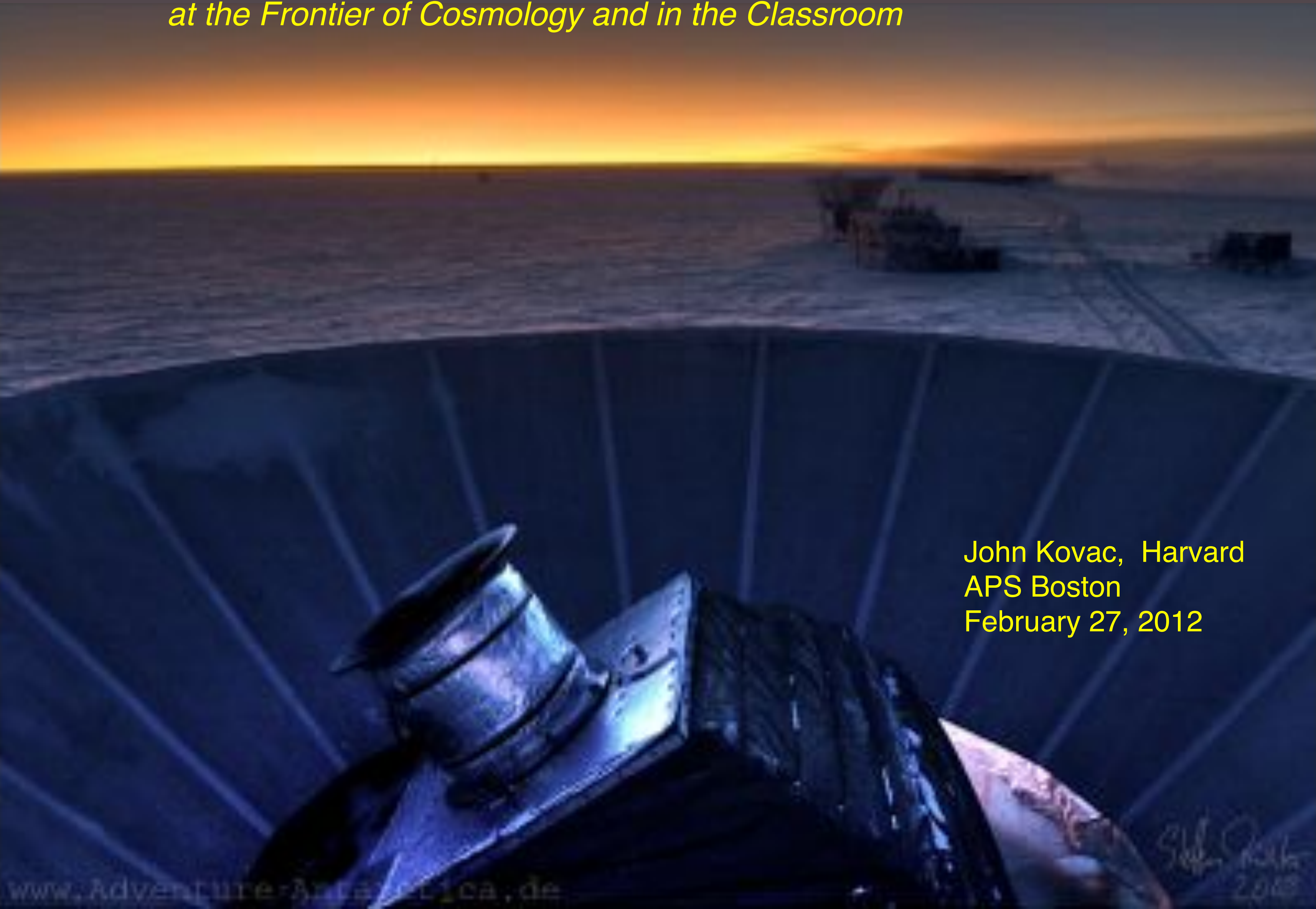
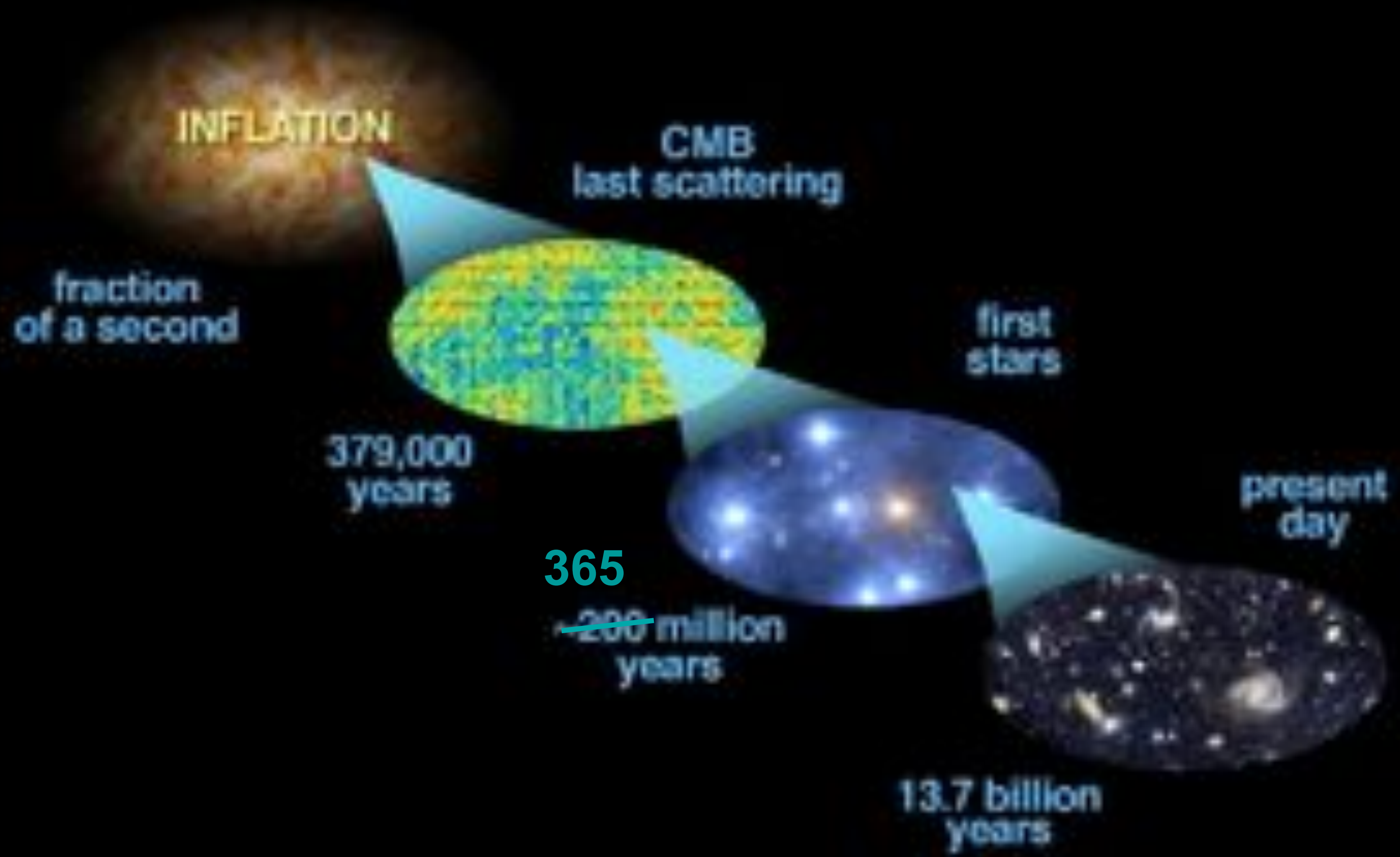
Detectors for the Cosmic Microwave Background

at the Frontier of Cosmology and in the Classroom

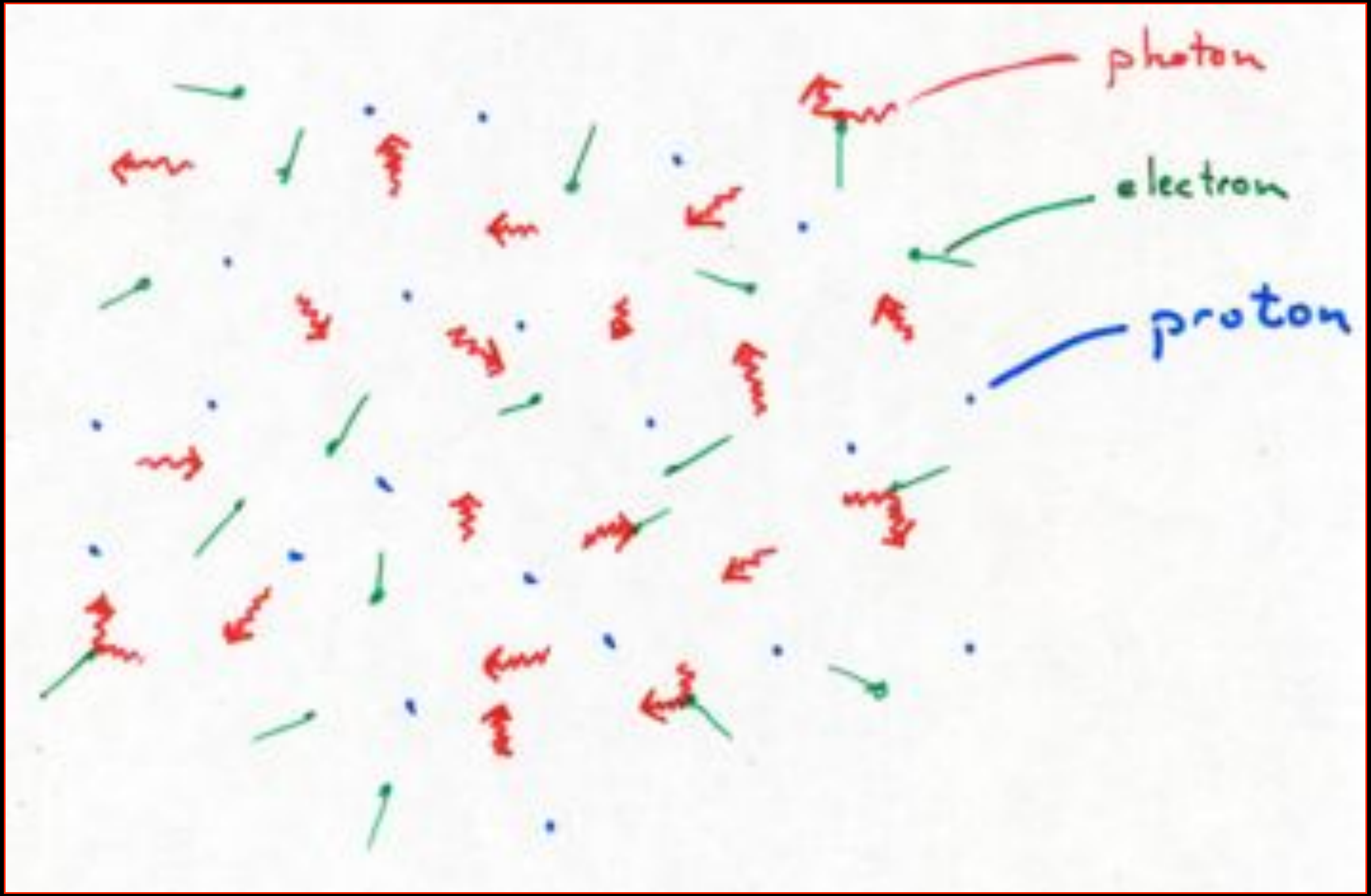


John Kovac, Harvard
APS Boston
February 27, 2012

Just how far can we see?

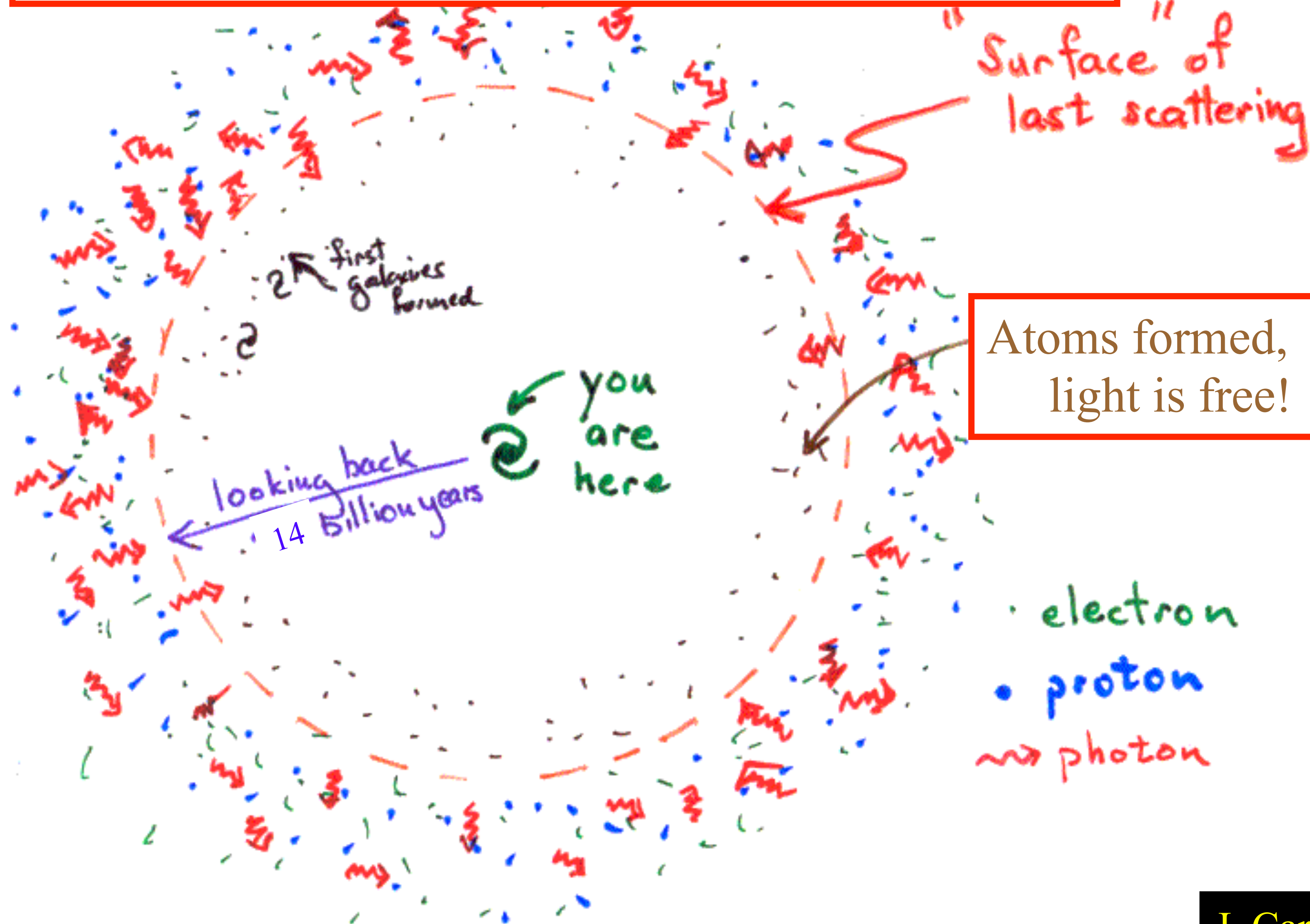

INFLATION
CMB
last scattering
fraction
of a second
379,000
years
first
stars
365
~200 million
years
present
day
13.7 billion
years

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



J. Carlstrom

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



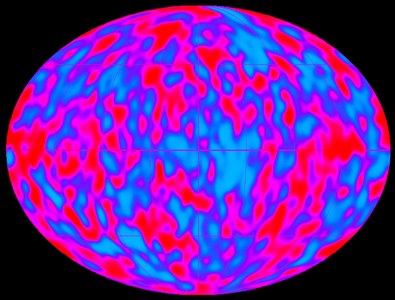
J. Carlstrom

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

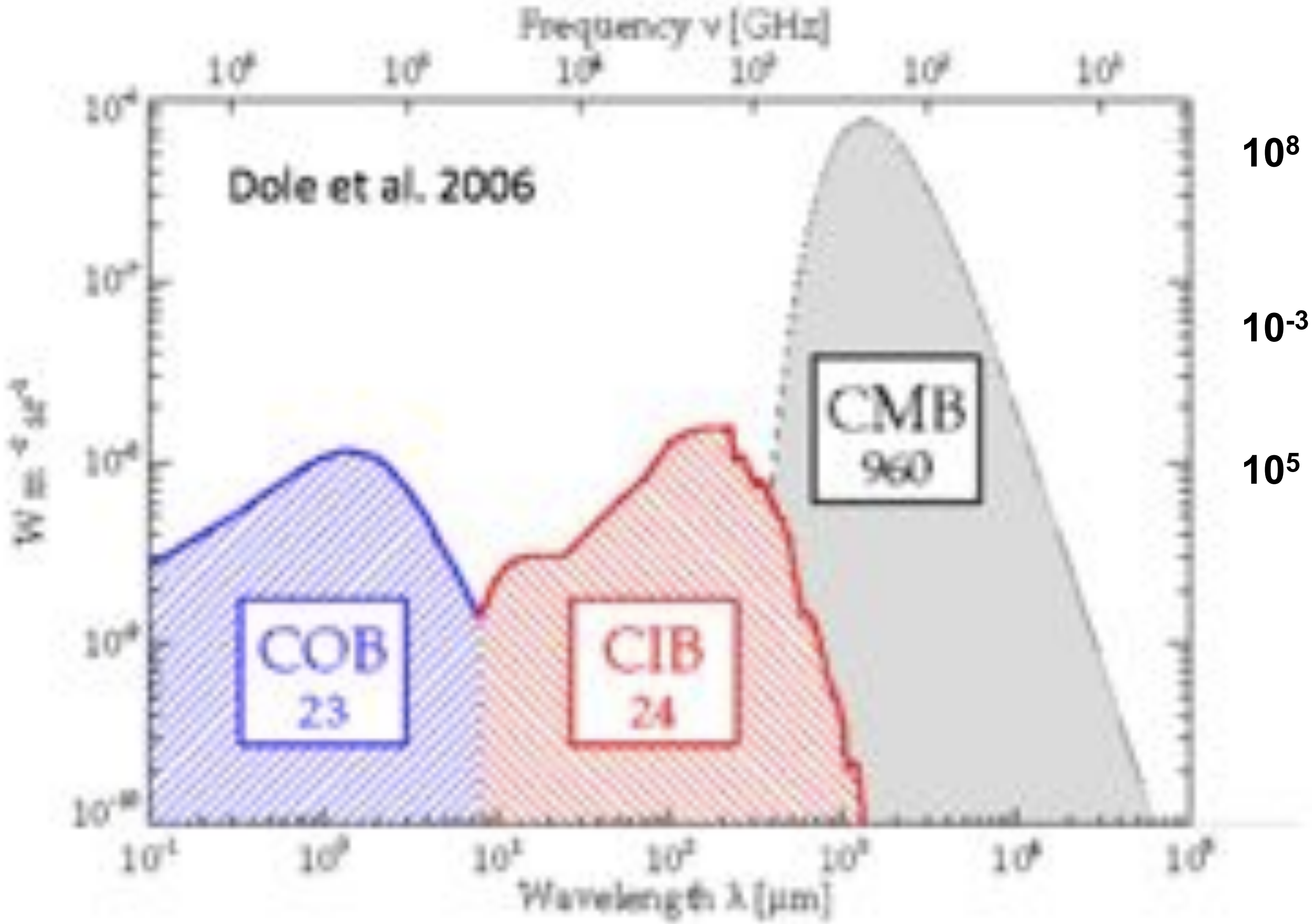
Comes from all directions --- very smooth.

(*too* smooth??)

Released at redshift z ~ 1000

3000K (then) → 3K (today)

CMB still dominates photons



10^8 CMB photons / m^3

10^{-3} eV / photon

10^5 eV / 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

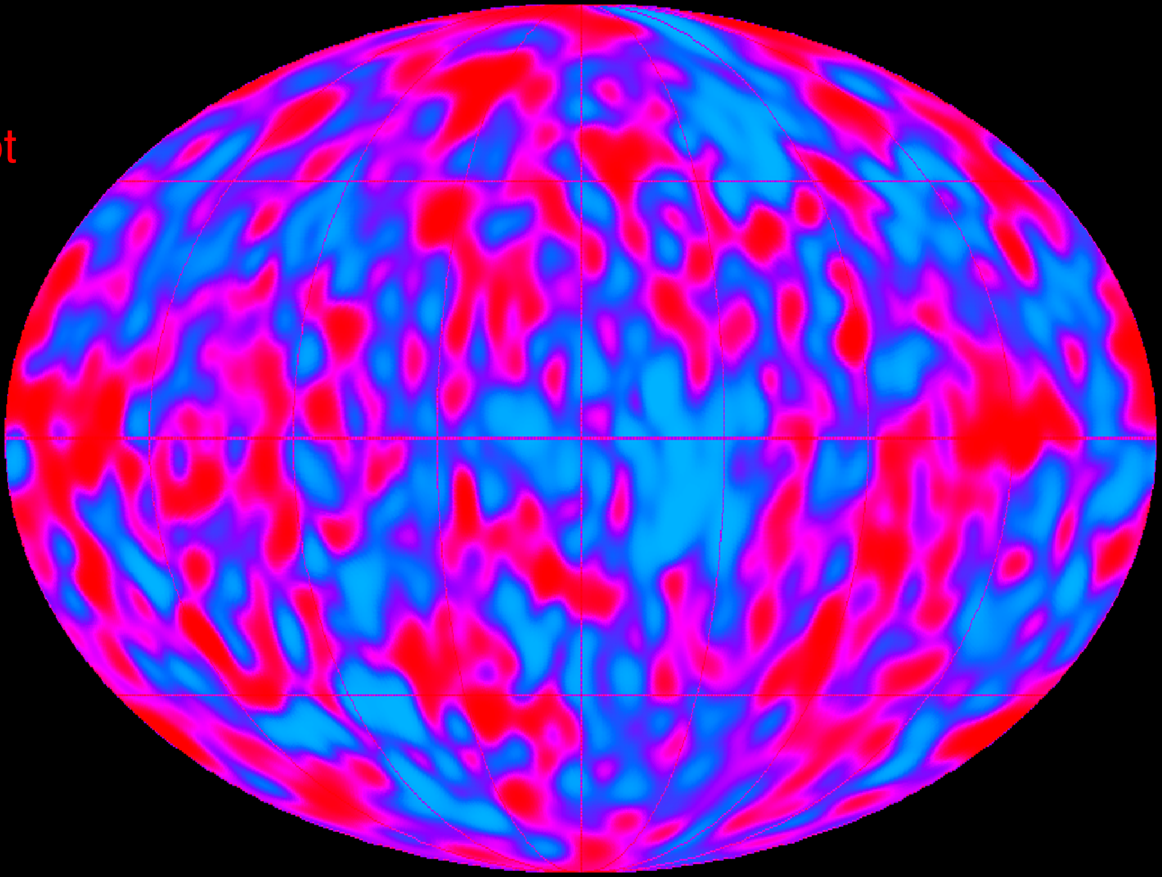
Received 1978 Nobel Prize

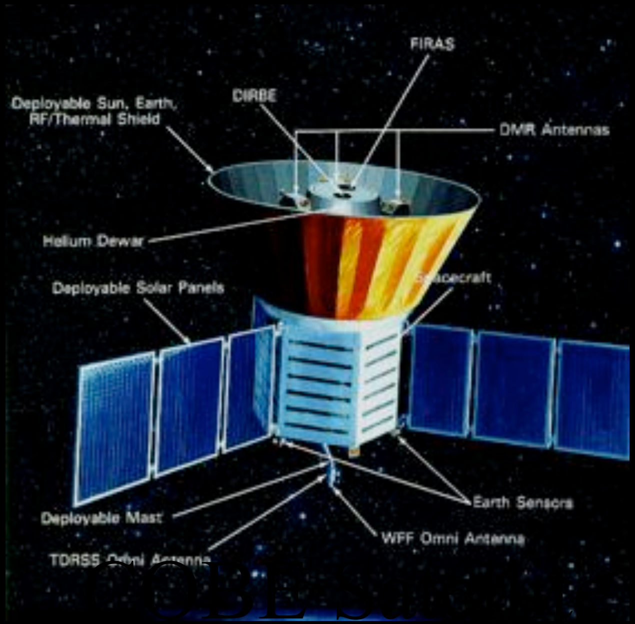
"smoking gun" evidence for the Big Bang

Enormous impact on Cosmology

Structure in background discovered in 1992

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

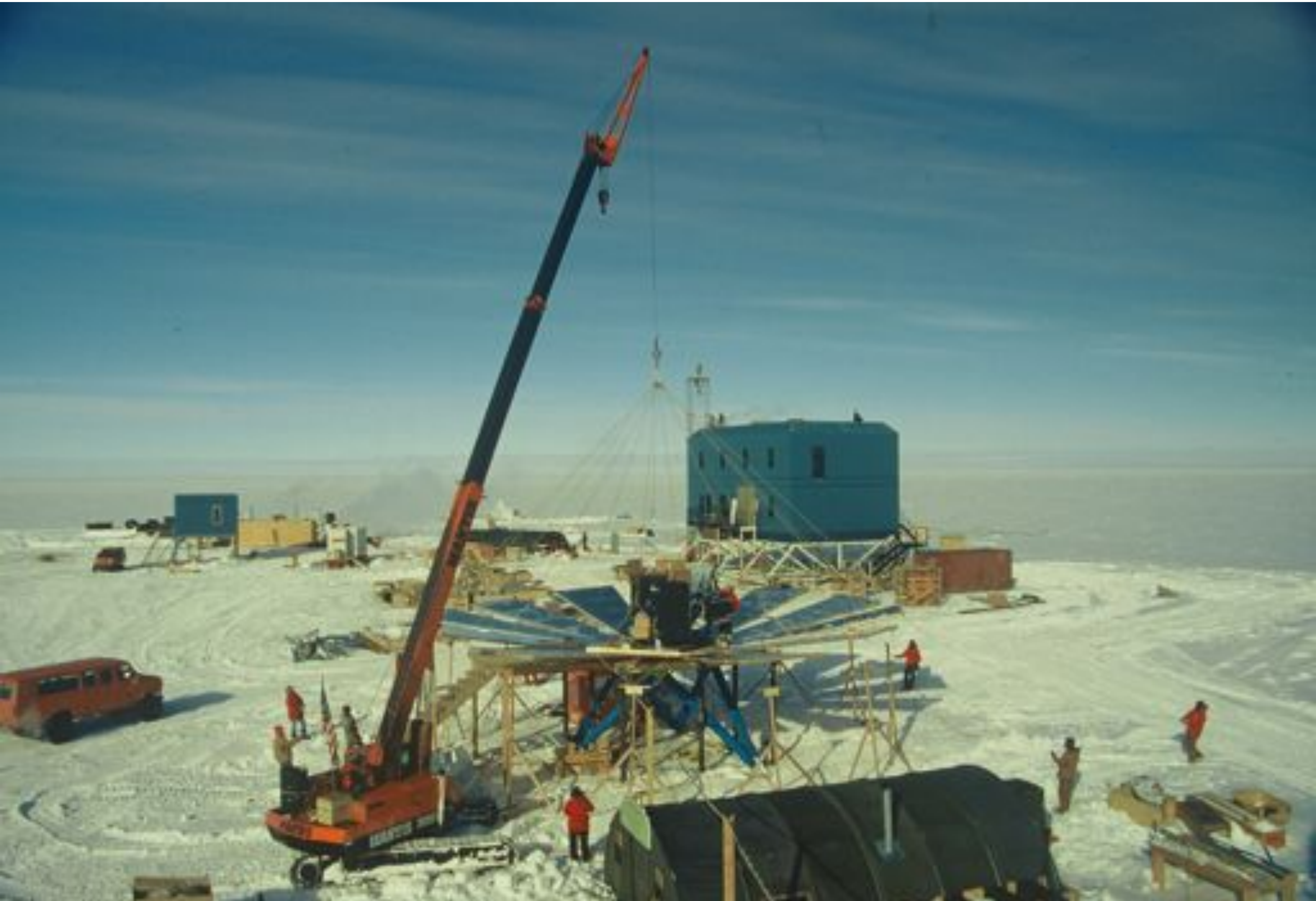




Smooth to a part in 100,000!

(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. 51,759 — MONDAY, APRIL 30, 2001

Listen Closely: From Tiny Hum Came Big Bang

By JAMES GLANZ

Scientists Hear the Tiny Hum They Say Ignited the Big Bang

Continued From Page A1

'Listening' to the Origin of the Universe

Continued on Page A1

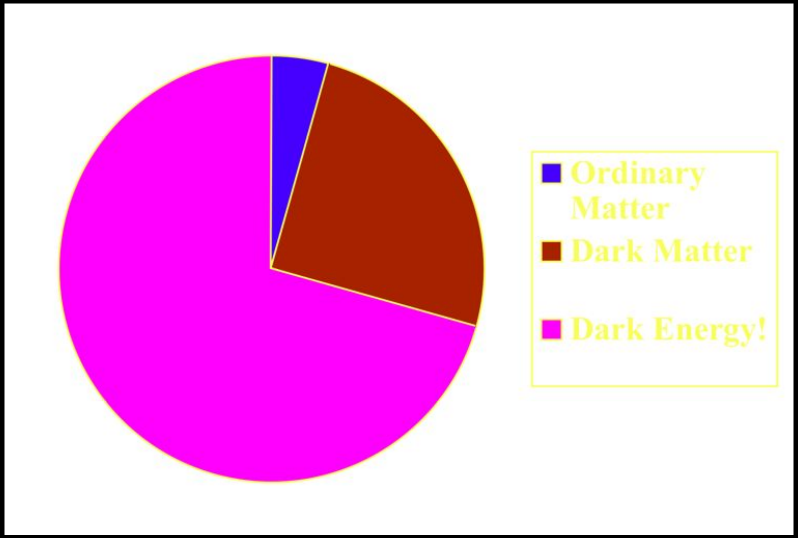
2001 APS: DASI/Boomerang Results

-Universe's Age: ***14 +/- 0.5 Gyr***

-Universe's Makeup:

- *4.5% Ordinary matter*
- *30% Dark matter*
- *65% Dark energy, Λ?*

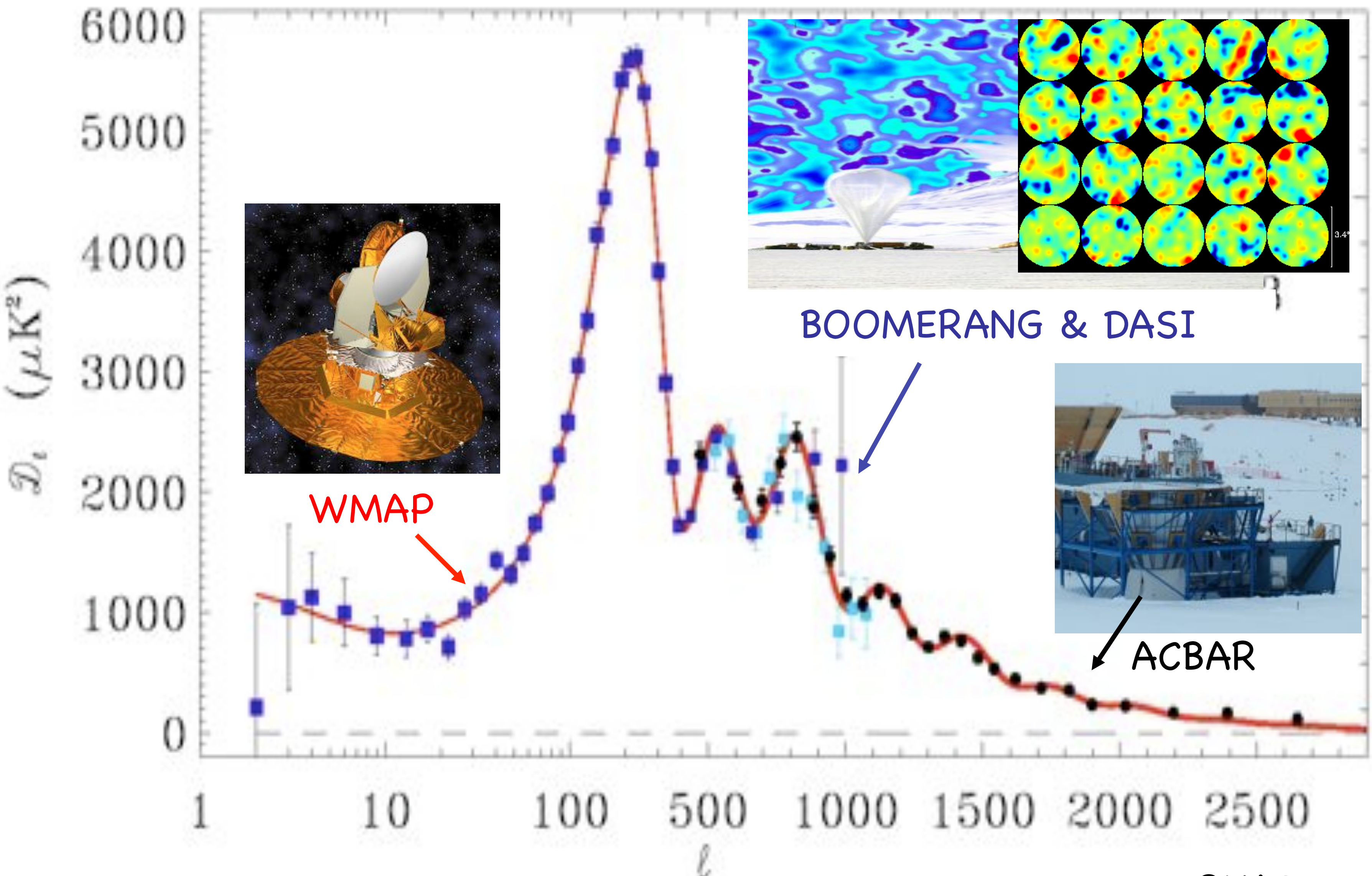
→ *consistent w/ supernovae results*



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

Can Inflation also explain where structure comes from?

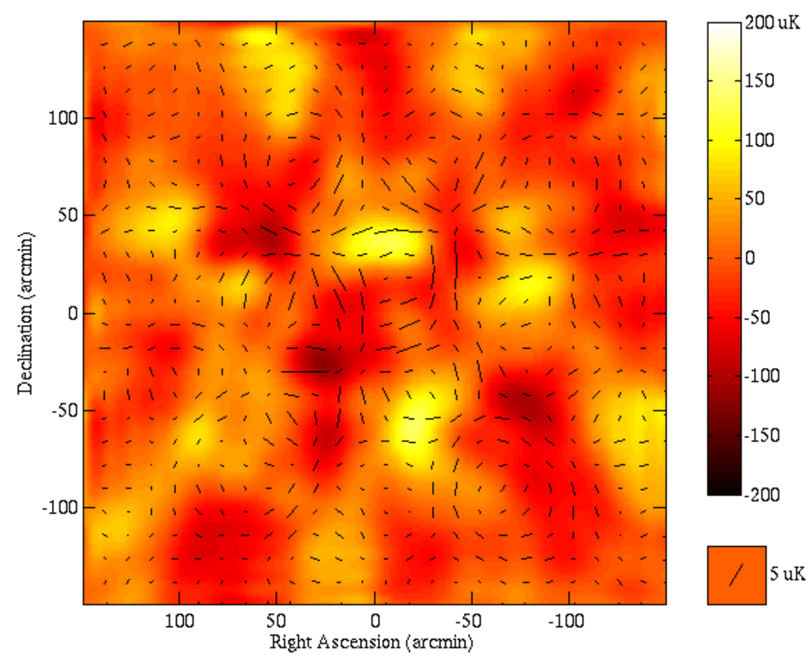
CMB temperature: easy stuff!



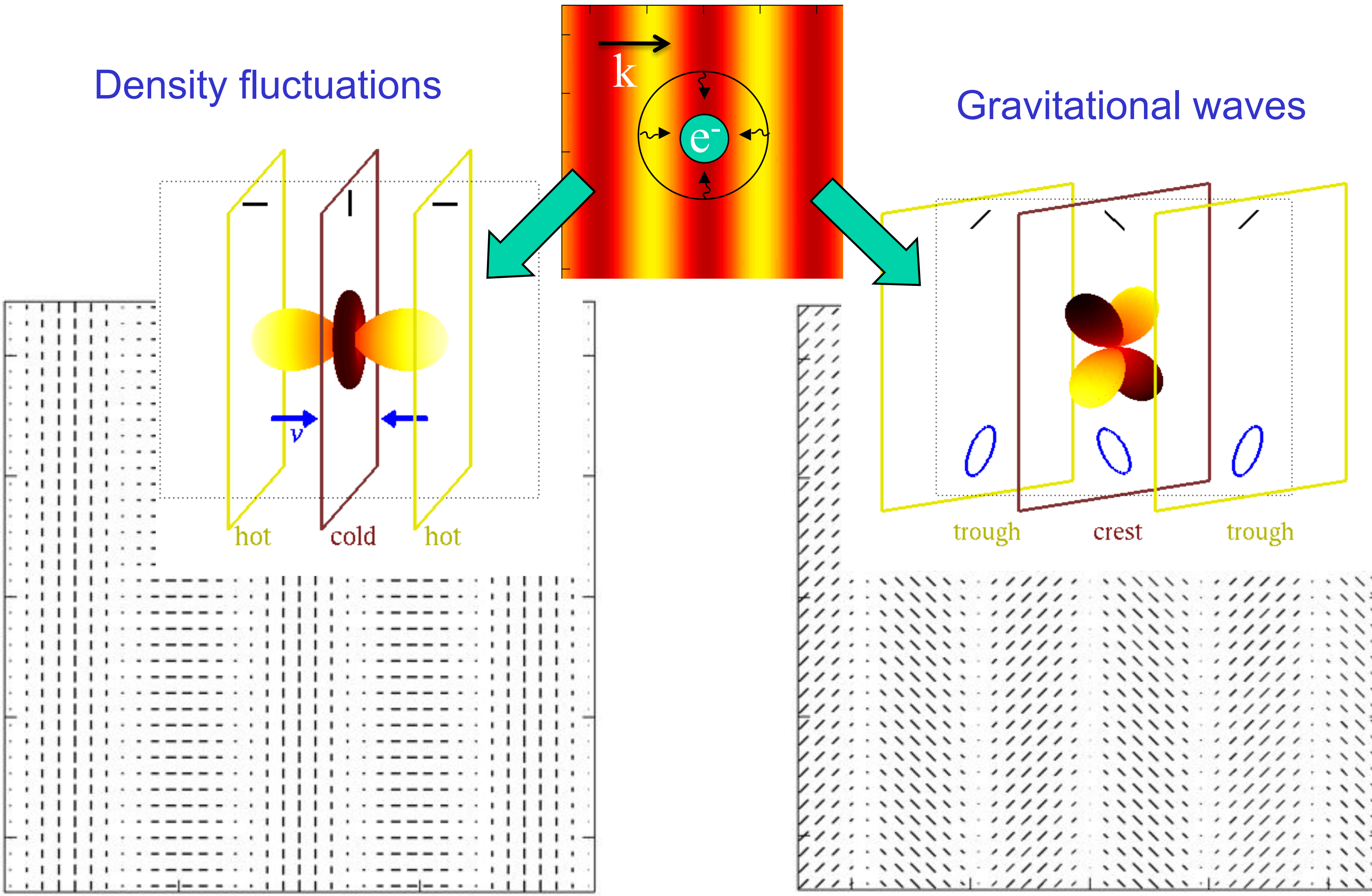
+ QUAD, + SPT!

2002: DASI first detects polarization of the CMB

(Level: 1 part in 1,000,000 !)



CMB Polarization: E-modes and B-modes



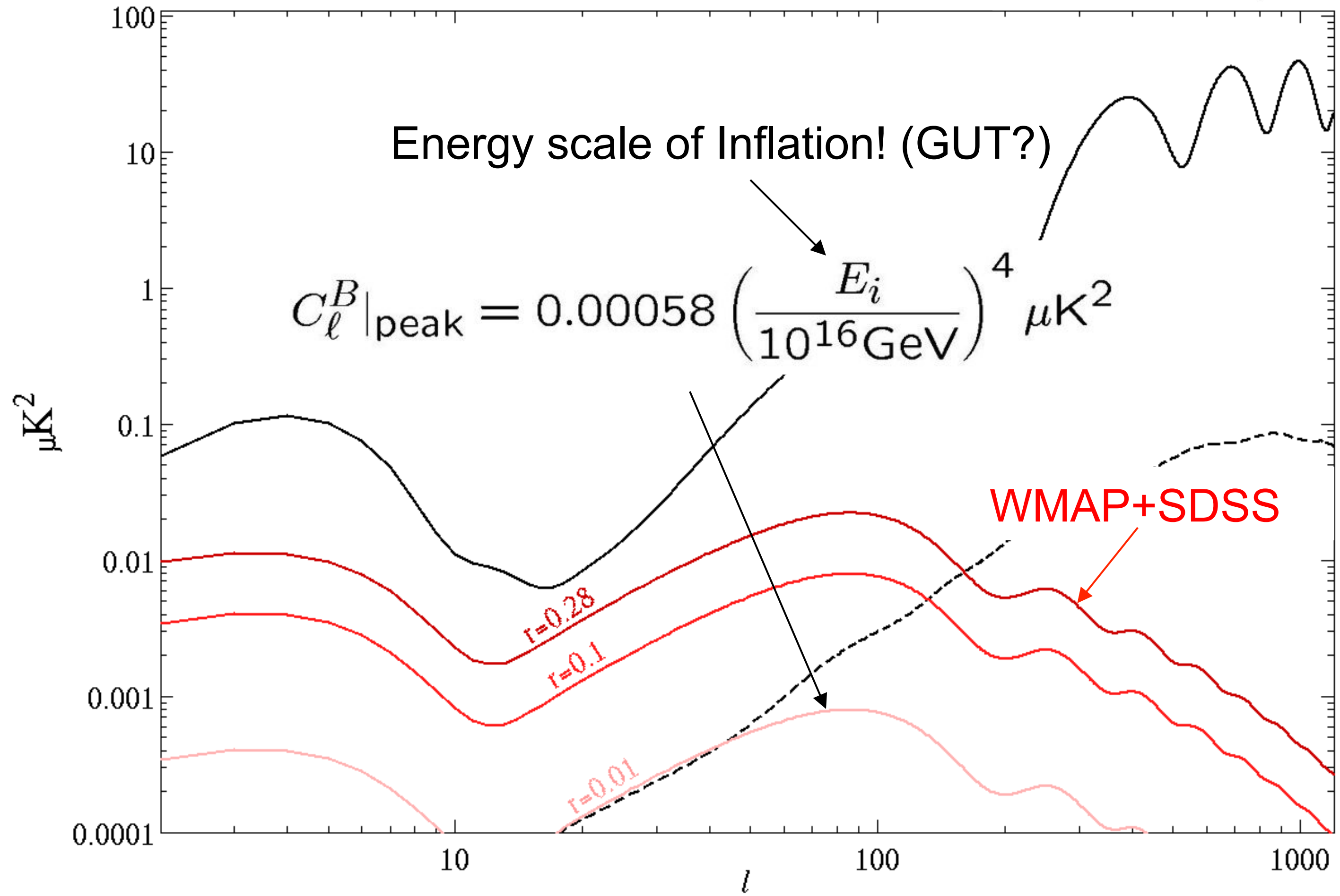
E-mode

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



CMB Detectors: Theory

Direct Detectors vs. Amplifiers (Zmuidzinas, 2003)

The 1 σ power sensitivity after integration time τ is:

Direct Detectors
CCDs, bolometers,
MKIDs

$$\sigma_P = \frac{h\nu}{\sqrt{\Delta\nu\,\tau}}\sqrt{\frac{n_0(1+\eta n_0)}{\eta}\Delta\nu} \quad \text{(second term due to bunching)}$$

$$\approx \frac{h\nu}{\eta\tau}\sqrt{\eta n_0 \Delta\nu\tau} = \frac{h\nu}{\eta\tau}\sqrt{N(\tau)} \quad \text{(Poisson statistics; for } \eta n_0 << 1\text{)}$$

$$\approx \frac{k_B T_0 \Delta\nu}{\sqrt{\Delta\nu\,\tau}} = \frac{h\nu}{\eta\tau}\frac{N(\tau)}{\sqrt{\Delta\nu\,\tau}} \quad \text{(Dicke formula; for } \eta n_0 >> 1\text{)}$$

Amplifiers
Masers, FETs,
HEMTs, SiS mixers

$$\sigma_P = \sqrt{\frac{\Delta\nu}{\tau}}\frac{h\nu}{\eta}(\eta n_0 + 1) \quad \text{(second term is quantum noise)}$$

$$\approx \frac{k_B T_0 \Delta\nu}{\sqrt{\Delta\nu\,\tau}} \quad \text{(Dicke formula; for } \eta n_0 >> 1\text{)}$$

$$\approx \frac{h\nu\Delta\nu}{\eta\sqrt{\Delta\nu\,\tau}} \quad \text{(quantum limit; for } \eta n_0 << 1\text{)}$$

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

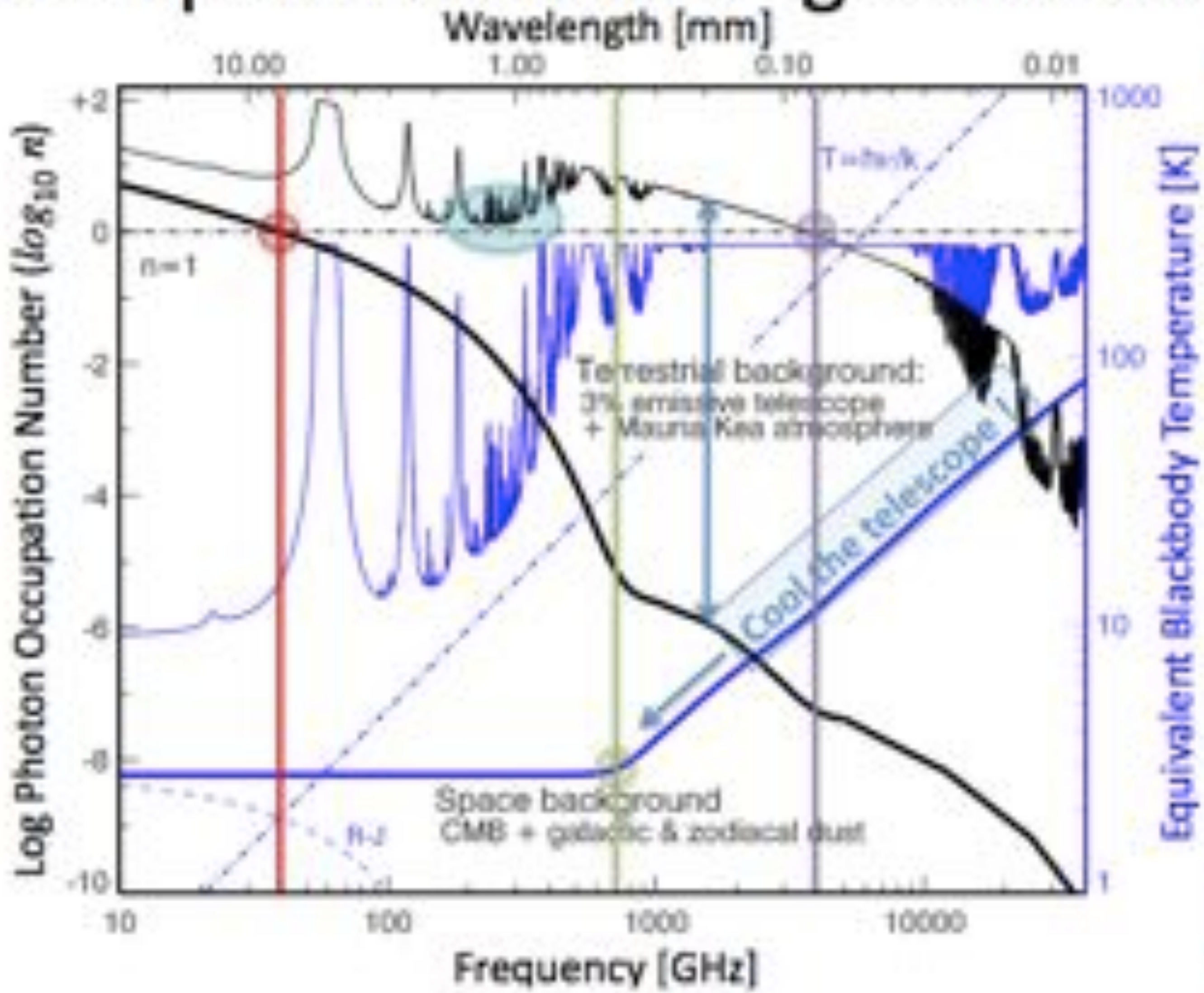
occupation number
is the key :

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

$h\nu >> kT \rightarrow n << 1$ Wien limit

$h\nu << kT \rightarrow n >> 1$ Rayleigh-Jeans limit

Occupation number: ground and space



$n < 1$ CMB, ν > 40 GHz
CMB dominates background from space for ν < 700 GHz
$n < 1$ from ground for ν > 4 THz
$n \sim 1$ from ground for ν ~ 200-300 GHz

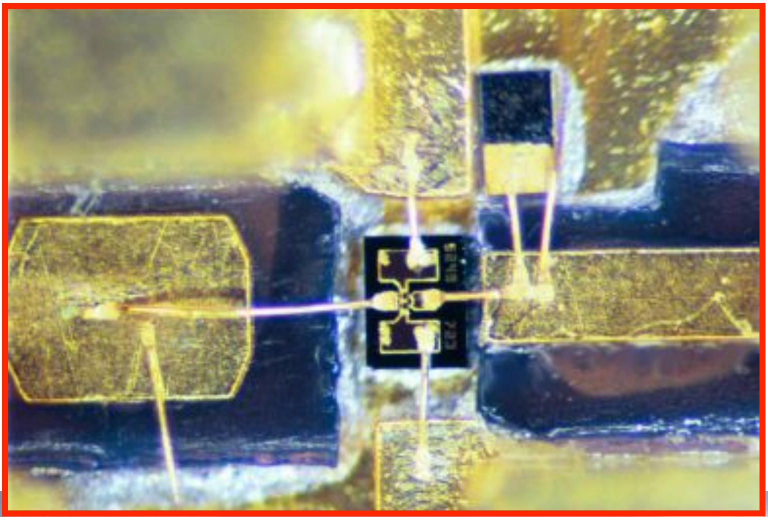
Zmuidzinas & Bradford 2008

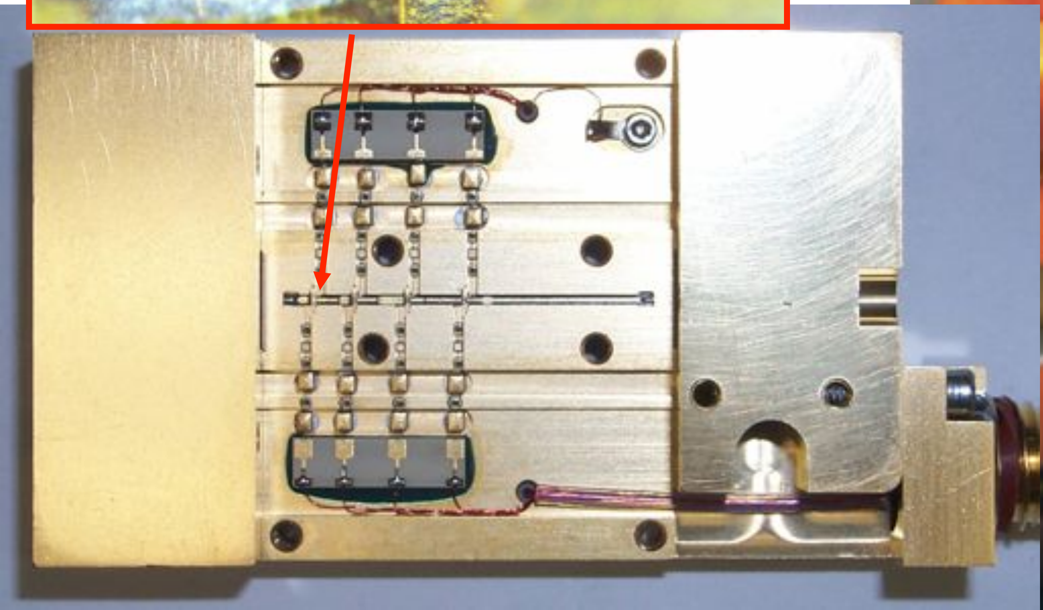
Radio (amplifiers) dominate ←

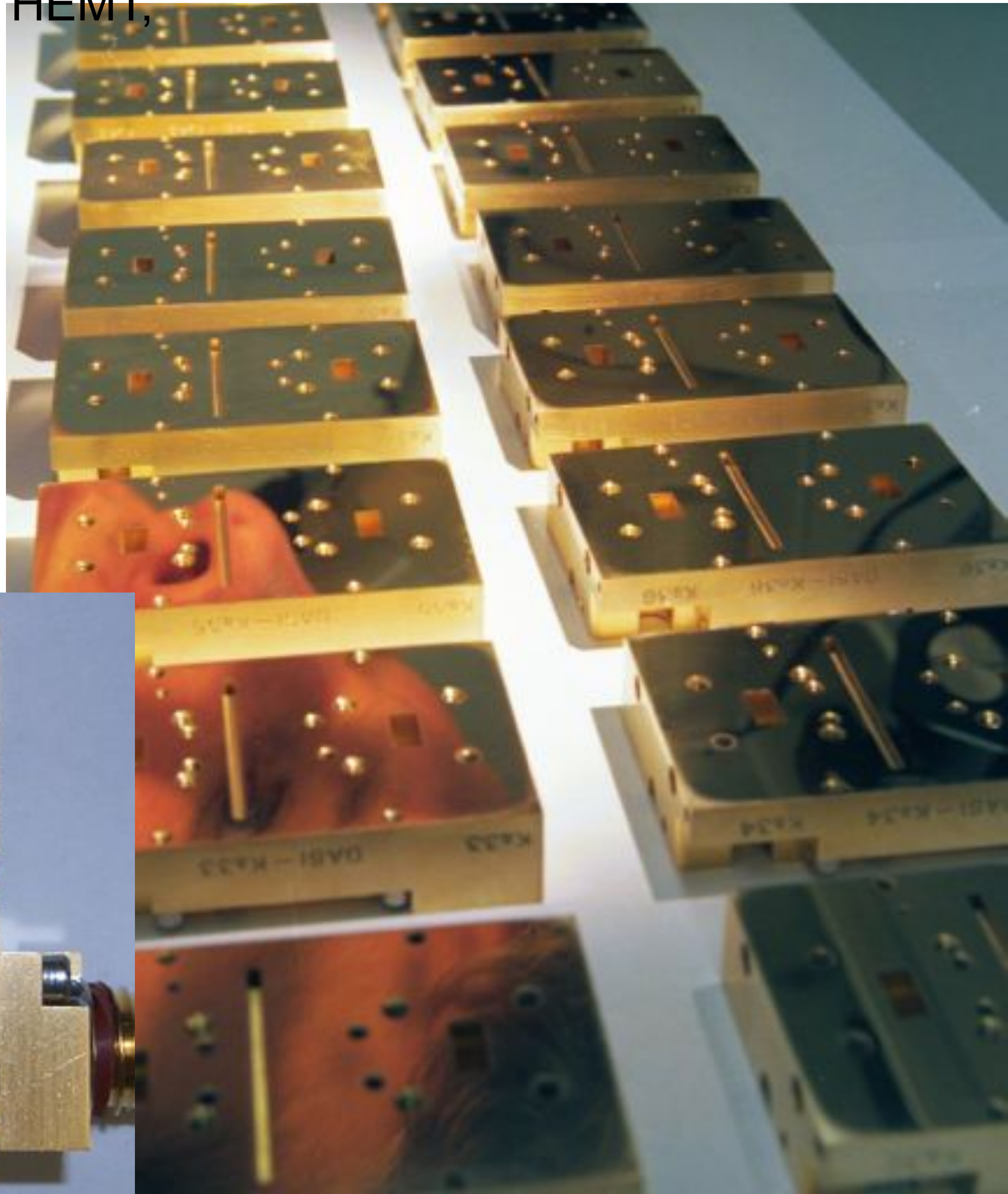
→ Direct Detectors dominate

HEMT Amplifiers – DASI 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

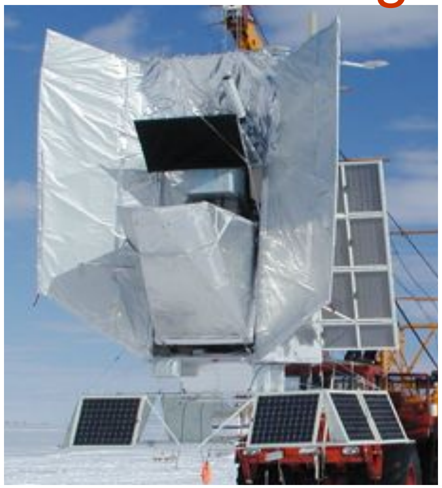






Polarization Sensitive Bolometers

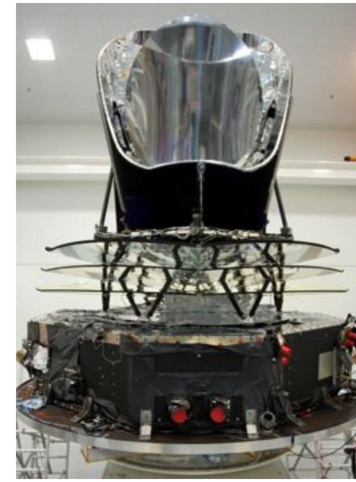
Boomerang03

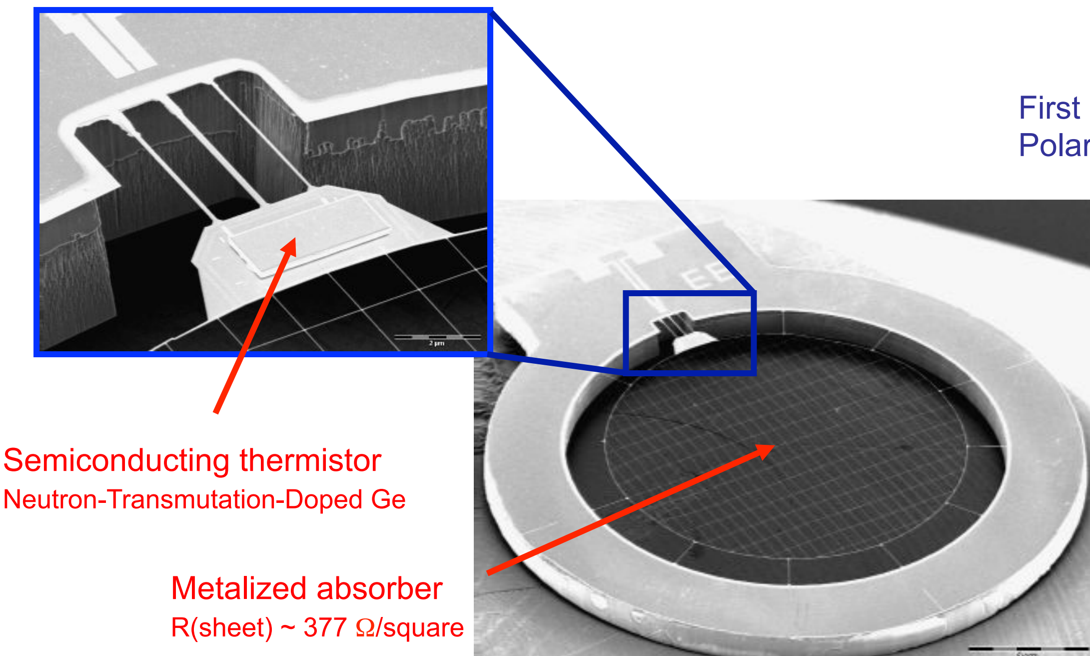


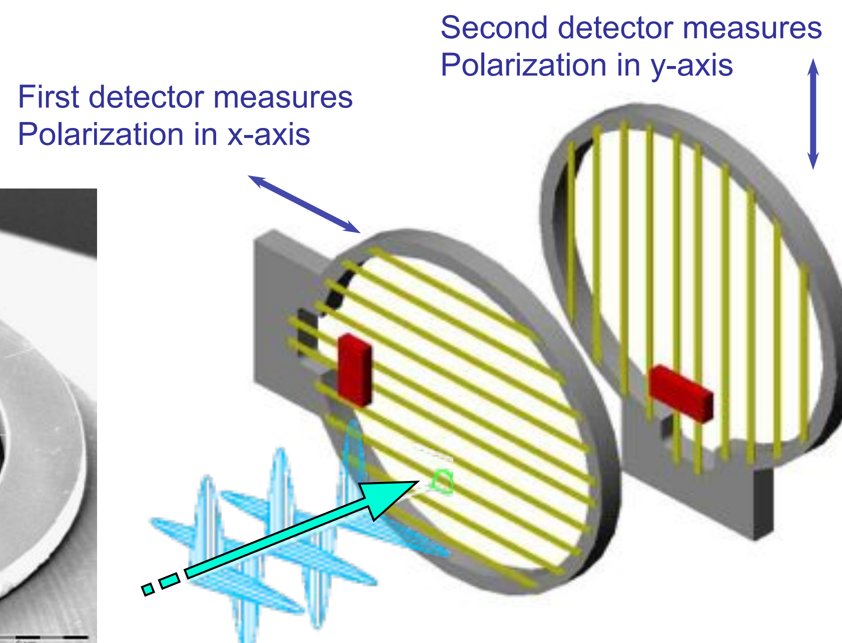
QUaD

BICEP

Planck HFI



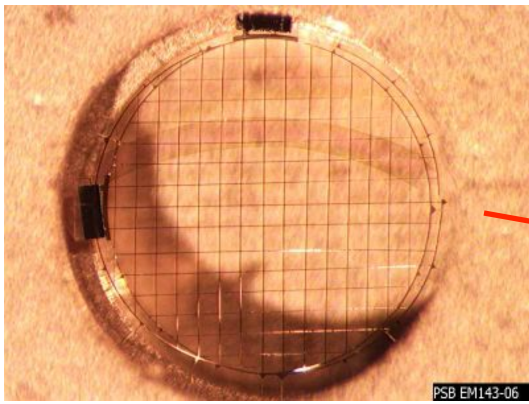




PSBs: Jamie Bock / Andrew Lange / Bill Jones

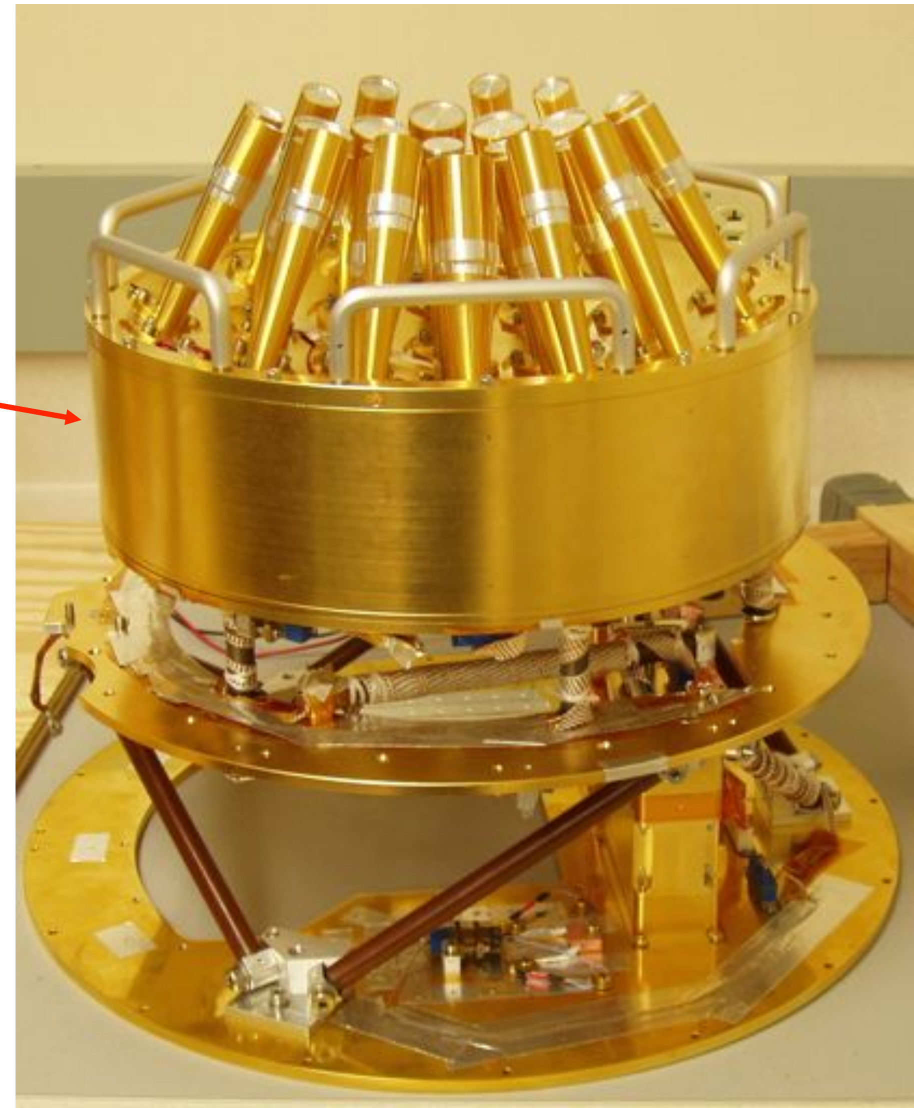
Aug 2004: QUAD focal plane assembled

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



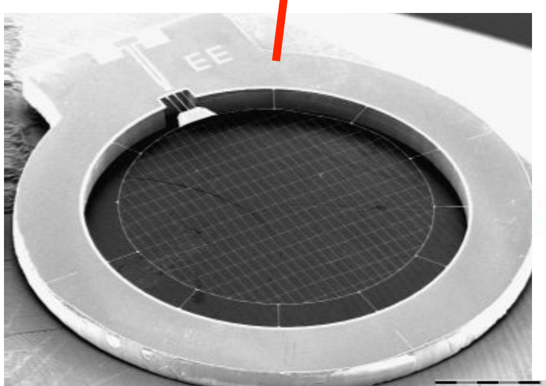
Freq. (GHz)	Beamsize (arcmin)	Number of Feeds
100	6.3	12
150	4.2	19

31 feeds

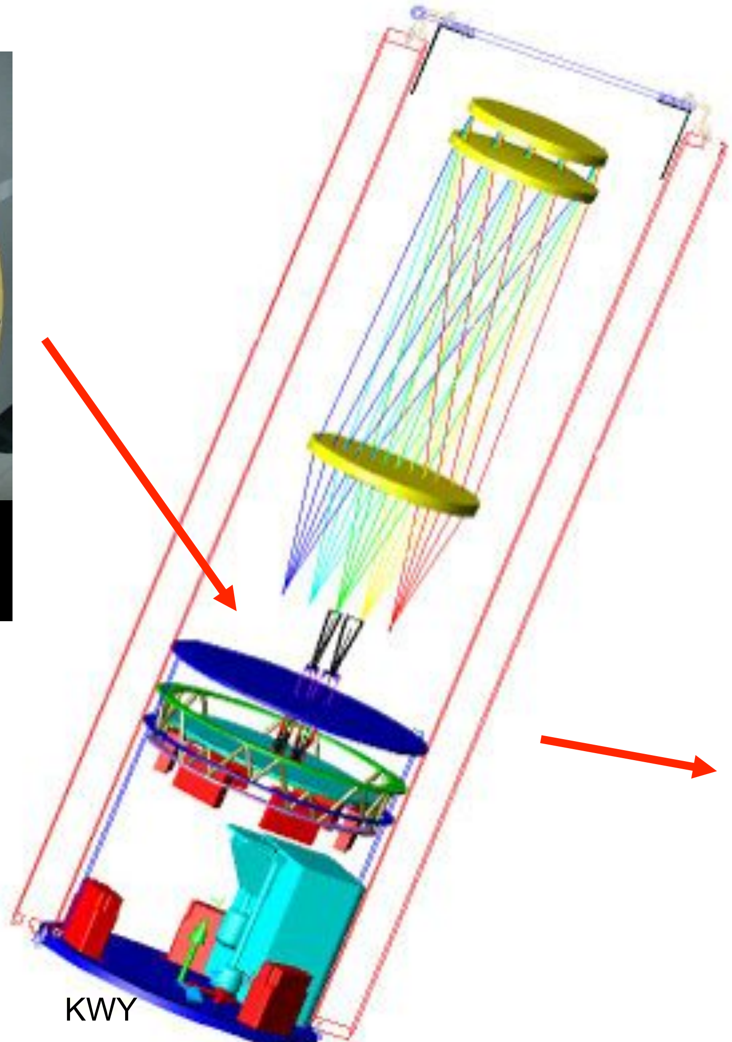


BICEP1: a **targeted** B-mode machine!

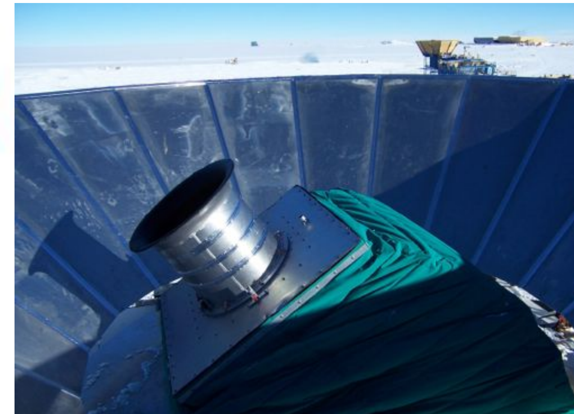
98 Detector Focal Plane (100 and 150 GHz)



Polarization-Selective Bolometers (JPL)



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

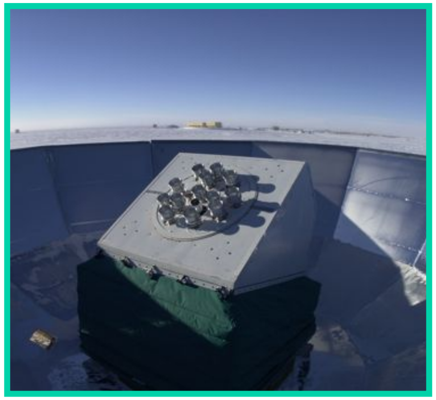


Feb 2006: working at Pole!

Fast-scan mount (5 d/s)

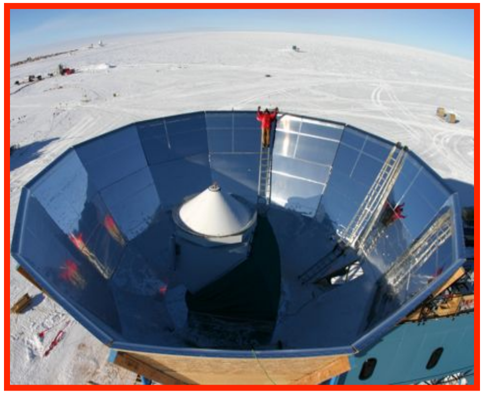
29 Nov 2005: BICEP installed into DSL

E-polarization measurements to date

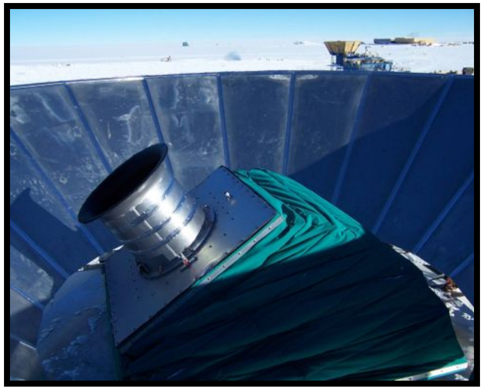


DASI
1999-2004

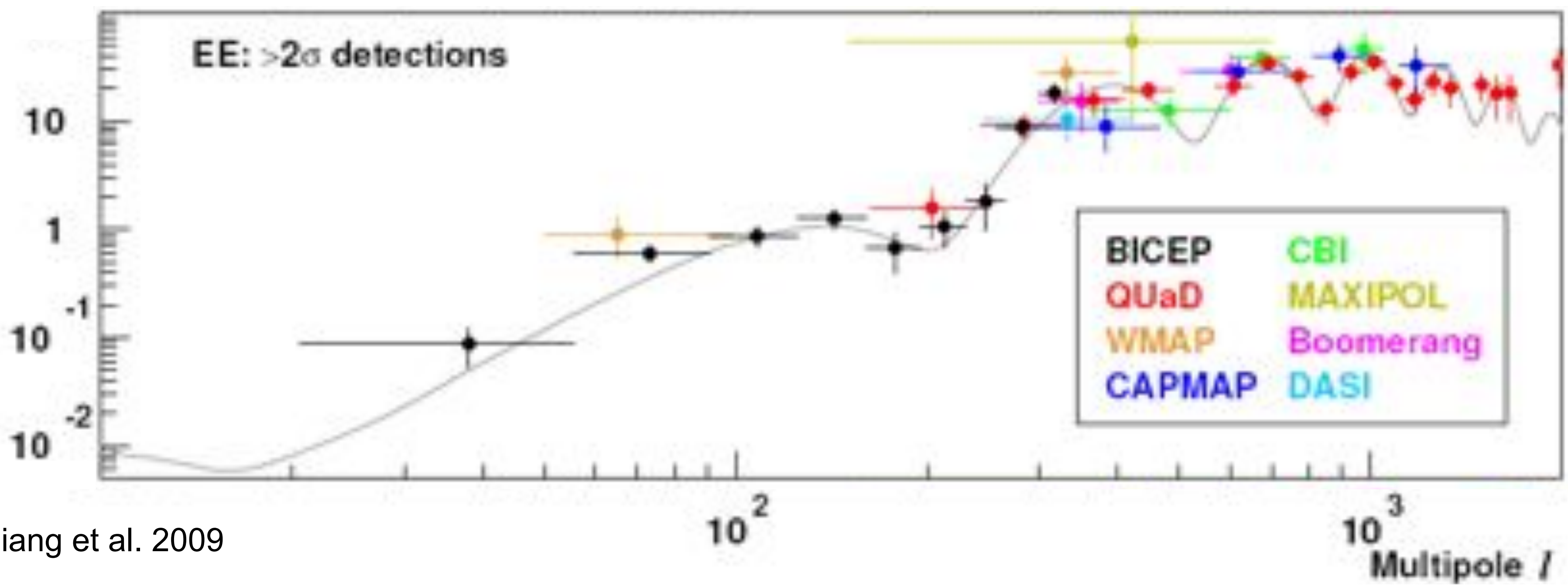
BOOMERANG
2003



QuAD
2005-2007

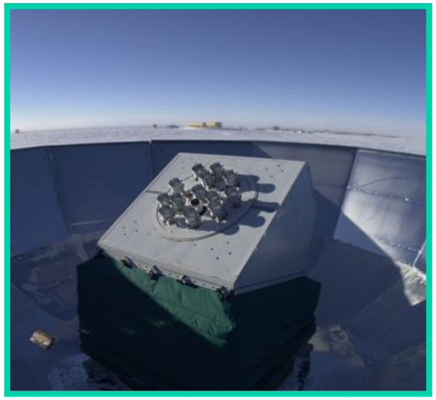


BICEP1
2006-2008



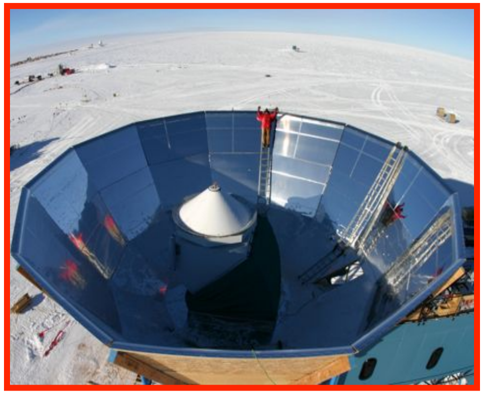
Chiang et al. 2009

B-polarization measurements to date

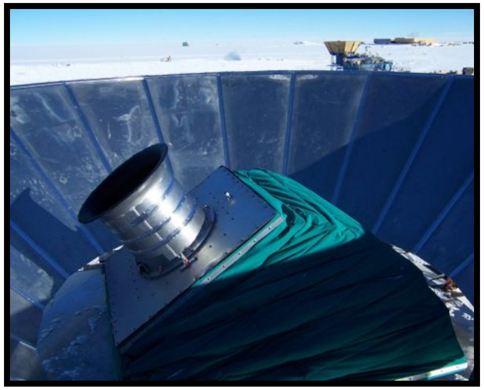


DASI
1999-2004

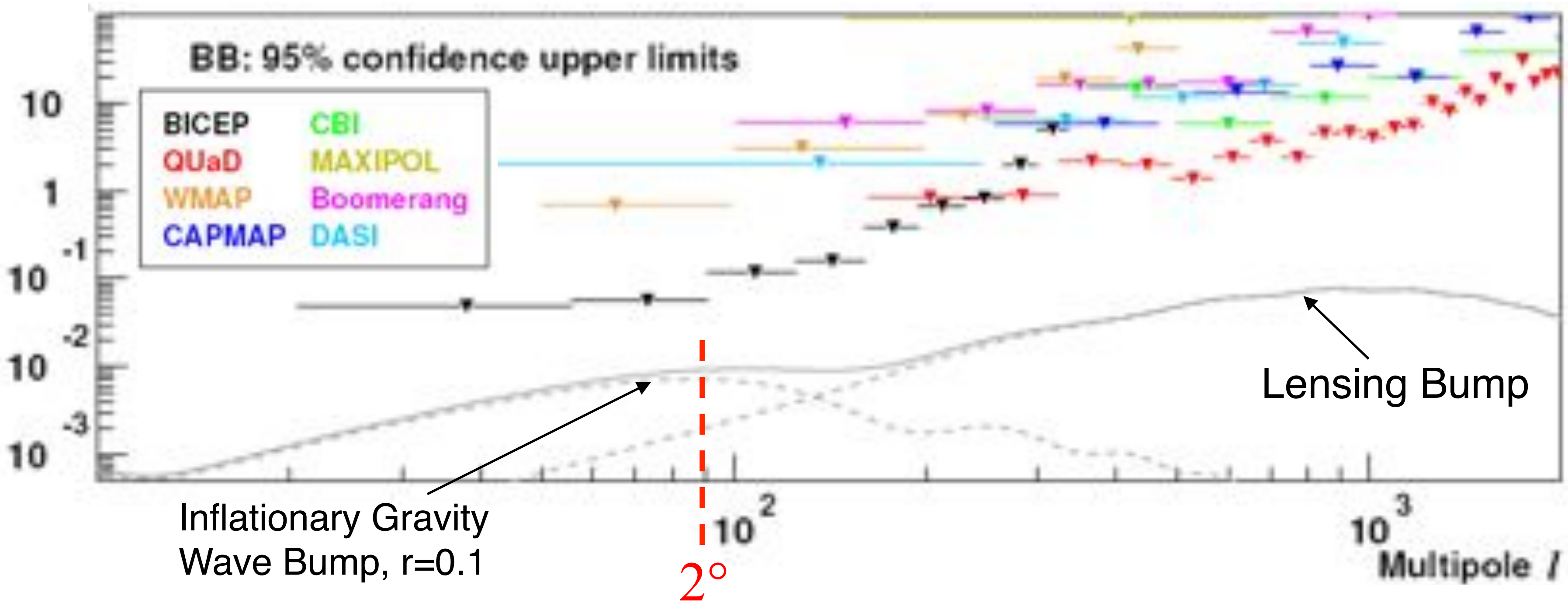
BOOMERANG
2003



QuAD
2005-2007



BICEP1
2006-2008



Different apertures – different angular scales

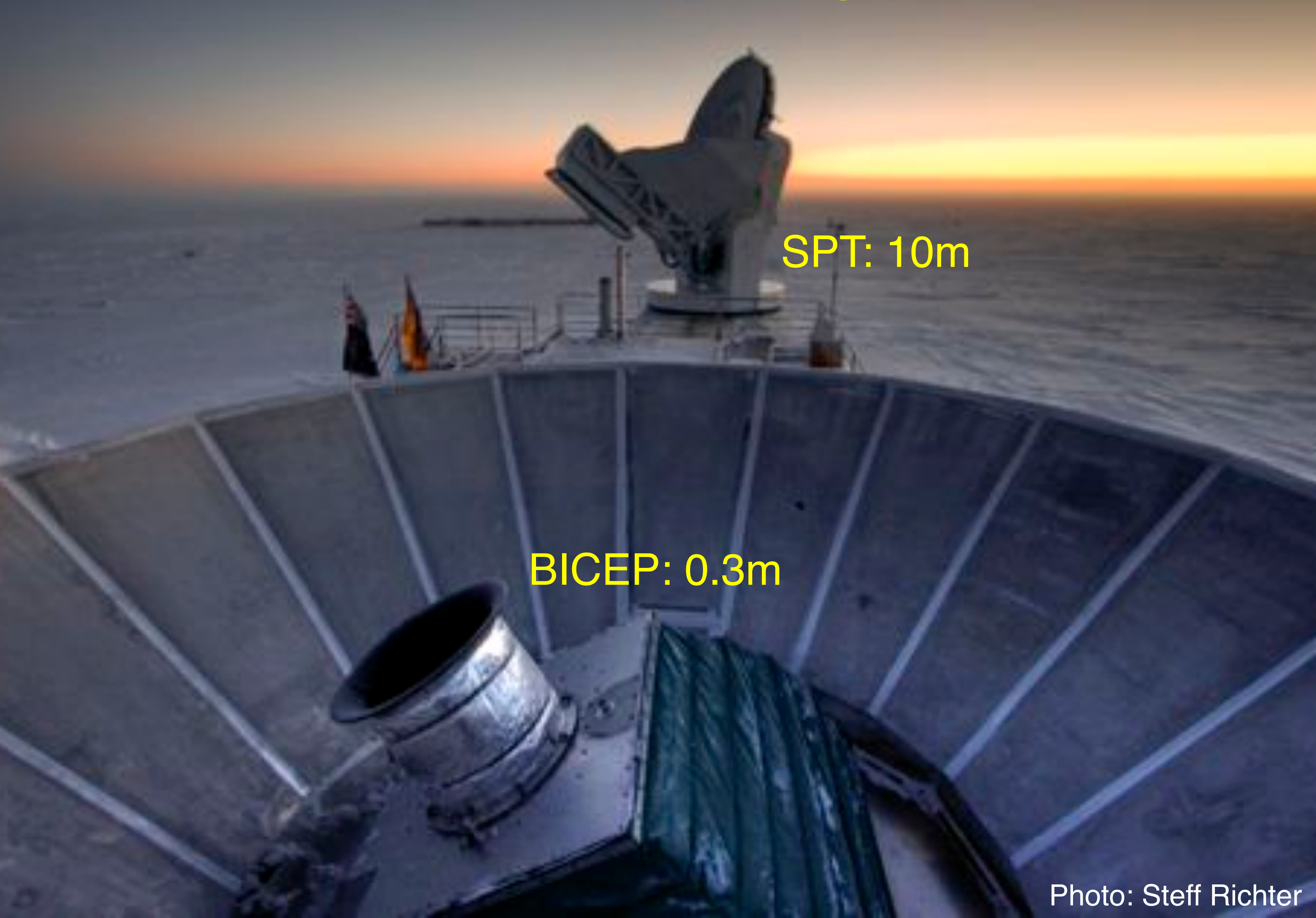
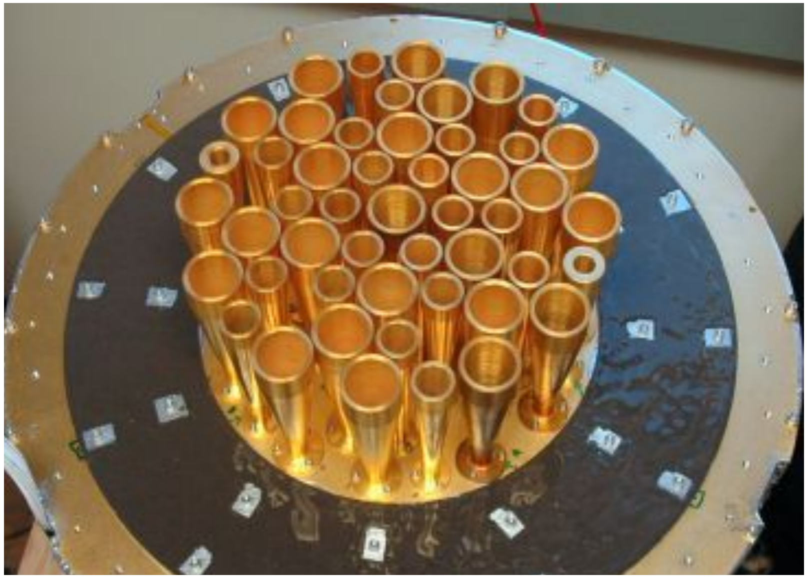
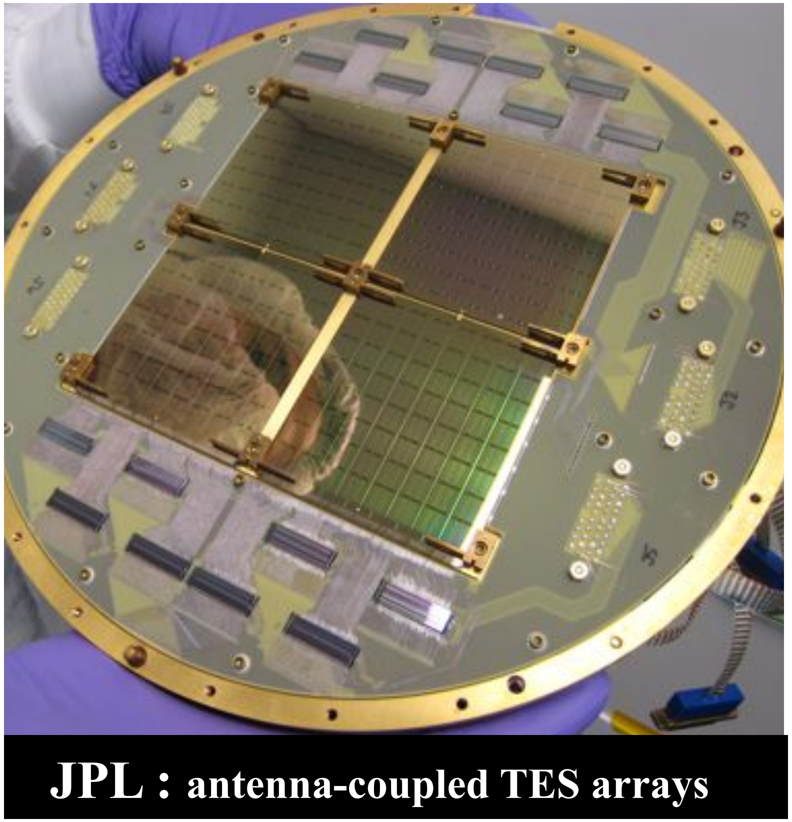


Photo: Steff Richter

BICEP2: 10-fold increase in mapping speed:

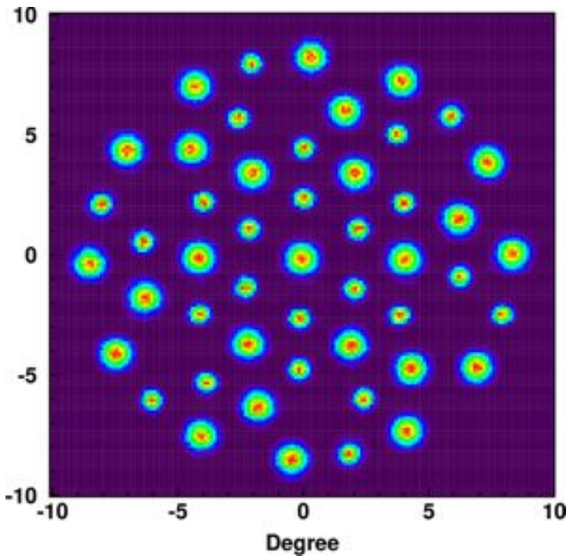


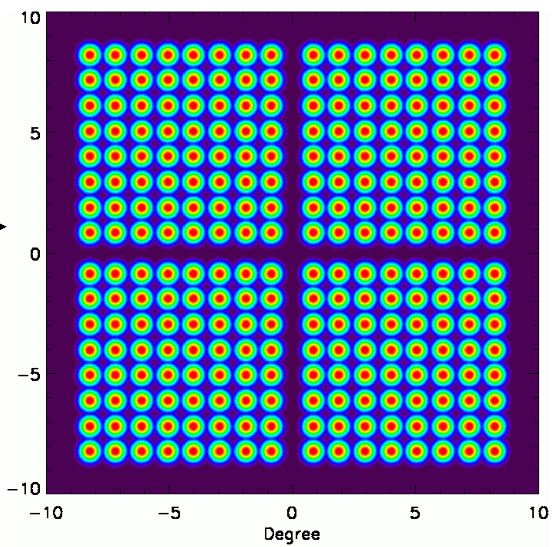


BICEP1

48

150 GHz detectors



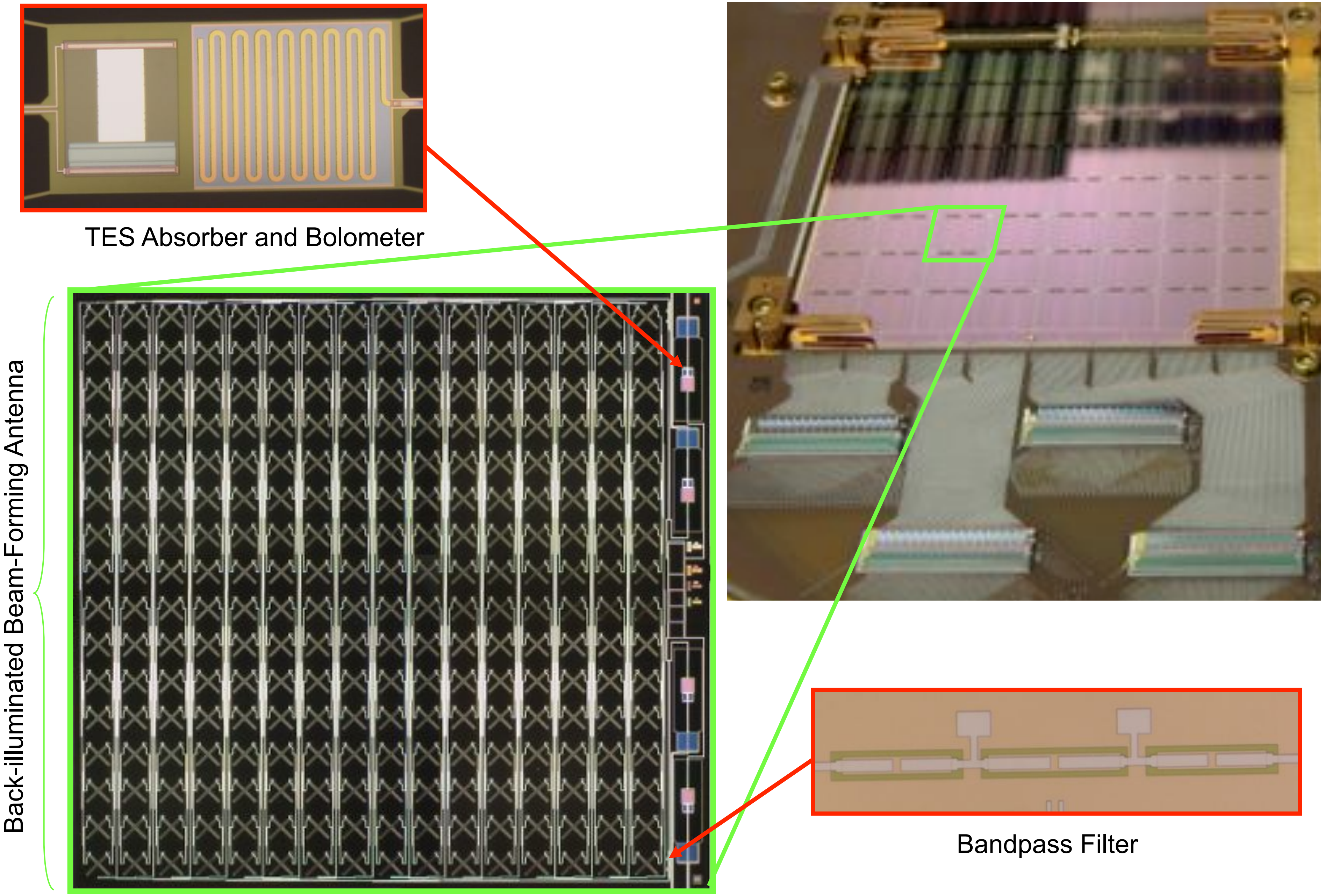


BICEP2

512

150 GHz detectors

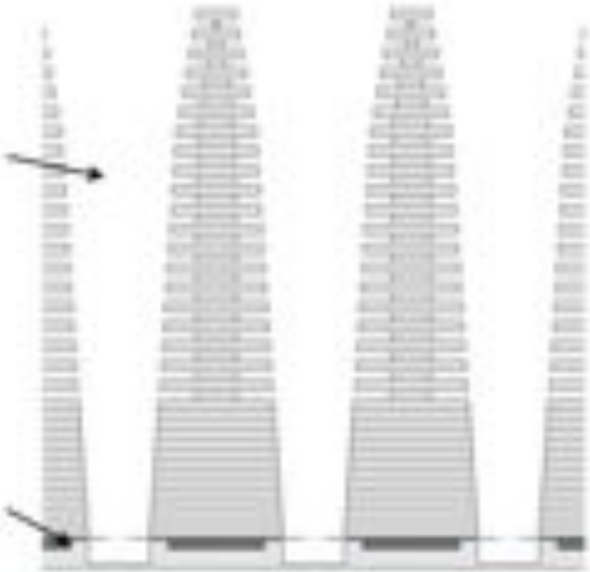
New Superconducting Detectors

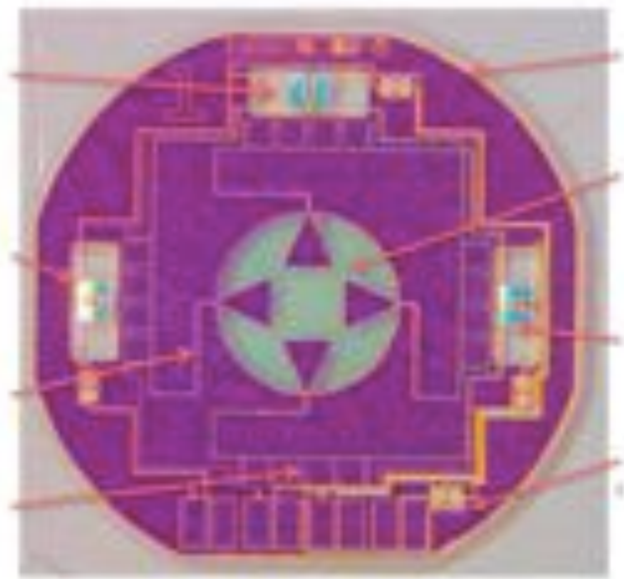


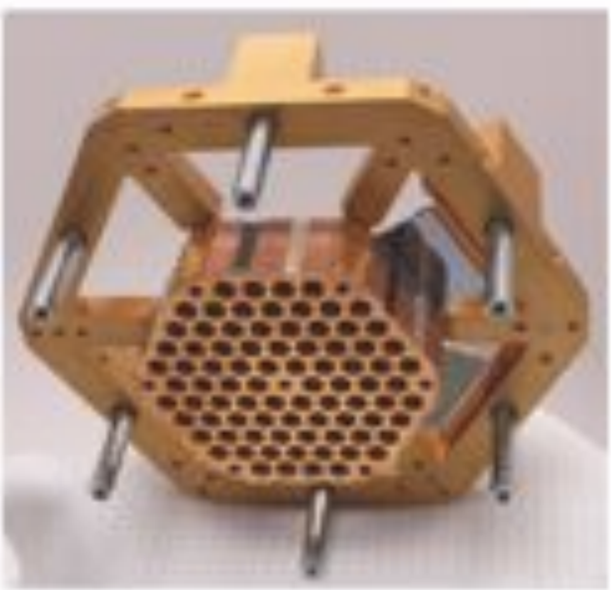
Putting BICEP2 together at South Pole

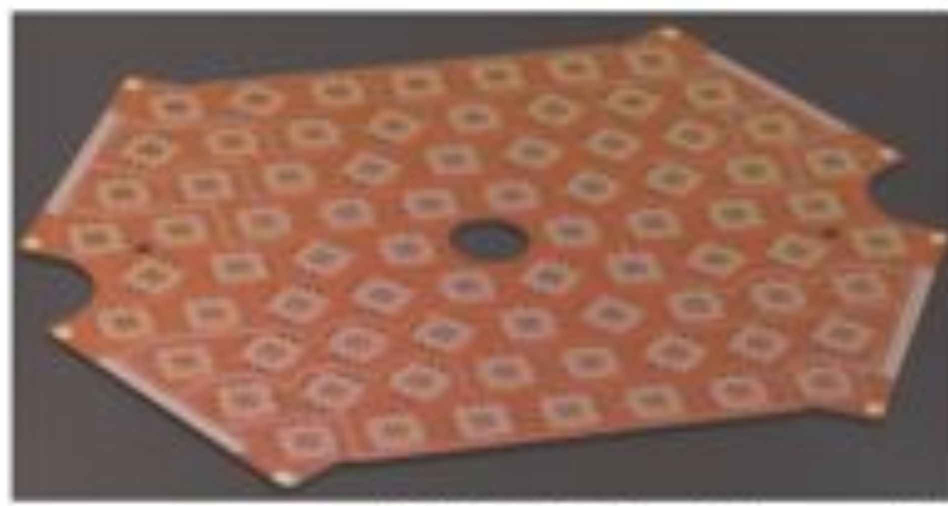
Justus Brevik

SPTpol camera (2012) - 1500 detectors





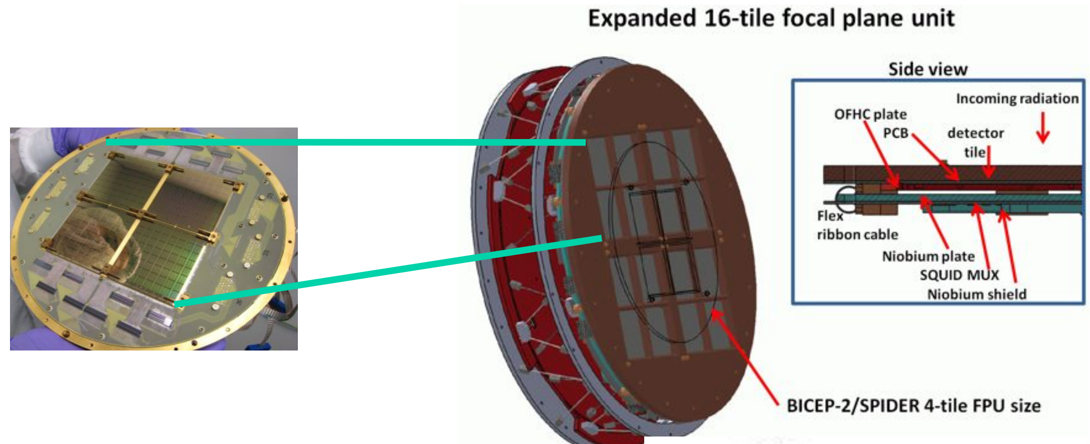




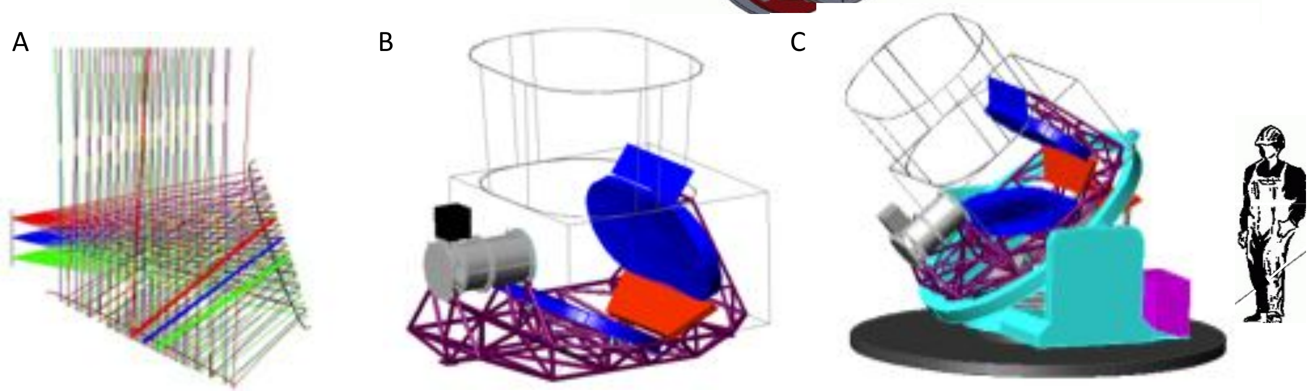
(NIST – Kent Irwin's group)

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 Σm_ν,
- evolution of Dark Energy
- curvature – pre-Inflationary relics

C. L. Kuo

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 → 1000's – 10,000's of detectors
  - 4' resolution → 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

Slides mostly from M. MacGregor, Harvard ‘11

Comparison to a Similar Experiment

University of Chicago	Harvard University
Experiment set-up ahead of time; lasts about one afternoon	Experiment is entirely student built; students delve more into basic physics and radio astronomy
Uses a 30 GHz receiver (cryogenic, low-noise, HEMT) → Not cheap!	Built from commercially available materials, < $5000

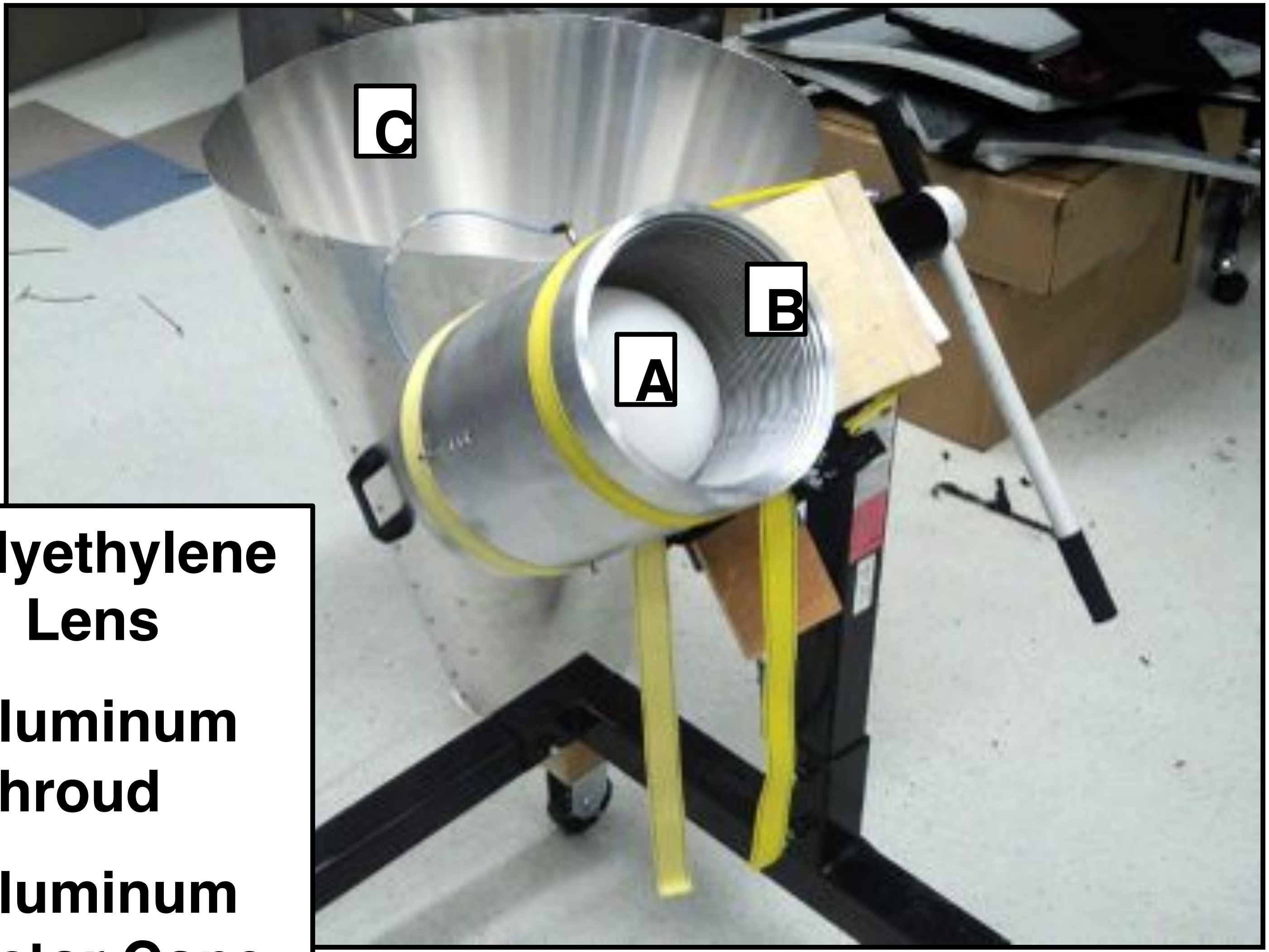
Both labs give students a feel for doing real experimental science!

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



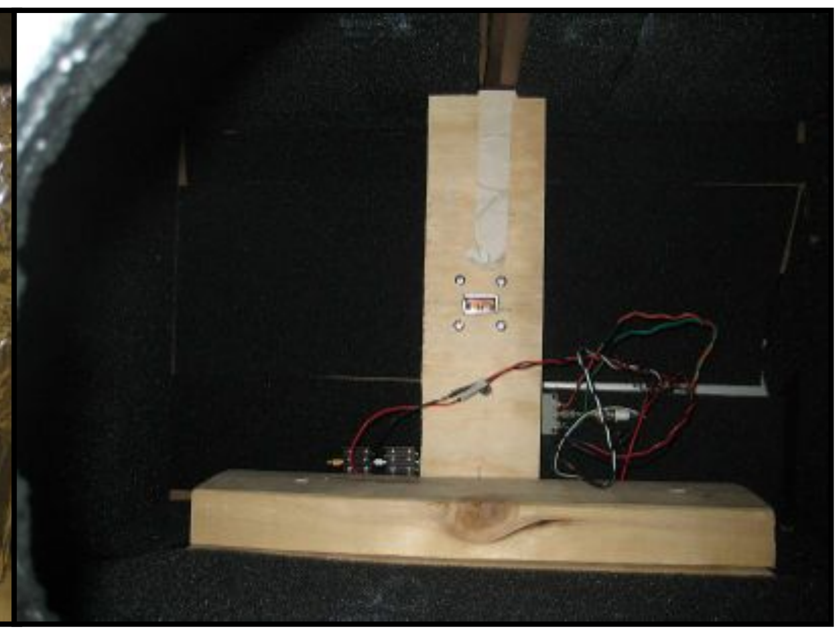
A) Polyethylene Lens

B) Aluminum Shroud

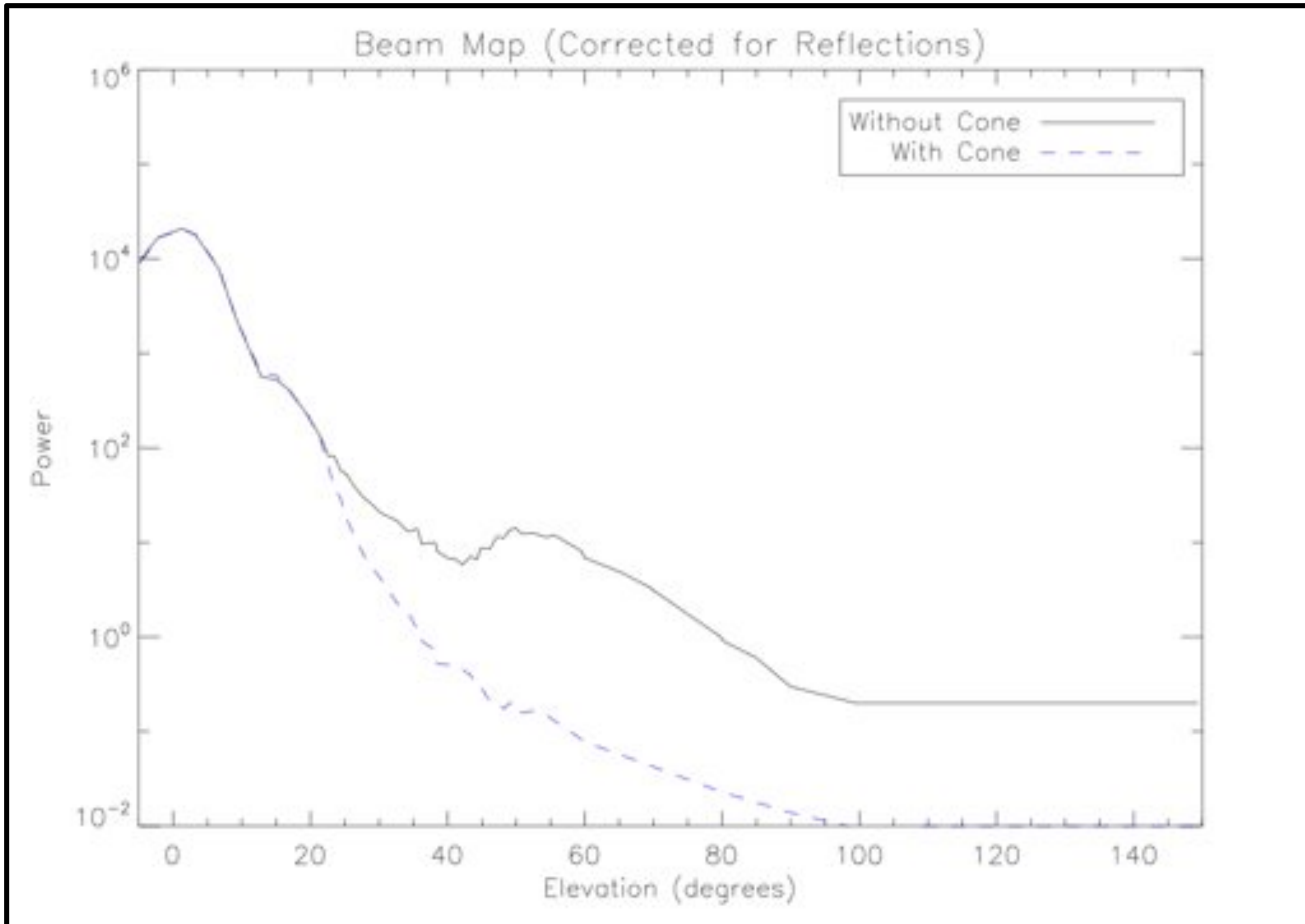
C) Aluminum Reflector Cone

Low-Sidelobe Antenna

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

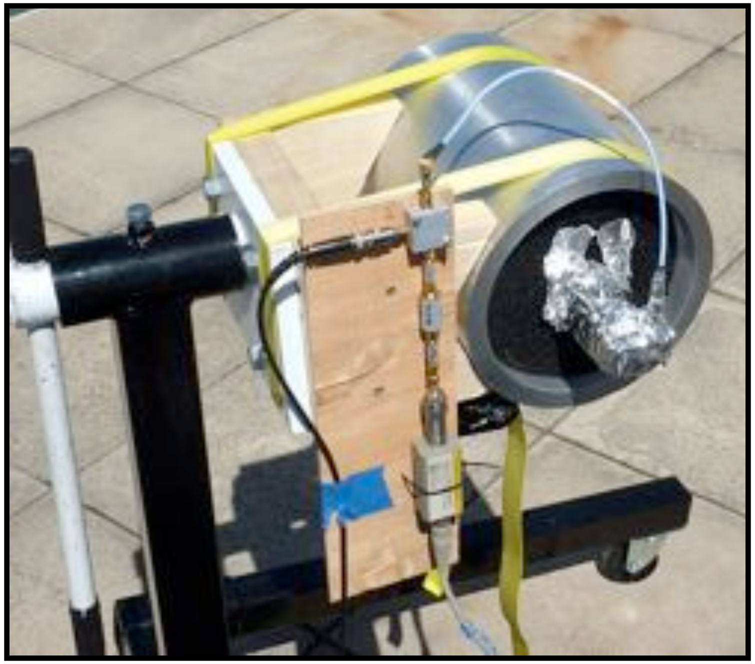


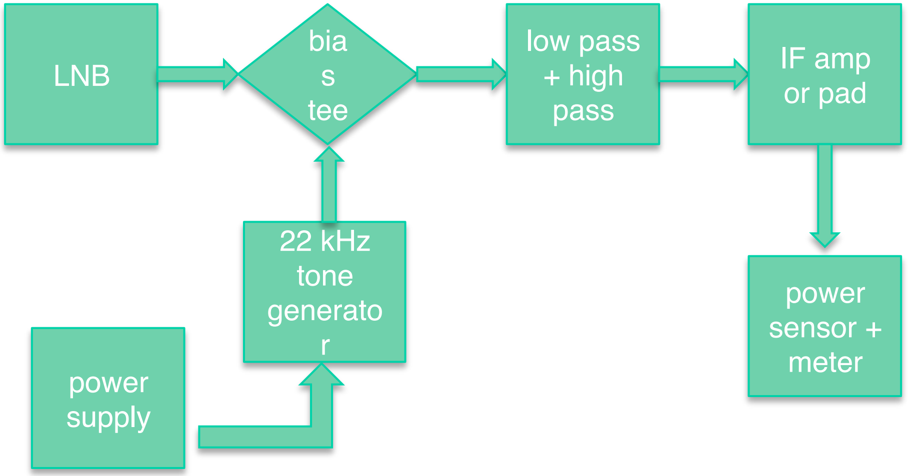
Low-Sidelobe Antenna



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

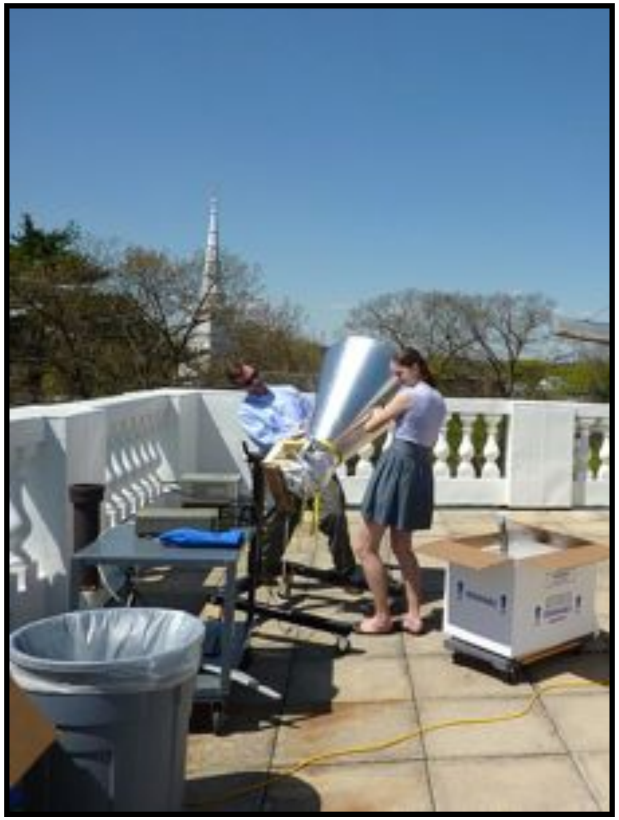
Calibration Scheme

Constructed three calibration loads:

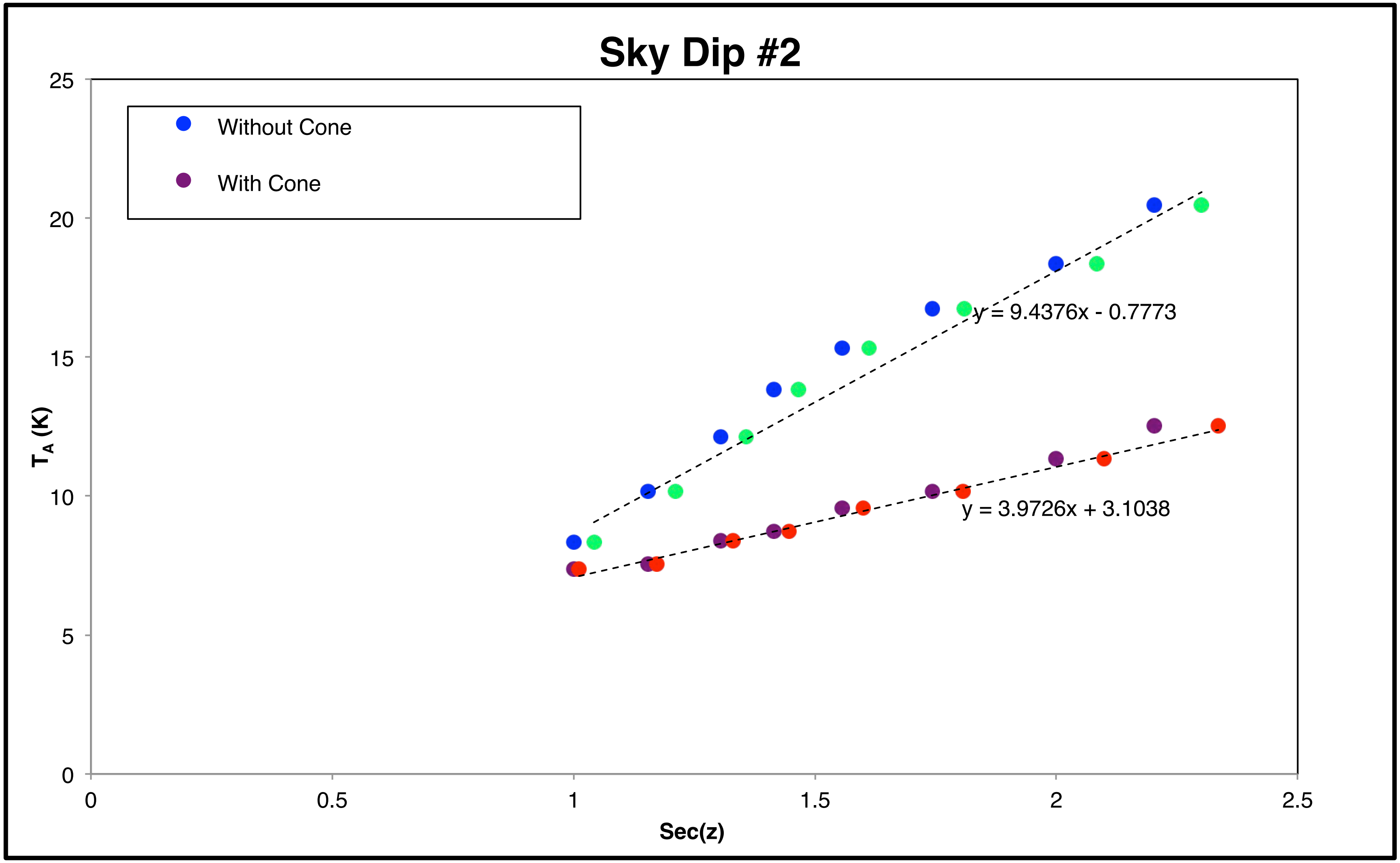
1. Room temperature
2. Liquid N_2
3. Liquid Ar (for linearity testing)

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:

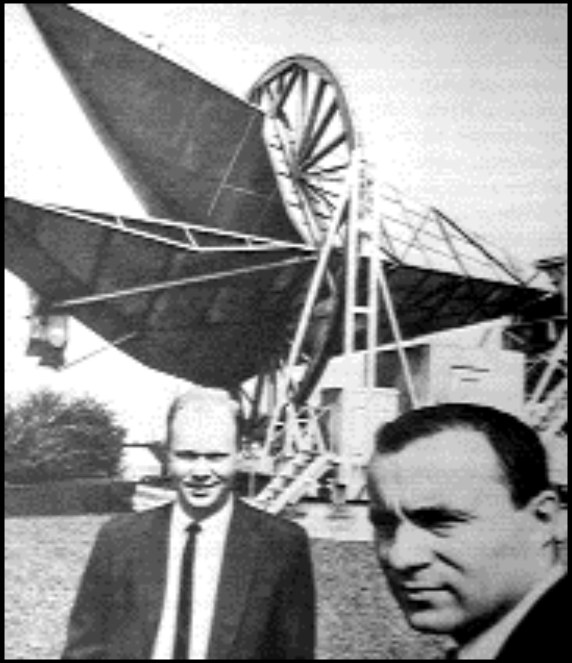
Edwin Hubble

1) The universe is expanding.

(Hubble, 1920's)

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

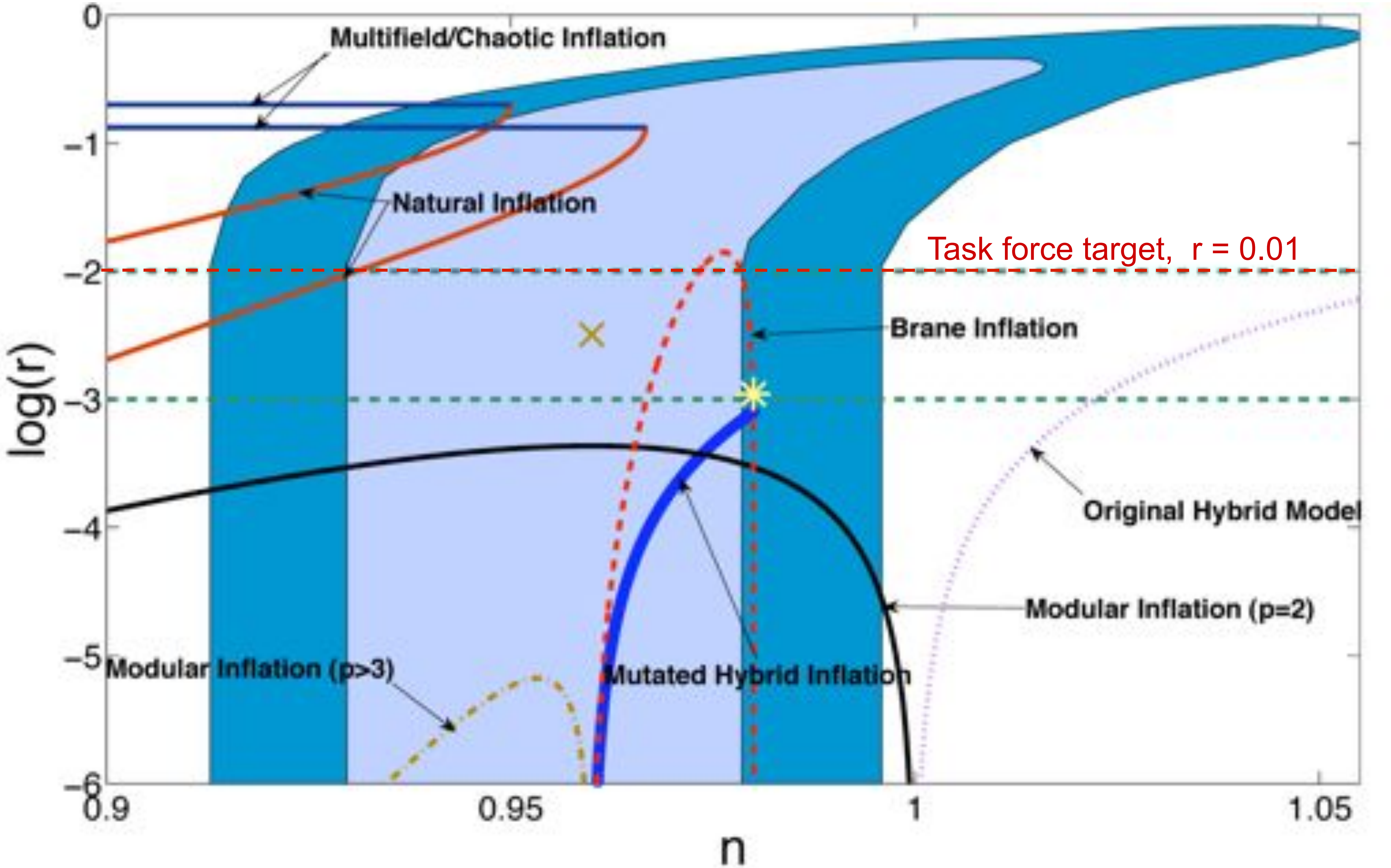
(Alpher, Gamow, Herman, 1940's)



3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1965)

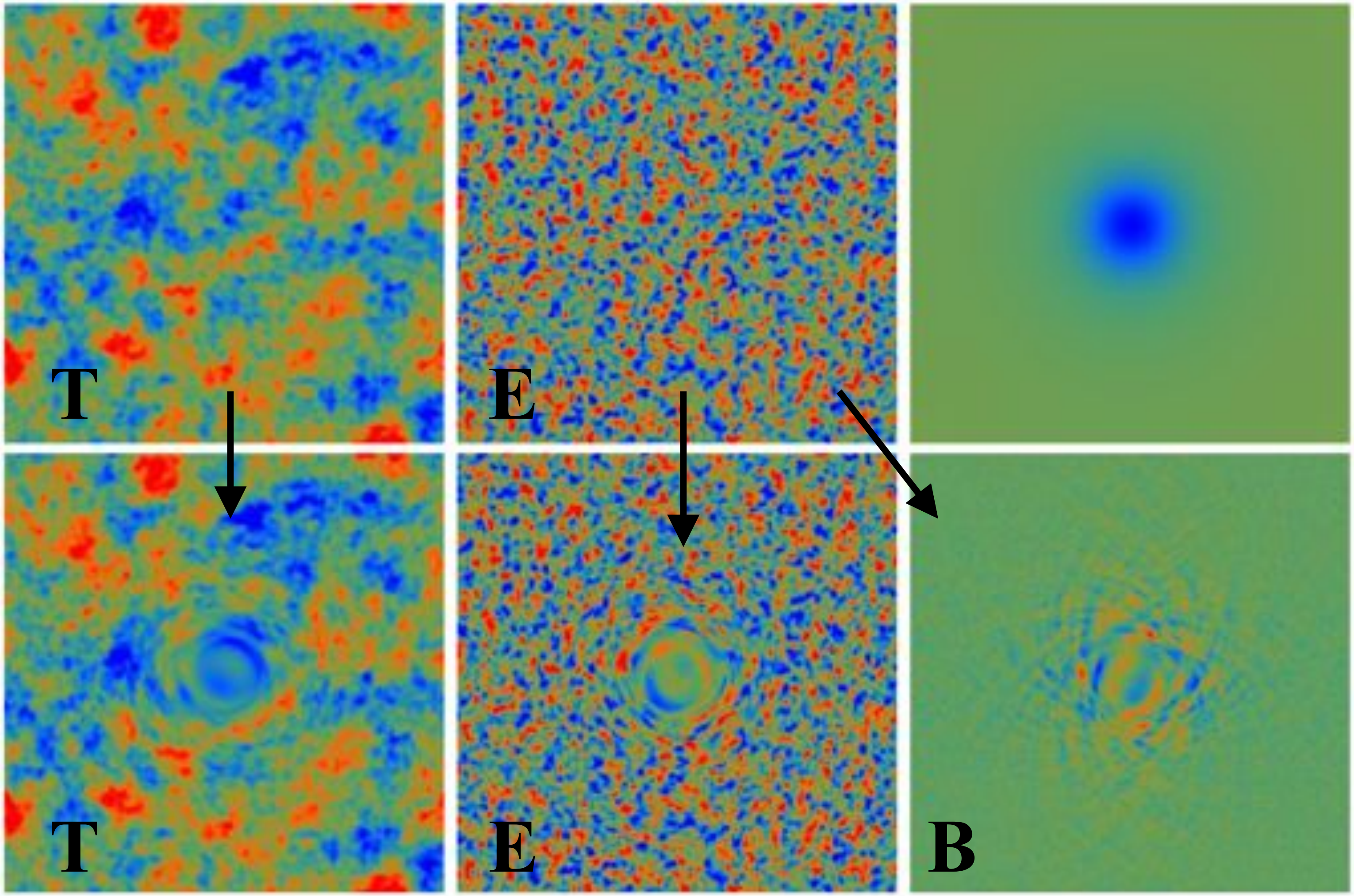
$\Rightarrow$ **"HOT BIG BANG"**

Inflationary parameters: n_s, r



Lyth, astro-ph/0702128

Lensing: converting E to B

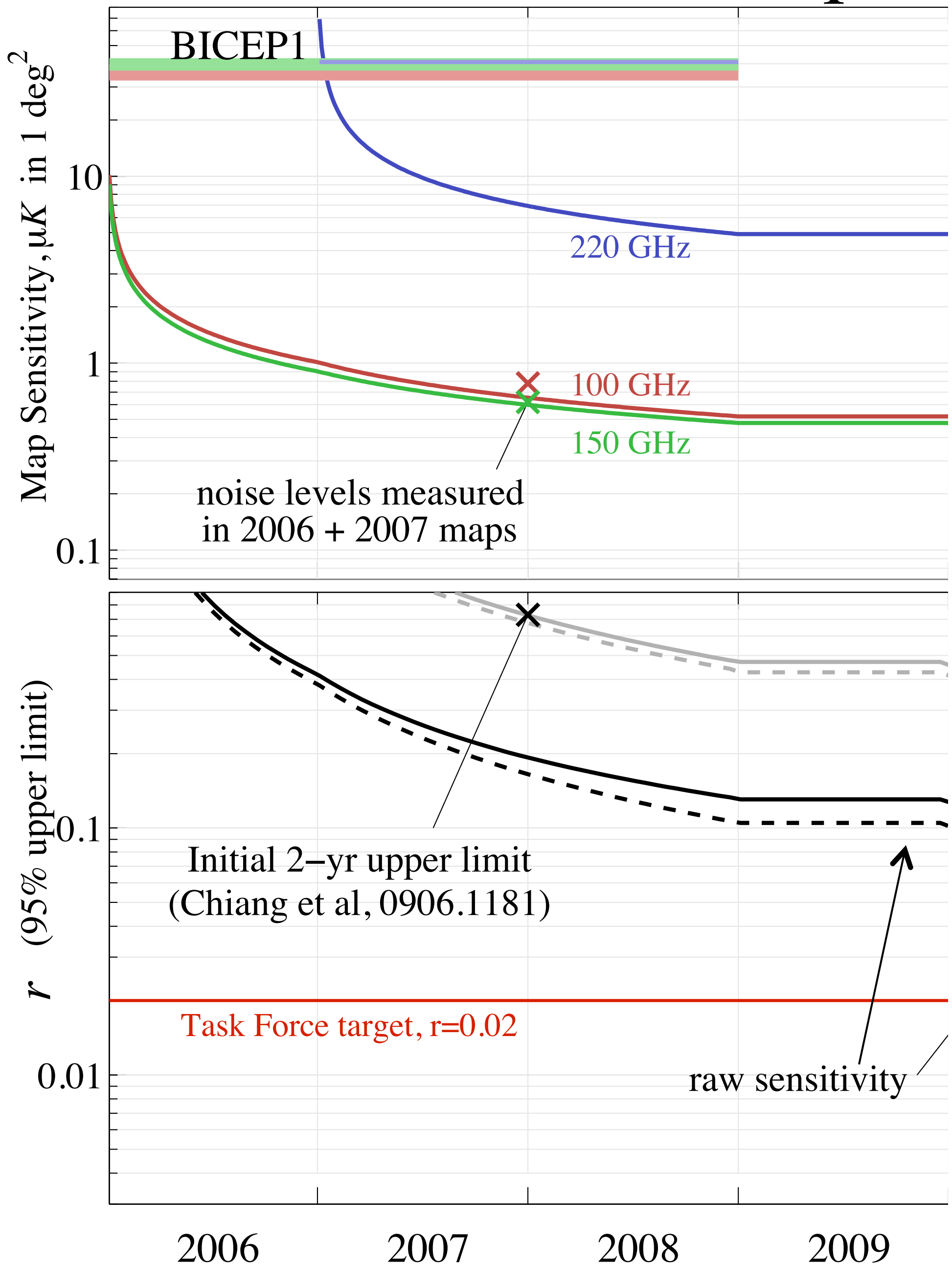


Hu and Okamoto, astro-ph/0111606

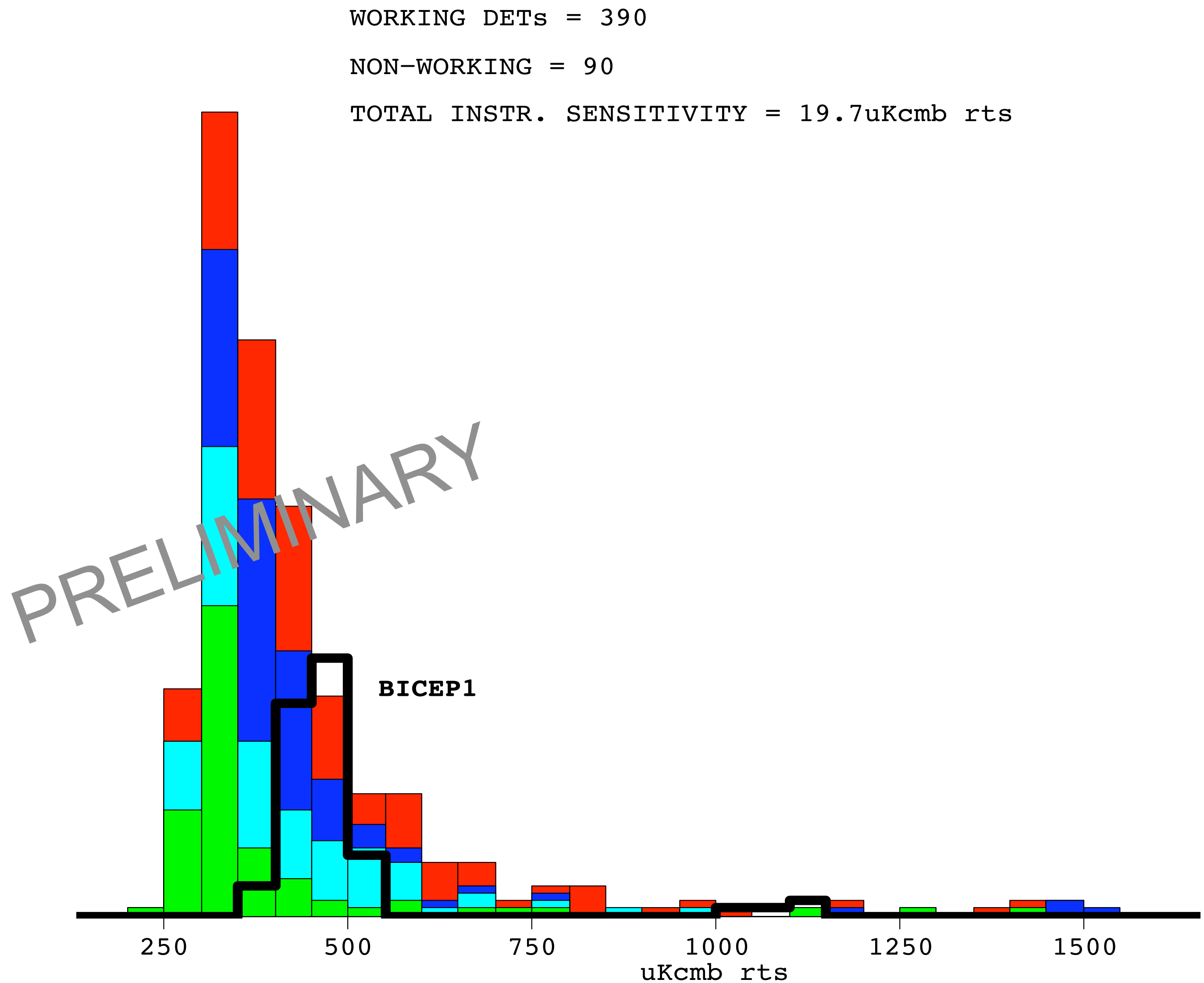
Realistic models predict ~2.6' rms deflection, coherence scale ~few degrees


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



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 1st acoustic peak, measured by Boomerang, MAXIMA, DASI, Archeops, …. WMAP1
  - ✔ **adiabatic fluctuations**
    - width of 1st 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 σ)
  - ✔ **super-horizon fluctuations**
    - TE polarization anti-correlation on >2° scales, measured by WMAP1
  - – **gravitational waves (tensors)**
    - B polarization: the “smoking gun”…no evidence yet.

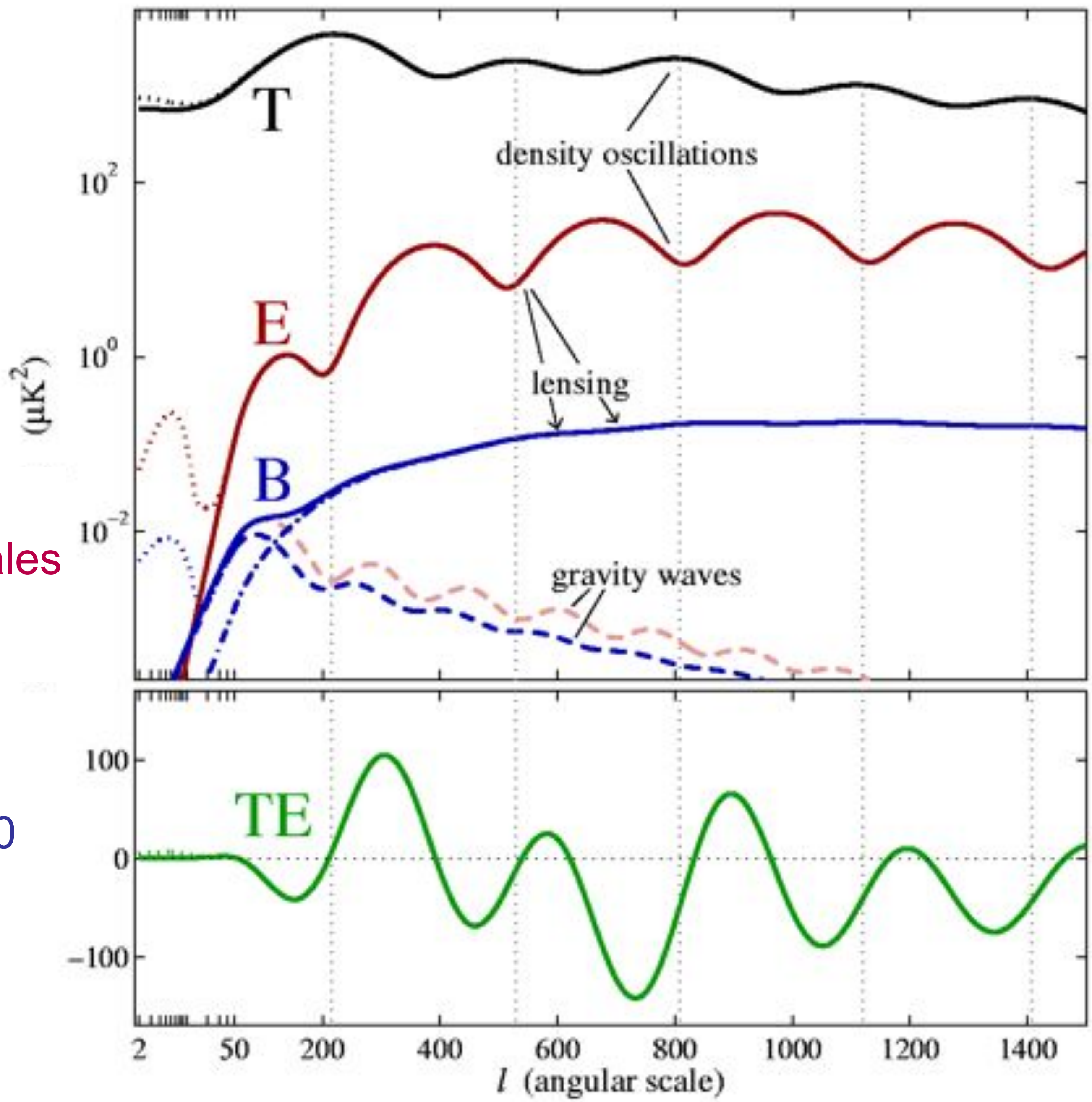
T spectrum traces density evolution of acoustic oscillations in early universe.

E spectrum features:

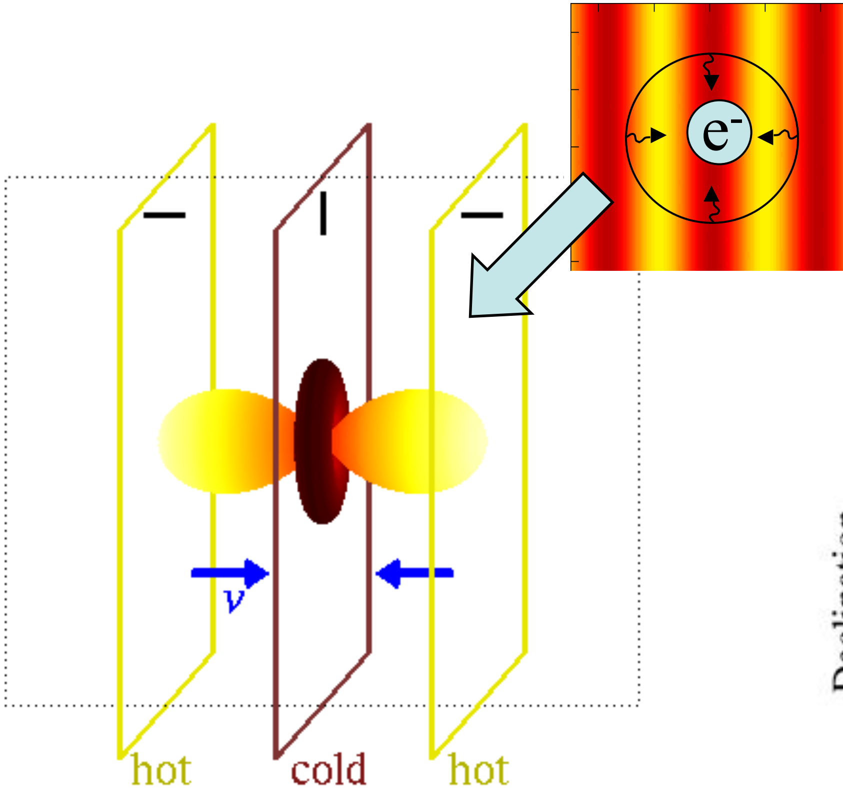
- 10^2 lower
- correlated with T but out of phase
- peaks at smaller scales

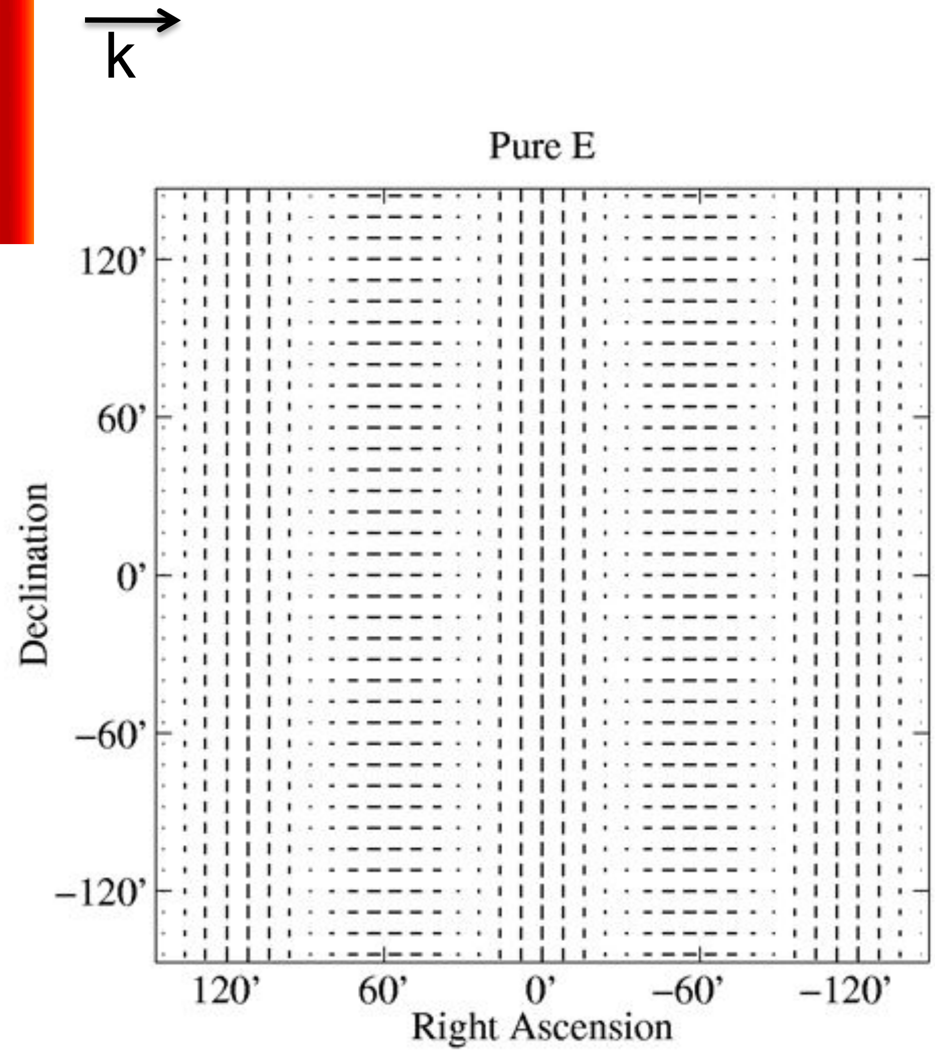
B spectrum features:

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



E-mode Polarization (curl free)

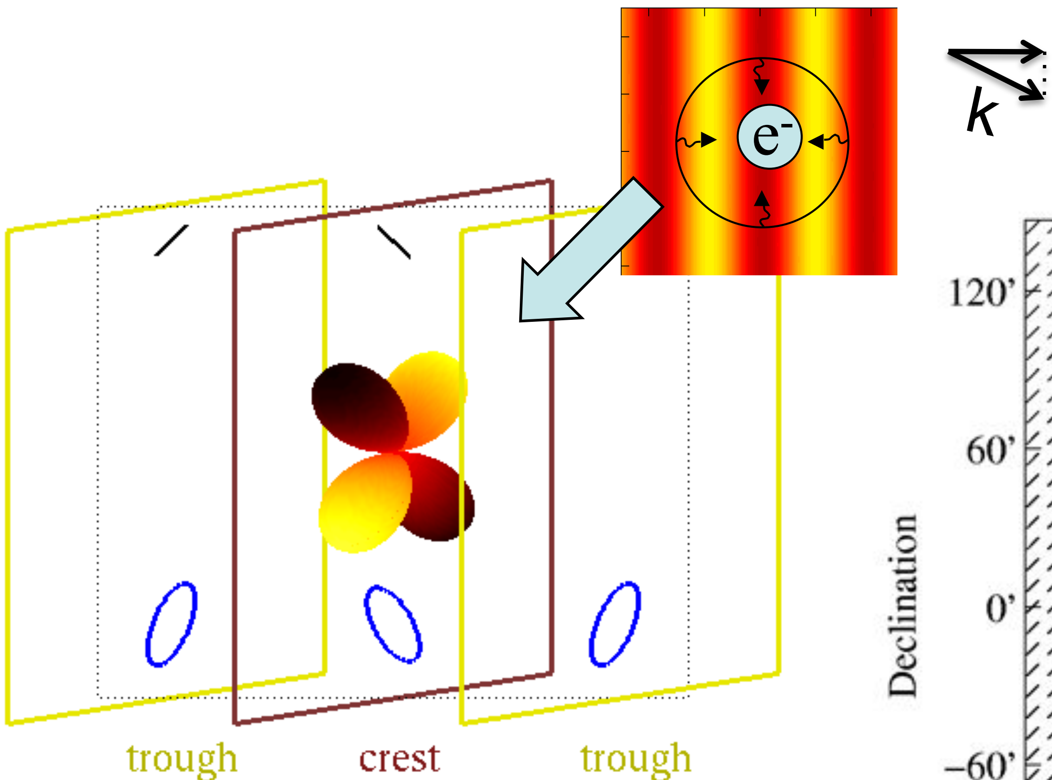


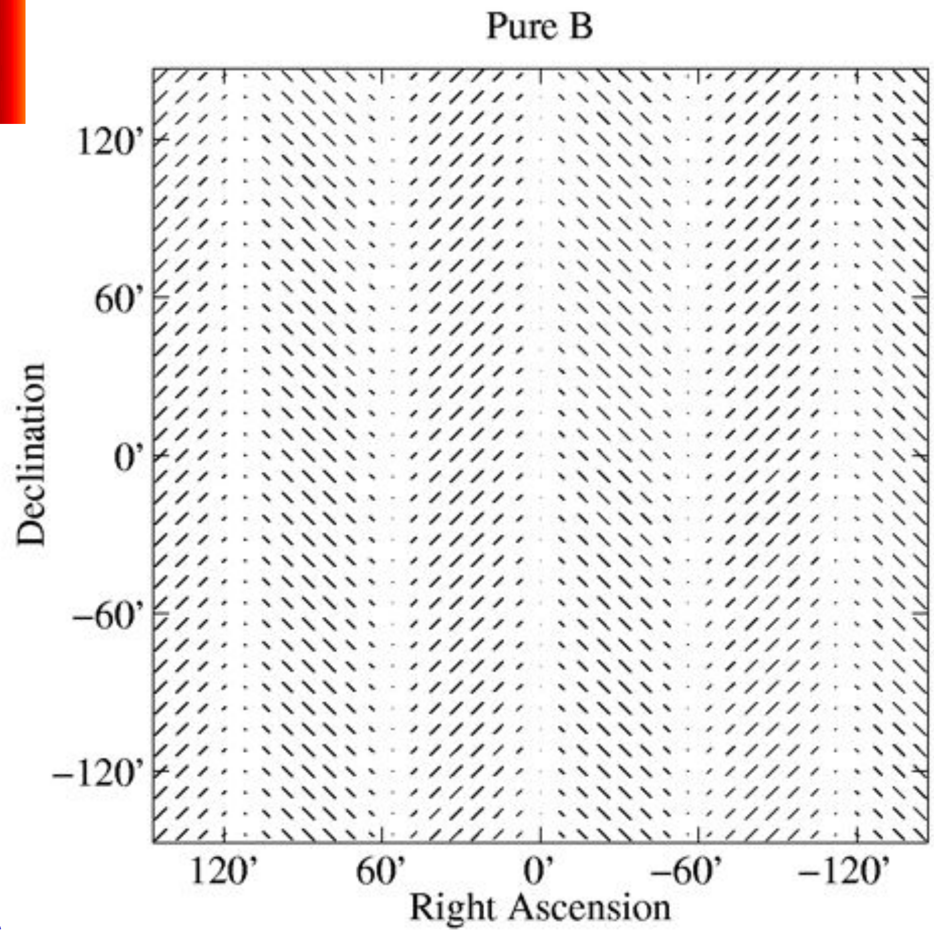


Polarization parallel or perpendicular to wave vector

Density (scalar) fluctuations generate only E-Polarization

B-mode Polarization (curl component)





Polarization oriented at 45 degrees
to wave vector

Not generated by density oscillations
only primordial source: **inflationary gravity waves**