Superconducting technology and Measuring the Cosmic Neutrino Background

Clarence Chang
Argonne National Lab

FNAL Research Techniques Seminar
March 12, 2013

Cosmic Neutrinos and a bit of history

Outline

- Intro to Transition Edge Sensors
- SQUIDs and Multiplexing

Outline

- Intro to Transition Edge Sensors
- SQUIDs and Multiplexing
- Applications in the mm-wave: CMB
  - SPT-SZE
  - SPTpol
  - SPT-3G

Outline

- Brief intro to the Cosmic Neutrino Background (CvB)
- Impact of CvB on cosmology and measurement techniques

- Intro to Transition Edge Sensors
- SQUIDs and Multiplexing
- Applications in the mm-wave: CMB
  - SPT-SZE
  - SPTpol
  - SPT-3G

Outline

- Brief intro to the Cosmic Neutrino Background (CvB)
- Impact of CvB on cosmology and measurement techniques

- Intro to Transition Edge Sensors
- SQUIDs and Multiplexing
- Applications in the mm-wave: CMB
  - SPT-SZE
  - SPTpol
  - SPT-3G
- New opportunities with the PTOLEMY experiment

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
  - $T_{C\nu B} \sim 1.9$ K

CνB and the Early Universe

- m_ν < a few eV; relativistic energy in the early Universe

$$\rho_{\mathrm{R}} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma$$

- Measurable via impact on the expansion rate
- BBN: $N_{\mathrm{eff}} = 3.71 \pm 0.46$ *Steigman, Adv. in HEP Vol 2012 (2012), 268321*
- CMB: Diffusion (Silk) damping

CνB and the Late Universe

- Oscillations: at least two of the neutrino species are massive
- non-relativistic in the late Universe, energy density set by n_ν and m_ν
- Free streaming smooths out small scale clumps
- Slows down the growth of structure, measurable by
    - Galaxy Cluster abundance (vs. redshift)
    - Weak lensing
    - other methods as well...

The Vintage Transition Edge Sensor

Andrews et al., Rev. Sci. Instrum., 13, 281 (1942)

JULY, 1942 R. S. I. VOLUME 13

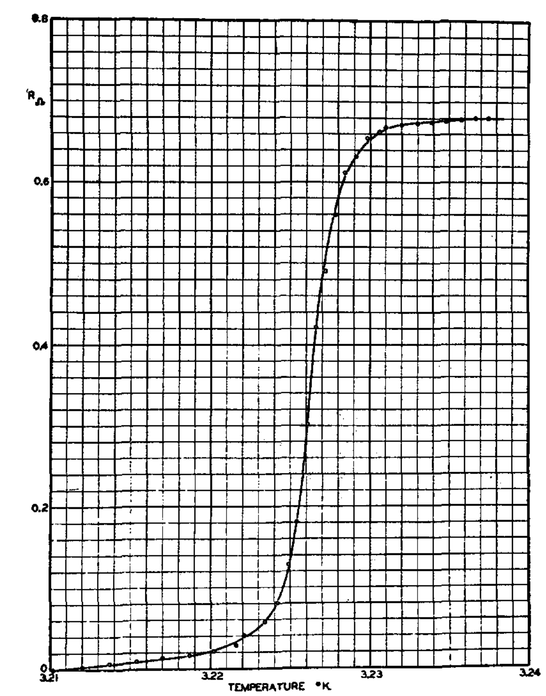
Attenuated Superconductors

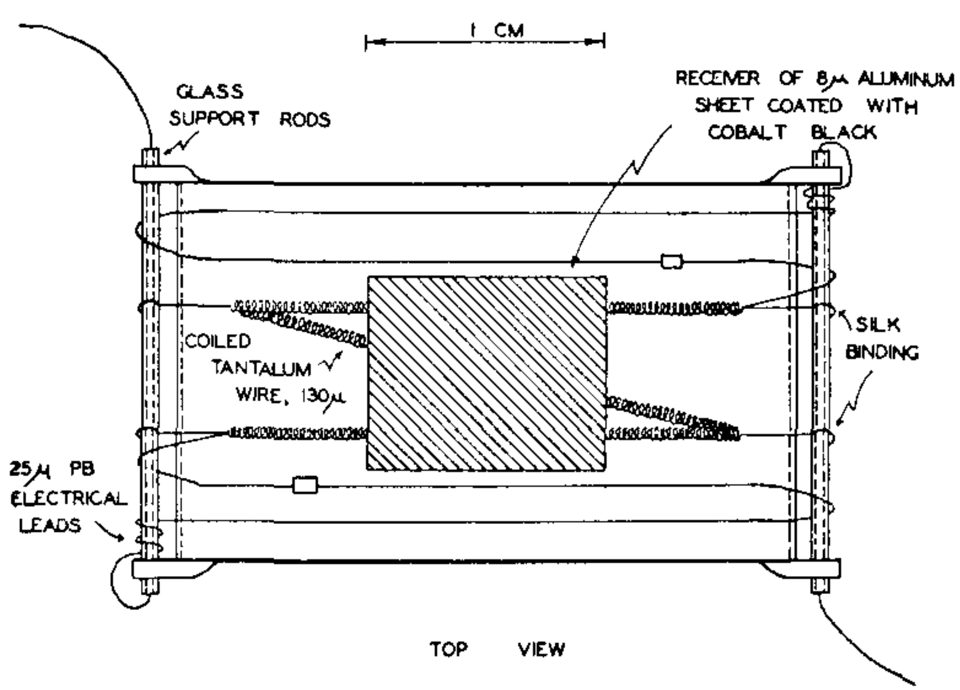
I. For Measuring Infra-Red Radiation

D. H. ANDREWS, W. F. BRUCKSCH, JR., W. T. ZIEGLER, AND E. R. BLANCHARD
Chemistry Department, The Johns Hopkins University, Baltimore, Maryland

(Received February 27, 1942)

An apparatus for measuring infra-red radiation has been constructed of fine tantalum wire, operating at a temperature of 3.22–3.23°K in the transition zone between superconduction and normal conduction. The tantalum coil is mounted on a thermostated plate with temperature electrically controlled and operates in a special self-regulating shunt circuit by which its own temperature is automatically maintained constant. The ratio of developed electrical potential to radiation flux received is 150 μv (erg cm^{-2} sec.$^{-1}$)$^{-1}$. Minimum detectable flux is *ca.* 10^{-3} erg sec.$^{-1}$. Absolute measurements of intensity of radiation from sources at temperatures between 24° and 55° are consistent with the Stefan-Boltzmann law showing that instrument corrections for reflectivity, window-absorption, and changes with wave-length are very small.





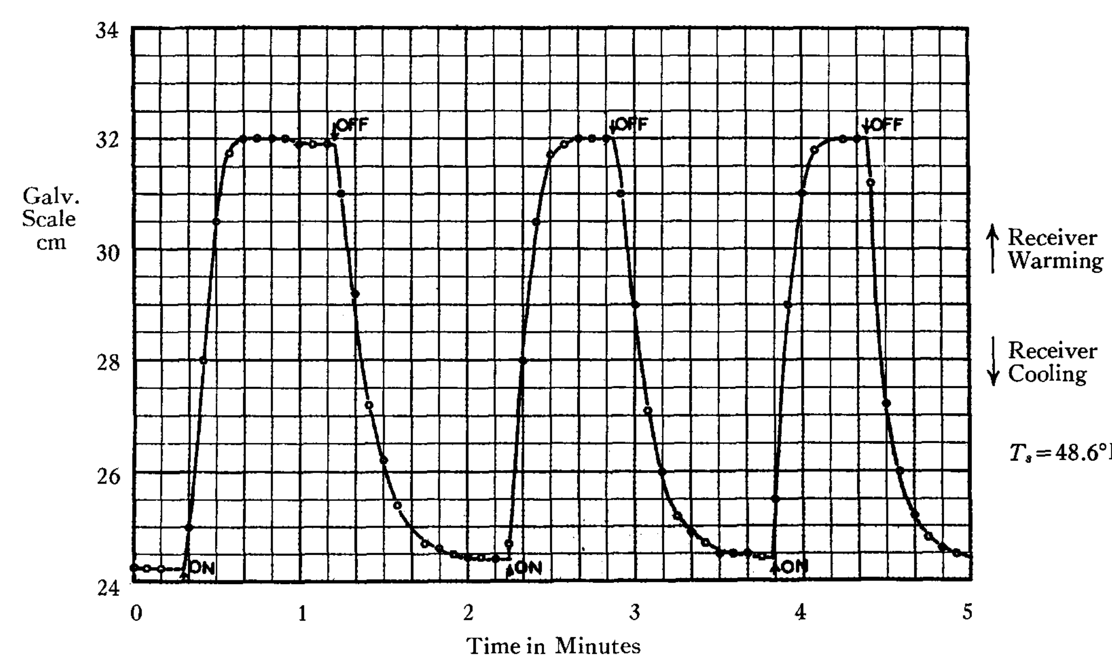


FIG. 6. Galvanometer response to radiation.

The Modern Transition Edge Sensor

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

An application of electrothermal feedback for high resolution cryogenic particle detection

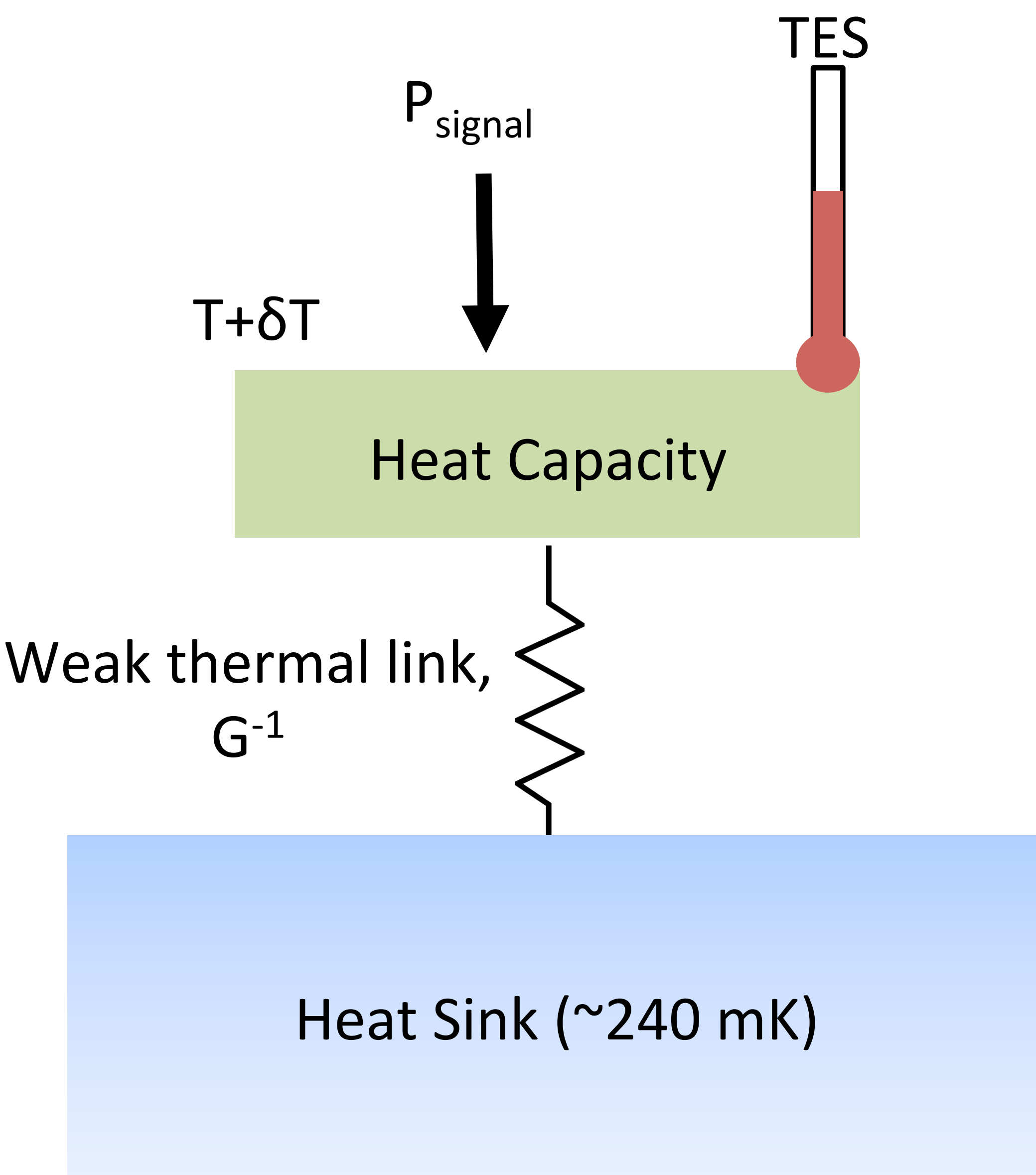
K. D. Irwin[a)]
Department of Physics, Stanford University, Stanford, California 94305-4060

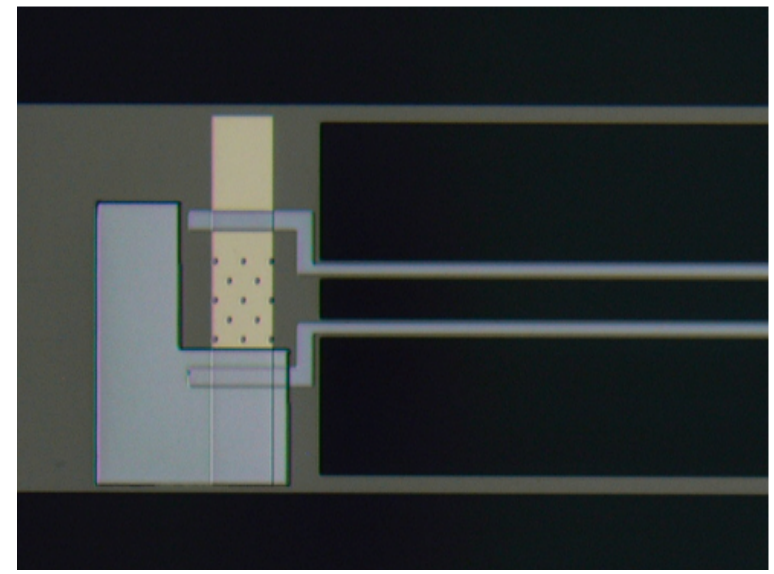
(Received 30 September 1994; accepted for publication 26 January 1995)

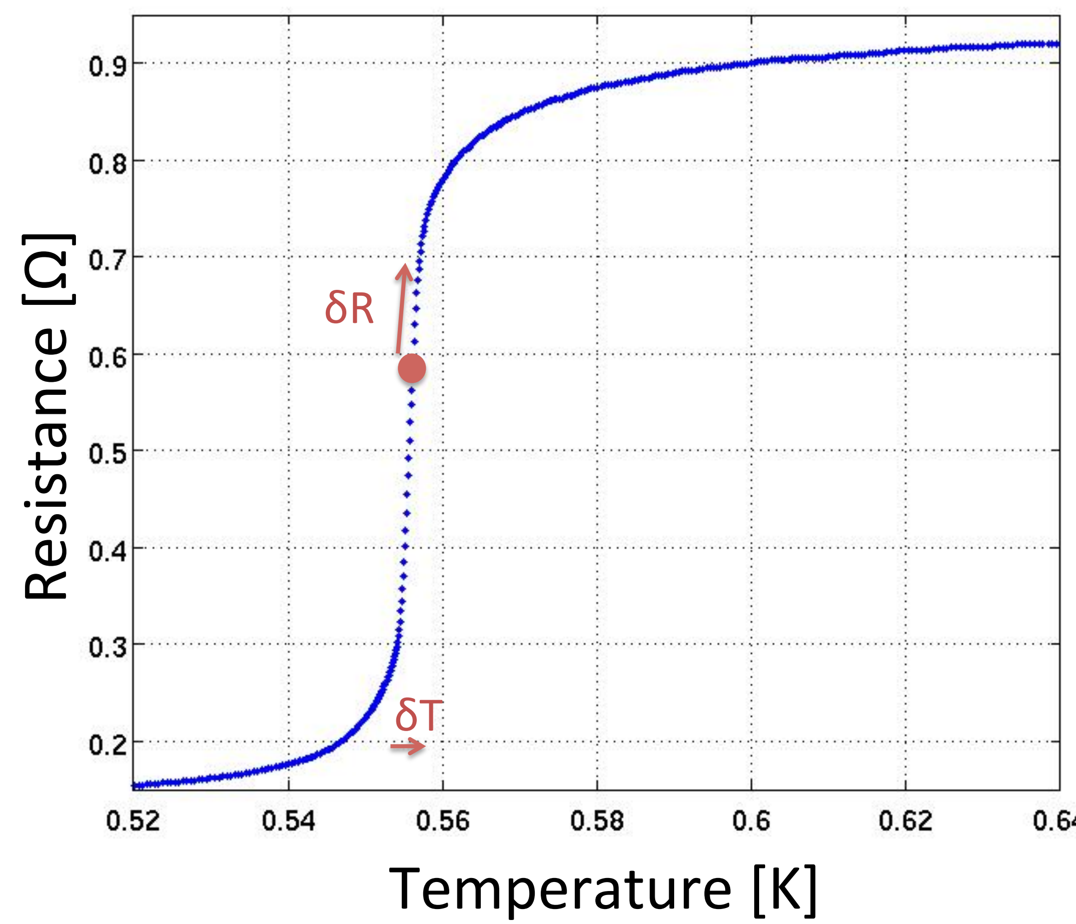
A novel type of superconducting transition edge sensor is proposed. In this sensor, the temperature of a superconducting film is held constant by feeding back to its position on the resistive transition edge. Energy deposited in the film is measured by a reduction in the feedback Joule heating. This mode of operation should lead to substantial improvements in resolution, linearity, dynamic range, and count rate. Fundamental resolution limits are below $\Delta E = \sqrt{kT^2C}$, which is sometimes incorrectly referred to as the thermodynamic limit. This performance is better than any existing technology operating at the same temperature, count rate, and absorber heat capacity. Applications include high resolution x-ray spectrometry, dark matter searches, and neutrino detection. © *1995 American Institute of Physics*.

- Voltage biased for stable operation

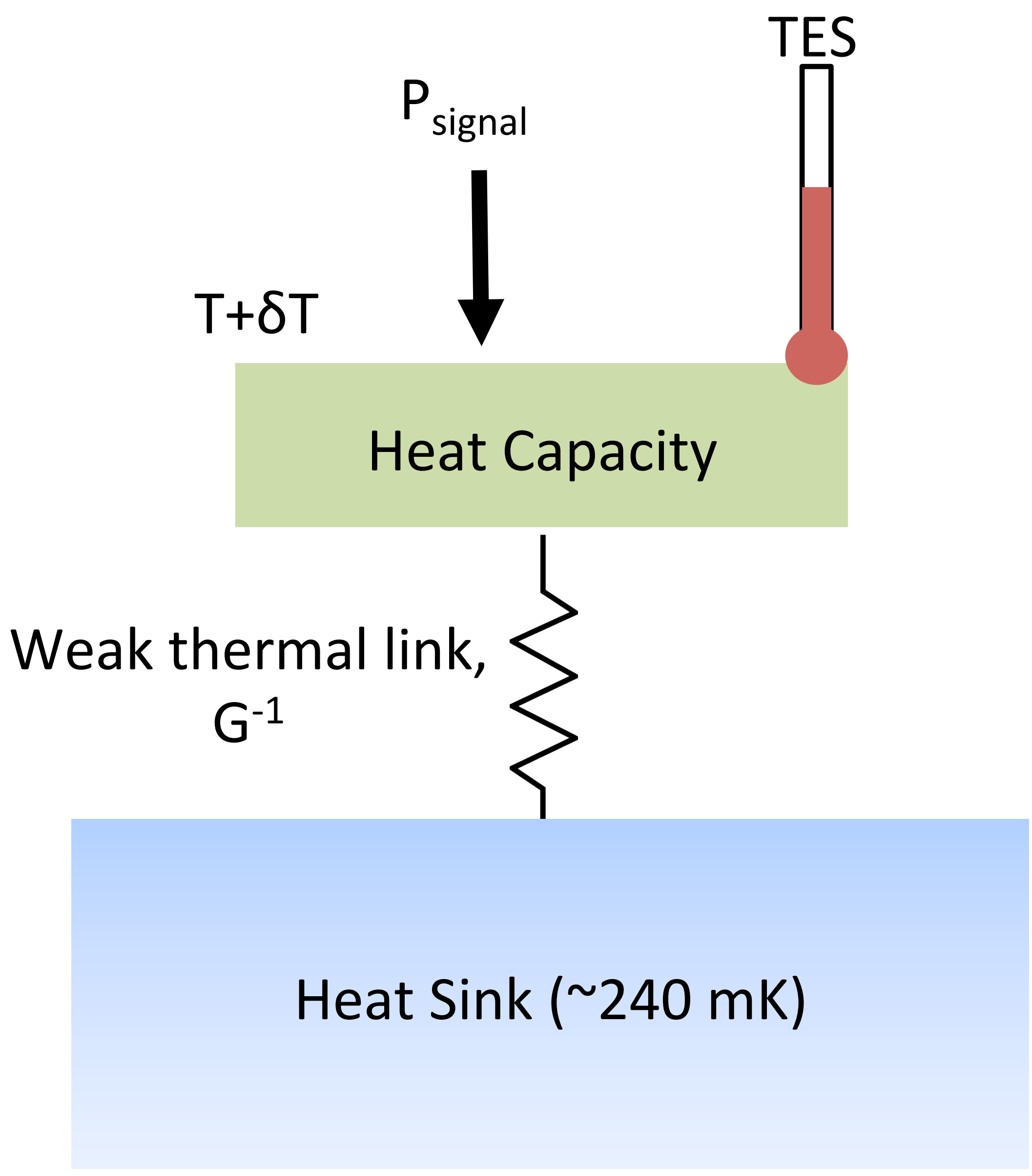
The Modern Transition Edge Sensor



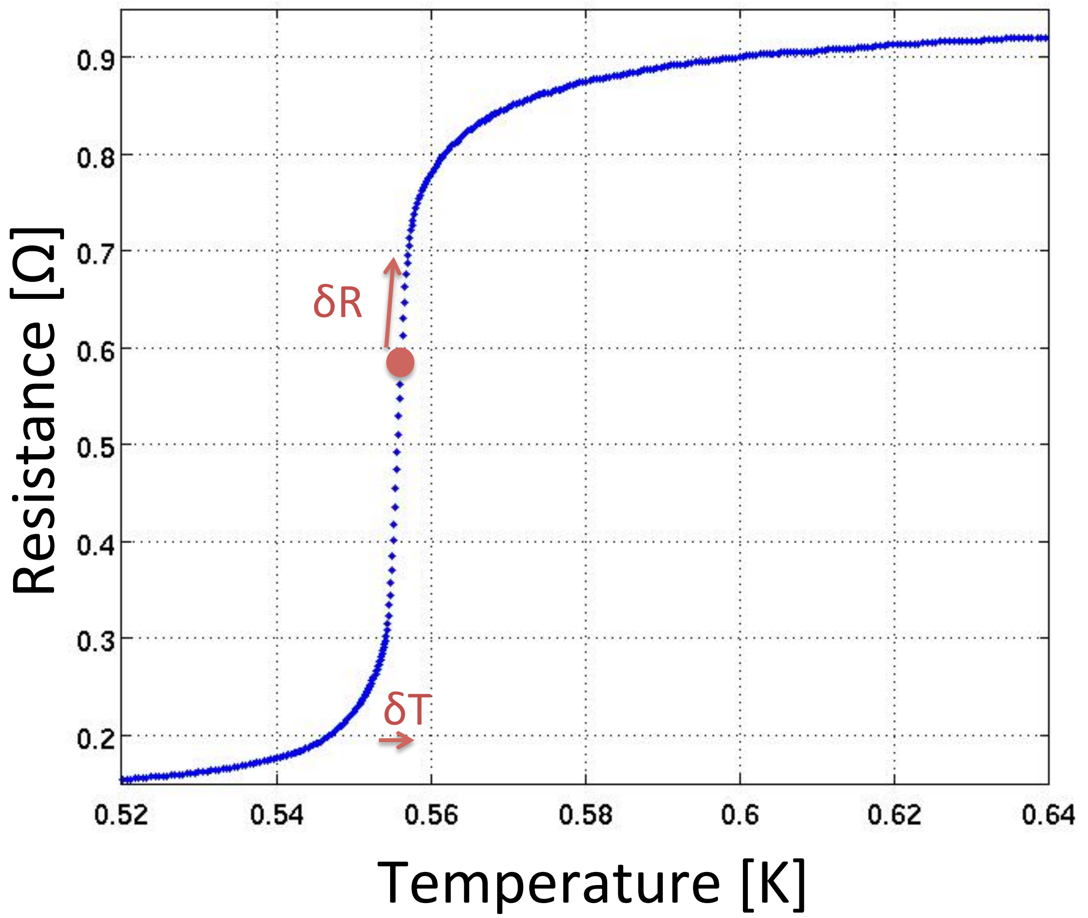




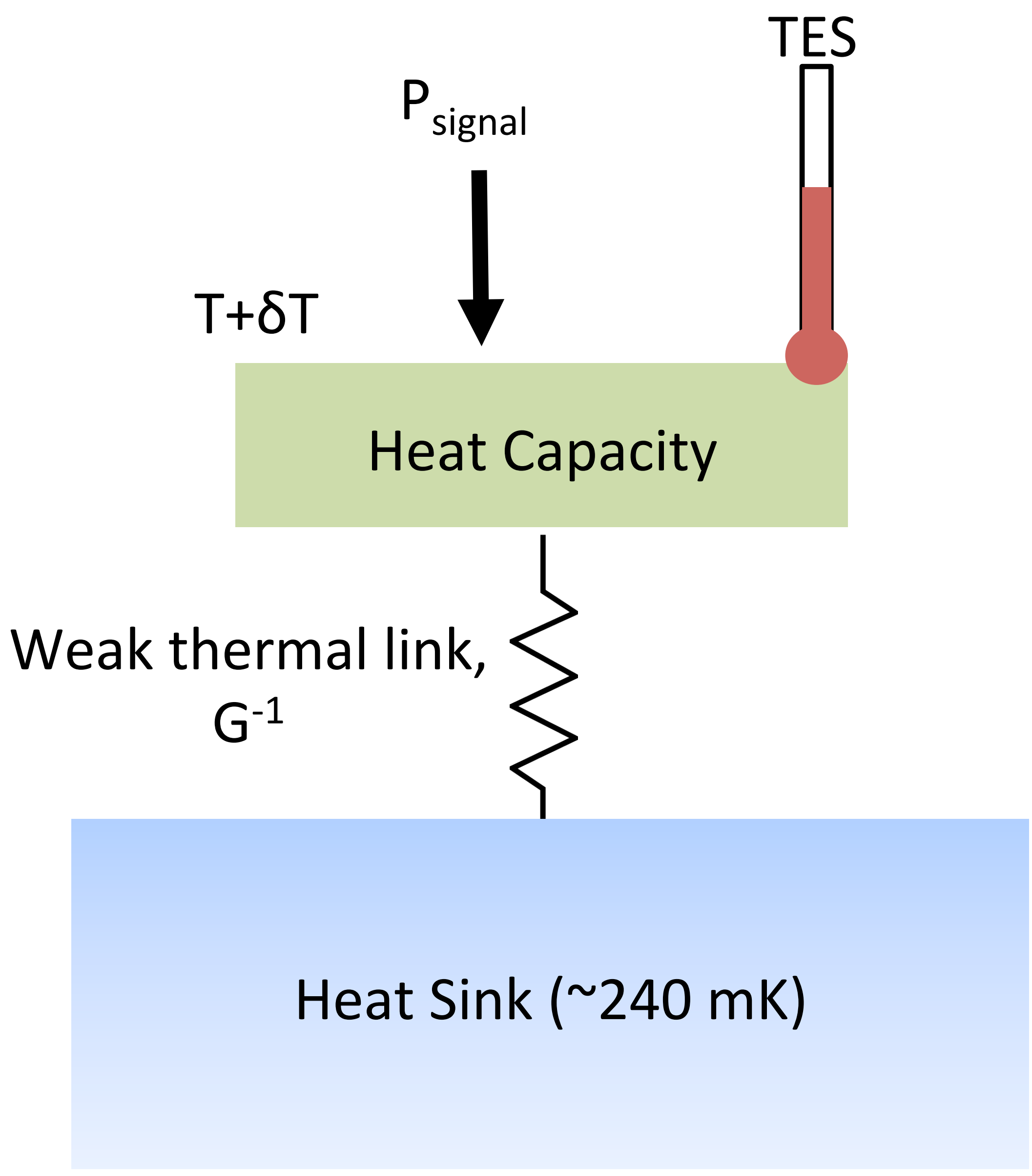
The Modern Transition Edge Sensor



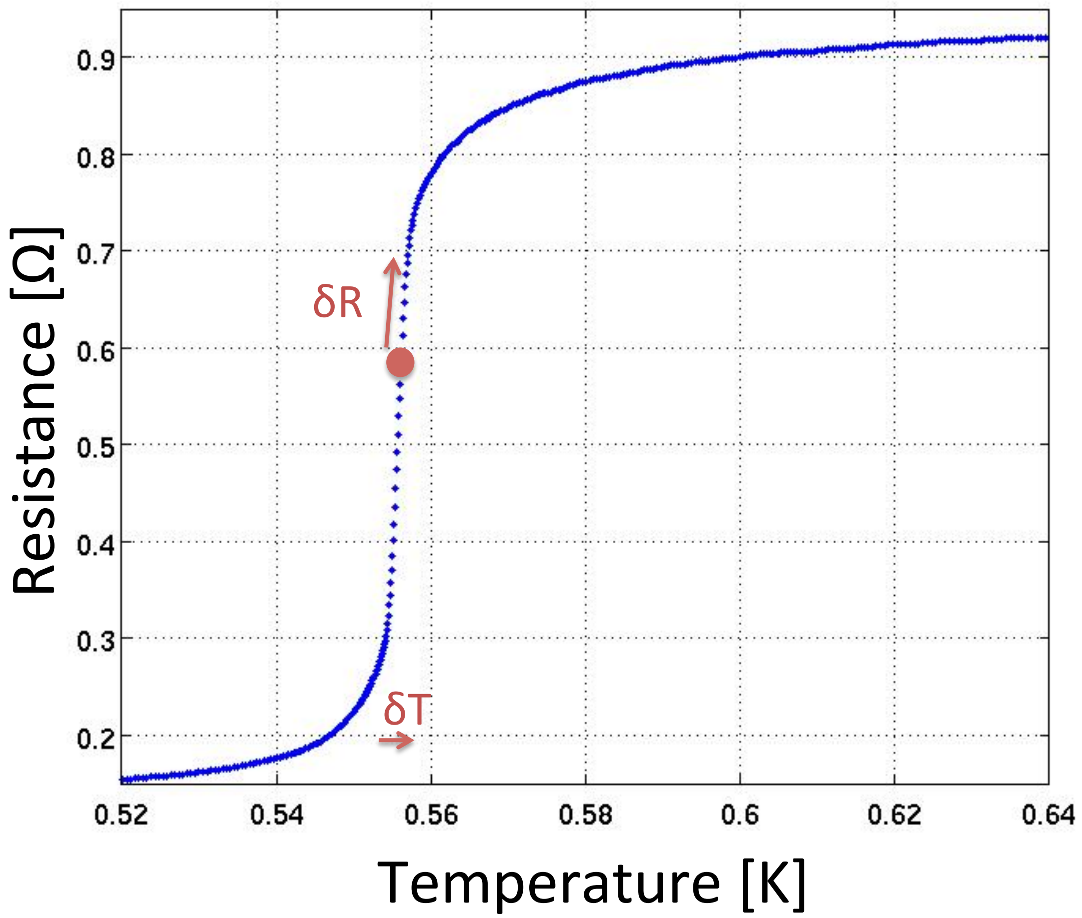
$$P_{Joule} = \frac{V_0^2}{R(T)}$$



The Modern Transition Edge Sensor



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



The Modern Transition Edge Sensor

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

An application of electrothermal feedback for high resolution cryogenic particle detection

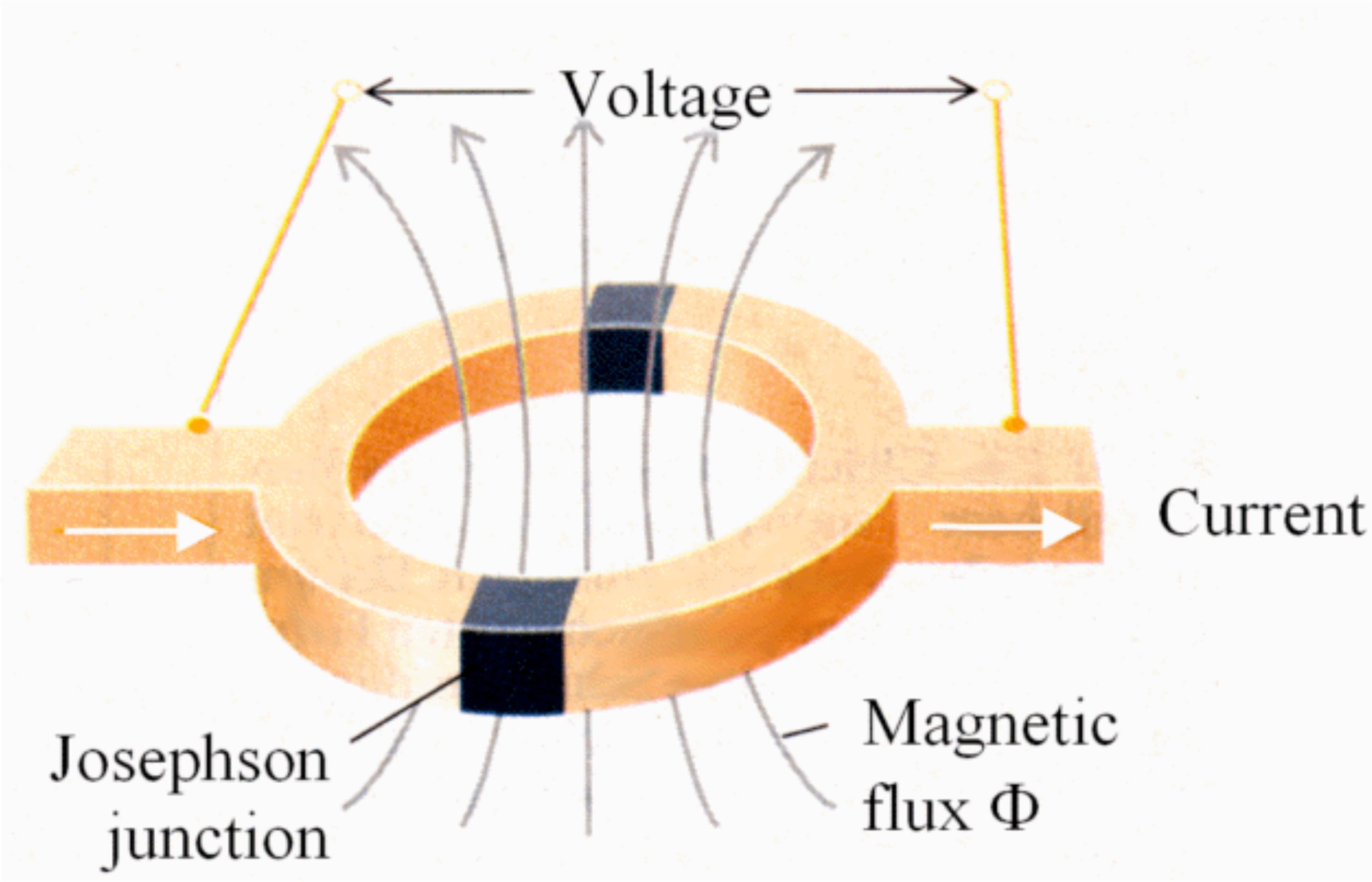
K. D. Irwin[a)]
Department of Physics, Stanford University, Stanford, California 94305-4060

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

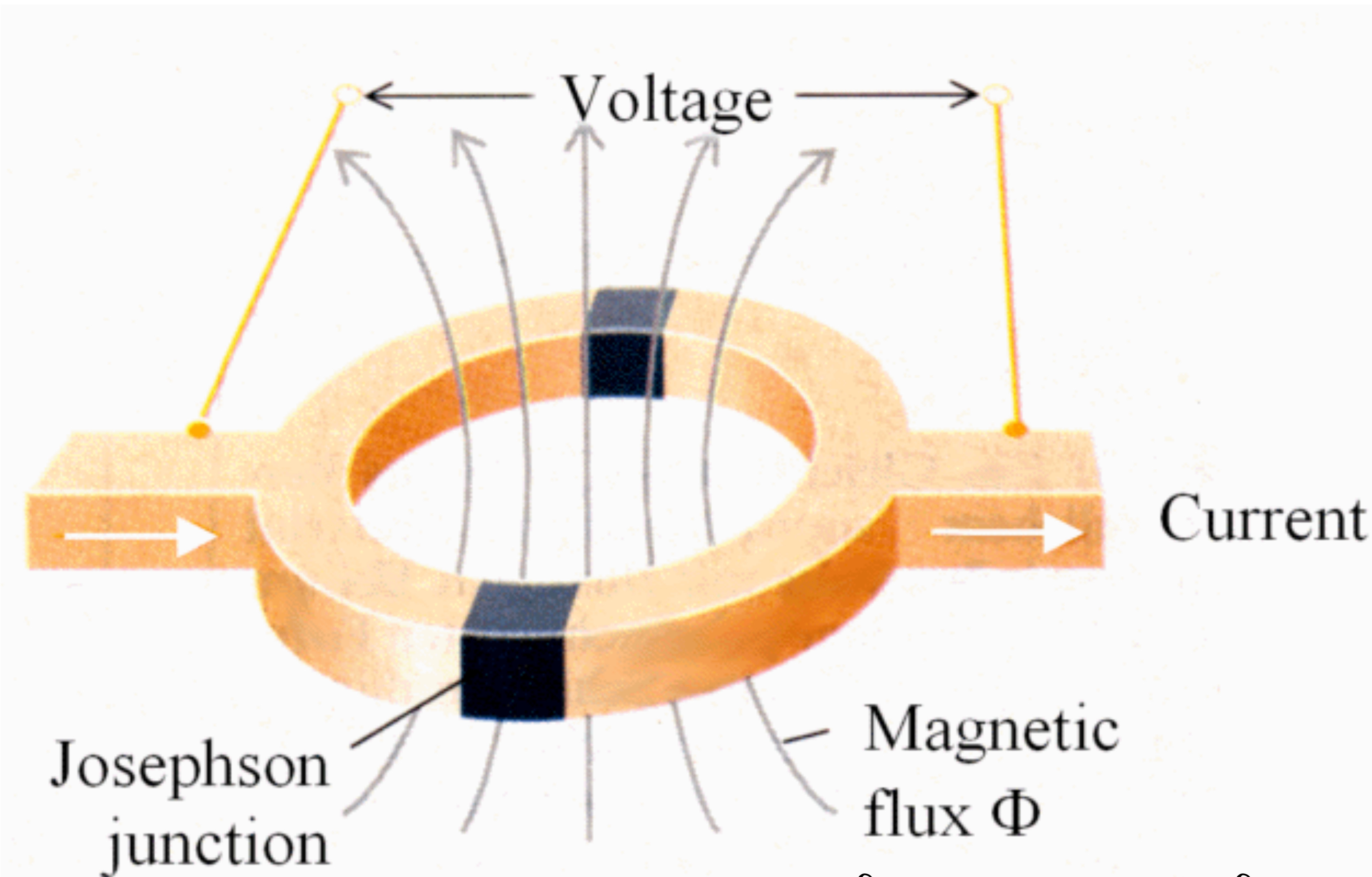
A novel type of superconducting transition edge sensor is proposed. In this sensor, the temperature of a superconducting film is held constant by feeding back to its position on the resistive transition edge. Energy deposited in the film is measured by a reduction in the feedback Joule heating. This mode of operation should lead to substantial improvements in resolution, linearity, dynamic range, and count rate. Fundamental resolution limits are below $\Delta E = \sqrt{kT^2C}$, which is sometimes incorrectly referred to as the thermodynamic limit. This performance is better than any existing technology operating at the same temperature, count rate, and absorber heat capacity. Applications include high resolution x-ray spectrometry, dark matter searches, and neutrino detection. © *1995 American Institute of Physics*.

- Connected to evolving superconducting technologies

Superconducting QUantum Interference Device



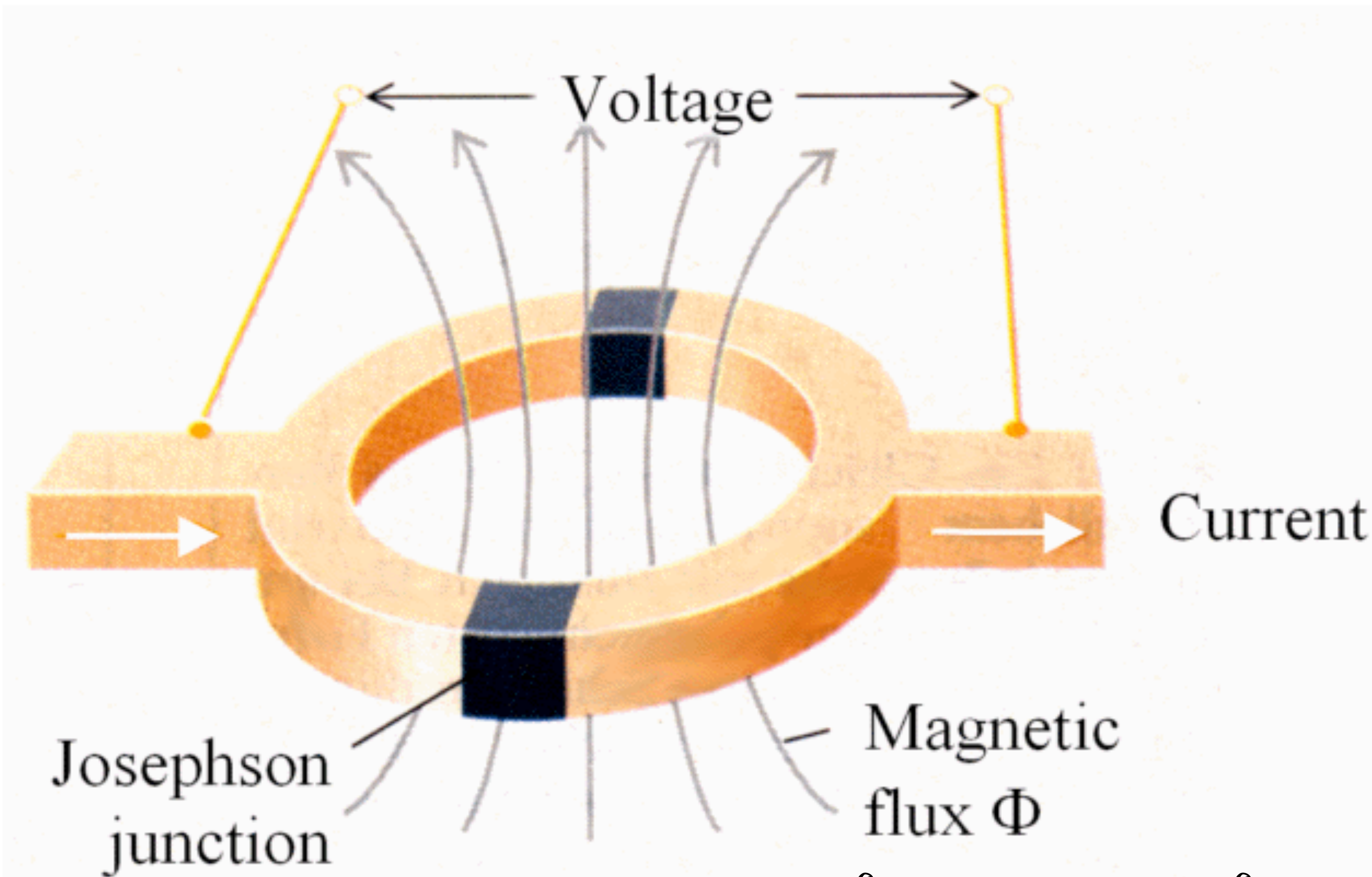
Superconducting QUantum Interference Device



$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

Flux quantization

Superconducting QUantum Interference Device

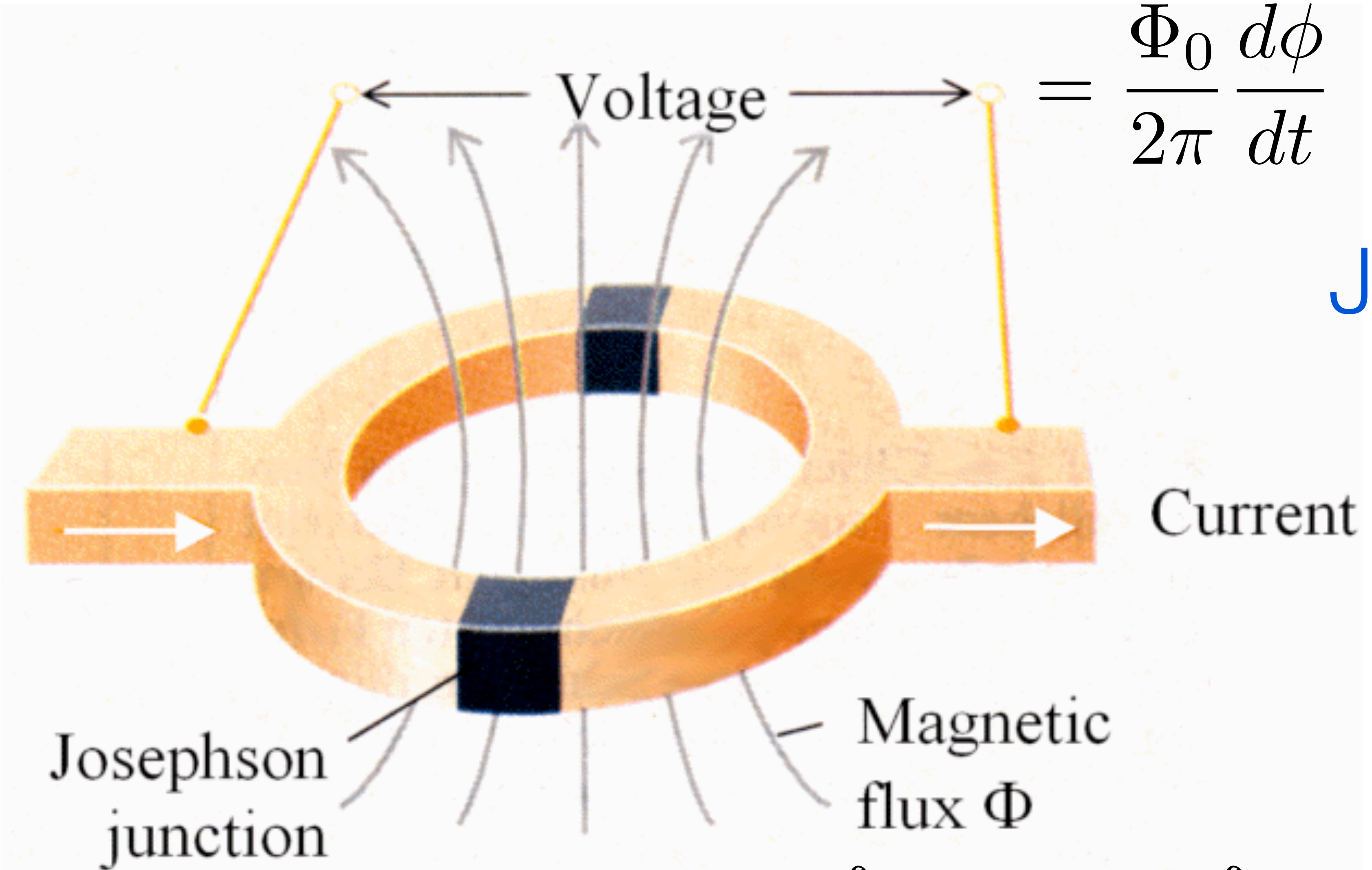


$$= I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

Flux quantization

Superconducting QUantum Interference Device



$$= \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

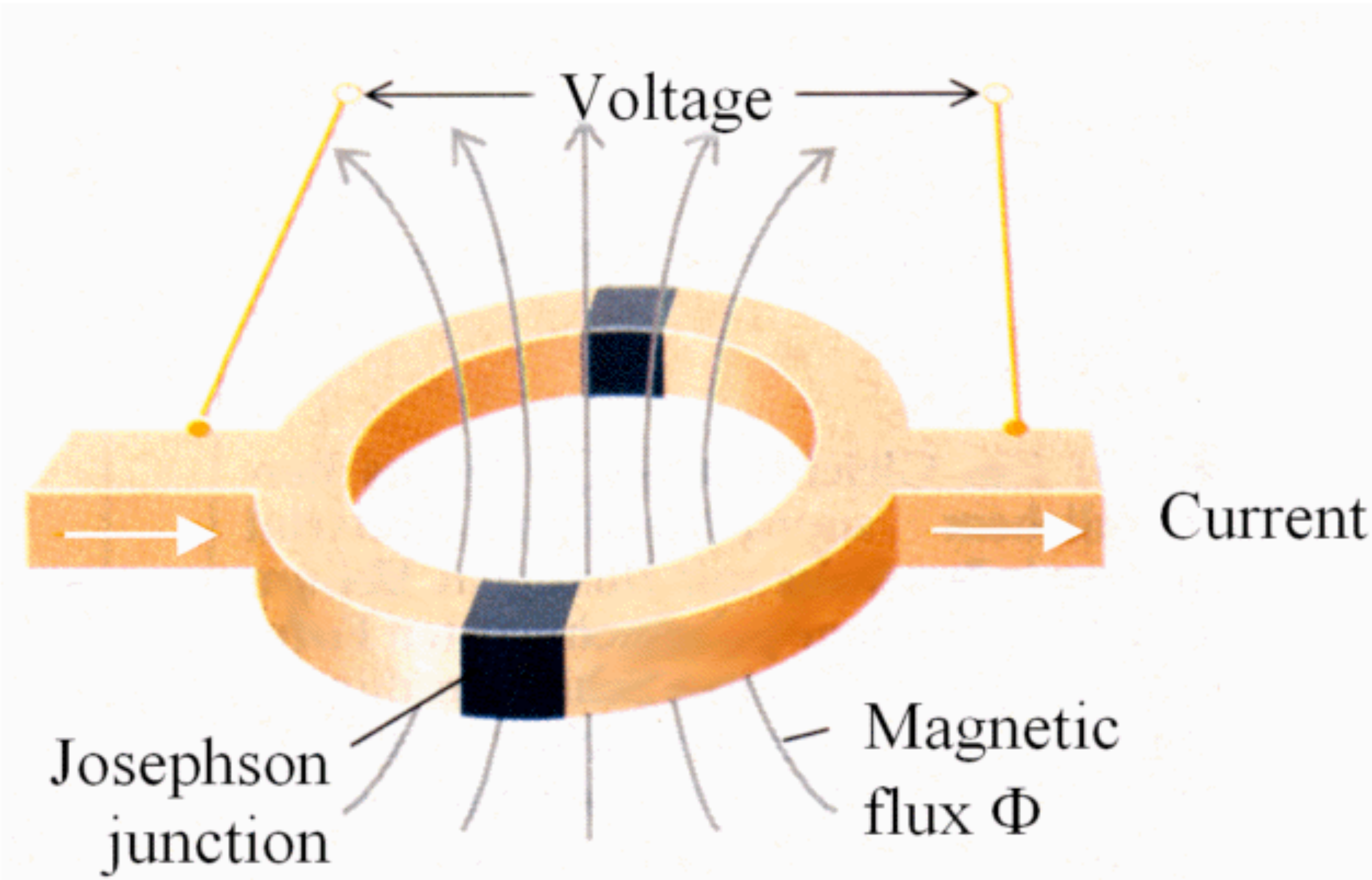
Josephson effect

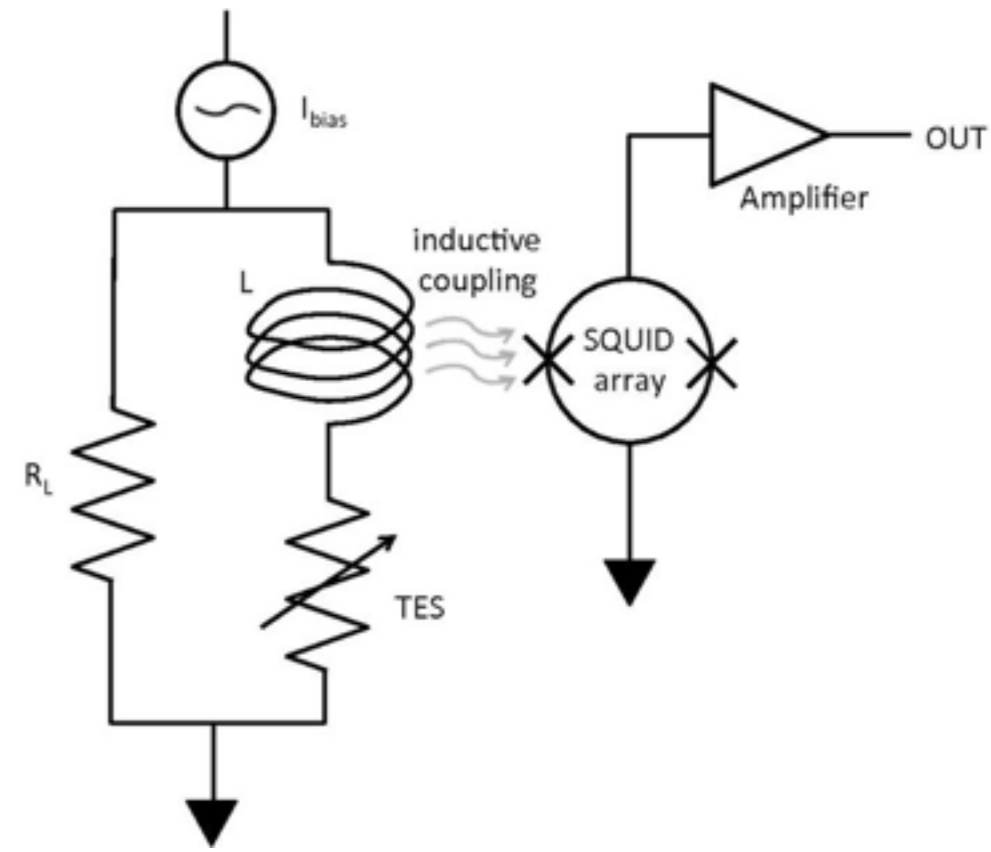
$$= I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

Flux quantization

Superconducting QUantum Interference Device





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

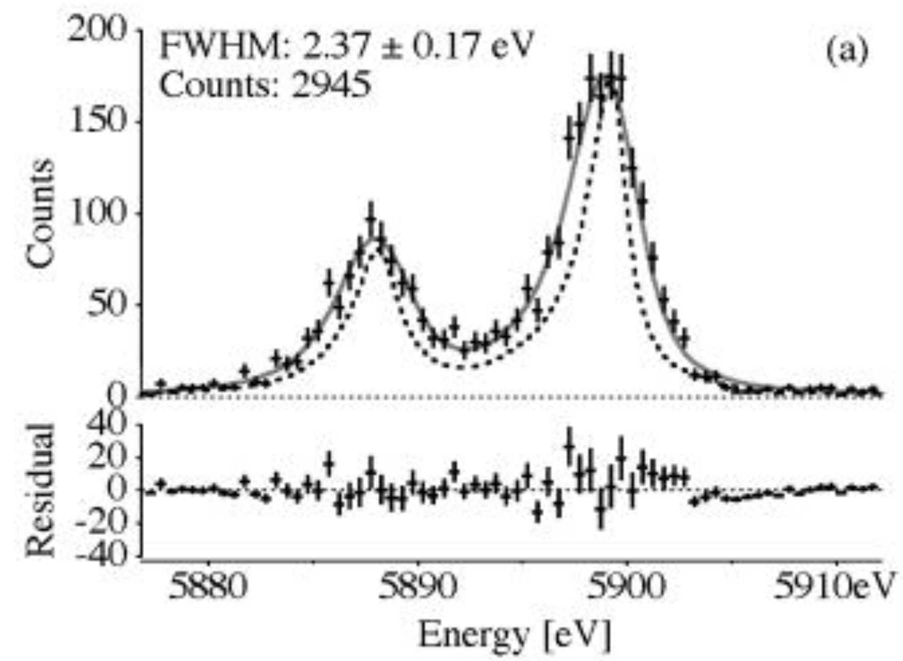
(Received 30 September 1994; accepted for publication 26 January 1995)

A novel type of superconducting transition edge sensor is proposed. In this sensor, the temperature of a superconducting film is held constant by feeding back to its position on the resistive transition edge. Energy deposited in the film is measured by a reduction in the feedback Joule heating. This mode of operation should lead to substantial improvements in resolution, linearity, dynamic range, and count rate. Fundamental resolution limits are below $\Delta E = \sqrt{kT^2C}$, which is sometimes incorrectly referred to as the thermodynamic limit. This performance is better than any existing technology operating at the same temperature, count rate, and absorber heat capacity. Applications include high resolution x-ray spectrometry, dark matter searches, and neutrino detection.

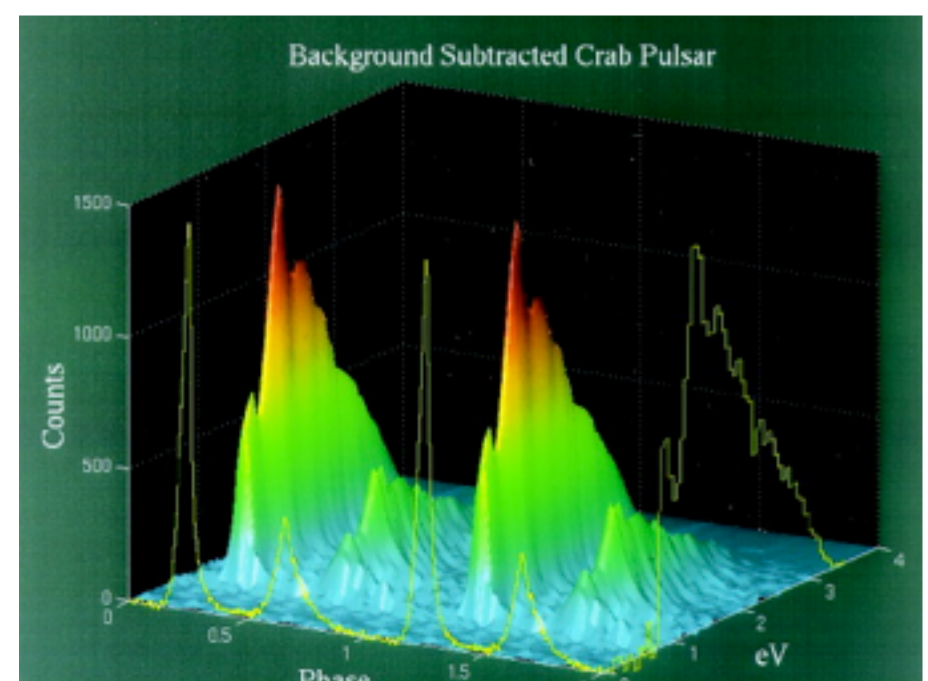
- Developed with science (Dark Matter and neutrinos) applications in mind

Broadly applicable

- energy per mode
  - $k_B T \sim 10$ ueV for TES
  - $E_{gap} \sim 1$ eV for diodes
- For CMB, detector noise from “G”and photon shot noise- same for TES and semiconductors
  - TES has broader bandwidth
  - Multiplexable

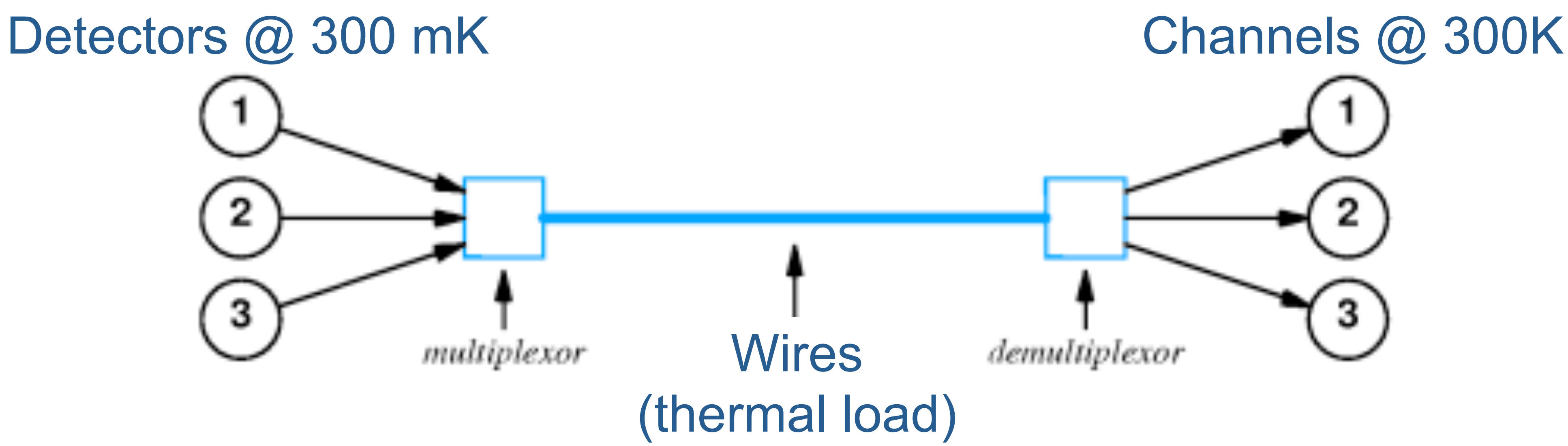


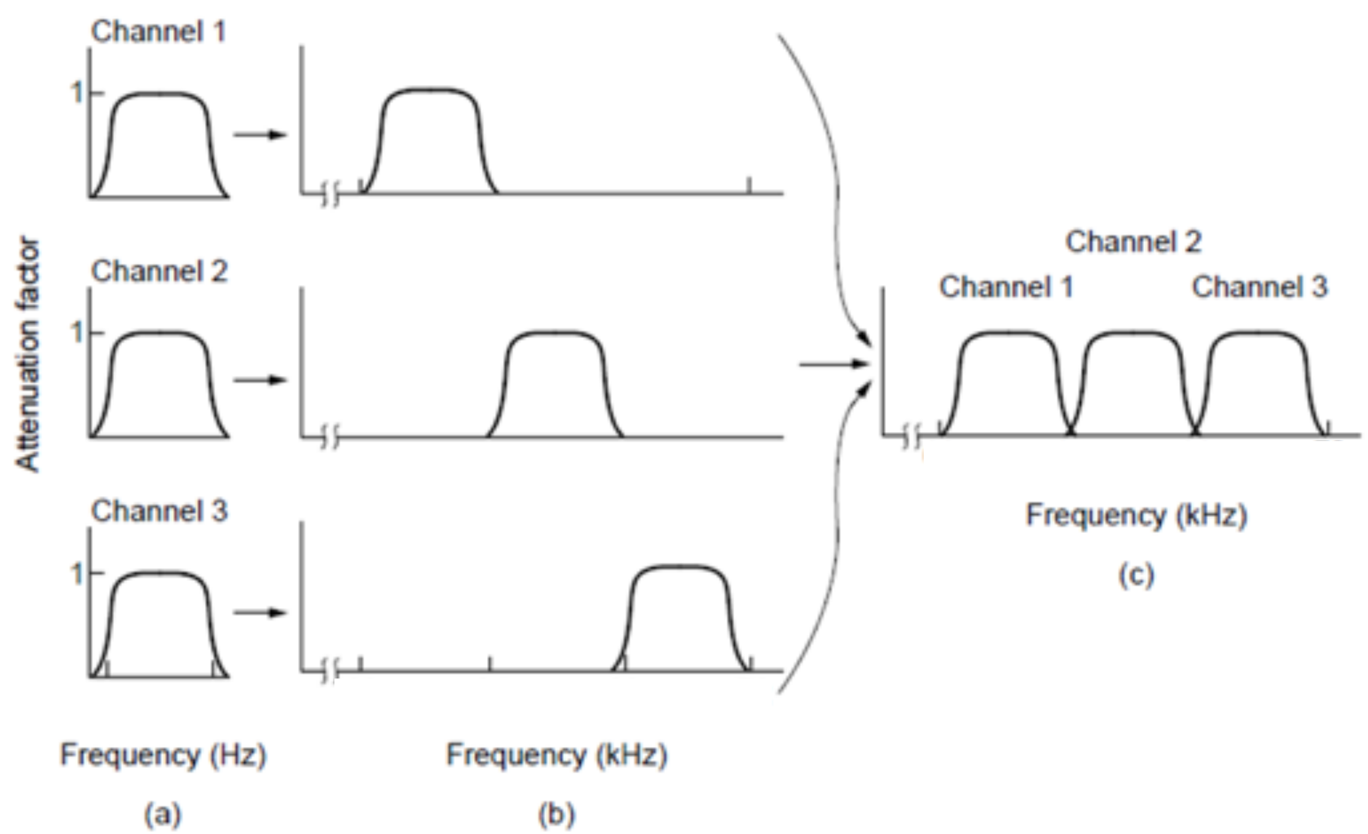
Iyomoto et al., Appl. Phys. Lett. 92, 013508 (2008)



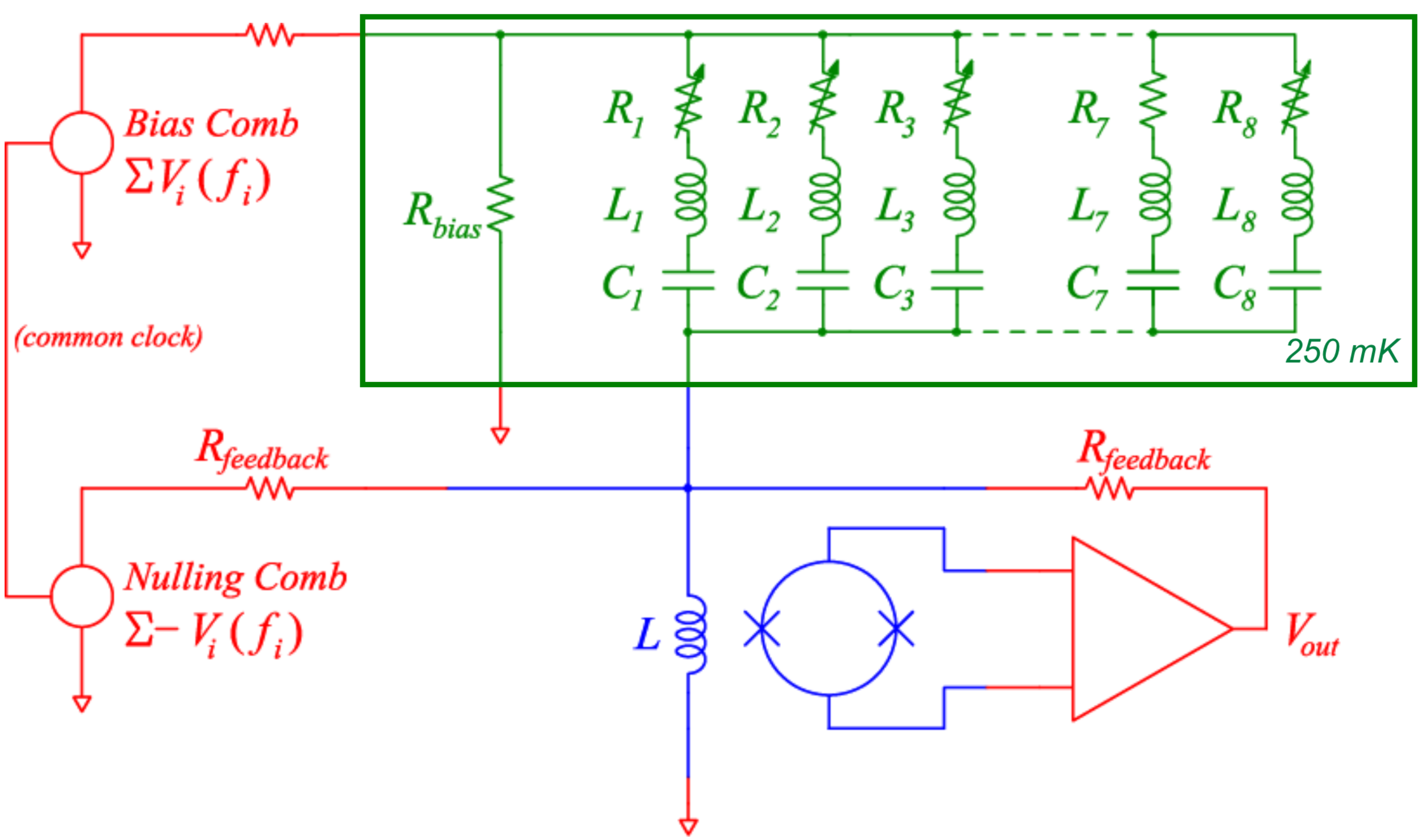
Romani et al., The Astrophysical Journal, 521:L153-L156, 1999

Multiplexing

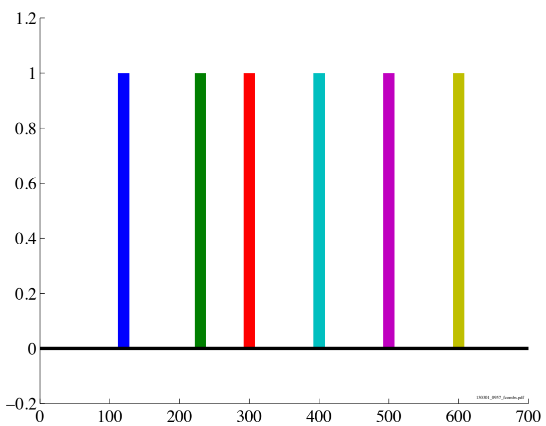


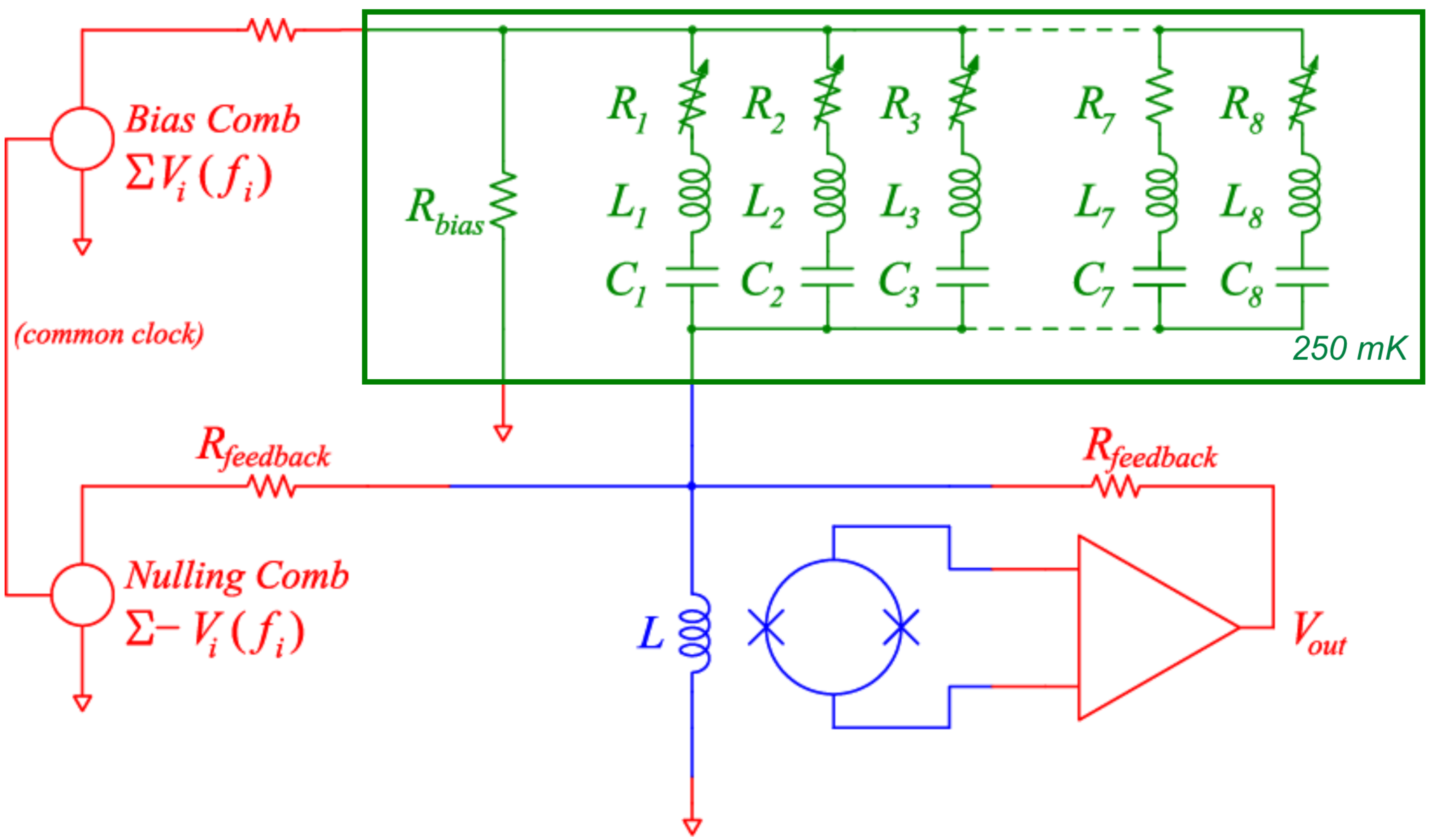


SQUID multiplexing

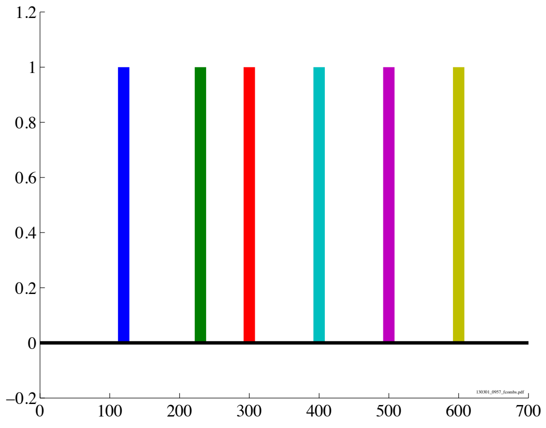


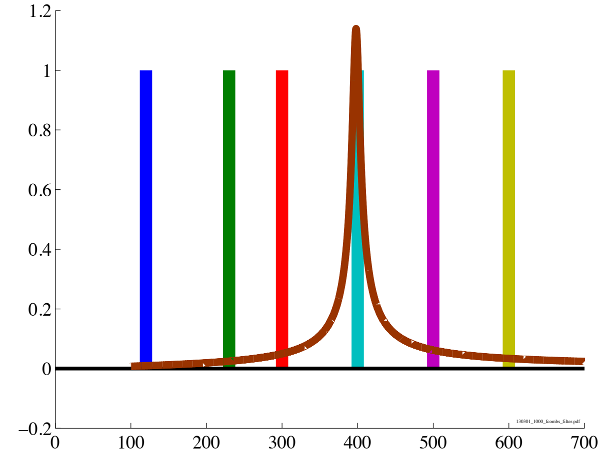
SQUID multiplexing

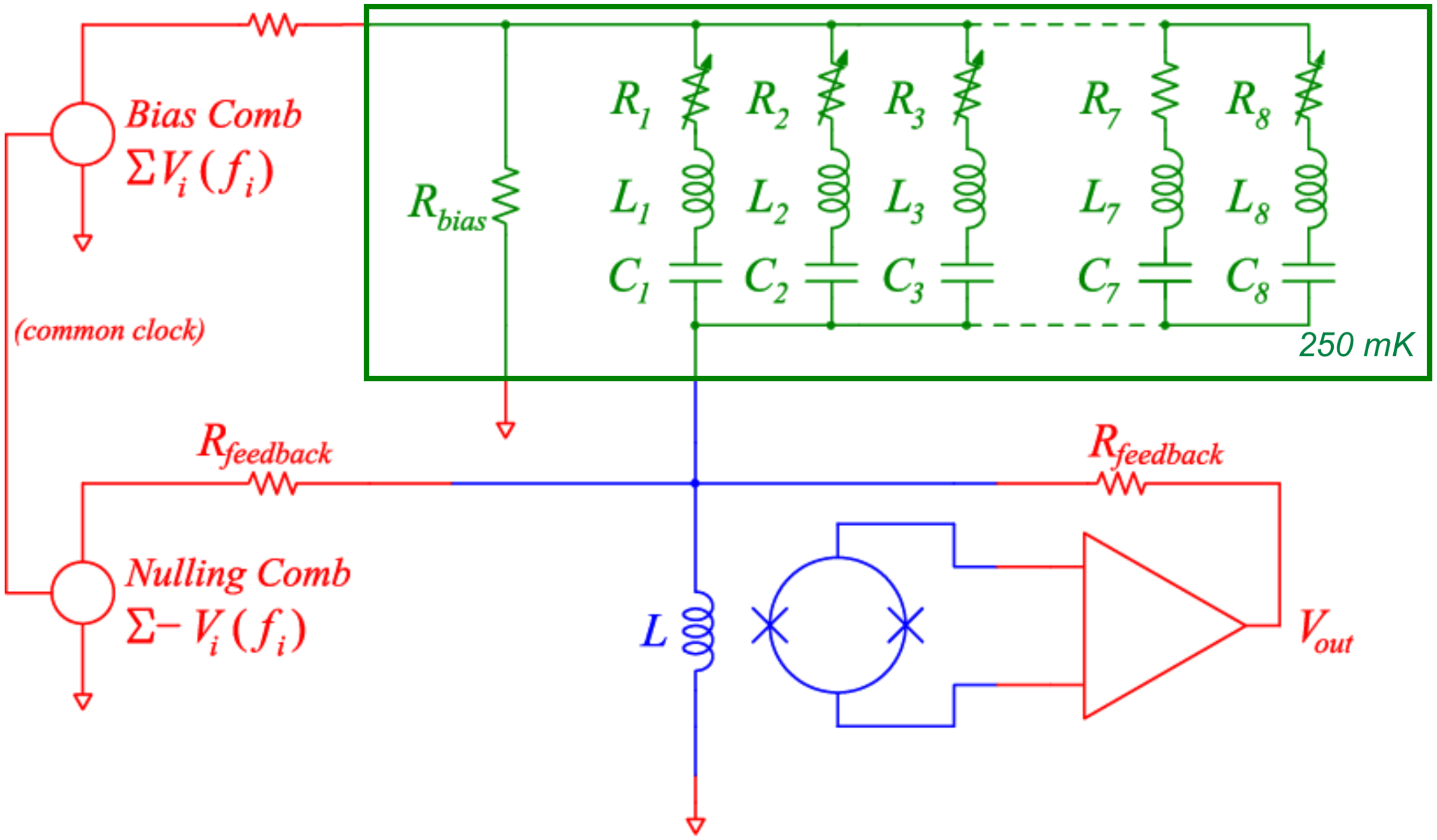




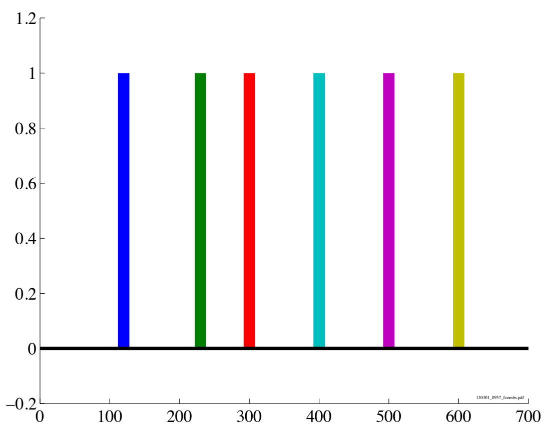
SQUID multiplexing

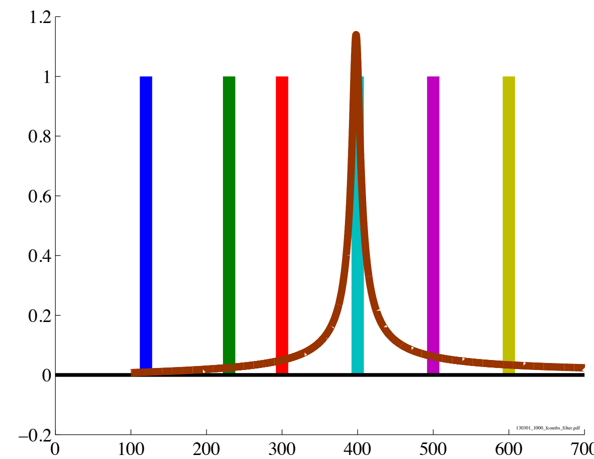


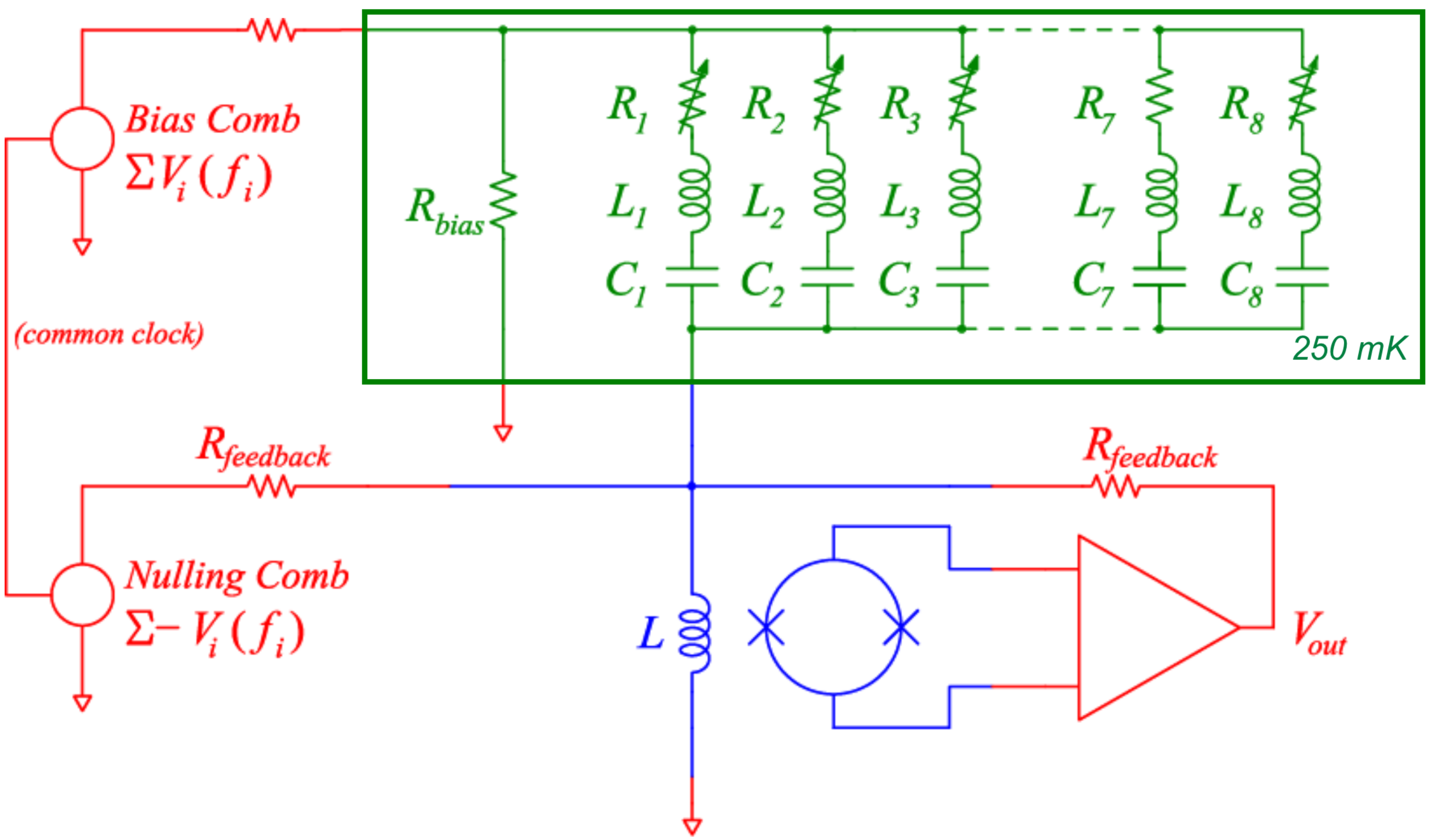




SQUID multiplexing

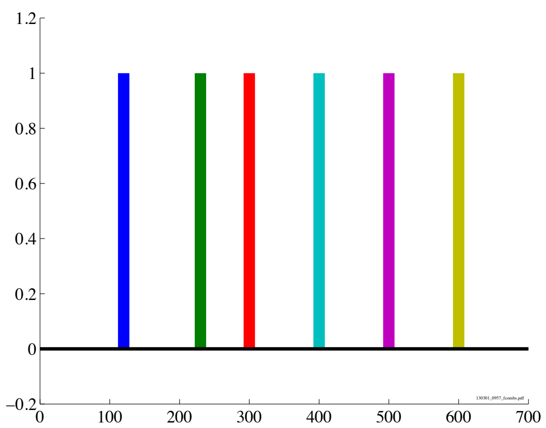




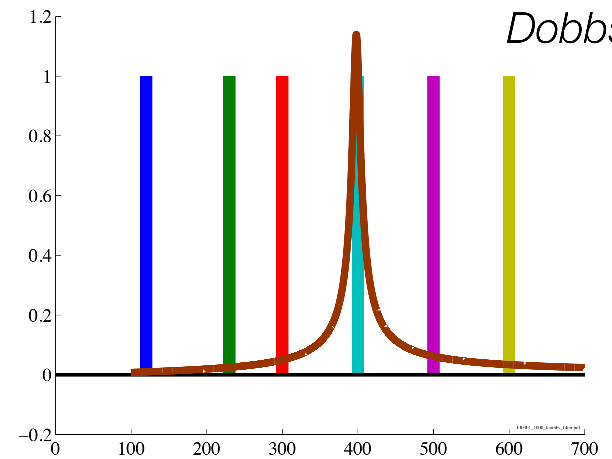


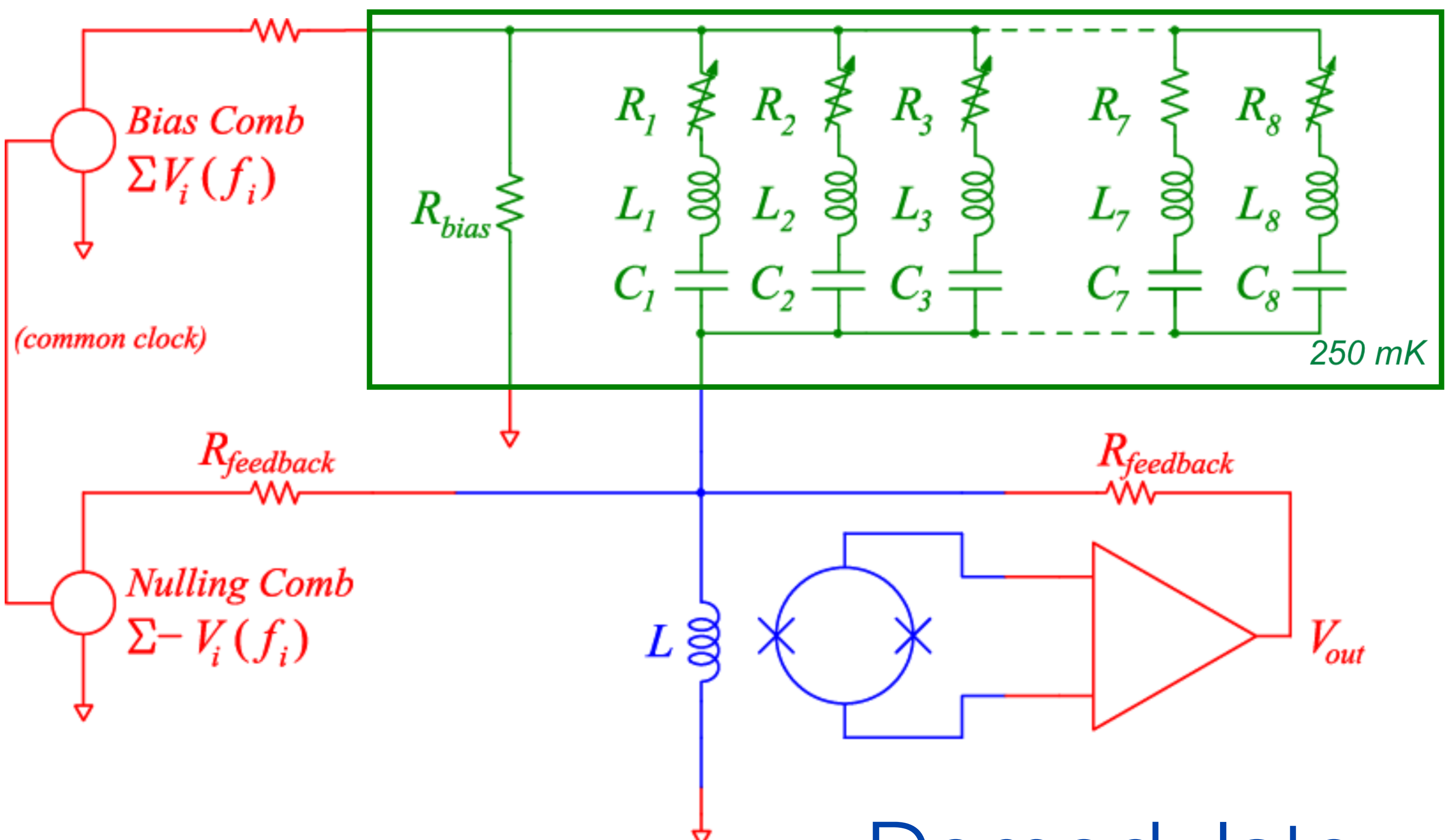
$$I_i = \frac{1}{R_i(t)} V \cos\left(f_i t\right)$$

SQUID multiplexing



Dobbs et al., Rev. Sci. Instrum. 83, 073113 (2012)

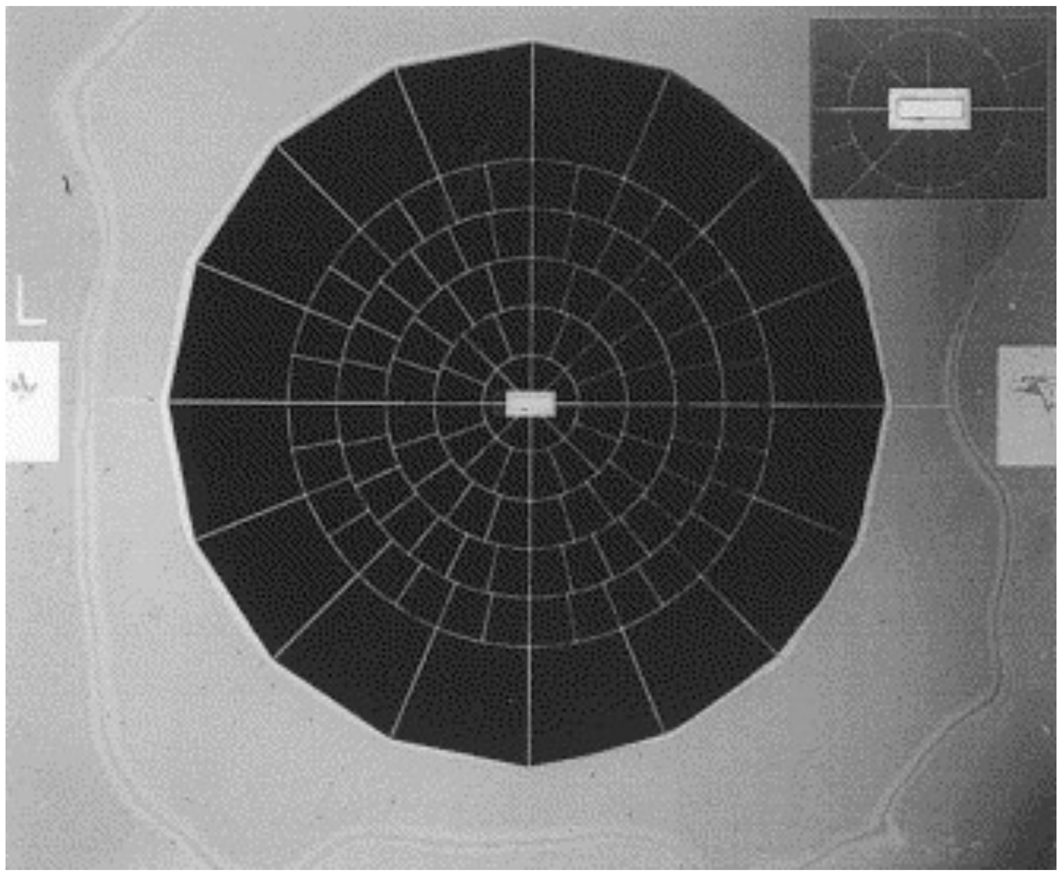




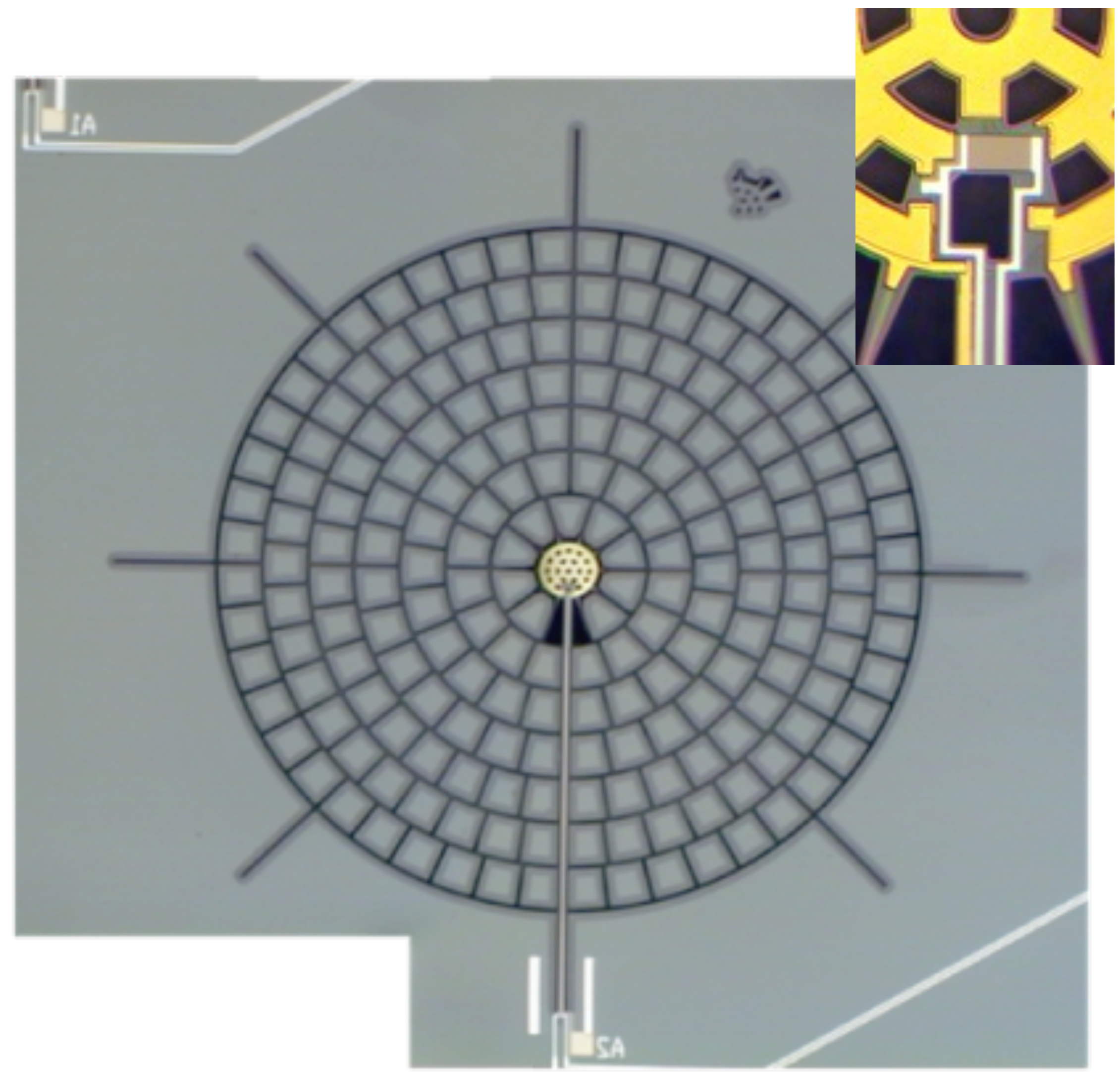
$$I_i = \frac{1}{R_i(t)} V \cos(f_i t)$$

Demodulate… just like AM radio

TES-based CMB bolometers

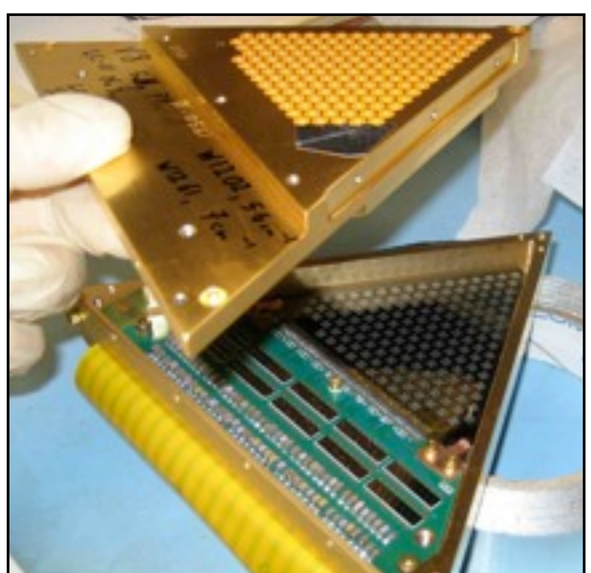


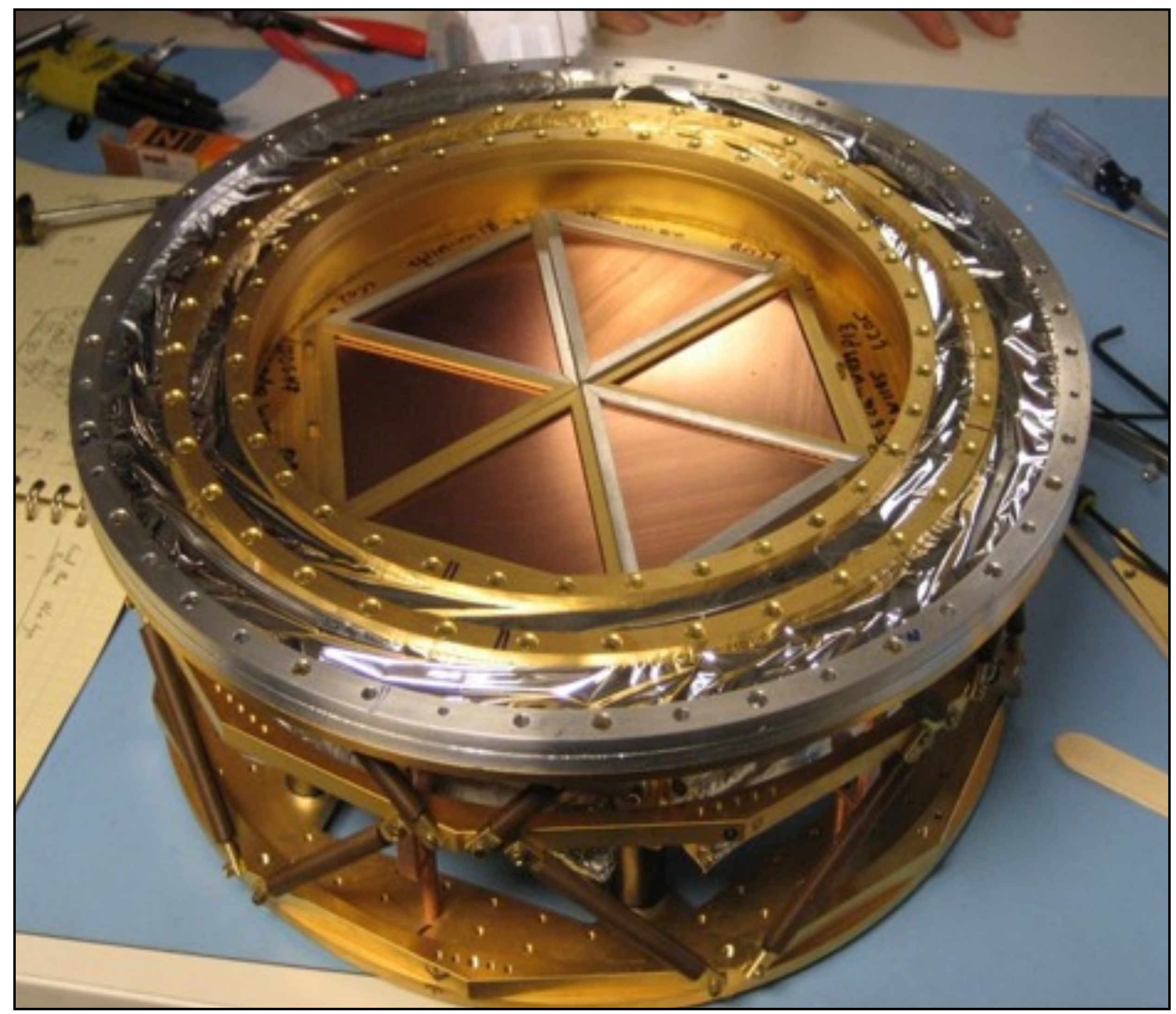
JPL



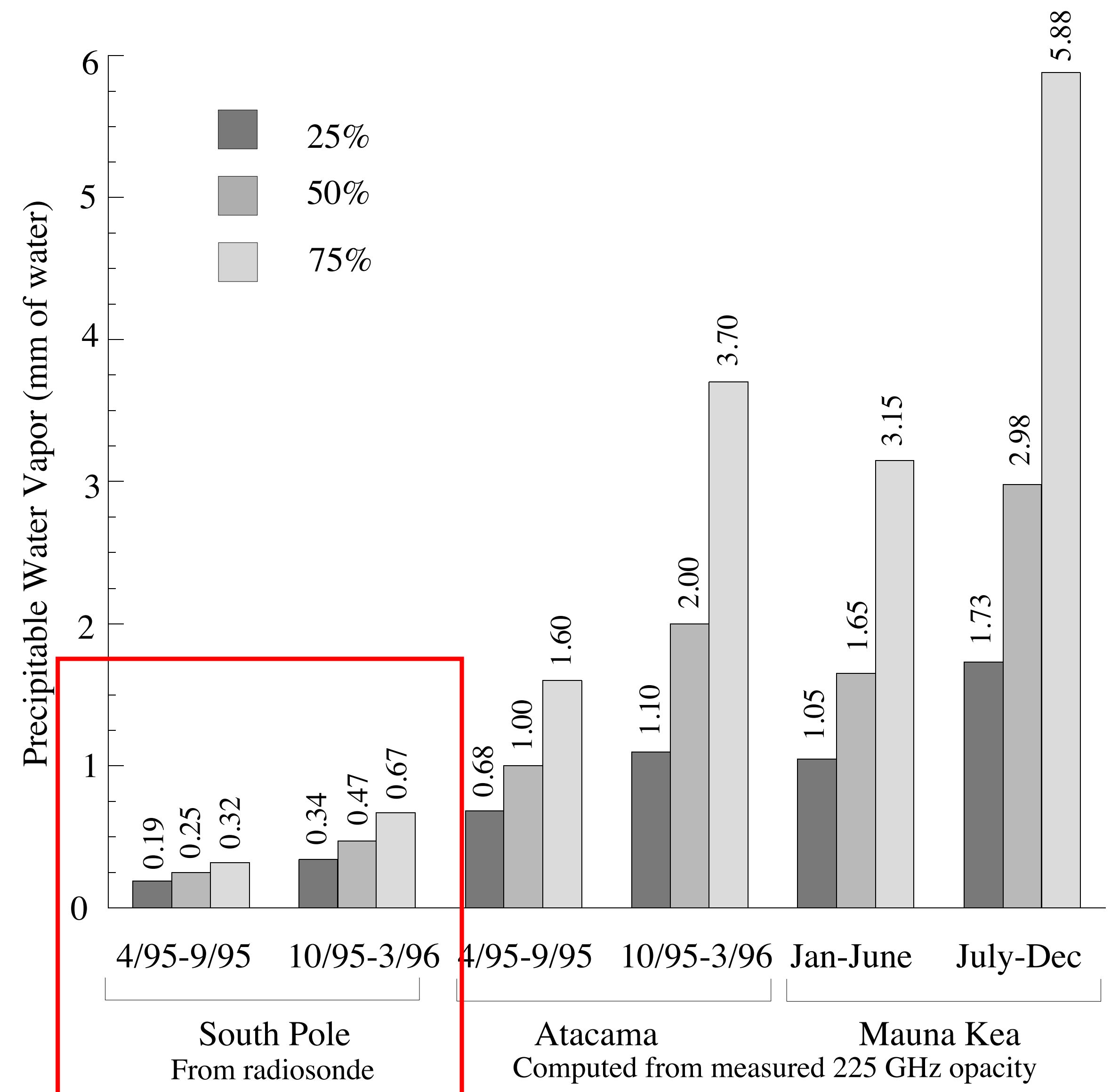
UCB

CMB bolometer arrays



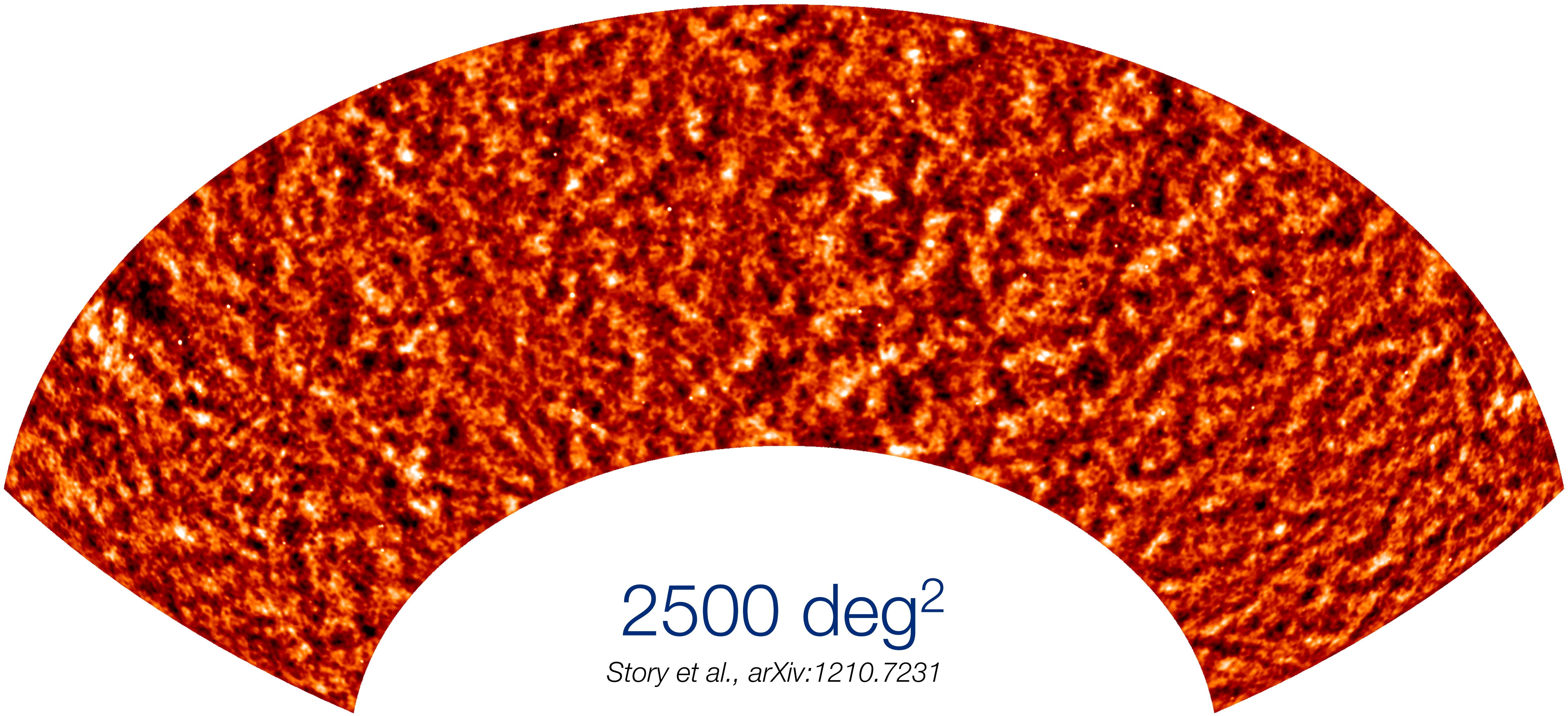


The South Pole Telescope

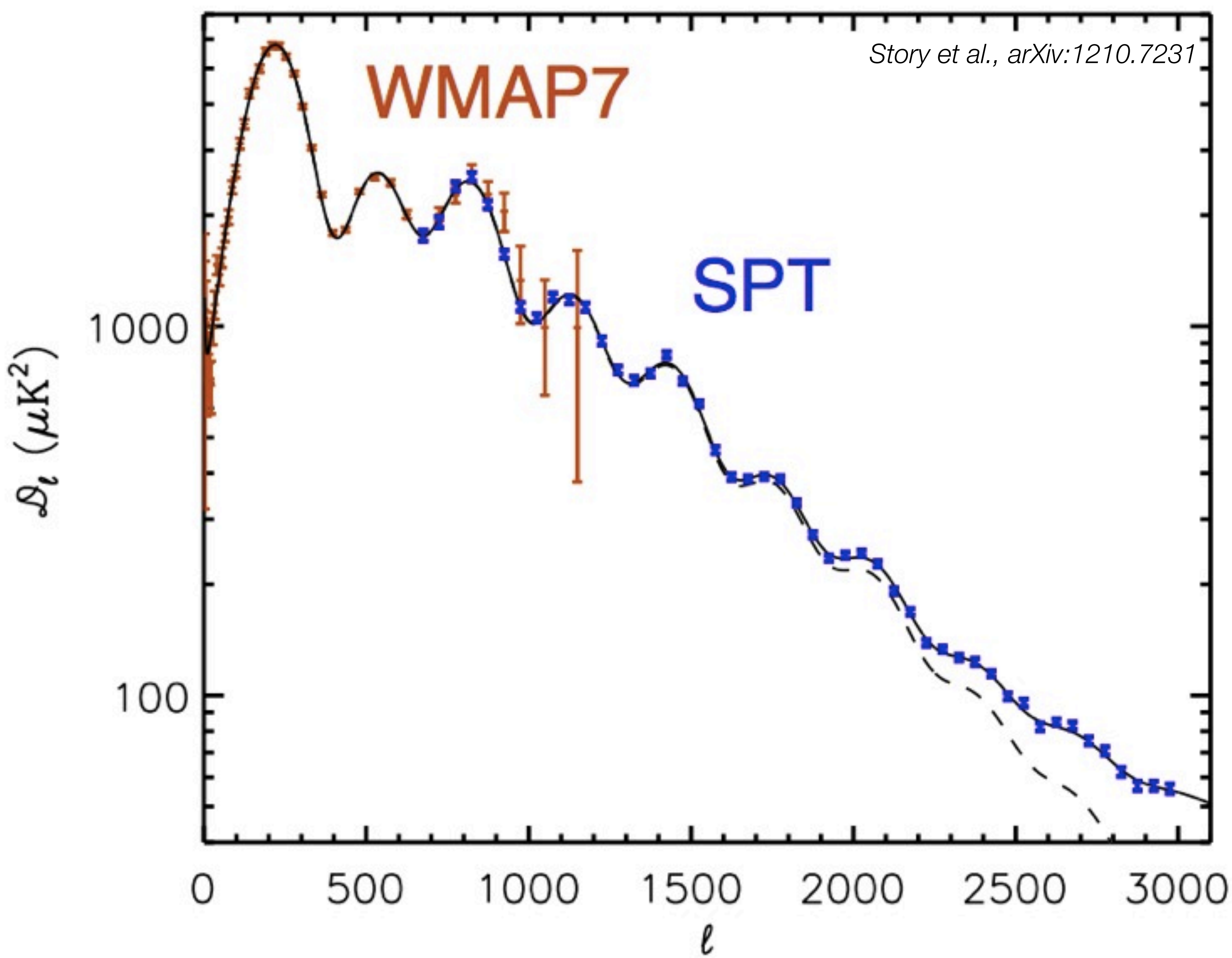


(A.P. Lane 1998)

They Work (very well)!

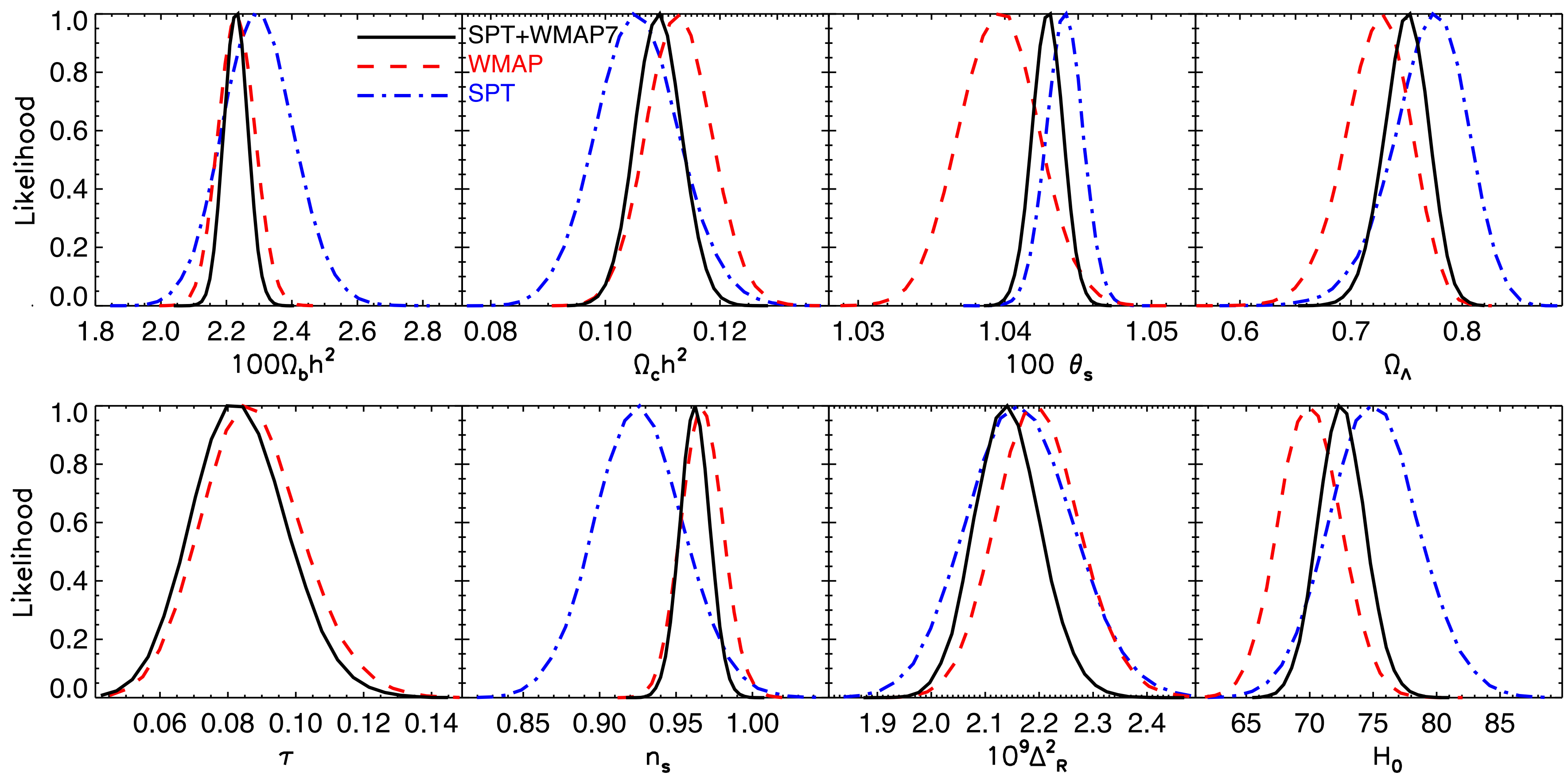


They Work (very well)!



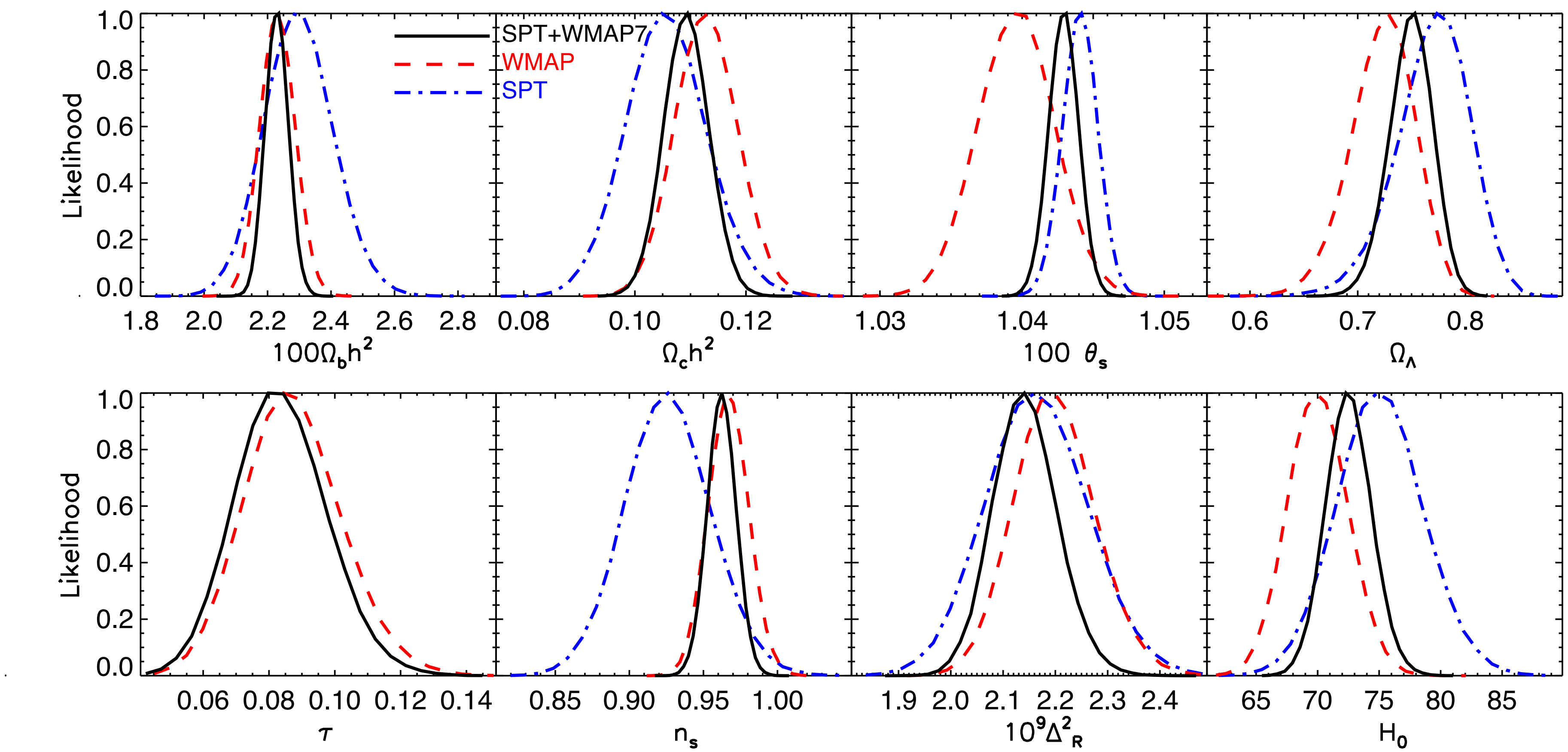
Signs of the CvB?

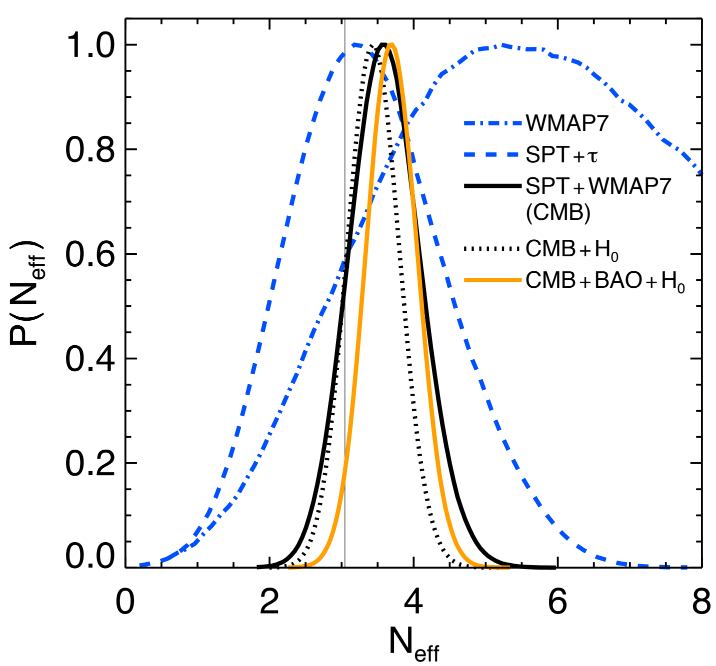
Story et al., arXiv:1210.7231



Signs of the CvB?

Story et al., arXiv:1210.7231





Including N_{eff} gives

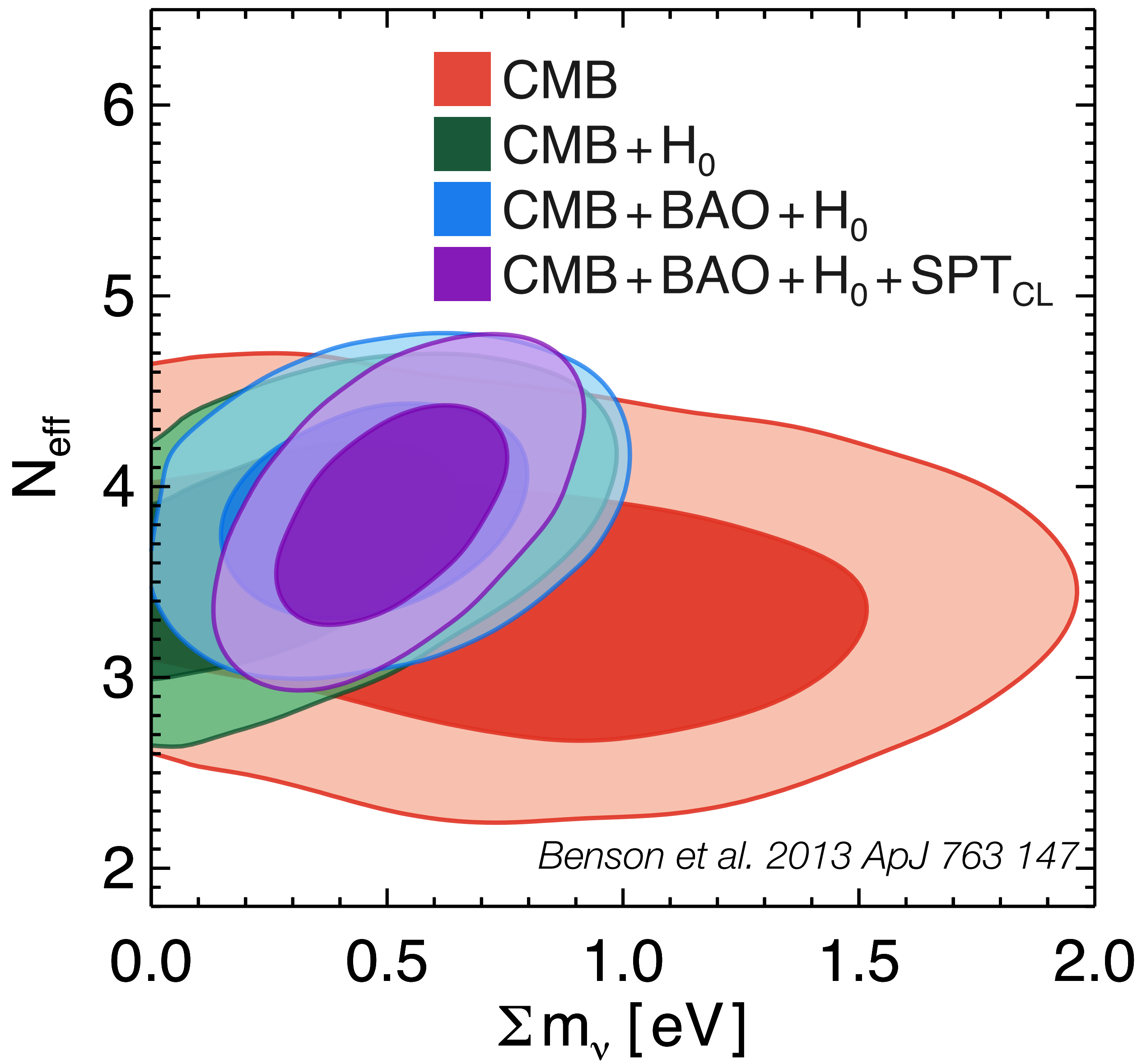
$N_{eff} = 3.62 \pm 0.48$ (SPT & WMAP7)

$= \mathbf{3.71 \pm 0.35}$ (SPT, WMAP7, BAO, H_0)

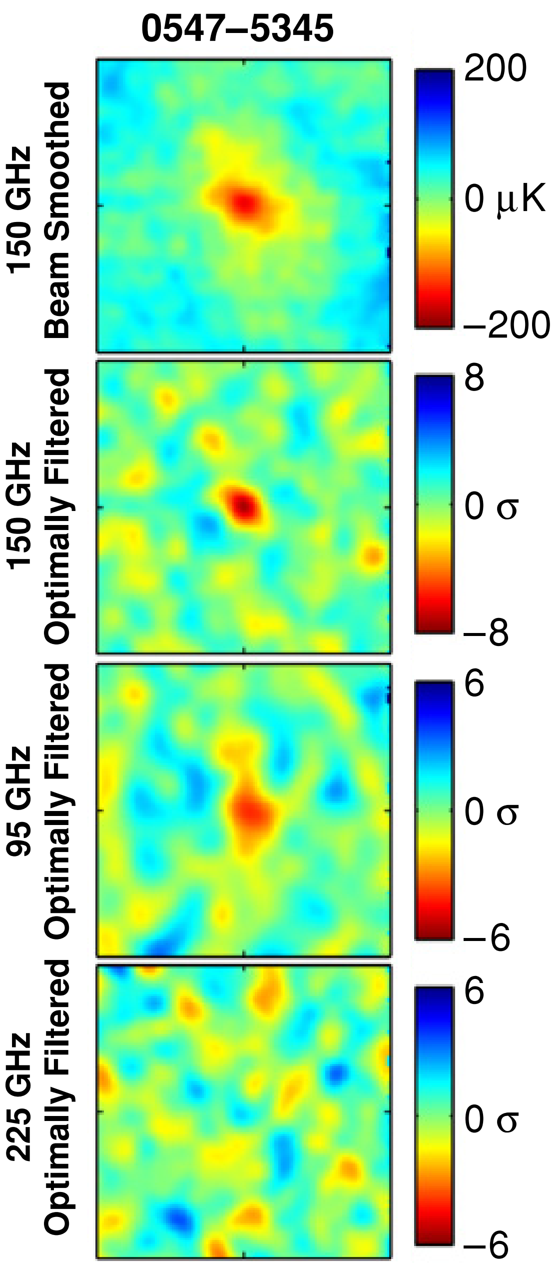
Hou et al., arXiv:1212.6267

First discovery of new clusters via SZ effect

- Inverse Compton scattering of CMB photons off hot cluster gas



Benson et al. 2013 ApJ 763 147

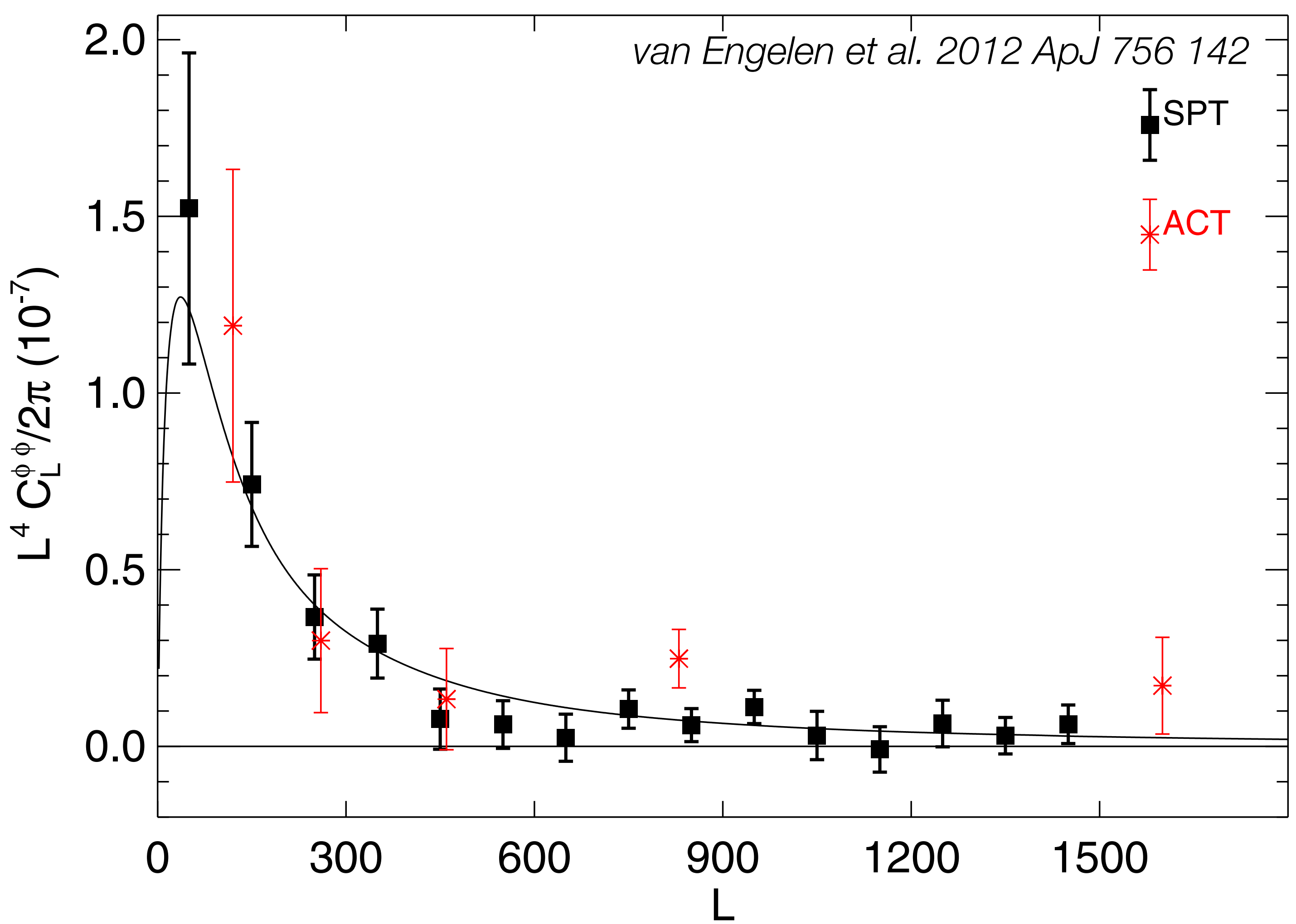


Staniszewski et al. 2009 ApJ 701 32

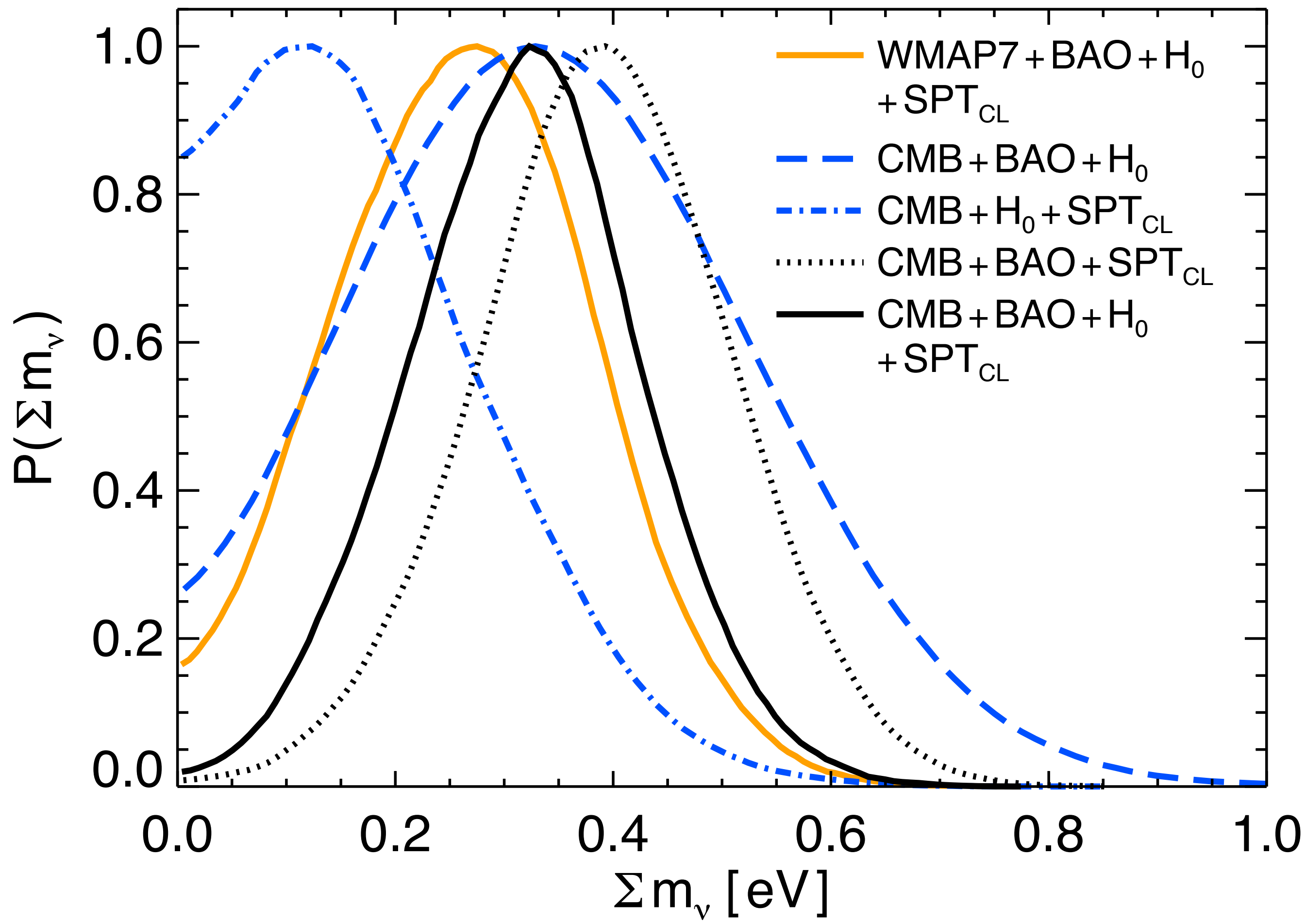
Weak lensing

- Measure “magnification” from weak gravitational lensing of the CMB

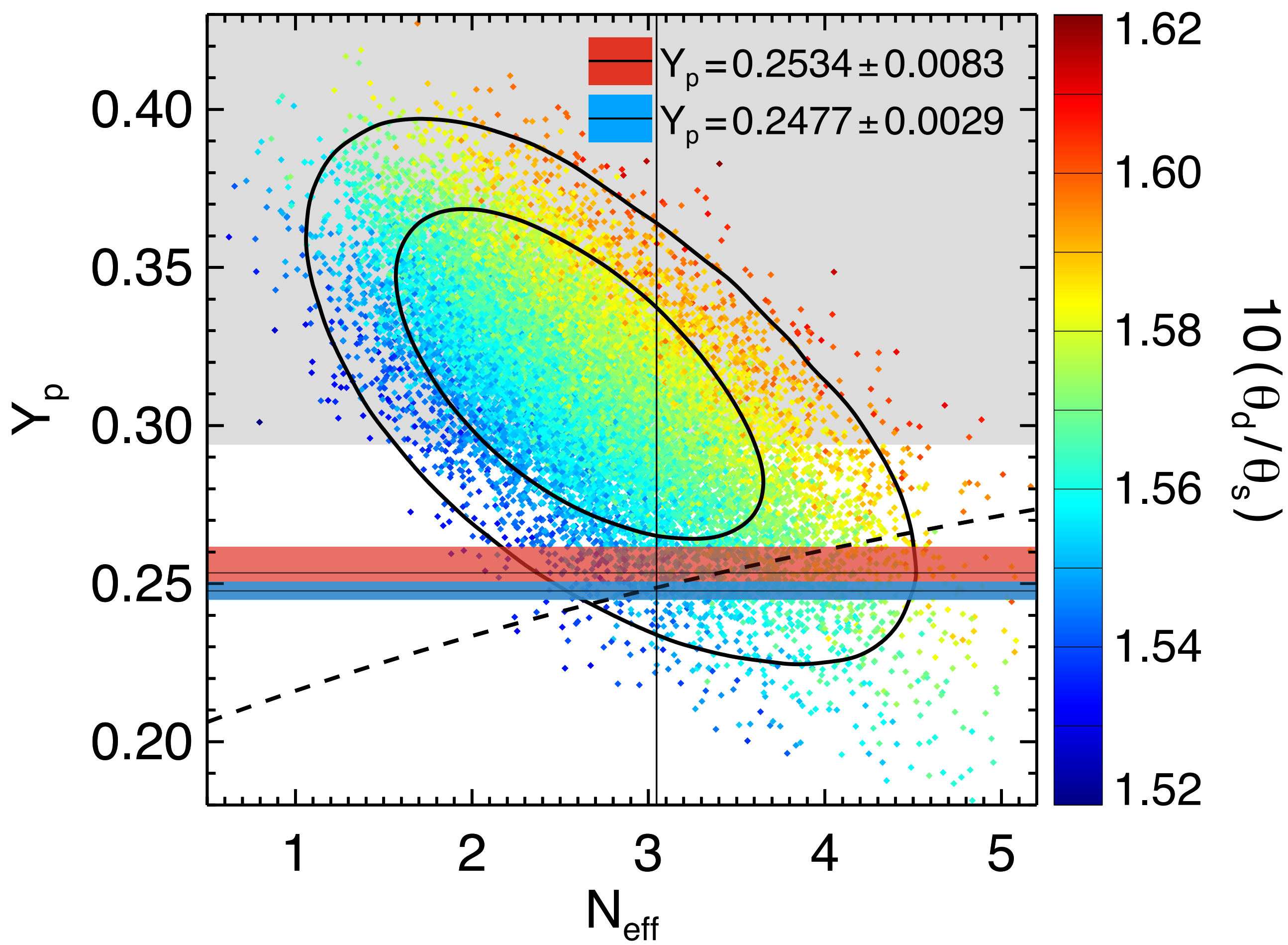
- Reconstruct deflection potential (DM distribution)



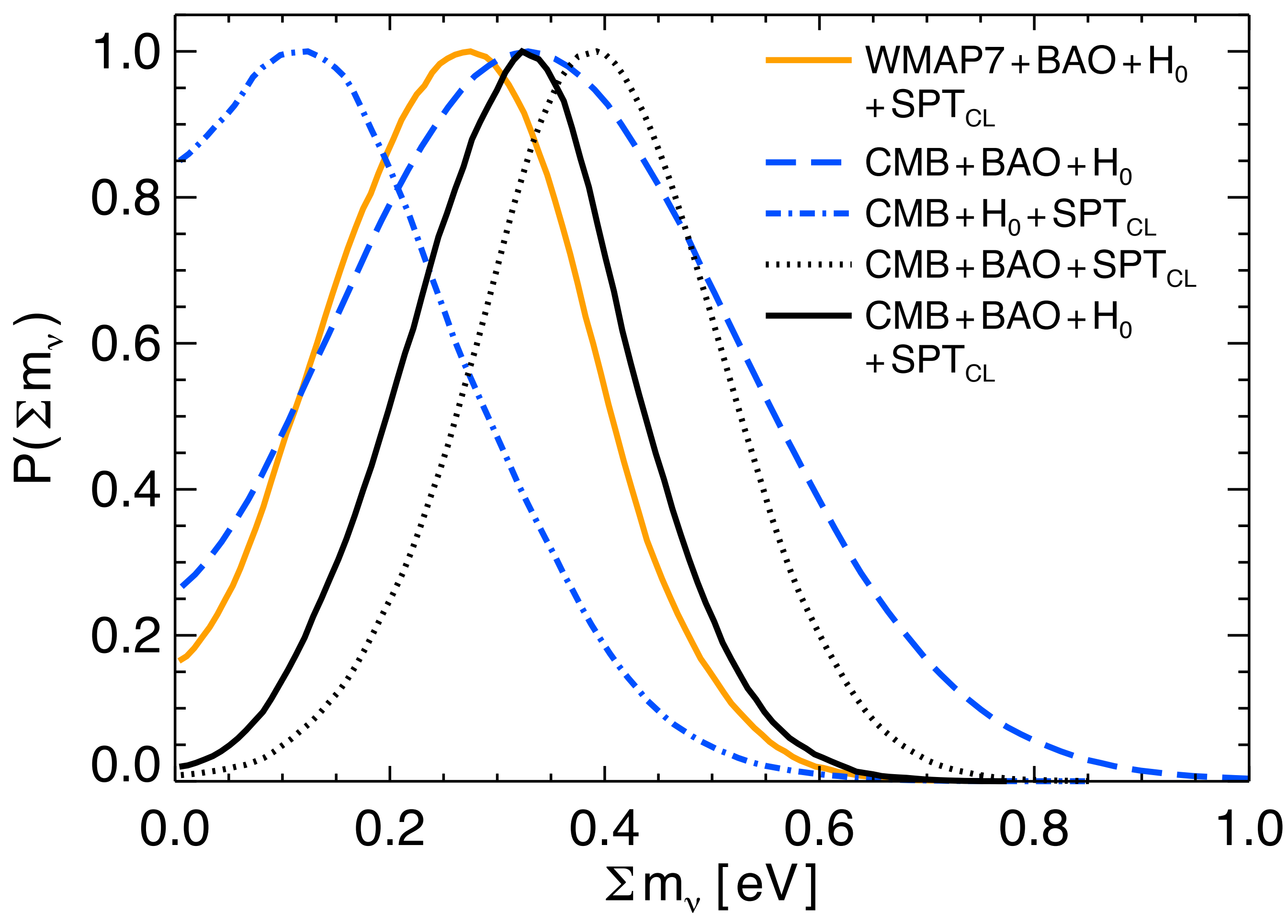
What to do?



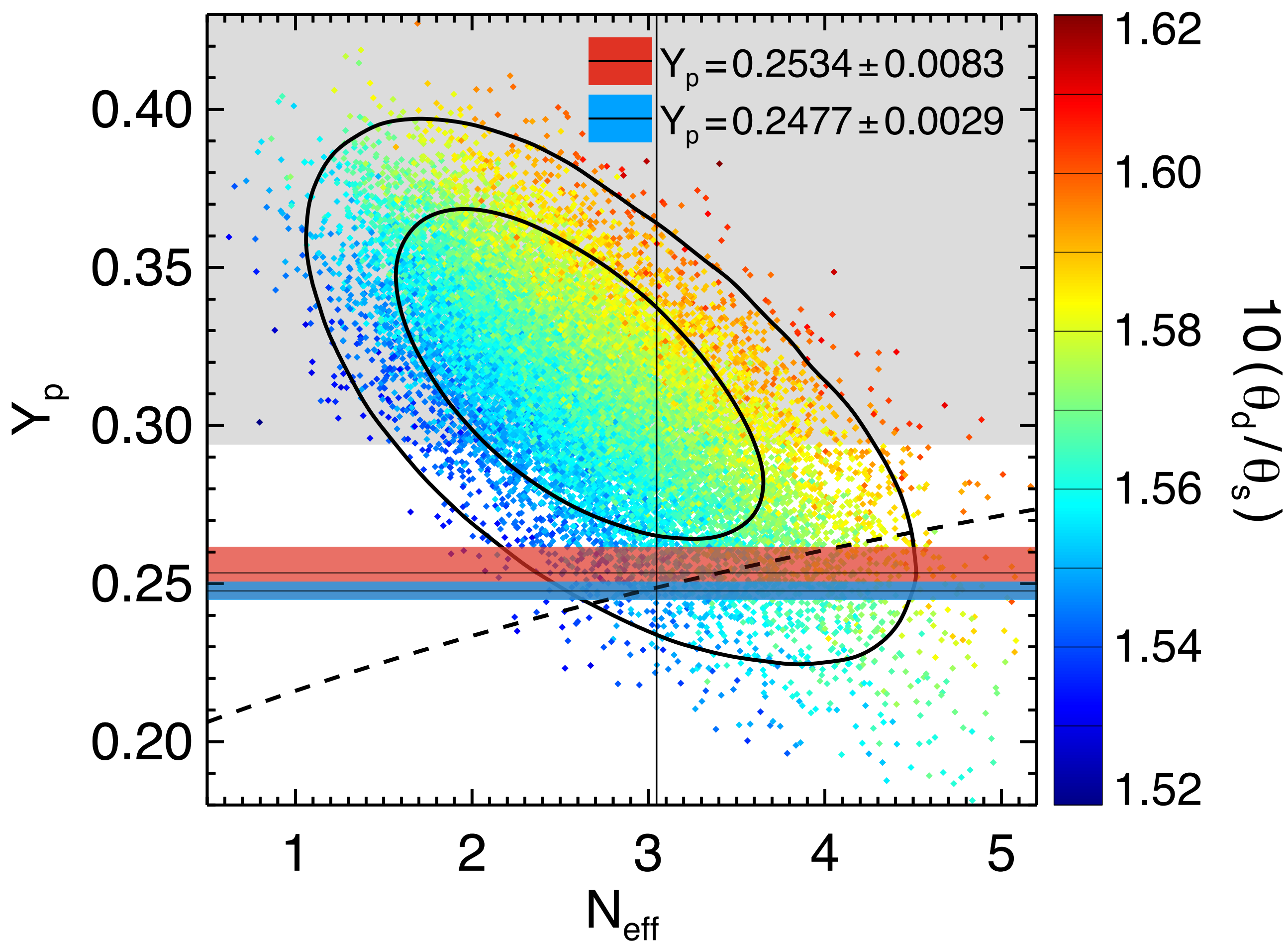
Hou et al., arXiv:1212.6267



What to do?



Hou et al., arXiv:1212.6267



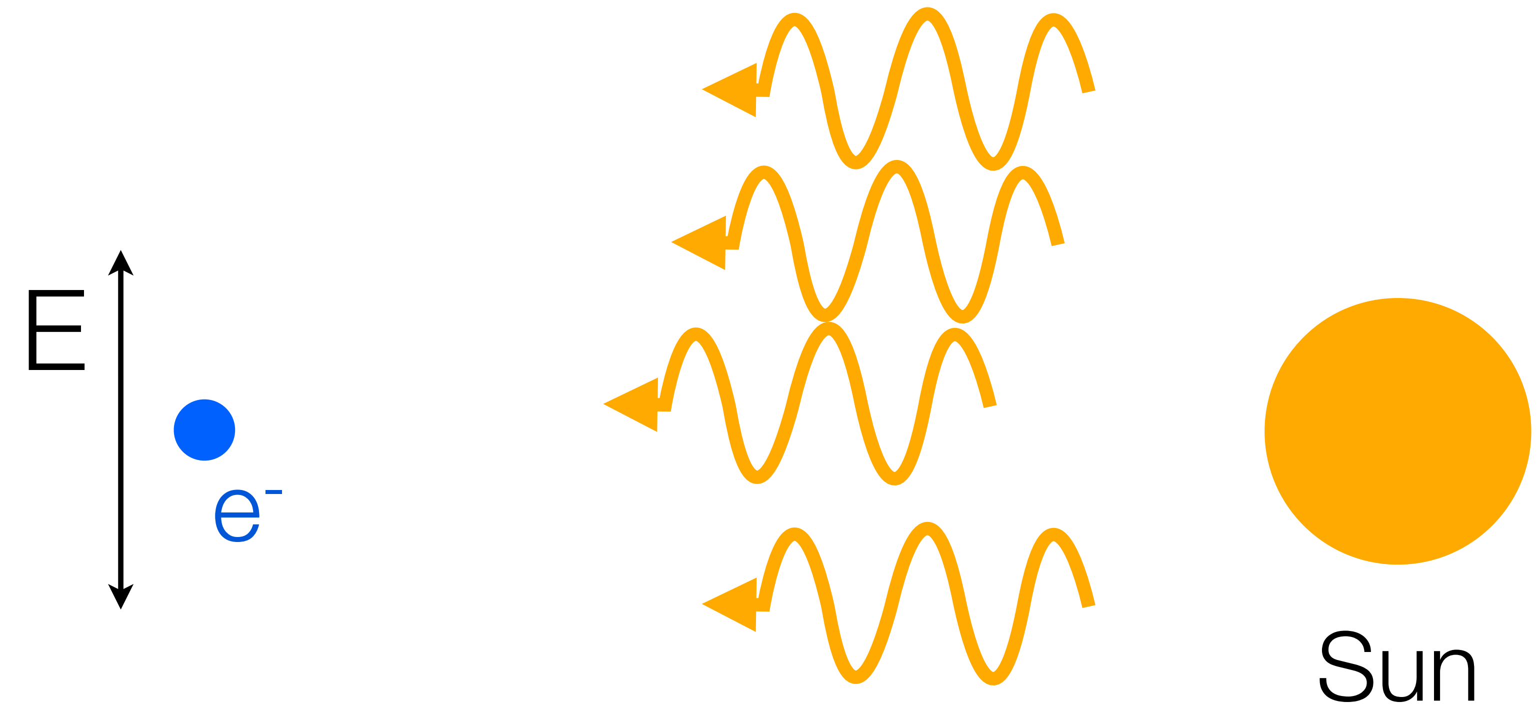
- "Classic" approach: new experiments
  - Systematic errors: do something different
  - Statistical errors: more of the same

Something different: CMB polarimetry

- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

Something different: CMB polarimetry

- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

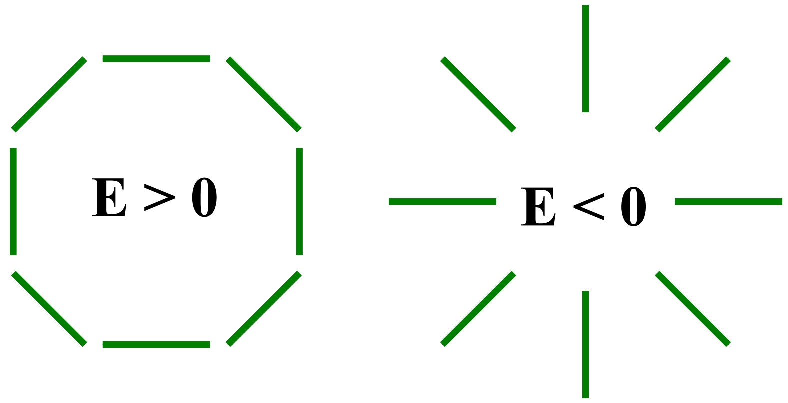


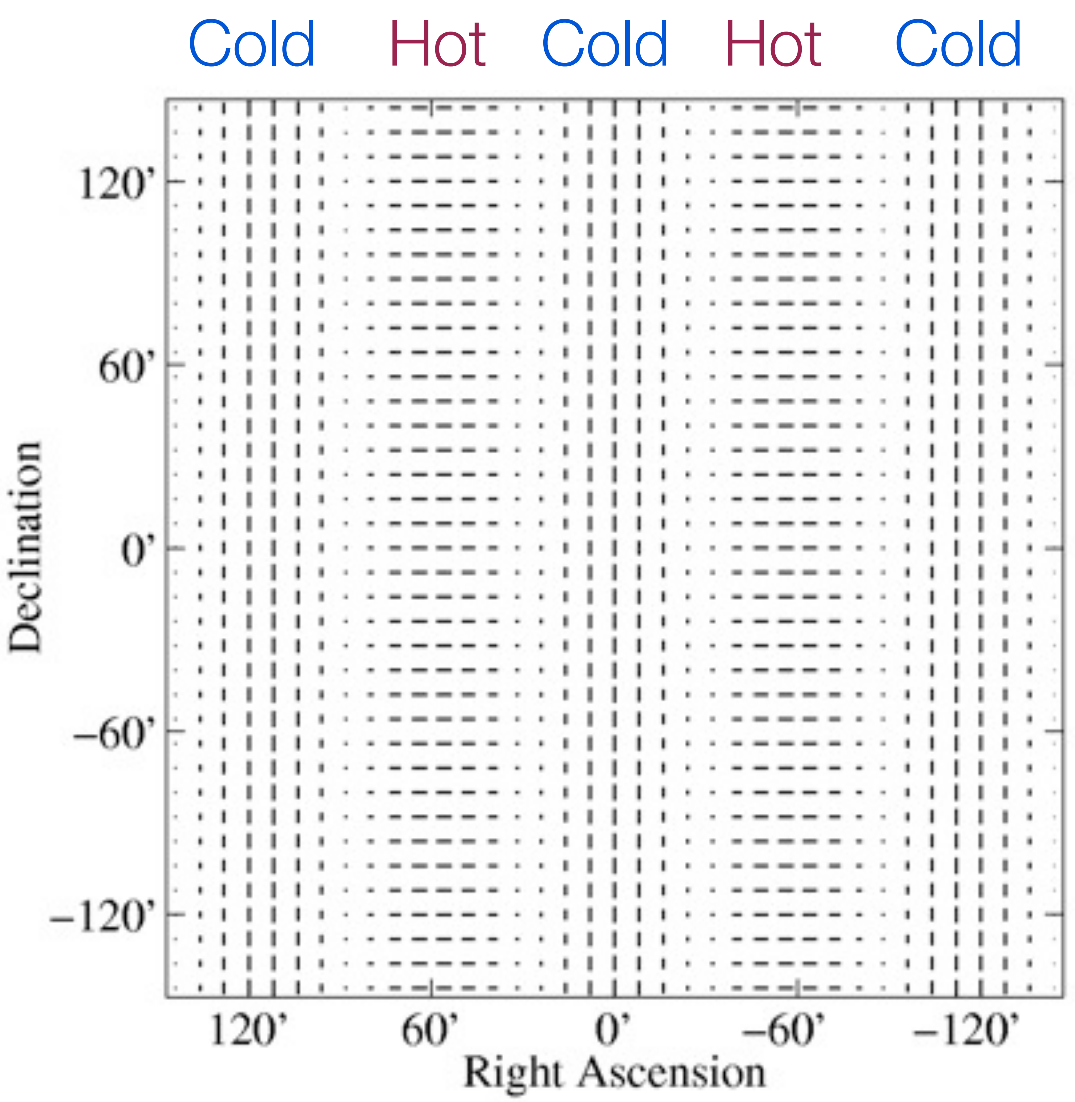
Something different: CMB polarimetry

- CMB polarized via Thomson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

- Density/Temperature anisotropy generates intrinsic CMB polarization

  - Polarization either parallel or perpendicular to anisotropy wave vector
  - Symmetric under "parity"
    $k \longrightarrow -k$
  - "E-mode"



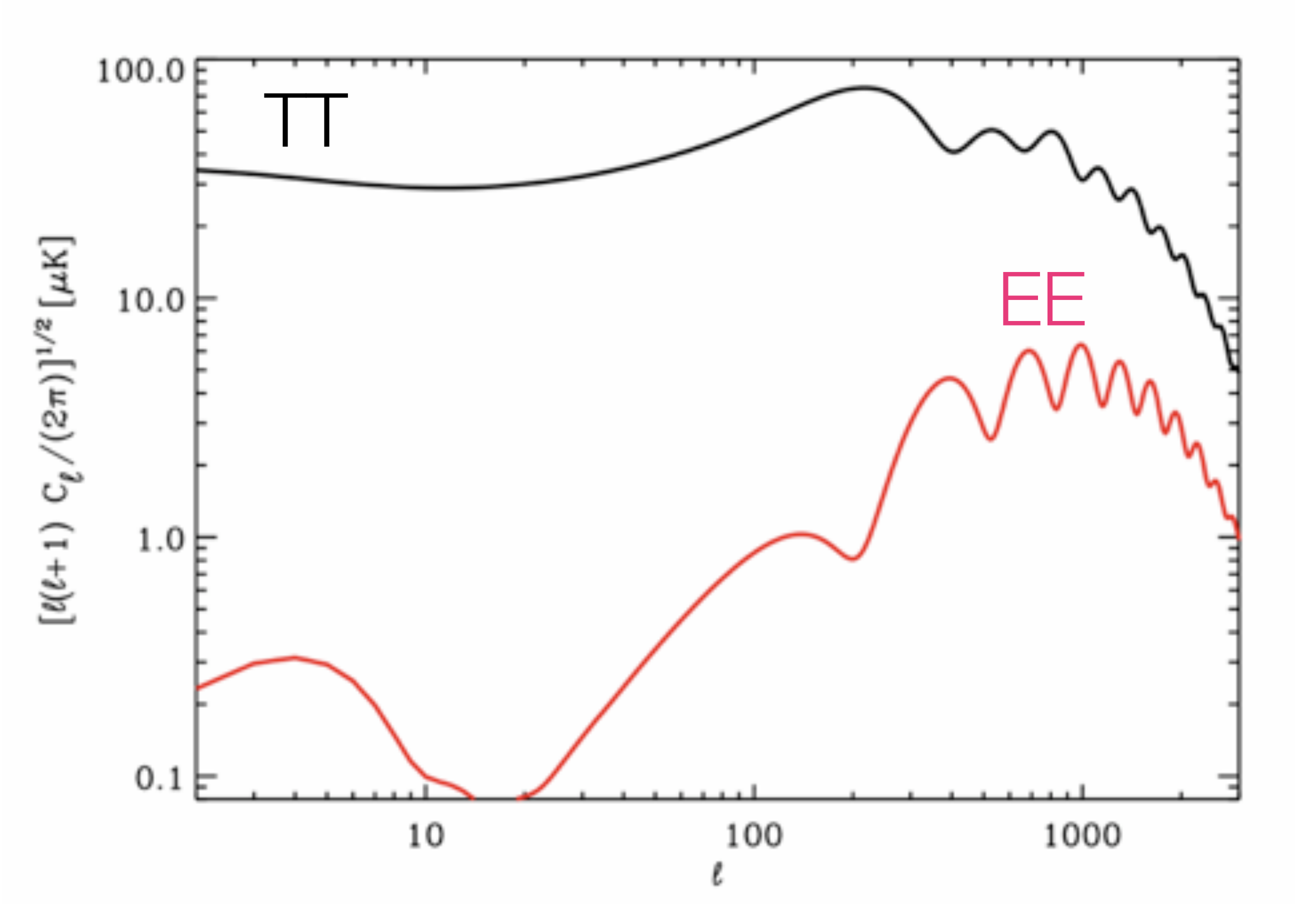


Something different: CMB polarimetry

- CMB polarized via Thompson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

- Density/Temperature anisotropy generates intrinsic CMB polarization

    - EE power spectrum is a different probe of same physics producing TT spectrum

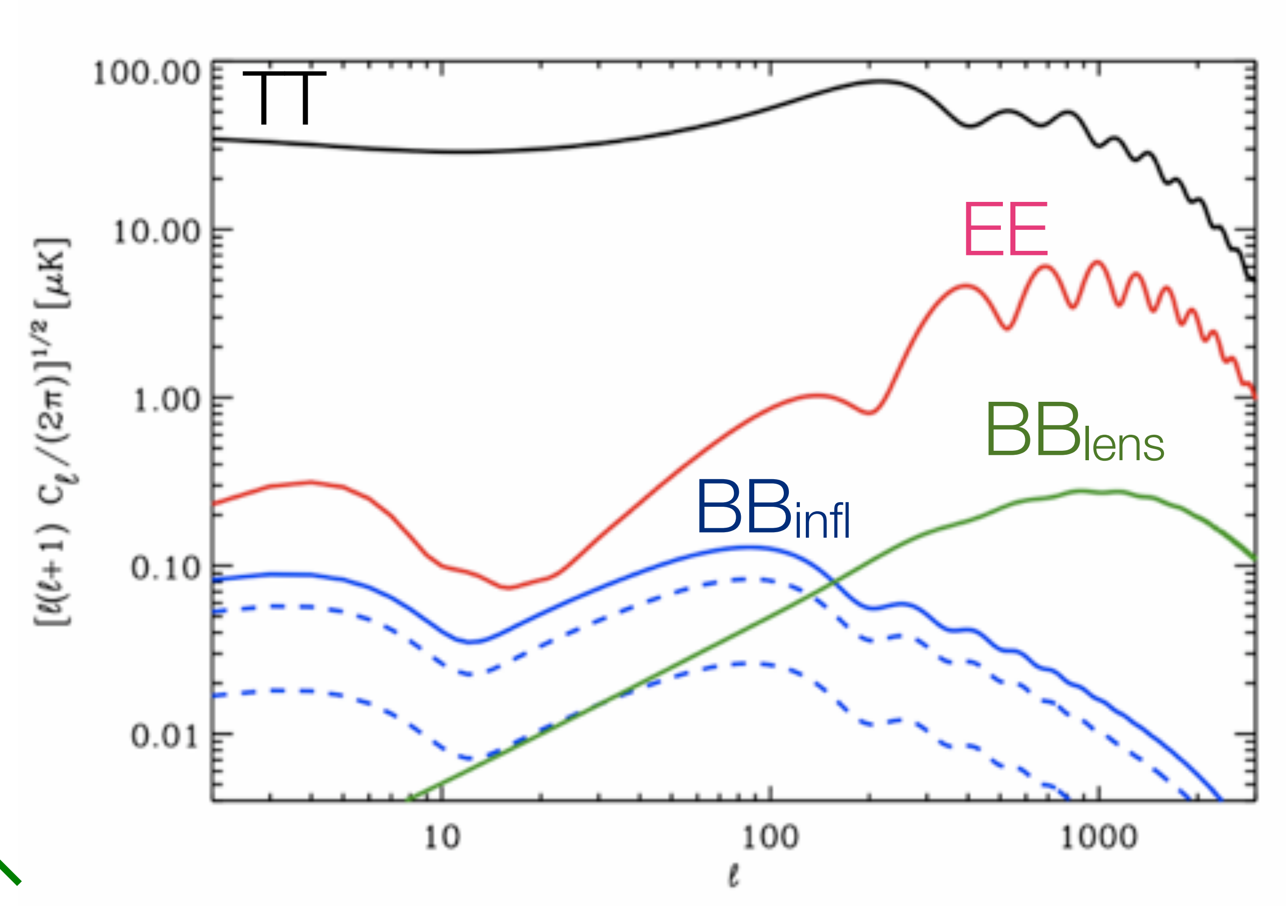


Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

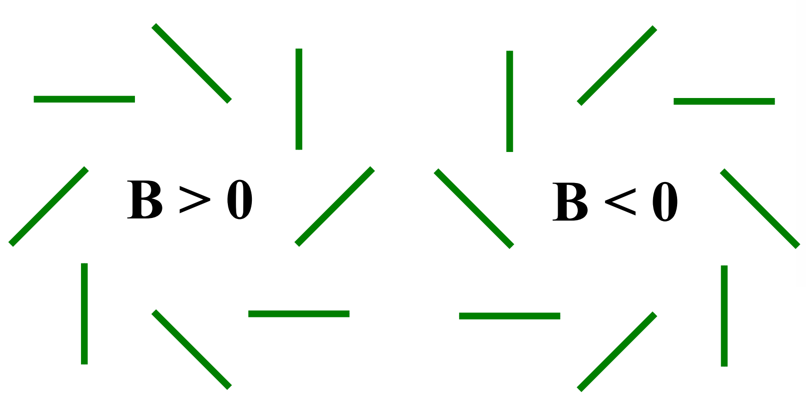
Something different: CMB polarimetry

- CMB polarized via Thompson scattering and local anisotropy (e.g. Sun scattering in atmosphere)

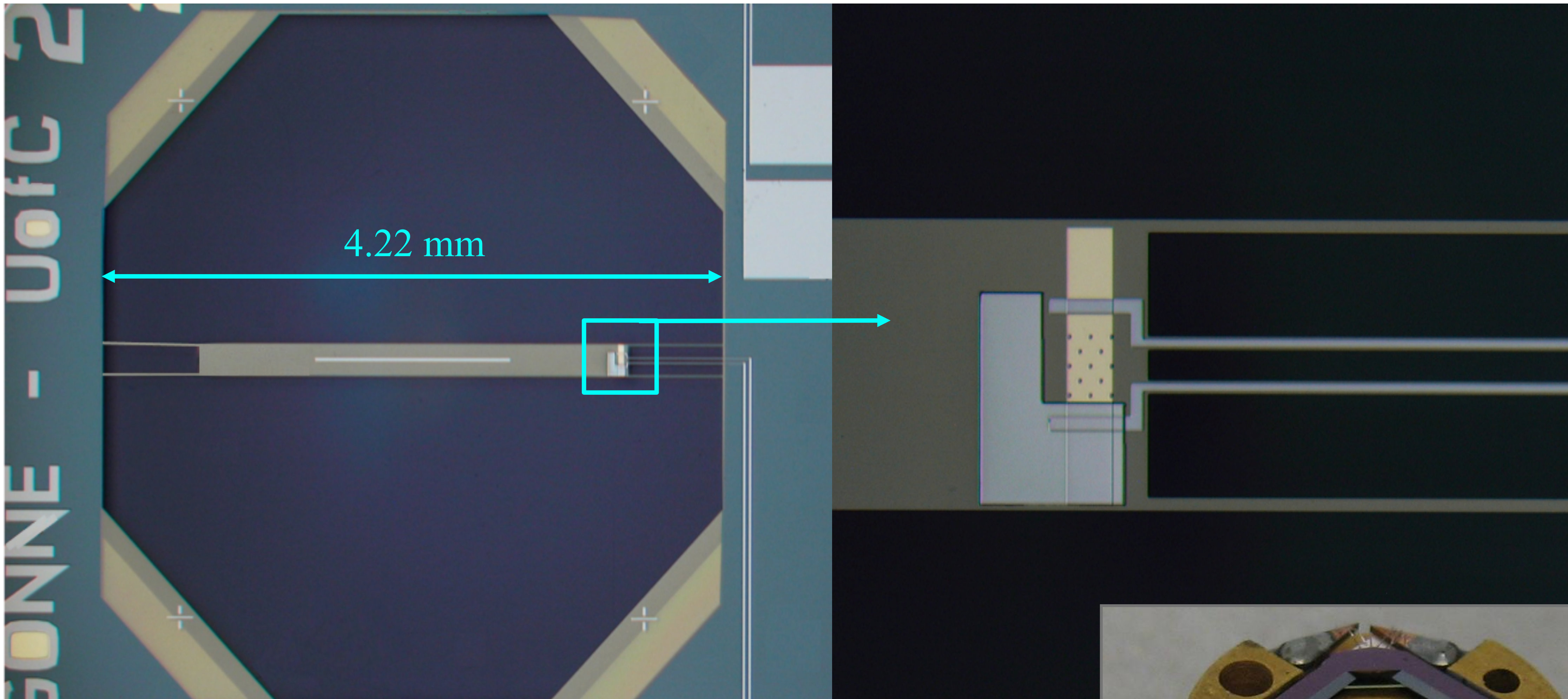
- Density/Temperature anisotropy generates intrinsic CMB polarization
  - parity odd patterns, “B-modes”
  - Gravitational lensing of “E-modes” (shearing)
  - Gravitational waves from inflation



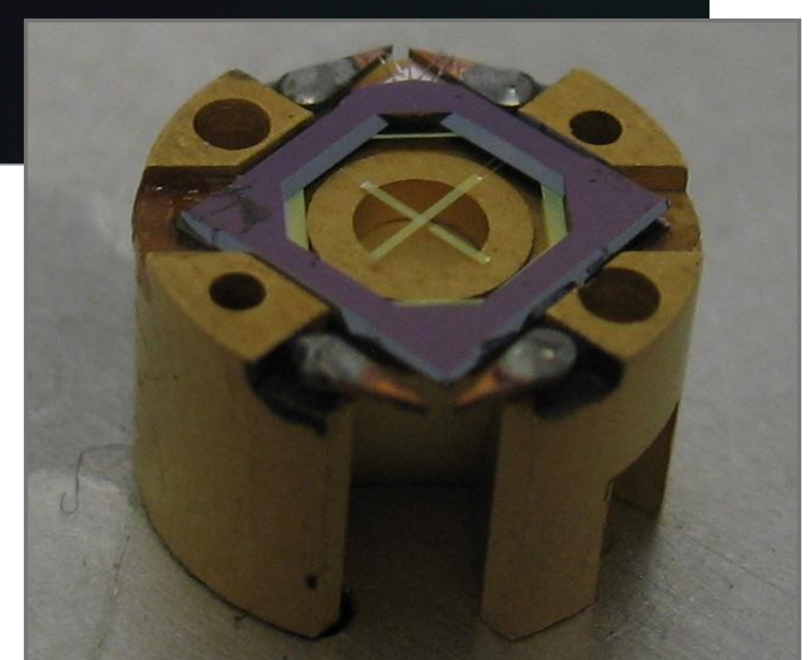
Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor



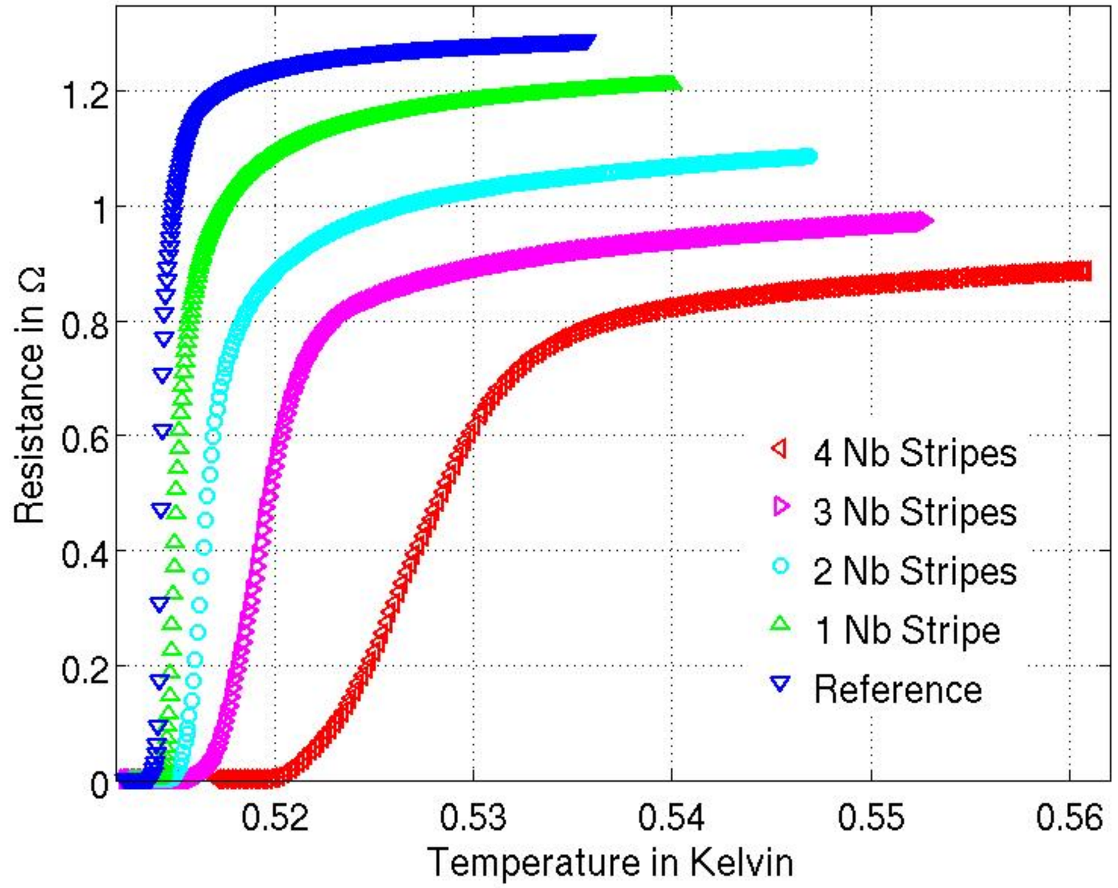
SPTpol detectors from ANL (100 GHz)



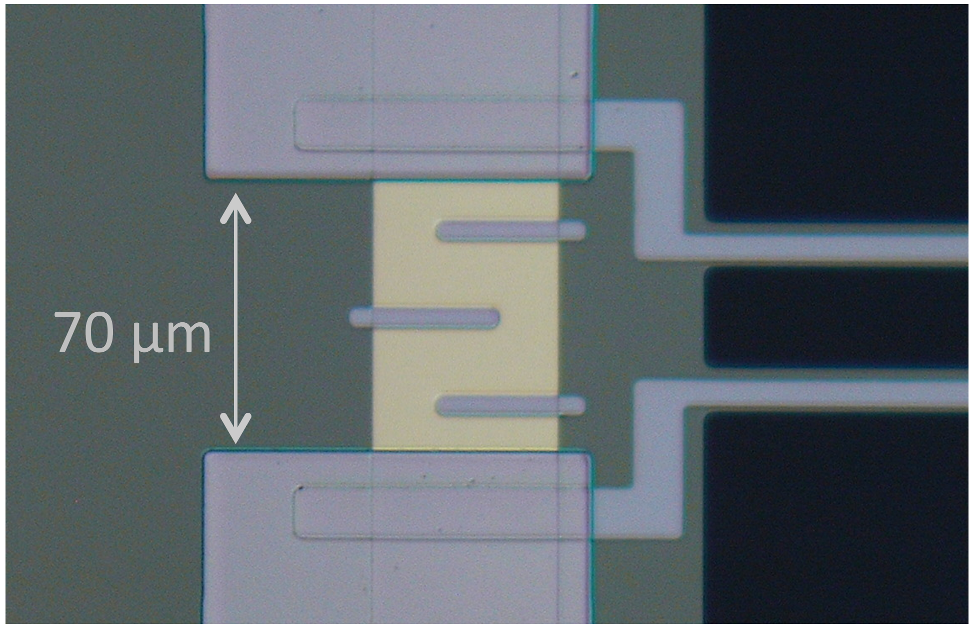
CLC et al., JLTP June 2012, Volume 167, Issue 5-6, pp 865-871



Transition Engineering

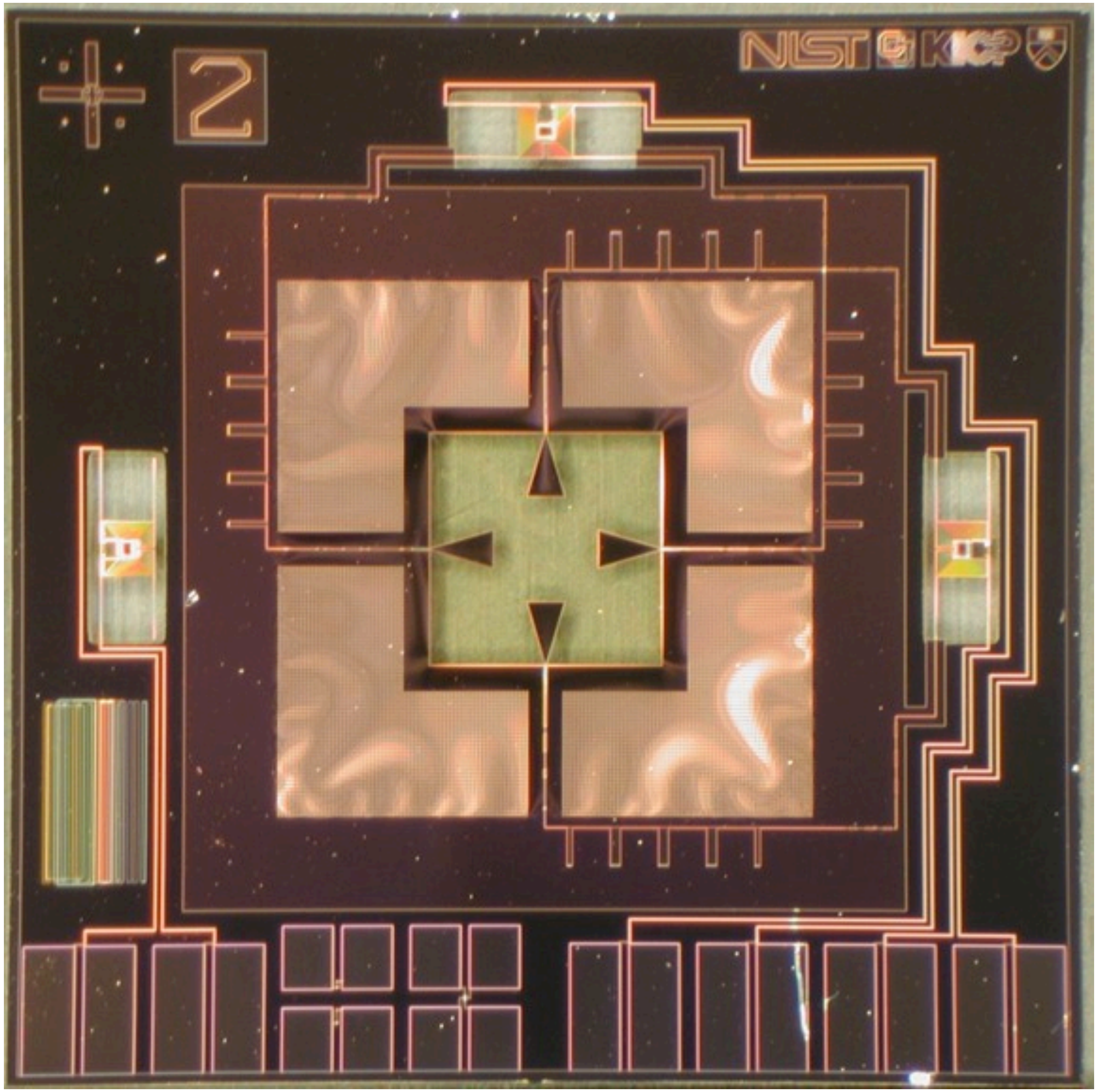


- Using proximity effect to smoothly vary T_c across TES
- Broadens effective transition width
- Tunes feedback “gain”



CLC et al., JLTP June 2012, Volume 167, Issue 5-6, pp 865-871
Wang et al., in prep

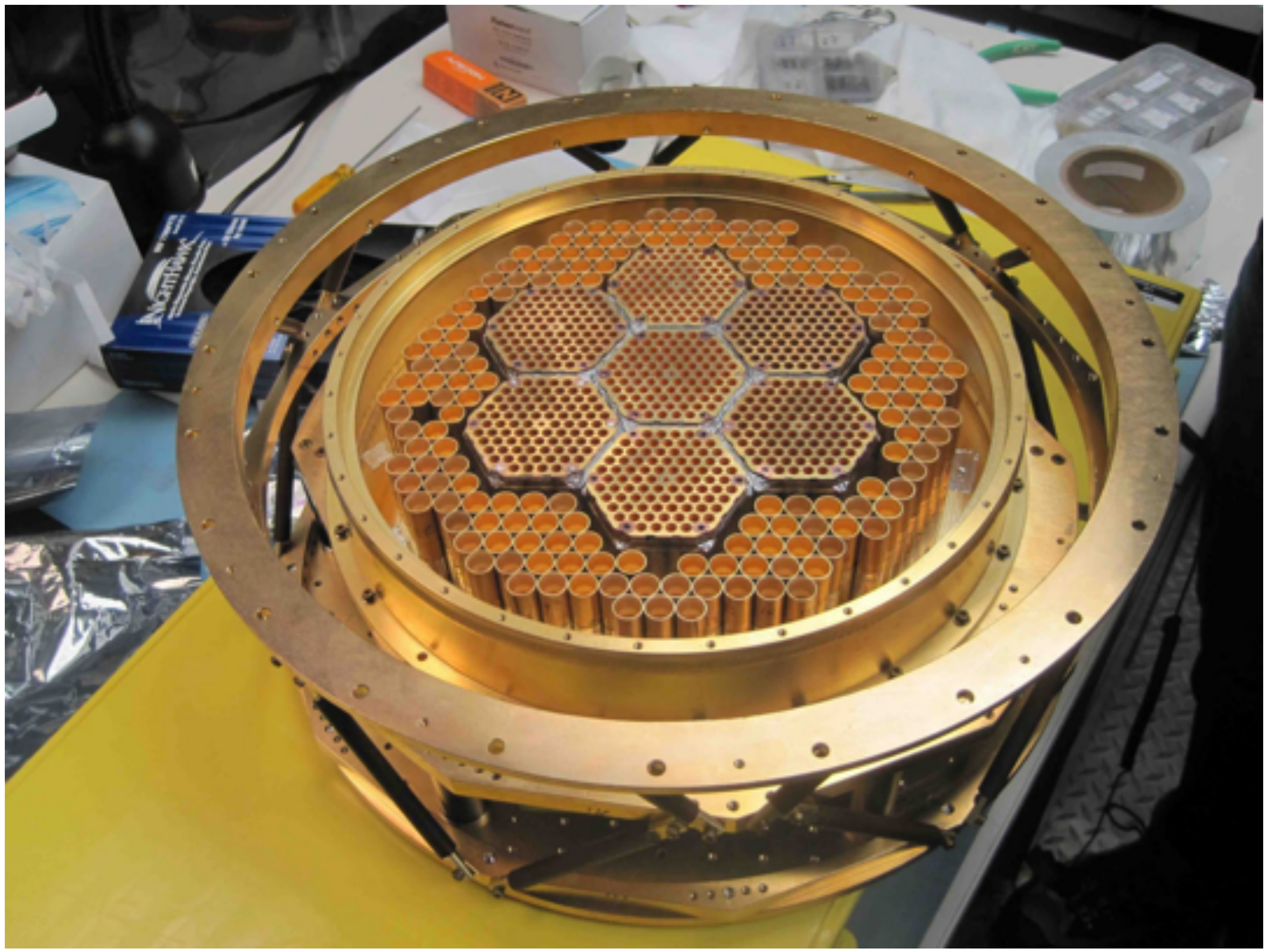
SPTpol detectors from NIST (150 GHz)



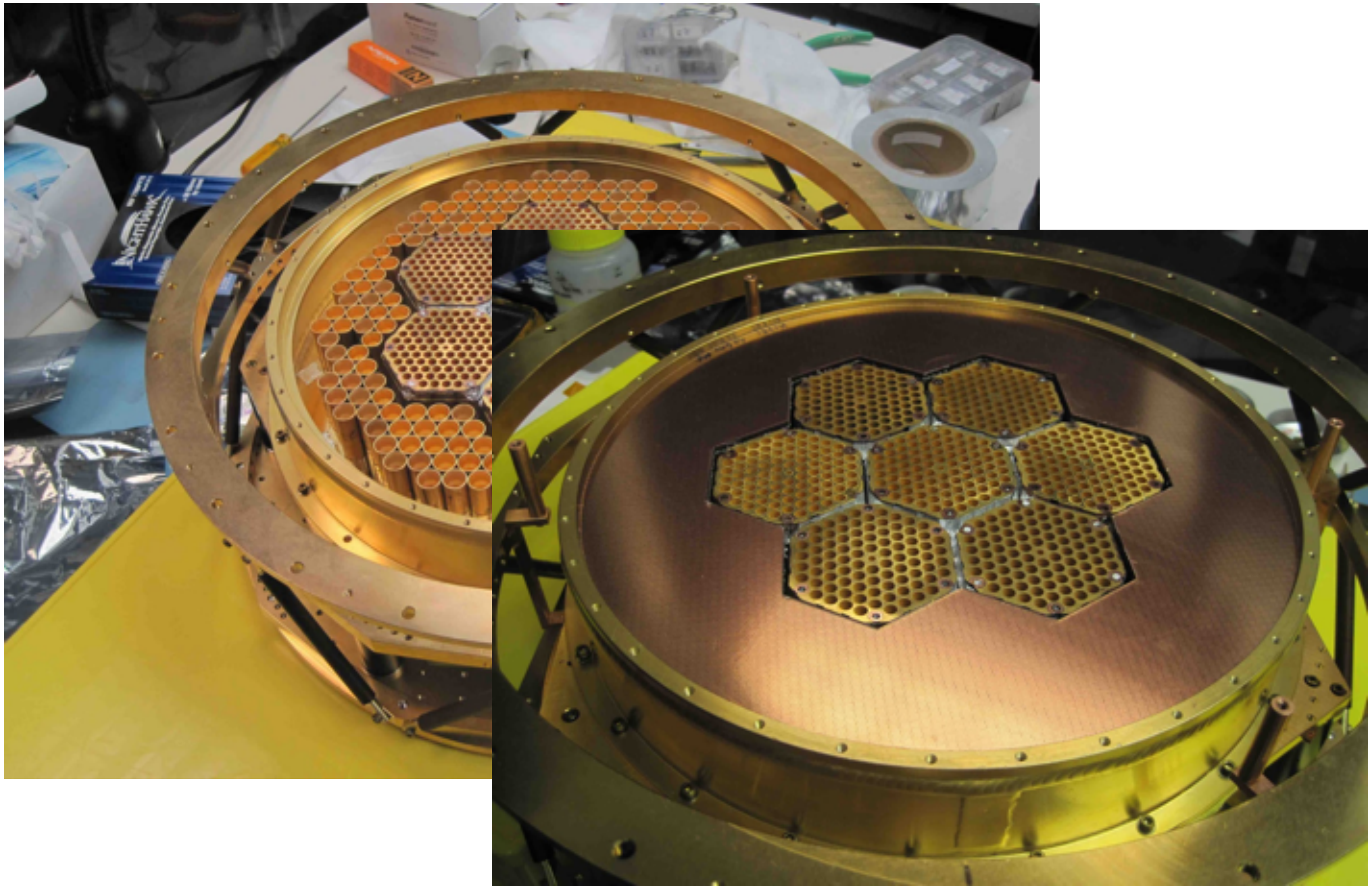
- Use “fins” to couple waveguide E-field onto superconducting transmission lines
- Thermalized and measured on TES islands
- Ortho-Mode Transducer (two orthogonal polarizations go to separate bolometers)

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

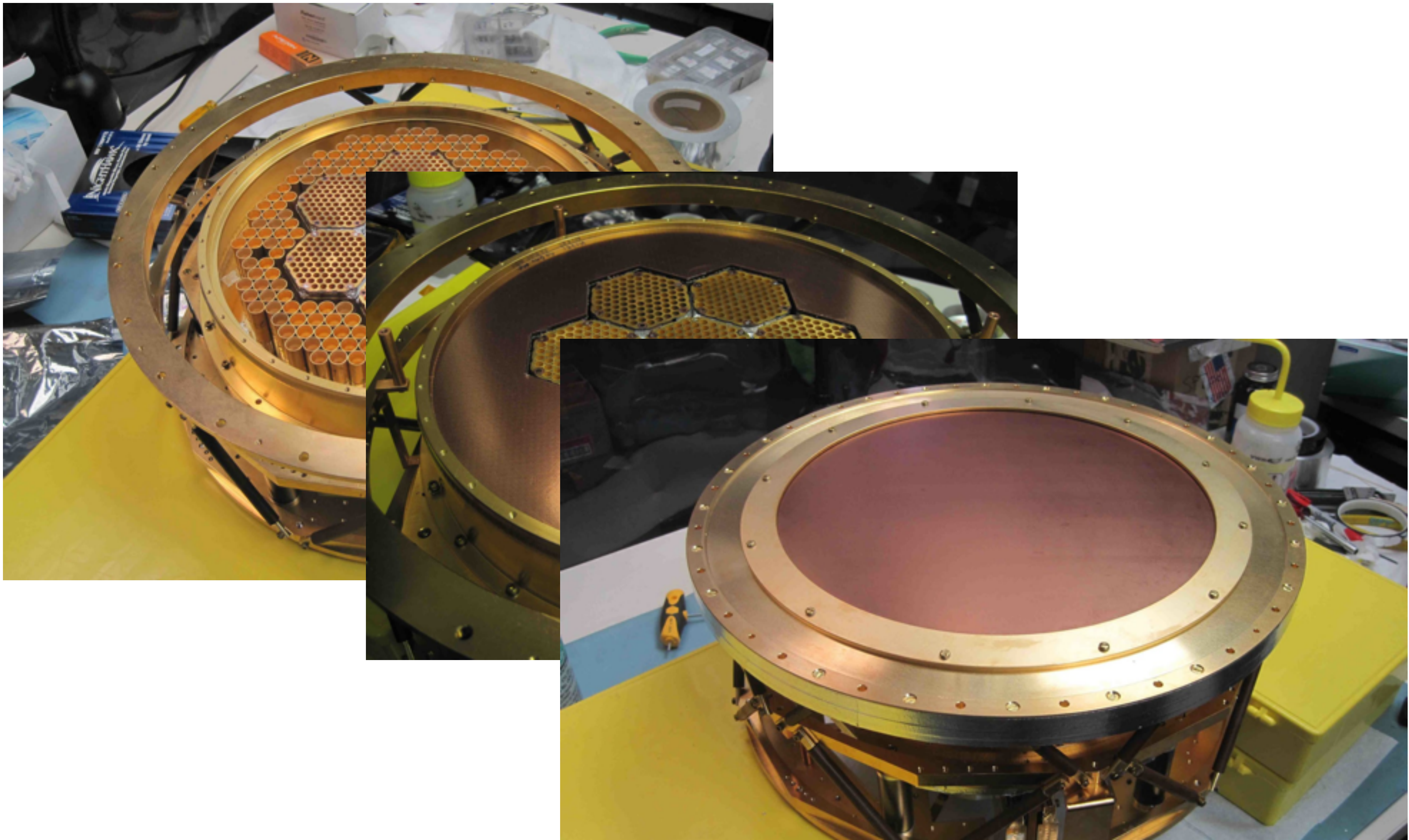
Install on SPT



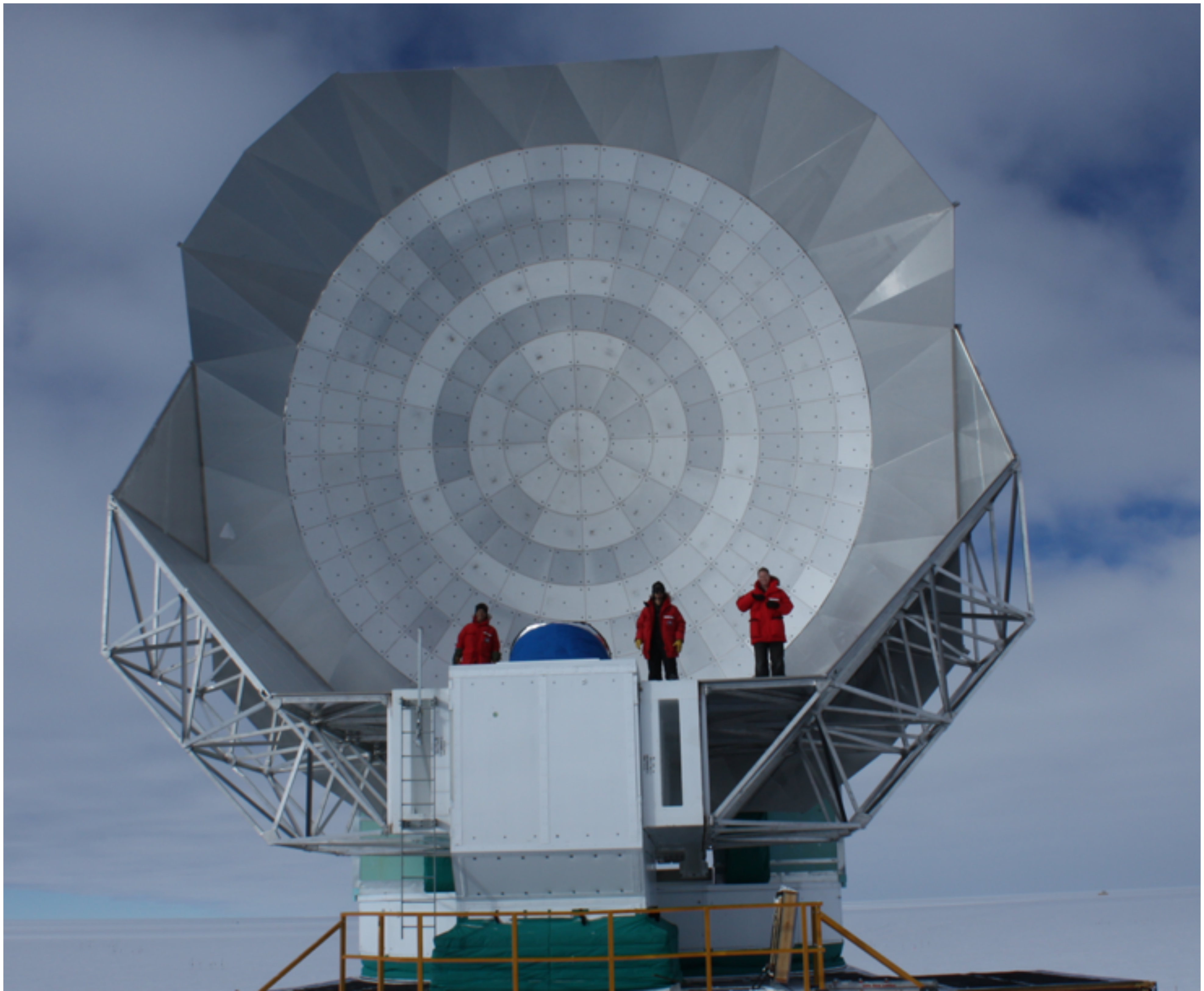
Install on SPT



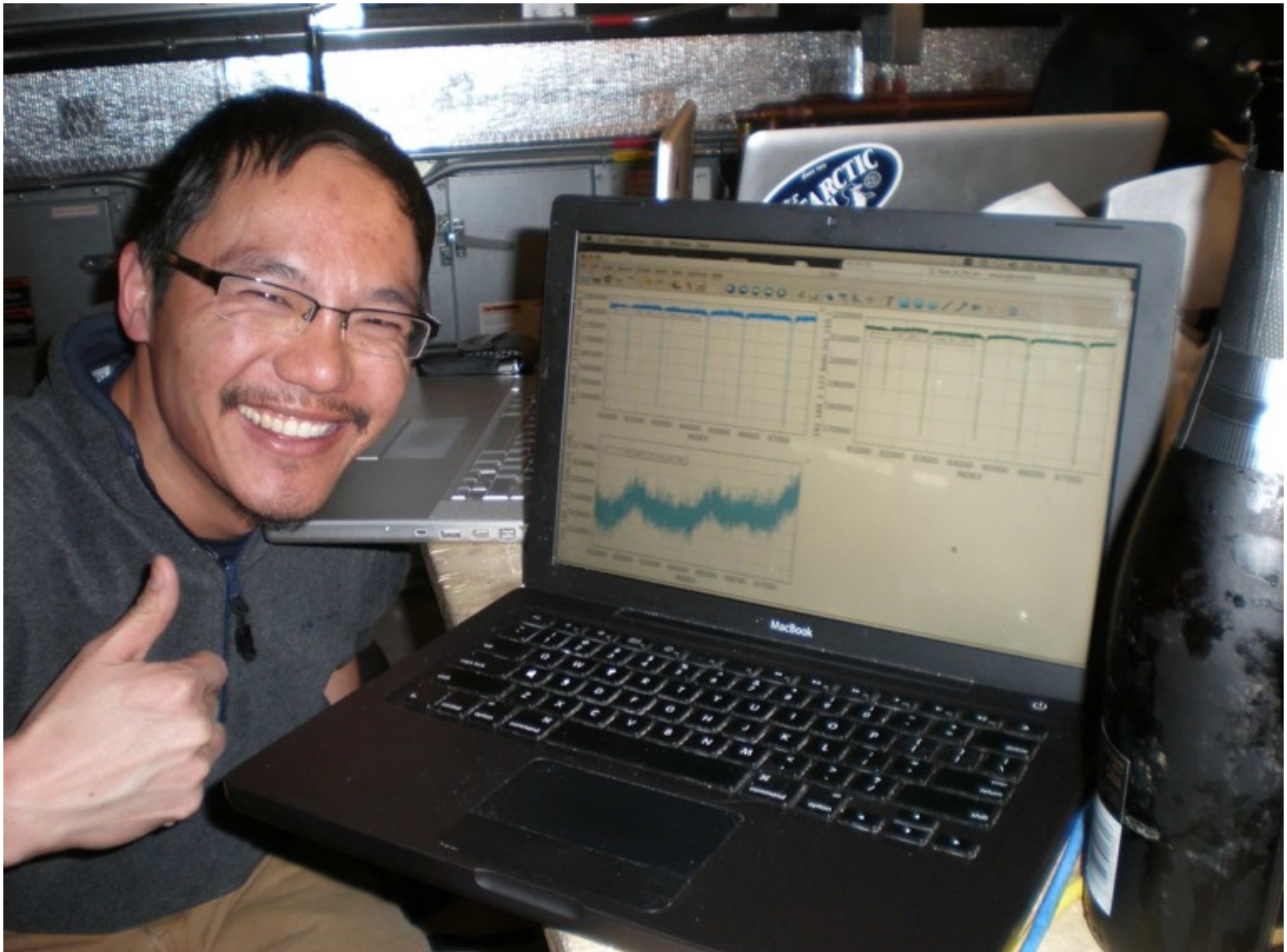
Install on SPT



Install on SPT

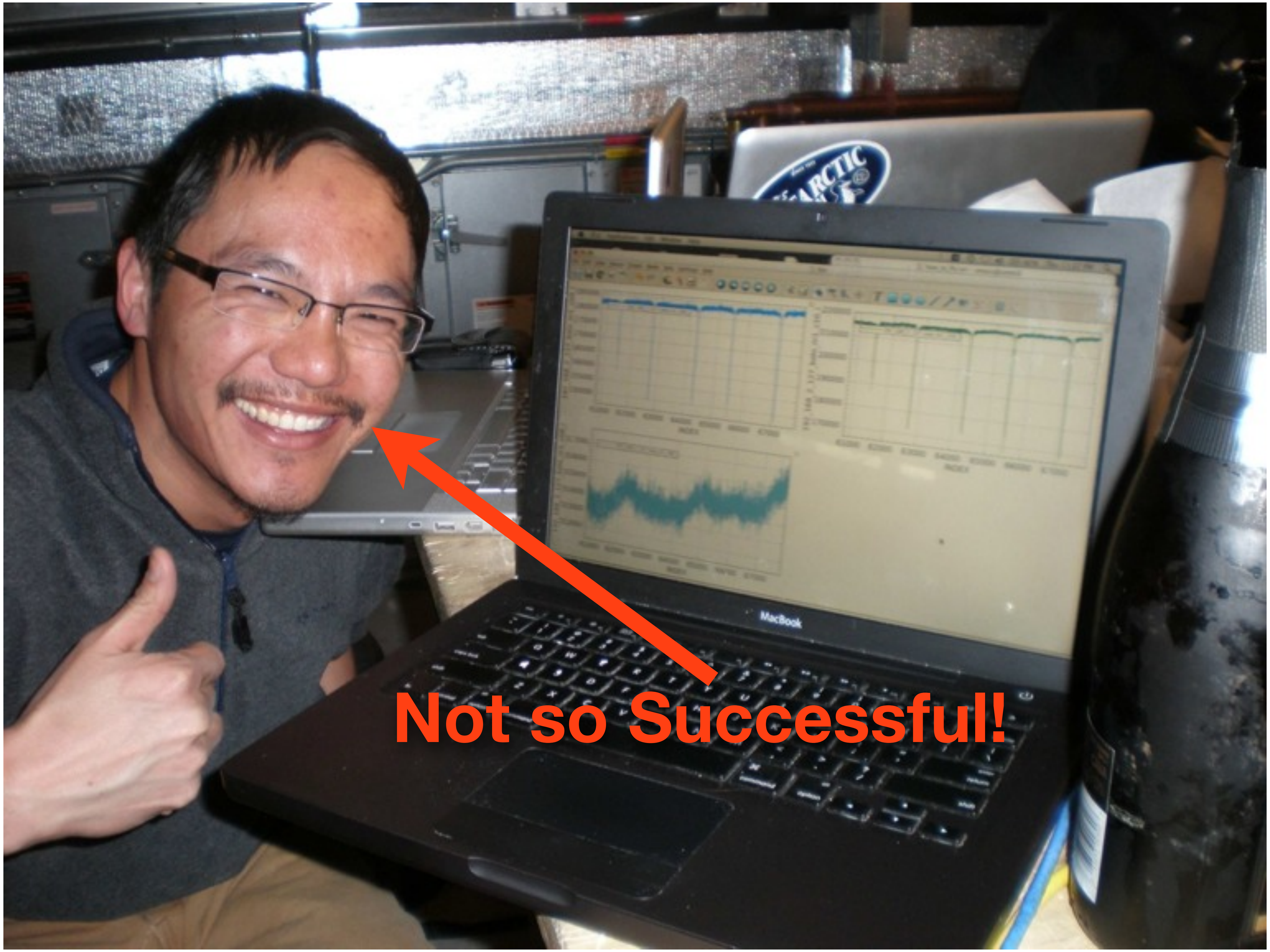


First light!

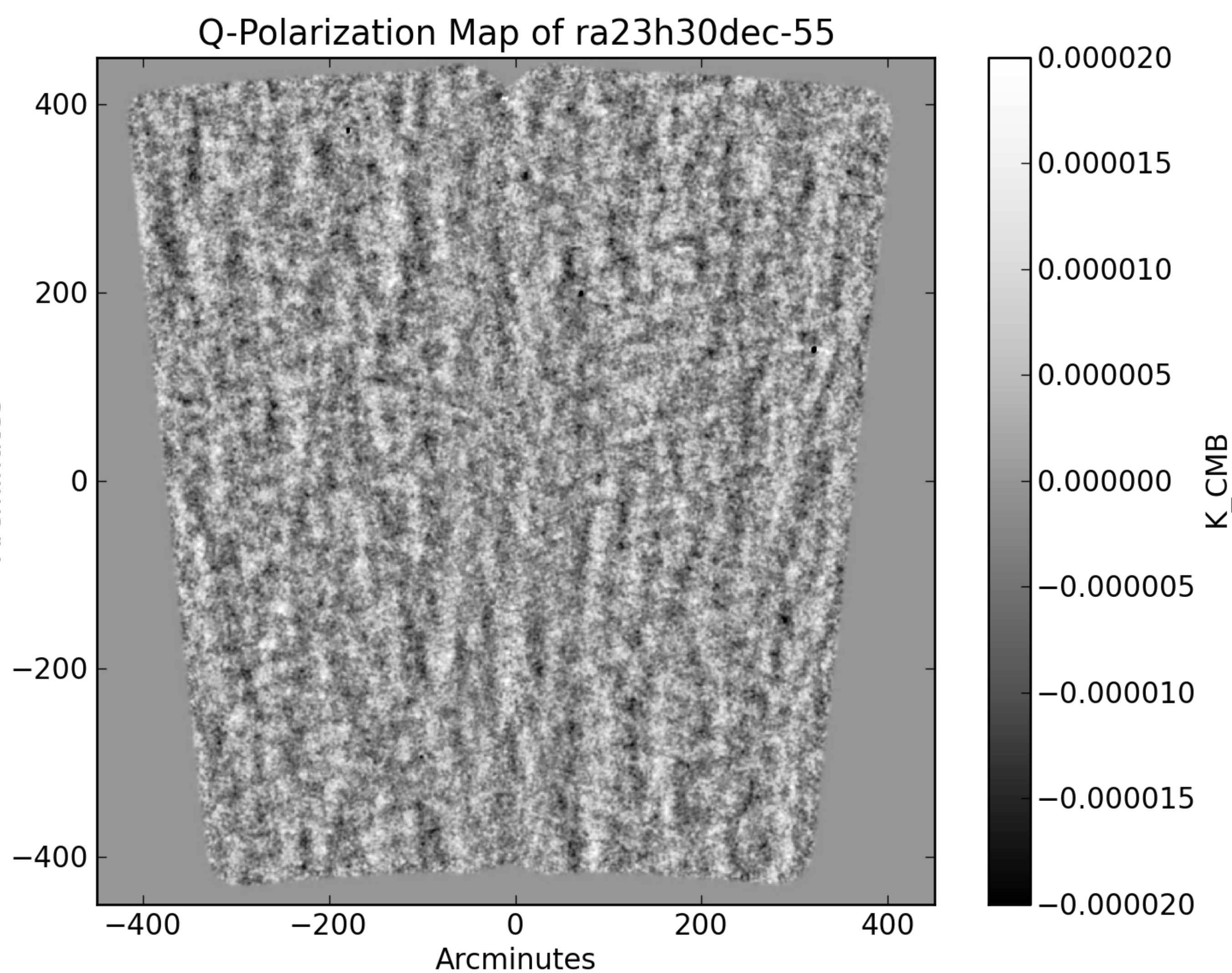


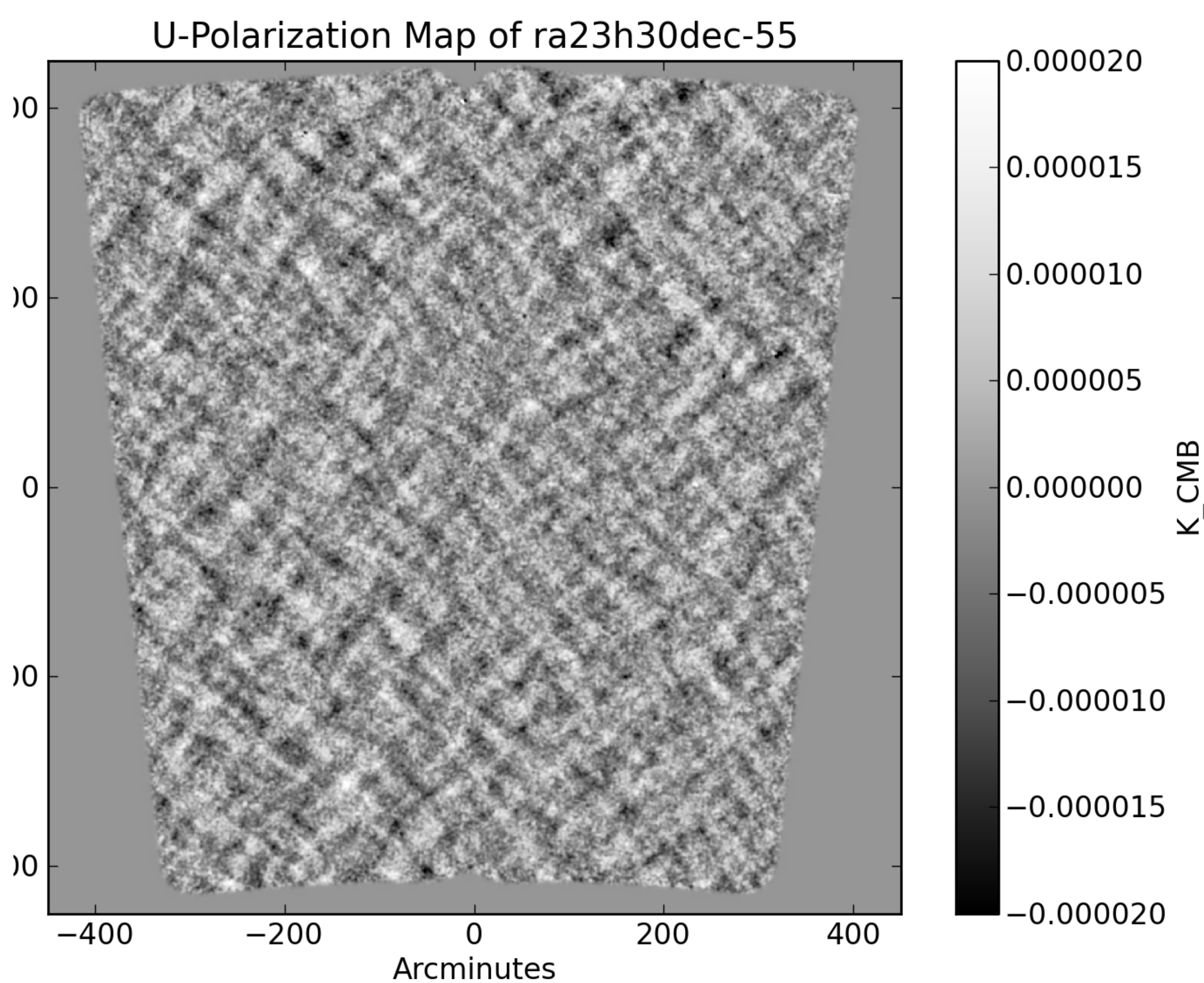
First light!

First light!



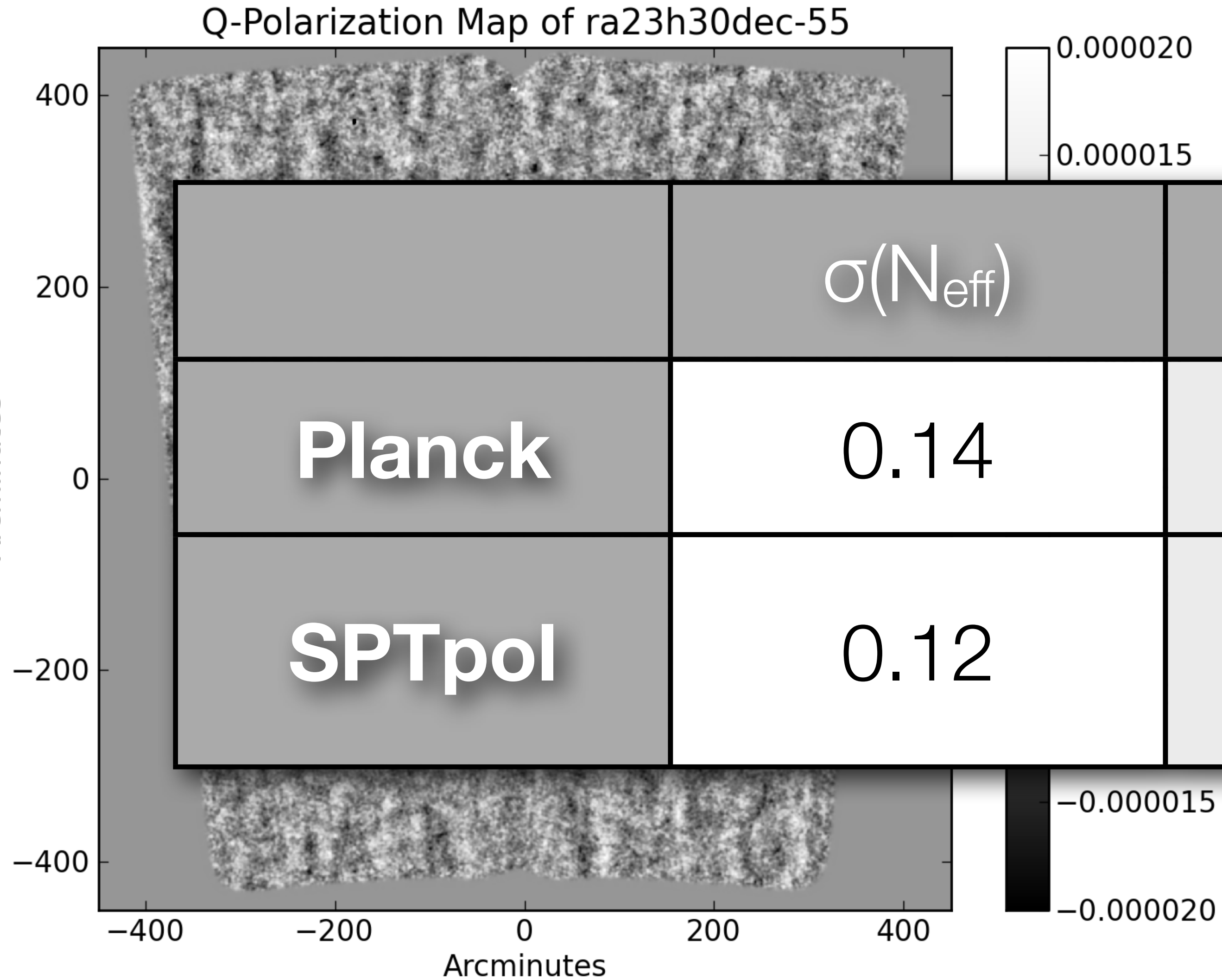
SPTpol status

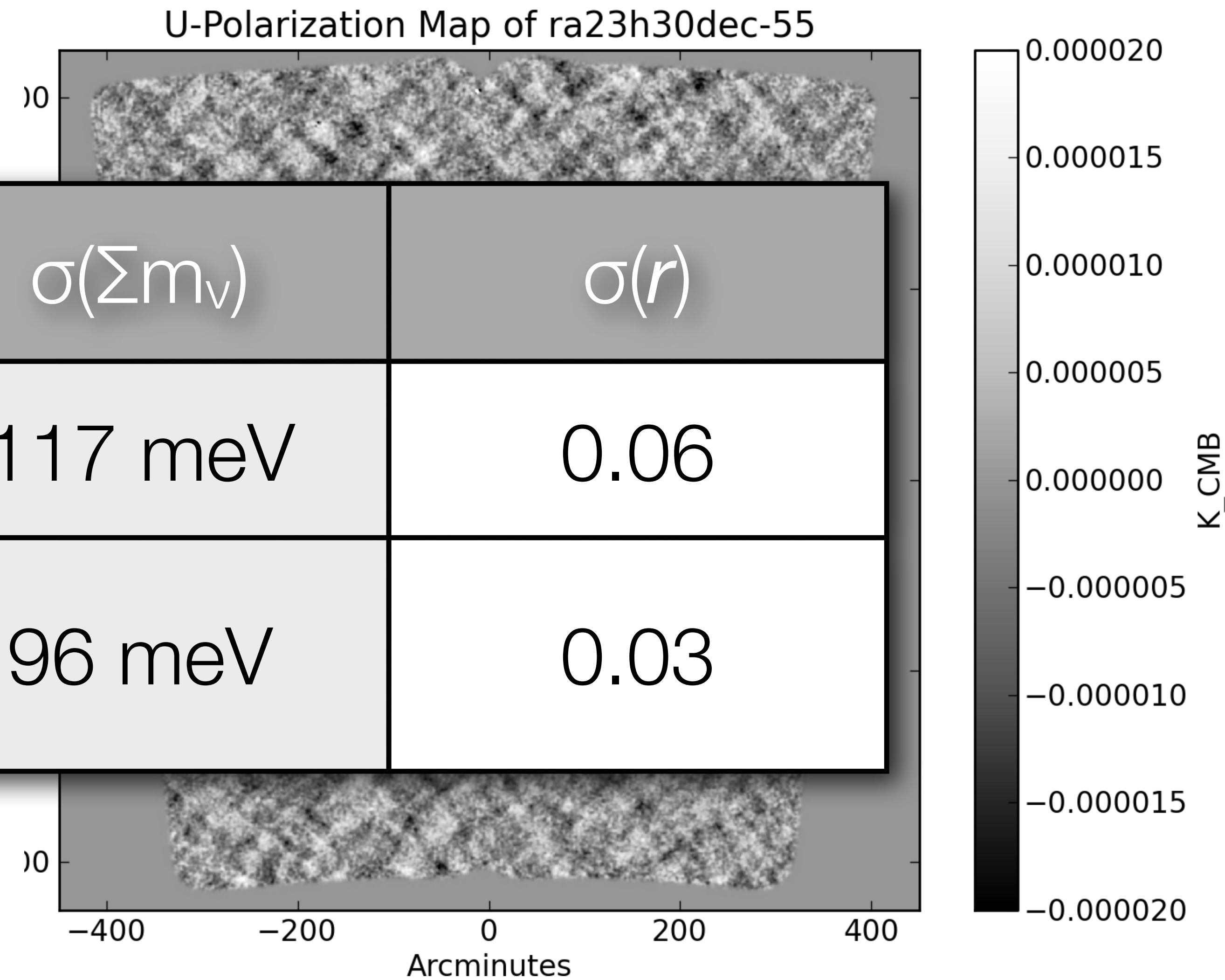




- First 6 months on 100 deg^2
- ~10 uK rms
- Observe 480 deg^2 over next 3 years (1600 detectors!)

SPTpol status





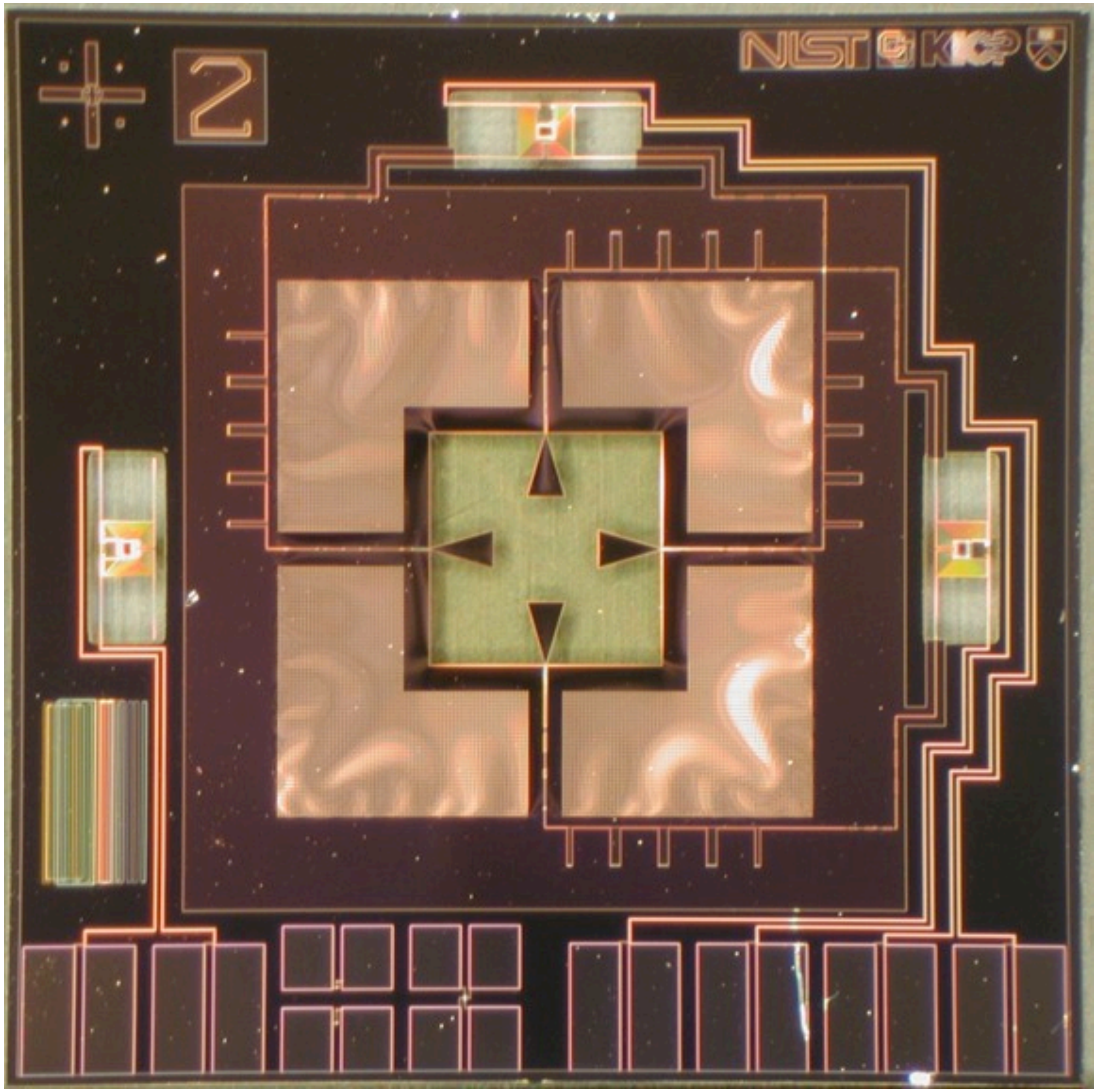
	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	$\sigma(r)$
Planck	0.14	117 meV	0.06
SPTpol	0.12	96 meV	0.03

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

SPT-3G: More of the same

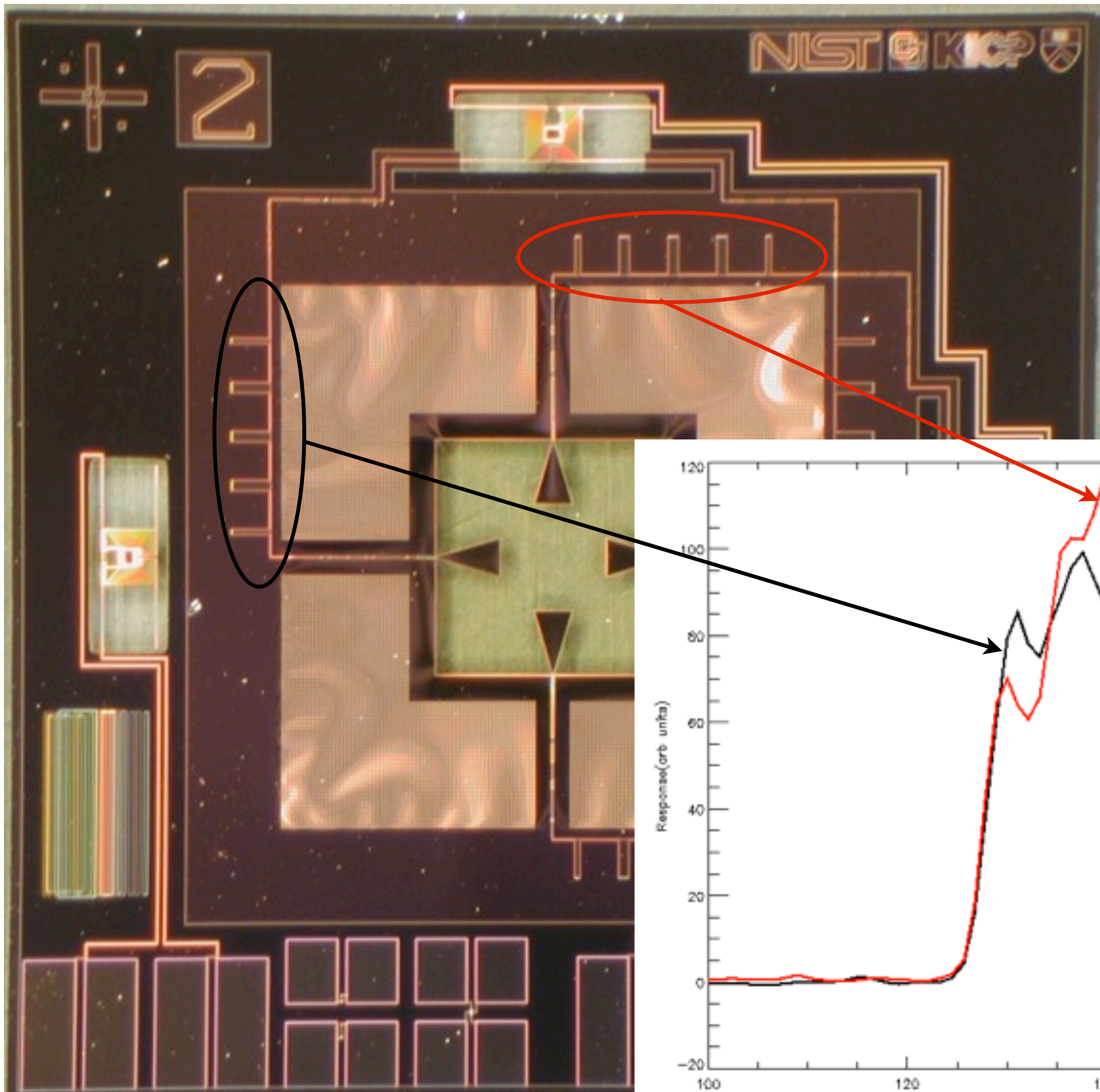
- Increase sensitivity with more detectors
  - Larger focal plane (bigger arrays and more of them)
  - Increase detector “density” (measure more optical modes per optical element)

Superconducting microstrip

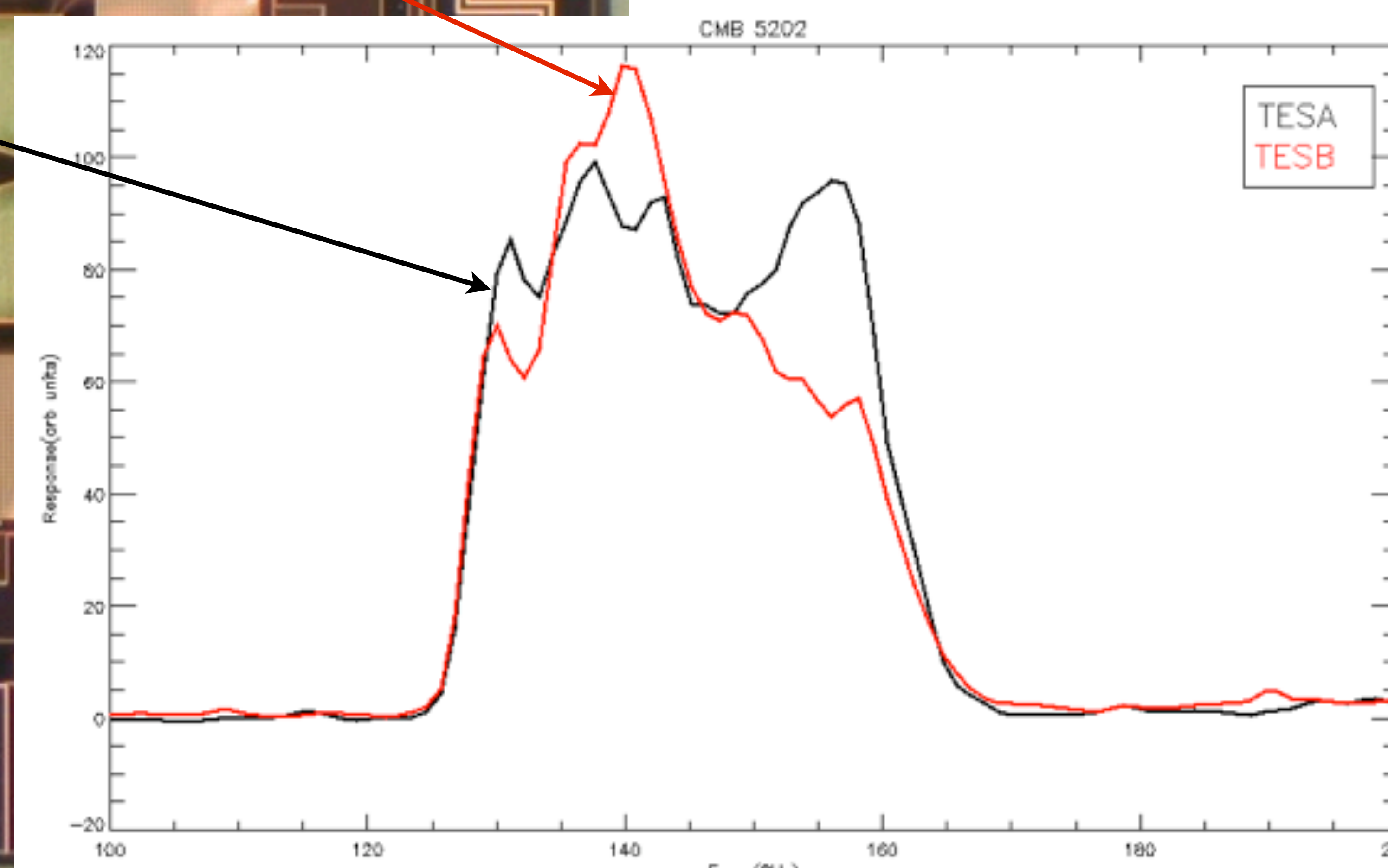


- Microstrip allows for manipulation of electric field
- Can move band pass “on chip”

Superconducting microstrip

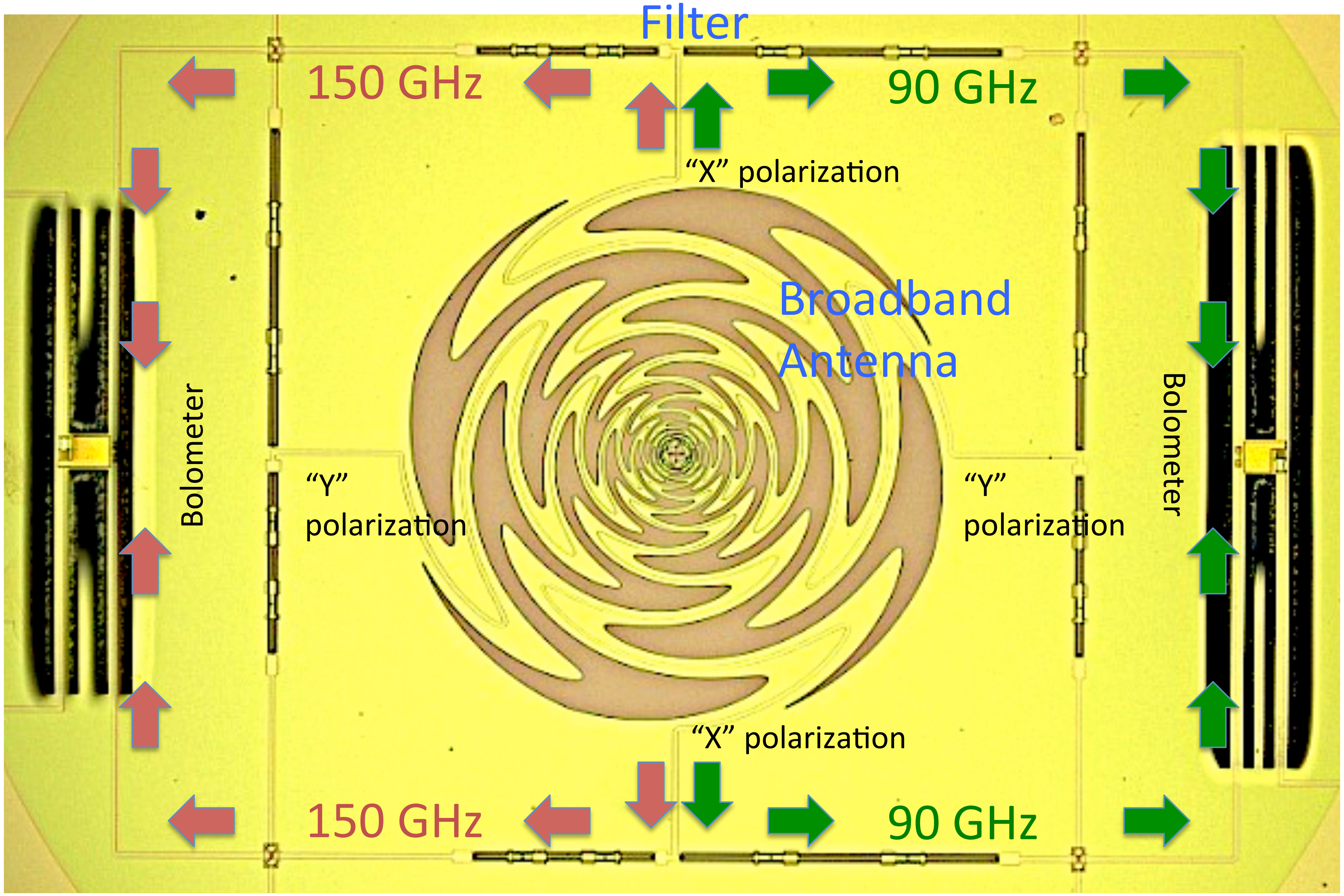


- Microstrip allows for manipulation of electric field
- Can move band pass "on chip"



Yoon et al., AIP Conf. Proc. 1185, pp. 515-518

Multi-chroic pixels

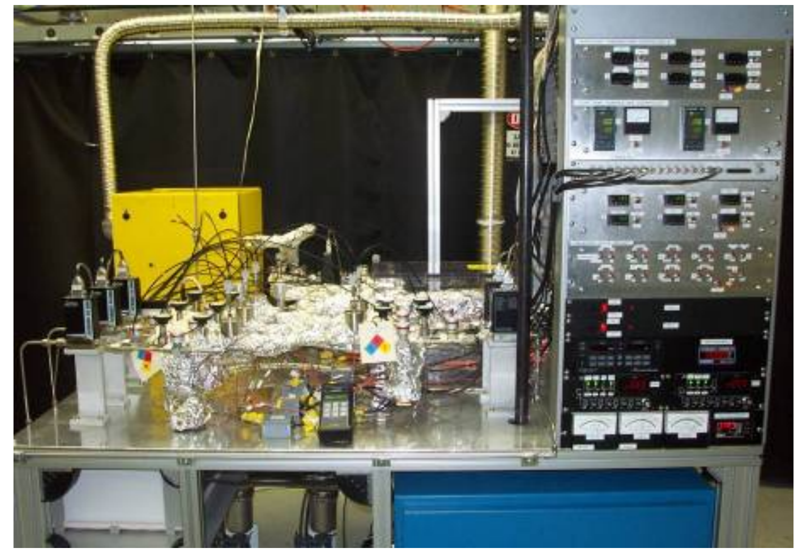


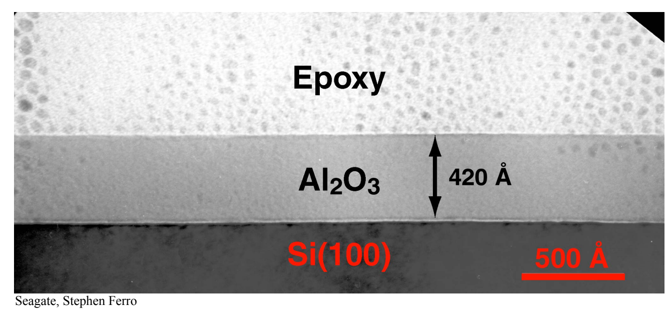
- Developing arrays of three-color pixels for SPT-3G
- Increase bolo density from 2 per pixel to 6 per pixel

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

New ideas? Atomic Layer Deposition

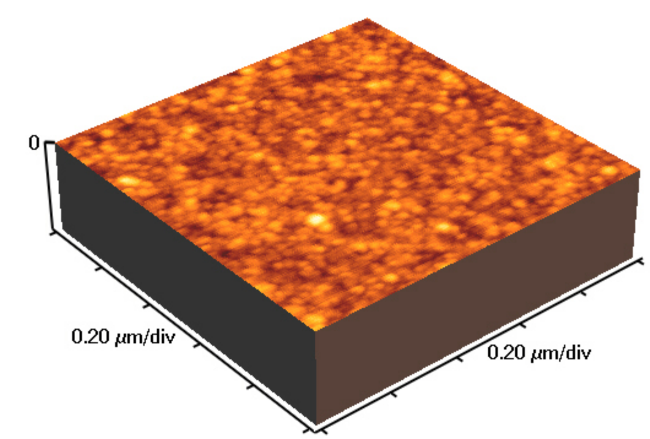
- Extremely conformal: uniform thickness over large irregular surfaces
- ANL expertise with superconductor+dielectric multilayers for RF cavities
- Potential for batch processing of films with tailored properties
- Implemented at RF frequencies for quantum computing





- Flat, Pinhole-Free Film

Atomic Force Microscopy

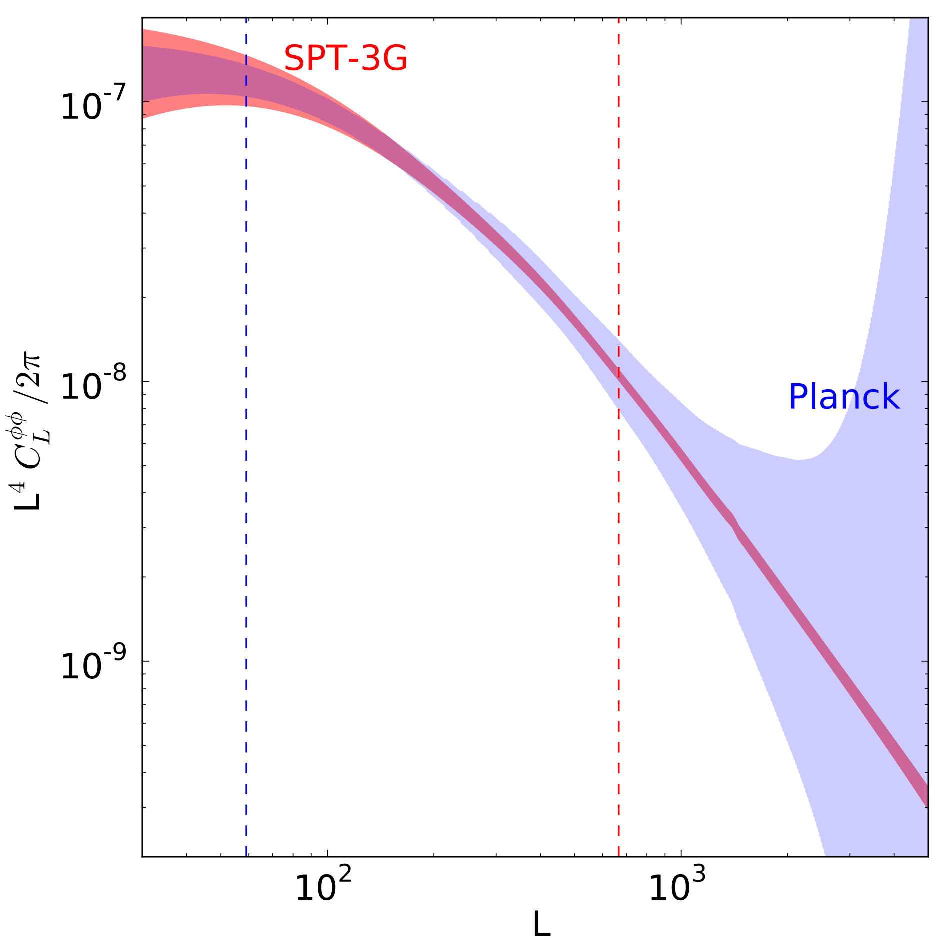


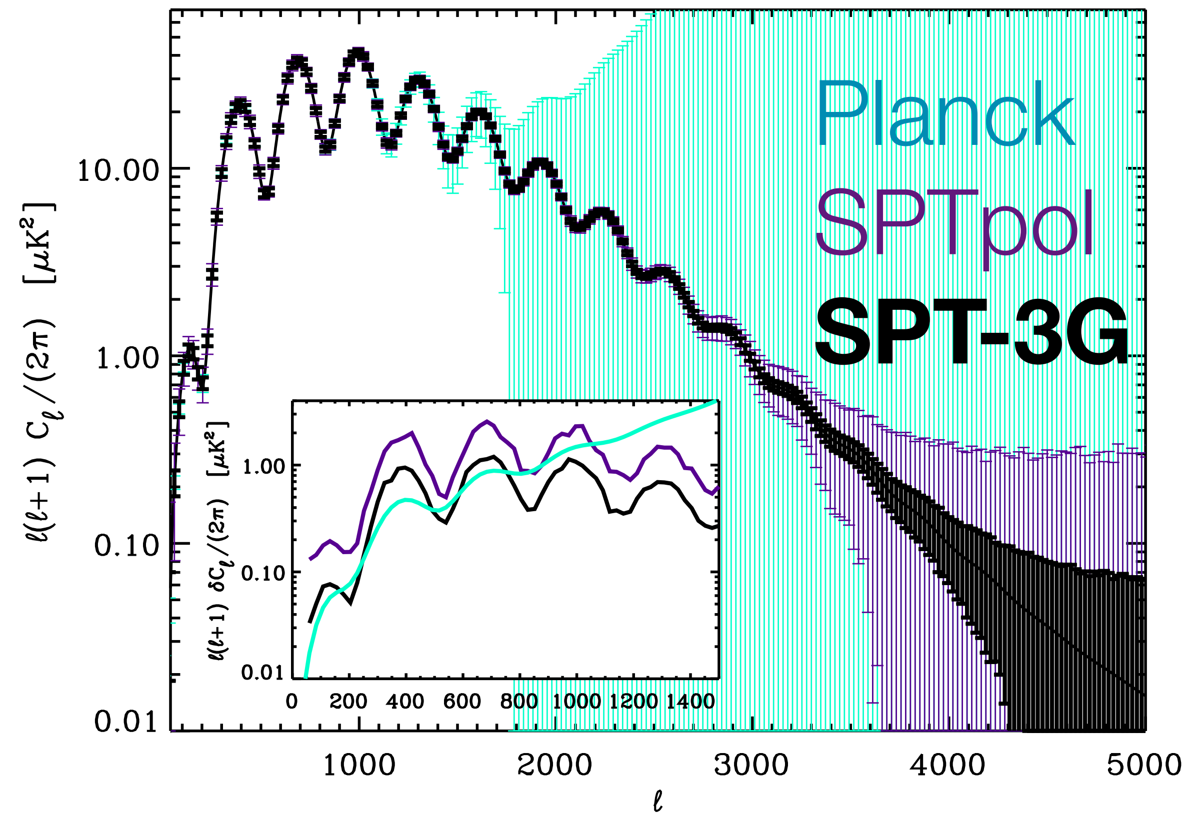
- RMS Roughness = 4 Å (3000 Cycles)
- ALD Films Flat, Pinhole free

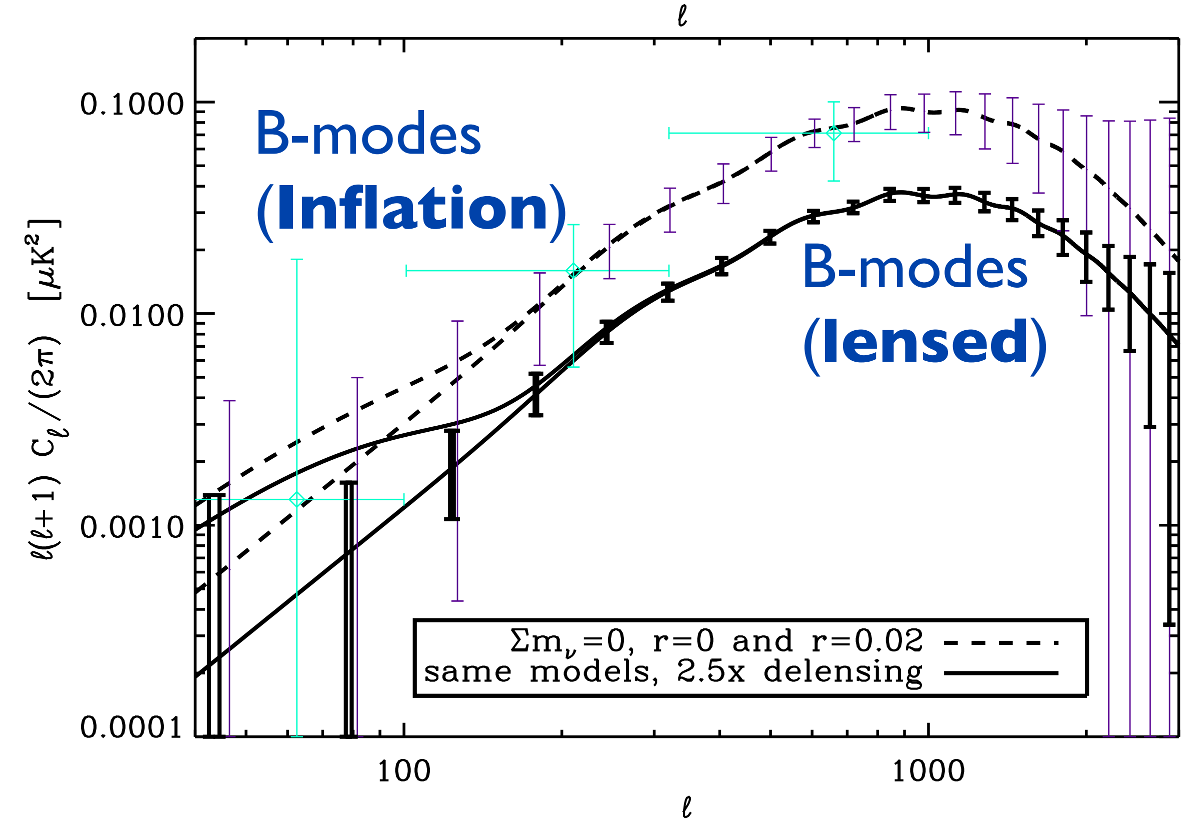
Coumou et al., Applied Superconductivity, IEEE Transactions on , vol.23, no.3, pp.7500404,7500404, June 2013

SPT-3G goals (first light early 2016)

- Target 10x mapping speed of SPTpol
  - 16,000 bolometer array
  - Reduce optical load
  - Double FOV
- Target 2500 deg^2 to 3 uK depth

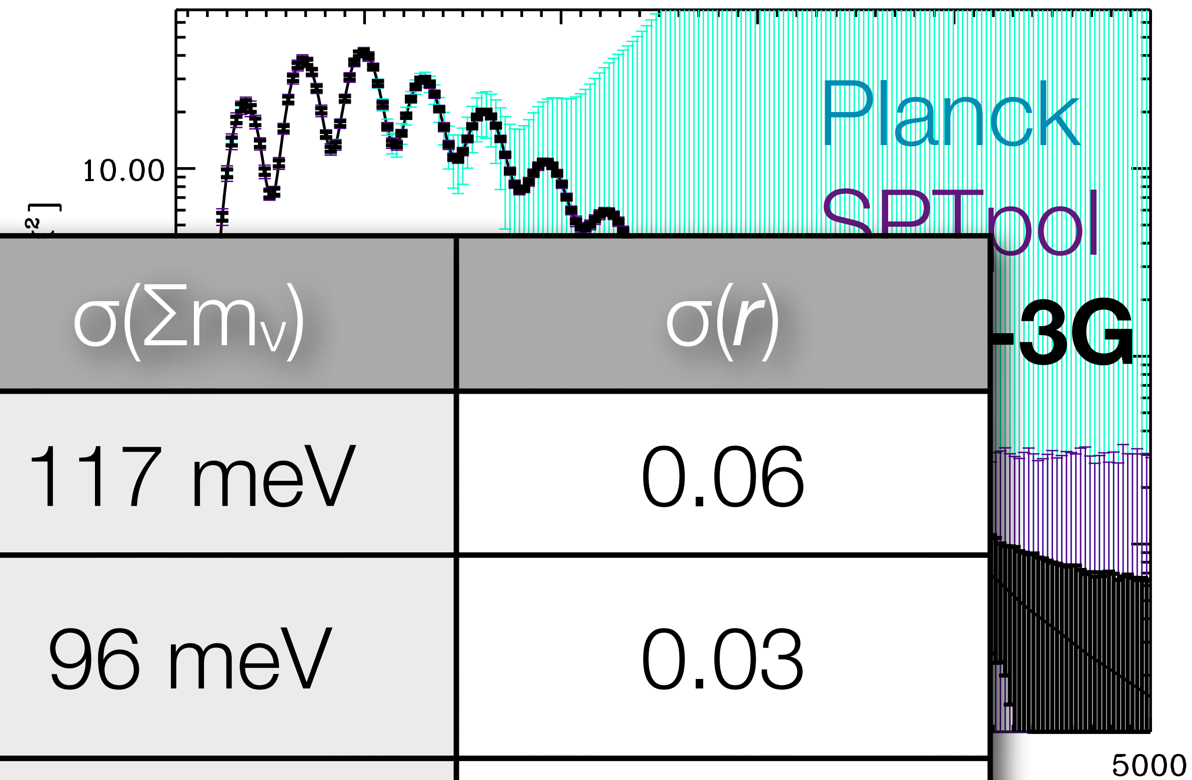






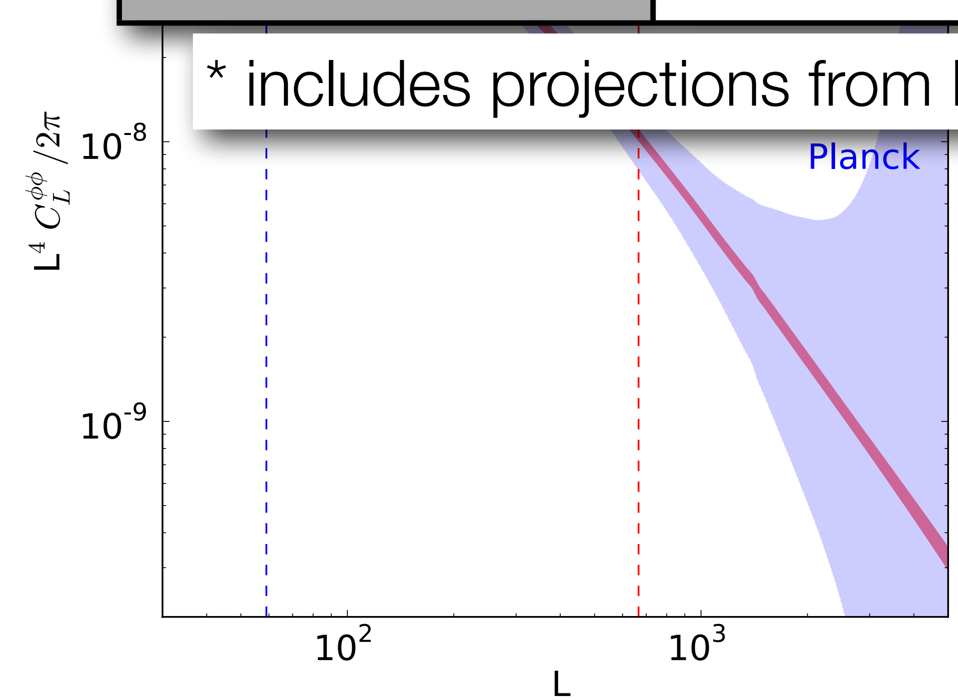
SPT-3G goals (first light early 2016)

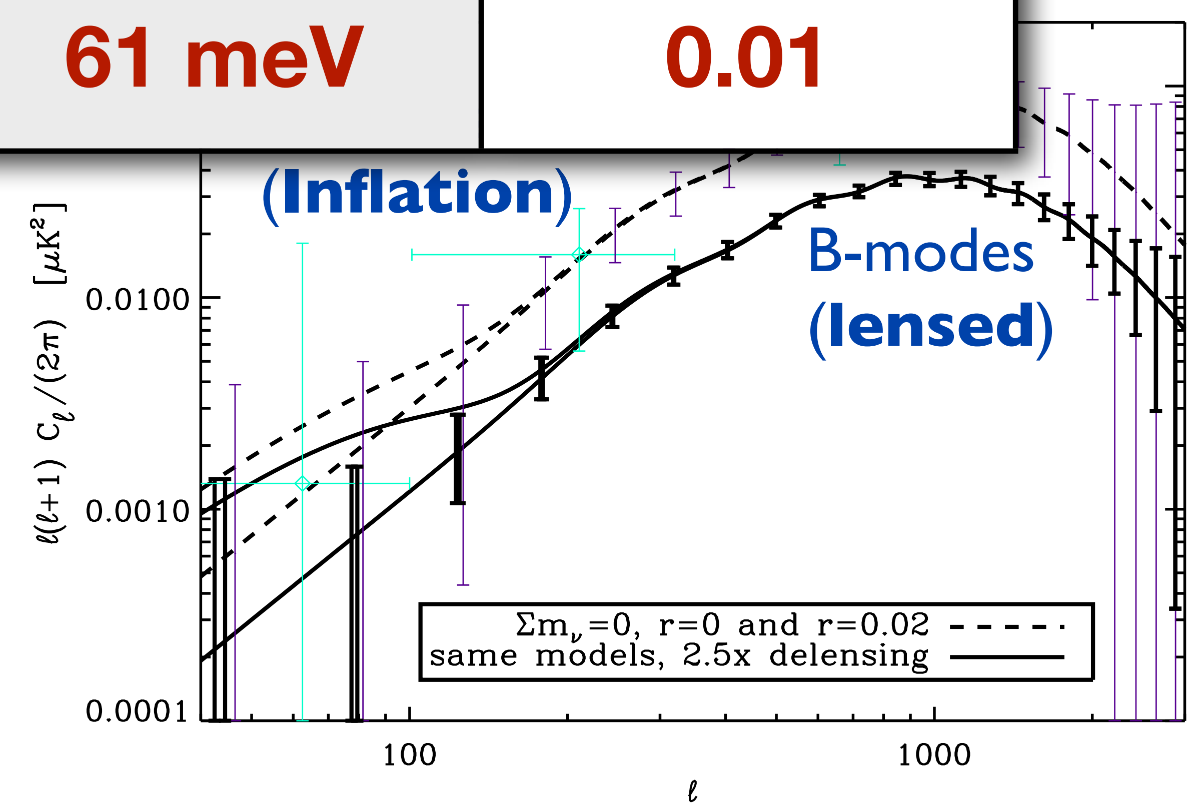
- Target 10x mapping speed of SPTpol



	σ(N_{eff})	σ(Σm_ν)	σ(*r*)
Planck	0.14	117 meV	0.06
SPTpol	0.12	96 meV	0.03
SPT-3G*	**0.06**	**61 meV**	**0.01**

* includes projections from BOSS





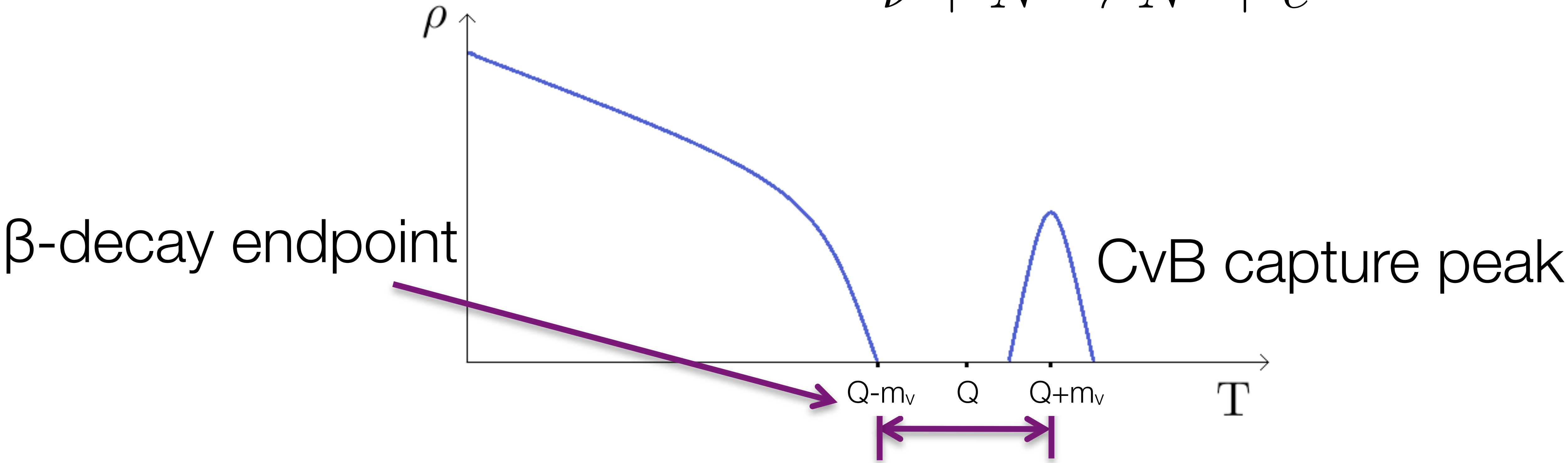
CvB detection

- "Indirect" detection
    - Expansion rate in early Universe
    - Growth of structure
    - Technically, measuring Hot Dark Matter, which includes CvB
- Direct detection
    - How do we know the HDM we see is made of neutrinos?

Direct detection of the CvB

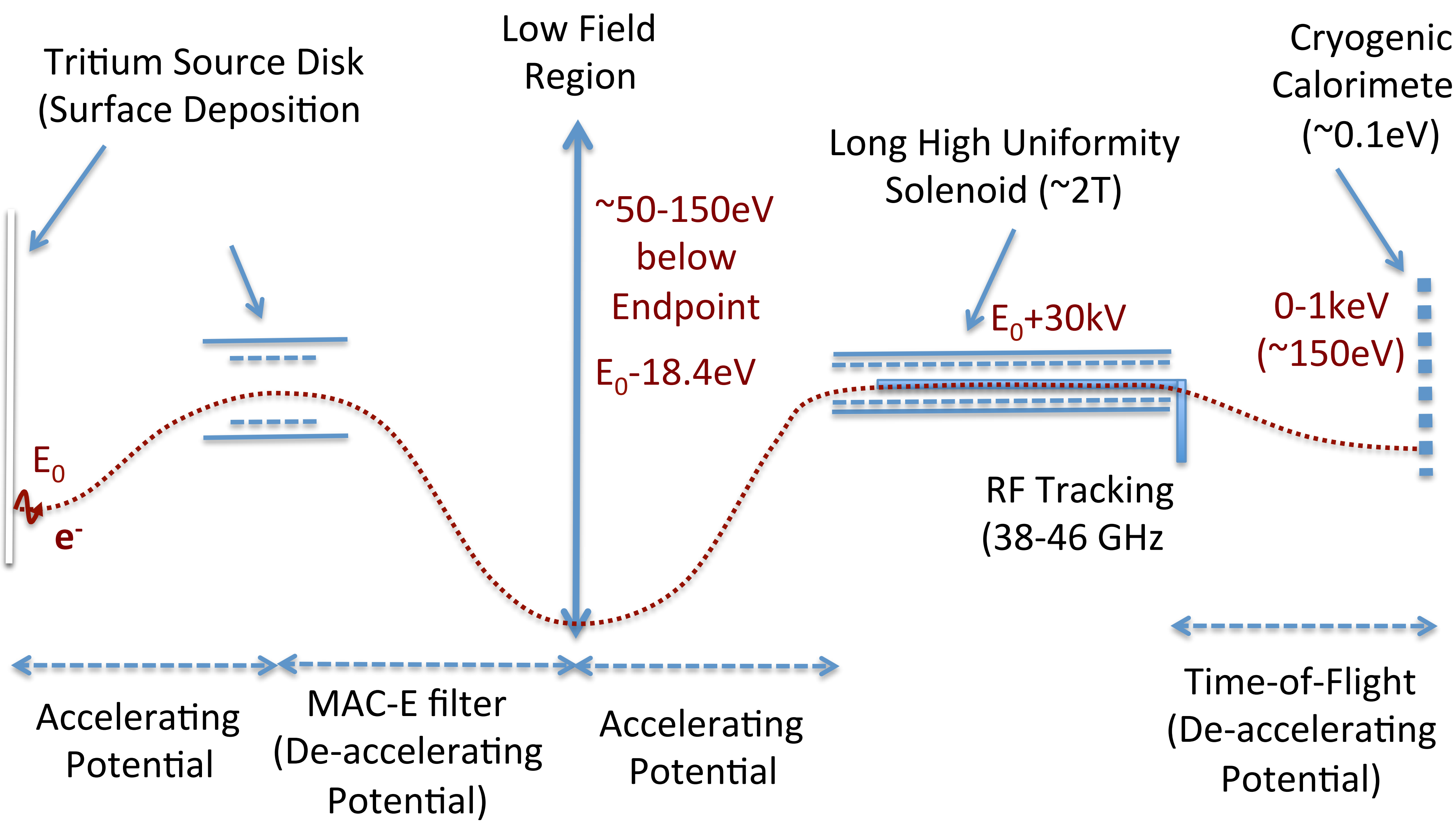
$$N \rightarrow N' + e^- + \bar{\nu}$$

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



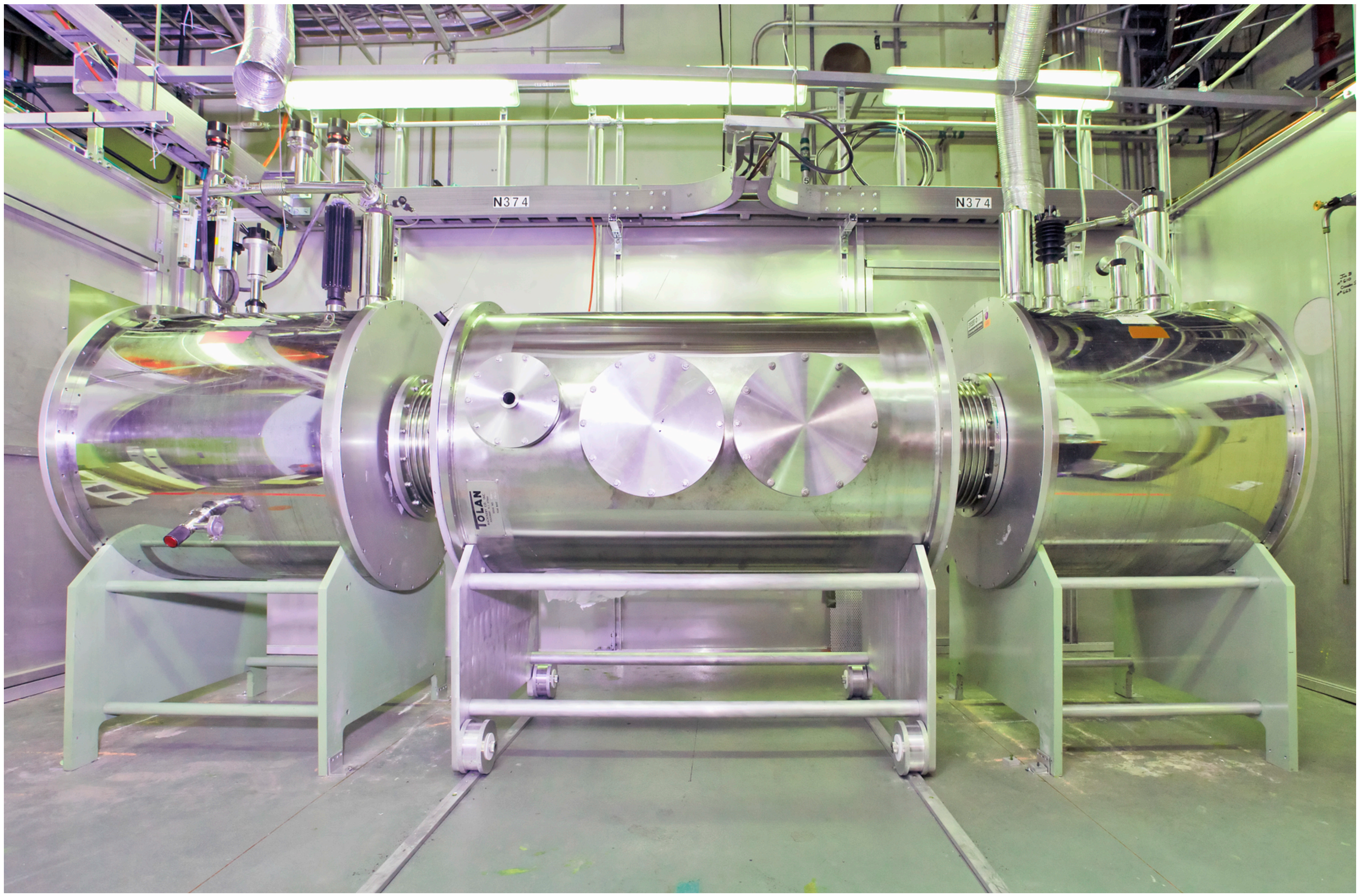
Weinberg, Phys. Rev. 128:3, 1457 (1962)
Lazauskas et al., J.Phys. G35 (2008) 025001

PTOLEMY



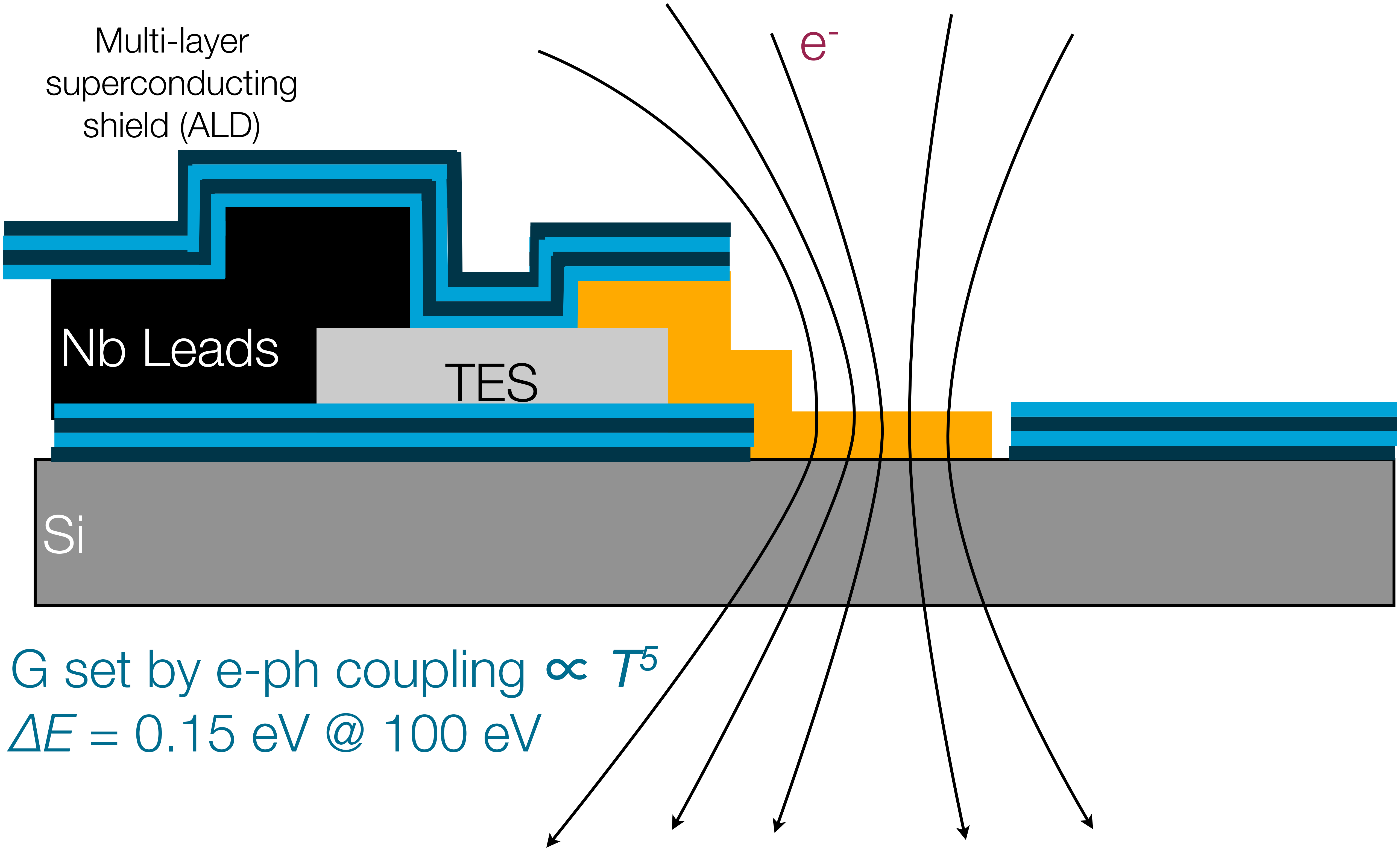
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

PTOLEMY in the works



Prototype at Princeton Plasma Physics Lab

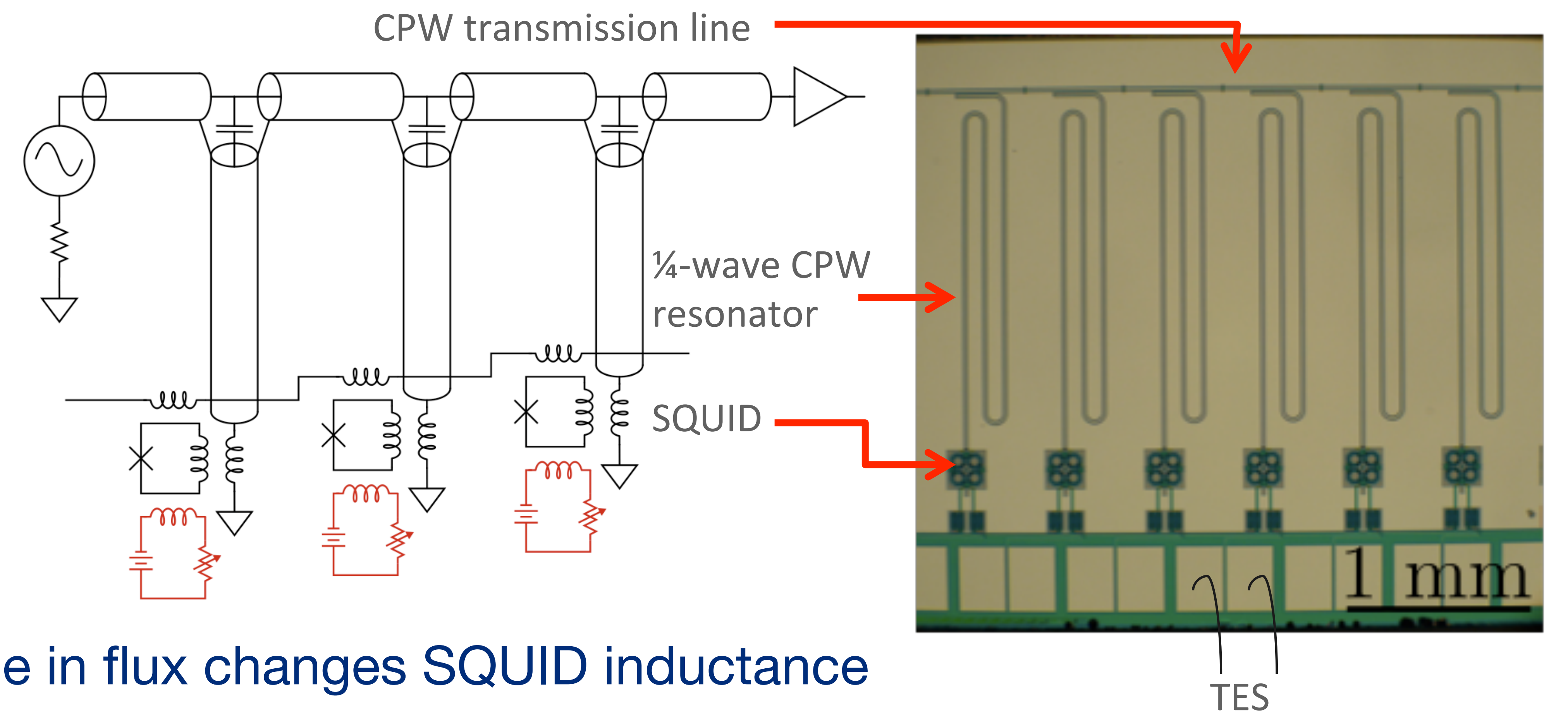
TES and PTOLEMY



G set by e-ph coupling ∝ T^5

ΔE = 0.15 eV @ 100 eV

Microwave-readout Massive SQUID Multiplexer



- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

Rough numbers

- 100 g ^{3}T (a lot) yields ~10 CvB neutrinos per year
- TES microcalorimeter with ~0.15 eV resolution would see CvB capture at 3σ for m_ν~0.45 eV (no background subtraction)
- Precise predictions and “indirect” evidence means a “Vanilla” detection would
    - Validate Hot Big Bang at time = 1 second
    - Validate standard CvB cosmology
    - Measure neutrino clustering
    - Measure the neutrino mass

Recap

- Broad connections are important
- Developments in superconducting technology are driving new TES applications
- Significant impact on CMB/mm-wave instruments
  - SPT-SZE: UCB completed
  - SPTpol: ANL & NIST running
  - SPT-3G: ANL upcoming
- New opportunities with PTOLEMY
- Precise expectations for CvB which we will probe soon!

Recap

"The interesting thing about doing new experiments is that you never know what the answer is going to be!" - Ray Davis

- Broad connections are important
- Developments in superconducting technology are driving new TES applications
- Significant impact on CMB/mm-wave instruments
  - SPT-SZE: UCB completed
  - SPTpol: ANL & NIST running
  - SPT-3G: ANL upcoming
- New opportunities with PTOLEMY
- Precise expectations for CvB which we will probe soon!