The Inflation Probe Science Analysis Group

Jamie Bock (Caltech/JPL)
for
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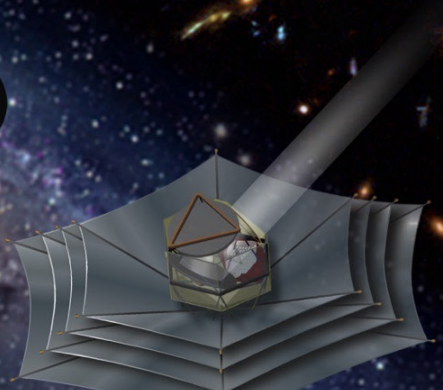
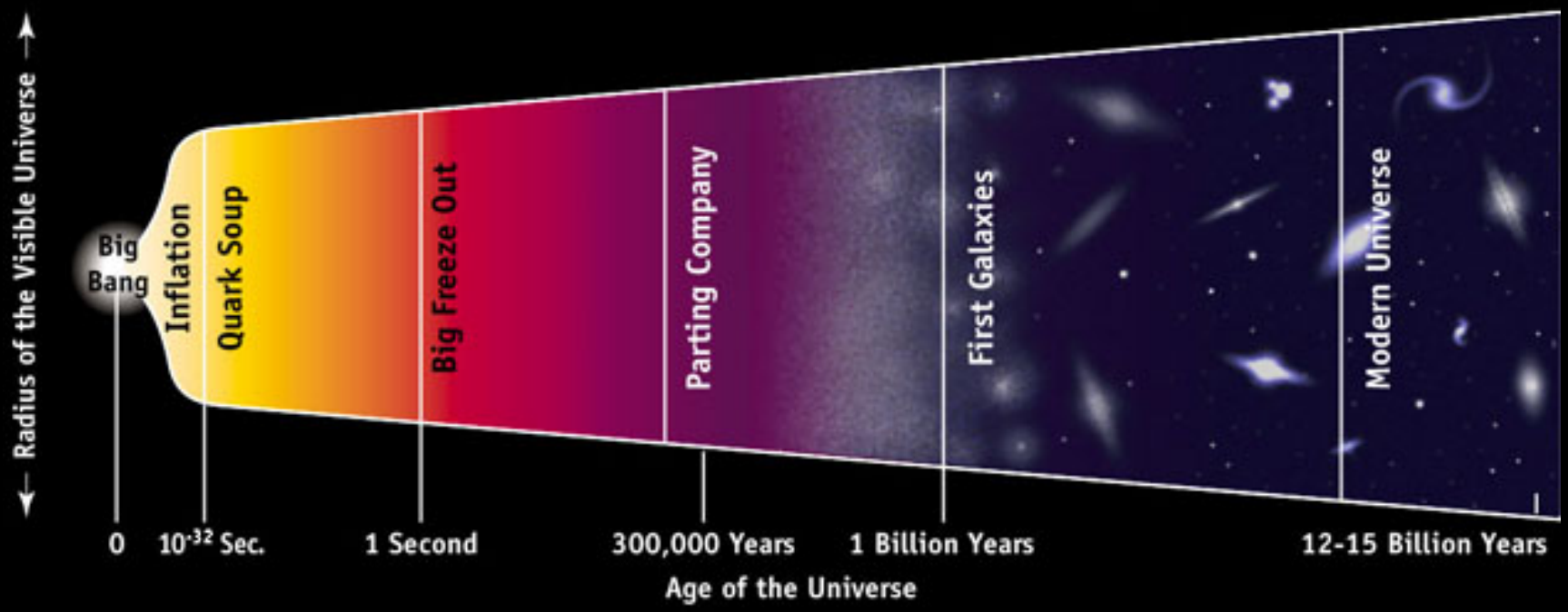


PhysPAG Meeting, AAS @ Long Beach, CA
6 January 2013

Testing Inflation with CMB Polarization



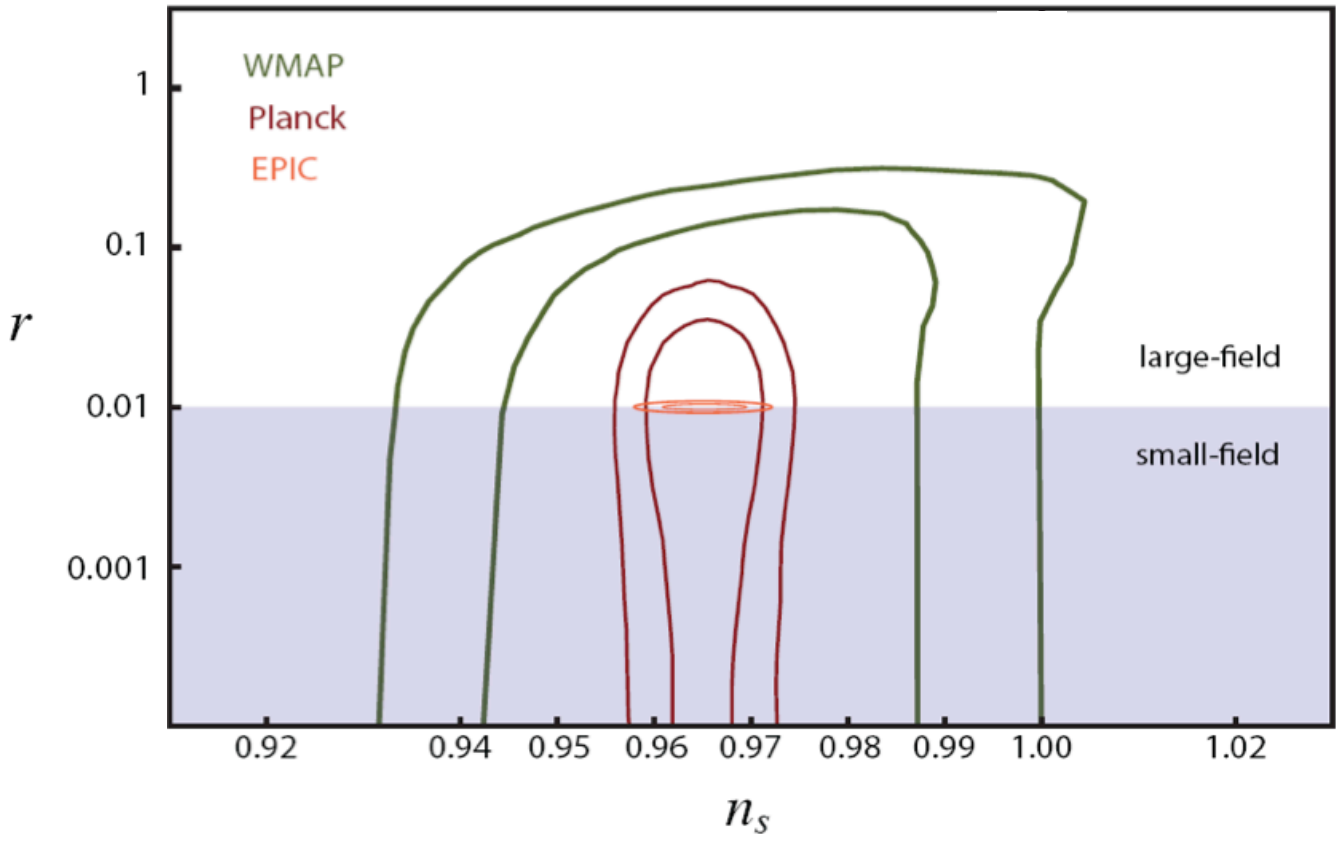
Key Inflationary Observables	First Definitive CMB Result
1. Nearly scale-invariant fluctuations	COBE
2. Flat universe	Boomerang + Maxima + TOCO
3. Adiabatic fluctuations	Boomerang + Maxima + WMAP
4. Nearly Gaussian fluctuations	WMAP
5. Super horizon fluctuations	WMAP
6. Departure from scale invariance?	Planck
7. Non-Gaussianity?	Planck
8. Inflationary gravitational waves?	**Inflation Probe**

Comprehensively measure inflationary CMB polarization signal corresponding to inflation at GUT energy scales

Significance of Inflationary Polarization

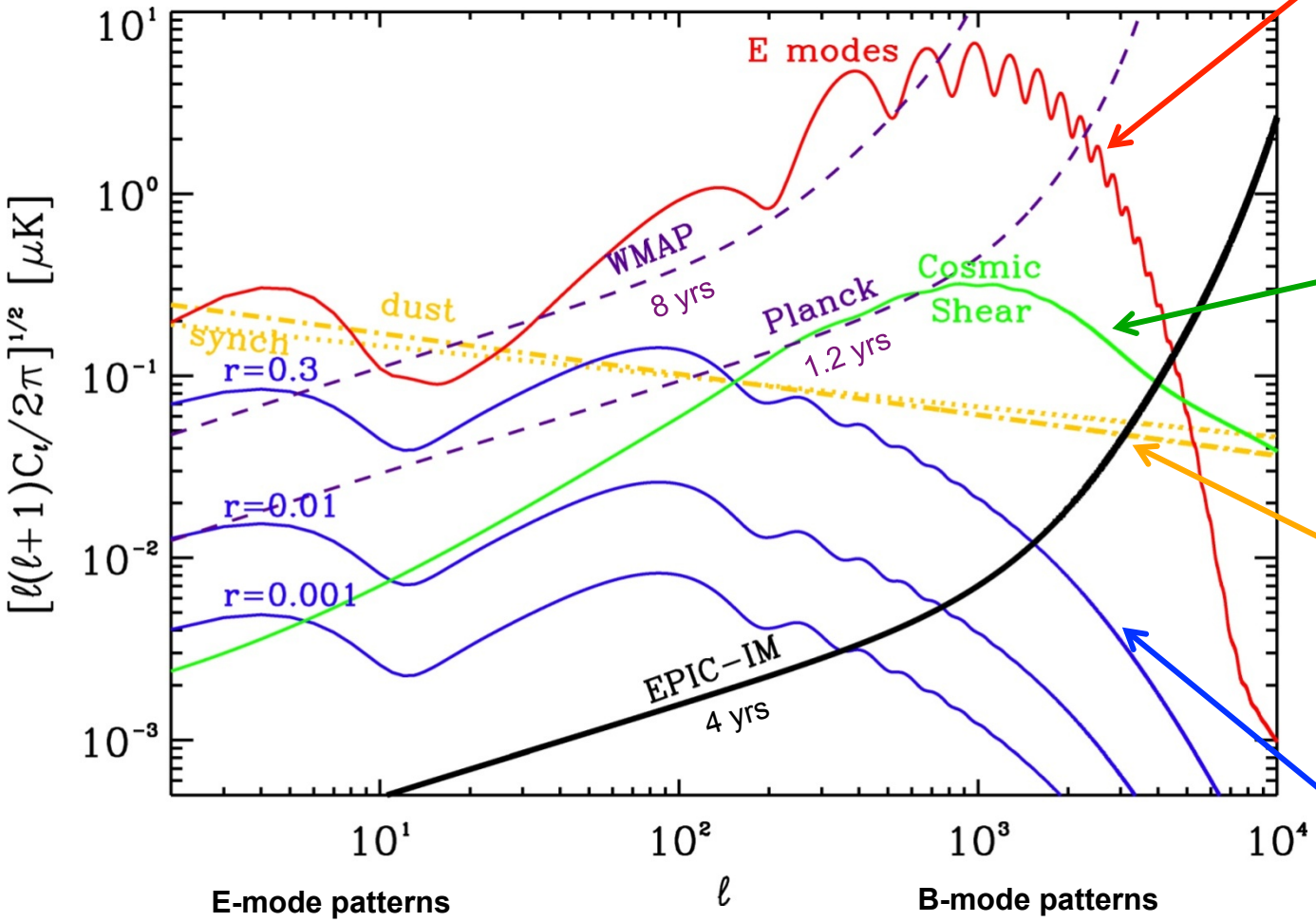
- B-modes *cannot* be produced by density variations
- Constrains Big Bang physics at GUT energy scales
- Simplest Inflation models predict a detectable level of r > 0.01
- Slow-roll models predict a relationship between $(1 - n_s)$ and r

"Detection of B-mode polarization in the CMB polarization … would represent a watershed discovery." - *New Worlds New Horizons*

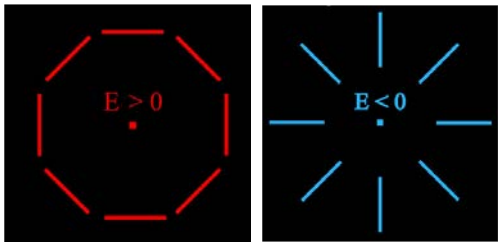


CMB Polarization Science is Deep and Broad

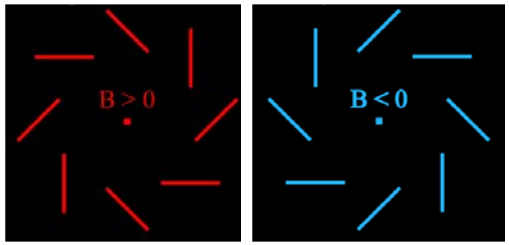
CMB Polarization Spatial Power Spectra



E-mode patterns



B-mode patterns



Scalar Perturbations
E-modes

- Precision cosmology
- Departure from scale inv.
- Reionization history

Gravitational Lensing
B-Modes

- Neutrino mass hierarchy
- Dark energy at z > 2

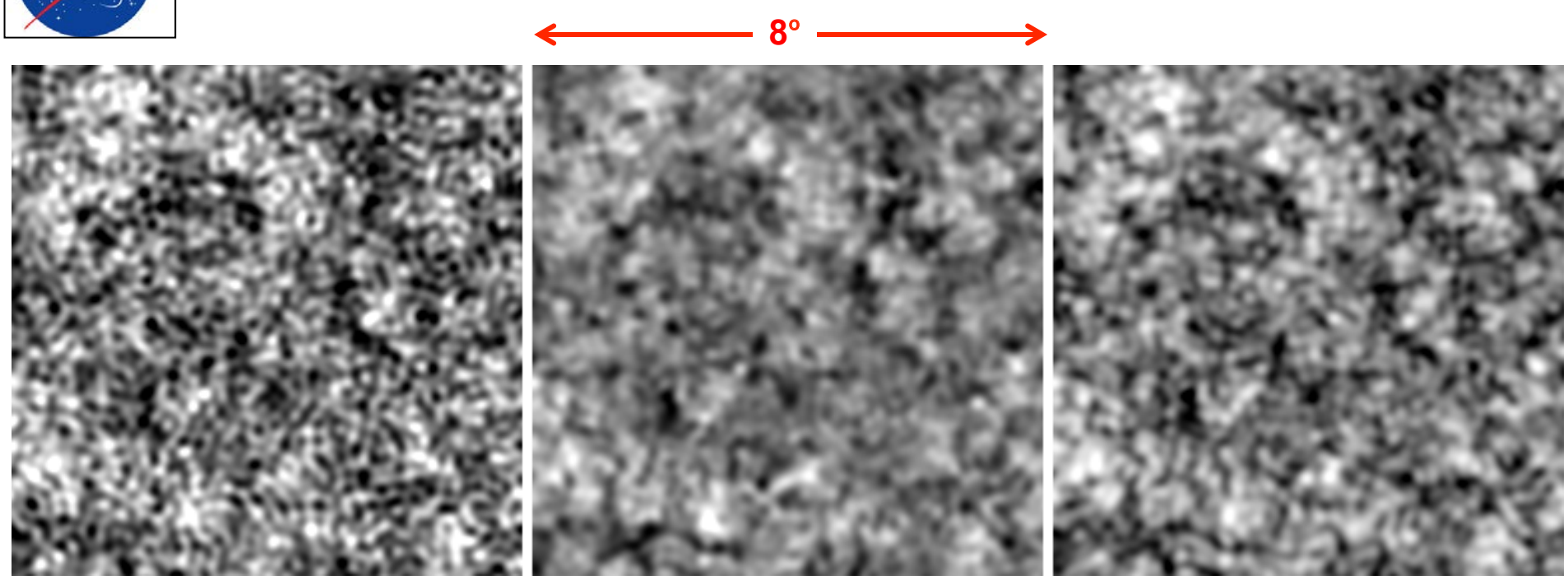
Galactic Magnetic Fields
E & B-Modes

- Star formation
- Large-scale fields

Inflationary Gravitational Waves
B-modes

- GUT energy scale
- Large field inflation
- n_t / r consistency test

Using CMB Lensing to Study Large Scale Structure



Theoretical projected potential

Optimal Quadratic
(Hu 2001)

Likelihood
(Hirata & Seljak 2003)

Caltech workshop to study space and ground-based surveys of CMB lensing

CMB polarization measures projected graviational potential

- neutrino masses
- late dark energy
- relation between galaxy formation and dark matter
- a legacy data product for galaxy-based studies of structure formation

New Worlds, New Horizons in Astronomy and Astrophysics

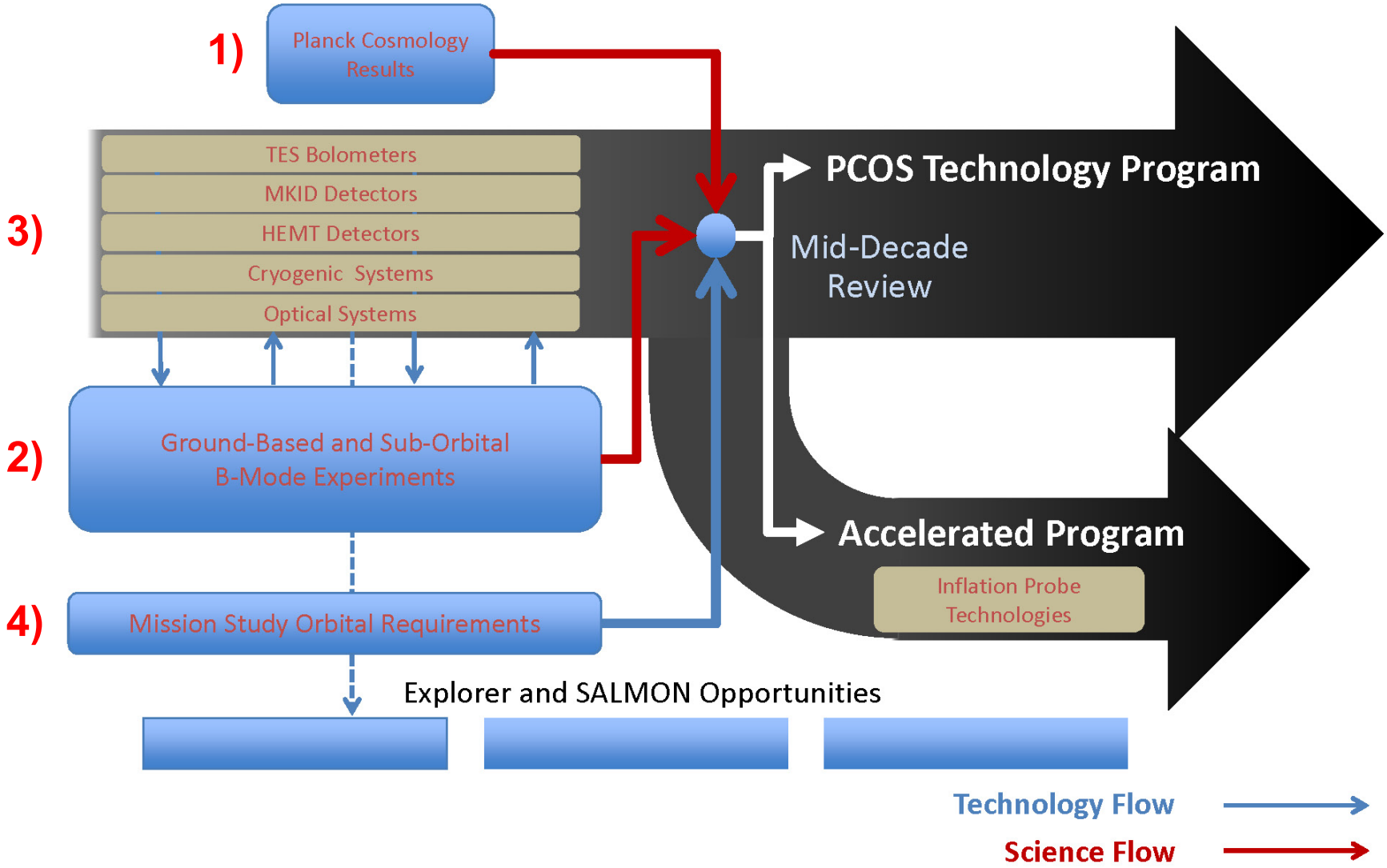
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]	Cross-Reference in Chapter 7
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M	Page 215
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M	Page 217

"A successful detection of B-modes from inflation could trigger a mid-decade shift in focus toward preparing to map them over the entire sky. In this case a notional decadal budget of $60 million is proposed. However, the level of late-decade investment required is uncertain, and the appropriate level should be studied by a decadal survey independent advice committee review. It could range between the notional budget used here up to a significant (perhaps on the order of $200 million) mission-specific technology program starting mid-decade."

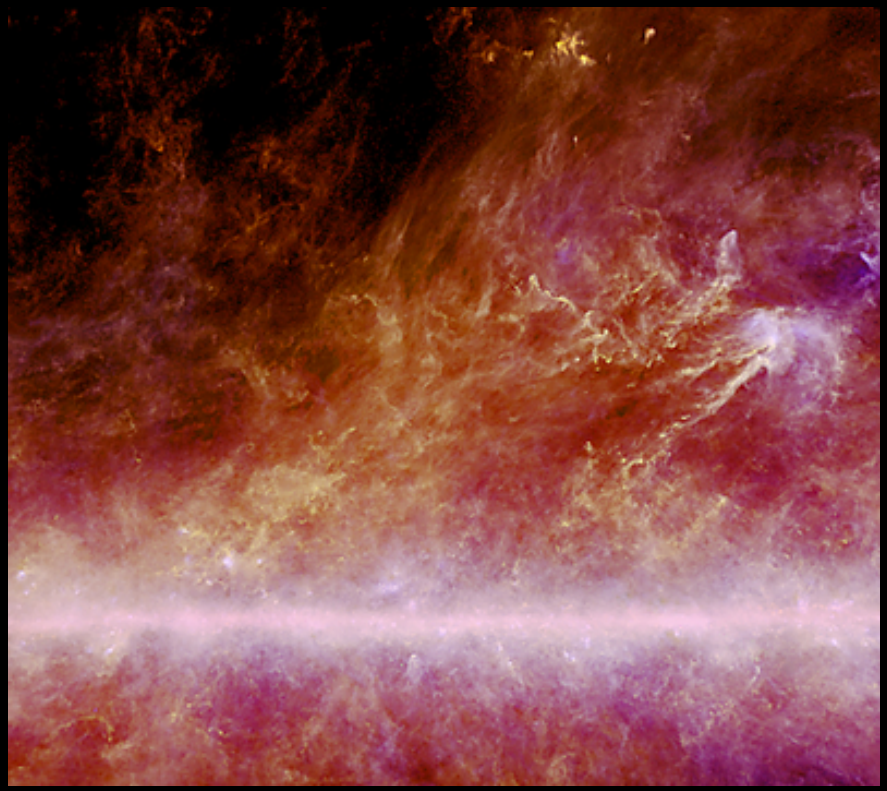
Timeline for the Decade

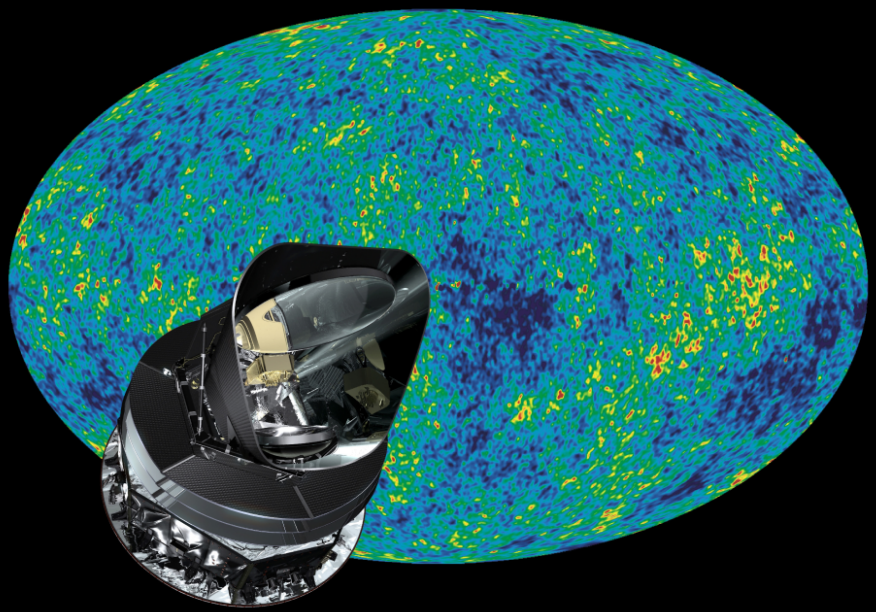


The ESA / NASA *Planck* Satellite

Instrument Status
- HFI sensitivity exceeds pre-launch goals
- Thermal system performance as expected
- 100 mK operations ended in January 2012
- Extended observations continuing

Planck Strengths
- Comprehensive temperature measurements
- 9 bands for foregrounds separation
- Good polarization sensitivity
  - High-fidelity E-mode polarization measurements
  - Sensitivity for B-mode detection?





Mission Events

• 14 May 2009	Launch
• March 2010	First sky map complete
• March 2011	Third sky map complete
• January 2012	End of HFI life (LFI continues)

Planned Data Releases

• January 2011	Point Source Catalog & Astrophysics
• March 2013	CMB Temperature
• Early 2014	CMB Polarization #1

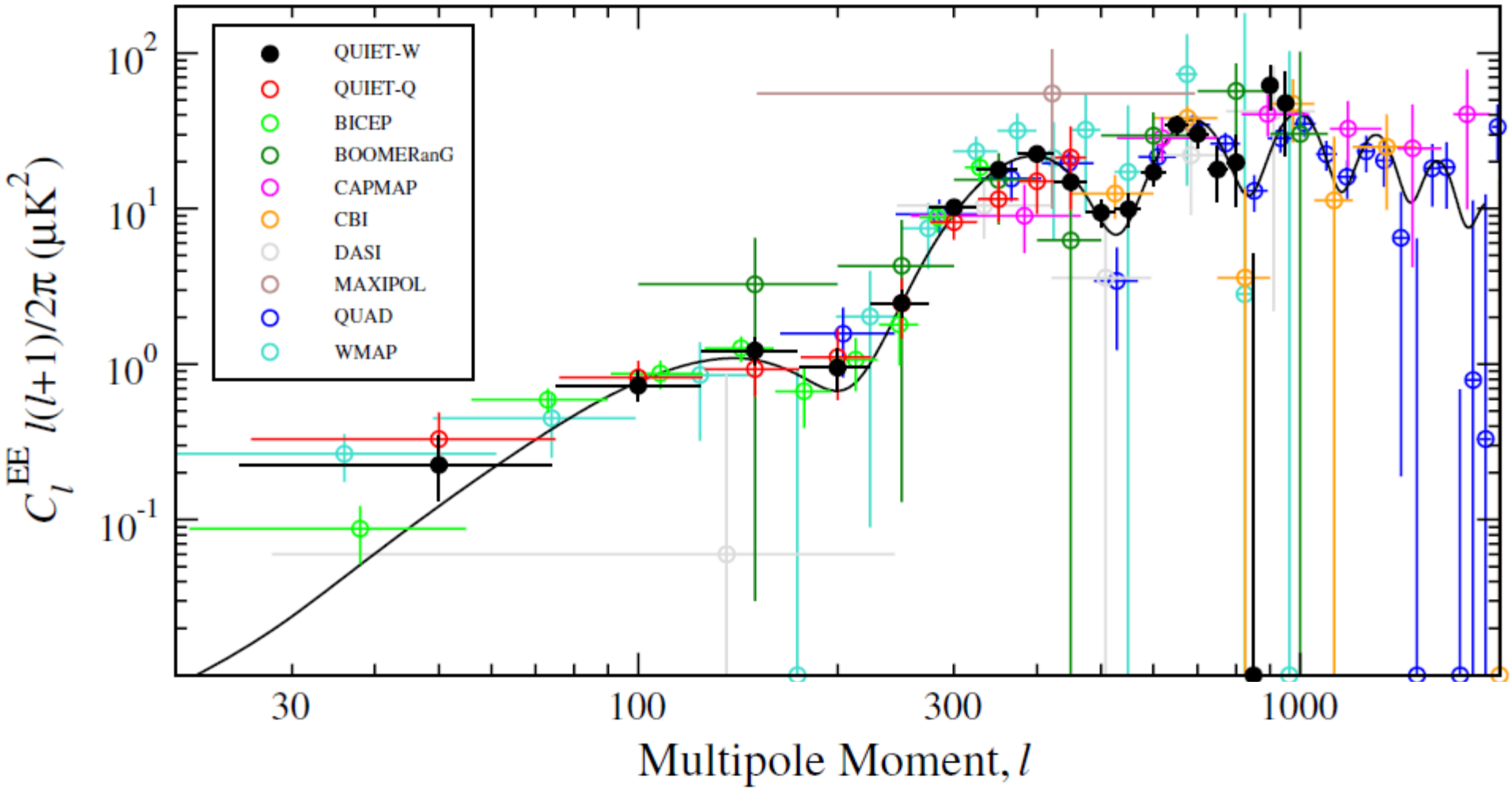
Sub-Orbital and Ground-Based Experiments

	Experiment	Technology	Resolution (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led Balloon	COFE	HEMT/MMIC	83/55/42	10/15/20	3/6/10	wire grid
	EBEX	TES	8	150/250/410	398/199/141	HWP
	PIPER	TES	21/15/12/7	200/270/350/600	2560	VPM
	SPIDER	TES	60/40/30	90/150/280	288/512/512	HWP
US-led Ground	ABS	TES	30	150	200	HWP
	ACTpol	TES	2.2/1.4	90/145	1500	-
	BICEP2	TES	40	150	256	-
	BICEP3	TES	22	95	1280	-
	C-BASS	HEMT	44	5	1	ϕ-switch
	CLASS	TES	80/34/22	40/90/150	36/300/60	VPM
	Keck	TES	60/40/30	96/150/220	288/512/512	HWP
	POLARBeaR	TES	7/3.5/2.4	90/150/220	637	HWP
	QUIET	HEMT/MMIC	42/18	44/90	19/100	ϕ-switch
	SPTpol	TES	1.5/1.2	90/150	768	-
Int'l Ground	AMiBA	HEMT	2	94	20	Int.
	QUBIC	TES	60	90/150	256/512	Int.
	QUIJOTE	HEMT	54-24	10-30	38	-

- **Push to higher sensitivity than Planck: new detector array technologies**
- **Focused on B-mode science: target small, deep fields**
- **Explore the diversity of technology approaches**
- **Test new methodologies for systematic error control**
- **Rapid progress in sensitivity and systematic error control**

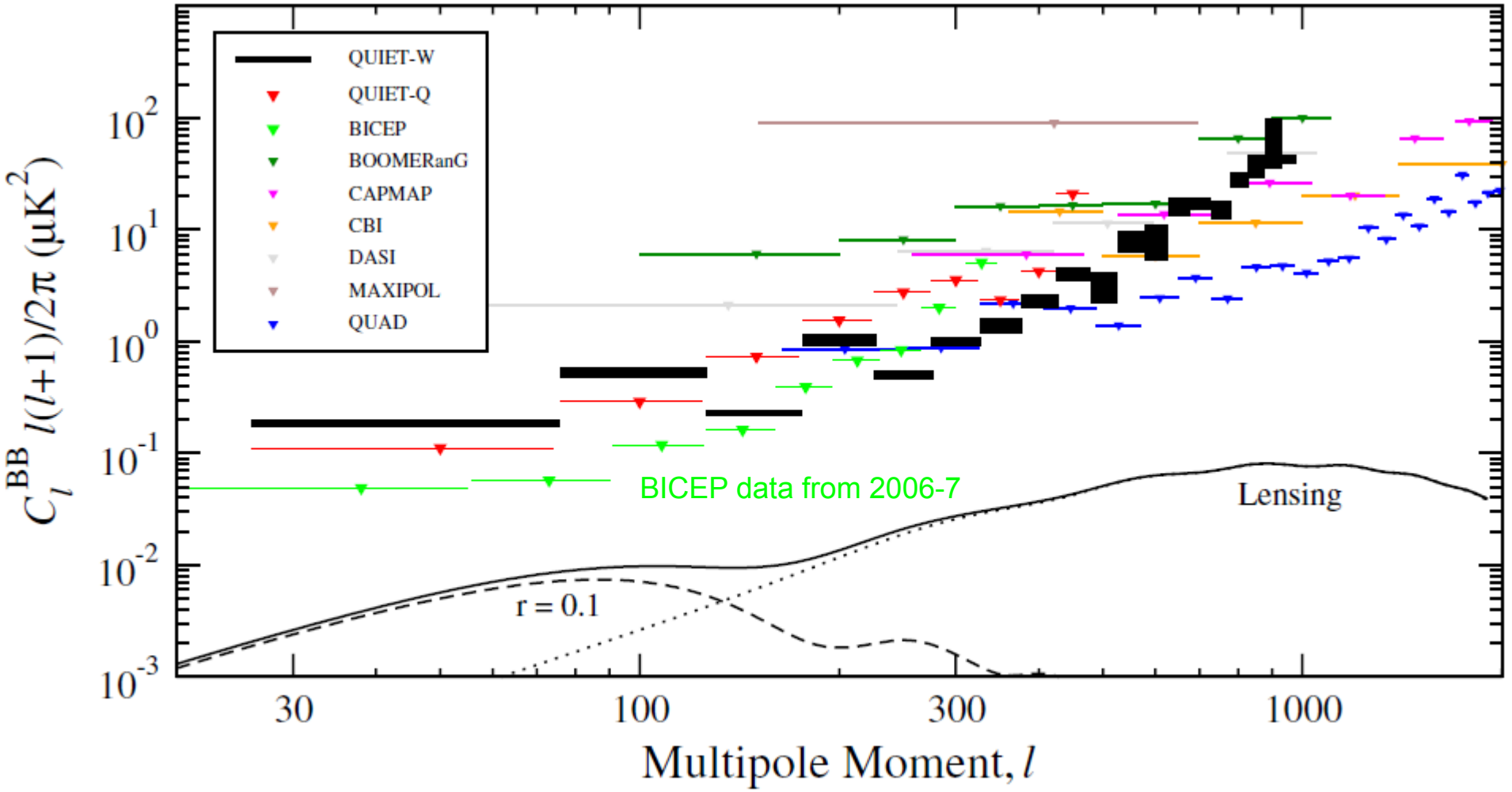
High Significance E-Mode Polarization Detections

QUIET Collaboration *et al*. (2012)

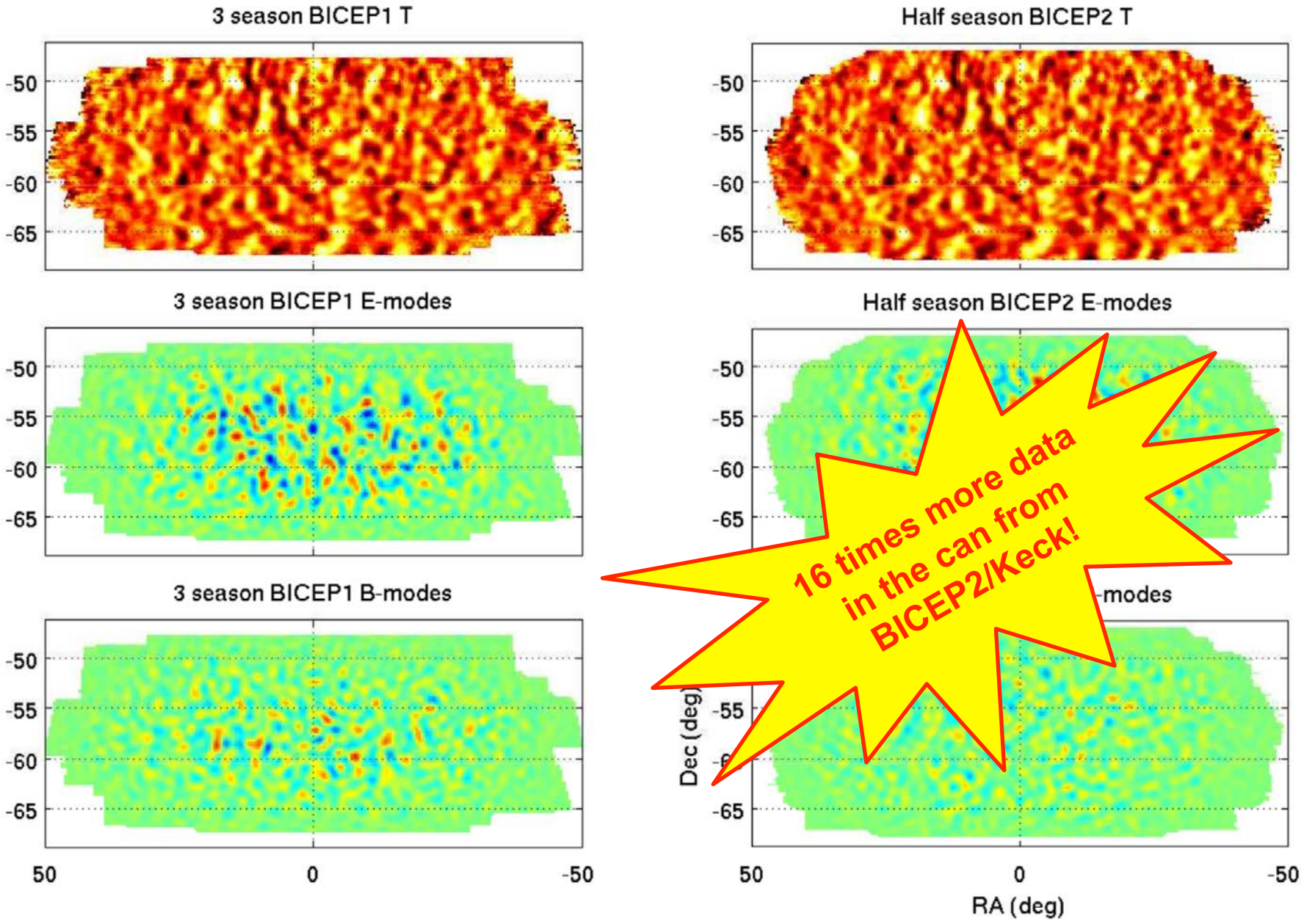


B-Modes? Improving Upper Limits

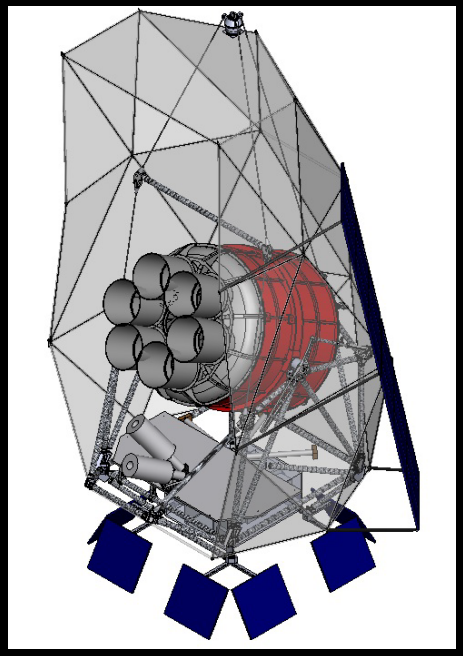
QUIET Collaboration *et al*. (2012)



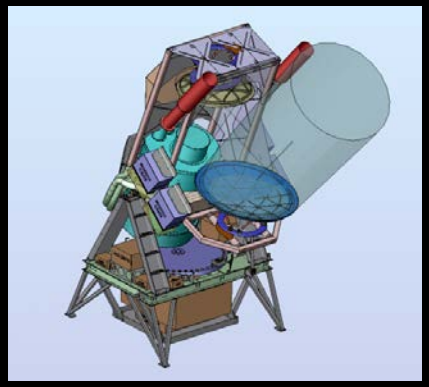
A Taste of What is to Come



The Race for Inflationary B-Modes

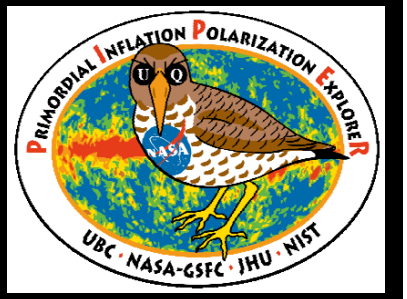


SPIDER

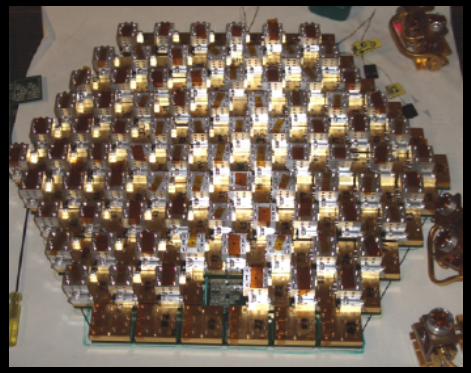


EBEX

POLARBEAR

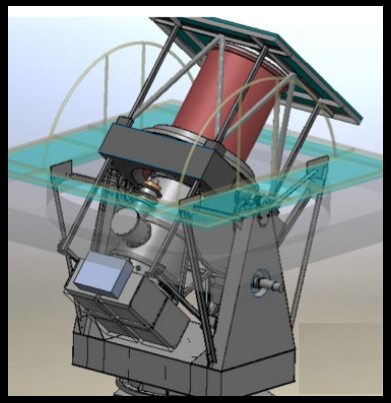


PIPER

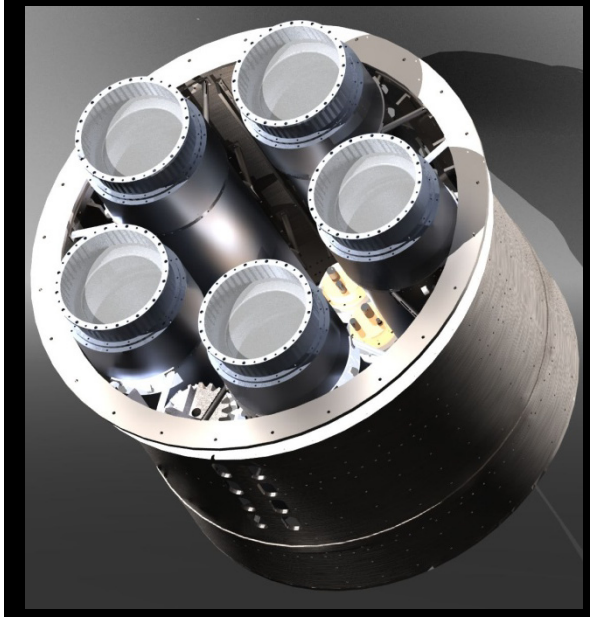


QUIET

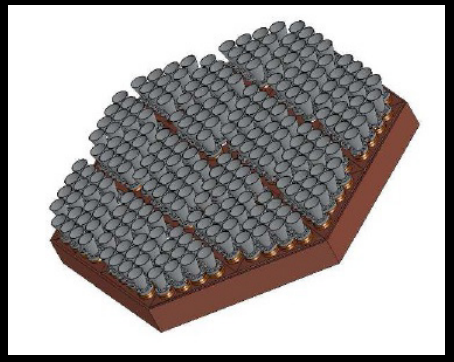
SPT-POL



BICEP3



BICEP2 / KECK



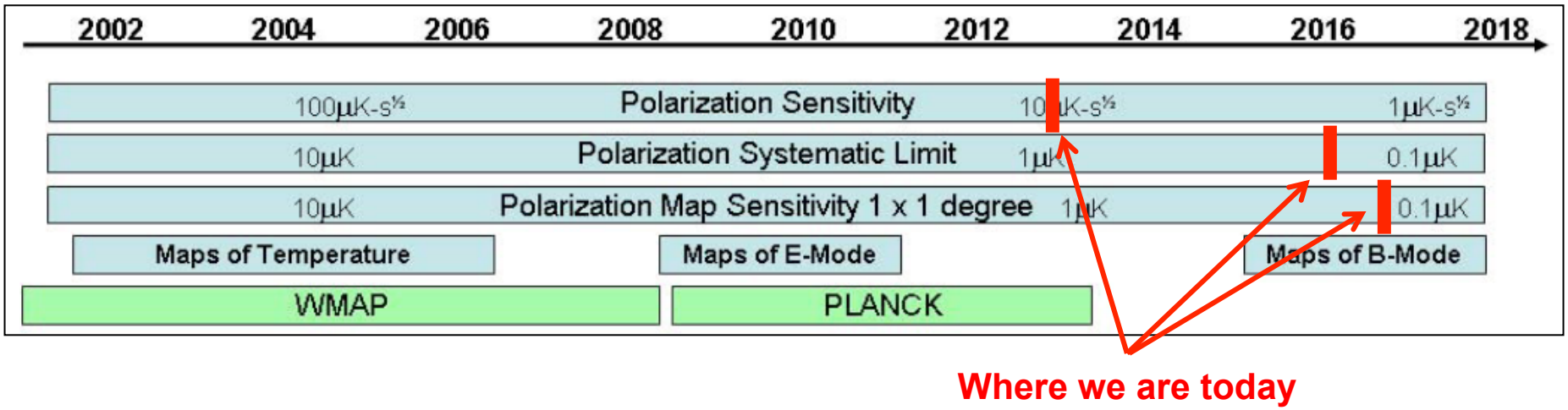
ABS

ACT-POL

RED indicates experiment has been fielded

The Weiss CMB Task Force Report in 2005

Task Force for CMB Research Weiss Report: Projected Timeline



Inflation Probe Technology Development

Priorities from the Inflation Probe Technology Roadmap

Technology	Priority	Timescale	Candidates	TRL
Detector Arrays	High	Sub-orbital experiments	TES+SQUID+Antenna HEMT / MMIC	4-5
Optics	Medium	Sub-orbital experiments	Polarization modulators AR coatings	2-5
Coolers	Low	Develop for space	Passive+mechanical+sub-K	3-9
Advanced Arrays		Develop for simplified space implementation. Connects to X-ray, far-IR and optical astronomy	MKID+RF resonator TES+RF resonator	3

Community Technology Plan

- Very directed: 4 technologies
- Effective: implement in sub-orbital and ground-based experiments
- Cross-cutting: overlap with X-ray and far-infrared needs
- Prioritization: clearly described

The IPSAG supports the streamlined PCOS/COR technology prioritization criteria

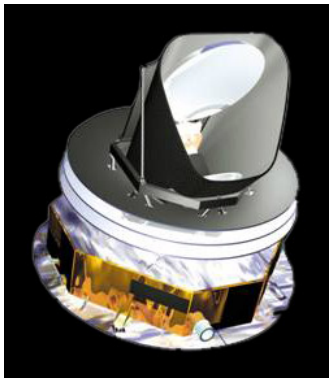
Technologies to Space: A Proven and Cost-Effective Path

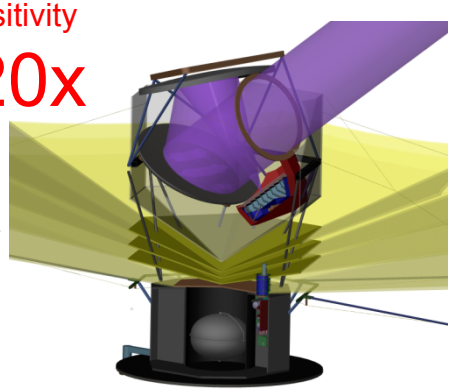
Satellite Mission

Sensitivity 60x

Sensitivity 20x

Sensitivity >20x





100 μK → 1 μK → 100 nK → few nK

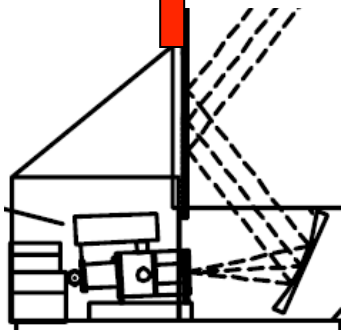
Sub-Orbital Precursor

COBE 1989

U2-DMR

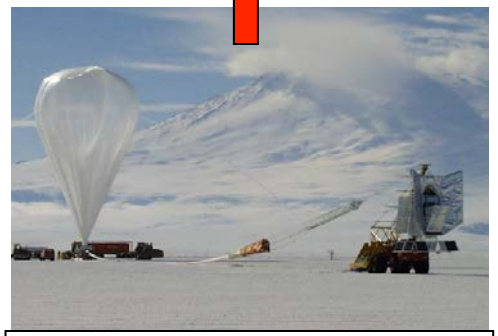
Woody-Richards

WMAP 2001



QMAP, SK, TOCO

Planck 2009



Archeops, Boomerang, Maxima

Inflation Probe 2022?

Multiple

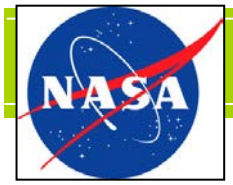
Ground-based

&

Balloon-borne

Historical Interplay: Suborbital Experiments serve to

- Shape scientific objective of a space mission
- Train leaders of future orbital missions
- Develop experimental methodologies
- Develop technologies at systems level



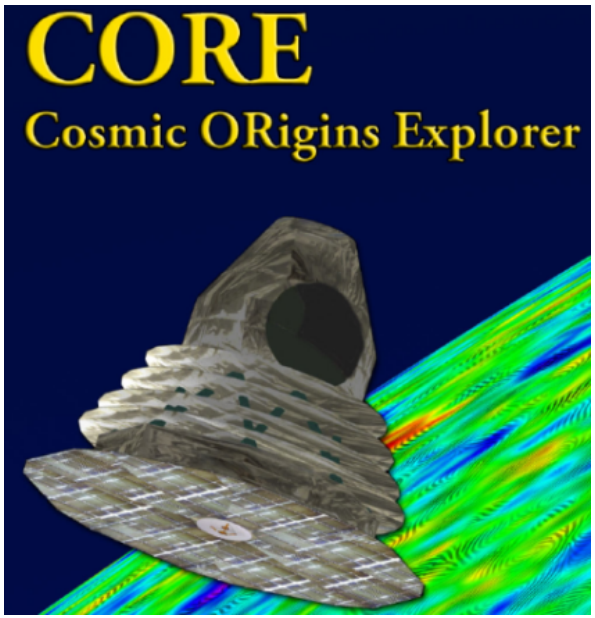
Inflation Probe Technology Challenges

- Most urgent Inflation Probe technology needs are at mid-TRLs
- CMB technology funding has been extremely limited to date
- Technology readiness is governing rate of scientific progress needed for the mid-decade assessment

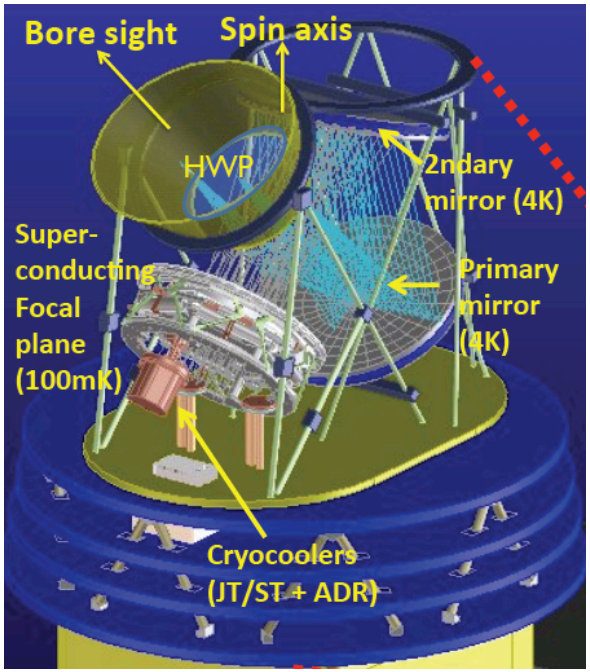
The IPSAG recommends increased mid-TRL funding for Inflation Probe technology development in preparation for the mid-decade assessment.

Inflation Probe Mission Studies: International

- The European CORE Consortium will propose an Inflation Probe mission for the next ESA opportunity, expected in 2014.
- The CORE Consortium held a "Workshop on Spectral Polarimetry" 11-12 December to explore a lost-cost polarized spectroscopic instrument concept
- JAXA is studying the Explorer-class LITEBIRD discovery mission, selectable as early as 2013



CORE
ESA 2010 proposal
1.2 m aperture



LITEBIRD
JAXA Explorer-class concept
60 cm aperture

Inflation Probe Mission Studies: US

- There is no US mission study activity at present. Study effort in was very effective with wide participation from the CMB community in 4 workshops
- The Astrophysics Implementation Plan states an Inflation Probe mission study is “under consideration for 2015”
- Advantages of starting Inflation Probe mission studies:
  - Needed for the mid-decade assessment
  - A probe option for the 2015 decision
  - Injects US participation in the European proposal during its development
- Disadvantages?
  - Planck polarization data will be released in 2014, but with significant analysis and concurrent interpretation by the Planck team in place
  - Readiness of sub-orbital and ground-based measurements is difficult to predict. But this does not gate studies which can proceed in parallel.

The IPSAG recommends starting mission study activities at the earliest opportunity, which provide advantages for NASA for little cost. We encourage NASA to engage the CMB community about starting a mission study effort in 2014.

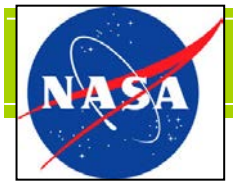
Summary

1) Planck data are excellent and will be released on schedule to inform the design of the Inflation Probe

2) The CMB community is making rapid progress in sub-orbital and ground-based experiments searching first detection of B-mode polarization. The lensing B-mode signal is in the detectable range and is a future cosmological tool

3) Technology funding has lagged behind expectations. We recommend augmenting mid-TRL technology funding, as this will gate progress towards the mid-decade assessment and beyond

4) We recommend starting mission study activities at the earliest opportunity



Backups

CMB Polarization Satellite Mission Concepts

Experimental Probe of Inflationary Cosmology

CMB community mission developed for Decadal

1.4 m Crossed Dragone Telescope

- Resolution to measure lensing signal cosmic limits

Large Focal Plane

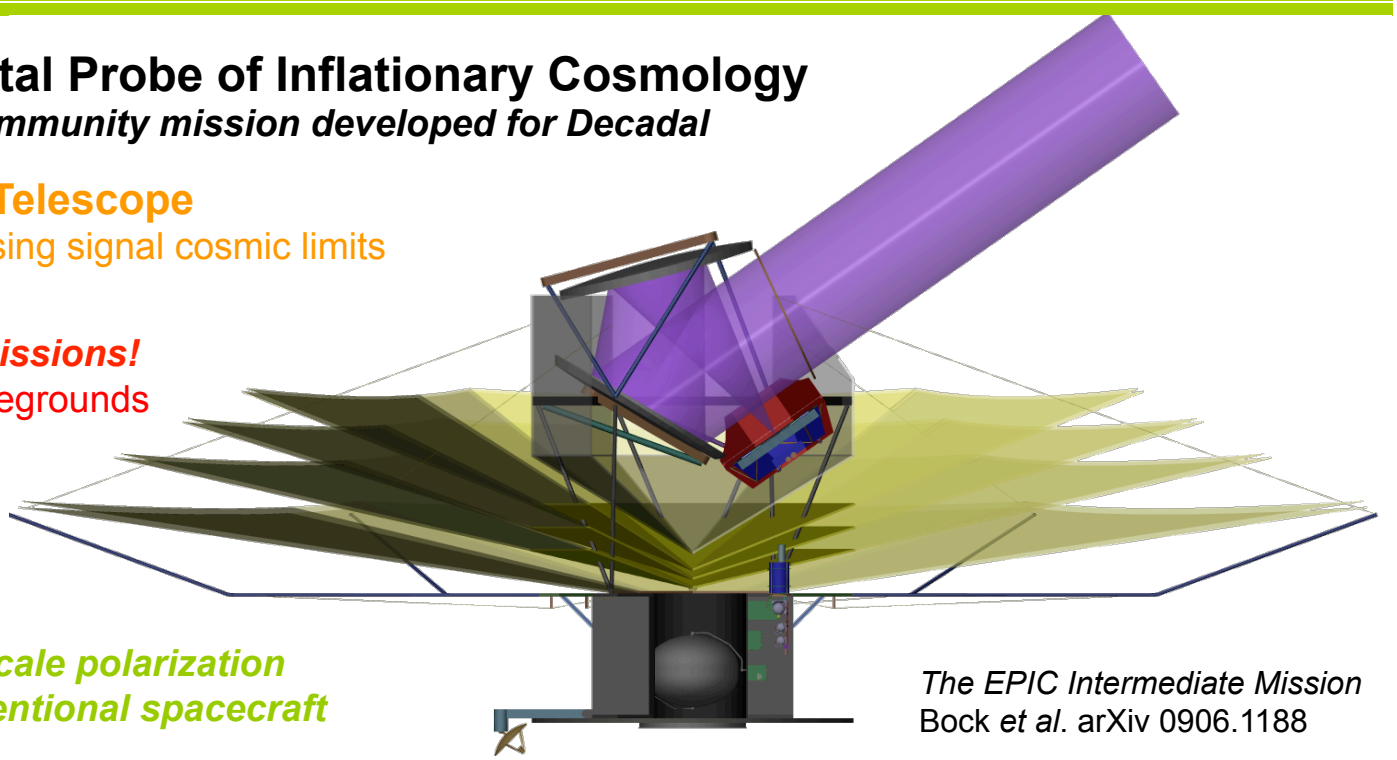
- ***equates to 1000 Planck missions!***
- Wide band coverage for foregrounds

Cooling system

- 100 mK
- ***Improved Planck system***

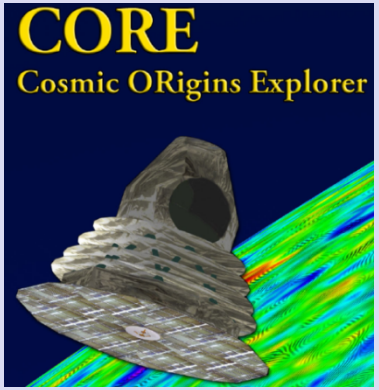
L2 Halo Orbit

- ***Scan strategy for large-scale polarization***
- ***Simple operations, conventional spacecraft***

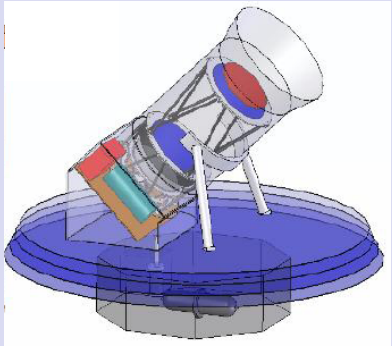


The EPIC Intermediate Mission
Bock *et al*. arXiv 0906.1188

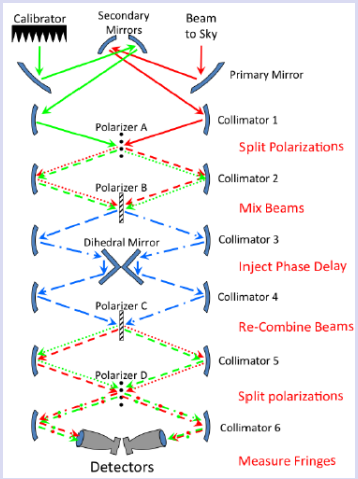
Alternative Concepts



CORE
ESA 2010 proposal
1.2 m aperture

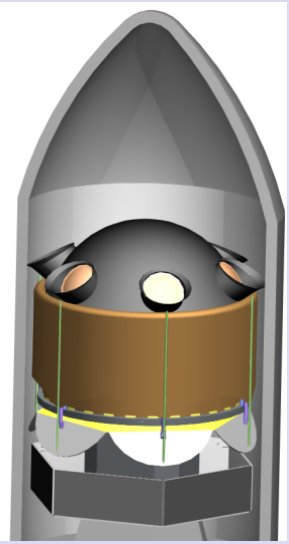


LITEBIRD
Japanese concept
30 cm aperture

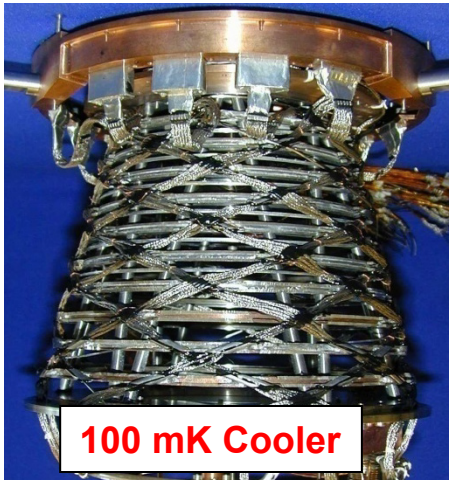


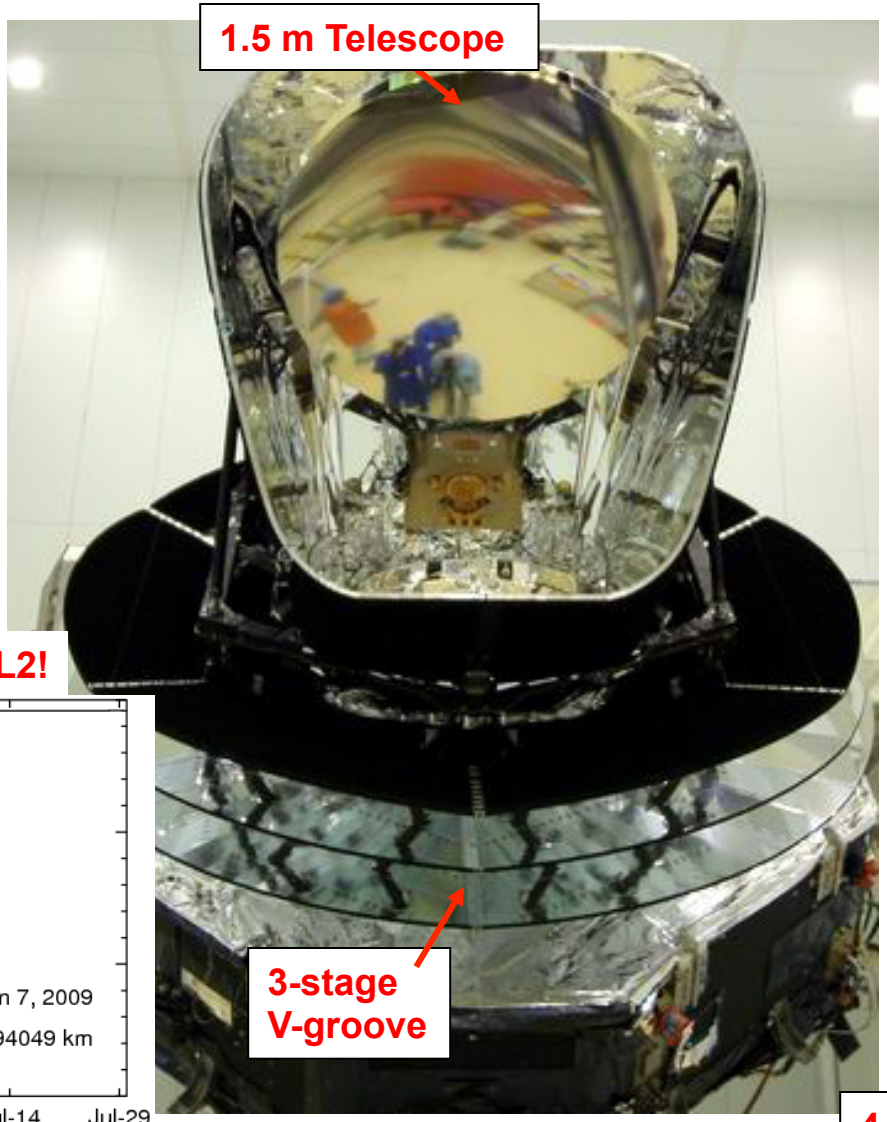
EPIC-*Low Cost*
JPL concept
30 cm apertures

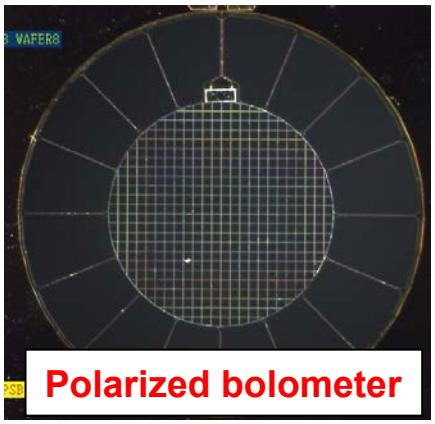
PIXIE
SMEX proposal
Multi-mode FTS



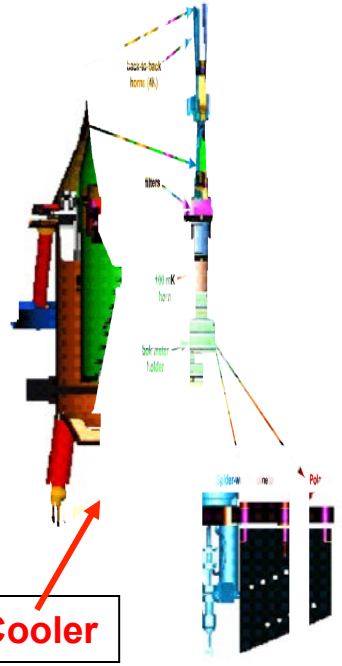
Technology Needed for Space: An Evolution from Planck



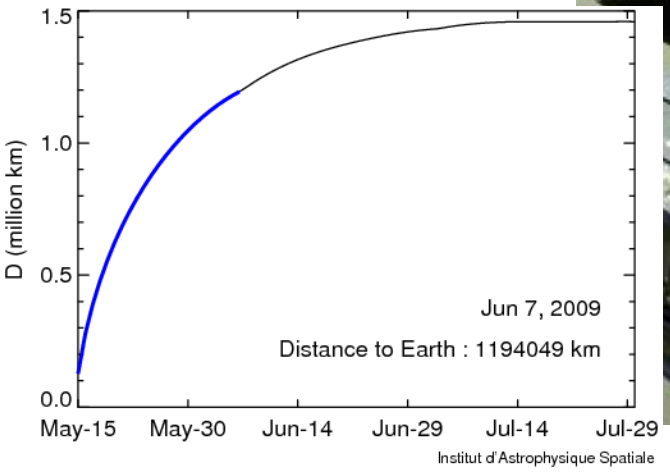




100 mK Focal Plane



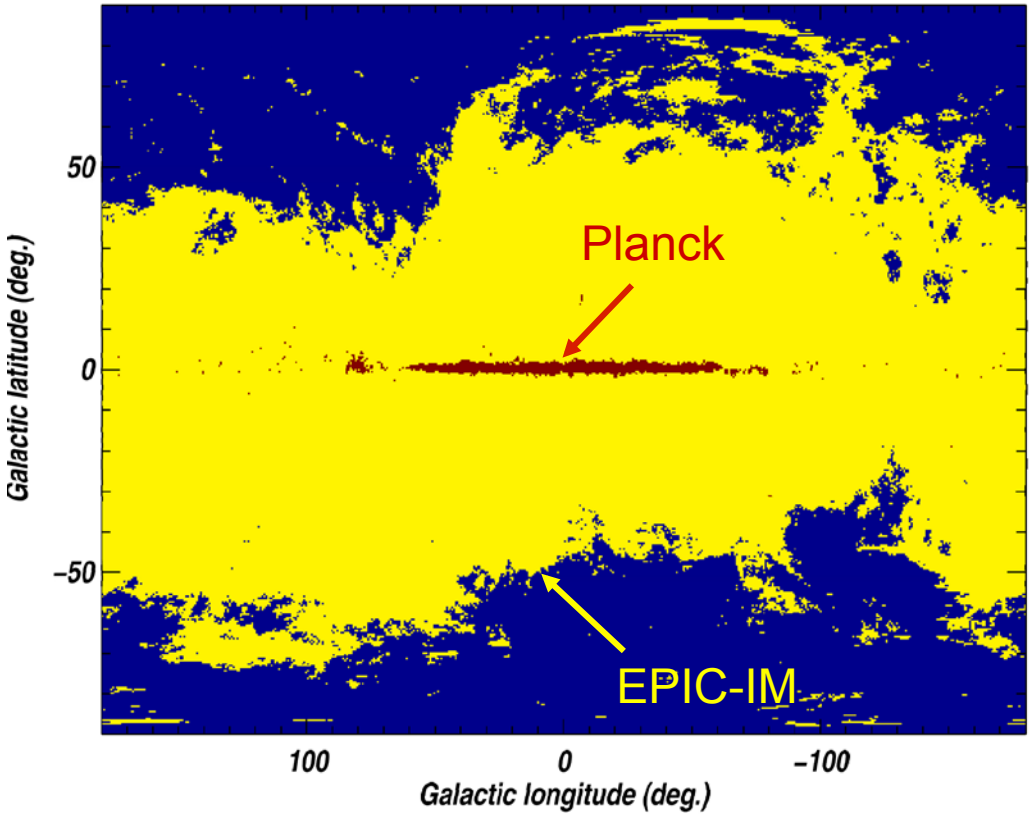
Planck Heading to L2!



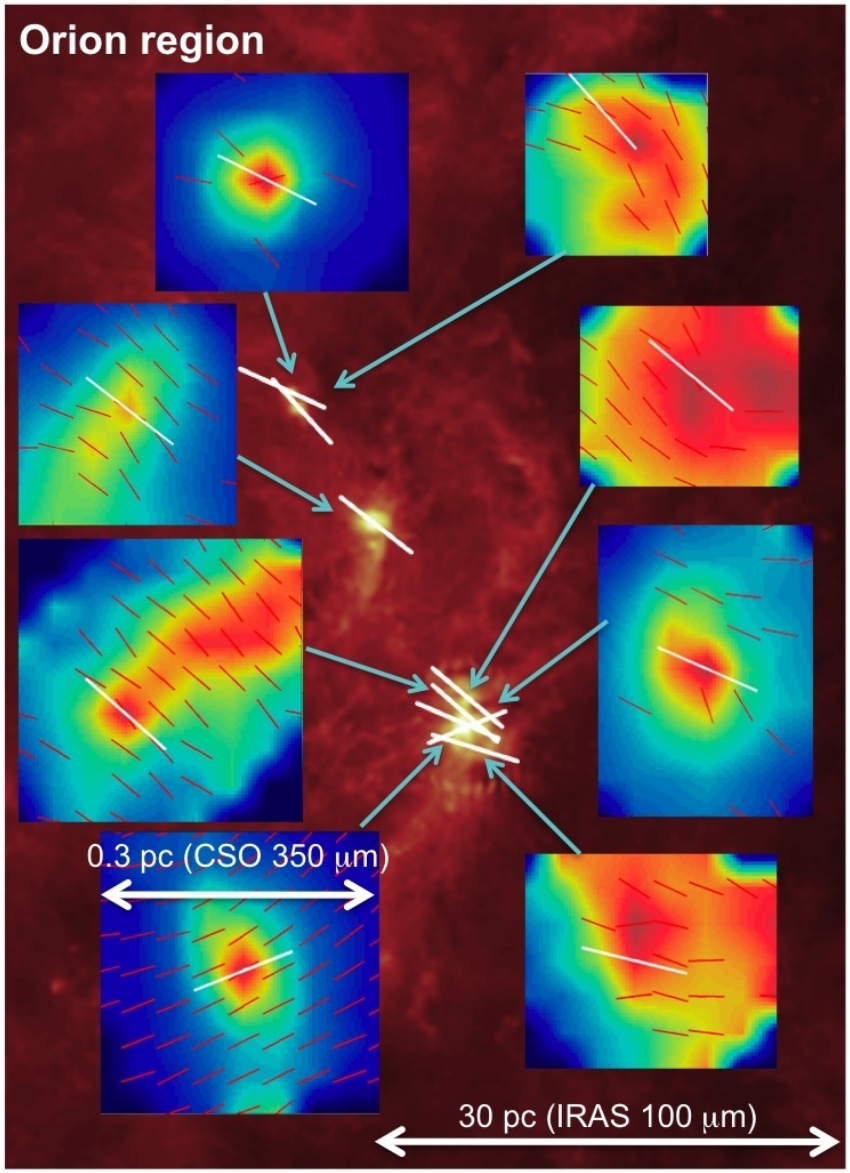
CMB Community Workshop:
Technology Development for a CMB Probe of Inflation, Boulder CO, 25-28 August 2008

Mapping Galactic Magnetic Fields over the Whole Sky

Map of full sky with $\sigma_P < 0.3$ %



Mission	Band GHz	FWHM arcmin	σ(Q) kJy/sr/beam	Pol. depth A_V
Planck	350	5	24	4
EPIC	500	2	0.9	0.06
	850	1	0.7	0.01



How does large-scale Galactic field related to field in embedded star-forming regions?

EBEX Launch