CMB and Kinetic Inductance Detectors

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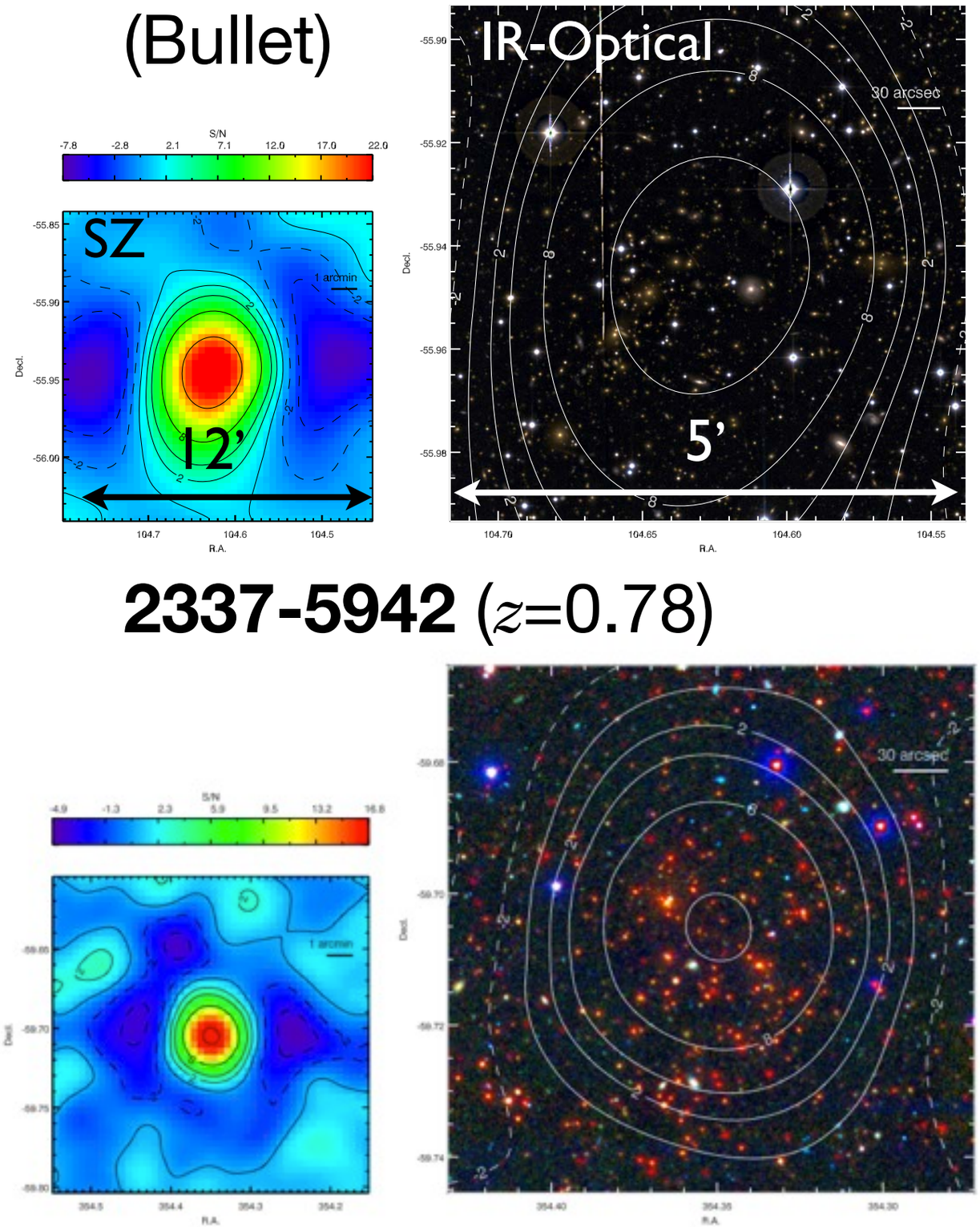
MKIDs & Cosmology Workshop
FNAL
August 26-27, 2013

Outline

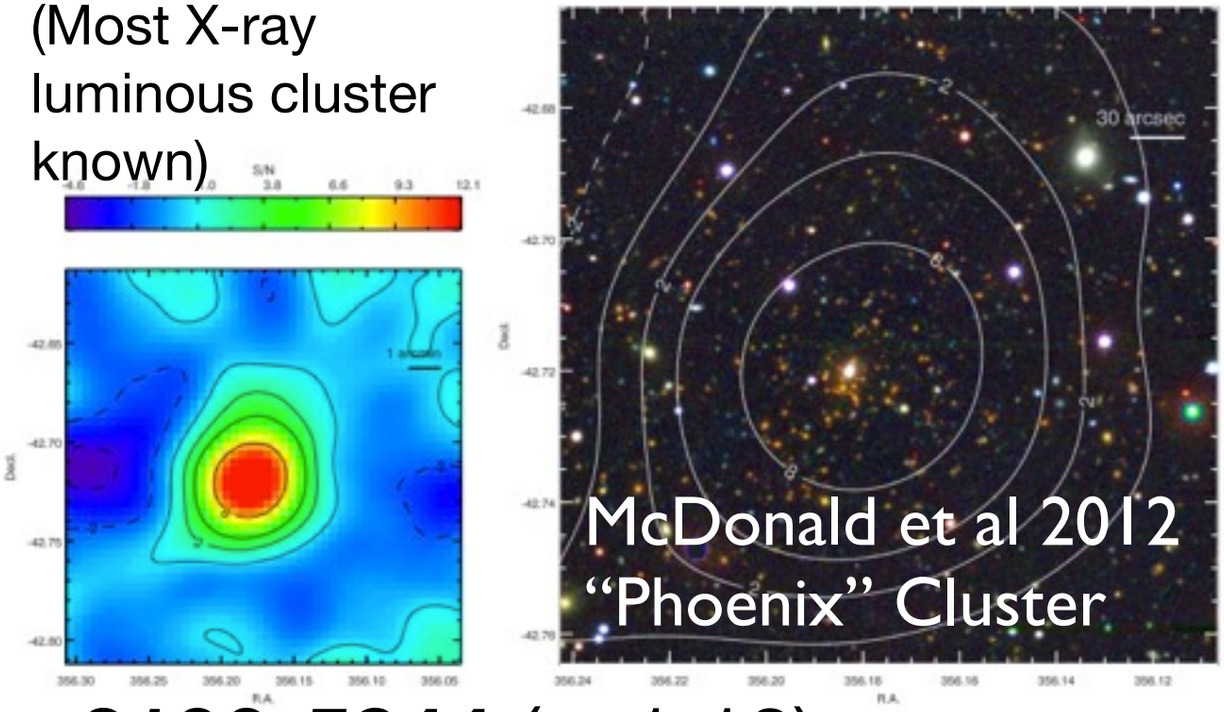
- Quick (and incomplete) overview of CMB science
- Key concepts for CMB technology
- Current & near-future CMB detectors
- KIDs at mm-wavelengths
- KID-based CMB experiments

SPT-SZ: ***Massive Cluster Gallery***

0658-5358 (z=0.30)
(Bullet)

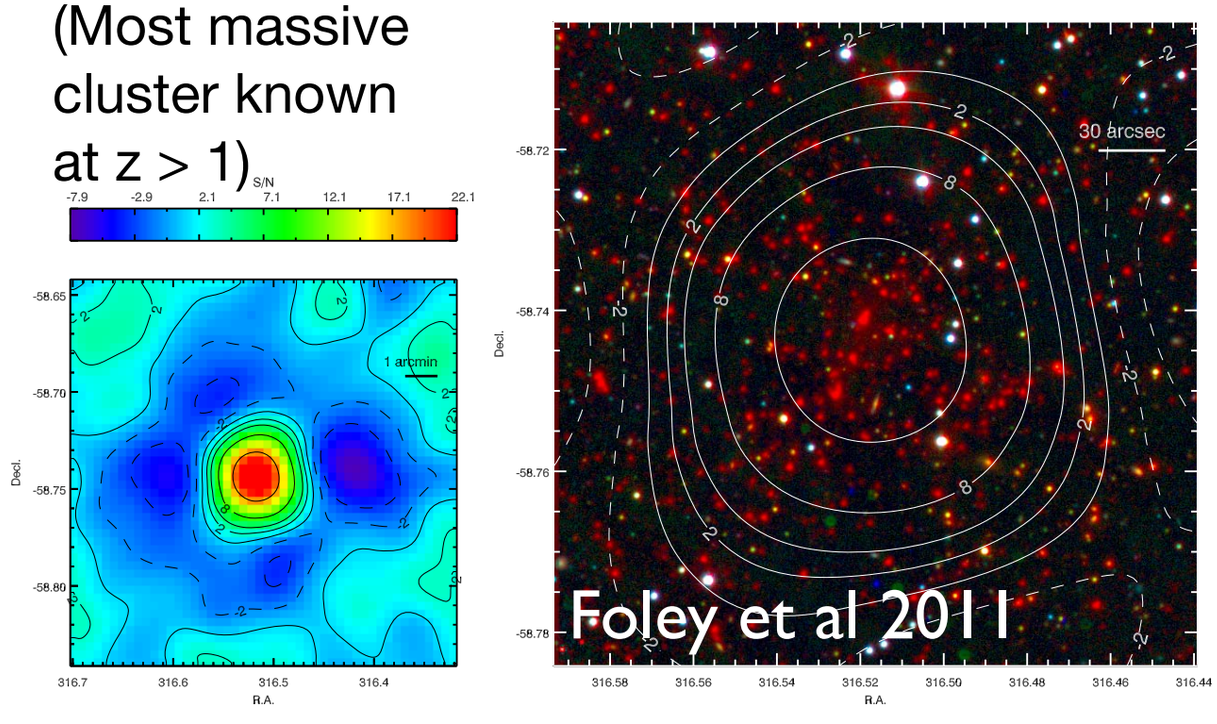


2344-4243 (z=0.60)
(Most X-ray luminous cluster known)

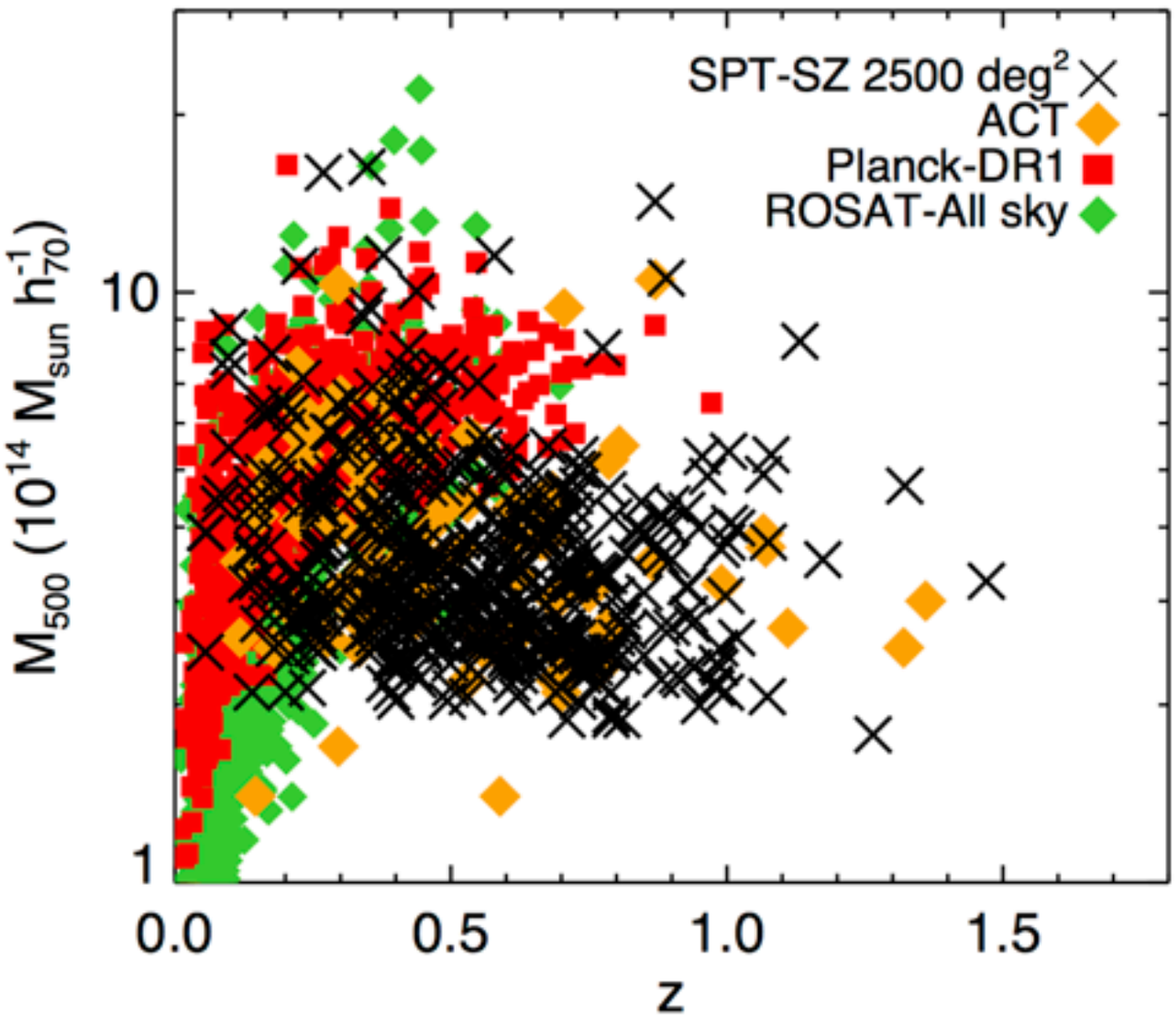


2337-5942 (z=0.78)

2106-5844 (z=1.13)
(Most massive cluster known at z > 1)



SZ Cluster Surveys: ***Mass vs Redshift***



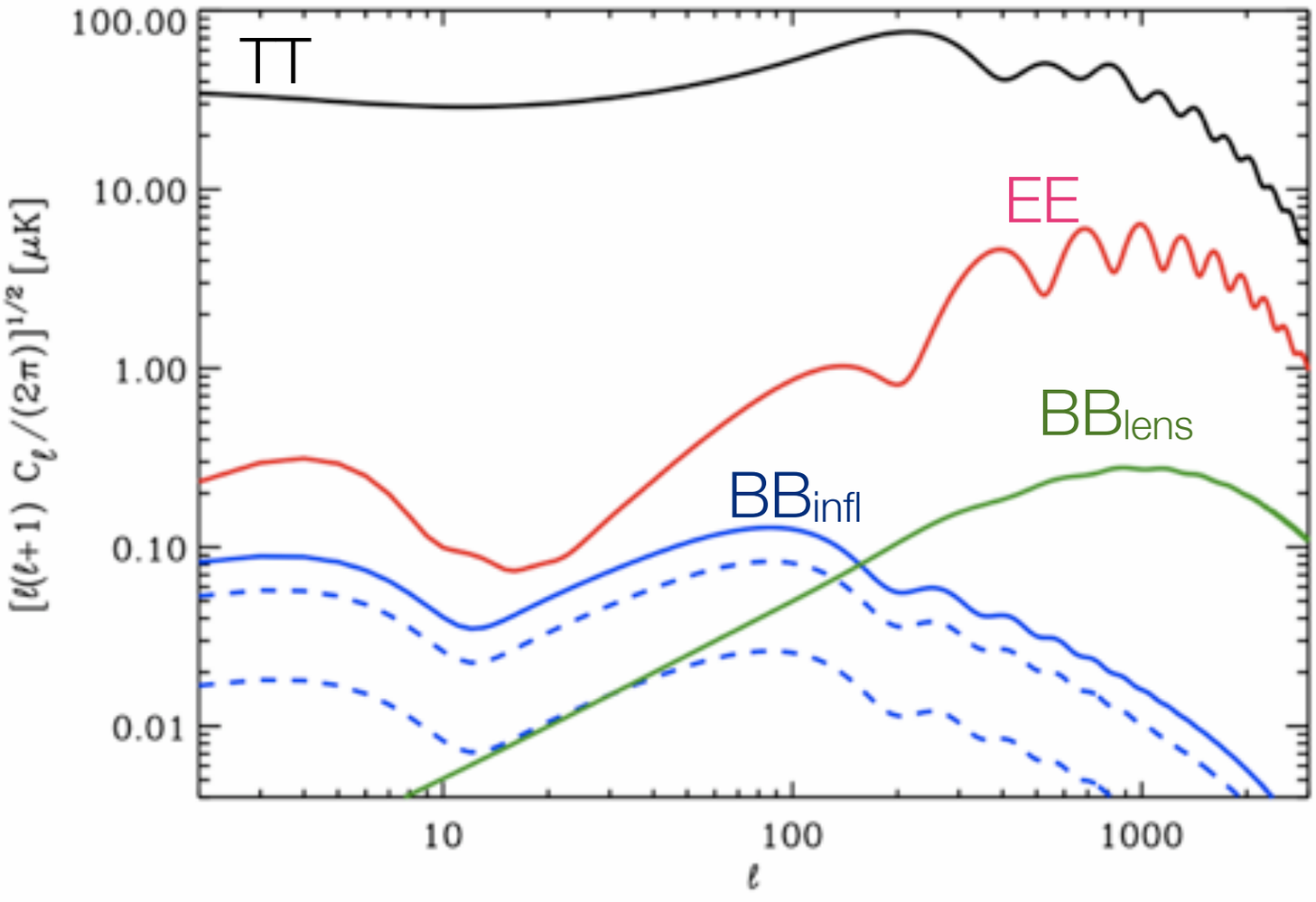
	Area (deg²)	**Depth** (uK-arcmin)	**$N_{clusters}$**
Planck	All-sky	45	861
SPT	2500	17	465
ACT	950	23-40	91

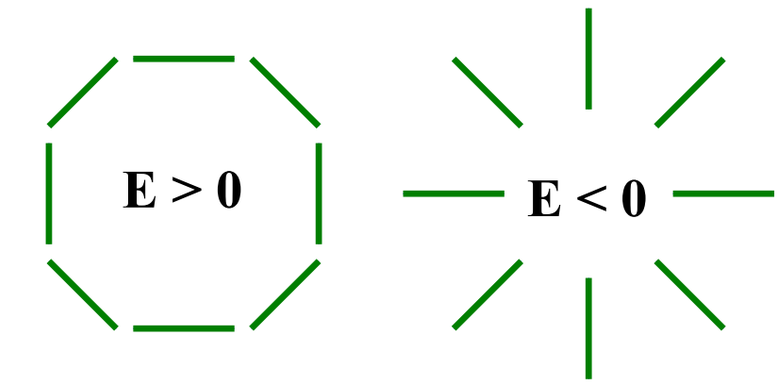
First SZ-discovered cluster was in 2008 *(Staniszewski et al)****; 5 years later there are > 1300 SZ-identified clusters!***

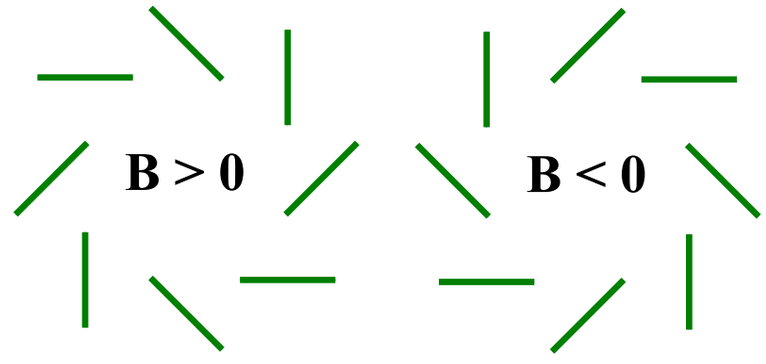
Notes:

- For each experiment, the 150 GHz depth is given, most important band for cluster counts
- Planck based on ~1/2 survey, cluster counts should ~double for full survey
- $N_{clusters}$ highly dependent on completeness of optical follow-up, which varies between each experiment

CMB Science

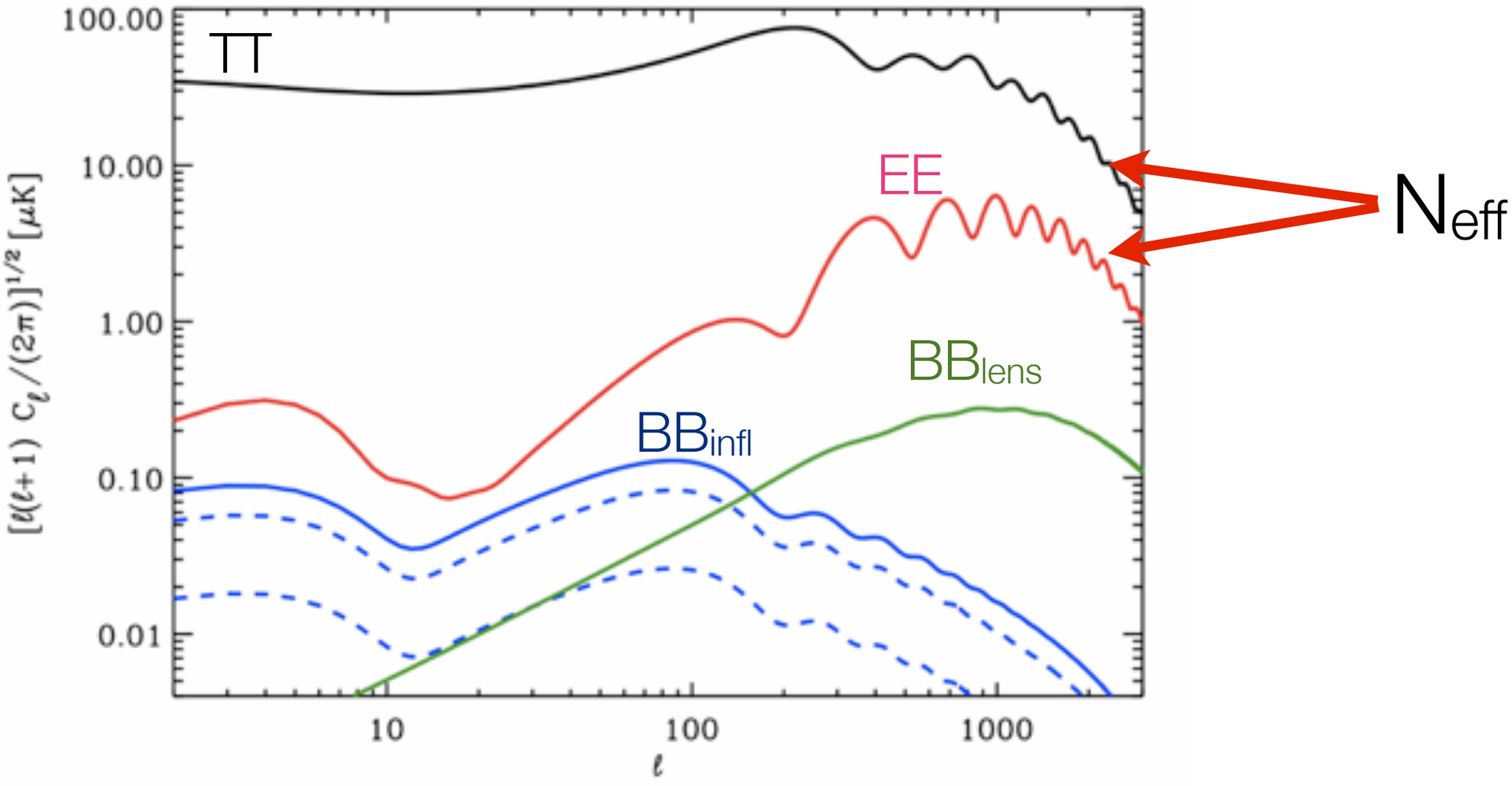






Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB Science



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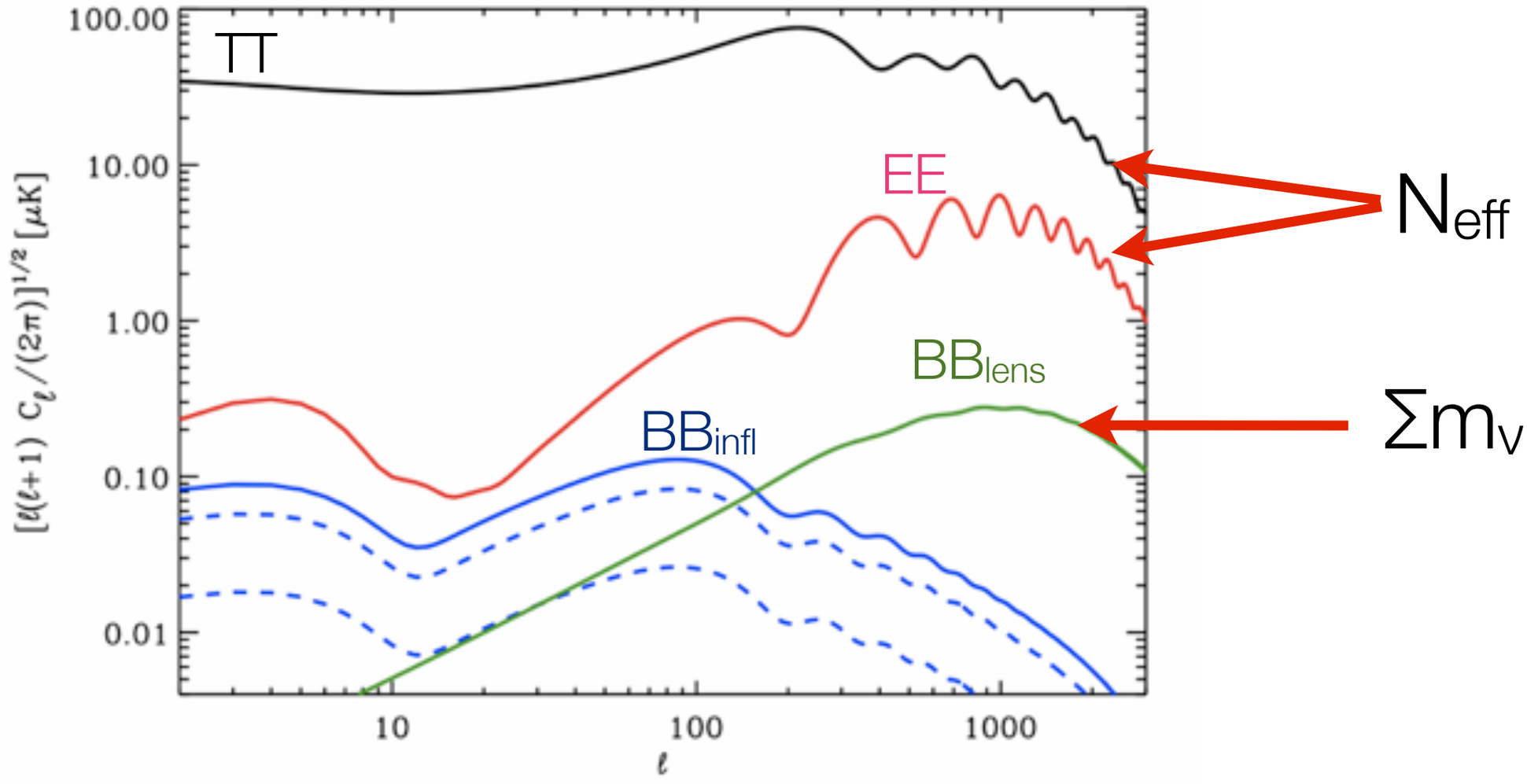

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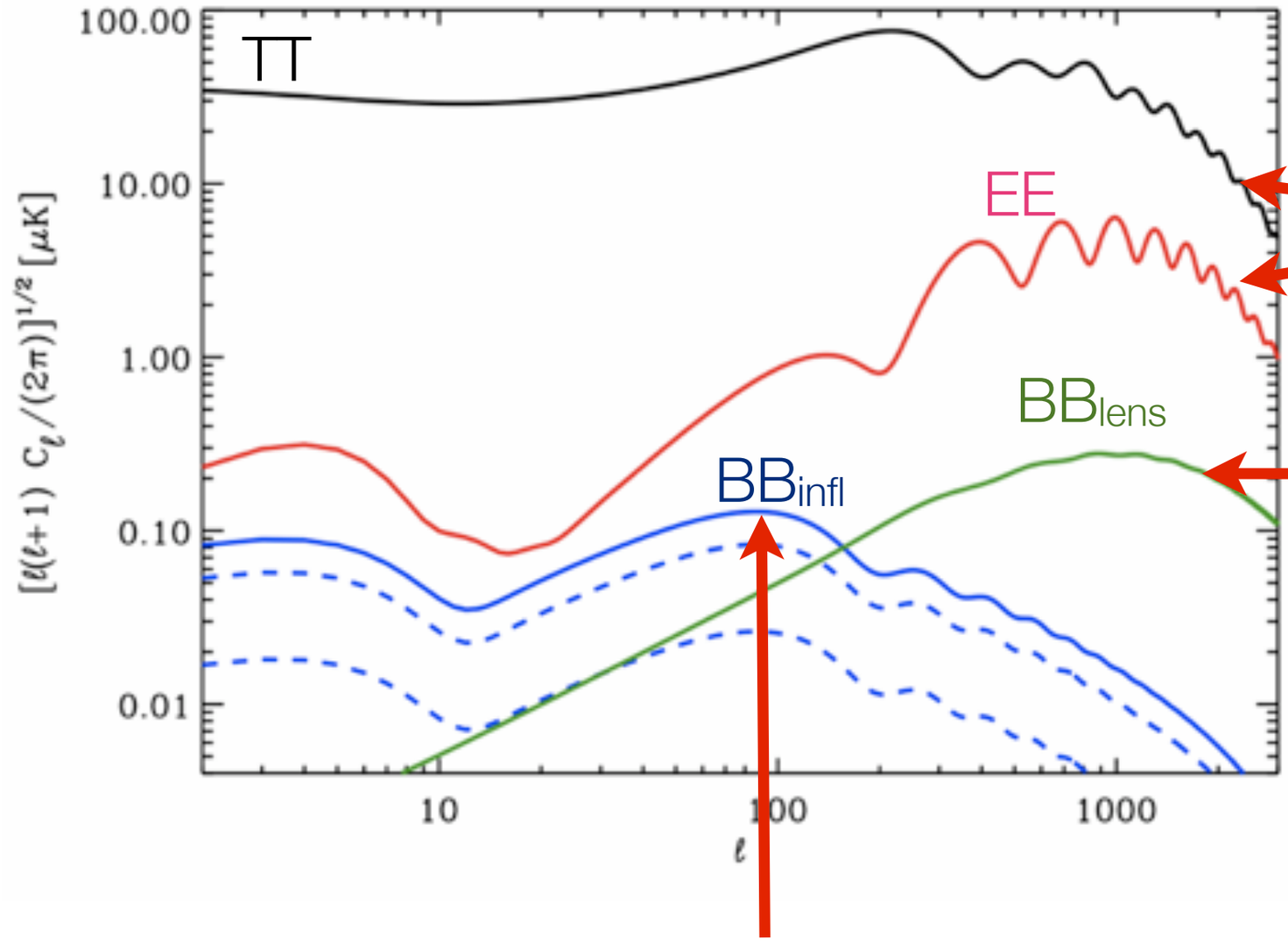


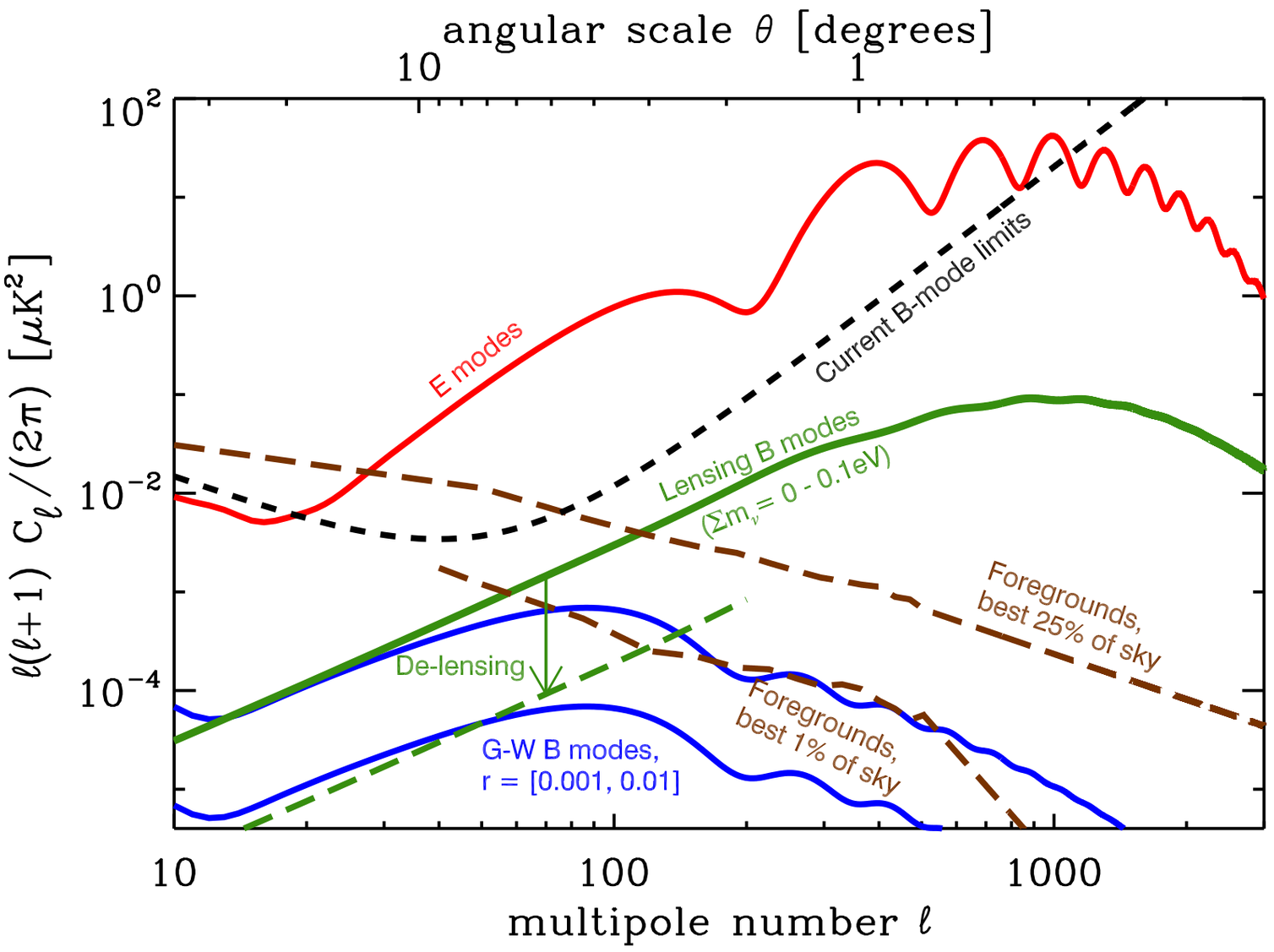
N_{eff}

Σm_ν

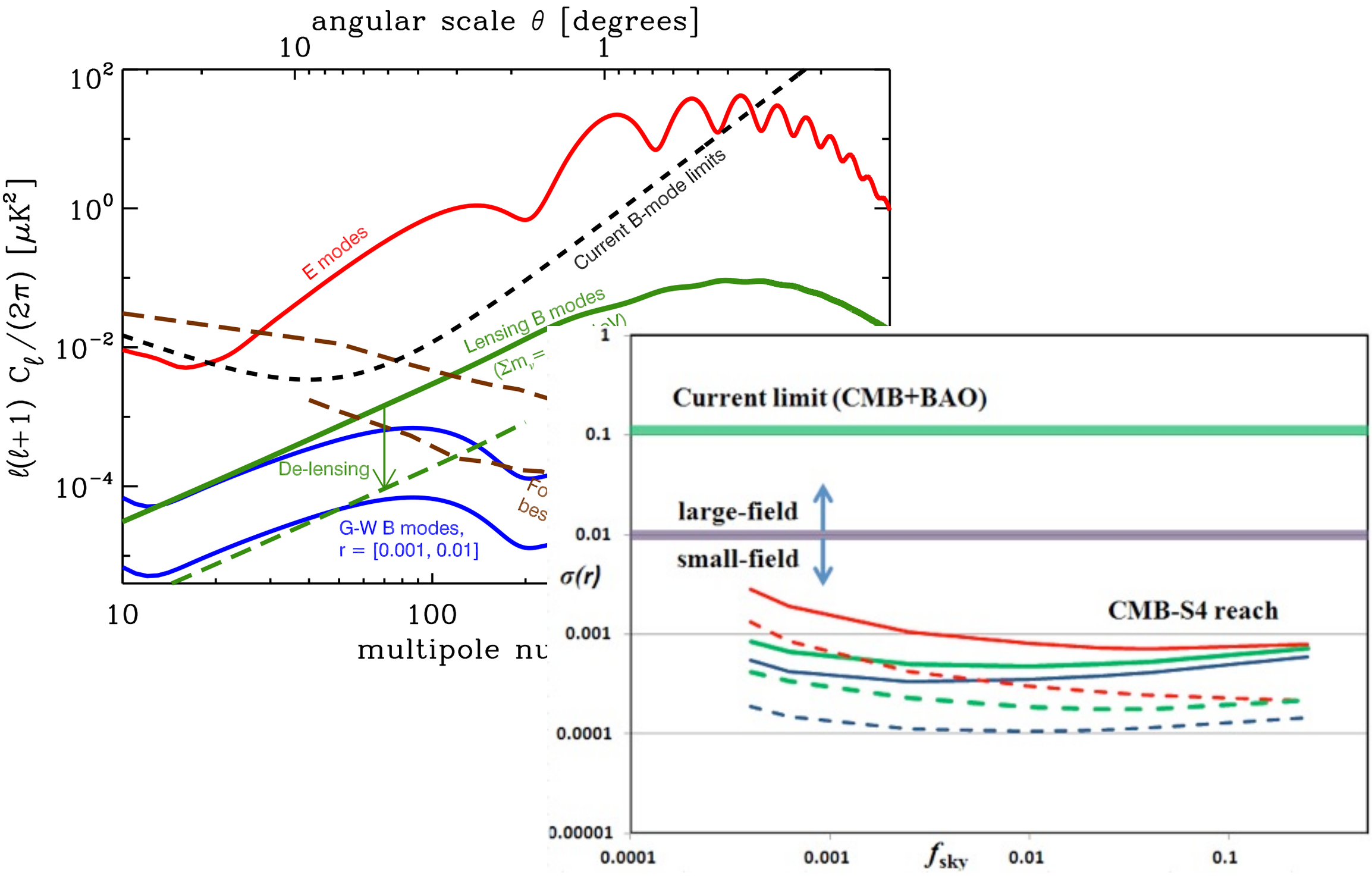
r [0.01:0.10]

Spectra generated with WMAP7 parameters using CAMB, Lewis and Challinor

CMB Science


angular scale θ [degrees]
10
1
10^2
10^0
10^{-2}
10^{-4}
$\ell(\ell+1)\,C_\ell/(2\pi)\ [\mu K^2]$
E modes
Current B-mode limits
Lensing B modes
(Σm_ν = 0 - 0.1eV)
Foregrounds,
best 25% of sky
De-lensing
Foregrounds,
best 1% of sky
G-W B modes,
r = [0.001, 0.01]
10
100
1000
multipole number ℓ

CMB Science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10
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$\ell(\ell+1)\ C_\ell/(2\pi)\ [\mu K^2]$
E modes
Current B-mode limits
Lensing B modes
(Σm_ν =
De-lensing
G-W B modes,
r = [0.001, 0.01]
10
100
multipole nu
Current limit (CMB+BAO)
0.1
large-field
0.01
small-field
σ(r)
CMB-S4 reach
0.001
0.0001
0.00001
0.0001
0.001
f_{sky}
0.01
0.1

Relevant numbers

- Lensing B-mode amplitude ~5 μK-arcmin
    - High S/N measurement requires very deep maps with better than 3 arcmin resolution
- Sample variance

$$\hat{C}_\ell = \langle |a_{lm}|^2 \rangle = \frac{1}{2\ell+1} \sum_m |a_{lm}|^2 \qquad \delta C_\ell \propto \frac{1}{\sqrt{(2\ell+1) f_{\rm sky}}}$$

    - Measure large areas of sky
- Instruments need lots of sensitivity!

BLIP: Background Limited Infrared Power

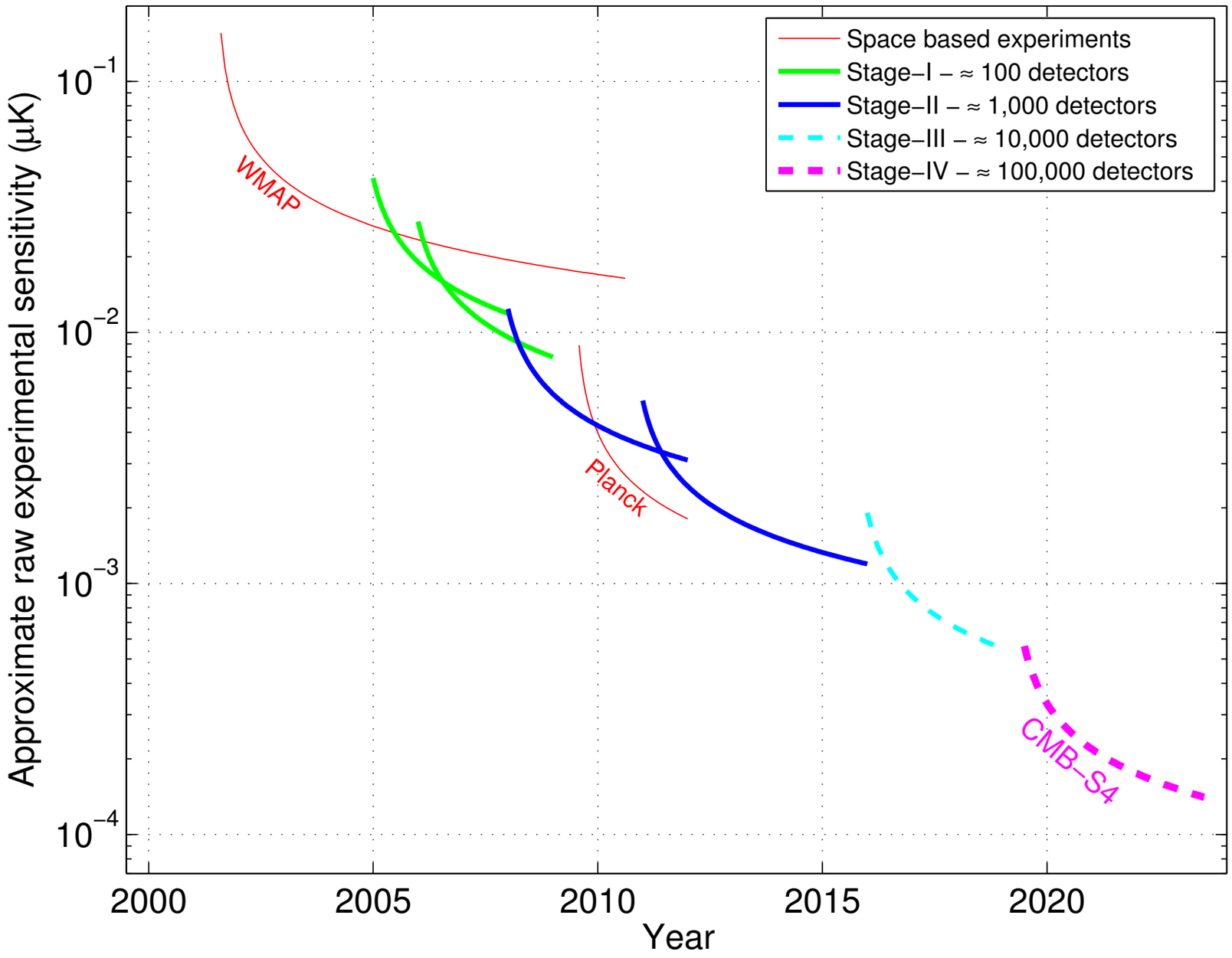
$$< n >= \frac{1}{e^{h\nu/kT} - 1}$$

$$< n^2 >= n(n+1)$$

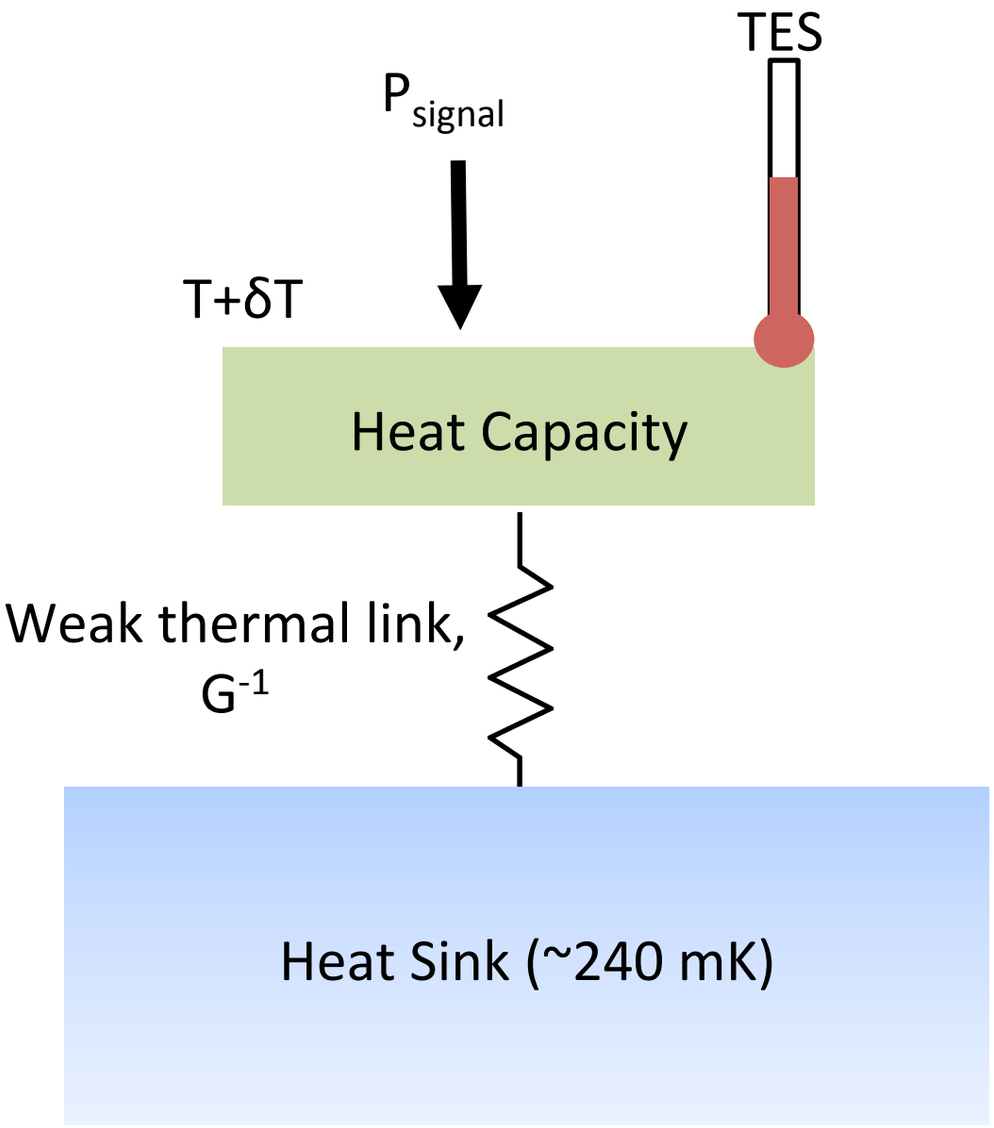
- Sensitivity of individual detectors is now limited by shot noise of the photon flux

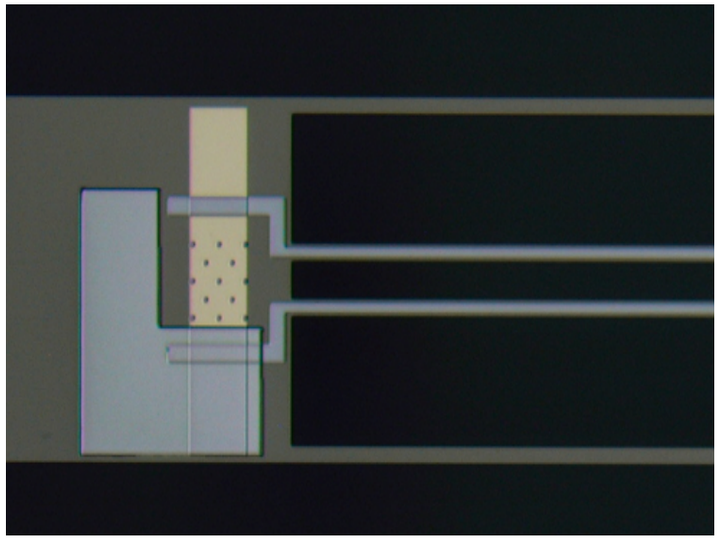
- Increasing sensitivity of an experiment requires increasing the number of detectors

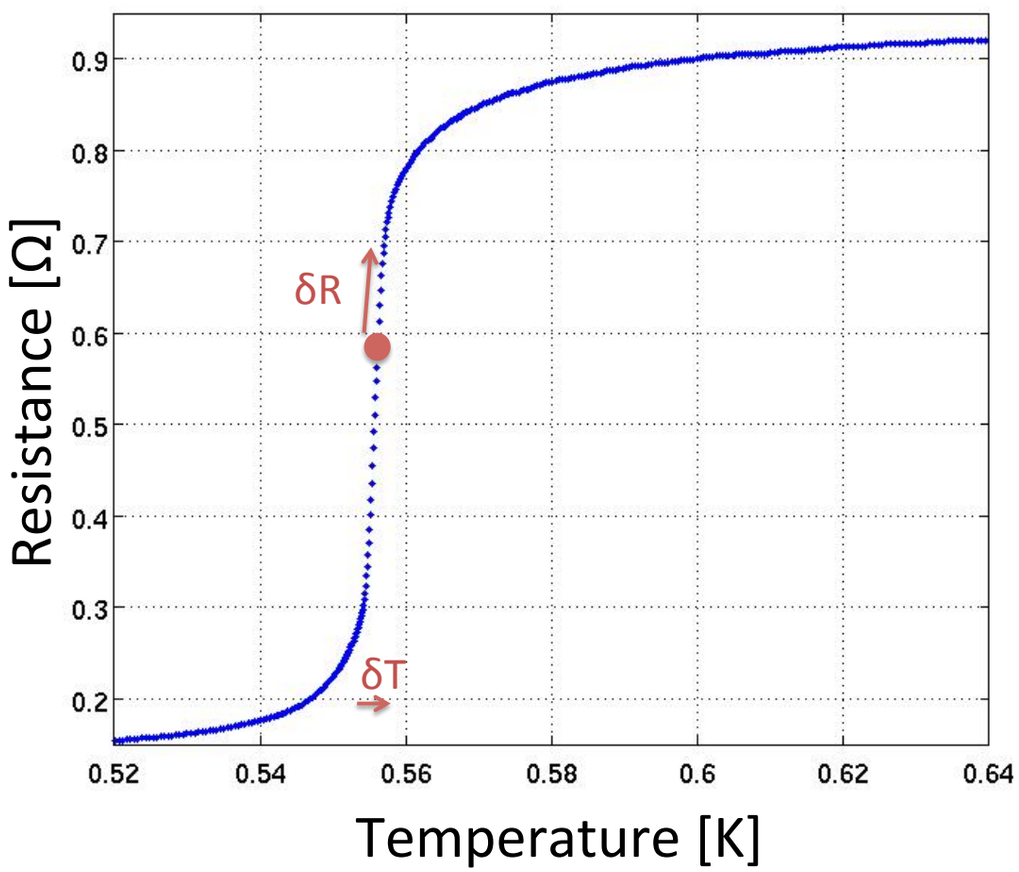
Stages of CMB experiment



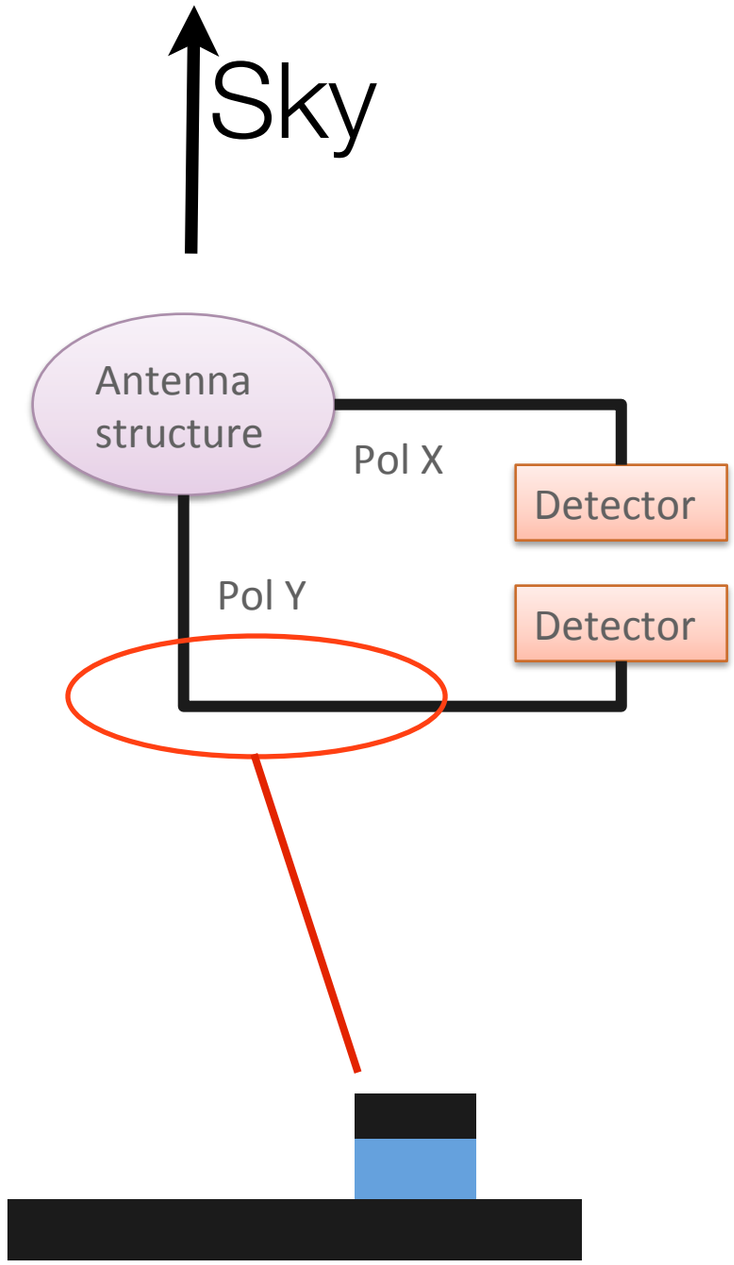
Current technology: Transition Edge Sensor

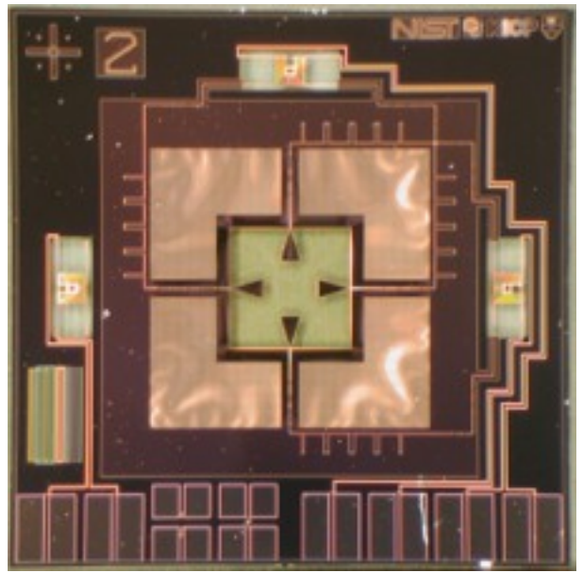




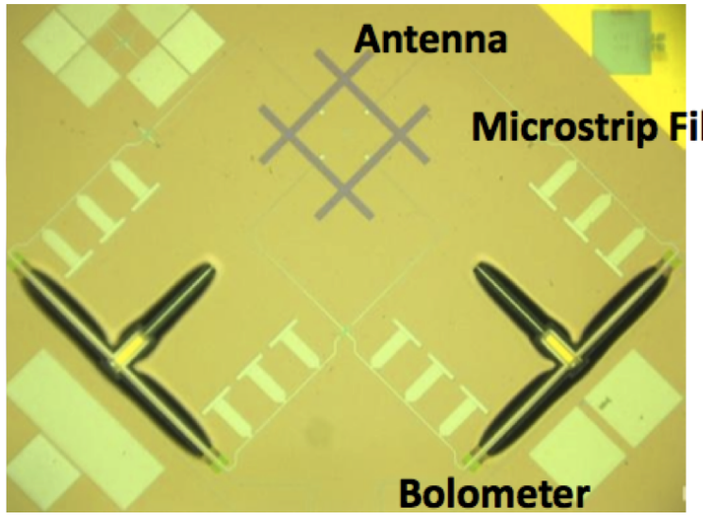


Current technology: TES (antenna coupled)

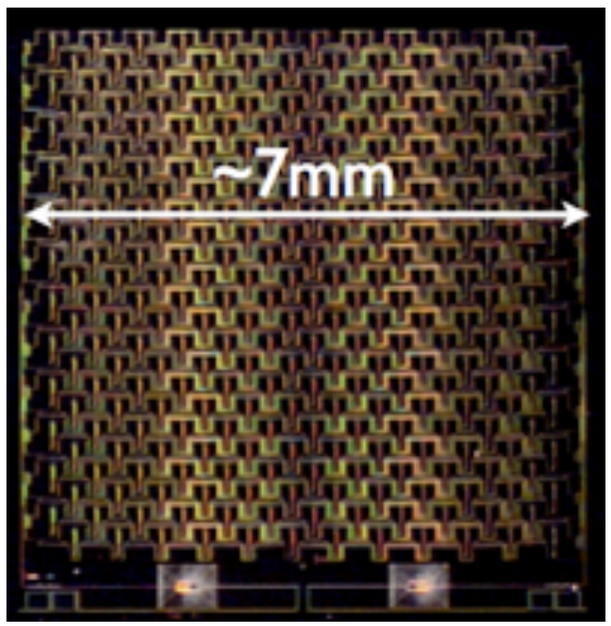




SPTpol (& ACTpol)



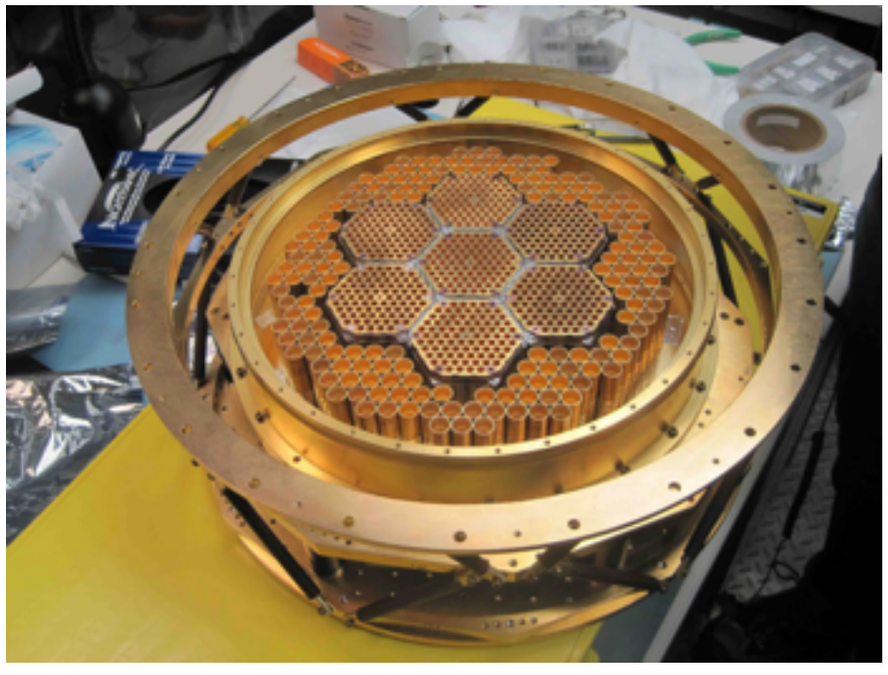
Polarbear



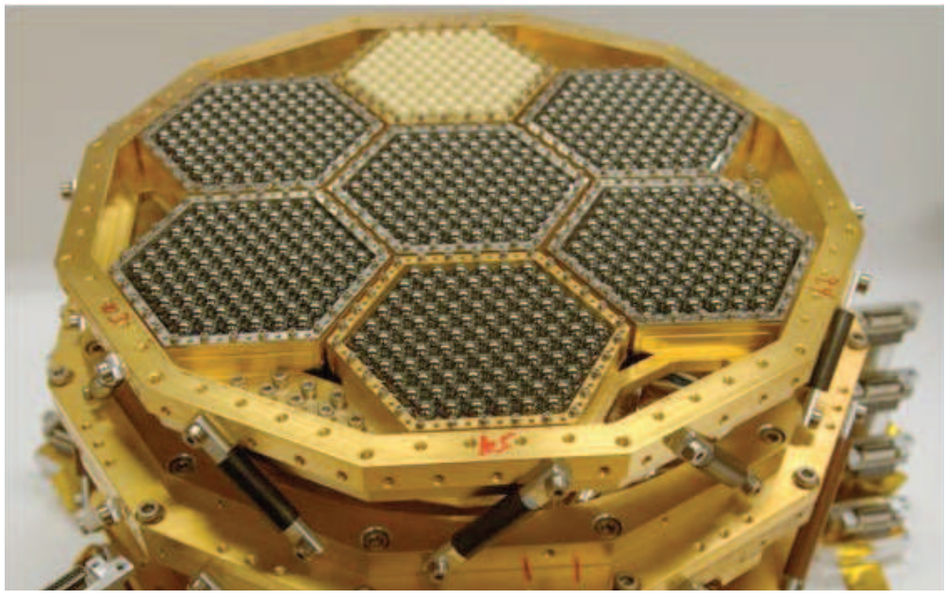
BICEP2/Keck & SPIDER

Focal plane arrays

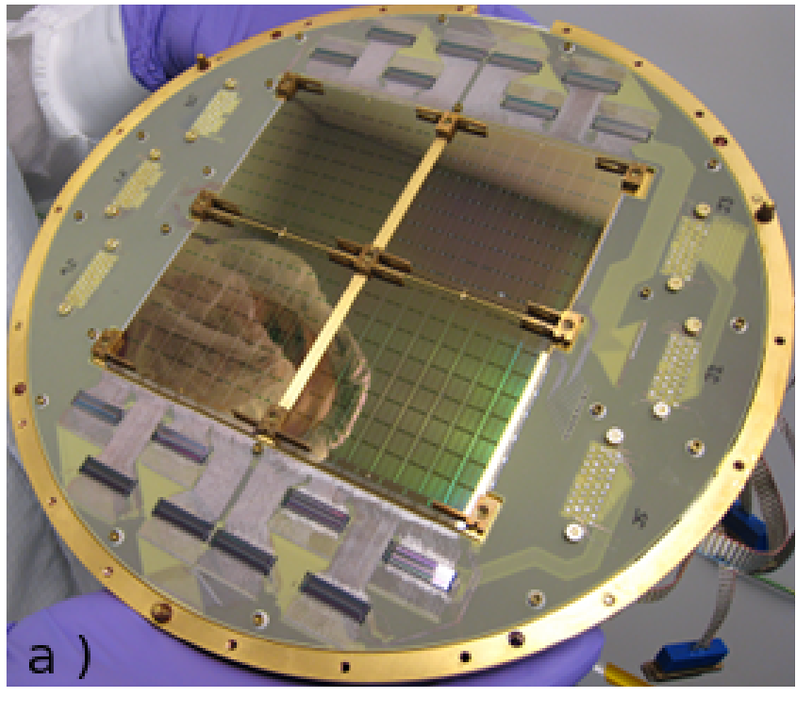
SPTpol



Polarbear

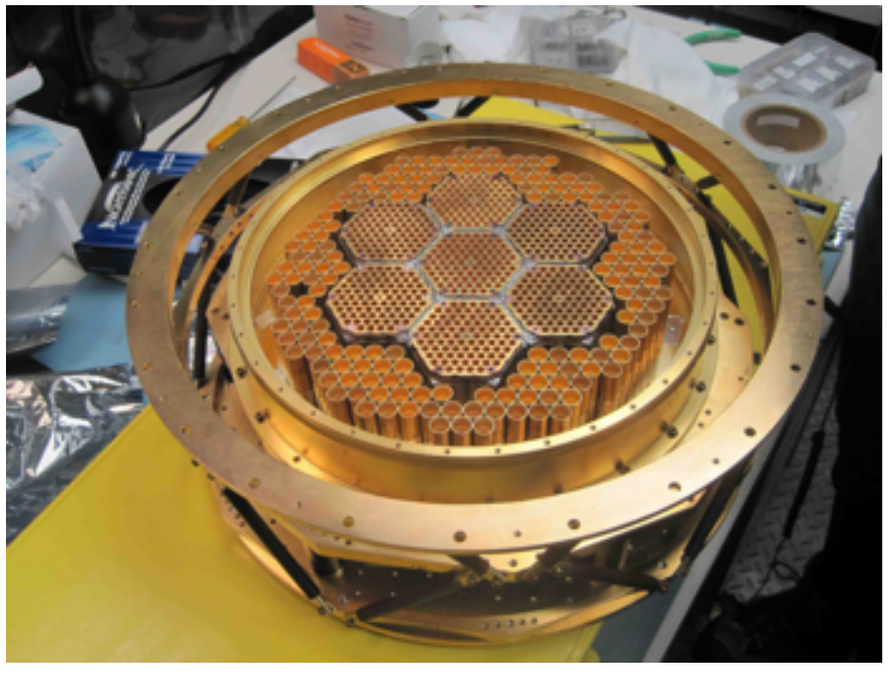


BICEP2/Keck & SPIDER



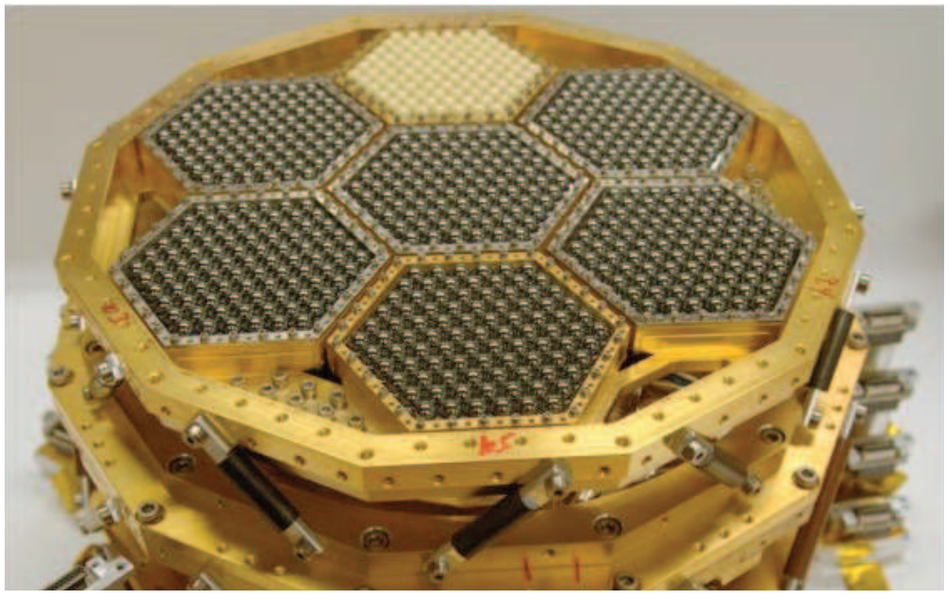
Focal plane arrays

SPTpol



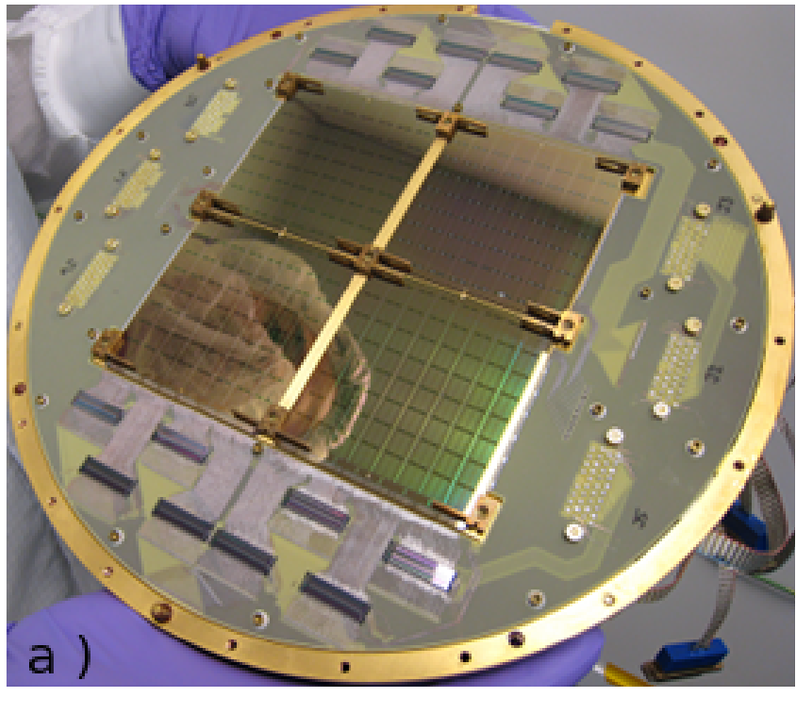
1600 bolos

1300 bolos Polarbear

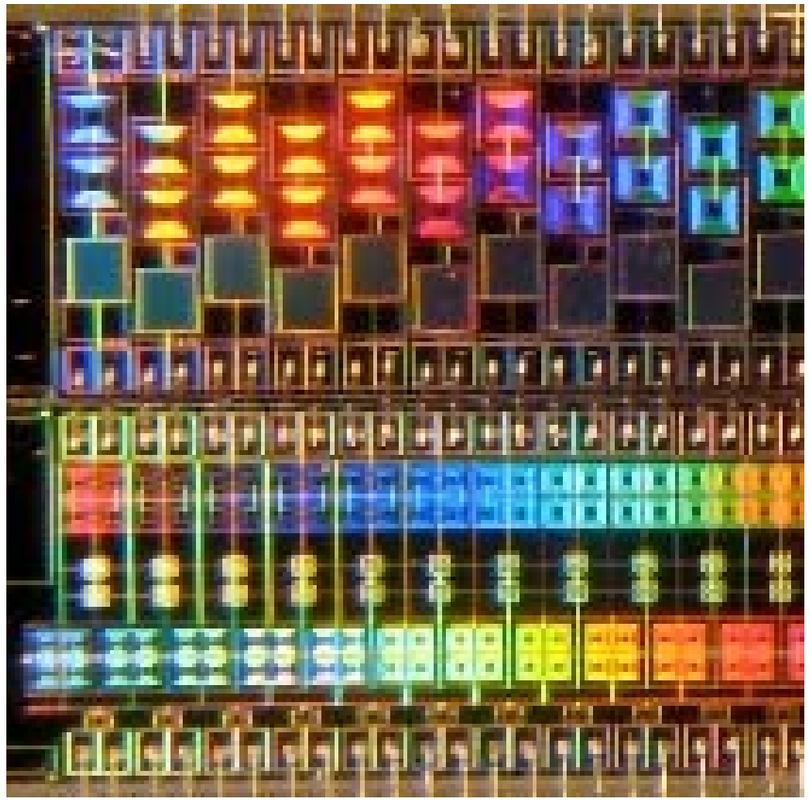


BICEP2/Keck & SPIDER

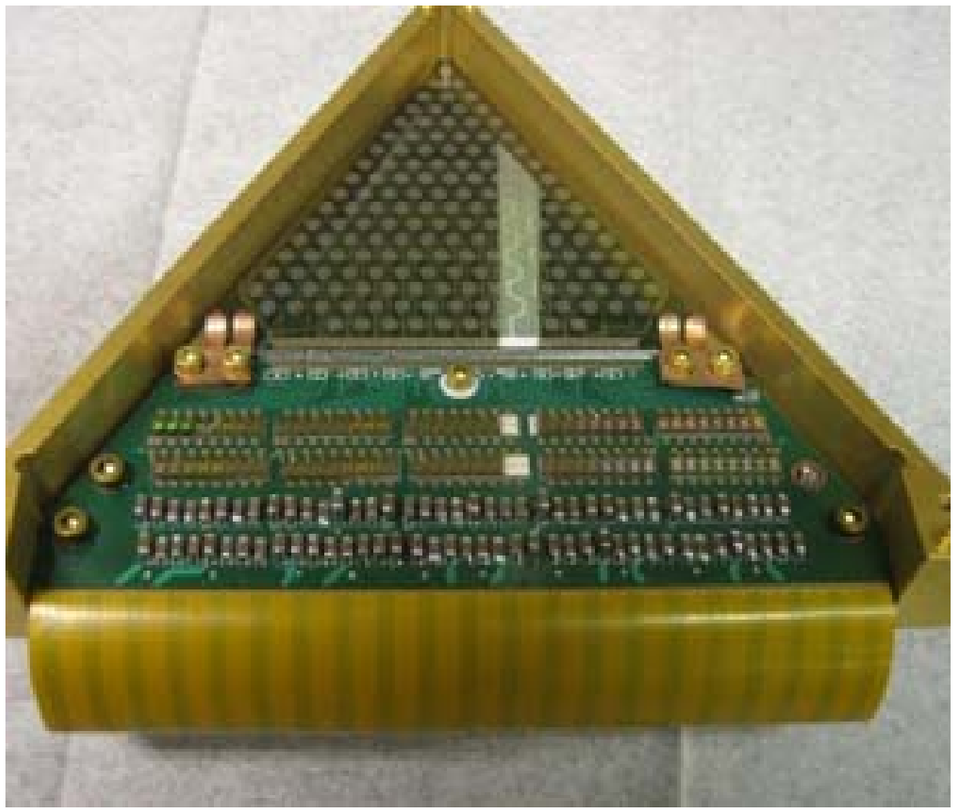
2500 bolos



Multiplexing (MUX)



Time-domain
(switching)

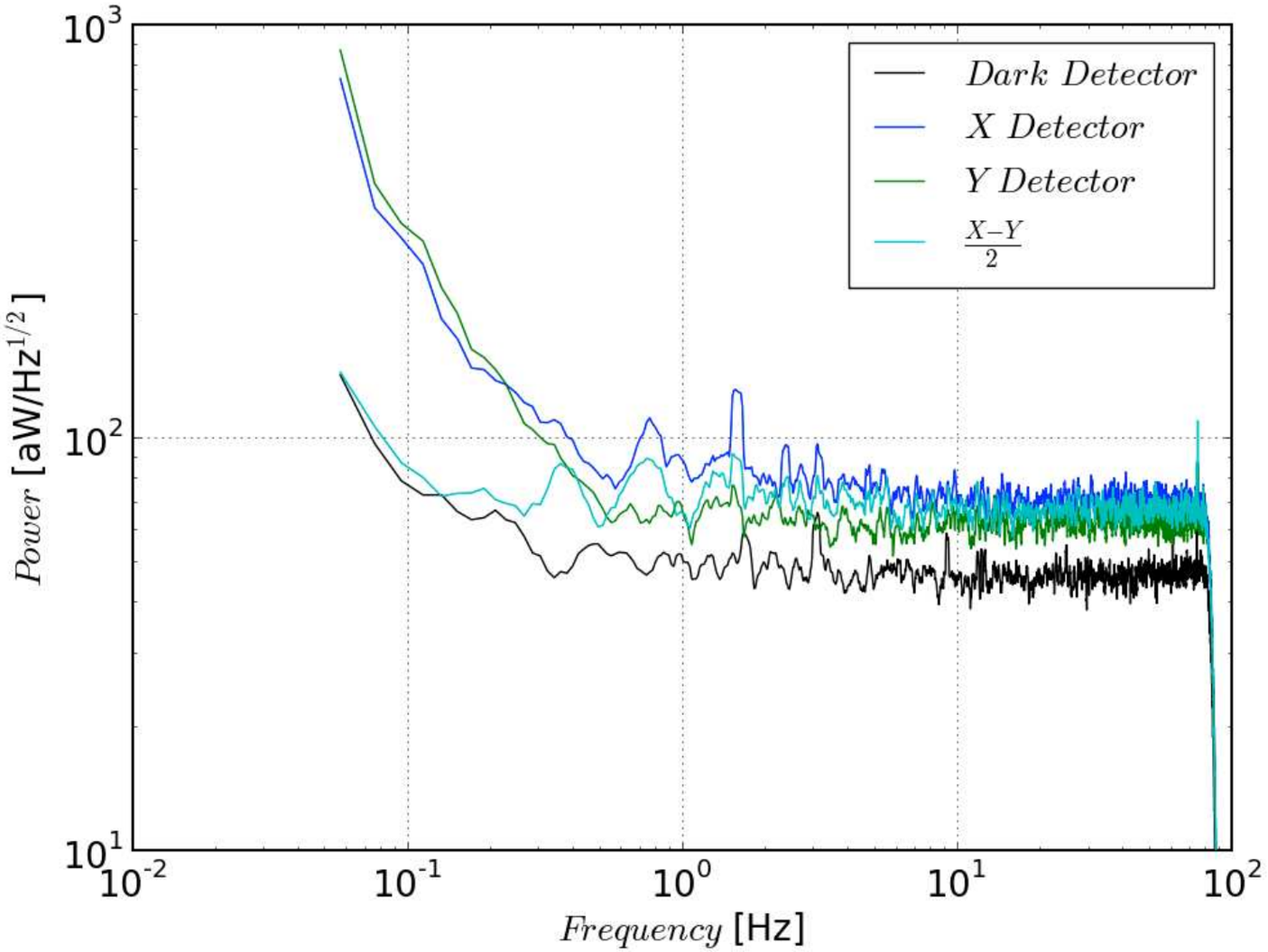


Frequency-domain
(AM radio)

O(10) MUX factor

Noise Equivalent Power (NEP)

Henning et. al., Proc. SPIE 8452, 84523A (October 5, 2012)



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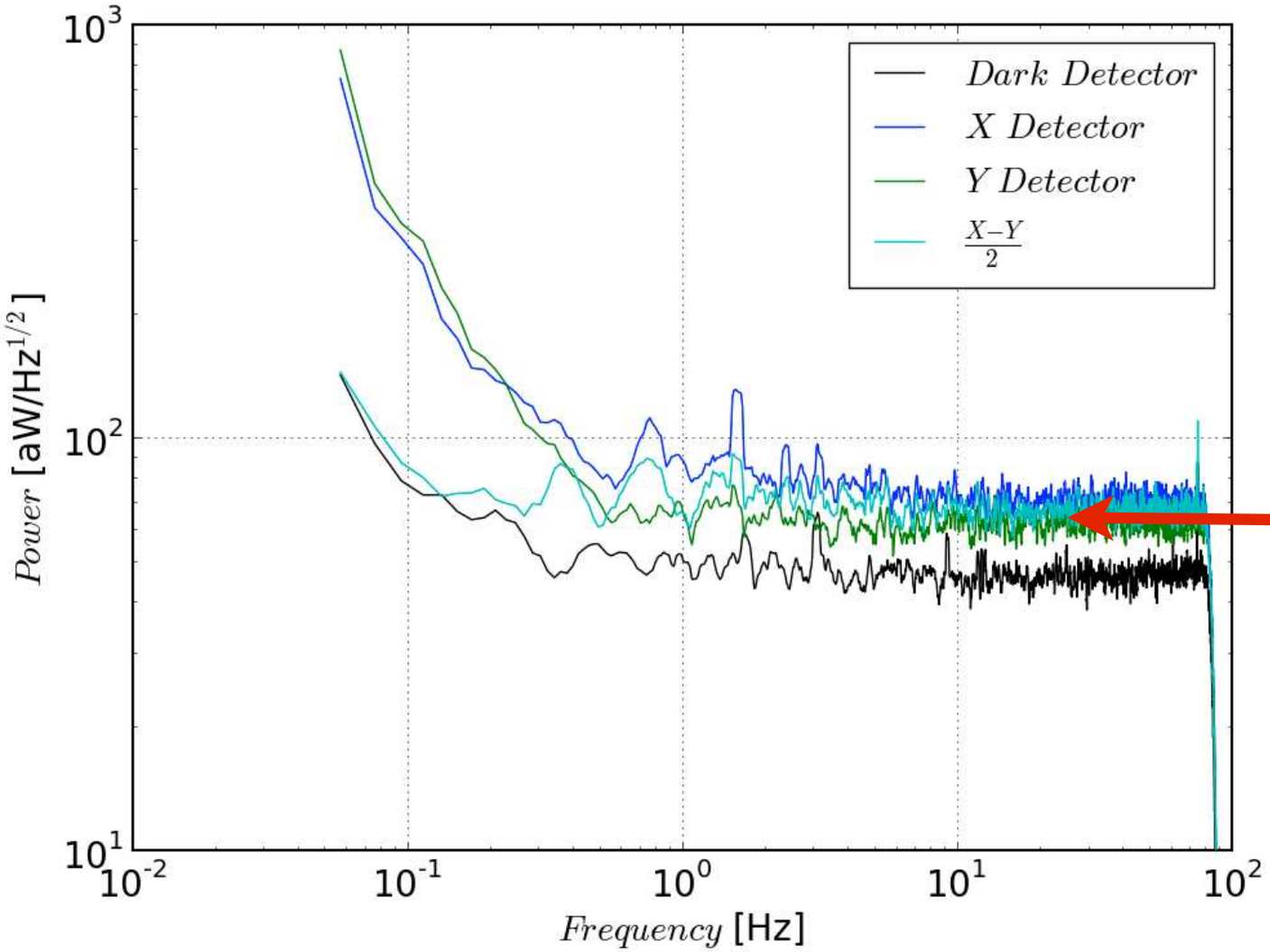
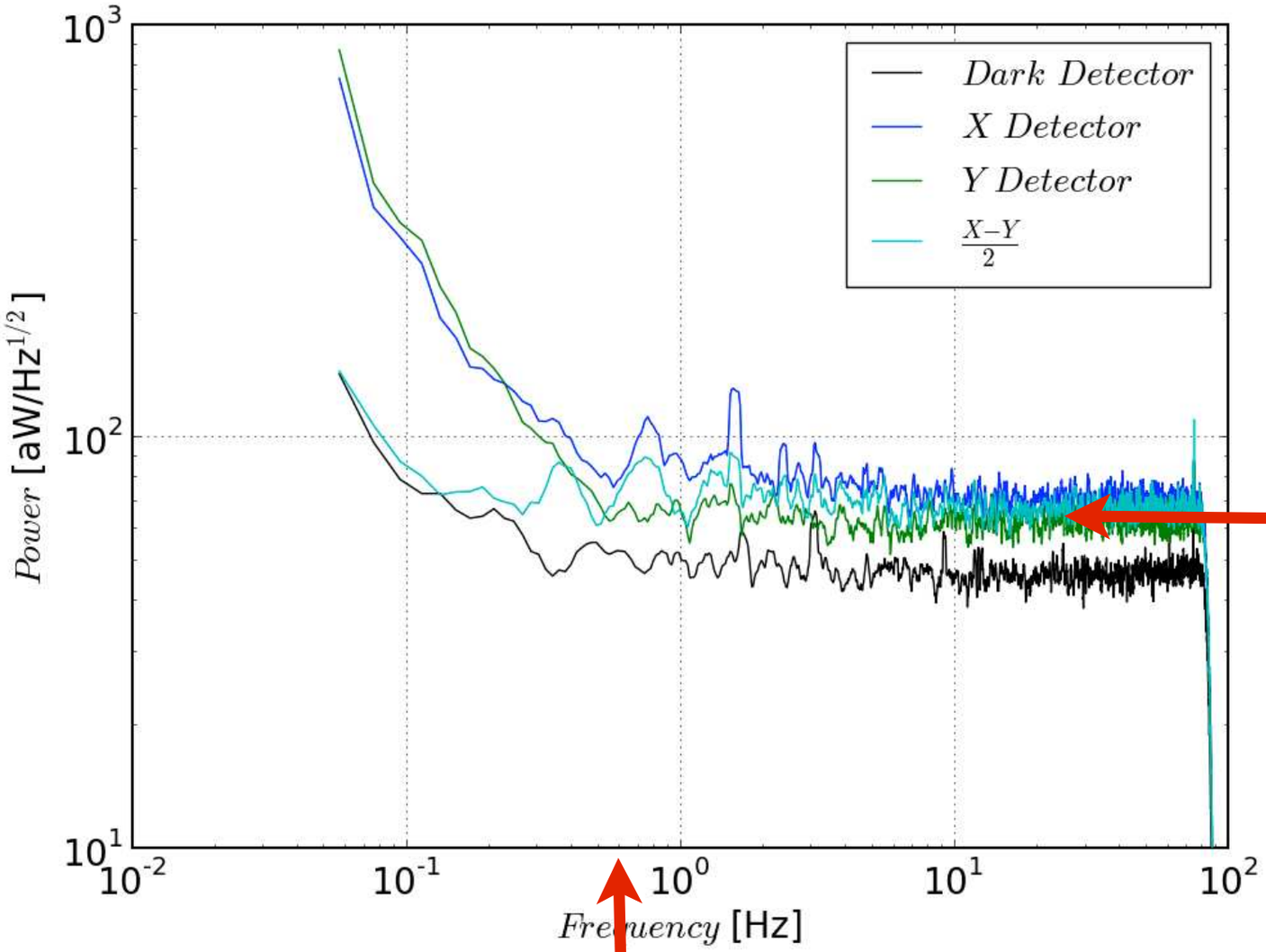


Photon shot noise
~5e-17 W/rtHz

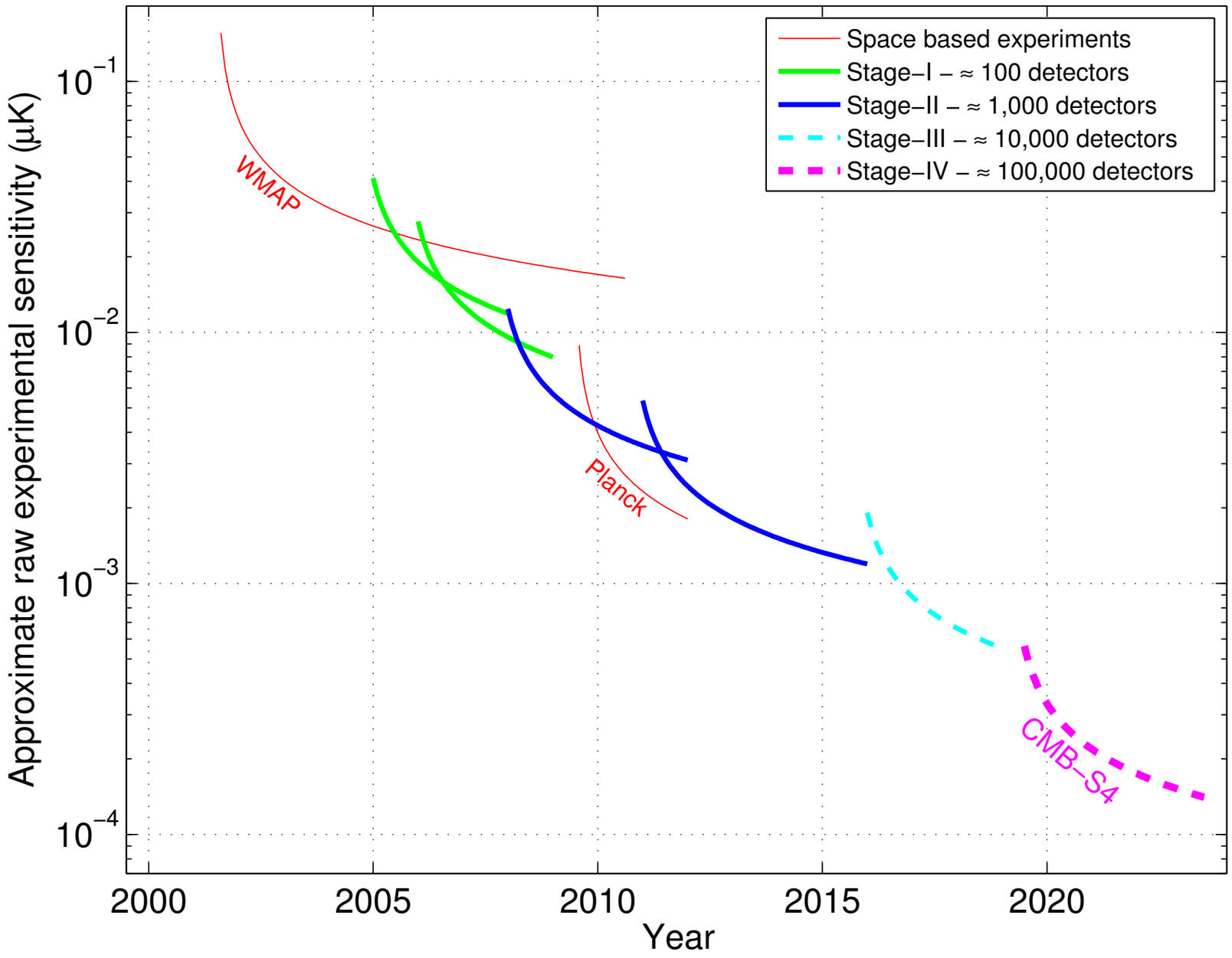
Noise Equivalent Power (NEP)



Photon shot noise
~5e-17 W/rtHz

0.5 deg/sec scanning puts 1 deg at 0.5 Hz

Stages of CMB experiment



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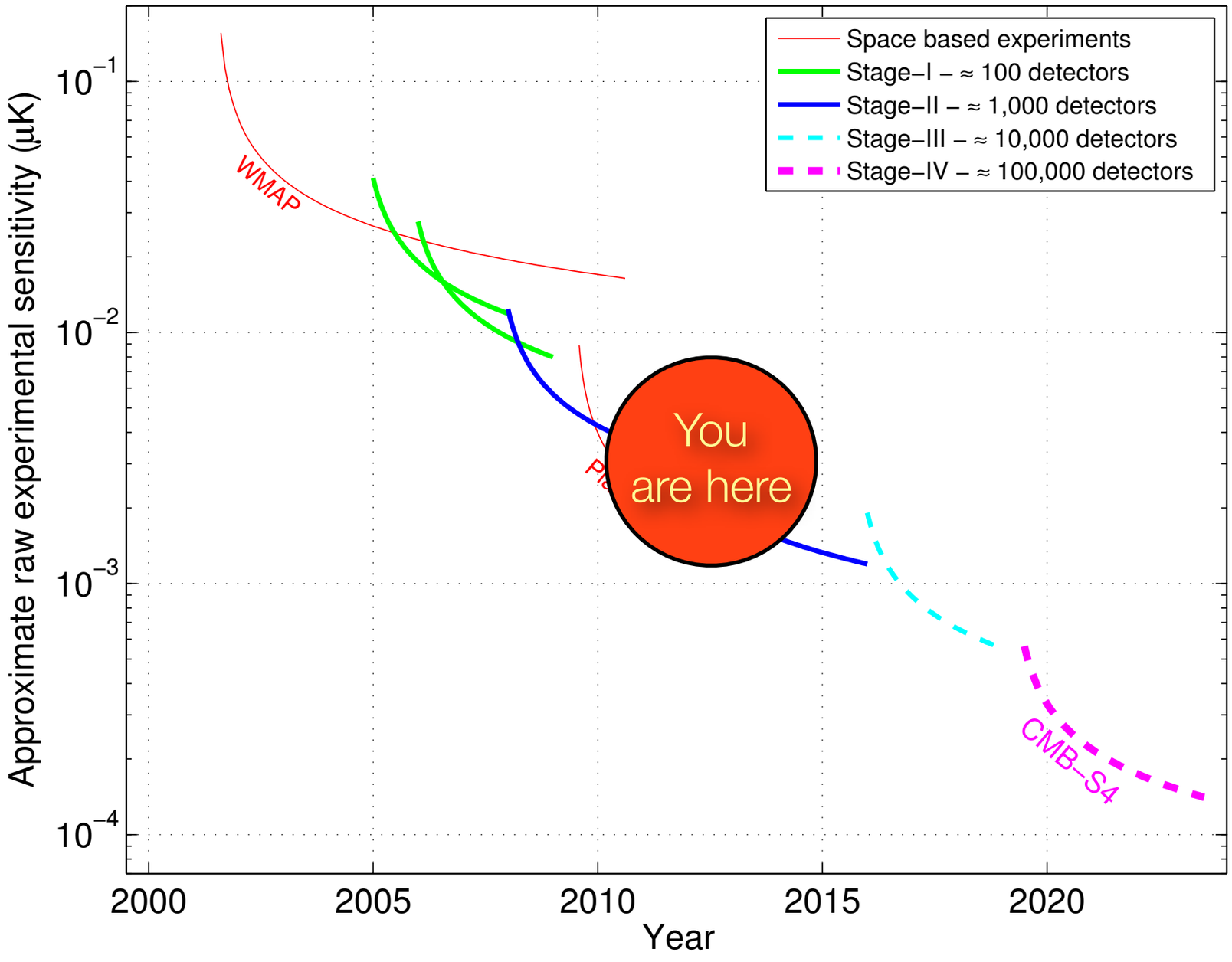
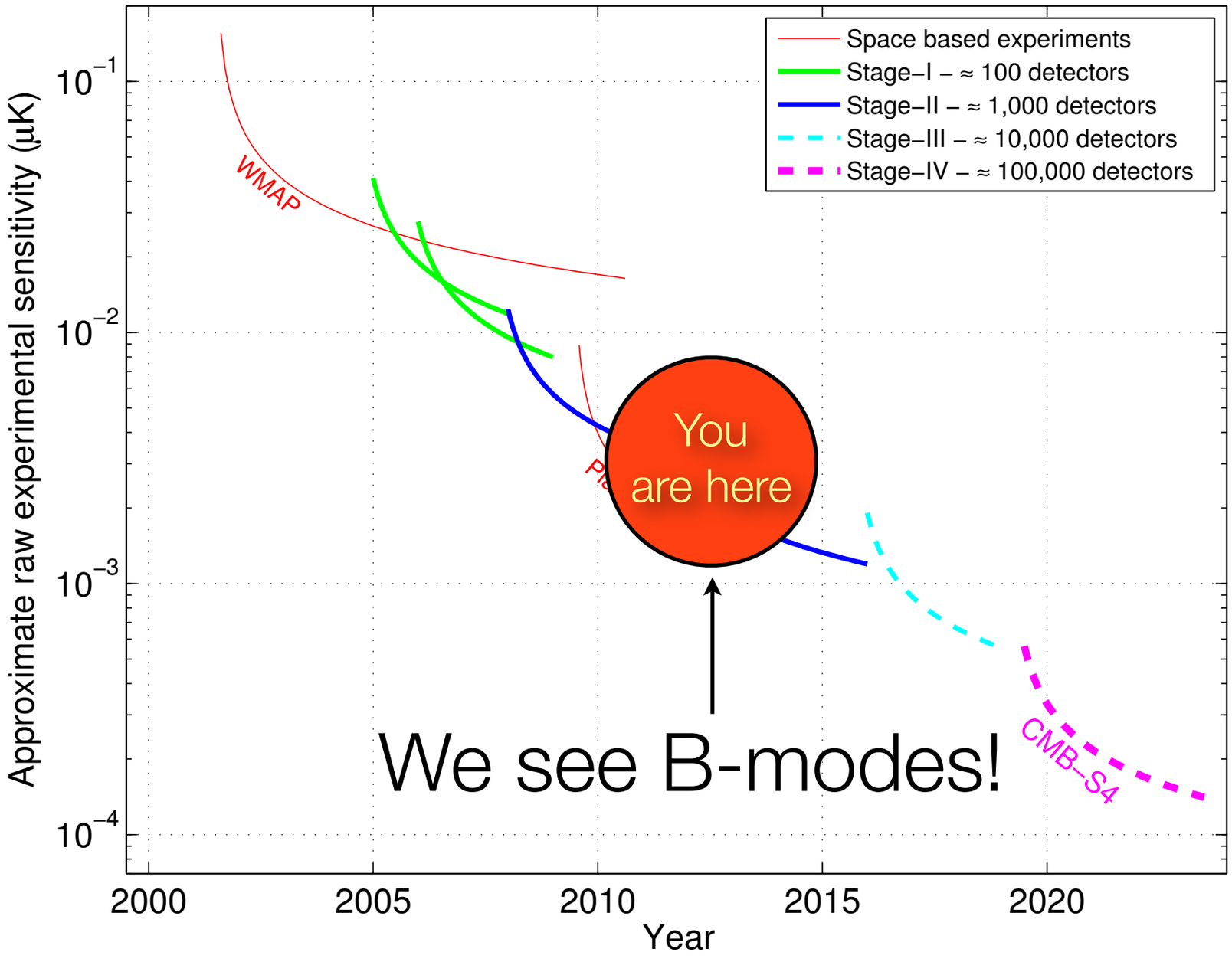
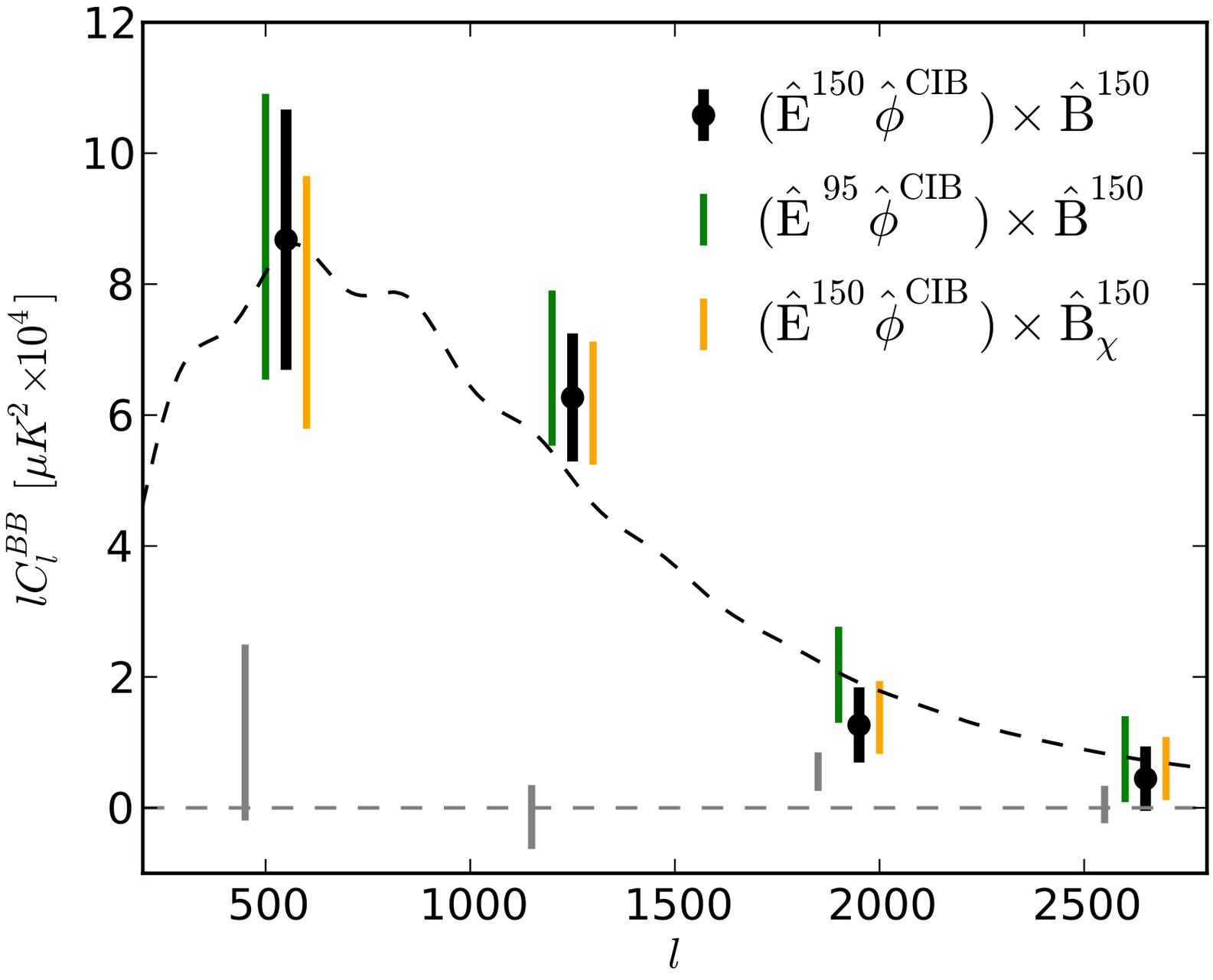
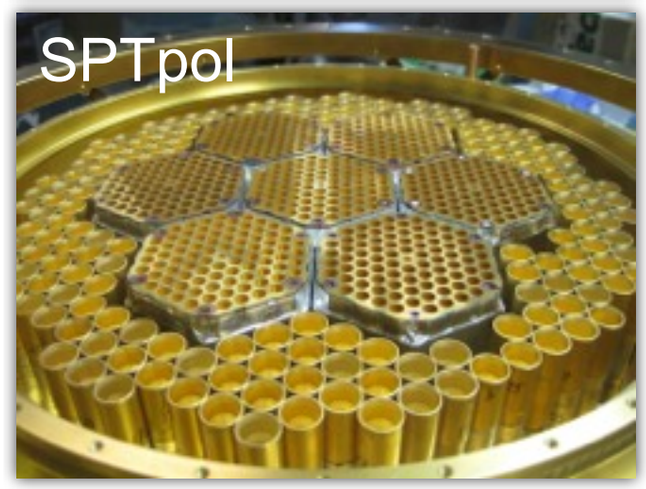


Stages of CMB experiment



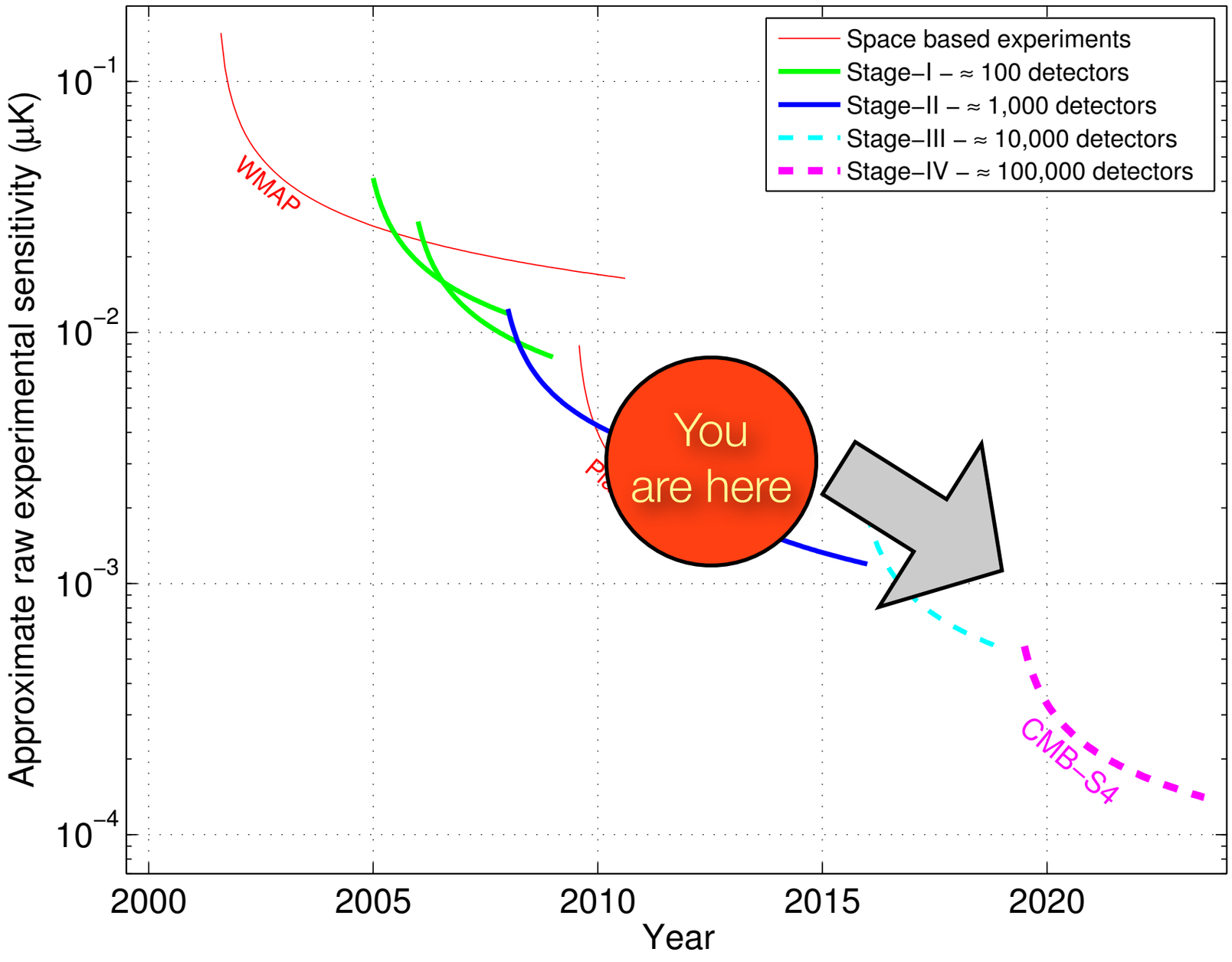
We see B-modes



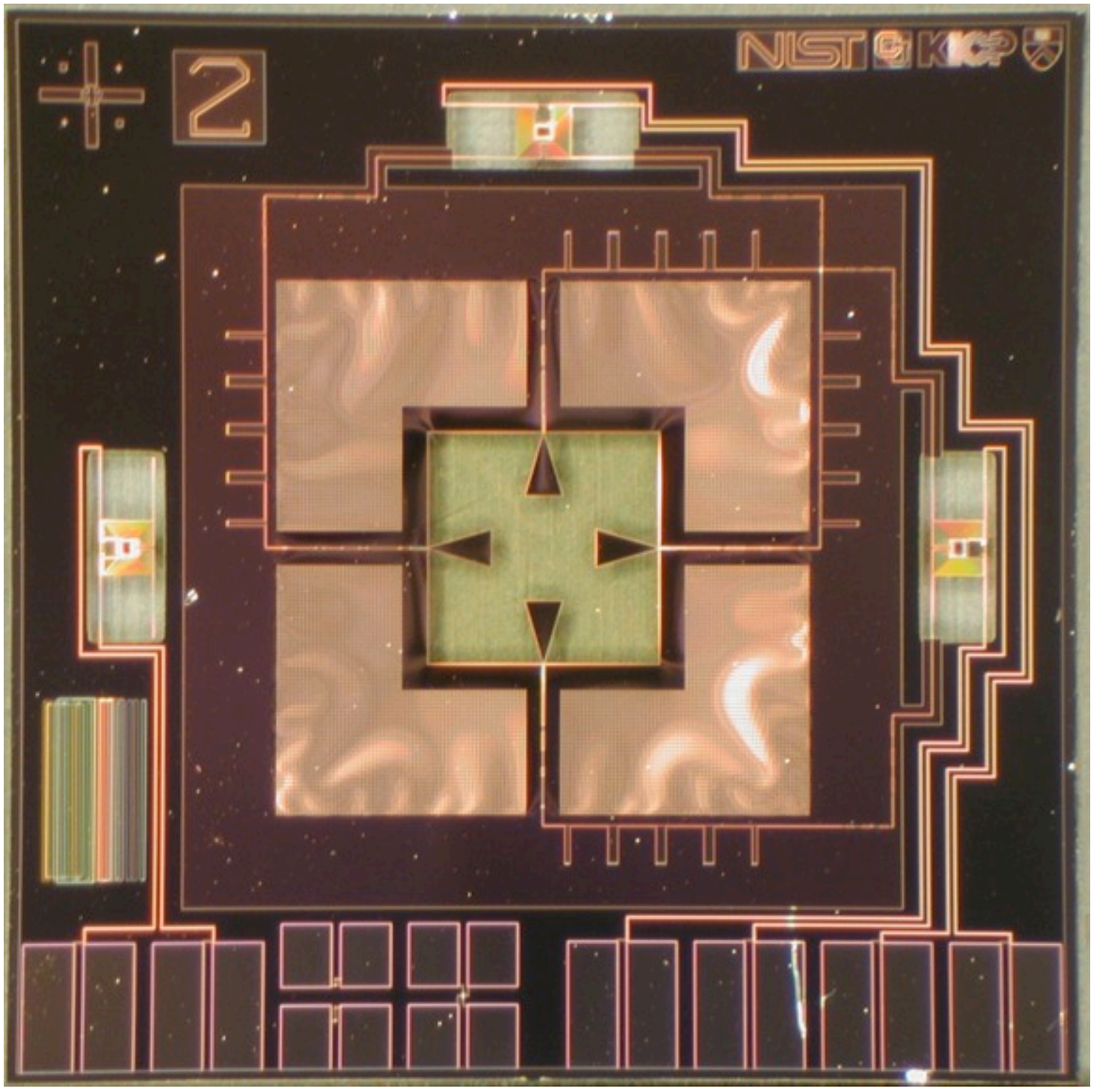


SPTpol: Hanson et al, arXiv:1307.5830 (PRL in press)

Stages of CMB experiment

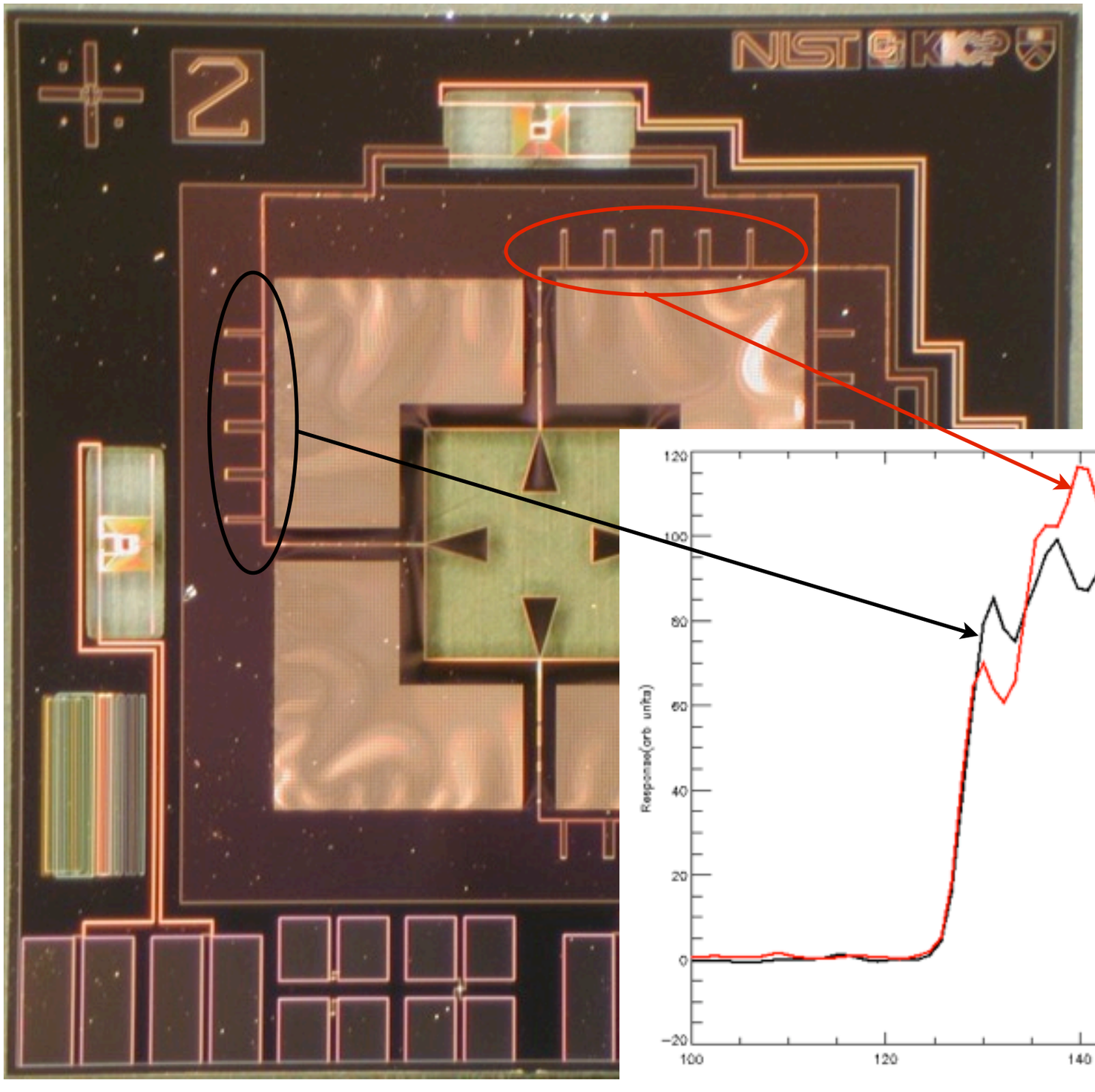


Superconducting microstrip



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

Superconducting microstrip



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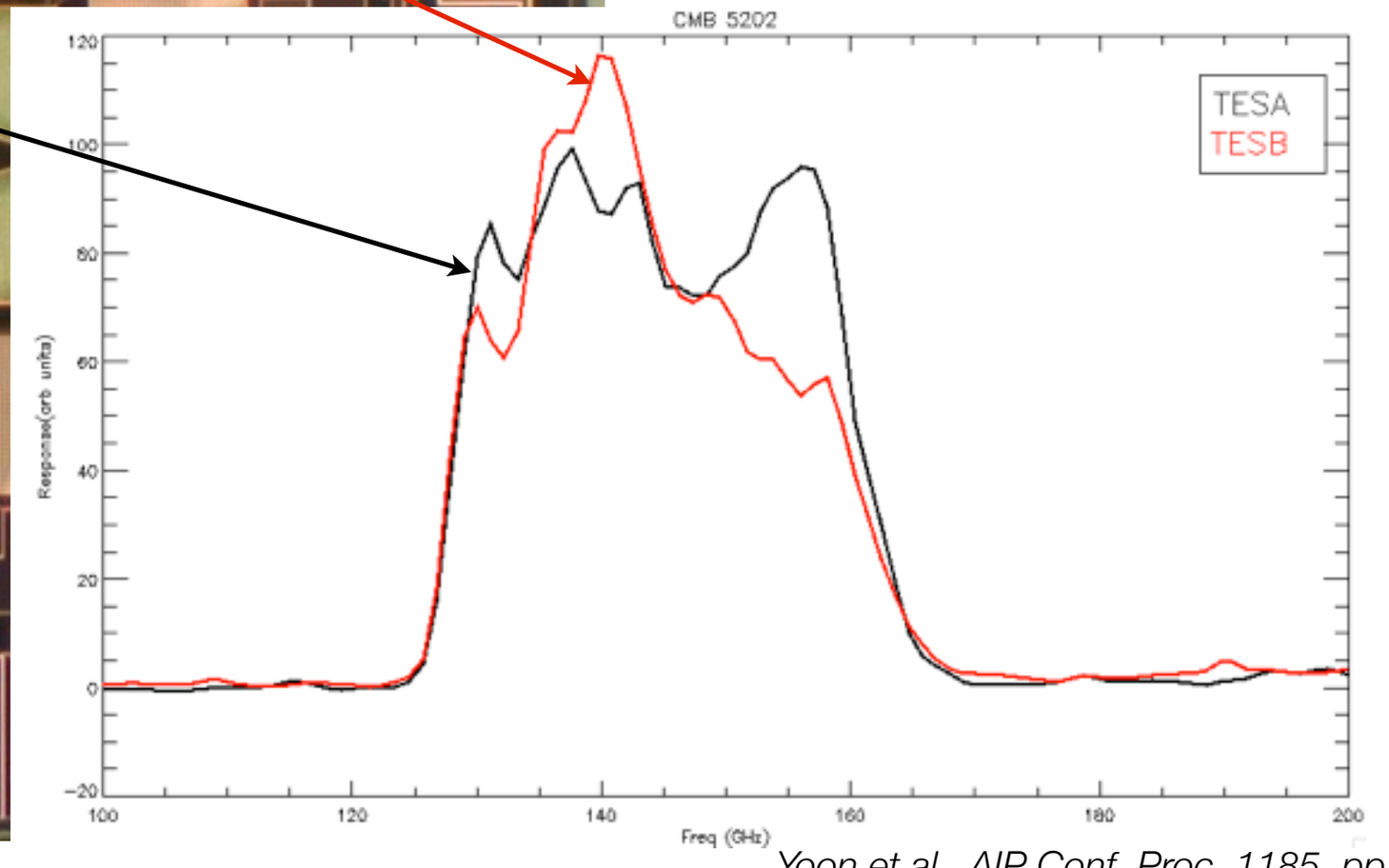
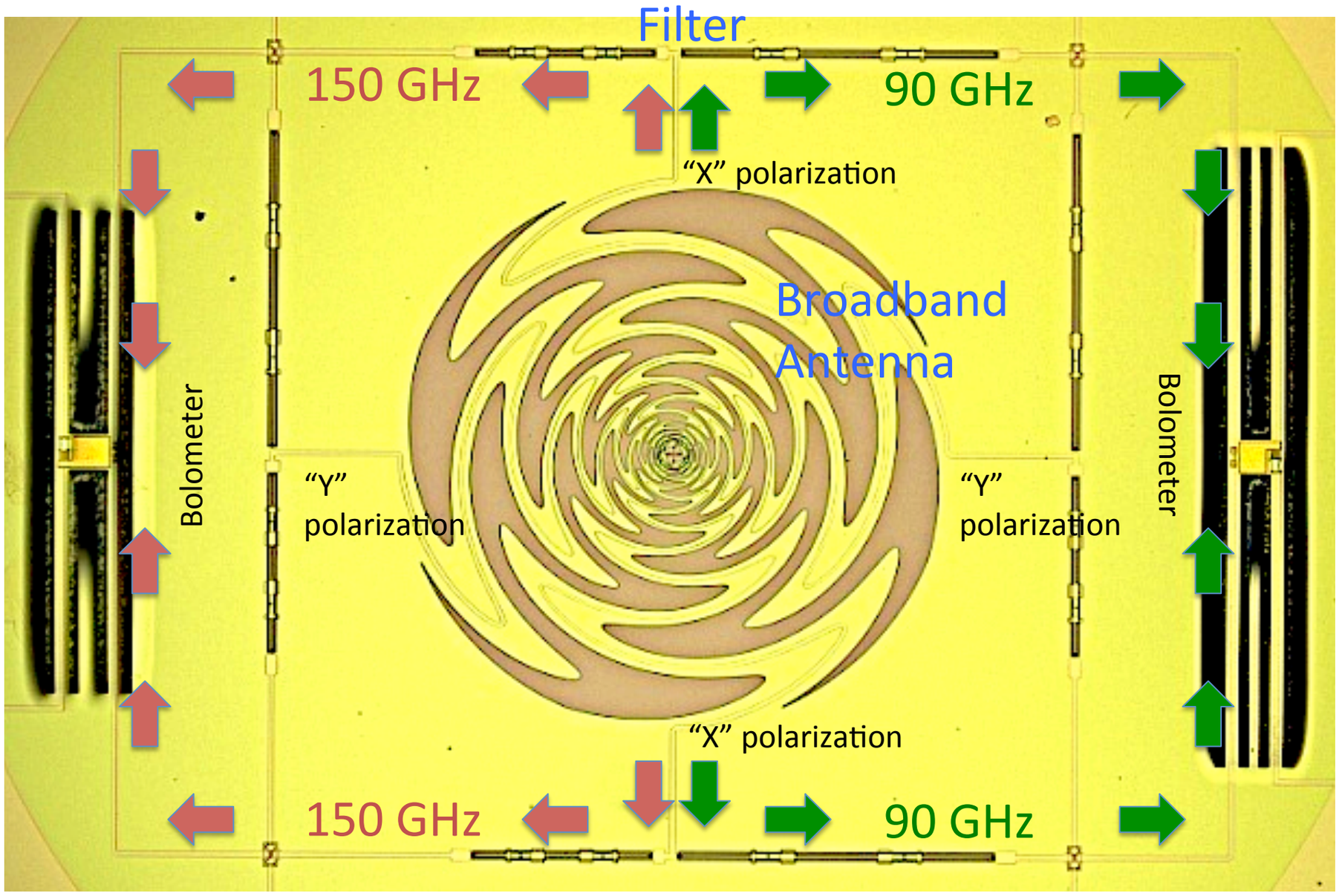


Yoon et al., AIP Conf. Proc. 1185, pp. 515-518

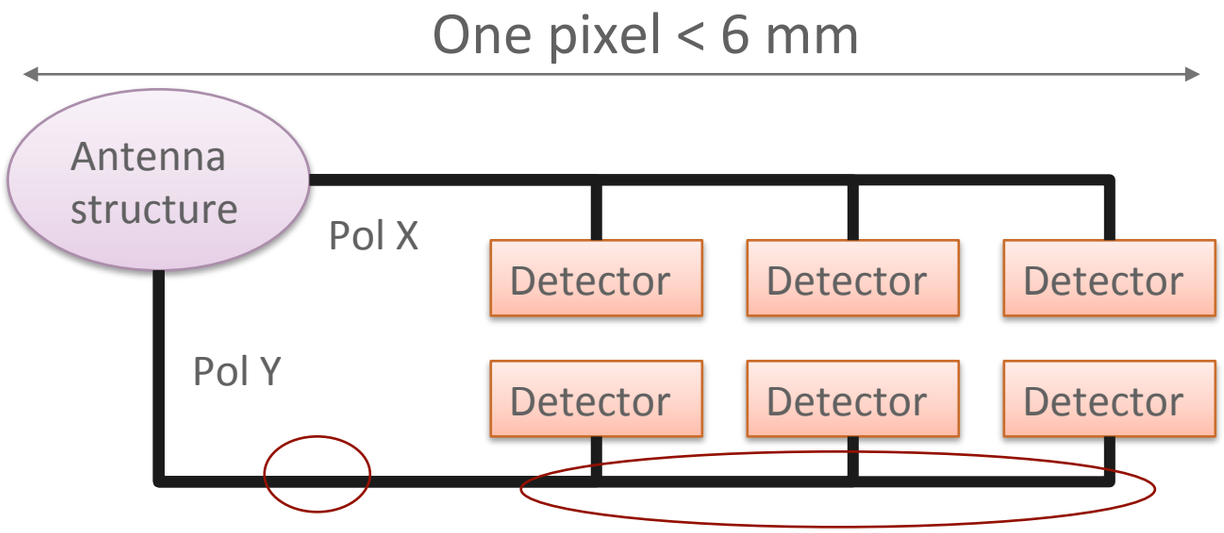
Multi-chroic pixels



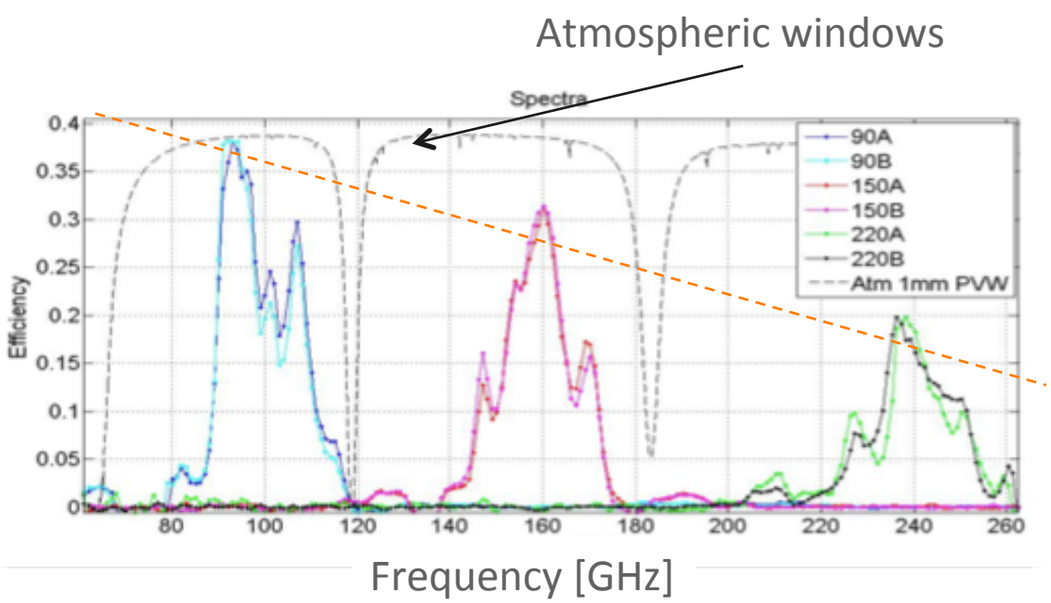
- Developing arrays of three-color pixels for SPT-3G
- Increase bolo density from 2 per pixel to 6 per pixel

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

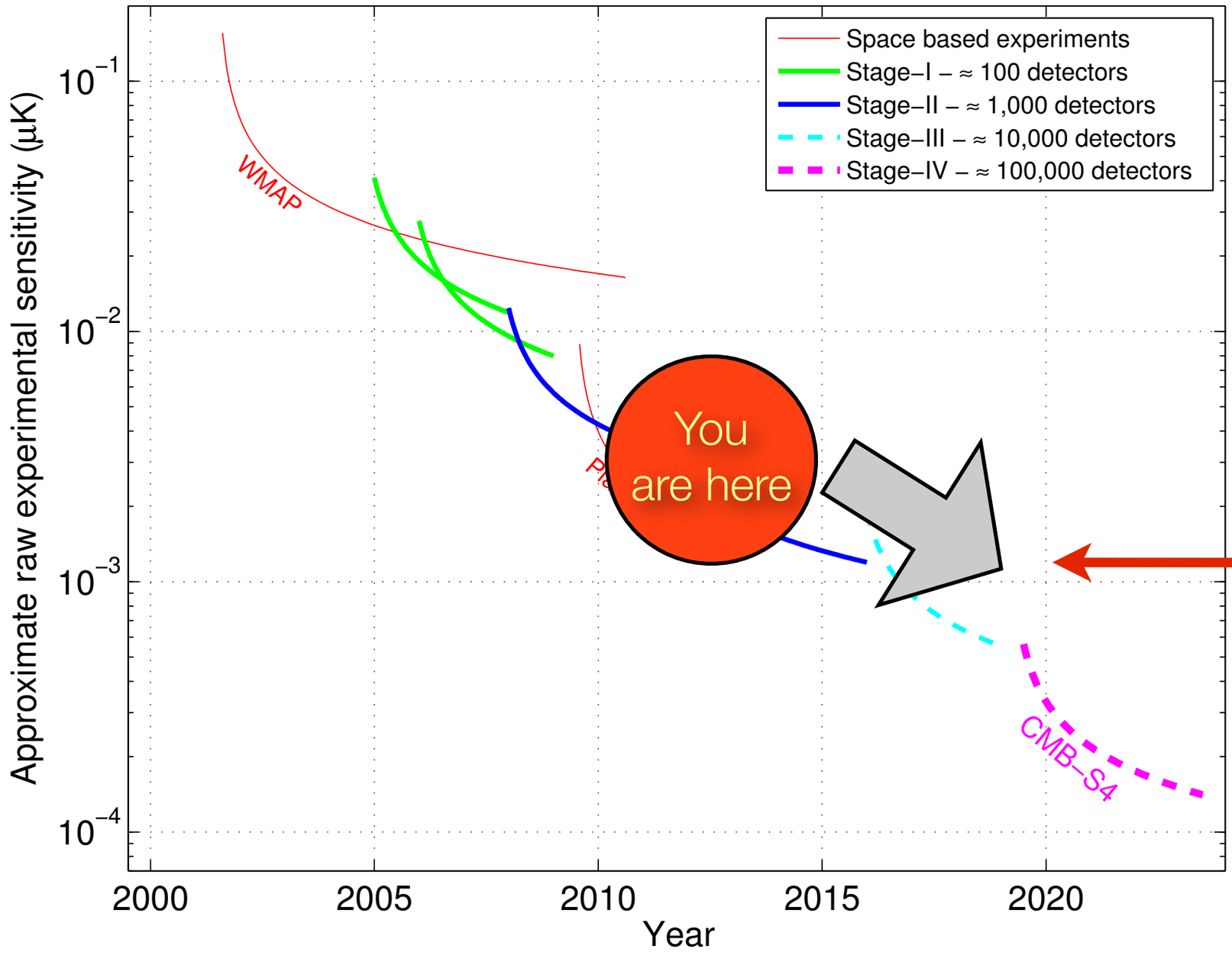
Fabrication challenge includes superconducting microstrip



3-way channelizer

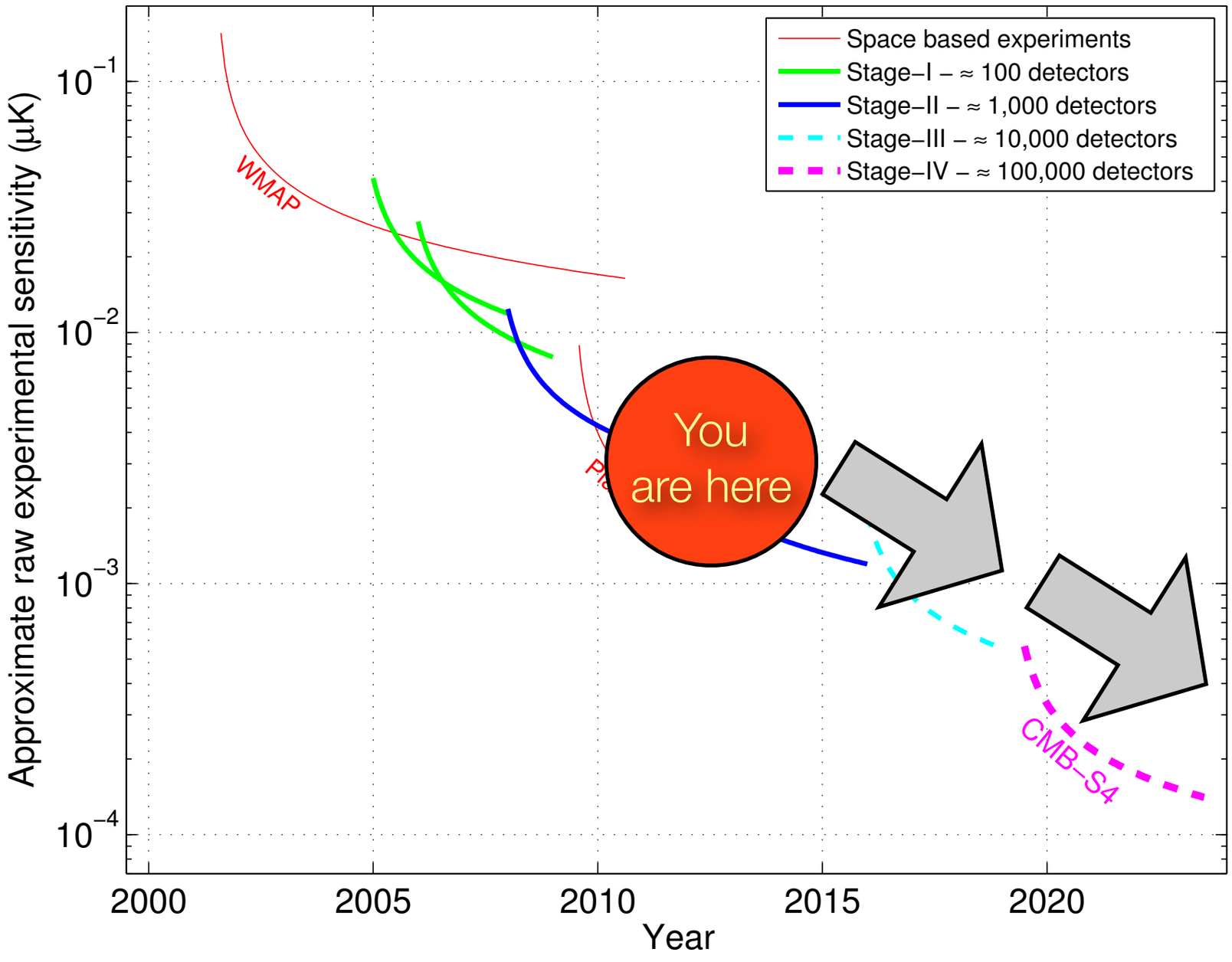


Stages of CMB experiment

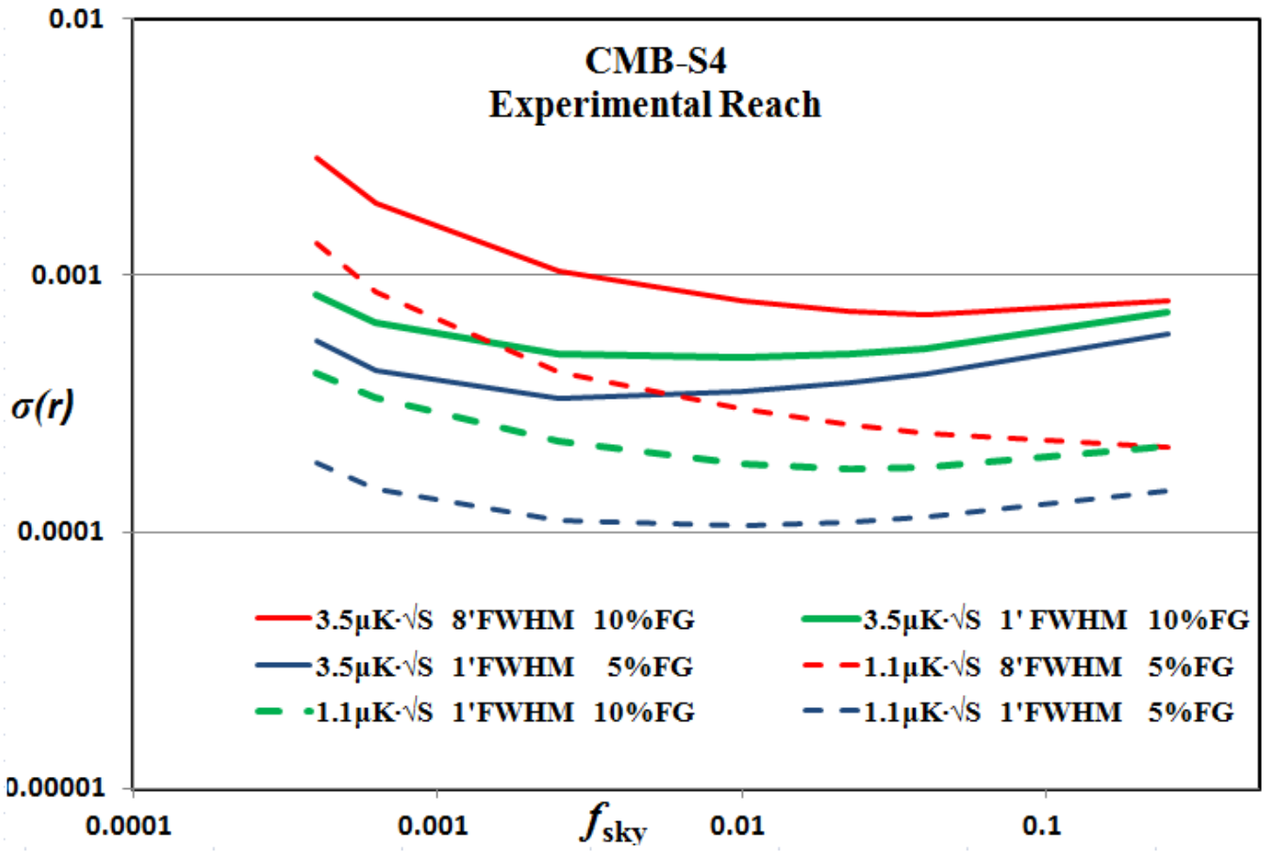


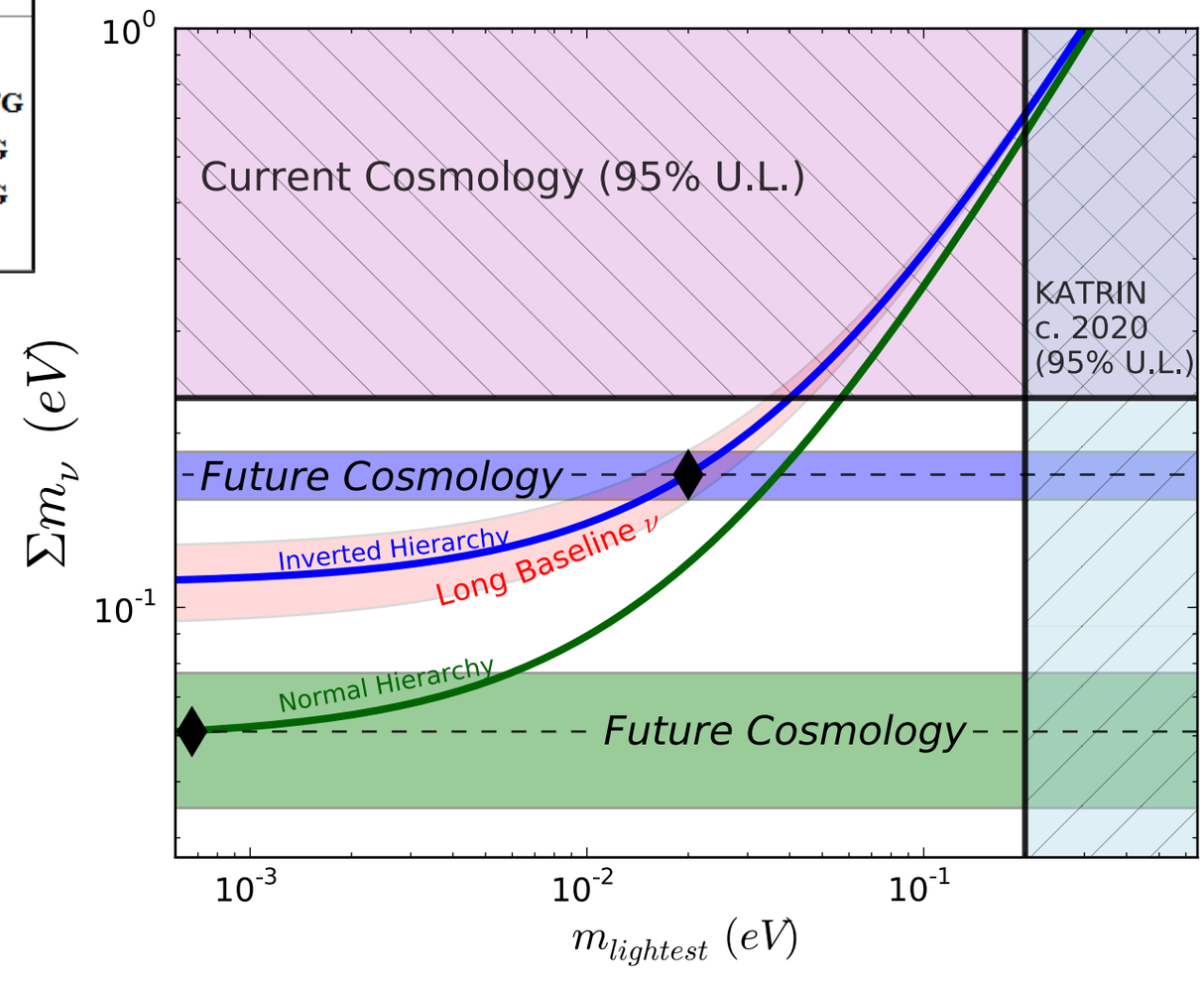
B-mode imaging

Stages of CMB experiment

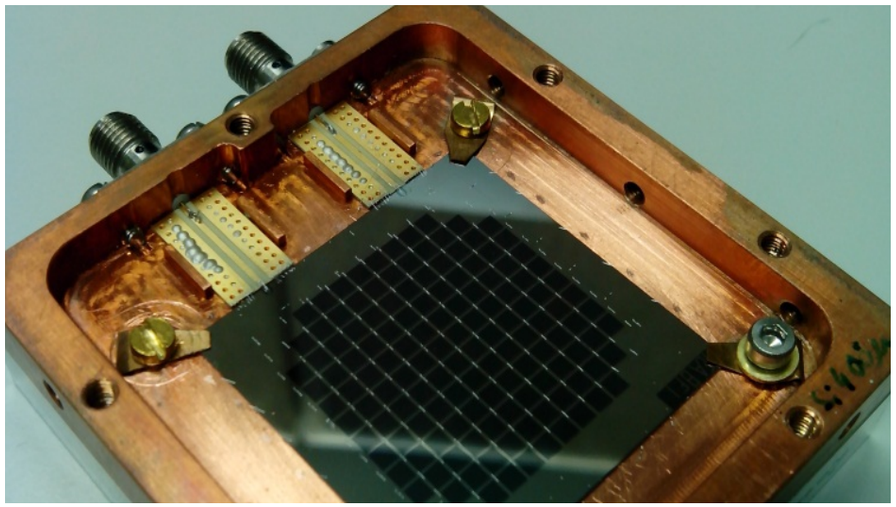


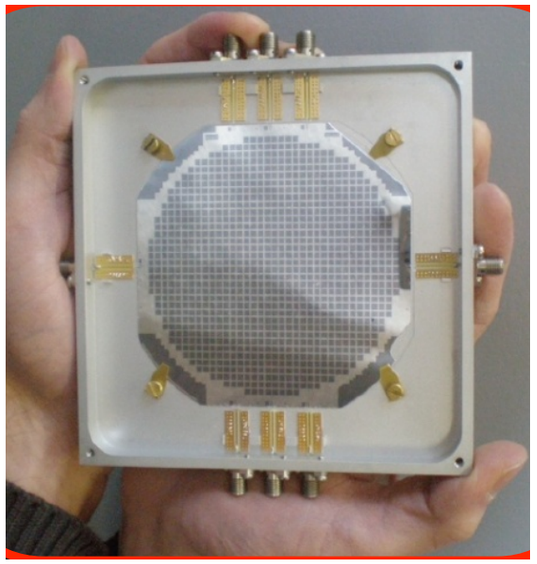
Stages of CMB experiment





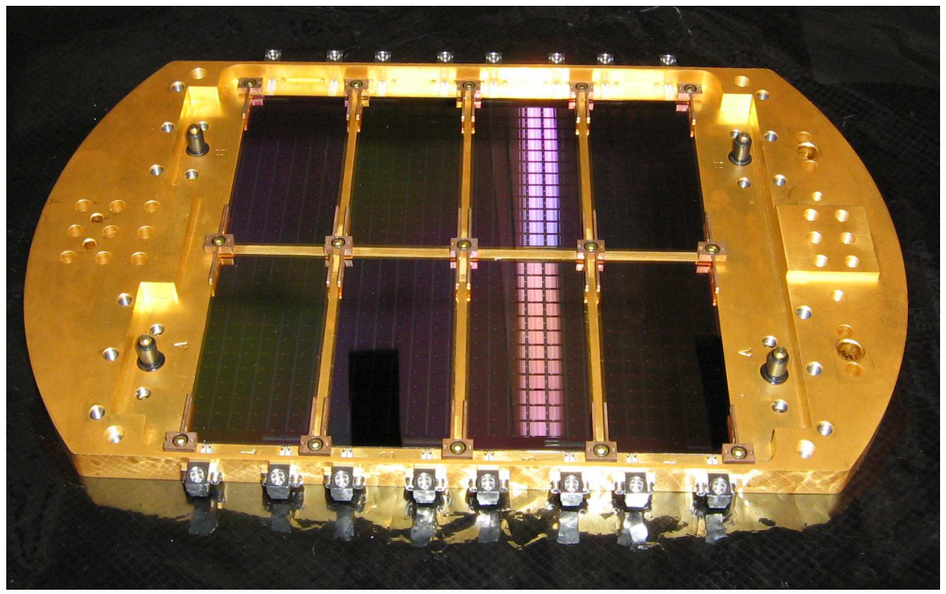
KIDs in mm-wavelengths



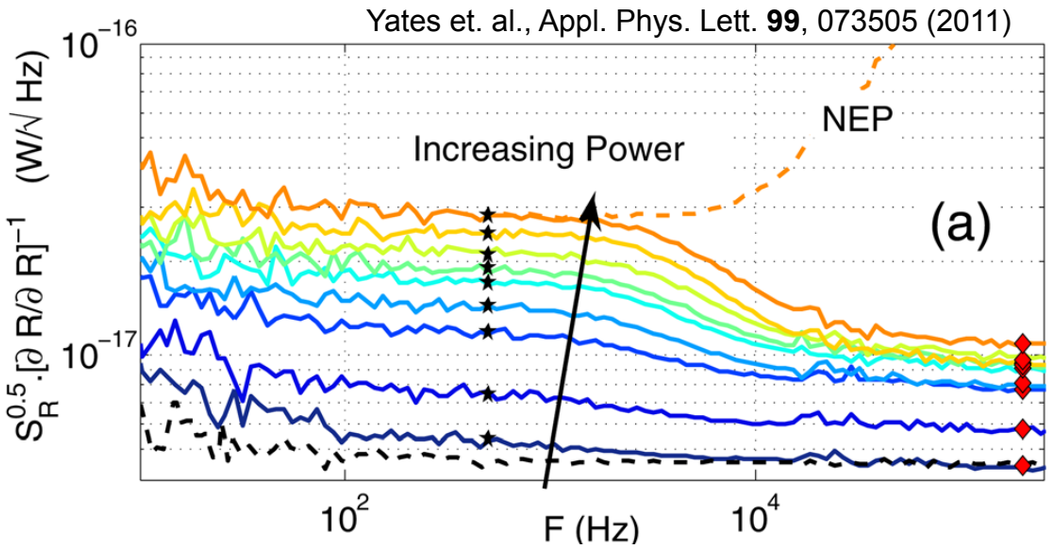


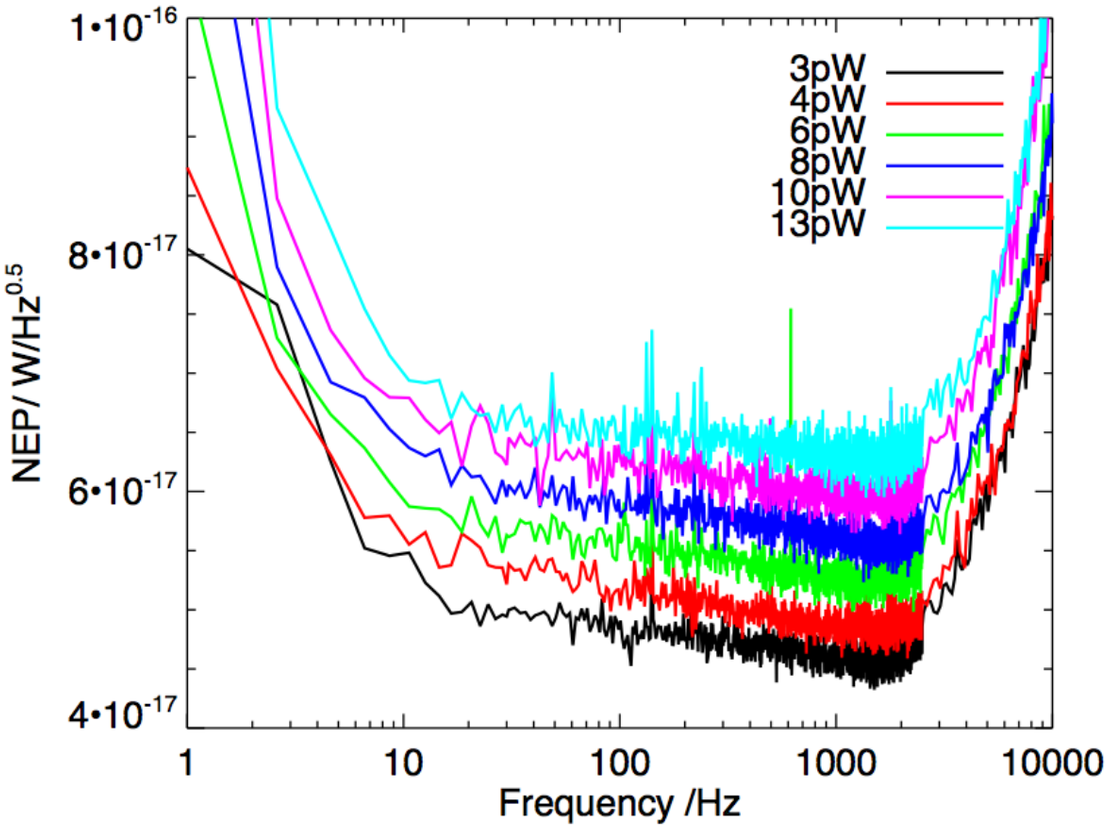
- NIKA (~200 detectors)/NIKA2 (5000 detectors) on IRAM

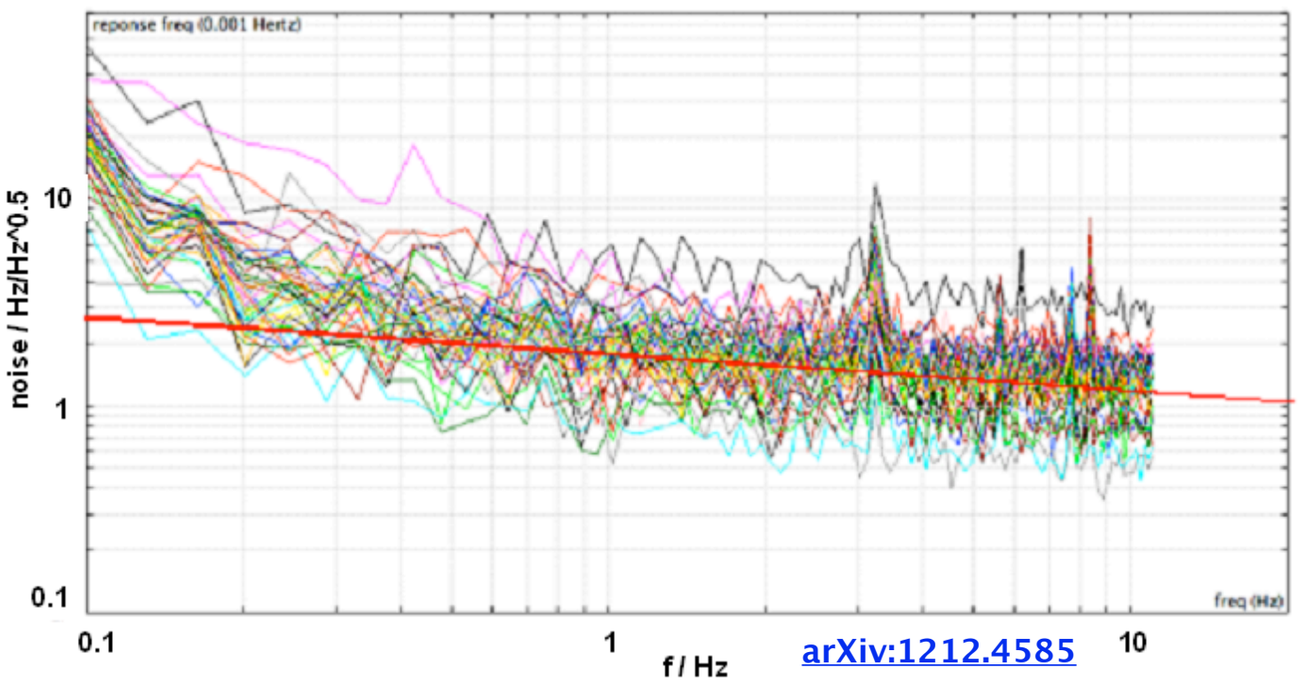
- MUSIC (~2300 detectors) on CSO



Photon noise limited (almost)

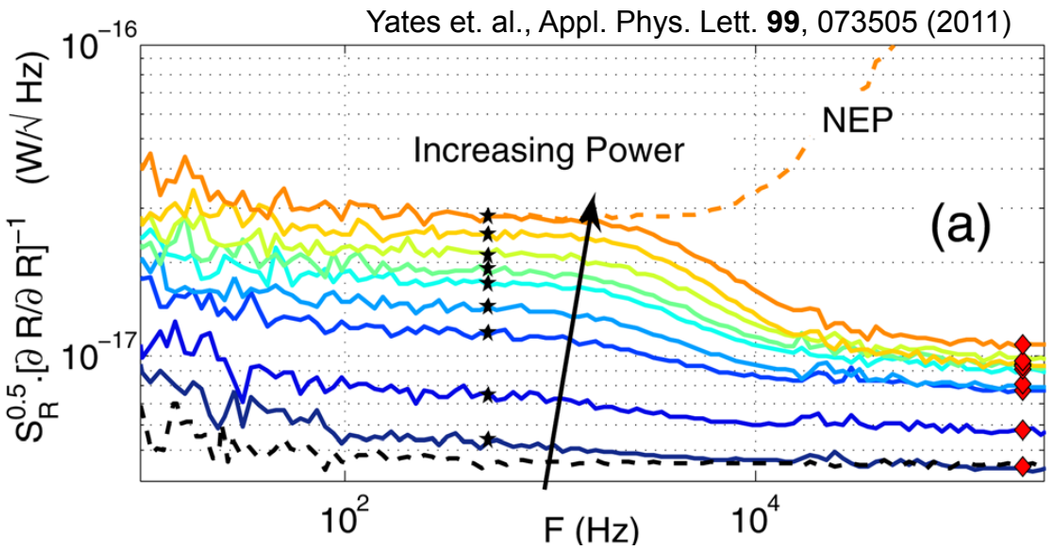


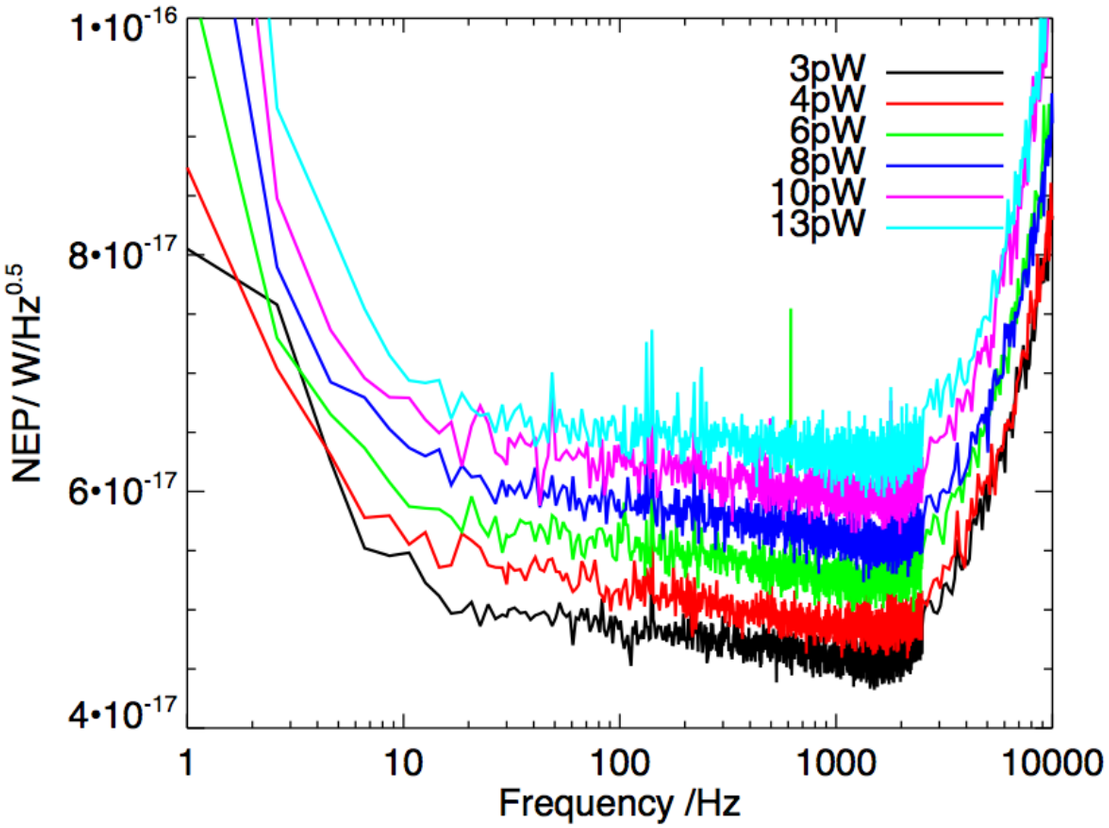


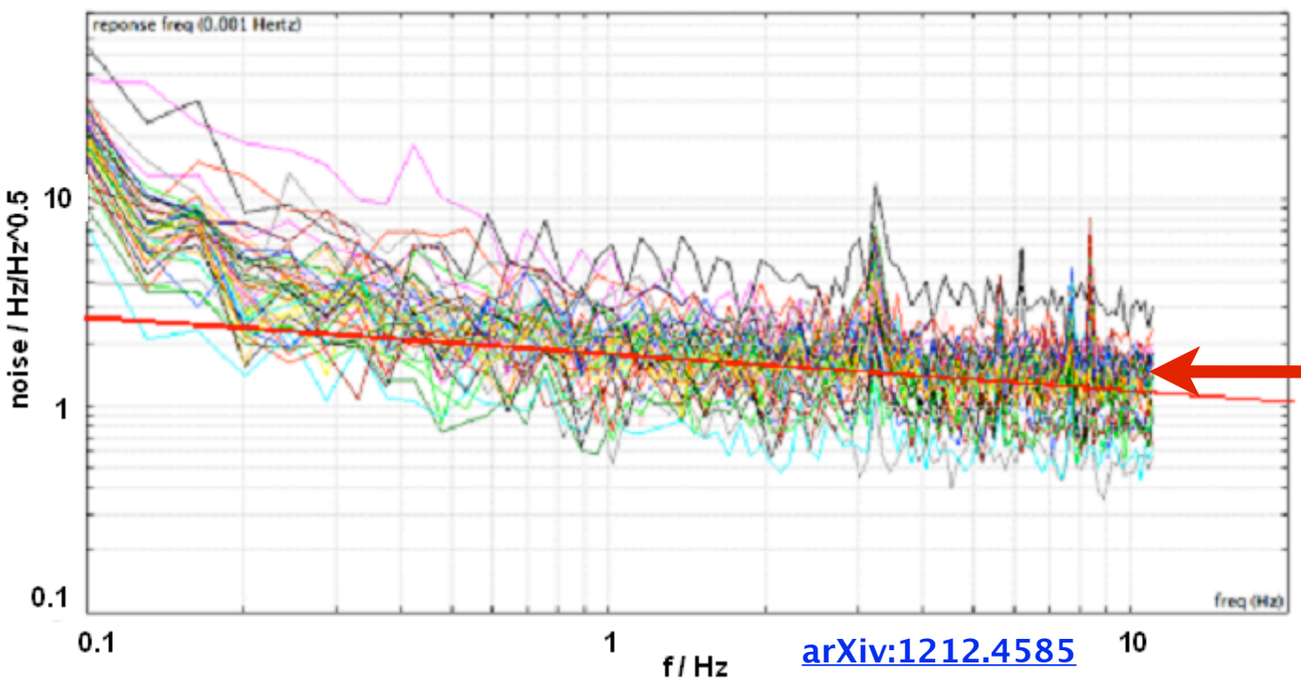


arXiv:1212.4585

Photon noise limited (almost)



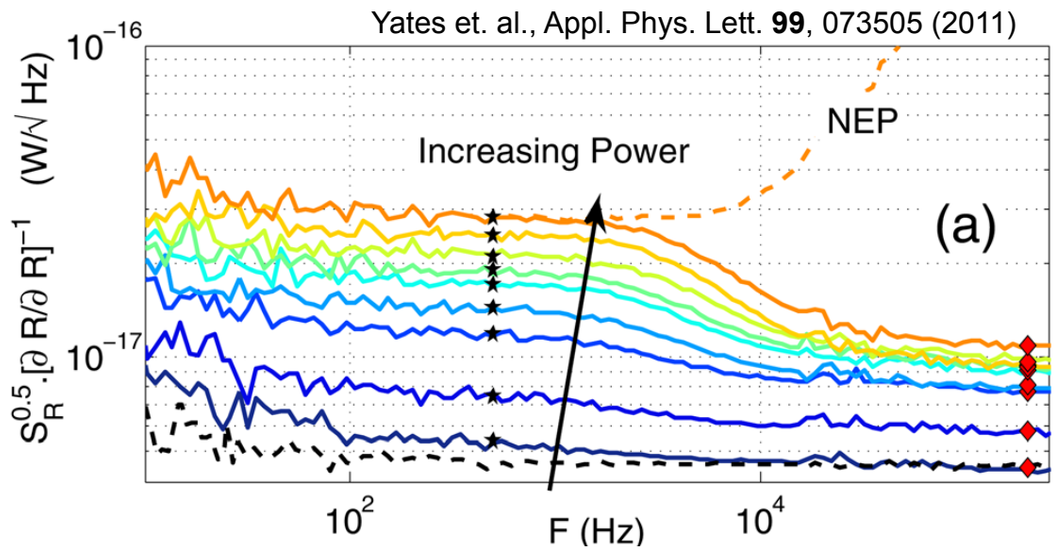


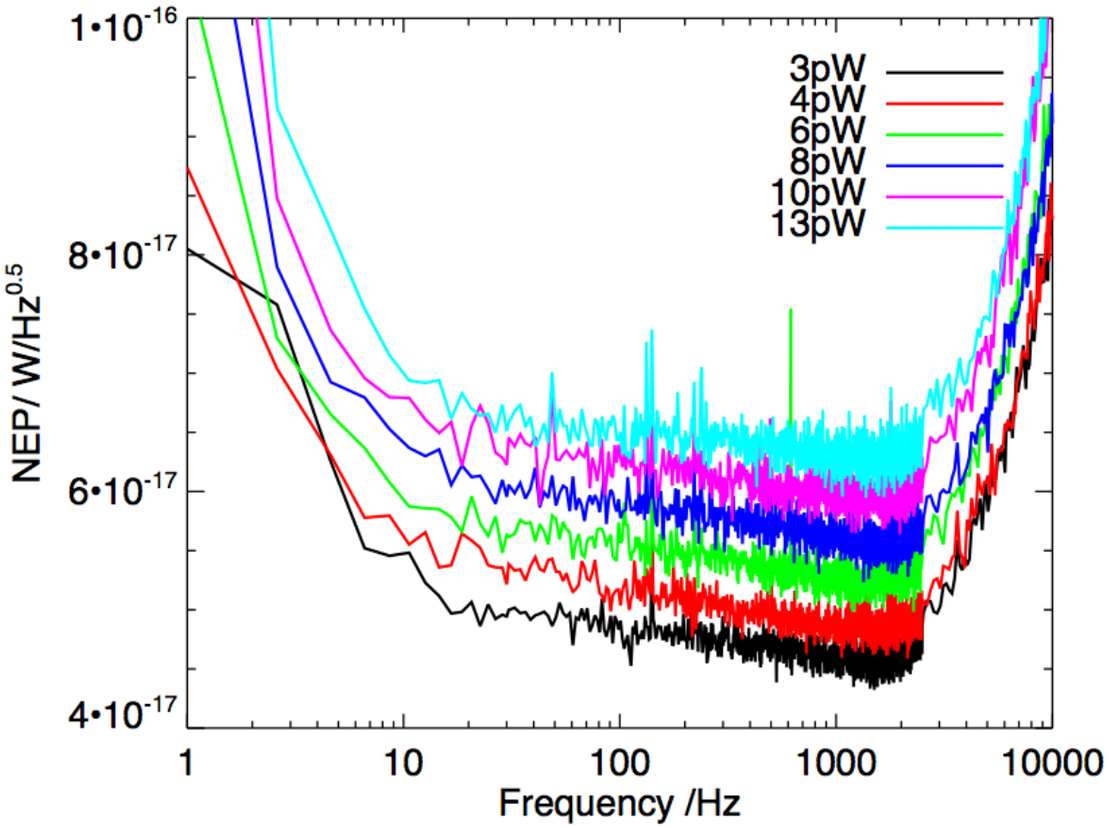


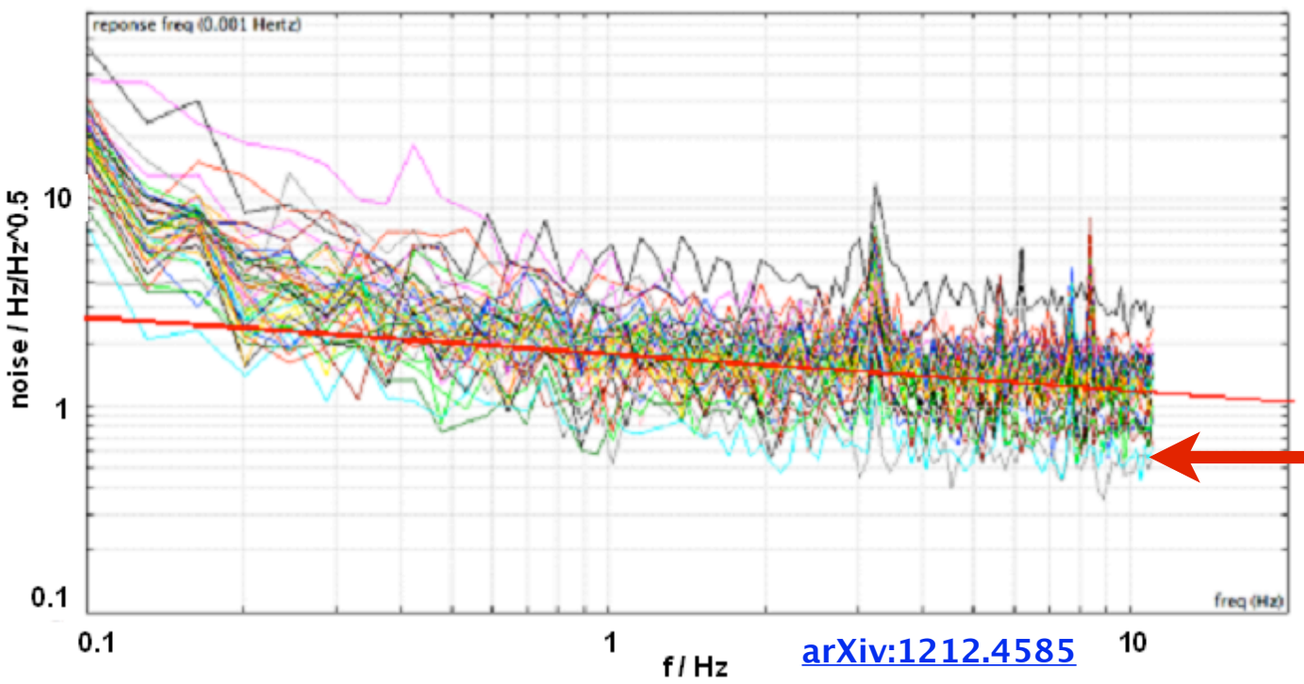
arXiv:1212.4585

~2e-16 W/√Hz

Photon noise limited (almost)



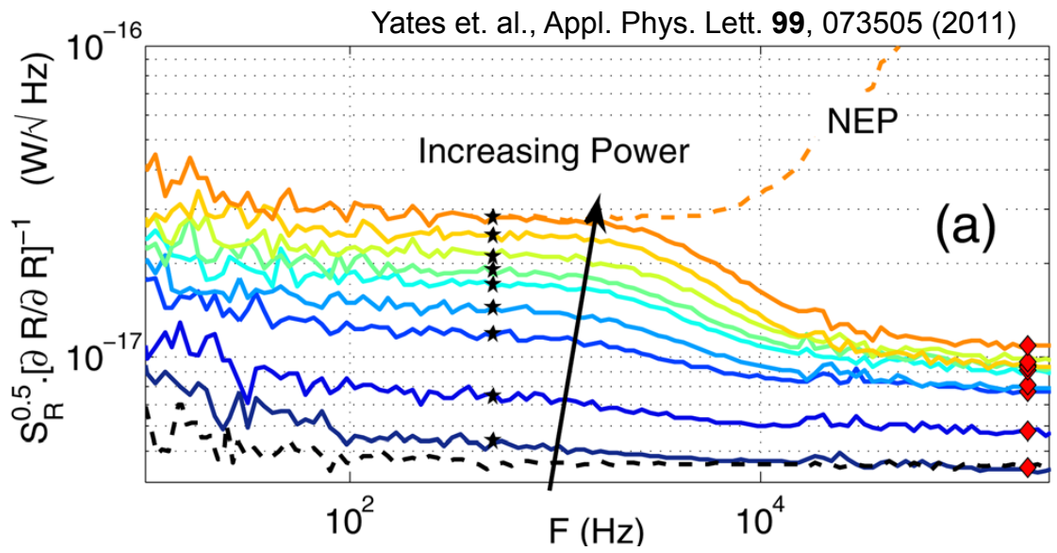


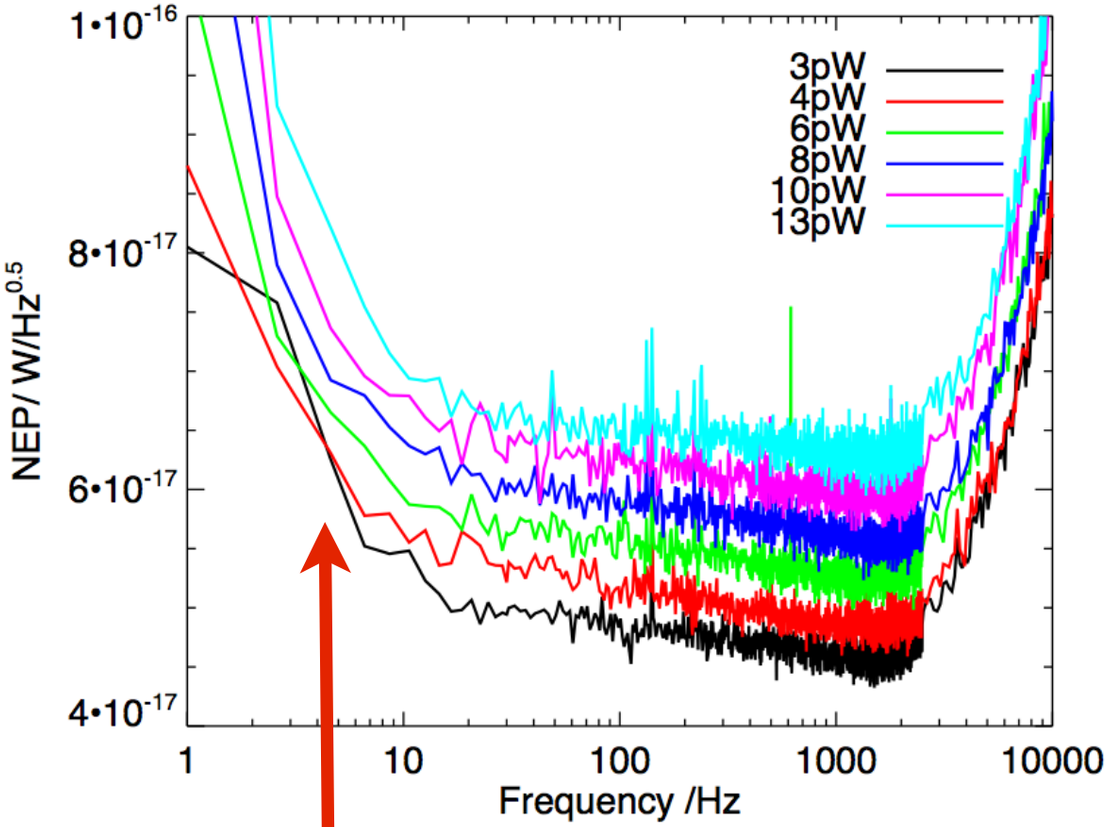


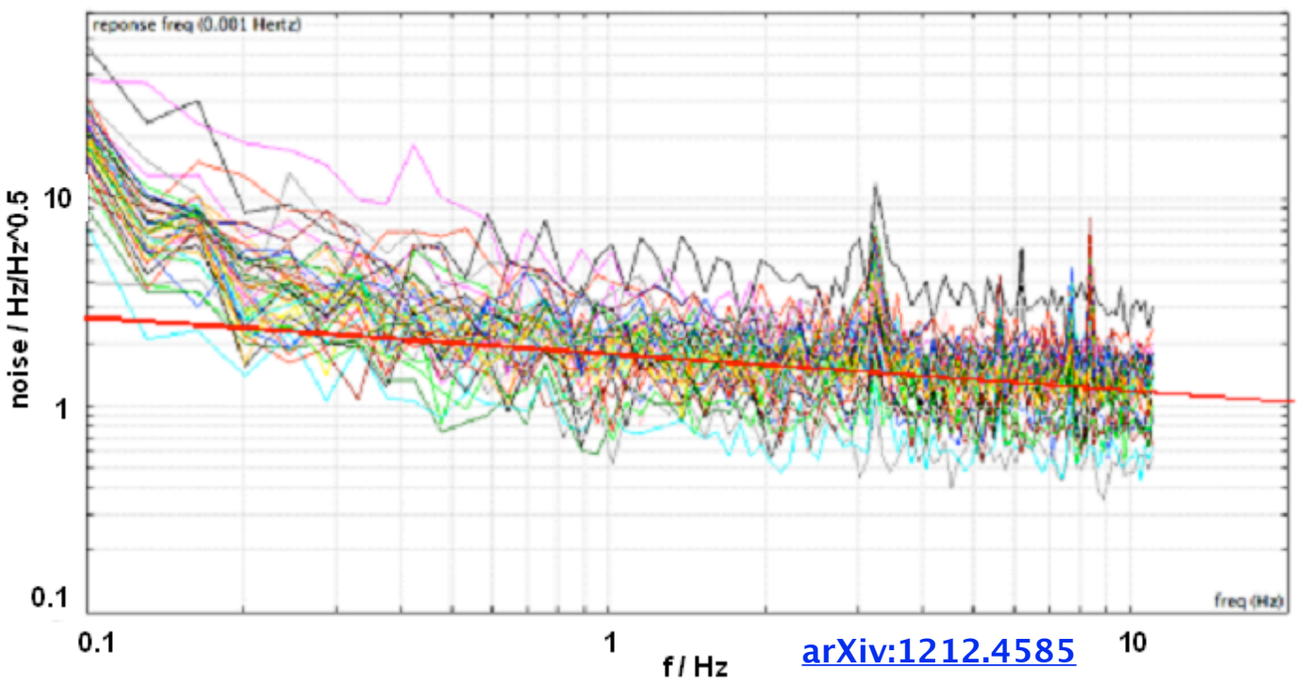
arXiv:1212.4585

~6e-17 W/√Hz

Photon noise limited (almost)







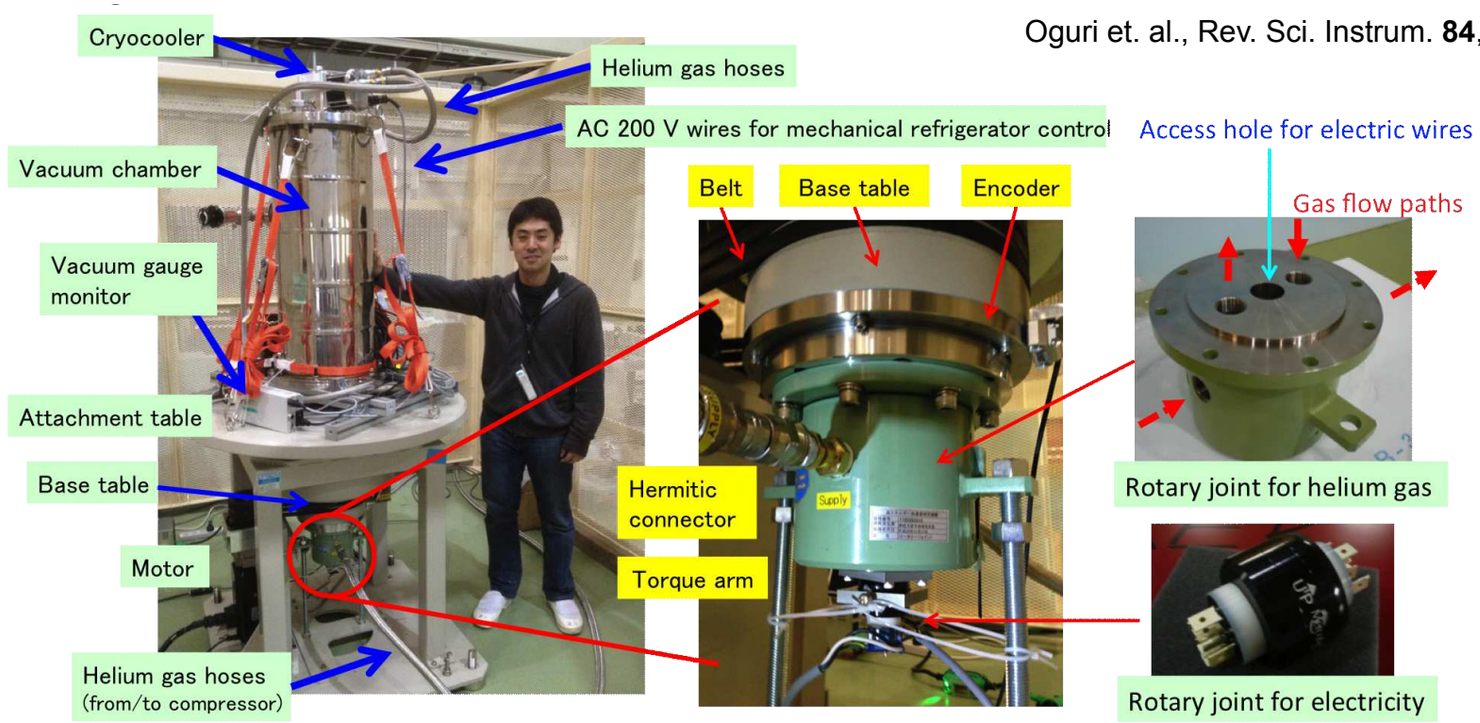
arXiv:1212.4585

TLS noise

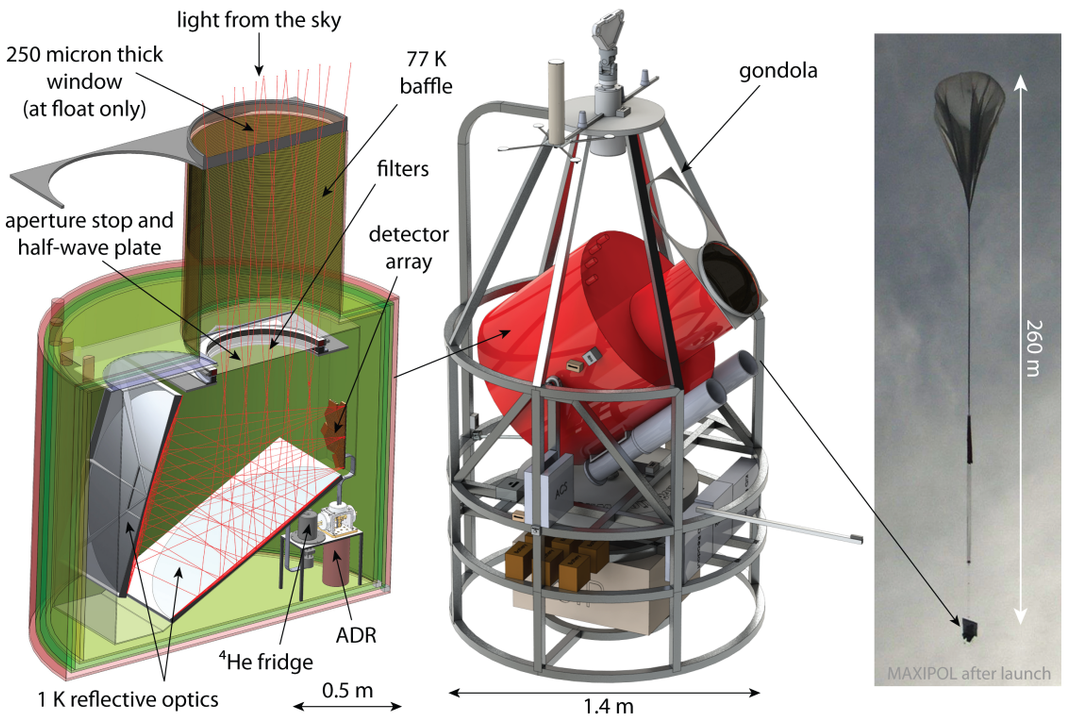
mKIDs in CMB experiments

- GroundBIRD

Oguri et. al., Rev. Sci. Instrum. **84**, 055116 (2013)



- SKIP (proposed)



arXiv:1308.0235

Conclusions

- Currently fielded CMB arrays (TES) have *O*(1000) detectors
- Next 3-5 years, will field arrays with *O*(10,000) detectors (SPT-3G, PBII/ Simons Array, BICEP3, extended ACTpol)
- 5+ years will need *O*(100,000) detectors
- KIDs nearing photon noise limit at higher frequencies
- Need to/will address TLS noise at low frequencies
- Challenges involve production of superconducting microstrip
- Modest increase to *O*(100) MUX, multiple radiometers