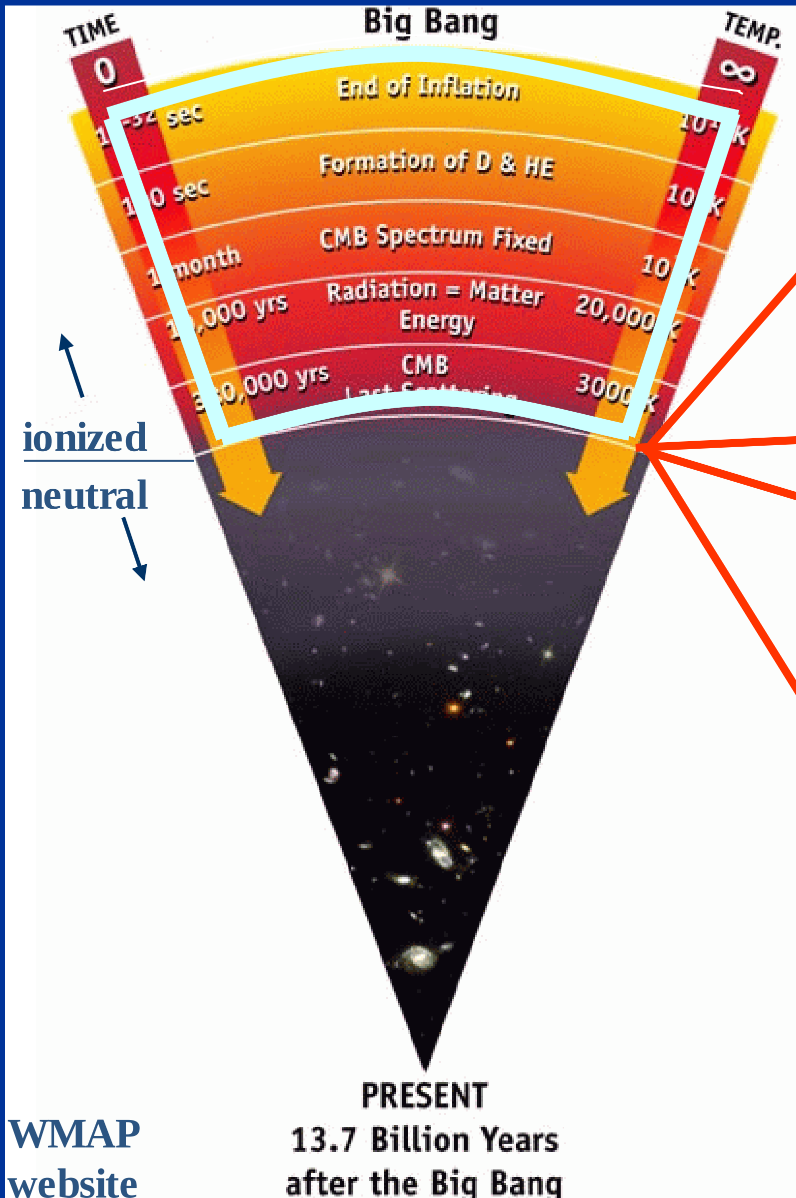
Exploring Cosmic Microwave Background

Chao-Lin Kuo
Physics Department & SLAC PPA, Stanford University
Kavli Institute for Particle Astrophysics and Cosmology

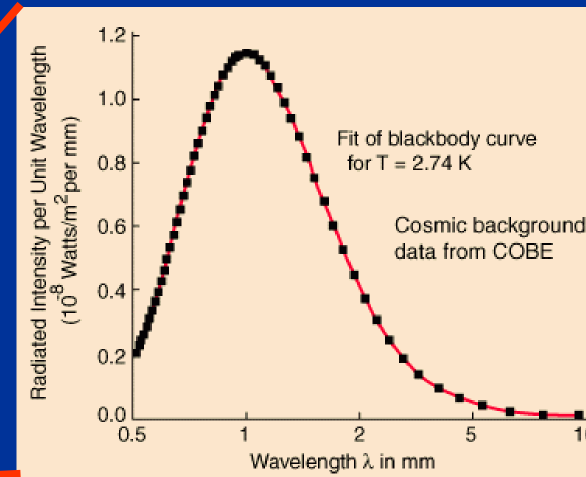
Cosmic Microwave Background (CMB)



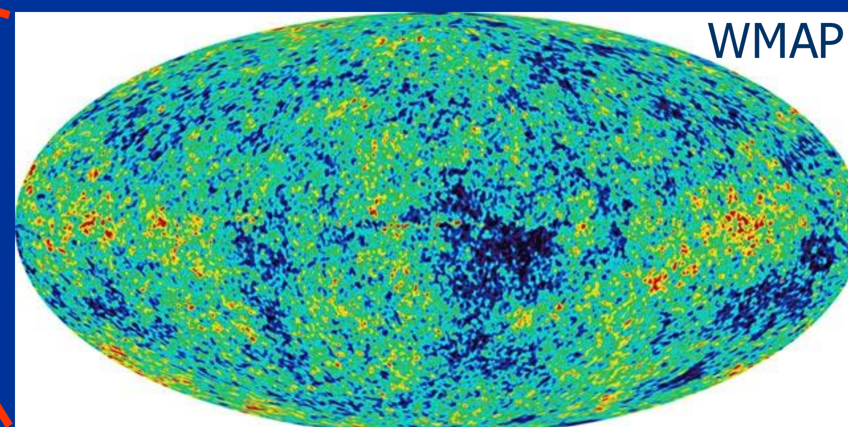
ionized

neutral

WMAP
website



1. blackbody emission law

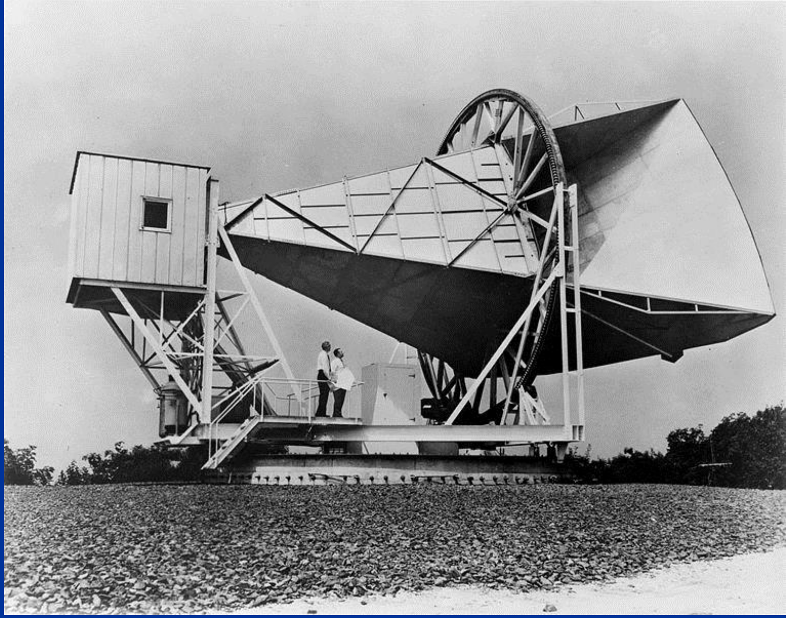


2. angular anisotropy → power spectrum

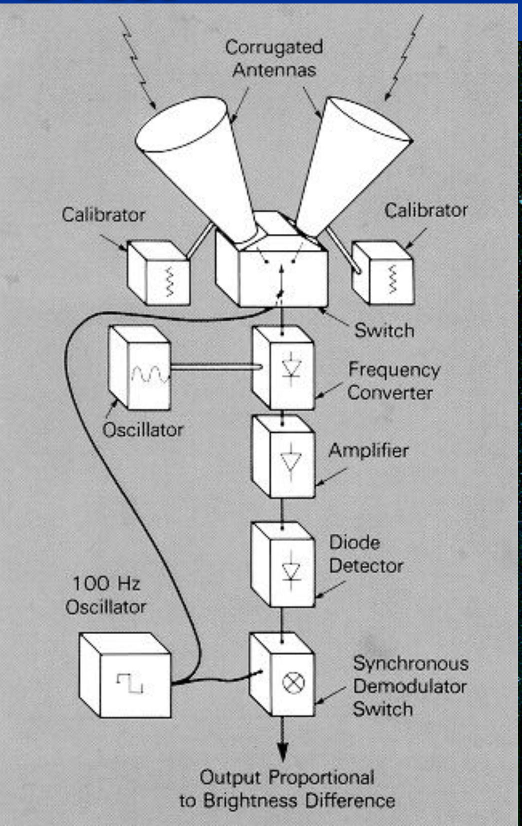
3. And, it is polarized! (Rees, 1968)

Cosmic Microwave Background

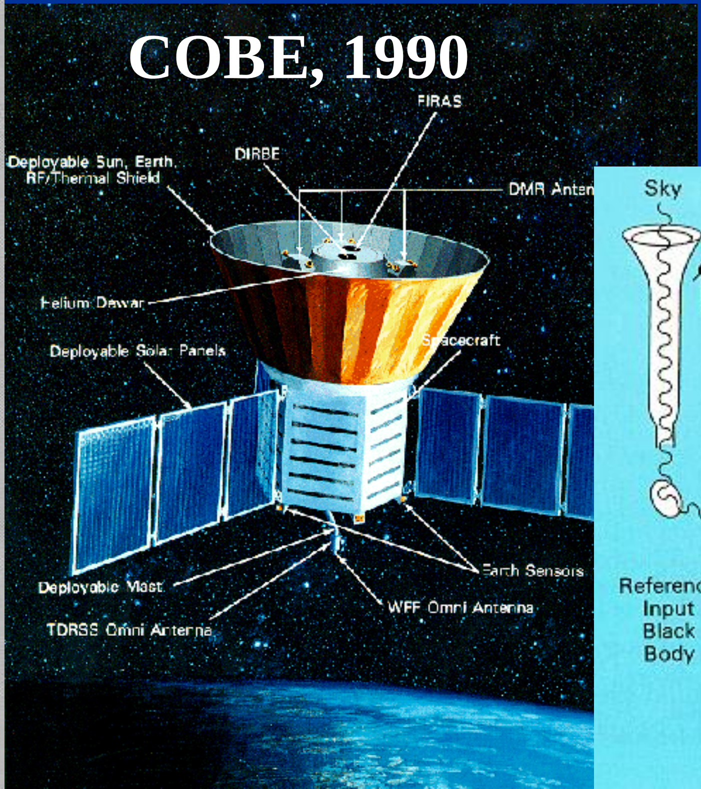
- THE Horn antenna
- COBE
    - DMR
    - FIRAS



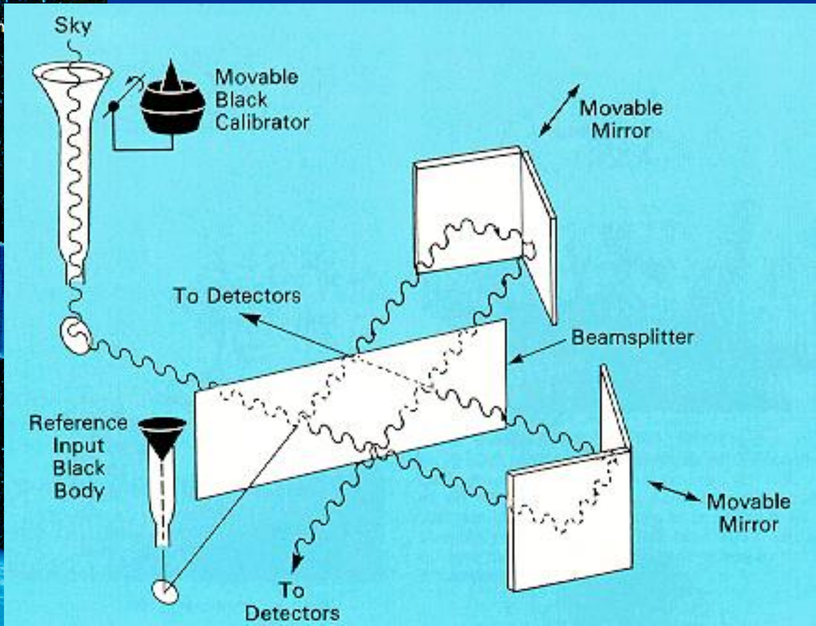
DMR



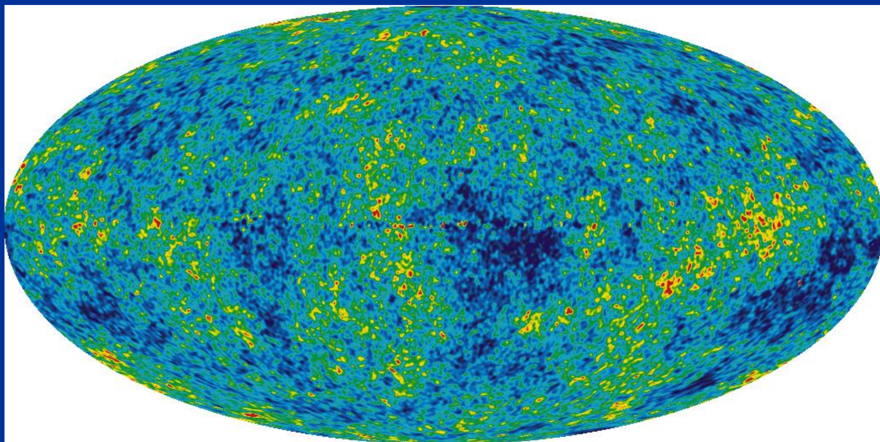
COBE, 1990



FIRAS



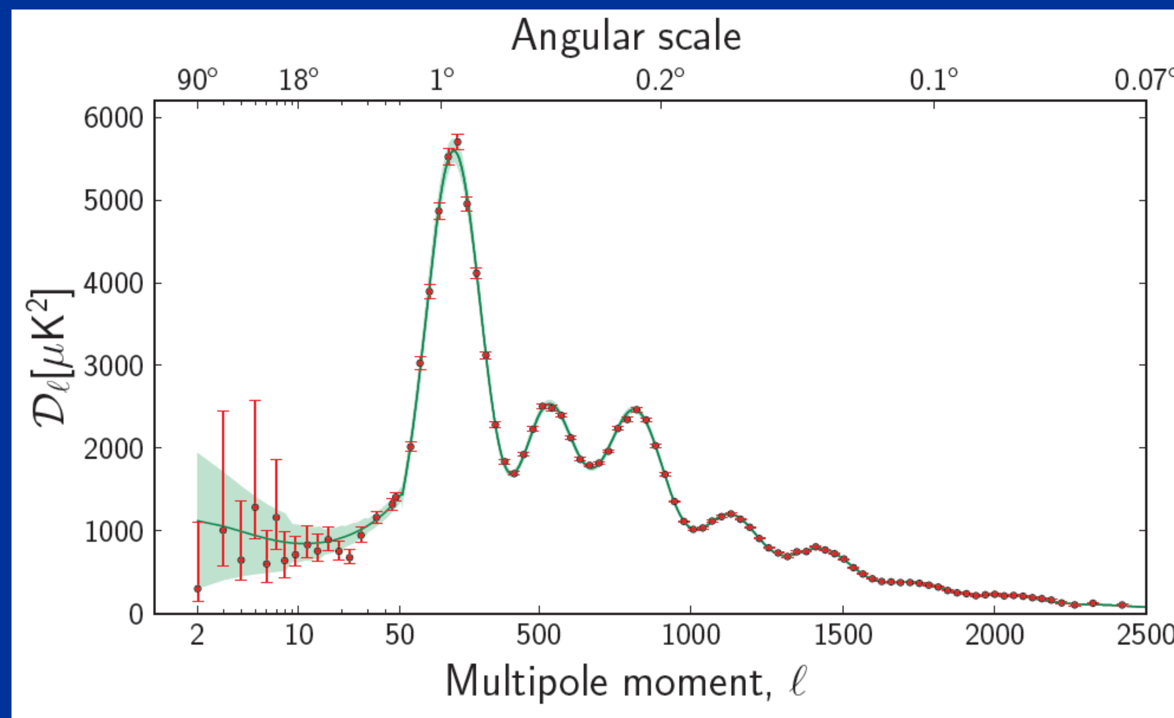
CMB angular power spectrum



Fourier Analysis

Large scales

Small scales



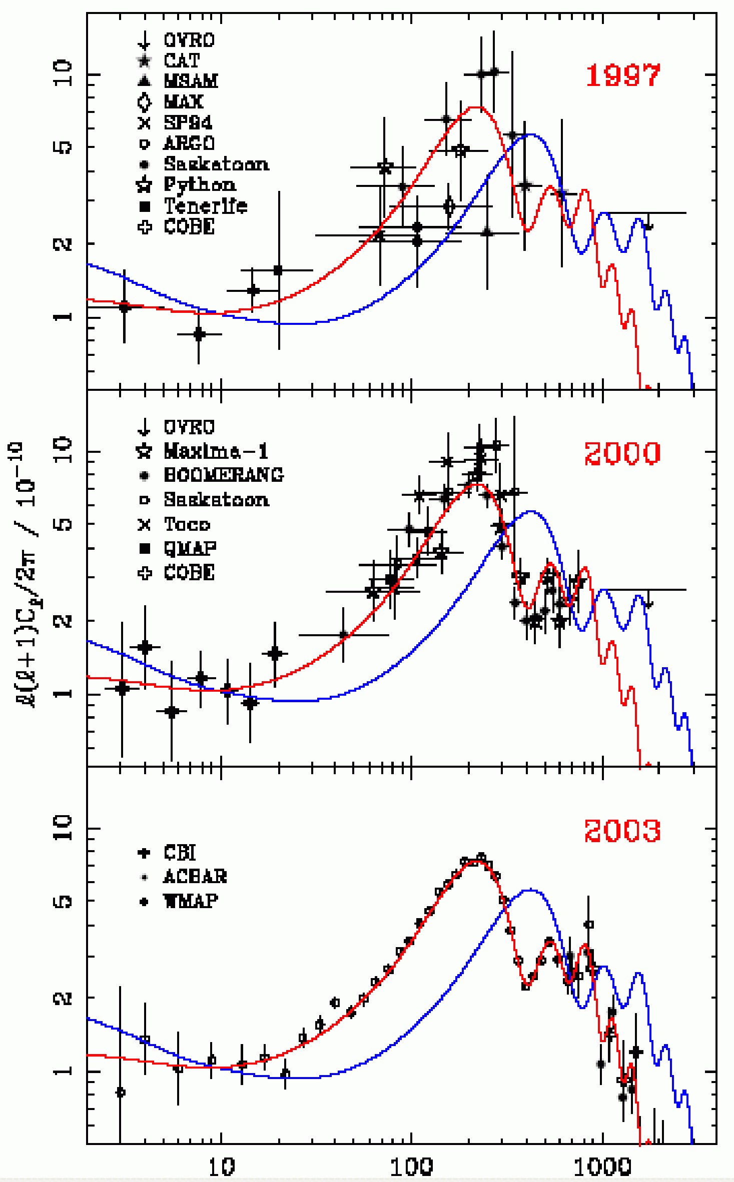
The *intrinsic* significance of the CMB

- ***Its effects:*** seeds for gravitational instability, which create everything you see today (galaxies, stars, planets, animals, …)
- ***Its origin:*** quantum gravity process in the very early universe (one of the very few ways to study QG)

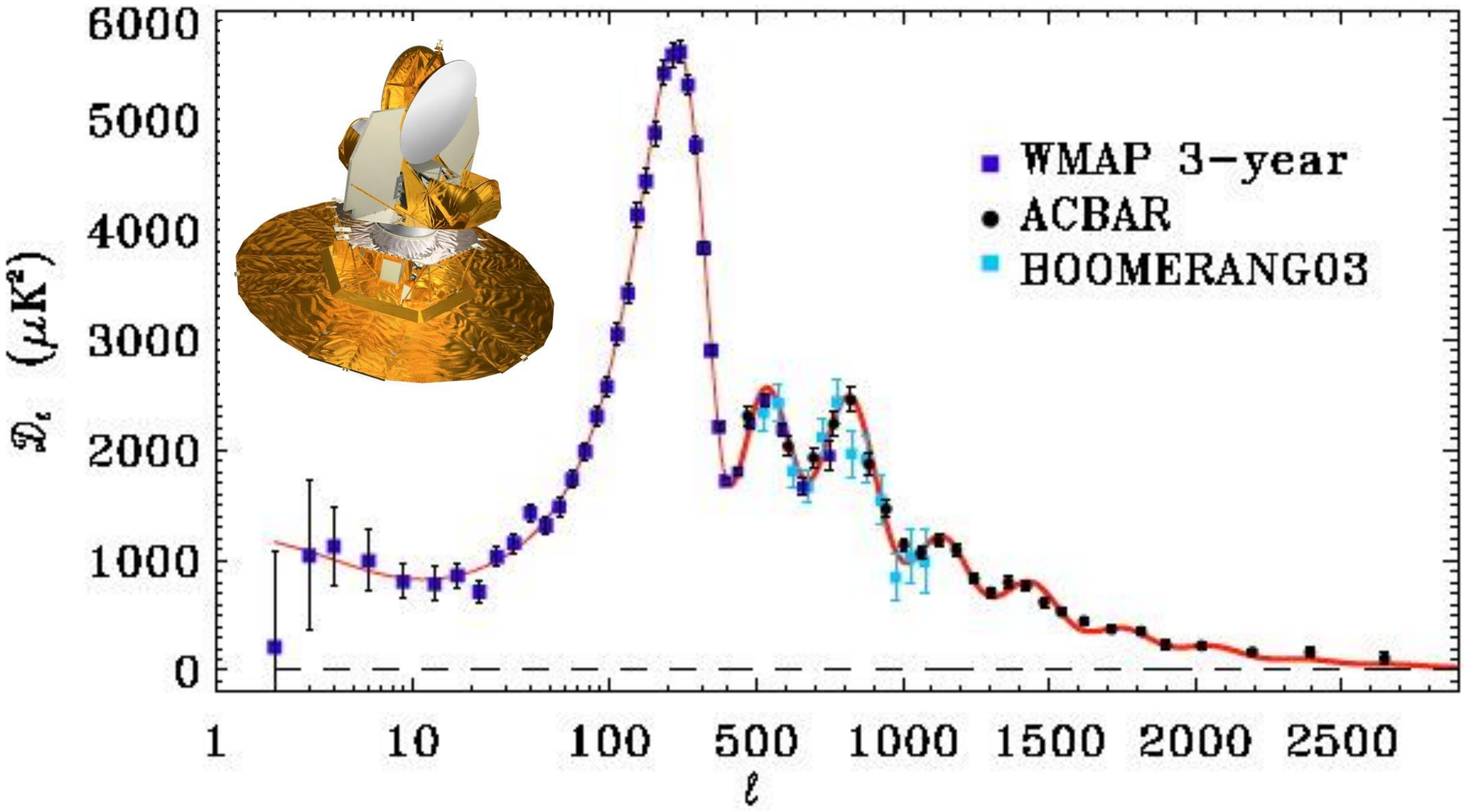
Boomerang, Maxima, DASI

The race to the peak..
1996-2001

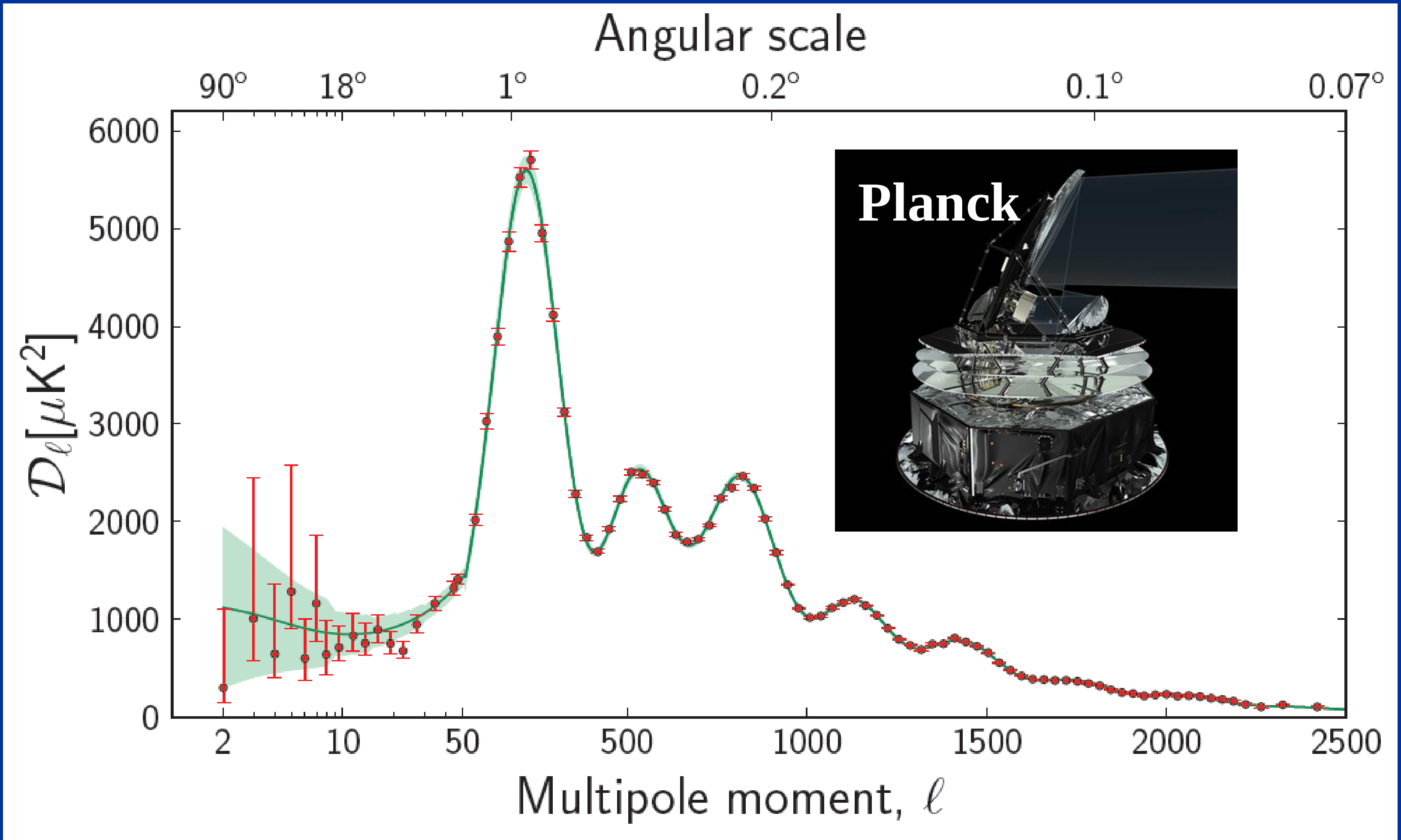
Progress in CMB experiments in the past 15 years

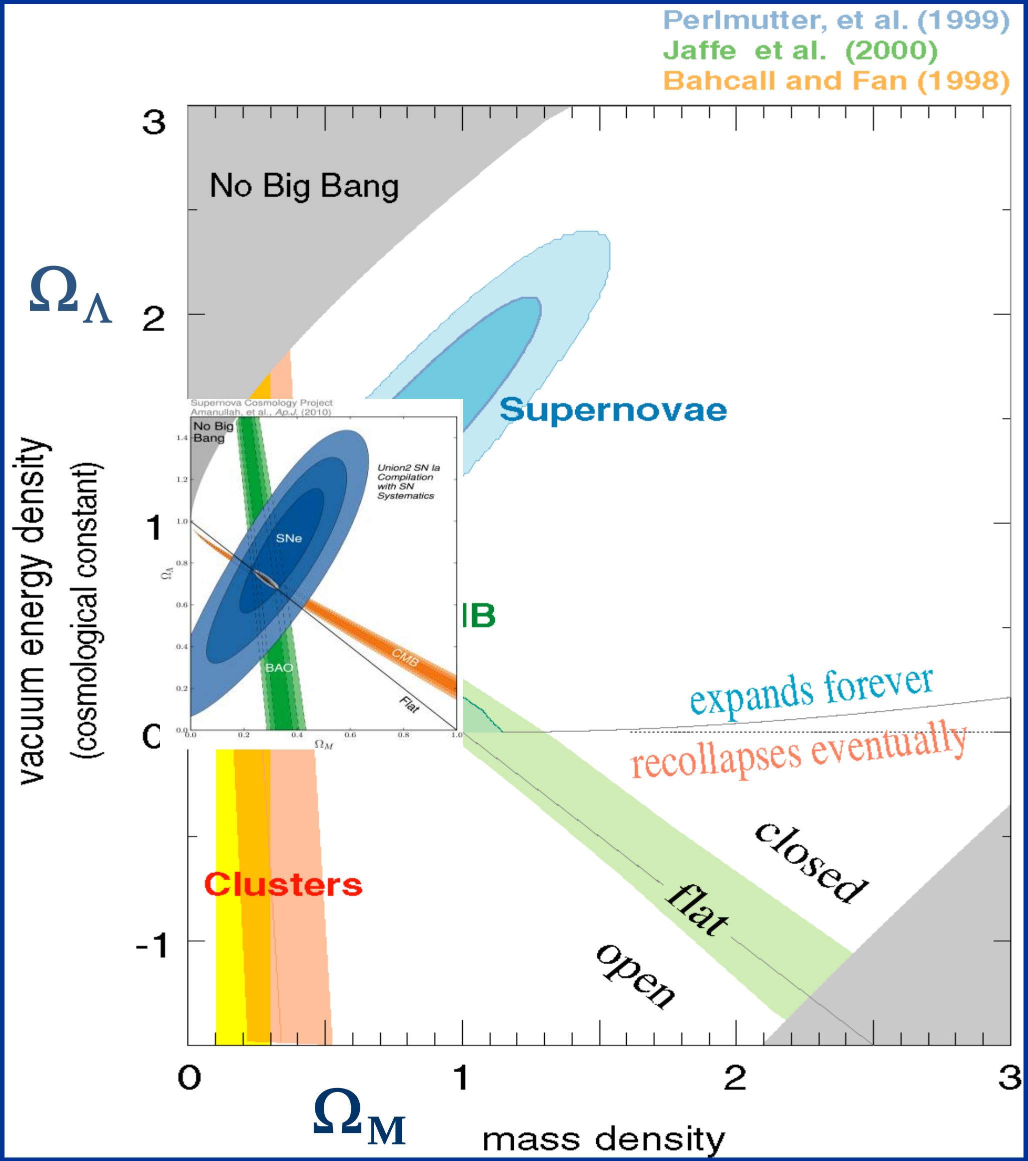


CMB temperature power spectrum circ. 2008



CMB temperature power spectrum, summer 2013





2000-2013

SN: Ω_M-Ω_Λ/2

CMB: Ω_M+Ω_Λ

LSS/Clusters: Ω_M

Flat geometry

Ω_{DM} (dark matter) ~ 25.9%

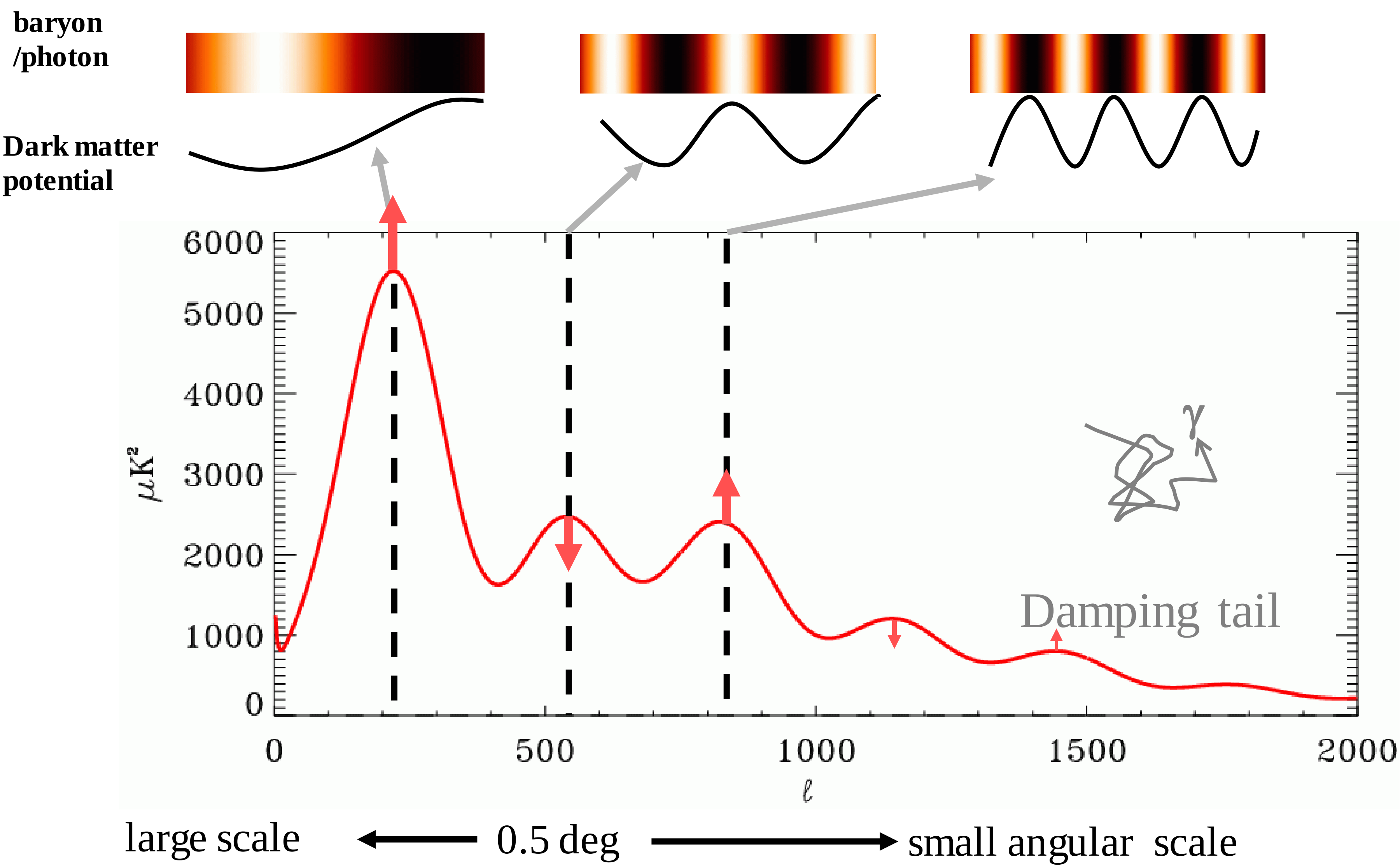
Ω_B (baryon) ~ 4.8%

Ω_Λ (dark energy) ~ 69.3%

Cosmological parameters

Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

CMB power spectrum



* Acoustic peaks (Sakharov) – compression/rarefaction of plasma in dark matter potential well

* Not are the acoustic peaks observed – they are in perfect agreement with BBNS !

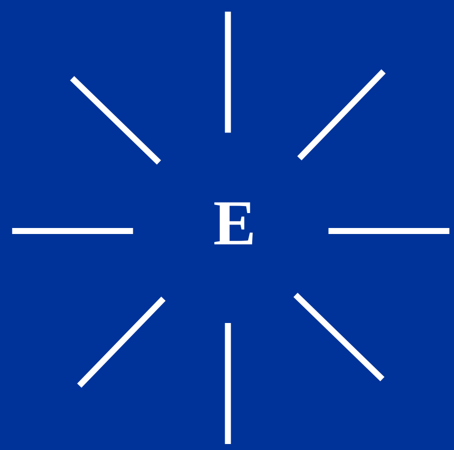
New Physics?

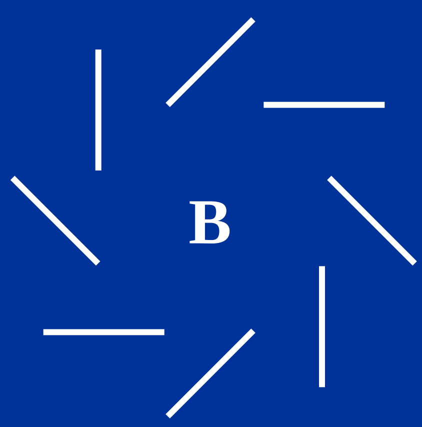
Planck Collaboration: Cosmological parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 95% limits	*Planck*+WP+BAO Best fit	*Planck*+WP+BAO 95% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 95% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include *Planck* combined with *WMAP* polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

B-mode theorem

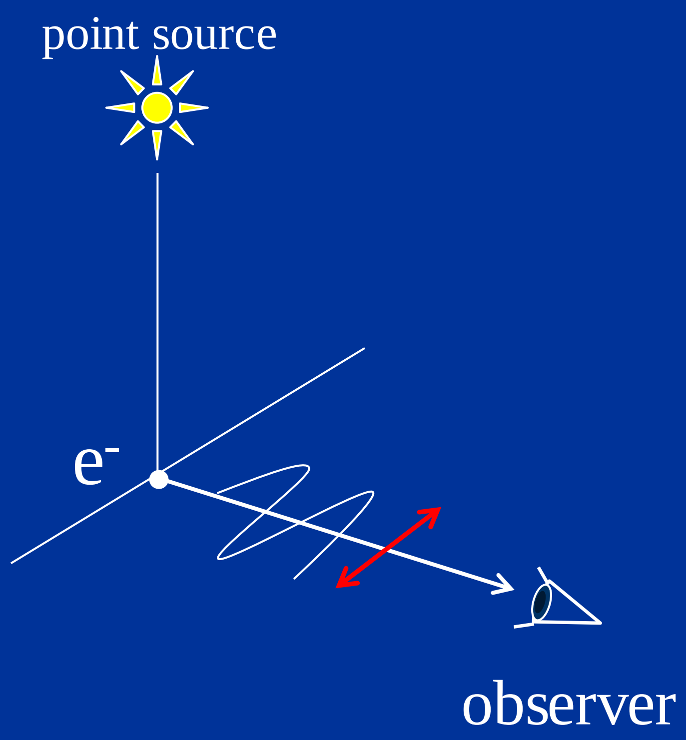




- Polarization fields can be linearly decomposed to E and B mode
- Linear, scalar perturbation cannot generate B-mode polarizations
- No cosmic variance

(Seljak & Zaldarriaga; Kamionkowski et al, 1997)

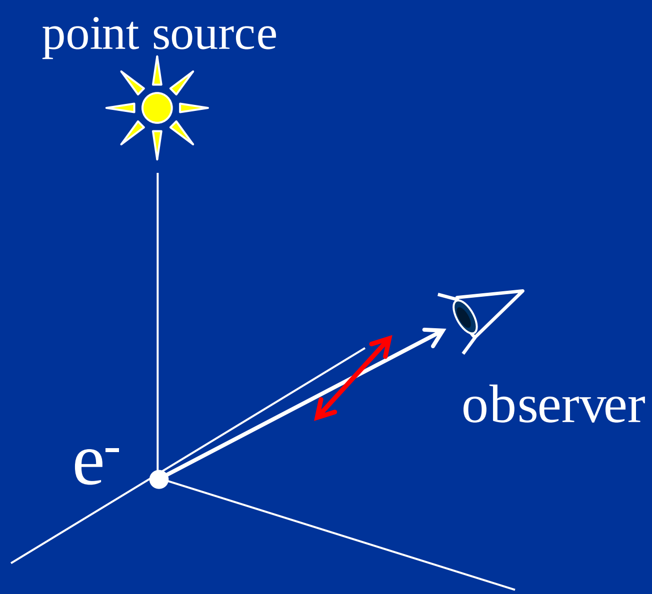
CMB is polarized. Why?

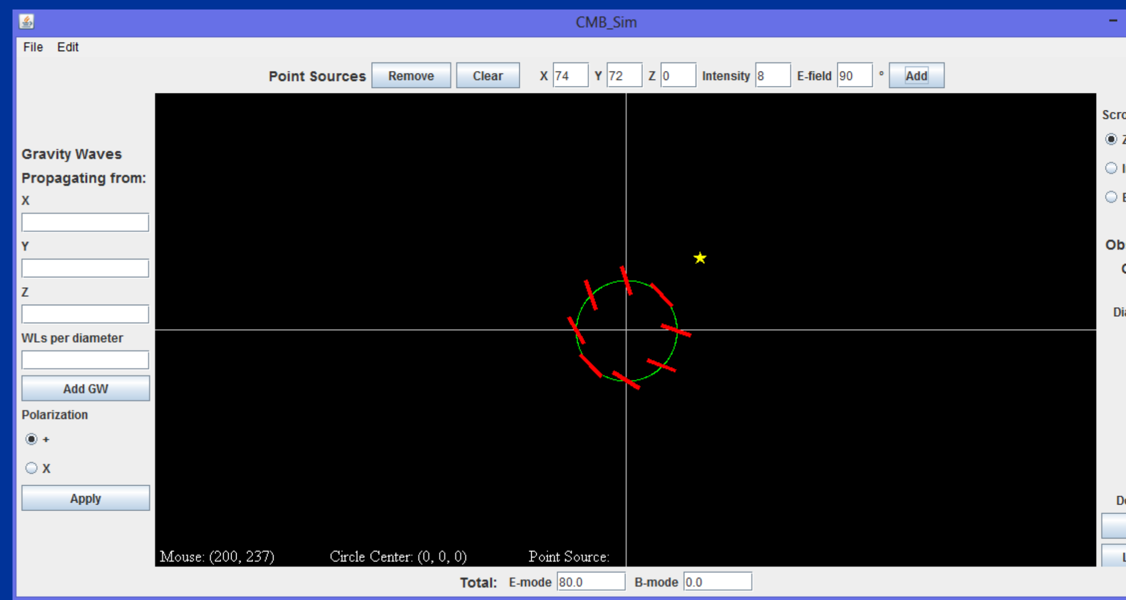


- Induced by radiation anisotropy through Thomson scattering
- *Generated only at the ionized/neutral interface (completely ionized: no anisotropy; completely neutral: no electrons to scatter)*

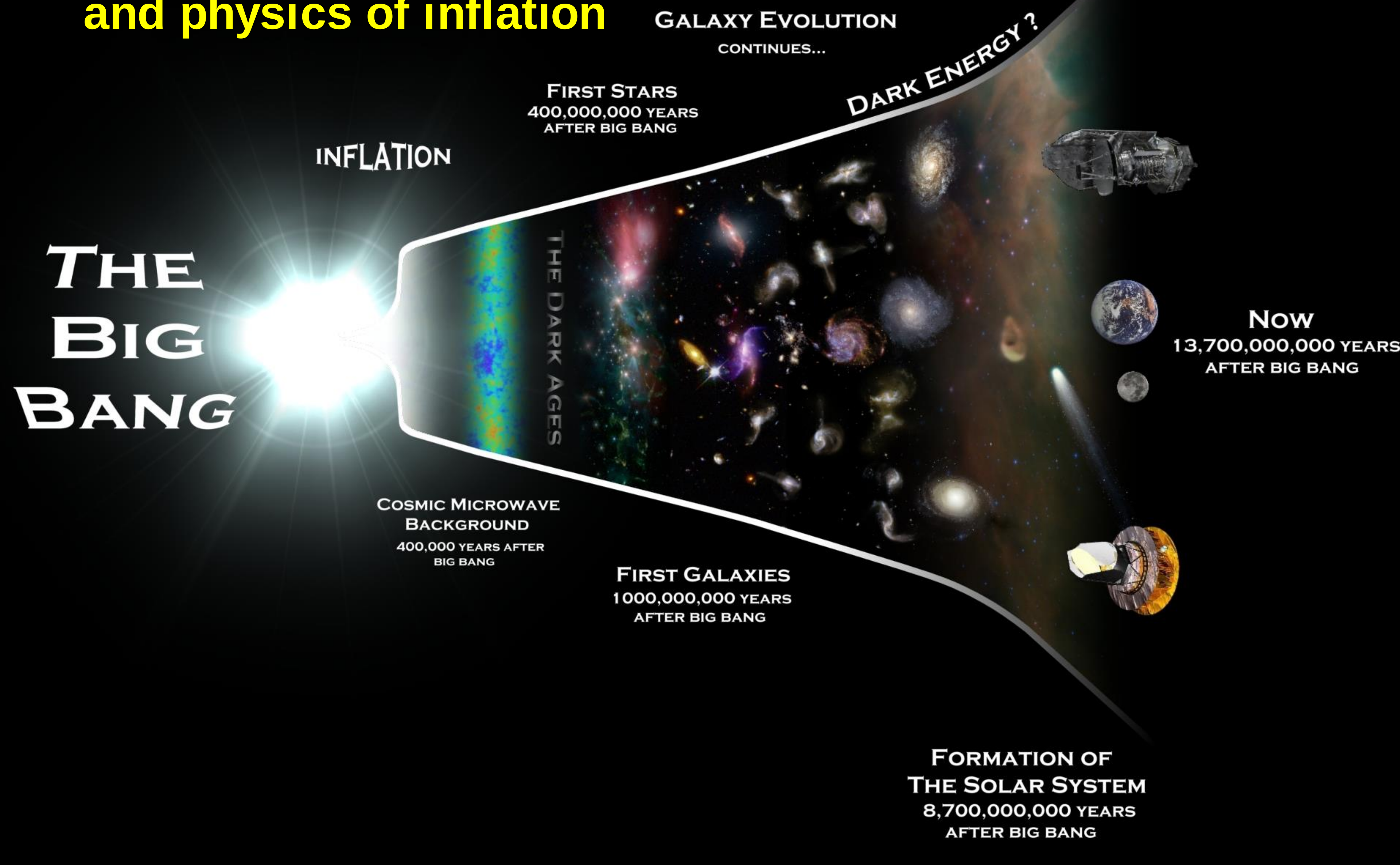
B-mode is forbidden *for density perturbations*

(Seljak& Zaldarriaga, 1997; Kamionkowski et al., 1997)

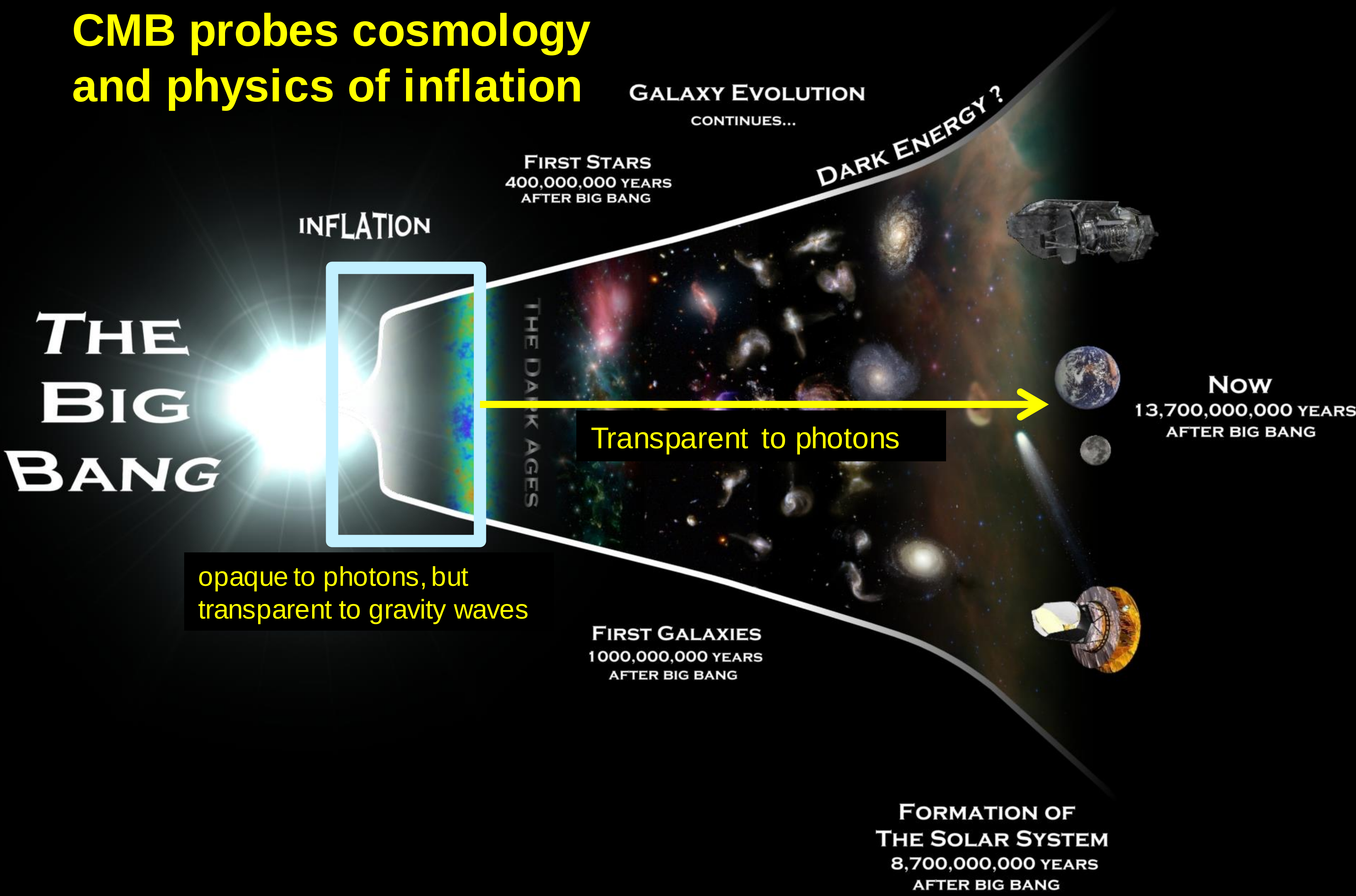




CMB probes cosmology and physics of inflation



CMB probes cosmology and physics of inflation



Experimental Probes of Inflation

SLAC

Inflation predicts

- Flatness; scalar perturbations with very specific properties/statistics
- All confirmed by ***Planck*** and other exp., except for **“tensor”**

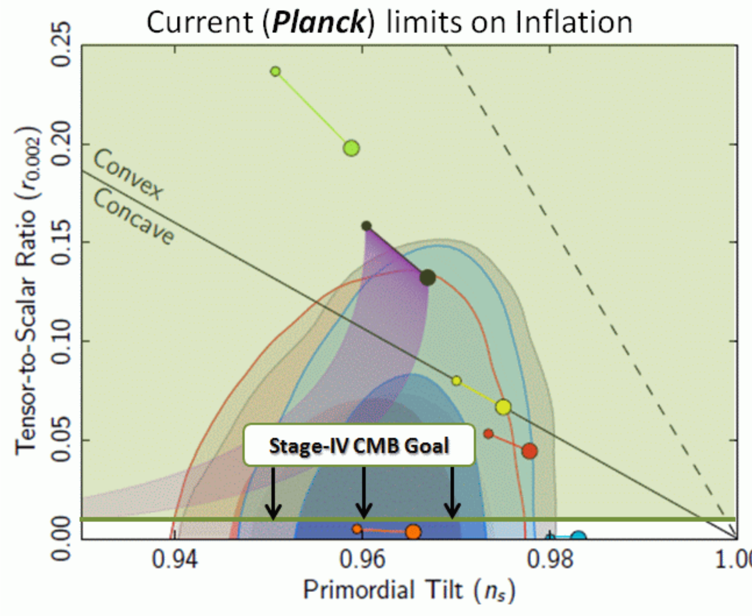
“Tensor” generates “B-mode” polarization in the CMB

- Measures the energy scale of Inflation, likely ~ 10^{16} GeV (grand unification)
- Unique probe of extreme high energy physics
- Evidence that gravity is quantized, if detected

- Inflation: nearly exponential growth of space (30 orders of magnitude)

Two related parameters: η, ε

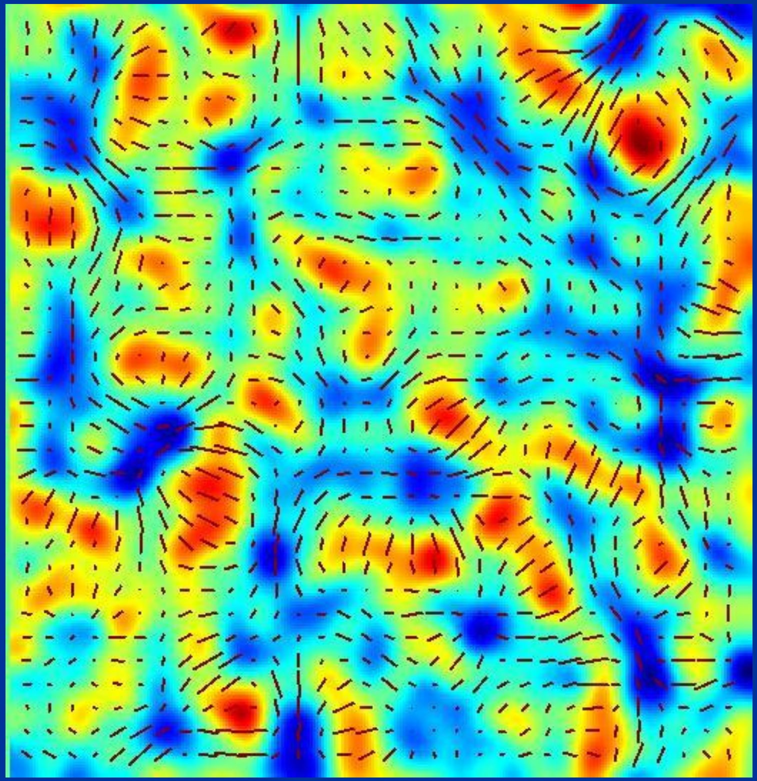
- $n_s = 1 - 4\varepsilon + 2\eta$ (<1 at 6σ !!)
- $r = 16\ \varepsilon$ (the goal)



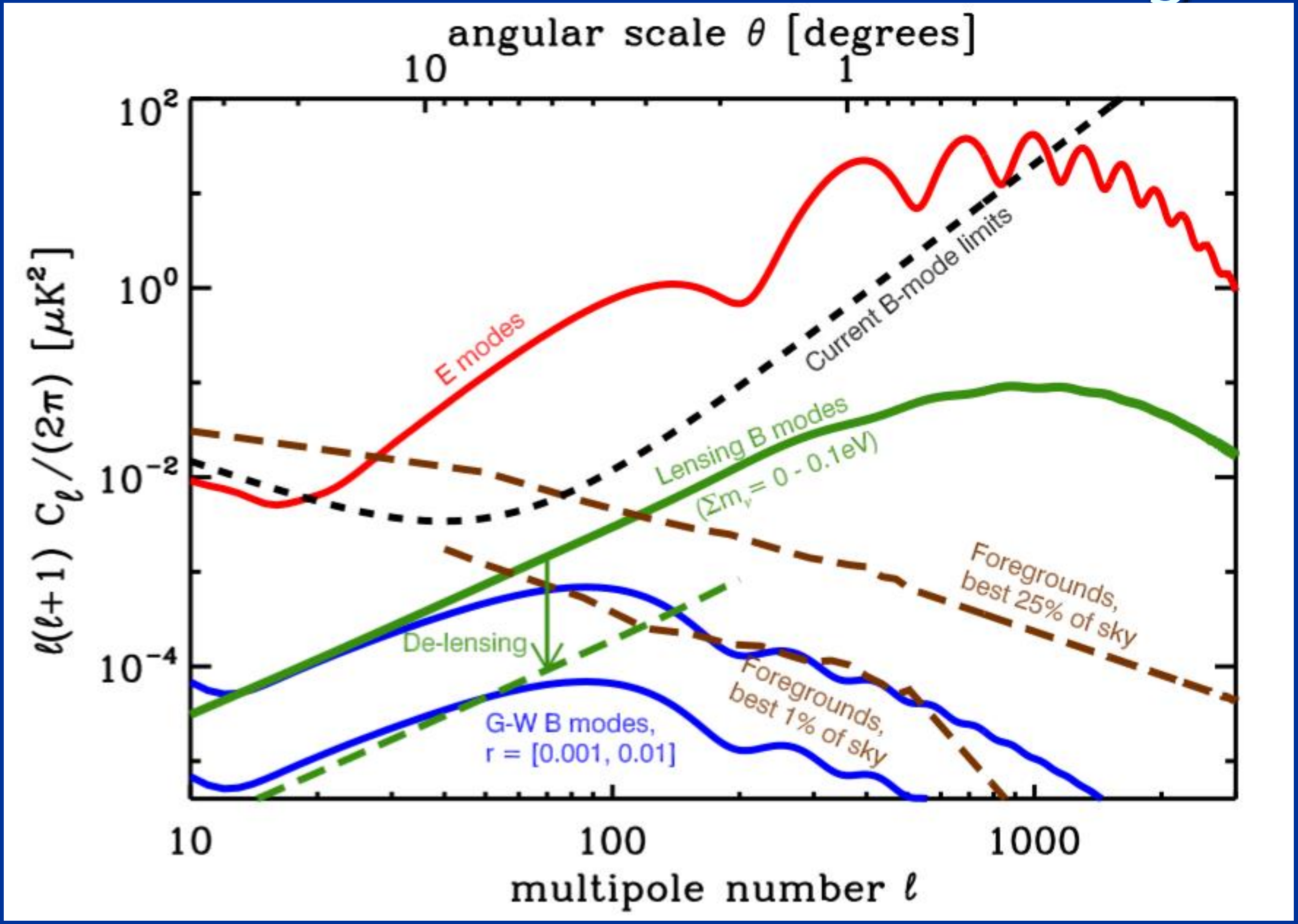
How big is the signal?

- CMB = 2.725 K blackbody (peaks at λ~1.5 mm)
- Temperature fluctuation ~ 100 μK
- Polarization ~ 10 μK
- B-mode polarization ~ ? μK
- [For ground based experiments]

  Atmosphere+telescope ~ 20 K
- Degree of polarization <10^{-7}



Gravitational Waves & Lensing



95% limits:

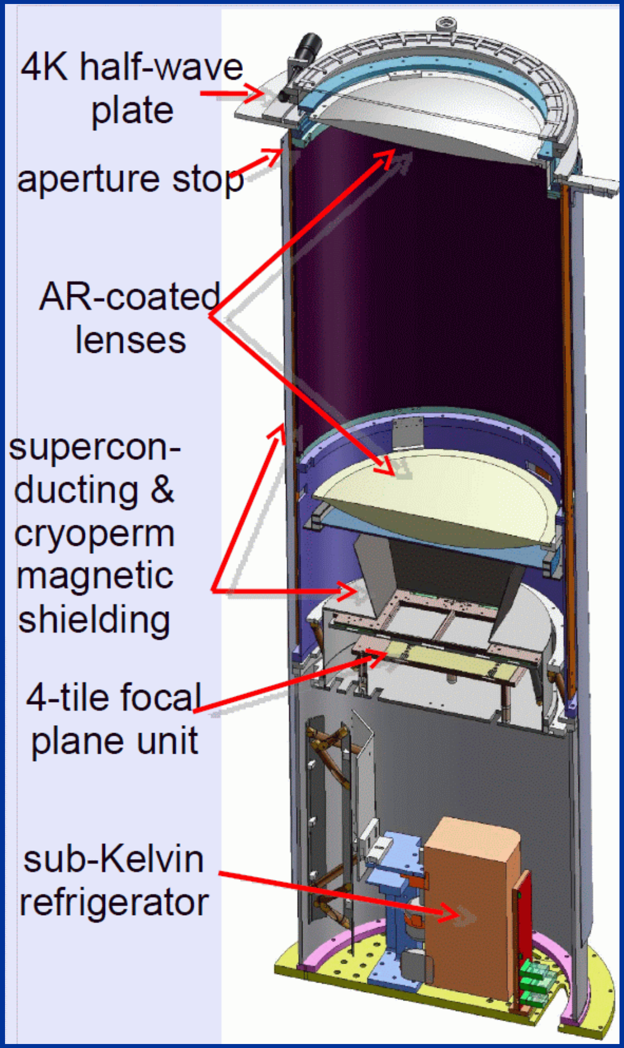
r< 0.72 BICEP '09

r< 2.2 QUIET '10

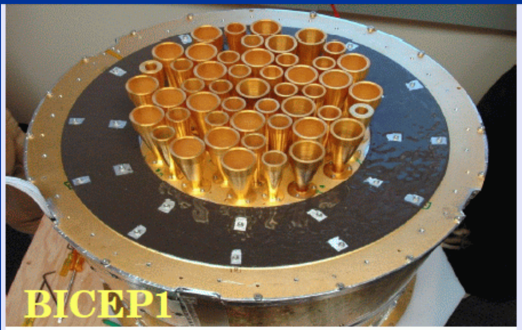
indirect limit (TT) r< 0.12 Planck+WMAP

+with more priors

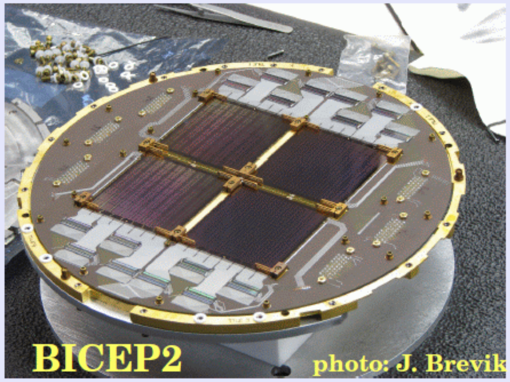
BICEP1/BICEP2/Keck Array (Caltech/Stanford/Harvard/UMN)



** All with small refractors (25cm) ; observing from the South Pole*
** Will likely reach T/S ~< 0.05 by 2013*



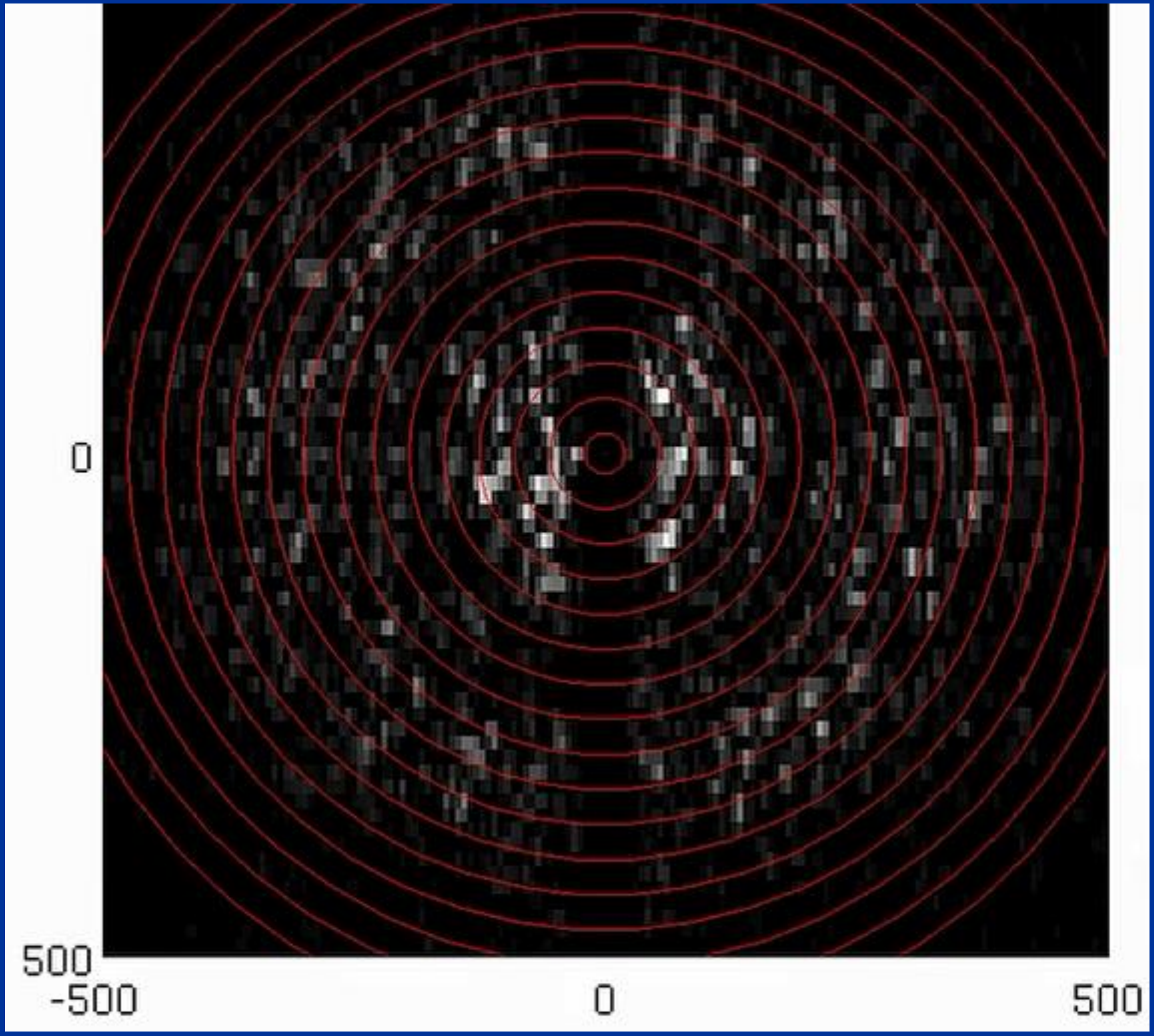
90/150GHz
25/24 elements
2005-2008
Best limit on B-mode



150GHz
256 elements
Taking data for 1yr
10x survey speed than BICEP1

150GHz
256x5 elements
Deployed in 2010/11
cryogen free Dewars

Integration



Cryogenic detectors in astronomy

- Operating temperature: 50 mK ~ 300 mK
- Very wide frequency coverage: cm through γ-ray
- Photon noise limited sensitivity down to cm-wave
- Photon counting capability for ν > far-IR
- *Spectrophotometric detector* for ν > optical
- Currently limited by pixel counts: ***multiplexing readout*** and large-scale fabrication processes needed

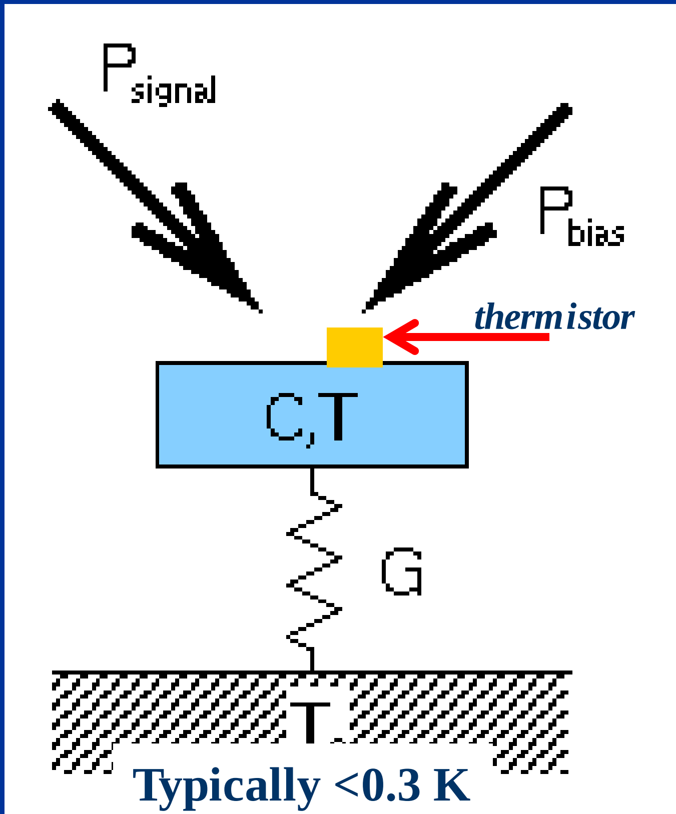
Heat detectors

- Bolometers:
  Superconducting (TES) &
  Semiconducting (NTD) detectors
- Hot electron bolometers (HEB)

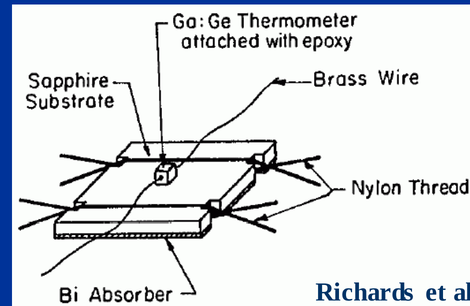
Photon direct detectors

- Superconducting tunnel junctions (STJ)
- Microwave kinetic inductance detectors (MKID)

Bolometric CMB detectors

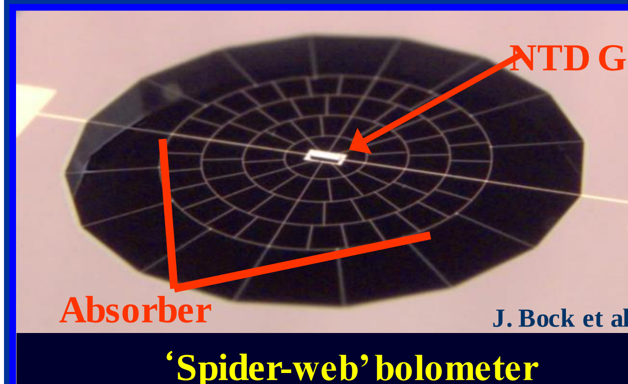


* *Bolometers: thermal photon detectors for far-IR through mm-wave*
* *Sensitivity determined by G, T*
* *Thermistor = semiconductor or superconductor (TES=Transition Edge Sensor)*

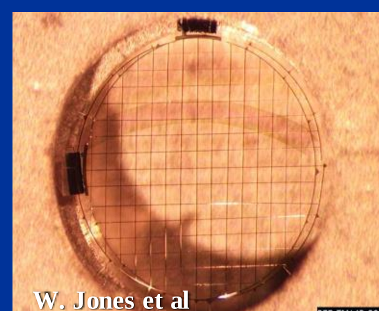


1980s

1990s

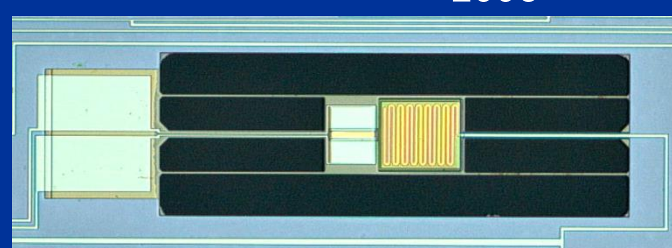


2000

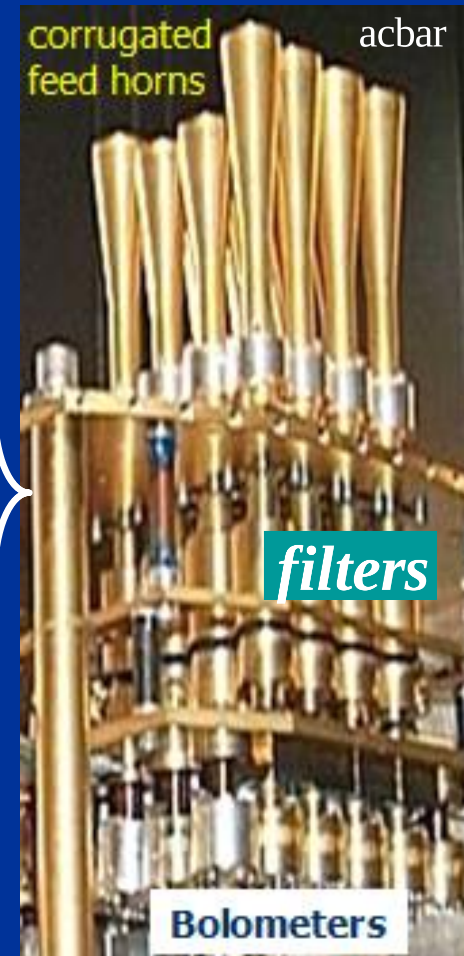


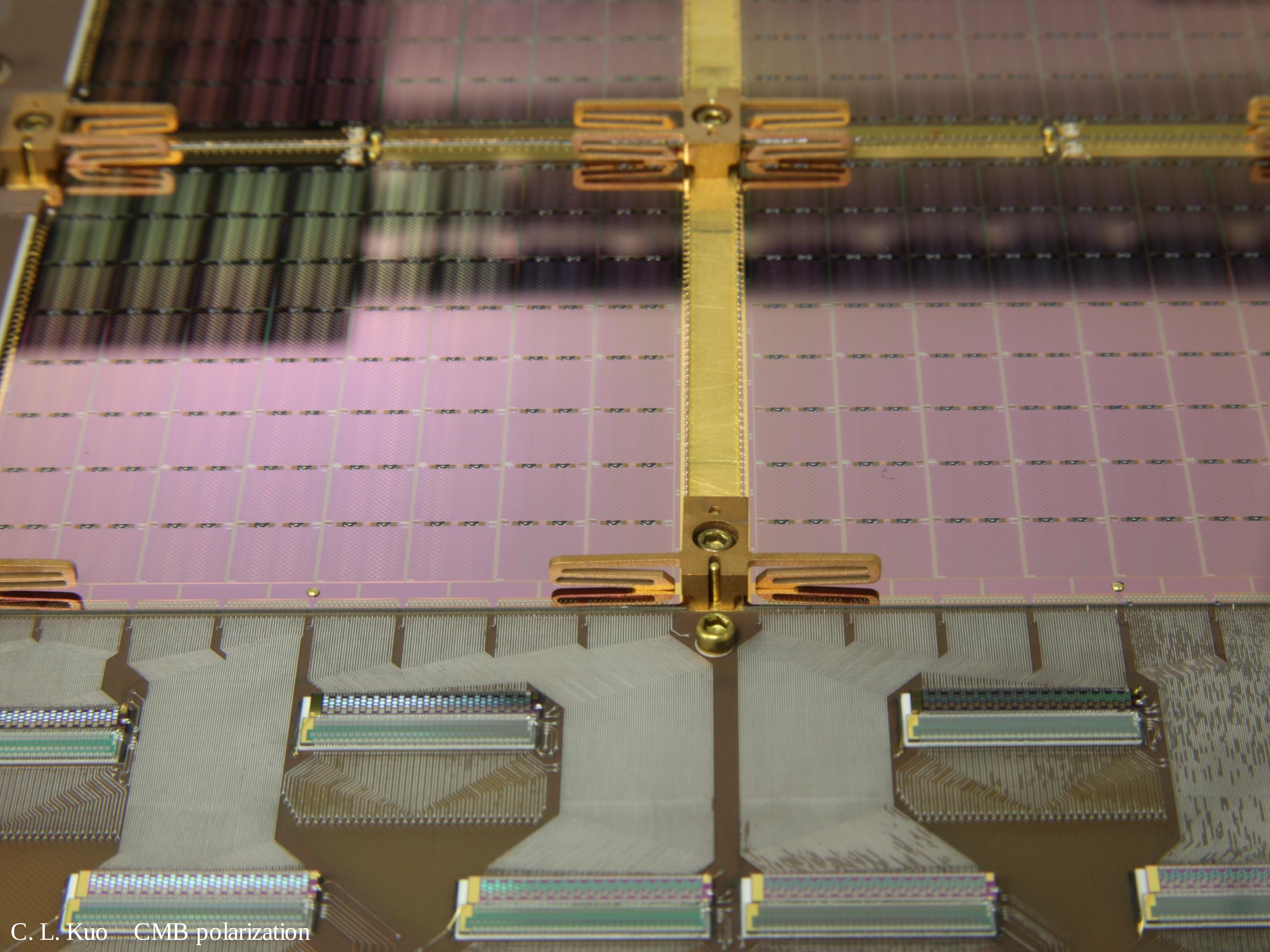
polarization sensitive bolometer

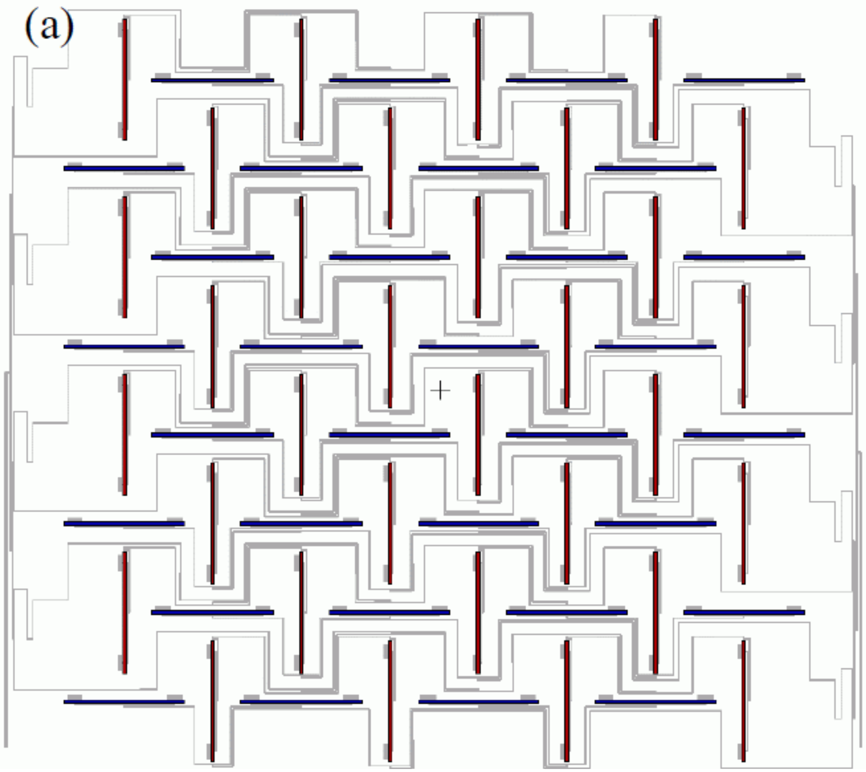
2006

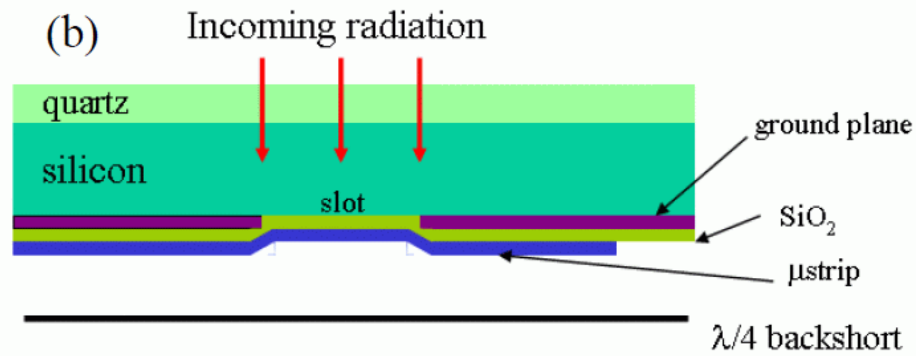


Microstrip-coupled TES bolometer Deposited Ti film

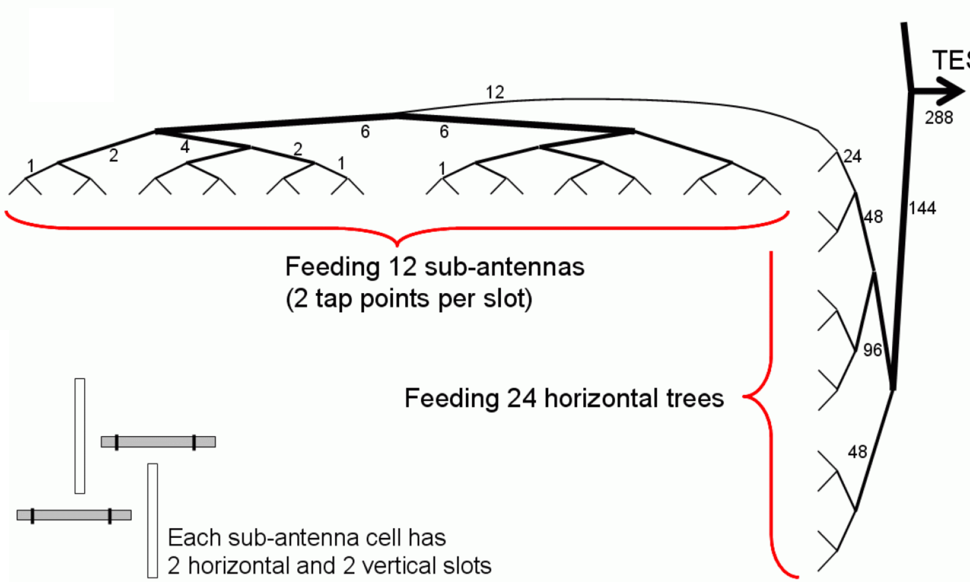


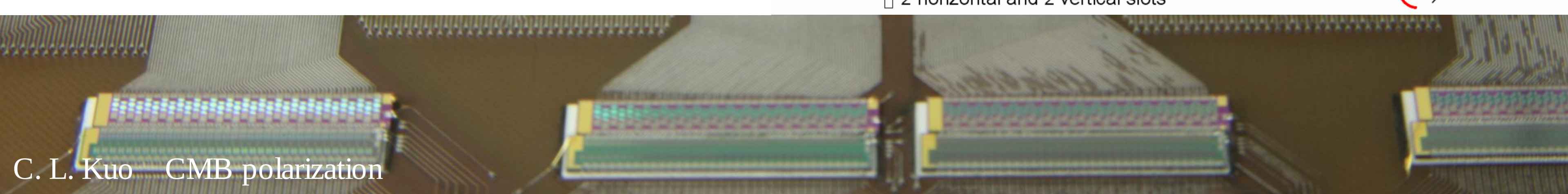






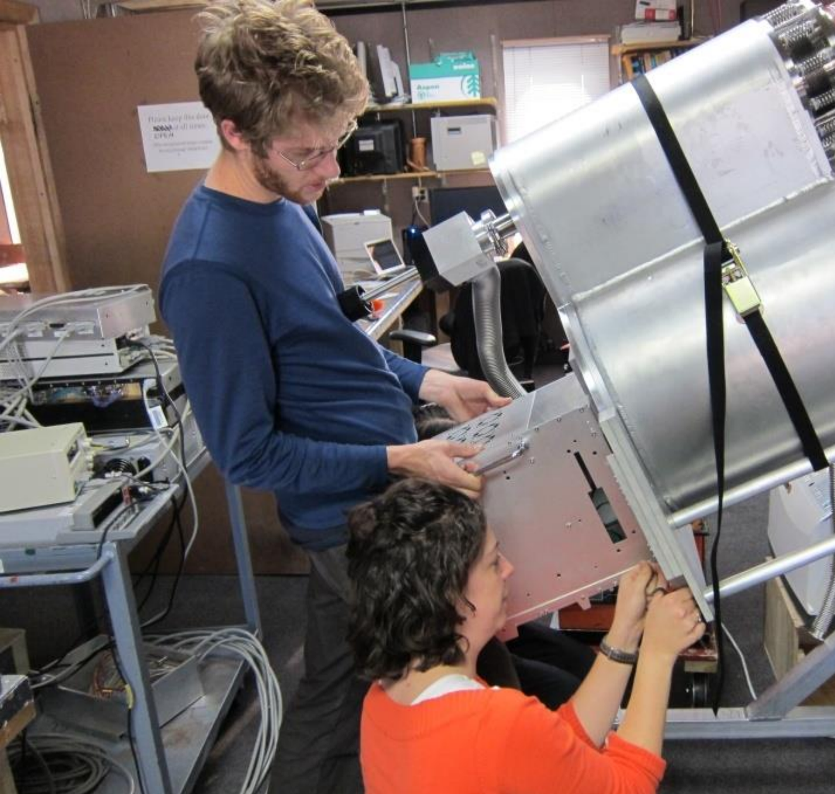
The summing network for one polarization

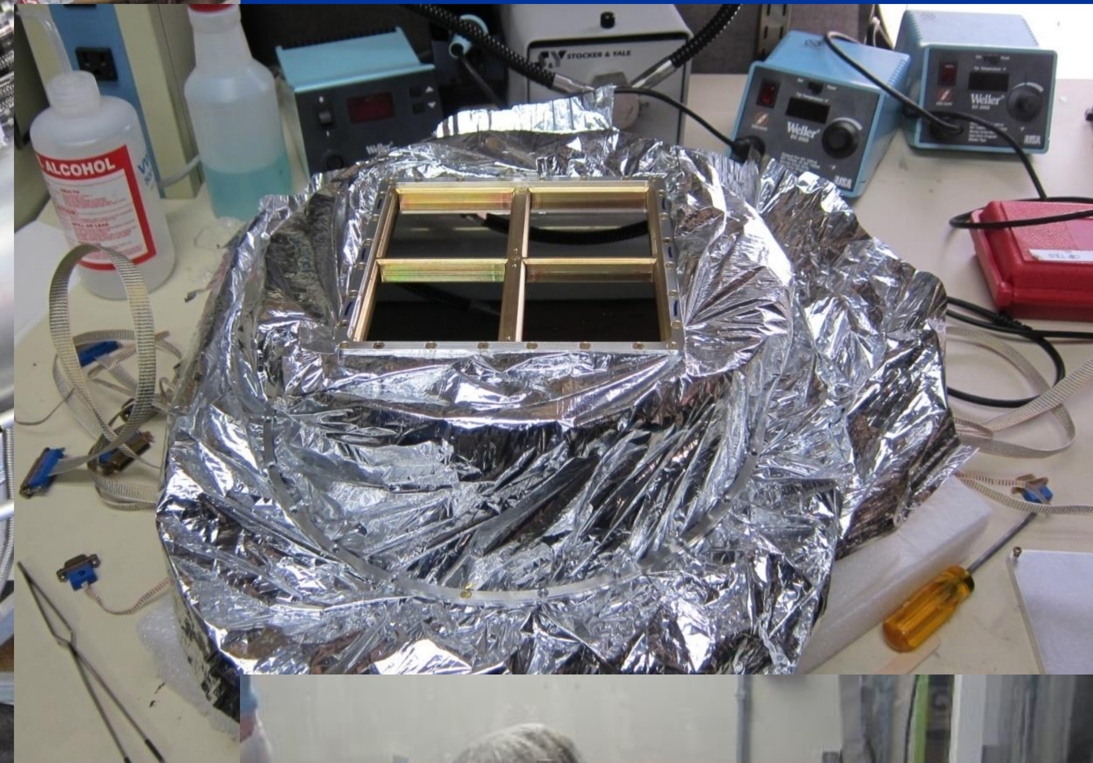


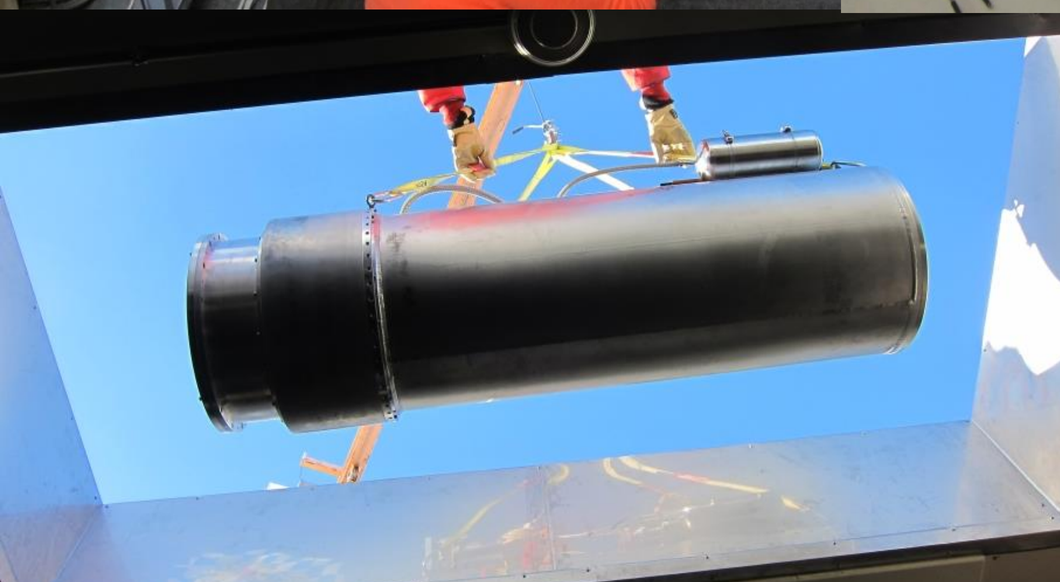


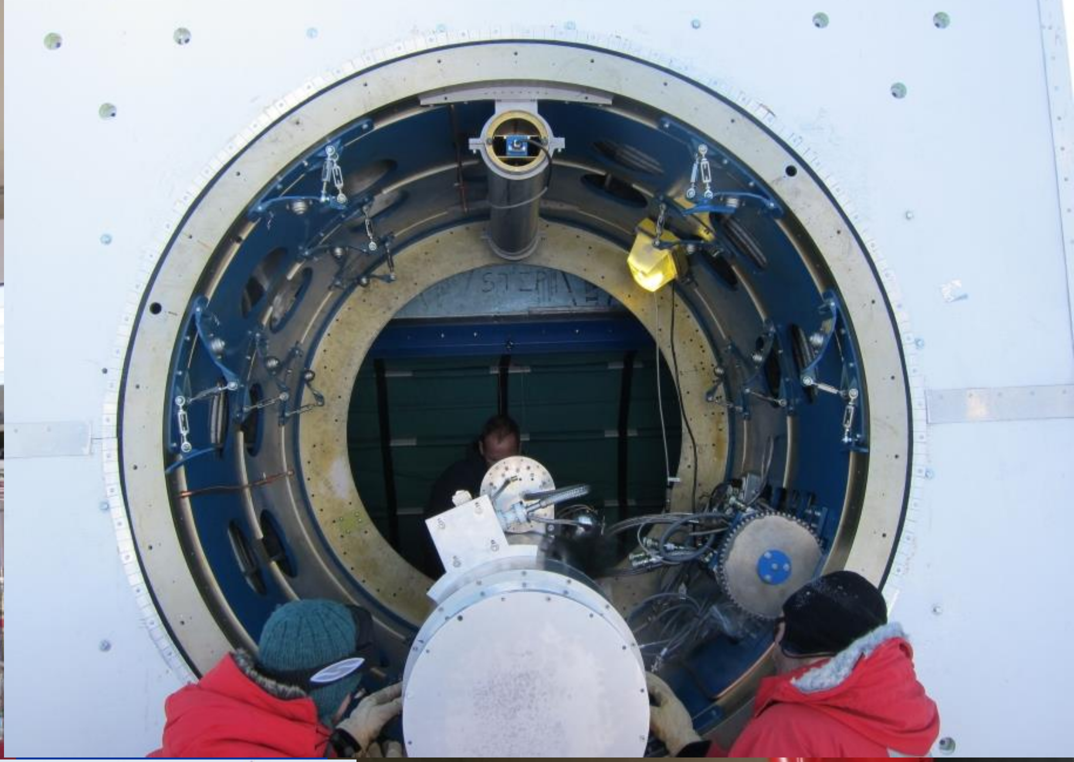
South Pole is an excellent site for CMB observation

- High elevation, low temperature → low water vapor
- Continuous observation for >9 months
- Excellent infrastructure/support (NSF-Office of POLAR Program)

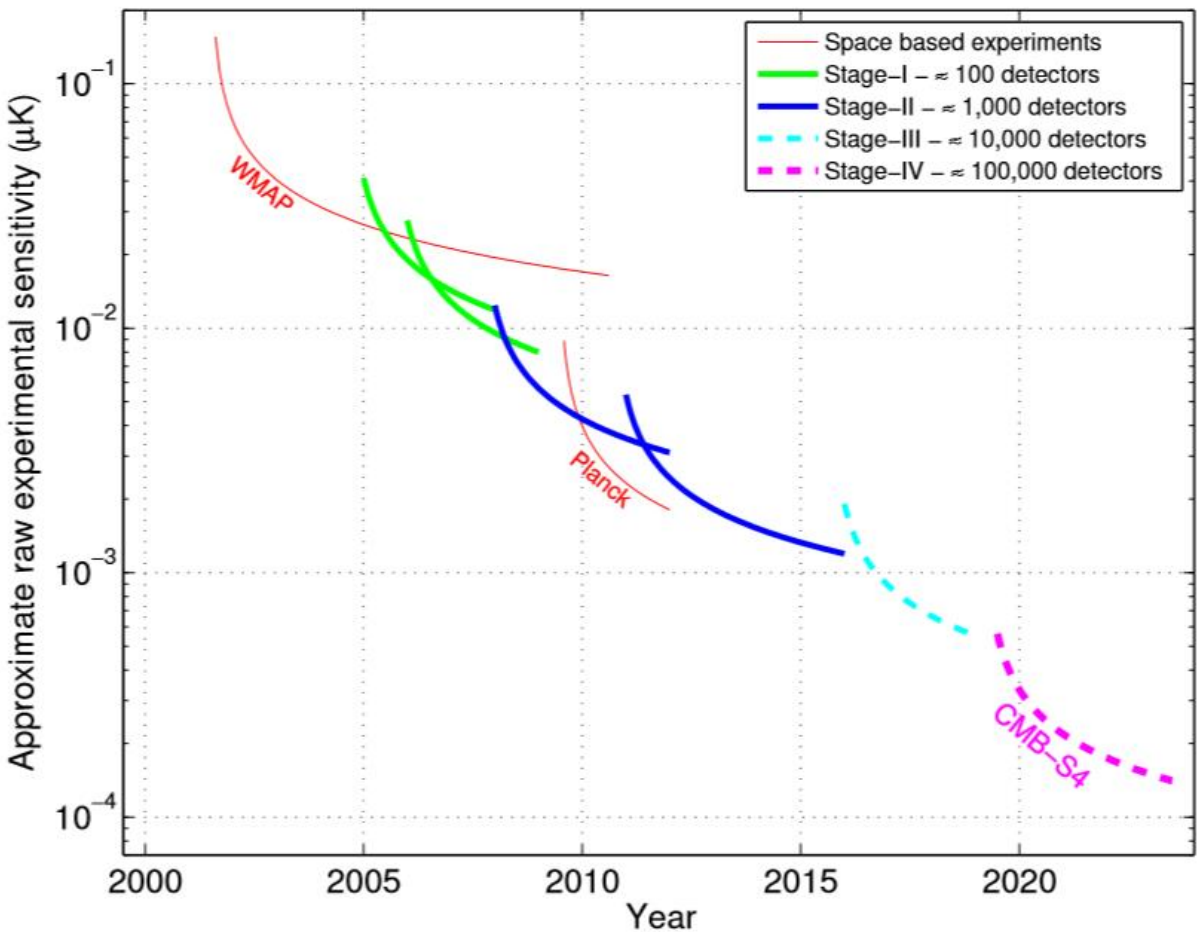



ALCOHOL
STOCKER & YALE
Weller

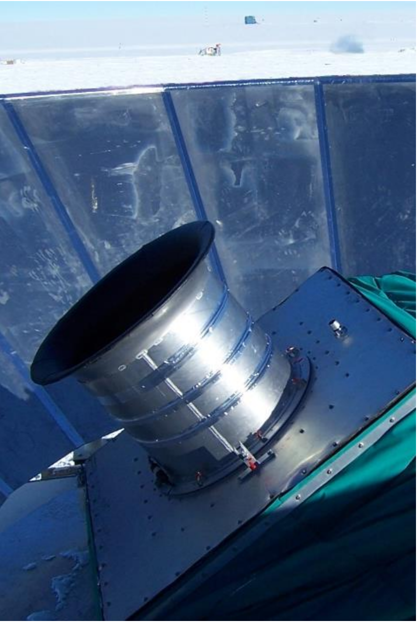


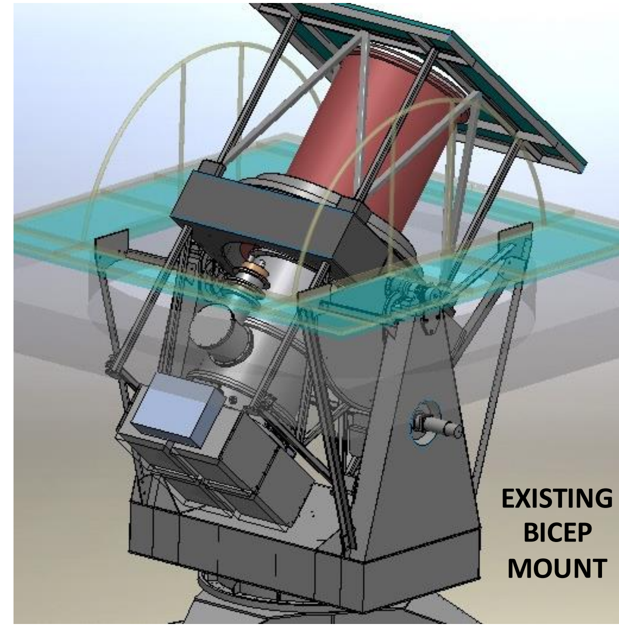


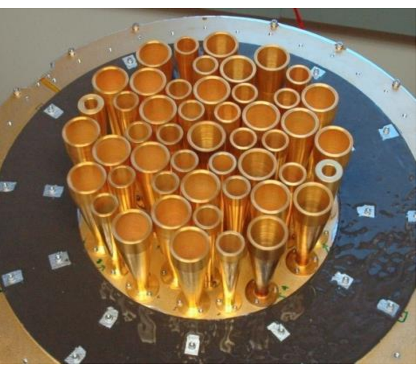
Experimental Progress

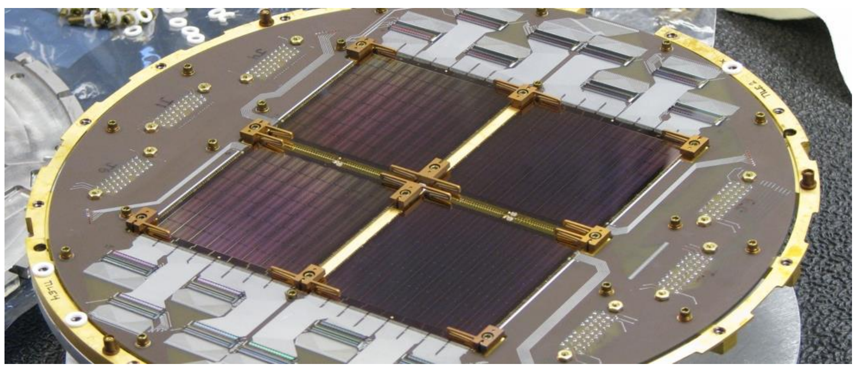


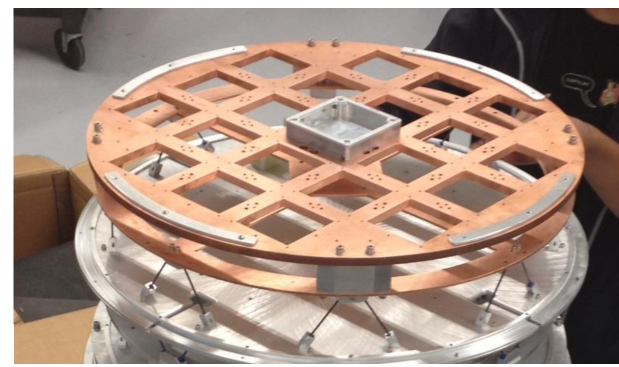
BICEP (2006–2008) | BICEP2 (2010–2012) | Keck (2011–) | **BICEP3 (2014-)**





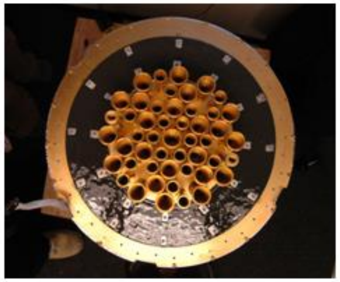


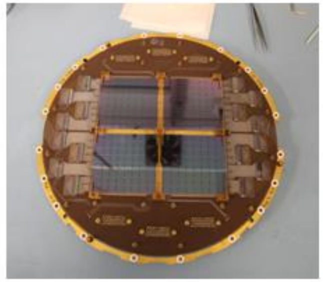


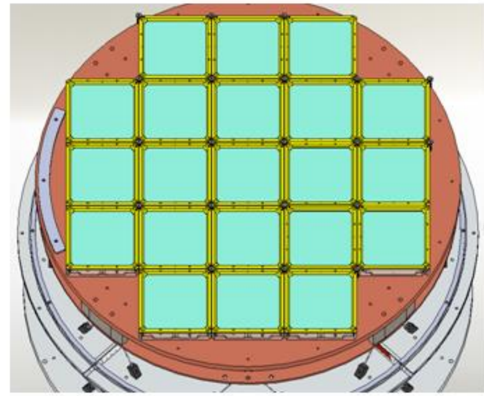


BICEP (2006–2008)	BICEP2 (2010–2012)	Keck (2011–)	BICEP3 (2014-)
98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)	**2560 TESs (95 GHz)**
0.93°/0.60° FWHM	0.52° FWHM		**0.37° FWHM**
18° FOV	17° FOV		**26° FOV**
44 m^2 deg^2 AΩ	44 m^2 deg^2 AΩ	222 m^2 deg^2 AΩ	**502 m^2 deg^2 AΩ optical throughput**

Large-scale instrumentation **at National Labs**







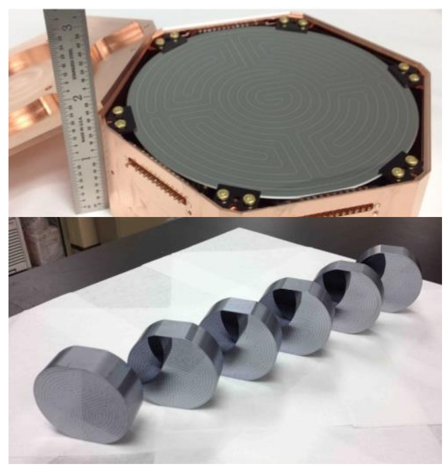
Stage-IV CMB
Duplicate (>10x)
Focal planes
(physical size limited by IR loading, size of vacuum window, lenses)

98 NTDs (95/150 GHz)	512 TESs (150 GHz) per F.P.	>4,000 TESs (150GHz) per F.P.

Fermi-LAT

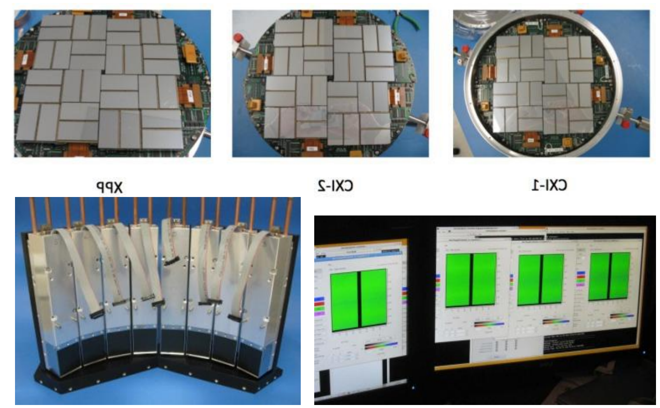
- 80 square meters of silicon sensors
- Silicon LAT assembled at SLAC

Super CDMS

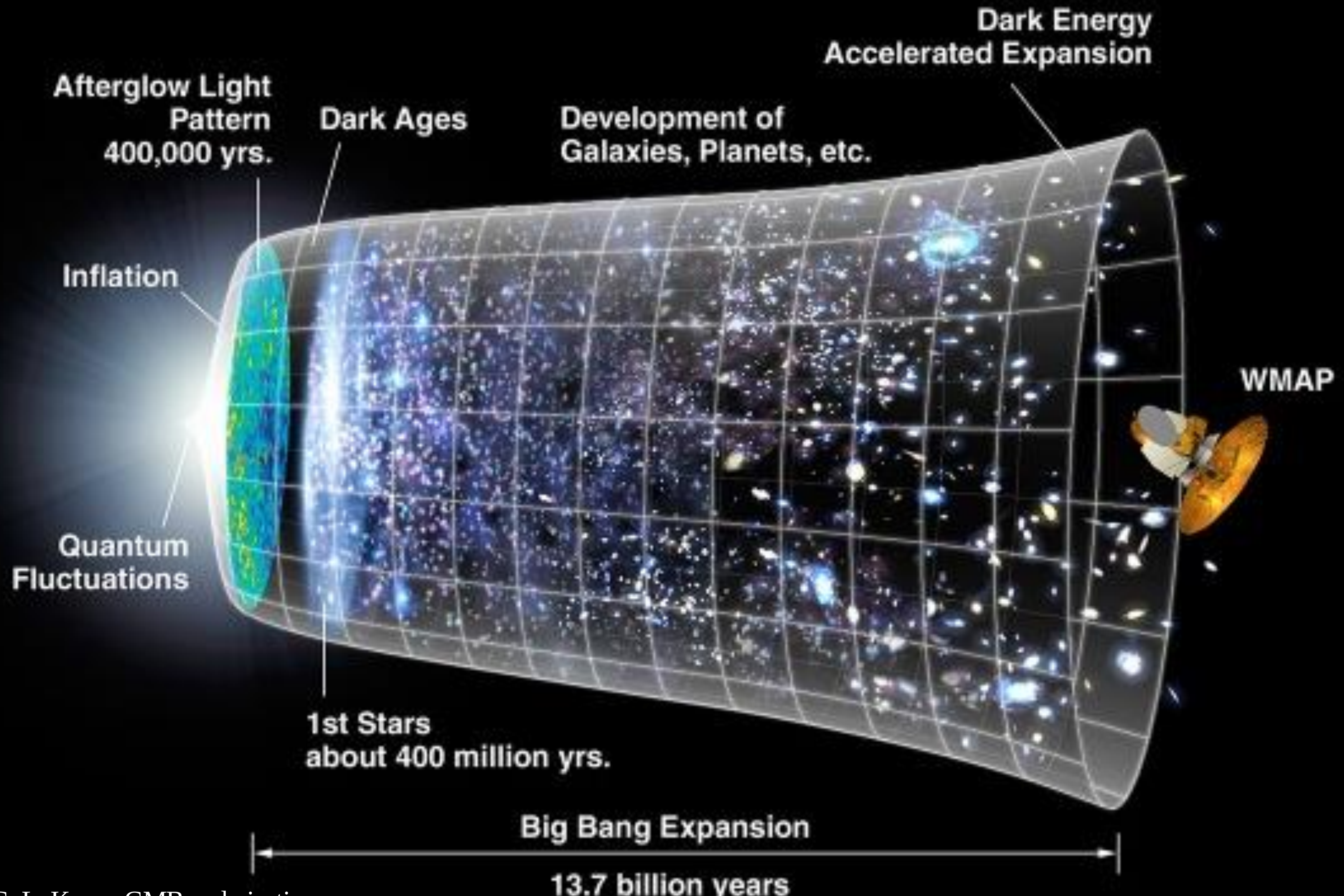


- Scaling up of Germanium sensors and fab throughput

LCLS Detectors

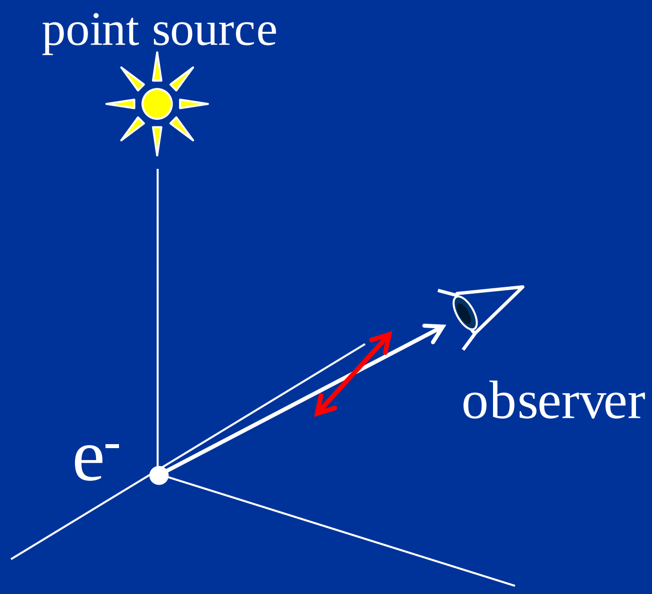


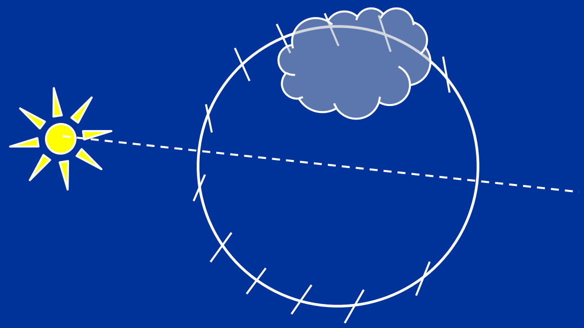
- R&D with Cornell Univ.
- SLAC made 10 million pixels in total so far via robotic assembly


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Lensing can generate B-mode

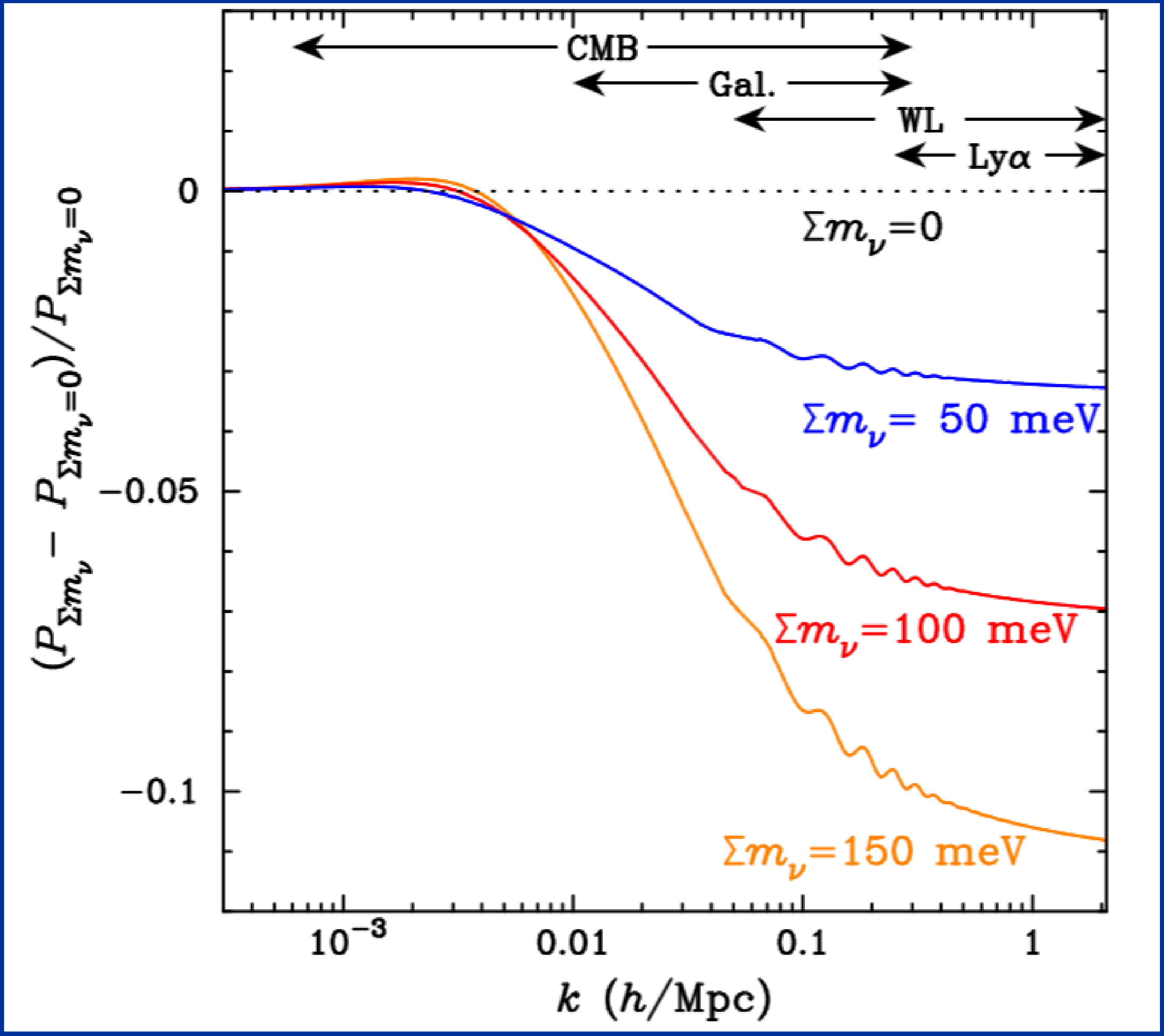
(Zaldarriaga & Seljak, 1999)



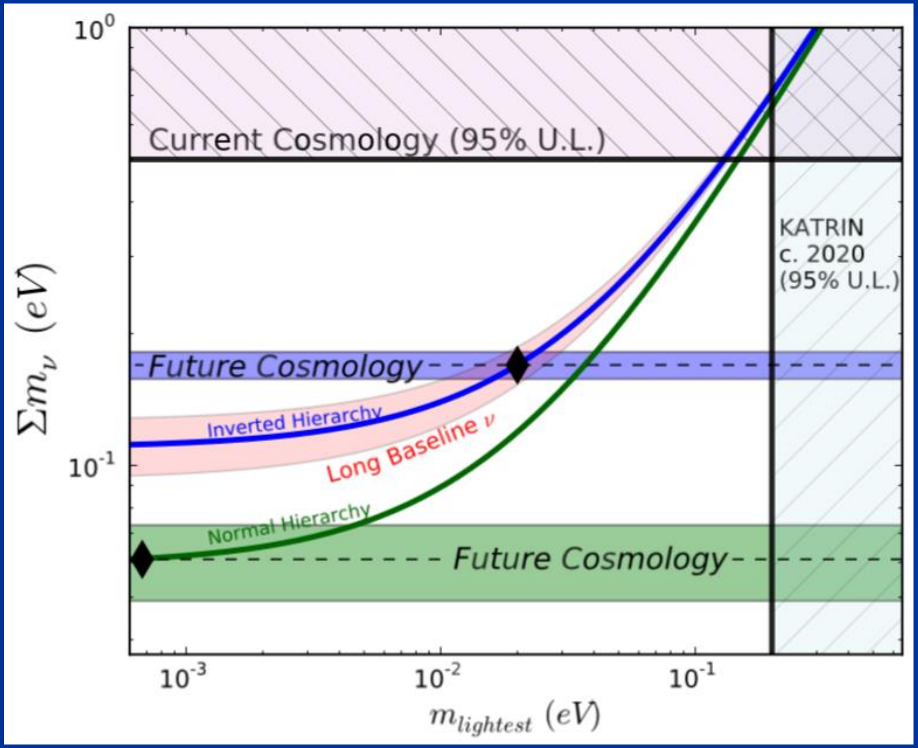


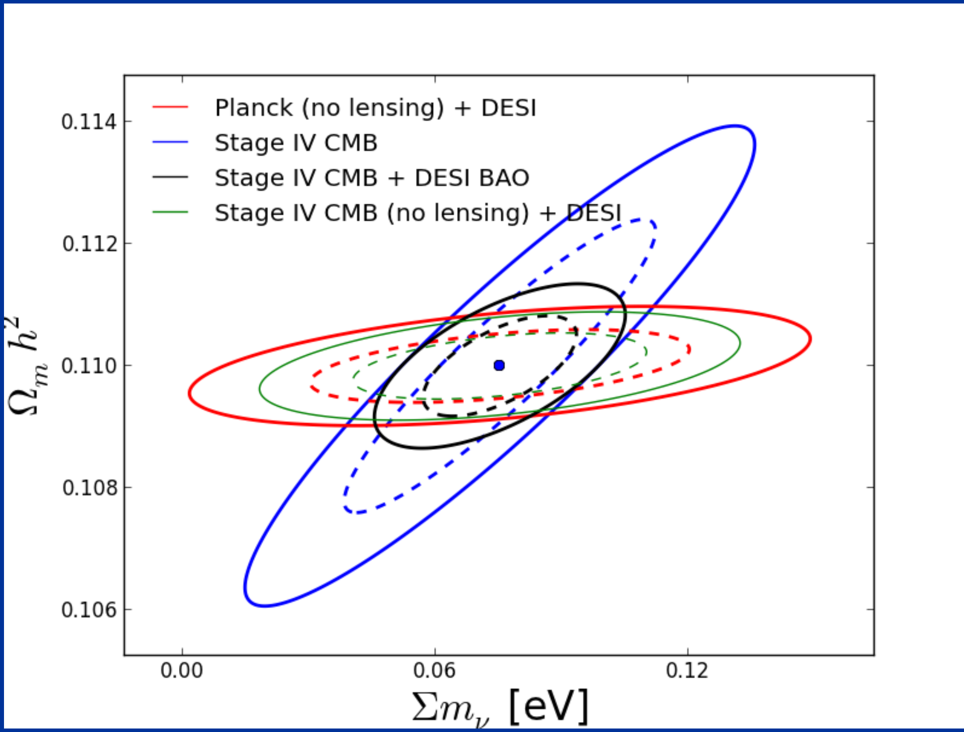
for an arbitrary circle
on the sky

Effects of neutrino mass



CMB Lensing as a neutrino exp.





Thank you !