Update on CMB Mission Concepts

APS 2018 April Meeting, IPSIG Mini-Symposium

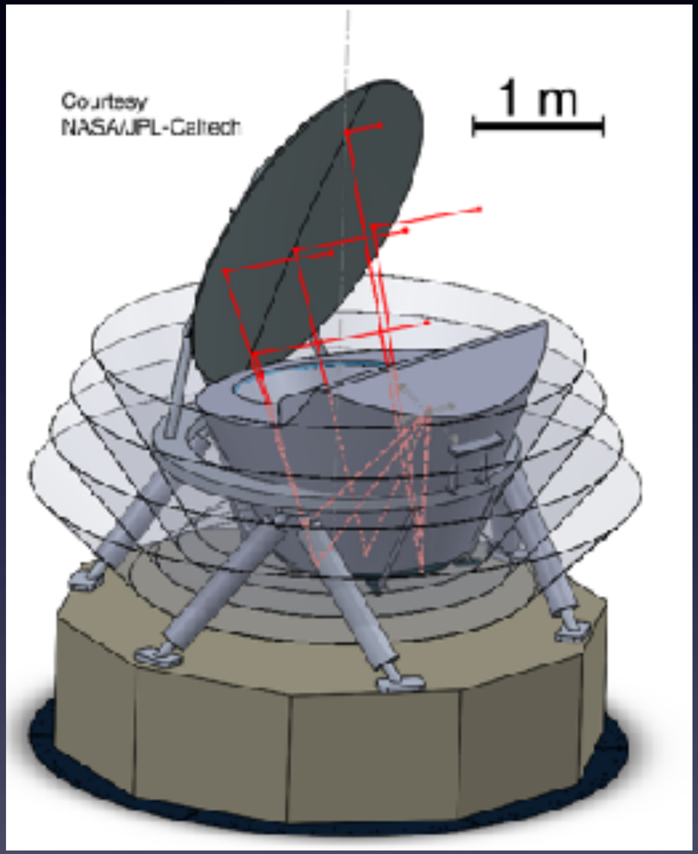
Shaul Hanany
University of Minnesota

(PIXIE Contributions by Kogut, LiteBIRD from Hazumi talk, CORE from available documents)

CMB Mission Concepts

Active

PICO



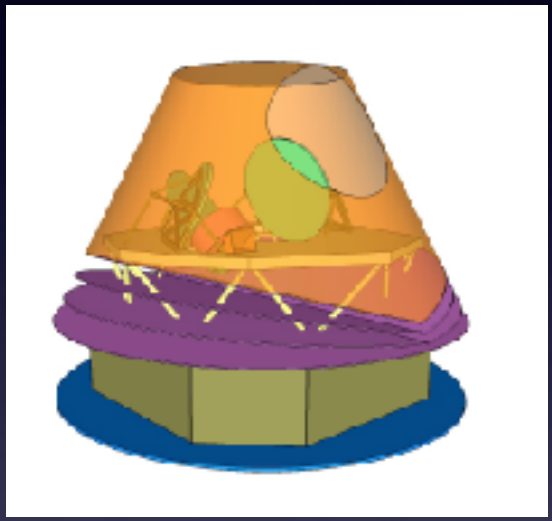
NASA Study

LiteBIRD

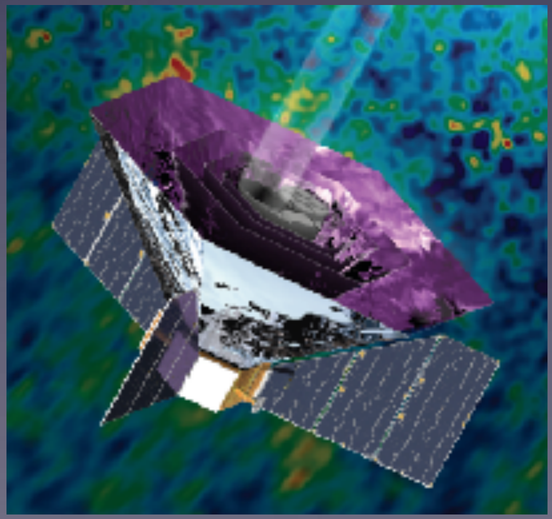
JAXA Phase A

On Hold

CORE (ESA)



PIXIE (NASA)

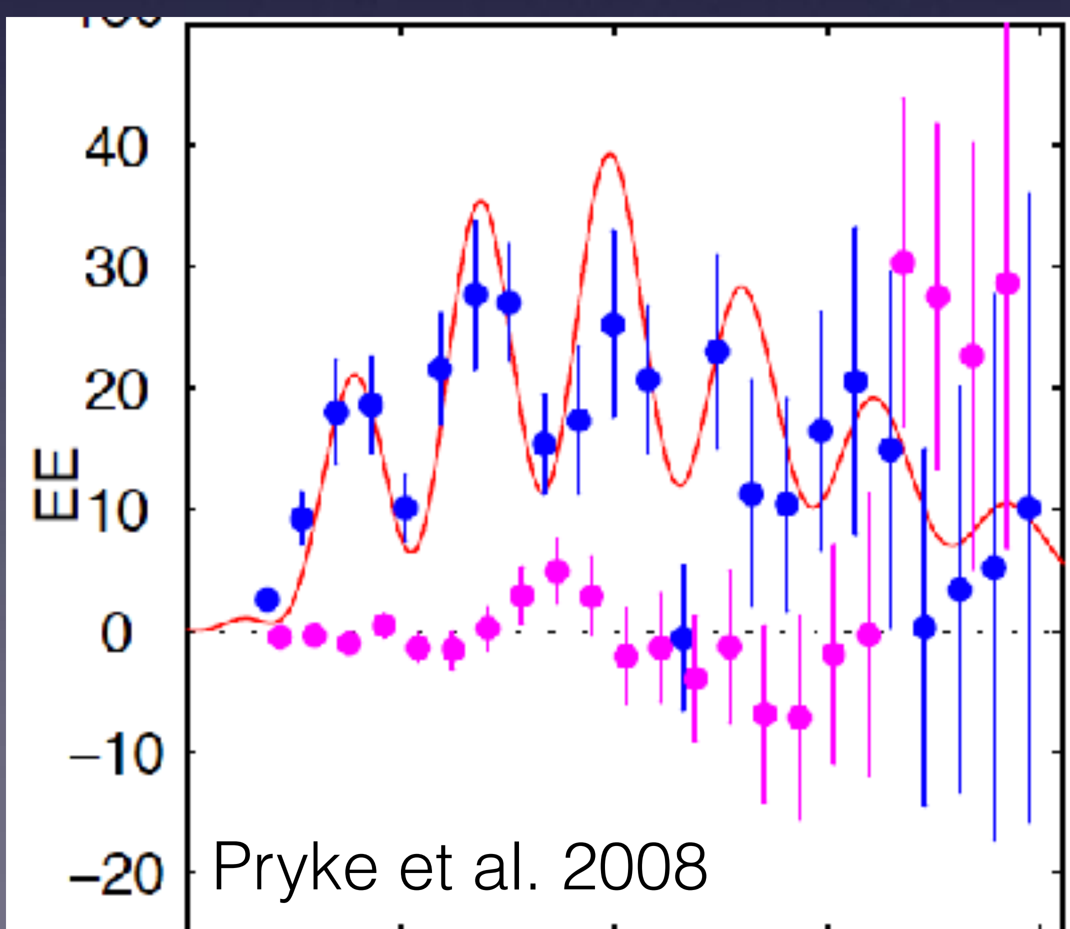


Proposed

CMB-BHARAT
(India)

Back 10 years

- WMAP was entering its year 8
- Planck a year from launch
- Few results on EE
- Pre-Planck



Pryke et al. 2008

National Aeronautics and Space Administration

The Experimental Probe of Inflationary Cosmology

A Mission Concept Study for NASA's Einstein Inflation Probe

EPIC Mission Study Team
Jet Propulsion Laboratory

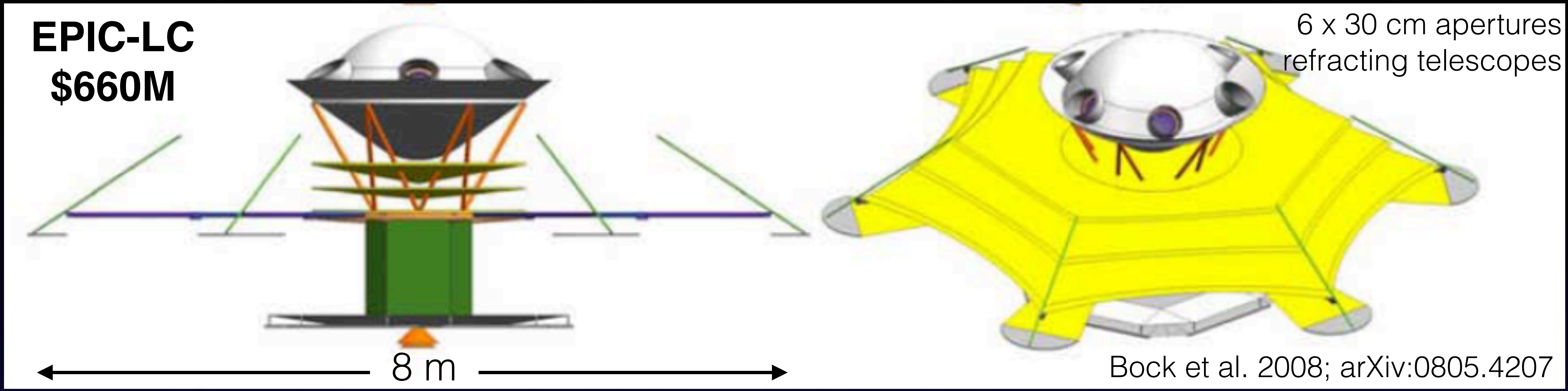
February 2008

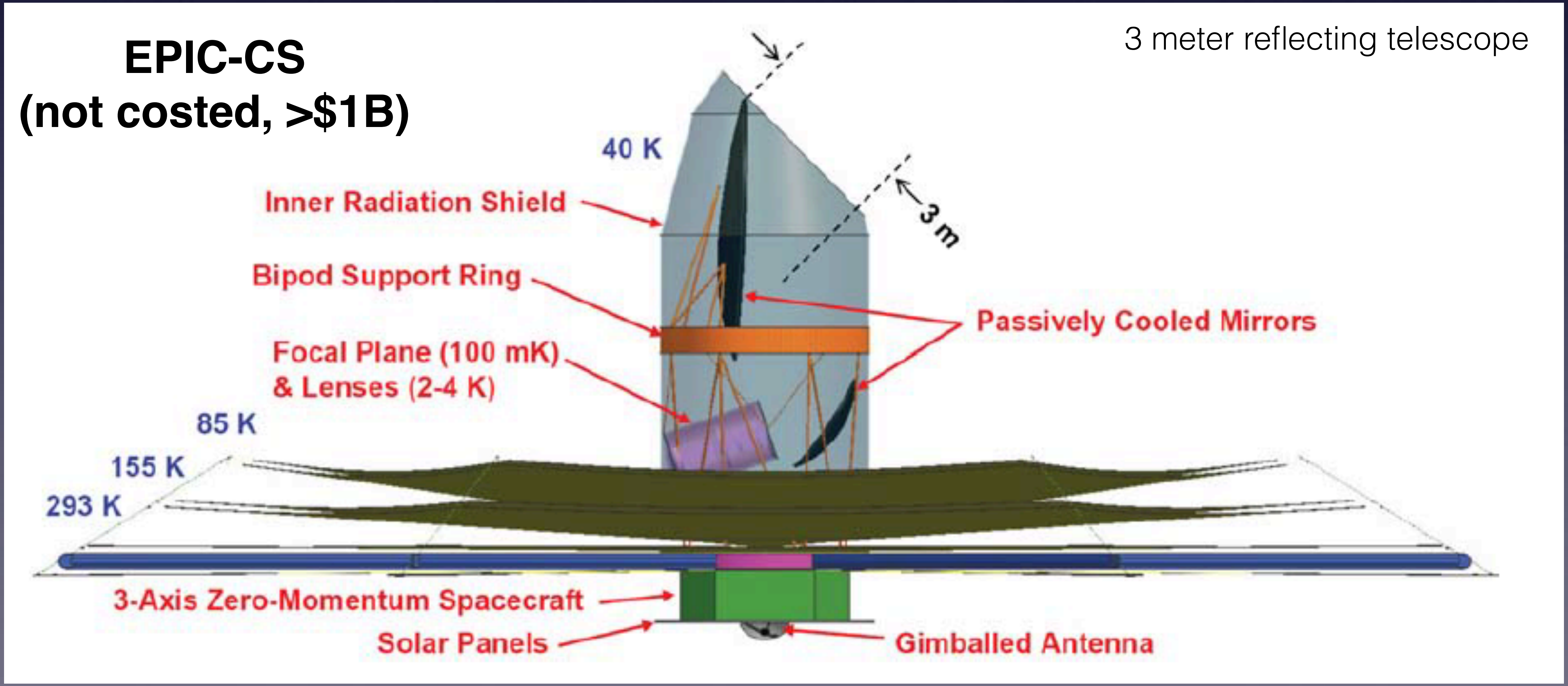
National Aeronautics and Space Administration

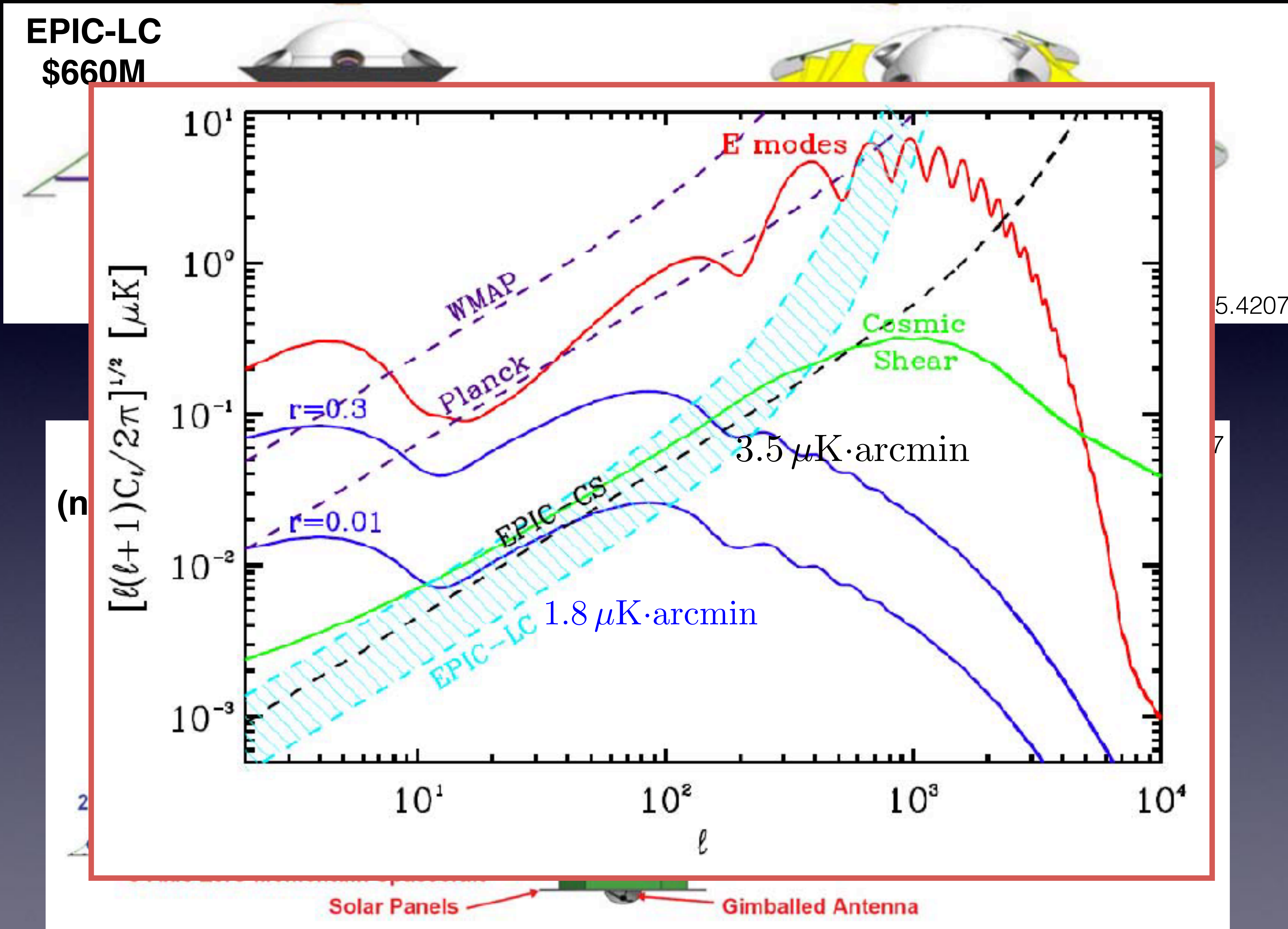
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Bock et al. May 2008


EPIC-LC
$660M
6 x 30 cm apertures
refracting telescopes
8 m
Bock et al. 2008; arXiv:0805.4207


EPIC-CS
(not costed, >$1B)
3 meter reflecting telescope
40 K
Inner Radiation Shield
Bipod Support Ring
Focal Plane (100 mK)
& Lenses (2-4 K)
Passively Cooled Mirrors
3 m
85 K
155 K
293 K
3-Axis Zero-Momentum Spacecraft
Solar Panels
Gimballed Antenna



EPIC-LC
$660M
5.4207
E modes
WMAP
Planck
Cosmic
Shear
r=0.3
r=0.01
EPIC-CS
EPIC-LC
3.5 μK·arcmin
1.8 μK·arcmin
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
10^4
ℓ
Solar Panels
Gimballed Antenna

A year later

astroph/0906.1188

EPIC - IM / June 2009

Study of the

Experimental Probe of Inflationary Cosmology - Intermediate Mission

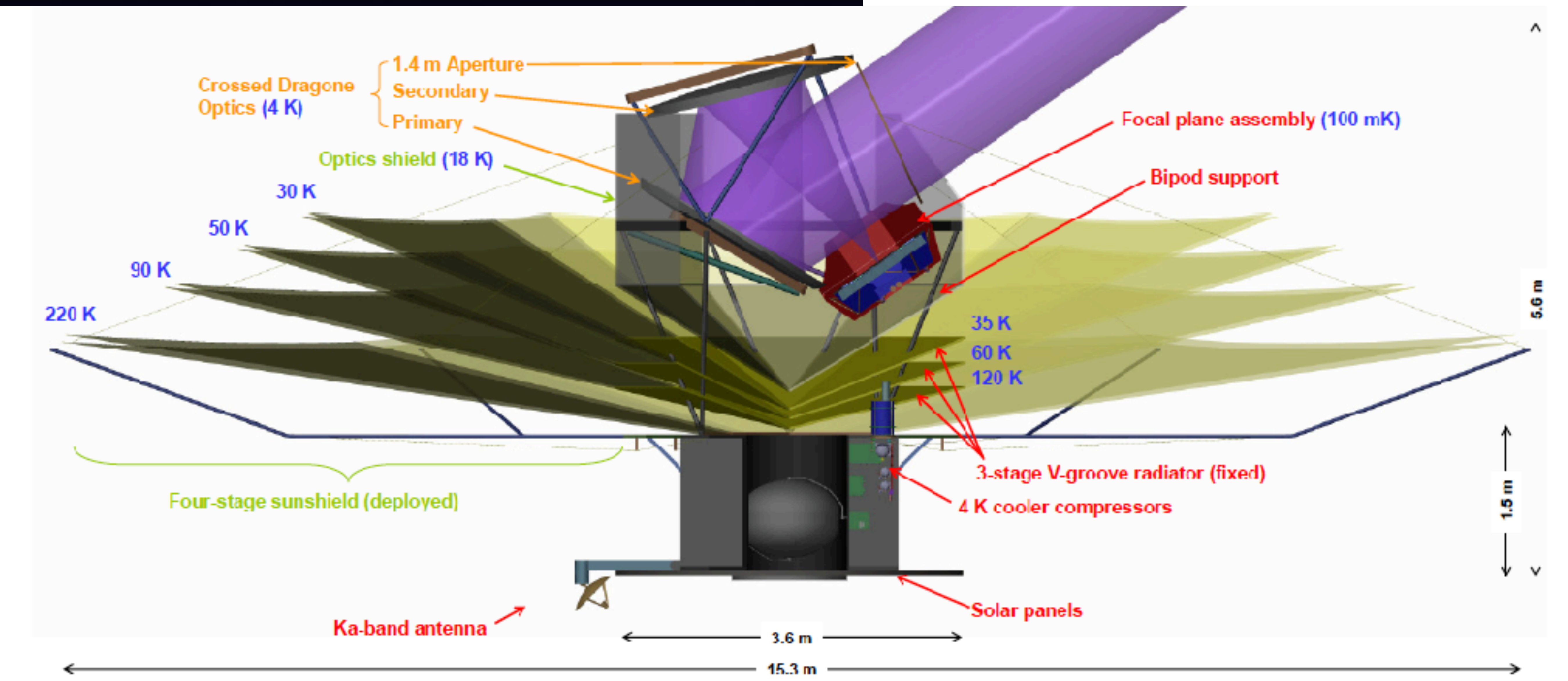
for NASA's Einstein Inflation Probe

4 June 2009

A year later

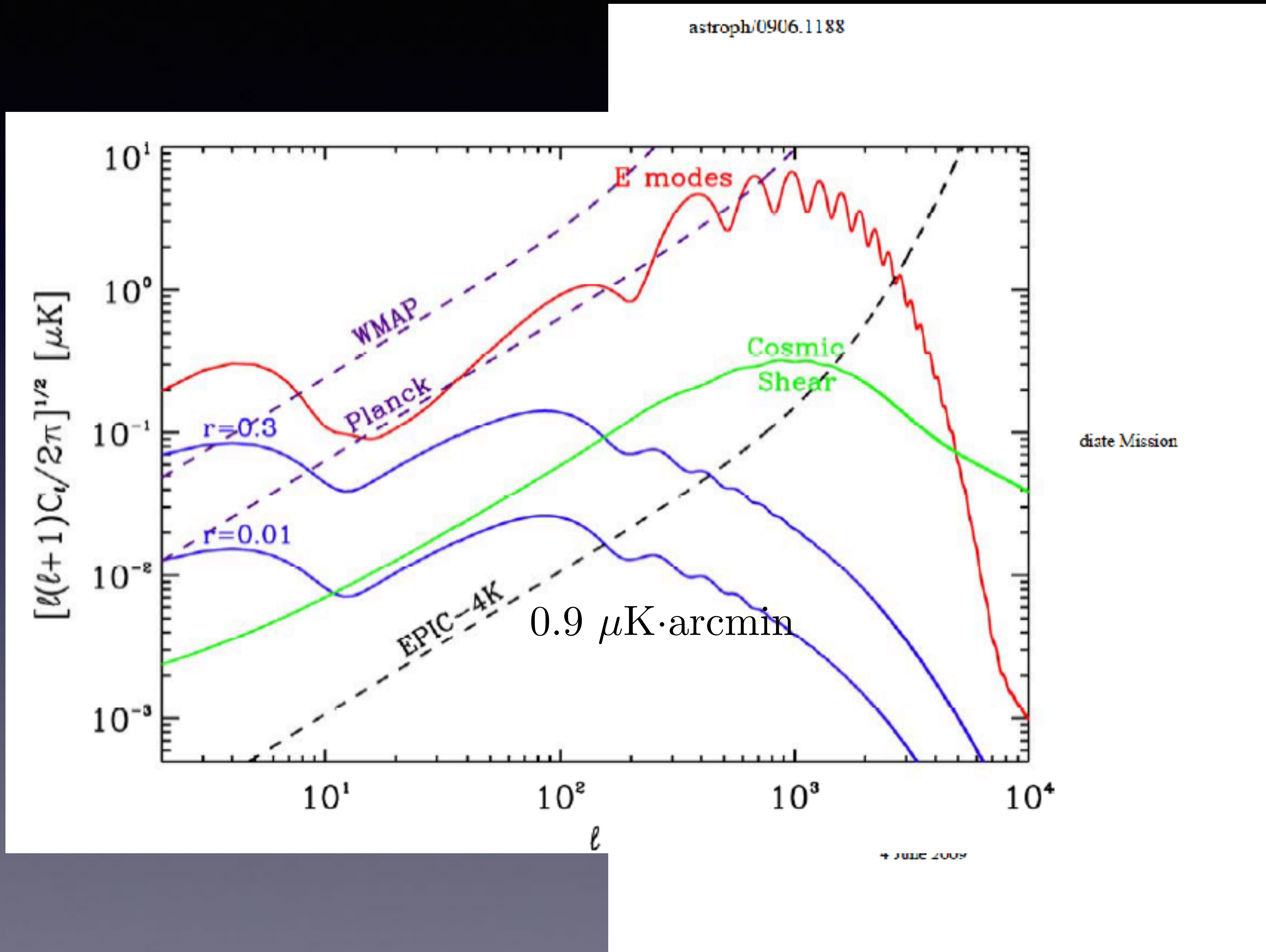
1.4 m, 2 mirror, Cross-Dragone Telescope
~$900M

astroph/0906.1188



4 June 2009

A year later

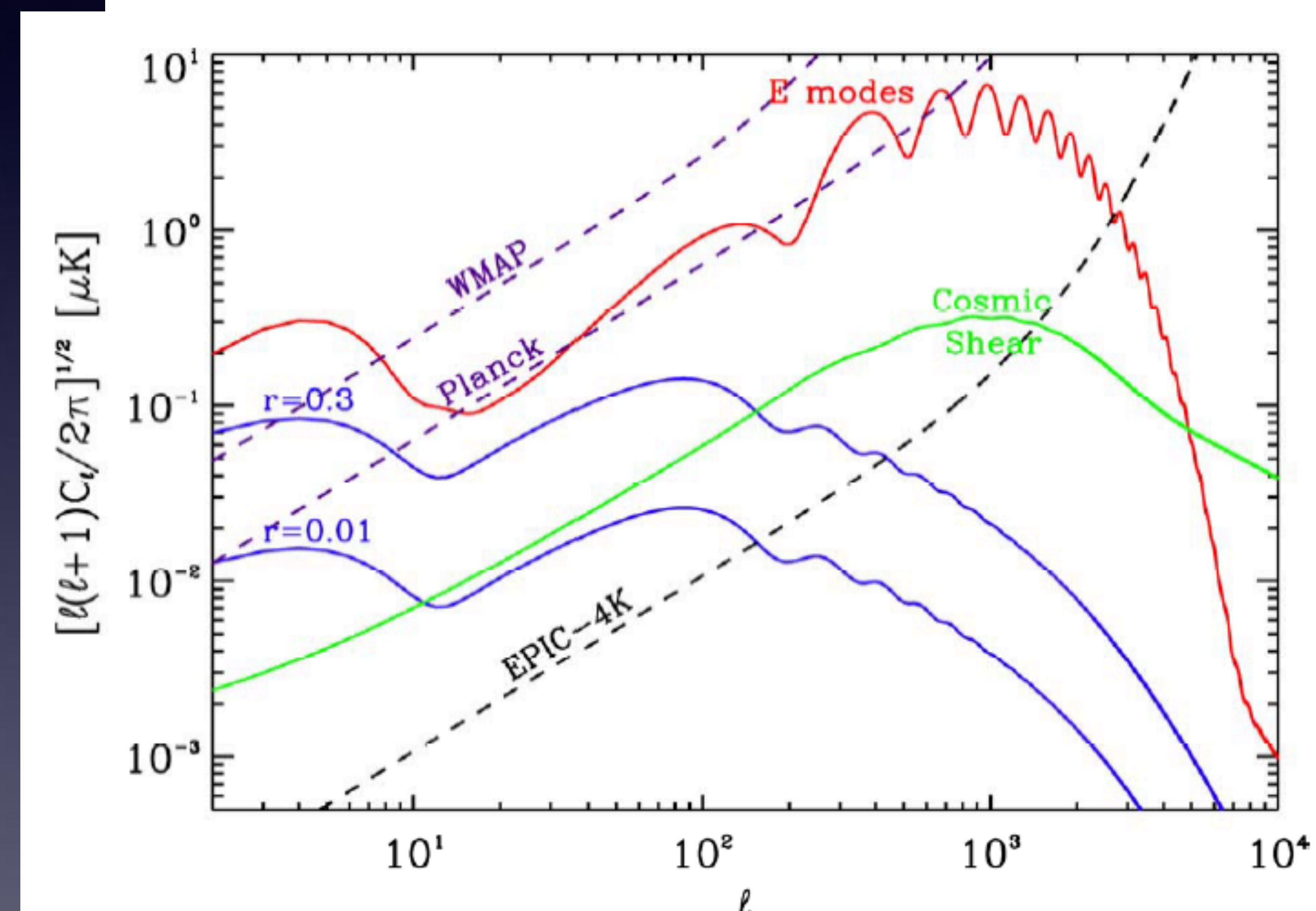

astroph/0906.1188
diate Mission
E modes
WMAP
Planck
r=0.3
r=0.01
Cosmic
Shear
EPIC−4K
0.9 μK·arcmin
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
ℓ
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
10^4

A year later

Planck Launches in May 2009

astroph/0906.1188

EPIC - IM



4 June 2009

Decadal Panel 2010:
New space Activities - Medium Projects

- CMB listed as a strategic program (priority 2, after exoplanet searches)

EPIC - IM

- Sub-orbital program to continue search for the B-mode signal
- Continued investment in technology development
- “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.”

Decadal Panel 2010

- WFIRST (>$1B)

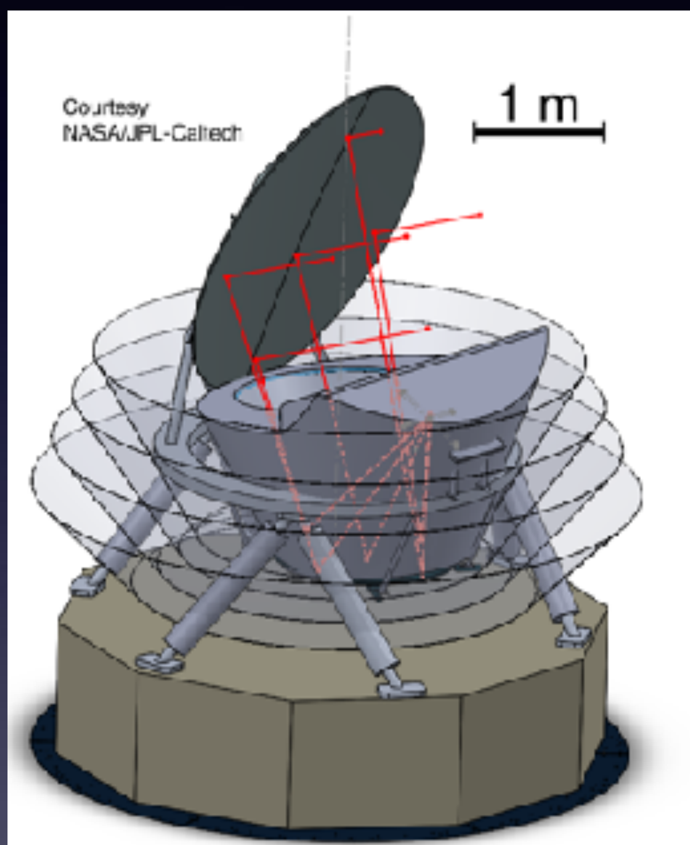
EPIC - IM

- Explorer Program
  - Missions of Opportunity $65M
  - Small Explorer ~$150M
  - Explorer $250M

CMB Mission Concepts

Active

PICO



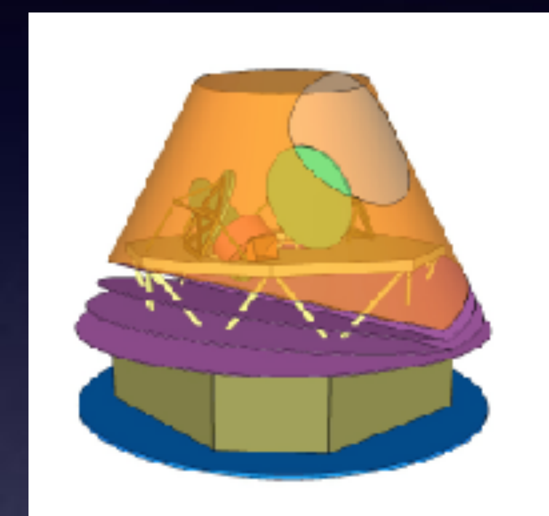
NASA Study

LiteBIRD

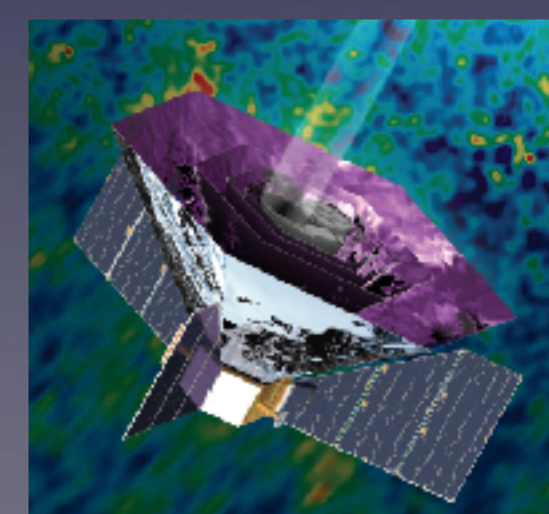
JAXA Phase A

On Hold

CORE (ESA)

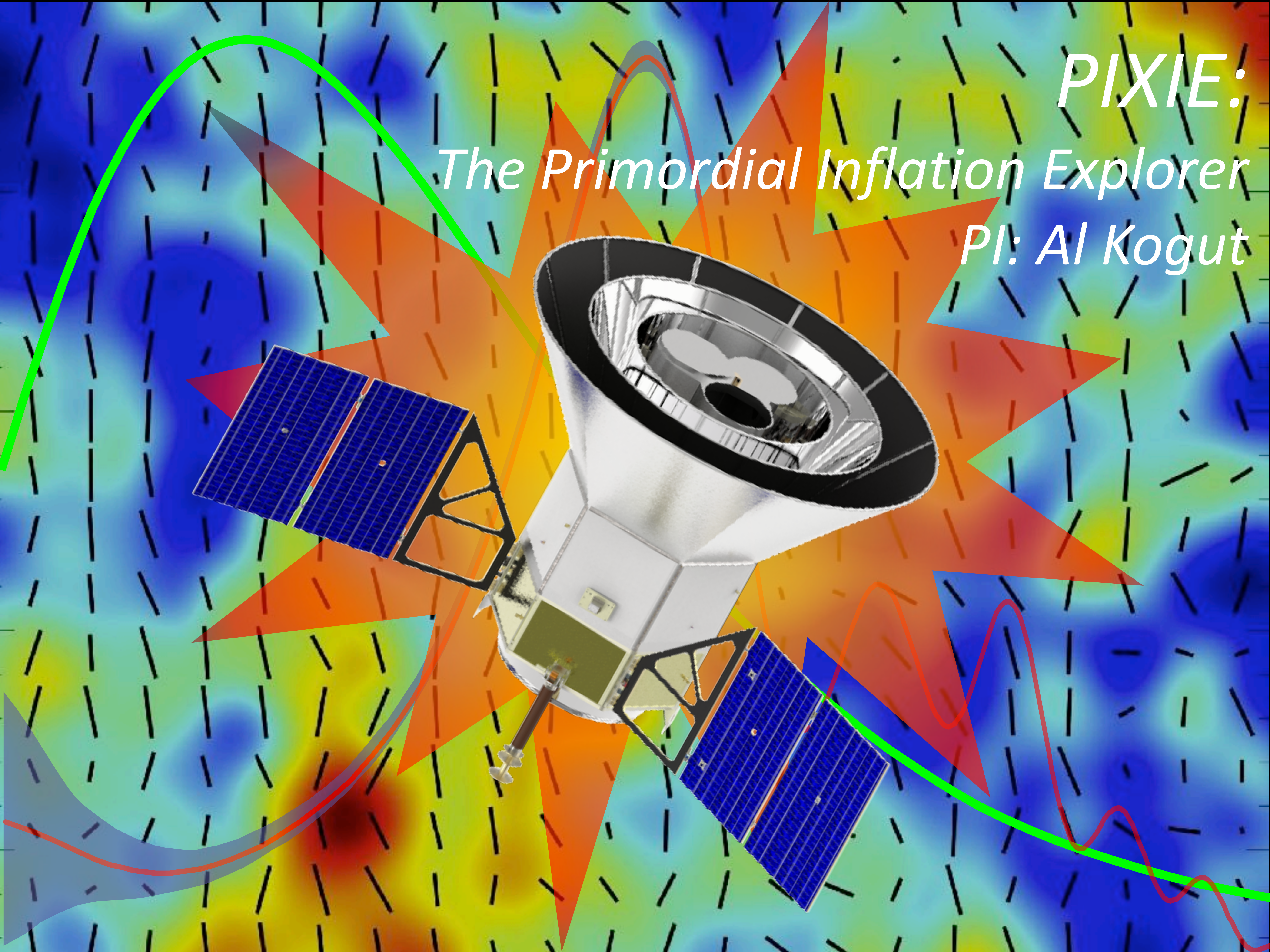


PIXIE (NASA)

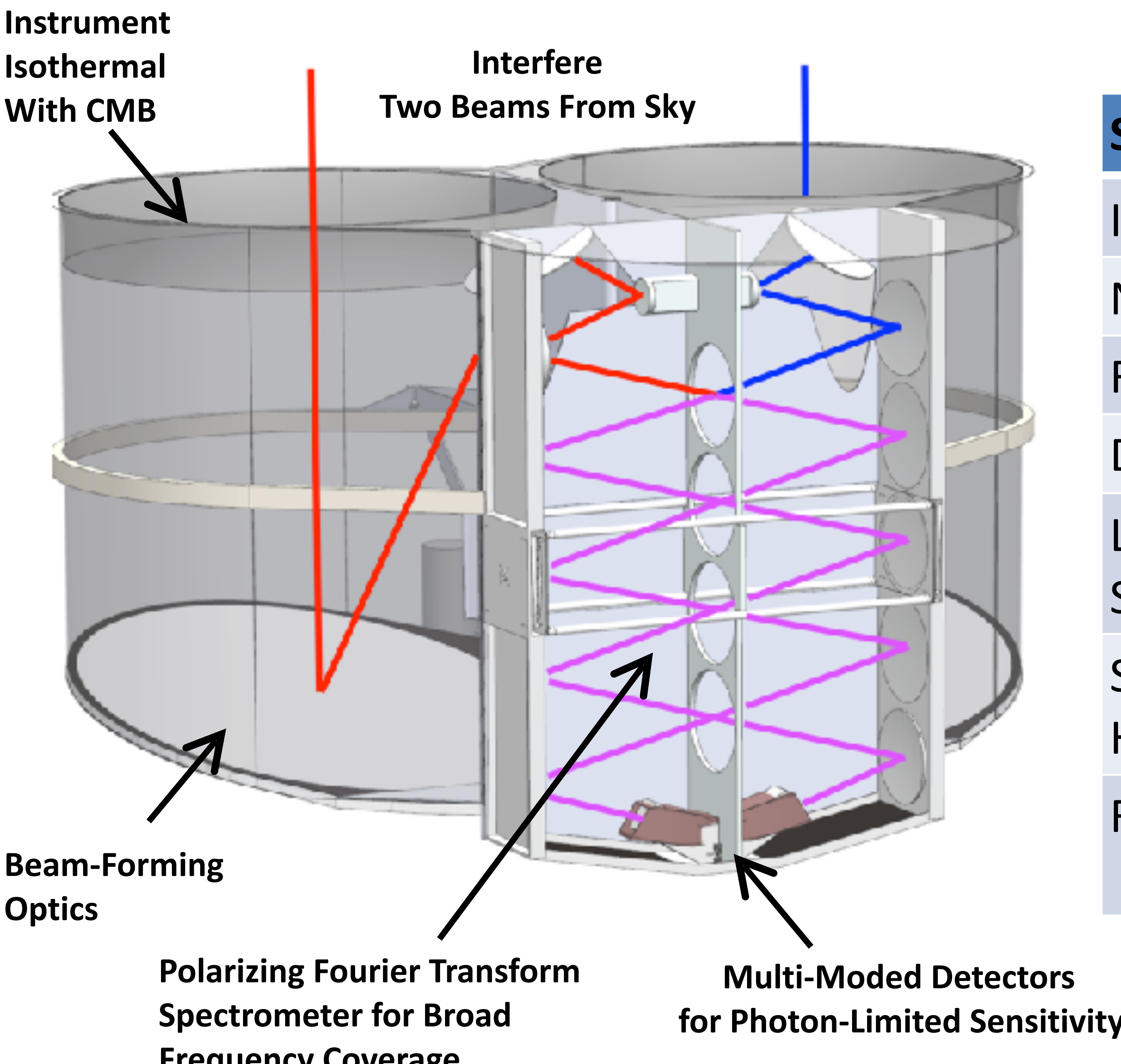


Proposed

CMB-BHARAT
(India)

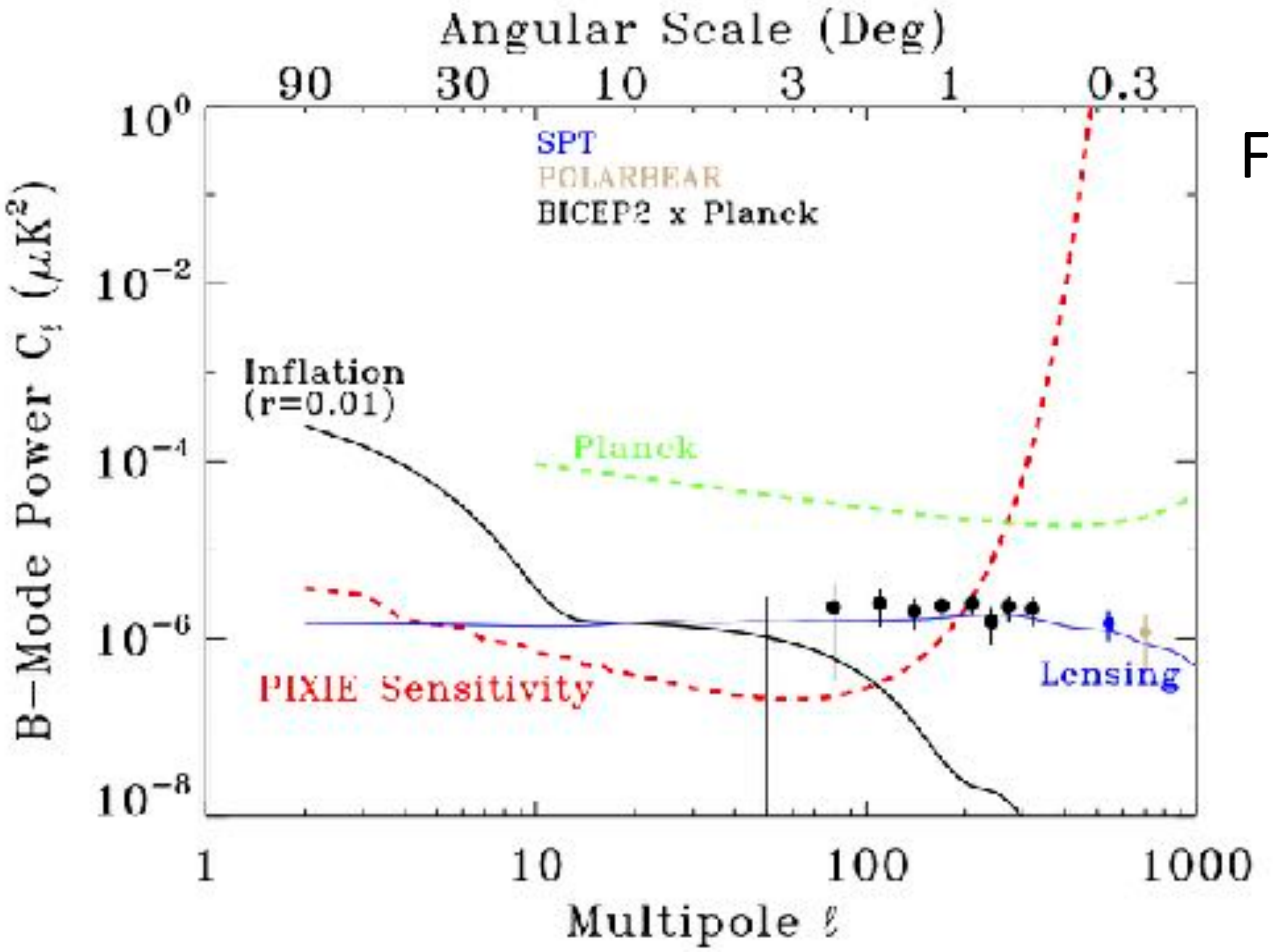

PIXIE:
The Primordial Inflation Explorer
PI: Al Kogut

PIXIE Nulling Polarimeter



Science Goal	PIXIE Measurement
Inflation	Polarization B-modes
Neutrino Mass	Polarization E-modes
Reionization	Polarization E-modes
Dark Matter	Spectral Distortion (μ)
Large-Scale Structure	Spectral Distortion (y)
Start Formation History	Far-IR Intensity Mapping
Radio Background	Synchrotron intensity+ polarization

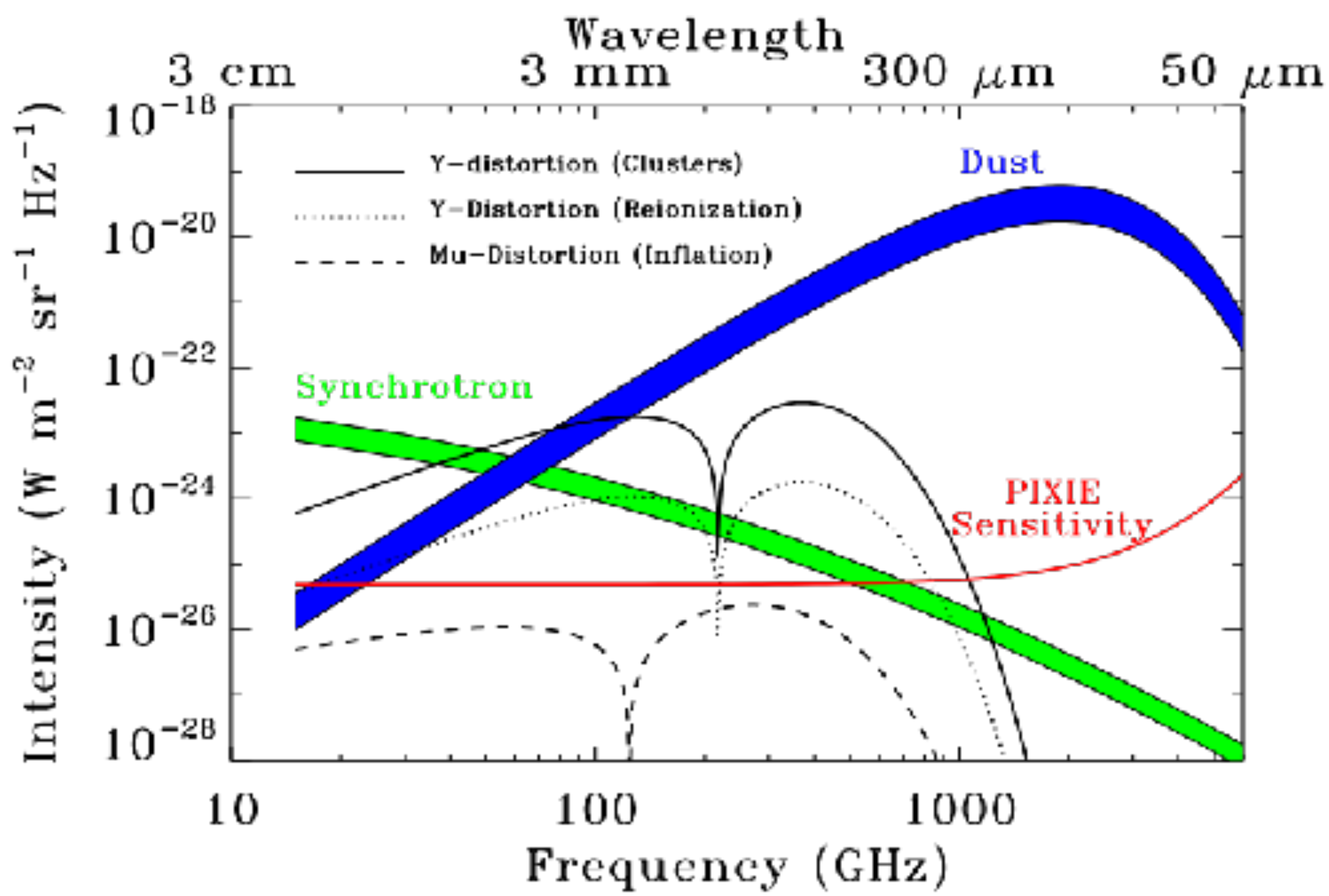
Unique Science Capability



Full-Sky Spectro-Polarimetric Survey

- 400 frequency channels, 30 GHz to 6 THz
- Resolution: 0.9°
- CMB sensitivity 70 nk RMS per pixel
- 4.8 uK*arcmin

Legacy Archive for far-IR Astrophysics



Multiple Science Goals

Polarization: r < 10^{-3} at 5 sigma

- Cosmic-variance limit EE (reionization)
- Neutrino mass at 5 sigma

Spectral distortions: |y| < 5 x 10^{-8}, |μ| < 10^{-7}

- Improve FIRAS constraints by factor 1000
- Total thermal energy in electrons
- Dark matter decay/annihilation

Intensity mapping of C+, CO lines

- Star formation history / turn-off

Status of PIXIE

Explorer Program

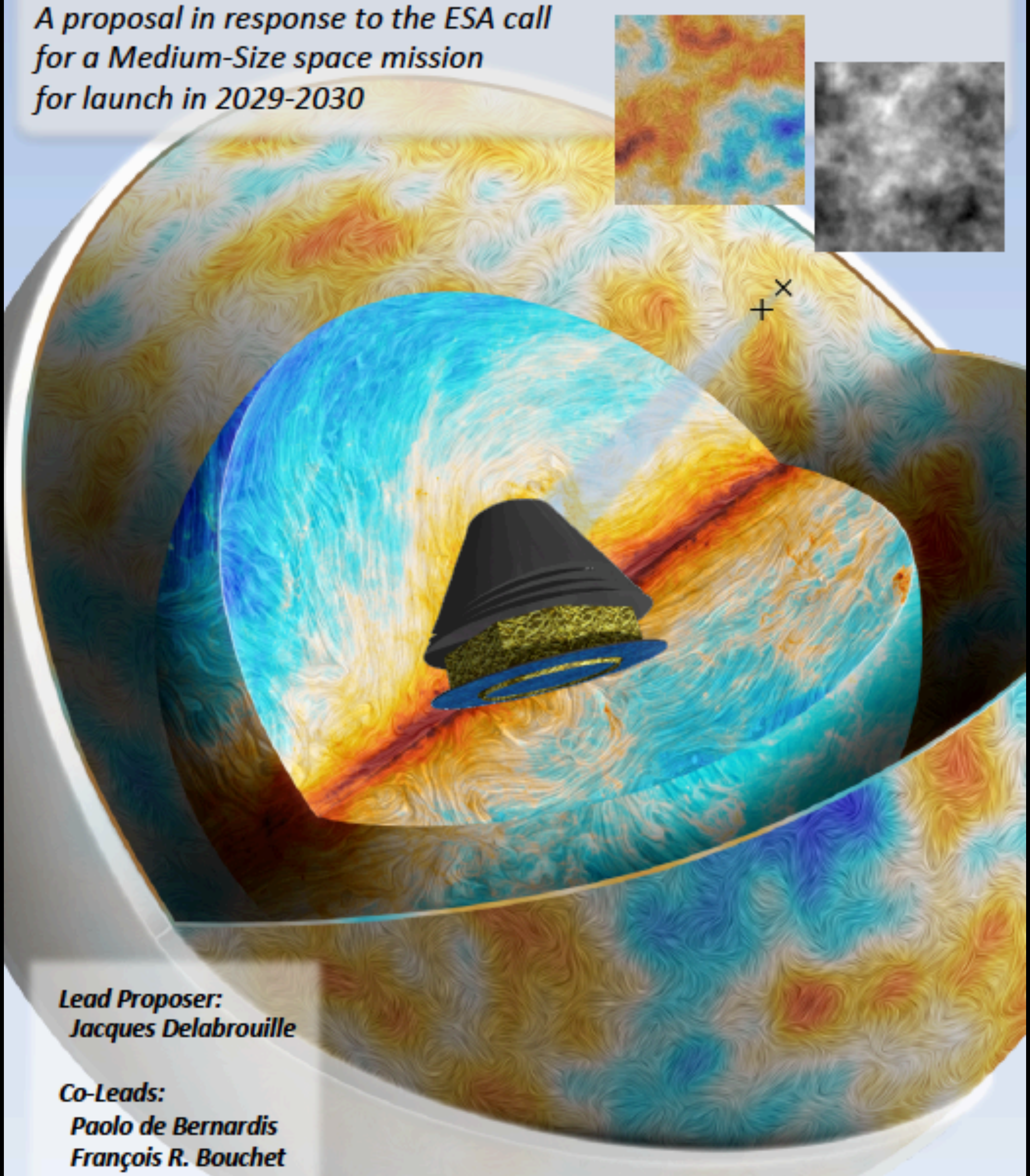
- 11 missions proposed Dec 2016
- PIXIE declined

Future plans

- Next MIDEX opportunity 2020/2021
- Also proposing Balloon-borne version for dust (Flight 2021?)

CORE The Cosmic Origins Explorer

A proposal in response to the ESA call for a Medium-Size space mission for launch in 2029-2030



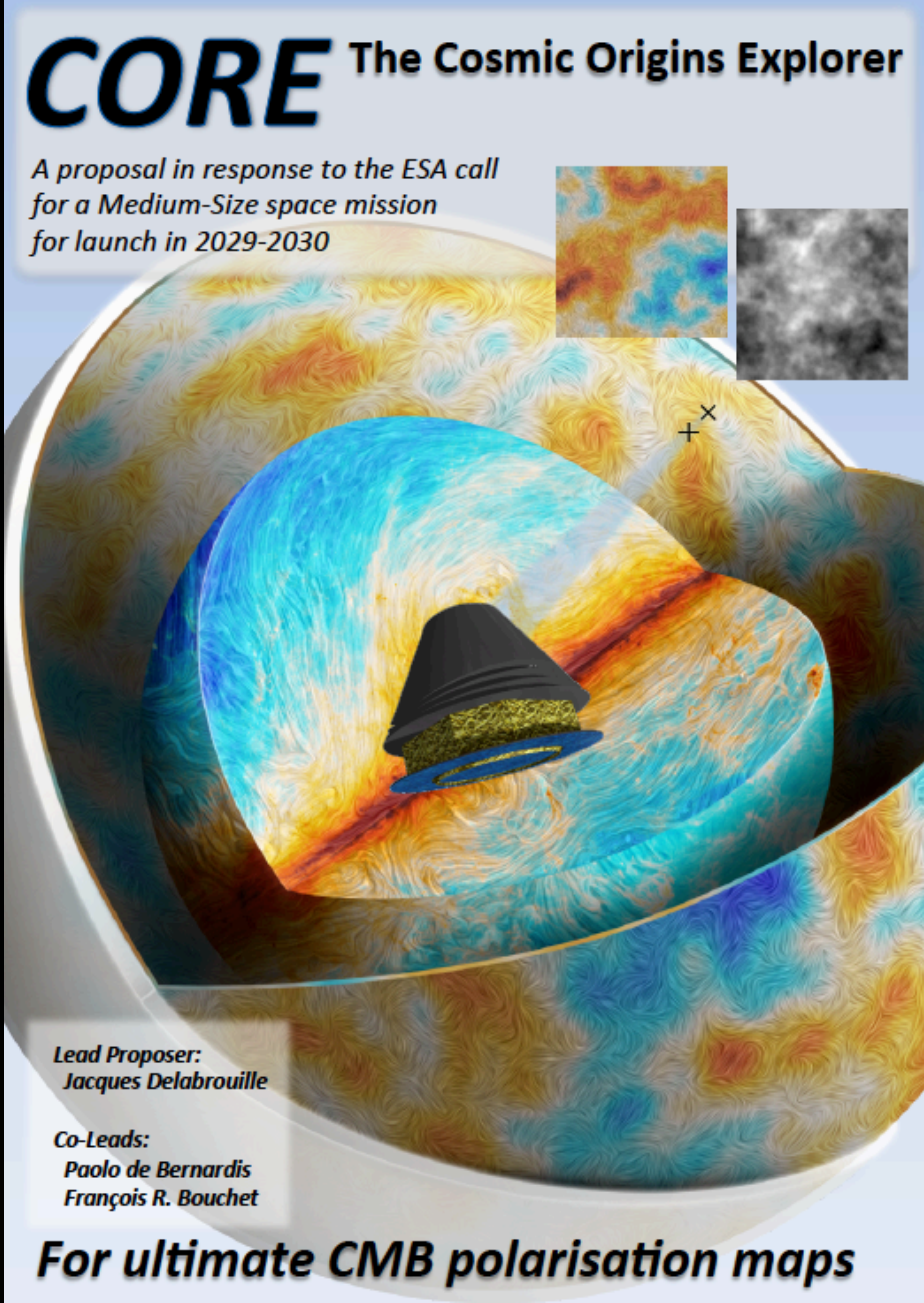
Lead Proposer:
Jacques Delabrouille

Co-Leads:
Paolo de Bernardis
François R. Bouchet

For ultimate CMB polarisation maps

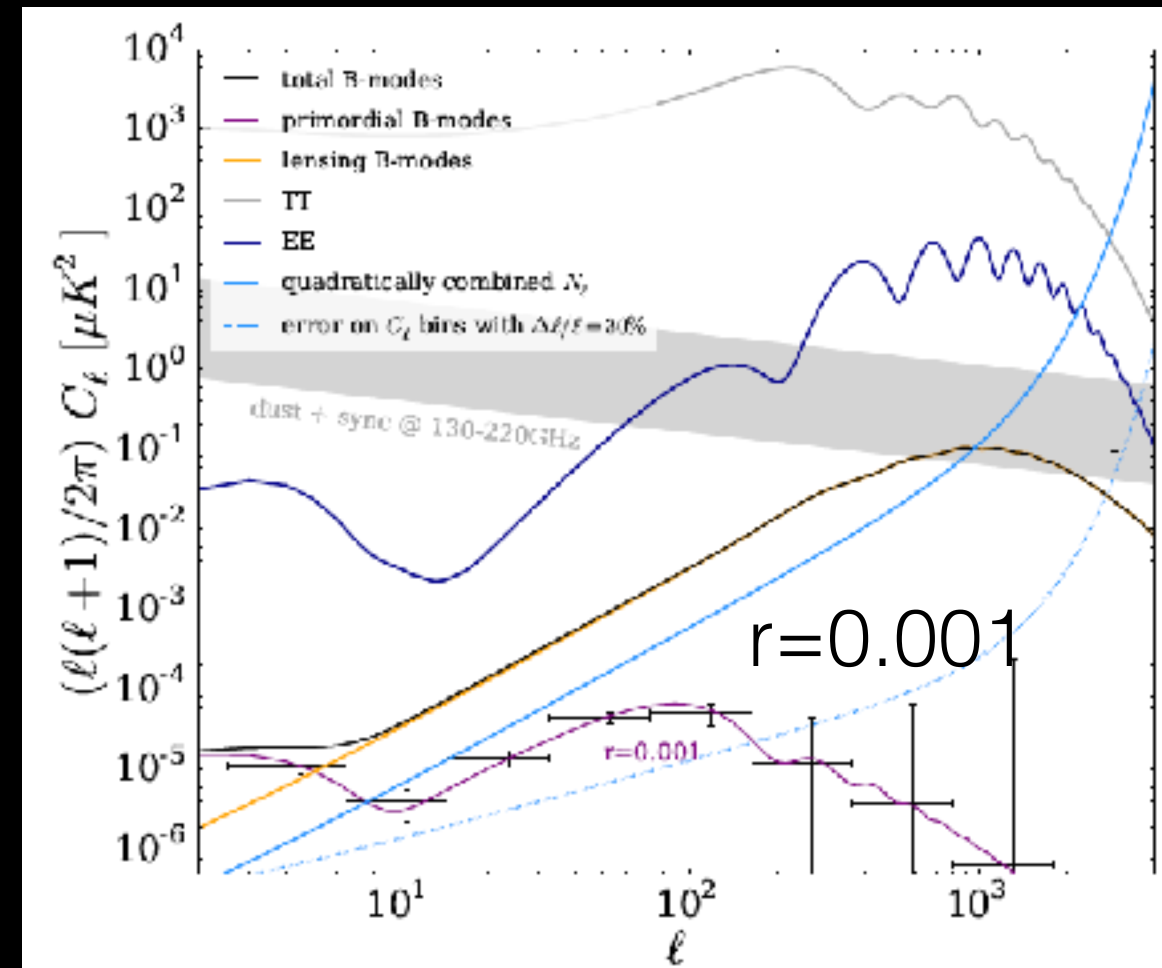
CORE

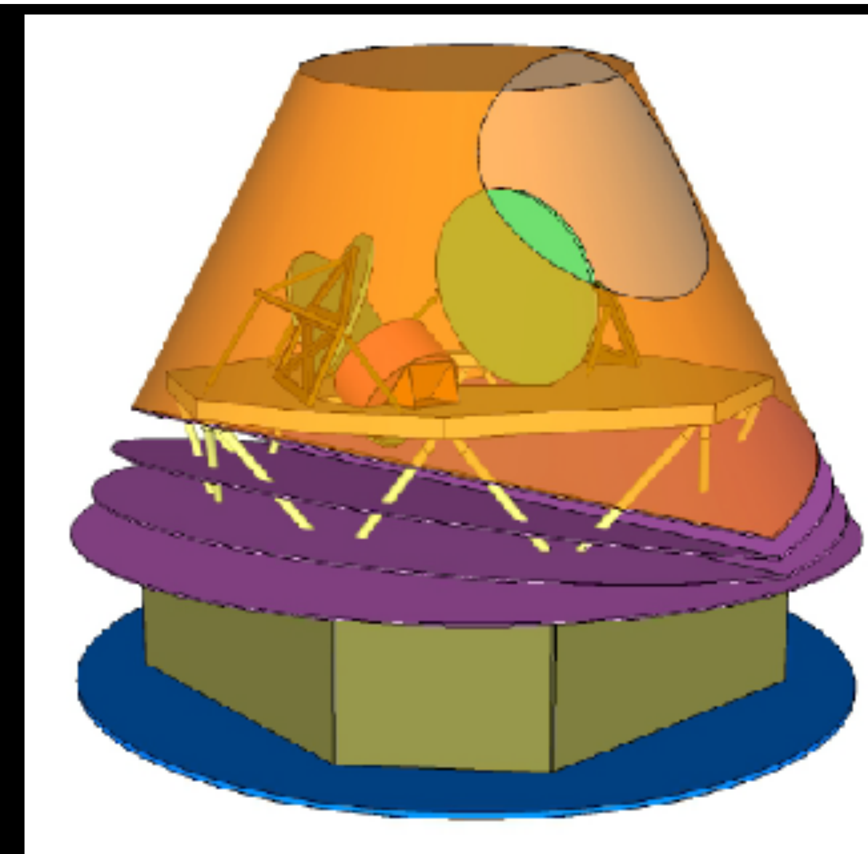
- Submitted to ESA Medium class (M5)
- Cost <= E750M, including member countries
- Most recent submission 10/2016



CORE

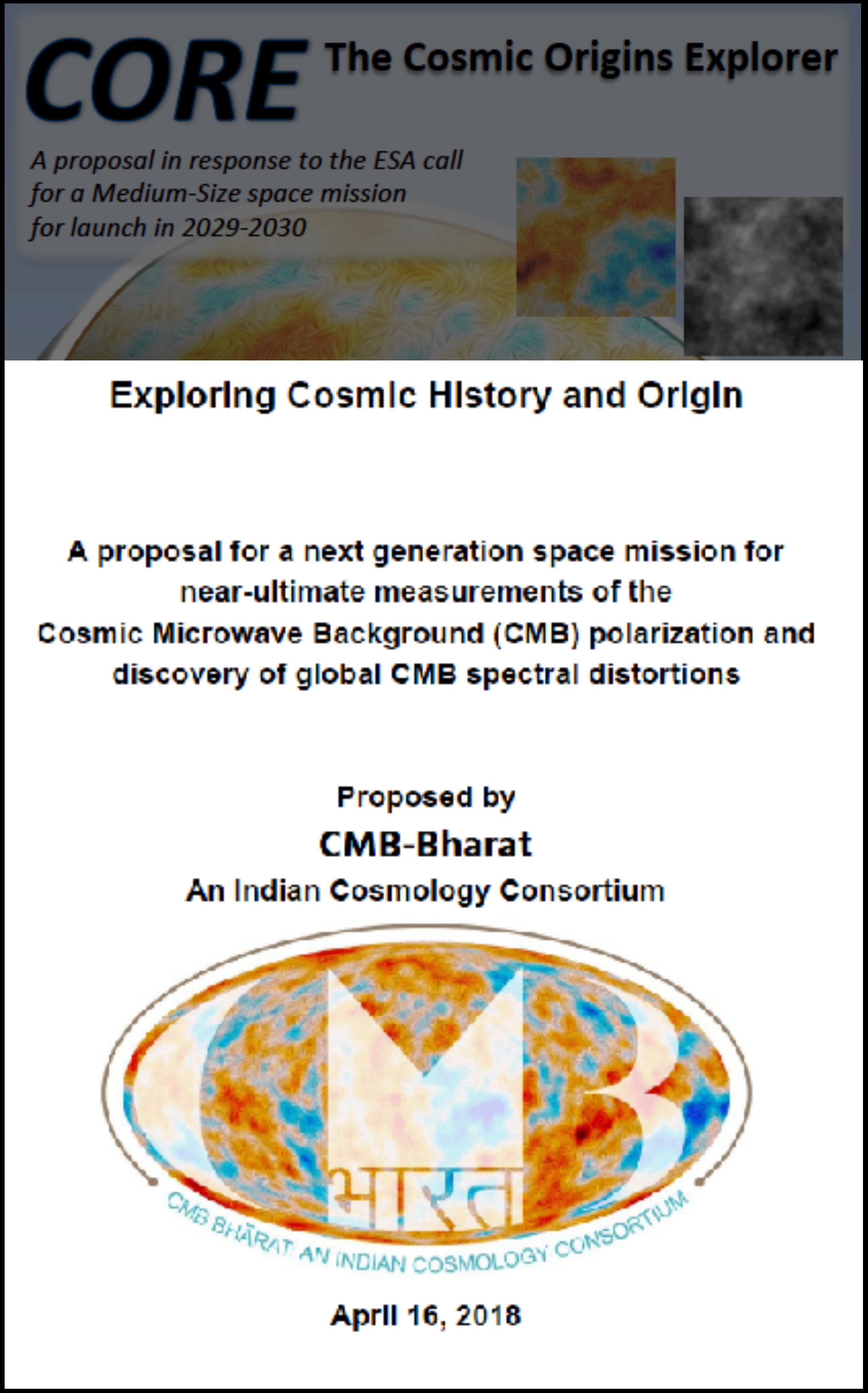
- Imager, 60 - 600 GHz
- 19 bands
- 1.2 m aperture; 3 mirror, Cross-Dragone
- 7.7’ resolution at 145 GHz
- $1.7\,\mu\mathrm{K}{\cdot}\mathrm{arcmin}$ in polarization



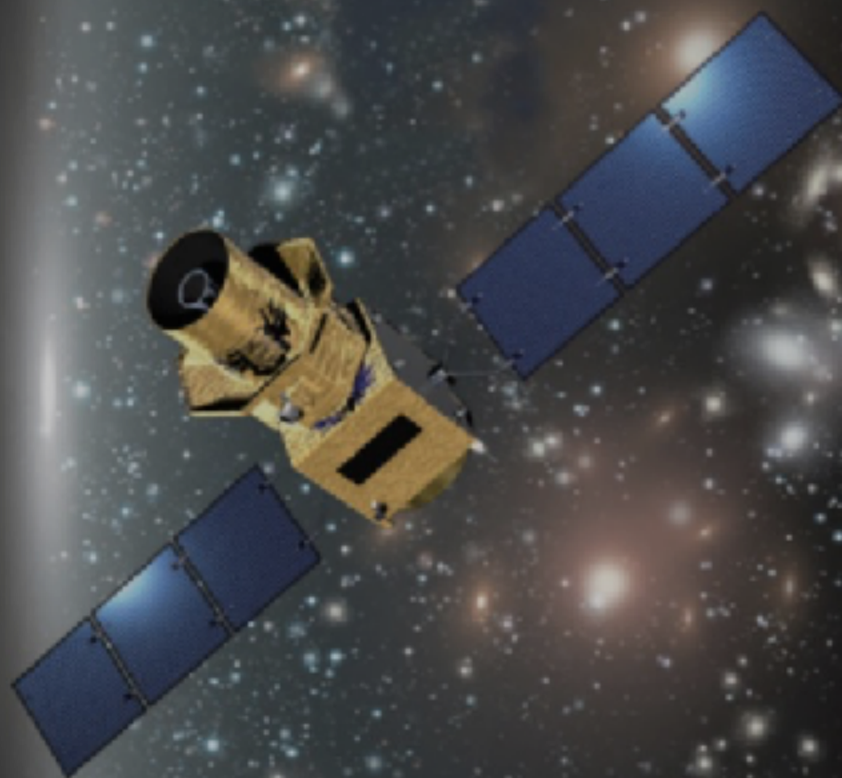


CORE Status

- Did not advance to PhaseA study (cost risk)
- Next ESA cycle - not clear
- Yesterday: submission of CMB-BHARAT - CORE-like - mission to Indian Space Research Organization



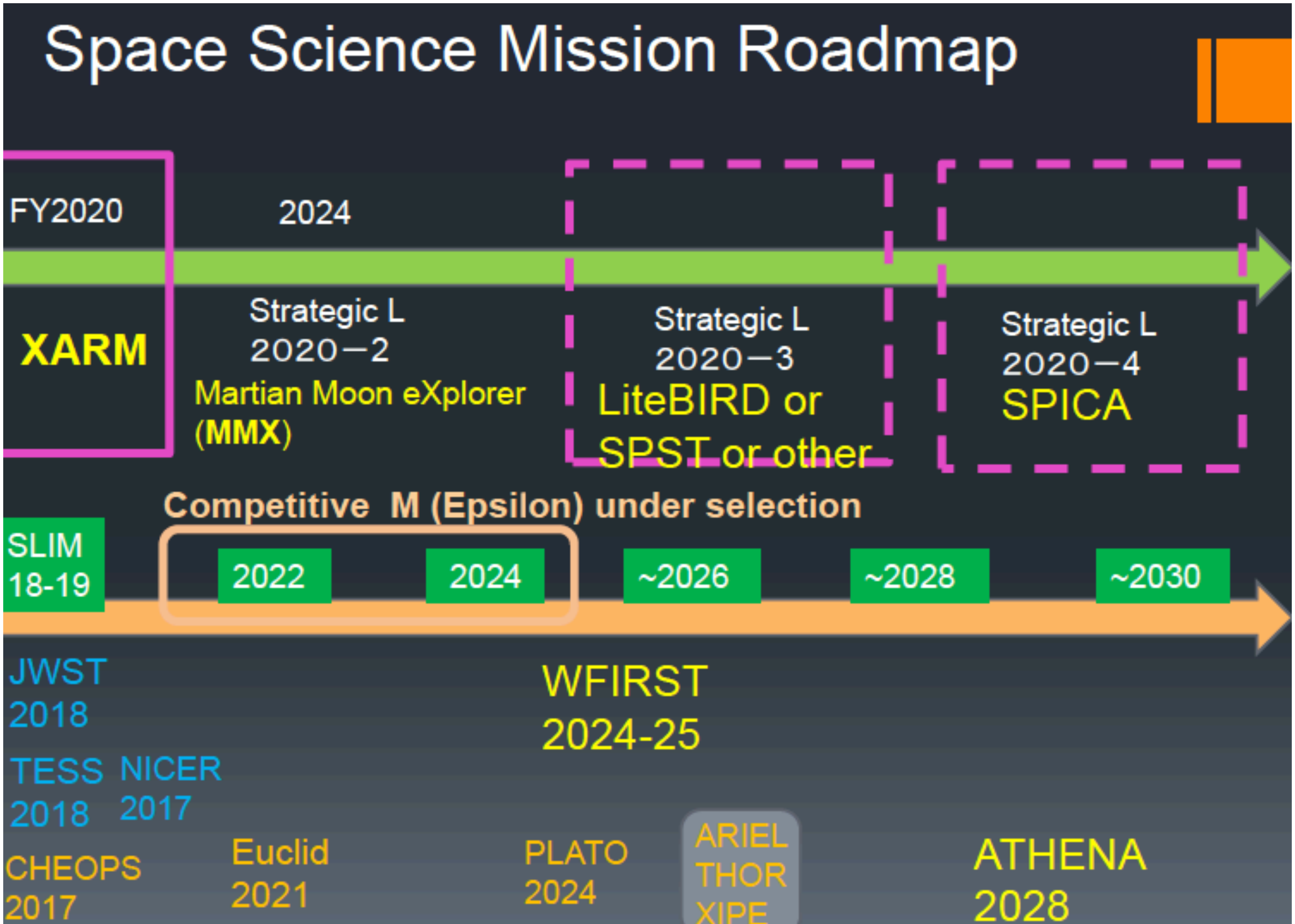
LiteBIRD



Masashi Hazumi

1) Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
2) Kavli Institute for Mathematics and Physics of the Universe (Kavli IPMU), The University of Tokyo
3) Graduate School for Advanced Studies (SOKENDAI)
4) Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)

"Current Status of LiteBIRD in JAXA" by Toru Yamada
(Former ISAS Director of International Strategy and Coordination)



Full success of LiteBIRD

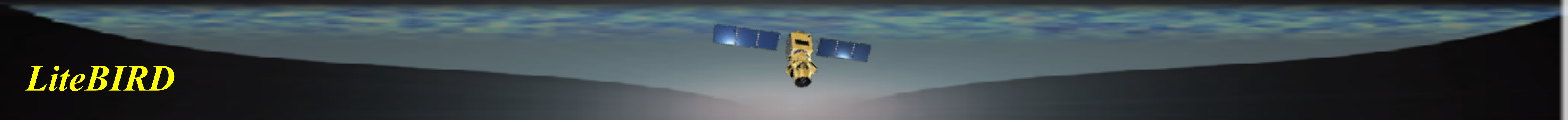
- $\sigma(r) < 1 \times 10^{-3}$ (for r=0)
- All sky survey (for $2 \leq \ell \leq 200$)*

Remarks

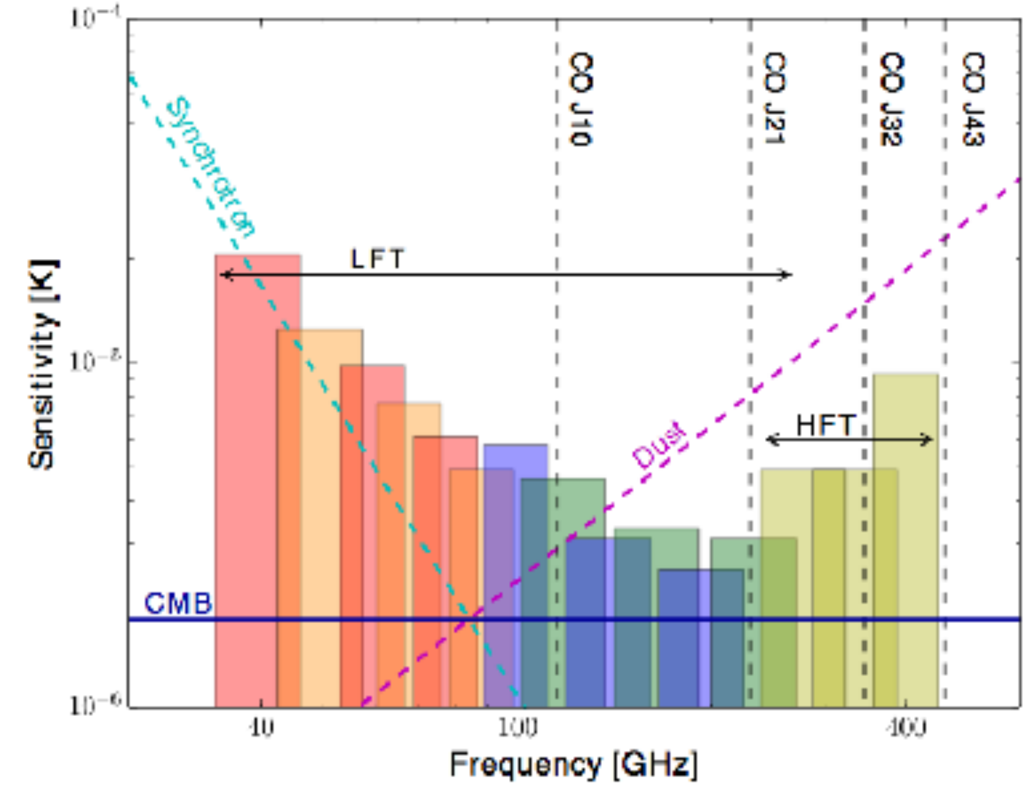
1. $\sigma(r)$ is the total uncertainty on the r measurement that includes the following uncertainties**
   - statistical uncertainties
   - instrumental systematic uncertainties
   - uncertainties due to residual foregrounds and bias
   - uncertainties due to lensing B-mode
   - cosmic variance (for $r > 0$)
   - observer bias
2. The above should be achieved without delensing.

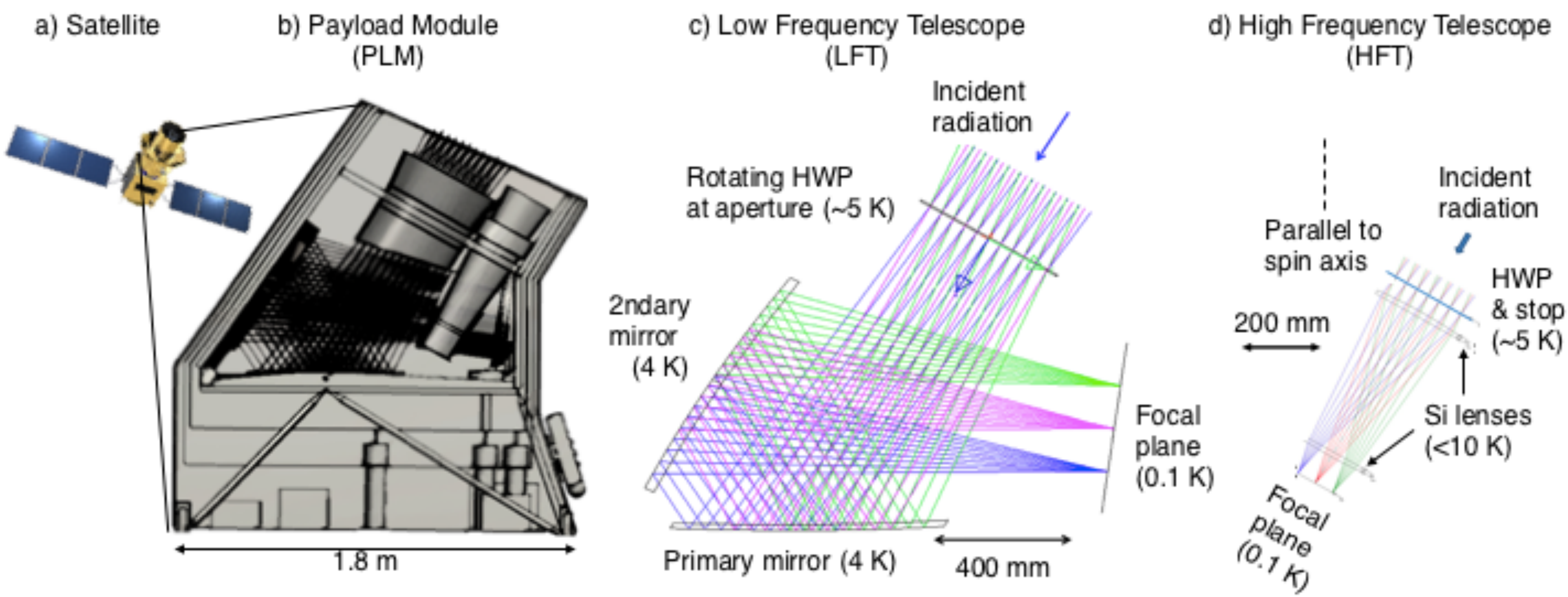
* **More precise (i.e. long) definition ensures >5sigma r detection from each bump for r > 0.01.**

** We also use an expression $\delta r = \sigma(r=0)$, which has no cosmic variance.



- $\sigma(r) < 0.001$ (for r=0)
- Imager, 35 - 450 GHz
- 15 frequency bands (some overlap)
- Two telescopes; 0.5 deg resolution at 100 GHz
- $2.5\,\mu\mathrm{K}{\cdot}\mathrm{arcmin}$ in polarization

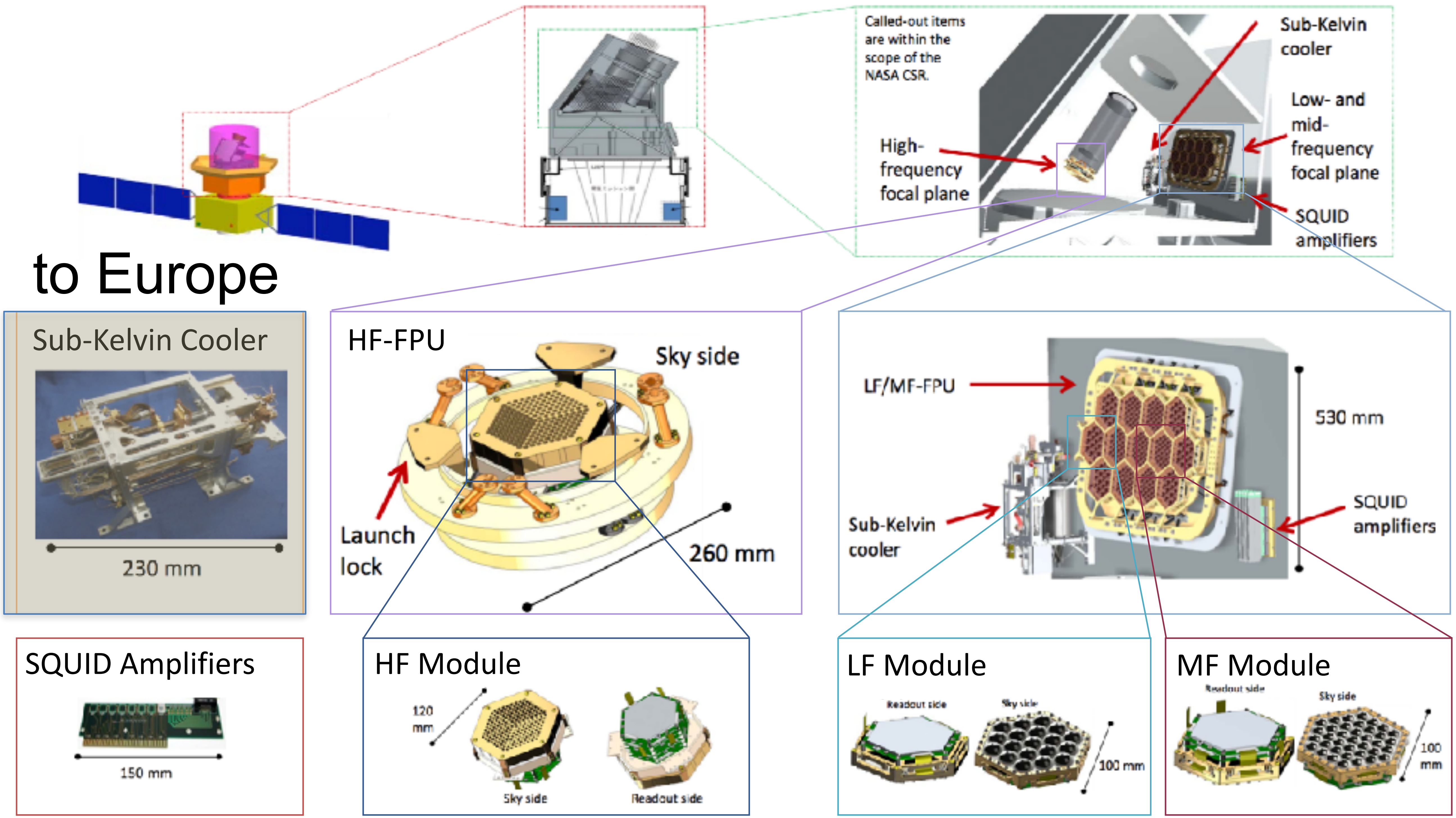




A. Lee

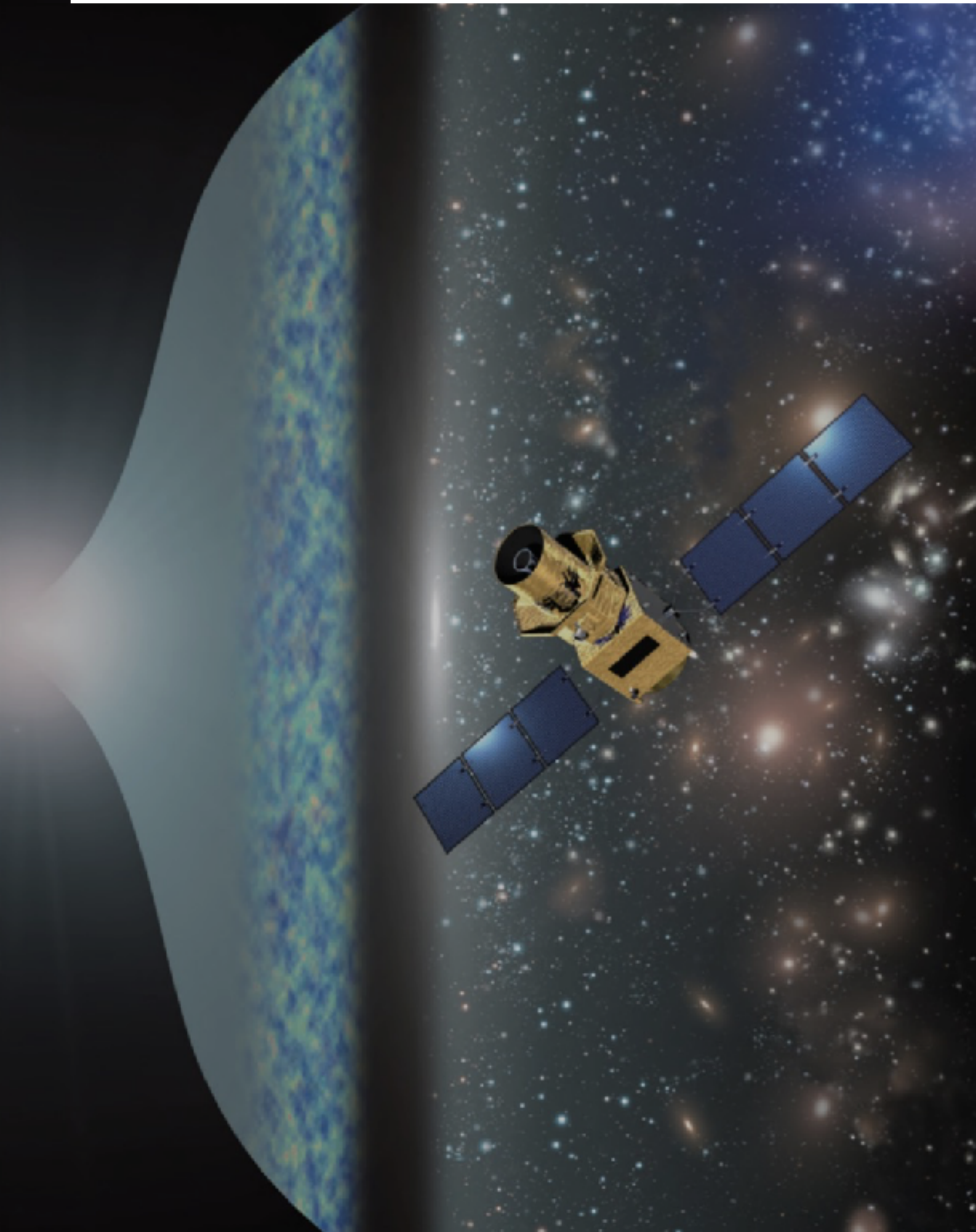
LiteBIRD U.S. Deliverables

HF = High Frequency, MF = Mid Frequency, LF = Low Frequency



LiteBIRD

LiteBIRD Status



- Japan:
  - Phase A1 will conclude in 8/2018
  - Downselect
- US:
  - 2016 Mission of Opportunity ($65M) proceeded to PhaseA; PhaseB declined
  - Technology development continues
  - Will submit at next MO (2019?)

Probe of Inflation and Cosmic Origins (PICO)

NASA Prep for 2020

Recall

- Decadal 2010 did not recommend space missions between \$250M - \$1000M

NASA Prep for 2020

- **Set up 8 Probe Mission Studies; Probe= $400M-$1000M**
  - Transient Astrophysics Probe (Camp, GSFC)
  - Cosmic Dawn Intensity Mapper (Cooray, UC Irvine)
  - Cosmic Evolution through UV Spectroscopy (Danchi, GSFC)
  - Galaxy Evolution Probe (Glenn, UColorado)
  - **Inflation Probe (Hanany, University of Minnesota)**
  - High Spatial Resolution X-Ray Probe (Mushotzky, UMaryland)
  - Multi-Messenger Astrophysics (Olinto, UChicago)
  - Precise Radial Velocity Observatory (Plavchan, Missouri State)

NASA Prep for 2020

- **Inflation Probe = Probe of Inflation and Cosmic Origin (PICO)**
- Studies will produce 50 pg. reports + cost estimates that will be submitted to NASA and to the Decadal Panel (12/2018)
- Possible outcomes:
  - Panel recommends a funding wedge. Probes are competed later.
  - Panel recommends specific missions
  - Any combination of the above
- Our desired outcome: panel recognizes the promise of a future space mission and gives high ranking (maintain 'strategic' status)

The PICO Collaboration

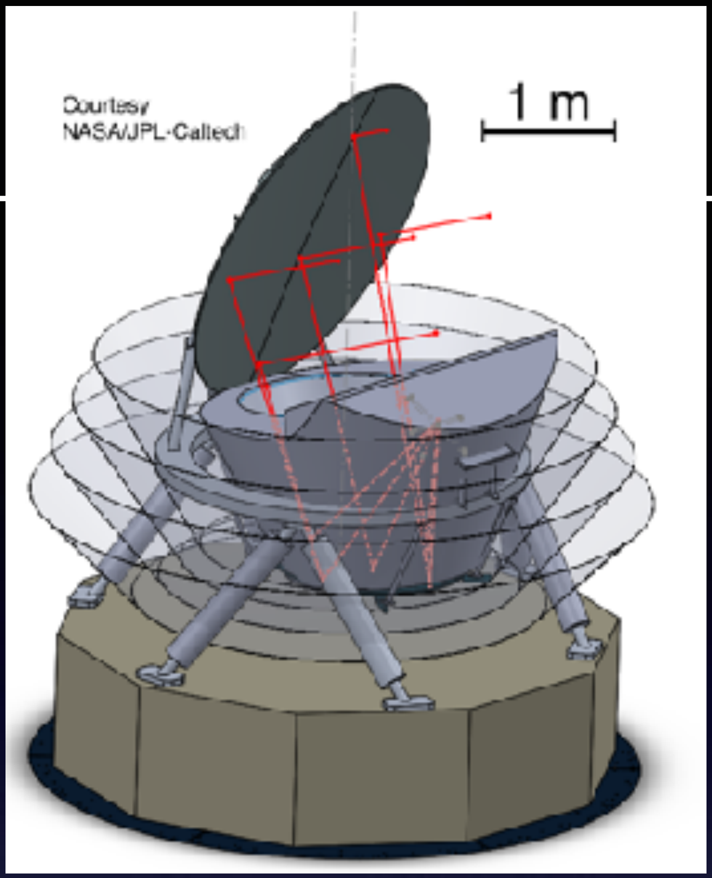
- **Open to all - subscribe, contribute**
- Steering Committee: Bennett, Dodelson, Page
- Executive Committee: Borrill, Bock, Crill, Devlin, Flauger, Jones, Hanany, Knox, Kogut, Lawrence, McMahon, Pryke, Trangsrud
- 7 working groups:
    - Fundamental physics (Flauger)
    - Extragalactic science (Battaglia)
    - Galactic science (Chuss+Fissel)
    - Foregrounds + Data challenge (Hanany, Borrill)
    - Imager (Hanany)
    - Spectrometer (Kogut)
    - Systematics (Crill)
- Wiki: https://z.umn.edu/cmbprobe
- Mailing list: cmbprobe@lists.physics.umn.edu

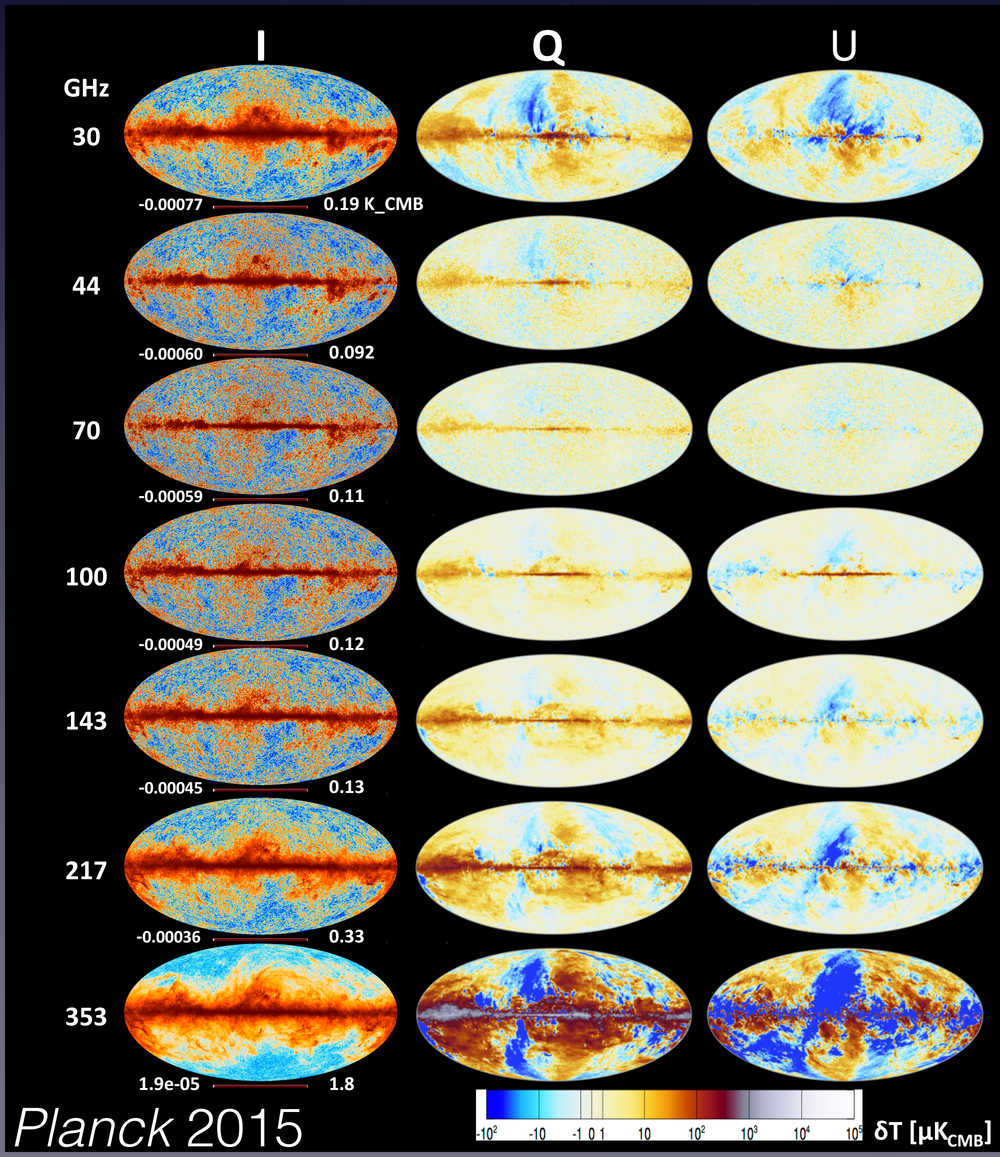
Spectrometer, Imager, or both?

- We began by considering which instrument(s) to implement
- The EC concluded that there is strong case for two Probe scale missions, one devoted to spectroscopy and another to imaging
- The EC considered the case for a combined mission and concluded that it will weaken both instruments
- PICO will be given detailed costing as an imaging mission.

PICO in Brief

- Millimeter/submillimeter-wave, polarimetric survey of the entire sky
- 21 bands between 20 GHz and 800 GHz
- 1.4 m aperture telescope
- Diffraction limited resolution: 38’ to 1’
- 13,000 transition edge sensor bolometers + multiplexed readouts
- 4 year survey from L2 (1 year margin)
- 0.6 uK*arcmin, 80 times the sensitivity of *Planck*



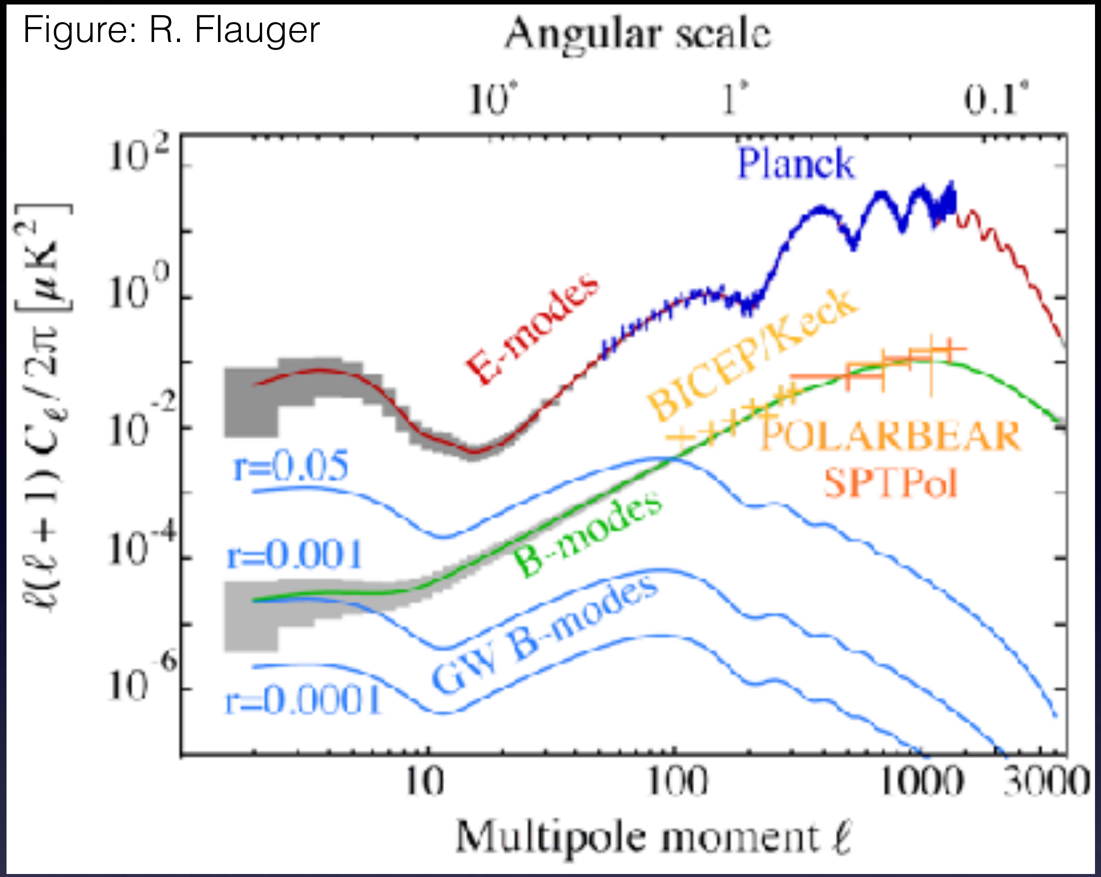


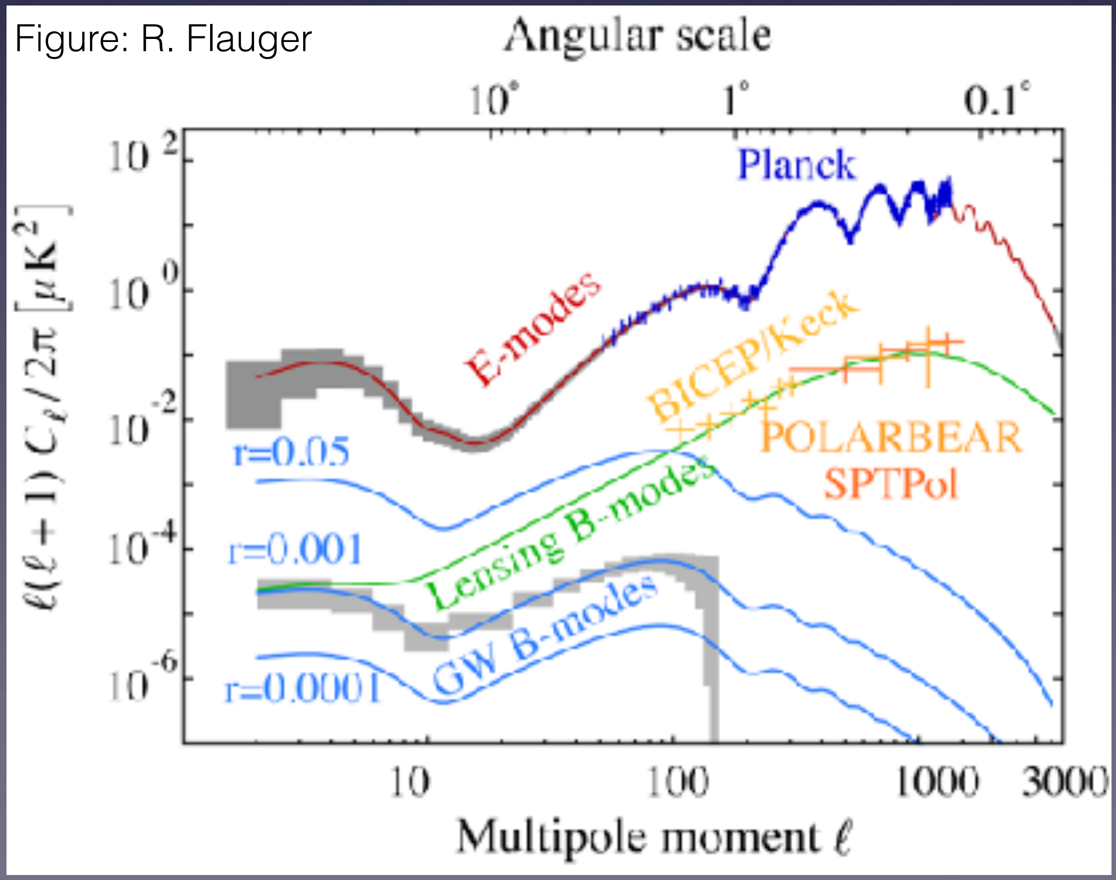
NASA Science Strategic Goals

- Explore how the Universe began
- Discover how the Universe works
- Explore how the Universe evolved

Explore How the Universe Began

- Detect or set upper bound on the energy scale of inflation
  - $E = 3.7 \cdot 10^{16} r^{1/4}$ GeV
  - $B_{80} = 0.08r \;\; \mu\mathrm{K}^2$
  - Currently $r < 0.07$ (95%)
  - PICO: $r < 10^{-4}$ (95%)
  - 700 times lower than current constraint
  - $\sigma(r) = 5 \cdot 10^{-5}$
  - $r,\ \sigma(r)$ quoted constraints include x2.5 margin
  - Includes internal delensing, removal of a simple foregrounds model; excludes systematic uncertainties; 40% of sky





Explore How The Universe Began

- Detection would point to specific large field inflation models as the drivers for inflation, and would motivate their connection to string theory

- An upper limit will exclude classes of inflation potentials

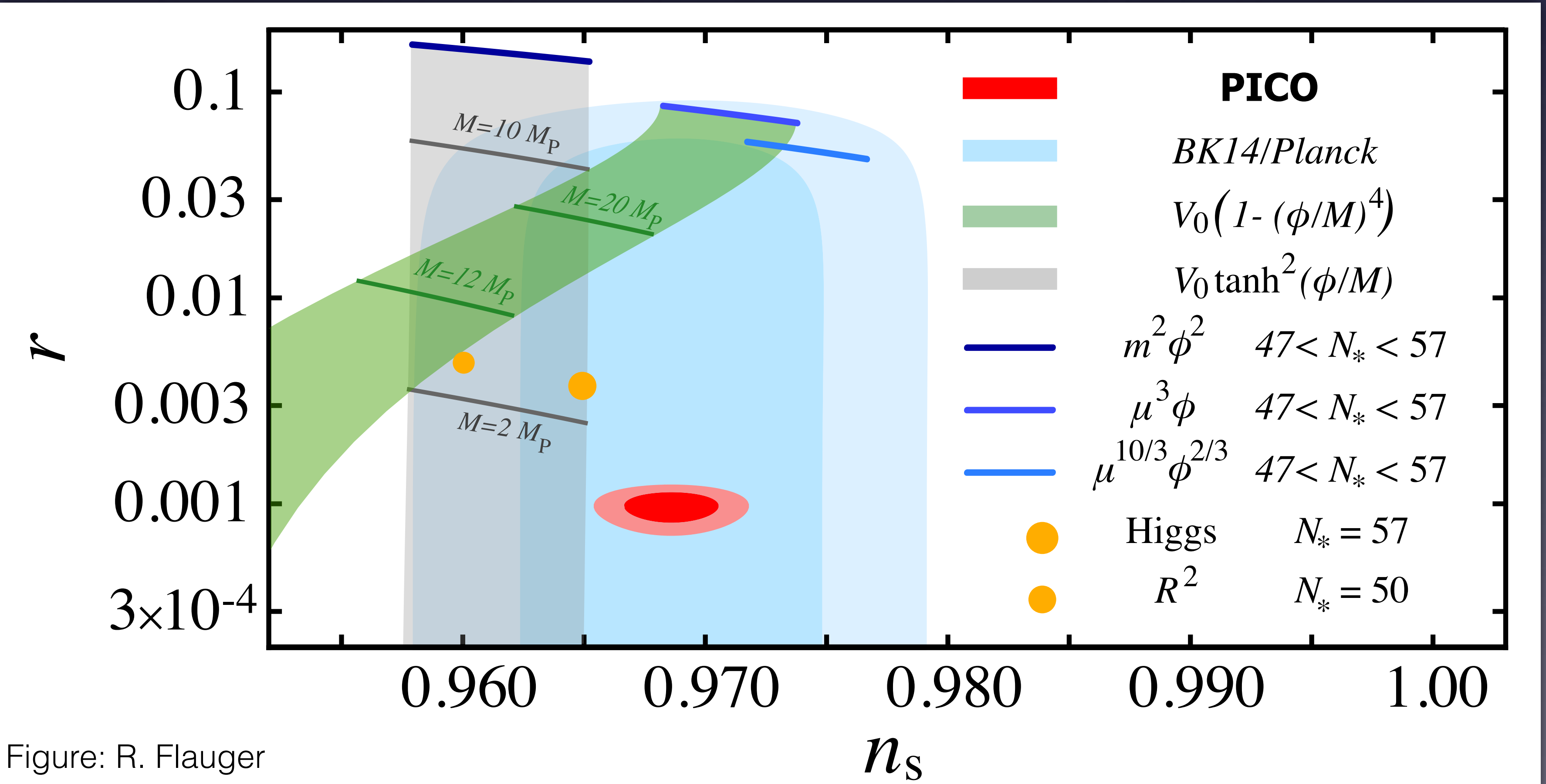
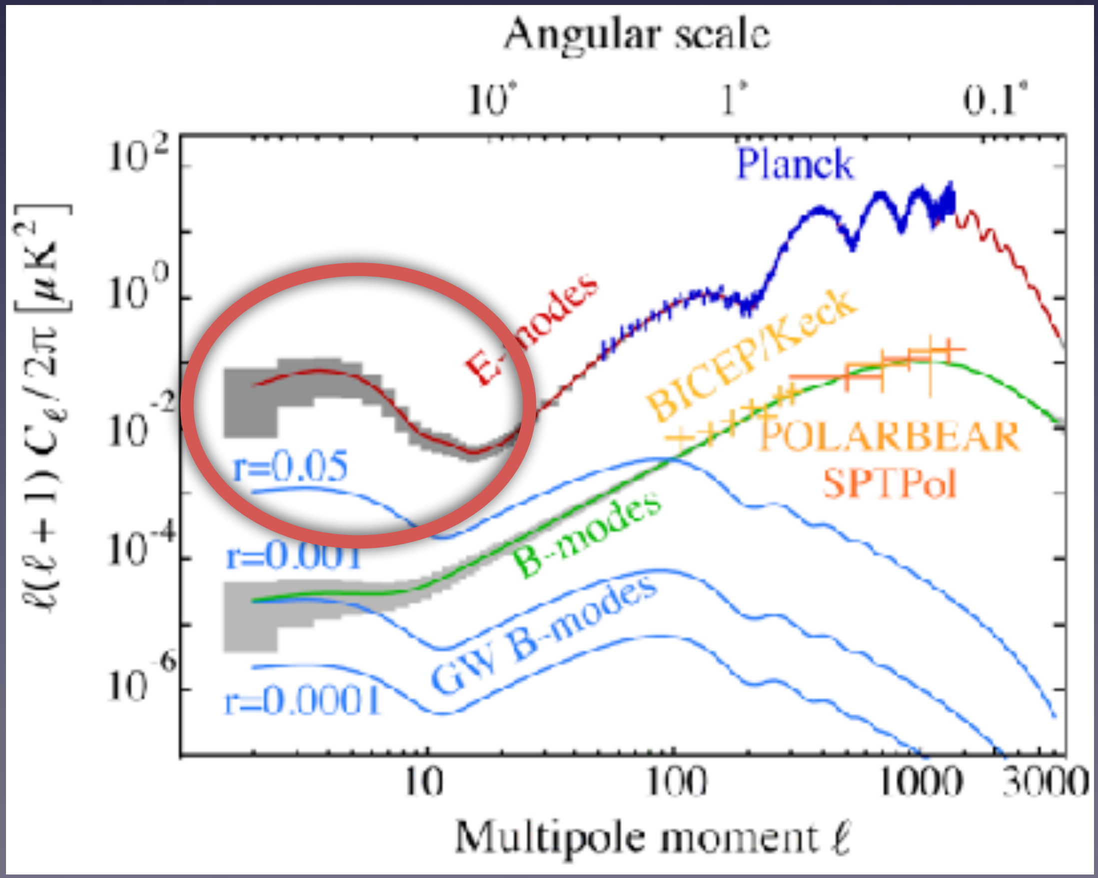


Figure: R. Flauger

Explore how the Universe Evolved

- Determine the reionization history of the Universe
- Measurement of the EE power spectrum on the largest angular scales gives a measurement of τ
- Planck: $\tau = 0.058 \pm 0.012$
- PICO: $\sigma(\tau) = 0.0019$
  cosmic variance limited



Constraining Models of Reionization

- $\tau \propto Z_{re}$ (Planck)
- $\left(\frac{\Delta T}{T}\right)_{ksz} \propto \Delta Z_{re}$ (S3, SPT)
- Transition from neutral to ionized Universe controlled by 'IGM Opacity' and 'Source Efficiency' parameters

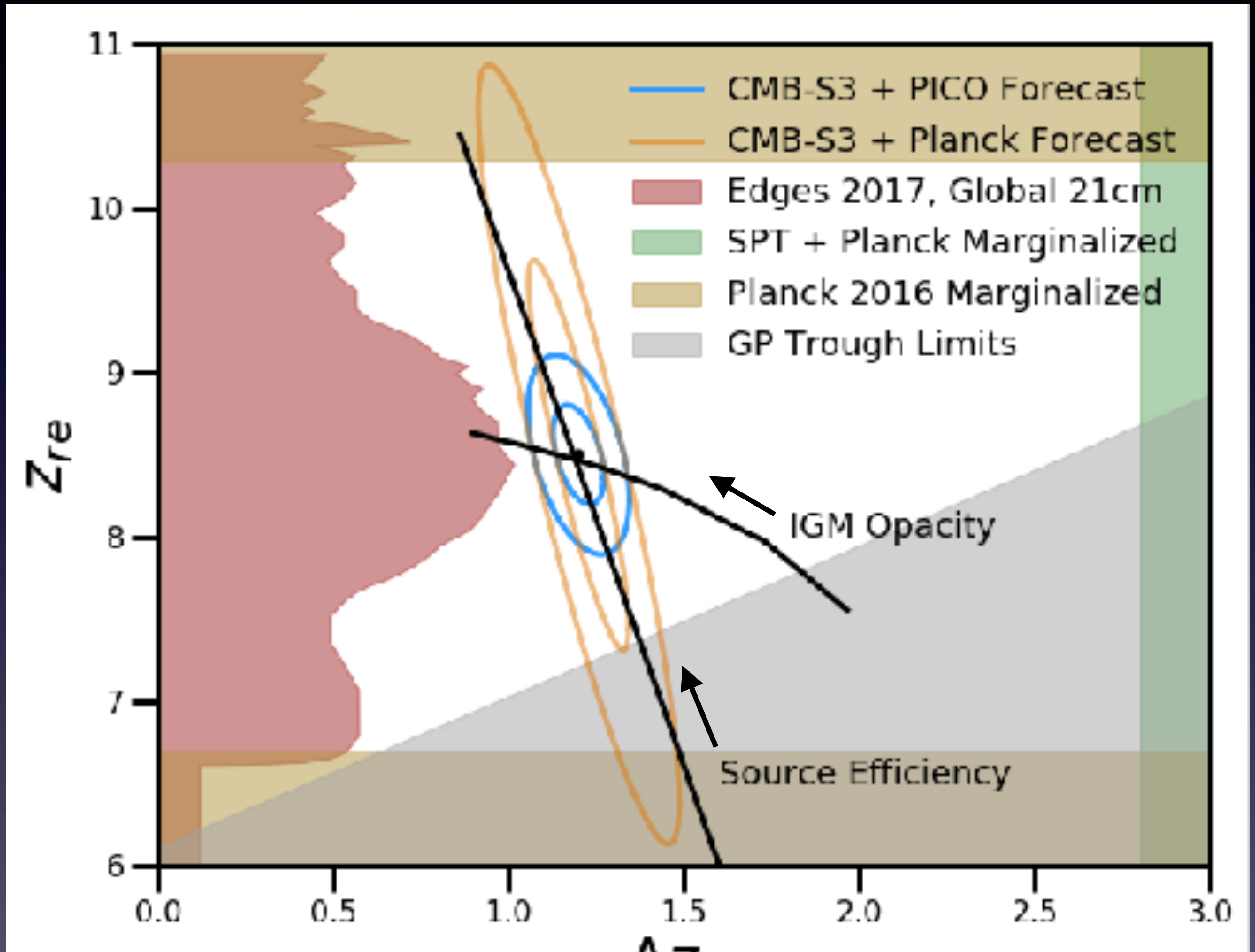
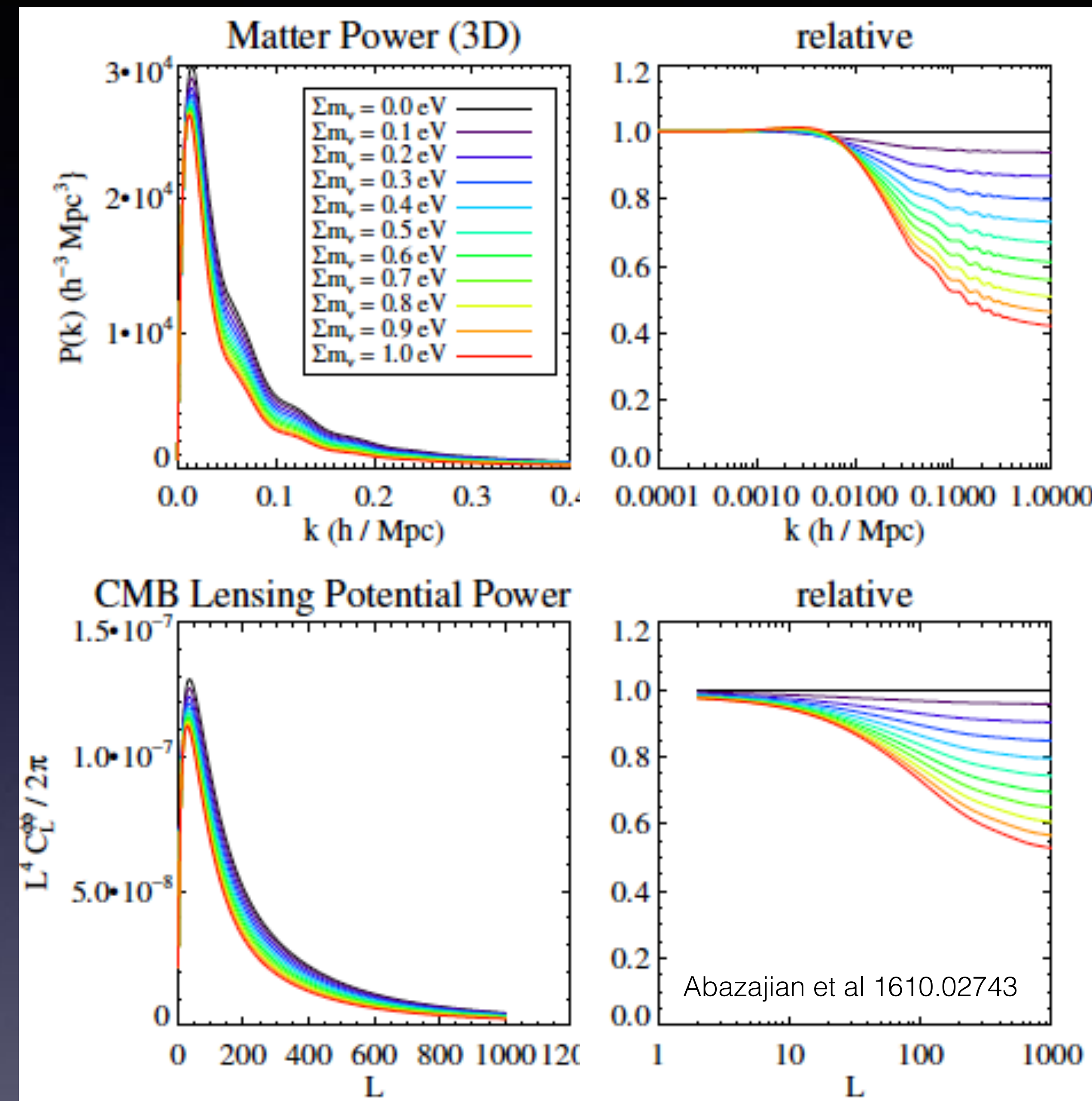


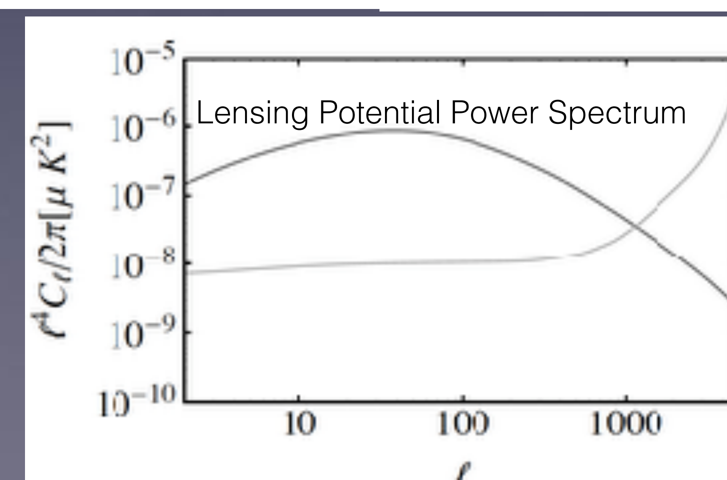
Figure: N. Battaglia, M. Alvarez

Discover How The Universe Works

- Determine the sum of neutrino masses
- Measurements of the matter power spectrum, primarily through the lensing potential power spectrum
- But degeneracy with τ and $\Omega_m h^2$
- Currently $\Sigma m_\nu < 0.17 \text{ eV } (95\%)$

  Couchot et al 1703.10829
- $\Sigma m_\nu \geq 0.058 \text{ eV}$ or $\Sigma m_\nu \geq 0.1 \text{ eV}$ depending on mass hierarchy





Neutrion Mass Constraint

- PICO: $\sigma(\Sigma m_\nu) = 14\ \mathrm{meV}$ using DESI BAO to break $\Omega_m h^2$ degeneracy
- 4σ or 7σ detection
- Determine mass hierarchy, or mass of the lightest neutrino (if mass hierarchy known)
- Measurement is unique to space

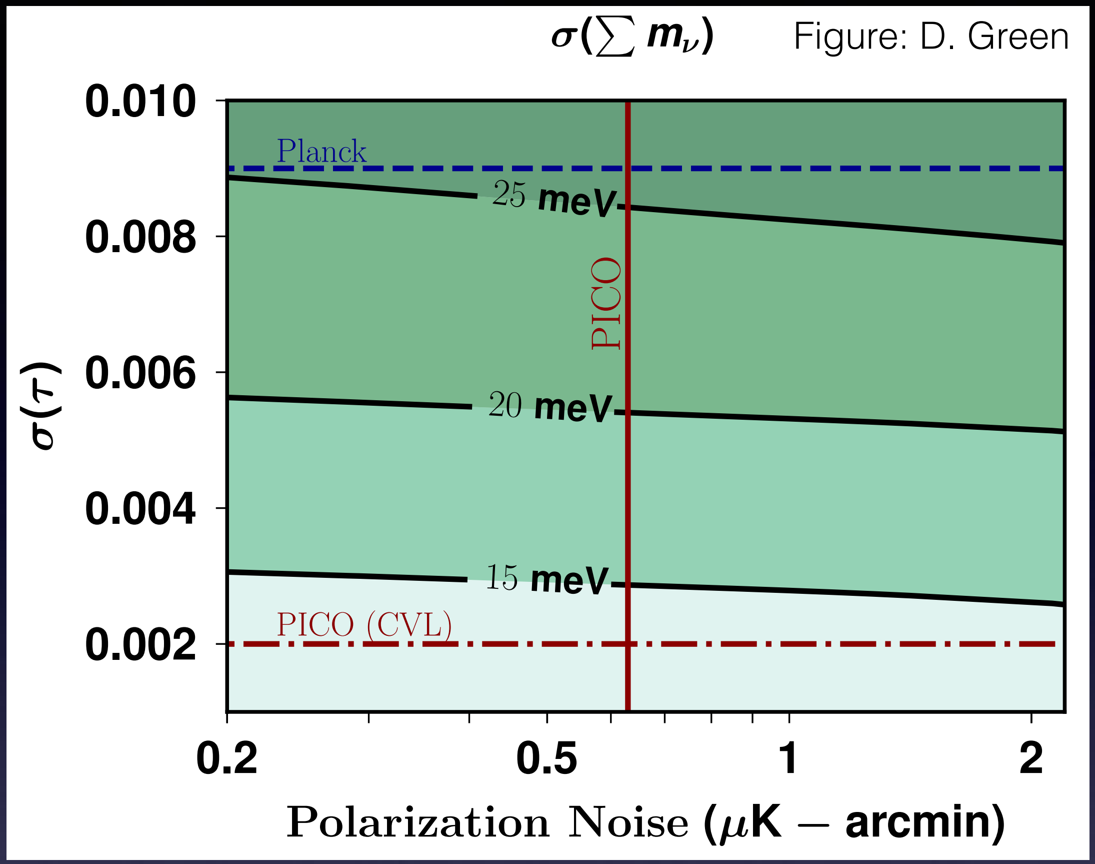


Figure: D. Green

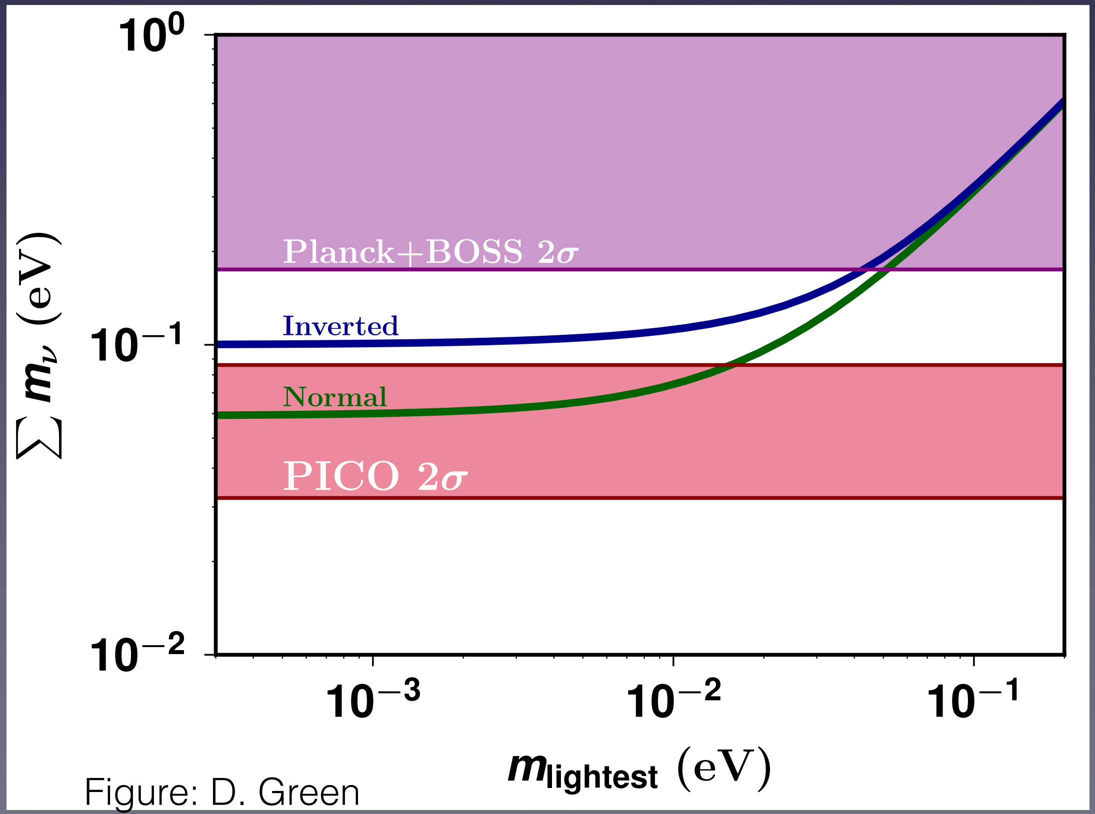


Figure: D. Green

Discover How The Universe Works

- Determine the number of relativistic species of particles in the early Universe
- Standard model:

  $N_{eff} = 3.046$
- *Planck*: $N_{eff} = 3.04 \pm 0.18$
- There could be other species
- The change in N_{eff} depends on the type of particle and its mass

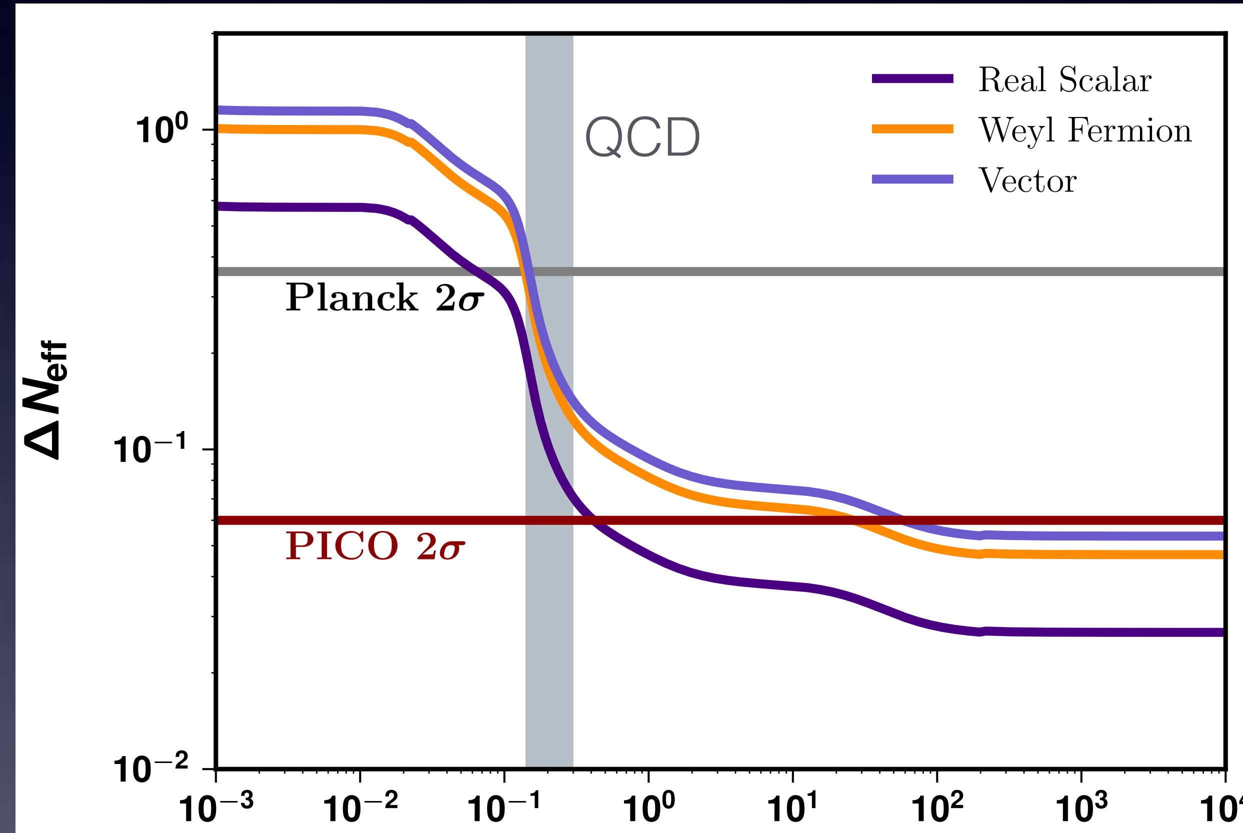


Figure: D. Green

- $\Delta N_{eff} \geq 0.027$ (= 0.027 for single, light scalar)

Constraints on Number of Light Relics

- PICO's constraint comes mostly from the EE power spectrum
- PICO: $\sigma(N_{eff}) = 0.03$
- Extend range of energy to exclude new species by
  - x300 for vector particle
  - x2.5 for scalar particle
  - Cross the QCD phase transition

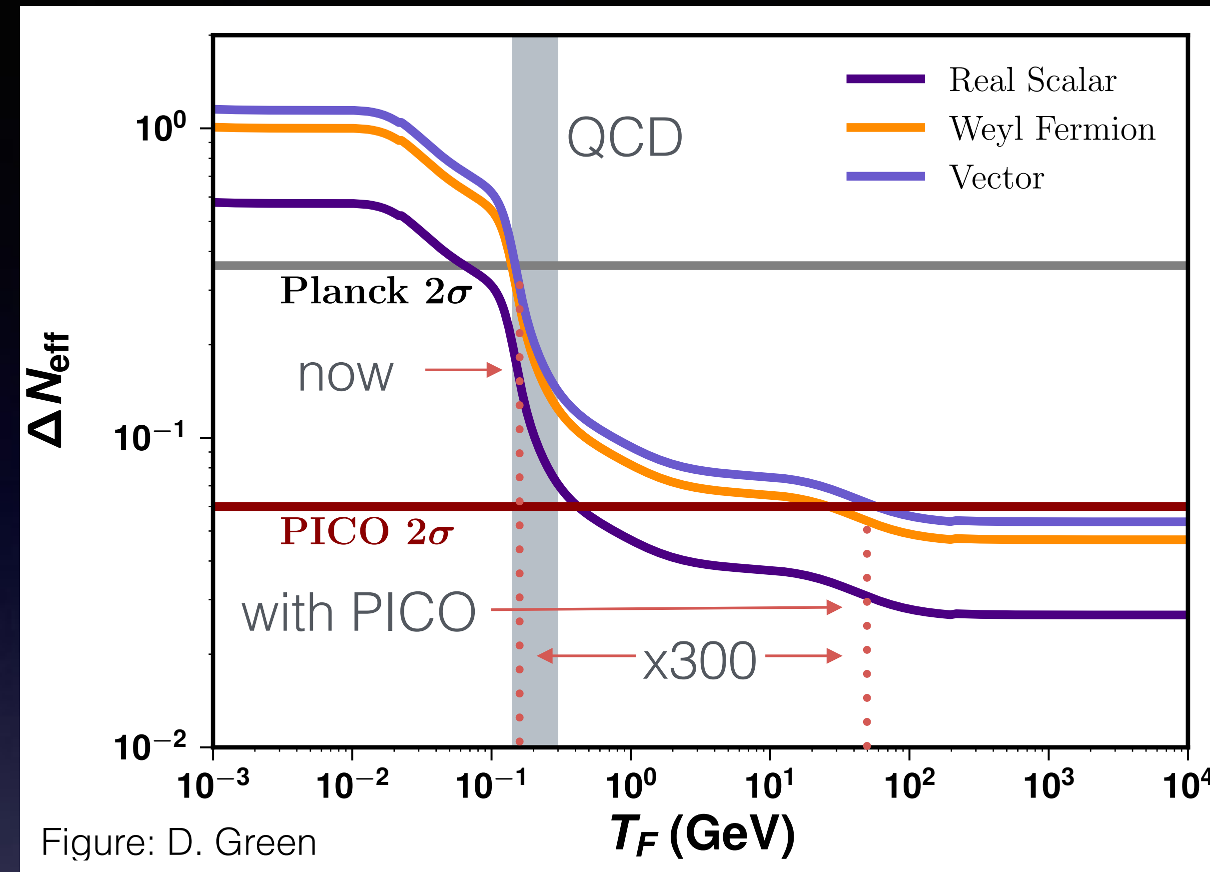


Figure: D. Green

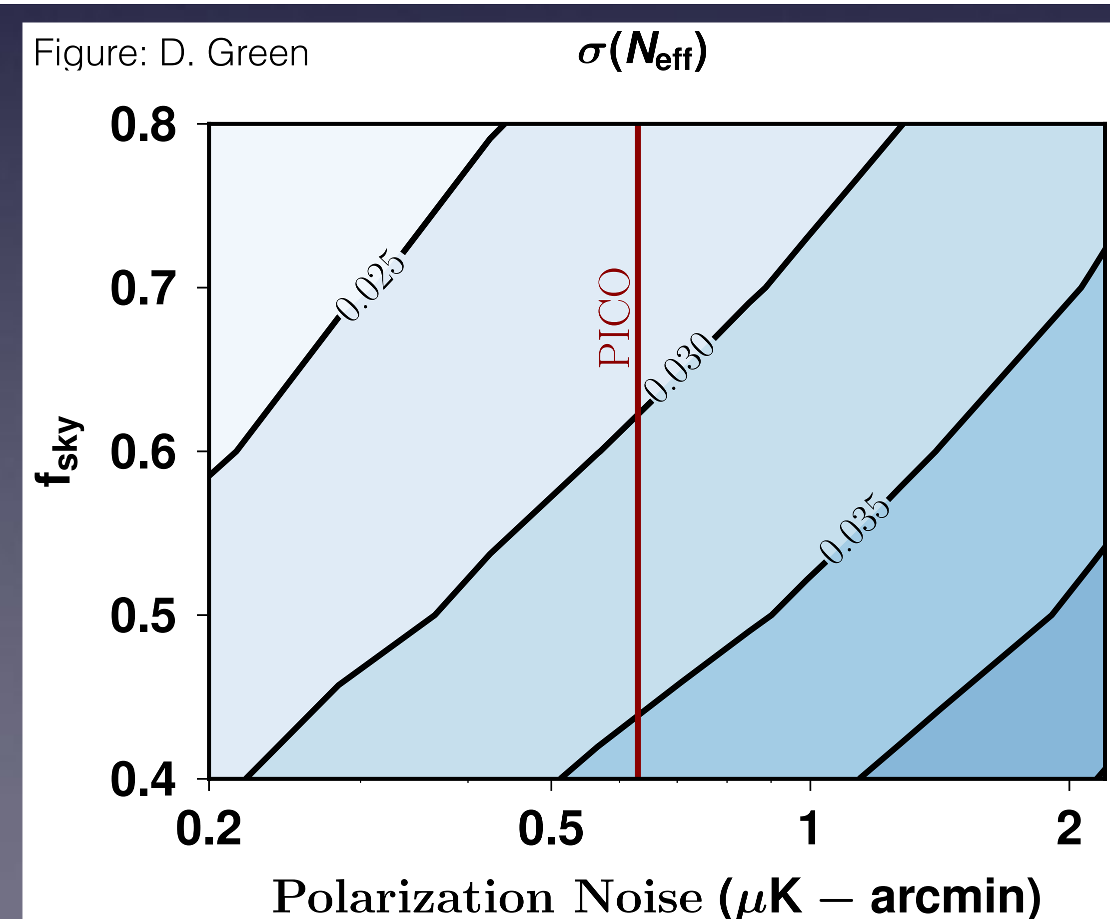
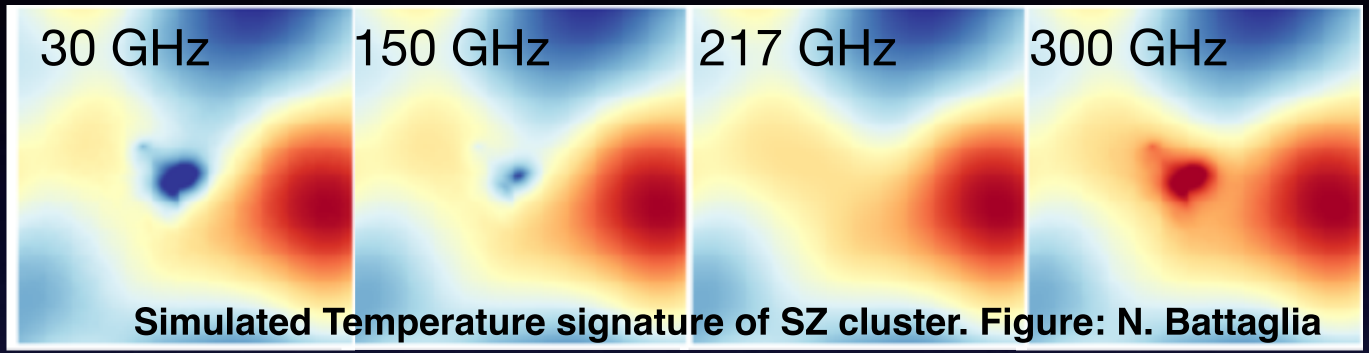


Figure: D. Green

Explore how the Universe Works

- Extract cosmological parameters with 140,000 clusters, 1000 with z>2
  - using thermal SZ
  - Planck: ~2000
  - S3: 20,000



Simulated Temperature signature of SZ cluster. Figure: N. Battaglia

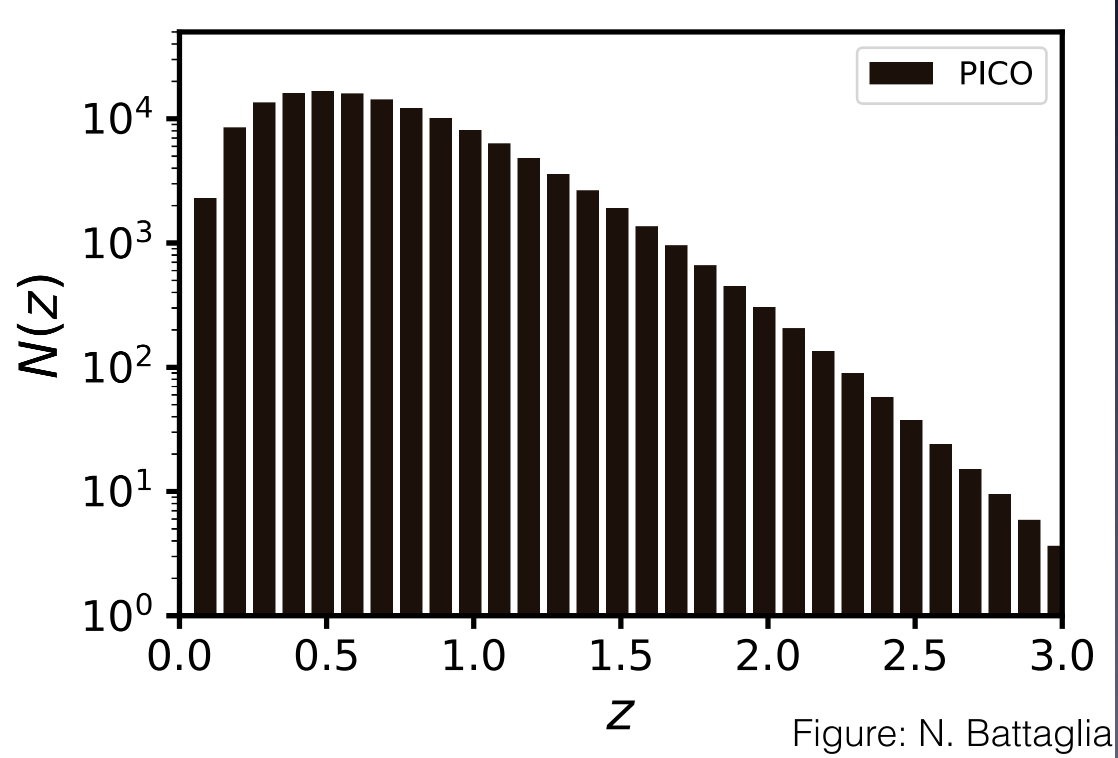


Figure: N. Battaglia

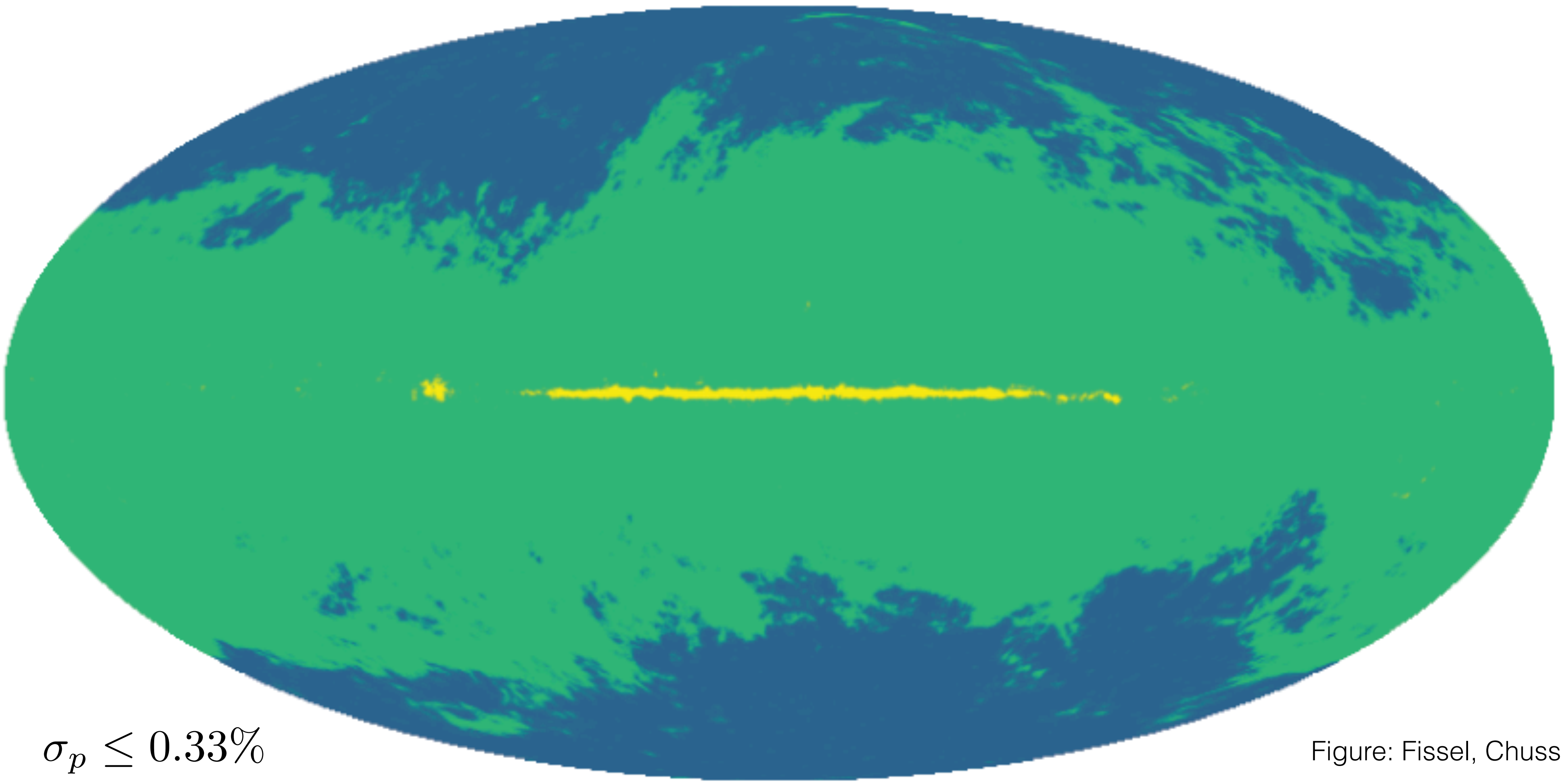
- $\sigma(\Sigma m_\nu) = 9 \ \mathrm{meV}$
  $\sigma(\omega_0) = 0.022$
  $\sigma(\omega_a) = 0.13$

Explore how the Universe Evolved

Map magnetic field for our Entire Galaxy

Planck, 5’ PICO, 1’

PICO, smoothed to 5’



$\sigma_p \leq 0.33\%$

Figure: Fissel, Chuss

Turbulence and Magnetic Field

- Determine the relative roles of turbulence and magnetic field in Milky Way dynamics and star formation efficiency
- Resolve Bfield structure in 8 nearby clouds at core scale (0.1pc), 10 at filament scale (0.5pc).
  - Currently: none.
- Resolve Bfield structure in >2000 galactic clouds with 1pc resolution to compare large scale turbulence and magnetic field.
  - Currently: 14 (Planck)

Nearby Molecular Clouds at < 1 pc resolution

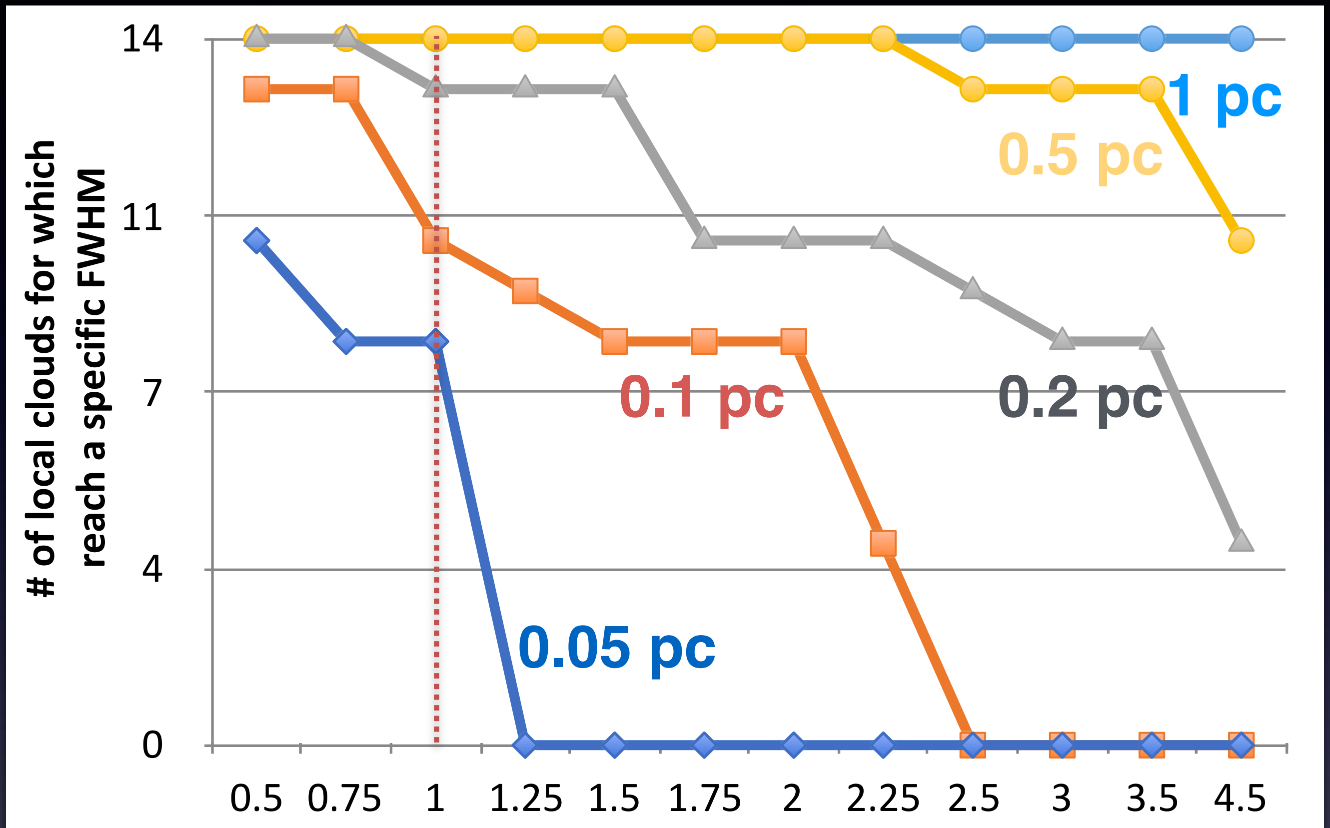


Figure: Fissel, Chuss

Far Molecular Clouds at 1 pc resolution from Bolocam Survey (0.3 of galactic plane)

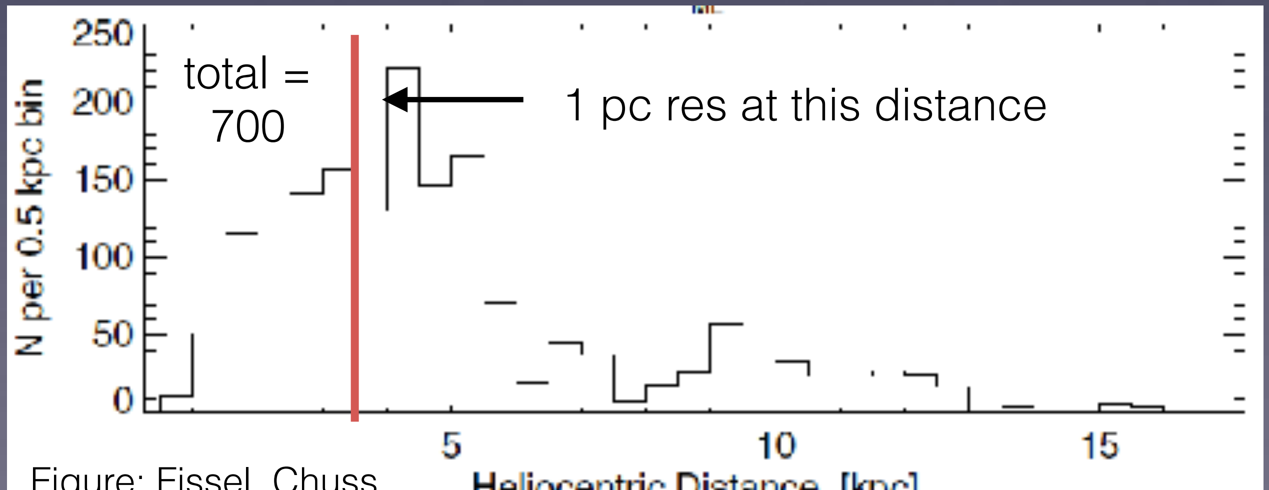
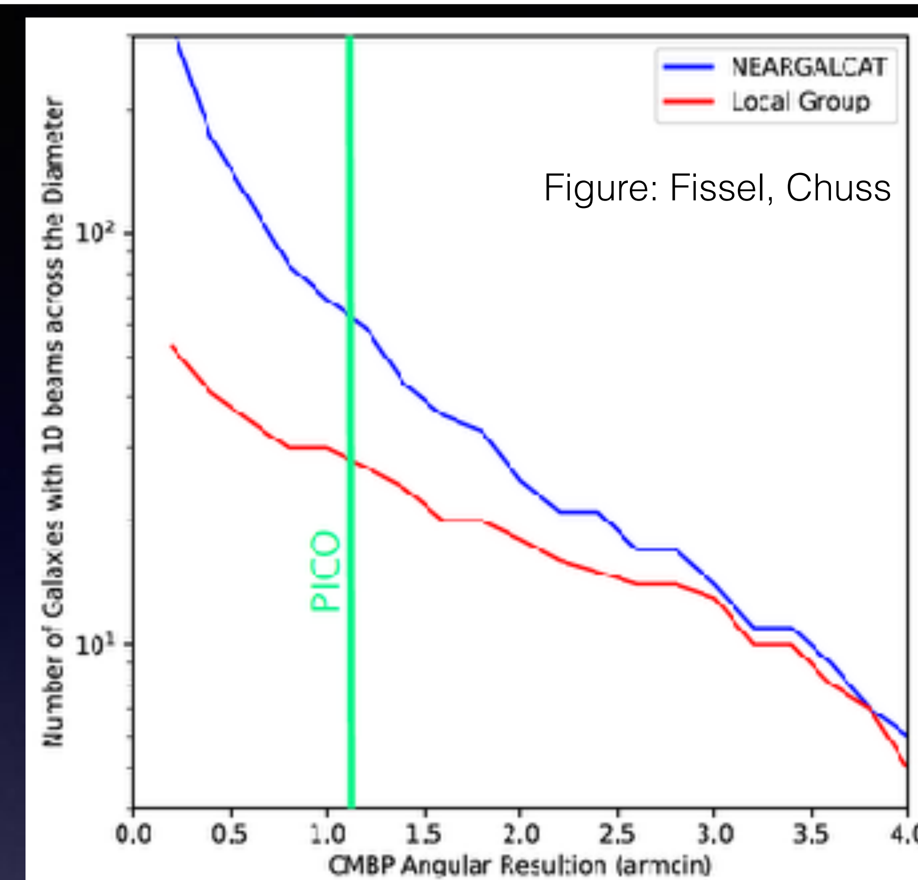
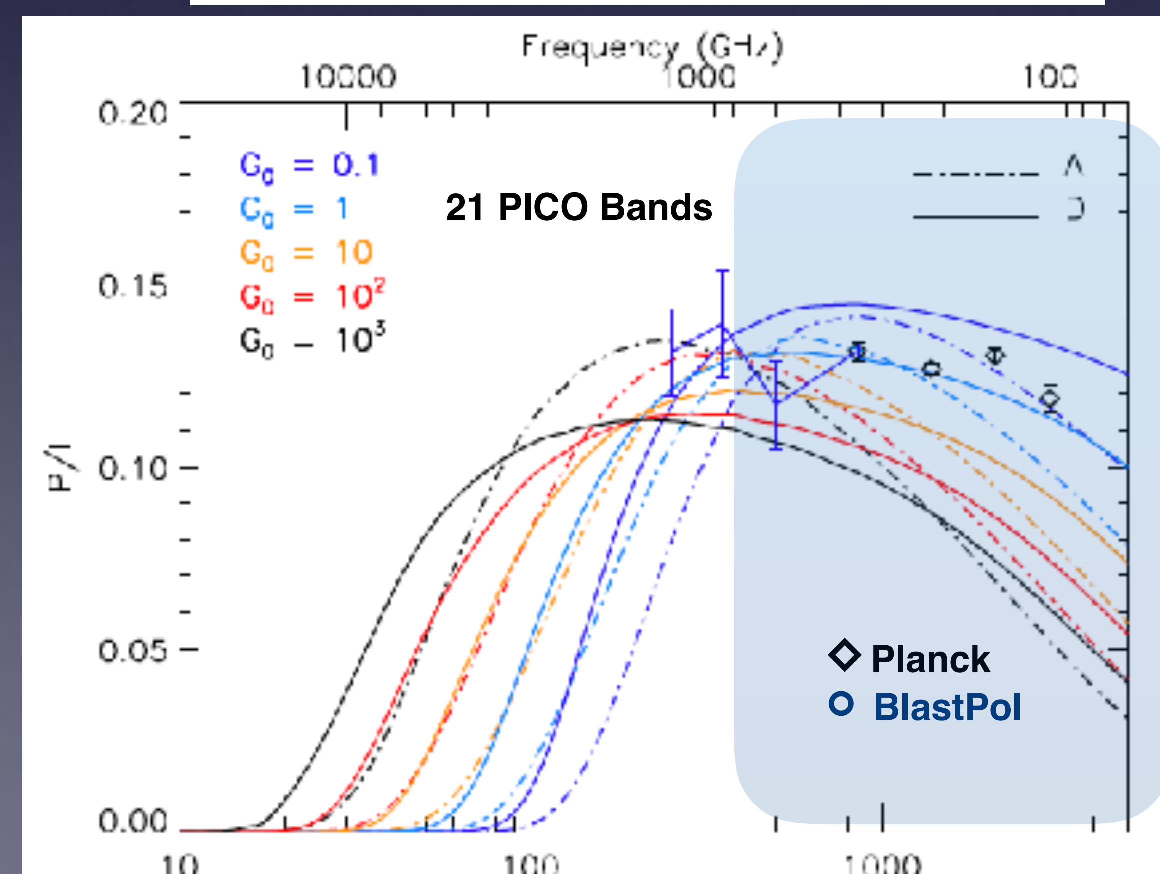


Figure: Fissel, Chuss

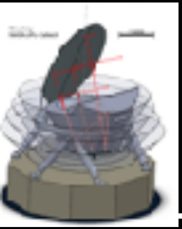
Is the Milky Way Typical? Dust in Milky Way

- Map sub-mm emission from the ISM in 70 nearby galaxies
  - Only handful mapped to date.
- Constrain the shape and composition of interstellar dust grains





Guillet et al. 2018

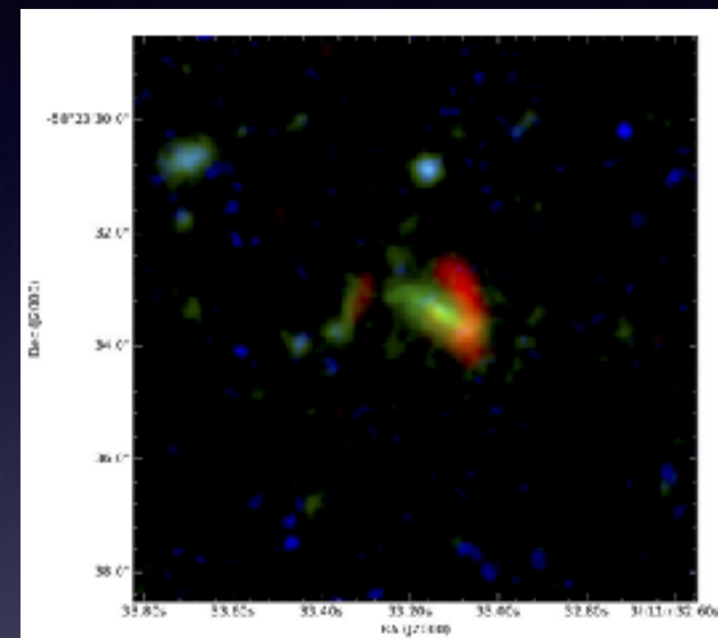


Legacy Science

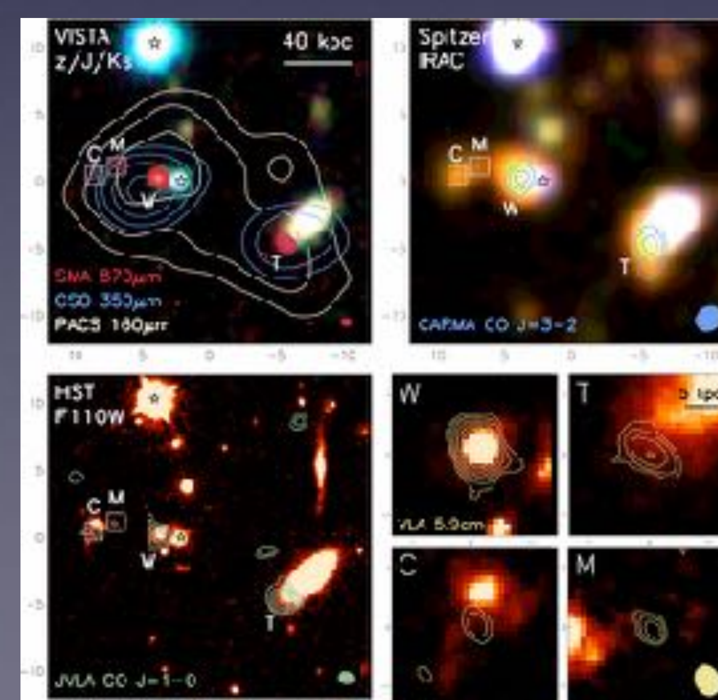
- Discover 3000 highly magnified dusty galaxies at z up to ~4.5;
- Discover 3000 proto-clusters over the sky and extending to high redshift;
- Detect polarization of 4000 radio and FIR-emitting galaxies;
- x10-100 more than known today
- Probe star formation history; determine galaxy and cluster formation and evolution; learn about dark matter substructure; and measure properties of jets in radio-loud sources.

NSF News Release Dec. 6, 2017

Massive primordial galaxies found in 'halo' of dark matter



Marrone et al. 2017; two strongly lensed massive galaxies, z=6.9 (SPT initial detection)



Ivison et al. 2013; proto-cluster core, z=2.4 (Herschel initial detection)

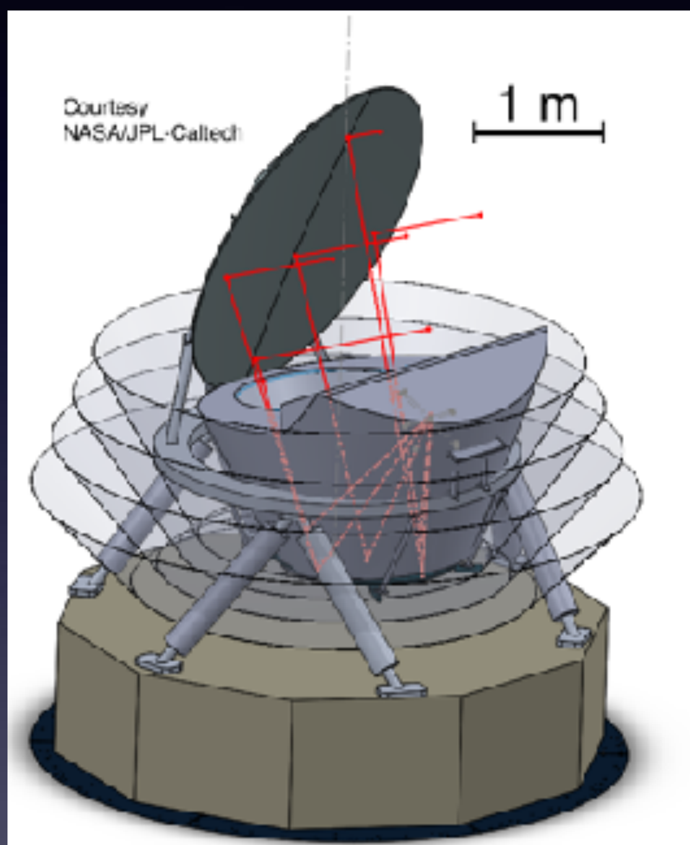
PICO Summary

- Inflation, quantum gravity, particle physics, extragalactic and galactic structure and evolution:
    - All unique goals for the measurements proposed,
    - PICO is the only instrument with the combination of sky coverage, resolution, frequency bands, and sensitivity to achieve all of this science with one platform.
- Initial engineering + costing study complete:
    - Technology implementation is a simple extension of today's technologies; no technological breakthroughs required
    - Mission is a good fit to the cost window

CMB Mission Concepts

Active

PICO



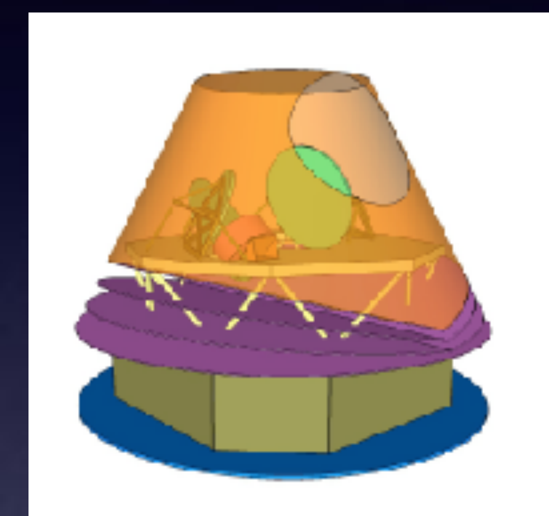
NASA Study

LiteBIRD

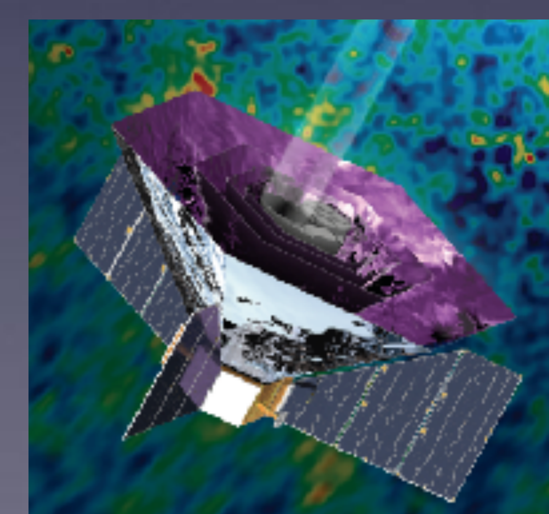
JAXA Phase A

On Hold

CORE (ESA)



PIXIE (NASA)



Proposed

CMB-BHARAT
(India)

Last Slide

- The CMB has more to give
- The decadal panel will soon decide our program for the next decade
- There is intense activity in both orbital and sub-orbital (ground, balloons) activities
- Attend PICO workshop: May 1,2,3, Minneapolis to discuss preparations for the decadal

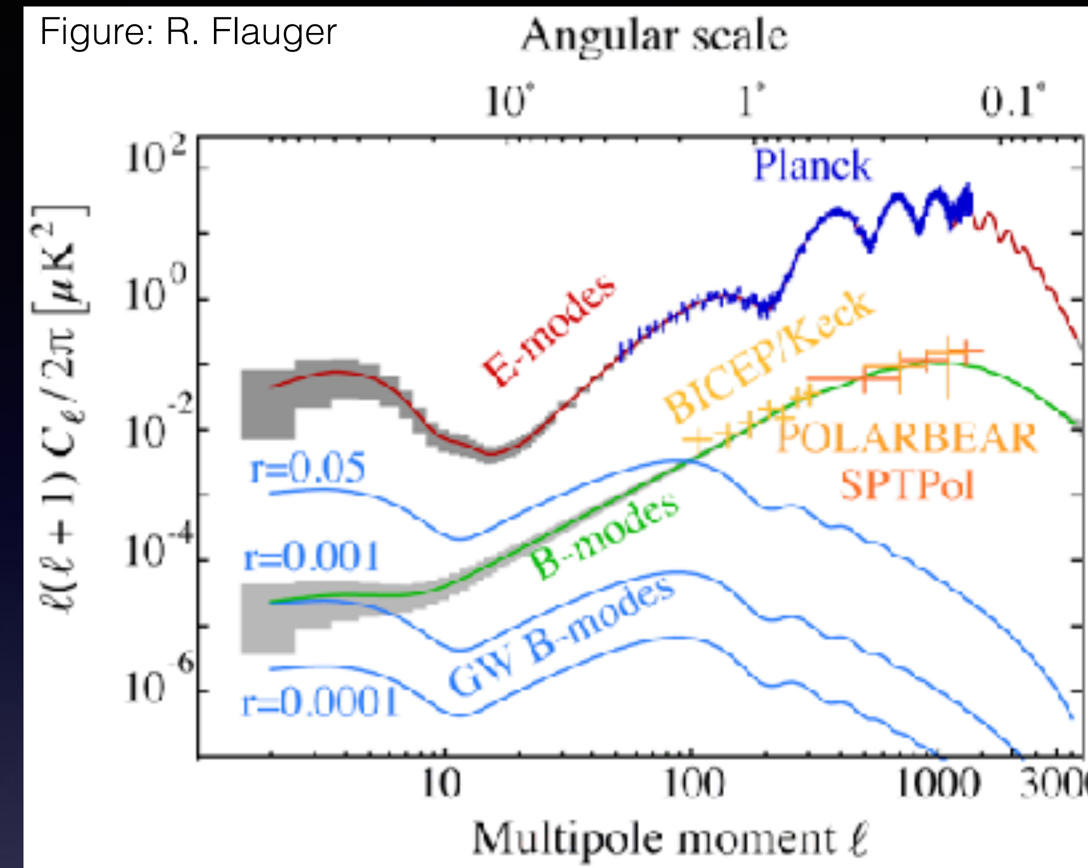
http://pico.umn.edu

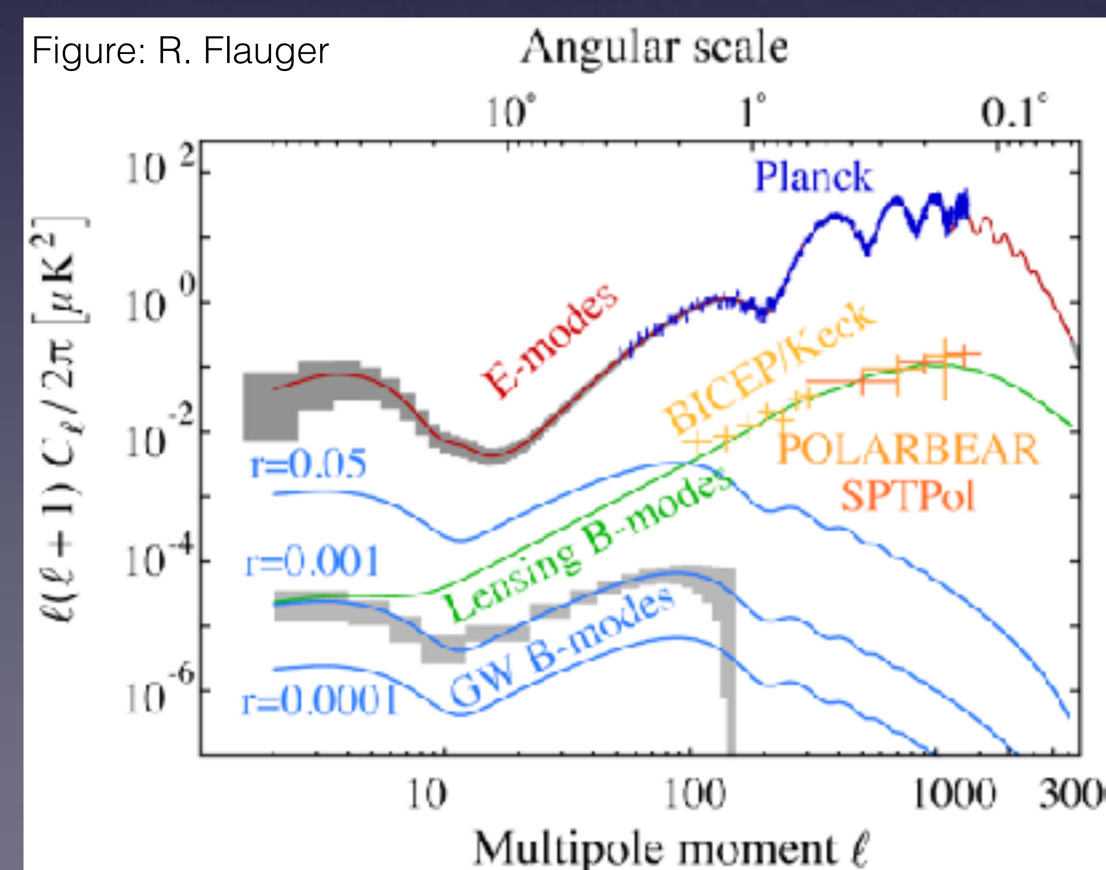
wiki: https://z.umn.edu/cmbprobe

Additional Slides

Simple Foreground Model

- 2 component dust model (a-la Finkbeiner et al)
- Synchrotron with power law frequency dependence
- ℓ dependence consistent with Planck and WMAP
- Includes correlation between dust and synchrotron, consistent with current data
- Model does not include:
    - spatial variation of the spectral index
    - spatial variation of dust temperature
- Foreground separation based on ILC
- 40% of sky (70% of sky reduces $\sigma(r)$)





Delensing

- Iterative delensing post-ILC foreground separation
- Lensing reduction by a factor of ~7: $A_L = 0.14$
- S/N > 10 on lensing potential power spectrum across broad range of ℓ

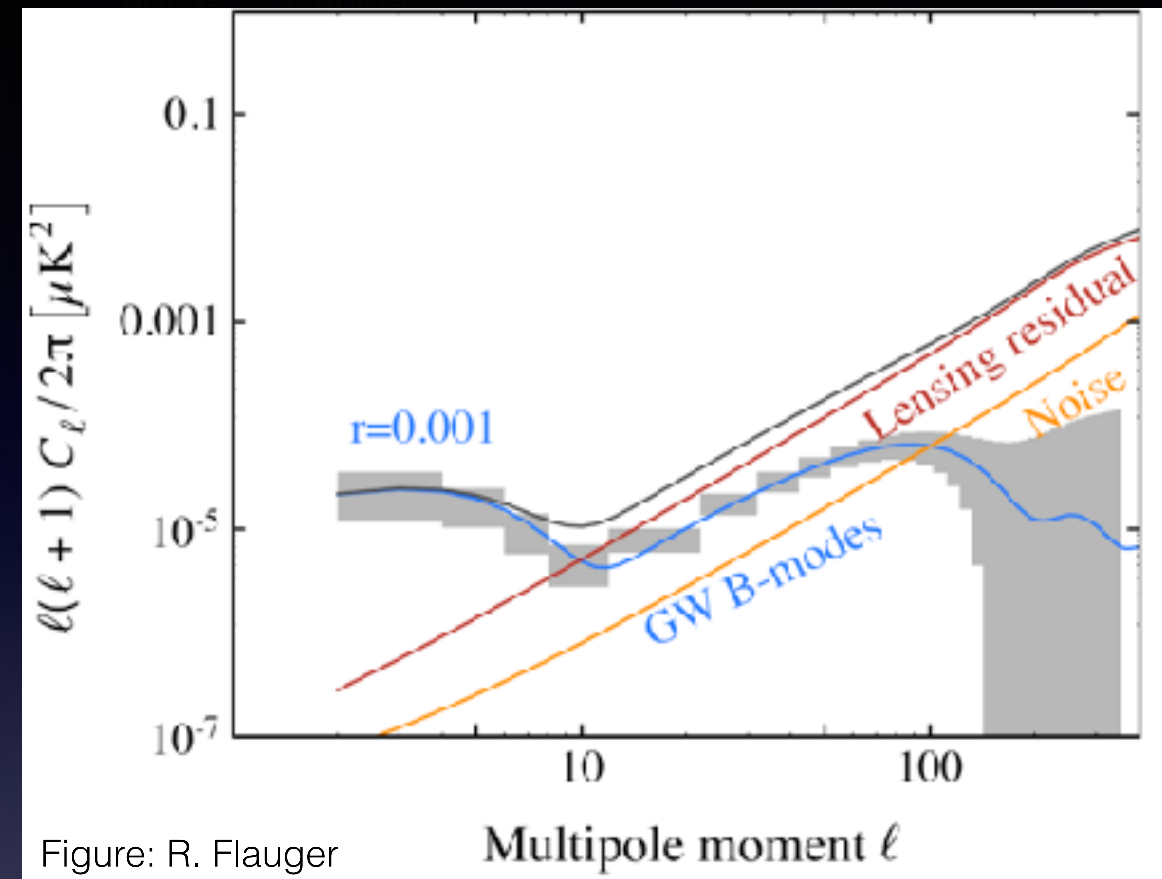
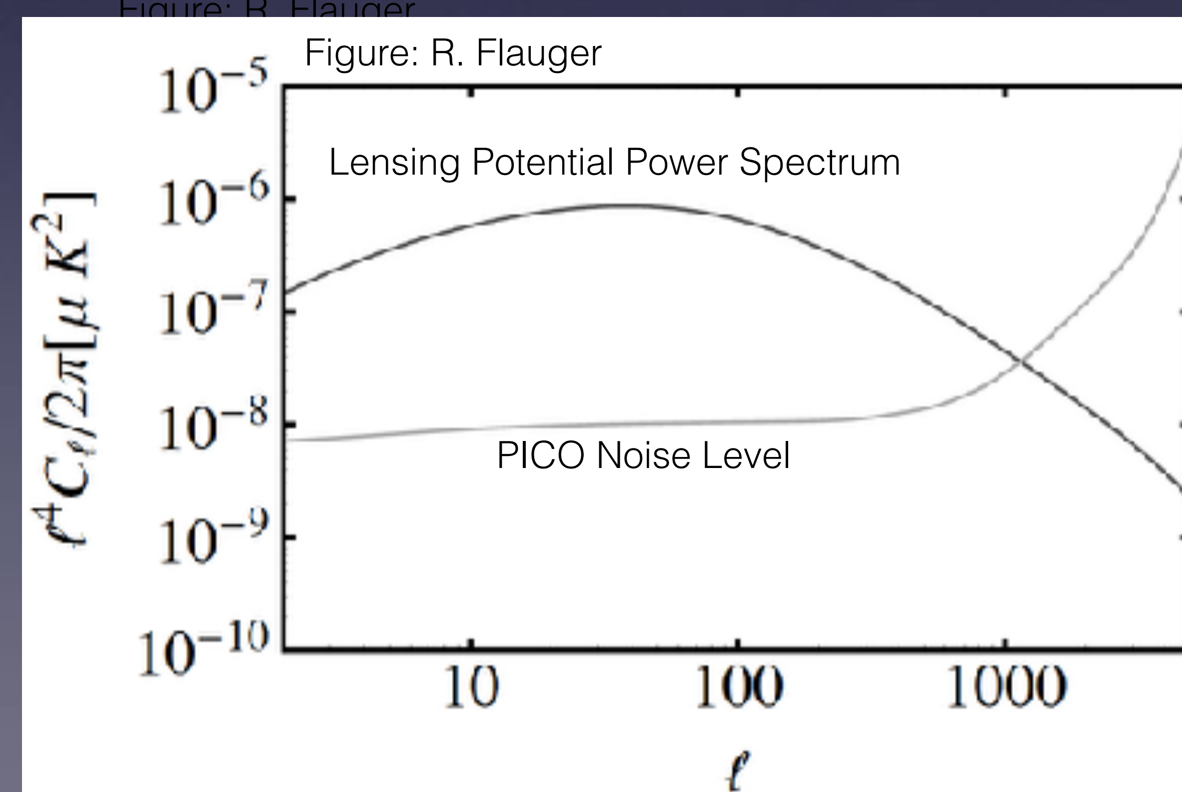
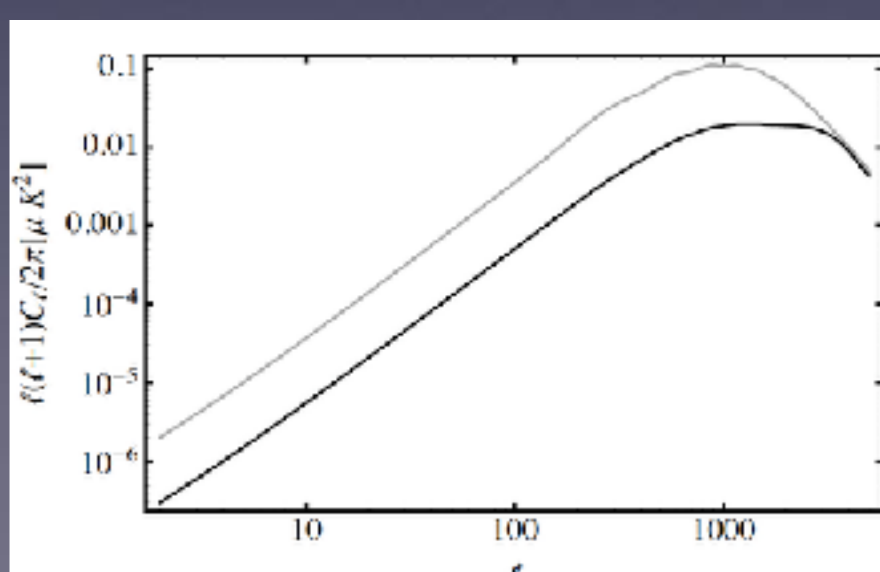


Figure: R. Flauger





What's at Stake

- NASA only invests in technology development or balloon payloads that lead to a future space mission.
- Over the years NASA has spent significant resources in CMB activities (space, balloons, tech development) because there was a mission in the future.
- NASA invests only in what the decadal panel recommends
- Many of us (most? all?) recognize the strengths of a future CMB space mission, the complementarity with sub-orbital, and the value of keeping NASA engaged with CMB

How to Make the Case

- Communicate breadth and importance of science goals
  - Those we own (r, Neff, tau)
  - Those that also appeal to the broader astrophysics community (structure formation and evolution on all scales)
- Present a *compelling* plan to the agencies, specifically both NSF and NASA
- Present a *coherent* plan - how all components work together, ground, balloons, space

S4 Neutrino Mass Constraints

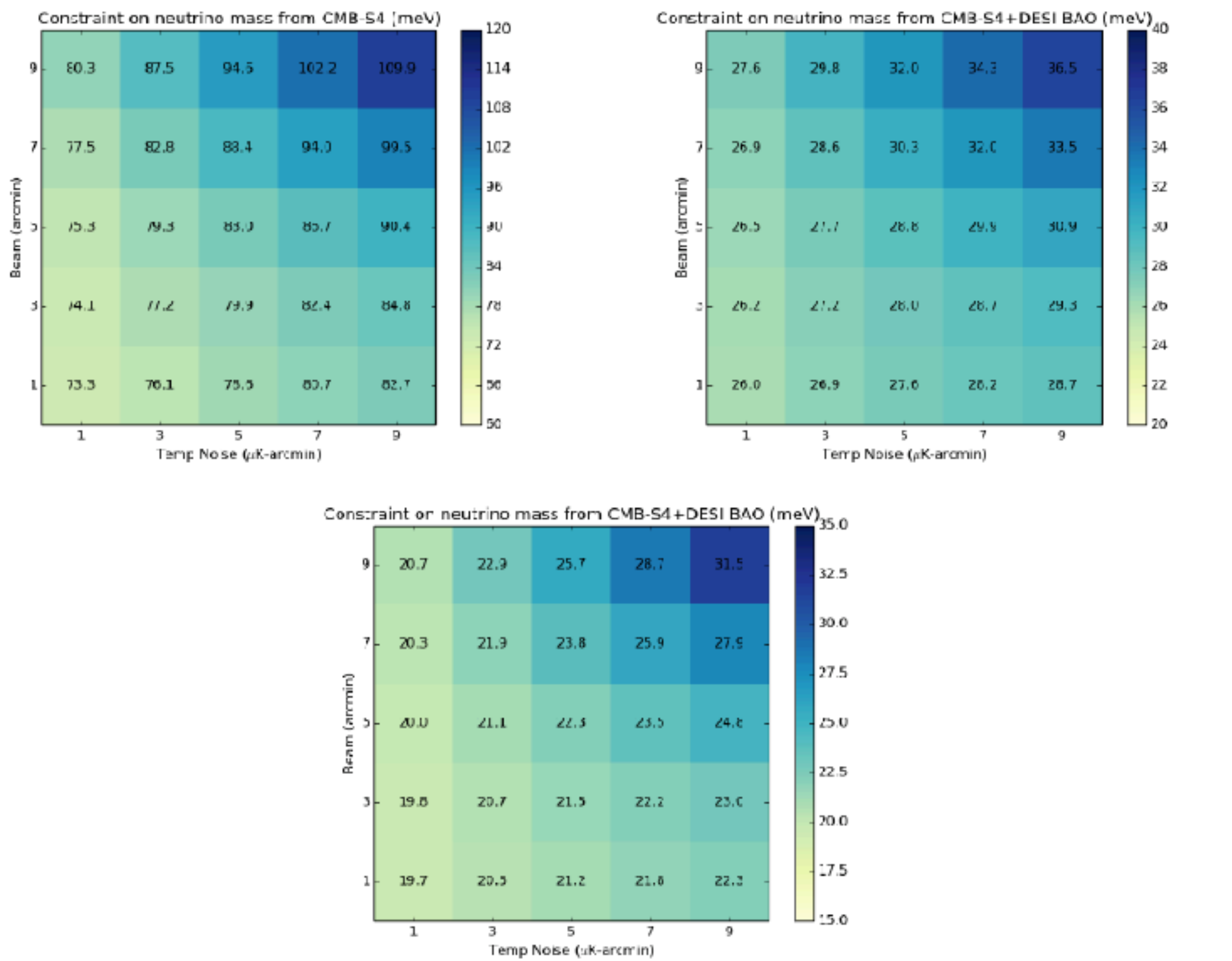


Figure 15. *Forecasts for $\sigma(\sum m_\nu)$ assuming $\Lambda CDM + \sum m_\nu$. All three figures vary beam size in arcmin and effective detector noise in μK-arcmin. Top Left: CMB-S4 alone with an external prior on $\tau = 0.06 \pm 0.01$. Top Right: CMB-S4 plus DESI BAO with an external prior on $\tau = 0.06 \pm 0.01$. Bottom: Forecasts assuming a prior $\tau = 0.06 \pm 0.006$, corresponding to the Planck Blue Book expected sensitivity.*

Figure: D.

"When we began our study we sought to answer five fundamental implementation questions:

- 1) can foregrounds be measured and subtracted to a sufficiently low level?;
- 2) can systematic errors be controlled?;
- 3) can we develop optics with sufficiently large throughput, low polarization, and frequency coverage from 30 to 300 GHz?;
- 4) is there a technical path to realizing the sensitivity and systematic error requirements?; and
- 5) what are the specific mission architecture parameters, including cost?

Detailed answers to these questions are contained in this report. Currently in Phase 2, we are exploring a mission concept targeting a ~2m aperture, in between the two options described in the current report with a small (~30 cm) and large (~4m) missions."

astroph/0906.1188

Study of the

Experimental Probe of Inflationary Cosmology - Intermediate Mission

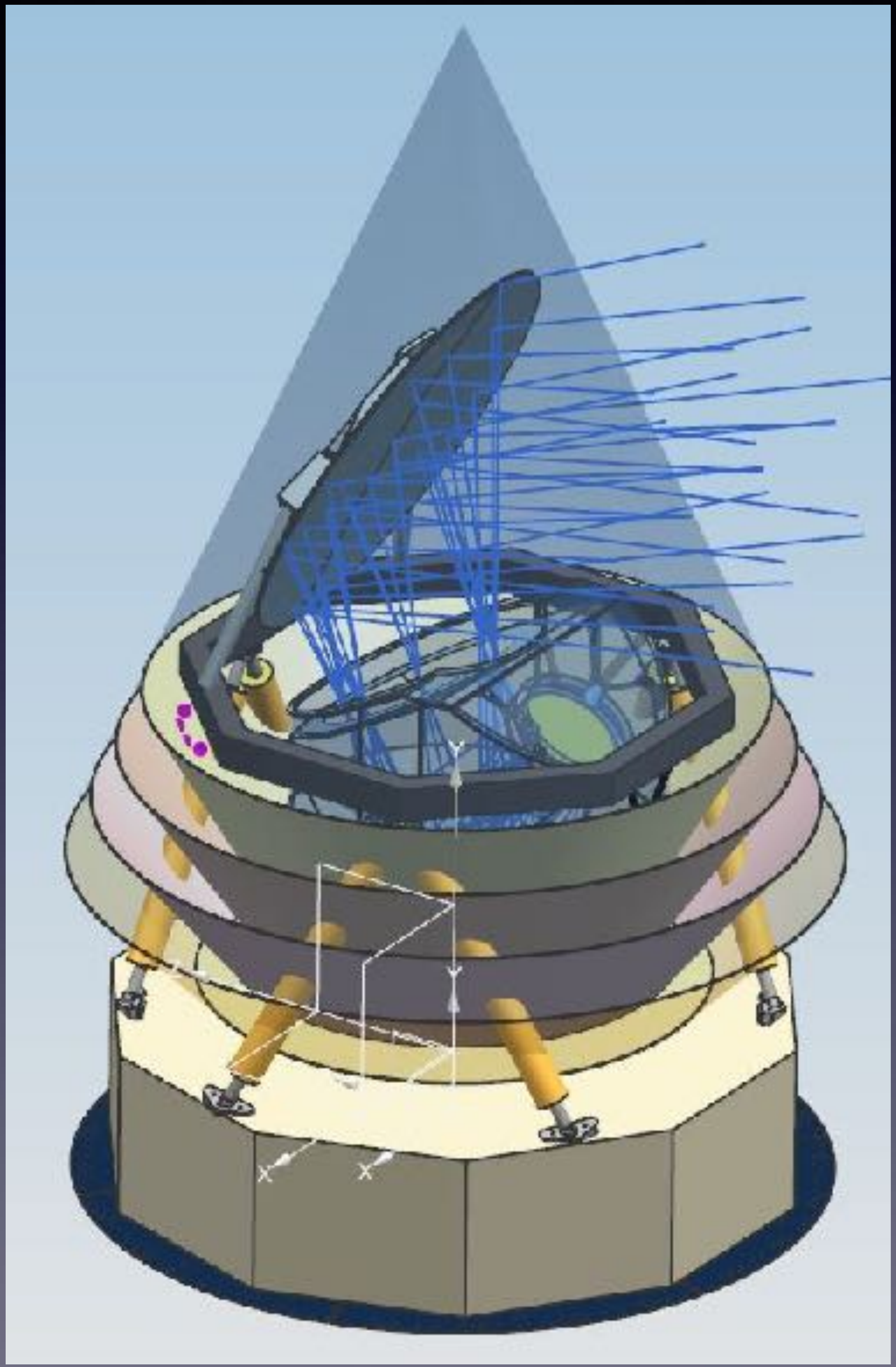
for NASA's Einstein Inflation Probe

4 June 2009

Bock et al. 2009
arXiv:0906.1188

The PICO Imager

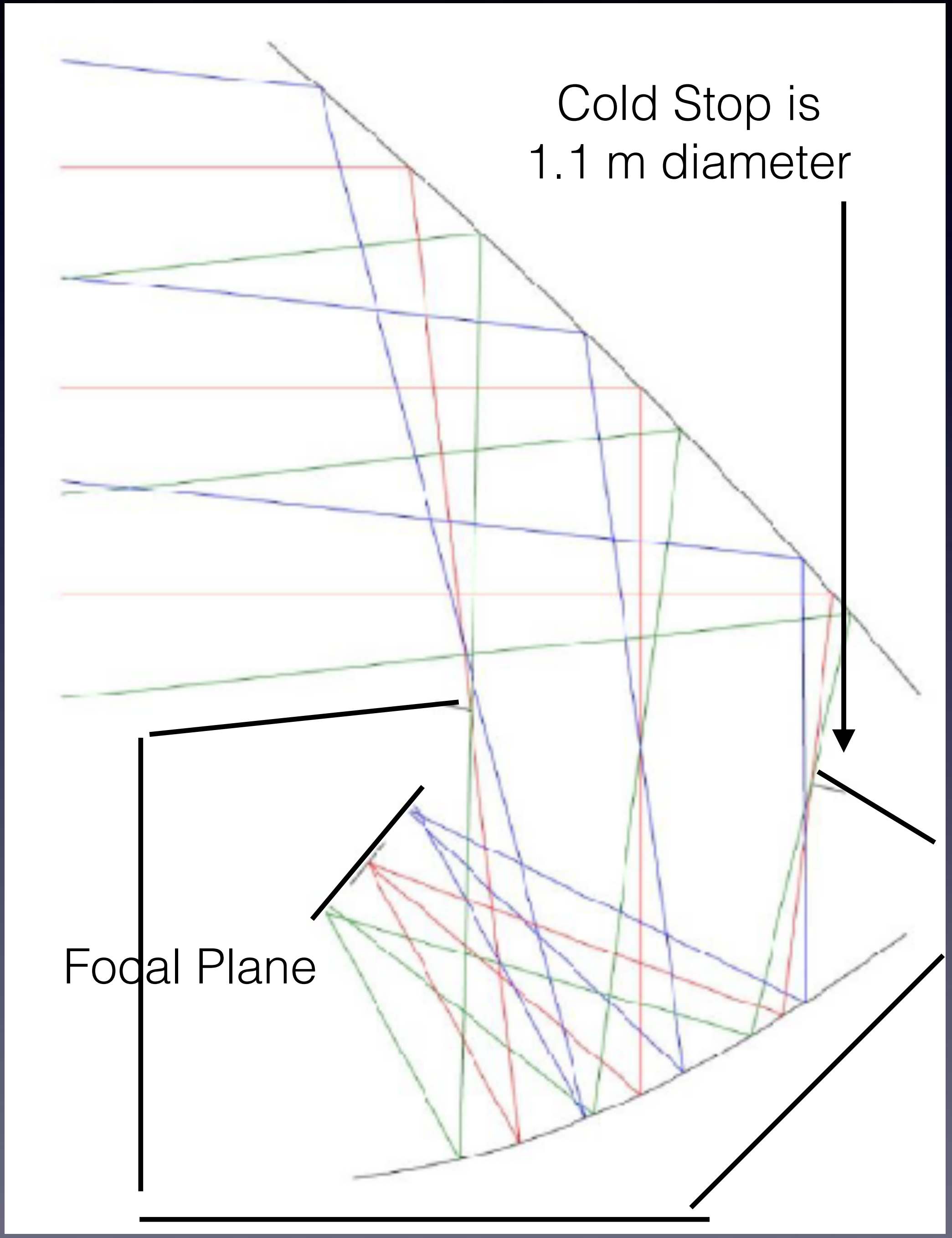
- 1.4 m aperture, open Dragone telescope
- 21 frequency bands between 21 and 799 GHz
- 7.6’ resolution at 155 GHz, 1’ at 799 GHz
- 12,060 detectors
  - Three-color TES arrays for 21-462 GHz; Single color PSBs for 555 - 799 GHz
- Multiplexed readouts



4.5 m

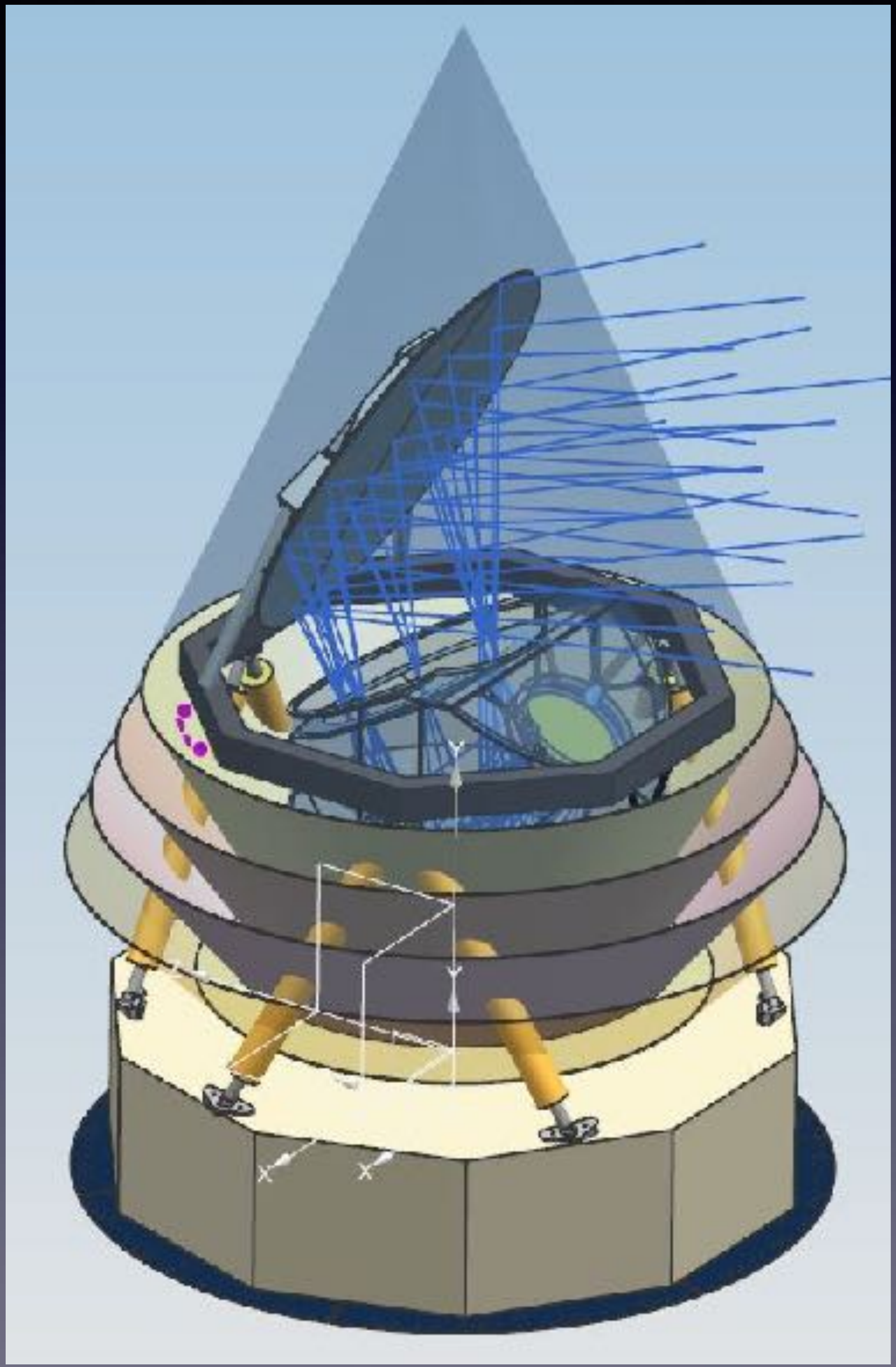
Optics + Cooling

- Open Dragone Telescope
  - No direct view to sky
  - No three-reflection sidelobe
  - Cold stop (without cooling primary mirror)
- Design includes enhancement to DLFOV through coma correction
- Primary mirror at ~40 K;
- Stop + secondary actively cooled to ~6 K;
- Focal plane @ 0.1 K with cADR



Mission

- L2
- 4 years
- Mass, Power - TBD
- alpha/beta: 30, 60
- spin: 1 RPM
- Data: 3.2 TBits/day
- polarization noise = 0.7 uK*arcmin



PICO and You

- PICO is an open collaboration
- wiki: z.umn.edu/cmbprobe
- list: cmbprobe@lists.physics.umn.edu
- You are invited to contribute
- Keeping NASA involved is good for all of us and it is excellent for CMB science.

Additional Slides

News from CORE

- The non-selection of CORE for the ESA M5 call was due to the lack of a major partner for what was perceived as an ambitious mission with a cost that could exceed the cost cap available for M5.

- The CORE consortium has been encouraged to look for a major international partner to propose/implement such a mission.

- Discussions of CORE proposal leaders with colleagues in India, initiated in the summer of 2017, identified a convergence of scientific interests.

- A proposal for an Indian CMB mission, to be implemented in collaboration with international partners and launched in ~2029, was proposed to ISRO on Apr. 16, 2018 by a consortium of ~90 scientists, in answer to an AO from ISRO issued Feb. 3, 2018.

- In Europe, participation to such a mission could be envisaged either through ESA (e.g. through a MO, or through a proposal in answer to the next M-class call, expected ~2019), or through contribution involving national agencies (e.g. CNES, ASI, …).

CMB-Bharat

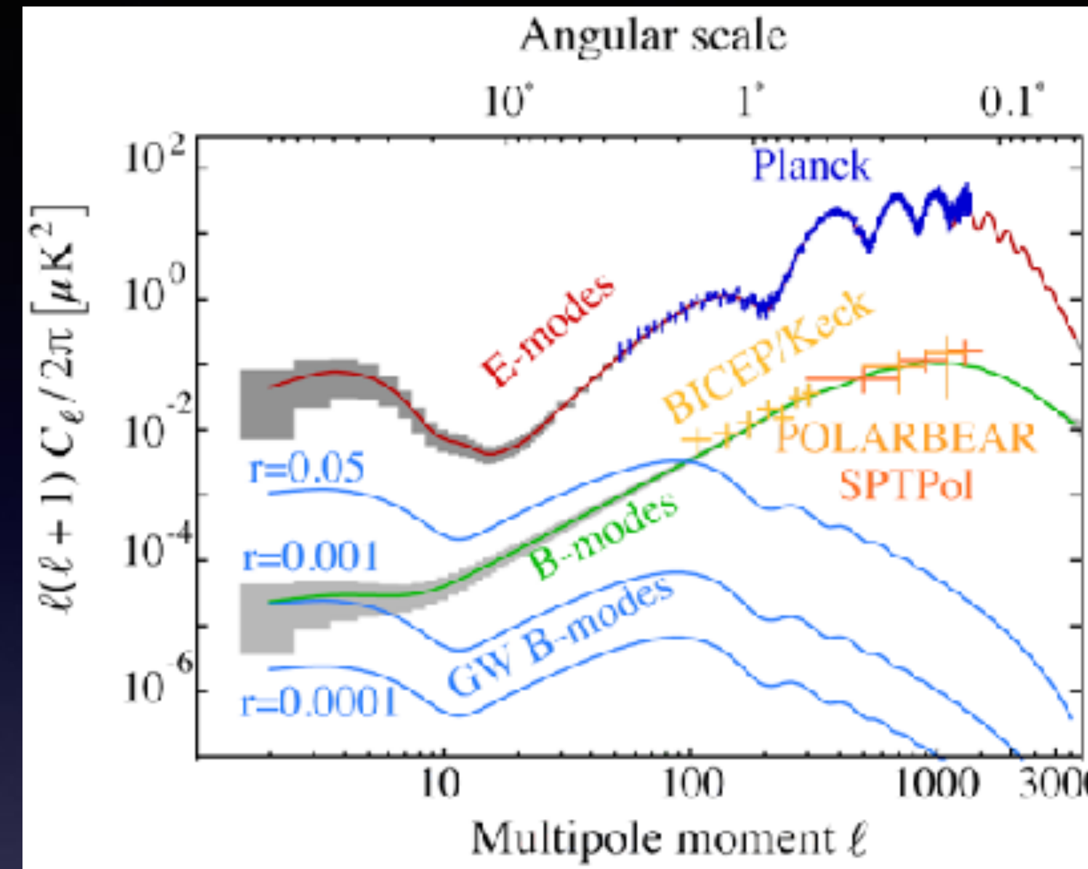
- The mission proposed to ISRO, CMB-Bharat, is conceptually close to CORE or PICO in terms of performance and implementation
  - 1.2-1.5m telescope passively cooled to 40-100 K
  - a focal plane array of a few thousands of detectors distributed among about ~20 frequency bands in the 30-900 GHz range
  - Final CMB sensitivity after component separation of ~1-2 uK.arcmin and few arcminute angular resolution.

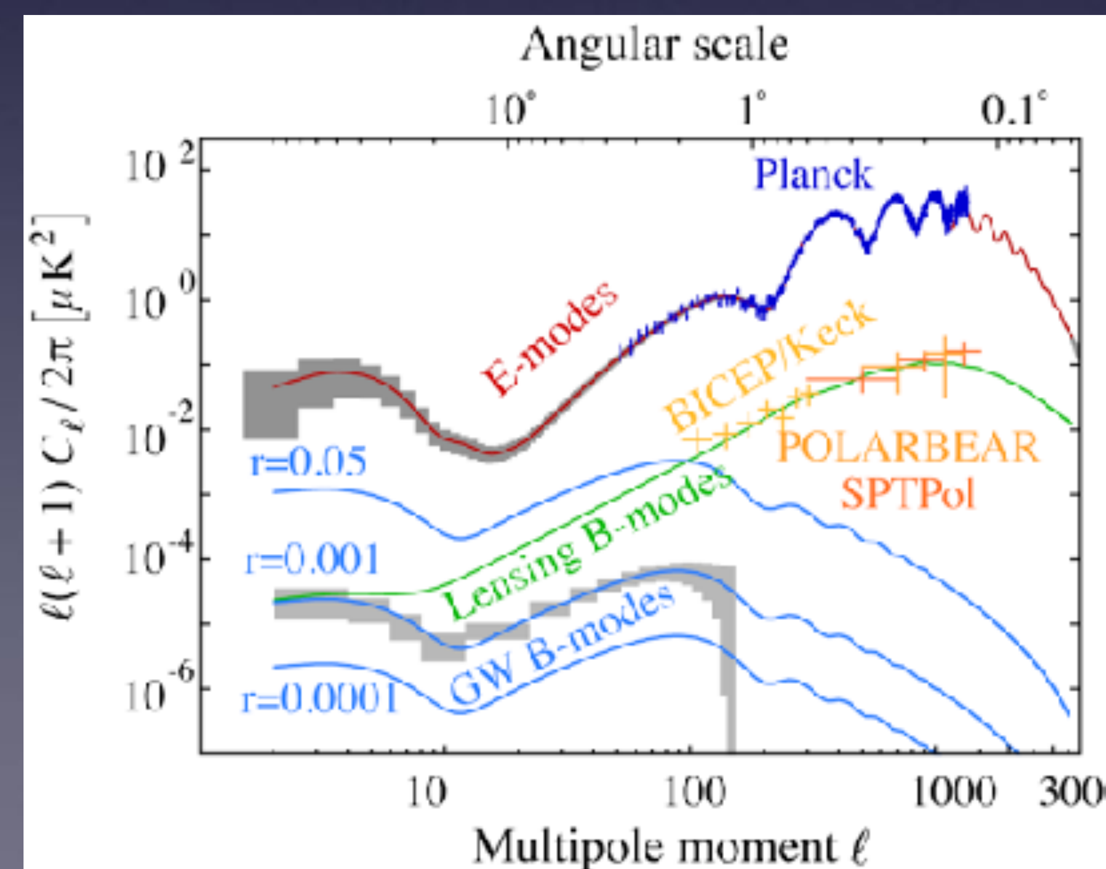
- Two interesting options, to be further assessed in a study phase, are proposed
  - A second instrument, a small FTS similar to a reduced version of PIXIE, for absolute calibration, zero-level of intensity maps, and observing large-scale polarization in many frequency bands. With sensitivity >100 times better than COBE/FIRAS, this instrument can also do CMB spectral distortion science, and is a pathfinder for a future very ambitious CMB spectral distortions space mission.
  - After 4 years of nominal full-sky observations in survey mode, a mission extension of ~2 years could be dedicated to pointed observations of small regions of sky for deep surveys. In observatory mode, targets could be selected through calls open to the wider scientific community.

PICO and Sub-Orbital CMB Efforts

PICO's capabilities are not matched by any other foreseeable experiment

- Full sky coverage with ~4' resolution (and the same depth S4 has on 5% of the sky)
- Access to the entire range of angular scales of the B-mode signal, including the largest, while maintaining the capability to delens
-





PICO and Sub-Orbital CMB Efforts

- Unmatched/unmatcheable frequency coverage
    - Galactic foregrounds are known to overwhelm the cosmological B-mode signal
    - Signals are at the nano-K level: even low level of residual foregrounds can bias the measurement
- Space gives the most systematic-error-robust platform
    - Signals are at the nano-K level