The Search for Primordial Gravitational Waves

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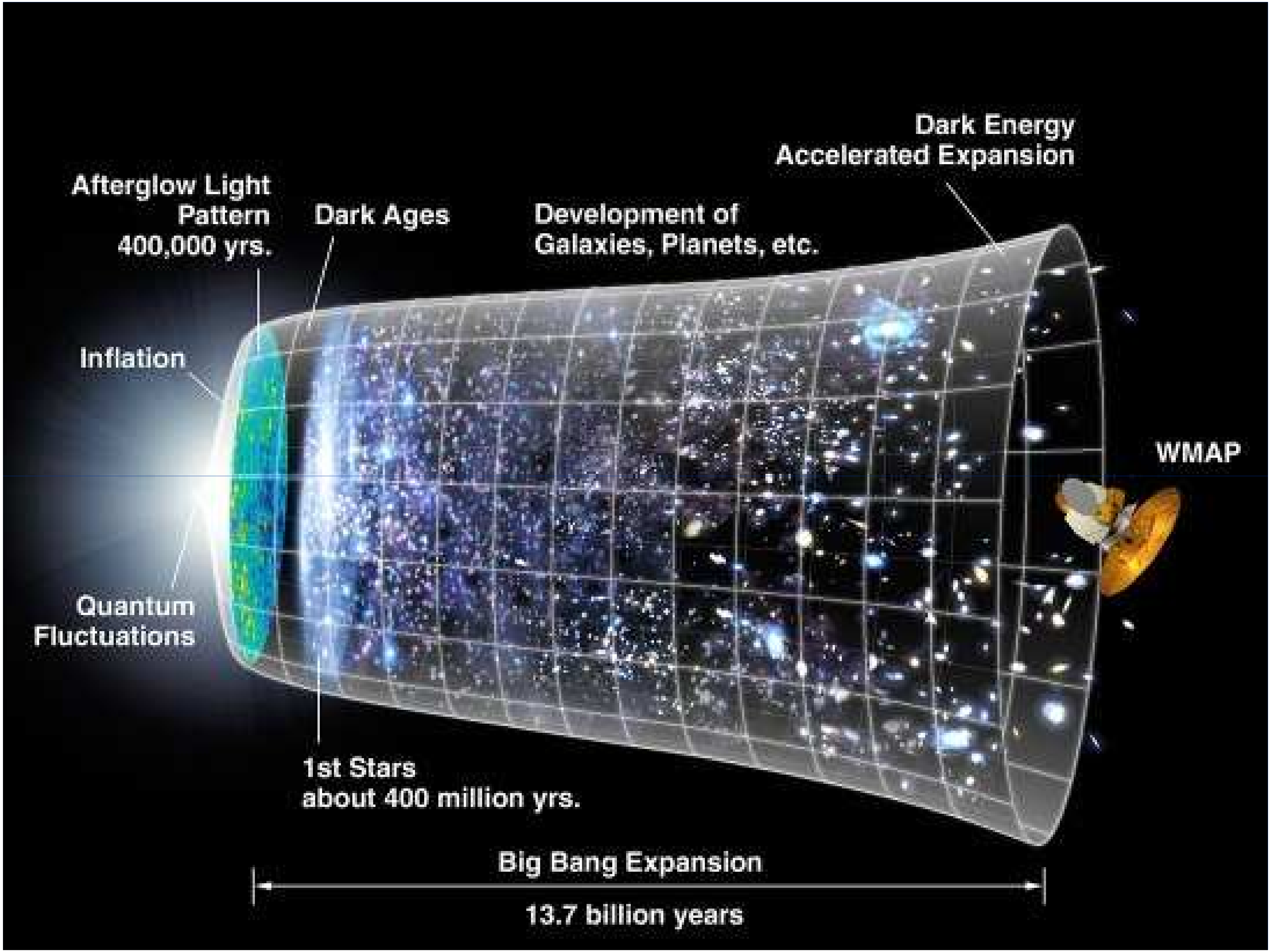
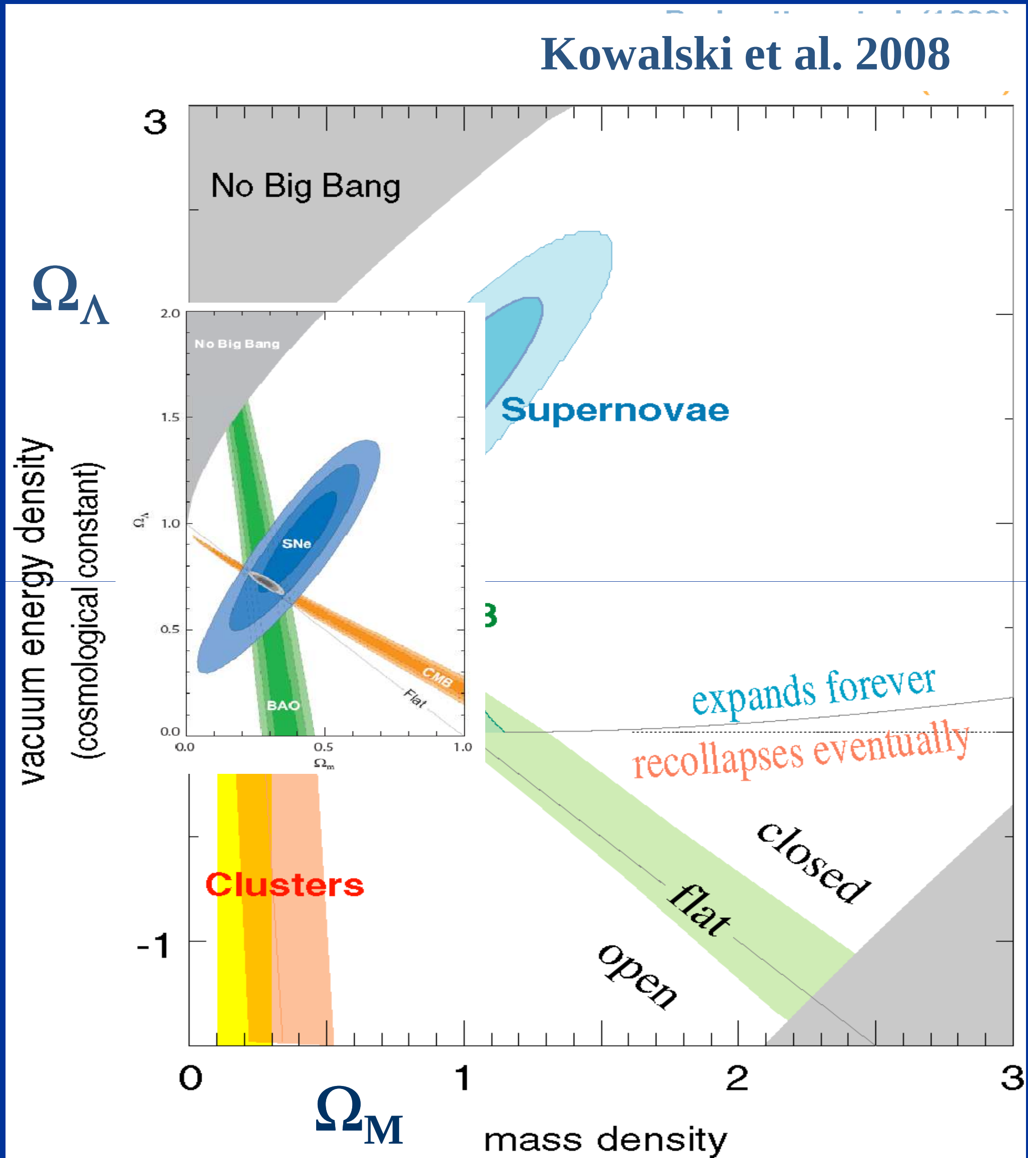

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

State of Cosmology

2000-2008



SN: $\Omega_M - \Omega_\Lambda/2$

CMB: $\Omega_M + \Omega_\Lambda$

LSS/Clusters: Ω_M

Flat geometry

Ω_M (dark matter) ~ 22%

Ω_B (baryon) ~ 4%

Ω_Λ (dark energy) ~ 74%

Cosmological parameters are well determined: what's next?

WMAP Cosmological Parameters

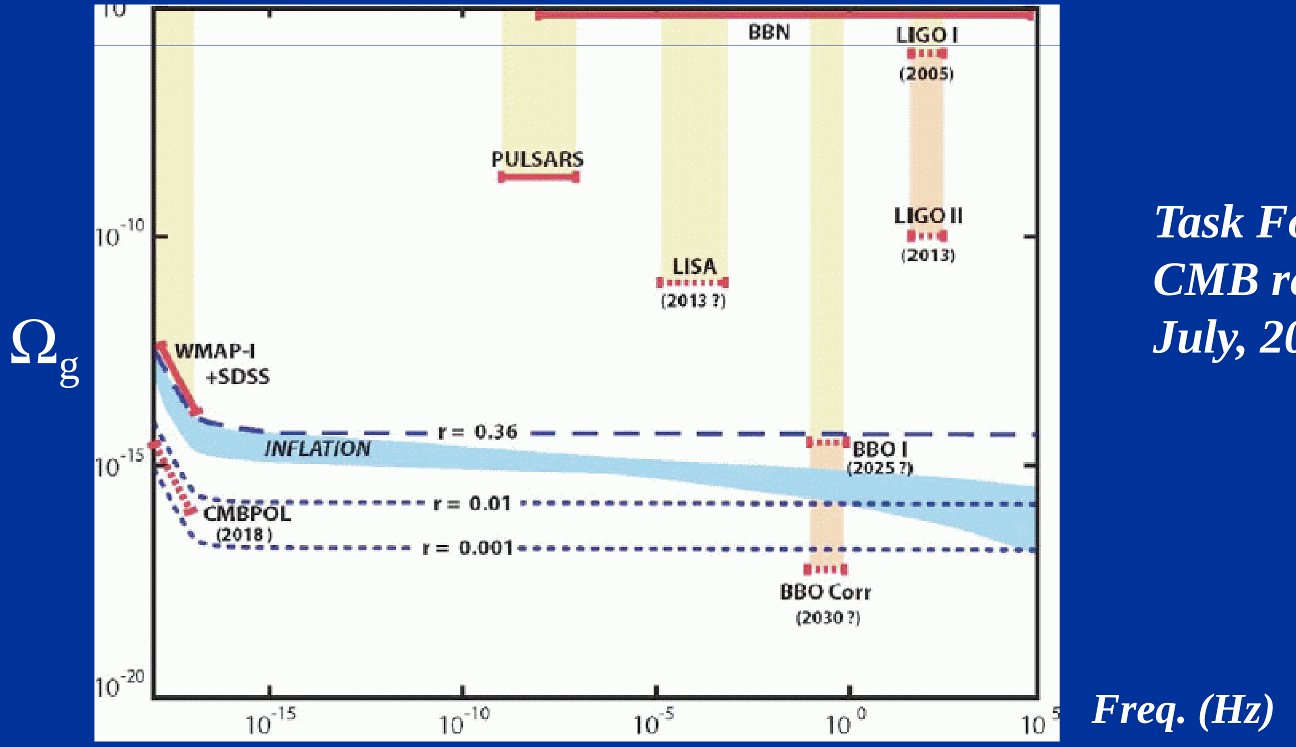
Model: lcdm+sz+lens+tens

Data: wmap7

$10^2\Omega_b h^2$	$2.313^{+0.073}_{-0.072}$	$1-n_s$	$0.018^{+0.019}_{-0.020}$
$1-n_s$	$-0.025 < 1-n_s < 0.054$ (95% CL)	$A_{\rm BAO}(z=0.35)$	0.445 ± 0.024
C_{220}	5766 ± 40	$d_A(z_{\rm eq})$	14329^{+164}_{-162} Mpc
$d_A(z_*)$	14166^{+166}_{-164} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.28 \pm 0.15) \times 10^{-9}$
h	0.735 ± 0.032	H_0	73.5 ± 3.2 km/s/Mpc
$k_{\rm eq}$	0.00949 ± 0.00044	$\ell_{\rm eq}$	$134.3^{+4.8}_{-4.9}$
ℓ_*	$302.08^{+0.84}_{-0.83}$	n_s	$0.982^{+0.020}_{-0.019}$
Ω_b	0.0430 ± 0.0030	$\Omega_b h^2$	$0.02313^{+0.00073}_{-0.00072}$
Ω_c	0.200 ± 0.028	$\Omega_c h^2$	$0.1068^{+0.0062}_{-0.0063}$
Ω_Λ	0.757 ± 0.031	Ω_m	0.243 ± 0.031
$\Omega_m h^2$	0.1299 ± 0.0060	r	< 0.36 (95% CL)
$r_{\rm hor}(z_{\rm dec})$	287.5 ± 3.4 Mpc	$r_s(z_d)$	153.8 ± 1.7 Mpc
$r_s(z_d)/D_v(z=0.2)$	$0.1988^{+0.0091}_{-0.0089}$	$r_s(z_d)/D_v(z=0.35)$	$0.1188^{+0.0048}_{-0.0047}$
$r_s(z_*)$	147.3 ± 1.6 Mpc	R	1.702 ± 0.023
σ_8	0.787 ± 0.033	A_{SZ}	$1.01^{+0.65}_{-0.67}$
t_0	13.63 ± 0.16 Gyr	τ	0.091 ± 0.015
θ_*	0.010400 ± 0.000029	θ_*	$0.5959 \pm 0.0016\ ^\circ$
t_*	382941^{+5977}_{-5905} yr	$z_{\rm dec}$	1087.3 ± 1.3
z_d	1021.1 ± 1.5	$z_{\rm eq}$	3112^{+143}_{-145}
$z_{\rm reion}$	10.5 ± 1.2	z_*	1089.8 ± 1.2

Primordial Gravitational Waves: Tool for studying Inflation

- Perhaps the *only* way to see through the opaque wall of the CMB.
- The Inflationary energy scale (~10^{16} GeV) is too large to be studied by particle colliders.
- Other predictions by Inflation, such as Gaussianity, ~scale-invariance, and adiabatic perturbations, have been verified very accurately
- The radiation mechanism: quantum field effect near the horizon (similar to the Hawking radiation) – a Bona fide quantum gravity effect!



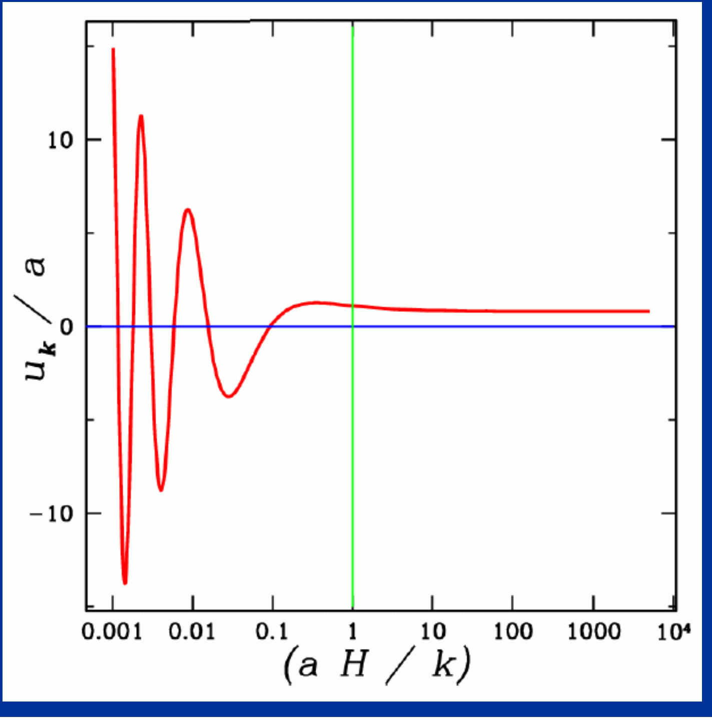
Task Force on CMB research July, 2006

Generation of Perturbations

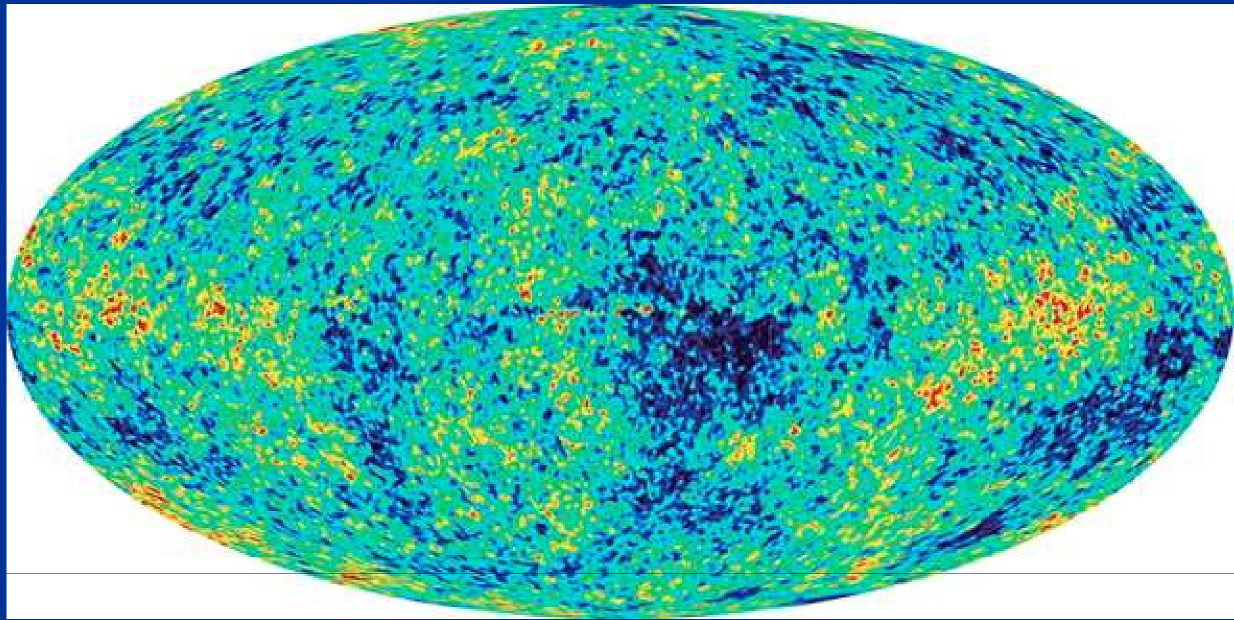
- QFT in curved spacetime (during Inflation)
- Same mechanism for scalar and tensor perturbations
- Two interesting regimes: deep inside the horizon (vacuum fluctuations) and superhorizon (frozen)

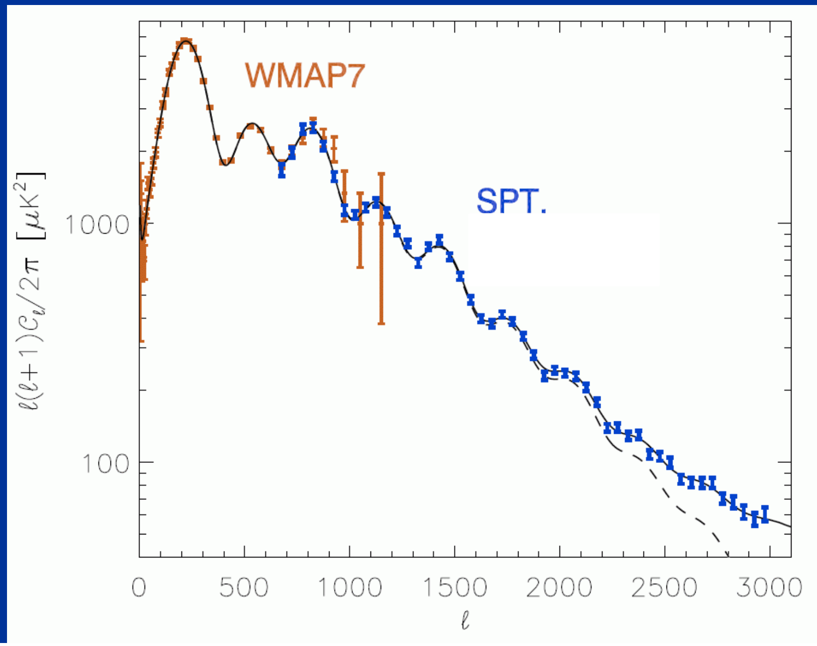
$$\mathcal{R}_q = \frac{\left(-\frac{\boldsymbol{H}}{\dot{\boldsymbol{\varphi}}}\right)\cdot\sqrt{-\pi\tau}}{2(2\pi)^{\frac{3}{2}}a(t)}\, e^{i\pi\left(\frac{\nu}{2}+\frac{1}{4}\right)} H_\nu^{(1)}(-q\tau)$$

$$\mathcal{D}_q = \frac{\sqrt{\boldsymbol{16\pi G}}\cdot\sqrt{-\pi\tau}}{2(2\pi)^{\frac{3}{2}}a(t)}\, e^{i\pi\left(\frac{\mu}{2}+\frac{1}{4}\right)} H_\mu^{(1)}(-q\tau)$$



Cosmic Microwave Background





The *intrinsic* significance of the CMB

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

CMB observational milestones

- Accidental discovery: Penzias and Wilson, 1965,
  recognized to be "cosmic" by R. Dicke
- The detection of dipole anisotropy (1970s)
- COBE/FIRAS measures its spectrum to be a blackbody (1990)
- COBE/DMR discovered anisotropy (1992)
- Boomerang discovered that the universe is flat (2000)
  (a result later confirmed by MAXIMA and DASI)
- DASI discovered polarization (2002)
- *???* discovers the imprints from gravitational waves (20xx)

Causal seeds versus acausal seeds

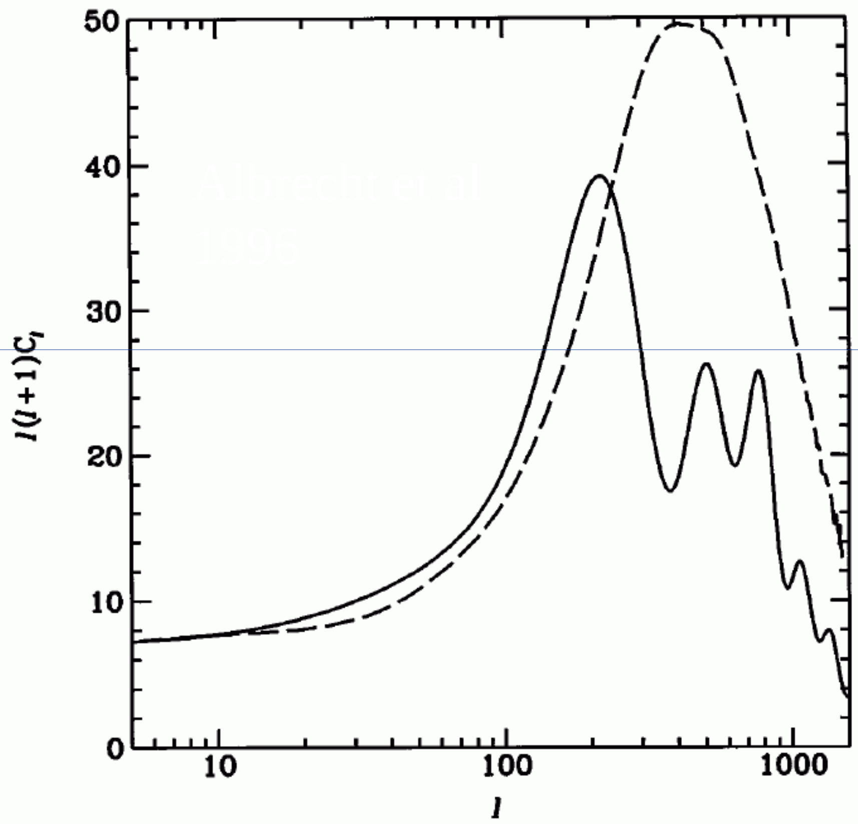
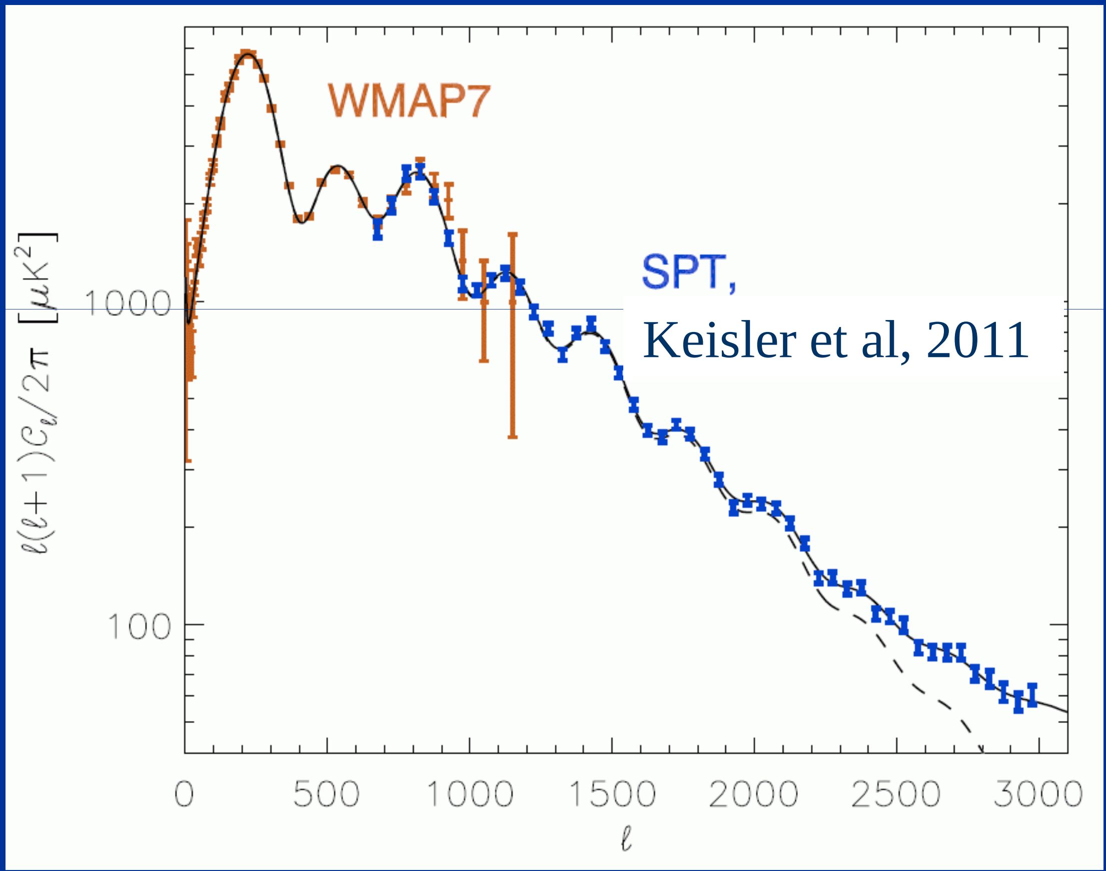


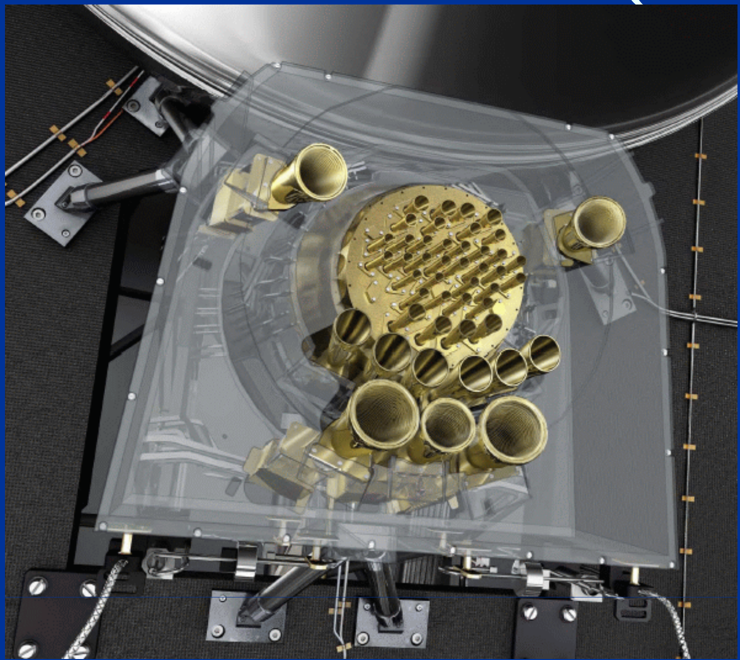
FIG. 4. Angular power spectrum of temperature fluctuations generated by cosmic strings (dashed) and arising from a typical model of scale invariant primordial fluctuations (solid) in arbitrary units. The all-sky temperature maps are decomposed

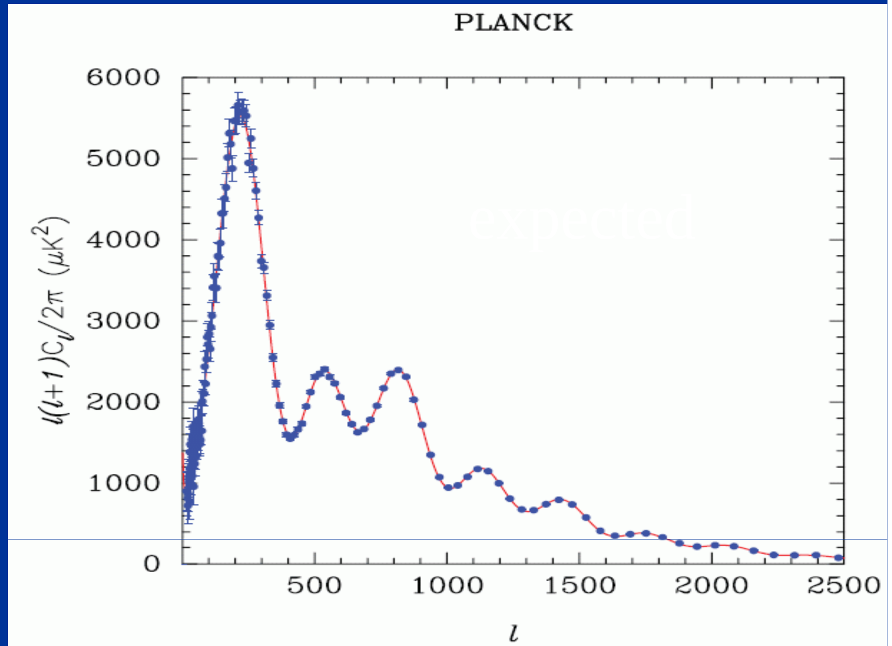
- Acausal perturbations are sometimes known as coherent perturbations
- Although, this does not mean there is any spatial phase relation between different Fourier modes
- Incoherently generated perturbations, such as those by defects (strings etc.) cause a single broad peak in the CMB power spectrum

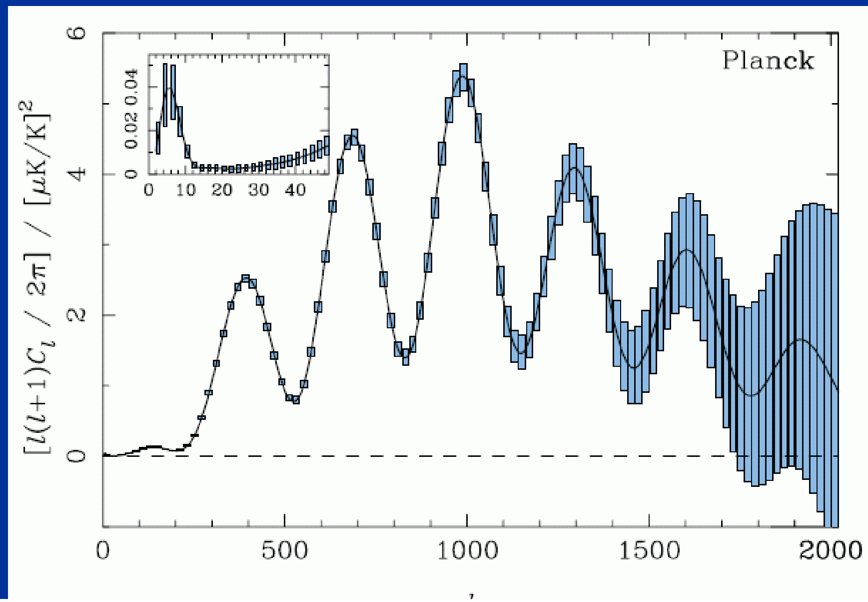
CMB temperature power spectrum, as of December 2011



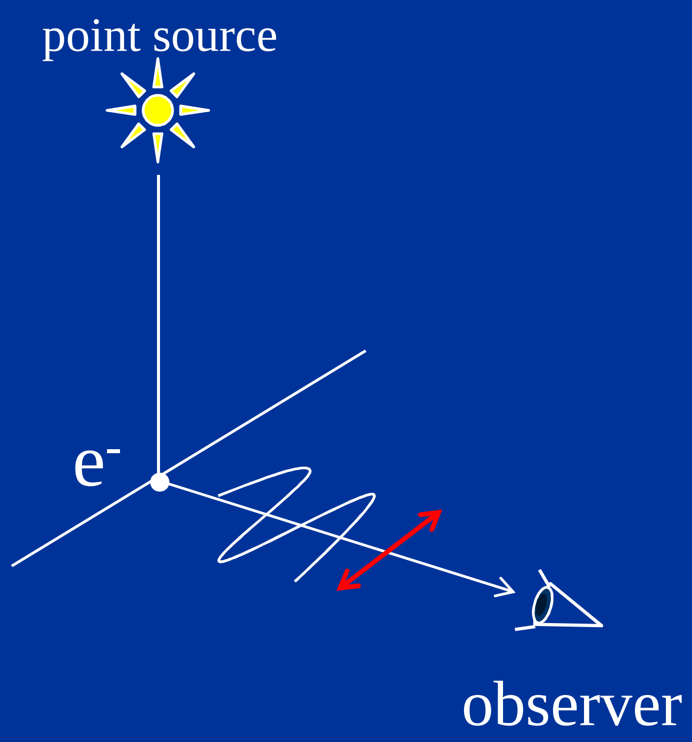
Planck (launched in May 2009)







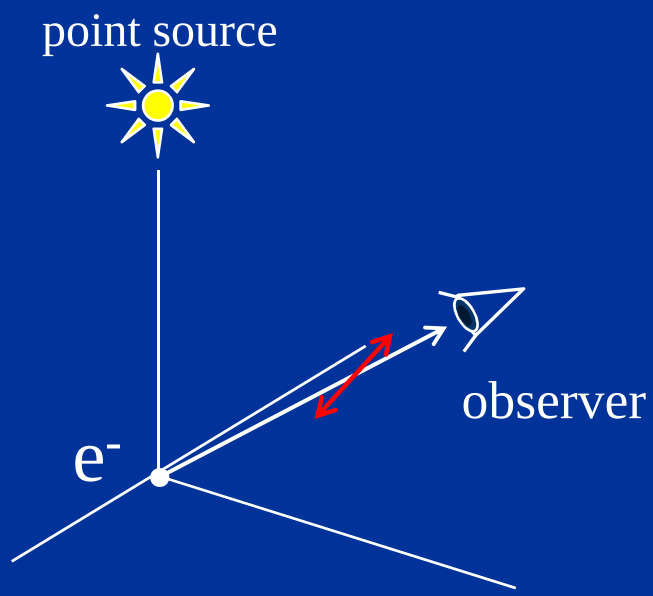
CMB is polarized. Why?



- 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)



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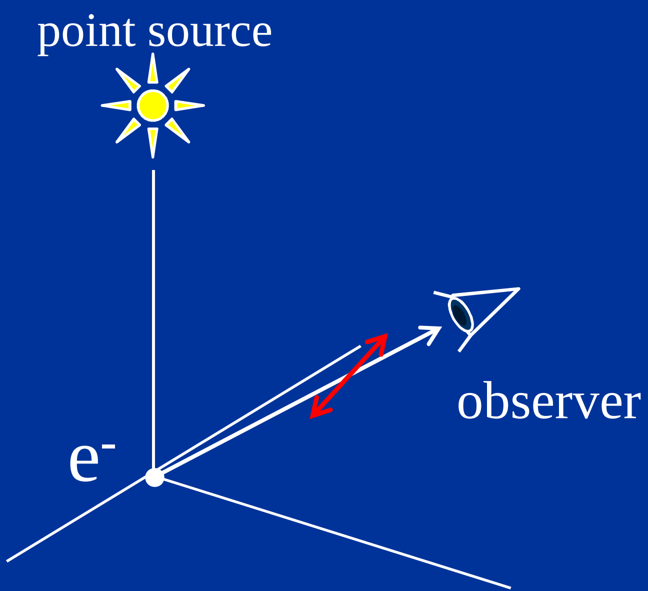

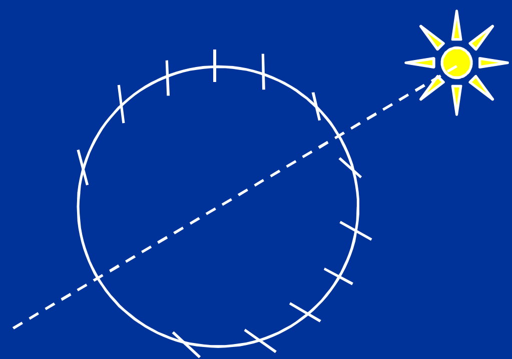

for an arbitrary circle
on the sky

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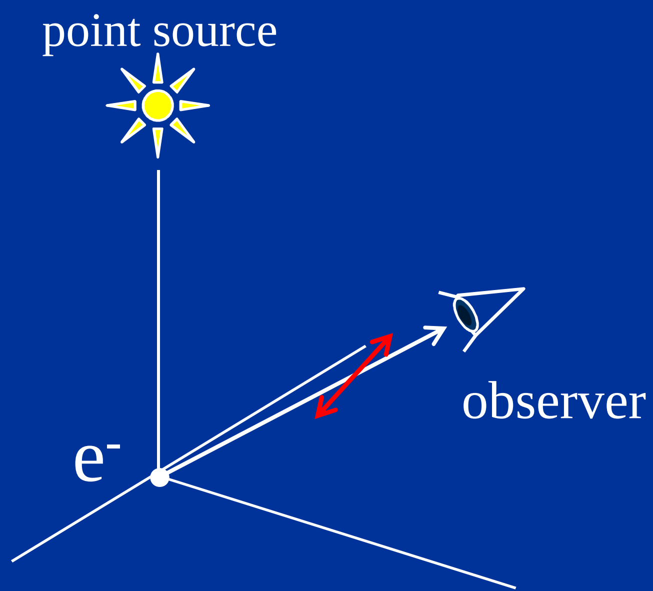

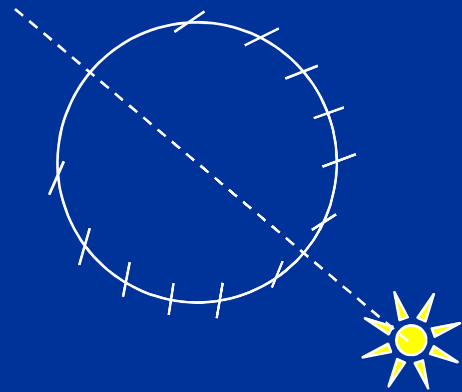

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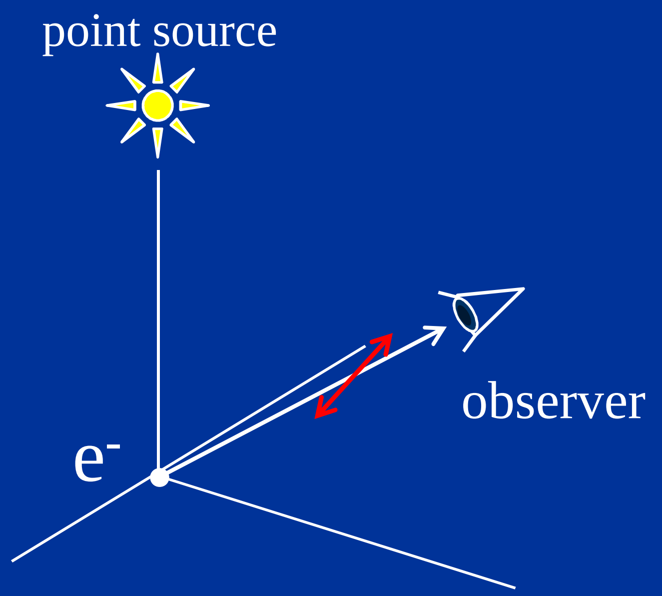
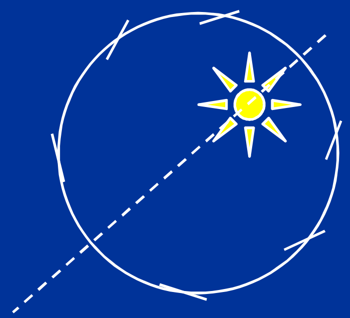


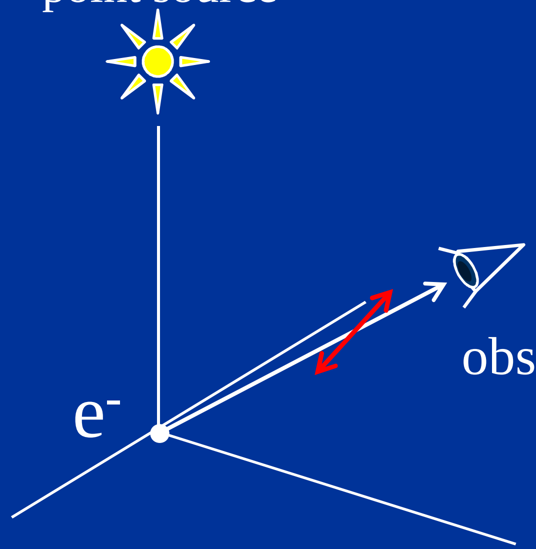


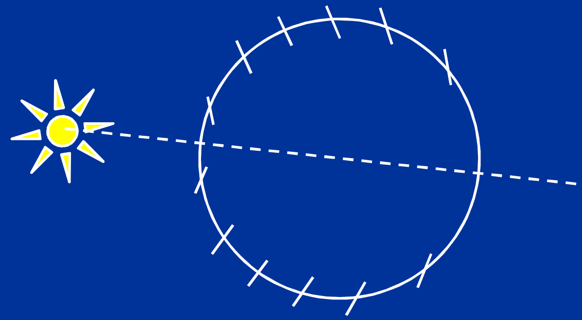
for an arbitrary circle
on the sky

B-mode is forbidden *for density perturbations*

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

point source





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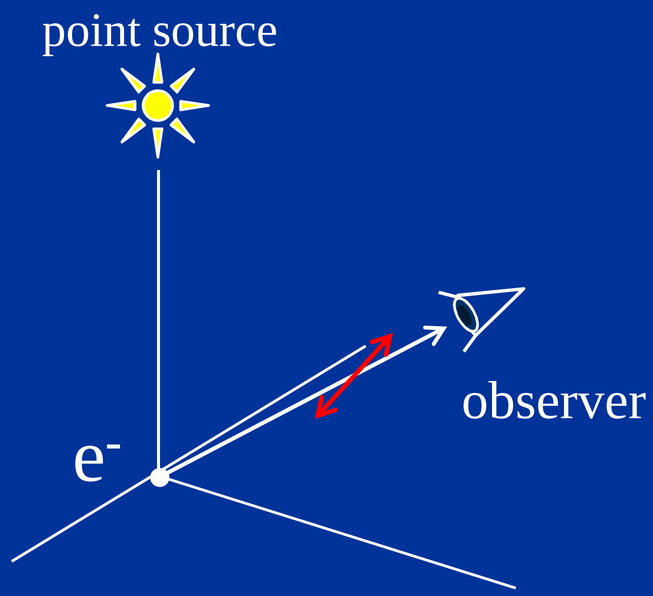
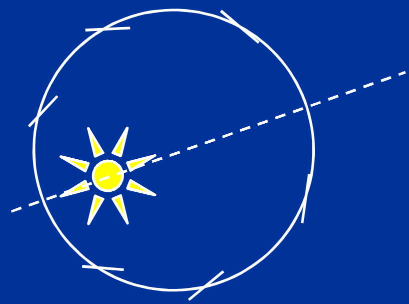


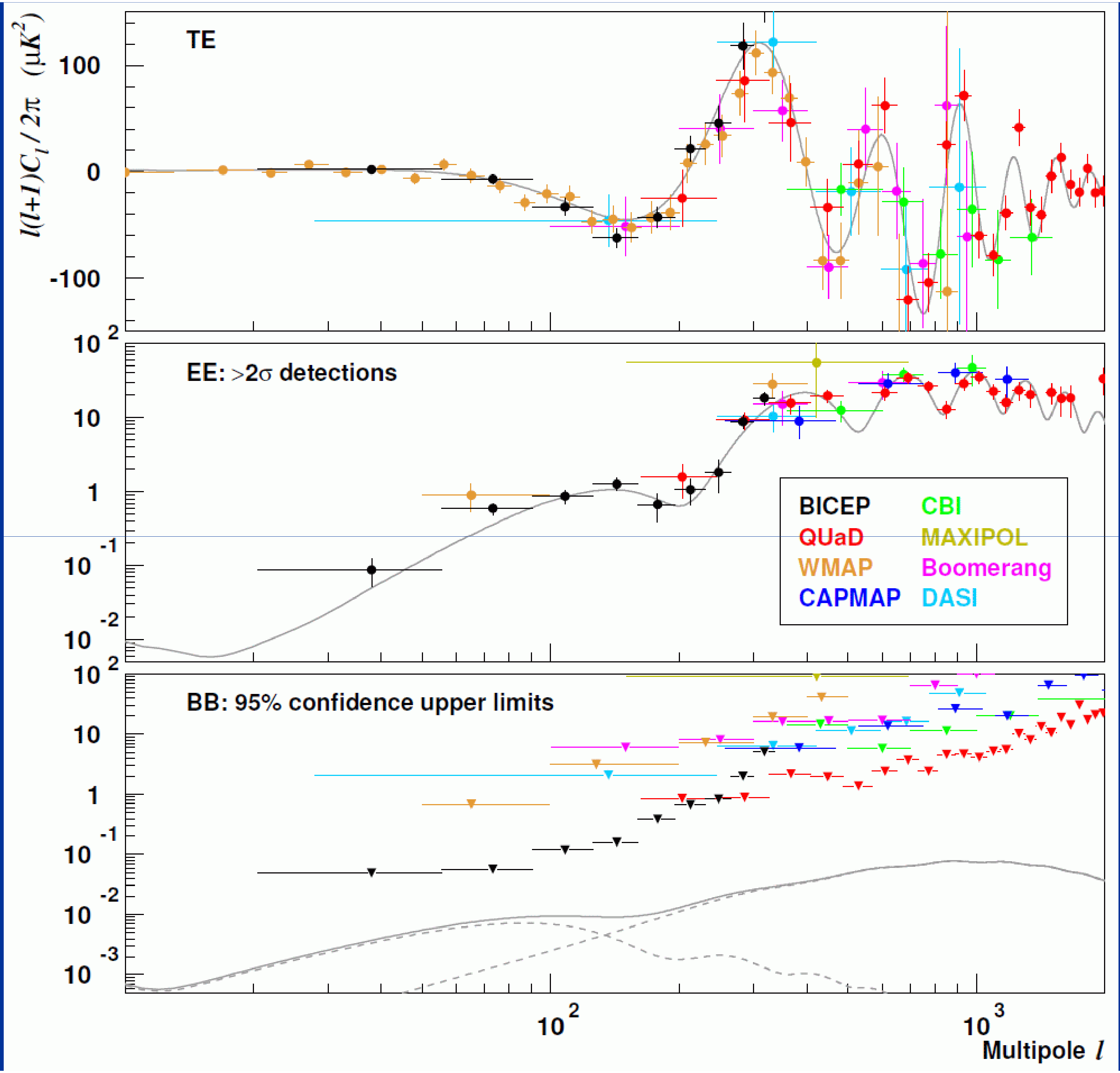


for an arbitrary circle
on the sky

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

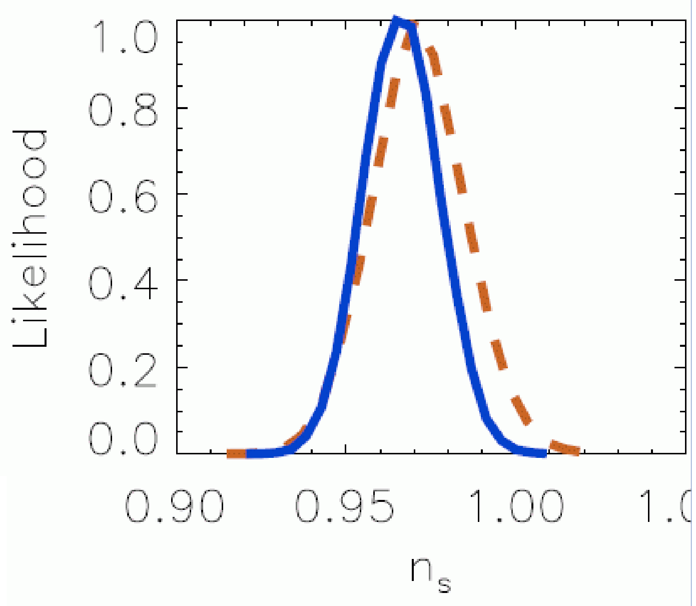
(Seljak & Zaldarriaga; Kamionkowski et al, 1997)



TE
EE: >2σ detections
BB: 95% confidence upper limits
$l(l+1)C_l / 2\pi$ (μK^2)
100
0
-100
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
BICEP
QUaD
WMAP
CAPMAP
CBI
MAXIPOL
Boomerang
DASI
Multipole l

Just how likely is this signal detectable ?

- Determined by the shape of Inflation potential V(ϕ)
  - V(ϕ) determines how ϕ evolves
  - Slow-roll inflation: ϕ roughly constant during inflation
  - Small quantities ε ~ decay rate ; η ~ deceleration
- Tensor to scalar ratio: T/S=16ε
- Scalar spectral index: n_S=1-4ε+2η
- Tensor spectral index: n_T= -2ε
- Already, we know $n_S \neq 1$!!



Dash: WMAP7
Solid: WMAP7+SPT

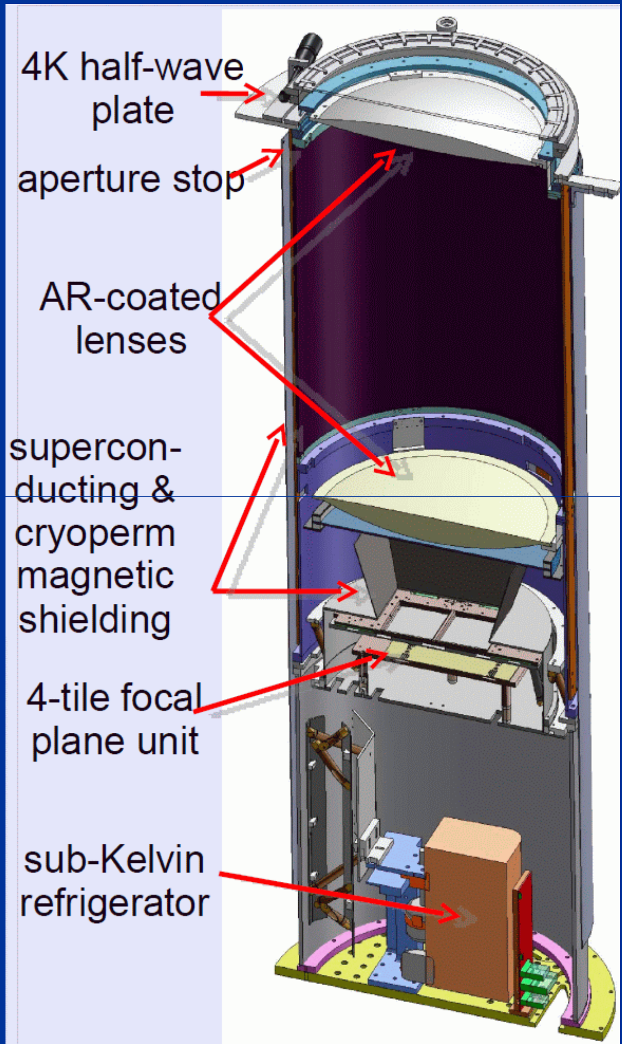
Global experimental efforts searching for *B*-mode

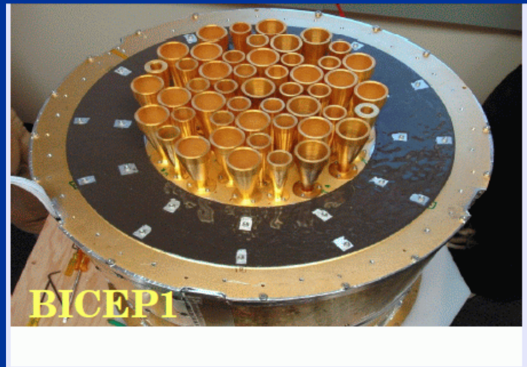
- BICEP, BICEP2, Keck Array
- POLAR-1, POLAR Array
- ABS
- POLARBEAR
- QUIET-I, QUIET-II
- SPTpol, ACTpol
- Ballooning: SPIDER, EBEX
- Satellite: Planck

South Pole is an excellent site for CMB observation

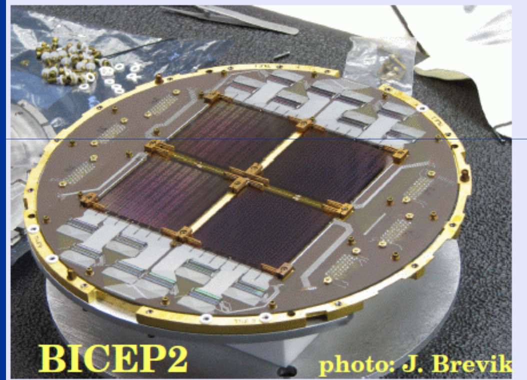
- High elevation, low temperature → low water vapor
- Continuous observation for >9 months
- Excellent infrastructure/support (NSF-Office of POLAR Program)

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





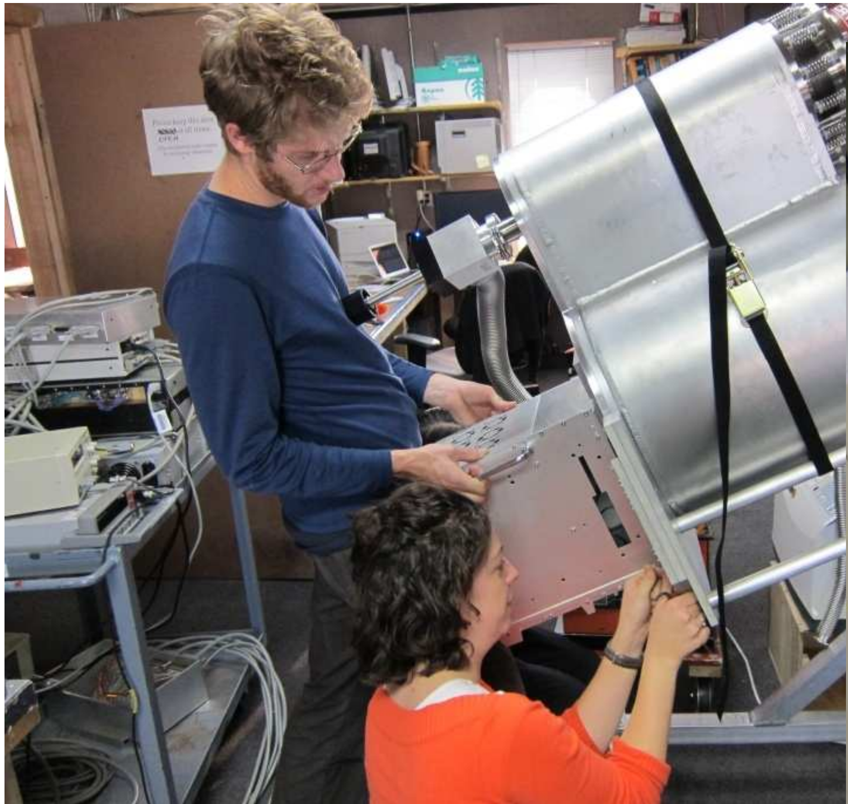
90/150GHz
25/24 elements
2005-2008
Best limit on B-mode



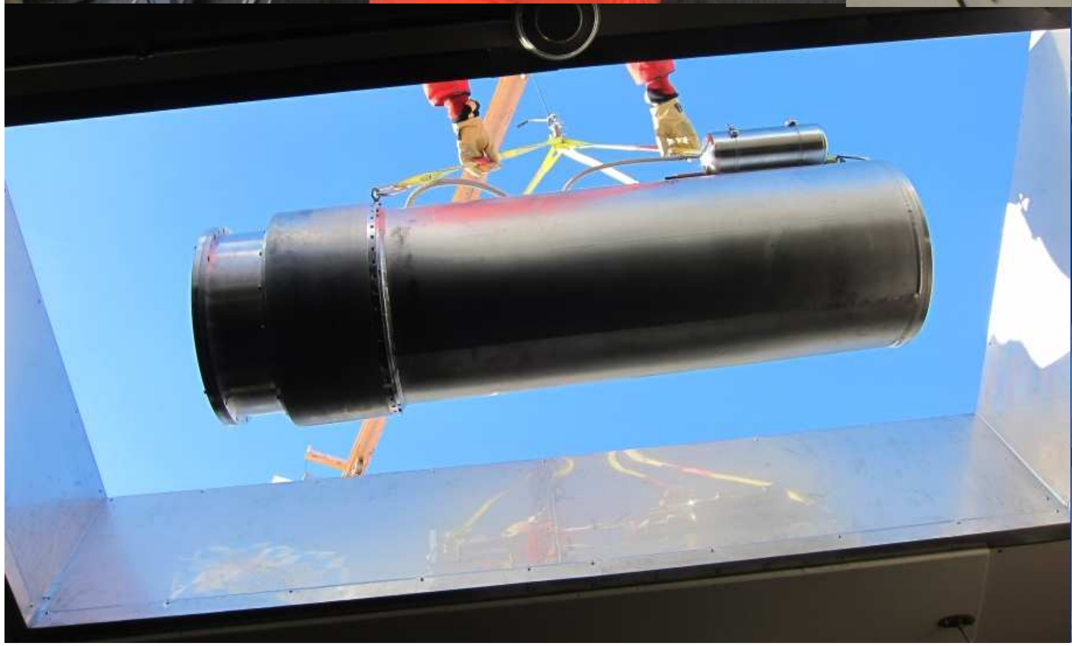
150GHz
256 elements
Taking data for 1yr
5x survey speed than BICEP1

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

** All with small refractors (25cm) ; observing from the South Pole*
** Will likely reach T/S ~< 0.02 by 2013*

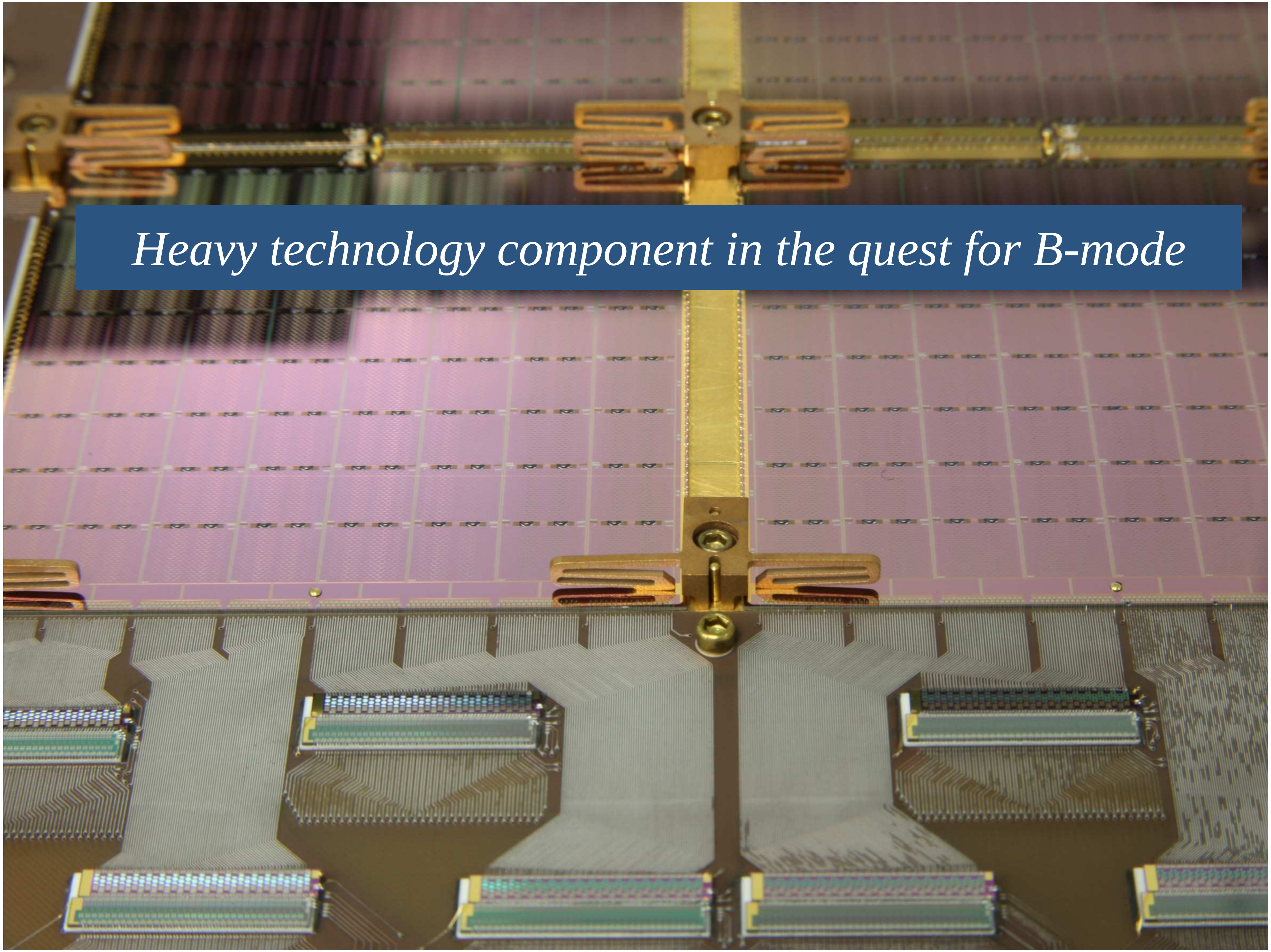



ALCOHOL
STOCKER & YALE
Weller
Weller

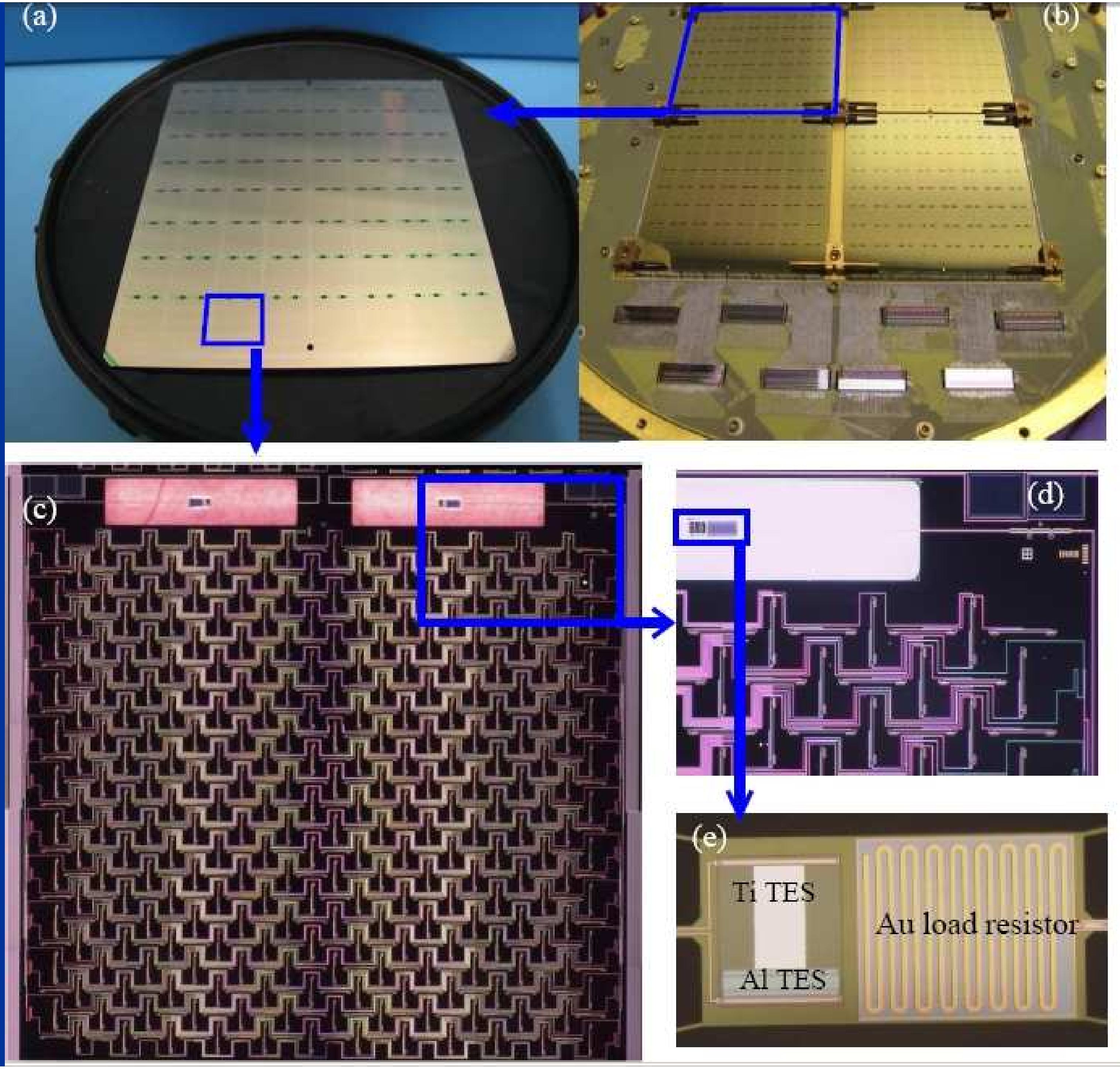




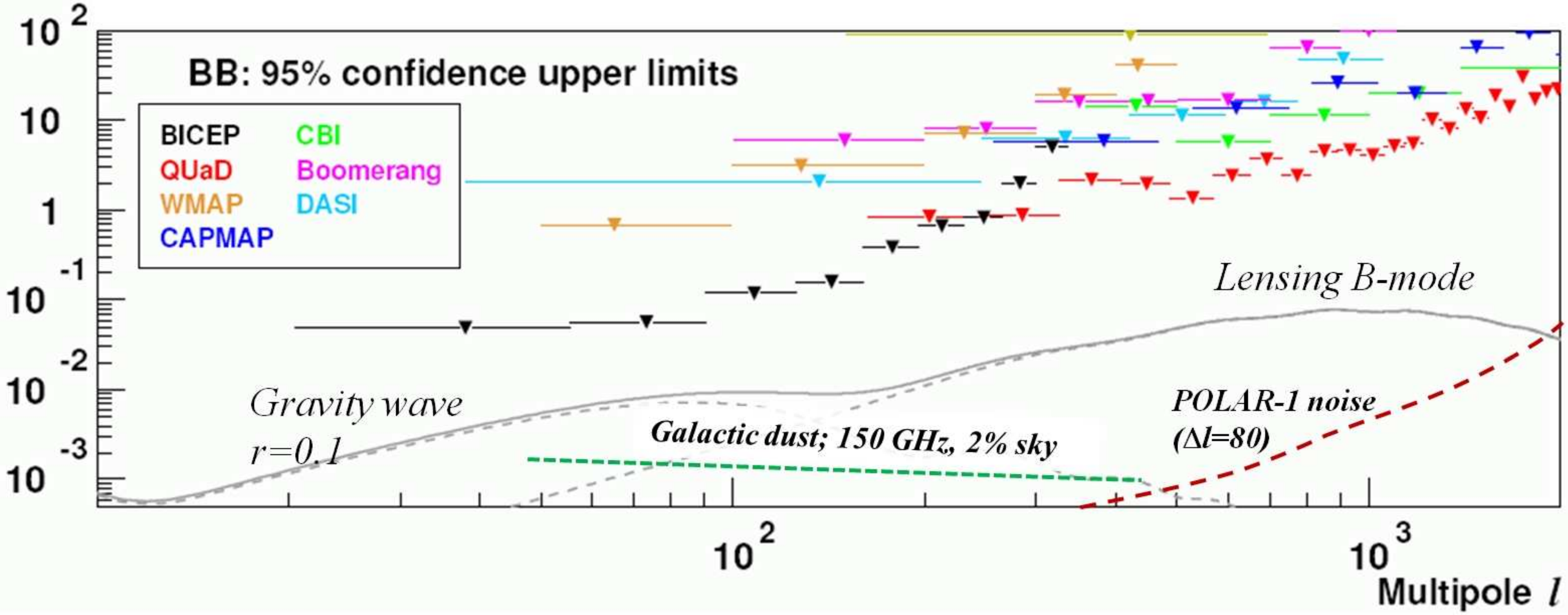

Heavy technology component in the quest for B-mode



New Detectors for the CMB



The B-mode polarization



* The gravity wave signal down to *r~0.02* is likely reachable in the next 5 years (e.g. Keck Array, POLAR1, …)

* *The prospect for lensing/de-lensing calls for big projects – 100× the current speed*

BICEP-BICEP2-Keck time line

• *All with small refractors (25cm) ; observing from the South Pole*

•BICEP (2005-2007) currently provides the best limit on B-mode

•BICEP2 (2009-) observing with x5 BICEP sensitivity

•Keck Array (2010 -) observing, x5 **BICEP2** sensitivity

• *Will likely reach T/S ~< 0.02 by 2013*

Lensing *B*-mode

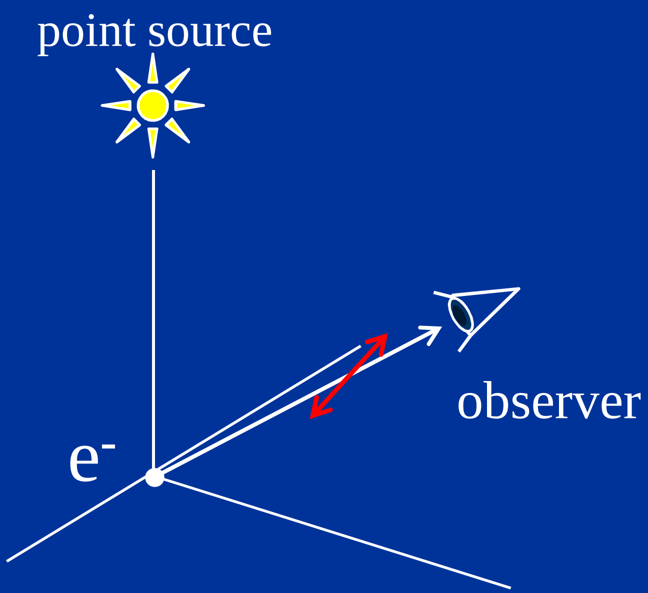
B-mode theorem

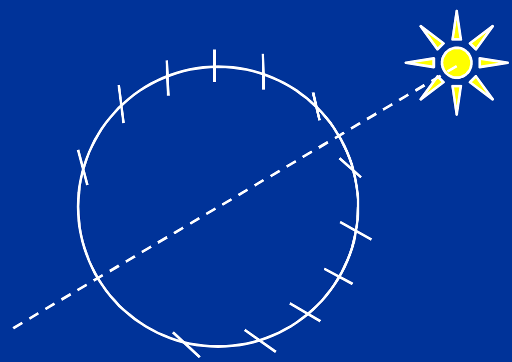
- Polarization fields can be linearly decomposed to E and B mode
- Linear, scalar perturbation cannot generate B-mode polarizations

(Seljak & Zaldarriaga; Kamionkowski et al, 1997)

B-mode is forbidden *for density perturbations*

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

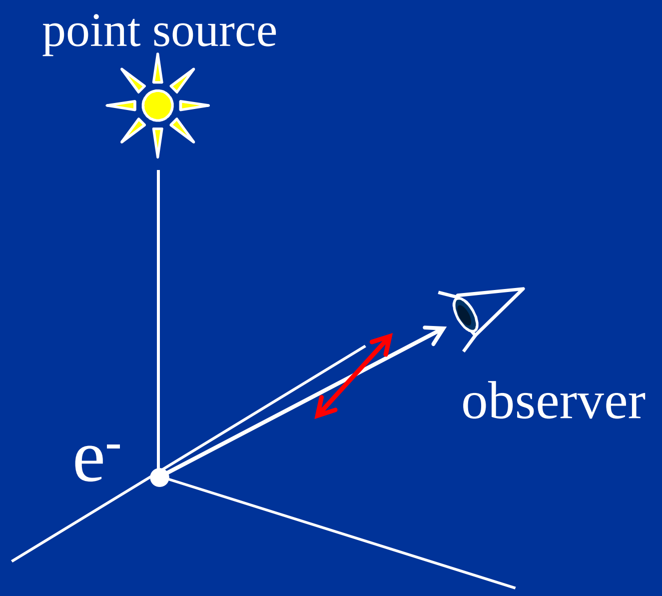


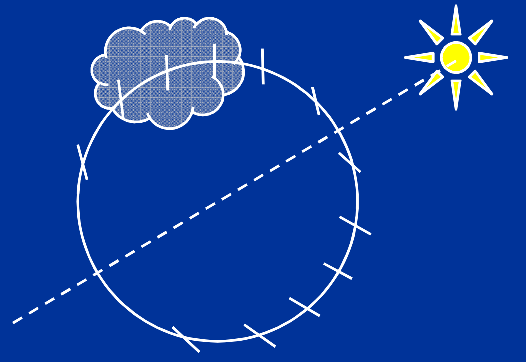


for an arbitrary circle
on the sky

Lensing can generate B-mode

(Zaldarriaga & Seljak, 1999)





for an arbitrary circle
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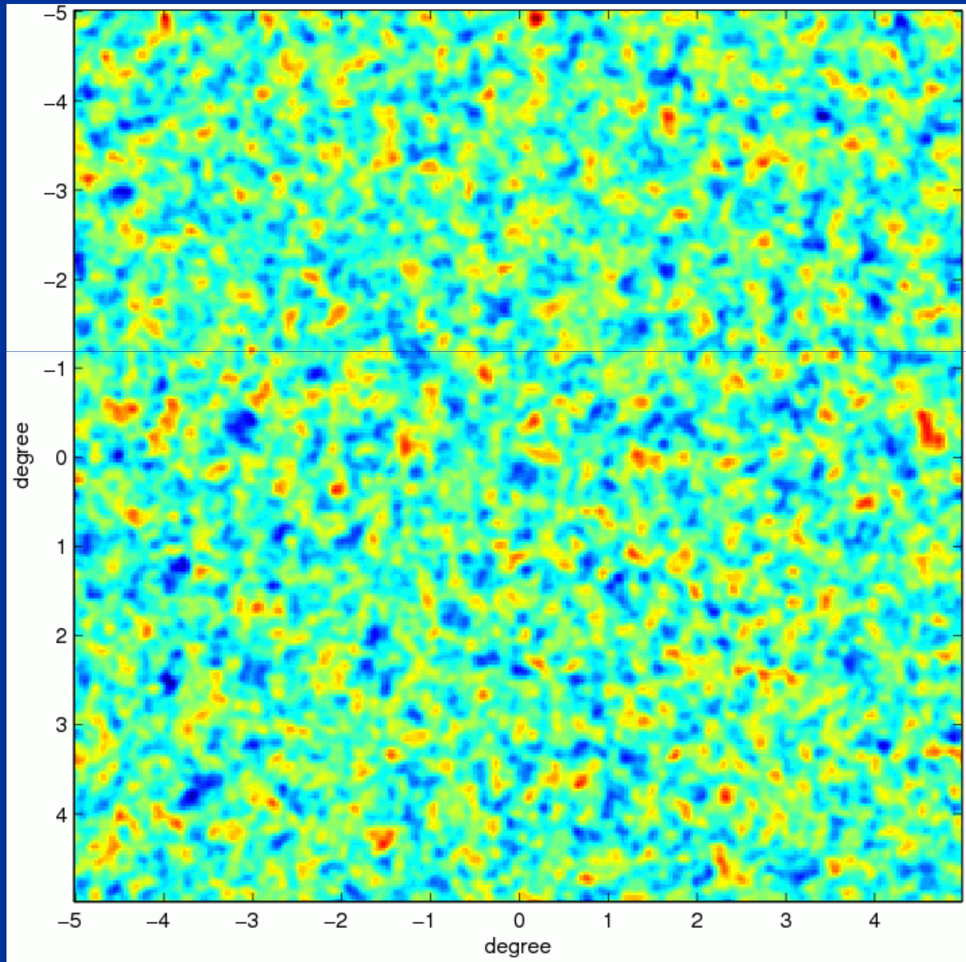
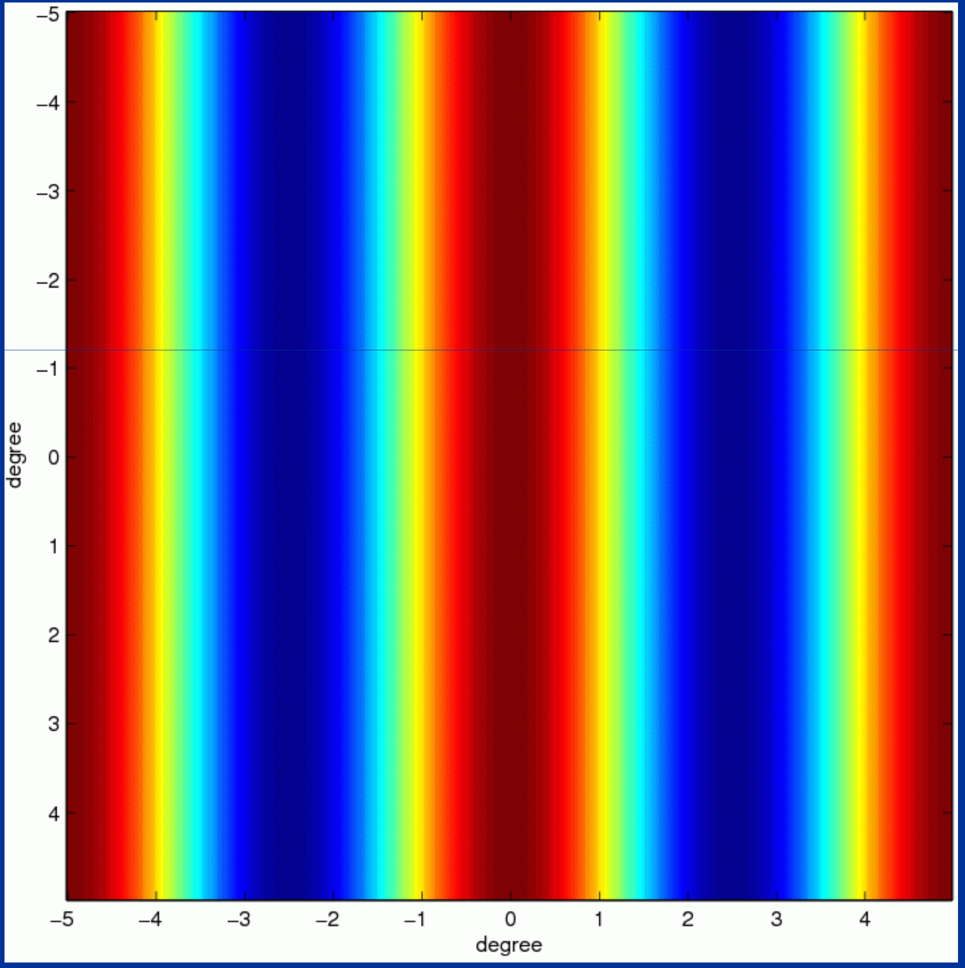
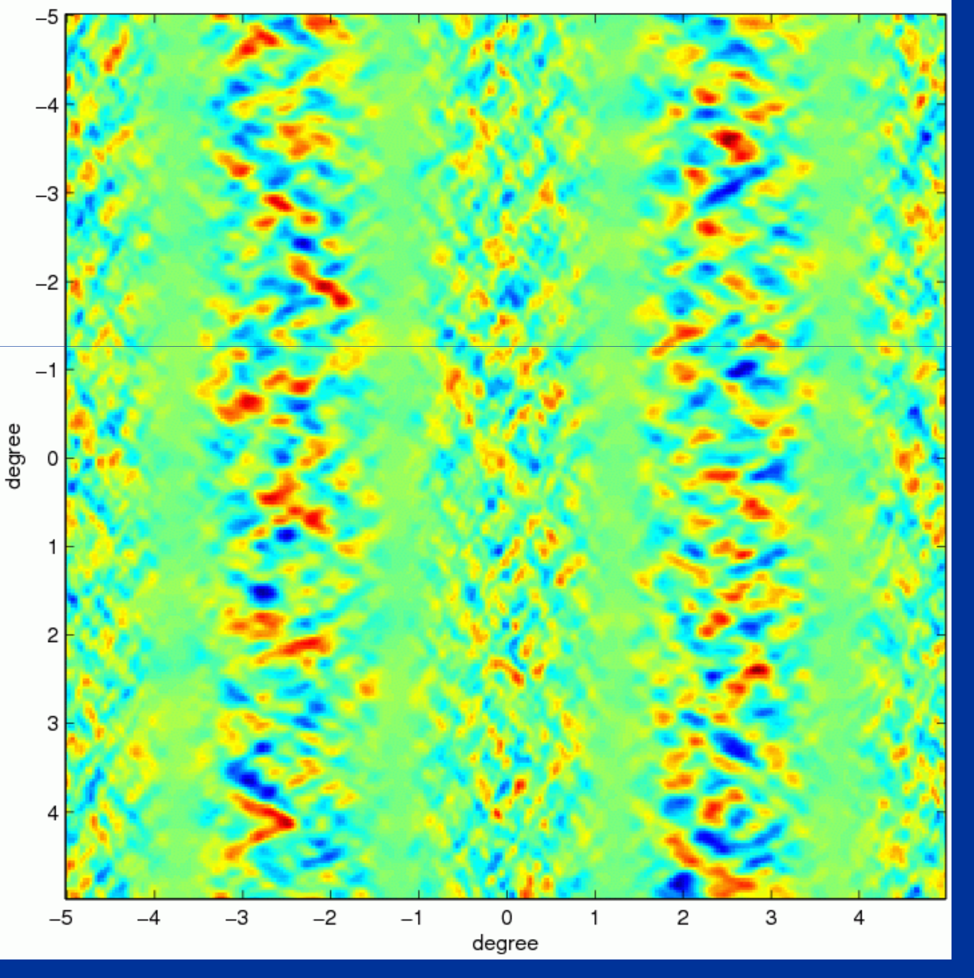
Unlensed pure *E*-mode



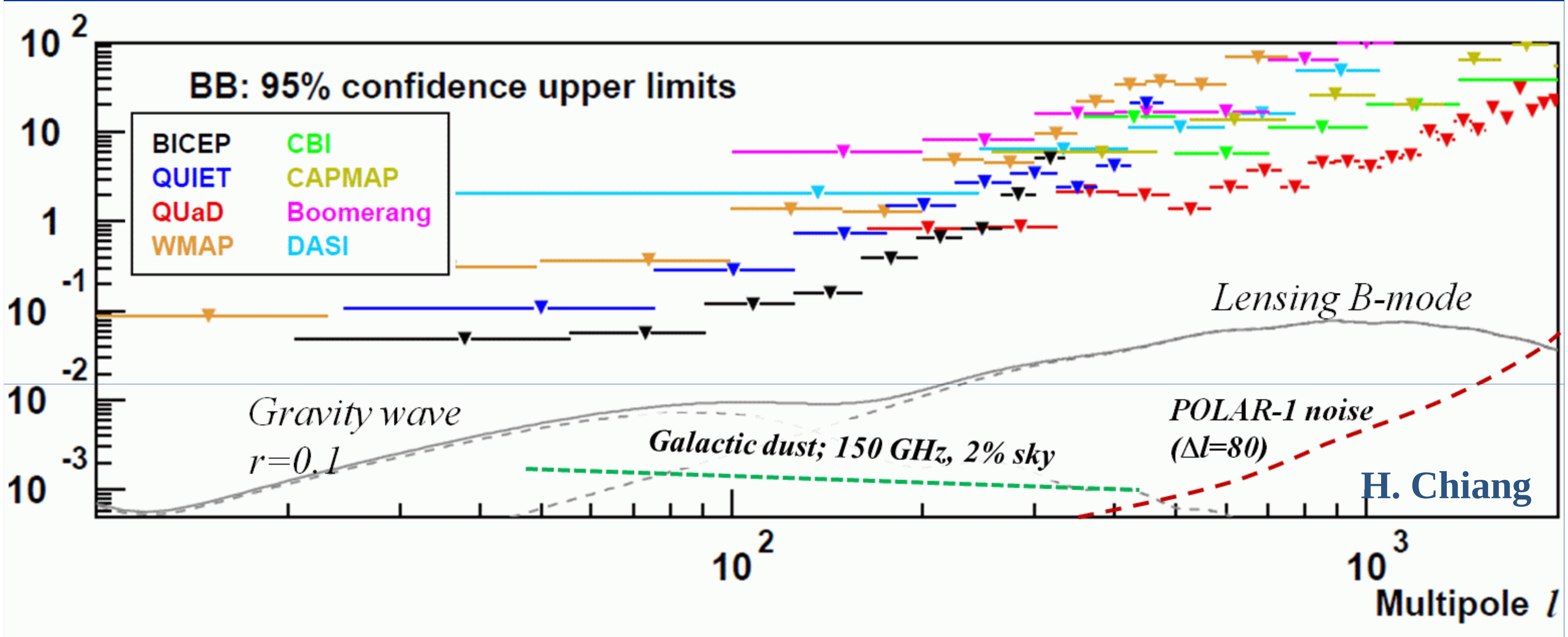
Lensing field



Lensed *B*-mode

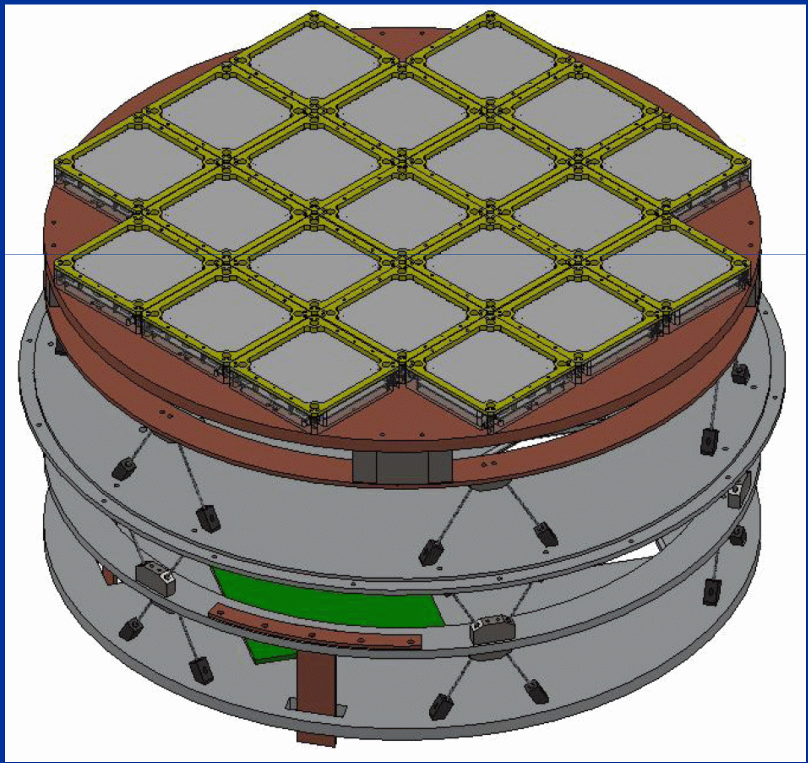


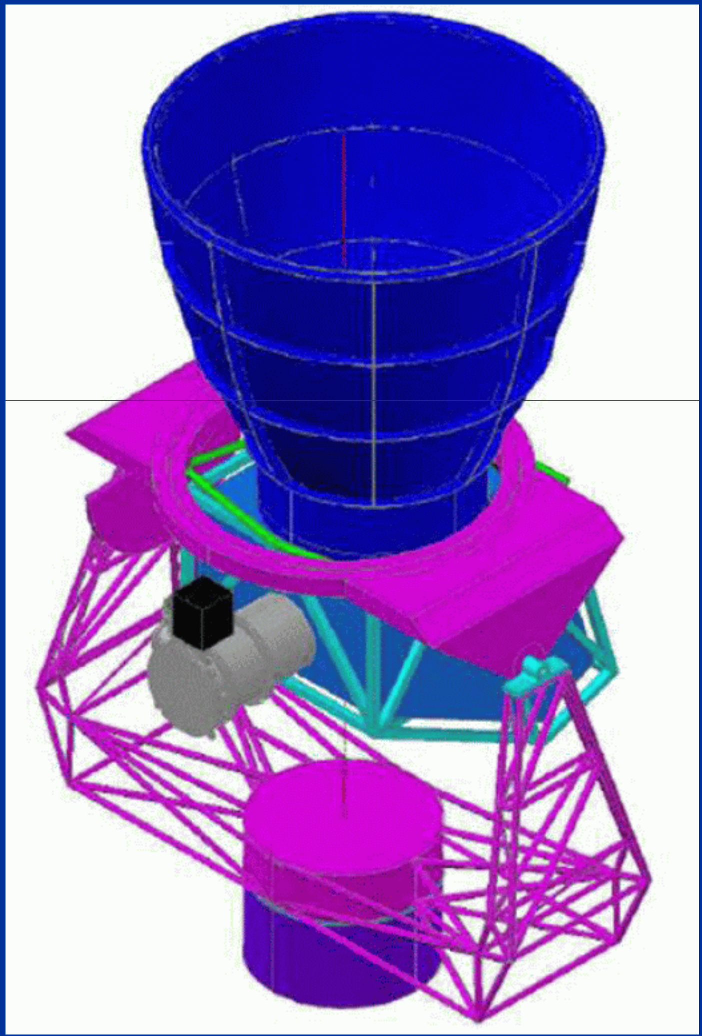
Lensing *B*-mode measurements as of December 2011



- QUaD/BICEP (50~100 detectors) still miss the *B*-polarization by ~ 2 orders of magnitude.
- To perform high S/N imaging of lensing *B*-polarization, one must increase the survey speed by 10^2.

POLAR1 experiment





POLAR Array at the South Pole

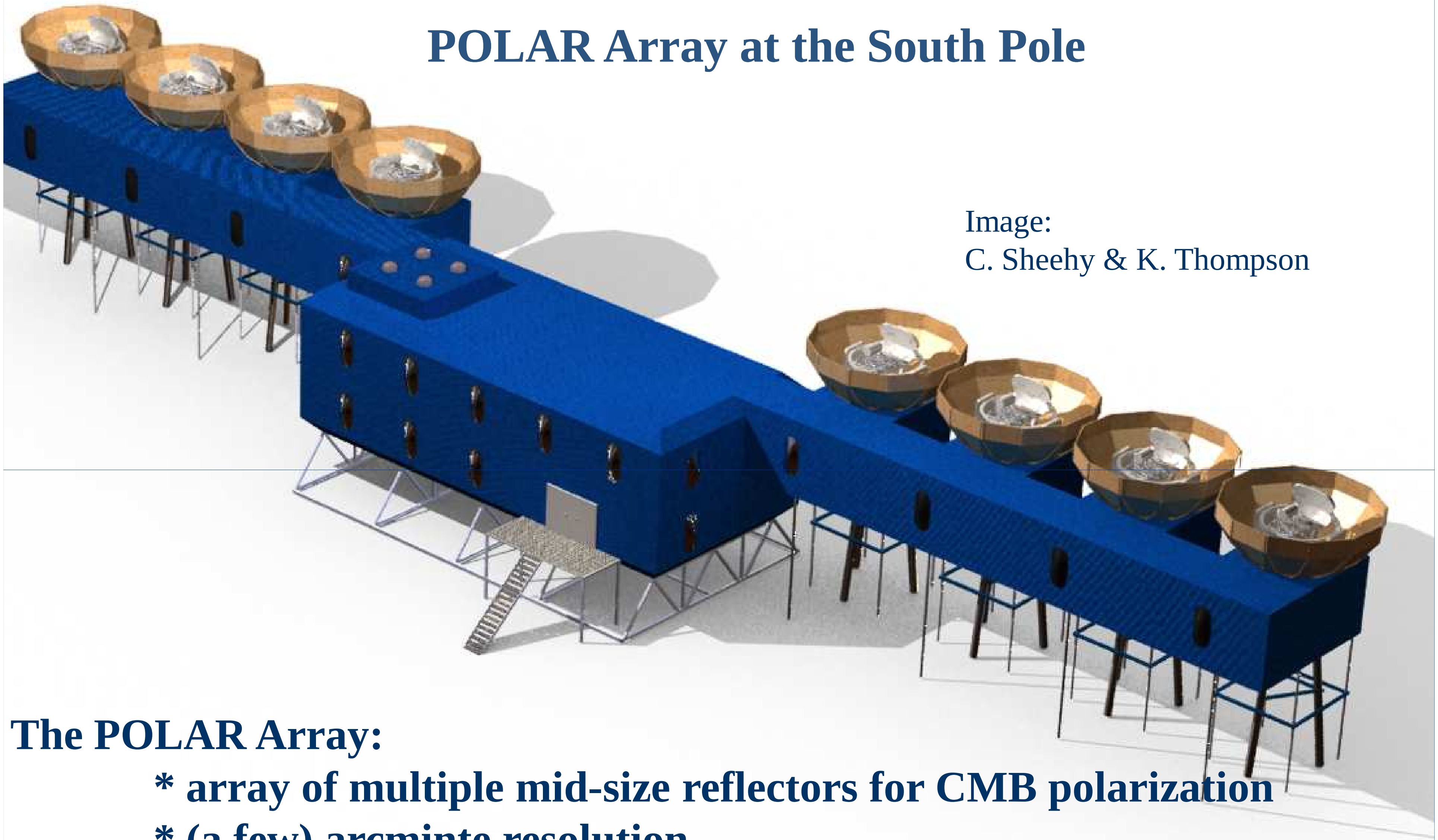


Image:
C. Sheehy & K. Thompson

The POLAR Array:

* array of multiple mid-size reflectors for CMB polarization
* (a few) arcminte resolution
* multi-frequency (distribution TBD)
* 10% the survey speed of CMBPOL, NASA’s next CMB mission

Lensing *B*-polarization is a LSS experiment

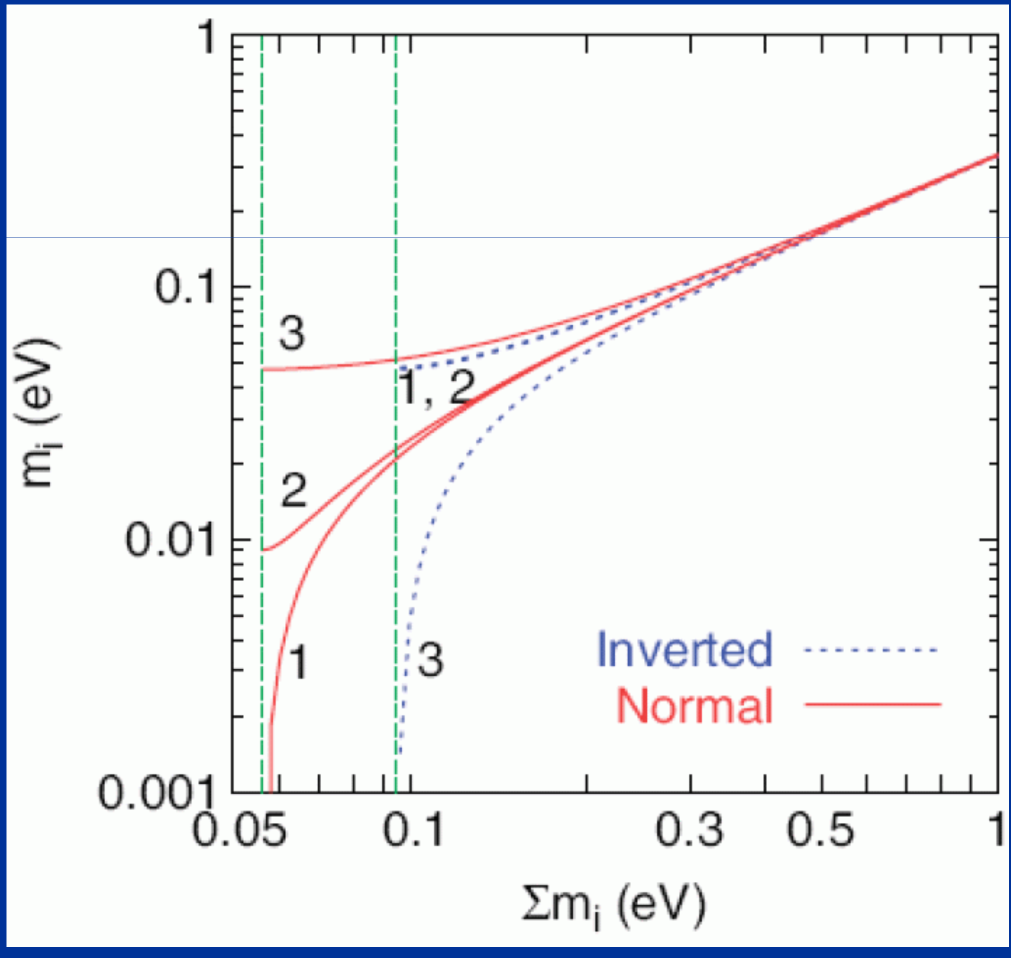
- Deep polarization measurements can significantly improve *Planck+WFIRST/Euclid's* constraints on $\{w, \Omega_k, \sum m_\nu\}$ etc.,
- If one assumes a prior of

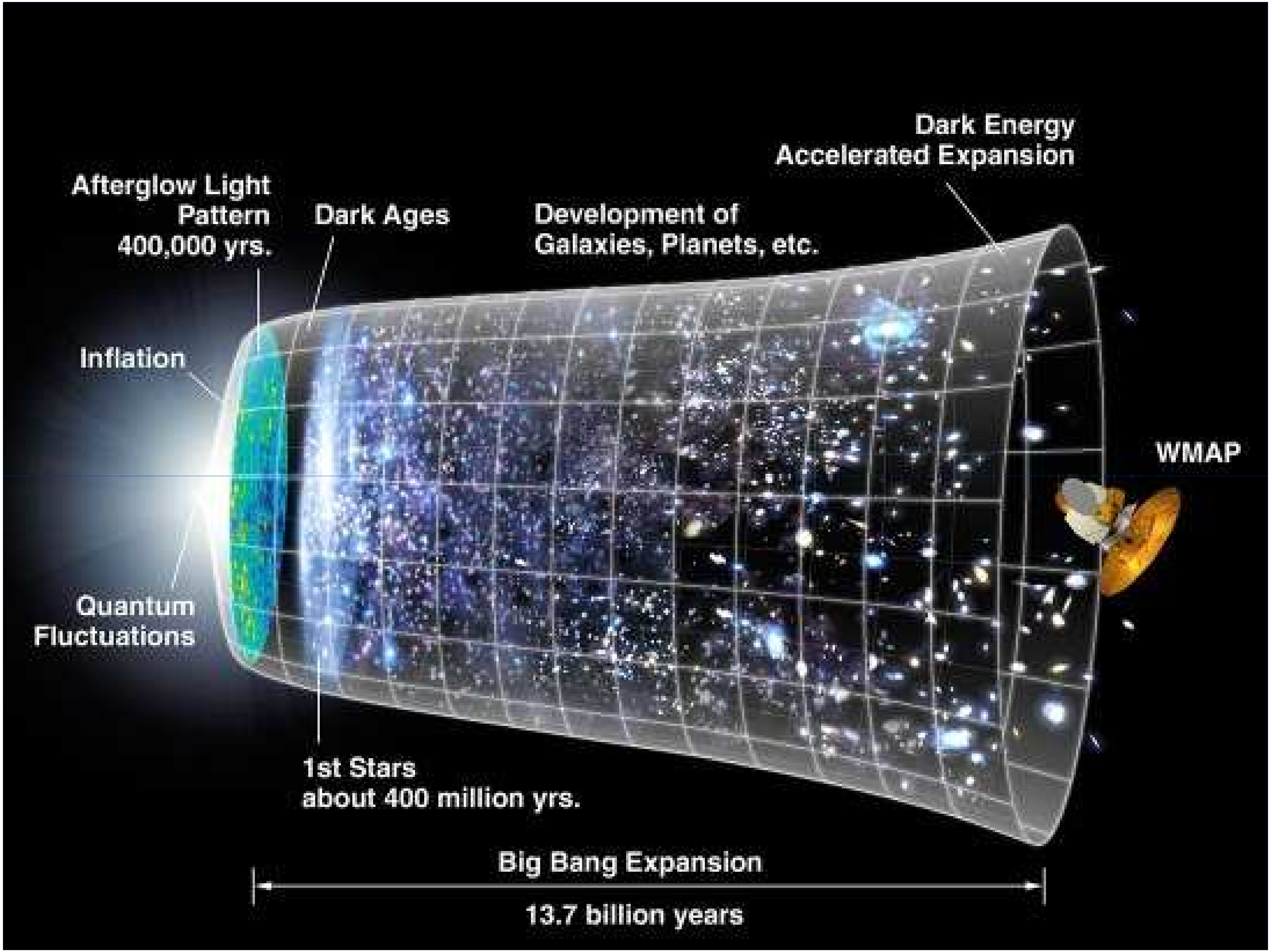
  $w_0 = -1$, $w_a = 0$, $\Omega_k < 10^{-4}$ → lensing *B* provides a constraint on $\sum m_\nu < 0.04$ eV

- This will either
  - *Detect* a neutrino mass
  - Rule out inverted hierarchy

Lesgourgues and Pastor
Physics Reports, 2006

also
Astro-2010 Panel Reports




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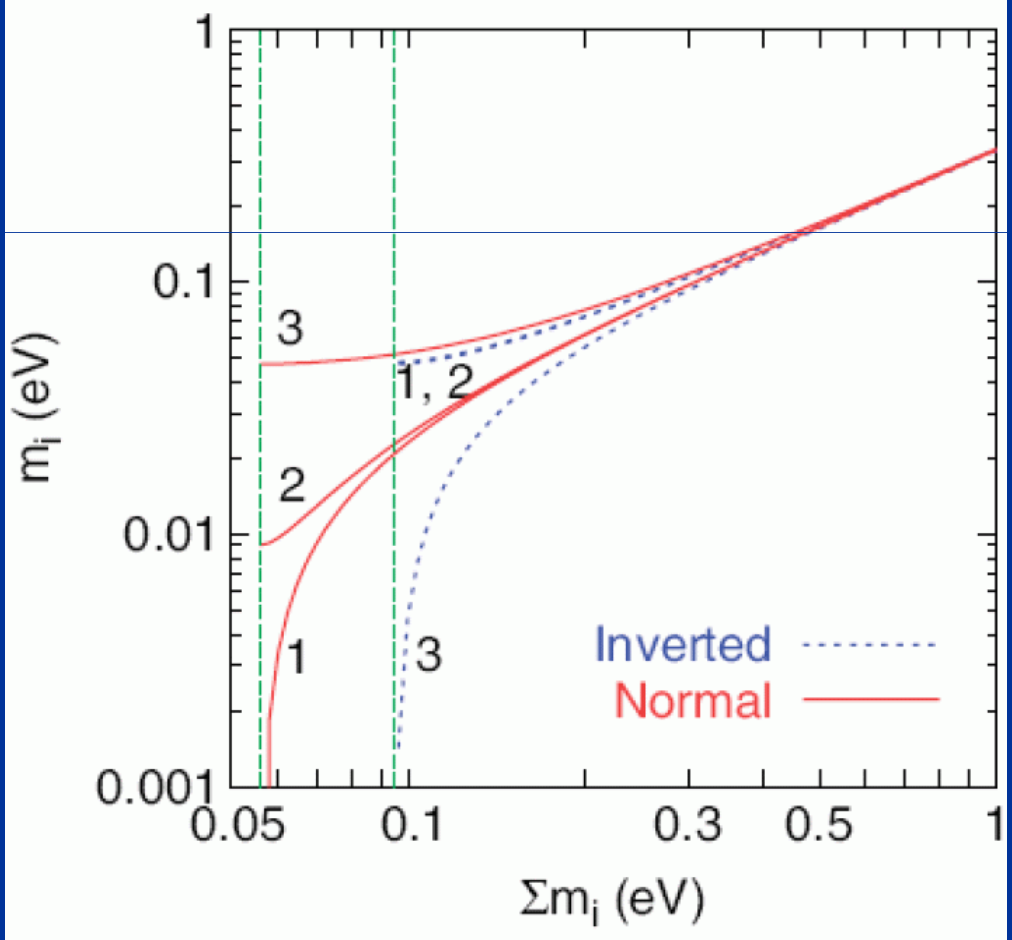
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Lensing *B*-polarization is a LSS experiment

- Deep polarization measurements can significantly improve *Planck+WFIRST/Euclid's* constraints on {w, Ω_k, $\sum m_\nu$} etc.,
- If one assumes a prior of

  w_0= -1, w_a=0, Ω_k <10^{-4} → lensing *B* provides a constraint on $\sum m_\nu$ <0.04 eV

- This will either
  - *Detect* a neutrino mass
  - Rule out inverted hierarchy



Lesgourgues and Pastor
Physics Reports, 2006

also
Astro-2010 Panel Reports

Summary

- The search for primordial gravity waves is among the most exciting quests in all of physics – it studies the birth of the universe, and quantum gravity
- There is real hope for a detection in the next 3-5 years, through a intense global effort in CMB polarimetry
- In addition, lensing of the CMB provides opportunities in neutrino physics