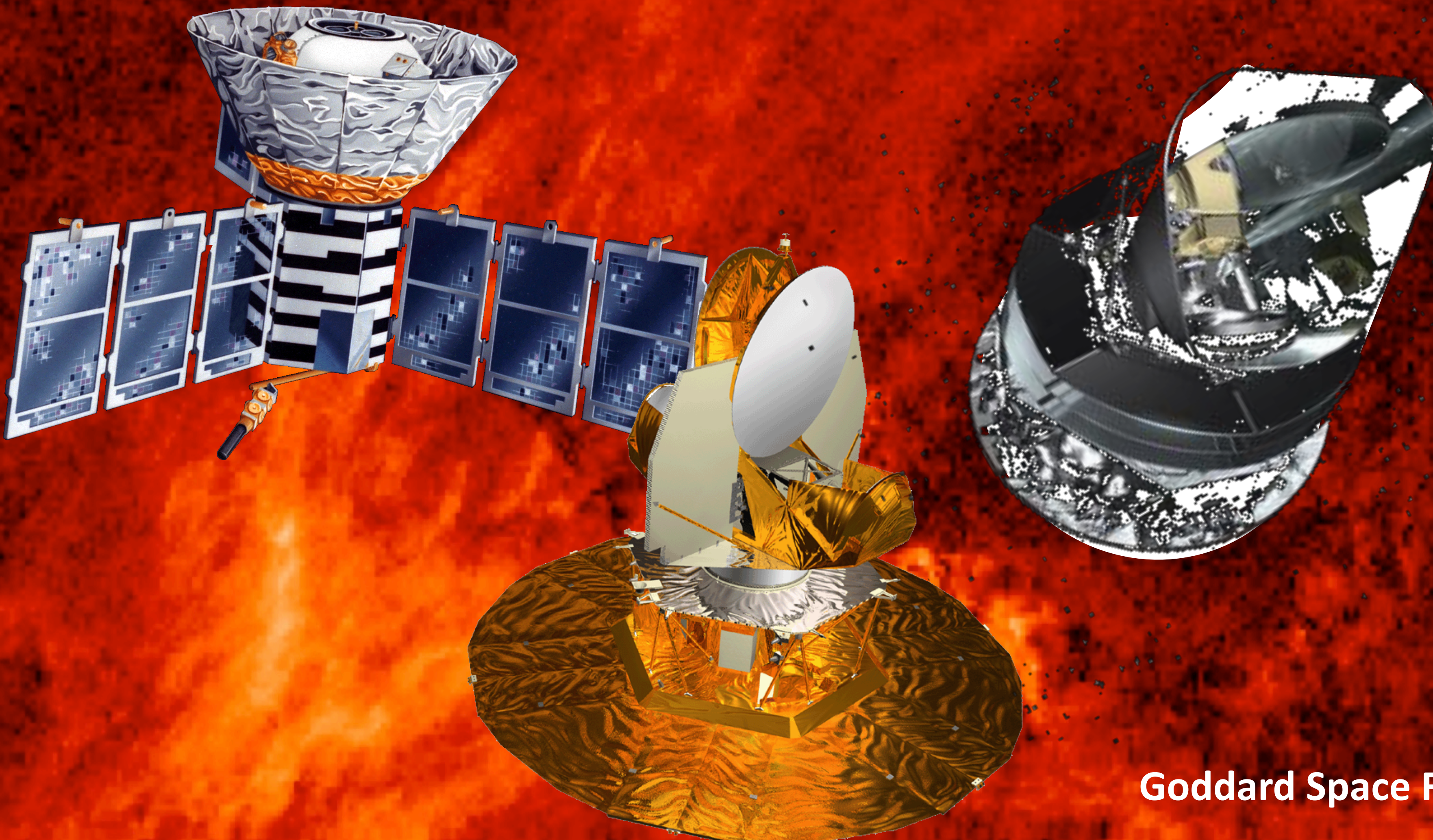
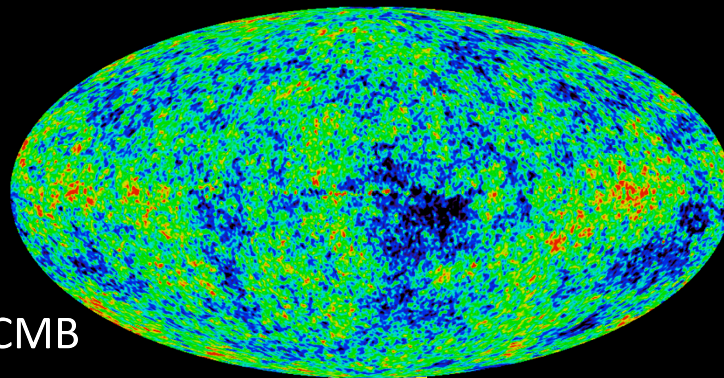
Design Challenges for Future CMB Experiments



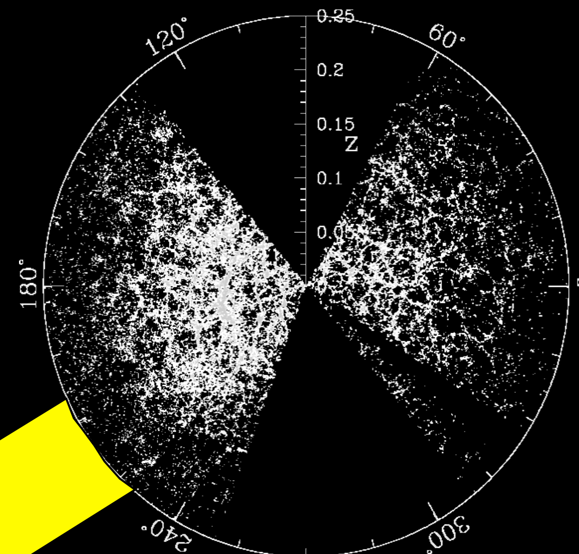
Al Kogut
Goddard Space Flight Center

Precision Cosmology

Lensing



CMB



Galaxy Surveys

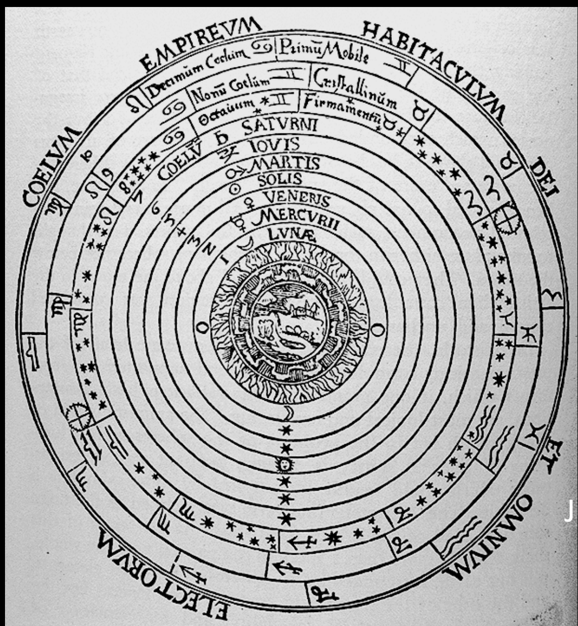
ΛCDM

6 adjustable parameters

"Standard Model" for cosmology

Successfully explains many disparate measurements

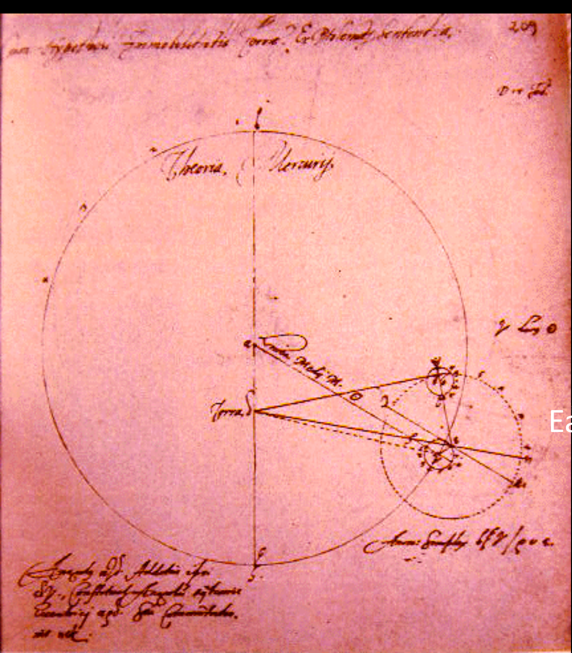
Another Successful Model

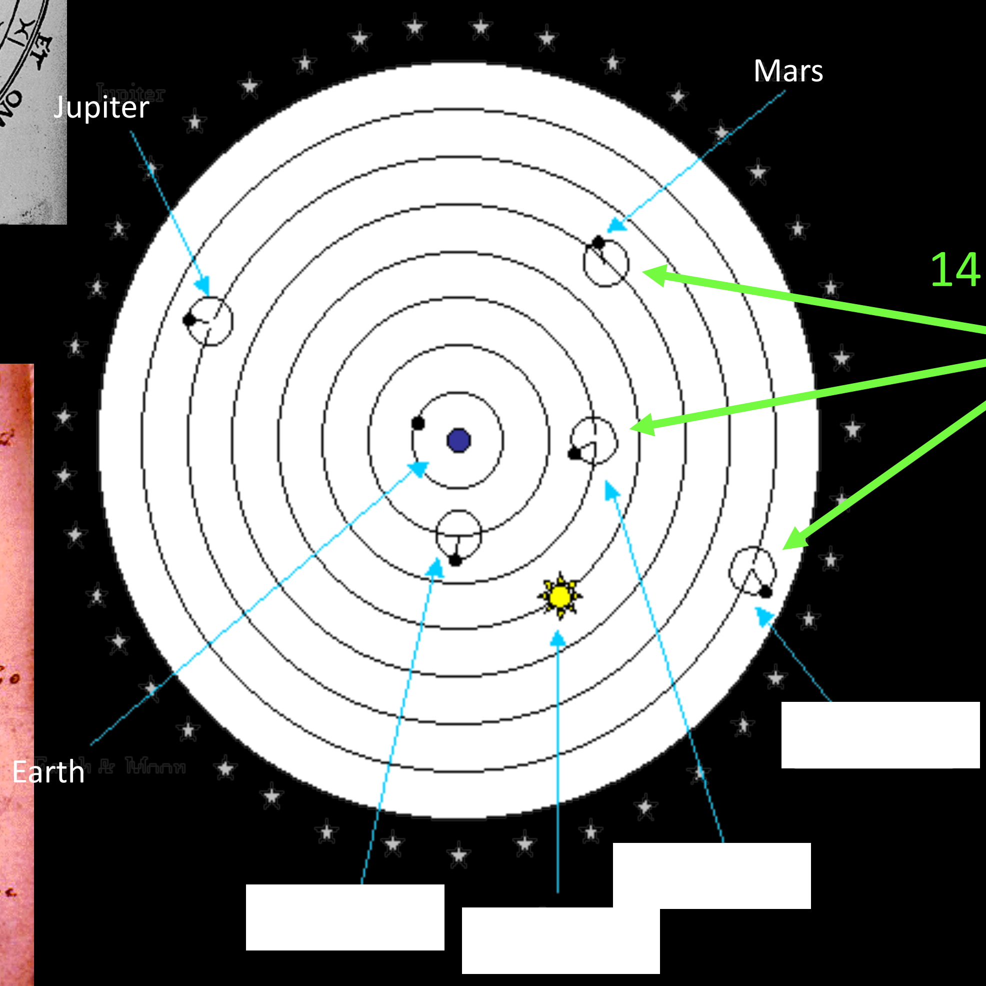


Aesthetics and Observation

Astonishingly successful

Modestly complicated

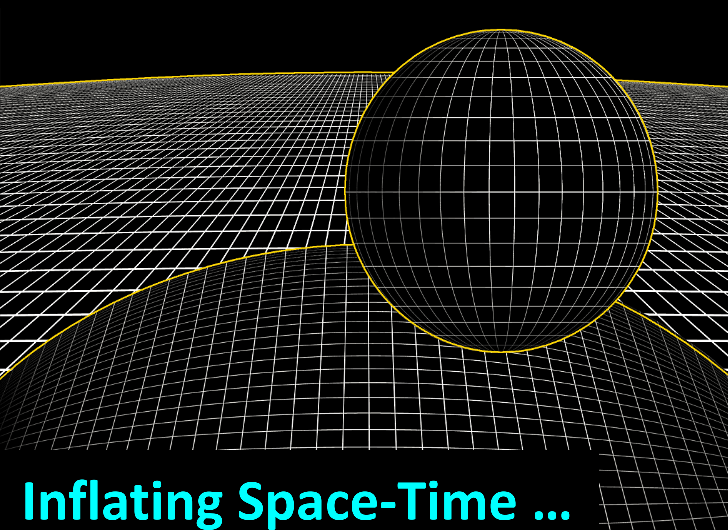




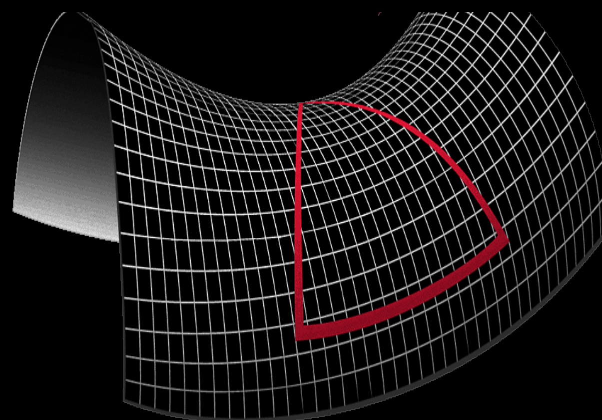
14 adjustable parameters

(eventually 28)

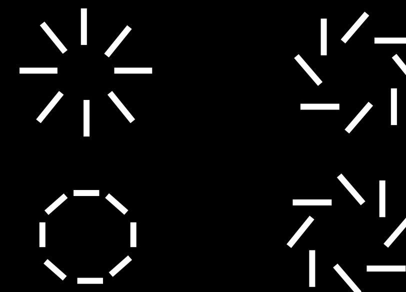
Testing Inflation with CMB Polarization

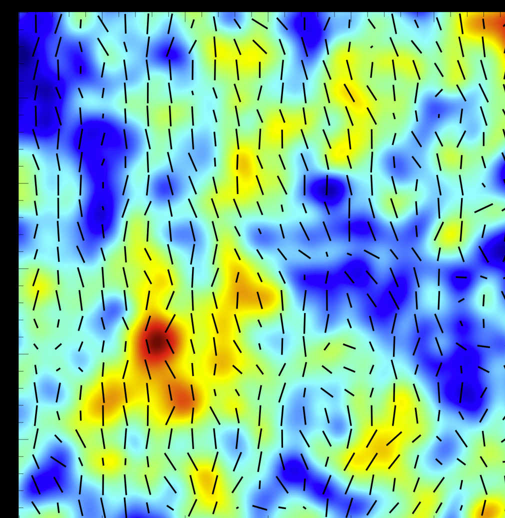


Inflating Space-Time …



Creates Gravitational-Wave Background …

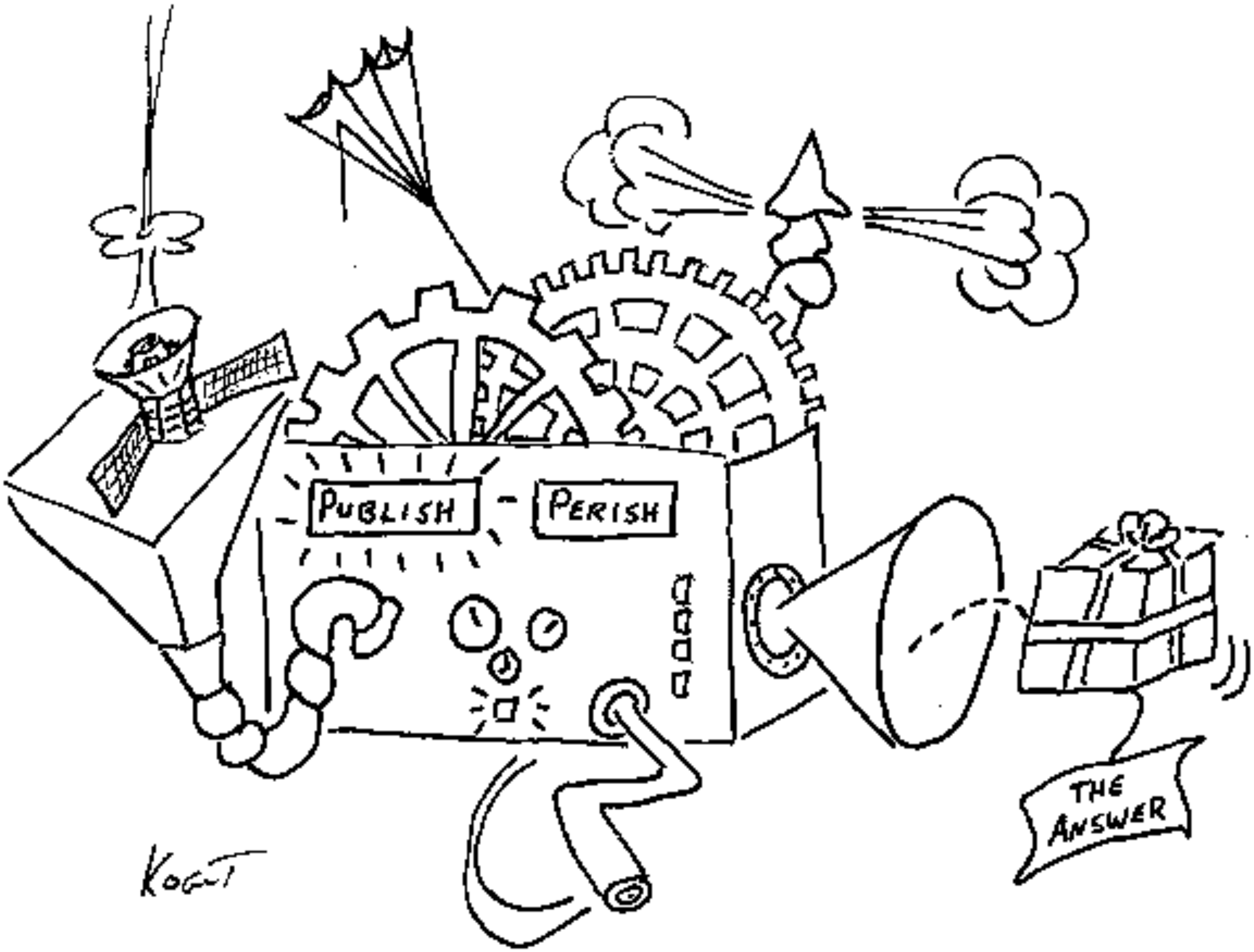




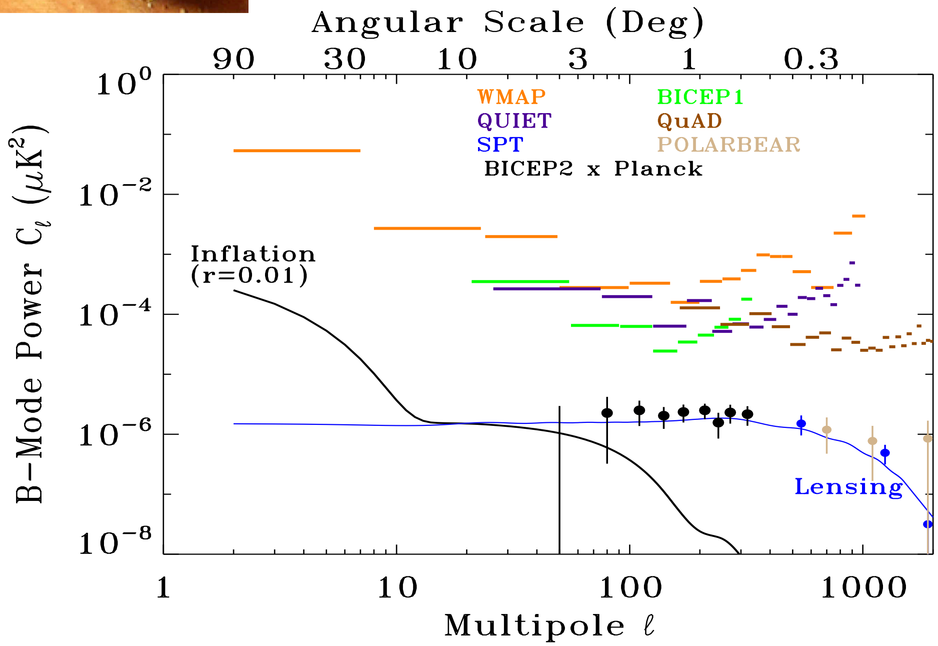
Which Sources CMB Polarization

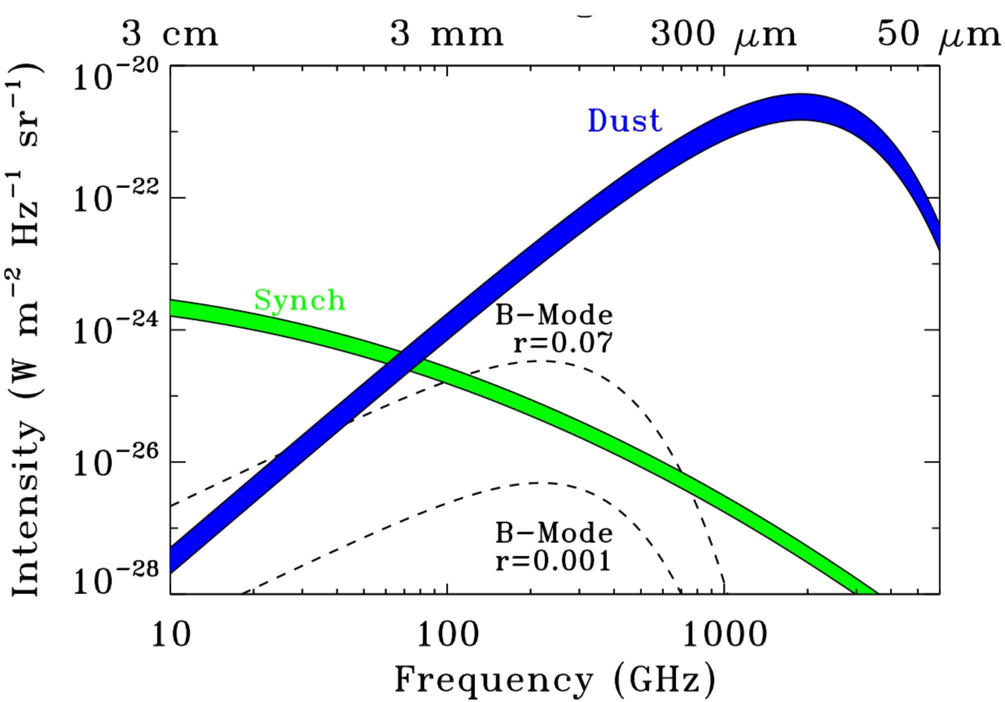
B-Mode Polarization:
“Smoking Gun” Signature of Inflation

A Theorist's View of Instrumentation



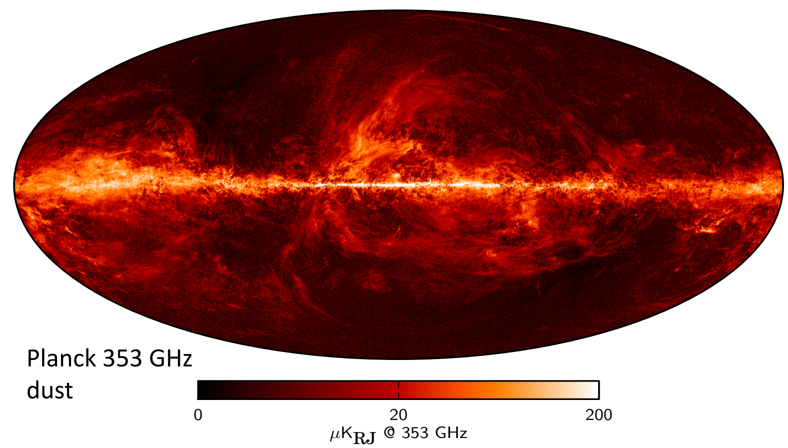
B-modes in a Nutshell



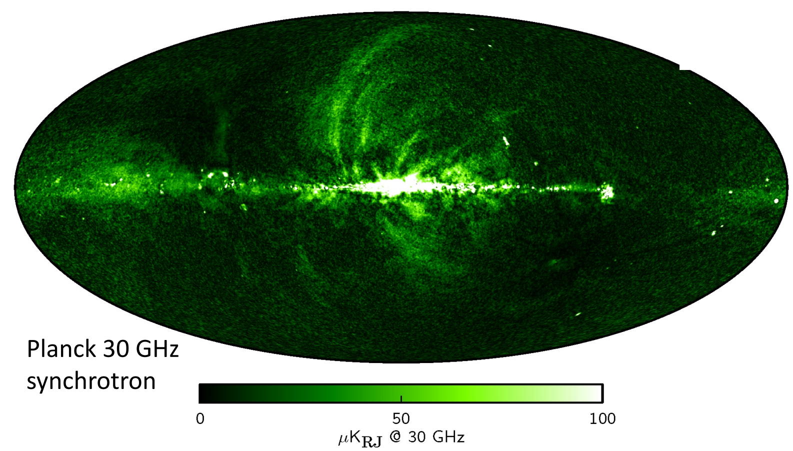


Requirements for Detection

- Photon-Limited Sensitivity
- Accurate Foreground Subtraction
- Immunity to Instrumental Effects



Planck 353 GHz dust



Planck 30 GHz synchrotron

Challenge #1: Sensitivity

Small Signal

CMB intensity $\sim 4 \times 10^{-18}$ W m^{-2} Hz^{-1} sr^{-1}
~ 2.725 K

B-modes (r=0.001) $\sim 4 \times 10^{-27\ 18}$ W m^{-2} Hz^{-1} sr^{-1}
~ 3 nK

Need to measure difference between two orthogonal polarization states to **part-per-billion accuracy**

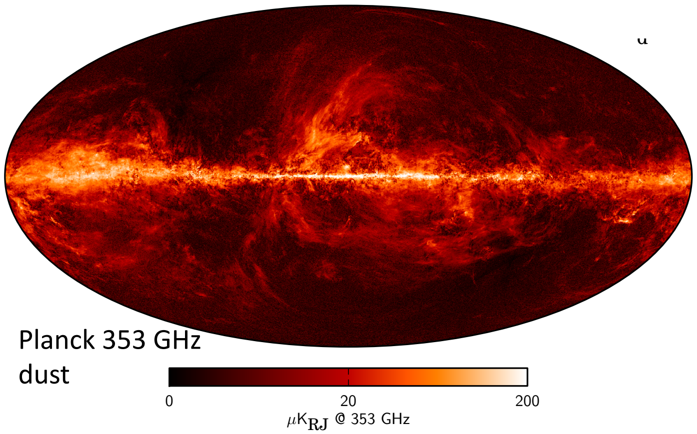
Photon Noise

$\Delta T \sim 25\ \mu K \sqrt{s}$ for single-mode bolometer with 30% bandwidth

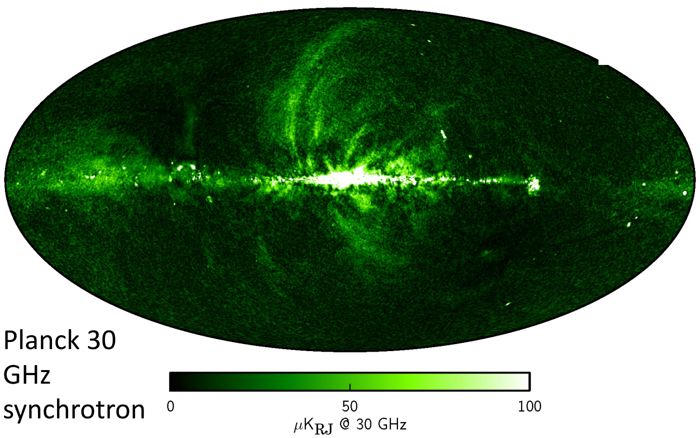
Reaching few nK requires $\sim 10^8$ s integration or 10^8 bolometers
(per beam spot on the sky)

Solution: Collect LOTS of photons!

Challenge #2: Foregrounds

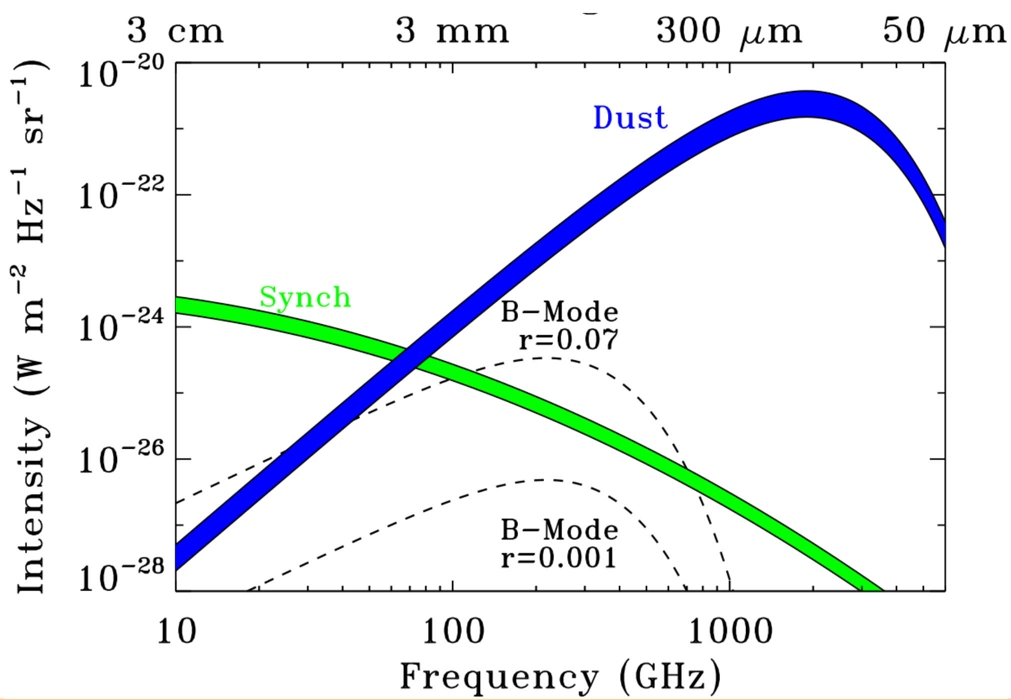


Planck 353 GHz dust



Planck 30 GHz synchrotron

Separate CMB from foreground emission using difference in frequency spectra and spatial distribution



Foregrounds Brighter Than Primordial Signal – Everywhere!

A Rogue's Gallery of Foregrounds

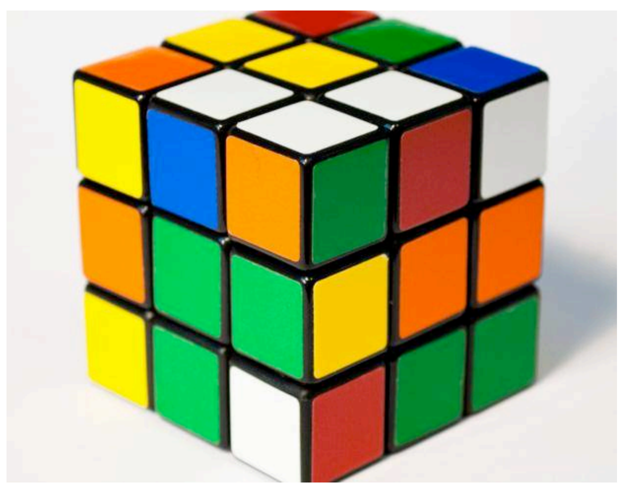
Definitely Polarized

Synchrotron
Thermal dust
Radio sources
CMB lensing

Probably not (very) polarized

Free-free emission
Anomalous microwave emission
Galactic lines (CO, C+, ...)
Cosmic infrared background

Sorting it out to part-per-thousand accuracy or better requires frequency, spatial, and astrophysical information

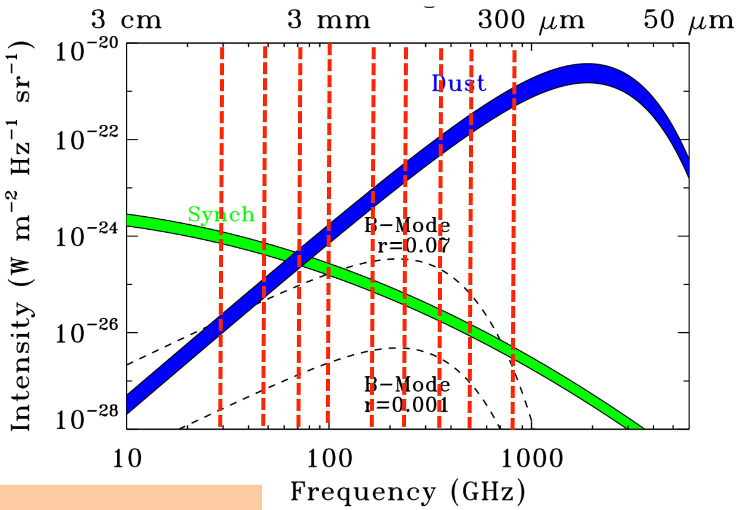


A Cautionary Tale

What can happen when your model is simple, but the Universe is not ...

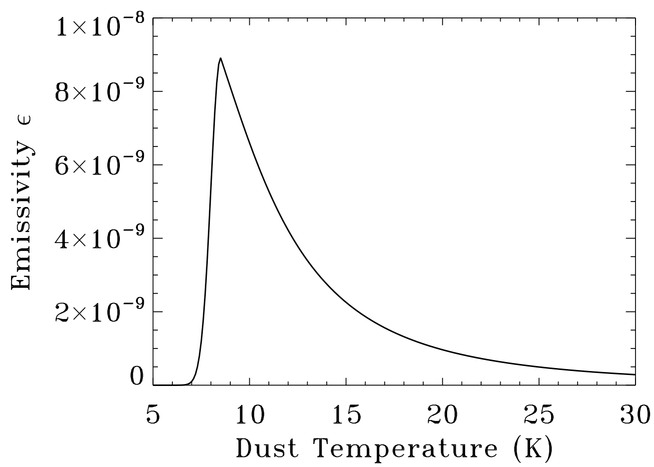
Phenomenological dust model $I(\nu) = \epsilon\, \nu^{\beta}\, B_{\nu}(T)$

How many components to fit?



Test:

- Generate simulated sky using broad distribution of dust temperatures
- Fit simulated sky using only two temperatures



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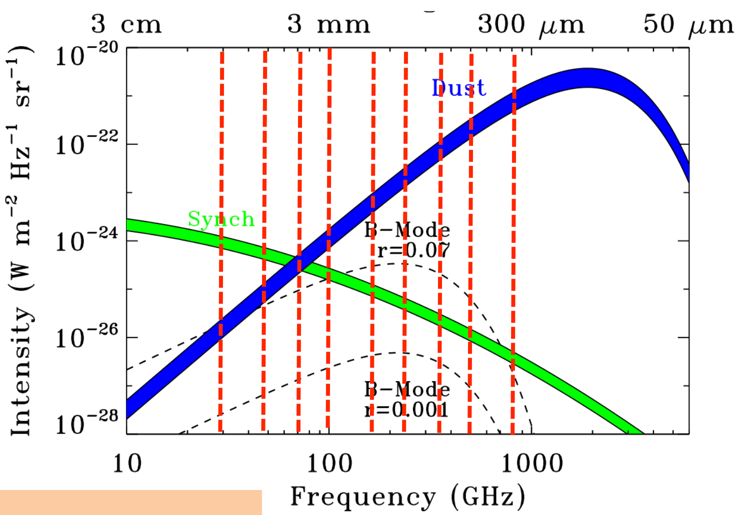

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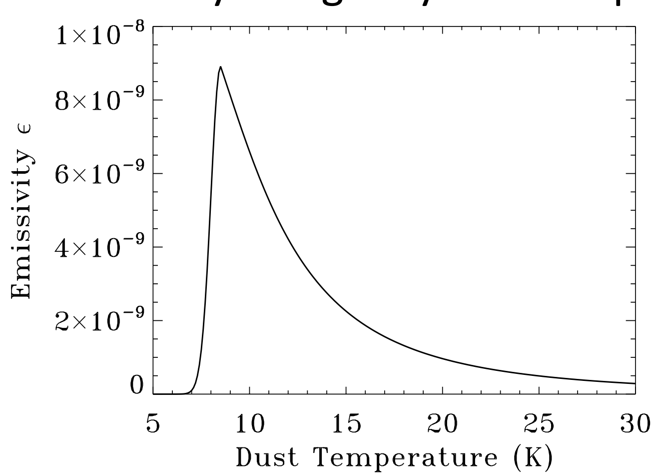
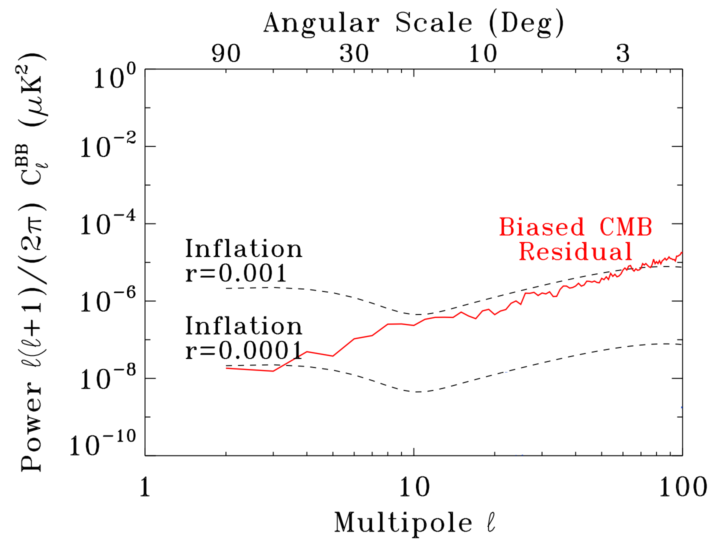
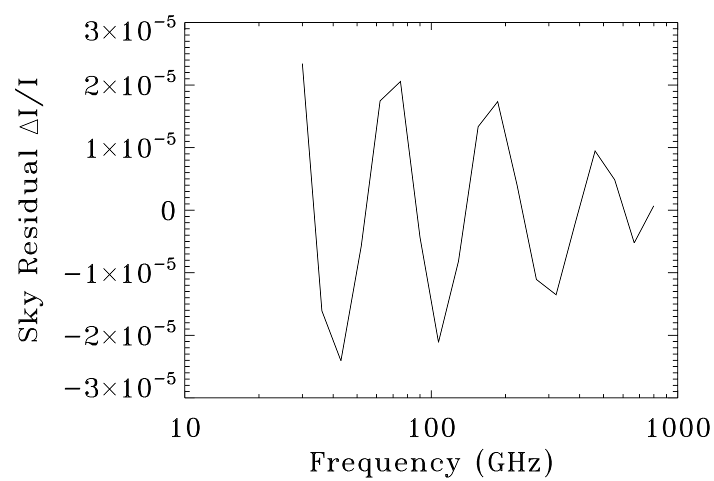


Results: CMB biased at r ~ 10^{-3}



While fitting combined emission to 30 parts per million precision



The Problem With Parametric Models

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

Solution:

Don't try to think more about the same data,

Think about getting more data!

Measure frequencies above 1 THz
or
CMB sensitivity 10^{-6} per channel

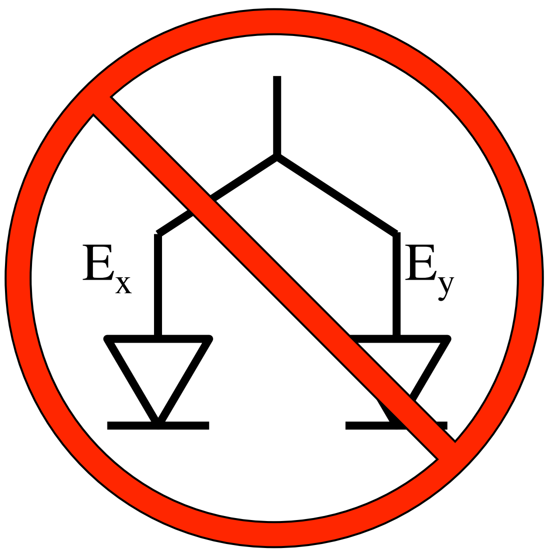
Systematic Errors:
What You Don't Know Can Hurt You

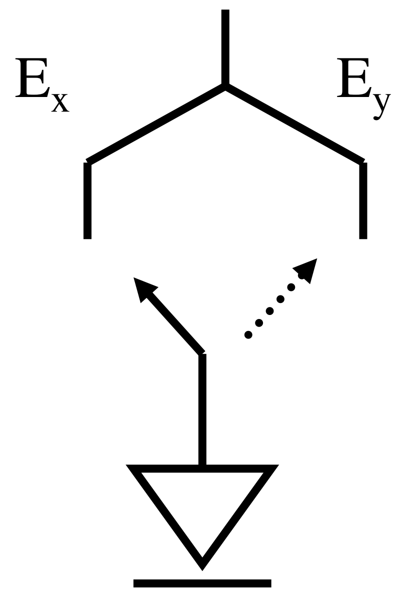
Challenge #3: Systematic Errors

How Do You Measure Signals at Parts-Per-Billion Level?

Everything in the Universe is hotter than a few nK!

- Stray light
- Instrumental emission
- Differential calibration

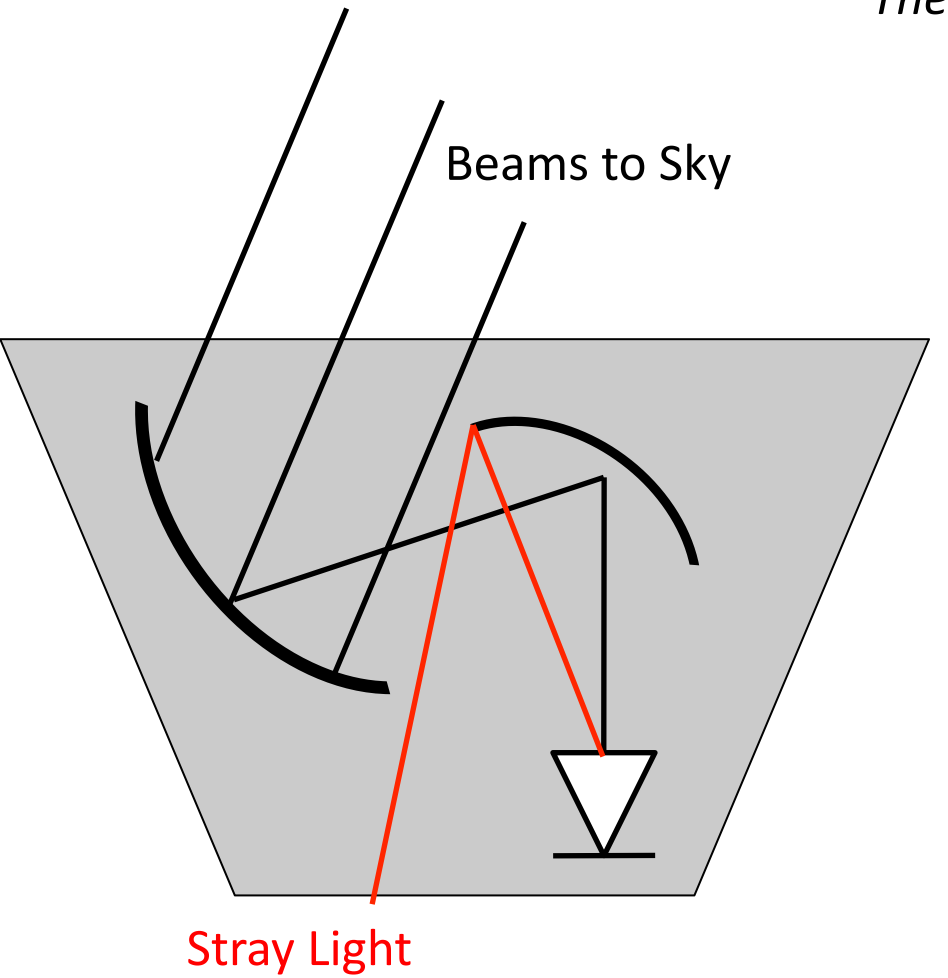




Solution: Modulate polarized signal

Challenge #3: Systematic Errors

The Joy of Nulling

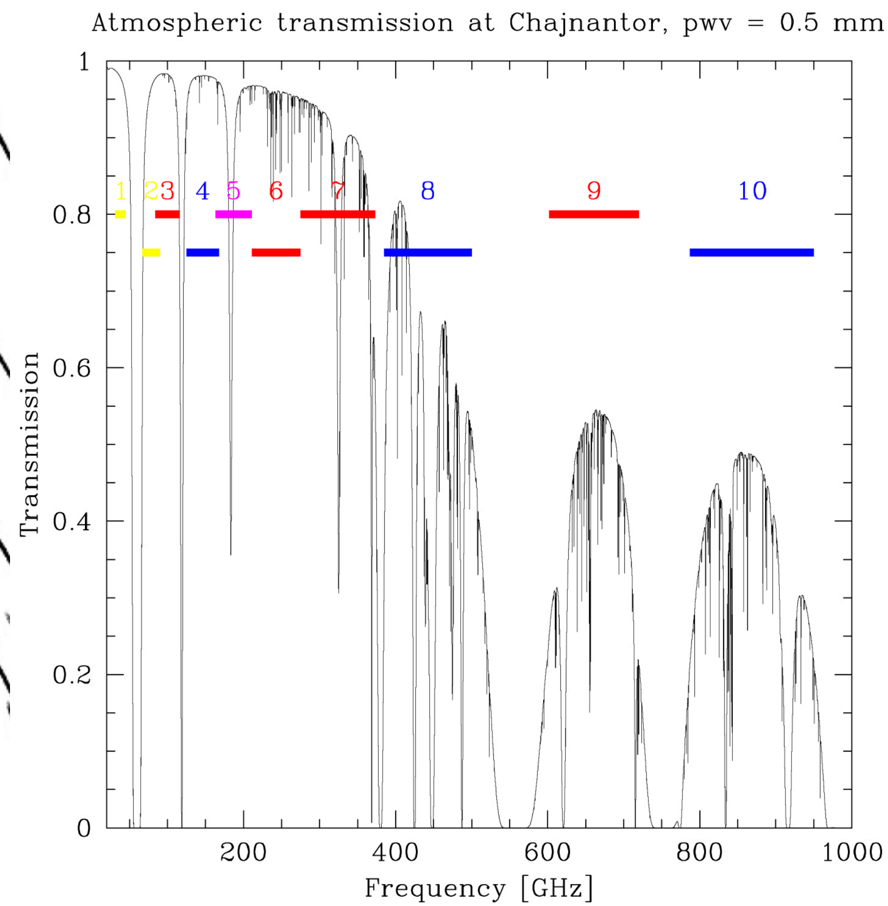


Stray Light Error Signal:

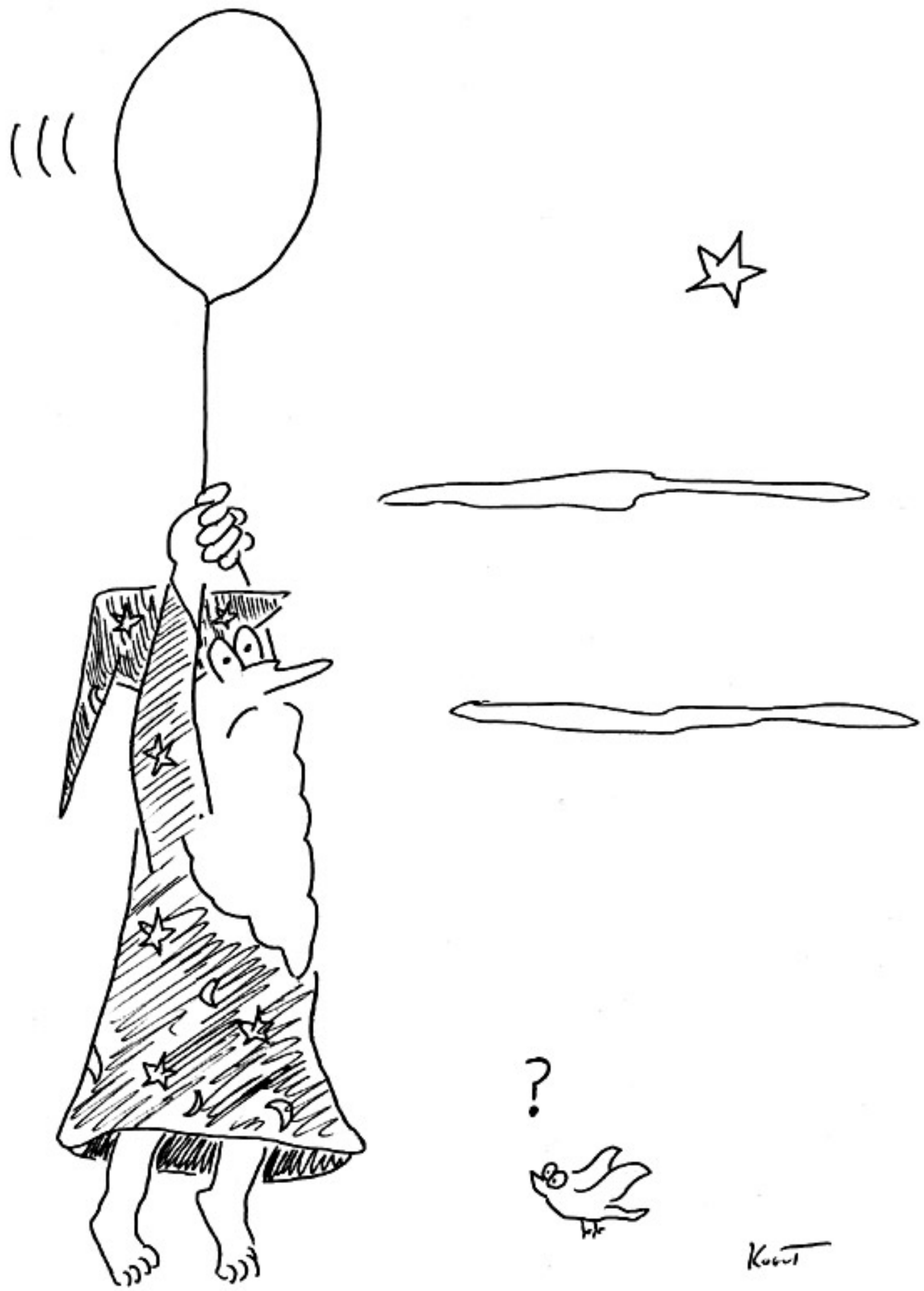
Emission from Instrument	T_{Inst}
minus	
Missing emission from sky	$- T_{Sky}$
Error Signal	$T_{Inst} - T_{Sky}$

Maintain instrument close to 2.7K CMB temperature

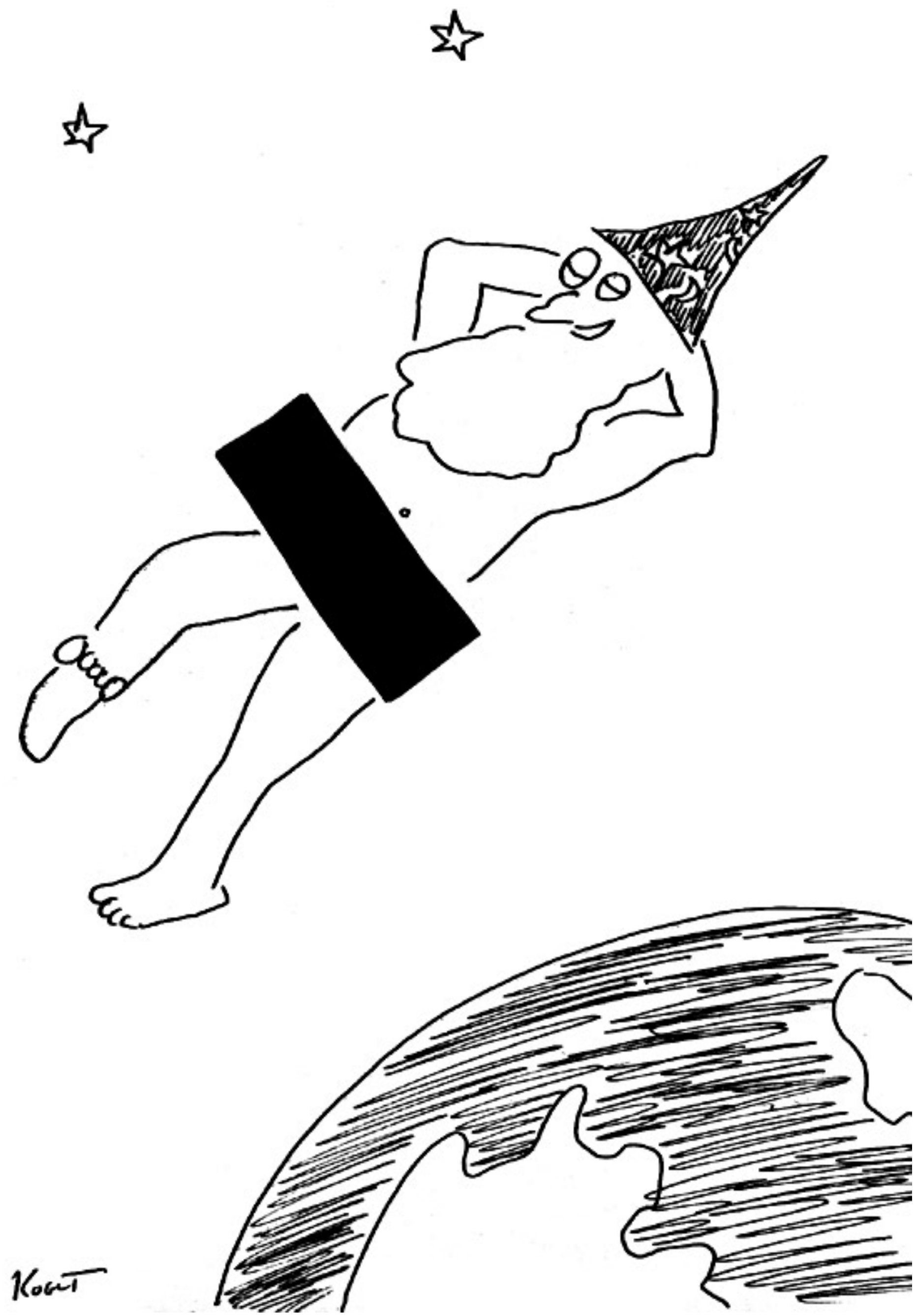
The Problem with Ground-Based Cosmology



Balloons Help, But Not Enough



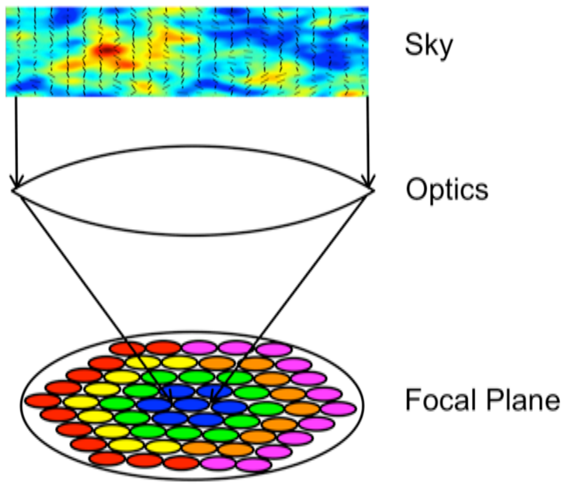
In Space, You Can Let It All Hang Out ...

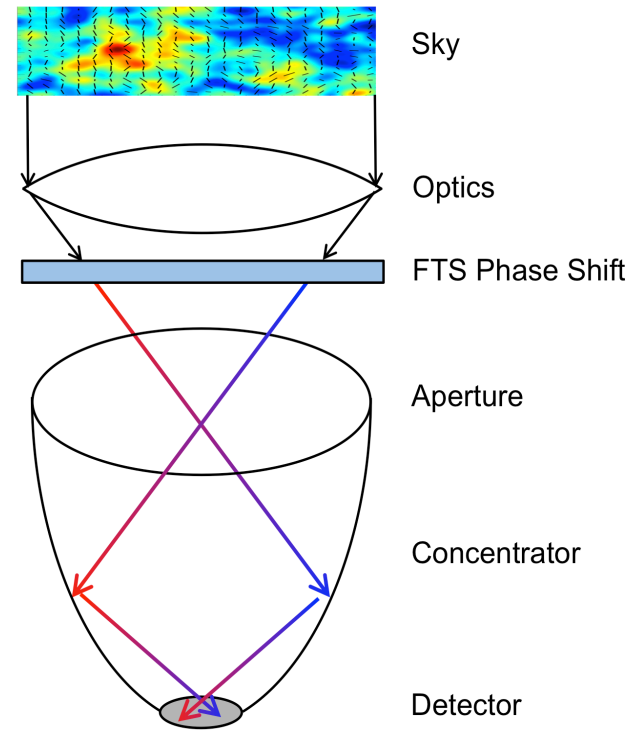


Long integration
Access to all electromagnetic frequencies
Stable thermal environment
No atmospheric noise / turbulence
No far-field reflections from surroundings

The Big Split

Single-Moded Optics	Multi-Moded Optics





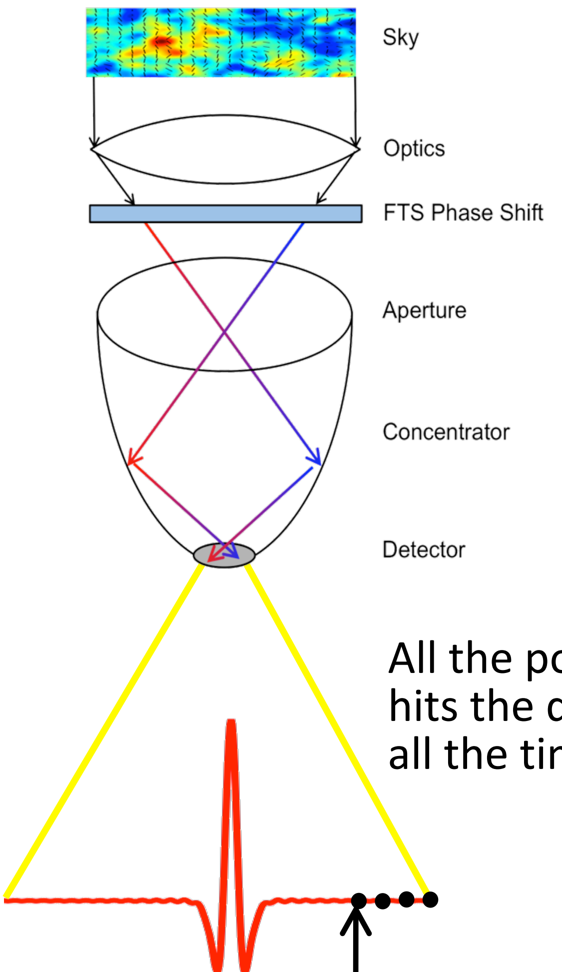
Diffraction Limit: $A\Omega = \lambda^2$
Single mode on each of 10,000 detectors

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

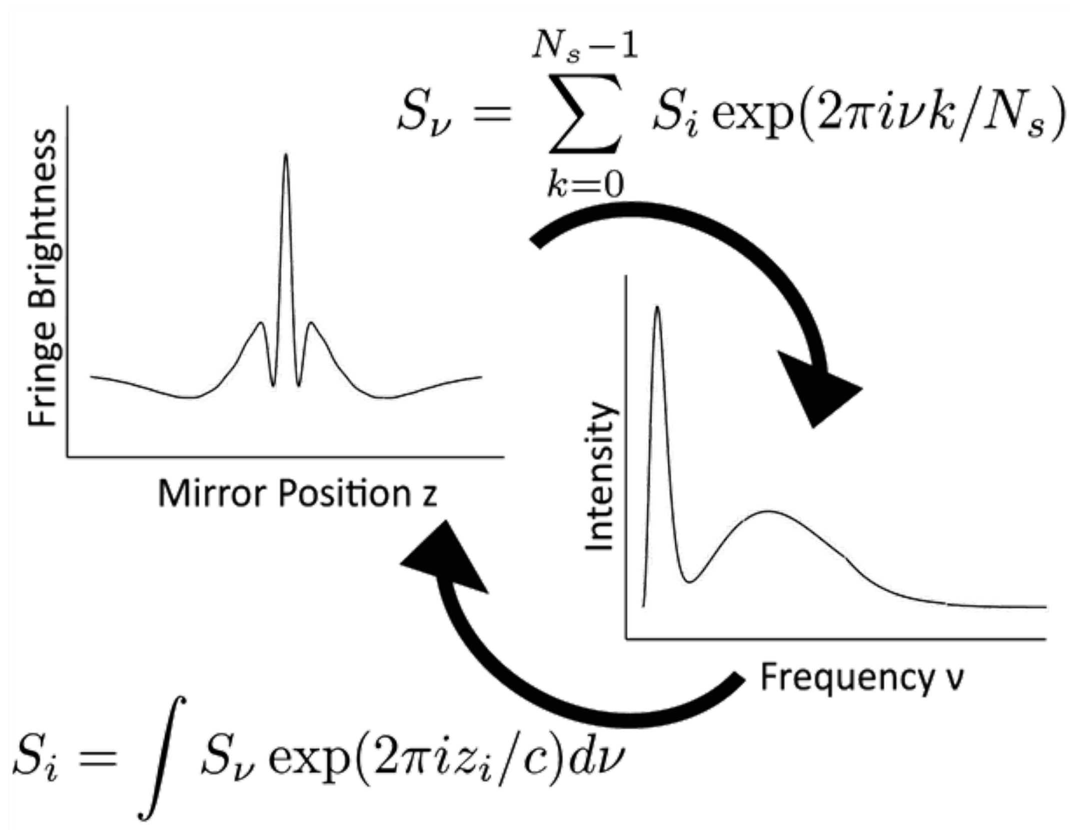
Trade angular resolution for frequency coverage

Adventures in Fourier Space

Fringe Pattern vs Frequency Spectrum



All the power hits the detector all the time



Sample Fringe Pattern

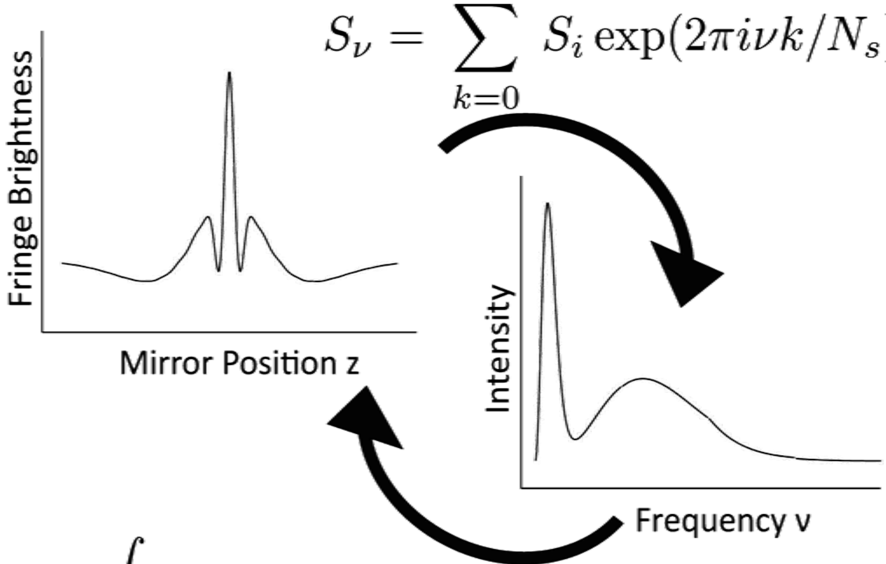
Fit sampled fringe pattern to Fourier series cos(k*x)

$a_0 + a_1\cos(x) + a_2\cos(2x) + a_3\cos(3x) + \ldots + a_N\cos(Nx)$

Adventures in Fourier Space

Channel Selection

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



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

Get N samples of fringe pattern
as phase delay goes from –L to +L

Maximum phase delay sets channel width
(hence lowest frequency)

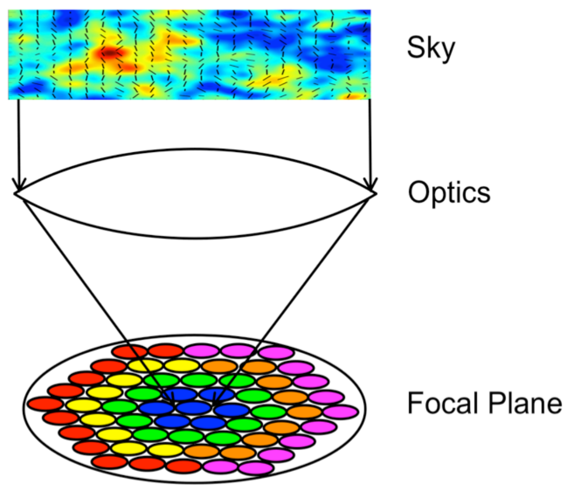
$$\Delta\nu = {}^{c}/_{L}$$

Number of samples N sets highest frequency

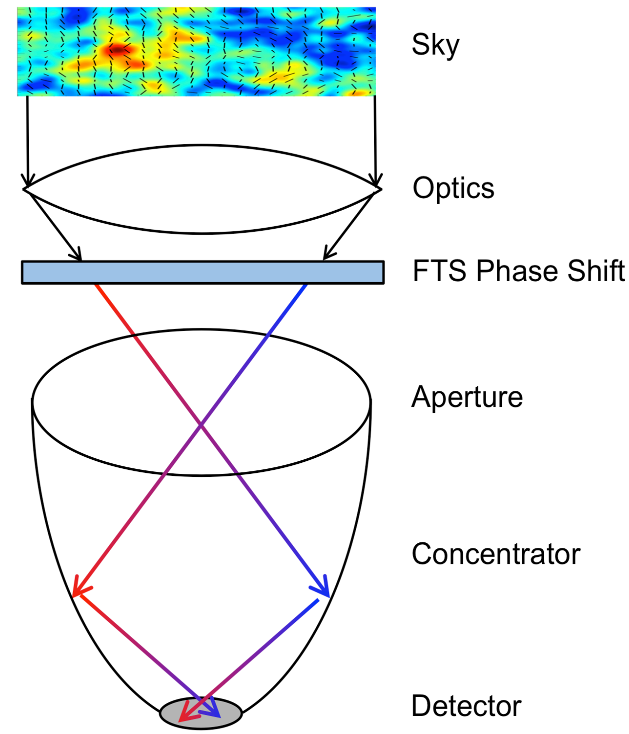
$$\nu_i = \Delta\nu, 2\Delta\nu, 3\Delta\nu, \cdots, \frac{N}{2}\Delta\nu$$

Sample more often → Get more (higher frequency) channels
Increase mirror throw → Decrease channel width (go to lower frequencies)

Trades: Angular Resolution



Photometer: Diffraction-limited resolution
$A\Omega = \lambda^2$
Can reach arc-min resolution at 150 GHz



Spectrometer: Fixed resolution
$A\Omega$ = Constant
30 arc-min resolution at all freqs

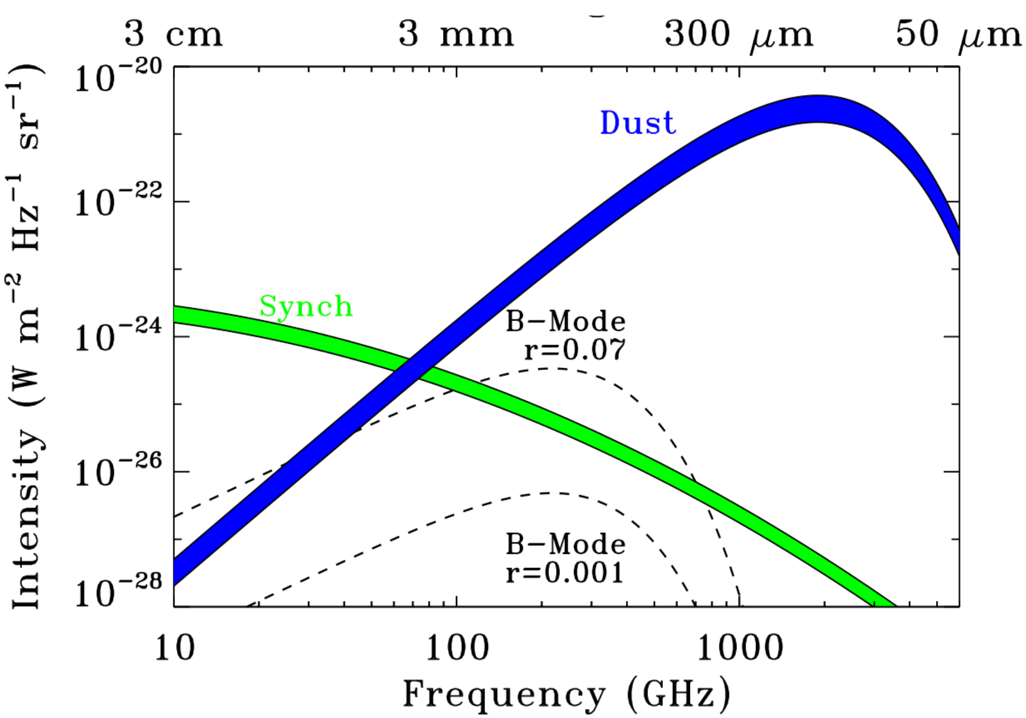
Advantage: Photometer

Trades: Sensitivity

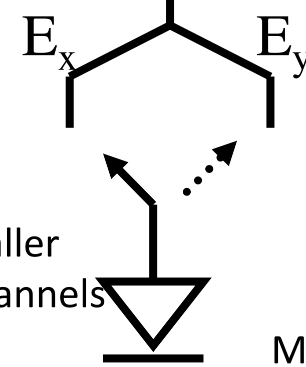
Photon Noise

$$\mathrm{NEP}^2 = \int h\nu P(\nu)d\nu$$

Proportional to Sqrt(Power) at detector



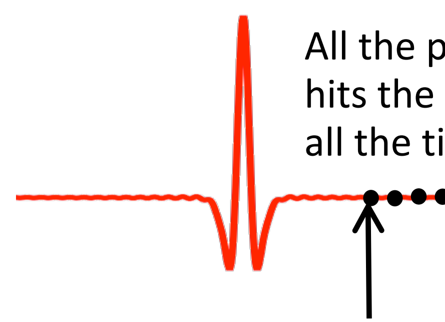
Bandpass-limited Photometer



Noise is smaller in darker channels

Measure in-band power

Fourier-Transform Spectrometer

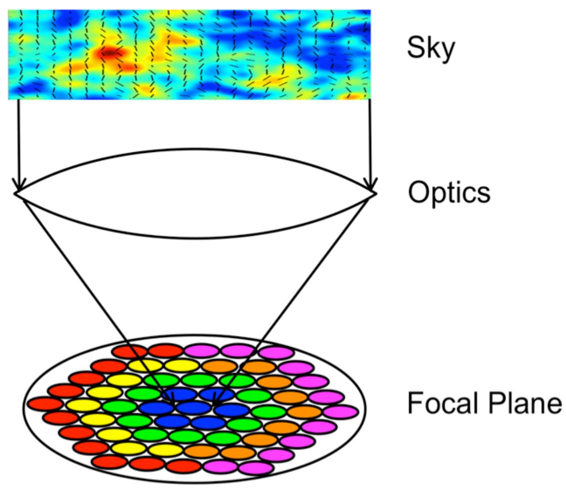


All the power hits the detector all the time

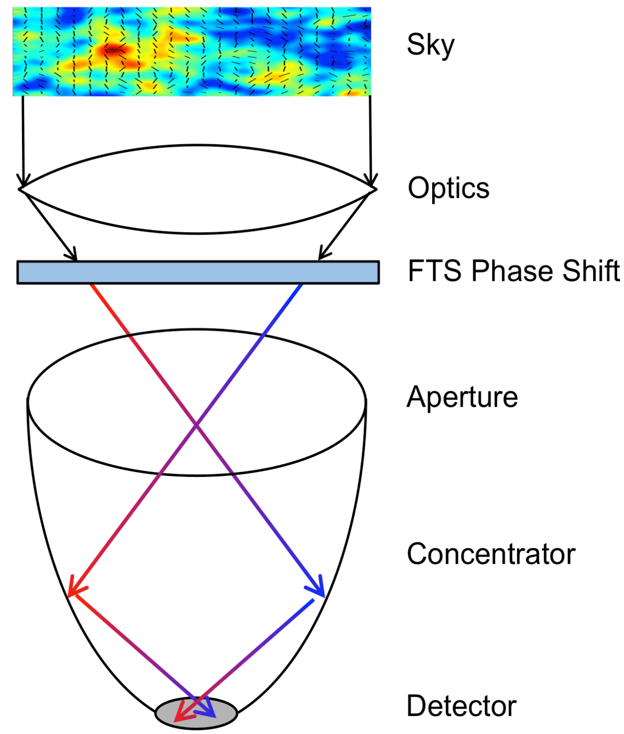
Sample Fringe Pattern

Advantage: Photometer

Trades: Spectral channels



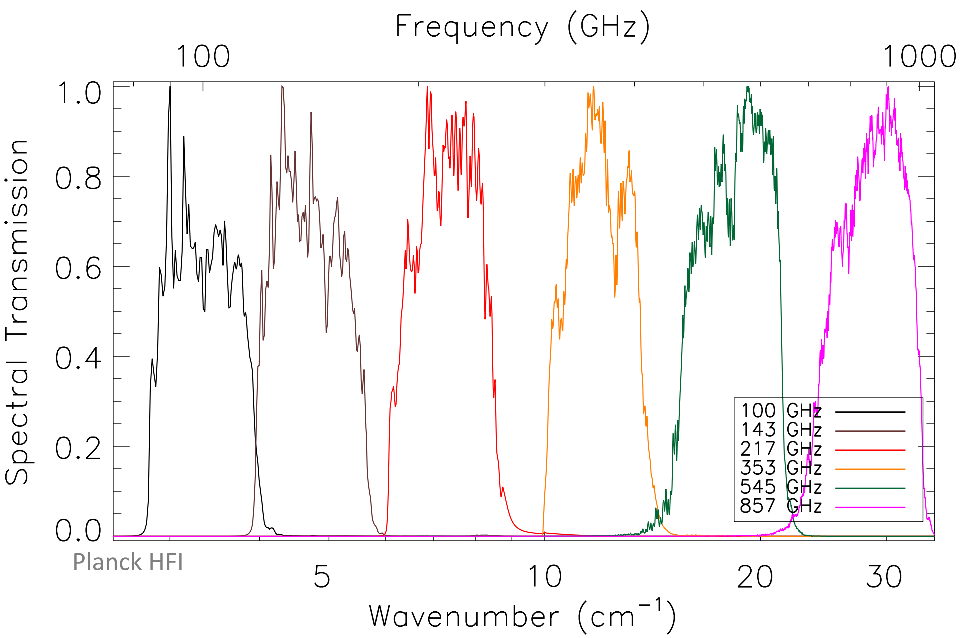
Photometer: One channel per detector



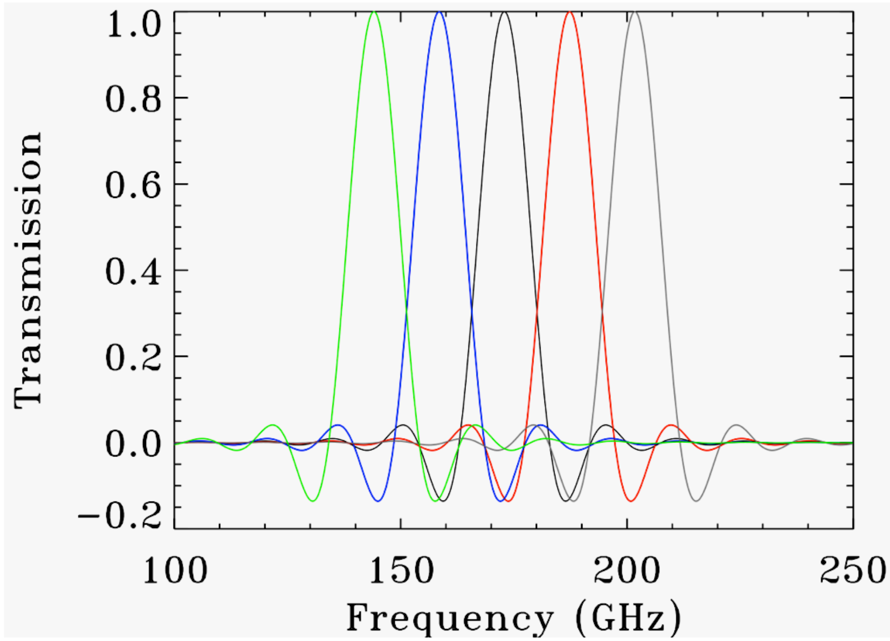
Spectrometer: Many channels per detector

Advantage: Spectrometer

Trades: Channel Shape



Photometer passbands set by filters
Complicated shape
Hard to control at few-percent level



FTS channel shape set by apodization
Trade resolution vs channel-to-channel correlations
- Weighted sampling → Nearest-neighbors
- Force CO lines to center of Nth channels

Band shape is fixed *a priori* by math!

Advantage: Spectrometer

Al's Crystal Ball

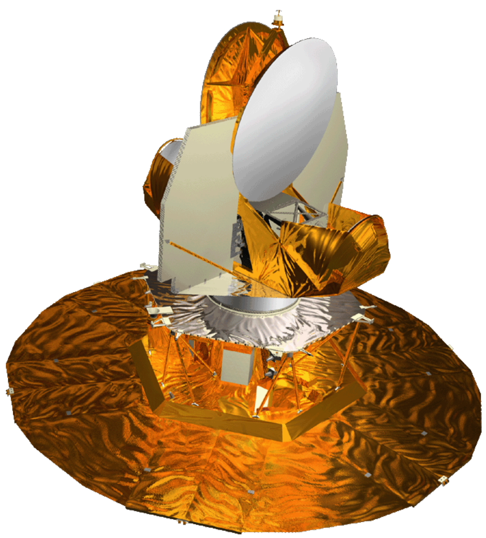
What should we expect from a future CMB space mission?

The Past as Prologue

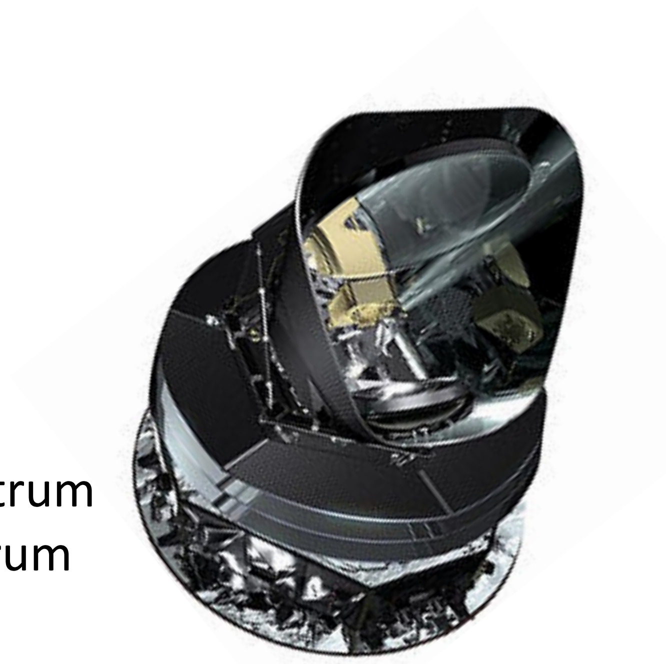
Dedicated CMB space missions have been indispensable for precision cosmology

COBE 1989—1993 (NASA)
Confirm blackbody spectrum
Discovery of primordial density perturbations

WMAP 2001—2010 (NASA)
Temperature power spectrum
Superhorizon modes
First look at polarization



Planck 2009—2013 (ESA)
Temperature power spectrum
Polarization power spectrum
Lensing power spectrum



Swing and a Miss ...

Recent attempts for CMB space mission not so successful

Mission	Agency	Instrument	Status
CoRE	ESA	Imager	Proposed but not funded
PIXIE	NASA	Spectrometer	Proposed but not funded
PRISM	ESA	Imager + Spectrometer	Proposed but not funded
LiteBIRD	JAXA	Imager	Phase A study

Meanwhile, steady progress from ground & balloon instruments

- BICEP2, Keck, Polarbear, CLASS, ACT, SPT, Simons Array, ...
- EBEX, SPIDER, PIPER
- Take advantage of "small ball" incremental approach
- CMB-S4 as final ground-based measurements?

What is the ultimate limit within fixed atmospheric windows?

Ultimate CMB Mission

Space probably is the final frontier for CMB missions

- Unique access across entire electromagnetic band
- Long integrations in ultra-stable observing environment
- Freedom to point/rotate/scan to minimize systematics

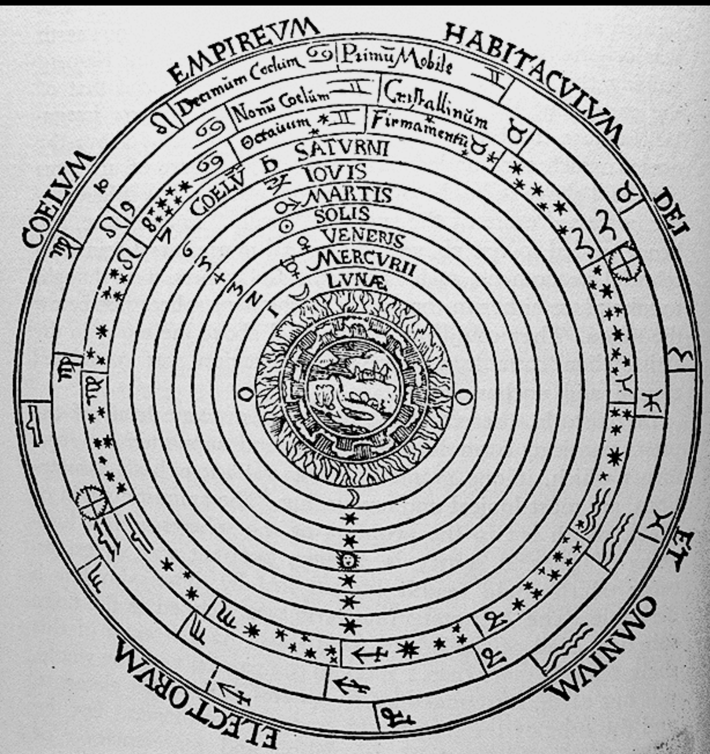
Continued interest from funding agencies

- JAXA: LiteBIRD Phase A study
- NASA: PICO concept study

Future: Multi-agency "ultimate mission"?

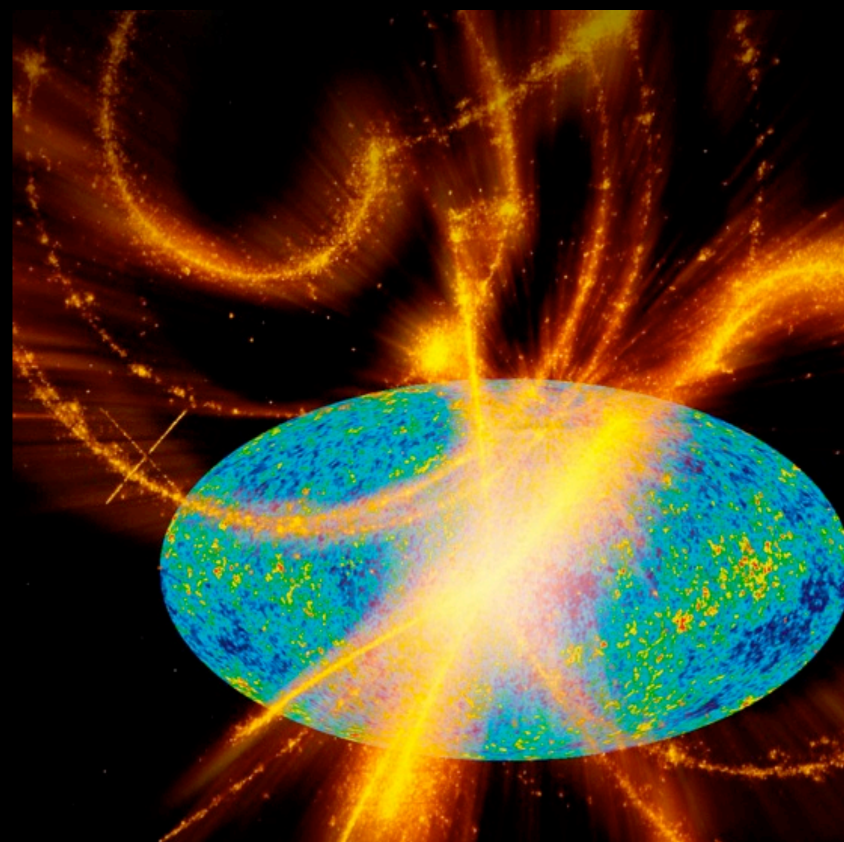
Swing For The Fences!

The Past and Future of Cosmology



"Big Picture" of cosmology

- Consistent theory fits many observations
- Flat universe dominated by dark matter and dark energy
- Stars, planets, chili dogs, etc are only 4% of the total



ΛCDM model has 6 free parameters

- Not so different from Ptolemy's 28
- Unknown stuff dominates the universe
- Will our picture last 1500 years?

Exciting new tests for fundamental physics

- Quantum gravity and inflation
- Particle physics "Theory of Everything"

Technology now allows next big test:
Stay Tuned!