CMBPol: Testing Inflation with Space-Borne Measurements of CMB Polarization

Jamie Bock (JPL/Caltech)
Scott Dodelson (FNAL)
Shaul Hanany (U. Minnesota)
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Representing
The Primordial Polarization Program Definition Team
The CMB Inflation Probe Astrophysics Strategic Mission Concept Study
The EPIC-IM Mission Study Team

Astro2010, Pasadena, 8 June 2009

The EPIC-IM Study Team

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CMB Inflation Probe ASMCS

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Steve Meyer (PI)	U. Chicago
Lyman Page	Princeton U.
John Ruhl	Case Western
Mike Seiffert	JPL
Matias Zaldarriaga	Harvard U.

+ 175 participants

Decadal White Papers

The Origin of the Universe as Revealed Through the Polarization of the CMB, Dodelson et al. and **211** Co-signers

Observing the Evolution of the Universe, Page et al. and **168** Co-signers

A Program of Technology Development and Sub-Orbital Observations of CMB Polarization Leading to and Including a Satellite Mission, Meyer et al. and **141** Co-signers

CMB Community Reports

Theory and Foregrounds: 5 Papers with **135** Authors and Co-Authors

- *Probing Inflation with CMB Polarization*, Baumann et al. 2008, ArXiv 0811.3919
- *Gravitational Lensing*, Smith et al. 2008, ArXiv 0811.3916
- *Reionization Science with the CMB*, Zaldarriaga et al. 2008, ArXiv 0811.3918
- *Prospects for Polarized Foreground Removal*, Dunkley et al. 2008, ArXiv 0811.3915
- *Foreground Science Knowledge and Prospects*, Fraisse et al. 2008, ArXiv 0811.3920

Systematic Error Control: 10 Papers with **68** Authors and Co-Authors

CMB Technology Development: 22 Papers with **37** Authors and Co-Authors

Path to CMBPol: Conference on CMBPol mission in July with 70 participants to date

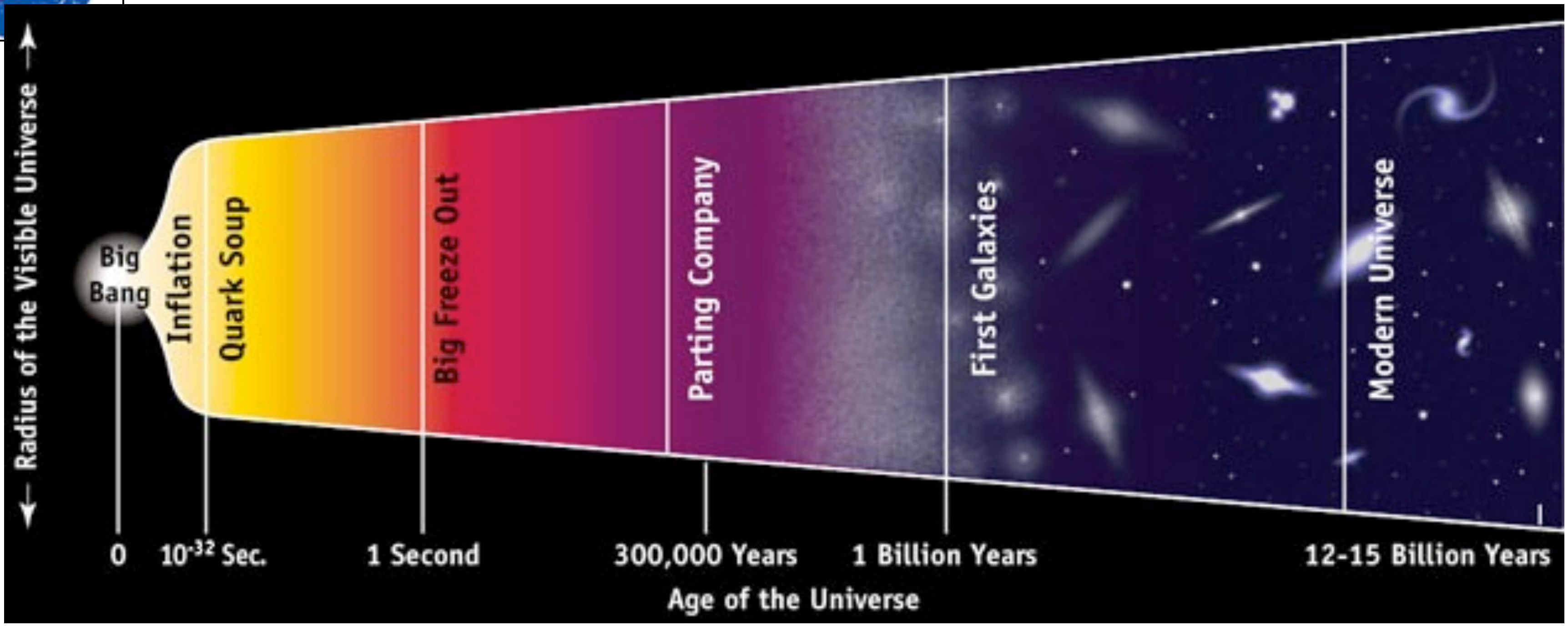
Mission Study Reports

Study of the EPIC-Intermediate Mission, Bock et al. 2009, ArXiv 0906.1188

The Experimental Probe of Inflationary Cosmology, Bock et al. 2008, ArXiv 0805.4207

See http://cmbpol.uchicago.edu for a full compilation

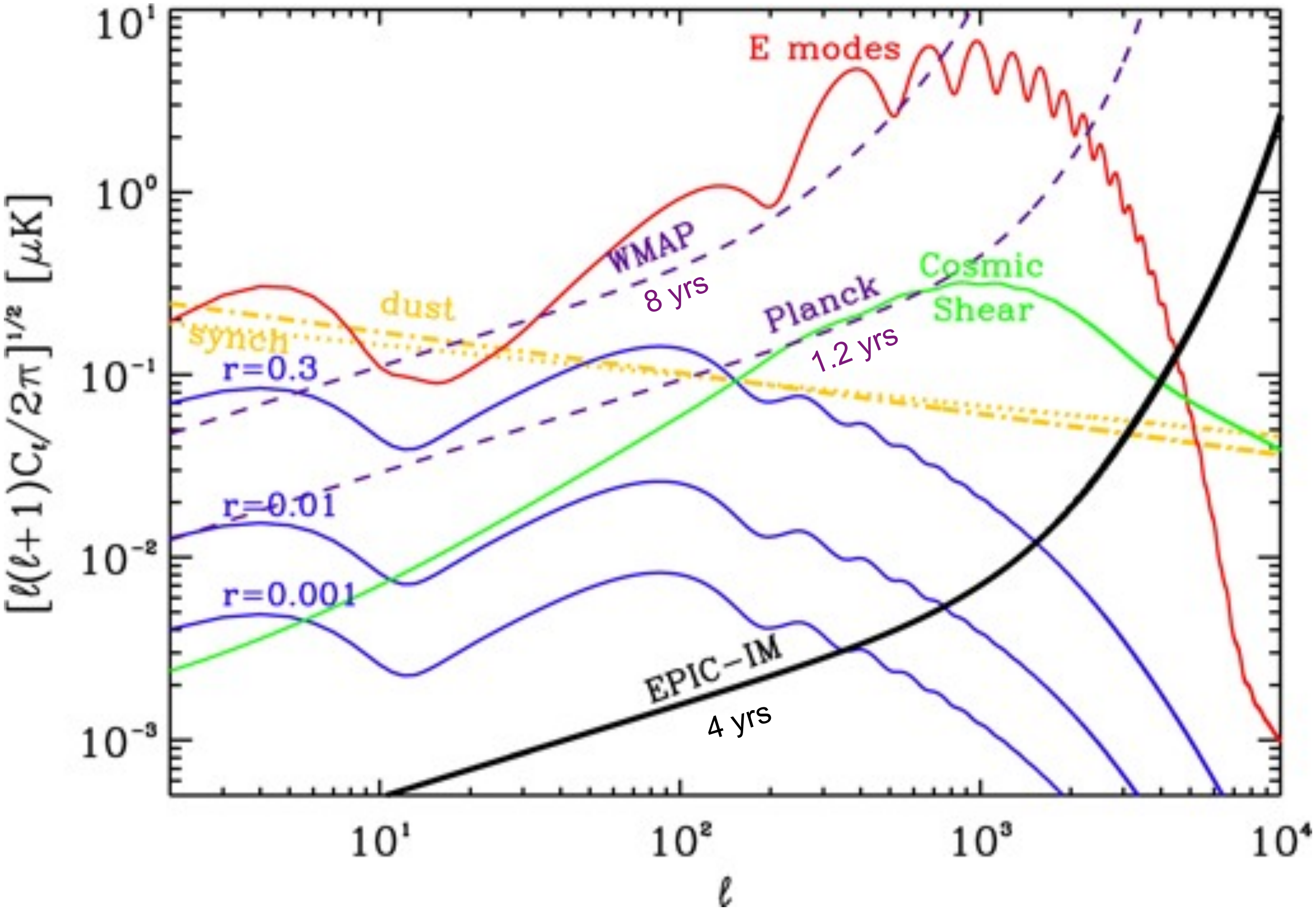
Inflation Science



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?	**CMBpol**

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

Science Objectives for a Space Mission



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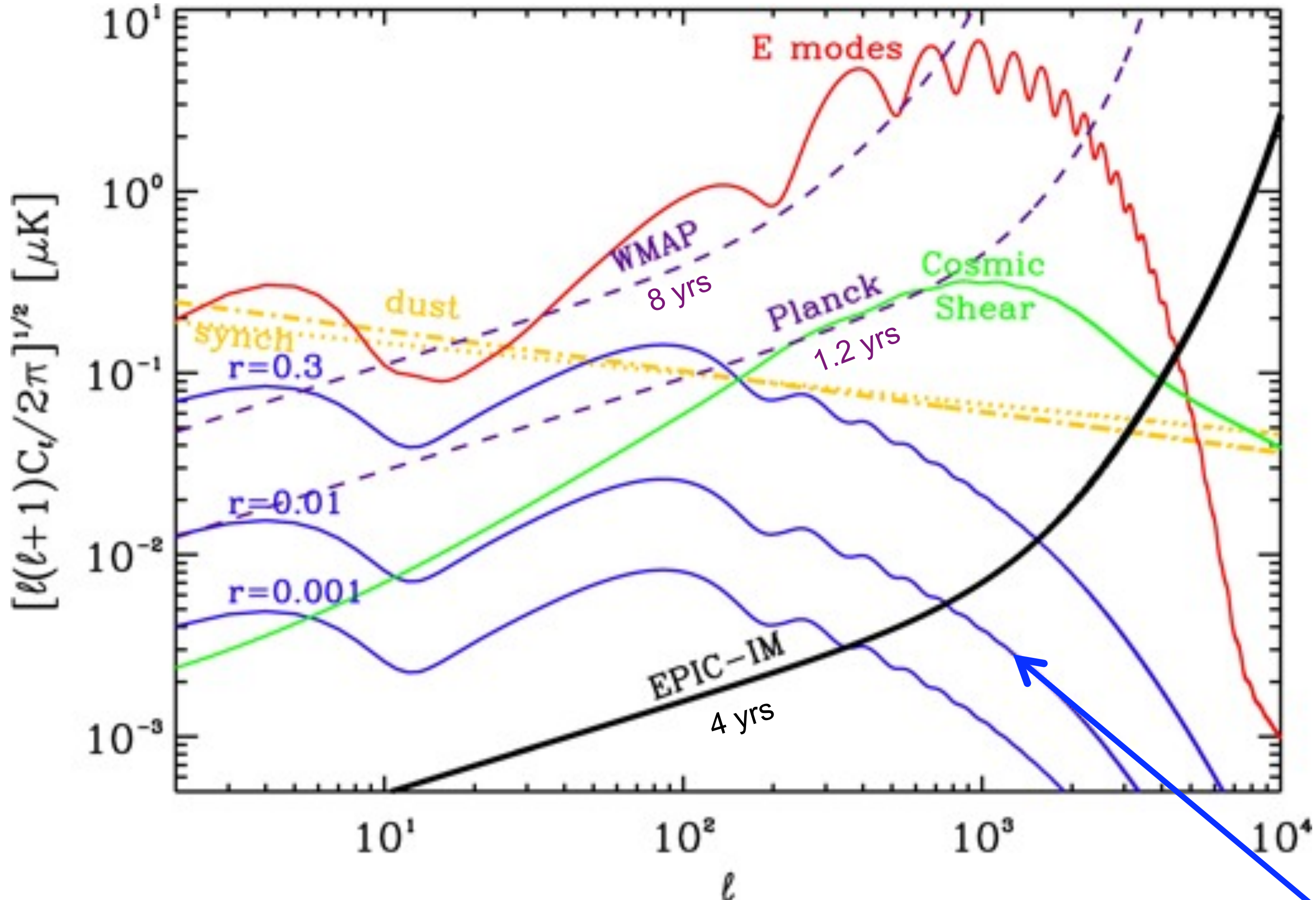

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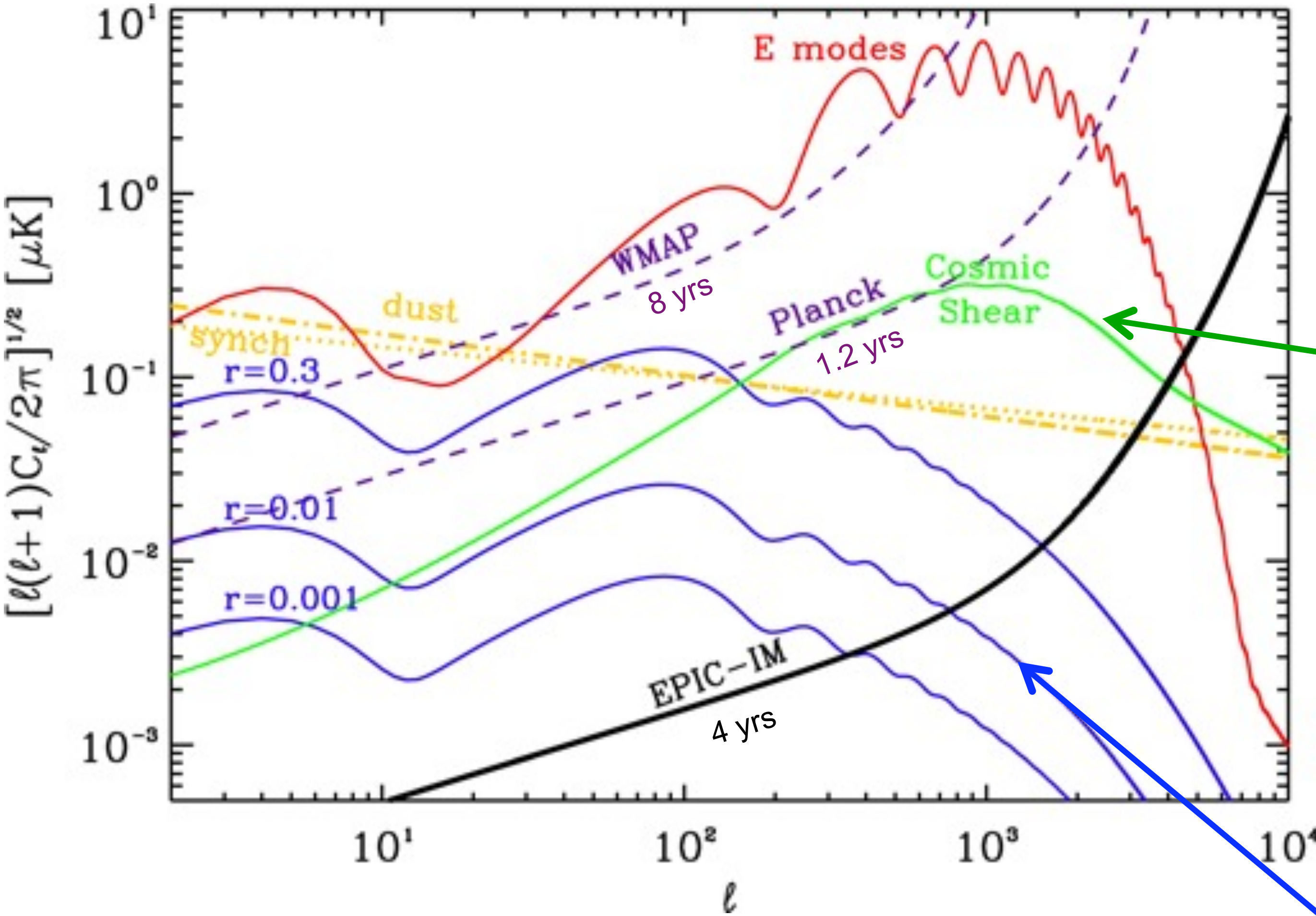
Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

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

Science Objectives for a Space Mission



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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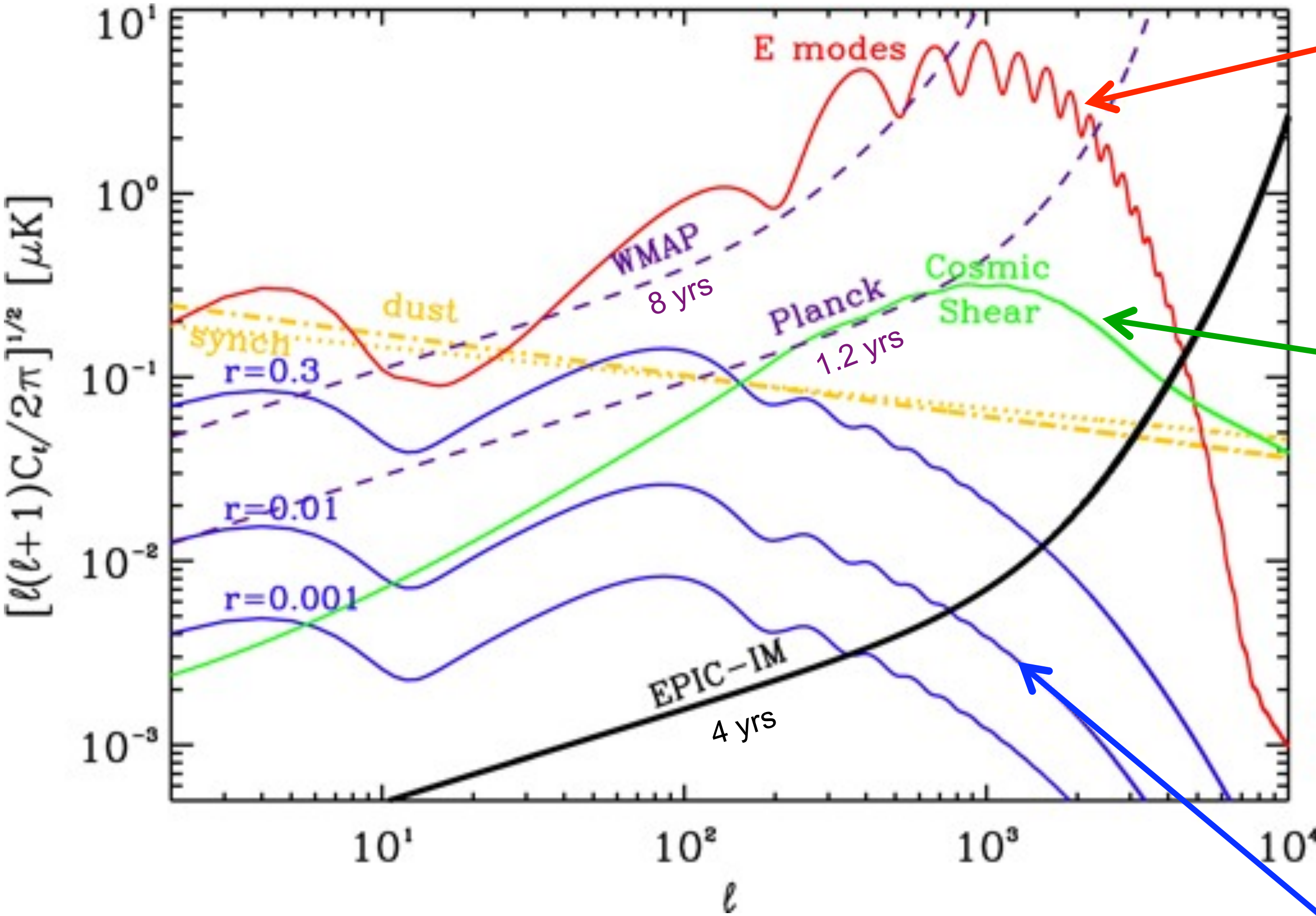

Measure E-mode spectrum to cosmic variance to damping tail

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

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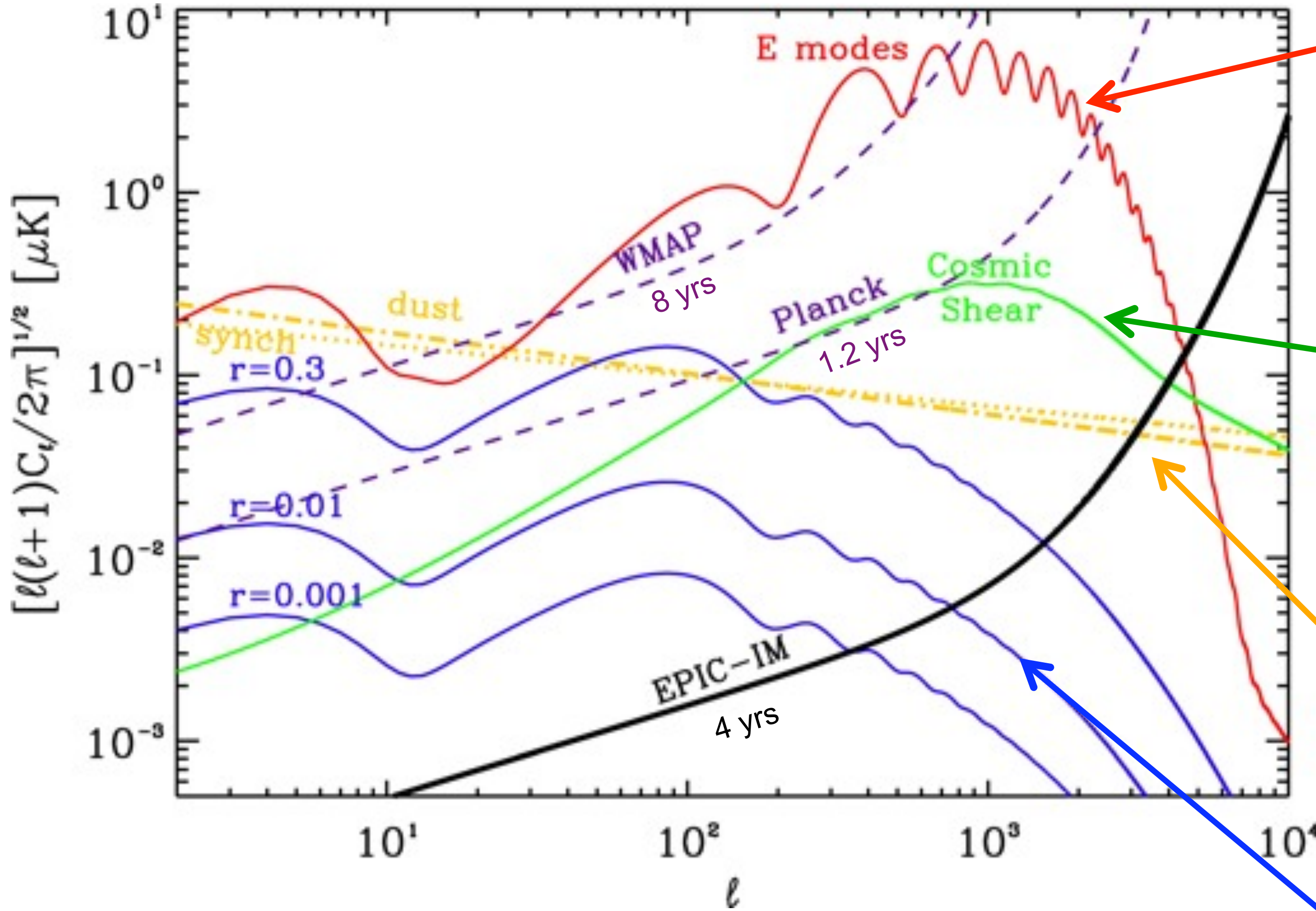

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- Precision cosmology
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Measure B-mode cosmic shear spectrum to cosmic limits

- Neutrino mass hierarchy
- Dark energy at z > 2

Map Galactic magnetic fields via dust polarization

- SF and large-scale B-field

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

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CMB Community Reports

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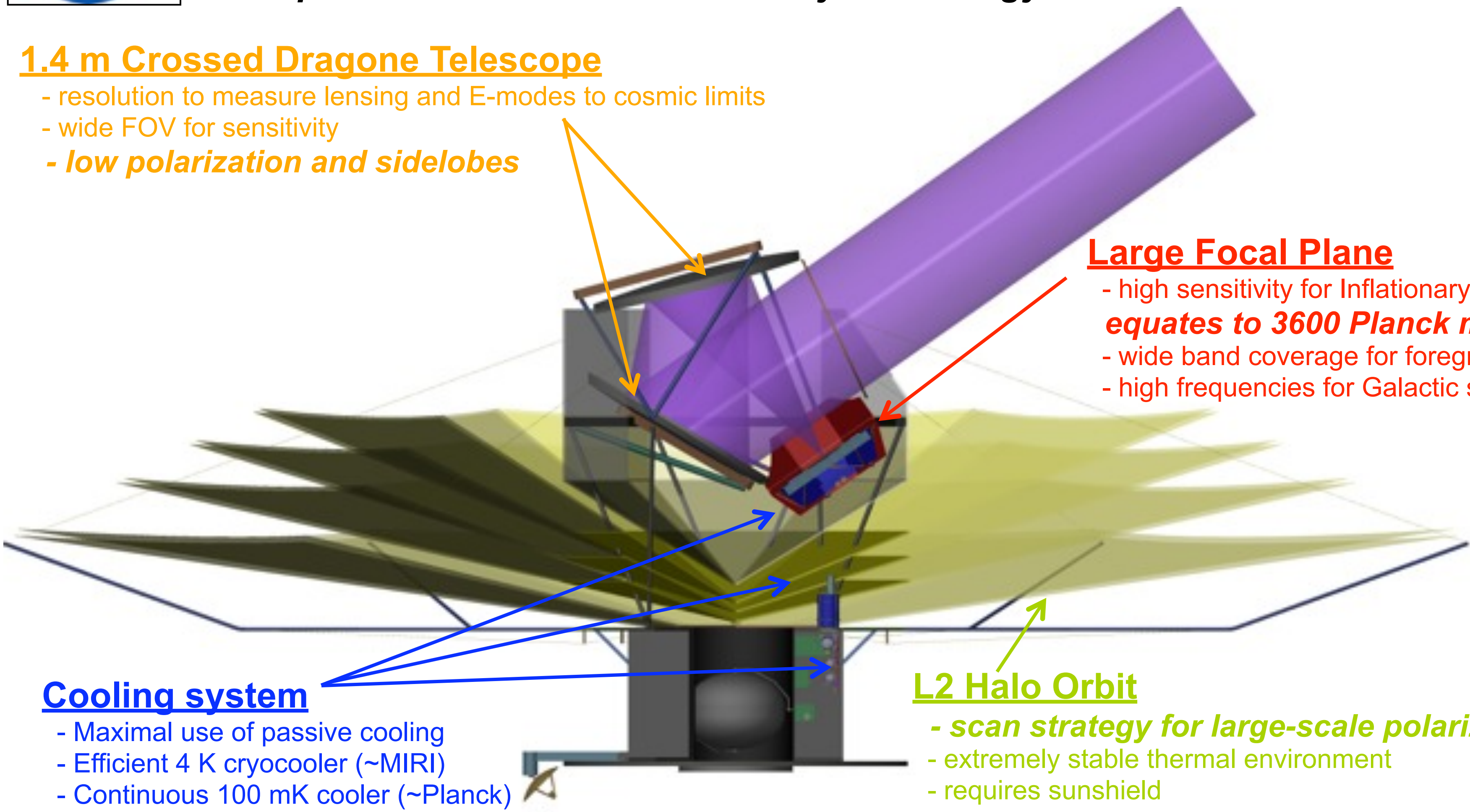
The EPIC-IM Concept in a Nutshell

Experimental Probe of Inflationary Cosmology – Intermediate Mission

1.4 m Crossed Dragone Telescope

- resolution to measure lensing and E-modes to cosmic limits
- wide FOV for sensitivity
- ***low polarization and sidelobes***



Large Focal Plane

- high sensitivity for Inflationary B-modes

equates to 3600 Planck missions!

- wide band coverage for foregrounds
- high frequencies for Galactic science

Cooling system

- Maximal use of passive cooling
- Efficient 4 K cryocooler (~MIRI)
- Continuous 100 mK cooler (~Planck)

L2 Halo Orbit

- ***scan strategy for large-scale polarization***
- extremely stable thermal environment
- requires sunshield
- ***simple operations, conventional spacecraft***

Resources similar to the Planck satellite mission

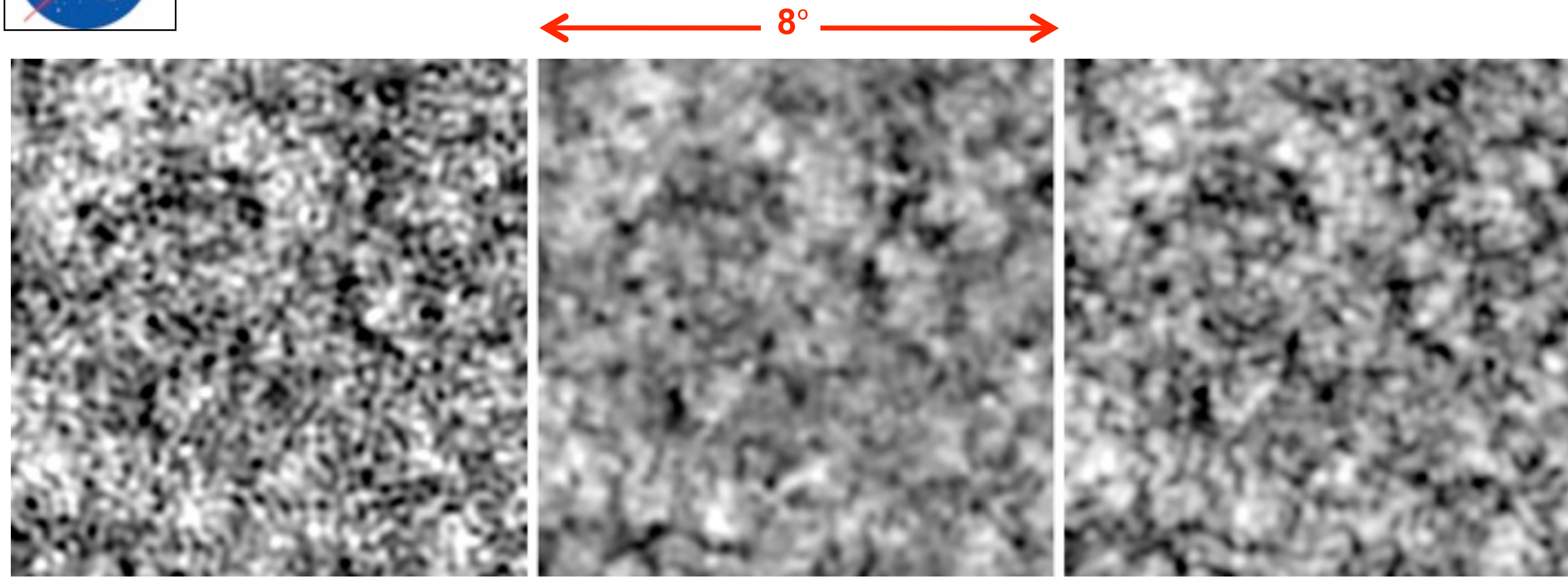
Further Information Available:

Study of the EPIC-Intermediate Mission, Bock et al. 2009, ArXiv 0906.1188

The Experimental Probe of Inflationary Cosmology, Bock et al. 2008, ArXiv 0805.4207

Path to CMBPol: Upcoming Measurements of CMB Polarization, Chicago, 1-3 July 2009

All Sky Maps of Projected Gravitational Potential



Theoretical projected potential

Optimal Quadratic *(Hu 2001)*

Likelihood *(Hirata & Seljak 2003)*

Gravitational potential determined from CMB polarization and temperature maps

Potential sensitive to

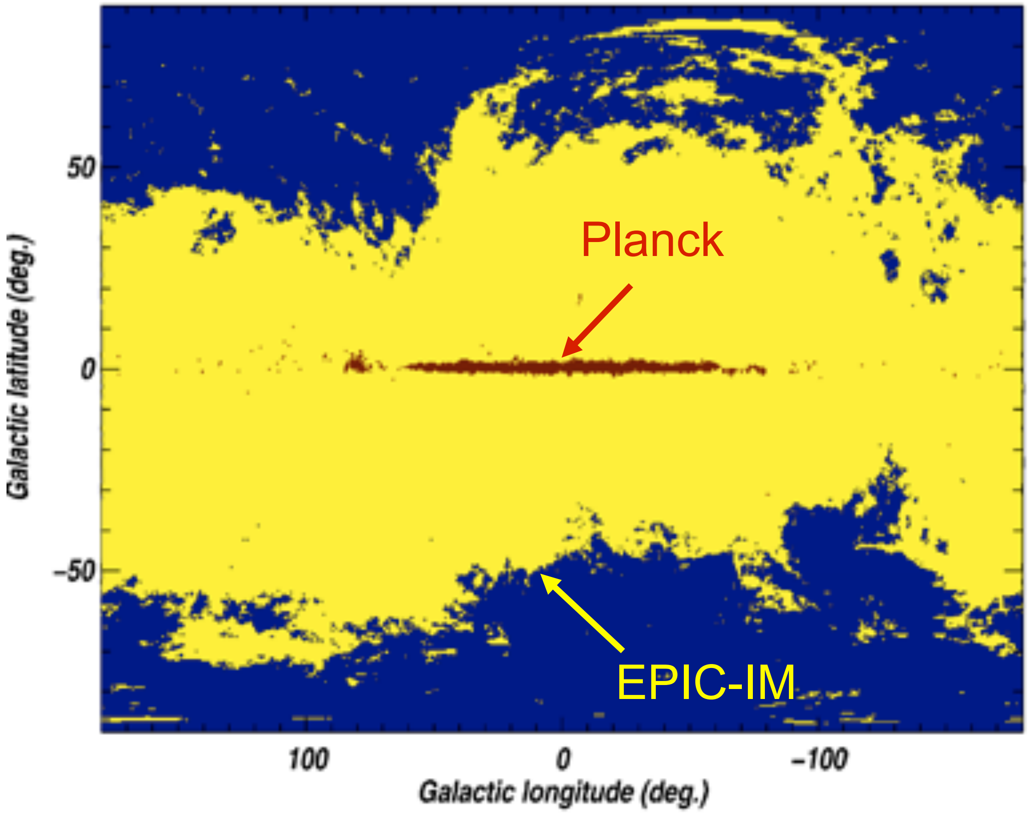
- neutrino masses
- late dark energy

All-sky potential map: 600 of these maps on the whole sky!

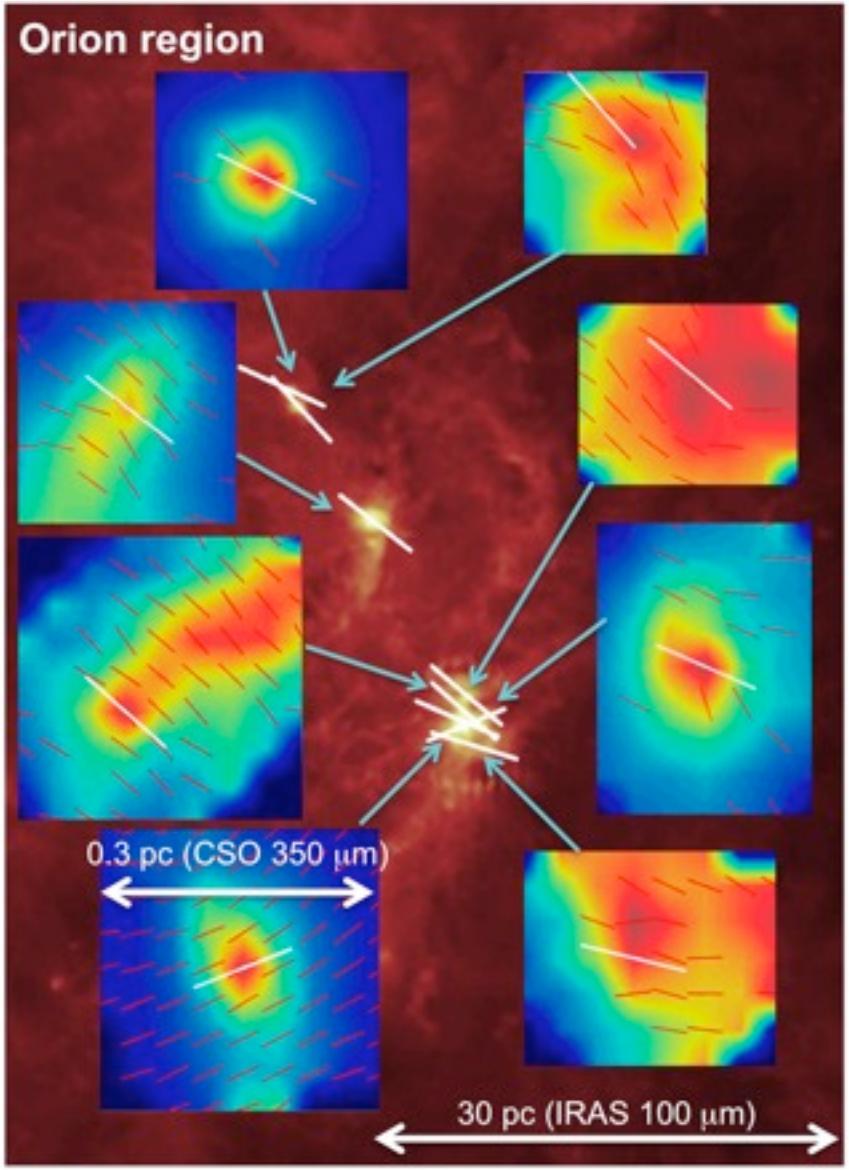
- **a legacy for every future study of structure formation**

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
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?

Q1: “What are the details of how the ground and suborbital programs lead to the space mission?”

How Sub-Orbital Program Benefits a Satellite Mission

Satellite Mission

Sensitivity
60x

Sensitivity
20x

Sensitivity
>20x

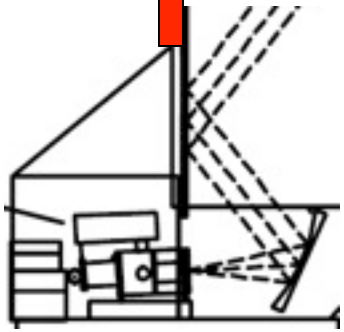
100 μK — 1 μK — 100 nK — few nK

COBE	WMAP	Planck	CMBPOL
1989	2001	2009	2022

Sub-Orbital Precursor

U2-DMR

Woody-Richards



QMAP, SK, TOCO

Archeops, Boomerang, Maxima

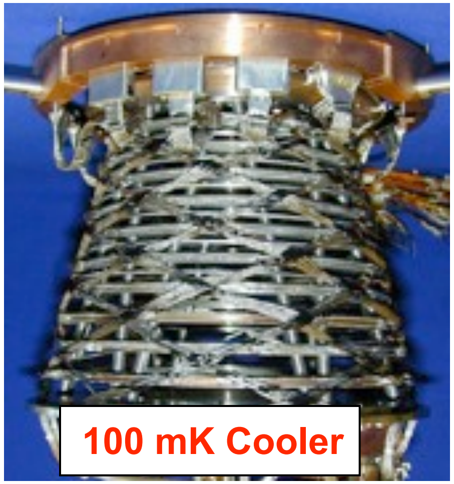
Multiple

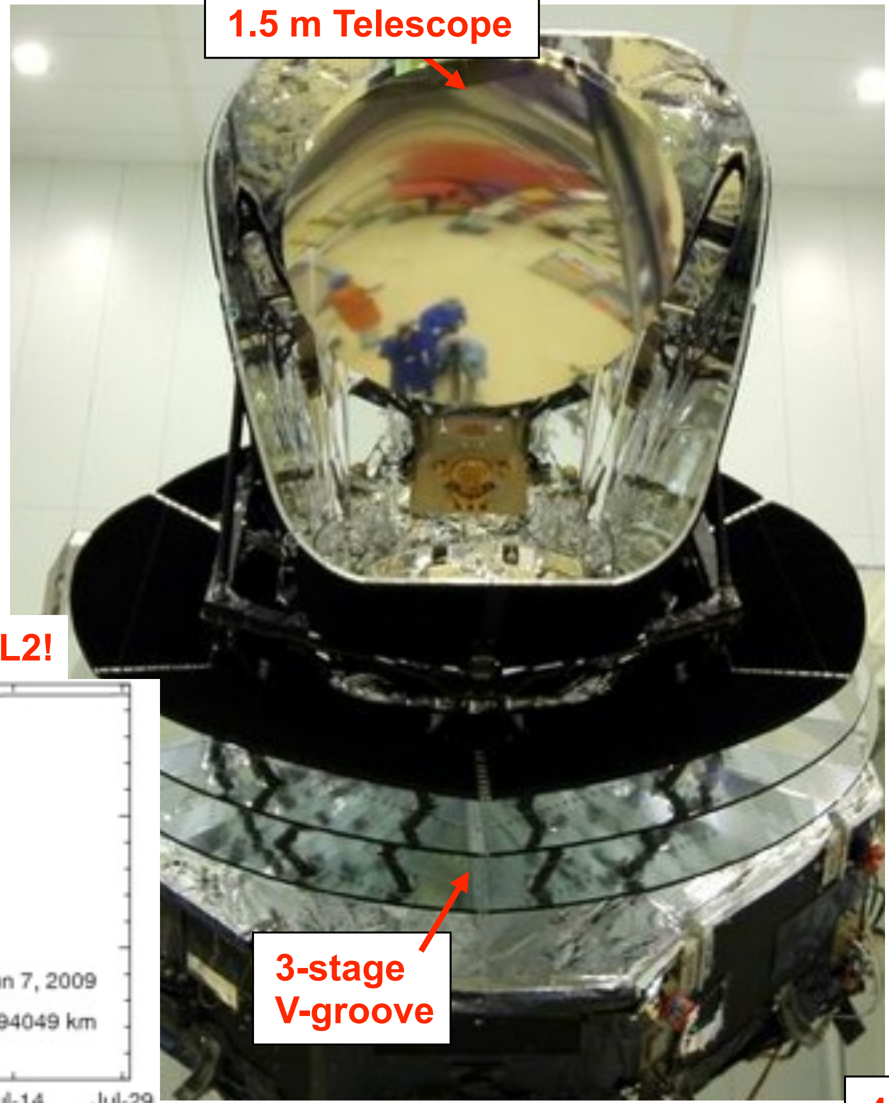
Ground-based
&
Balloon-borne

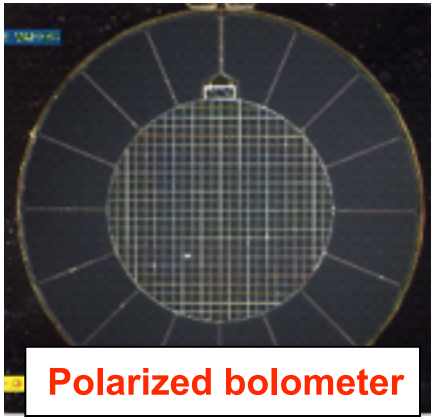
Historical Interplay: Suborbital Experiments serve to

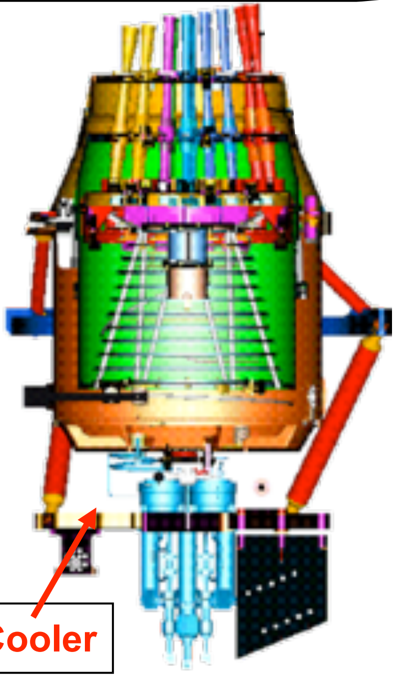
- **Shape scientific objective of a space mission**
- **Train leaders of future orbital missions**
- **Develop experimental methodologies**
- **Develop technologies at systems level**

Technology Needed for Space: An Evolution from Planck

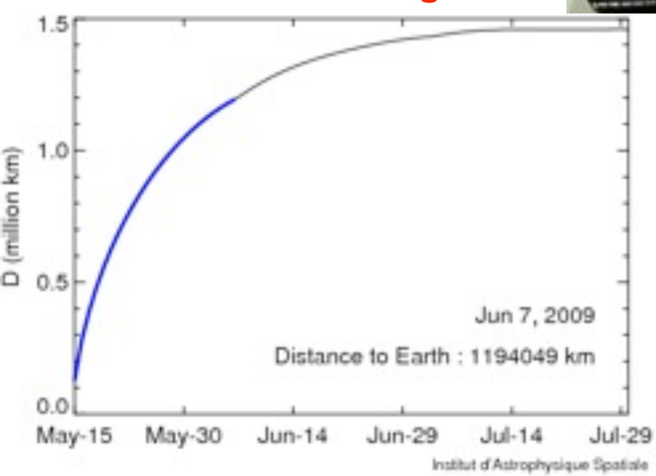






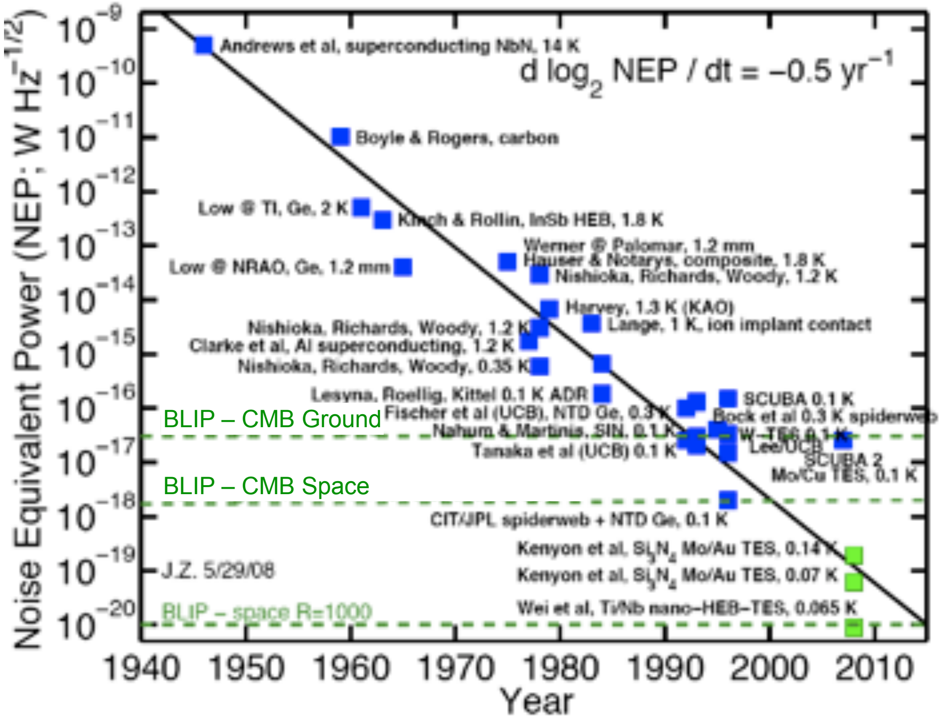


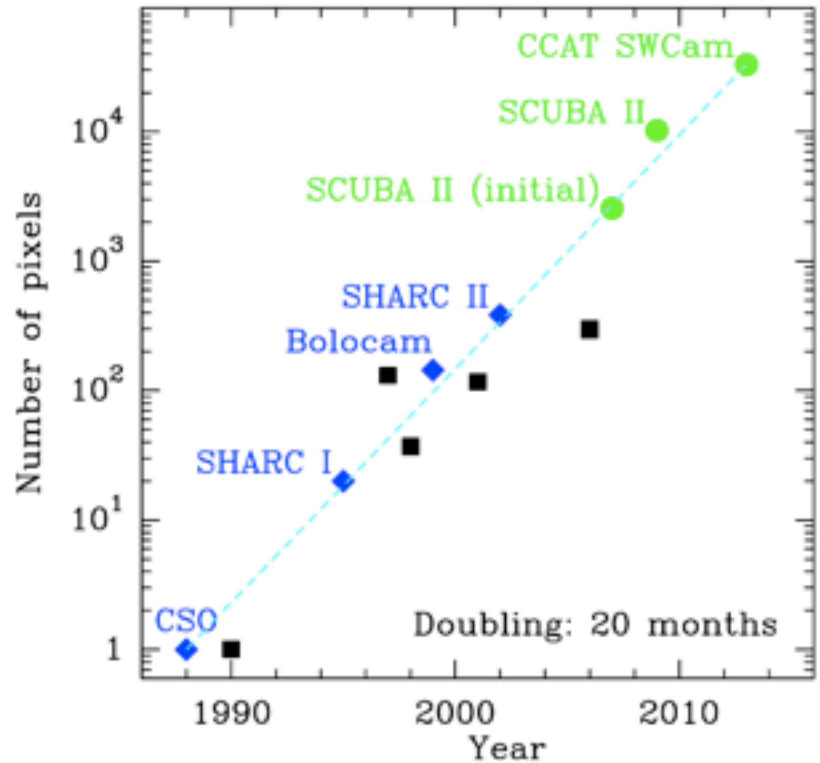
Planck Heading to L2!



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

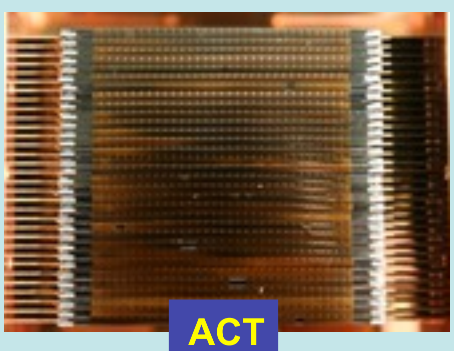
Rapid Progress in Detector Development

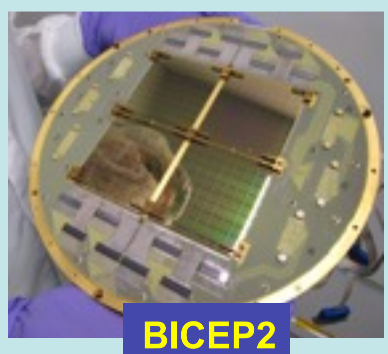


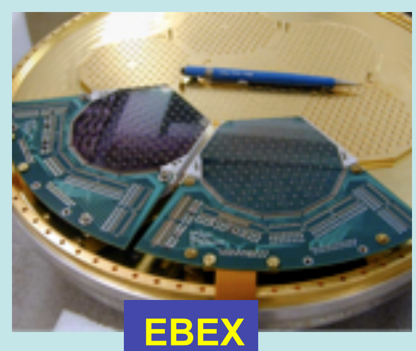


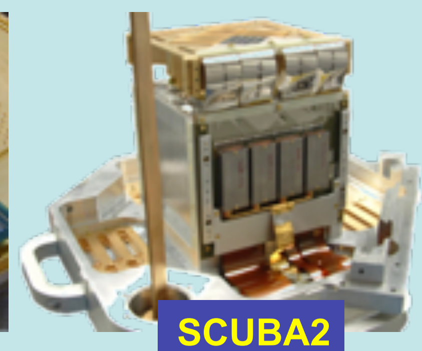
- Rapid progress in arrays
- Development synergy with far-IR and X-ray astronomy

Technology & Sub-Orbital Program

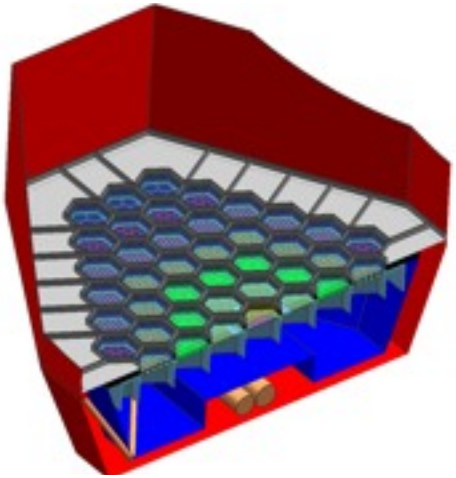






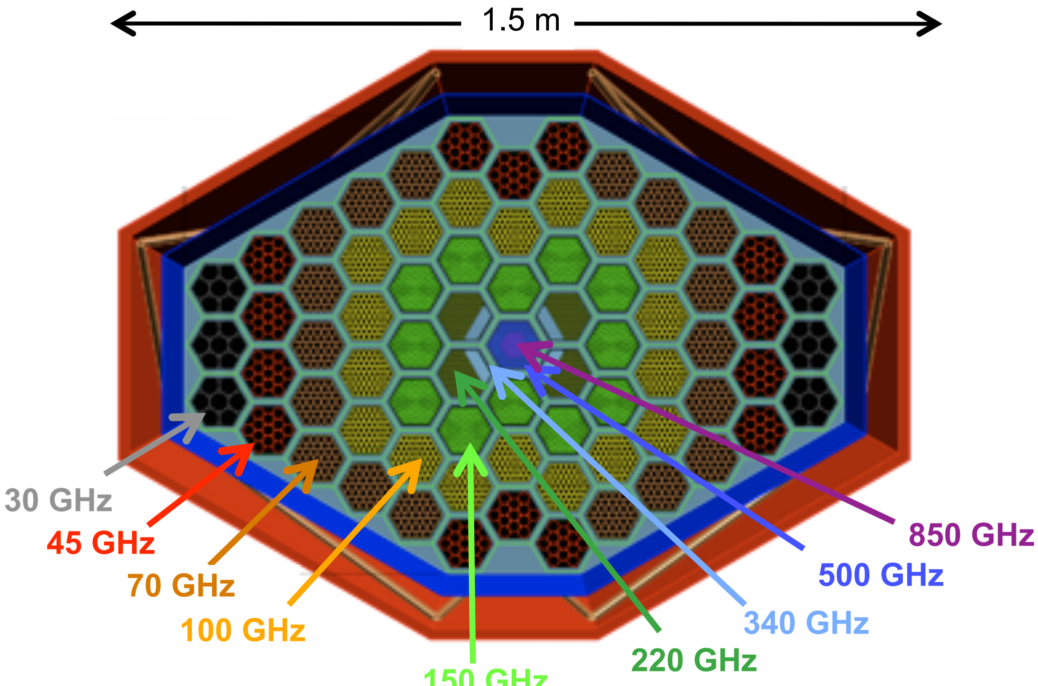


Sub-Orbital Predecessors to EPIC-IM Focal Plane



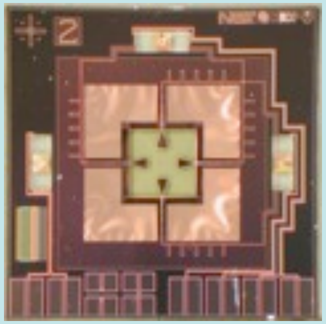
T_0 = 100 mK
Ndet = 11,094
9 Bands

- Much larger AΩ and sensitivity than any planned sub-orbital experiment
- Sub-orbital platforms demonstrating technology options

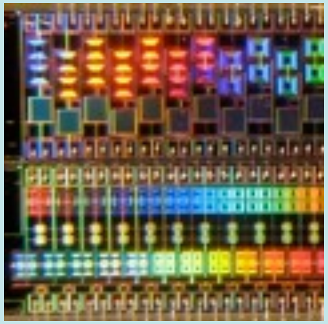


Technology & Sub-Orbital Program

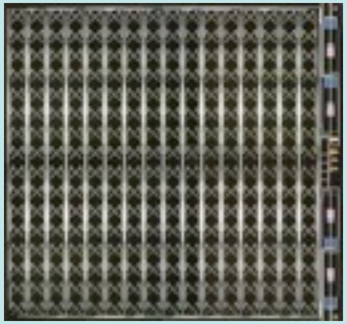
Optical Coupling | **Detector / Readout**



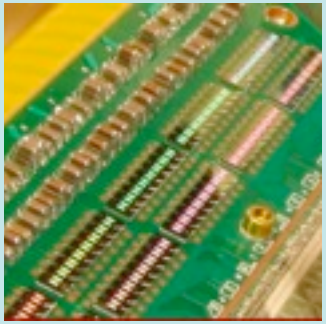
Feed Coupled



Time-Domain SQUID

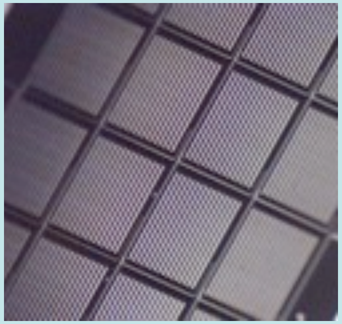


Planar Antennas



Freq-Domain SQUID

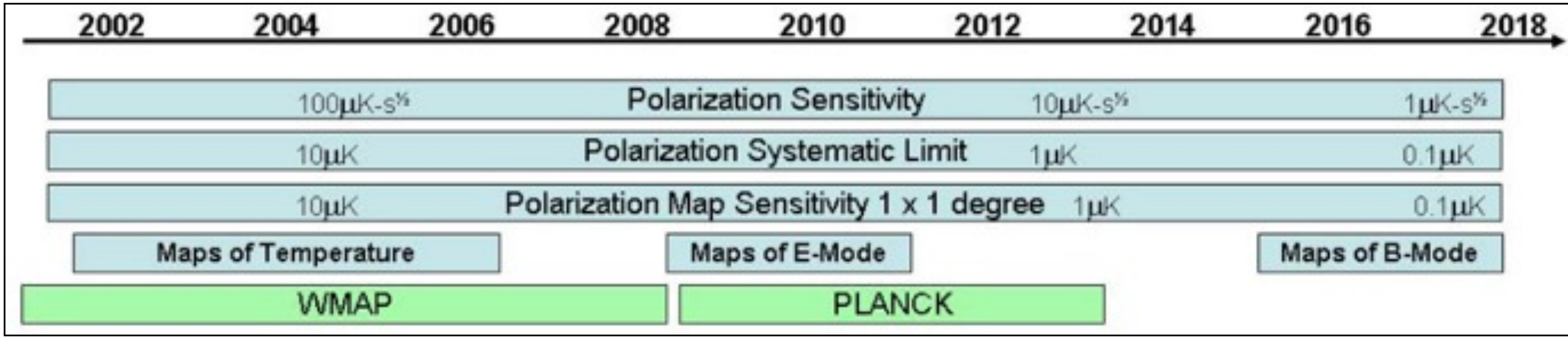
Lens-Coupled Antennas



RF-Muxed MKID

Transition from Sub-Orbital Experiments to Space

Task Force for CMB Research Weiss Report 2005: Projected Timeline



<u>Current Sub-Orbital and Ground-Based Experiments</u>

US Balloons
EBEX
SPIDER
PIPER

US Ground-based

ABS	ACT	BICEP2
Keck Array	MBI	Poincare
PolarBeaR	QUIET	SPT

European Ground-based
BRAIN
QUIJOTE

Vigorous 'Market-Driven' Scientific Niches

- Wide variety of technologies
- Wide range of frequencies, resolution, and sky coverage
- Diverse approaches to systematic error control

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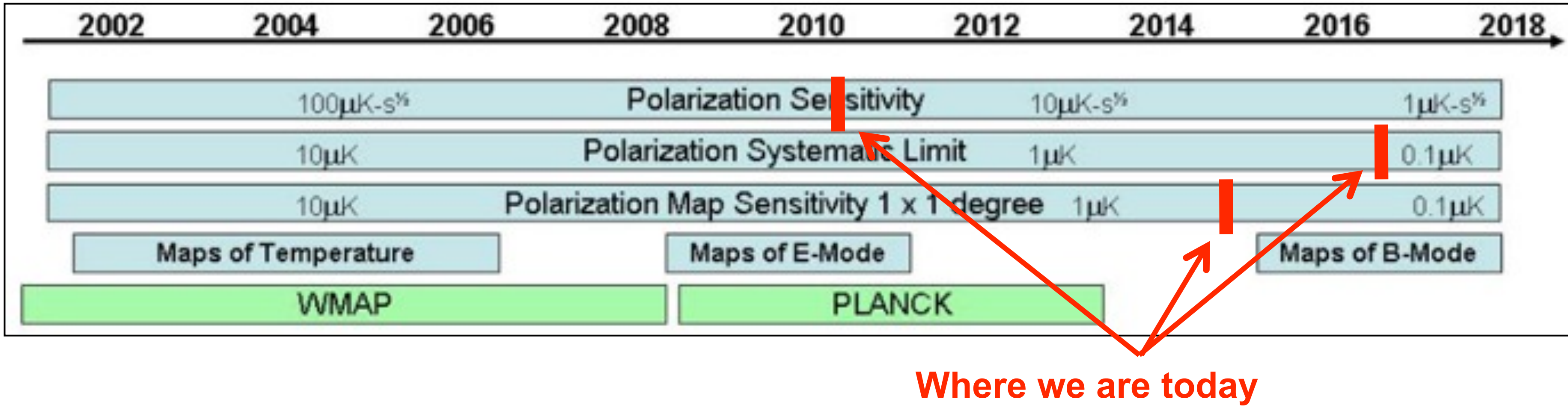

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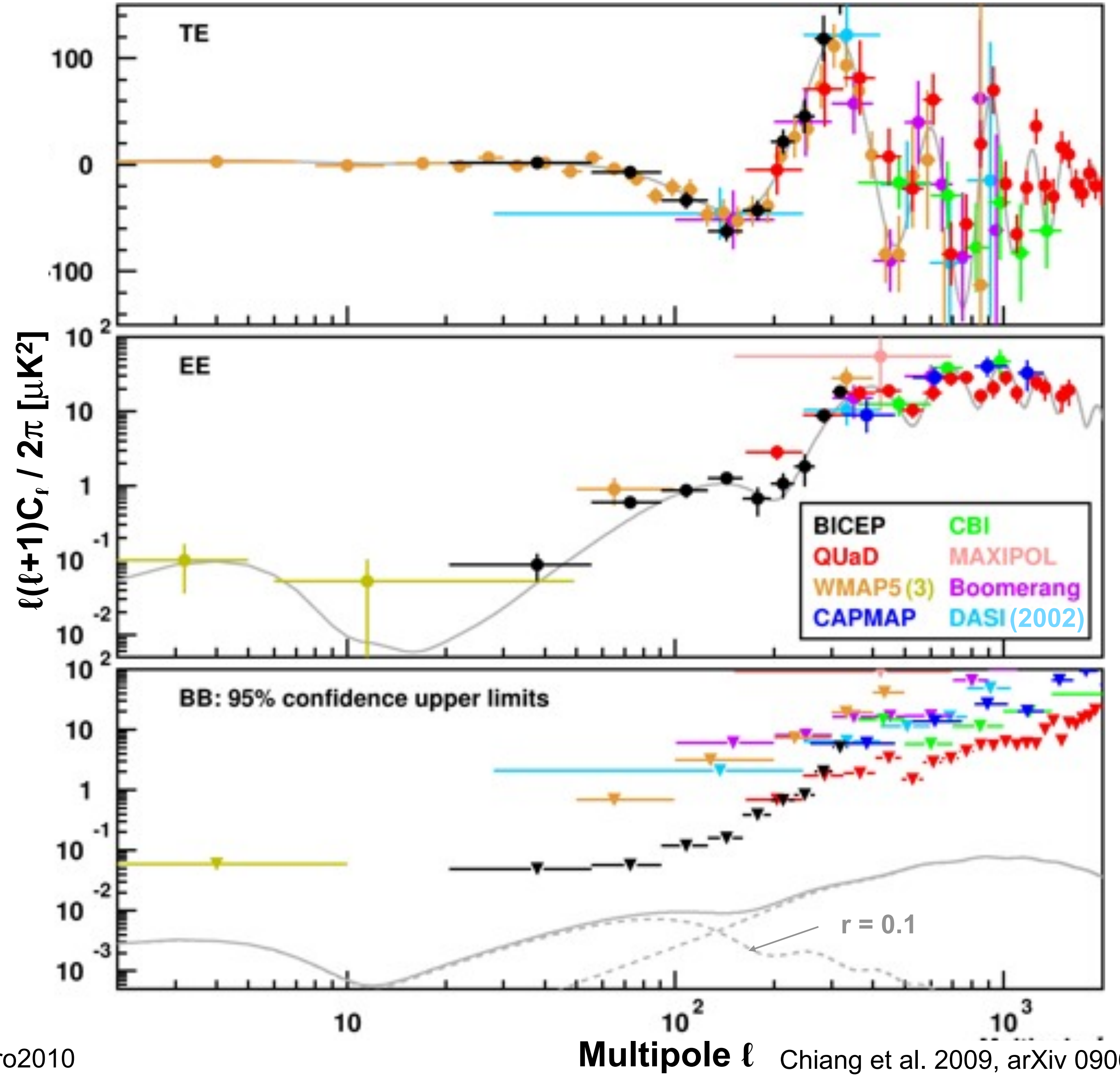
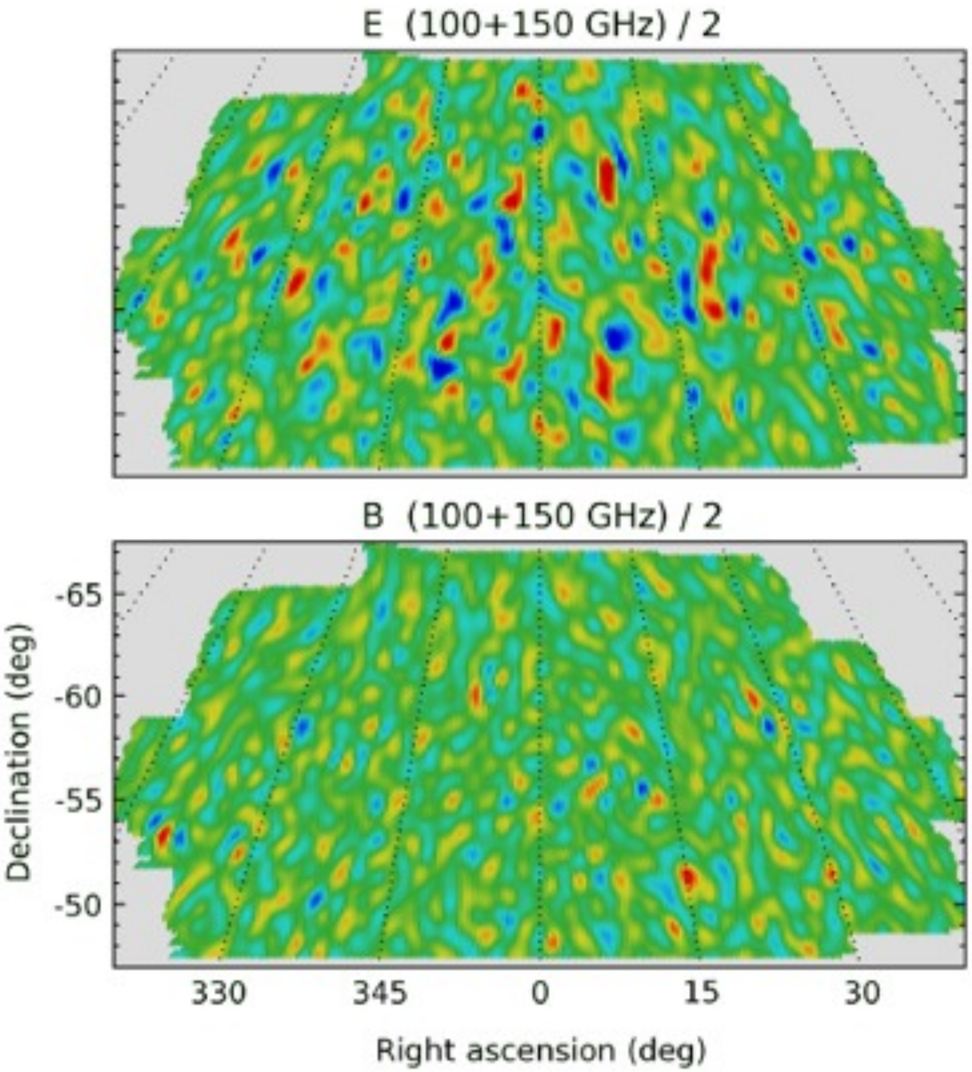
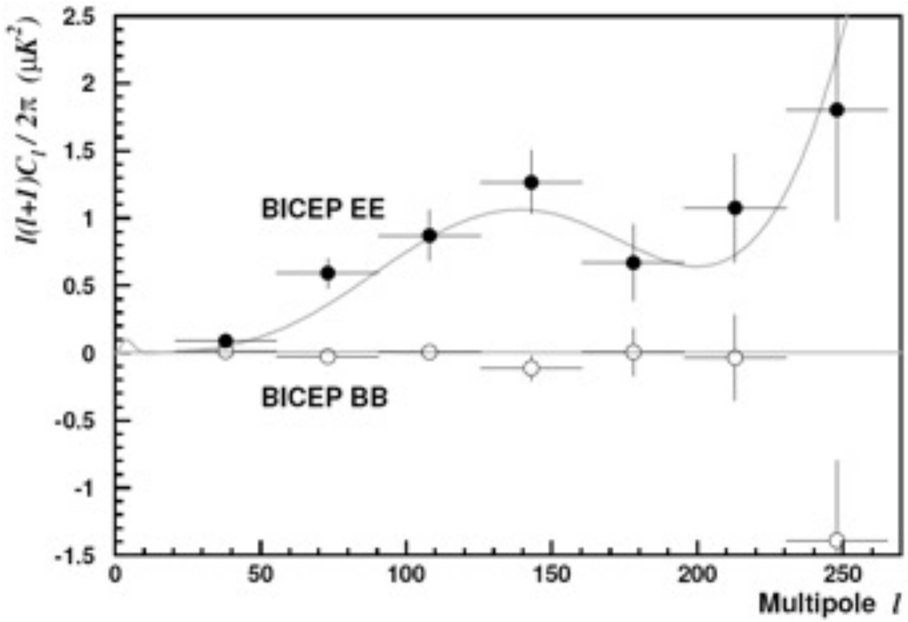
Recent Measurements of CMB Polarization



Chiang et al. 2009, arXiv 0906.1181 & 1003

High Fidelity Separation of E and B





- Map sensitivity = 0.5 μK / sq. degree
- Systematic errors << noise
- No E/B mixing

Chiang et al. 2009, arXiv 0906.1181

Scientific Transition from Sub-Orbital to Space

Sub-Orbital Program Optimized to Detect Inflationary Polarization Signal

Most methods use deep searches on small patches of sky

- Most experiments are targeting ℓ = 100 peak
- Expect detections or upper limits to r õ 0.05 in limited ℓ range in 5 years

Satellite Designed for Comprehensive Measurements of CMB Polarization

Measures the entire sky to fundamental limits

- Entire Inflationary B-mode spectrum to astrophysical limits
- Lensing and E-mode signals to cosmological limits

Why is Space Necessary?

EPIC-IM Designed to Measure Polarization Spectra to Fundamental Limits

Science Objective	Attribute	Why Space is Needed
Measure Inflationary B-mode spectrum for $2 < \ell < 200$	**All-Sky Coverage**	High fidelity measurements of low spatial multipoles
Remove foregrounds to measure r = 0.01 to astrophysical limits	**Frequency Coverage**	Full access to the electromagnetic spectrum without degradation from Earth's atmosphere
Measure E-mode and lensing B-mode to cosmological limits	**Sensitivity**	Large improvement due to lower backgrounds, large system throughput, longer integration time
Measure Inflationary B-mode spectrum to astrophysical limits	**Systematic Error Control**	Superior control, stability, redundancy, and monitoring of systematic errors

Primary Science Objective

Secondary Science Objective

Transitioning from Sub-Orbital Program to Space

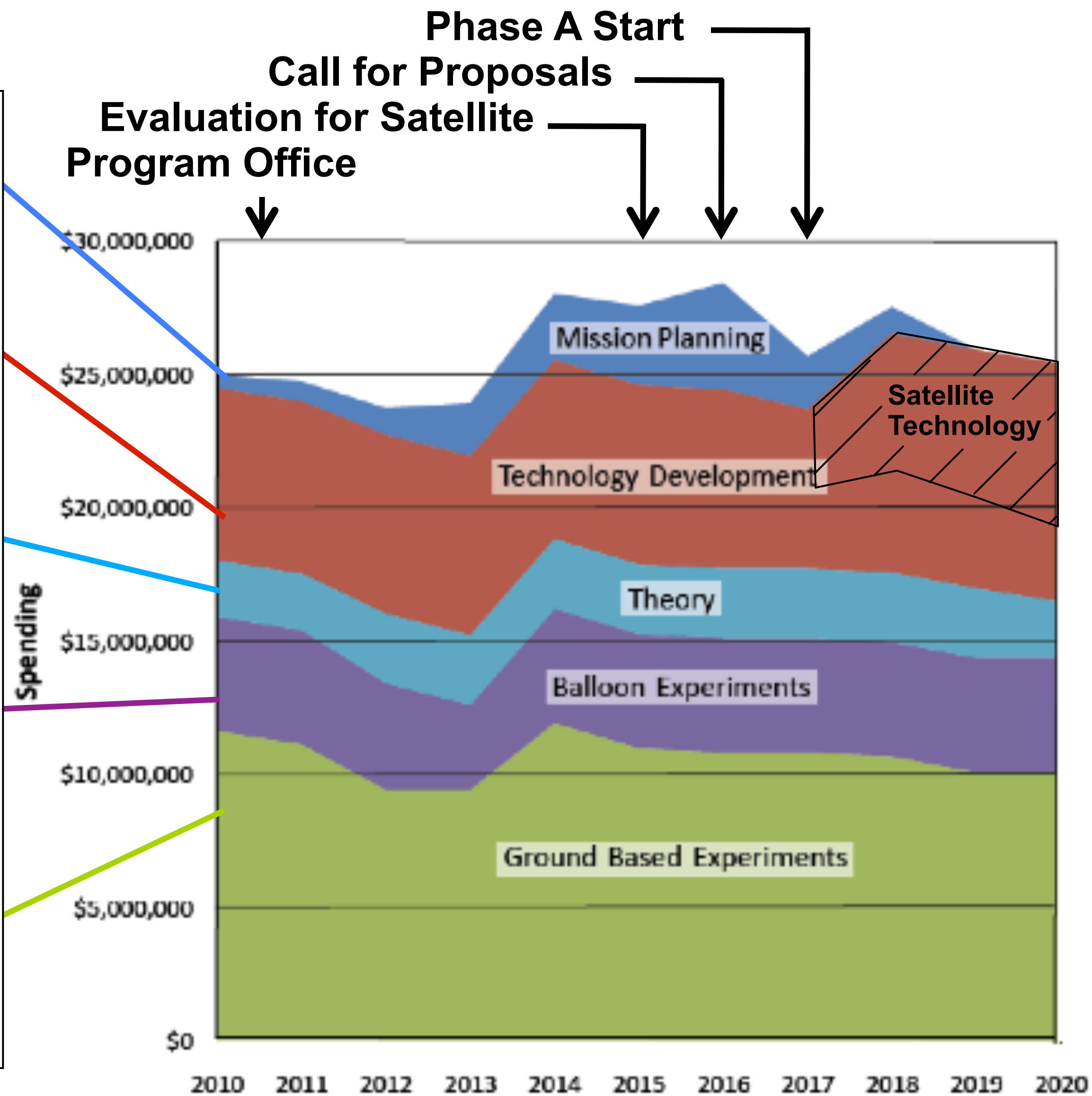
Mission Planning
- Space systems design
- Set technology needs

Technology Development
- Center funding for arrays
- $1M/yr University directed

Theory
- Lensing, foregrounds, models

Balloon Experiments
- Technology implementation
- Systems development
- ‘Science-market’ driven

Ground-Based Experiments
- Technology implementation
- Systems development
- ‘Science-market’ driven



Satellite funding wedge not shown

These cost profiles are notional and have not been negotiated with or agreed to by NASA HQ, the NSF, or the NIST

Q3: "What aspects of the program need to continue during/after the space mission?"

Programs to Continue After Mission Start

- **Theory program should continue**

  Supports investigations useful to satellite program

- **Technology for satellite borne by mission funding**

- **Expect CMB B-mode polarization experiments will taper down**

  But: Let scientific marketplace decide

Examples of reasons for a continued level of experiment funding:

Complementary polarization experiments

- Foreground measurements at low frequencies
- High resolution polarization experiments

Sub-orbital demonstration of satellite-specific technologies

- Buys down risk. Very successful in the past

CMB temperature experiments

- High-resolution ground-based observations
- Absolute spectrum experiments

Experiments we can't foresee today

Decadal White Paper on High-Resolution Temperature Measurements
Observing the Evolution of the Universe, Page et al.

Q2: “What metrics are used to determine that the program has achieved enough to proceed with a space mission?”

Evaluation for Start of Satellite Program in 2015

Expected State of CMB Polarization in 2015

Scientific

- **Lensing BB signal detected**
- **Either Inflationary B-modes detected,**
  Case for satellite start very compelling in 2015
- **Or upper limit to r õ 0.05**
  Reassess role for satellite in 2015

We are not recommending a fixed metric for a satellite start.
We are recommending a 2015 evaluation for a satellite start.

Foregrounds

- **Measured in deep regions from ground & balloons**
- **Measured over entire sky by Planck**
- **Subtraction tested both deep and shallow**

Technology readiness

- **Focal plane arrays to TRL = 6**

Systematic error control

- **Polarization effects, E $\rightarrow$ B conversion, etc.**

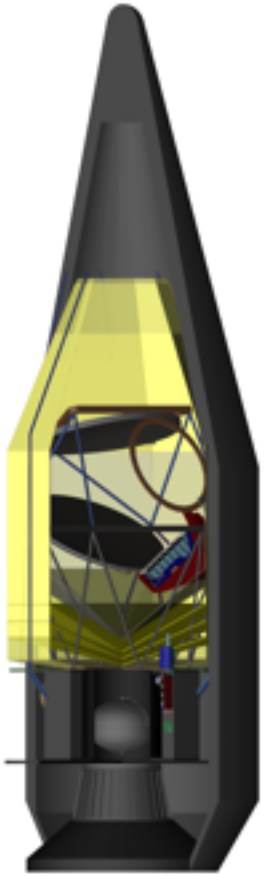
Field will be ready to transition to a satellite experiment mid-decade,
fully armed with scientific case and demonstrated technology

We recommend:

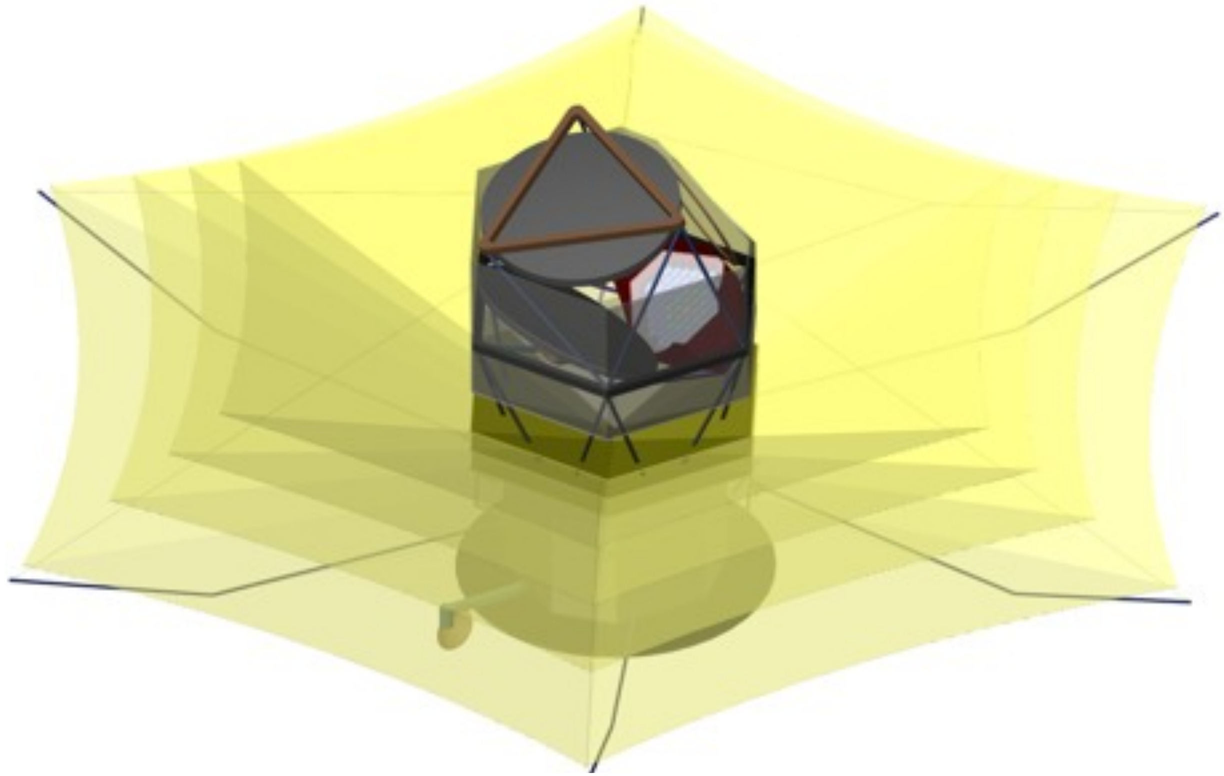
1) Funding the program proposed in white paper through 2015
2) External evaluation in 2015 of case for satellite start

Backup Materials

EPIC-IM Summary



Launch Configuration

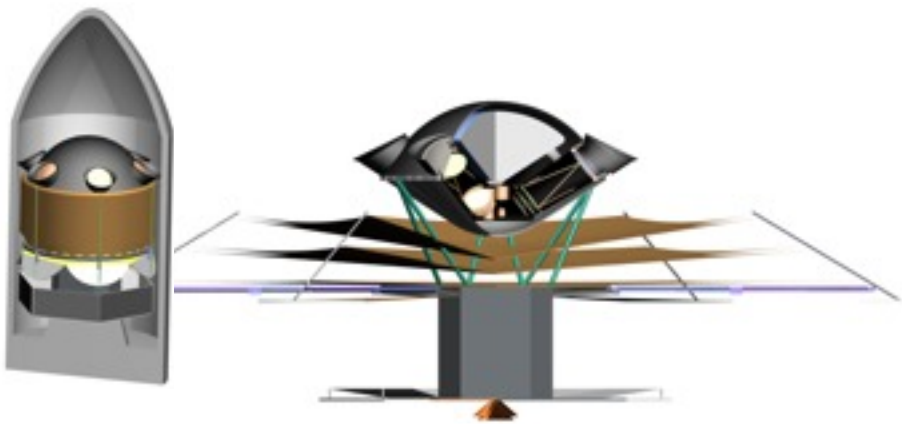


Deployed Configuration

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

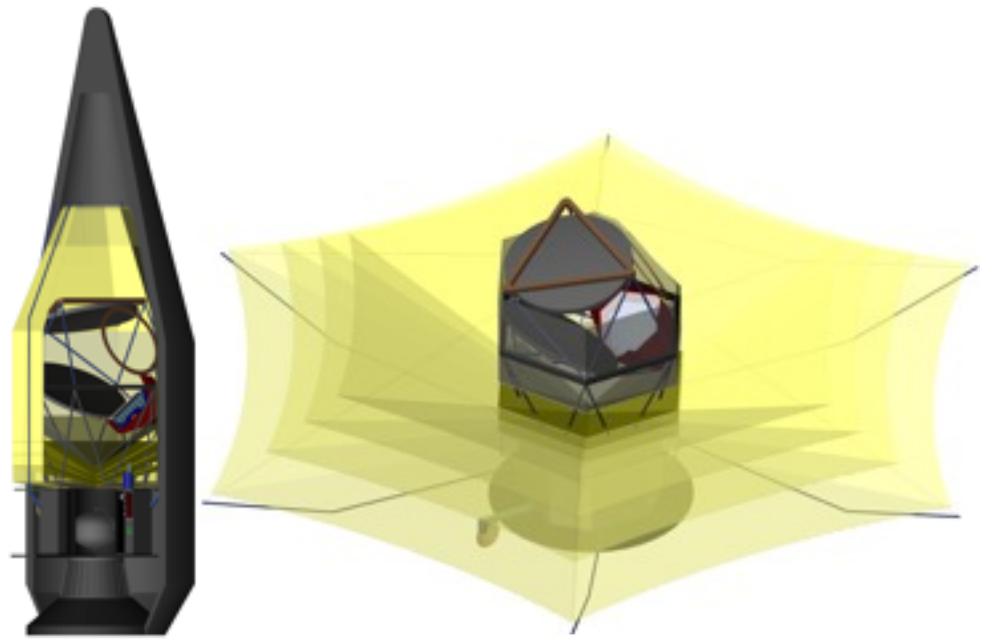
If B-Modes Detected: Low-Resolution Low-Cost Mission

Note: Configurations not shown on same scale



← 3 m →

Report: ArXive 0805.4207 (192 pages)



← 4 m →

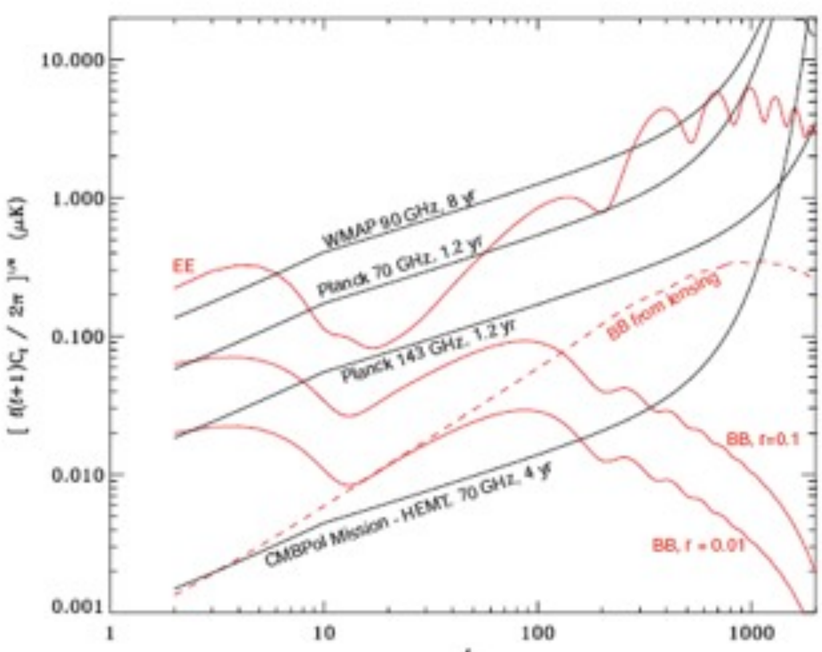
Report: ArXive 0906.1188 (157 pages)

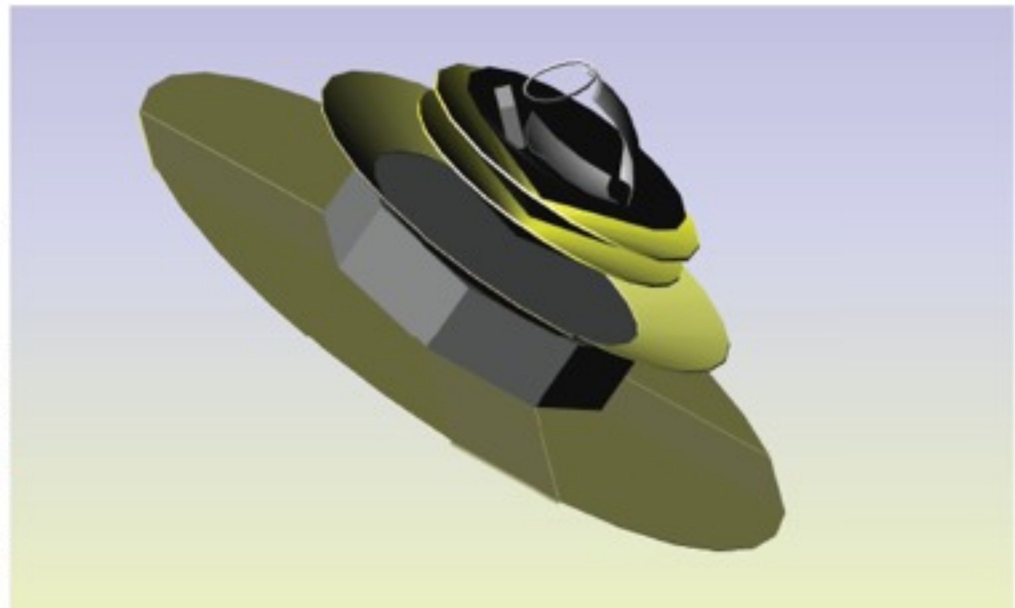
EPIC-	***Low Cost***	***Intermediate Mission***
Science	Inflationary B-mode polarization only	Inflationary B-modes, E-modes to cosmic variance, gravitational lensing to cosmic limits, neutrino mass, dark energy, Galactic astronomy
Speed	500 Plancks	3600 Plancks
Detectors	2400	11,000 (TES bolometer or MKID)
Aperture	Six 30 cm refractors	1.4 m Crossed Dragone telescope
Bands	30 – 300 GHz	30 – 300 GHz + 500 & 850 GHz
Cooling	LHe cryostat + ADR	4 K Cryo-cooler + ADR
Mass	1320 kg CBE	1670 kg CBE
Cost	$660M (FY07)	$920M (FY09)

PILOT: Low-Cost Amplifier-Based Satellite Concept

If Planck or suborbital experiments detect B-modes at $r \geq 0.01$, a low-cost option would be possible
+ Knowledge of foregrounds may permit more limited frequency coverage

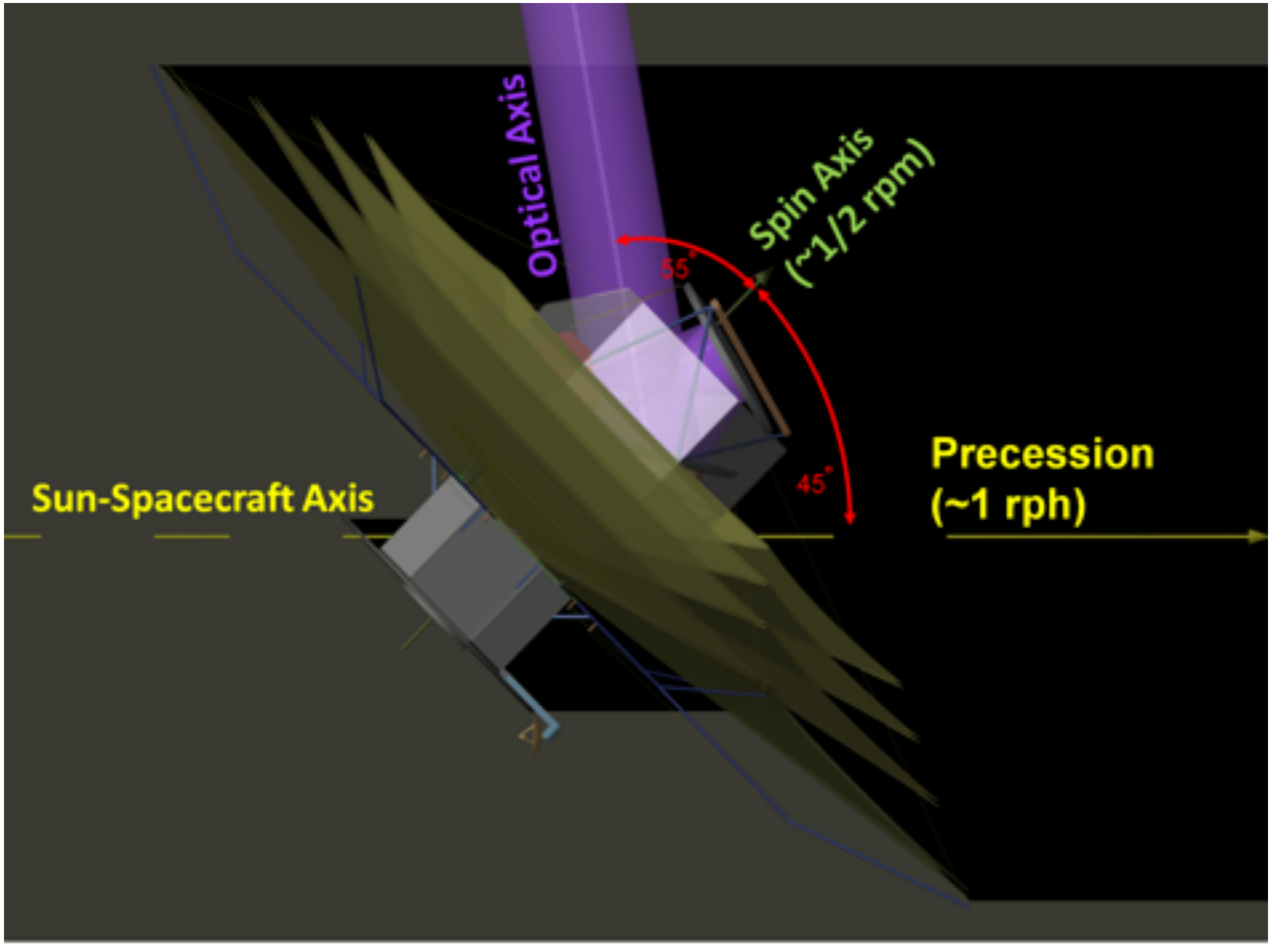
- Same telescope, orbit, and scan strategy as EPIC
- Similar mass and size $\Rightarrow$ same rocket
- Key differences:
  - Based on amplifiers at 20 K
  - Total power, including cooler, $\sim$ 2 kW, so solar panel much larger

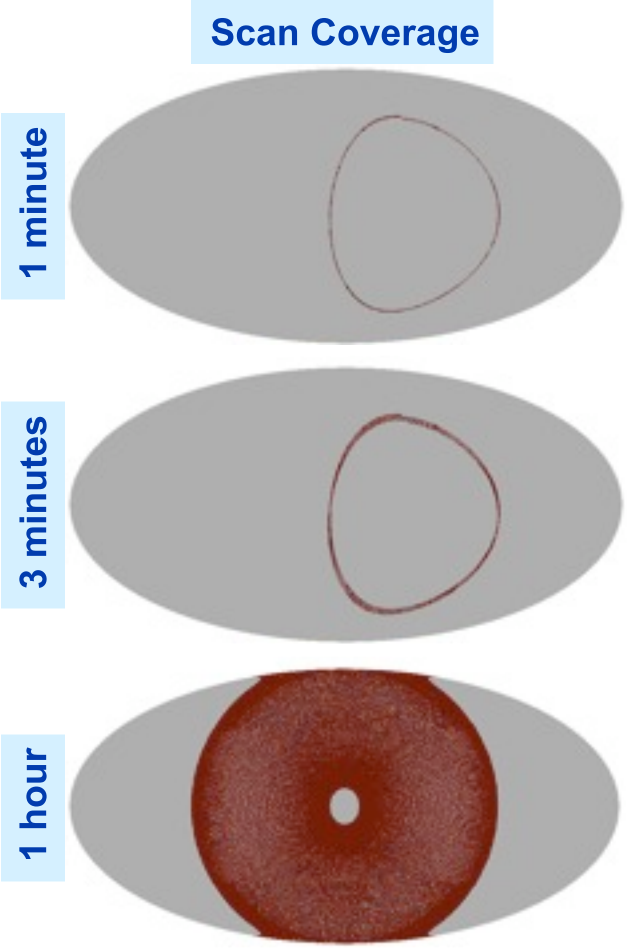




Frequency [GHz]	N	Power [mW]	T_{sys} [K]	NEQU [μK s$^{1/2}$]	NEQU/freq [μK s$^{1/2}$]	Q,U Noise/2 deg^2 4-yr [nK]
30	4	4	10	81.6	40.8	375
40	50	7	11	87.0	12.3	115
70	160	10	13	77.7	6.1	63
100	75	12	15	75.0	8.7	100
150	75	15	23	93.9	10.8	250
Total N .	364	Total power dissipated = 4 W				

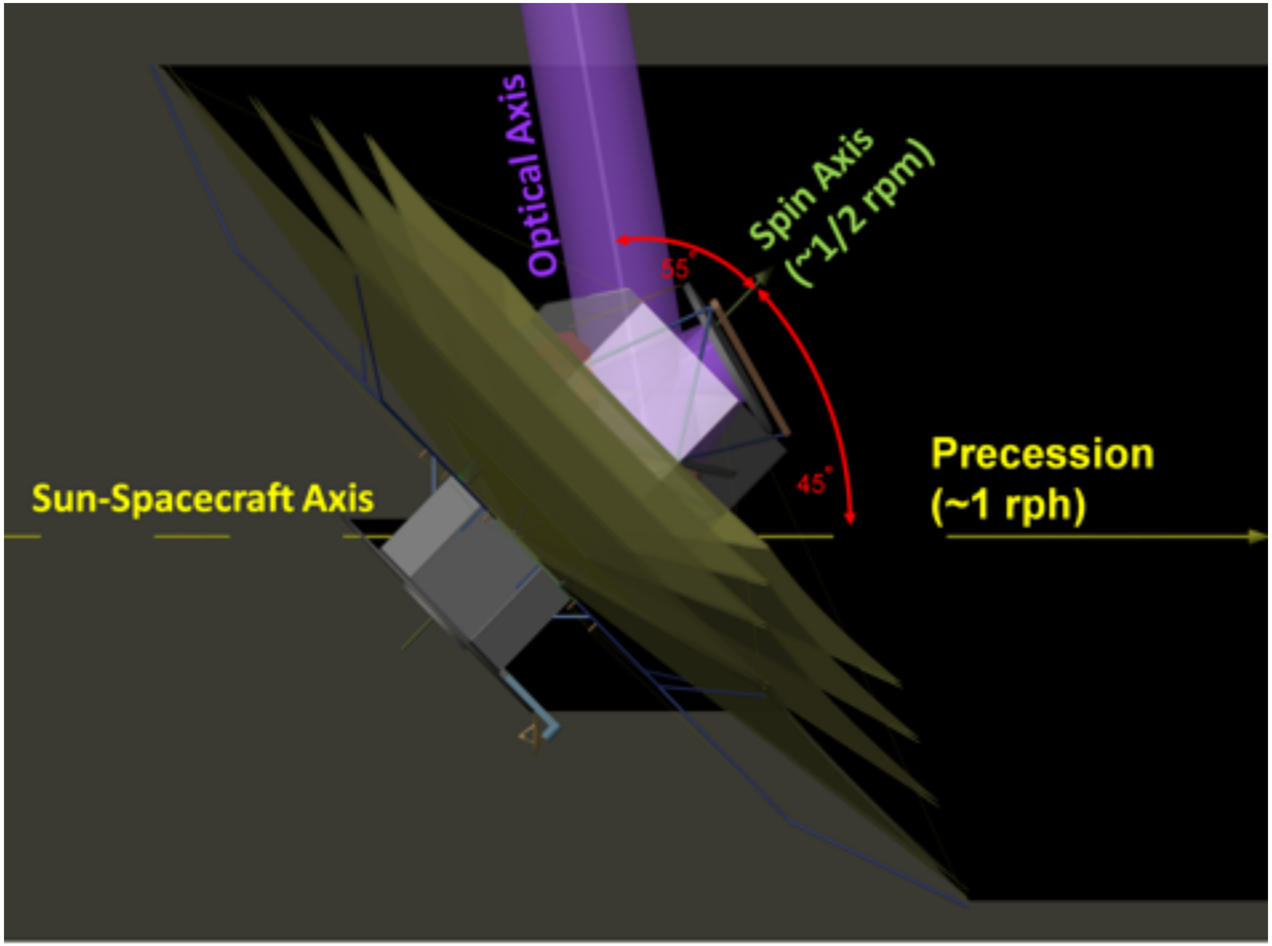
Measuring Low Multipoles in Space-Borne Observation



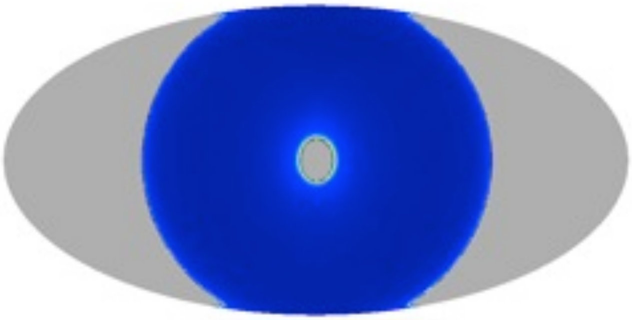


CMB Community Workshop:
Mitigating Systematic Errors In Space-Based CMB Polarization Measurements
Annapolis MD, 28-30 June 2008

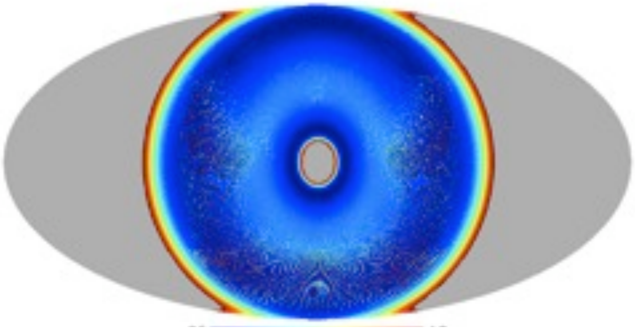
Measuring Low Multipoles in Space-Borne Observation



1 Day Maps



Spatial Coverage



Angular Uniformity

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Mitigating Systematic Errors In Space-Based CMB Polarization Measurements
Annapolis MD, 28-30 June 2008

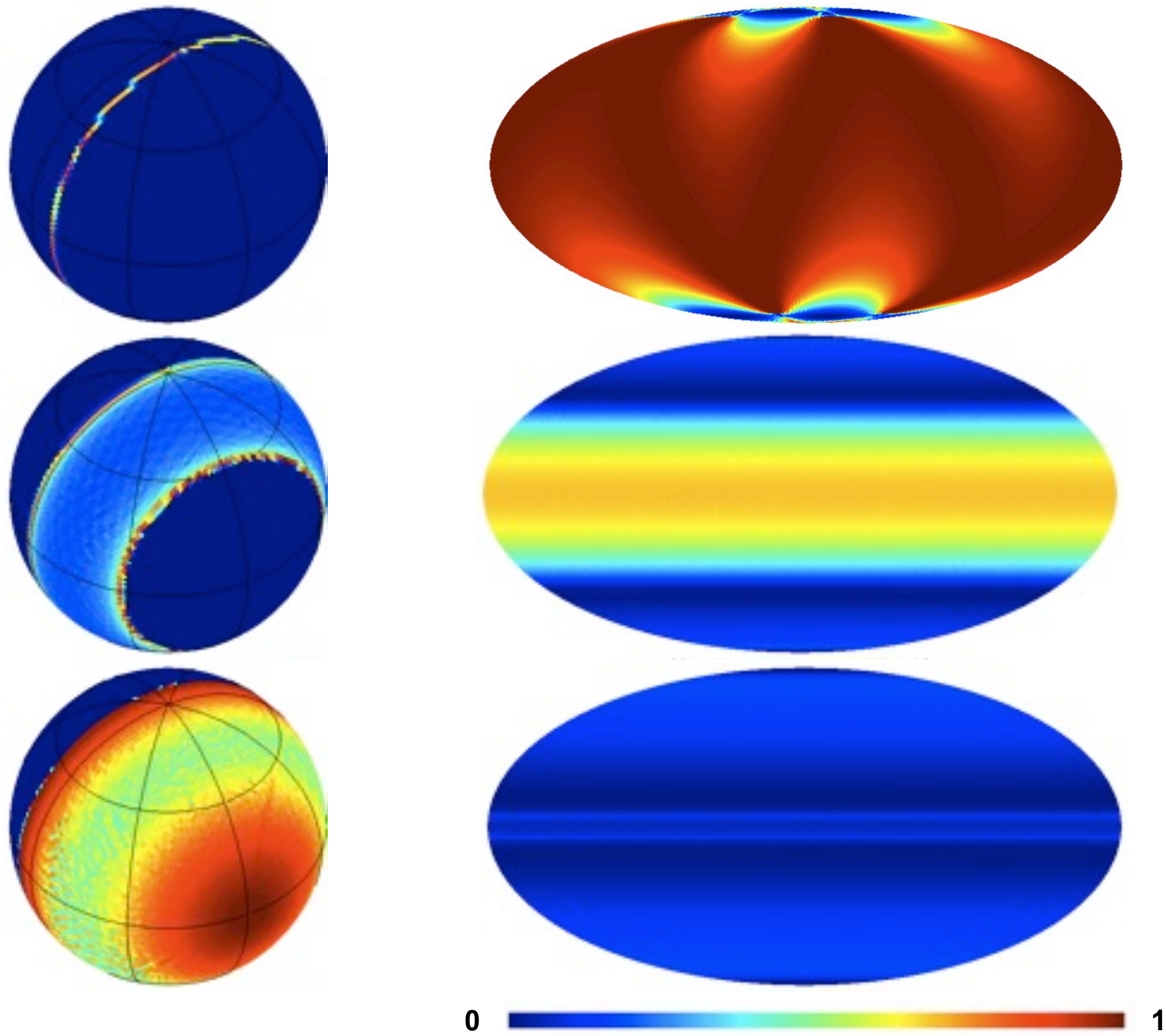
Ideal Scan Strategy for All-Sky Polarization Measurement

N-hits (1-day) **Angular Uniformity* (6-months)**

Planck

WMAP

EPIC



$^*\langle \cos 2\beta \rangle^2 + \langle \sin 2\beta \rangle^2$

Technology Plan for CMBPOL