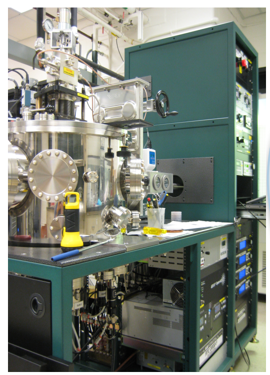
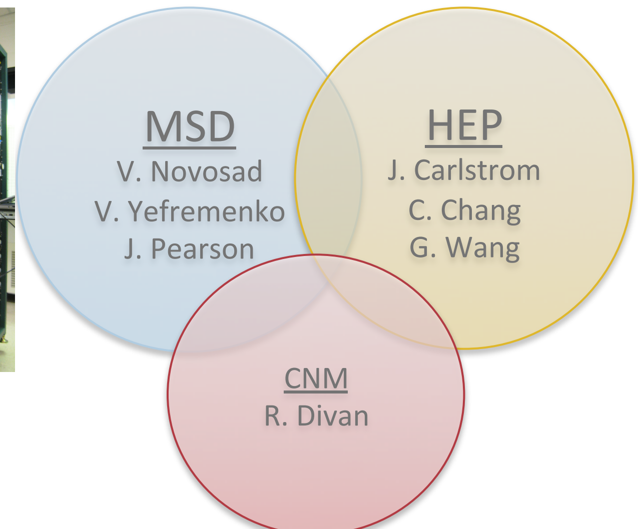
Transition Edge Sensors

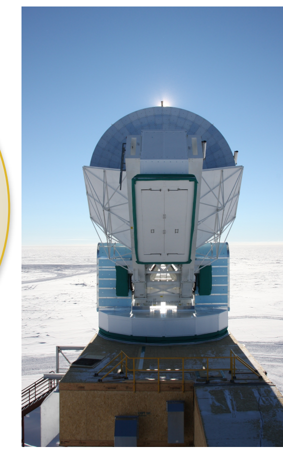
Clarence Chang

DOE KA-15 Review

July 25, 2012

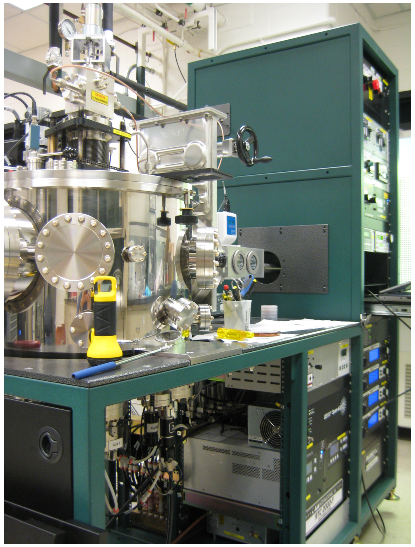






U.S. DEPARTMENT OF ENERGY

Unique multi-disciplinary program

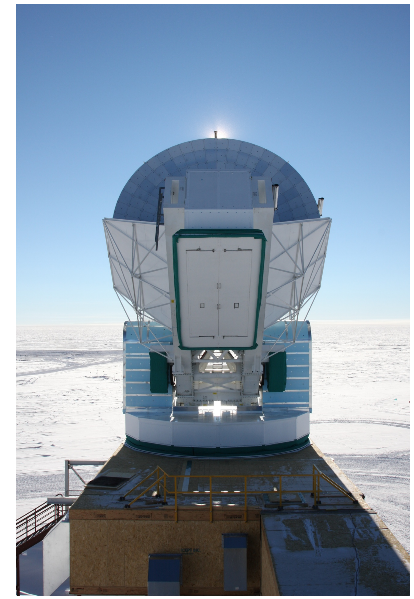


MSD

- Thin film expertise
- Materials characterization
- Dedicated deposition equipment

CNM

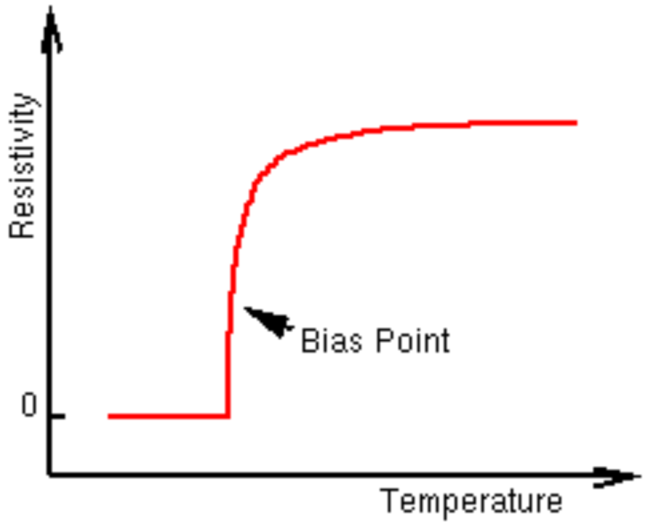
- Lithography & etching resources
- Scientific Users facilities

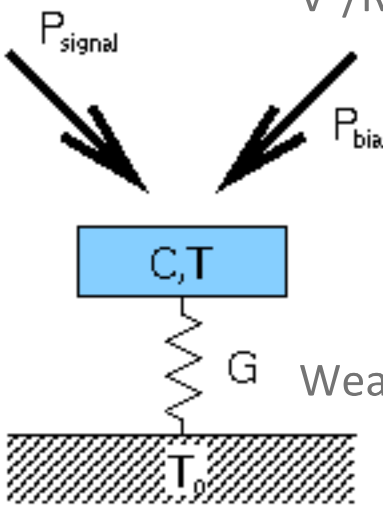


HEP

- Scientific context
- Detector testing & characterization
- Experiment delivery

Transition Edge Sensor





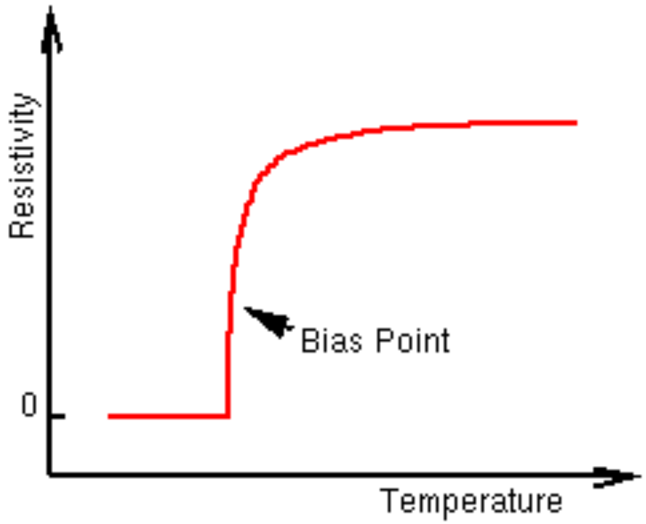
- Low impedance
- SQUID readout
- Multiplexable

↑P_{signal} -> ↑R -> ↓P_{bias}

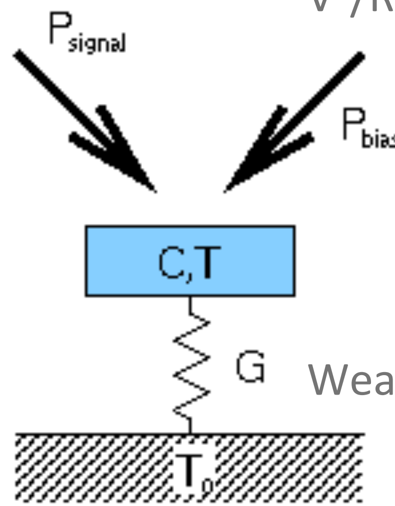
Negative Feedback

- Linearity
- Faster
- Gain α transition width

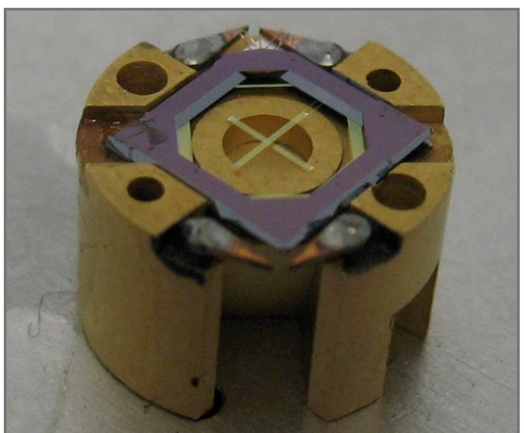
Transition Edge Sensor

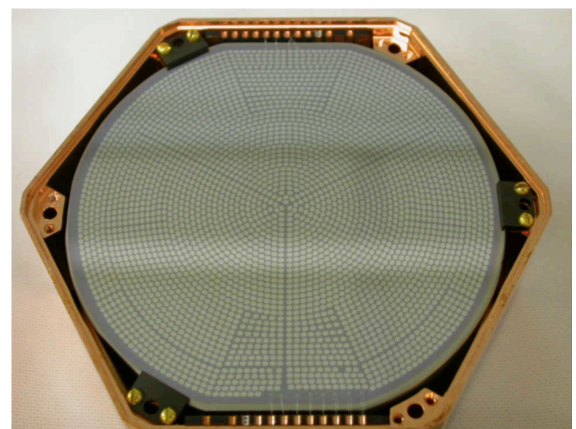


V^2/R; voltage biased



Weak thermal link





CMB bolometers, low energy, slow

Dark Matter detectors, higher energy, fast

From idea to "instrument ready"

- Mm-wave bolometers
- Optical/IR spectrophotometers
- X-ray microcalorimeters
- Gamma-ray spectrometers
- Alpha calorimeters
- Heavy ion/particle detectors
- Etc…

History of innovation

TES Array Technology

Science potential

- CMB
- Dark Matter
- Beta decay
- Synchrotron Light Source
- Nuclear Non-proliferation
- Heavy Ion Physics
- National Security
- Quantum Information
- Astrophysics & Astronomy
- Etc …

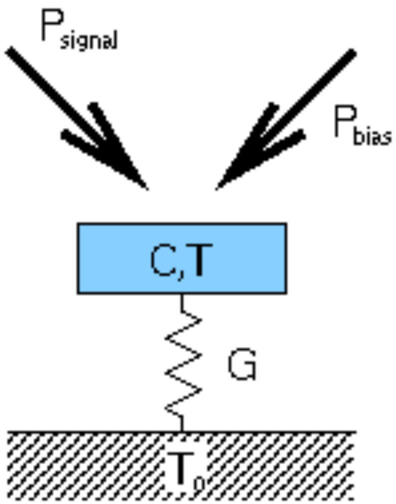
Taking from "good ideas" to "instrument ready"

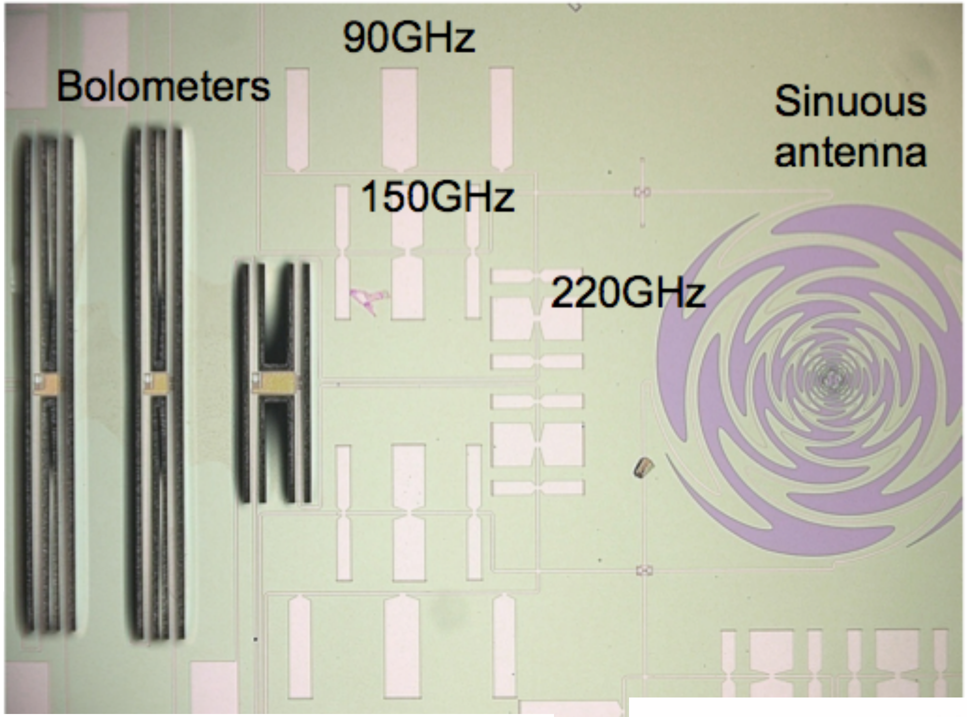
FY13-15 program

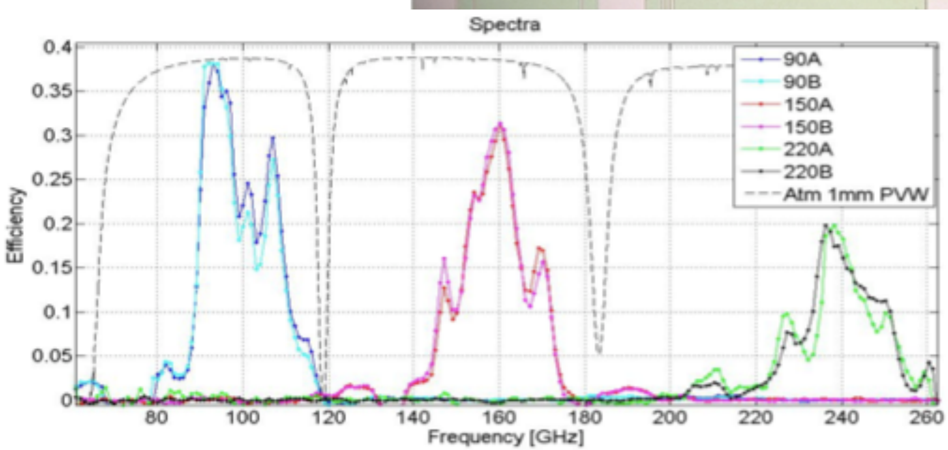
- Develop low-loss microstrip for mm-wave radiation coupling
- Demonstrate proof-of-concept new TES multiplexer

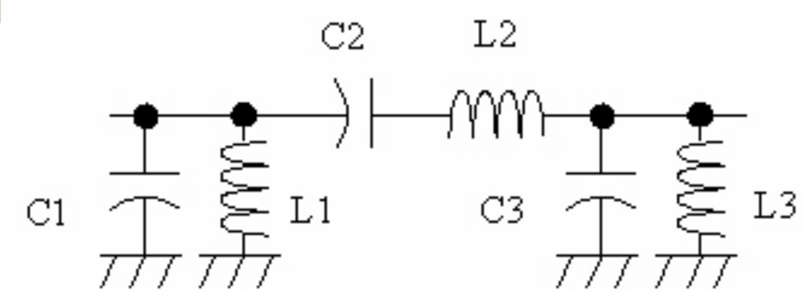
- High impact for future HEP science
  - Dark Matter
  - CMB
- Leverages unique multi-disciplinary resources at ANL
  - MSD, CNM, HEP
- Strong history and collaborations with experts in the field
  - NIST, Berkeley, UC-Boulder, McGill, CWRU
- Local support
  - KICP Detector initiative (including Berkeley, ANL, JPL)
  - opportunities for launching/exporting technologies into science applications

Low-loss microstrip detectors









Performance limited by loss

Challenges

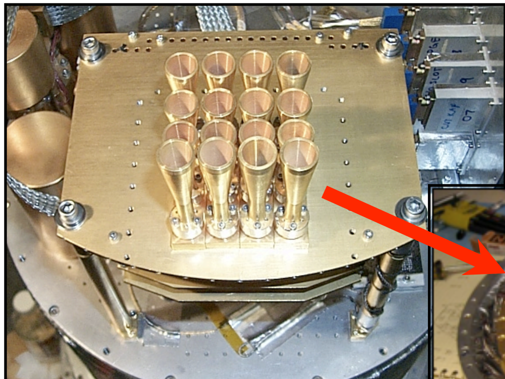
- Optimal filter performance requires low loss microstrip
- Loss dictated by microstrip thin film material properties ("two level systems")
  - Process dependent
  - Environment dependent

Goal:

- Characterize, understand, and control the loss in superconducting microstrip
- Fabricate ultra-low loss microstrip for optimal performance
- Develop high-throughput, consistent manufacturing

Impact: high-density focal plane arrays

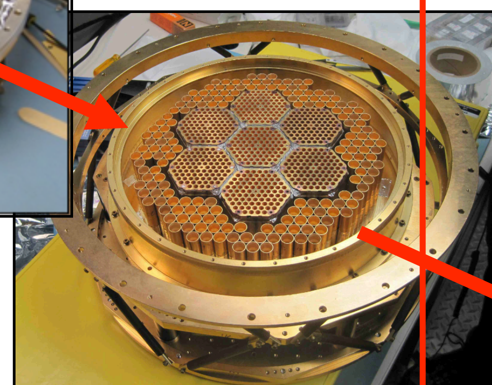
2001: ACBAR
16 detectors



Detector performance governed by material properites

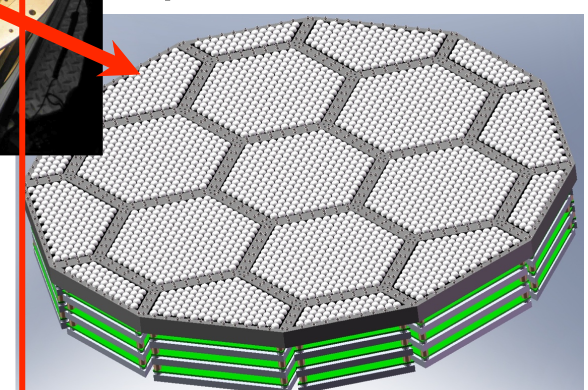
2007: SPT
960 detectors

2012: SPTpol
~1600 detectors
+pol



FY13-15 R&D

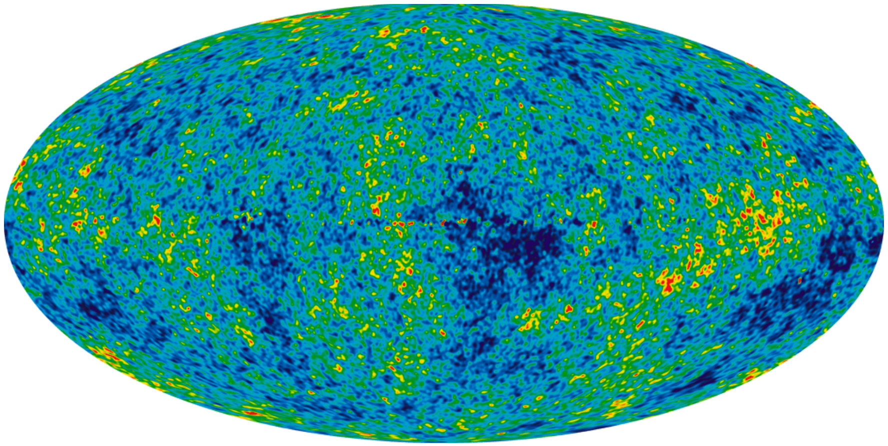
2016: SPT-3G
~15,200 detectors
+pol, multichroic

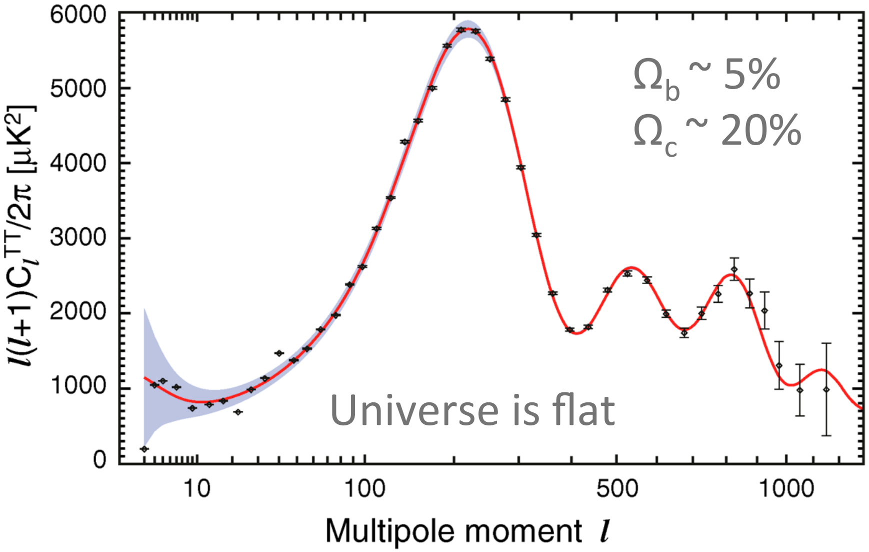


ACBAR was the first experiment to make a background limited detector

Requires high-throughput production

Frontier of CMB





well understood physics permits accurate calculation of features

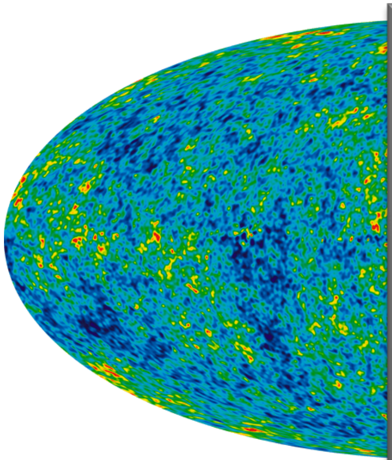
Depends on energy density and expansion during the early Universe

Better measurements explore fundamental physics

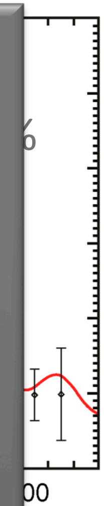
Beyond WMAP:

- N_{eff}
- Σm_ν
- Dark Energy, w
- Inflation & GUT scale physics

Frontier of CMB



For presentation only



well understood
accurate calcula

Depends on ene
expansion durir

Better meas ysics
explore fundamental physics

Summary: Low-loss microstrip

Capability Gap

CMB science pushing to large focal planes… more sensitivity

- Superconducting microstrip enables high focal plane density
- Microstrip loss limits performance; dictated by material properties of thin films

Approach

Unique resources & relationships

- Materials experts and resources @ MSD
- Fabrication tools @ CNM & MSD
- Strong collaboration with TES experts (Berkeley, NIST)
- Local support at ANL, FNAL, and UofC for science and detector development (KICP detector initiative)

Benefit

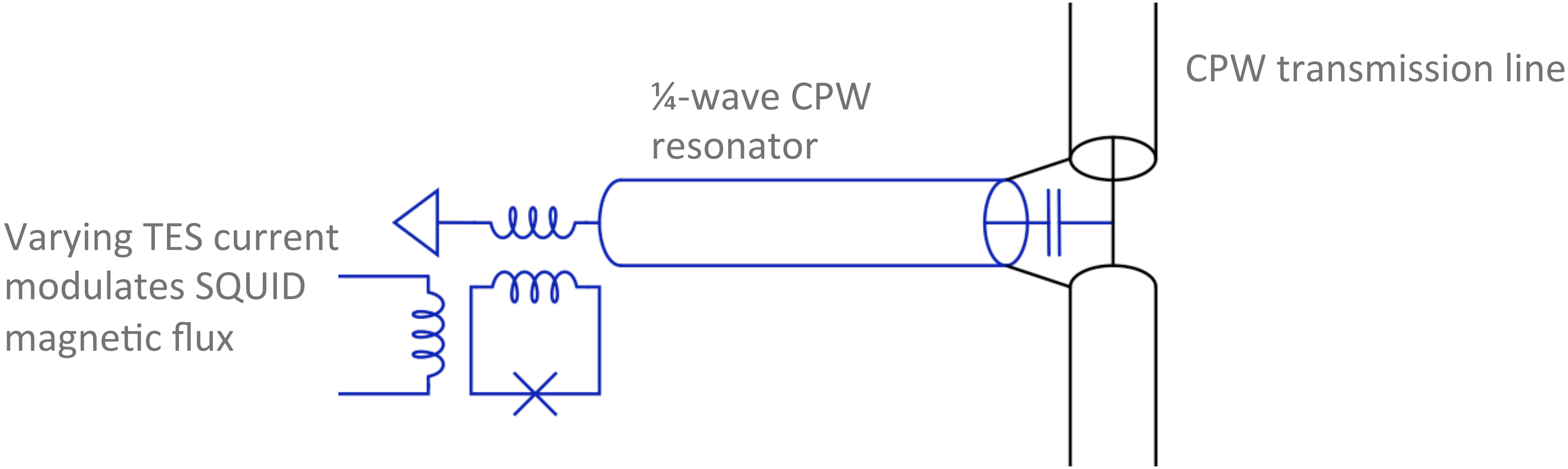
CMB beyond WMAP (& Planck)

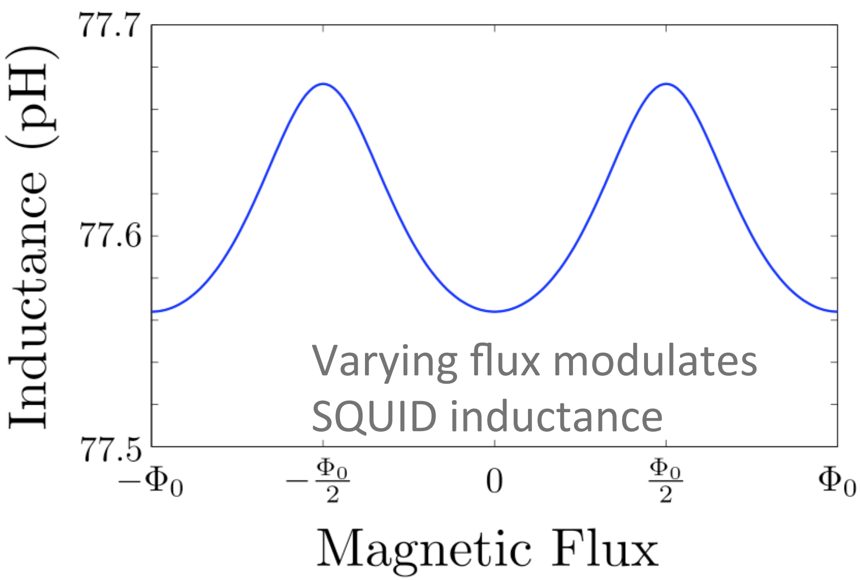
- N_{eff} : # neutrino-like species
- Σm_{ν} : energy scale of neutrino mass
- w: Dark Energy equation of state (growth based)
- r: Inflation (unique window into 10^{16} GeV physics)

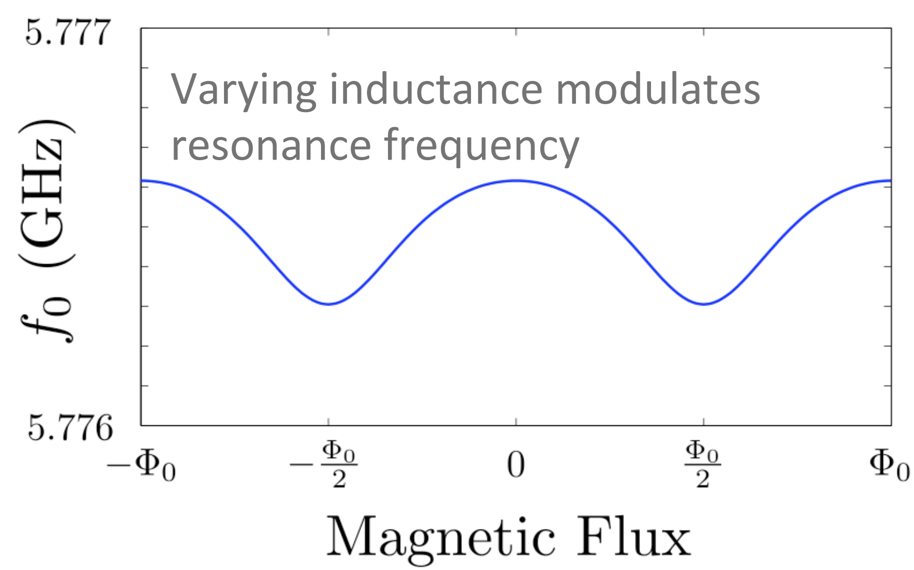
Results and Deliverables

- Determine loss dependencies on fabrication process
- Reduce loss for optimal performance
- Systematize processing for high-throughput fabrication

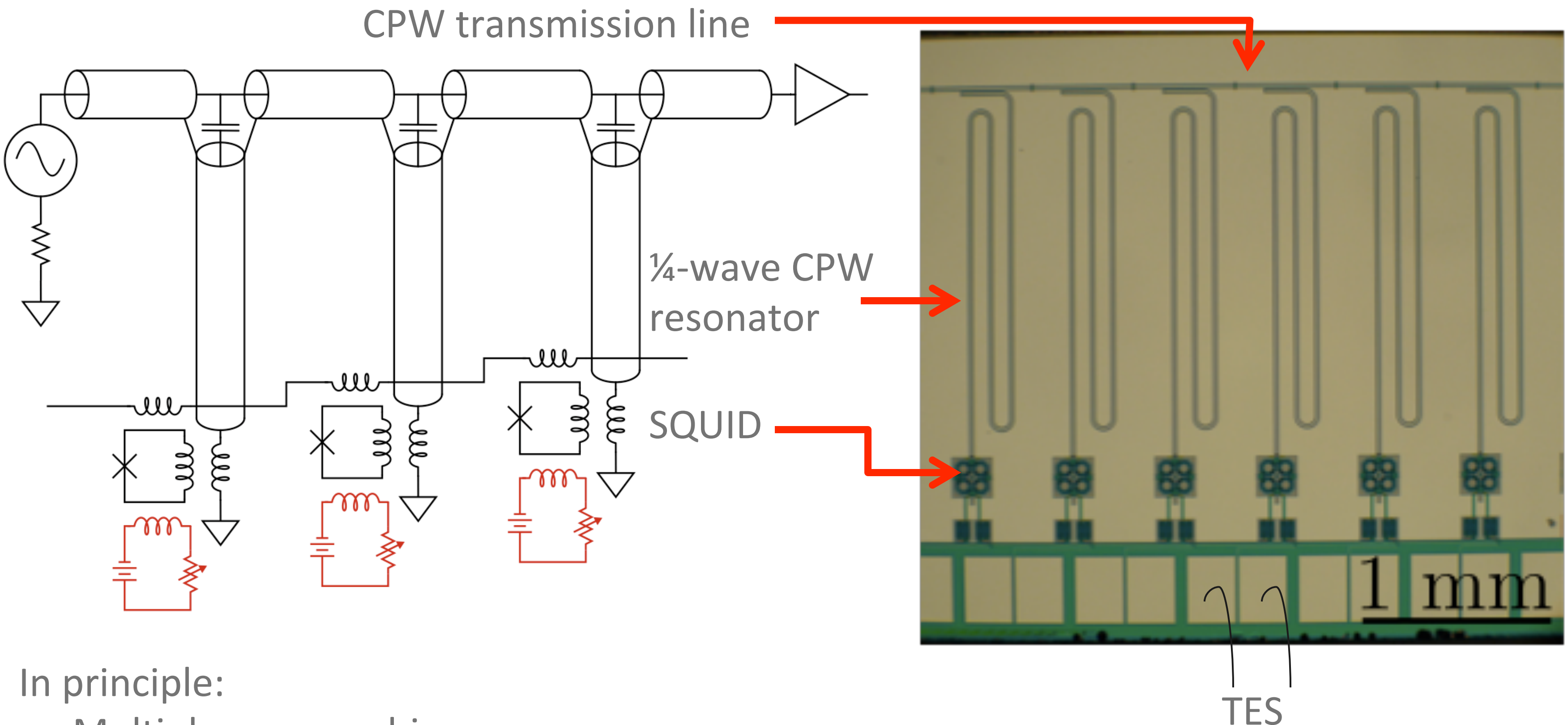
MUX: SQUID coupled microwave resonators







TES multiplexer on a chip



In principle:

- Multiplexer on a chip
- 1000s of detectors on a single pair of coax-CPW
- ~1 MHz of bandwidth (required for DM background rejection)

Goal: ANL provides detectors & conducts proof of principle demonstration

Multiplexer proof-of-principle

Capability Gap

- Broad TES applicability. Limited by array size due to readout
- Current MUX has O(50) per line (<10 kpixel array)
- Current MUX has <5 kHz bandwidth

Approach

SQUID based Microwave MUX

- High bandwidth (1 MHz): enables multiplexing w/ background rejection for DM
- Large MUX factor (~1000 channels per line)
- Collaboration with NIST

Benefit

- Dark Matter (eg: CDMS/GEODM)
- Beta decay (eg: MARE II)
- “Blue sky” technology
  - Enables Megapixel TES arrays
  - X-ray spectroscopy
  - IFU for astronomy
  - Nuclear physics calorimetery

Results and Deliverables

Demonstrate MUX works for particle counting applications w/ required bandwidth

- Use ANL made TES based x-ray detectors
- Commission microwave test bed
- Demonstrate/characterize MUX performance
- “Proof-of-concept” before G3 Dark Matter technology decision

From idea to "instrument ready"

- Mm-wave bolometers
- Optical/IR spectrophotometers
- X-ray microcalorimeters
- Gamma-ray spectrometers
- Alpha calorimete
- Heavy ion/parti detectors
- Etc…

History of inno

Unique ANL resources
- MSD
- CNM

TES Array Technology

TES expertise
- Expert collaborators
- Development history

Scientific connections
- ANL
- KICP
- FNAL

Science potential

- CMB
- Dark Matter
- Beta decay
- Synchrotron Light Source
- uclear Non-proliferation
- on Physics
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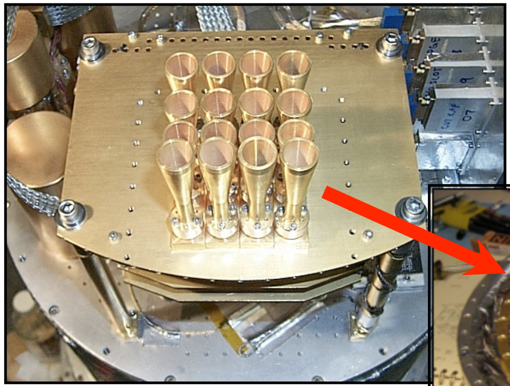
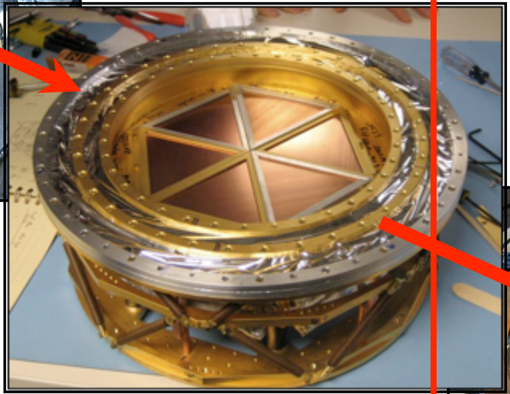
- s & Astronomy

From concept to science

2001: ACBAR
16 detectors

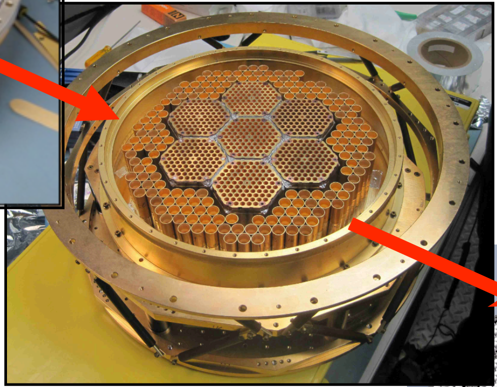


2007: SPT
960 detectors

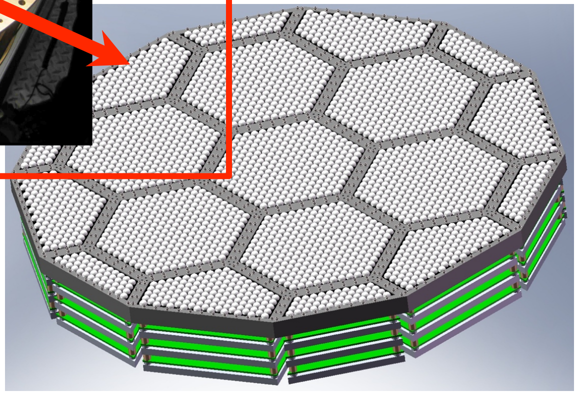


ANL 90 GHz &
NIST 150 GHz;
Built from scratch

2012: SPTpol
~1600 detectors

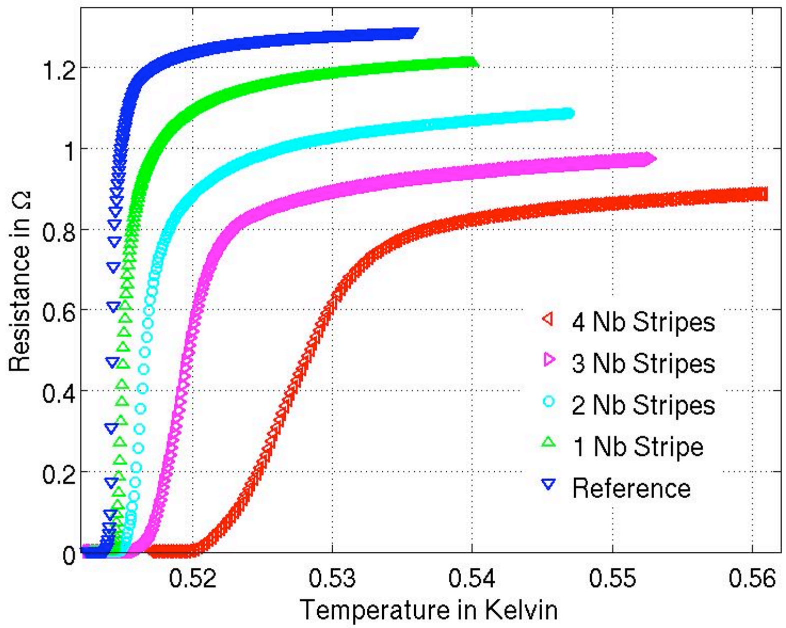


2016: SPT-3G
~15,200 detectors



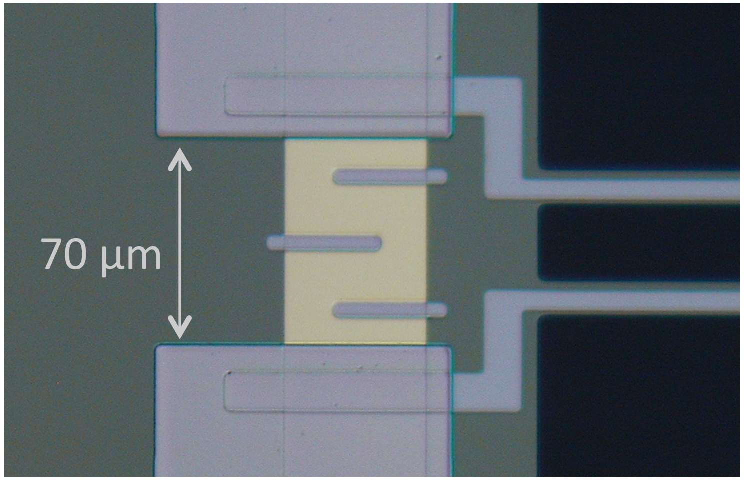
SPTpol detector collaboration
includes UChicago, UCB,
CWRU, CU, NIST, McGill

New technology: transition engineering

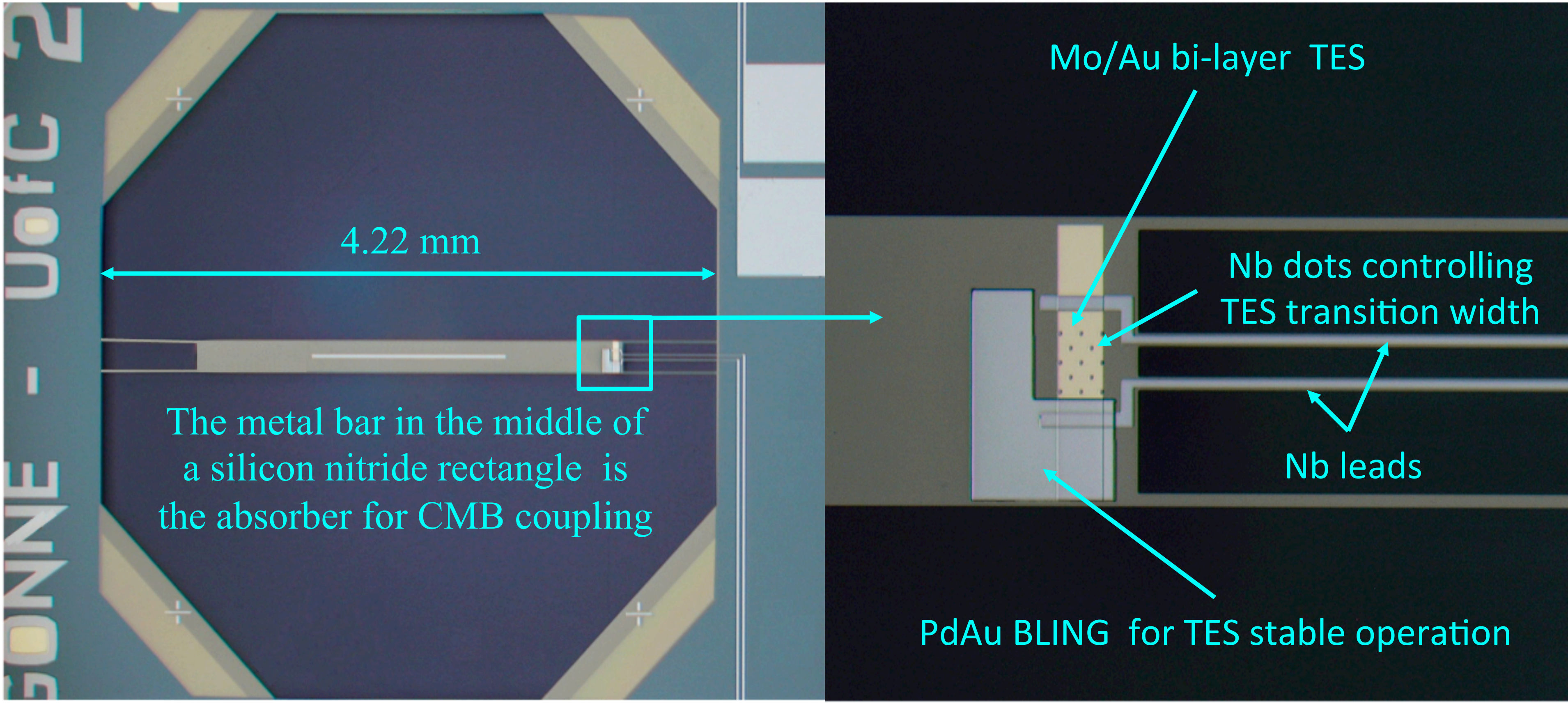


Steeper -> faster; more linear
Broader -> more stable

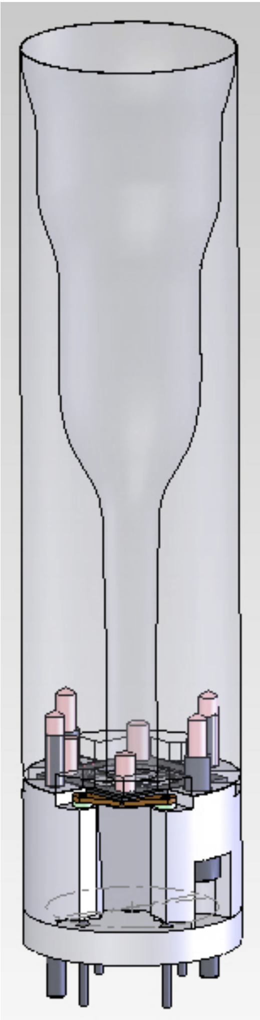
Use structures to optimize

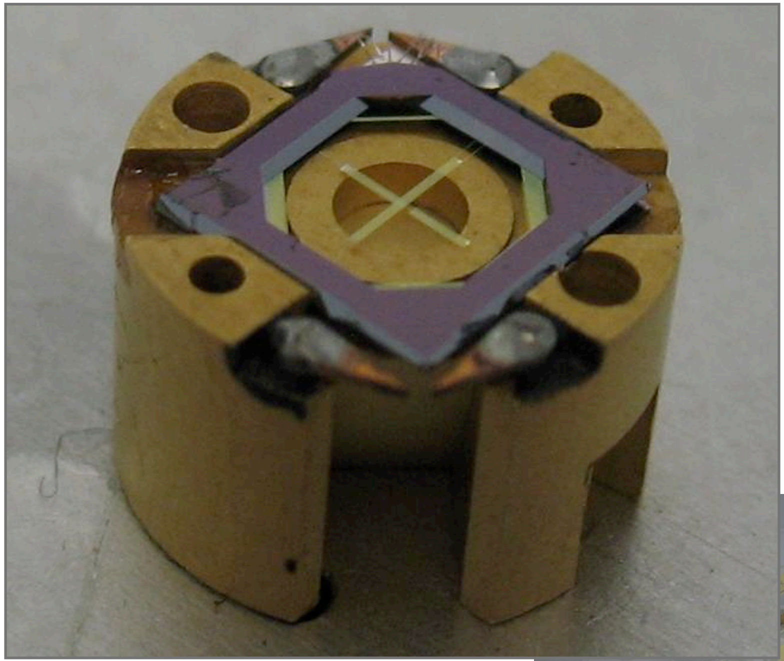


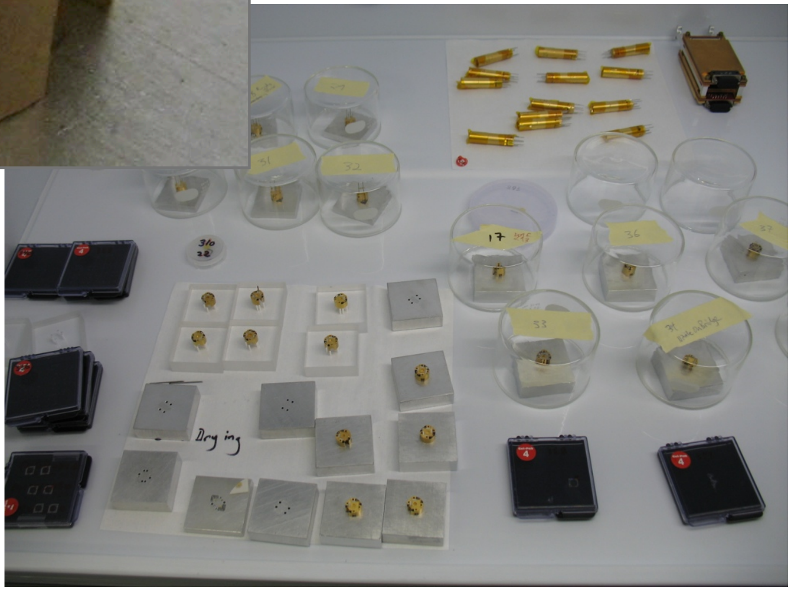
ANL TES bolometers: built from scratch

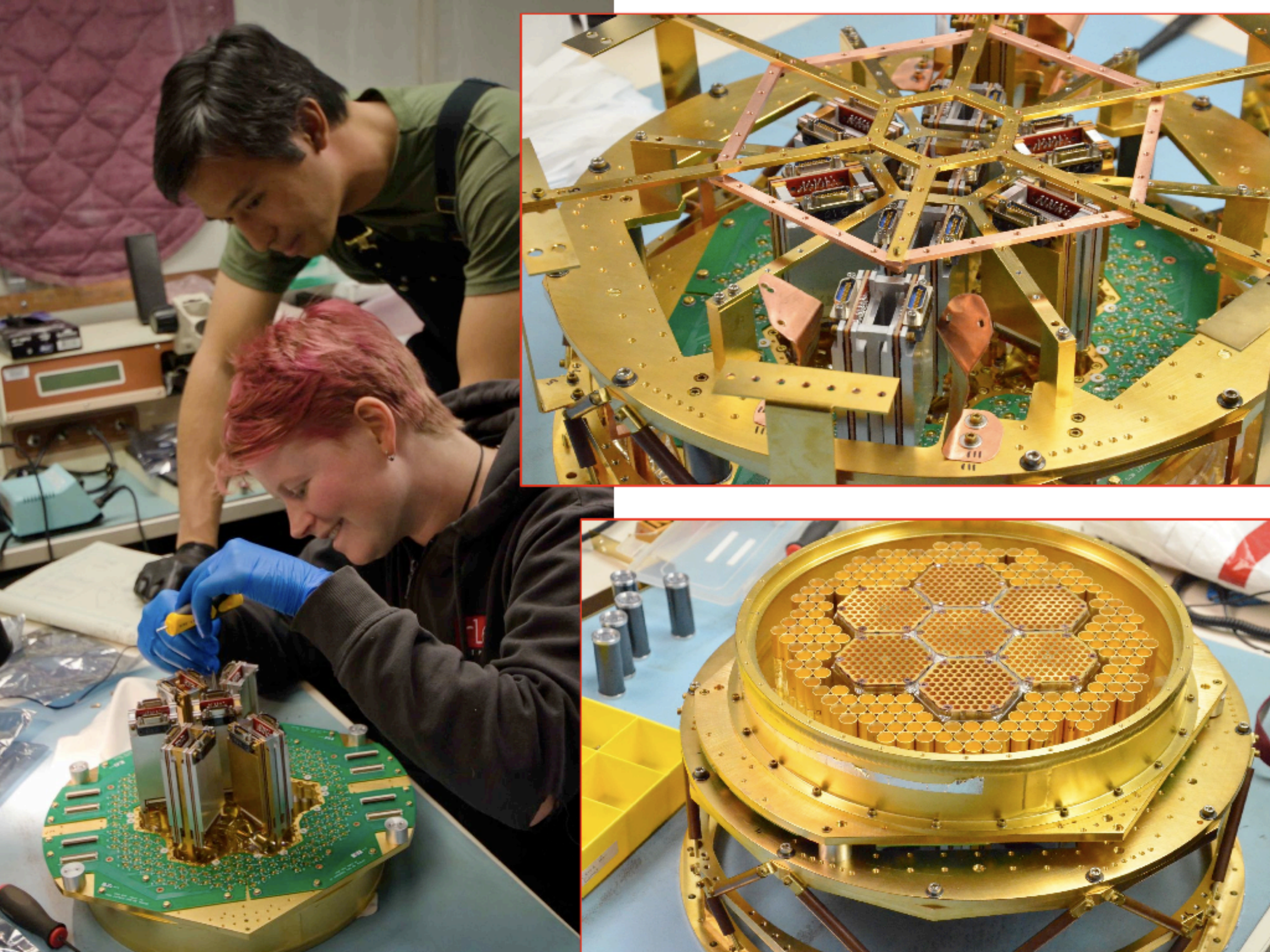


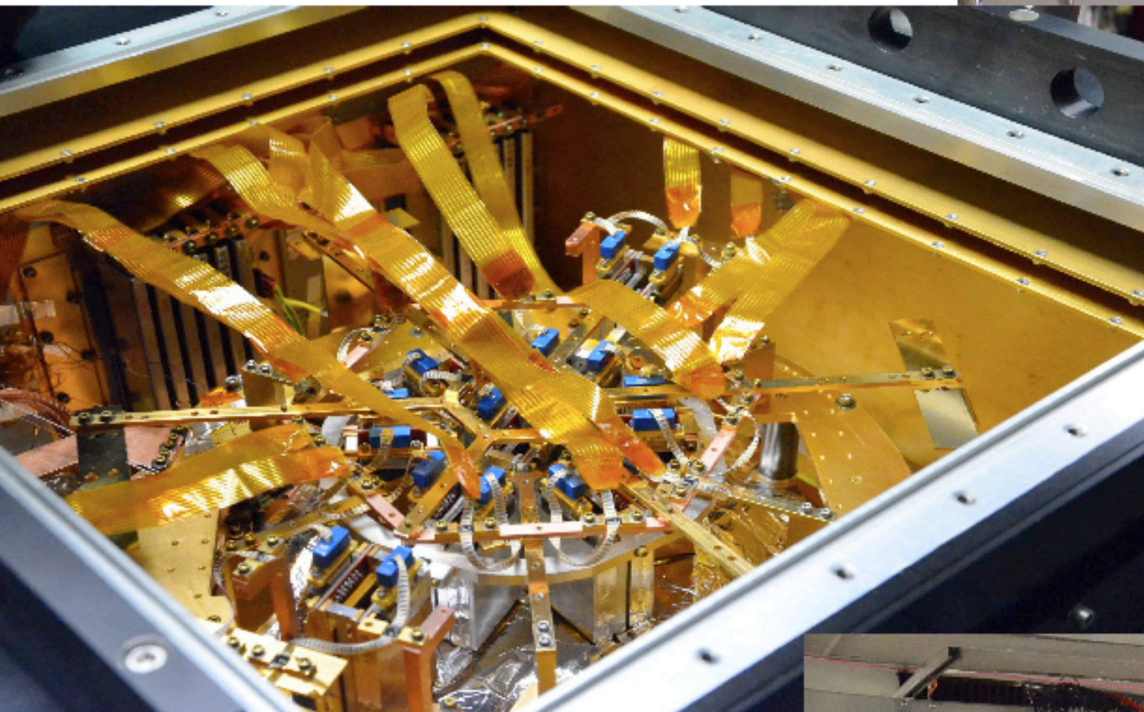
Detector production and assembly

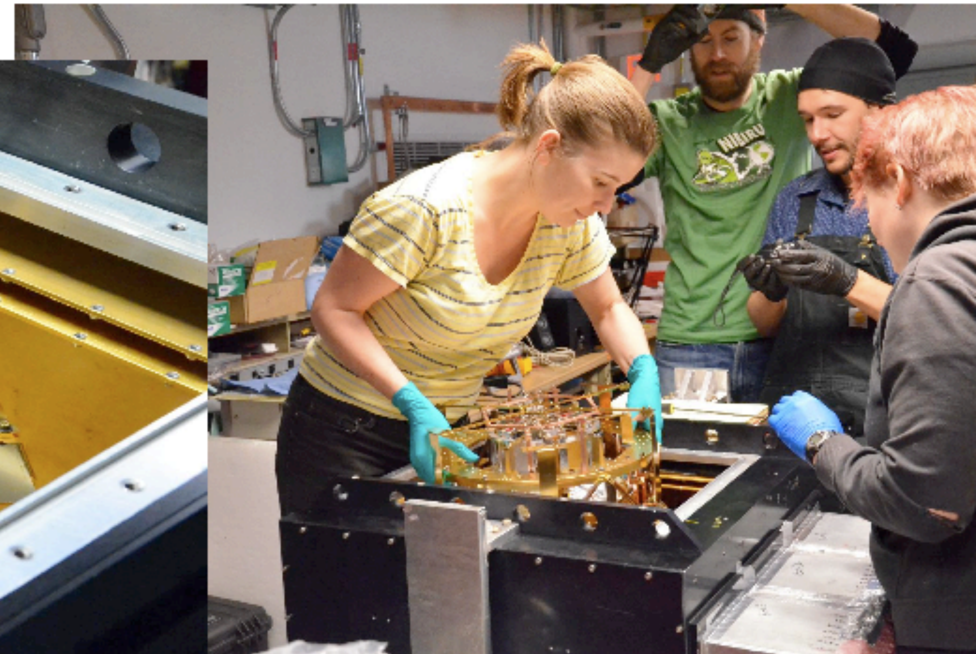


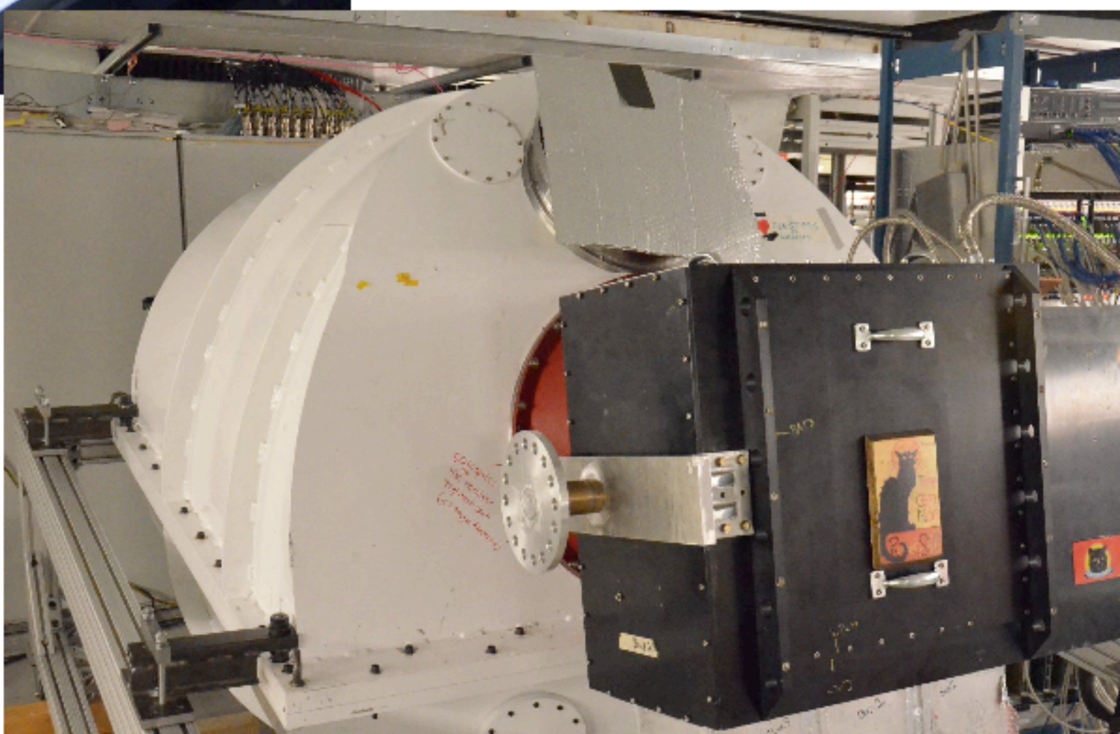






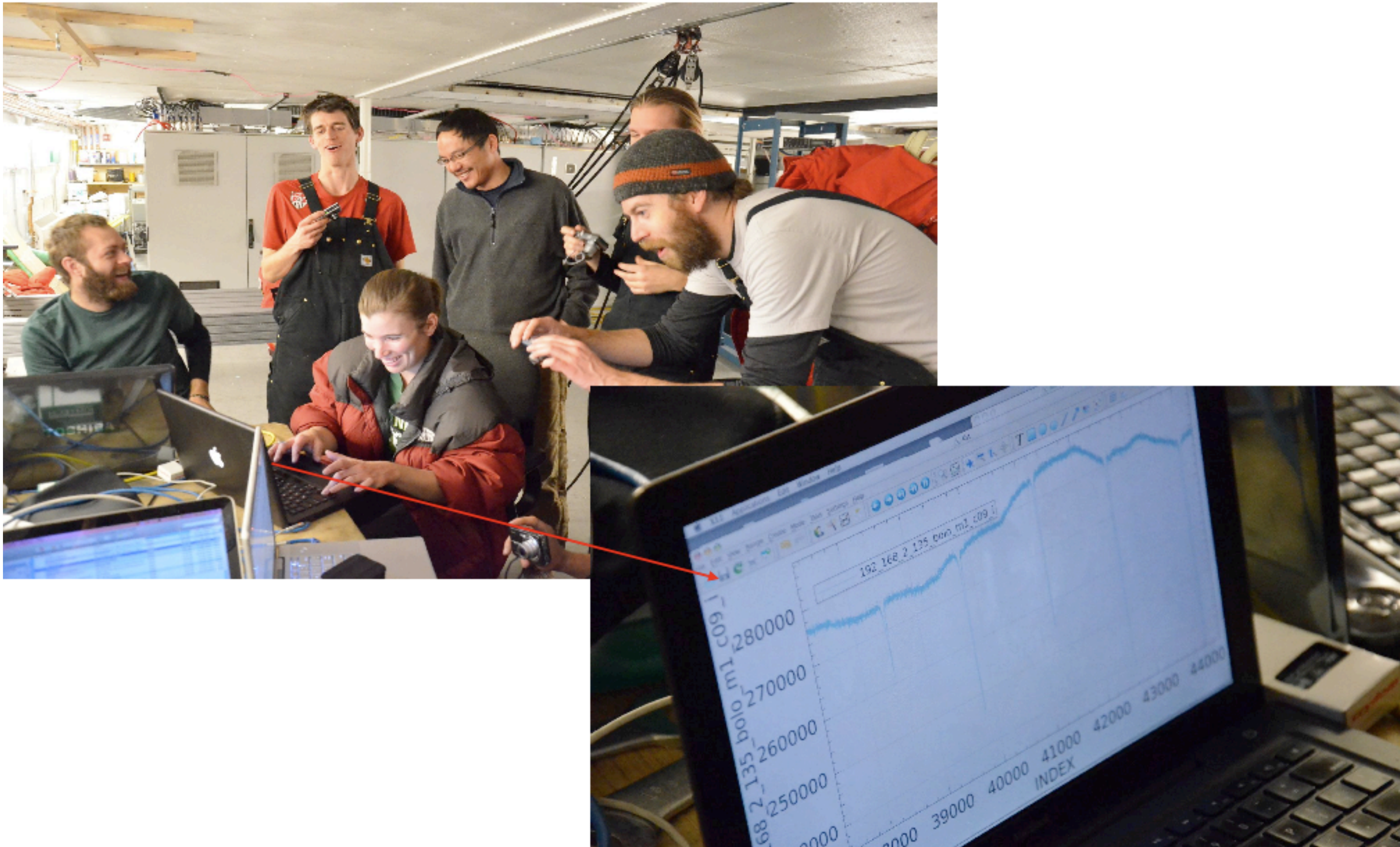







I ♥ CLUSTERS of GALAXIES

First light!



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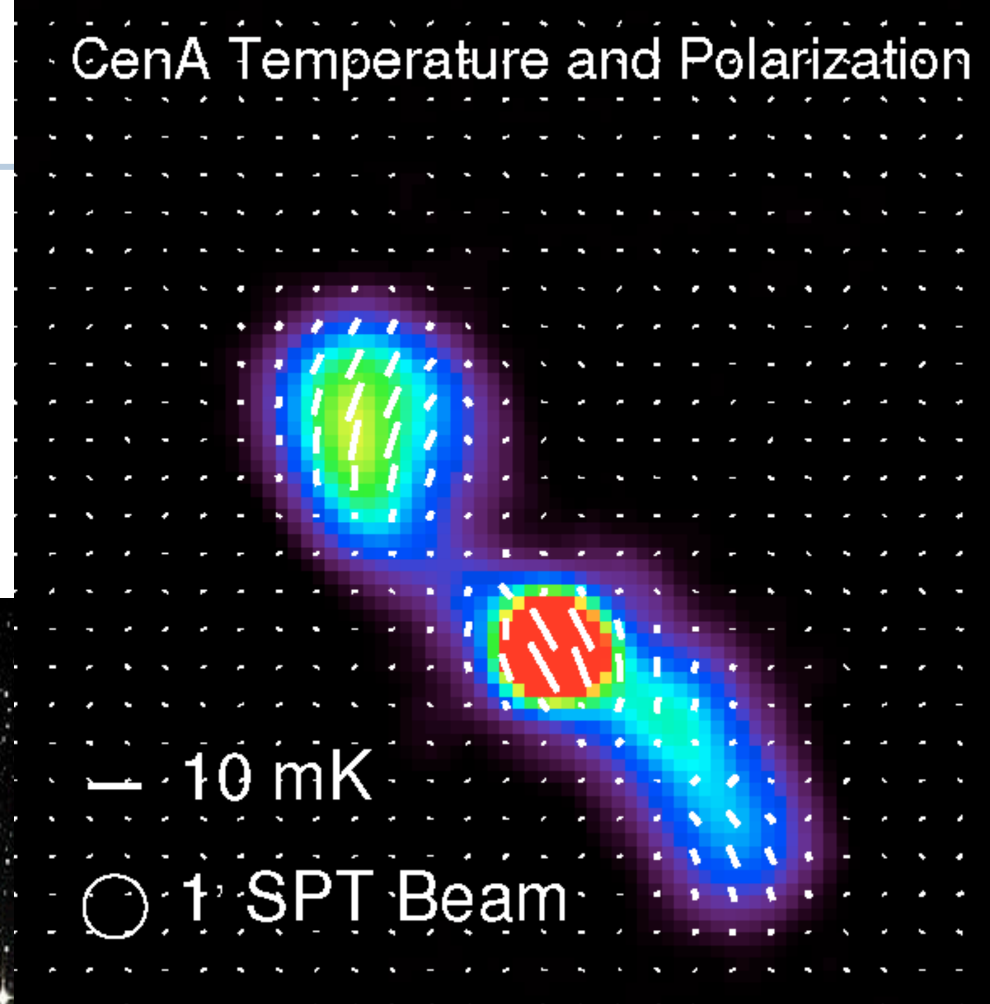
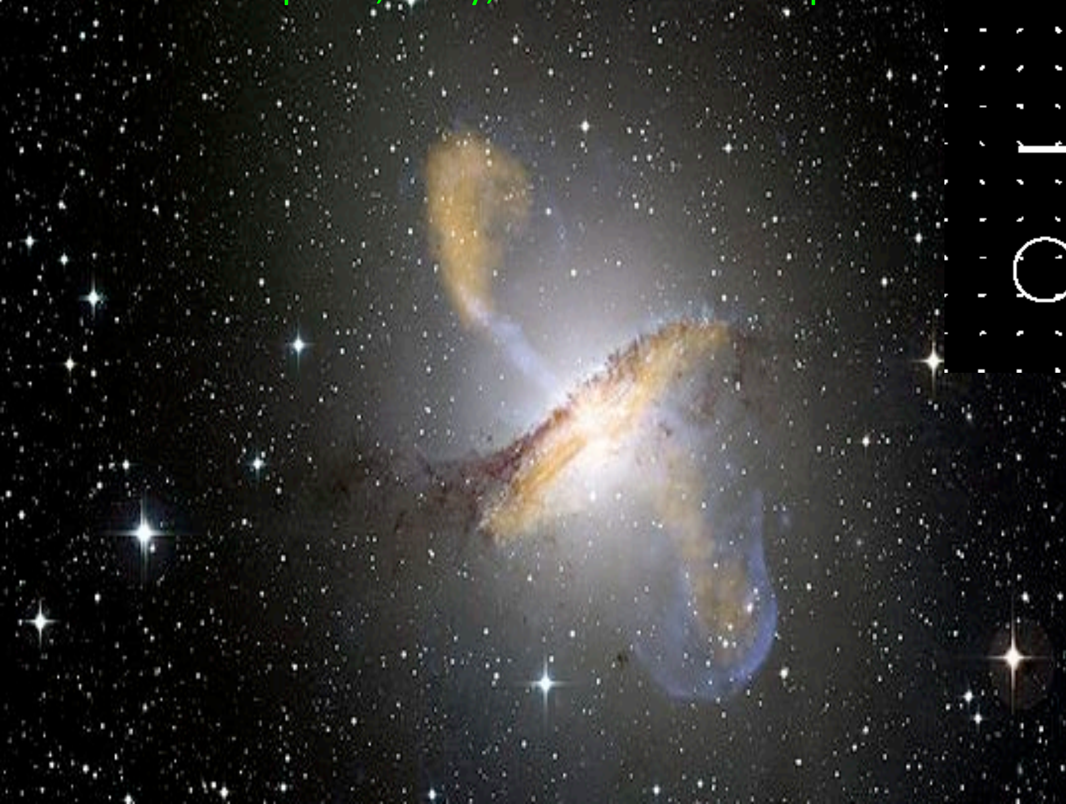
Data from commissioning

- Commissioning observations (40 mins) of highly polarized radio loud galaxy, CenA.

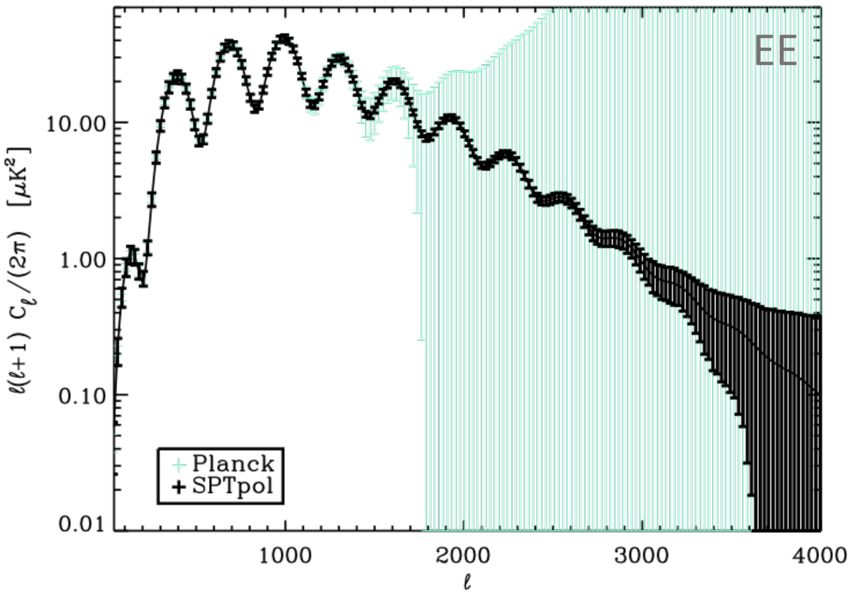


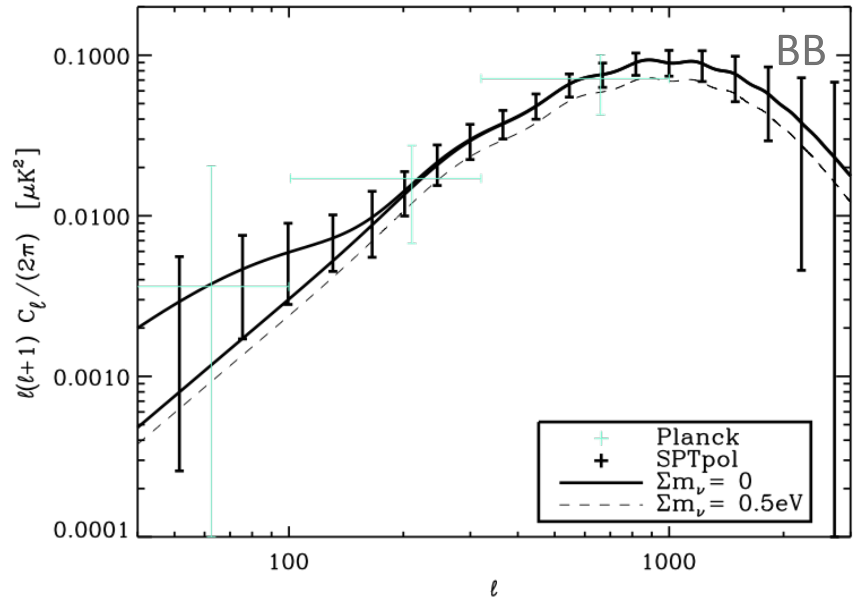
SPT-POL Polarization Map

Centaurus A: Optical, X-ray, and sub-mm composite



SPTpol: Enabling and delivering new physics





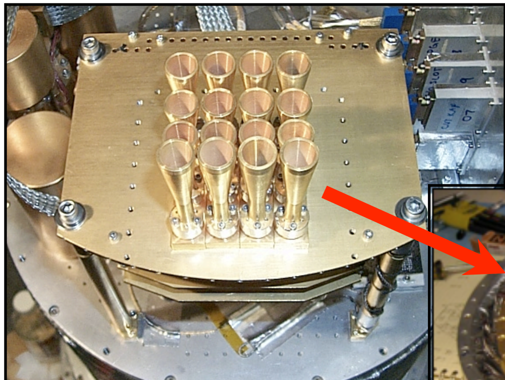
Beyond SPT-SZE (& Planck):

- N_{eff} (pol cross check)
- Σm_ν (pol cross check)
- Dark Energy, w
- Inflation (10^{16} GeV)

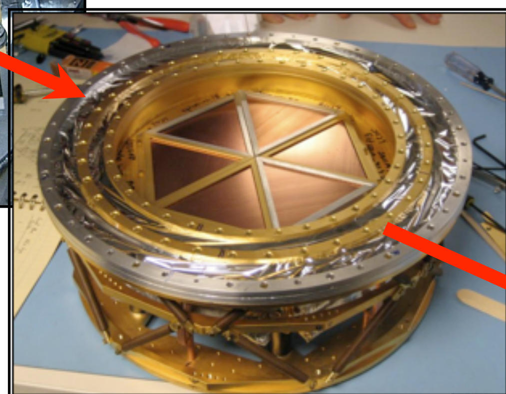
ANL delivered 90 GHz detectors. Targeting the first BB detection in 1 year!

Evolution of CMB technology

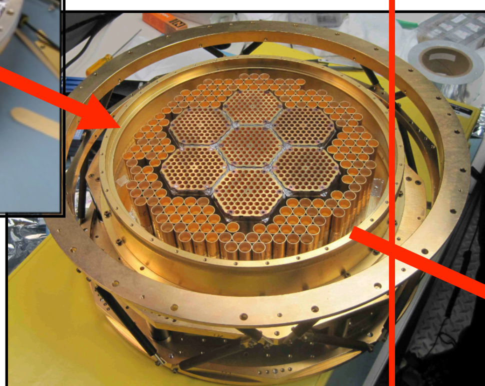
2001: ACBAR
16 detectors



2007: SPT
960 detectors

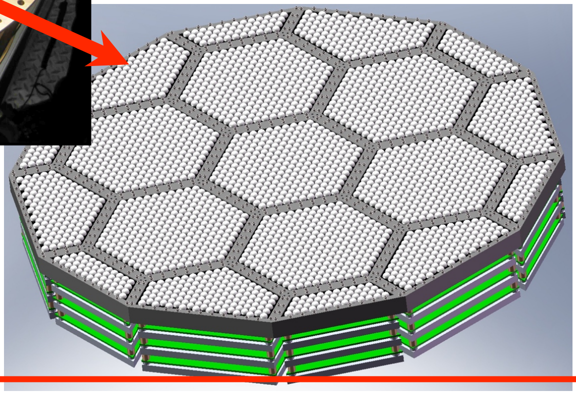


2012: SPTpol
~1600 detectors



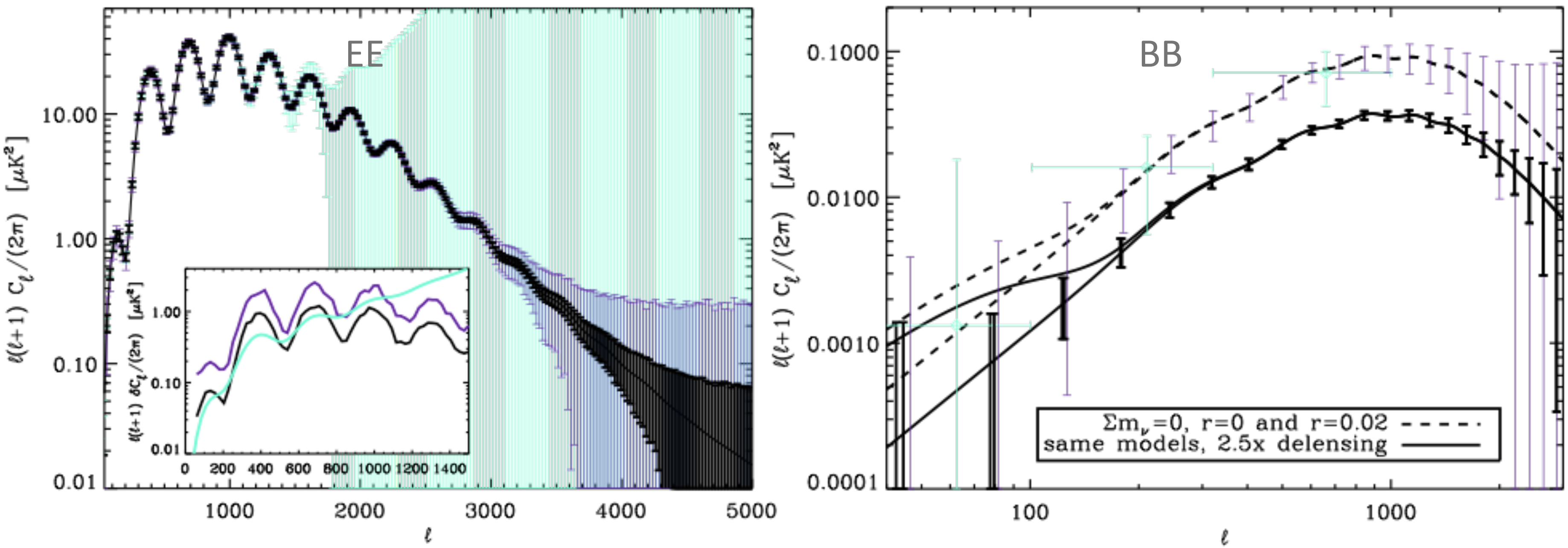
FY13-15 R&D

2016: SPT-3G
~15,200 detectors



Ongoing collaboration with university groups and labs that delivered SPTpol
(UChicago, UCB, CWRU, CU, NIST, McGill)

Beyond Planck (4 yrs w/ 3G)



Planck SPTpol **SPT-3G**

Dataset	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	$\sigma(r)$
Planck	0.14	117 meV	0.06
+SPT-3G	0.076	74 meV*	0.01

*61 meV including BOSS

Summary

Capability Gap

Take from ideas to "instrument ready" technology

- Global TES R&D effort w/ strong history
- Broadly applicable
- Lots of good ideas ready to move to the next step

Approach

Unique resources & relationships

- Multi-disciplinary resources via MSD, CNM, HEP
- Strong collaborative structure w/ TES experts (KICP Detector initiative)
- Significant scientific interest at ANL, FNAL, and UofC (both HEP and beyond)
- History of successful delivery

Benefit

CMB beyond WMAP (& Planck)

- N_{eff} : # neutrino-like species
- Σm_{ν} : energy scale of neutrino mass
- w: Dark Energy equation of state (growth based)
- r: Inflation (unique window into 10^{16} GeV physics)

Ton-scale Cryogenic Dark Matter experiment

Technology relevant outside of HEP

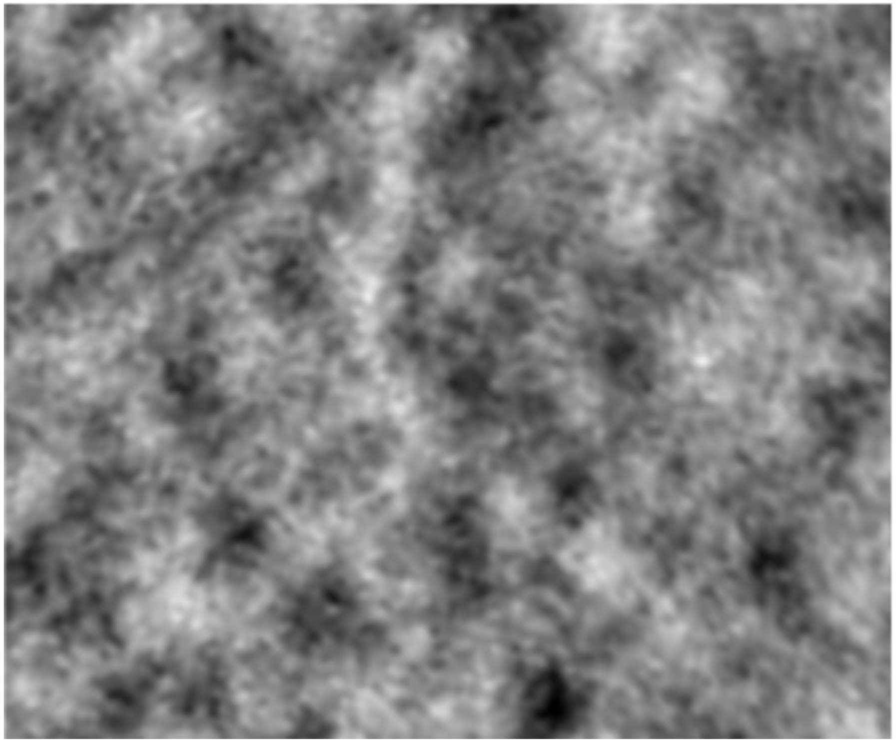
Results and Deliverables

- Develop low loss microstrip technology for array fabrication
- Demonstrate proof-of-concept multiplexer

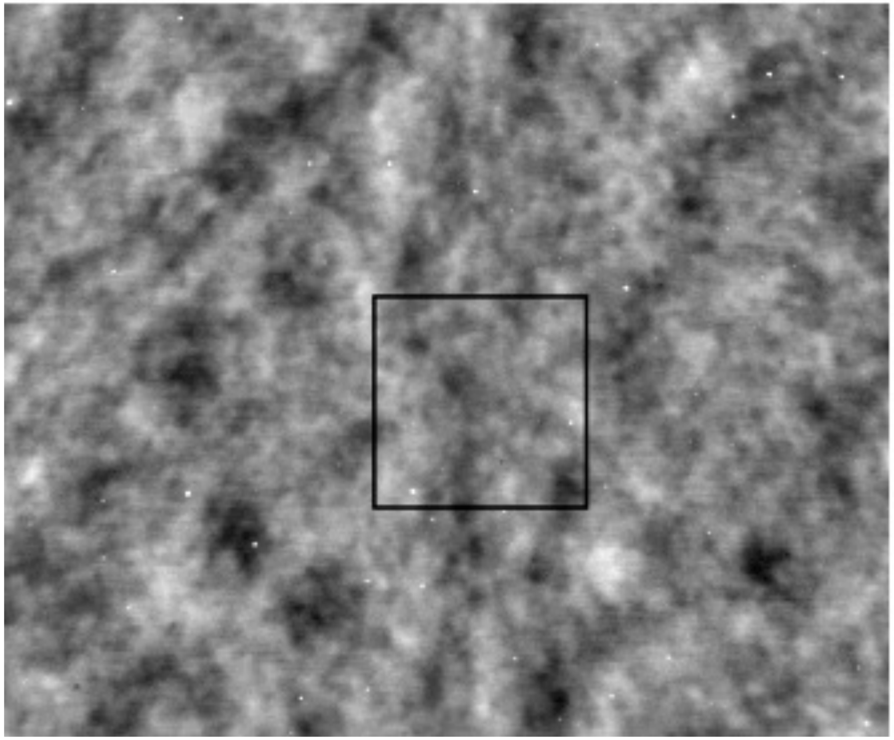
Extra slides

CMB ca. today (150 deg^2 of WMAP vs SPT)

WMAP



SPT



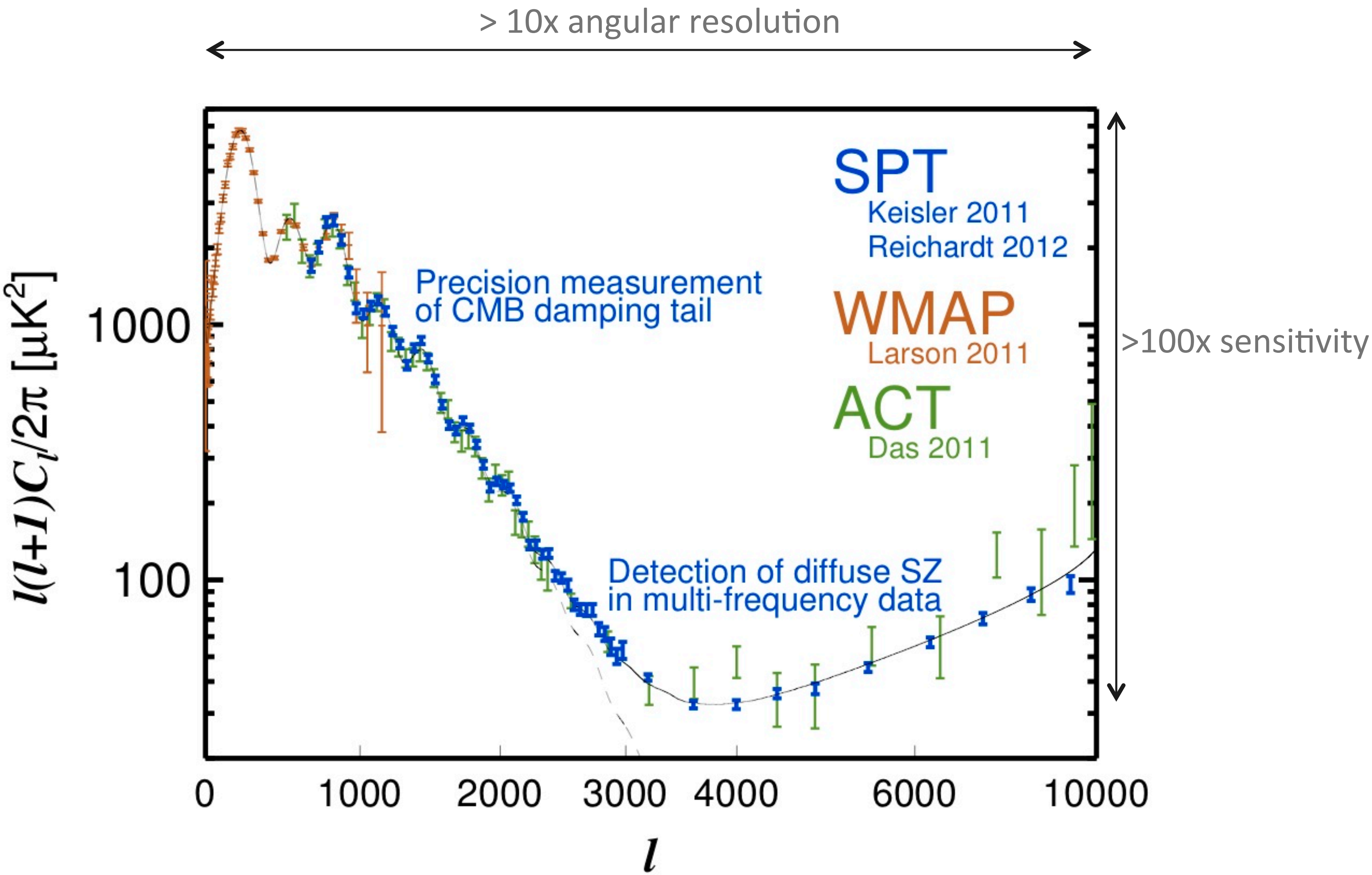
13x resolution and 17x deeper than WMAP

5x higher resolution and 3x deeper than Planck blue book

Shows structure from degrees to arc minutes:

from large-scale CMB to SZ & unresolved sources.

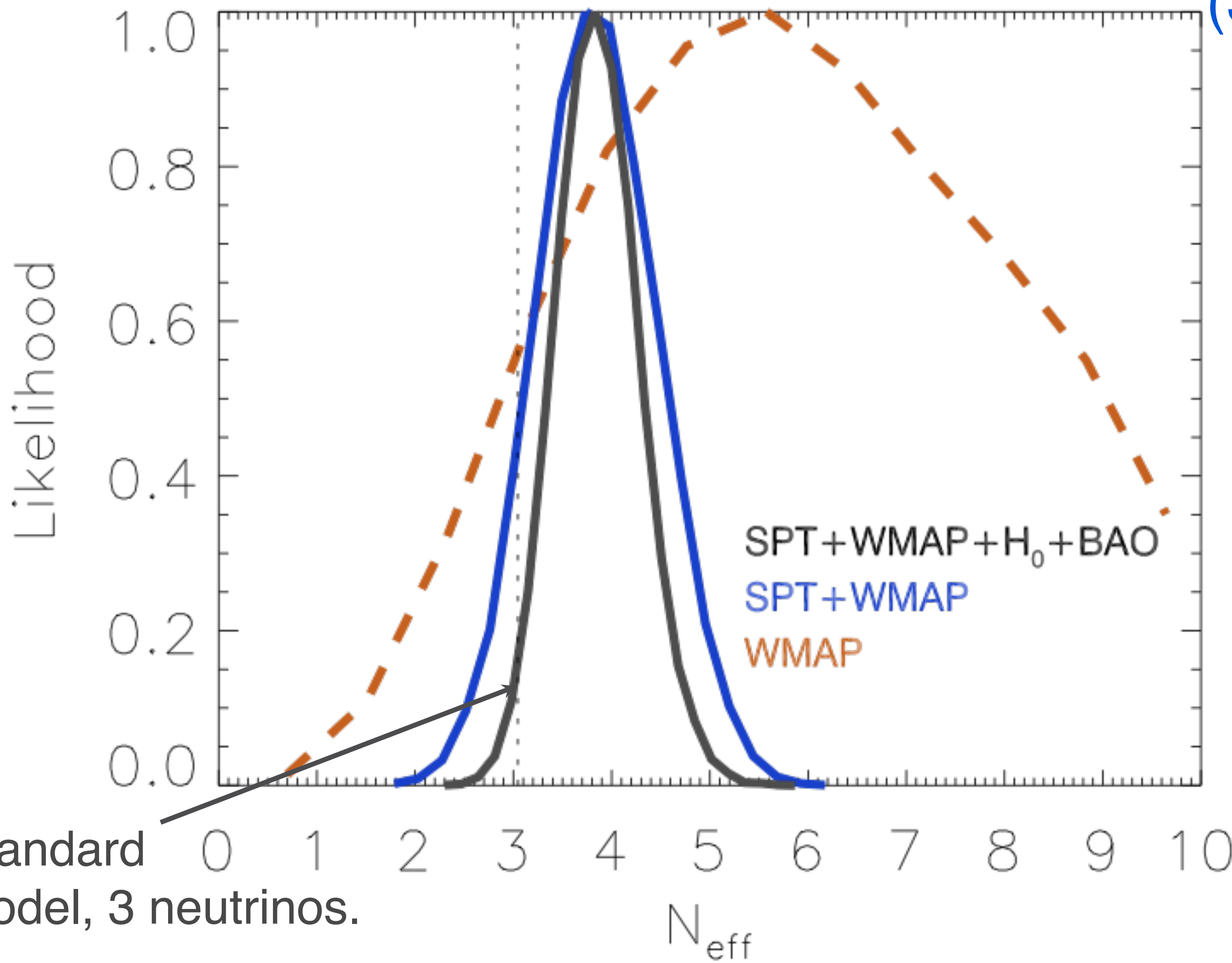
Increased sensitivity and resolution



Primordial relativistic degrees of freedom

Keisler et al 2011, ApJ, 743, 28

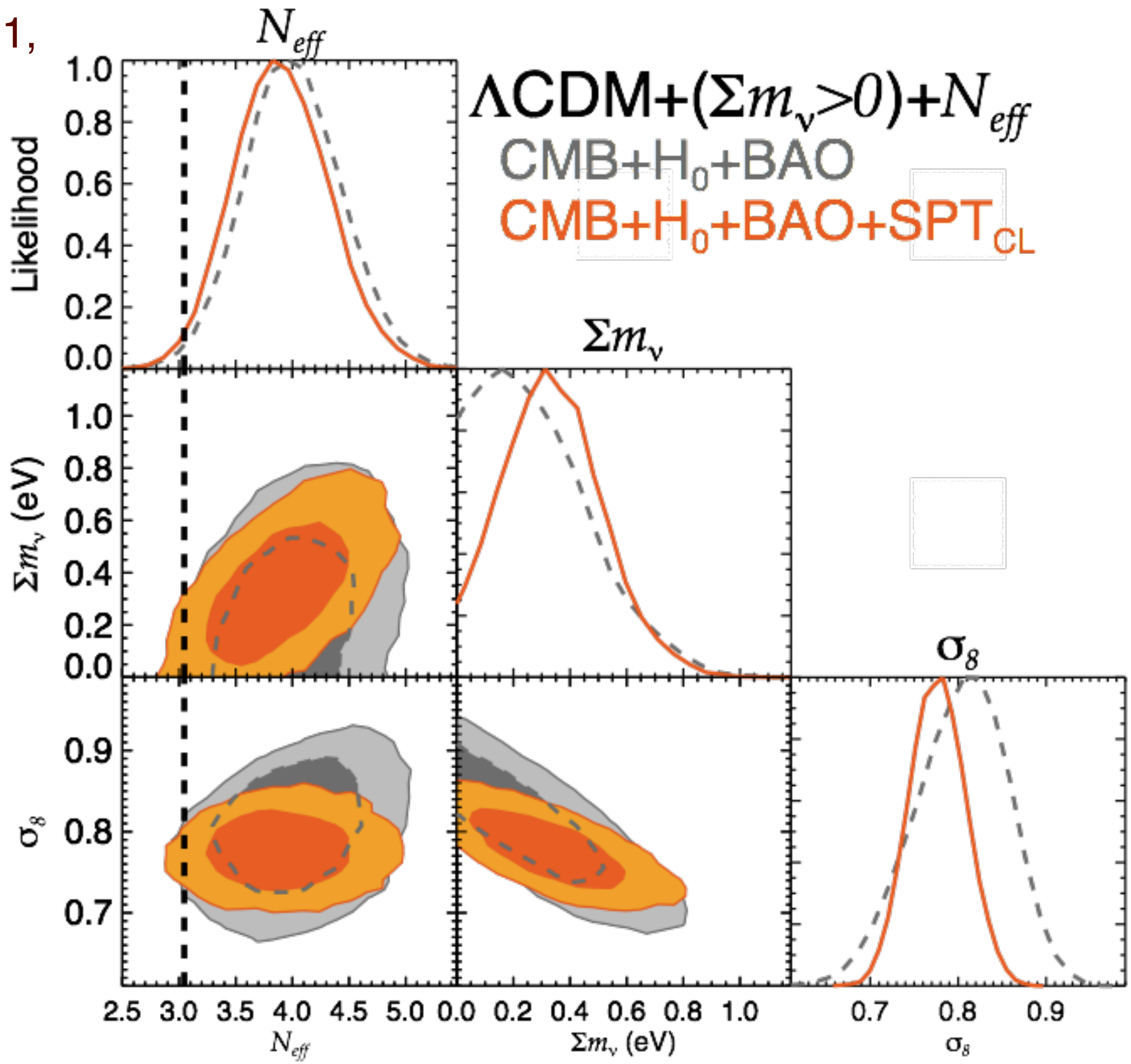
N_{eff} = 3.86 ± 0.42
(SPT+WMAP
+H_0+BAO)



Standard
Model, 3 neutrinos.

Measuring neutrino mass

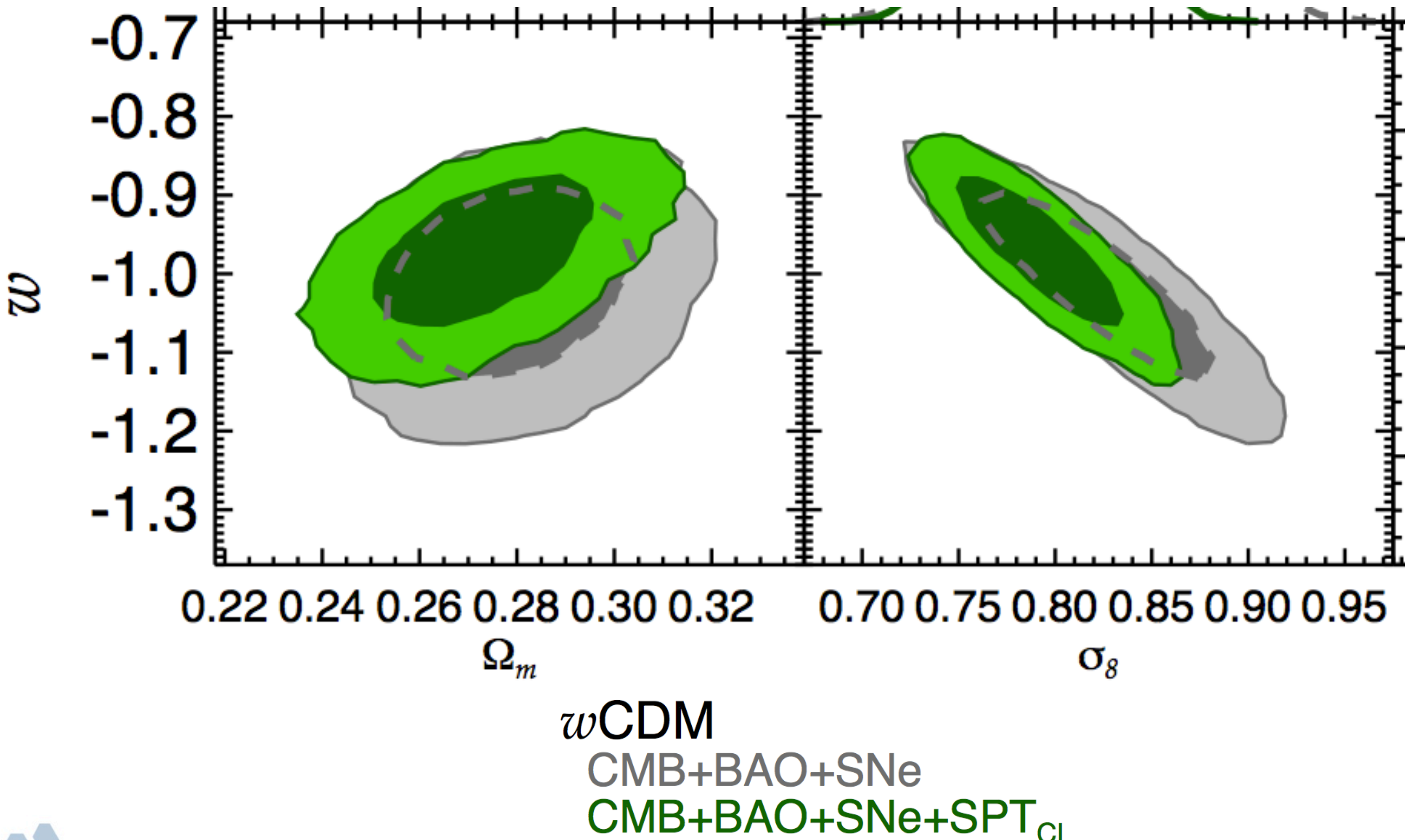
Benson et al 2011,
arXiv: 1112.5435



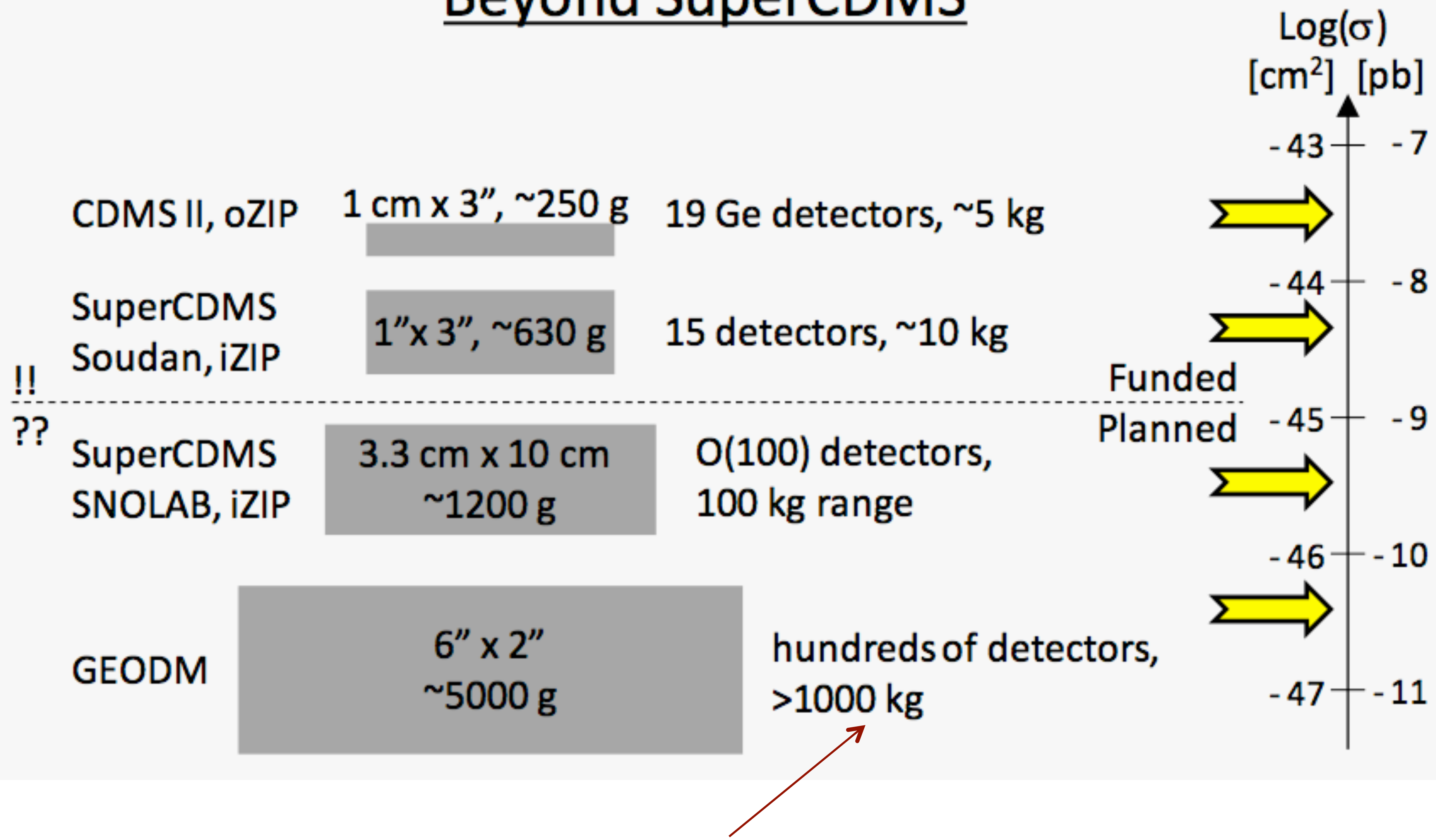
Probing Dark Energy

Benson et al 2011,
arXiv: 1112.5435

w= -0.97 +/- 0.06

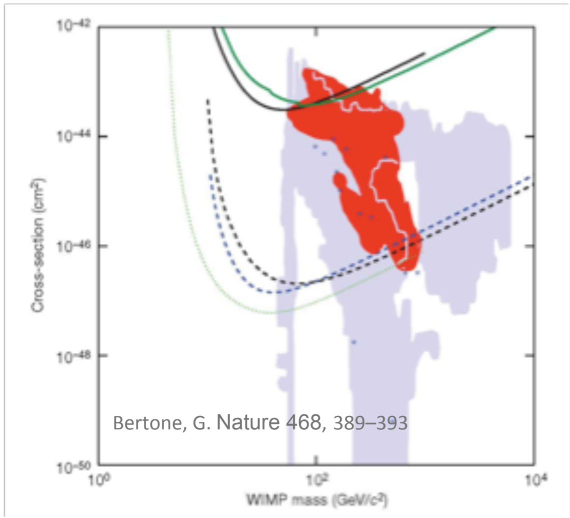


Beyond SuperCDMS



Challenging heat load from wiring without Multiplexing

1 ton cryogenic Dark Matter detector?



- Current MUX operate at 300 kHz - 2 MHz
  - 1 ms resolution per channel
- Develop high frequency MUX at 1-10 GHz
  - 1 µs per channel
  - High speed digital electronics + superconducting microwave resonators
  - Required for background rejection
- Makes existing SuperCDMS detector technology scalable to 1-ton