CMB (Polarization) Science in the Next Decade and Report from the IPSAG

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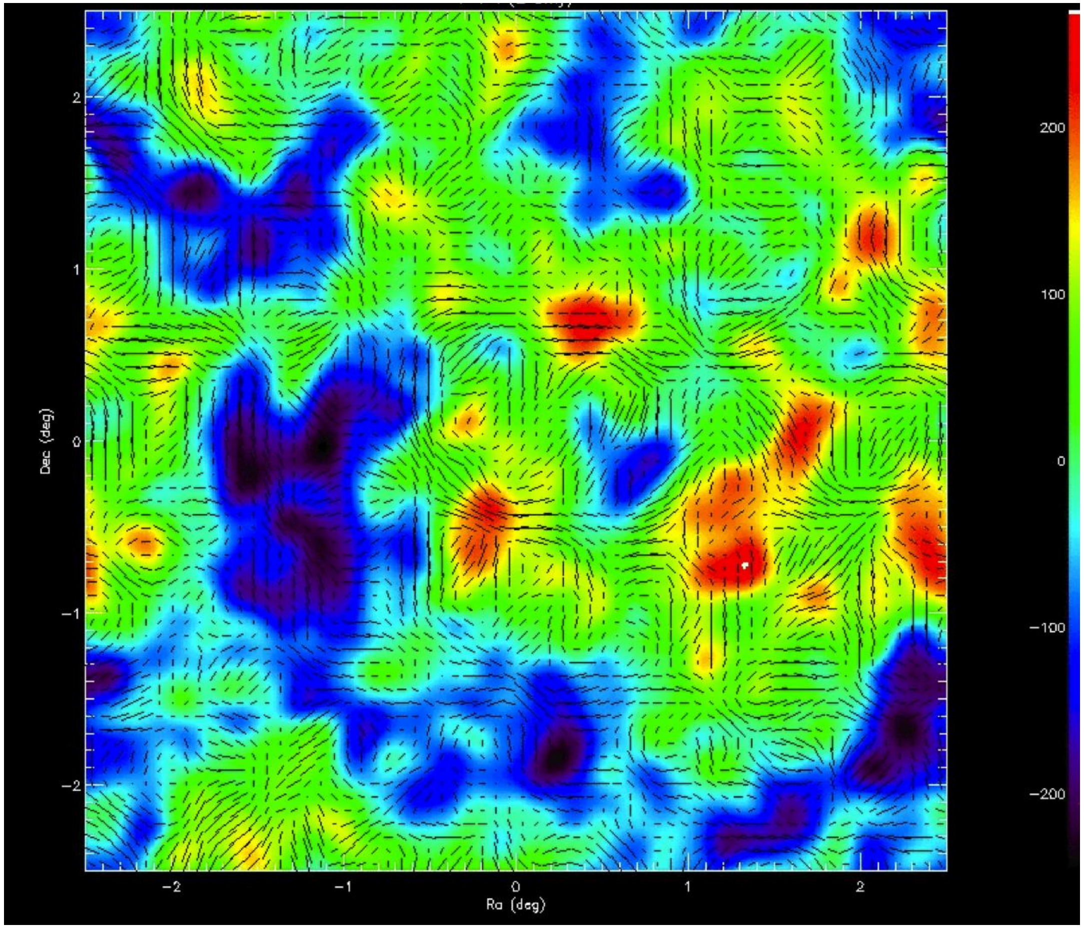
With input from

The Inflation Probe Science Analysis Group
The EPIC-IM Mission Study Team

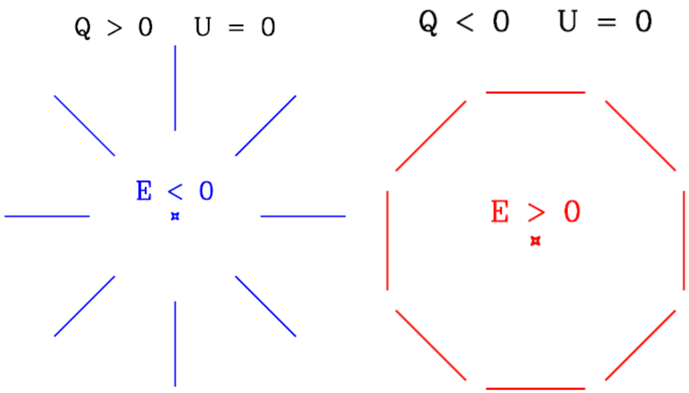
CMB Polarization: E and B Modes

Simulated Map of Temperature
Anisotropy and Polarization

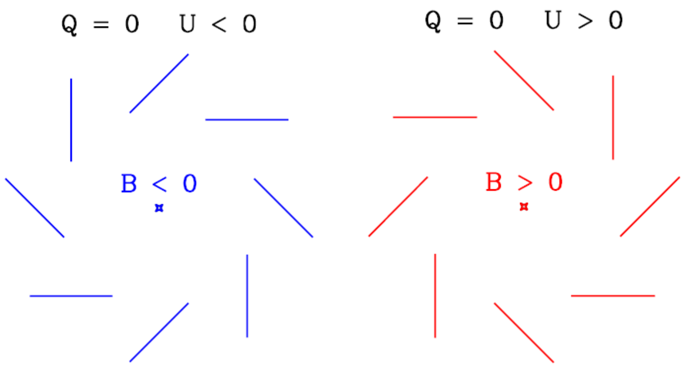


Bars indicated polarized intensity and orientation

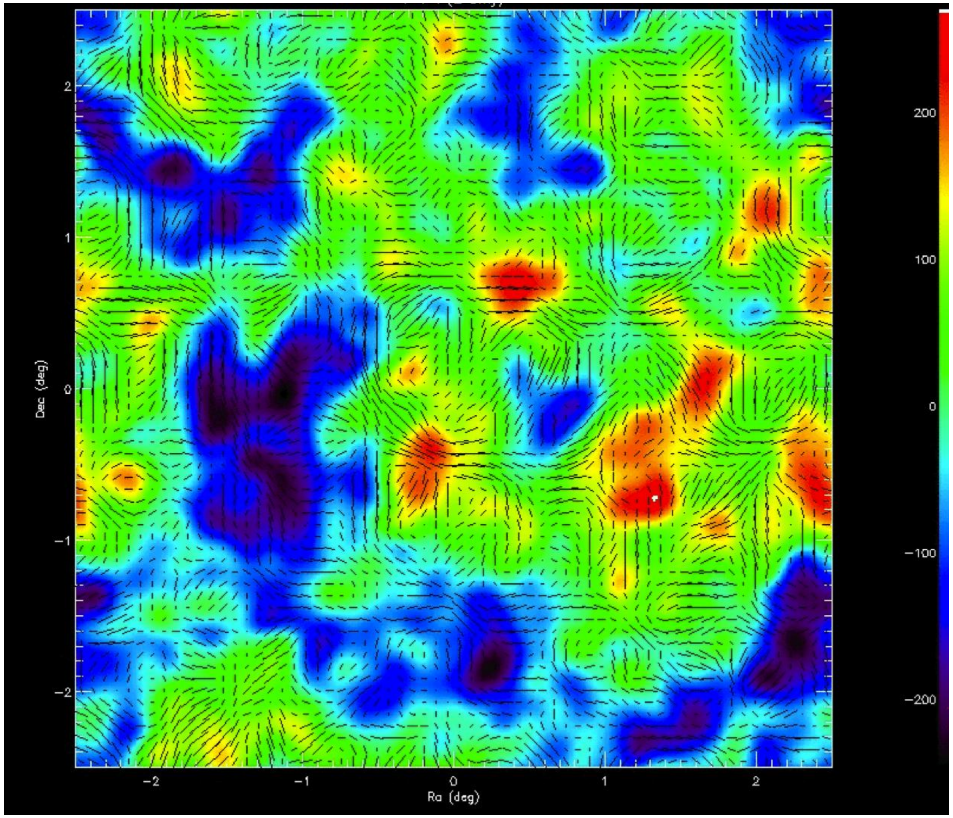
Curl Free E-Mode



Divergence Free B mode



Significance of E and B Modes

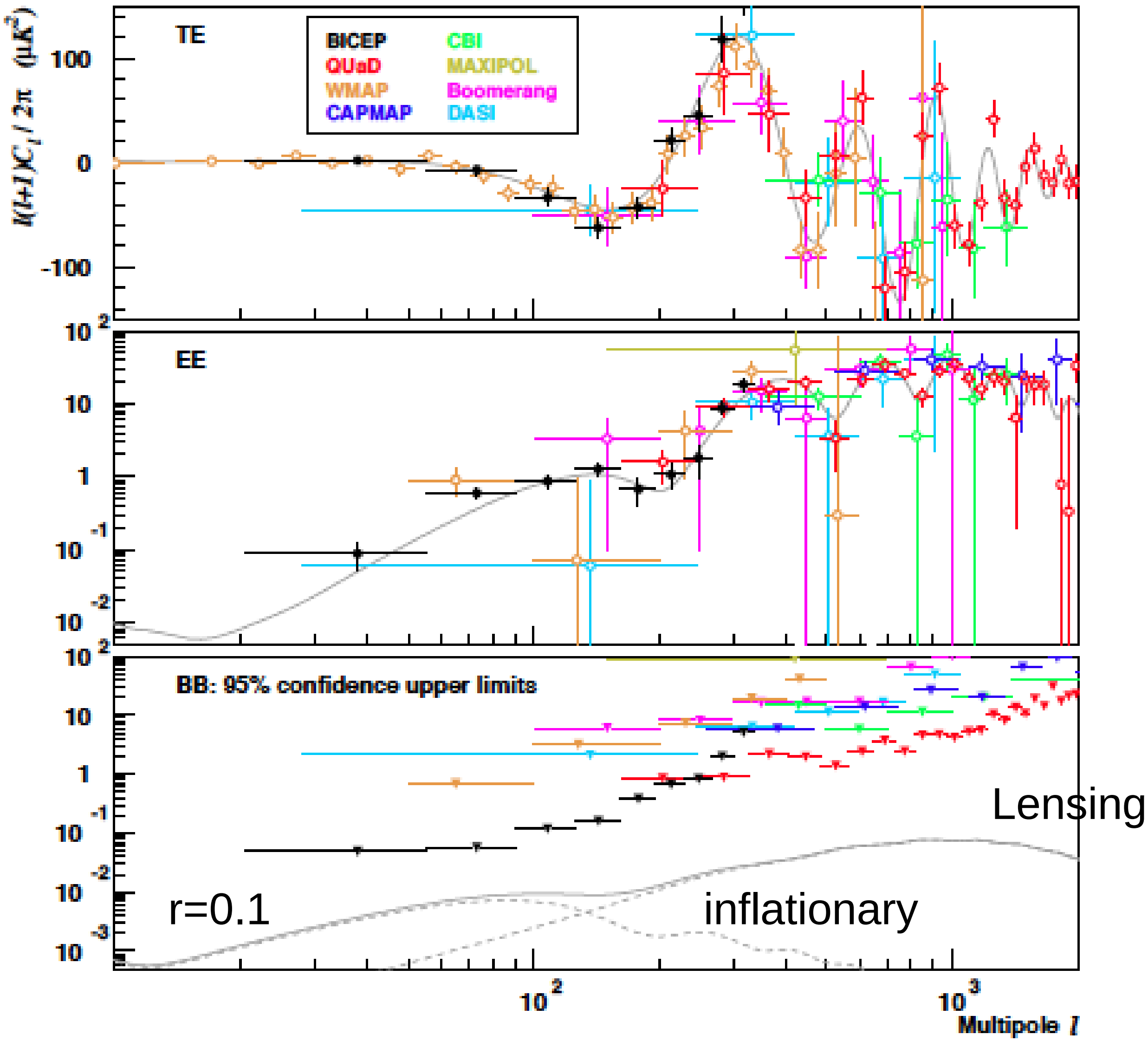


"The convincing detection of B-mode polarization in the CMB … would represent a watershed discovery." (from New Worlds, New Horizons)

- Inflation produces density perturbations + gravitational waves
- Density perturbations produce E mode <u>only</u>; Gravitational waves produce both E,B polarization patterns
- Only gravity waves produce B-mode polarization
- Detection (or constraint) on B-polarization is direct signature (or constraint) on Inflation

Current State of Knowledge

Chiang et al. 2010



- Tensor to Scalar ratio - r
- Current limit: r<0.24 (95%)

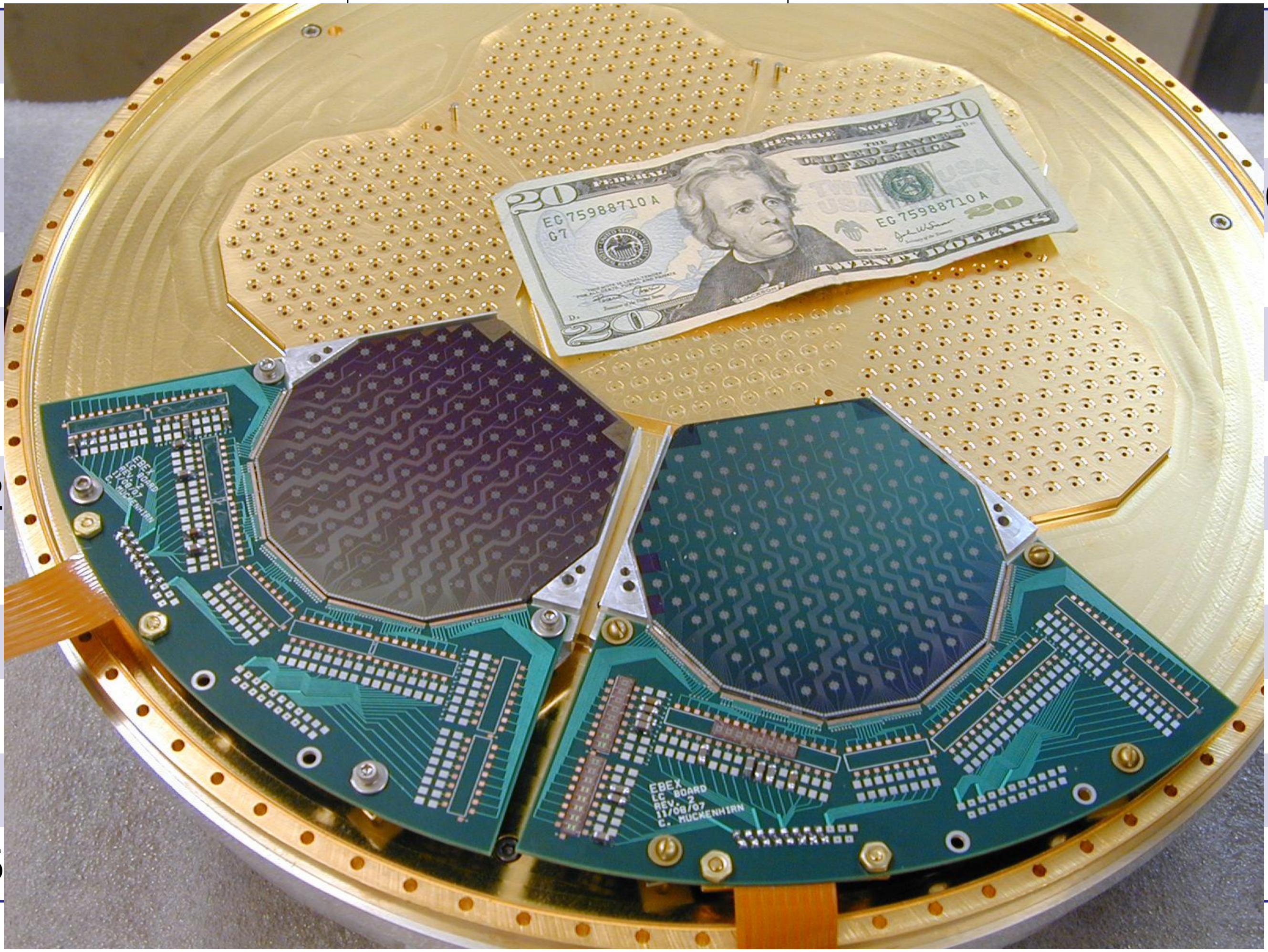
Note: Results from the QUIET experiment (not shown) agree with other available data.

Funded US Sub-Orbital Polarization Experiments

Experiment	Resolution (‘)	Frequency (GHz)	Number of Detector Pairs
Balloon-Borne			
EBEX	8	150 / 250 / 410	398 / 191 / 141
PIPER	21 / 15 / 14 / 14	200 / 270 /350 /600	2560 / 2560 / 2560 /2560
SPIDER	60 / 40 / 30	96 /145 /225	288 / 512 / 512
Ground-Based			
ABS	30	150	200
ACTPol	2.2 / 1.4 / 1.1	90 / 145 / 217	~1000
BICEP2	37	150	256
CLASS			
KeckArray	55 / 37 / 26	100 / 150 / 220	288 / 512 / 512
Polarbear	7 / 3.5 / 2.4	90 / 150 / 220	637
SPTPol	1.5 / 1.2 / 1.1	90 / 150 / 225	~1000

Funded US Sub-Orbital Polarization Experiments

Experiment	Resolution (‘)	Frequency (GHz)	Number of Detector Pairs
EBEX	8		
PIPER	21		60
SPIDER	60		
ABS	30		
ACTPol	2.2		
BICEP2	37		
CLASS			
KeckArray	55		
Polarbear	7 /		
SPTPol	1.5		



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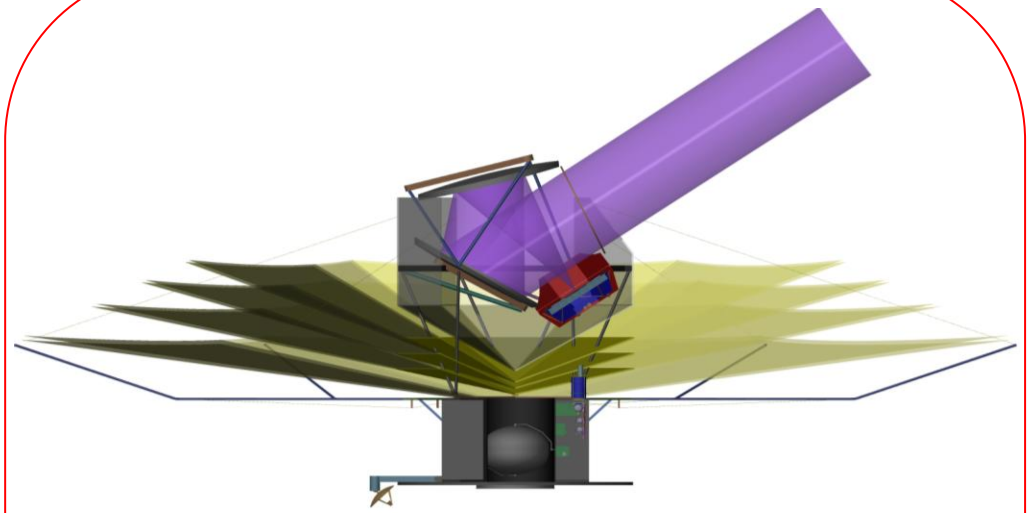
A Healthy Variety of Experimental Approaches + Technologies

Target r: ~0.05 ; Time scale: <= 2015

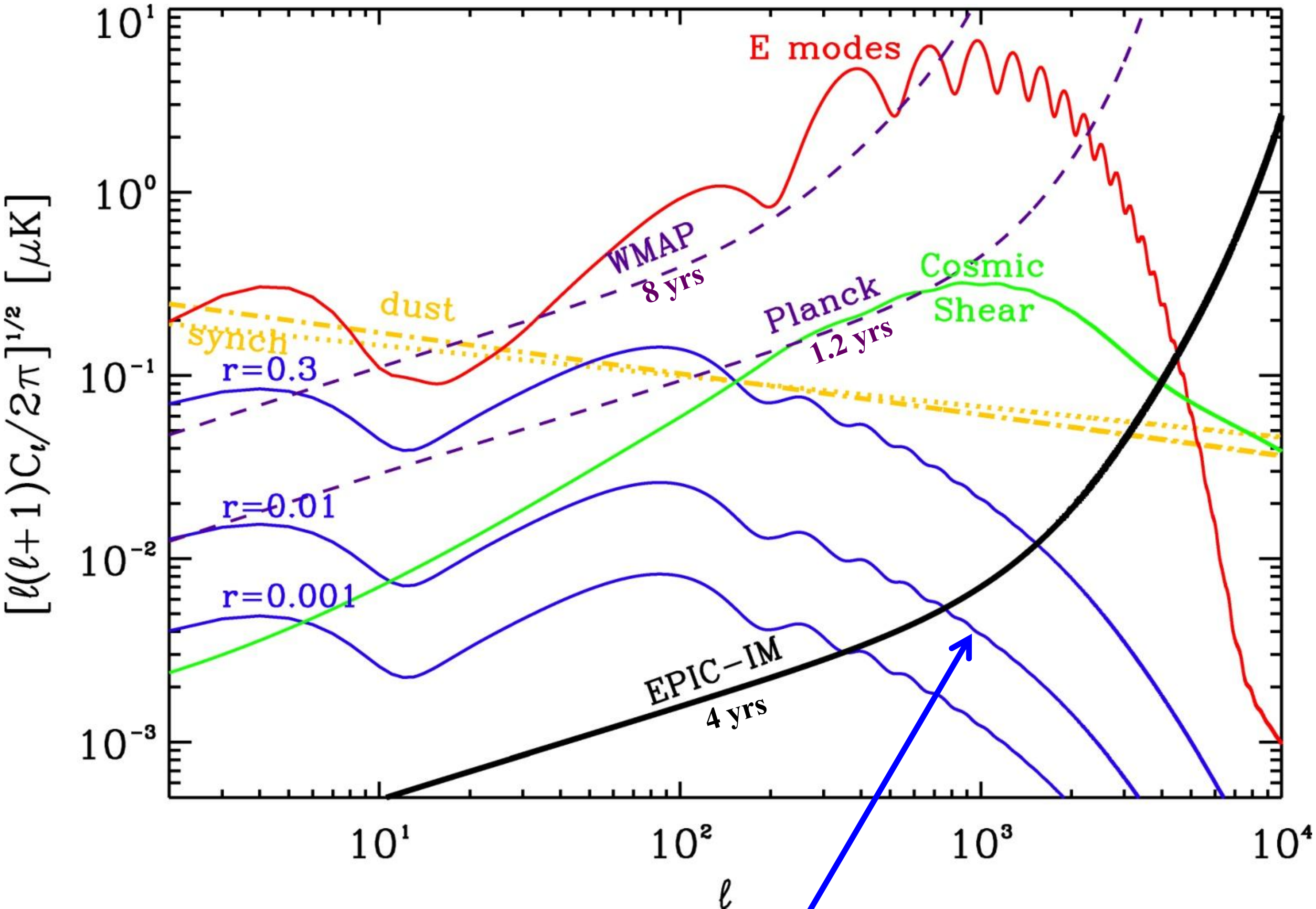
EPIC - A Definitive Space Mission

- Will map the entire sky, accessing the largest angular scales that are difficult to get from the ground
- Will give the sensitivity necessary to definitively determine the E, B spectra
- Will have the frequency coverage to suppress foregrounds to required levels
- Will have un-paralleled control of systematic uncertainties



- 11,094 TES or MKID detectors
- 9 frequency bands between 30 and 880 GHz
- Focal plane maintained at 100 mK
- ***Sensitivity equates to 3500 Planck missions!***
- *Mass similar to Planck*

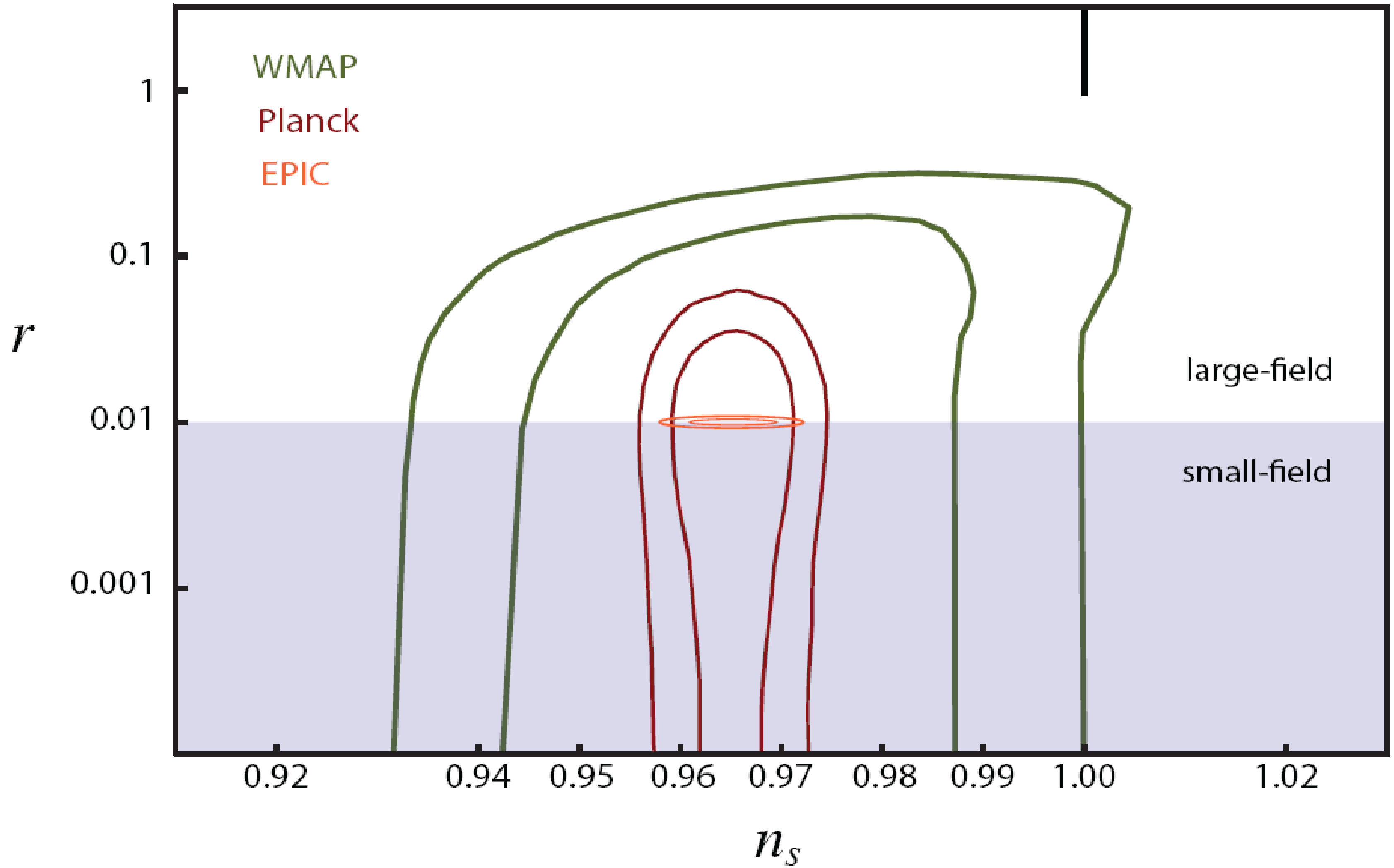
Richness of the CMB Polarization Landscape



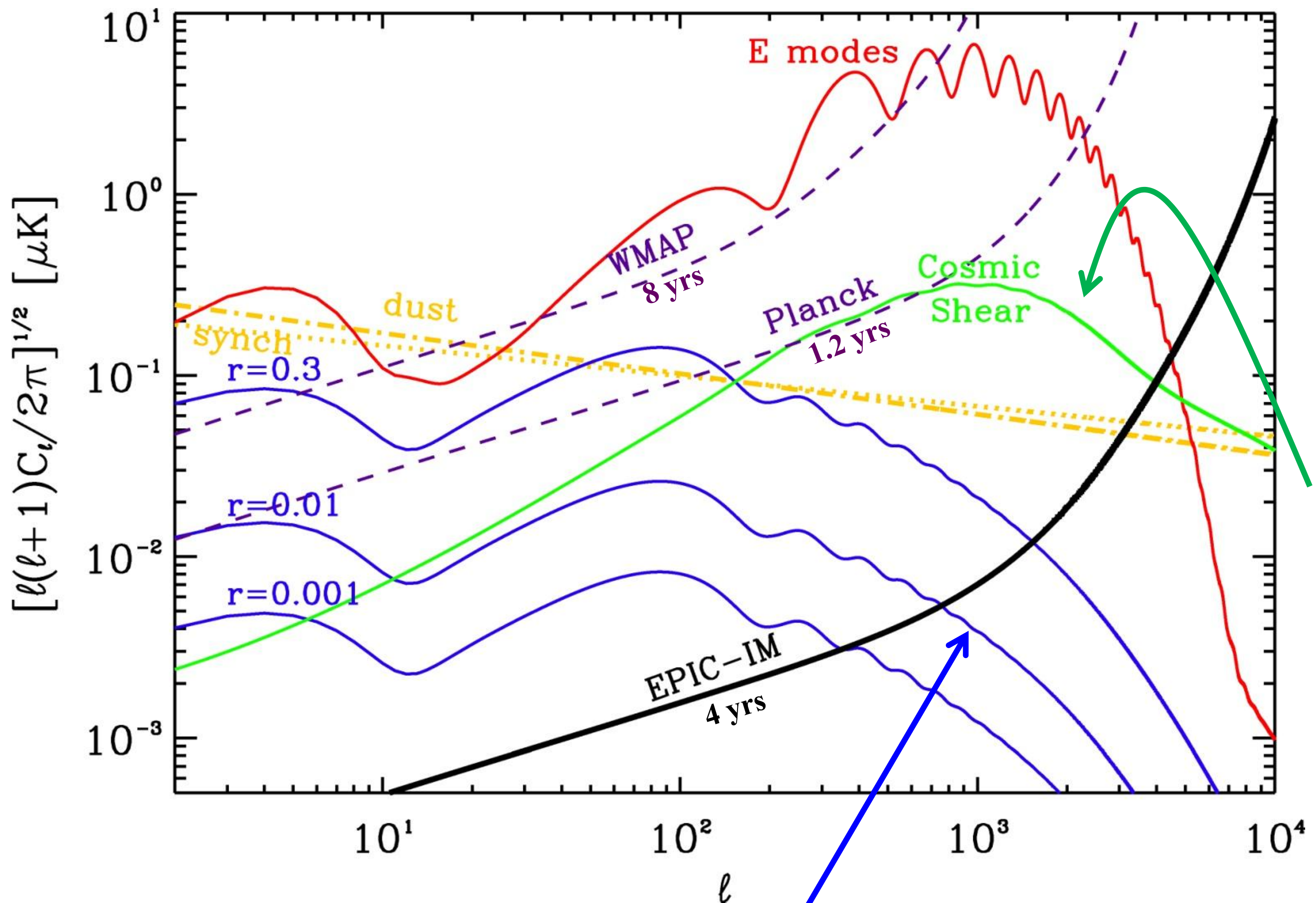
Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

- **GUT energy scale**
- **Large field inflation**

Confirm or Reject Large Field Inflation



Richness of the CMB Polarization Landscape



Measure B-mode cosmic shear spectrum to cosmic limits

- **Neutrino mass hierarchy**
- **Dark energy at z > 2**

Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

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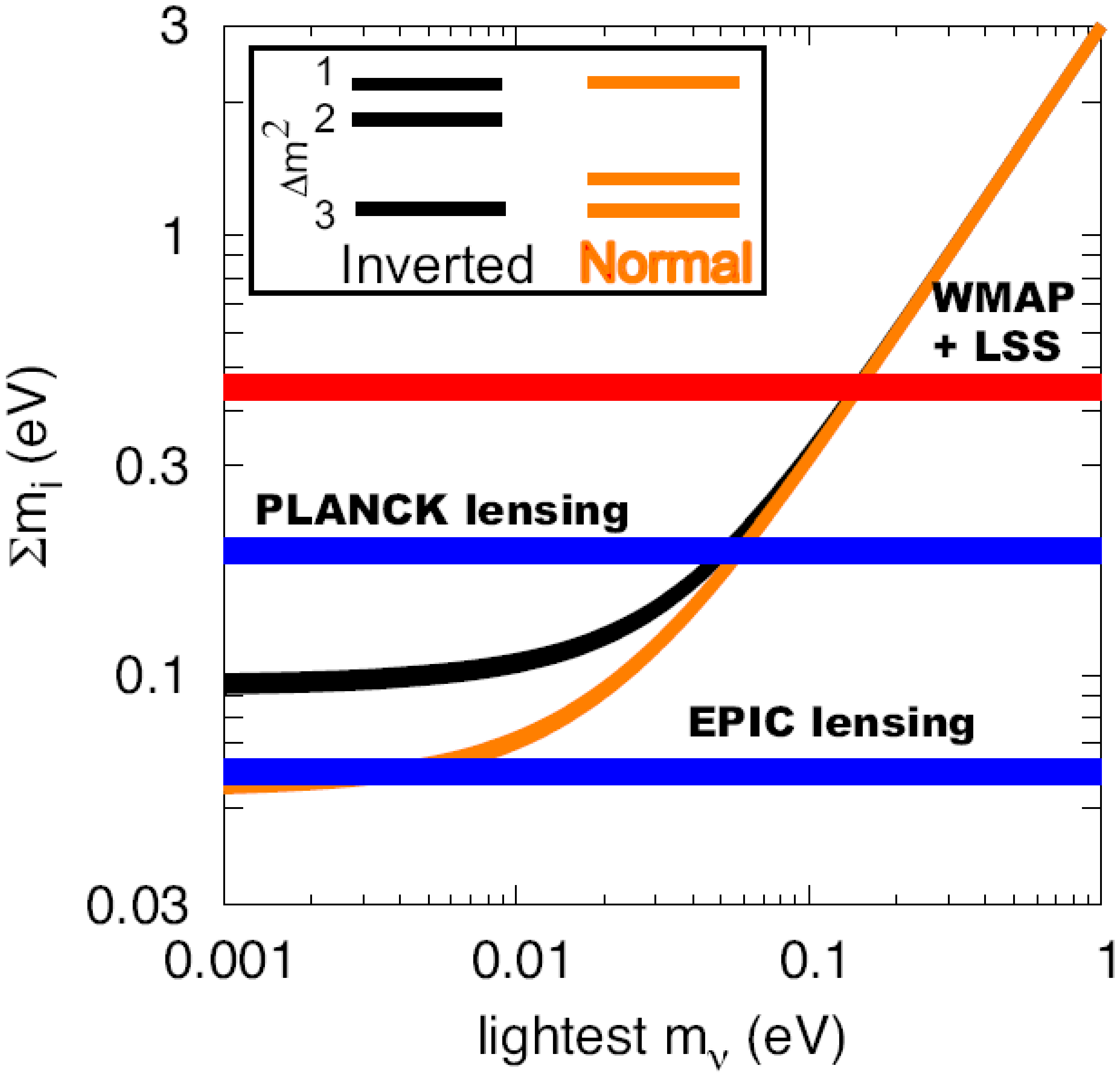
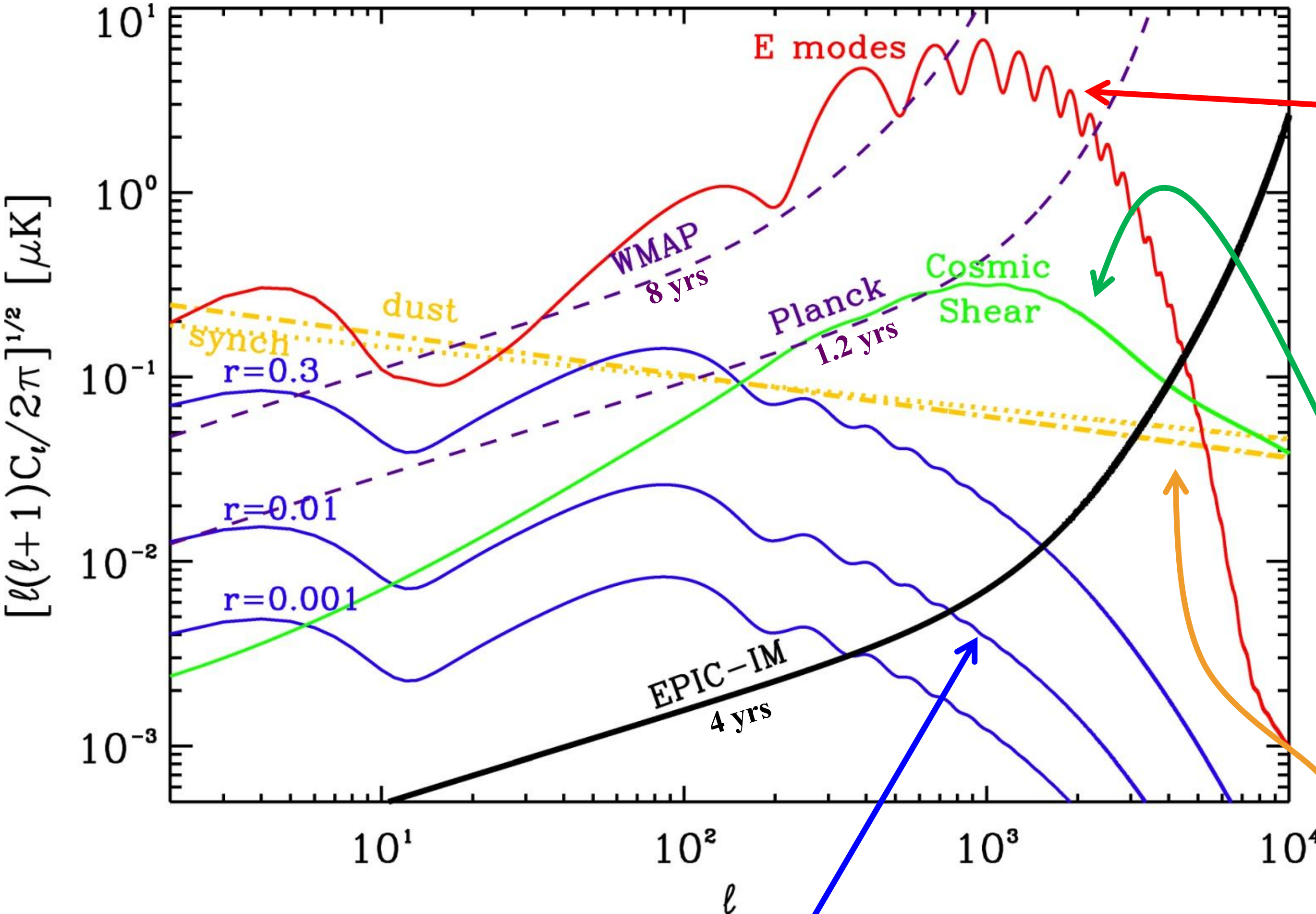
Neutrino Masses



Richness of the CMB Polarization Landscape



Measure E-mode spectrum to cosmic variance to damping tail

- Precision cosmology
- Reionization history

Measure B-mode cosmic shear spectrum to cosmic limits

- Neutrino mass hierarchy
- Dark energy at z > 2

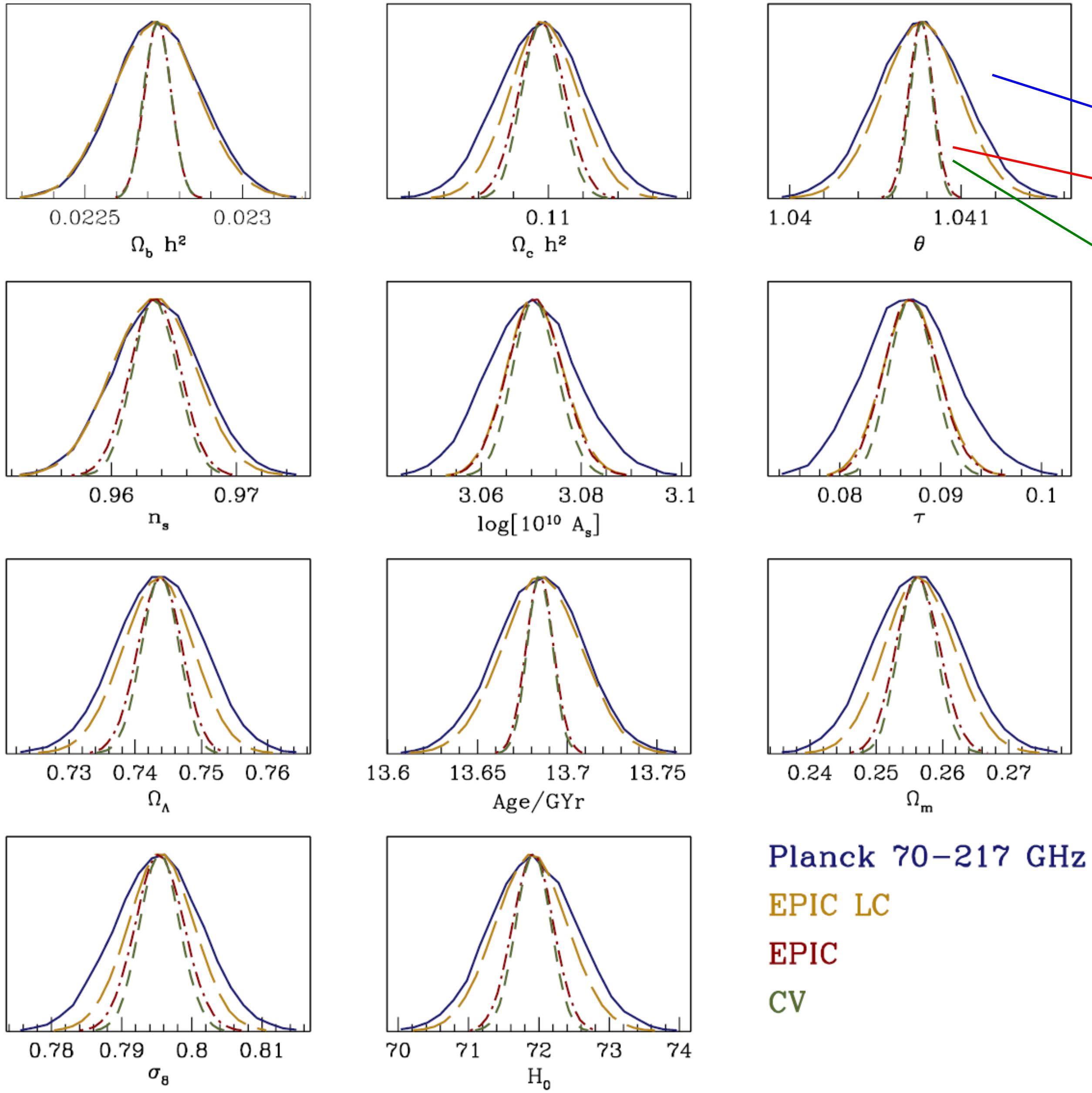
Map Galactic magnetic fields via dust polarization

- Star Formation
- Large-scale B-field

Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

- GUT energy scale
- Large field inflation

Precision Cosmology



<u>Compare</u>

Planck (Blue)

EPIC (Red)

Cosmological Limit (Green)

IPSAG Statement of Task

- Review and update mission science goals following current developments in the field (e.g. Planck, sub-orbital measurements),
- Review and update information about and requirements on potential foreground contaminants and their removal,
- Review and update requirements on and developments in control of systematic errors,
- Assess necessary technology developments and prioritize areas for increased technical emphasis.

The IPSAG work will build upon pre-New Worlds and New Horizons community and agency investments as summarized by reports from NASA’s 2009 Strategic Mission Concept Study and white papers submitted to NWNH.

IPSAG Current Status

- Dear Colleague letter sent March 10
- To date 40-45 members are signed on (~10 international)
  http://pcos.gsfc.nasa.gov/sags/ipsag.php
- First Telecon April 21 (~30 participants)
- Telecon Agenda:
  – Background for IPSAG
  – View from HQ
  – View of Program Office and of Advanced Concepts and Technologies Office
  – Summary of pre-decadal activities
  – Status of satellite mission abroad
  – Discussion

Telecon Discussion

- We have a space mission candidate.
- A number of sub-orbital experiments are now implementing various candidate technologies; support for sub-orbitals should continue consistent with NWNH recommendations.
- We have carried out extensive theoretical studies prior to NWNH; more information will come from Planck and the sub-orbital experiments.
- The field is ready to move toward more concrete definition of technical requirements, and toward identifying technology areas of emphasis.
- Some discussion of mid-decade review and how this will work.

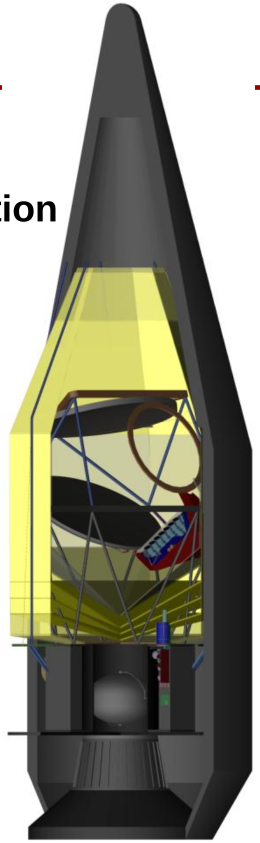
IPSAG: Outcome of First Telecon

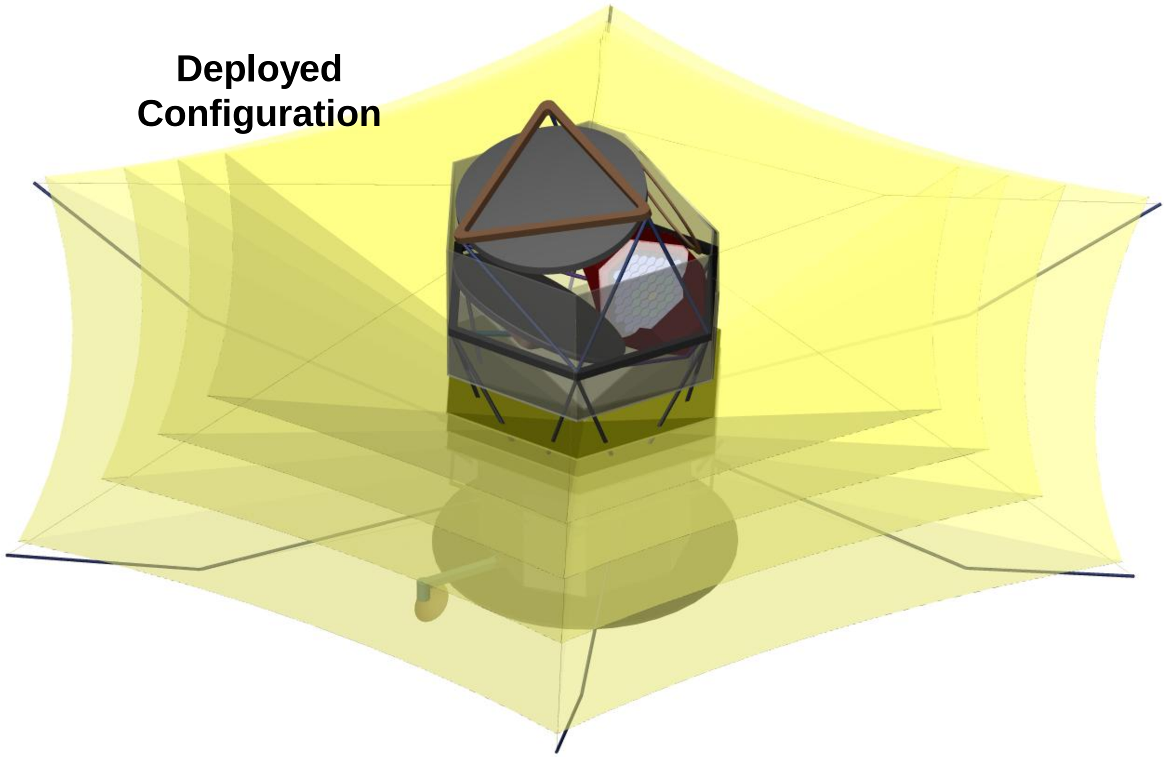
- Work with Office of Advanced Concepts and Technologies to define technology needs for space mission and necessary developments toward it.

- Community reiterates importance of mid-decade review of status.

Back Up Material

EPIC-IM Specification Sheet



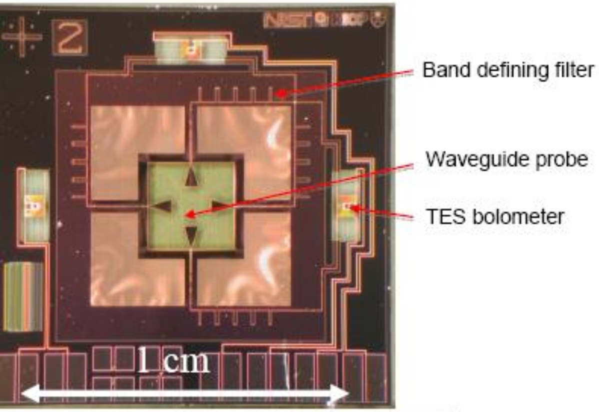


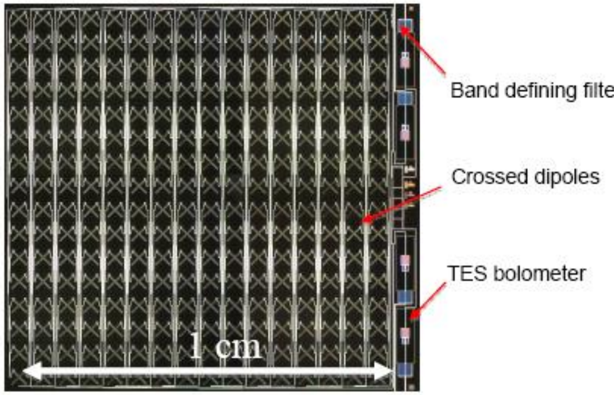
Optics	1.4 m wide-field crossed Dragone	**Total Delta-V**	170 m/s
Orbit	Sun-earth L2 halo	**Payload Power**	440 W (CBE)
Mission Life	4 years	**Spacecraft Power**	533 W (CBE)
Launch Vehicle	Atlas V 401	**Total Power**	1392 W (w/ 43 % cont.)
Detectors	11094 TES bolometer or MKID detectors	**Payload Mass**	813 kg (CBE)
Bands	30, 45, 70, 100, 150, 220, 340, 500 & 850 GHz	**Spacecraft Mass**	584 kg (CBE)
Sensitivity	0.9 mK arcmin; 3600 Planck missions	**Total Mass**	2294 kg (w/ 43 % cont.)
Spacecraft	3-axis commercial	**Vehicle Margin**	1287 kg (36 %)
Data Rate	7.7 Mbps	**Cost**	$920M FY09

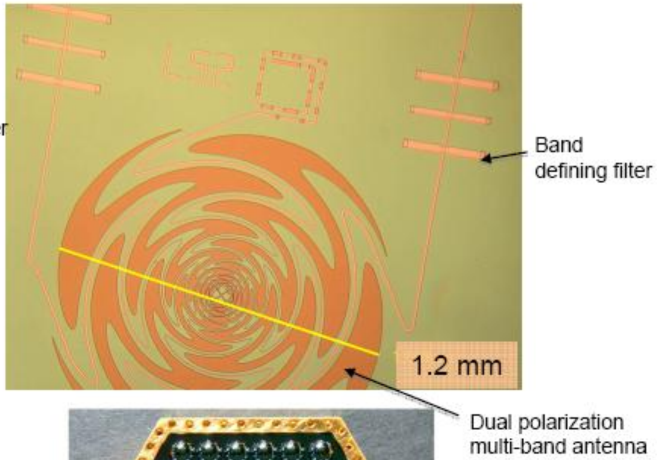
Mass similar to the Planck satellite mission

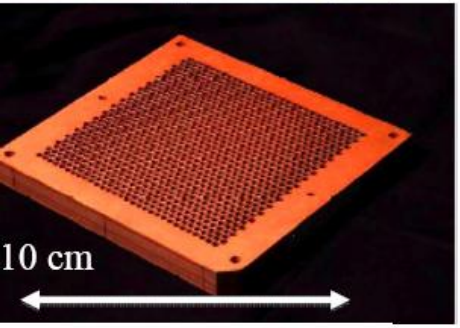
Technology Commissioning

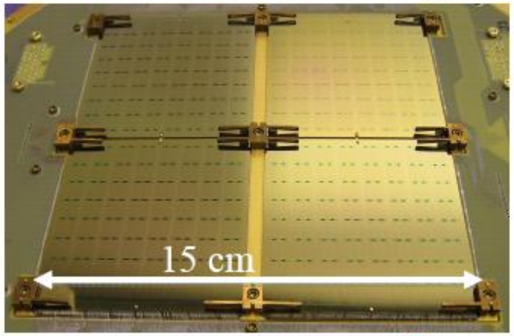
EPIC Focal Plane Technologies

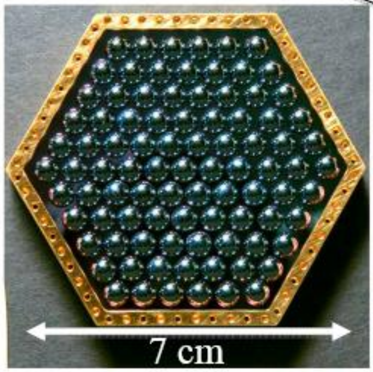


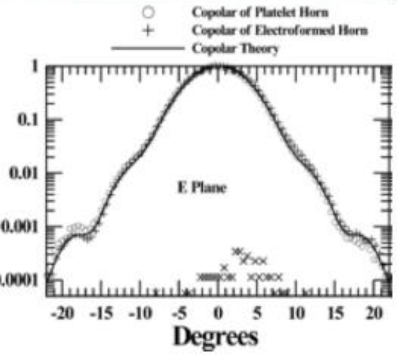


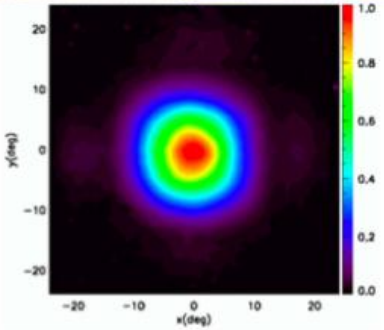


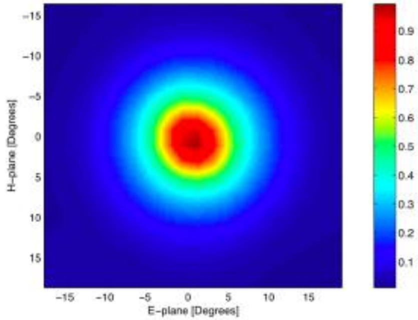






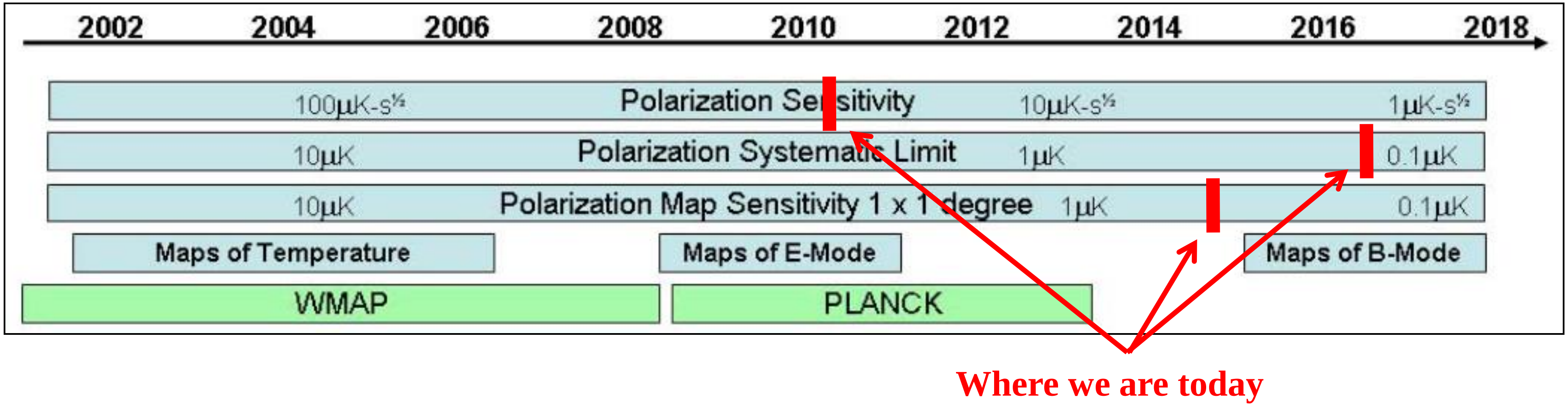






The Path to CMBPol

Task Force for CMB Research Weiss Report 2005: Projected Timeline



Sub-Orbital Program:

Strong push to detect the inflationary signal by mid decade

Satellite Mission:

A definitive, comprehensive measurement of the CMB Polarization

Funded US Sub-Orbital Experiments

Table 1: Future Suborbital CMB Polarization Experiments.

	Technology	FWHM (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led balloon-borne:					
EBEX (Oxley et al., 2004)	TES	8	150/250/410	398/199/141	HWP
Spider (Montroy et al., 2006)	TES	60/40/30	96/145/225	288/512/512	HWP/Scan
PIPER I	TES	21/15	200/270	2560/2560	VPM
PIPER II	TES	14	350/600	2560/2560	VPM
US-led ground-based:					
ABS(Staggs et al., 2008)	TES	30	150	200	HWP
ACTpol(Fowler et al., 2007)	TES	2.2/1.4/1.1	90/145/217	~ 1000	Scan
BICEP 2(Nguyen et al., 2008)	TES	37	150	256	HWP/Scan
Keck Array(Nguyen et al., 2008)	TES	55/37/26	100/150/220	288/512/512	HWP/Scan
MBI(Korotkov et al., 2006)	NTD	60	100	4	Int.
Poincare(Chuss, 2008)	TES	84/30/24	40/90/150	36/300/60	VPM
PolarBeaR(Lee et al., 2008)	TES	7/3.5/2.4	90/150/220	637	HWP
QUIET I(Samtleben, 2008)	MMIC	20/10	44/90	~100/1000	ϕ-switch
SPTpol(Ruhl et al., 2004)	TES	1.5/1.2/1.1	90/150/225	~ 1000	Scan
European-led ground-based:					
BRAIN(Polenta et al., 2007)	TES	60	90/150	256/512	Int.
C_ℓOVER(Piccirillo et al., 2008)	TES	7.5/5.5/5.5	97/150/225	3x96	HWP
QUIJOTE(Rubino-Martin et al., 2008)	HEMT	54-24	10-30	34	HWP

From CMB project paper submitted to Astro2010

A Healthy Variety of Experimental Approaches and Technologies

Target r: ~0.02-0.05

Time scale: few years