PICO - Probe of Inflation and Cosmic Origins

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NASA Prep for Decadal2020

- **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 → Probe of Inflation and Cosmic Origins** (Hanany, University of Minnesota)
  - High Spatial Resolution X-Ray Probe (Mushotzky, UMaryland)
  - Multi-Messenger Astrophysics (Olinto, UChicago)
  - Precise Radial Velocity Observatory (Plavchan, Missouri State)

Process + Outcomes

- Studies are 18 months long
- Studies will produce 50 pg. reports
- Reports will include cost estimates
- NASA will conduct independent cost review
- Report + independent cost review will be submitted to the Decadal Panel
- Reports are due by 12/2018
- Mission start 2023
- Mission launch 64 months after start.

Taken from Colin Hill's SO talk

PICO Science Goals and Probes

primordial fluctuations
large scale B-modes
→ tensor-to-scalar ratio (BB)

relativistic species
damping tail
→ N_{eff} (TE, TT, EE)

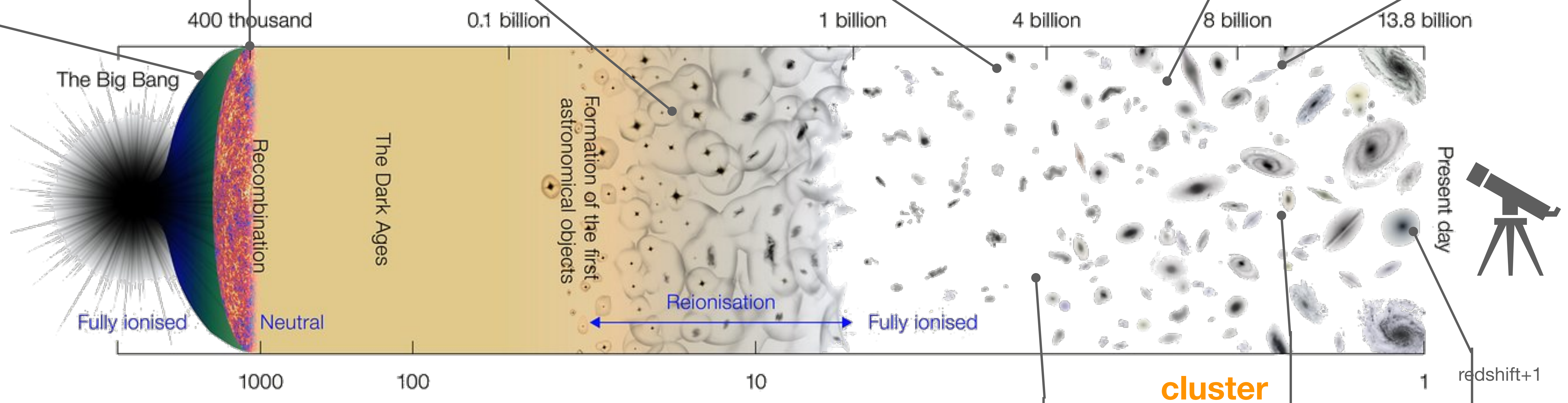
reionization
Optical Depth
→ tau (EE)

neutrino mass
lensing potential + tau (EE, EB)
→ Σm_ν

galaxy evolution
Strongly Lensed IR Sources

dark energy
Lensing, Cluster Counts

credits: ESO



dark matter
(TT, TE, EE)

cluster evolution
Proto Clusters

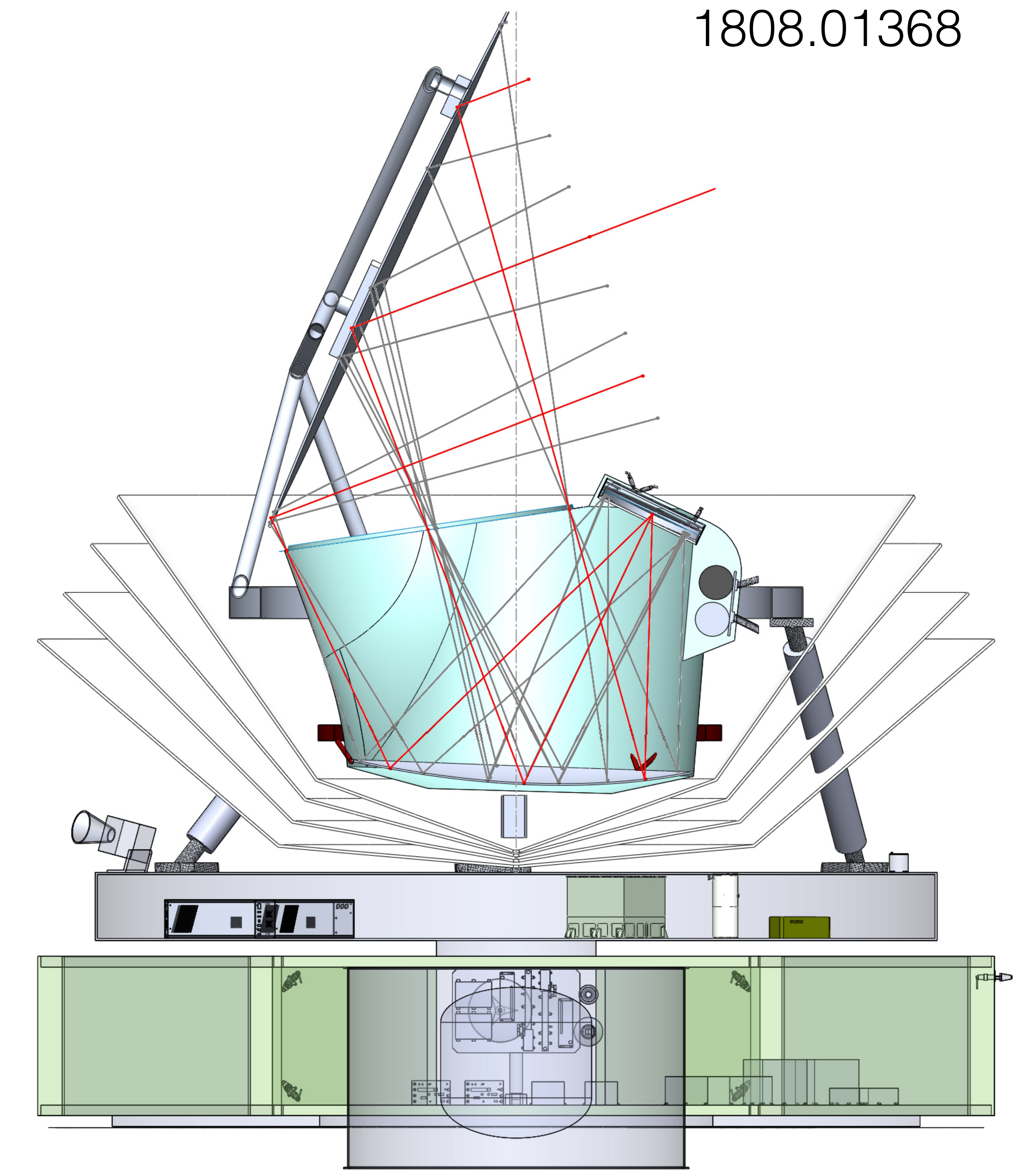
Milky Way Dynamics and Star Formation
Magnetic Field

All with a single instrument,
executing a simple repeated scan,
of the entire sky,
with 21 bands (20 - 800 GHz),
with unmatched stability,
and with 0.6-0.9 uK*arcmin

PICO in Brief

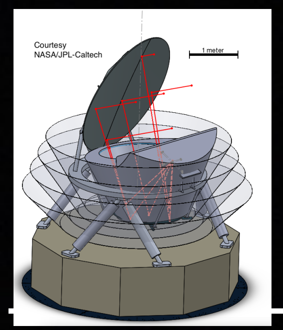
- Millimeter/submillimeter-wave, polarimetric survey of the entire sky
- 21 bands between 20 GHz and 800 GHz
- 1.4 m aperture telescope
- Diffraction limited resolution: 38’ to 1’
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- 0.87 uK*arcmin requirement; 0.61 uK*arcmin goal (=CBE)

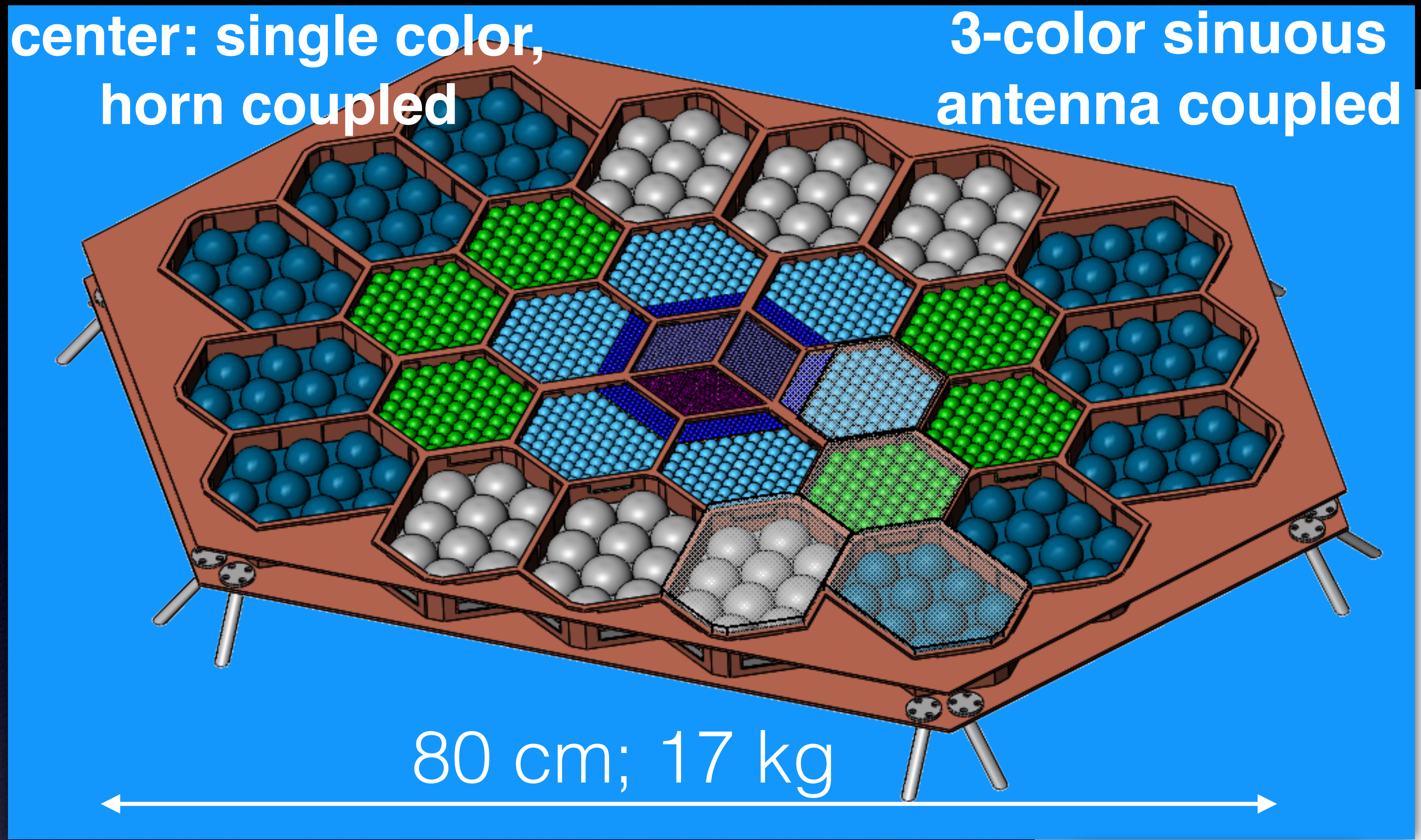
Jet Propulsion Laboratory



Sutin et al. SPIE Vol.10698; 1808.01368

PICO Implementation





- 2-reflector “Open Dragone” Telescope
- Ambient temperature primary
- 4 K aperture stop
- 4 K secondary reflector
- 0.1 K focal plane
- Spinning instrument, static bus
- Spin: 1 rpm; Precess: 10 hours
- 50% sky coverage in 10 hours

Young et al. SPIE Vol.10698; 1808.01369

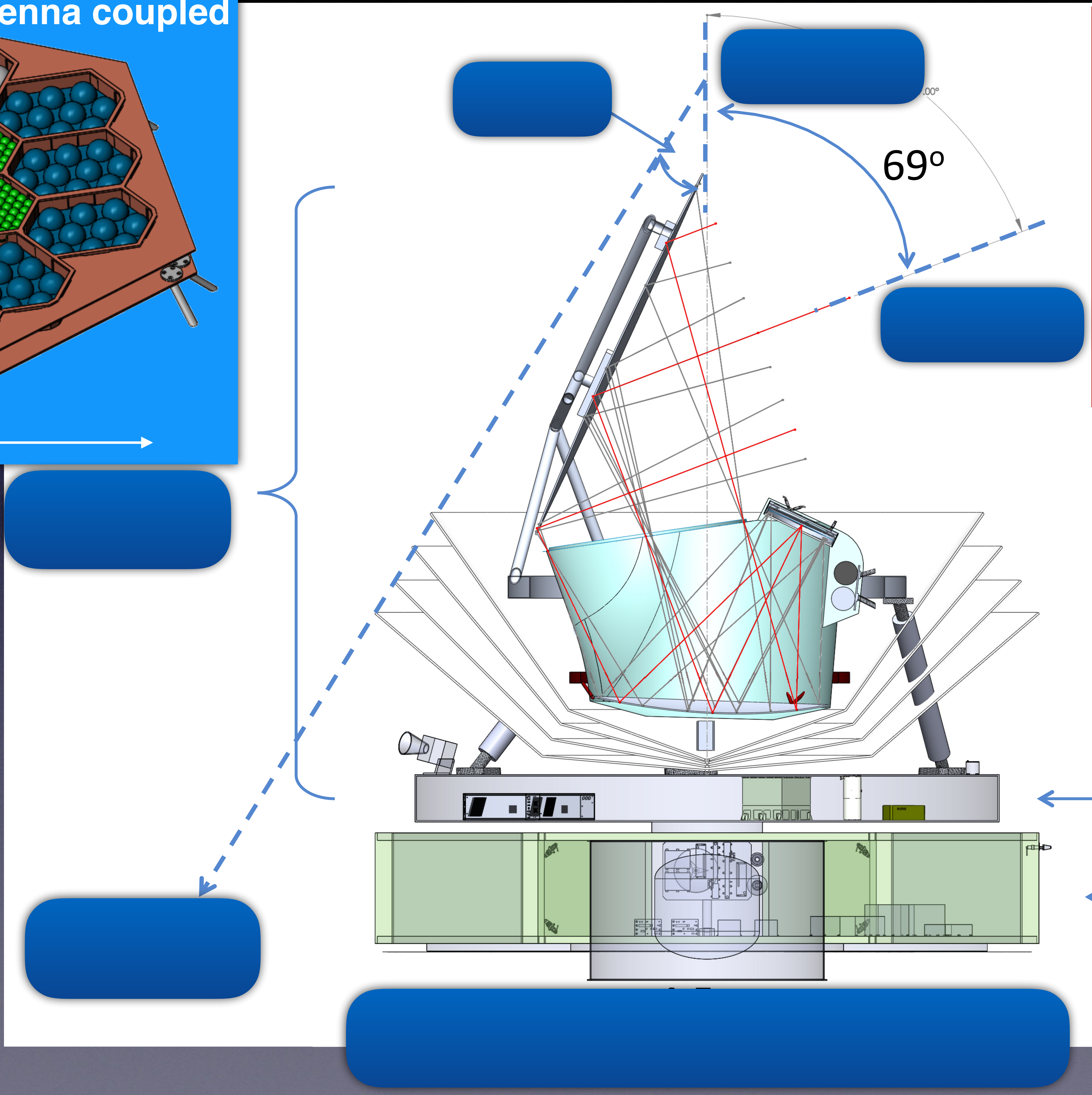


Figure: JPL

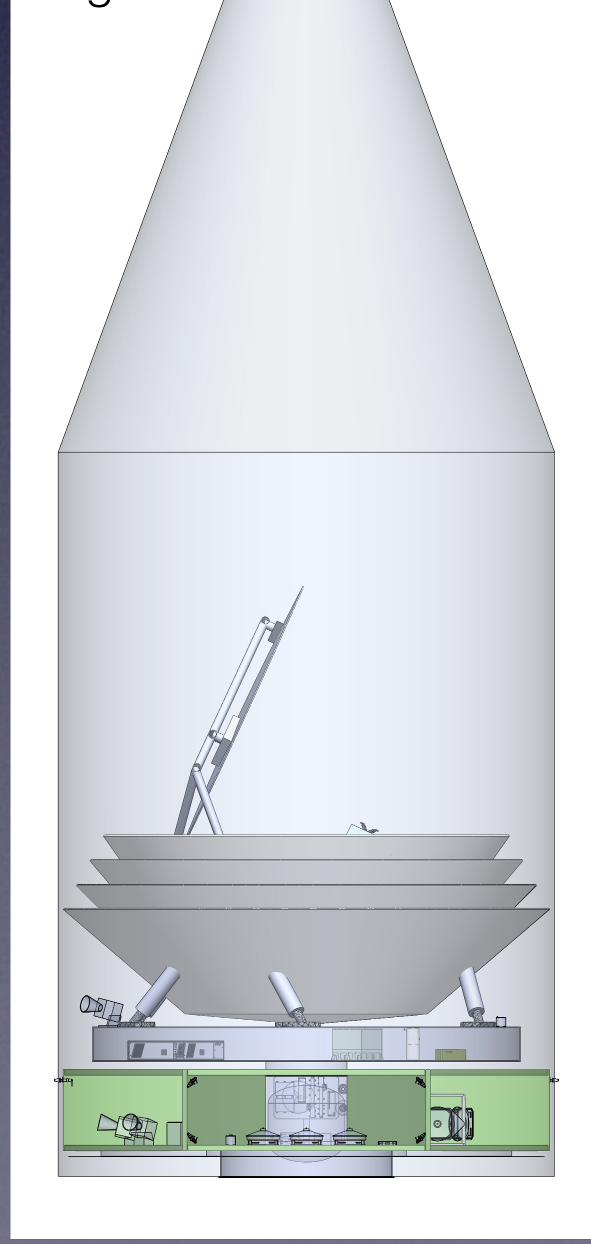


Figure: JPL

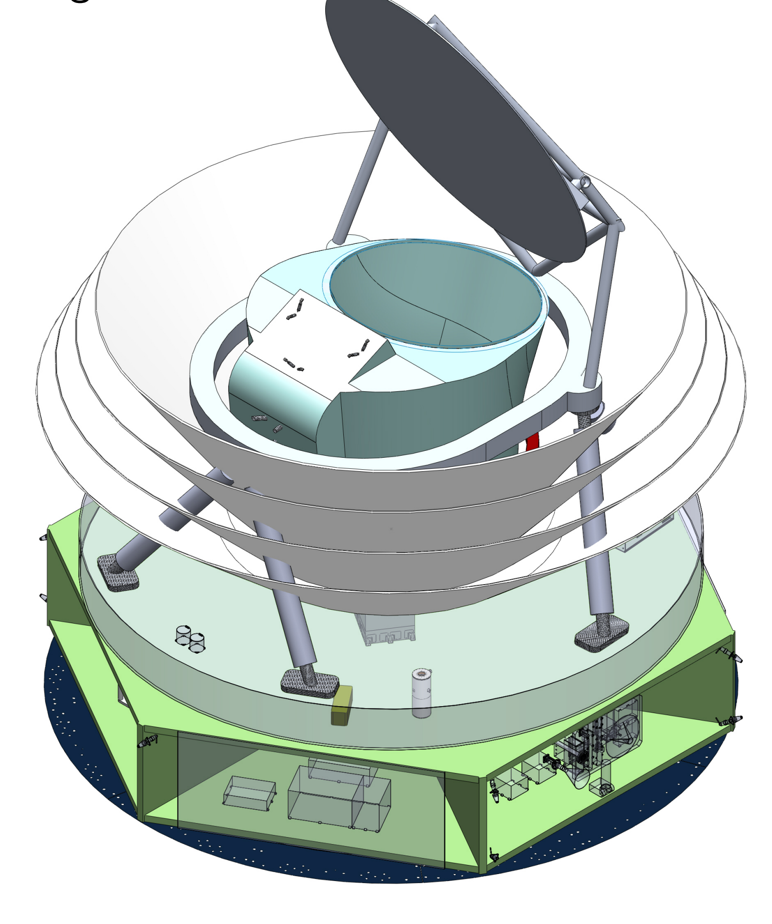
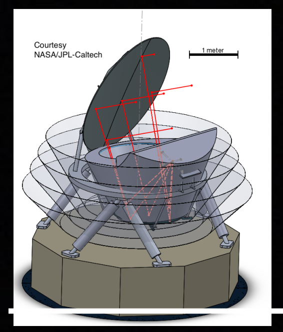
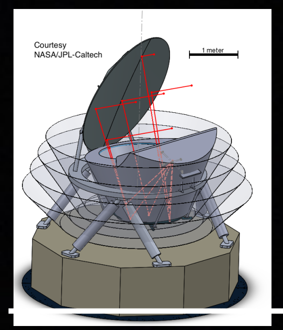


Figure: JPL



PICO Responds to all NASA Science Goals

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



Explore How the Universe Began - Inflation

- Detect / set upper bound on the energy scale of inflation; constrain inflation models
  - Requirement: $\sigma(r, r=0) \leq 1 \cdot 10^{-4}$
    $\sigma(n_s) = 1 \cdot 10^{-3}$
  - CMB4Cast (Fisher), (Feeney + Errard JCAP 2016)
    - Internal delensing (80%)
    - Maximum likelihood parametric fitting of Planck 2015-constrained foreground sky
    - Dust+Synch spectral indices varying (15 deg patches)
    - 60% of sky
  - Does not include systematic uncertainties
  - Is not map-based foreground separation

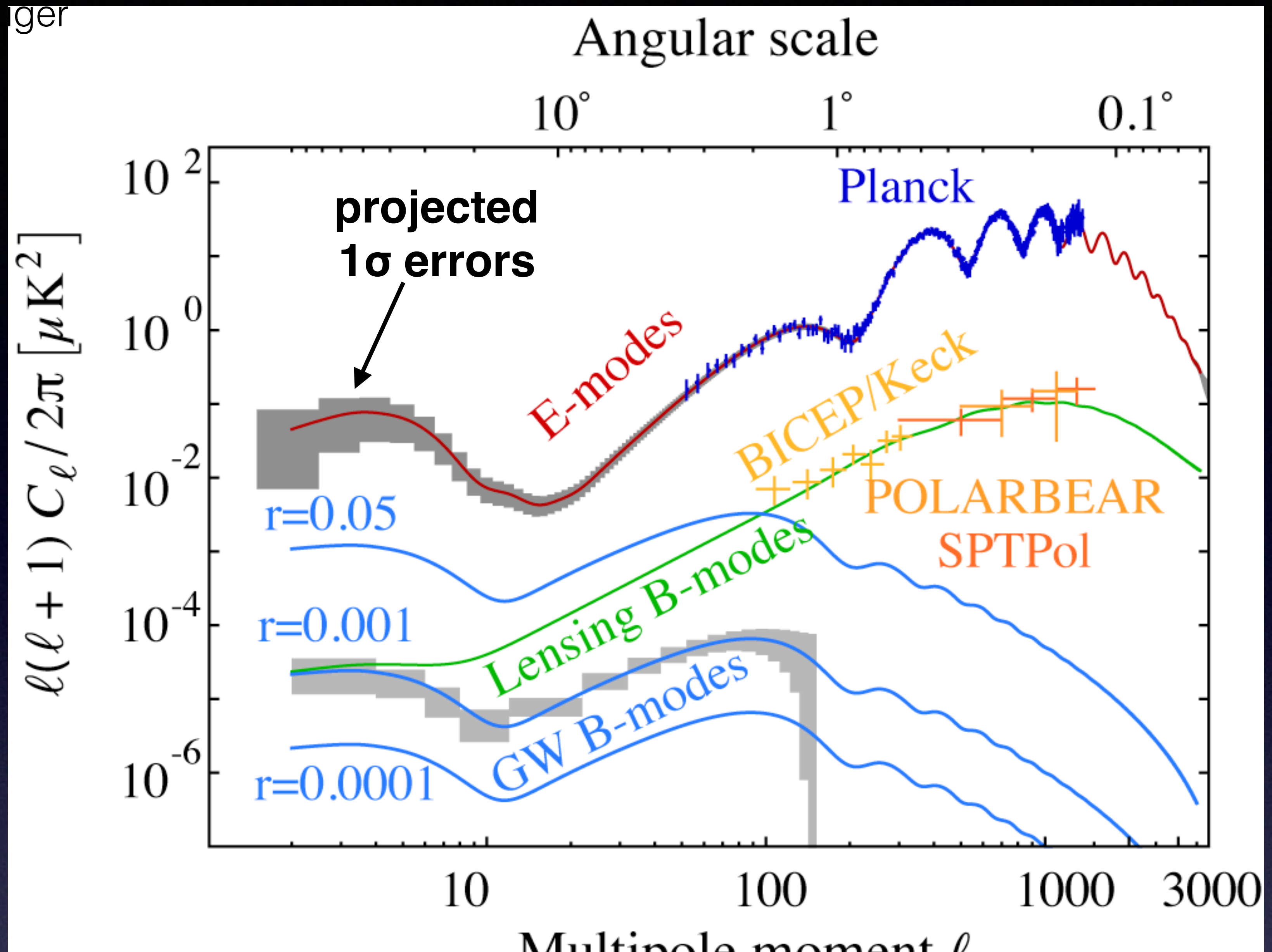


Figure: R. Flauger

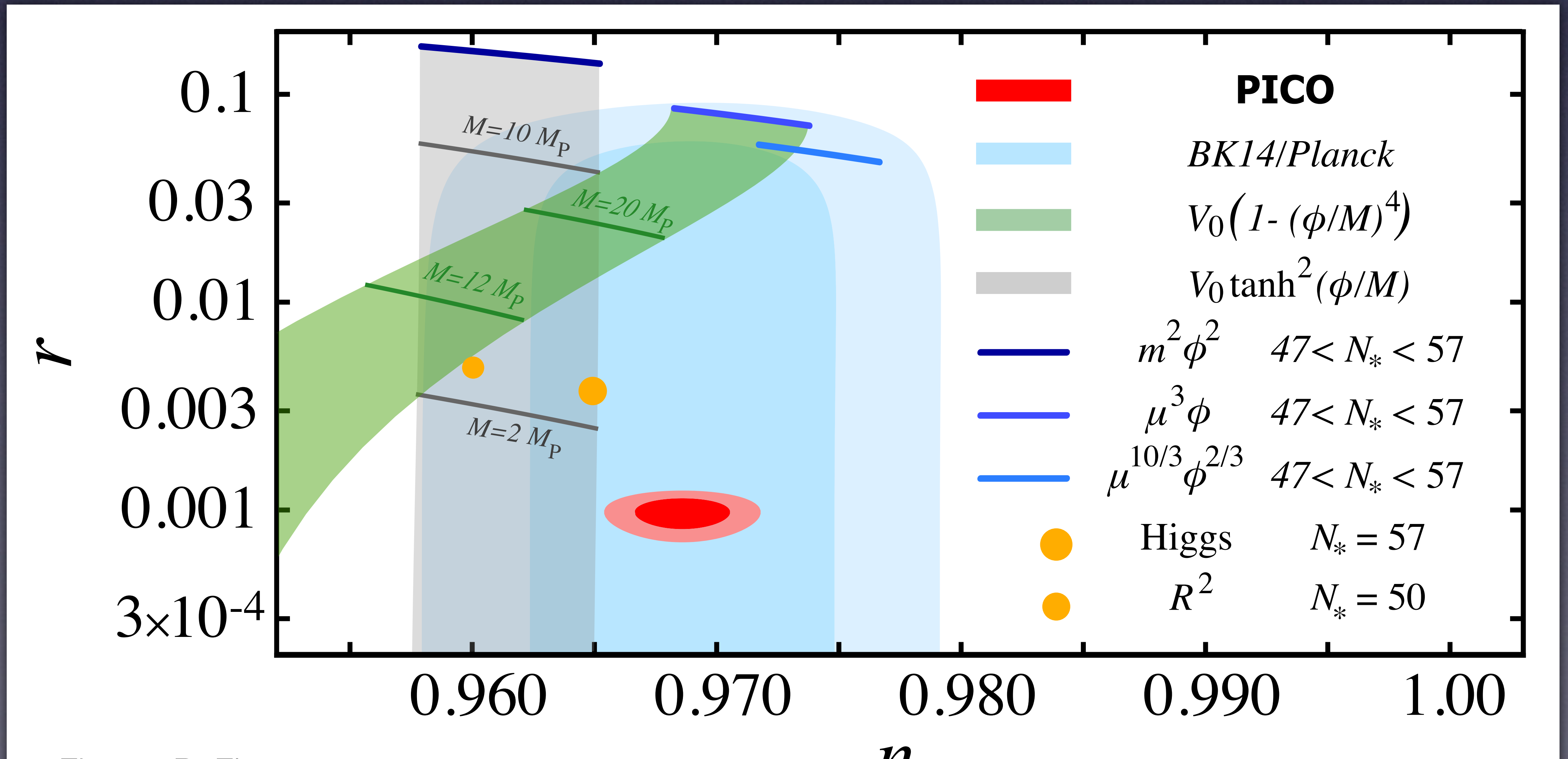
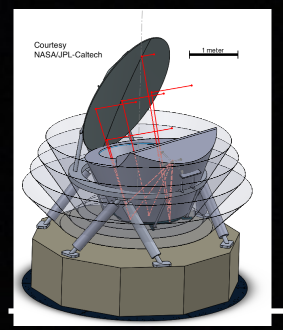
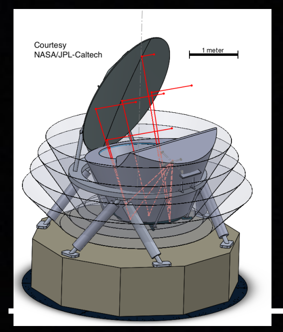


Figure: R. Flauger



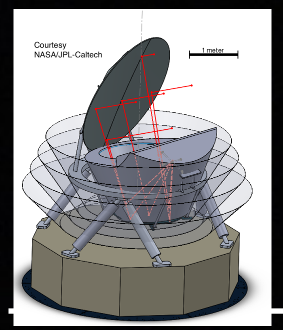
Map Based

- Working also with map-based cleaning
- 7 different full sky models, all consistent with Planck but somewhat different foreground realizations; 100 noise realizations, 50 w/r=0, 50 w/r=0.003; each in various degrees of (fake) delensing levels (1, 0.3, 0.15, 0.003); also PSM
- Several component separation approaches
  - Commander1 (PSM; Remazeilles)
  - NILC (Basak)
  - SEVEM (Barreiro)
  - + GNILC (Remazeilles), Commander2 (Wehus+), xForecast + multi-patch (Errard)

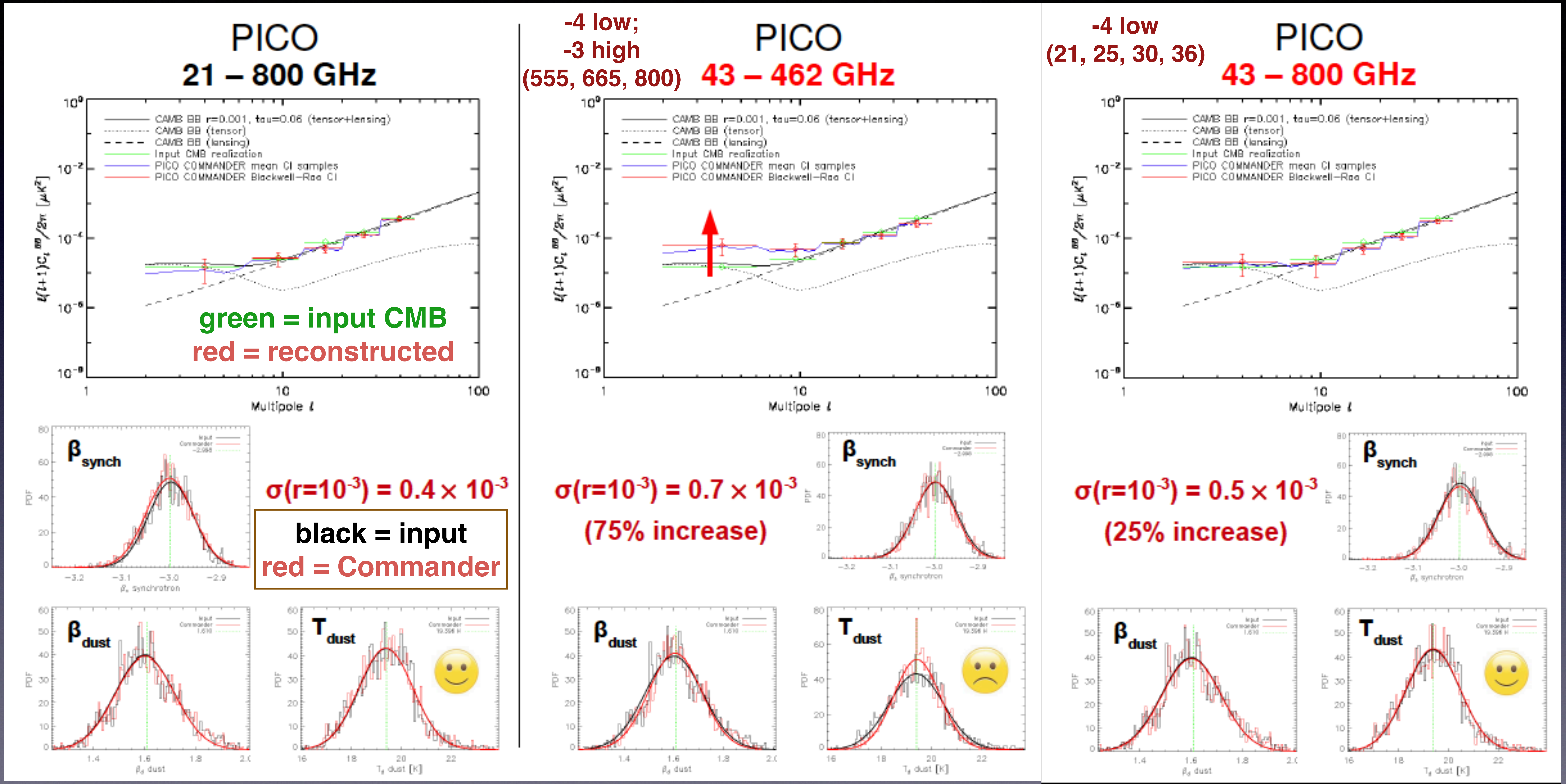


Map Based Models

- Models:
  - 90 - Gaussian dust and synchrotron, uniform amplitude
  - 91 - PySM a1d1f1s1 ; 1608.02841
  - 92 - PySM a2d4f1s3
  - 93 - PySM a2d7f1s3
  - 96 - Brandon’s MHD
  - 98 - Delabrouille ++, Multi-layer dust; 1706.04162
  - 99 - Vansyngel; 1611.02577



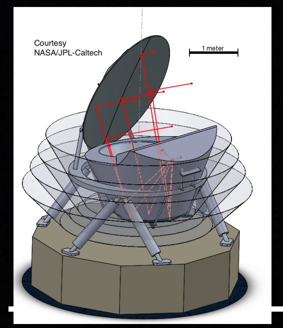
The Role of High Frequency Bands



M. Remazeilles

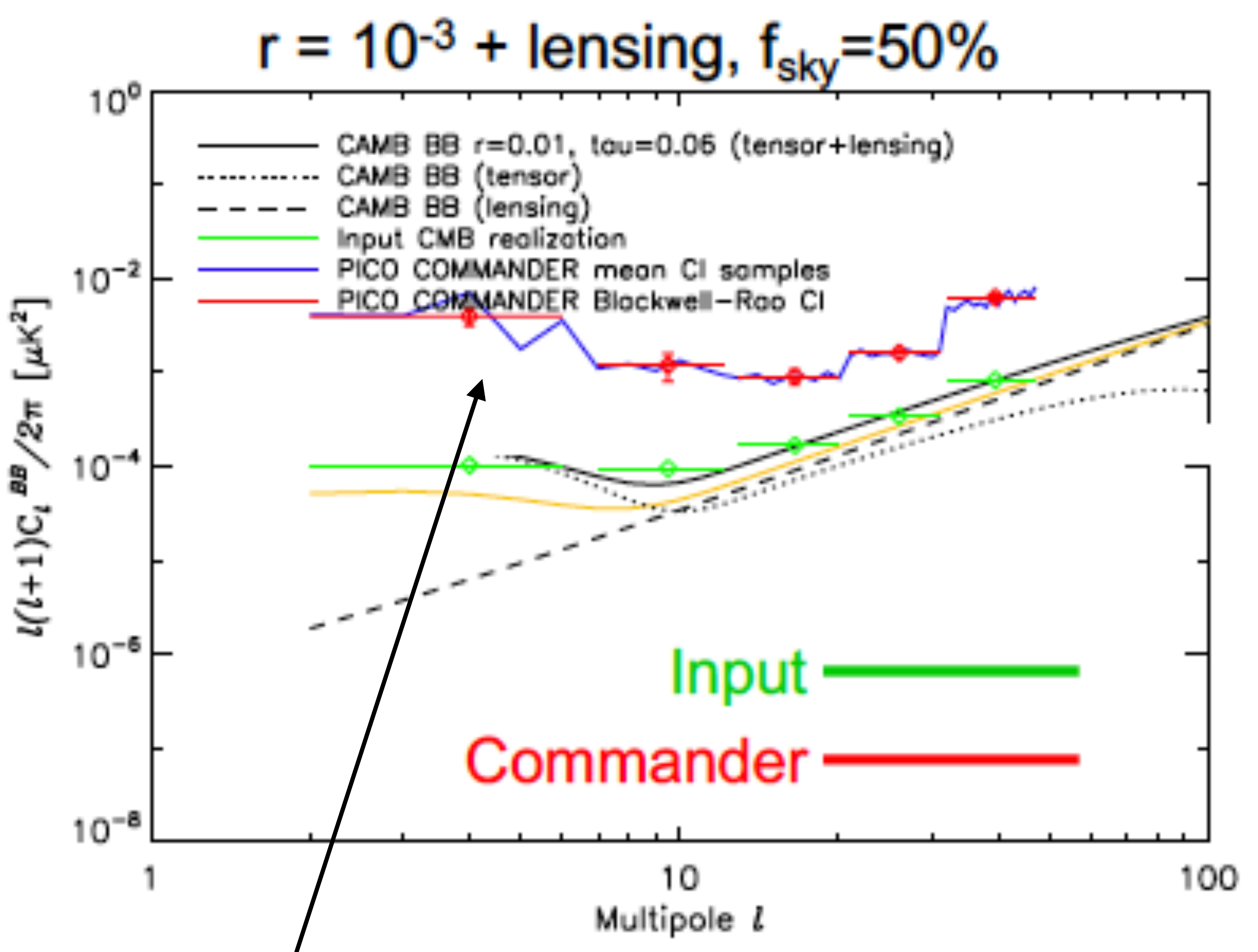
Synchrotron curvature, Cs = 0.3 over the entire sky, also fitted

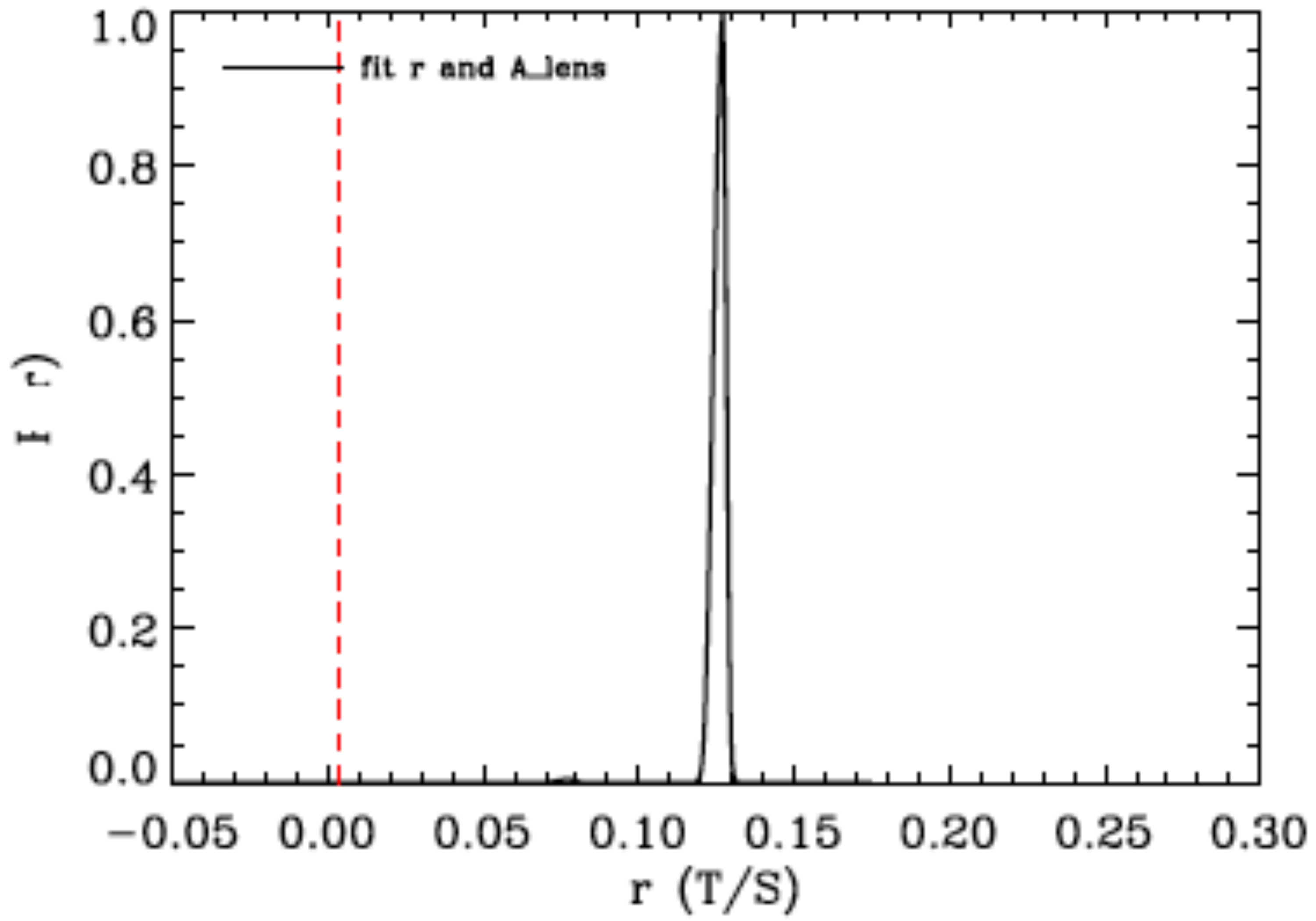
The Effects of Averaging



Commander reconstruction of CMB B-modes

PySM 90.91 (a1d1f1s1)





Strong bias

$2 \leq \ell \leq 50$

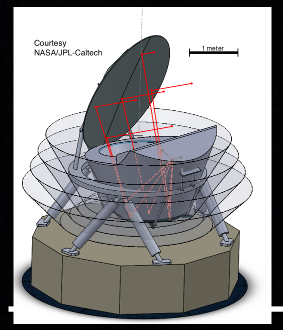
Native resolution nside=512

Commander analysis nside = 16

PySM 90.91 simulation (Clem Pryke)

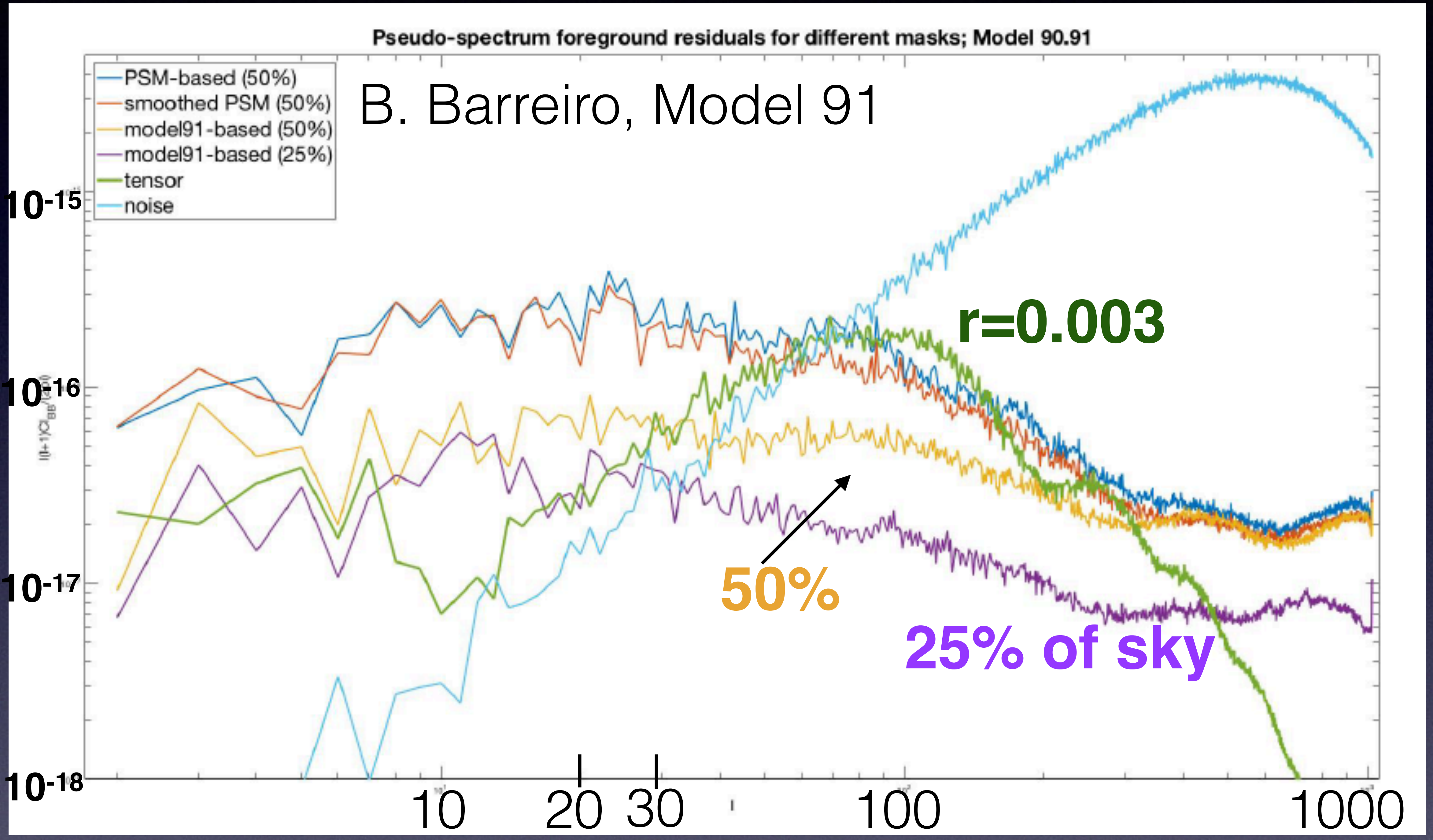
<u>Bias due to averaging issues</u>, as expected: by degrading the native Nside=512 sky maps to Nside=16, the foreground SEDs are mixed up (no longer MBB and power laws) → mismatch between the fitted foreground model and the effective Nside=16 model

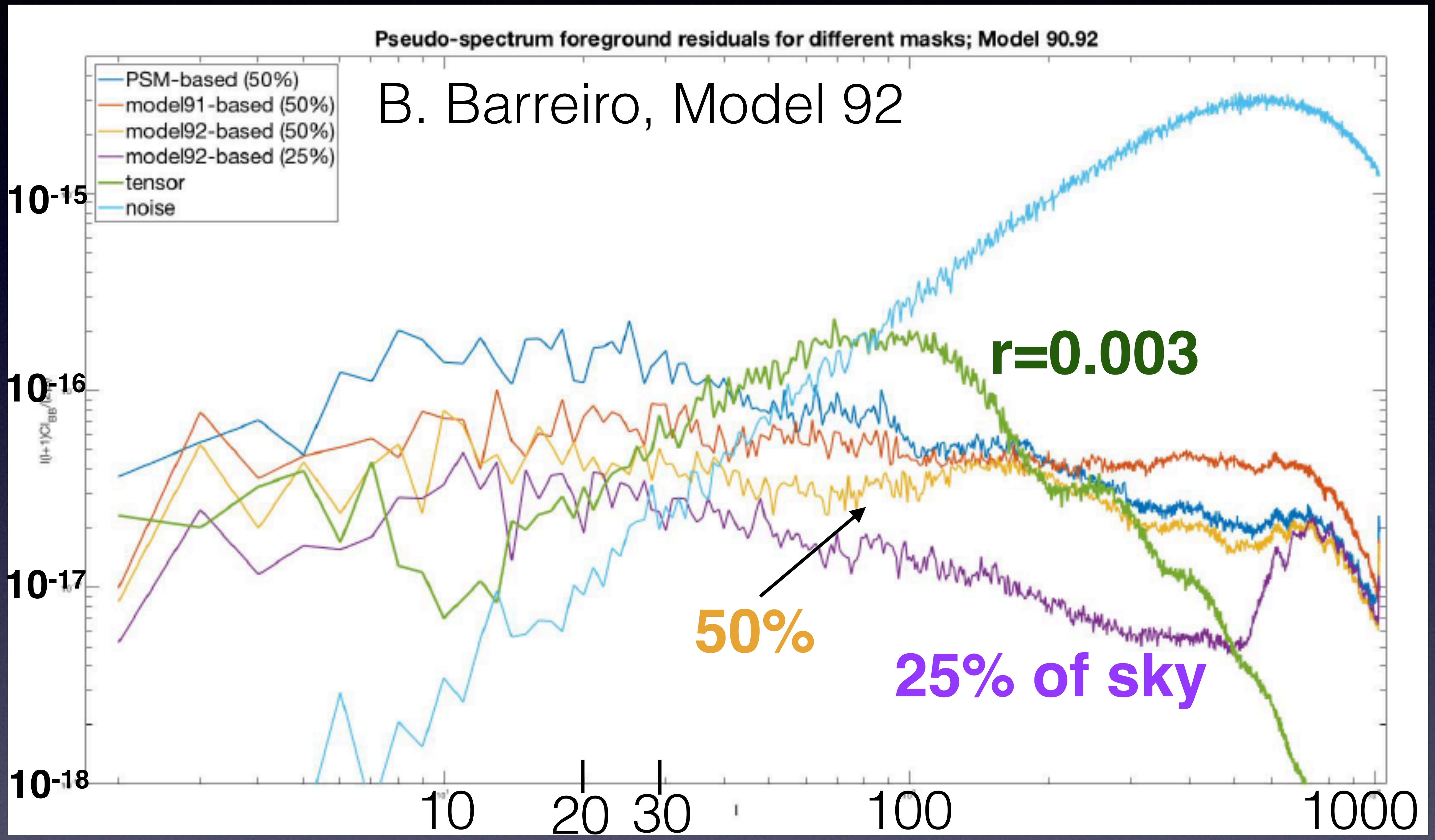
M. Remazeilles



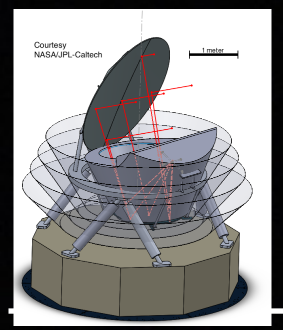
The Challenge of low \ell Foregrounds - SEVEM

Preliminary Results

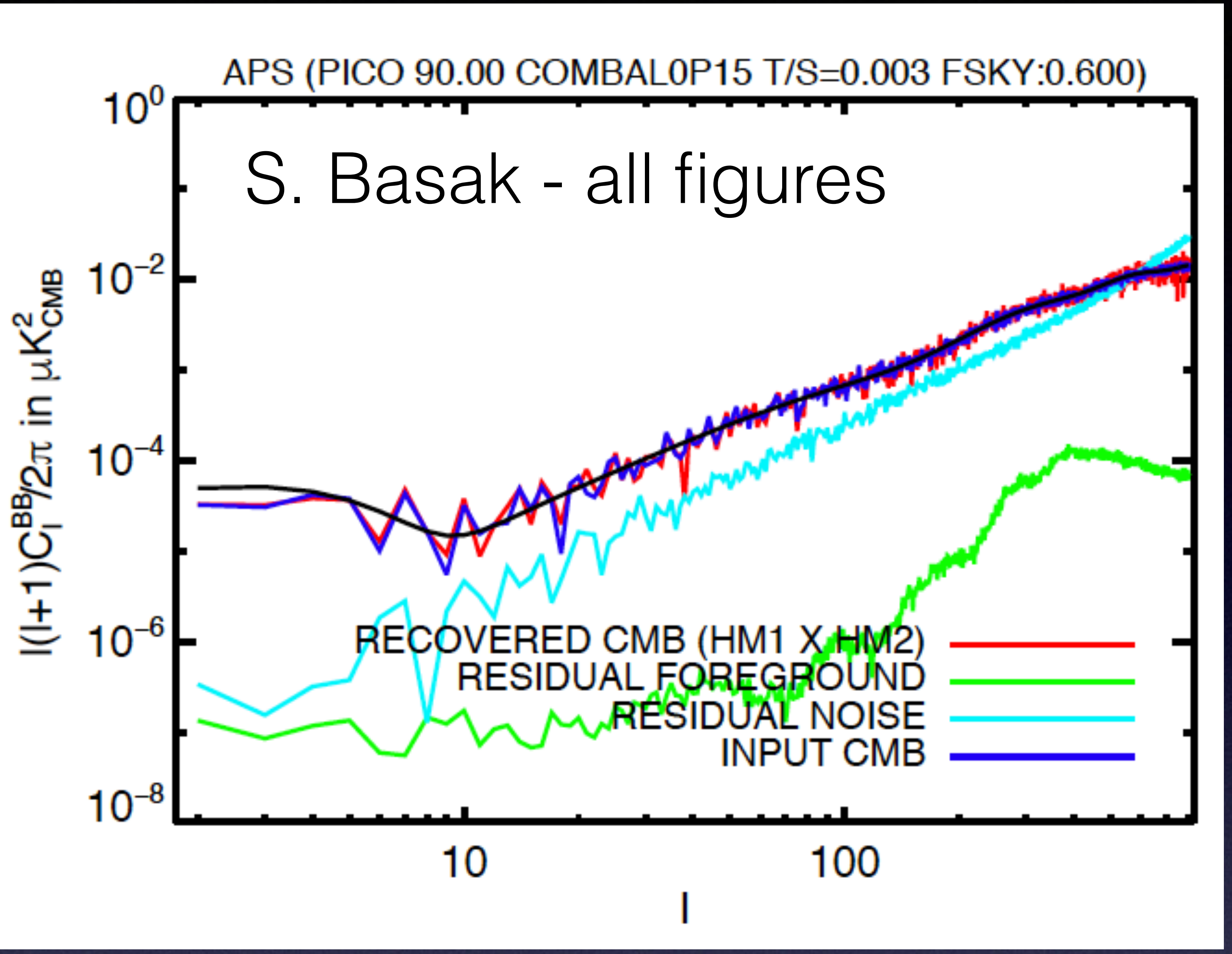


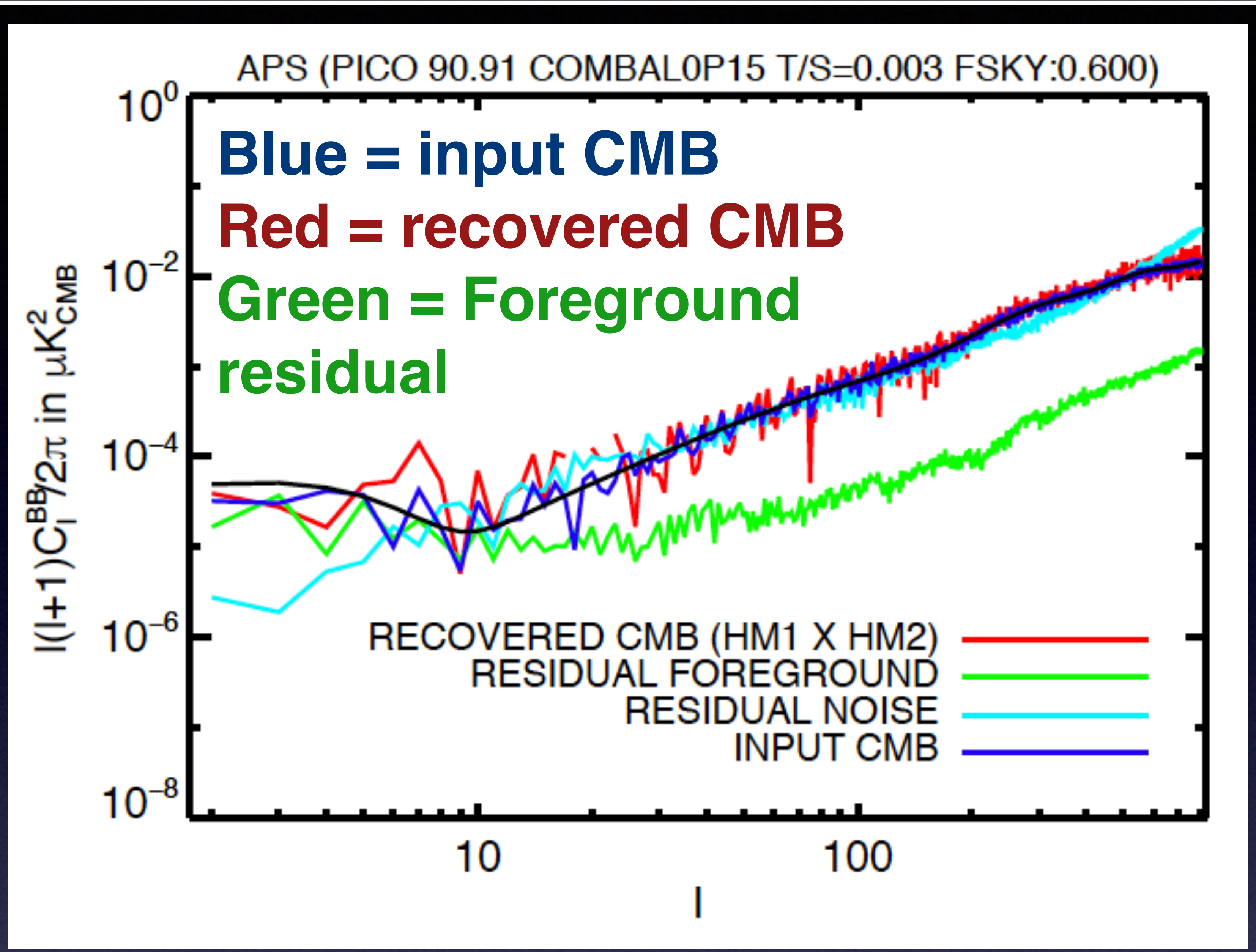


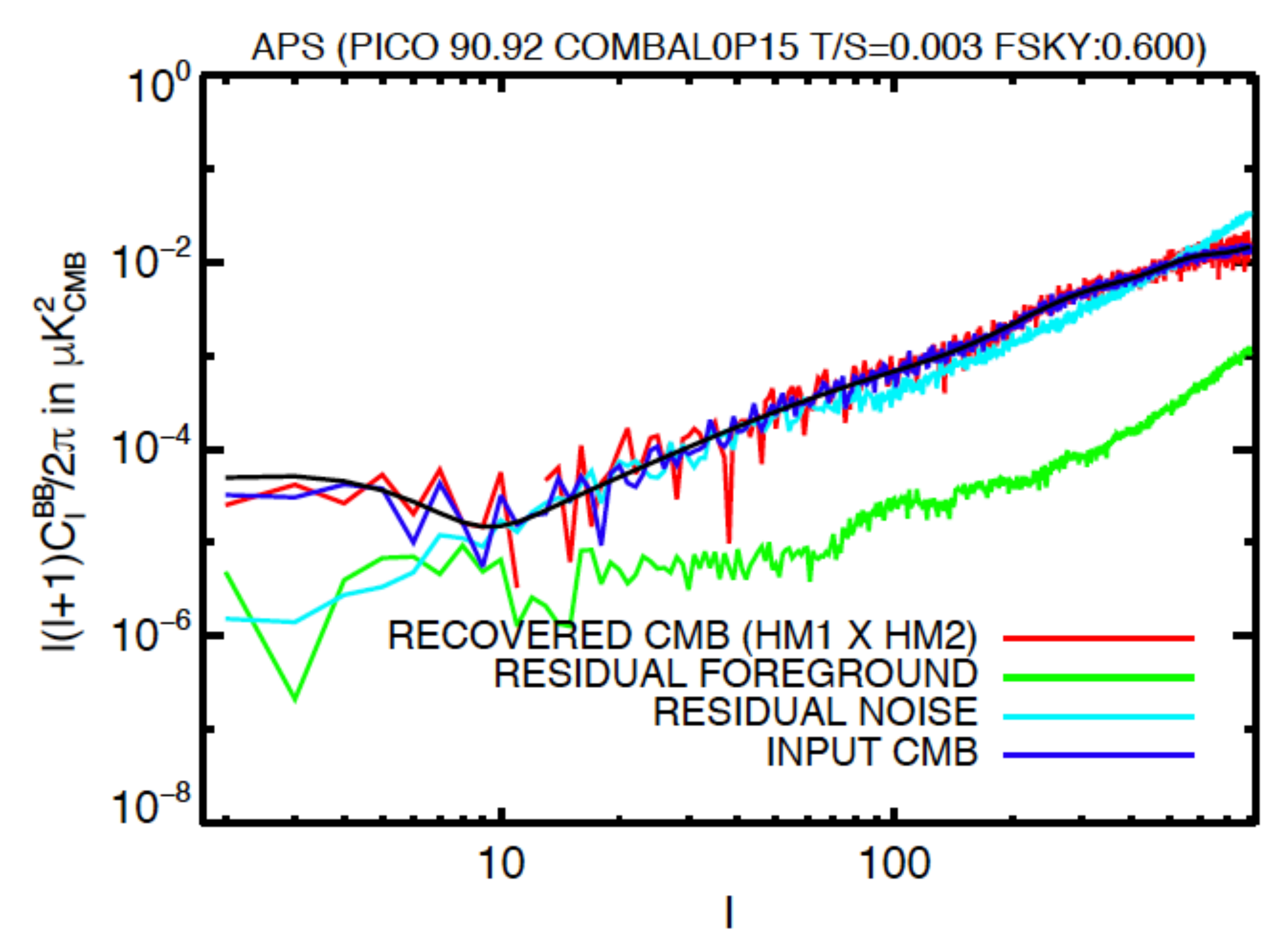
- Experiments with masks
- For spectra shown, masks are based on residuals of that model

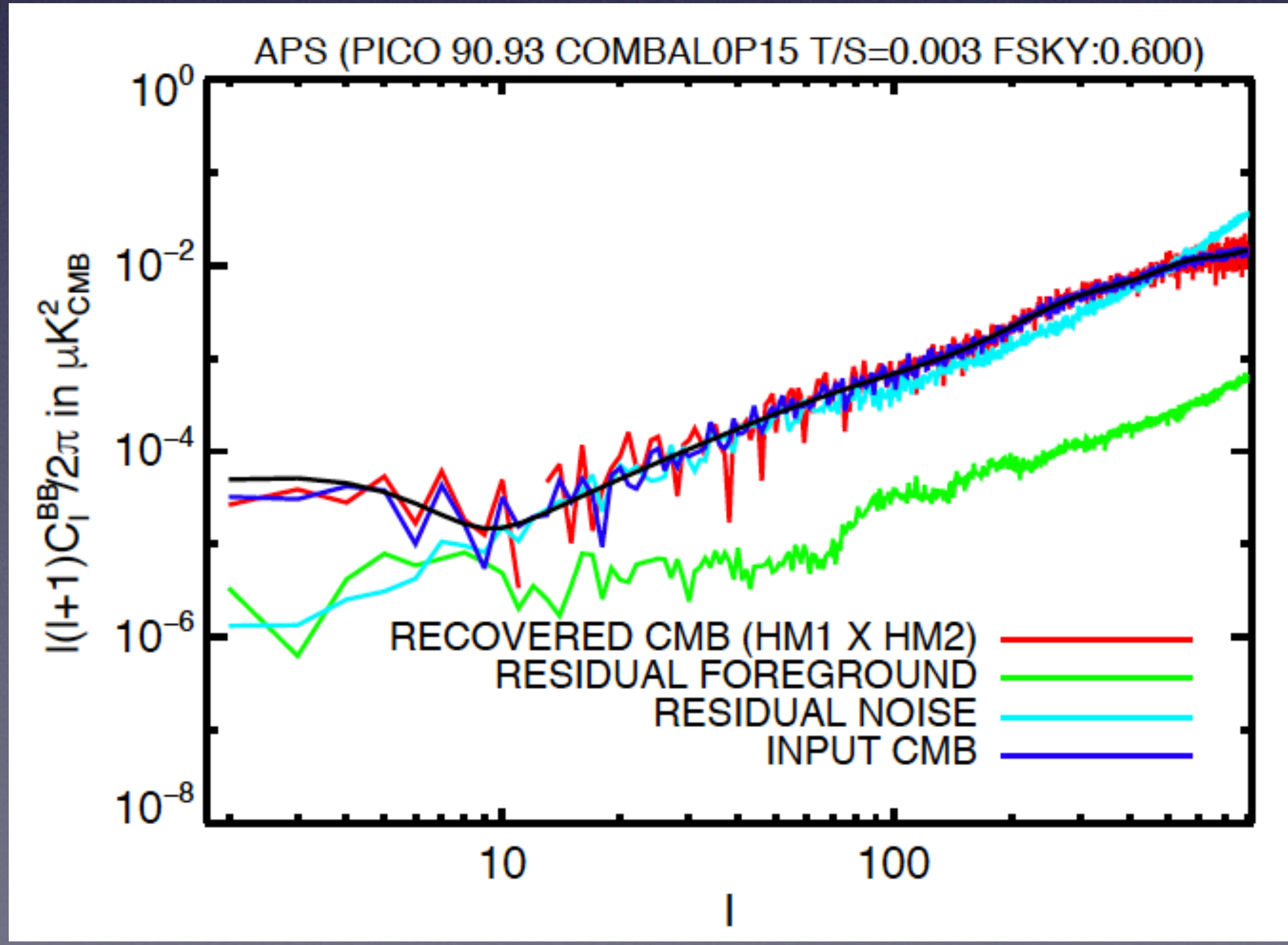


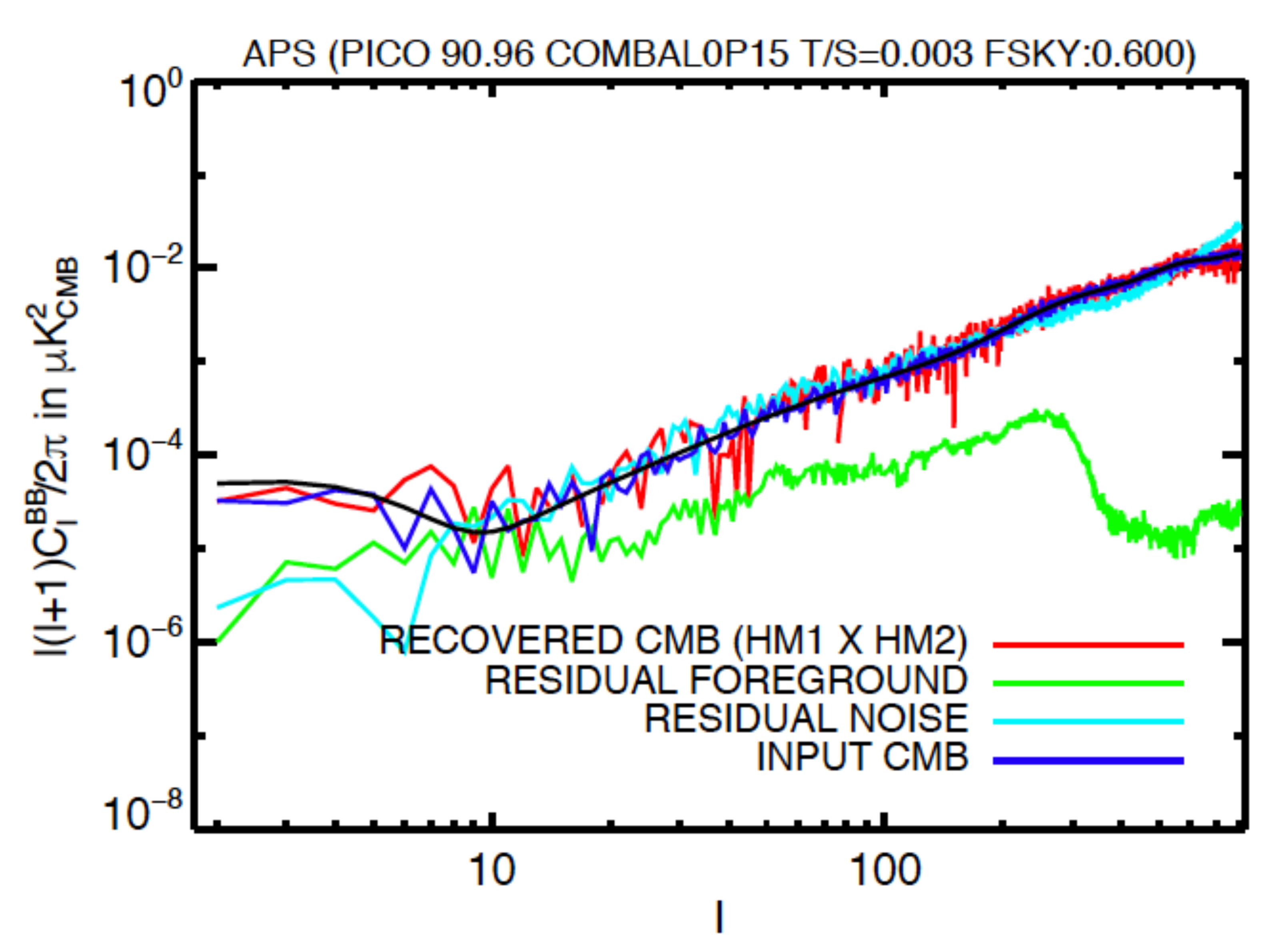
The Challenge of low \ell Foregrounds - NILC

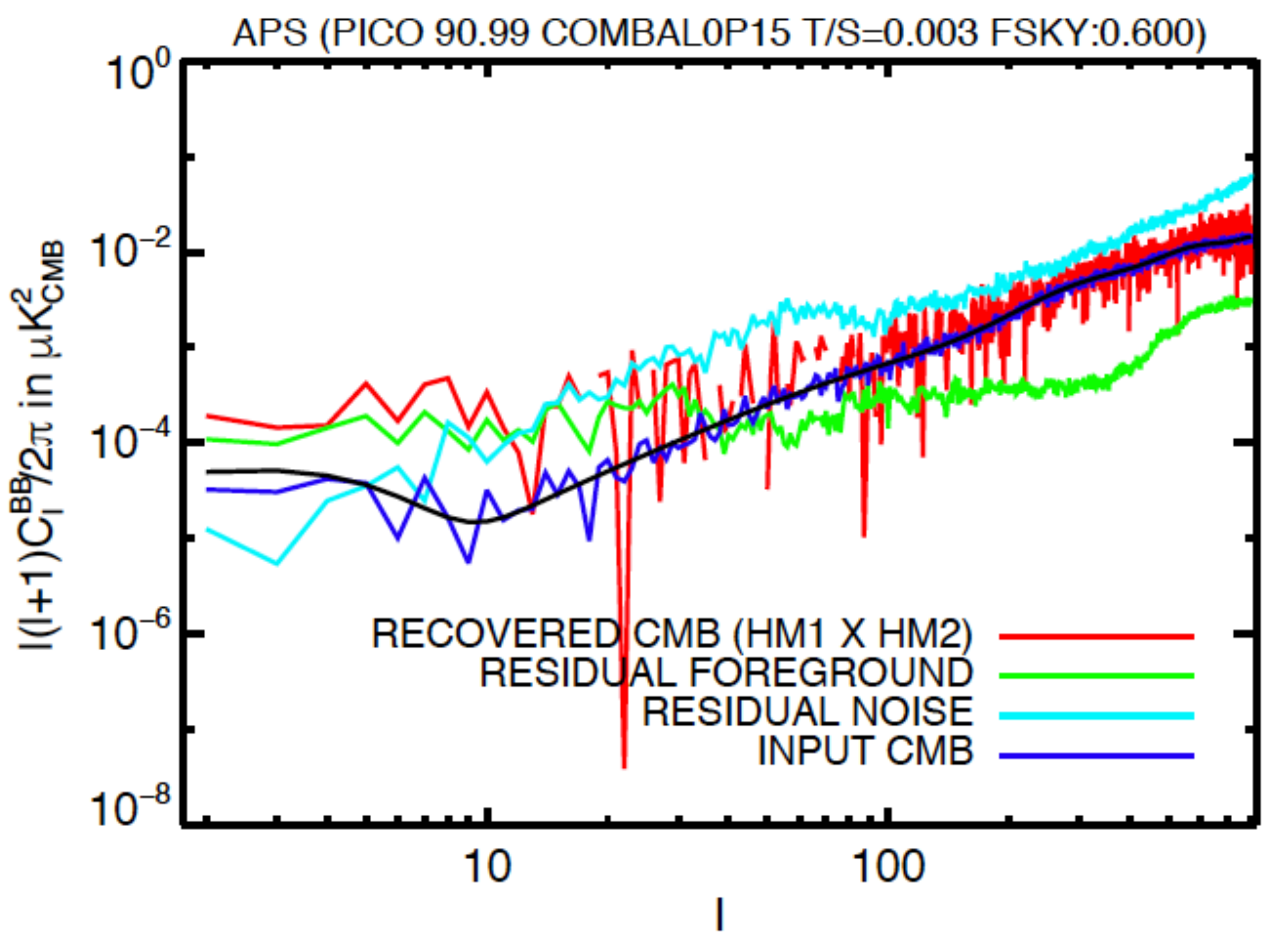


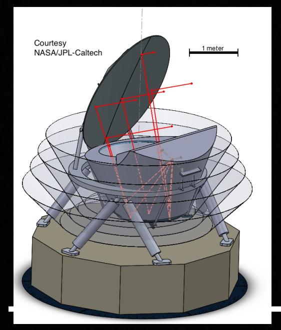






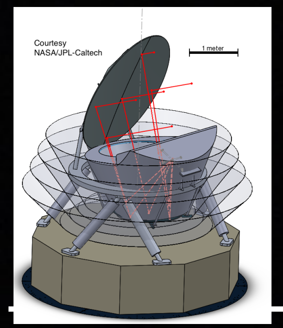






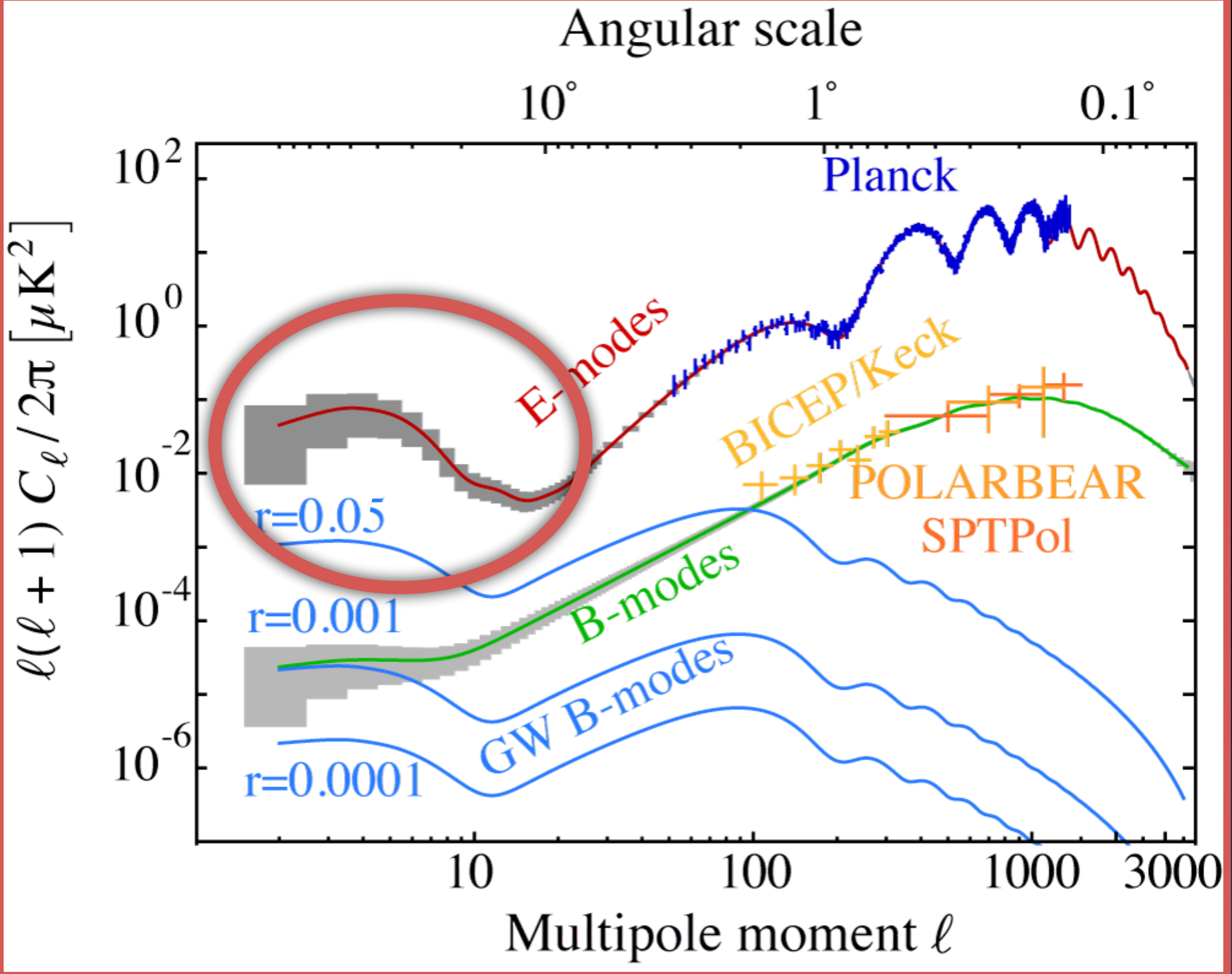
The Challenge of low \ell Foregrounds

- What’s next
  - SEVEM - attempting coarser resolution
  - NILC - more realizations
  - Graca is estimating parameters
  - More methods soon



Explore how the Universe Evolved - Reionization

- Determine the reionization history of the Universe
- $\sigma(\tau) = 0.002$ CV limited



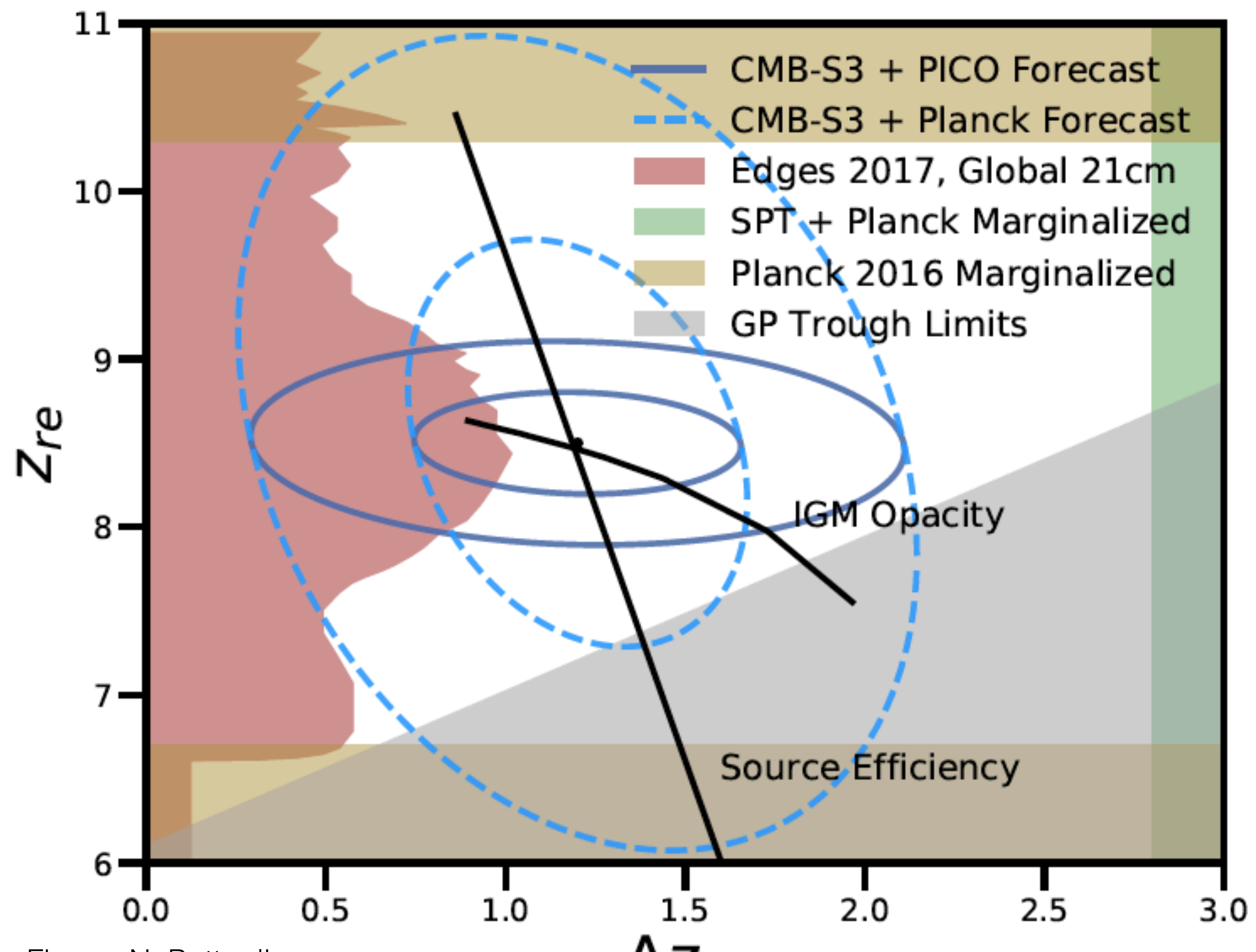
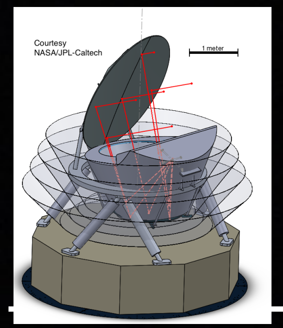


Figure: N. Battaglia

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



Discover How The Universe Works - Neff

- Constrain the number of light relics in the early Universe
- $\sigma(N_{eff}) = 0.03$
- Constraint is proportional to number of ℓ modes in TT, TE, and EE
- Extend range of energy to exclude new species by
  - x300 for vector particle
  - x2.5 for scalar particle
  - Cross the QCD phase transition

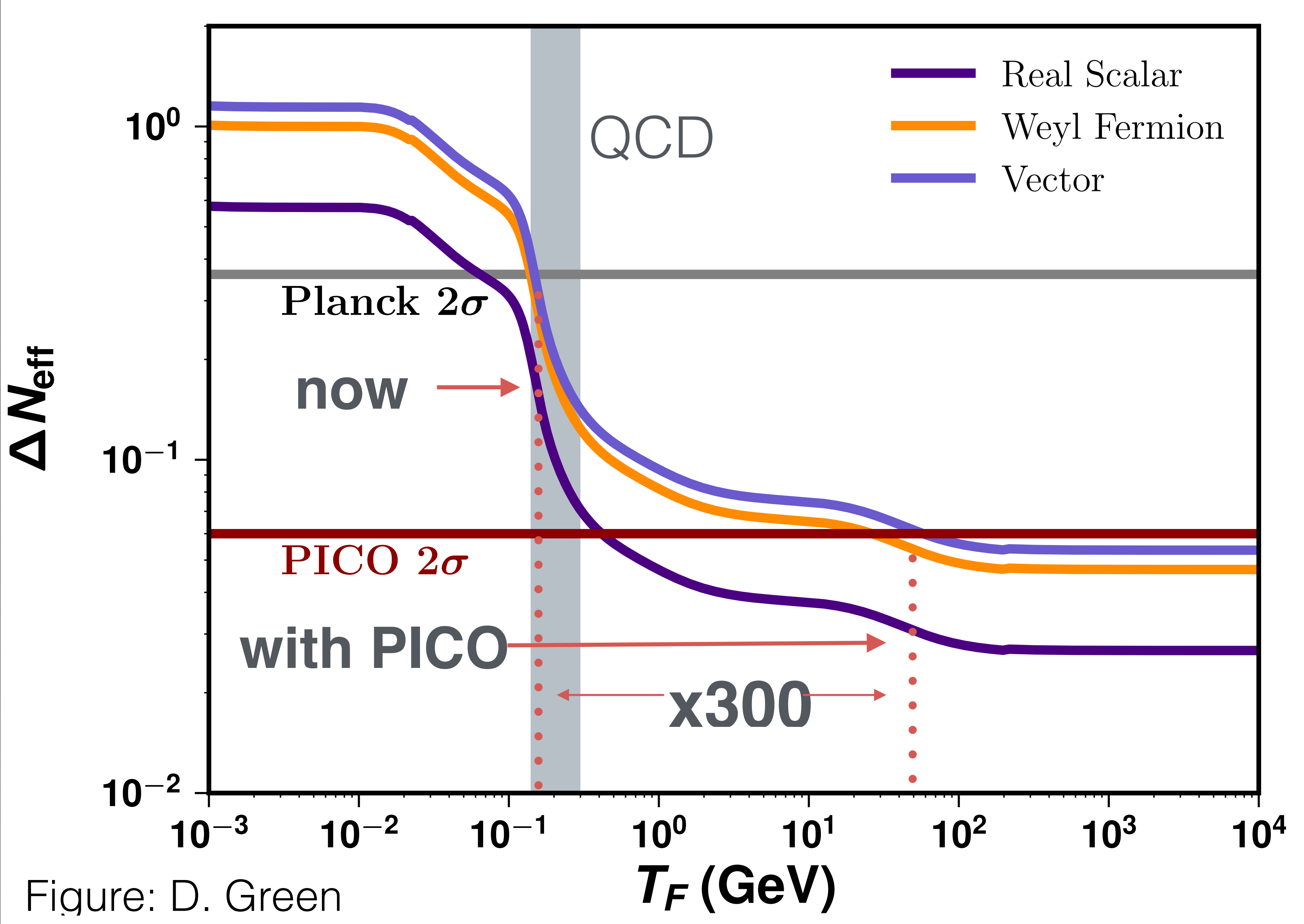


Figure: D. Green

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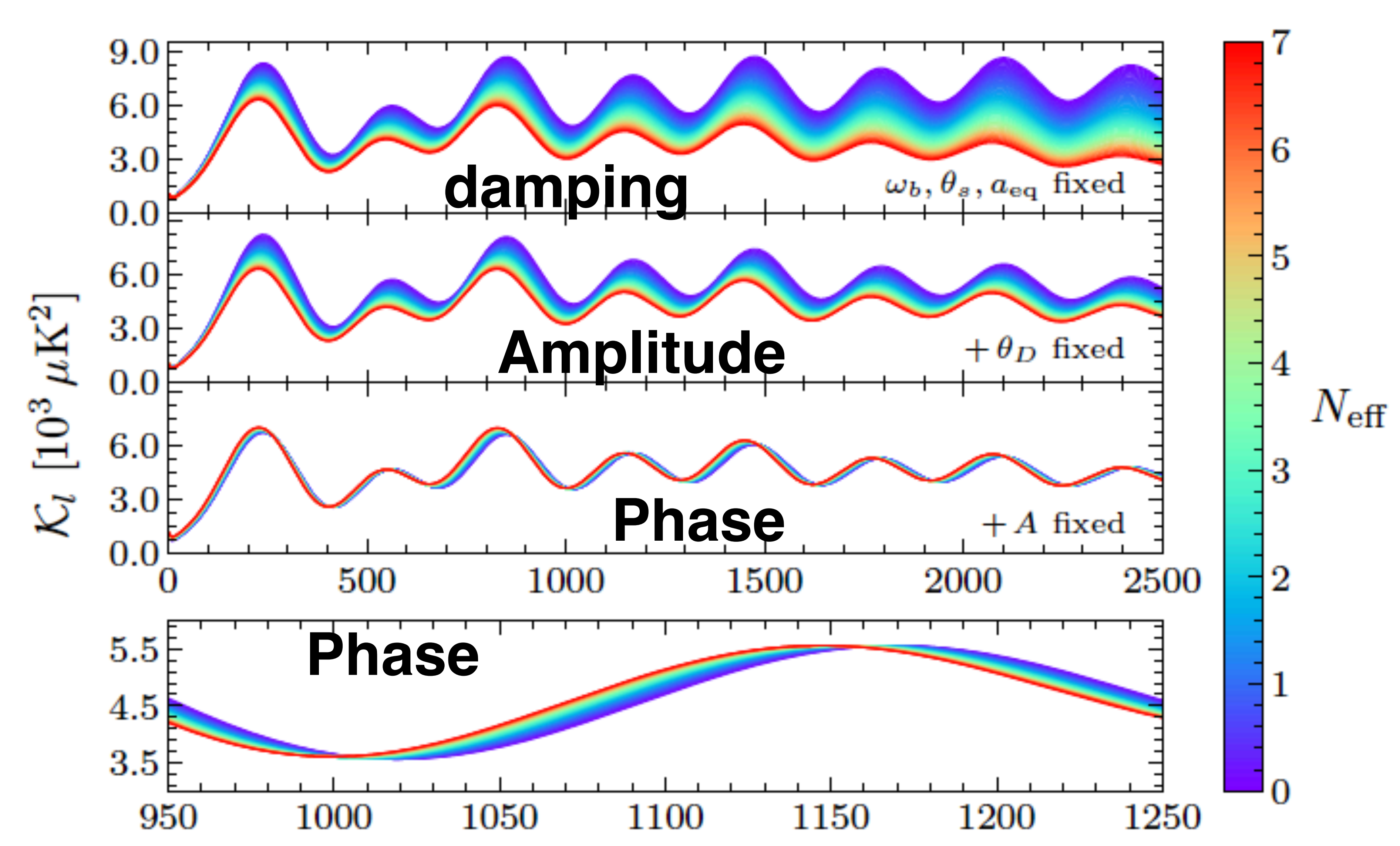
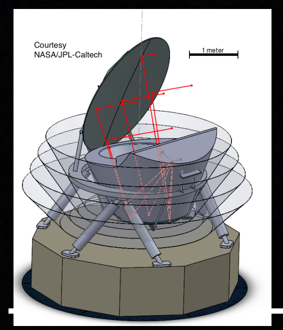


Baumann et al. 2017



Discover How The Universe Works - Neutrino Mass

- Determine the sum of neutrino masses
- Measurements of the matter power spectrum, primarily through the lensing potential power spectrum (\ell~1000)
- Break degeneracy between τ and $\Omega_m h^2$ with DESI-BAO
- $\sigma(\Sigma m_\nu) = 14 \ \text{meV}$
- 4σ or 7σ detection
- Similar, independent constraint from PICO cluster counts
- PICO gives both tau and lensing

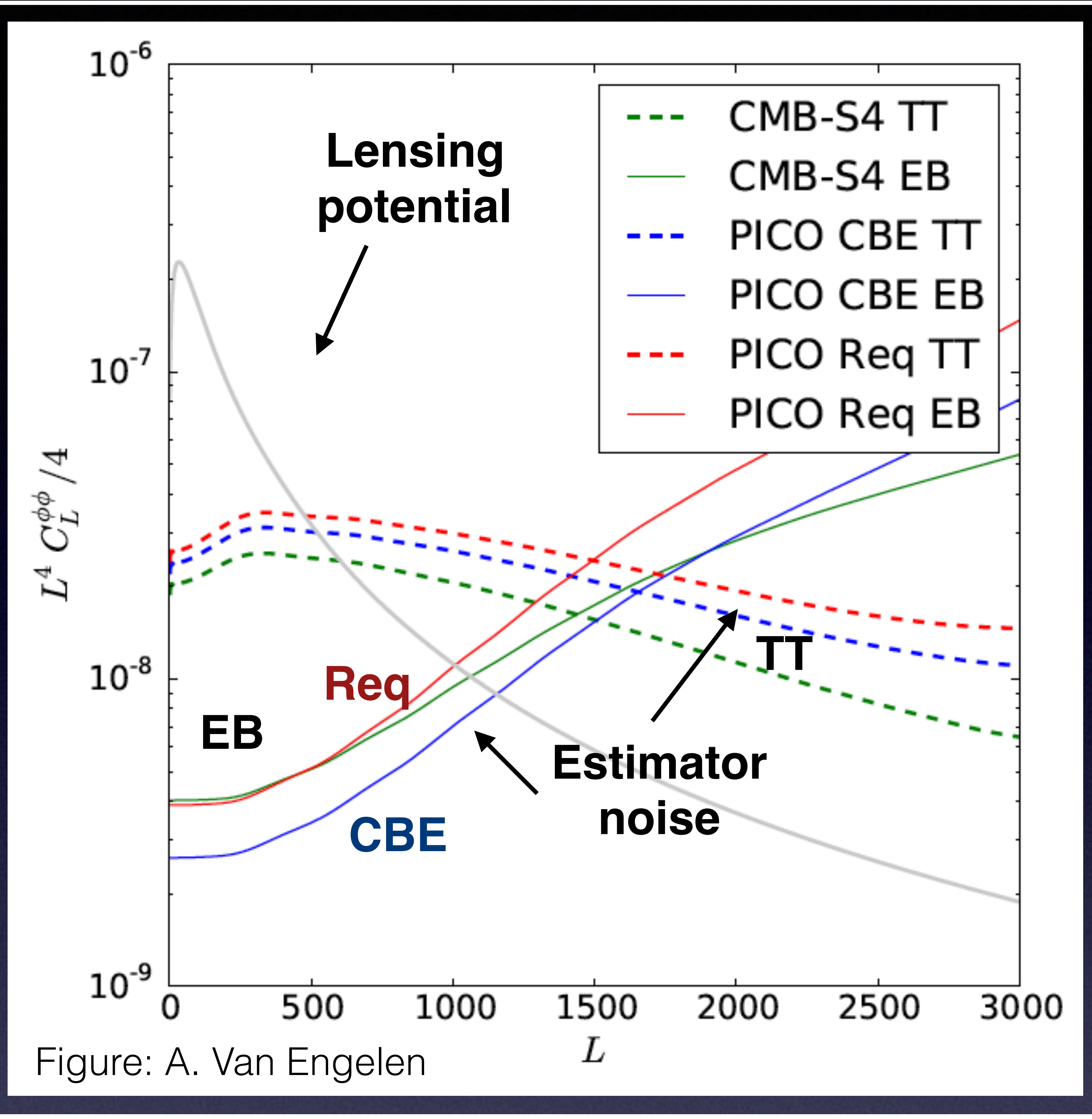


Figure: A. Van Engelen

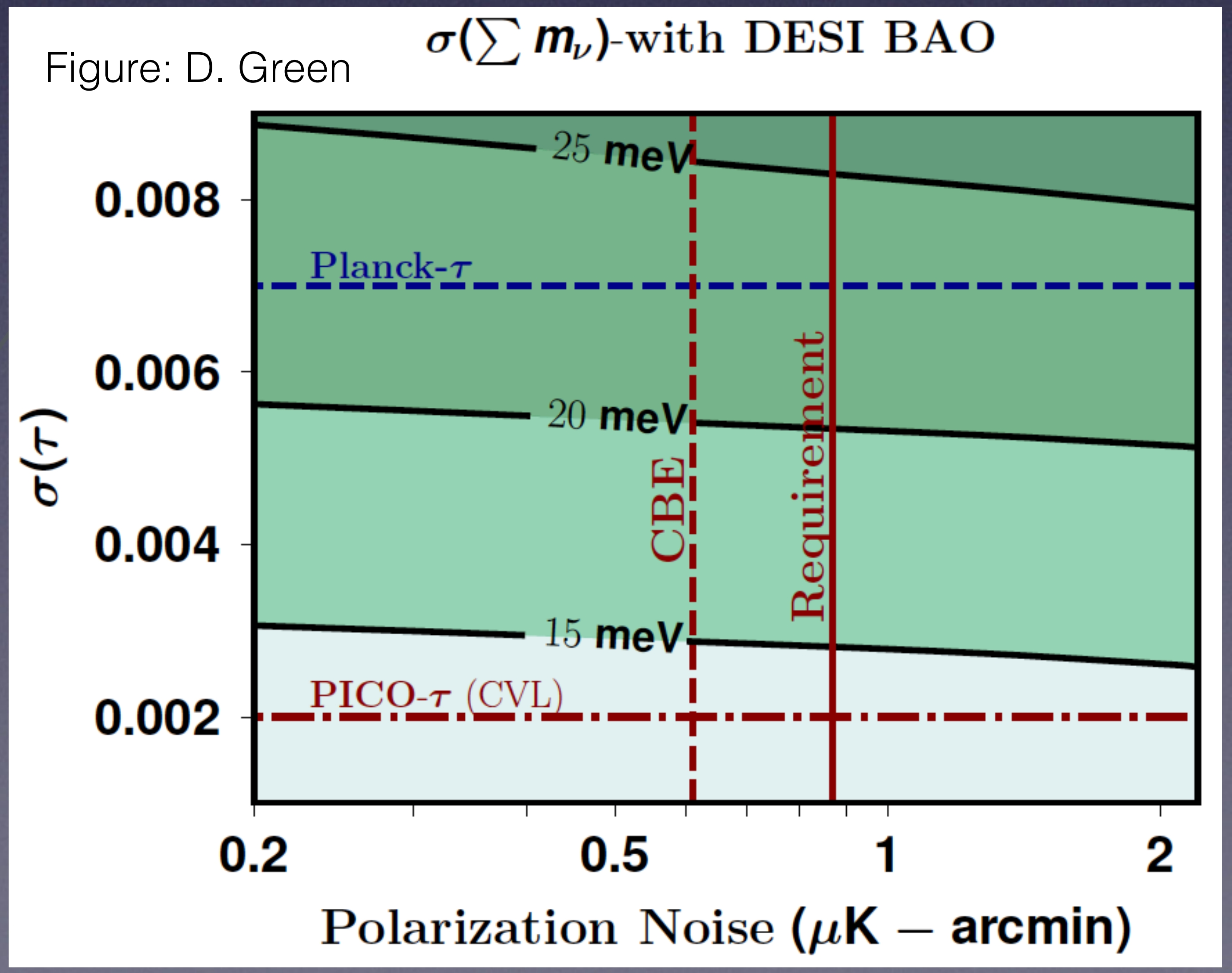
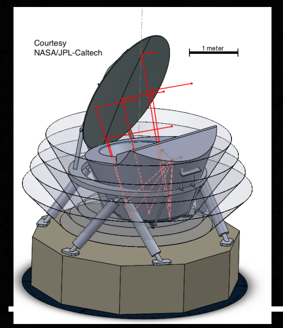


Figure: D. Green

Foreground Effects on phi-phi and delensing



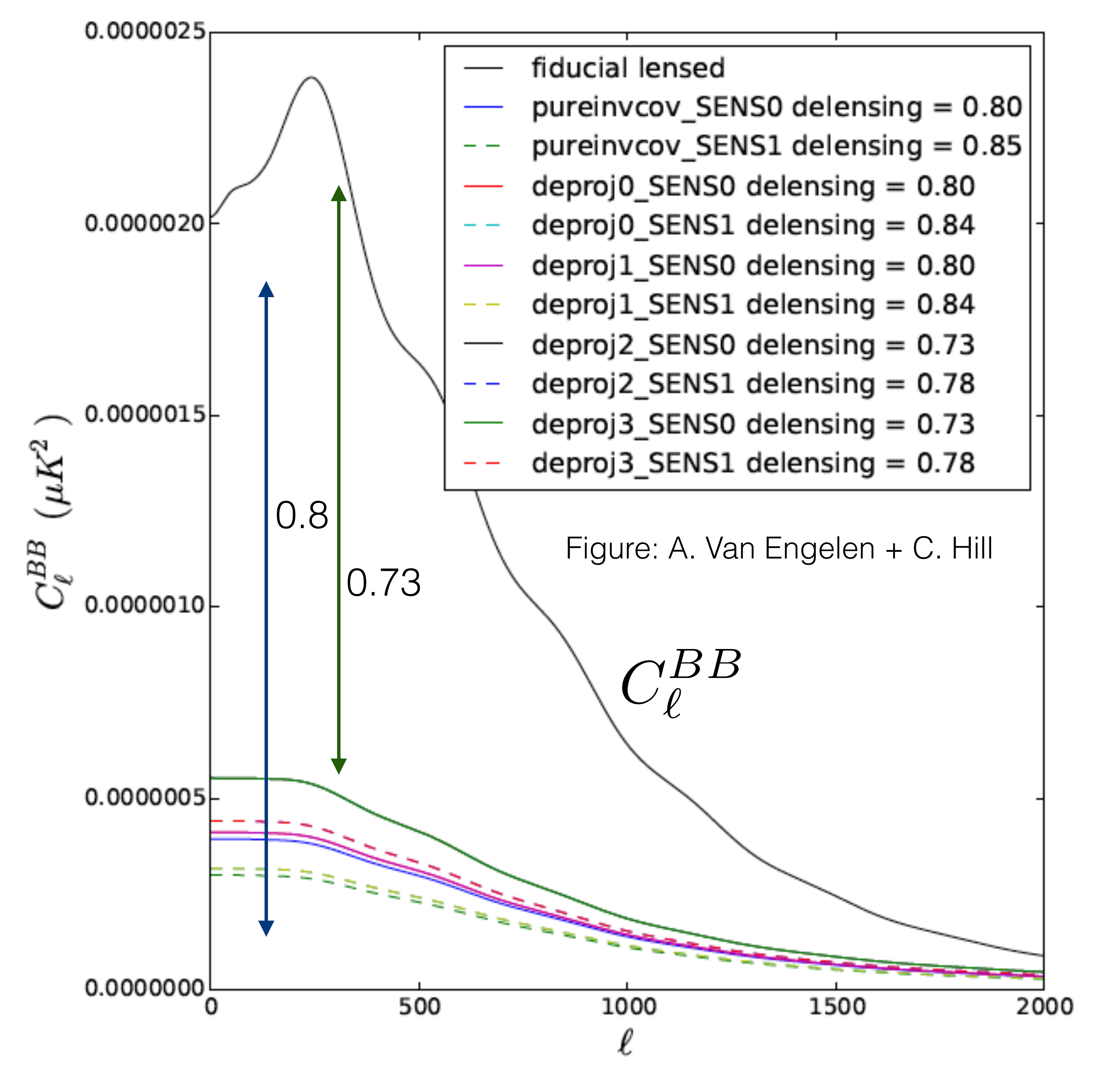


Figure: A. Van Engelen + C. Hill

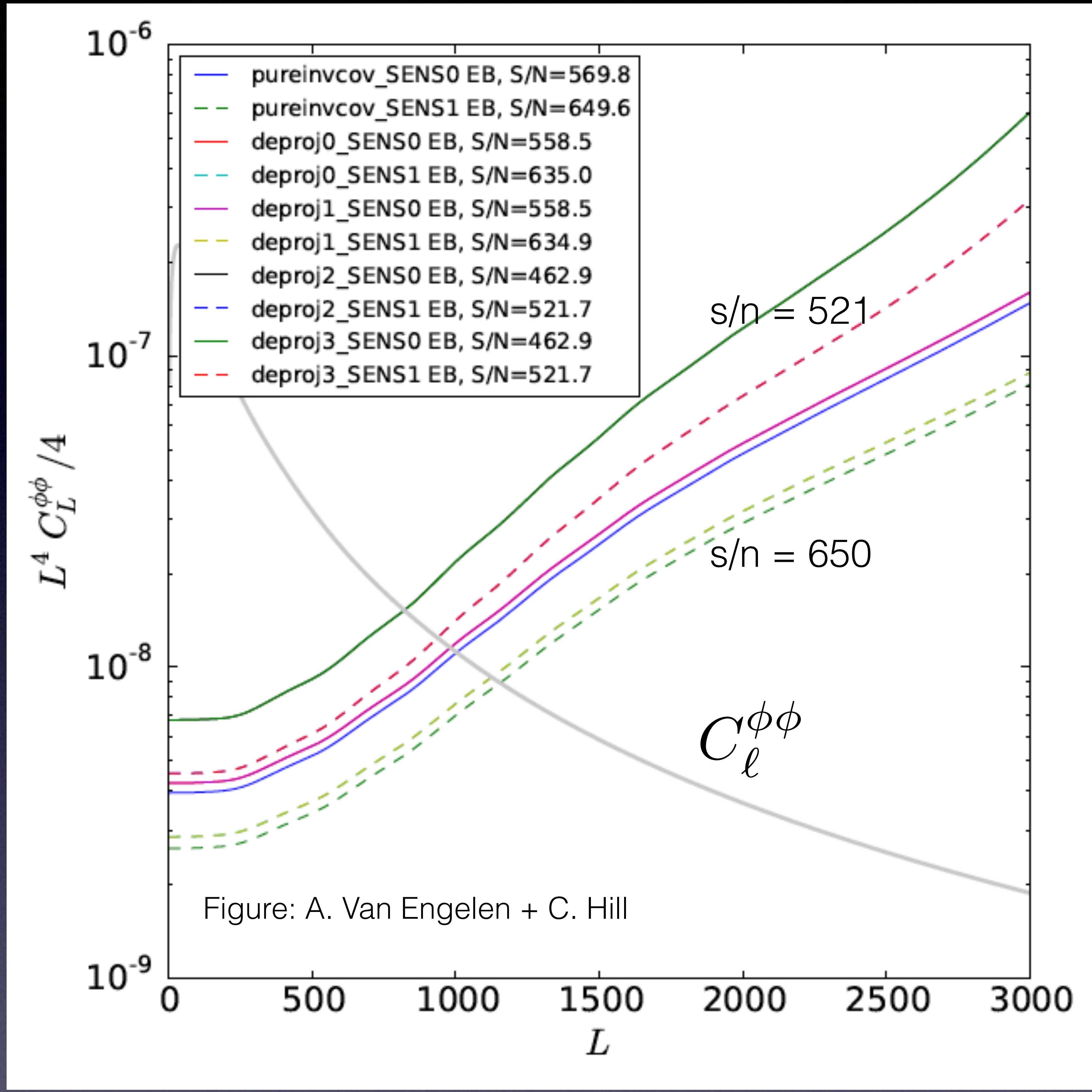


Figure: A. Van Engelen + C. Hill

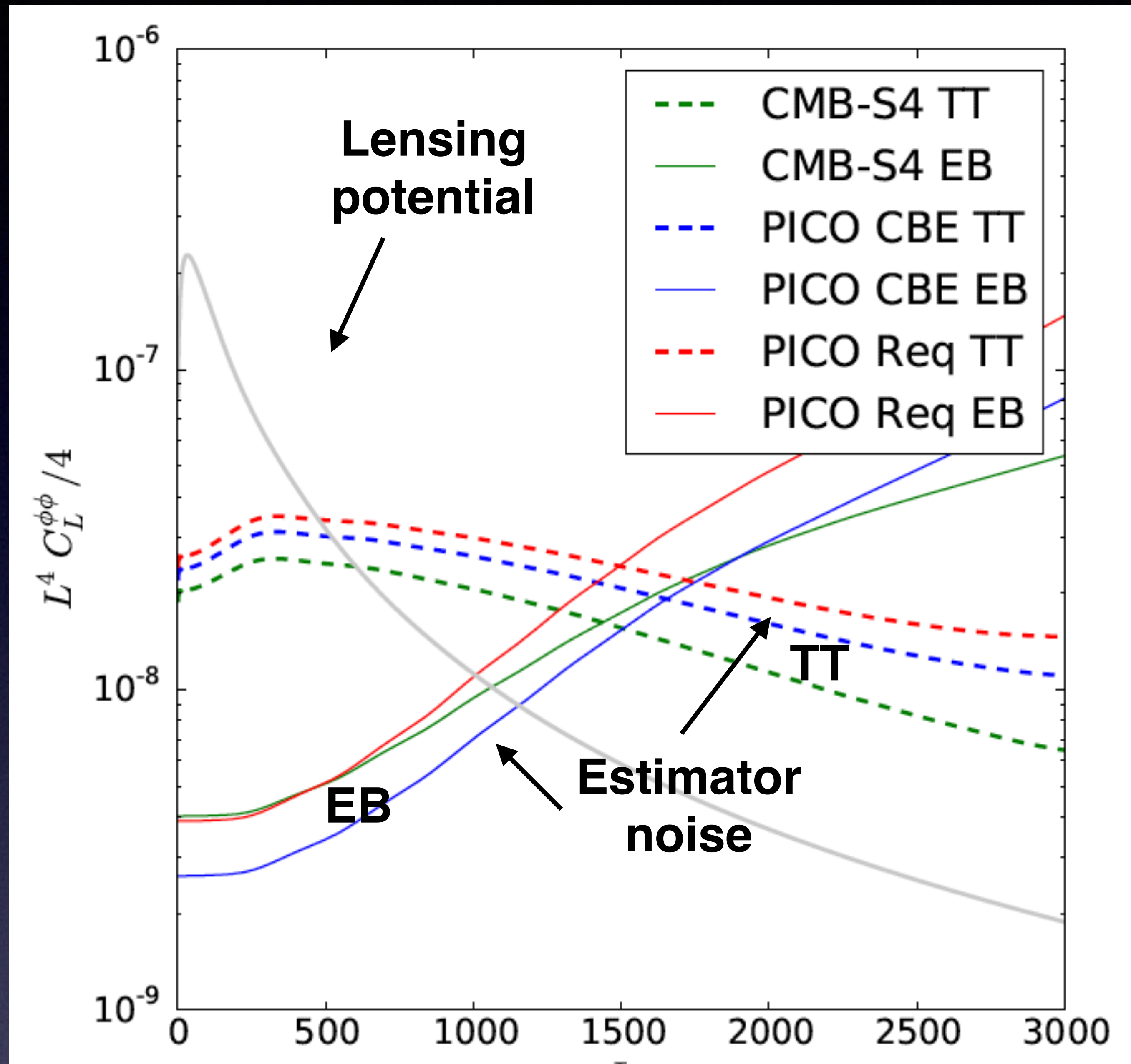
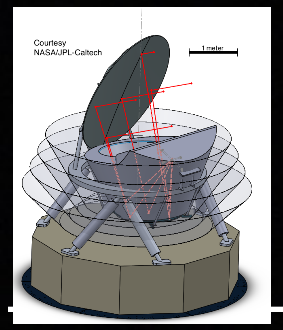


Figure: A. Van Engelen

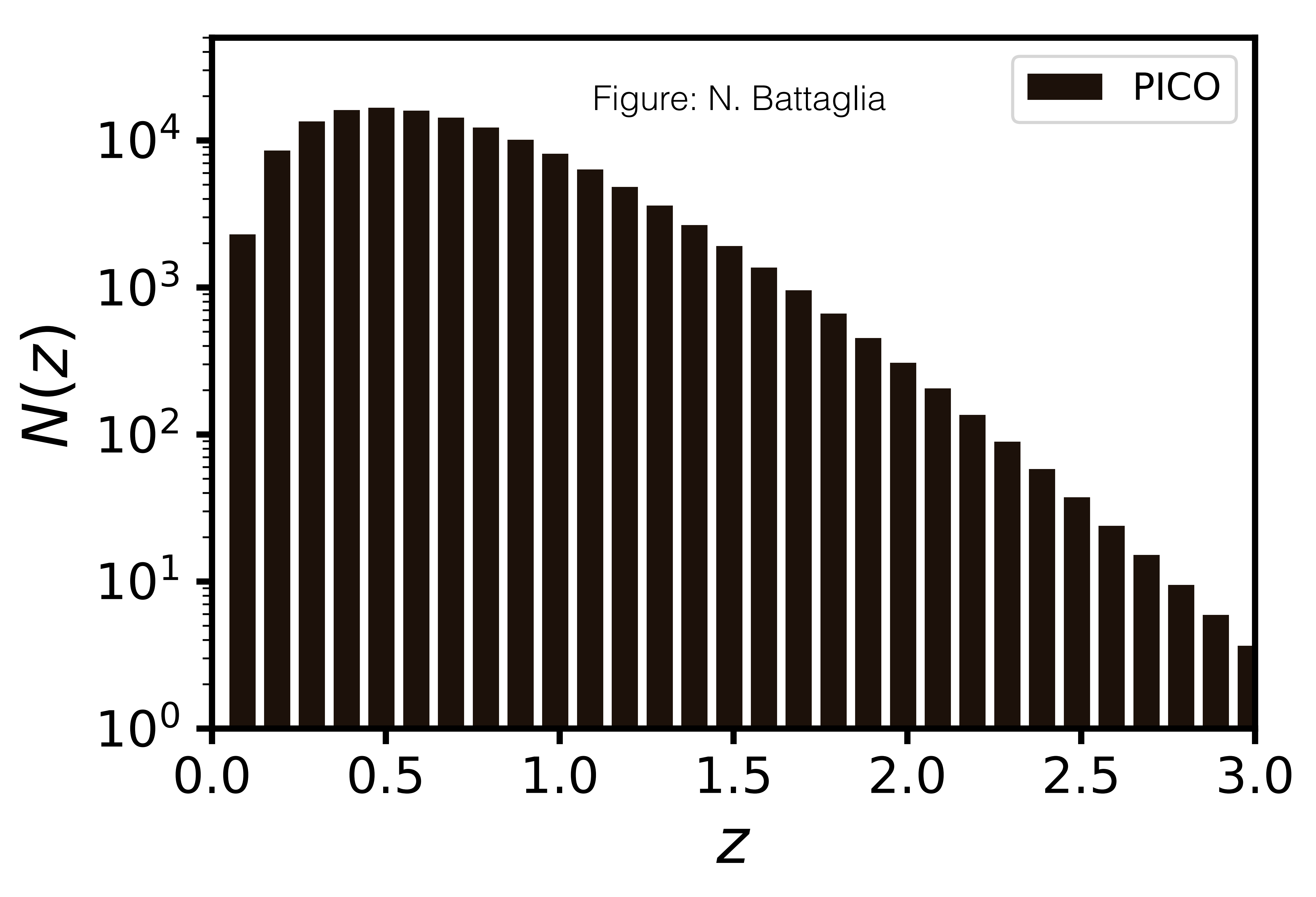
Colin applies ILC Foreground separation in the power spectrum using PICO noise (model includes frequency + EE+ BB from planck/WMAP + extrapolated to high \ell) gives post subtraction (higher) noise levels to Alex

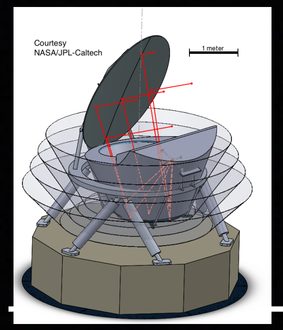
Alex recalculates S/N for phi-phi or for delensing level on BB



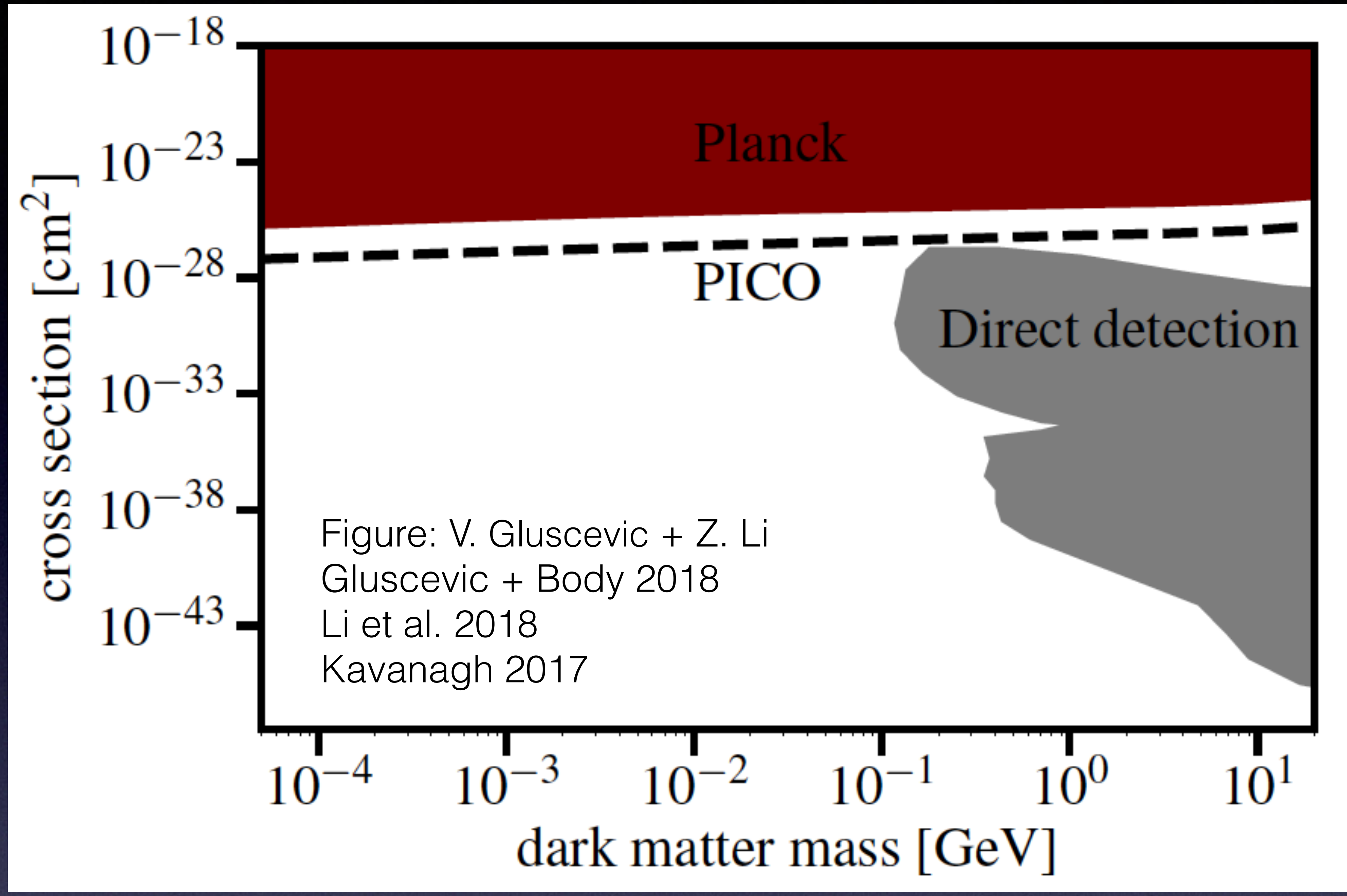
Discover how the Universe Works - Dark Energy

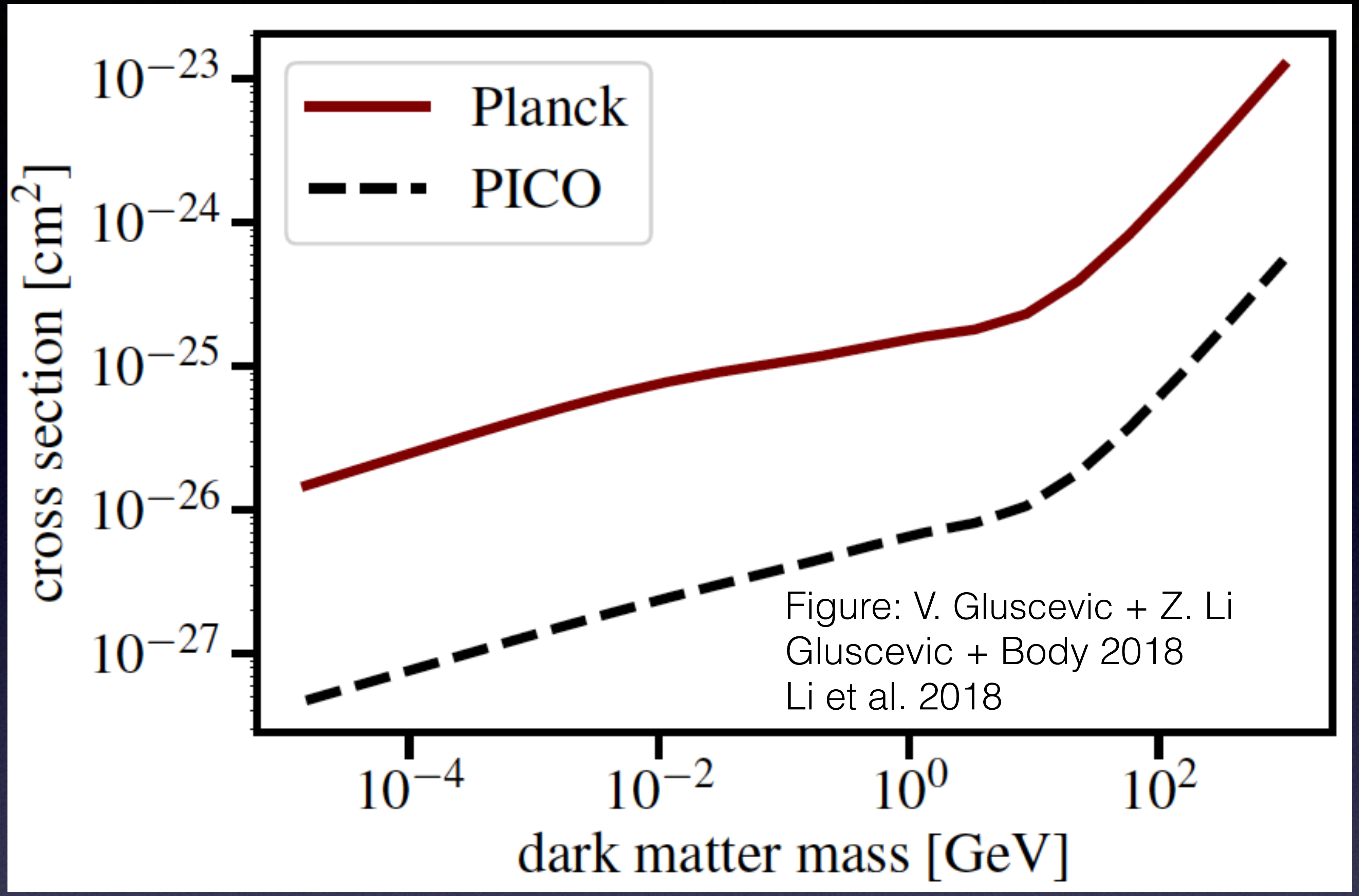
- Extract cosmological parameters with 140,000 clusters, 1000 with z>2
  - using thermal SZ, full sky
  - Planck: ~2000
  - S3: 20,000
- $\sigma(\Sigma m_\nu) \simeq 15\ \text{meV}$
- $\sigma(\omega_0) = 0.022$ (x3.5 planck)
  $\sigma(\omega_a) = 0.13$ (x2.5 planck)



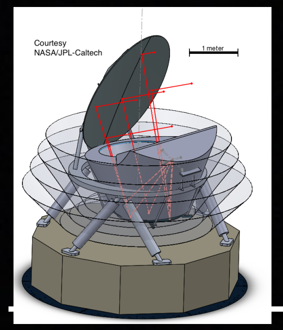


Discover How The Universe Works - Dark Matter





- Constrain low energy dark matter cross section
- Region not accessible to direction detection experiments
- x25 improvement relative to PlancK



Explore how the Universe Evolved

Map magnetic field for our Entire Galaxy

Planck, 5'   PICO, smoothed to 5'   PICO, 1'

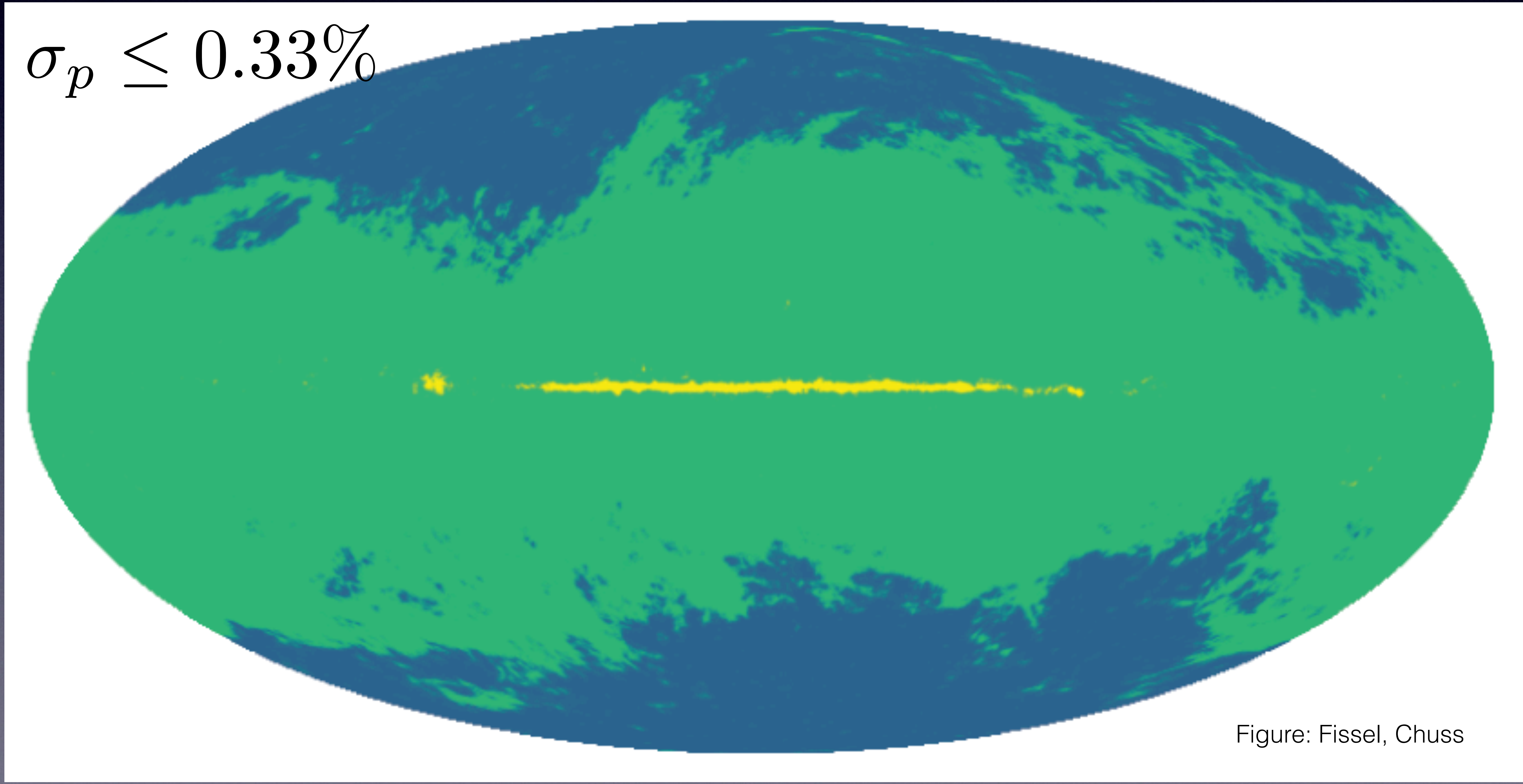
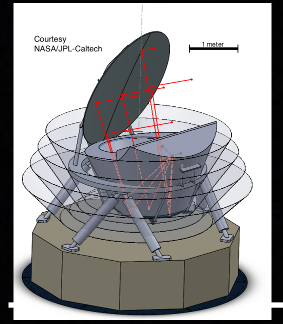


Figure: Fissel, Chuss

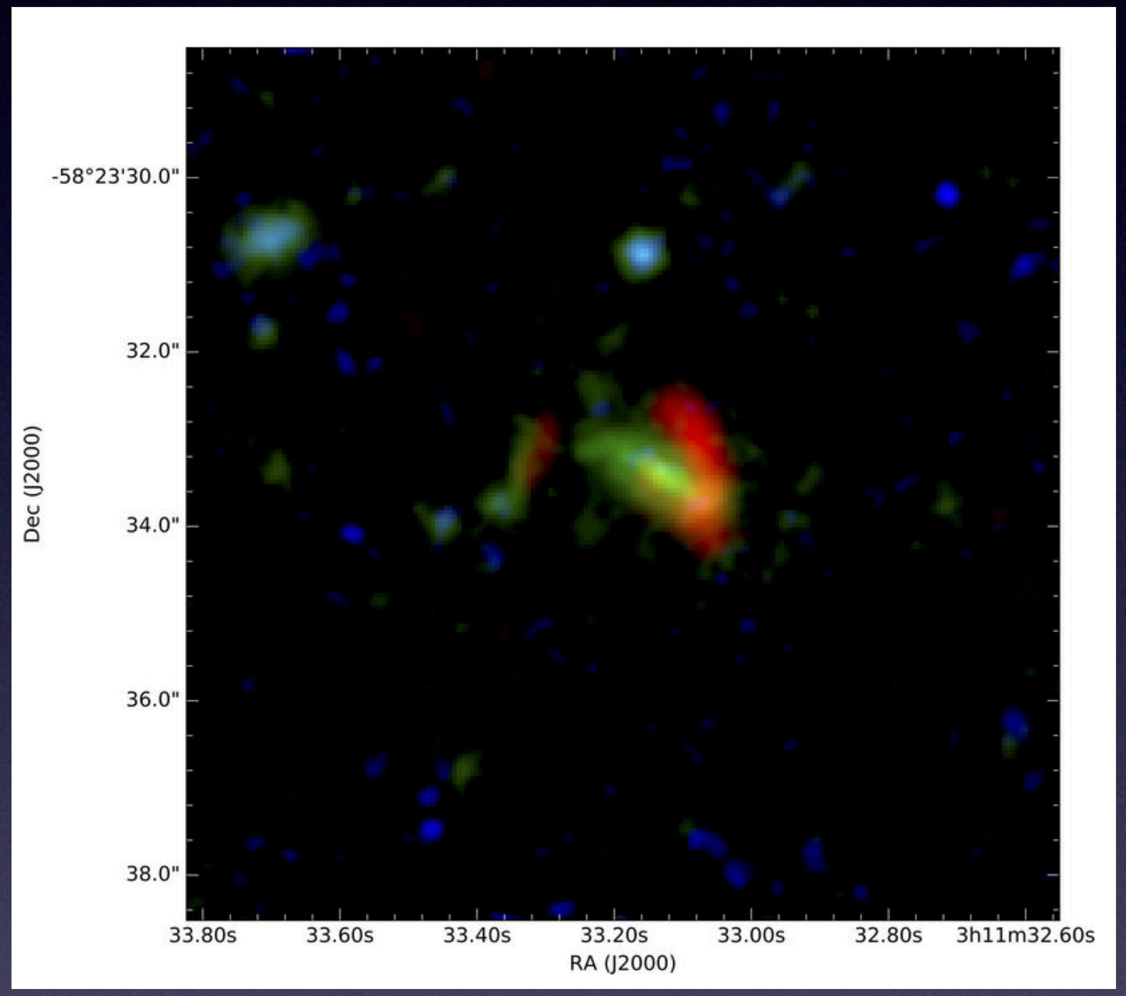


Legacy Science

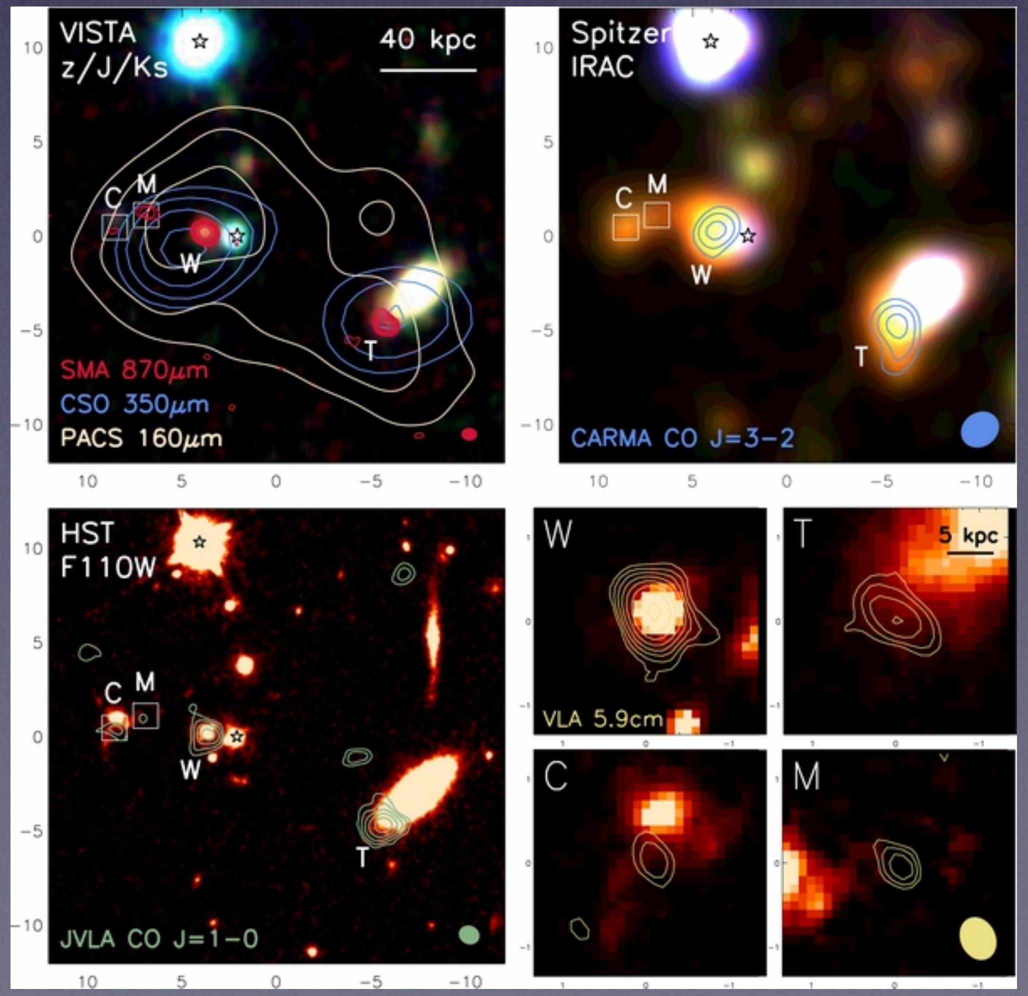
- Discover 4500 highly magnified dusty galaxies at z up to ~5;
- Discover tens of thousands proto-clusters extending to high redshift (z~4);
- Detect polarization of 4000 radio and FIR-emitting galaxies;
- x10-1000 more than known today
- Probe star formation history; determine galaxy and cluster formation 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)



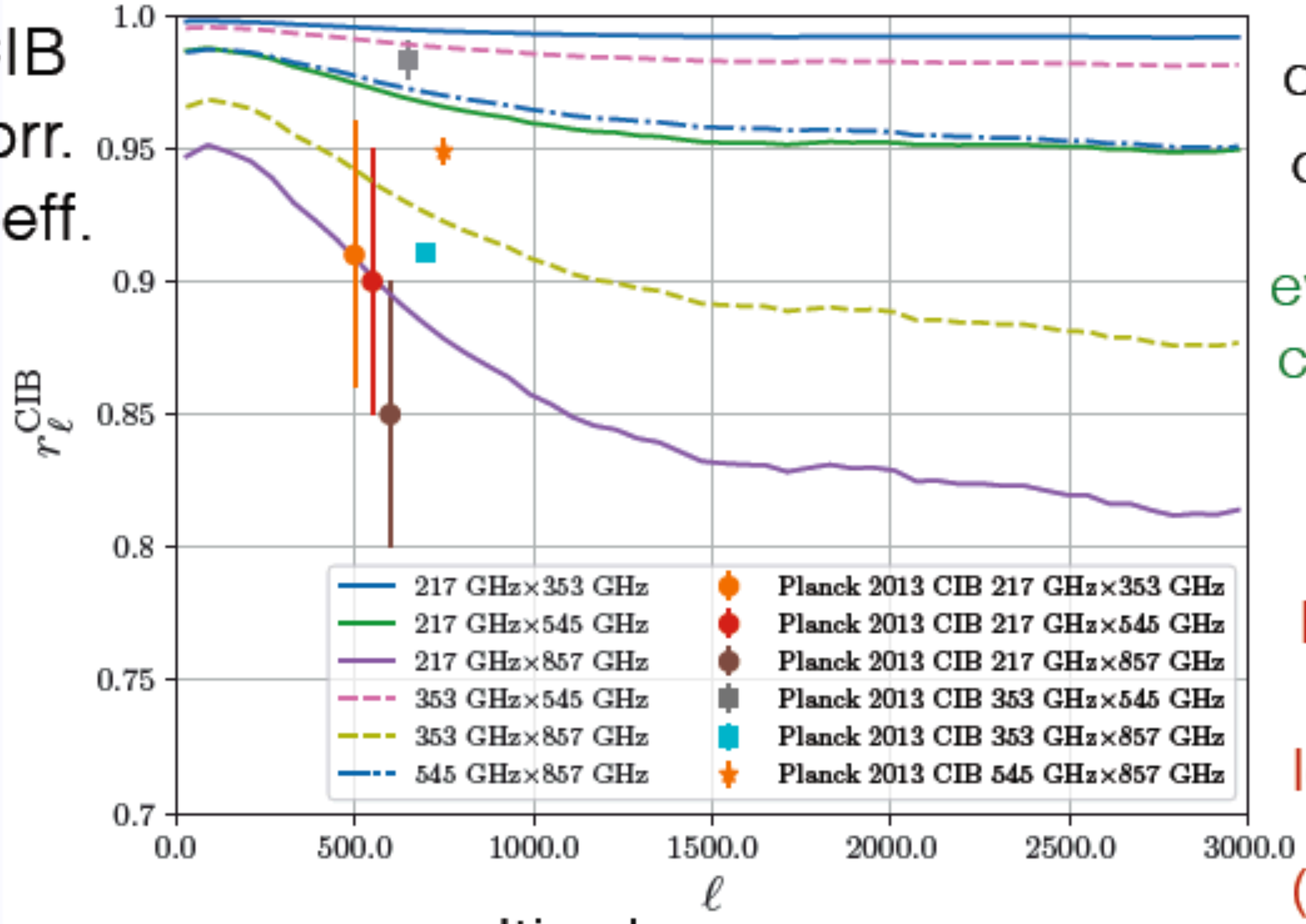
Ivison et al. 2013; proto-cluster core, z=2.4 (Herschel initial detection)

Colin Hill
IAS/CCA

High-ell Foregrounds

CIB decorrelation may ultimately limit high-ell component separation for tSZ/kSZ science

CIB corr. coeff.



multipole

data points = Planck
curves = CITA sims.

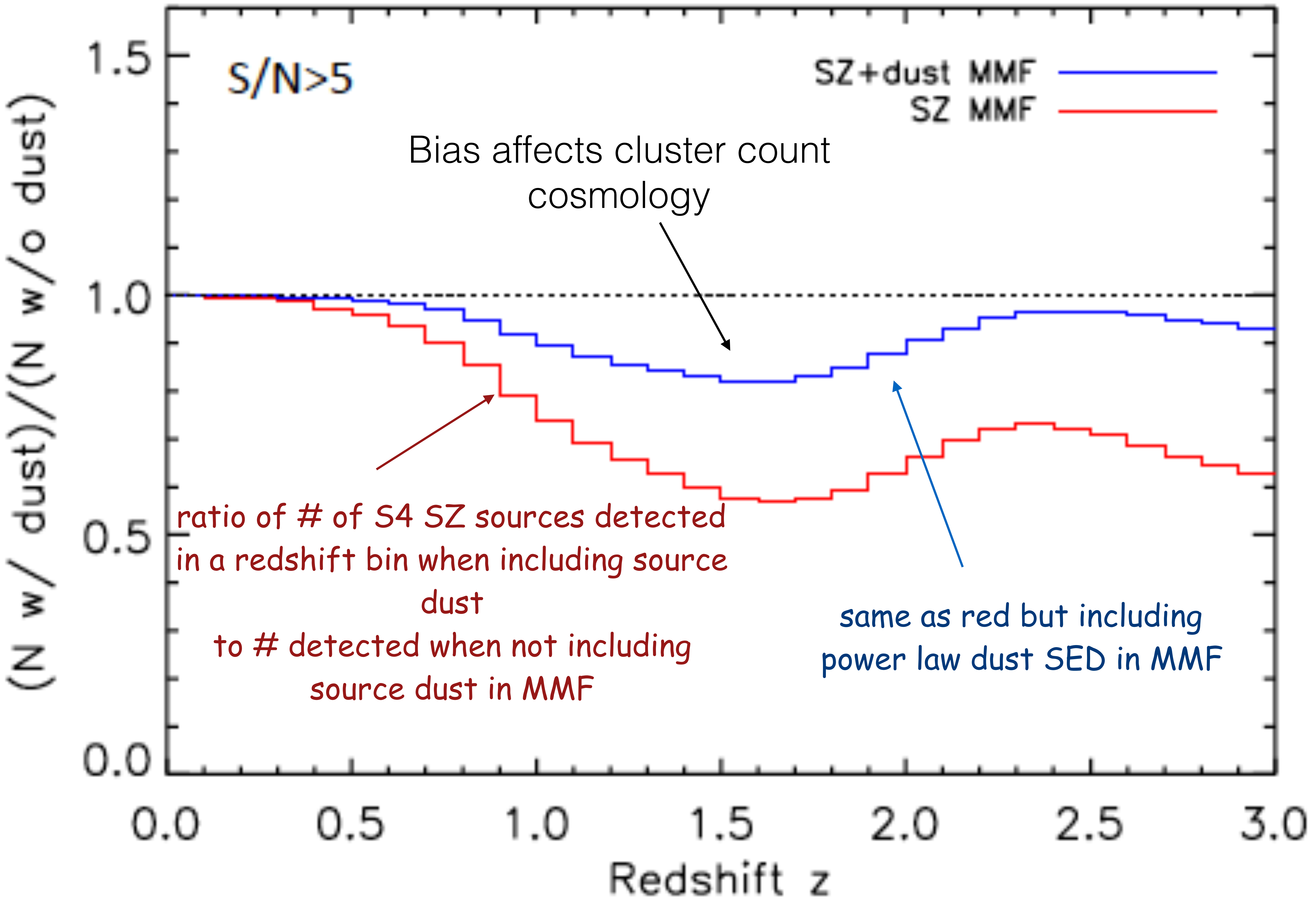
even 1% residual CIB could be an issue for some SZ science

synergy: high-freq. PICO channels can be used to clean lower-freq. S4 maps

(ideally w/ comparable angular resolution)

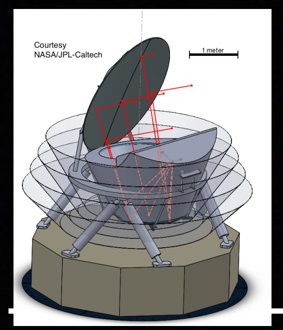
Planck+ (2013); Mak+ (2017); Alvarez/CITA Peak-Patch Sim.

Bartlett + Melin



MMF = Multifrequency Matched Filter

➔ SZ+dust MMF (assuming dust SED is a power law at all z)



Systematics - (Absolute) Gain Calibration

B. Bar

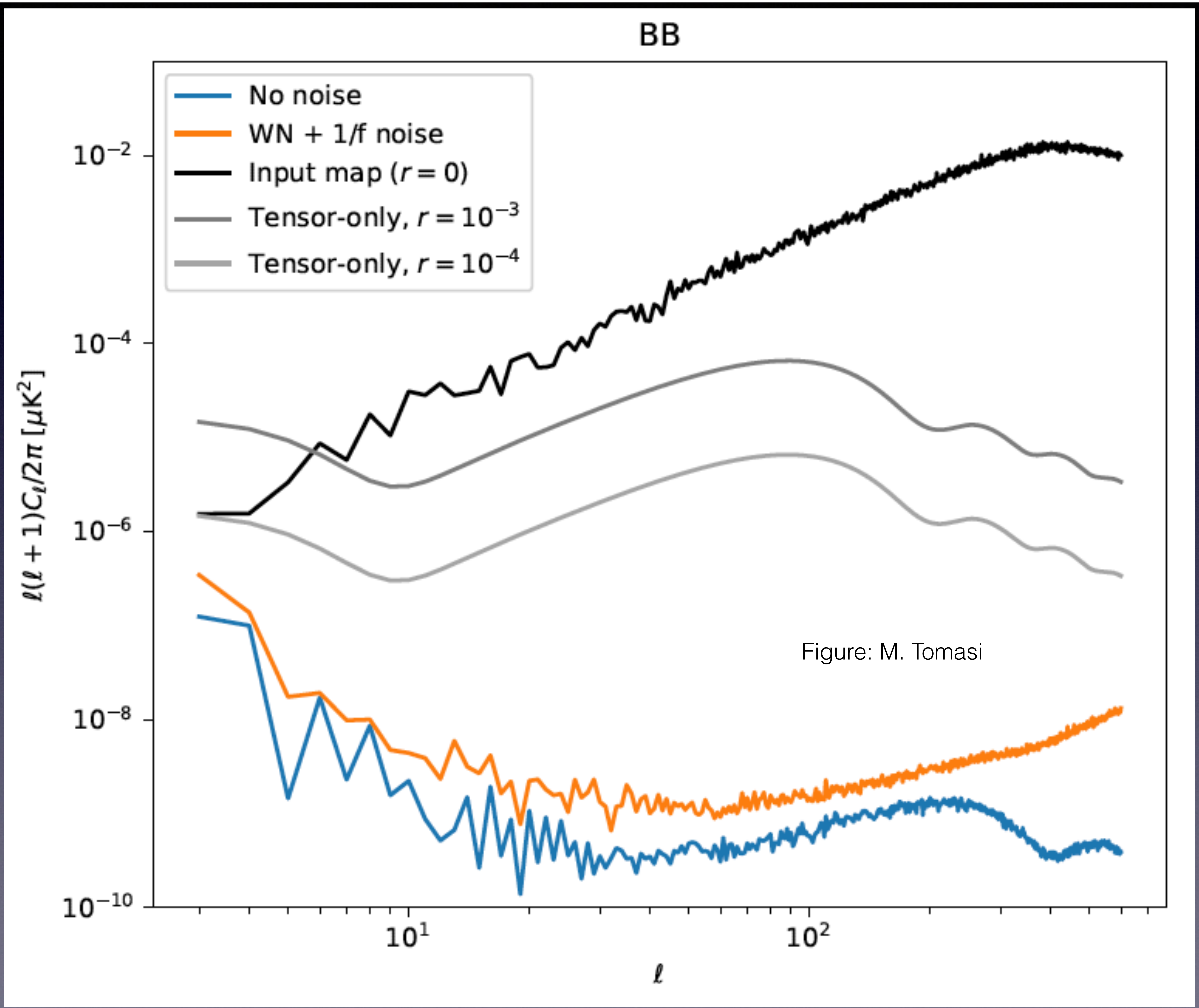
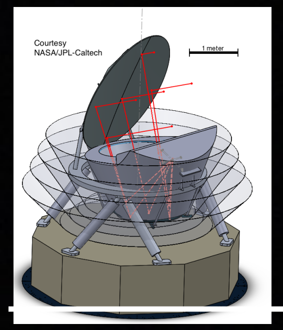
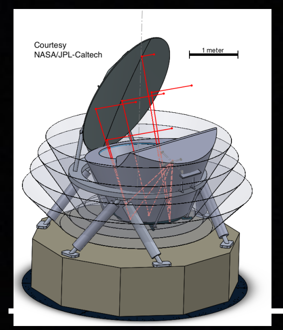


Figure: M. Tomasi



FAQ

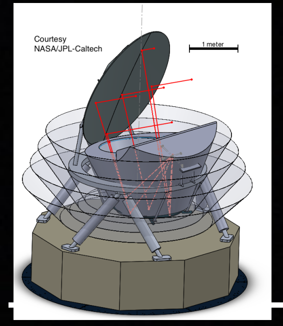
- Did you consider a spectrometer?
  - Yes
- Did you consider a LiteBIRD type mission
  - Yes and No
- What does ‘endorsing the report’ imply?
  - That you think there are still opportunities for CMB in space and you encourage NASA to stay in the CMB business



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 a single, optimally stable platform.
- Engineering + costing study complete:
  - Technology implementation is a straightforward extension of today's technologies; no technological breakthroughs required
  - Mission is a good fit to the cost window
- We very much hope to see NASA continue to support CMB from space in the next decade

Additional Slides



Galactic Dynamics + Star Formation

- 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

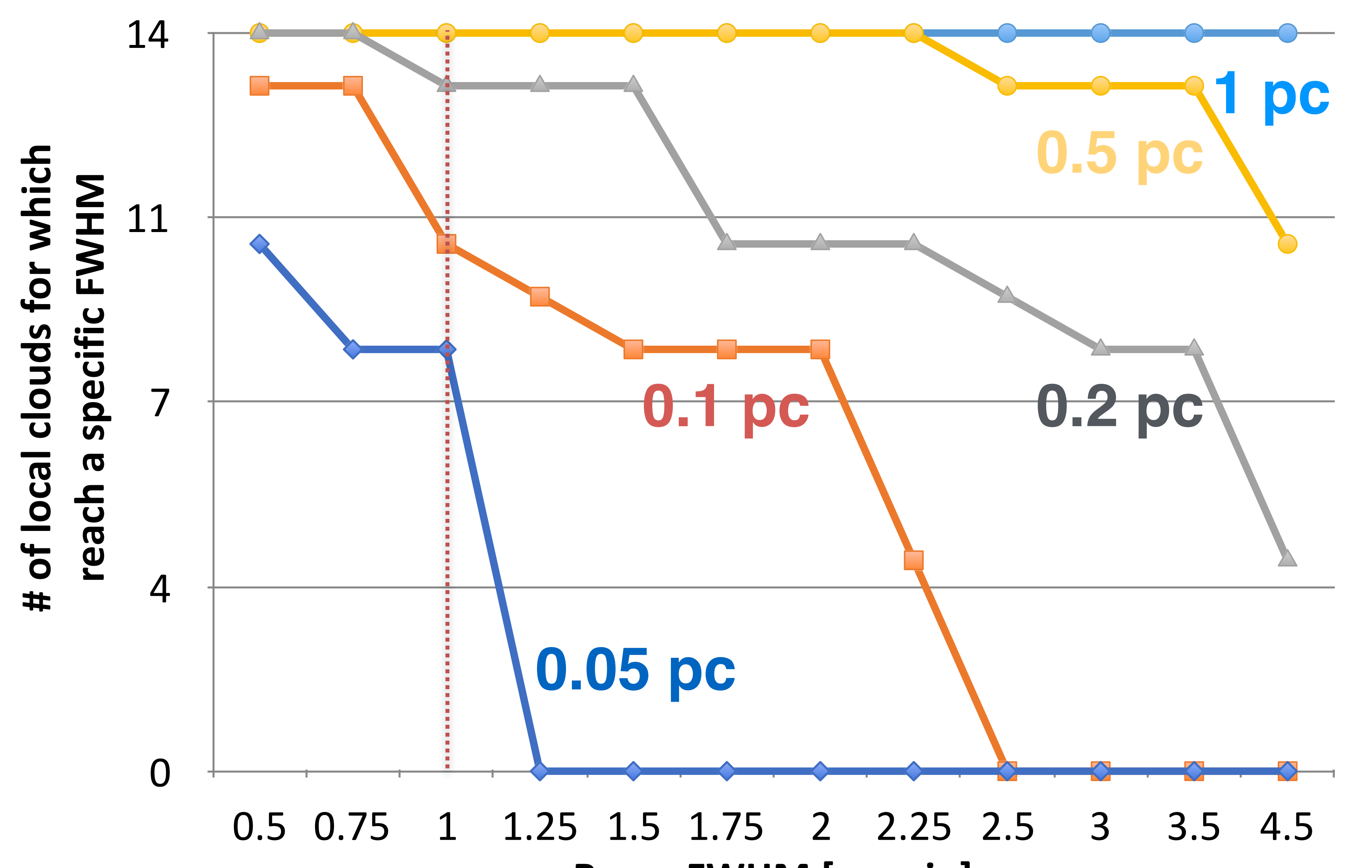
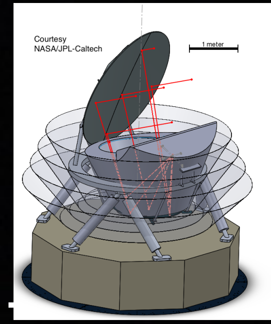


Figure: Fissel, Chuss

Discover How The Universe Works - Neutrino Mass



- Determine the sum of neutrino masses
- Measurements of the matter power spectrum, primarily through the lensing potential power spectrum (\ell~1000)
- Break degeneracy between τ DESI-BAO
- $\sigma(\Sigma m_\nu) = 14\ \text{meV}$
- 4σ or 7σ detection
- Similar, independent constraint from PICO cluster counts
- PICO gives both tau and lensing

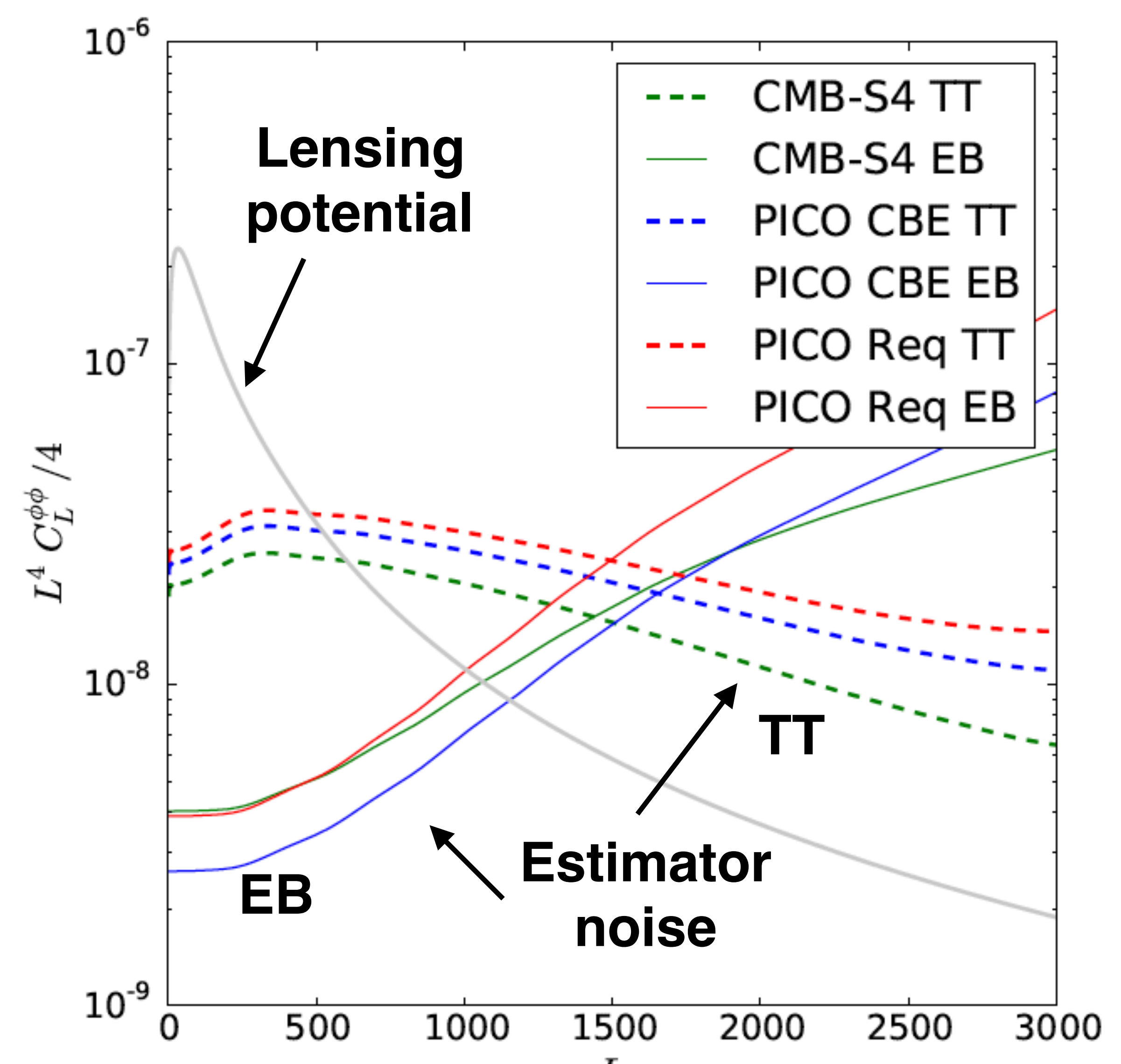


Figure: A. Van Engelen

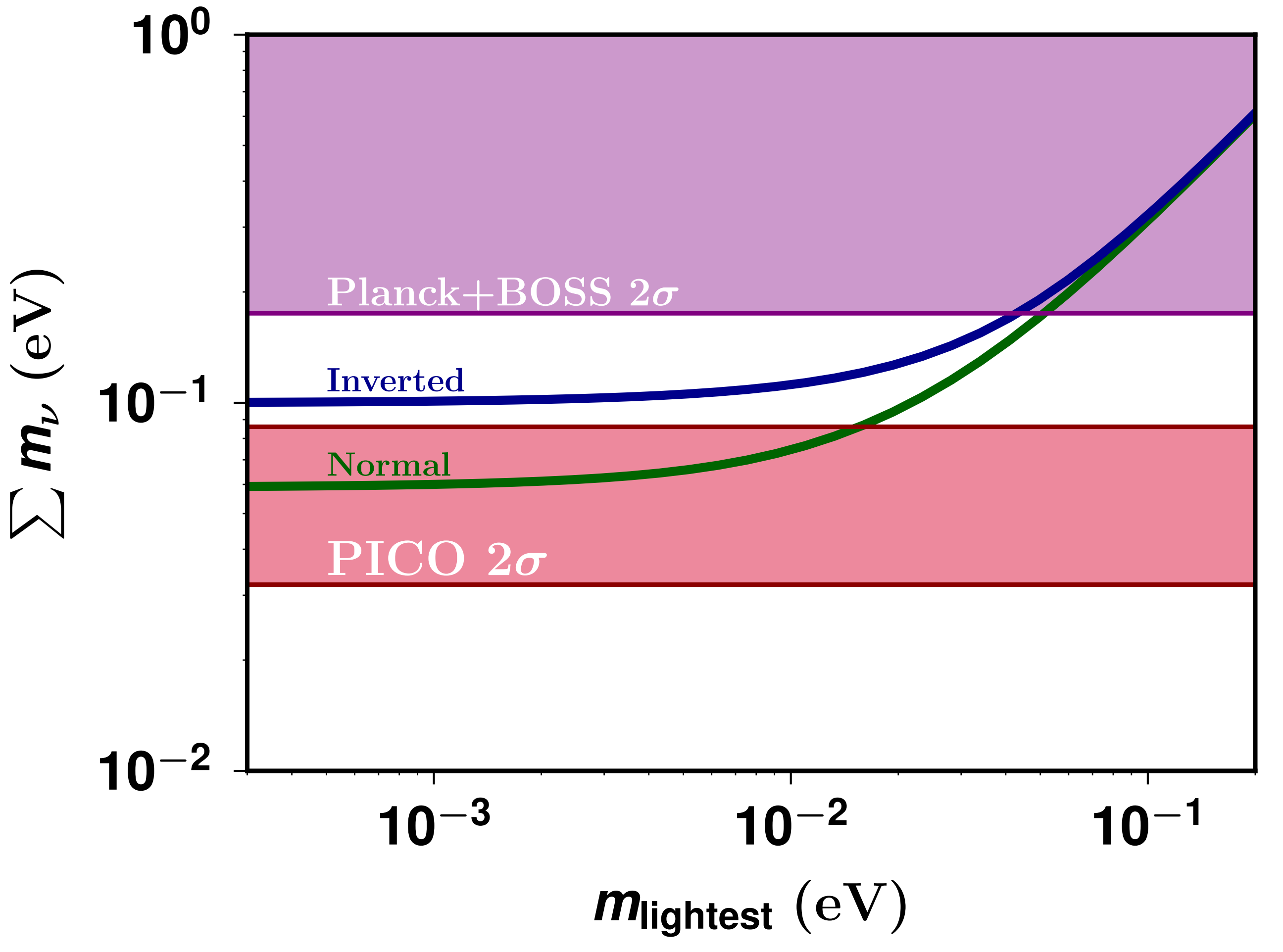
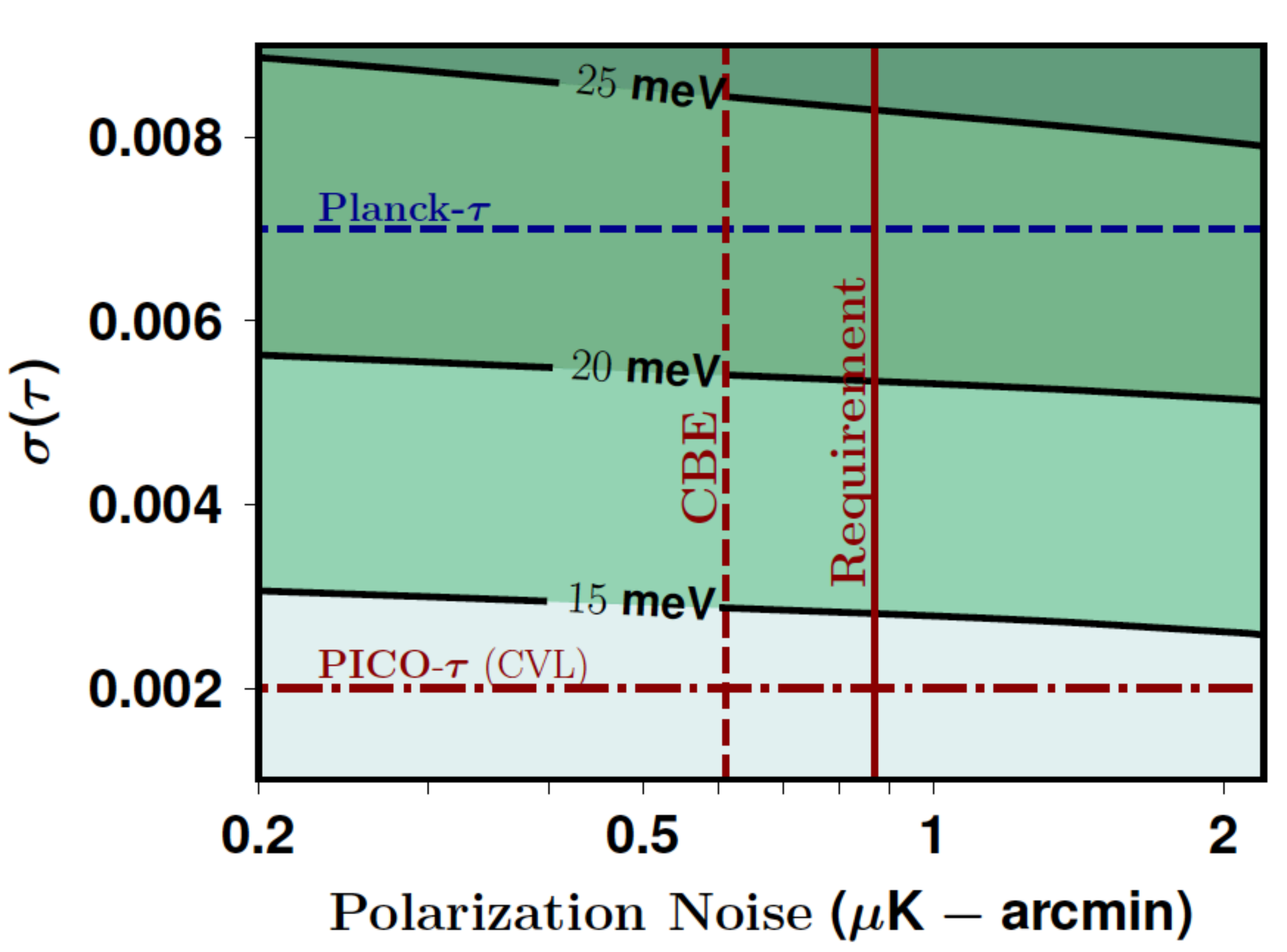
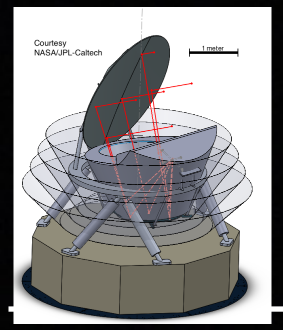


Figure: D. Green





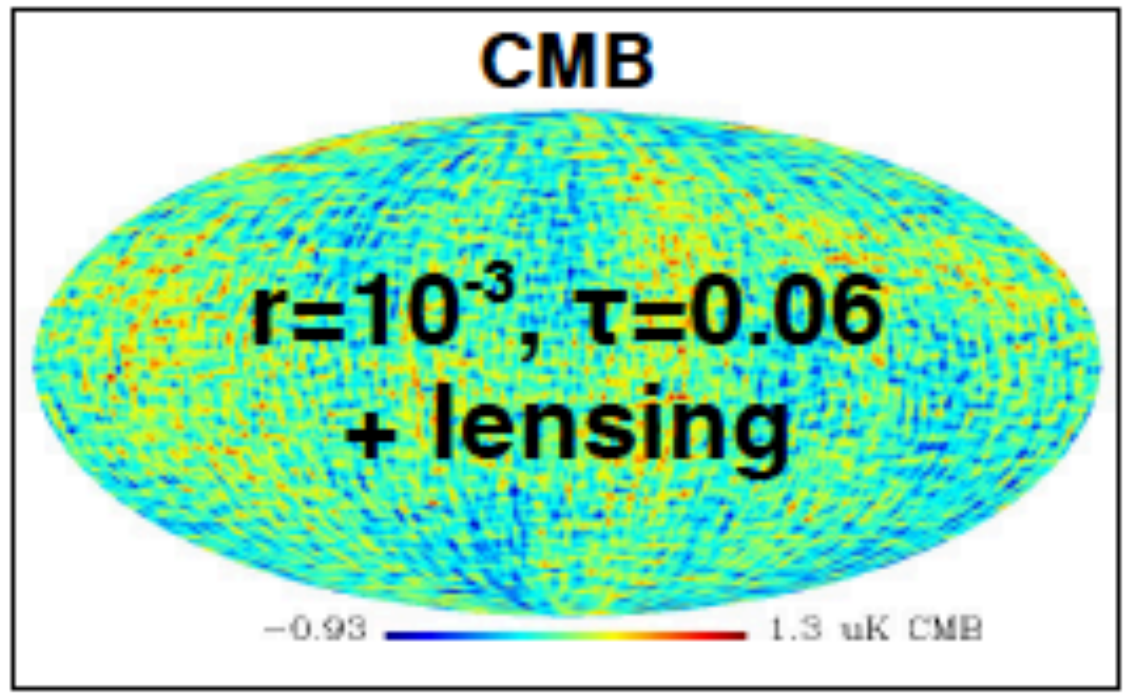
Schedule for Launch

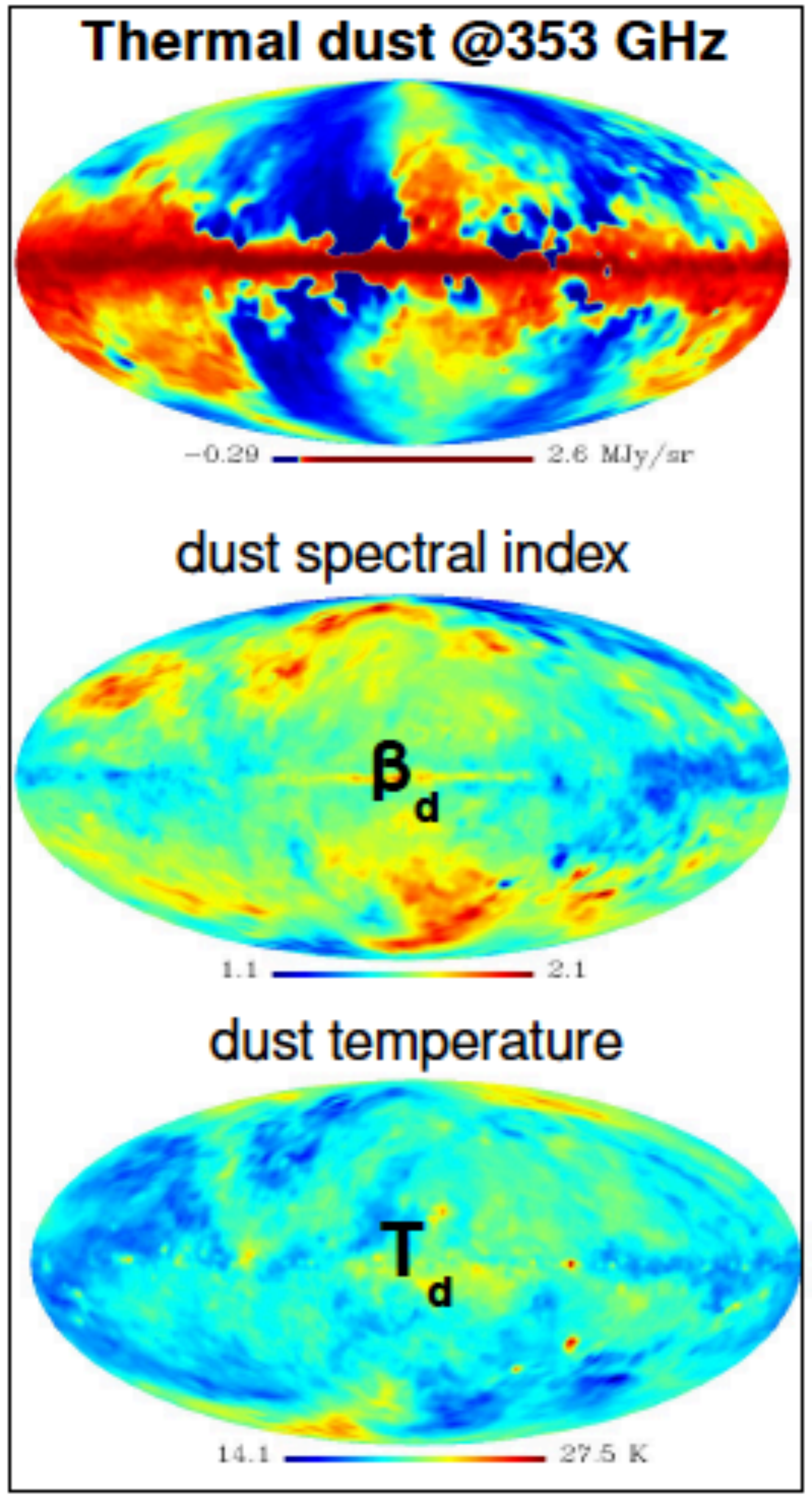
Schedule and Tasks

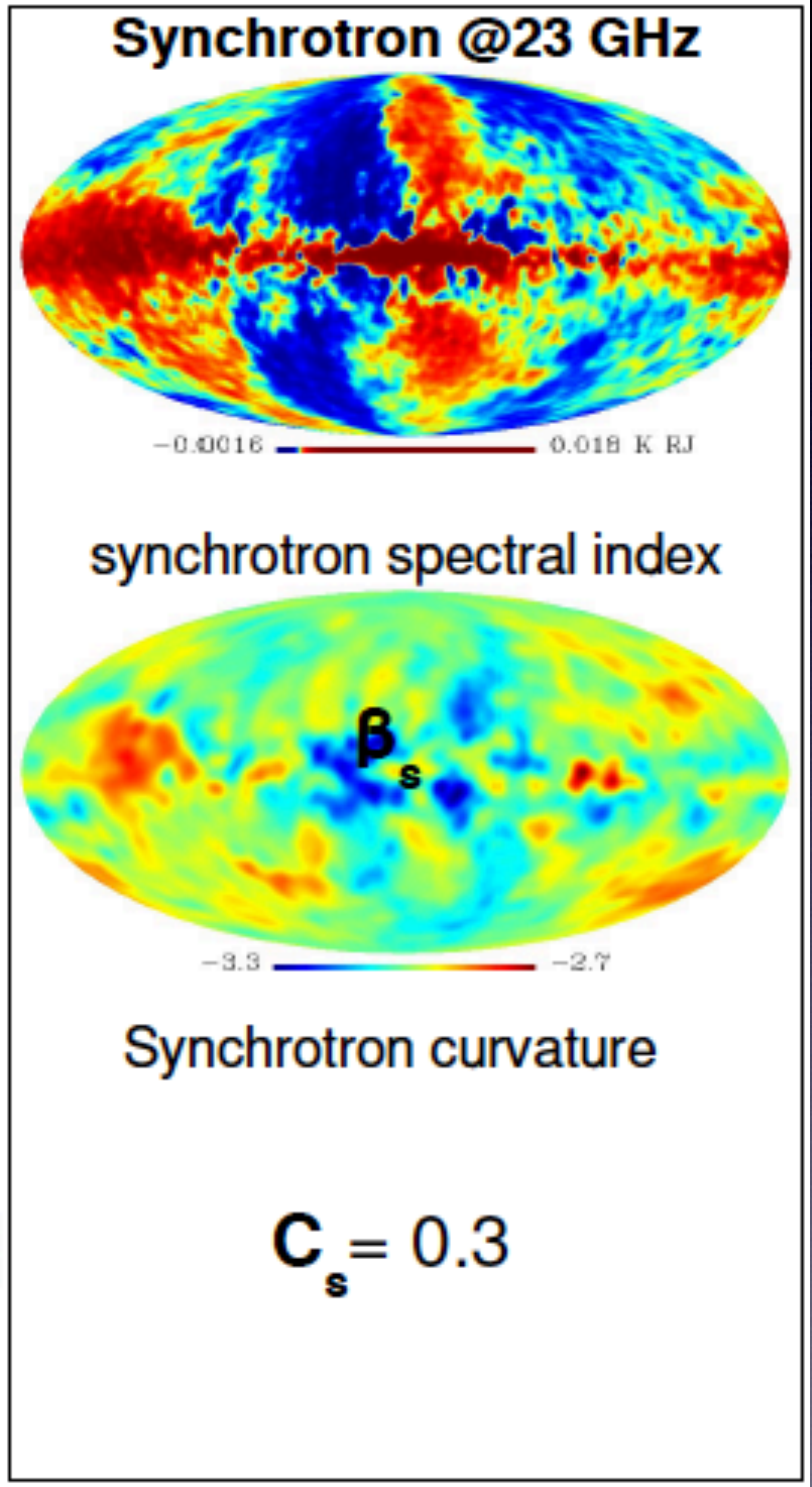
- Phase A (12 months): No I+T
- Phase B − Device Level (12 months):
    - Device level detector testing [Foundries, University Labs] (Slide 3)
- Phase C − Subsystem Level (22 months):
    - Phase C1 (10 months):
        - Cooler qualification (Slide 4)
        - Reflector cryogenic photogrammetry (Slide 4)
    - Phases C2 (12 months):
        - Focal plane + SubK cooler I&T (Slide 5)
- Phase D − System I&T + Launch (18 months)
    - Phase D1 (14 months)
        - Integration of reflectors and focal plane (slide 6)
        - Observatory end-to-end I&T (slide 6)
    - Phase D2 (4 months)
        - Launch Ops

Commander1

Sky simulations 1: **PSM**





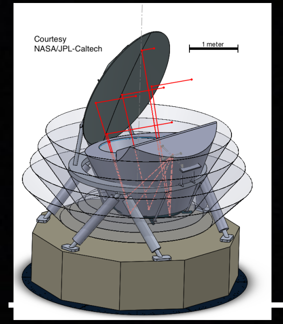


<u>"Simple" sky</u>:

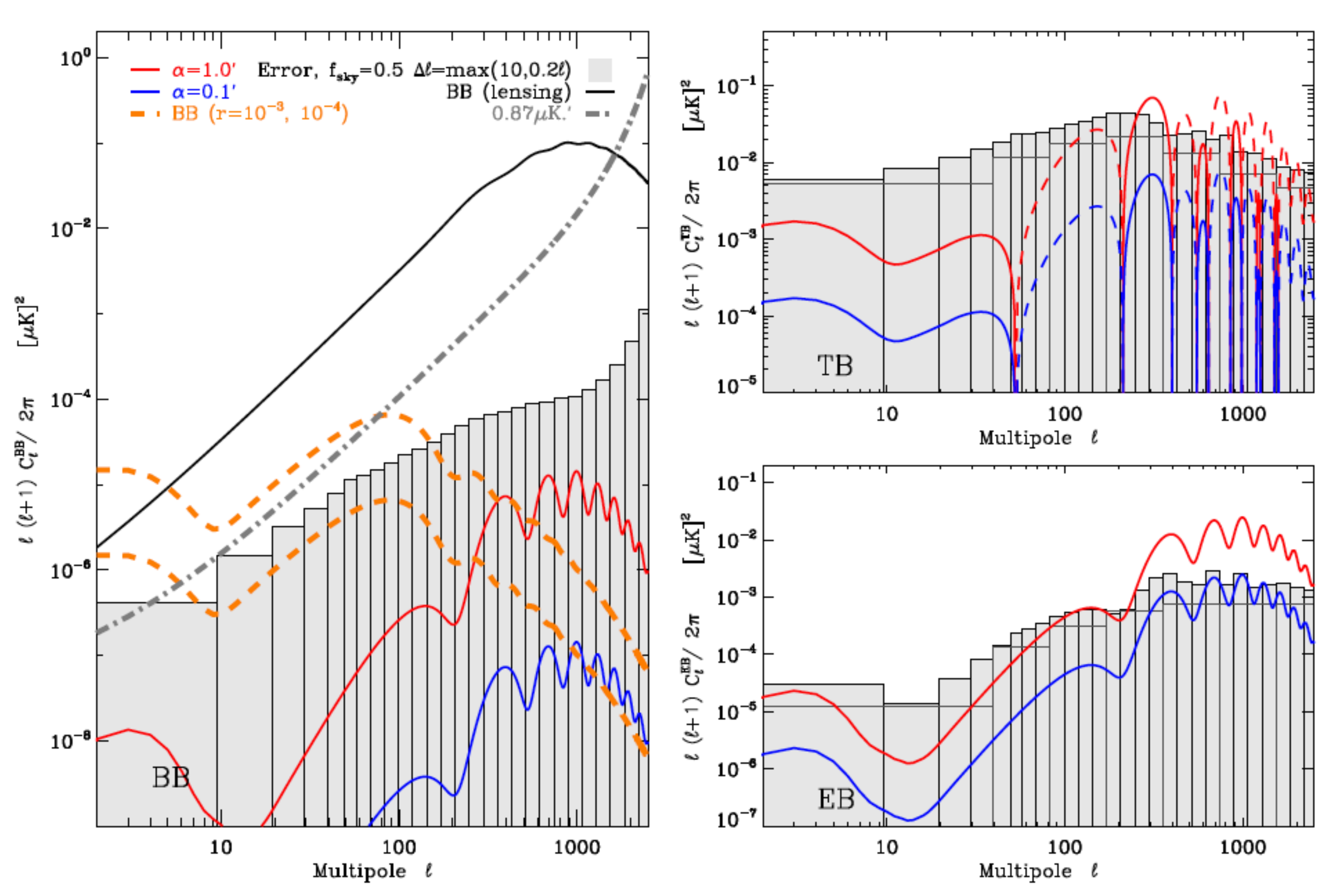
- dust: modified blackbody
- synchrotron: curved power-law
- CMB: $r = 10^{-3}$ + lensing

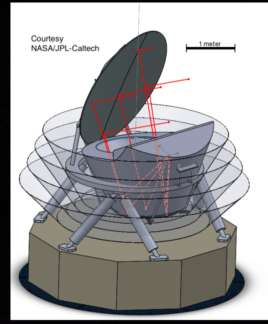
The PSM tool has been widely used and validated for many years by the Planck collaboration

smoothed to 1 degree for illustration purposes



Systematics - Polarization Rotation





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

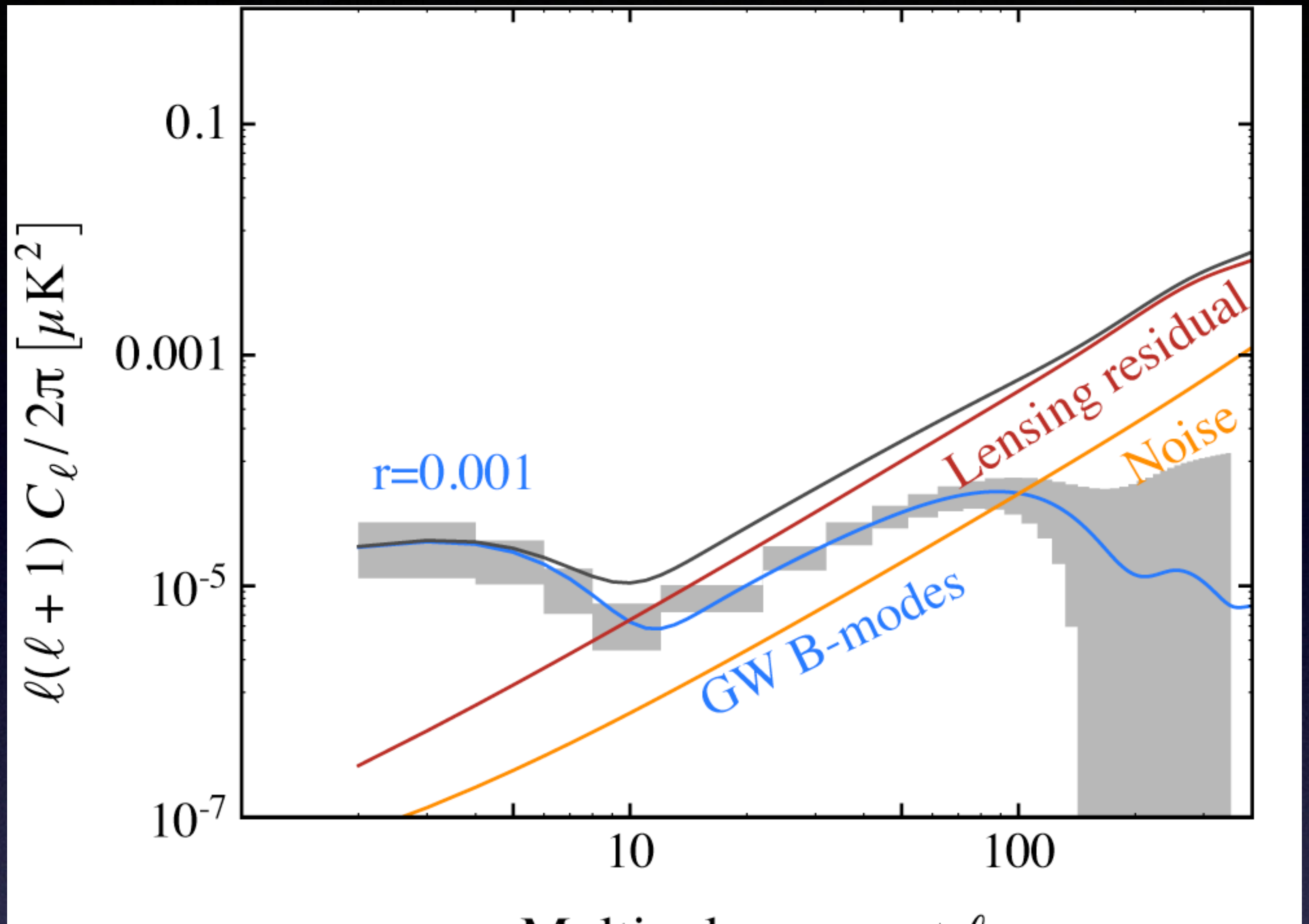
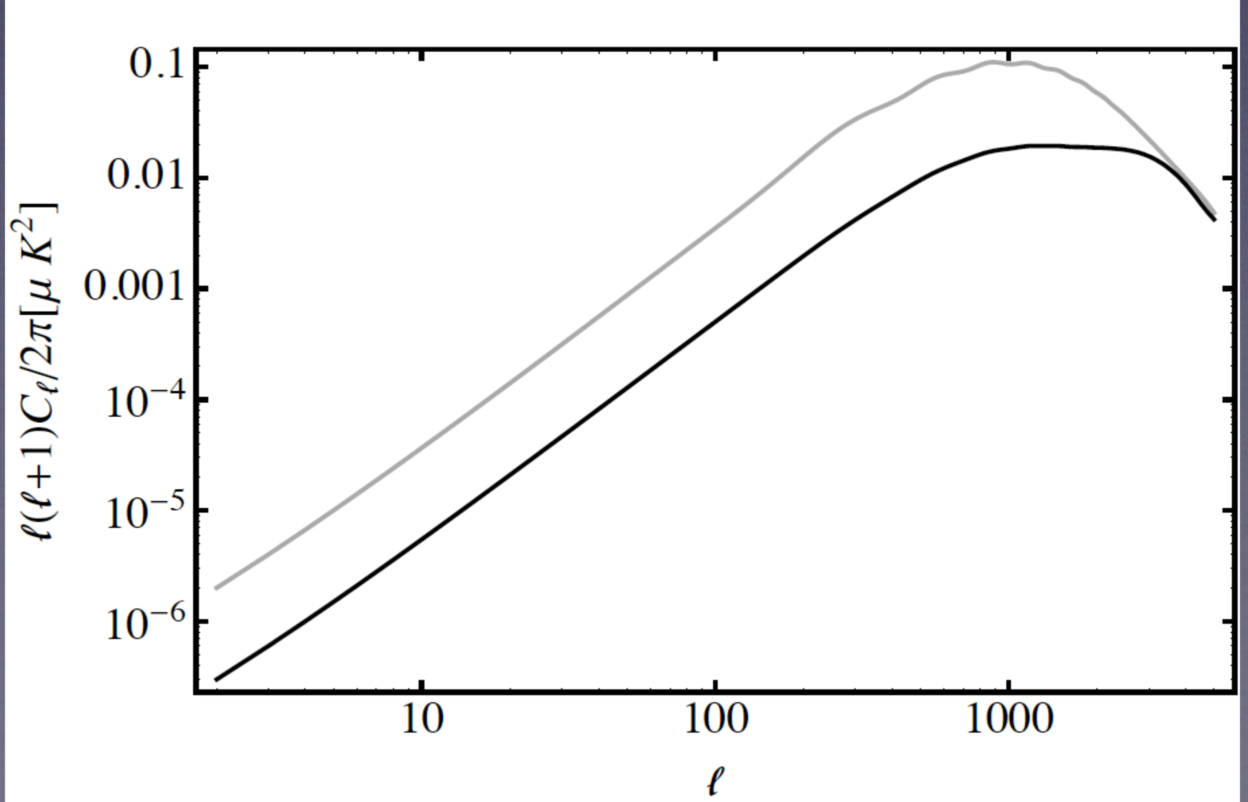


Figure: R. Flauger



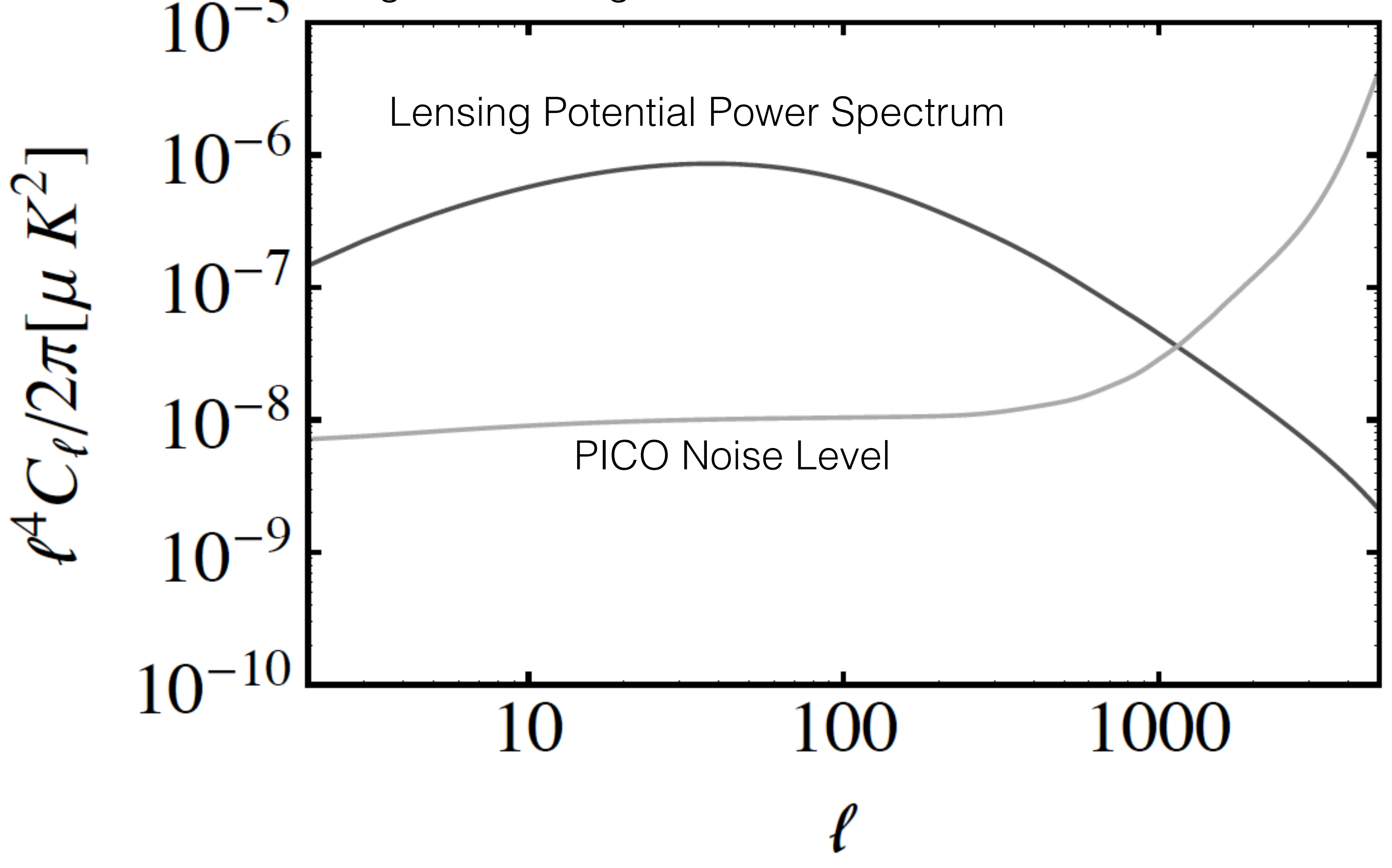
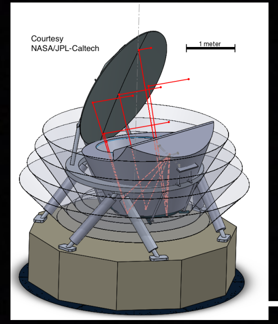


Figure: R. Flauger

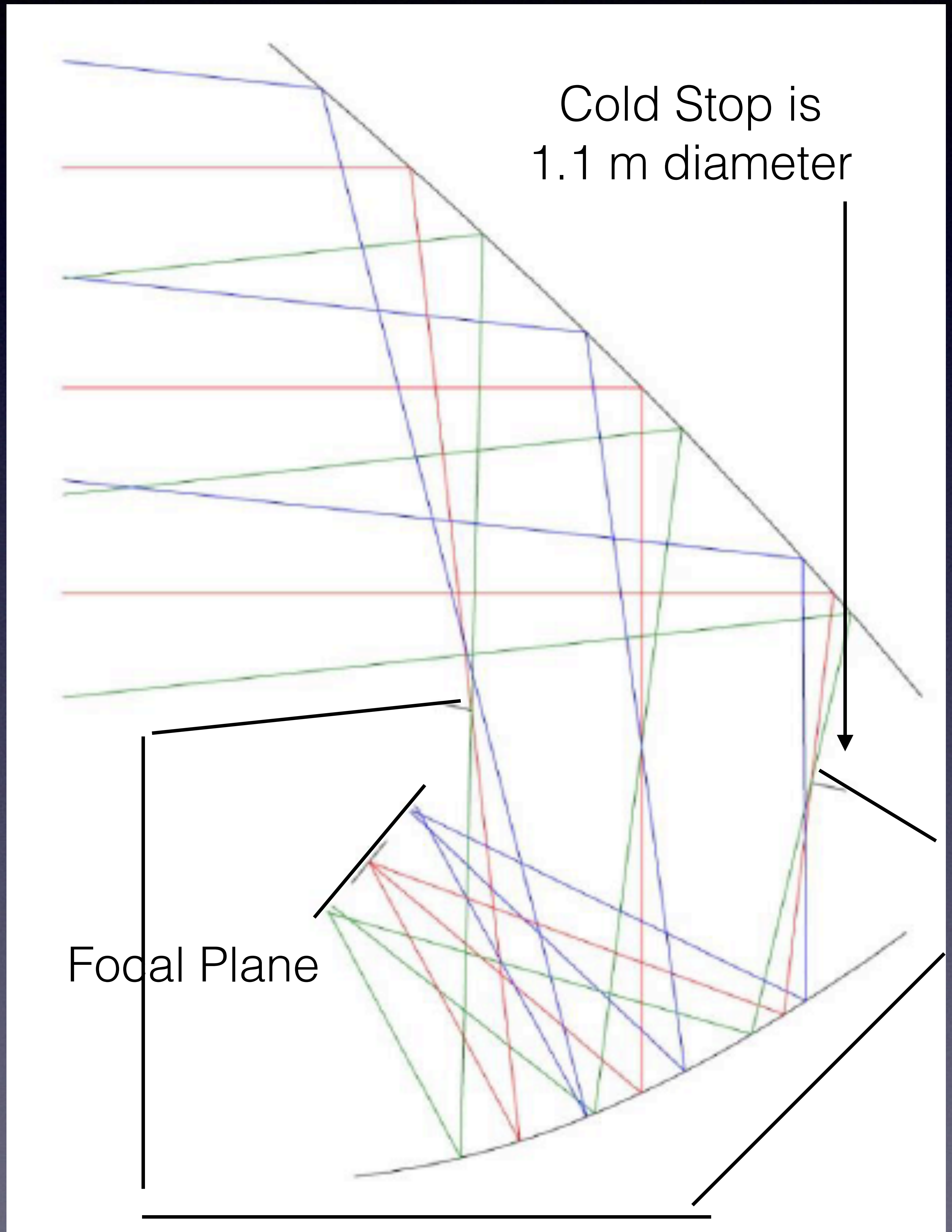


S4 Inflation Constraints

- 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



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.

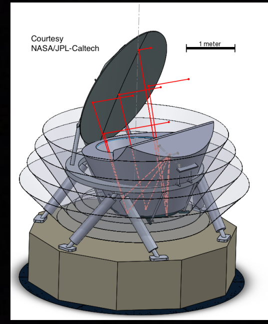
Decadal Panel 2010:
New space Activities - Medium Projects

- 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.”

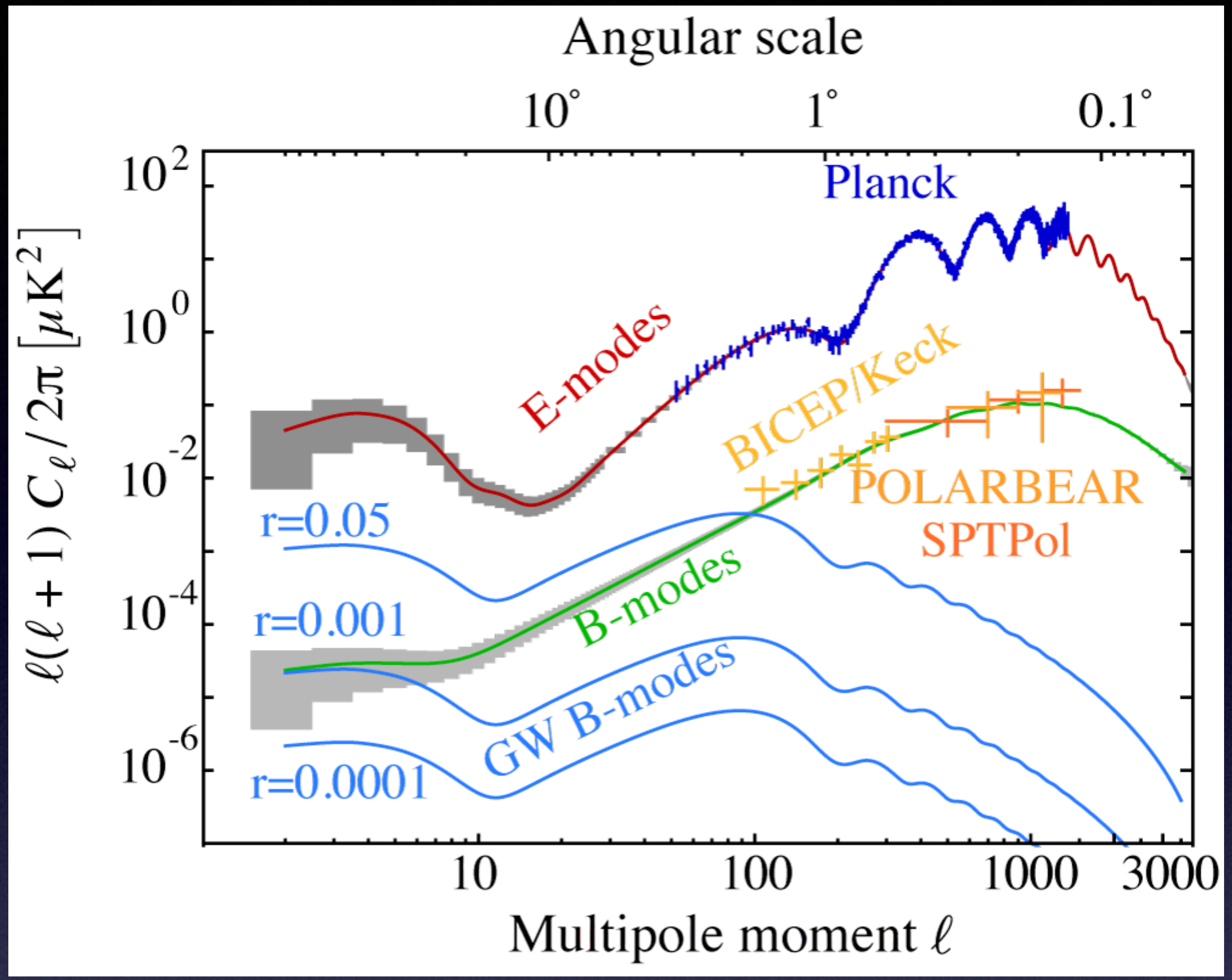
- “Wait and see what we learn from Planck”

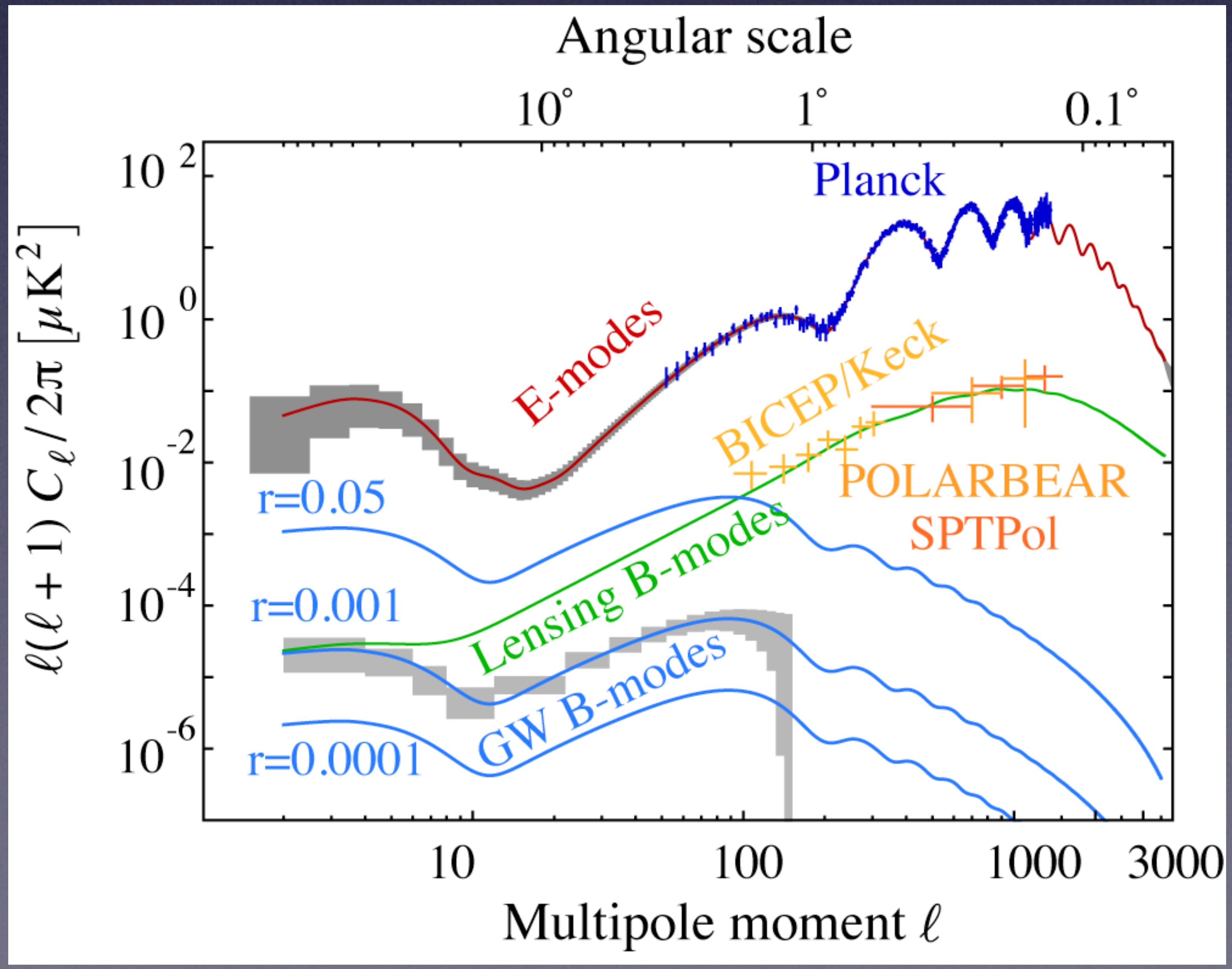


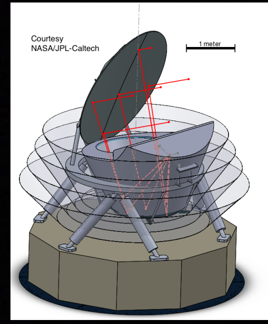
PICO and Sub-Orbital CMB Efforts

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
-

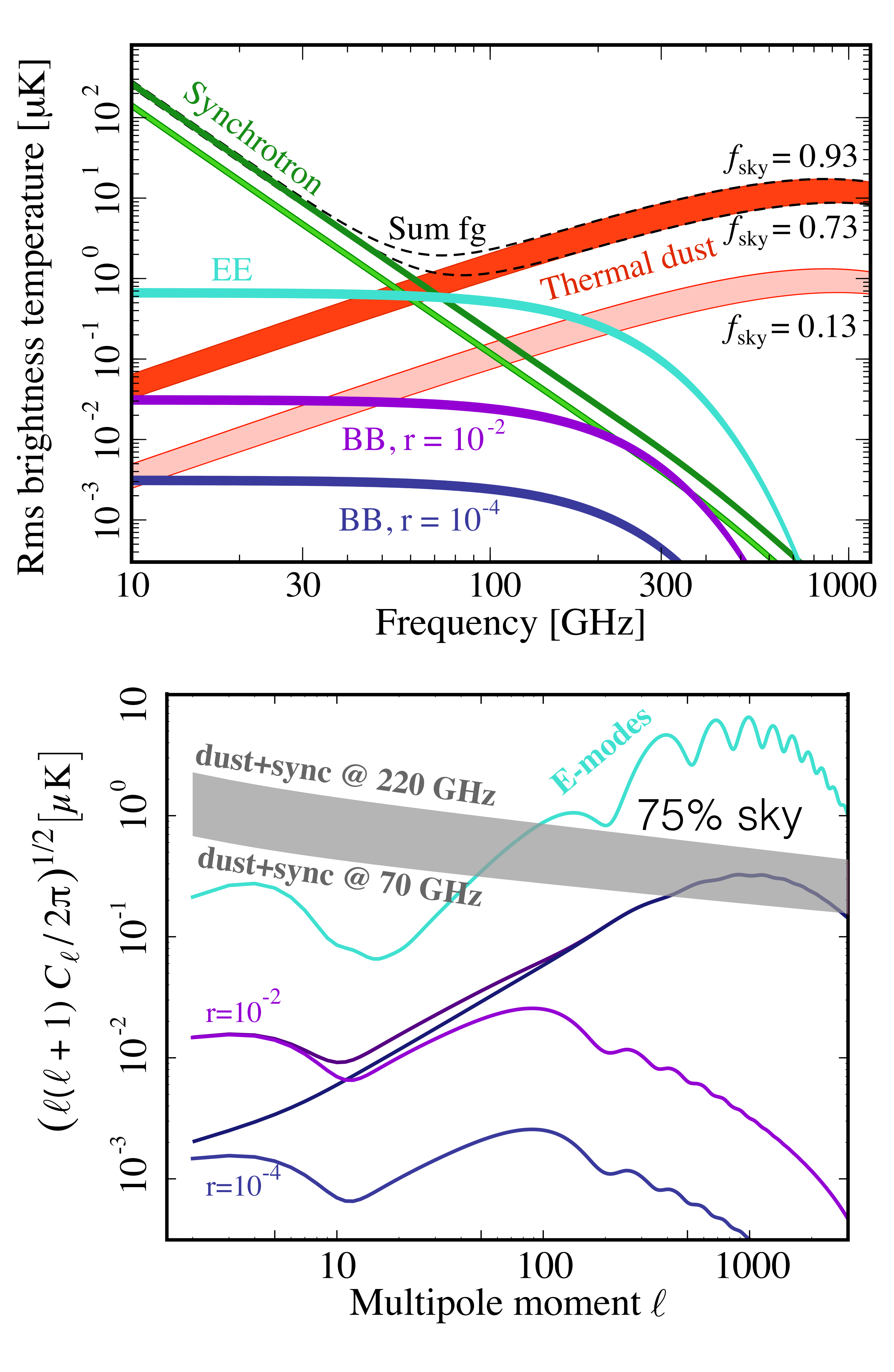


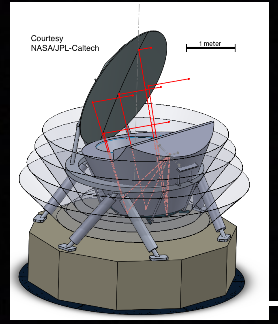




PICO and Sub-Orbital CMB Efforts

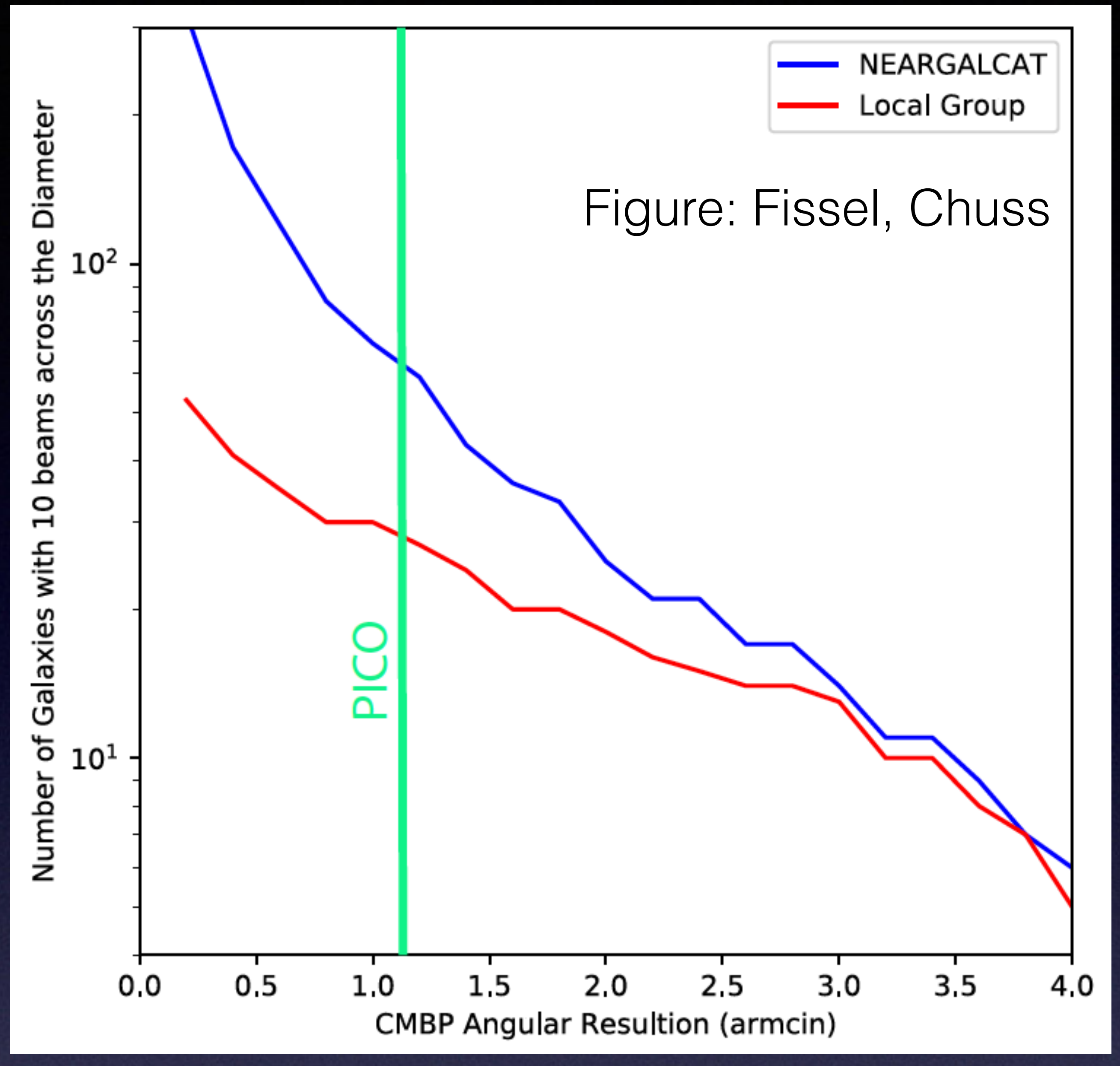
- Unmatched/unmatcheable frequency coverage
  - Galactic foregrounds are known to overwhelm the cosmological B-mode signal
  - Signals are at the nano-K level: even low level of residual foregrounds can bias the measurement
- Space gives the most systematic-error-robust platform
  - Signals are at the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



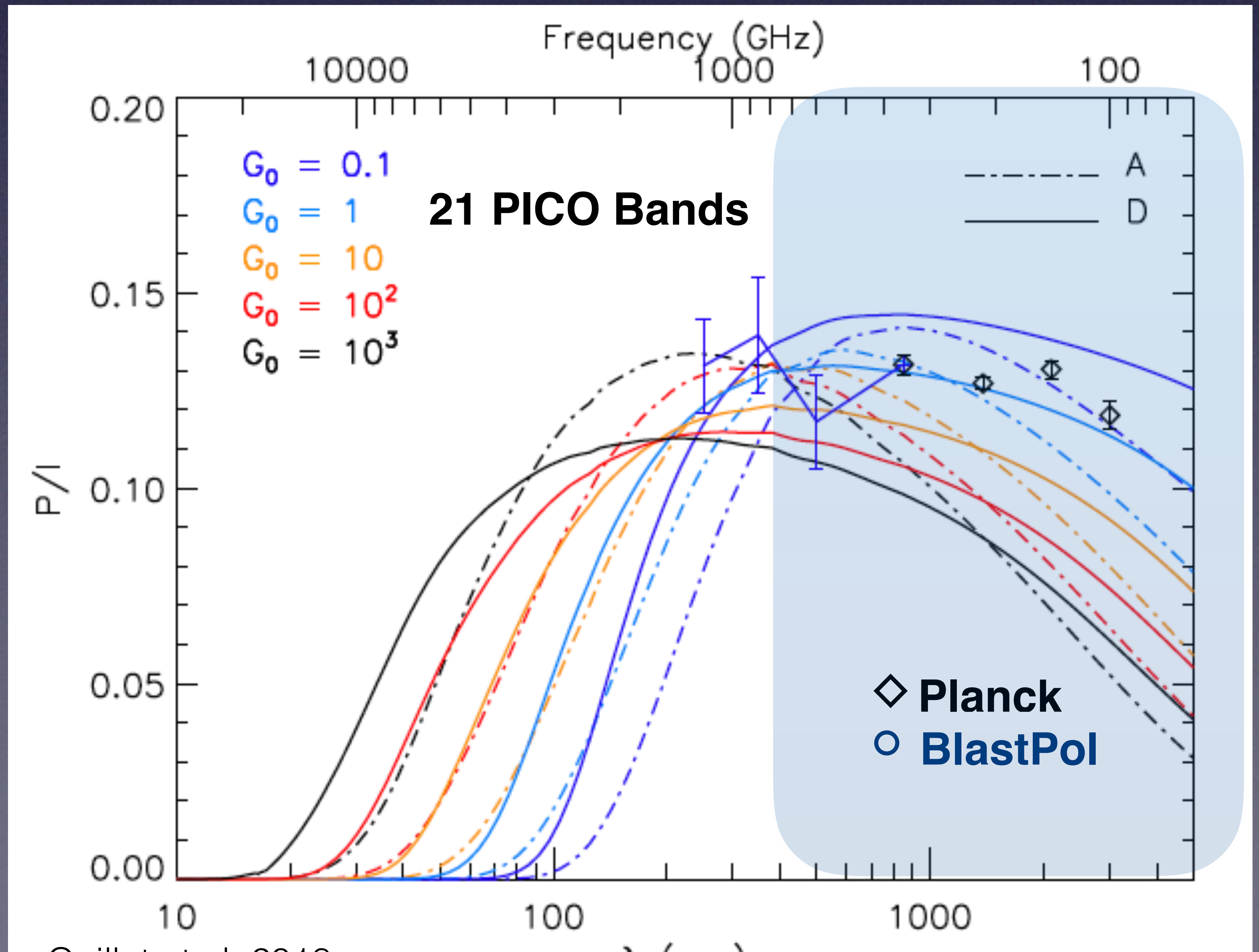


Is the Milky Way Typical? Dust in Milky Way

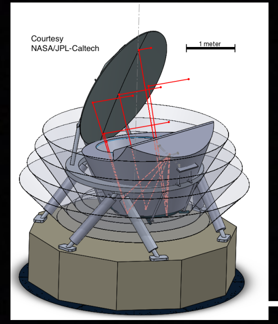
- Map sub-mm emission from the ISM in 70 nearby galaxies
  - Only handful mapped to date.



- Constrain the shape and composition of interstellar dust grains



Guillet et al. 2018



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 $\sigma(r)$)

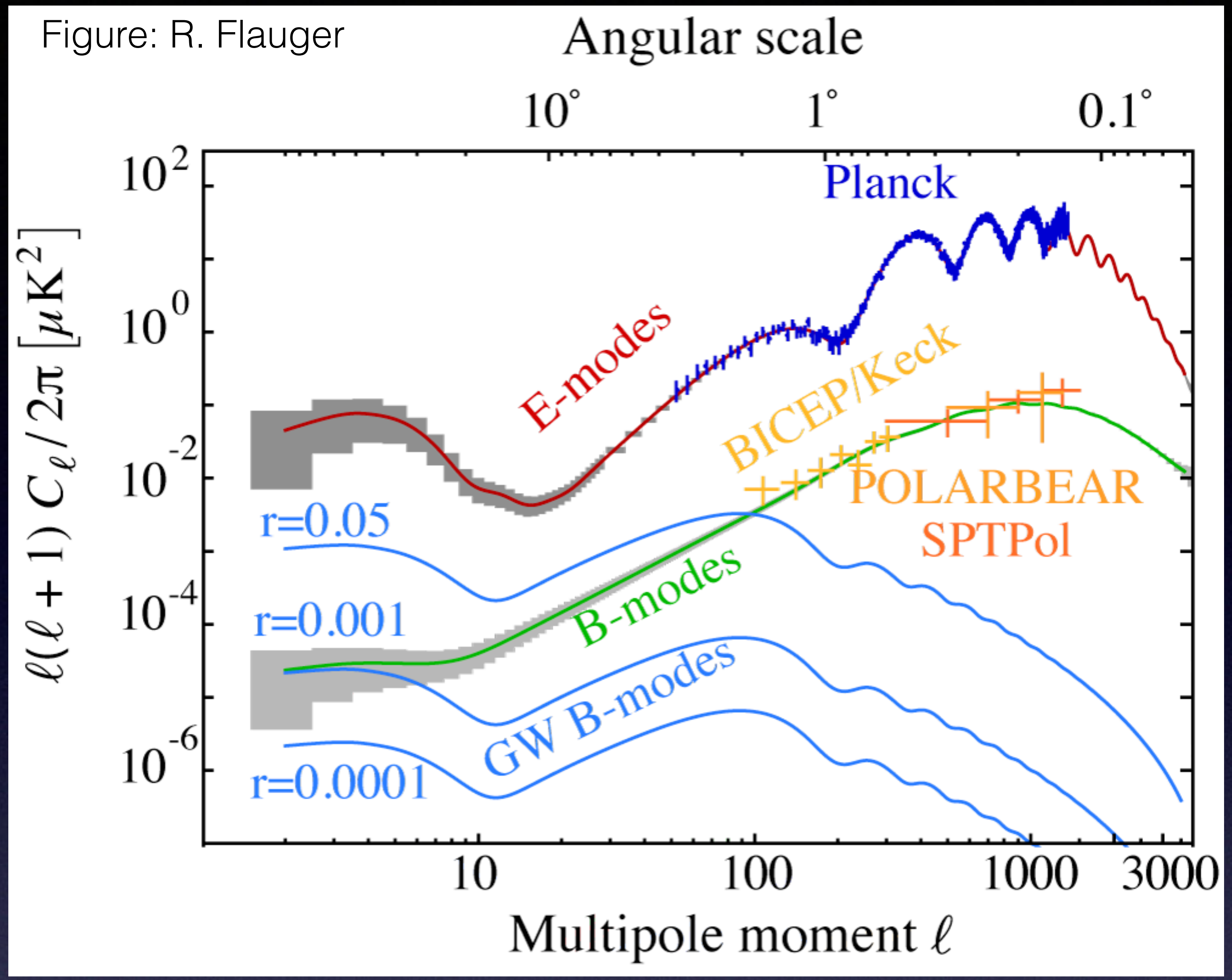


Figure: R. Flauger

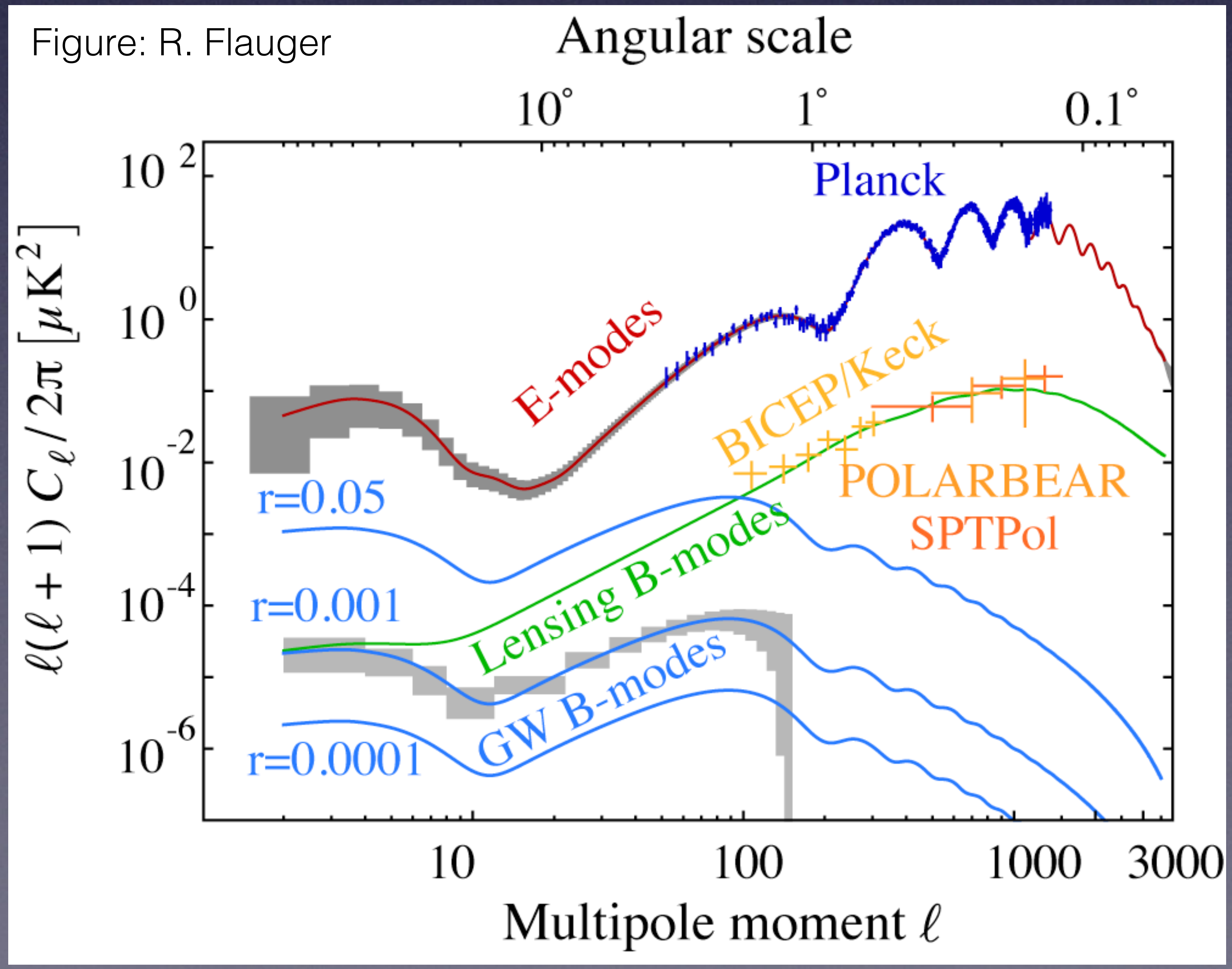


Figure: R. Flauger