DEVELOPMENT OF LARGE SCALE CMB DETECTOR ARRAYS AT ARGONNE


Photo: Joshua Montgomery

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- Fermi National Acceleratory Lab
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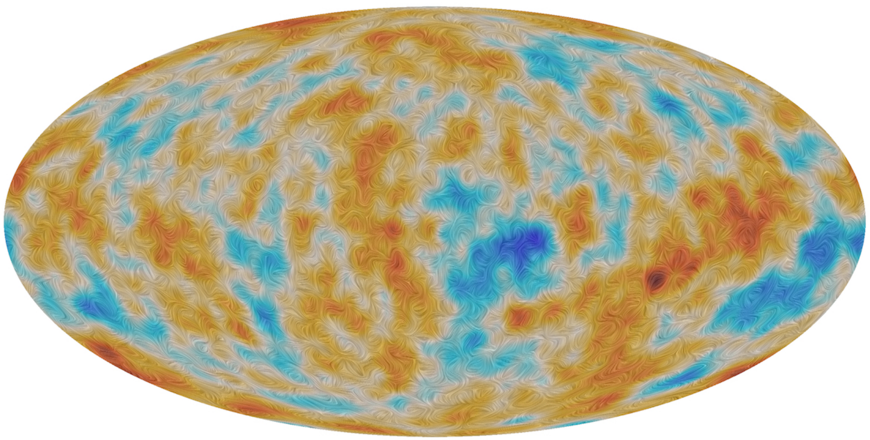
- University of Toronto

OUTLINE

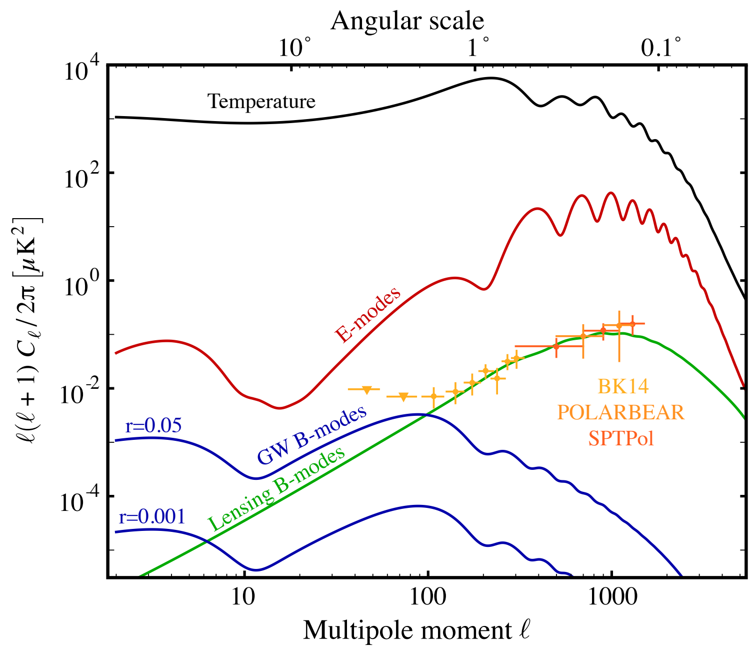
- Motivation
- CMB Detector Arrays
- Detector Array Fabrication
- Future Developments – Moving towards CMB-S4

COSMIC MICROWAVE BACKGROUND

CMB Science



Credit: ESA/Planck

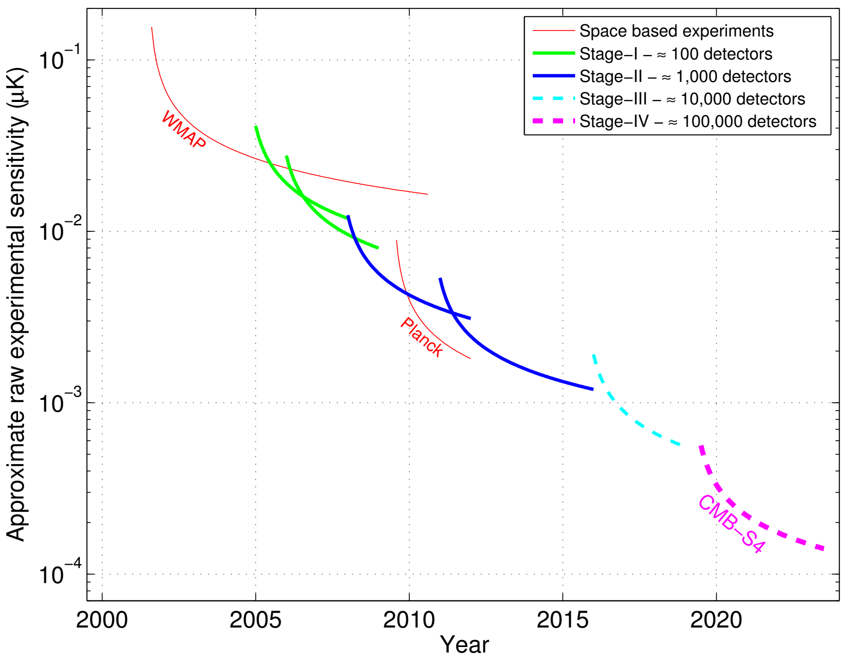


- Temperature variations tell us about distribution of matter in the universe
- E-mode (curl free) polarization from density perturbations
- B-mode (divergence free) polarization from lensed E-modes and gravitational waves
- Science products
  - scalar-to-tensor ratio, r
  - effective number of relativistic species, ∆Neff
  - sum of neutrino masses, $\sum m_v$

COSMIC MICROWAVE BACKGROUND

CMB Experimental Scaling

- Detectors in ground-based experiments are already mostly background-limited (largest noise source is photon noise from the sky)
- Measurements of B-modes requires increasingly sensitive experiments
- More sensitivity = More detectors



Year	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015, 2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS SPT clusters)
2017, 2018, 2019, 2020	Stage 3 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI SZ Clusters)
2021, 2022, 2023, **Target**	Stage 4 CMB-S4 ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	**0.015eV** (DESI BAO $+\tau_e$ prior)	**1250** (DESI +LSST S4 Clusters)

COSMIC MICROWAVE BACKGROUND

CMB-S4

- Single experiment bringing together the CMB community
  - Two sites: South Pole and Atacama
  - Both small (0.5 m) and large (6 m) aperture telescopes
- ~ 510K detectors in 9 frequency bands
  - TES detectors
  - Feedhorn coupling
  - Dual-polarization, dichroic pixels
- Community fabrication effort with detectors made at several sites (ANL, LBNL/SeeQc, SLAC, others….)

SAT receivers

- 18 SATs with a total of 153,232 detectors

	LF	CF_{low}	CF_{high}	HF
Center frequency (GHz)	30/40	85/145	95/155	220/270
Primary lens diam. (cm)	55	55	55	44
FWHM (arcmin)	72.8	25.5	22.7	13
Fractional bandwidth	0.3	0.24	0.24	0.22
NET ($\mu K\sqrt{s}$) per detector	177/224	270/238	309/331	747/1281
N_{det} per optics tube	288	3524	3524	8438
Number of optics tubes	2	6	6	4
Number of detectors	576/576	21,144/21,144	21,144/21,144	33,752/33,752

LAT receivers

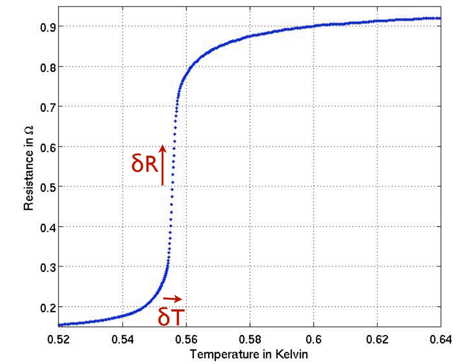
- 3 LATS with a total of 357,952 detectors

	ULF	LF	MF	HF
Center frequency (GHz)	20	27/39	93/145	225/278
FWHM (arcmin)	10.0	7.4/5.1	2.2/1.4	1.0/0.9
Fractional bandwidth	0.25	0.22/0.46	0.38/0.28	0.27/0.16
NET ($\mu K\sqrt{s}$) per detector	438	383/250	302/356	737/1840
N_{det} per optics tube	160	320/320	3460/3460	3744/3744
N_{tubes} wide survey (2 LATs)	0	2	12	5
N_{tubes} delensing (1 LAT)	1	2	12	4
Number of detectors	576/576	21,144/21,144	21,144/21,144	33,752/33,752

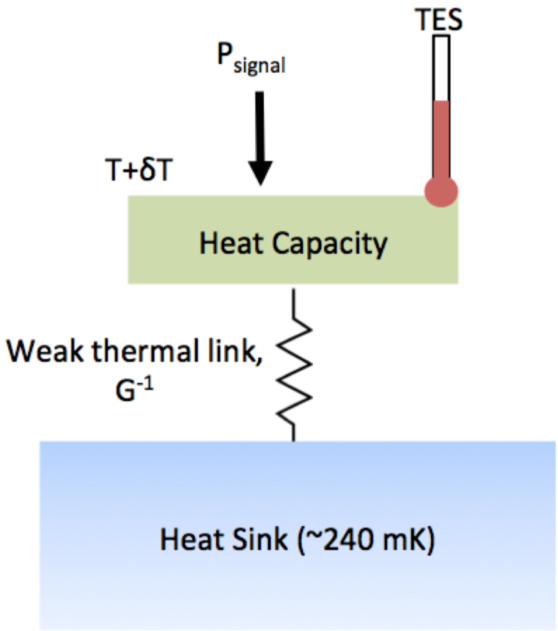
CMB-S4 Science Case, Reference Design, and Project Plan; arXiv:1907.04473

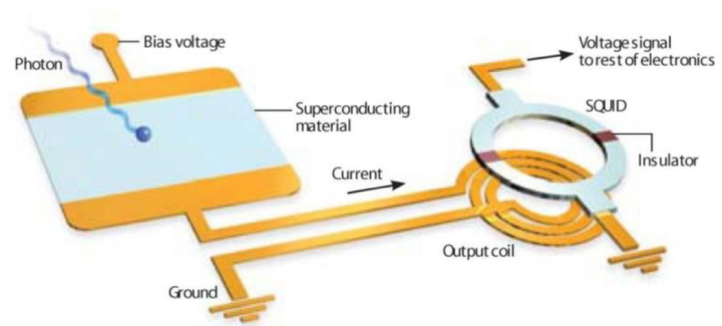
CMB DETECTOR ARRAYS

Transition Edge Sensors (TES)



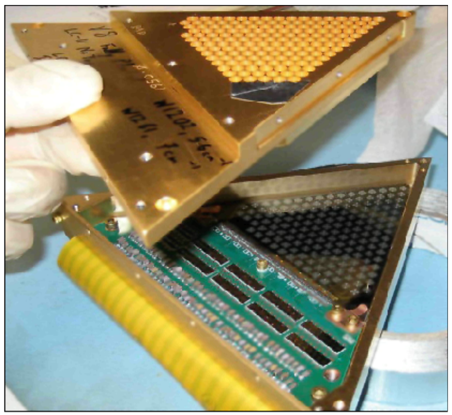
- Most commonly used detector in current CMB experiments
- Superconducting Thermistor
- Voltage bias in the middle of superconducting – normal transition
  - Negative ETF stabilizes bias points and speeds up detector response
  - Can be DC or AC biased
- SQUID amplifier based readout
  - Time Domain Mux (TDM)
  - Frequency Domain Mux (FDM)
- Noise levels sub-dominate to other noise sources (e.g. readout and sky)

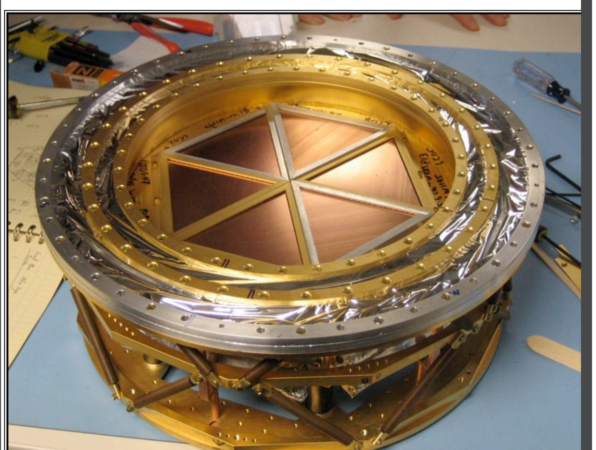




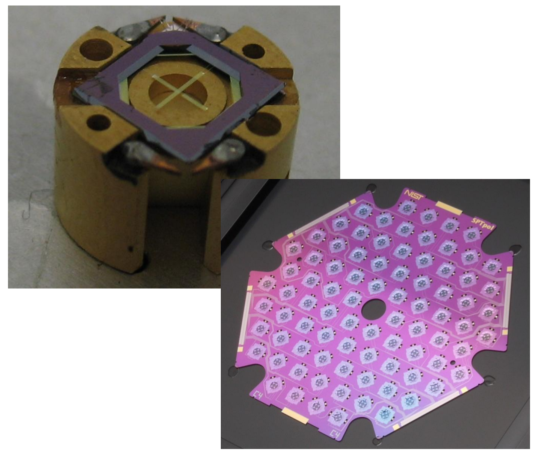
CMB DETECTOR ARRAYS

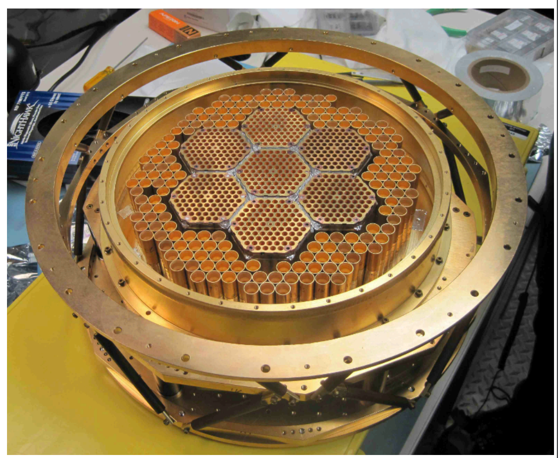
SPT stages



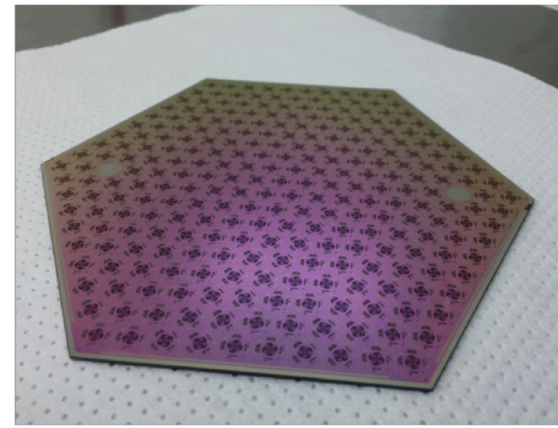


SPT-SZ
960 detectors
Single-Pol, single-chroic pixel





SPT-Pol
1,536 detectors
Dual-Pol, single-chroic pixel

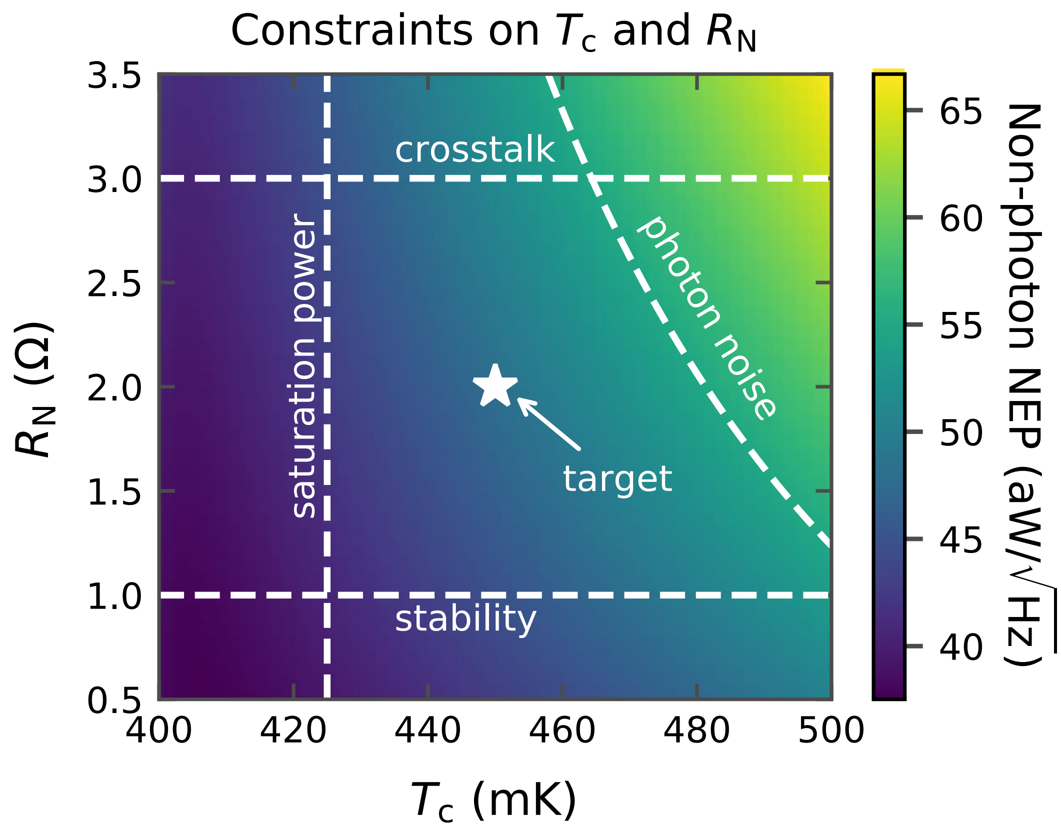


SPT-3G
16,260 detectors
Dual-Pol, multi-chroic pixel

FABRICATION OF SPT-3G DETECTOR ARRAYS

Detector Design

- Science drivers
  - Frequency Bands
  - Saturation Powers
  - Noise levels
- Practical Drivers
  - Cryostat base temperature
  - Telescope optics
  - Readout system
- Need control over detector parameters
  - T_C
  - Rn
  - G
- Depending on design, parameters are degenerate

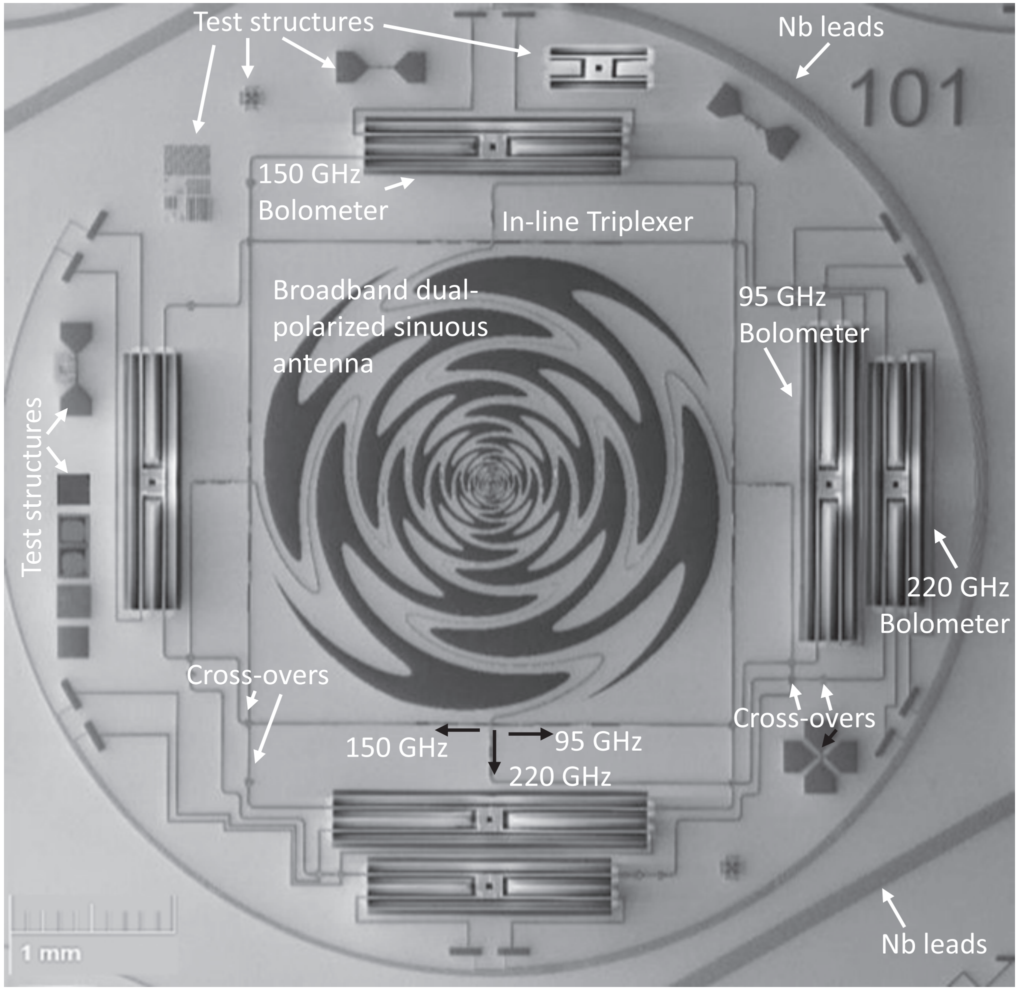


F.W. Carter, et. al. in J. Low Temp. Phys. 1 (2018).

FABRICATION OF SPT-3G DETECTOR ARRAYS

Pixel Layout

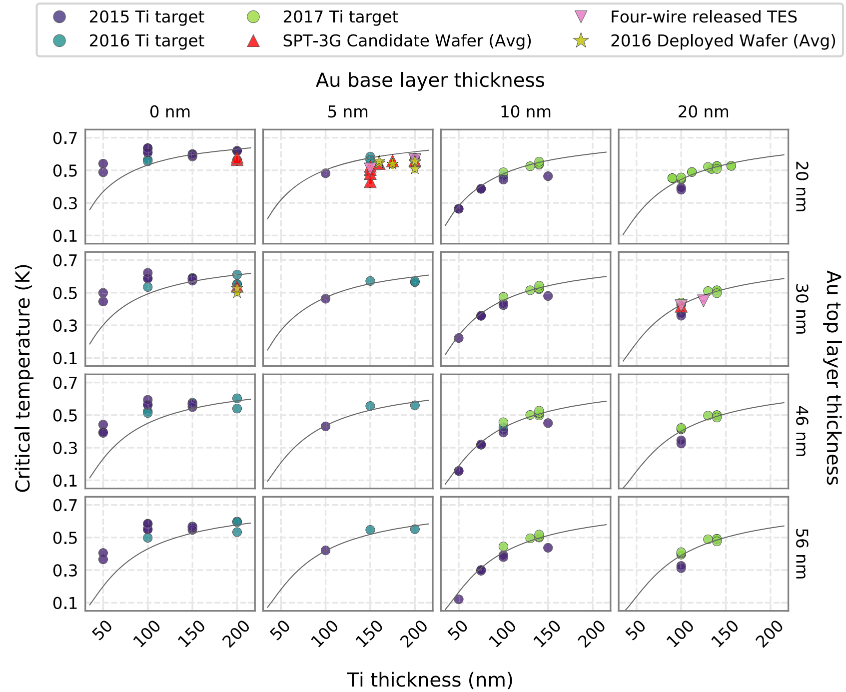
- 6 TES per pixel
  - Dual polarization
  - Tri-chroic (95, 150, and 220 GHz)
- Key components
  - Broadband sinuous antenna
  - In pixel channelizing
  - Microwave crossovers
- 271 pixels on a 6” wafer (1626 TES per wafer)
- 17 Step Fabrication process
- Batch of 5 wafers takes ~ 1 month to produce



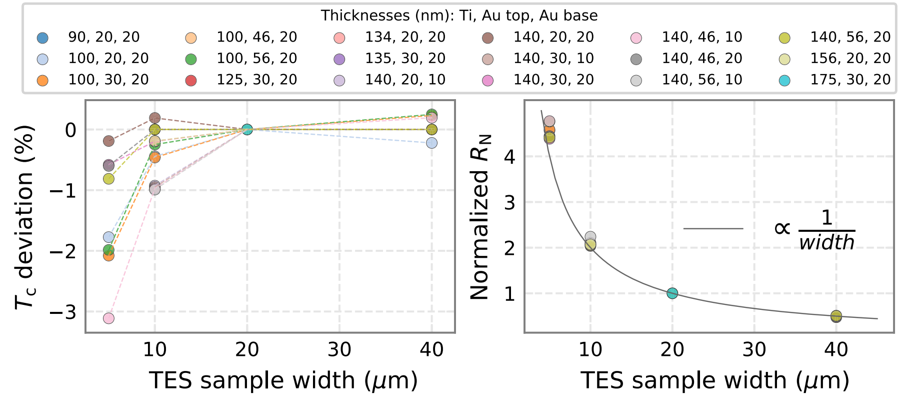
C.M. Posada, et.al. in Supercond. Sci. Technol. **28**, 1 (2015).

FABRICATION OF SPT-3G DETECTOR ARRAYS

T_C Engineering



- Ti/Au/Ti/Au Quadlayer
  - Base Ti helps adhesion
  - Both Au layers help to suppress T_C
  - Top Au layer limits oxidation of the Ti
- Control T_C using layer thickness
- Control R_n using TES width
- Material properties can very with each new sputtering target



F.W. Carter, et. al. in J. Low Temp. Phys. 1 (2018).

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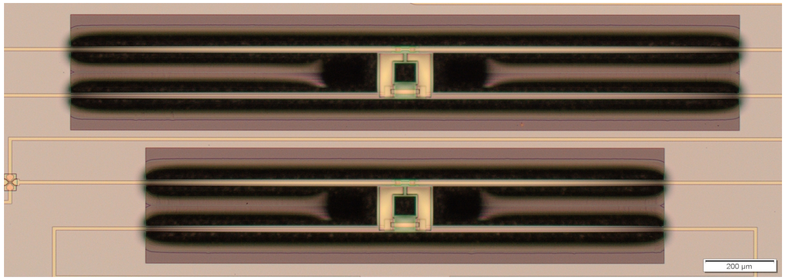
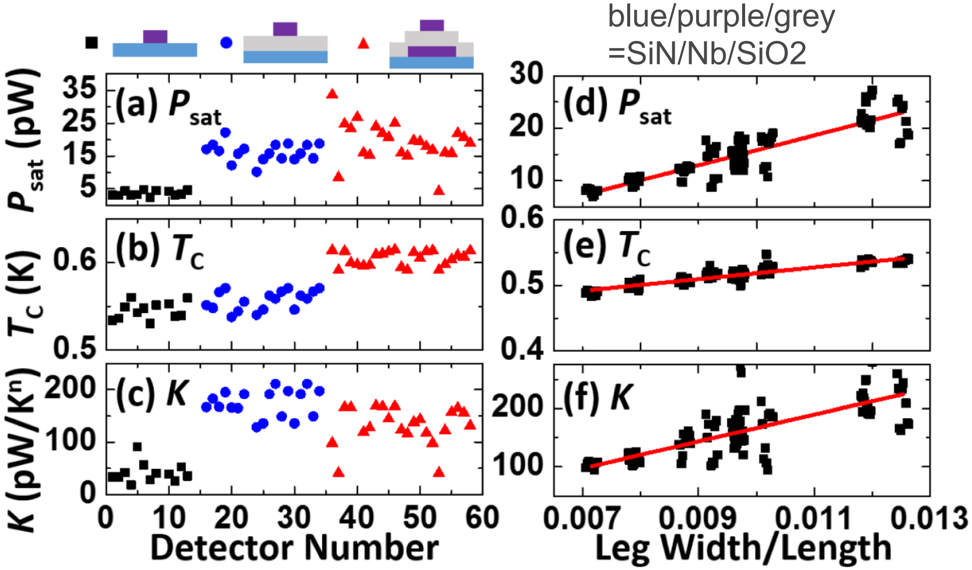
FABRICATION OF SPT-3G DETECTOR ARRAYS

‘G’ Engineering

- G is a function of leg geometry and material parameters
- G is determined from measurements of detector saturation power vs temperature
  - $P_{sat} = G^*(T^n - T^n_{bath}) / nT^{n-1}$
- Measurements confirm that:
  - Conductance scales as leg width / length for constant thickness
  - Microstrip dielectric has major impact on G





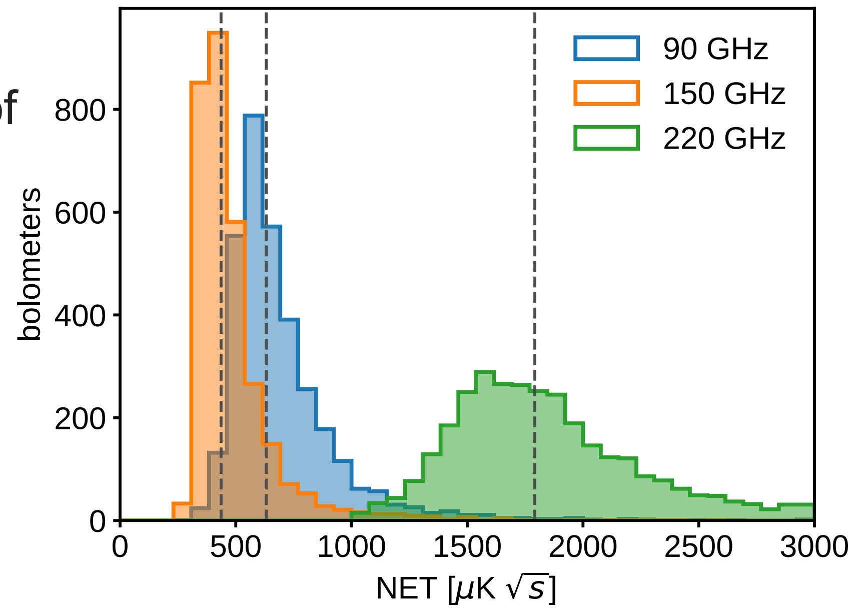
J. Ding, et.al. in IEEE Trans. Appl. Supercond. **27**, 1 (2017).

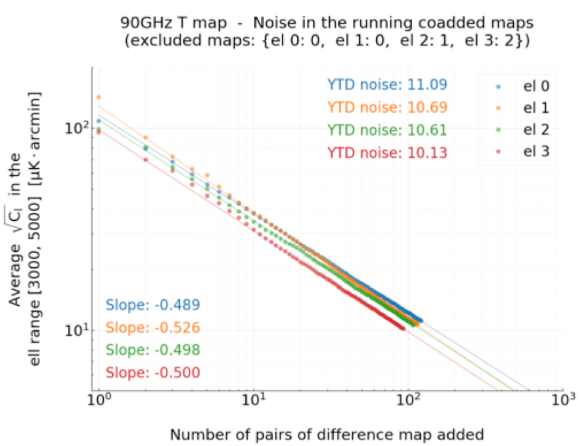
FABRICATION OF SPT-3G DETECTOR ARRAYS

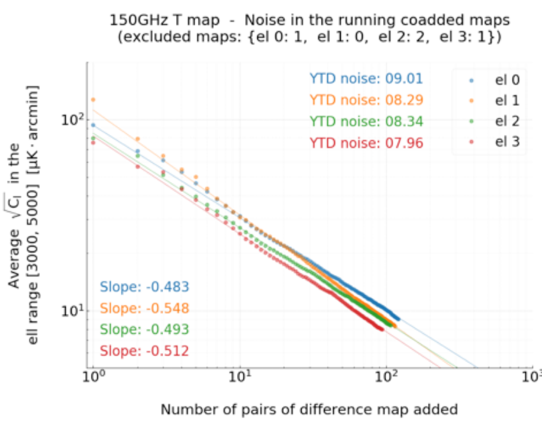
SPT-3G Array Performance

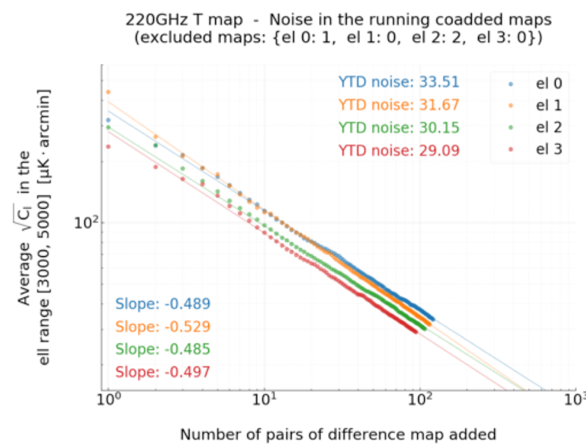
Detectors are as good as one can get!

- Detector noise dominated by fluctuations of absorbed photons
  - measured on sky
  - NO GAIN from lower noise detectors
- Array mapping speed
  - 9 / 7.5 / 30 μK √s in 90 / 150 / 220 GHz



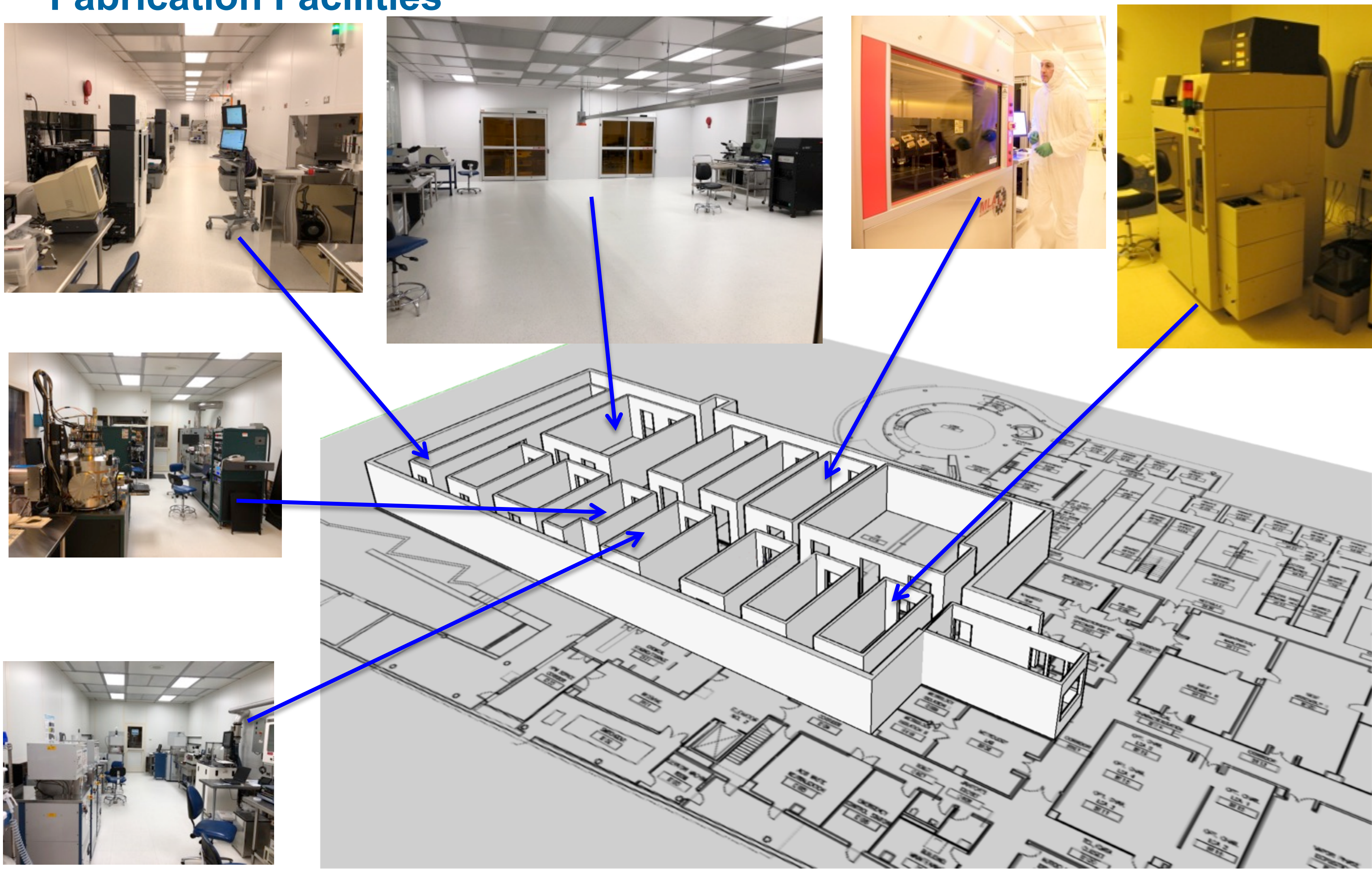






MOVING TOWARDS CMB-S4

Fabrication Facilities

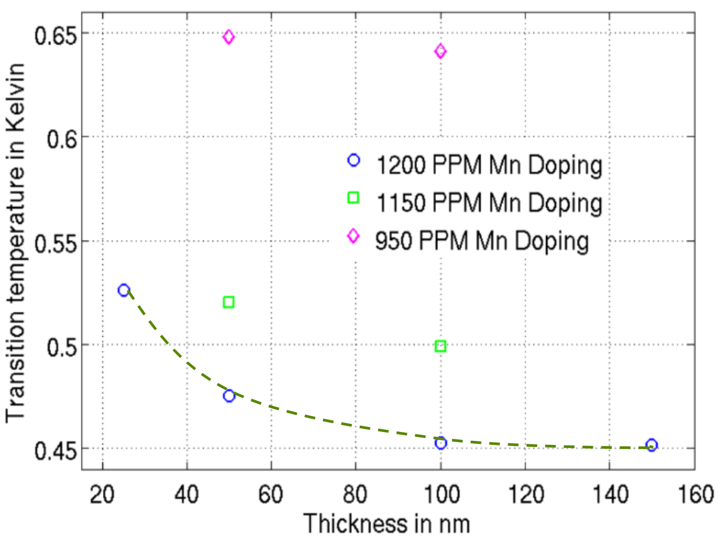


17,500 sq. ft. - Class 100-1000 - Bay-and-chase design

MOVING TOWARDS CMB-S4

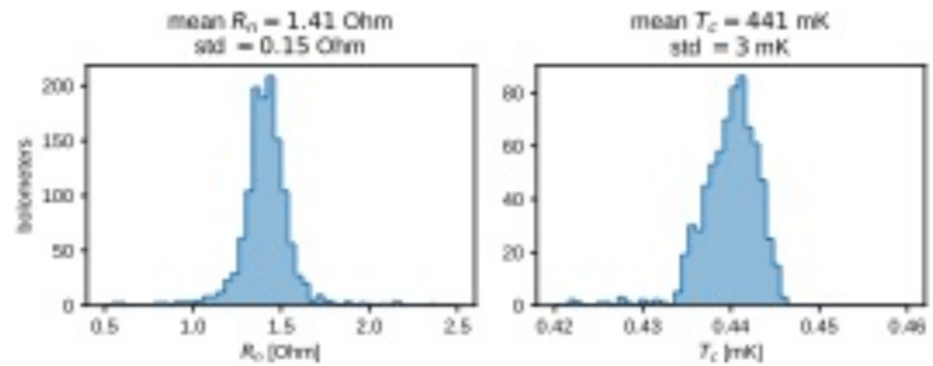
AlMn TES: Doping with magnetic materials

- Control Tc by doping Al with Mn.
- Fine tune Tc with post deposition bake

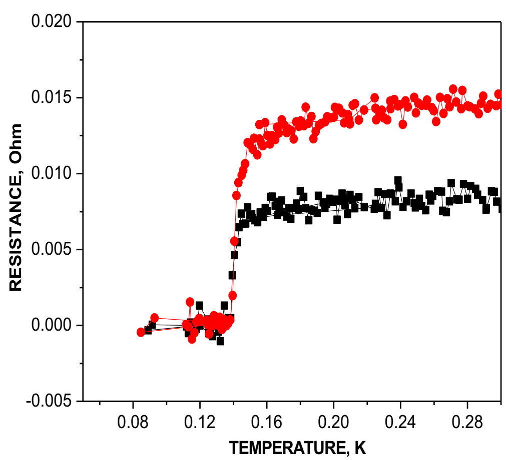


- <u>Demonstrated control of TES Tc in range 130-450mK</u>

- AlMn TES deployed on SPT-3G in 2018



Distribution of normal resistance (left) and Tc (right) measured in the field



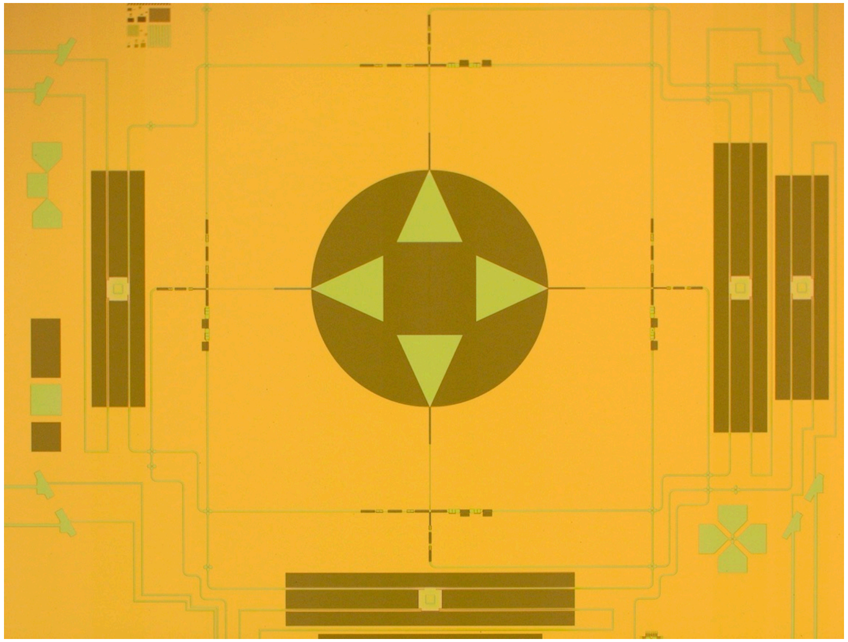
Resistance as a function of temperature for AlMn(200 nm, 2000ppm)\Ti(15nm)\Au(15nm) films with T_C of ~ 140 mK. The TES are 10 um long by 80 um (140 um) wide for the red (black) data.

D. Li *et al., J. Low Temp. Phys.*, vol. 184, no. 1–2, pp. 66–73, Jul. 2016.
A. J. Anderson *et al.*, *J. Low Temp. Phys.*, Nov. 2019.

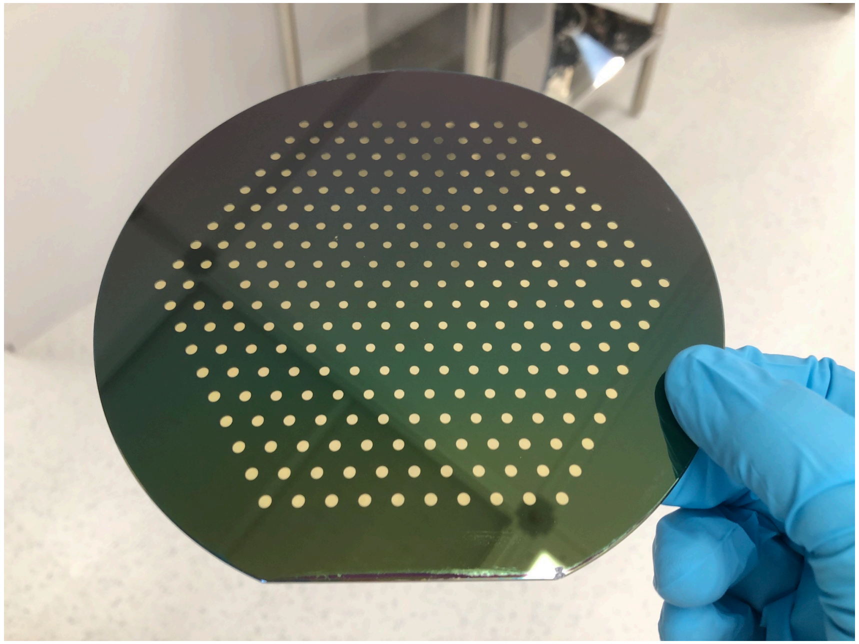
MOVING TOWARDS CMB-S4

OMT Fabrication

- OMT likely to be used on several bands for CMB-S4
- OMT fabrication requires silicon deep reactive ion etcher (DRIE)
  - PlasmaTherm DRIE installed at CNM in July 2019



90 GHz OMT probes in SPT3G layout

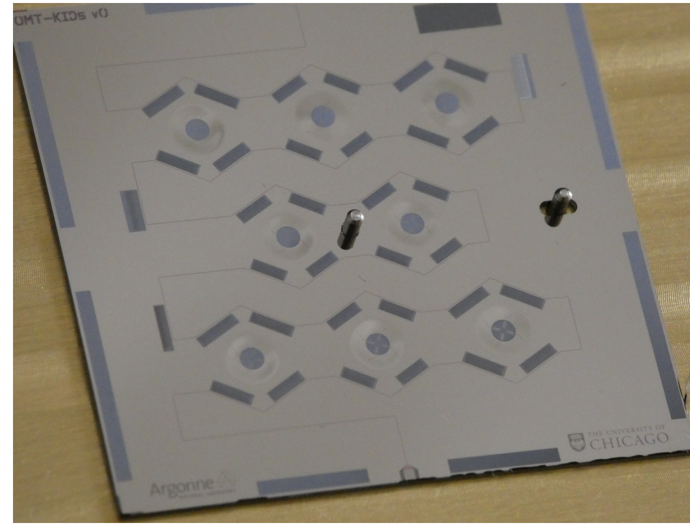


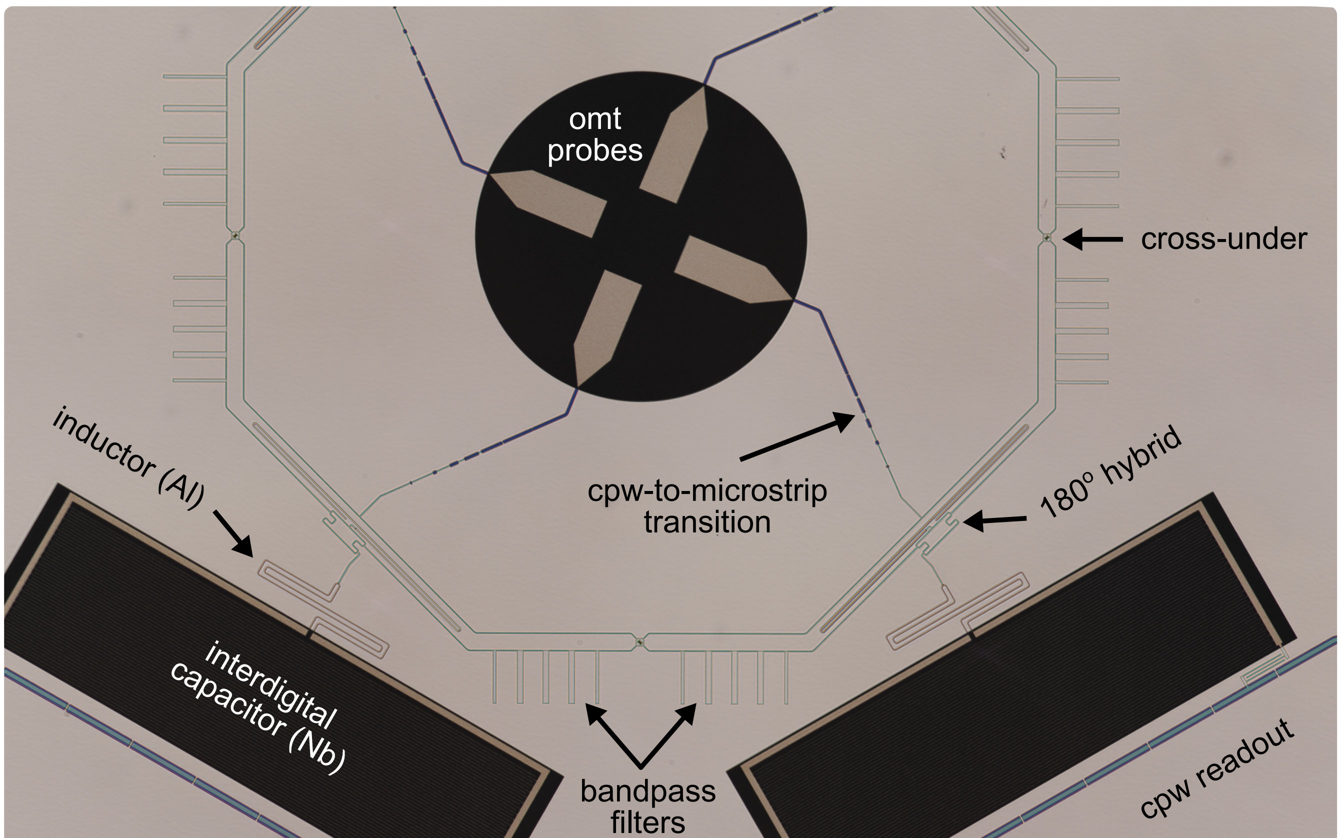
SiN membranes created by DRIE

MOVING TOWARDS CMB-S4

MKIDS

- Could significantly reduce number of optics tubes needed for higher frequency bands
- Fabrication of first released devices (220/270 GHz) now completed





FINAL THOUGHTS

- Advances in detector arrays have enabled new CMB Science
- Making/using large detector arrays is hard
- Argonne successfully fabrication and deployed the SPT-3G focal plane
- We are developing the necessary processes for CMB-S4 compliant detectors
- Effort from the entire community will be required to deploy CMB-S4

THANK YOU