Instrument and Science for the SPT-3G Cosmic Microwave Background Receiver

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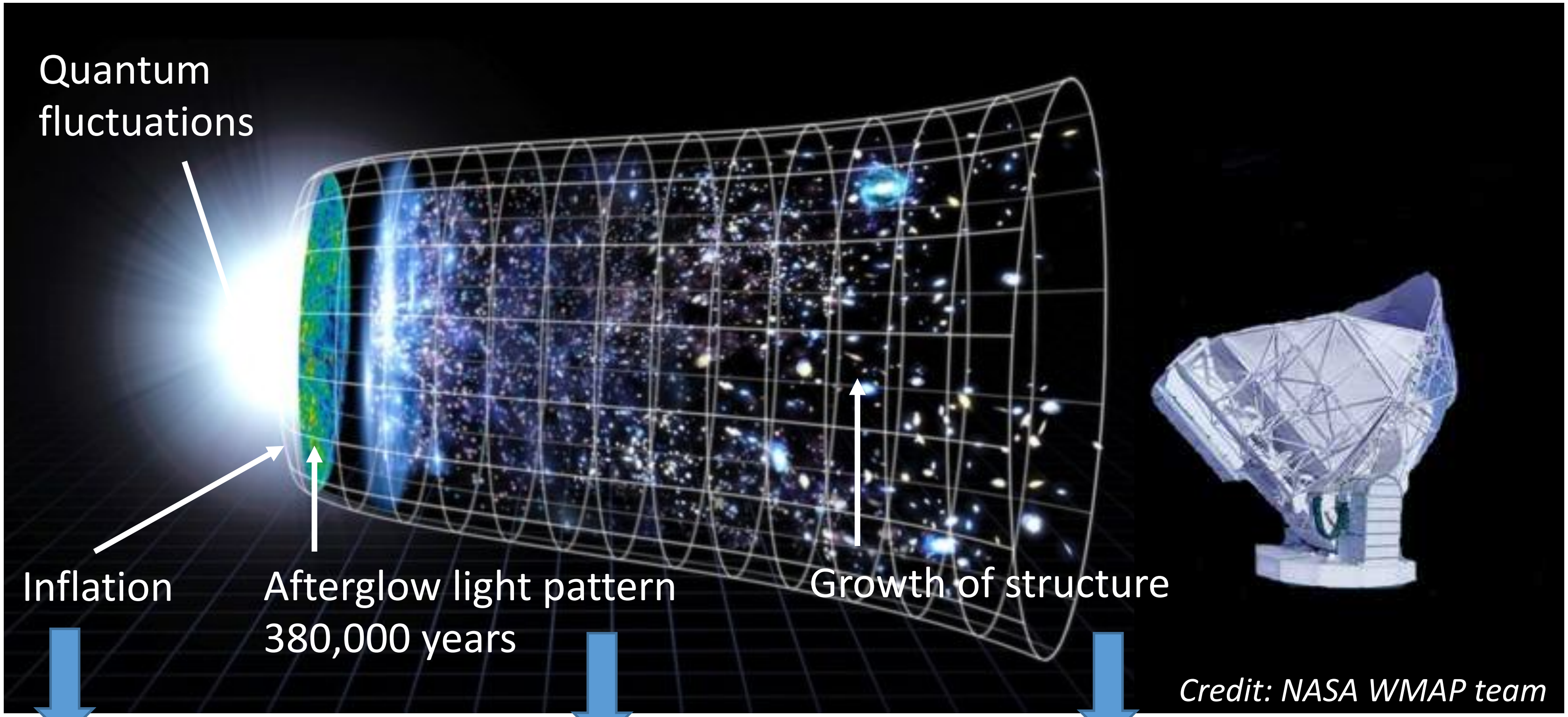
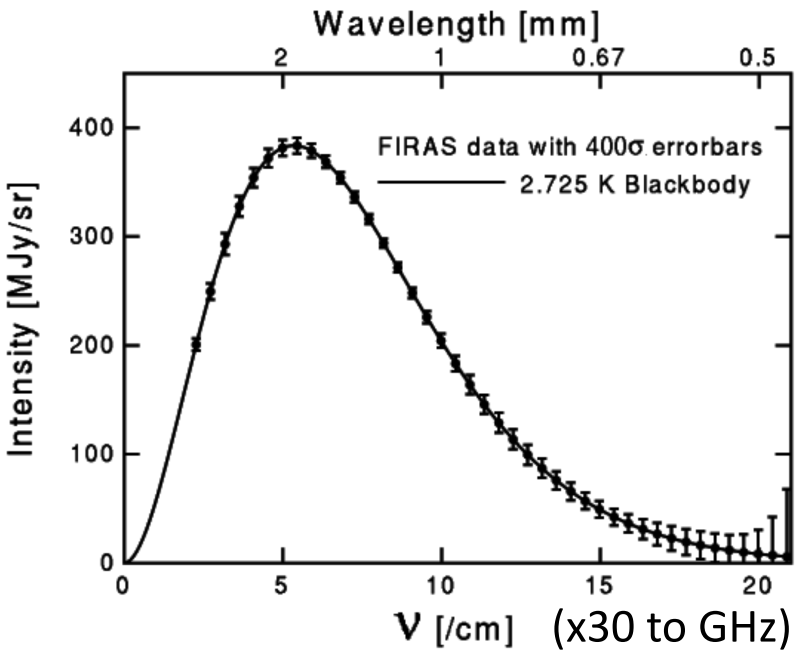
Photo credit to Joshua Montgomery

CMB and the cosmic history

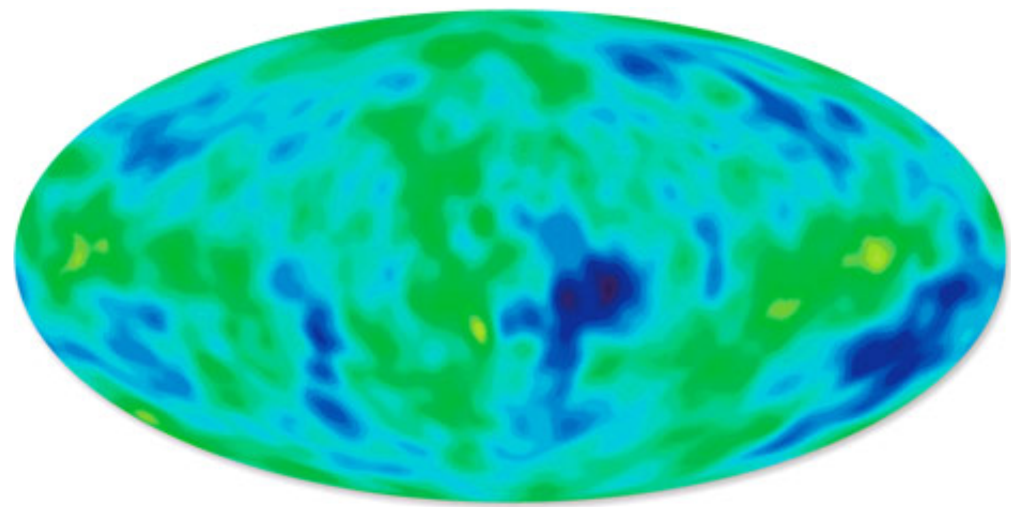


Inflation leaves signature in CMB polarization (B-mode) • Tensor-to-scalar ratio r • The energy scale of inflation • Inflation models	CMB is the image of the universe at recombination • Encodes the thermal history • Can probe the content of the universe, number of relativistic species, and other initial conditions.	Growth of structure affect the CMB at later times • Gravitational lensing • Imprint of galaxy clusters • Can probe dark energy, sum of neutrino masses, and test general relativity

COBE (1992): 3K blackbody with anisotropy

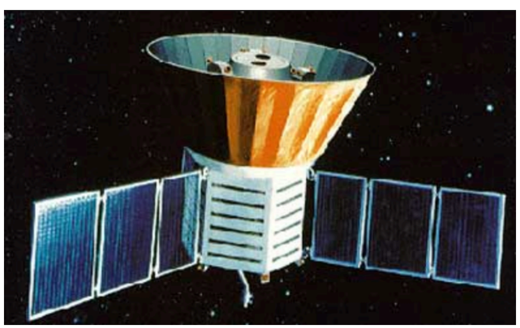


(x30 to GHz)



CMB power spectrum with 400σ error bar
Close to a 3K blackbody

CMB temperature anisotropy by COBE
Anisotropy at 0.01% level

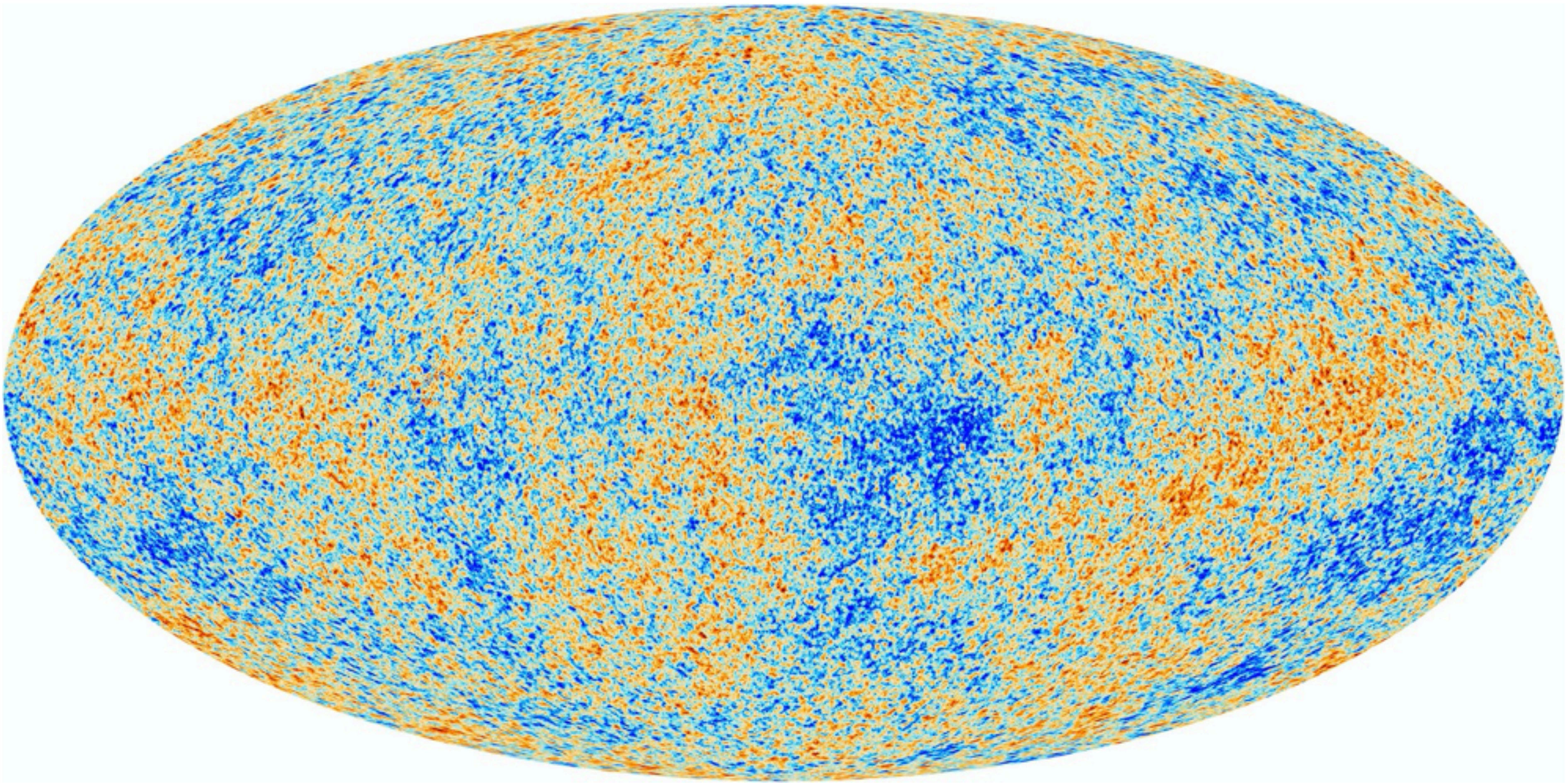


Rendering of the COBE satellite

Credit: NASA COBE team

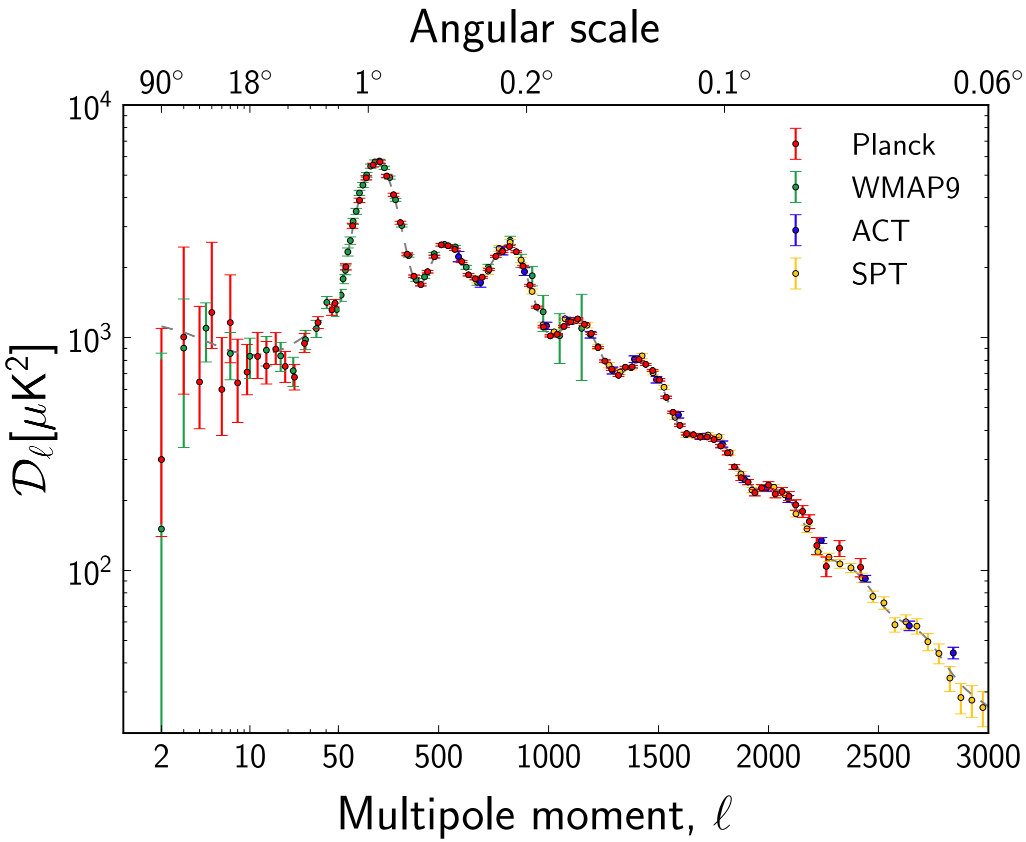
Nobel prize in 2006
John C. Mather and George F. Smoot

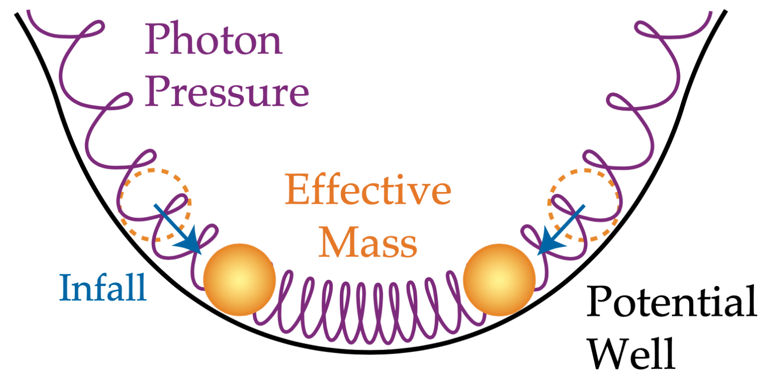
Planck (2014): CMB temperature anisotropy



0.01% rms fluctuation on a 3K blackbody

Planck (2014): CMB temperature anisotropy





Credit: Wayne Hu

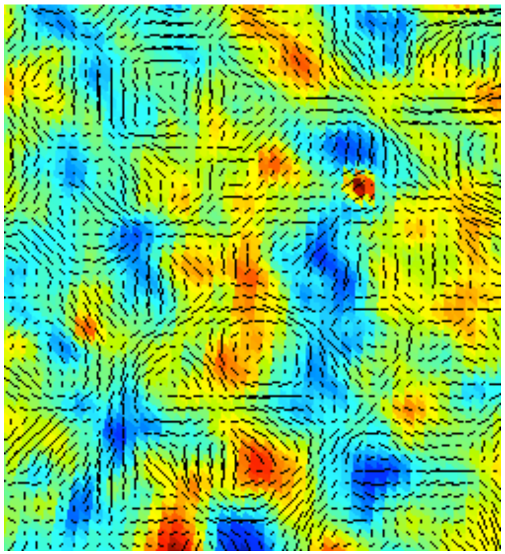
The harmonic structure in the CMB power spectrum is from acoustic oscillation of the photon-baryon plasma.

Encodes cosmological information

- Fits well to a 6-parameter standard cosmological model.
- Probes the content of universe with percent-level precision.
- Measures the Hubble constant at high redshift.

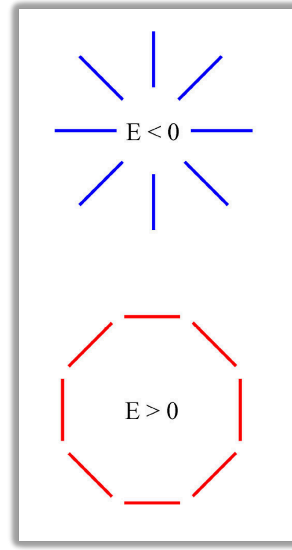
CMB – polarizations

5 deg

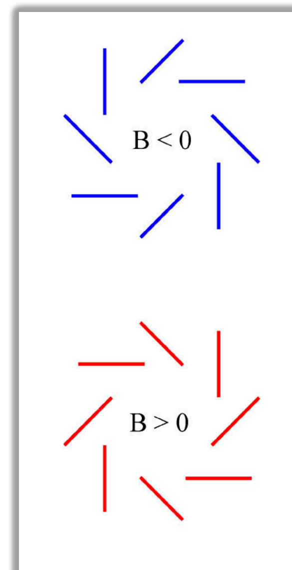


Credit: Boomerang Collaboration

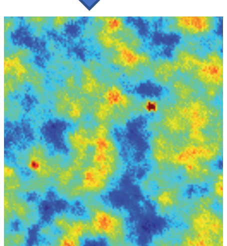
E mode



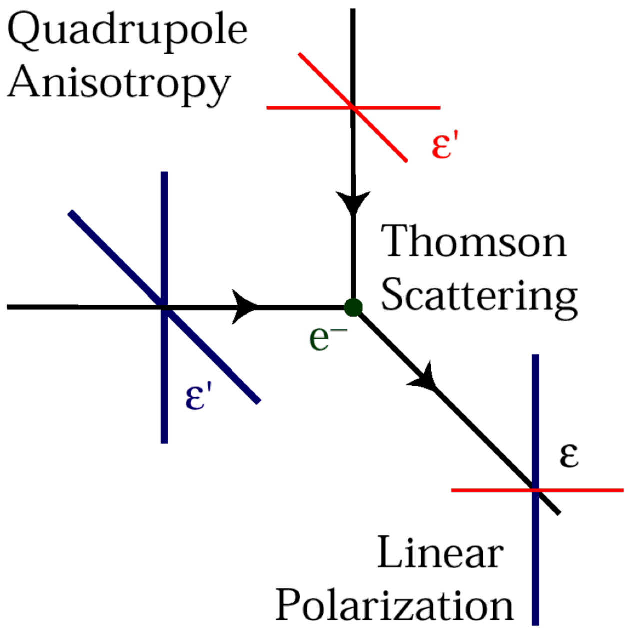
B mode



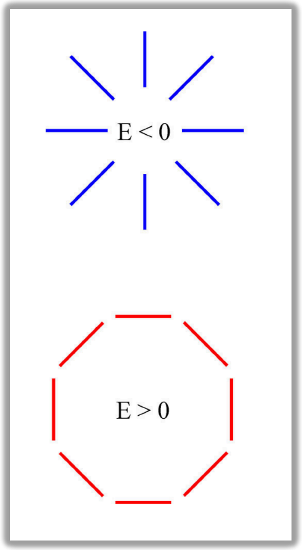
Temperature

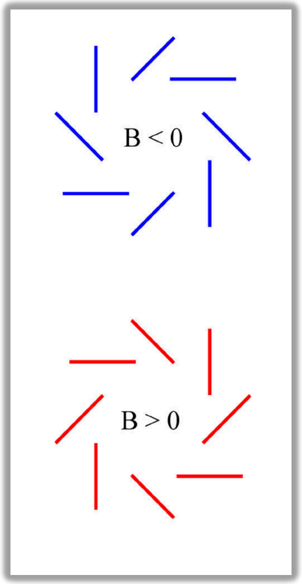


CMB – physics behind polarizations



Scalar anisotropy



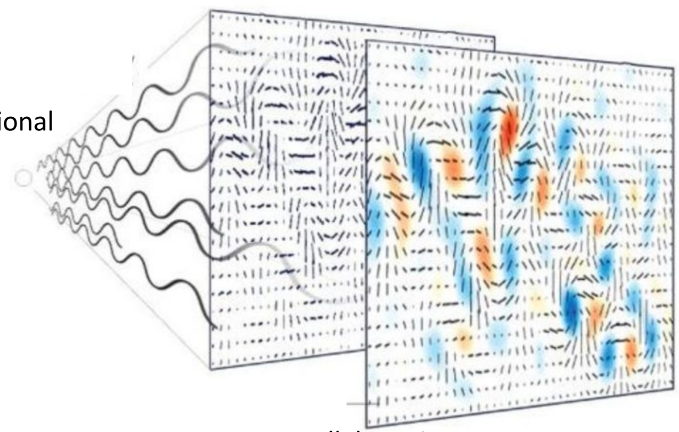


- Radiation with local quadrupole scattering off electrons -> CMB polarization
- Quadrupole sources
  - Scalar anisotropy (density fluctuation) – E
  - Tensor anisotropy (gravitational waves) – E and B

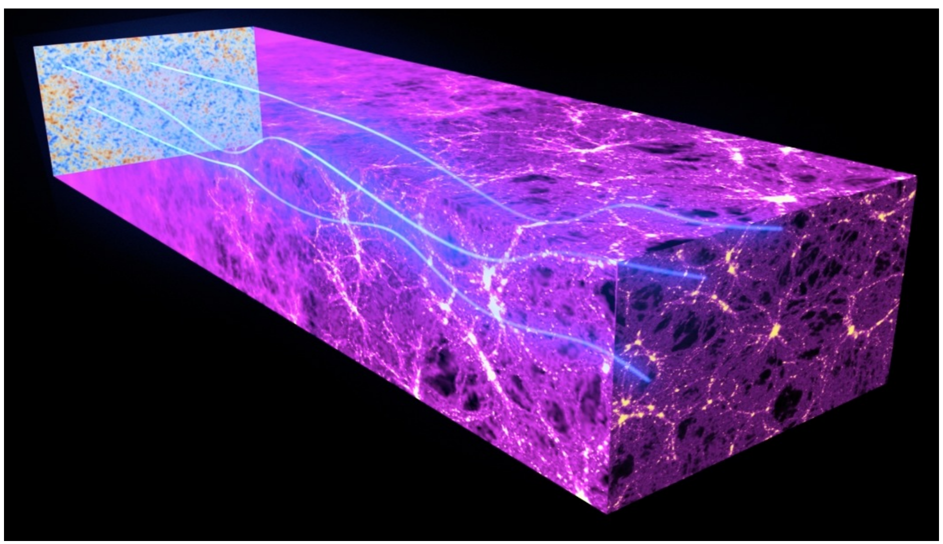
Hu and White. arXiv: astro-ph/9706147 (1997).

CMB – physics behind B-mode polarizations

Gravitational waves

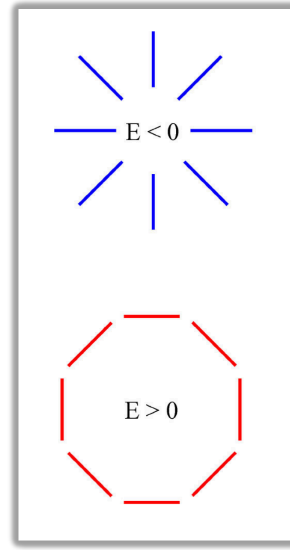


BICEP2 collaboration

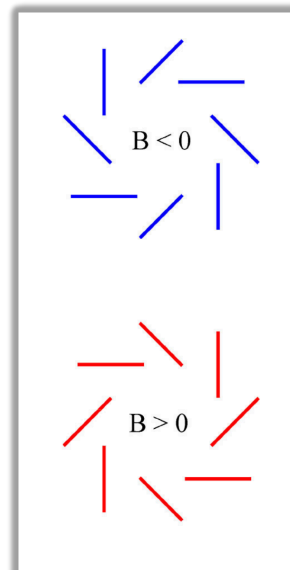


ESA Planck Collaboration

Inflationary gravitational waves (tensor perturbation)

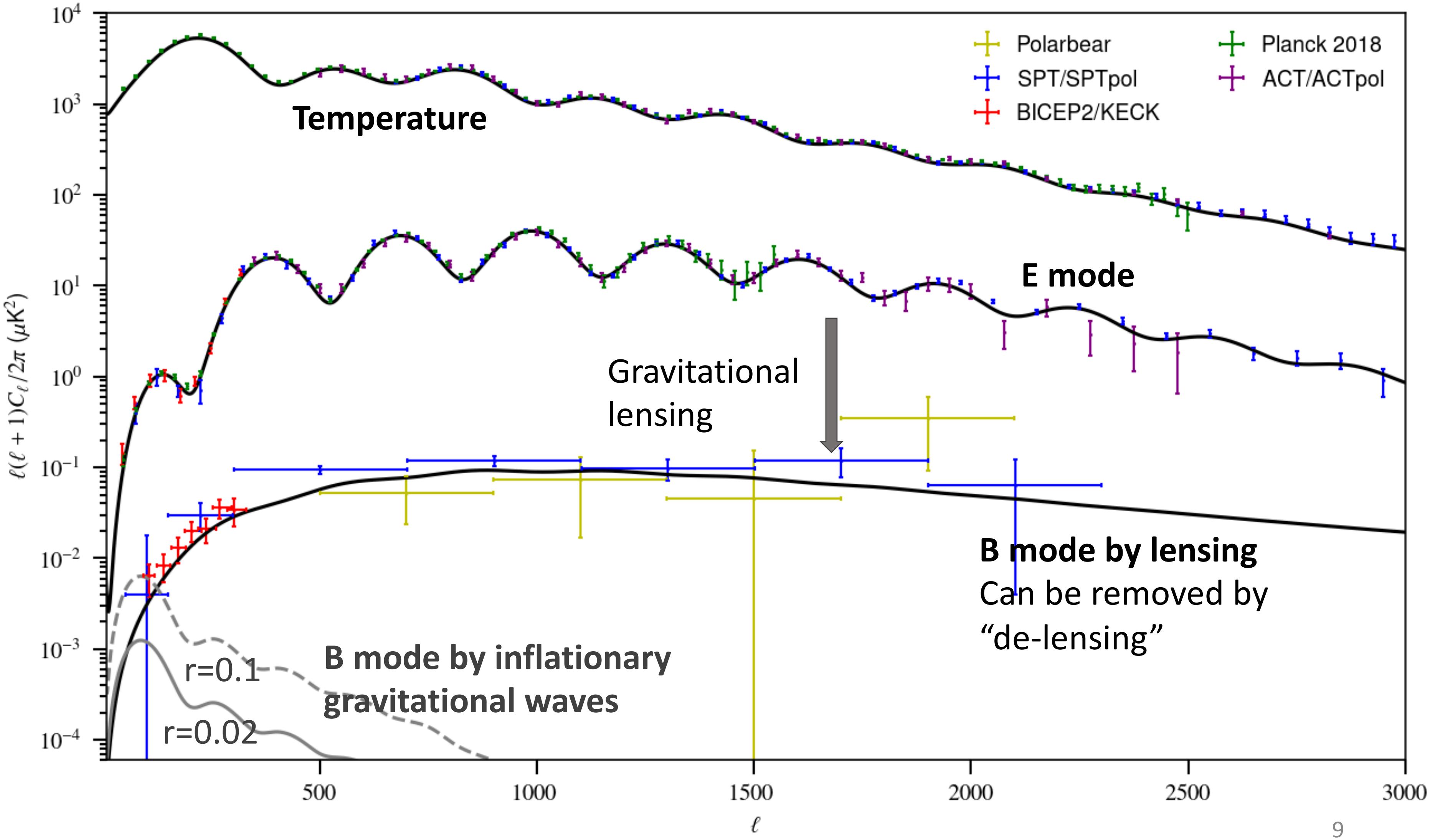


Gravitational lensing

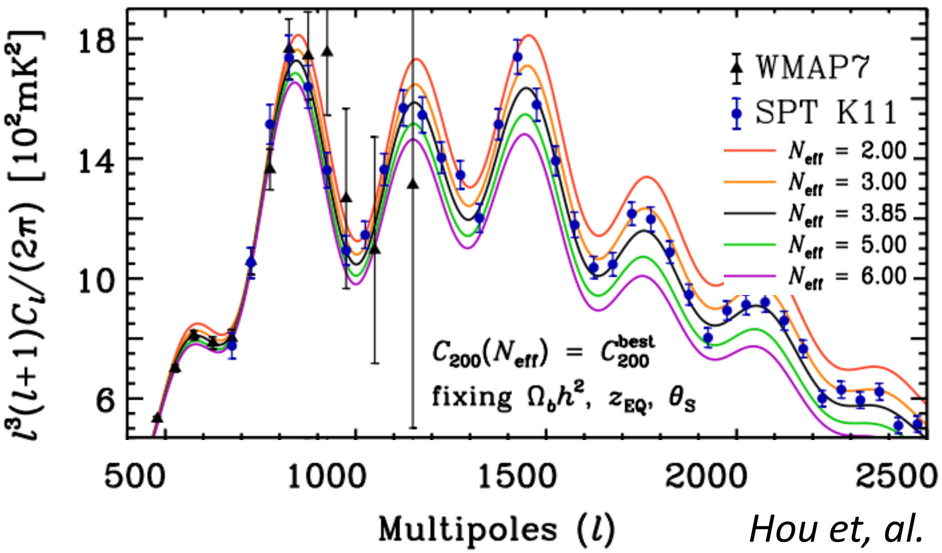


Seljak, Hirata. Physical Review D 69.4 (2004): 043005.
Seljak, Zaldarriaga, Physical Review Letters 78.11 (1997): 2054.

CMB power spectra and related science



CMB and neutrino physics: N_{eff}

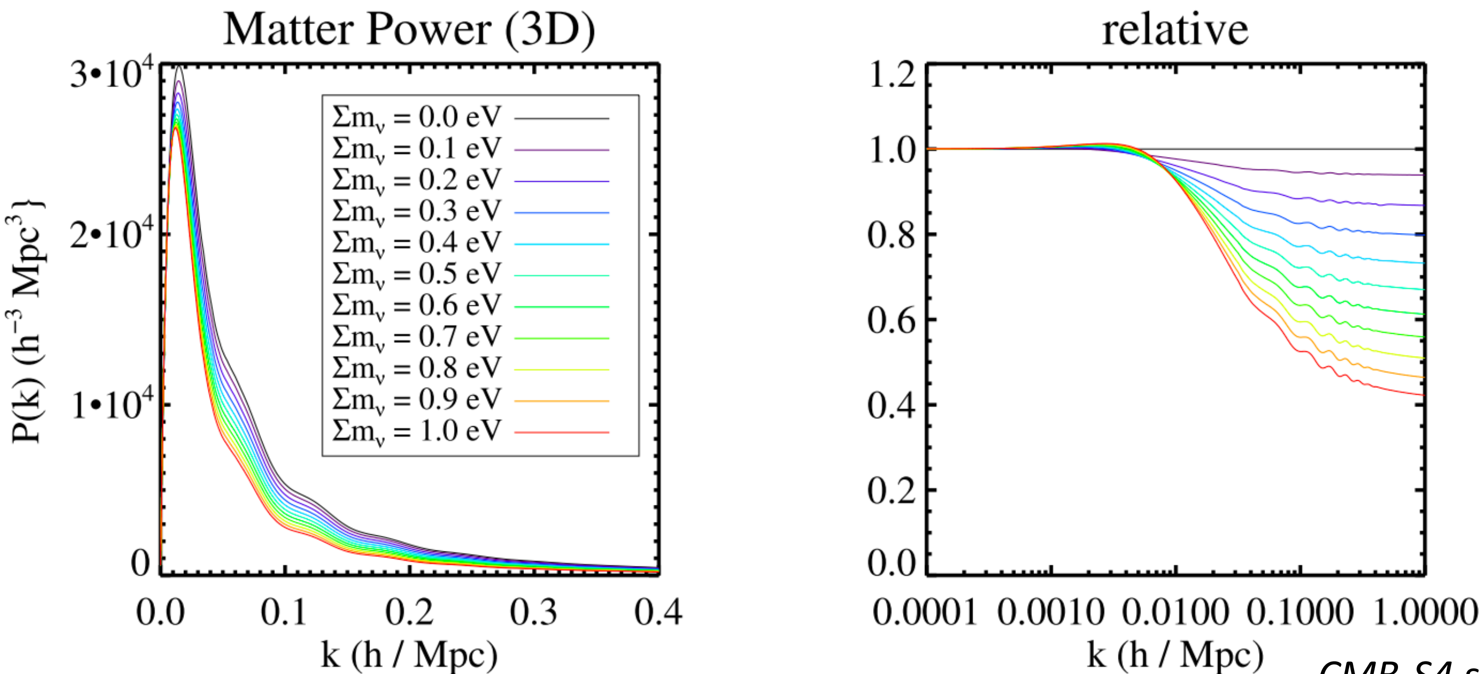


Hou et, al.

- Number of relativistic species N_{eff}
- Weakly interacting or noninteracting species that is relativistic at recombination.
- A parameter describing radiation-like energy density.
- Standard model prediction: 3.046

- Affects the expansion history – characteristic scale of CMB fluctuations
- Affects sound waves of photon-baryon plasma – mean free path
- The ratio of these two scales is precisely measured by the CMB
- Planck constraint: $\Delta N_{eff} = 0.19\ (1\sigma)$

CMB and neutrino physics: Σm_ν



CMB-S4 science book

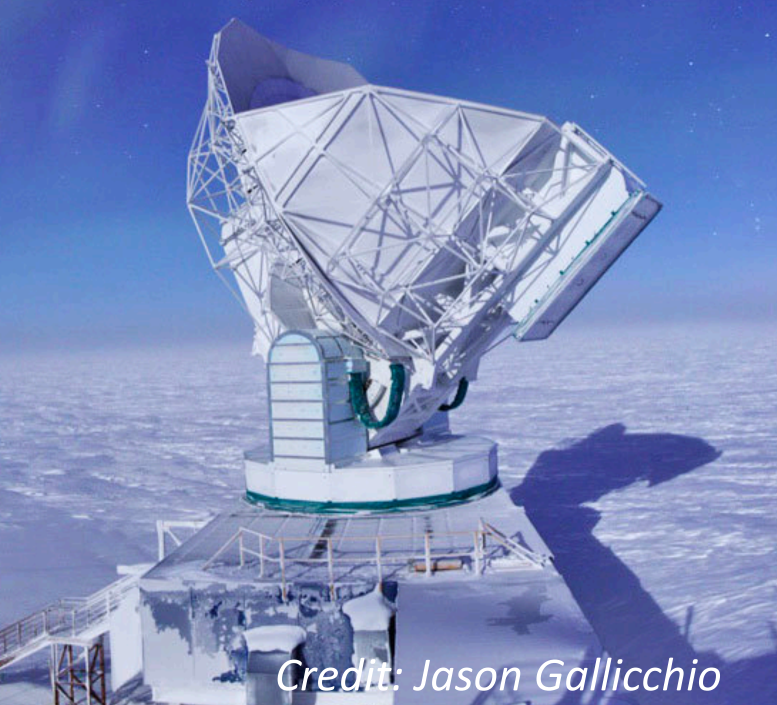
- At early times, neutrinos behave like radiation.
- As the universe expands, neutrinos lose energy and are bound to large scale structure (like dark matter).
- Radiation (neutrinos behaving like radiation) suppresses growth of structure.

South Pole Telescope

Ten meter sub-mm quality telescope

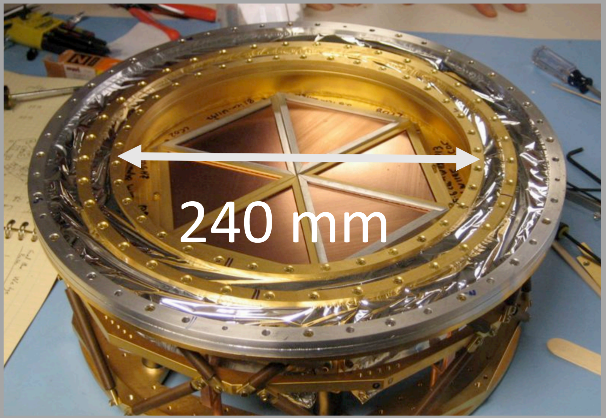
95, 150, 220 GHz and

1.6, 1.2, 1.0 arcmin resolution

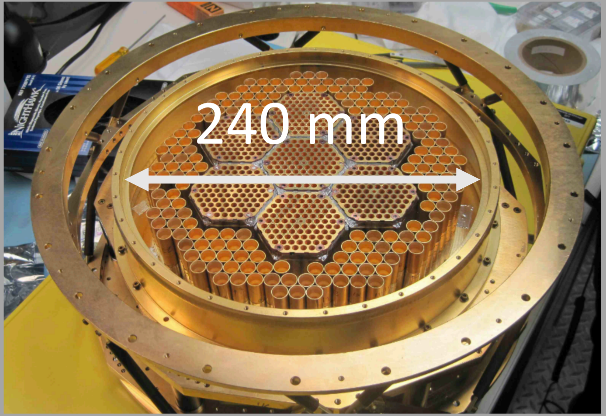


Credit: Jason Gallicchio

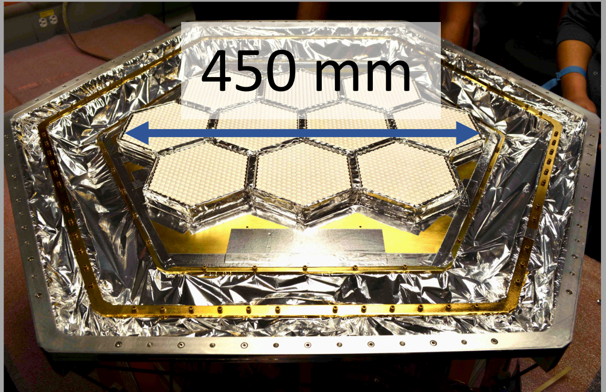
Focal planes (3 generations)



2007: SPT-SZ
960 Detectors
95, 150, 220 GHz

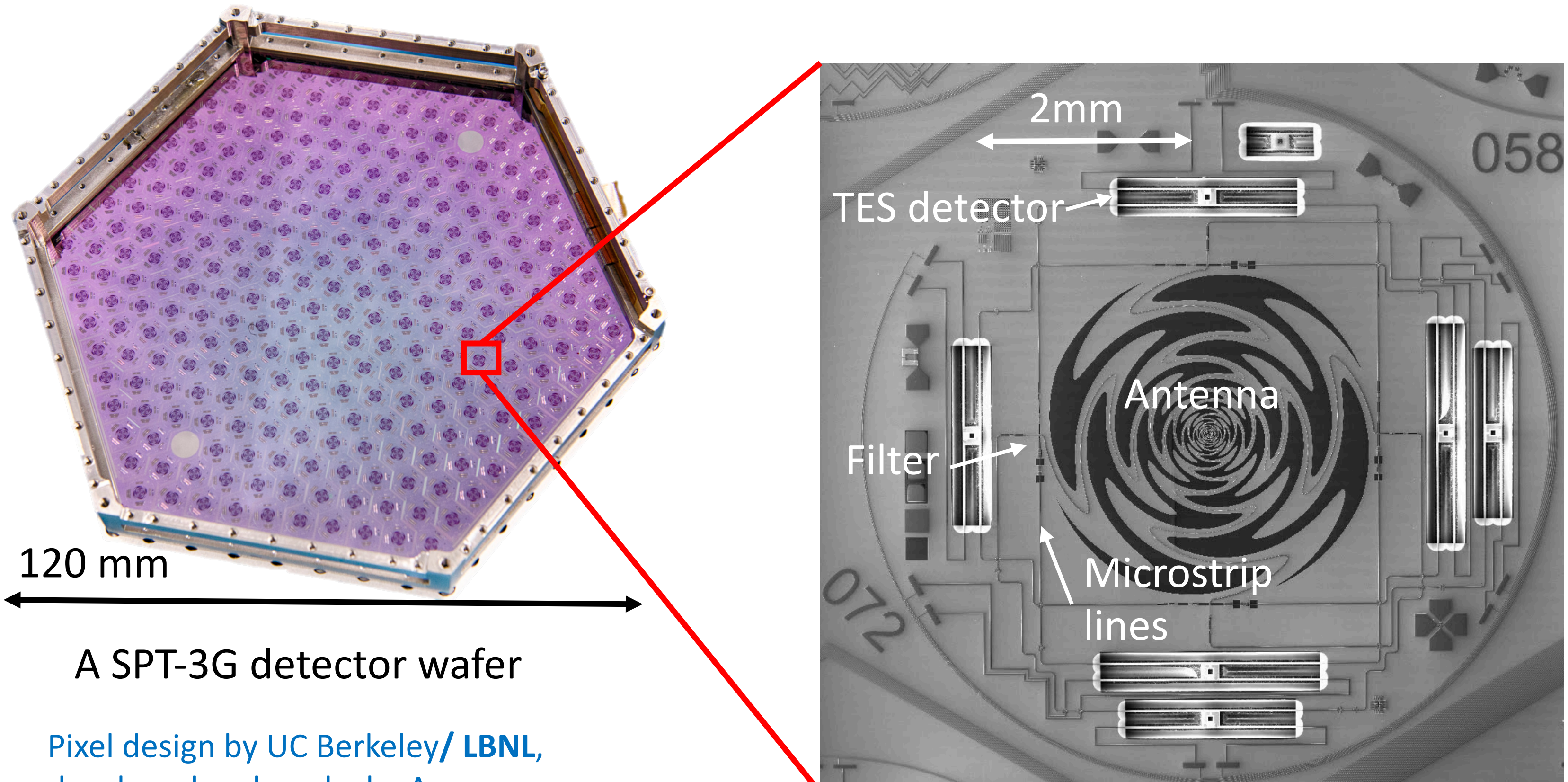


2012: SPTpol
1,500 Detectors
95, 150 GHz
+Polarization



2017: SPT-3G
~16,000 Detectors
95,150,220 GHz
+Polarization

Detector structure



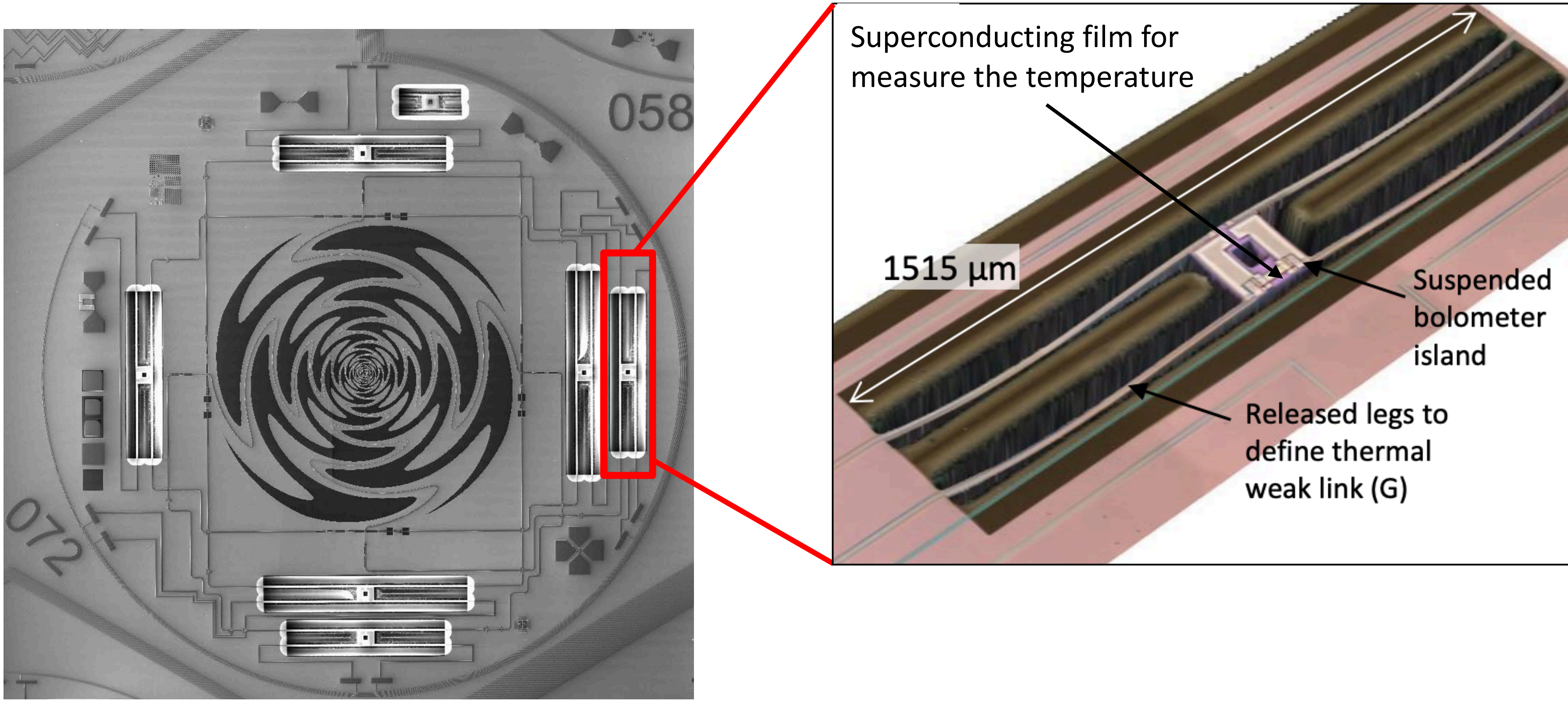
A SPT-3G detector wafer

Pixel design by UC Berkeley/ **LBNL**,
developed and made by Argonne.

- Noise is dominated by photon fluctuations → need more detectors
- Total detector count is 16,000.
- Broadband sinuous antenna coupled to TES bolometers through in-line filters and superconducting Nb striplines
- 6 transition-edge sensors (TESs) per pixel, (95, 150, 220 GHz) x 2 polarizations

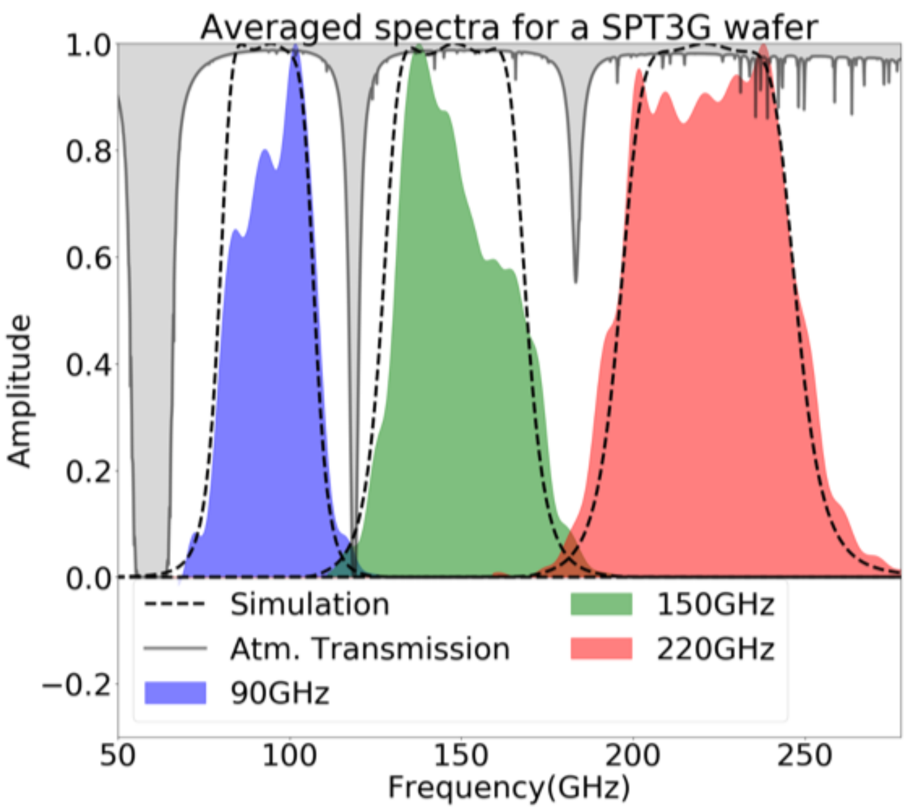
C. Posada et, al J Low Temp Phys (2018) 193: 703.

Detector structure and properties



- Tightly-controlled thermal properties, including superconducting transition temperature, saturation power, etc.
- Linearity: 2.7%, 4.3%, and 1.2% responsivity variation for the 90, 150, and 220 GHz detectors over the observation field.

Detector optical characterization

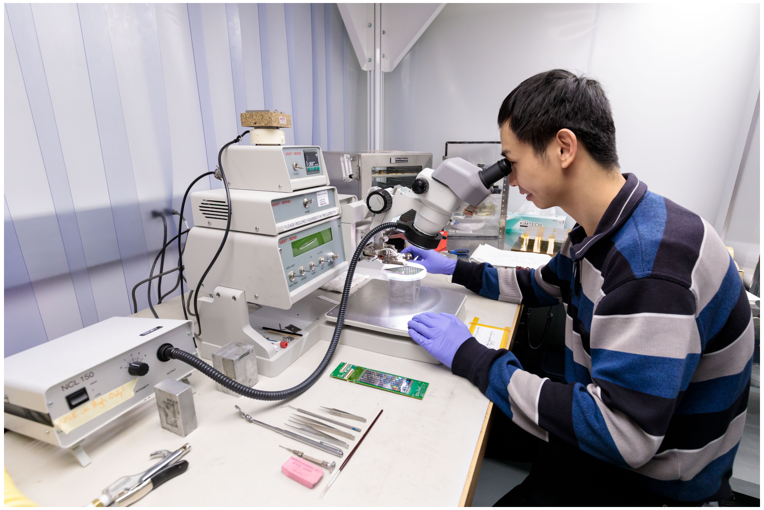


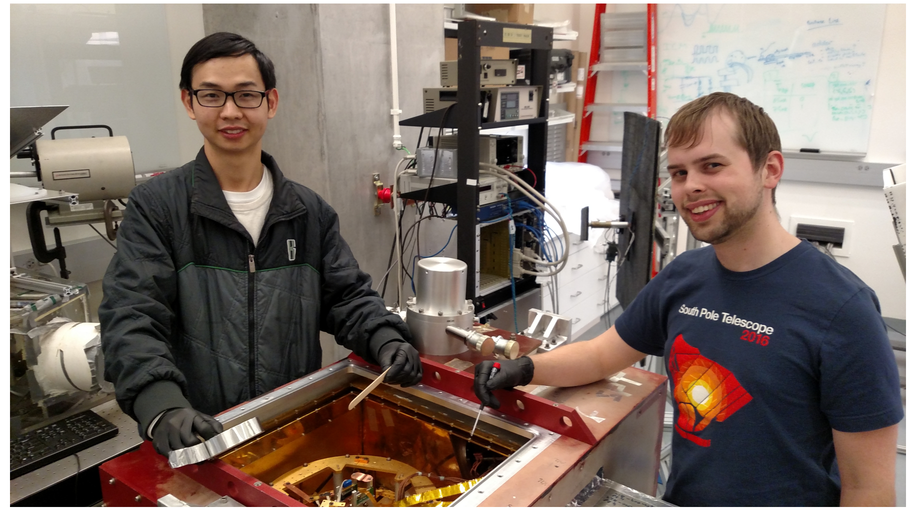
Z. Pan et, al arXiv:1805.03219

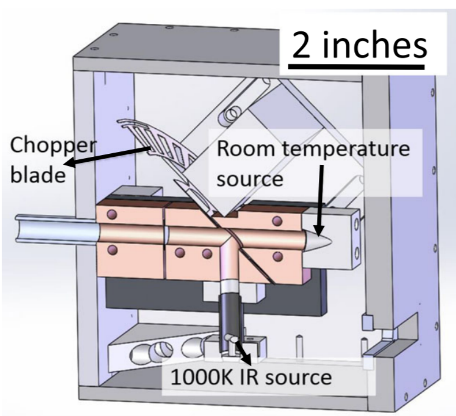
- Three frequency bands within the atmosphere transmission window.
- Frequency band edges agree with simulation within 3%.
- High uniformity: different wafers agree within 2%.
- Good optical efficiency: 0.81, 0.83, 0.73 for the 95, 150, and 220 GHz frequency bands (pixel + lenslet).

Detector characterization at UChicago

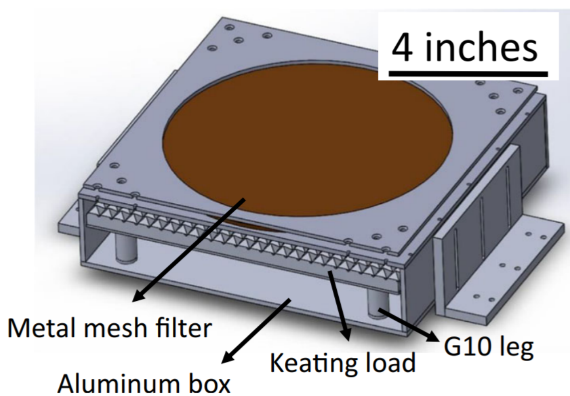
Out of the 120 wafers tested for SPT-3G, 30 were tested at UChicago



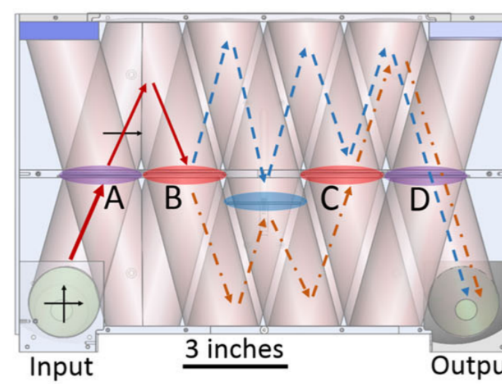




Calibrator for measuring the **optical response** and **time constants**

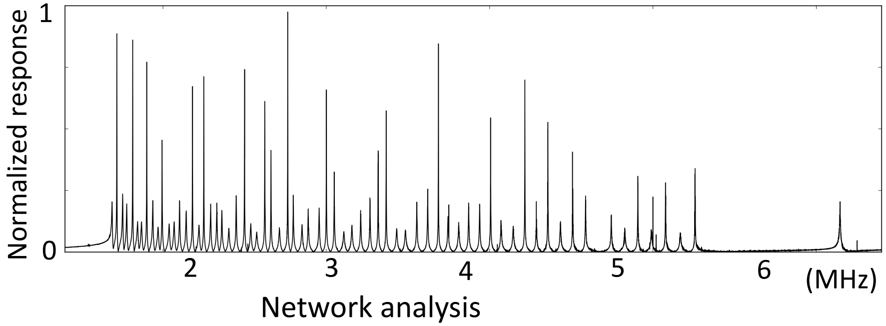


Temperature-controlled blackbody for measuring the **optical efficiency**

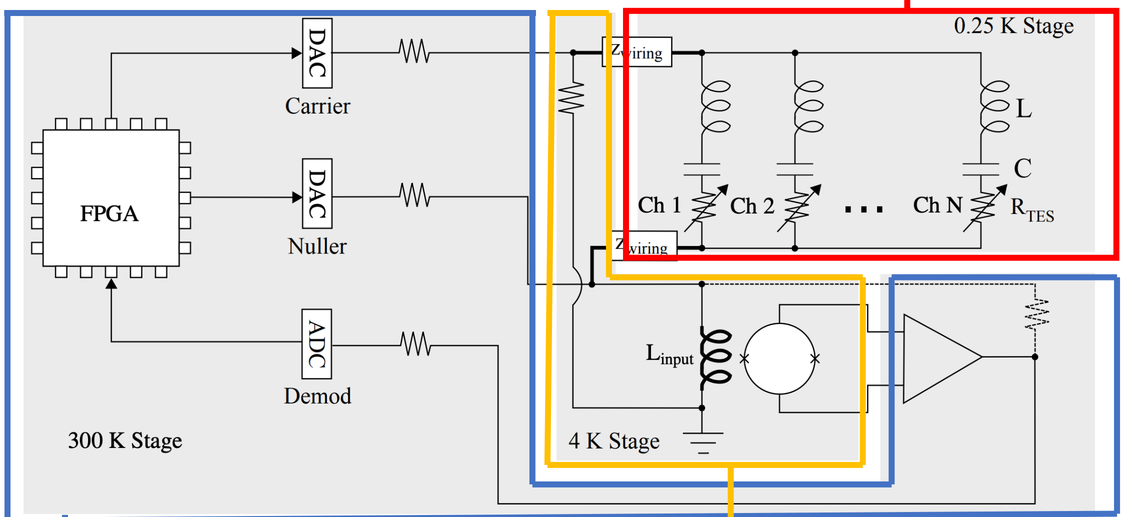


Spectrometer for measuring the **spectral bands**

Readout



Frequency-domain multiplexing:
68x multiplexing factor
Multiplexing resonators: fabricated on-chip by UC Berkeley and **LBNL**



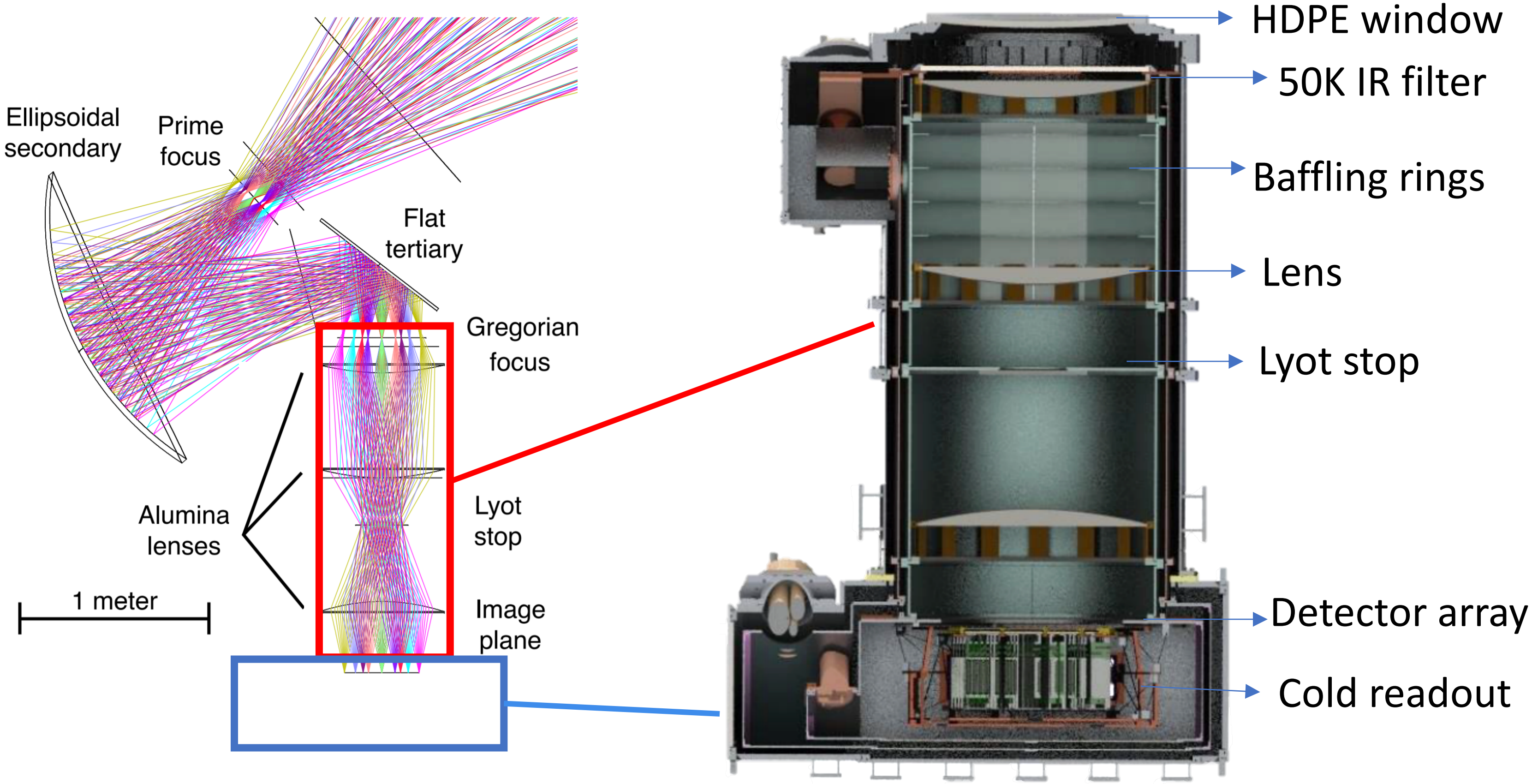
Warm electronics: made by Mcgill University.

SQUID amplifiers: fabricated by NIST, transimpedance > 300 Ohms (good)

- Readout noise ~< photon noise
- 1/f noise knee frequency is low.
- Crosstalk level ~< 0.5%.

A. Bender, et al. Proc. of SPIE (2016) Vol. 9914, p. 99141D
J. Avva, et al. J Low Temp Phys (2018) 193: 547
A. Bender, et al. arXiv 1809.00033.

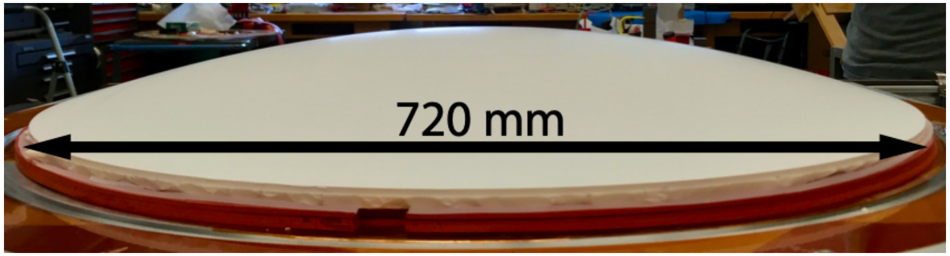
Optics



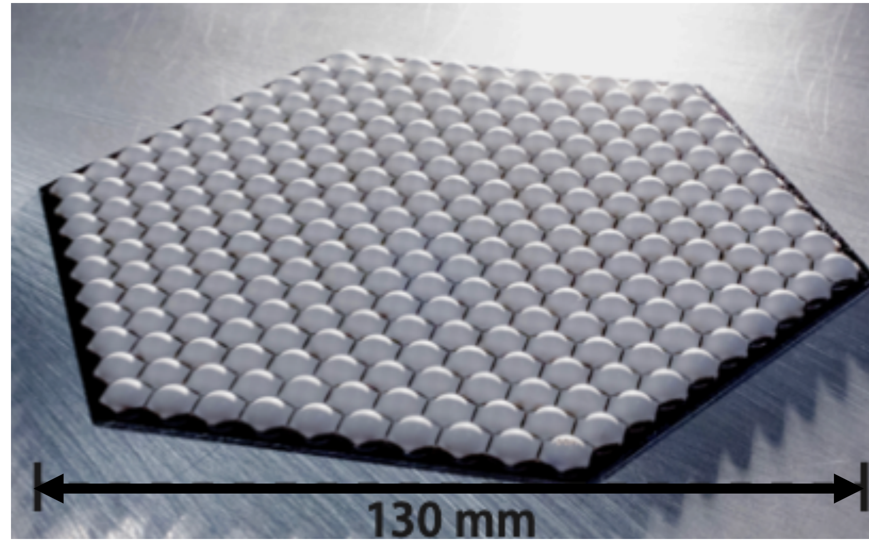
Large field of view: 2.8 deg^2 field-of-view.
Large lenses: 700mm-diameter alumina lenses with three-layer PTFE anti-reflection coating. The lenses are cooled to 4K to reduce loading.
Lyot stop and low-pass filter for cutting the stray reflections and out-of-band radiation. Low scatter.
Large focal plane: 450mm across.
Low loading

B. Benson, et al arXiv 1407.2973
J. Sobrin, et al Proc. of SPIE (2018) Vol. 10708, p. 107081H

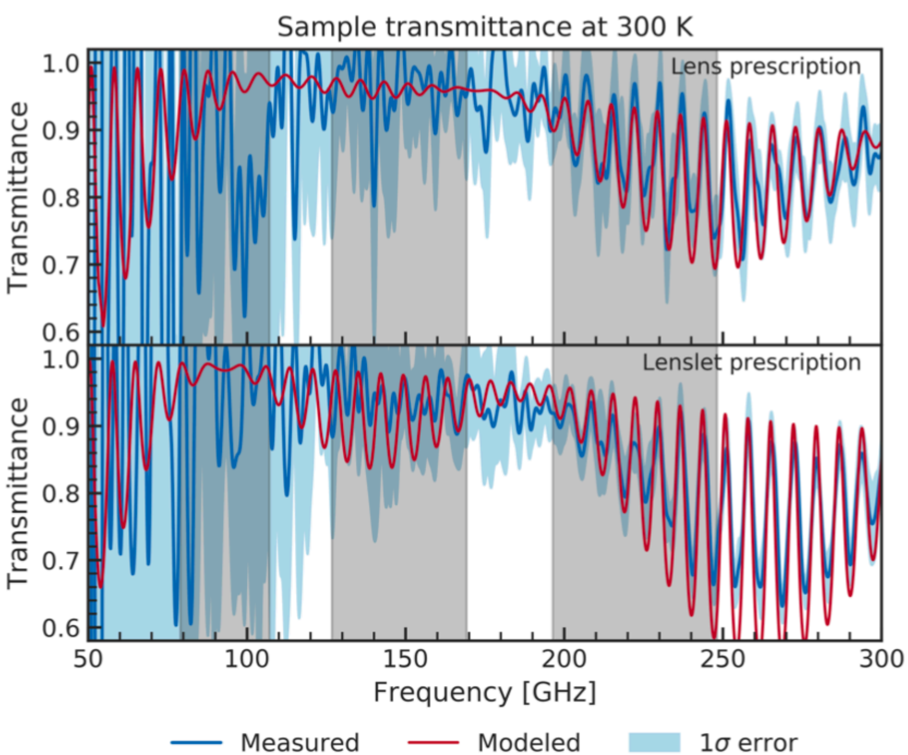
Optics – lens, lenslets, and AR coating



A lens for SPT-3G



A lenslet for SPT-3G

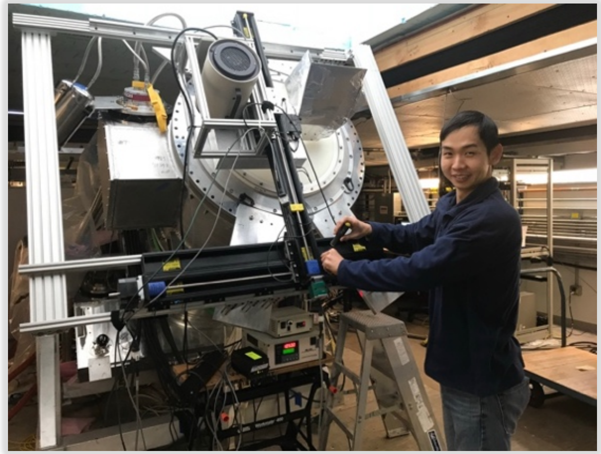


Transmissions of the AR-coated lens and lenslet

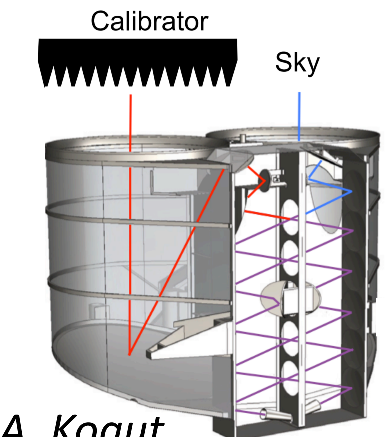
- Base material for the lenses and lenslets is alumina
- 3-layer PTFE-based thermal-formed AR coating, off-the-shelf materials, tunable
- The coated lens and lenslet samples, as well as individual coating materials, were measured by an FTS.
- Broadband transmission.

Nadolski, A, et ,al, in preparation

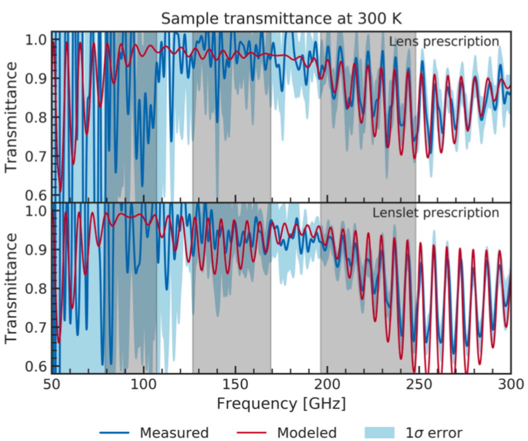
Spectrum measurement - FTS



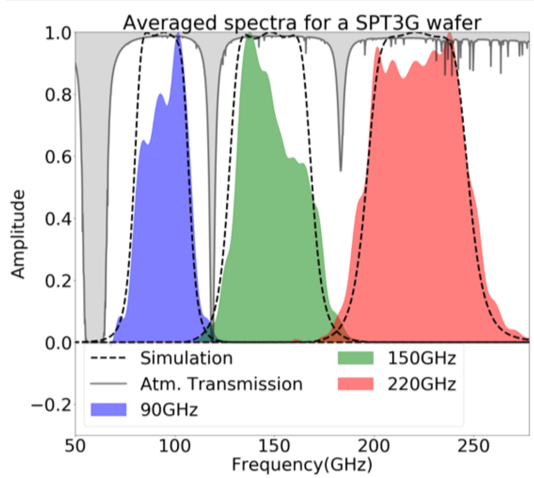
PIXIE (proposed)



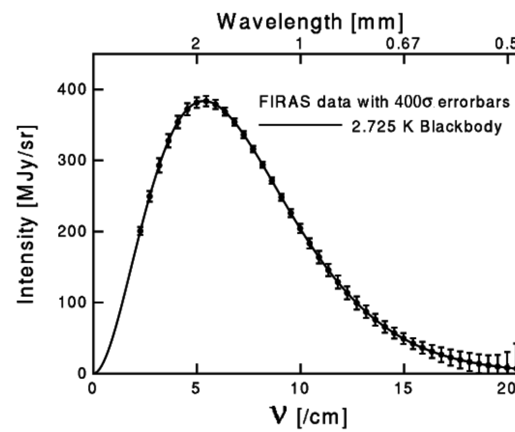
A. Kogut



Lens transmission measurement

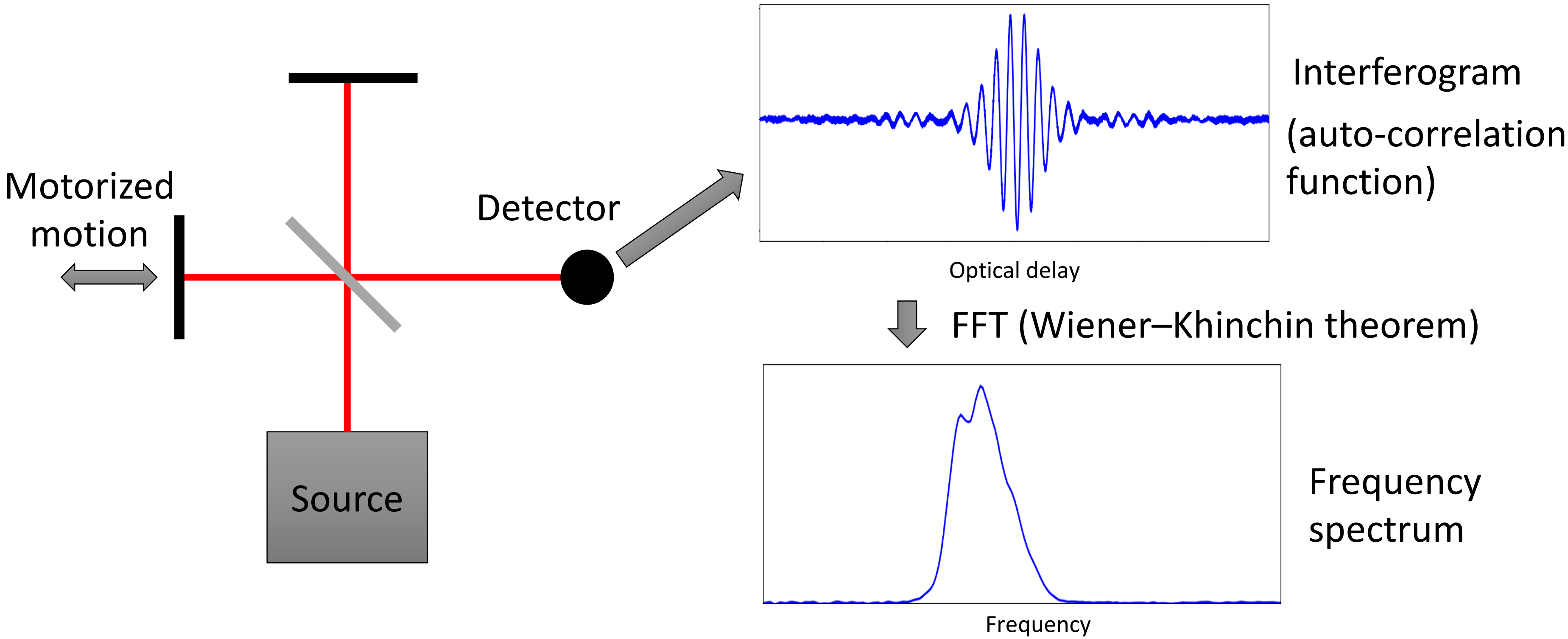


Detector spectral response measurement



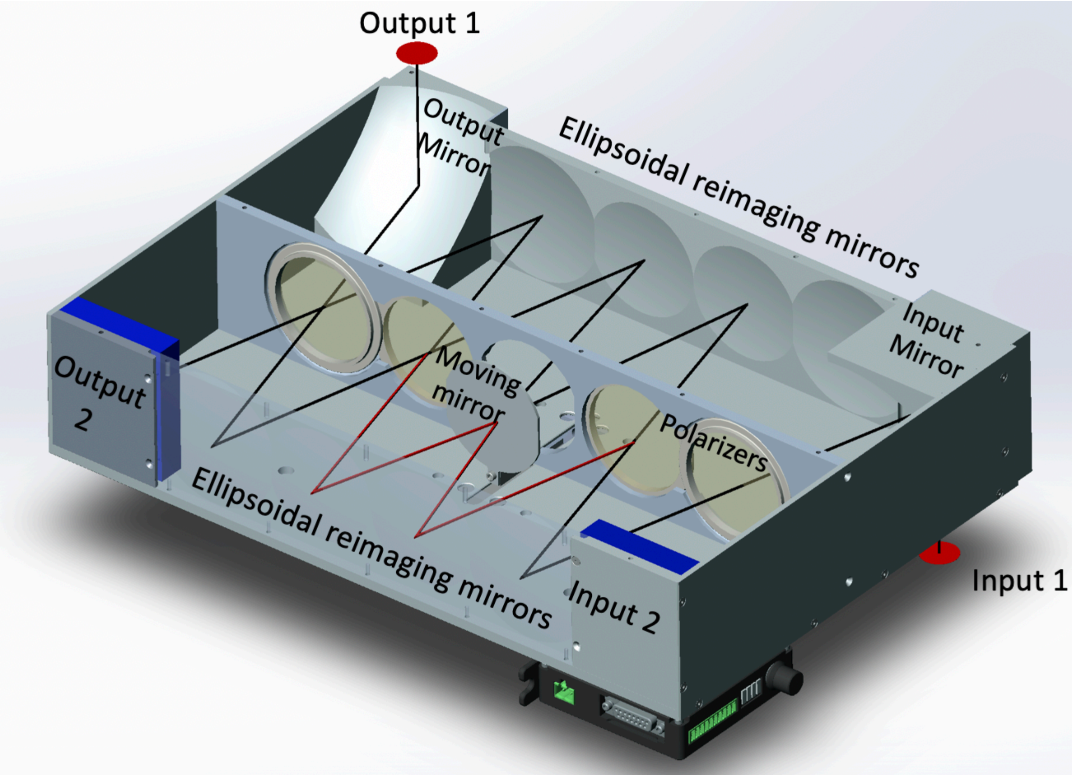
CMB power spectrum measurement

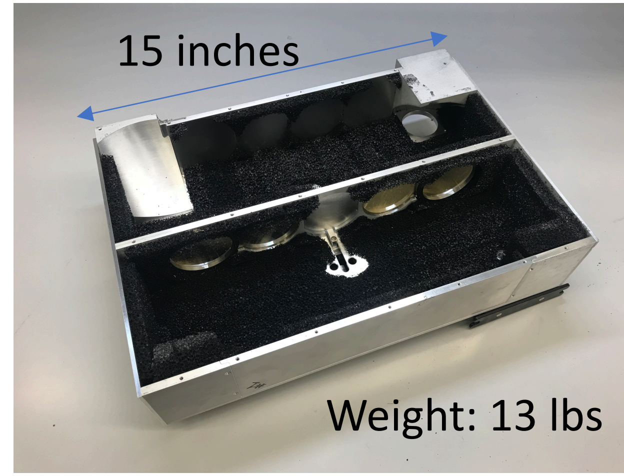
Spectrum measurement - FTS



- Detector measures power vs. optical delay (auto-correlation function of the source's radiation).
- FFT of power vs. optical delay is the power spectrum of the source, including the detector's response function.

Spectrum measurement - FTS





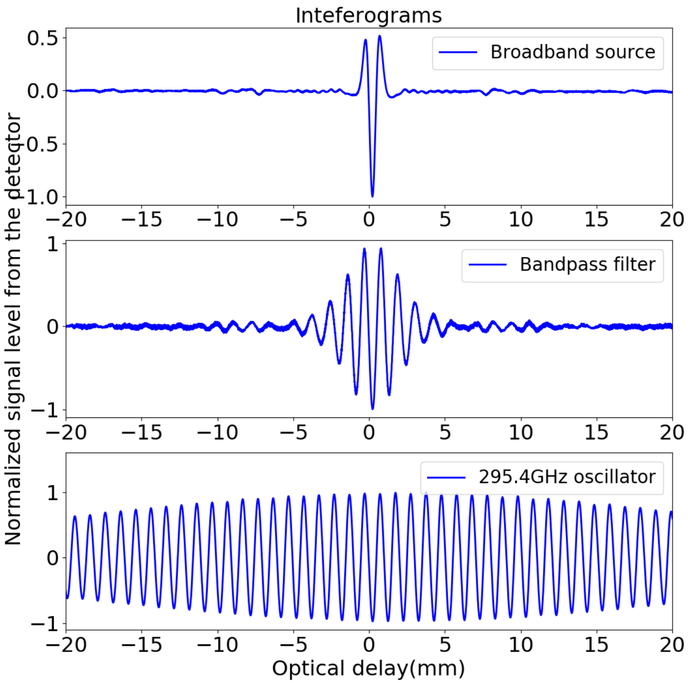
A fabricated FTS
Throughput is x 2 of COBE FIRAS
Volume is x10 smaller

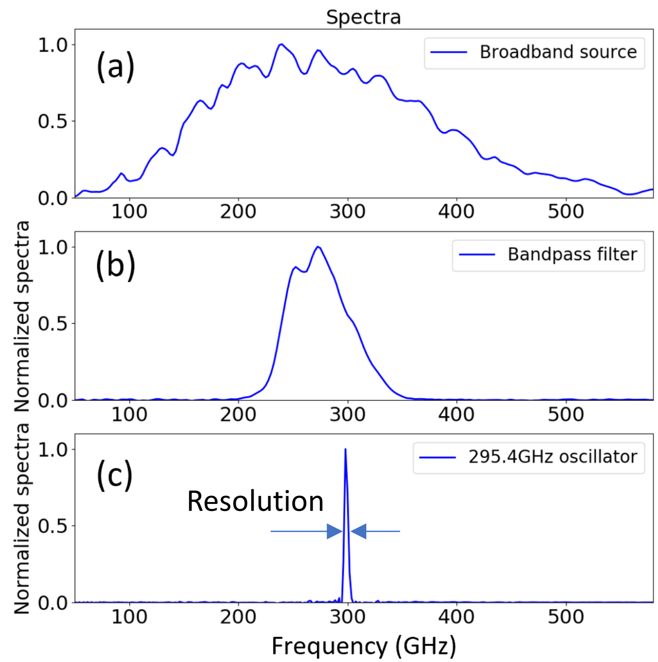
- The same FTS used for SPT-3G detector measurements is also a prototype for the proposed PIXIE satellite.
- Goal: high throughput for more modes, small volume for space.
- Generically useful for material and detector characterization
- Frequency range 50- 300 GHz (can be tuned).

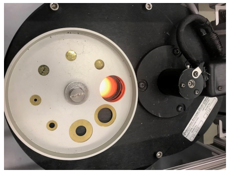
Z. Pan., *et al., Appl. Opt. 58, 6257-6267 (2019).*

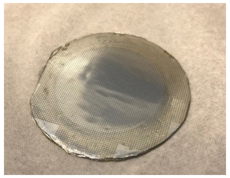
FTS- sample interferograms and spectra

Interferograms of different sources —FFT→ Spectra






1300K Blackbody


Metal-mesh filter

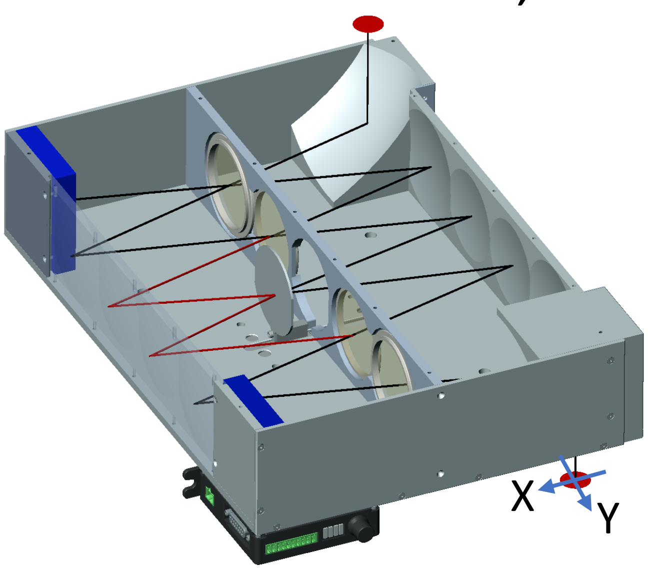

Gunn oscillator

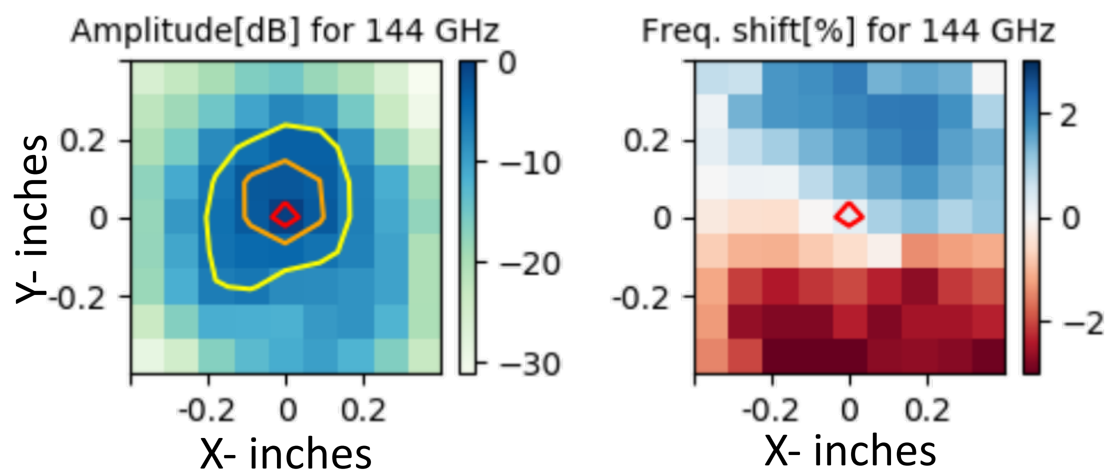
- The bands for these sources match our expectations.
- The narrower the band, the longer the coherence length.
- Transfer efficiency is 92±5%.

Z. Pan., *et al., Appl. Opt. 58, 6257-6267 (2019).*

FTS- frequency resolution and shift

- Resolution is 4 GHz, measured by a Gunn oscillator
- Frequency shift is mapped using a Gunn oscillator. The accurate frequency is 144.3 GHz.
- The frequency shift is ± 4GHz.
- The FWHM widths for the interference intensity map are 0.3 in, 0.2 in, and 0.1 in for 90, 144, and 294 GHz sources.
- More: coherence, contrast, …

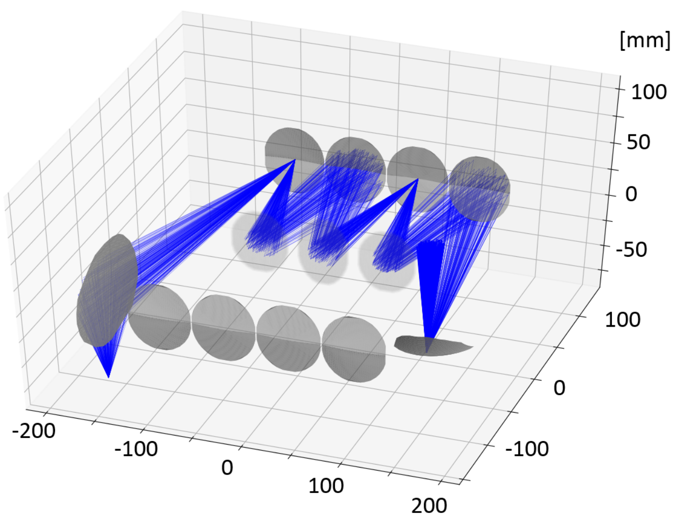


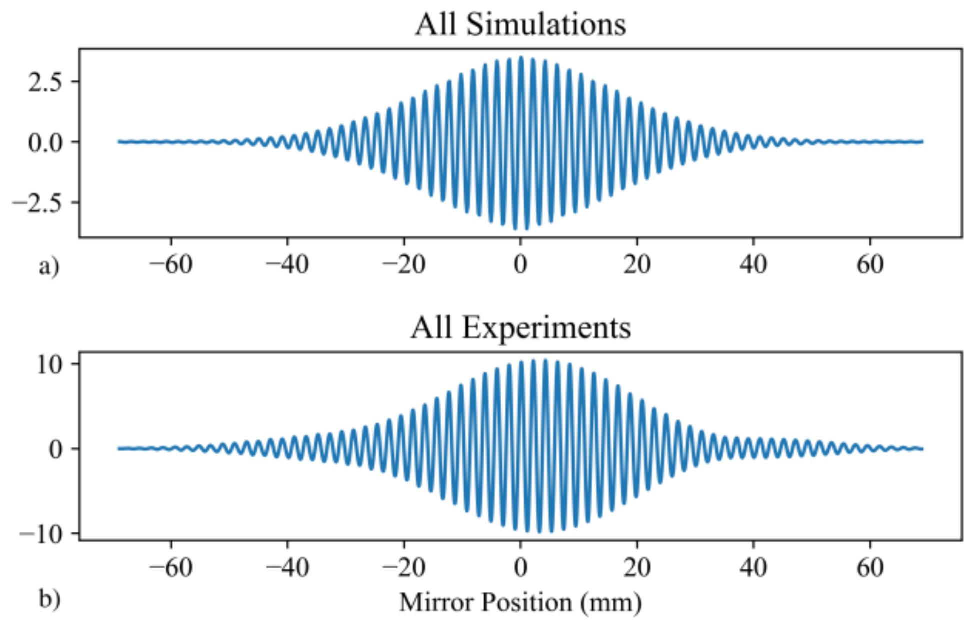


Z. Pan., et al., Appl. Opt. 58, 6257-6267 (2019).

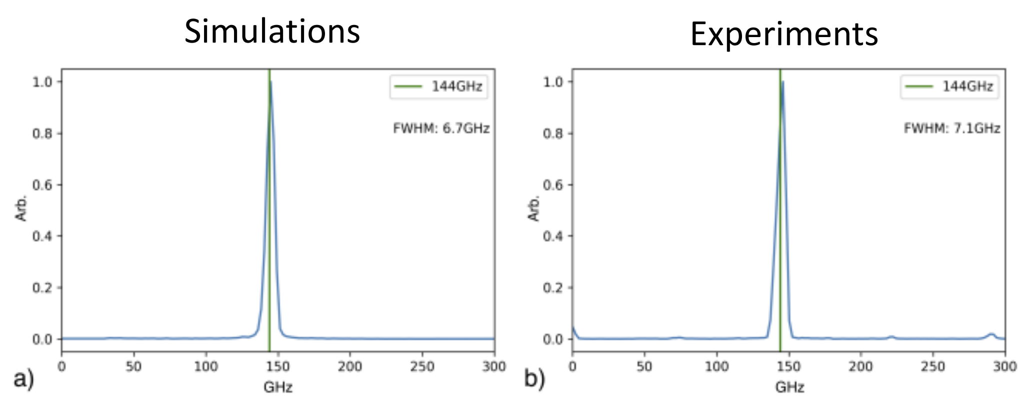
Measured amplitude and frequency vs. source location

A raytrace-based FTS simulation





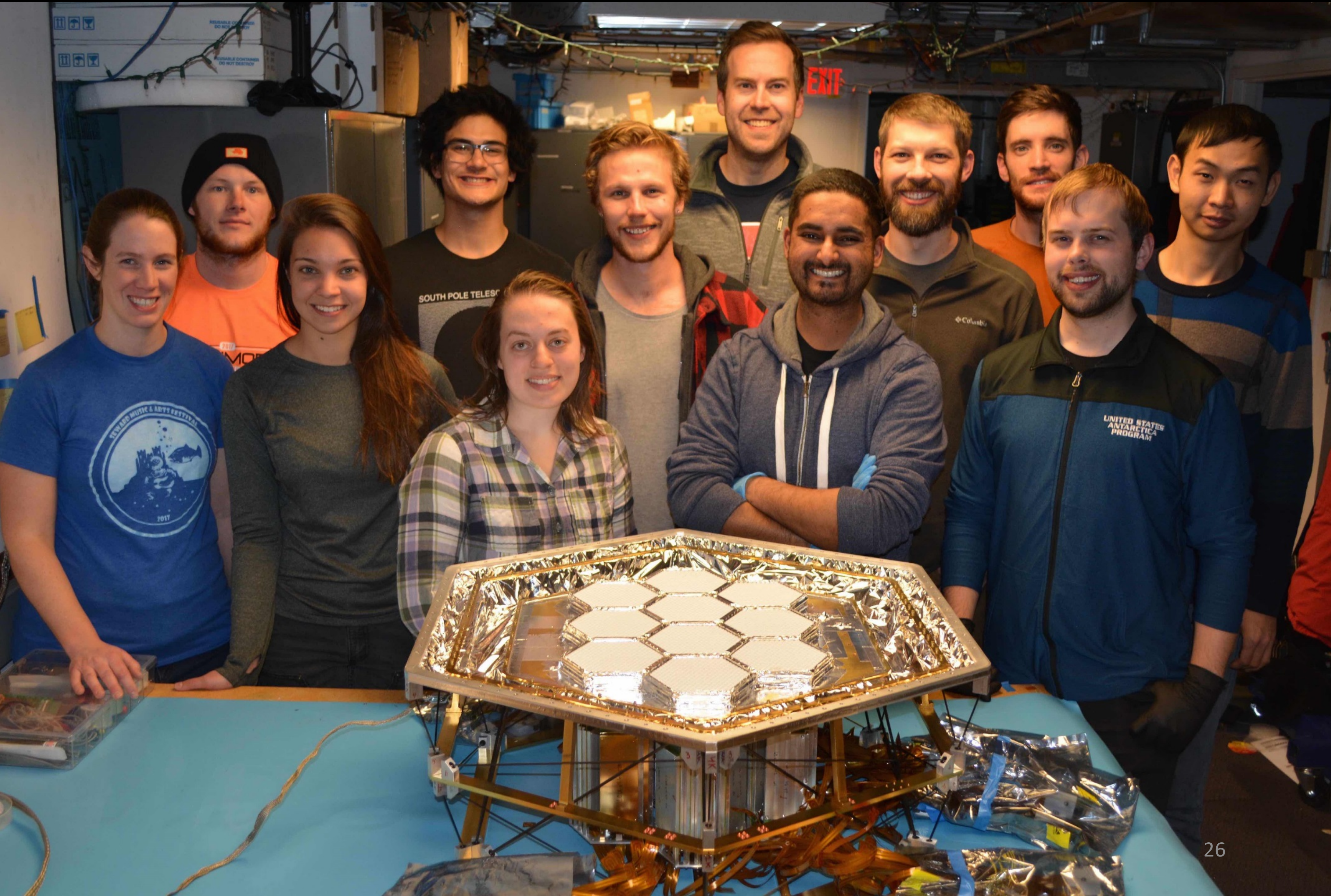
- A bundle of light rays are transferred within the box according to principles of reflection.
- Phase, amplitude, polarizations were also tracked.
- Transfer efficiency, frequency shift pattern and the frequency resolution can be simulated.
- Useful for FTS design.



Interferogram and spectrum
Simulation vs. experiments

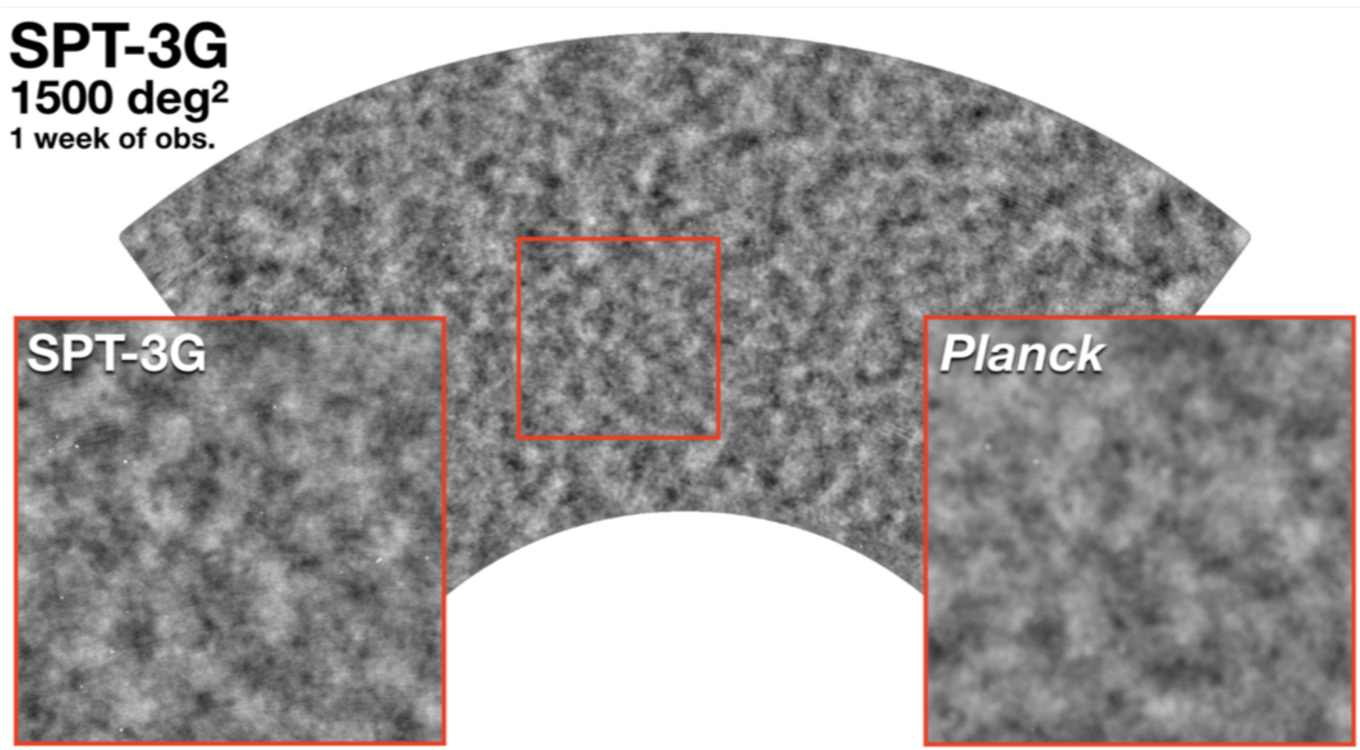
*M. Liu, **Z. Pan**, et al., To be submitted to Appl. Opt.*

South Pole integration



Integrated performance and status

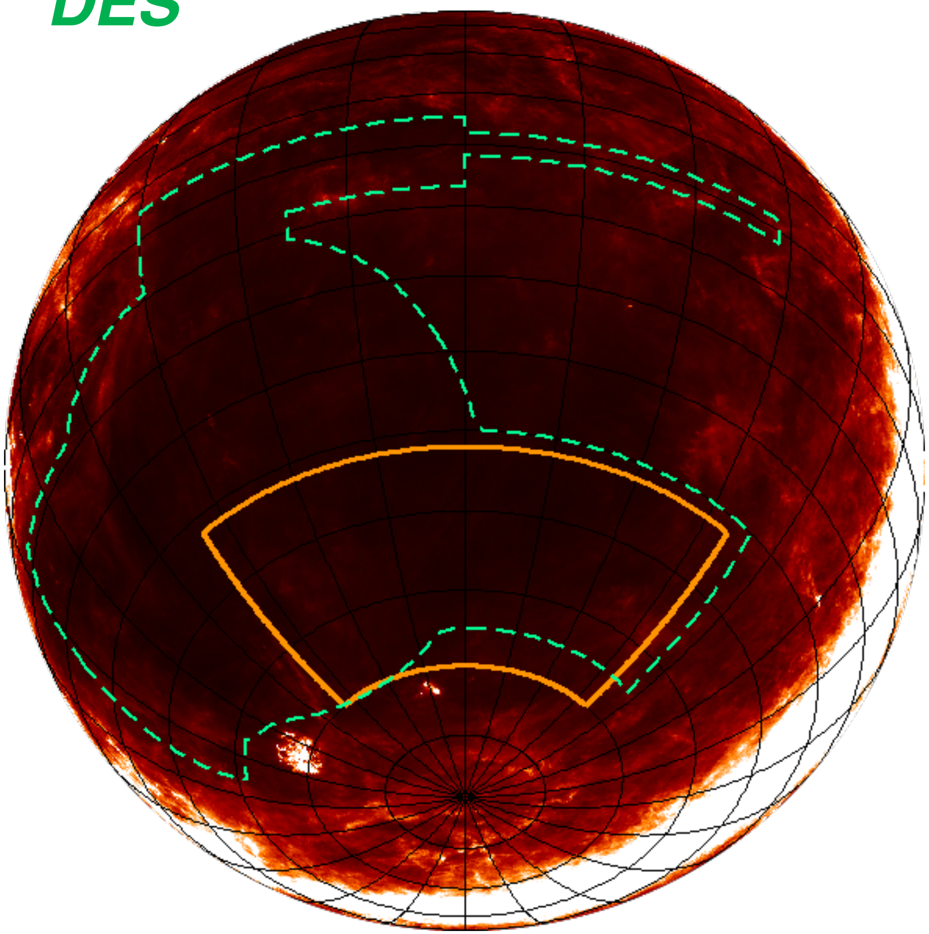
- First light on Jan 30, 2017
- 6-year 1500 deg^2 observation began in Feb, 2018.
- Improvements in 2019
  - two new detector wafers,
  - a more stable detector stage compared to 2018.
- We do not plan to open the cryostat this deployment season



One week of SPT-3G data is deeper than Planck in a 1500 deg^2 patch.

SPT-3G survey: overview

SPT-3G (+BICEP Array)
DES

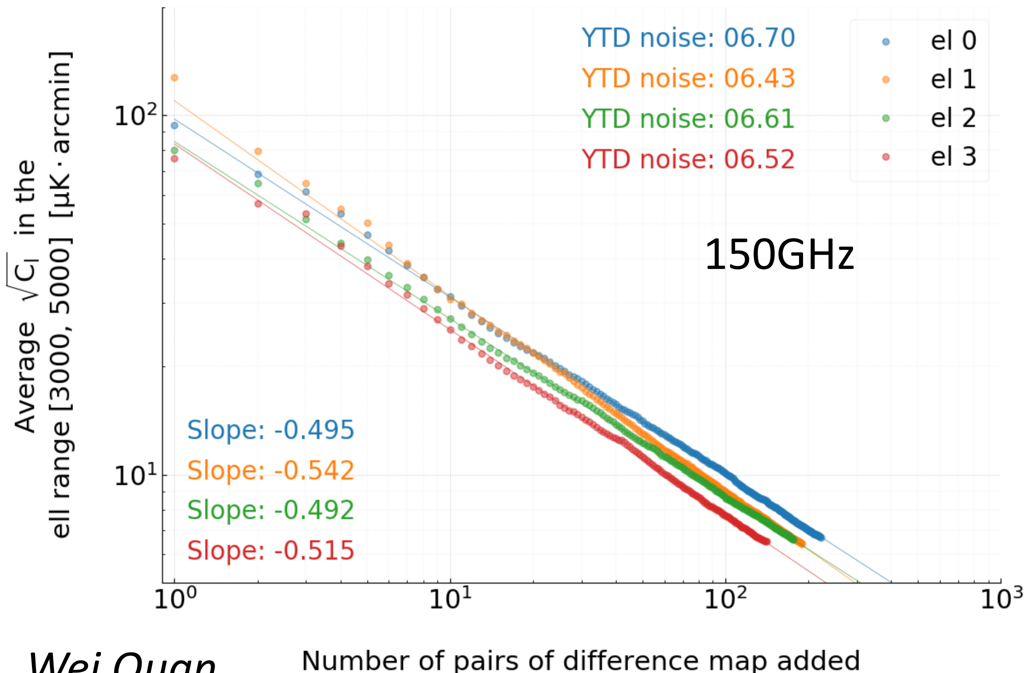


Background is IRAS dust map

- Deep, high resolution (1 arcmin) measurement for 1500 deg^2 of sky.
- Overlaps with BICEP Array to separate the lensing-induced B-mode from B-mode signature of primordial gravitational waves.
- Overlaps with Dark Energy Survey (DES) for cross-correlation.
  - CMB lensing, cluster lensing, galaxy lensing, pairwise kSZ, and more.

SPT-3G survey: status

Noise vs. map number (integration time)



- Noise is integrating down smoothly for 2019
- Current 2019 noise: 8.1, 6.5, 23.7 uK arcmin for the 95, 150, 220 GHz bands
- Keep going!
- As a reference, Planck noise level is 33 uK arcmin at 143 GHz.

Wei Quan

Noise table	90 GHz	150 GHz	220 GHz
NET (array) $\mu K_{CMB}\sqrt{s}$	10	8	30
Current year map depth (μK_{CMB} arcmin, T)	7.7	6.1	22.6
Six-year map depth (μK_{CMB} arcmin, T)	3.0	2.2	8.8

Ongoing science analysis

E-mode power spectrum measurement (2018 data)

- The most sensitive measurement of the CMB E mode in the ell range of 1000 to 1700 from SPT.
- Cover 3x the area of the previous generation SPTpol.

Lensing power spectrum measurement (2018 data)

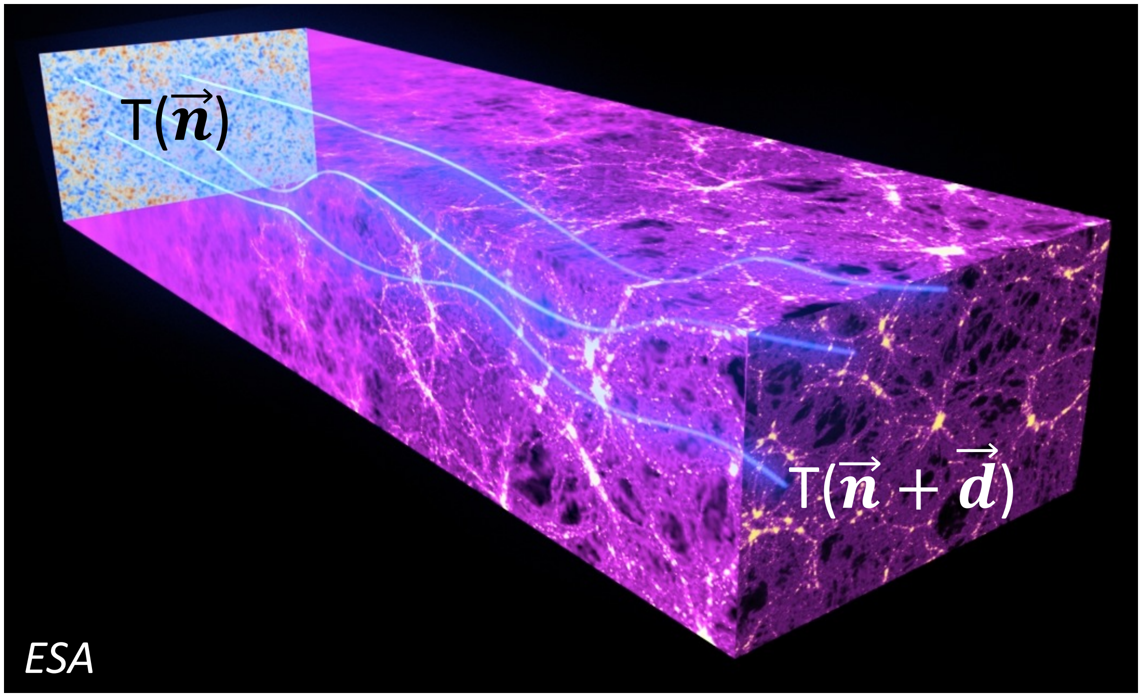
- Per mode noise is slightly worse than SPTpol's 500 deg^2 field (arXiv:1905.05777).
- Larger area (x3 area) --> reduced sample variance --> better cosmological parameter constraints compared to SPTpol.

Galaxy cluster finding (2019 data)

- Preliminary cluster finding using 2019 data, optical follow-up.

Point source finding

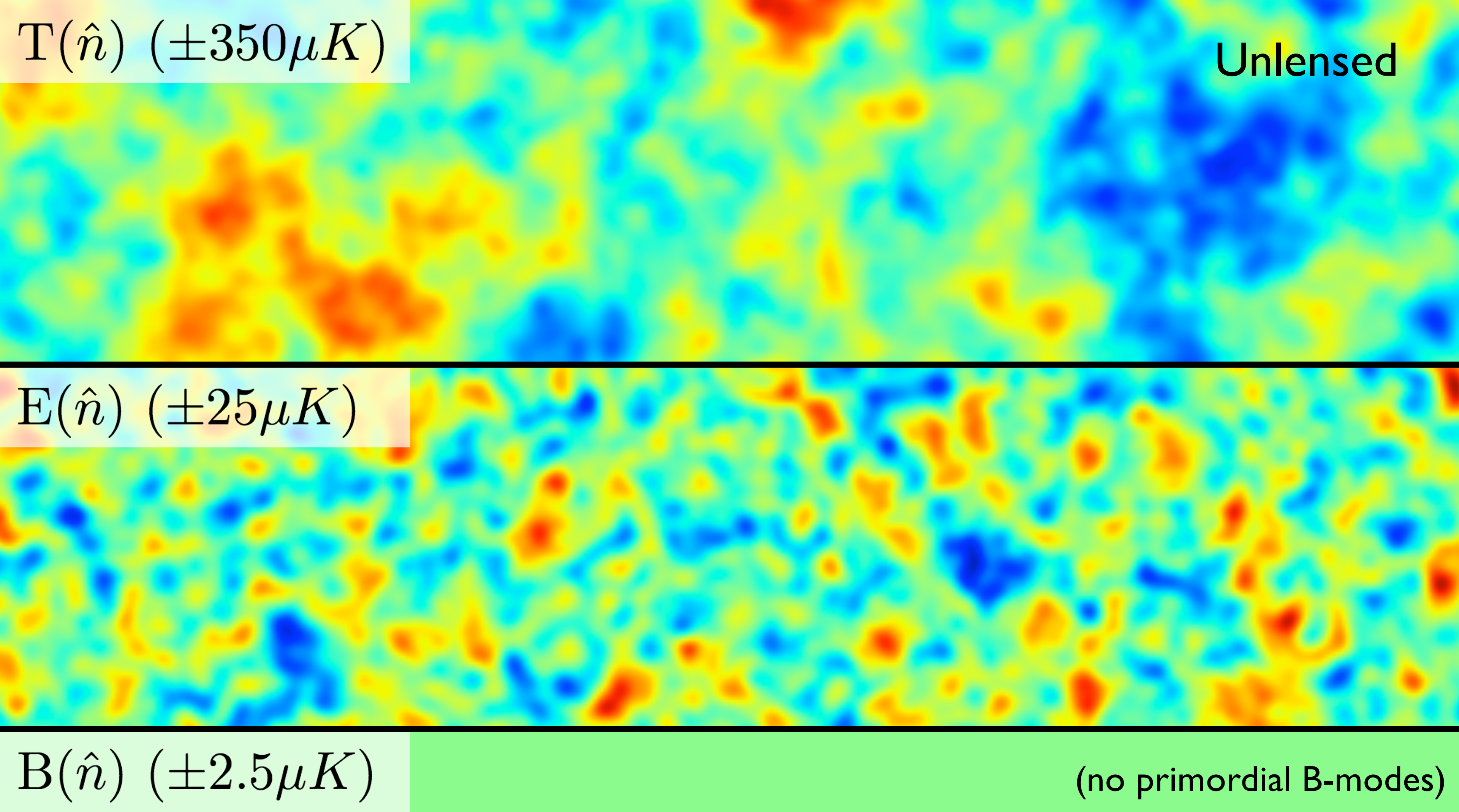
Gravitational lensing of the CMB



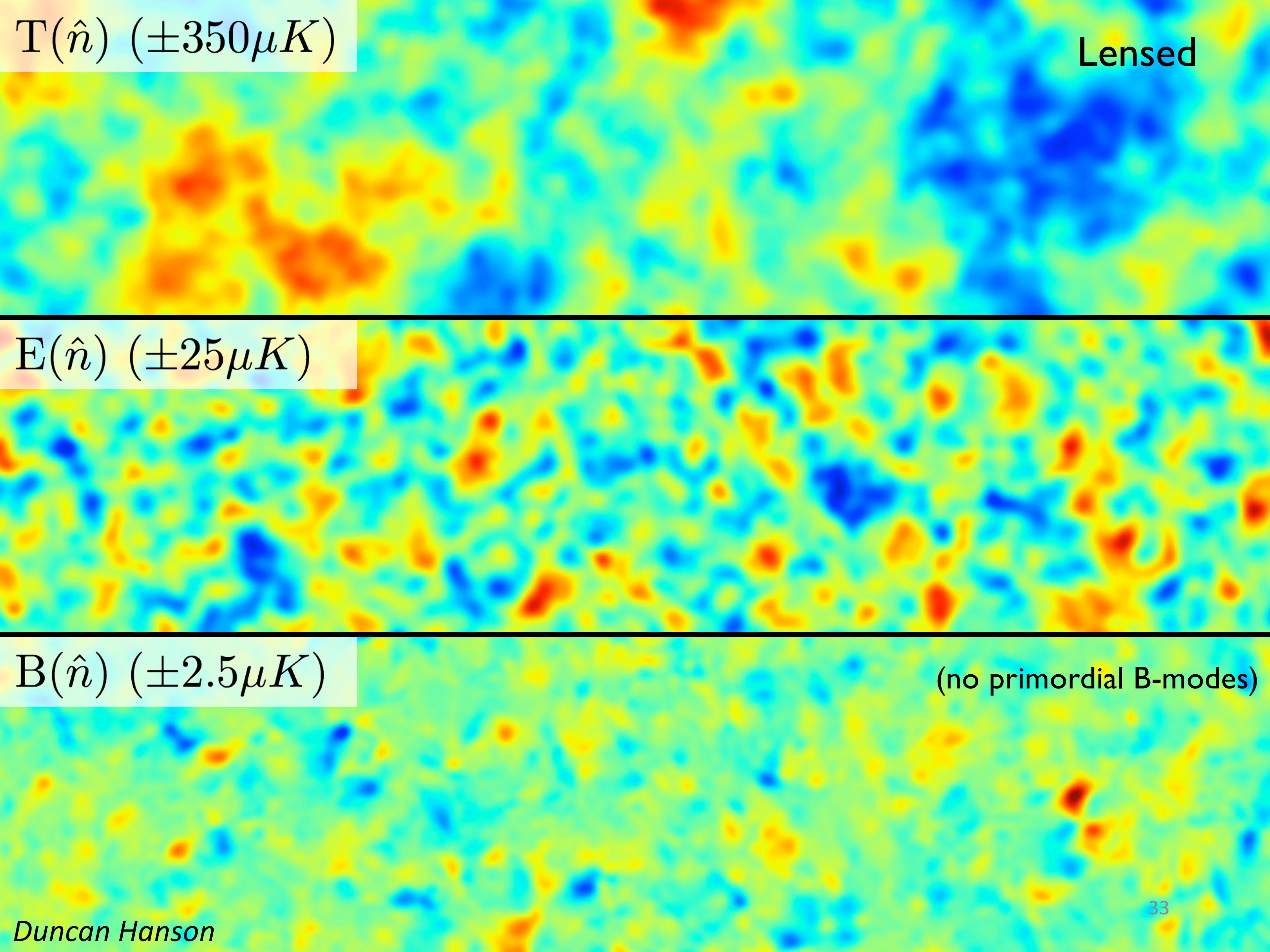
$$T_{Lensed}\,(\hat{n}) = T_{Unlensed}\,(\hat{n}+\vec{d})$$

↑ Lensing deflection

$\vec{d} = \nabla\phi(\hat{n})$ Thin-lens approximation



Duncan Hanson


$T(\hat{n})$ $(\pm 350\mu K)$
Lensed
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)
Duncan Hanson

Lensing reconstruction

- Expand the lensed CMB field to the first order

Lensed — Unlensed — Taylor expansion

$$x(\hat{\boldsymbol{n}}) = \tilde{x}(\hat{\boldsymbol{n}} + \nabla\phi(\hat{\boldsymbol{n}})) = \tilde{x}(\hat{\boldsymbol{n}}) + \nabla_i\phi(\hat{\boldsymbol{n}})\,\nabla^i\tilde{x}(\hat{\boldsymbol{n}}) + \ldots$$

Lensing potential — Higher order terms, neglect

FFT

$$x(\boldsymbol{l}) = \tilde{x}(\boldsymbol{l}) + (\nabla\phi * \nabla\tilde{x})\,(\boldsymbol{l})$$

Correlation

$$< x(\boldsymbol{l})y^*(\boldsymbol{l}') > = f(\boldsymbol{l},\boldsymbol{l}')\,\phi(\boldsymbol{l} - \boldsymbol{l}')$$

Here x and $y \in [T, E, B]$

Off-diagonal correlation — Function of the unlensed spectra

- CMB (Fourier) modes differed by $\boldsymbol{L} = \boldsymbol{l} - \boldsymbol{l}'$ can be correlated by lensing modes at $\boldsymbol{L}$

Lensing reconstruction

$$\phi(\boldsymbol{L}) = \mathrm{R}(\boldsymbol{L})^{-1} \int d^2\boldsymbol{l}\ F(\boldsymbol{l}, \boldsymbol{l}-\boldsymbol{L})\ X(\boldsymbol{l}) Y^*(\boldsymbol{l}-\boldsymbol{L})$$

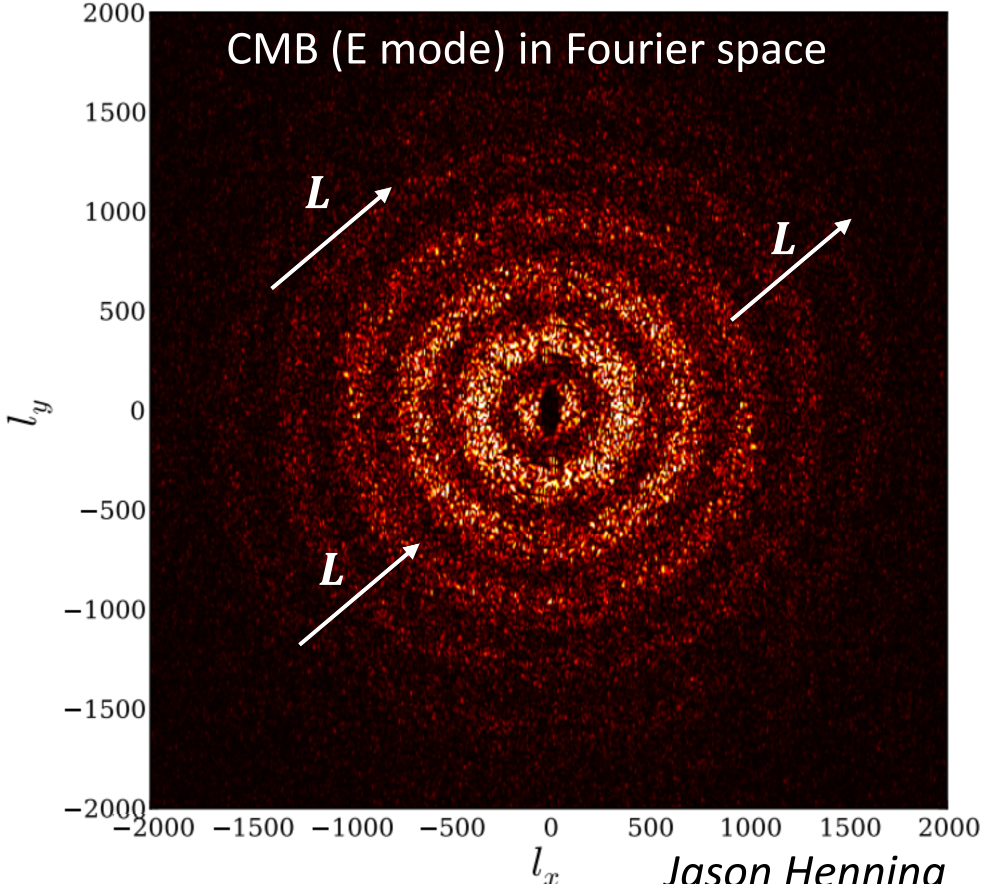
Normalization

Differ by $\boldsymbol{L}$

Lensing potential

Optimal weight function

Filtered CMB maps



Jason Henning

ϕ at $\boldsymbol{L}$ is reconstructed from weighting pairs of CMB modes differed by $\boldsymbol{L}$.

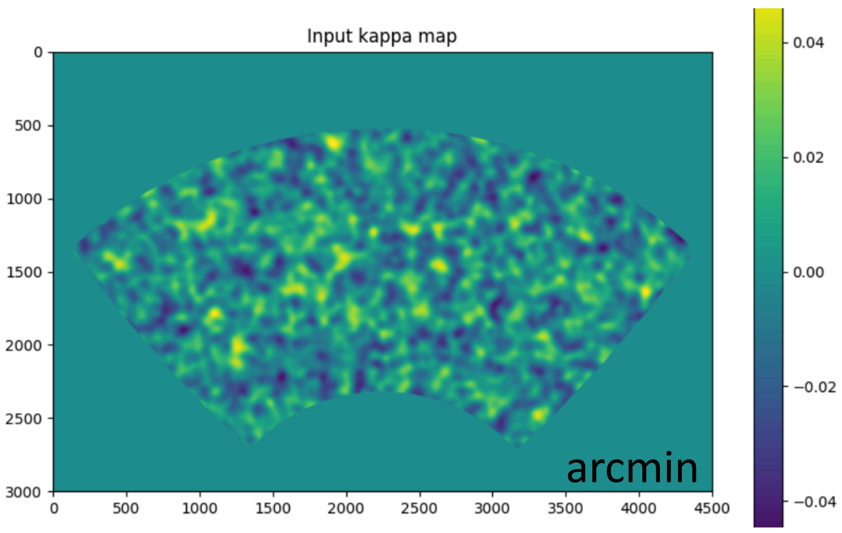
The two CMB fields can be from T, E, B, forming many pairs of estimators.

Lensing reconstruction

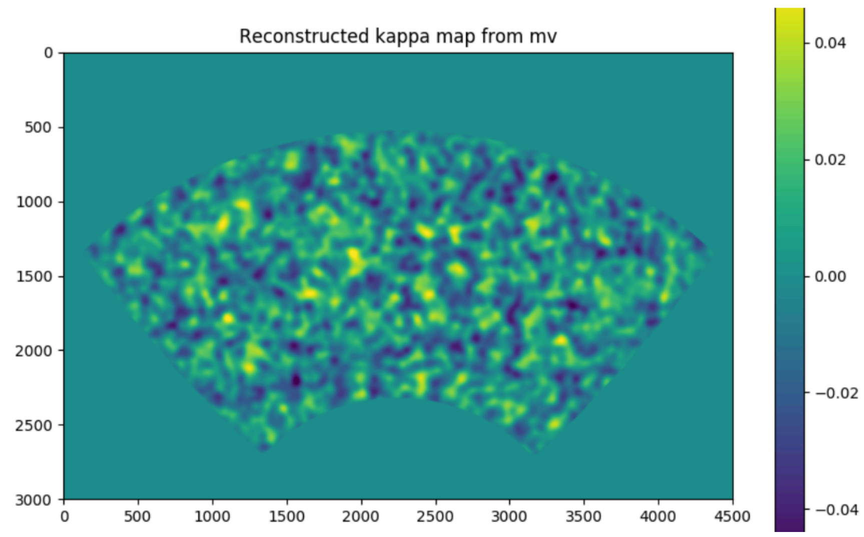
- Inverse-variance filter the map to suppress non-CMB modes.
- Convolve two CMB fields with the weight function
- Correct for the bias terms:
  - Mean field – gradient in the mask (map boundary, and around point source masking holes) can mimic lensing
  - N0, N1 bias – $< \hat{\phi}\hat{\phi} > \sim C_L^{\phi\phi} + < \phi\phi >^0 + < \phi\phi >^1 + \ldots$
- Normalize the power spectrum
  - Filters applied to the map
  - Weight function

Test the pipeline on simulation

- I have finished building the pipeline.
- Below is a test on a simulation, plotted is the convergence ($\kappa = -\nabla^2\phi/2$).
- The simulation has the same white noise level and patch size as SPT-3G 2018 data.
- My thesis project.

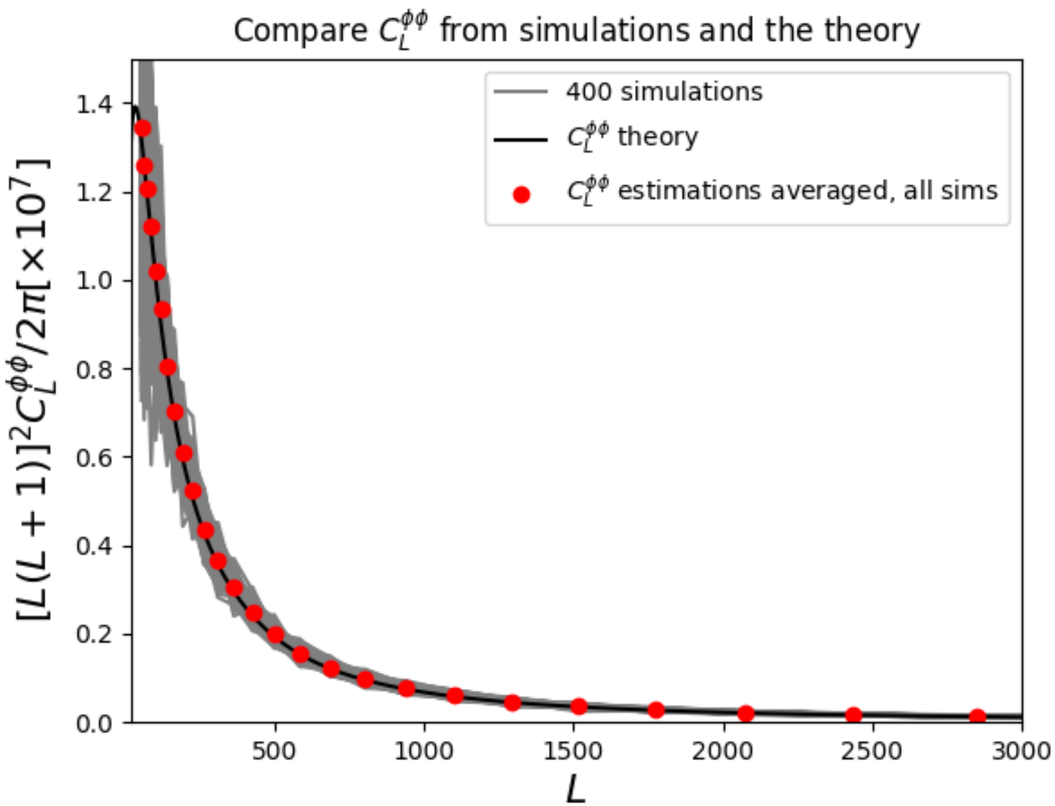


Input κ map for simulating the input CMB map.



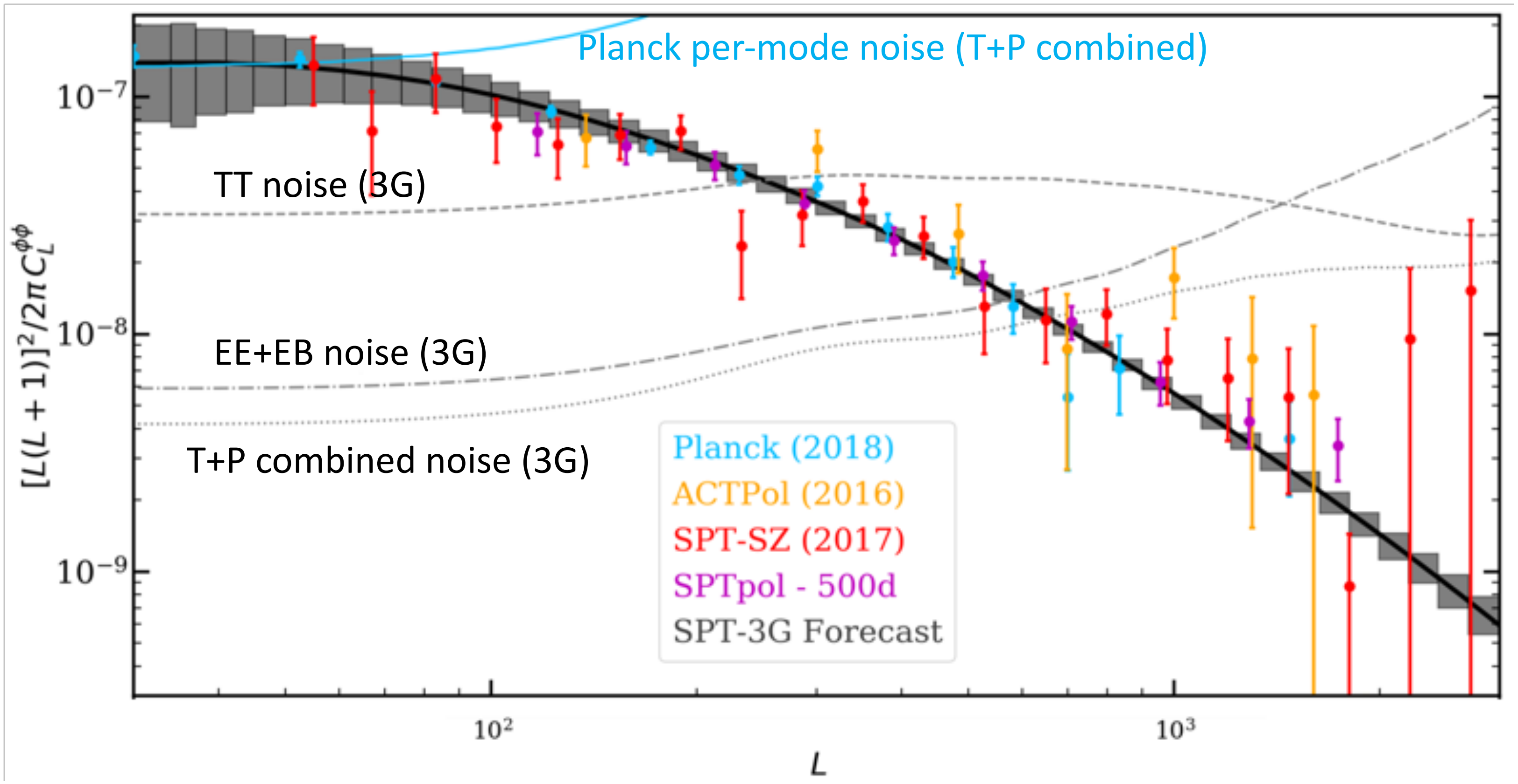
Reconstructed κ map from a lensed CMB map with SPT-3G noise level.

Power spectrum from simulations, data is next



- The reconstructed power spectrum agree with the input data.
- To do: apply this on real data.
- Status:
    - CMB maps have been made.
    - Simulations were generated.
    - Need to mock-observe to obtain the transfer functions in data processing
- Will help us constrain growth of structure, including sum of neutrino mass and the amount of large-scale structure.
- 2018 data is a small fraction. Future data is exciting!

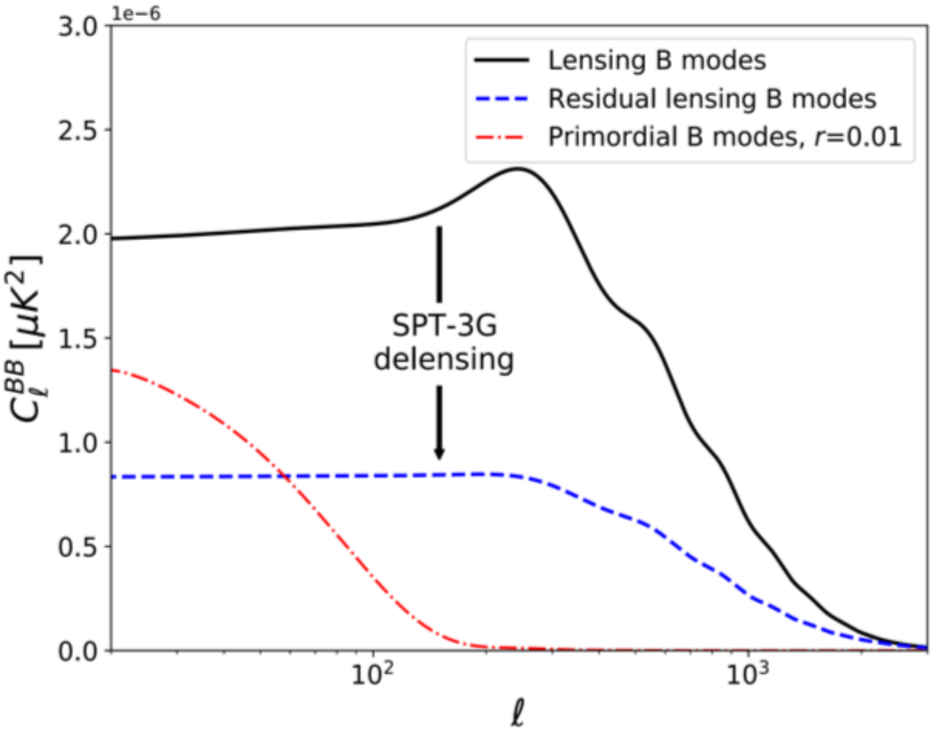
The full survey – lensing forecast

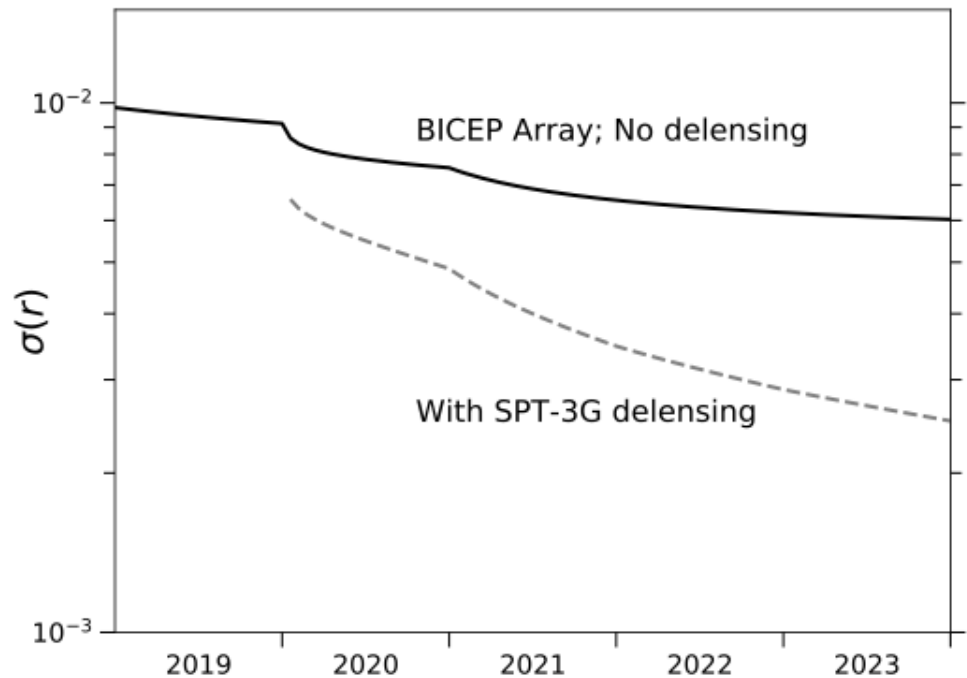


Lensing potential power spectrum forecast (Jason Henning)

- Measurement of lensing features at scale of ~14 arcmin for 1500 square degrees
- Overlaps with DES/LSST for cross-correlation
- Constrains growth of structure
- CMB lensing around known galaxy clusters → cluster lensing
- New estimators: maximum a posteriori estimator, foreground-immune…

Delensing

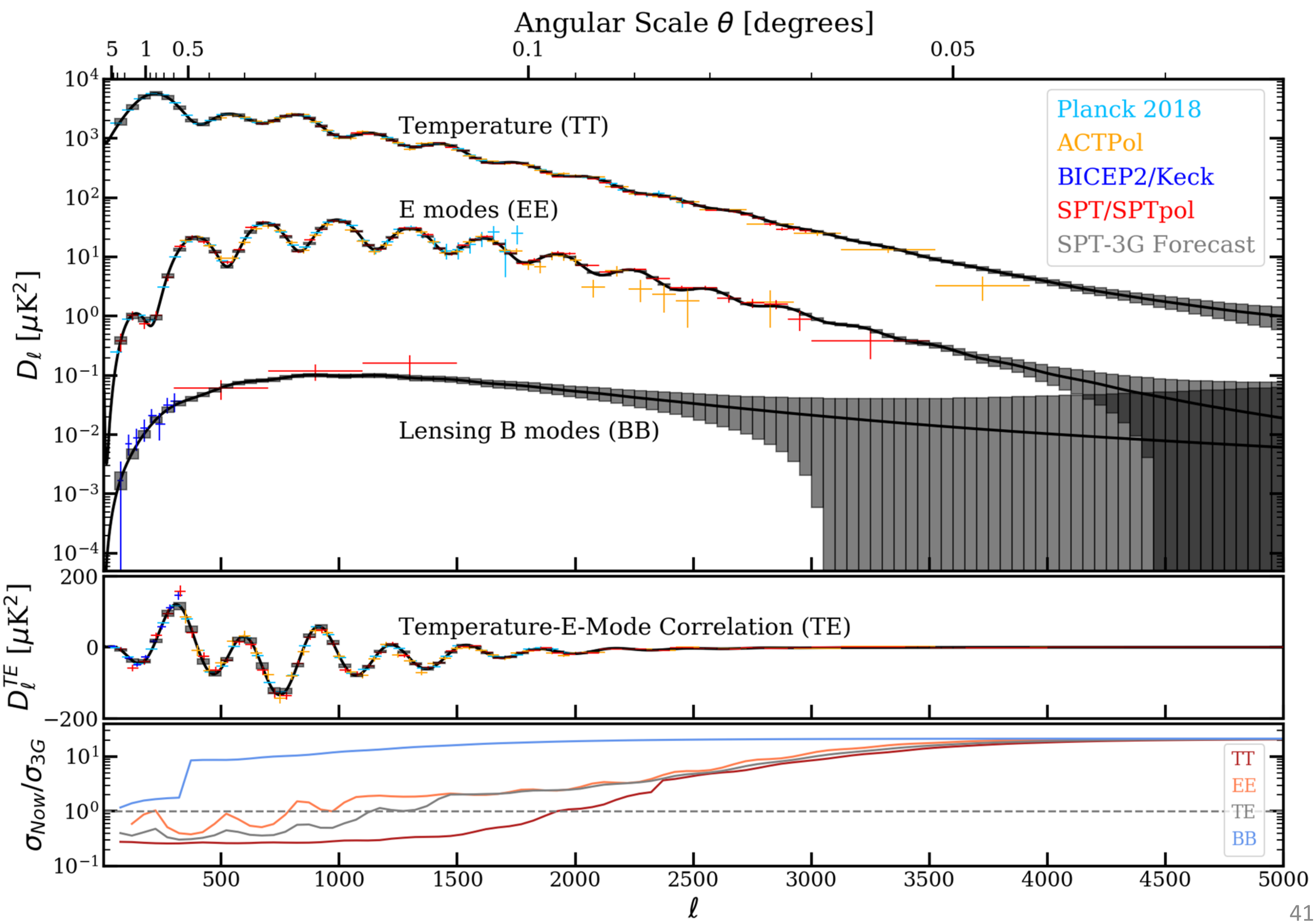




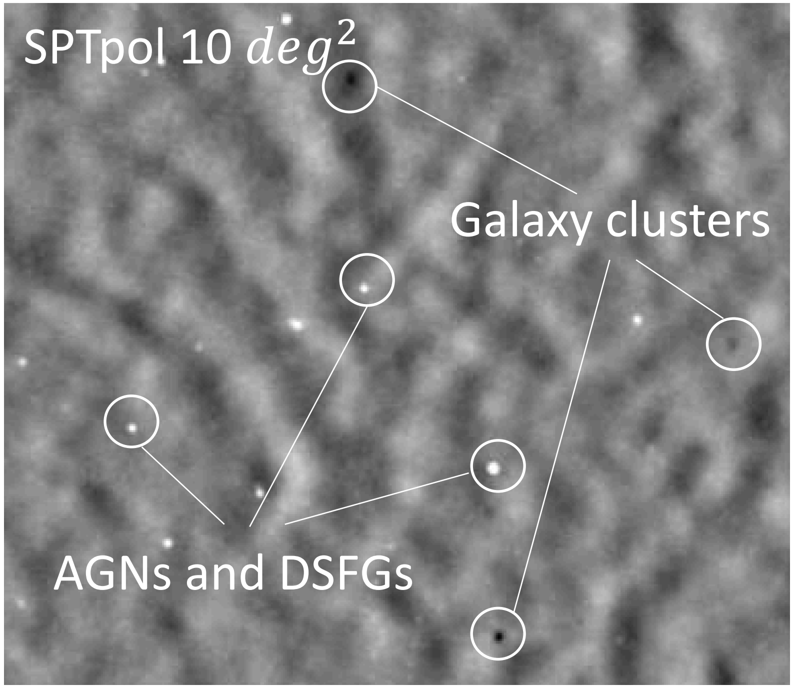
Joint SPT-BICEP delensing forecast (*Kimmy Wu*)

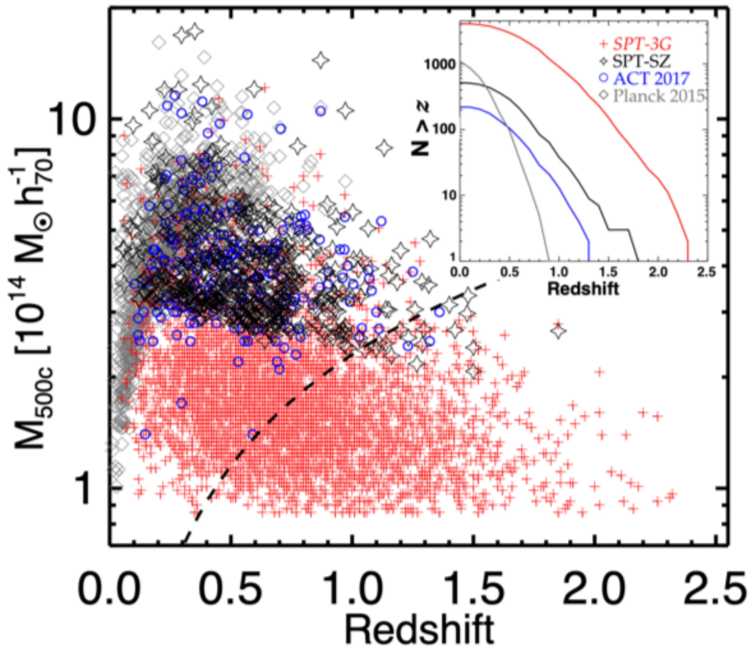
- Both CMB lensing and primordial gravitational waves generates B-modes.
- SPT-3G overlaps with BICEP for lensing B-mode removal.
- Joint SPT-BICEP delensing can help improve $\sigma(r)$ to 0.003. Without delensing it's 0.006.

Science goals – power spectra forecast



Science goals- clusters, astrophysics

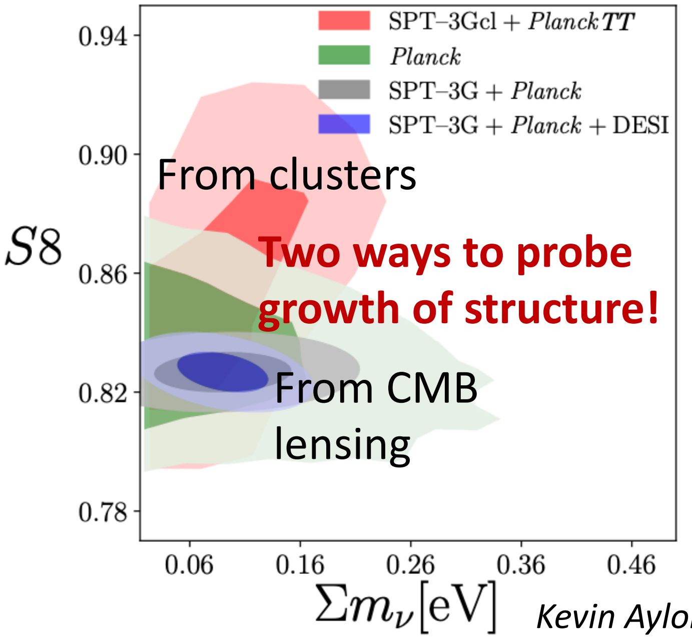




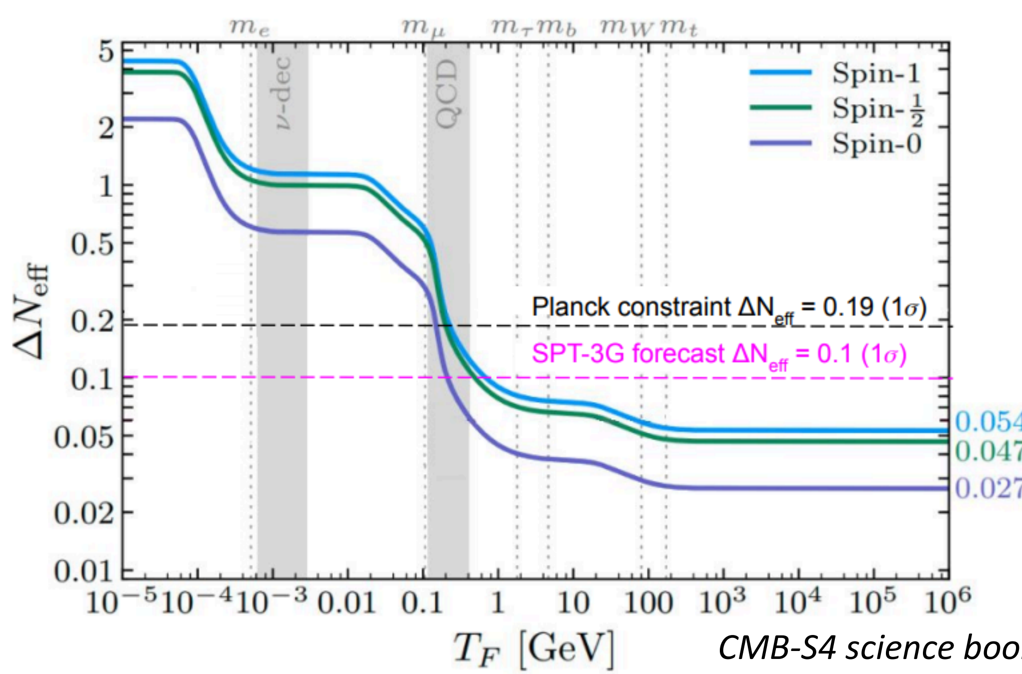
Cluster forecast (*Lindsey Bleem*)

- Can find more clusters (~4000), especially at lower mass and higher redshift, can constrain the growth of structure (x10 deeper than SPT-SZ).
- Better catalogs of extragalactic mm-wave point sources (>15000 sources, including high-redshift star-forming galaxies, AGNs, and protoclusters, many of which are strongly lensed)
- Transient search (GRB, FRB ...)
- Planets (including planets from outer solar system), ...

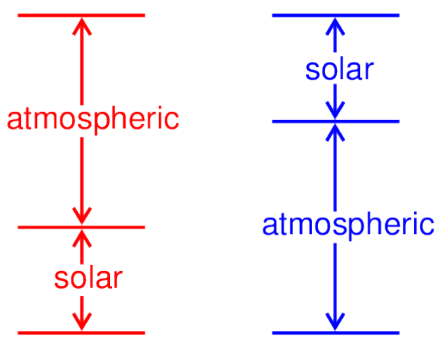
Science goals- neutrinos



Kevin Aylor



CMB-S4 science book



Normal hierarchy
Minimum total mass
0.11 eV

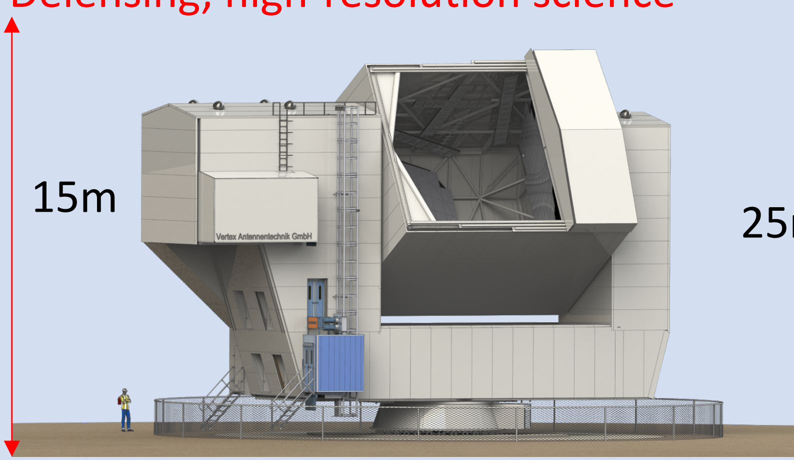
Inverted hierarchy
Minimum total mass
0.06 eV

- SPT-3G has $\sigma(\Sigma m_\nu)$ =0.038 eV
- Σm_ν sensitivity will be able to provide evidence between inverted hierarchy and normal hierarchy, (compare to Nova, T2K)
- Combine with baryon acoustic oscillation data to remove degeneracy.
- SPT-3G has $\sigma(\mathrm{N_{eff}}) = 0.1$
- $\mathrm{N_{eff}}$ sensitivity will be able to probe beyond QCD phase transition

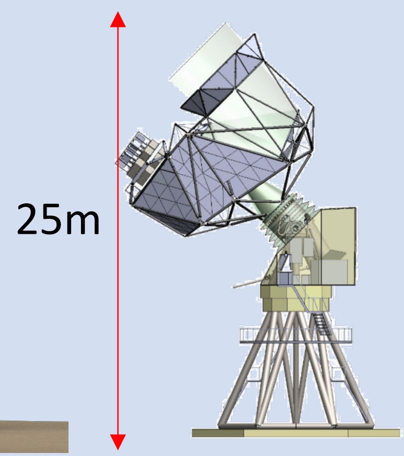
CMB-S4: the next generation

- **~500,000 detectors**, an order of magnitude larger than all current stage-3 experiments combined
- Enough sensitivity to **push through critical thresholds** for probing fundamental science (inflation, dark energy, neutrino mass, number of relativistic species …)
- **7 frequency bands** from 20 to 270 GHz for component separation
- **Two best sites** on the earth: South Pole and Atacama Plateau
- Received CD0 approval from DOE, endorsed by P5 report

3 large aperture (6m primary) telescopes, 350,000 detectors
Delensing, high-resolution science

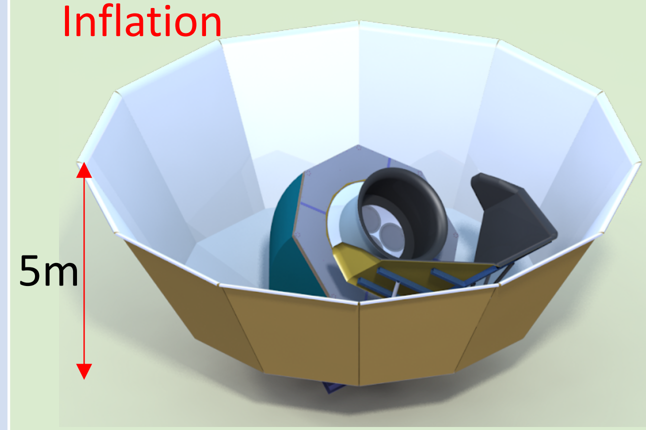


Simons Observatory Design



TMA design

18 x small aperture telescopes
153,000 detectors
Inflation



BICEP Array design

Summary

- CMB can help probe fundamental physics, including cosmic inflation, dark energy, neutrino physics, and growth of structure.
- SPT-3G is a current experiment in operation with lots of technological innovations
  - Multichroic detectors with 3-frequency antenna
  - Background-noise limited frequency-domain multiplexing readout
  - Large aperture optical system, 3-layer 700mm AR coating
- SPT-3G science analyses are ongoing. Future is exciting.
  - 2018 EE/TE analysis ongoing, improvement in ell range 1000-1700.
  - Lensing analyses are ongoing, competitive parameter constraint.
  - Neutrino physics: $\sigma(\Sigma m_\nu)$ =0.038 eV, $\sigma(\mathrm{N_{eff}}) = 0.1$ (forecast)
  - Delensing joint analysis with BICEP Array -> $\sigma(r)$ 0.003
  - 4000 galaxy clusters, >15000 point sources, and more
- Next generation: CMB-S4, half a million detectors

Thank you!

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