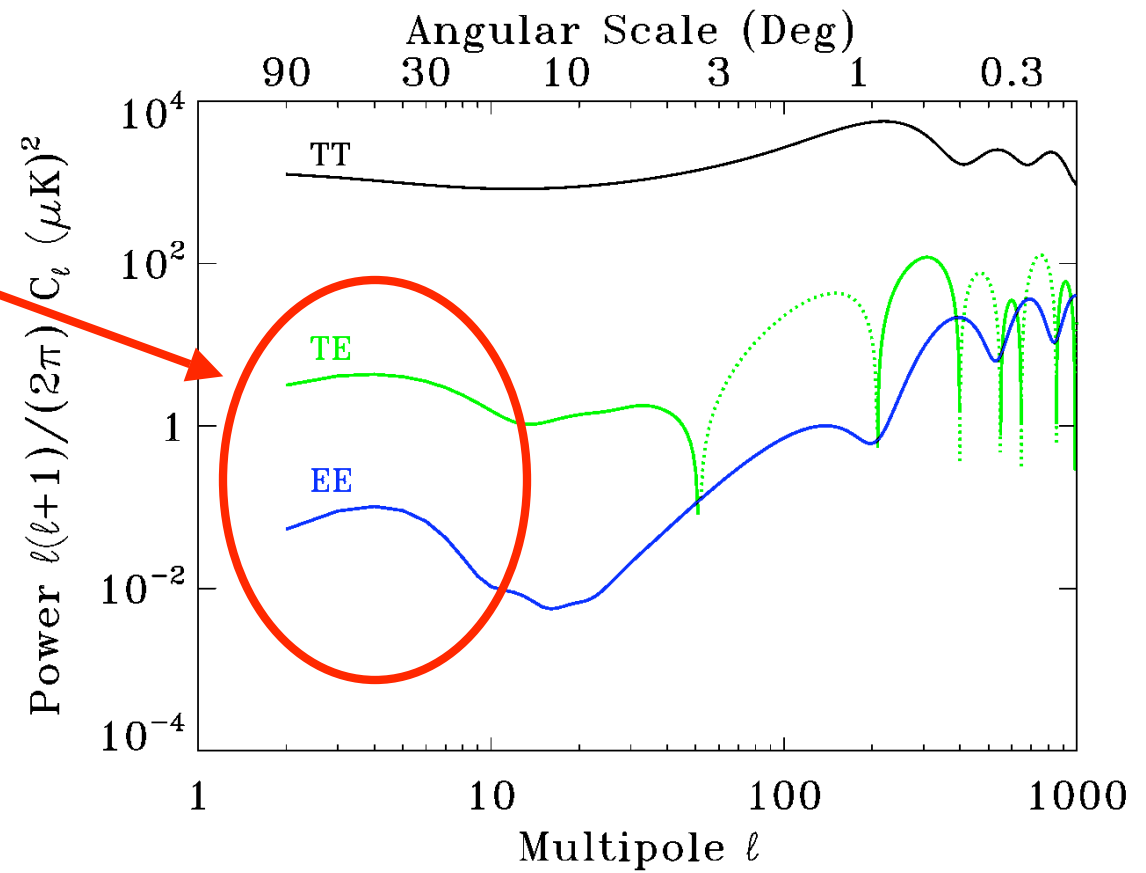
Polarization Angular Scale vs Redshift

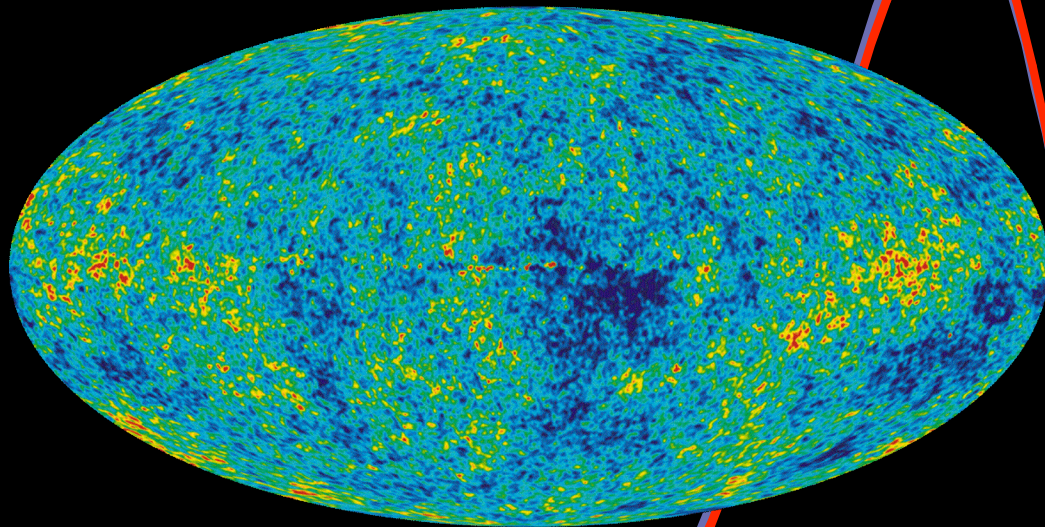


“Reionization” Power Spectra

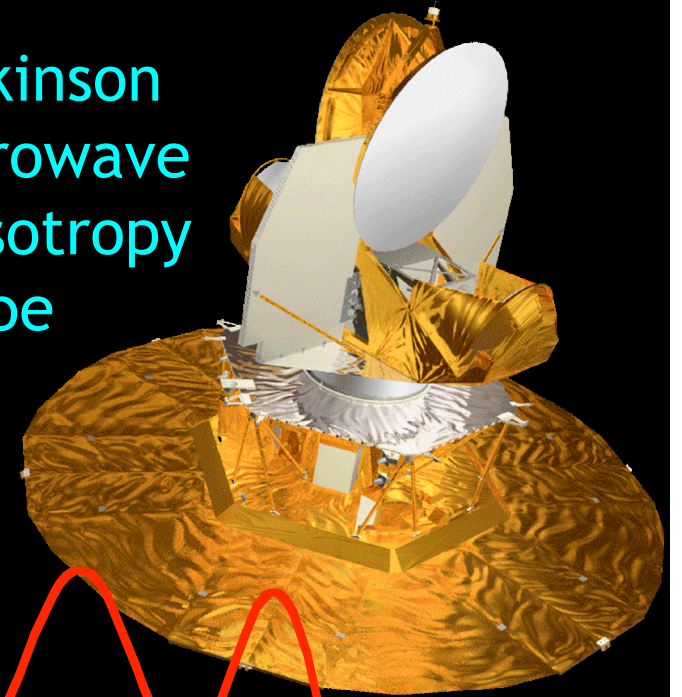
Reionization

Large angular scales
= full sky coverage:
Space Mission!





Wilkinson
Microwave
Anisotropy
Probe



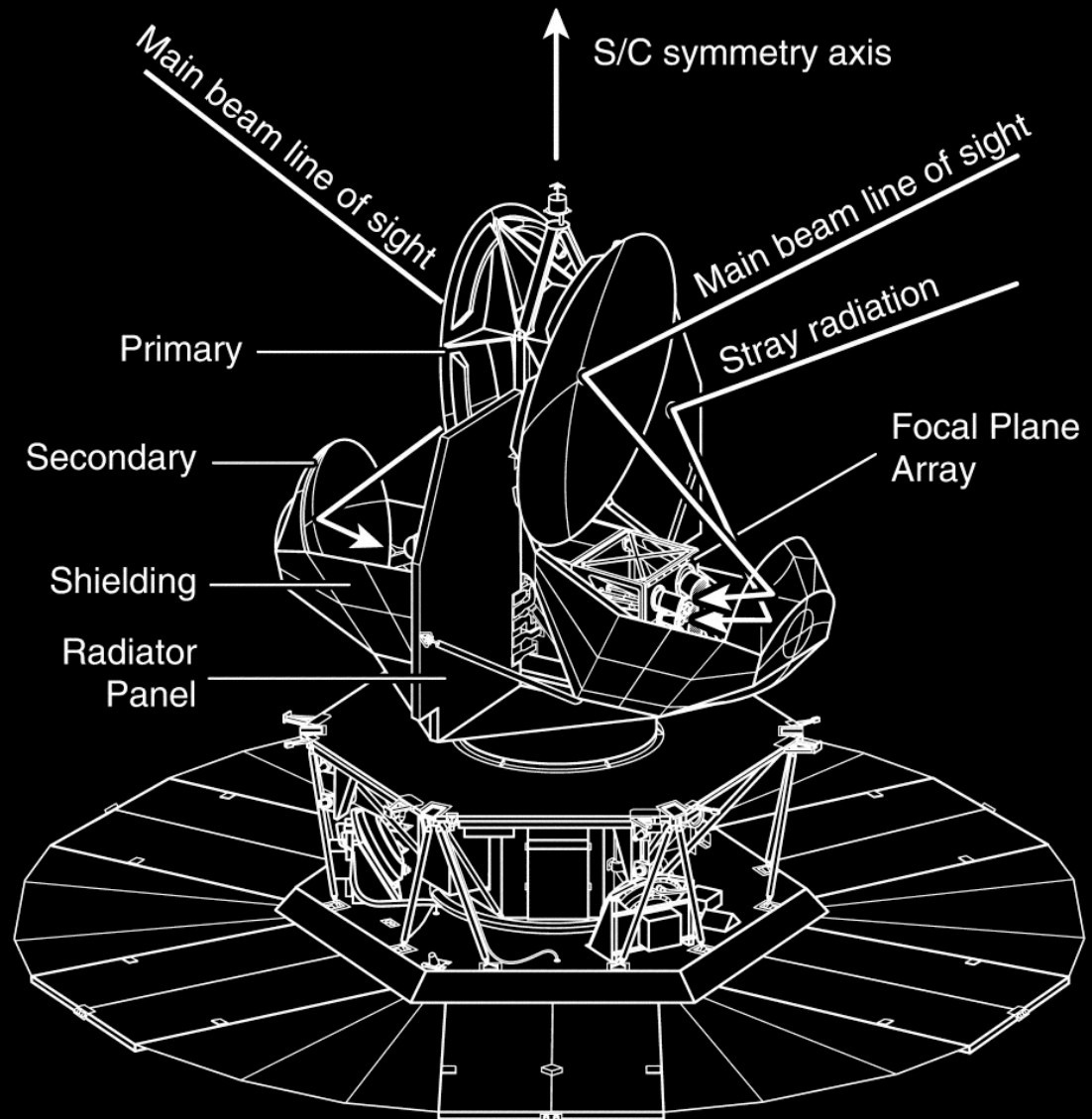
Launched 2001

Measure CMB Anisotropy to Cosmic Variance Limit

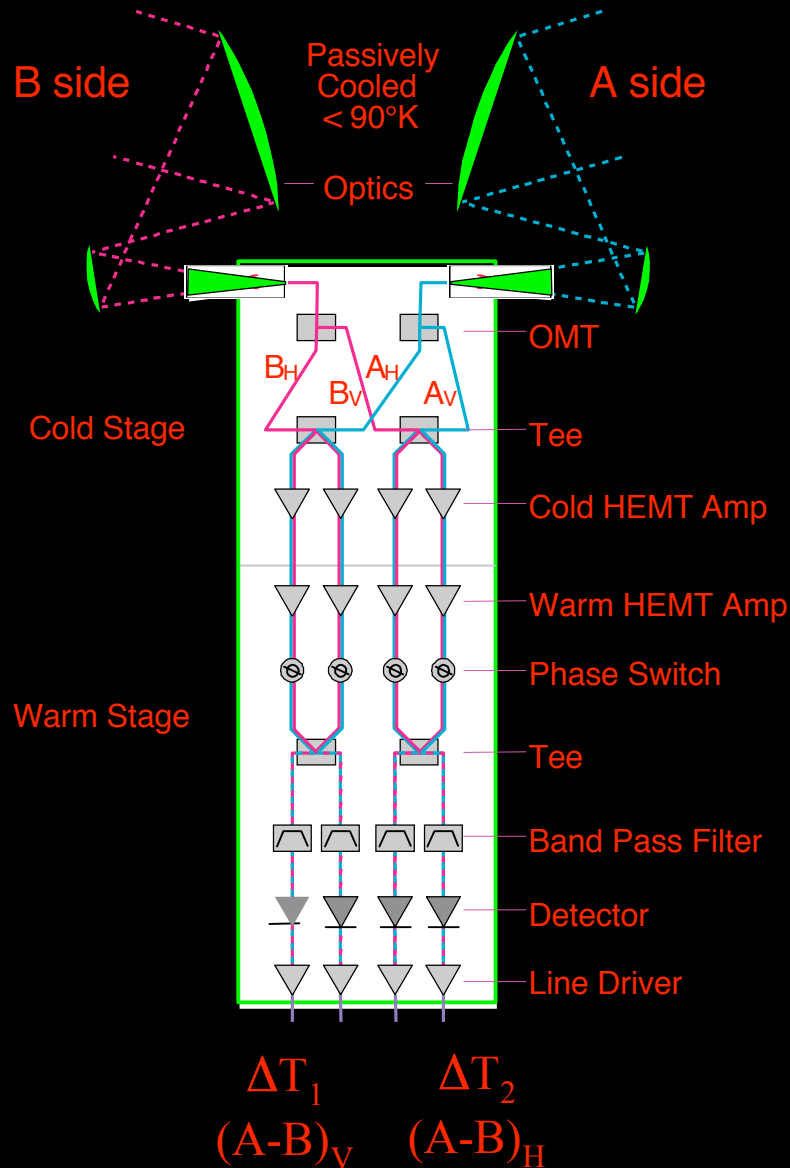
Measure CMB Polarization

WMAP Design

- Differential Optics
- Multiple Frequencies
- Multiple Channels
- Interleaved Scan Pattern
- Stable Calibration
- L2 Orbit Far From Earth



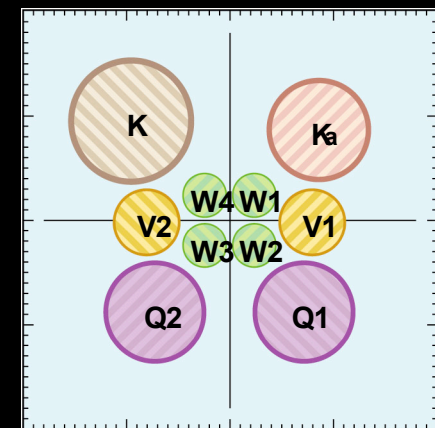
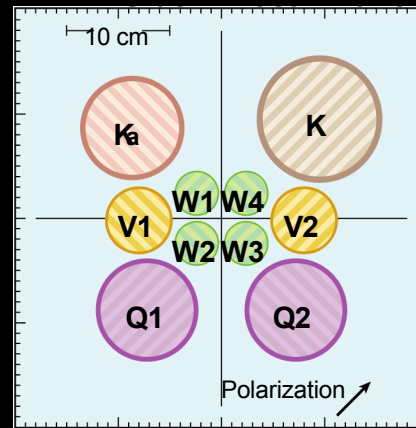
WMAP and Polarization



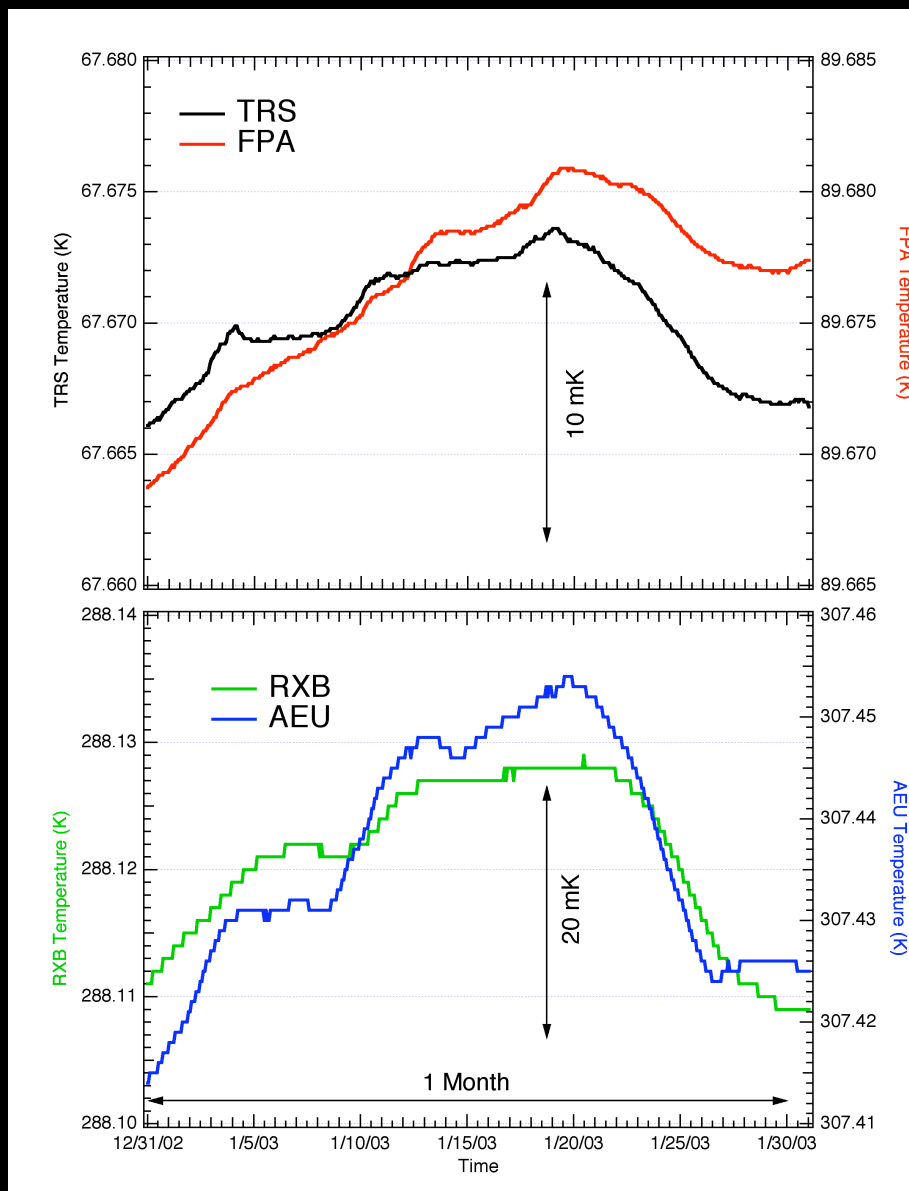
Two Radiometers per Feed

- Sum $(\Delta T_1 + \Delta T_2) \propto$ Intensity
- Difference $(\Delta T_1 - \Delta T_2) \propto$ Polarization

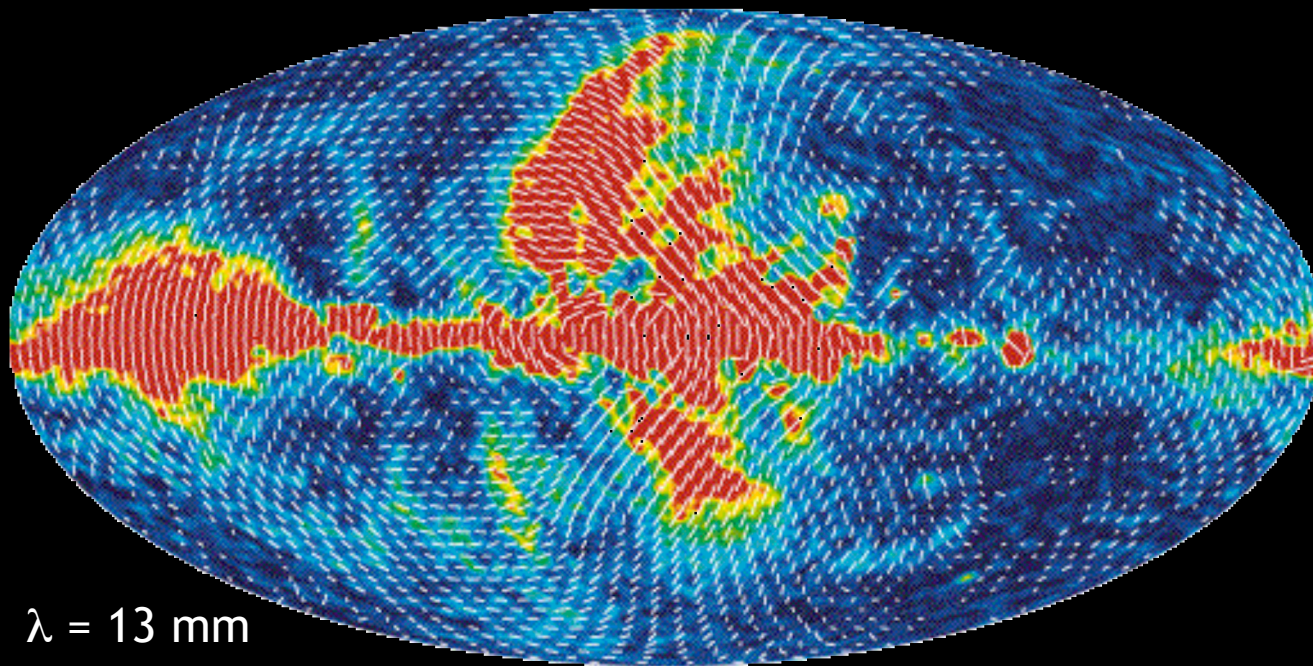
Sensitive to polarization, but not an optimized polarimeter



L2: An Ultra-Stable Observing Environment



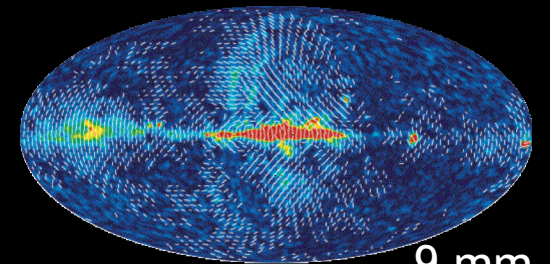
WMAP Full-Sky Polarization



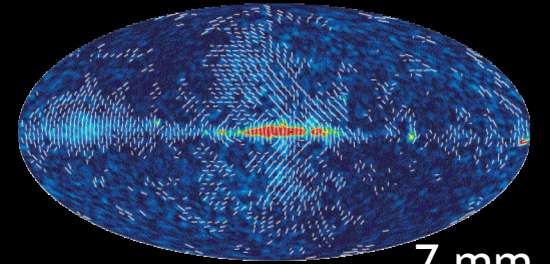
$\lambda = 13$ mm

0  50
T (μK)

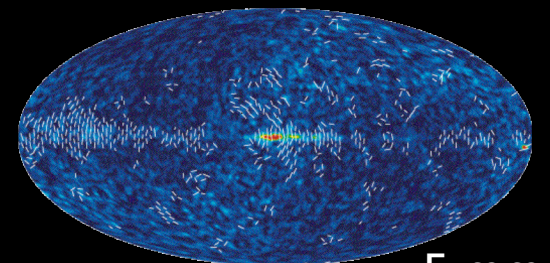
Foregrounds brighter than CMB



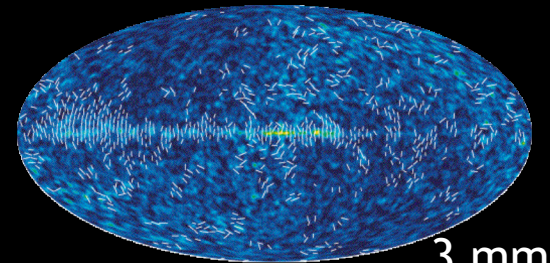
9 mm



7 mm



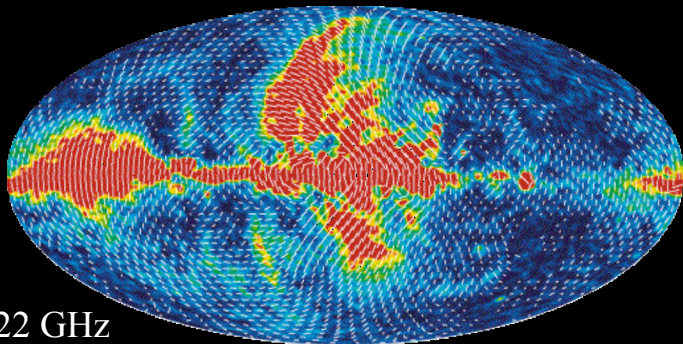
5 mm



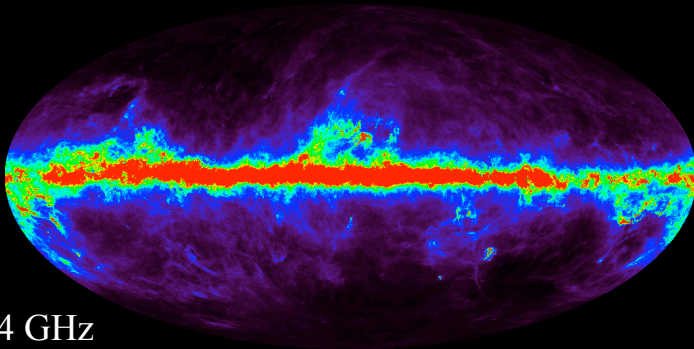
3 mm

Foreground Subtraction

Method 1: Template

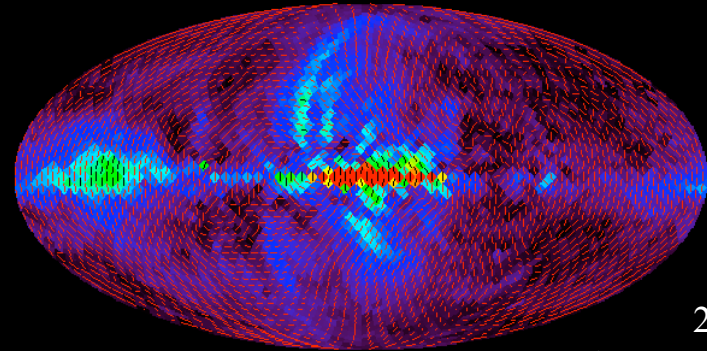


22 GHz
Synchrotron Template

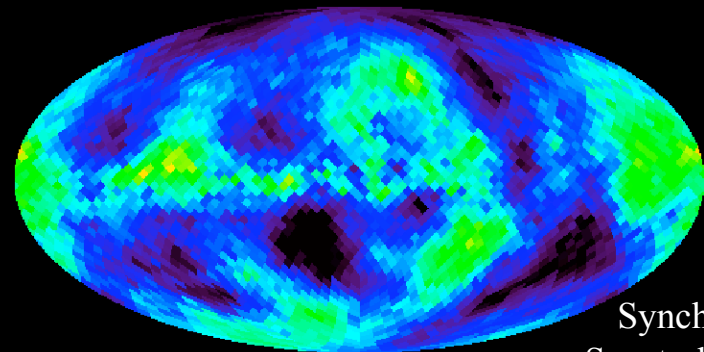


94 GHz
Dust Template

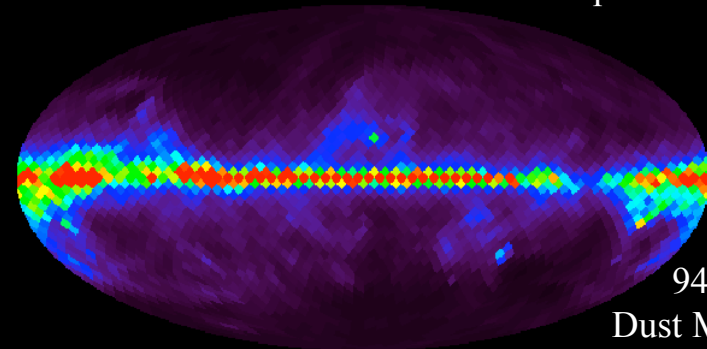
Method 2: Model



22 GHz
Synchrotron Model

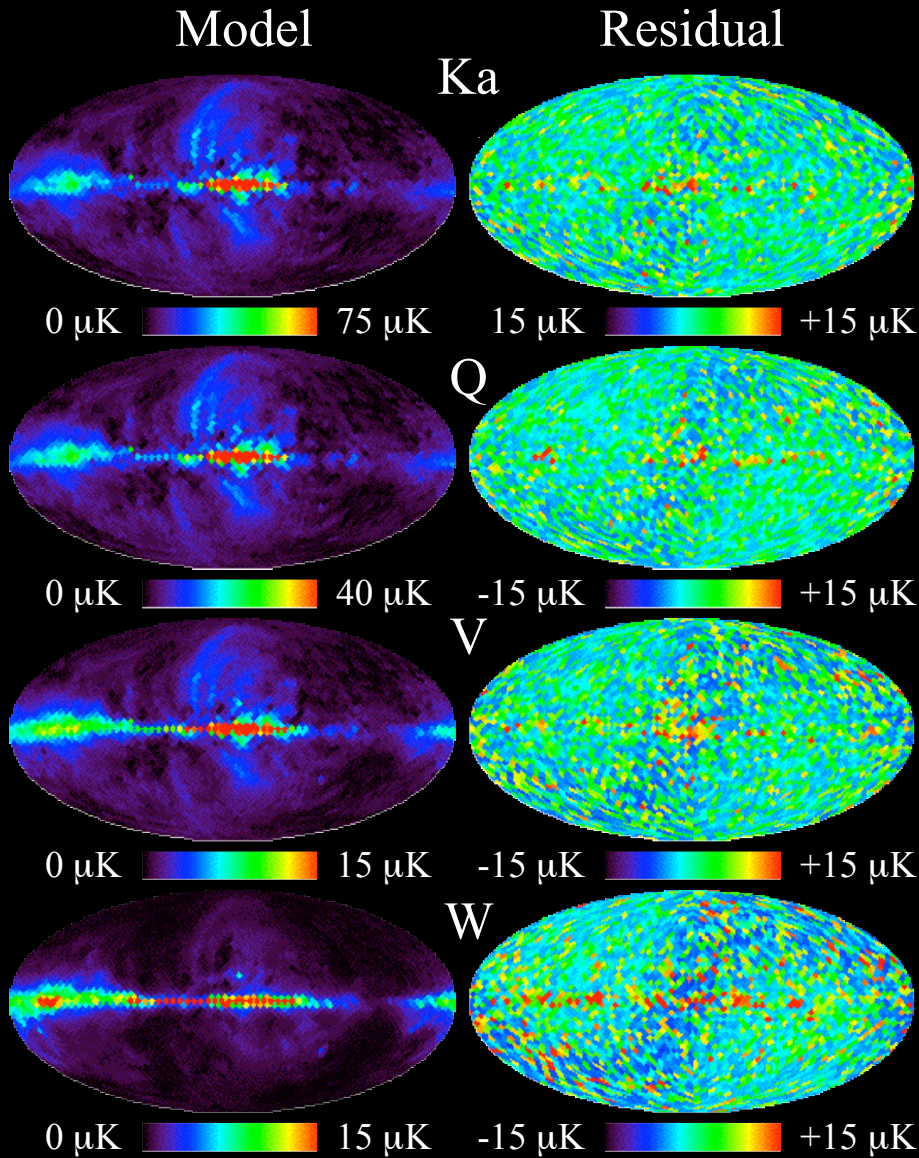


Synchrotron
Spectral Index



94 GHz
Dust Model

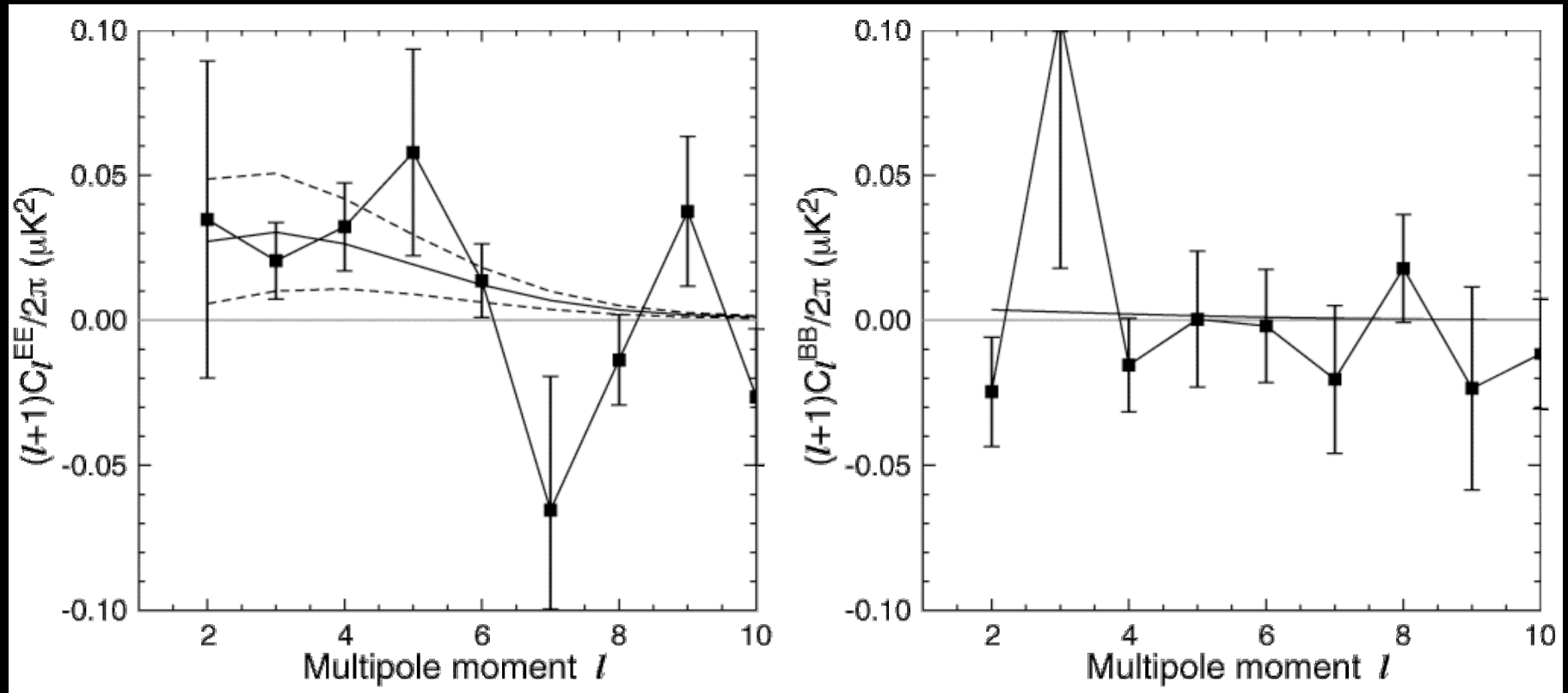
Cleaned Maps



χ^2 Outside P06 Mask

Band	χ^2	DOF
Ka	4604	4524
Q	4521	4524
V	4600	4524
W	4774	4524

Large-Angular-Scale EE Detection



Page et al. 2007, ApJS, 170, 335

$$\frac{l(l+1)}{2\pi} C_l = 0.086 \pm 0.029 \mu\text{K}^2$$

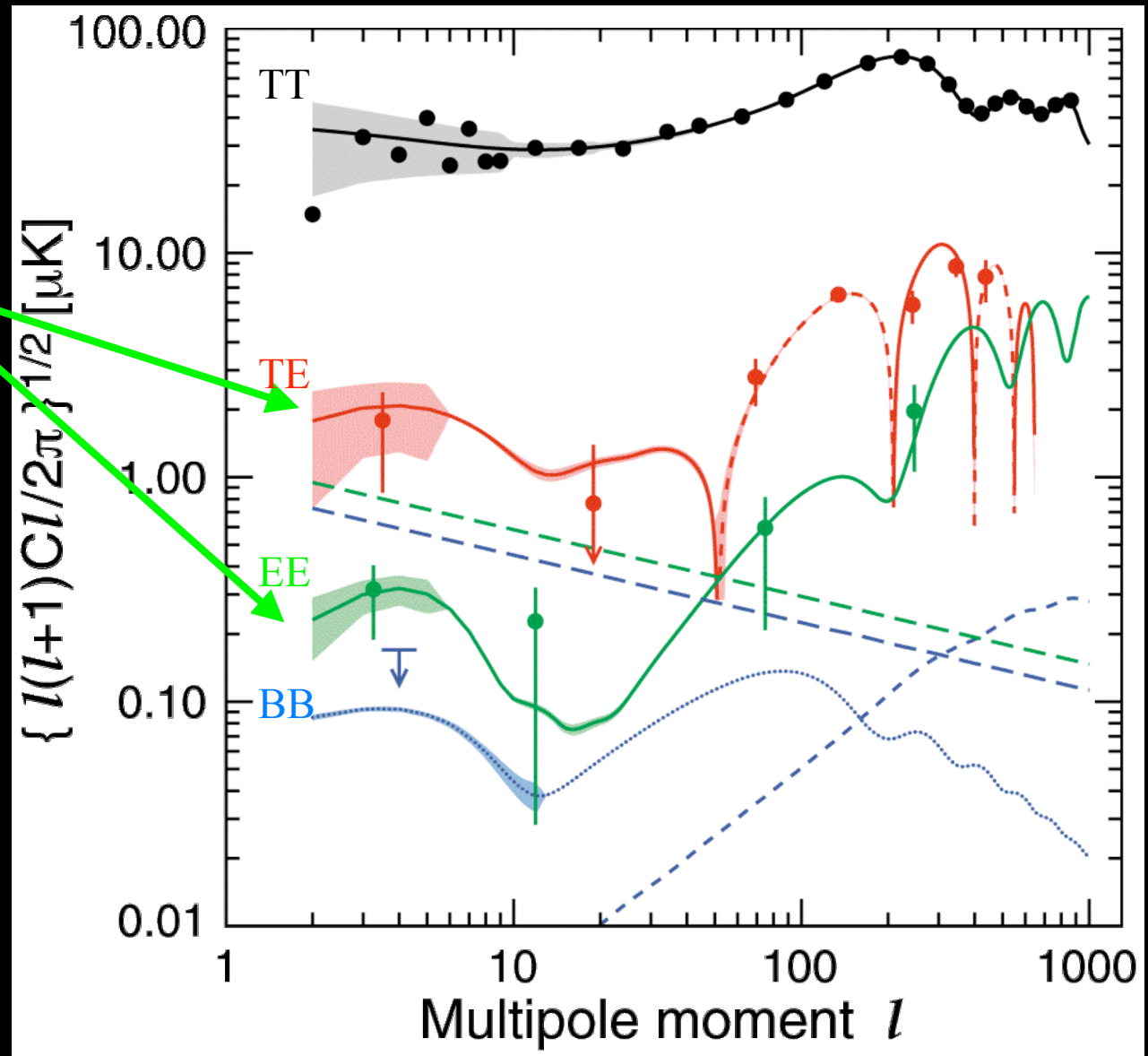
$$\tau = 0.10 \pm 0.03$$

$l = 2--6$, EE only

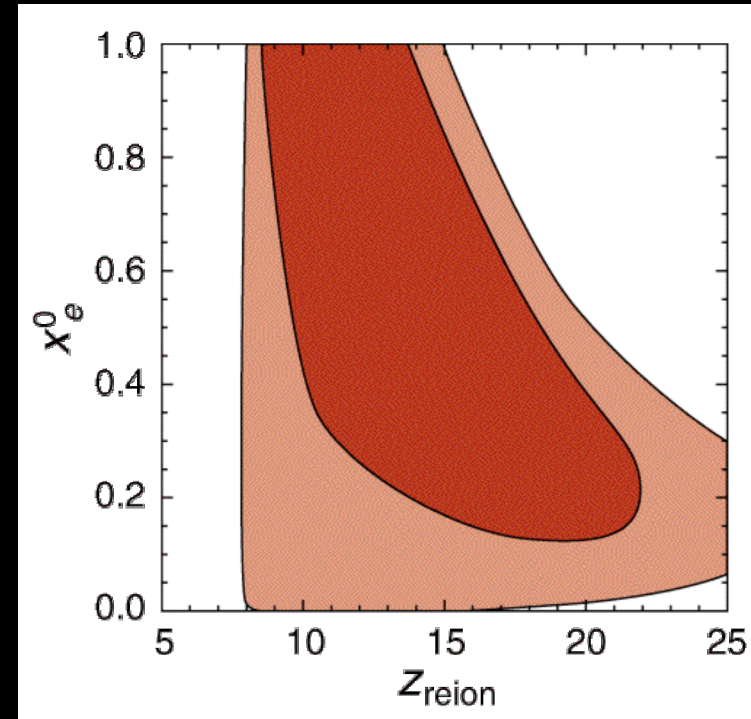
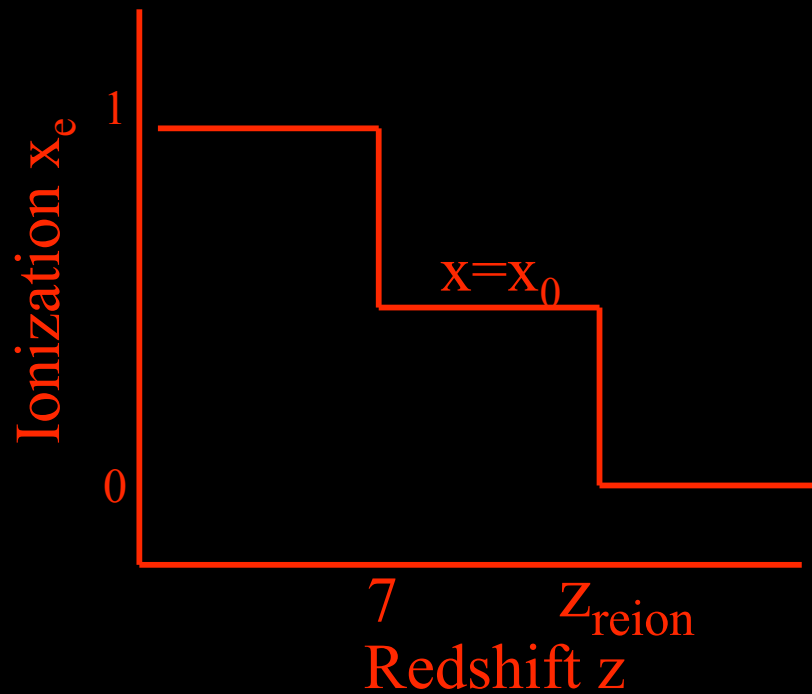
WMAP and CMB Power Spectra

“Reionization
Bump”
Clearly
Detected

$\tau = 0.09 \pm 0.03$
(TT, EE, TE)



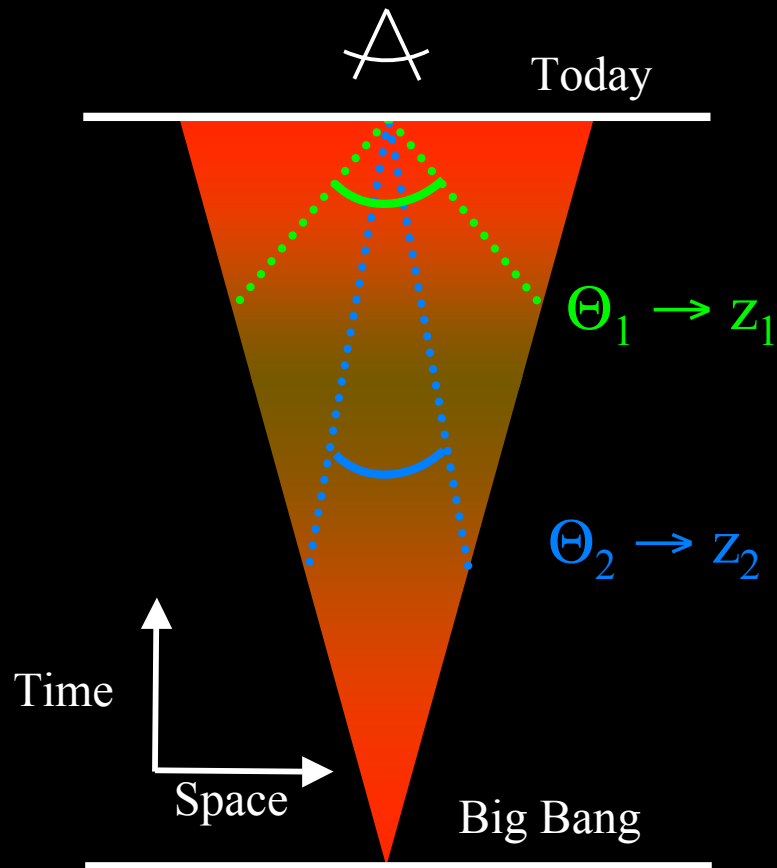
Implications for reionization



Reionization not (yet) well constrained

- “Instantaneous” $x \rightarrow 1$ at $z \sim 11$
- “Two-Step” consistent with $7 < z_r < 30$

(When) Can We Do Better?

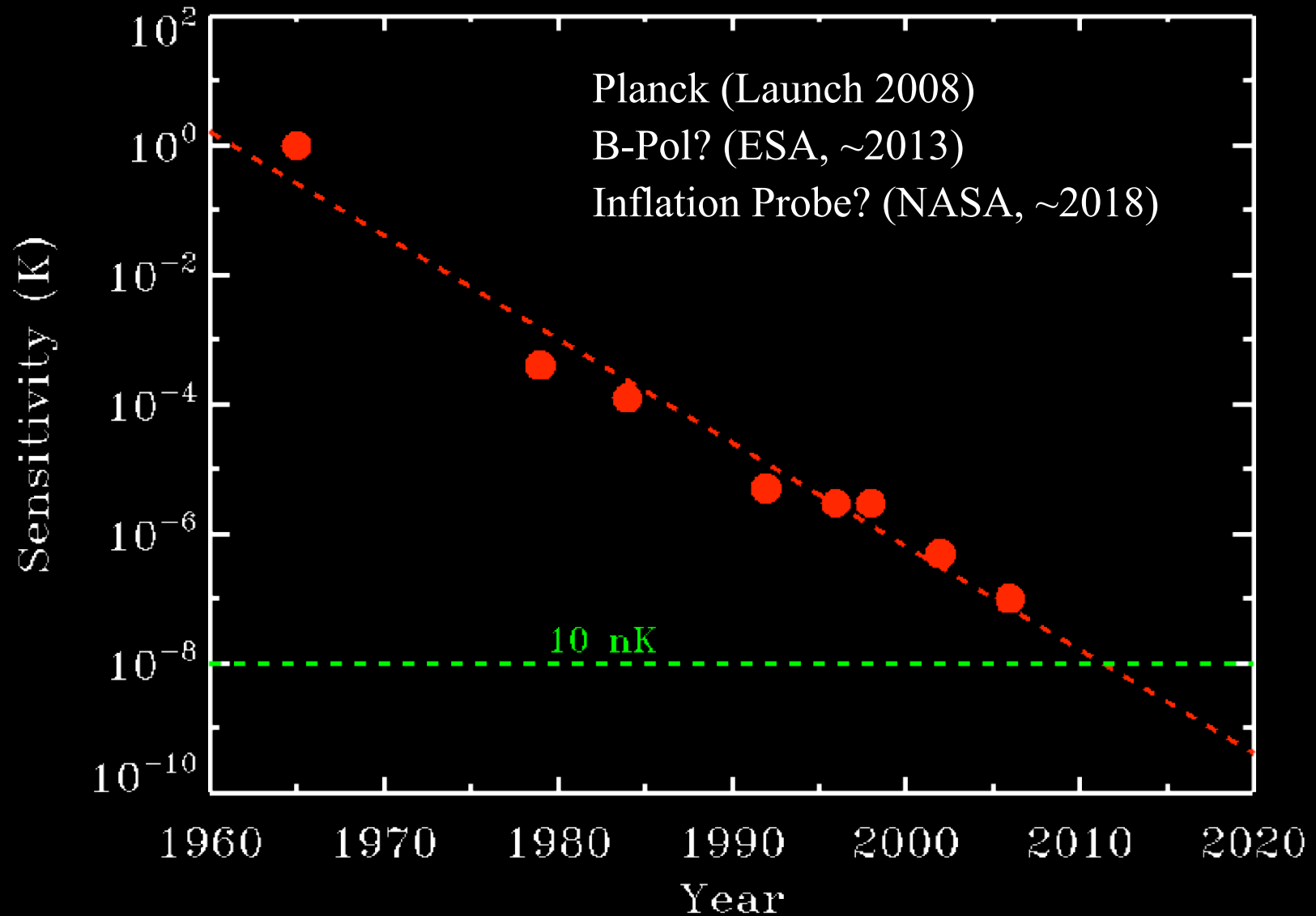


Recall that ...

- Polarization sourced by quadrupole
- Simple mapping of horizon to angle

Hence, invert $EE(\Theta)$ to get $x(z)$

AI's Mystical Crystal Ball

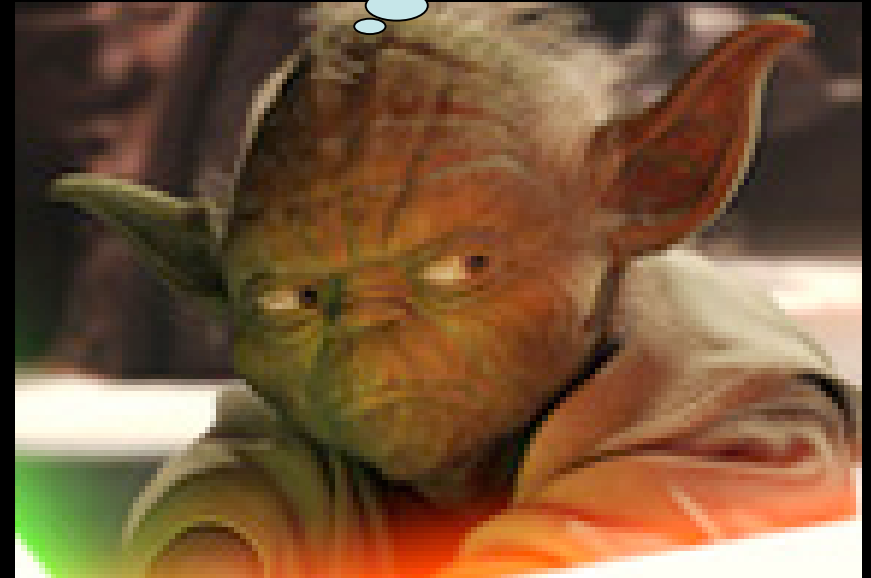


Waiting For ~~Good~~ More Data

Who Knows What Data Lurks In The CMB?

Wait You Must ...

- WMAP: Next Data Release Soon
- Planck: Launch 2008
- Beyond Einstein: Who Knows?



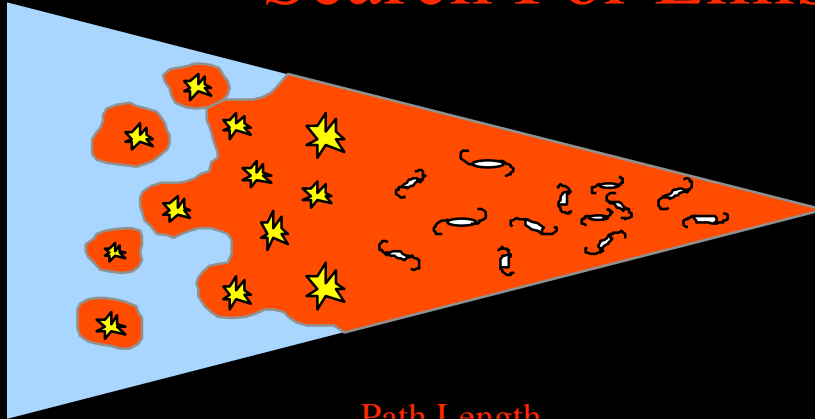
Want Independent Test of Reionization

And We Want It Now!

And Now For Something Completely Different

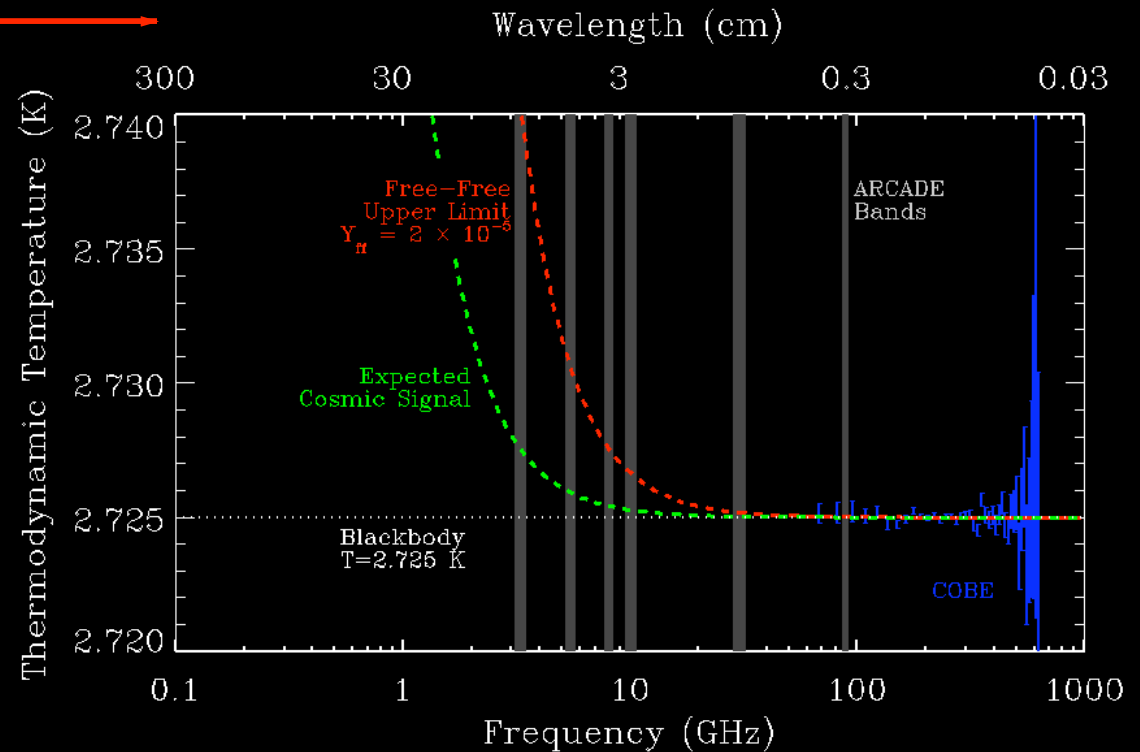


Reionization Part 2: Search For Emission From Ionized Gas



$$\text{Free-free } \Delta T = \int n_e^2 dz$$

Expected Cosmic Signal:
Few mK at 10 cm wavelength



ARCADE:

*Absolute Radiometer for
Cosmology, Astrophysics,
and Diffuse Emission*

A New View of the First Light

Detect Heating From First Stars

- End of cosmic "Dark Ages"
- Beginning of "modern" universe

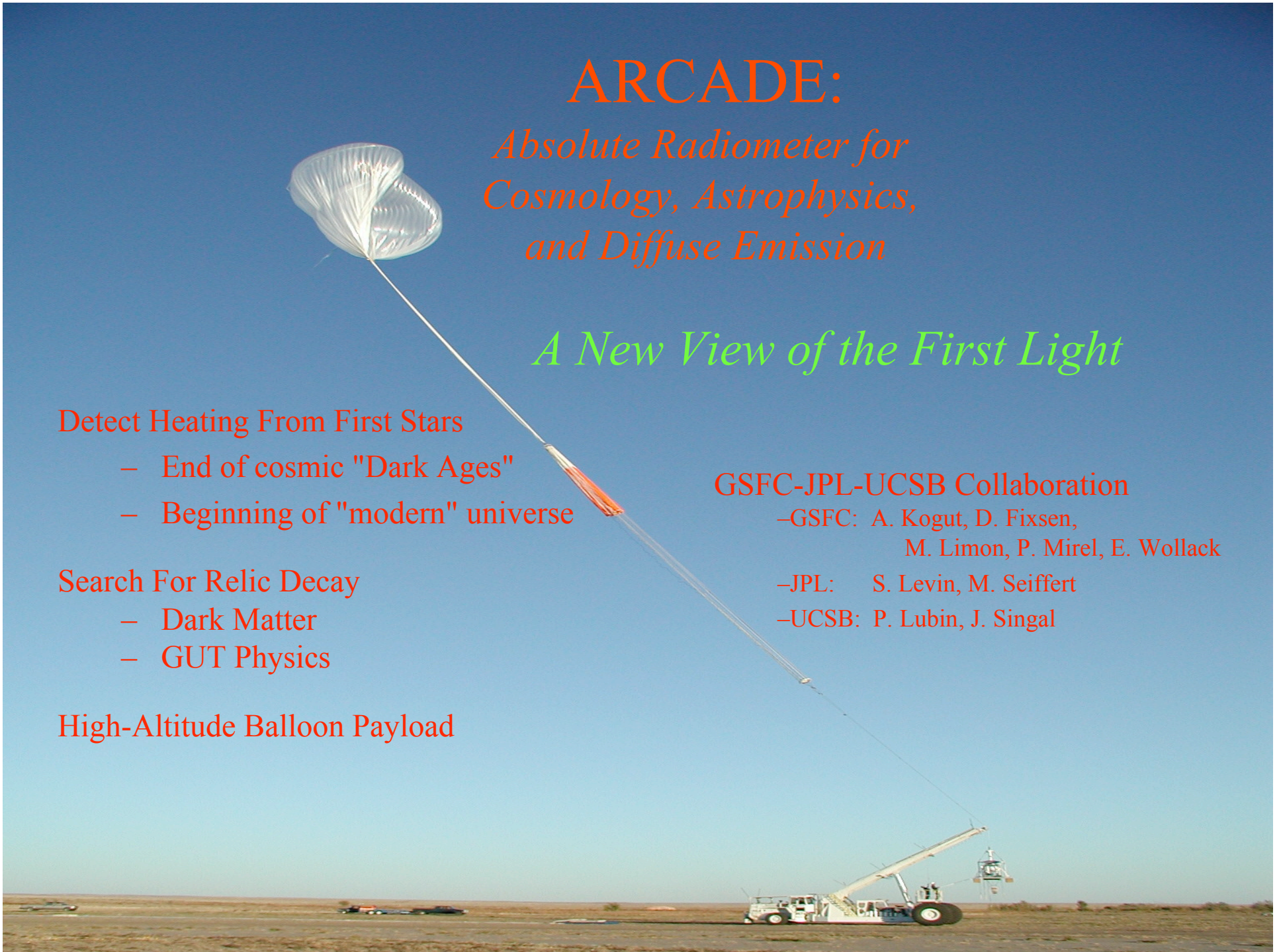
Search For Relic Decay

- Dark Matter
- GUT Physics

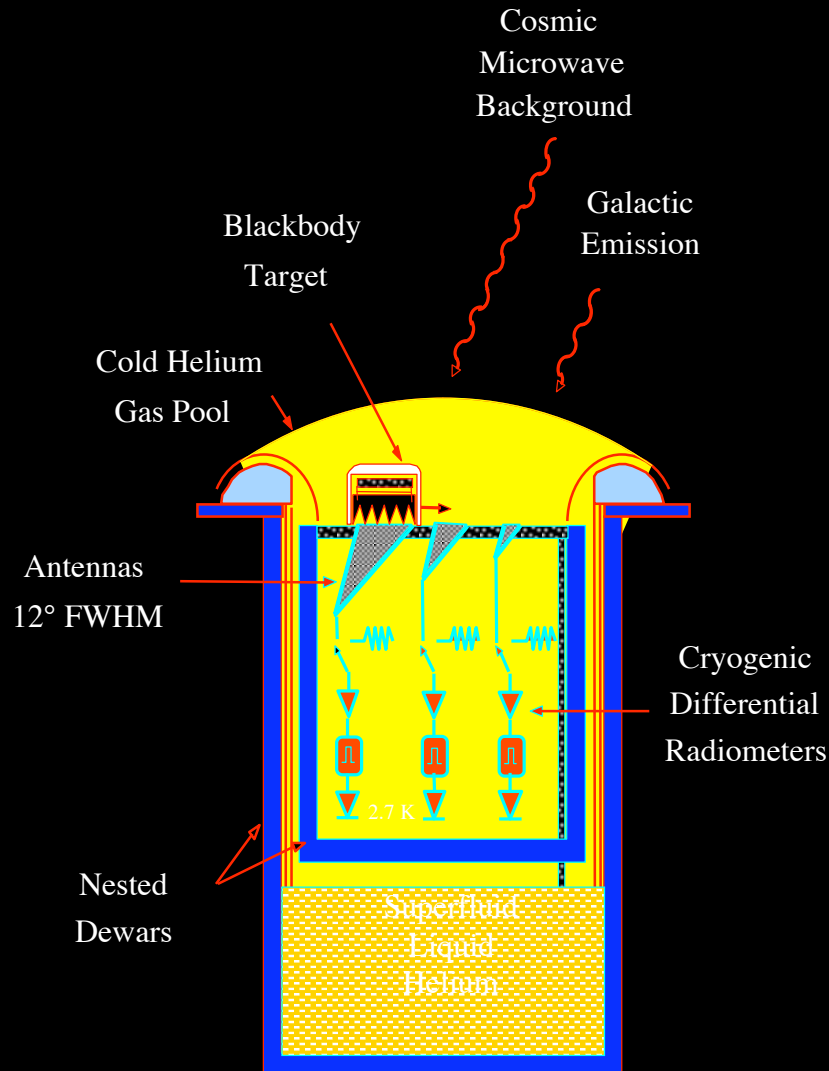
High-Altitude Balloon Payload

GSFC-JPL-UCSB Collaboration

- GSFC: A. Kogut, D. Fixsen,
M. Limon, P. Mirel, E. Wollack
- JPL: S. Levin, M. Seiffert
- UCSB: P. Lubin, J. Singal



ARCADE: Systematics, Not Sensitivity



Eliminate Emission From Warm Objects

- Entire instrument isothermal at 2.7 K
- Open aperture -- no windows

Double-Nullled Design

- Compare sky horn to internal load
- Exchange sky with external calibrator

Thermal Experiment, Not Radiometric

- Lots of superfluid plumbing
- Absolute scale verified via Λ transition

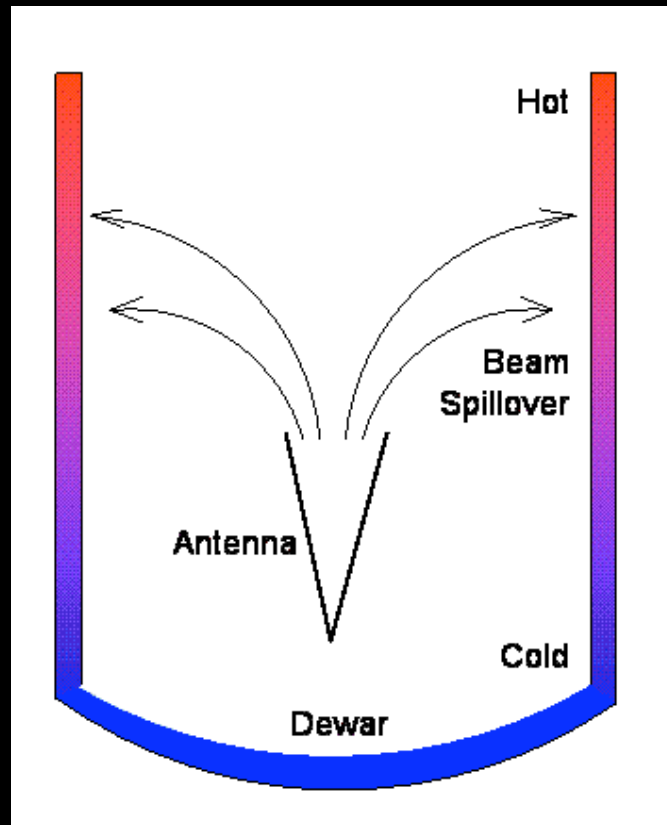
Measure CMB Spectrum to mK precision from 3 GHz to 100 GHz

Stupid Dewar Tricks



It ain't easy
being cold ...

Where, oh where do my cold optics go?

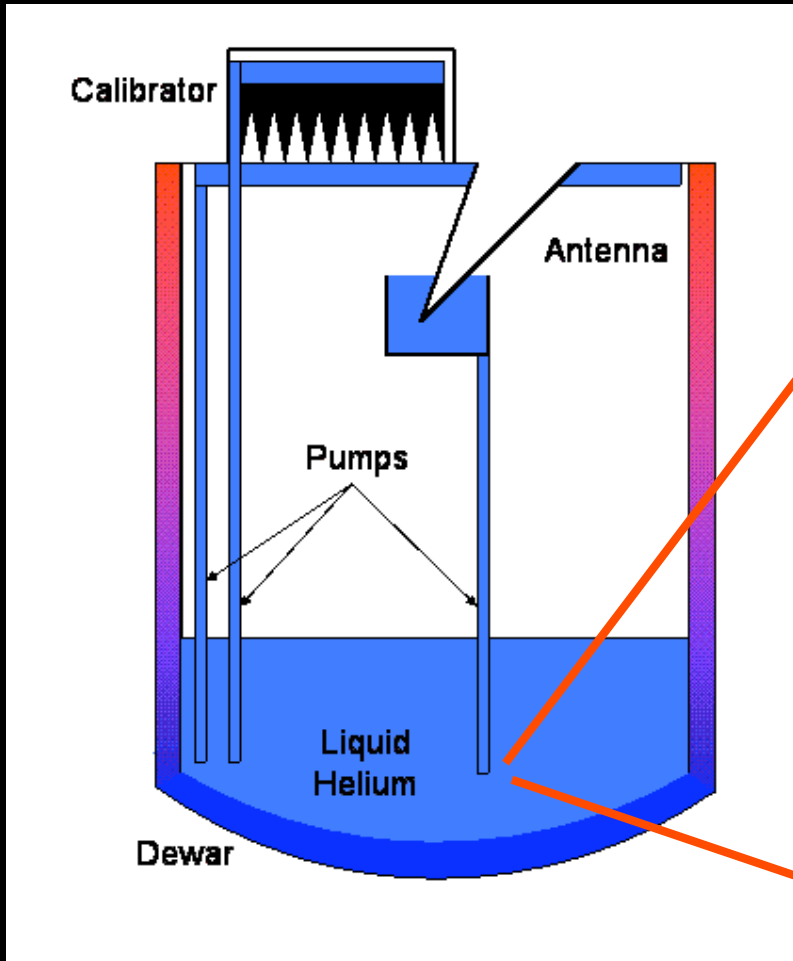


Beam Spillover:

*Put the instrument at the TOP
of the dewar*

Put the instrument where the interference ain't

Chilling Out

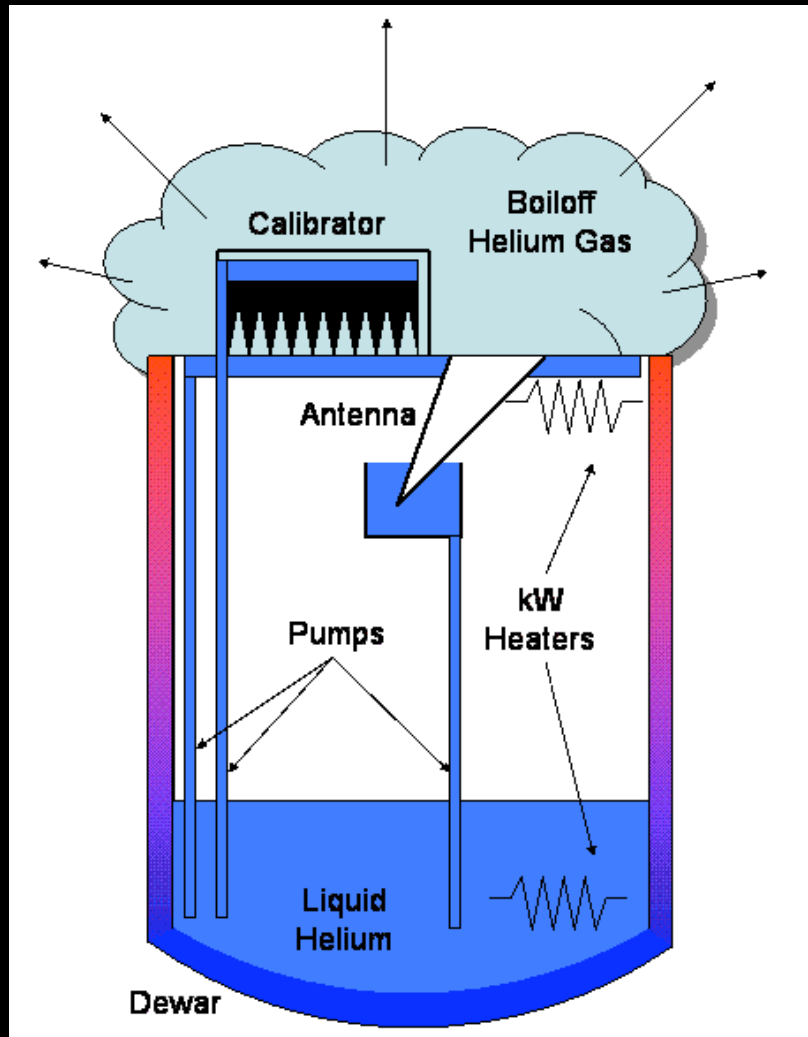


Fountain-effect pumps move superfluid LHe on industrial scales



Use superfluid LHe to force isothermality

Scrape THIS Off Your Windshield ...

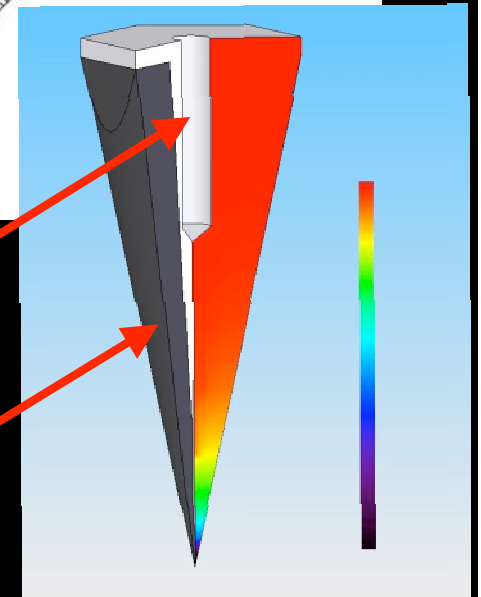
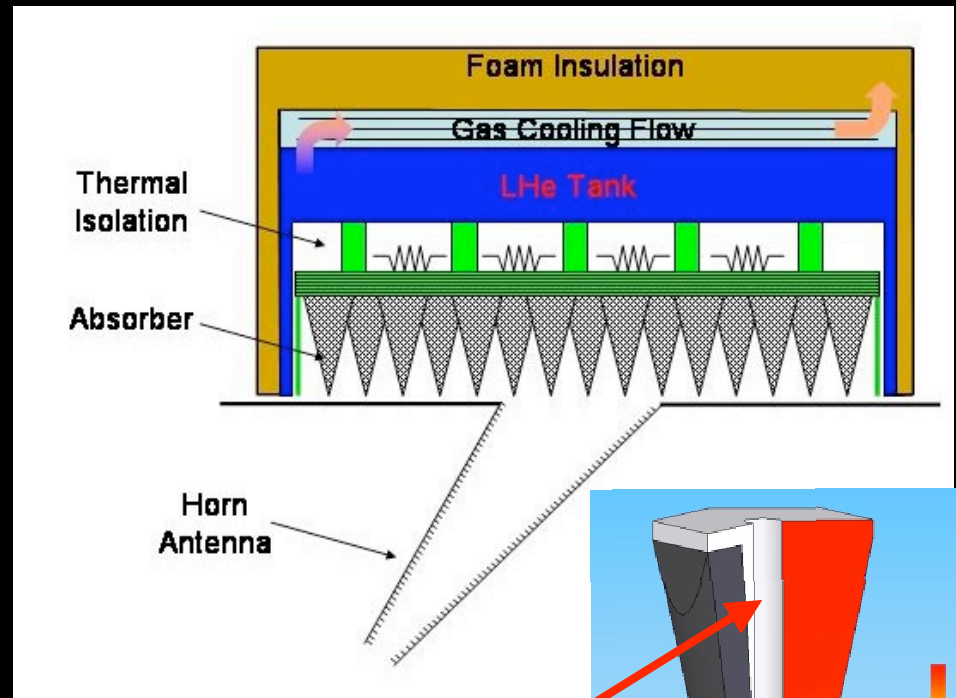
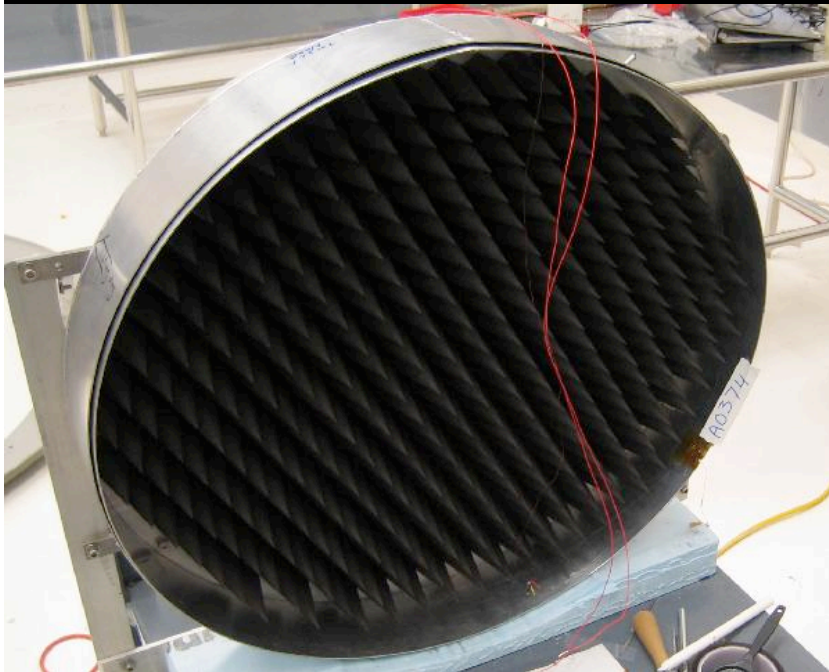


No Windows: Cryogenic Open Aperture

- 3500 liter open bucket dewar
- 2100 liters at launch
- kW heaters to force boiloff at float

5 cubic meters per second outgassing at float!

External Calibrator



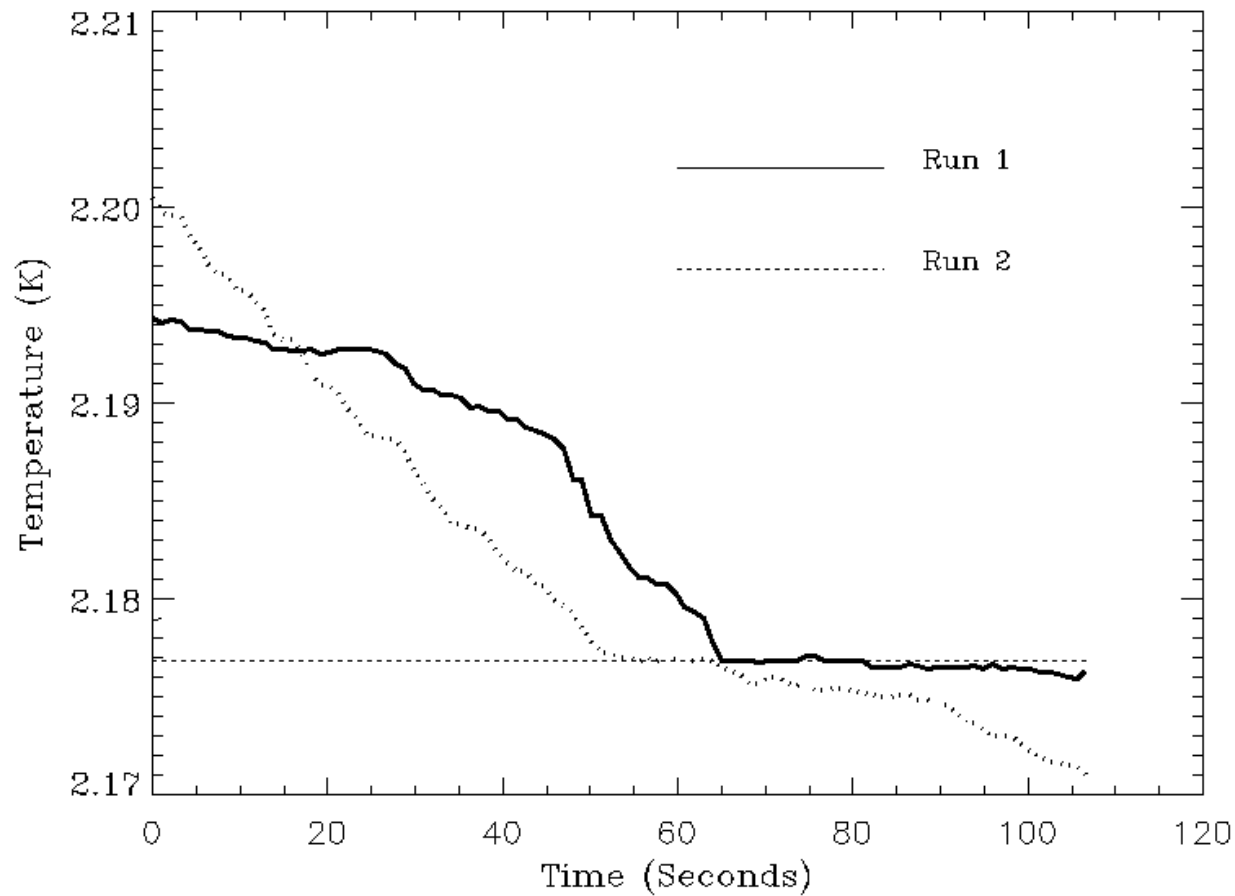
Thermally
conductive core

Emissive skin

Black: Emissivity > 0.99997 across 5 octaves

Isothermal: 95% of volume within 5 mK

Thermometry and Lambda Transition



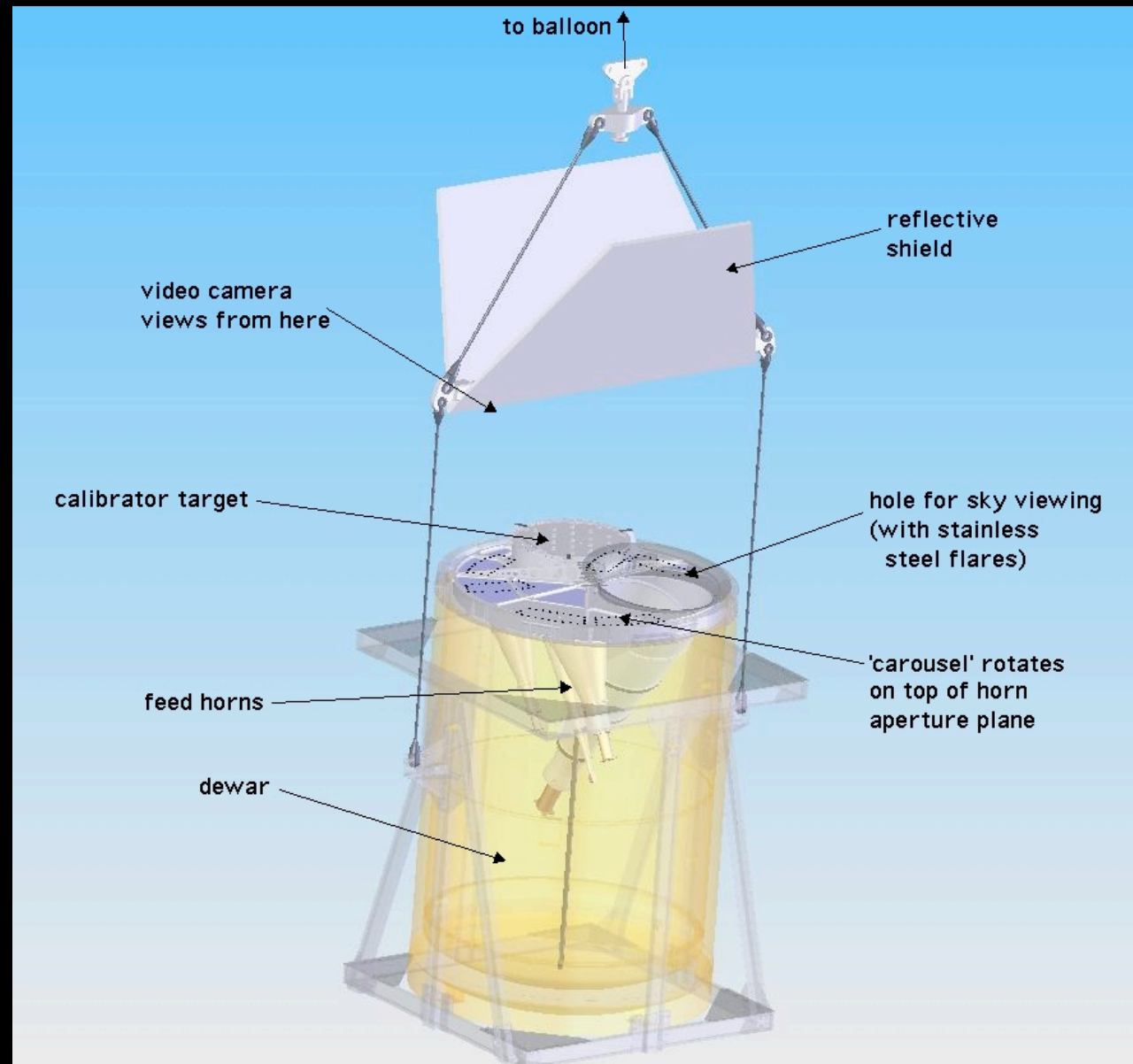
Accurate within 1 mK
Stable over 6 years!

2006 Payload: Flying Hot Tub



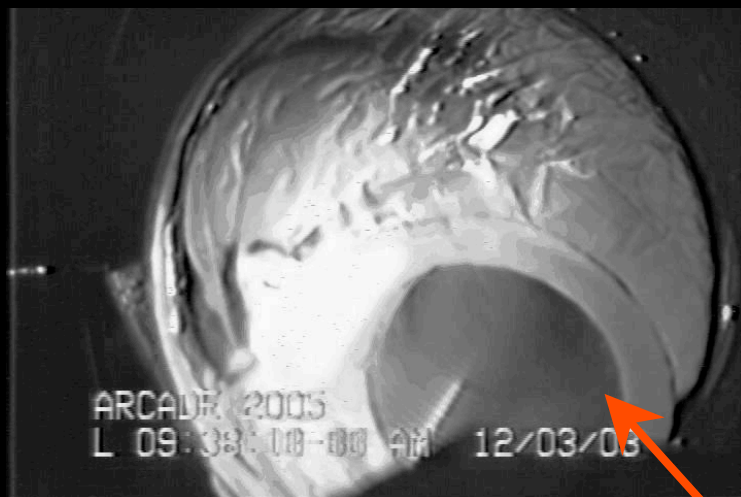
But Did It All Work?

2006 In-Flight Video



Open-Aperture Concept Works!

Data from July 2006 Flight



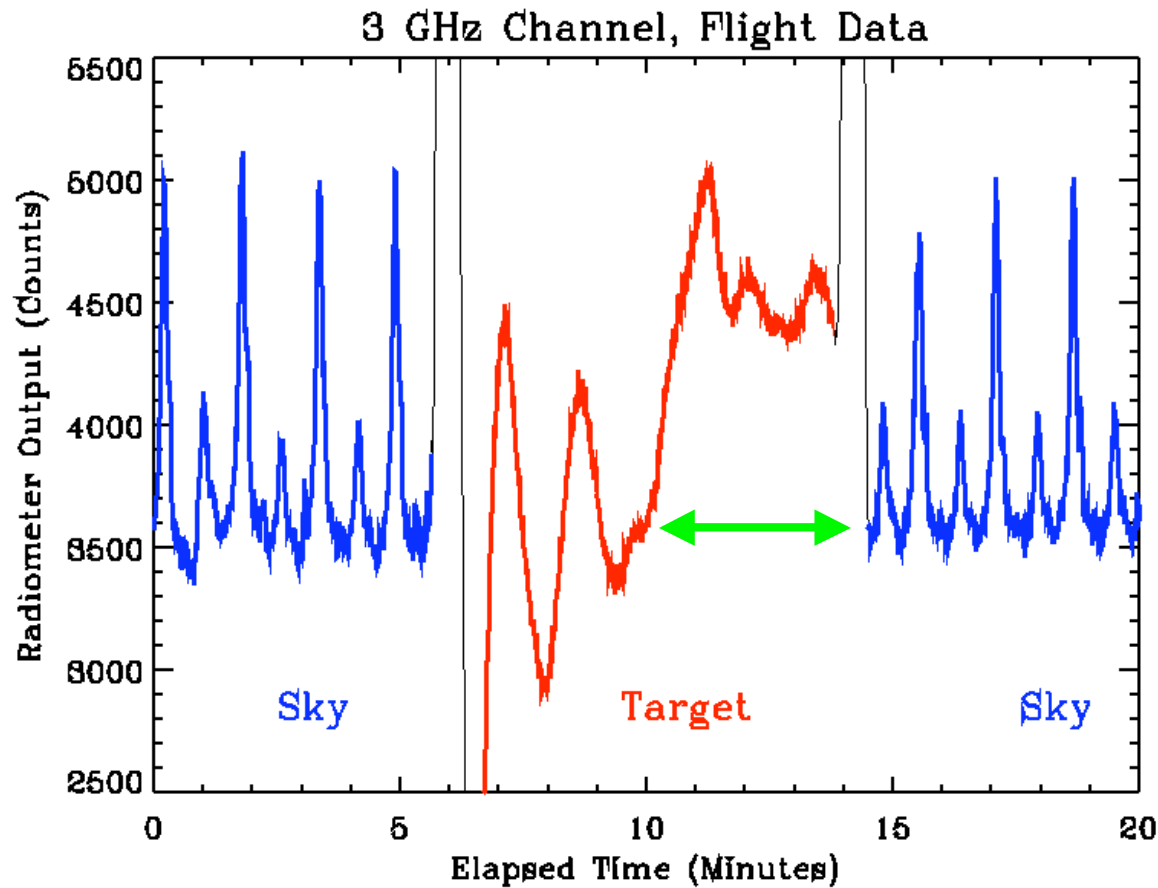
No Nitrogen Ice Accumulation
After 2 Hours Open Operation!

*Interesting implications for future
sub-mm missions ...*



3 GHz Antenna
0.7 m diameter

Thermal Nulling Works!

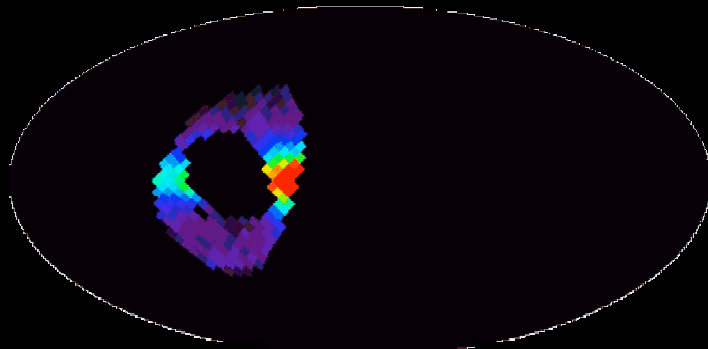


Galactic plane crossings


High-latitude sky

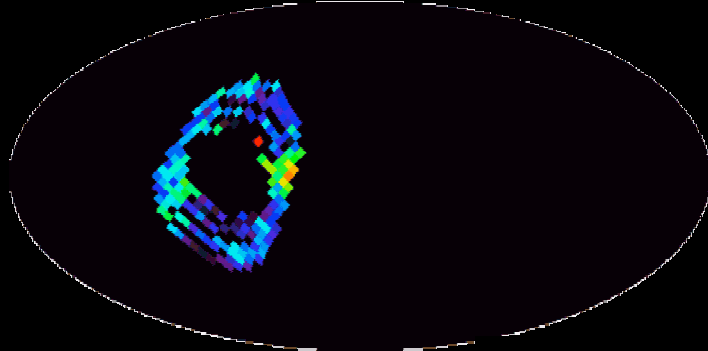
Command target to
match voltages,
then simply read off
sky temperature

Sky Coverage

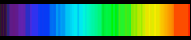


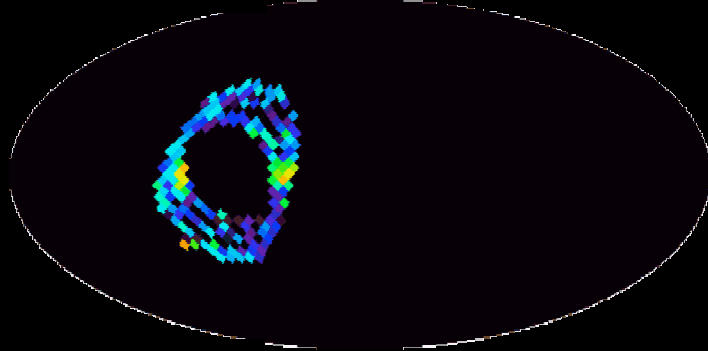
3 GHz

0 mK  300 mK




7 GHz

0 mK  70 mK



10 GHz

0 mK  35 mK

2006 Flight Summary

3+ Hours of data at float

$\langle T_{\text{cal}} \rangle = 2.7206 \text{ K}$ Mean

RMS = 162 mK Commanded

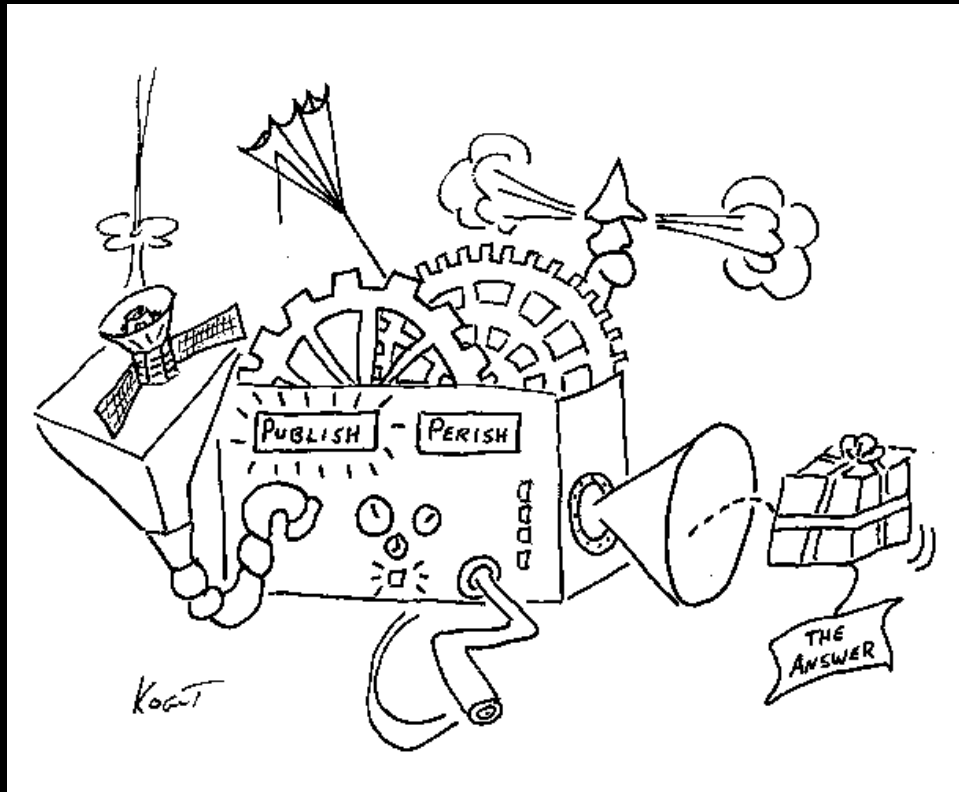
Radiometers linear to $\ll 1 \text{ mK}$

Data analysis nearly
complete ...

Stay tuned!

CMB and Reionization: What Next?

Data Required to Constrain Ionization At High Redshift



CMB Polarization: Reionization

- WMAP Detection (EE and TE)
 $\tau = 0.09 \pm 0.03$
 $z_r \sim 11$ for instantaneous transition
- WMAP continues to operate; multiple new experiments planned/in progress
- Future detection through E x E can be inverted to yield ionization history $x_e(z)$

CMB Spectrum: High-z Structure

- ARCADE shows viable technology
- 2006 flight should see signal from reionization & structure formation
- Refly payload (or space mission) for ultimate limits