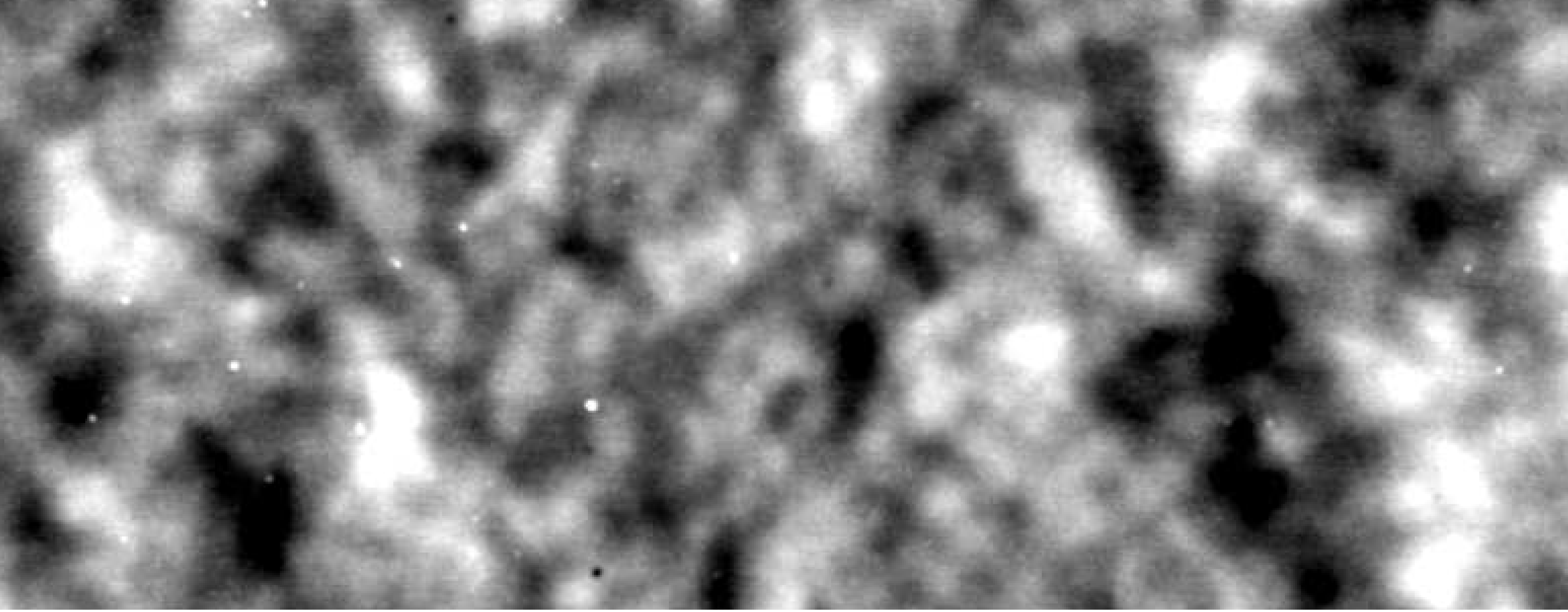
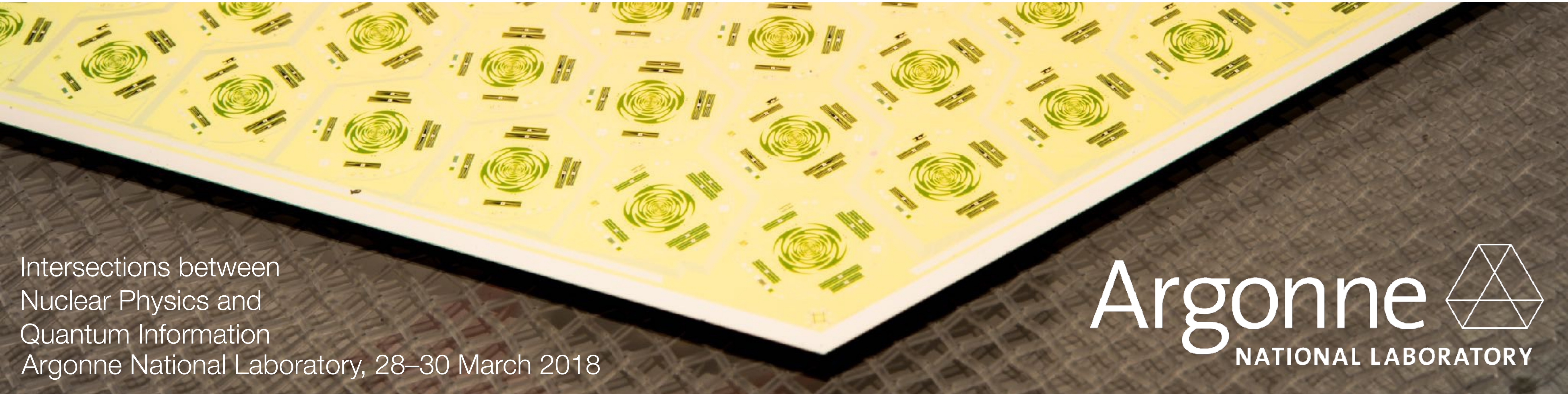


Large arrays of superconducting devices

Clarence Chang



Intersections between
Nuclear Physics and
Quantum Information
Argonne National Laboratory, 28–30 March 2018

Argonne NATIONAL LABORATORY

Cosmology

NP ∩ QI

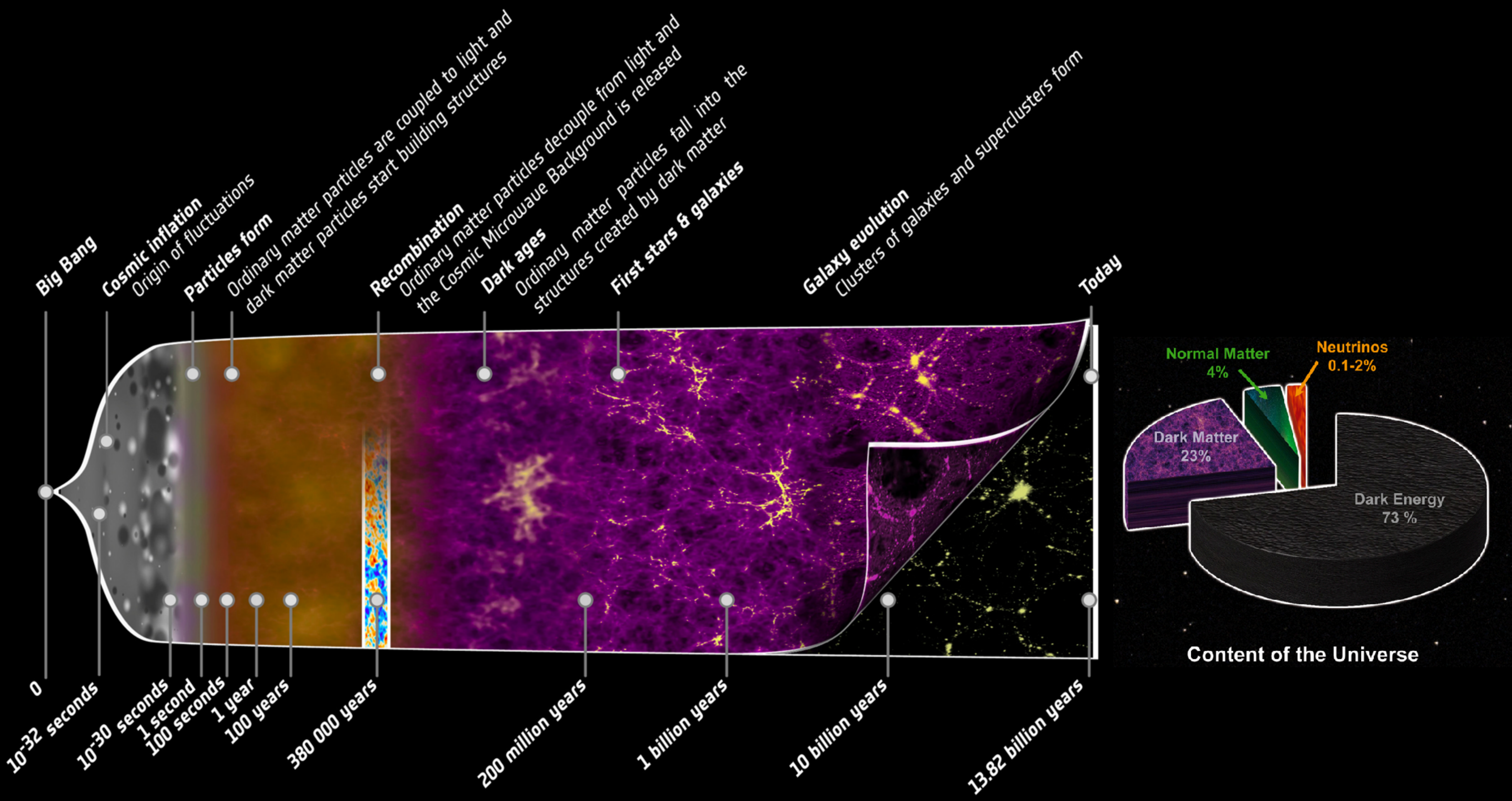
Cosmology

Cosmology - Wikipedia

https://en.wikipedia.org/wiki/Cosmology ▾

Cosmology (from the Greek κόσμος, kosmos "world" and -λογία, -logia "study of") is the study of the origin, evolution, and eventual fate of the universe.

Religious cosmology · Physical cosmology · Cosmology (philosophy) · Cosmogony



L'EXPANSION DE L'UNIVERS (1)

Je voudrais développer ici quelques aspects, quelques aspects seulement, de ce sujet de « l'Expansion de l'Univers ». Ce sujet est en effet fort vaste, non seulement au sens matériel du mot, mais vaste par le nombre de questions qu'il met en jeu ; il touche à la relativité, il touche à des conceptions assez abstruses de géométrie. Je voudrais me borner à vous dire les consé-

PHYSICAL REVIEW VOLUME

Letters to the Editor

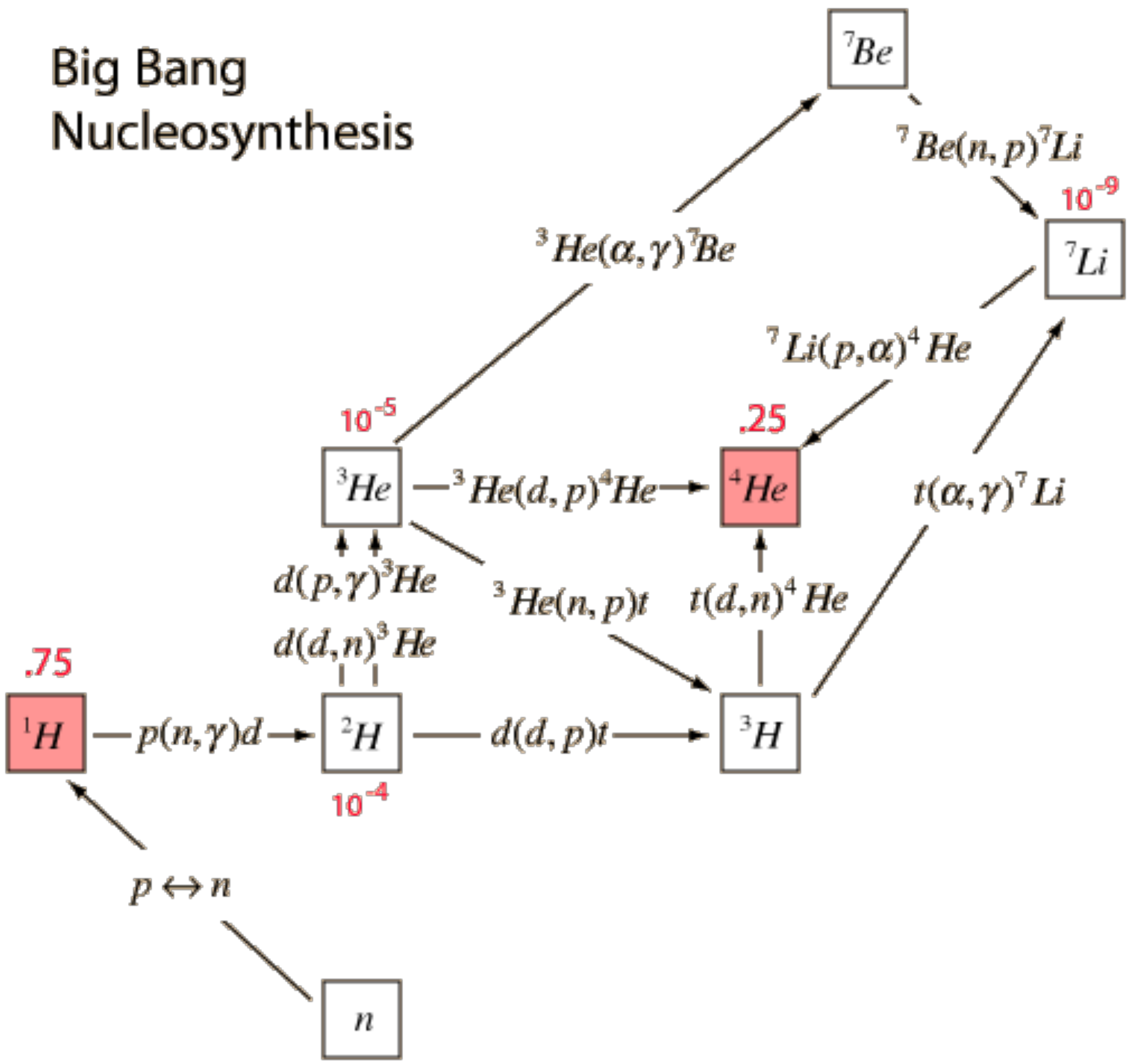
PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

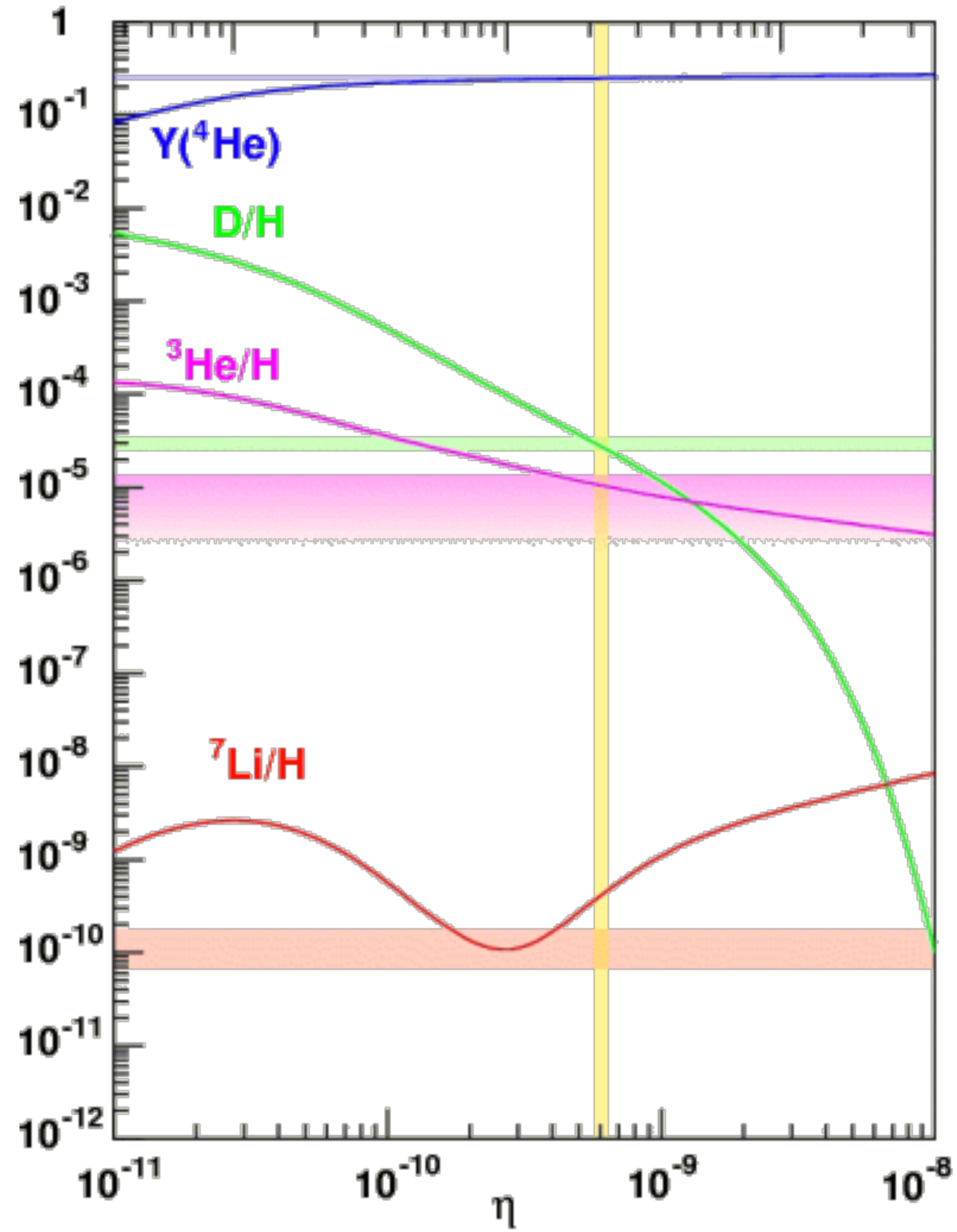
The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It

Big Bang Nucleosynthesis

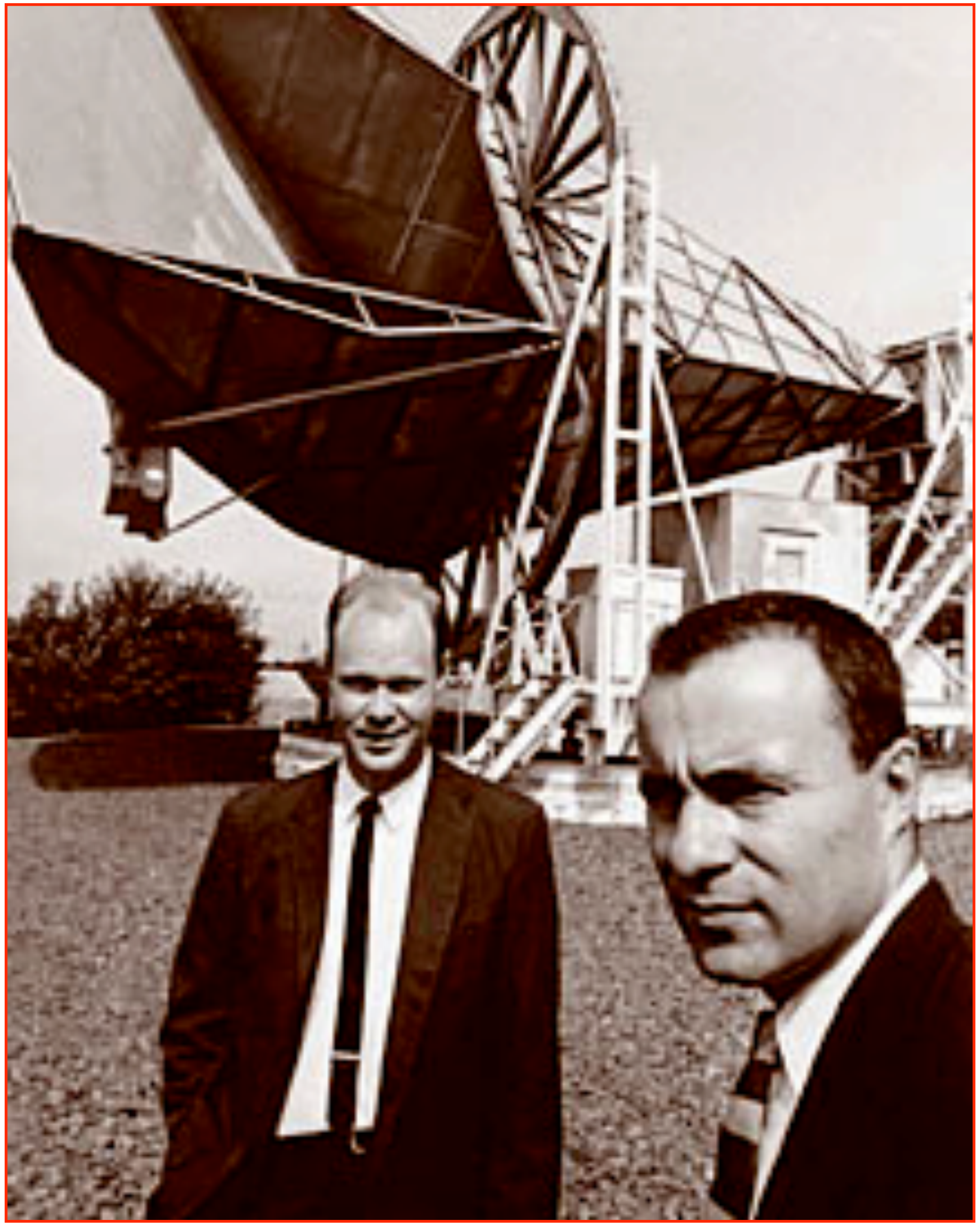




Also predicts relic abundance of photons

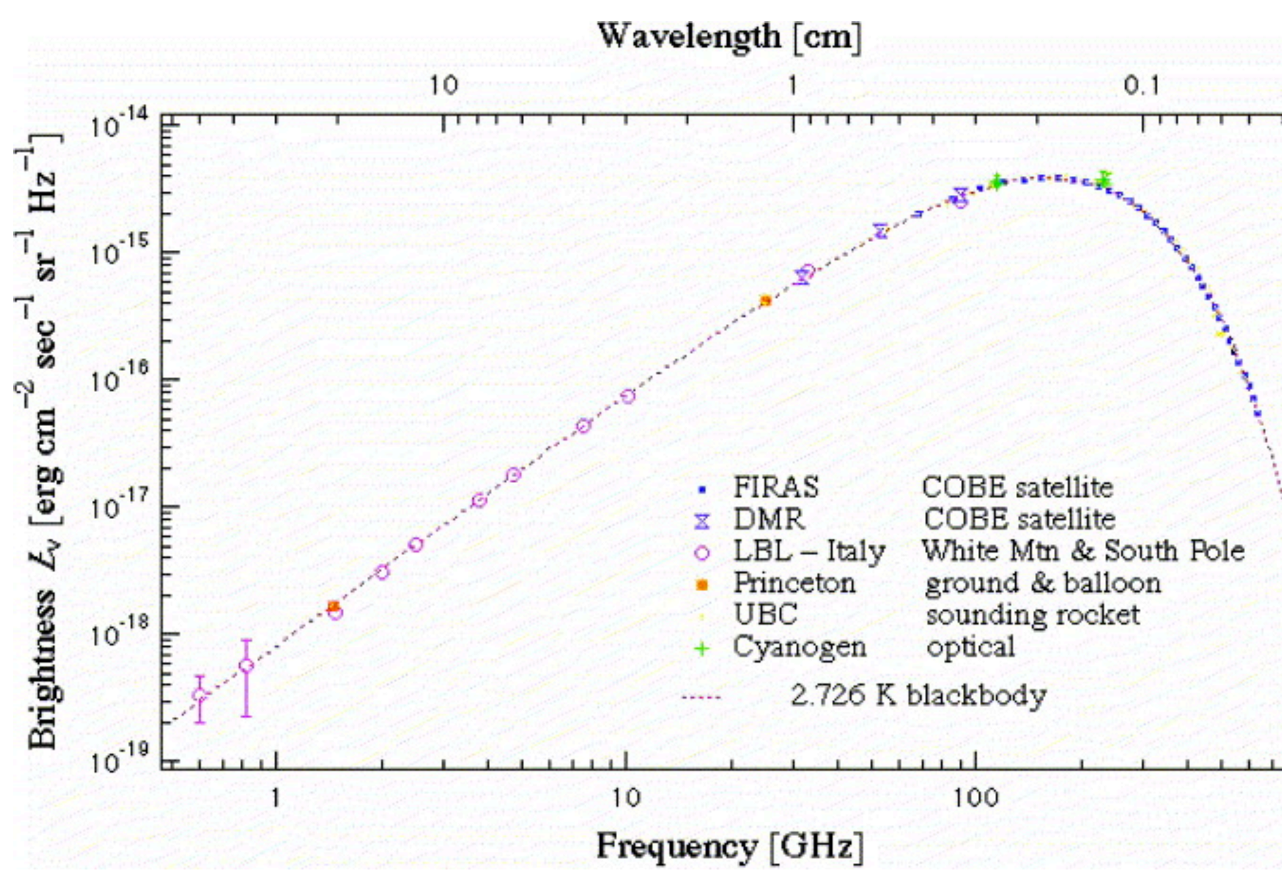
Adapted from an image by E. Vangioni, Institut d'Astrophysique de Paris

Discovery of the Cosmic Microwave Background (CMB)

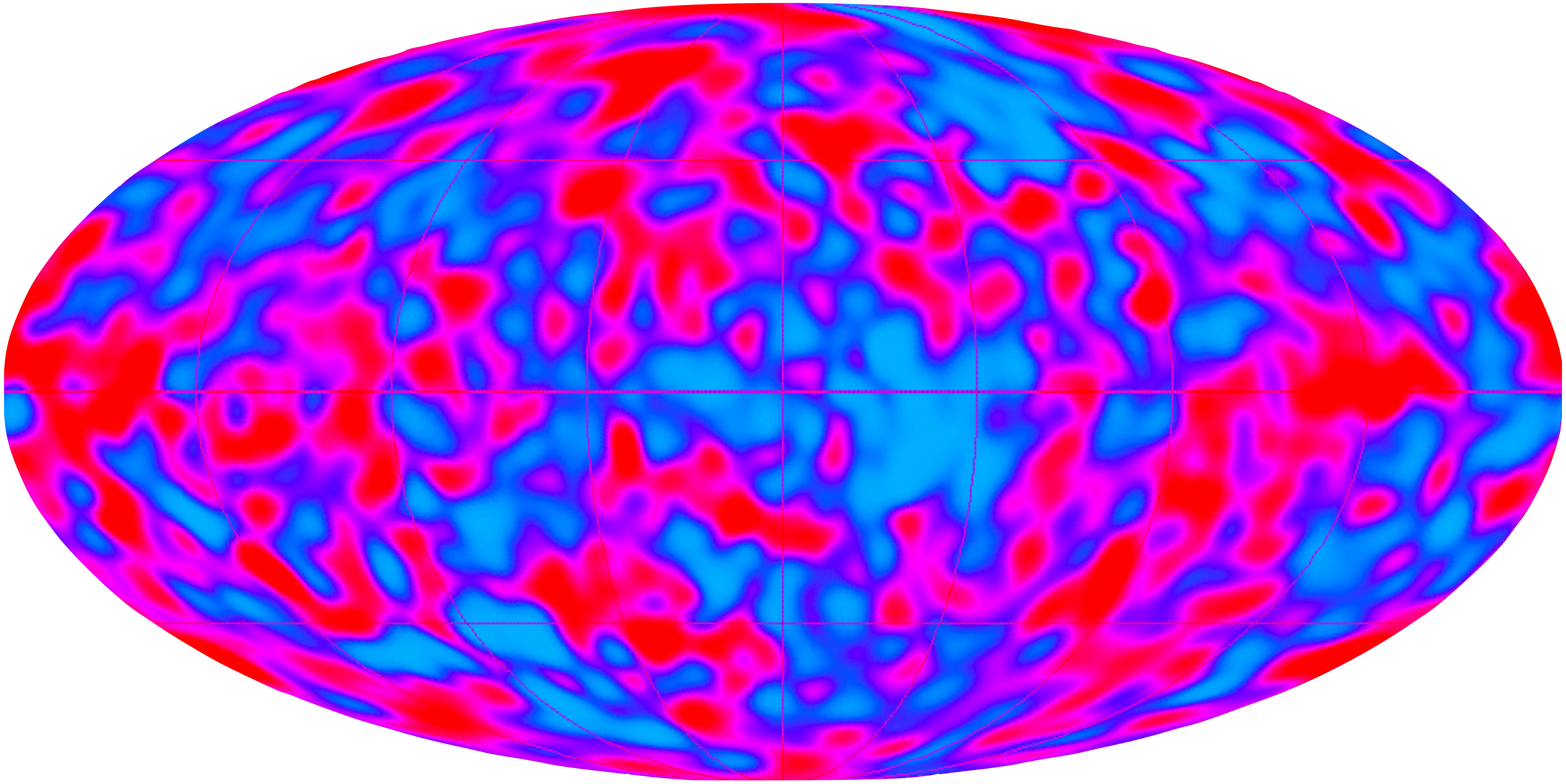


Arno Penzias & Robert Wilson in front of the 20 ft Bell Labs antenna used to discover the microwave background in 1965

“Smoking Gun” evidence for the Big Bang



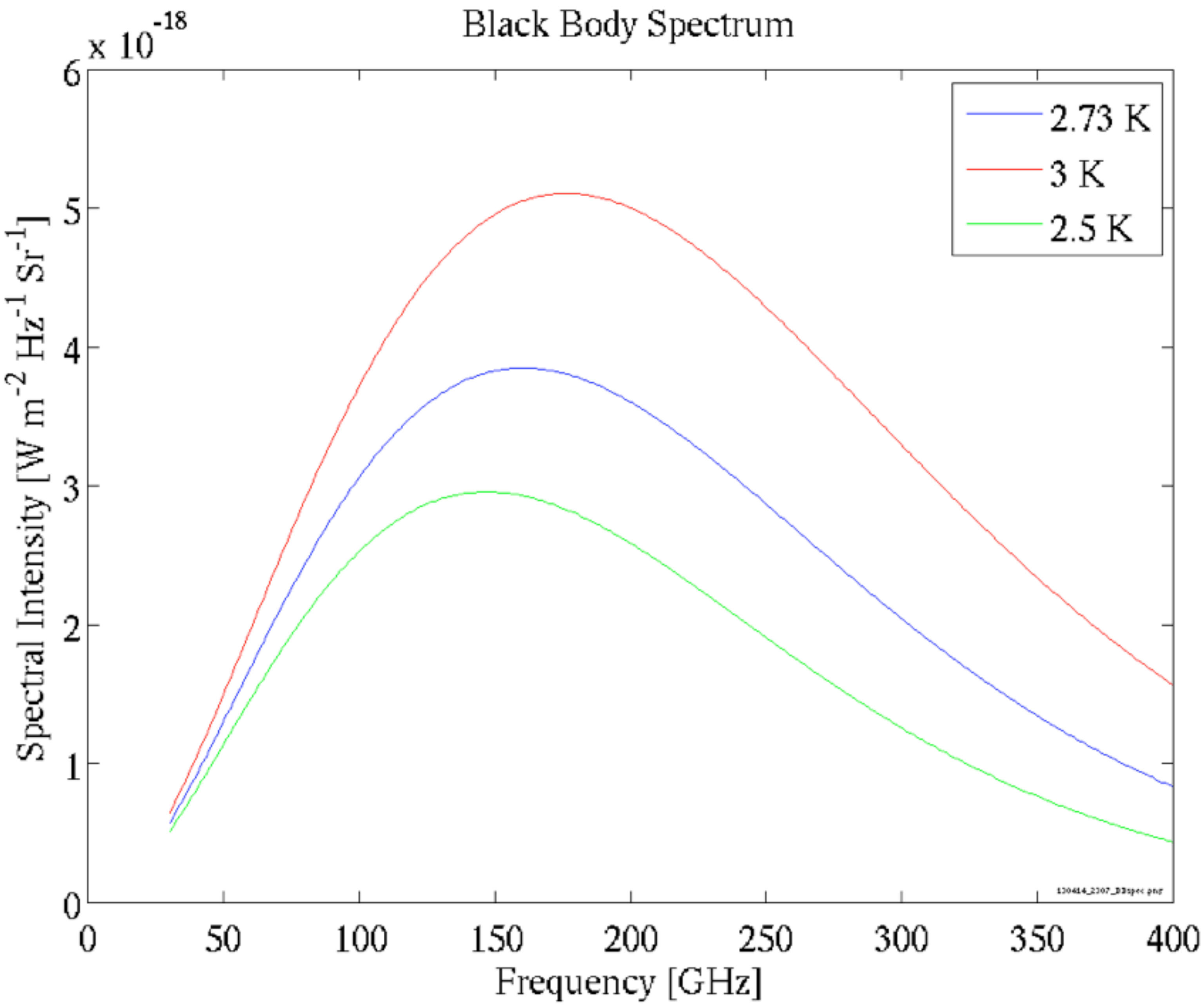
CMB: from prediction to tool



- Detect anisotropy!
- Superhorizon scales
- Small 1e-5.

Can see entire early universe. Understanding content limited by fidelity of measurement.

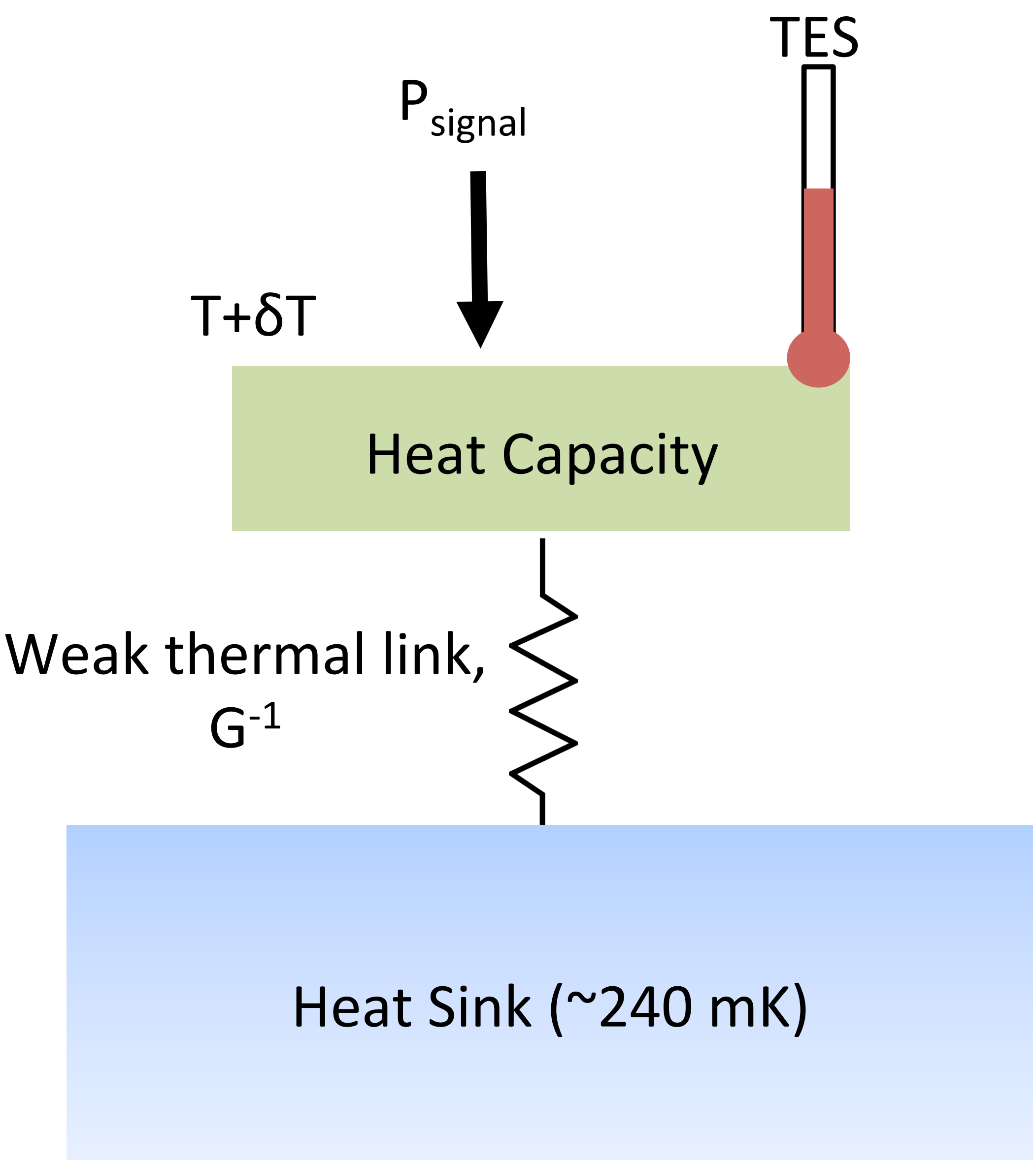
$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

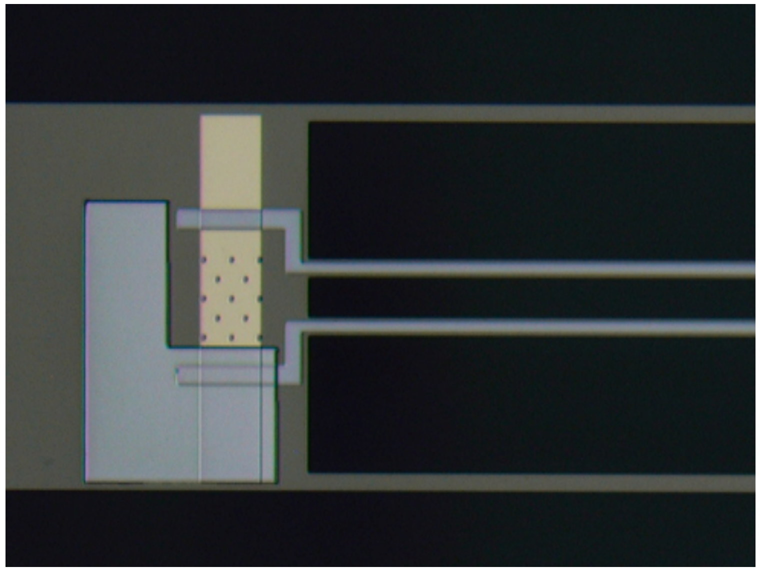


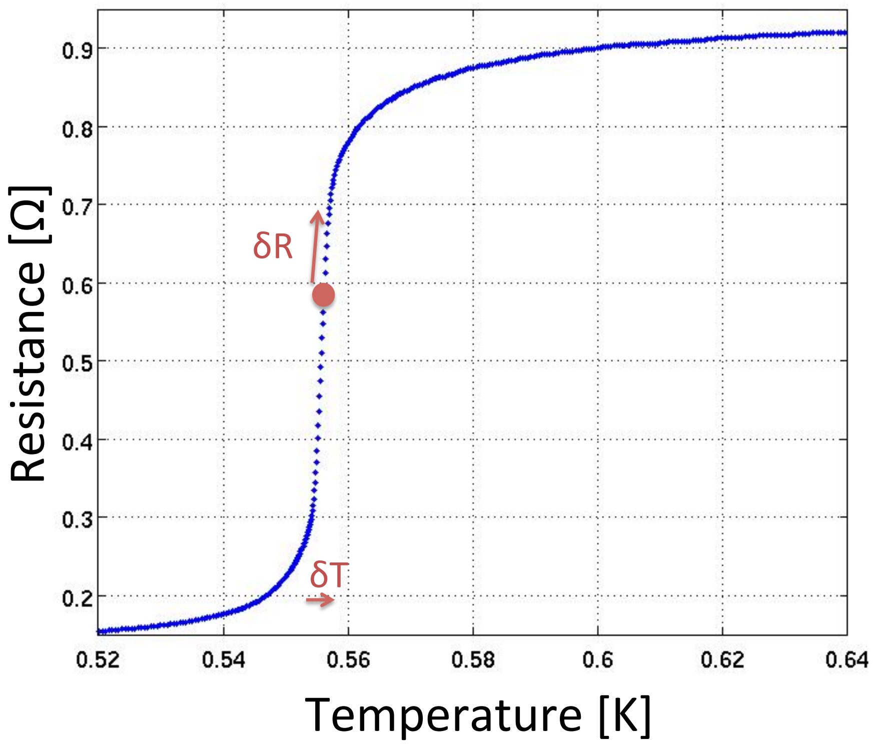
- Radiation at all frequencies (broadband)
- At all frequencies, higher (lower) temperature gives more (less) intensity
- Turn it around: at a given frequency, measuring intensity measures the temperature

- Point at spot in sky
- Measure flux
- Move to new target
- Repeat

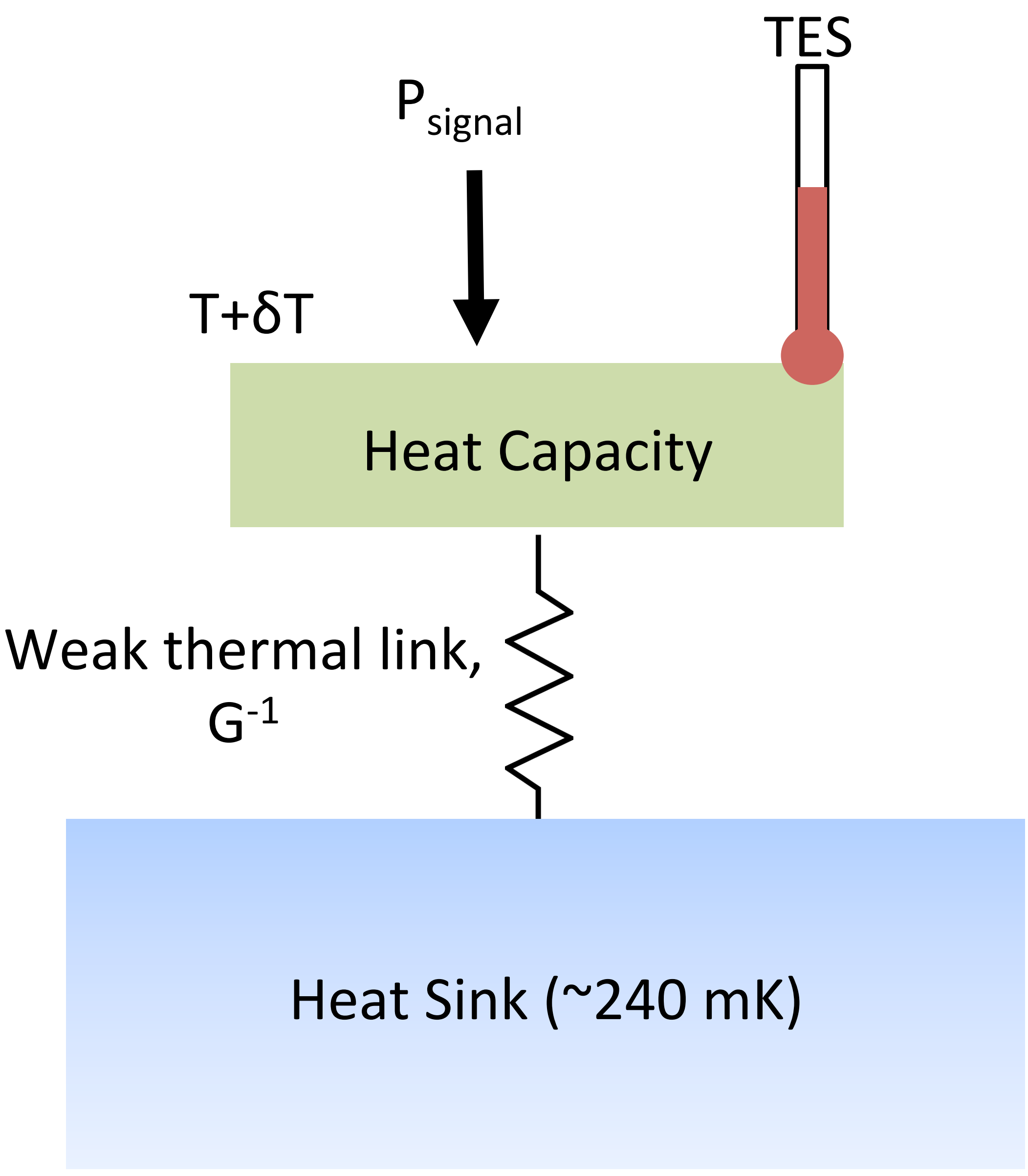
The Modern Transition Edge Sensor



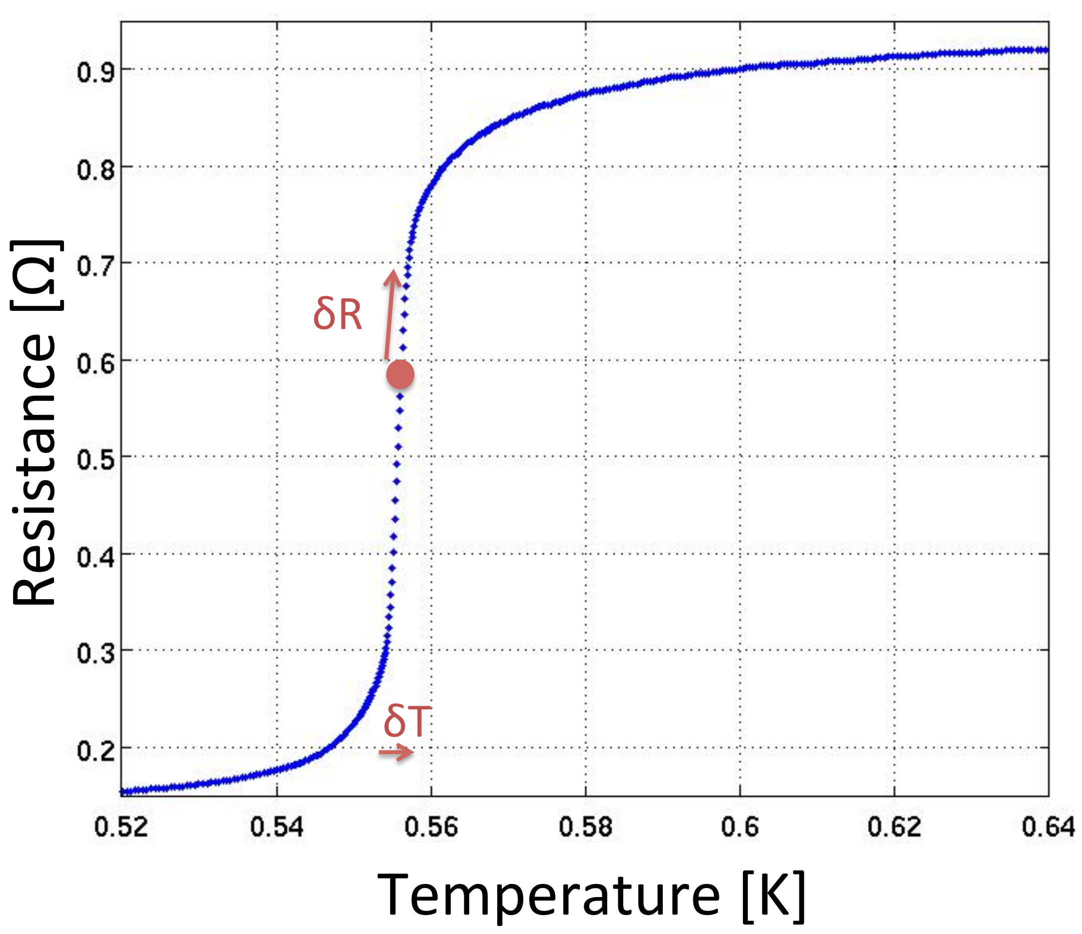




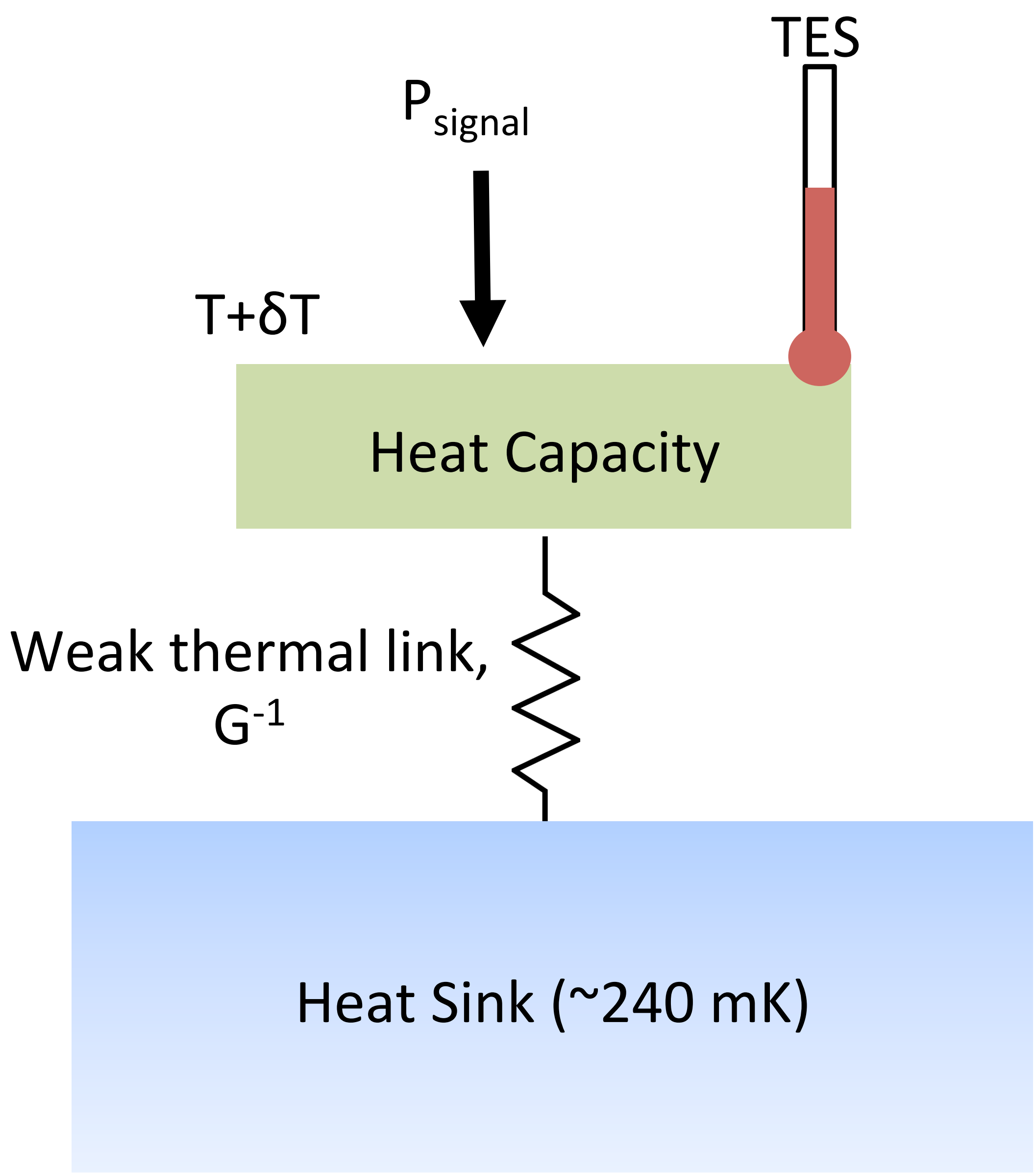
The Modern Transition Edge Sensor



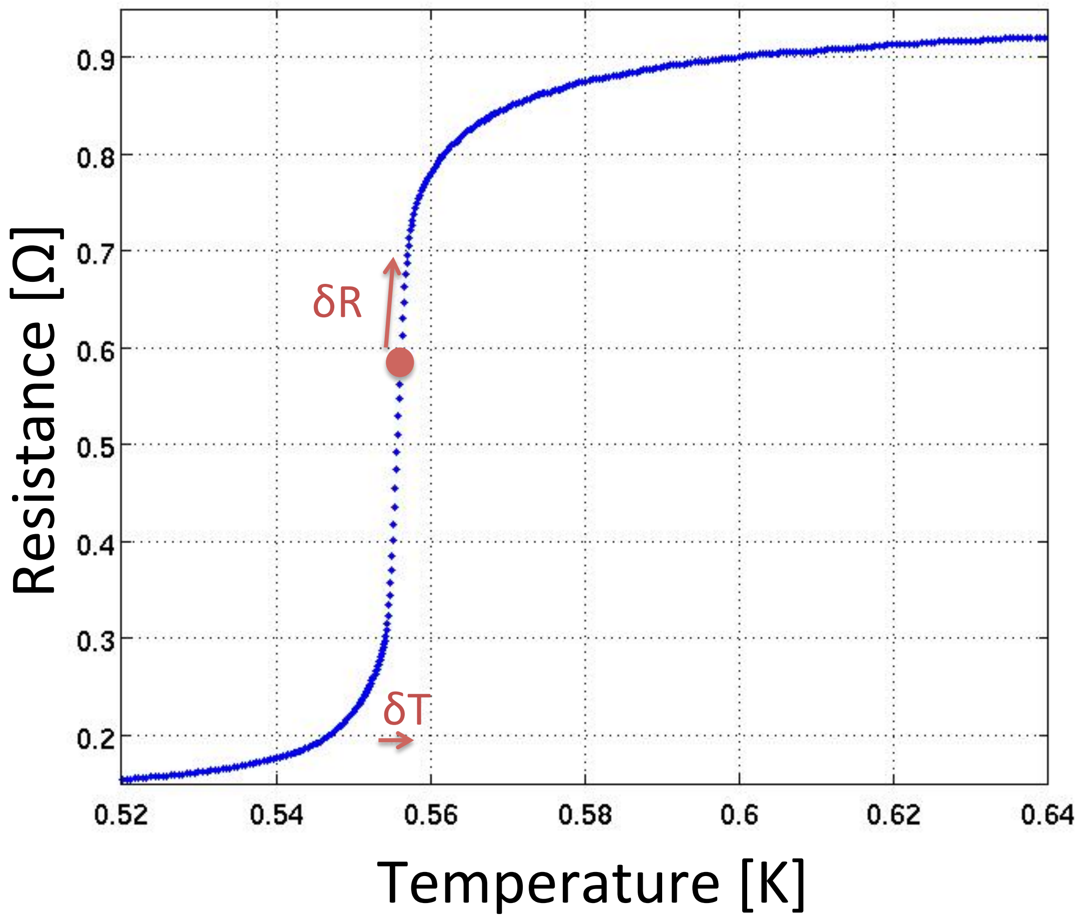
$$P_{Joule} = \frac{V_0^2}{R(T)}$$



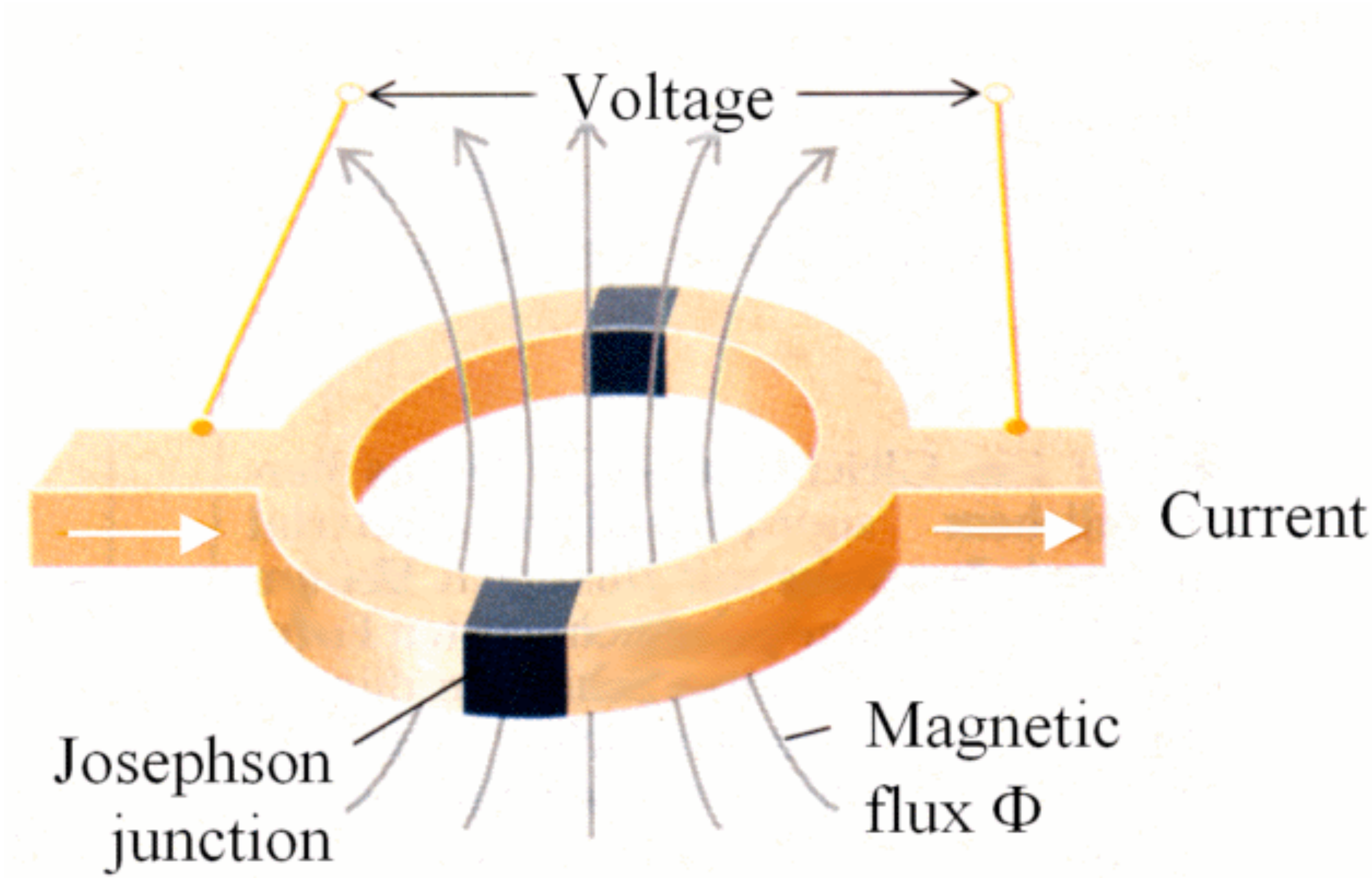
The Modern Transition Edge Sensor

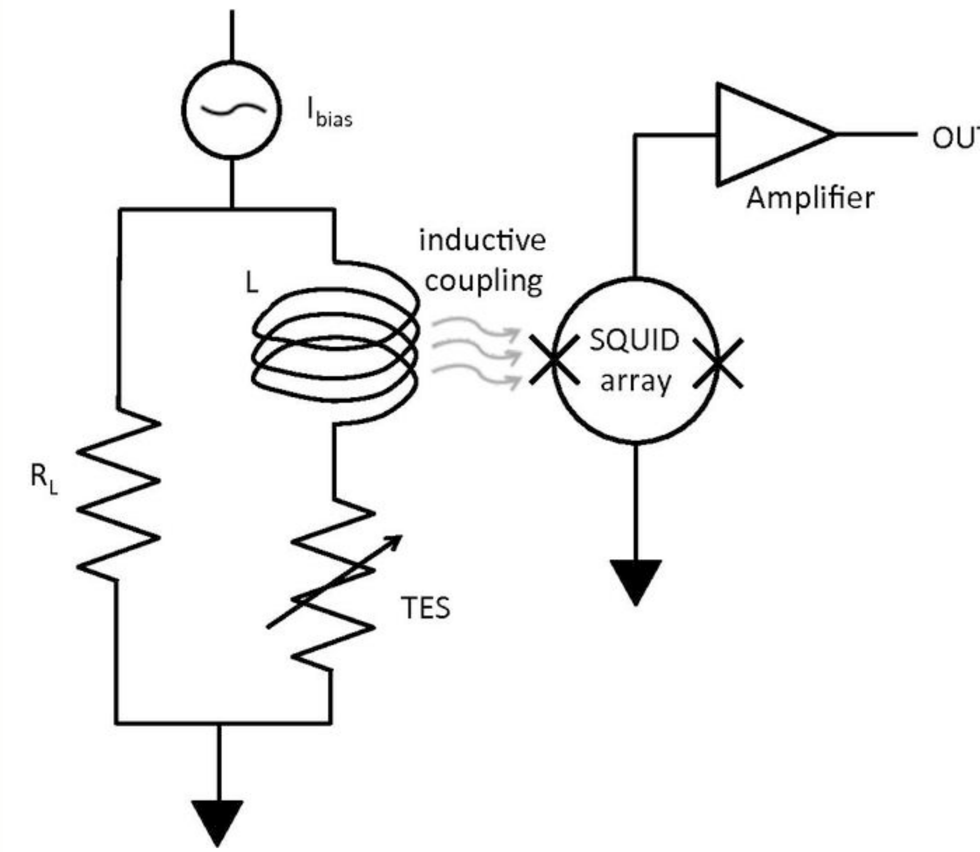


$$\delta P_{Joule} = \frac{d}{dT}\left(\frac{V_0^2}{R(T)}\right) = -\left(\frac{V_0}{R}\right)^2 \frac{dR}{dT}\delta T$$



Superconducting QUantum Interference Device





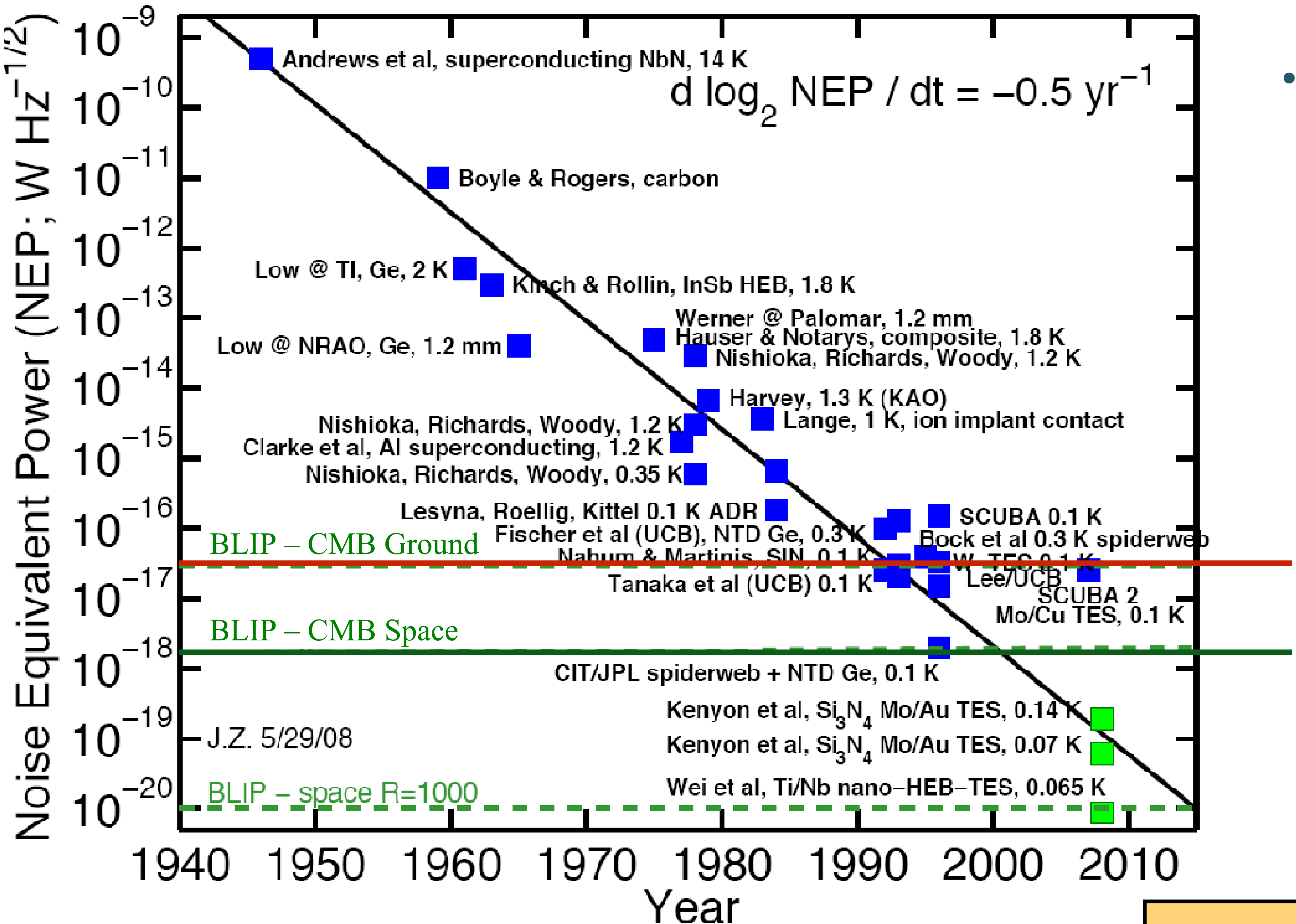
Fundamental limits of CMB measurement

- Uncertainty on measured photon power in time, τ

$$\sigma_P = \frac{h\nu\sigma}{\eta} = \frac{h\nu}{\sqrt{\Delta\nu\tau}} \sqrt{\frac{n_0(1+\eta n_0)}{\eta}} \Delta\nu$$

Jonas Zmuidzinas
Applied Optics, Vol. 42, Issue 25, pp. 4989-5008 (2003)

Background limited detectors



Plot from Jonas Zmuidzinas

Ground

Space

- Phonon noise: $\sigma_G = 4k_B G T^2$; subdominant with T~0.5K

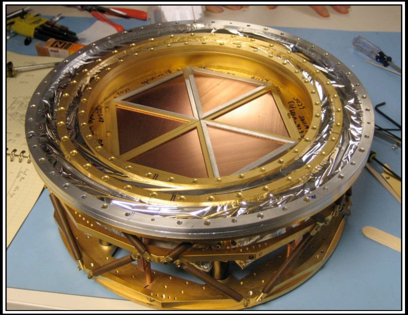
Need lots of detectors!

The South Pole Telescope (SPT)

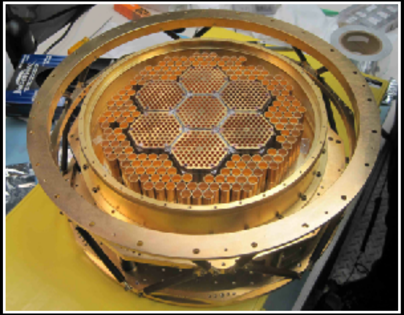
10-meter sub-mm quality wavelength telescope

95, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

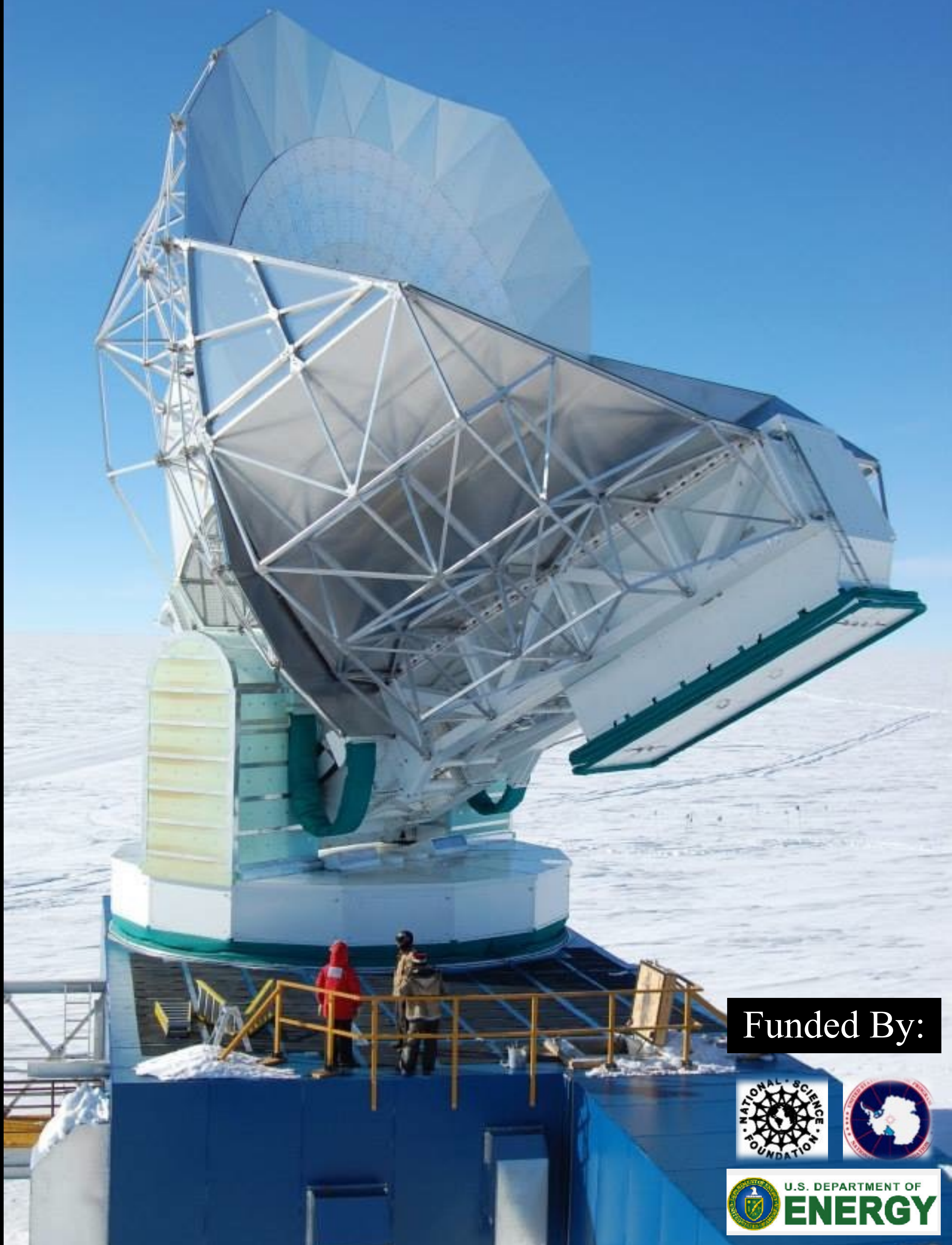
2007: SPT-SZ
960 detectors
95,150,220 GHz

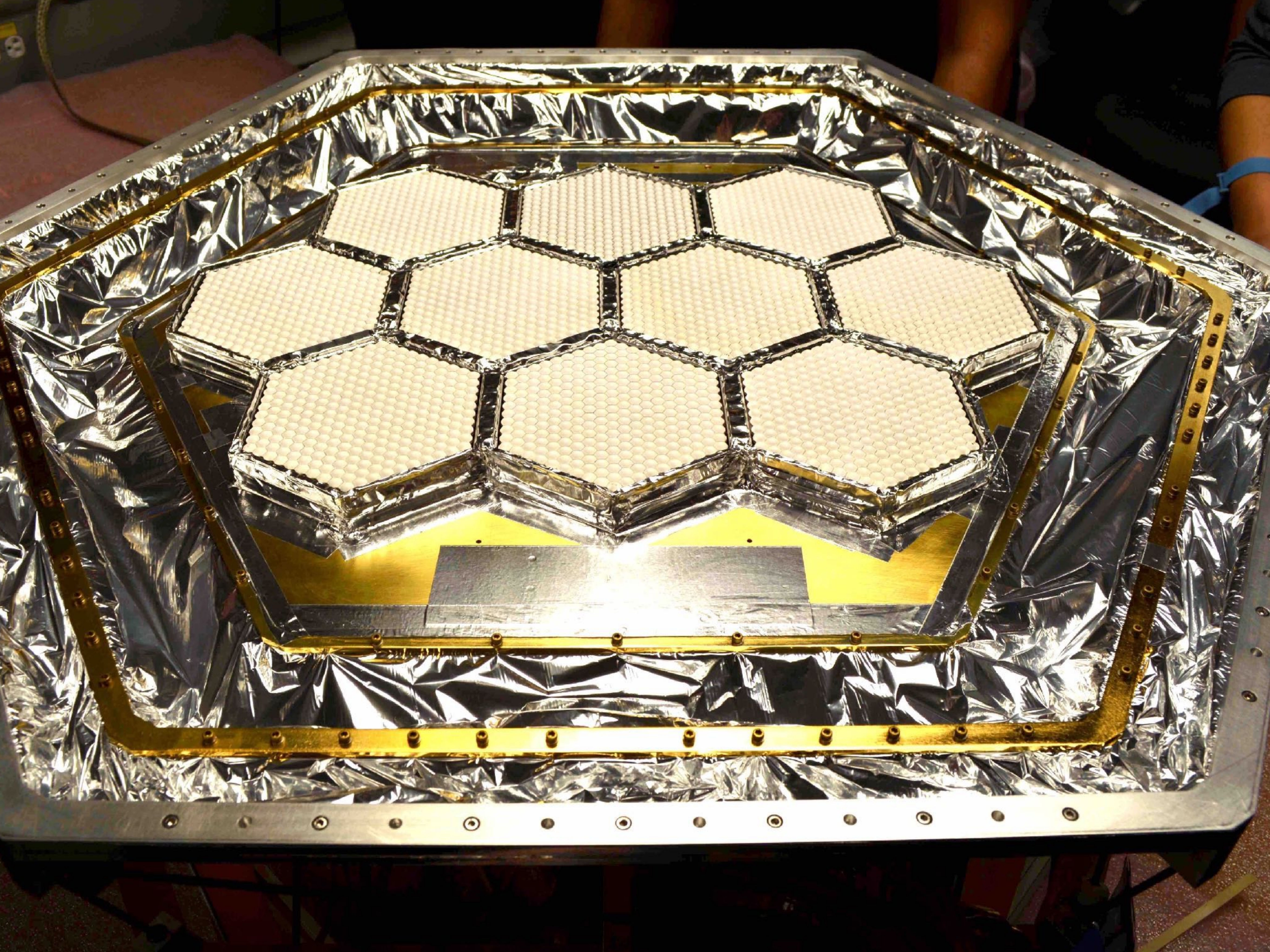


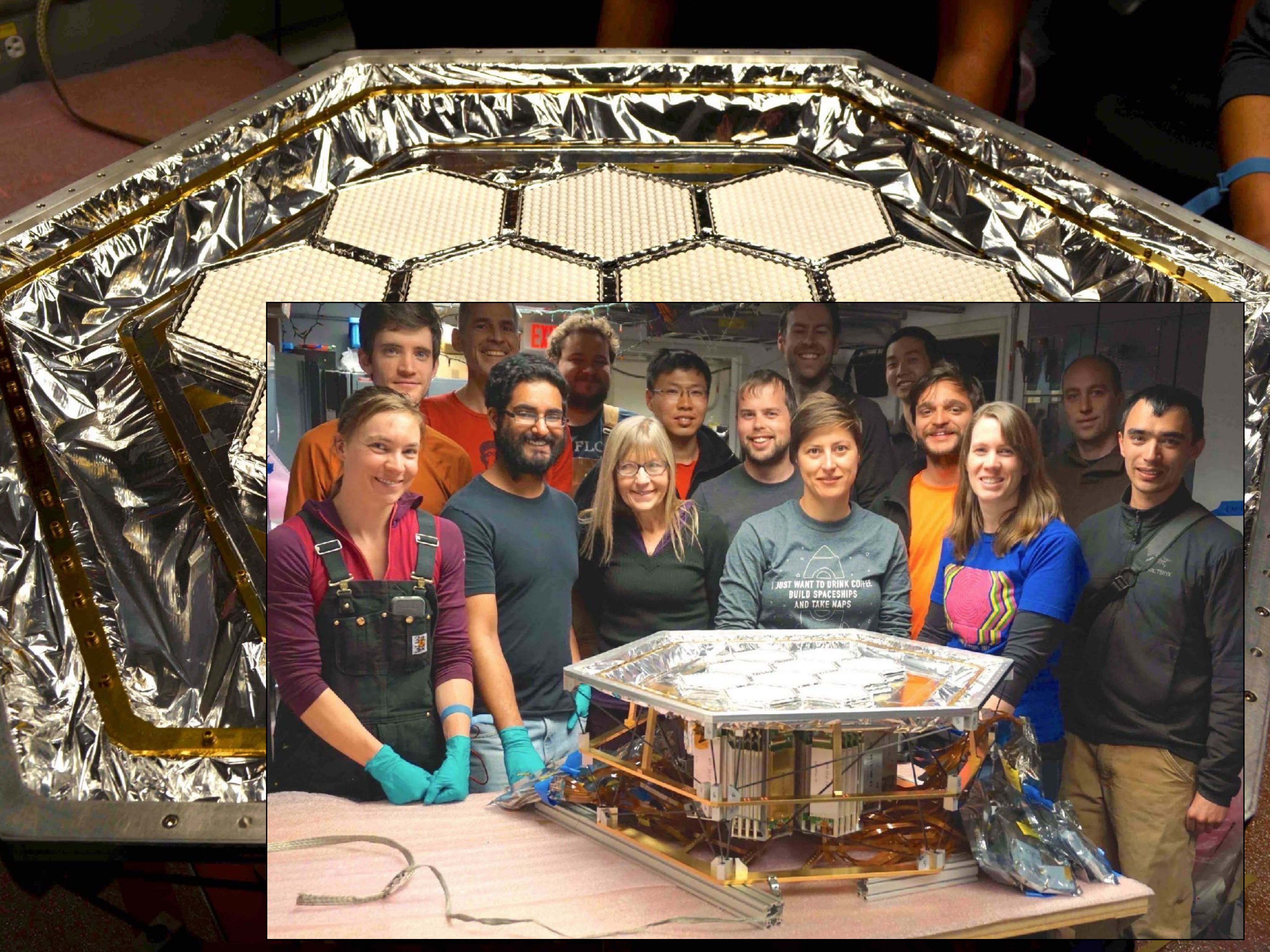
2012: SPTpol
1600 detectors
95,150 GHz
+Polarization

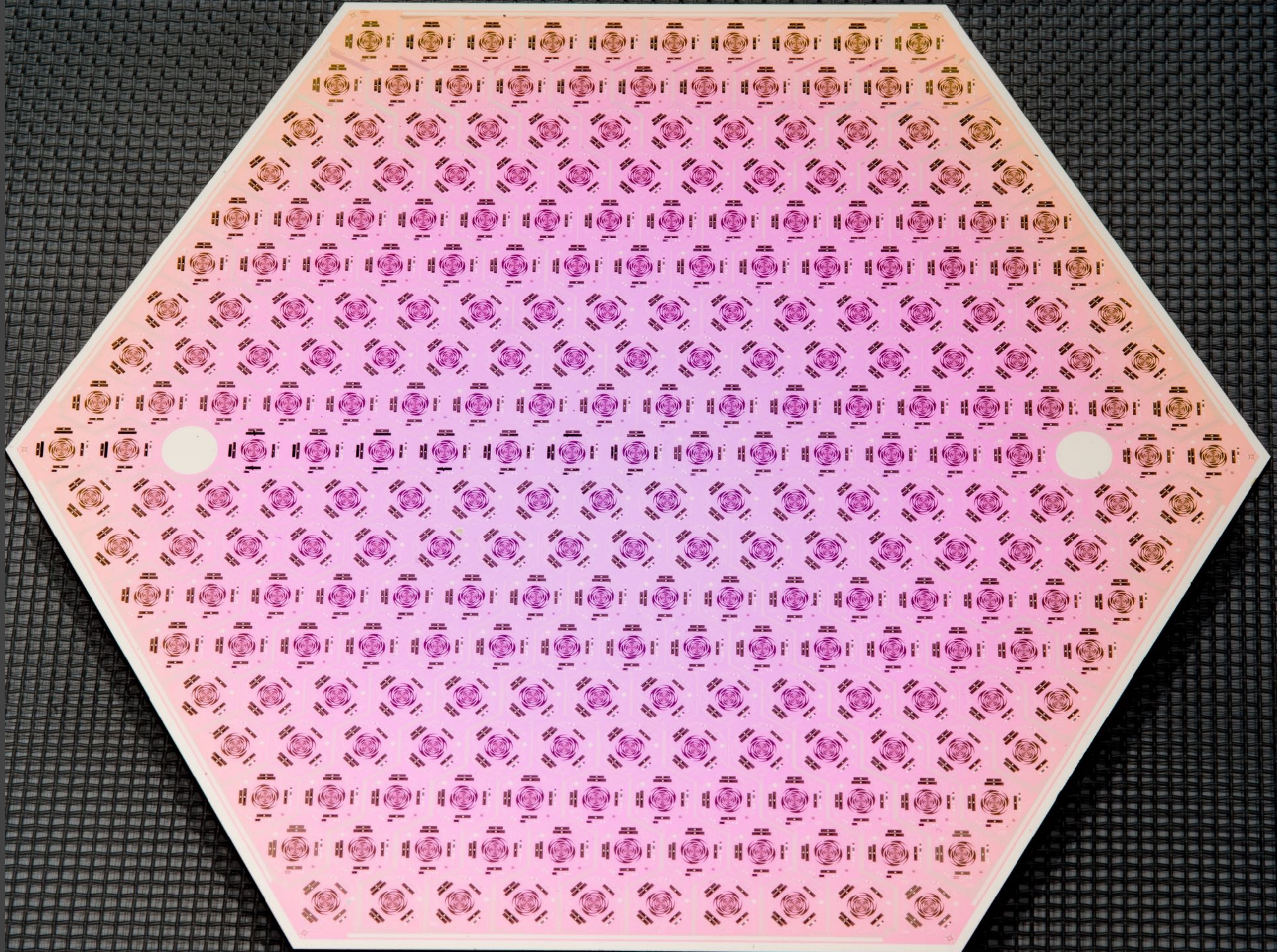


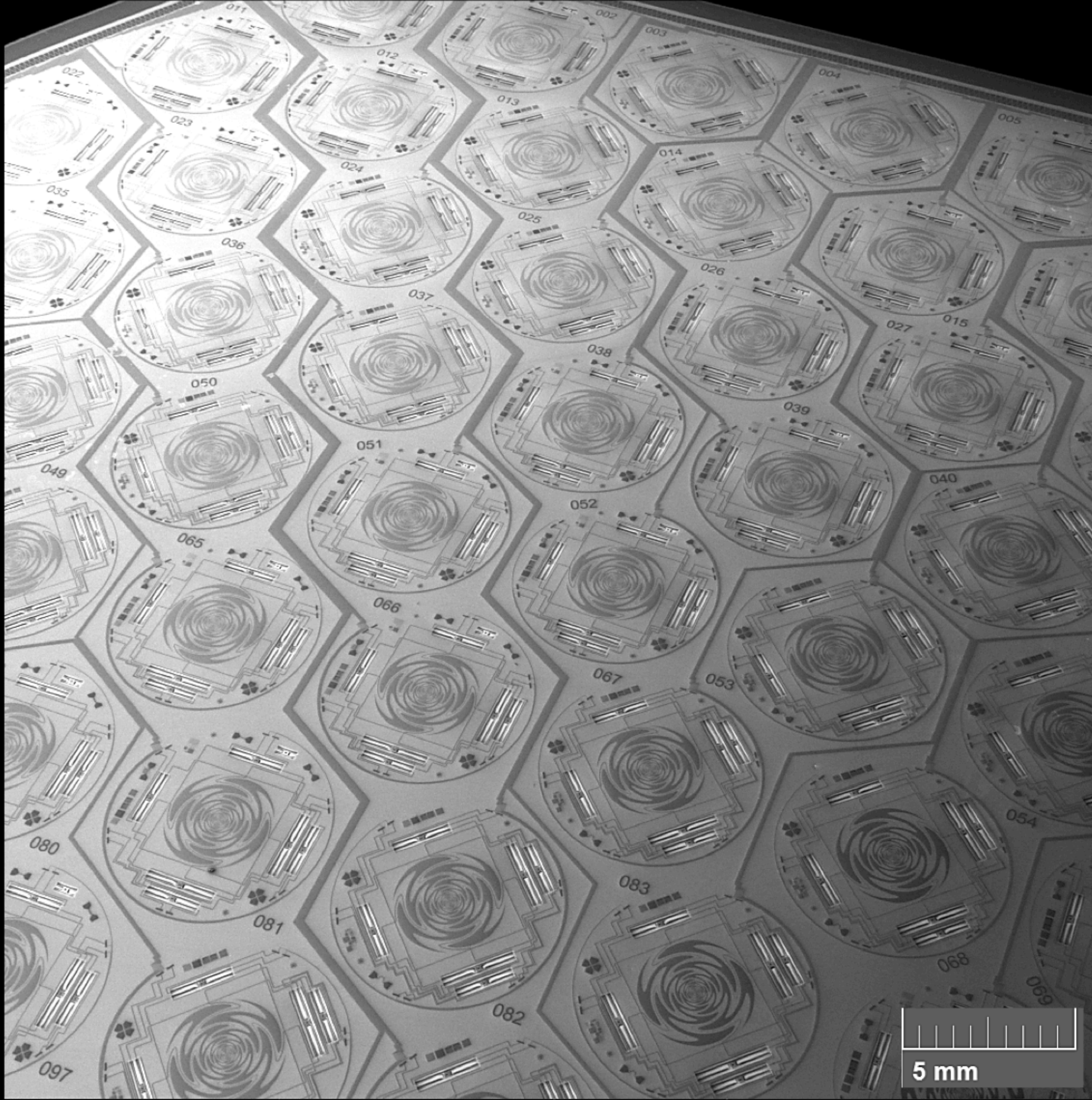
2017: SPT-3G
~16,000 detectors
95,150,220 GHz
+Polarization






I JUST WANT TO DRINK COFFEE
BUILD SPACESHIPS
AND TAKE NAPS





002
003
004
005
011
012
013
014
015
022
023
024
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035
036
037
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049
050
051
052
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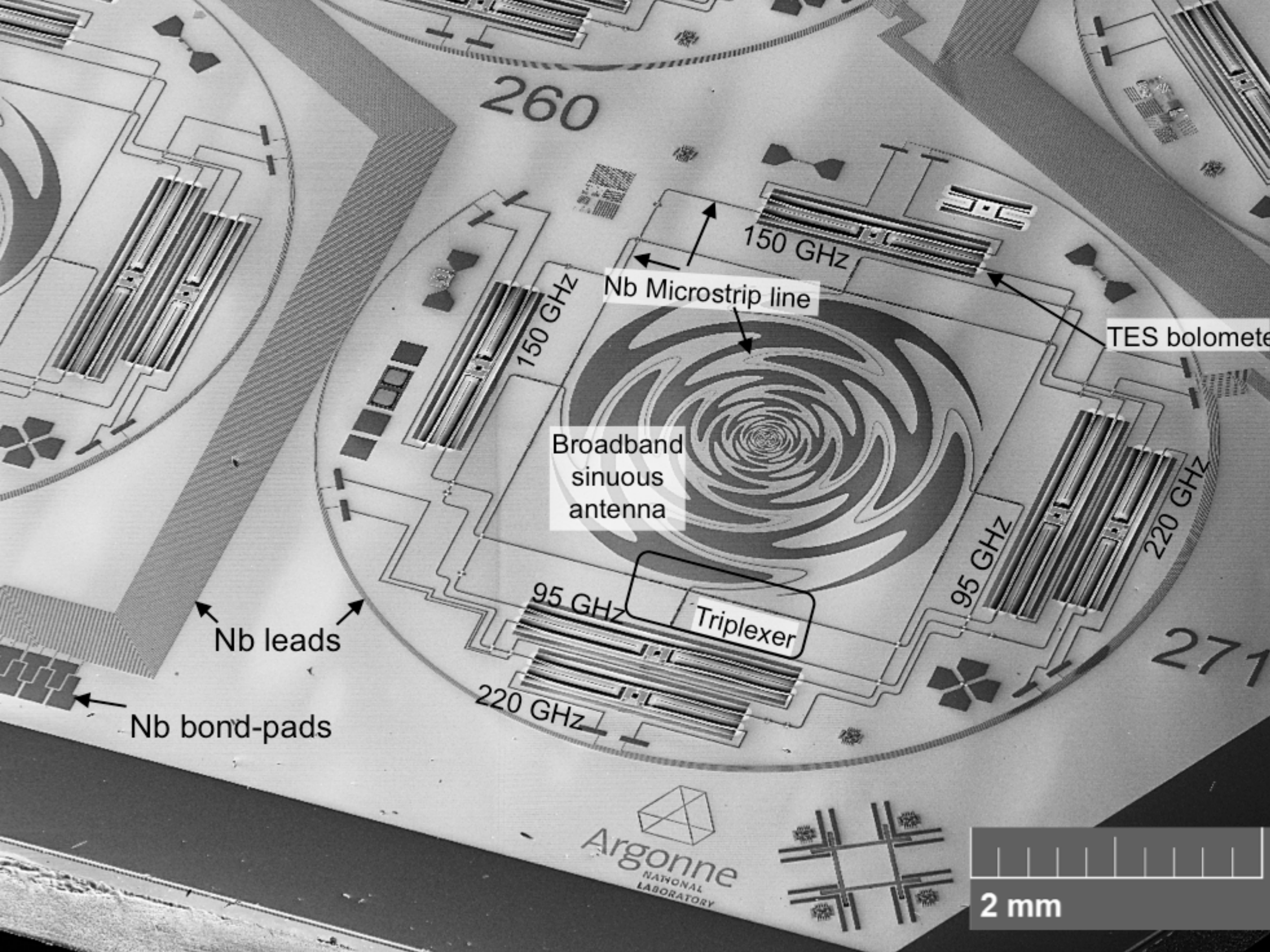
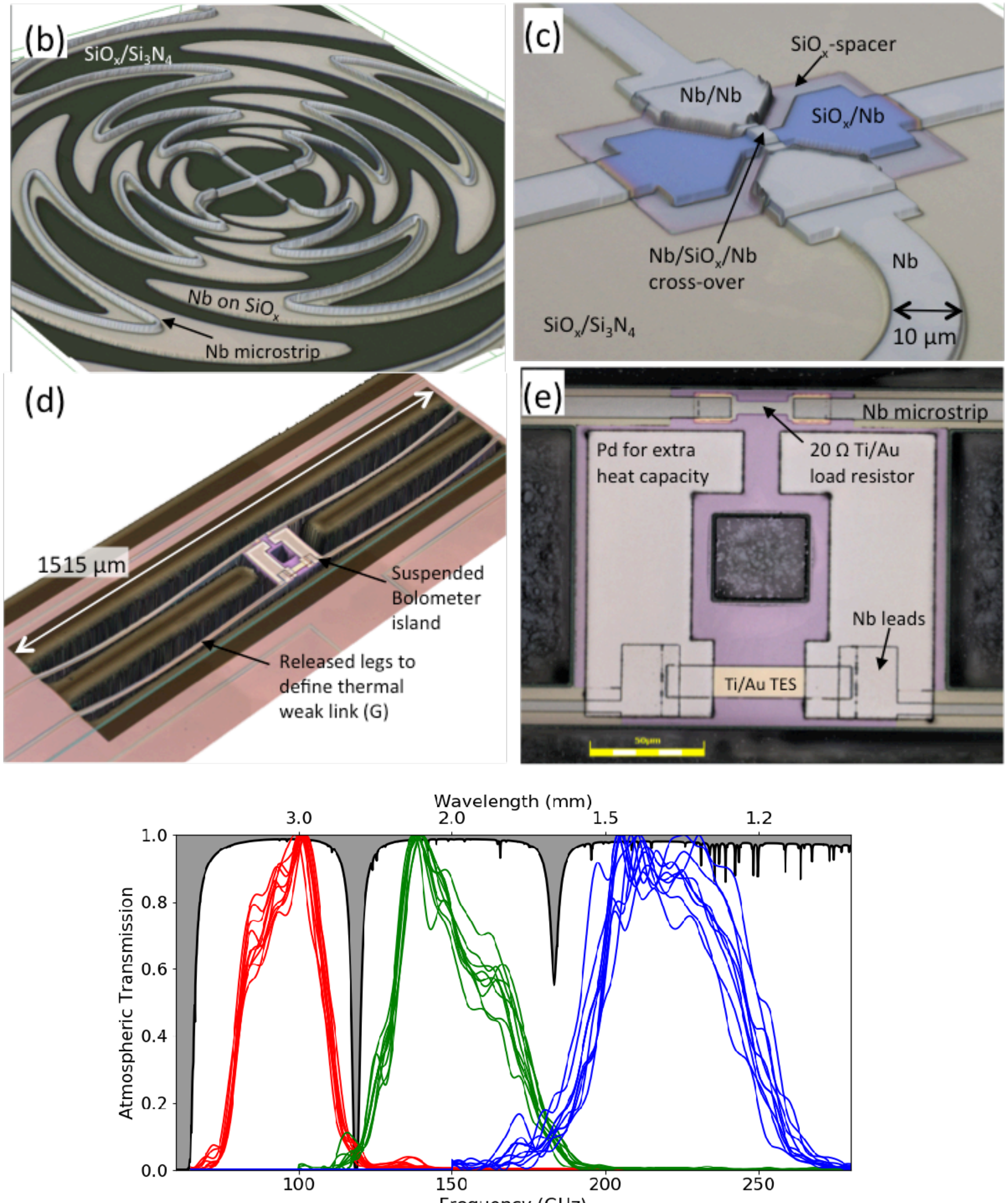
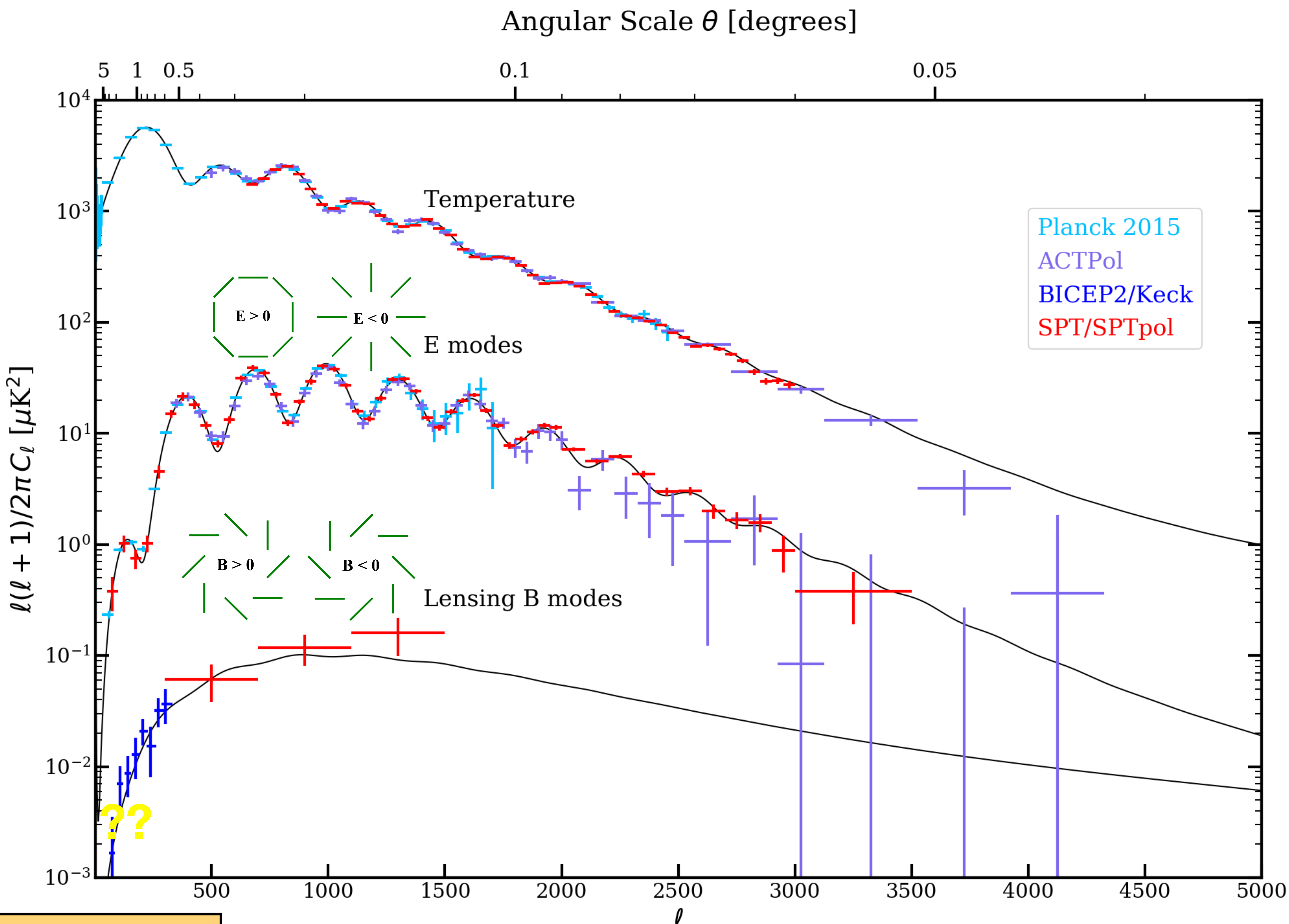
054
065
066
067
068
069
080
081
082
083
097
5 mm

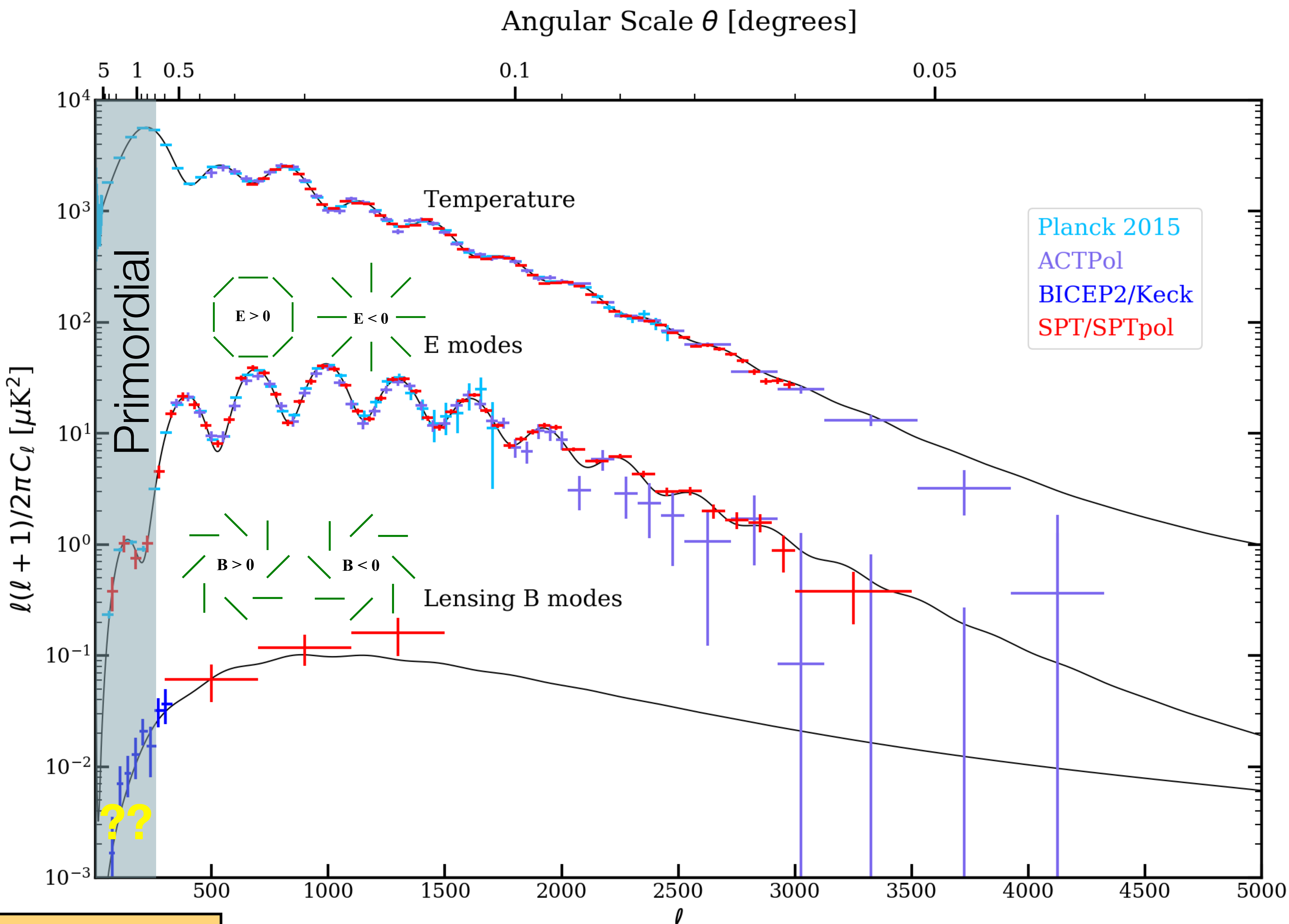

260
150 GHz
Nb Microstrip line
150 GHz
TES bolomete
Broadband
sinuous
antenna
220 GHz
95 GHz
95 GHz
Triplexer
271
Nb leads
220 GHz
Nb bond-pads
Argonne
NATIONAL
LABORATORY
2 mm



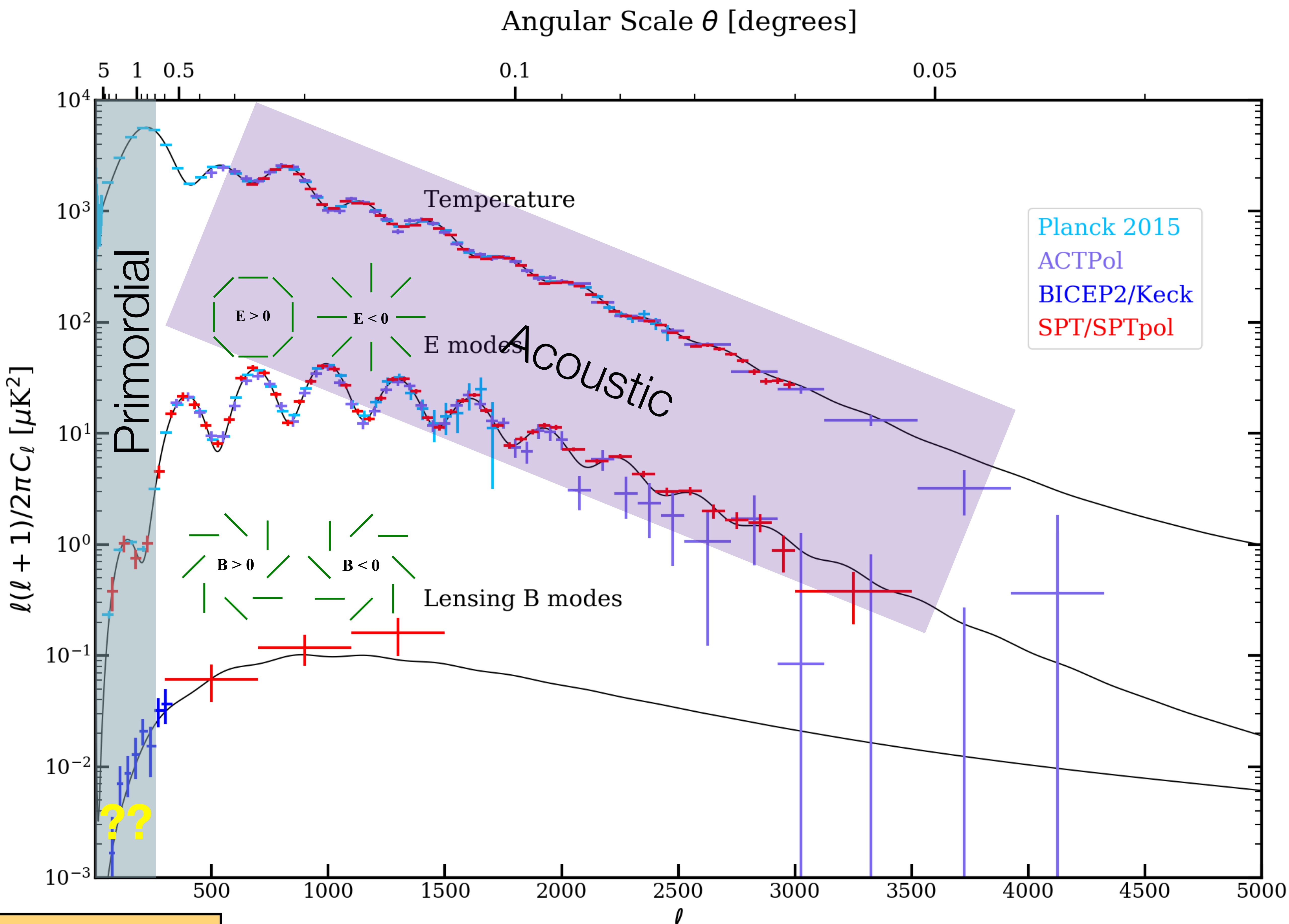
1. Antenna couples to free space radiation field. Separates polarizations
2. Transition to low loss superconducting microstrip.
3. Cross-overs manage topology.
4. Triplexer lumped element filters channelize signal into three bands.
5. Power dissipated on suspended island.
6. Thermally measured by TES. Tune thermal circuit to manage feedback stability.


Angular Scale θ [degrees]
5
1
0.5
0.1
0.05
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Temperature
E modes
E > 0
E < 0
B > 0
B < 0
Lensing B modes
??
Planck 2015
ACTPol
BICEP2/Keck
SPT/SPTpol
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
ℓ

Inflation?

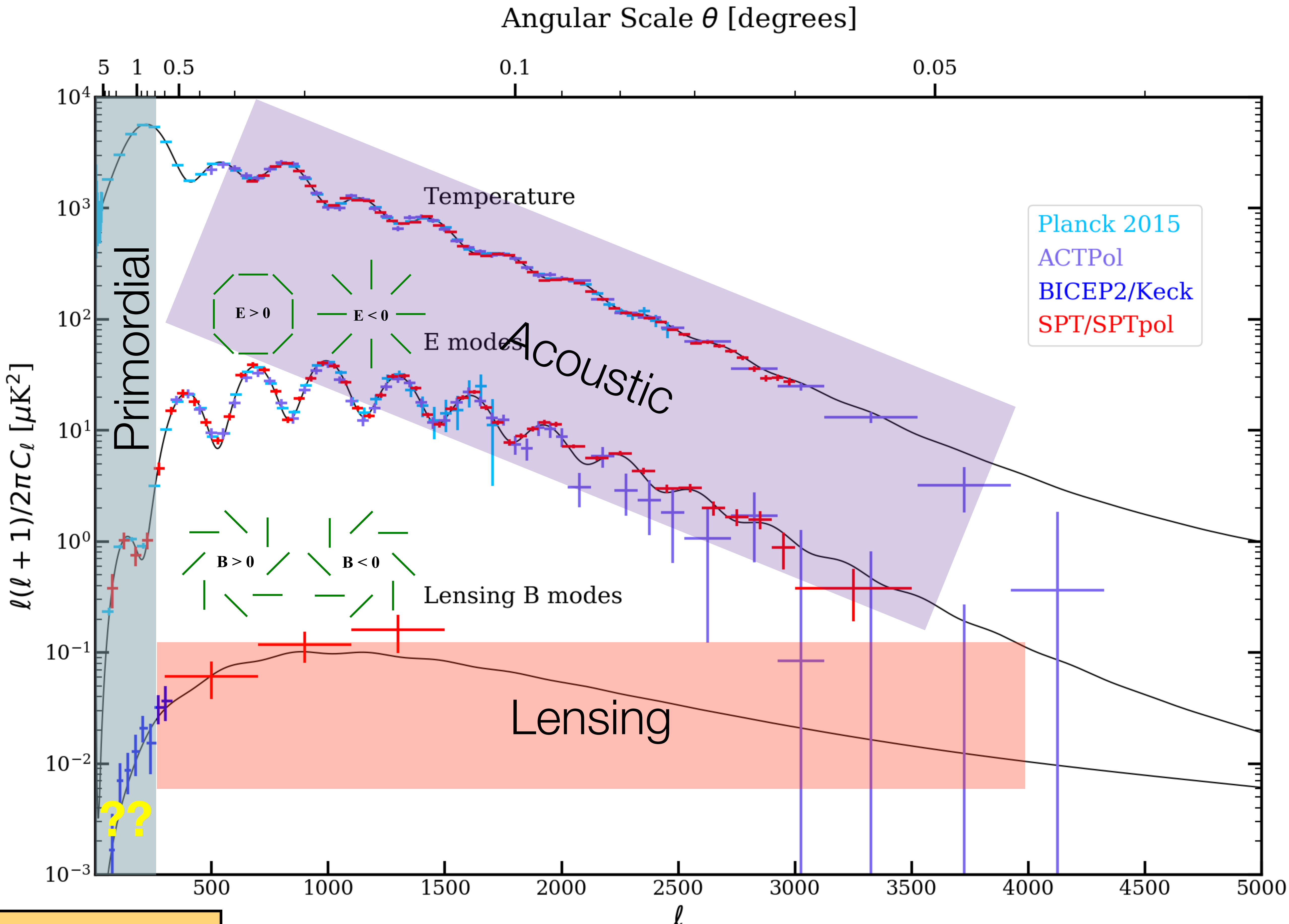

Angular Scale θ [degrees]
5
1
0.5
0.1
0.05
Temperature
E modes
Lensing B modes
E > 0
E < 0
B > 0
B < 0
Primordial
??
Planck 2015
ACTPol
BICEP2/Keck
SPT/SPTpol
ℓ(ℓ + 1)/2π C_ℓ [μK²]
ℓ
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Inflation?



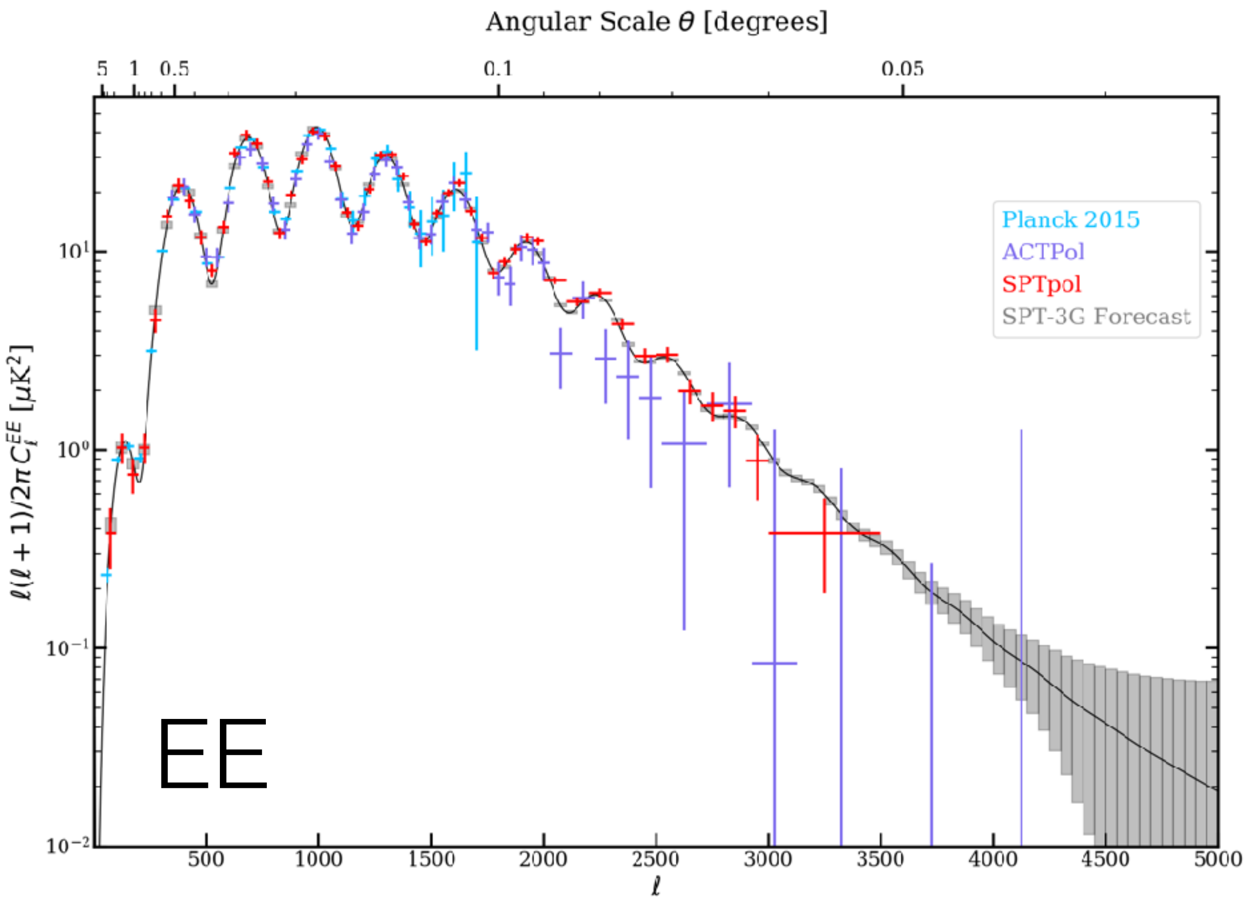
Angular Scale θ [degrees]
5 1 0.5 0.1 0.05
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3}
500 1000 1500 2000 2500 3000 3500 4000 4500 5000
ℓ
Primordial
Acoustic
Temperature
E modes
Lensing B modes
E > 0
E < 0
B > 0
B < 0
??
Planck 2015
ACTPol
BICEP2/Keck
SPT/SPTpol

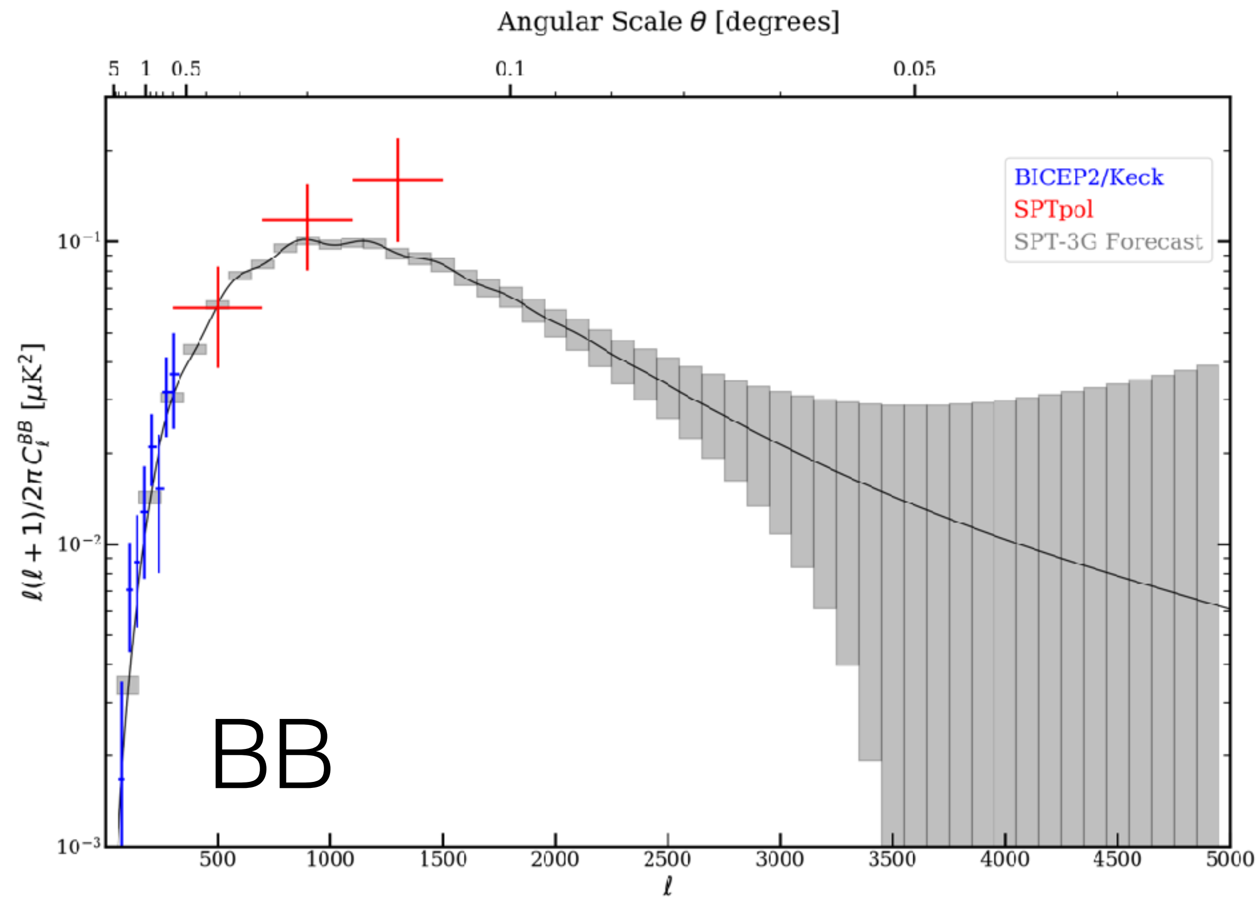
Inflation?



Angular Scale θ [degrees]
5
1
0.5
0.1
0.05
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
Primordial
Temperature
Acoustic
E > 0
E < 0
E modes
B > 0
B < 0
Lensing B modes
Lensing
??
Planck 2015
ACTPol
BICEP2/Keck
SPT/SPTpol
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
ℓ

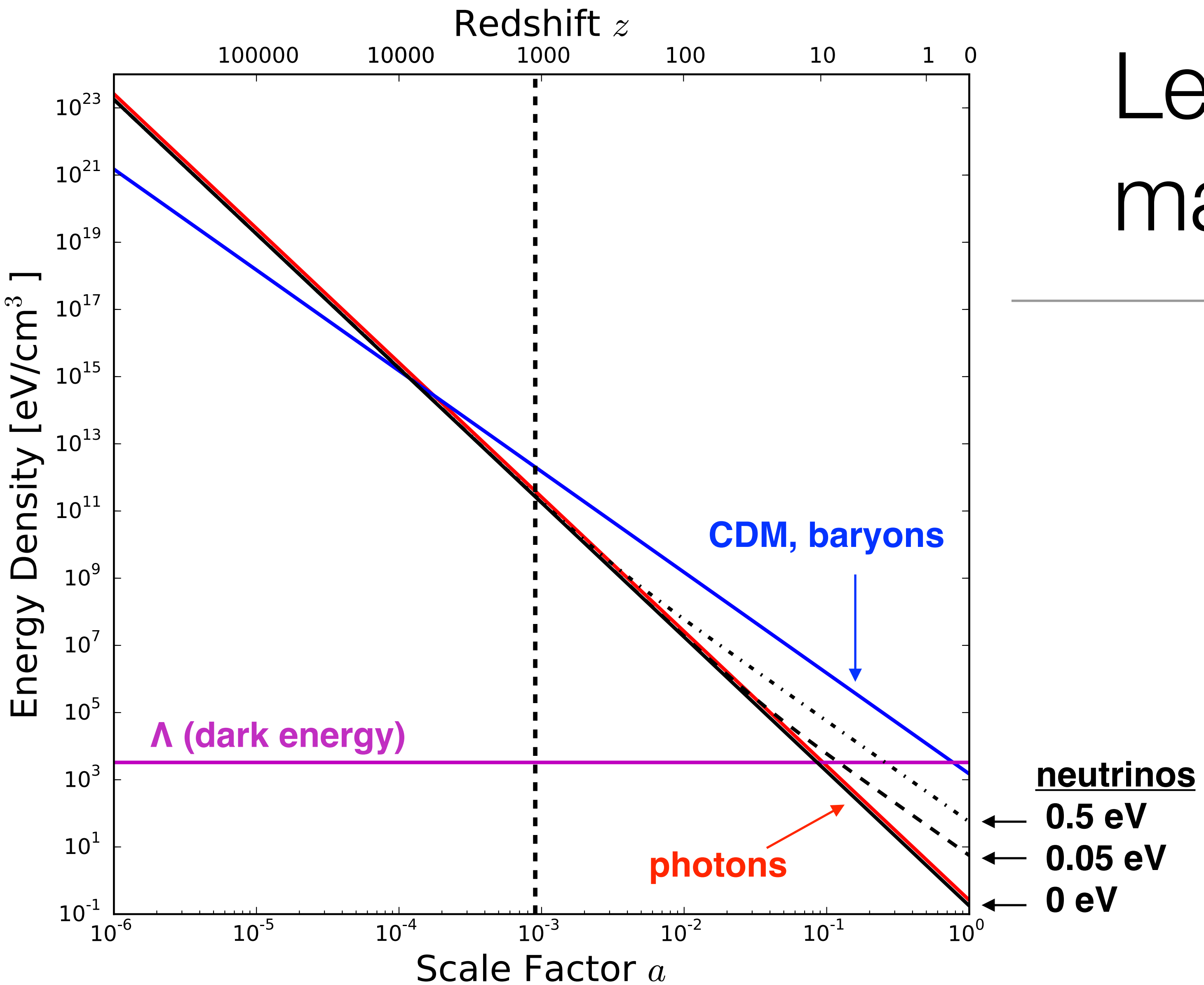
Inflation?



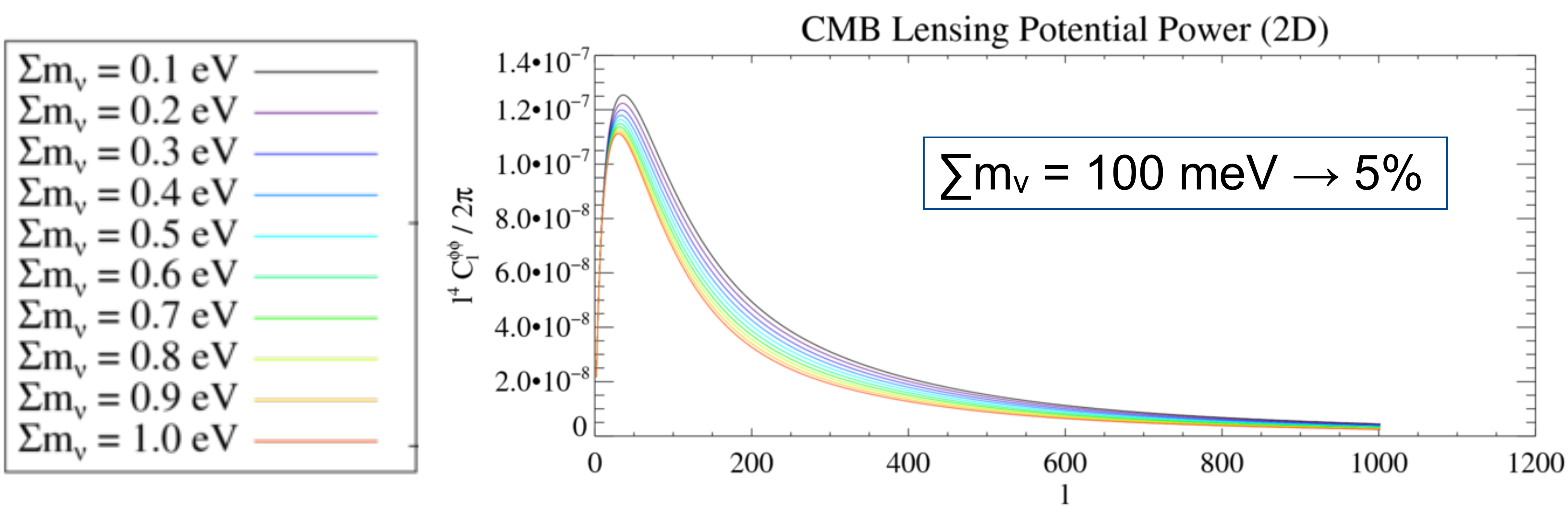


- Primordial features - inflation
- Acoustic features - “dark sector” (light dark matter, new light degrees of freedom)
- Lensing features - measures large scale structure, neutrino mass

Lensing and Neutrino mass

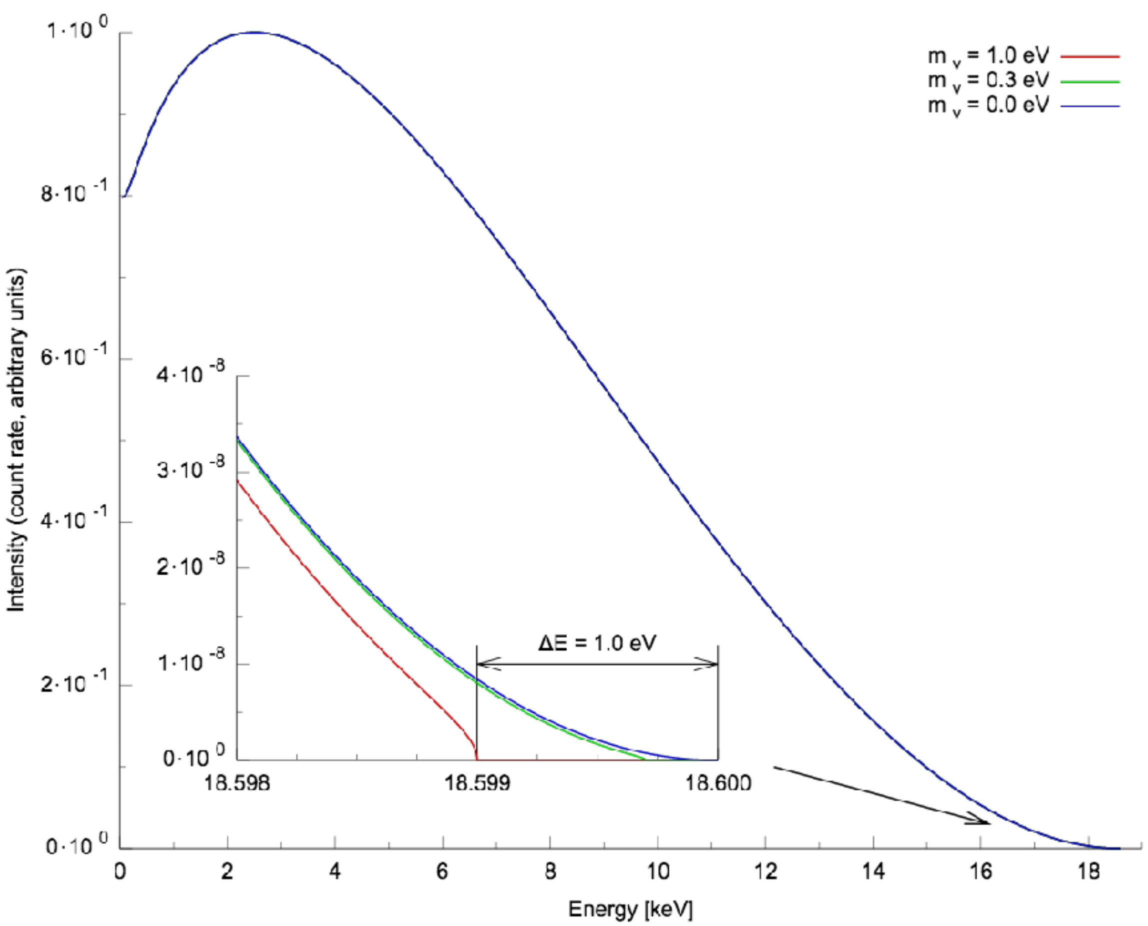


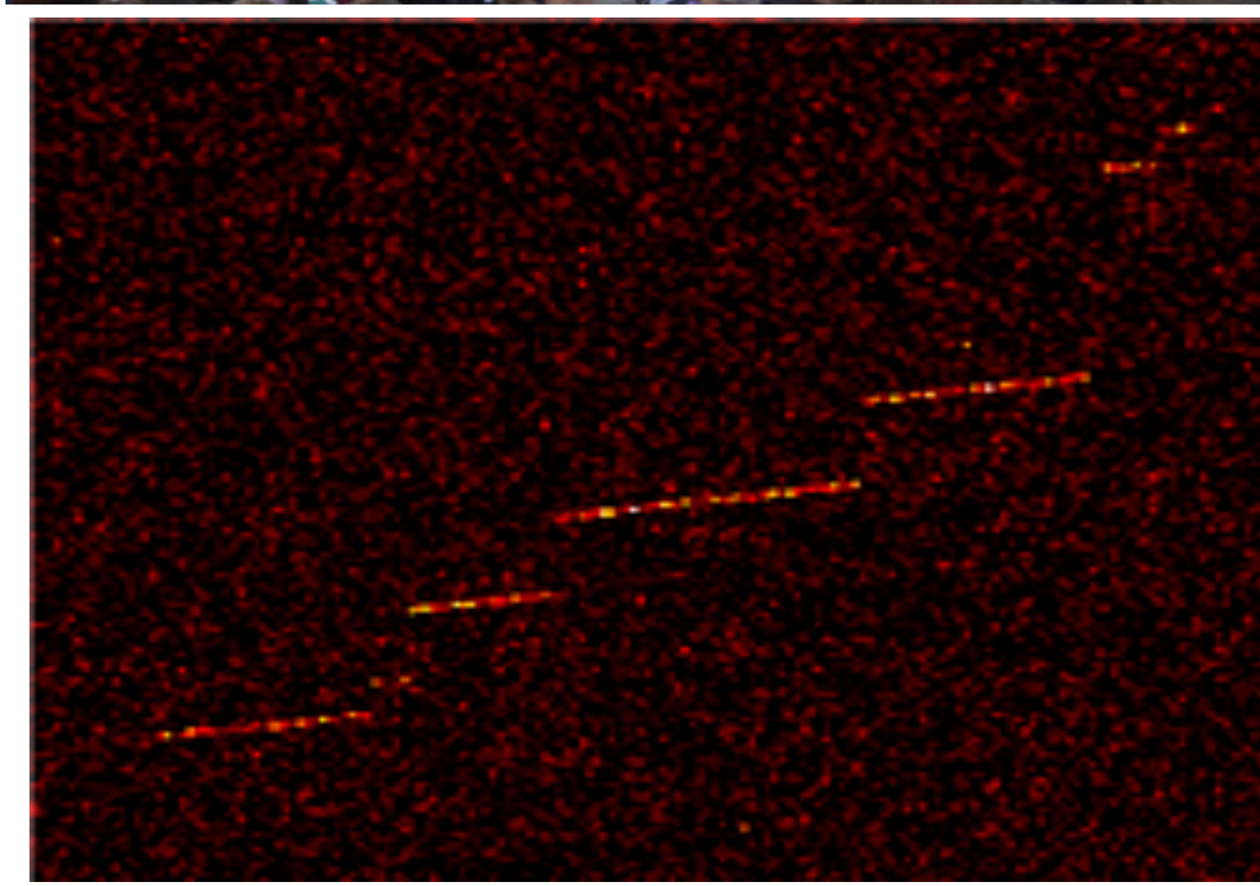
- Neutrinos only particle acts as radiation early, (warm, smooth) matter late
- More mass slows down structure formation, less lensing



Neutrino mass

- Complements measurements of neutrino mass from Tritium end point (beta decay)





Fermion mass mechanisms

$$L = -m\overline{\psi}\psi + h.c.$$

Dirac mass

$$L = -m\overline{\psi}_R\psi_L - m\overline{\psi}_L\psi_R + h.c.$$

Majorana mass

$$L = m\overline{(\psi_R)^C}\psi_R + h.c.$$

$(\psi_R)^C \leftarrow$ Charge conjugate

Charged particle cannot have Majorana mass.

Fermion mass mechanisms

$$L = -m\overline{\psi}\psi + h.c.$$

Dirac mass

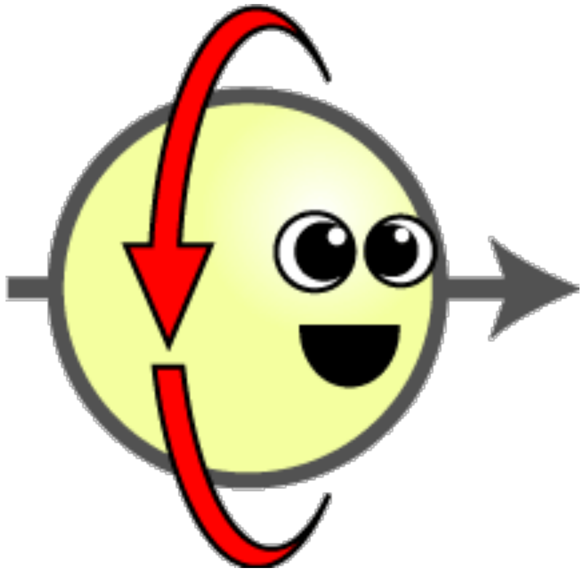
$$L = -m\overline{\psi}_R\psi_L - m\overline{\psi}_L\psi_R + h.c.$$

Majorana mass

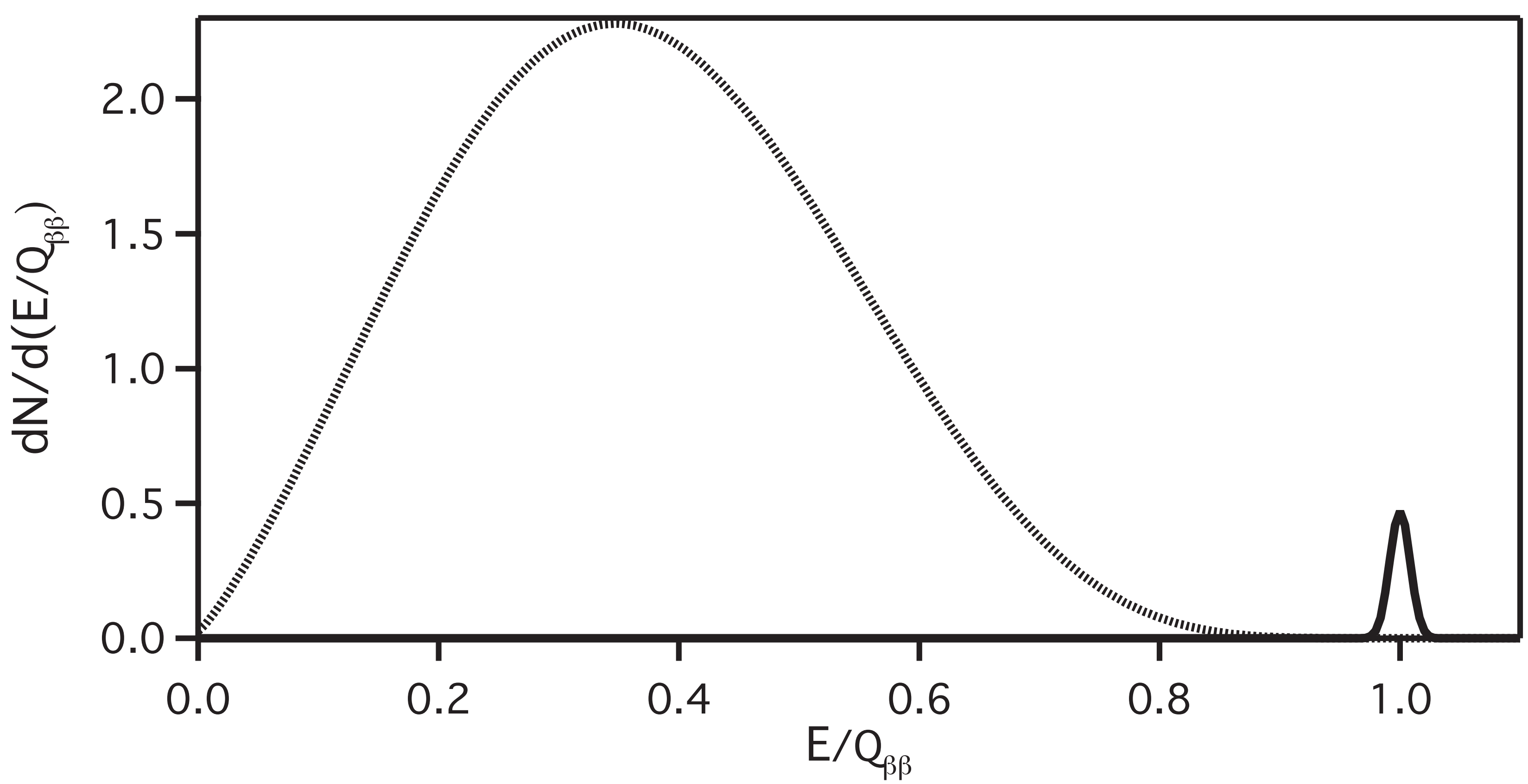
$$L = m\overline{(\psi_R)^C}\psi_R + h.c.$$

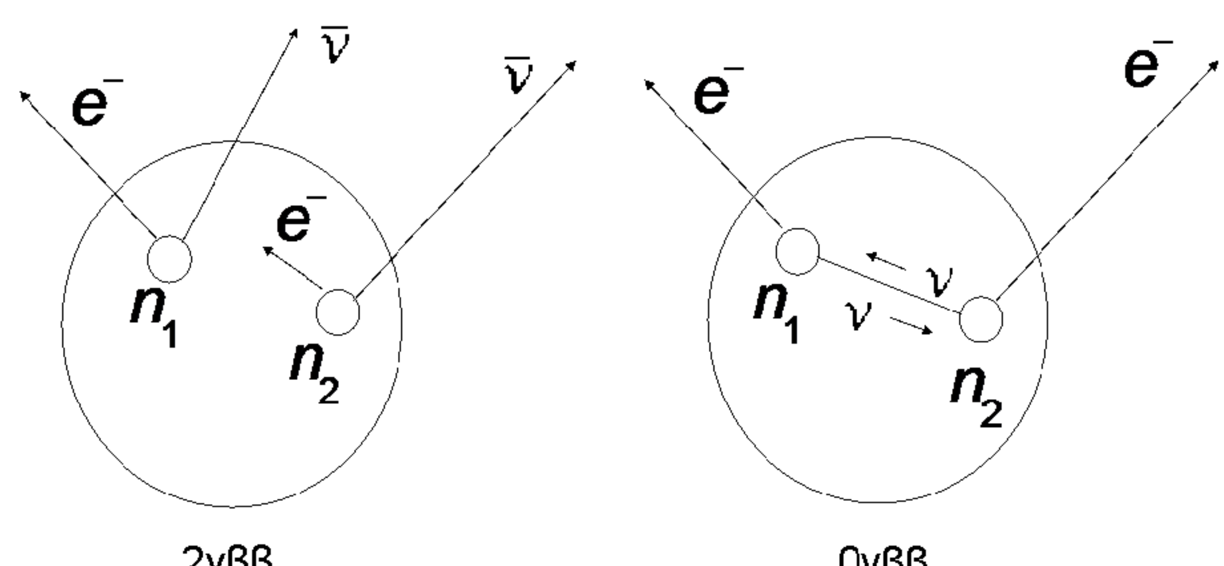
$(\psi_R)^C$ ← Charge conjugate

Charged particle cannot have Majorana mass.



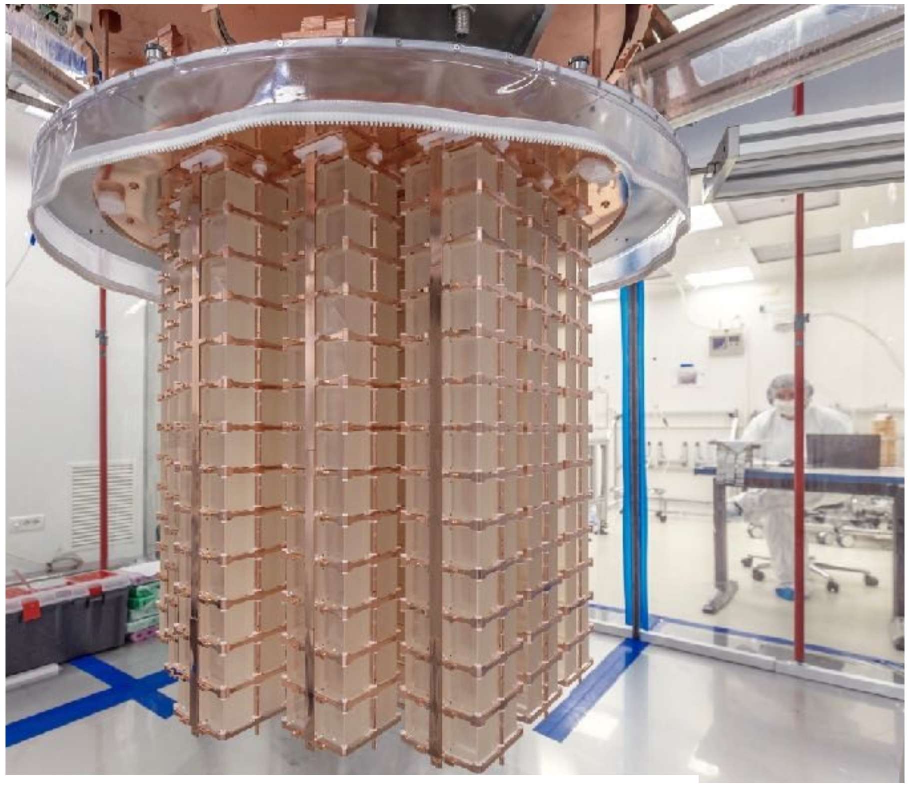
0νββ

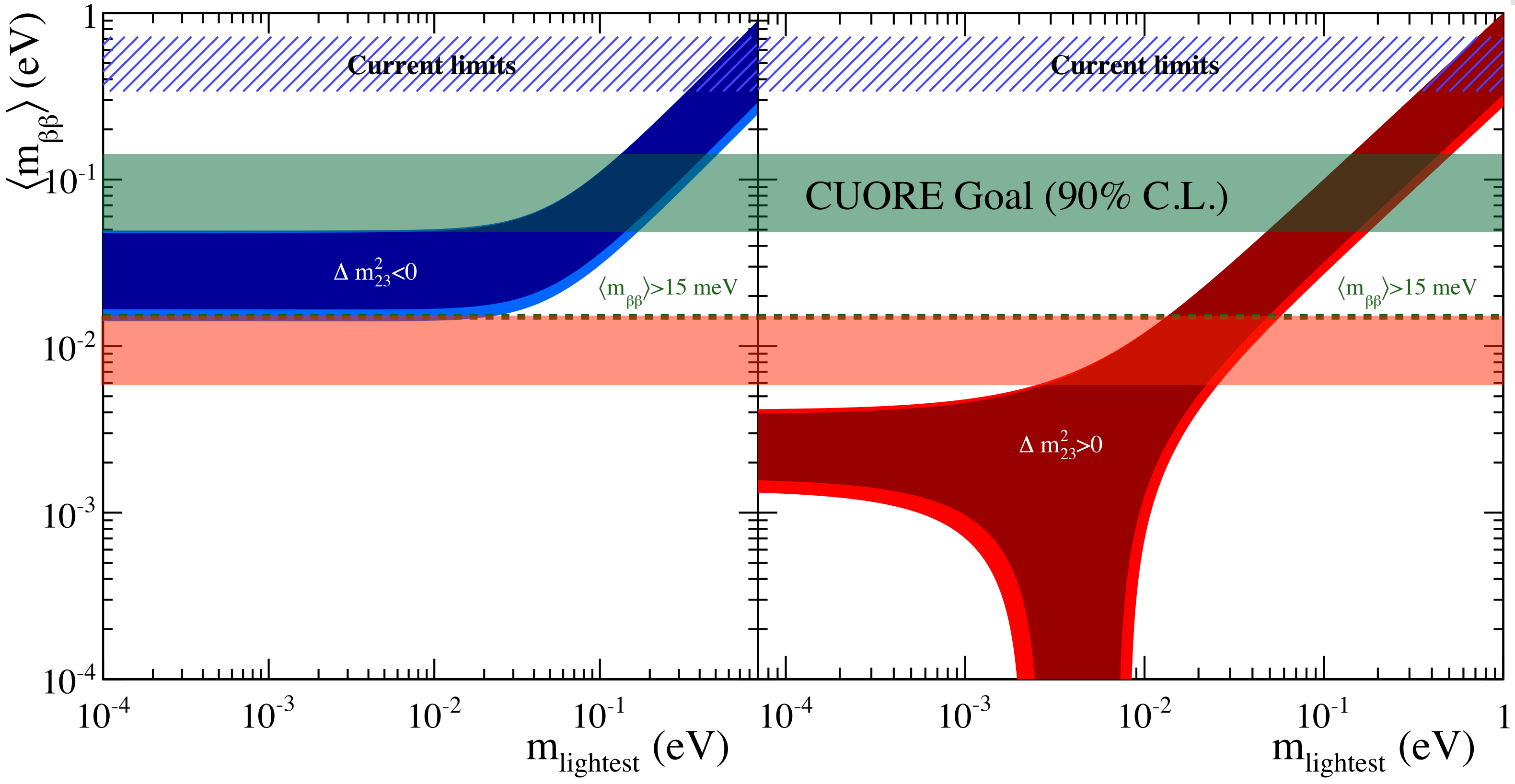

dN/d(E/Qββ)
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
E/Qββ


e⁻
ν̄
ν̄
e⁻
n1
n2
2νββ
e⁻
e⁻
ν
ν
n1
n2
0νββ

CUPID (CUORE Upgrade with Particle ID)

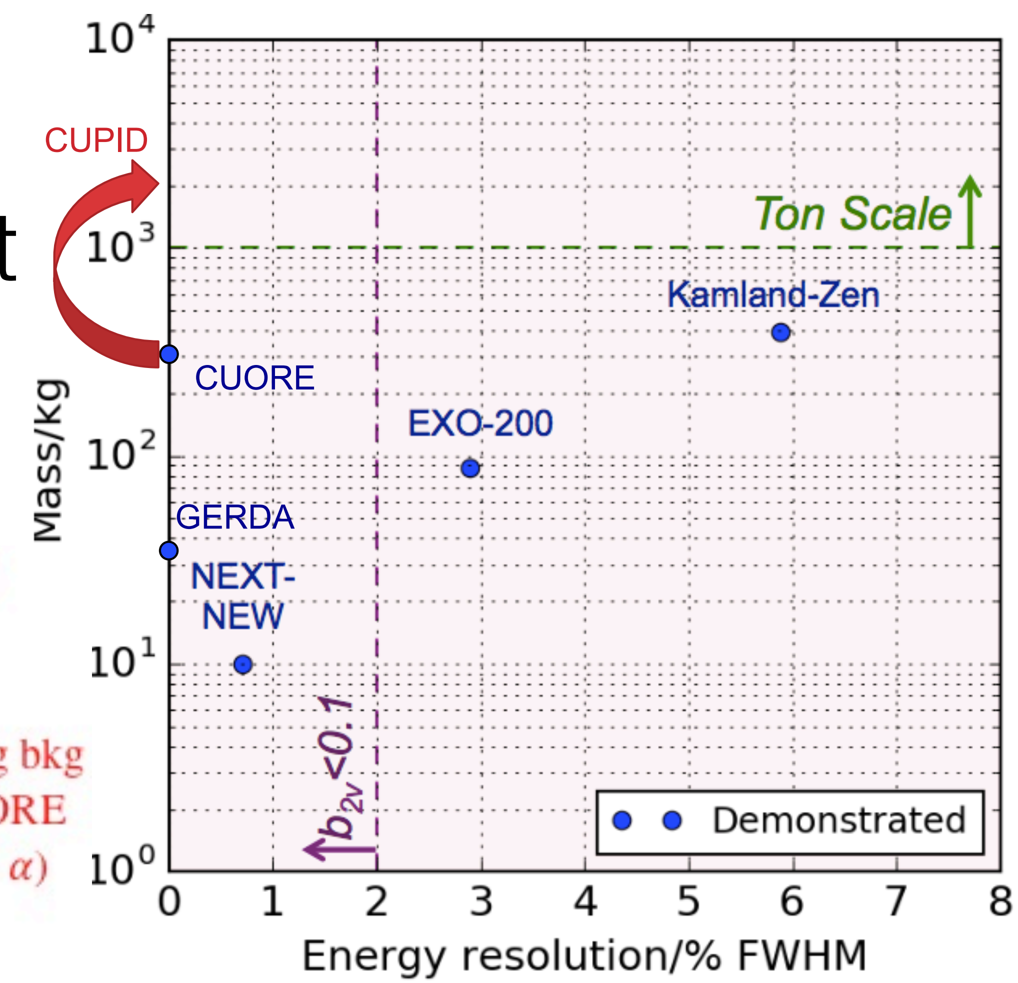
- CUORE (currently operating)
  - ~1 ton of TeO_2 cooled to ~6 mK
- CUPID upgrade targets inverted hierarchy

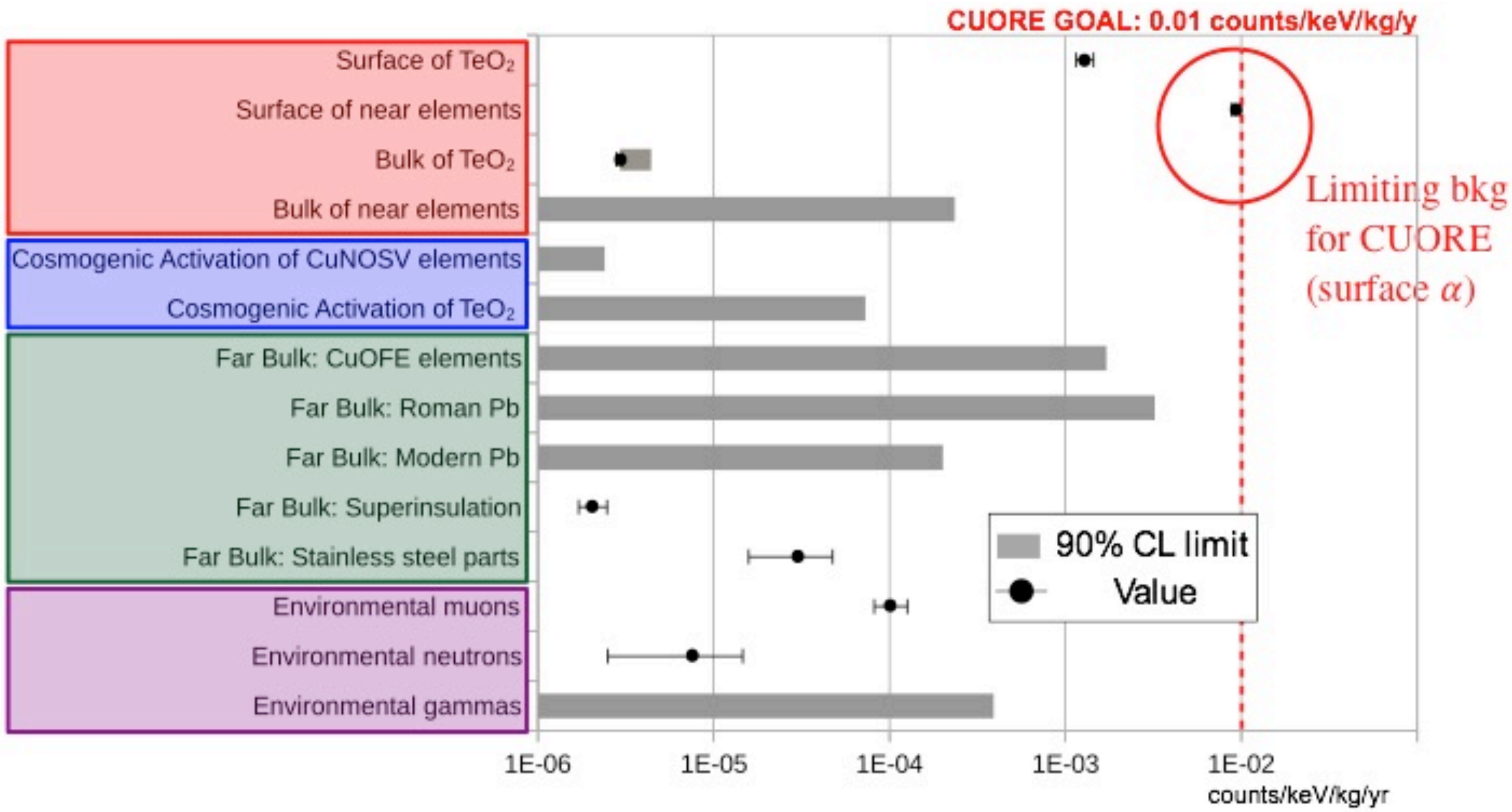




Background rejection is critical

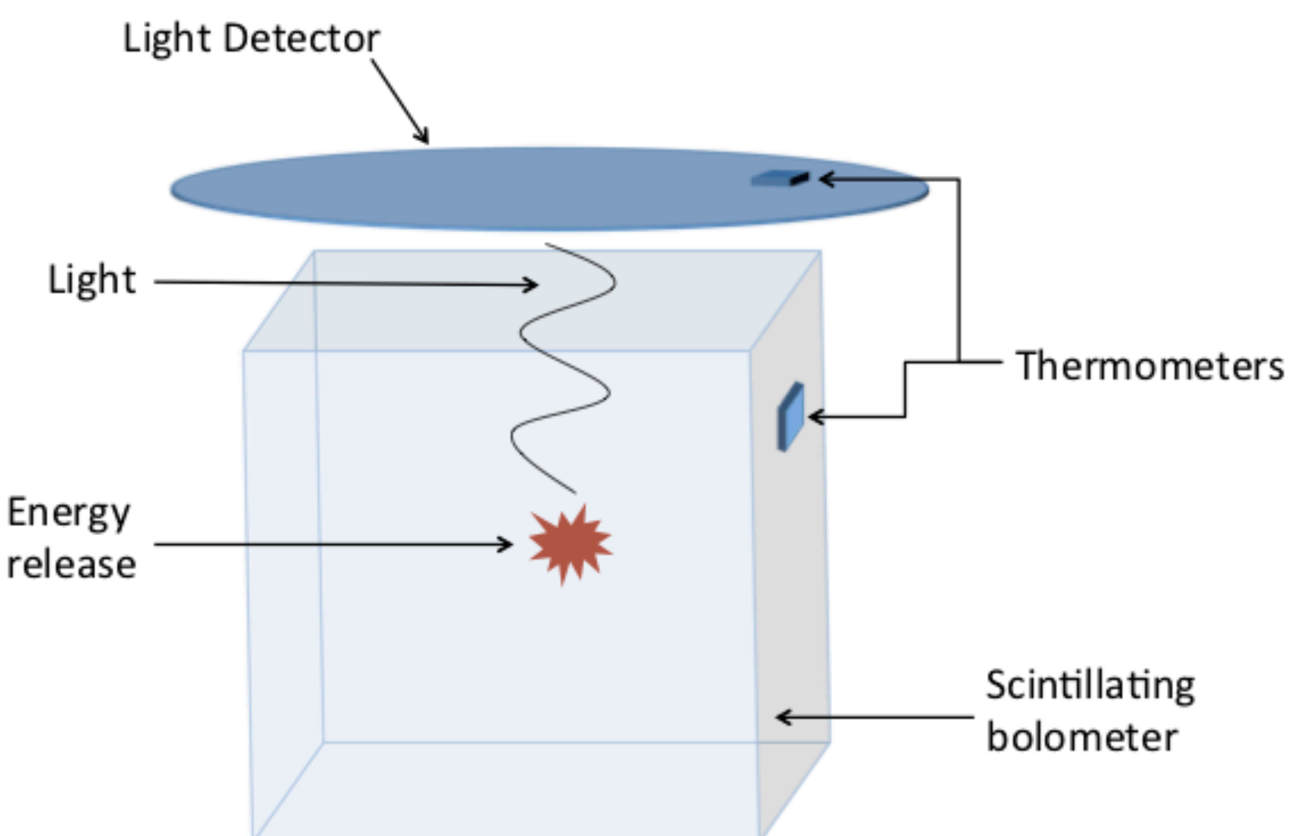
Target enrichment

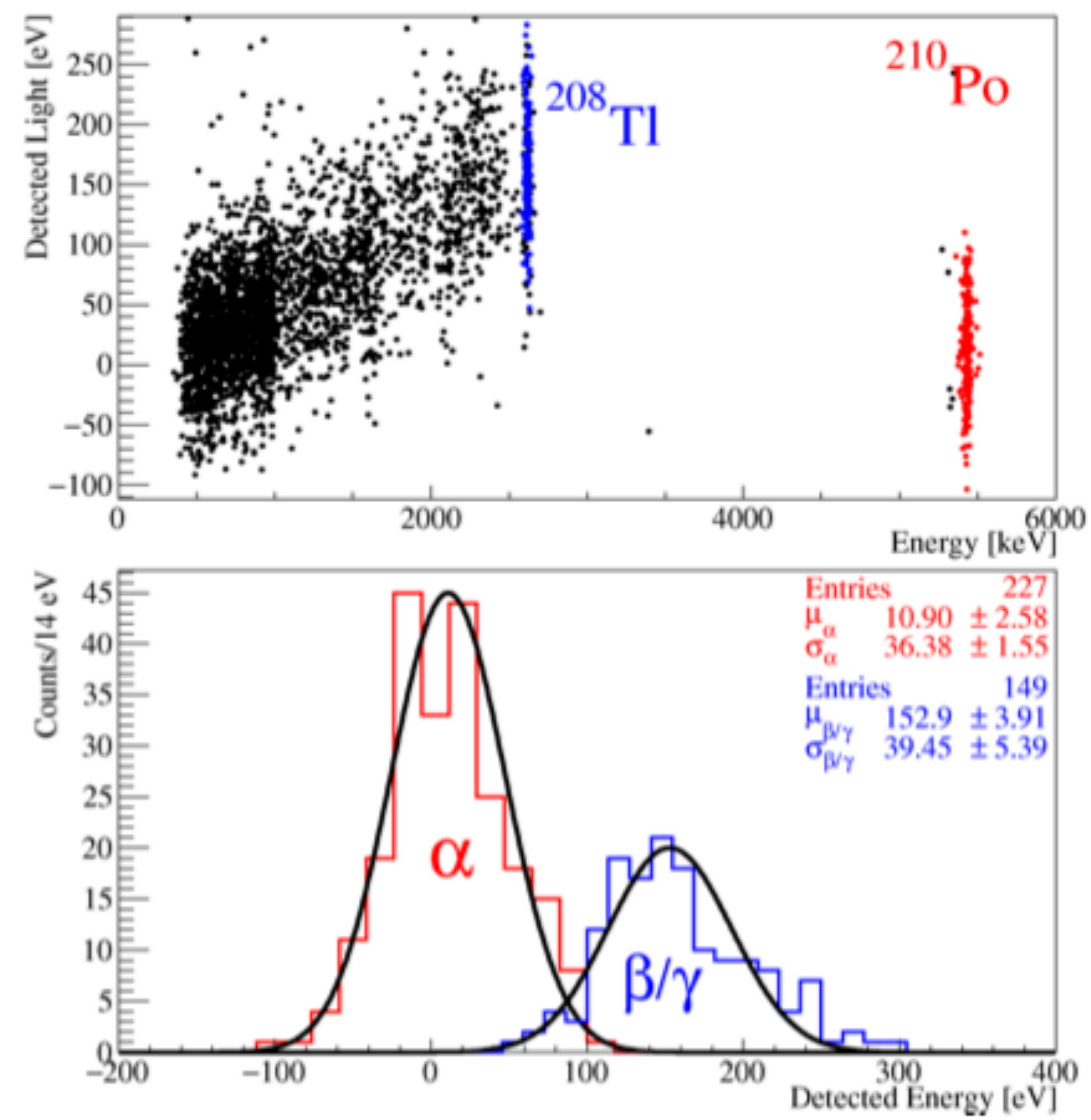




Alduino, C., Alfonso, K., Artusa, D.R. et al. Eur. Phys. J. C (2017) 77: 543.

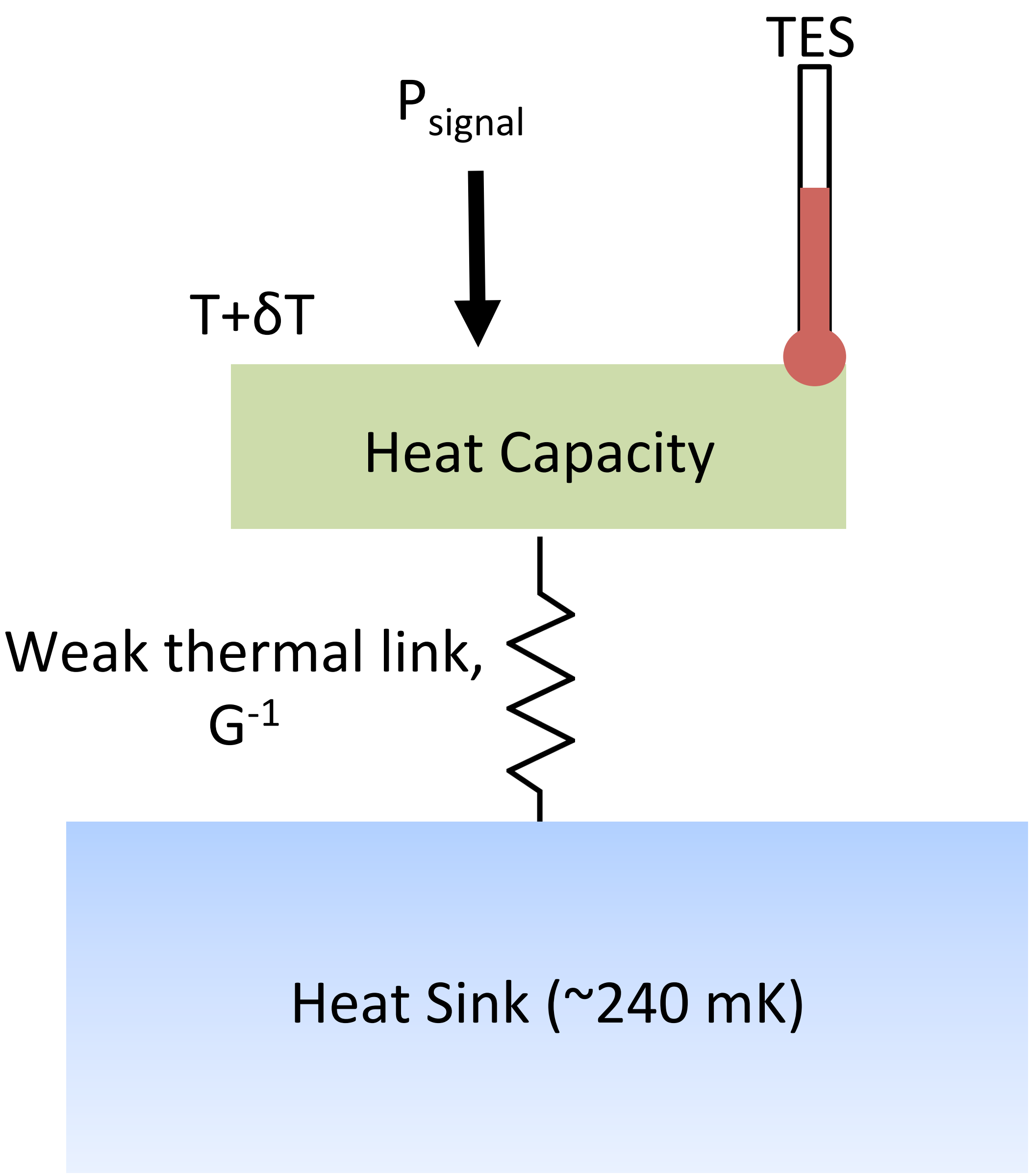
Discriminate between bulk and surface events by measuring Cherenkov light with a 2nd detector

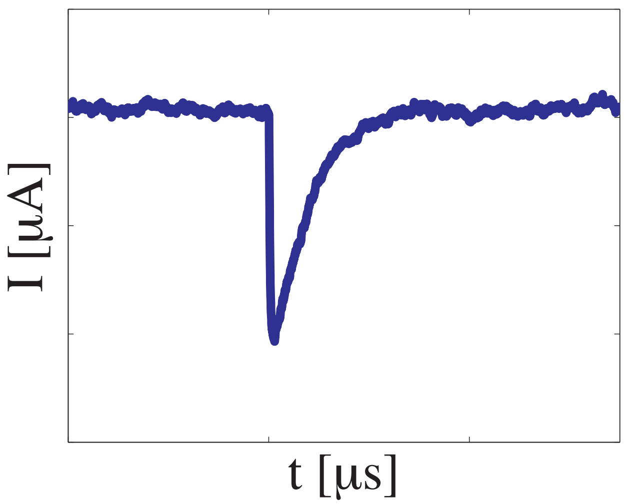




arXiv:1610.03513

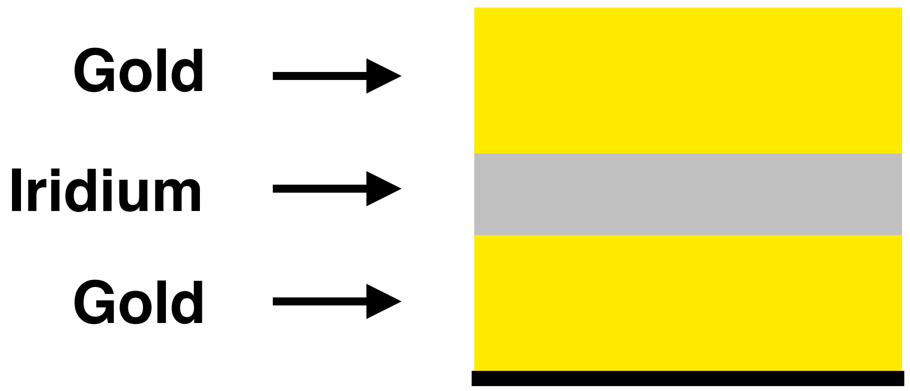
The Modern Transition Edge Sensor

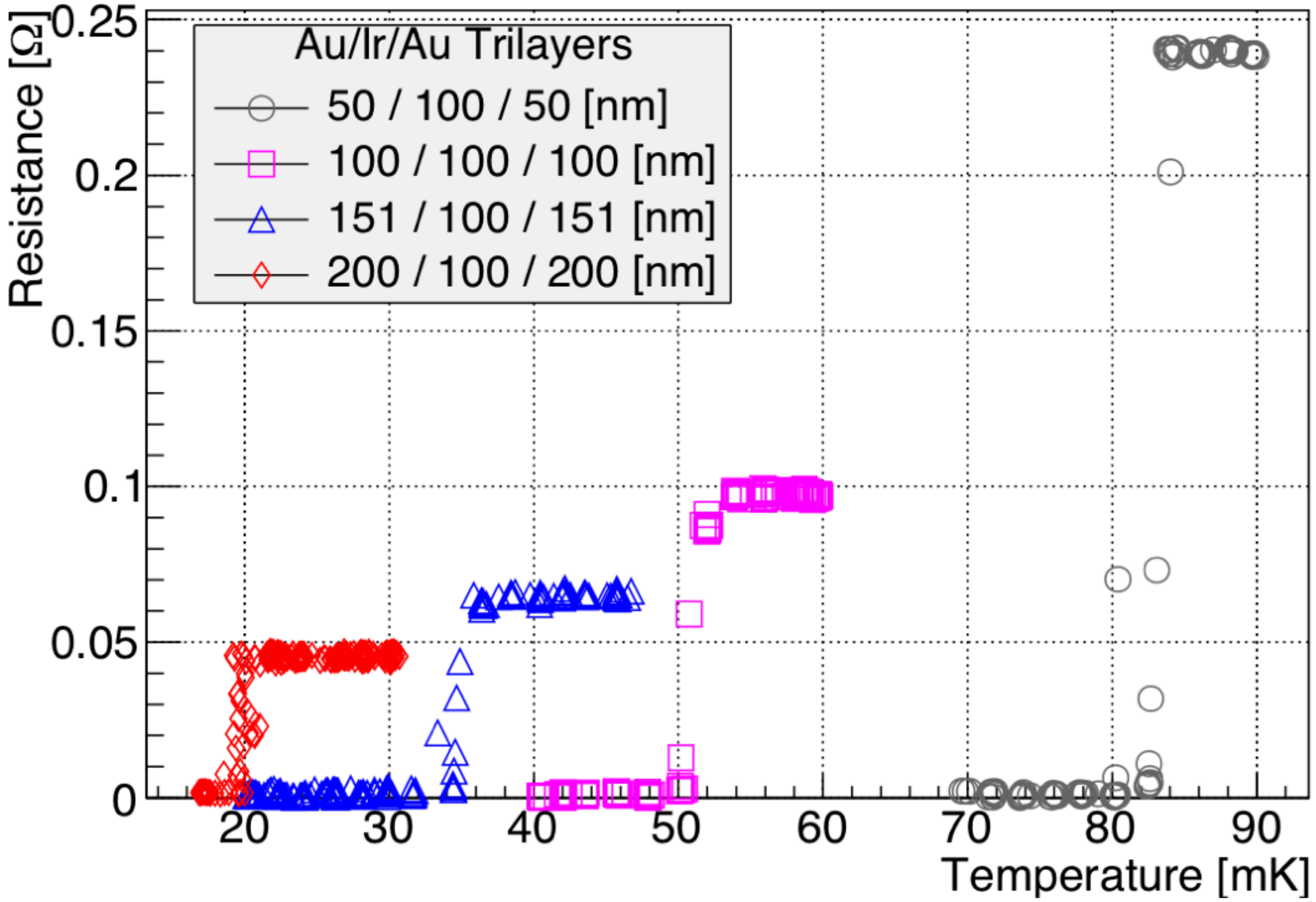


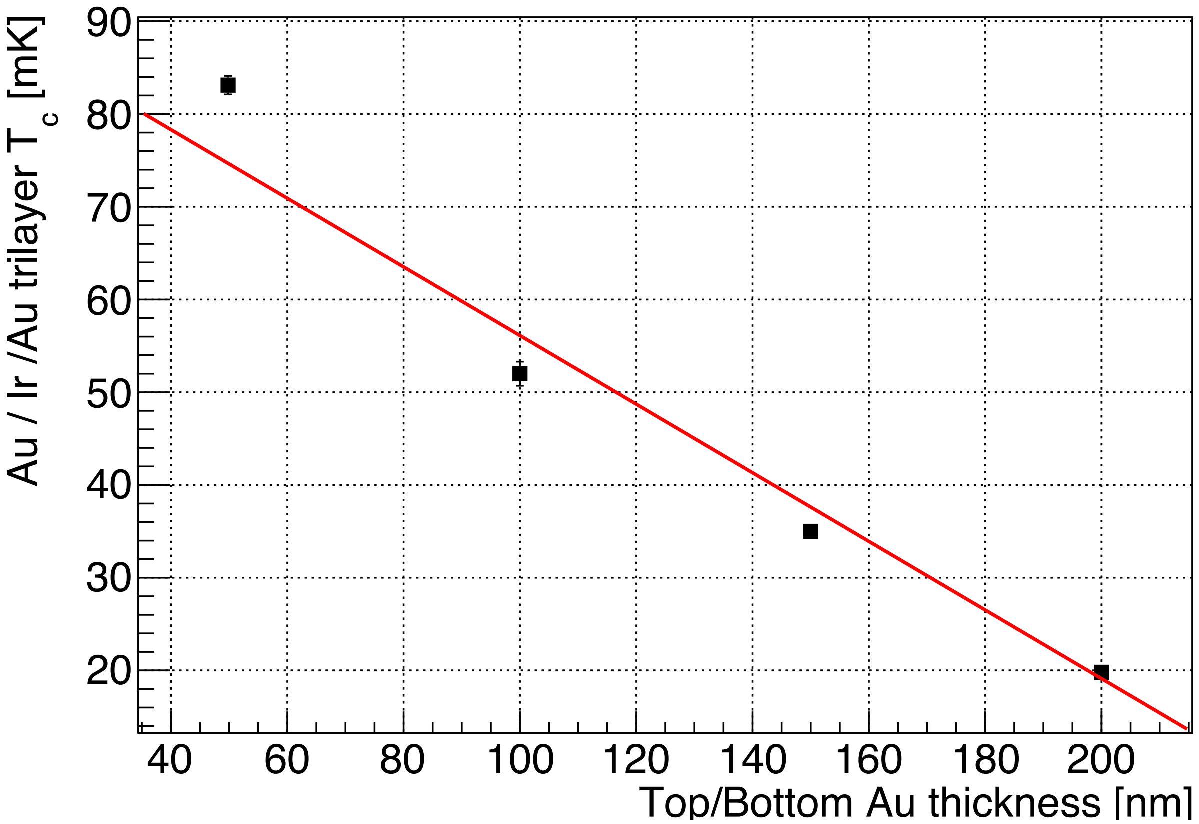


$$\Delta E \propto \int G^{1/2} T \propto C^{1/2} T$$

Tc suppression in Gold/Iridium/Gold Trilayers

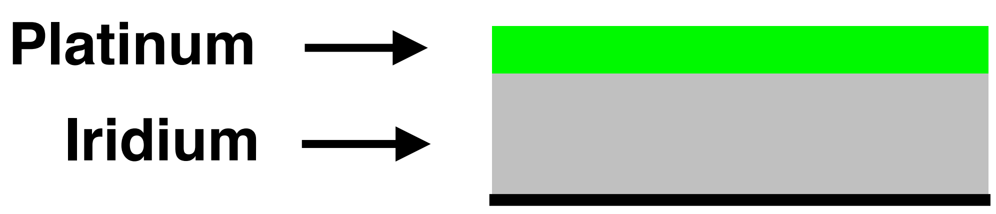


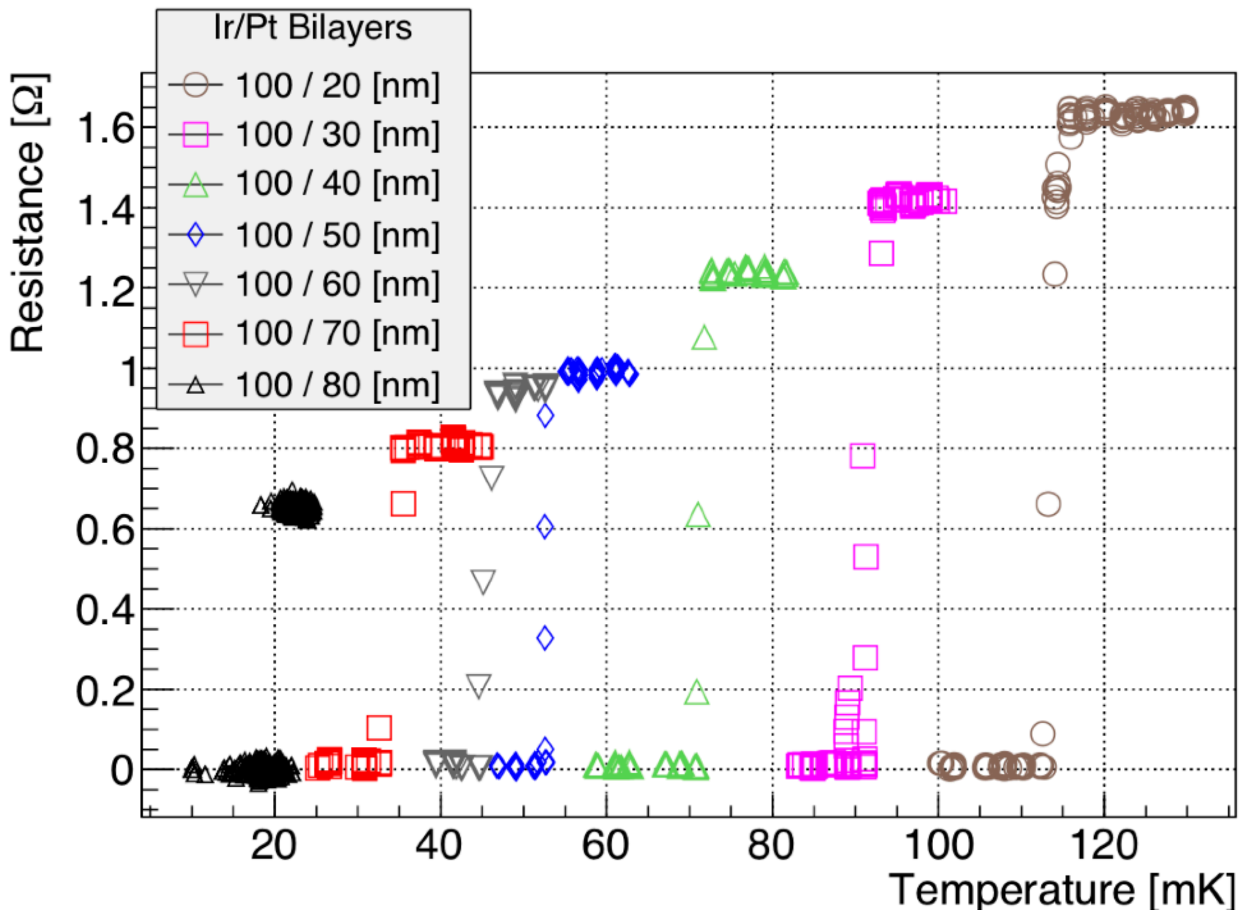


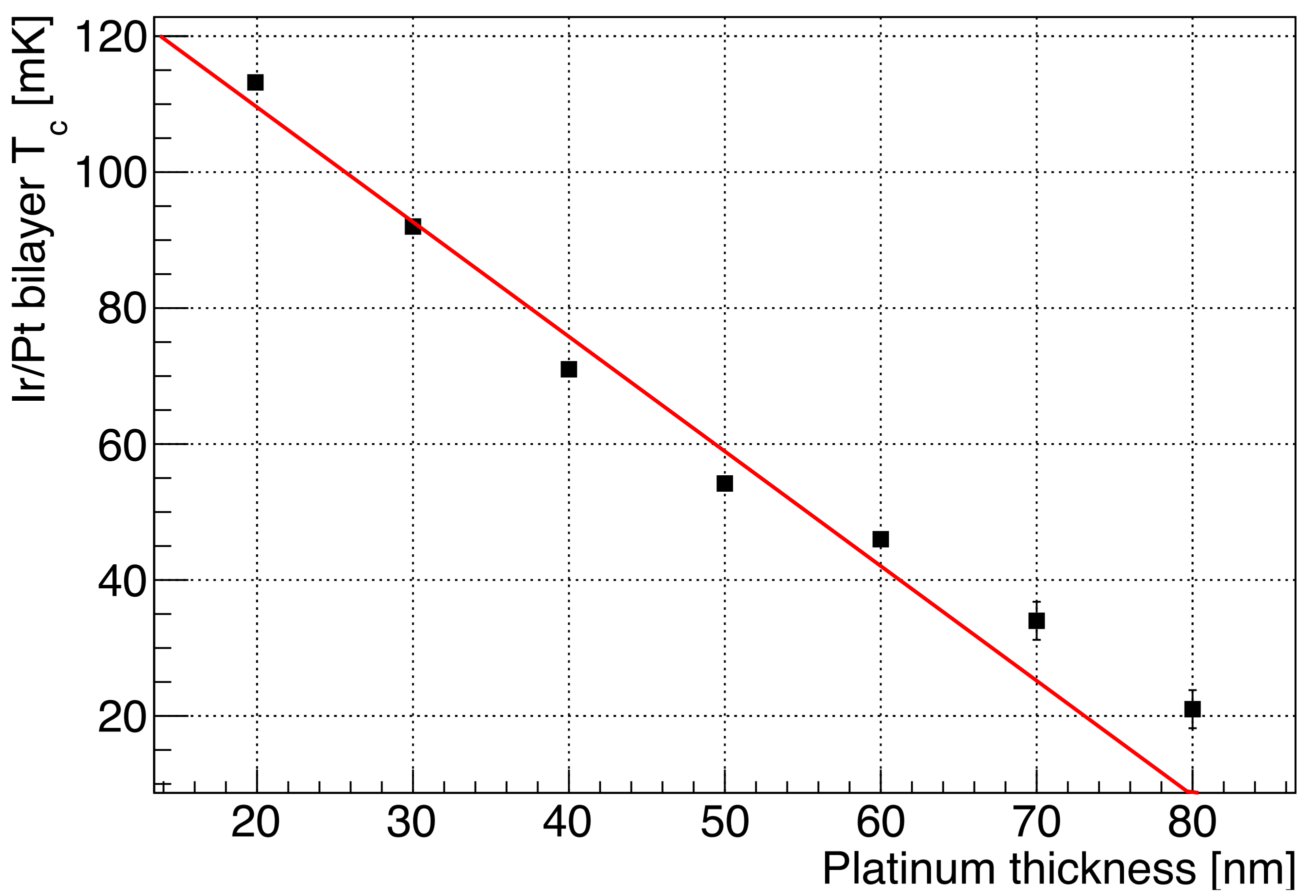


Hennings-Yeomans et al., in prep.

Tc suppression in Iridium/Platinum Bilayers

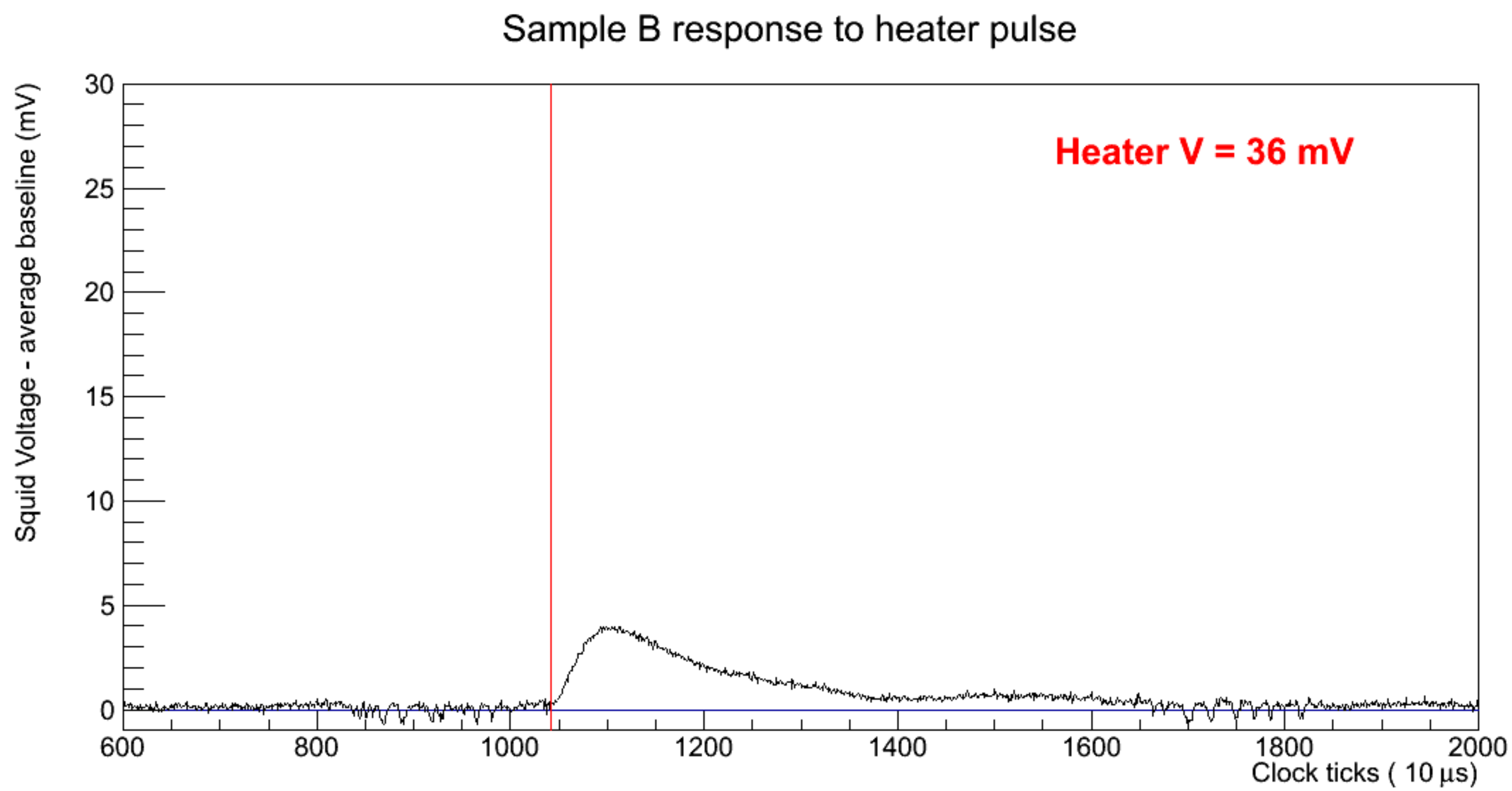


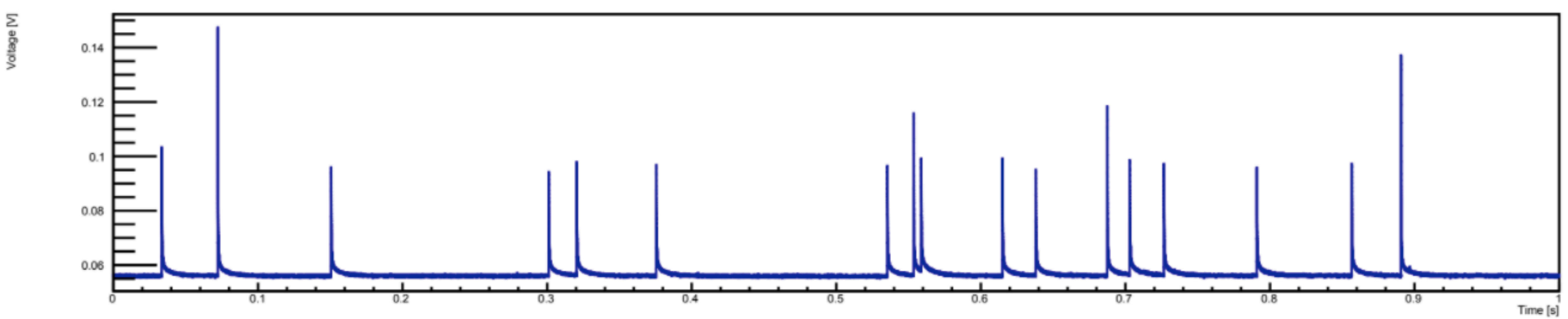




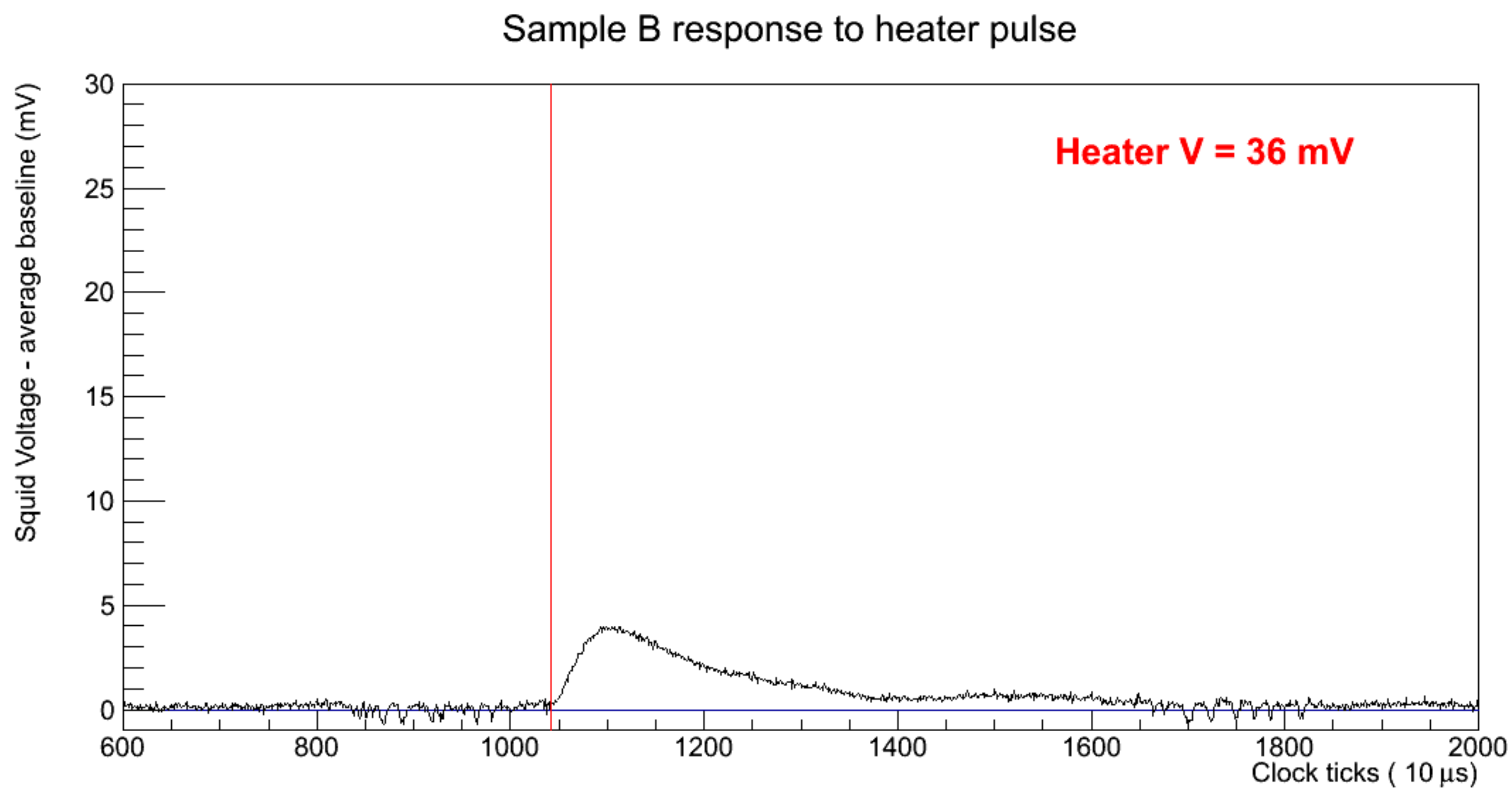
Hennings-Yeomans et al., in prep.

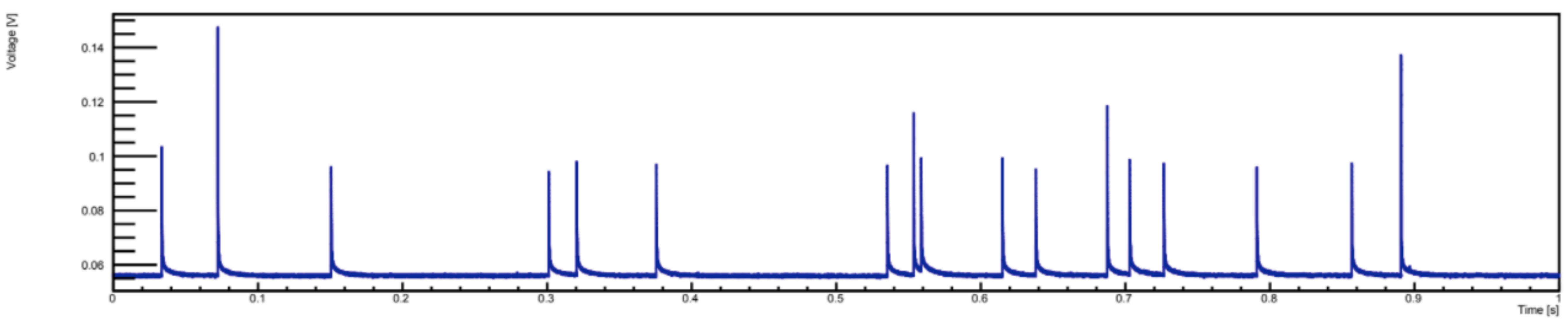
First bolometric signals using Ir/Pt TES





First bolometric signals using Ir/Pt TES





NP $\cap$ QI

?

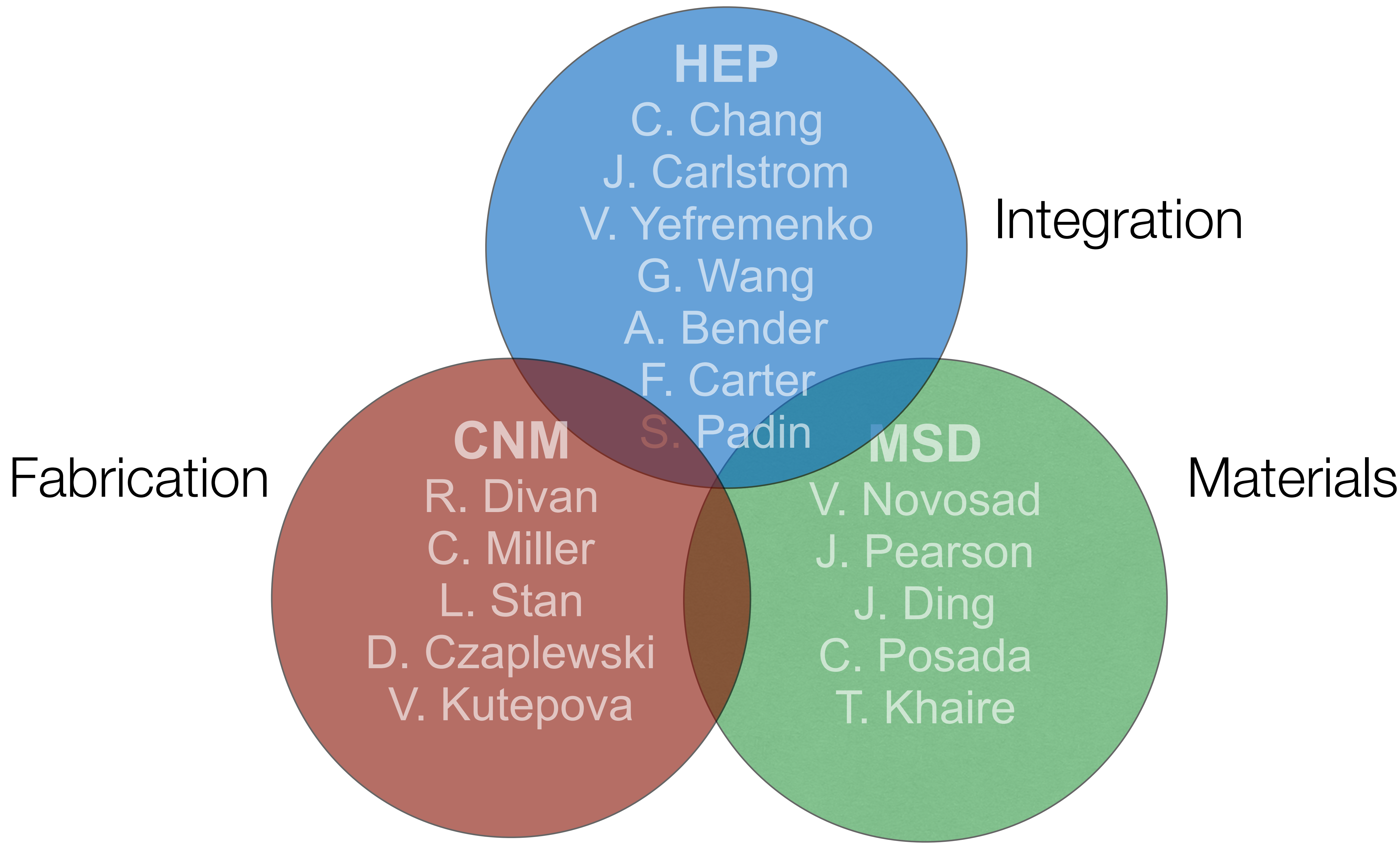
Cosmology

NP@QI

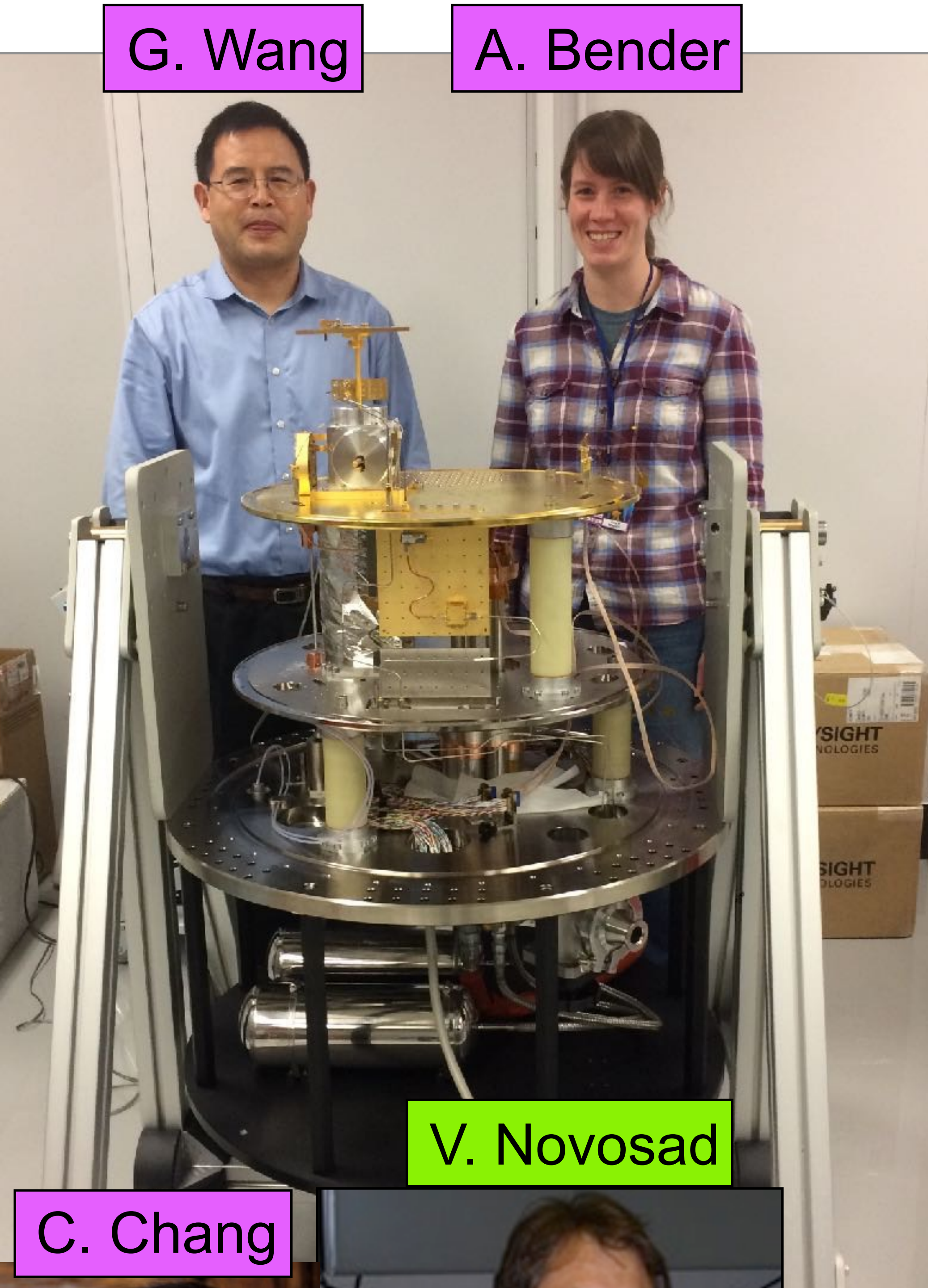
Superconducting technology

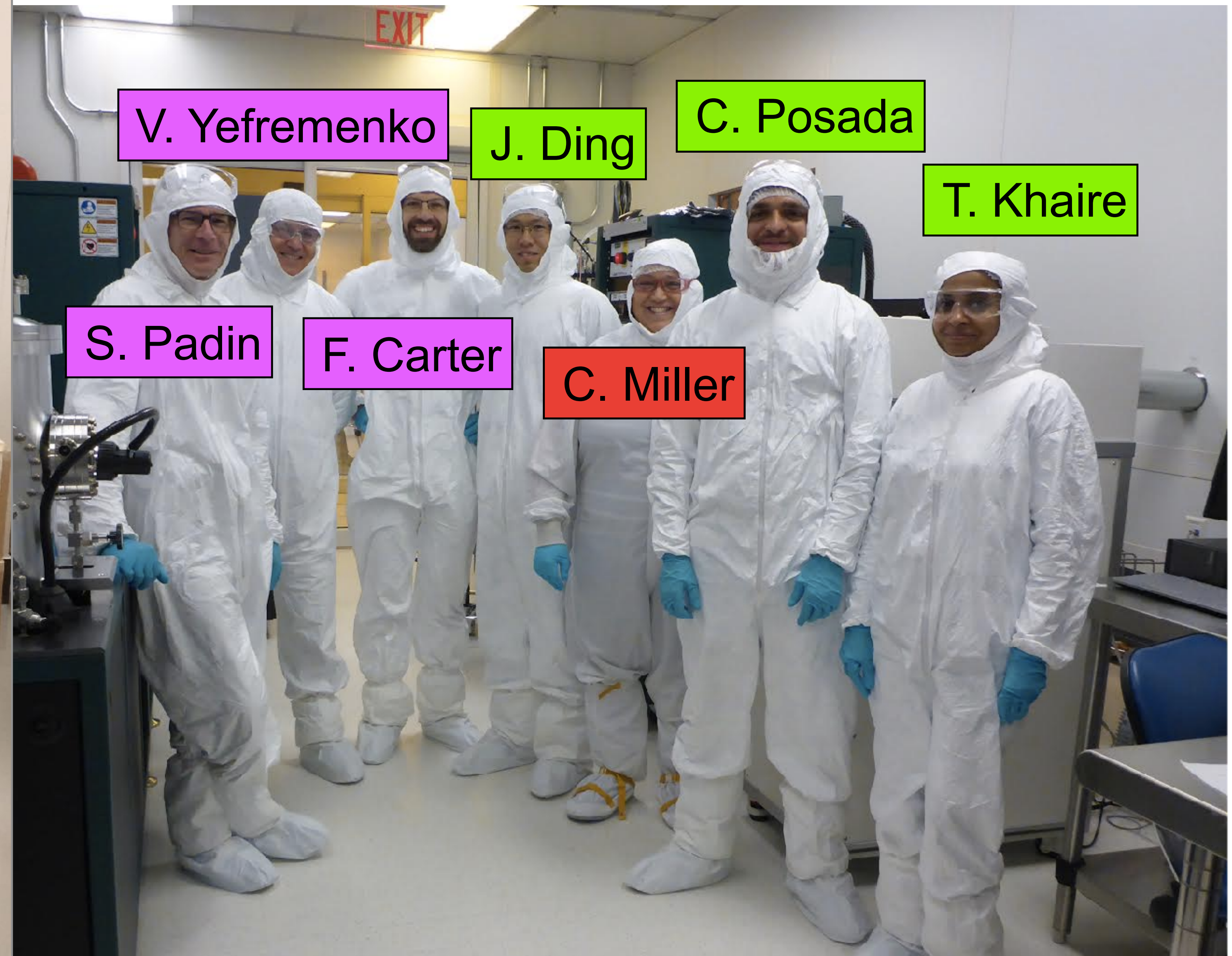
Cosmology

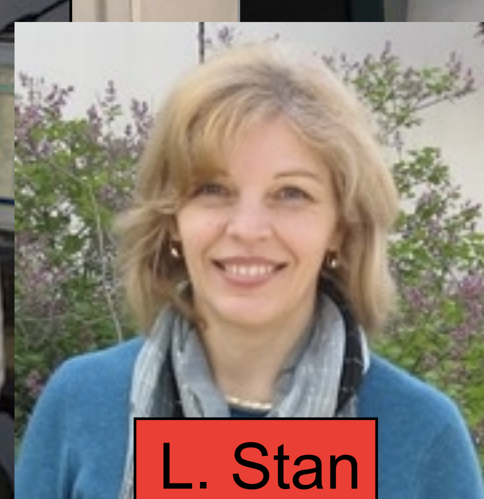
Address challenge of superconducting materials, complex fabrication and scaled production via multidisciplinary lab expertise and facilities



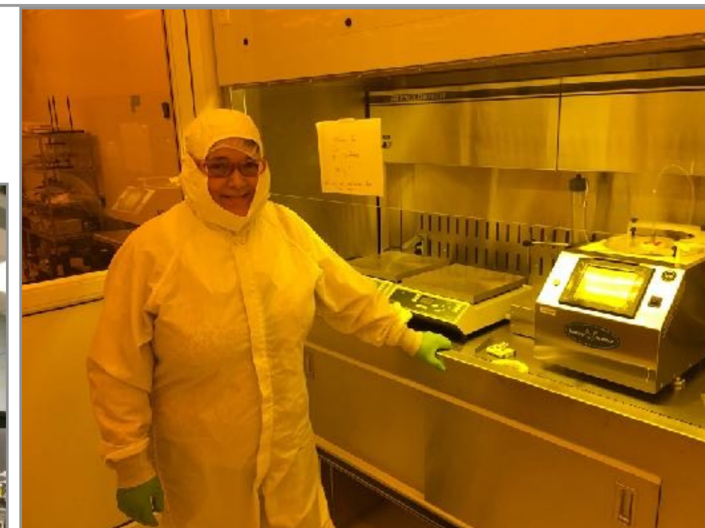
People: CNM, MSD, HEP

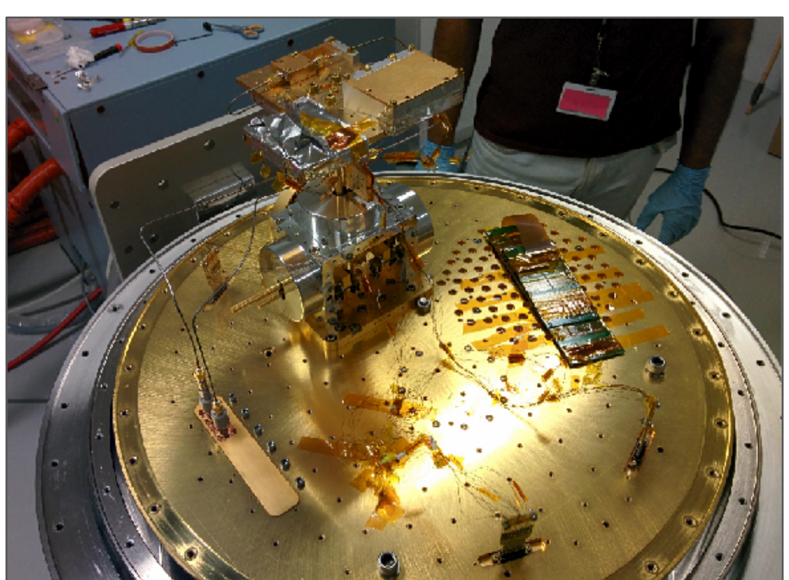




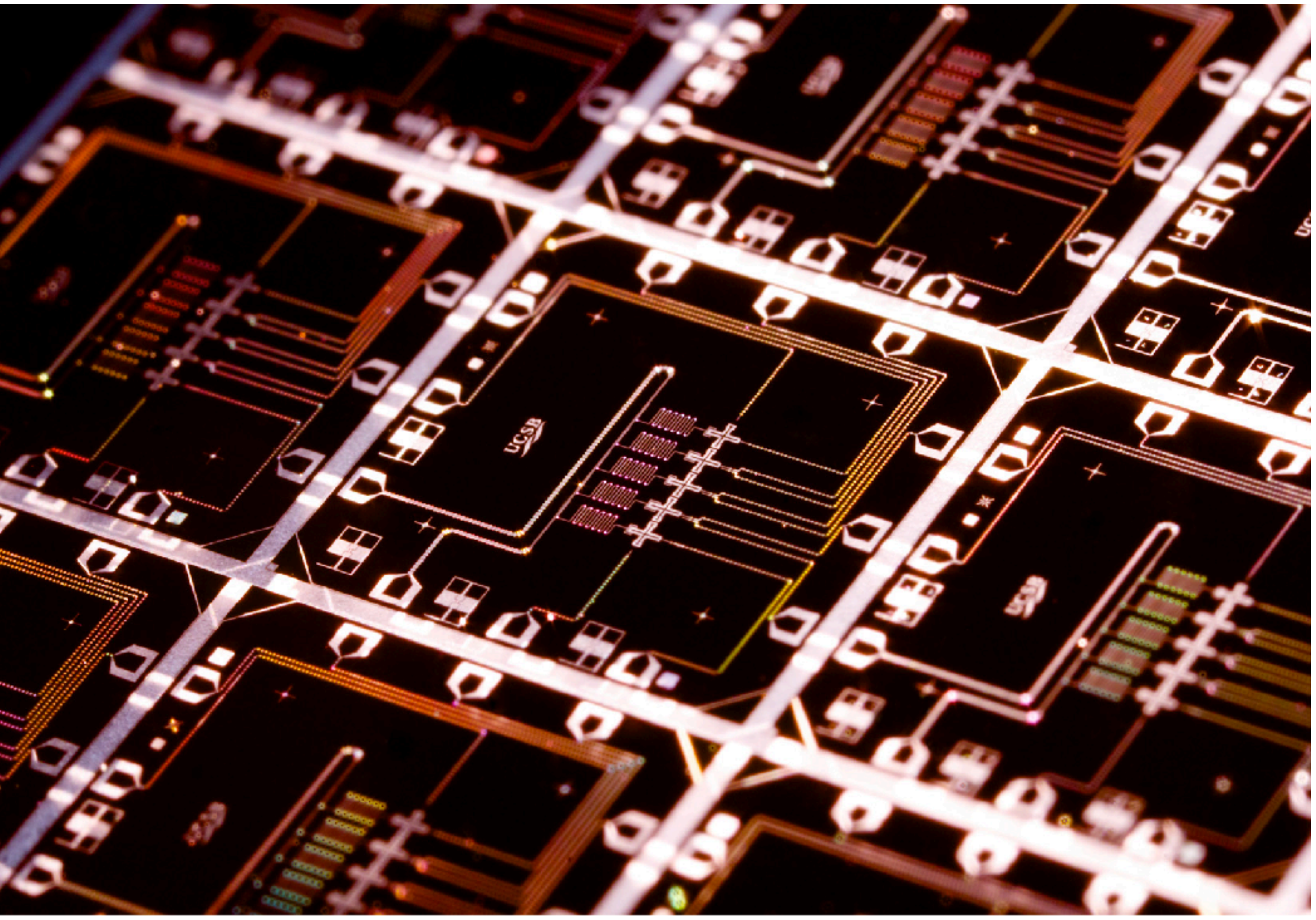


Facilities

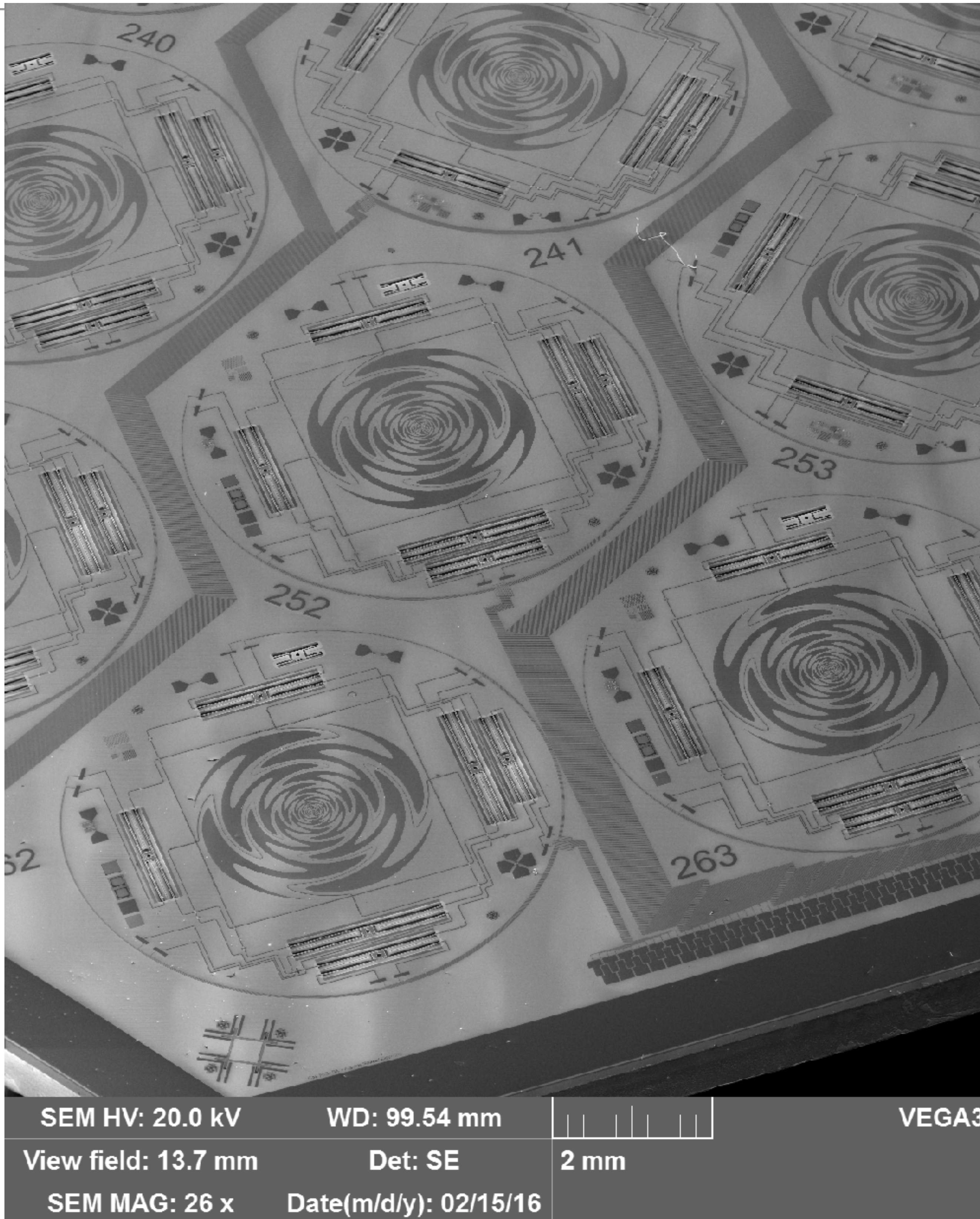




Lots of overlap with superconducting QI technology



- qubits
- JPA
- SNSPD



OUTLOOK

- Lots of interesting CMB science yet to come
  - Inflation, dark sector, neutrino mass
- Large arrays of superconducting detectors drive the field
- At Argonne, we're building up inter-disciplinary teams to address the challenge. Leveraging to pursue new directions like NLDBD.
- Superconducting devices are a core part of QIS technologies. Lots of overlap and opportunity.

Credit: A. Lowitz