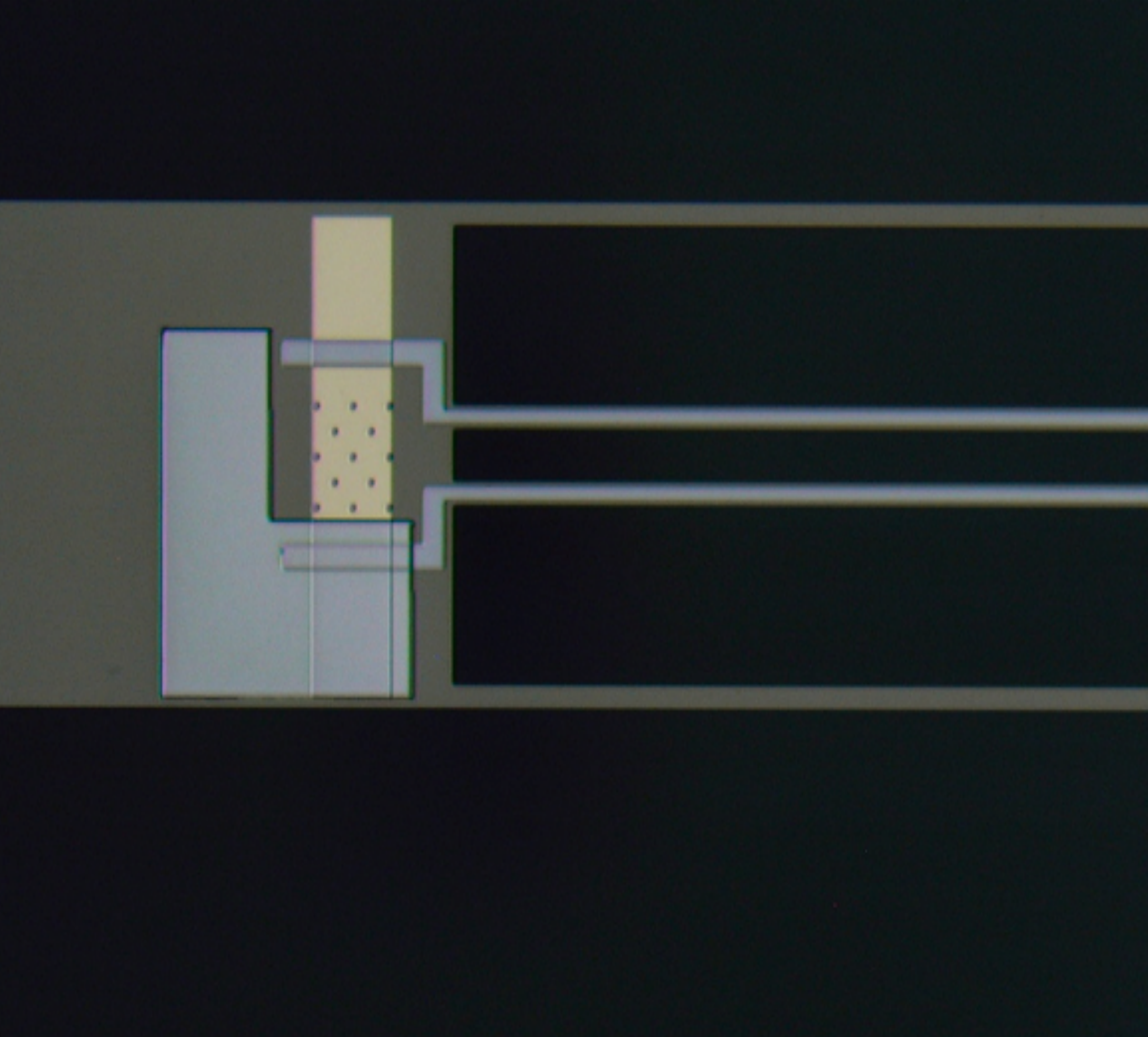
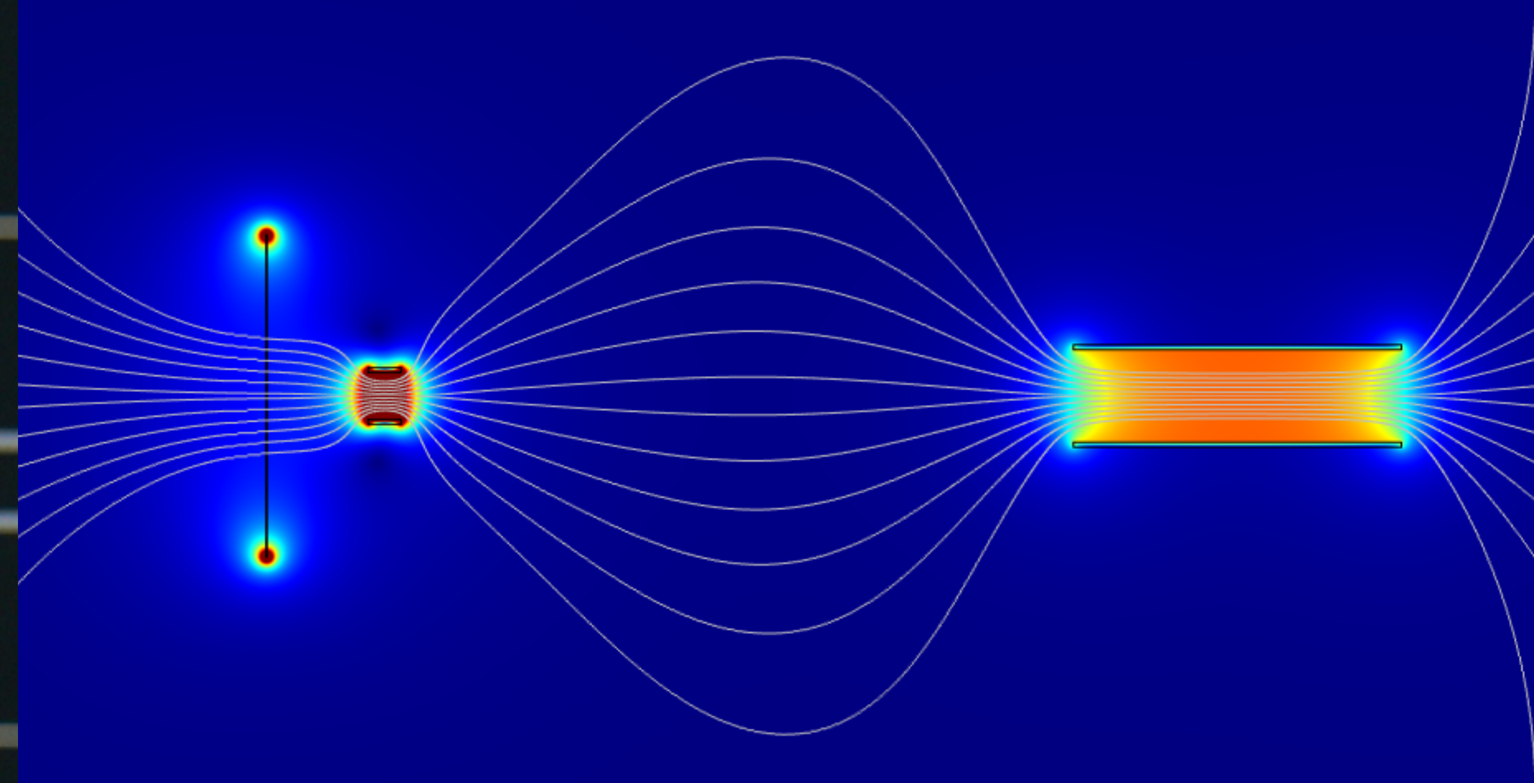
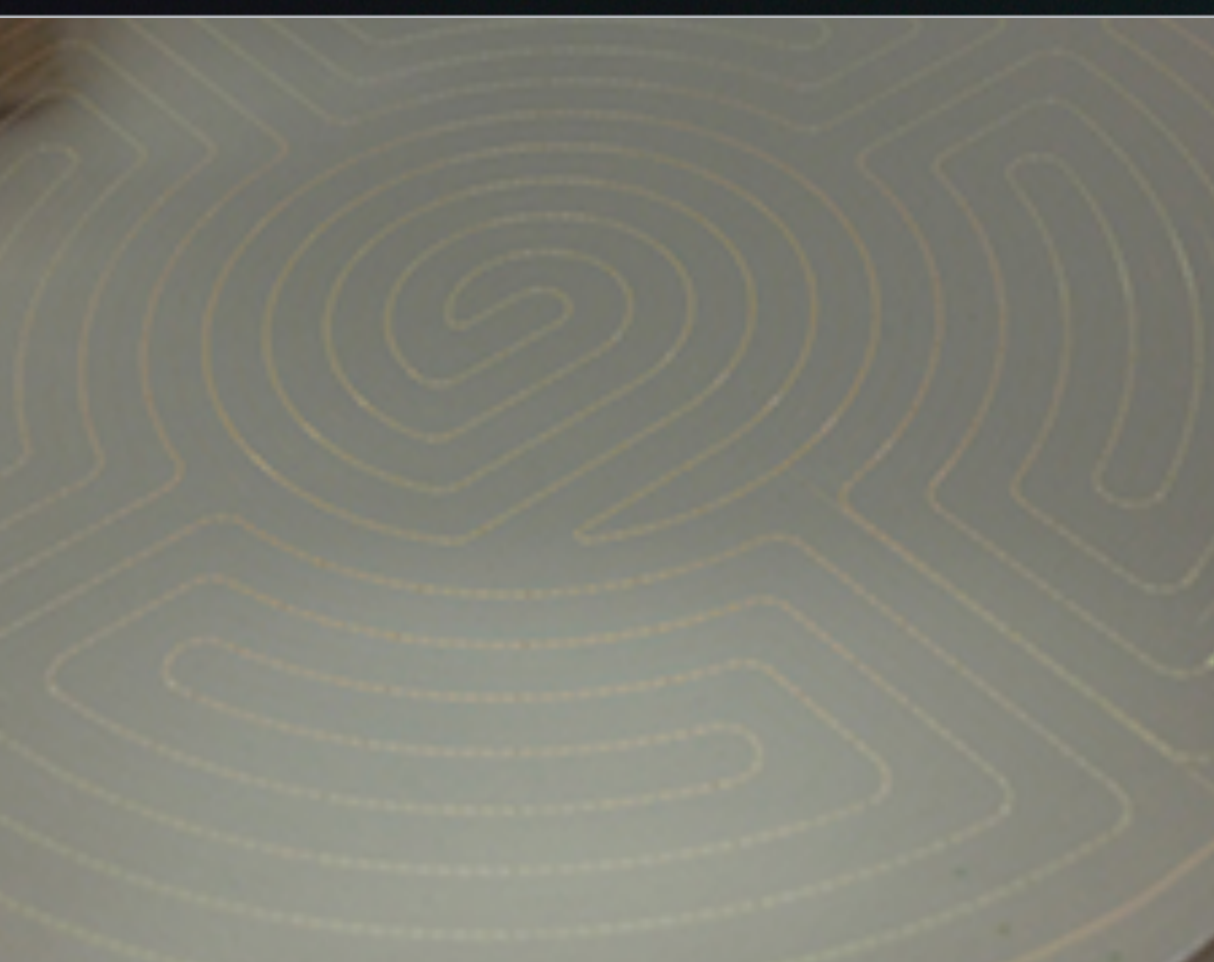
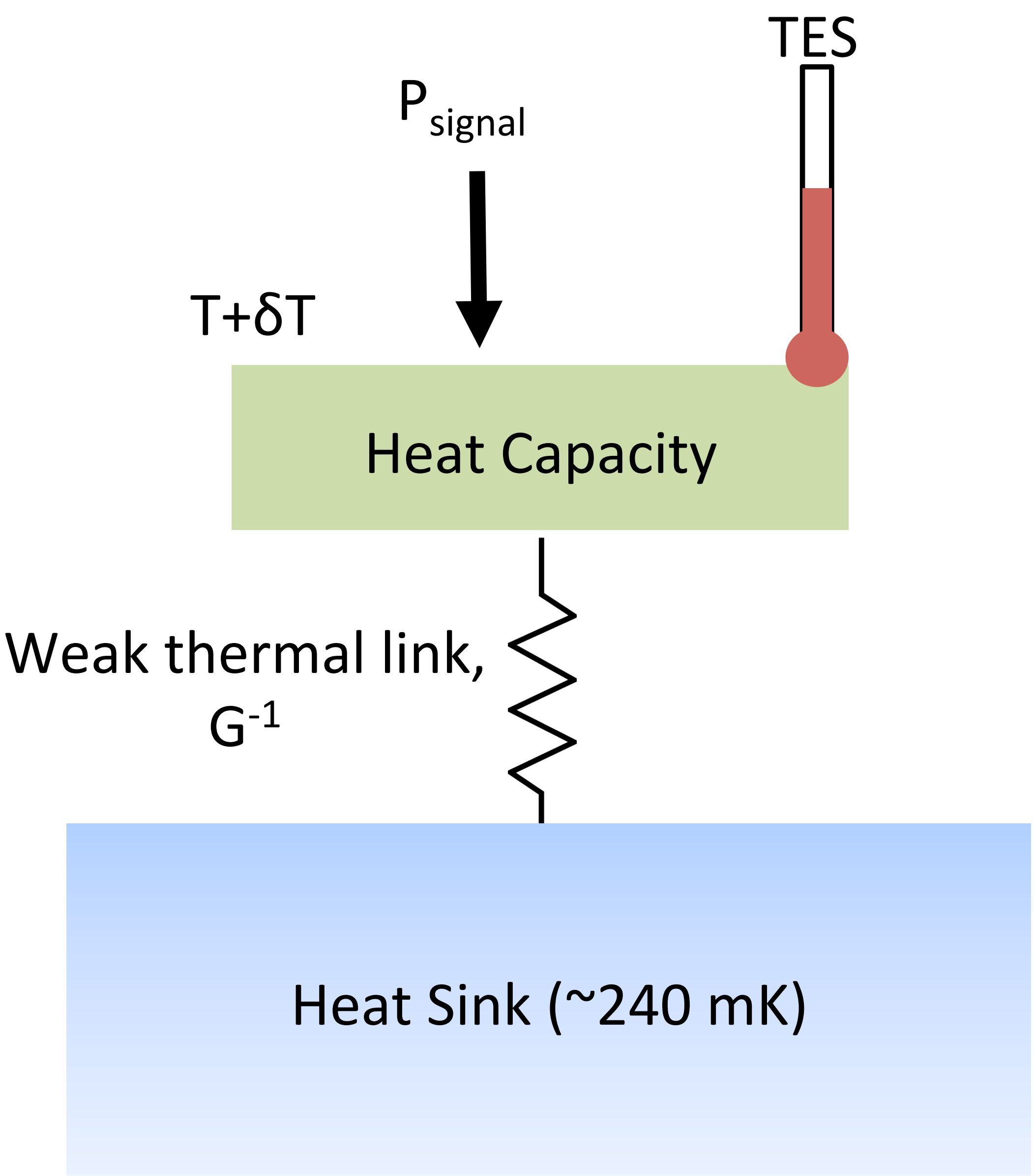
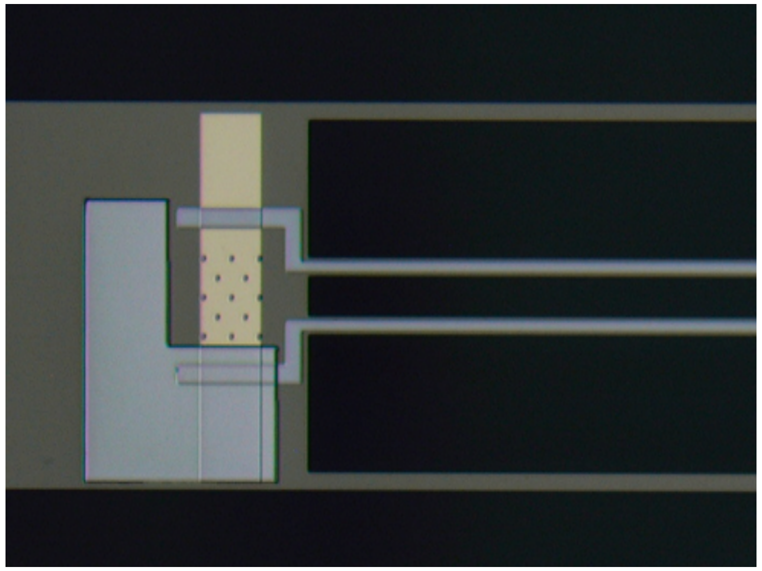
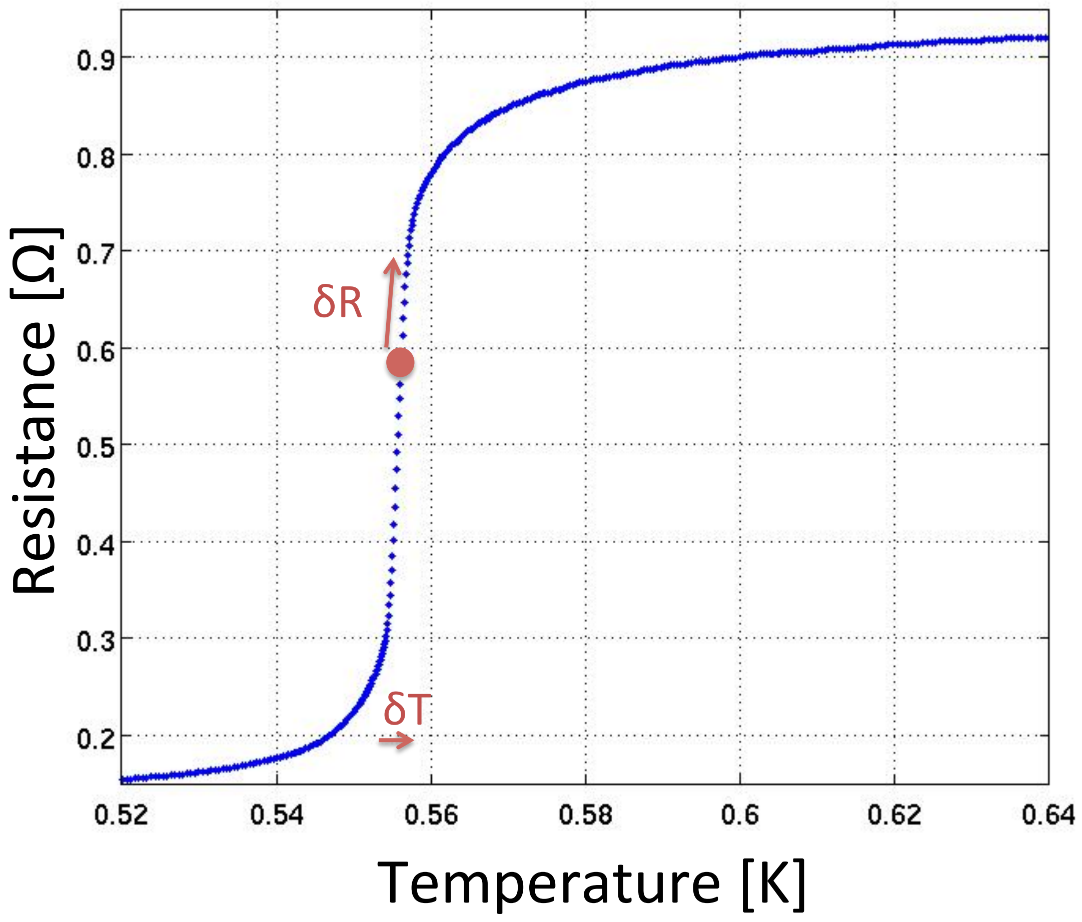





The Modern Transition Edge Sensor







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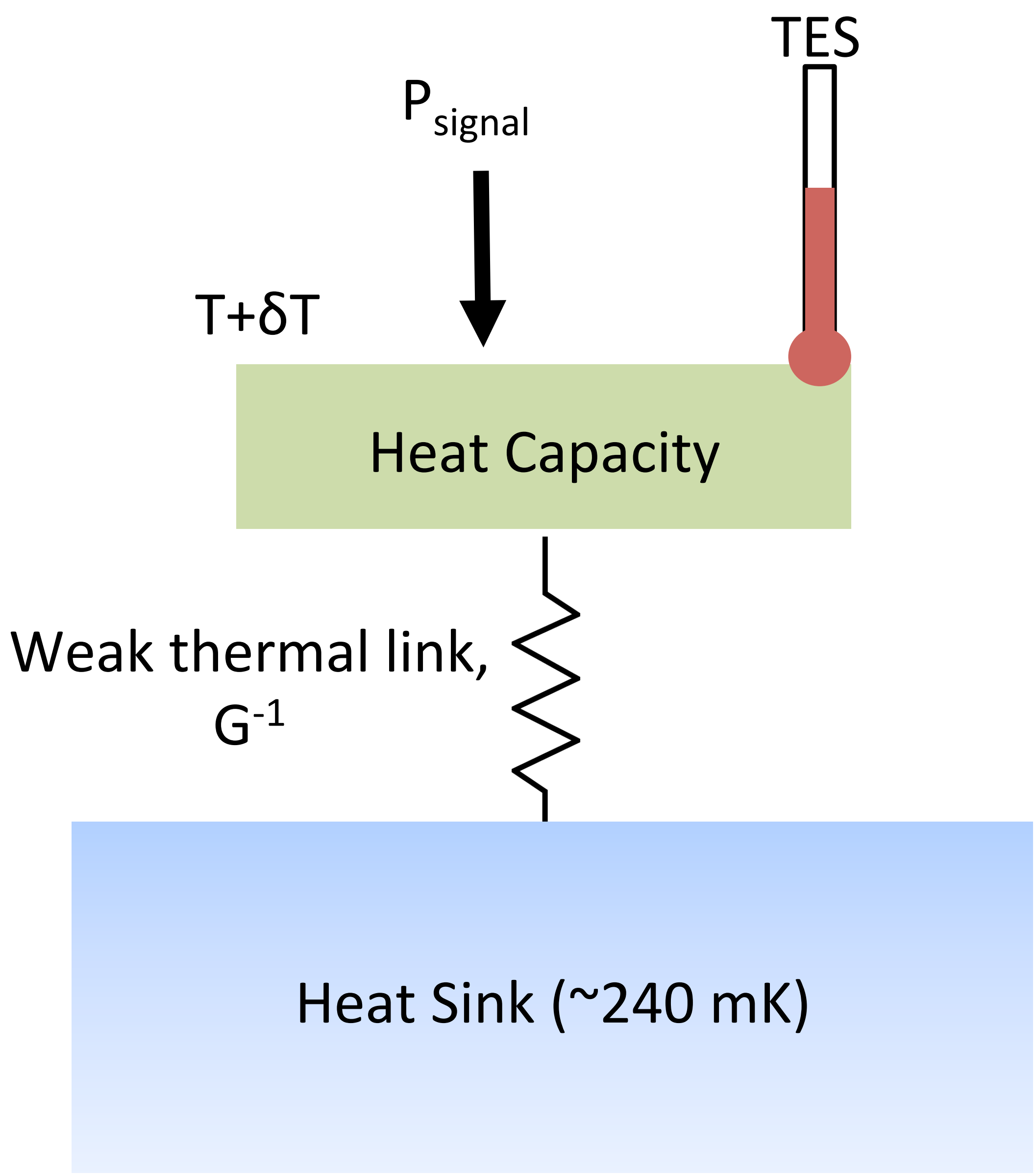
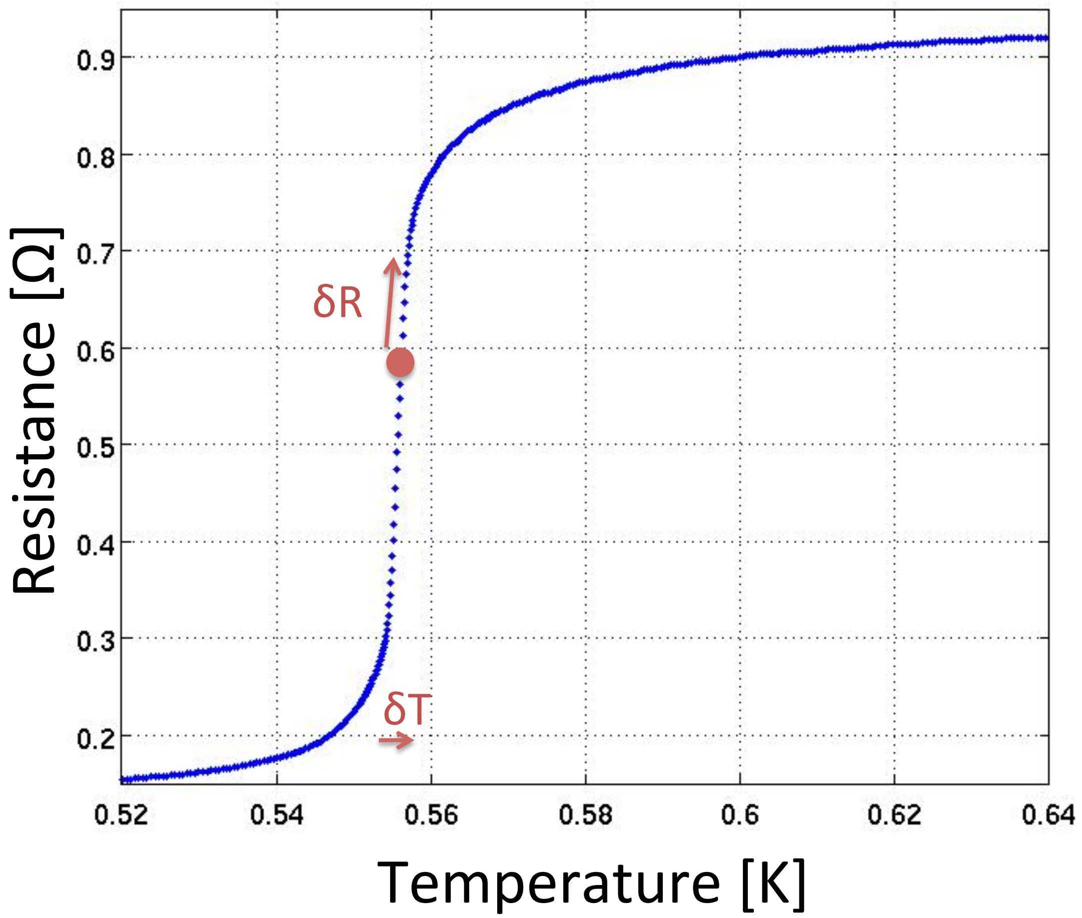
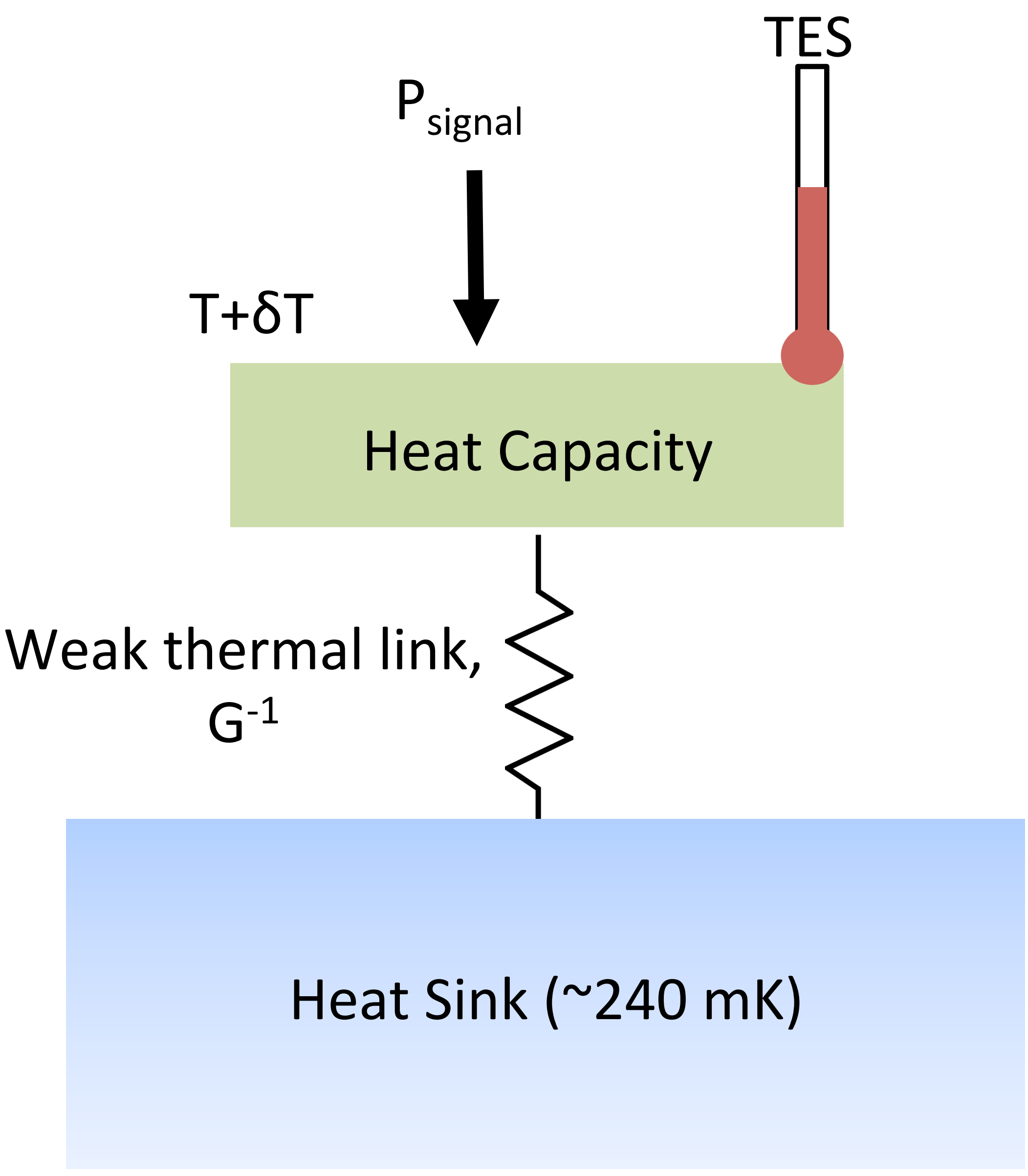


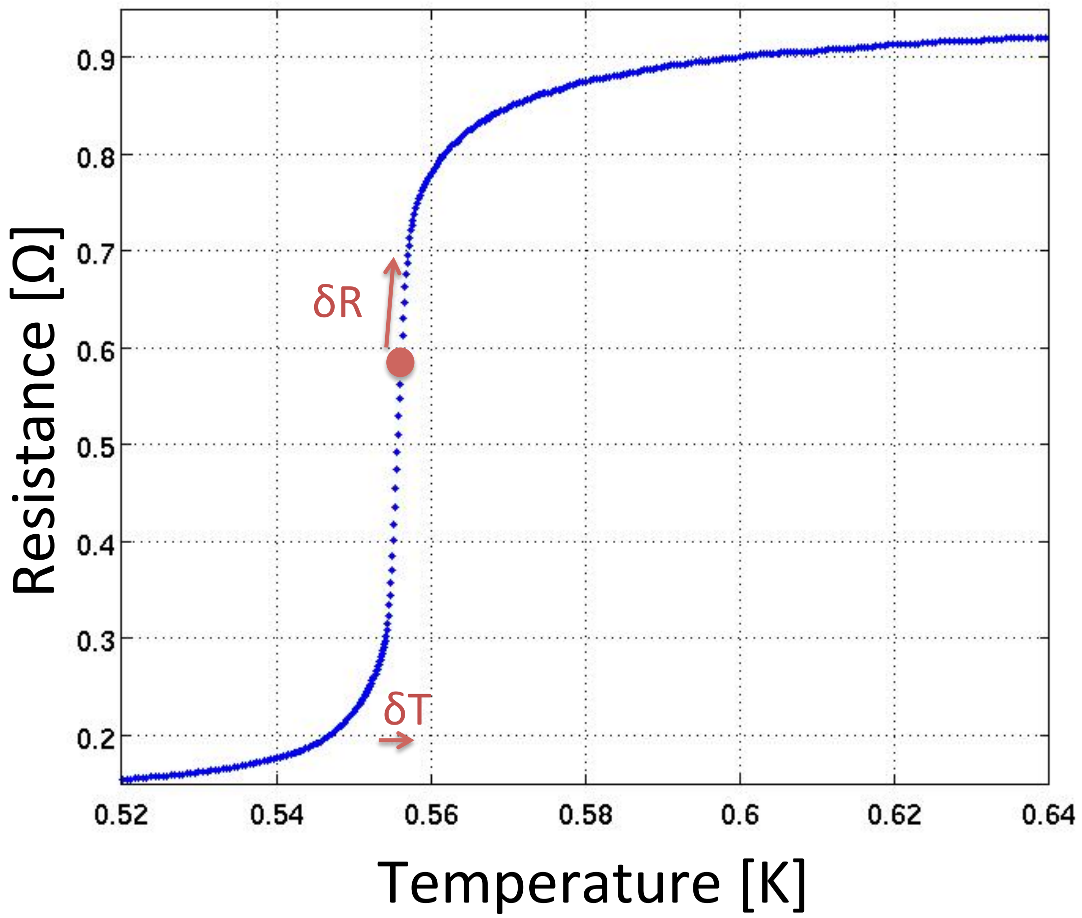
$$P_{Joule} = \frac{V_0^2}{R(T)}$$



The Modern Transition Edge Sensor



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



TES detectors

- Invented by HEP for DM
- HEP scientists using TES technology for leadership beyond DM
  - CMB
  - Neutrinos
  - Astro, national security, quantum information, synchrotron, etc...
- Strong case for continued HEP R&D to continue leadership in HEP science
  - coordinate/communicate/partner across TES resources/expertise

The Modern Transition Edge Sensor

Irwin, Appl. Phys. Lett., 66, 1998 (1995)

An application of electrothermal feedback for high resolution cryogenic particle detection

K. D. Irwin[a)]
Department of Physics, Stanford University, Stanford, California 94305-4060

(Received 30 September 1994; accepted for publication 26 January 1995)

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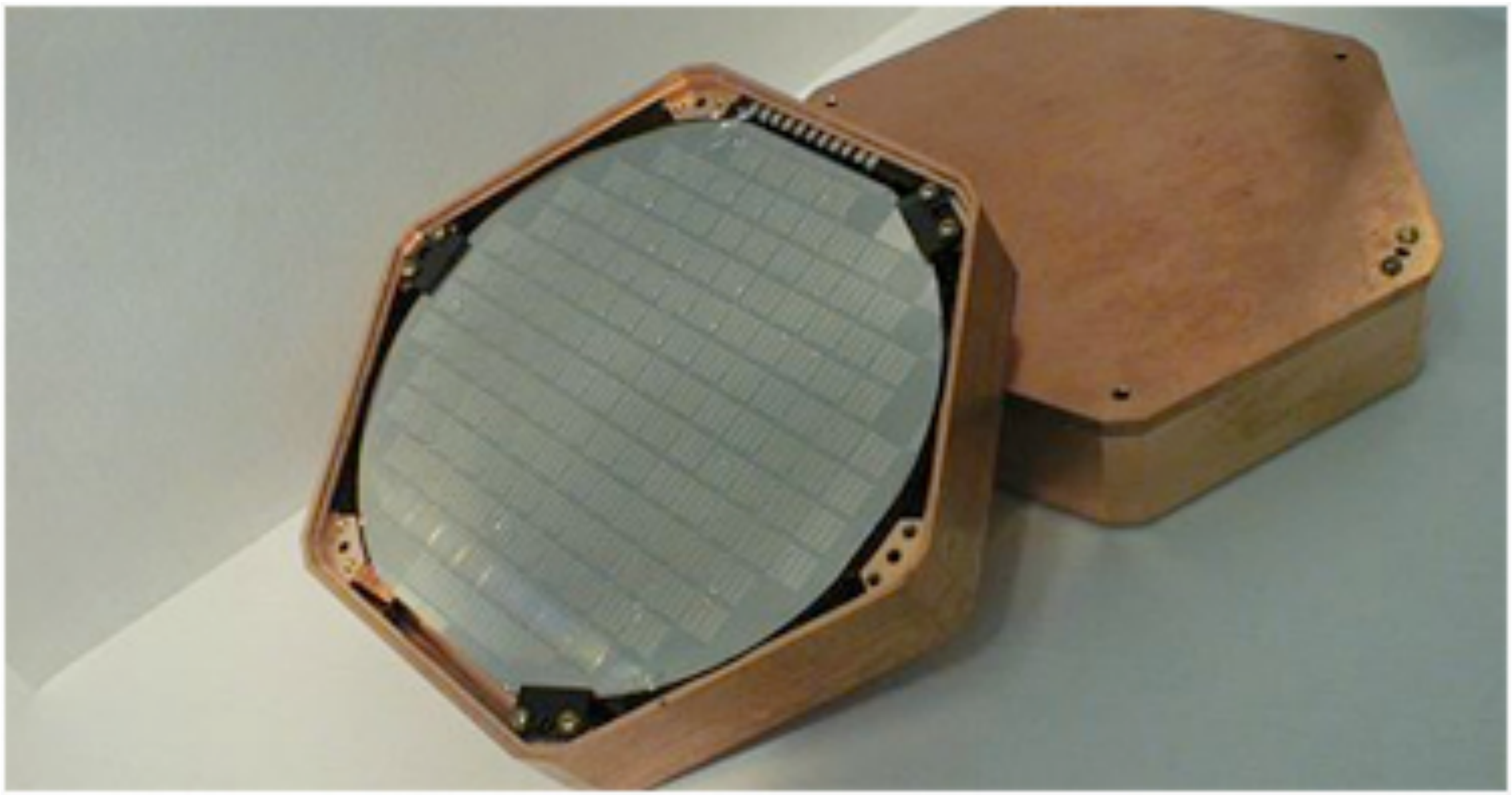
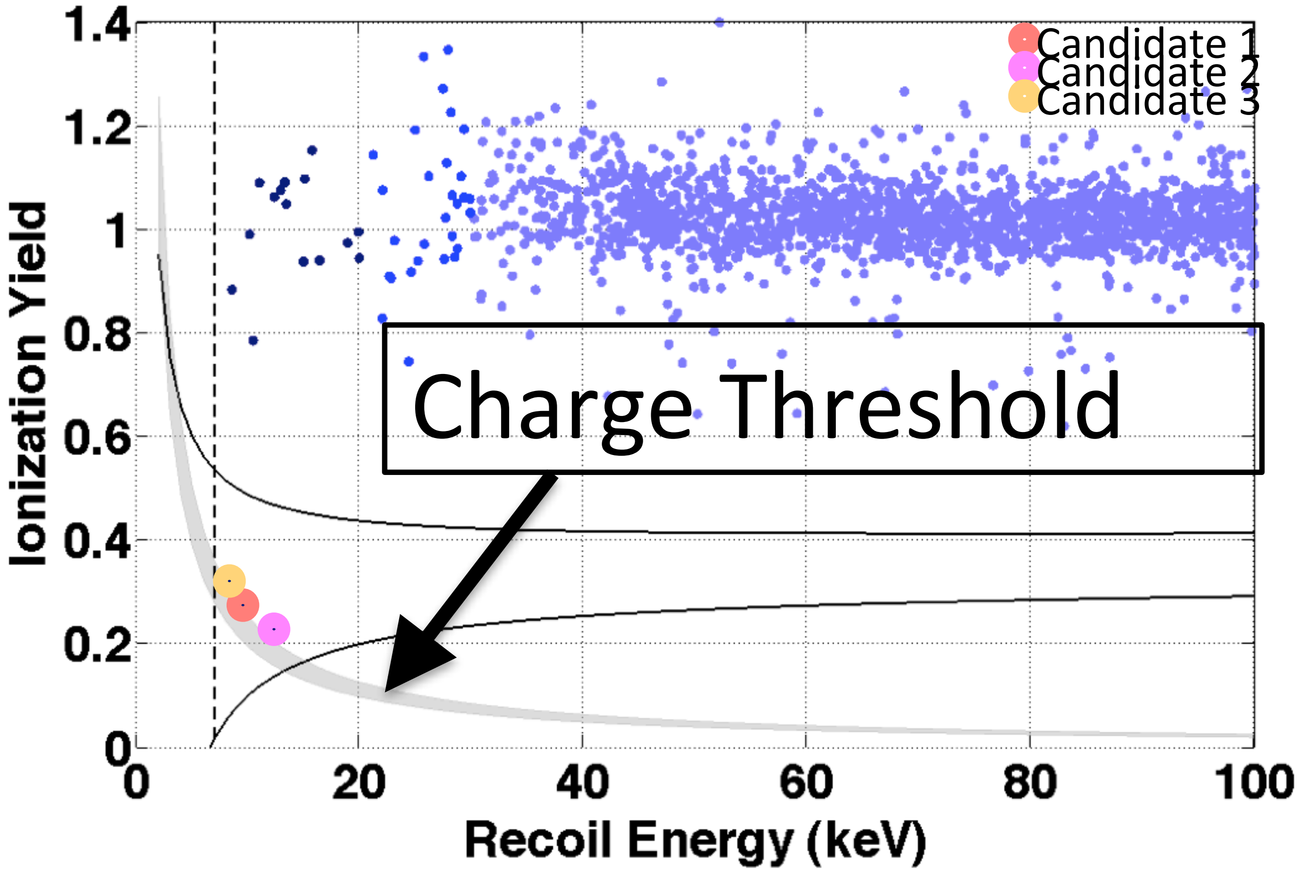
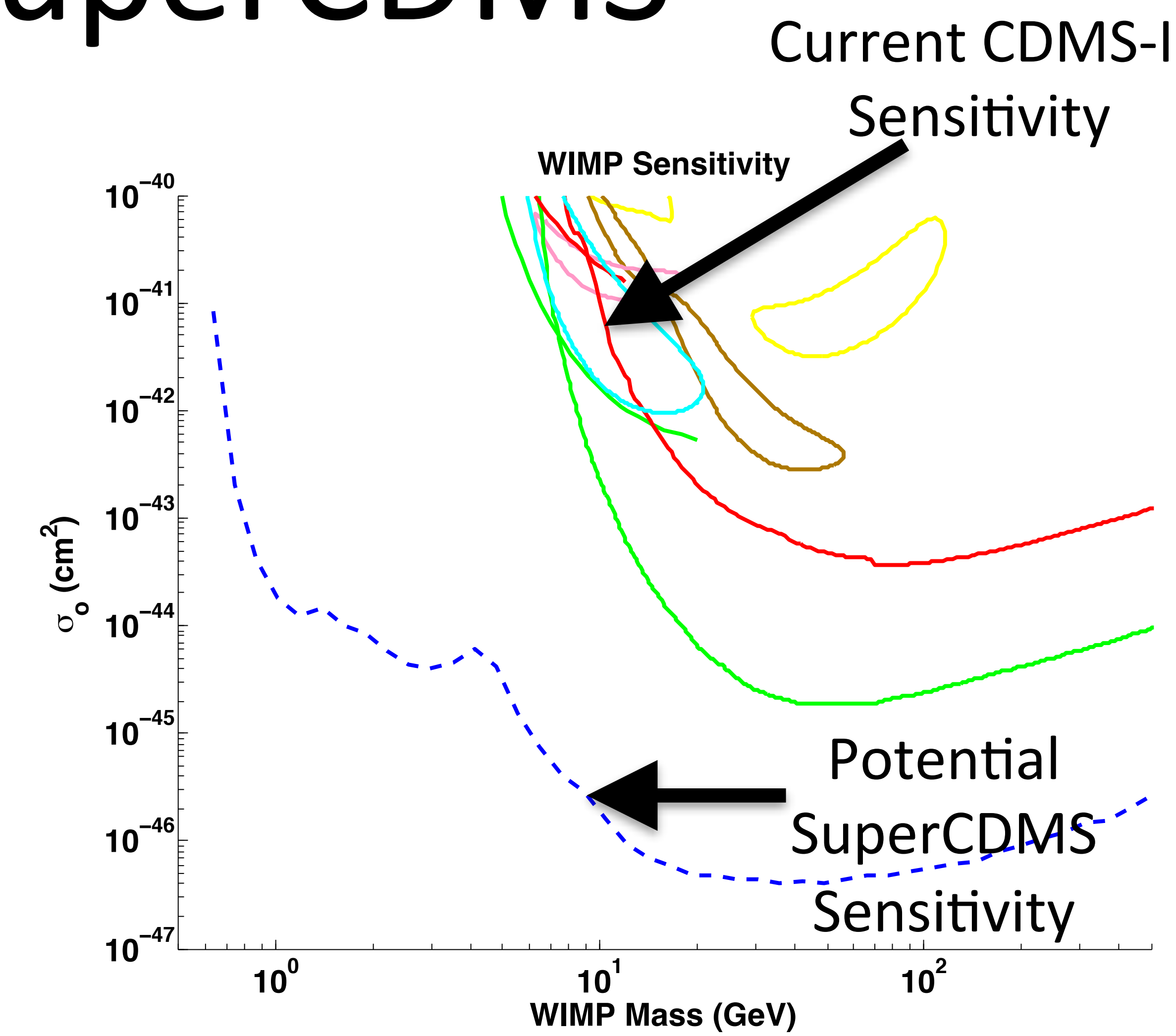
- TES invented by HEP for Dark Matter science

CDMS: TES-based Dark Matter detector ca. 2002



CDMS II -> SuperCDMS



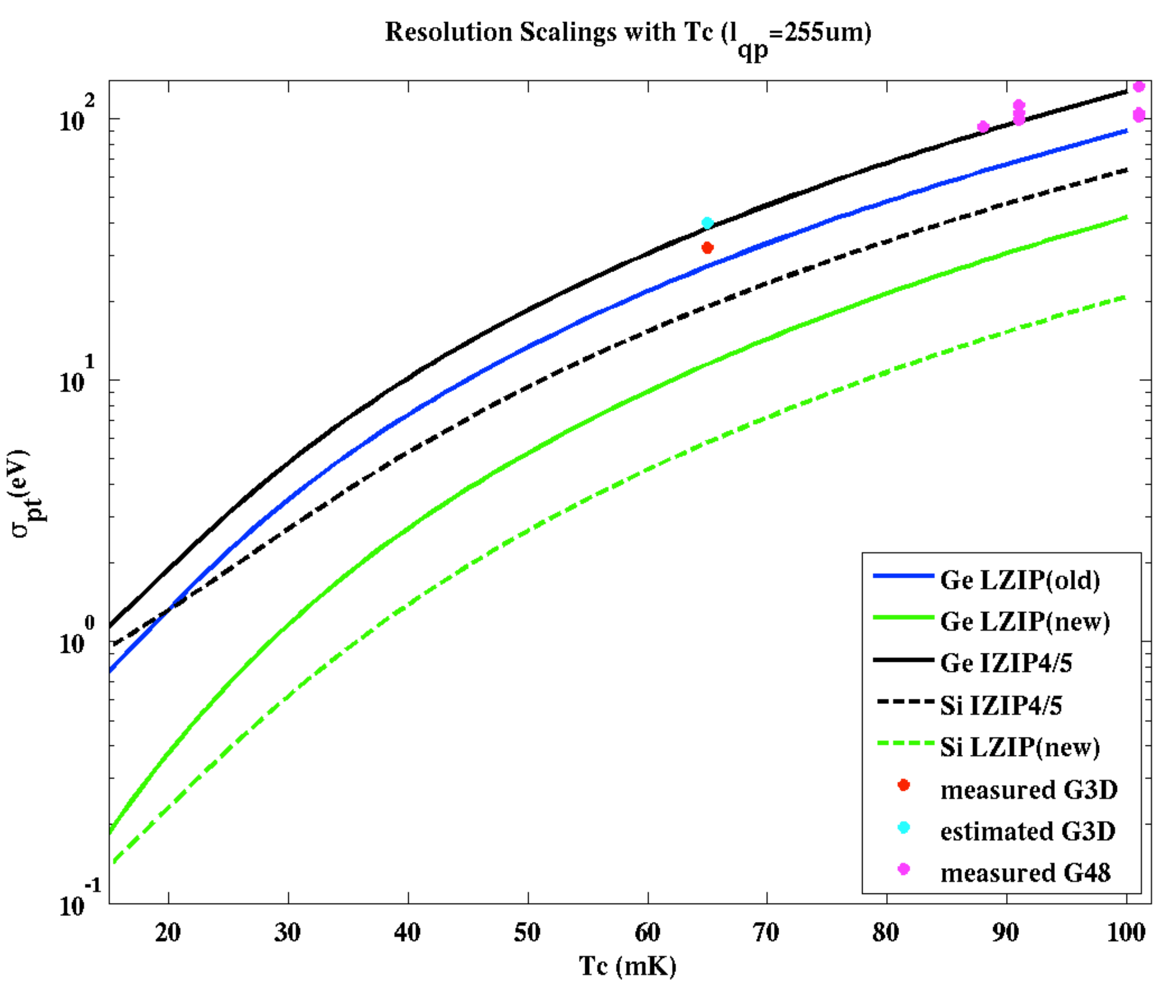


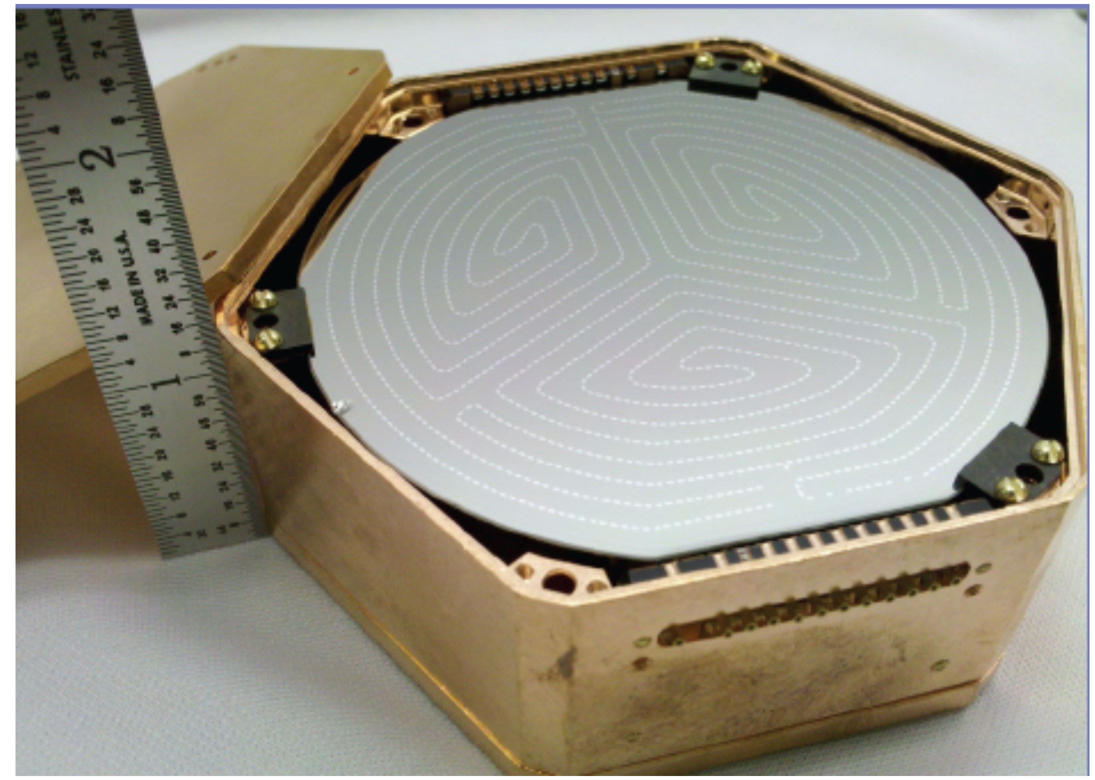
- Increasing SuperCDMS sensitivity to Light Mass Dark Matter is almost exclusively driven by improving detector position sensitivity (Instrumentation Improvements)

M. Pyle

SuperCDMS R&D Path

- Improve Charge & Phonon Position Sensitivity: Interdigitated Design





- Lower Noise
  - Charge: HEMTs
  - Phonon: Sensor/ Signal Bandwidth Mismatch

M. Pyle

The Modern Transition Edge Sensor

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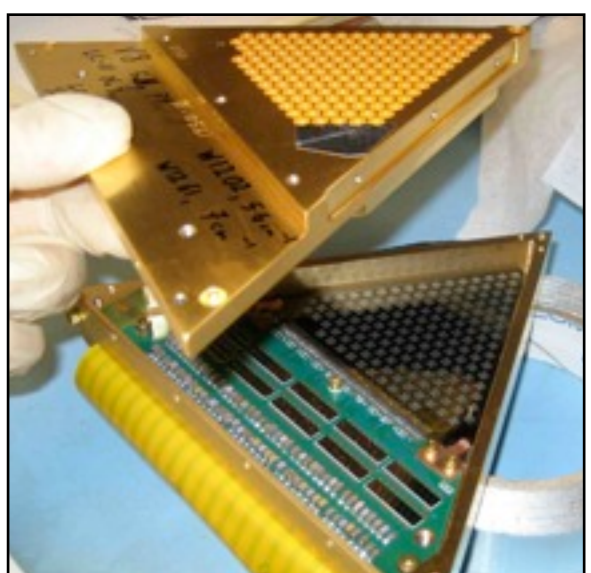
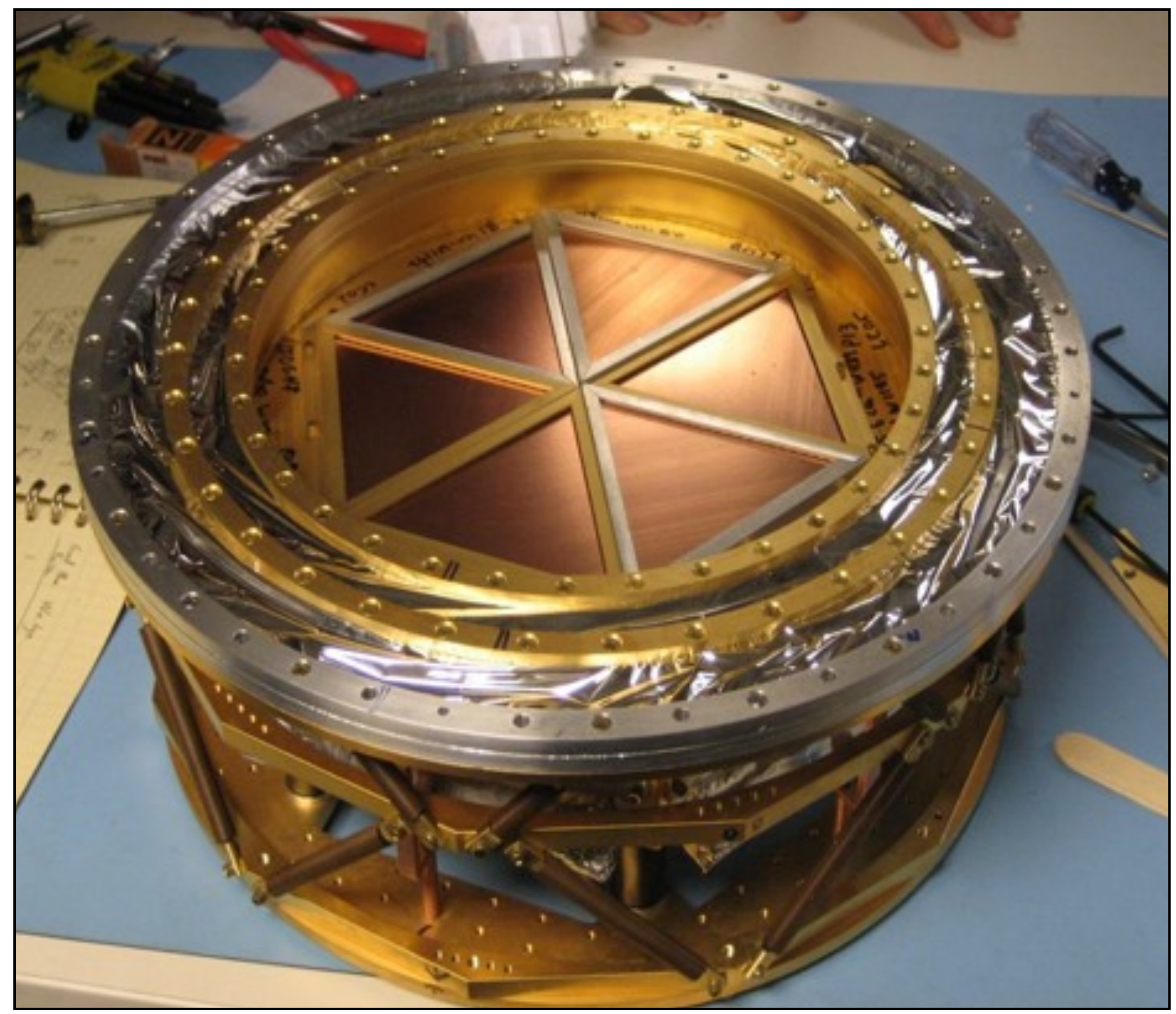
- TES invented by HEP for Dark Matter science
- From Dark Matter to leading CMB

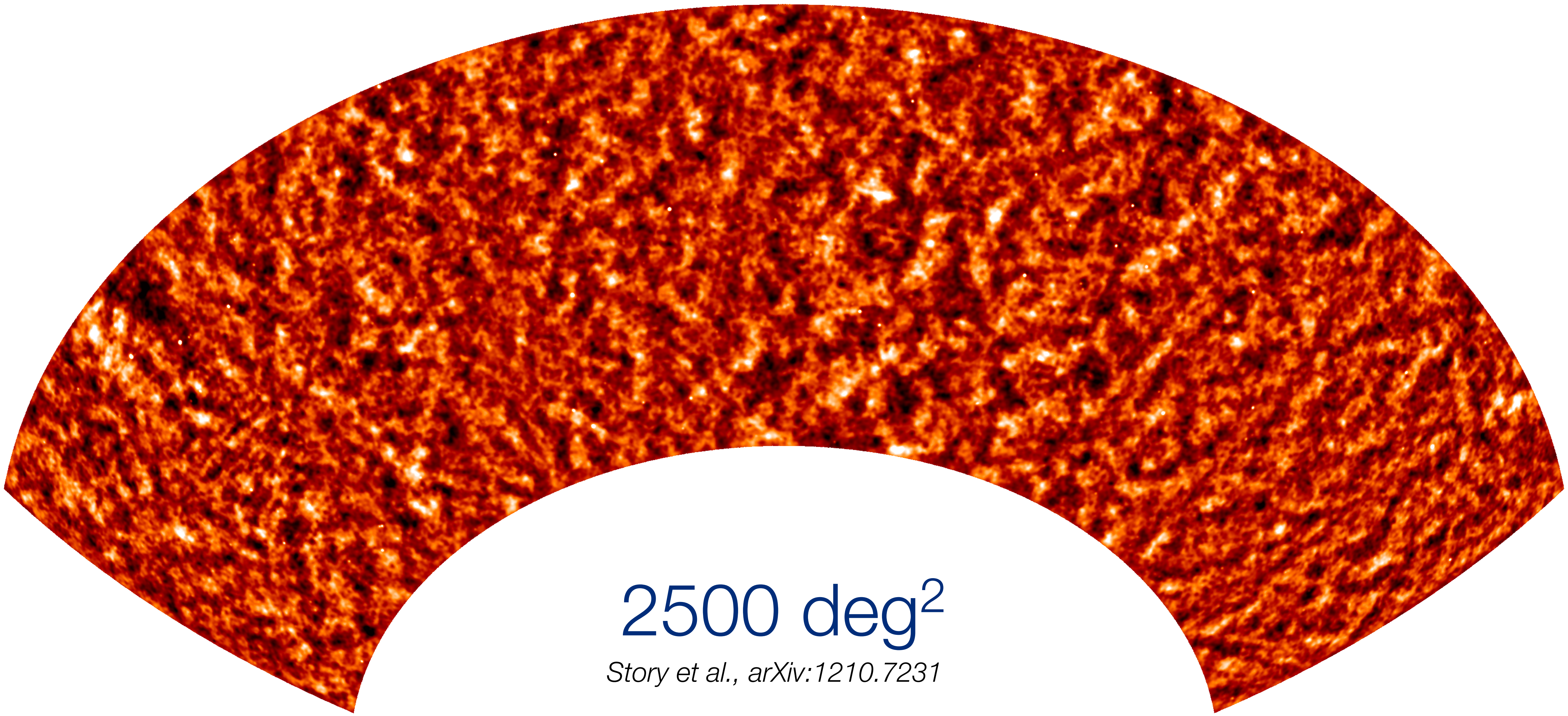
SPT: TES-based CMB bolometers ca. 2007



UCB, *A.T. Lee*



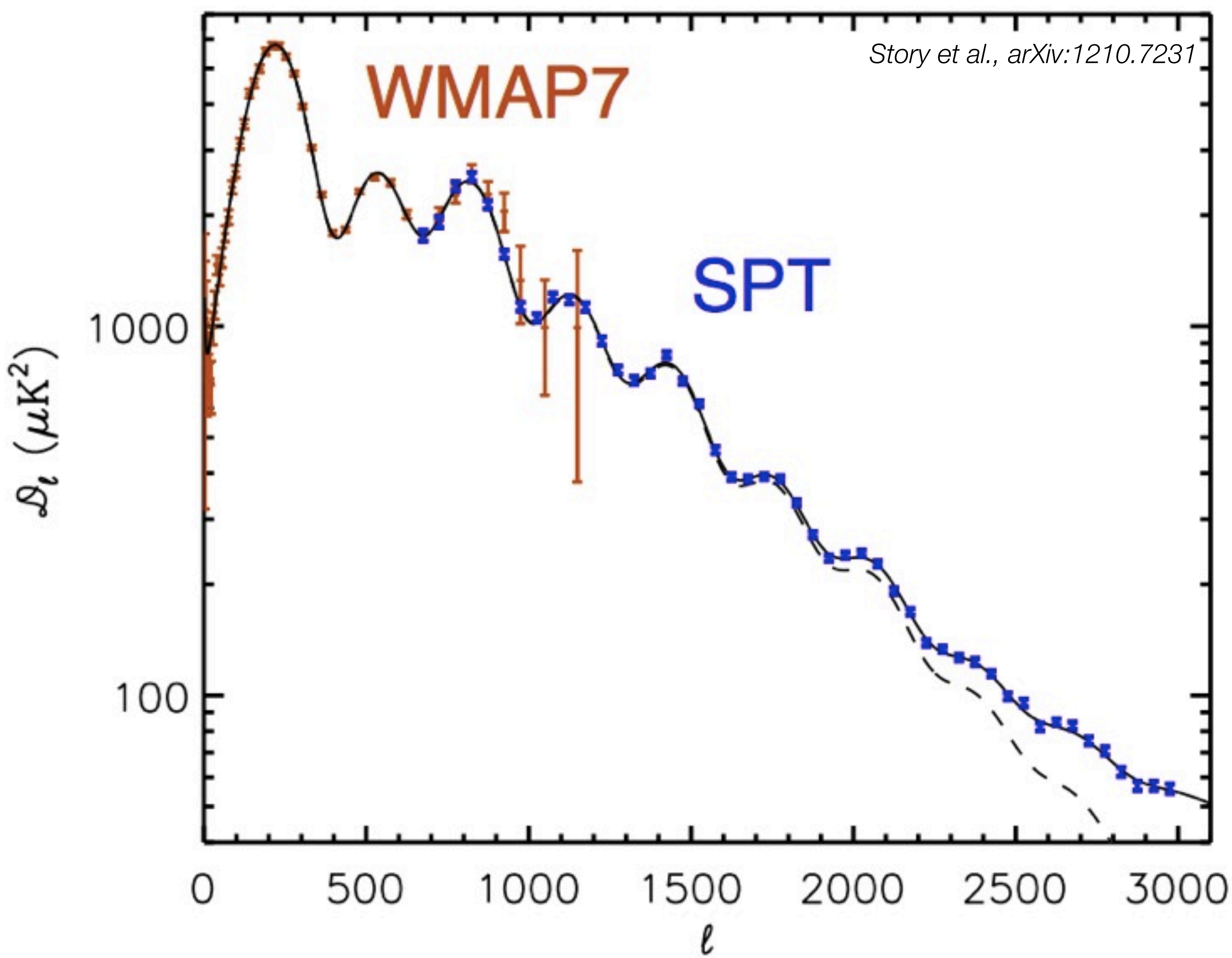
CMB from SPT



2500 deg^2

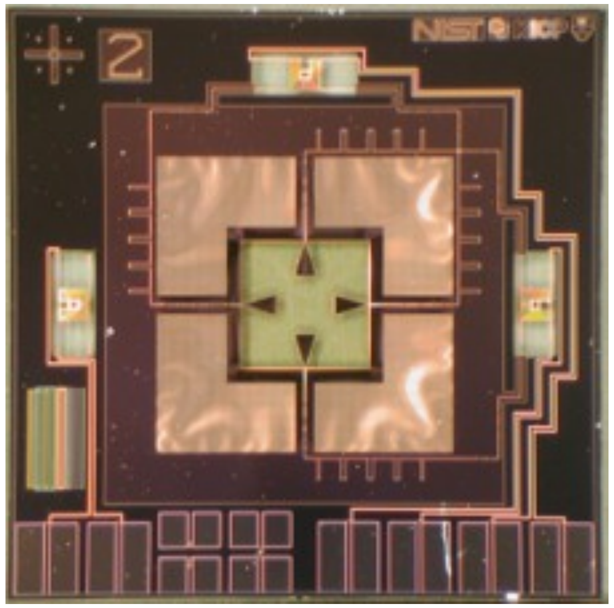
Story et al., arXiv:1210.7231

CMB from SPT

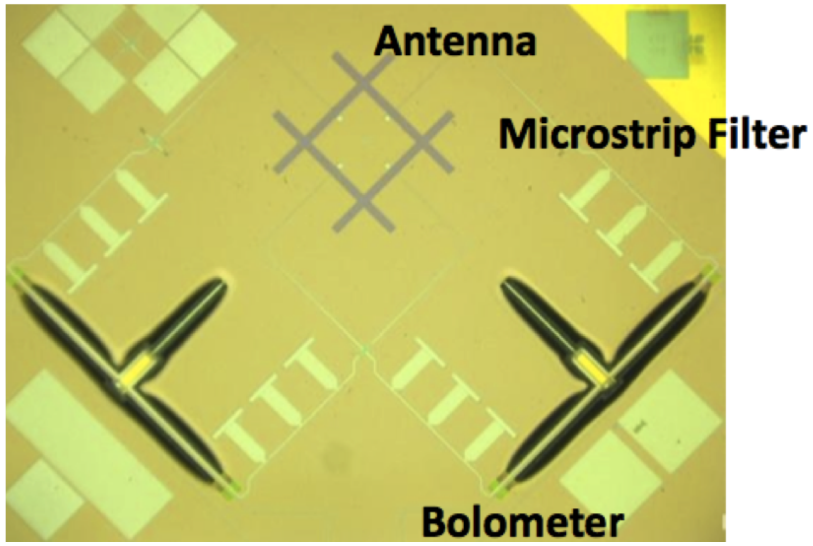


Story et al., arXiv:1210.7231
WMAP7
SPT
1000
100
$\mathcal{D}_\ell$ (μK^2)
0
500
1000
1500
2000
2500
3000
ℓ

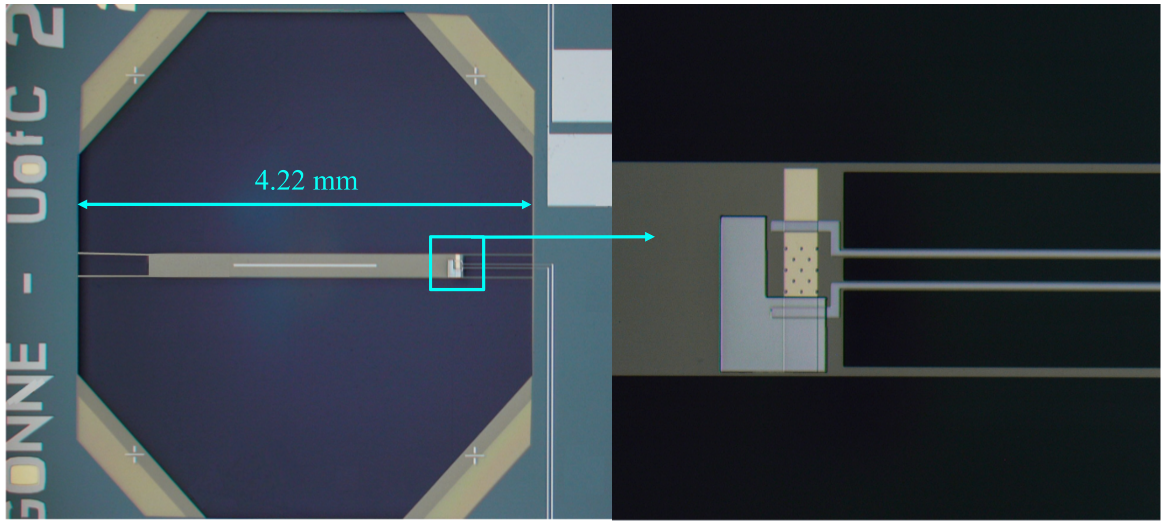
CMB polarimetry: Active field of TES detector development (completed for Stage II CMB)



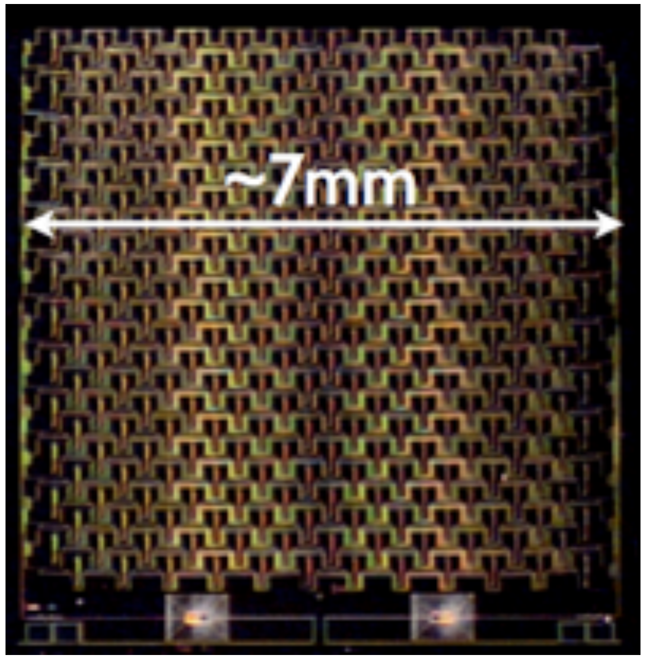
SPTpol (& ACTpol)



Polarbear

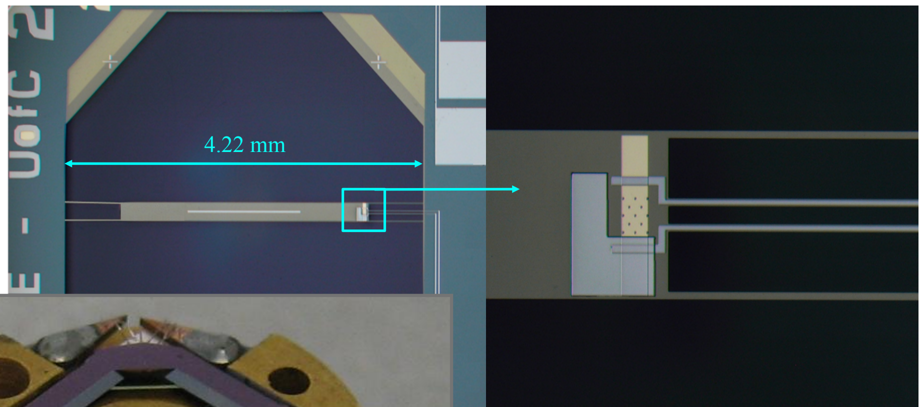


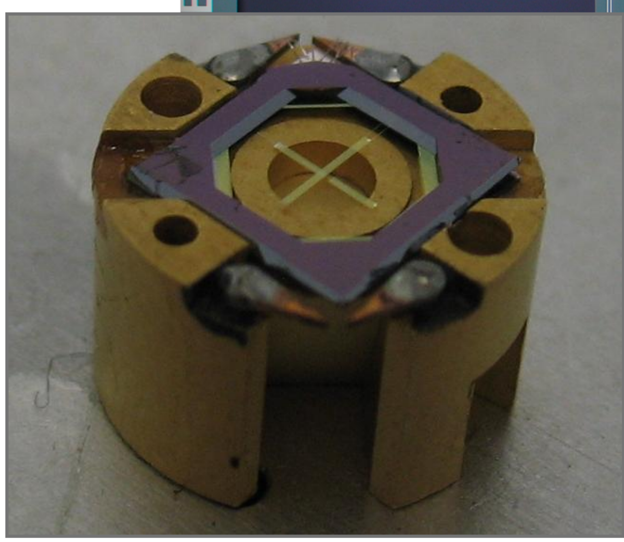
SPTpol



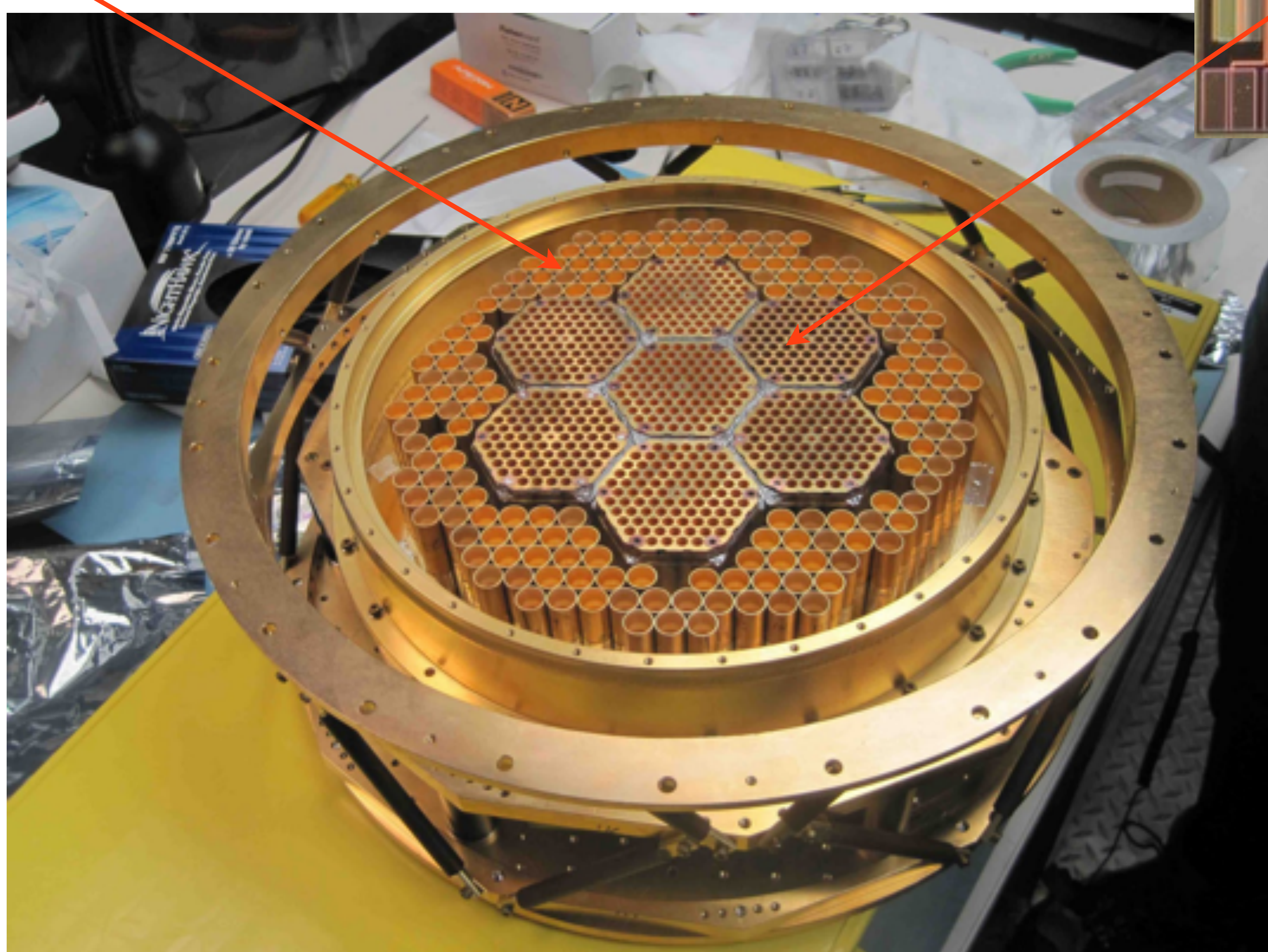
BICEP2/Keck

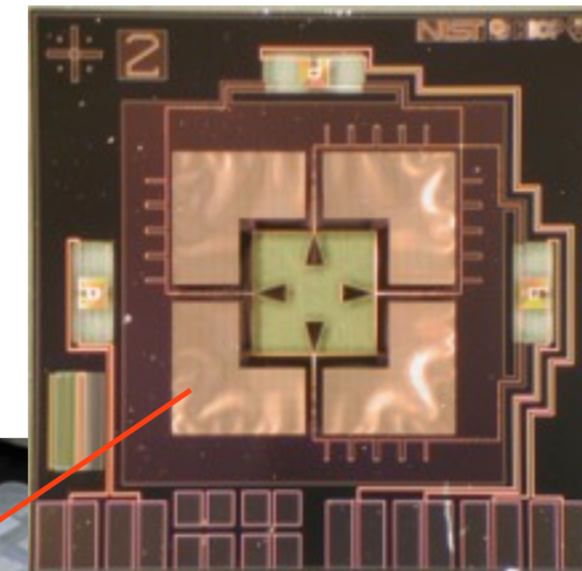
Stage II: e.g. SPTpol (ca. 2011)





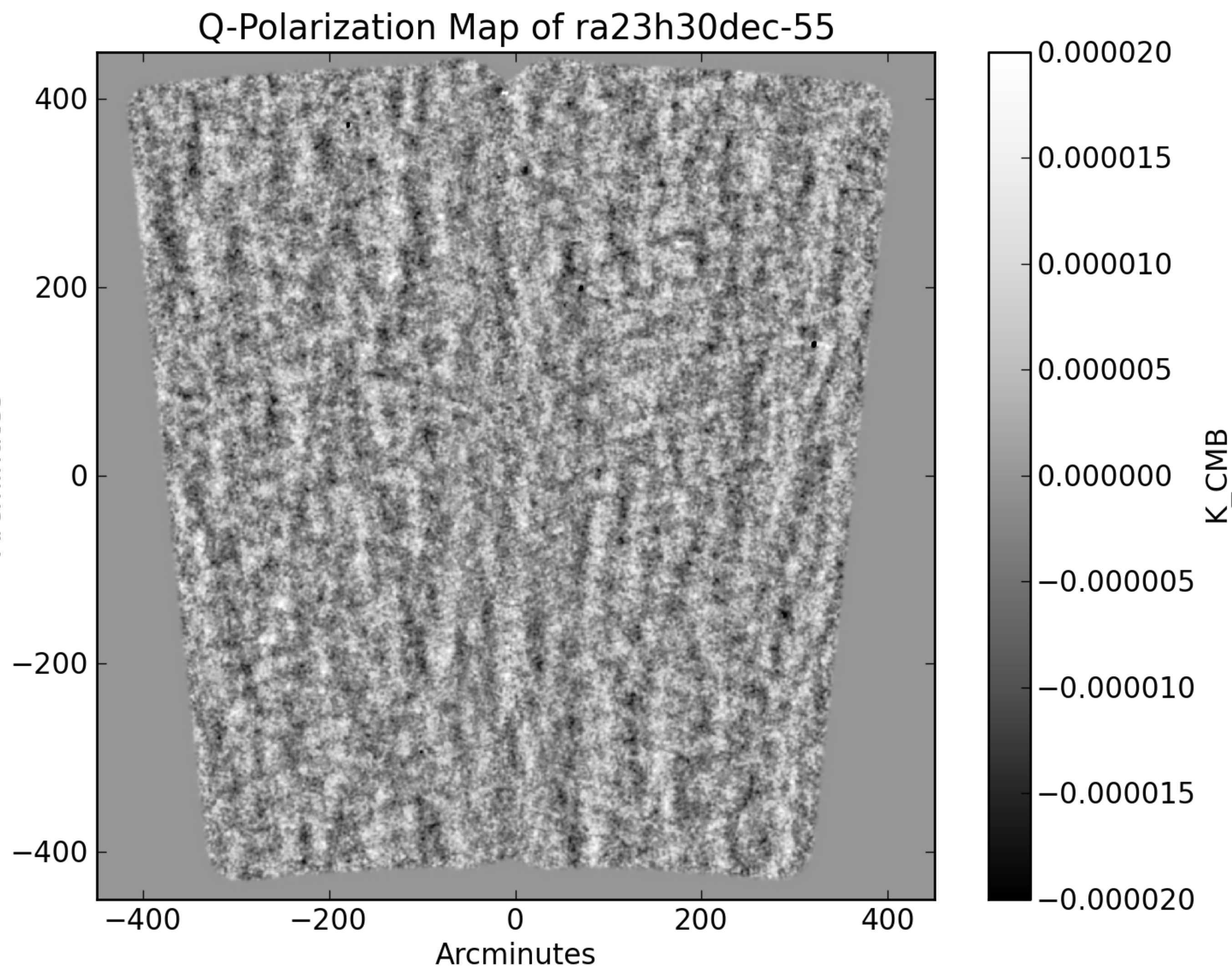
ANL,
C.L.Chang

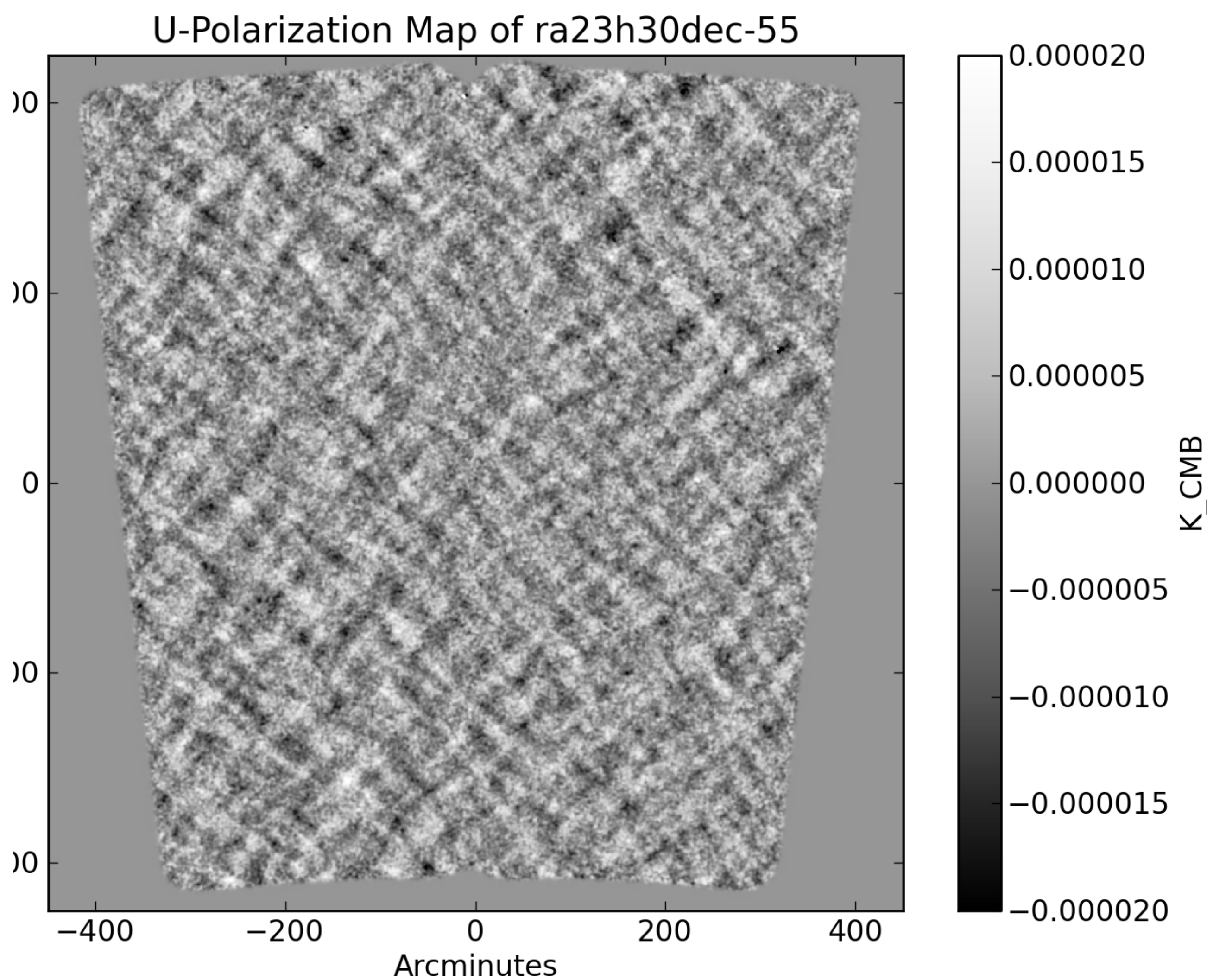




NIST,
K.D. Irwin

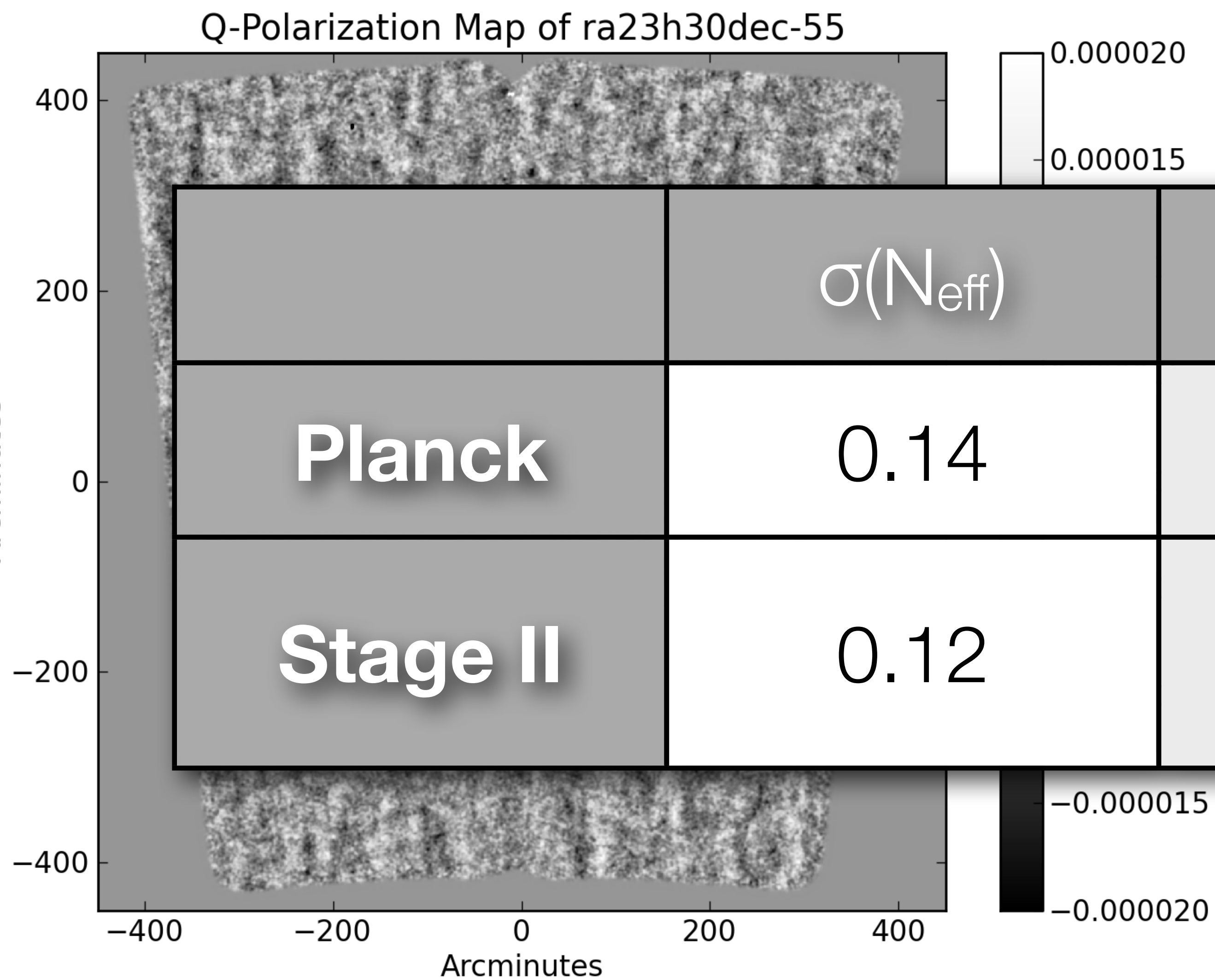
Stage II: e.g. SPTpol

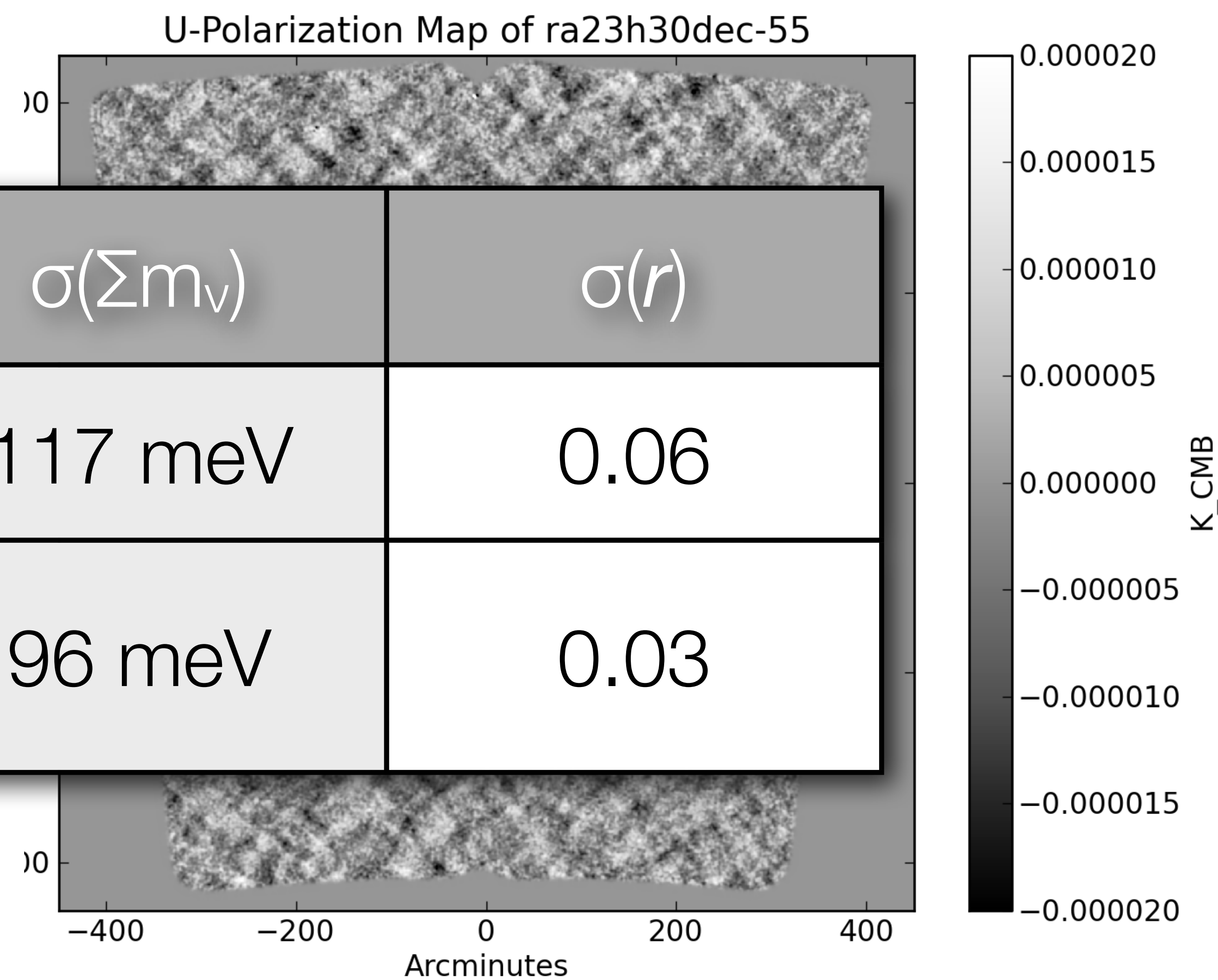




- First 6 months on 100 deg^2
- ~10 uK rms
- Observe 480 deg^2 over next 3 years (1600 detectors!)

Stage II: e.g. SPTpol



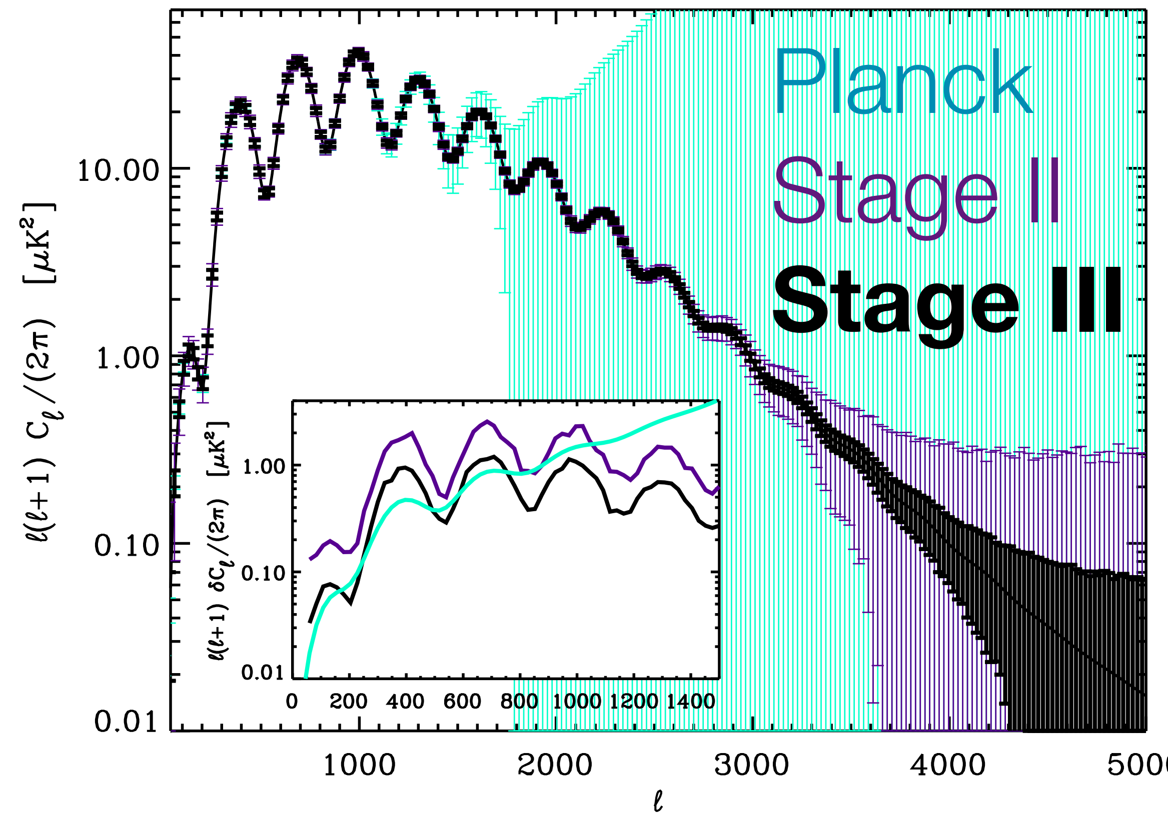


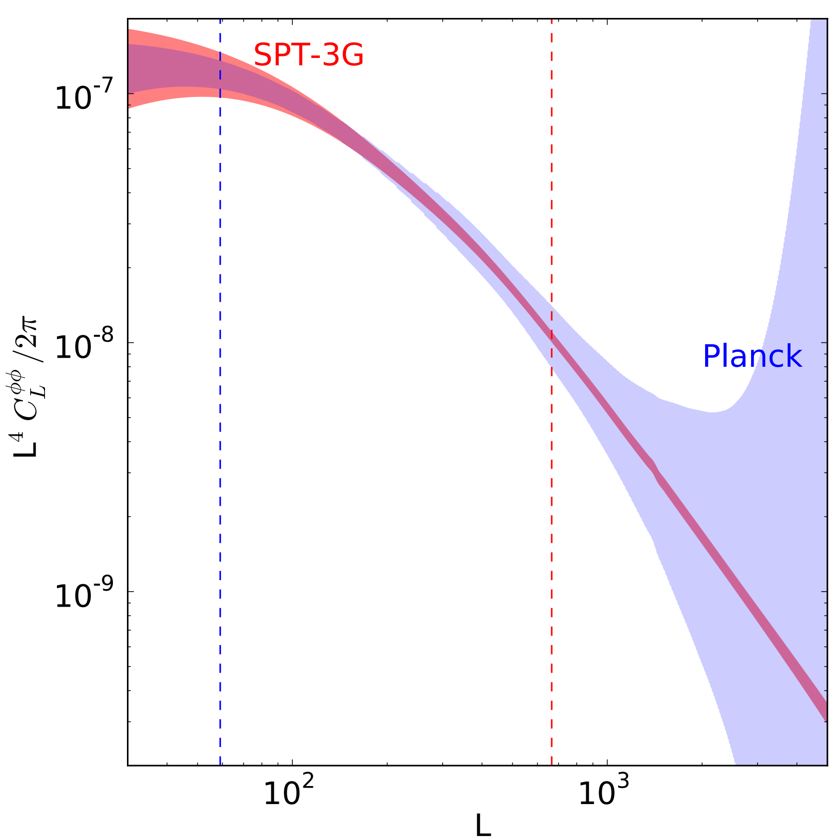
	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	$\sigma(r)$
Planck	0.14	117 meV	0.06
Stage II	0.12	96 meV	0.03

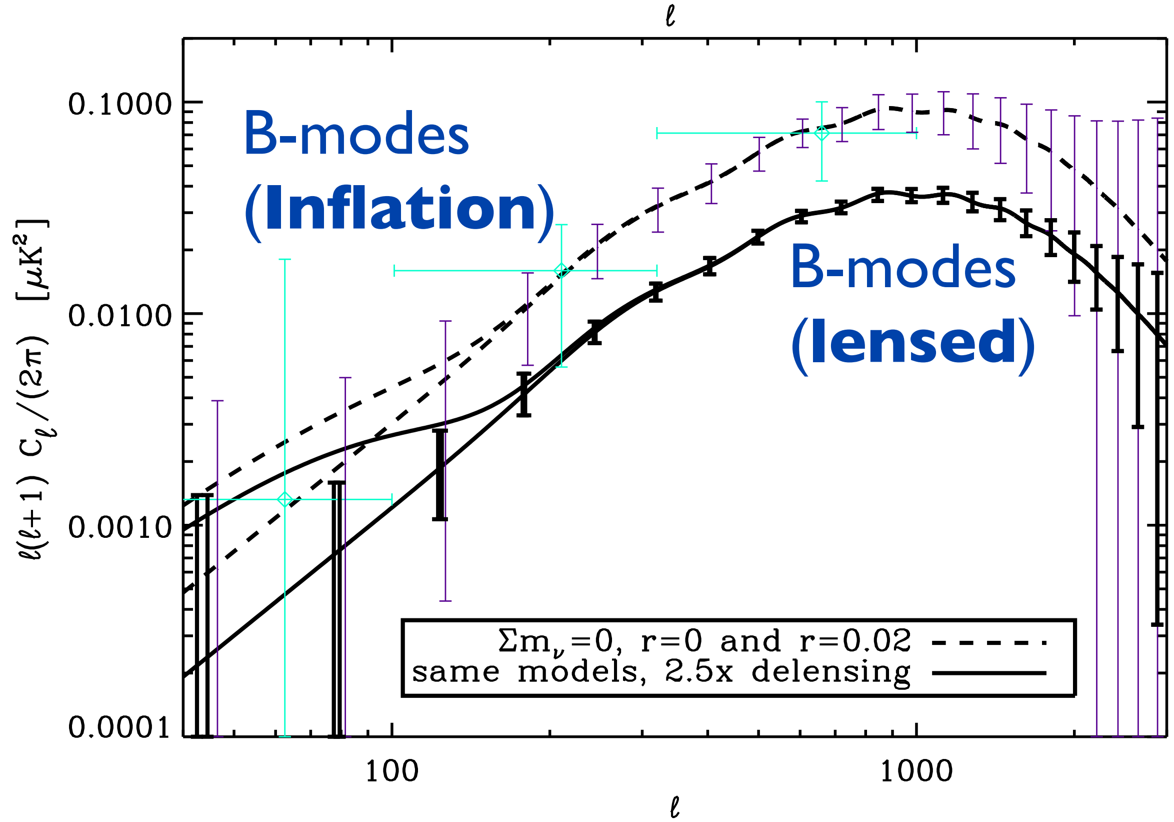
- First 6 months on 100 deg^2
- ~10 uK rms
- Observe 480 deg^2 over next 3 years

Beyond Planck: Stage III & IV

- Target 10x mapping speed of Stage II
    - O(10,000) optical modes vs O(1000) for Stage II
    - σ(r) = 0.01
    - σ(Σm$_\nu$) = 60 meV
- Stage IV another 10x

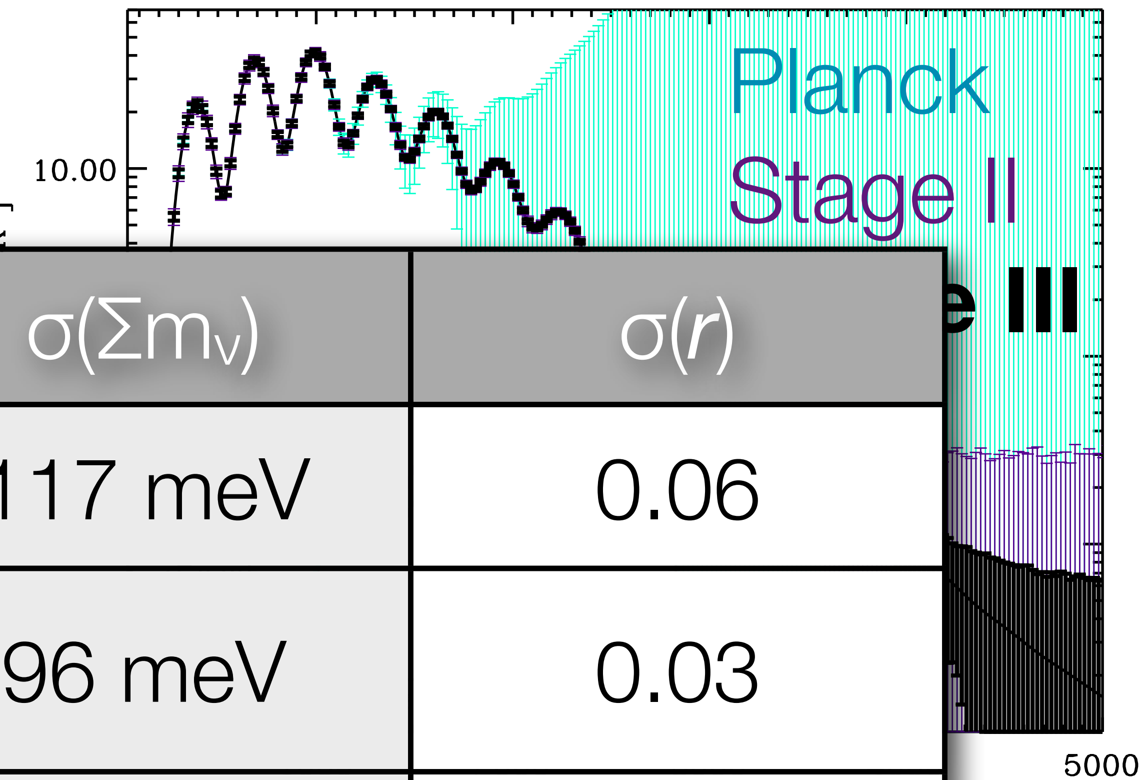






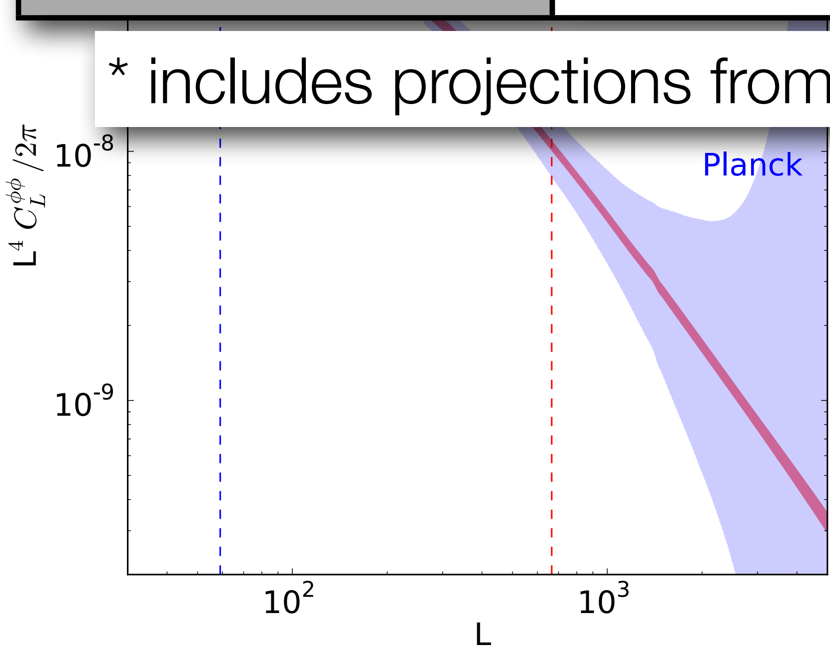
Beyond Planck: Stage III & IV

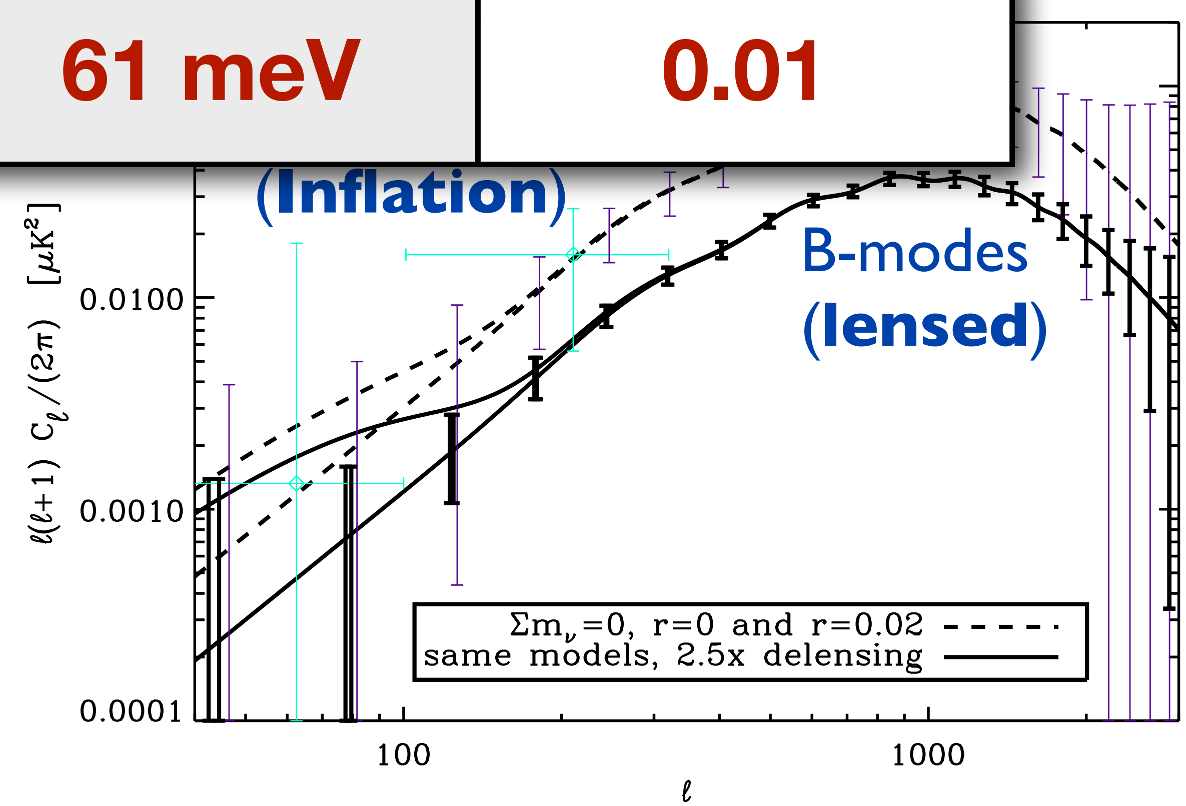
- Target 10x mapping speed of Stage II
  - O(10,000) optical modes vs O(1000)
- St



	σ(N_{eff})	σ(Σm_ν)	σ(r)
Planck	0.14	117 meV	0.06
Stage II	0.12	96 meV	0.03
STAGE III*	**0.06**	**61 meV**	**0.01**

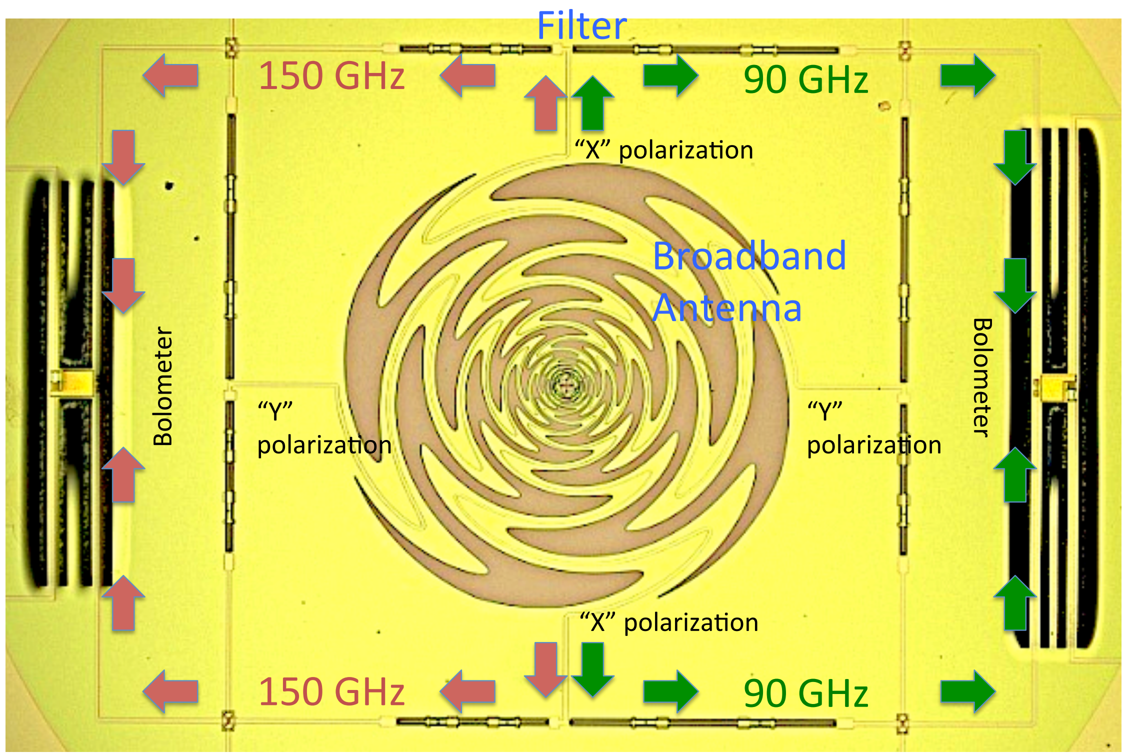
* includes projections from BOSS





Development for Stage III & IV

Suzuki et al., Proc. SPIE 8452, Mm, Sub-mm, and Far-IR Detectors and Instr. for Astro. VI, 84523H (October 5, 2012)



- Reminder: BACKGROUND LIMITED... need more detectors
- Post Stage II building block: large monolithic detector arrays
- Increase detector density and readout
- Develop mass production of many large arrays of detectors

CMB Science & “Roadmap”

- Science goals
  - Unique probe of Inflation, ~10^{16} GeV (Planck will not do this)
  - CMB lensing constrains/measures neutrino mass
  - CMB polarization is an opportunity for US leadership
- Stage III: (>10K detector elements)
  - 10x mapping speed over Stage II
  - deploy latter half of the decade
- Stage IV: (>100K detector elements)
  - 100x mapping speed over Stage II
  - deploy ~2020, observe for 5 years

The Modern Transition Edge Sensor

Irwin, Appl. Phys. Lett., 66, 1998 (1995)

An application of electrothermal feedback for high resolution cryogenic particle detection

K. D. Irwin[a)]
Department of Physics, Stanford University, Stanford, California 94305-4060

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- TES invented by HEP for Dark Matter science
- From Dark Matter to leading CMB
- ...and beyond

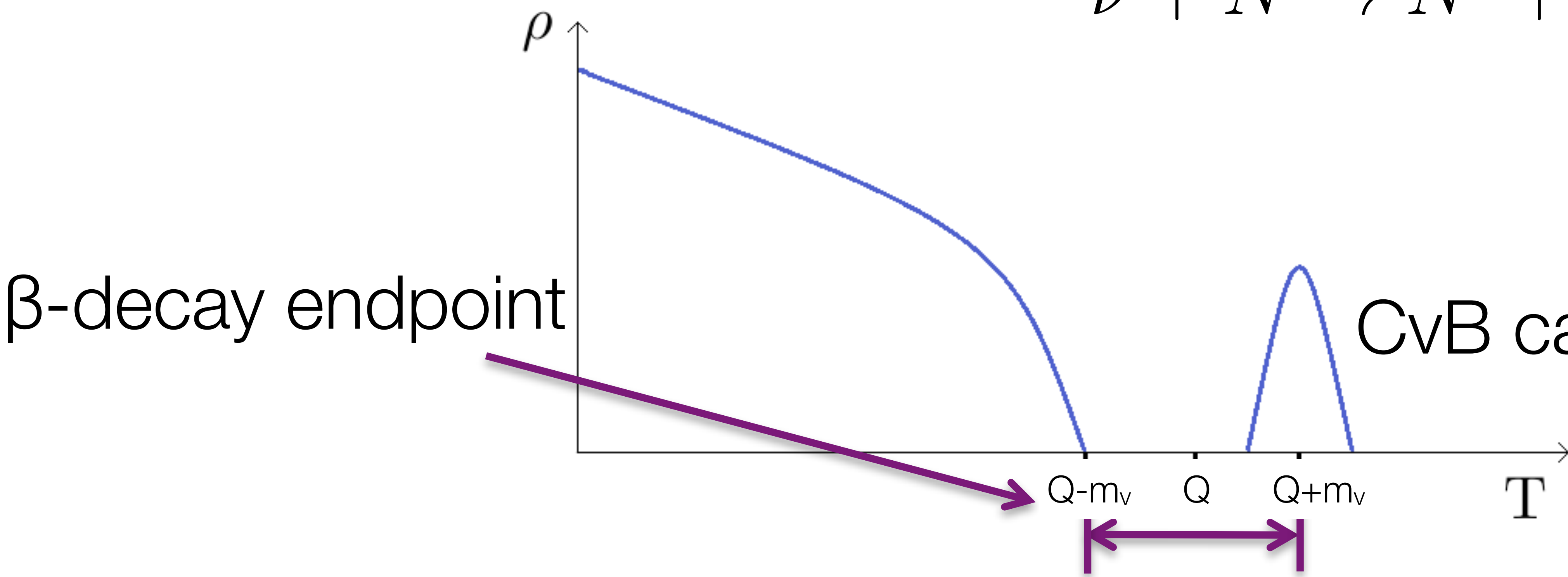
Ambitious new directions: Cosmic Neutrino Background

- Initially, entire Universe was a hot dense state
- Weak interactions keep neutrinos in thermal equilibrium with rest of primordial plasma
- Neutrino decoupling
    - at t~1 sec ($k_B T$~1 MeV) Weak interaction rate too slow to keep up with expansion
    - ~113 cm^{-3} per neutrino specie
    - $T_{C\nu B}$ ~ 1.9 K

Direct detection of the CvB

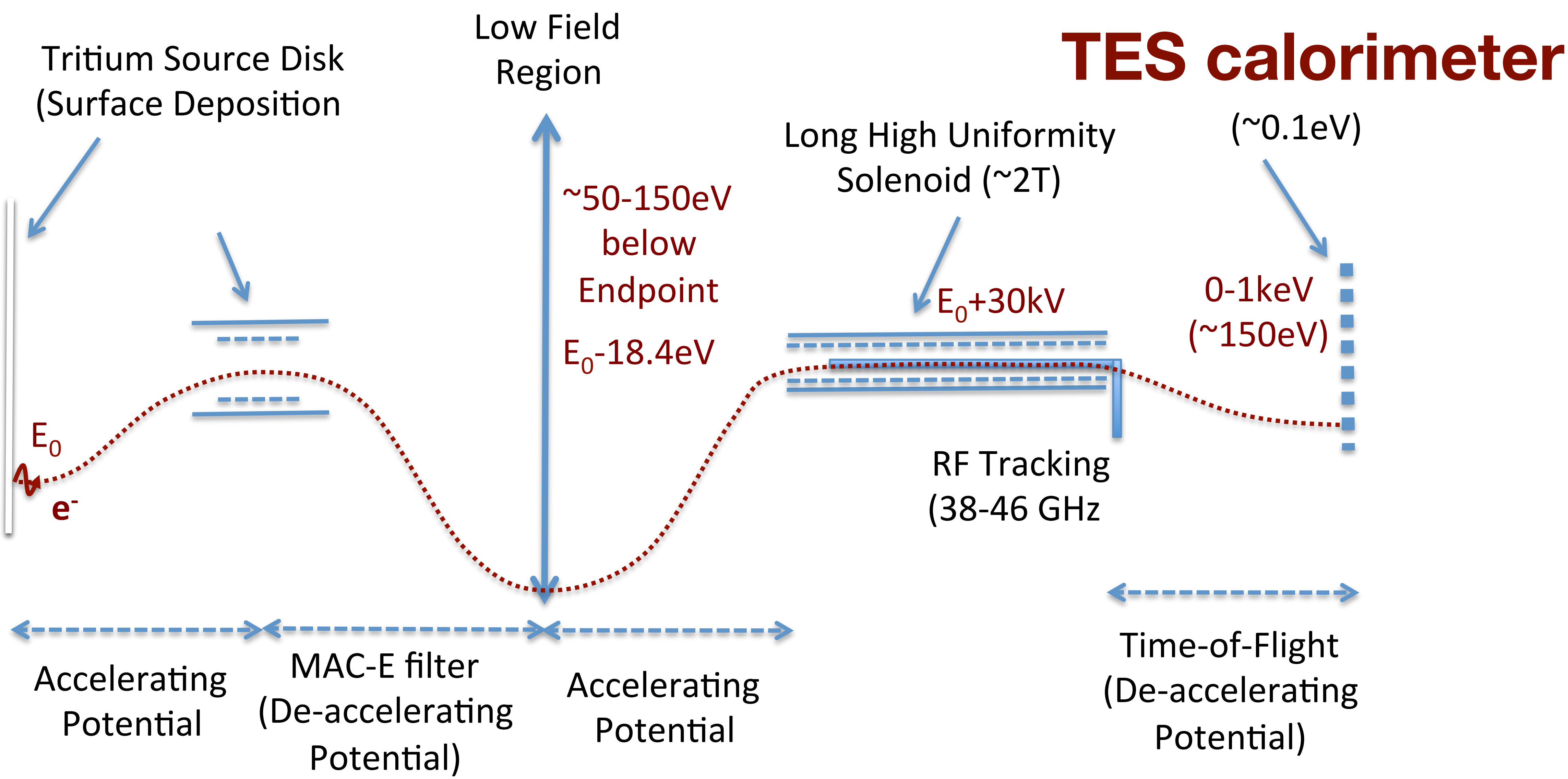
$$N \rightarrow N' + e^- + \bar{\nu}$$

$$\nu + N \rightarrow N' + e^-$$



Weinberg, Phys. Rev. 128:3, 1457 (1962)
Lazauskas et al., J.Phys. G35 (2008) 025001

PTOLEMY



Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

[http://if-neutrino.fnal.gov/whitepapers/ptolemy.pdf - W.R. Blanchard et al.,](http://if-neutrino.fnal.gov/whitepapers/ptolemy.pdf)

C.G. Tully, C.L. Chang, et. al.

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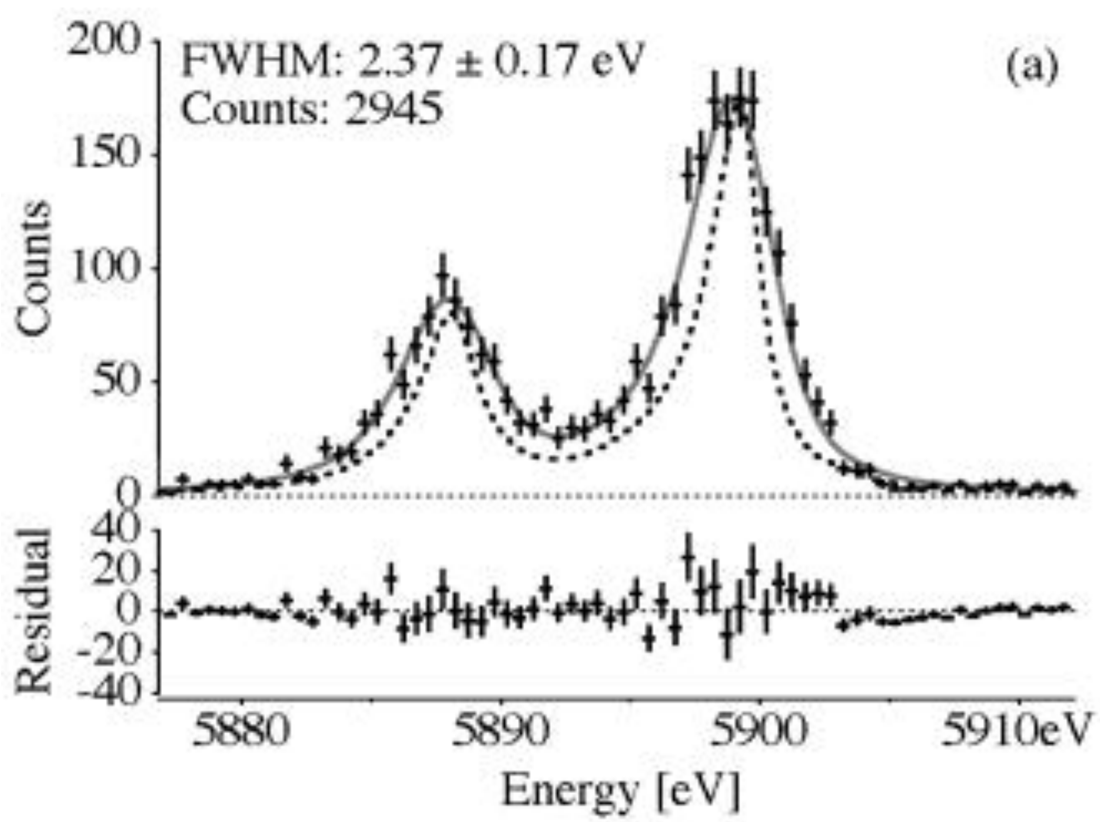
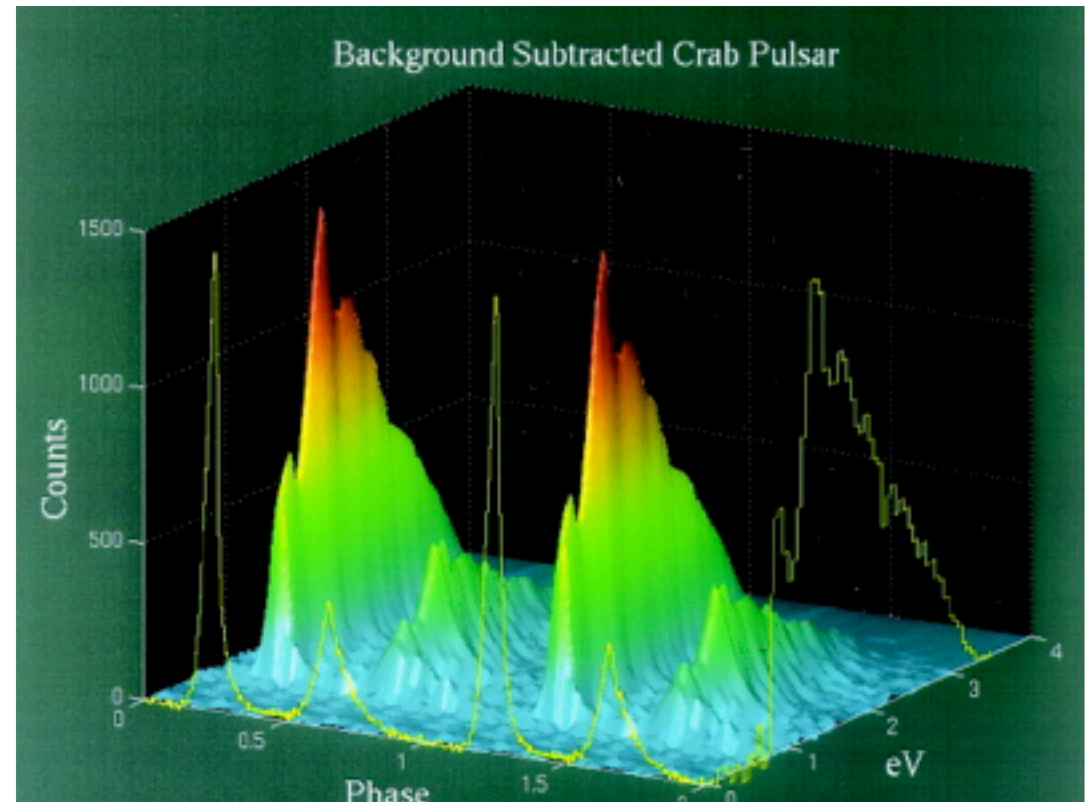
- From Dark Matter to leading CMB
- ...and beyond

Multi/inter-disciplinary

Iyomoto et al., Appl. Phys. Lett. 92, 013508 (2008)





Romani et al., The Astrophysical Journal, 521:L153-L156, 1999

- Optical: spectrophotometry & quantum cryptography
- X-ray: astrophysics & synchrotron science
- mm-wave thermal imaging for national security
- “gamma” ray spectroscopy for nuclear non-proliferation
- calorimeters for beta decay

TES detectors

- Invented by HEP for DM
- HEP scientists using TES technology for leadership beyond DM
    - CMB
    - Neutrinos
    - Astro, national security, quantum information, synchrotron, etc...
- Strong case for continued HEP R&D to continue leadership in HEP science
    - coordinate/communicate/partner across TES resources/expertise