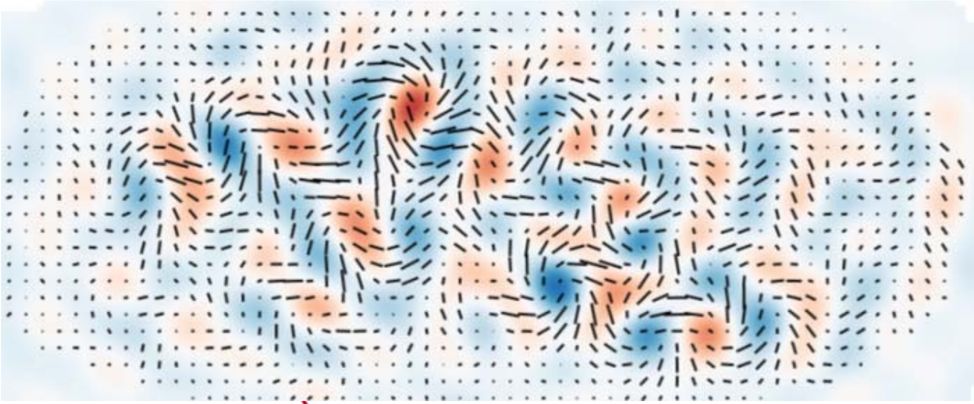
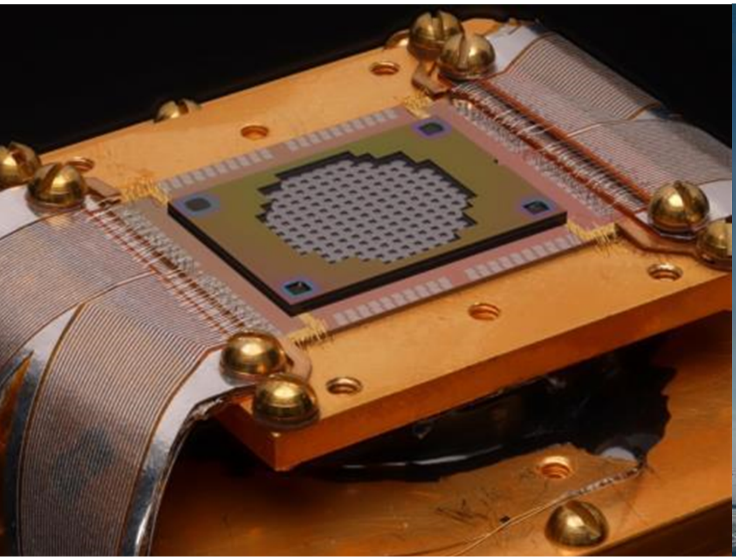


Superconducting detectors

for x-ray beamline applications and cosmology

Kent Irwin
Stanford University and SLAC



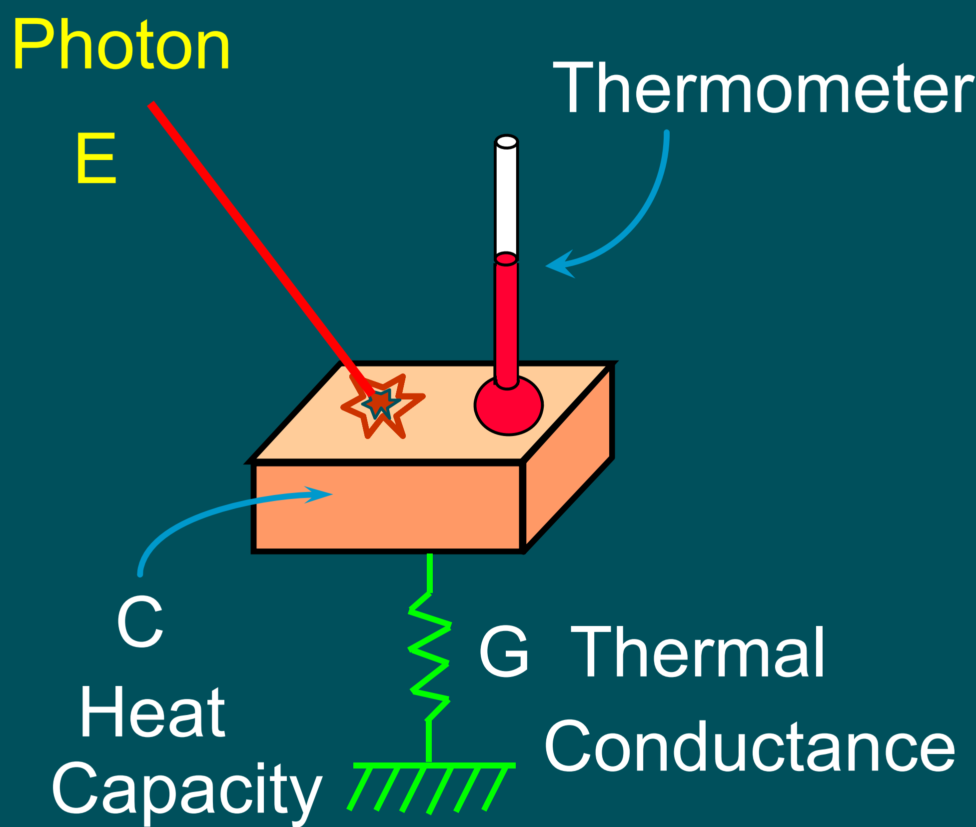
SLAC NATIONAL ACCELERATOR LABORATORY

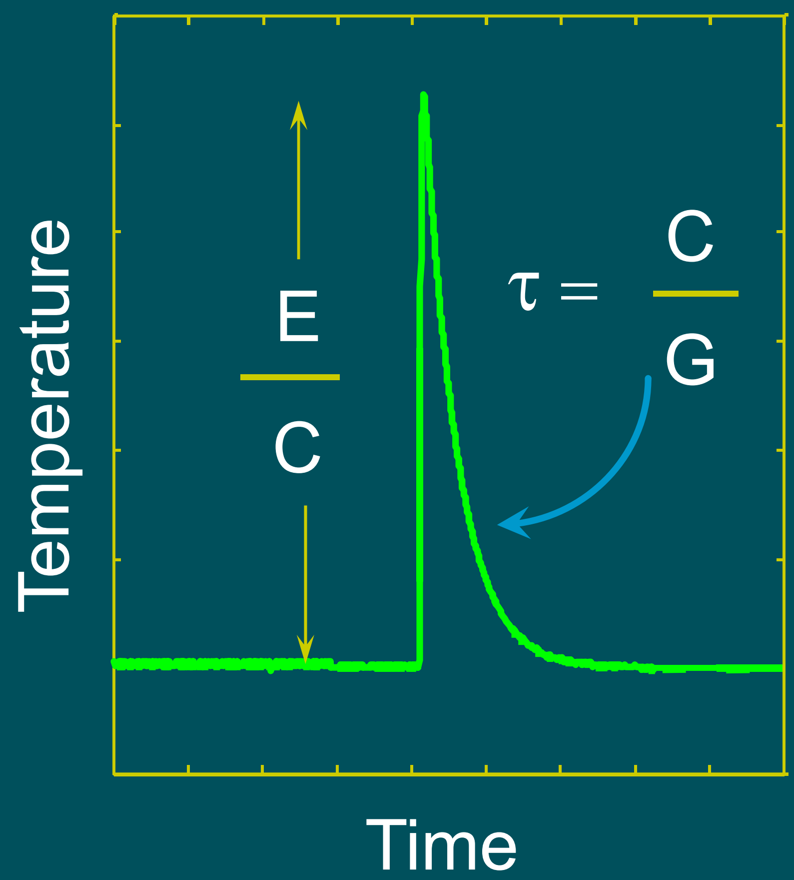
Outline

An adventure in applied superconductivity:
from cosmology to x-ray beamline science

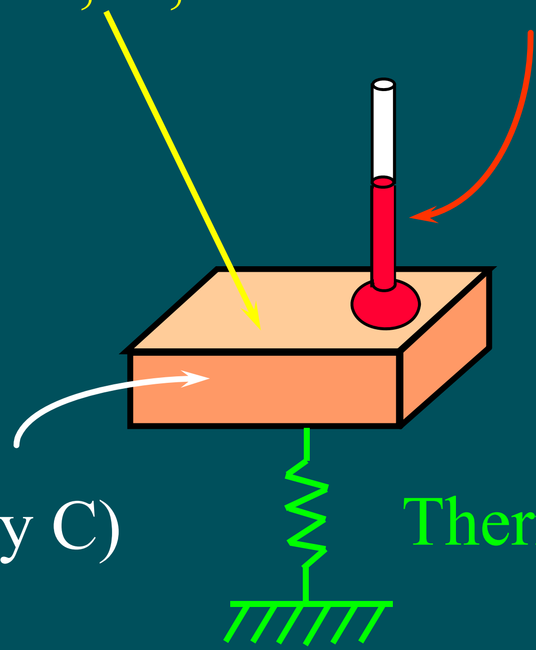
- Superconducting Transition-Edge Sensors
- Photon detection from microwaves to x-rays
- Multiplexing for large arrays
- Microwave polarimetry for cosmology
- X-ray spectroscopy at synchrotron and FEL light sources

Anything that can be converted to heat can be measured with a thermometer





Photon $\rightarrow$ **Heat**



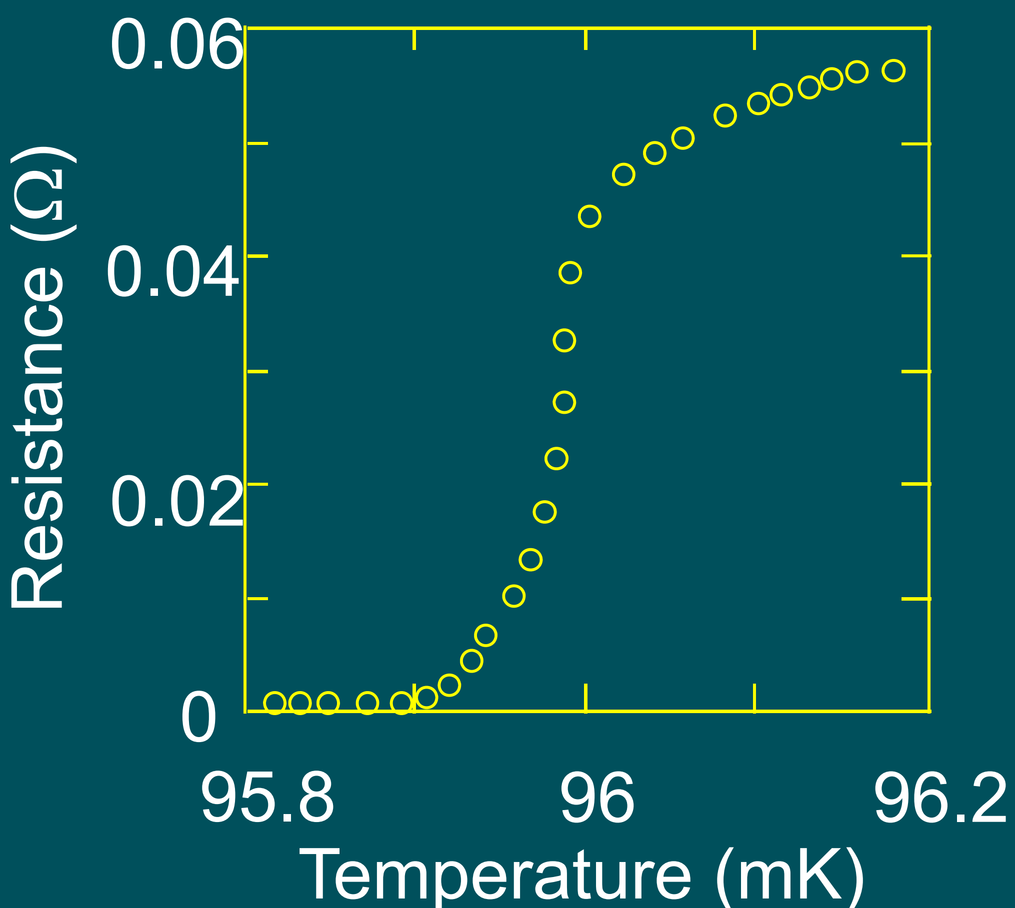
$P = G \times \Delta T$ Bolometer

$E = C \times \Delta T$ Calorimeter

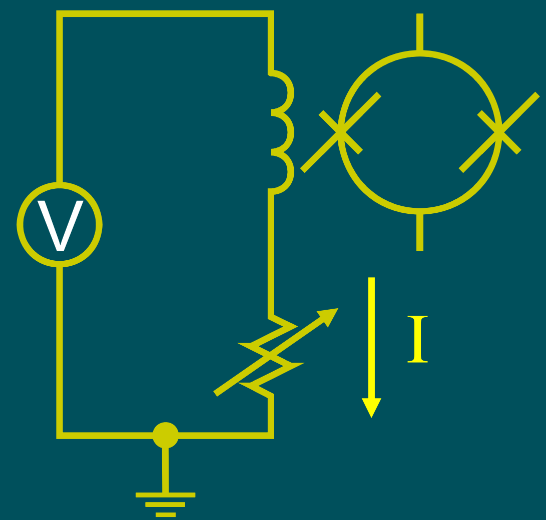
Thermodynamic power noise: $NEP^2 = 4k_B T^2 G$ $(W/\sqrt{Hz})^2$
Energy fluctuations: $\Delta E_{rms}{}^2 = k_B T^2 C$ $(J)^2$

Operate at low temperatures (T~ 0.1K to 0.3K) where C, G and thermodynamic fluctuations are small.

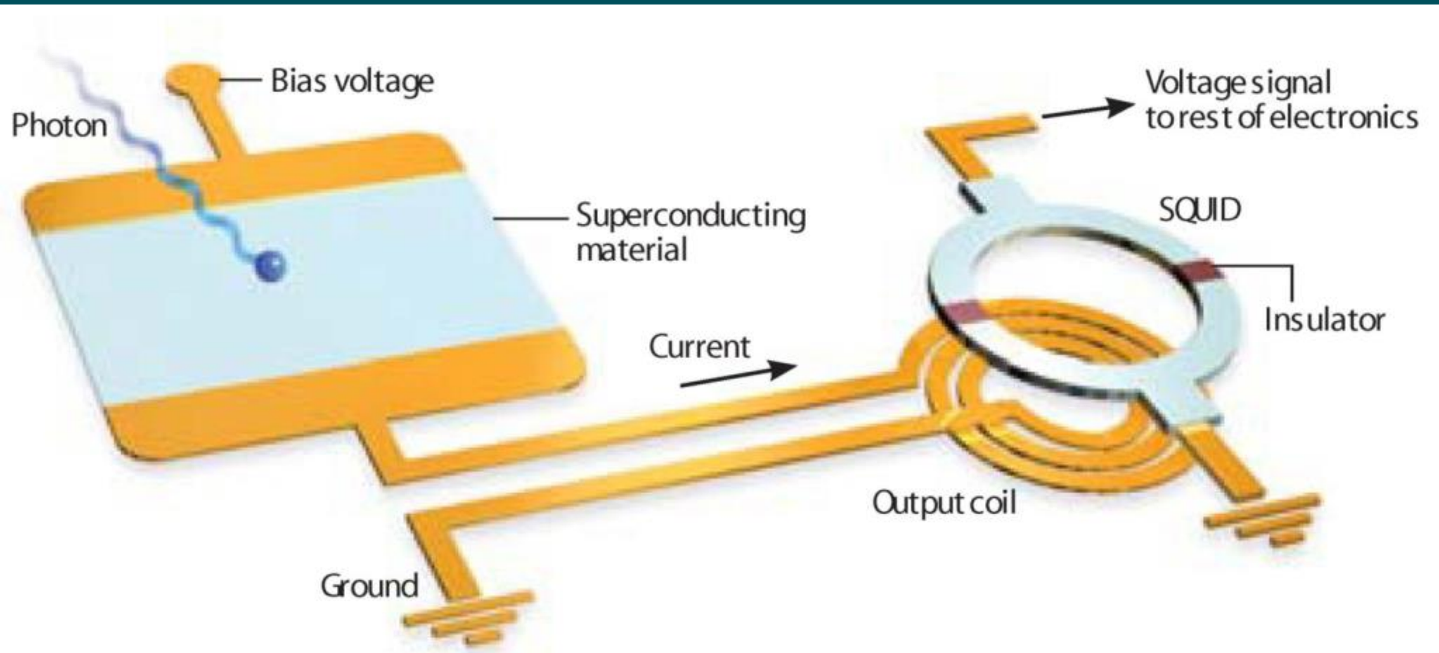
Transition-Edge Sensor (TES)

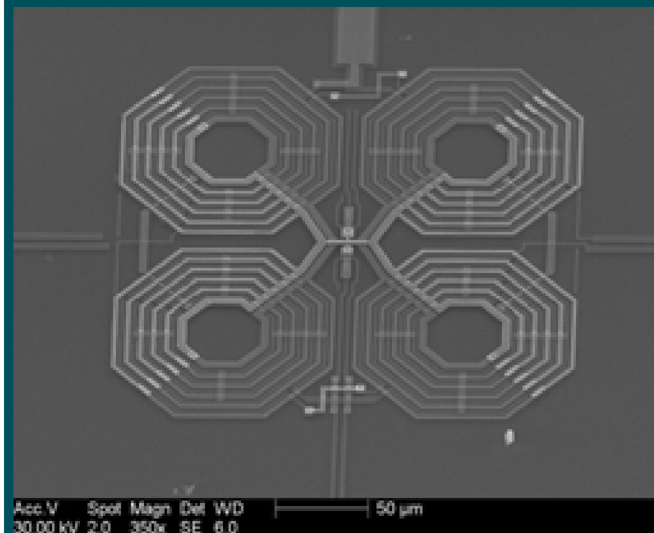


SQUID current amplifier



Photon → Heat → Resistance → Current

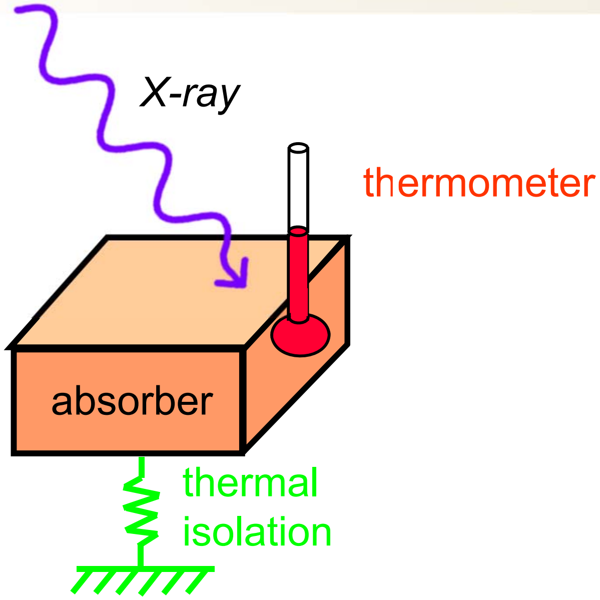


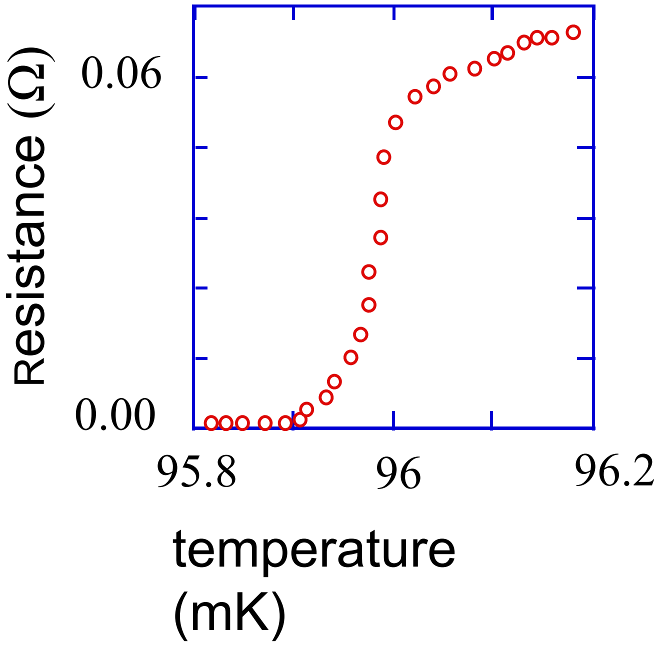


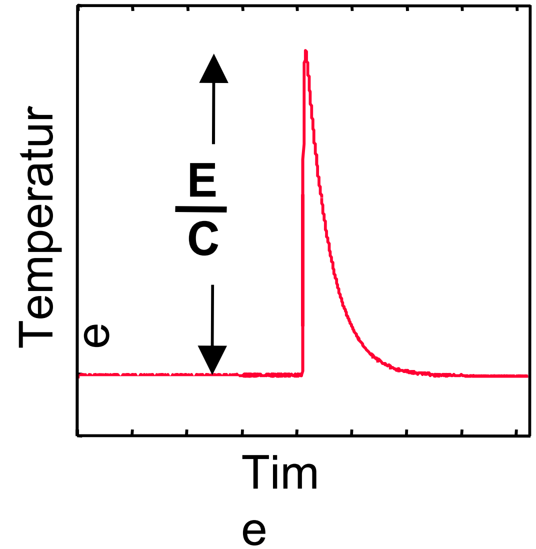
- Measure current with a Superconducting Quantum Interference Device (SQUID) amplifier

- Can be multiplexed to enable large arrays

TES spectrometers





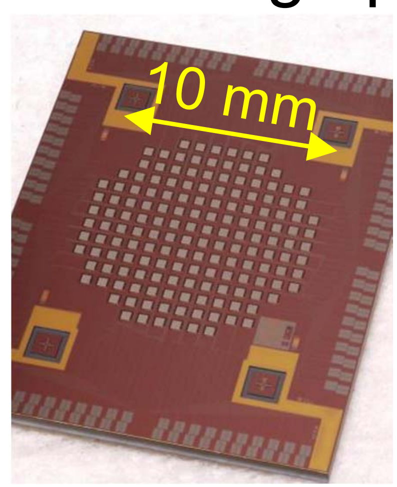


TES spectrometers provide a unique combination of spectral resolution, efficiency, and broadband coverage

$$\Delta E \propto \sqrt{k_B T E_{max}}$$

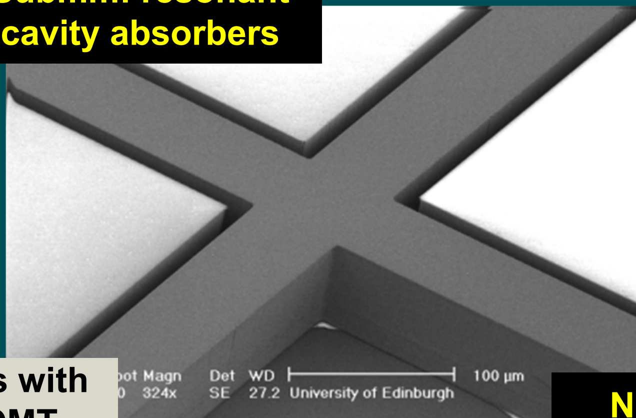
Irwin et al., Appl. Phys. Lett. 69, 1945 (1996)

But we need large pixel arrays!

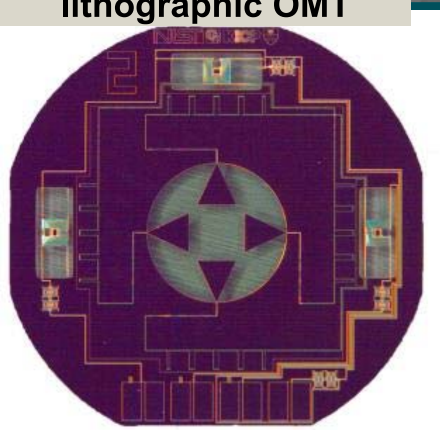


TES photon detection across the spectrum

Submm: resonant cavity absorbers



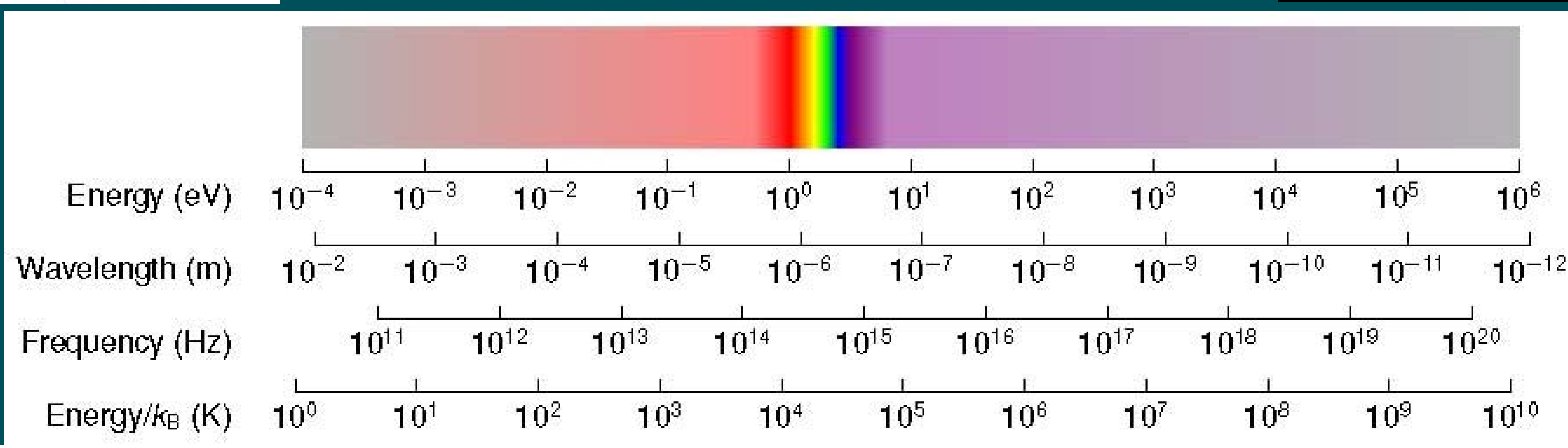
CMB: feedhorns with lithographic OMT



Soft x-ray: Bi thin fims

Near IR & optical: TES with antireflection coating (Sae Woo Nam et al., NIST)

Gamma-ray: thick superconducting foil



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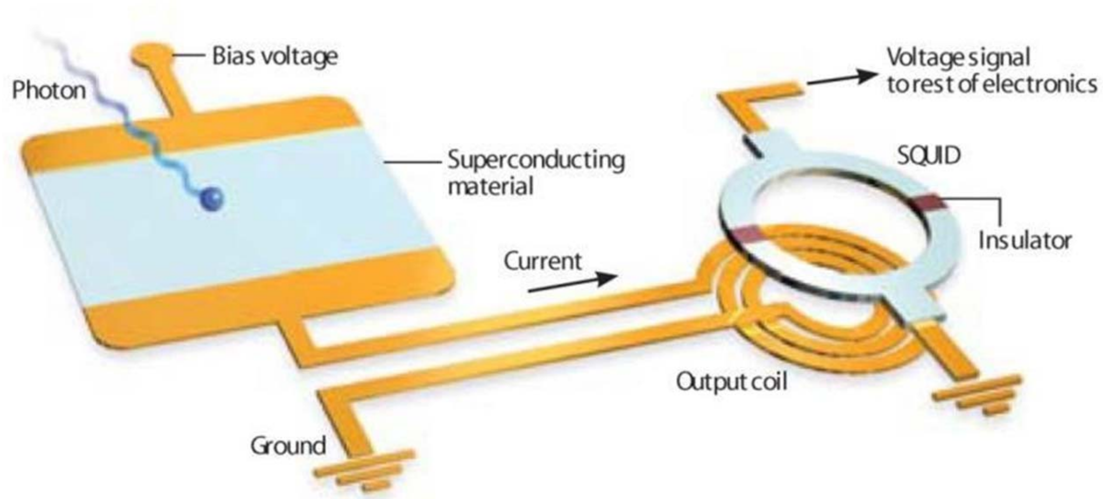
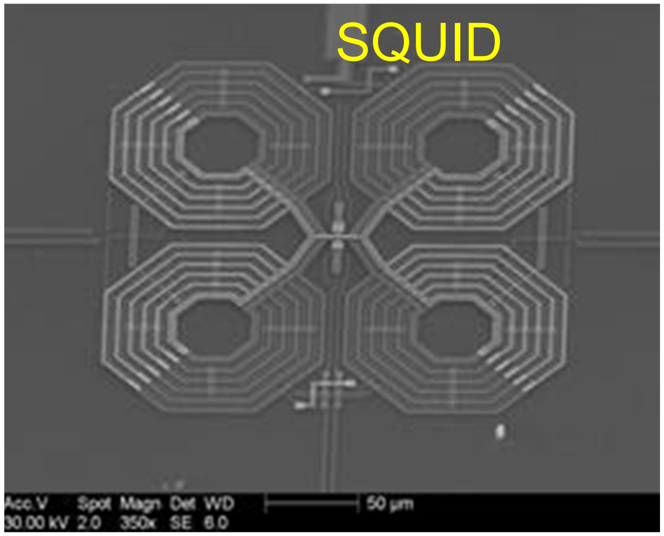
SQUID readout



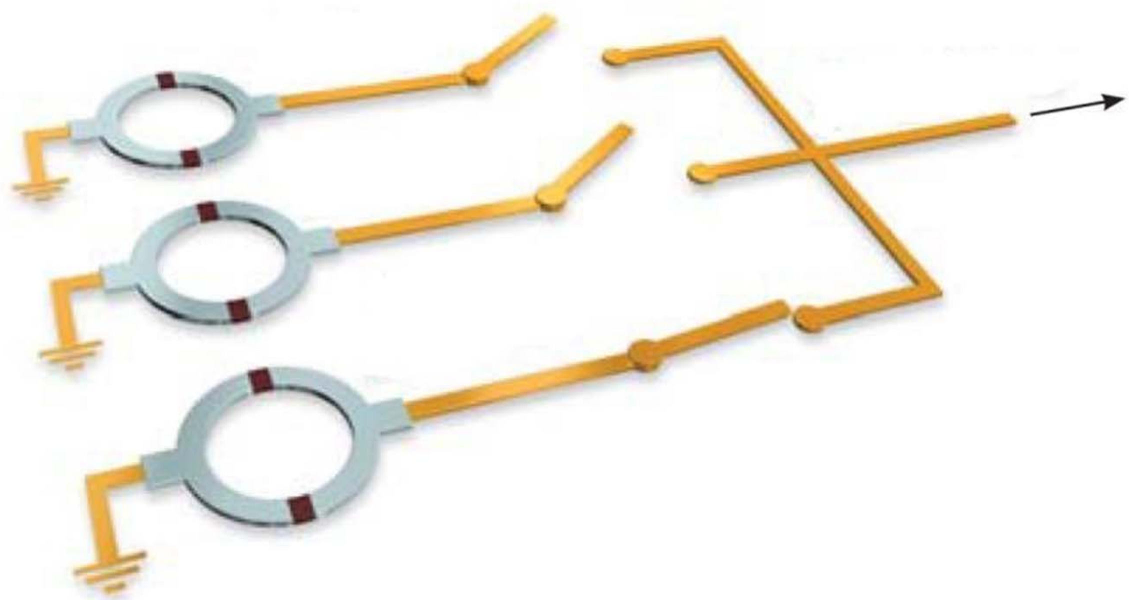


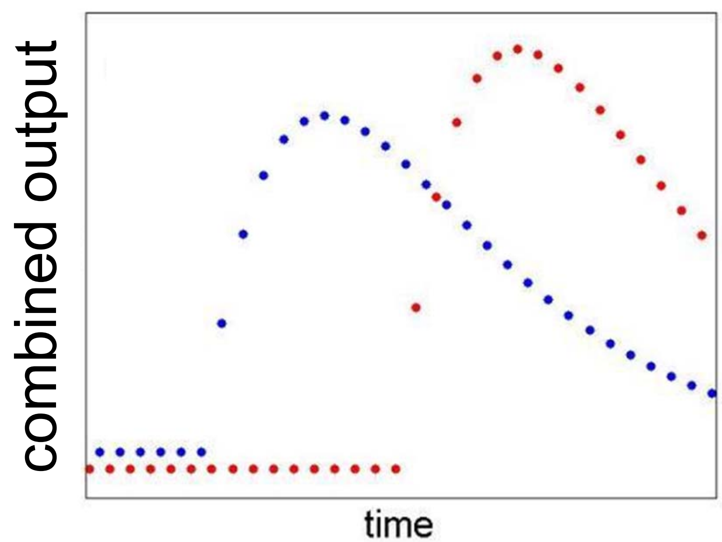
- Quantum-limited amplifier based on superconducting quantum interference : Superconducting Quantum Interference Device (SQUID)
- Current through the sensor is a function of the photon signal
- The current flows through a coil to create a magnetic field
- The SQUID transduces the magnetic field into a measurable voltage signal

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

Multiplexed SQUIDs for large arrays

For large TES arrays, multiplexing becomes necessary to minimize complexity and heat load from wires

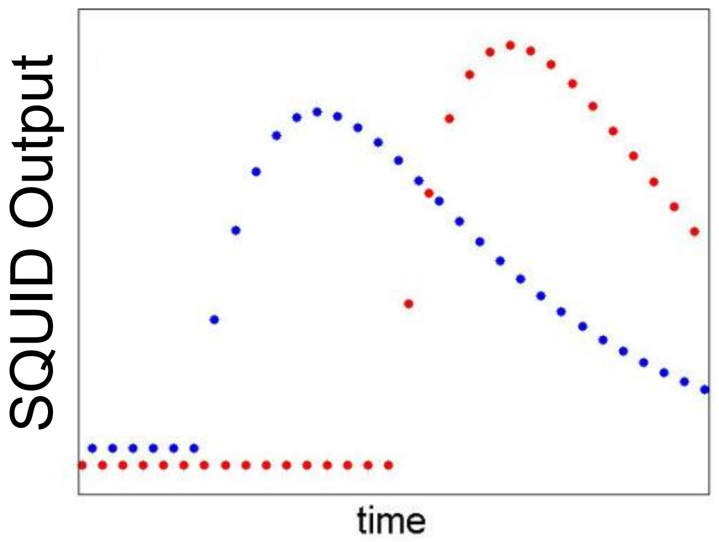


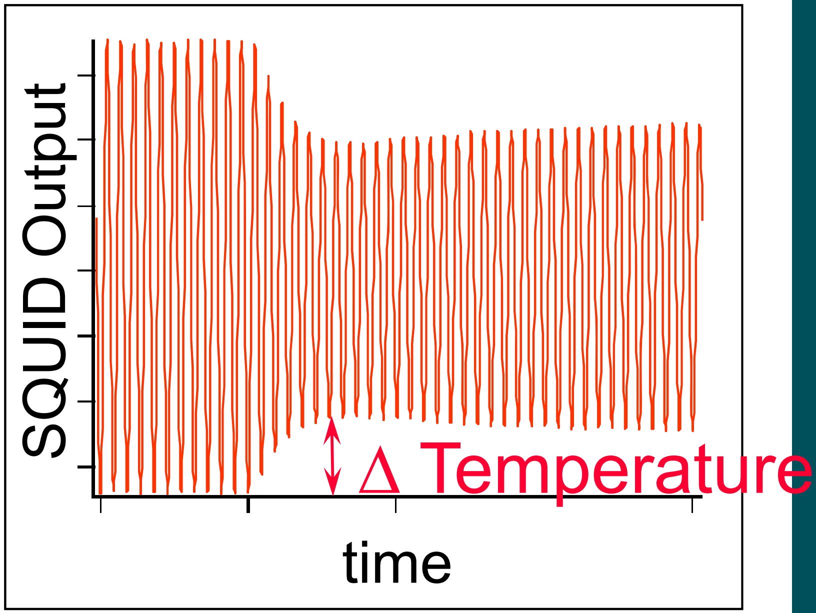


Multiplexing allows many TES detectors to be sampled with one output line

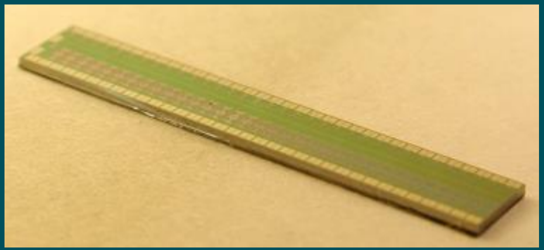
Chervenak et al., Appl. Phys. Lett. 74, 4043 (1999)

Different ways to multiplex



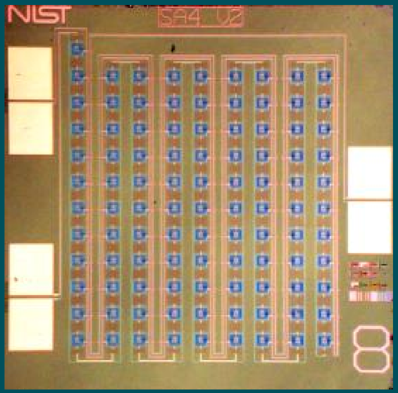


Time division (TDM): different pixels sampled at different times



TDM SQUID array

Frequency division (FDM): different pixels operated at different frequencies



100-SQUID series array for *~MHz frequency-domain readout with Berkeley/LBNL/McGill*

Same idea, different orthogonal modulation functions

Outline

SLAC

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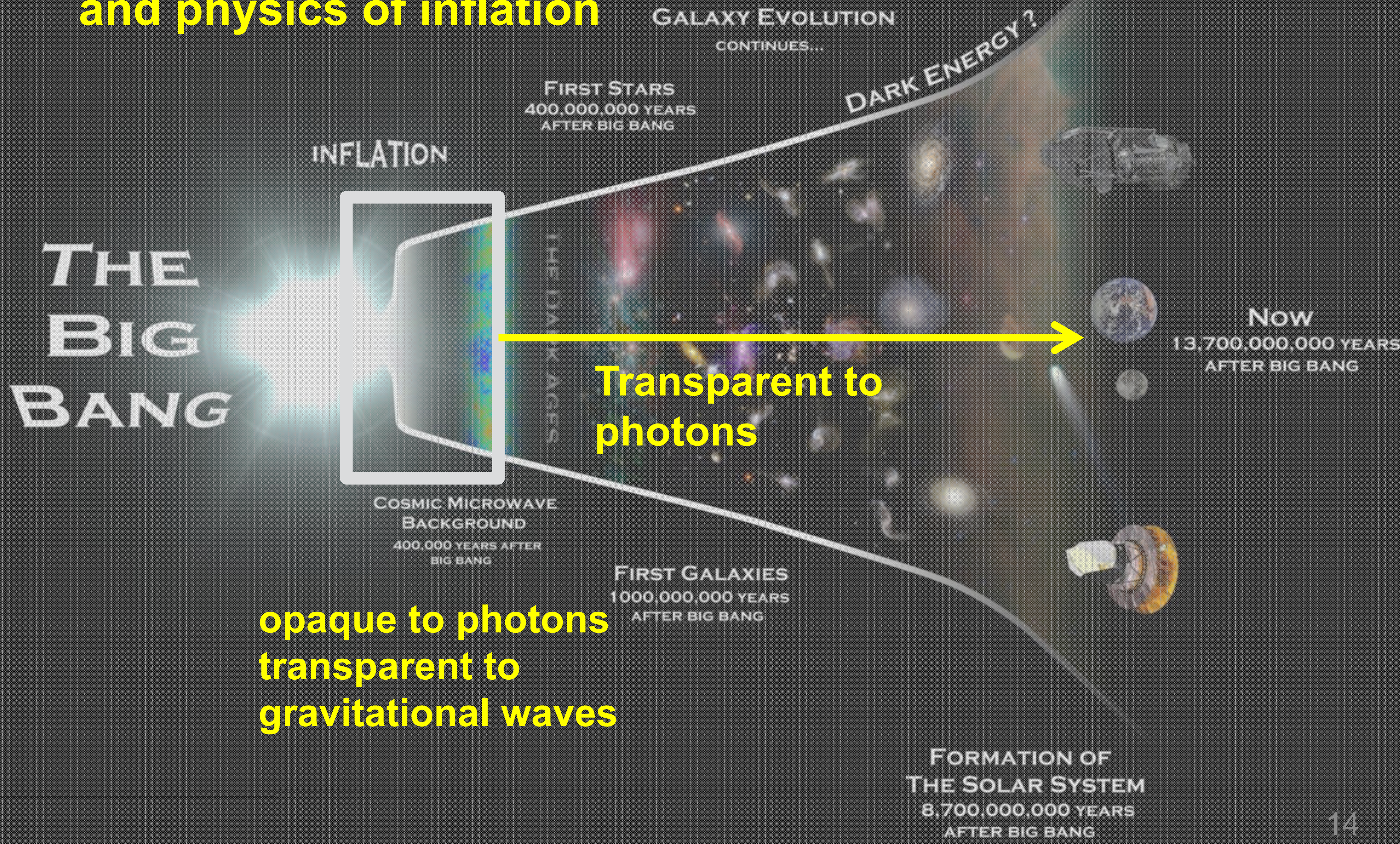
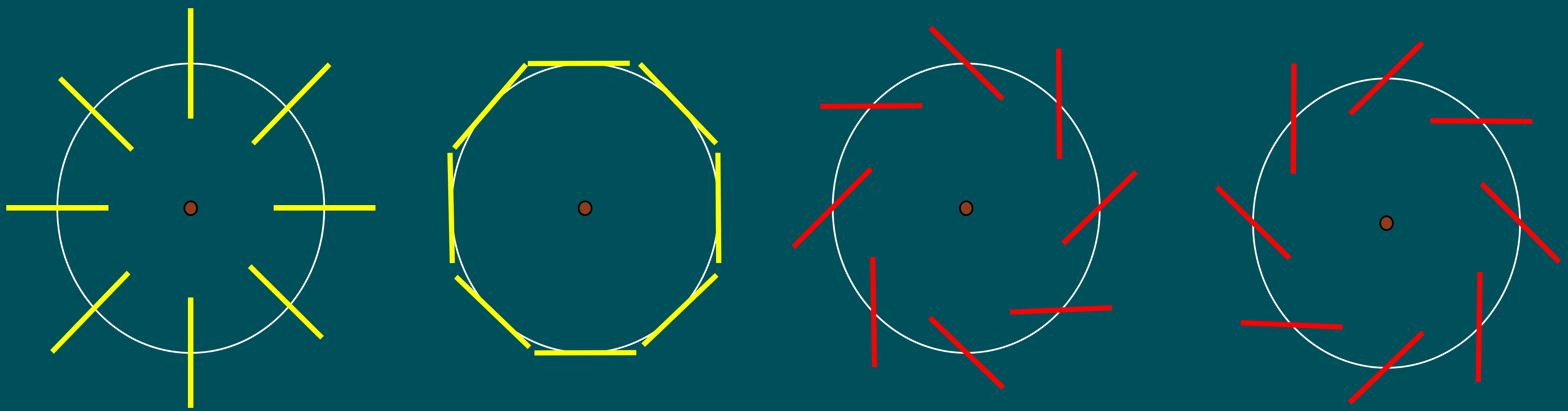
CMB probes cosmology and physics of inflation



The CMB is slightly polarized

Vertical / Horizontal differ by a very small amount

Polarization maps broken into mathematical basis sets

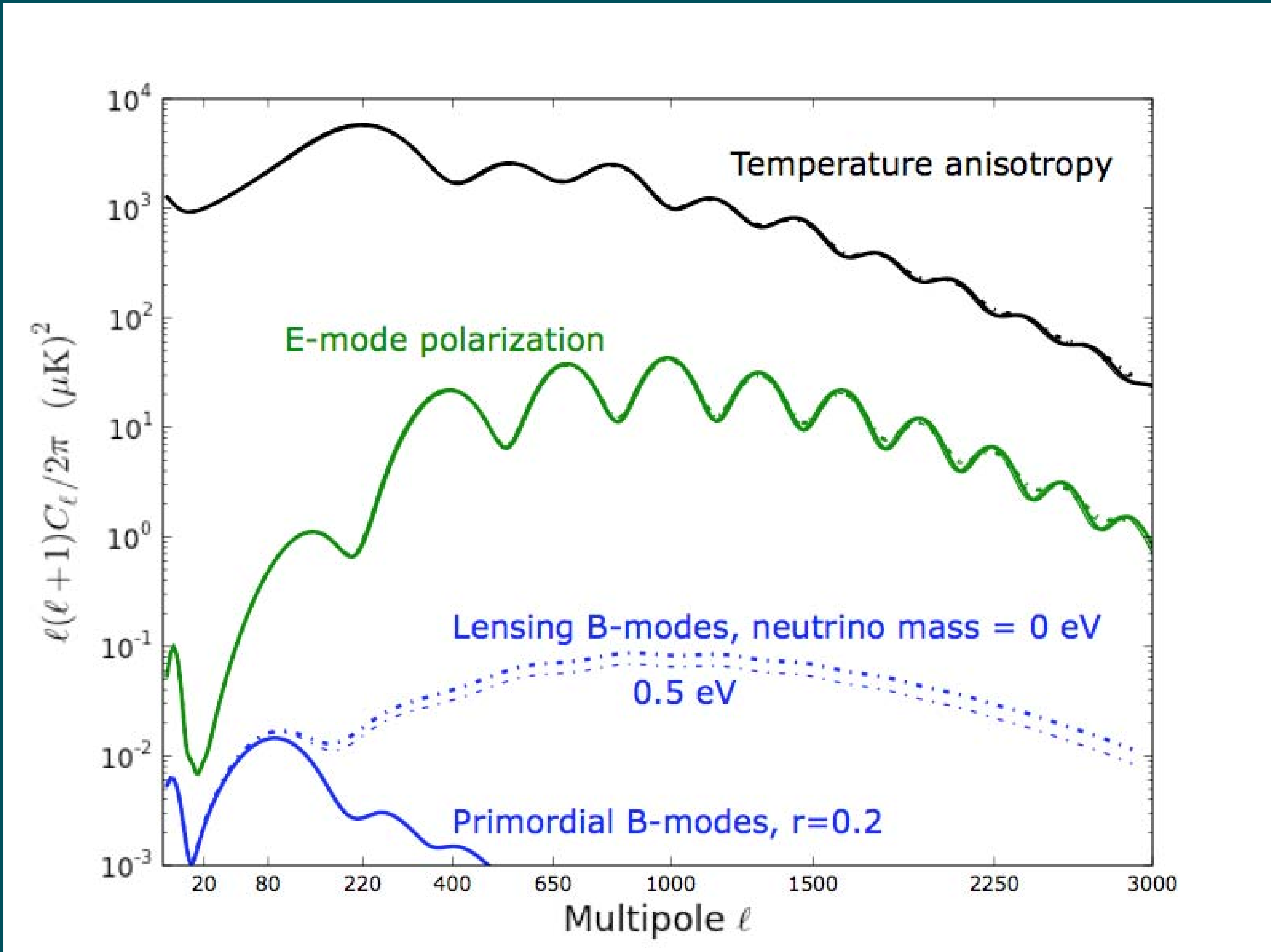


Density waves:
"divergence", but no "curl"
"E modes"

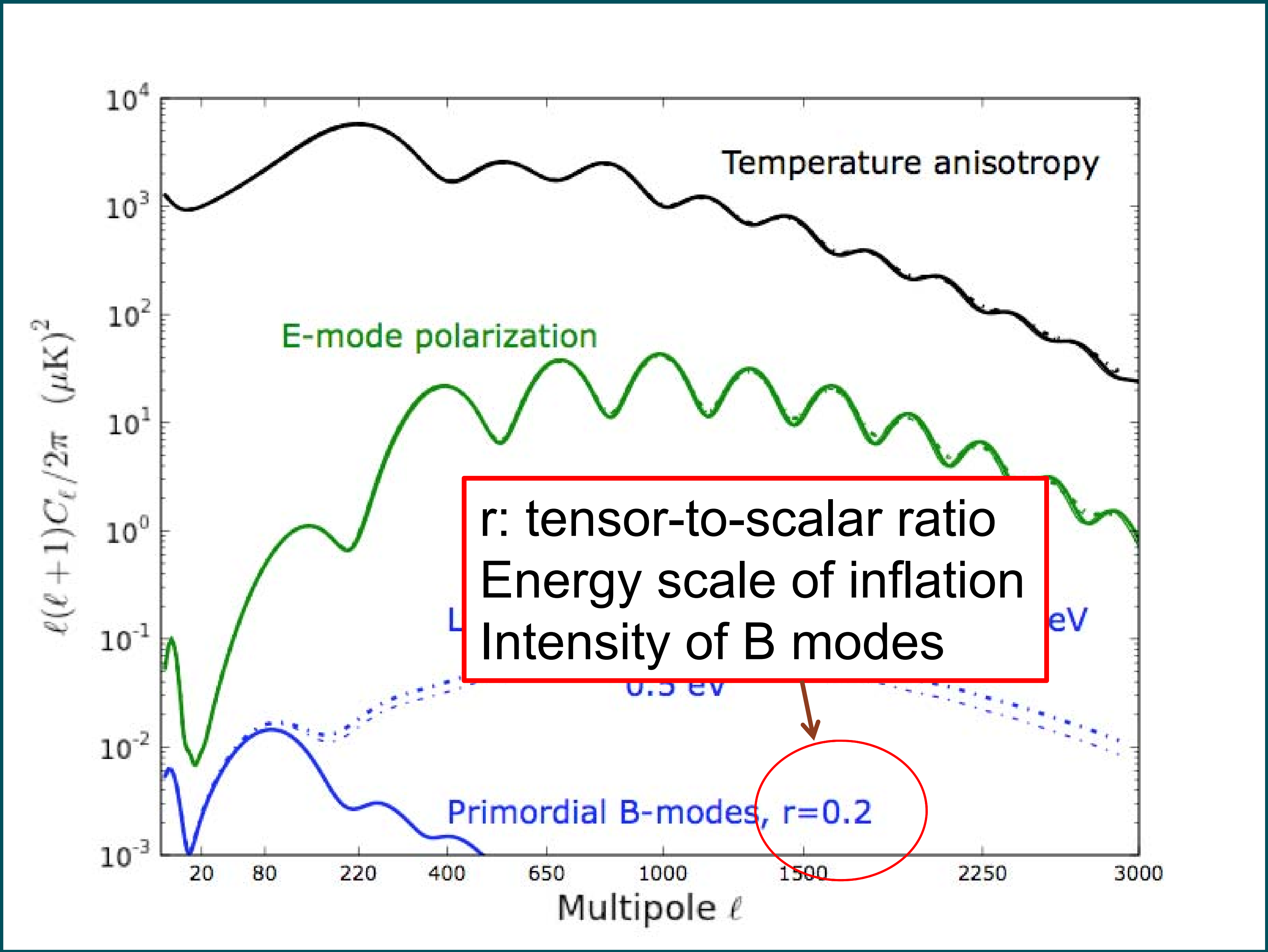
Unique gravity wave signature: "curl" mode
"B modes"

Similar to the fundamental theorem of vector calculus (Helmholtz theorem), but for a tensor field

Gravitational waves from inflation are only source of primordial B

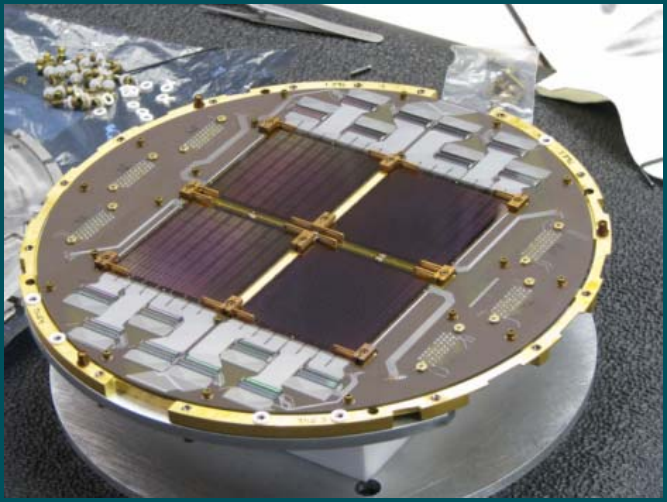


Gravitational waves from inflation are only source of primordial B

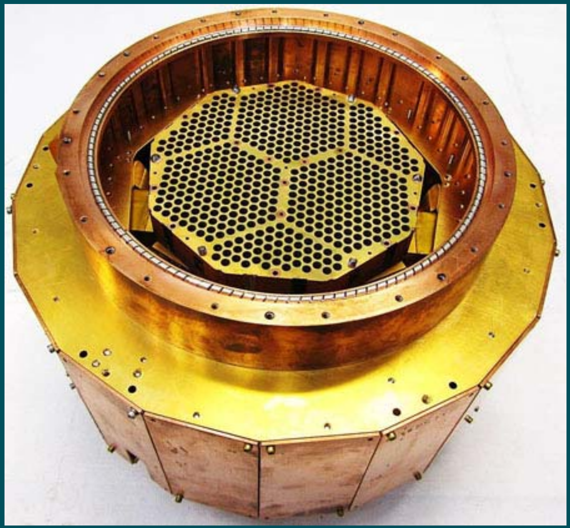


CMB polarimeters in the field

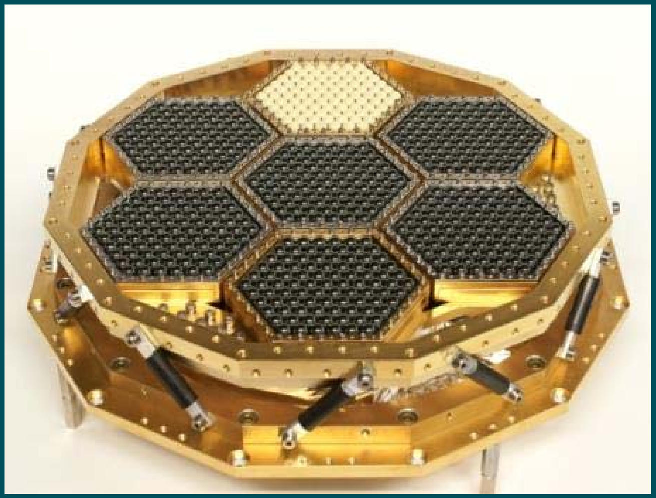
BICEP-2



ACTpol

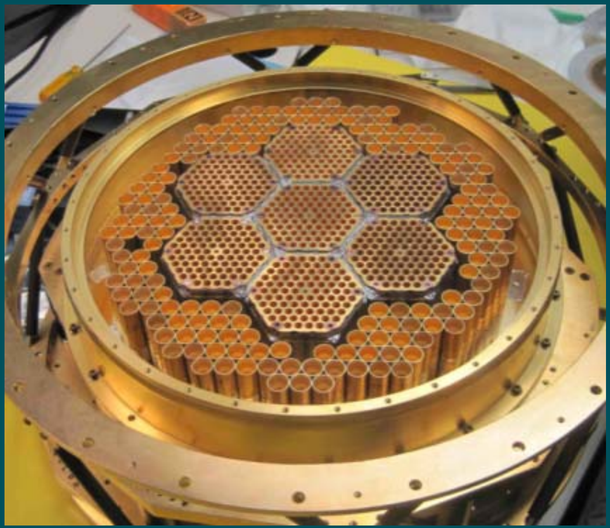


POLARBEAR

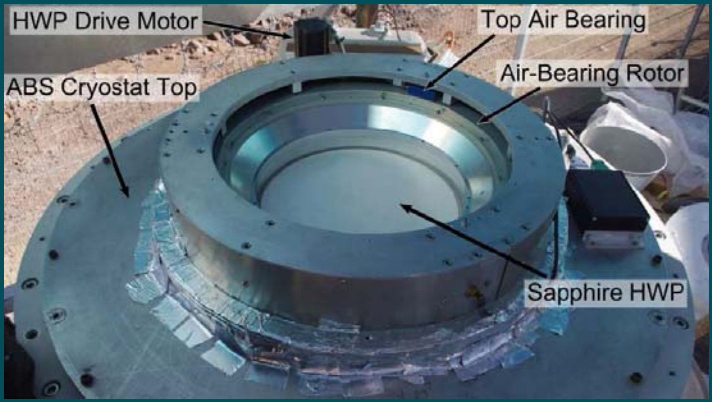


Keck Array

SPTpol



ABS



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Nicholas Huang

Selected for a Viewpoint in *Physics*
PRL **112,** 241101 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] G. C. Hilton,[11] V. V. Hristov,[2] K. D. Irwin,[12,13,11] K. S. Karkare,[5] J. P. Kaufman,[14] B. G. Keating,[14] S. A. Kernasovskiy,[12] J. M. Kovac,[5,*] C. L. Kuo,[12,13] E. M. Leitch,[15] M. Lueker,[2] P. Mason,[2] C. B. Netterfield,[4,16] H. T. Nguyen,[6] R. O'Brient,[6] R. W. Ogburn IV,[12,13] A. Orlando,[14] C. Pryke,[9,7,†] C. D. Reintsema,[11] S. Richter,[5] R. Schwarz,[9] C. D. Sheehy,[9,15] Z. K. Staniszewski,[2,6] R. V. Sudiwala,[1] G. P. Teply,[2] J. E. Tolan,[12] A. D. Turner,[6] A. G. Vieregg,[5,15] C. L. Wong,[5] and K. W. Yoon[12,13]

(BICEP2 Collaboration)

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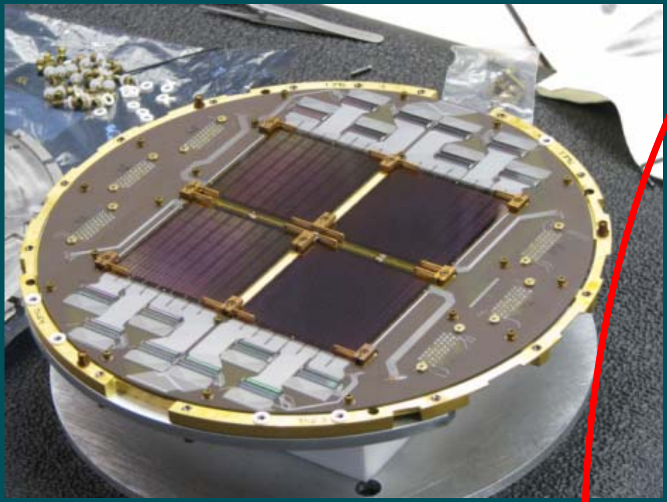
CMB polarimeters in the field

BICEP-2



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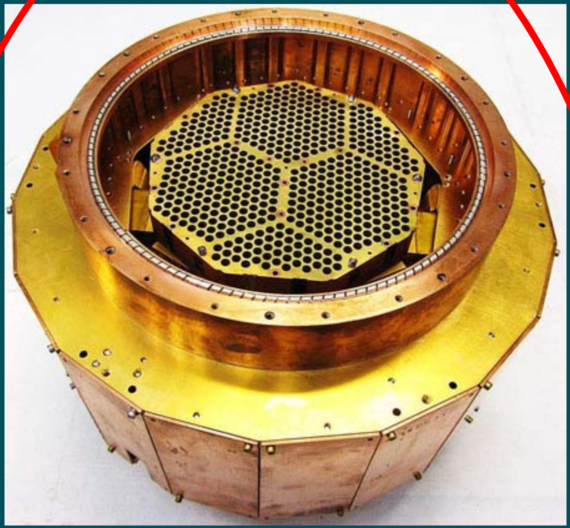

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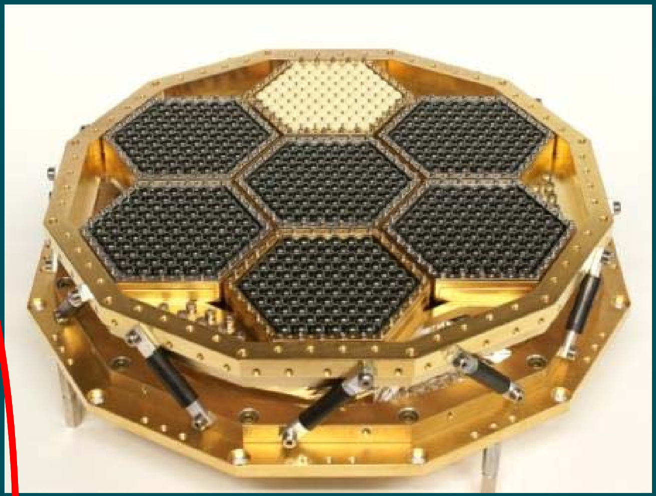
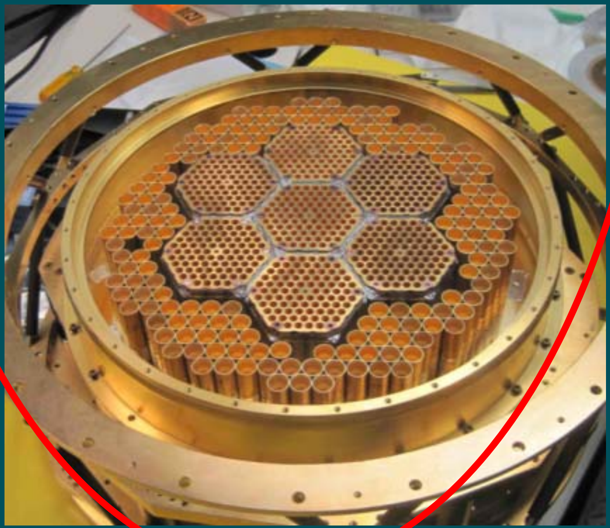


Keck Array

SPTpol



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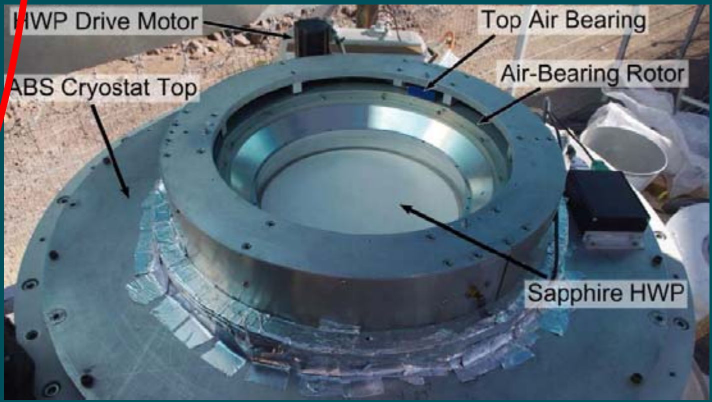
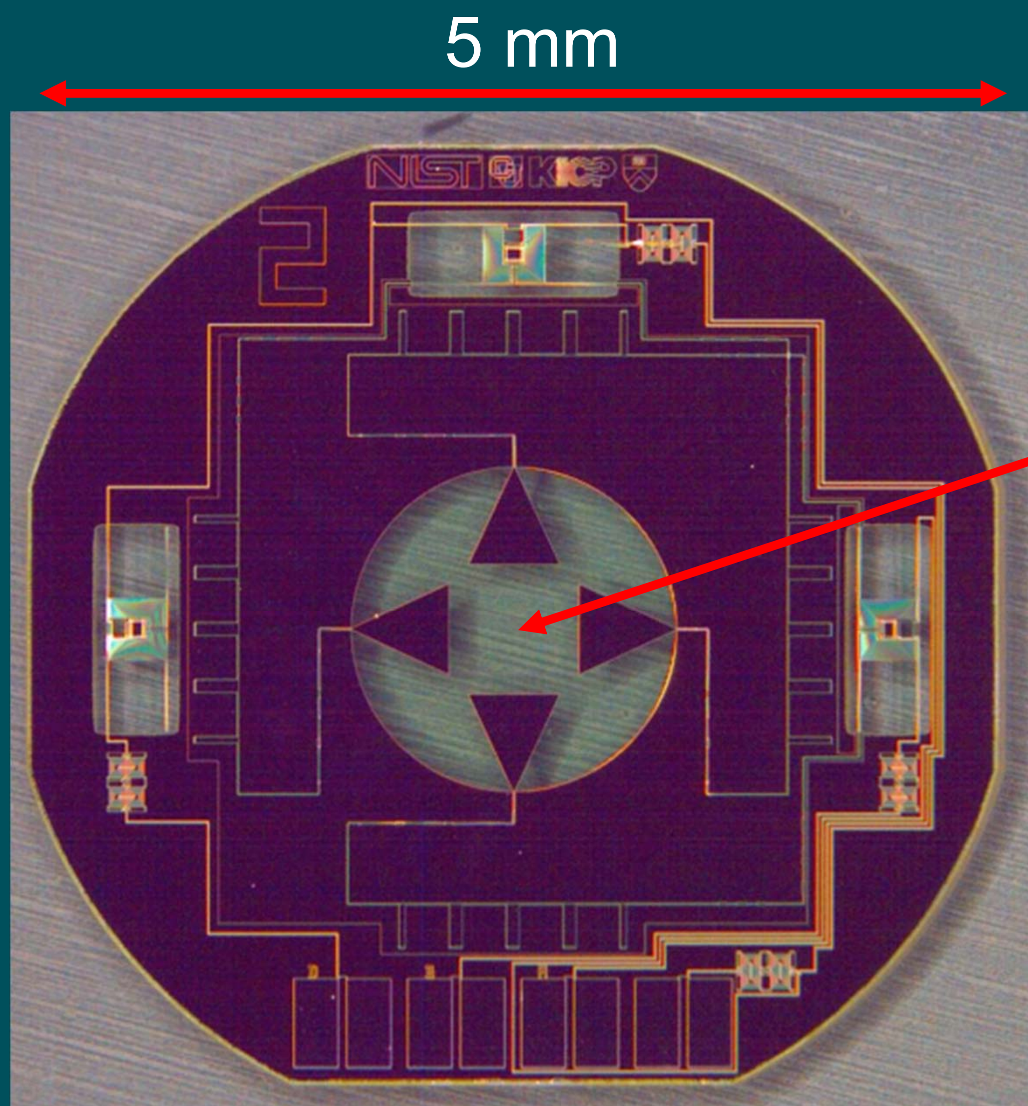


Example TES CMB polarimeter

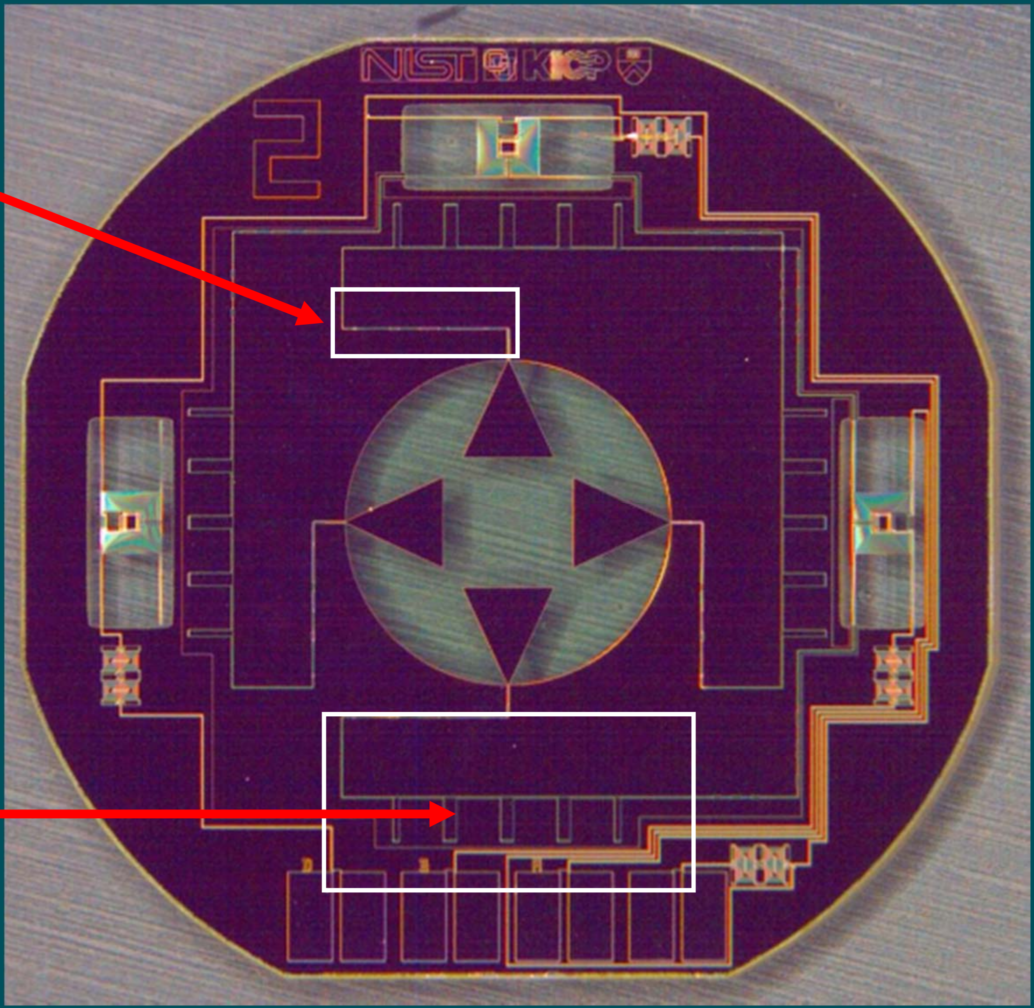


Ortho-mode transducer couples to Si feedhorn

Example TES CMB polarimeter

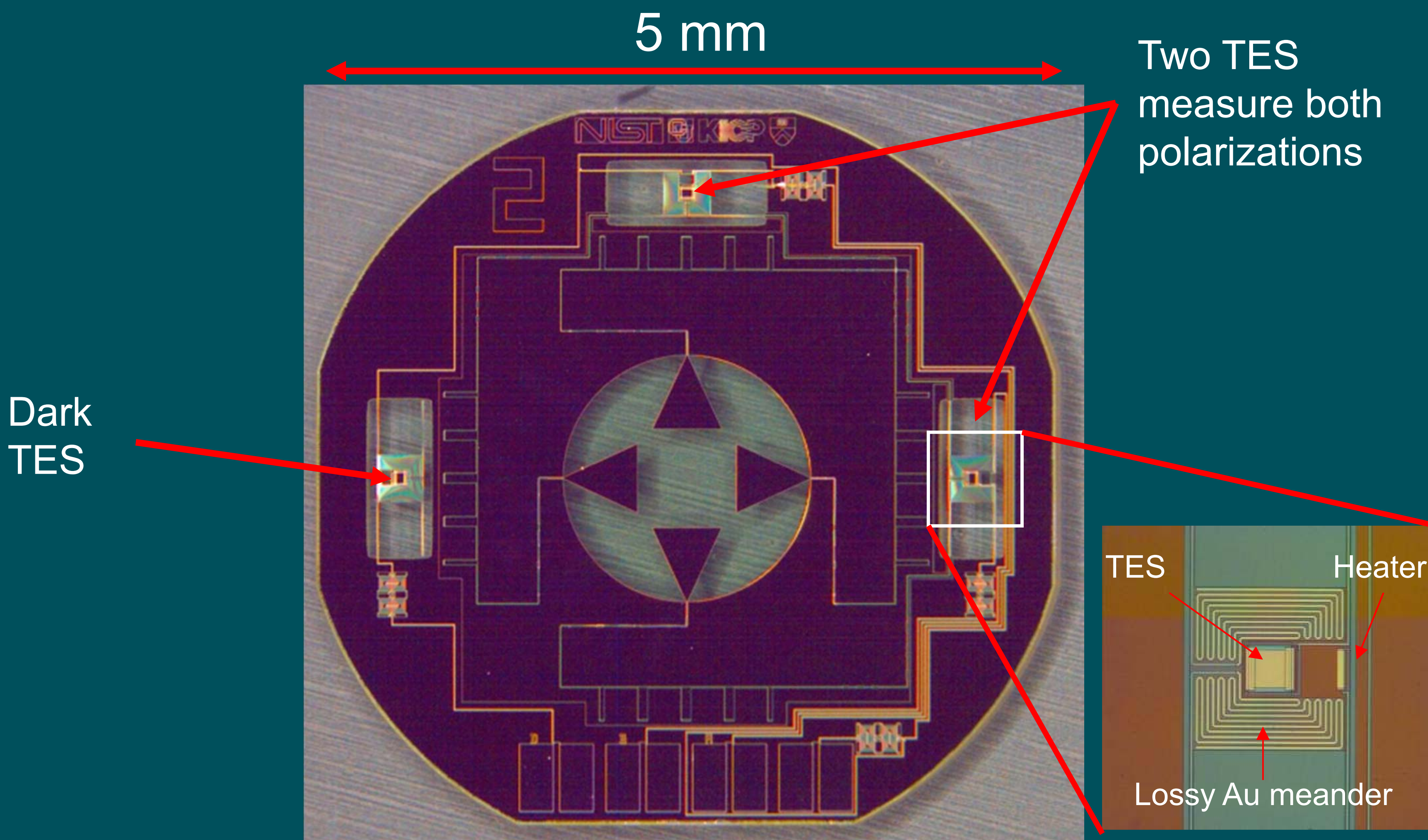
5 mm

CPW-to-microstrip transition



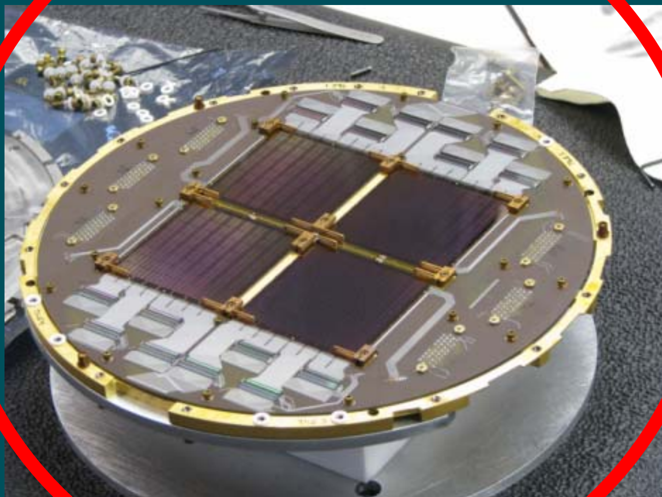
Band-defining stub filter & stepped-impedance LPFs

Example TES CMB polarimeter



CMB polarimeters in the field

BICEP-2

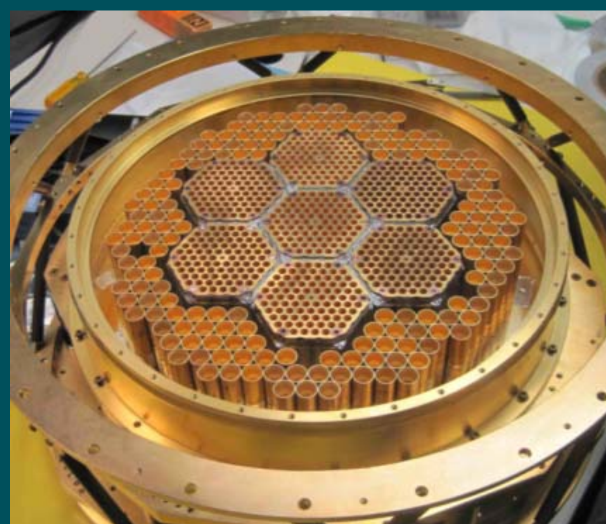


ACTpol

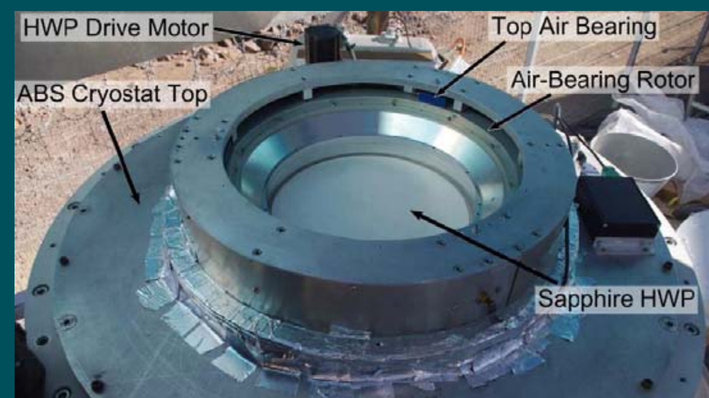
POLARBEAR

Keck Array

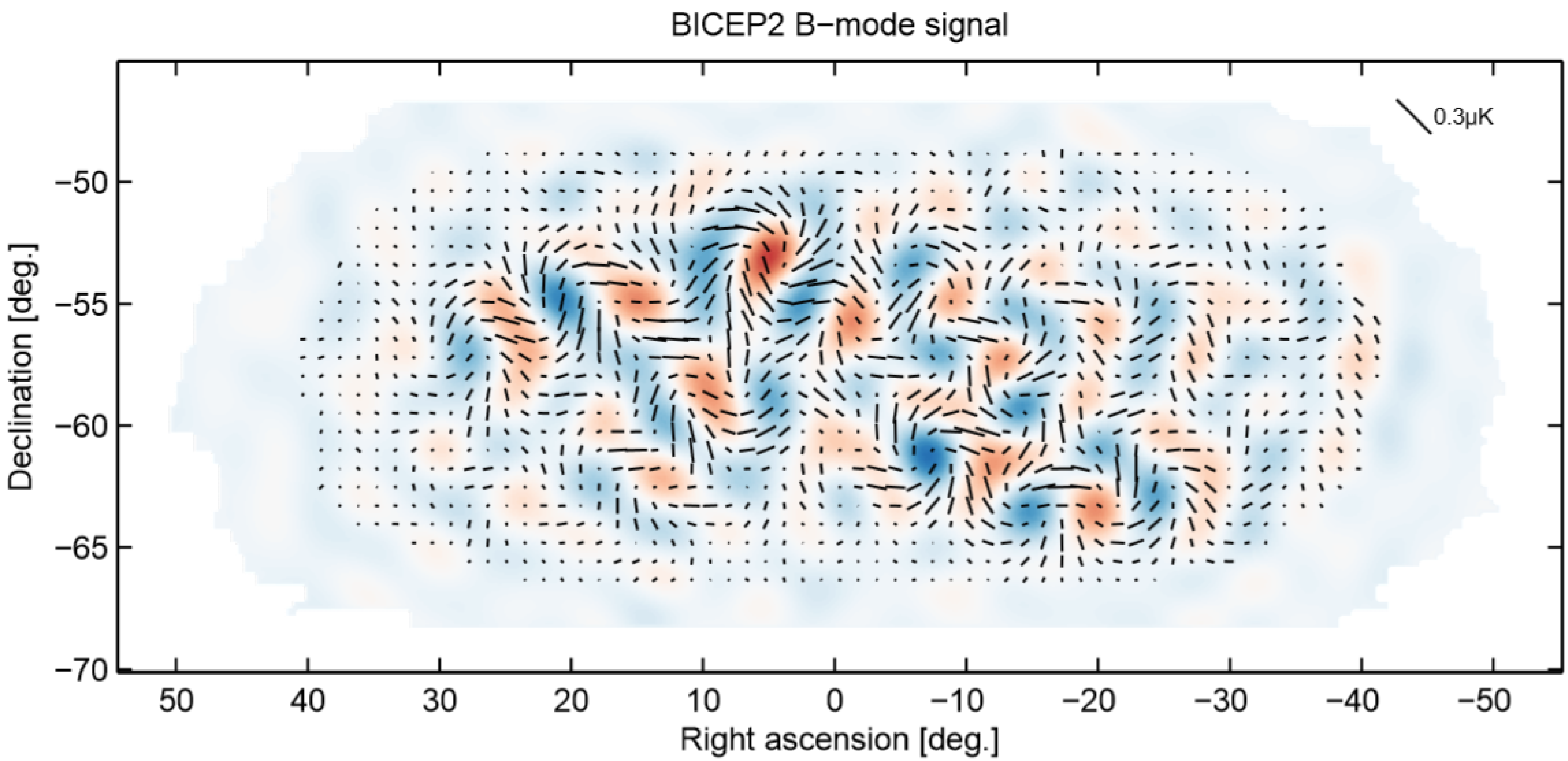
SPTpol

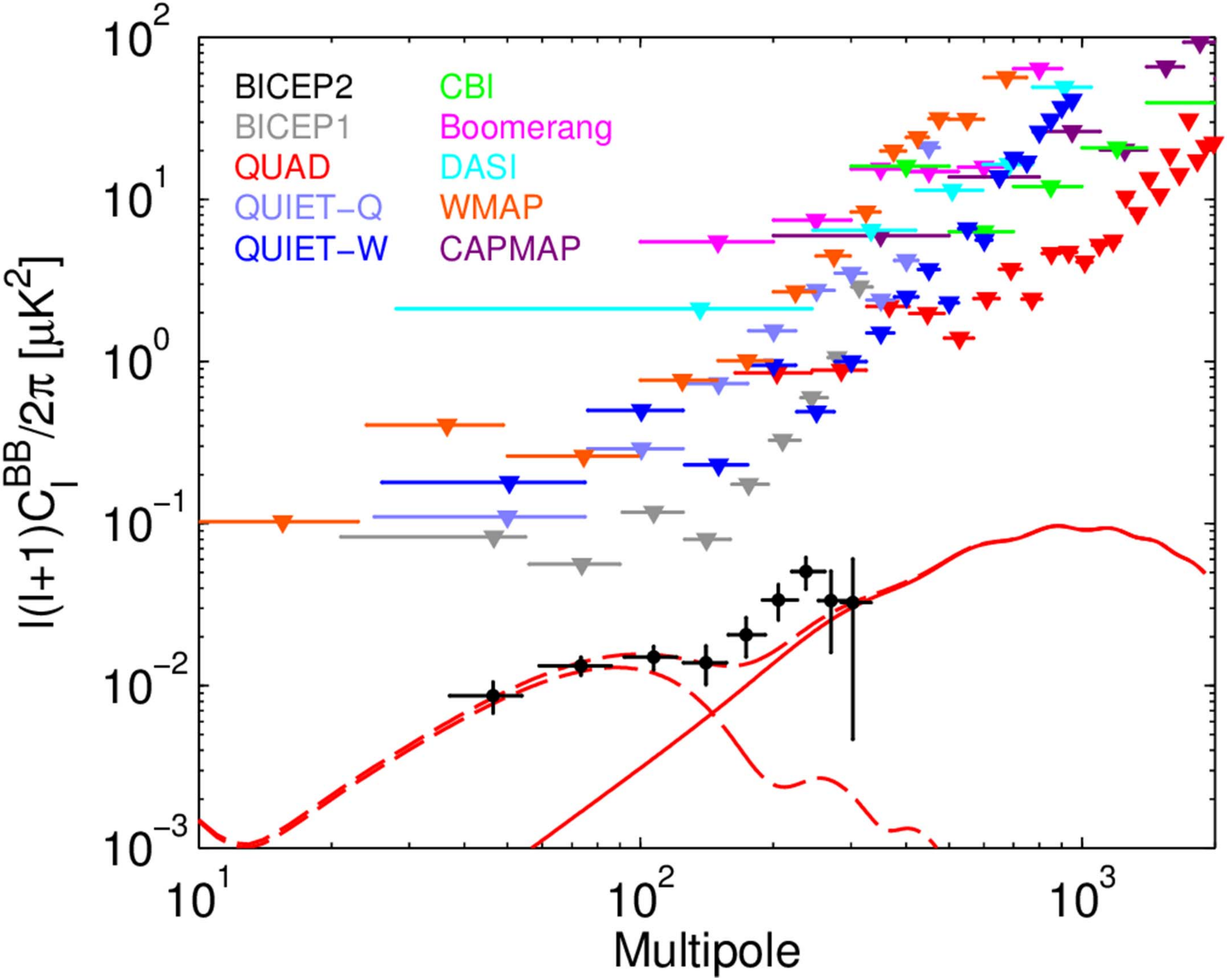


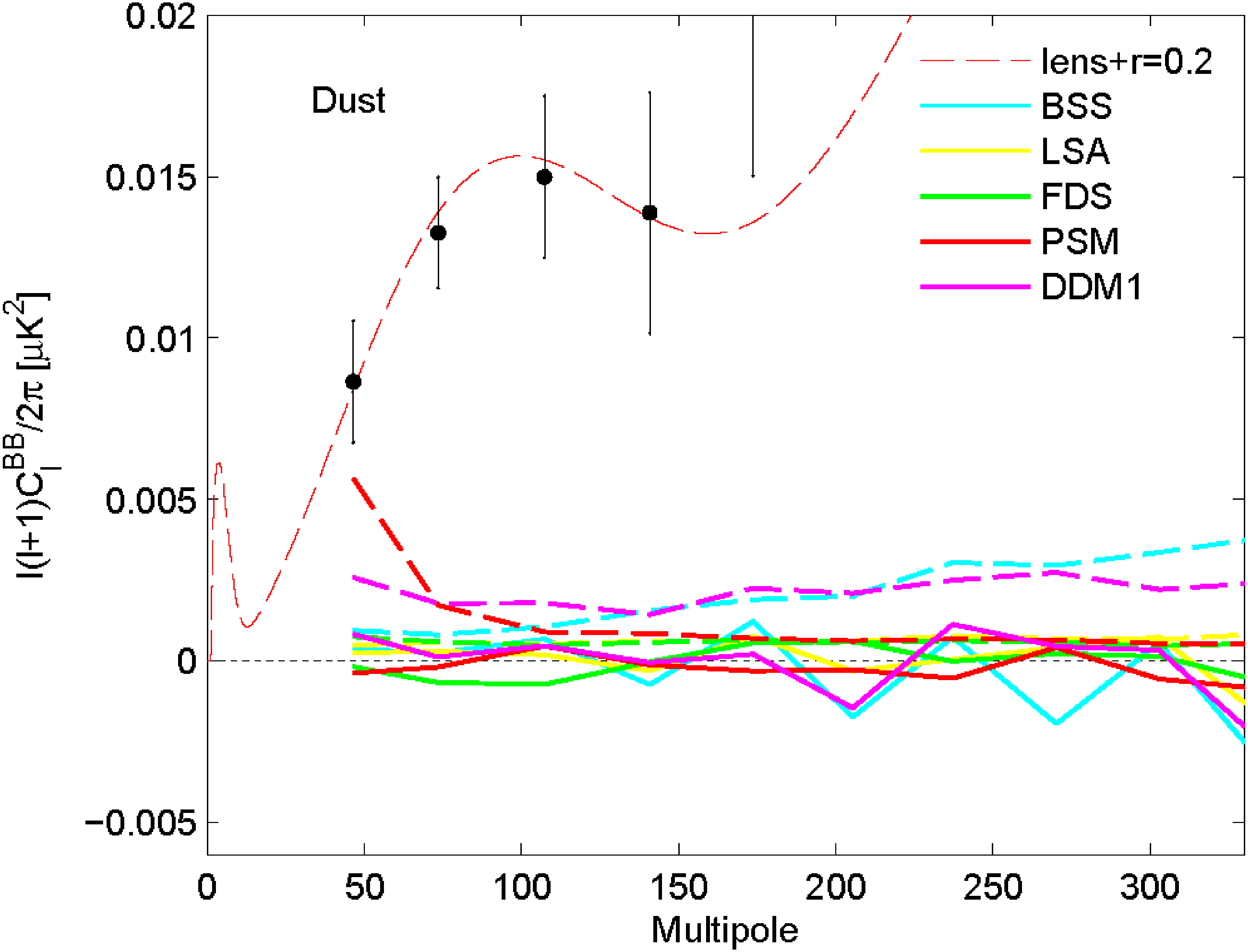
ABS



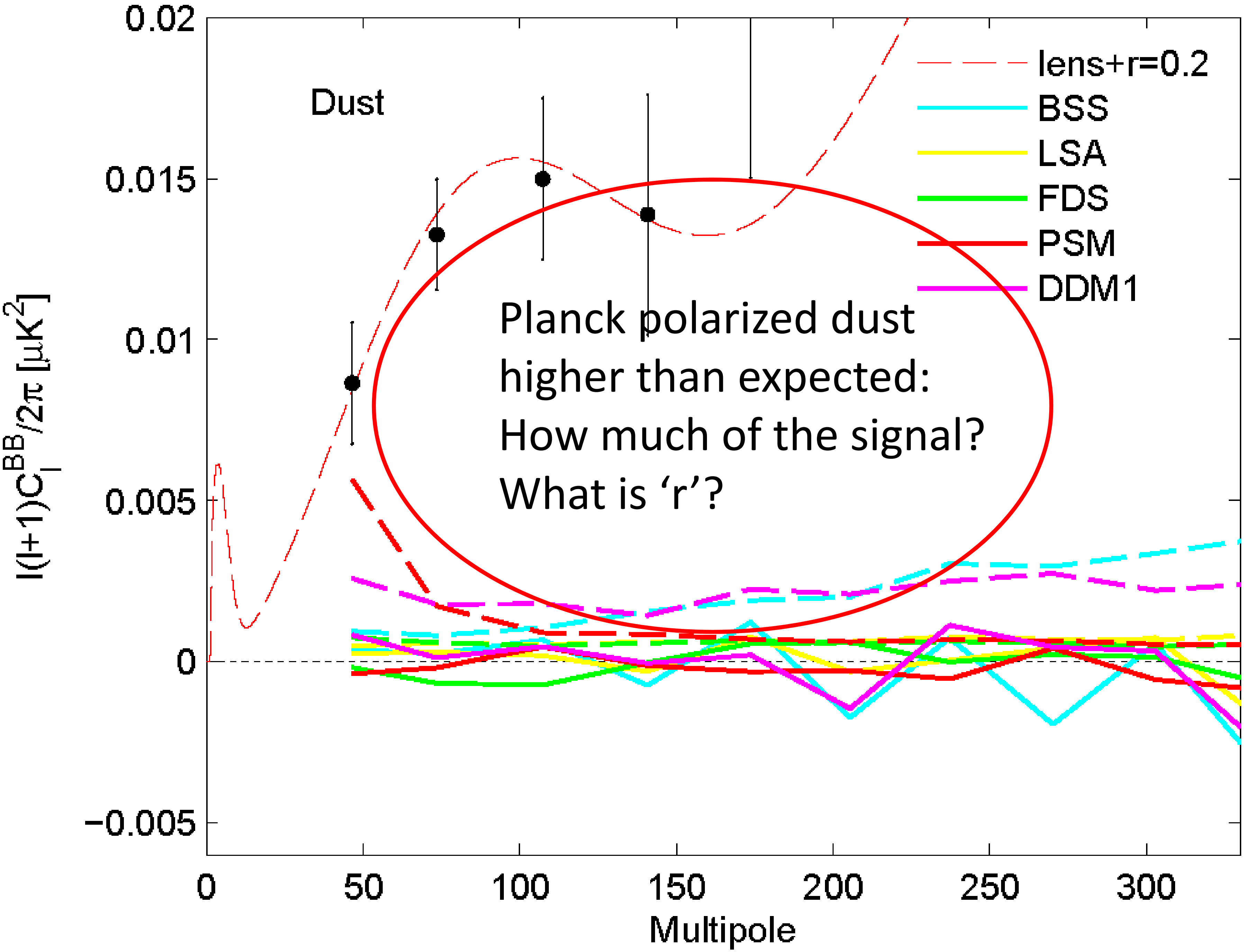
BICEP2 high s/n *B*-mode map




BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3



Dust
lens+r=0.2
BSS
LSA
FDS
PSM
DDM1
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
250
300


0.02
0.015
0.01
0.005
0
−0.005
0
50
100
150
200
250
300
Multipole
l(l+1)C_l^BB/2π [μK^2]
Dust
lens+r=0.2
BSS
LSA
FDS
PSM
DDM1
Planck polarized dust
higher than expected:
How much of the signal?
What is 'r'?

How to definitively measure the energy scale of inflation

Multiple frequency observations to constraint and clean foregrounds

- Cross-correlation with Planck 353 GHz channel *now*
- Keck array 100 GHz channels: data being analyzed
- BICEP-3 100 GHz: deploying this season
- Multichroic pixels (ACTpol multichroic deploying soon)

Higher angular resolution measurements to delense

- SPT, ACT, Polarbear

Deeper maps $\rightarrow$ sky variance limited

Greater sky coverage in Chile

- Better constraint on ‘r’
- Consistency ratio of inflation

All these steps will use more advanced TES arrays

Outline

SLAC

An adventure in applied superconductivity from cosmology to x-ray beamline science

- Superconducting Transition-Edge Sensors
- Photon detection from microwaves to x-rays
- Multiplexing for large arrays
- Microwave polarimetry for cosmology
- X-ray spectroscopy at synchrotron and FEL light sources

Collaboration

SLAC

SLAC / Stanford

Saptarshi Chaudhuri
Hsiao-Mei Cho
Kelly Gaffney
Kent Irwin
Chris Kenney
Dale Li
Michael Minitti
Dennis Nordlund
Tsu-Chien Weng
Christopher Williams

NIST

Doug Bennett
Randy Doriese
Dan Swetz
Galen O'Neil
Joel Ullom
Joe Fowler
Carl Reintsema
Gene Hilton
Dan Schmidt

NSLS

Daniel Fischer
Cherno Jaye

Lund Kemicentrum (Lund, Sweden)

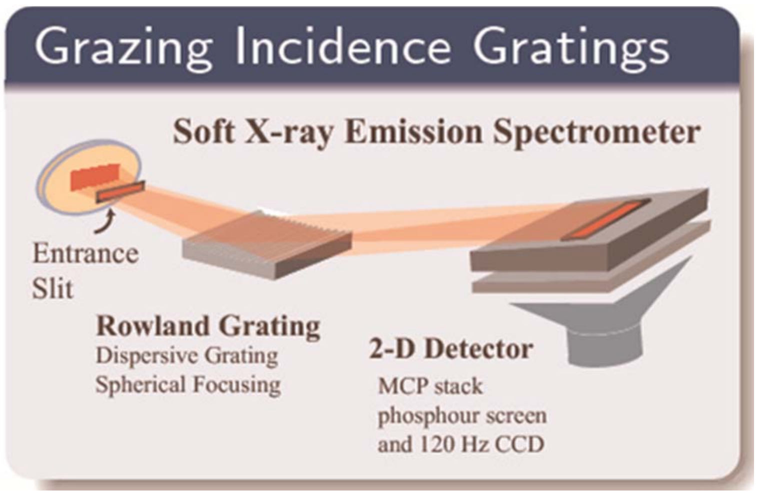
Jens Uhlig

Soft X-ray Detection: Conventional Technology

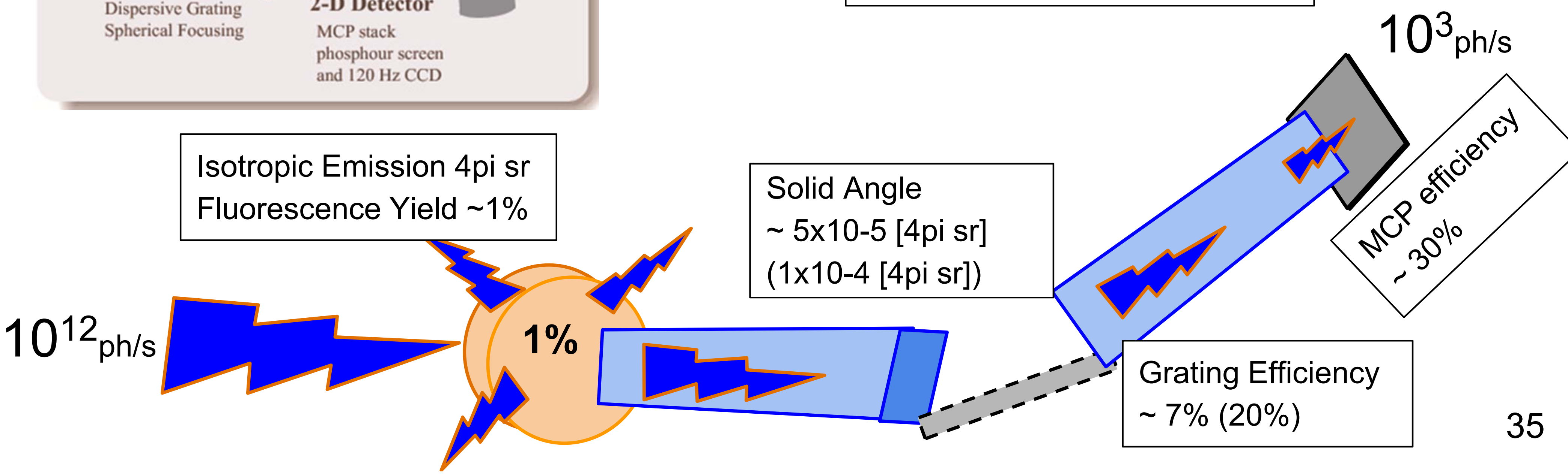
Soft X-ray Grazing Incidence Grating Spectrometers and its limitations

Conventional Soft X-ray Grating Spectrometer

- Limited Solid Angle
- Low Detection Efficiency
- High Resolution Possible (at a cost)
- Small Spot Size



Fraction Detected
Fluorescence Yield **x**
Solid Angle **x**
Detection Efficiency =
1% x 5x10^{-5} x 7% x 30%
~10^{-9} (~10^{-8})



Sensitivity of TES based X-ray Spectrometers at SSRL (in development)

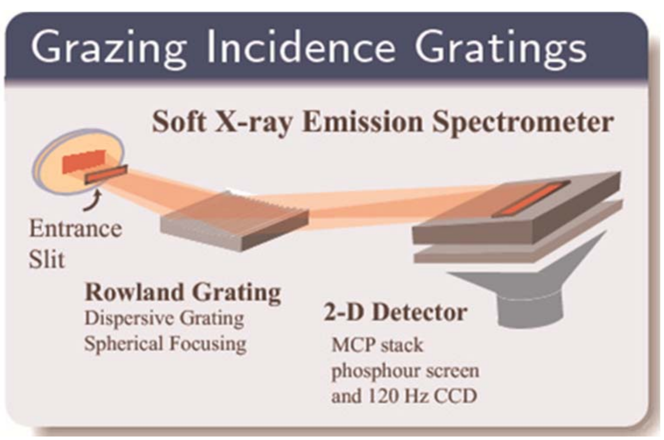
Enabling Ultra-low Concentrations (ppm)

SLAC

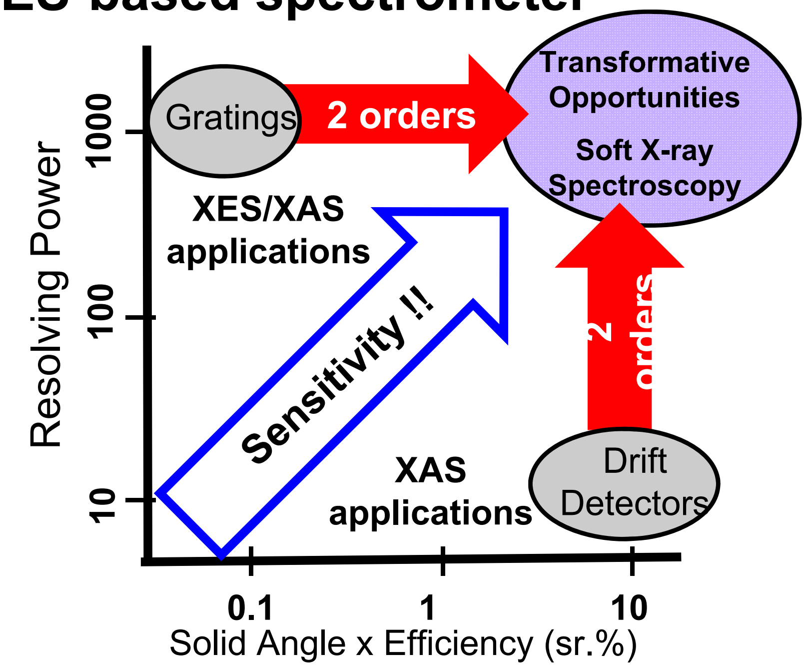
Defects/Dopants	10^{19}-10^{20}/cm^3	=>	10^{17}-10^{18}/cm^3
Surface Sensitivity	1-10% monolayer	=>	0.01-0.1% ML
Solute Sensitivity	10-100 mM	=>	100-1000 uM
Spot Size	10-100um	=>	1-10mm

New Science Opportunities in Material Science, Chemistry, and Biology

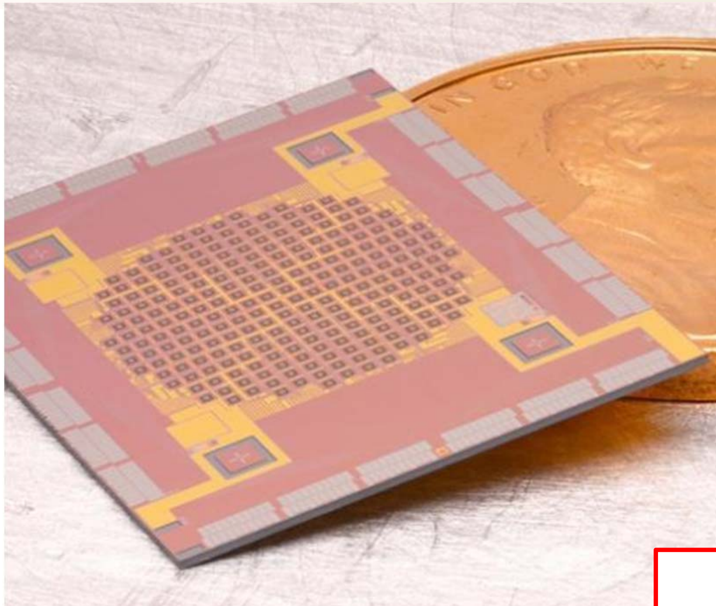
Grating Spectrometer

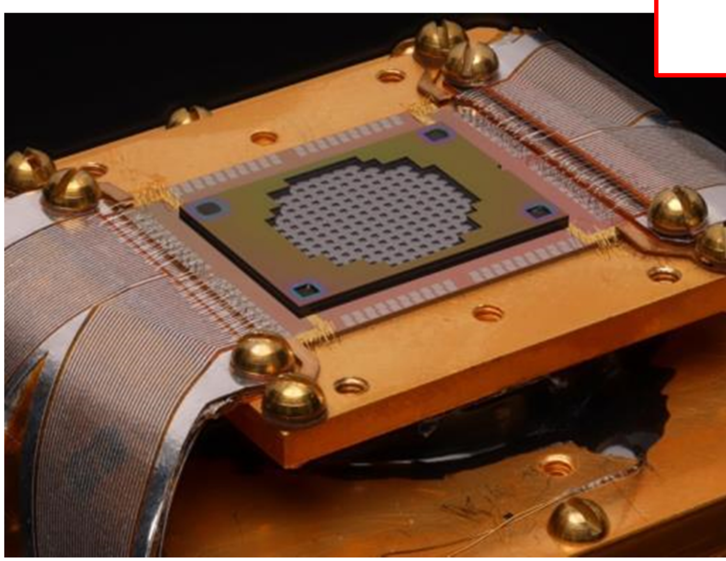


TES-based spectrometer



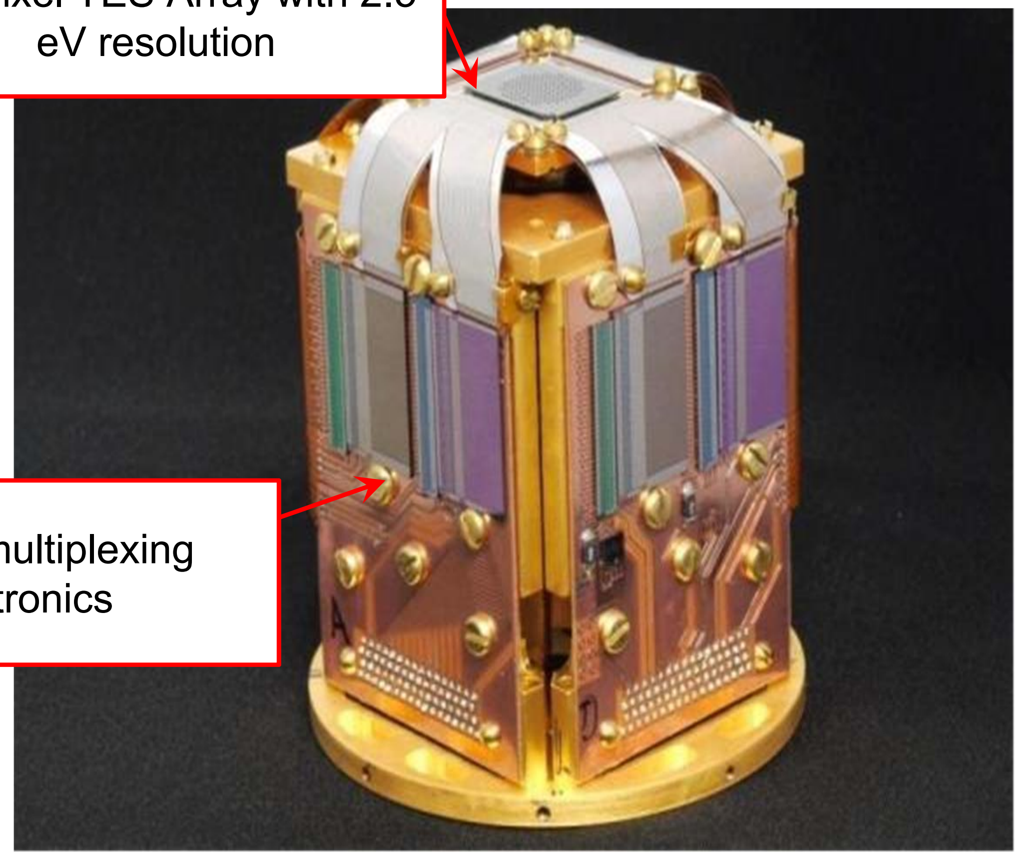
TES Spectrometer Arrays





160 Pixel TES Array with 2.5 eV resolution

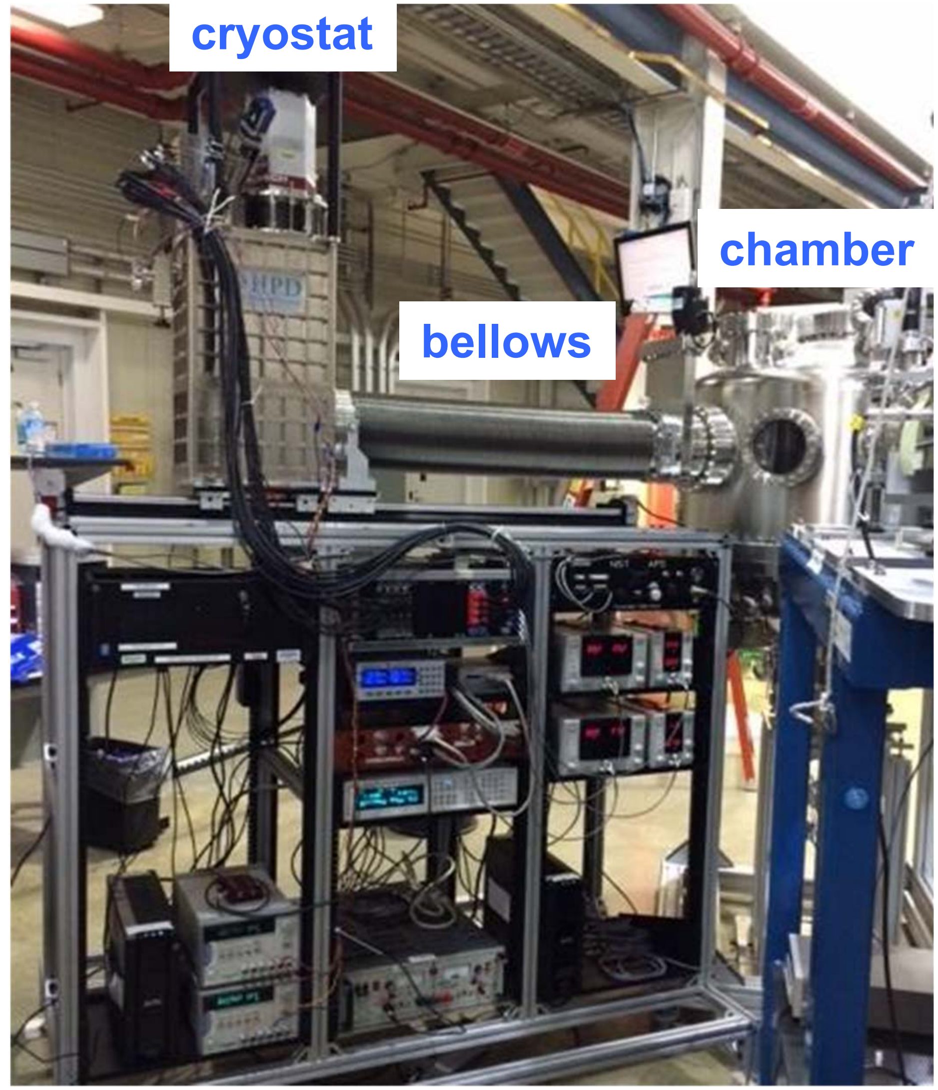
SQUID multiplexing electronics



We are now deploying a 240-pixel soft x-ray spectrometer array on SSRL BL-10-1

Beamline hardware

NSLS U7A beamline
- 200-1400 eV
- Prototype installed Dec., 2011



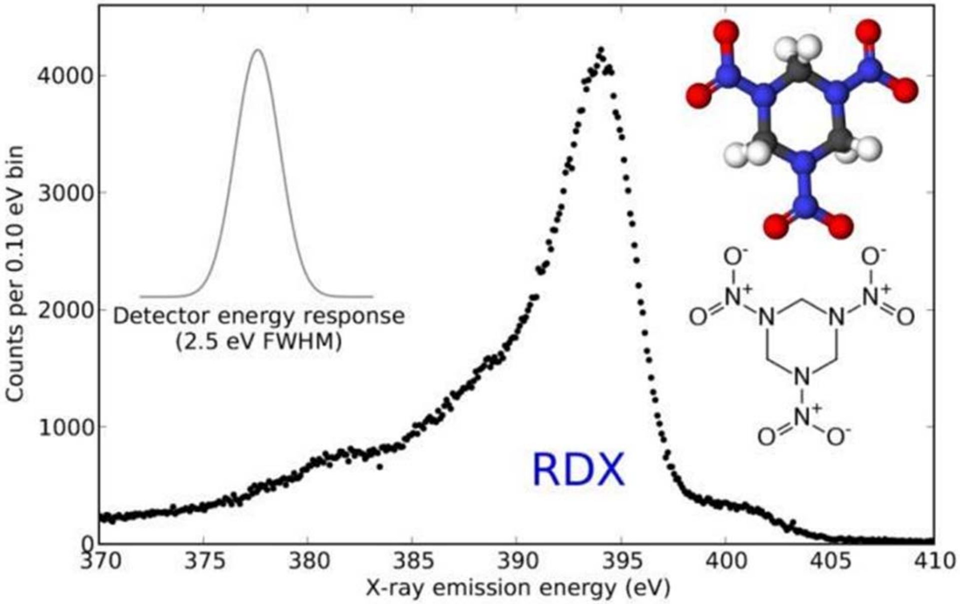
APS 29ID IEX beamline
- 400-2500 eV
- Installed August, 2014

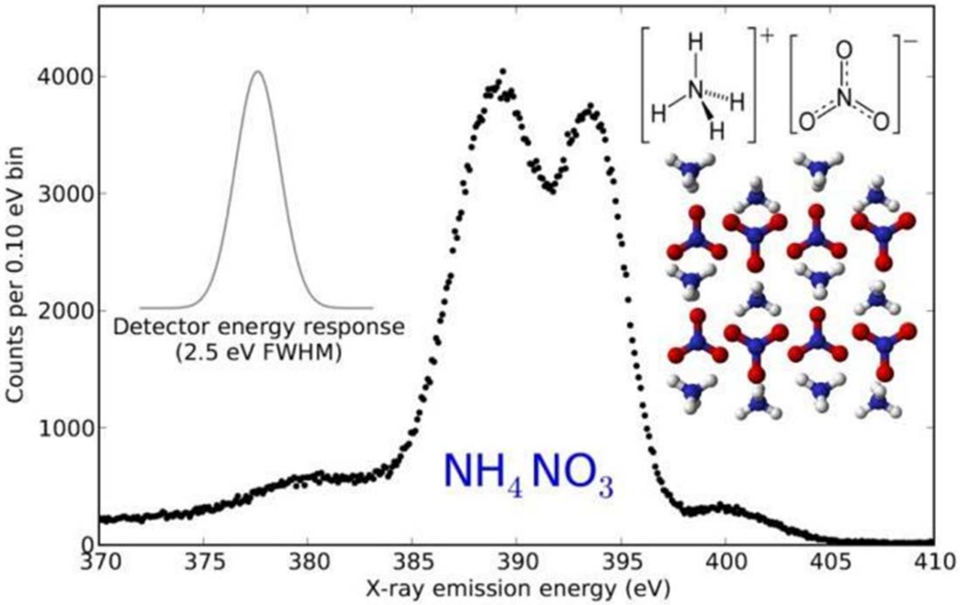
Demonstration spectra

Prototype NSLS 45-pixel spectrometer:

- XES of eV-scale chemical shifts (chemistry of occupied valence states)
- partial-fluorescence-yield absorption spectroscopy (chemistry of unoccupied valence states)

XES for forensics

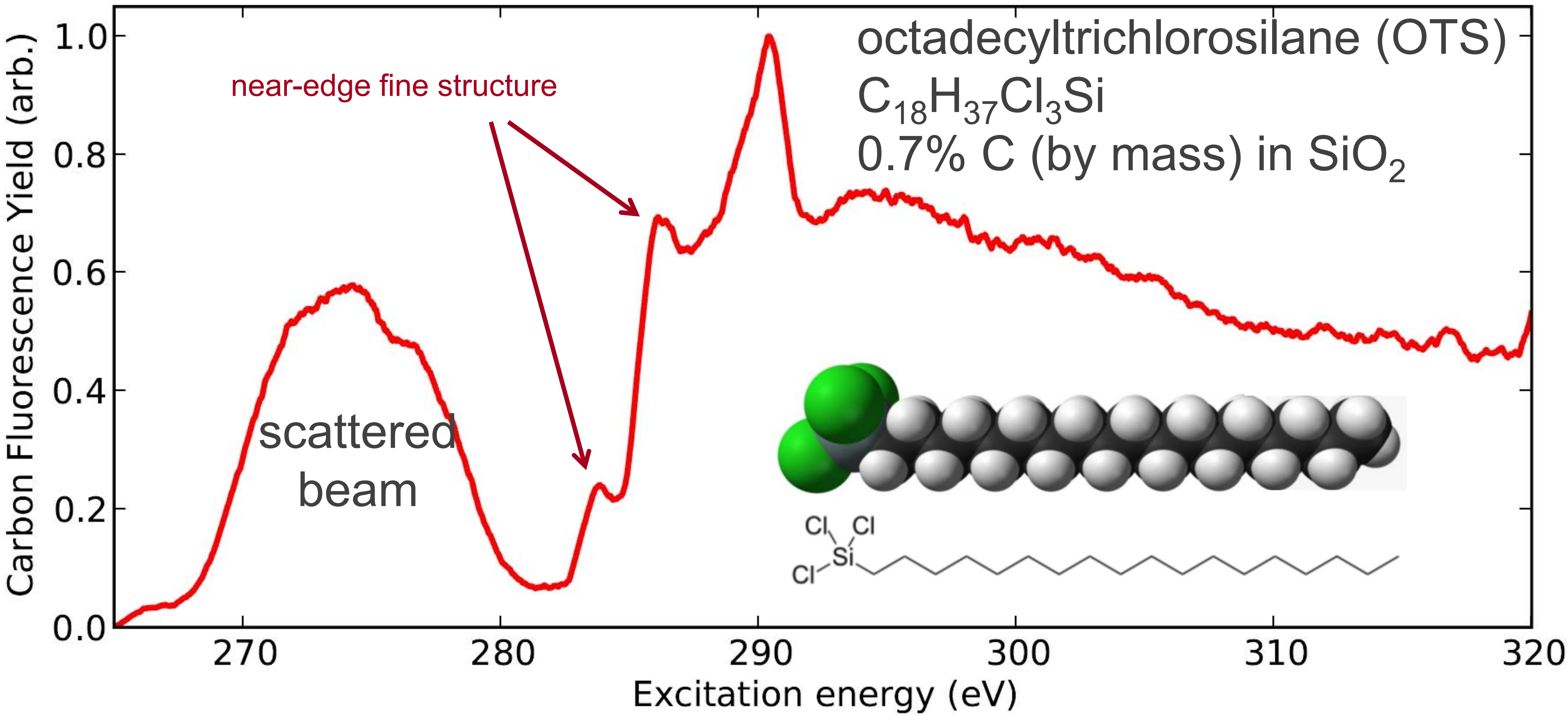




N emission in RDX is clearly distinguishable from NH_4NO_3.

XES probes the nitrogen chemical environment

PFY-NEXAFS of ODTC



resulting NEXAFS spectrum

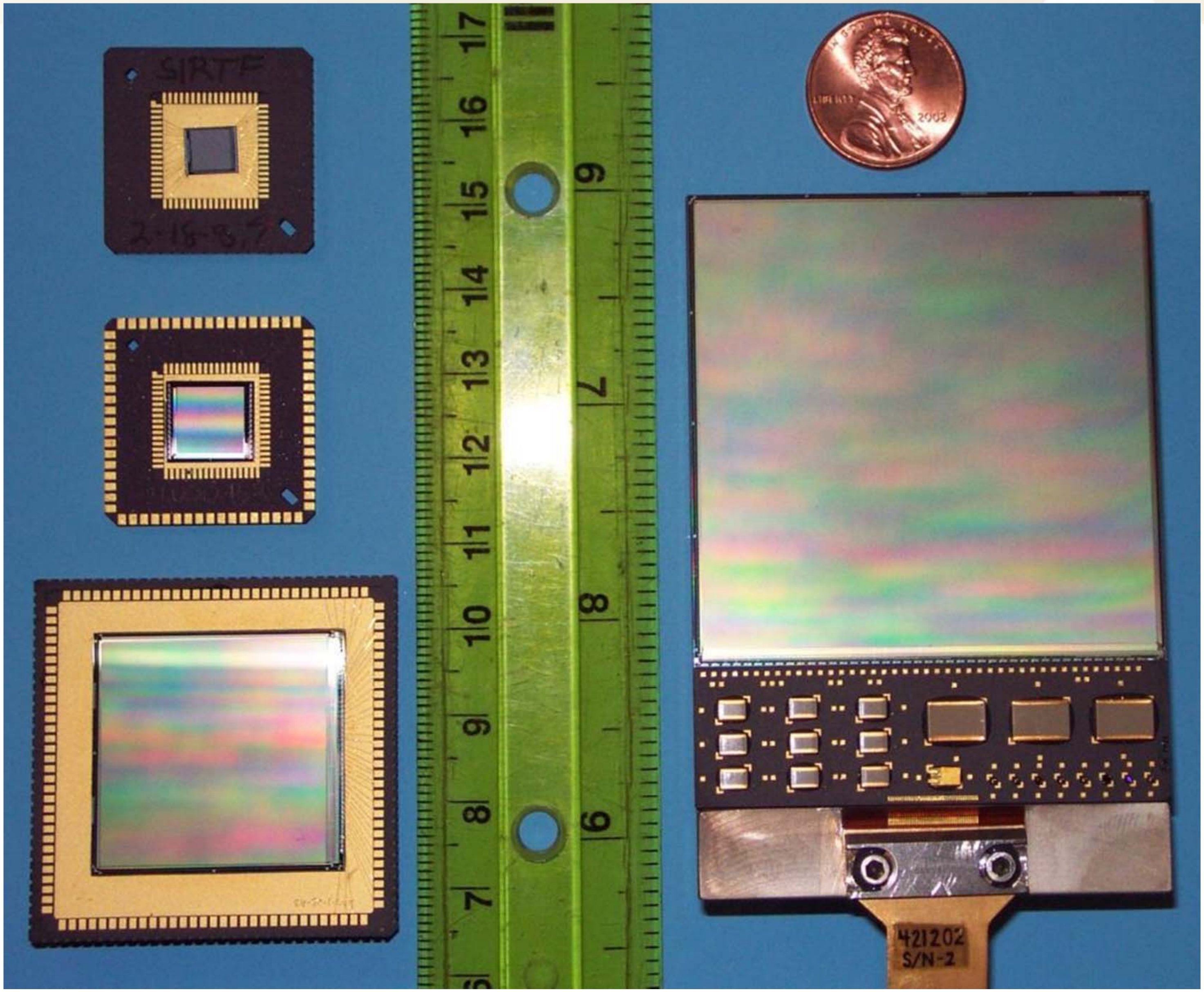
- Better than MultiLayer Mirror (MLM) spectrum of same sample
- Unlike MLM, also works at N, O, … all other edges

NIR detector array Moore's Law

32x32
1983

58 x 62
1988

256x256
1998

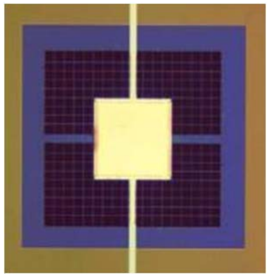


2048^2
2008

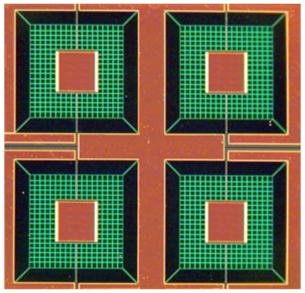
Pipher et al.

TES spectrometer Moore's Law: ~2 years doubling

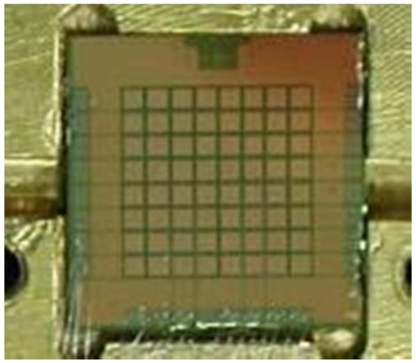
1 pixel
1996

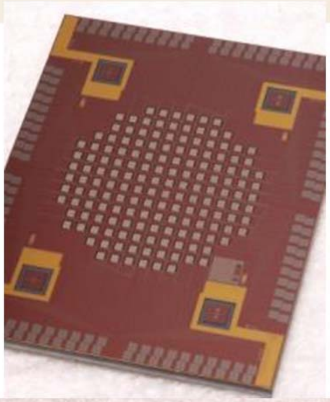


4 pixel
2000

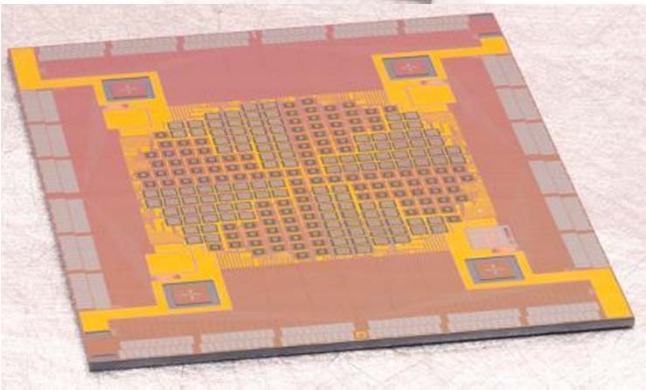


24 pixel
2004

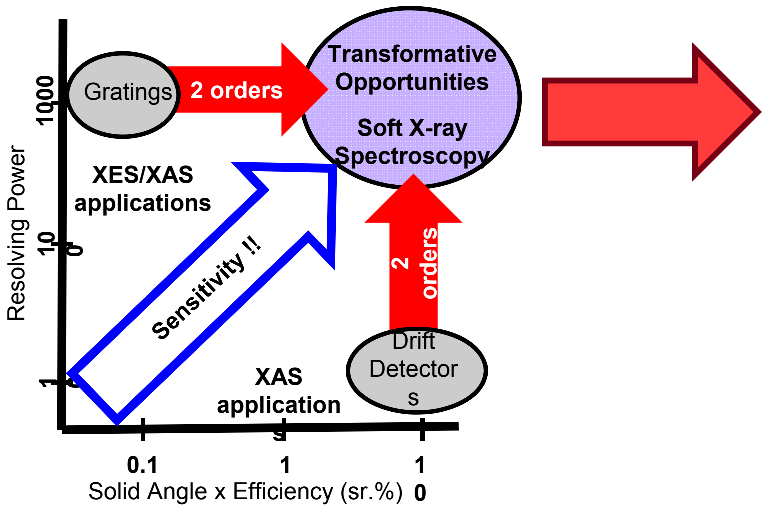




45 pixel
2008



240 pixel
2014



Long-term effort will double solid angle & count rate every ~ two years