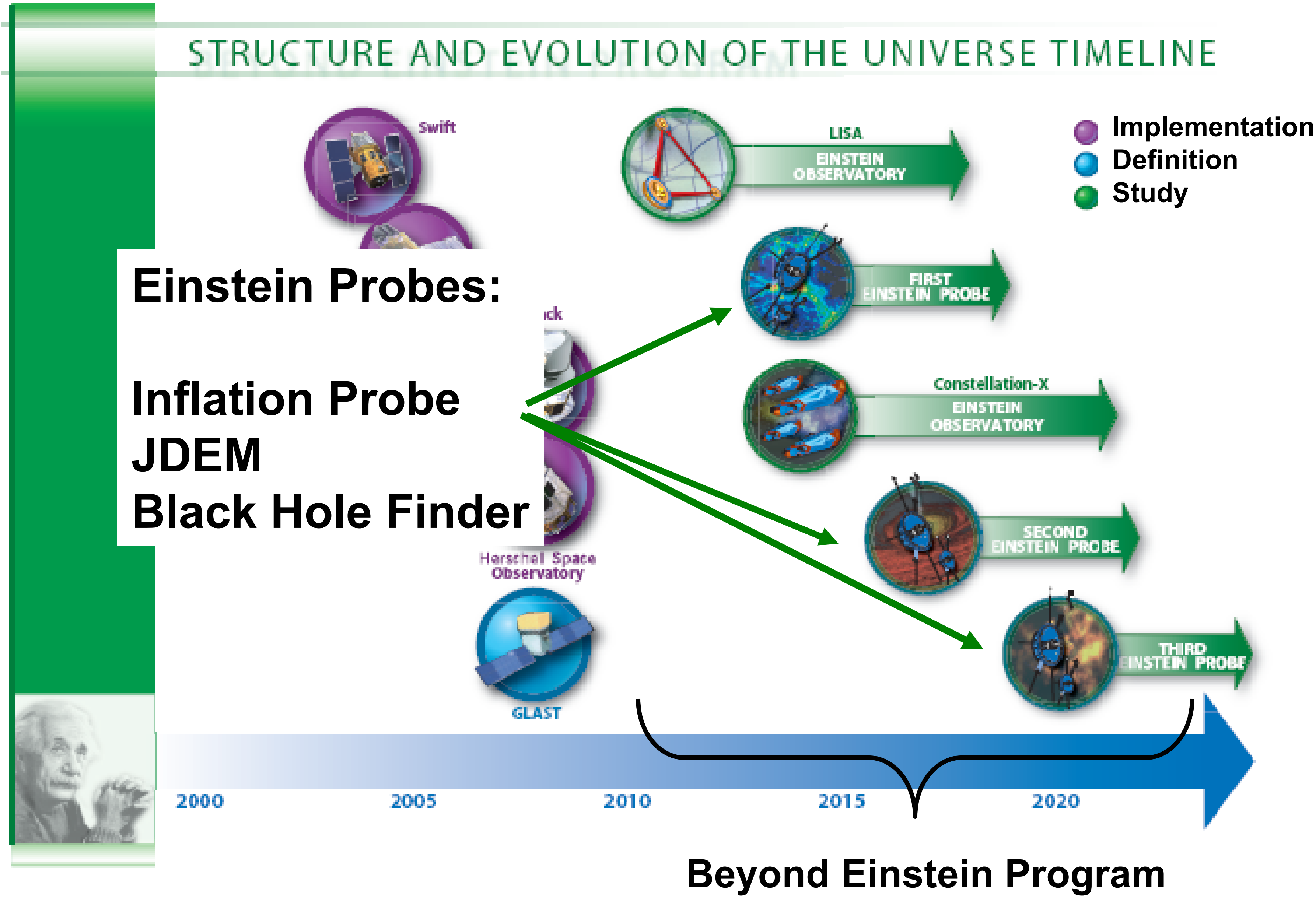
Status of a Future CMB Polarization Satellite

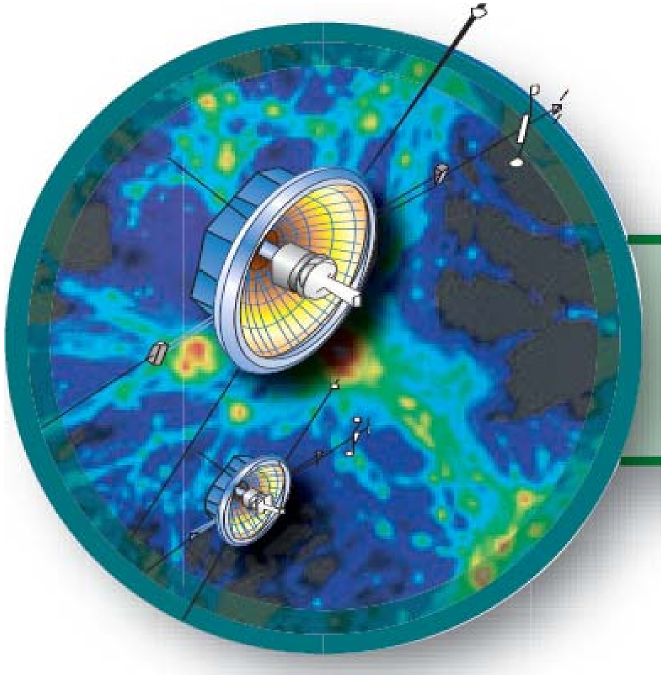
Shaul Hanany
(for the PPPDT and for the
Mission Concept Study Team)

NASA's Strategic Plan, circa 2003



CMB Mission Concept Studies, 2004

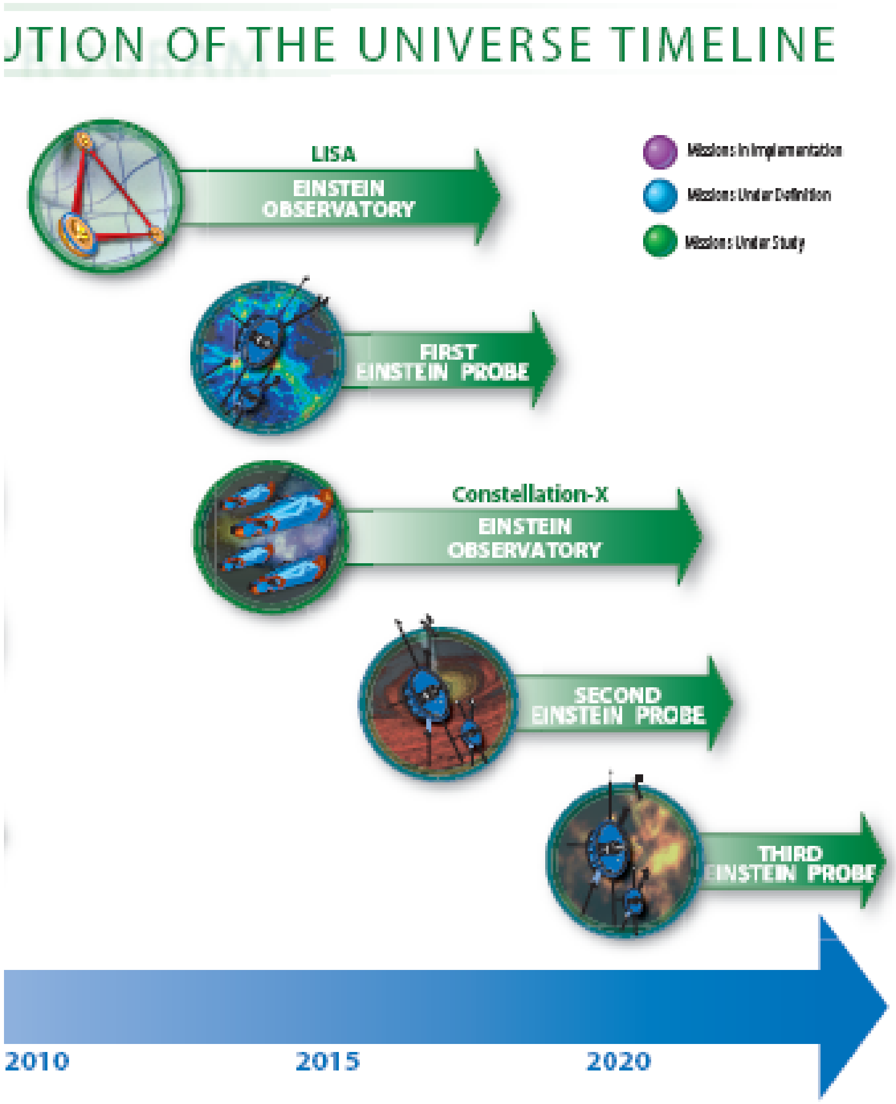
- CMBPol (Gary Hinshaw, Goddard)
- EPIC (Experimental Probe of Inflationary Cosmology, Jamie Bock, JPL)
- EPIC (Einstein Polarization Interferometer for Cosmology, Peter Timbie, Wisconsin)
- ~$250,000 for two years each



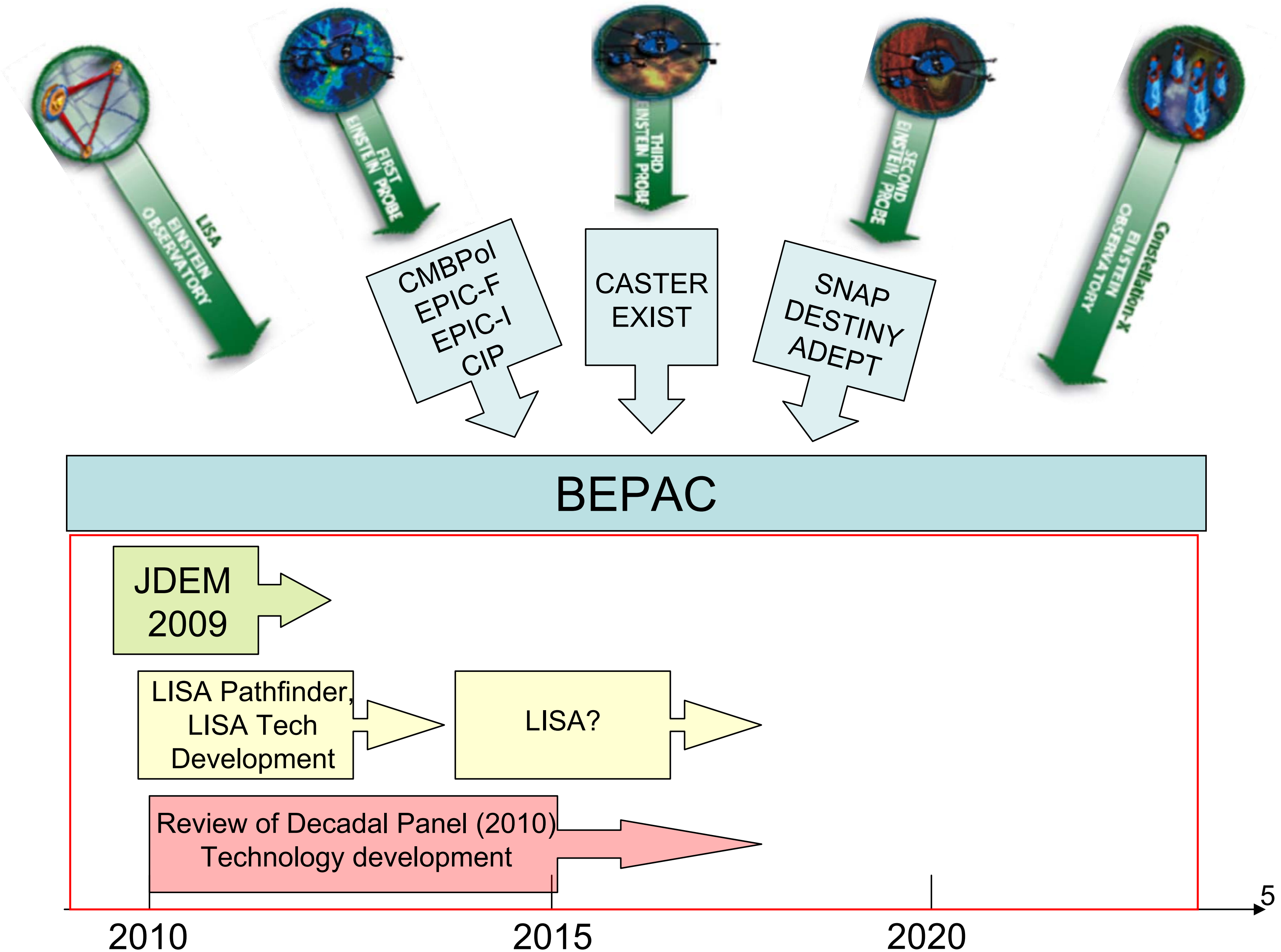
NASA Forms BEPAC, 2006

- BEPAC = Beyond Einstein Program Advisory Committee

- Charter: "Committee is to assess the five Beyond Einstein missions and **recommend one mission for first development and launch** "



BEPAC Recommendations



The CMB Inflation Probes

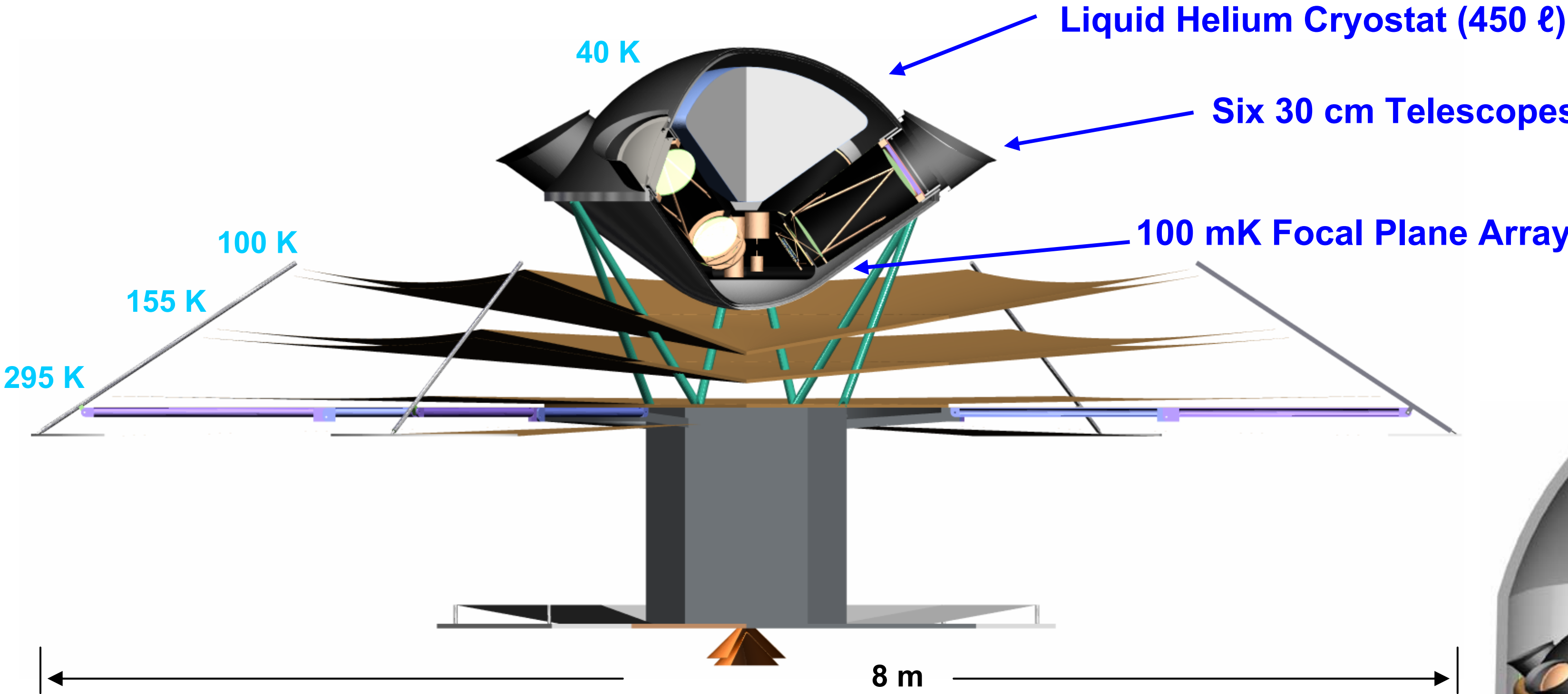
- EPIC, Timbie, Bolometric Interferometry
  (*New Astr. Rev.* 2006, Vol. 50, Pg. 999)
- CMBPol, Hinshaw, TES bolometer array

<u>EPIC, Bock</u>

EPIC Low Cost (LC)
Small Telescope = Large Beam

EPIC Comprehensive Science (CS)
Large Telescope = Small Beam

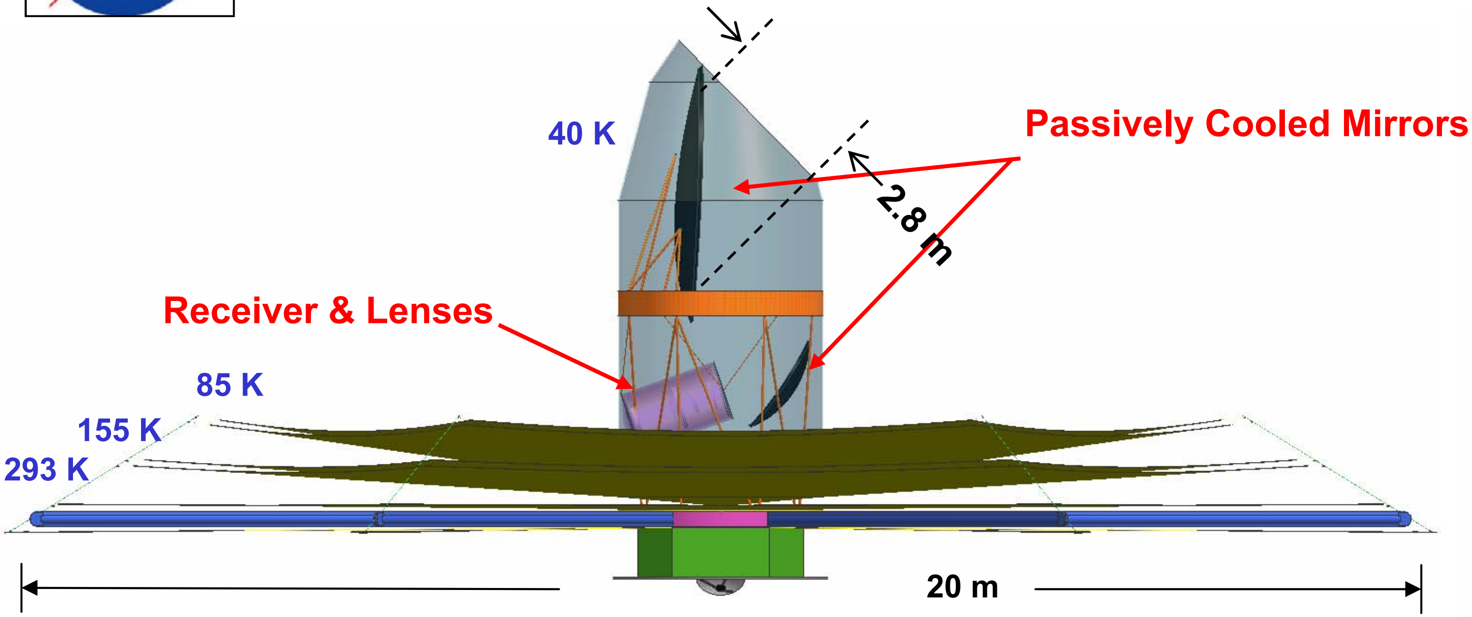
EPIC *Low-Cost* Mission Architecture

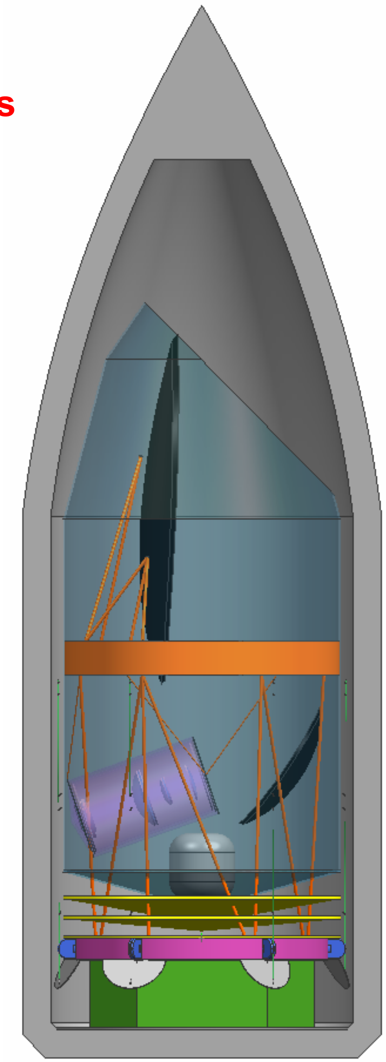


Main Features			
6 independent 30 cm Telescopes		Orbit	L2 Halo
Frequency Bands	30 – 300 GHz	Req'd Lifetime	1 year
Resolution	0.9˚ at 90 GHz	Design Lifetime	2 year
Detectors	830 NTD Ge bolometers		
	2366 TES Bolometers		

Delta 2925H 3-m

Comprehensive Science Mission Architecture

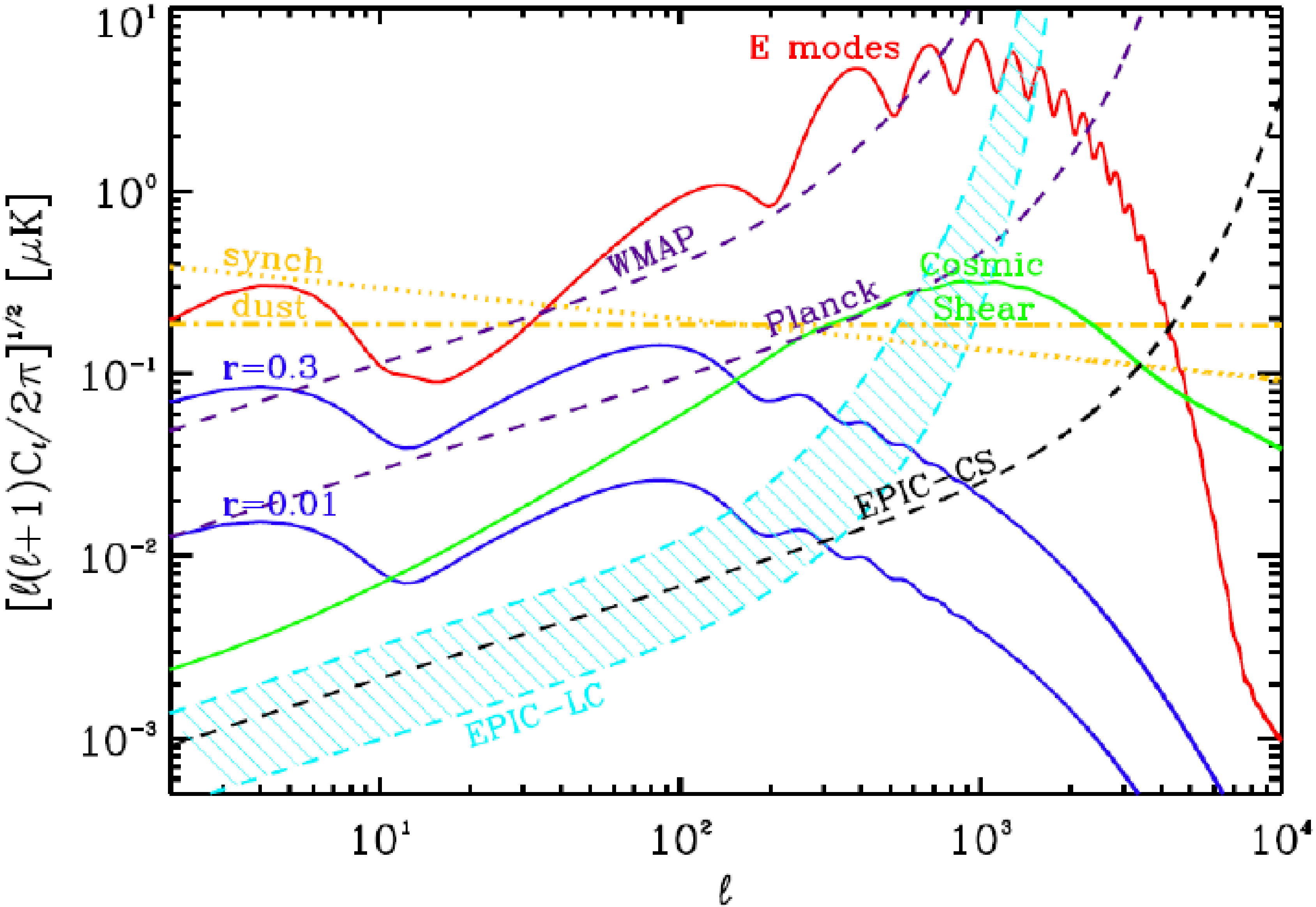




Atlas V 551

Main Features			
2.8 meter Telescope + Cold Lenses		Orbit	L2 Halo
Frequency Bands	30 – 300 GHz	Req'd Lifetime	1 year
Resolution	4.6' at 100 GHz	Design Lifetime	2 years
Detectors	1520 TES Bolometers		

EPIC Anticipated Performance



BEPAC on Inflation Probe

From the report

- Risk of null signal
- Technology not ready
- Challenging foreground subtraction

Verbal communications

- Science goal narrow
- Has science case shown to be sufficiently compelling?

Primordial Polarization Program Definition Team - PPPDT

- NASA forms virtual CMBPol ‘project office / science team’ = PPPDT
- Charter
  - represent CMB community vis-à-vis CMBPol
  - advocate for CMBPol
  - organize community around CMBPol
- Token funding

PPPDT

- 15 Member:

Charles Bennett	Jamie Bock	Julian Borrill
Josh Gundersen	*Shaul Hanany*	Gary Hinshaw
Alan Kogut	Lawrence Krauss	Adrian Lee
Amber Miller	Harvey Moseley	*Lyman Page*
Charles Lawrence	Tony Readhead	Peter Timbie

- http://groups.physics.umn.edu/cosmology/PPPDT/index.html
- First Telecon ~ Aug. 2007
- Simultaneous with NASA Solicitation for ‘Strategic Mission Concept Studies’

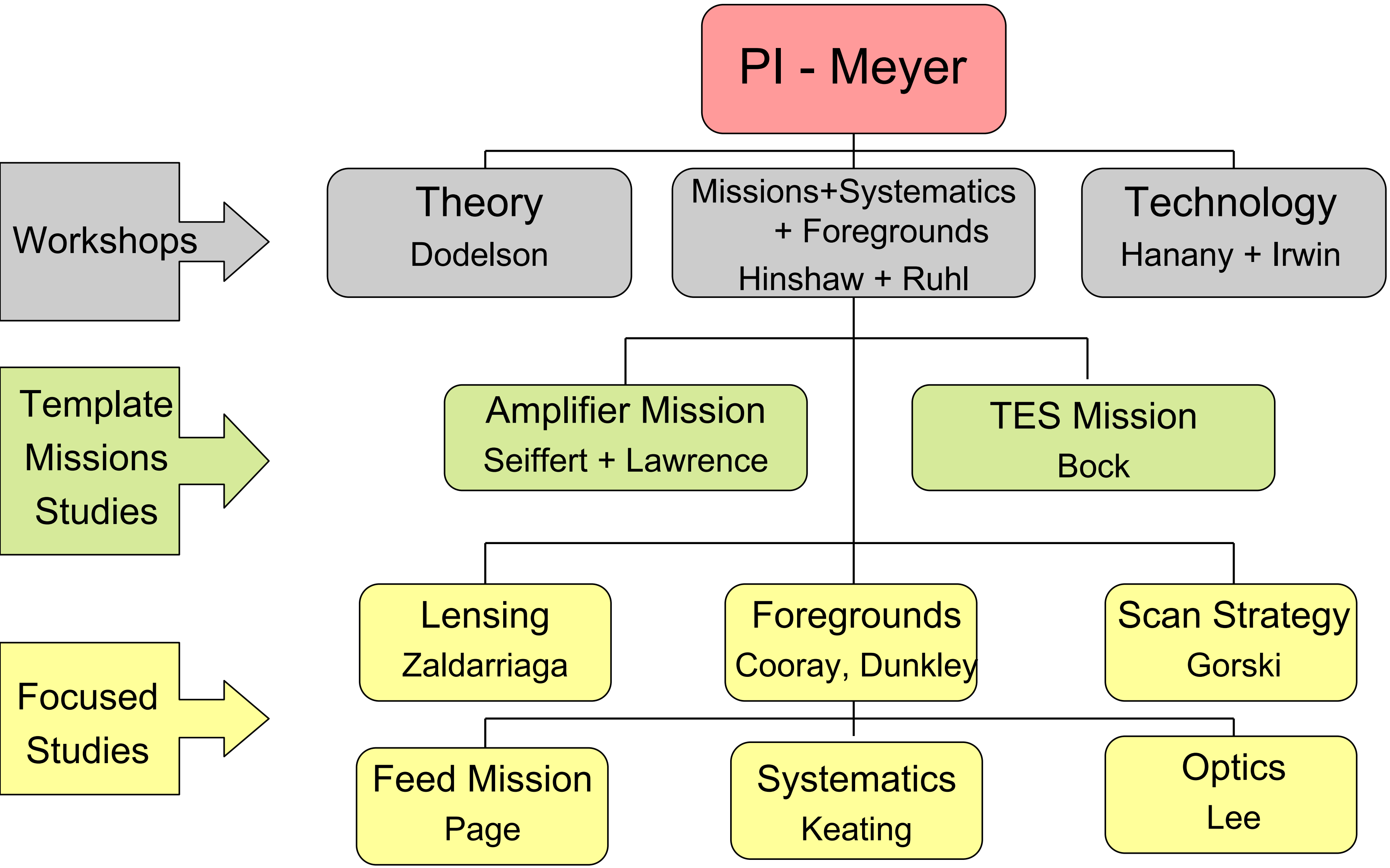
NASA's Strategic Mission Concept Studies

- Solicit ~40 satellite missions for next decade (Nov. 2007)
- Fund ~10 (~Feb. 2008)
- Produce detailed concept + costing (~Jan. 2009)
- Have decadal panel rank concepts in decadal report
- Ranking serves as guide for NASA's priorities

PPPDT Response to NASA's Solicitation

- Concentrate on forthcoming report of decadal panel
- Propose to form a coherent program that will lead to CMBPol late in the decade
- Program will represent entire CMB community
- Work will address major BEPAC points
  - Science
  - Foreground subtraction
  - Technology
  - Control of systematics
- Make program concrete with 'example missions'

Premise: Plan should build upon the conclusions of the Weiss report


PI - Meyer
Workshops
Theory
Dodelson
Missions+Systematics + Foregrounds
Hinshaw + Ruhl
Technology
Hanany + Irwin
Template Missions Studies
Amplifier Mission
Seiffert + Lawrence
TES Mission
Bock
Focused Studies
Lensing
Zaldarriaga
Foregrounds
Cooray, Dunkley
Scan Strategy
Gorski
Feed Mission
Page
Systematics
Keating
Optics
Lee

l - Meyer

What is the impact of an upper limit r<0.01?

Workshops

Theory

Dodelson

M

Hin

What is the impact of detection of B?

chnology

anany + Irwin

<u>June 23 – 27; Fermilab</u>

(dodelson)

Inflationary B mode

Lensing B mode

Ancillary Science

Foreground Removal

Alternate Inflation Probes

Science return vs angular resolution and sensitivity

What is the ancillary science?

Techniques for removal of foregrounds

Are other inflation probes compelling?

PI - Meyer

Missions+Systematics
+ Foregrounds
Hinshaw + Ruhl

Technology
Hanany + Irwin

Workshops

Template missions
angular resolution, sensitivity, detectors, optics, cooling

Optimal scan strategies

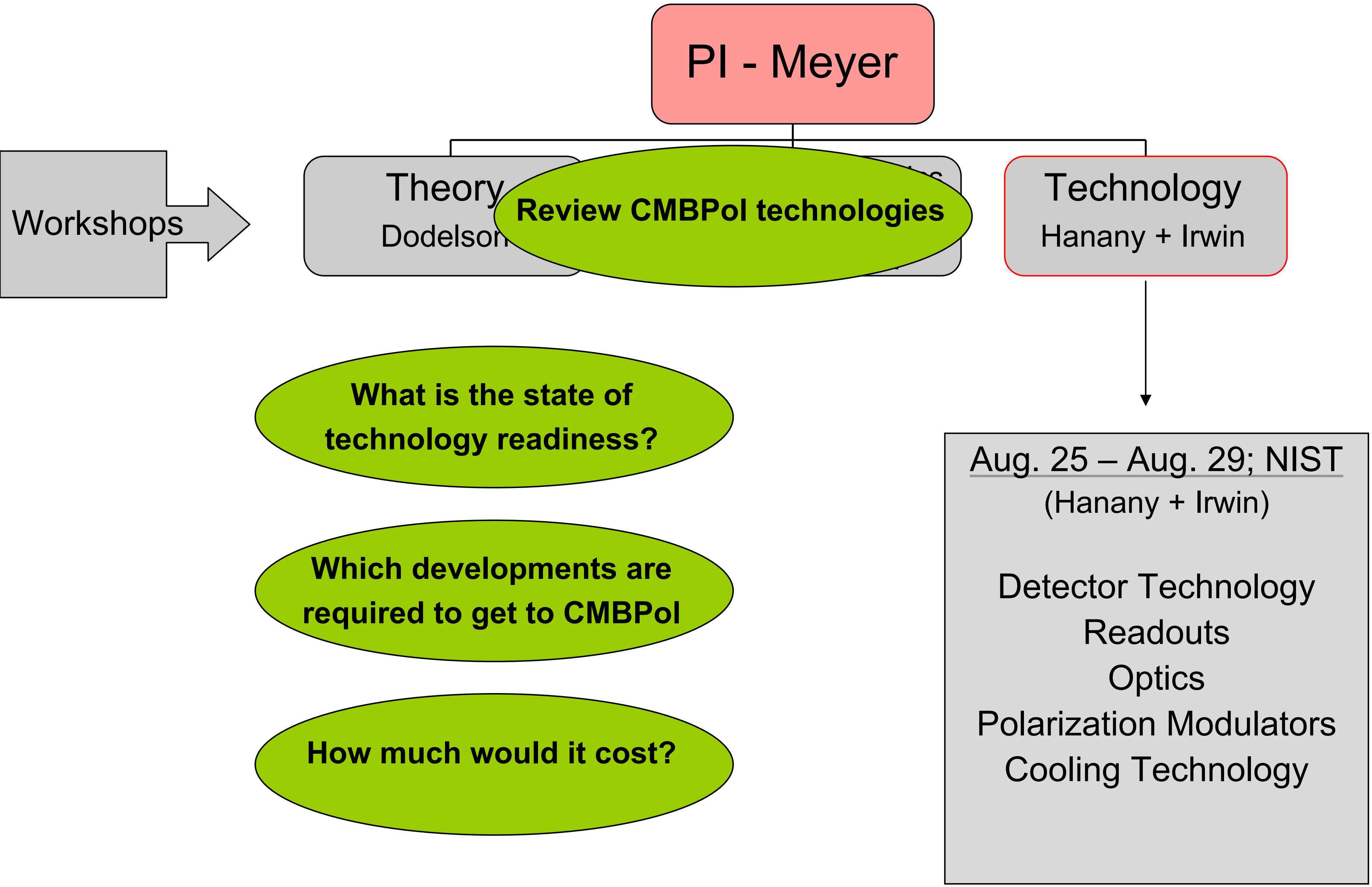
Suborbital experiments pre-CMBPol

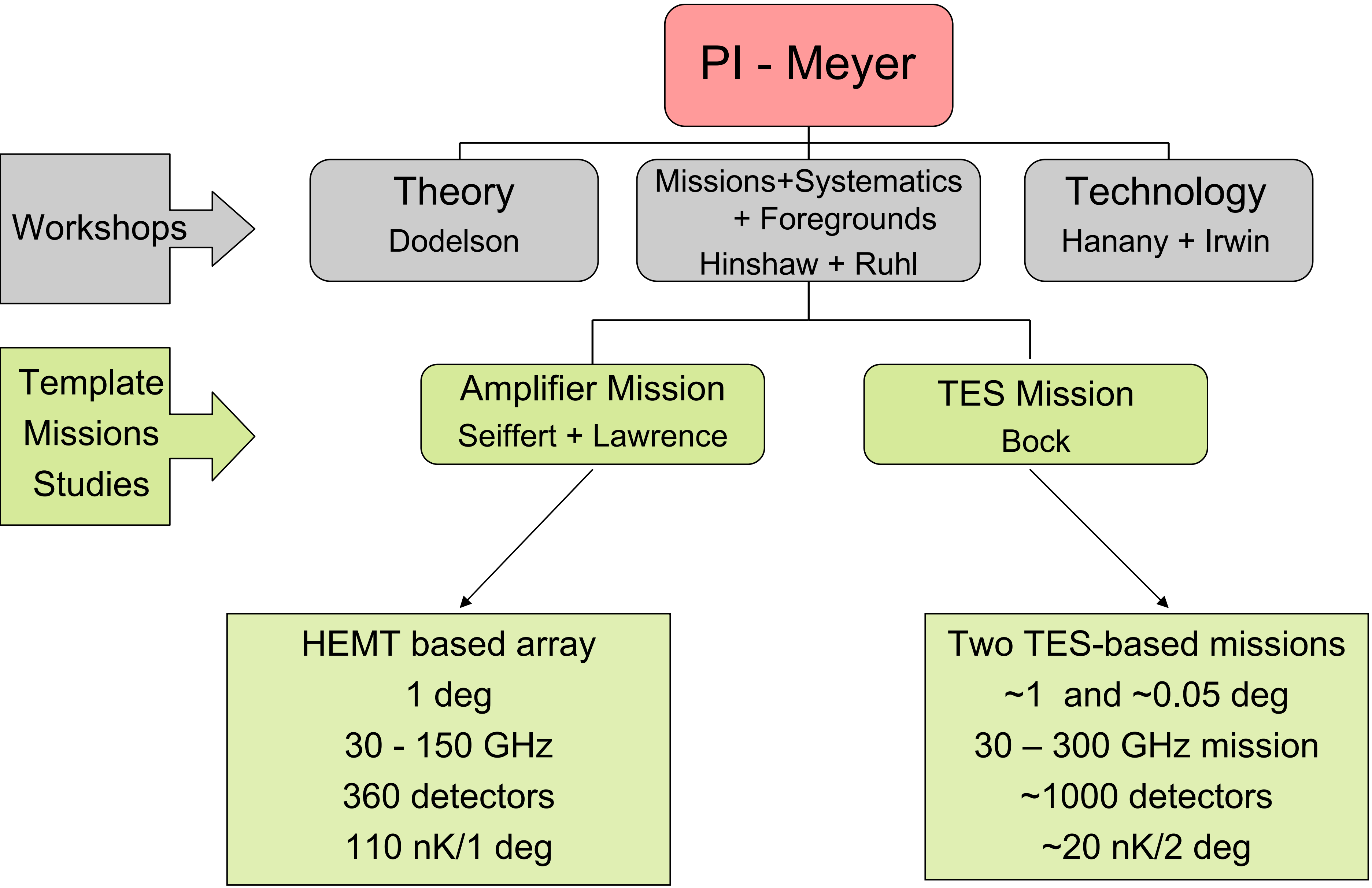
Mitigation of systematic errors

Frequency band optimization and foreground subtraction

<u>July 28 – Aug. 1; Goddard</u>
(Hinshaw + Ruhl)

Template Missions
Suborbital Experiments
Systematics
Scan Strategy
Foreground Mitigation


PI - Meyer
Workshops
Theory
Review CMBPol technologies
Technology
Hanany + Irwin
What is the state of technology readiness?
Which developments are required to get to CMBPol
How much would it cost?
Aug. 25 – Aug. 29; NIST
(Hanany + Irwin)
Detector Technology
Readouts
Optics
Polarization Modulators
Cooling Technology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Workshops
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Missions+Systematics
+ Foregrounds
Hinshaw + Ruhl
Technology
Hanany + Irwin
Template
Missions
Studies
Amplifier Mission
Seiffert + Lawrence
TES Mission
Bock
HEMT based array
1 deg
30 - 150 GHz
360 detectors
110 nK/1 deg
Two TES-based missions
~1 and ~0.05 deg
30 – 300 GHz mission
~1000 detectors
~20 nK/2 deg

Complementary Goals, Separate Functions

PPPDT

Appointed by NASA
Longer Term
Advocate for CMBPol
Provide Community Focus Point

Mission Concept Study Team

Answer to NASA Solicitation
Limited to 1 year
Conduct Technical Studies
Produce Report

PPPDT Sponsored Theory Telecons

- BEPAC fallout: how compelling is a CMBPol satellite?

- Initiate theory telecons: two theorists each
  - What would be the impact of a positive B-mode detection?
  - What would be the impact of no B-mode detection at a level of r=0.01?
  - What are the arguments that r is larger than 0.01?
  - What would be the value of a mission that measured lensing B modes very well, but did not detect primordial B modes?
  - What priority would you give a $1B investment in a CMB polarization mission compared to other possible astrophysics space missions?
  - If you think it is worthwhile, how would you articulate this to colleagues?

- Start 12/2007, 2 telecons so far: Zaldarriaga, Kinney, Steinhardt, Kamionkowski

A View of CMBPol in 2015 and Beyond

- Technology
  - will not be the limiting factor
  - APEX, SPT, ACT, BICEP, QUIET, EBEX, SPIDER, Clover, …
  - But funding must increase to bring technologies to maturity
- Instrument sensitivity
  - will not be the limiting factor
  - EPIC already demonstrates necessary sensitivity
- Systematics
  - We are learning how to control (BICEP, QUIET, EBEX, SPIDER, Clover, …)
  - But yet to be demonstrated
- Foregrounds
  - Subtraction necessary over large areas of the sky
  - Likely necessary even on small patches
  - Yet to be demonstrated

A View of CMBPol in 2015 and Beyond

- Funding
  - Depends on detections/upper limits
  - Depends on the case we make for primary and ancillary science

- Discussion: How do we make CMBPol (and B-mode physics) highly ranked in the decadal panel?

- http://www.physics.umn.edu/PPPDT

- http://cmbpol.uchicago.edu/

Additional Material

Not included in 15 min. Talk

Low-Cost Mission Focal Plane Options

Input Assumptions

Fractional bandwidth $\Delta\nu/\nu$ = 30 %
Focal plane temperature = 100 mK
Waveplate temperature = 20 K, with 2 % coupling
P_{sat}/Q = 5 for TES bolometers

Optical efficiency h = 40 %
Optics temperature = 2 K, with 10 % coupling
Baffle at 40 K with 0.3 % coupling (measured)
G_0 = 10 Q / T_0 for NTD bolometers

NTD Bolometer Option

Freq [GHz]	θ_{FWHM} [′]	Nbol[3] [#]	Required Sensitivity[1]				Design Sensitivity[2]			
			NET[4] [μK√s]		δT-θ[5] [μK ′]	δTpix[6] [nK]	NET[4] [μK√s]		δT-θ[5] [μK ′]	δTpix[6] [nK]
			bolo	band			bolo	band		
30	155	8	98	34.6	106	630	69	24.5	53.1	315
40	116	54	85	11.5	35.4	210	60	8.2	17.7	105
60	77	128	70	6.2	18.9	110	49	4.4	9.5	56
90	52	256	59	3.7	11.3	67	42	2.6	5.6	34
135	34	256	53	3.3	10.2	61	38	2.4	5.1	30
200	23	64	58	7.2	22.1	130	41	5.1	11.0	66
300	16	64	135	16.7	51.4	310	95	11.8	25.7	150
Total[7]		**830**		**2.1**	**6.5**	**39**		**1.5**	**3.3**	**19**

TES Bolometer Option

Freq [GHz]	θ_{FWHM} [′]	Nbol[3] [#]	Required Sensitivity[1]				Design Sensitivity[2]			
			NET[4] [μK√s]		δT-θ[5] [μK ′]	δTpix[6] [nK]	NET[4] [μK√s]		δT-θ[5] [μK ′]	δTpix[6] [nK]
			bolo	band			bolo	band		
30	155	8	87	30.8	66.7	560	62	22	33.4	280
40	116	54	77	10.4	22.7	190	54	7.4	11.3	95
60	77	128	66	5.8	12.7	107	47	4.1	6.3	53
90	52	512	59	2.6	5.6	47	41	1.8	2.8	24
135	34	512	59	2.6	5.7	48	42	1.9	2.8	24
200	23	576	72	3.0	6.5	55	51	2.1	3.2	27
300	16	576	145	6.0	13.0	110	100	4.2	6.5	55
Total[7]		**2366**		**1.5**	**3.2**	**27**		**1.0**	**1.6**	**13**

[1] Sensitivity with √2 noise margin in a 1-year mission
[2] Calculated sensitivity in 2-year design life
[3] Two bolometers per focal plane pixel
[4] Sensitivity of one bolometer in a focal plane pixel
[5] Sensitivity δT in a pixel θ_{FWHM} x θ_{FWHM} times θ_{FWHM}
[6] Sensitivity δT in a 120′ x 120′ pixel
[7] Combining all bands together

Comprehensive Science Mission Focal Plane

Table 6.5.2 Detailed Bands and Sensitivities for TES Option

Freq [GHz]	θ_{FWHM} [′]	N_{bol}[1] [#]	τ_{req}[2] [ms]	τ [ms]	Required Sensitivity[3,4] NET[5] [$\mu K\sqrt{s}$] bolo	band	$w_p^{-1/2}$ [μK-′][6]	δTpix[7] [nK]
30	15.5	20	9.7	1.2	85	19	41	240
45	10.3	80	6.4	0.9	72	10	22	130
70	6.6	220	4.1	0.7	62	4.2	9	54
100	4.6	320	2.9	0.6	58	3.2	7	41
150	3.1	380	1.9	0.6	61	3.1	7	40
220	2.1	280	1.3	0.6	88	5.2	11	67
340	1.4	120	0.9	0.6	270	25	53	320
500	0.9	100	0.6	0.3	2100	210	450	2700
Total[8]		**1520**				1.8	3.5	21

Notes:

[1]Two bolometers per focal plane pixel

[2]$\tau_{req} = (1/2\pi)\ \theta_{FWHM}/d\theta/dt$ at 1 rpm

[3]Calculated sensitivity with 2-year mission life

[4]Sensitivity margin of √2 applied to all NETs

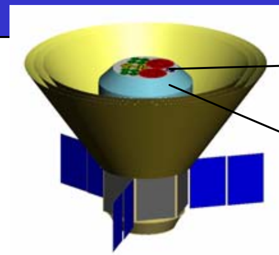
[5]Sensitivity of one bolometer in a focal plane pixel

[6]$[8\pi\ NET_{bolo}{}^2/(T_{mis}\ N_{bol})]^{1/2}(10800/\pi)$

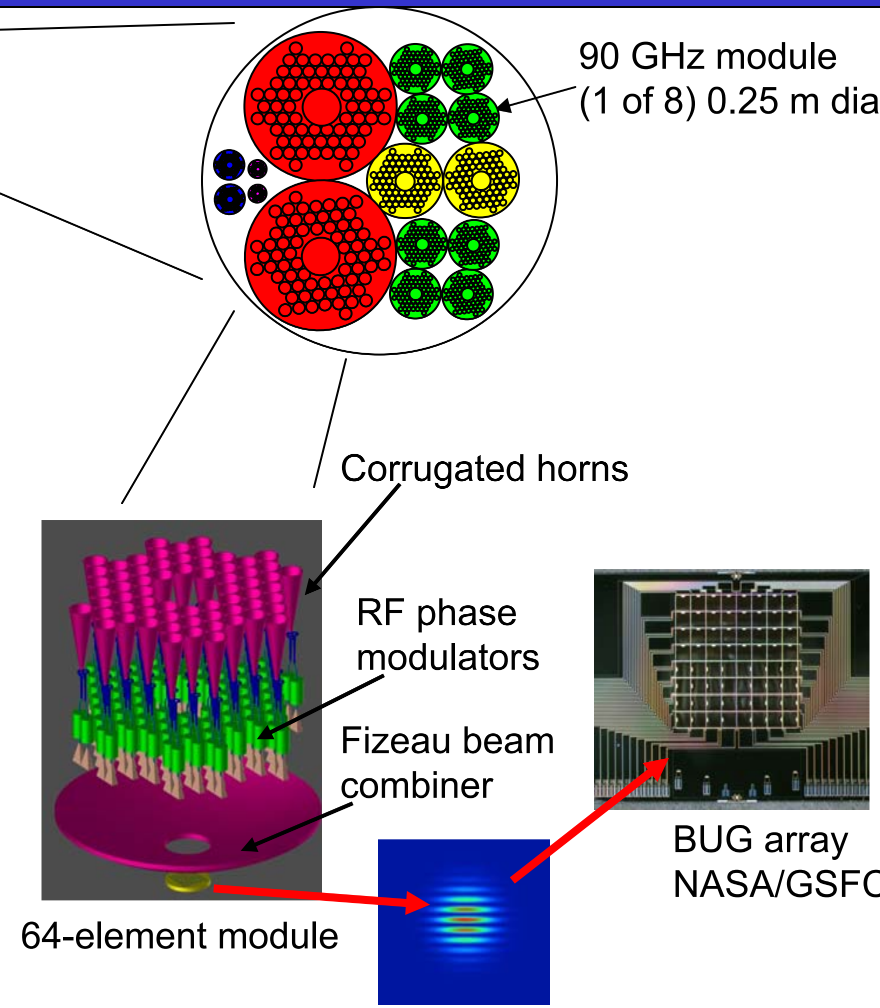
[7]Sensitivity δT in a 120′ x 120′ pixel

[8]Combining all bands together

EPIC Interferometer Mission Concept

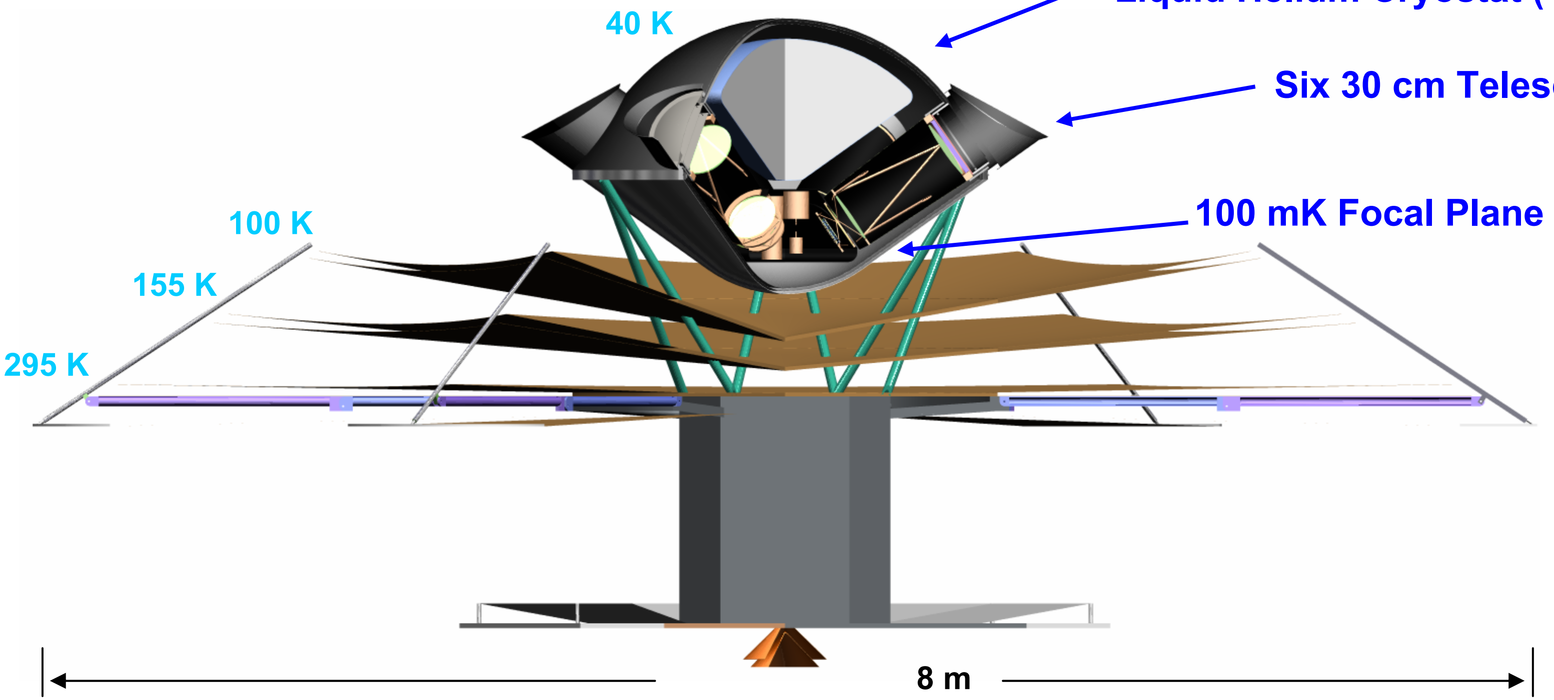


- Measures CMB Temp, E and B mode polarization over full sky to foreground limits (T/S ~ 0.01)
- 15° FOV, ~ 1° synthesized beams
- Close-packed corrugated horn arrays: scaled modules from 30-300 GHz
- Fizeau interferometer: signals cross-correlated, detected on bolometer arrays. Recovers both visibilities and images (for large-scale power).
- Low systematics: sky viewed directly by corrugated horns; low sidelobes, no beam-forming mirrors, no off-axis aberrations
- Lifetime > 1yr from 900 km low Earth orbit (*COBE*)
- See *New Astr. Rev.* 50, 999 (2006)
- Team at Brown, UW-Madison, Richmond, UIUC, Manchester, Maynooth, General Dynamics, Ball Aerospace

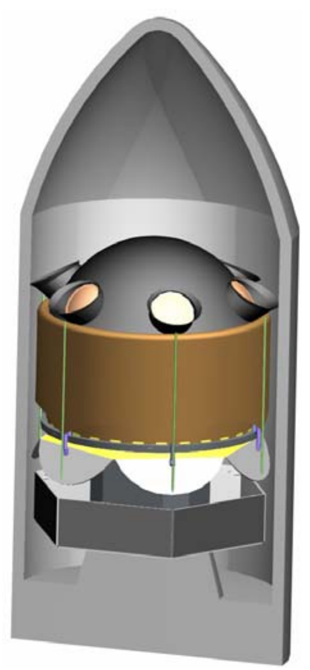


Interference fringes measured in focal plane by bolometer array; phase modulators separate visibilites.

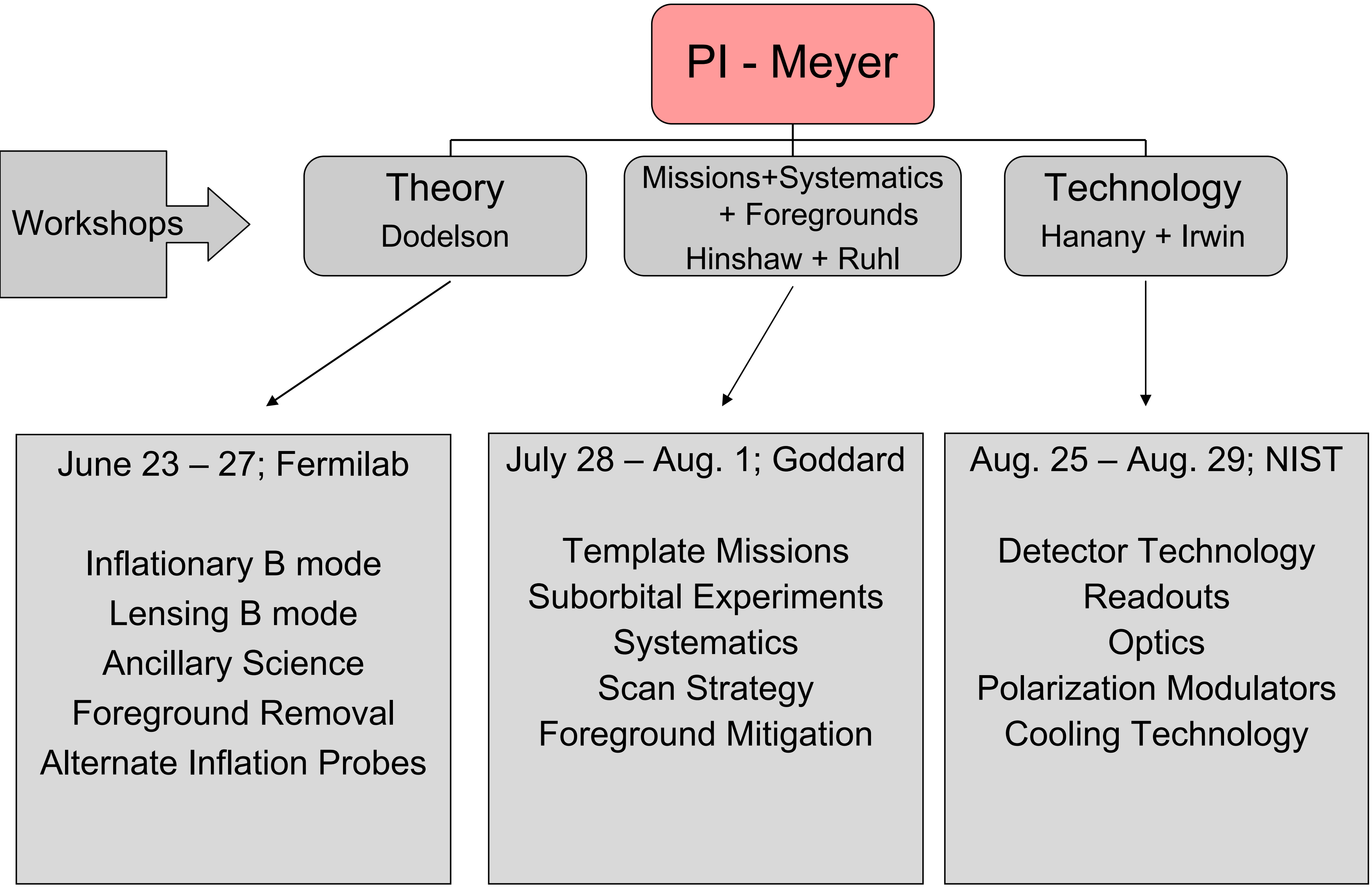
EPIC *Low-Cost* Mission Architecture



Main Features			
6 independent 30 cm Telescopes		Orbit	L2 Halo
Frequency Bands	30 – 300 GHz	Req'd Lifetime	1 year
Resolution	0.9˚ at 90 GHz	Cost	$660M
Detectors	830 NTD Ge bolometers		
	2366 TES Bolometers		



Delta 2925H 3-m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July 28 – Aug. 1; Goddard
Template Missions
Suborbital Experiments
Systematics
Scan Strategy
Foreground Mitigation
Aug. 25 – Aug. 29; NIST
Detector Technology
Readouts
Optics
Polarization Modulators
Cooling Technology

PPPDT Physics + Astrophysics outreach

- Assemble arguments for CMBPol
  - Outcome of theory telecons
  - Outcome of mission concept study
- Organize seminars + colloquia around the country
- Organize talks in APS, AAS, SPIE conferences