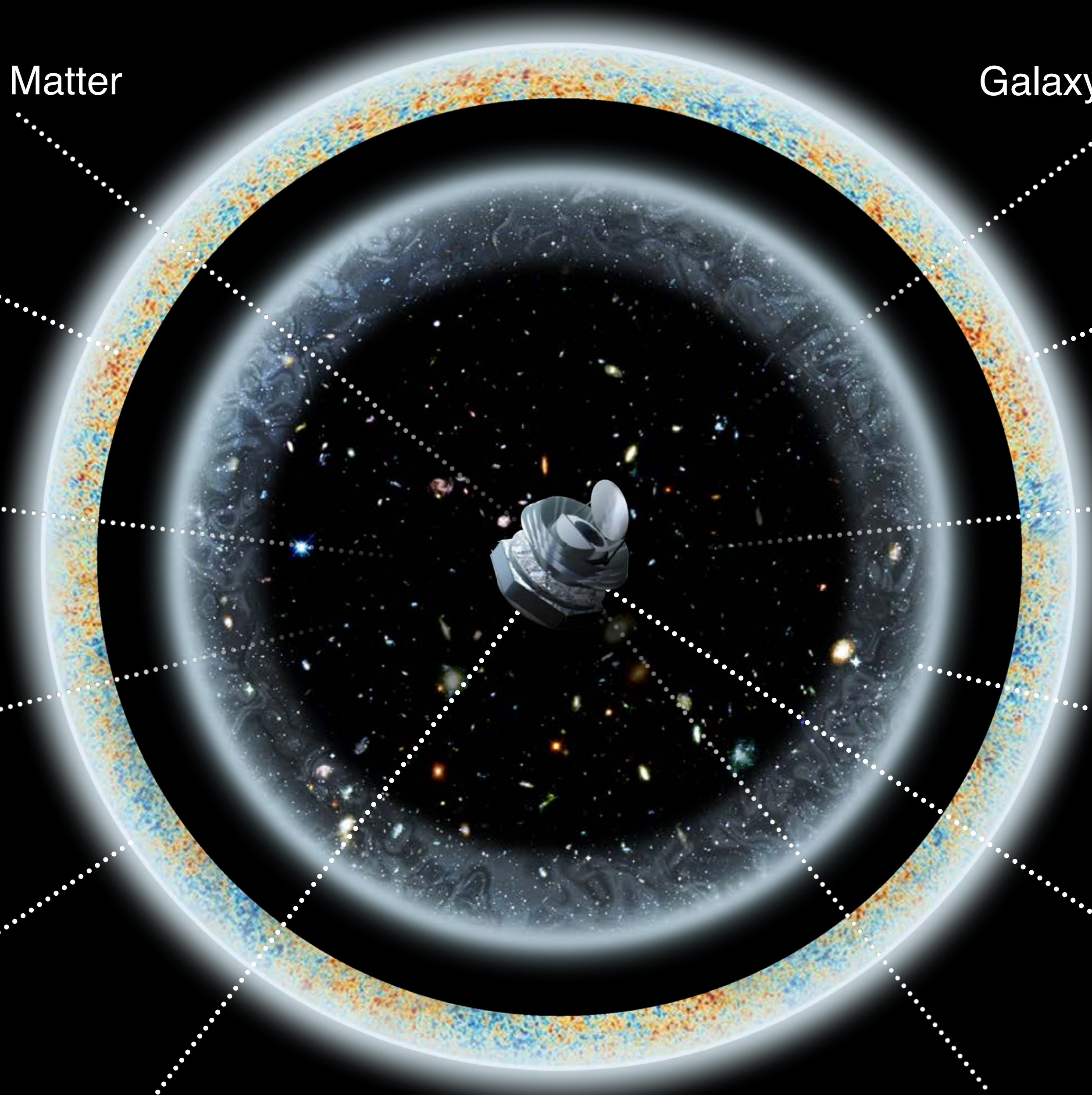
PICO

PROBE OF INFLATION
AND COSMIC ORIGINS

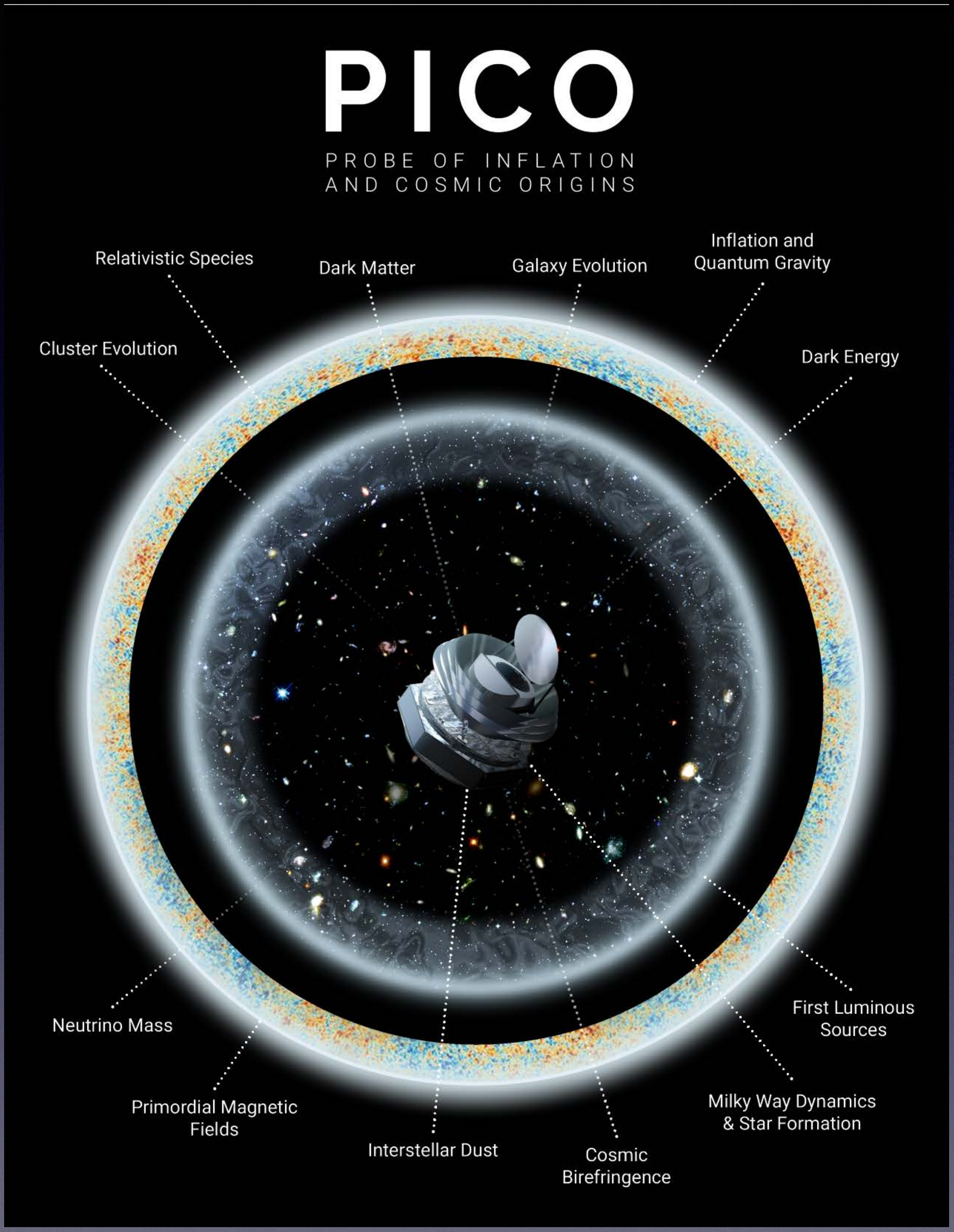
SHAUL HANANY
UNIVERSITY OF MINNESOTA



https://z.umn.edu/picomission

Astro-ph/1902.1054; astro-ph/1908.07495

- Concept for Probe-scale, next decade space mission
- Probe-scale: $400M - $1000M
- Concept development supported by NASA (05/2017 - 12/2018)
- Product: a report to the US Astro2020 decadal panel



Astro-ph/1902.1054
Full report 50 pgs

astro-ph/1908.07495
White paper 10 pgs

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PICO

PROBE OF INFLATION AND COSMIC ORIGINS

Report from a Probe-Scale Mission Study
January, 2019

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Open community effort; 213 authors and endorsers

Primordial Magnetic Fields

Interstellar Dust

Cosmic Birefringence

Milky Way Dynamics & Star Formation

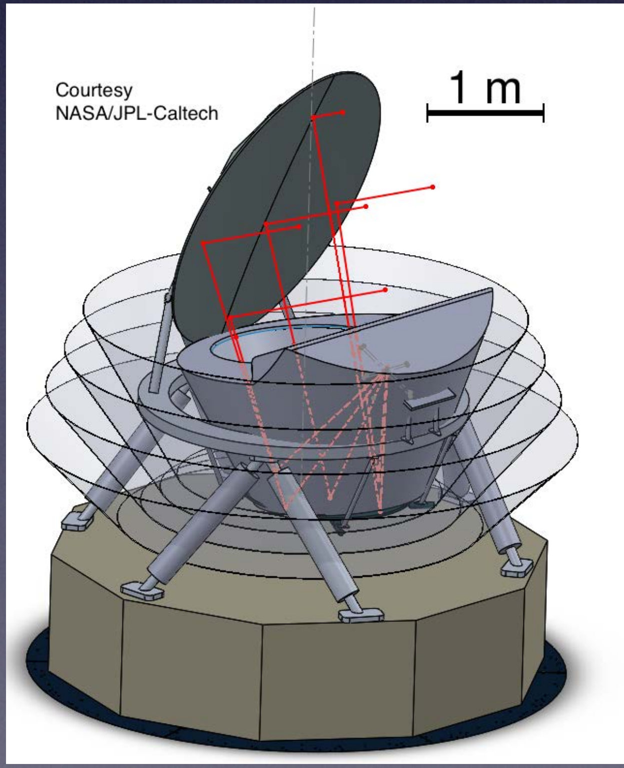
https://z.umn.edu/picomission

Astro-ph/1902.1054 — **Full report 50 pgs**

astro-ph/1908.07495 — **White paper 10 pgs**

PICO in Brief

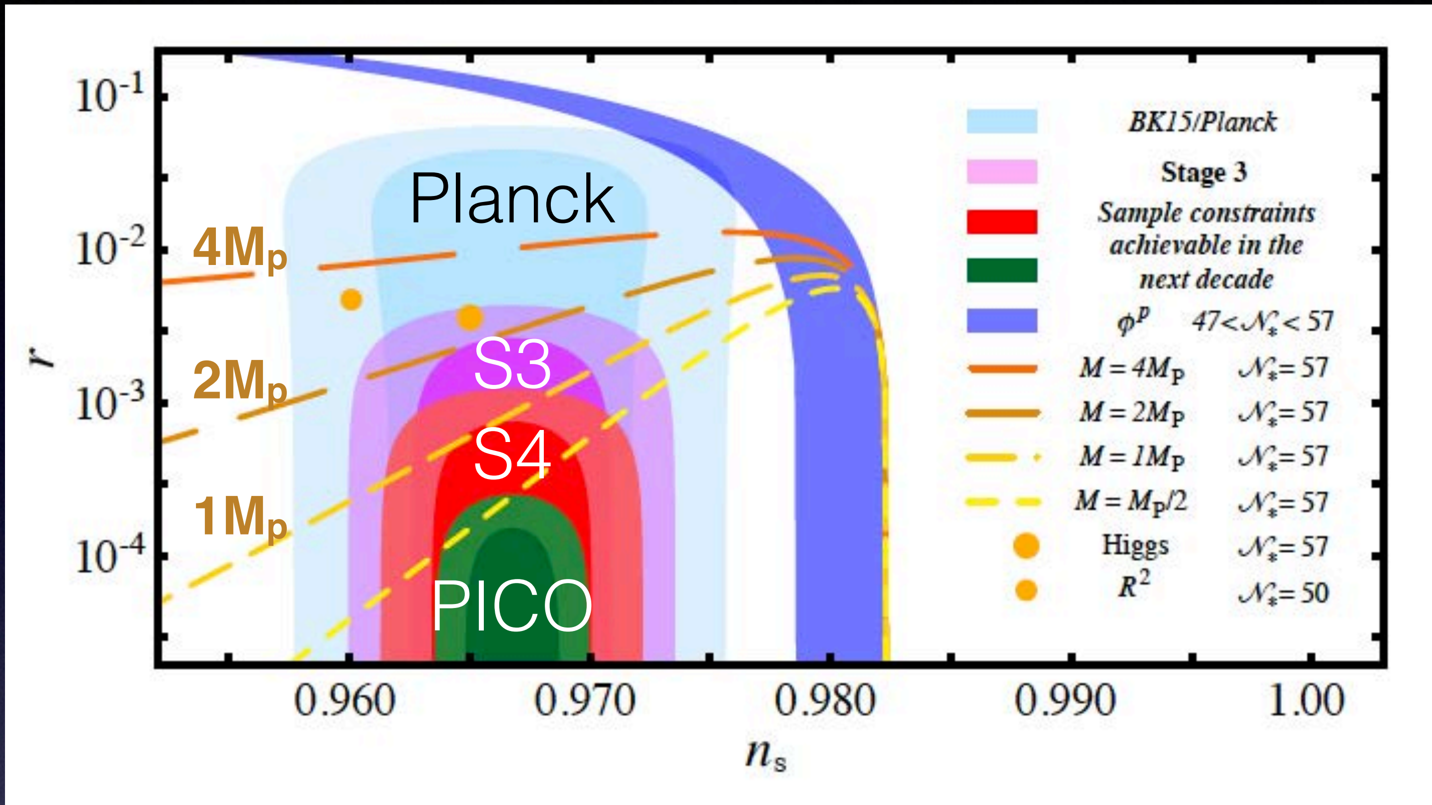
- Millimeter/submillimeter-wave, polarimetric survey of the entire sky
- 21 bands between 20 GHz and 800 GHz
- 1.4 m aperture telescope
- Diffraction limited resolution: 38' to 1'
- 13,000 transition edge sensor bolometers + multiplexed readouts
- 5 year survey from L2
- Requirement: 0.87 uK*arcmin, 3300 *Planck* misions
- Current estimate: 0.61 uK*arcmin, 6700 *Planck* misions



Sutin et al. SPIE Vol.10698; 1808.01368

PICO SO1: Inflation r

- Textbook Inflation models that naturally explain the spectral index and have super-Planckian mass scale in the potential have: $r \gtrsim 5 \times 10^{-4}$



- PICO requirement: $r < 5 \times 10^{-4}\,(5\sigma)$

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)

Can the Foregrounds be Handled

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

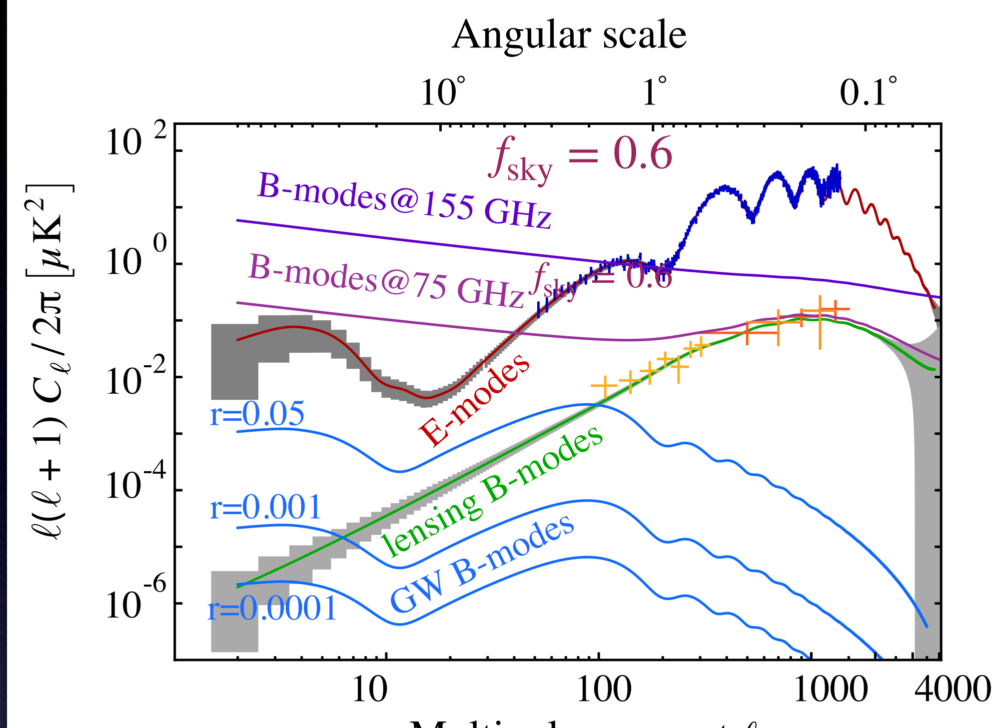


Figure: R. Flauger

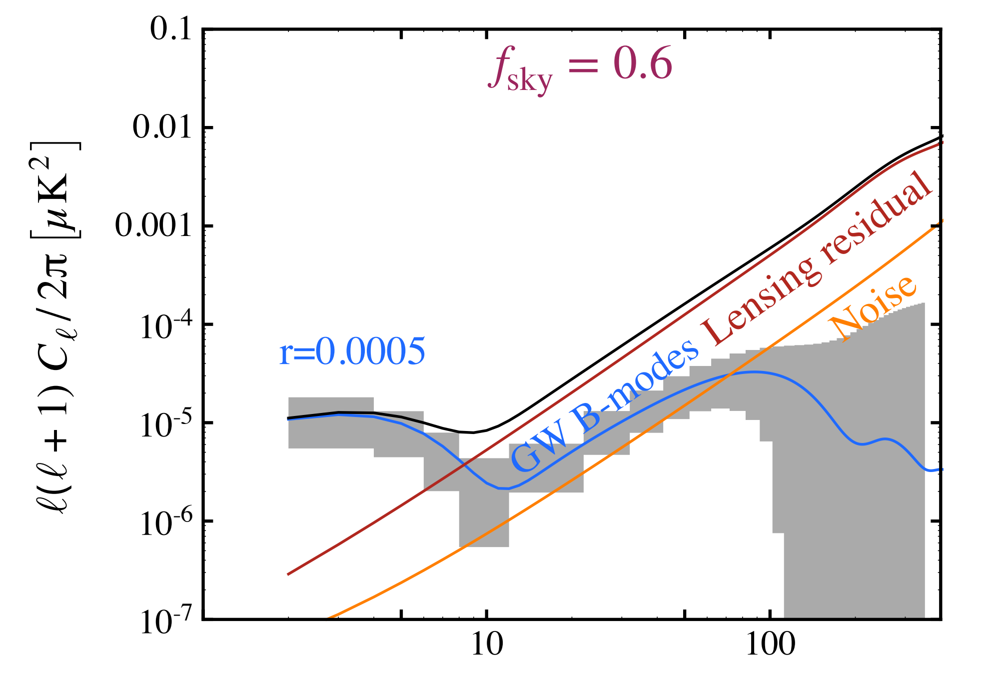


Figure: Flauger

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
- For \ell=100, residual is x4 lower
- Results approximately reproduced with other models

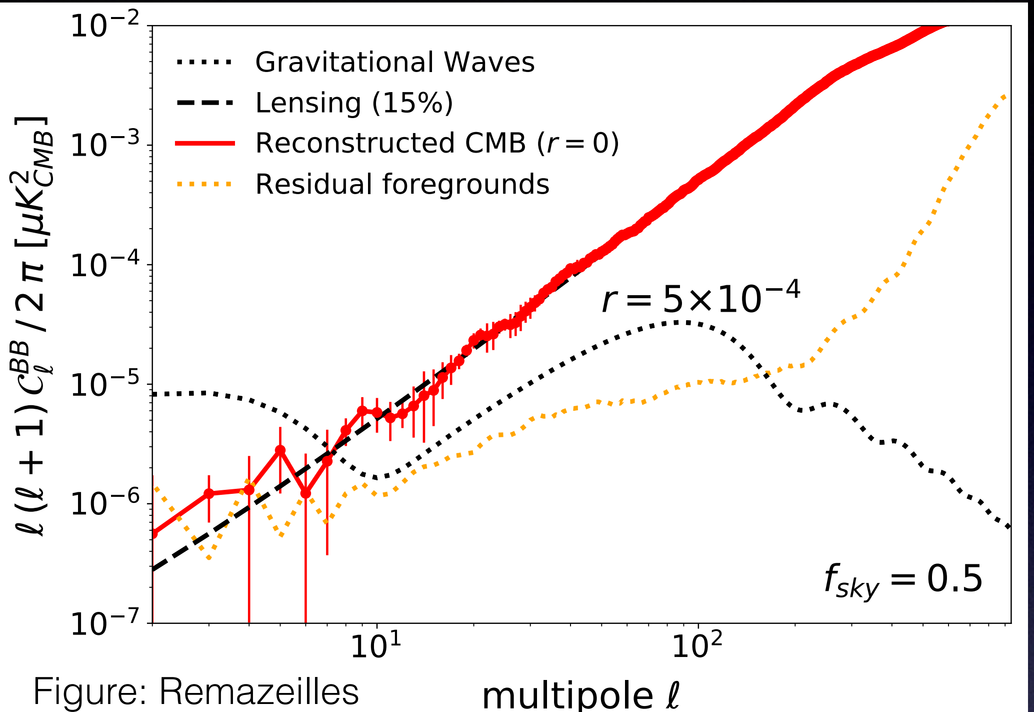


Figure: Remazeilles

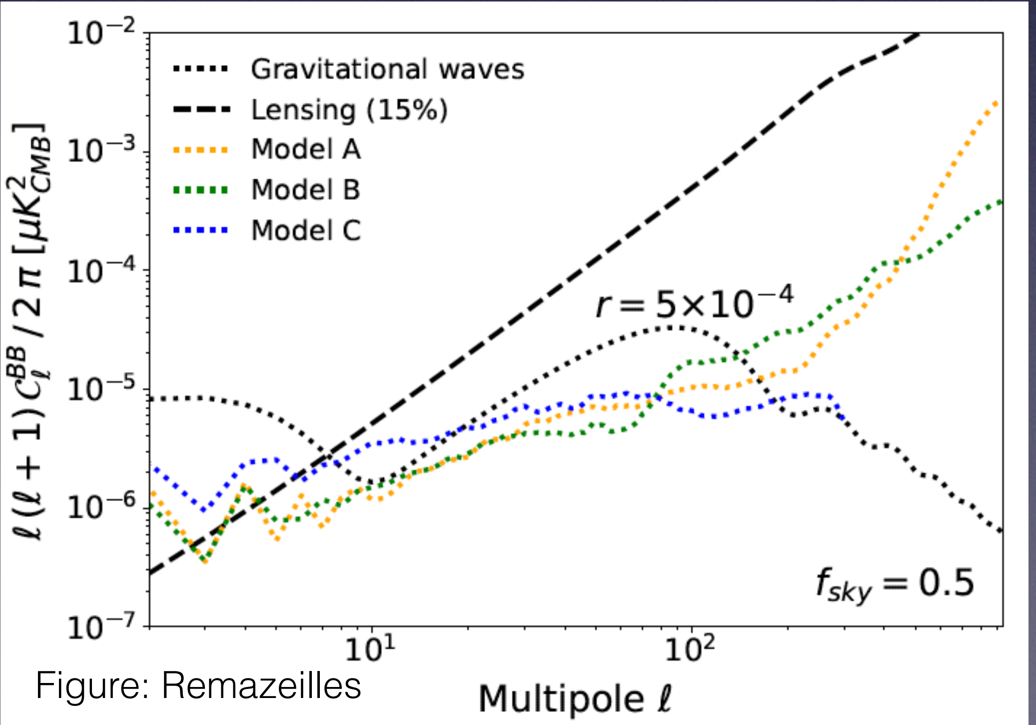


Figure: Remazeilles

PICO SO2: Constrain Inflation-Models

- Models of inflation differ in their reheating scenarios

- Measure n_s and n_{run} with

$$\sigma(n_s) = 0.0015 \quad \sigma(n_{run}) = 0.002$$

x3 tighter than P*lanck*

- Give 3σ discrimination between models that have different reheating scenarios

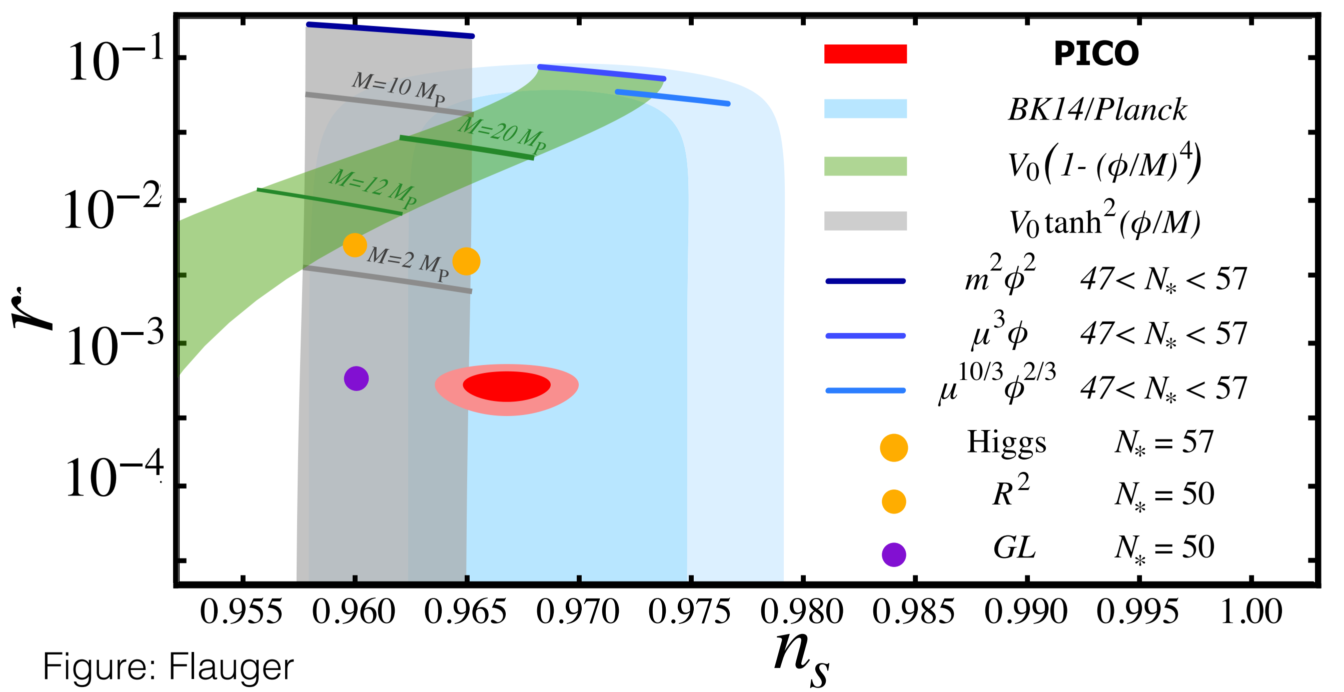
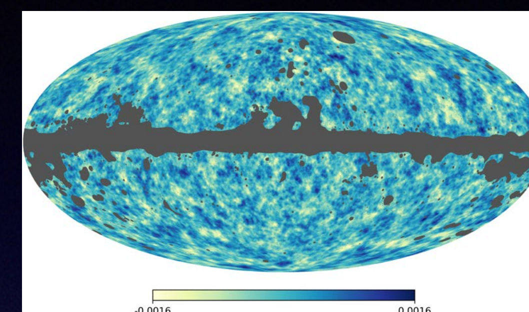


Figure: Flauger

PICO Science - Inflation: non-Gaussianity

- Single-field models have nearly Gaussian fluctuations, $f_{\rm NL}^{\rm local} < 1$
- Detection of $f_{\rm NL}^{\rm local} > 1$ evidence for multi-field inflation
- Planck: $f_{\rm NL}^{\rm local} = 0.8 \pm 5$
- PICO_ϕ + LSST galaxies: $f_{\rm NL}^{\rm local} \leq 1\,(2\sigma)$
  - LSST: i<27, L_{min}>4
- PICO_ϕ + LSST galaxies: $f_{\rm NL}^{\rm local} \leq 2\,(3\sigma)$
  - LSST: i<25.3, L_{min}>8

Figure: R. Flauger



X

PICO Lensing X LSST Galaxies

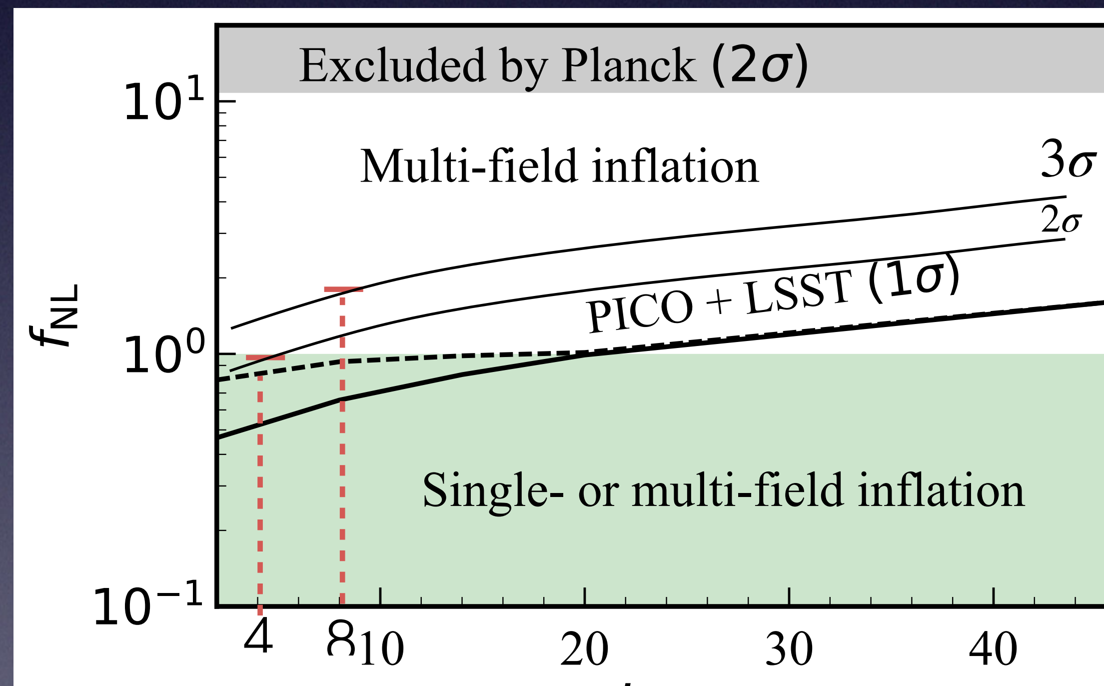
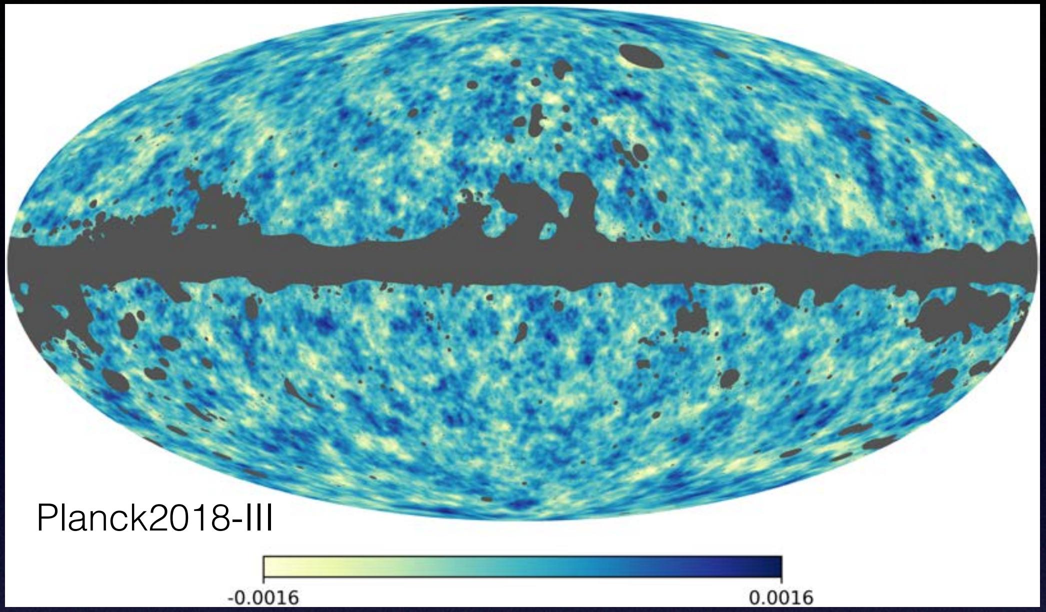


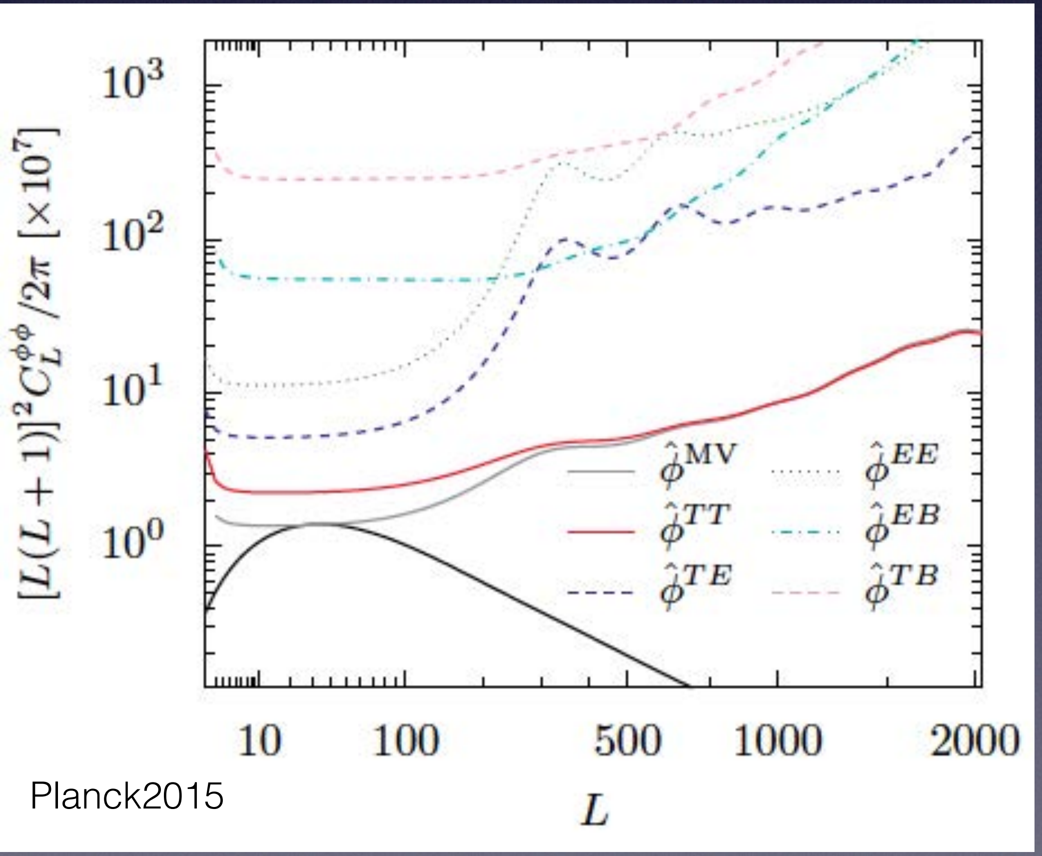
Figure: Schmittfull

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 is a sensitive probe of the growth of structure



Planck2018-III



Planck2015

PICO SO3: 4σ Detection of Neutrino Mass

- Only cosmology can determine the absolute mass scale if it is near the minimum allowed sum $\Sigma m_\nu = 58 \text{ meV}$
- Growth of structure is affected by neutrino mass, and the projected gravitational potential is a sensitive probe of the growth of structure
- 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, $\sigma(\tau) = 0.002$
- $\sigma\left(\Sigma m_\nu\right) = 14 \text{ meV}$ 4σ; one of three independent measurements

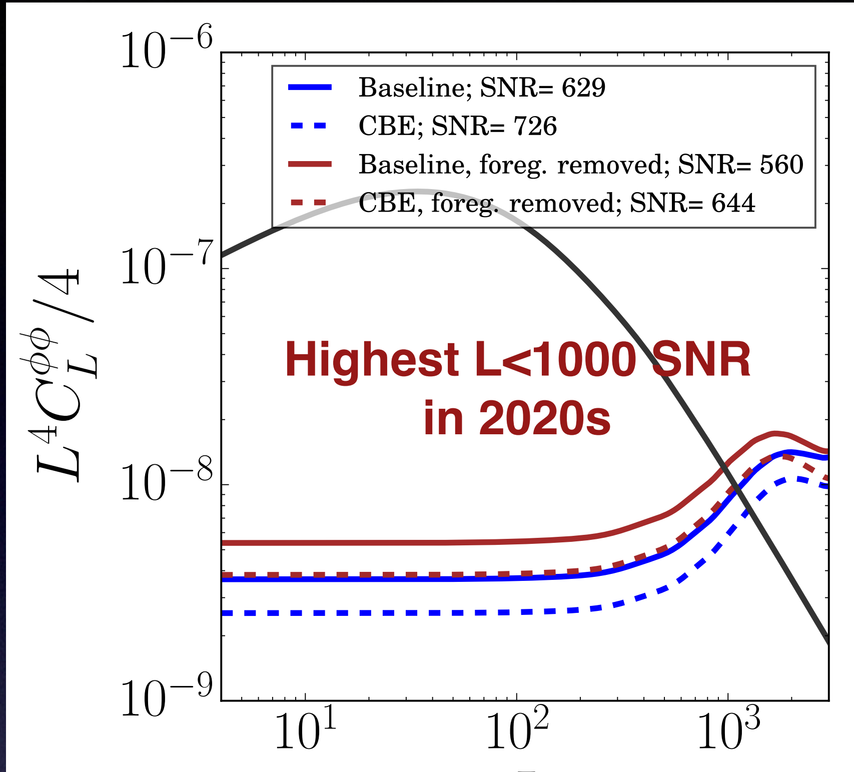
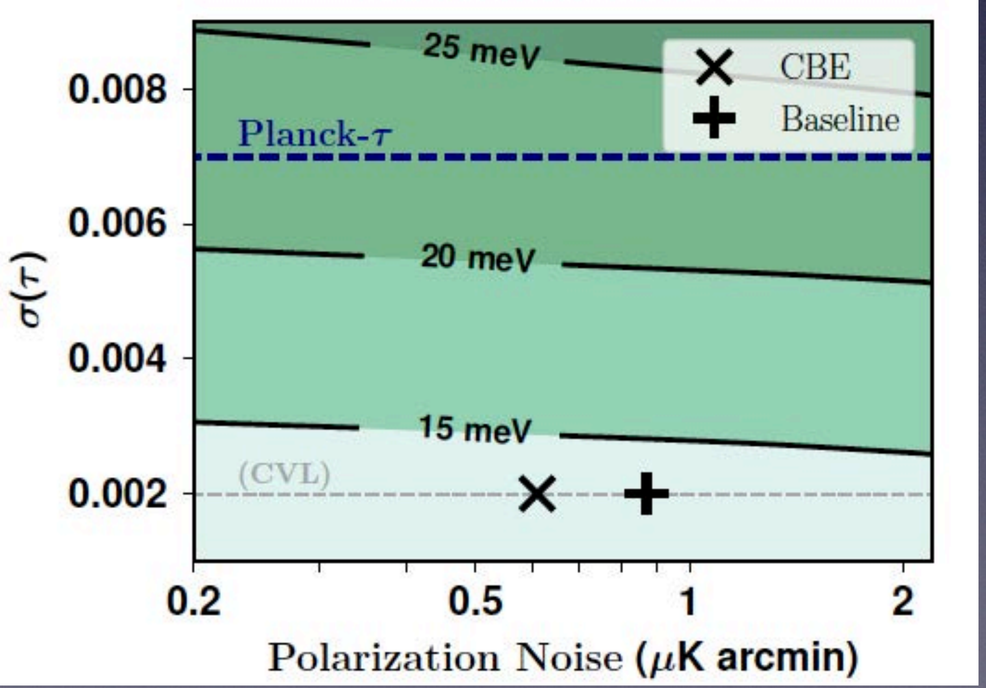


Figure: van Engelen

Figure: Green



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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: Constraint on 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: Neff = 3.046
- Planck + BAO : 2.92 ± 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

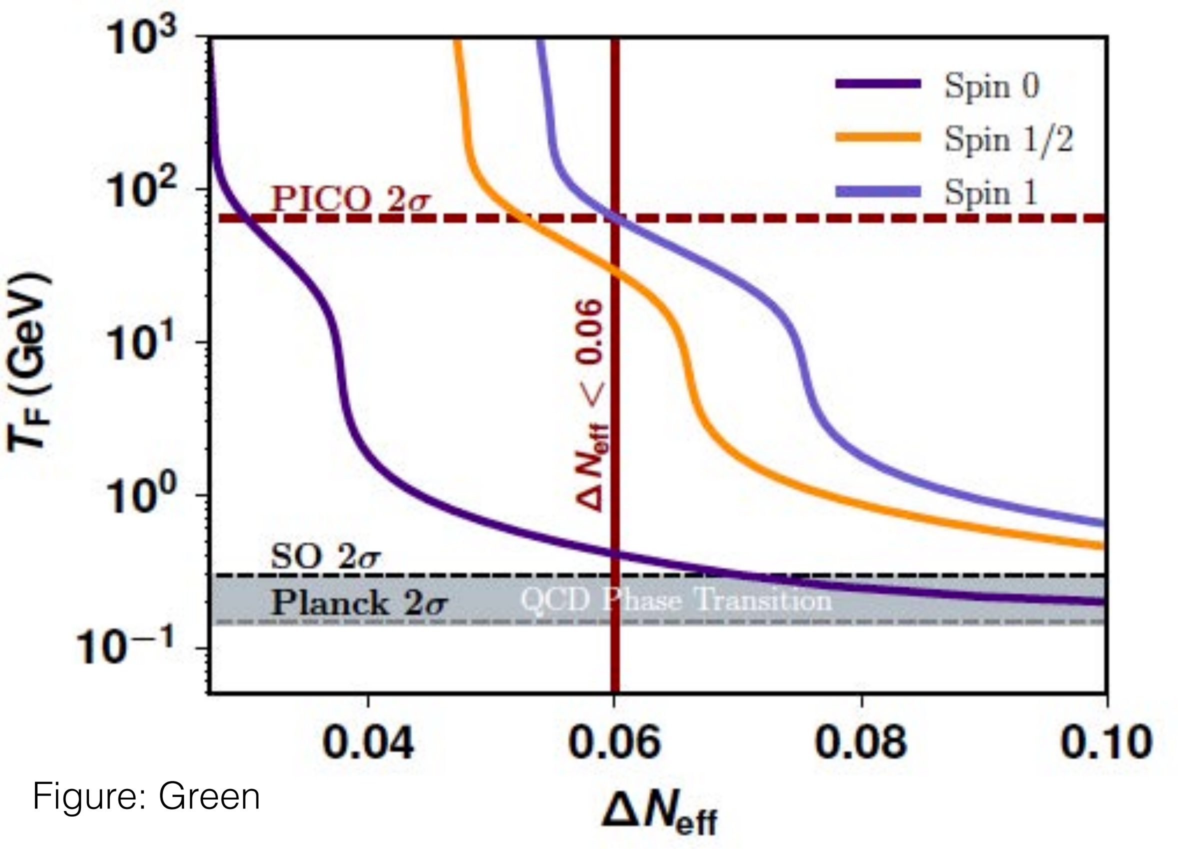


Figure: Green

PICO SO5: First Luminous Sources

- Formation of first luminous sources affects the optical depth to reionization
- Low ℓ EE -> probe of the optical depth
- PICO $\sigma(\tau) = 0.002\ \mathrm{CVL}$ => determine z_{re}
- With kSZ (Δz_{re}) constrain models of reionization (kSZ from S3)

Planck + S3

PICO + S3

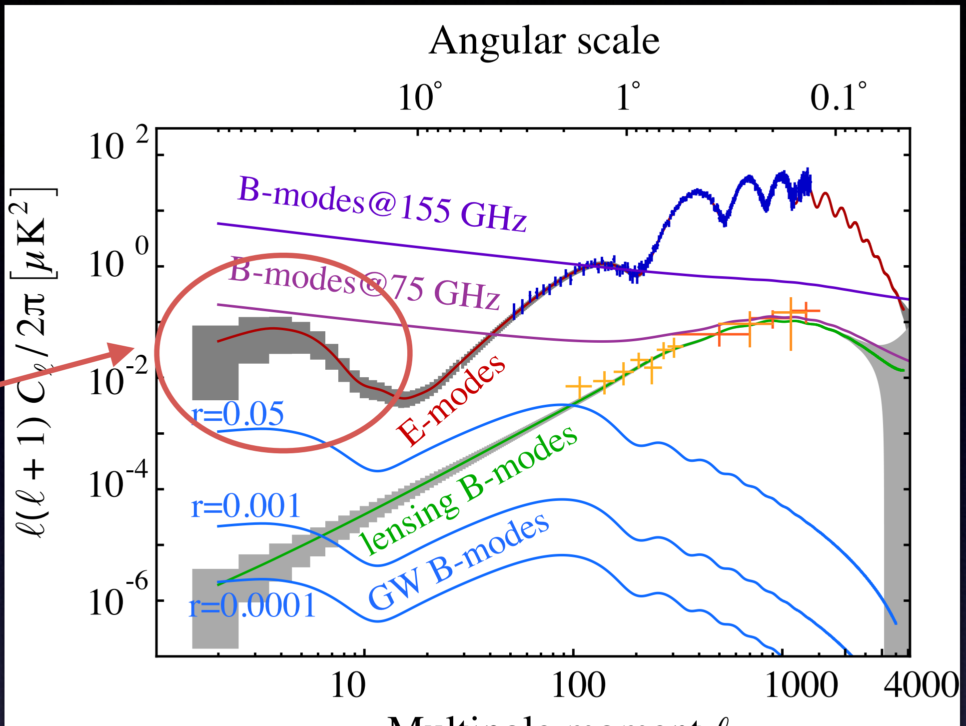


Figure: Flauger

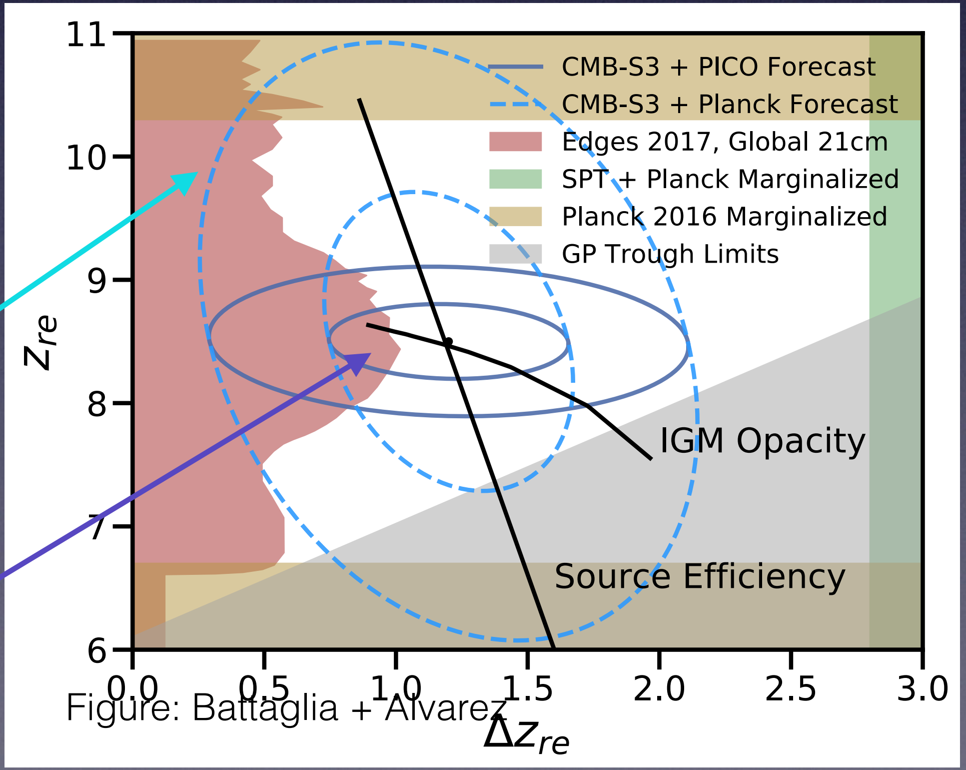
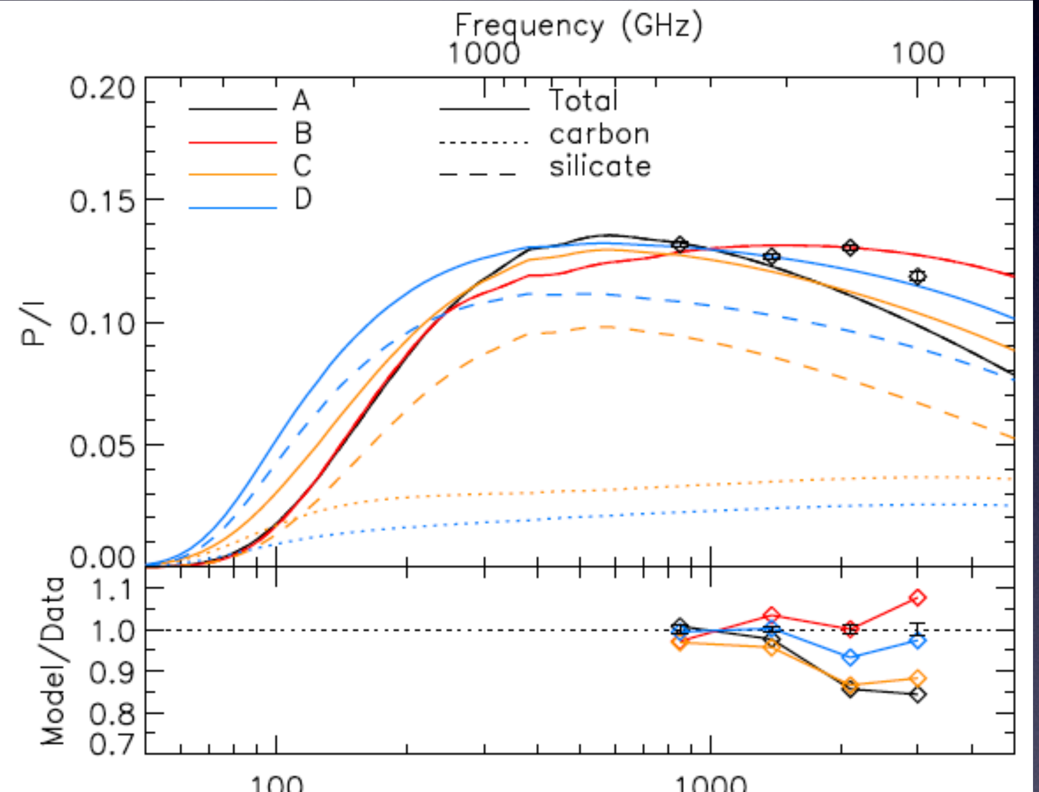


Figure: Battaglia + Alvarez

PICO SO6: Settle Composition of Interstellar Dust

- Carbons and silicates are major components
- Are there distinct populations, with distinct growth paths, or are the components completely mixed on the grains?

Dust fractional polarization as a function of wavelength for different dust composition models



Guillet et al. 2018

PICO SO6: Settle Composition of Interstellar Dust

- Carbons and silicates are major components
- Are there distinct populations, with distinct growth paths, or are the components completely mixed on the grains?
- PICO: 3% per component per frequency band
    - Support or rule out the distinct two populations model
- Better characterization will lead to better separation of dust from B-mode science

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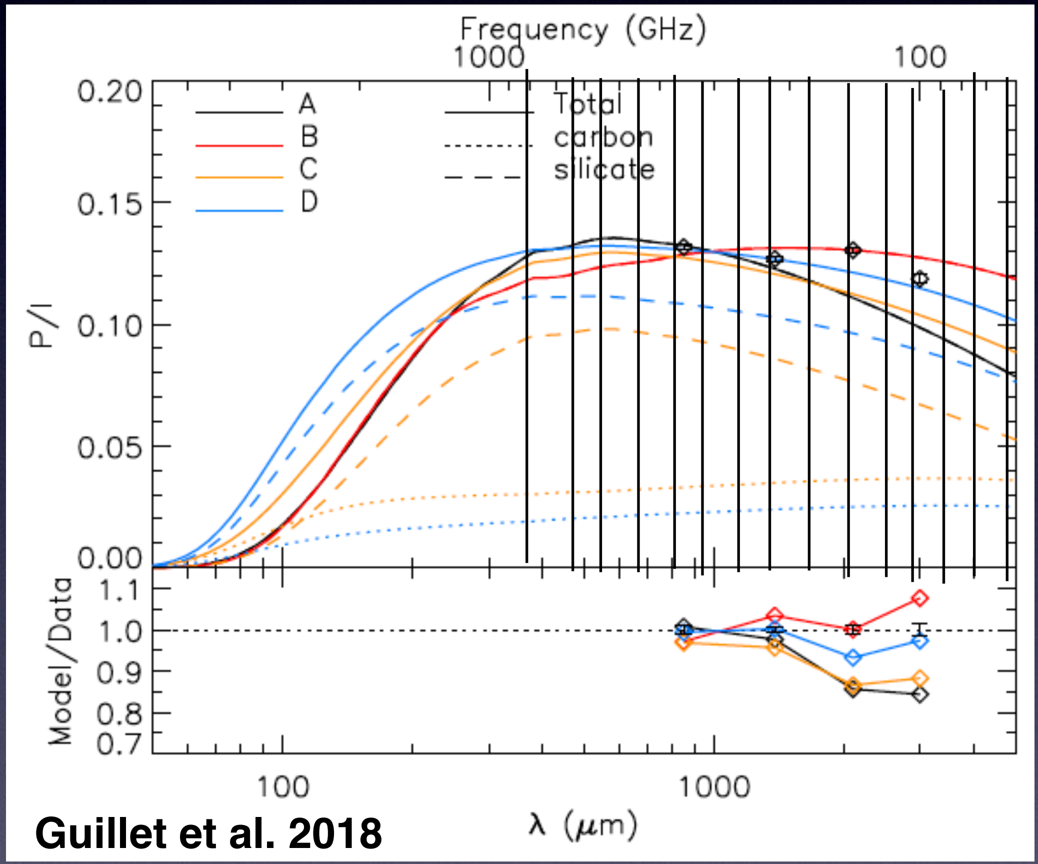

+6 lower frequency bands

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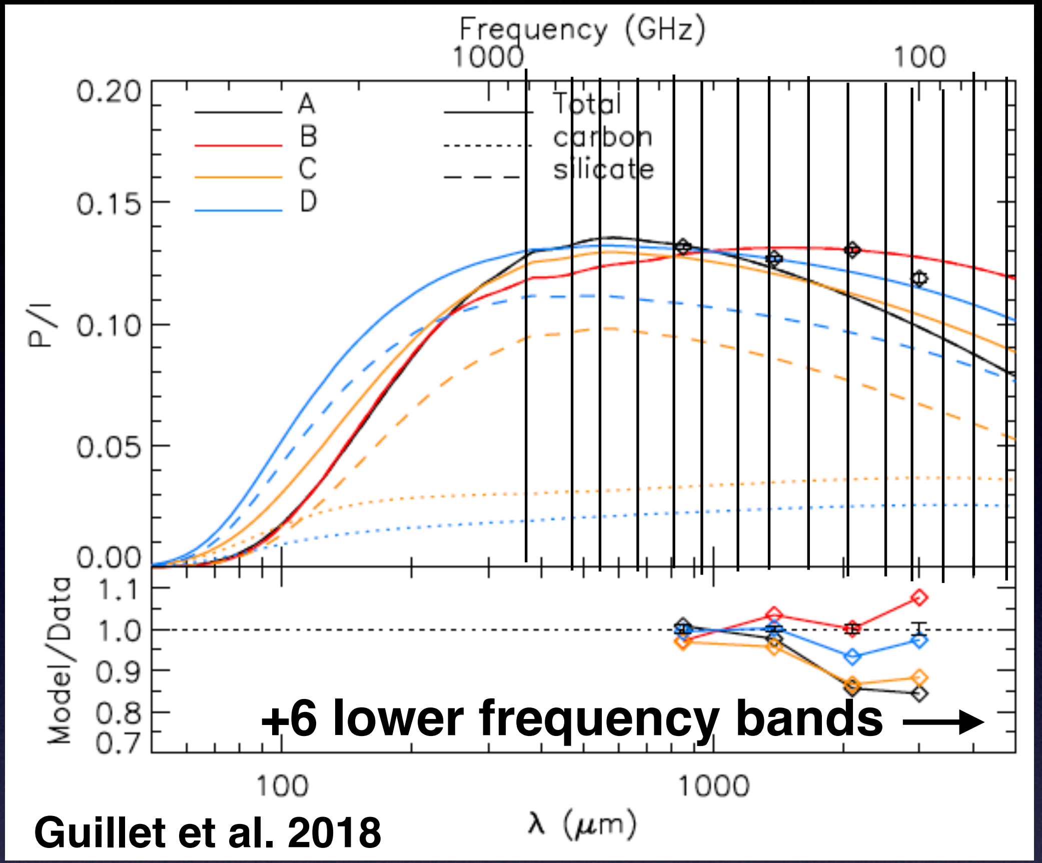
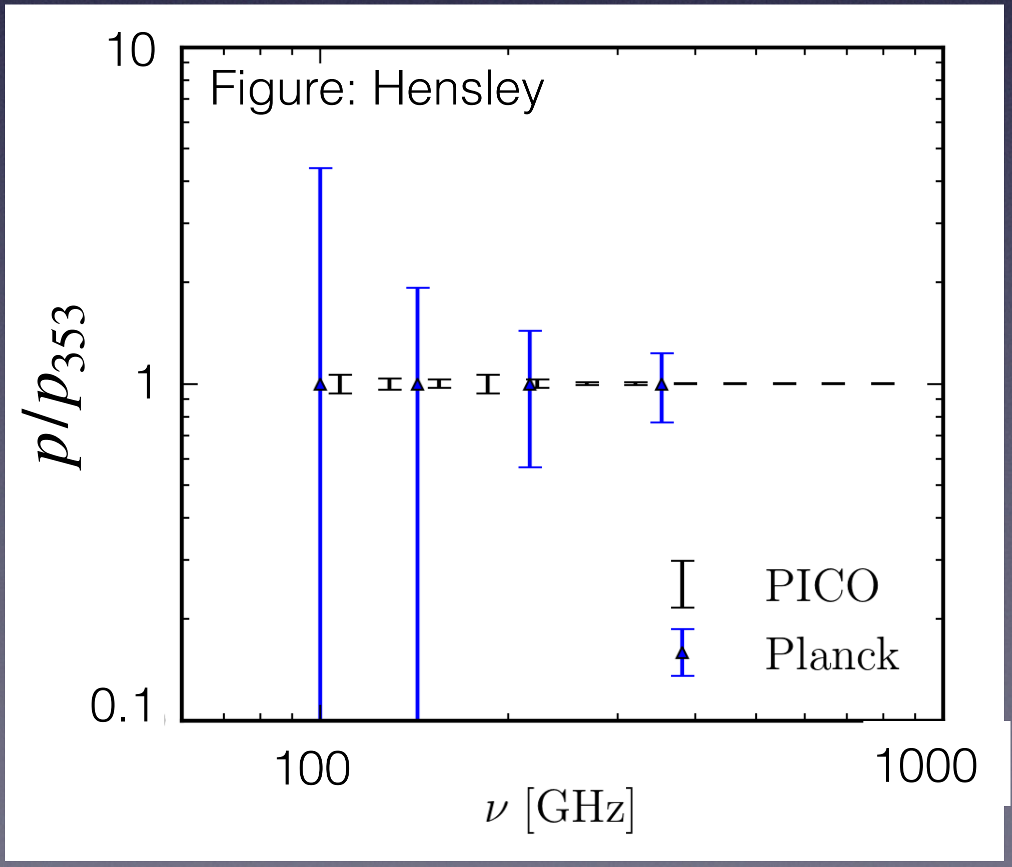




PICO SO7: Why the Low Star Formation Efficiency?

- Milky Way stars form at rate 10 - 100 lower than would be expected from gravitational collapse

Figure: R. Flauger

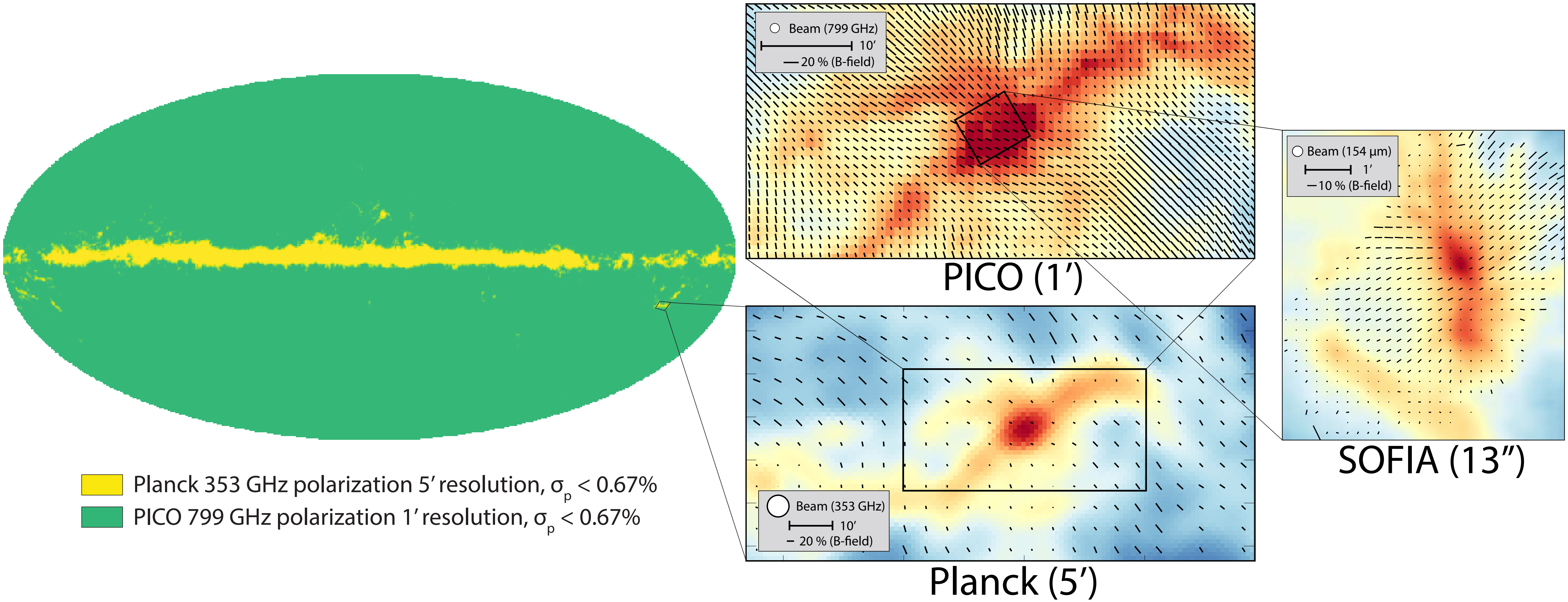
- Turbulence + magnetic fields slow collapse from the diffuse ISM to molecular clouds, to star forming regions

- 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 magnitudes: 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, x3000 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)

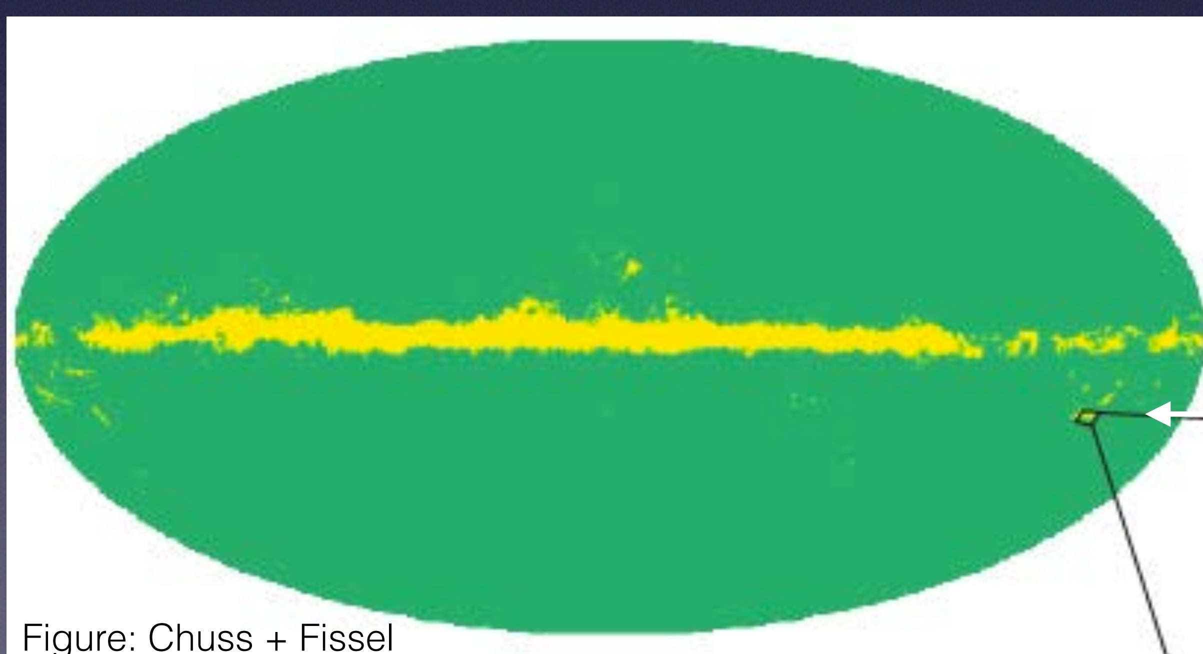
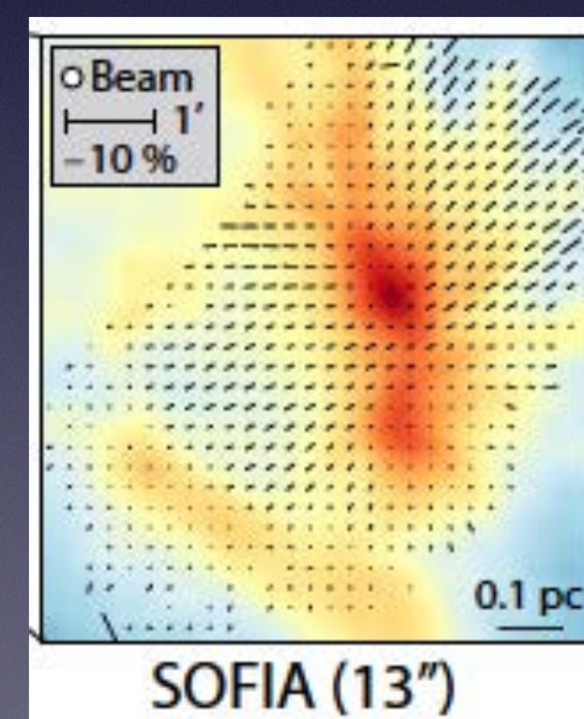


Figure: Chuss + Fissel

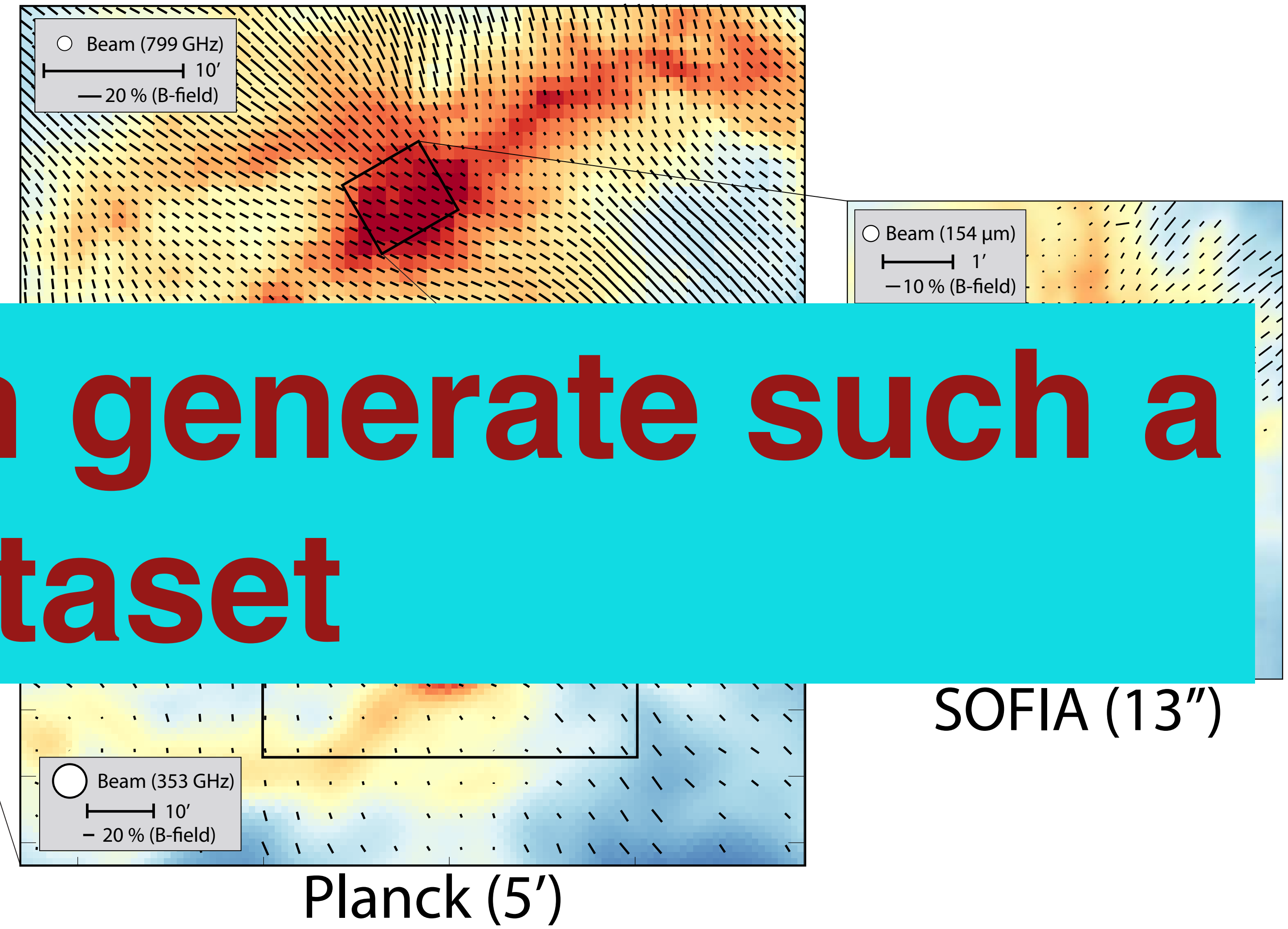
Factor of 10^4 in spatial scale



PICO SO7: Why the Low Star Formation Efficiency?

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

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



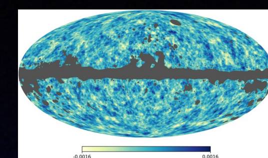
Orion Region

Only PICO can generate such a dataset

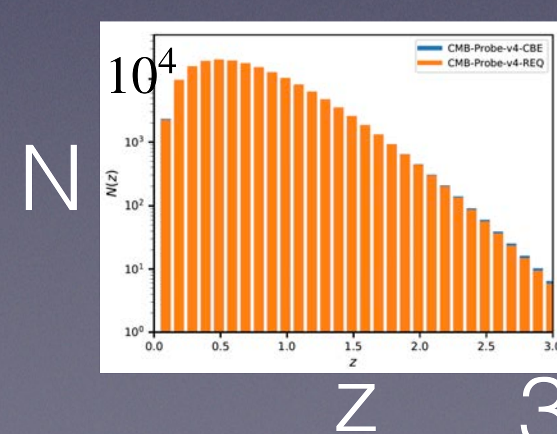
Figure: Chuss + Fissel

PICO Science : σ_8 - Amplitude of Matter Fluctuations

- Correlations of lensing map with LSST galaxies

 x 

- Sub-percent accuracy in each red-shift bin
- 150,000 PICO clusters + redshifts from optical and IR surveys (+ internal mass calibration)
- Sub-percent accuracy for 0.5<z<2
- Determine dark energy parameters, constrain modified gravity, determine neutrino mass



σ_8 error as a function of L_{max}

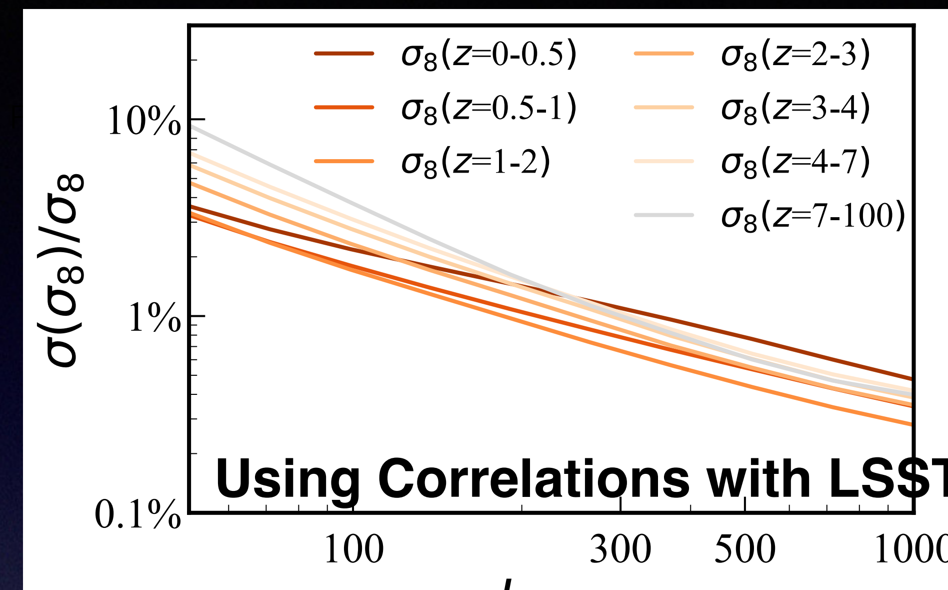


Figure: Schmittfull

σ_8 error vs redshift

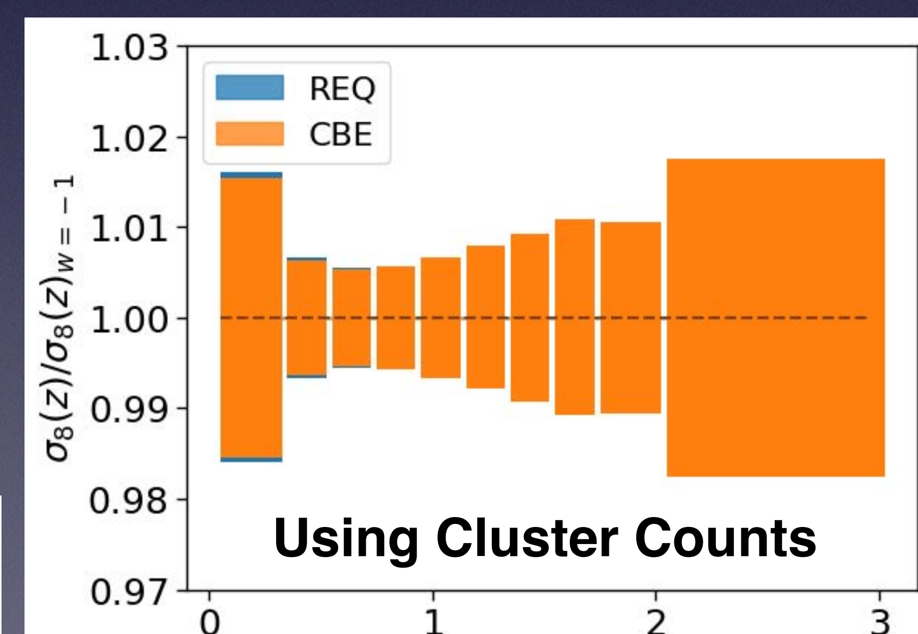


Figure: Battaglia

PICO Science : tSZ Compton-y map

- tSZ: scattering of CMB from hot cluster electrons => integrated electron pressure along line of sight
- PICO 21 frequency bands enable signal separation to give thermal SZ signature over the full sky
- SNR for yy spectrum is ~x100 higher than Planck
- SNR = 3000 for cross-correlations with LSST gold weak lensing sample
- Perform correlations in multiple tomographic redshift bins to track evolution of electron pressure with z => constrain the role of energetic feedback in structure formation

Compton-y power spectrum

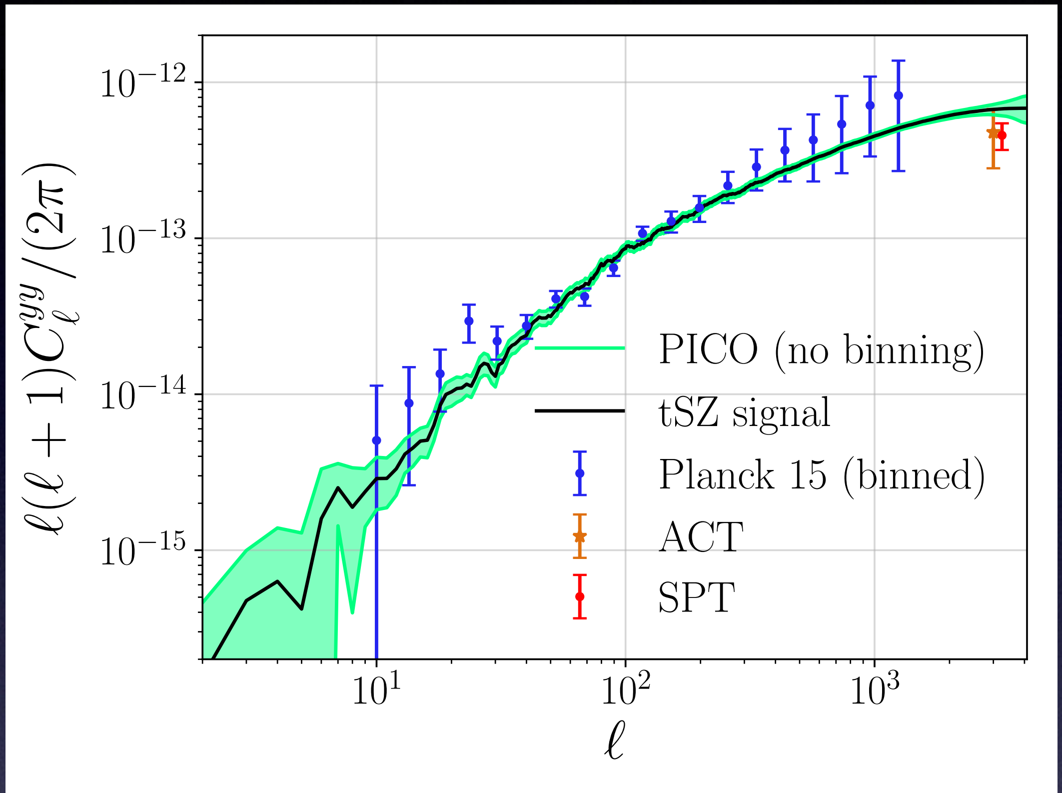


Figure: Hill

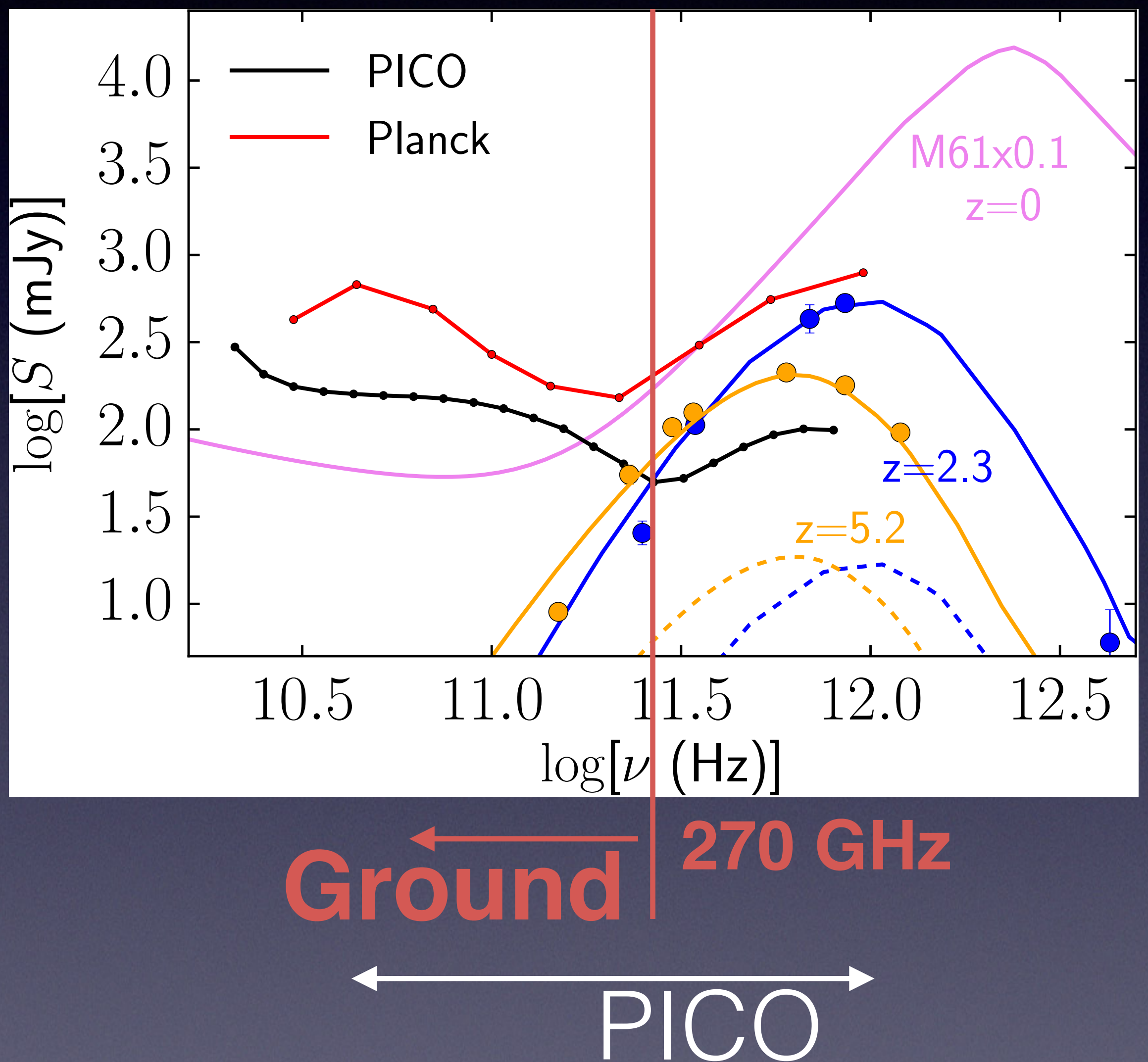
Only PICO has the resolution over the full sky

Only PICO has 21 bands to separate the foregrounds

PICO Science : Legacy Surveys Unique to PICO Data

- 4500 strongly lensed galaxies, z~5; early galaxy formation (currently 13)
- 50,000 proto-clusters, z~4.5; early cluster formation (currently few tens)
- 30,000 galaxies, z<0.1; dust SED vs galaxy properties (currently 3400 candidates)
- 2000 polarized radio sources; physics of jets (currently 200)
- Polarization of few thousand dusty galaxies; ordering of magnetic fields in external galaxies

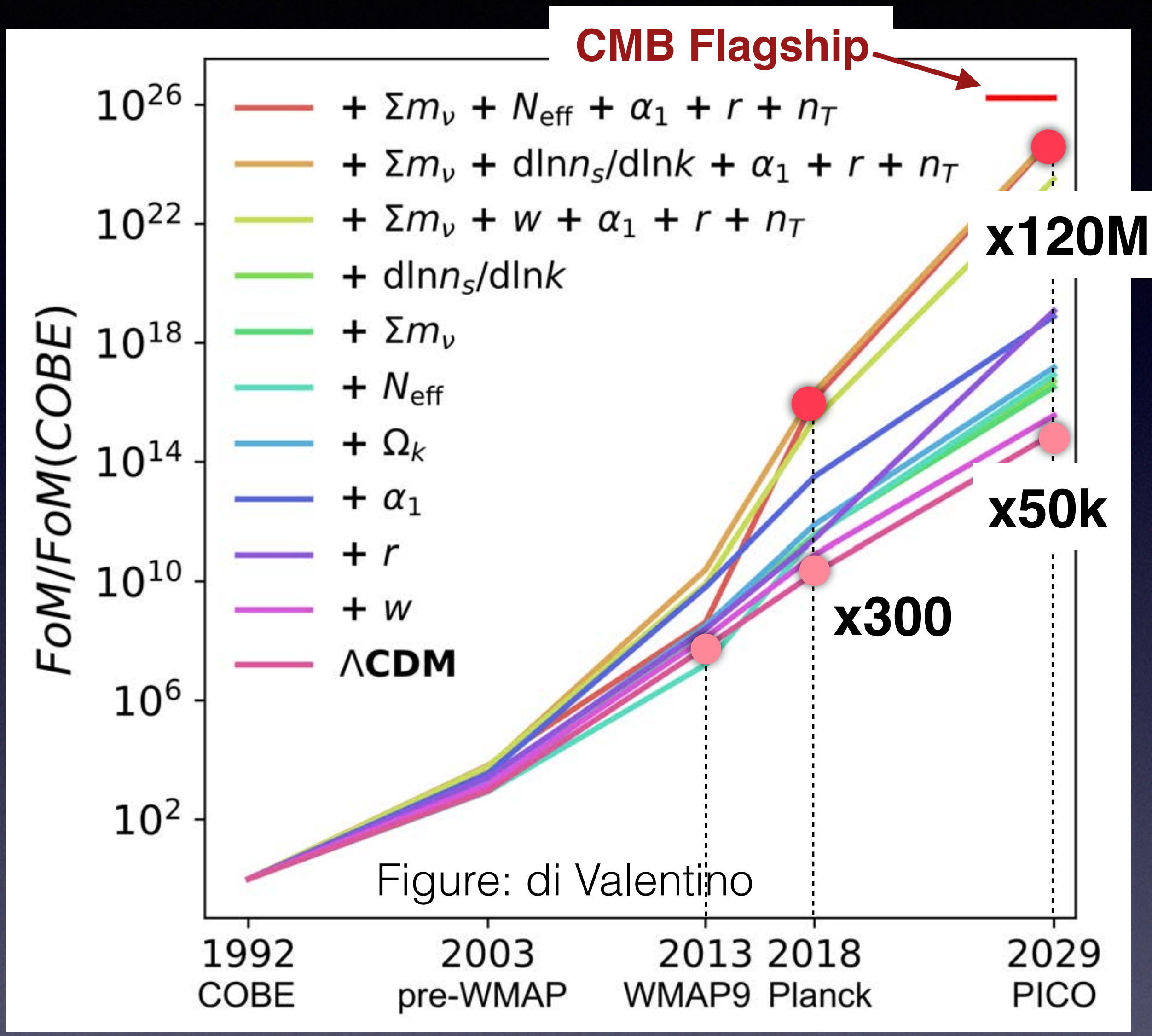
SED of high-z strongly lensed galaxies



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
  - 4.4σ between supernovae and CMB measurements of Ho
  - 2σ in measurements of σ_8
  - 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

Discovery Space : Primordial Magnetic Fields + Birefringence

- Were there primordial magnetic fields?
  - Some young galaxies show magnetic fields that are too strong to be explained by simple dynamo effect
  - PICO: B<0.1 nG (1σ) => rule out purely primordial origin of the largest observed B fields {Through Faraday rotation / EB, TB correlations}
- Extensions to standard model have parity violating particles in the early universe => cosmic birefringence => EB, TB correlations
  - PICO: x300 improvement in constraints on rotation due to birefringence

Discovery Space

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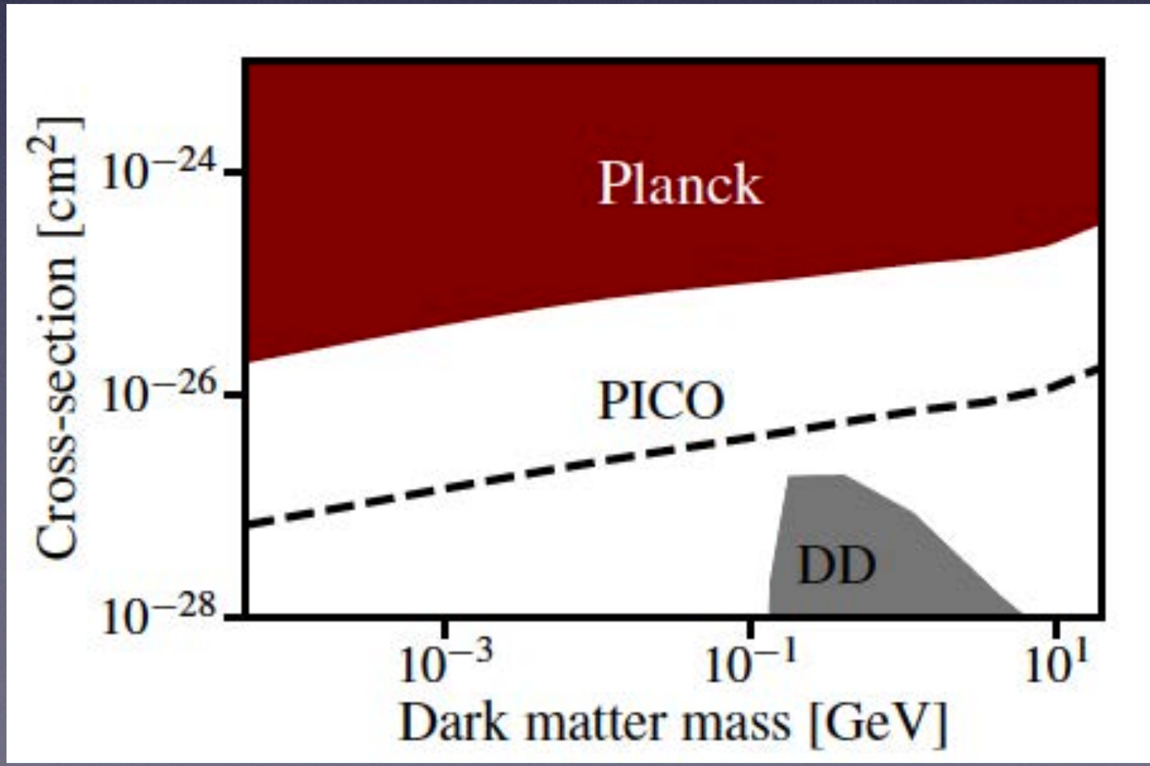
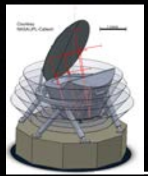
- Extensions to standard model have **parity violating particles in the early universe** => cosmic birefringence => EB, TB correlations
    - PICO: x300 improvement in constraints on rotation due to birefringence

- What is the **nature of dark matter**?
    - x25 improvement relative to planck for cold dark matter
    - x10 improvement relative to planck for axion dark matter

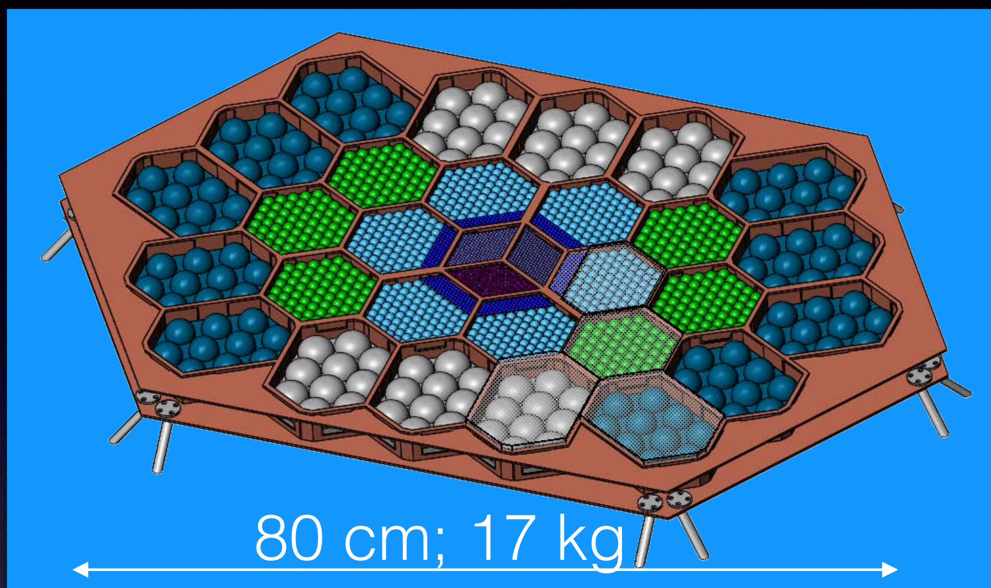


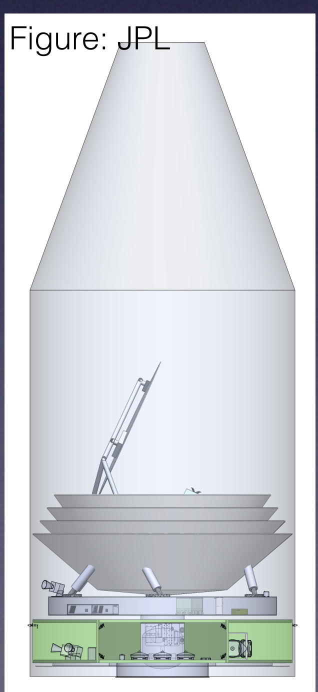


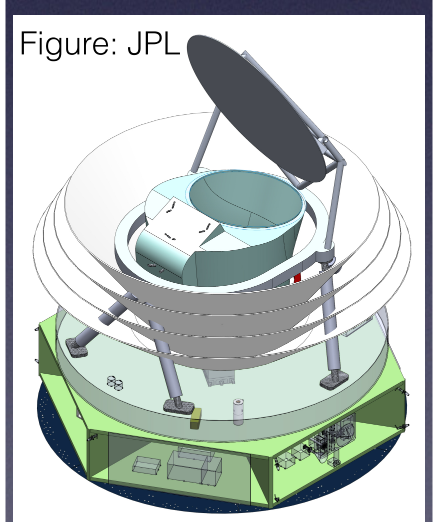
PICO Implementation

center: single color, horn coupled

3-color sinuous antenna coupled







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

Young et al. SPIE Vol.10698; 1808.01369

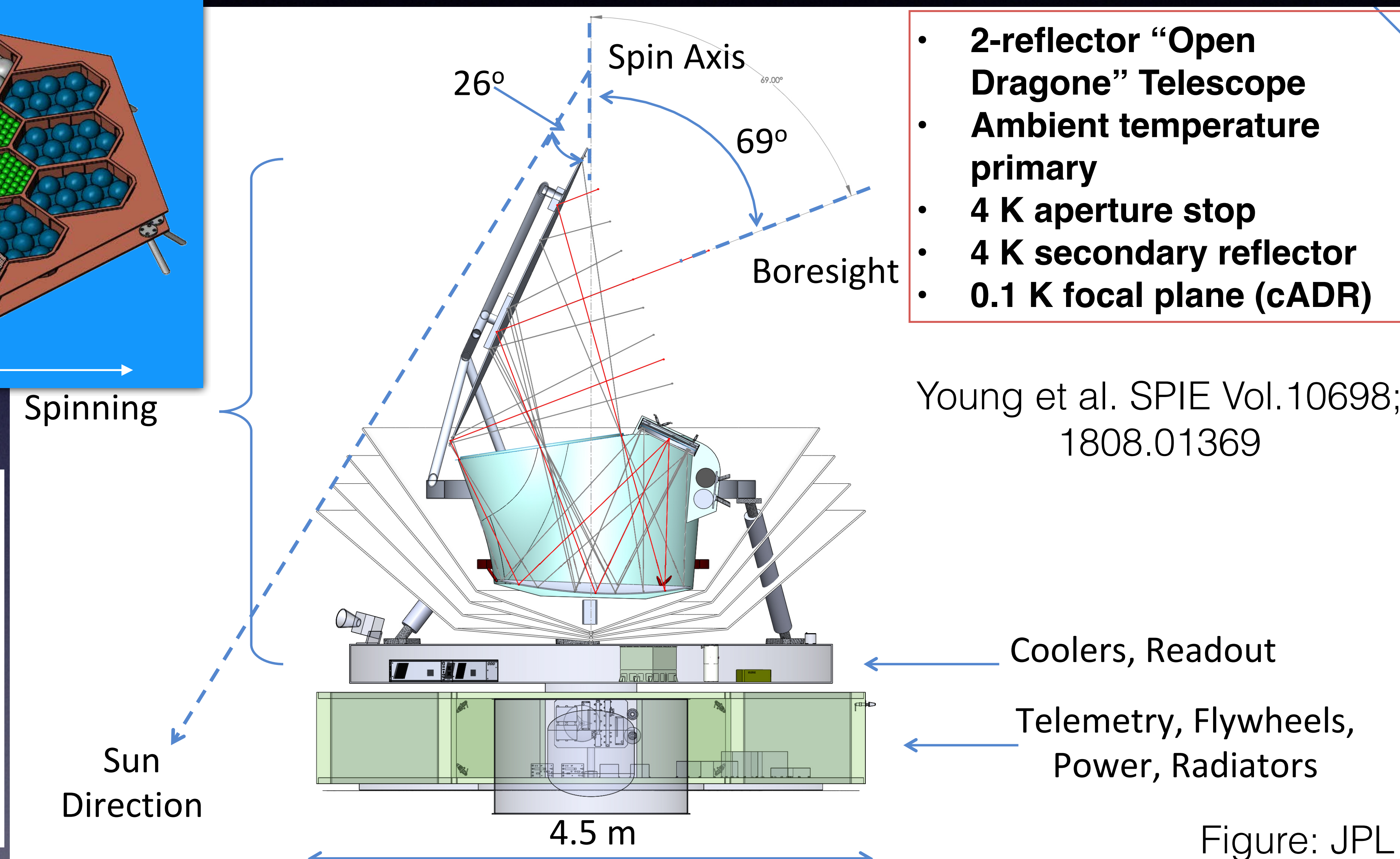
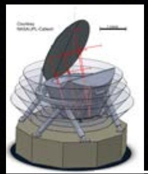


Figure: JPL



PICO Scan and Systematics

Unparalleled Thermal stability

Extreme Redundancy

- 50% sky coverage in two weeks
- Full sky in 6 months
- 13,000 detectors will make 10 independent full sky T, Q, U maps

Strong continuous calibration signal

Single instrument

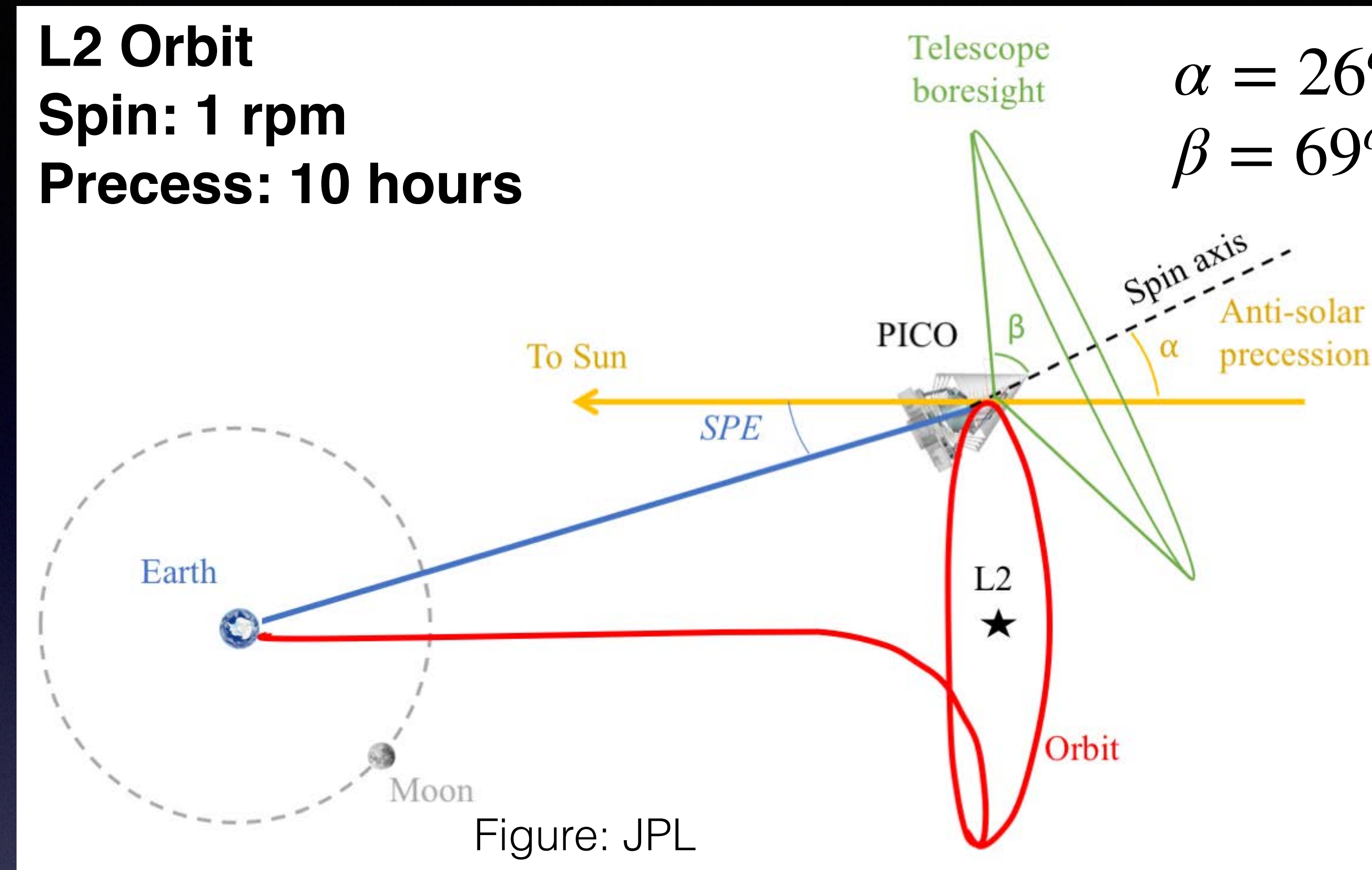
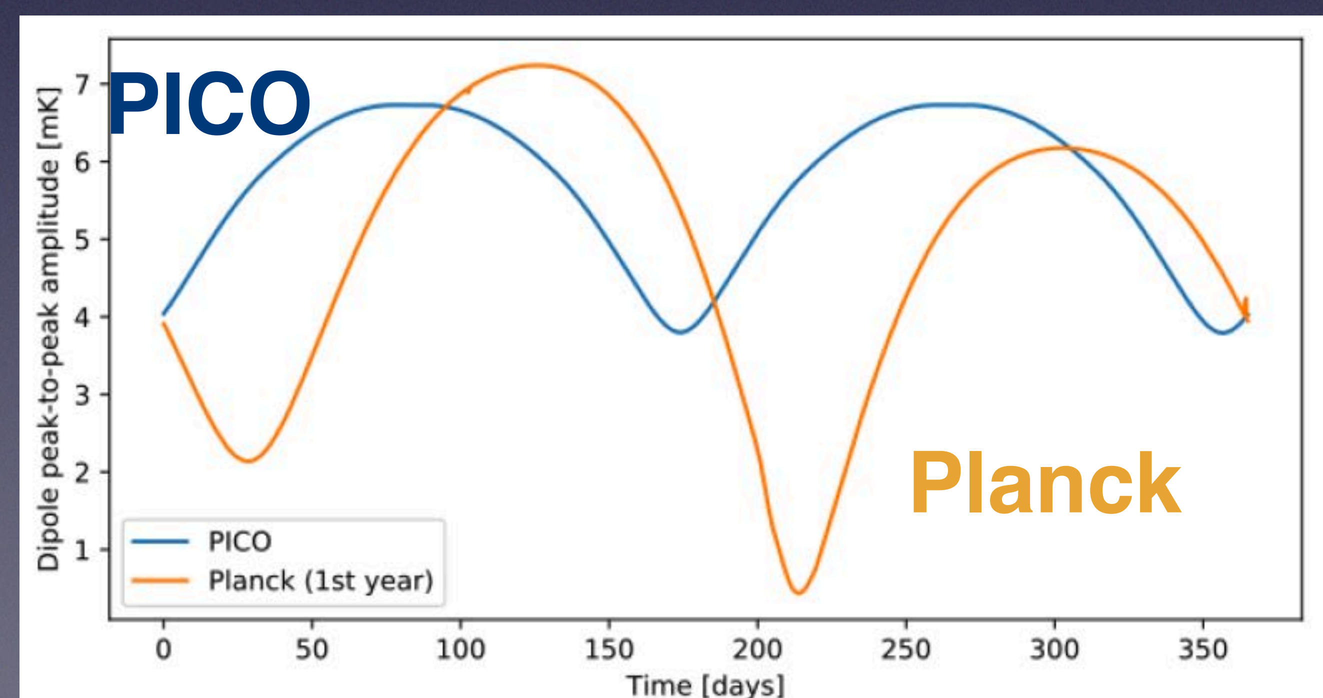


Figure: JPL



signals are always > 4 mK

Why PICO, Why Now

Figure: R. Flauger

- Transformative science that is unique to PICO
- 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.

Figure: R. Flauger

- Further progress with CMB requires a leap in sensitivity, foreground characterization, and systematic control. PICO is the most cost-effective approach.

Extra Slides

Foreground Removal: the Role of High Frequencies

Commander reconstruction of CMB and foregrounds (r=0.001):

- Top: with 21 bands find no r bias

- Bottom: removing low+high frequencies introduces bias

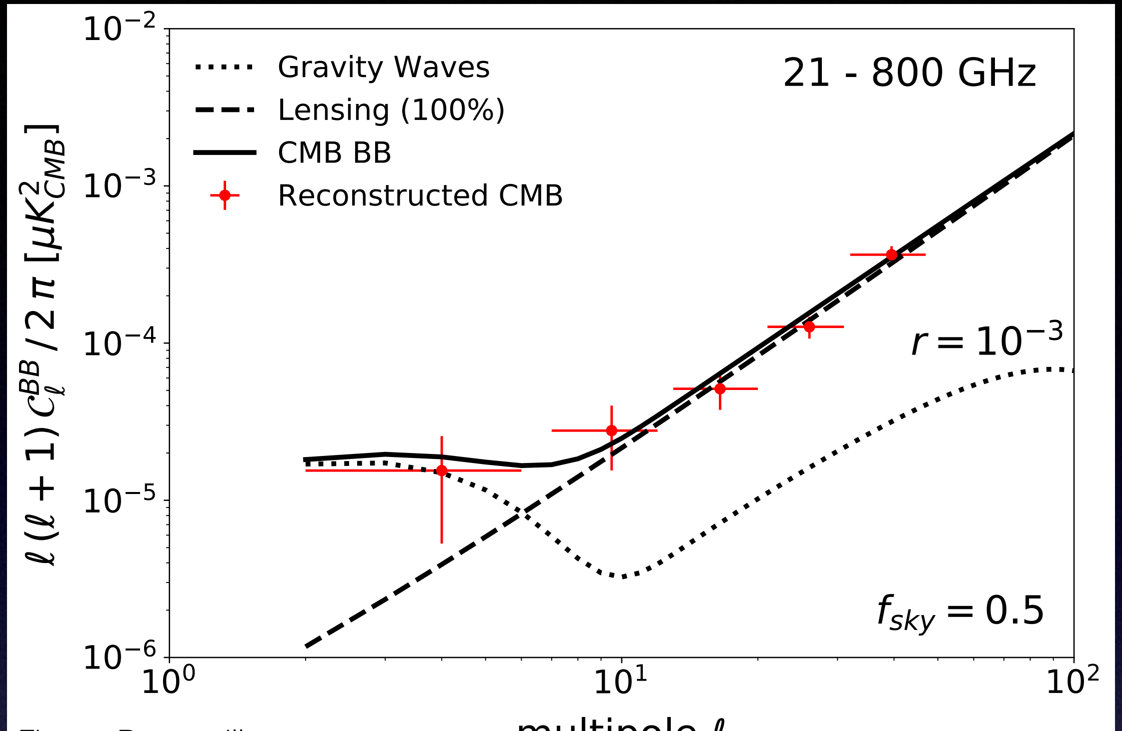


Figure: Remazeilles

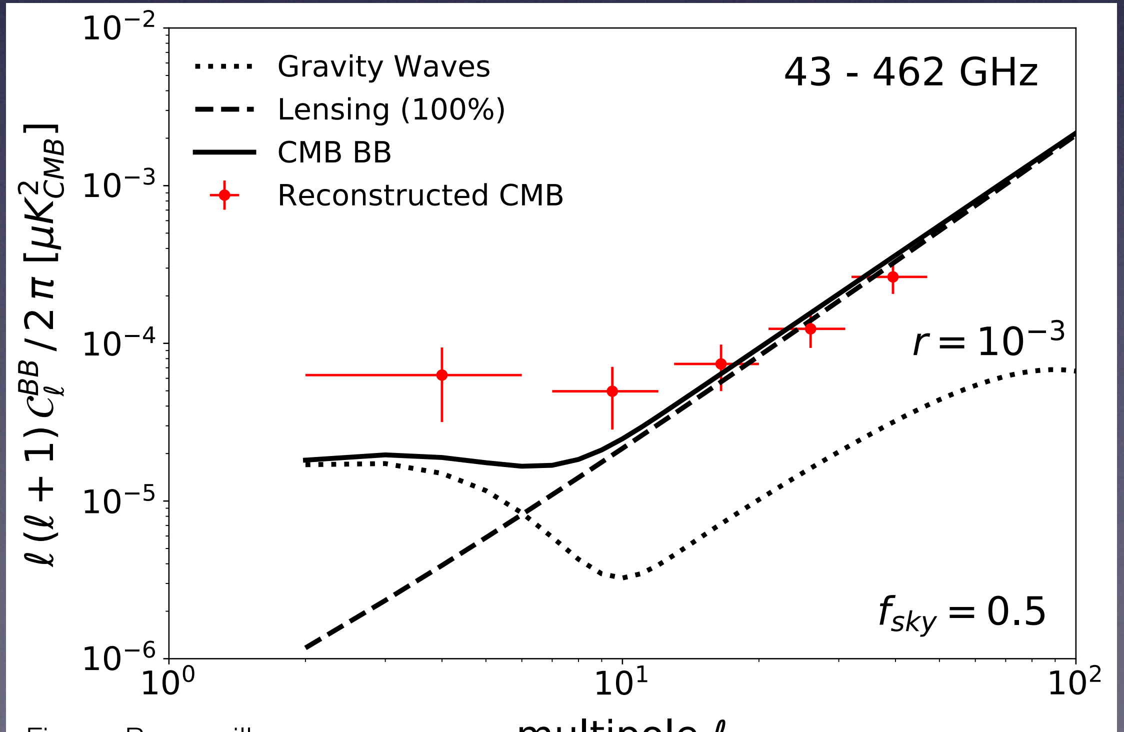


Figure: Remazeilles

A Path for the Next Decade

Figure: R. Flauger

- Space: PICO (International consortium of interested parties: US, Japan, Europe)

- Ground: concentrate on strength of ground = high \ell

Figure: R. Flauger

Why PICO, Why Now

- 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.
- Only a space-platform can provide the level of control of systematic uncertainties that PICO will have
  - Each of PICO's 13,000 detectors will make 10 redundant maps of I, Q, U over the entire sky enabling multiple cross-checks and opportunities to identify systematic uncertainties.
  - The thermal environment at L2 is among the most stable available
- Some evidence that PICO has the combination of frequency bands and sensitivity to account for Galactic foregrounds; more verification required
- The implementation relies on current technologies or straightforward extensions
- PICO is the obvious extension to the progress we have made in the last decade.

Systematic Uncertainties

Figure: R. Flauger

Figure: R. Flauger

Figure: Remazeilles

- Bottom left: reconstructing CMB and foregrounds with 21 bands has no r bias (r=0.001)
- Bottom right: removing low/high frequencies introduces bias

Figure: Remazeilles

Figure: Remazeilles

Inflation - Models that explain n_s

Figure: R. Flauger

- Models for which $n_s - 1 = -\dfrac{p+1}{N}$
- N = number of e-folds between the time the pivot scale exits the horizon and the end of inflation
- Mukhanov (2013), Roest (2014), Creminelli+(2015)

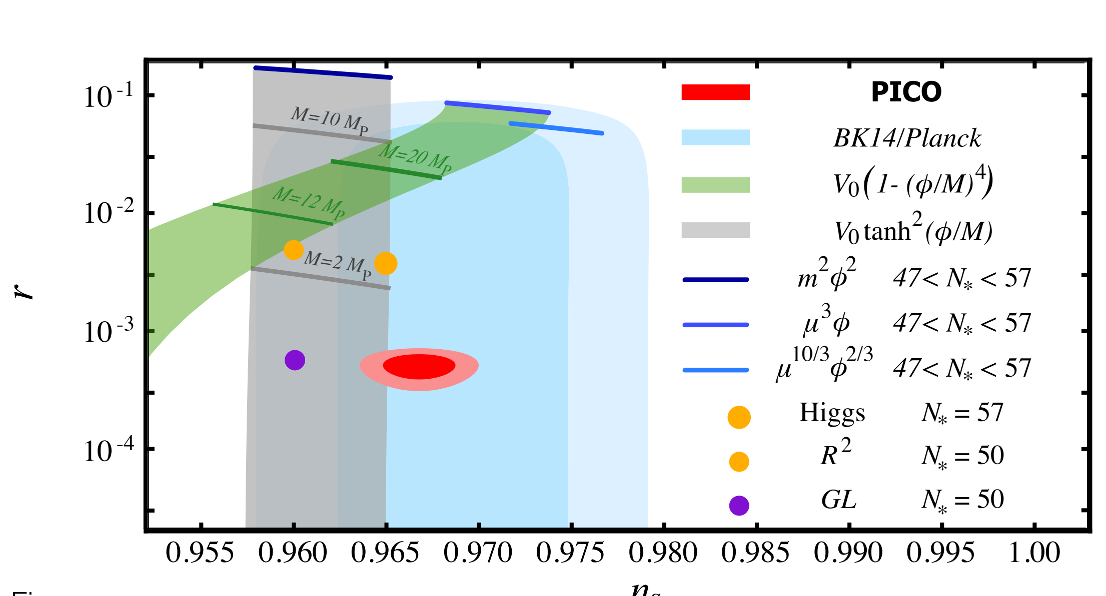


Figure:

PICO Science Objective - 1: Inflation r

Figure: R. Flauger

- Textbook Inflation models that naturally explain the spectral index and have $r \gtrsim 5\times 10^{-4}$ superPlanckian mass scale
Goal: detect $r = 5\times 10^{-4}\,(5\sigma)$

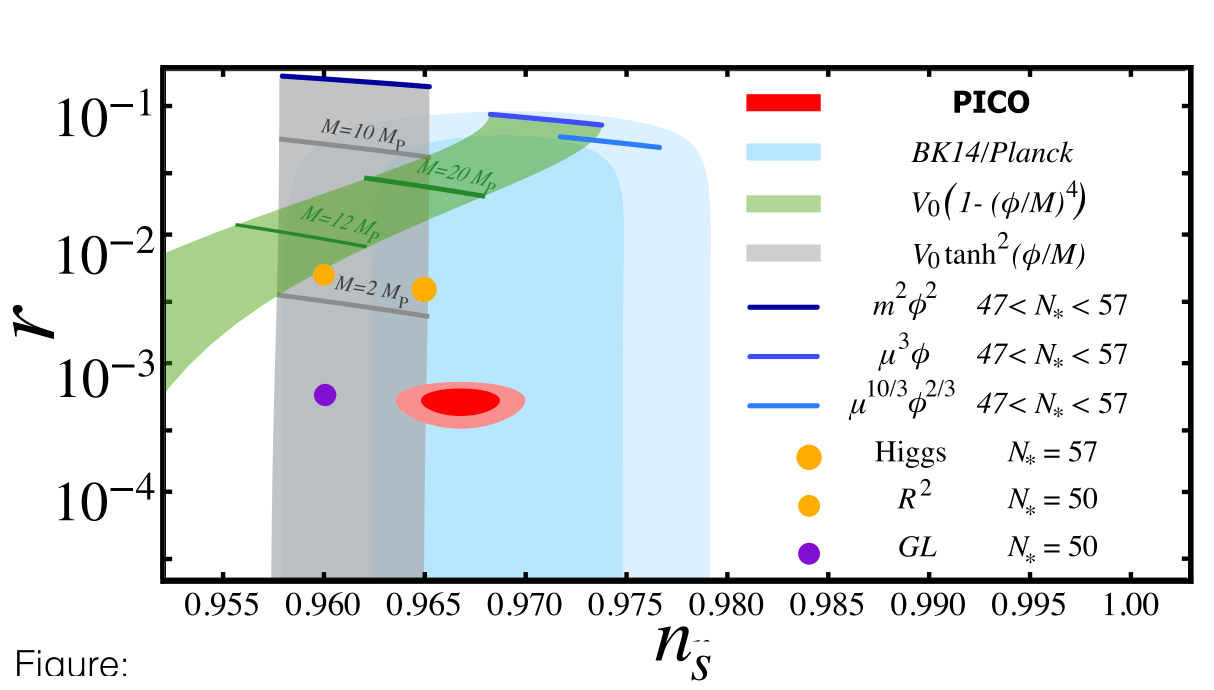
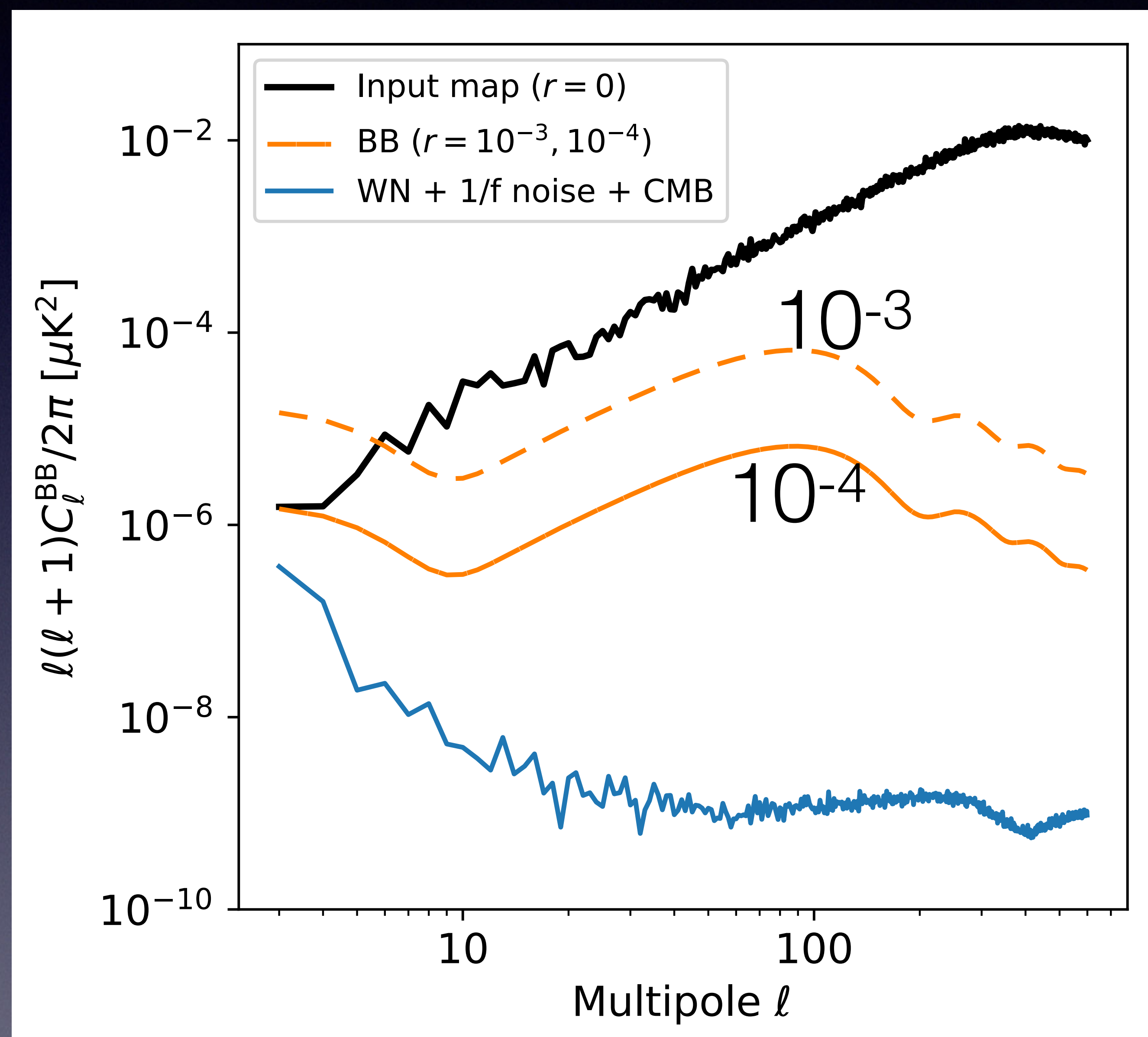


Table 3.2: PICO has 21 partially overlapping frequency bands with band centers (ν_c) from 21 GHz to 799 GHz and each with bandwidth $\Delta\nu/\nu_c = 25\,\%$. The beams are single mode, with FWHM sizes of $6\farcm2 \times (155\,\mathrm{GHz}/\nu_c)$. The CBE per-bolometer sensitivity is photon-noise limited (§ 3.2.3). The total number of bolometers for each band is equal to (number of tiles) × (pixels per tile) × (2 polarizations per pixel), from Table 3.1. Array sensitivity assumes 90 % detector operability. The map depth assumes 5 yr of full sky survey at 95 % survey efficiency, except the 25 and 30 GHz frequency bands, which are conservatively excluded during 4 hr/day Ka-band (26 GHz) telecom periods (§ 4.2).

Band Center [GHz]	Beam FWHM [arcmin]	CBE Bolo NET [$\mu\mathrm{K_{CMB}\,s^{1/2}}$]	N_{bolo}	CBE Array NET [$\mu\mathrm{K_{CMB}\,s^{1/2}}$]	Baseline Array NET [$\mu\mathrm{K_{CMB}\,s^{1/2}}$]	Baseline polarization map depth [$\mu\mathrm{K_{CMB}}$ arcmin]	[Jy sr^{-1}]
21	38.4	112	120	12.0	17.0	23.9	8.3
25	32.0	103	200	8.4	11.9	18.4	10.9
30	28.3	59.4	120	5.7	8.0	12.4	11.8
36	23.6	54.4	200	4.0	5.7	7.9	12.9
43	22.2	41.7	120	4.0	5.6	7.9	19.5
52	18.4	38.4	200	2.8	4.0	5.7	23.8
62	12.8	69.2	732	2.7	3.8	5.4	45.4
75	10.7	65.4	1020	2.1	3.0	4.2	58.3
90	9.5	37.7	732	1.4	2.0	2.8	59.3
108	7.9	36.2	1020	1.1	1.6	2.3	77.3
129	7.4	27.8	732	1.1	1.5	2.1	96.0
155	6.2	27.5	1020	0.9	1.3	1.8	119
186	4.3	70.8	960	2.0	2.8	4.0	433
223	3.6	84.2	900	2.3	3.3	4.5	604
268	3.2	54.8	960	1.5	2.2	3.1	433
321	2.6	77.6	900	2.1	3.0	4.2	578
385	2.5	69.1	960	2.3	3.2	4.5	429
462	2.1	133	900	4.5	6.4	9.1	551
555	1.5	658	440	23.0	32.5	45.8	1580
666	1.3	2210	400	89.0	126	177	2080
799	1.1	10400	360	526	744	1050	2880
Total			12 996	0.43	0.61	0.87	

Calibration and 1/f

217 GHz



Flauger

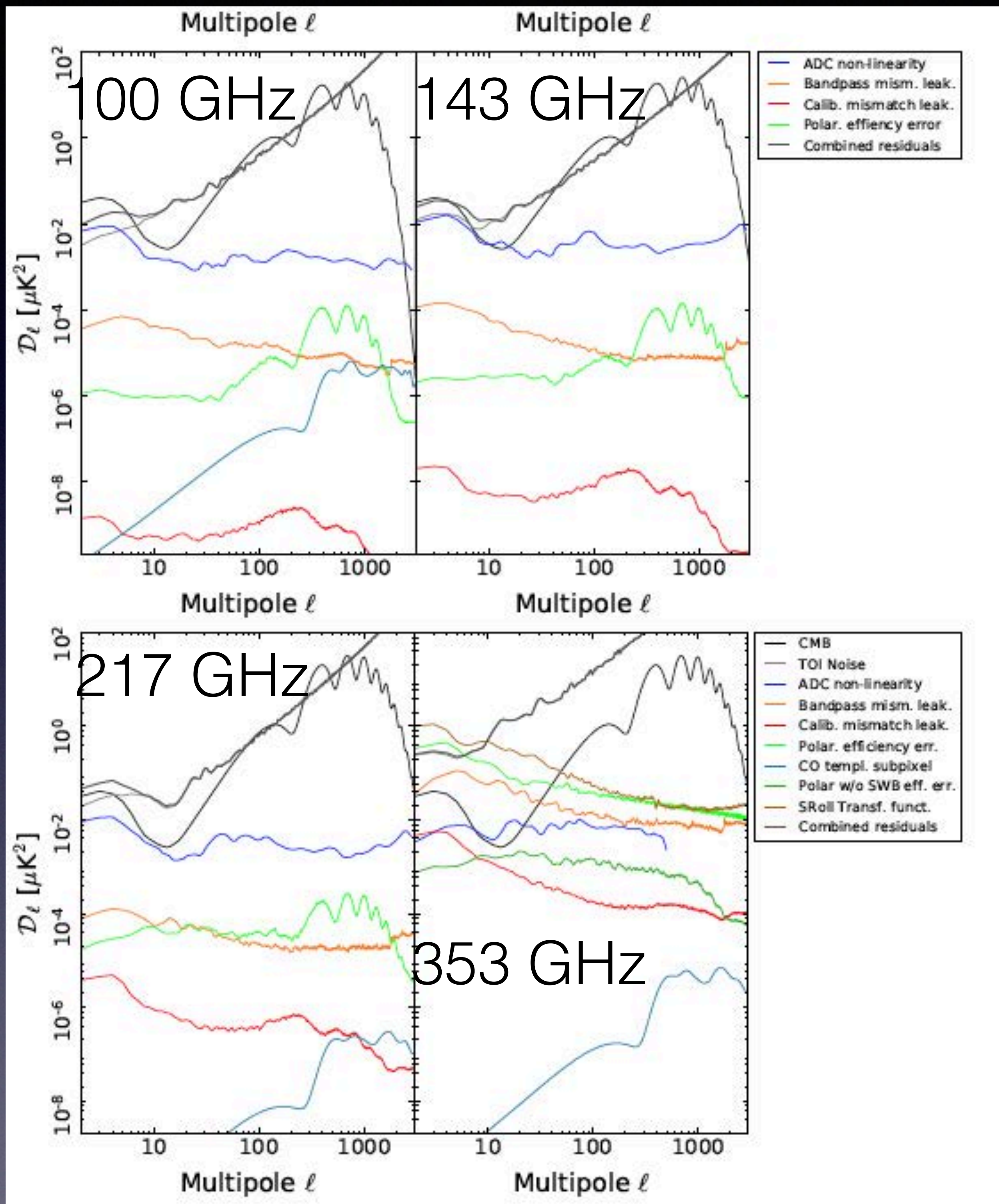
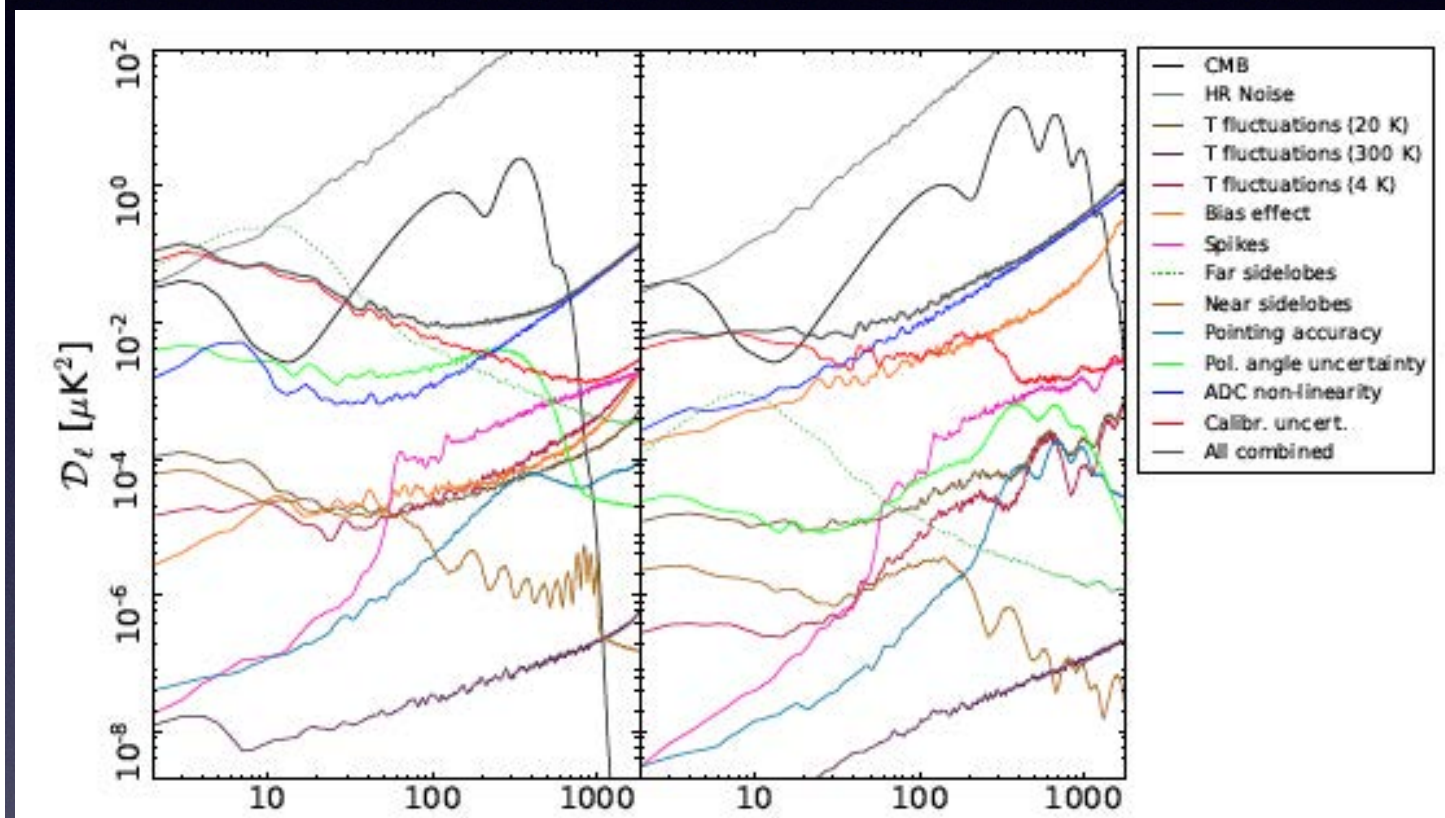


Figure: R. Flauger

30 GHz 70 GHz



Foreground Removal

- Top Right: PySM model a2d4s1f3; Full sky; nside=512; analyzed with GNILC; 50% of sky; using PICO bands and noise; 85% delensing
- residual foregrounds are x10 below r for \ell=5; x4 below r for ell=100

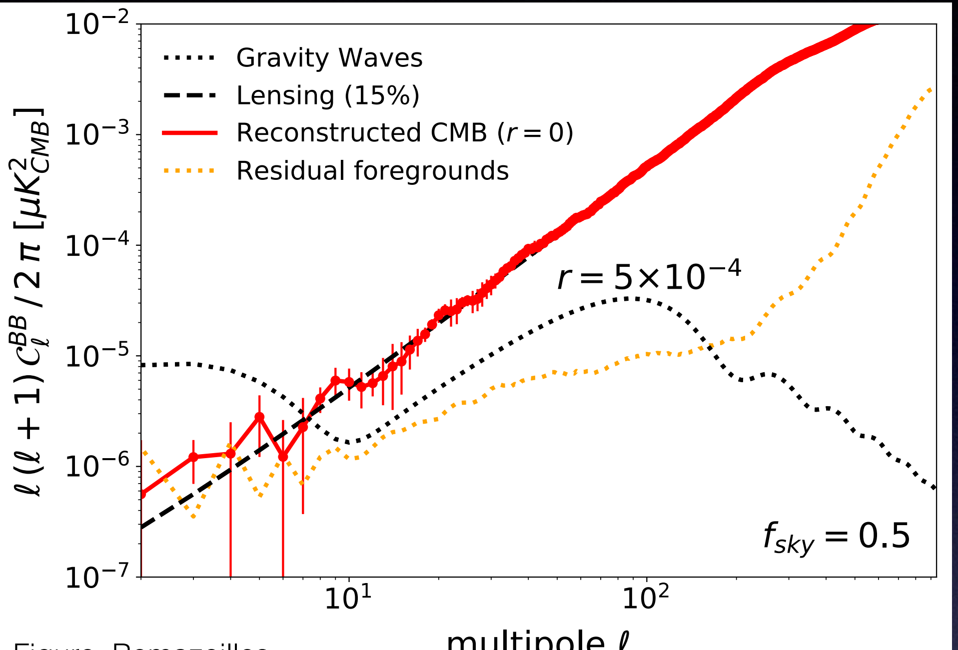


Figure: Remazeilles

- Bottom left: reconstructing CMB and foregrounds with 21 bands has no r bias (r=0.001)
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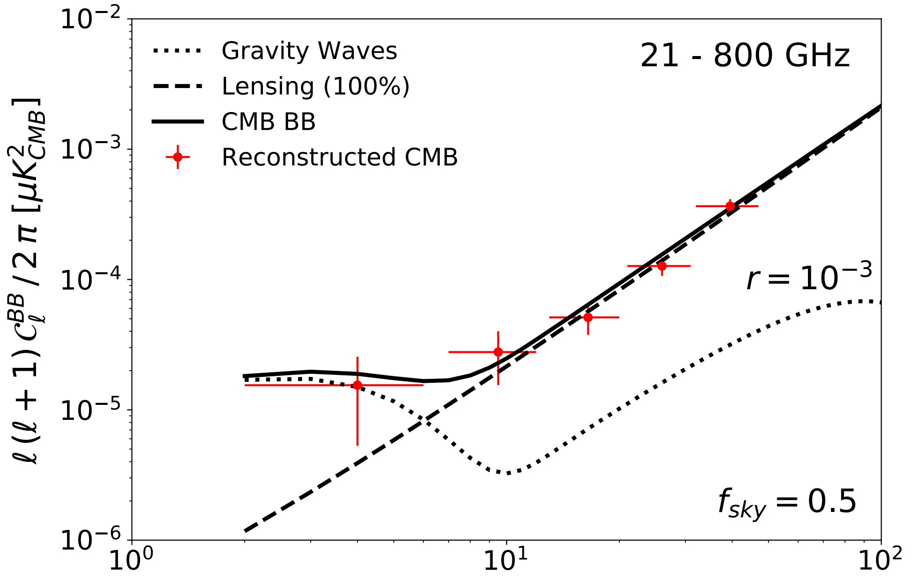


Figure: Remazeilles

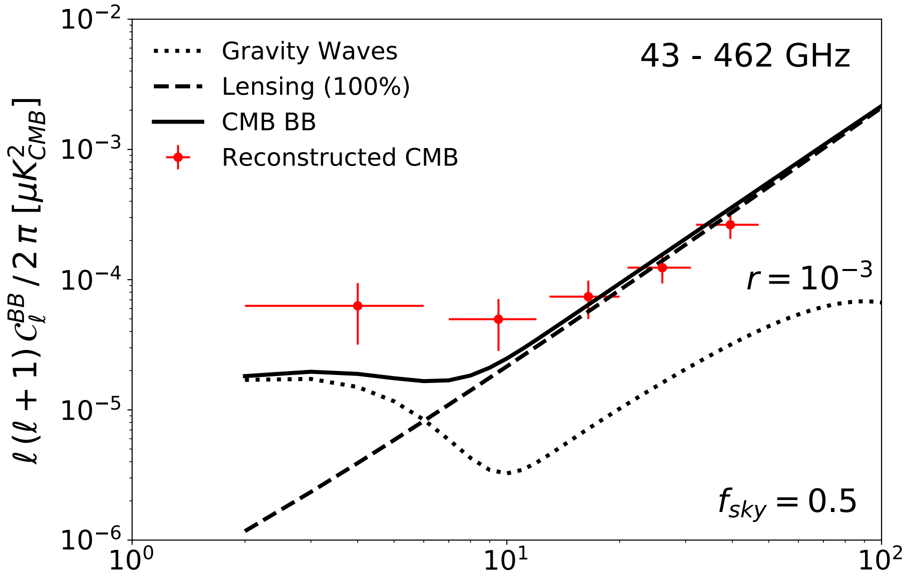
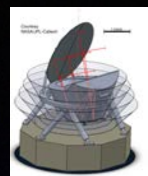
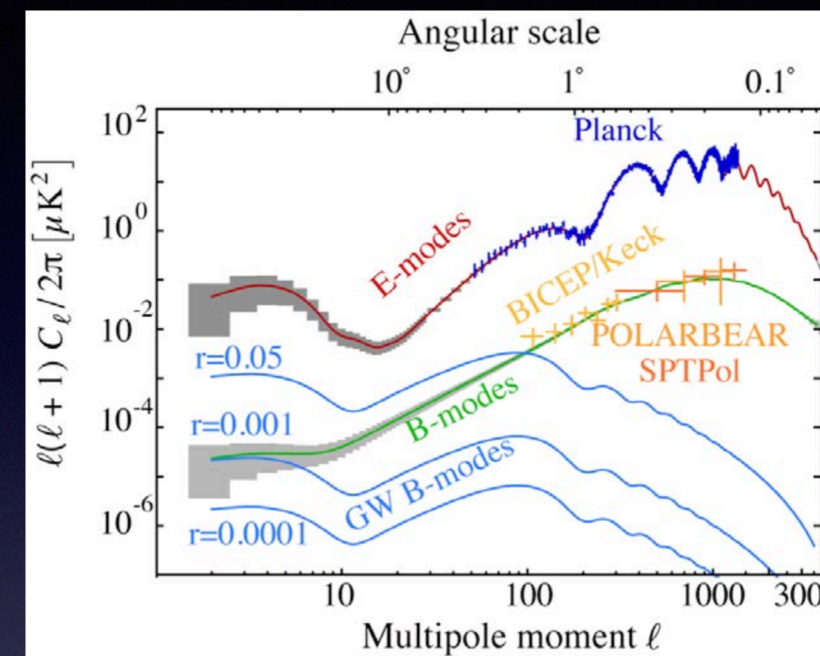


Figure: Remazeilles

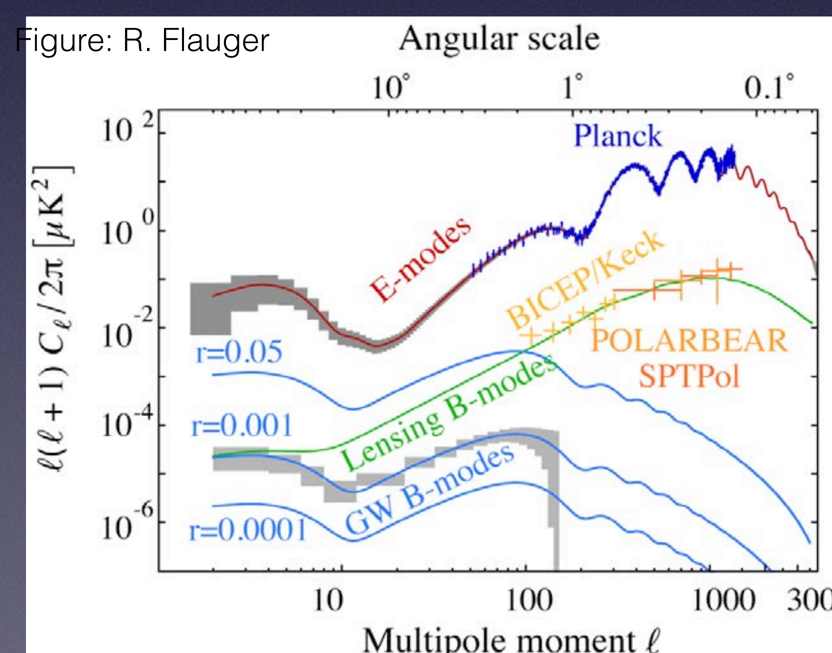


Simple Foreground Model

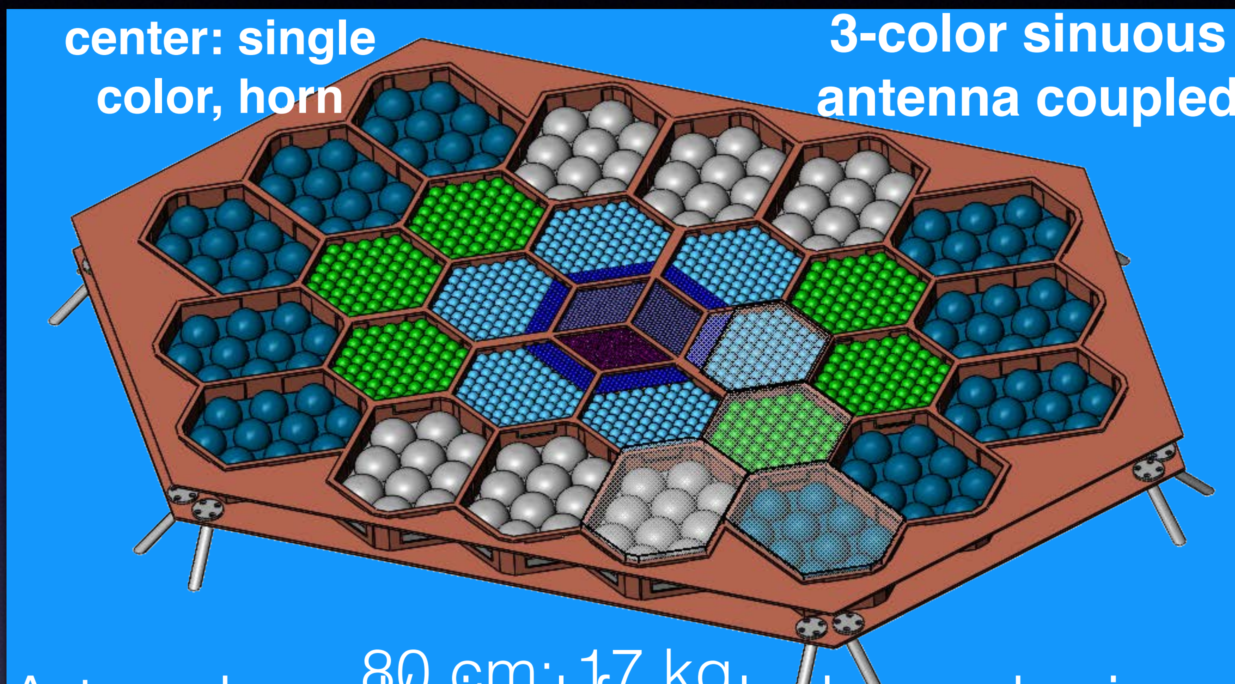


- 2 component dust model (a-la Finkbeiner et al)
- Synchrotron with power law frequency dependence
- ℓ dependence consistent with Planck and WMAP
- Includes correlation between dust and synchrotron, consistent with current data
- Model does not include:
  - spatial variation of the spectral index
  -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

Figure: R. Flauger



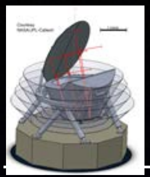
PICO Implementation



- A two-band/pixel focal plane design also available
- 19 bands, same noise (bands are broader, but less spill-over on stop)
- A monochroic focal plane design also available
- 21 band, higher noise but within requirements (only 20% margin)

Tile type	N_{tile}	Pixels/ tile	Pixel type	Bandcenters [GHz]	Sampling rate [Hz]
1	6	10	A	21, 30, 43	45
2	10	10	B	25, 36, 52	55
3	6	61	C	62, 90, 129	136
4	6	85	D	75, 108, 155	163
		80	E	186, 268, 385	403
5	2	450	F	223, 321, 462	480
6	1	220	G	555	917
		200	H	666	
		180	I	799	

Time Domain Multiplexing
128 x 102; 75 W

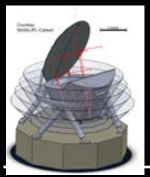


PICO Implementation - 2 Bands

- 19 bands, same noise (bands are broader, but less spill-over on stop-> higher efficiency)

- Corrugated feeds with dipole antenna (NIST+)

Pi xel	Bands	# of Pixel	# of holes/	# of holes
A	21, 31	30	60	120
B	26, 38	50	100	200
C	47, 70	170	340	680
D	59, 87	250	500	1000
E	108,	400	800	1600
F	135,	410	820	1640
G	248,	320	640	1280
H	308,	280	560	1120
I	555	220	440	440
J	666	200	400	400
K	799	180	360	360
				8840



PICO Implementation - Monochromatic Pixels

- 21 bands, 20% higher noise (0.74 uK*arcmin), but within requirements (with less margin)
- Relies on higher packing density
- Phased dipole slot antennas (JPL)

band	nu	# of Pixels	# of bo
1	20.8	30	
2	25	35	
3	30	40	
4	36	45	
5	43.2	50	
6	51.8	55	
7	62.2	160	
8	74.6	175	
9	89.6	200	
10	107.5	230	
11	129	270	
12	154.8	300	
13	185.8	270	
14	222.9	250	
15	267.5	240	
16	321	230	
17	385.2	210	
18	462.2	180	
19	554.7	110	
20	665.6	100	
21	798.7	90	
			6

PICO Additional Science

Figure: R. Flauger

- Dark matter / Axions:
  - 25 times stronger constraints than Planck, for ~MeV mass, not constrainable by direct detection experiments
  - x10 stronger constraints than Planck on axion mass between 10^{-26} and 10^{-30} eV
- Rule out primordial magnetic fields as source of largest galactic magnetic field

Figure: R. Flauger

- Improve by x300 constraints on rotations due cosmic birefringence
- Source Catalog for Evolution of Structure:
  - 4500 strongly lensed galaxies (z up to 5)
  - 50,000 proto-clusters (z up to 4.5)
  - 30,000 dusty galaxies (z<0.1)