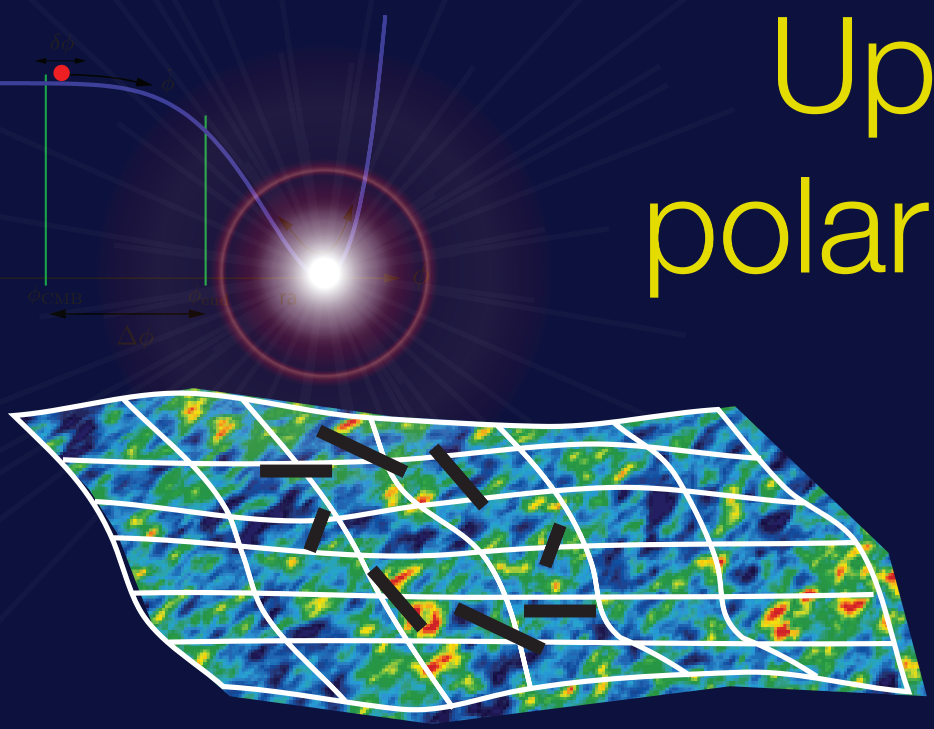
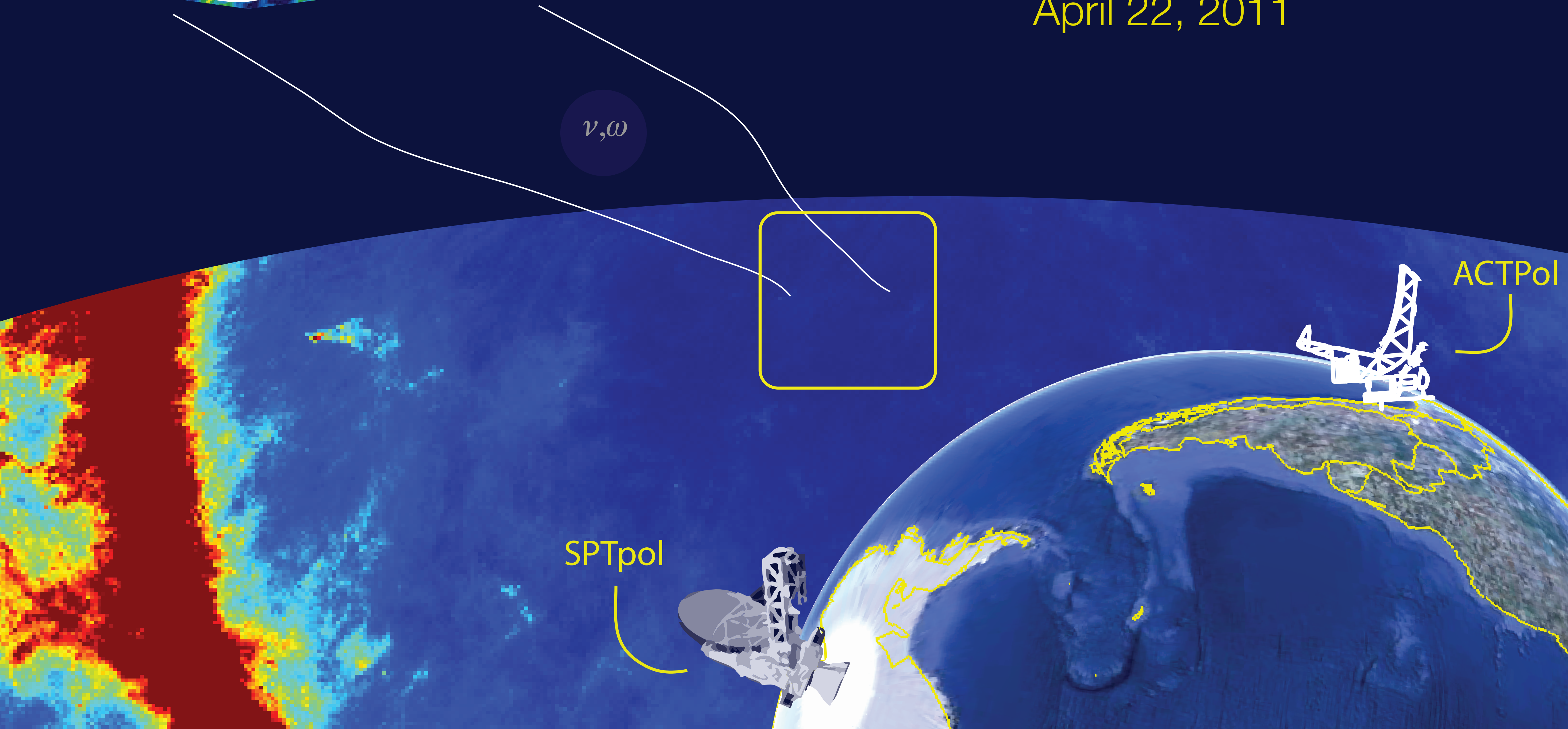
Upcoming arcminute resolution polarization (lensing) measurements



Jeff McMahon • University of Michigan

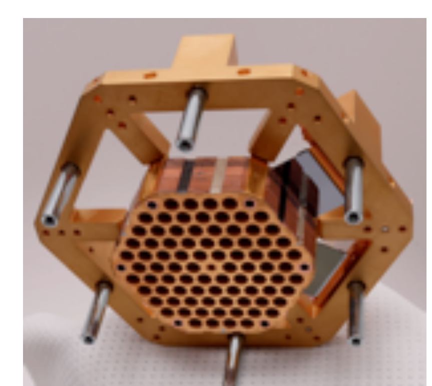
Berkeley Lensing Symposium

April 22, 2011



The Truce collaboration

- Truce collaboration: NIST, UC Berkeley, University of Chicago, University of Colorado, NASA Goddard, University of Michigan, Princeton

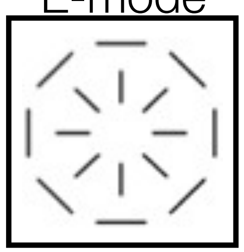


- 150 GHz detectors for ACTPol and SPTpol

CMB Power Spectra: current state

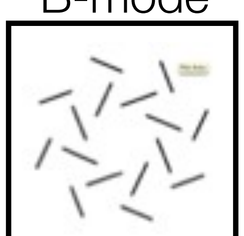
- Temperature spectrum well measured (and getting better every day)
- E-polarization (constraints, but more precision is needed)
- curl free

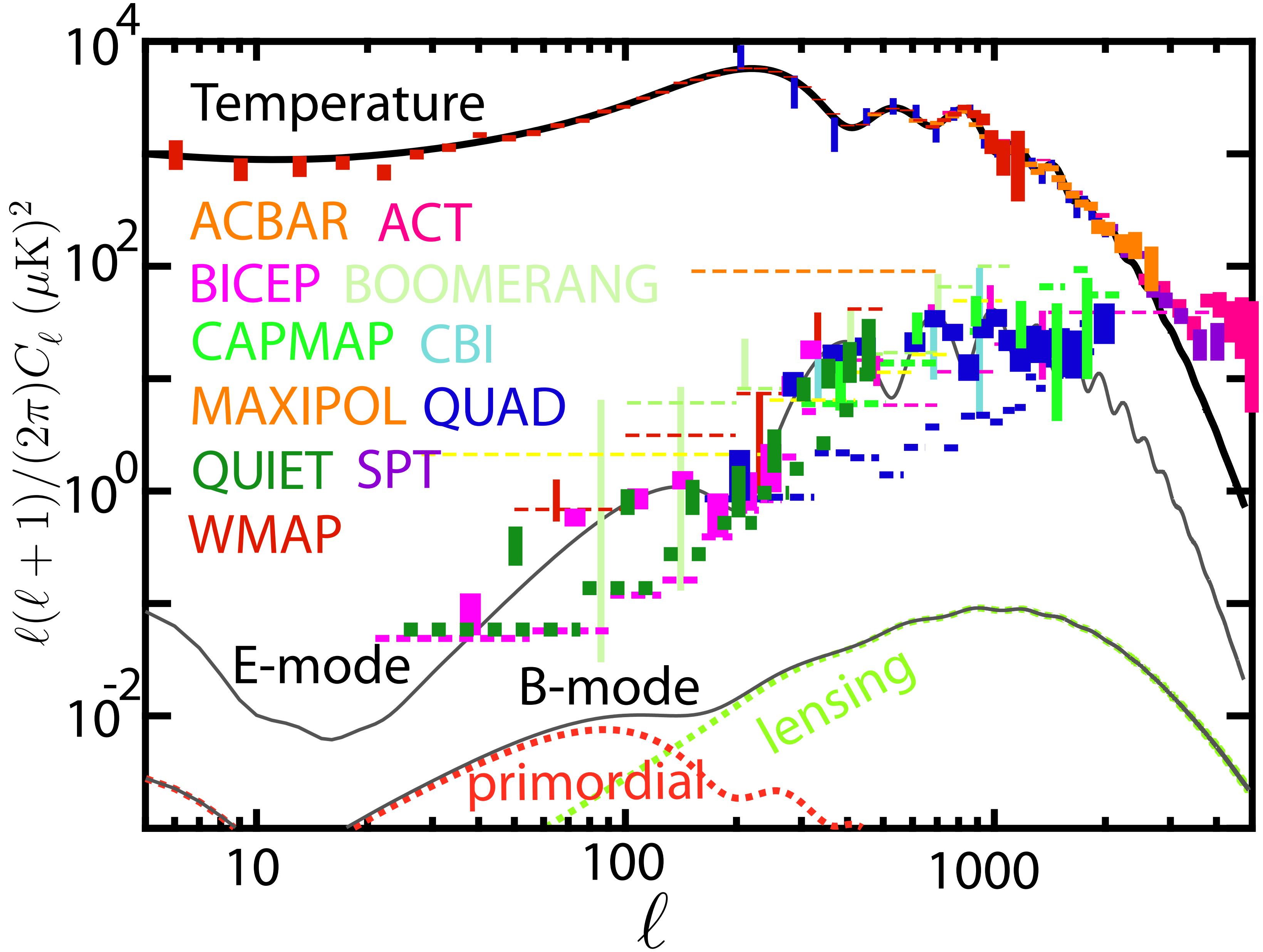
E-mode



- B-polarization spectrum (only limits)
- divergence free

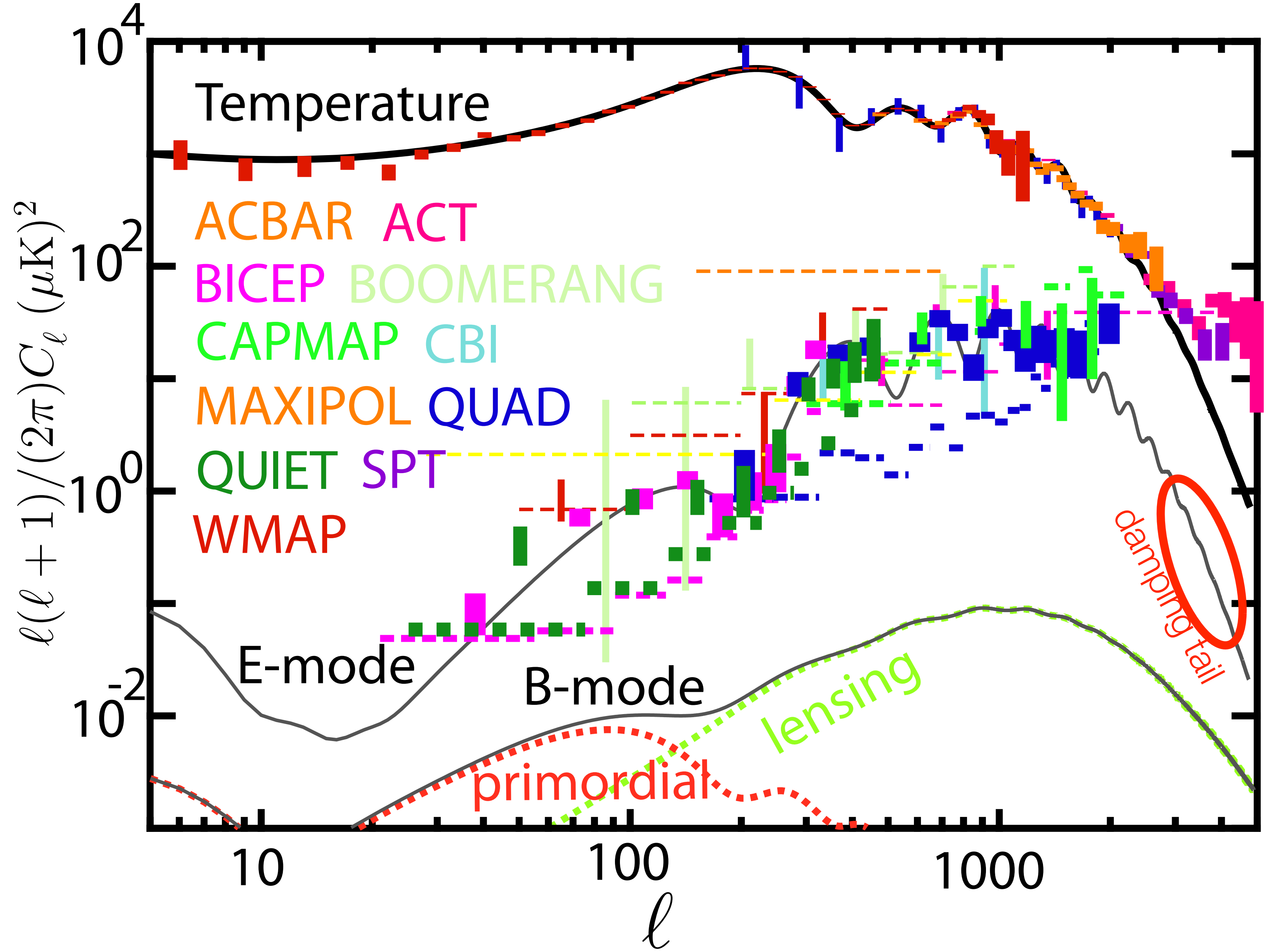
B-mode





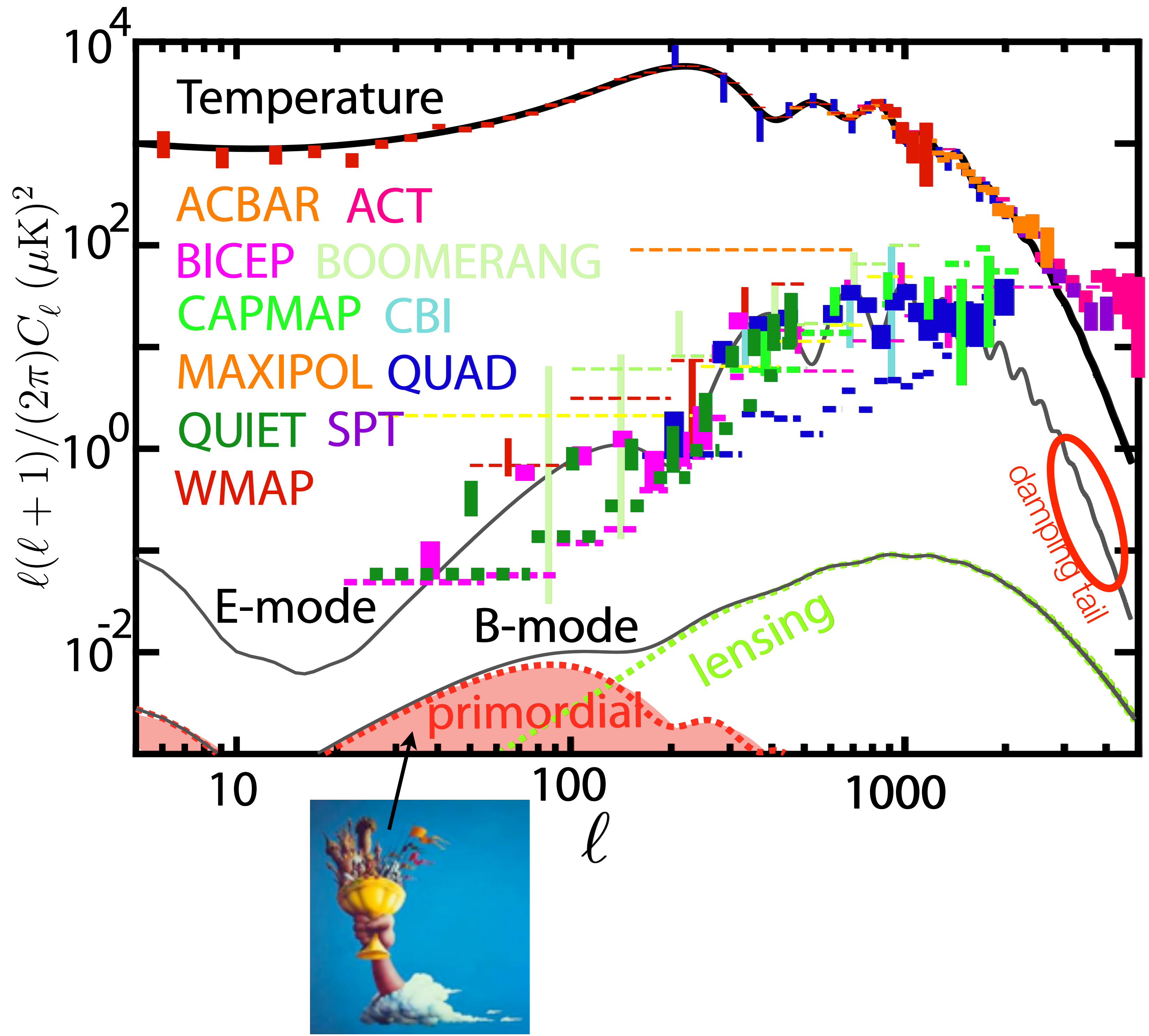
CMB Power Spectra: upcoming science

- E-mode polarization
  - damping tail
    - scalar index of inflation (and running)
    - helium abundance



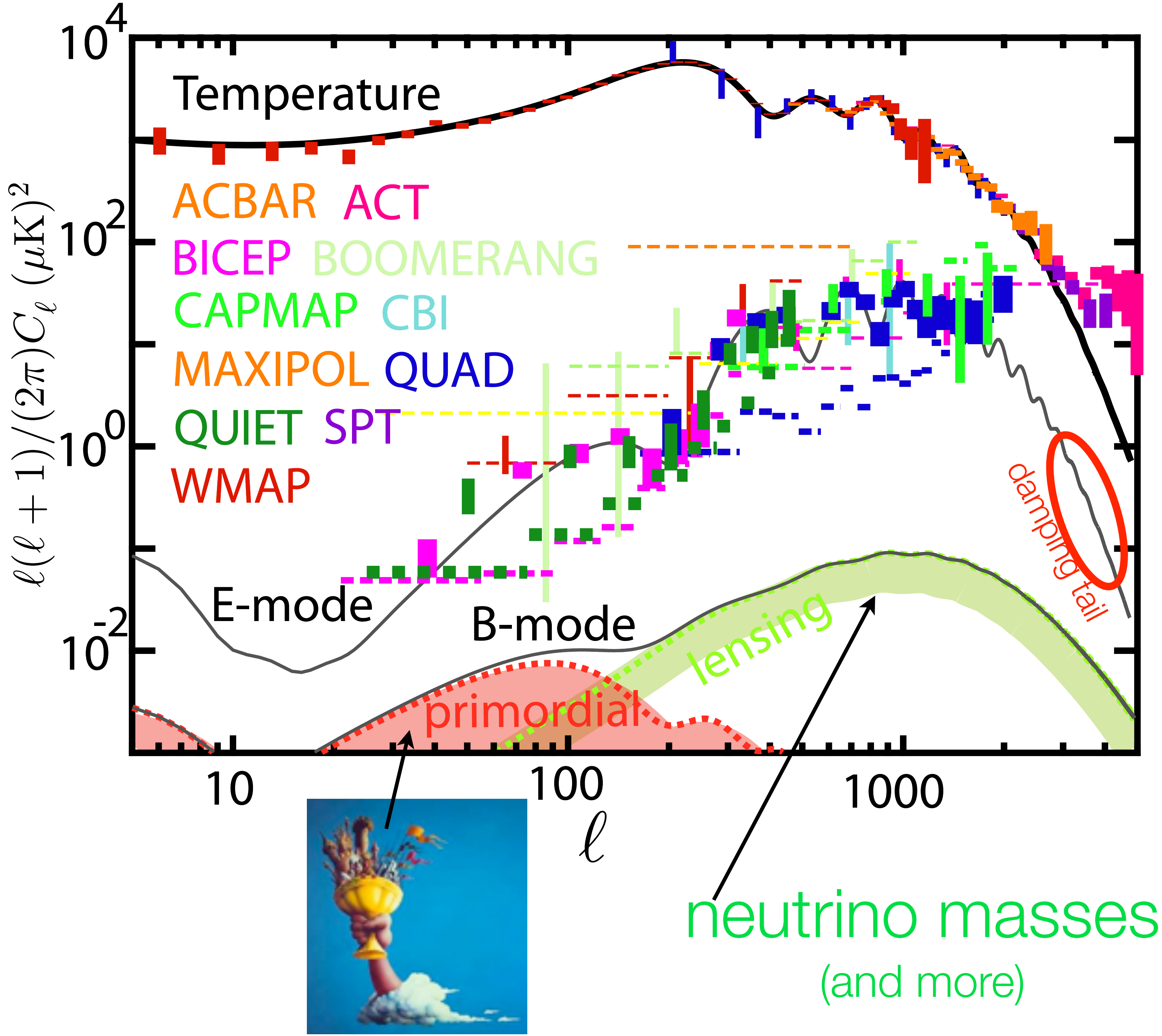
CMB Power Spectra: upcoming science

- E-mode polarization
  - damping tail
    - scalar index & running
    - helium abundance
- B-mode polarization
  - gravitational waves from inflation



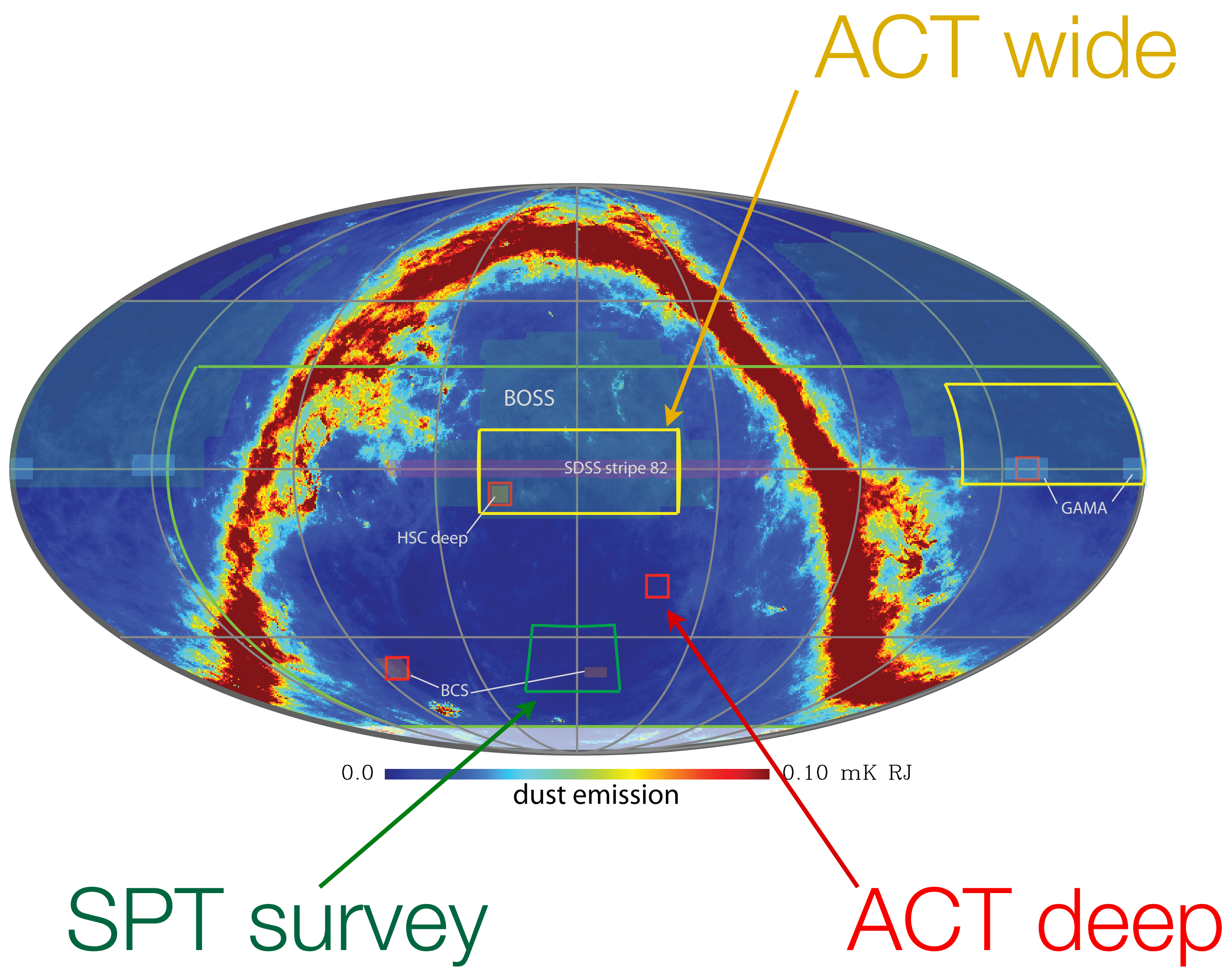
CMB Power Spectra: upcoming science

- E-mode polarization
  - damping tail
    - scalar index of inflation
    - helium abundance
- B-mode polarization
  - gravitational waves from inflation
  - lensing
    - neutrino masses
    - dark energy
    - curvature



ACTpol and SPTpol are complementary

- SPTPol optimized for inflationary gravitational waves and lensing
    - survey cleanest 500 deg. sq. patch to ~ 5 uK arcmin
- ACTPol is optimized for small scale CMB, lensing, and cross-correlations
    - deep fields (150 sq deg ~2 μK arcmin)
    - wide fields (~4000 sq deg @ ~20 μK arcmin)

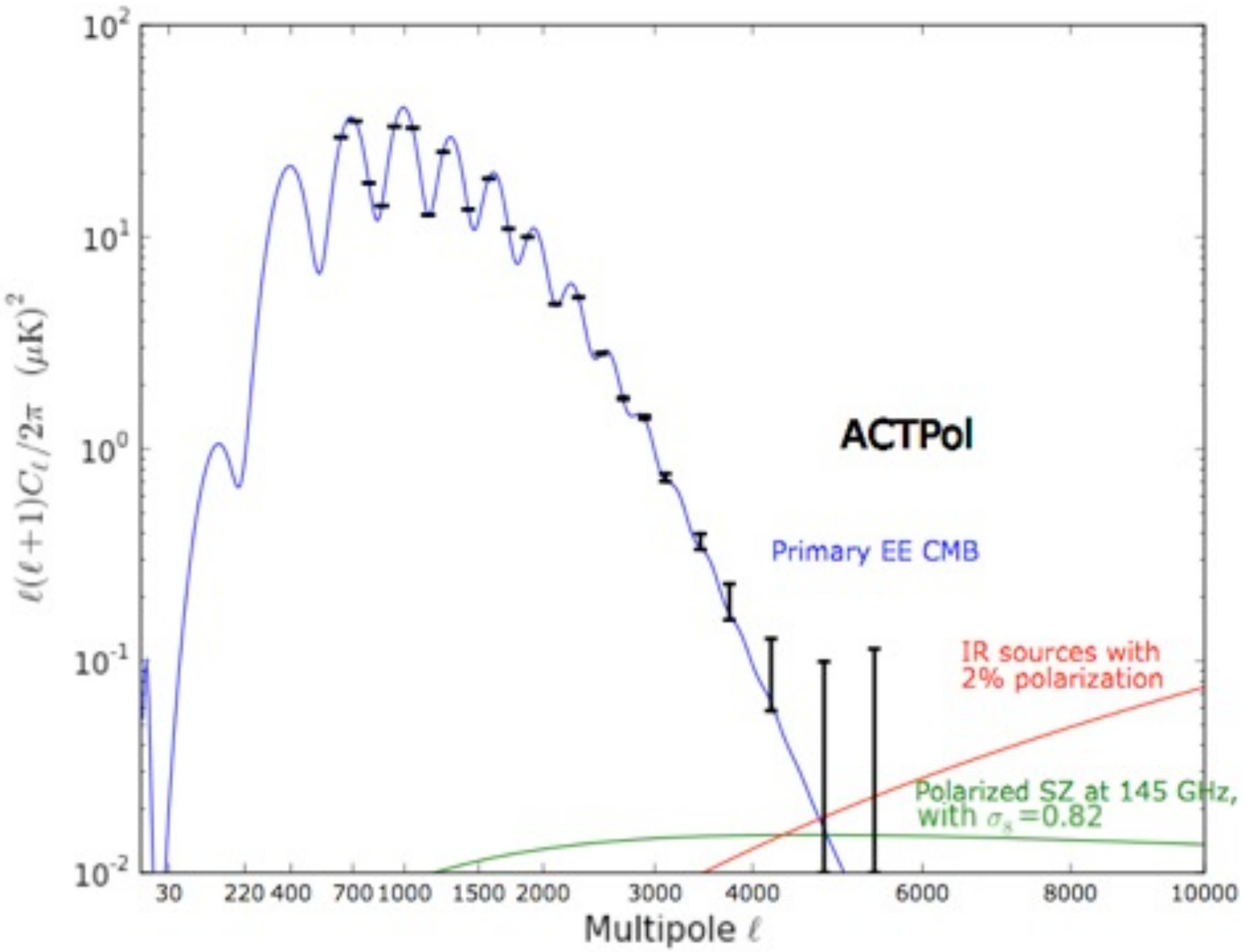


Small angular scale E-mode Polarization

- E-mode signal > foregrounds to ℓ ~ 5,000 (vs. ℓ ~2,500 for temperature)
  - EE is ~10% of TT amplitude
  - point sources are ~1% polarized
  - n_s from temperature
  - n_s running from E-modes

- He recombination imprint
  - => He abundance to ~1%
  - constrain BBN & Neutrino number

ACTPol E-mode Projection

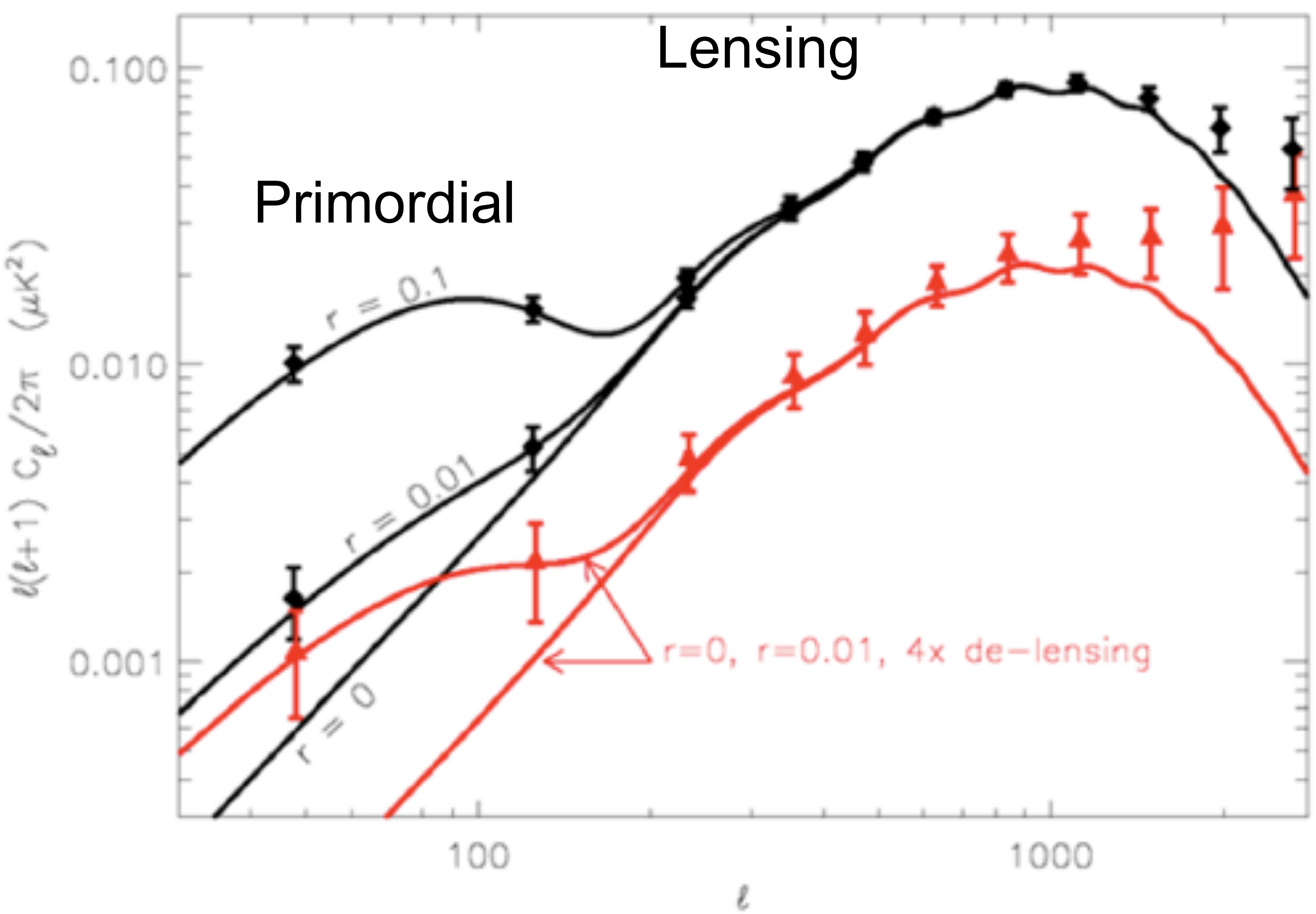


(Niemack et al., SPIE 2010)

B-polarization power spectra (SPTPol)

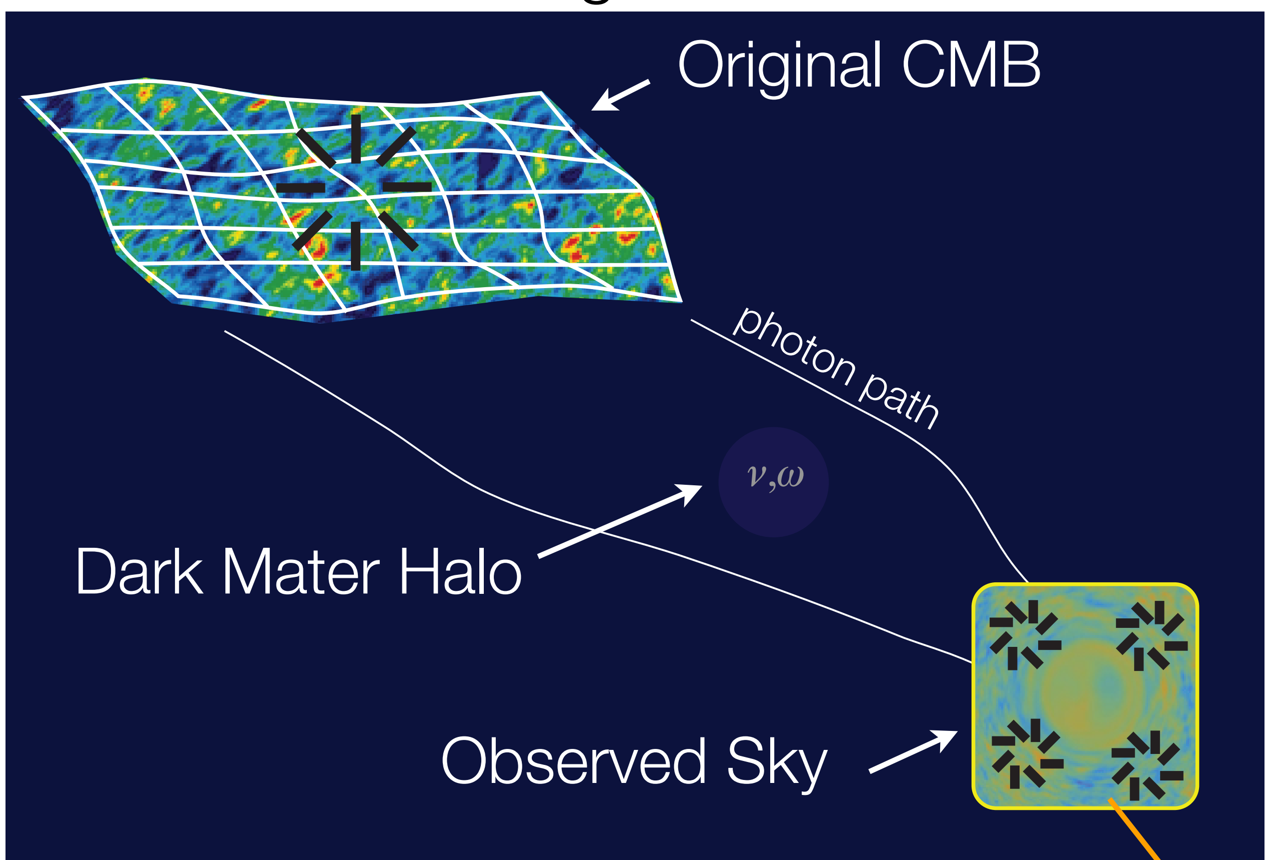
- SPTpol optomized fo measure the power spectrum over a range of l's
  - Sensitive to r with σ_r = 0.004
  - lensing constraints

SPTPol B-mode Projection



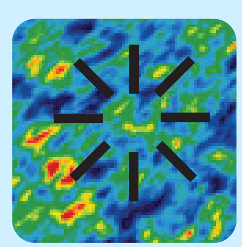
CMB lensing

CMB lensing schematic

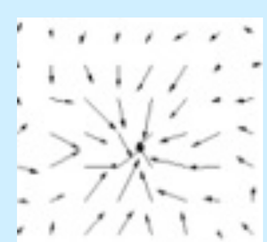


Lensing creates arc-minute scale features correlated on degree scales

analysis products



de-lensed maps



deflection field

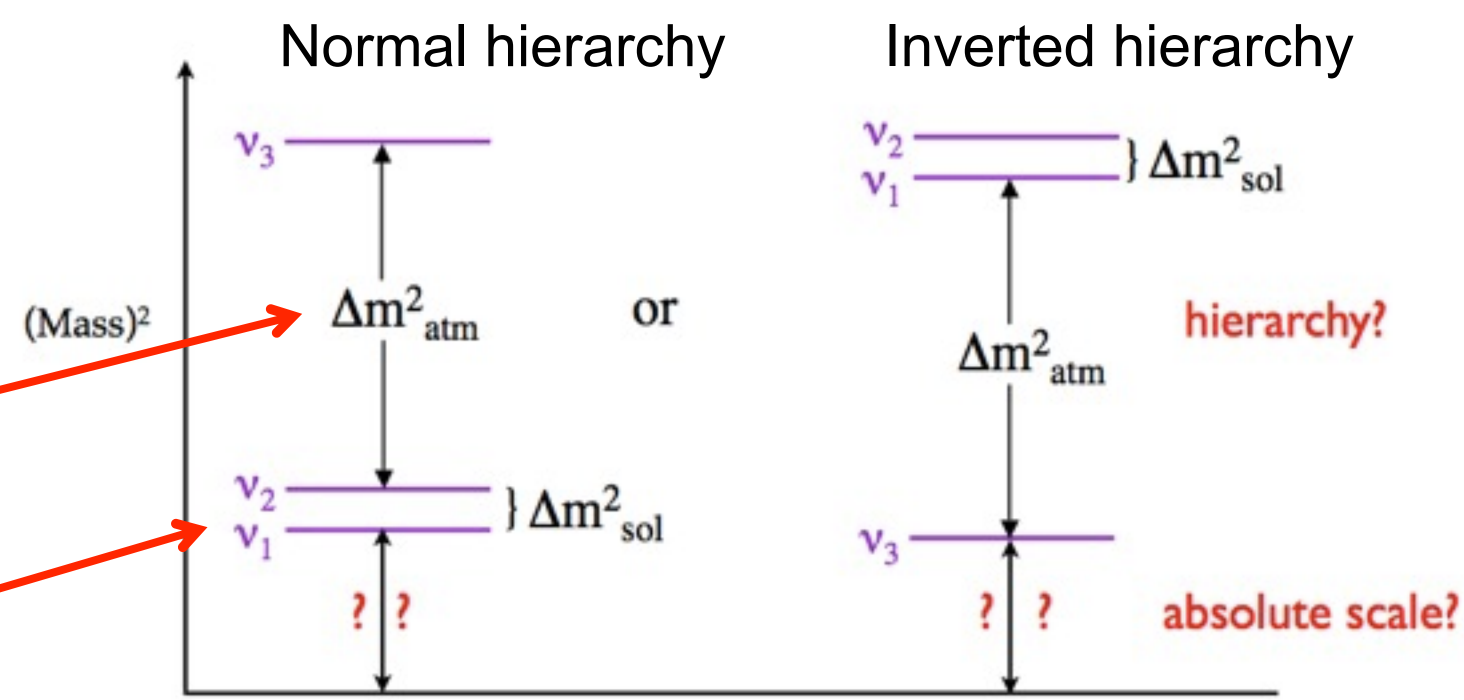
- CMB lensing sensitive to the matter power spectrum at z~2
- cross-correlating the lensing reconstruction with spectroscopic data sets (eg BOSS) leads to constraints on the matter power spectrum at lower redshift
- massive neutrinos, dark energy, etc. affect structure leading to measurable effects in the deflection field
- measuring lensing allows its removal improving measurements of the primordial power spectrum

Gravitational Lensing as an opportunity: neutrinos

- 3 types of neutrinos
  - oscillation measurements determine mass differences
    - Atmospheric neutrinos

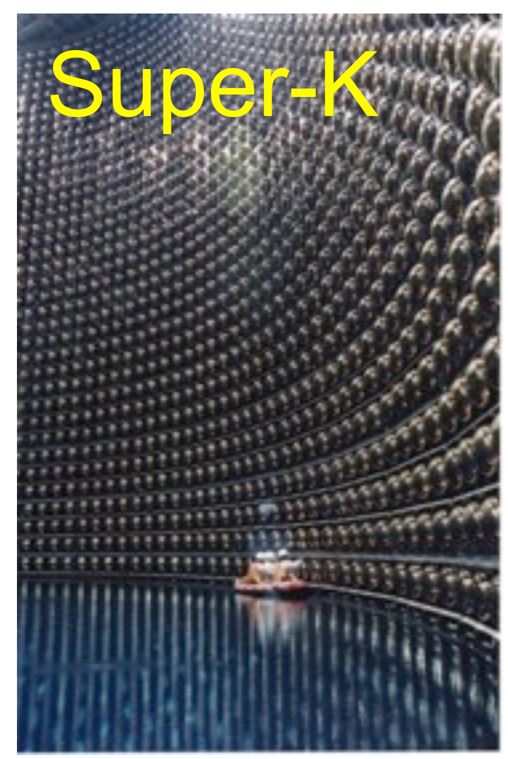
      => $\Delta\ m_{\nu 23}$ = 0.05 eV
    - Solar neutrinos

      => $\Delta\ m_{\nu 12}$ = 0.009 eV



(Haxton 2010)

$\Rightarrow \Sigma\ m_\nu$ > 0.05 eV, but unknown
- two cases, inverted and normal hierarchy.

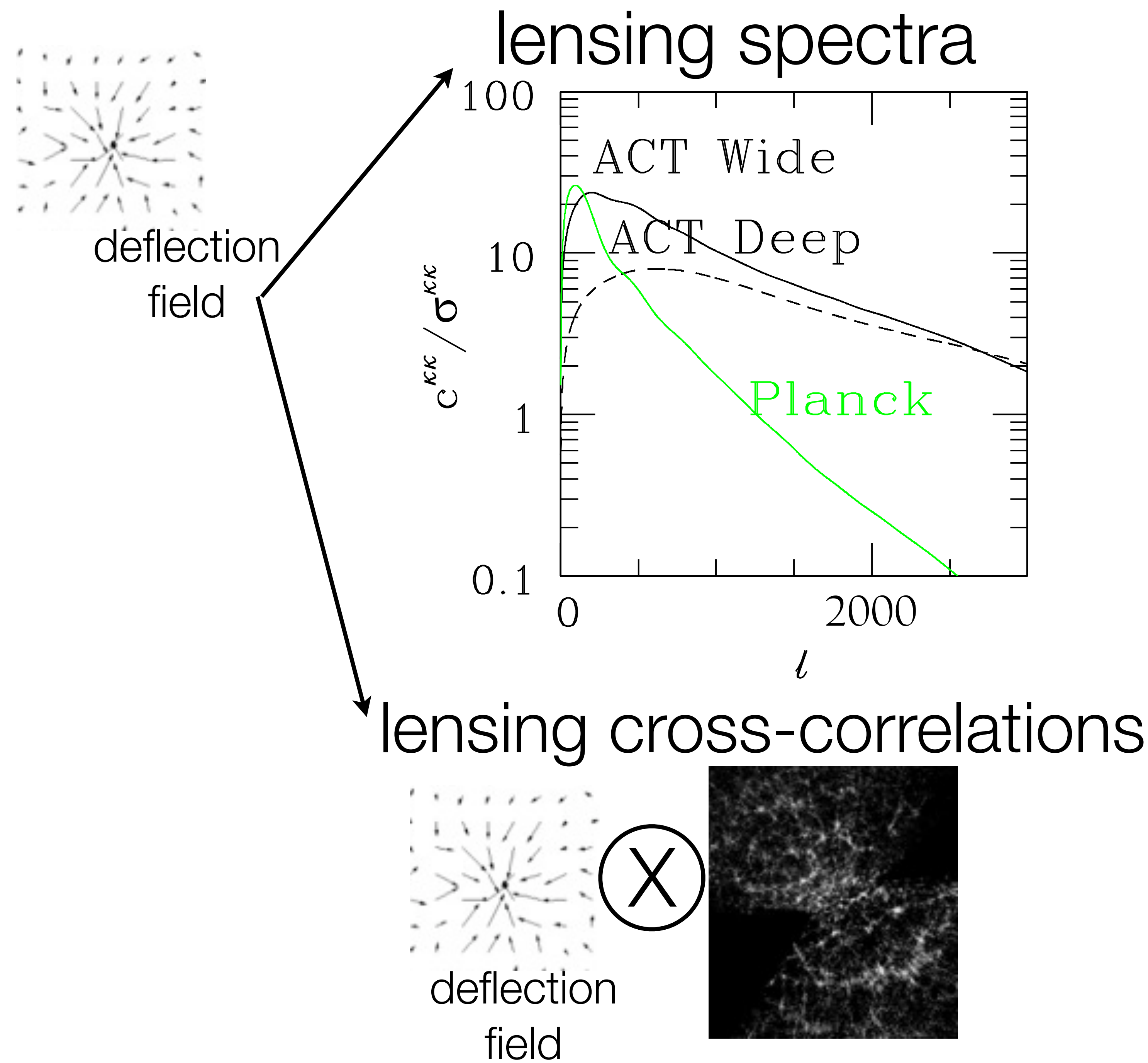


- Big opportunity for CMB measurements to tell the difference

neutrinos from lensing

- Lensing power spectrum
  - z ~3 measurement of the matter power spectrum
  - sum of the neutrino masses to ~0.07 eV
- cross-correlate with Lya from BOSS (Vallinotto et al. 2009)
  - measurement of the z~1 Lya power spectrum leading to an independent constraint on neutrinos at the ~0.05 eV
- cross-correlate with LRGs from BOSS (Acquaviva et al. 2009.)
  - additional neutrino measurement ~0.05 eV centered at z~ 0.05

getting science

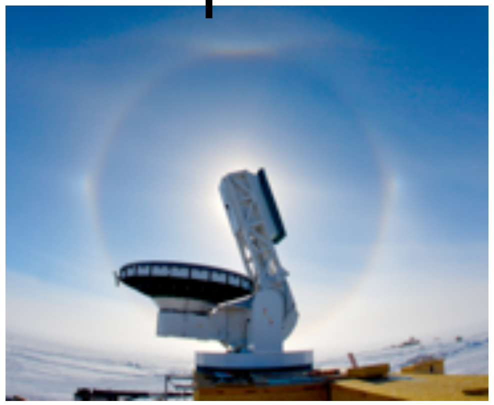


Requirements for a lensing measurement

- High resolution
- control of systematics
- lots of sensitivity

Requirements for a lensing measurement

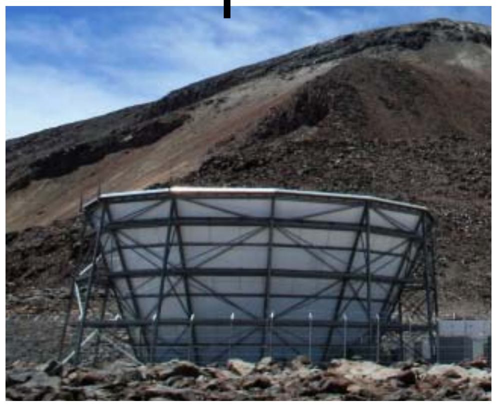
SPTpol



- Beam ~1’

- High resolution
- control of systematics
- lots of sensitivity

ACTpol

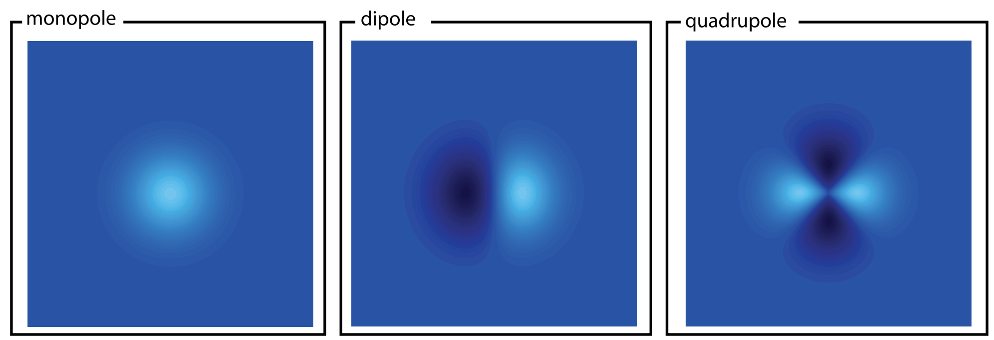


- Beam ~1.6’

Polarization Systematics

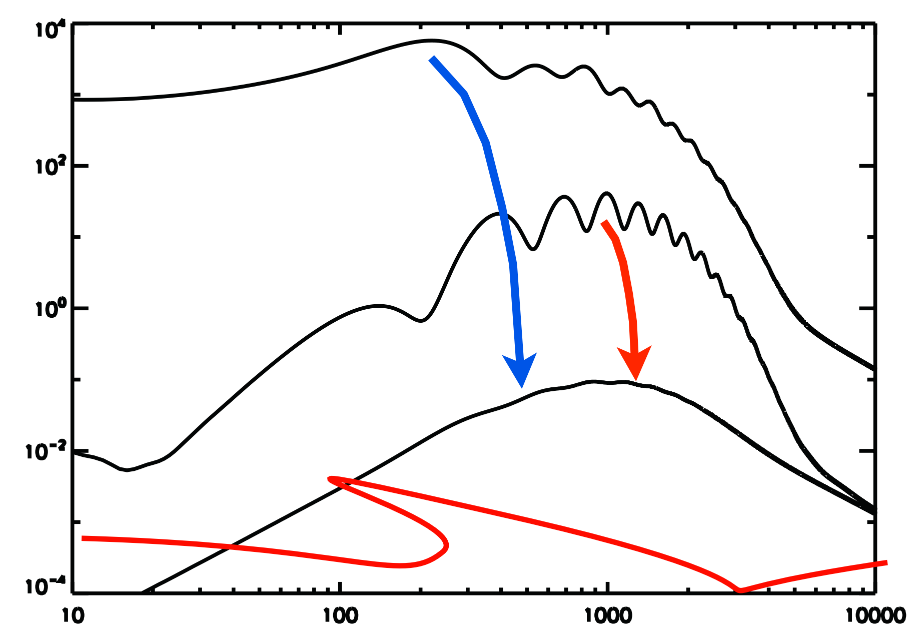
- effects mixing T->E,B (temperature to polarization leakage)
- effects mixing E<->B (detector angle)
- spurious signals
    - foregrounds
    - ground pickup

beam systematics (mixing T->E and B)



$$\begin{bmatrix} E_m \\ B_m \end{bmatrix} = \begin{bmatrix} \cos 2\theta_\epsilon & -\sin 2\theta_\epsilon \\ \sin 2\theta_\epsilon & \cos 2\theta_\epsilon \end{bmatrix} \begin{bmatrix} E \\ B \end{bmatrix}$$

systematics mix T, E, and B

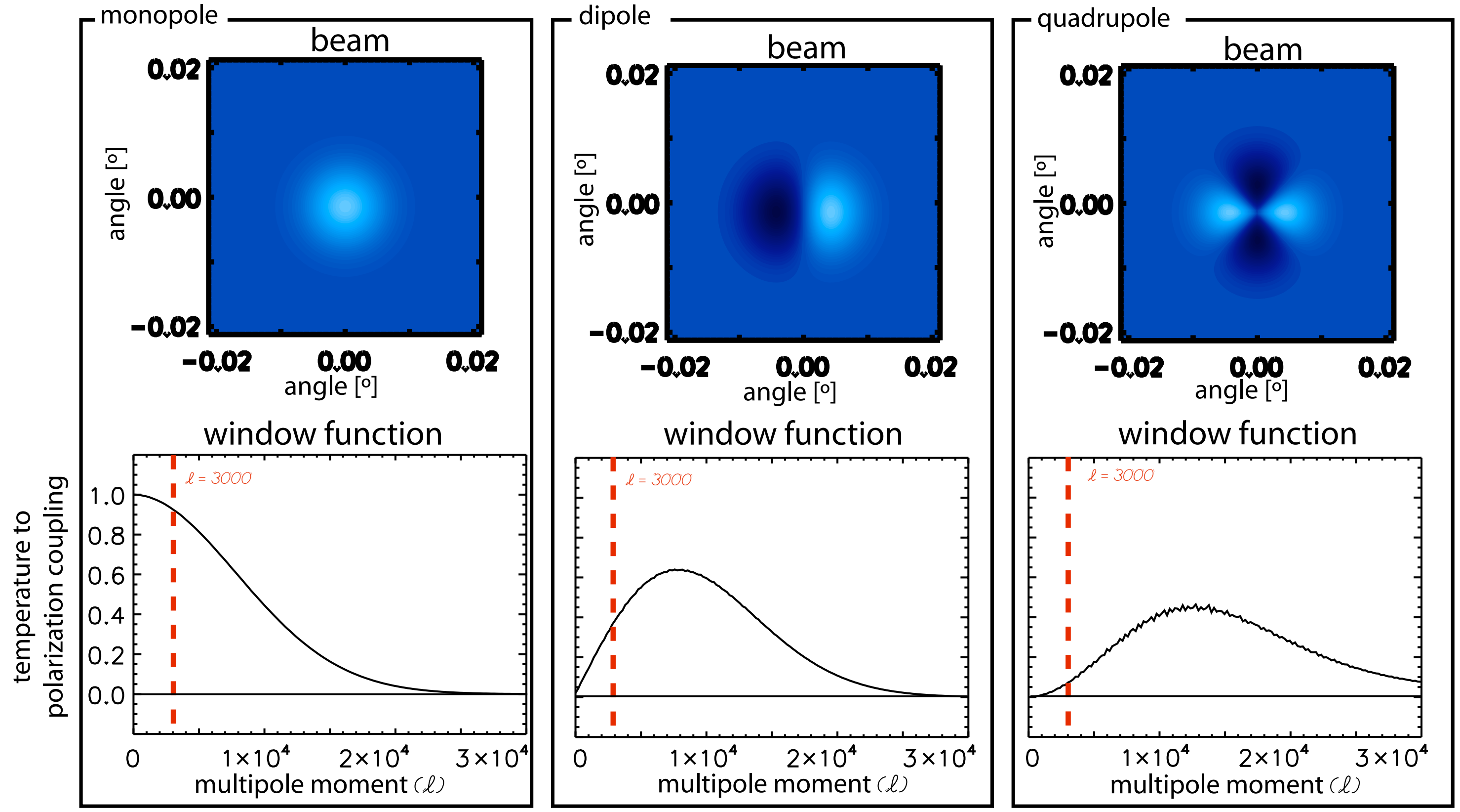


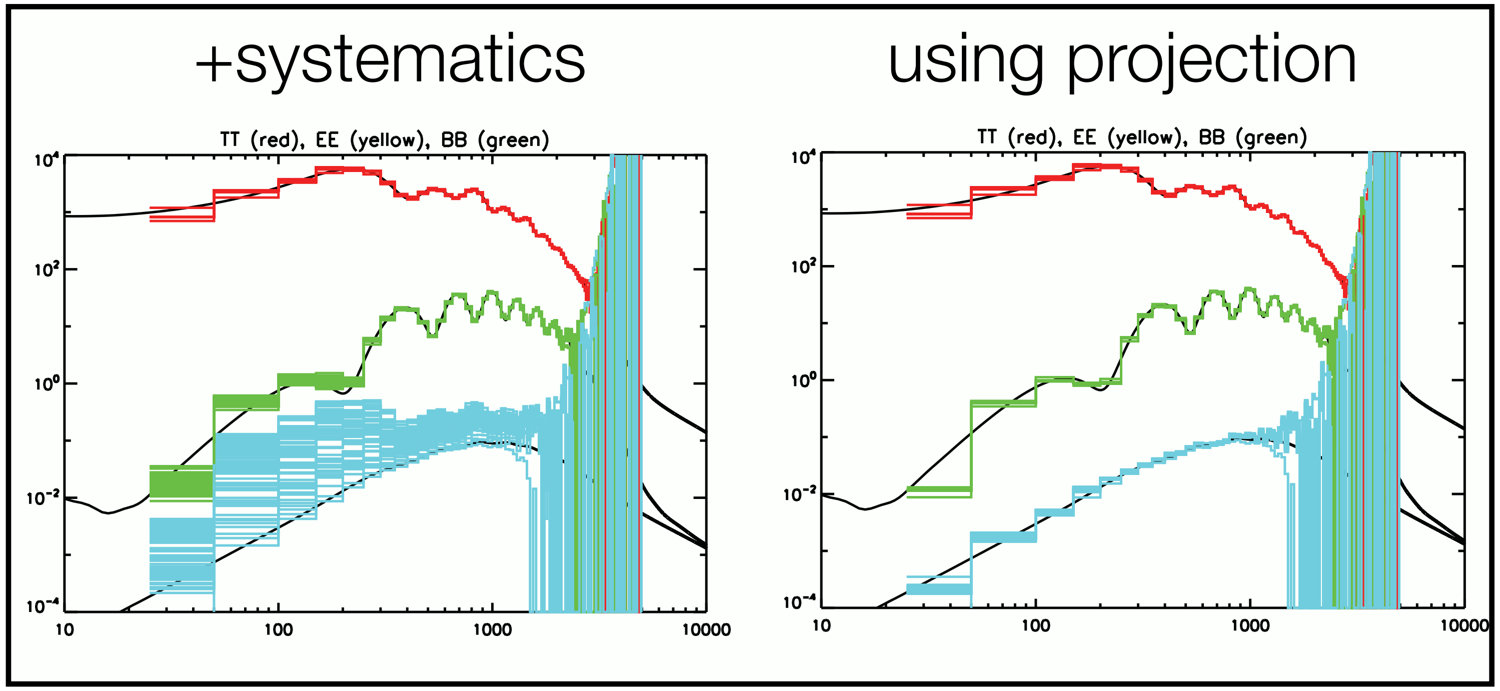
systematics add noise power

First pass requirements are ~0.1° on detector angles and <0.1% on T->P leakage. Looks hard. But is it?

I->P leakage (not a problem)

- dipole and quadrupole leakage
  - small beam size suppresses these effects at the scales of interest
- monopole leakage
  - projecting the T map from the Q and U map eliminates this systematic (also works for dipole and quadrupole)
  - sky rotation in chile helps, but this shows these effects can be controlled with little loss





Detector angles (not a problem)

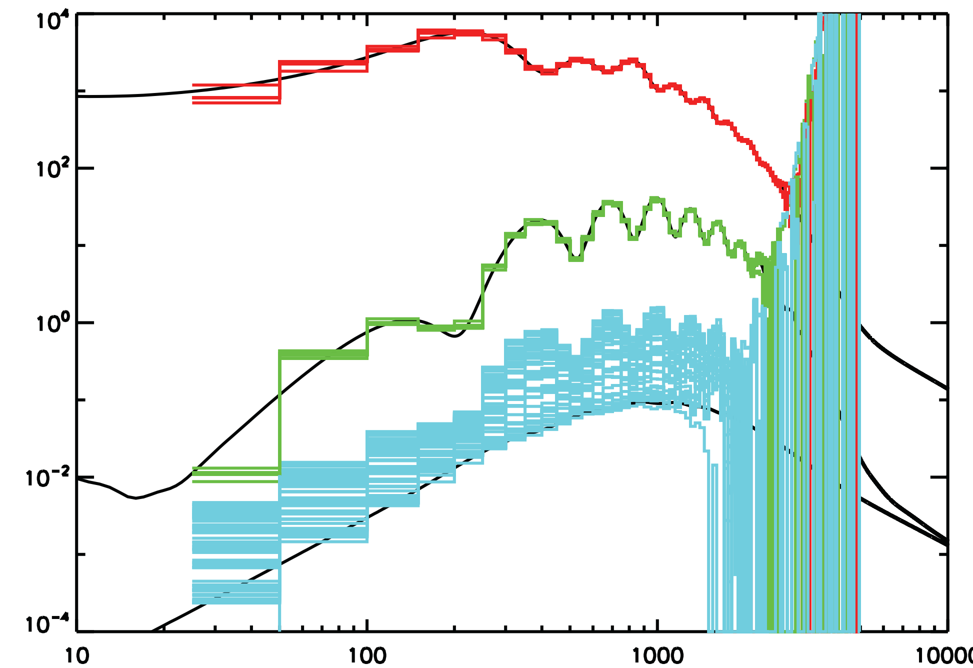
- calibration to 1° with astrophysical sources is easy
- <EB> provide an internal calibration

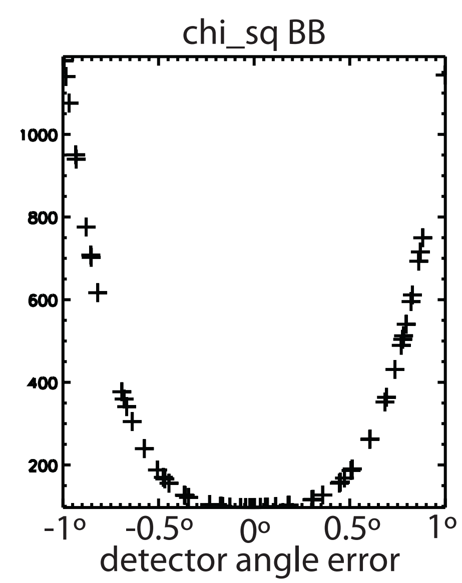
$$< EB >_m = < EE > \cos(\theta_\epsilon)\sin(\theta_\epsilon)$$

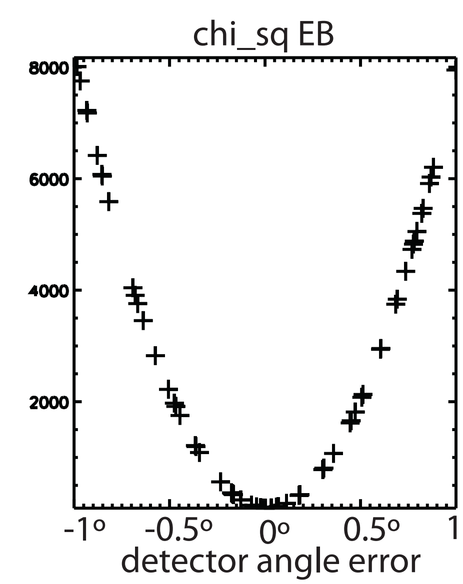
$$< BB >_m = < BB > \cos^2(\theta_\epsilon) + < EE > \sin^2(\theta_\epsilon)$$

  - Key fact: EB is first order, BB is second order in detector angle errors
- loose sensitivity to global rotations below 1°, but this shouldn't compromise other science goals
- **SPTpol will use a tower to calibrate to 0.1°**

Simulations of this internal calibration method



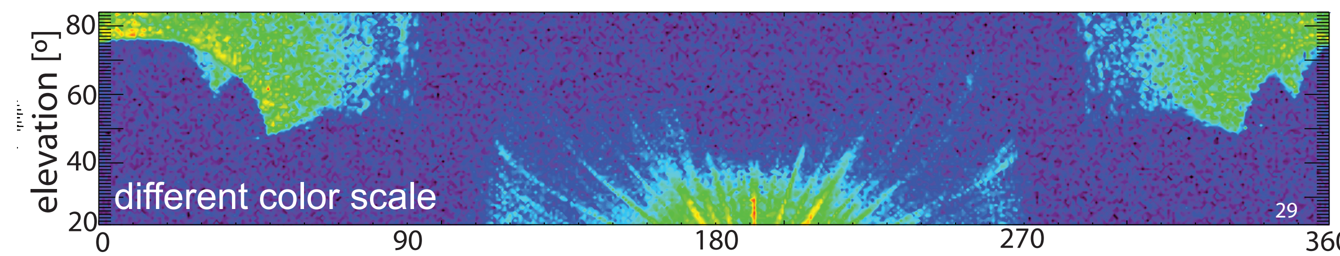




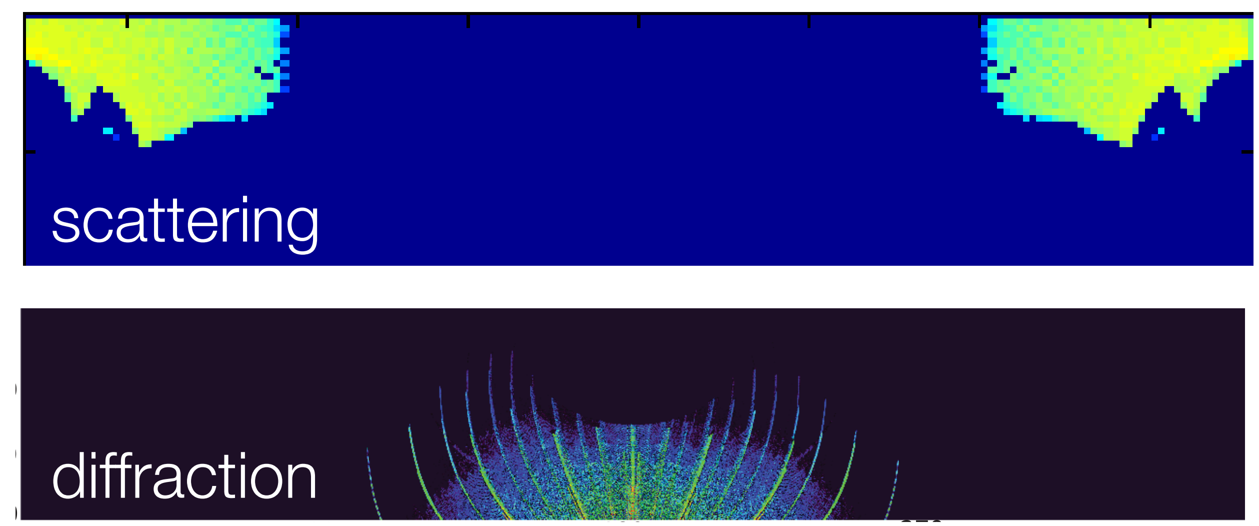
controlling ground pickup (SPT as an example)

- Ground pickup comes from light that is scattered or diffracts into the beam
    - this can be measured, modeled, and mitigated
    - expected improvement ~100x suppression in scan synchronous signals

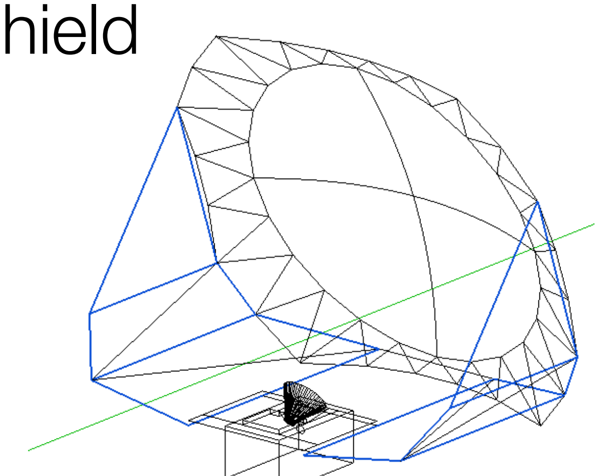
measurement

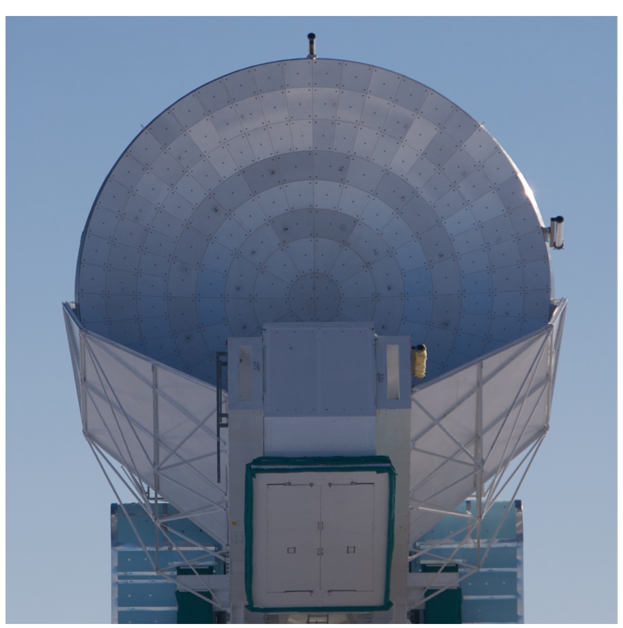


simulations



mitigation: new ground shield
(eliminates scattering)





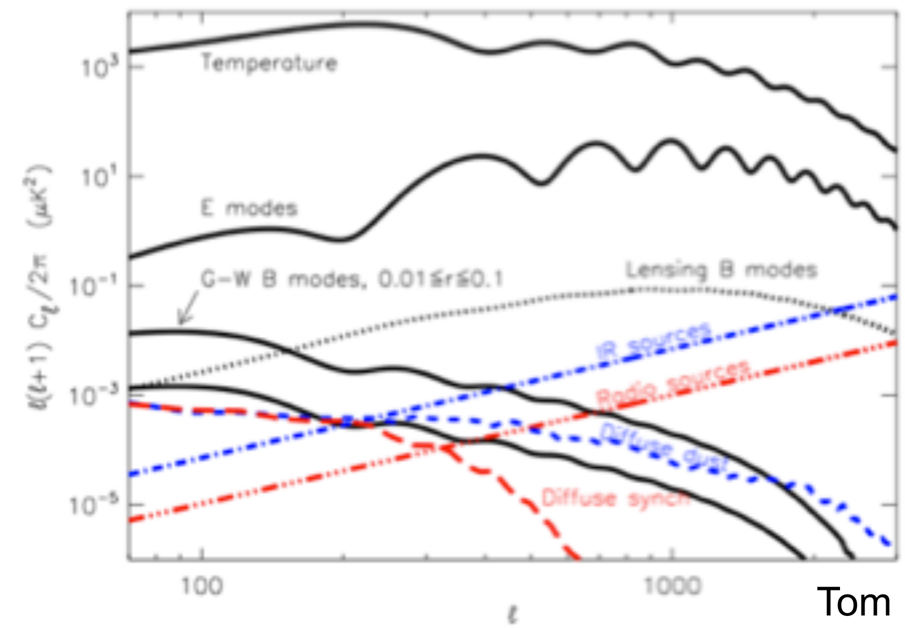
with Jared Mehl (U Chicago)

Foregrounds: SPTpol version

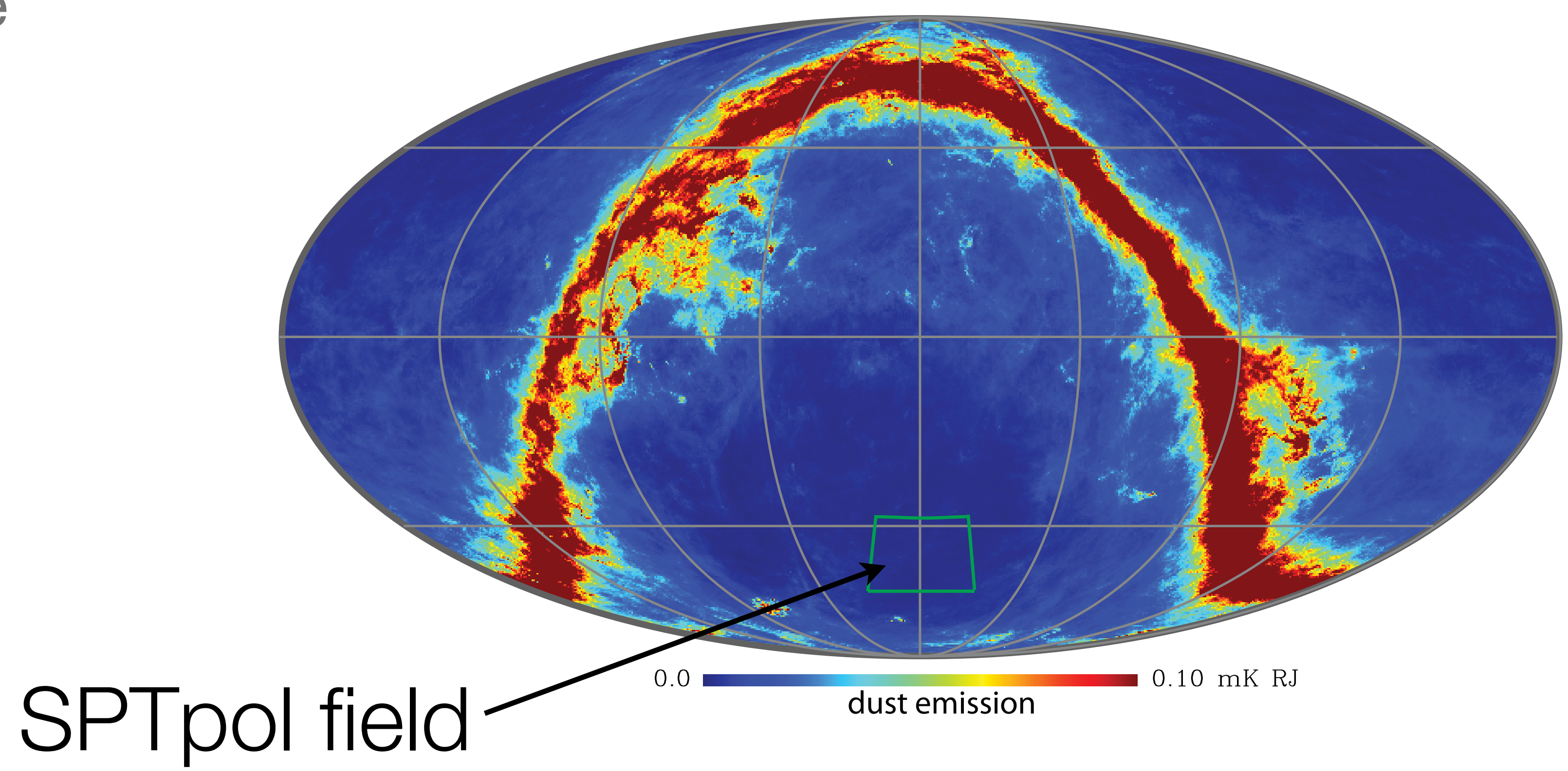
- at small angular scales points sources are expected to be the dominant foreground, but only ~1% polarized, shouldn't be a show stopper

- at larger angular scales dust may be a problem, but there are very clean patches that are projected to be clean down to T/S = 0.01

- SPT is optimized to measure BB from ~50 to ~2000

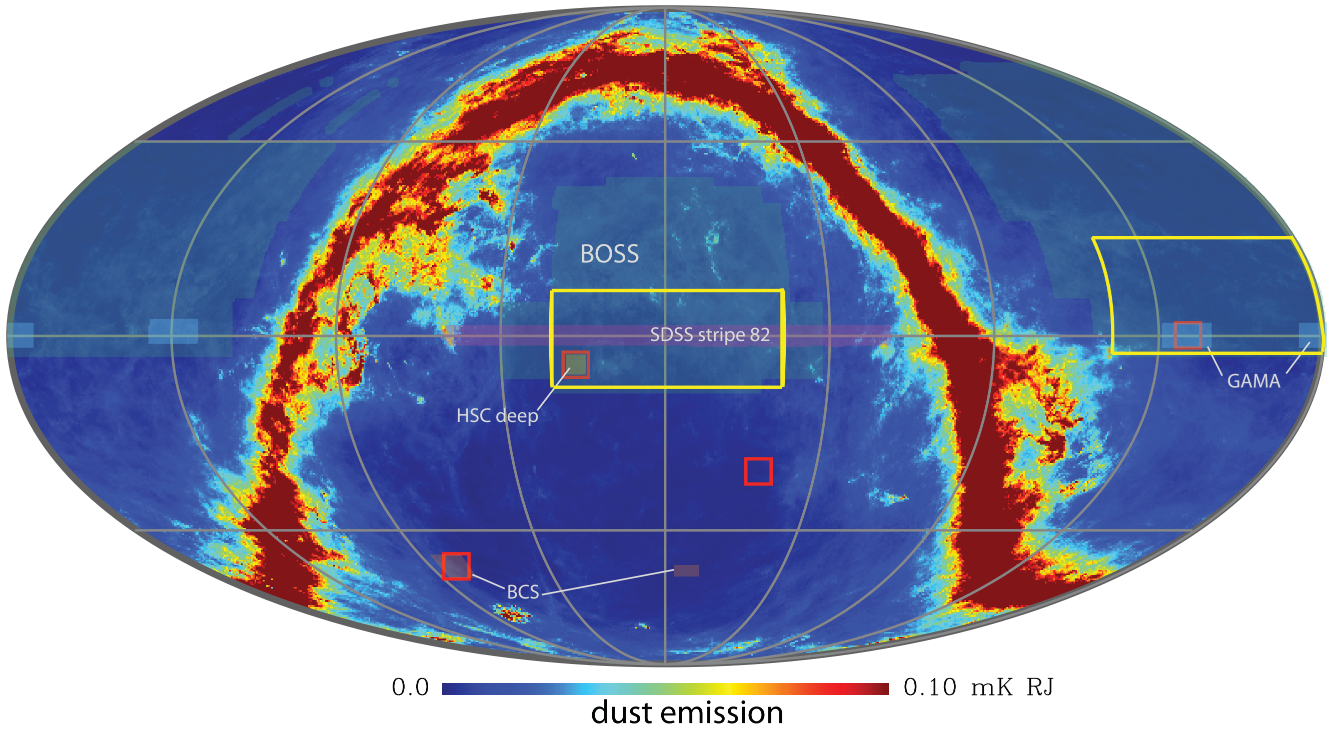


Tom Crawford



Foregrounds: ACTpol version

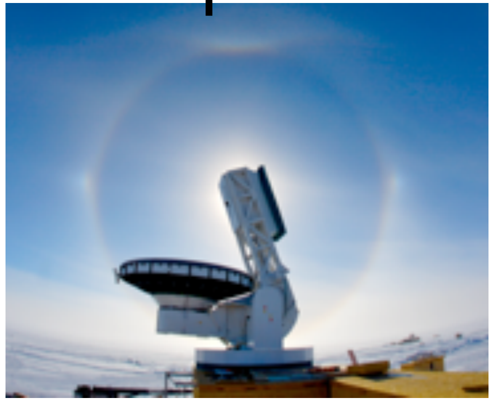
- Optimized for lensing and cross-correlation science
  - wide fields
  - deep fields
- IR sources expected to be the dominant foreground, (but not at a limiting level)
- cross correlations with BOSS and HSC provide a wide variety of exciting measurements and additional insulation from foregrounds



Requirements for a lensing measurement

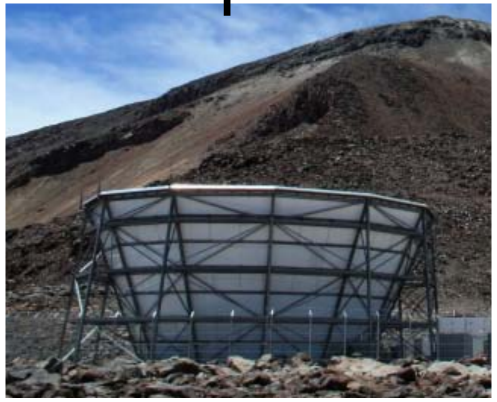
- High resolution
- control of systematics
- lots of sensitivity

SPTpol



- Beam ~1.2’

ACTpol



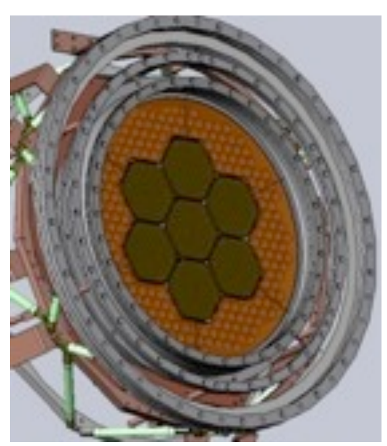
- Beam ~1.5’

Requirements for a lensing measurement

- High resolution
- control of systematics
- lots of sensitivity

SPTpol

- Beam ~1’
- new camera (late 2011)
  - 588 pol. @150 GHz (Truce)
  - 192 pol. @ 90 GHz (Argonne)

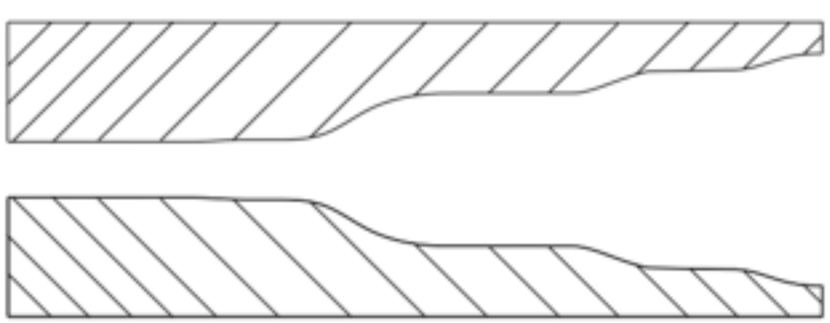


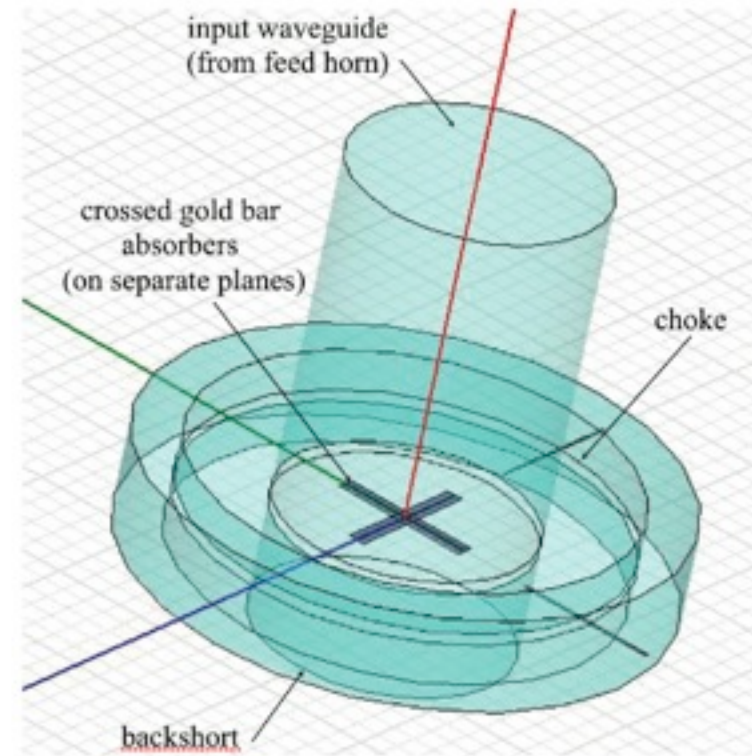
ACTpol

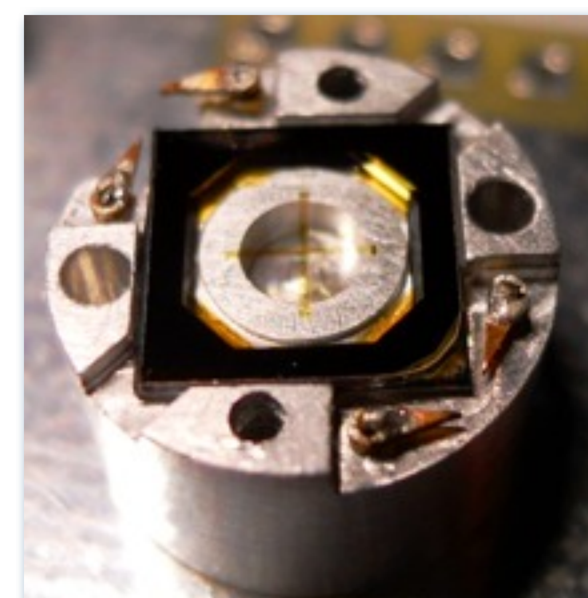
- Beam ~1.6
- new camera (mid 2012)
  - 1024 pol. @150 GHz (Truce)
  - 256 horn. multi-chroic array @ 90 and 150 GHz (Truce)

90GHz detectors for SPTpol (Argonne National Lab)

- a simplest and extremely robust polarimeter design
- excellent coupling ~90%
- low cross polarization <1%
- excellent beam properties (contoured feed horn)
- (some assembly required)

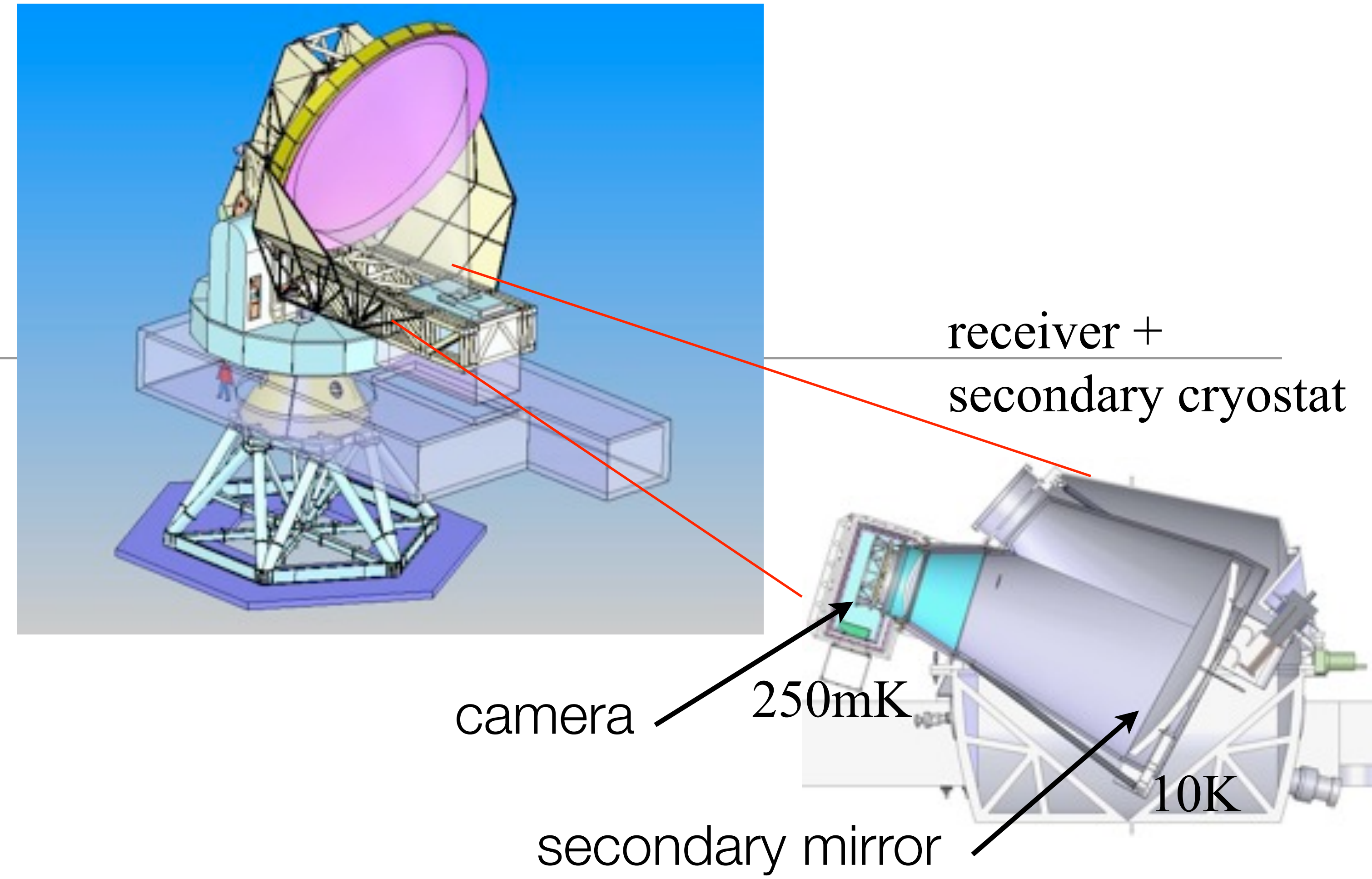




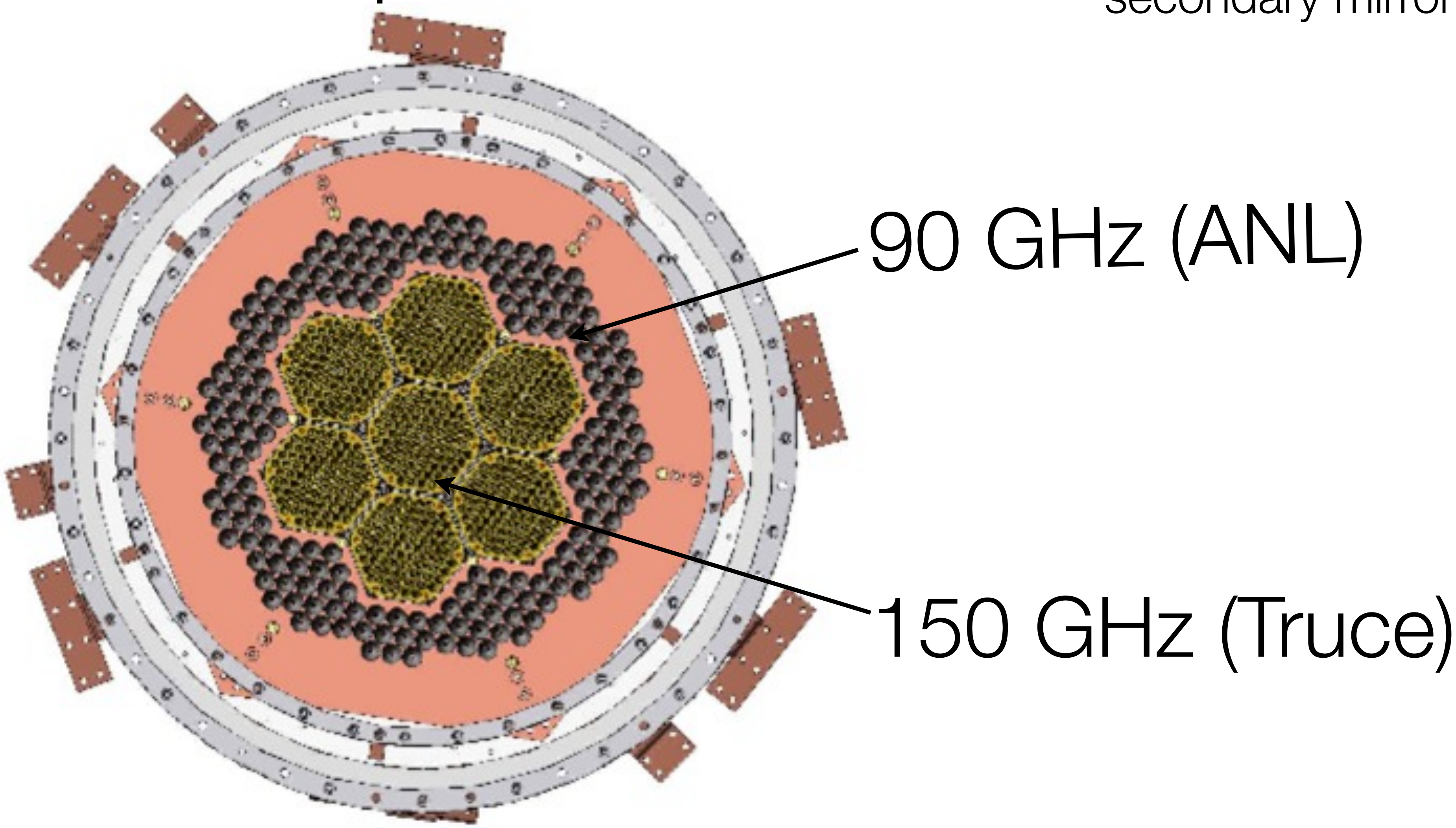


SPTpol focal plane

- new focal plane, but no major changes from SPT design

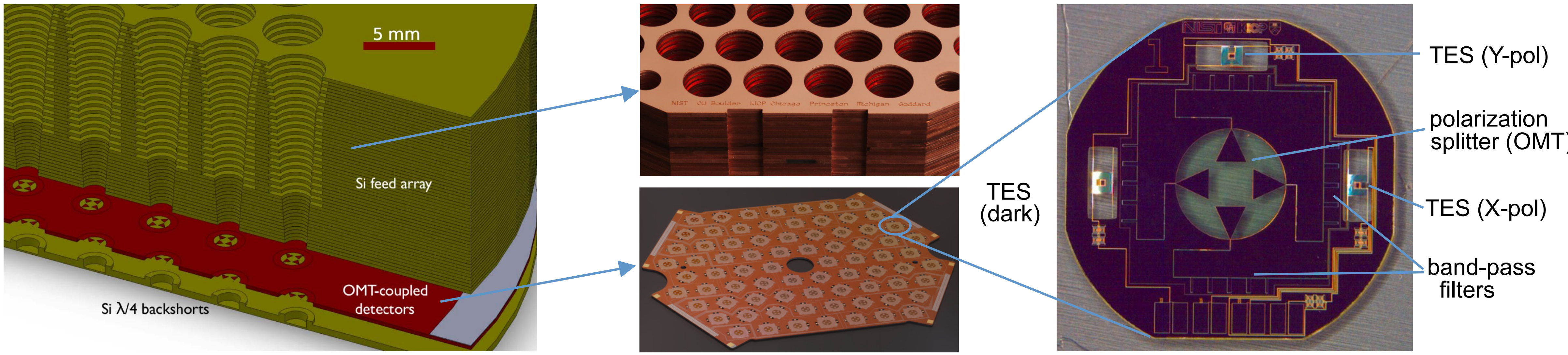


new focal plane



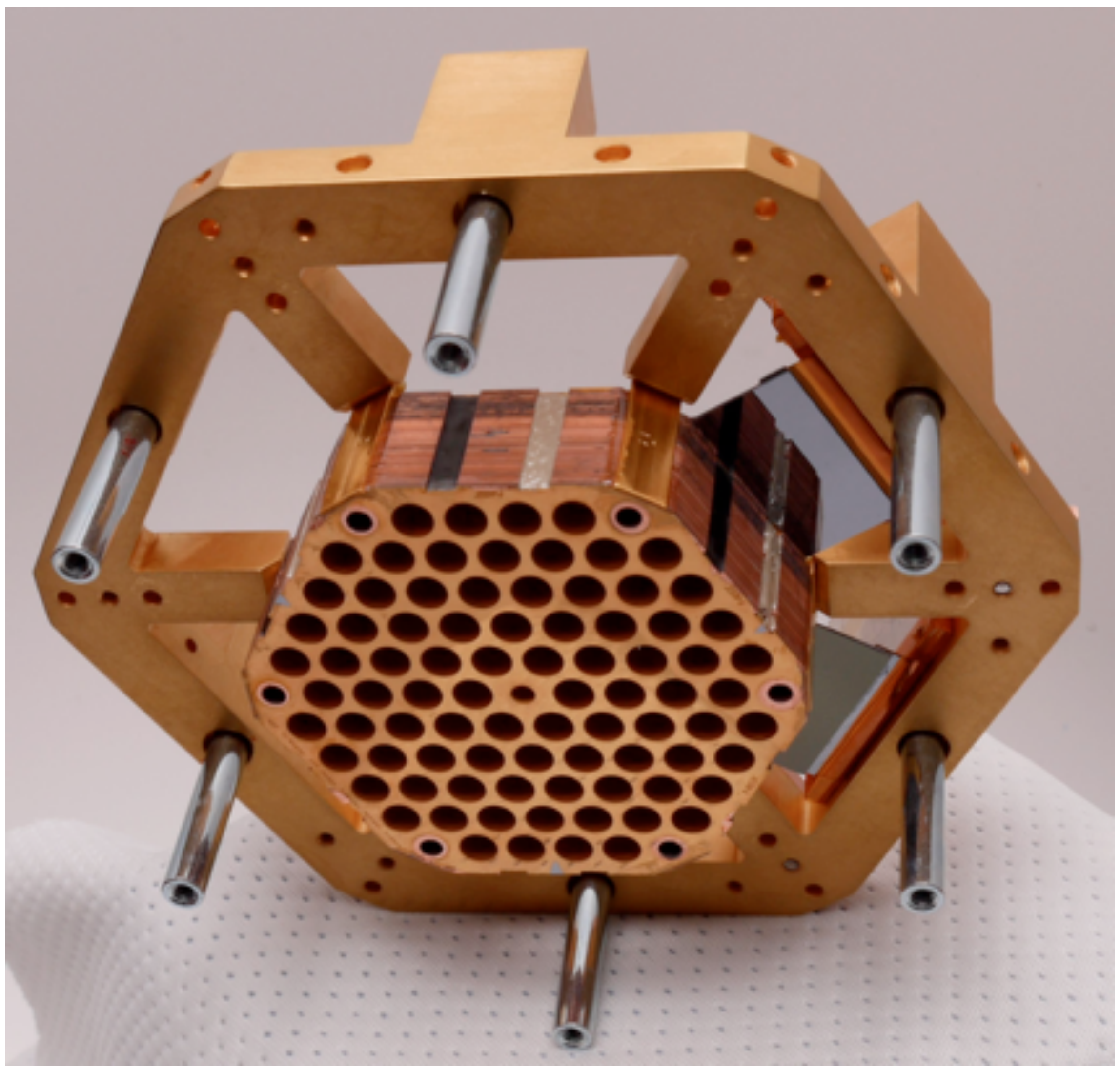
Truce Polarimeter Development

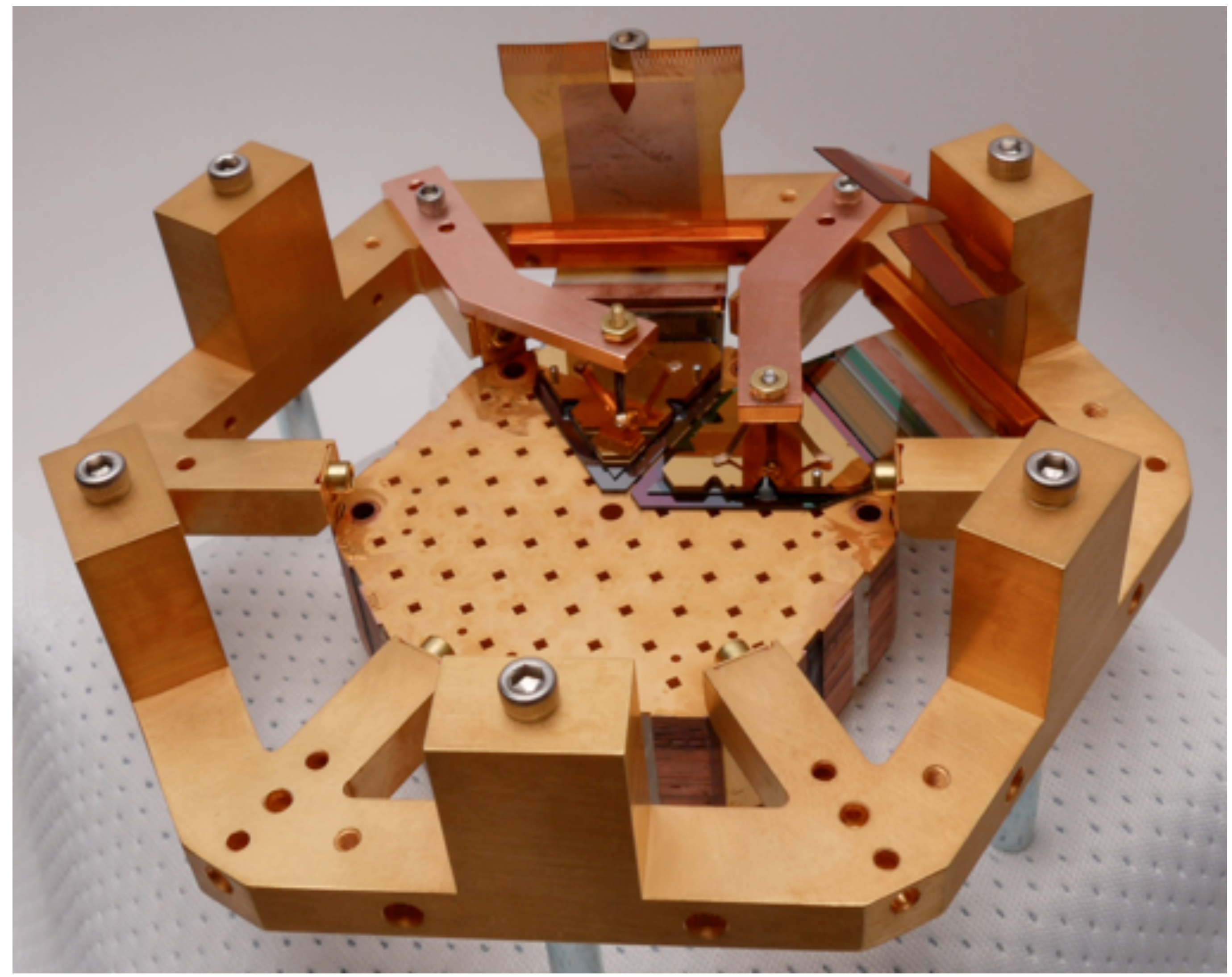
Detector array concept | Prototype array | Polarimeter



- Feedhorn coupled TES polarimeter arrays
- Extensive Prototype testing
  - Bandpass is on target
  - Wafer uniformity is sufficient
  - Noise is consistent with thermal background
  - The hair:
    - coupling ~55% working to improve dielectric
    - out of band leakageBlue leak solution: LPF & absorber

Pictures of the prototype array

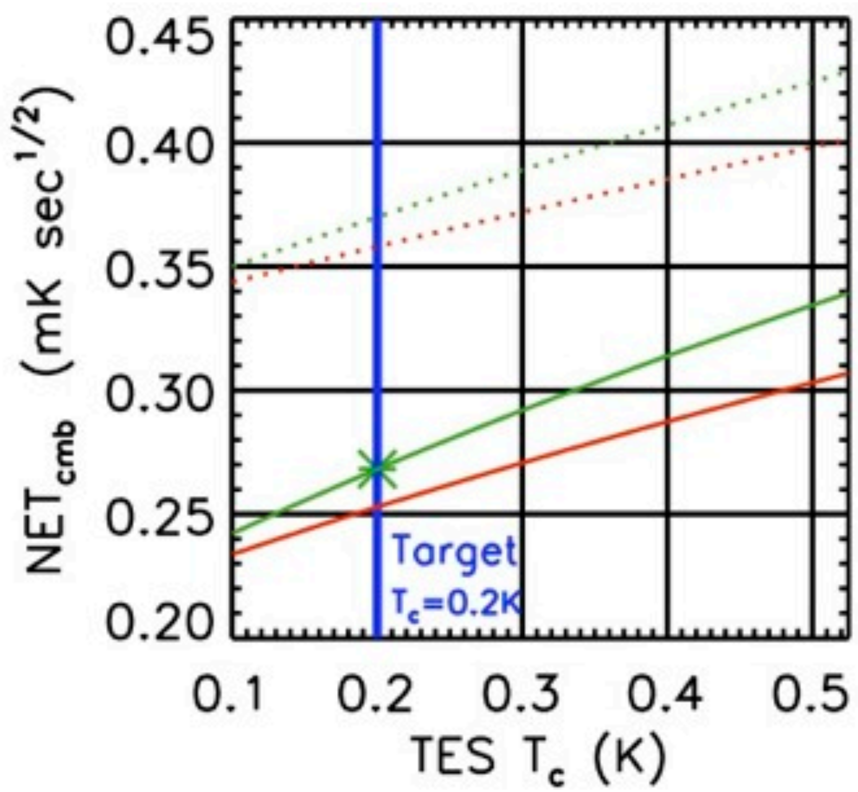


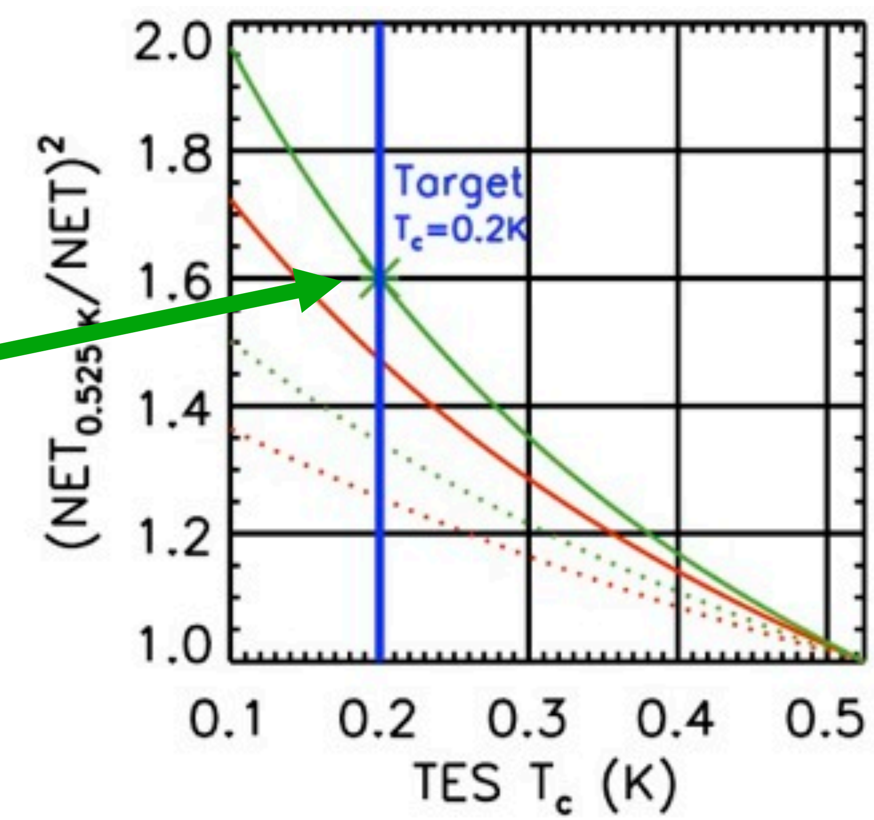


Noise vs. Detector Temperature

- Noise calculation
  - Bose, shot, and G noise
  - ACTPol optics + 0.7 detector efficiency
  - Median ACT PWV ~ 0.5 mm for two saturation powers
- What happens when you drop T_{bath} and T_c?
  - Noise drops steadily
  - T_c ~ 0.15 K increases mapping speed by ~70% of T_c ~ 0.5 K

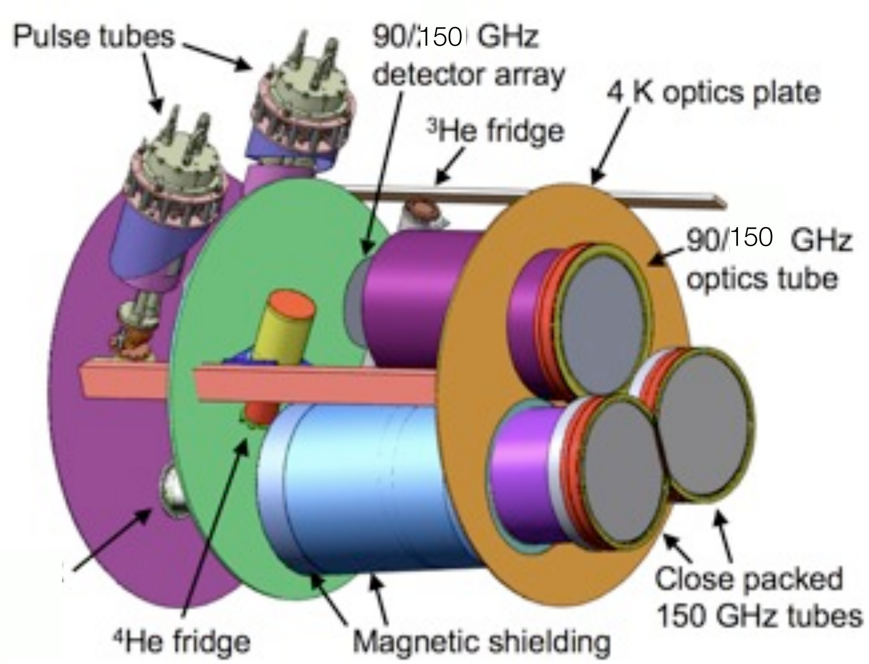
ACTPol using a dilution fridge for T_{bath} ~ 90 mK and T_c ~ 0.15 K



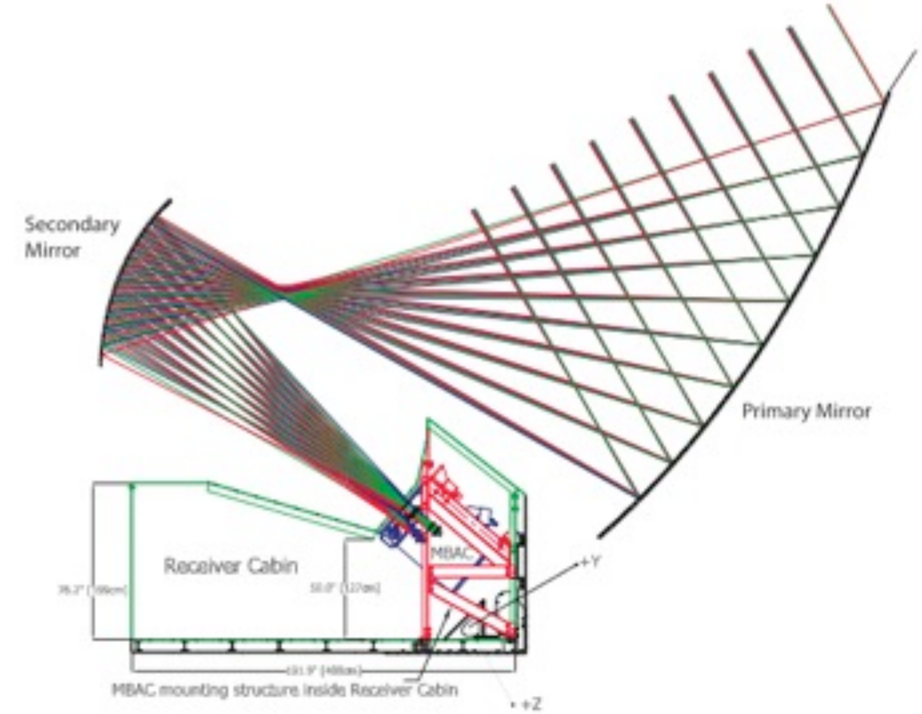


ACTpol dilution insert

- Jannis
- ~100 uW of cooping at 90 uK
- pulse tube backed
- Not shown: computer controlled gas handling system with “get cold button”

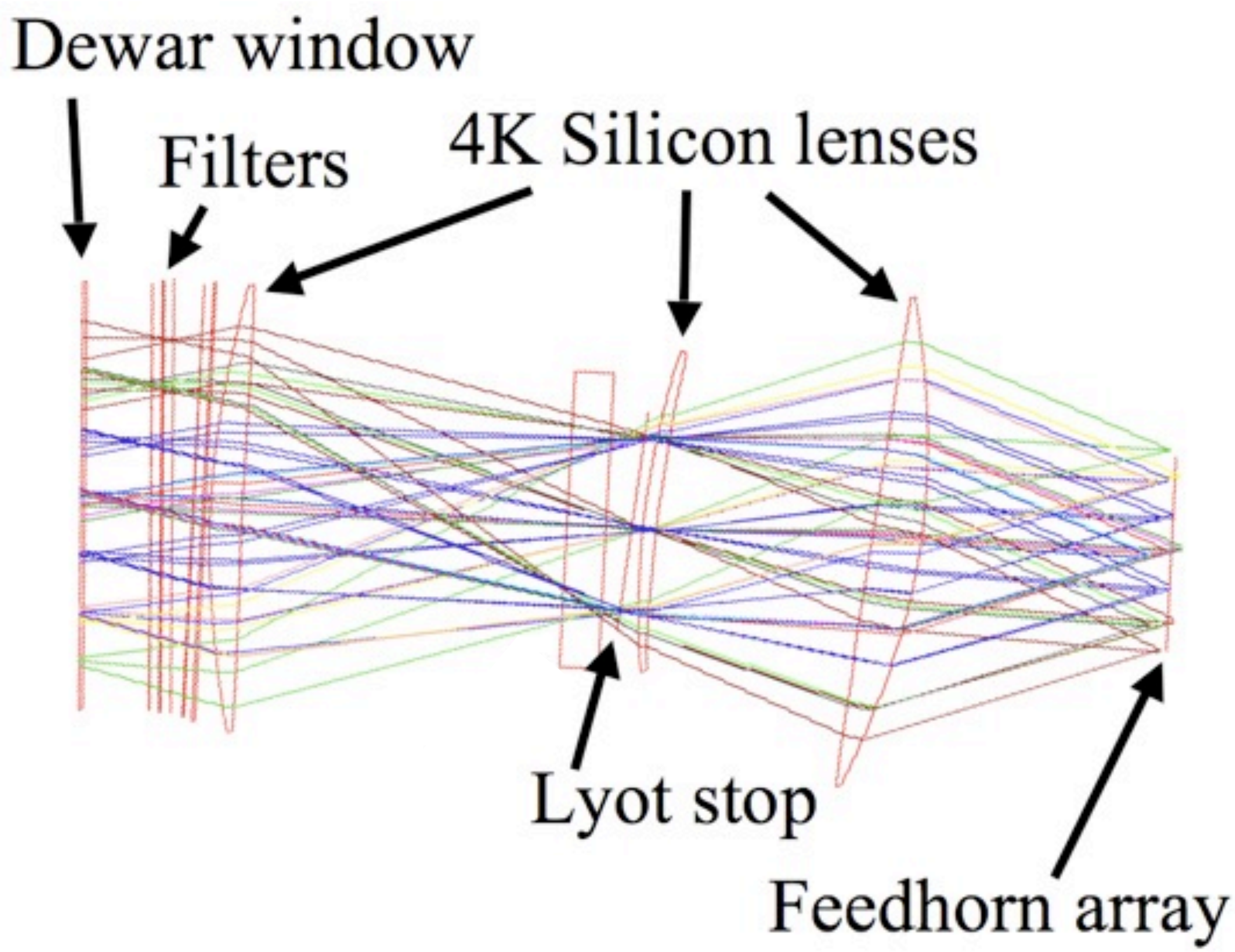


Optical design (ACTPol)

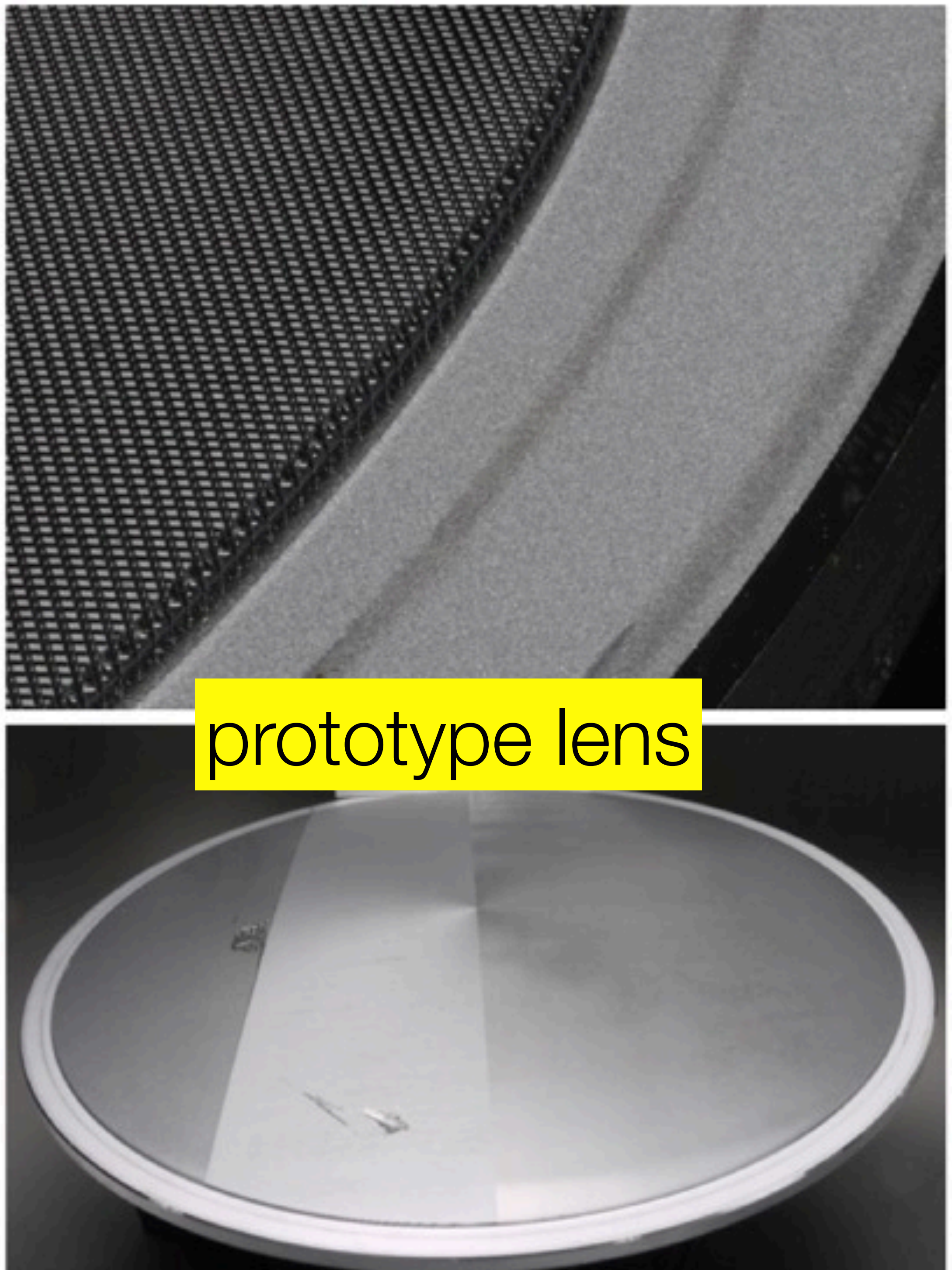


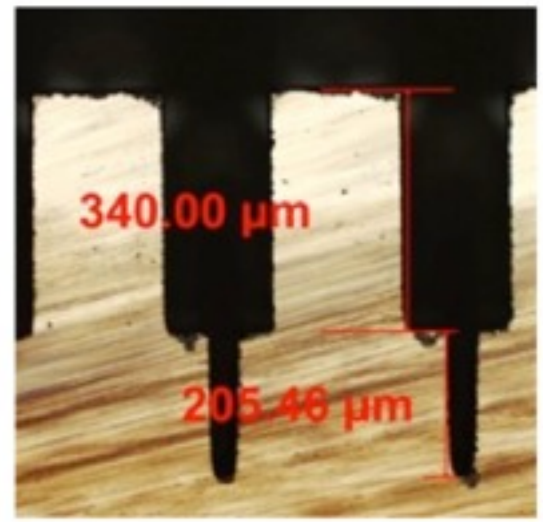
Three independent optical paths

- Two 150 GHz optical paths
- 90/150 multi-chroic array

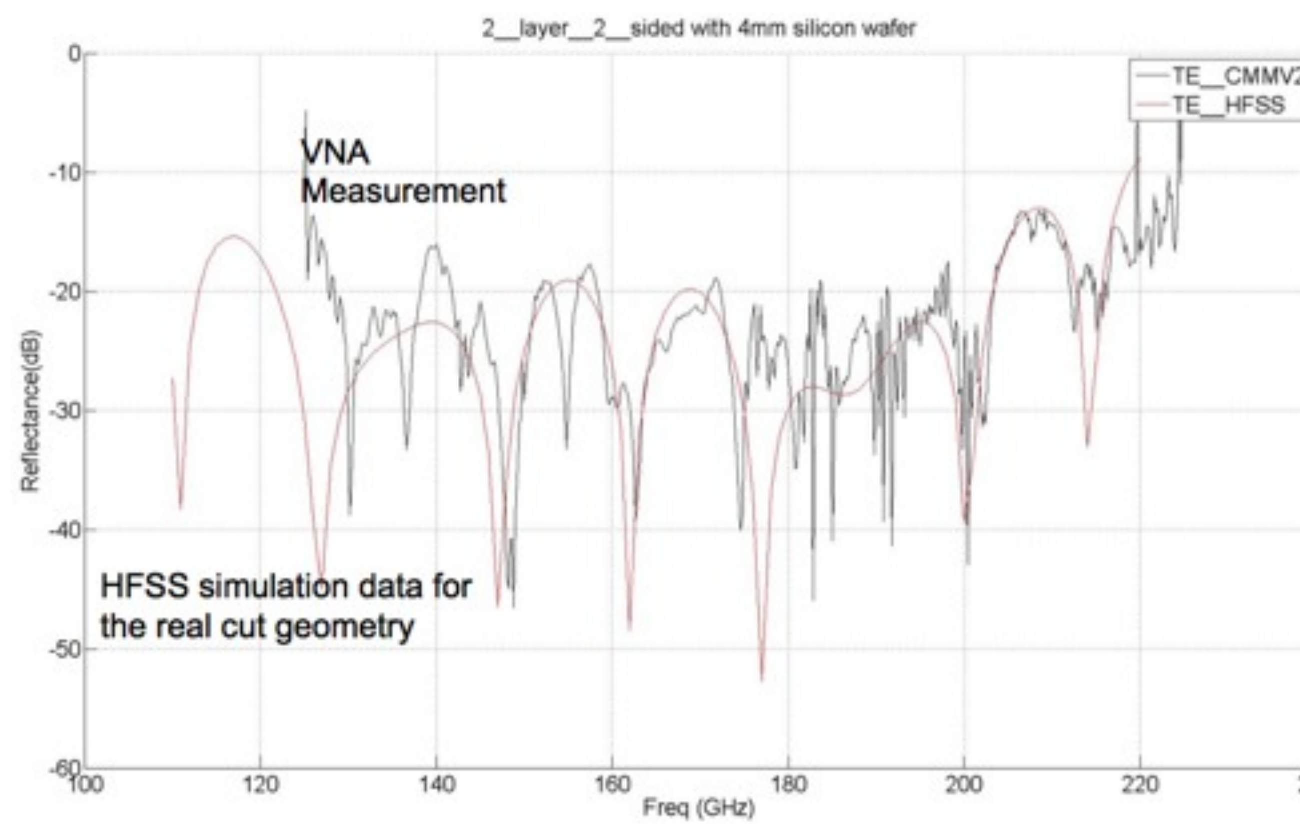


Two layer machined AR coating on Silicon



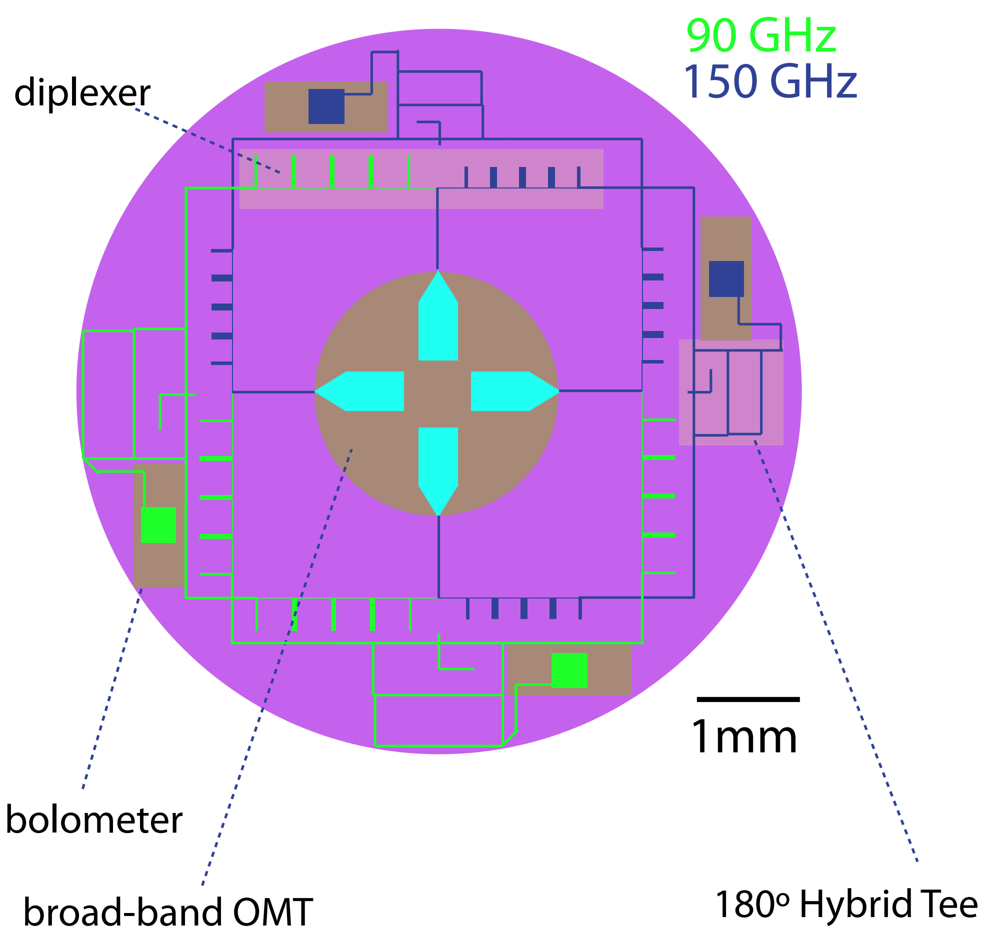


- control reflections to ~0.1%
- octave bandwidth possible
- ~10 µ precision

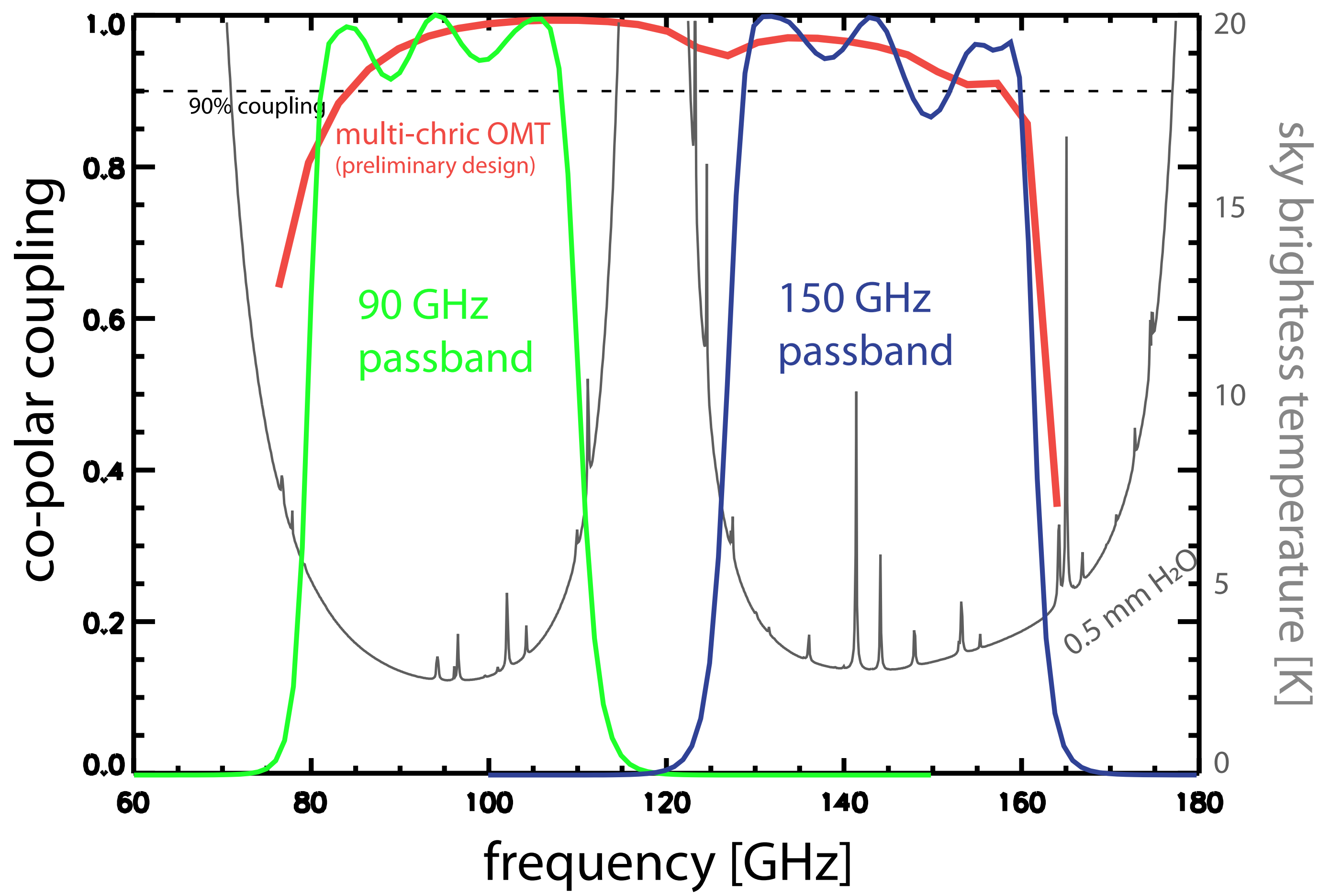


The Third ACTPol Array (multi-chroic 90/150)

multi-chroic detector layout



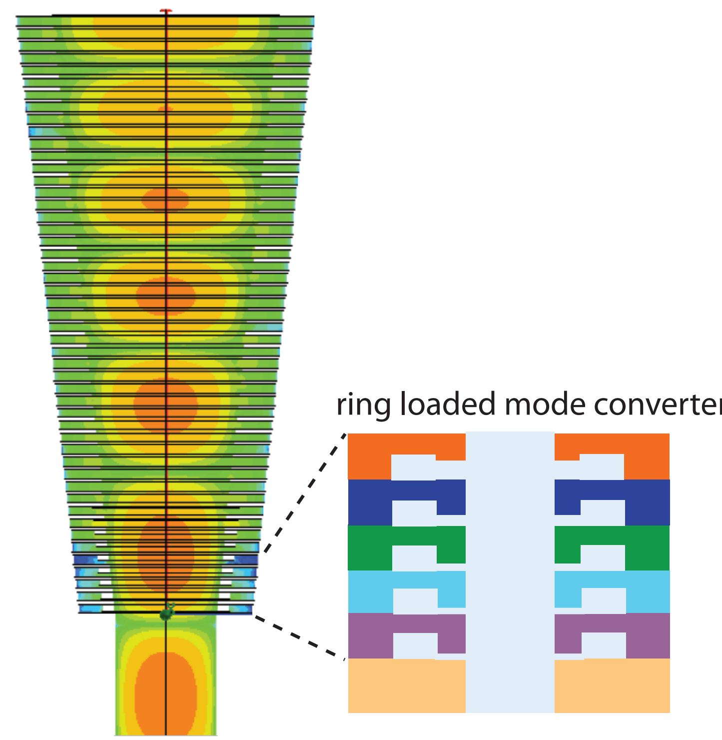
simulated performance

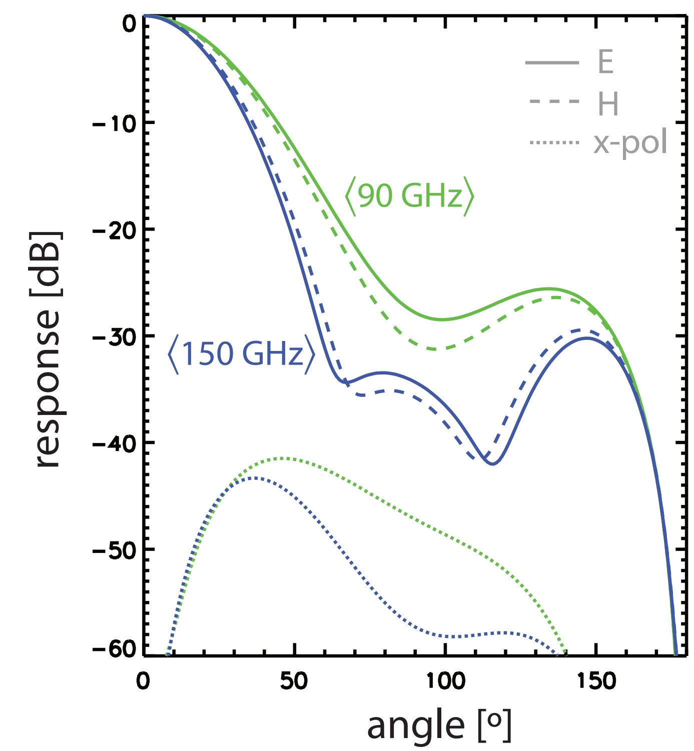


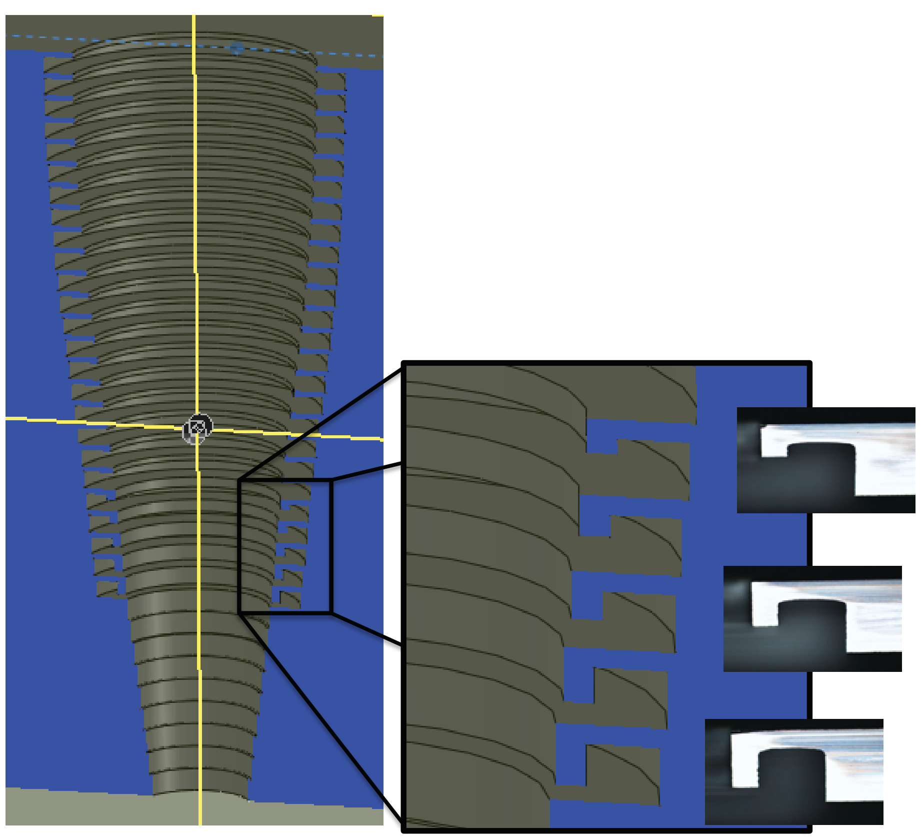
- Optimal mapping speed at 90 GHz
- 150 GHz mapping speed = 0.75 of an optimal single frequency array (since horn size was optimized for 90GHz performance)
- improves lensing signal to noise
- Prototypes early this summer
- Goal: array in 2013

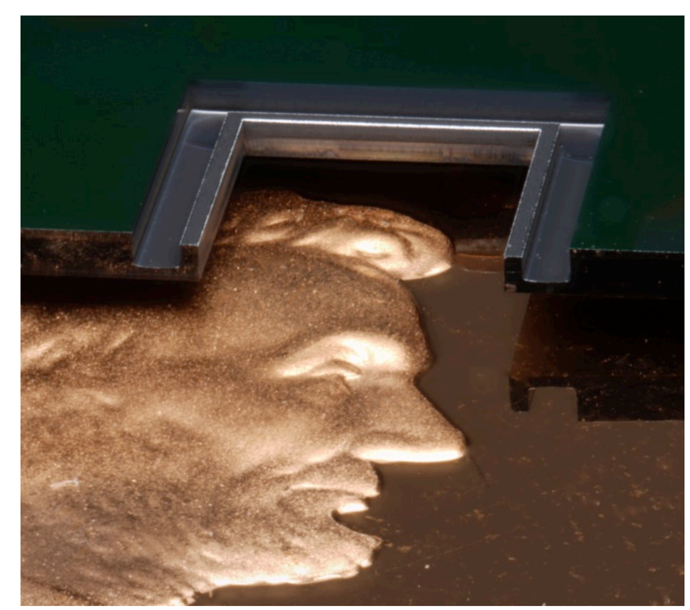
Wide Band feed horn

- ring loaded throat offers sufficient band-width
- easy to manufacture as a platelet array



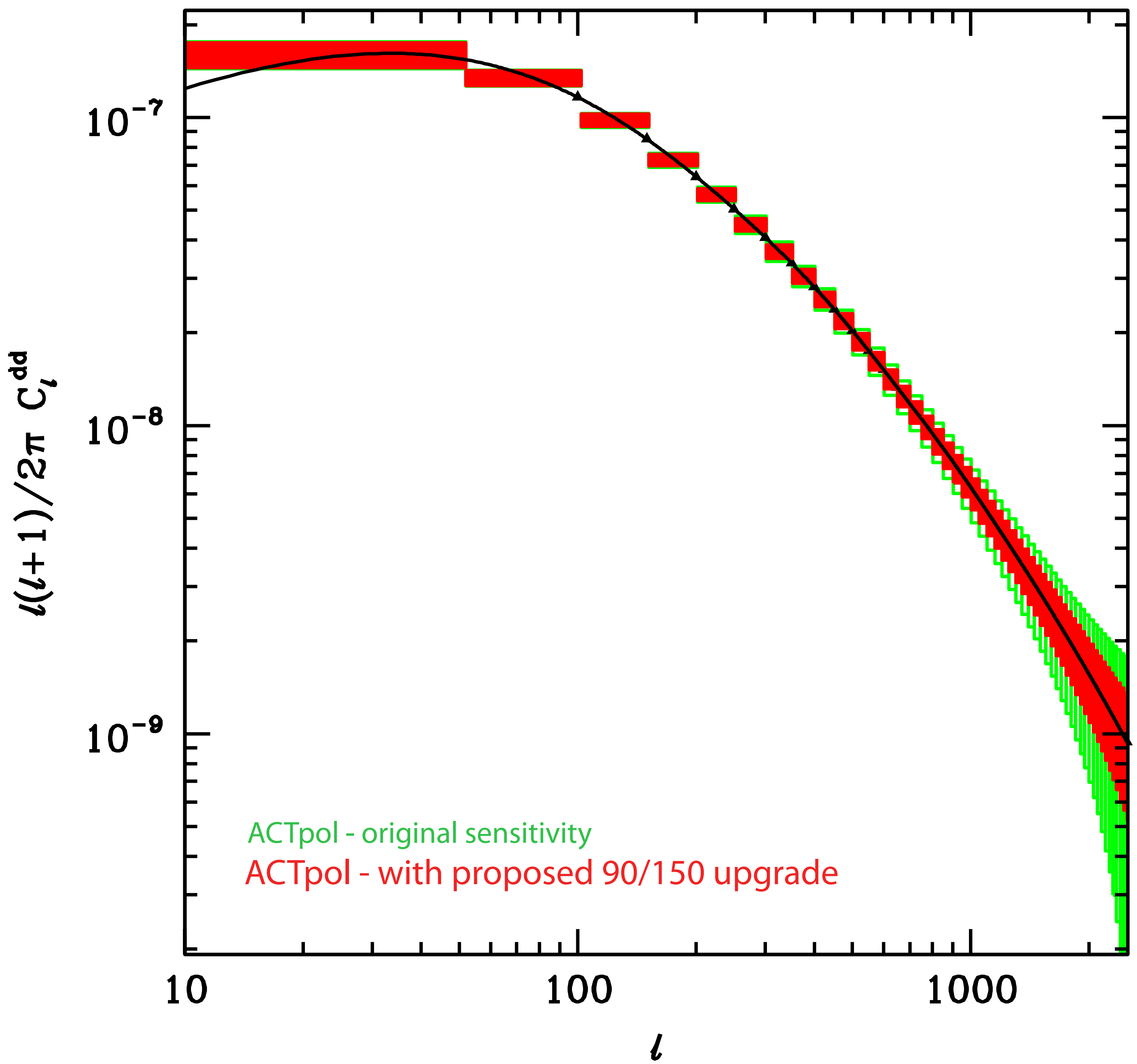




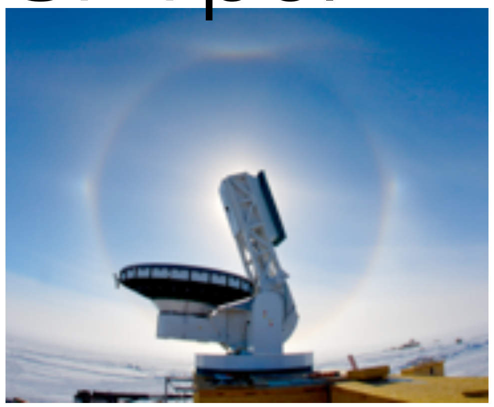


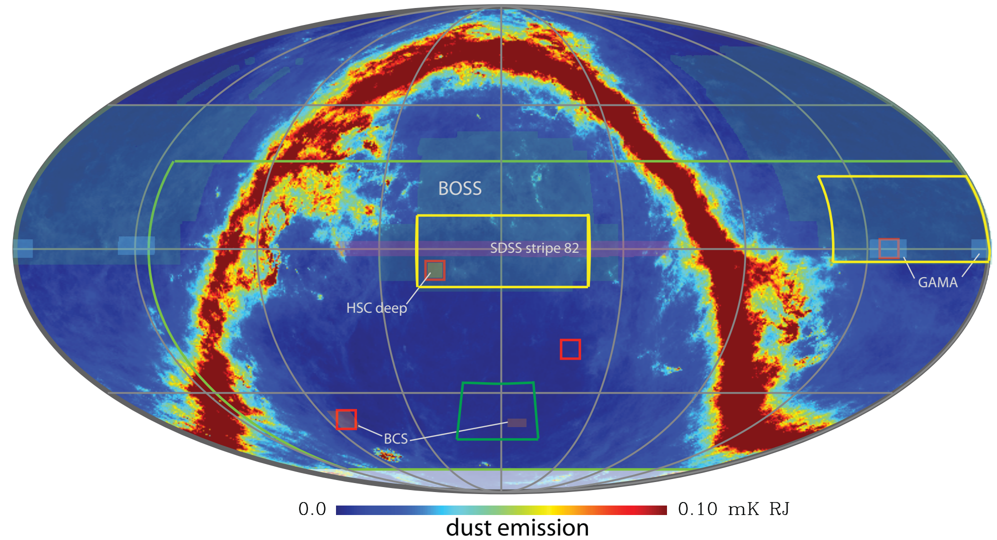
Lensing Science impact of multi-chroic array

- Boosts ACTPol mapping speed
  - by ~1.65 (compared to original 150/150/220 plan)
  - (150 GHz mapping speed by 1.37)
- improves neutrino constraints
  - from lensing to ~0.05eV from 0.07
  - improves cross-correlation measurements from 0.05 to ~0.035

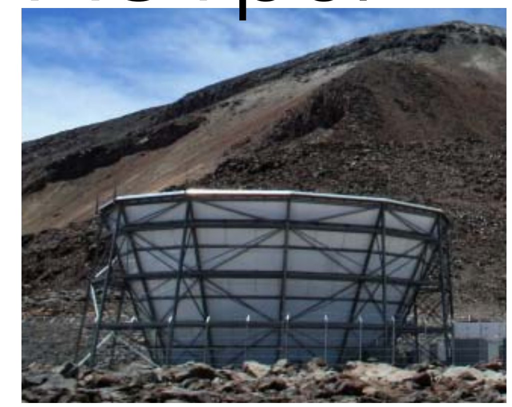


SPTpol

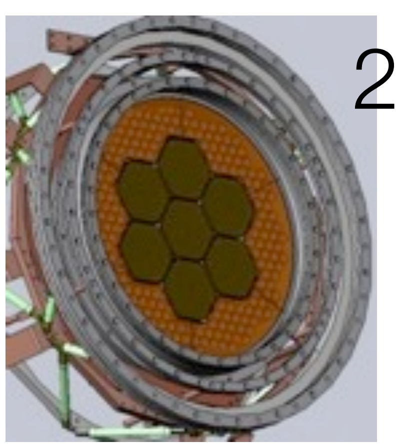




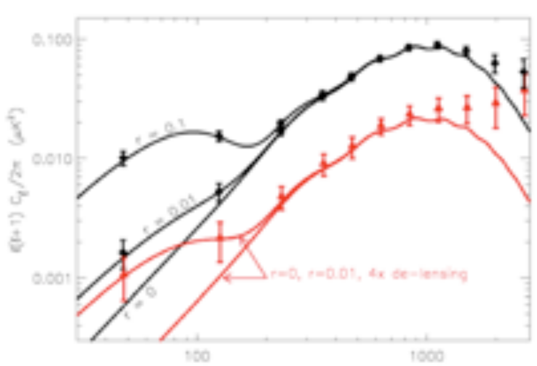
ACTpol

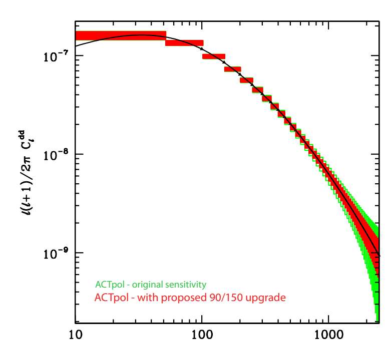


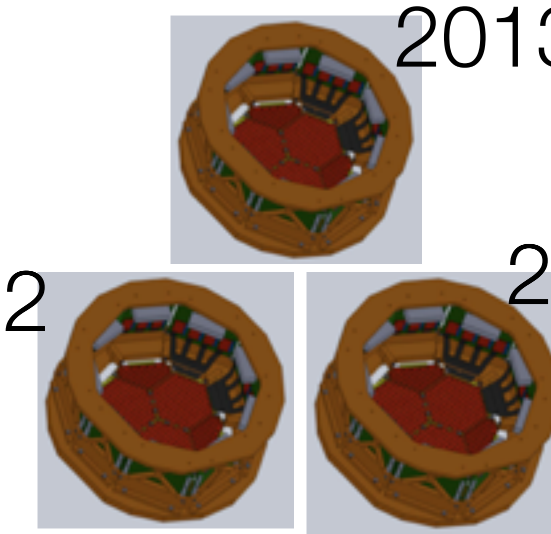
2012 a exciting year for lensing science



2012







2013

2012

2013