PICO

PROBE OF INFLATION AND COSMIC ORIGINS

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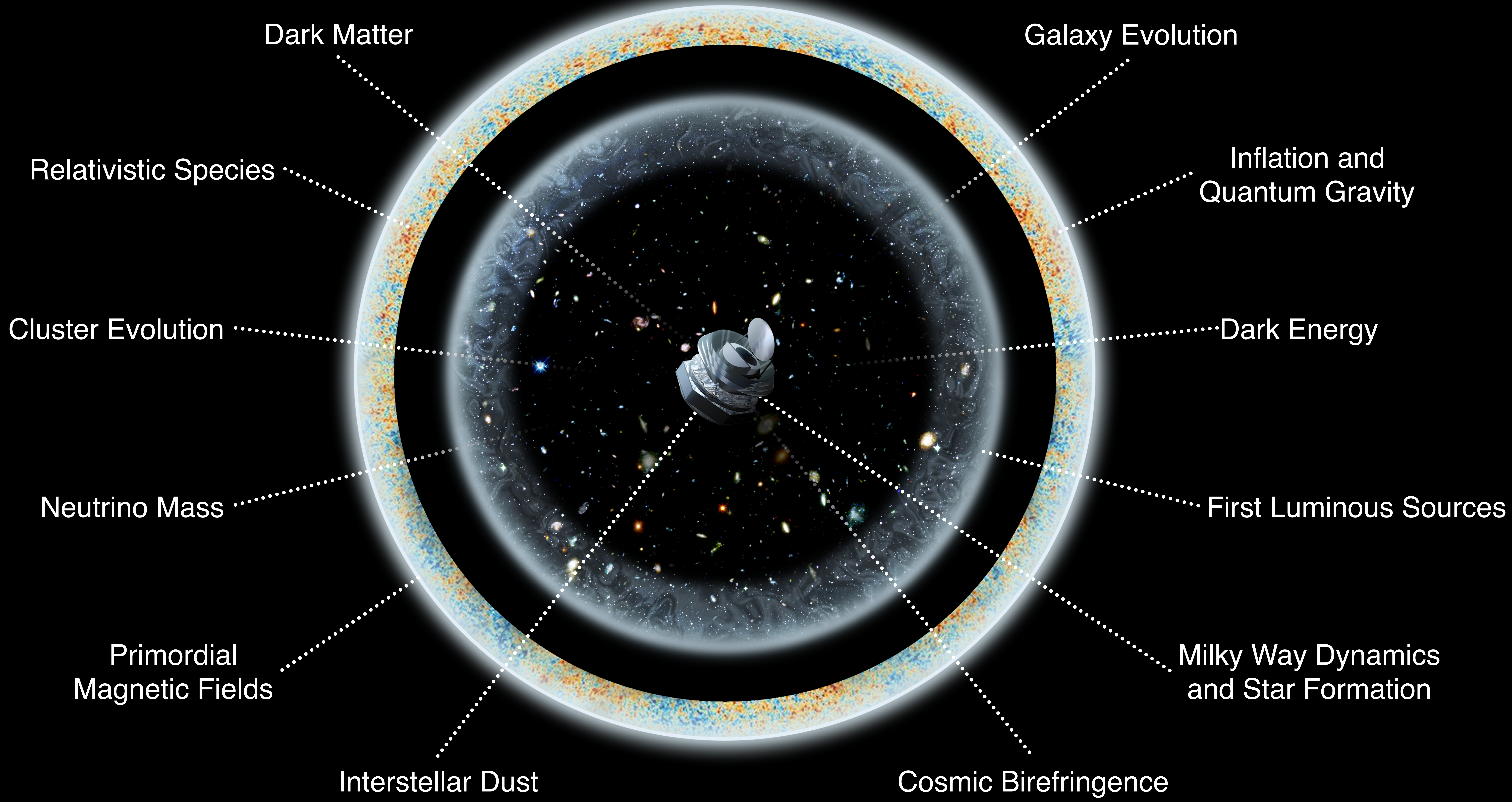
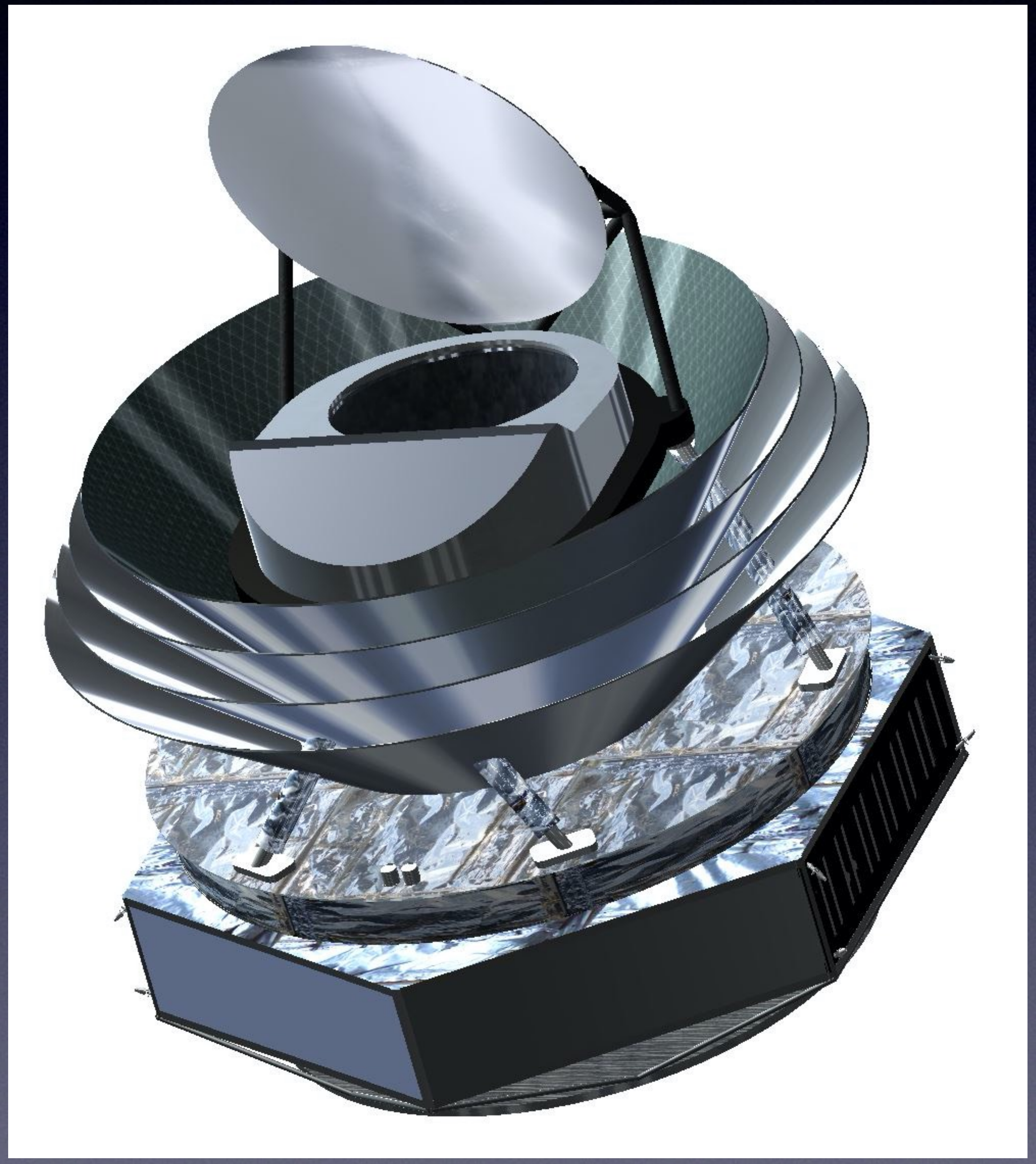
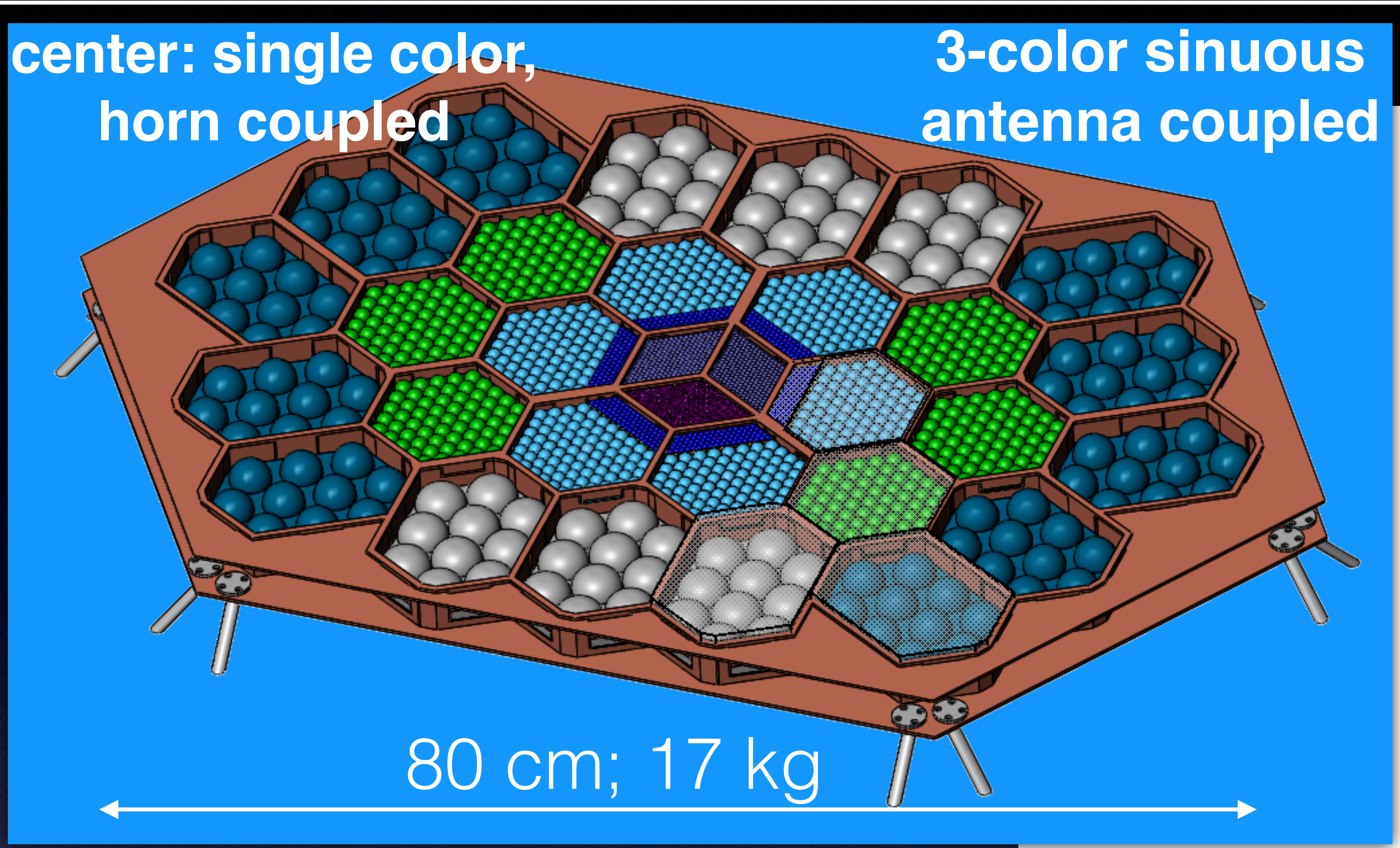


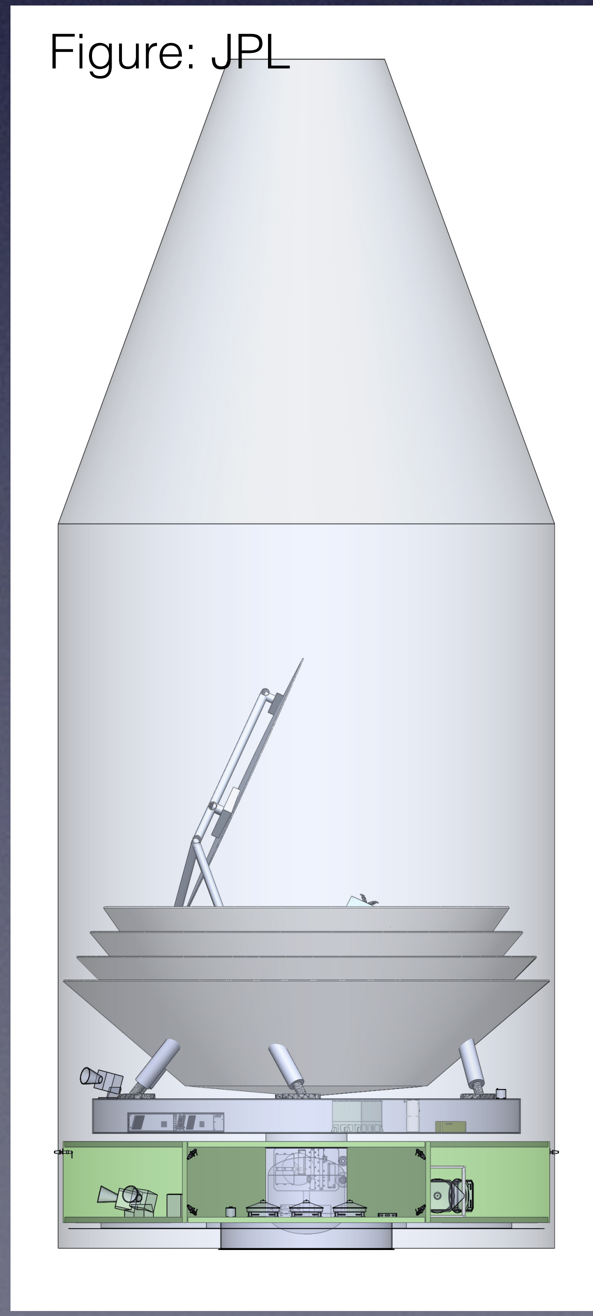
PICO: mm/submm All Sky Imaging Polarimetric Survey

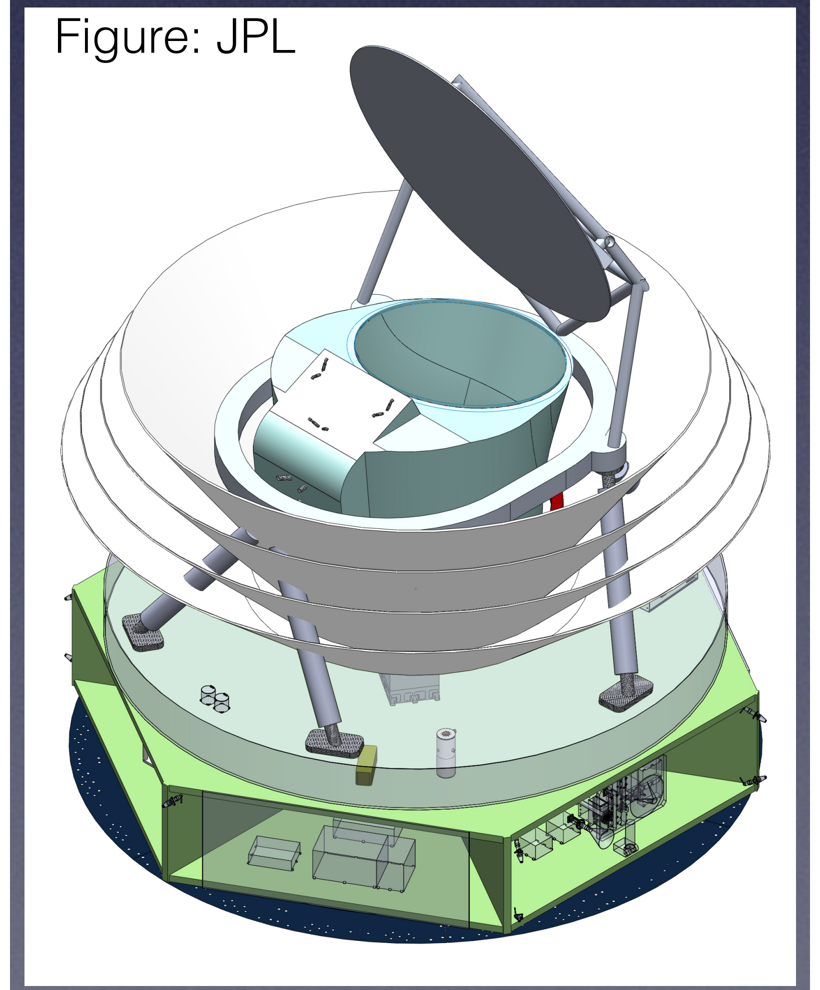
- PICO will produce the deepest maps of Stokes I, Q, U in 21 frequency bands between 20 and 800 GHz
- Maps will have resolution between 38' and 1'.
  8 maps, >200 GHz: highest resolution, full sky maps
- Ten redundant surveys: stringent control of systematic errors
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- Noise baseline: 3300 *Planck* missions (0.87 uK*arcmin)
- Noise Current estimate: 6400 *Planck* missions (0.61 uK*arcmin)

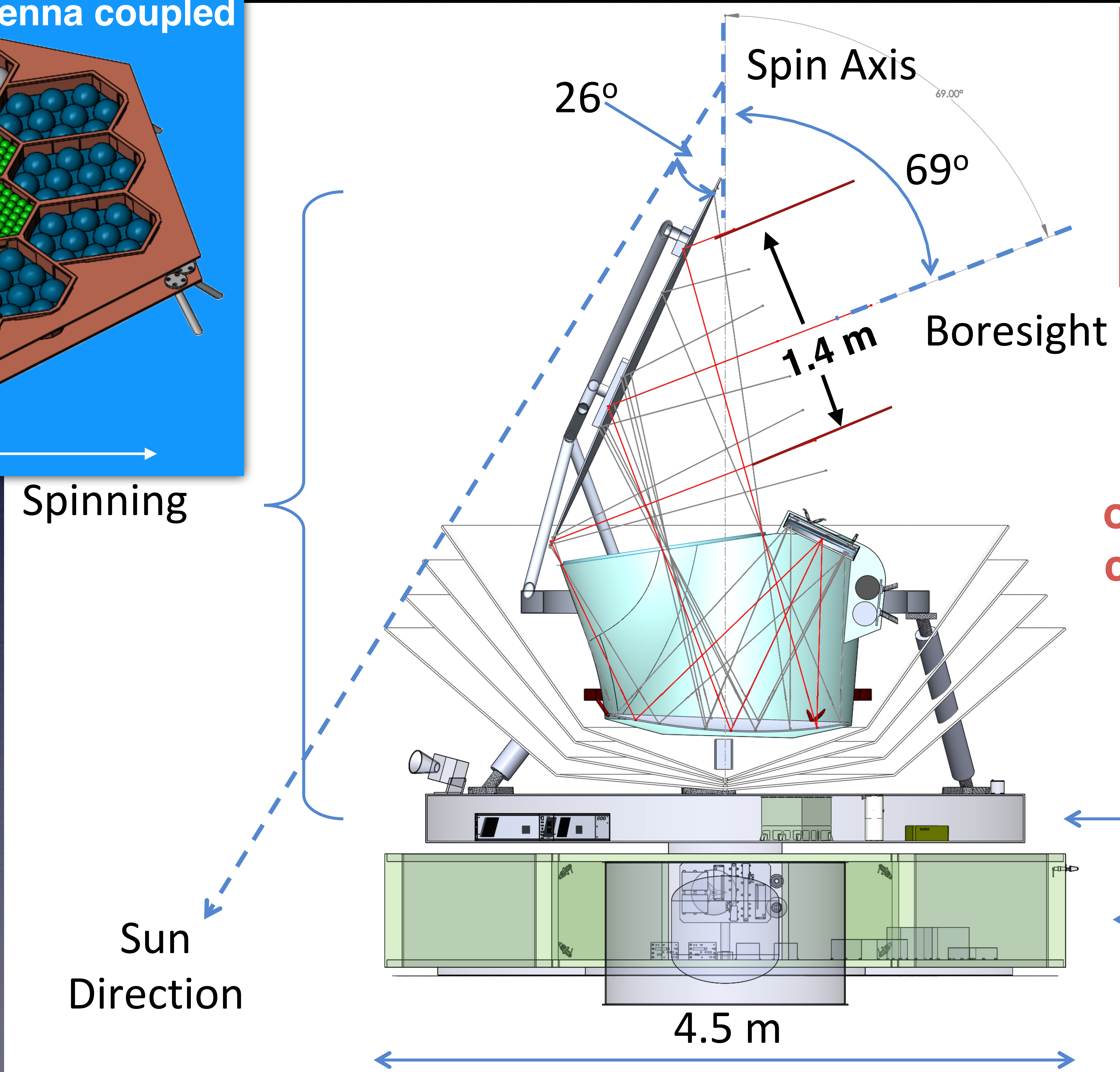


PICO Implementation: Heritage of Planck



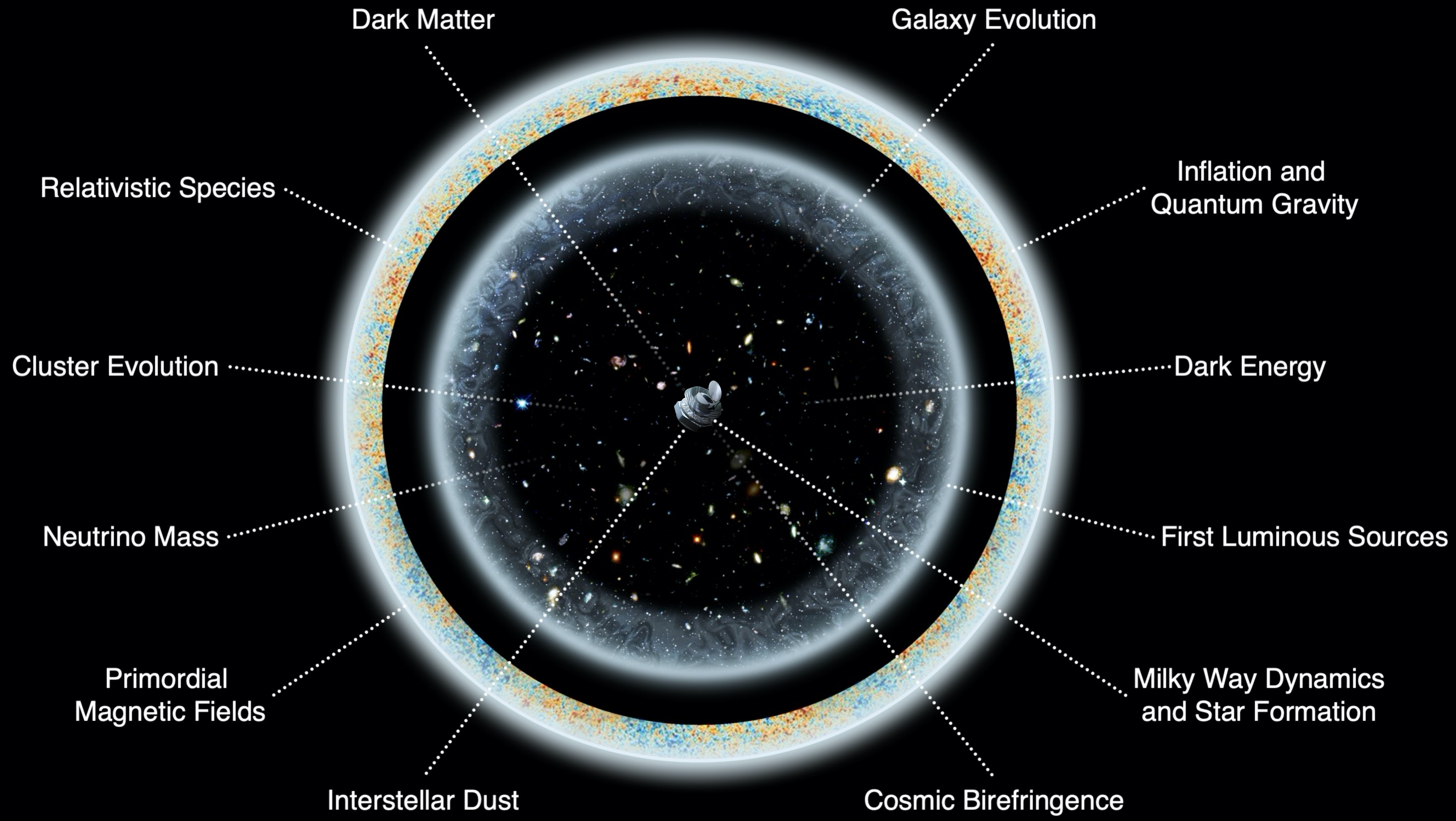






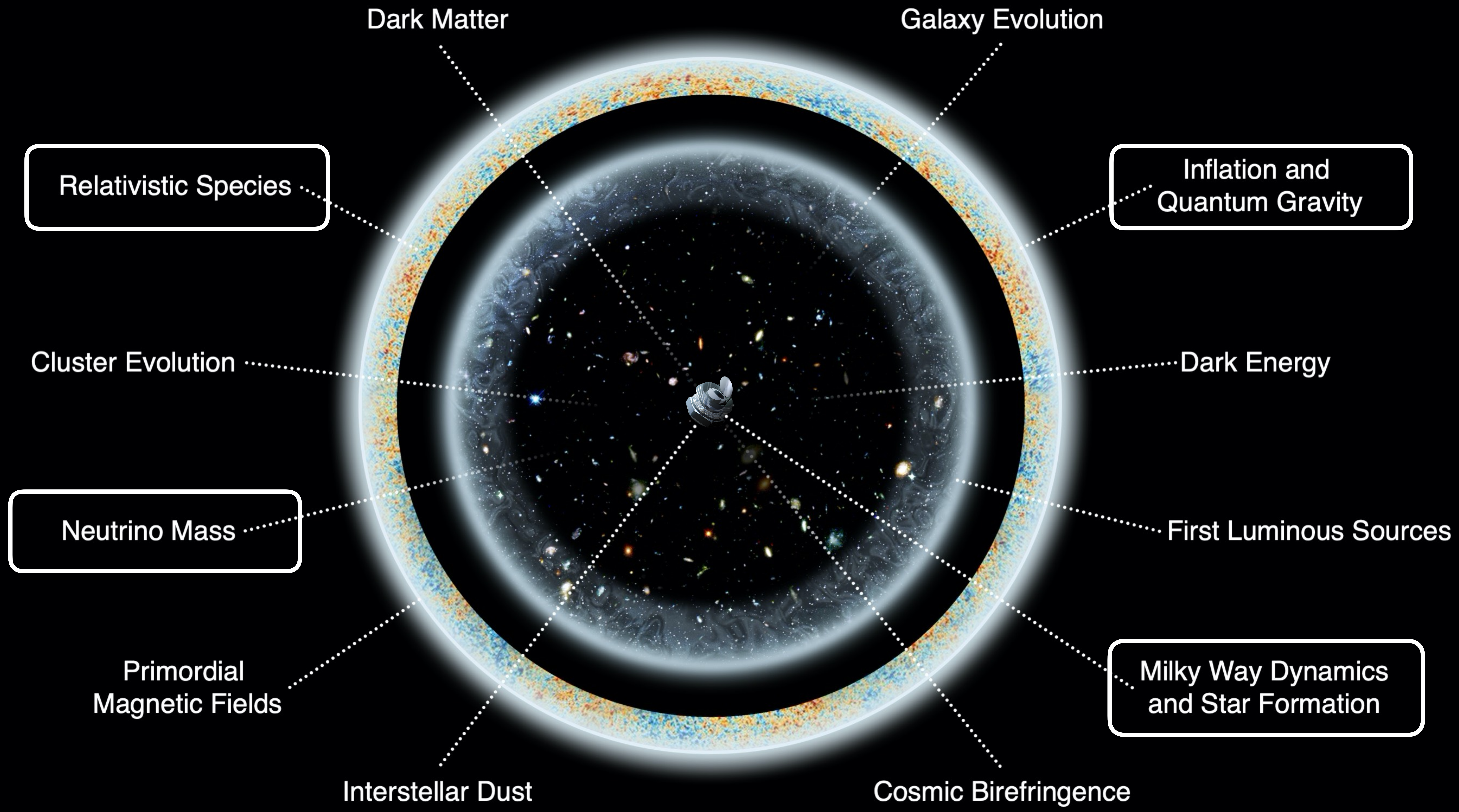
- **2-reflector "Open Dragone" Telescope**
- **Ambient temperature primary**
- **4 K aperture stop**
- **4 K secondary reflector**
- **0.1 K focal plane (cADR)**

PICO echnologies are based on extensions of technologies currently used with space and sub-orbital instruments



https://z.umn.edu/picomission

Hanany et al. arXiv 1902.10541; 1908.07495



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PICO SO1: Tightest Constraint on Inflation r

- Textbook Inflation models that naturally explain the spectral index and have super-Planckian mass have:

$$r \gtrsim 5 \times 10^{-4}$$

- PICO requirement:

$$r < 2 \cdot 10^{-4}\ (95\%);\ \ r = 5 \cdot 10^{-4}\ (5\sigma)$$

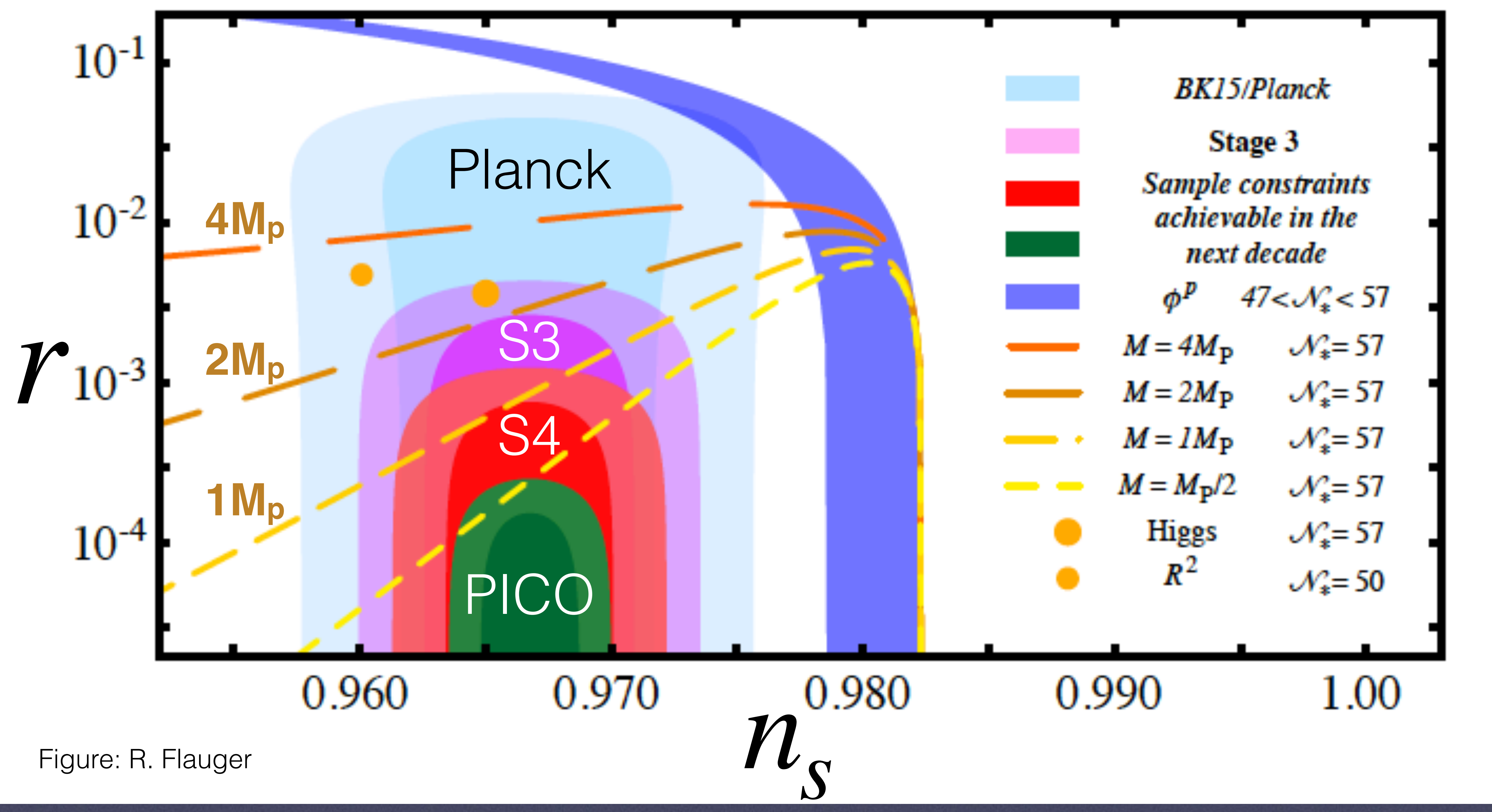

Figure: R. Flauger

Only the PICO exclusion will reject all models with superPlanckian scale in the potential with high confidence

"If this threshold is passed without detection, most textbook models of inflation will be ruled out, and the data would force a significant change in our understanding of the primordial Universe"
(Shandera et al. 2019, Community endorsed decadal white paper)

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- If $r \sim 1 \times 10^{-3}$ - PICO has:
  - Systematics control: Highest SNR, most stable thermal platform, simplest design
  - Foreground control: Multiple detections in independent patches of the sky

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Can the Foregrounds be Handled

- Fisher forecast that includes correlated foregrounds, foreground separation, 40% sky, and delensing gives $\sigma(r) = 2 \times 10^{-5}$

Can the Foregrounds be Handled

- Map based simulations (PySM + others), r=0, 50% of sky, 15% lensing, PICO noise, GNILC foreground removal with 21 bands
- Lowest \ell has x2 bias relative to lensing, x10 lower than $r = 5 \times 10^{-4}\,(5\sigma)$
- For \ell=100, residual is x4 lower
- Results approximately reproduced with other models

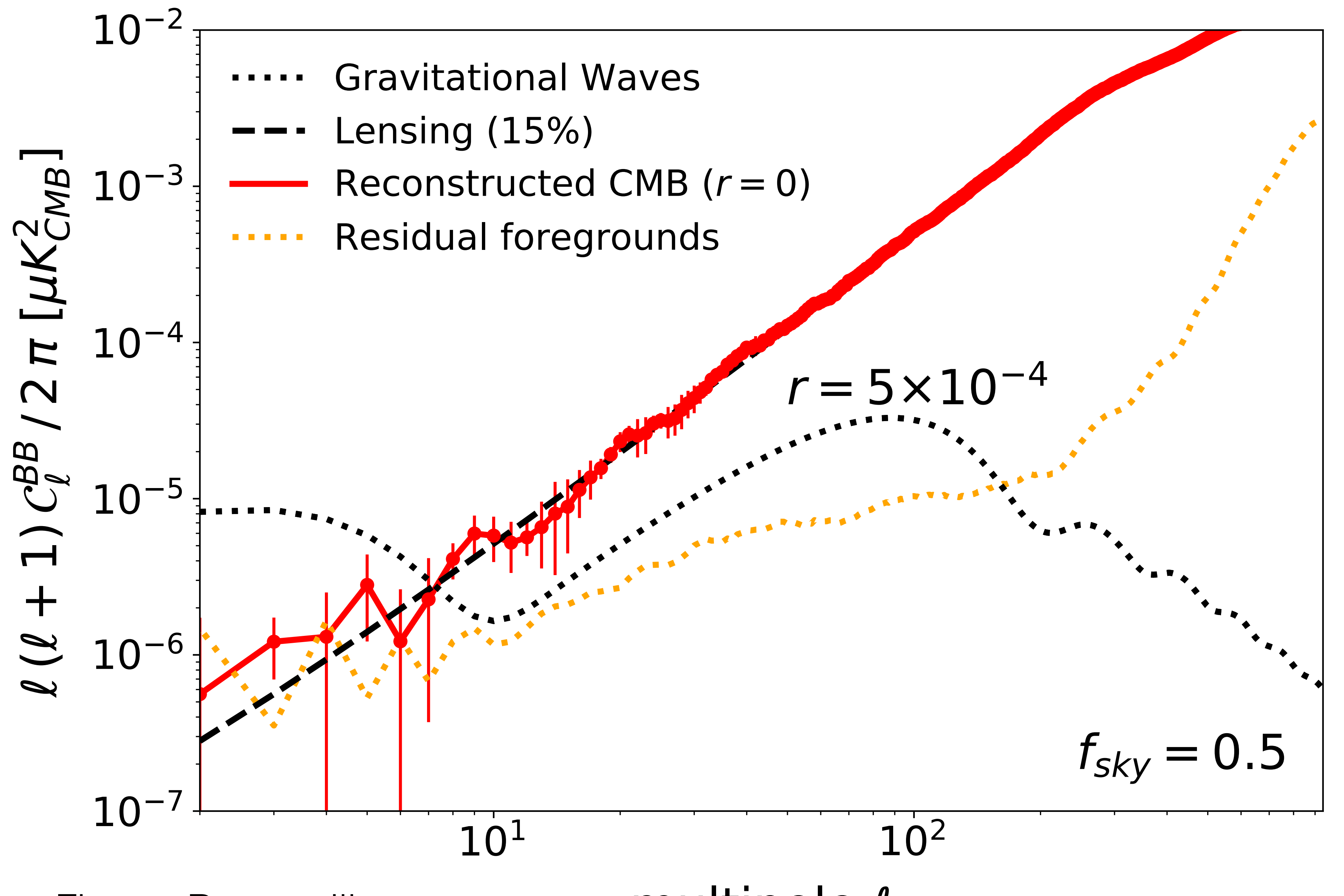


Figure: Remazeilles

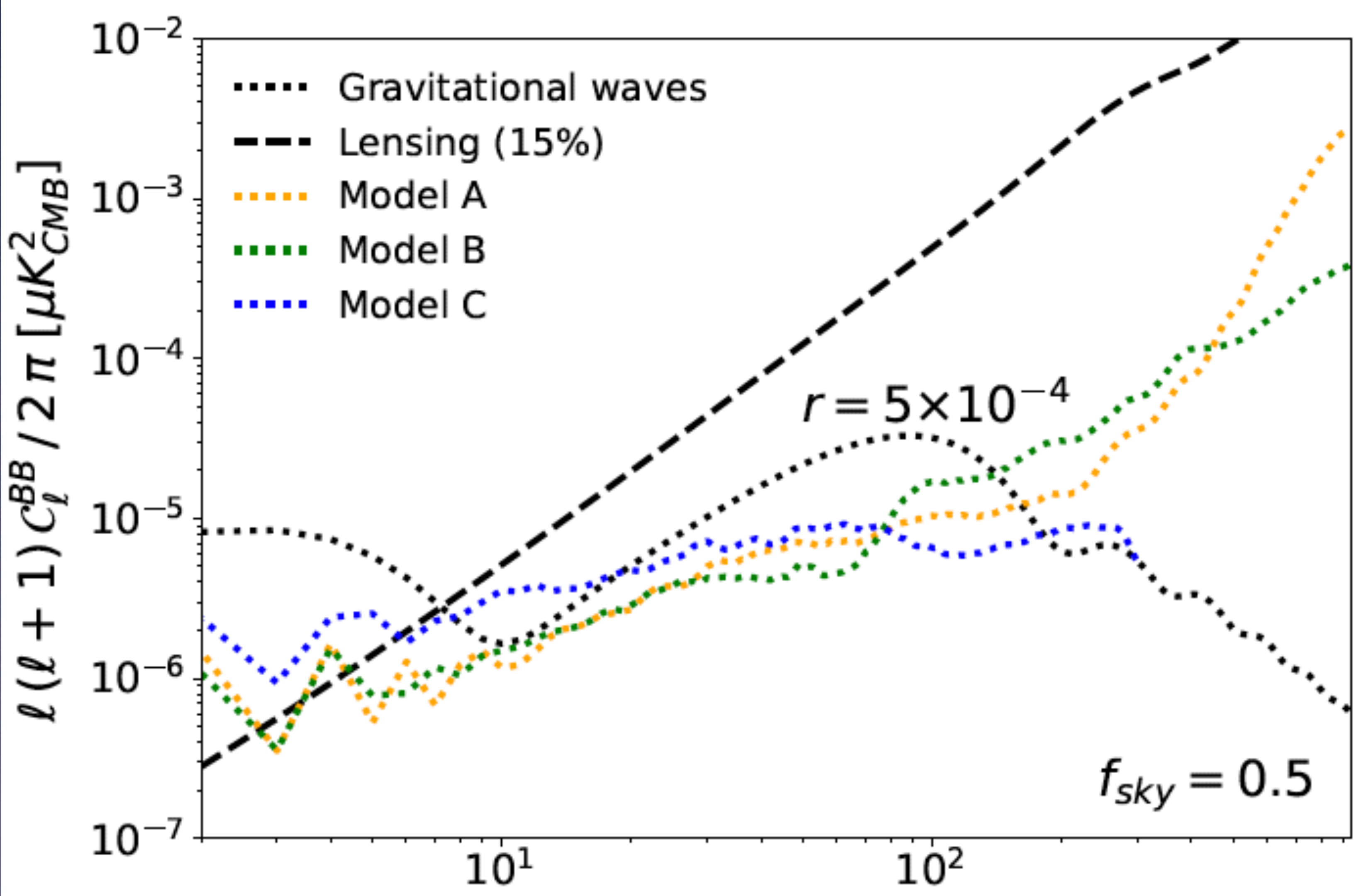
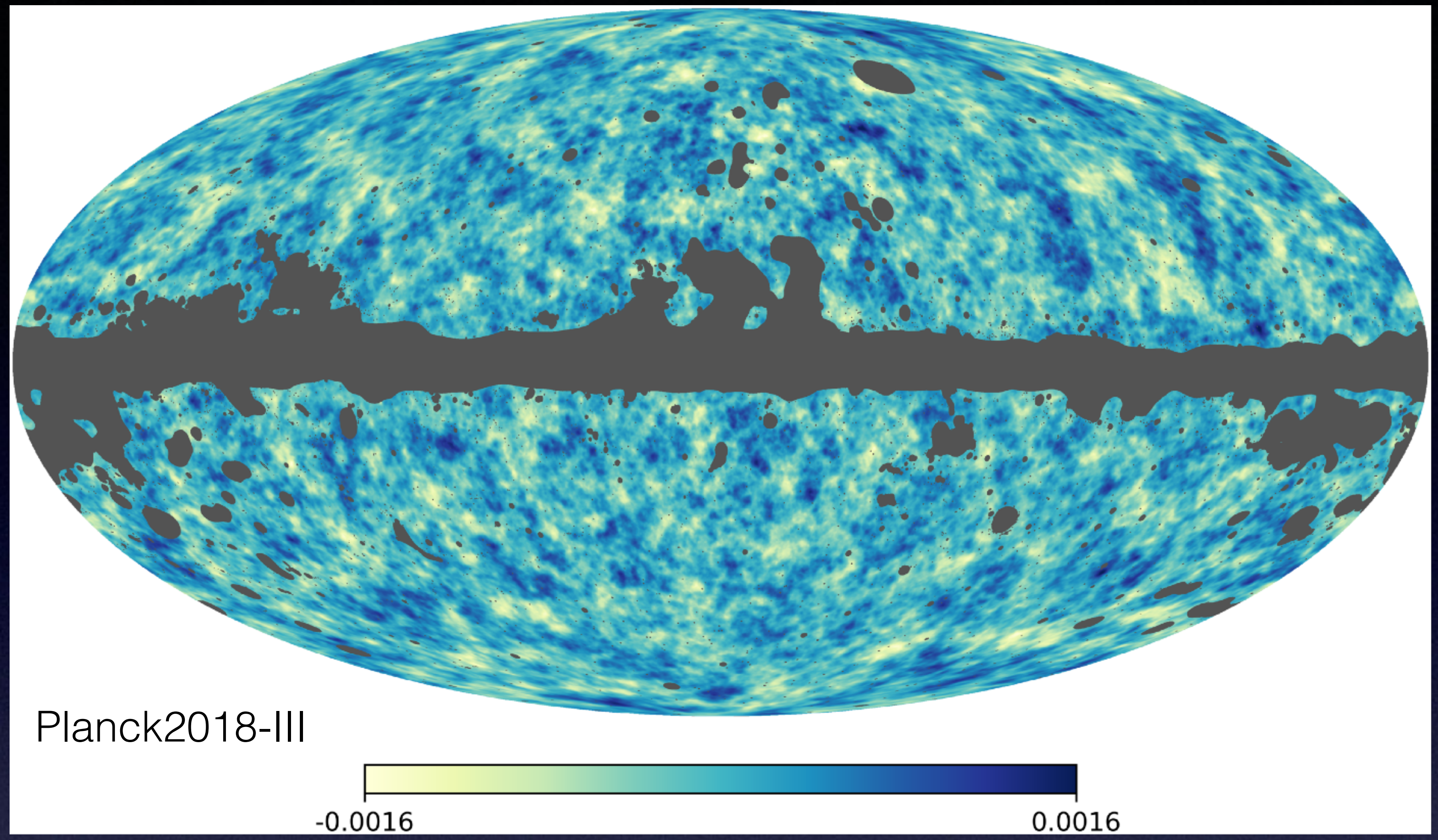


Figure: Remazeilles

PICO SO3: 4σ Detection of Neutrino Mass

- Only cosmology can determine the absolute mass scale if it is near the minimum allowed sum $\Sigma m_\nu = 58\ \mathrm{meV}$
- Growth of structure is affected by neutrino mass, and the projected gravitational potential - revealed through CMB lensing maps - is a sensitive probe of the growth of structure



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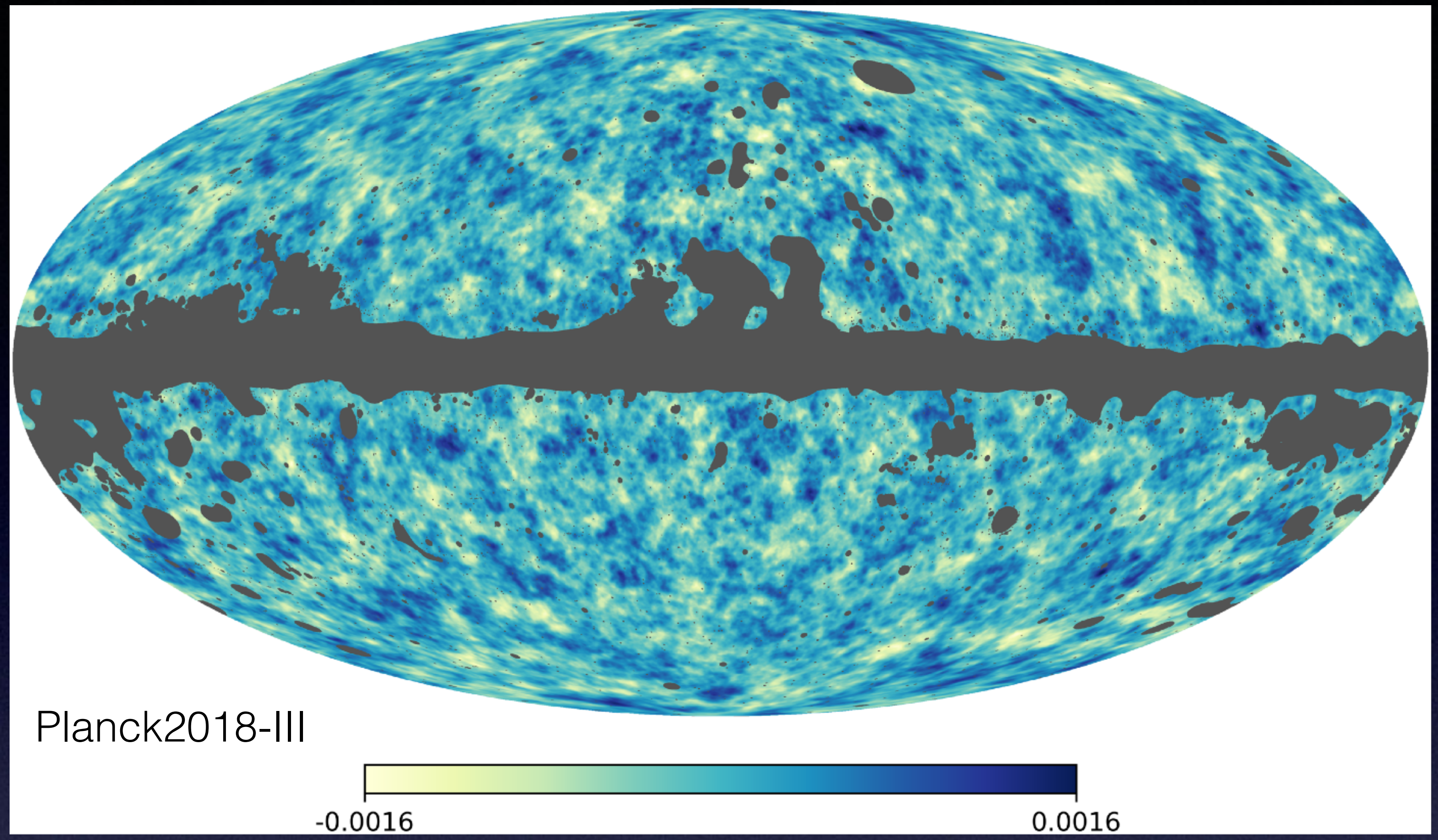
- Sum of neutrino mass requires:
  - Matter density (Baryon acoustic oscillations: DESI/Euclid)
  - Growth of structure (PICO SNR=560; *Planck* SNR=40)
  - Optical depth to reionization (PICO $\sigma(\tau) = 0.002$)



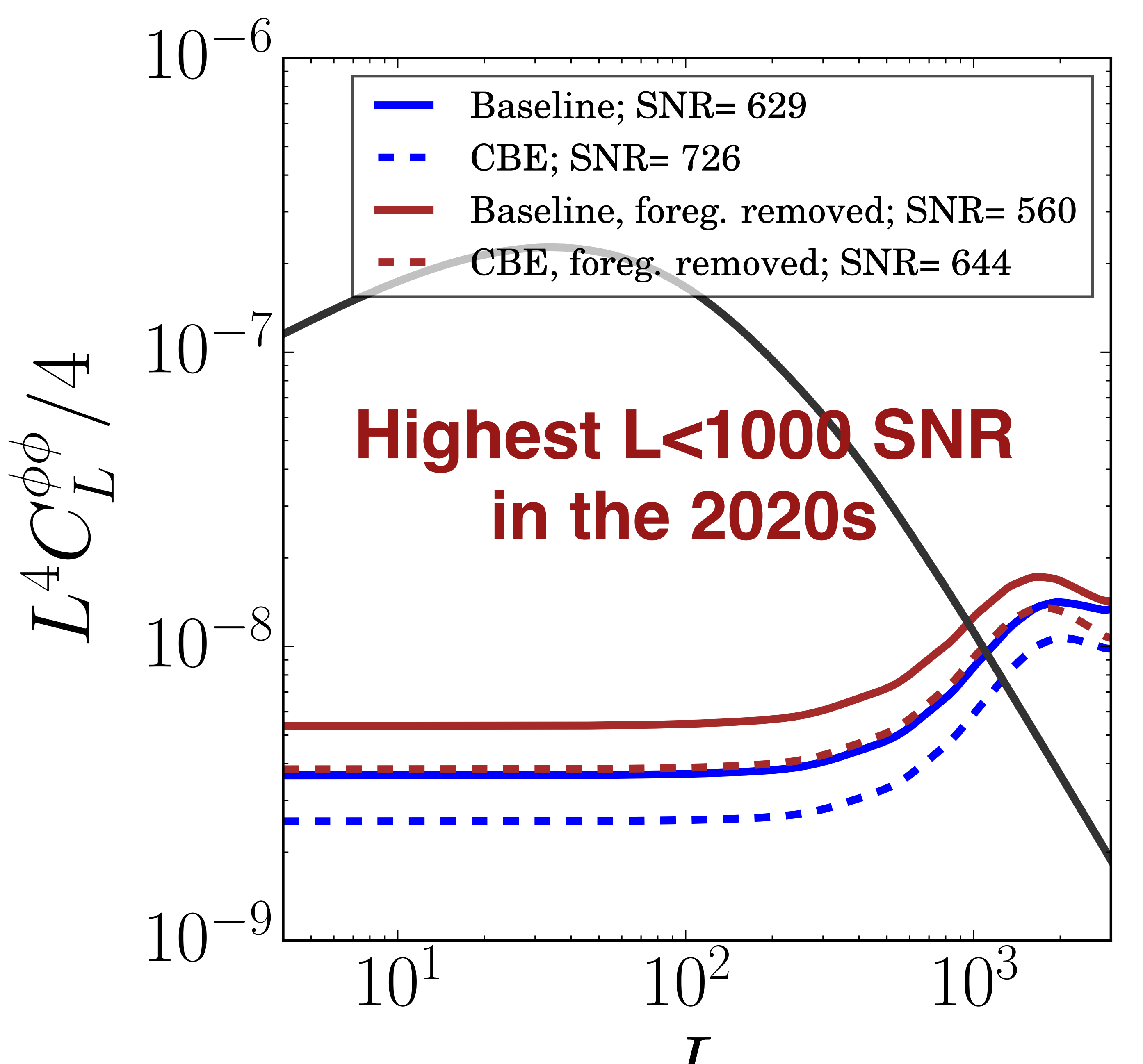


Figure: van Engelen

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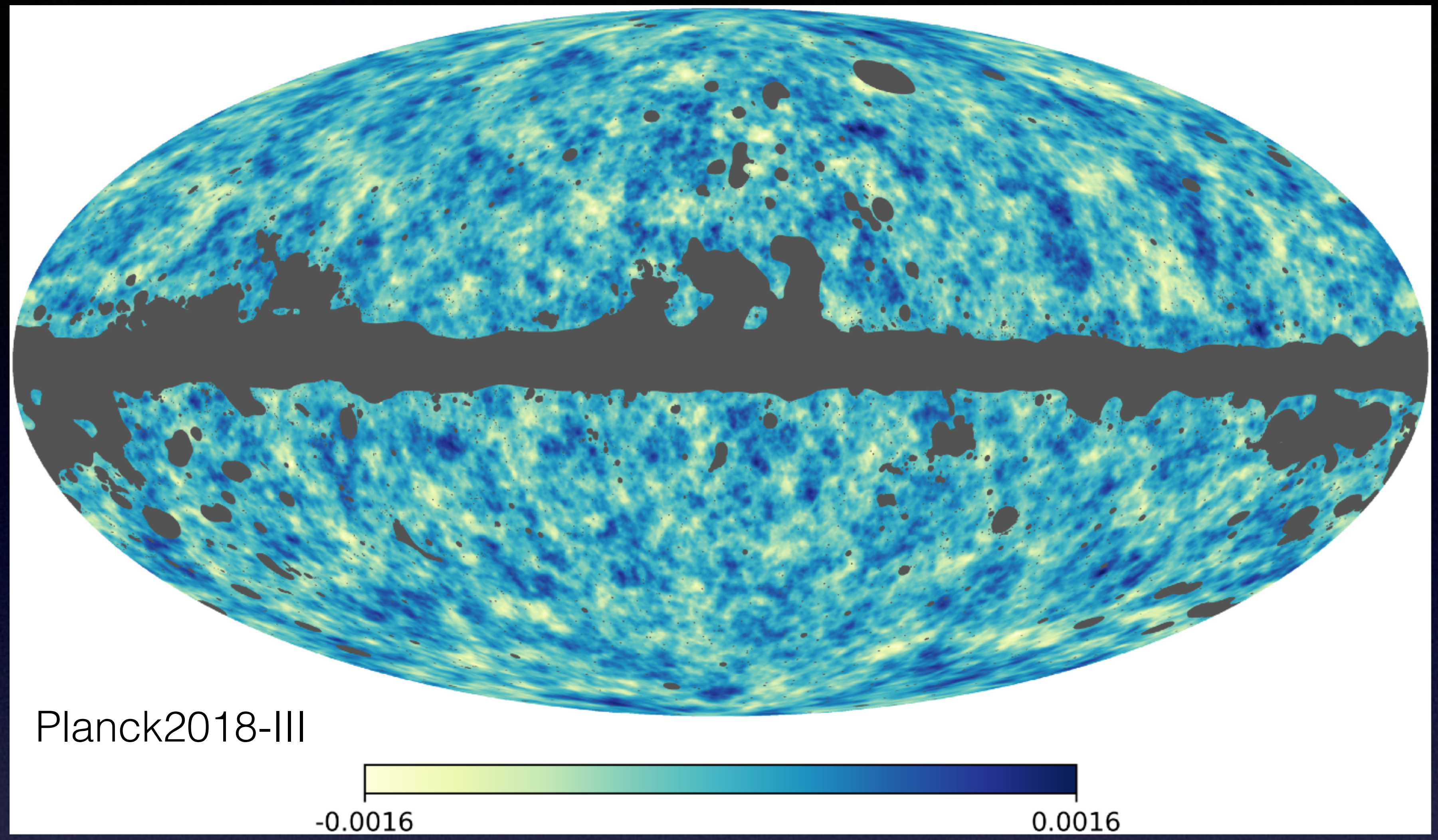

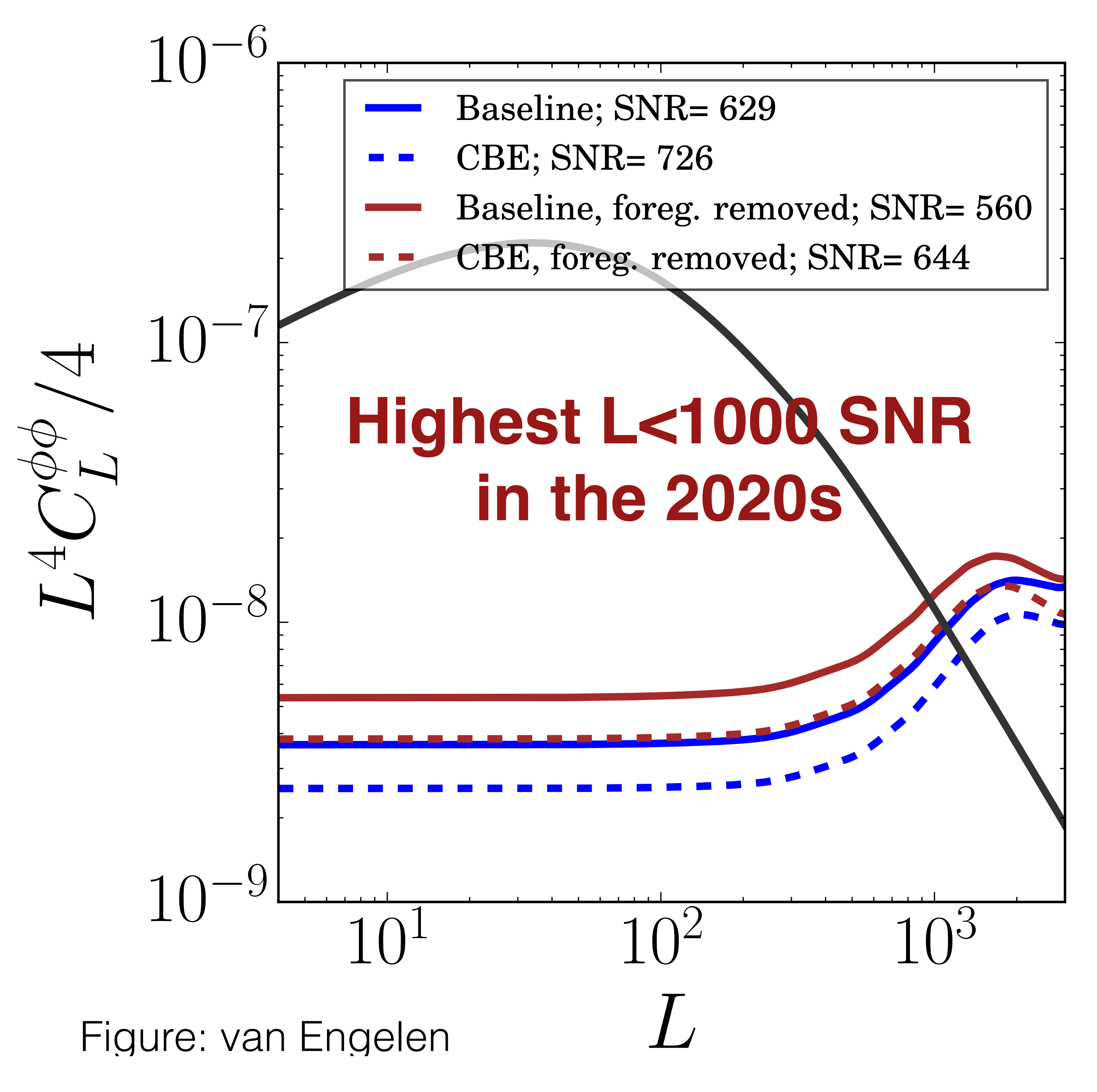

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Only PICO can provide two of the three inputs within a consistent, self-calibrated dataset

No other constraint is expected to be tighter

PICO SO4: New Particles

- Light species, beyond 3 neutrinos, could have existed in the early universe and fallen out of thermal equilibrium at high temperature T_F.
- CMB spectra are sensitive to the number of light species N_{eff}
- Only 3 neutrinos gives: $N_{\mathrm{eff}} = 3.046$
- Planck + BAO: $2.92 \pm 0.36\,(95\%)$
- PICO: $\Delta(N_{\mathrm{eff}}) = 0.06\,(95\%)$

Decoupling temperature as a function of ΔNeff relative to neutrinos only for additional particle species

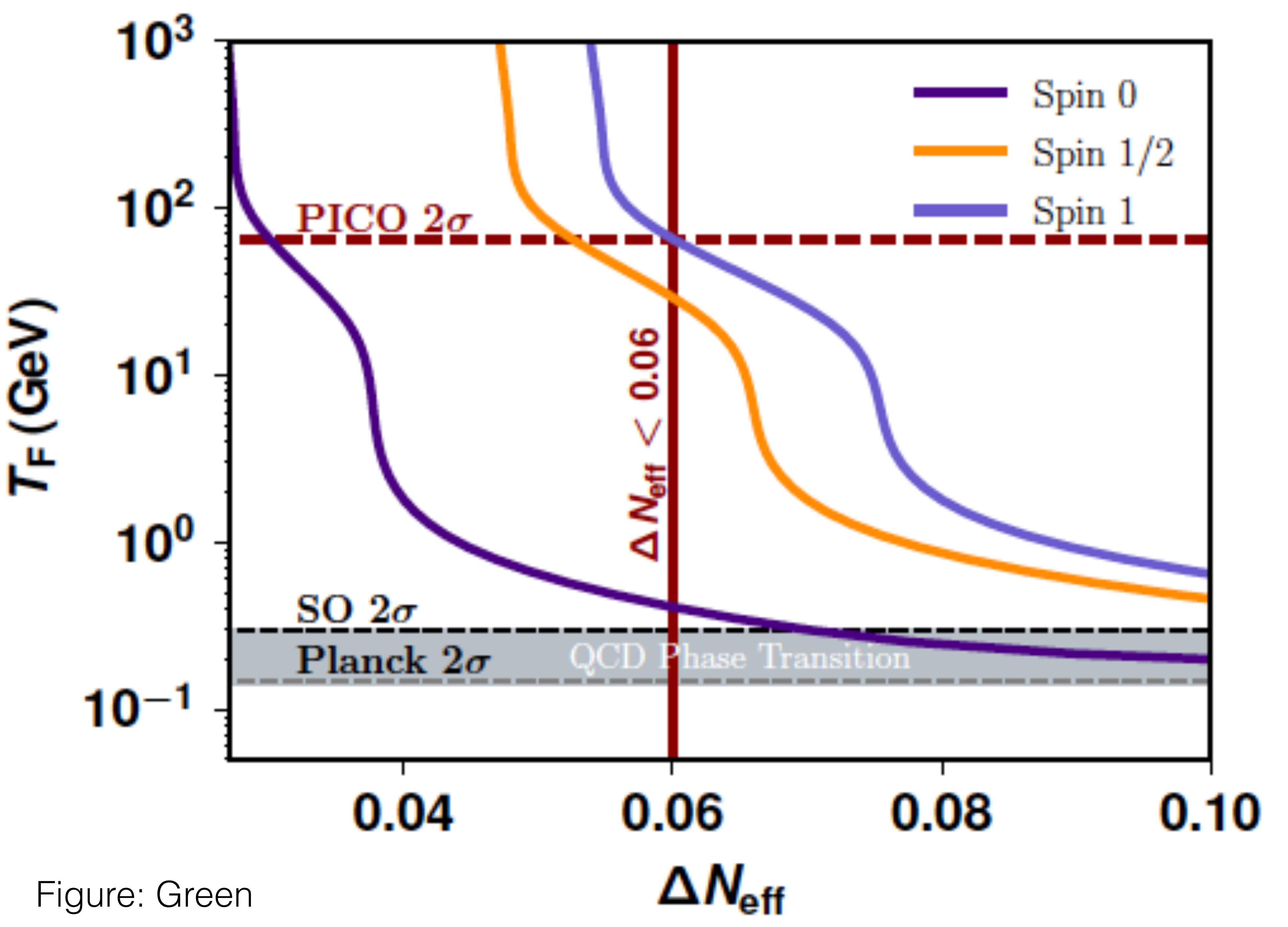


Figure: Green

No other constraint is expected to be tighter

PICO SO7: Why the Low Star Formation Efficiency?

- Milky Way stars form at much lower rate than would be expected from gravitational collapse
- Turbulence + magnetic fields slow collapse from the diffuse ISM to molecular clouds, to star forming regions
- What is the ratio of energy stored in the magnetic field to that stored in turbulent motion over spatial scales from the diffuse ISM to dense cores?
- Need measurements of magnetic fields over four orders of magnitude: entire galaxy (10^4 pc) down to dense cores (0.1-1 pc)

PICO SO7: Why the Low Star Formation Efficiency?

86,000,000 independent B field measurements
x1000 more than Planck

Orion Region

Figure: Chuss + Fissel

PICO Science : Galactic Magnetic fields

- Map magnetic fields in 70 external galaxies, with 100 measurements per galaxy (currently 2 are mapped)

- Map 10 nearby clouds with 0.1 pc resolution => scale of cloud cores (currently no data are available to connect magnetic fields in the diffuse ISM to that in cloud cores)

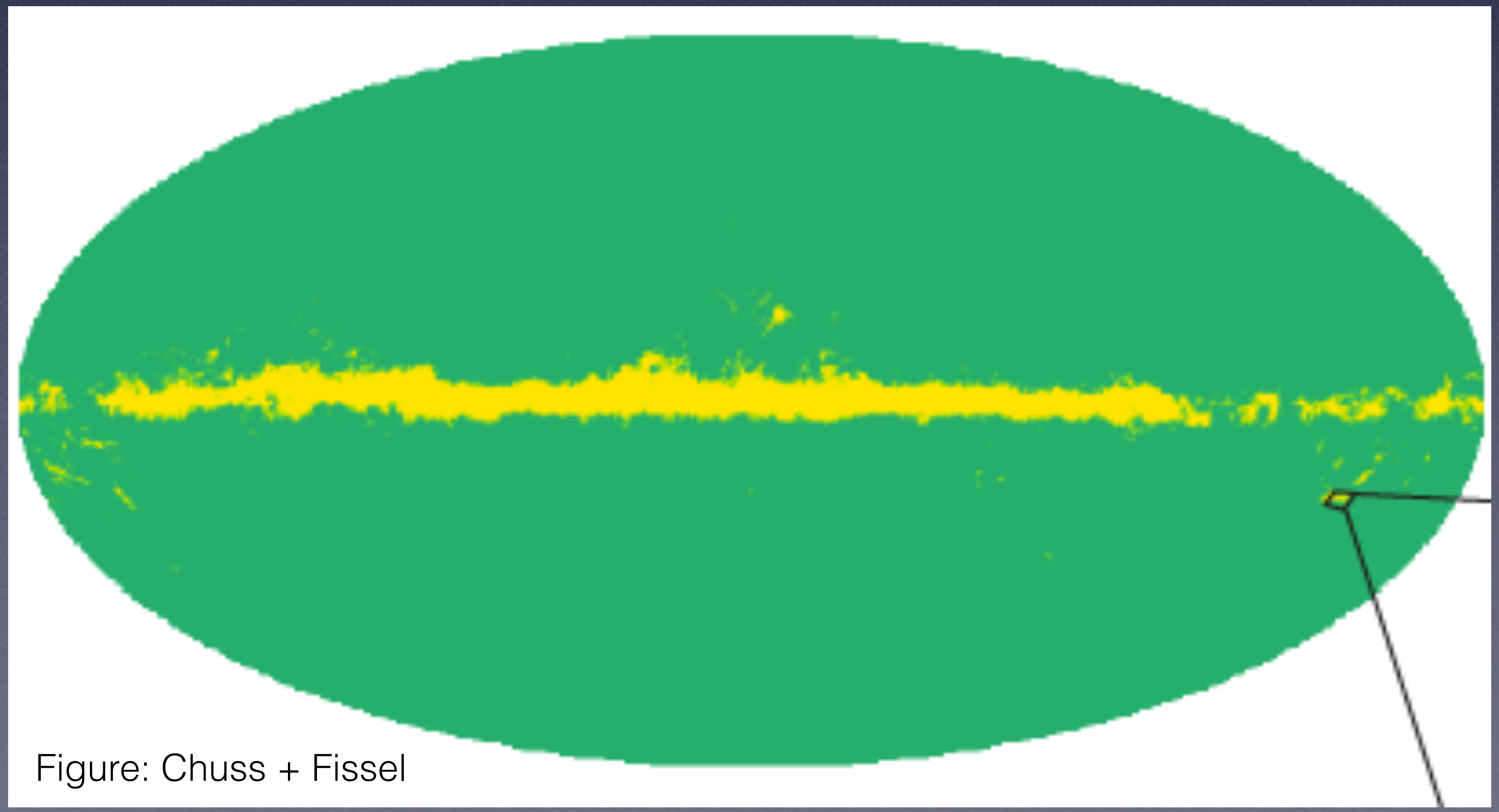
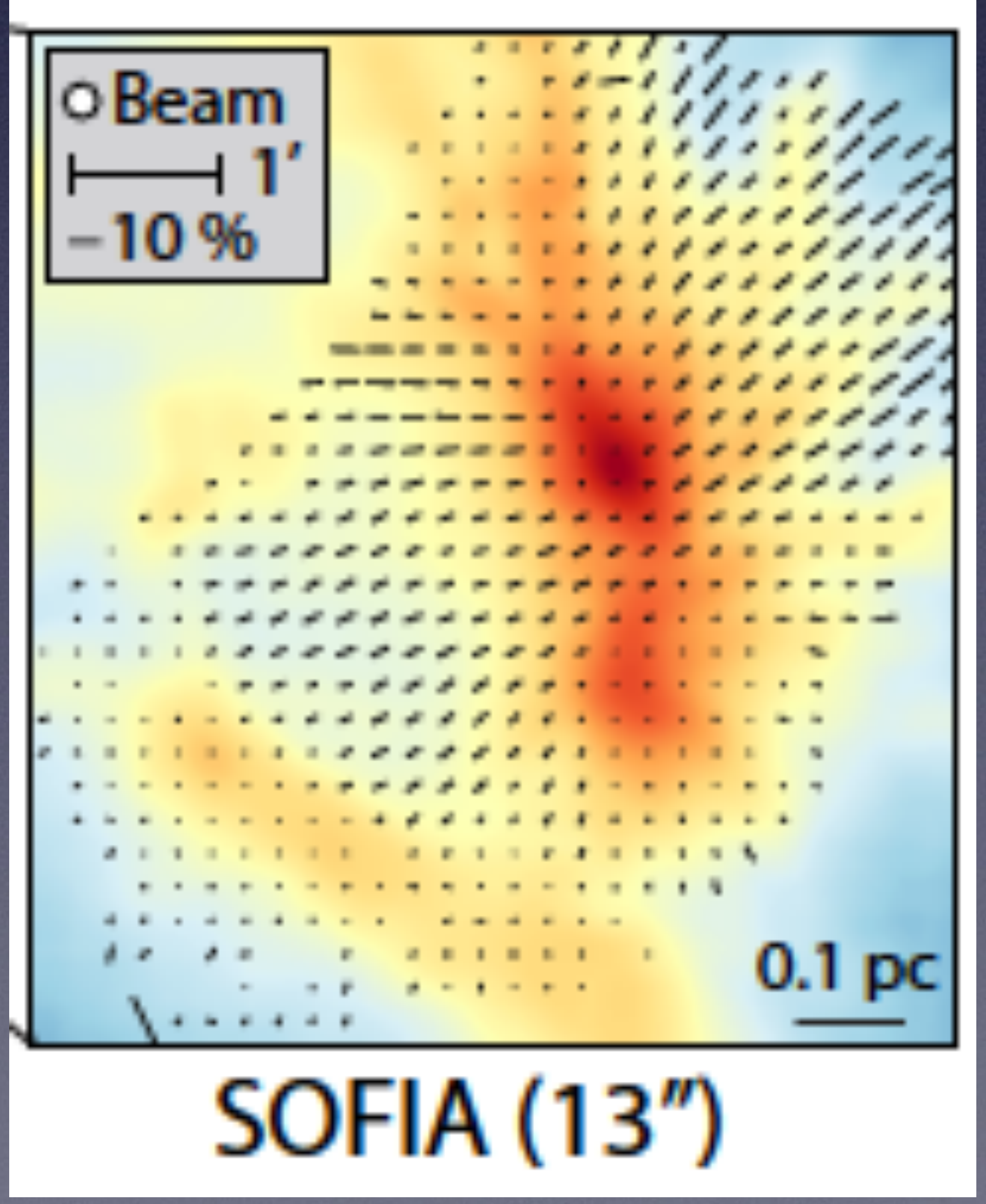


Figure: Chuss + Fissel

Factor of 10^4 in spatial scale



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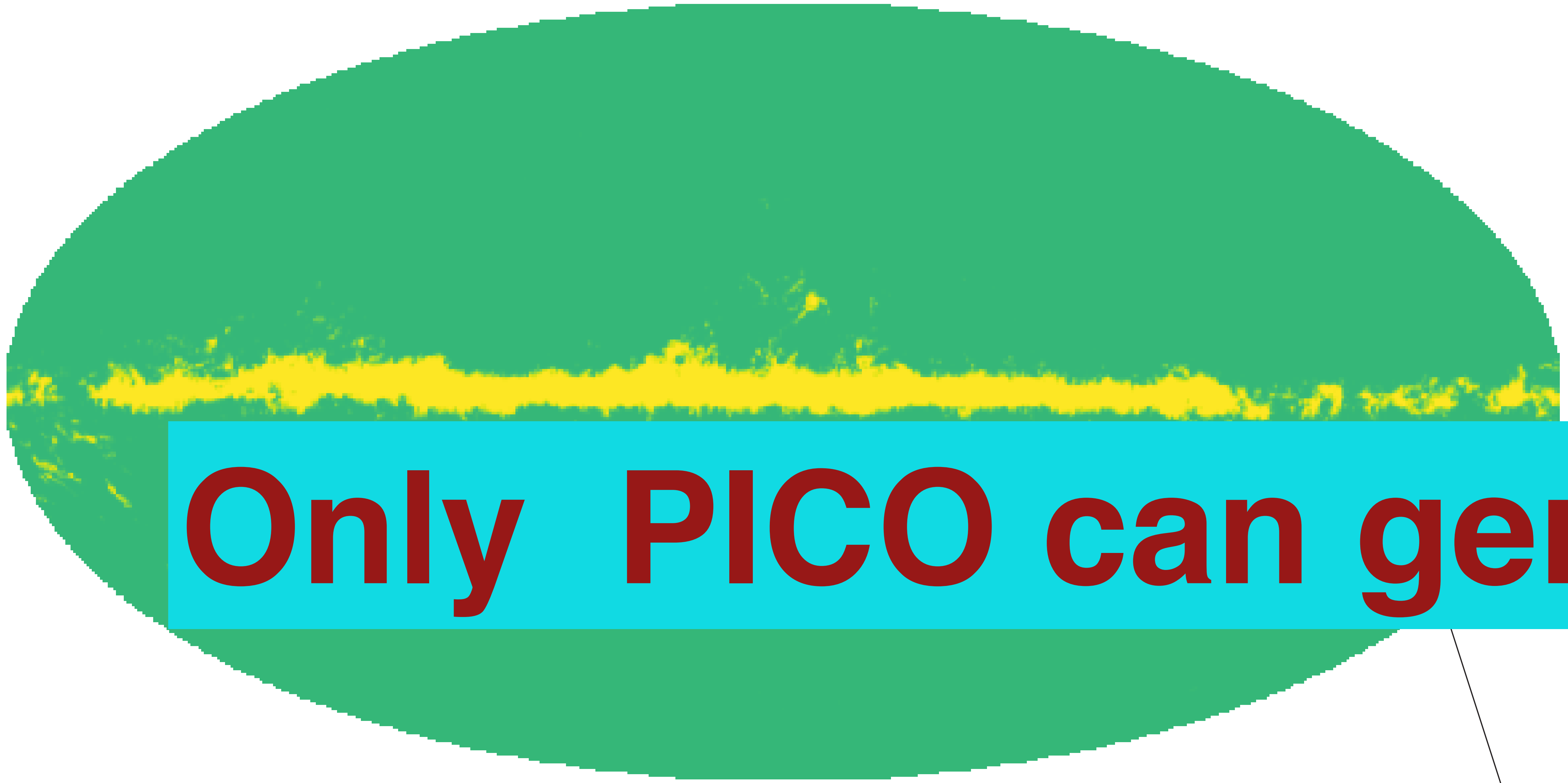
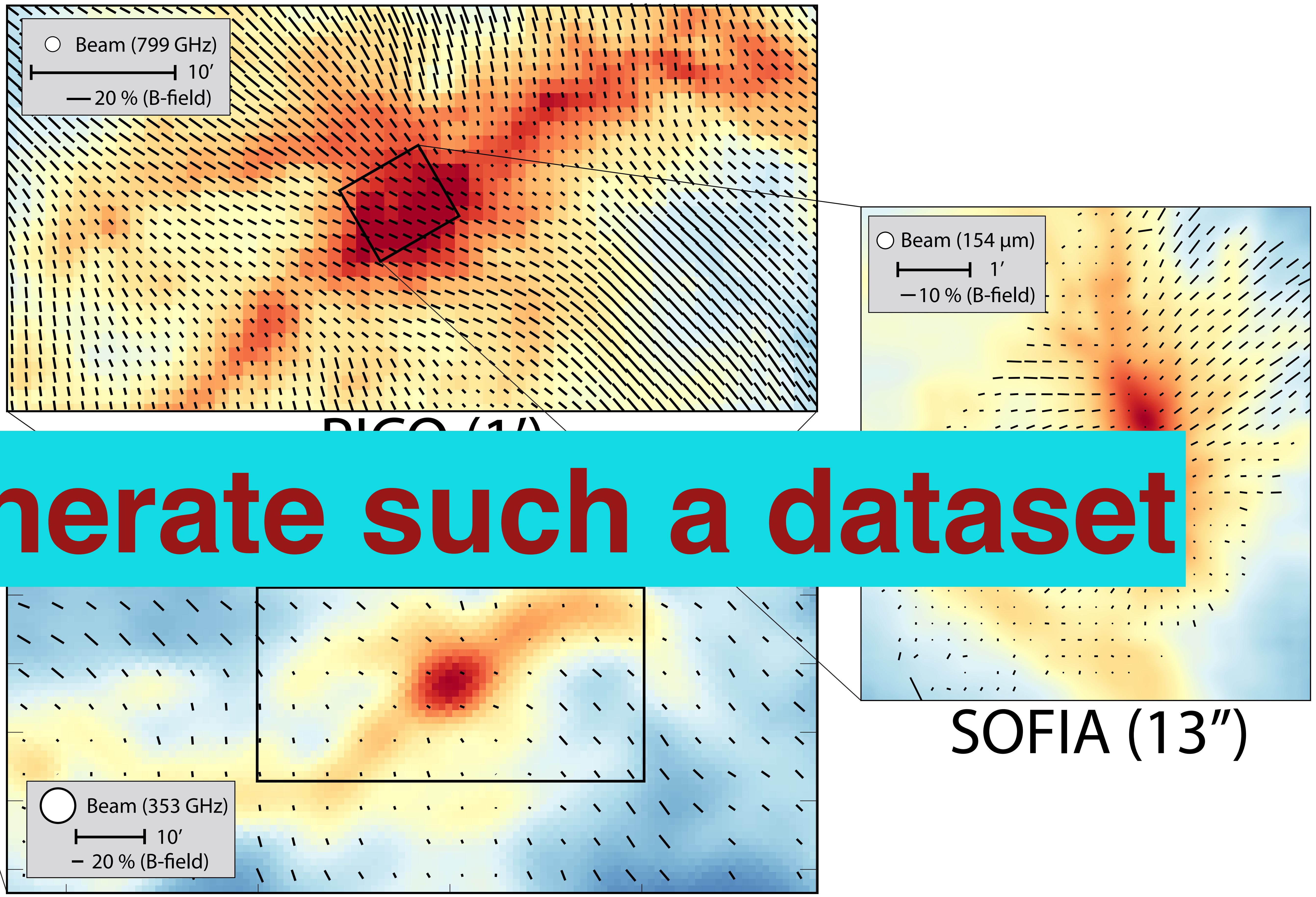


Planck 353 GHz polarization 5′ resolution, $\sigma_p < 0.67\%$
PICO 799 GHz polarization 1′ resolution, $\sigma_p < 0.67\%$

Only PICO can generate such a dataset



SOFIA (13″)

Planck (5′)

Orion Region

Figure: Chuss + Fissel

Legacy Surveys Available only with PICO Data

Science

- Early galaxy formation and dark matter substructure
- Early cluster formation
- Correlation of dust with galaxy properties
- Physics of jets in radio sources
- Ordering of magnetic fields in external galaxies

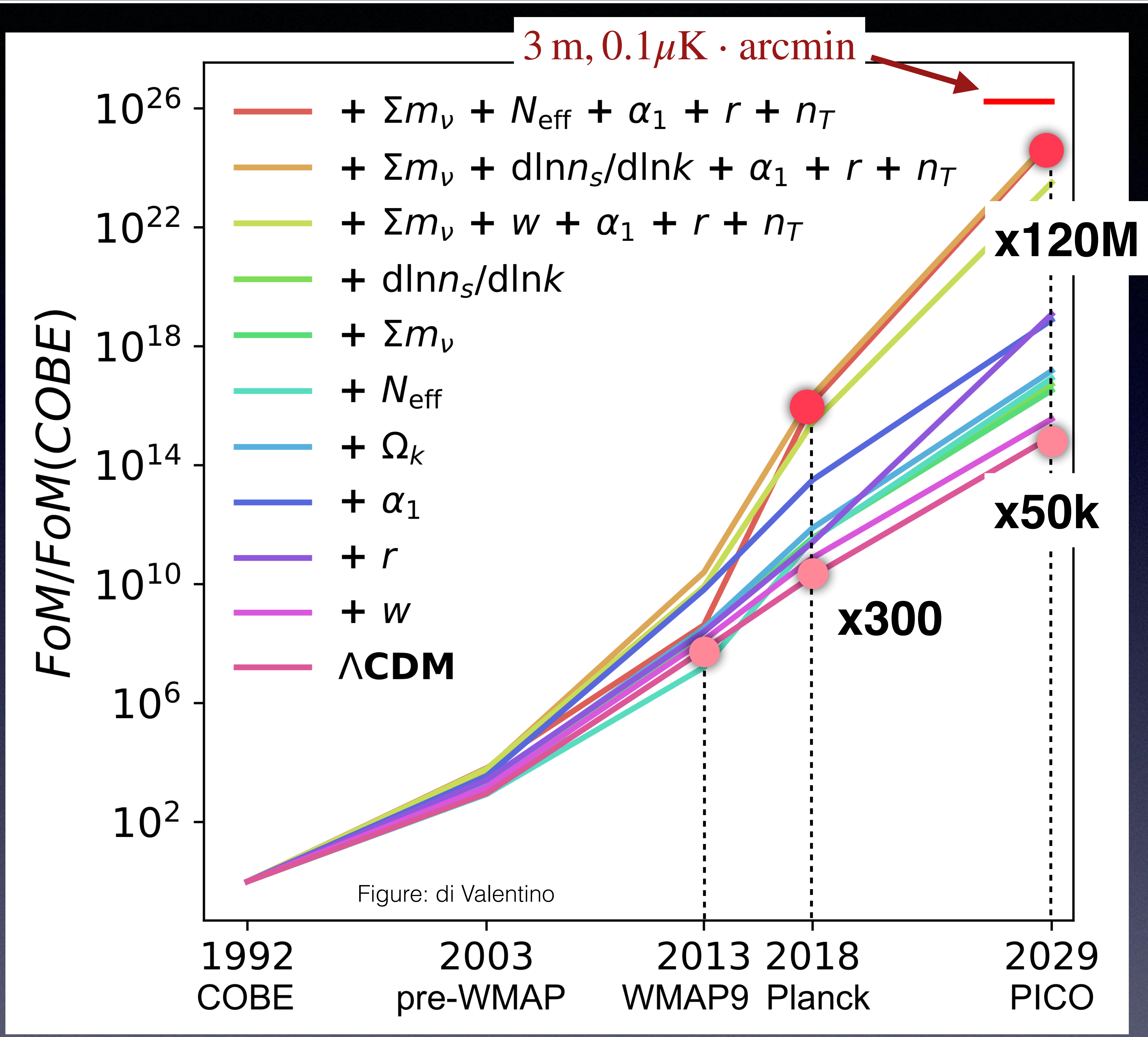
Catalog

- 4500 strongly lensed galaxies, z~5; (x400)
- 50,000 proto-clusters, z~4.5; (x1000)
- 30,000 galactic dust SEDs, z<0.1;(x10)
- 2000 polarized radio sources; (x10)
- Polarization of few thousand dusty galaxies (x1000);

Data will be mined for years by astrophysicists in many sub-disciplines

Set Cosmological Paradigm for the 2030s

- 6-parameter ΛCDM describes the Universe well
- But tensions exist
  - 4σ between supernovae and CMB measurements of Ho
  - 2σ in measurements of σ_8 (amplitude of fluctuations)
  - What is most of the Universe made of?
- Constraint on 6-parameter ΛCDM:
  - PICO/Planck = 50,000 (Planck/WMAP9 = 300)
- Constraint on 11-parameter ΛCDM+:
  - PICO/Planck = 1.2×10^8



ΛCDM will either survive this stringent scrutiny, or a new cosmological paradigm will emerge

PICO's Status

- 50 pg PICO report publicly available (astroph/1902.10541)
- Project paper submitted in 7/2019 (astroph/1908.07495)
- Additional information has been provided to the sub-panel on Electromagnetic Observations from Space II (12/2019)
- Work on PICO will be restarting (initial focus is on foregrounds)

Why PICO, Why Now

- Transformative science; Much of the science can only be done from space.

- Further progress with CMB requires a leap in sensitivity, foreground characterization, and systematic control. Space is best suited to provide this leap.

Figure: R. Flauger

- PICO is the only instrument with the combination of sky coverage, resolution, frequency bands, and sensitivity to achieve all of the science with one platform.

- Next decade ground-based efforts are equivalent in cost to PICO. With more bands, higher sensitivity, better control of systematics, and simpler instrument implementation, PICO is the most cost effective path for progress.

PICO - community-wide effort + support

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Dark Matter · Relativistic Species · Cluster Evolution · Interstellar Dust · Cosmic Birefringence · Dark Energy · Quantum Gravity · Galaxy Evolution

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