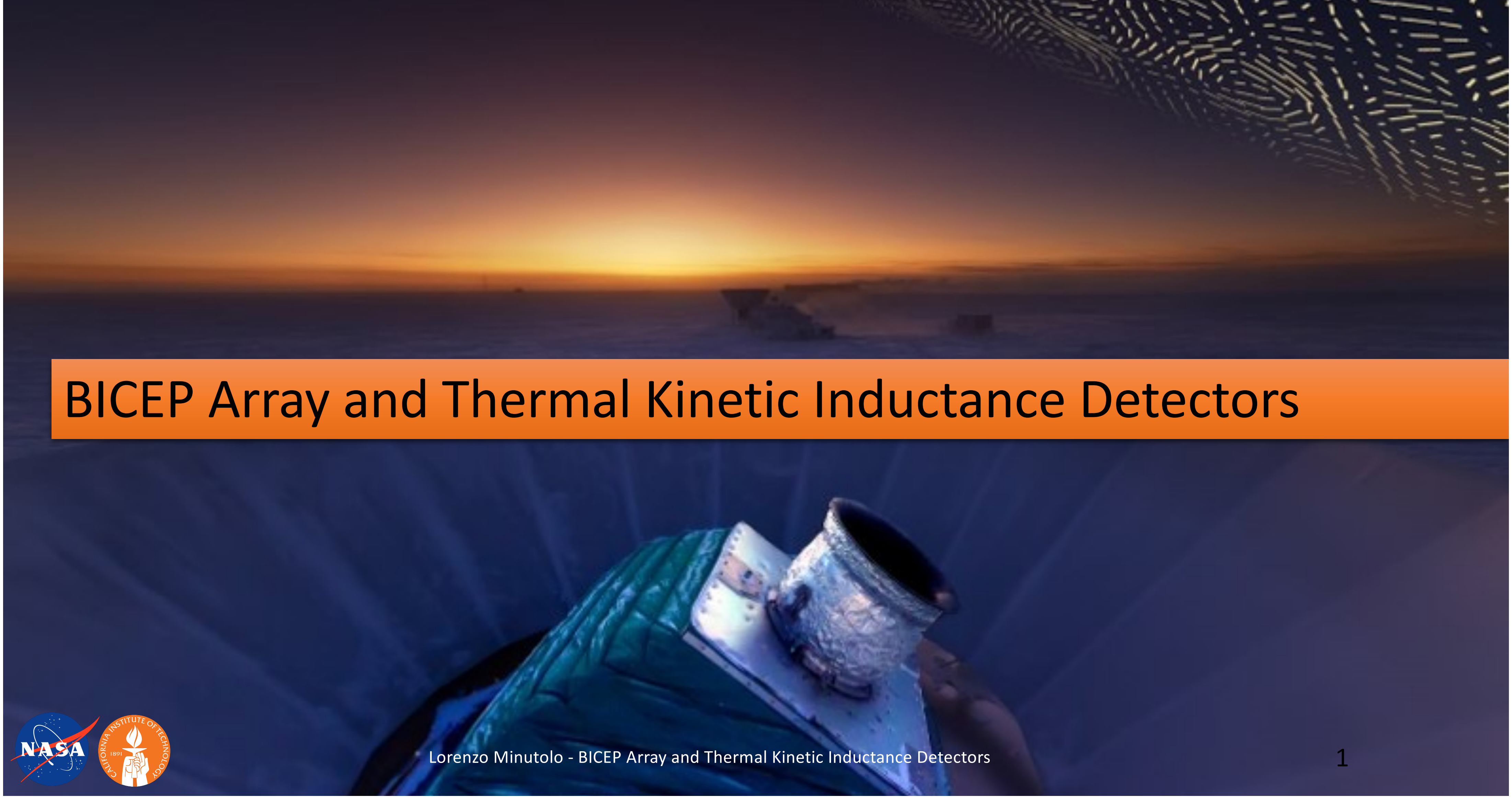
Roger O’Brient – NASA JPL; Bryan Steinbach – Caltech; Albert Wantui – Caltech; Lorenzo Minutolo* – Caltech; Anthony Turner – NASA JPL; Cliff Frez – NASA JPL; James Bock Caltech/JPL; Jonas Zmuidzinas Caltech JPL

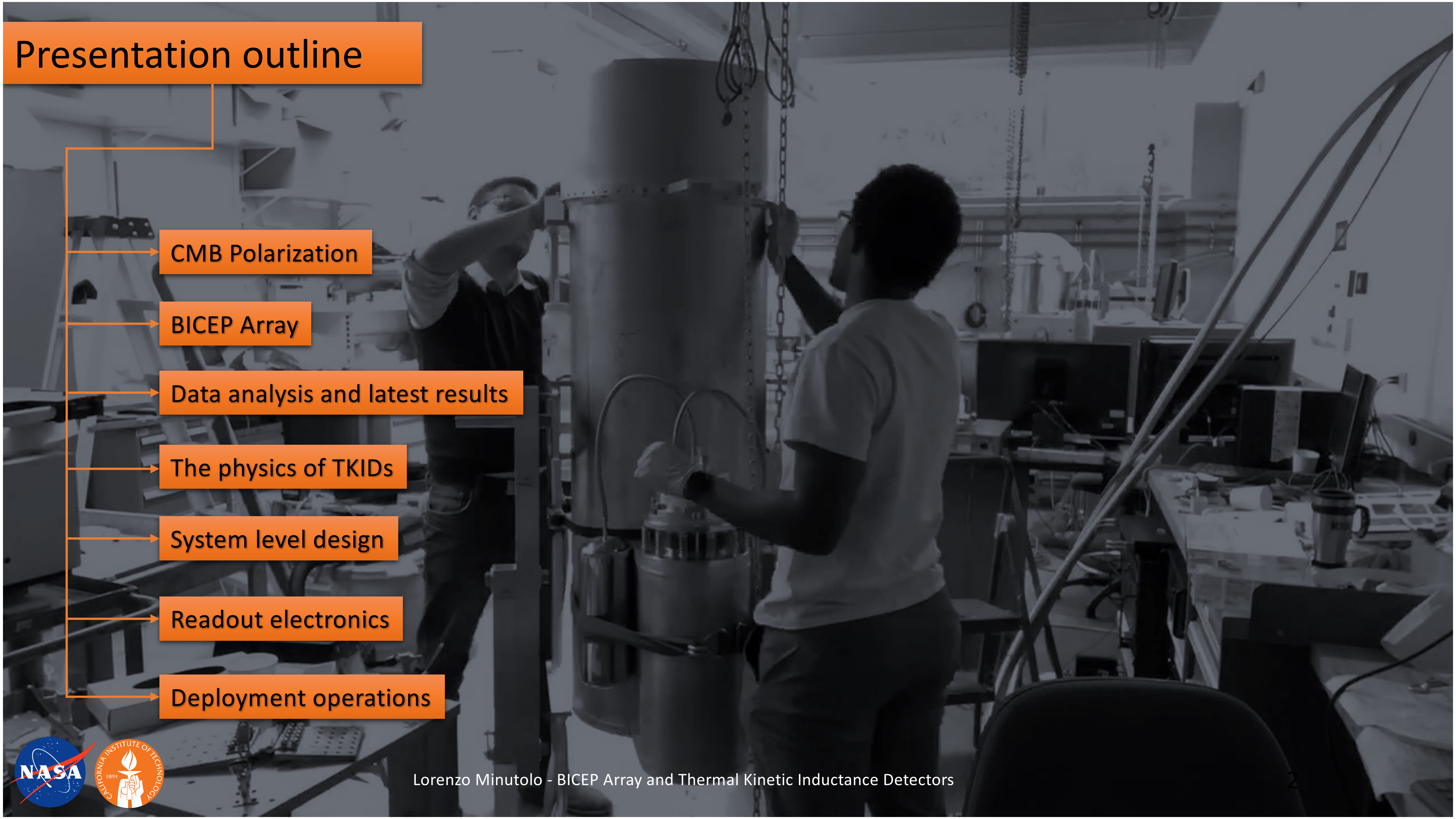
Support: JPL RTD program (2016-19) Strategic support for TKIDs & readout; President Director Funds, 2018-2020; NASA SAT: started 2020 (JPL); Moore Foundation: started 2019 (Caltech)



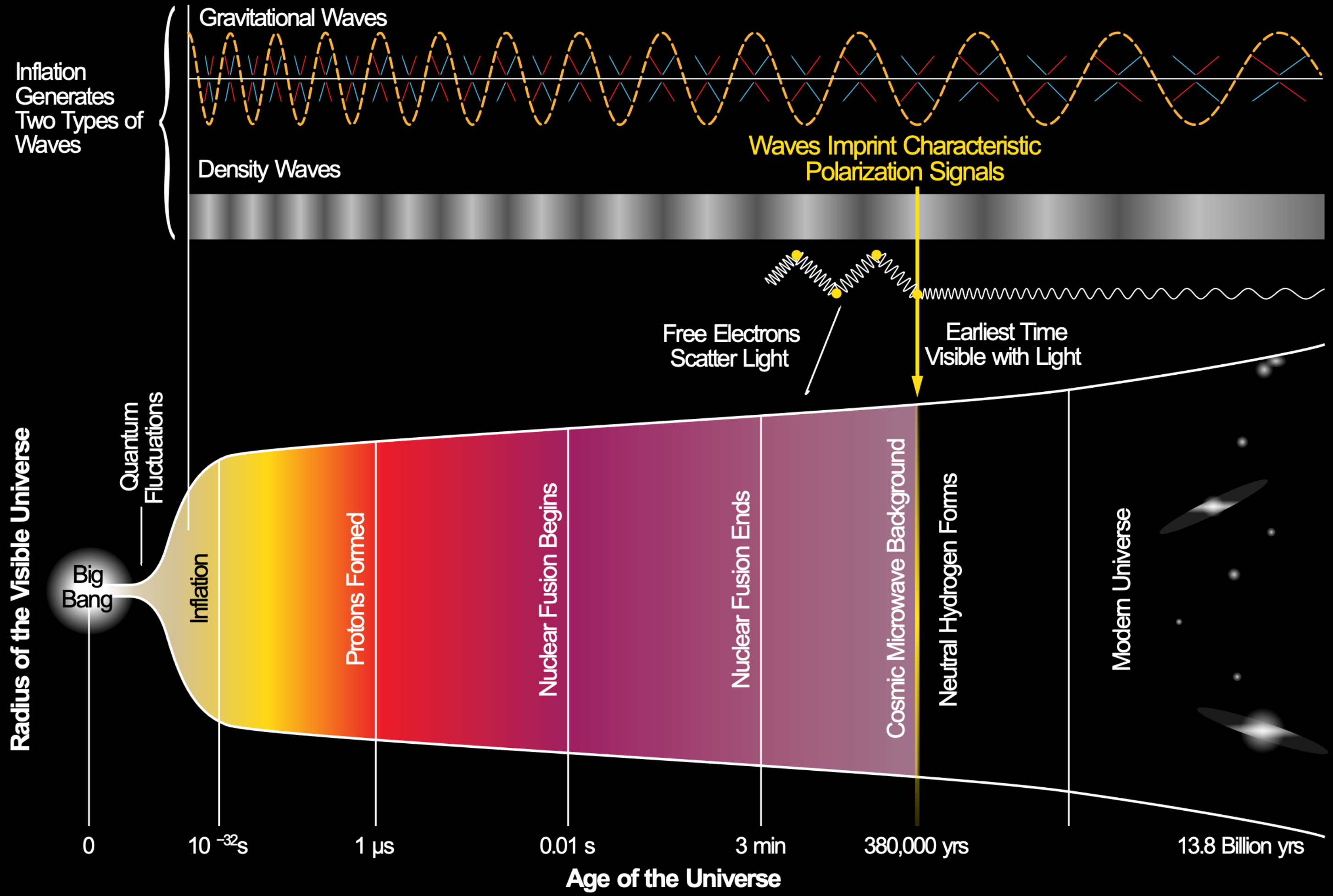
BICEP Array and Thermal Kinetic Inductance Detectors

Presentation outline

- CMB Polarization
- BICEP Array
- Data analysis and latest results
- The physics of TKIDs
- System level design
- Readout electronics
- Deployment operations



CMB Polarization: modern cosmology in a nutshell

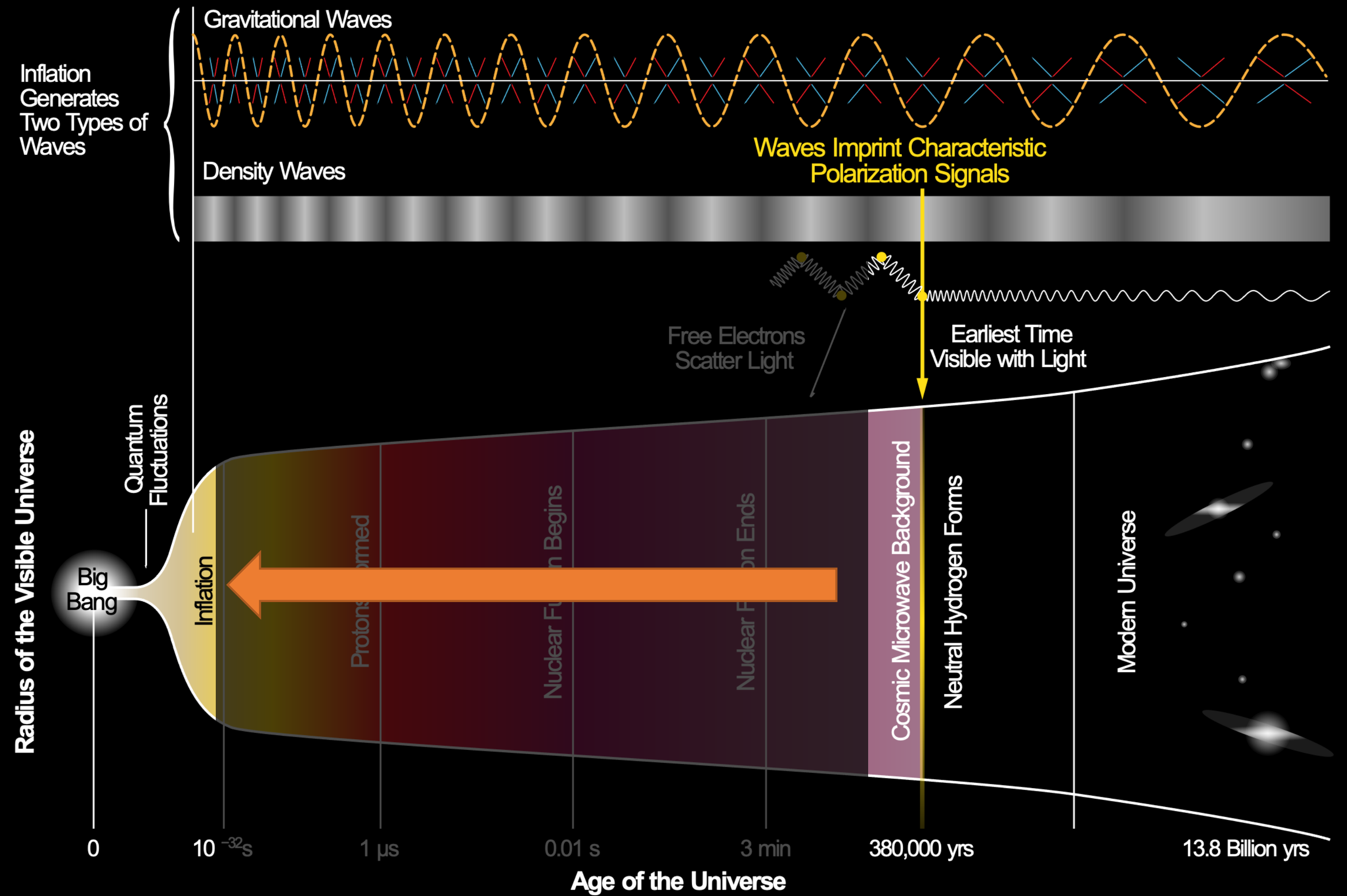


1) **The universe is expanding.** (Hubble, 1920s)

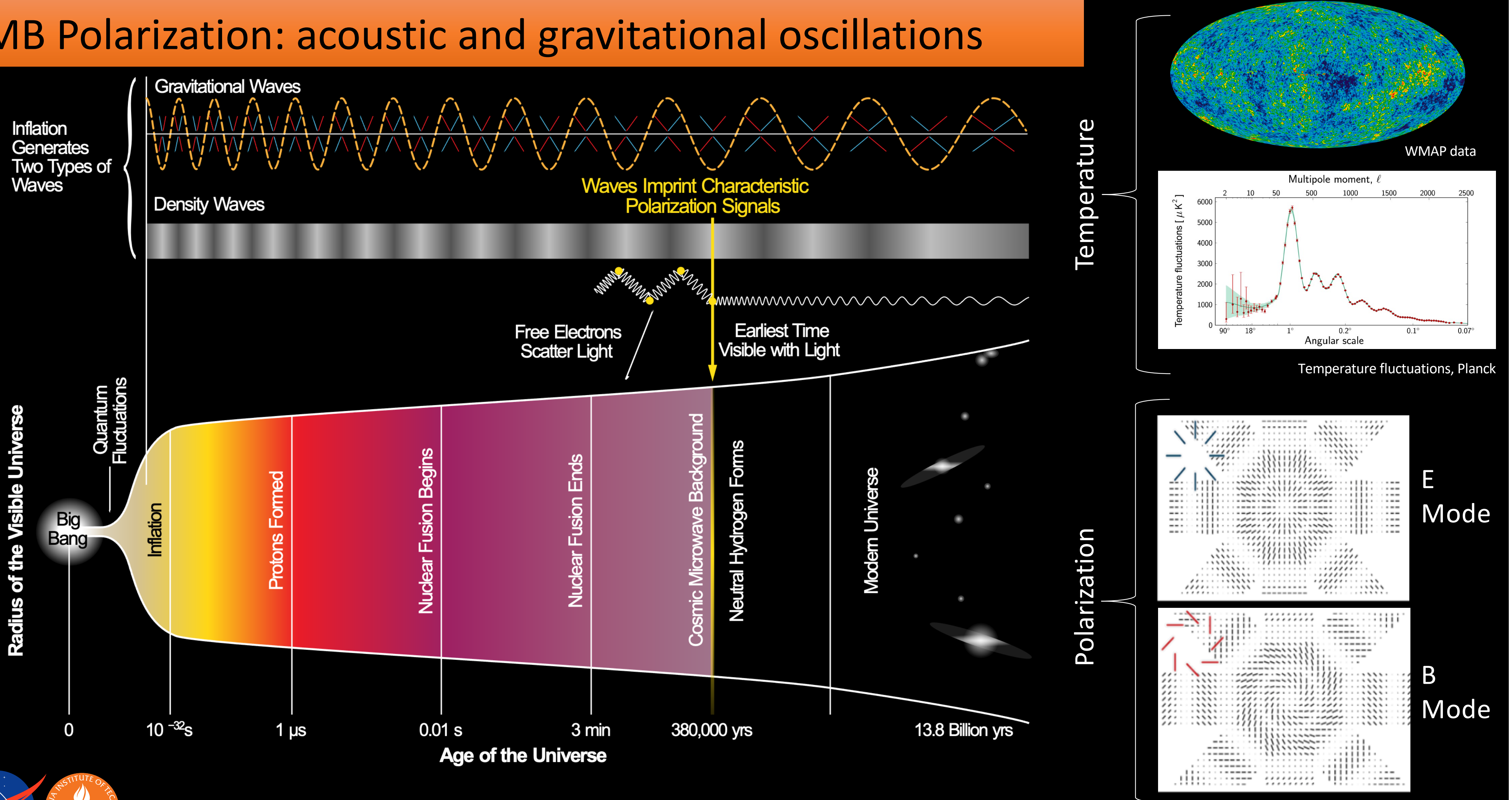
2) **It was once hot and dense, like the inside of the Sun.** (Alpher, Gamow, Herman, 1940s)

3) **You can still see the glow! The Cosmic Microwave Background** (Penzias & Wilson, 1964)

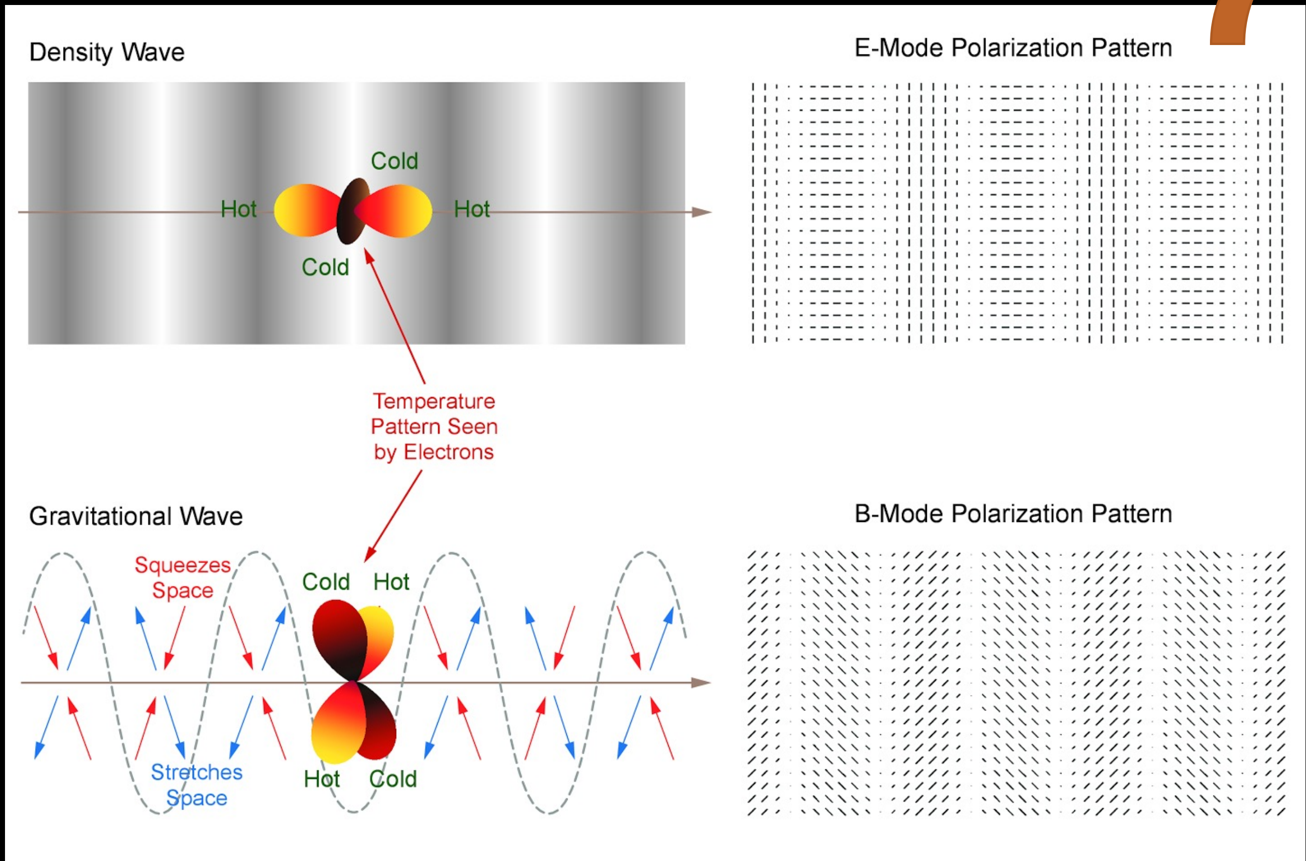
CMB Polarization: acoustic and gravitational oscillations



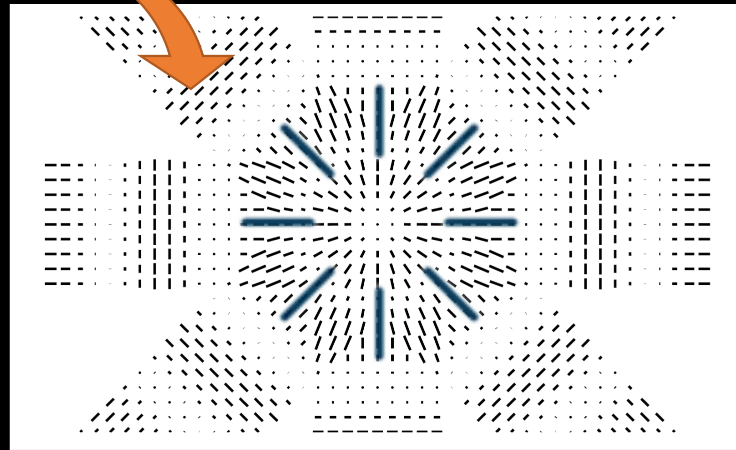
CMB Polarization: acoustic and gravitational oscillations

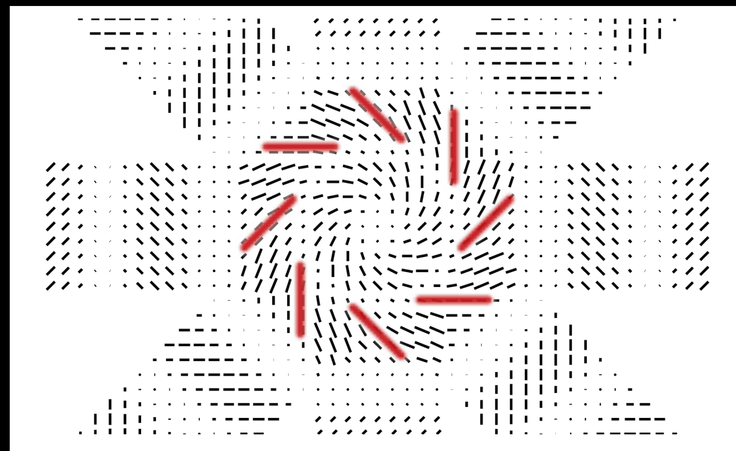


CMB Polarization: patterns



On a 2D plane

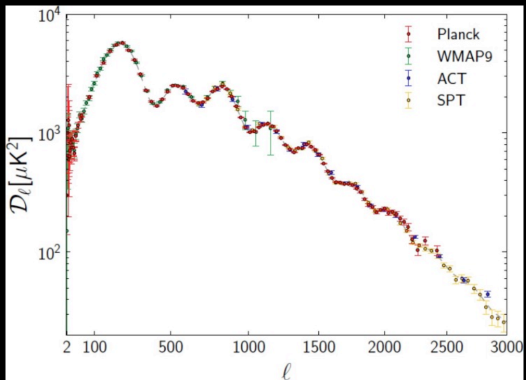




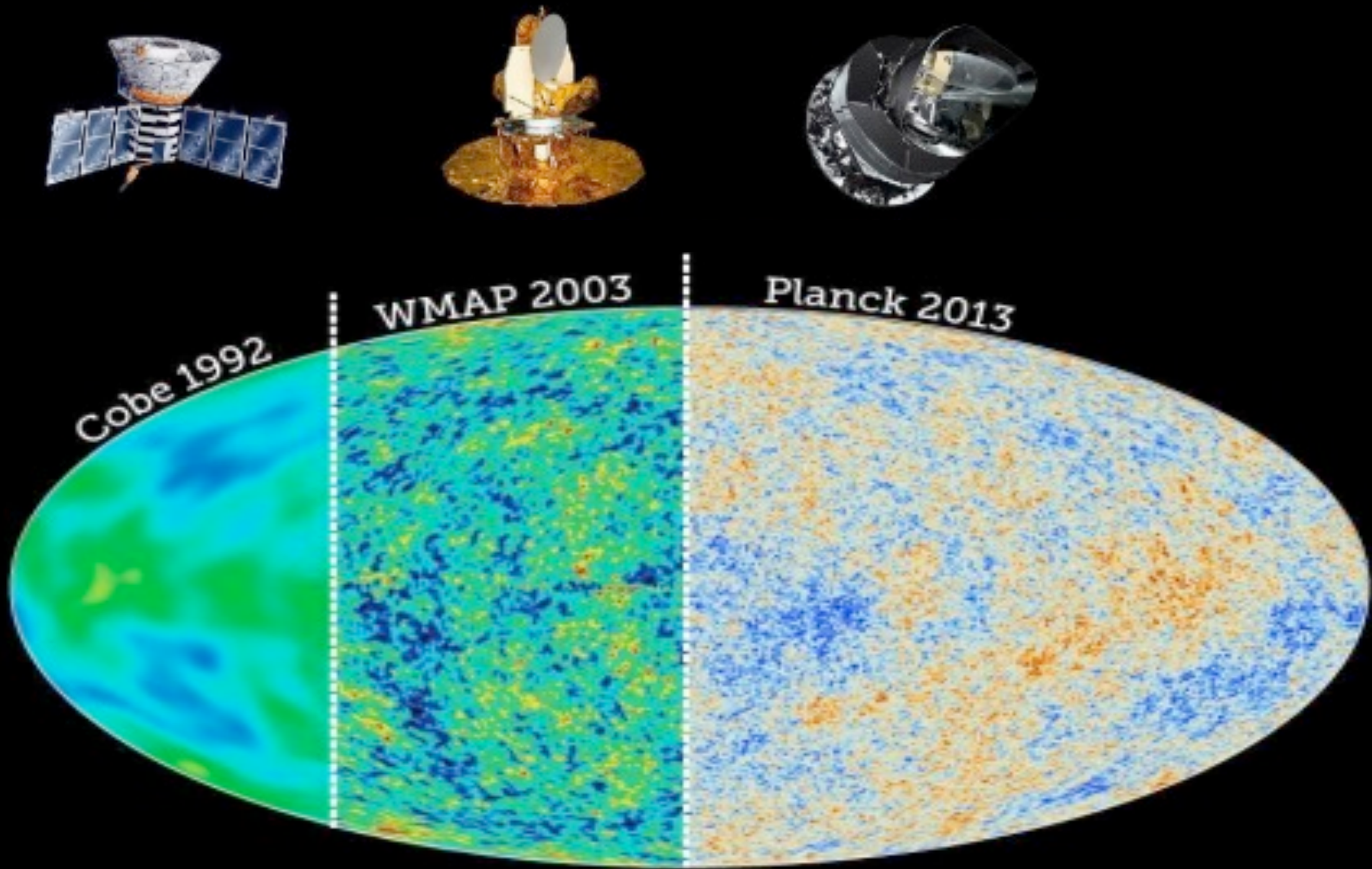
$$r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} \left(\frac{V}{[2 \times 10^{16} \mathrm{GeV}]^4} \right)$$

CMB Polarization

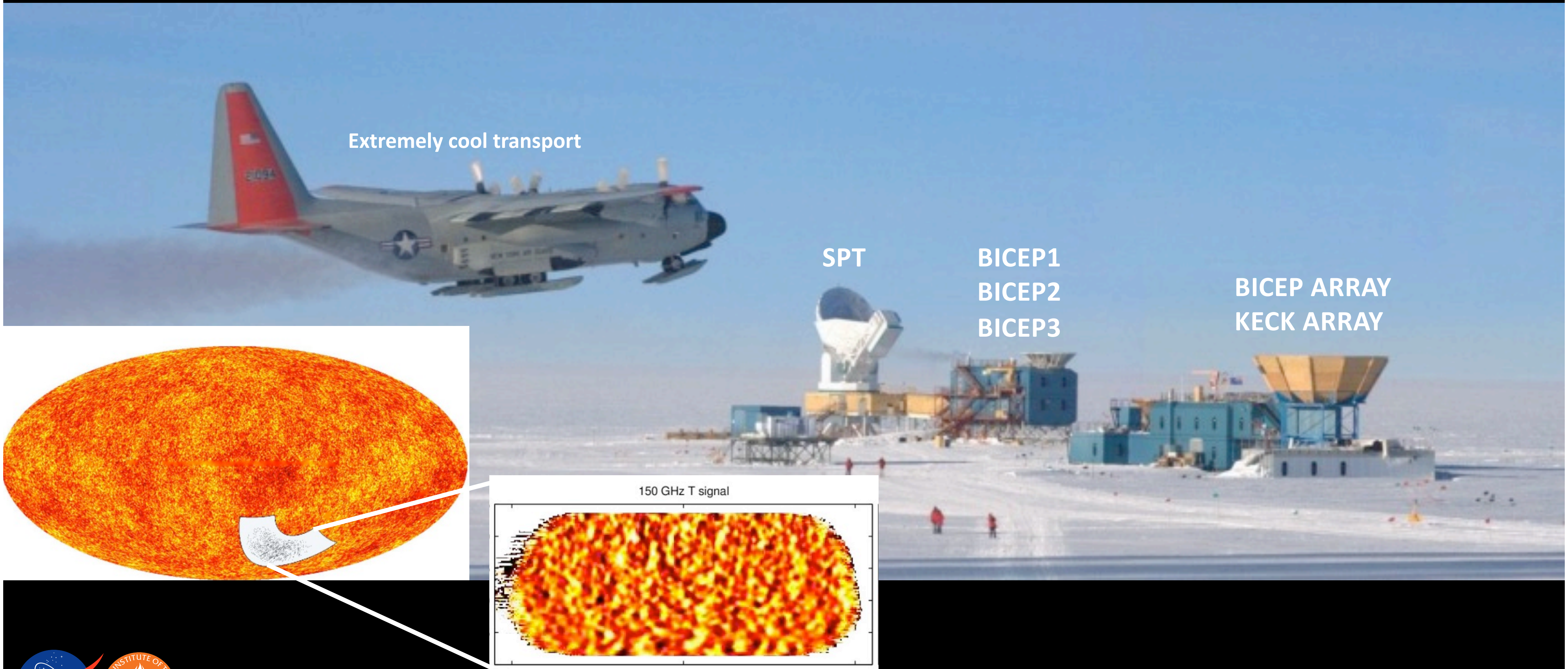
Precision measurements of the CMB temperature have provided a wealth of cosmological information consistent with the inflationary paradigm.



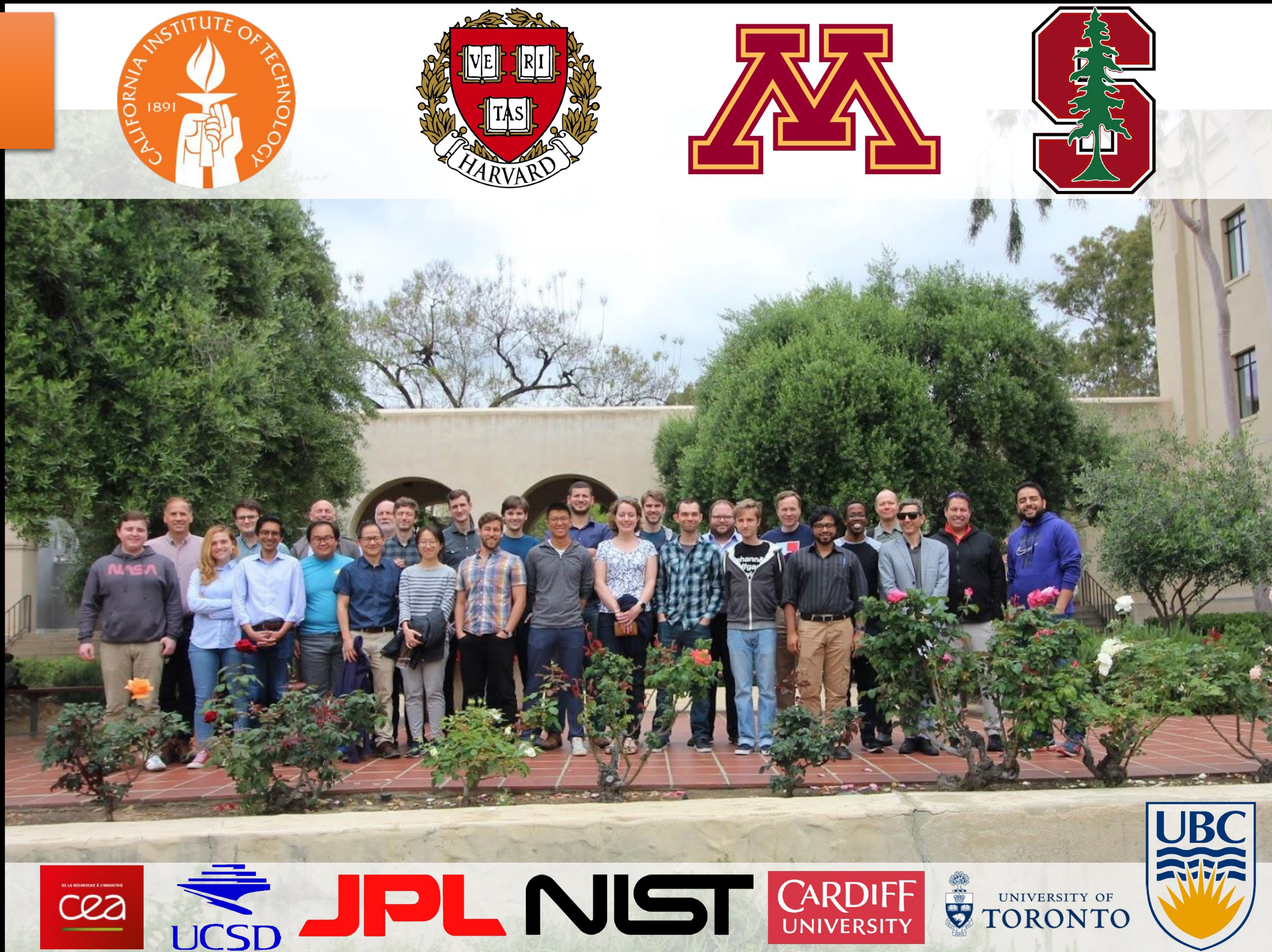
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.



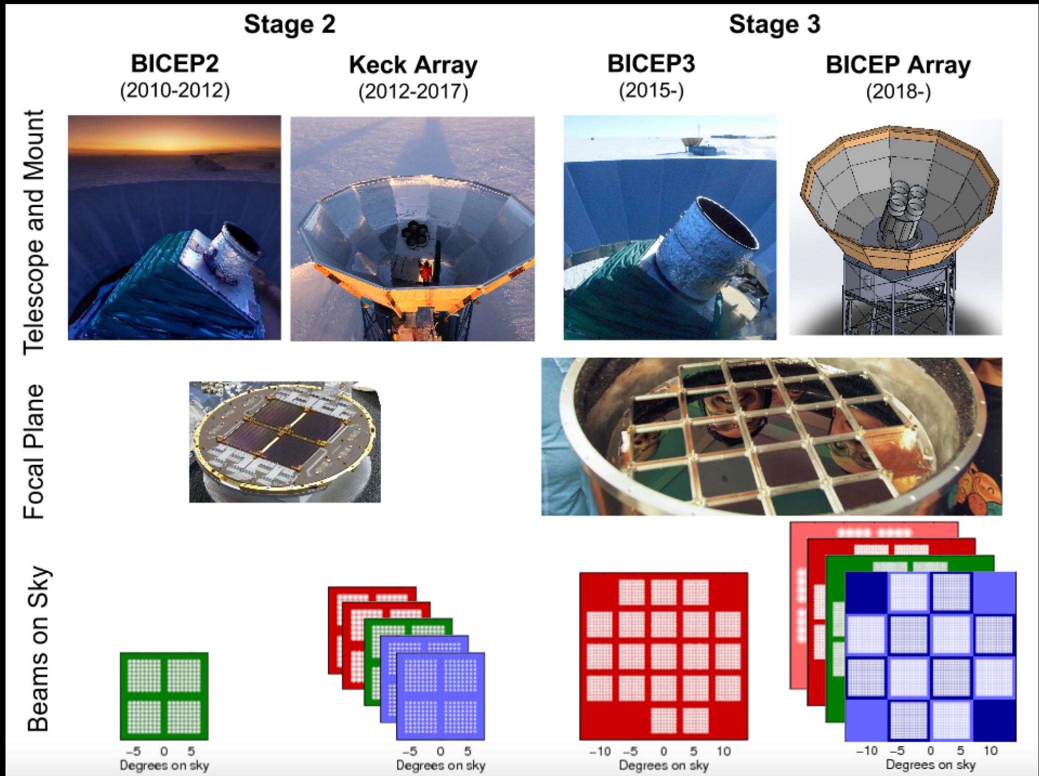
BICEP Array: target and location



BICEP array: the collaboration



BICEP Array: the BICEP program

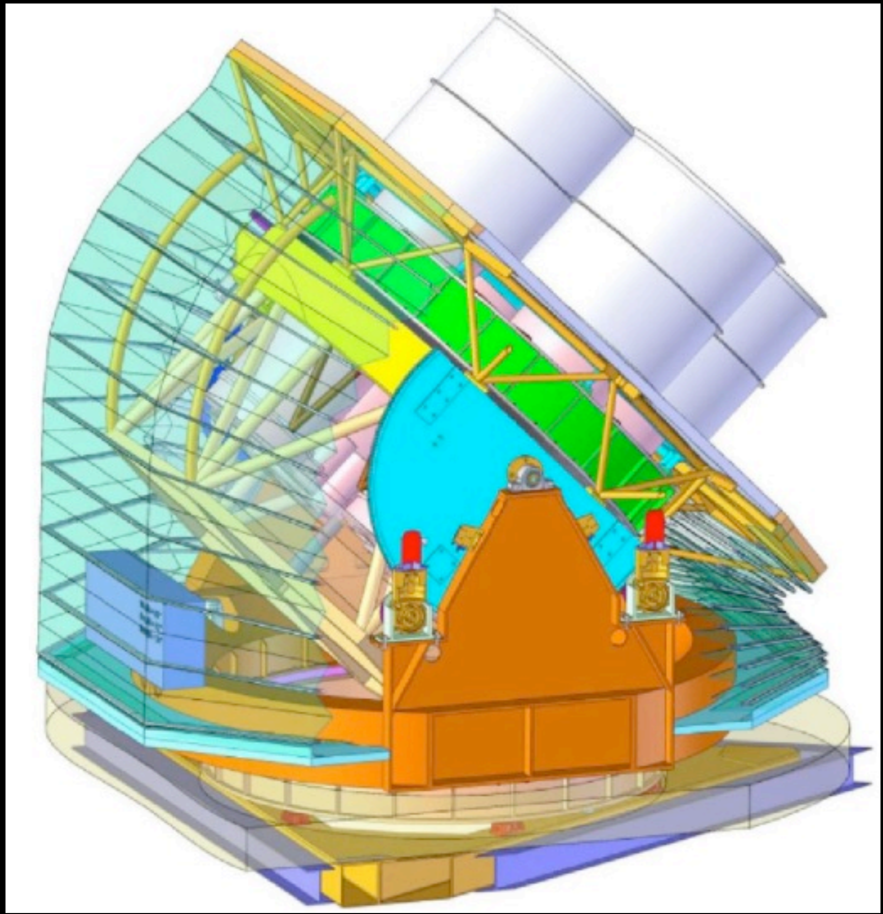


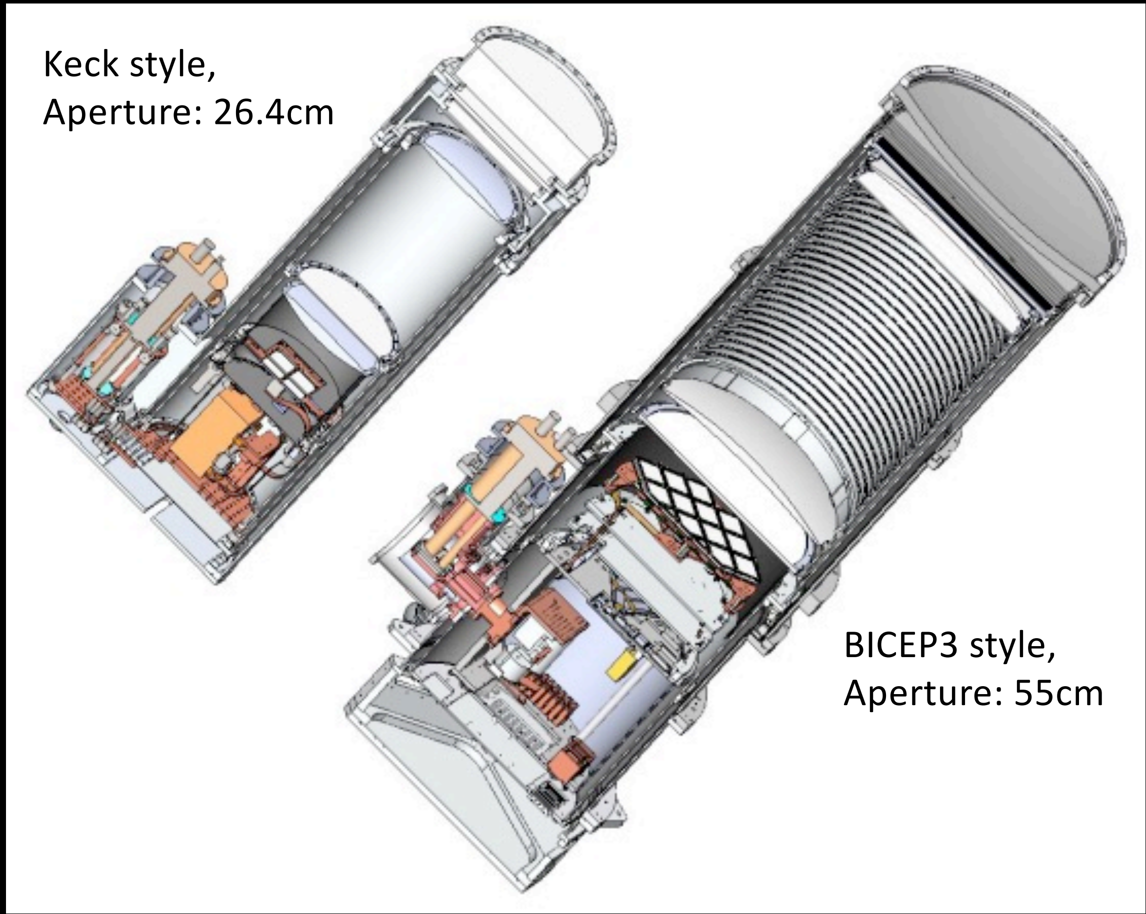
BICEP Array

Four sub-millimeter wave telescope synchronously scanning a patch of sky with angular degree resolution

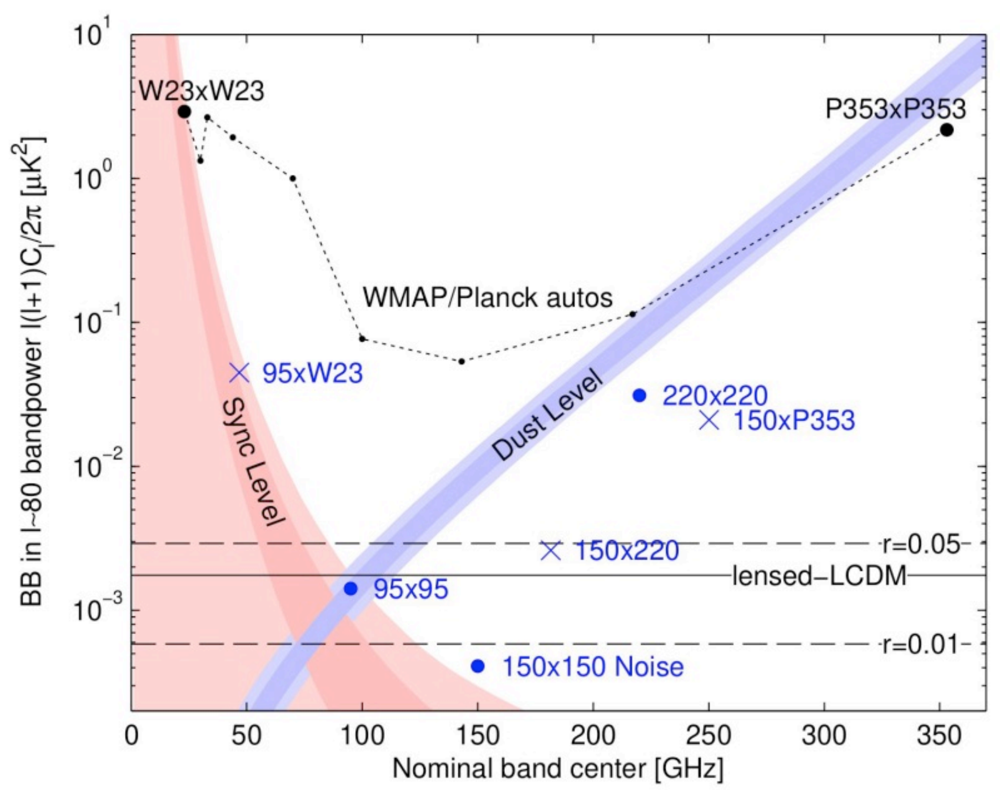
All science data have been collected using TES (transition edge sensors) technology

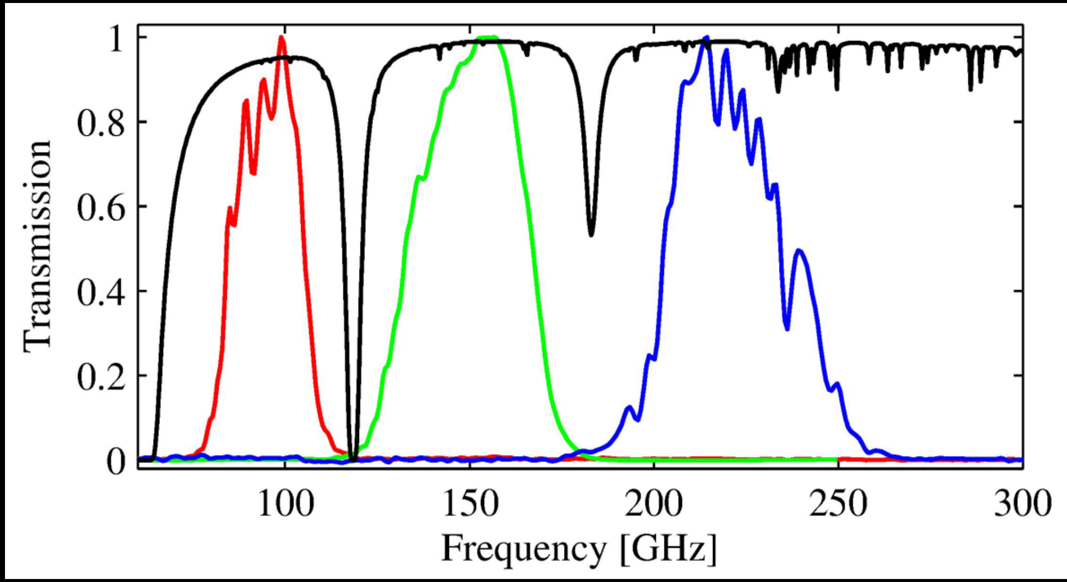
BICEP Array: the BICEP Array mount





BICEP array: frequency selection





The dry South Pole atmosphere provides excellent observing conditions most of the year.

The approx. 30% fractional bandpasses fit within atmospheric transmission windows straddled by oxygen and water lines.

The detector passbands are defined by a filter printed directly onto the focal plane wafers

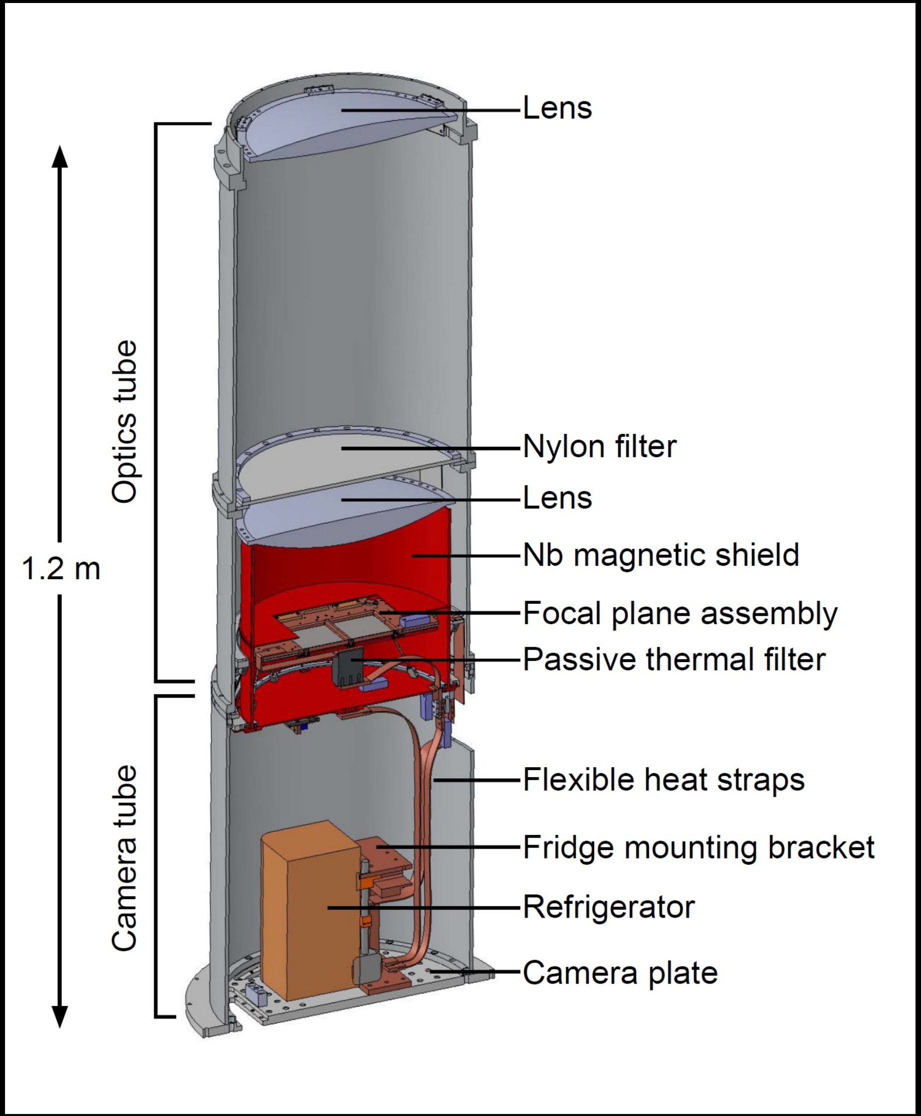
BICEP array: the BICEP/Keck telescope

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

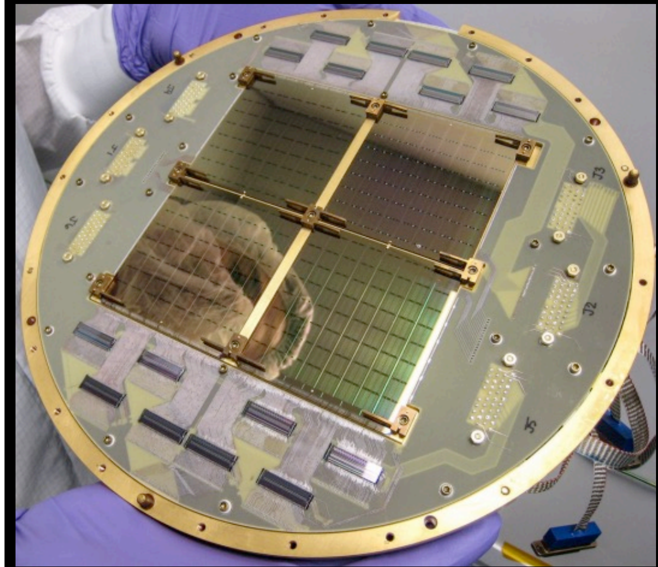
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Pulse tube cooler cools the optical elements to 4.2 K.

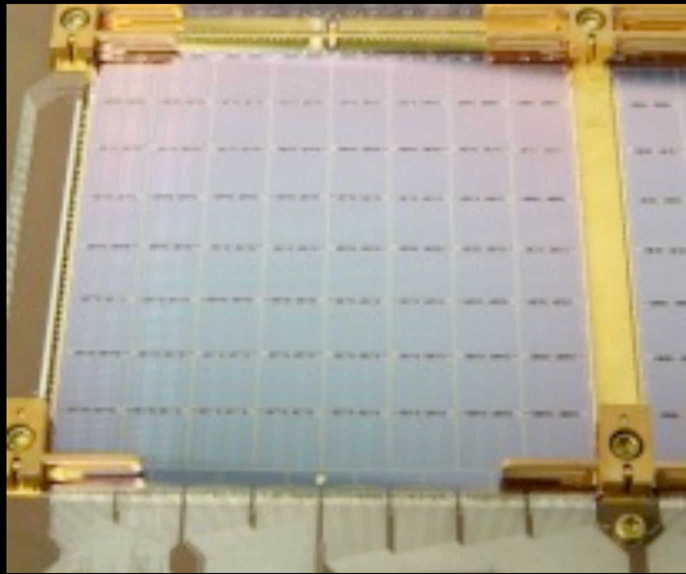
A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



BICEP array: focal plane and TES technology



1) Focal plane



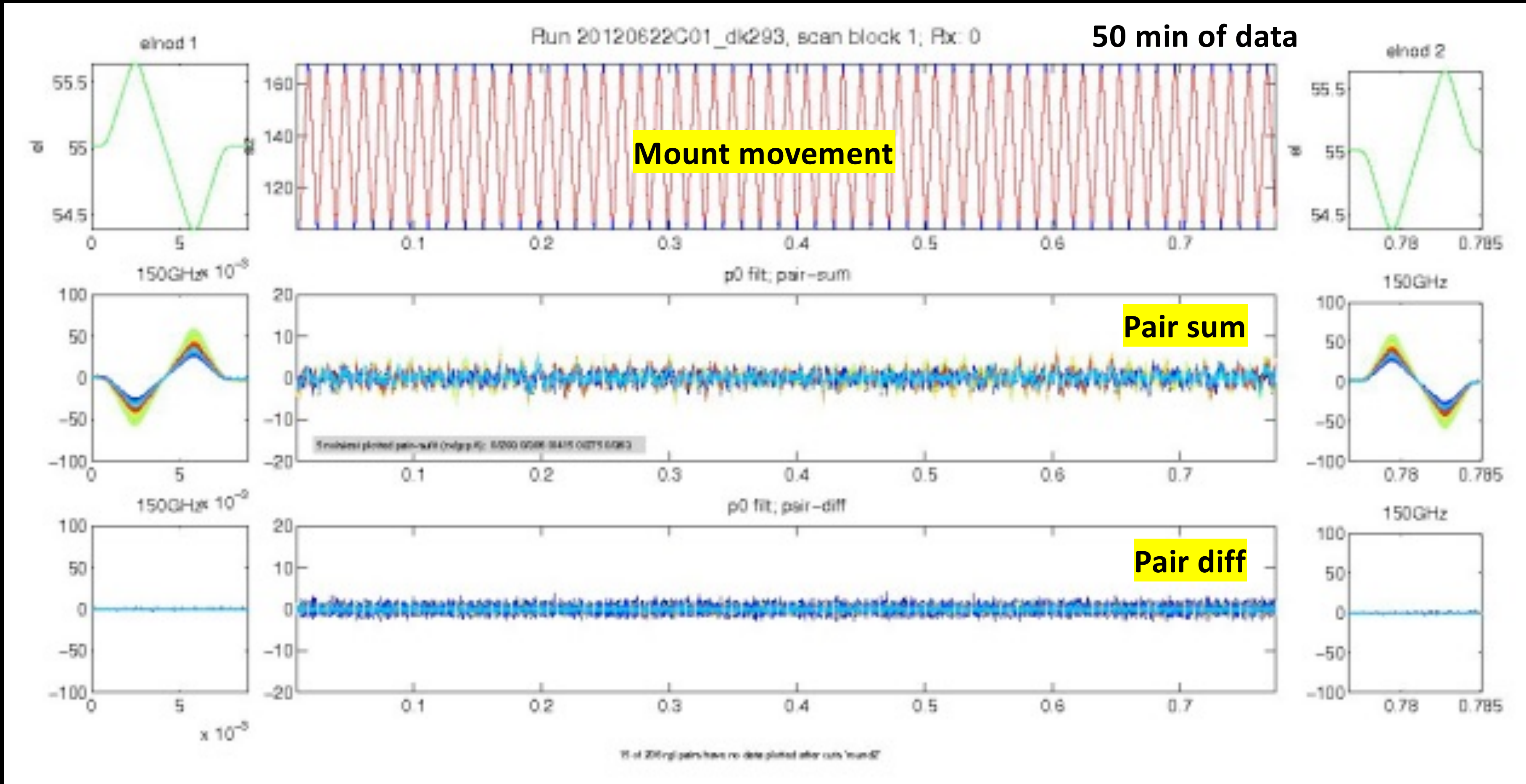
2) A single tile

3) A single pixel with antenna

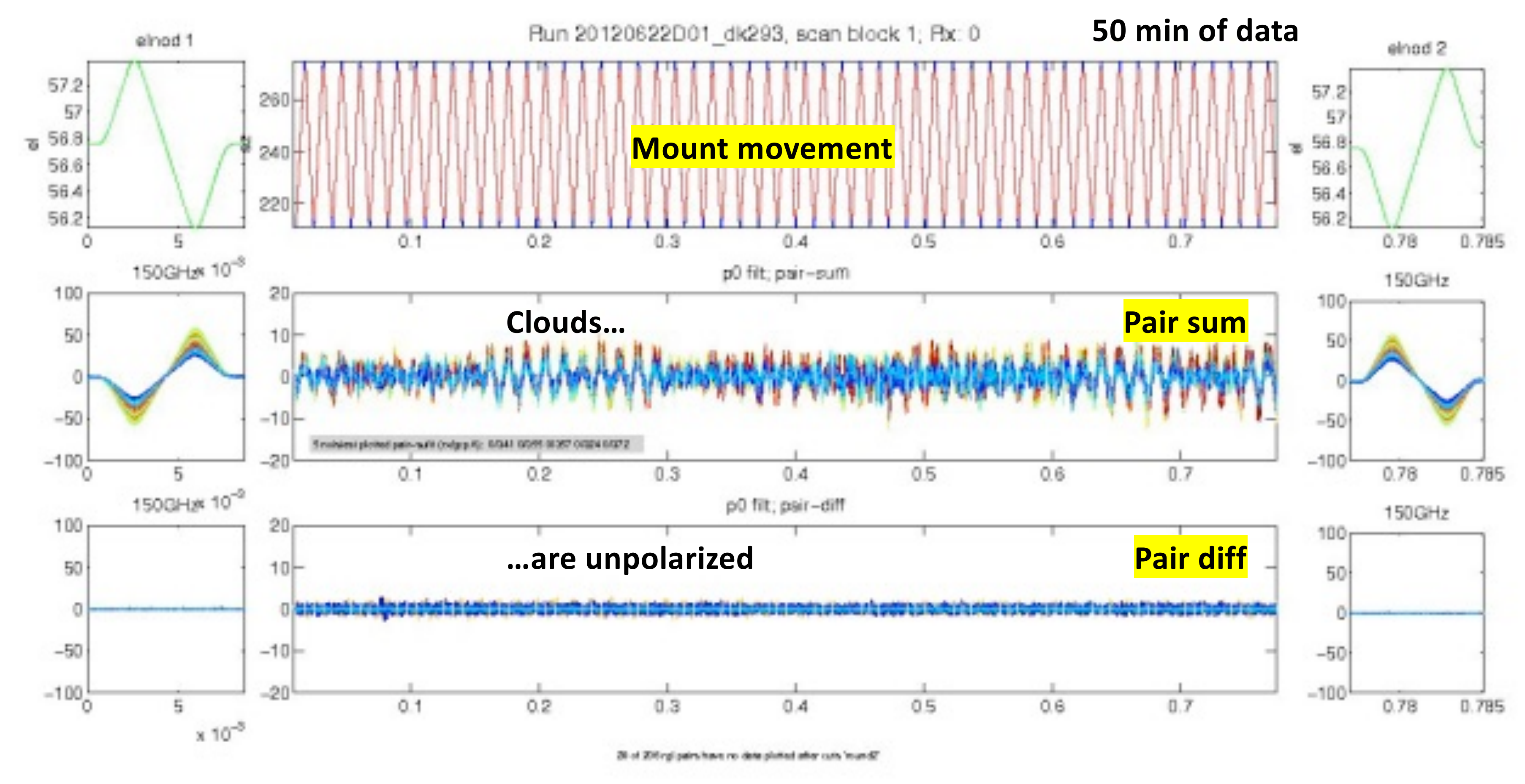
3) A single TES

Frequency	30/40 GHz	95 GHz	150 GHz	220/270 GHz
# Detectors	192/300	3456	7776	13824/16224
# Det/Tile	32/50	288	648	**1152/1352 !**
Beam FWHM (arcmin)	76/57	24	15	10/8.5

Data analysis: example of data quality control



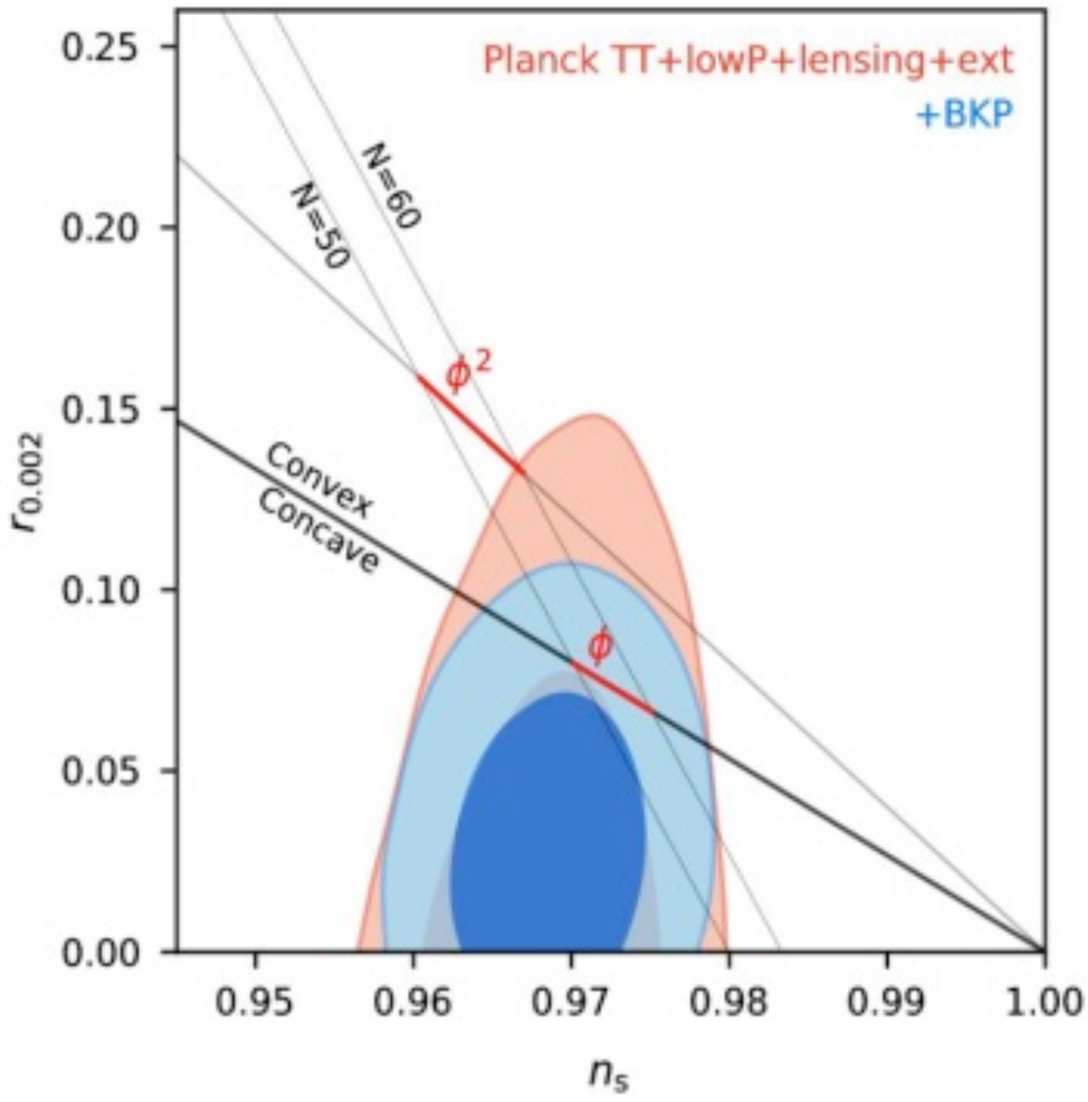
Data analysis: example of data quality control



Latest results

BK

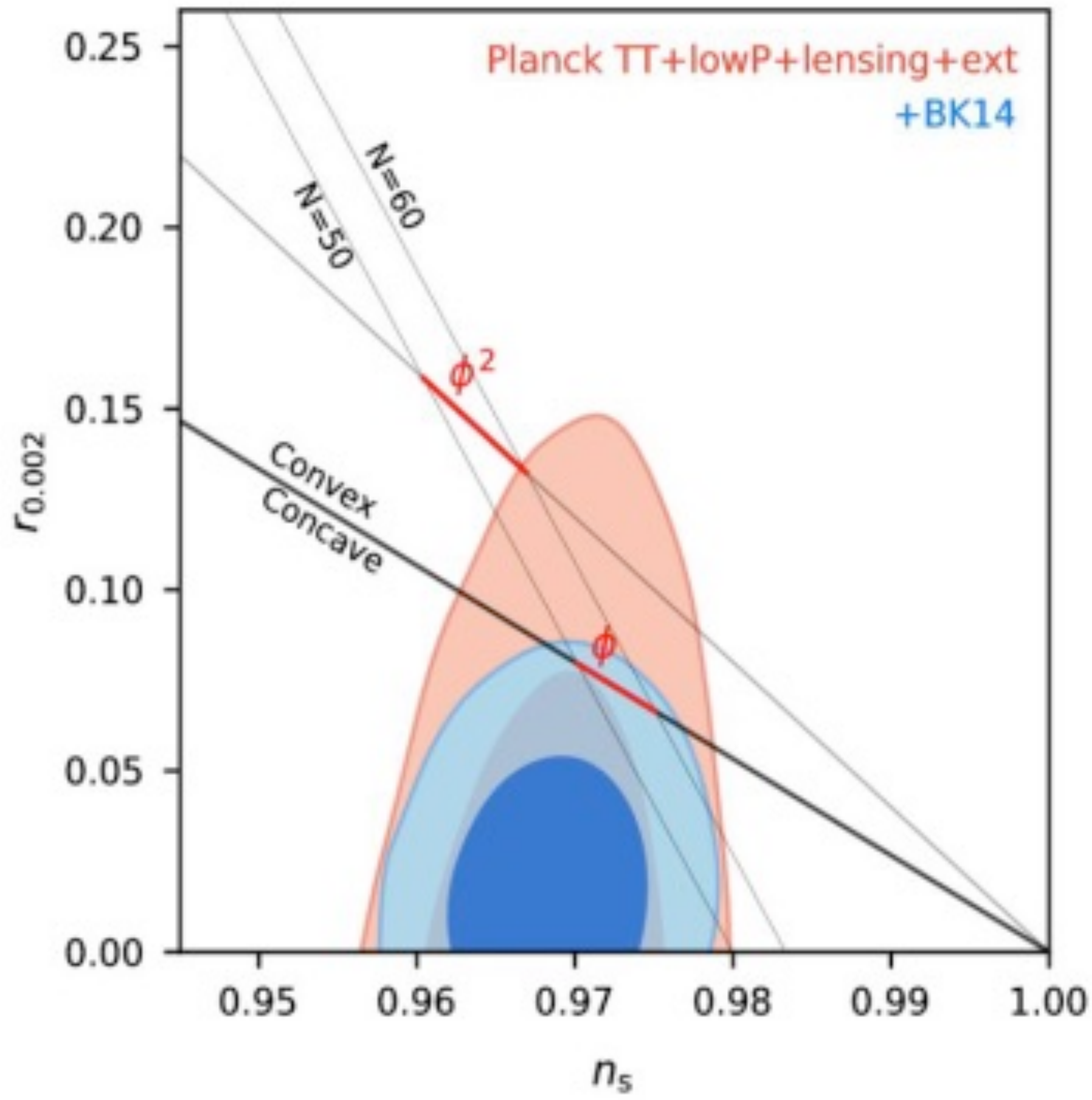
r < 0.09



Latest results

BK14

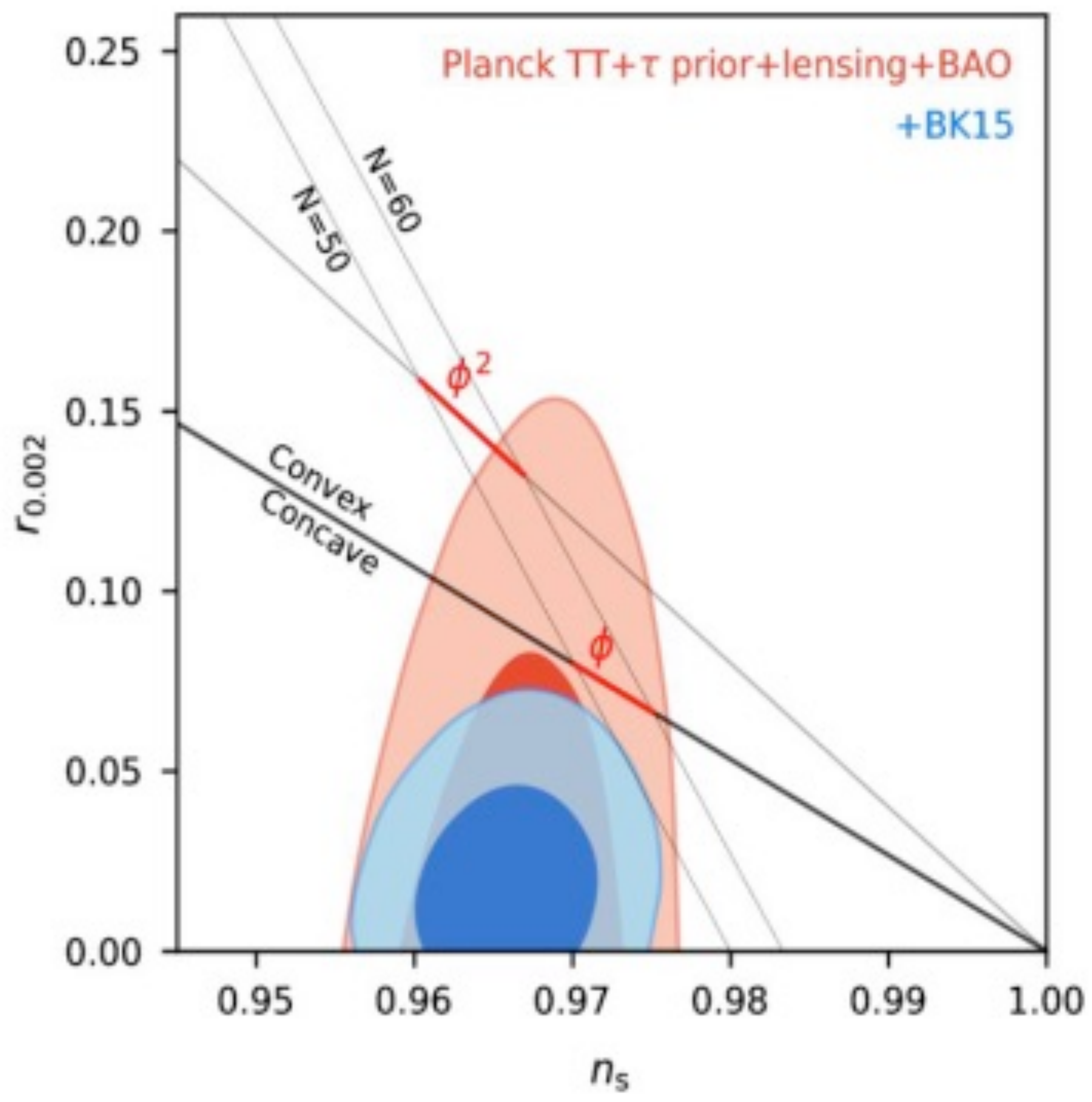
r < 0.07



Latest results

BK15

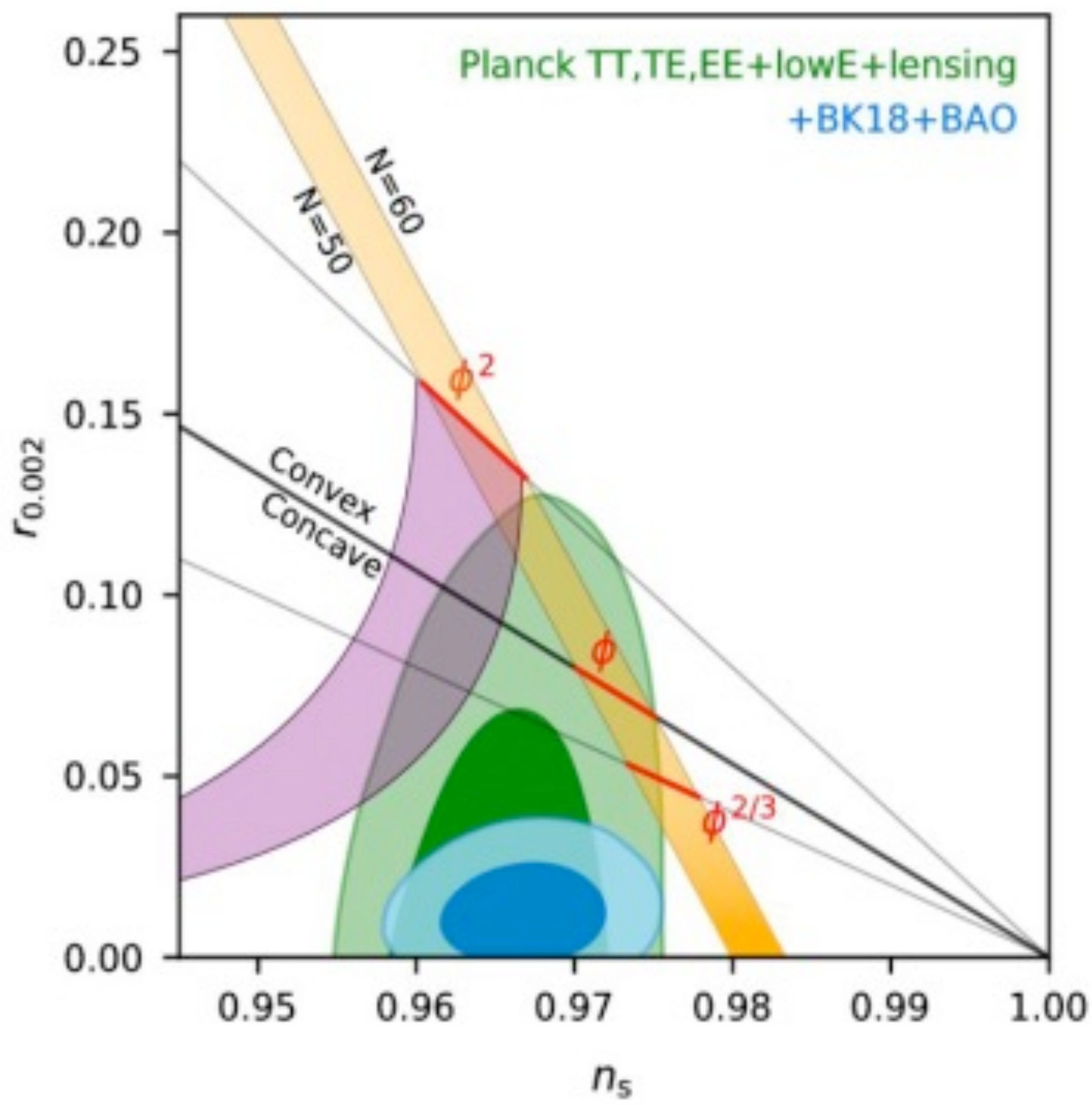
r< 0.06



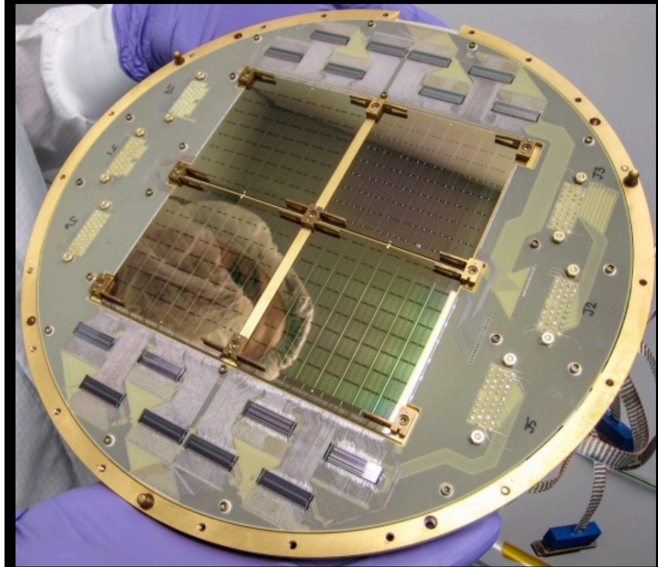
Latest results

BK18

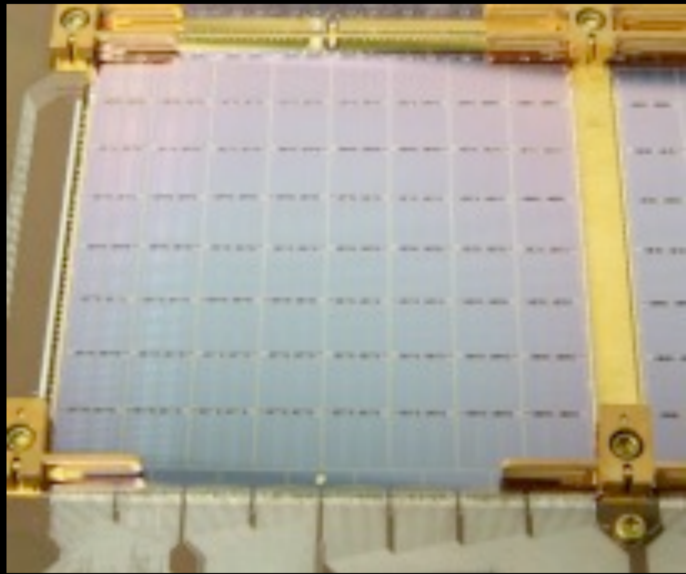
r < 0.035



BICEP array: focal plane and TES technology

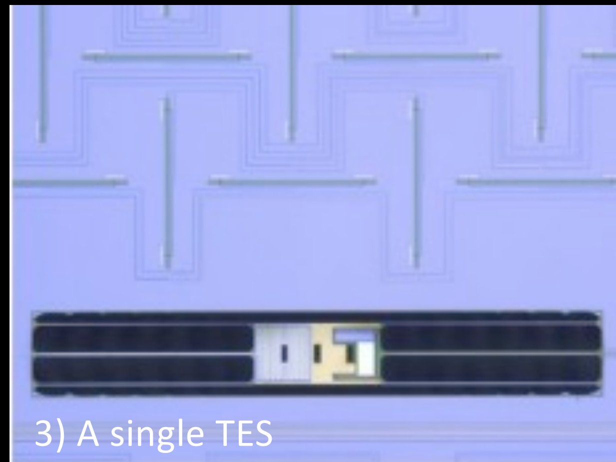


1) Focal plane



2) A single tile

3) A single pixel with antenna



3) A single TES

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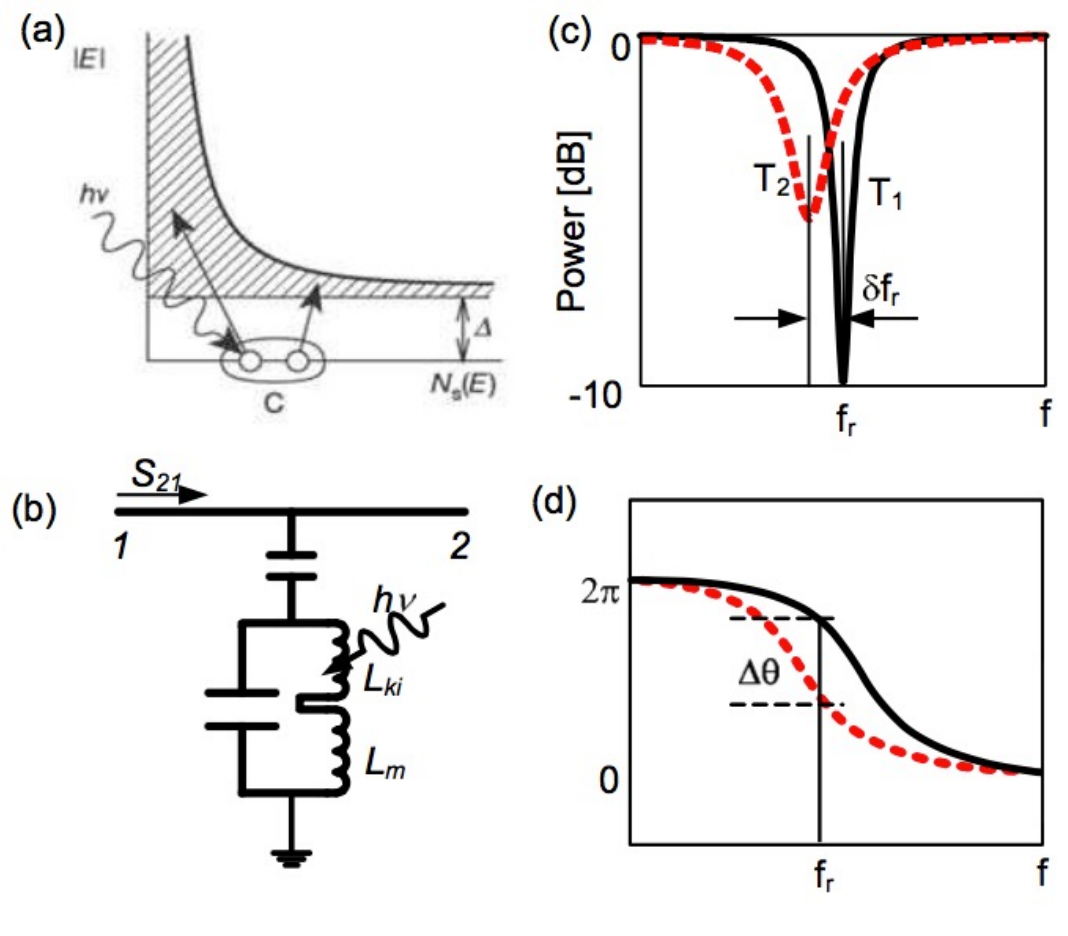
Beam FWHM (arcmin)	76/57	24	15	10/8.5

TKIDs physics: kinetic inductance detectors 101



A) A photon or phonon breaks a Cooper pair
B) The photon or phonon is absorbed in an inductor used in a resonant circuit changing the kinetic part of the inductance.
C) By probing the resonant circuit with a "tone" close or on resonance, the transmitted power variation can be measured as well as
D) The variation in phase.

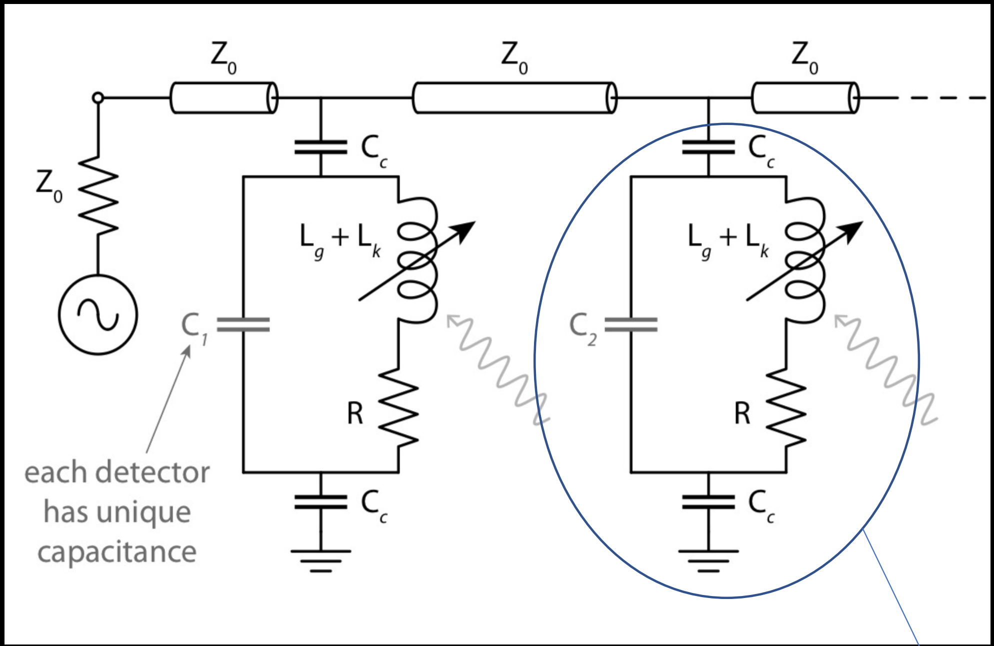
Quasiparticles count in function of temperature:

$$n_{th}(T) = 2N_o\sqrt{2\pi k_B T \Delta}\, e^{-\Delta/k_B T}$$

$$\Delta = 1.76 k_B T_c$$

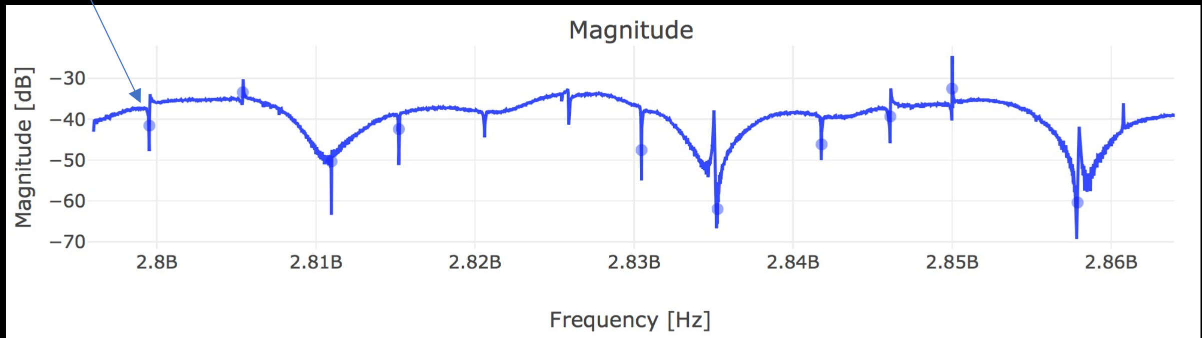
A small variation in quasiparticle population drastically changes the transmission function

TKIDs physics: kinetic inductance detectors 101

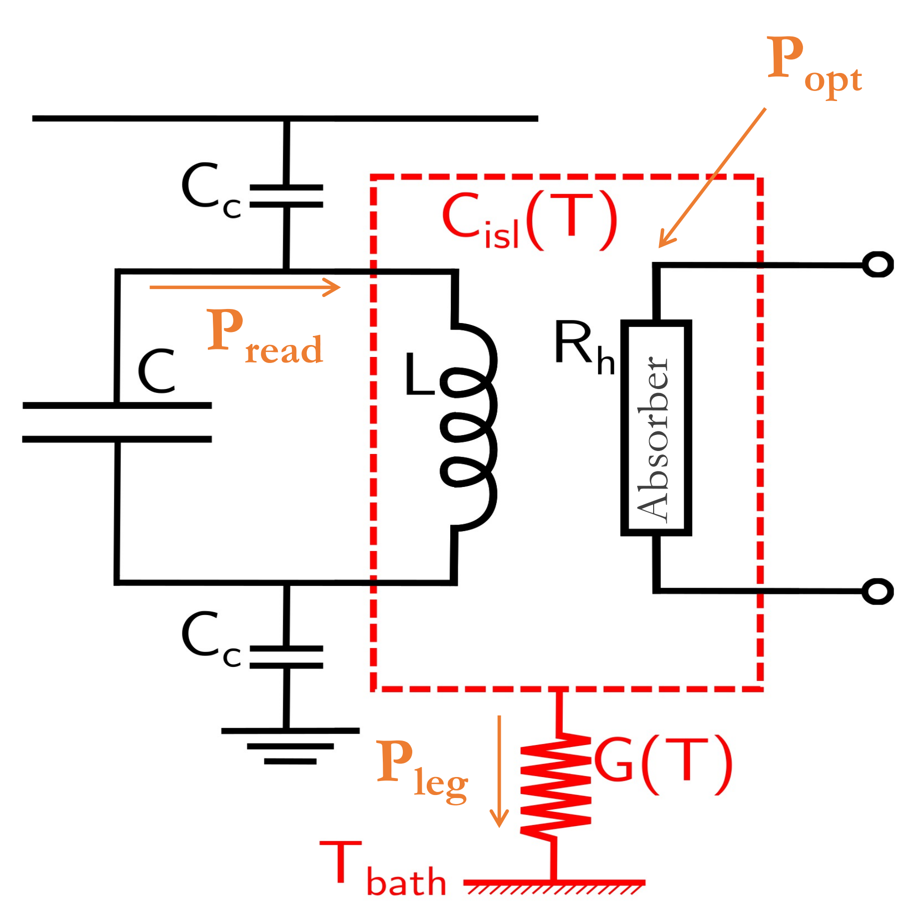


- Because each detector has a unique resonant frequency, we can couple multiple KIDs to a single RF line
- There is no need for SQUIDs or other cold electronic (other than a good LNA amplifier)
- Potentially, many wafers can be daisy chained.

S21 transfer function example using superconductive resonators

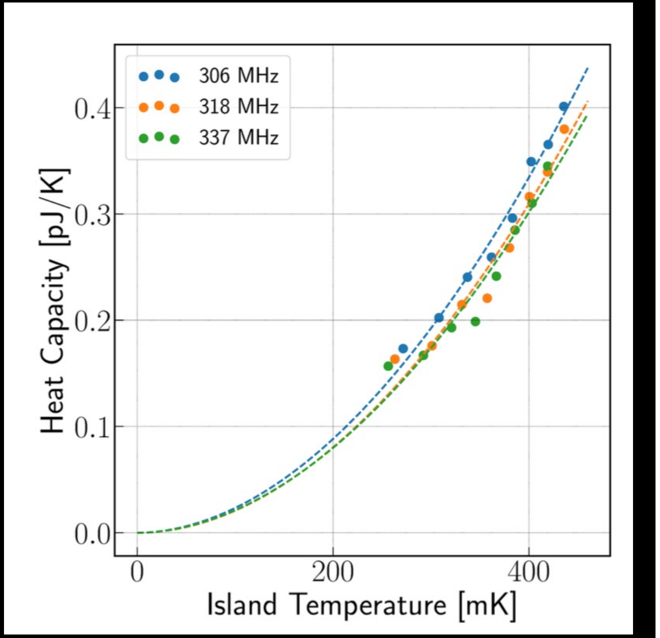


TKIDs physics: thermal kinetic inductance detectors

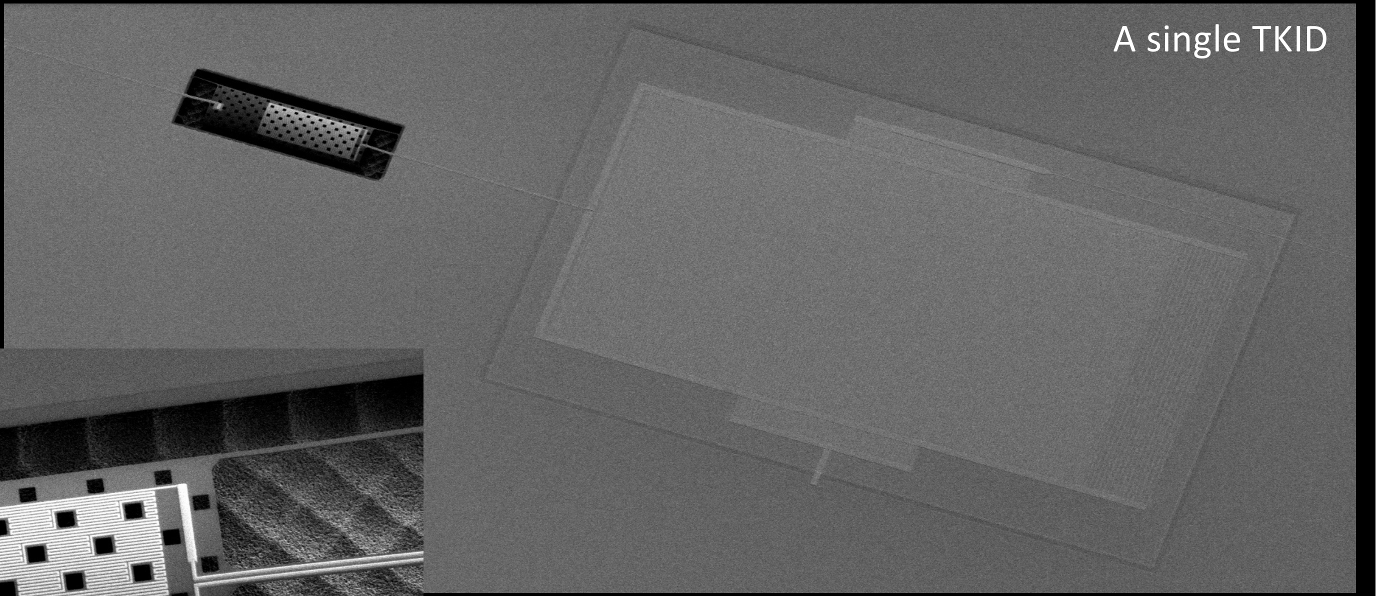


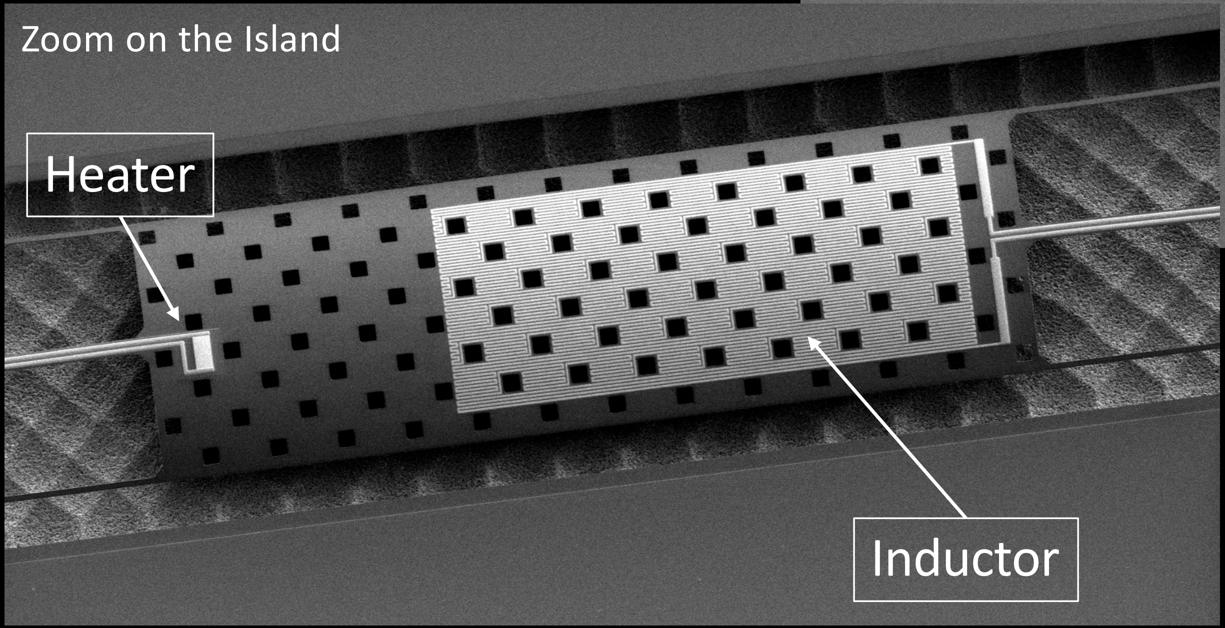
- The photon does not impact directly on the inductor
- Quasiparticle production is mediated by phonons
- The absorber can be a resistor (for calibration) or an antenna: **AC-TKIDs**
- Decoupling design parameters (the inductor is not the antenna)
- The island (in red) is connected to the rest of the wafer via small supports or legs

- $\mathbf{P}_{\mathbf{opt}}$ is the incoming optical power
- $\mathbf{P}_{\mathbf{read}}$ is the readout power
- $\mathbf{P}_{\mathbf{leg}}$ is the power dissipated by the island through the supports

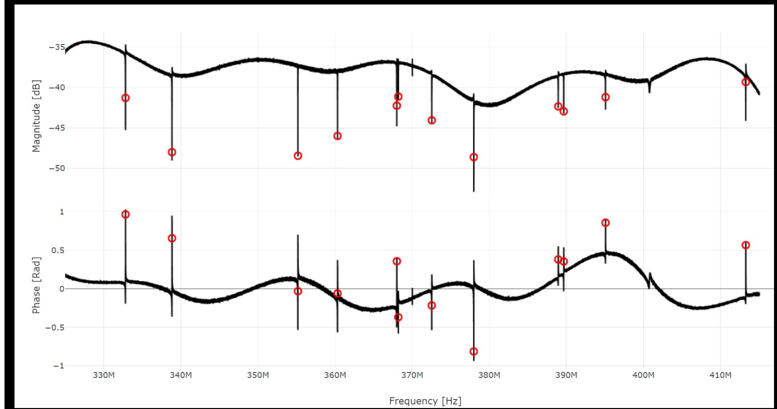


TKIDs physics: thermal kinetic inductance detectors





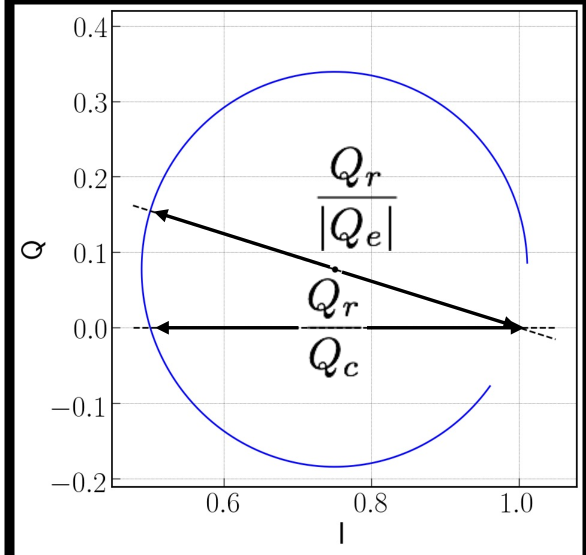
TKIDs physics: thermal kinetic inductance detectors

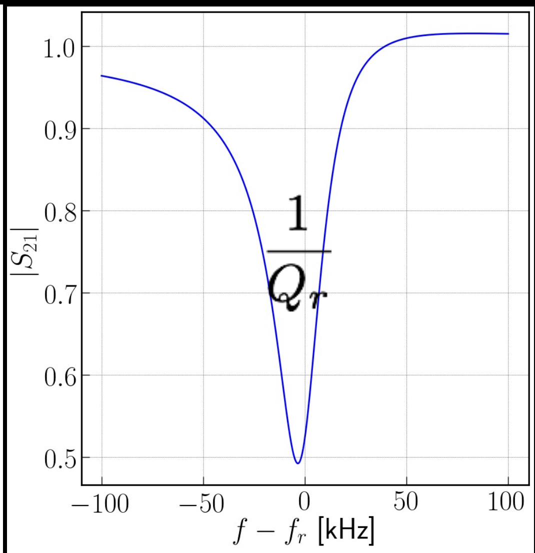


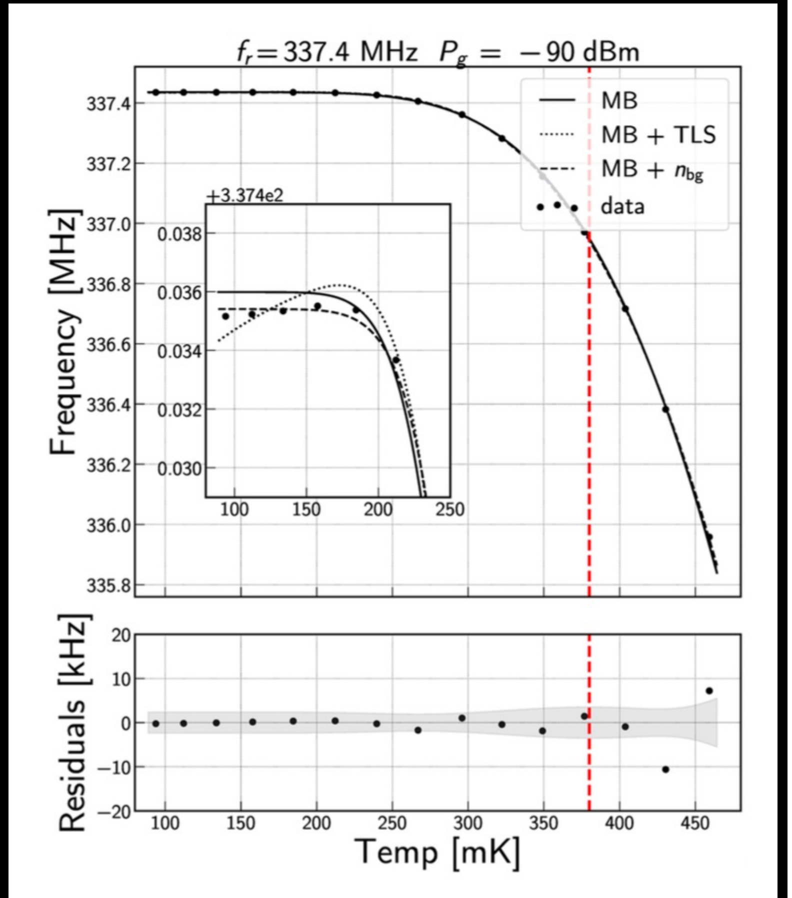
$$S_{21} = 1 - \frac{Q_r}{Q_e} \frac{1}{1 + 4Q_r^2 x^2}$$

Effective coupling

$$Q_e = Q_c \cos(\phi_c) e^{j\phi_c}$$



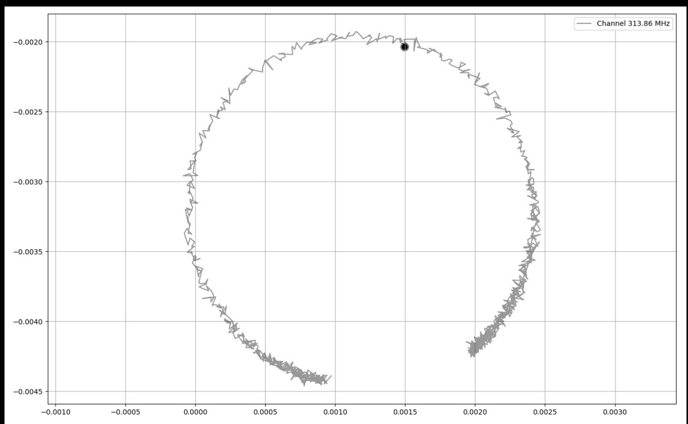




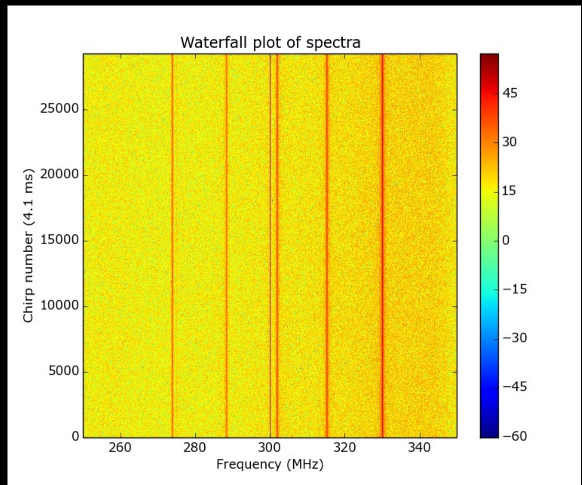
Mattis Bardeen + background quasiparticles is the best fit

Readout strategies

Fixed multi-tone readout:
An RF signal is transmitted on resonance on each detector.
The return signal phase and magnitude are monitored and, using the measured transfer function, converted into frequency and quality factor shifts.
Available on our opensource software



Chirp readout:
A sinusoid with increasing frequency is transmitted on the full bandwidth.
The energy accumulated by the chirp pulse in the resonators is released shortly after.
The return signal spectrum contains the resonators ringdown.
Available on our opensource software

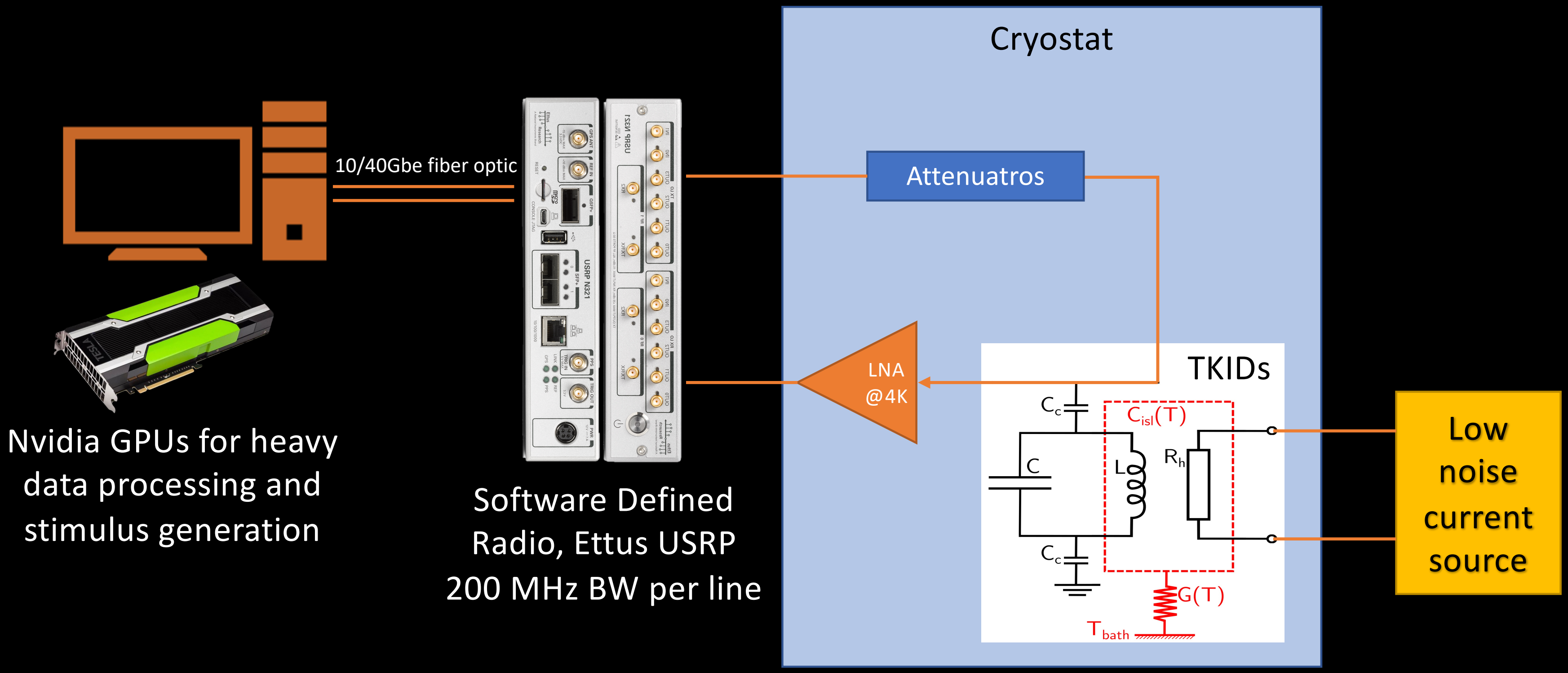


Tone tracking:
Like the single tone readout but in this case the frequency of the generated tones follows the shift of the resonators.
Requires a short loop latency between tx signal generation and rx analysis.
Currently only available on custom FPGAs firmware due to GPU – DAC/ADC loop latency.
https://ui.adsabs.harvard.edu/link_gateway/2018JLTP..193..570K/arxiv:1805.08363

Software available at http://www.its.caltech.edu/~minutolo/gpu_sdr_doc.html

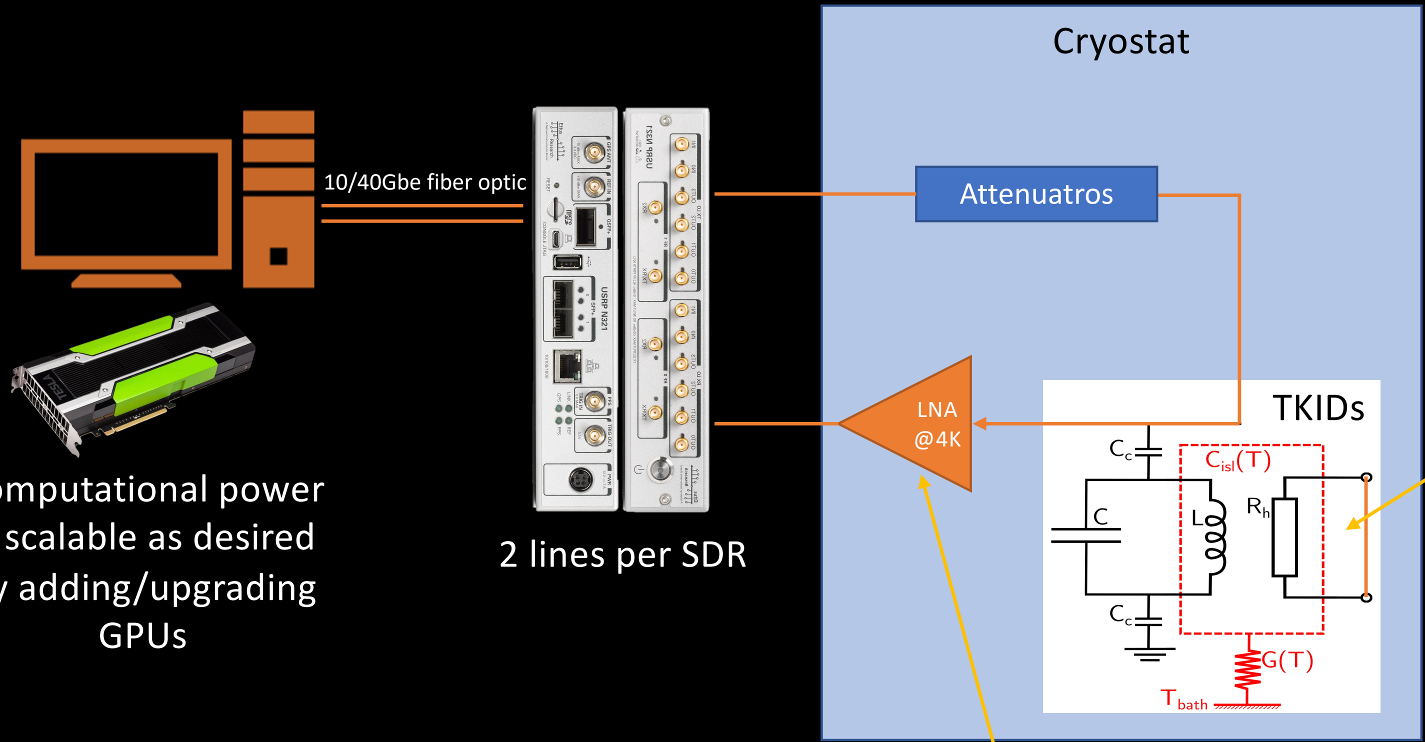
System level design: test arrays

Test arrays have a resistor instead of an antenna on the island



System level design: AC-TKIDs

AC arrays have a 150 GHz antenna on the island: the optical band has been selected to benchmark the camera against existing TES measurements.



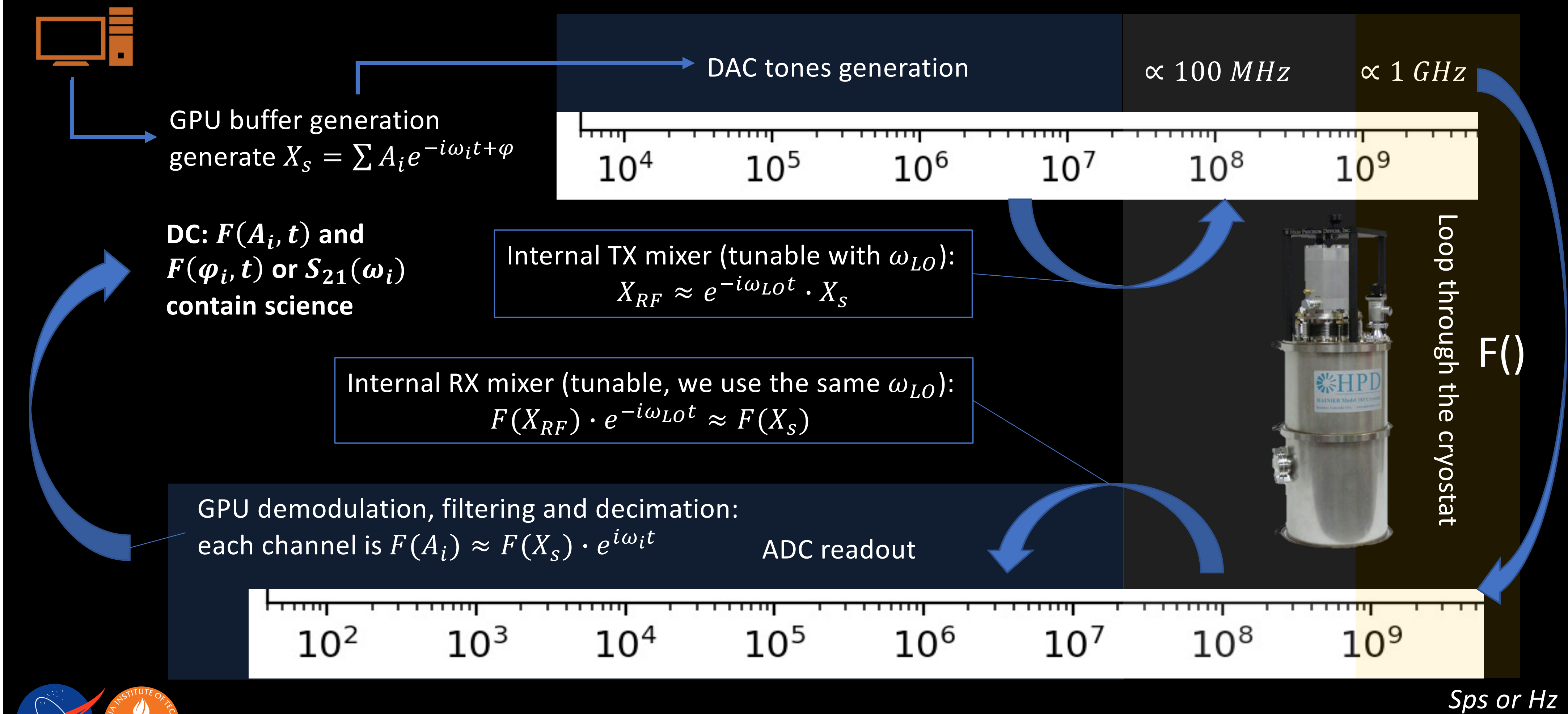
Computational power is scalable as desired by adding/upgrading GPUs

2 lines per SDR

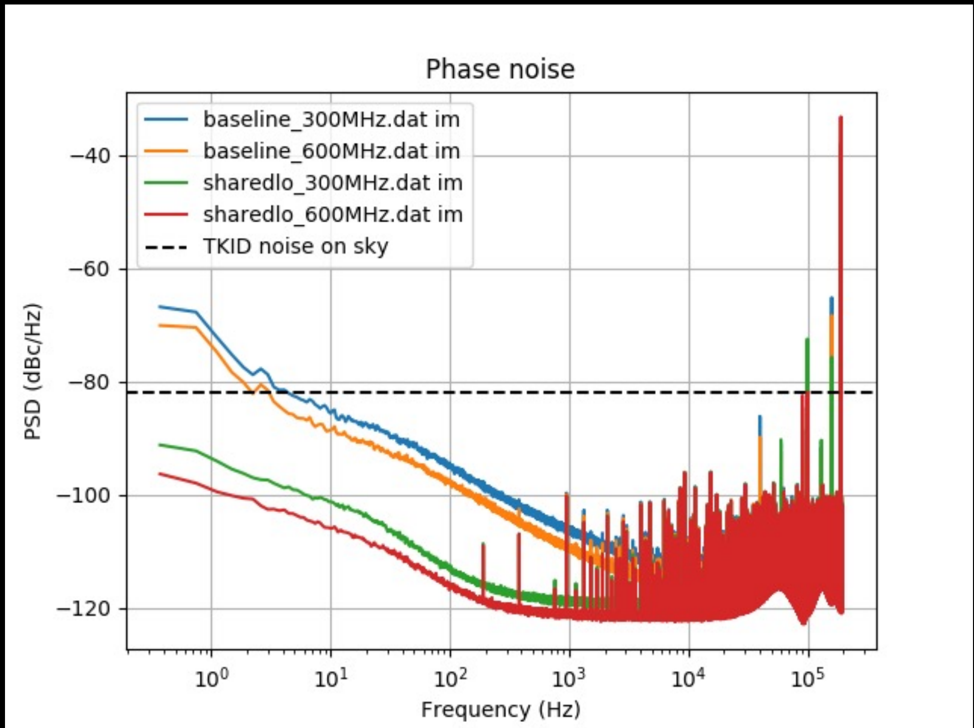
The island has both an antenna and a resistor for calibration purposes

Scaling the technology to multiple tiles introduces one more LNA per line

System level design: frequencies

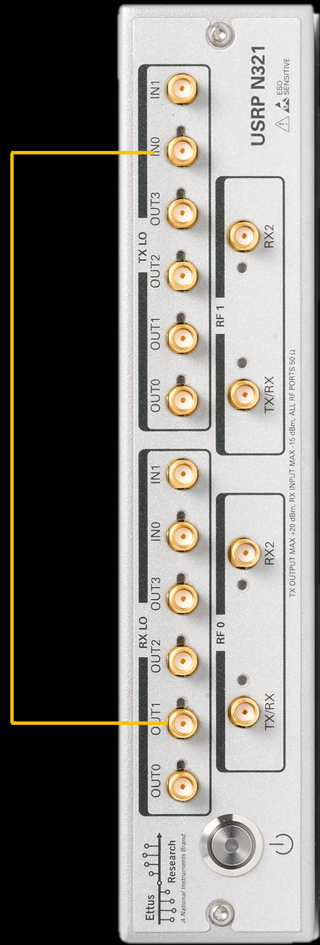


System level design: digression on electronics



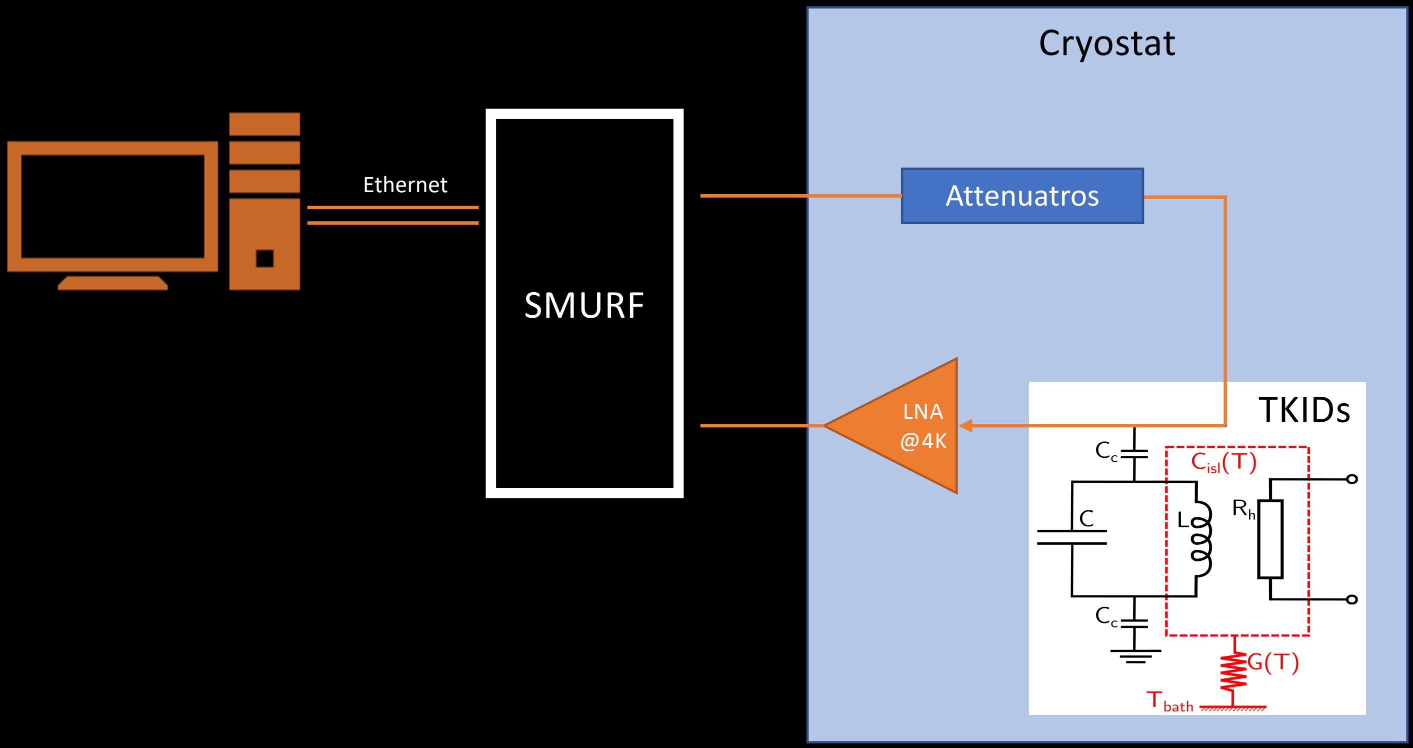
Using a single LO to upmix/downmix the signal improves performance

We could also evaluate using a low phase noise external LO to do this



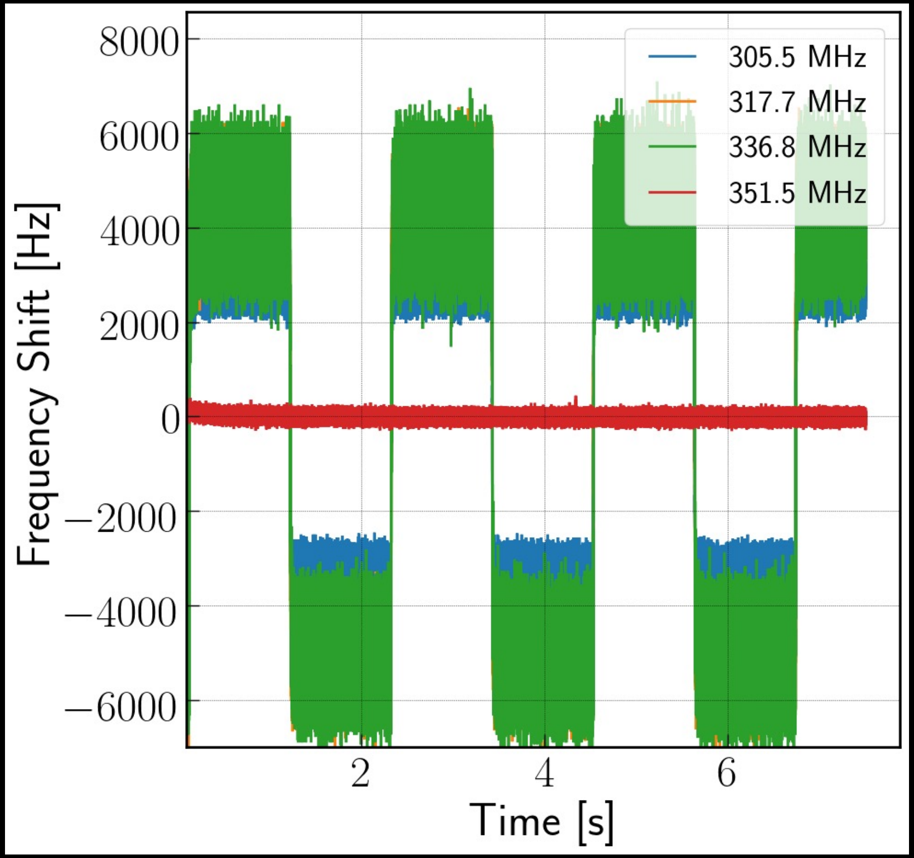
Electronics: TKID – SMURF, tone tracking

SMURF uses tone tracking technology to read the detectors combining the best of both worlds: low noise and high responsivity.

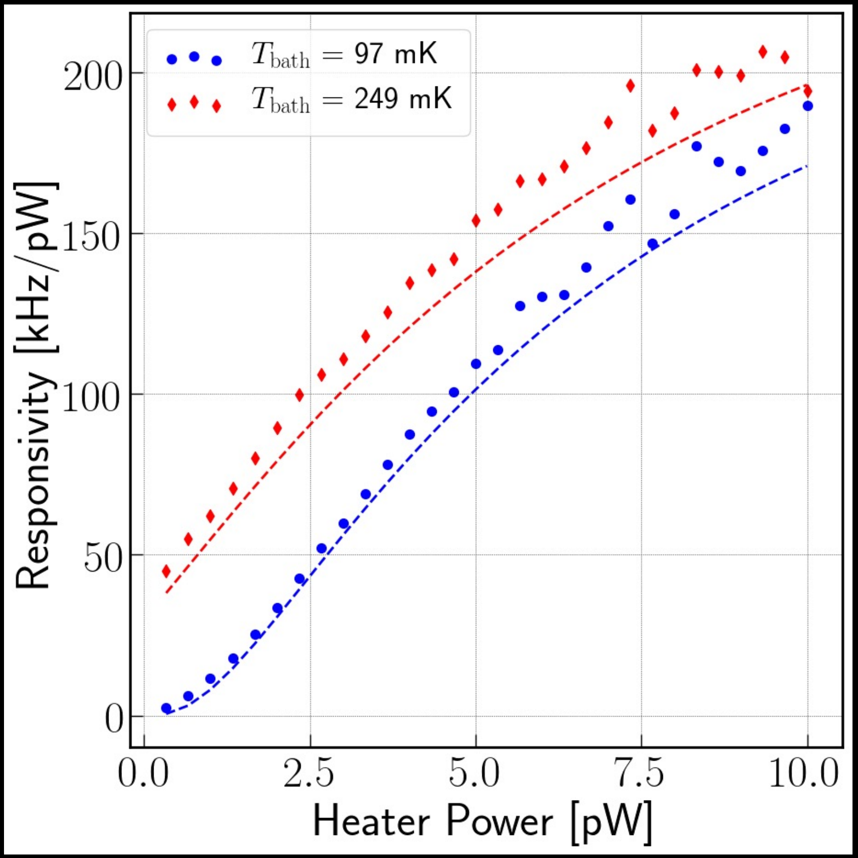


Calibration and responsivity

Driving the resistors on the island with a known current we can calibrate our detectors

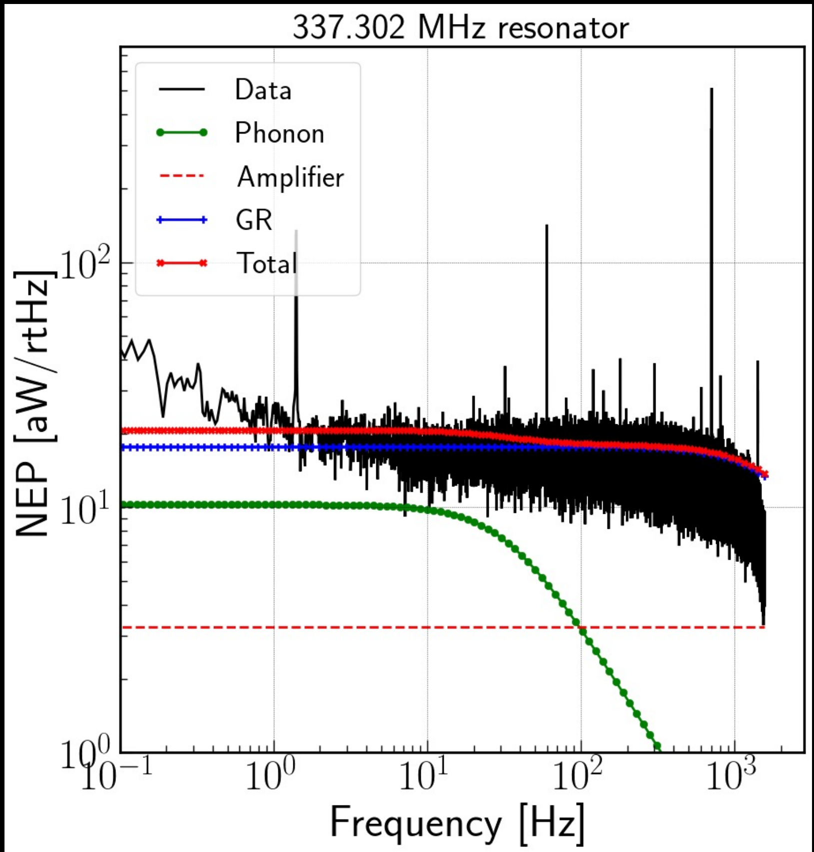


150GHz South Pole atmosphere provides ~5pW loading

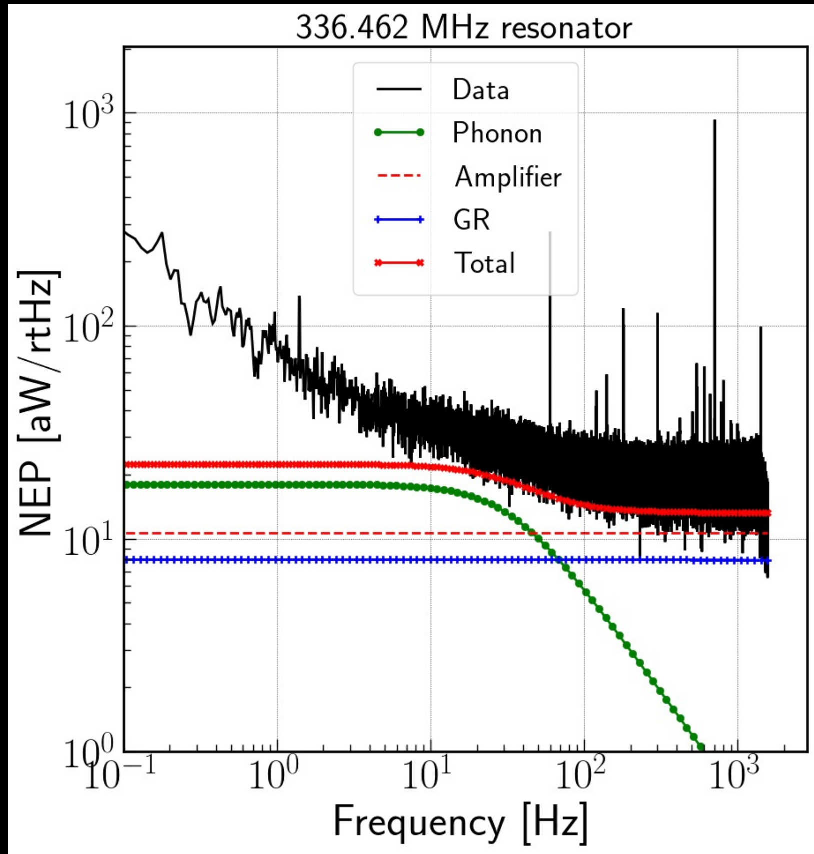


Noise performance (dark)

P_{heater}=4pW T_{isl}=320mK



P_{heater}=10pW T_{isl}=422mK

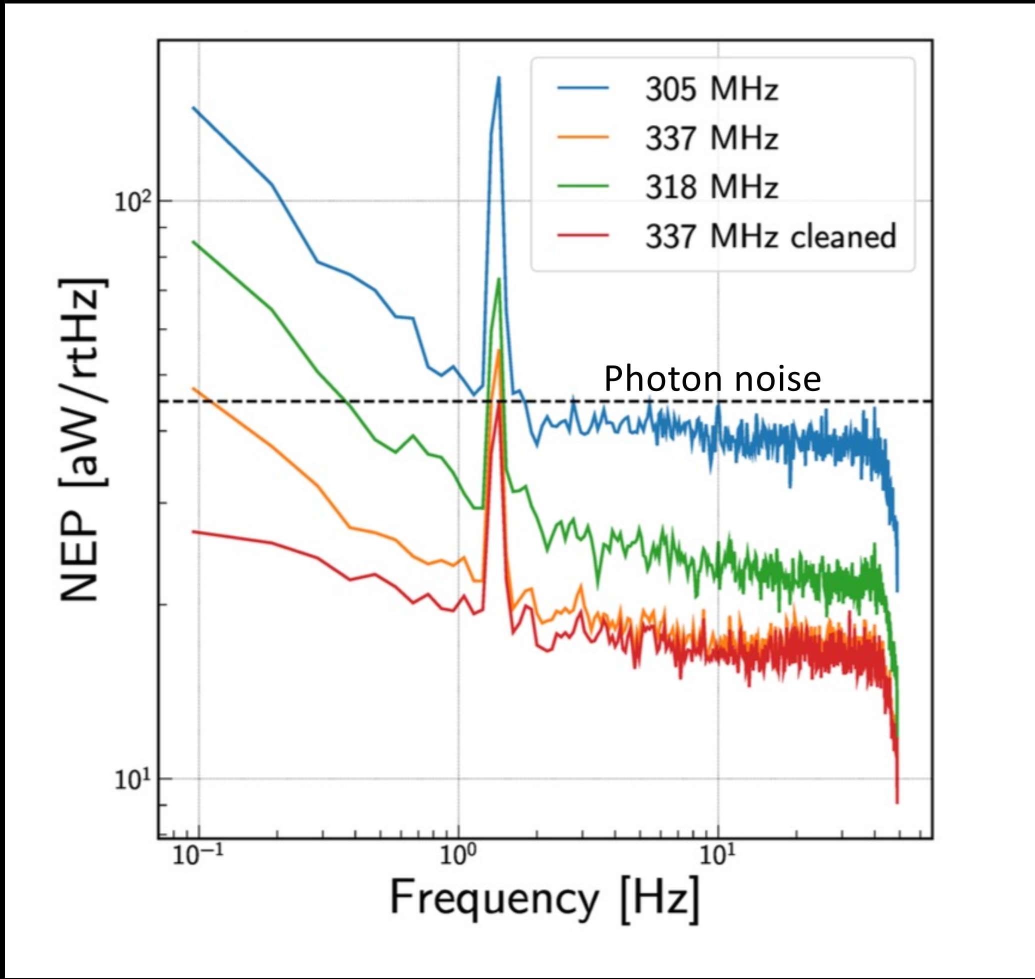


At the South pole we expect ~350mK and 6pW

Detector stability

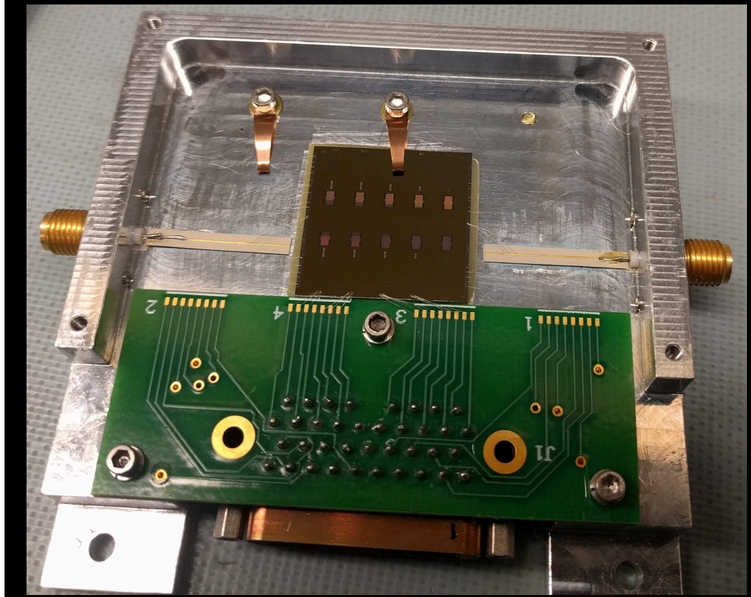
1/f Noise will be reduced by using the electronics in a configuration in which a single LO is present

Furthermore the polarization signal is obtained as a combination between two detectors with polarized antennas – common mode noise won't be critical

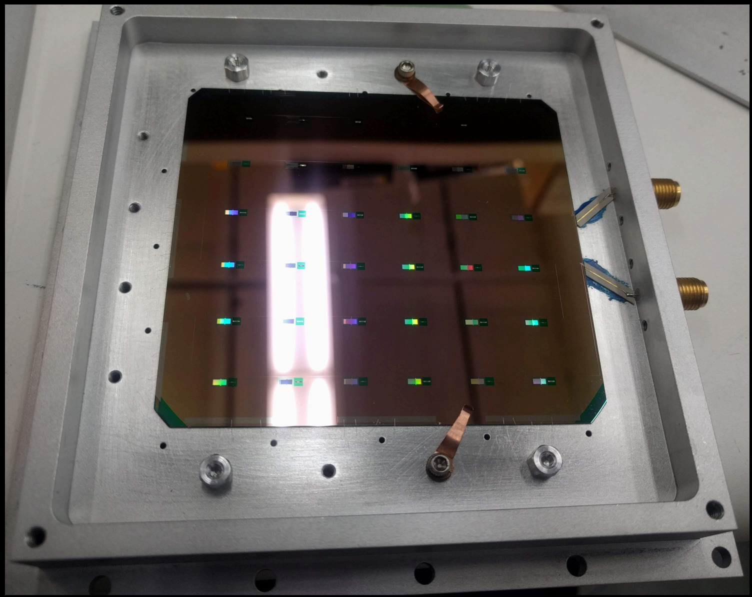


1.4 Hz is the frequency of our pulse tube

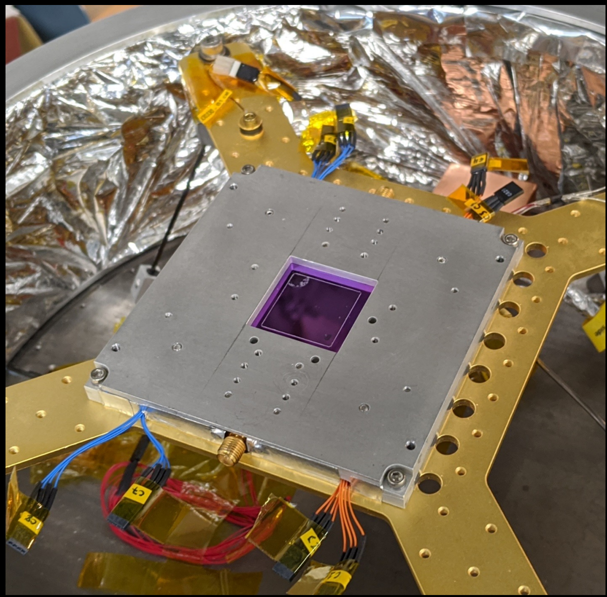
TKID Arrays



Dark device, 10 TKIDs



Dark device, 36 TKIDs, half with island not released from wafer. Allowed cosmic ray susceptibility testing

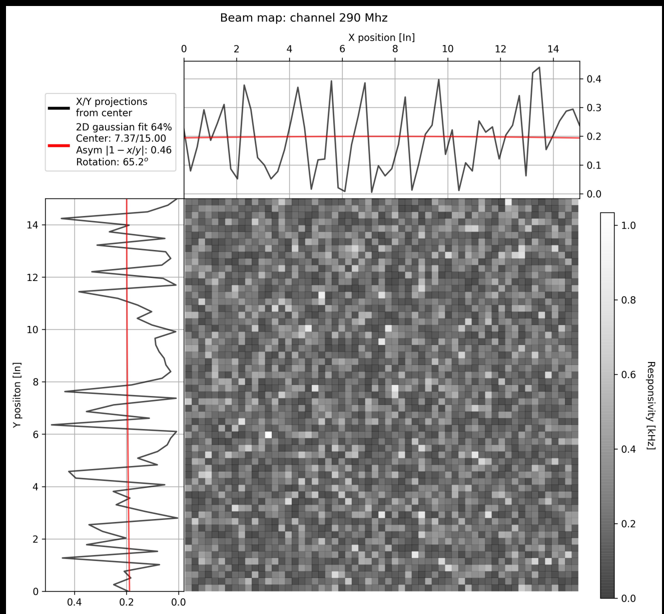


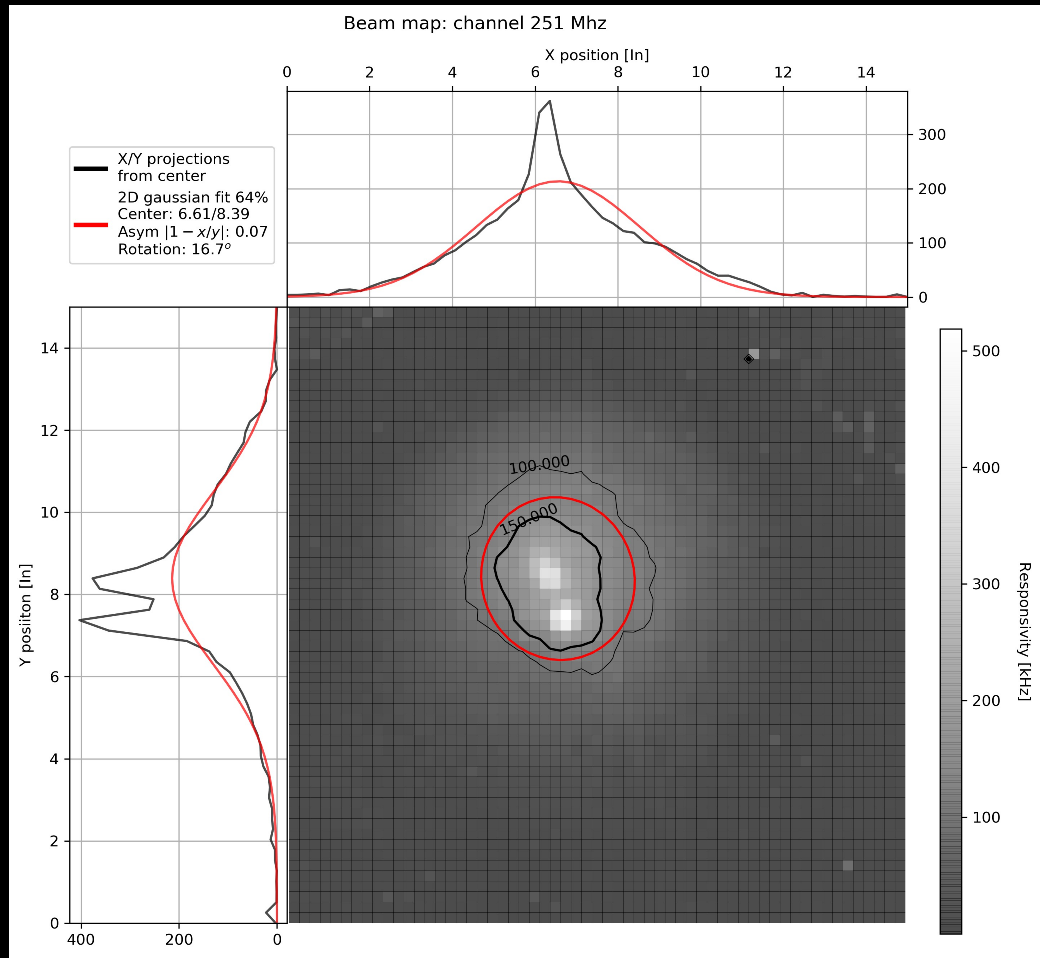
12 AC-TKIDs:
First light

First light: beam maps

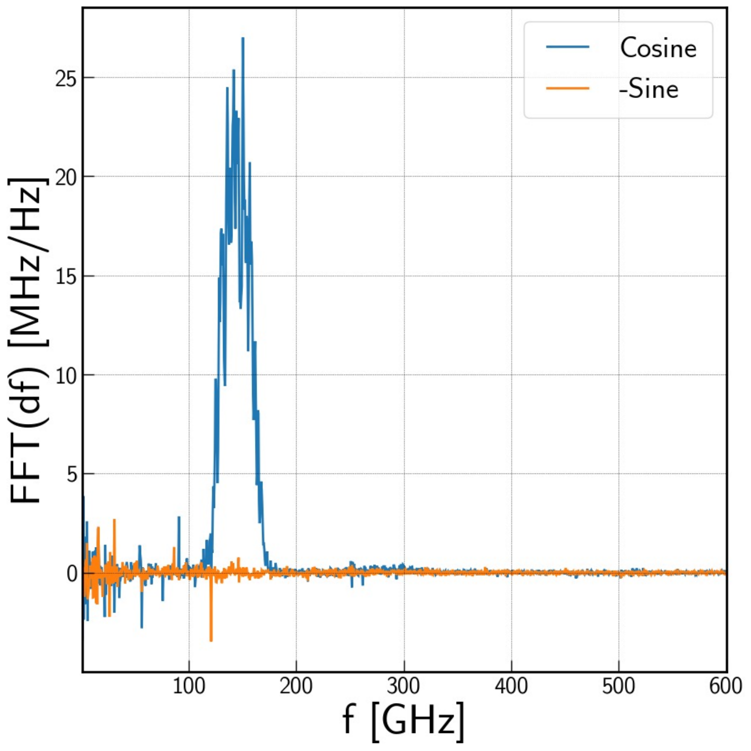
First AC-TKIDs beam map:

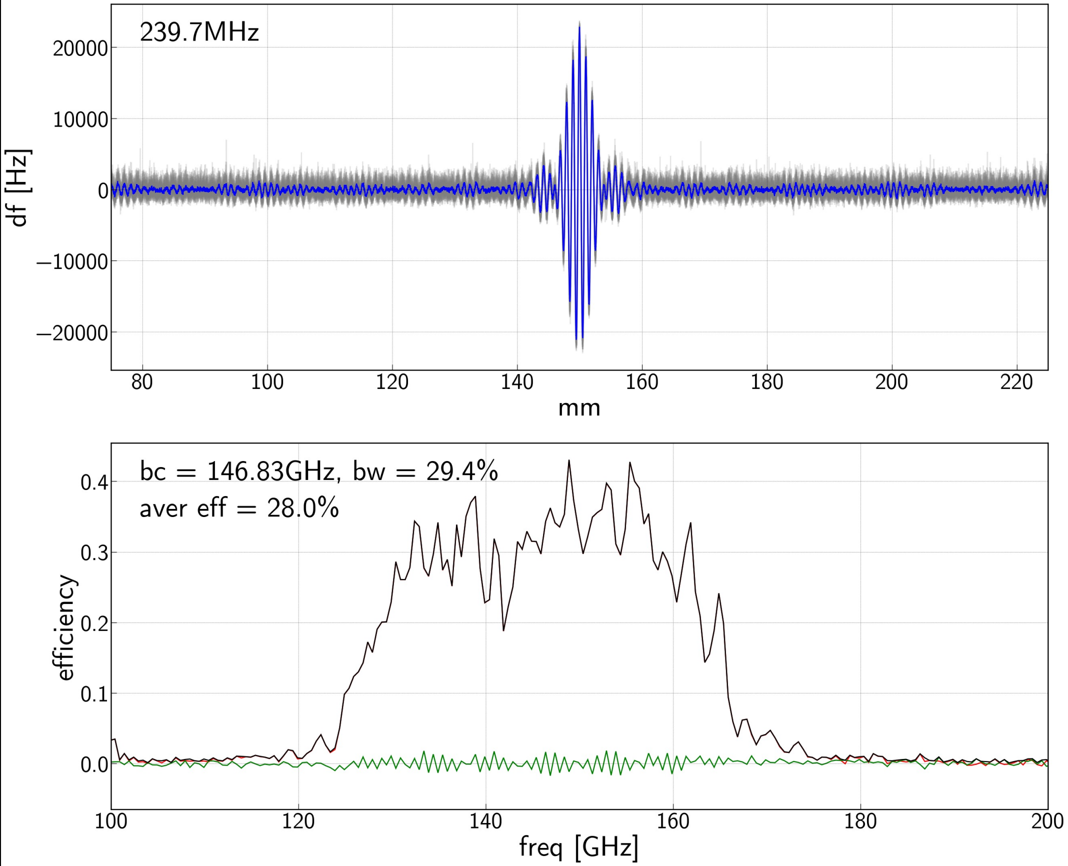
- the beam profile look gaussian(ish)
- Next iteration has learned a lot from this run
- Detector non-linearity has been addressed using fast-chirp readout
- On the same tile *dark* detectors were present: the pickup of detectors without antenna is negligible (!)





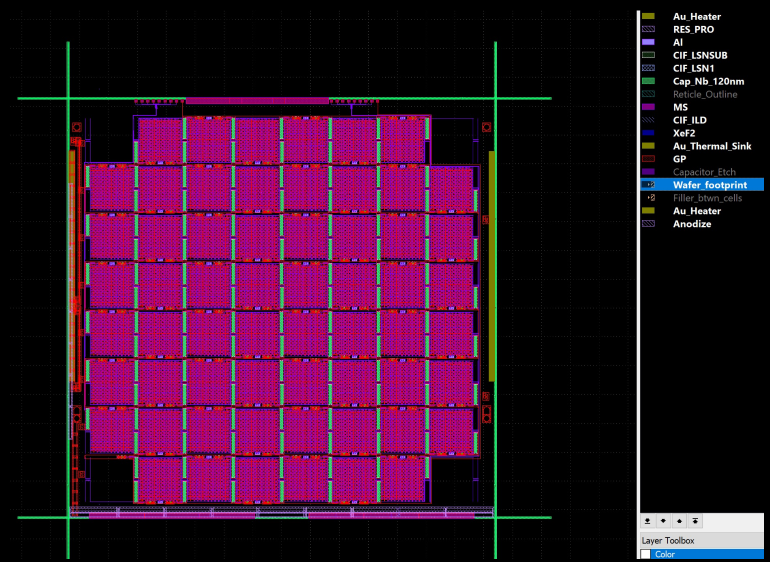
FTS Spectroscopy



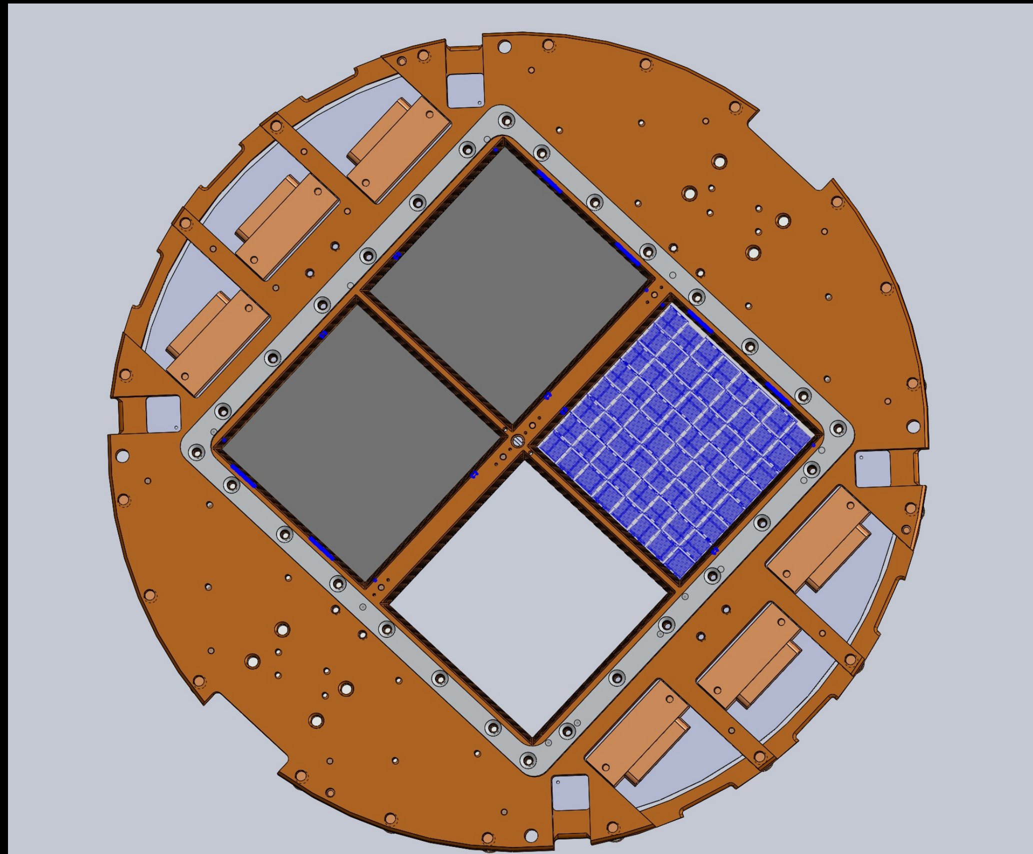


- Band determined by microstrip filter between antenna & bolometer
- Design: 27% around 145GHz
- Used Fast chirp readout to deal with nonlinearity also in this case
- Optical efficiency: 28%

Current development and plans

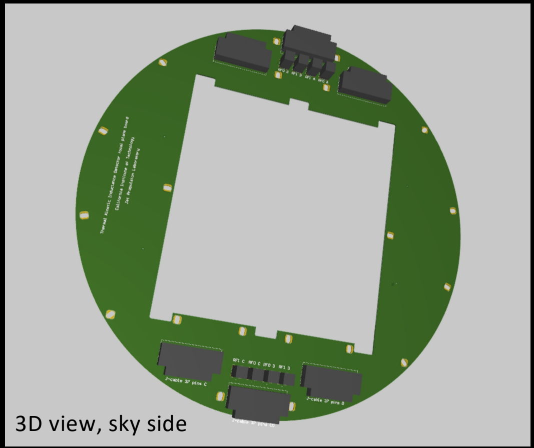


- Currently fabricating full arrays of antenna-coupled TKIDs
- Retrofitting Keck Array camera for a 150GHz Focal Plane
- To deploy to BICEP Array in 2021-22 austral winter
- Developing modular version for a BICEP Array camera
- Will deploy 220-270GHz camera 2022-23 austral winter
  - part microwave-mux TESes
  - Part TKIDs

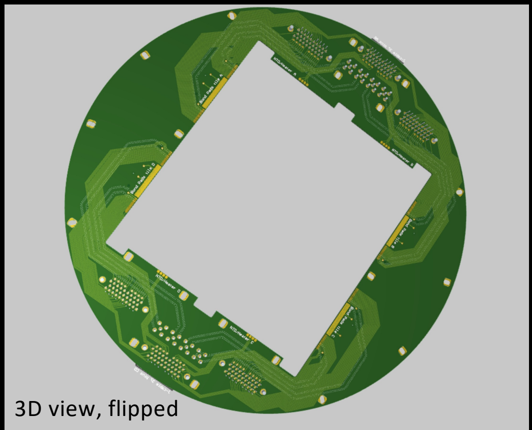


128 TKIDs per tile, 4 tiles

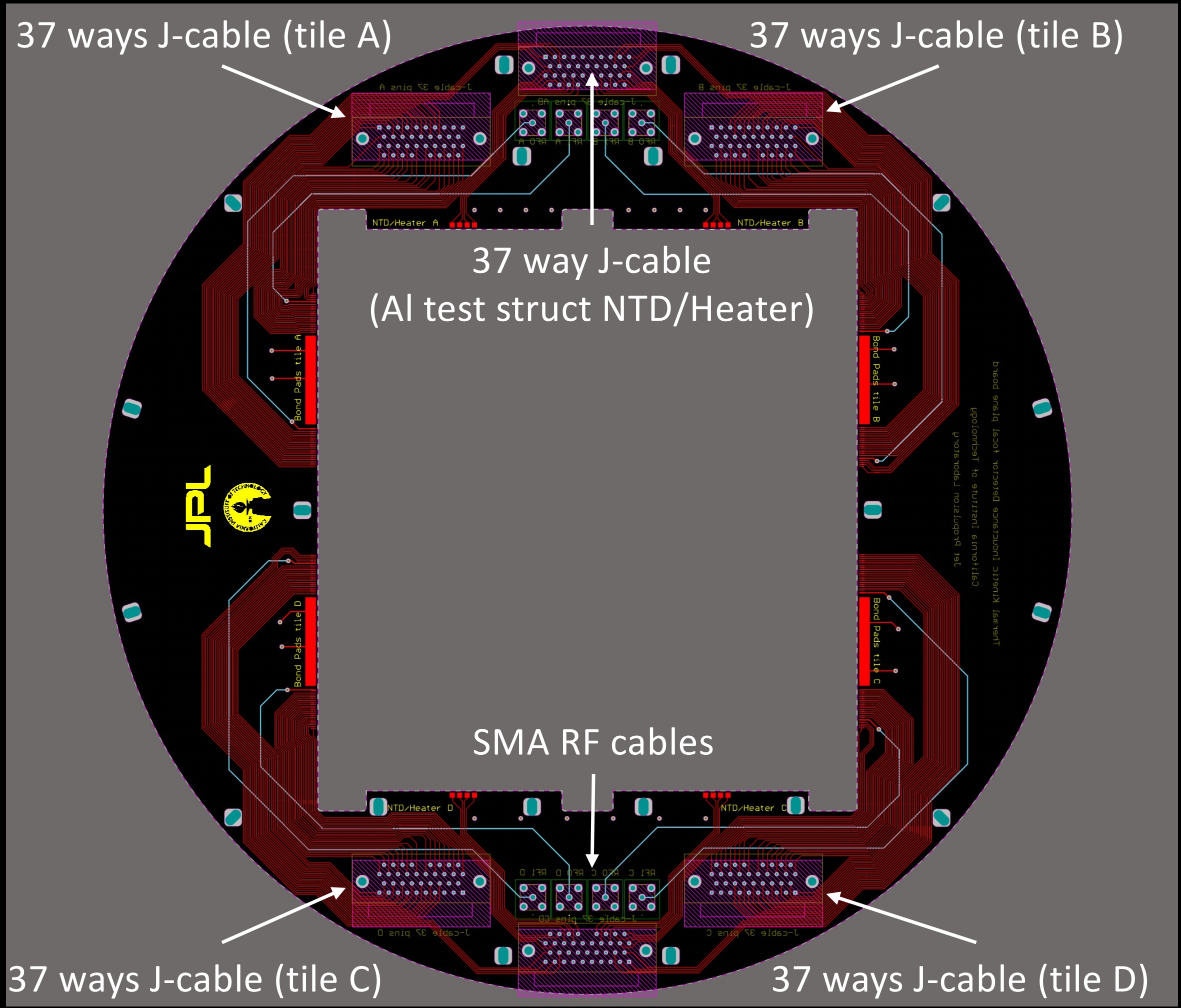
Current development and plans: focal plane distribution board



3D view, sky side



3D view, flipped

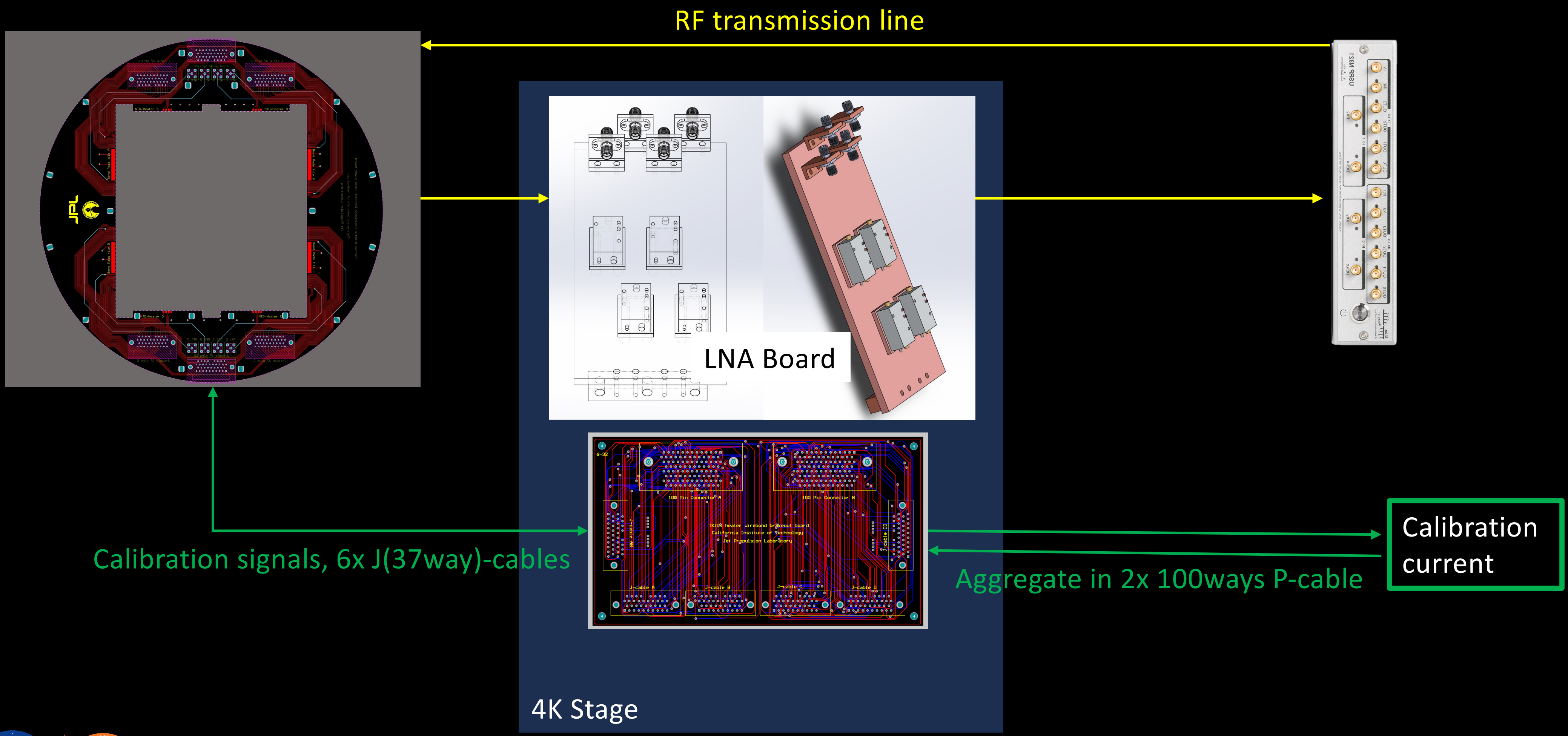


Lines breakout per tile: total

- 8 diff heater: 64
- 2 diff AL test structure: 16
- 4NTD+/Heater: 16
- 2 RF lines per tile: 8 SMA

Six layers board: heater signals separated from RF signals with 2x ground planes

Current development and plans: calibration signal distribution



Deployments plans