Welcome to the PICO Workshop

- WIFI
  - use the ‘eduroam’ network
  - if you don’t have your account, look at the back of your name tag
  - Use ‘username@umn.edu' + provided password.
- Dinners (both walking distance, please sign dinner sheet)
  - today 6:30 pm Cafe421 (Italian/American, white tablecloths)
  - tomorrow 6:30 pm Bona (Vietnamese, no tablecloths)
- Poster session tomorrow
- Please upload your talks
- Please stay on time
- Discussions: leave enough time for audience participation
- If you are not on the microphone - webexers can not hear you

PICO-
Context, Design, Capabilities, Workshop

Shaul Hanany

PICO Workshop, May 2018

2010 Decadal Panel:
New space Activities - Medium Projects

- CMB listed as a strategic program (priority 2, after exoplanet searches)
- Sub-orbital program to continue search for the B-mode signal

EPIC - IM

- 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.”
- To paraphrase: wait and see what we learn from Planck

2010 Astrophysics Decadal Panel Recommendations

- Flagship: WFIRST (>$1B)
- Explorer
  - Missions of Opportunity $65M
  - Small Explorer ~$150M
  - Explorer $250M
- No Probe-class astrophysics missions with $250 - $1000M
- Planetary Science Decadal Survey
  - New Frontier-class missions: <=$1000M
  - Juno (2011); OSIRIX-REx (2016); now competing next

EPIC - IM

NASA's Preparations 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)

Study Outcomes

- 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

PICO Study

- Phase 1: decide on science goals and overall design drivers
  - Spectrometer, Imager, or both; resolution, survey type, frequency coverage, depth
- Phase 2:
  - instrument + mission design and costing;
  - assess performance
- Phase 3: write report
- Submit report by end of December 2018

Spectrometer, Imager, or both?

- Which instrument(s) to implement?
  - Considered superPIXIE = x10 PIXIE sensitivity
  - Considered combined PIXIE + Imager
- EC conclusion: there is strong case for two separate missions, one devoted to spectroscopy and another to imaging (or a more expensive single mission)
- A combined mission within $1B cap will weaken both instruments
- Design and costing exercise will concentrate on an imager.
- Paradigm: design the most scientifically compelling mission within the cost cap

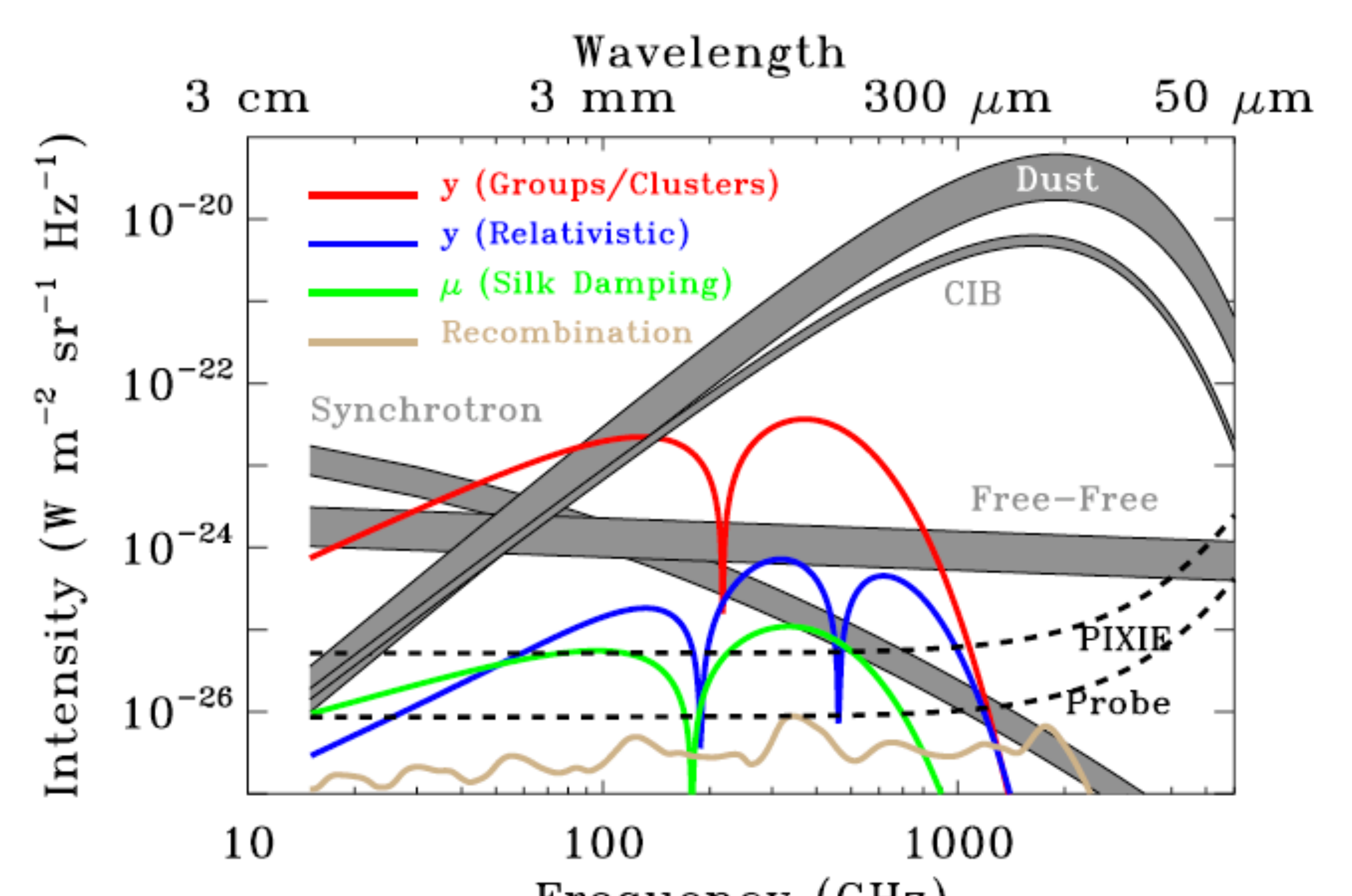
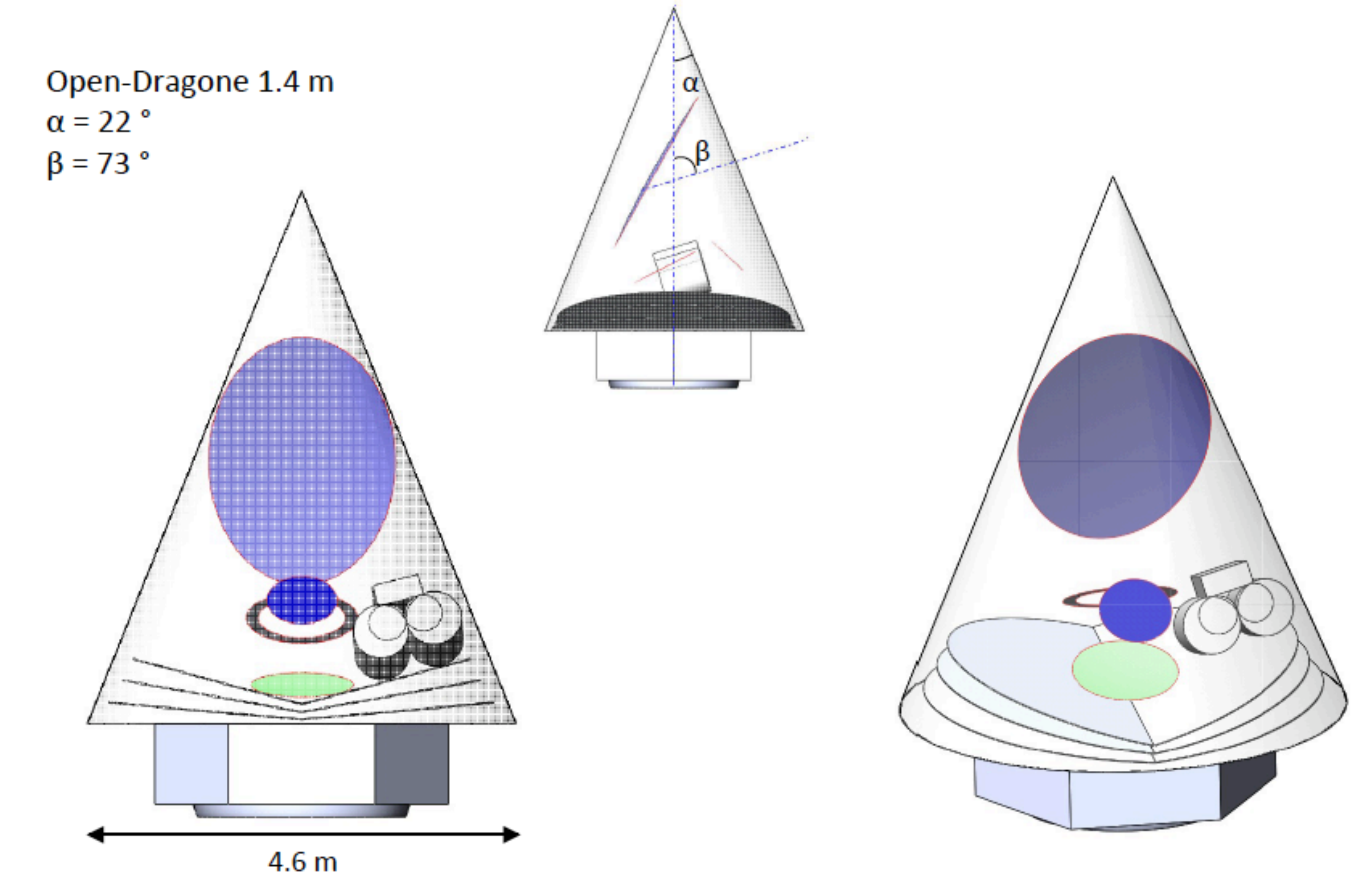


Figure from: A. Kogut

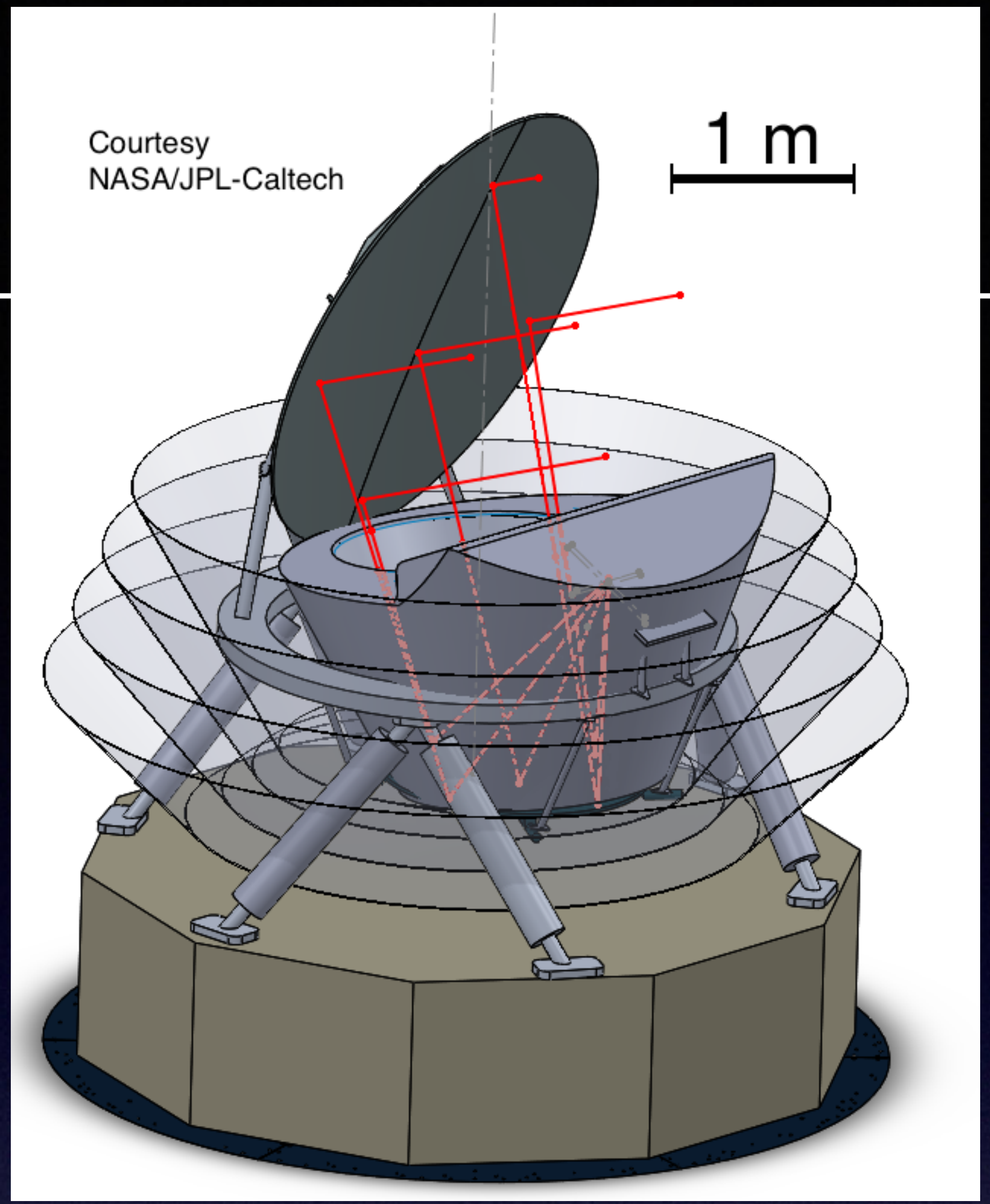


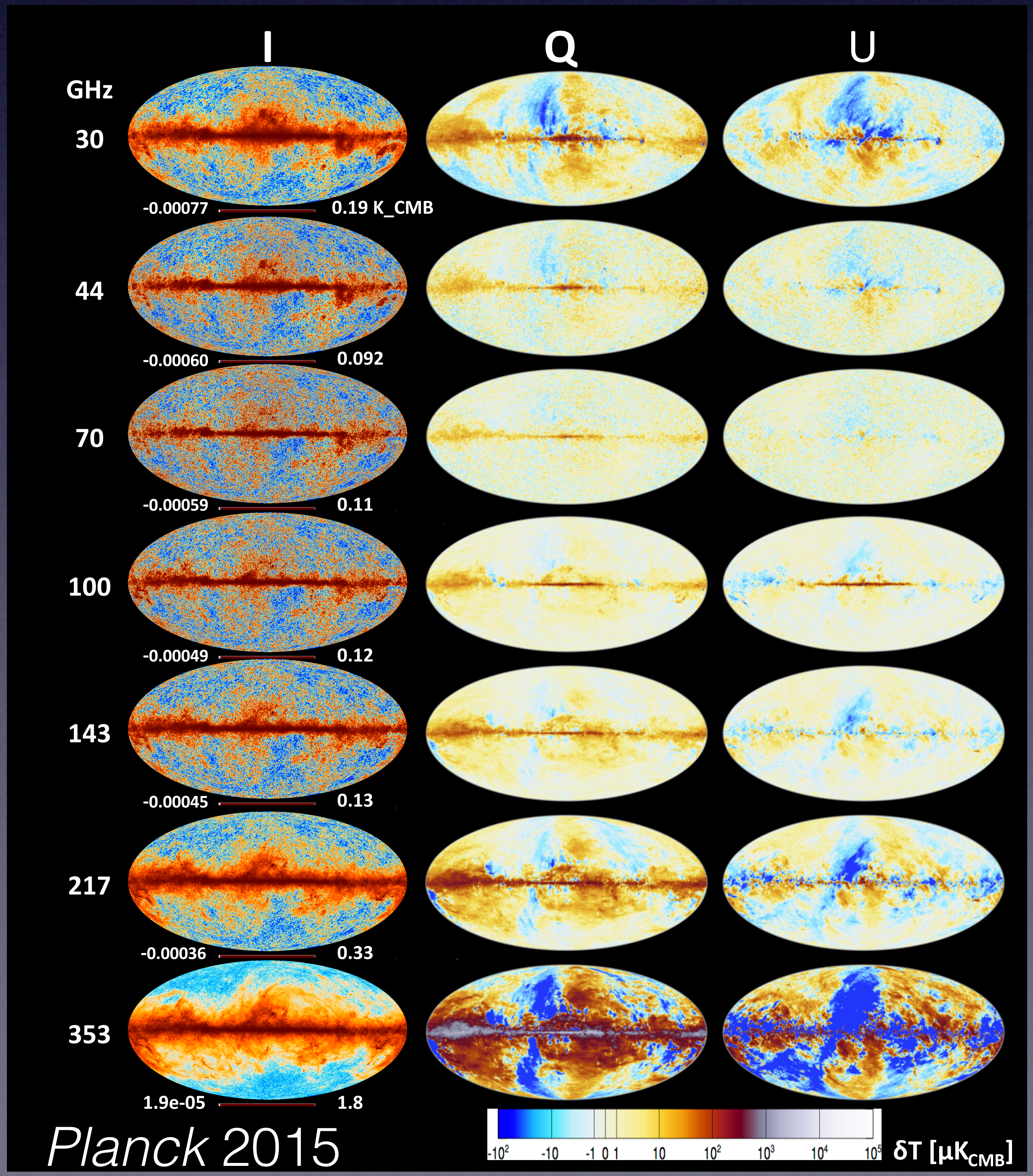
Design Basics

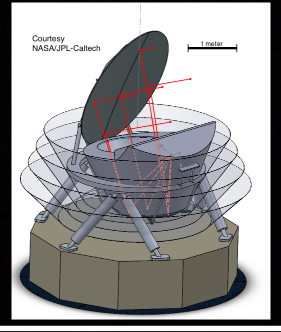
- Full sky
  - Inflation including the reionization peak
  - Star formation history
- Broad frequency coverage
  - Galactic emissions (on their own and for foregrounds)
- Resolution
  - Neff
  - Inflation, neutrino mass (through lensing potential and delensing)
  - Galactic science

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
- 5 year survey from L2
- 0.6 uK*arcmin (*Planck* =50 ; S4 =0.8 uK*arcmin, 3%)







PICO Science

- Inflation: $r < 10^{-4}\ (95\%),\ \sigma(r) = 5 \cdot 10^{-5}$
- Cosmic variance limited τ, $\sigma(\tau) = 0.002$
- Neutrino mass: $\sigma(\Sigma m_\nu) = 14\ \mathrm{meV}$ (inc. DASI BAO; equivalent independent limit from cluster counts)
- $\sigma(N_{eff}) = 0.03$
- $\sigma(\omega_0) = 0.023$, $\sigma(\omega_a) = 0.13$ with 140,000 clusters
- Correlate lensing map with other mass tracer surveys

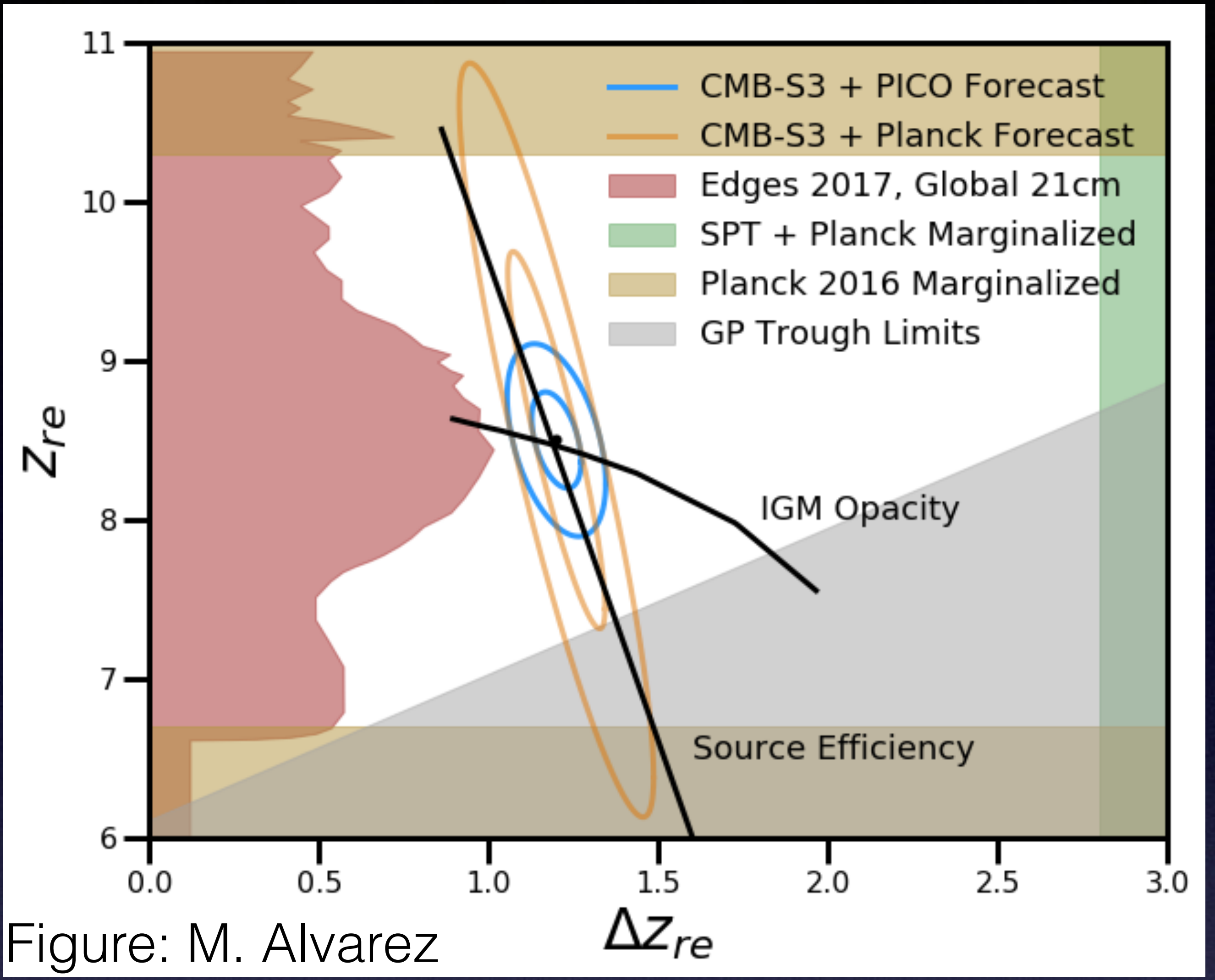


Figure: M. Alvarez

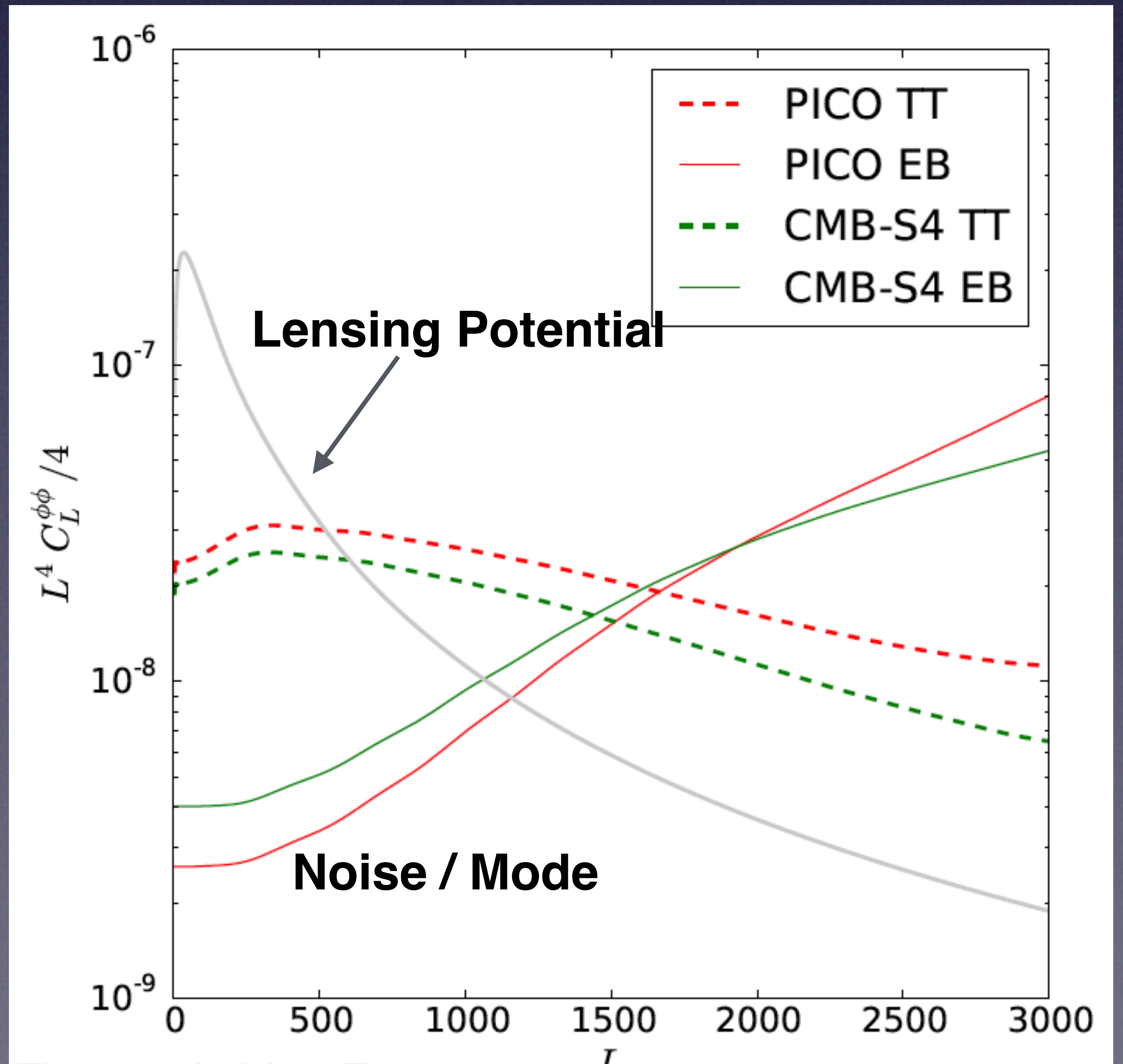
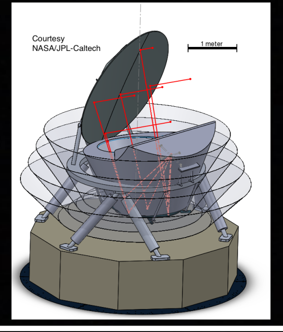
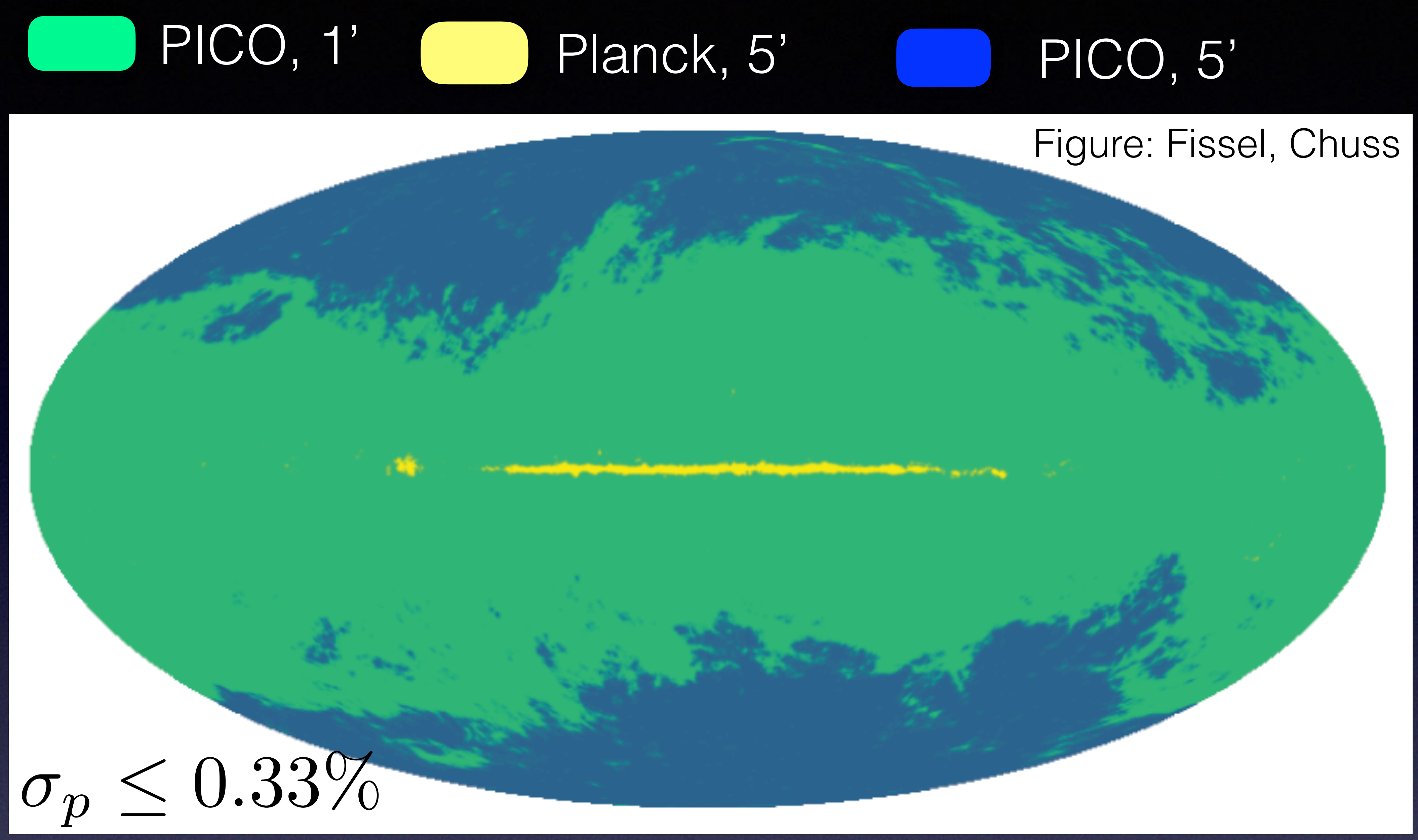


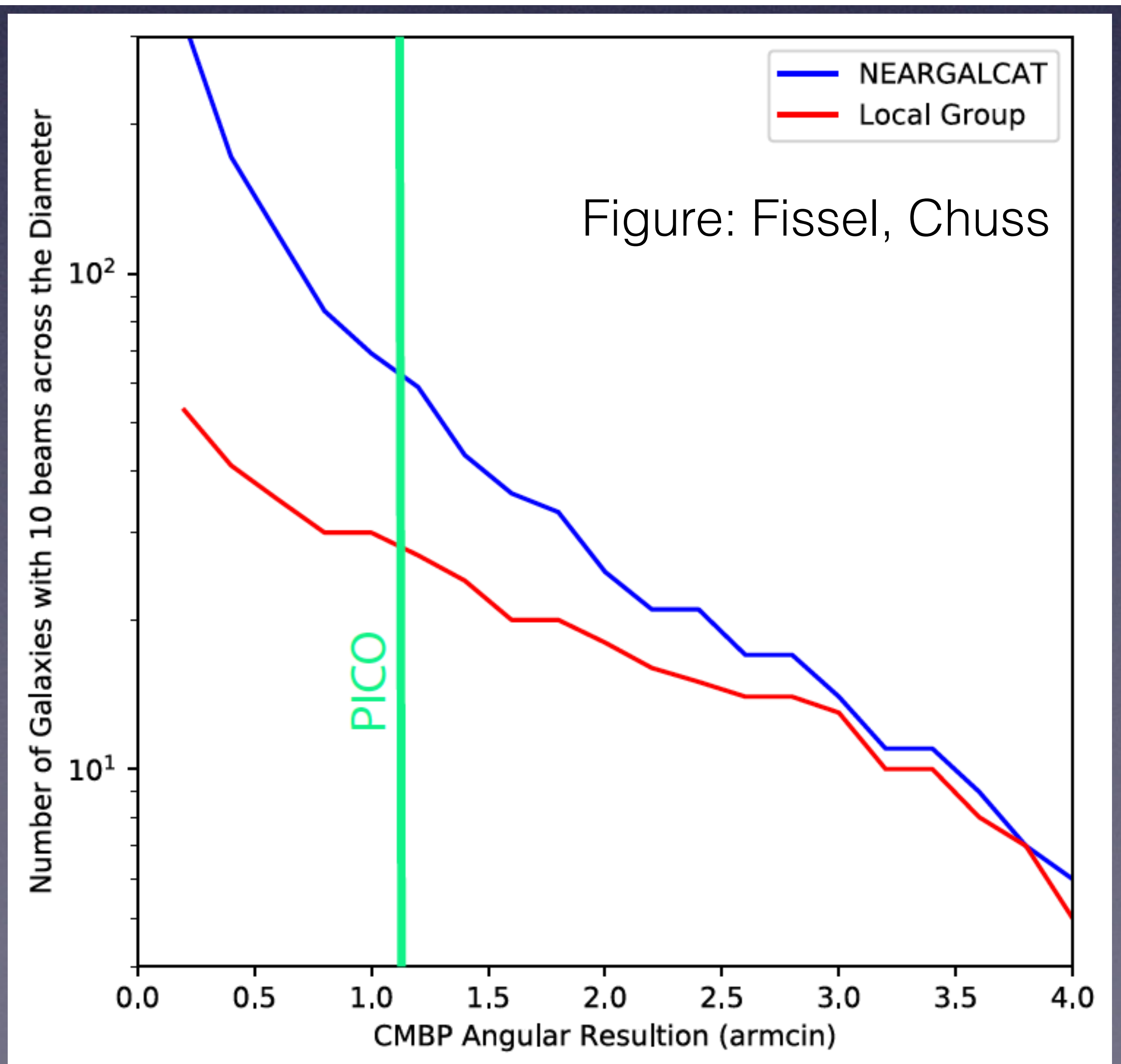
Figure: A. Van Engelen

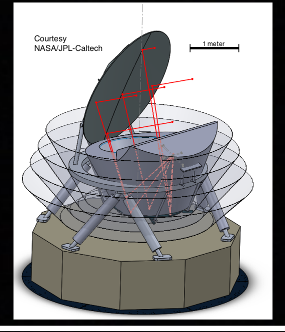


PICO Science Goals

- Map magnetic field over 70% of galaxy with 1’ resolution
- Resolve B-field structure in 8 nearby clouds on core scale (0.1 pc) (currently none)
- Resolve B-field structure in 2000 clouds with 1 pc resolution to compare roles of turbulence and B-field in star formation efficiency (currently 14)
- Map sub-mm emission in ISM of 70 nearby galaxies (handful to date)





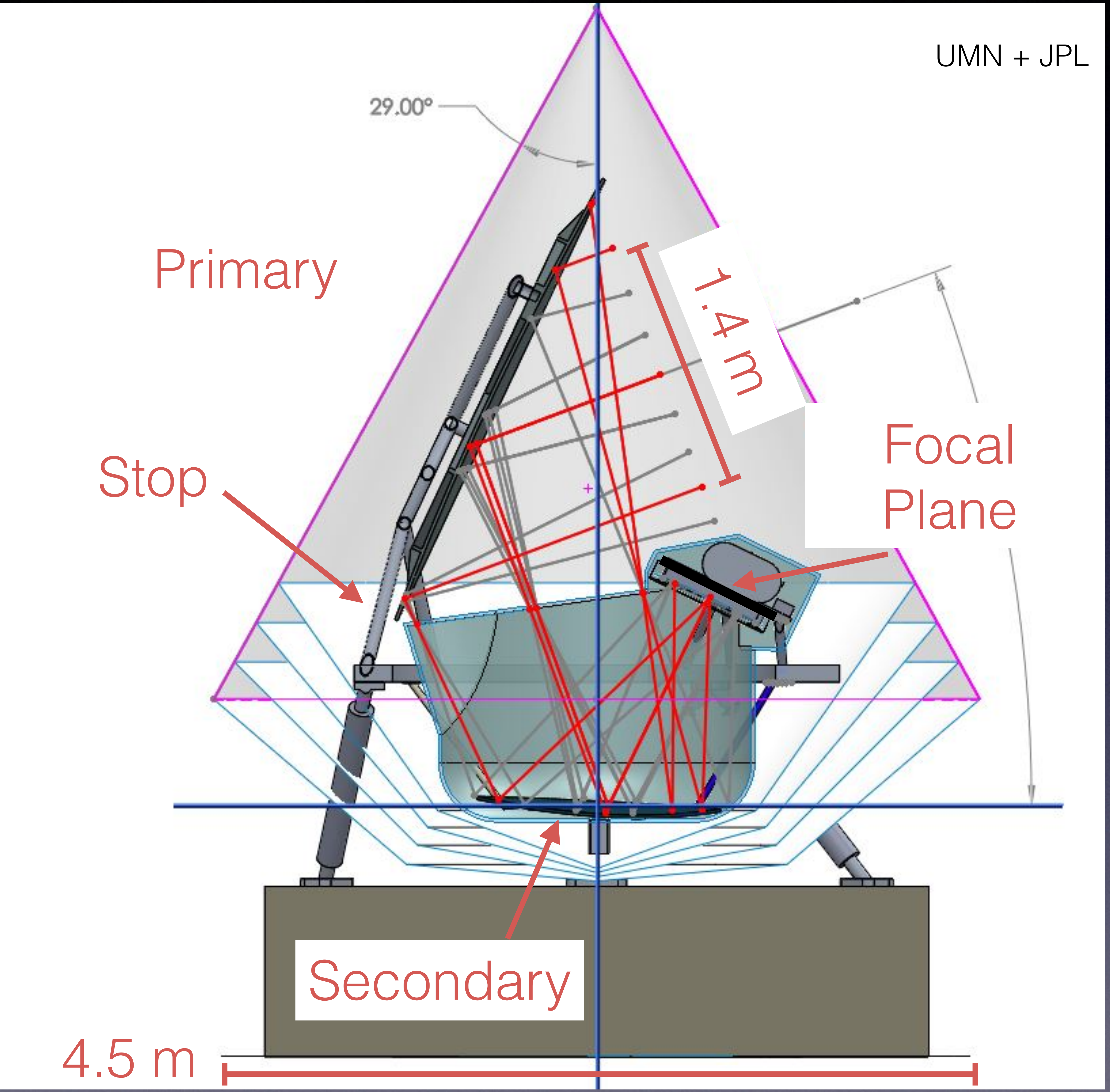


PICO Science Goals

- 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.

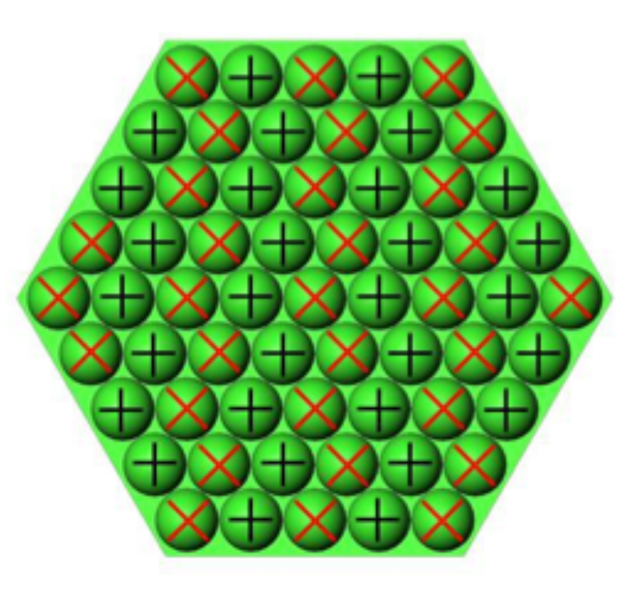
Instrument Design

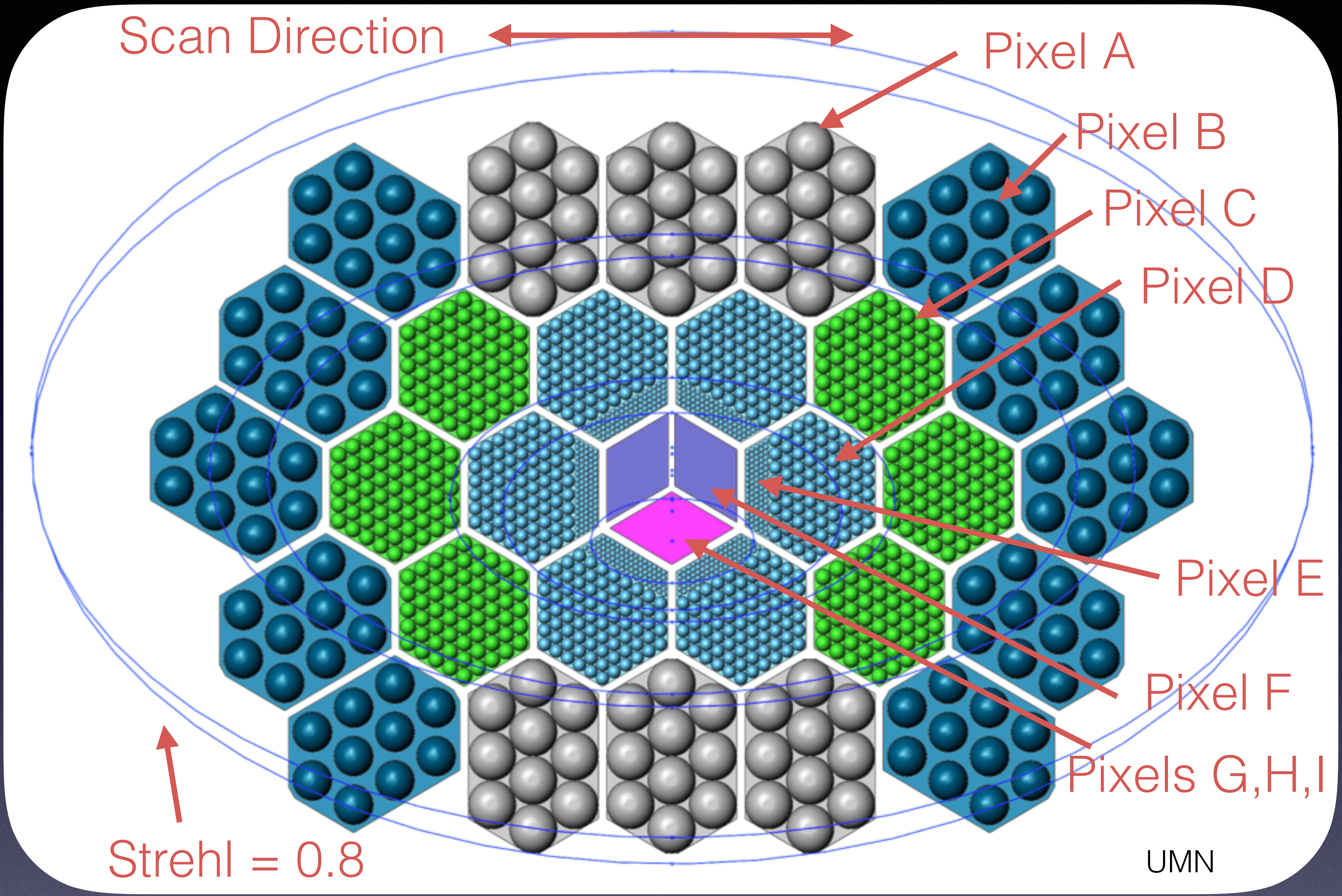
- 2 mirror, Open-Dragone, 1.4 aperture telescope
- Primary at ambient temperature
- 4-6 K-cooled Stop + Secondary
- 0.1 K focal plane



Focal Plane

- 3 color antenna coupled for pixels A - F $\nu \leq 500\ \mathrm{GHz}$
- Single color, horn-coupled, absorber-based pixels for G,H,I $\nu > 500\ \mathrm{GHz}$
- All based on TES bolometers
- Total bolometer count = 12,996
- Multiplexed readouts (TDM: x128 columns x 102 rows)
- Alternating columns are oriented as Q / U pixels



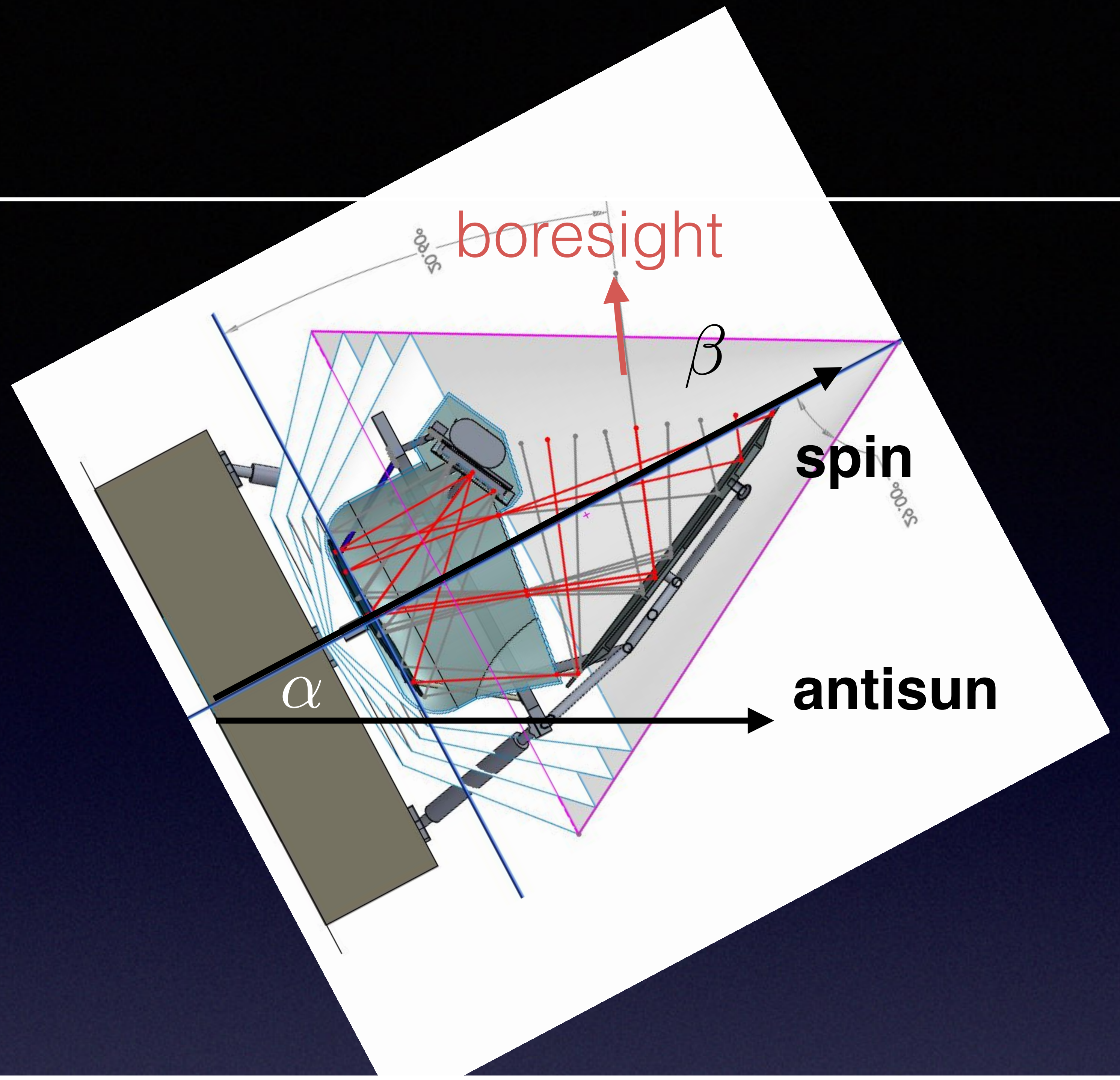


A	21, 30, 43
B	25, 36, 52
C	62, 90, 129
D	70, 108, 155

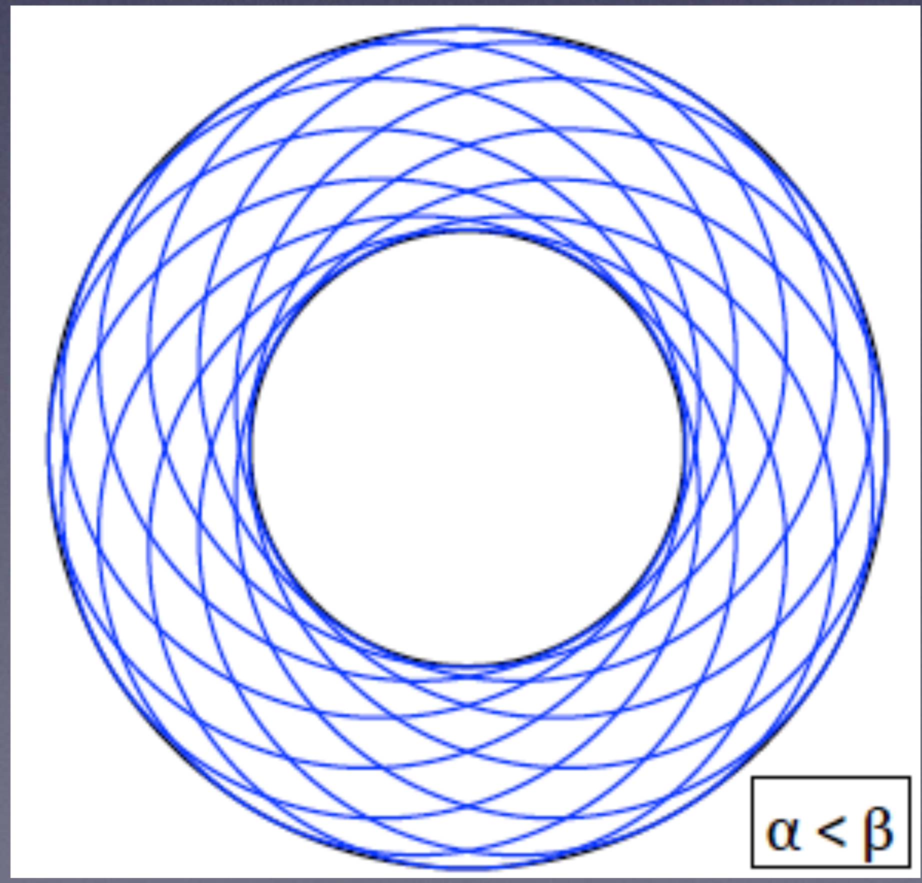
E	186, 268, 385
F	223, 321, 462
G, H, I	555, 666, 799

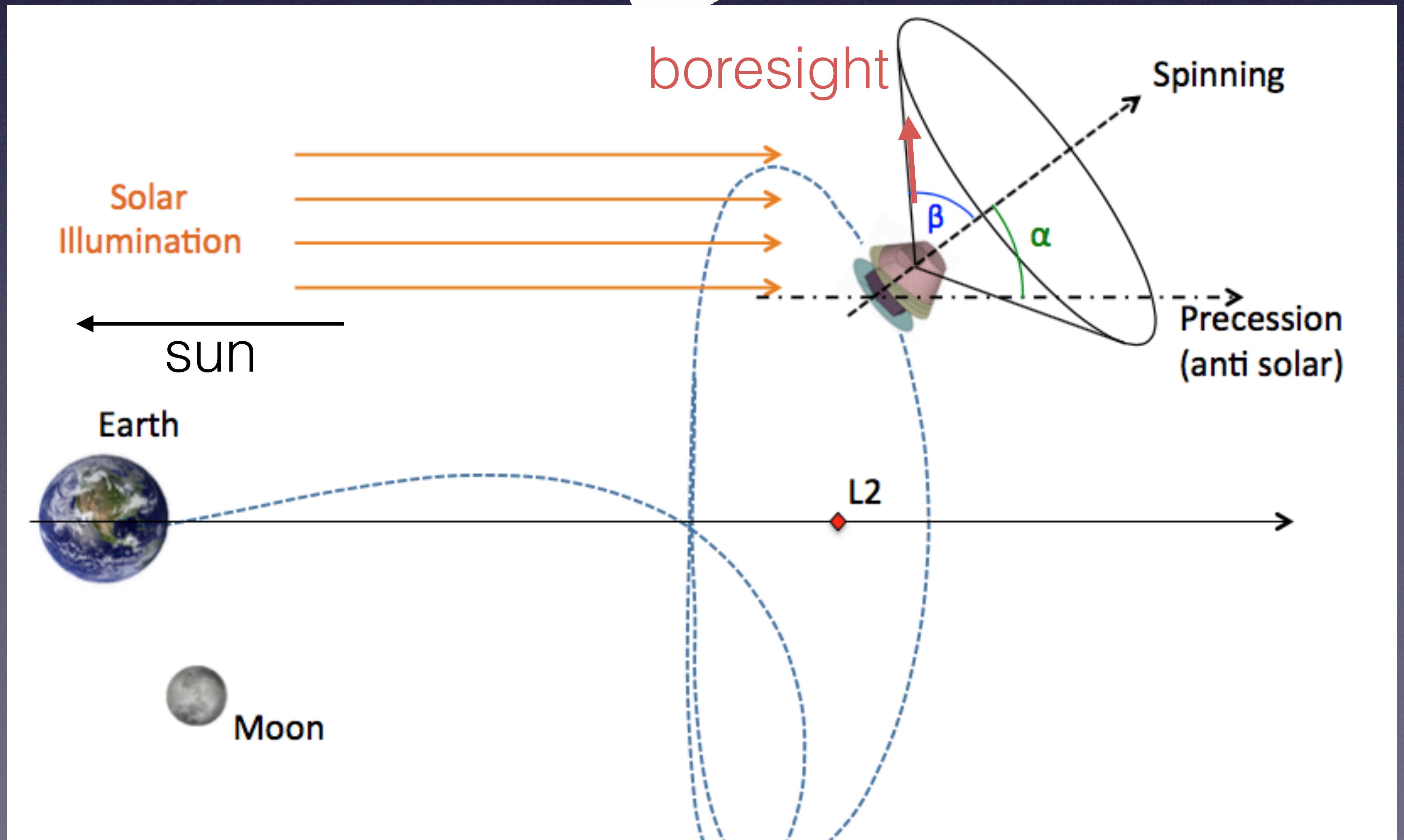
Orbit + Scan

- Orbit around L2
- alpha =~ 25, beta =~ 70
- Spin = 1 rpm
- Precess = 10 hours
- ~6 months for single full sky survey
- 5 year total survey



- Each circle is one spin
- OD = alpha + beta
- ID = alpha - beta

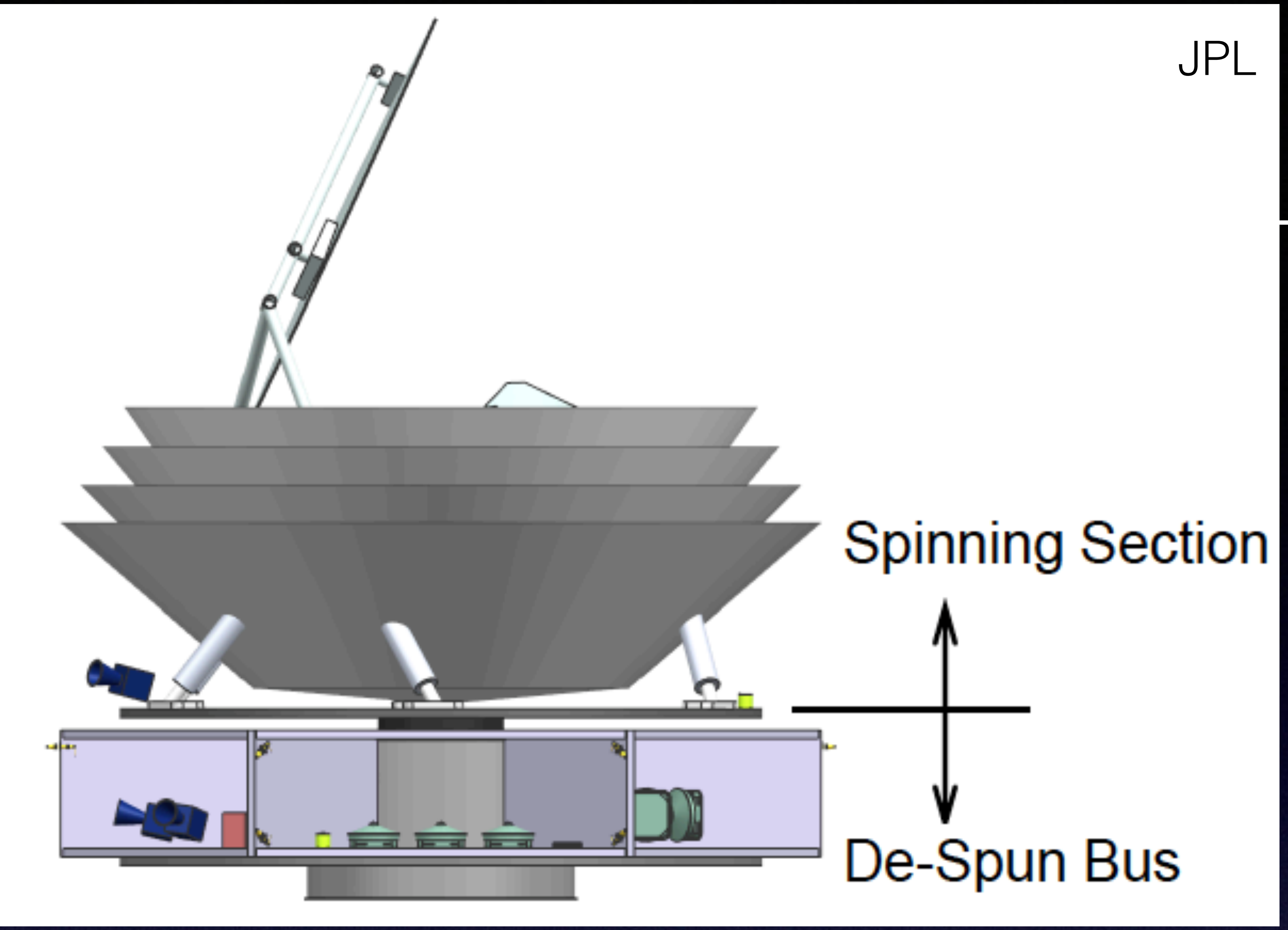


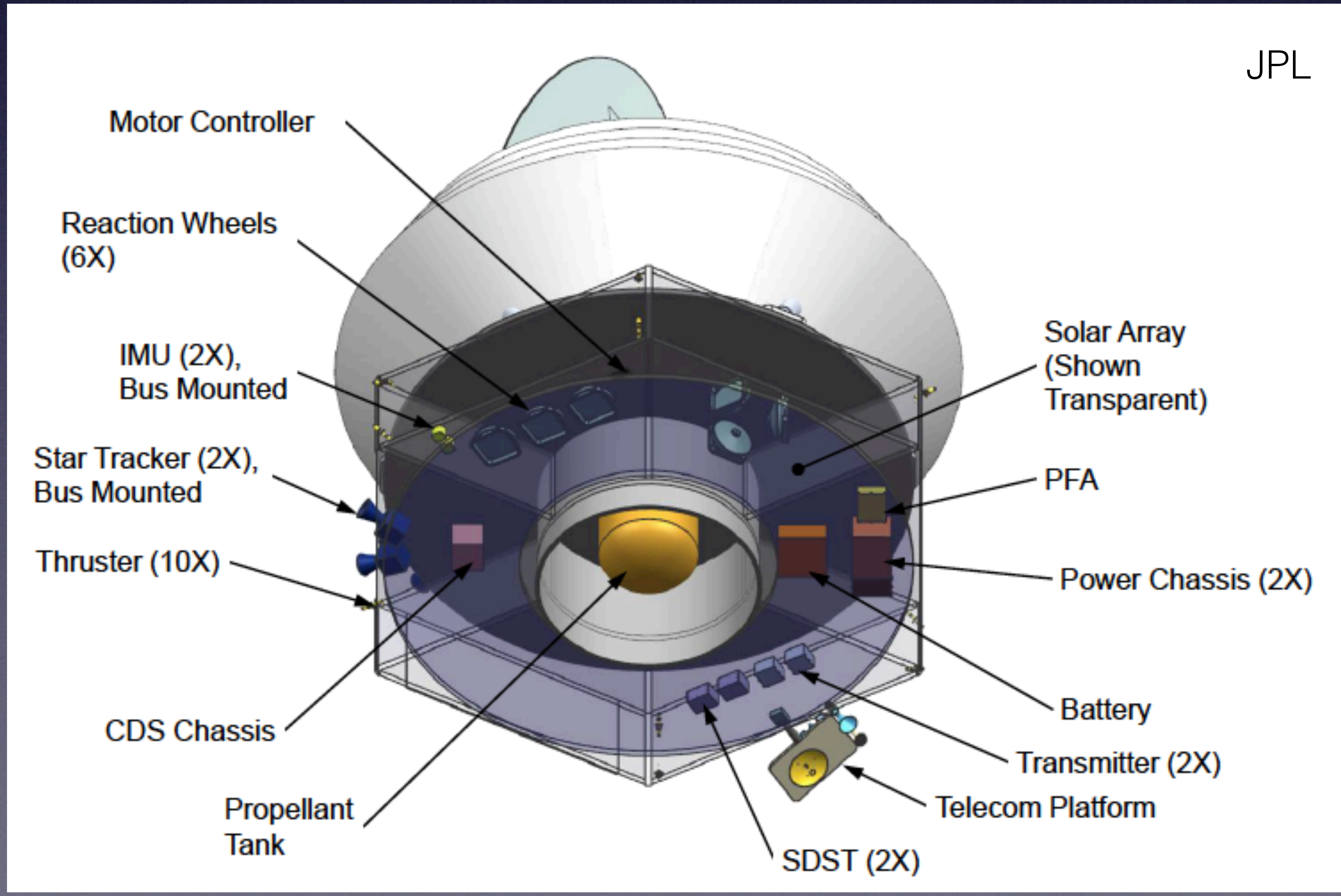


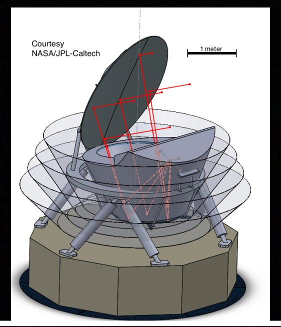
Delabrouille et al 2018

Spacecraft

- Split spinning, non-spinning spacecraft
- Coolers spin with instrument
- Power, electronics, telemetry on non-spinning section
- Real time attitude determination: 10” ; Attitude knowledge: 1”.







PICO Summary

- Inflation, quantum gravity, particle physics, extragalactic and galactic structure and evolution:
  - All unique goals for the PICO measurements
  - 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

PICO Study

- Phase 1: decide on science goals and overall design drivers
  - Spectrometer, Imager, or both; resolution, survey type, frequency coverage, depth
- Phase 2:
  - instrument + mission design and costing: Completed two TeamX studies + costing
  - assess performance
- Phase 3: write report
- Submit report by end of December 2018

Workshop Goals

- Review where we are, decide what else to do for the report, discuss what goes into the report, distribute writing assignments
- File with candidate 'Issues to Discuss' posted
- Day 1, Science:
  - What classes of models is it compelling to rule out in addition to and at levels of r below the Starobinsky-type class of models?
  - Which science goals have we not included yet? What other science targets that are well suited for space have we not yet thought about?
  - Ancillary science: are we properly reaching out to other communities?
  - Is there a science argument for a Guest Observer program?
  - How are the various science goals affected by foregrounds?
- Throughout: how do PICO and S3/S4 complement and strengthen each other?

Additional Slides

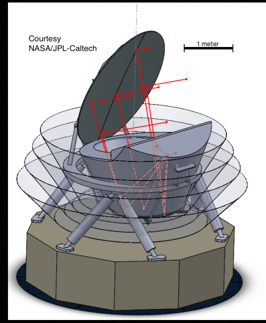
LiteBIRD

- It would have been reasonable to consider a smaller aperture mission
- It would have been reasonable to consider how such smaller aperture mission complements S4

- A smaller aperture mission (a-la LiteBIRD) is more limited in its science capabilities (Galactic science, Cluster science, Lensing (=neutrino mass) and Neff)
- A US-based smaller aperture mission is not much cheaper than PICO

- LiteBIRD is in a proposal stage

- We saw our task as putting forth the most scientifically compelling mission that is safely within the cost window



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 $\sigma(r)$)

Figure: R. Flauger

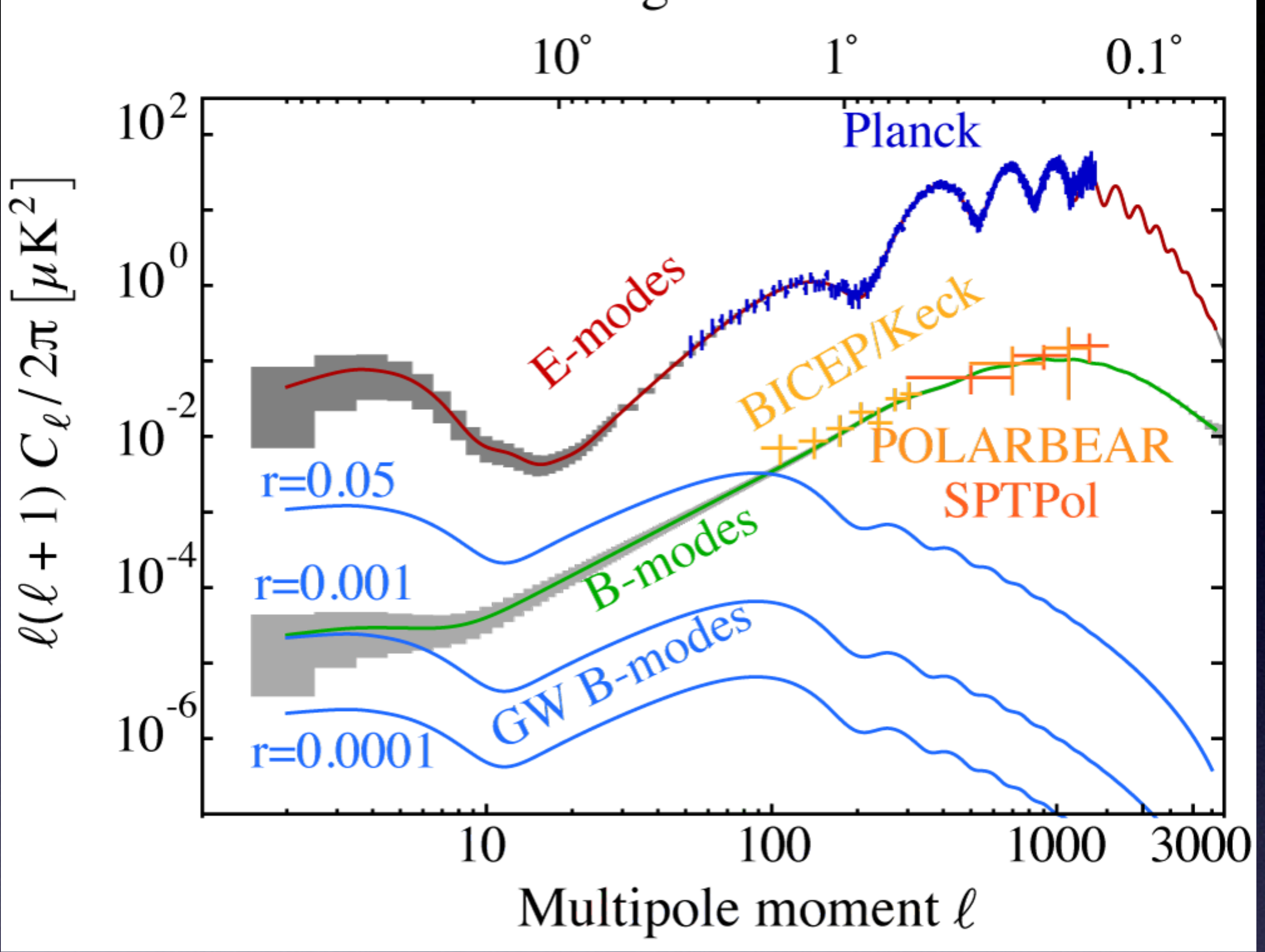
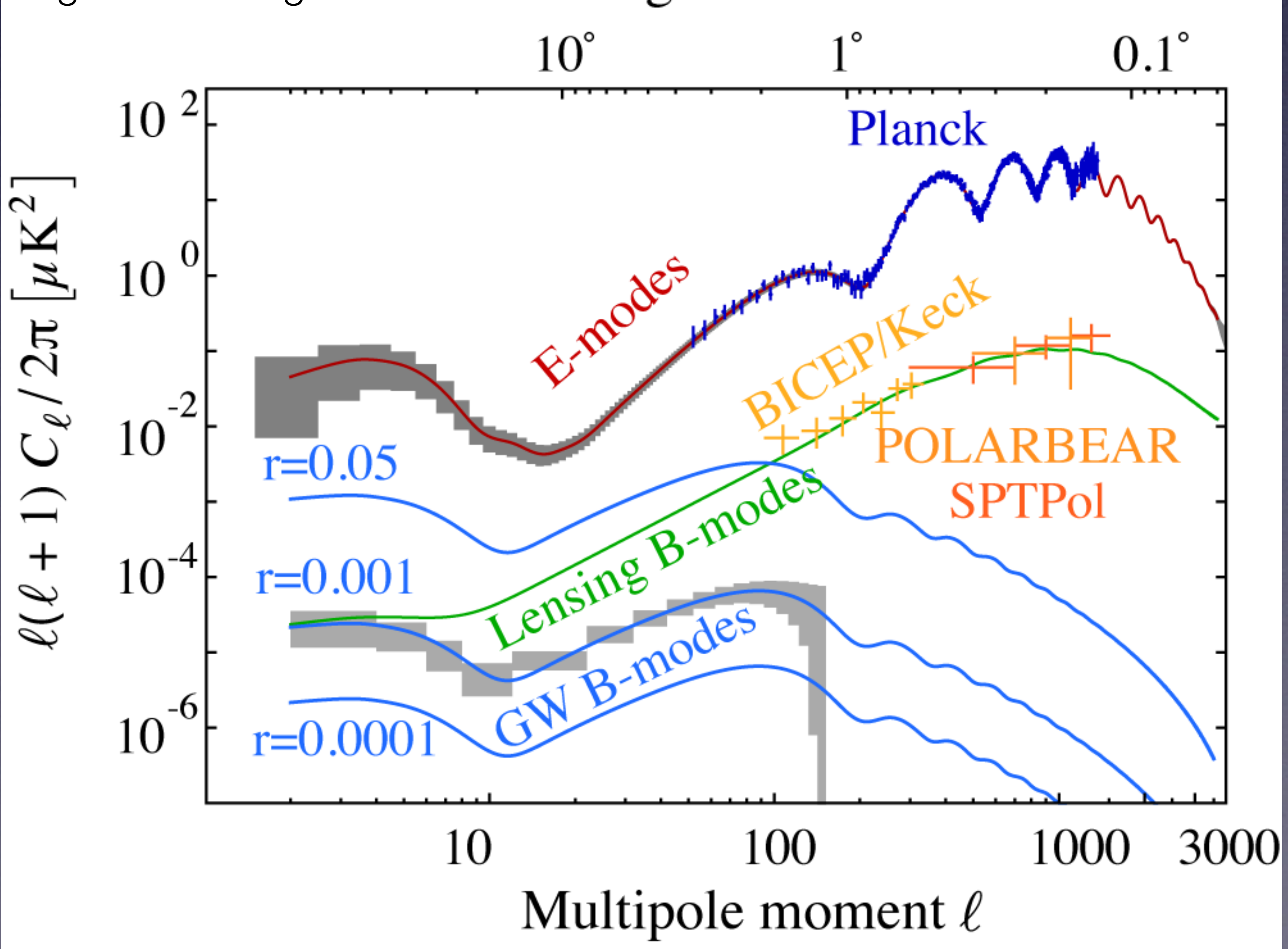
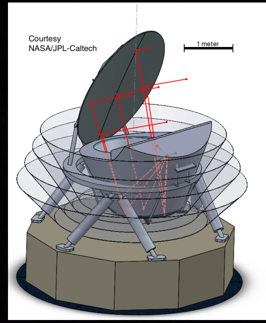


Figure: R. Flauger





Delensing

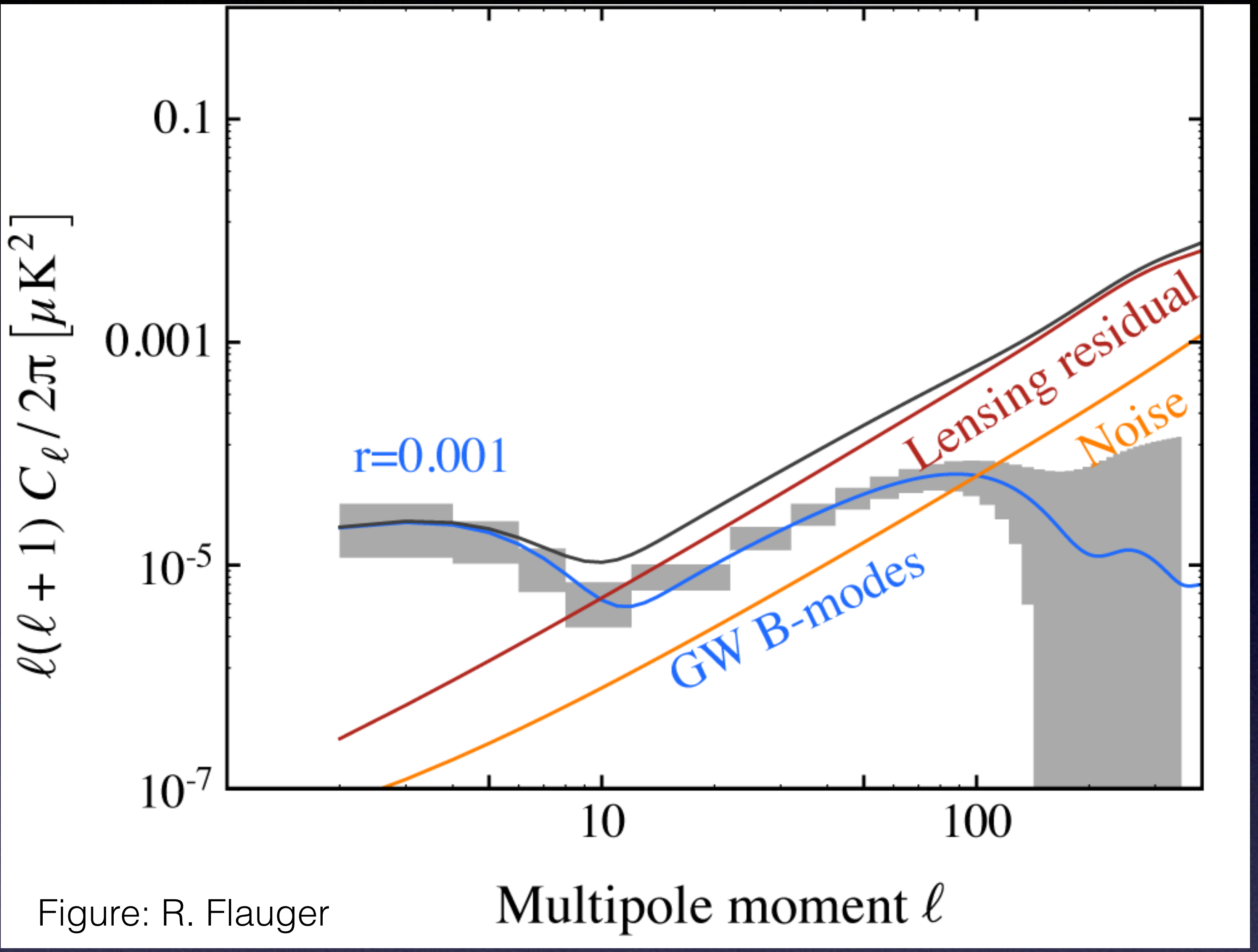
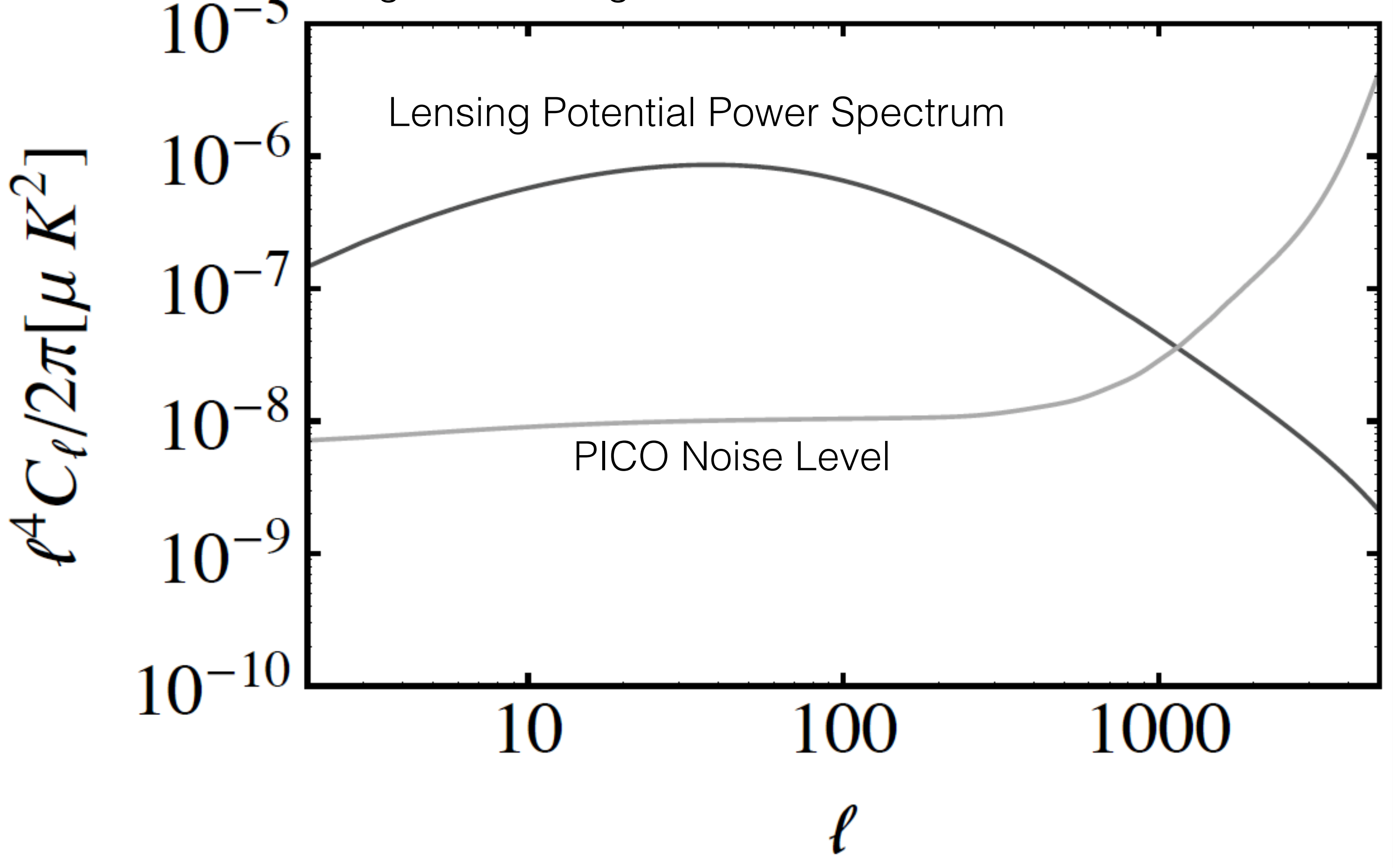
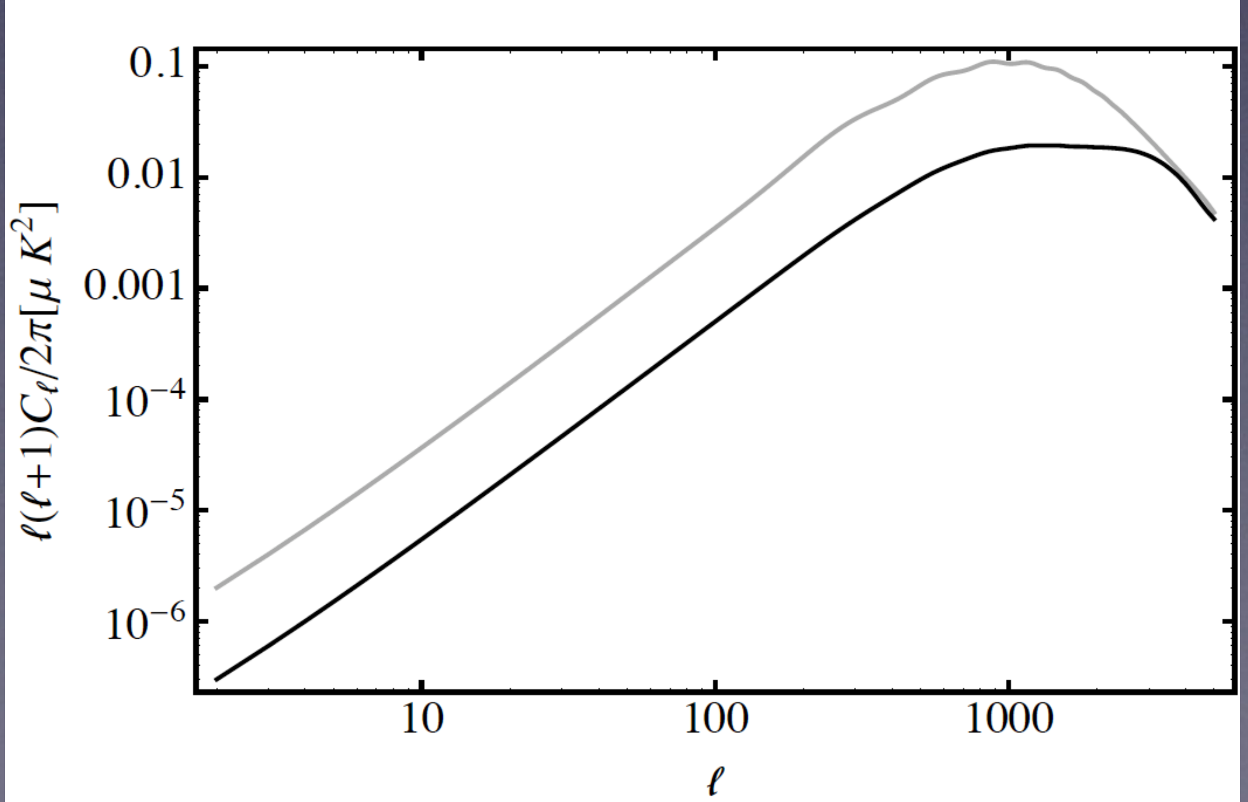


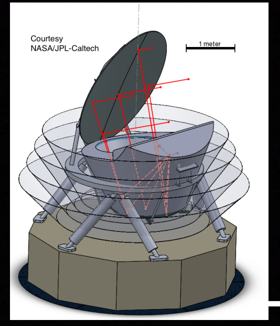
Figure: R. Flauger

- 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





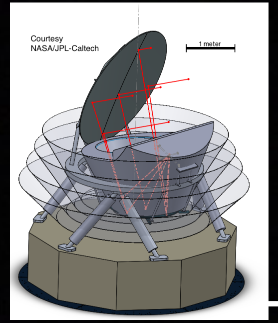


Balloons

- Currently funded: PIPER, SPIDER (2nd flight)
- Proposed: IDS, BFORE, Dust Buster
- IDS:
  - 20,000 detectors,
  - 7 bands, 150 - 360 GHz
  - Combined observations with BICEP/Keck (10 bands total)

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

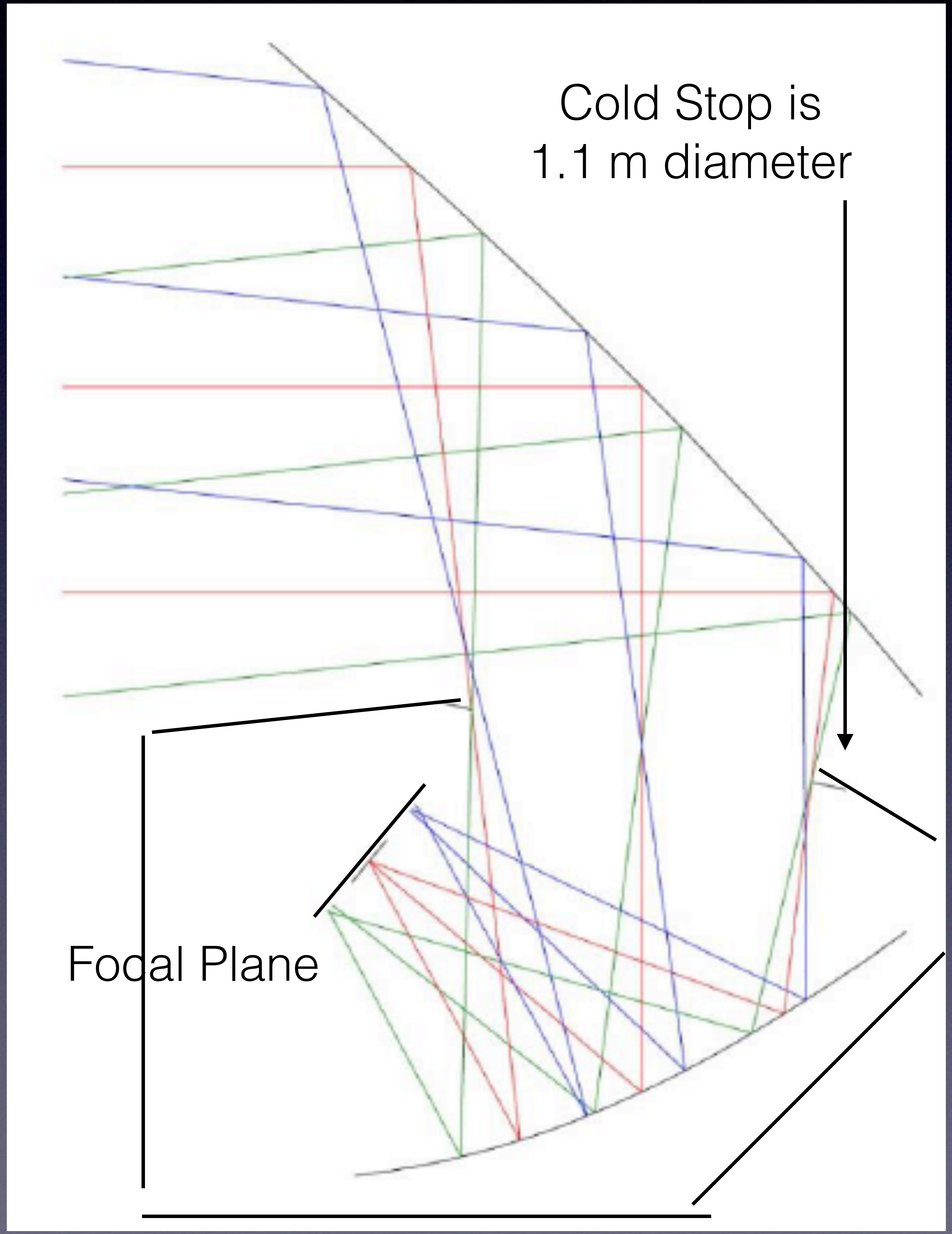


S4 Inflation Constraints

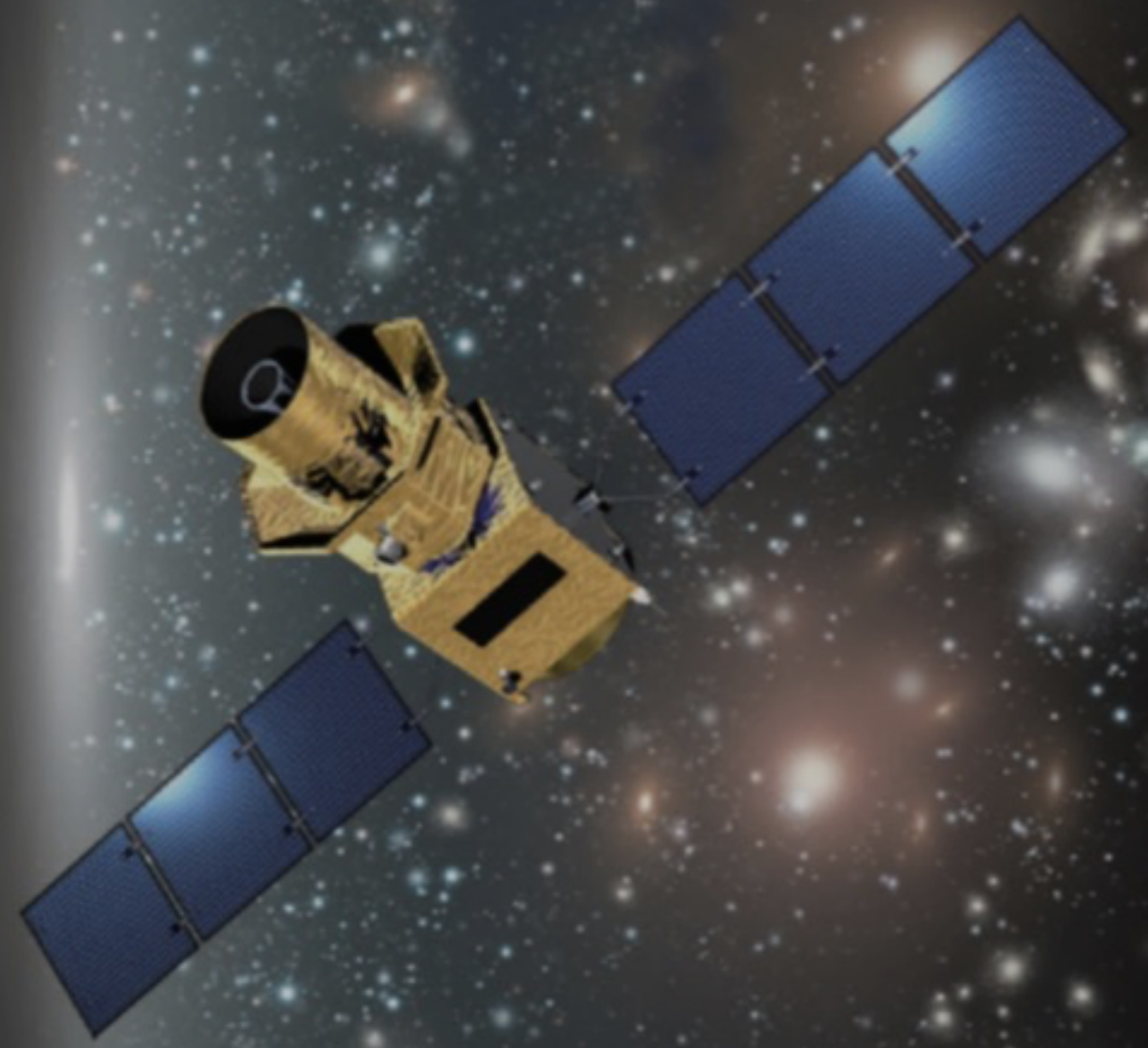
- Designed to provide detection of r>0.003
- $r < 0.001\ (95\%)$
- 3-8% of sky
- r >= 0.004 (5 sigma) in 4 years
- r >= 0.003 (5 sigma) in 8 years

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



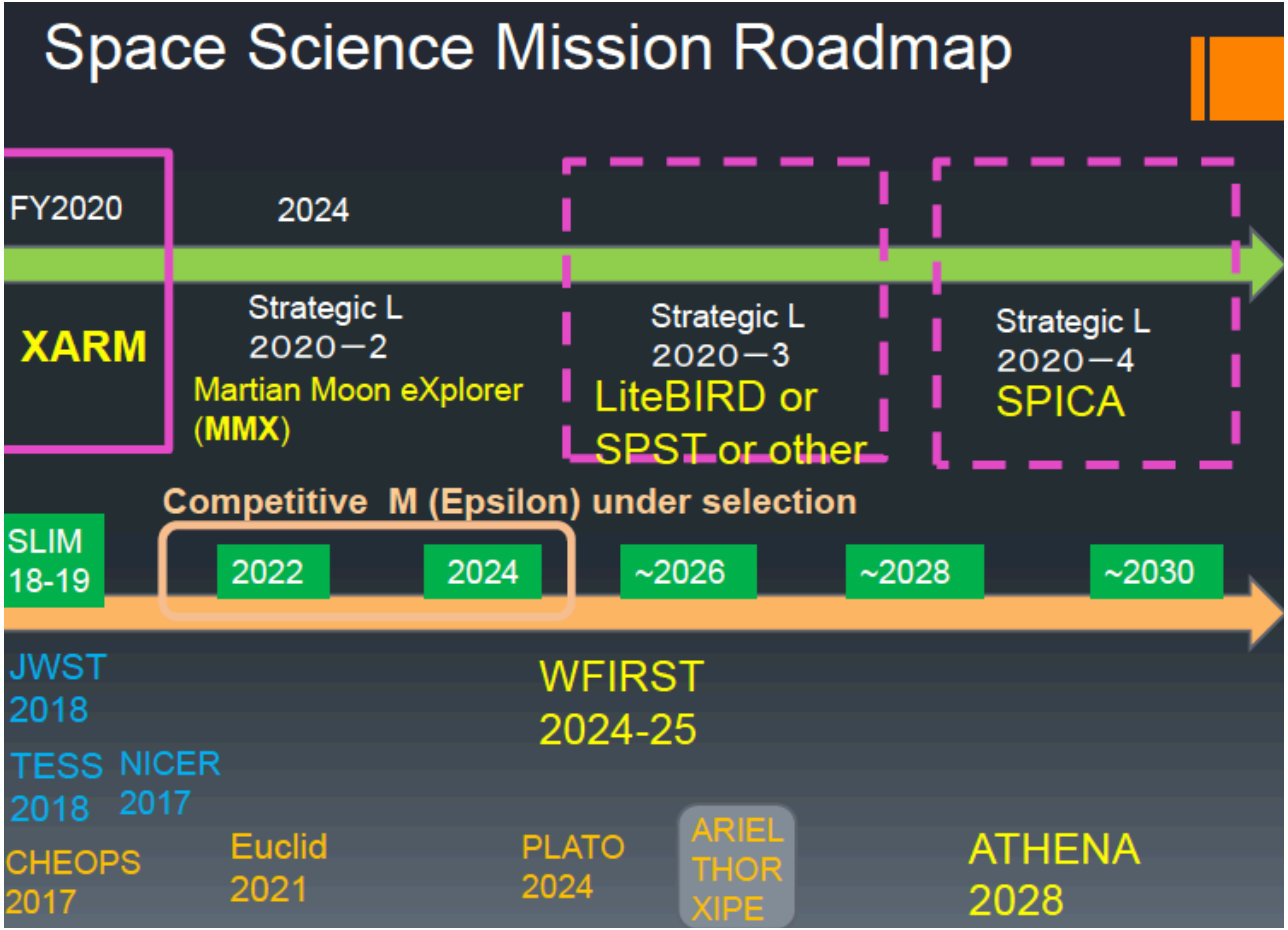
LiteBIRD



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

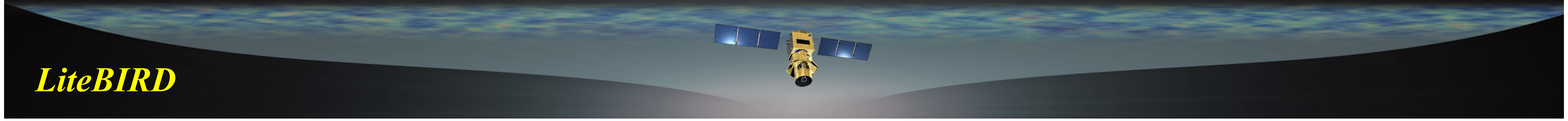
- $\sigma(r) < 1 \times 10^{-3}$ (for r=0)
- All sky survey (for $2 \leq \ell \leq 200$)*

<u>Remarks</u>

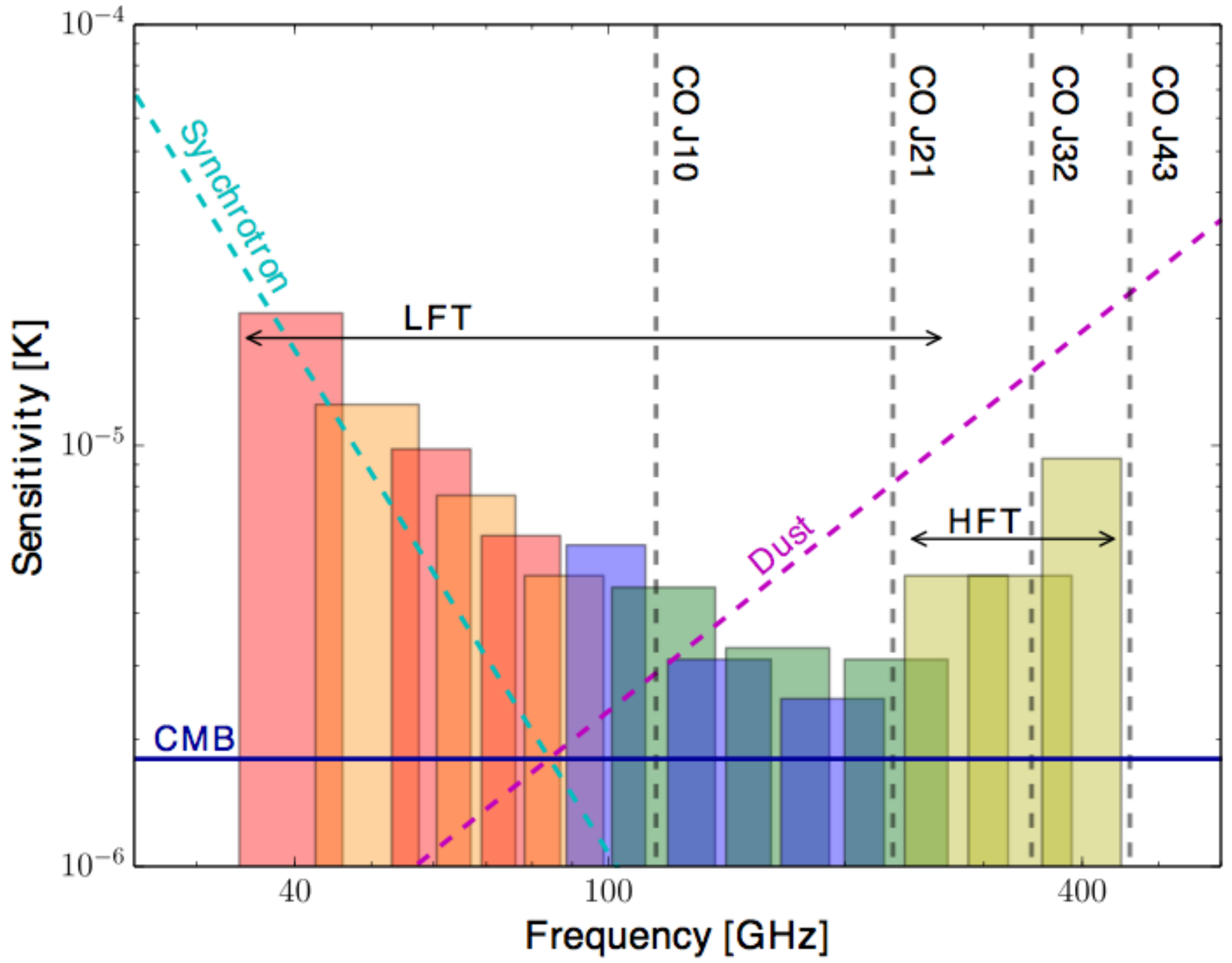
1. $\sigma(r)$ is the total uncertainty on the r measurement that includes the following uncertainties**
   - statistical uncertainties
   - instrumental systematic uncertainties
   - uncertainties due to residual foregrounds and bias
   - uncertainties due to lensing B-mode
   - cosmic variance (for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

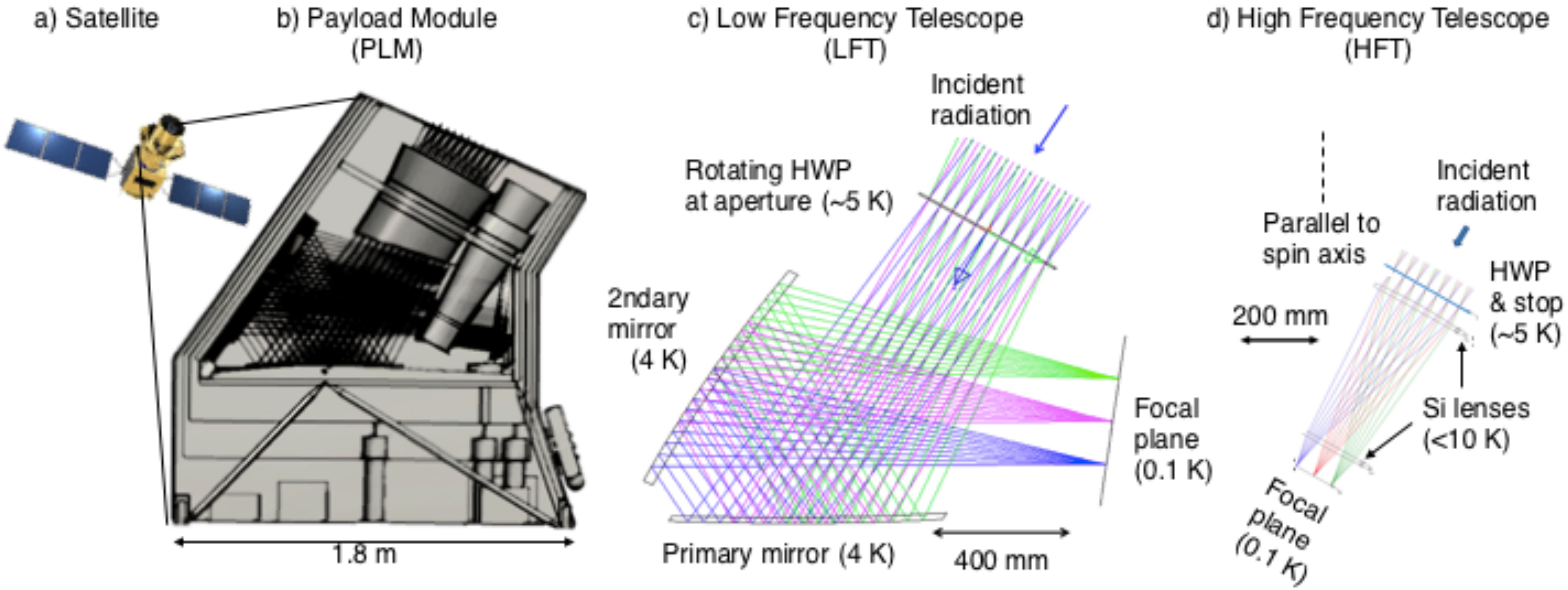
* **More precise (i.e. long) definition ensures >5sigma r detection from each bump for r > 0.01.**

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



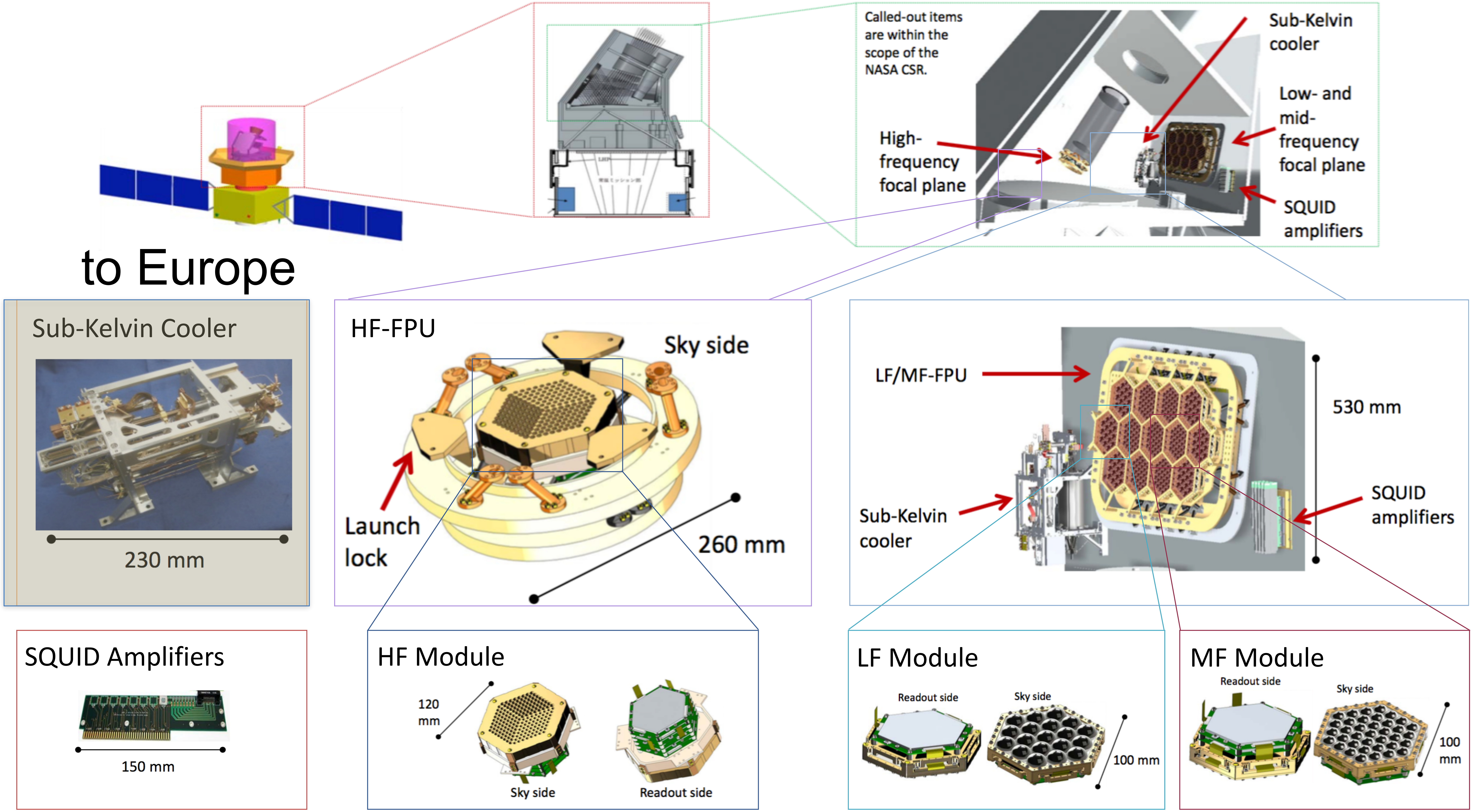
- $\sigma(r) < 0.001$ (for r=0)
- Imager, 35 - 450 GHz
- 15 frequency bands (some overlap)
- Two telescopes; 0.5 deg resolution at 100 GHz
- $2.5\,\mu\mathrm{K}{\cdot}\mathrm{arcmin}$ in polarization





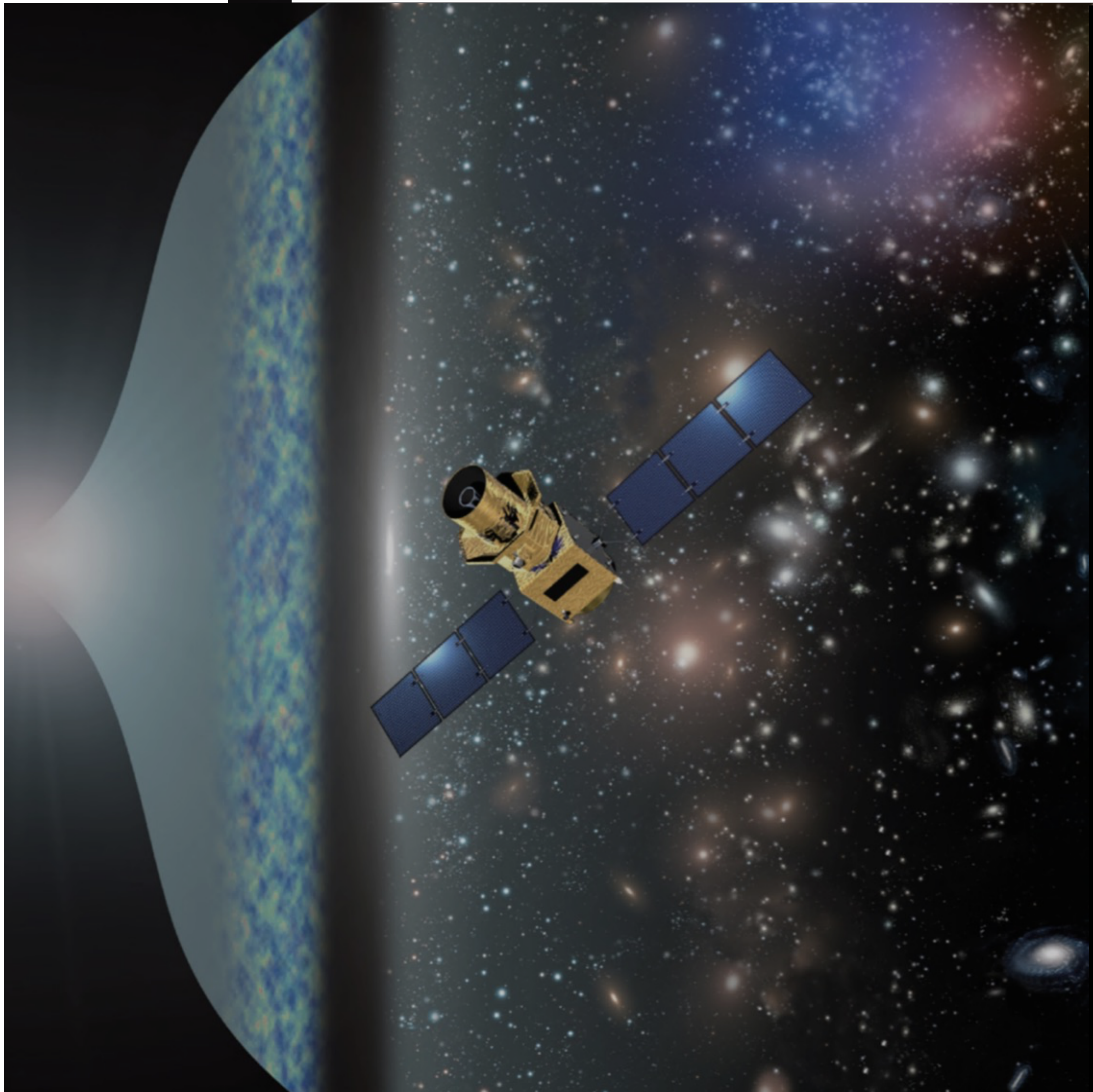
LiteBIRD U.S. Deliverables (A. LEE, US PI)

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

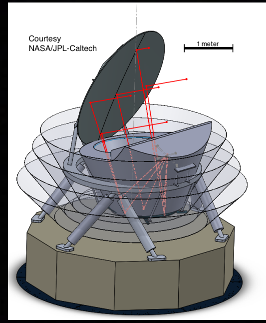


LiteBIRD

LiteBIRD Status



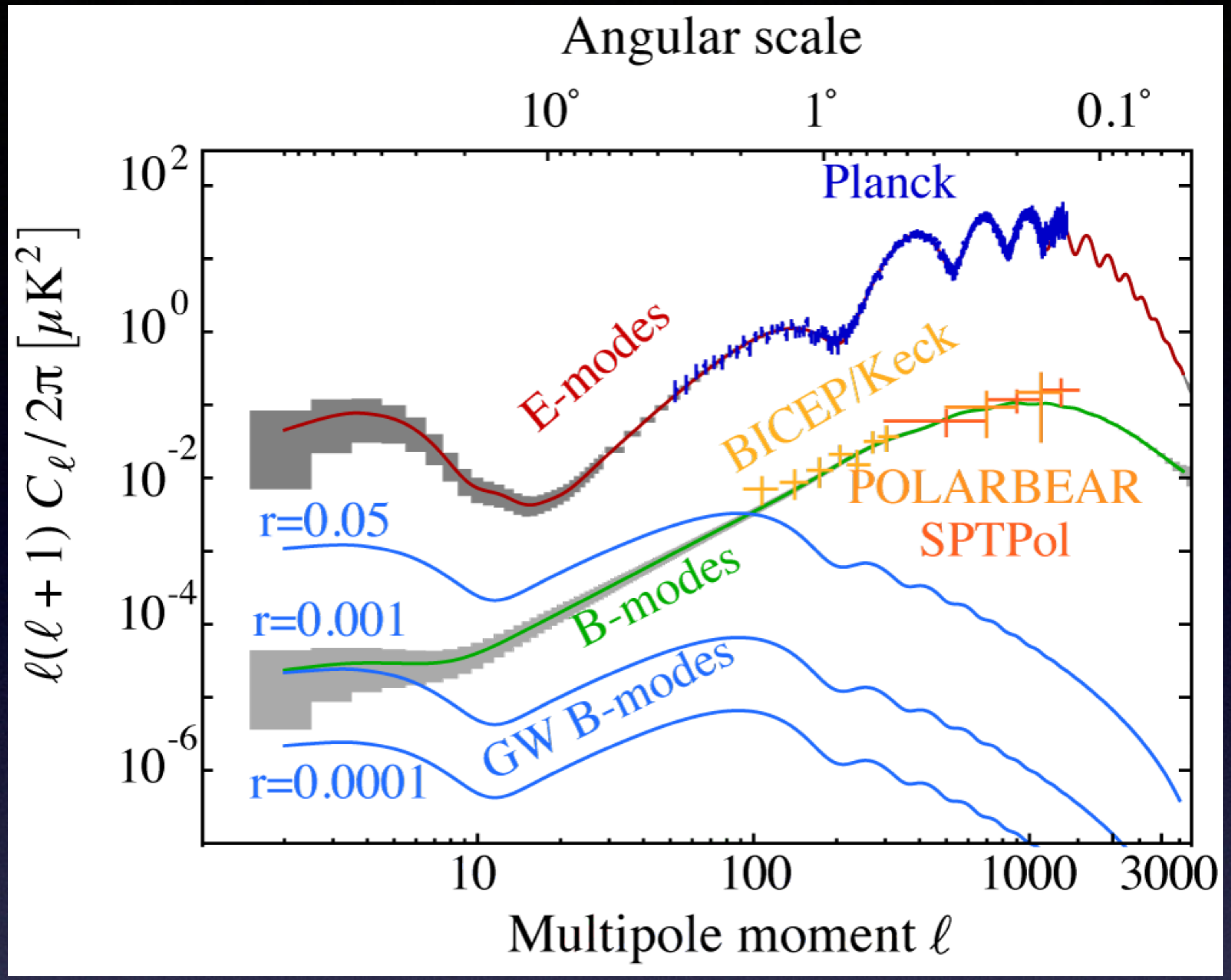
- Japan:
  - Phase A1 will conclude in 8/2018
  - Then downselect
- US:
  - 2016 Mission of Opportunity ($65M) proceeded to PhaseA; PhaseB declined
  - Technology development continues
  - Will submit at next MO (2019?)

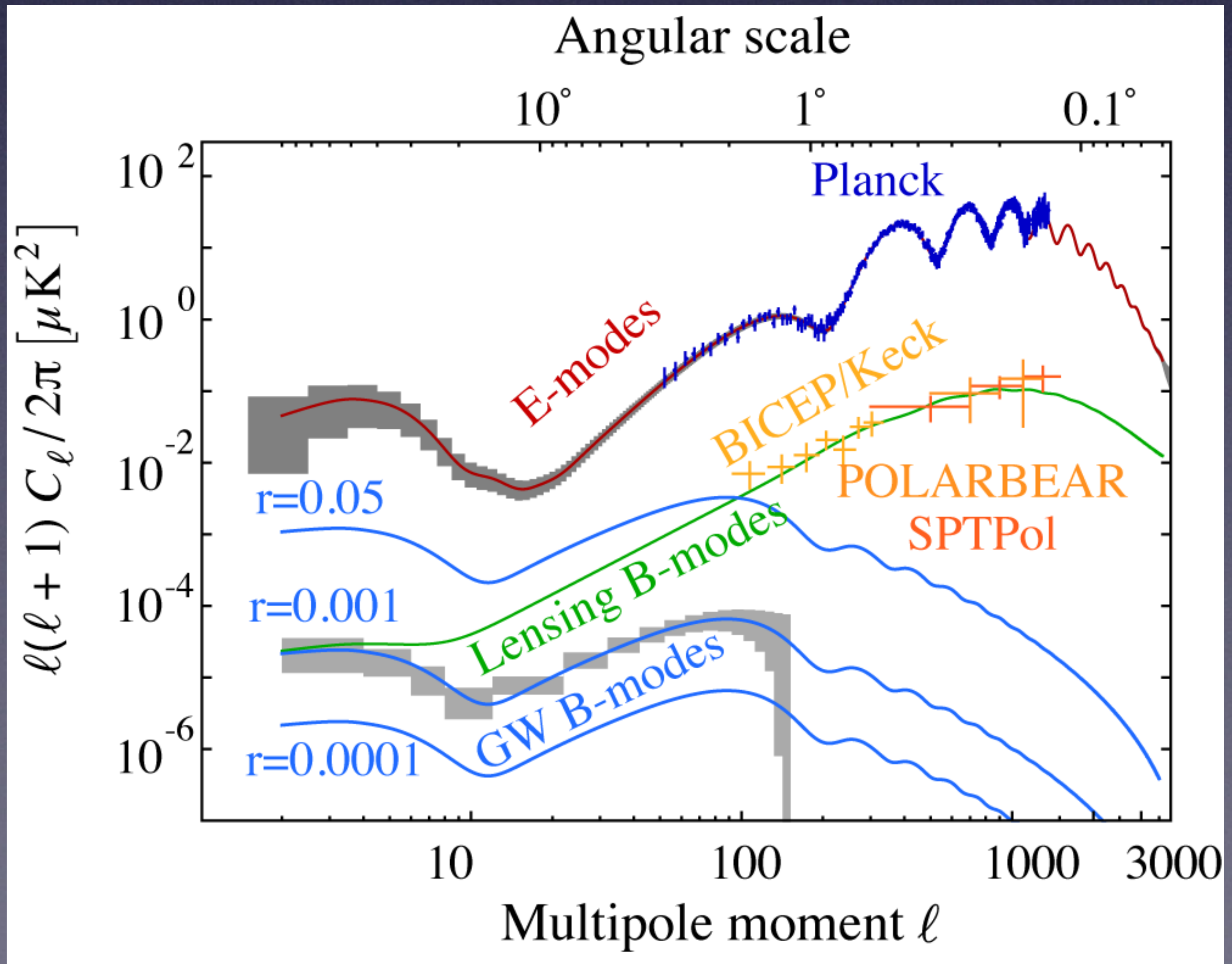


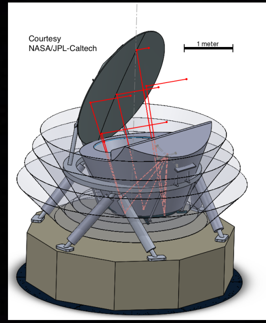
PICO and Sub-Orbital CMB Efforts

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