ECAN

Argonne NATIONAL LABORATORY 75 1946–2021

(SUPERCONDUCTING) DETECTORS FOR CMB & HEP

CLARENCE CHANG
High Energy Physics Division
Argonne National Lab

Texas A&M University
June 9, 2023

(NOT SO-) EARLY CAREER AWARD

Advancing CMB science through new detectors

- Fiscal Year 2022 Award Abstracts
- Fiscal Year 2021 Award Abstracts
- Fiscal Year 2020 Award Abstracts
- Fiscal Year 2019 Award Abstracts
- Fiscal Year 2018 Award Abstracts
- Fiscal Year 2017 Award Abstracts
- Fiscal Year 2016 Award Abstracts
- Fiscal Year 2015 Award Abstracts
- Fiscal Year 2014 Award Abstracts
- Fiscal Year 2013 Award Abstracts
- Fiscal Year 2012 Award Abstracts
- Fiscal Year 2011 Award Abstracts
- Fiscal Year 2010 Award Abstracts

DOE Office of Science Early Career Research Program Awardee Abstracts Fiscal Year 2013

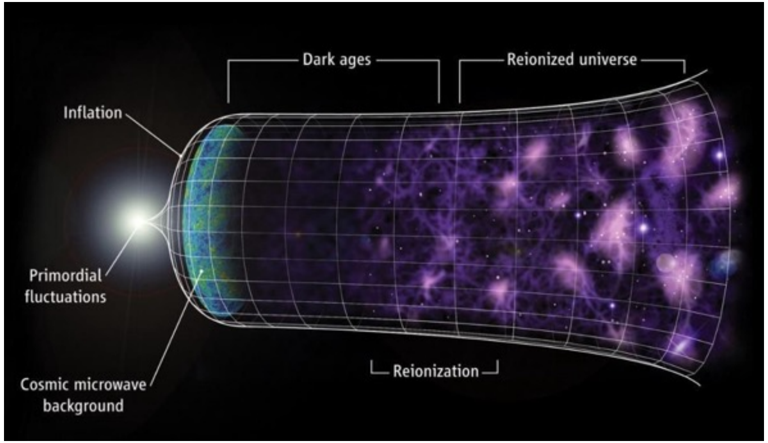
Exploring Fundamental Physics through New Measurements of the Cosmic Microwave Background Polarization

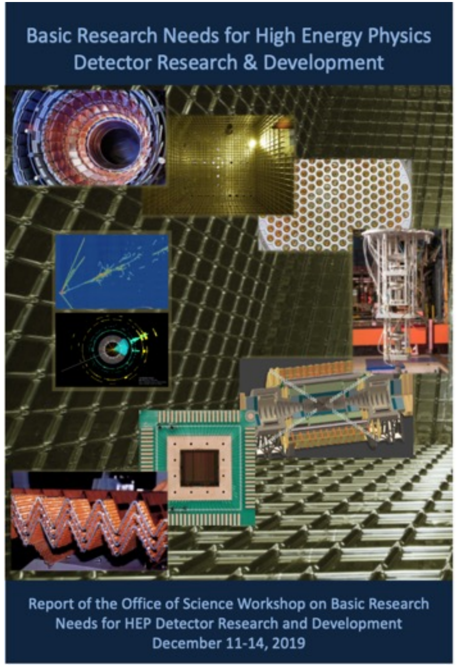
Dr. Clarence L. Chang, Assistant Scientist
Astrophysics and Cosmology Group
High Energy Physics Division
Physical Sciences and Engineering Directorate
Argonne National Laboratory
Lemont, IL 60439

The Cosmic Microwave Background (CMB) is the relic radiation from 400,000 years after the Big Bang. The CMB is an image of the early universe and a unique window into fundamental physics. The goal of this research program is to measure a faint signal embedded in the polarization pattern of the CMB. This signal, called "B-modes," has never been seen and will explore two scientific topics. The first topic is the nature of inflation, the theorized rapid exponential expansion of the early universe, taking place between 10^{-36} and 10^{-32} seconds after the Big Bang. CMB "B-modes" are the unique probe of this physics. Interestingly, the physics of inflation connects directly to our understanding of physics at high energies. Inflation is expected to take place at energies of about 10^{16} GeV, the same energy scale favored by Grand Unified Theories of Particle Physics. The second scientific goal of this program is to use

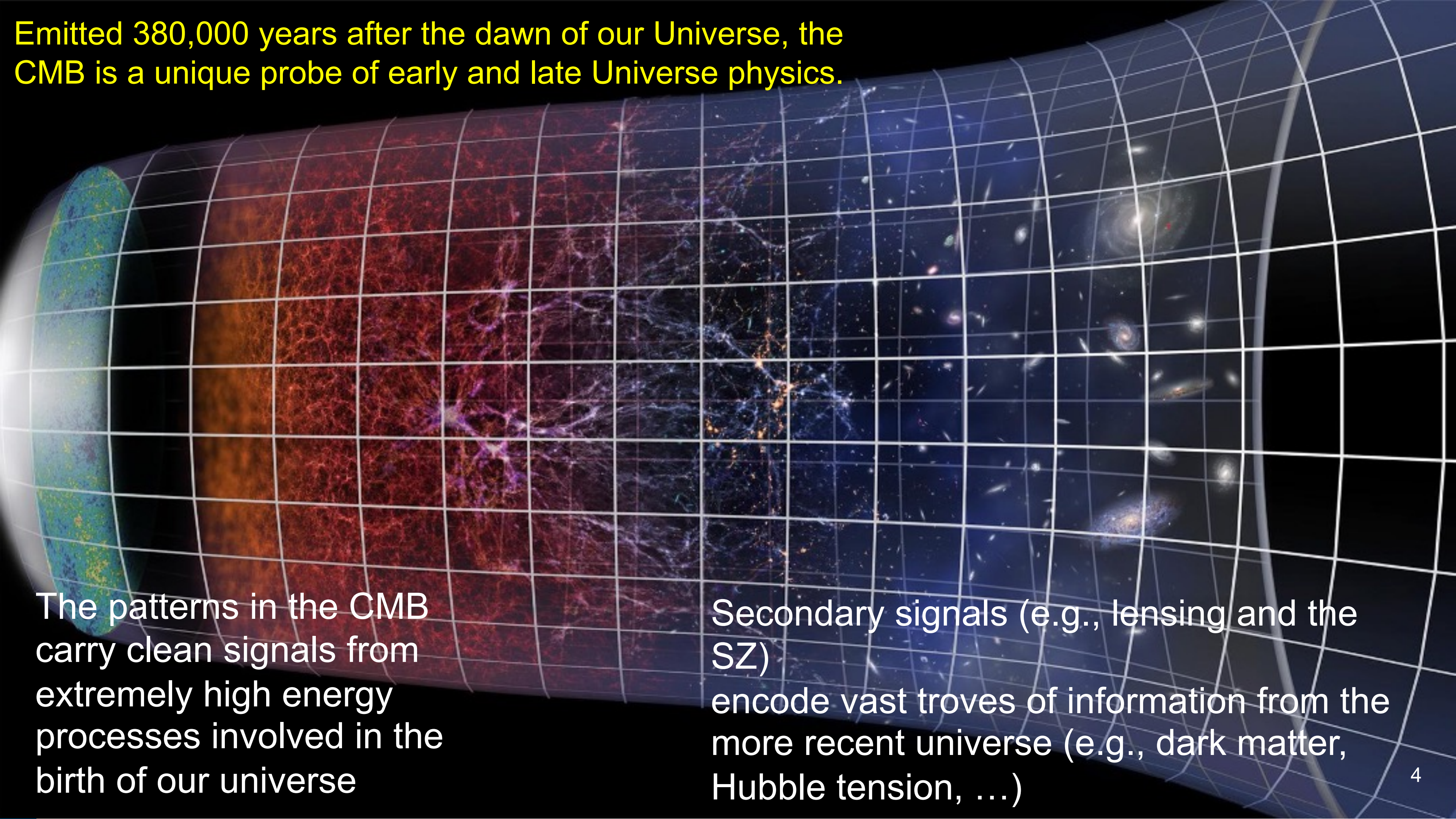
COSMIC FRONTIER AND DETECTORS

- Cosmic Frontier: Understand the nature of early & late cosmic acceleration
  - Cosmic surveys
- Generic Detector R&D
  - More direct connection to Cosmic Frontier





Emitted 380,000 years after the dawn of our Universe, the CMB is a unique probe of early and late Universe physics.



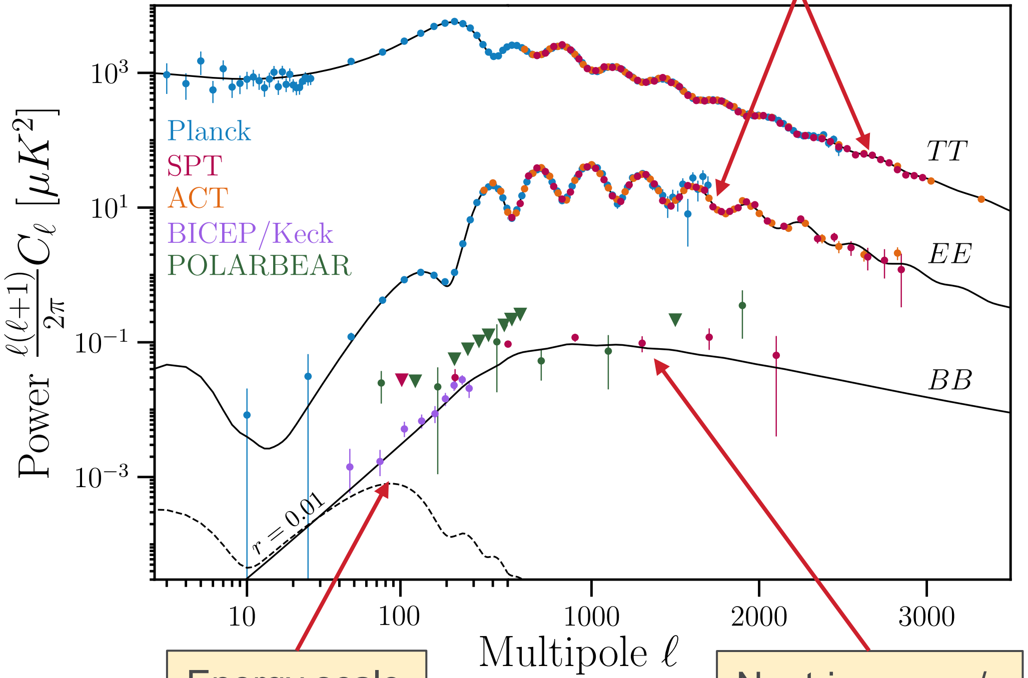
The patterns in the CMB carry clean signals from extremely high energy processes involved in the birth of our universe

Secondary signals (e.g., lensing and the SZ)
encode vast troves of information from the more recent universe (e.g., dark matter, Hubble tension, …)

POWERFUL APPROACH TO FUNDAMENTAL PHYSICS

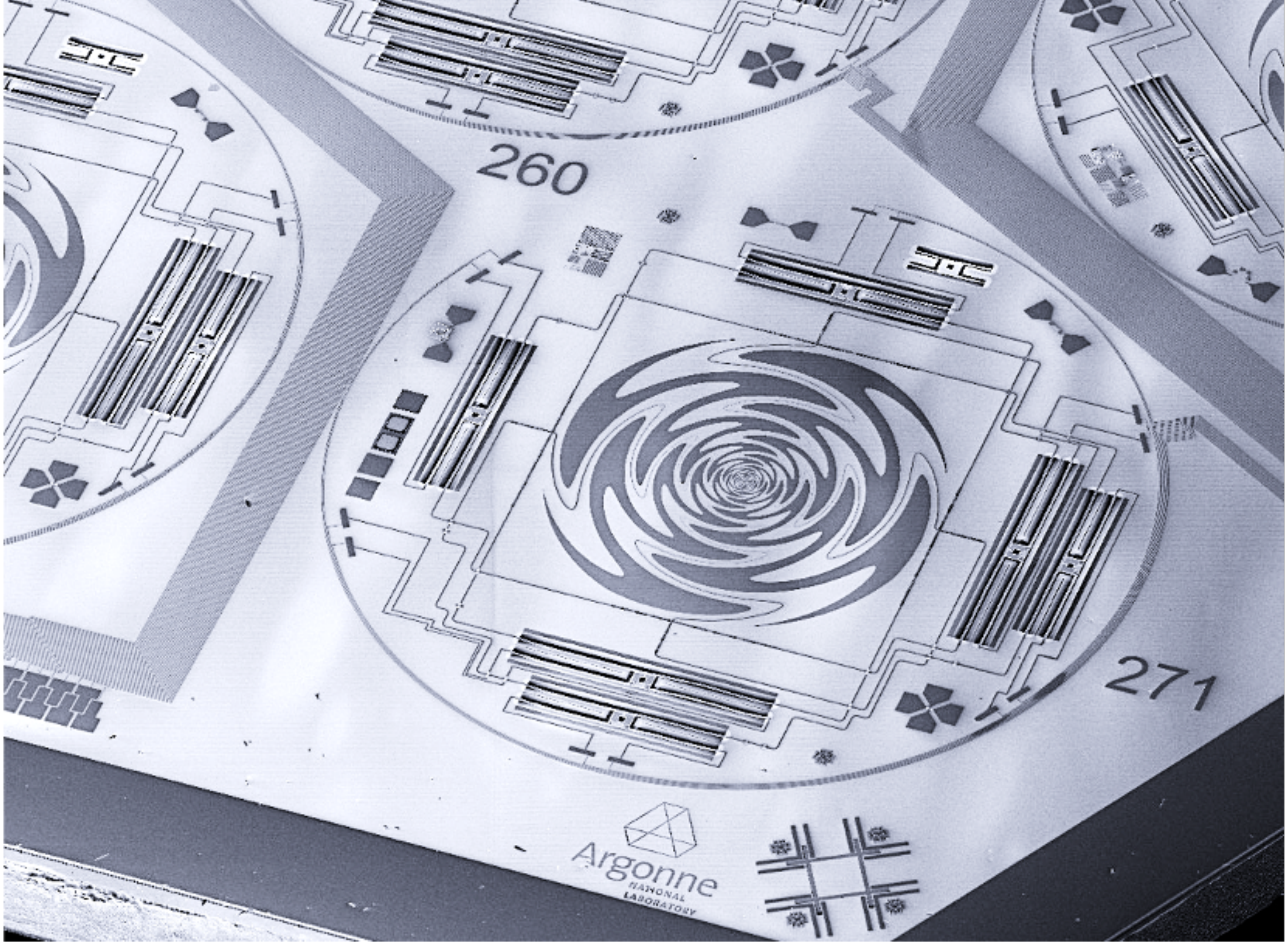
- Anchors our cosmological model
- Precision test of our thermal history
  - Are there light BSM particles?
- Unique method for measuring the energy scale of Inflation
  - Would correspond to GUT-scale
- Signal is faint. Requires measuring lots of photons.
  - Need lots of detectors.

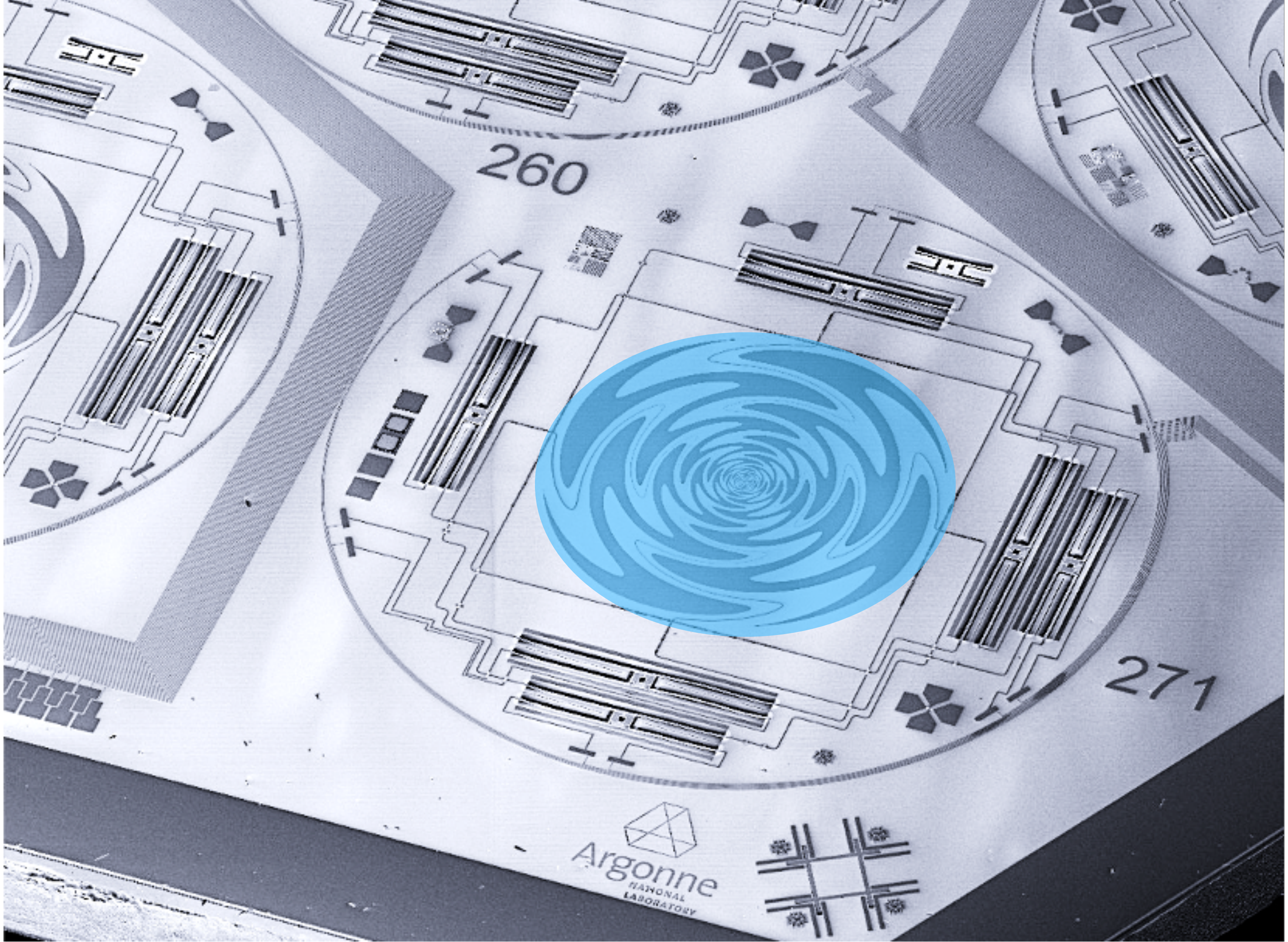
- Precision tests of early thermal history
- New relic particles
- Precision cosmology



Energy scale of inflation

Neutrino mass/ hot dark matter


260
271
Argonne
NATIONAL
LABORATORY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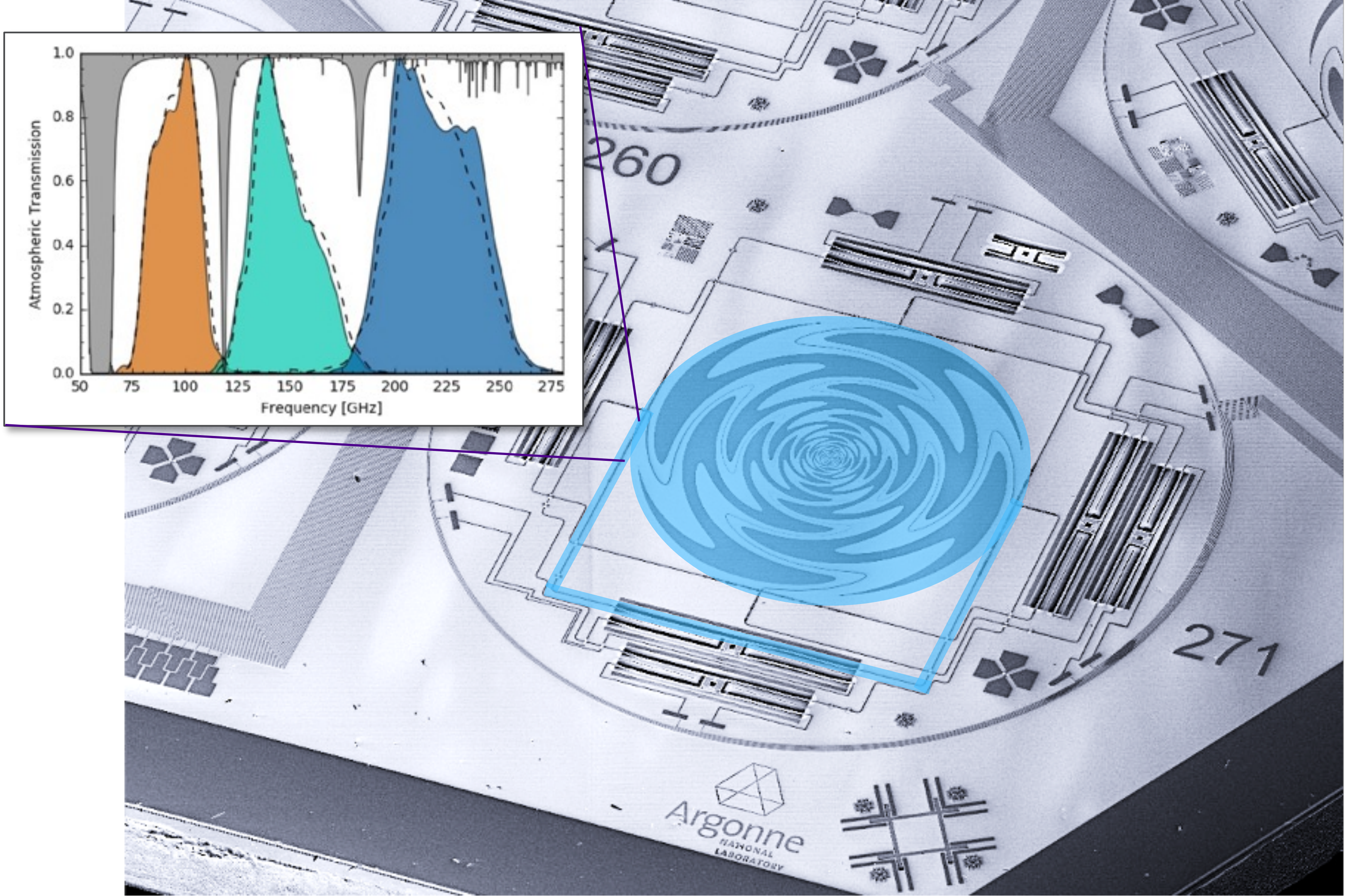
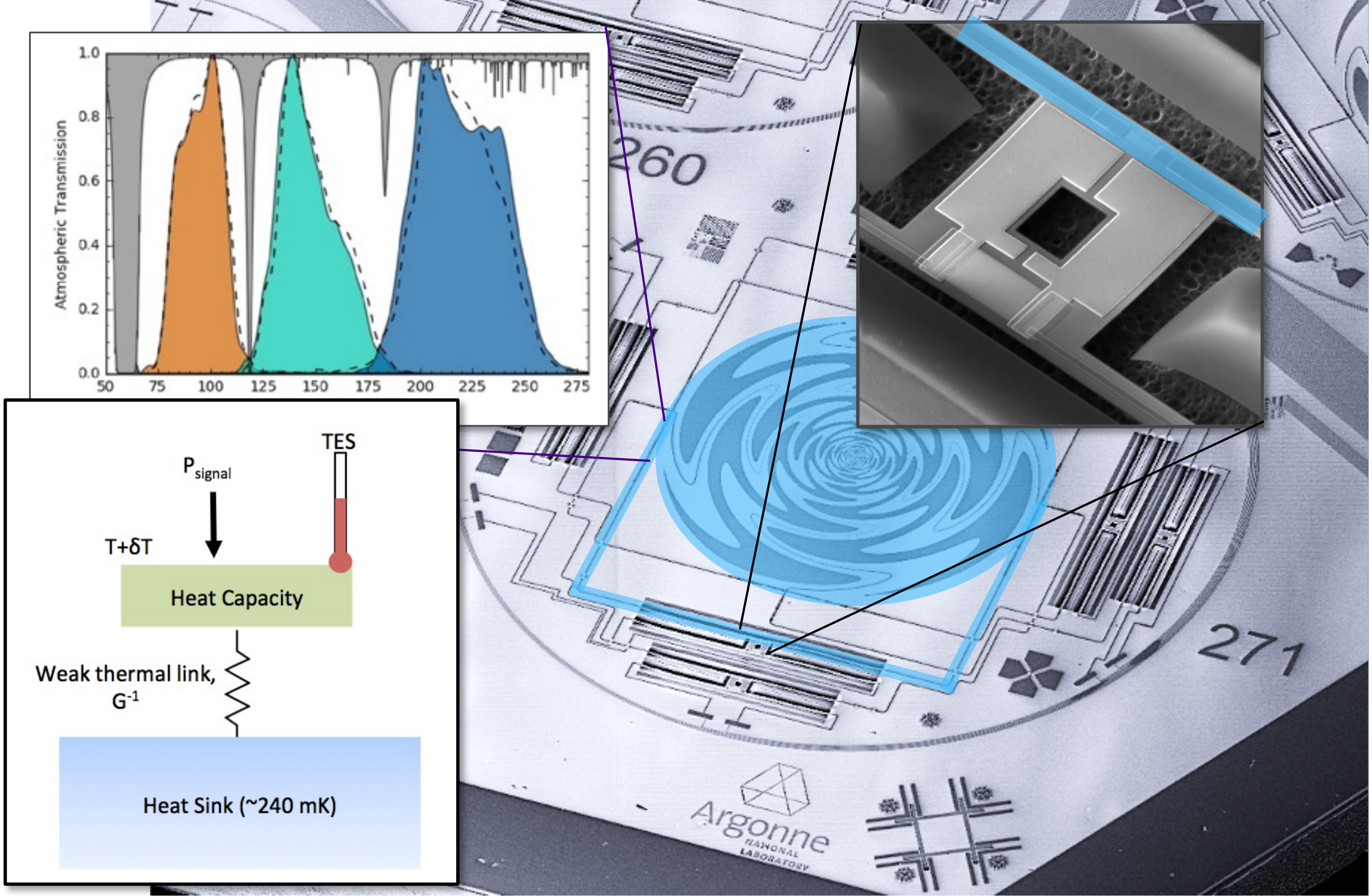
NATIONAL
LABORATORY


1.0
0.8
0.6
0.4
0.2
0.0
Atmospheric Transmission
50
75
100
125
150
175
200
225
250
275
Frequency [GHz]
260
271
Argonne
NATIONAL LABORATORY



Atmospheric Transmission
1.0
0.8
0.6
0.4
0.2
0.0
50
75
100
125
150
175
200
225
250
275
TES
P signal
T+δT
Heat Capacity
Weak thermal link, G-1
Heat Sink (~240 mK)
260
271
Argonne
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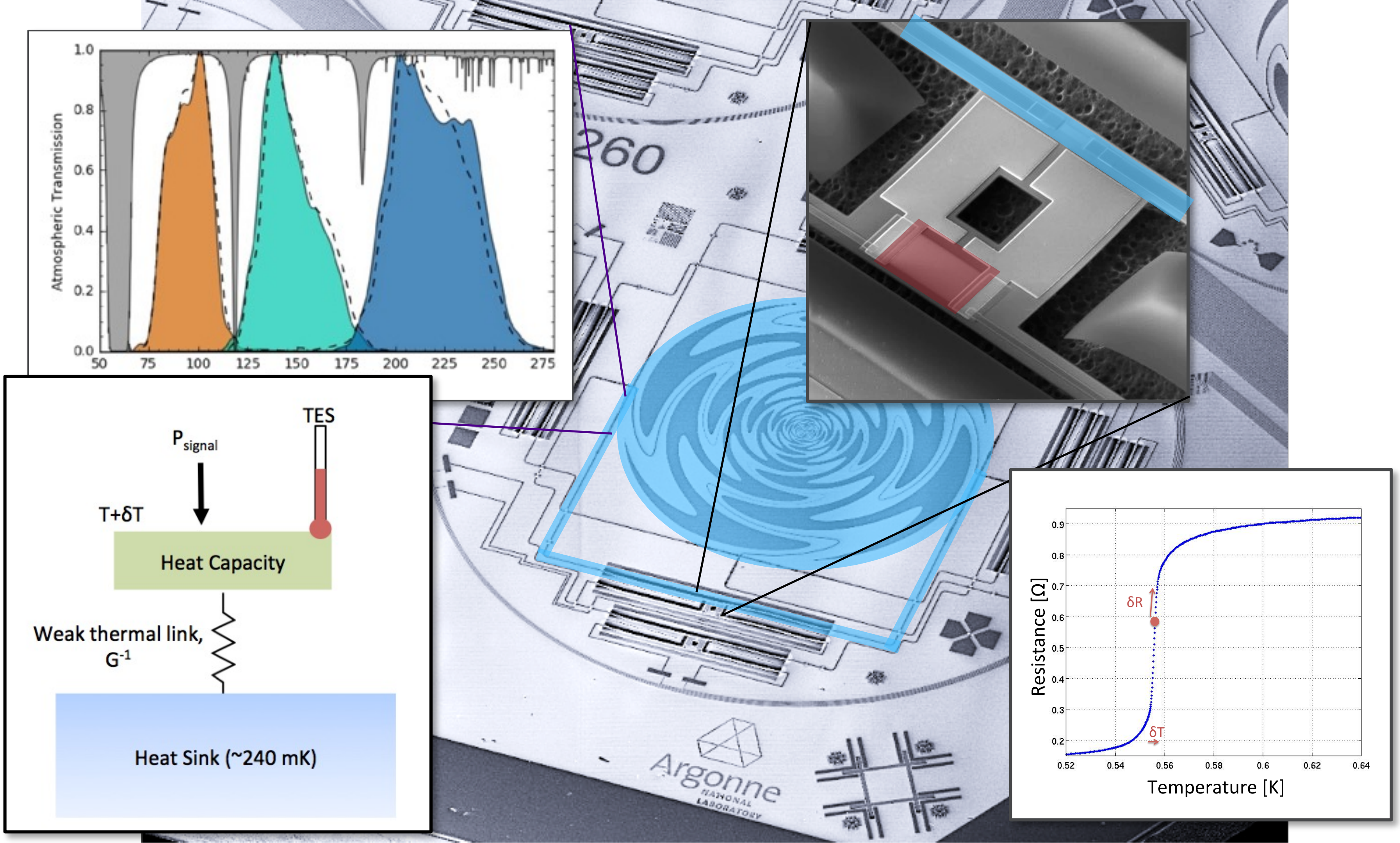

Atmospheric Transmission
1.0
0.8
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0.4
0.2
0.0
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175
200
225
250
275
260
TES
P_{signal}
T+δT
Heat Capacity
Weak thermal link,
G^{-1}
Heat Sink (~240 mK)
Resistance [Ω]
Temperature [K]
δR
δT
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.52
0.54
0.56
0.58
0.6
0.62
0.64
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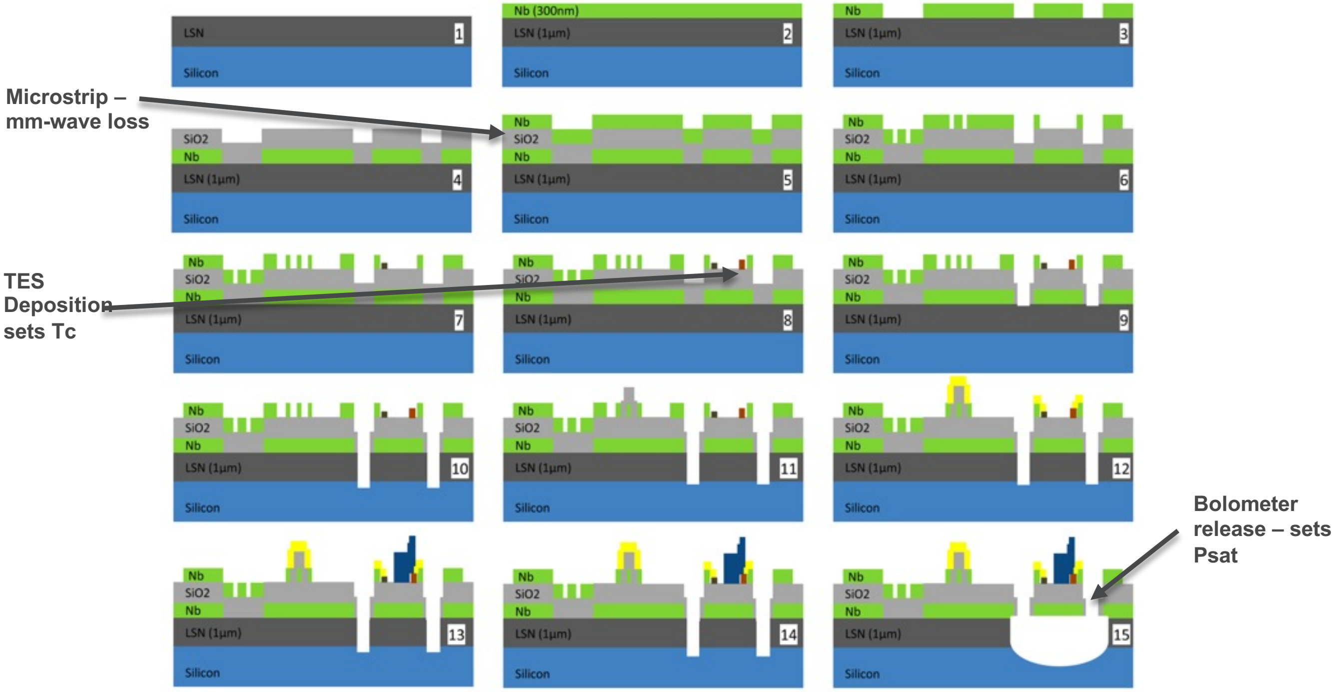
TES FOR CMB

Detectors possess multiple functionalities, components, materials

- Antenna collects photons from telescope
- Photons transmitted via superconducting transmission line. Signal is filtered and channelized.
- Photons thermalize on suspended island, changing the island temperature.
- Change in temperature changes electrical resistance of TES.
- TES is held at constant voltage, change in resistance results in a change in TES current.
- TES current is measured by a low noise Superconducting Quantum Interference Device amplifier.

BUILD ARRAY THROUGH LAYERING

For SPT-3G full process has 15 steps requiring 18 stepper masks and direct write of wiring pattern. CMB-S4 is similar.



SUPERCONDUCTING DEVICES

Multi-disciplinary Lab facilities & expertise

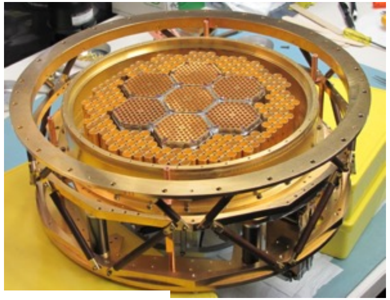
17,000 ft^2 class 100-1000 cleanroom facility
Complete suite of lithography, deposition, etching, and metrology tools

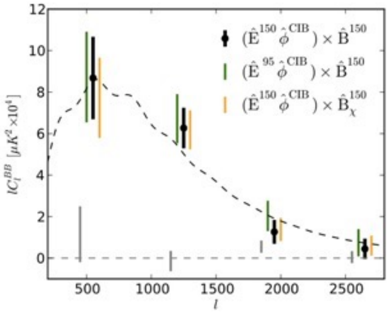
Expertise in materials synthesis
Capabilities for characterization and modeling of materials properties

- Cross-Lab applications
  - HEP: CMB, Dark Matter, CEvNS
  - PHY: Neutrinoless Double Beta Decay, EIC
  - APS: X-ray micro-calorimeters
  - Quantum Information Science

ECA ENABLES SCALING UP CMB DETECTORS

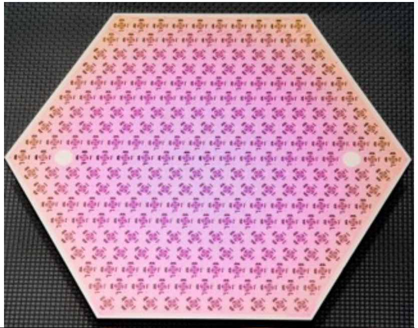
Sensitivity of CMB detector is set by detected photon flux. Increasing experiment sensitivity requires more detectors.

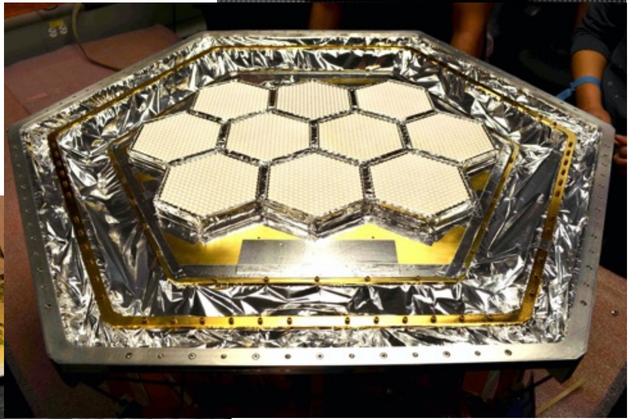


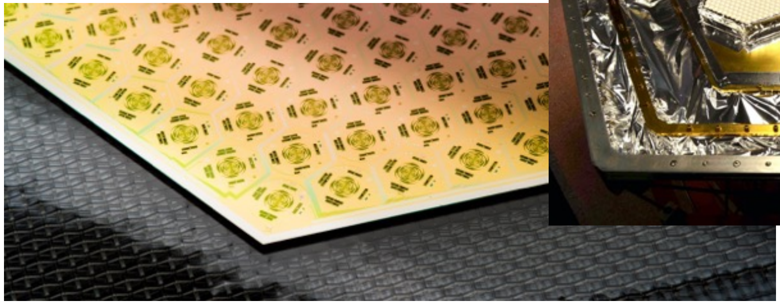


SPTpol camera
(2012-2017)

SPT-3G camera
(2017-)

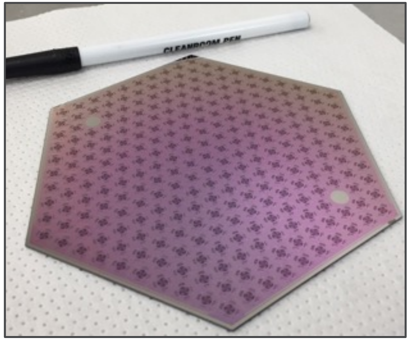


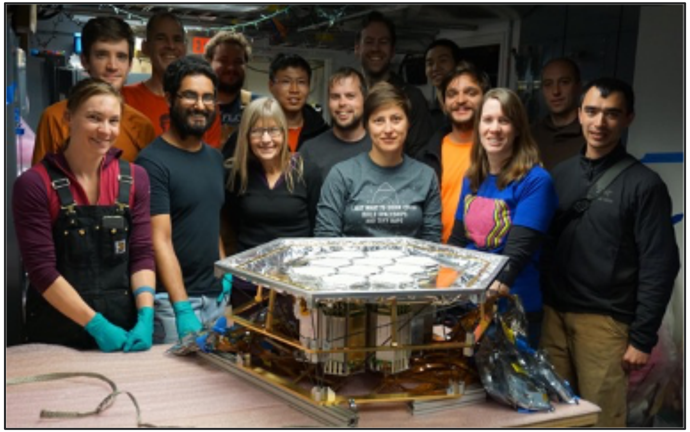


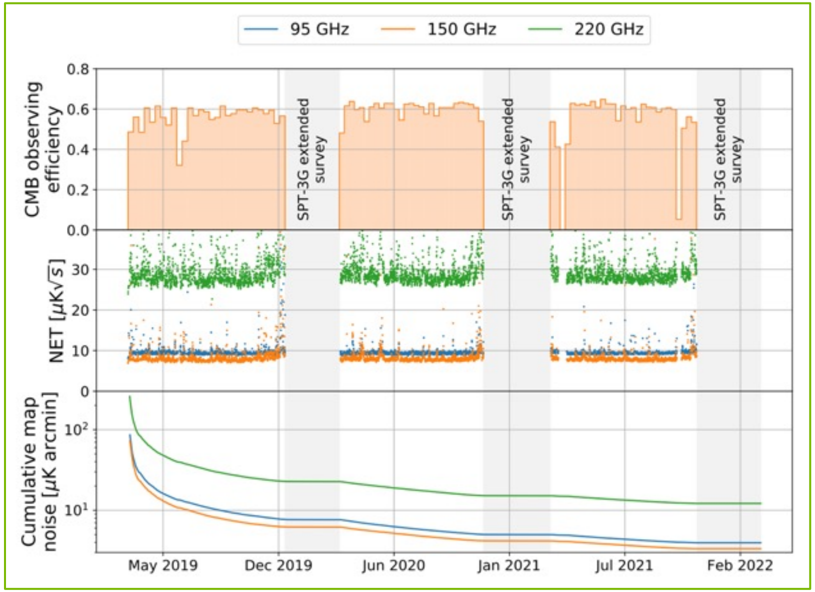


BUILDING ON THE ECA

SPT-3G (2017-)





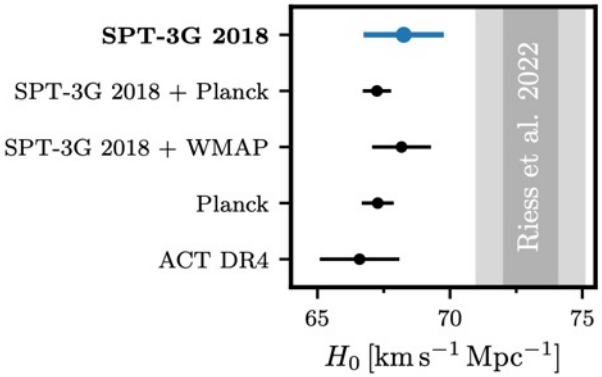


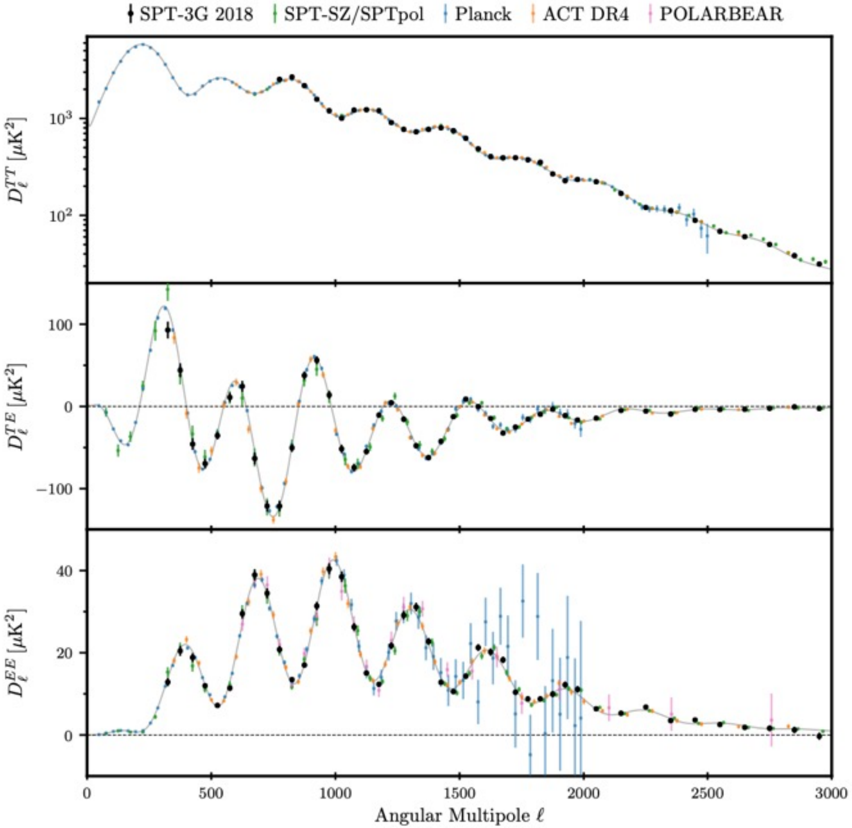
SPT-3G is a currently observing Stage-3 CMB camera.

- Performance is excellent and on-track to meet 5-year survey sensitivity goal

SPLAT forecasting for CMB-S4 is based off its performance.

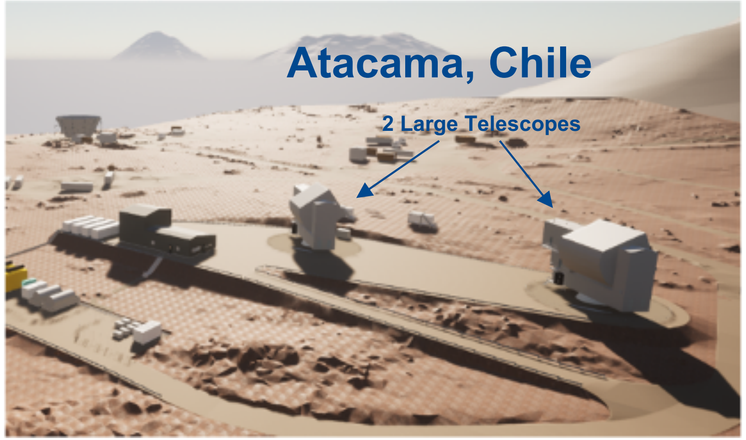
SPT-3G MEASUREMENTS

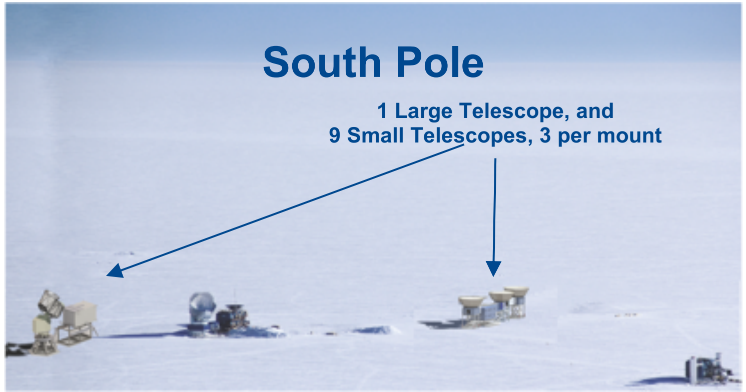


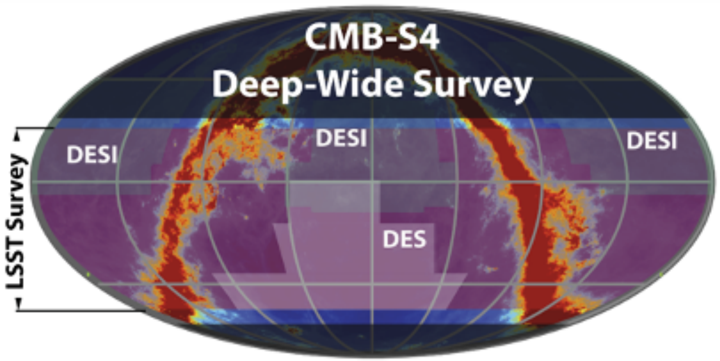


arXiv:2212.05642

CMB-S4: TWO SUPERB SITES, ONE COLLABORATION

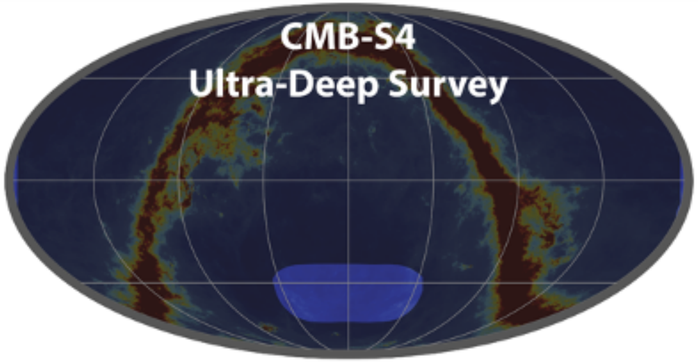






Observed from Chile

Large area survey motivated by N_{eff}, matter mapping, and time domain science and enabled by the mid-latitude site

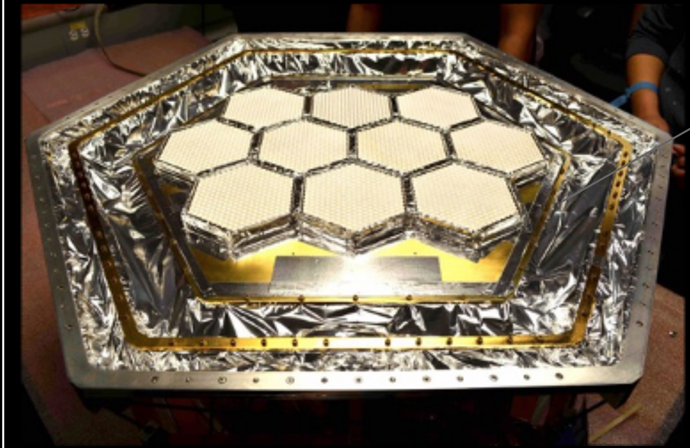


Observed from South Pole

Small area survey primarily targeting inflationary gravitational waves, enabled by the sky coverage, low horizon blockage, and ultra stable atmosphere of the polar site.

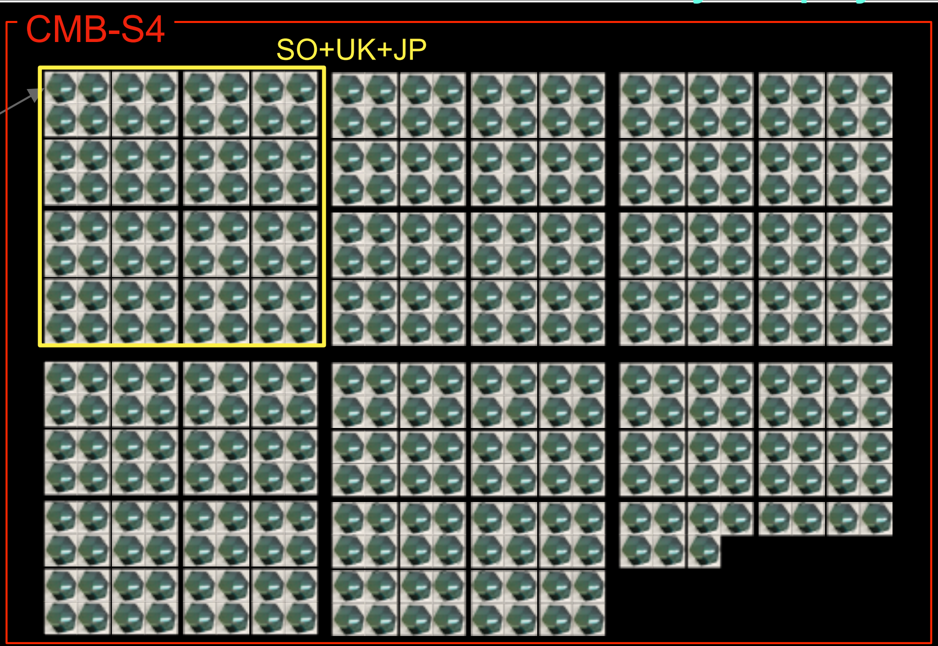
Sensitivity CMB detectors are background limited. The only way to meet our science targets is to deploy more detectors.

State-of-the-art: SPT-3G



- 16k superconducting TES detectors
- 10 detector wafers (0.17 sq. meters)
- The largest deployed focal plane

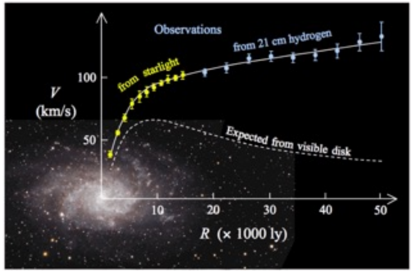
CMB-S4: more than 10x all CMB detectors yet deployed!

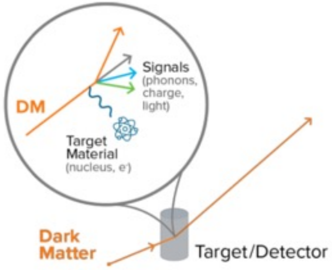


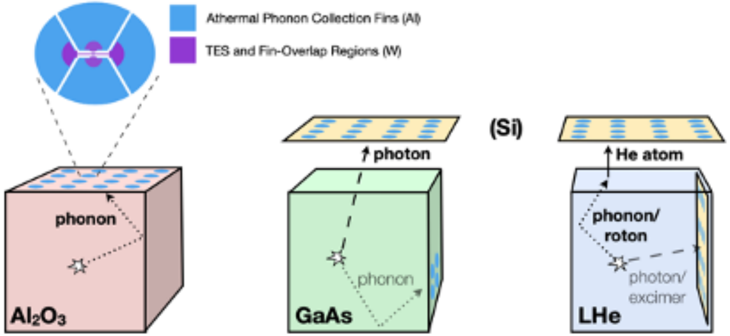
- 496k superconducting TES detectors
- **363 detector wafers (6.4 sq. meters)**
- A major scale-up requiring the expertise of DOE labs

NEW PHYSICS VIA RARE EVENT SEARCHES

Dark Matter

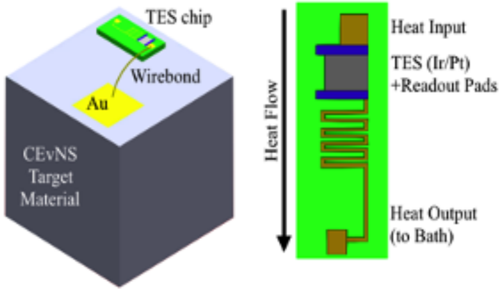






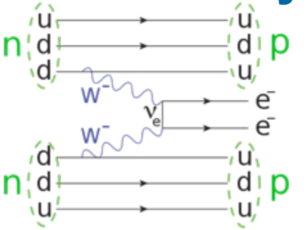
TESSERACT

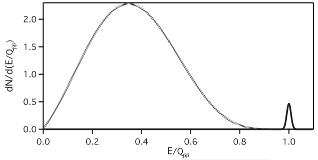
Coherent Elastic Neutrino-Nucleus Scattering

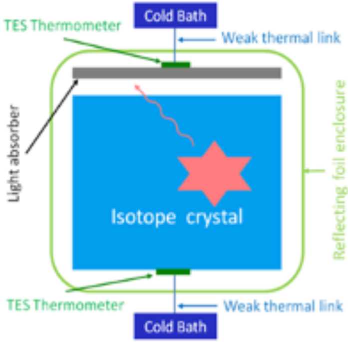


RICOCHET

Neutrinoless Double-beta Decay

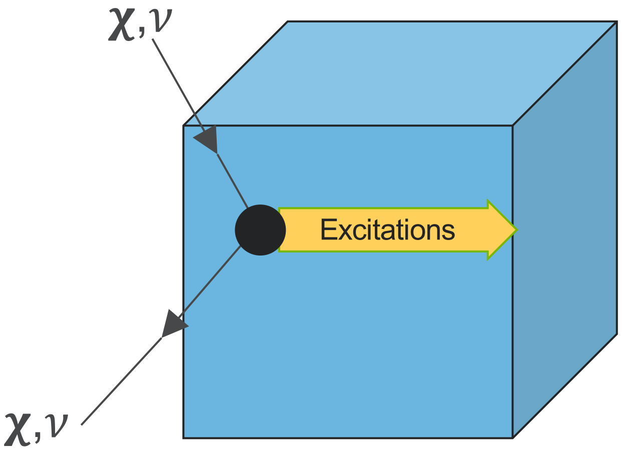






CUPID

RARE EVENT SEARCHES



Recoil energy from particles (dark matter, neutrinos) interacting w/ target

- **ns**: Initial recoil
- ***μs***: athermal excitations
  - Collective excitations: Phonons, rotons, magnons
  - Ionization, scintillation
  - Photon emission
- **ms**: thermalization

Recoil spectrum for low mass DM and CEvNS rising exponentially at lower energy

– Pushes for lower thresholds

NEW MATERIALS TO TUNE TC

Au/Ir/Au proximity trilayers: Tc is tunable close to 20 mK (graph at lower left)

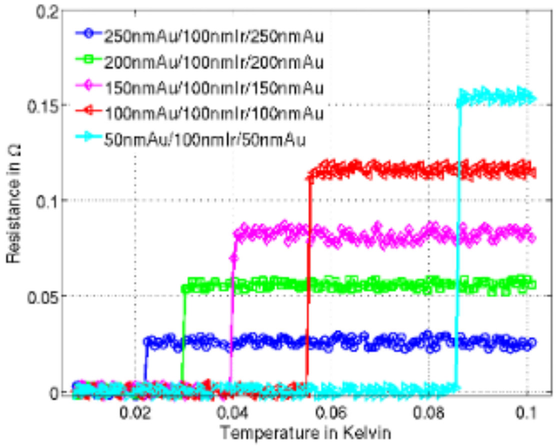
Ir/Pt proximity bilayers: Tc is tunable close to 20 mK (graph in lower middle)

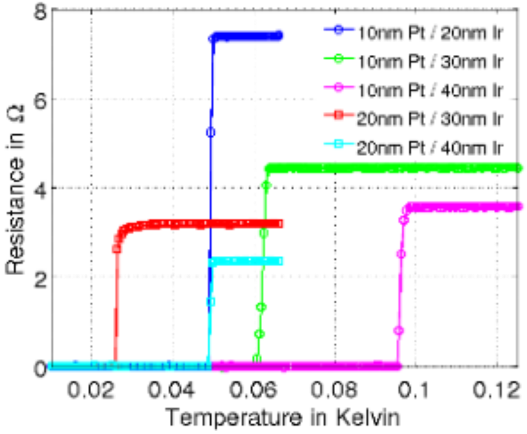
Mn doped Al films: Tc is tunable close to 20 mK (graph at lower right)

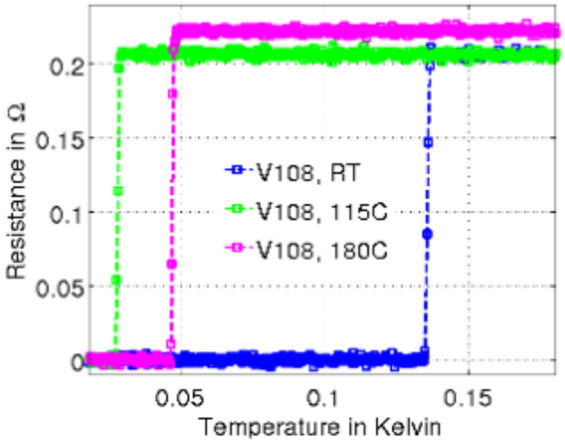

Au/Ir/Au trilayer


Ir/Pt bilayer

Mn doped Al

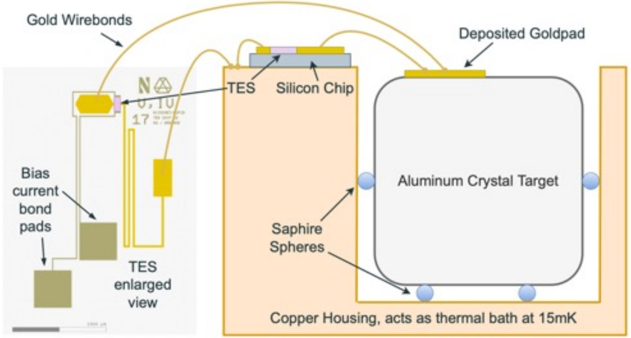


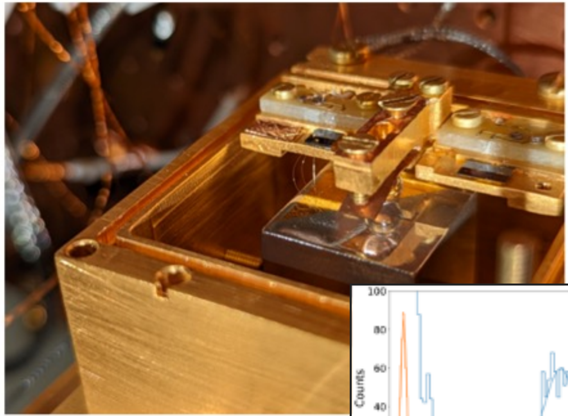


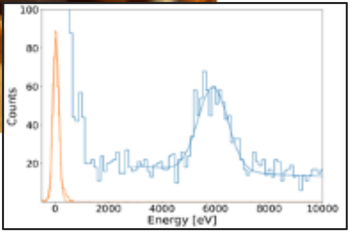


TES FOR RARE EVENT SEARCHES

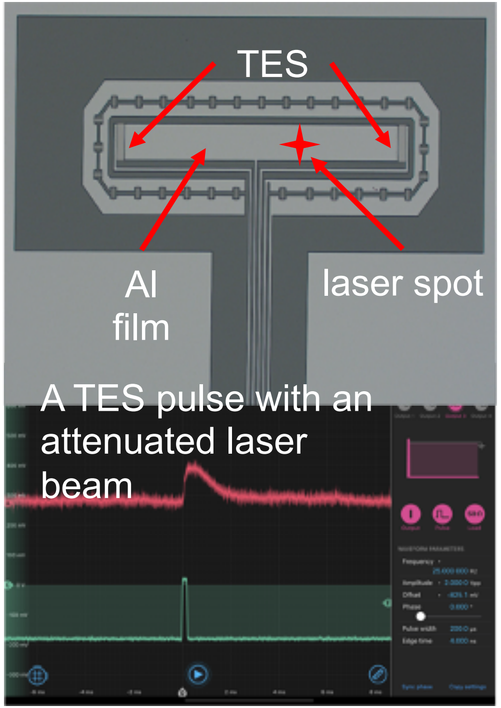
- Couple to target masses instead of antennas



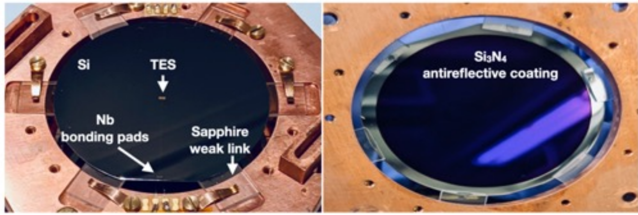


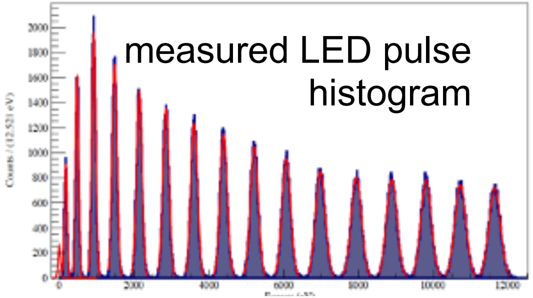


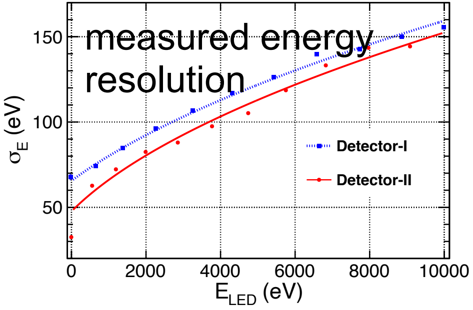
CEvNS



Dark Matter







NLDBD

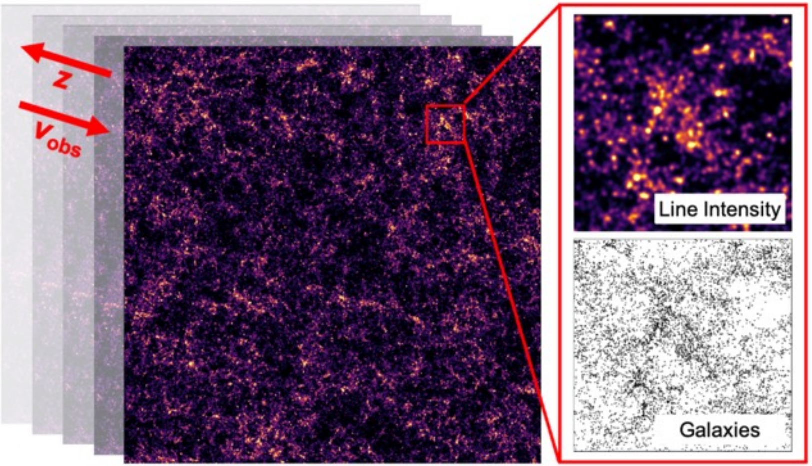
MM-WAVE LINE INTENSITY MAPPING

Future cosmic surveys

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

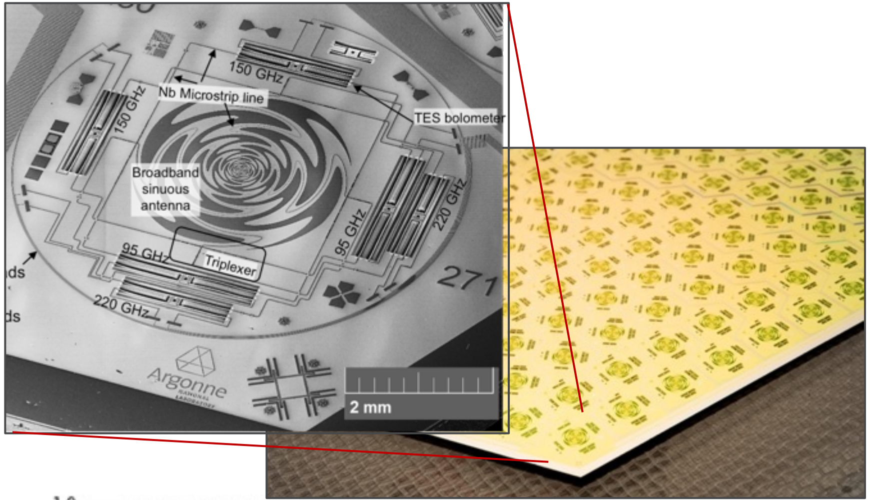
Snowmass 2021 Cosmic Frontier White Paper: Cosmology with Millimeter-Wave Line Intensity Mapping

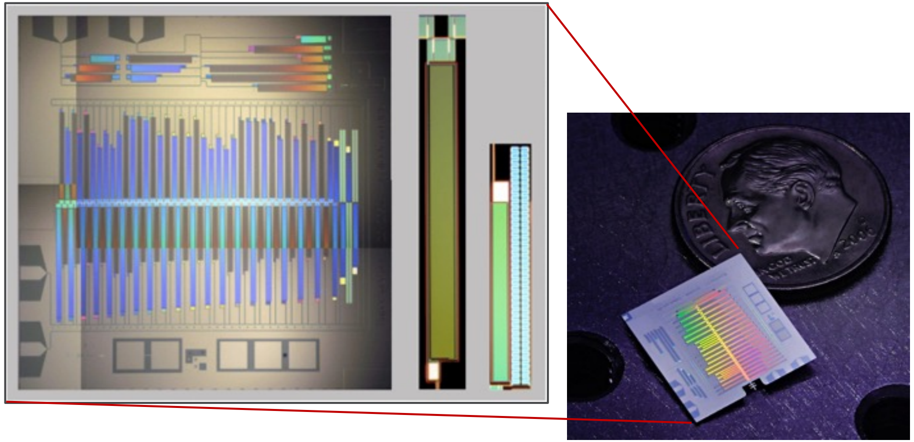
Kirit S. Karkare[1,2], Azadeh Moradinezhad Dizgah[3], Garrett K. Keating[4],
Patrick Breysse[5], Dongwoo T. Chung[6,7],
for the Snowmass 2021 Cosmic Frontier 5 Topical Group ,

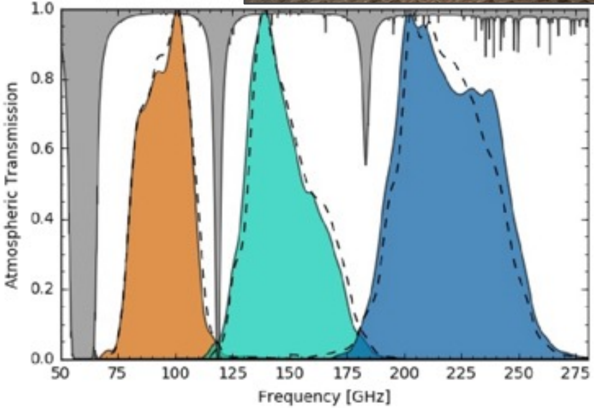


Spec-hrs	Example	Time-scale	$\sigma(f_{NL})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{eff})$	$\sigma(w_0) \times 10^2$	$\sigma(w_a) \times 10^2$
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 (65)	0.1 (0.11)	13 (14)	51 (52)
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)
10^7	SPT-like 1 tube	2028	3.1 (4.2)	23 (28)	0.043 (0.051)	2 (2.2)	8.5 (9.7)
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	0.013 (0.016)	0.61 (0.73)	2.1 (2.8)

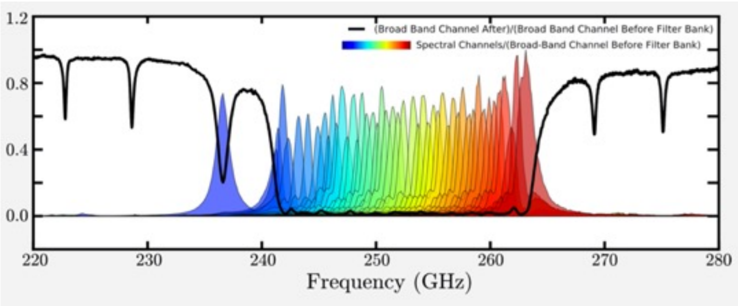
R&D FOR MM-WAVE LIM







- 100X channel count
- 10X spectral resolution (R~100)
- Developing MKIDs



THOUGHTS

ECA played a critical role in establishing HEP superconducting detectors at Argonne National Lab

- Connects HEP science with expertise and capabilities at Argonne
  - Materials expertise
  - Thin film processing facilities & associated testing
- Enables leadership science
  - SPT-3G
  - CMB-S4
- Established capabilities that lead to new opportunities
  - Dark matter
  - Neutrinos
  - Cosmic surveys

THANK YOU