The Inflation Probe Science Analysis Group

Technology Plan for the 2010-20 Decade

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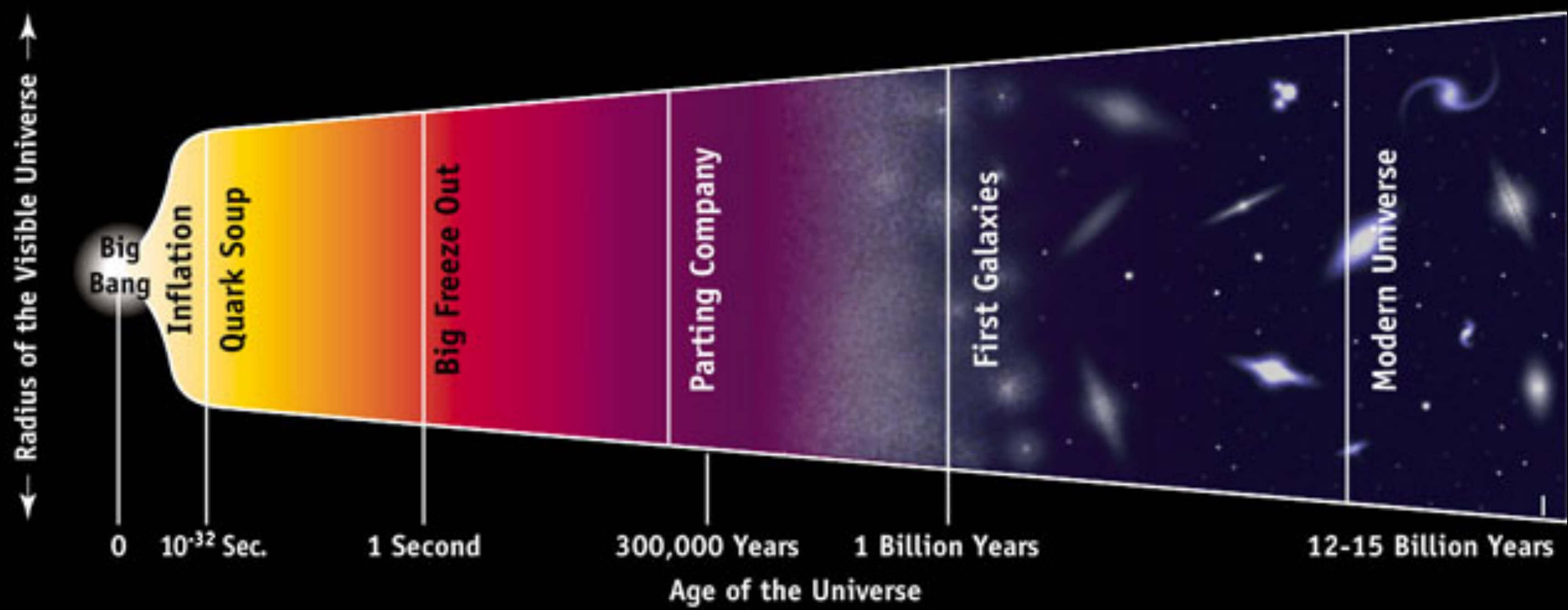
PhysPAG Meeting, AAS @ Austin, TX
8 January 2012

Testing Inflation with CMB Polarization

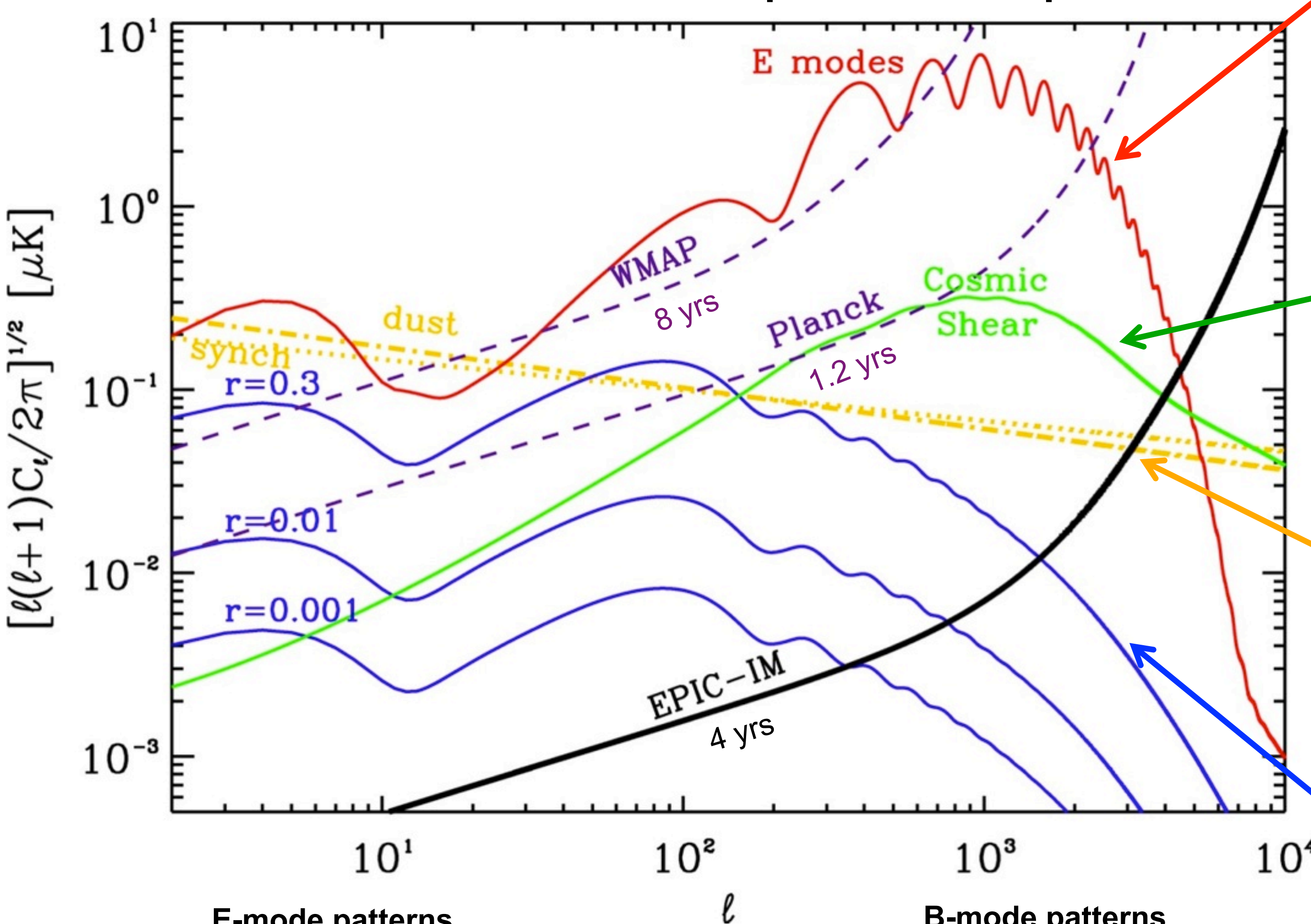


Key Inflationary Observables	First Definitive CMB Result
1. Nearly scale-invariant fluctuations	COBE
2. Flat universe	Boomerang + Maxima + TOCO
3. Adiabatic fluctuations	Boomerang + Maxima + WMAP
4. Nearly Gaussian fluctuations	WMAP
5. Super horizon fluctuations	WMAP
6. Departure from scale invariance?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

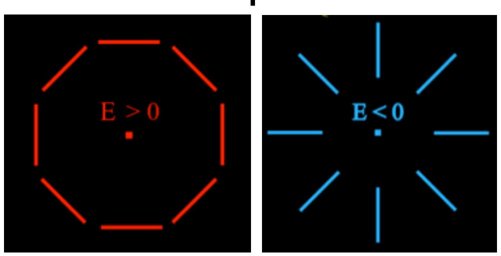
Comprehensively measure inflationary CMB polarization signal corresponding to inflation at GUT energy scales

CMB Polarization Science is Deep and Broad

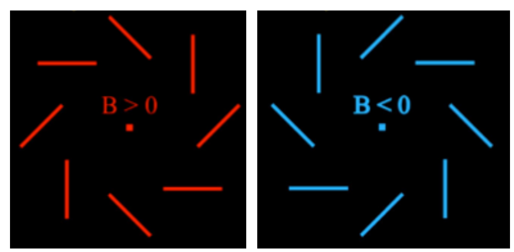
CMB Polarization Spatial Power Spectra



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

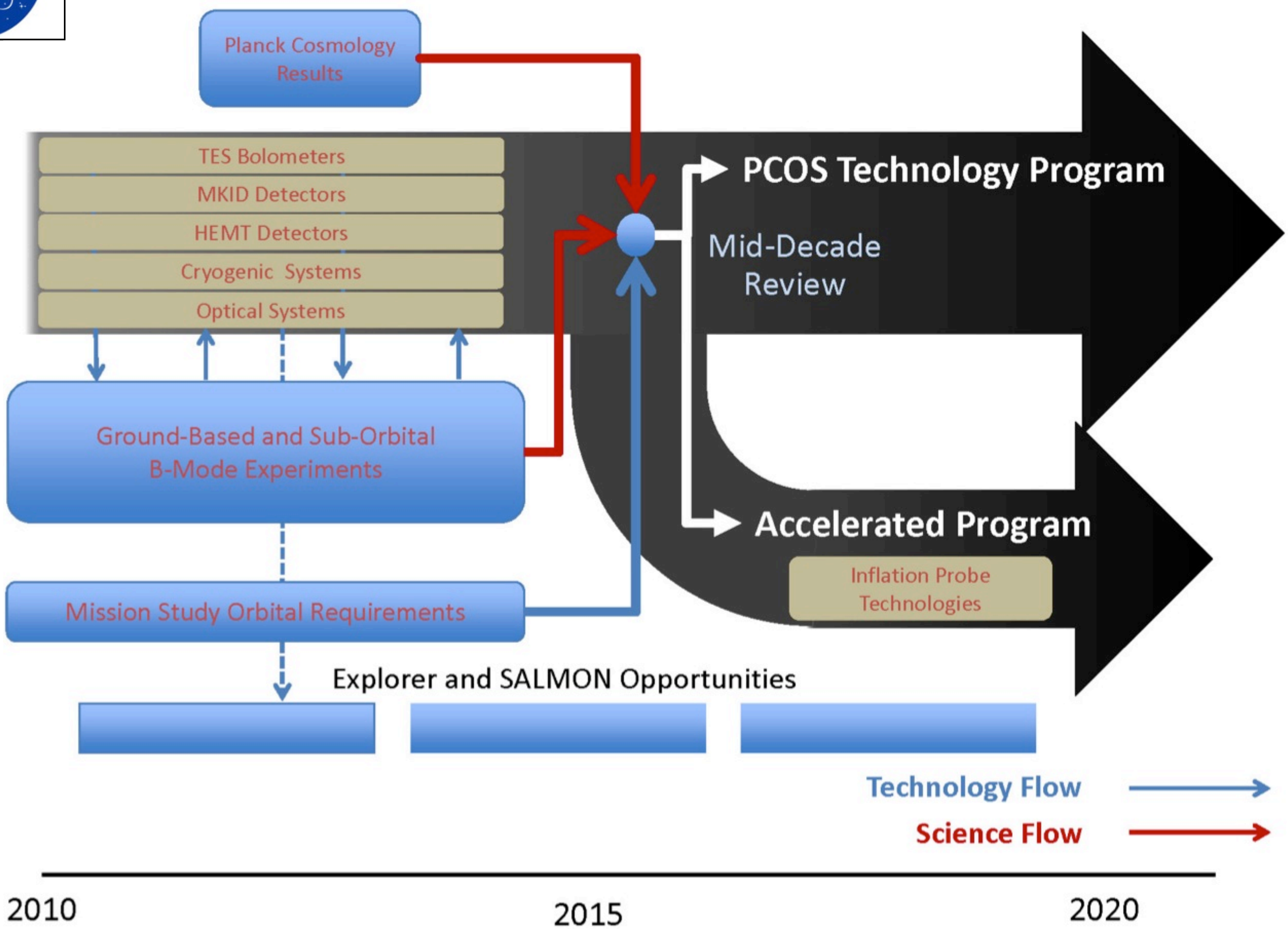
Galactic Magnetic Fields
E & B-Modes

- Star formation
- Large-scale fields

Inflationary Gravitational Waves
B-modes

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

Timeline for the Decade

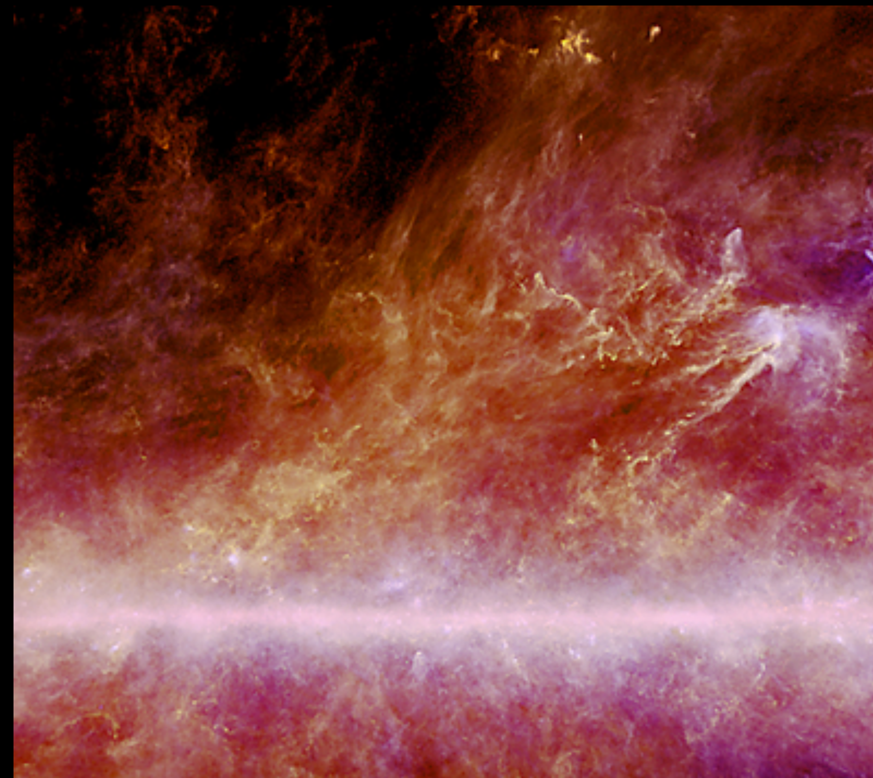


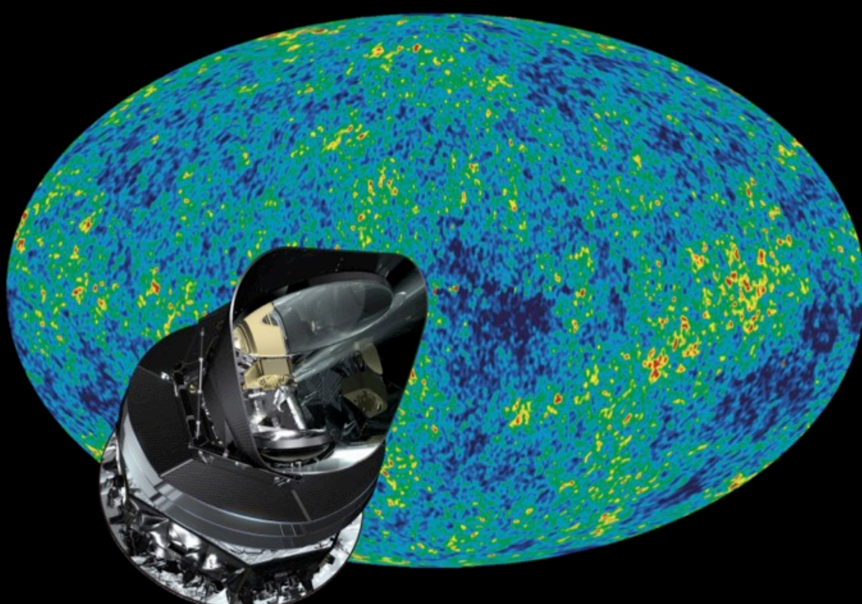
CMB community plan presented to the Decadal → Reflected in Astro2010 report

Current CMB Research: The ESA / NASA *Planck* Satellite

Instrument Status
- All systems working nominally
- HFI sensitivity exceeds pre-launch goals
- Thermal system performance as expected
- End of 100 mK cooling coming ~next week
- LFI operations will continue

Planck Strengths
- Comprehensive temperature measurements
- 9 bands for foregrounds separation
- Good polarization sensitivity
  - High-fidelity E-mode polarization measurements
  - But not enough sensitivity for B-modes





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	ERCSC & first astro results
• January 2013	Cosmology first 15 months
• February 2014	Cosmology first 30 months

Current CMB Research: Sub-Orbital and Ground-Based

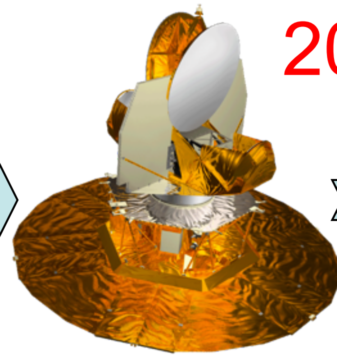
	Experiment	Technology	Resolution (arcmin)	Frequency (GHz)	Detector Pairs	Modulator
US-led Balloon	COFE	HEMT/MMIC	83/55/42	10/15/20	3/6/10	wire grid
	EBEX	TES	8	150/250/410	398/199/141	HWP
	PIPER	TES	21/15/12/7	200/270/350/600	2560	VPM
	SPIDER	TES	60/40/30	90/150/280	288/512/512	HWP
US-led Ground	ABS	TES	30	150	200	HWP
	ACTpol	TES	2.2/1.4	90/145	1500	-
	BICEP2	TES	40	150	256	-
	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
	POLAR	TES	5.2	150	2000	-
	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**
- **Expect rapid progress in Inflationary B-mode limits in next few years**

How Sub-Orbital Program Benefits a Satellite Mission

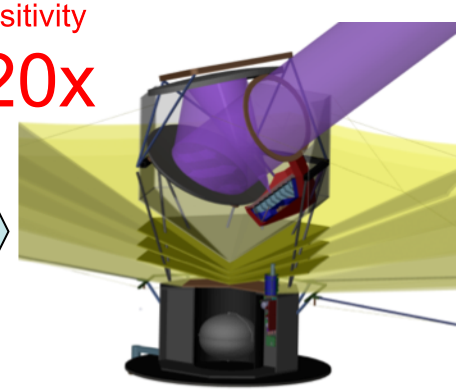
Satellite Mission

Sensitivity
60x



Sensitivity
20x

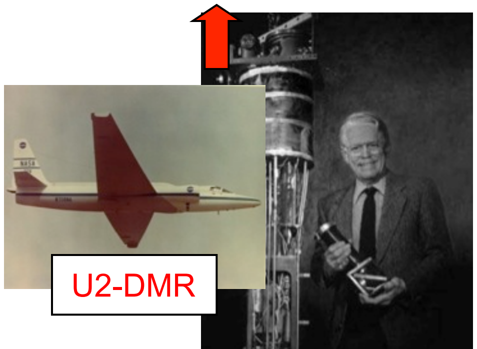
Sensitivity
>20x



100 μK — 1 μK — 100 nK — few nK

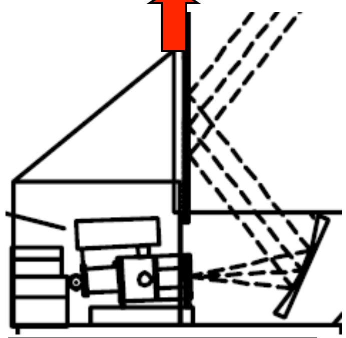
COBE	WMAP	Planck	Inflation Probe
1989	2001	2009	2022?

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 <u>systems</u> <u>level</u>**

CMB Polarization Satellite Mission Concepts

Experimental Probe of Inflationary Cosmology

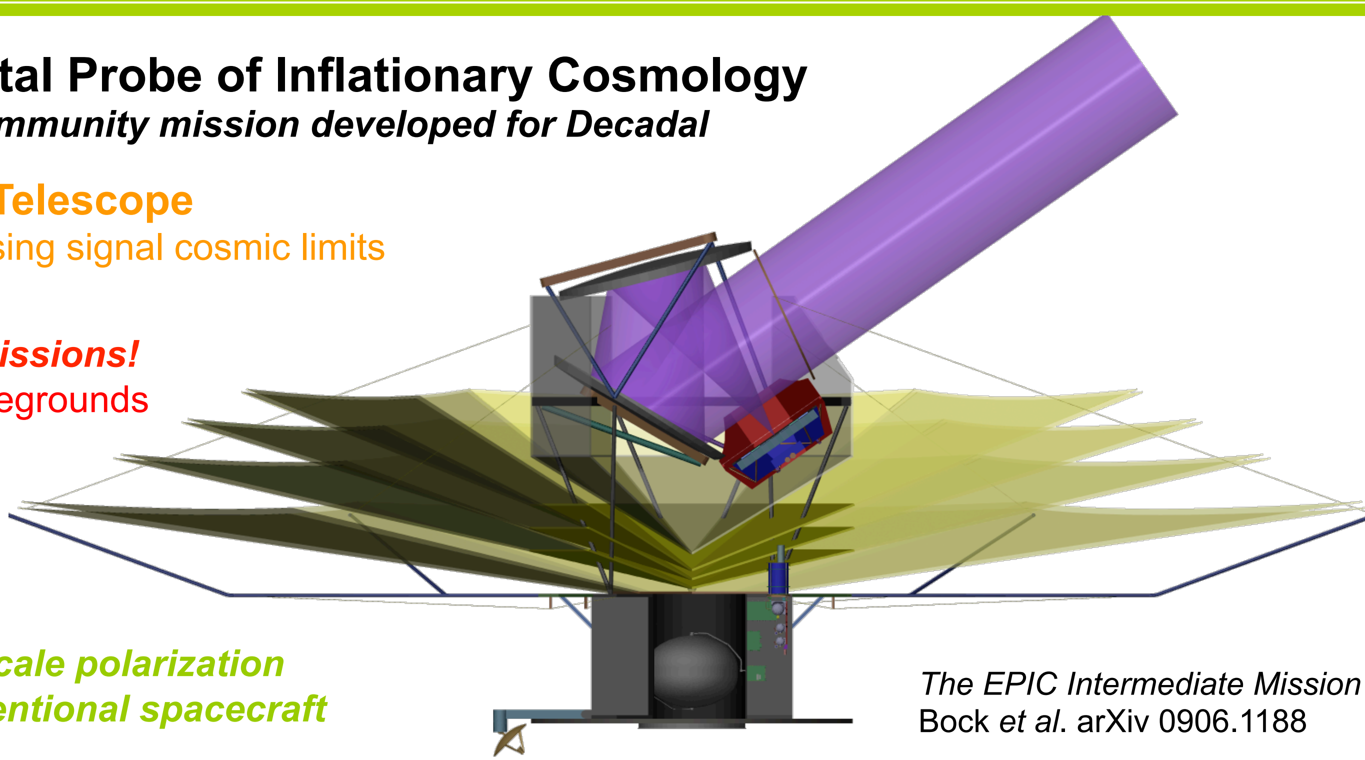
CMB community mission developed for Decadal

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

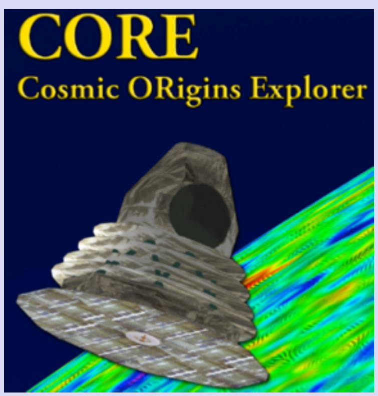
Cooling system
- 100 mK
- ***Improved Planck system***

L2 Halo Orbit
- ***Scan strategy for large-scale polarization***
- ***Simple operations, conventional spacecraft***

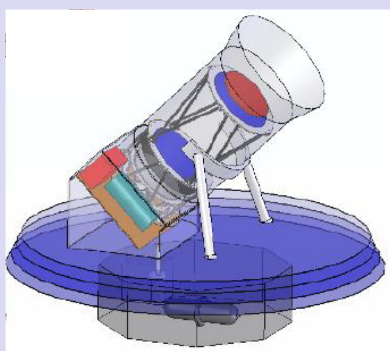


The EPIC Intermediate Mission
Bock *et al*. arXiv 0906.1188

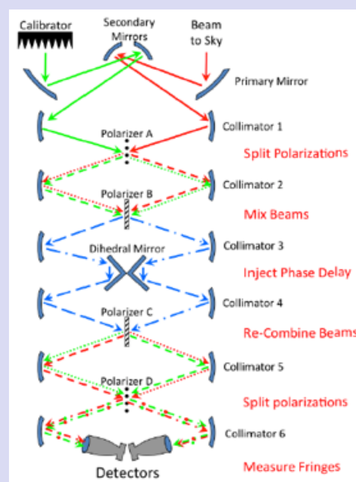
Alternative Concepts



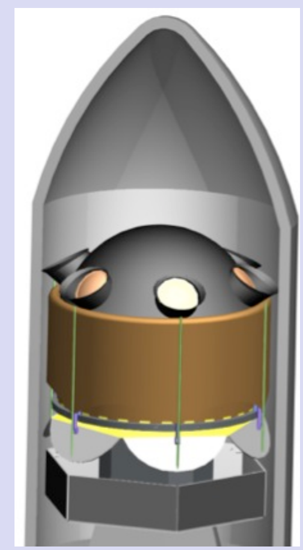
CORE
ESA 2010 proposal
1.2 m aperture



LITEBIRD
Japanese concept
30 cm aperture



EPIC-*Low Cost*
JPL concept
30 cm apertures



PIXIE
SMEX proposal
Multi-mode FTS

The Inflation Probe Science Analysis Group

Participation: Open to all members of the astrophysics community
Currently 50 registered plus 10 unregistered participants
Includes Astro2010 Inflation Probe study team members
Reports to the PhysPAG via Shaul Hanany
Active participation from NASA's PCOS office

Role: Open community input to Inflation Probe planning
- science goals following developments in the field
- mission planning for foreground removal, systematic errors
- technology development and prioritization

Communication: Open invitation issued March 2011
Email list
Website: http://pcos.gsfc.nasa.gov/sags/ipsag.php
Telecons to date: April and November 2011

Planning Docs: *CMB Technology Roadmap for the NASA Inflation Probe*, Sept. 2011

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

The Bottom Line

- Must immediately develop and field these technologies for the mid-decade review
- The highest priority development: detector arrays at medium TRL
- Fully exploit advantages of fielding technologies in active experiments

Further Notes

- Need a mission planning activity to update requirements for mid-decade review
- Continue low-TRL detector array technology development for the future

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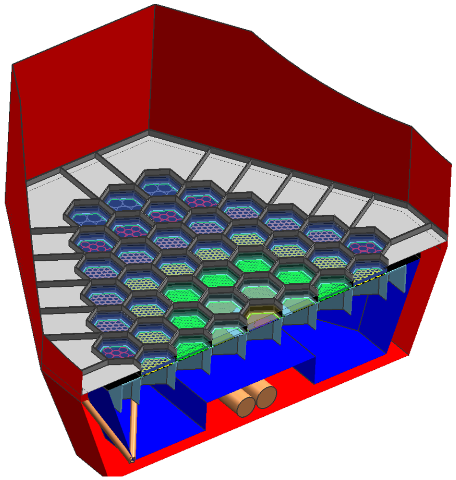
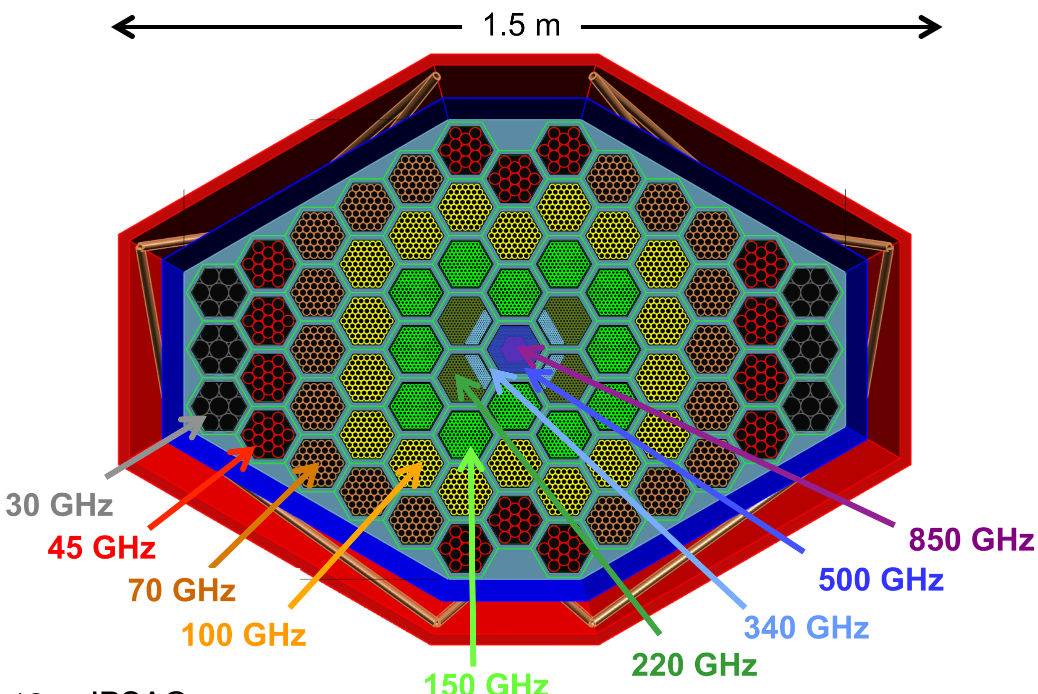
- Time is short to the mid-decadal review, and significant work remains
- Ground-based and suborbital missions are critical to probe for an inflationary B-mode signal, and to mature technology options.
- However, significant advances specific to a satellite are needed: sensitivity, wavelength coverage, statistics and systematics, and cosmic-ray rejection.
- An additional concerted effort is required now to be prepared for the detection of hints of B-modes, and the likely high prioritization of a satellite that would follow.

Detector array overview

Example: EPIC-IM



T_0 = 100 mK
Ndet = 11,094
9 Bands

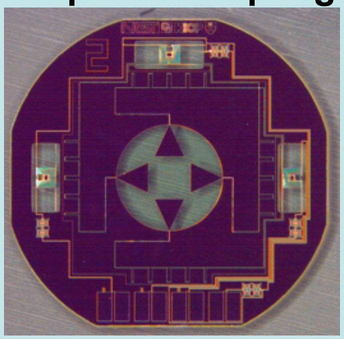


- Much larger AΩ and sensitivity are required than any planned sub-orbital experiment.
  - Lower detector NEPs
  - Better systematic control
  - More detectors
- Much broader wavelength coverage than any planned sub-suborbital experiment
- Detectors designed to be robust against particle hits
- The highest priority is the development, testing, and characterization of detector arrays. Development is needed in

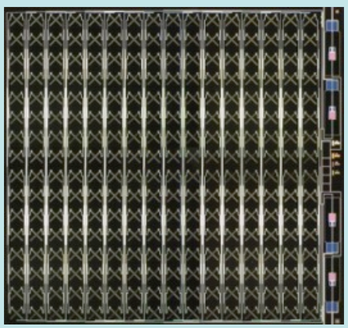
  1. Sensor arrays
  2. Optical coupling elements
  3. Multiplexed readout circuits

Sensor Arrays

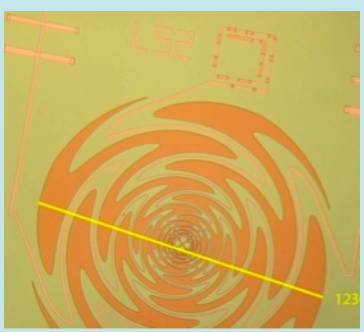
Optical Coupling



Feed Coupled

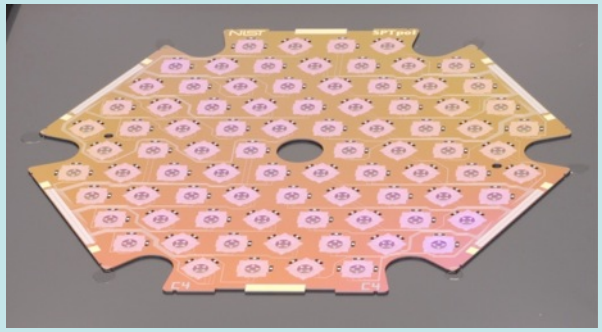


Planar Antennas

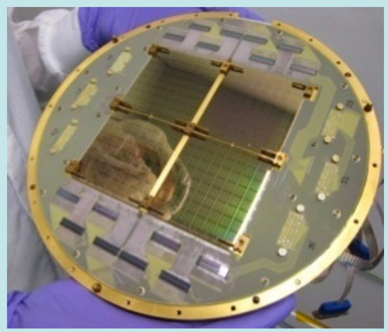


Lens-Coupled Antennas

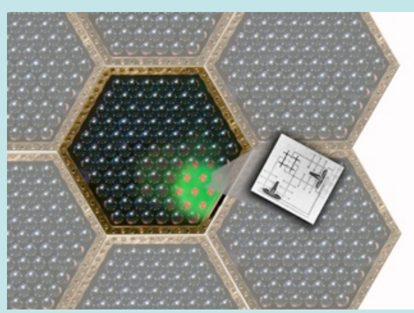
SPTpol 150 GHz



BICEP-2 150 GHz



POLARbear



To reach the sensitivity required for the Inflation Probe, we need

- Polarized detectors with noise below the CMB photon noise (much lower NEP).
- Large frequency coverage with many bands over 30 GHz-1 THz
- Large numbers of detectors (1->10 kpixel)
- Exquisite control of systematics

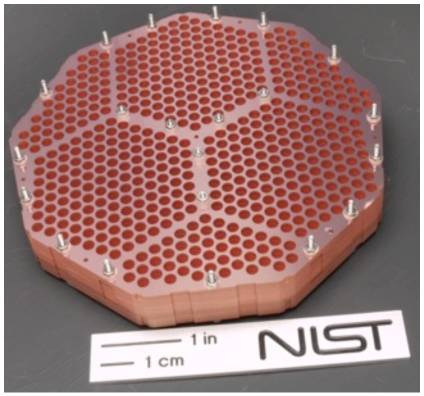
• The most mature large polarimeter array sensor, the superconducting transition-edge sensor, is now being fielded in ground-based and suborbital experiments.

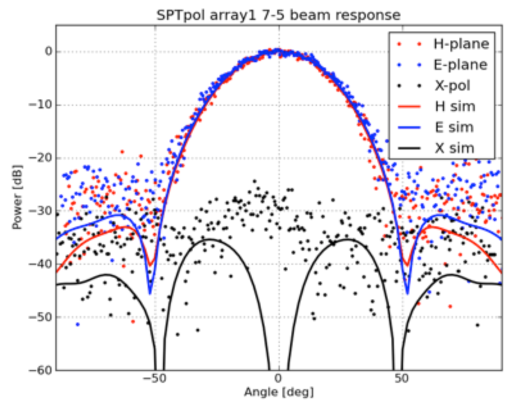
• Three optical coupling options are being developed and deployed. New work will be required to project the performance of these options in a satellite environment.

• MMICs are also being developed at a lower level

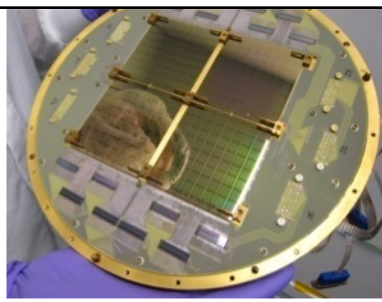
Optical coupling / beam forming

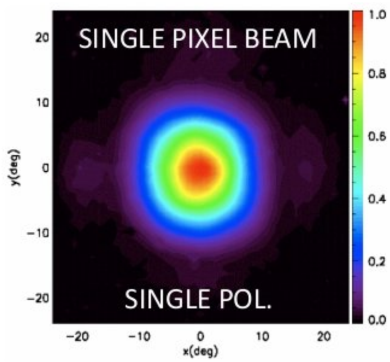
ACTpol feeds



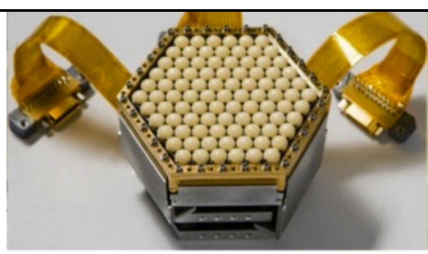


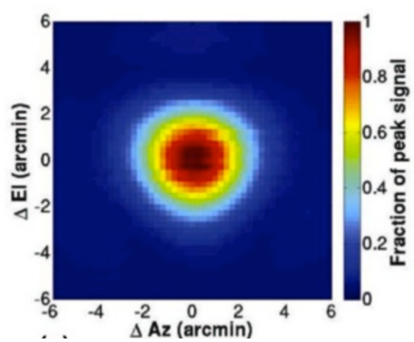
BICEP-2 phased arrays





POLARbear lenselets





<u>Feedhorn arrays</u>

- Long heritage in flight missions
- Excellent beam symmetry & crosspol
- ACTpol, SPTpol, ABS

<u>Phased antenna arrays</u>

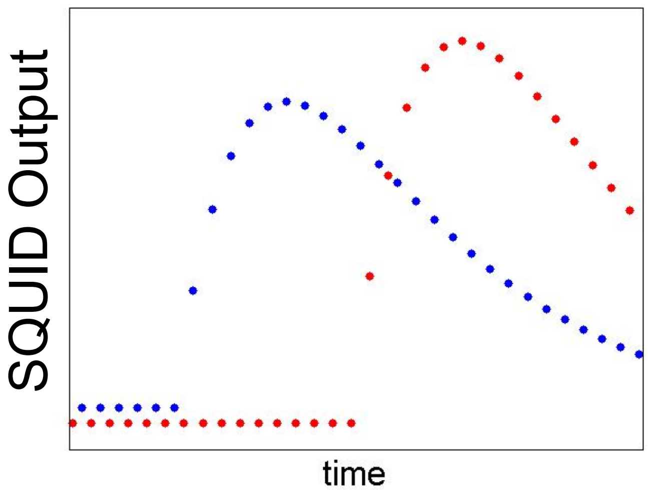
- Compact; very low mass, simple
- BICEP-2, Keck, SPIDER, POLAR

<u>Lenselet arrays</u>

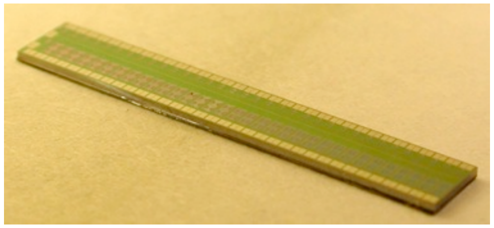
- Large bandwidth
- POLARbear

Three options are being pursued to meet Inflation Probe requirements

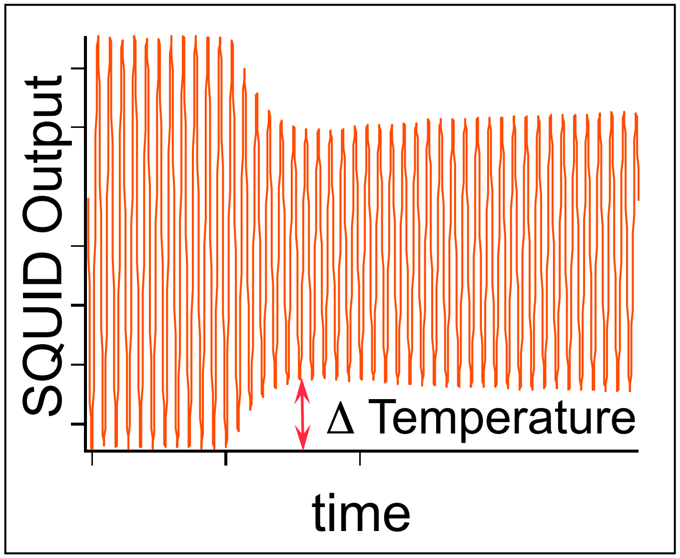
Multiplexed readout



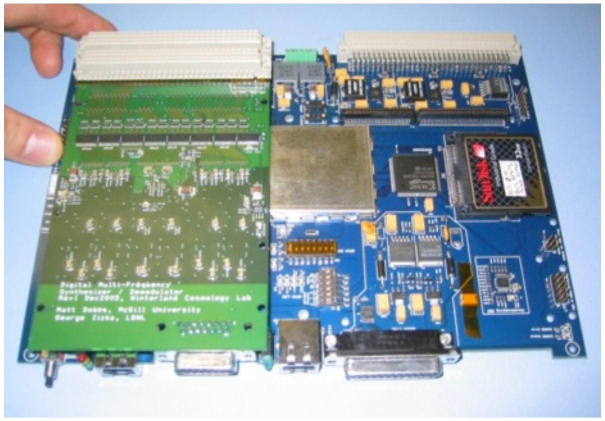
Time division (TDM): different pixels at different times



TDM SQUID switches



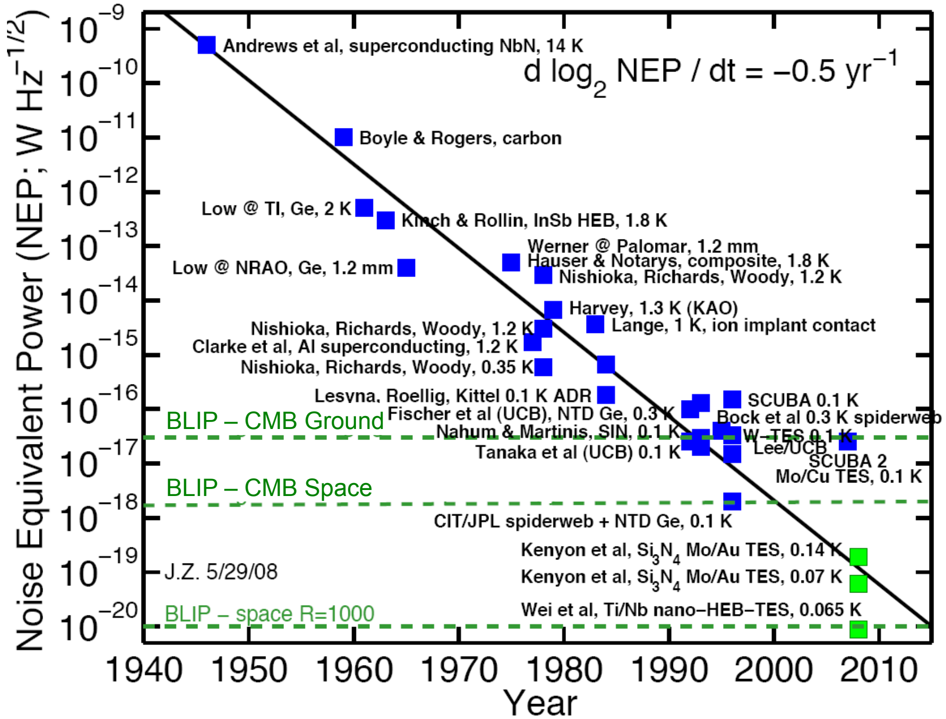
Frequency division (FDM): different pixels at different frequencies

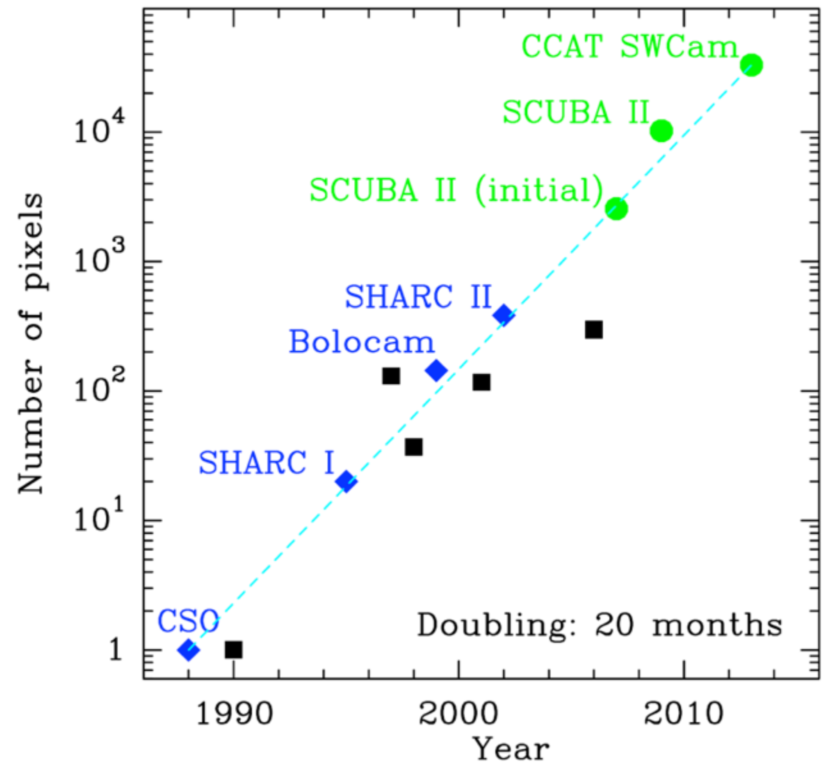


Room-temperature electronics for FDM

Need to develop robust, radiation hard cryogenic components and low-power, flight-qualified readout electronics

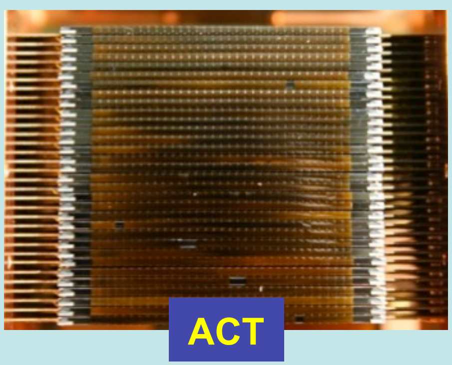
Rapid Progress in Detector Development

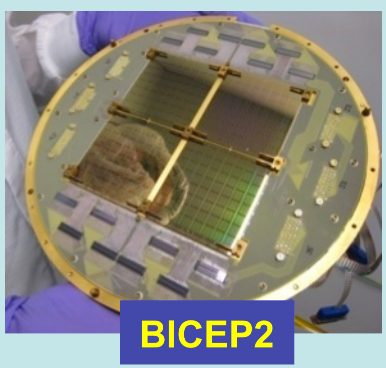


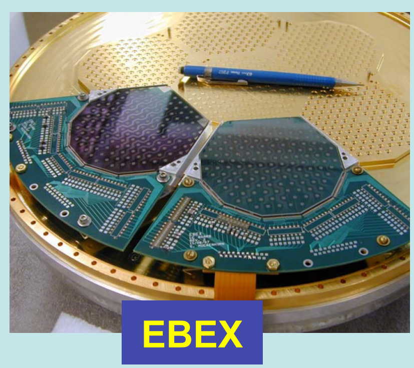


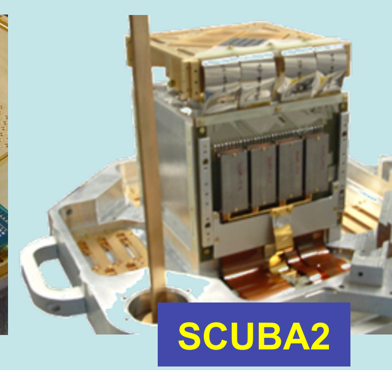
- Rapid progress in arrays
- Development synergy with far-IR and X-ray astronomy

Technology & Sub-Orbital Program

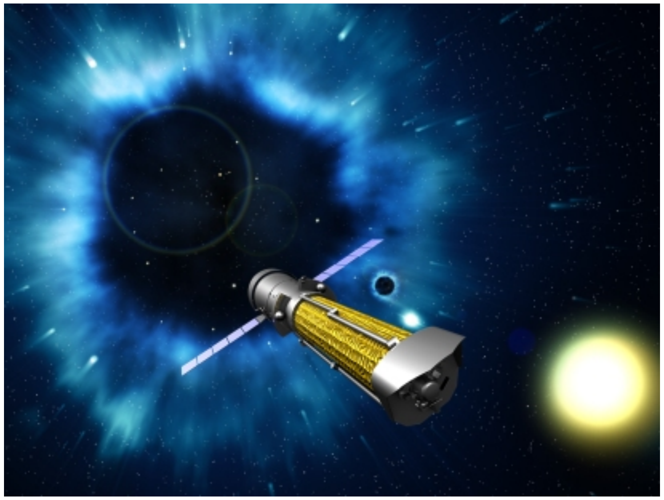




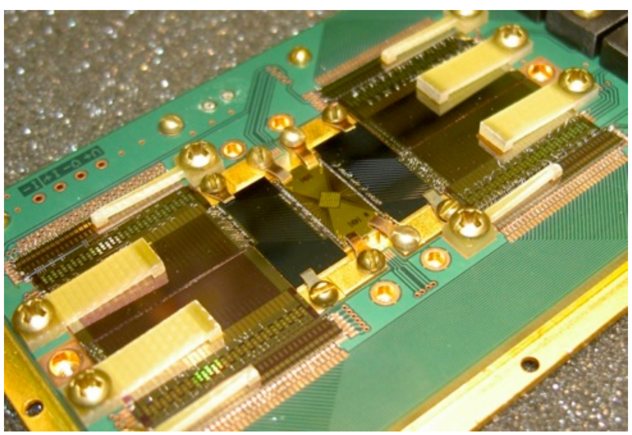




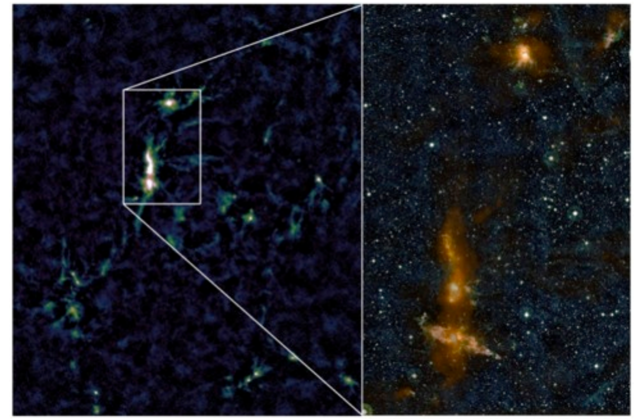
Synergy with x-ray and submillimeter



TES thermometer and readout are similar to x-ray sensors needed for to successors to IXO, including Athena.

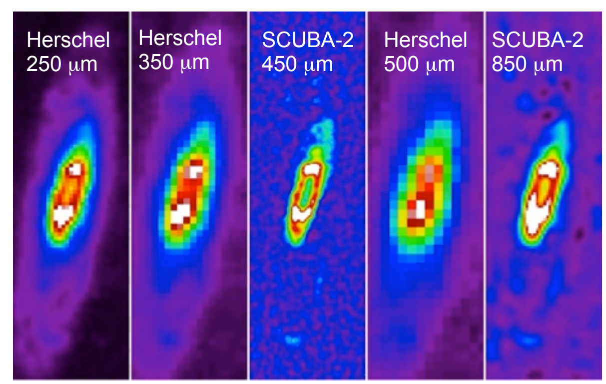


James Clerk Maxwell Telescope



The DR21 star forming region. The left hand panel shows the SCUBA-2 850 μm image while the right-hand panel is a close up region where the 850 μm data has been overlayed on a UKDISS infrared image (Image credit:JAC)

TES thermometer and readout also leverage the development of submillimeter cameras, such as SCUBA-2 at the JCMT

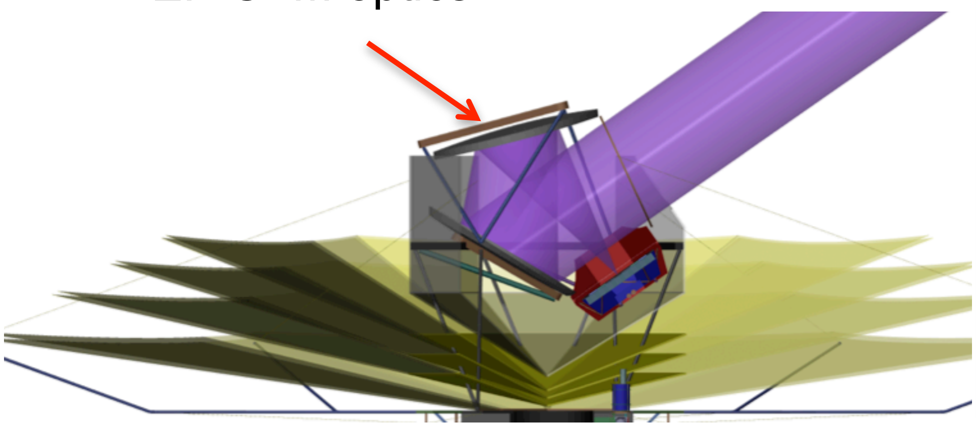


NGC7331 at 5 wavelengths. The central ring-link structure is clearly visible in the submillimeter dust emission. (Image credit: JAC, Herschel KINGFISH consortium)

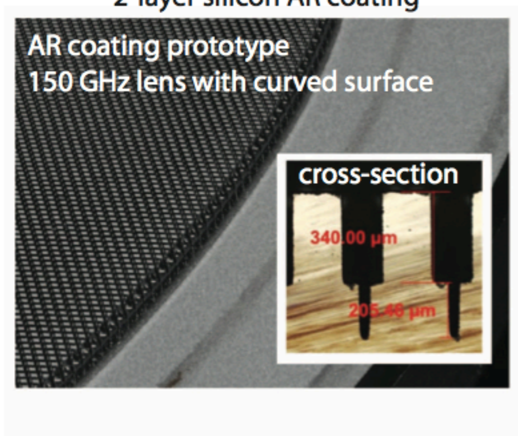
Optical system

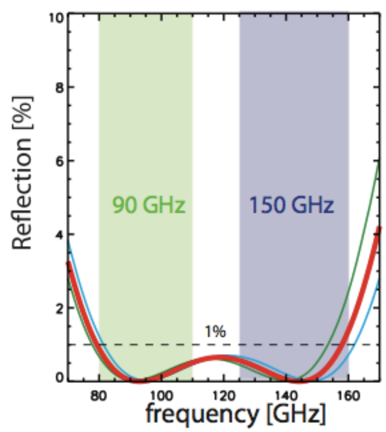
- Relevant optical system designs for the Inflation Probe must be developed and analyzed
- Crossed-Dragone optics provide larger FOV with more detectors; demonstrated in QUIET, being deployed in ABS and POLAR. Basis of EPIC-IM mission concept.
- Other concepts include smaller apertures for less costly missions; B-POL with large, rotating half-wave-plate for polarization modulation, PIXIE with FTS, etc. Some require mm-wave lenses with AR coating.

EPIC-IM optics



2-layer silicon AR coating

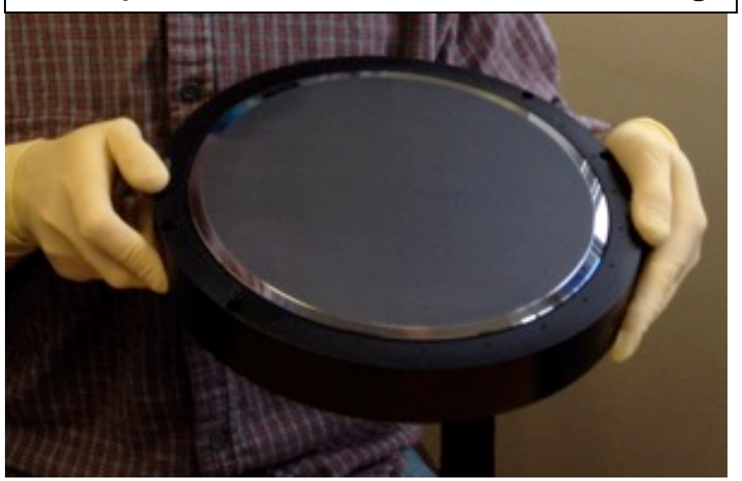




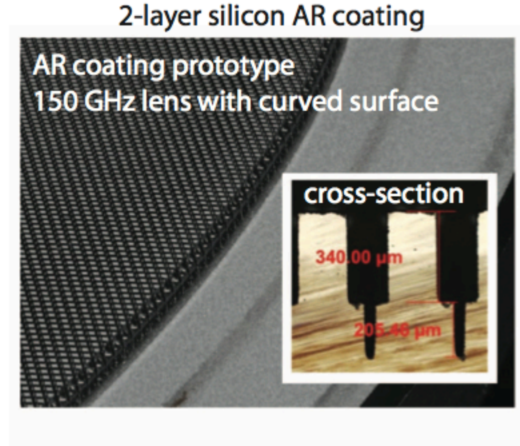
Optical system

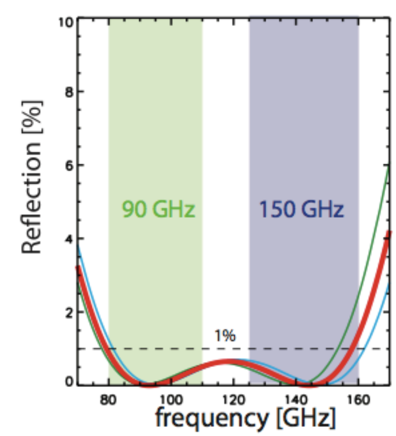
- Relevant optical system designs for the Inflation Probe must be developed and analyzed
- Crossed-Dragone optics provide larger FOV with more detectors; demonstrated in QUIET, being deployed in ABS and POLAR. Basis of EPIC-IM mission concept.
- Other concepts include smaller apertures for less costly missions; B-POL with large, rotating half-wave-plate for polarization modulation, PIXIE with FTS, etc. Some require mm-wave lenses with AR coating.

ACTpol Si lense with AR coating



2-layer silicon AR coating

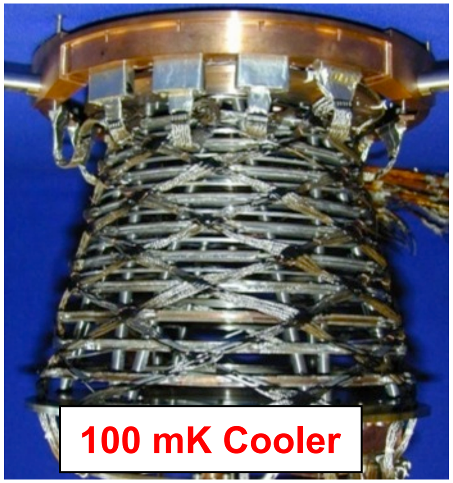




Cryogenic system

- The Inflation Probe requires passive radiators, mechanical cryocoolers, and sub-Kelvin coolers
- Technology options include He-3 sorption refrigerators, adiabatic demagnetization refrigerators, and dilution refrigerators. TRL for all options varies from TRL 3-9.
- Planck, Herschel, and SUZAKU/ASTRO H, provide flight heritage for some of these systems
- Space cooling systems can be leveraged on current technology efforts, but must be very stable

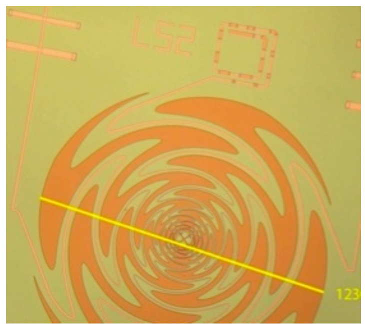
100 mK dilution refrigerator for Planck
Working at earth-sun L2



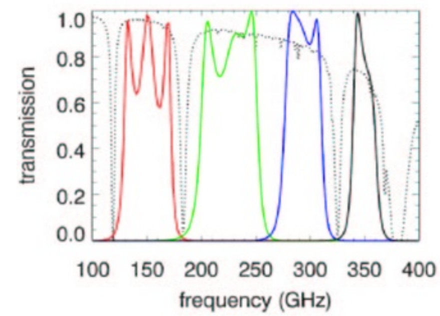
Advanced array technology: multichroic

- One possible advance for the Inflation Probe is the development of multichroic arrays with uncompromised polarization performance. This might be accomplished with feedhorns, lenselets, and phased arrays

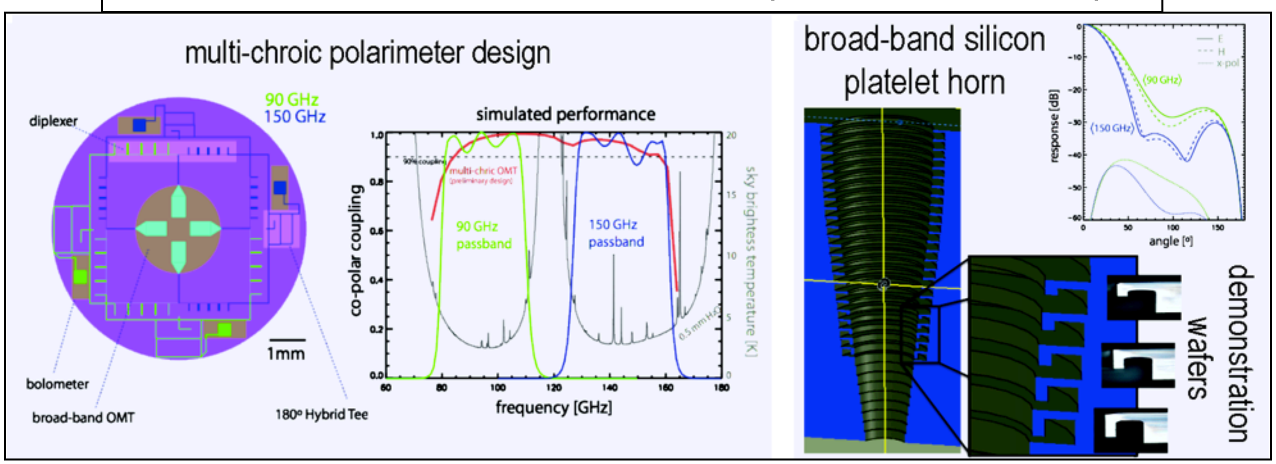
Broadband log-spiral antenna for POLARbear



4-color phased antenna array bandpasses



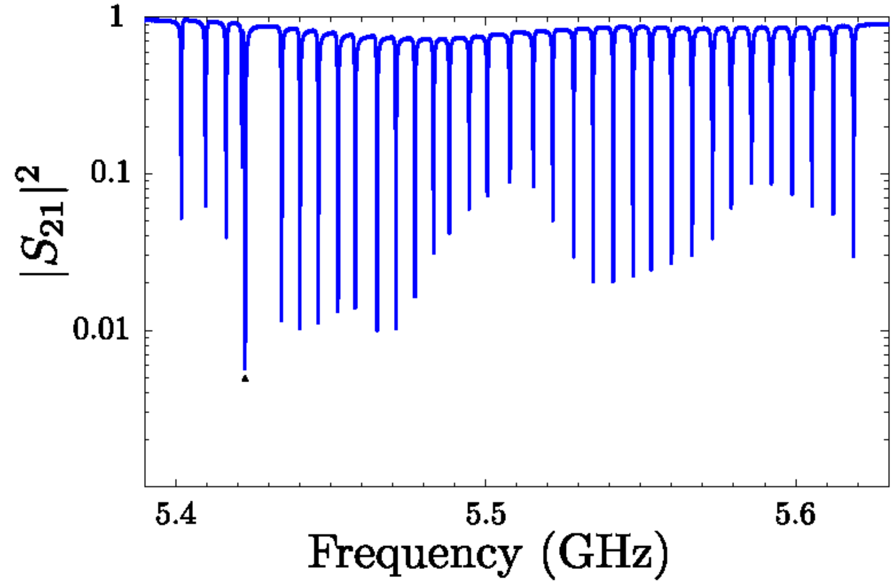
90 GHz / 150 GHz dual-color feedhorn polarimeter for ACTpol



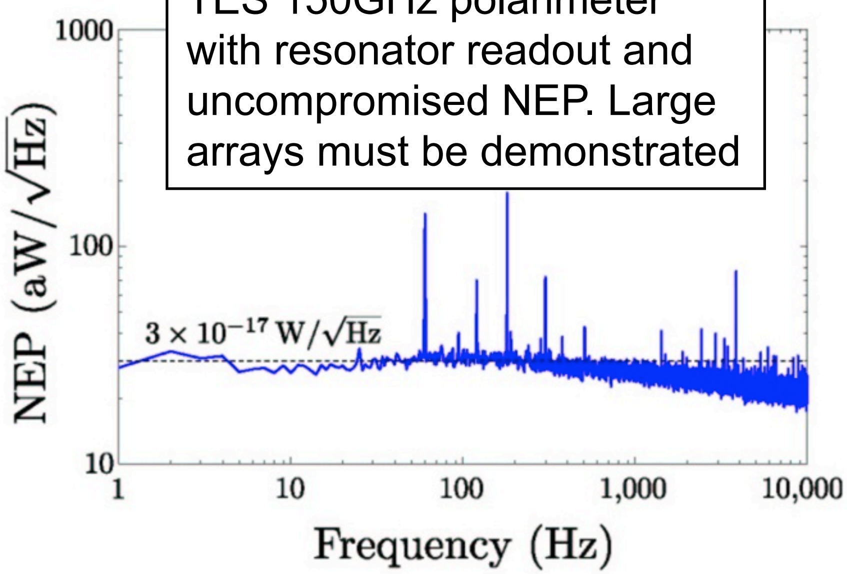
Advanced array technology: microresonators

- Another advanced array technology is the superconducting microwave resonator. Detectors read out with high-Q resonators can have much higher multiplex factors, enabling larger arrays
- Advanced, flight-qualified, low-power room-temperature electronics must be developed

P. Day et al., Nature (2003).



TES 150GHz polarimeter with resonator readout and uncompromised NEP. Large arrays must be demonstrated



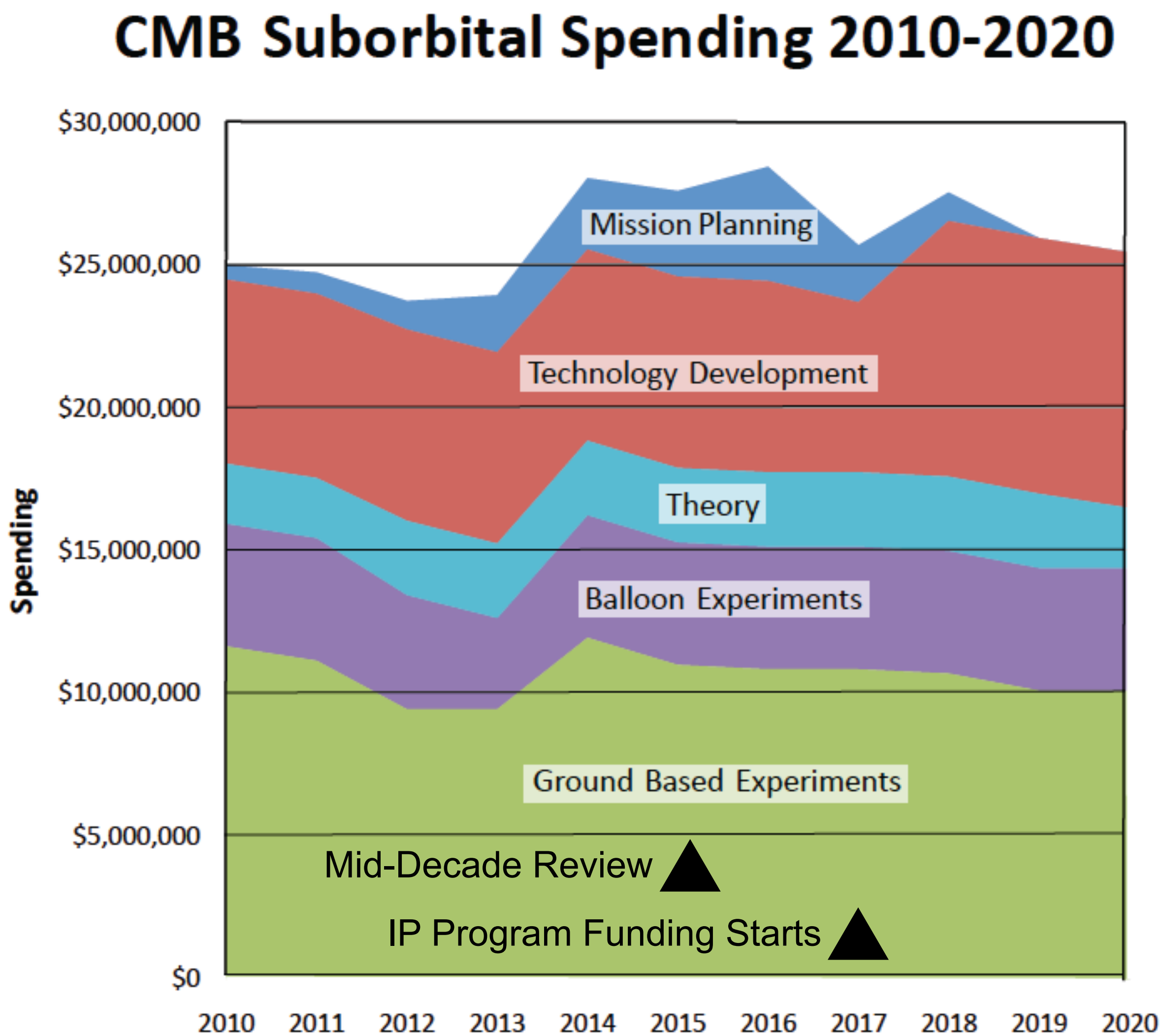
- In the microwave kinetic inductance detector (MKID), the resonator itself is the sensor. This is a great simplification, but appropriate sensitivity needs to be demonstrated in the CMB.

The Inflation Probe Technology Roadmap

Technology	Priority	Timescale	Candidates	TRL
Detector Arrays	High	Current experiments	TES+SQUID+Antenna HEMT / MMIC	4-5
Optics	Medium	Current 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

An additional concerted effort is required now to be prepared for the detection of hints of B-modes, and the likely high prioritization of a satellite that would follow.

Community Funding Profile Requested from Decadal

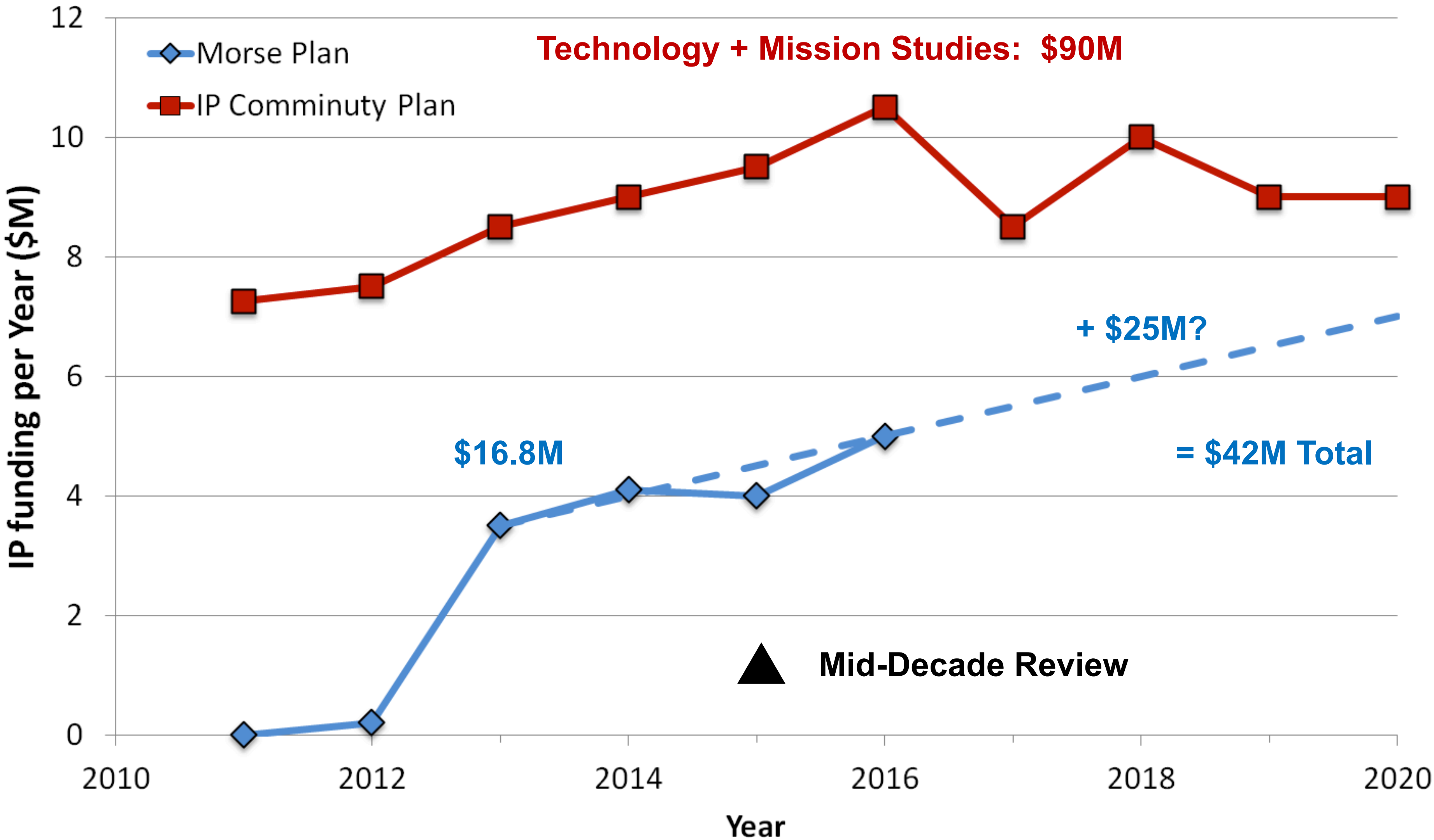


- Plan endorsed by 142 members of the CMB community
- **Theory**, **Balloon** and **Ground-Based** experiment funding come from existing, competition-based programs
- **Technology Development** and **Mission Planning** come from new NASA program
- **Technology Development** comprises $1M/yr in University Research plus $5.5 M/yr in development at Detector Centers
- **Mission Planning** wedge is crucial for mid-decade review, but not in current NASA plan

Taken from *"A program of Technology Development and Sub-Orbital Observations of the CMB Polarization Leading to and Including a Satellite Mission"*

Current Profile of Inflation Probe Funding

Decadal Recommendation: $60M - $200M



Recommendations

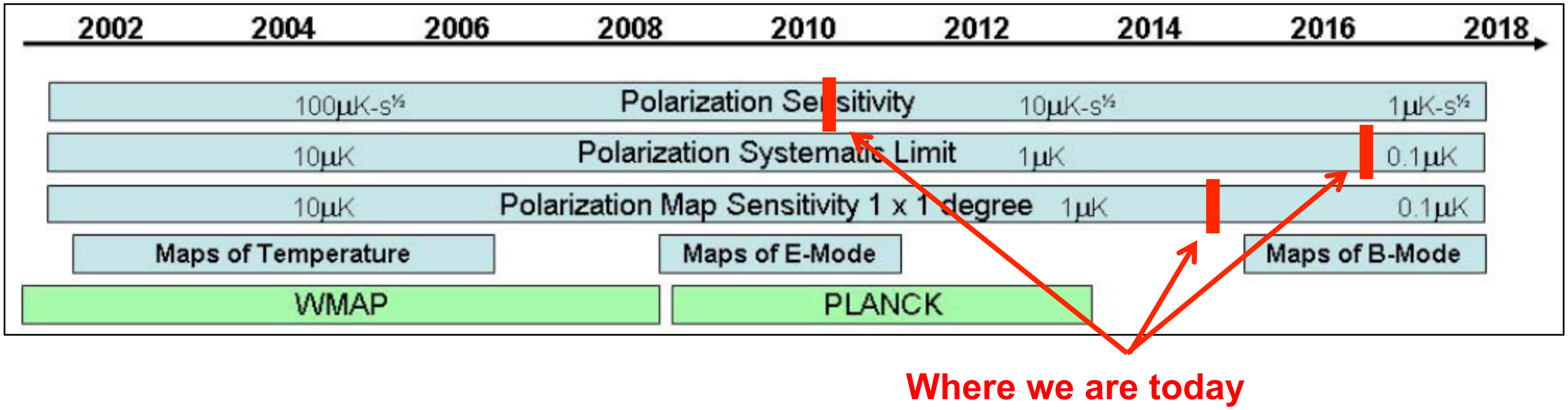
The PhysPAG recommends that dedicated technology development for the Inflation Probe should commence as soon as possible in order to properly prepare the Inflation Probe for the planned mid-decade review, at a total funding level for the decade that is consistent with the Astro2010 Decadal Review.

The IPSAG will continue to provide technical recommendations to the NASA PCOS office through the PhysPAG.

Backups

Transition from Sub-Orbital Experiments to Space

Task Force for CMB Research Weiss Report 2005: Projected Timeline



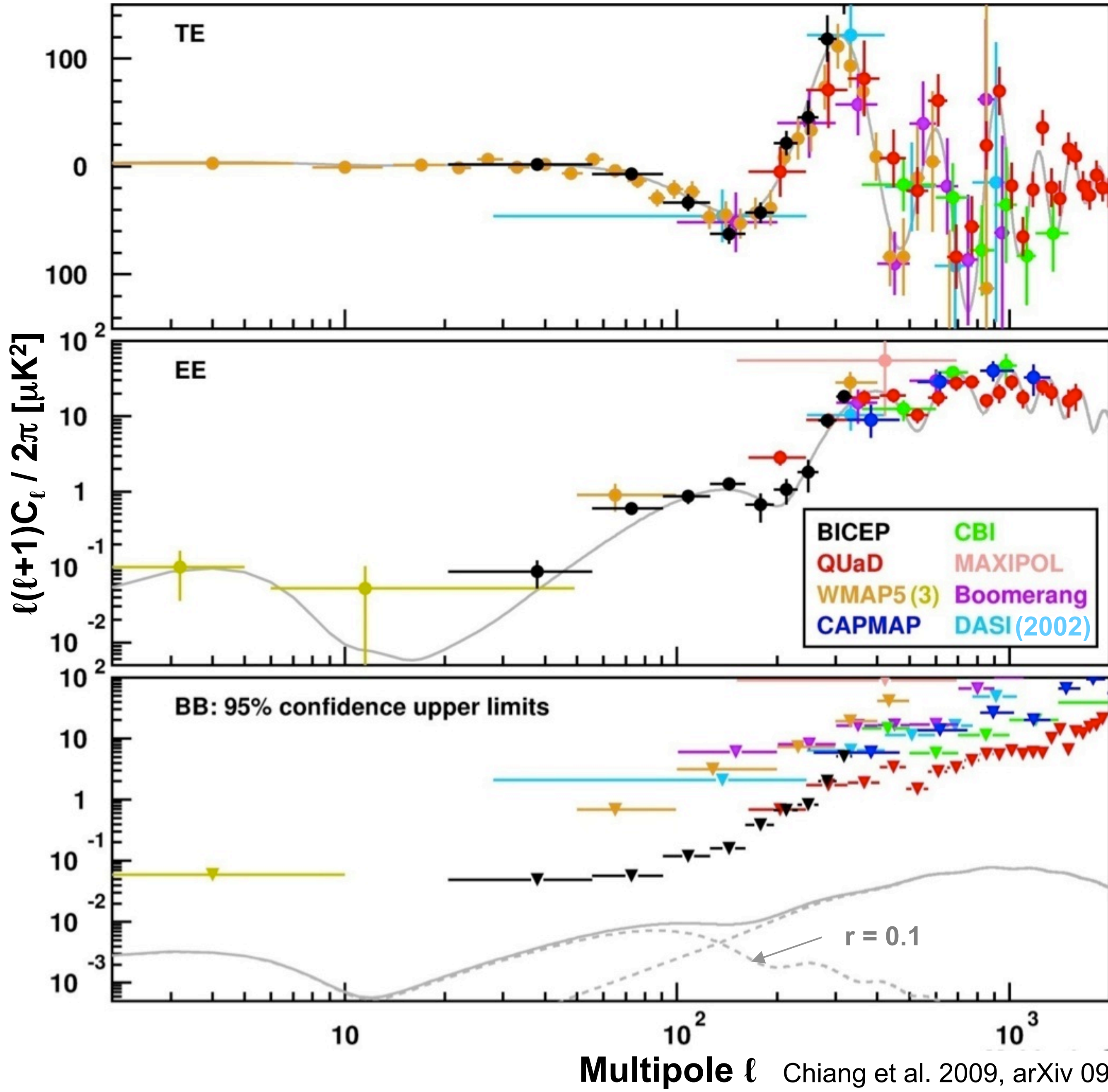
Current Sub-Orbital and Ground-Based Experiments

US Balloons	US Ground-based			European Ground-based
EBEX	ABS	ACT	BICEP2	BRAIN
SPIDER	Keck Array	MBI	Poincare	QUIJOTE
PIPER	PolarBeaR	QUIET	SPT	

Vigorous ‘Market-Driven’ Scientific Niches

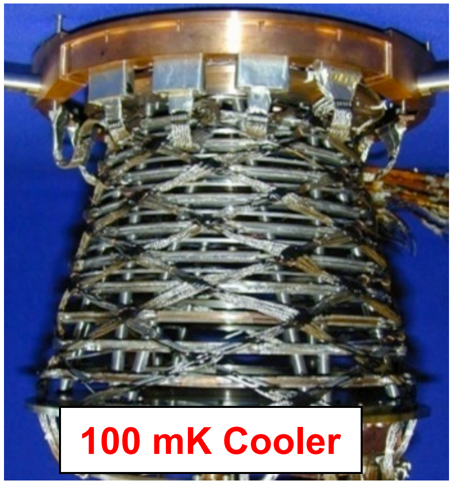
- Wide variety of technologies
- Wide range of frequencies, resolution, and sky coverage
- Diverse approaches to systematic error control

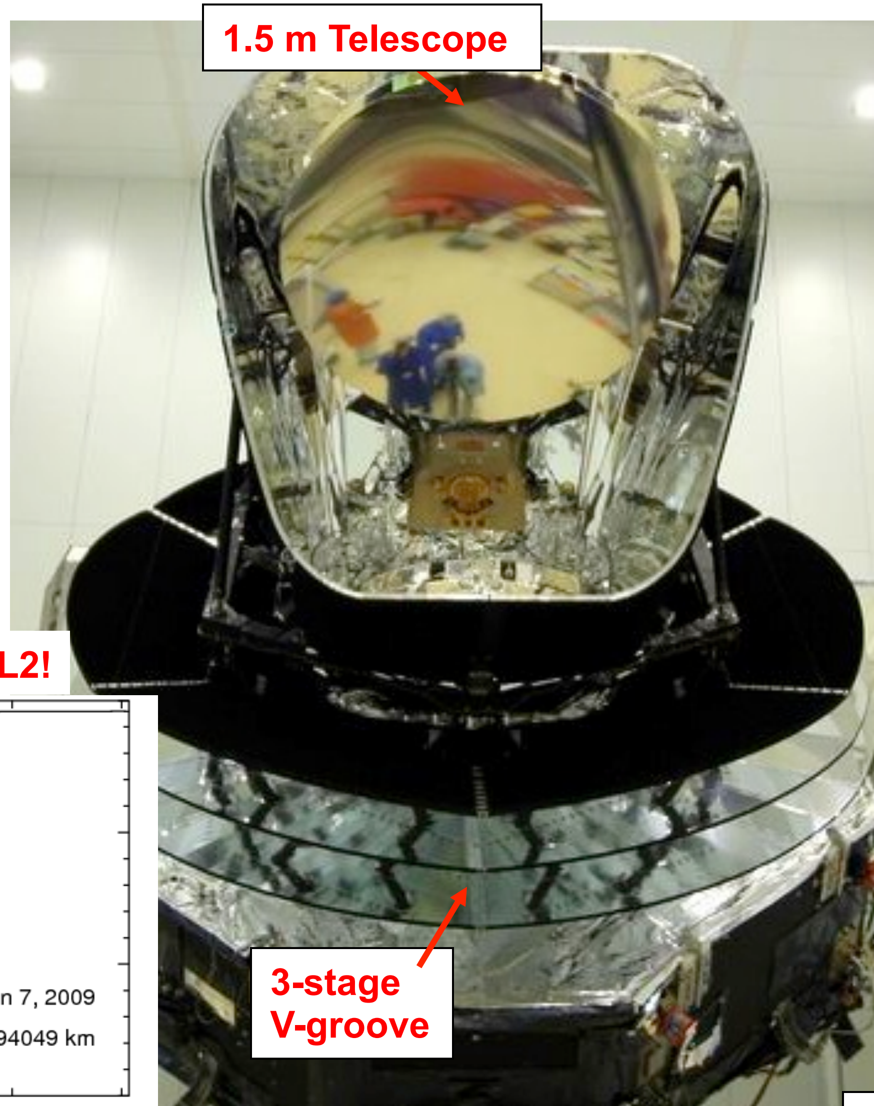
Recent Measurements of CMB Polarization

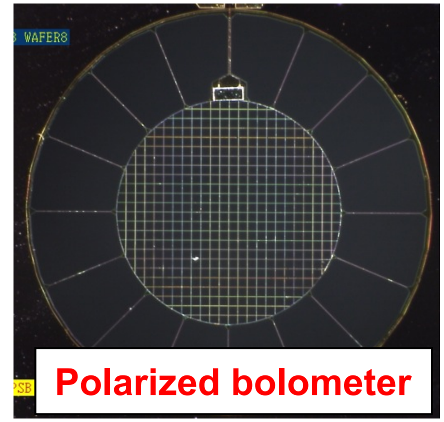


Chiang et al. 2009, arXiv 0906.1181 & 1003

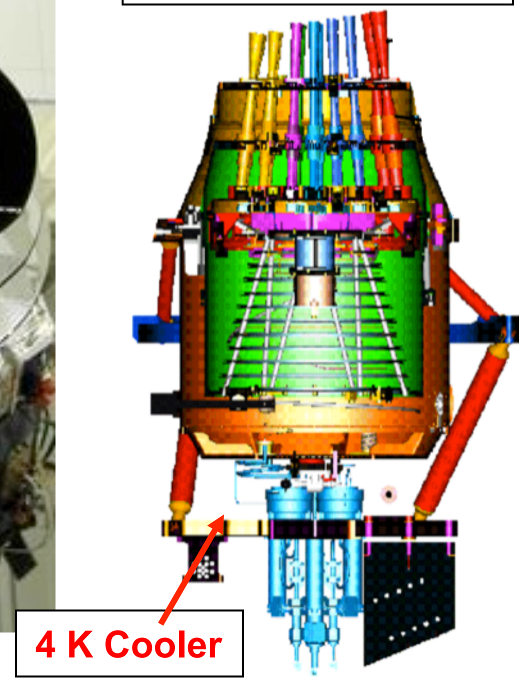
Technology Needed for Space: An Evolution from Planck



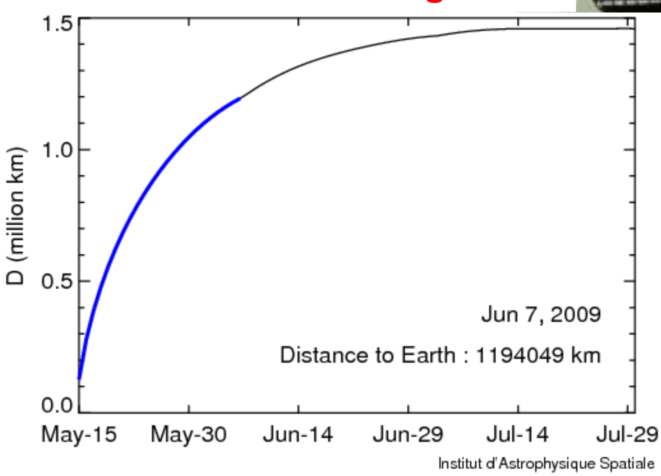




100 mK Focal Plane

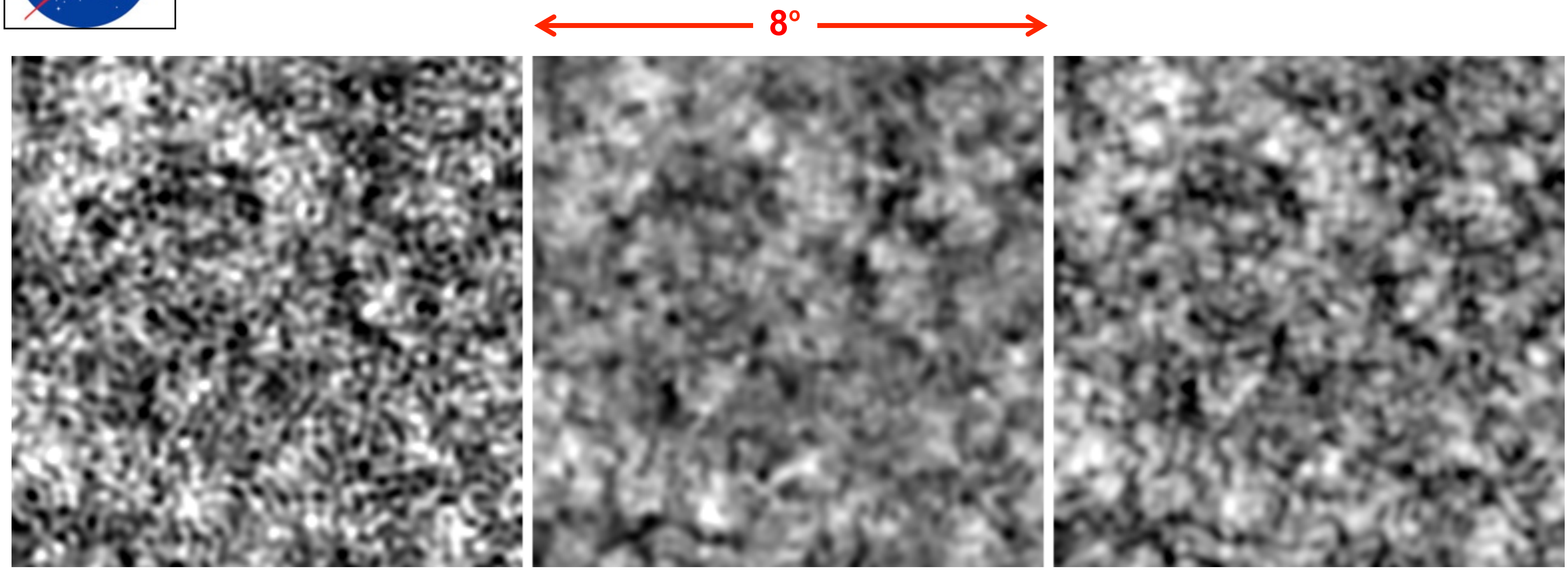


Planck Heading to L2!



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

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

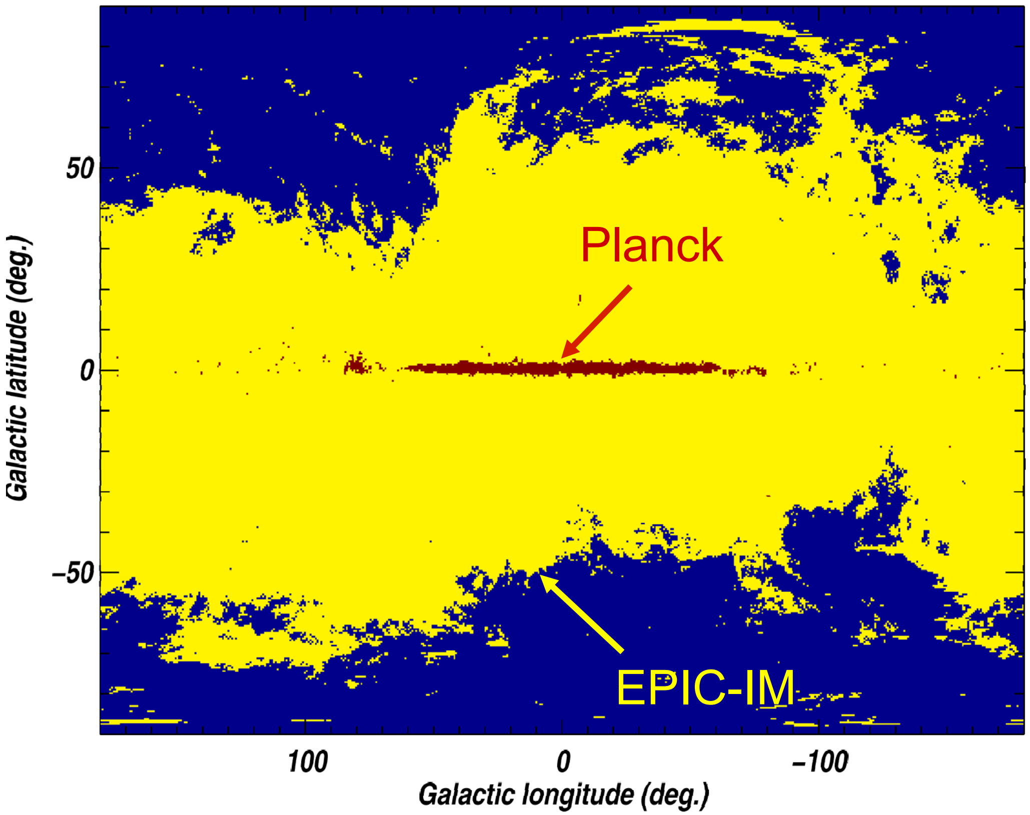
- neutrino masses
- late dark energy

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

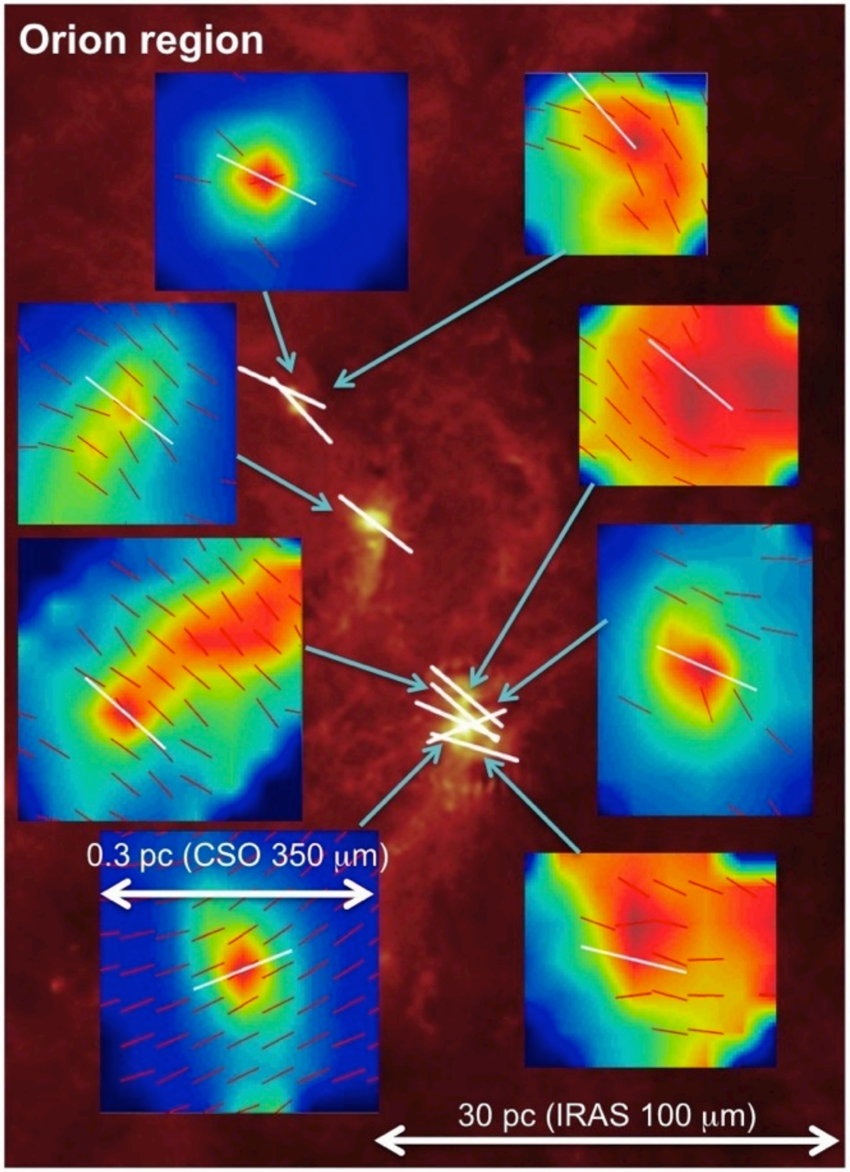
- a legacy for every future study of structure formation

Mapping Galactic Magnetic Fields over the Whole Sky

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



Mission	Band GHz	FWHM arcmin	$\sigma(Q)$ 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?