

# Detectors for the Cosmic Microwave Background

*at the Frontier of Cosmology and in the Classroom*

John Kovac, Harvard  
APS Boston  
February 27, 2012

**Just how far can we see?**



INFLATION

CMB  
last scattering

fraction  
of a second

379,000  
years

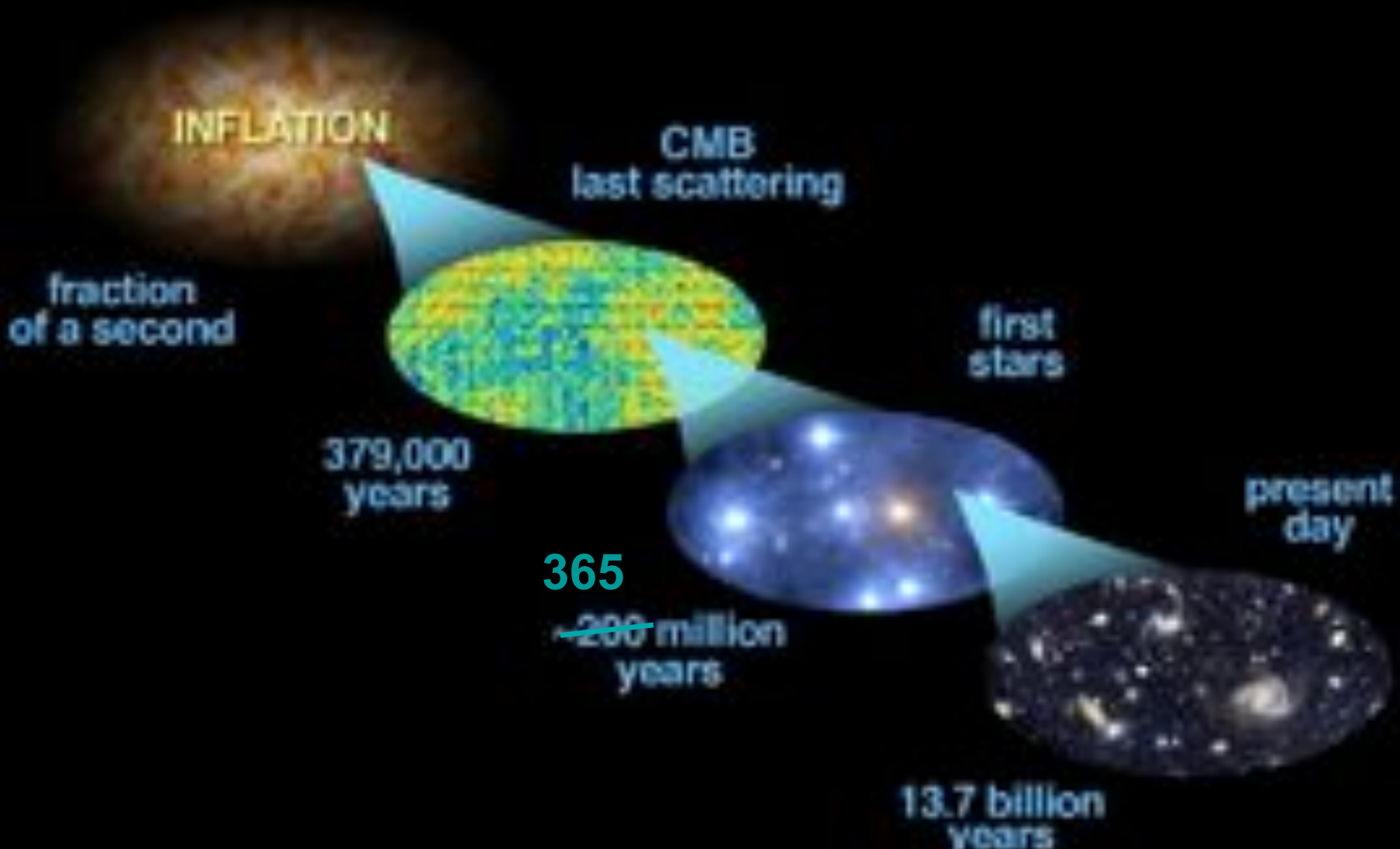
first  
stars

present  
day

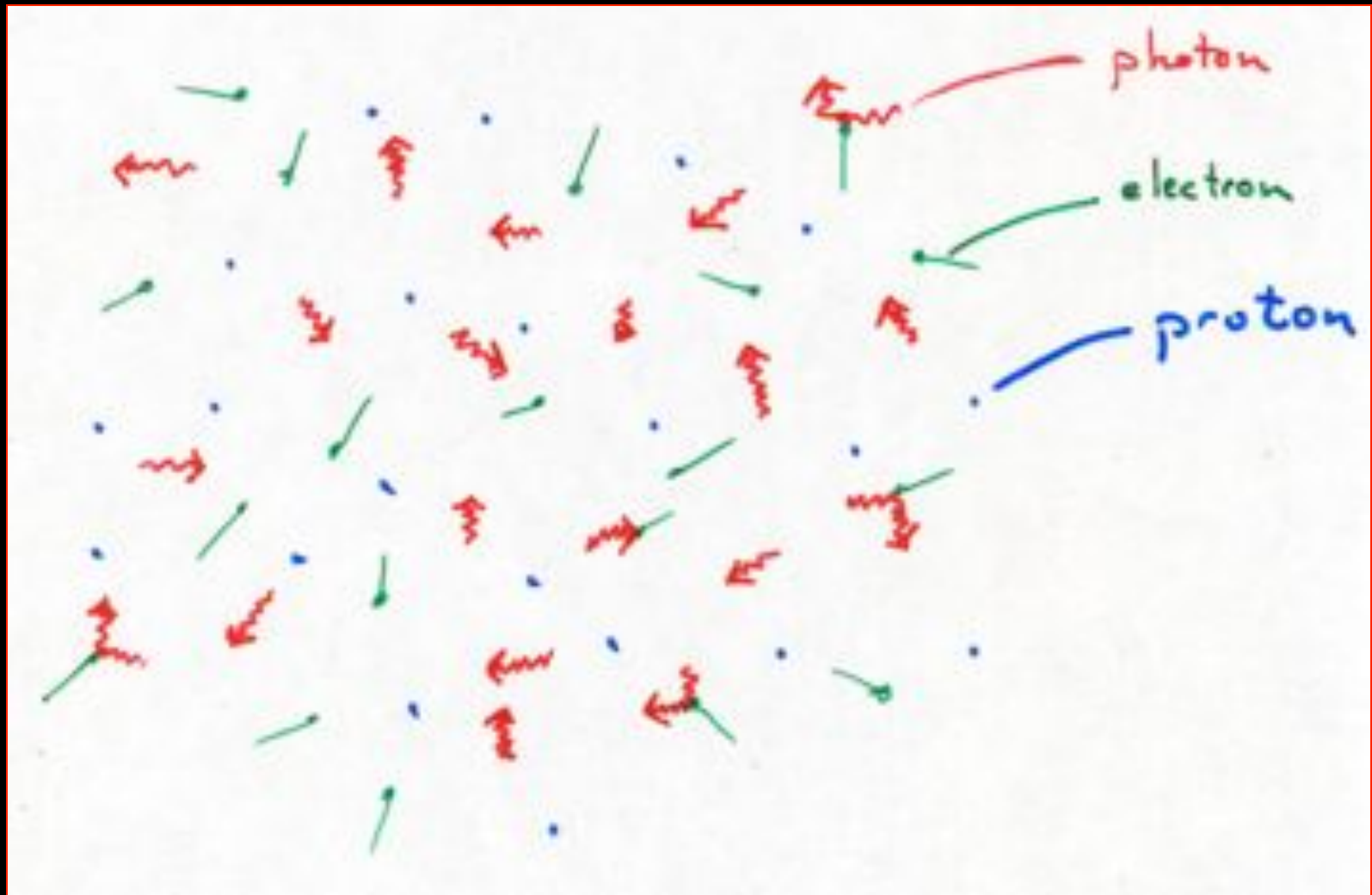
365

~~200~~ million  
years

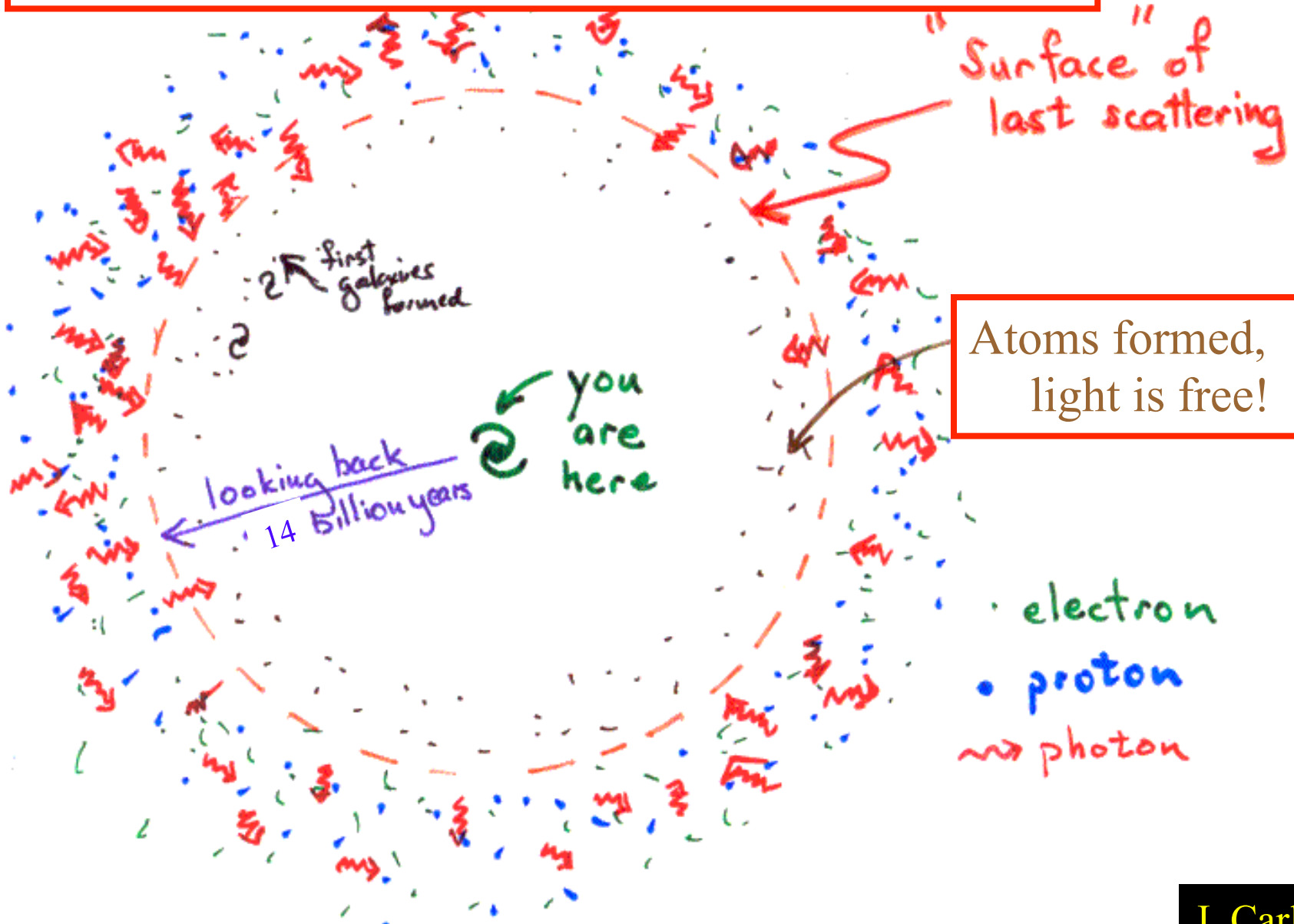
13.7 billion  
years



Physics is simple in the young universe –  
It's just an ionized gas with sound waves



# Cosmic Microwave Background Telescopes look back as far as light can take us.



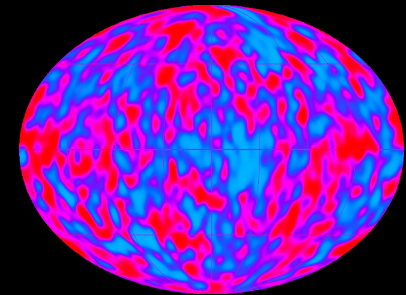
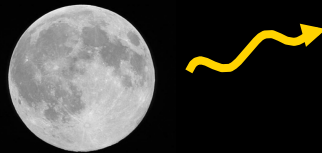
# Cosmic Microwave Background (CMB)

Except for the Sun and the Moon, it's the most powerful source of radiation from the cosmos!

SUN:  
1000 W



MOON:  
0.002 W



CMB:  
0.000005 W

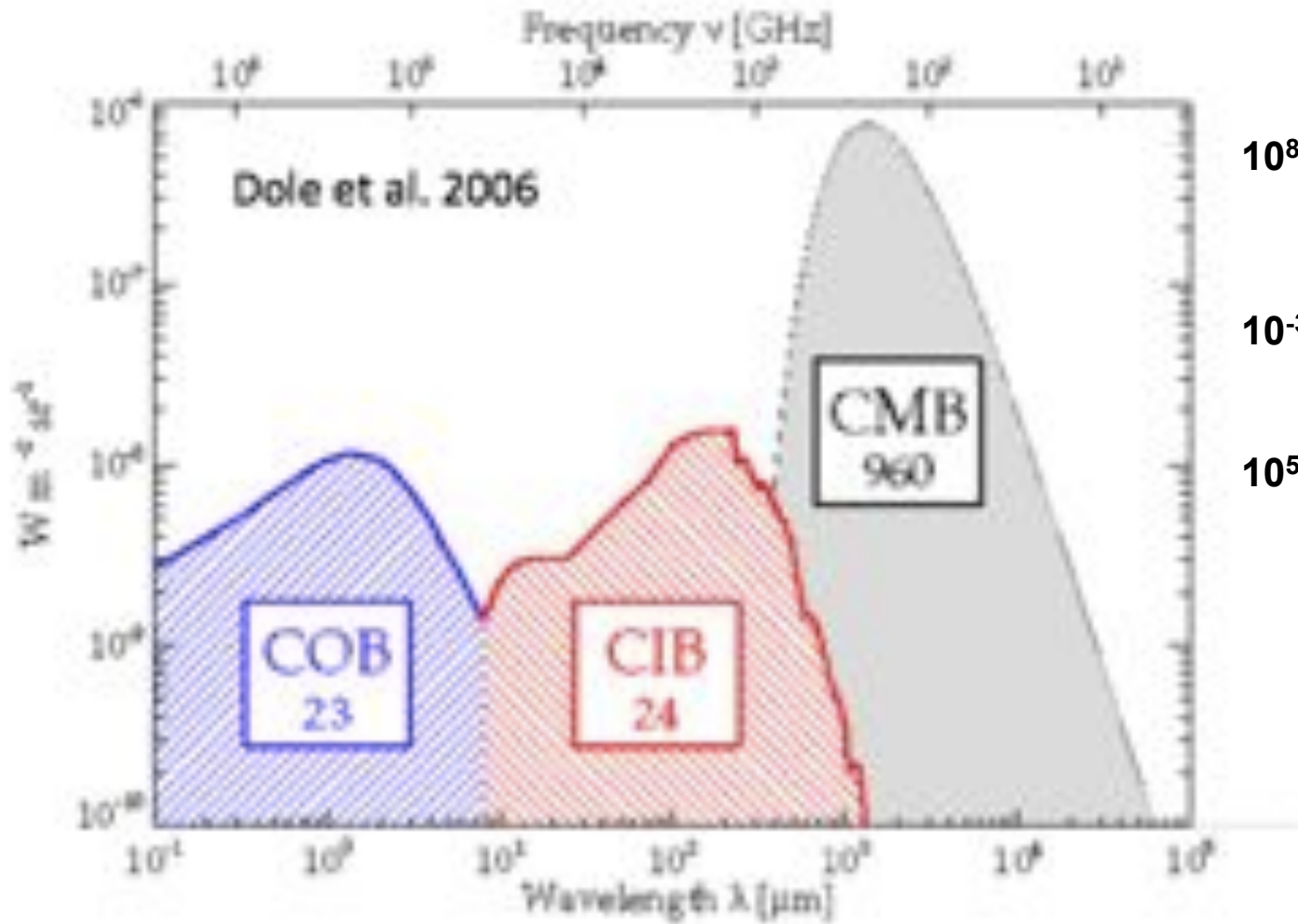
Comes from all directions --- very smooth.

(*too smooth??*)

Released at redshift  $z \sim 1000$

3000K (then)  $\rightarrow$  3K (today)

# CMB still dominates photons

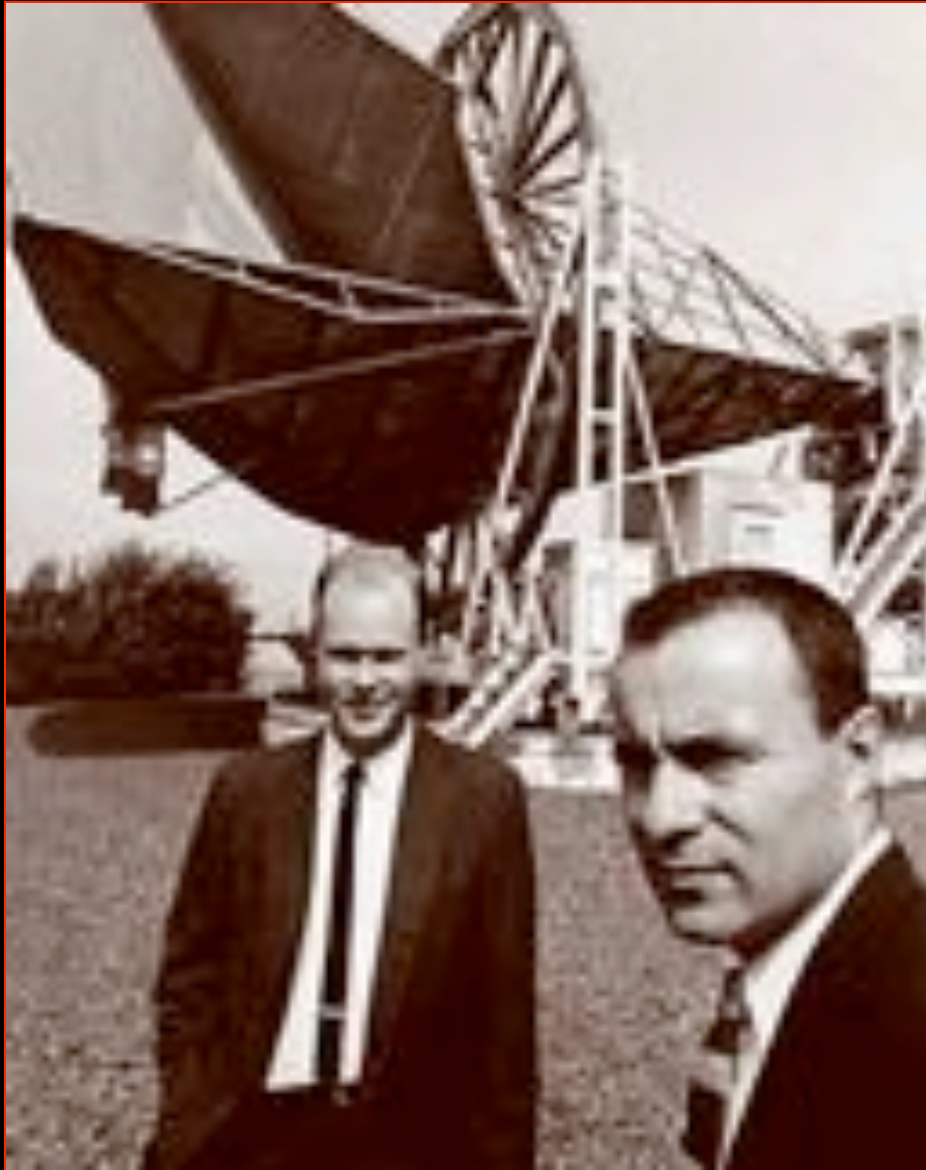


$10^8$  CMB photons /  $\text{m}^3$

$10^{-3}$  eV / photon

$10^5$  eV /  $\text{m}^3$

# Discovery of the Cosmic Microwave Background



Arno Penzias & Robert Wilson in front of the 20ft Bell Labs antenna used to discover the microwave background in 1965

Detector: 4 GHz traveling-wave maser amp and absolute radiometer

Received 1978 Nobel Prize

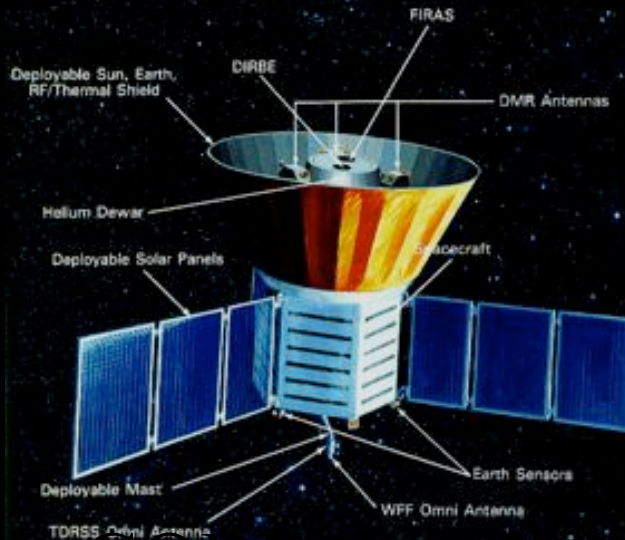
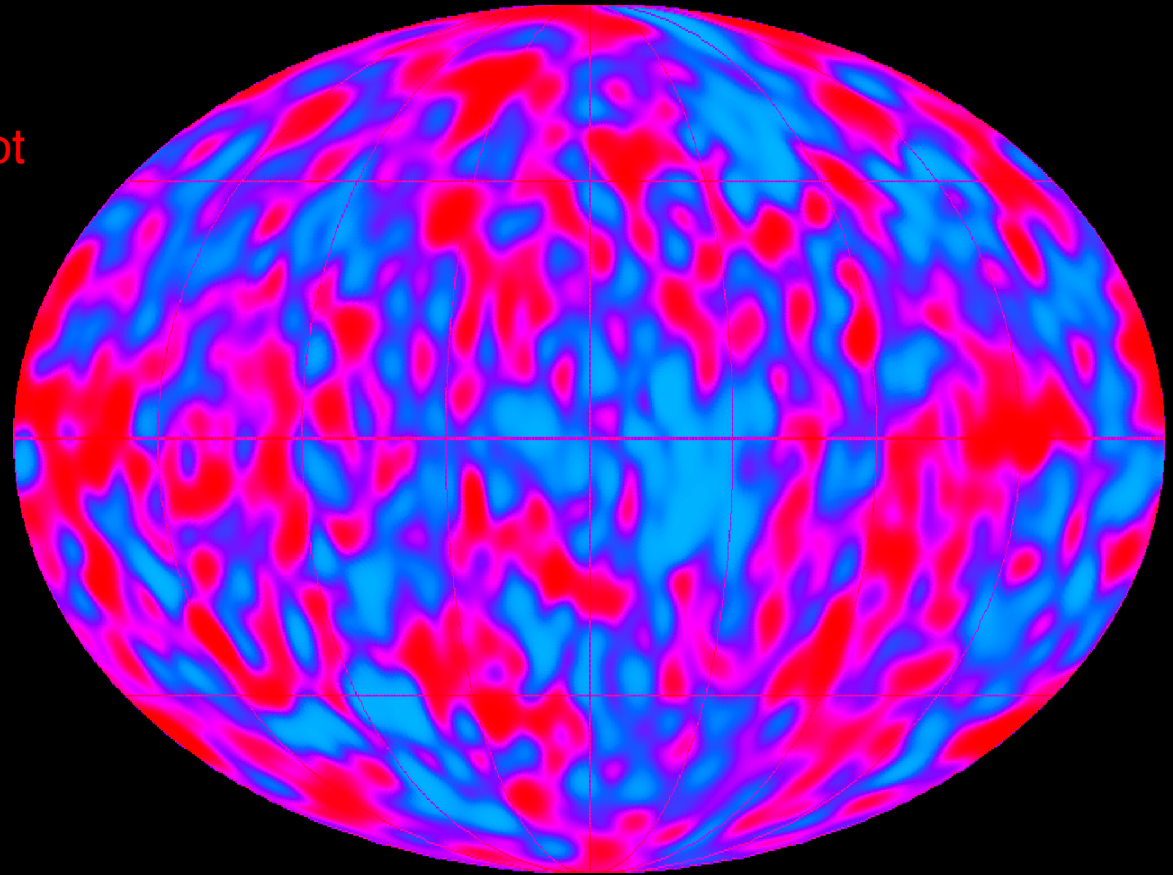
“smoking gun” evidence for the Big Bang

**Enormous impact on Cosmology**



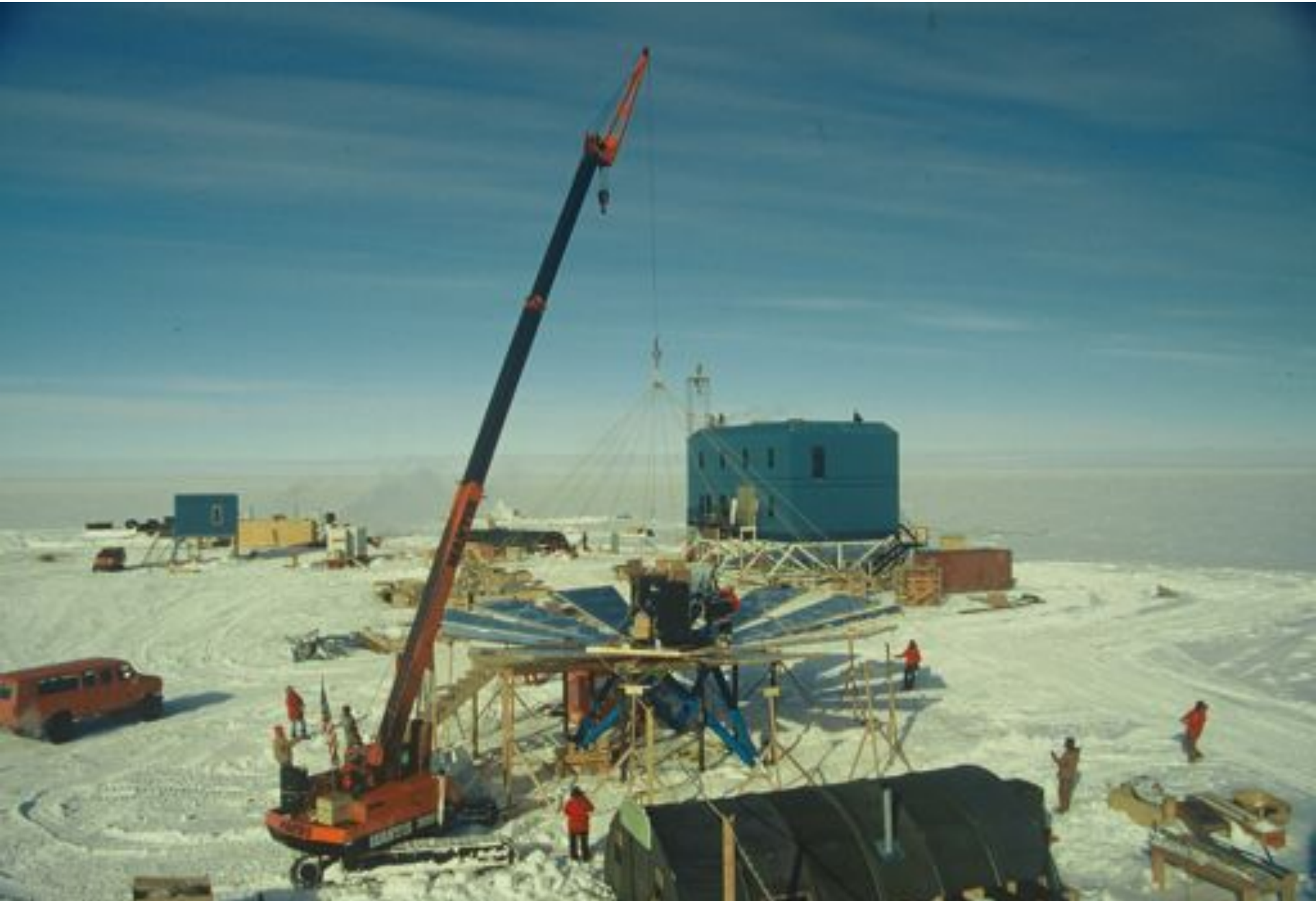
# Structure in background discovered in 1992

COBE team leaders  
John Mather & George Smoot  
received 2006 Nobel Prize



**Smooth to a part in 100,000!**  
*(the smoothness problem)*

# Python (1992-97): first “permanent” CMB installation at Pole



# 1994: first CMB winter operations



# 50mK 4 x 90GHz bolometer array



A hard learning curve...



# DASI & BOOMERANG South Pole -- 2001 results

"All the News  
That's Fit to Print"

## The New York Times

VOL. CL . . . . No. 32,739

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MONDAY, APRIL 30, 2001

### Listen Closely: From Tiny Hum Came Big Bang

### Scientists Hear the Tiny Hum They Say Ignited the Big Bang

Continued From Page A1

By JAMES GLANE

WASHINGTON, April 29 — Two detectors in Antarctica have discovered minute patterns in a glow from primordial quanta, possible tracks of the cosmic dust that ignited the Big Bang and led to the creation of the universe 14 billion years ago, astronomers announced here today.

The patterns, astronomers said, were probably created by microscopic processes — energy fluctuations at the quantum scale — that were at work when the universe was a tiny fraction of a second old and cooler than a human fire.

The new observations do not see the quantum fluctuations directly, but instead have found traces of colossal waves, much like sound waves, that the fluctuations probably set in motion, riding the young universe.

The results rest on the most detailed observations ever made of a glow from the hot gases of the early universe. That glow, called cosmic microwave background radiation, carried an imprint of those waves to the detectors on Earth.

The news comes as a relief for astronomers, some of whom started to worry last year that their basic picture of the origins of the universe might be flawed, after detailed observations failed to find the wave patterns.

"We see the structure of the universe in its infancy," said Dr. John Carlstrom, a University of Chicago astrophysicist who leads the team operating the Degree Angular Scale Interferometer, or DASI (pronounced *dash*), a microwave detector at a South Pole research station operated by the National Science Foundation.

Dr. Michael Turner, a cosmologist

Continued on Page A1

at the University of Chicago who was not involved in the measurements, said that the precise times the fluctuations took place remained to be determined by future measurements, but that the process was likely to have taken place in a fraction of a second comparable to a decimal point followed by 22 zeros and a 1.

"We are living in the most exciting time ever in cosmology," he added.

Boulder DASI, which also involved astronomers at the California Institute of Technology, the announcement today included the so-called Boomerang team. This group flew a balloon-borne detector around Antarctica, and includes astronomers from the United States, Italy, Canada and Britain. Antarctica is essential for such observations because the air is thin and dry and does not strongly absorb microwave radiation.

Dr. John Kubi of the University of California at Santa Barbara presented results today for the Boomerang team. The announcements took place at a meeting of the American Physical Society.

The Antarctica studies were buttressed today when another group of researchers reported that they had made new *indirect* observations of the wave patterns from the United States. That team, called Maxima, includes astronomers at the University of Minnesota and the University of California at Berkeley.

The leading theory of how the universe would have exploded out of the primordial singularity, known as the theory of inflation, predicts that the quantum fluctuations should have seeded the universe in such a way that it resembled like a vast organ pipe, with one main tone, or wavelength, and a series of overtones or harmonics.

Last year, the Boomerang team detected the main tone but found no clear evidence for the overtones, raising the possibility that the inflation theory could be wrong. Issue

much of the information about the fluctuations, like their relative intensity and spectrum, would reside in the characteristics of the overtones. Those results raised the prospect that few remnants of the initial spark might be found.

Today, the three teams announced that they had seen two of the overtones for the first time. In statistical terms, the observations saw the first two harmonics above the main tone.

"We do see two more bumps and wiggles out there," Dr. Kubi said. "It can move in the question of 'What do these bumps and wiggles tell us?'"

Dr. Max Tegmark, a cosmologist at the University of Pennsylvania, said that while the new results were still far from absolute proof of the inflation theory, their agreement with the theory was exciting and would cast doubt on alternative models. "It's even scarier that things agree this well," he said. "This is a very fast day for the cosmologist."

Some other scientists, including Dr. Andrew Lange of Cornell, a member of the Boomerang group, said the results strikingly showed that cosmologists understood the competition and behavior of the universe at the first few hundred thousand years of its life. It was then that the sound waves were humming through the young cosmos, astronomers believe the microwave background radiation was emitted as the universe cooled below a critical temperature when it was about 400,000 years old.

"We've really been waiting for the other shoe to drop," Dr. Lange said in reference to the lengthy search for the overtones. "What we're celebrating for the first time is a very generic prediction of modern cosmology."

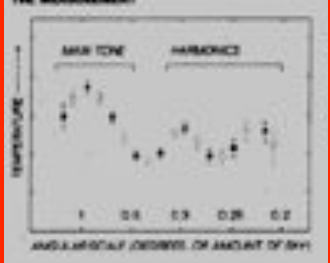
Although astronomers said much more detailed observations, including the discovery of further overtones, would be required to define the quantum fluctuations and to verify inflation, the results are likely to be seen as major victories for two scientists in particular.

The first, Dr. Alan Guth of the

### 'Listening' to the Origin of the Universe

Measurements of a faint, pervasive radiation throughout space bolster a theory of the universe's origin.

#### THE MEASUREMENT



Fluctuations in the temperature of wide patches of sky carry the imprint of a wave of sound like one resonating from an organ pipe. The main tone is a tall wave, and the overtones, or harmonics, are smaller peaks. This "ringing" is produced by the theory of inflation.

#### INFLATION THEORY AND THE BIG BANG



Source: Dr. John Carlstrom, Dr. Wayne Hu, University of Chicago.

Photo: Tom Ralston/Science Source/University of Chicago

Massachusetts Institute of Technology, developed the germ of the inflation model in 1981, a theory he has called "the ultimate free lunch" because it shows how the entire universe could have expanded out of nothing and impressed the quantum fluctuations on the cosmos.

The results also provide major support for ideas closely associated with Dr. David Spergel, a Chicago cosmologist who died in a plane crash last in 1997. Dr. Spergel and his colleagues worked out a theory, unrelated to inflation, using three elements created in the Big Bang explosion to gauge the amount of ordinary matter in the universe.

Those values agree closely with the amounts deduced from the intensity of the sound waves overtones; that intensity is affected by the clumping of matter in the sound waves' peaks and troughs.

On the other hand, the results also leave cosmologists with some deep and perhaps troubling questions.

For example, the new observations confirm that most of the cosmos seems to be made of so-called dark matter and dark energy, possibly particles or energy lurking somewhere in space but still never detected directly. Dr. Turner, of Chicago, said scientists might well term that picture "the absurd universe, or the

preposterous universe."

Sir Martin Rees, an astrophysicist at Cambridge University, said scientists were left with the question of whether fundamental physical laws would someday explain that strange mixture of ingredients, or whether the precise answers were a sort of accident of how the universe came into being — something like accidents, each of which has a benign-sounding symmetry but carries a pattern that is otherwise unique.

"It may well turn out that the underlying laws do not give us these numbers, any more than they give the detailed pattern of a snowflake," Sir Martin said.

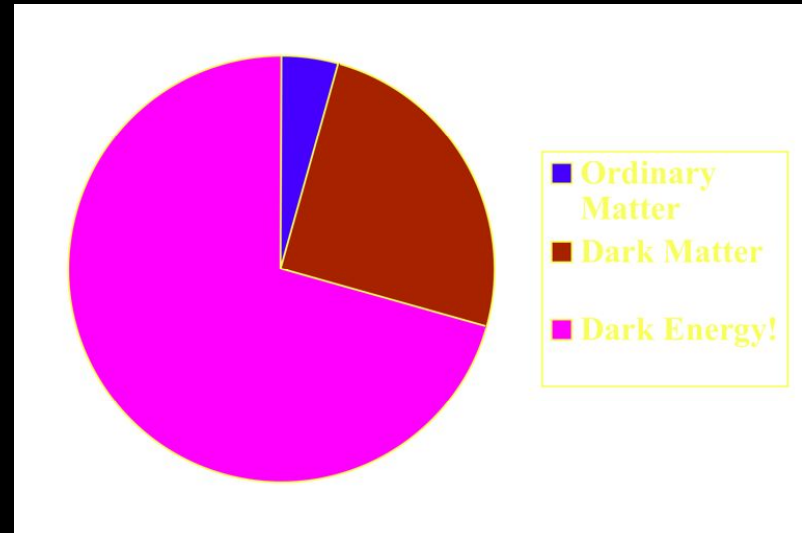
# 2001 APS: DASI/Boomerang Results

**-Universe's Age:  $14 \pm 0.5$  Gyr**

## **-Universe's Makeup:**

- $4.5\%$  Ordinary matter
- $30\%$  Dark matter
- $65\%$  Dark energy,  $\Lambda$ ?

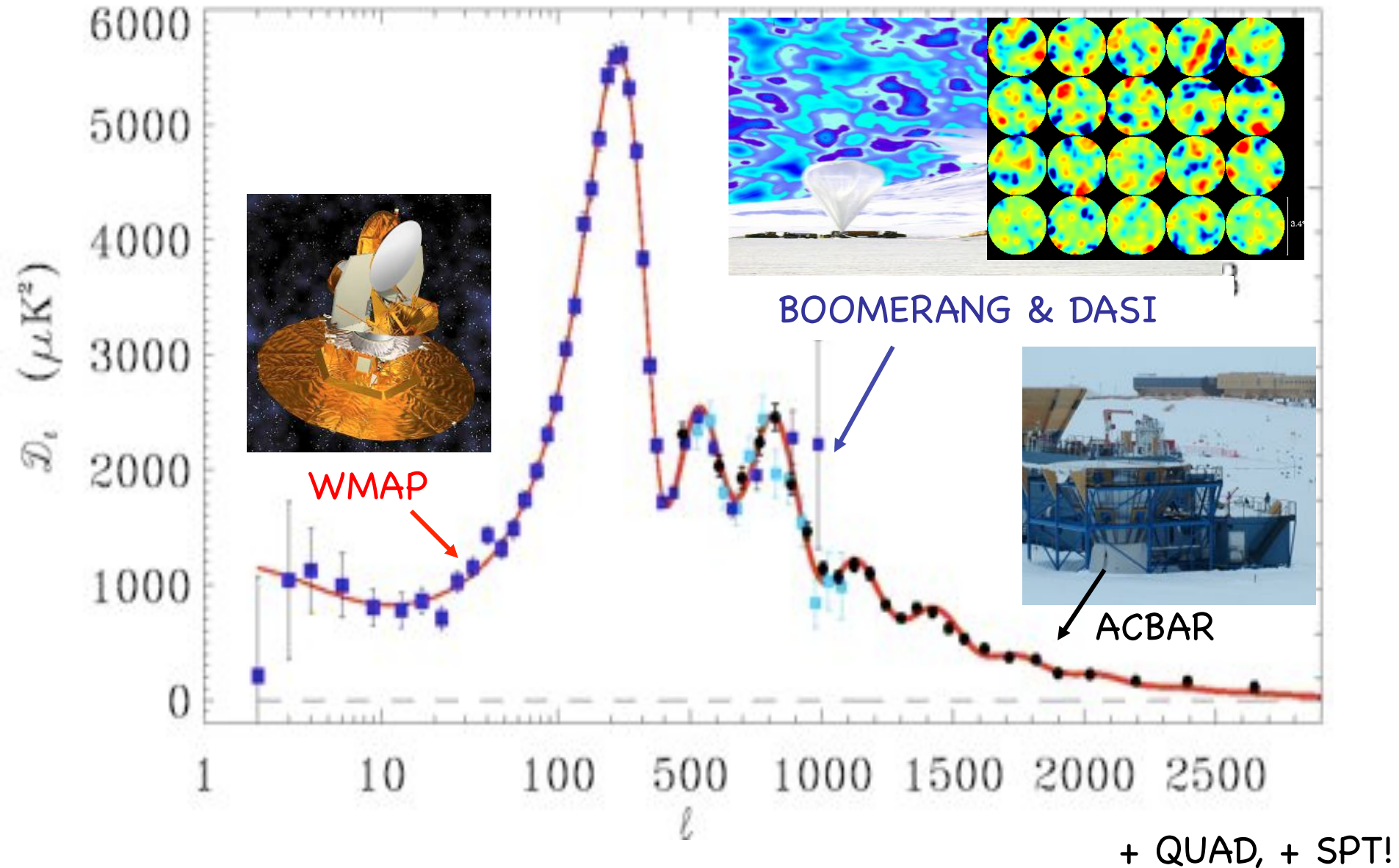
→ consistent w/ supernovae results



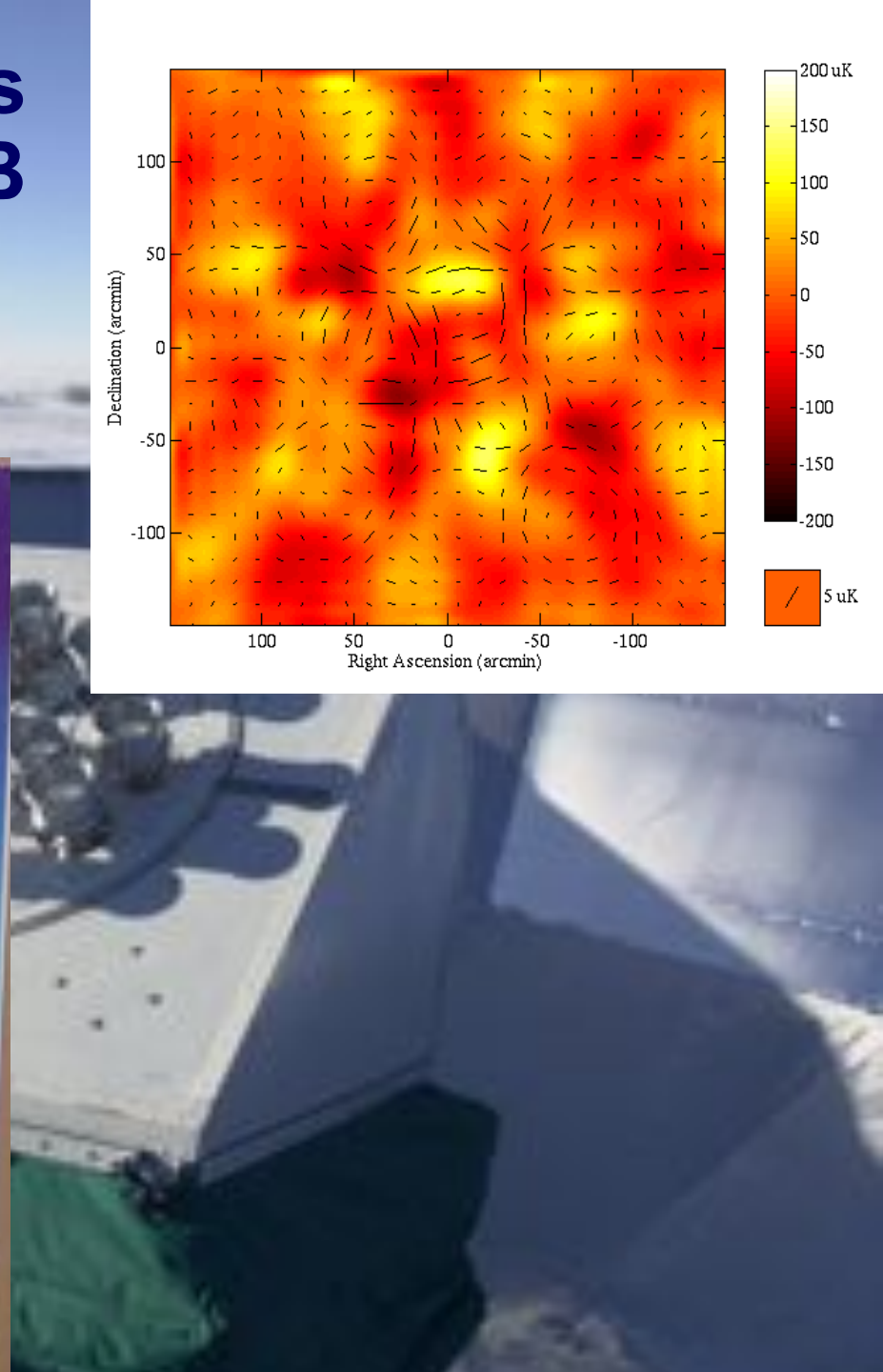
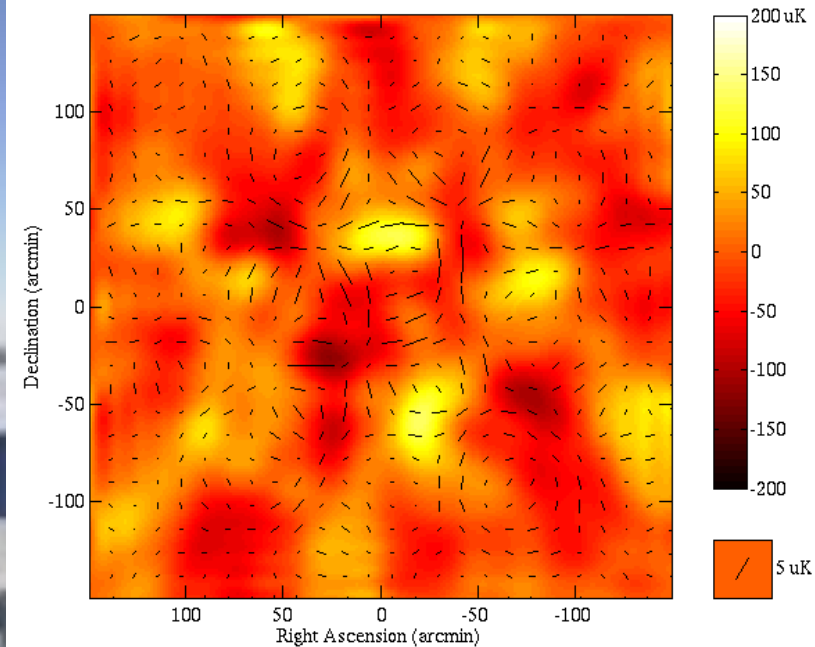
**A Strange Brew...but FLAT and SMOOTH to  $1/100,000$ , consistent with Inflation!**

***Can Inflation also explain where structure comes from?***

# CMB temperature: easy stuff!



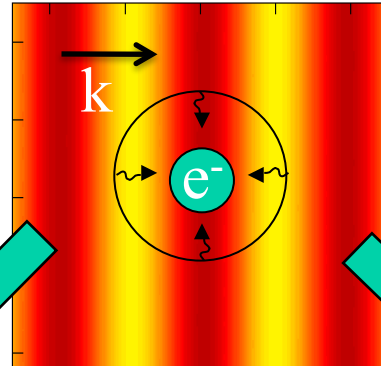
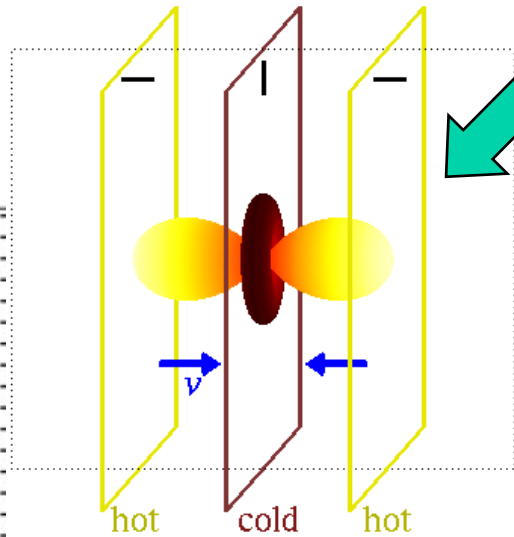
# 2002: DASI first detects polarization of the CMB (Level: 1 part in 1,000,000 !)



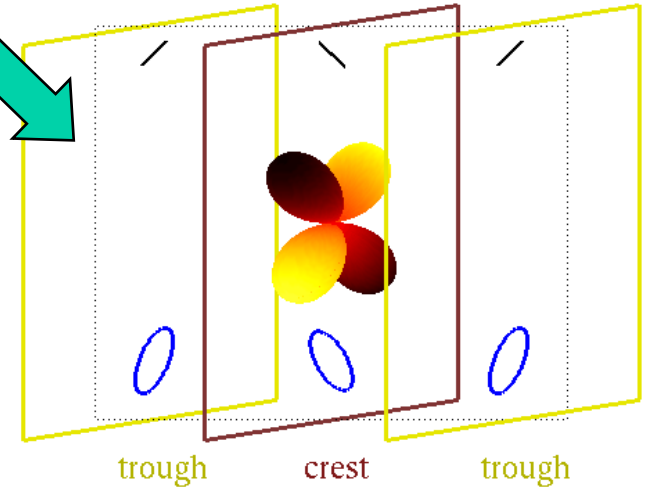


# CMB Polarization: E-modes and B-modes

Density fluctuations



Gravitational waves



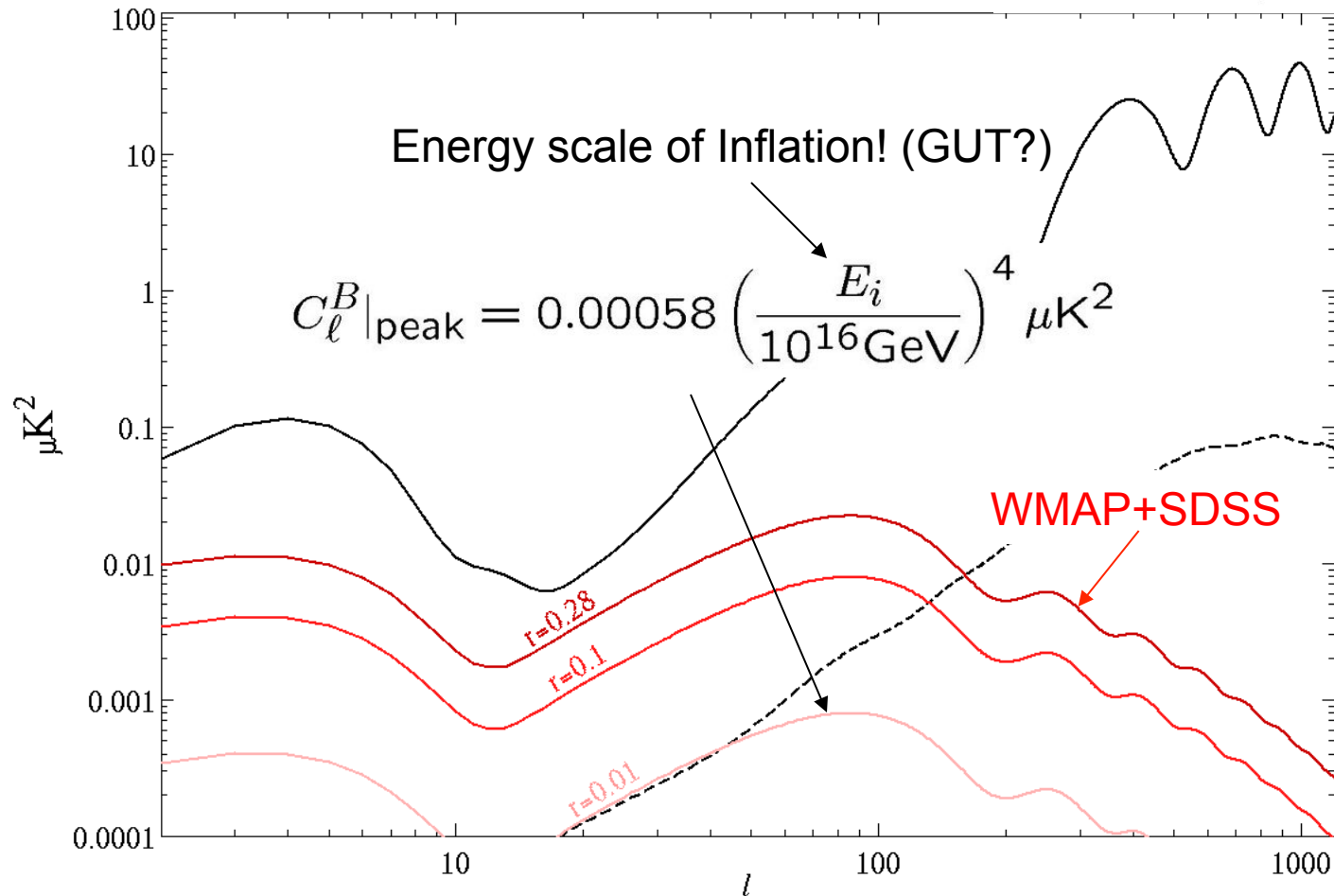
E-mode

B-mode

# Inflationary Gravity waves (Tensors)

black hole:  $kT_{\text{Hawking}} = \frac{\hbar}{4\pi} \left[ \frac{1}{r_s} \right]$  ← event horizon scale

inflation:  $kT_{\text{deSitter}} = \frac{\hbar}{2\pi} \left[ \frac{1}{H^{-1}} \right] \implies \Delta_{\text{GW}}^2 \sim \frac{H^2}{m_{\text{P}}^2} \sim \frac{V}{m_{\text{P}}^4}$



# CMB Detectors: Theory

Direct Detectors vs. Amplifiers (Zmuidzinas, 2003)

The  $1\sigma$  power sensitivity after integration time  $\tau$  is:

$$\begin{aligned} \sigma_P &= \frac{h\nu}{\sqrt{\Delta\nu\tau}} \sqrt{\frac{n_0(1+\eta n_0)}{\eta}} \Delta\nu && \text{(second term due to bunching)} \\ &\approx \frac{h\nu}{\eta\tau} \sqrt{\eta n_0 \Delta\nu\tau} = \frac{h\nu}{\eta\tau} \sqrt{N(\tau)} && \text{(Poisson statistics; for } \eta n_0 \ll 1) \\ &\approx \frac{k_B T_0 \Delta\nu}{\sqrt{\Delta\nu\tau}} = \frac{h\nu}{\eta\tau} \frac{N(\tau)}{\sqrt{\Delta\nu\tau}} && \text{(Dicke formula; for } \eta n_0 \gg 1) \end{aligned}$$

$$\begin{aligned} \sigma_P &= \sqrt{\frac{\Delta\nu}{\tau}} \frac{h\nu}{\eta} (\eta n_0 + 1) && \text{(second term is quantum noise)} \\ &\approx \frac{k_B T_0 \Delta\nu}{\sqrt{\Delta\nu\tau}} && \text{(Dicke formula; for } \eta n_0 \gg 1) \\ &\approx \frac{h\nu \Delta\nu}{\eta \sqrt{\Delta\nu\tau}} && \text{(quantum limit; for } \eta n_0 \ll 1) \end{aligned}$$

Direct detection is *more sensitive* by the factor  $\sqrt{\eta n_0}$  when  $\eta n_0 \ll 1$ .

$$n = \frac{1}{e^{h\nu/kT} - 1}$$

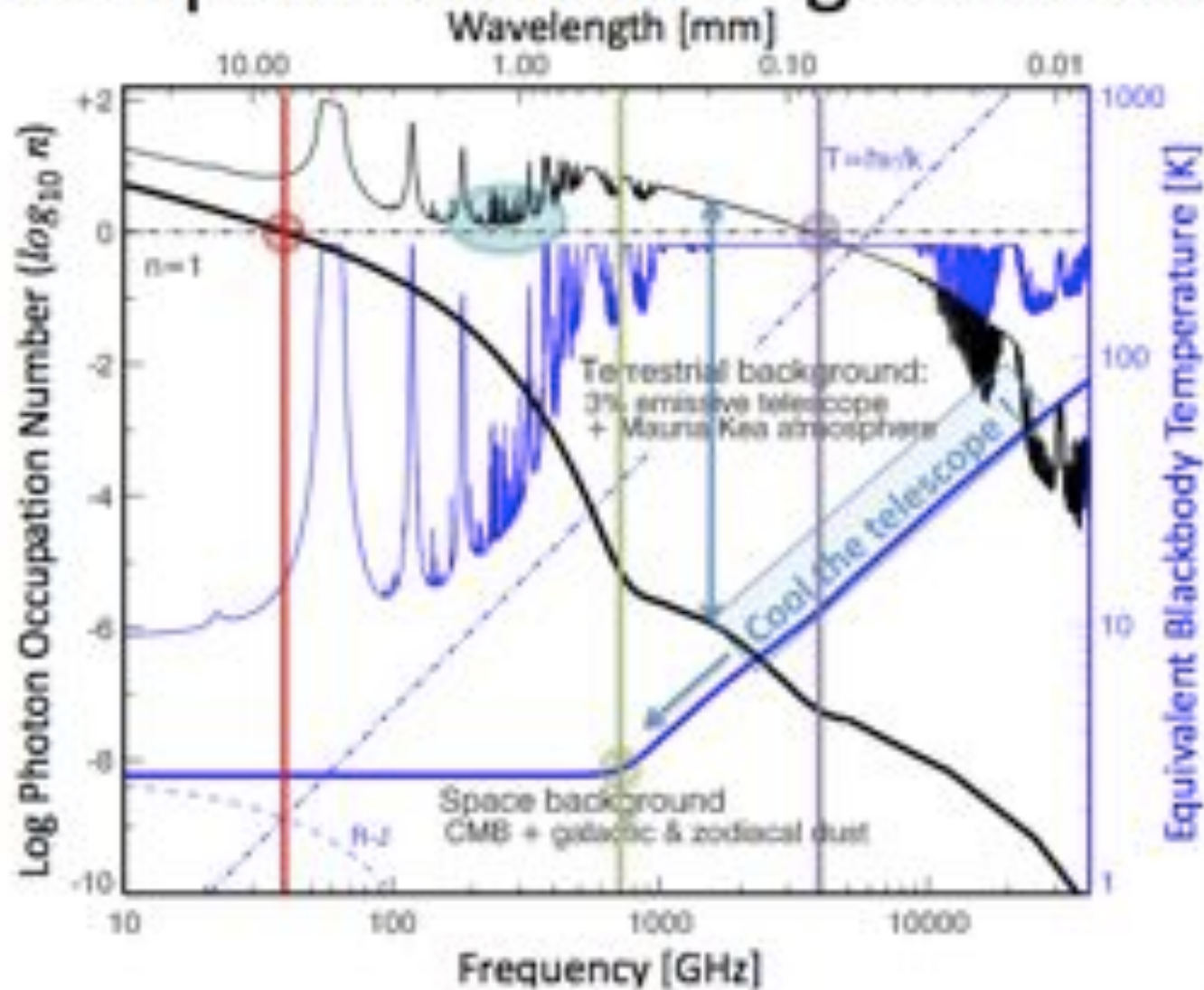
$h\nu \gg kT \rightarrow n \ll 1$  Wien limit  
 $h\nu \ll kT \rightarrow n \gg 1$  Rayleigh-Jeans limit

**Direct Detectors**  
CCDs, bolometers,  
MKIDs

**Amplifiers**  
Masers, FETs,  
HEMTs, SiS mixers

**occupation number**  
is the key :

# Occupation number: ground and space



$n < 1$   
CMB,  $\nu > 40$  GHz

CMB dominates  
background from  
space for  
 $\nu < 700$  GHz

$n < 1$   
from ground for  
 $\nu > 4$  THz

$n \sim 1$   
from ground for  
 $\nu \sim 200$ -300 GHz

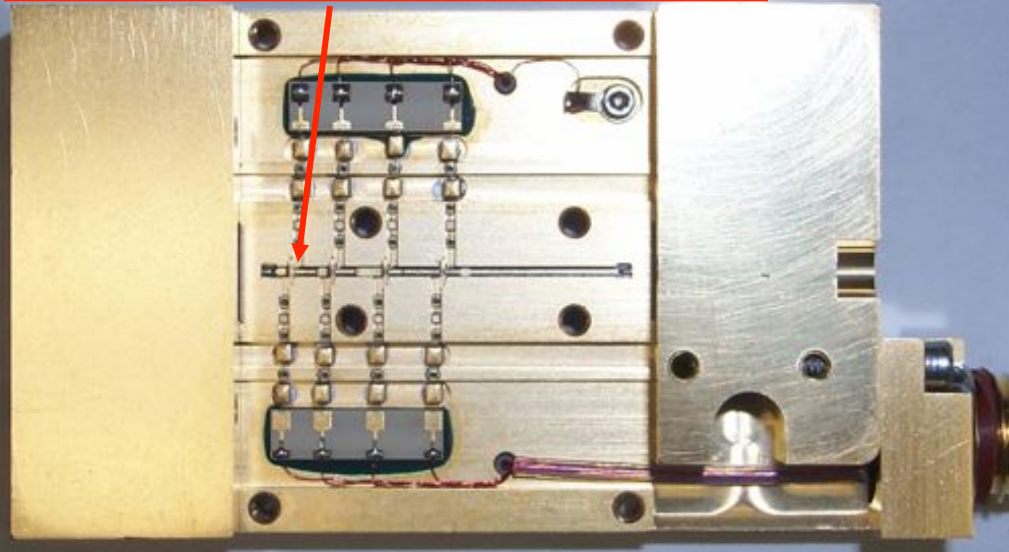
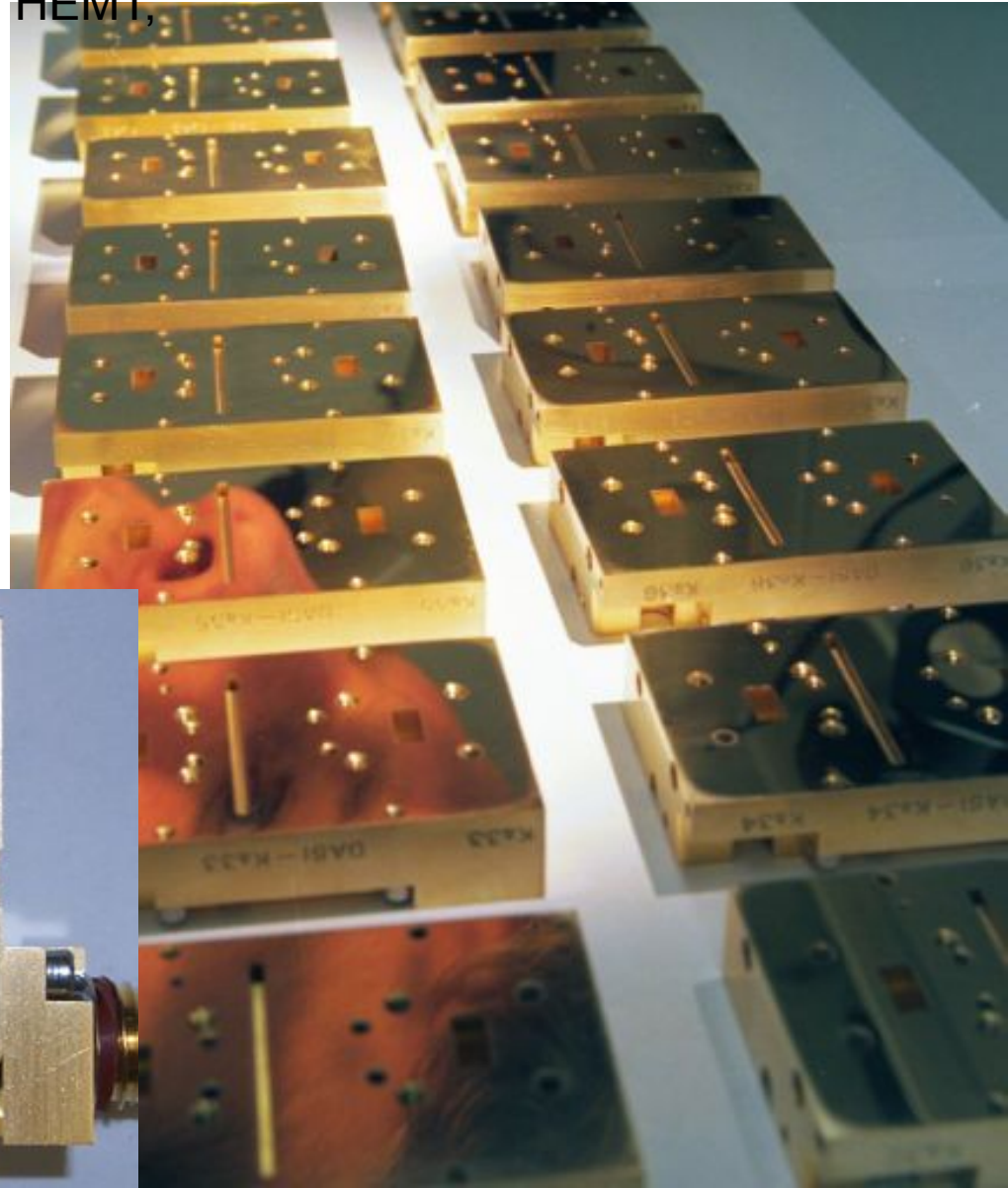
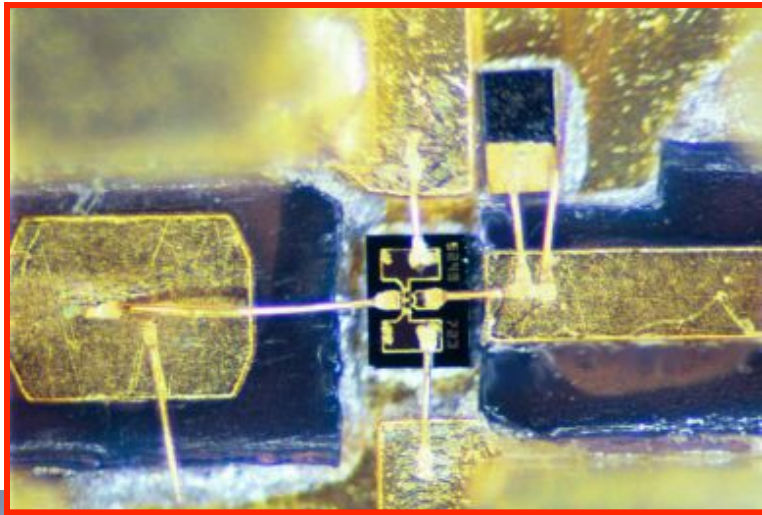
Zmuidzinas & Bradford 2008

Radio (amplifiers) dominate ←

→ Direct Detectors dominate

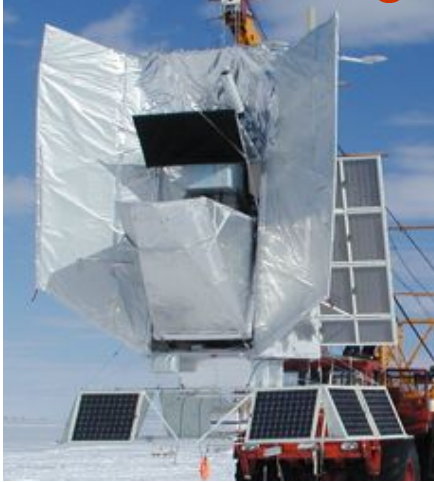
# HEMT Amplifiers – DASIS 2000-2004

DASI/SZA Ka-Band amplifier production at Chicago  
NRAO/Pospieszalski design, 4 stage InP HEMT,  
40dB gain, 10-15K over 26-36 GHz



# Polarization Sensitive Bolometers

Boomerang03



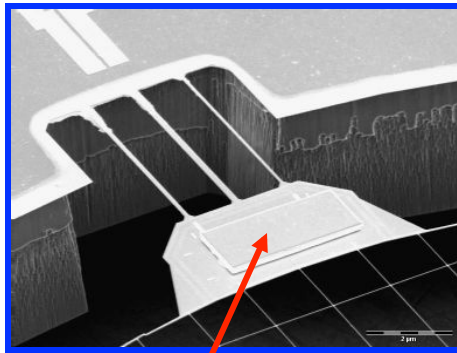
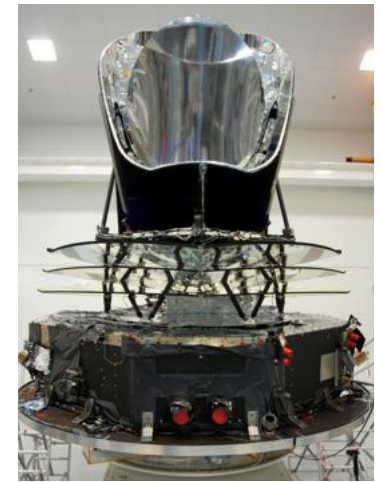
QUaD



BICEP

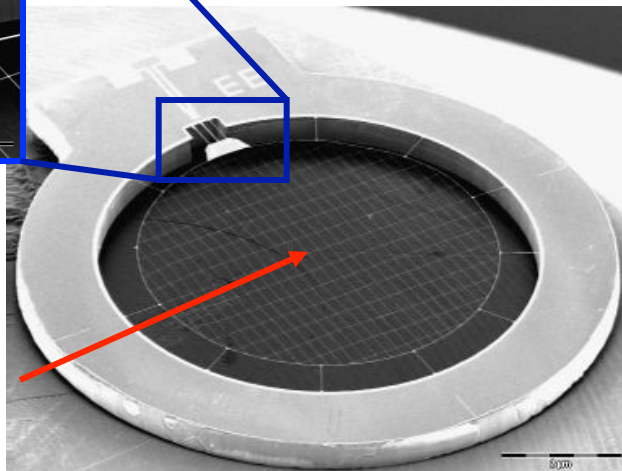


Planck HFI



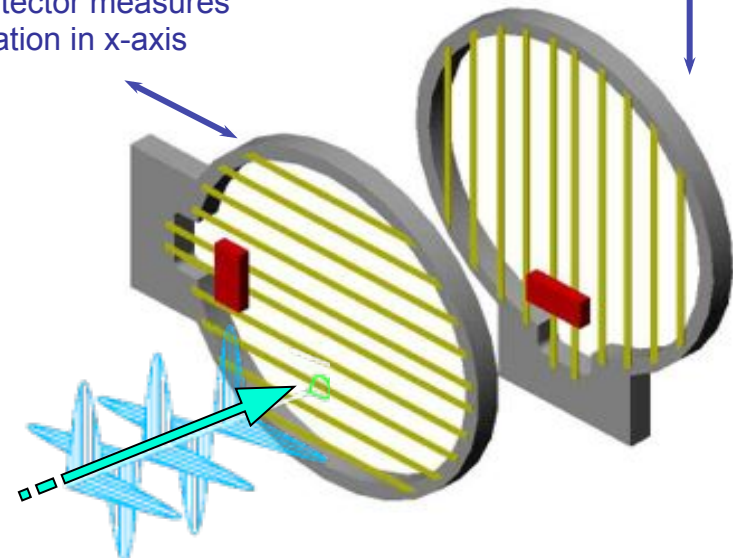
Semiconducting thermistor  
Neutron-Transmutation-Doped Ge

Metalized absorber  
R(sheet)  $\sim 377 \Omega/\text{square}$



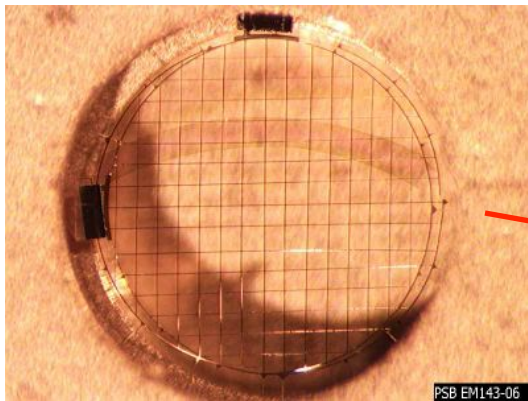
First detector measures  
Polarization in x-axis

Second detector measures  
Polarization in y-axis



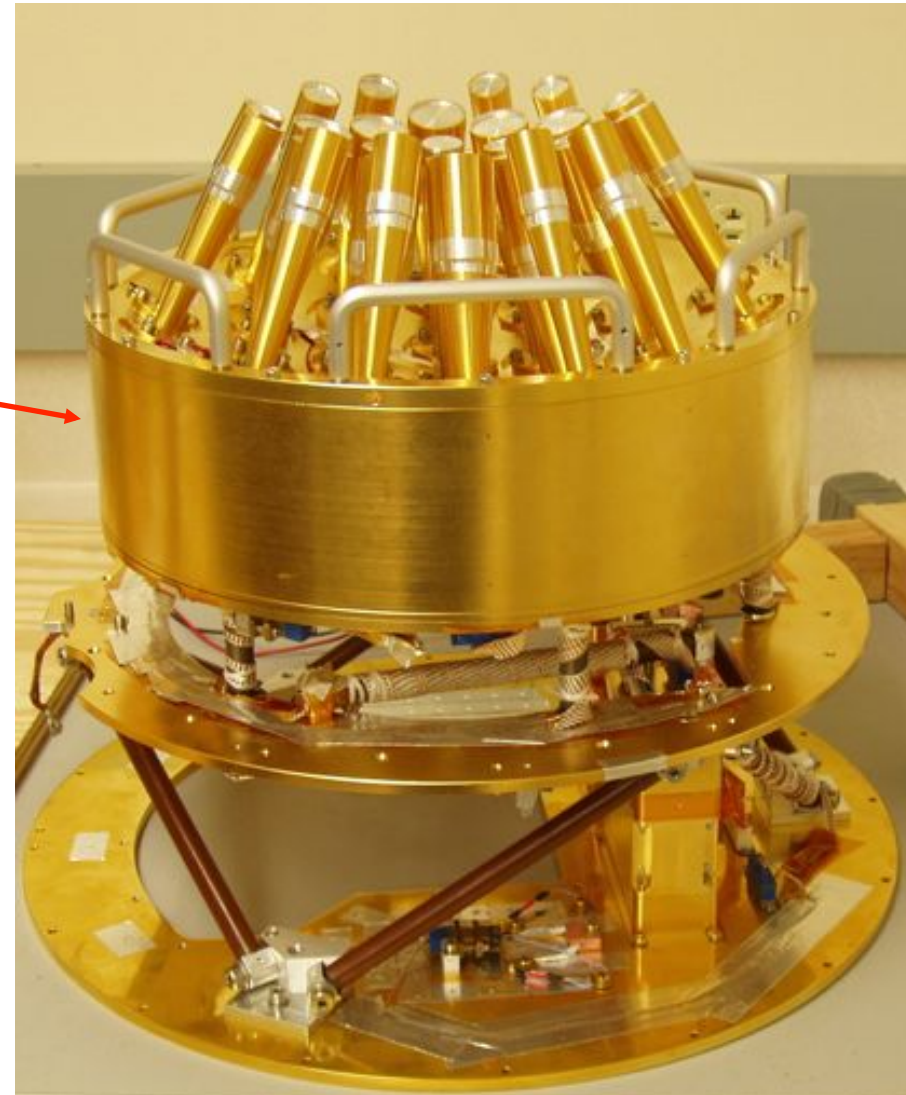
# Aug 2004: QUAD focal plane assembled

Goal: maximum instantaneous sensitivity,  
concentrated on a 80 sq. deg. survey...high S/N E-map

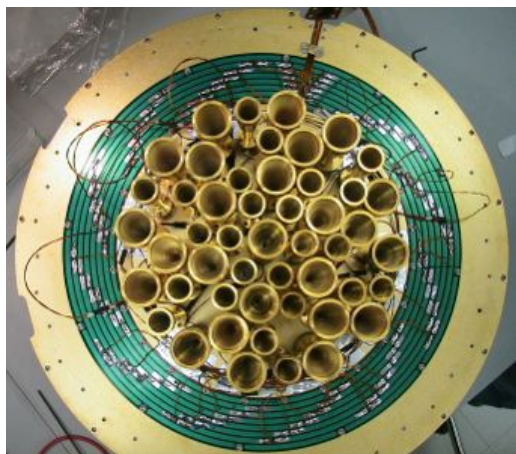


31 feeds

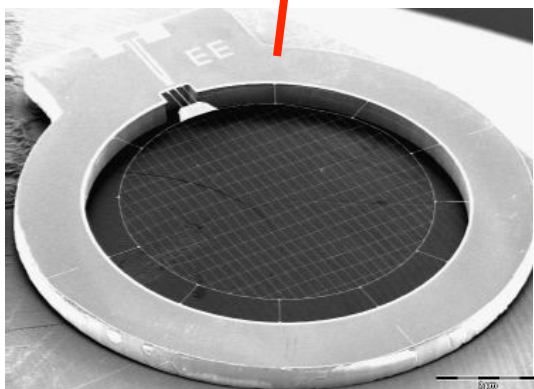
Freq. (GHz)	Beamsize (arcmin)	Number of Feeds
100	6.3	12
150	4.2	19



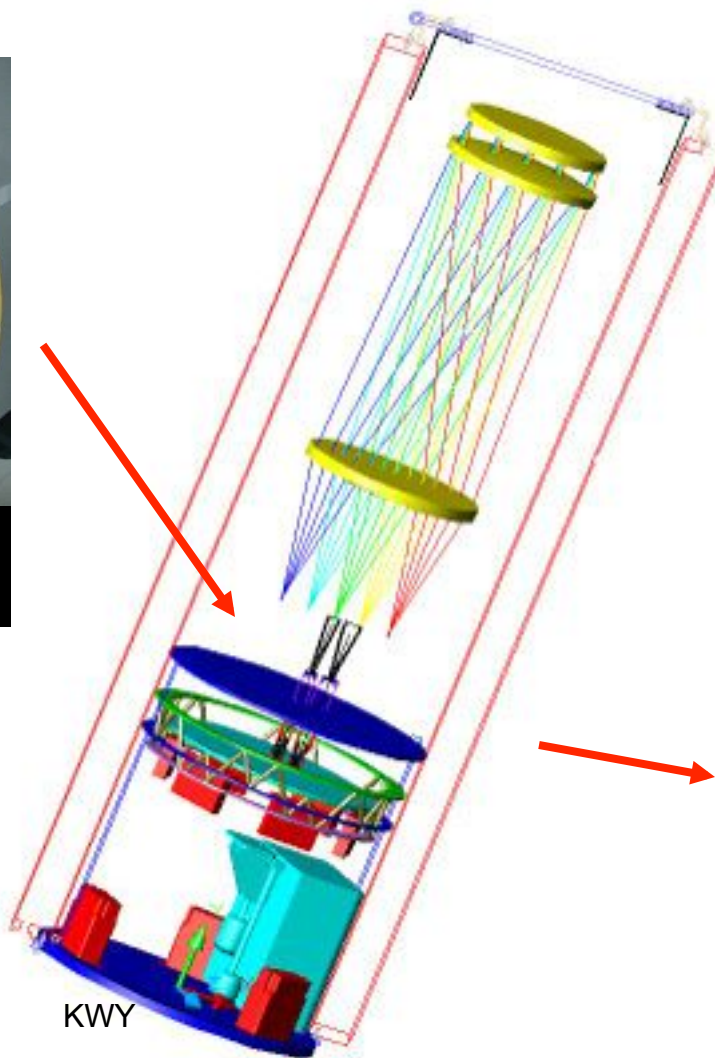
# BICEP1: a targeted B-mode machine!



98 Detector Focal Plane  
(100 and 150 GHz)



Polarization-Selective  
Bolometers (JPL)



Telescope: 30 cm wide-field  
refractor, all optics at 4 K



Feb 2006: working at Pole!



Fast-scan mount (5 d/s)

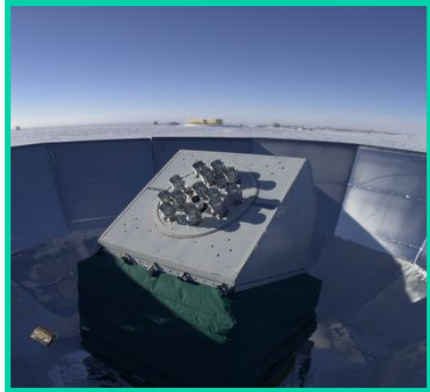


29 Nov 2005: BICEP installed into DSL





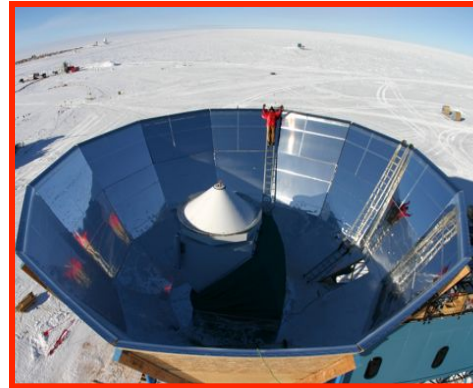
# E-polarization measurements to date



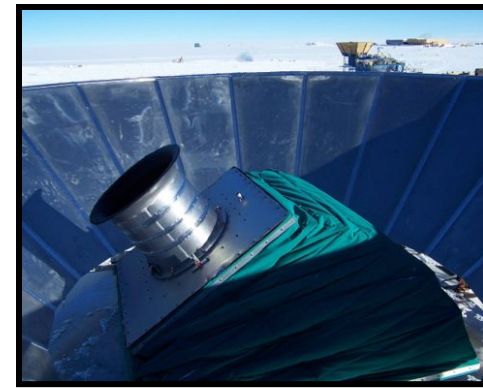
DASI  
1999-2004



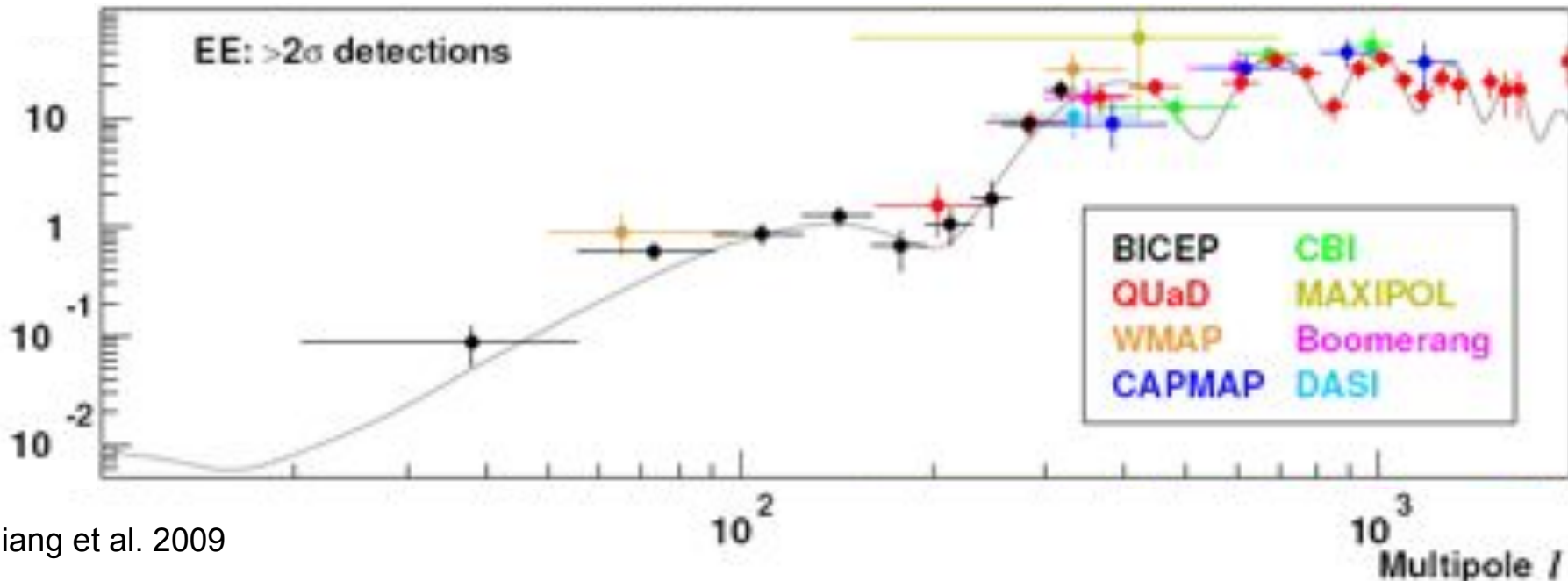
BOOMERANG  
2003



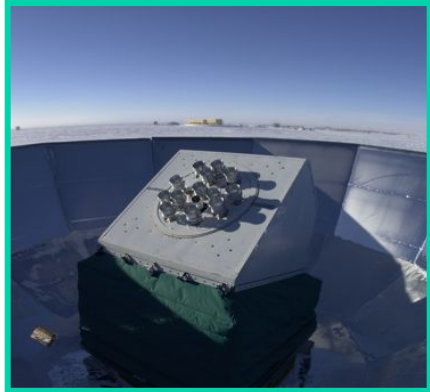
QuAD  
2005-2007



BICEP1  
2006-2008



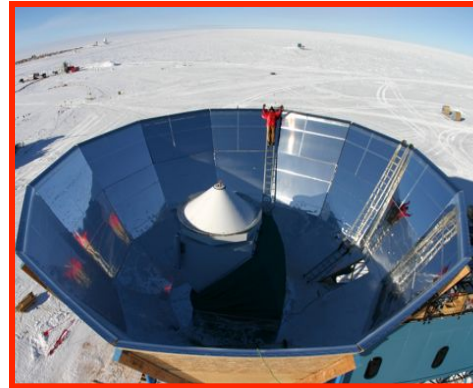
# B-polarization measurements to date



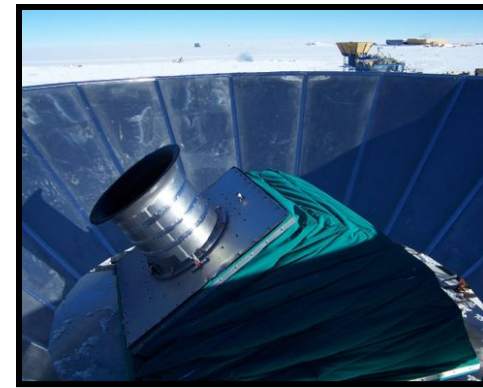
DASI  
1999-2004



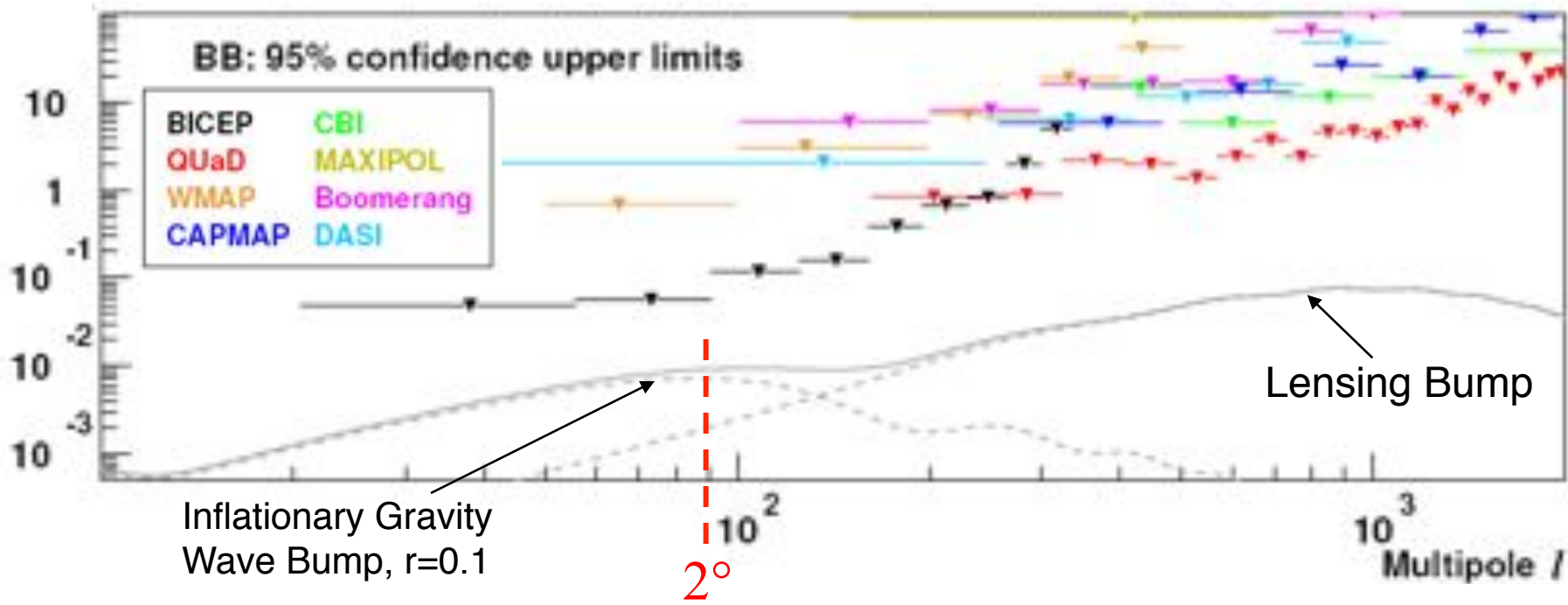
BOOMERANG  
2003



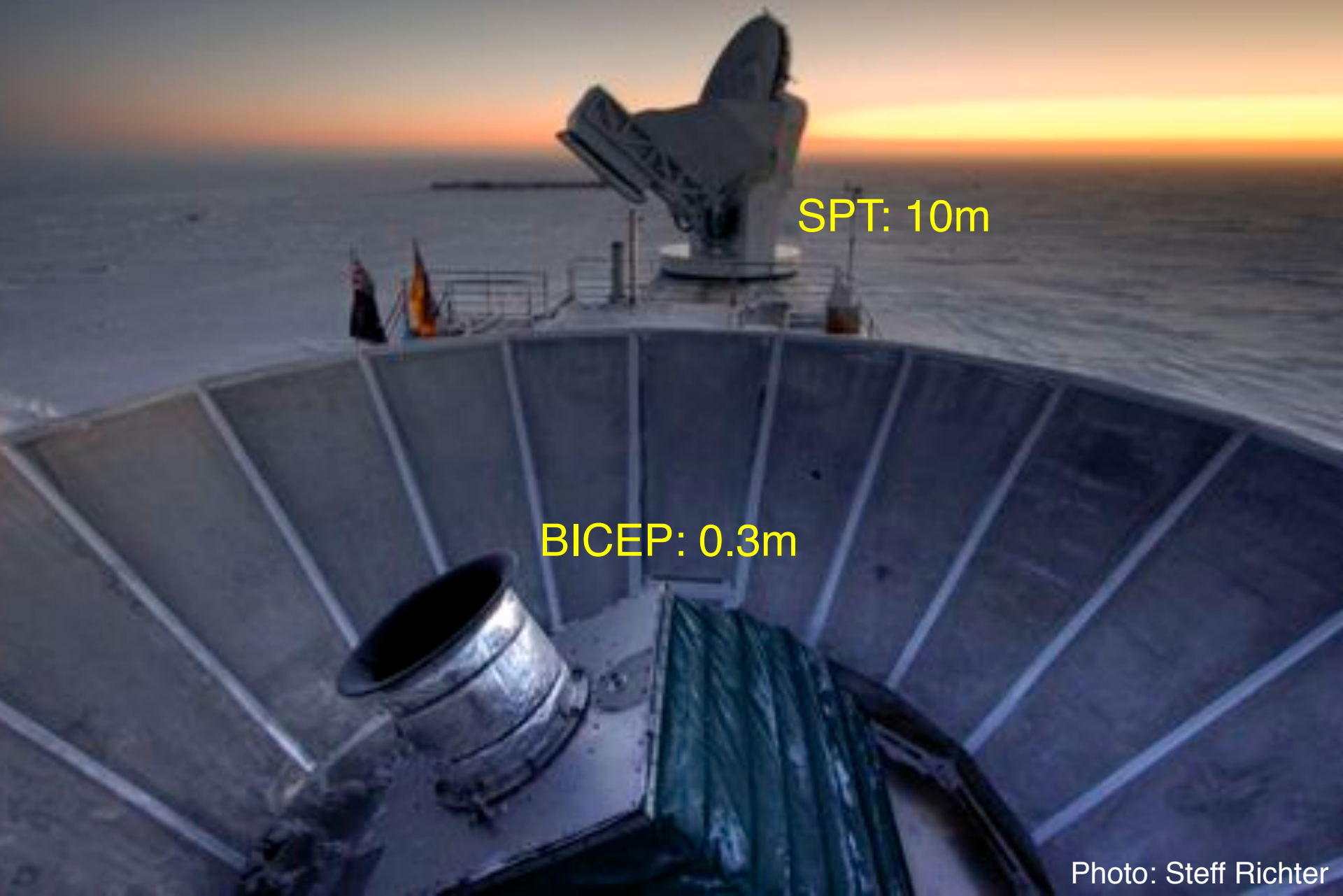
QuAD  
2005-2007



BICEP1  
2006-2008



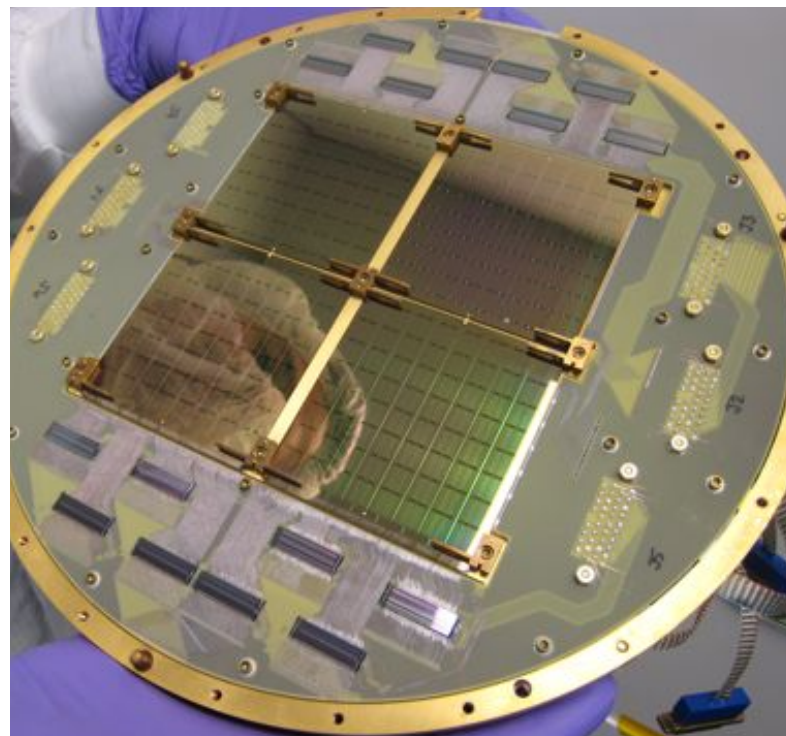
# Different apertures – different angular scales



SPT: 10m

BICEP: 0.3m

# BICEP2: 10-fold increase in mapping speed:

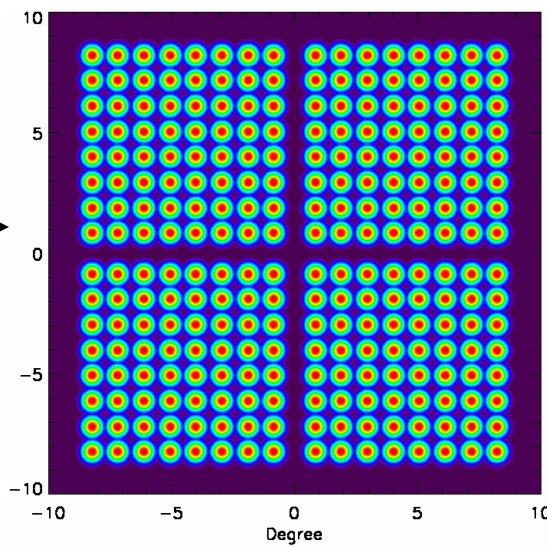
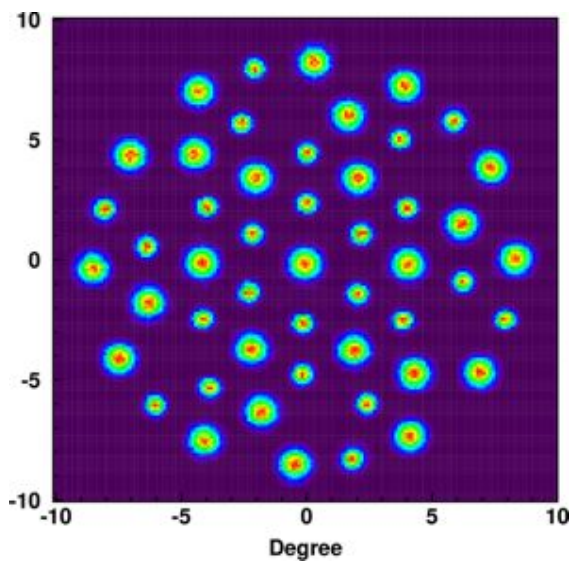


**JPL : antenna-coupled TES arrays**

**BICEP1**

**48**

150 GHz  
detectors

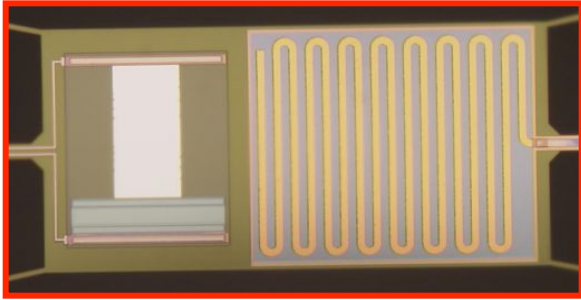


**BICEP2**

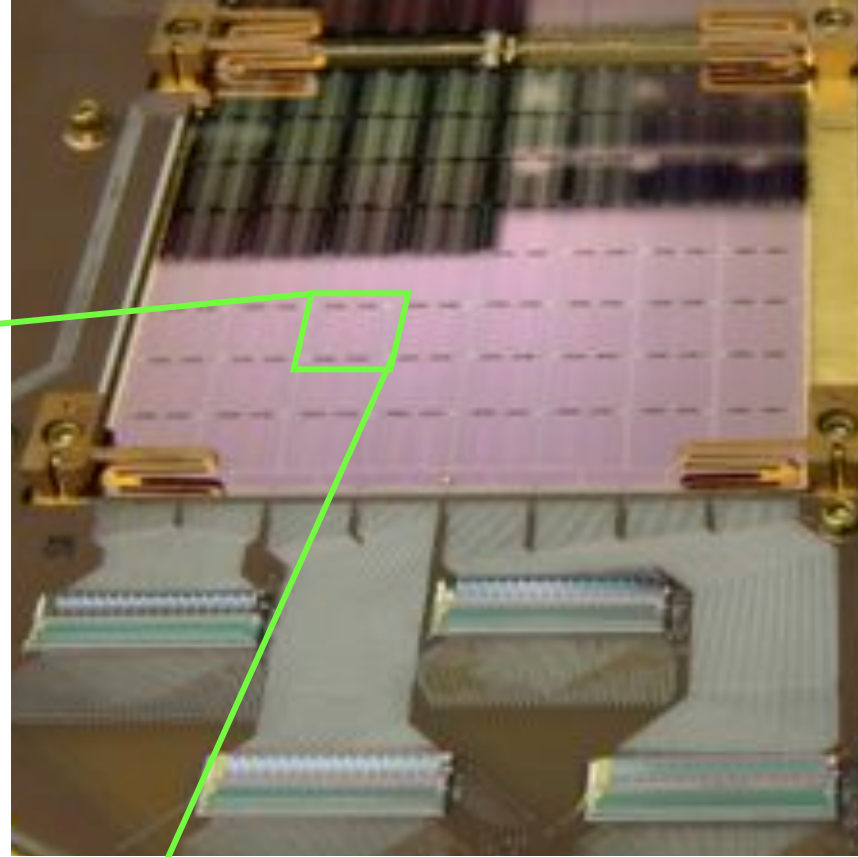
**512**

150 GHz  
detectors

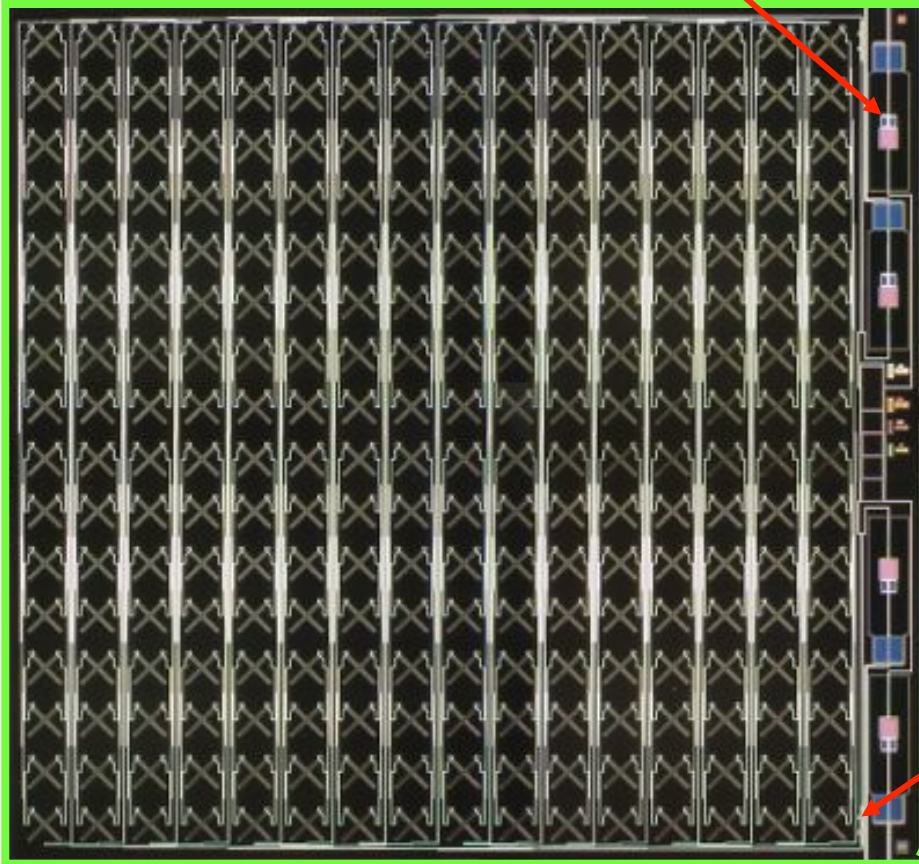
# New Superconducting Detectors



TES Absorber and Bolometer



Back-illuminated Beam-Forming Antenna



Bandpass Filter

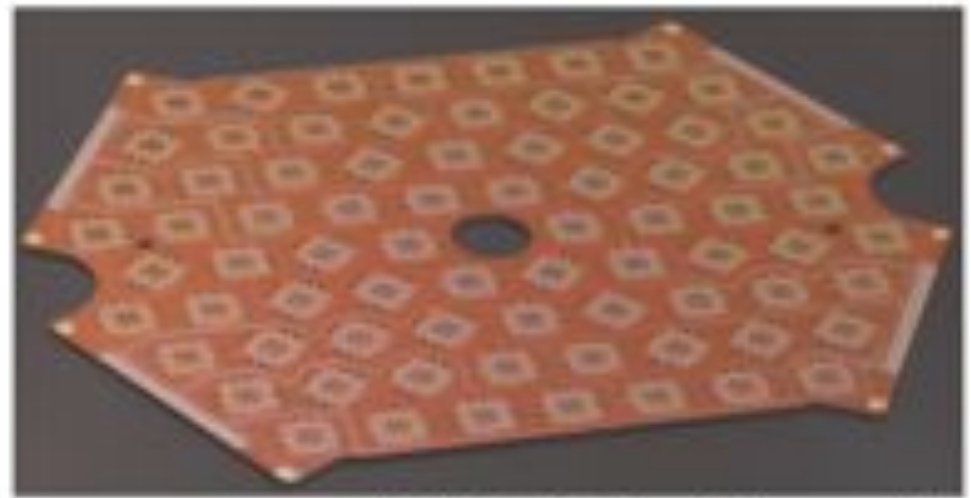
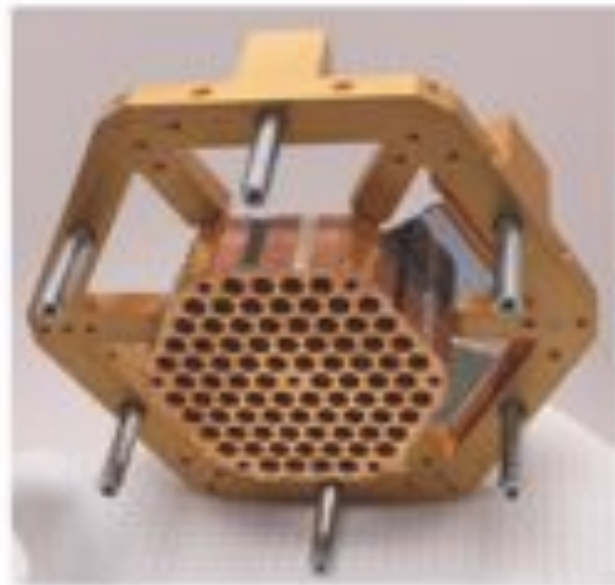
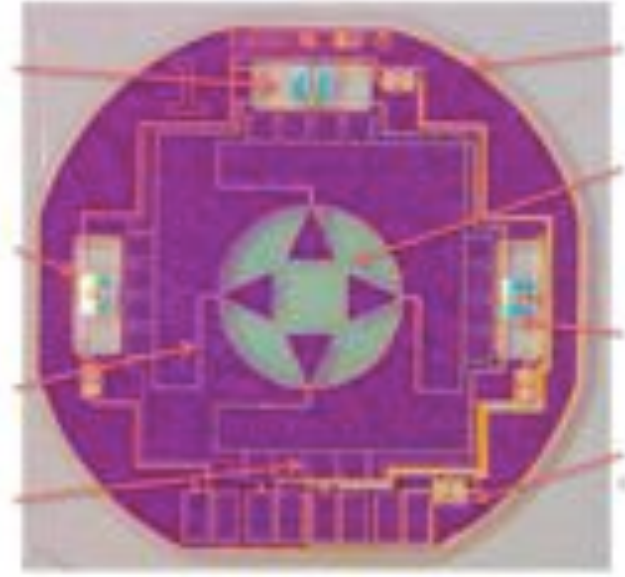
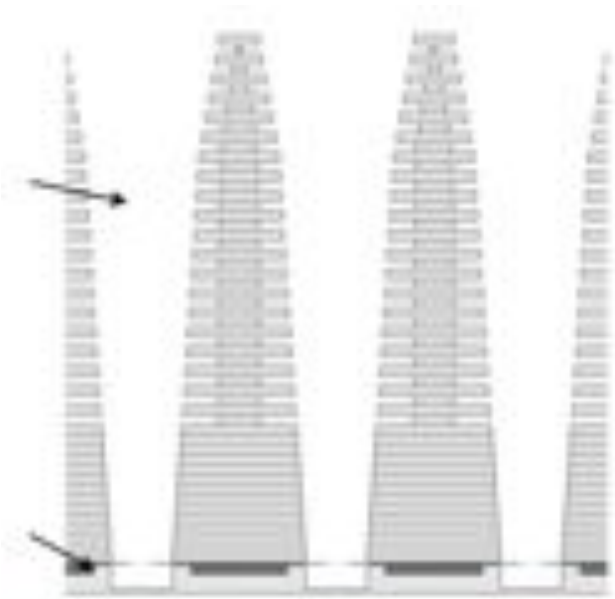
# Putting BICEP2 together at South Pole



Justus Brevik



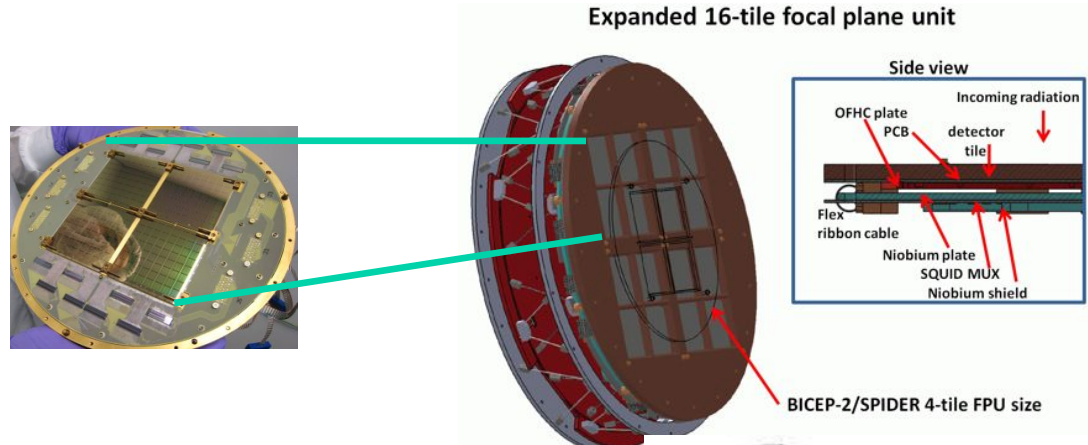
# SPTpol camera (2012) - 1500 detectors



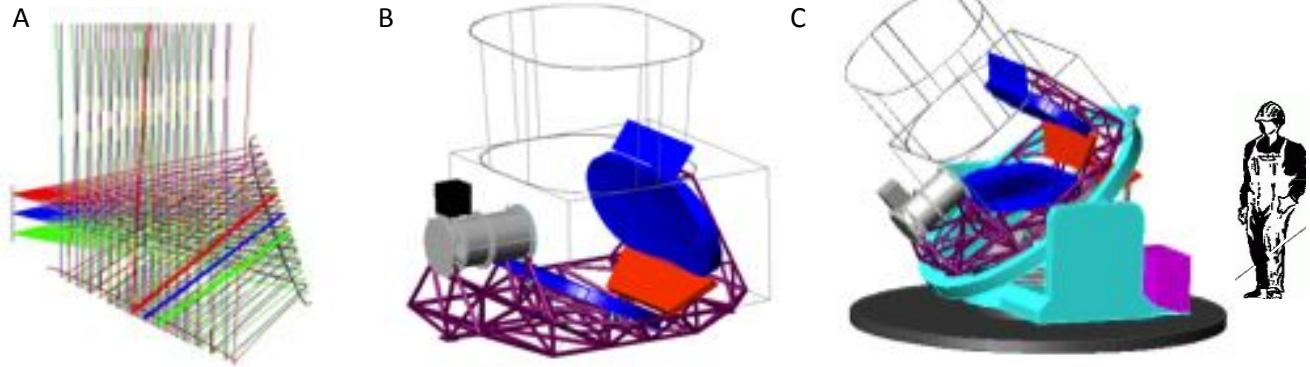
(NIST – Kent Irwin's group)

# POLAR-1: a very high throughput CMB polarimeter

- 5,000-10,000 TES detector focal planes



- 2m aperture cross-Dragone telescopes



Science target: Lensing B-modes

- neutrino masses  $\Sigma m_\nu$ ,
- evolution of Dark Energy
- curvature – pre-Inflationary relics

# Outlook for CMB polarization

- **South Pole** has led the way in precision CMB polarimetry
  - **DASI, QUAD, BICEP1**
- **Now: B-modes from Inflation**
  - **BICEP2** meets sensitivity spec; new systematics challenges
  - **The Keck Array – 2500 detectors now operating!**
  - Together will probe Inflation to  $r \sim 0.01$  (lensing confusion limit)
- **Next step: B-mode lensing**
  - nK sensitivity  $\rightarrow$  1000's – 10,000's of detectors
  - 4' resolution  $\rightarrow$  Larger telescopes
  - **SPTpol (2012) - 1500 detectors**  
and **POLAR-1 (2014) - 4000 detectors ( x N )**

# CMB detection and teaching

- Harvard Astro191  
CMB lab
  - Undergraduate fieldtrip to Bell Labs at Crawford Hill, New Jersey
  - Unique chance to work with Bob Wilson



# Comparison to a Similar Experiment

University of Chicago	Harvard University
<p data-bbox="272 522 929 708">Experiment set-up ahead of time; lasts about one afternoon</p> <p data-bbox="285 868 915 1062">Uses a 30 GHz receiver (cryogenic, low-noise, HEMT) → Not cheap!</p>	<p data-bbox="1060 522 1634 853">Experiment is entirely student built; students delve more into basic physics and radio astronomy</p> <p data-bbox="1041 936 1653 1130">Built from commercially available materials, &lt; \$5000</p>

Both labs give students a feel for doing real experimental science!

# Design of the Experiment

Three main parts of the design:

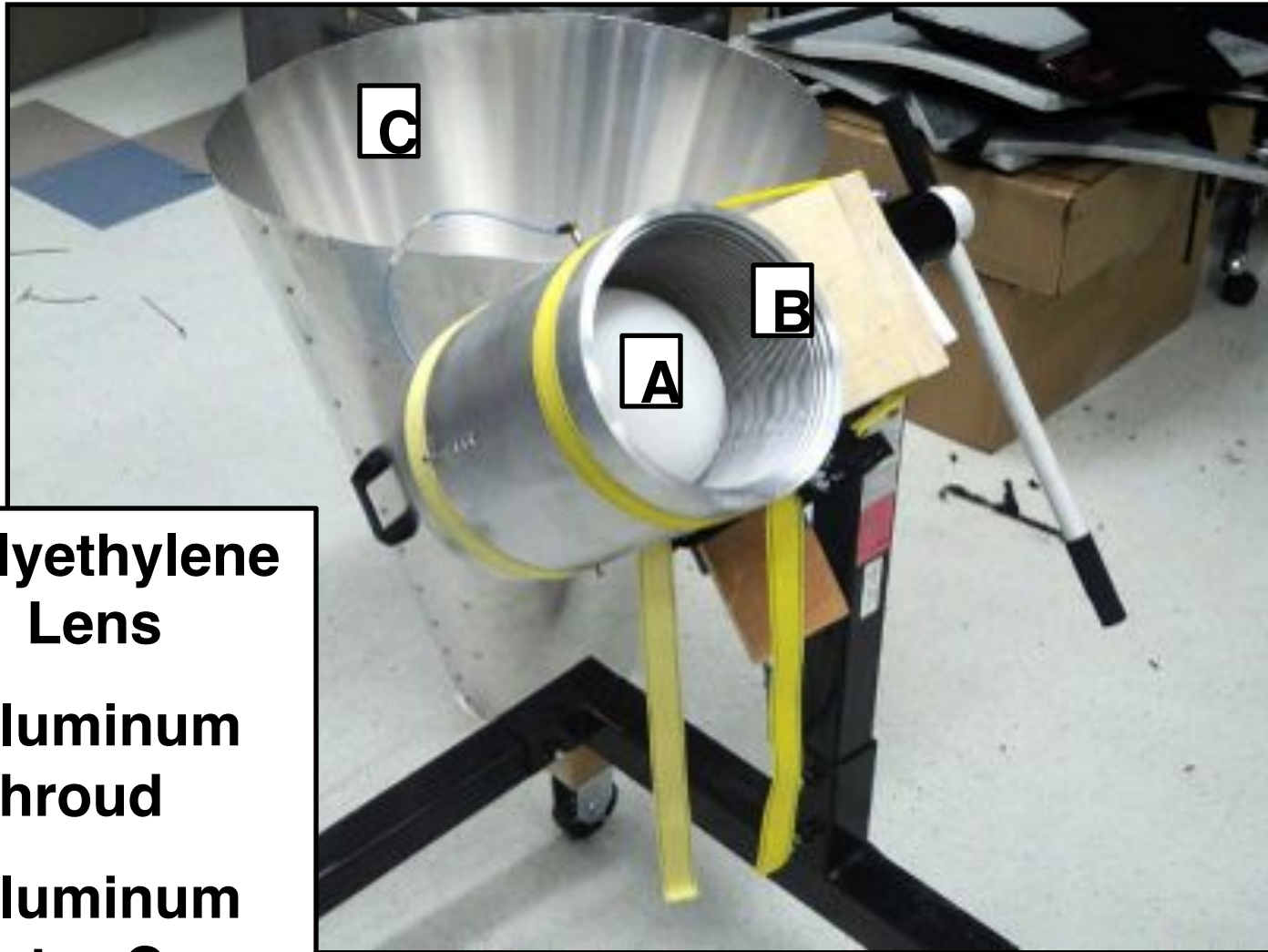
1.  
Low-sidelobe  
antenna

2.  
Stable, low-noise  
radiometer

3.  
Calibration  
Scheme



# Low-Sidelobe Antenna



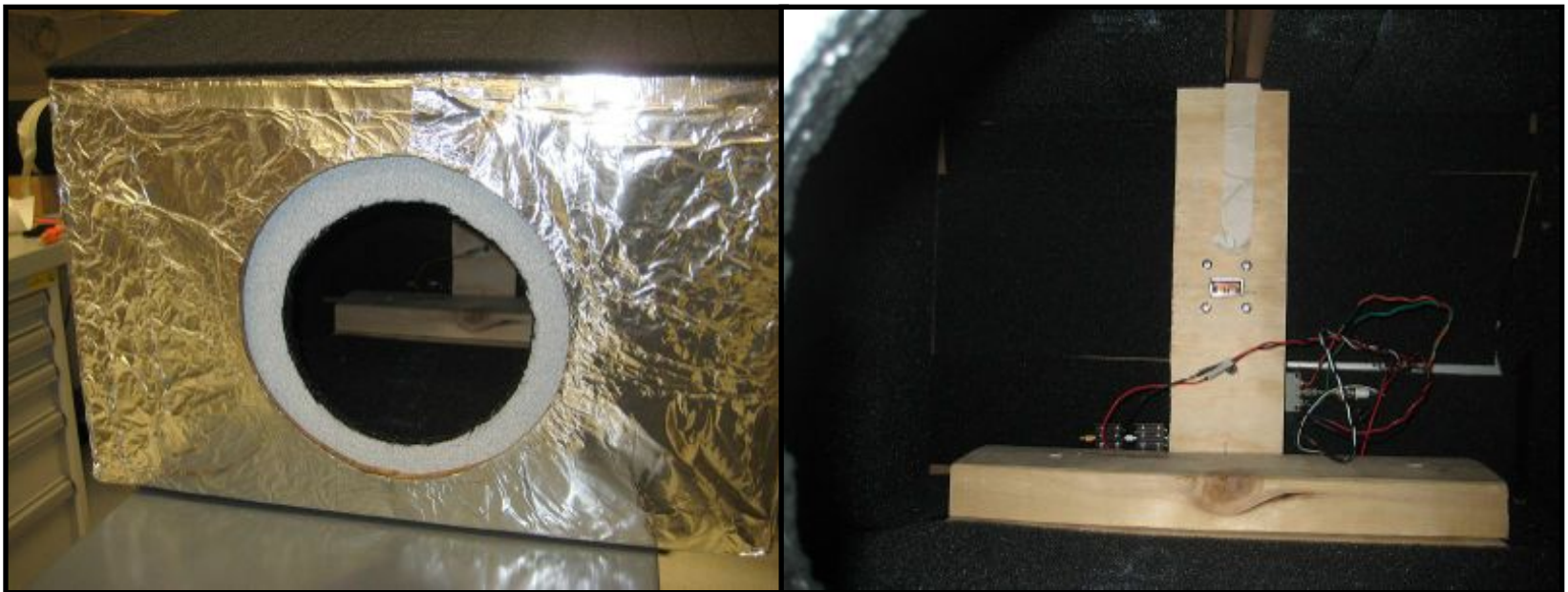
**A) Polyethylene  
Lens**

**B) Aluminum  
Shroud**

**C) Aluminum  
Reflector Cone**

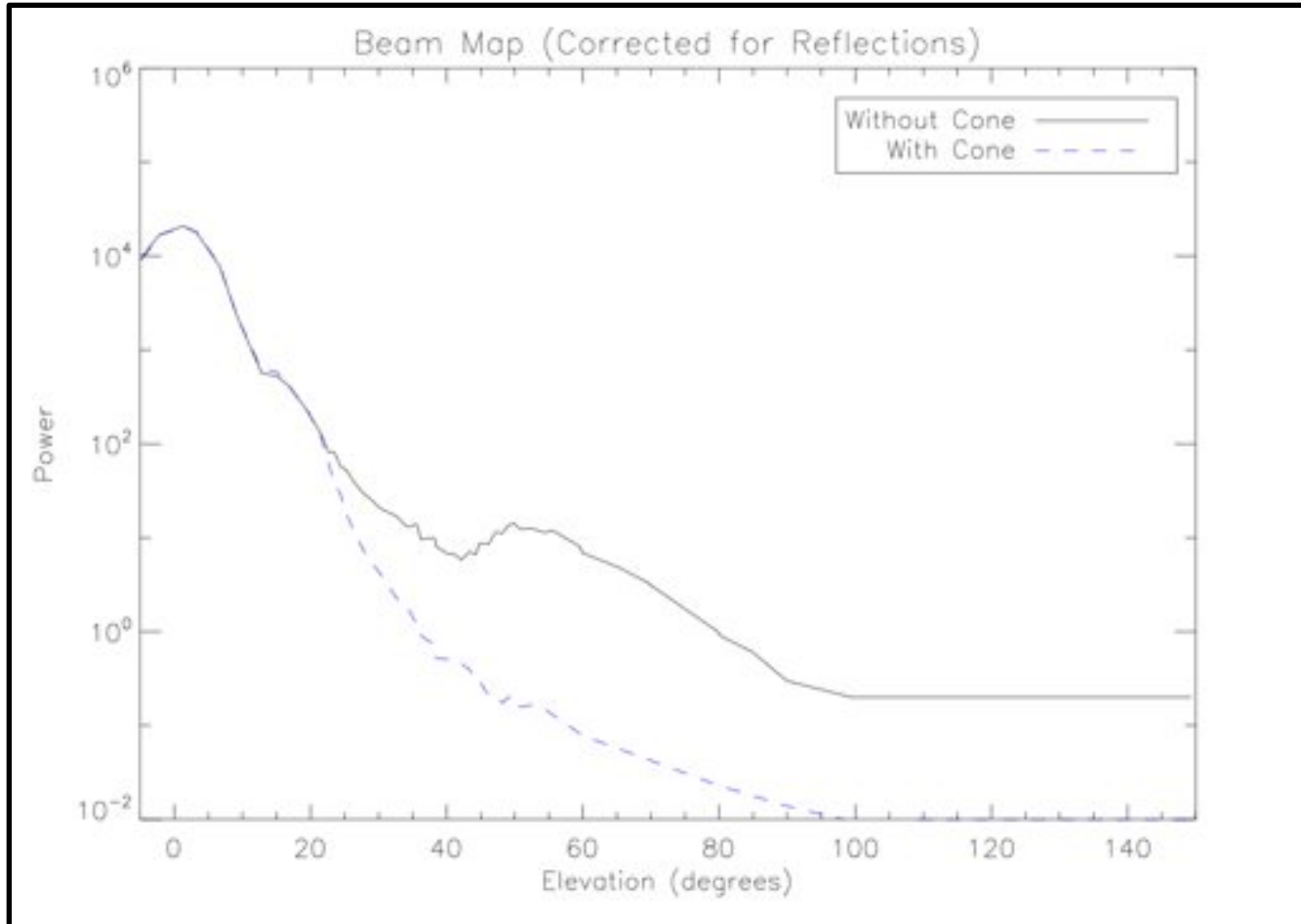
# Low-Sidelobe Antenna

Beam mapping carried out using a uniform conical emitting source placed in a box lined with HR-25 microwave absorber



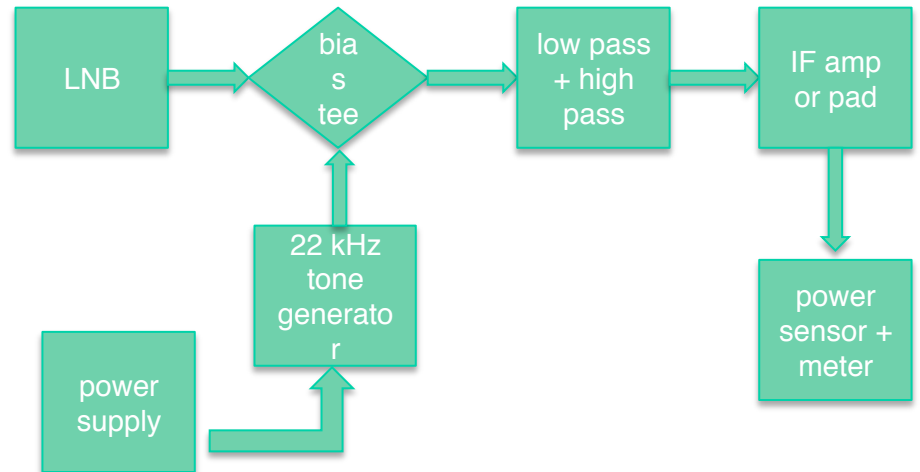


# Low-Sidelobe Antenna



An example of the resulting beam map

# Stable, Low-Noise Radiometer



Constructed entirely from commercially available components

# Stable, Low-Noise Radiometer

Main component of the radiometer is the Low-Noise Mixing Block (LNB)



## Important Characteristics of the LNB

- Two frequency bands: 10.7 – 11.7 GHz and 11.7 – 12.75 GHz
  - Both vertical and horizontal polarization
    - IF range: 950 -2150 MHz
    - \$40

# Calibration Scheme

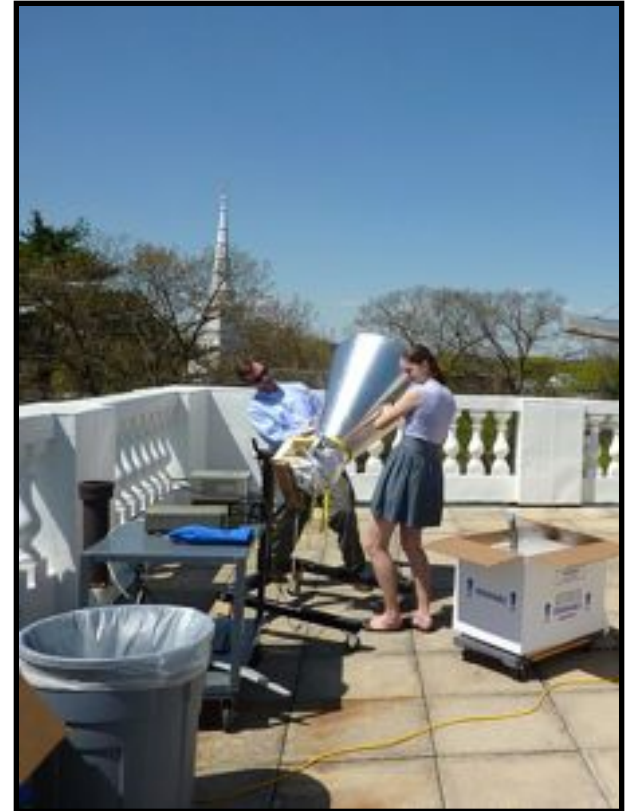
Constructed three calibration loads:

1. Room temperature
2. Liquid N<sub>2</sub>
3. Liquid Ar (for linearity testing)

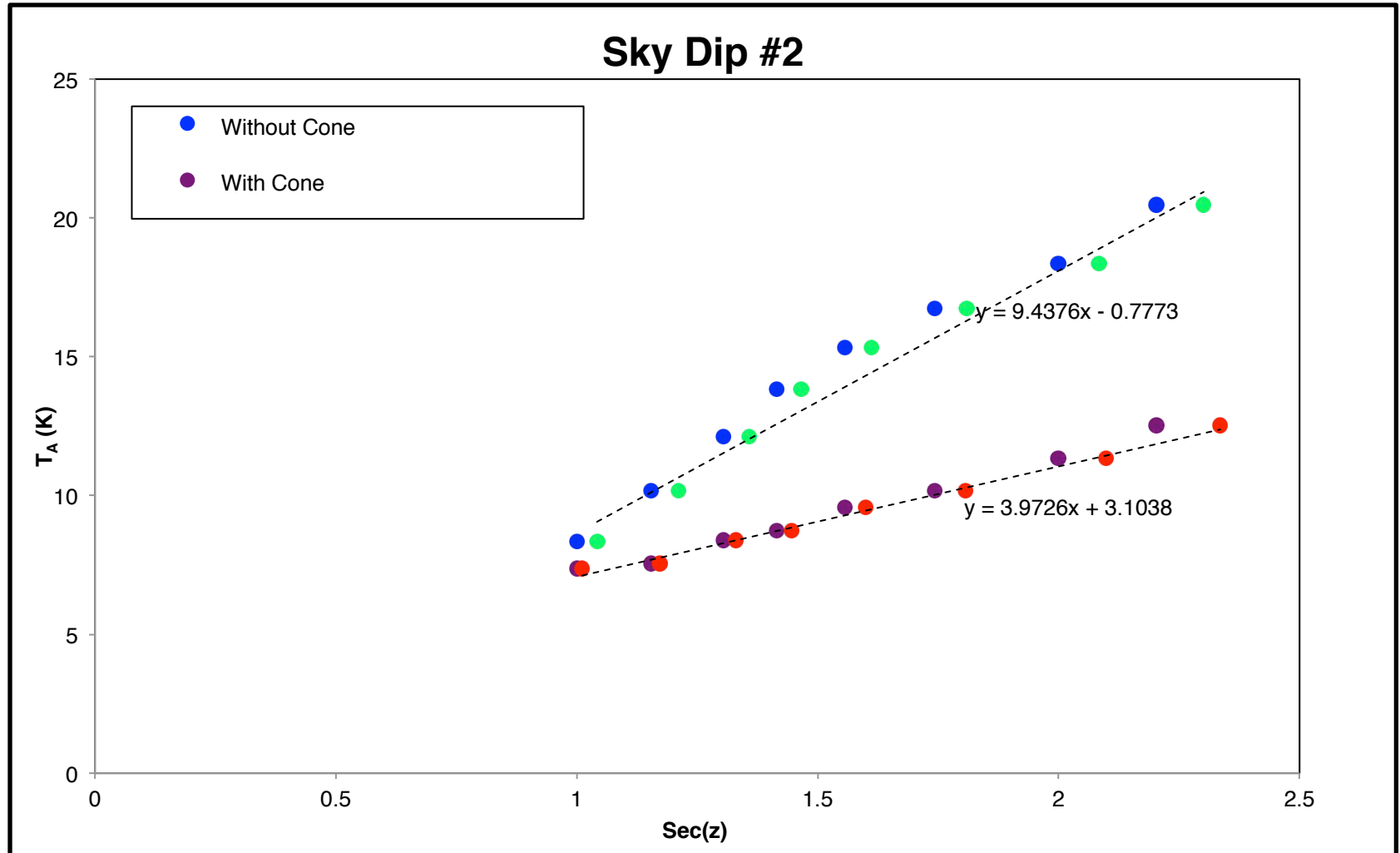


# Observations

- Telescope affixed to a tilt mount
- Used both hot and cold calibration loads in between sky dips to monitor system temperature
- Started with telescope pointing at zenith
- Dipped telescope towards the horizon
- Took measurements with and without cone



# A Sample of the Results...



# Systematics and Errors



## Systematics Considered

- Effective airmass
- Rayleigh-Jeans assumption
  - Exponential vs. linear attenuation
    - Flat Earth
    - Linearity error

## Other limits on accuracy

- Weather conditions
- Careful procedure

Students typically claim total error  
 $< 0.5K$

# Continuing Improvements

- Fitting the 11 GHz instrument with a new mount and encoders to allow for full-sky mapping
- Repeating the measurement using a 30 GHz cryogenic DASI receiver
- One afternoon graduate student lab using the 11 GHz instrument



Students conducting observations with the 30 GHz instrument



# Concluding Thoughts

It is possible for undergraduates to build an instrument capable of detecting the CMB using only commercially available parts

By completing such an experiment, students have a chance to learn basic physics, introductory radio astronomy, and how to control systematics







photo: Keith Vanderlinde

# Modern cosmology in a nutshell:



Edwin Hubble

1) The universe is expanding.

(Hubble, 1920's)

2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940's)



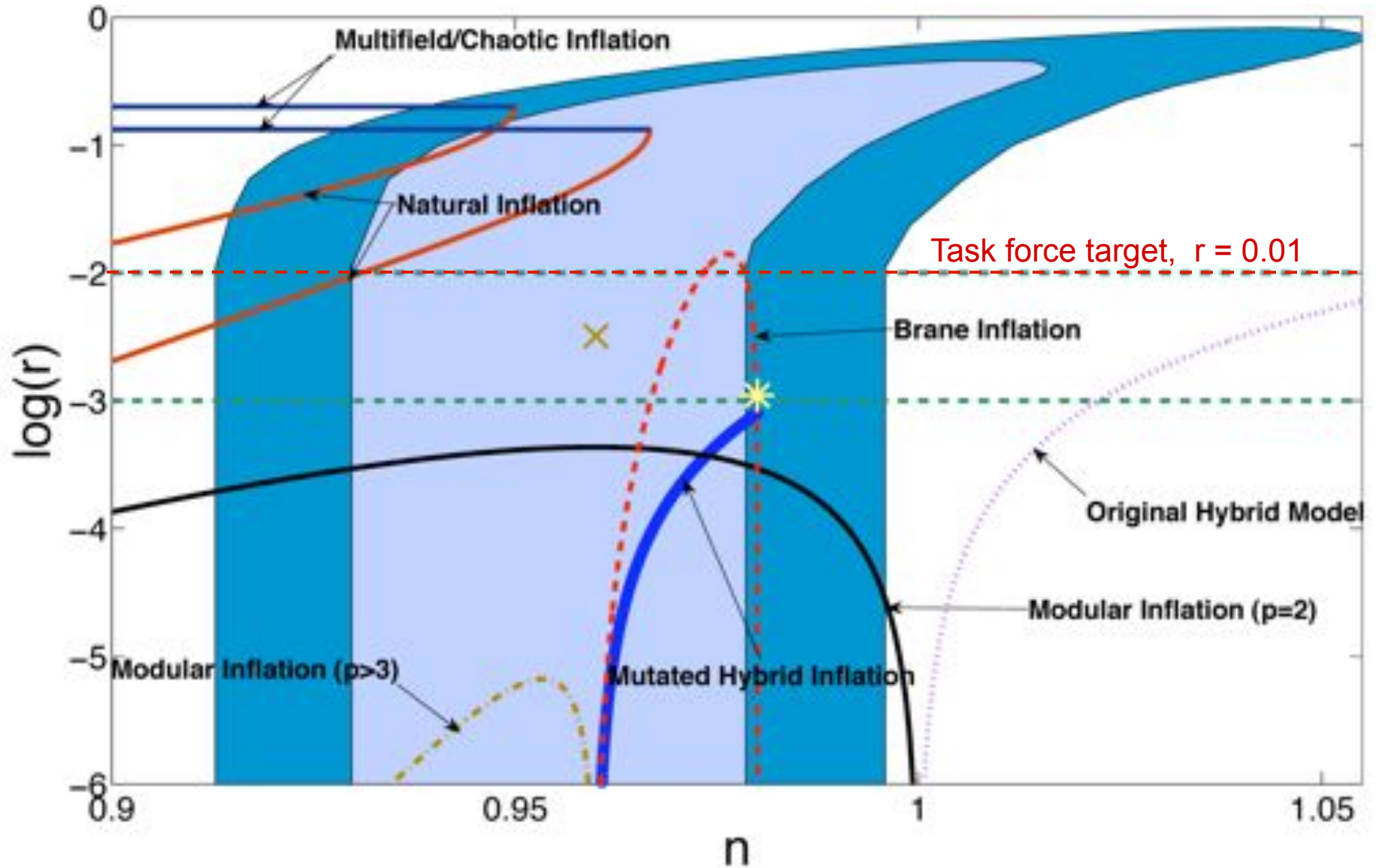
3) You can still see the glow!

The *Cosmic Microwave Background*

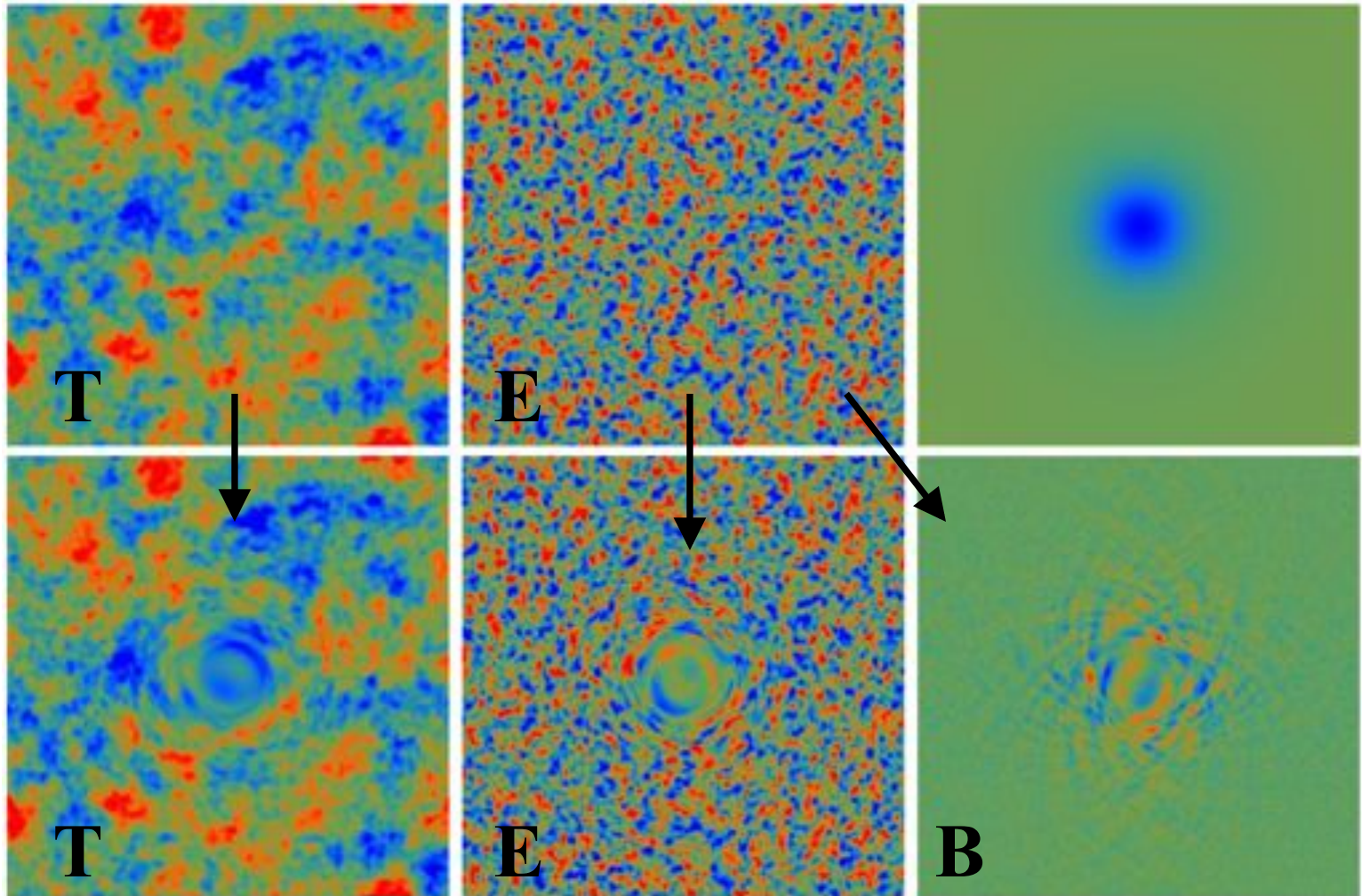
(Penzias & Wilson, 1965)

⇒ **“HOT BIG BANG”**

# Inflationary parameters: $n_s$ , $r$



# Lensing: converting E to B



Hu and Okamoto, astro-ph/0111606

Realistic models predict  $\sim 2.6'$  rms deflection, coherence scale  $\sim$  few degrees

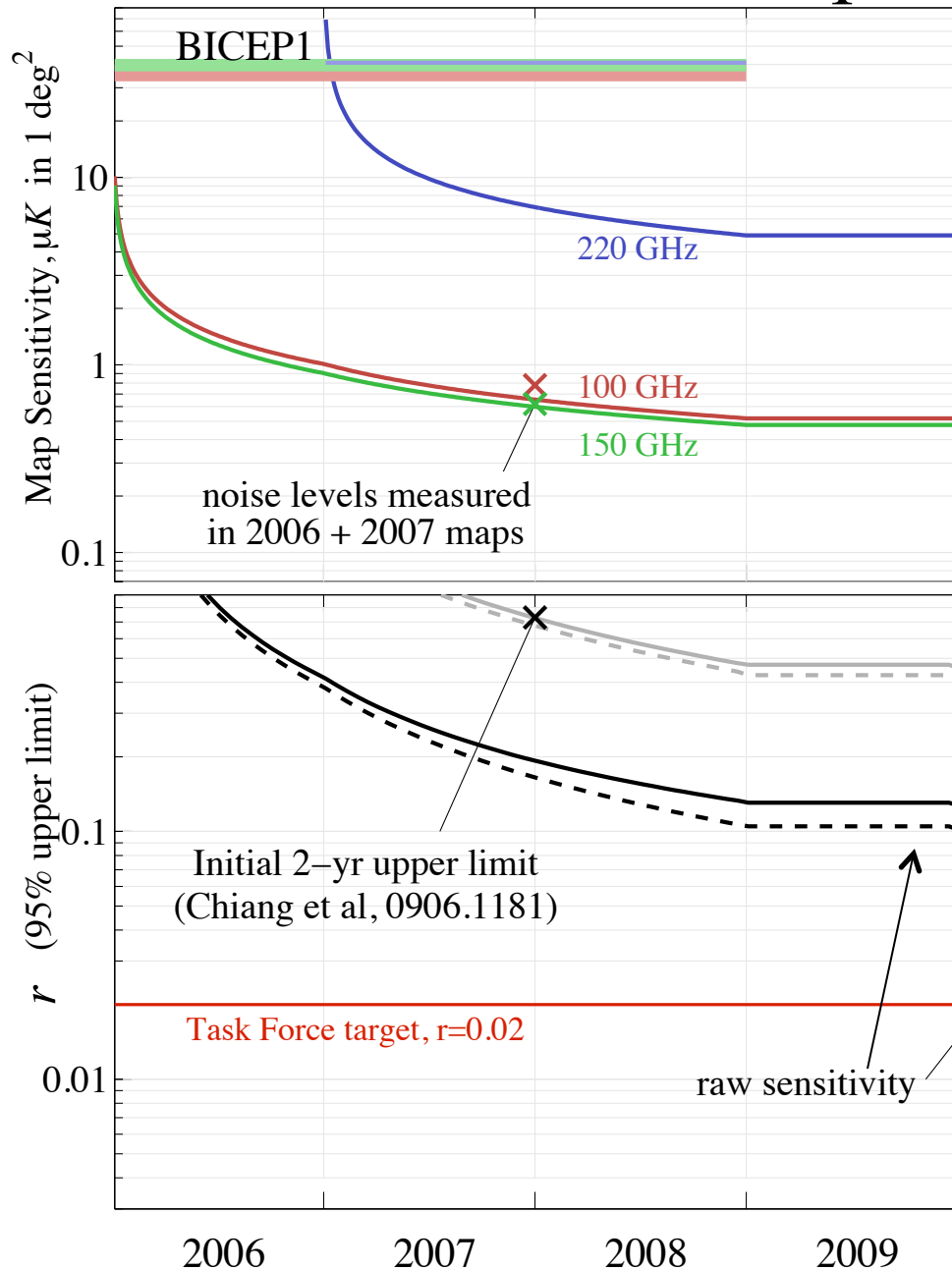


Keck Array

South Pole Station (1km)

BICEP

# BICEP / Keck : map depth & sensitivity to $r$





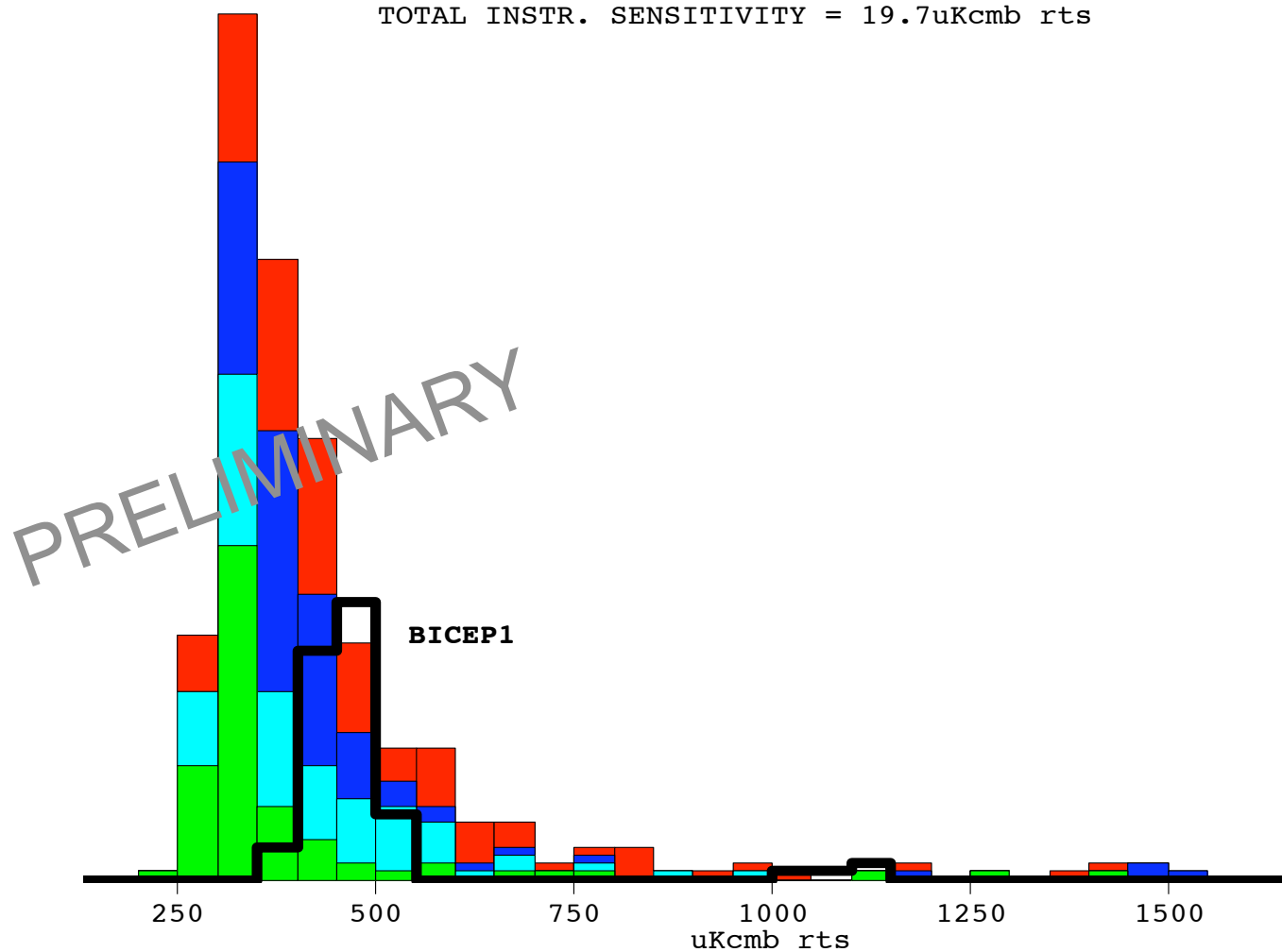
# Jan 2010 - BICEP2 initial sensitivity estimates:

## 9x greater mapping speed than BICEP1

WORKING DETs = 390

NON-WORKING = 90

TOTAL INSTR. SENSITIVITY = 19.7uKcmb rts



Justus Brevik

# Inflation from the ground:

- **BICEP2** is probing Inflation right now (Feb 2010)!
  - Meets sensitivity projections
  - Initial CMB results coming very soon! (Chiang et al.)
- **Systematics** are controllable down to at least  $r=0.01$ 
  - No exotic polarization modulators – just careful optical design and scanning
- **Sensitivity** is gated by availability of high-efficiency focal planes
  - Detector support is crucial to continued progress!
- **Suborbital B-mode Experiments** (BICEP2, Keck and many others) have a huge role in the next 5 years:
  - In Southern Hole, will probably push to  $r < 0.01$  and beyond...
  - Will continue to prove and improve technology for an orbital mission.

# Seven Tests of Inflation

- The following are “generic” predictions of inflation, items for which we had little evidence when inflation was introduced (from Paul Steinhardt):
  - ✓ **near scale invariance**
    - slope of spectrum, measured with ~20% precision by COBE
  - ✓ **flatness**
    - position of 1<sup>st</sup> acoustic peak, measured by Boomerang, MAXIMA, DASI, Archeops, .... WMAP1
  - ✓ **adiabatic fluctuations**
    - width of 1<sup>st</sup> acoustic peak, measured by Boomerang, MAXIMA, DASI, Archeops, ..., WMAP1
  - ✓ **nearly gaussian fluctuations**
    - limits on  $f_{NL}$ , best to date by WMAP
  - ✓ **spectral tilt,  $n_s < 1$** 
    - favored by Boomerang 2003, ....., WMAP3 (~ 2 -> 3  $\sigma$ )
  - ✓ **super-horizon fluctuations**
    - TE polarization anti-correlation on  $>2^\circ$  scales, measured by WMAP1
  - **gravitational waves (tensors)**
    - B polarization: the “smoking gun”...no evidence yet.

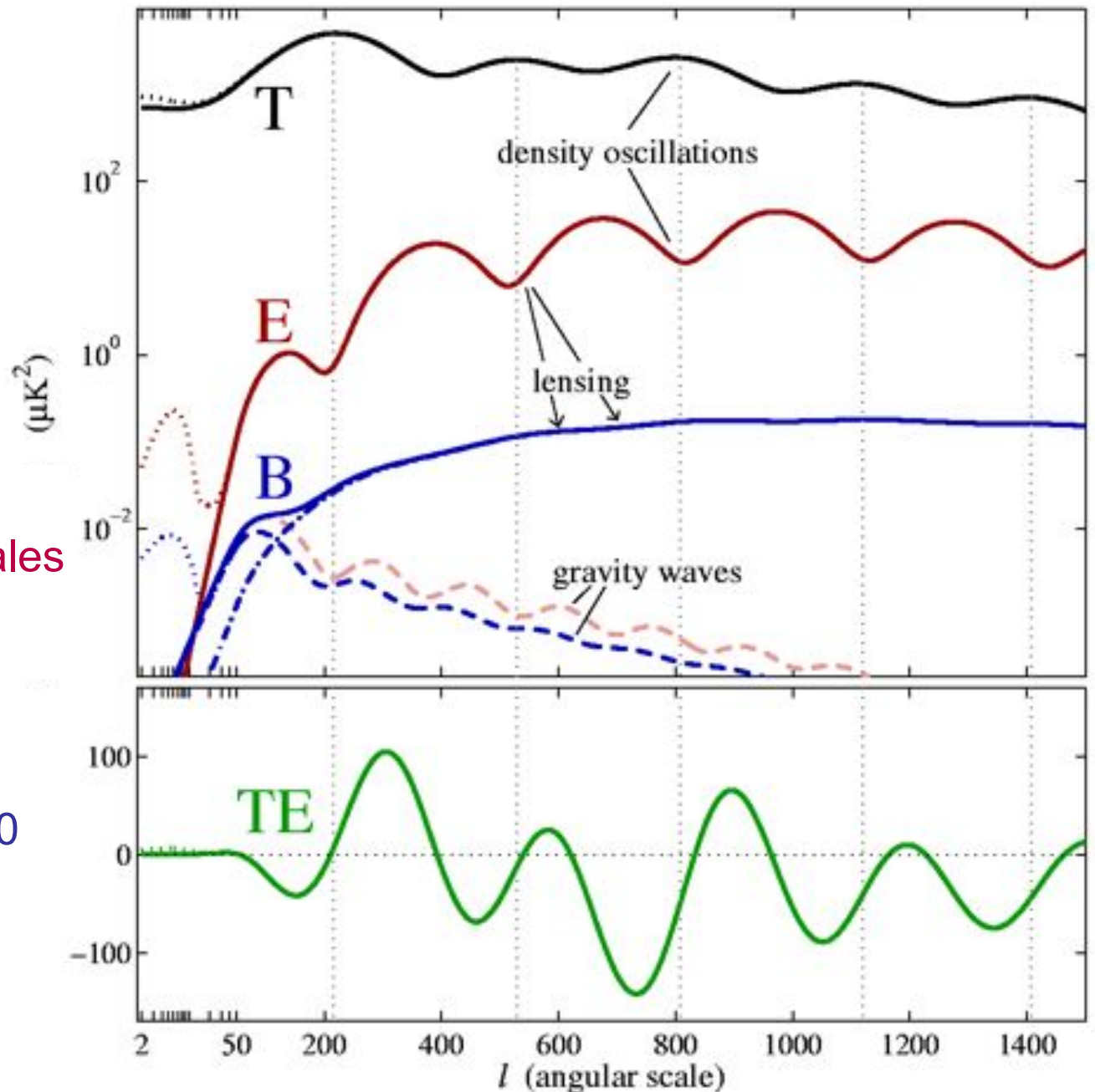
T spectrum traces density evolution of acoustic oscillations in early universe.

E spectrum features:

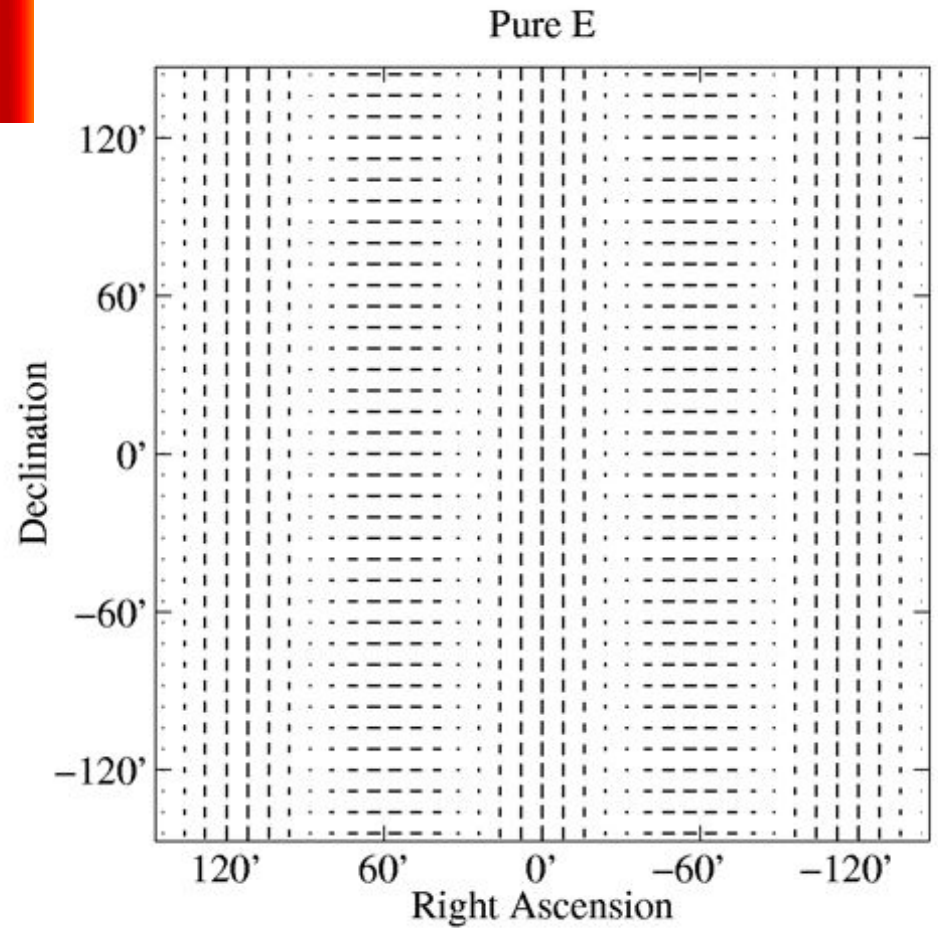
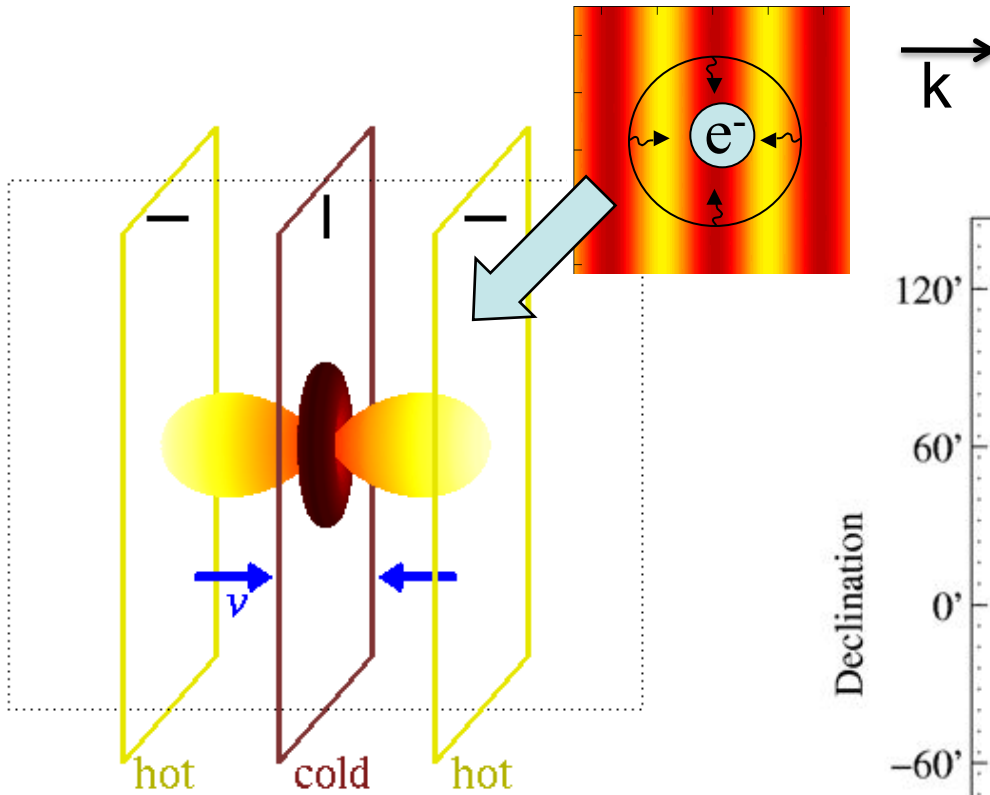
- $10^2$  lower
- correlated with T but out of phase
- peaks at smaller scales

B spectrum features:

- $10^2 - 10^3$  lower still!
- gravity waves  $l < 100$
- lensing  $l > 100$



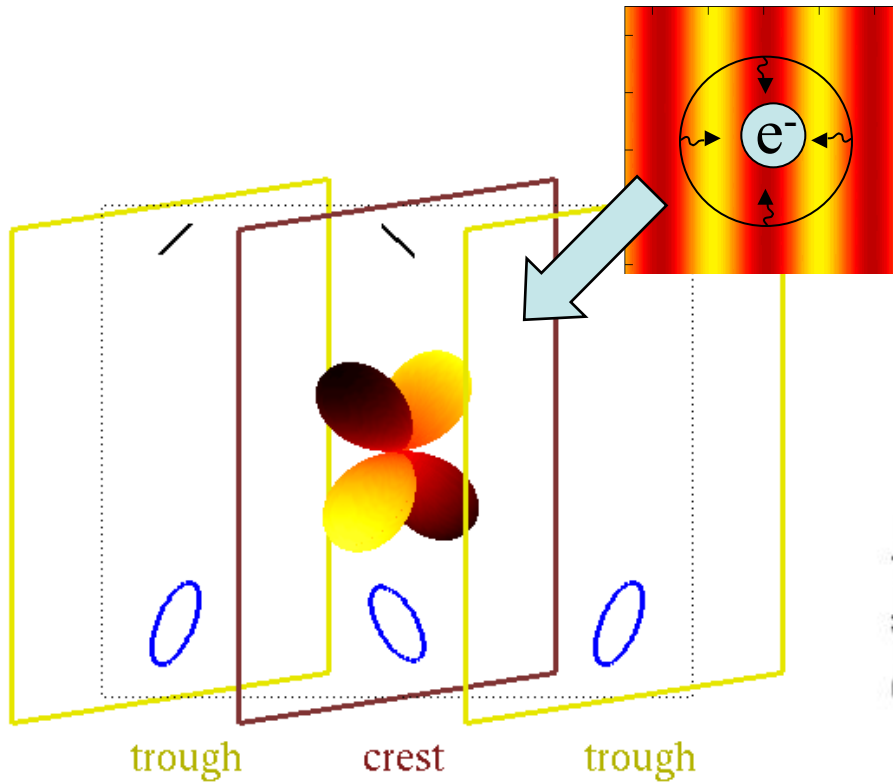
# E-mode Polarization (curl free)



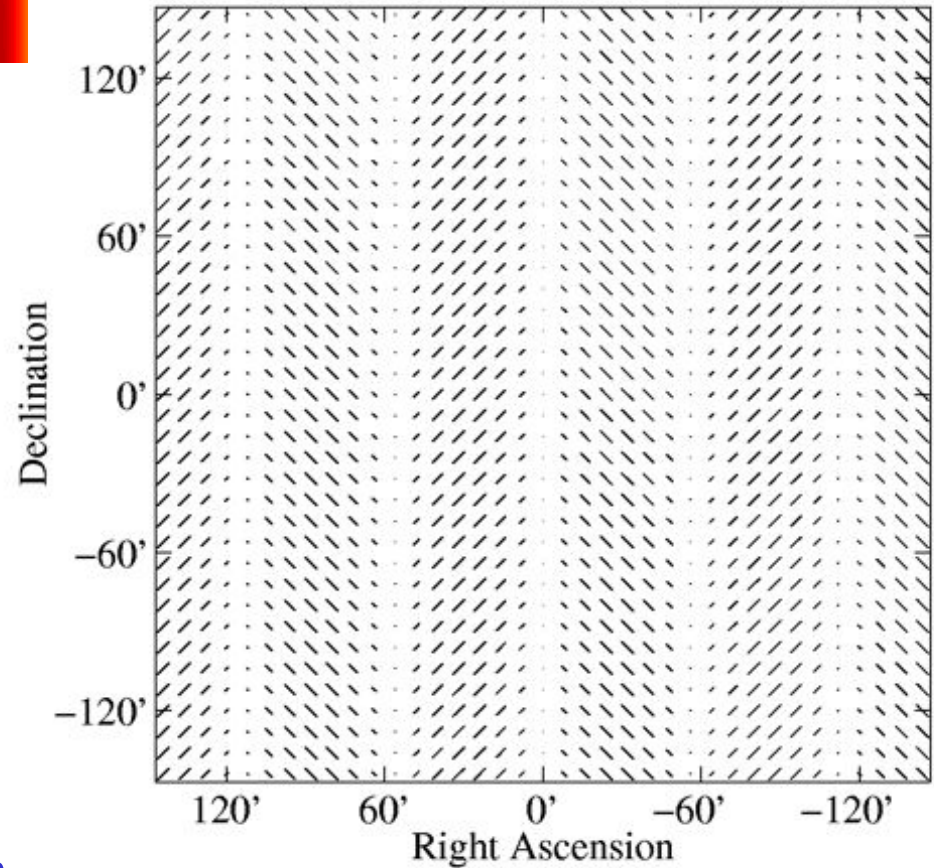
Polarization parallel or perpendicular to wave vector

Density (scalar) fluctuations generate only E-Polarization

# B-mode Polarization (curl component)



Pure B



Polarization oriented at 45 degrees  
to wave vector

Not generated by density oscillations

only primordial source: **inflationary gravity waves**