Next Generation Radio Arrays:
CMB and Early Universe Astrophysics

Steven T. Myers

National Radio Astronomy Observatory

Socorro, NM

Cosmology Questions

- How was the Universe born, how did it evolve, and what is its future?
- What is the dark sector – "dark energy" and "dark matter" – made of?
- What happened during the cosmic "Dark Ages"?

from Report of the Radio,Millimeter, and Submillimeter Planning Group (RMSPG), Oct 2005

also see Connecting Quarks to the Cosmos

Key Events in the Early Universe

- Planck era – 10^{19} GeV
  - string gas era? extra dimensions?
- Inflation - 10^{15} GeV?
  - Reheating – create matter and radiation
- Baryogenesis – establish matter-antimatter asymmetry
  - coupled to phase transition? (GUT, EW)
- Nucleosynthesis – create light nuclei (H,He,Li,…) ~ 3min
- Matter-Radiation Equality (z~10000)
- CMB decoupling – recombination (z~1000) ~ 400,000yrs

- Relics: cosmic paleontology
  - radiation (CMB), neutrinos, gravity waves, scalar gravitational potential fluctuations, dark matter, dark energy, spacetime structure, exotica (defects, primordial black holes)

Where we are: 2006

2006 : The Big Mysteries

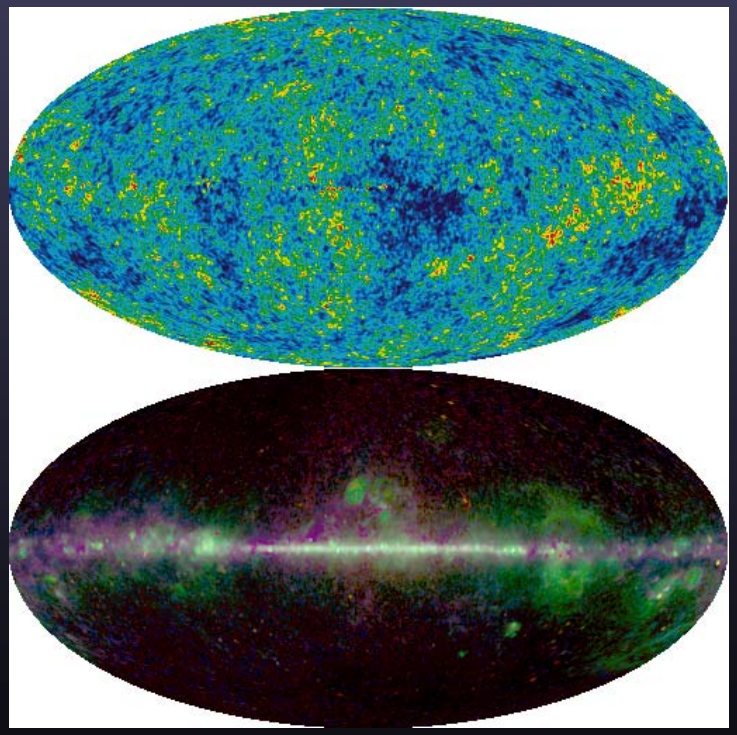
- Cosmography
  - CMB nearly isotropic, Universe nearly homogeneous
  - nearly flat geometry
  - Universe expanding, currently accelerating
  - 3 macroscopic accessible spatial dimensions
- Standard Cosmological Model – ingredients
  - 24% matter, 20% dark (higher in past?)
  - 76% “dark energy” (lower in past? or tracking?)
  - baryons subdominant, negligible anti-baryons
- Particle Physics
  - many candidates for Dark Matter! (WIMPs, axions)
  - neutrino oscillations (possible sterile species)
  - vacua poorly understood (why is Dark Energy so small!)

2006 – the players

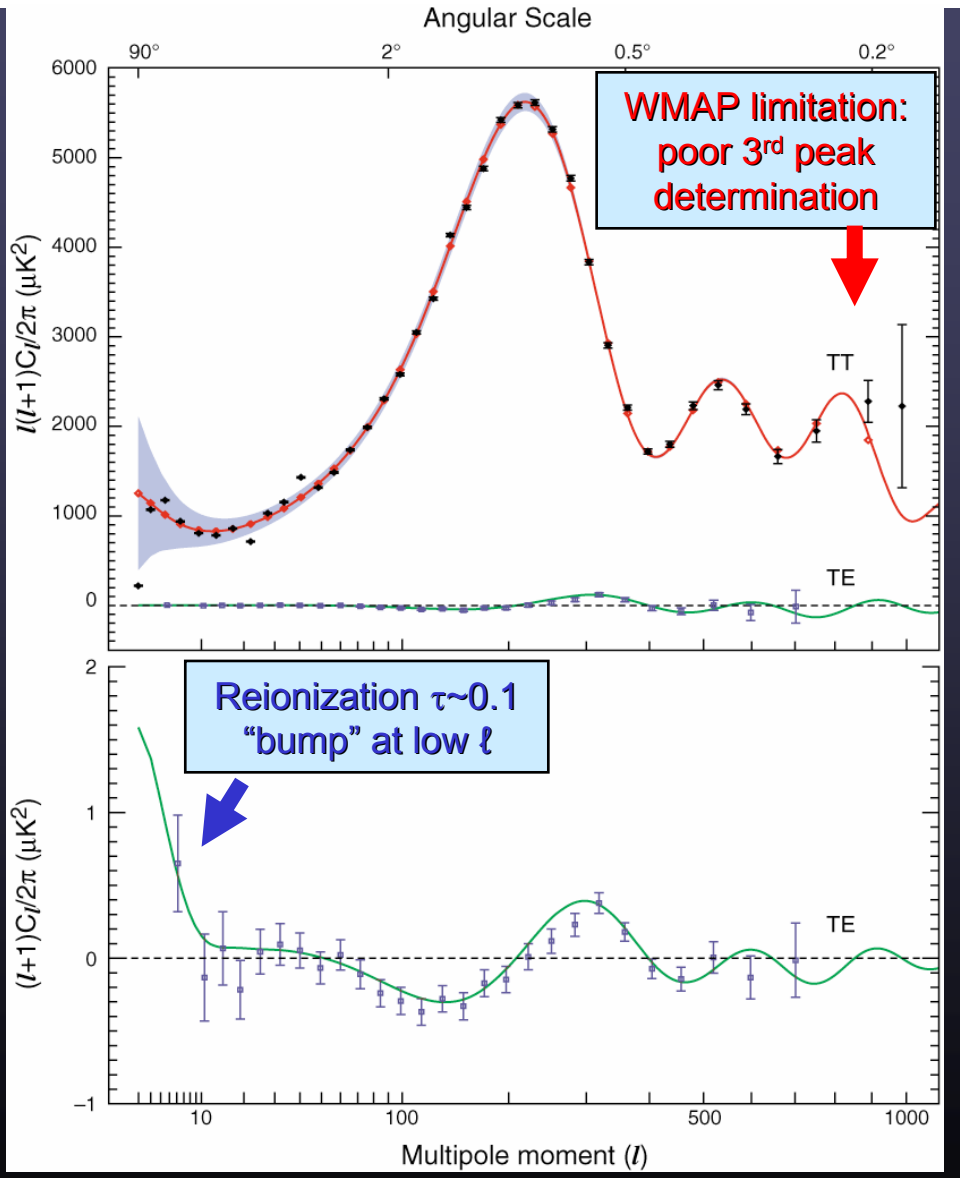
- CMB
  - WMAP plus balloon and ground-based (Boomerang, ACBAR, CBI)
  - snapshot of Universe at z=1000, in linear regime
- Large Scale Structure
  - SDSS and 2DF and Ly-α surveys
    - combine with CMB (e.g. ISW correlation)
  - weak lensing surveys (e.g. CFHT)
  - Xray and O/IR cluster surveys
    - allow measurement of "growth factor" ➔ cosmology
- Other
  - SNe-Ia measure current acceleration of Universe
  - dark matter searches, neutrino observatories
  - study dark matter in galaxies through lensing, velocities

State of the Art: WMAP 3-yr (2006)

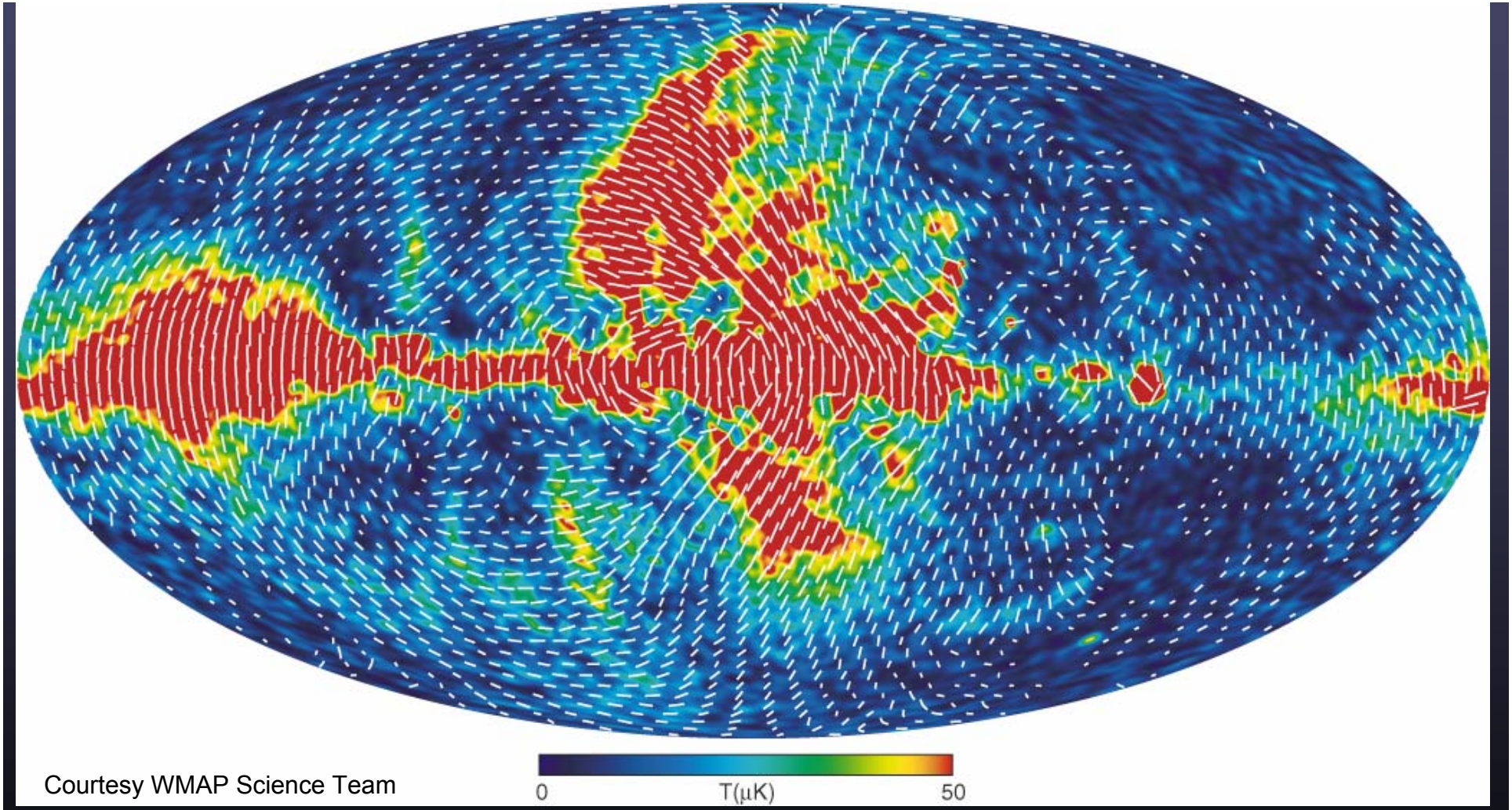
- Hinshaw et al. (2006)
- released March 2006
- TT & TE spectrum (right)
- ILC vs. 61GHz foreground model



Courtesy WMAP Science Team *http://lambda.gsfc.nasa.gov*



Danger Ahead - polarized foreground

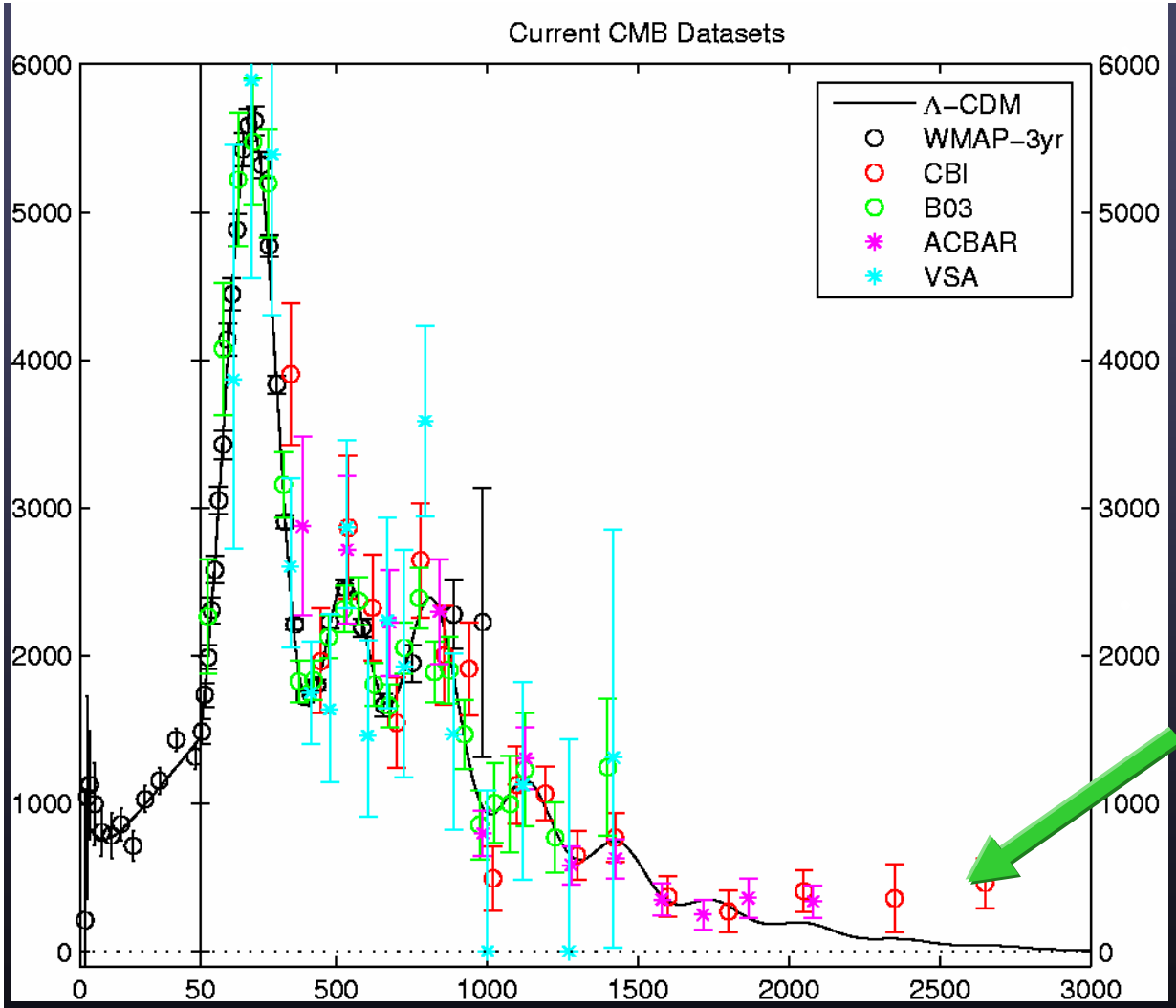


Courtesy WMAP Science Team

WMAP 3-yr 22 GHz polarization map (galaxy)

- linear scale 0 to 50 μK

Beyond WMAP: high-ℓ TT spectrum



Note: sensitivity poor at 3rd peak and beyond
– not yet precision cosmology!

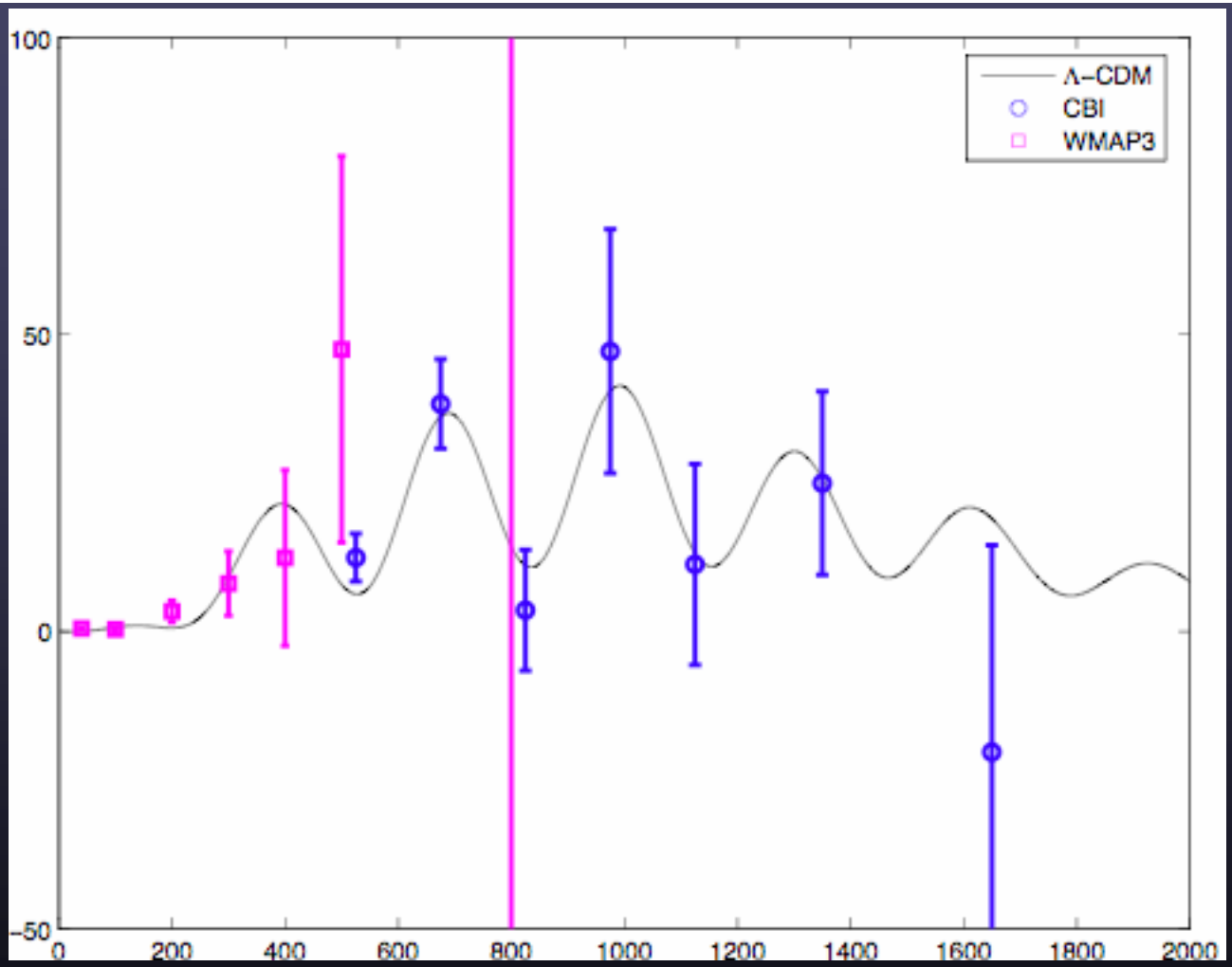
CMB angular power spectrum to high ℓ

- detected past 6th peak
- well into damping tail
- consistent with Standard or Concordance Models
- agreement of ACBAR, Boomerang, CBI, DASI, VSA and WMAP3 at ℓ < 1000 is excellent

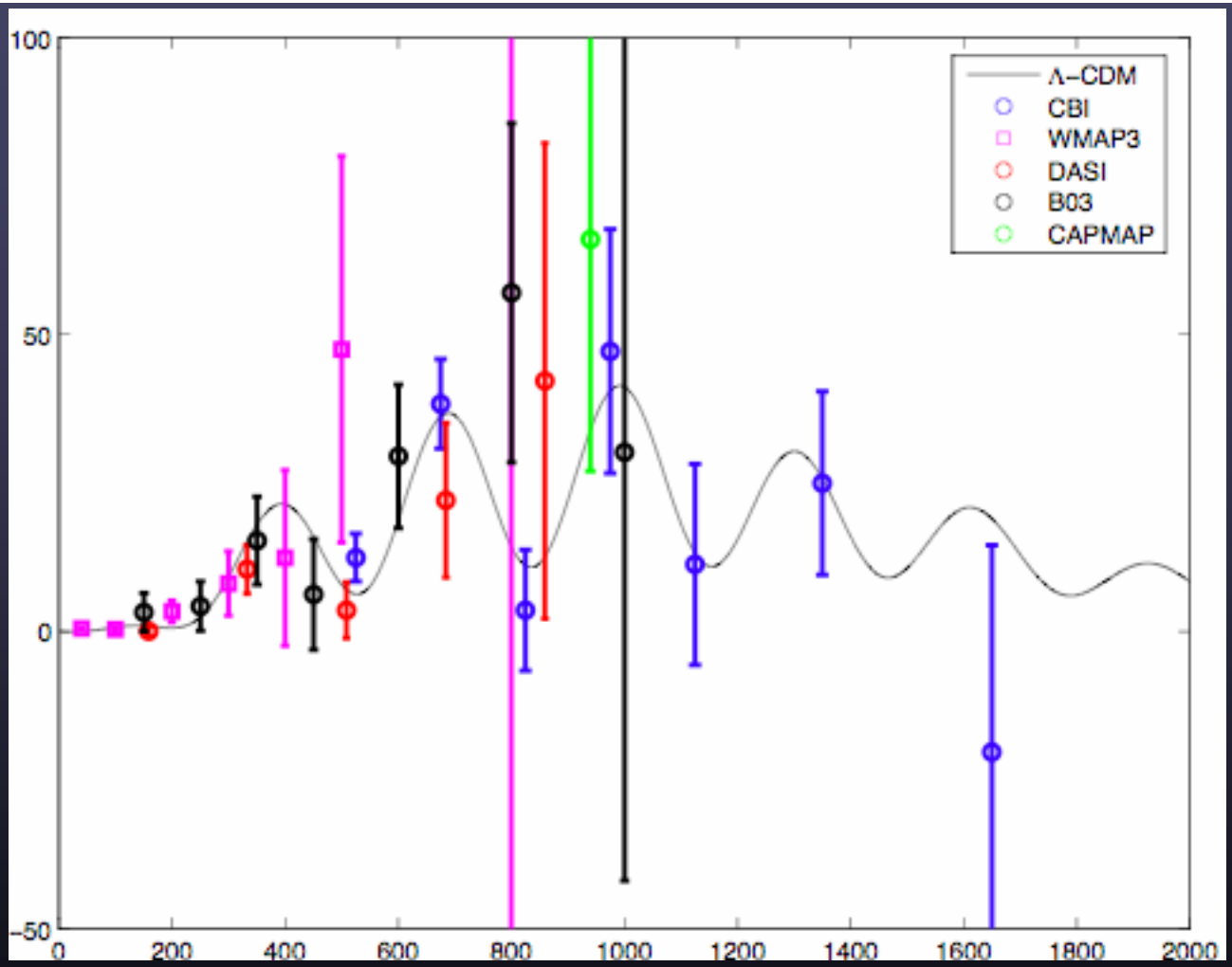
At 2000 < ℓ <3500, ACBAR, CBI & BIMA find power ~ 3σ above the standard models

- Not consistent with any likely model of discrete source contamination
- Suggestive of secondary anisotropies, especially the SZ effect

CMB Pol EE: CBI + WMAP3



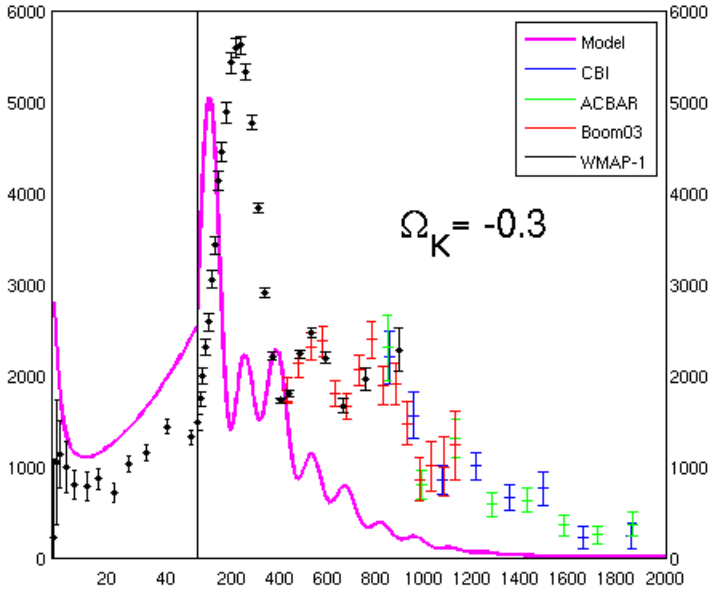
CMB Pol EE: + others

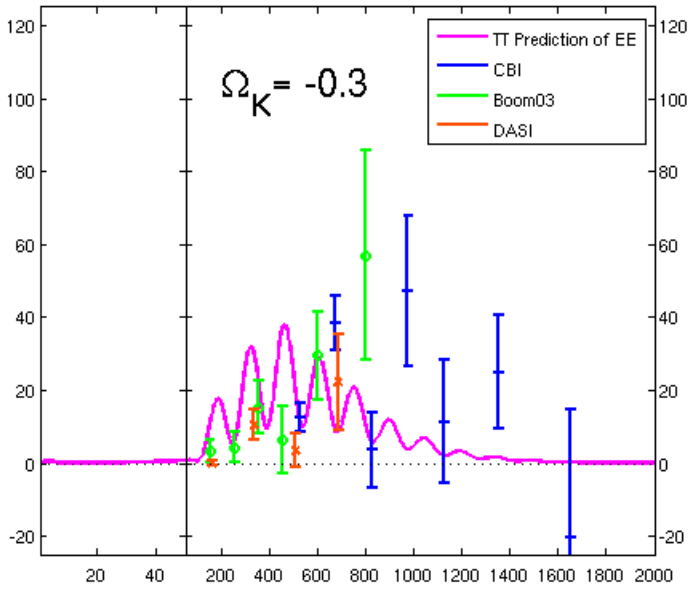


Uncanny Agreement

- CMB Polarization
  - E-modes: pol at 0°,90° to wave vector
    - from density perturbations and GW
  - B-modes: pol at ±45° to wave vector
    - only from Gravity Waves
- EE Predictable from TT oscillations
  - from velocity, EE 90° out-of-phase vs. TT [sin(ks) vs. cos(ks)]
- Primarily controlled by curvature
  - comoving distance to recombination
  - WMAP TT spectrum consistent with flat Universe (k=0)
  - check whether EE pattern is at predicted position

EE spectrum shifted as expected





Where we will be: 2010

CMB Task Force Report

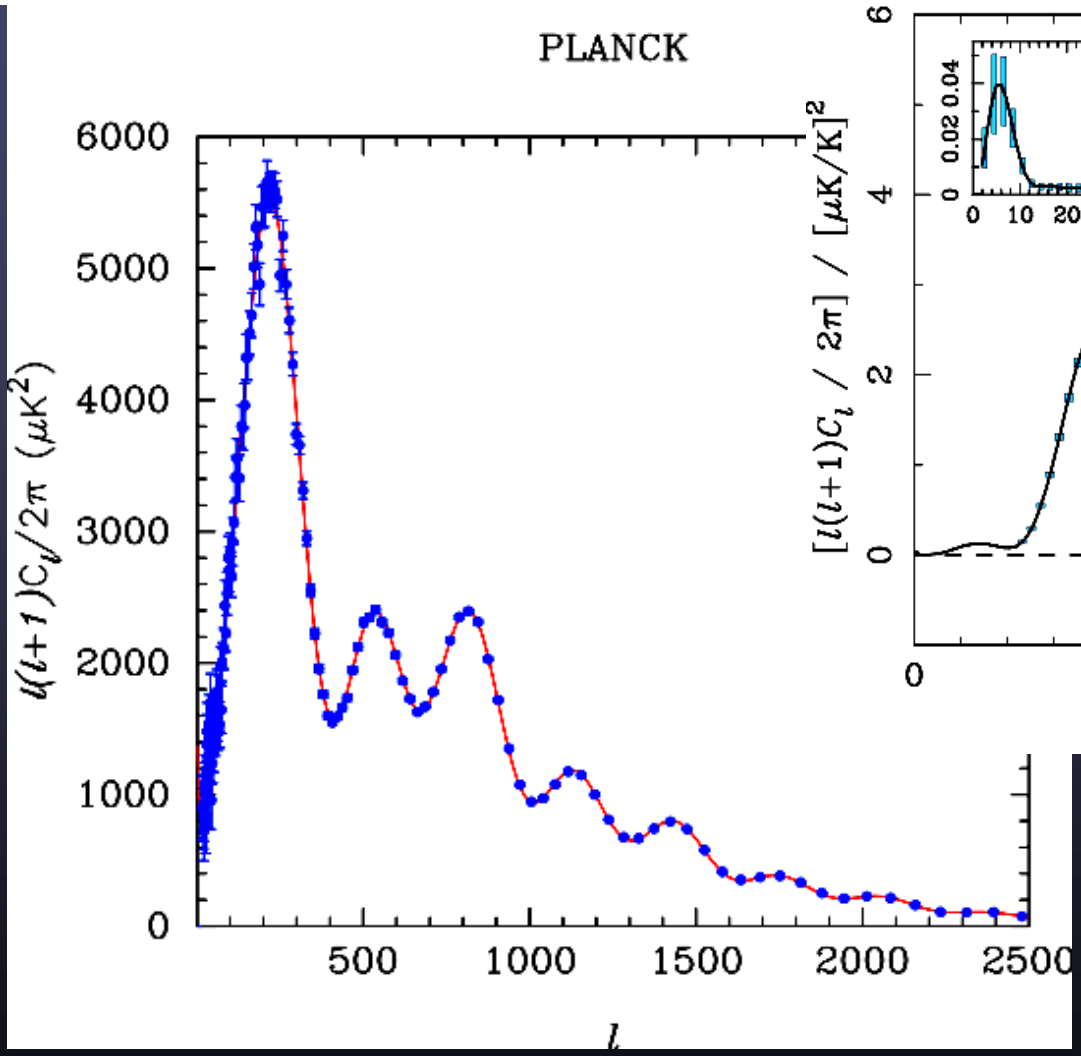
- Rai Weiss (MIT) chair

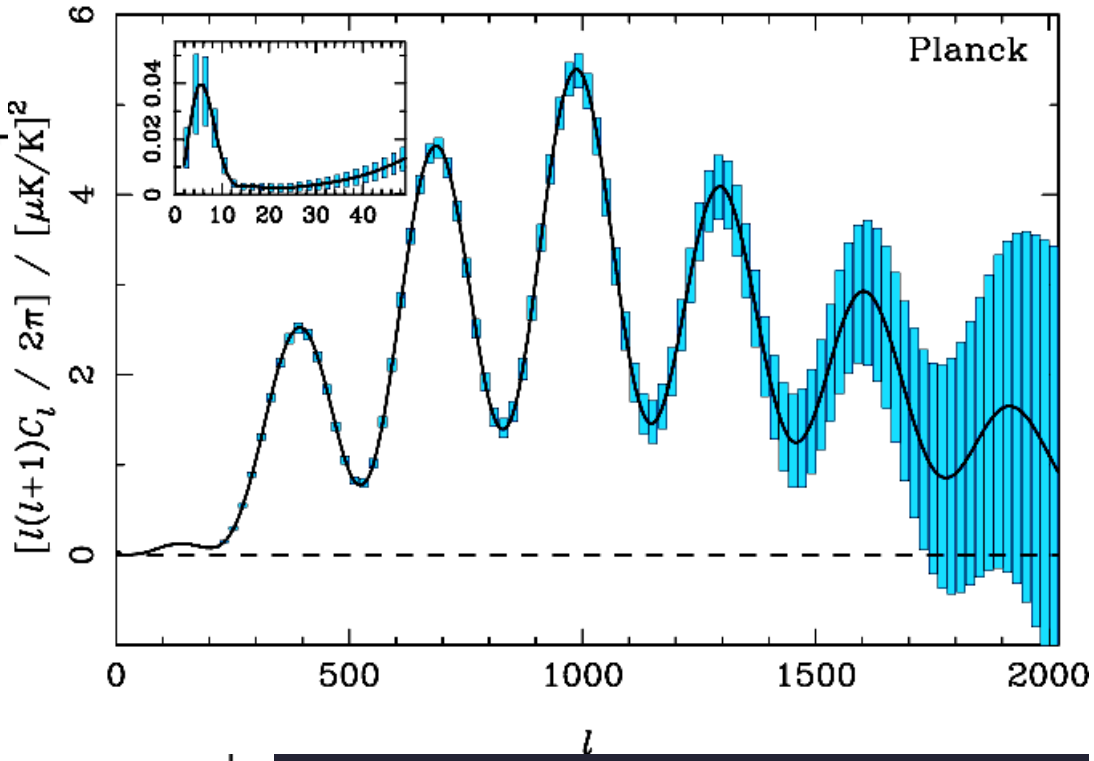
  http://www.nsf.gov/mps/ast/tfcr_final_report.pdf
- Science 1 – large angle polarization from inflation
  - phased program of ground + ballon ➔ space (2018)
- Science 2 – small-scale anisotropy & SZ effect
  - coherent ground-based program
  - **within scope of general-use radio instruments**
- Science 3 – intensity & polarization foregrounds
  - **focus is above 20 GHz, but clear connections to cm/m wave**
- Technology development
  - big bolometer cameras and coherent focal-plane arrays
  - alternative approaches
  - development towards CMBpol satellite mission
  - also theory, modeling, analysis algorithm development

Dark Energy Task Force

- NSF / DOE / NASA joint, reviewed white papers
  - not yet released (but some people have copies)
- set down clear metrics for performance
  - figure of merit ~ area in w – dw/dz plane
  - relative to Stage II (current ongoing projects)
  - near-term Stage III (DES, Pan-STARRS, CCAT)
- towards big-ticket Stage IV (JDEM,LSST,SKA,other)
  - SNe1a surveys, weak lensing, BAO, cluster surveys
  - **SKA prominent (HI structure/BAO, weak lensing, maser H_0)**
- my impressions
  - big winner: weak lensing (O/IR)
  - not-so-good: SNe-Ia (only factor 2 gain after Stage 3)
  - best combo: WL plus BAO
  - jury out on: SKA contributions

Next big thing: Planck!

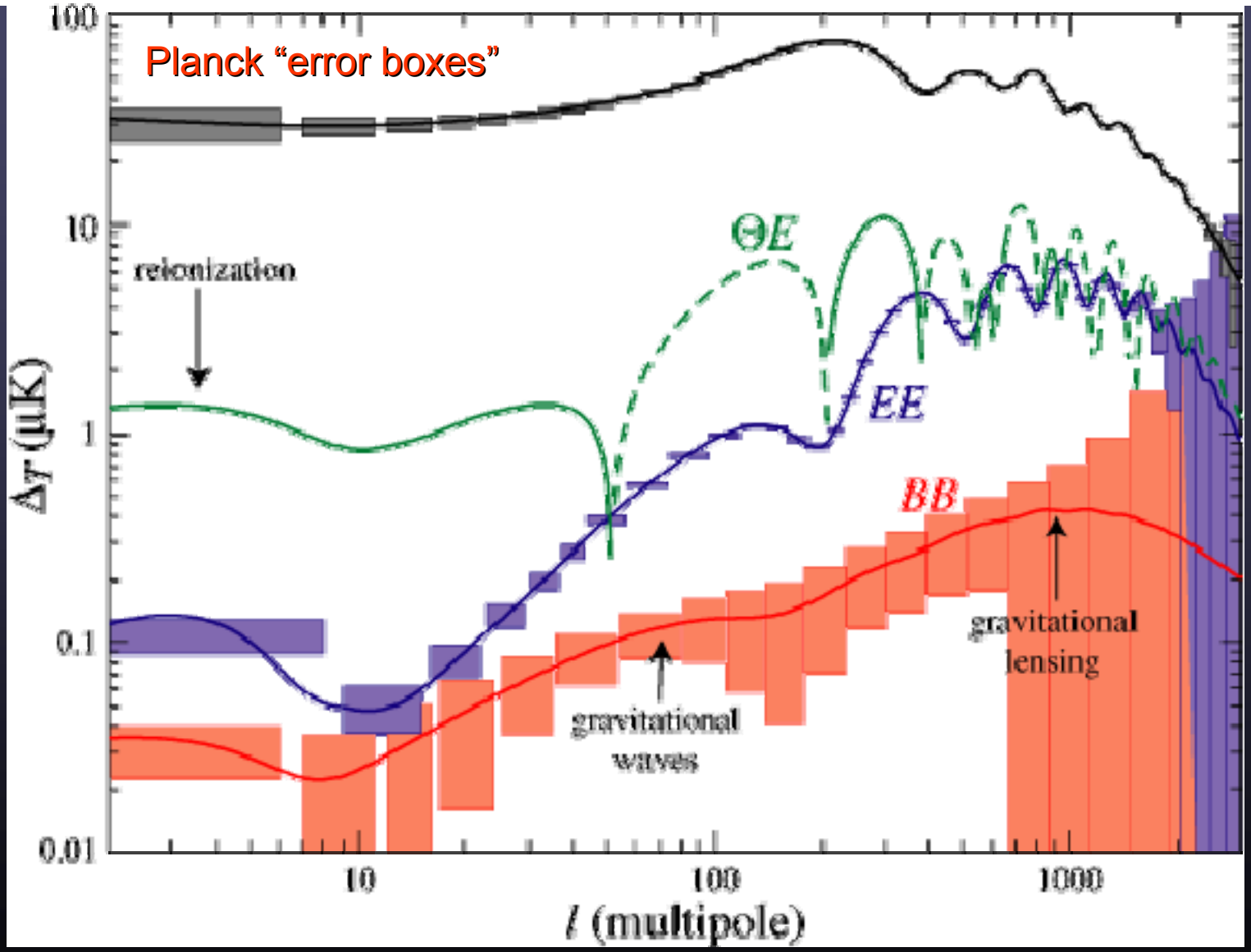




- Planck sensitivity, frequency & sky coverage critical:
  - TT: 3rd and higher peaks!
  - reach lensing BB modes
  - push towards tensor BB modes
  - determine foregrounds

Figures courtesy Martin White

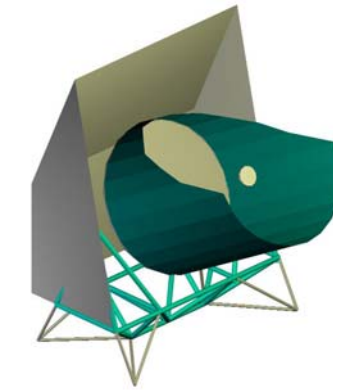
B-modes: Planck Projections

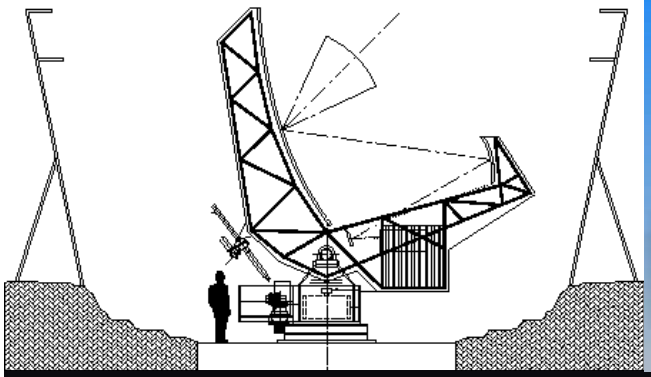


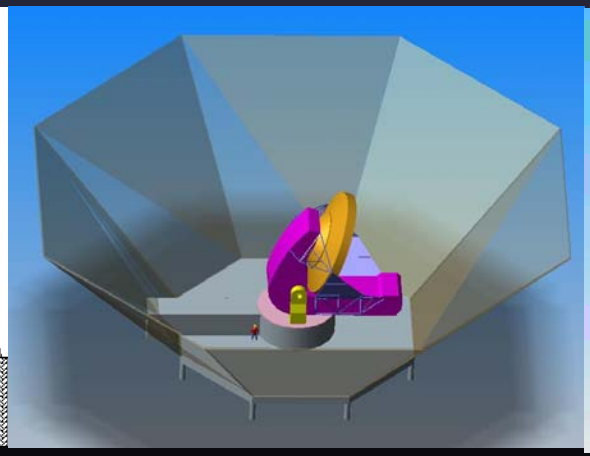
Hu & Dodelson *ARAA 2002*

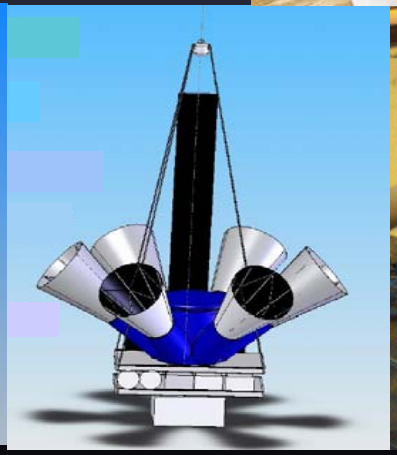
Current & Future "CMB" Experiments

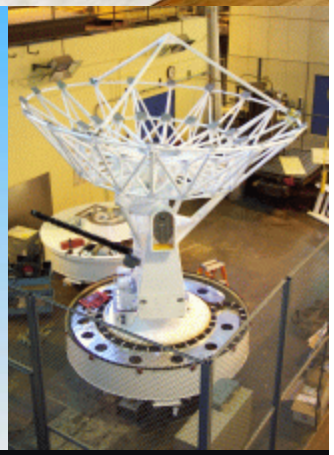
- Beyond Planck (a sampling):
  - ACT [6m] (Chile) – high-ℓ CMB
  - SZA [8x3.5m] (OVRO) – clusters, high-ℓ CMB
  - South Pole Telescope [8m] (SP) – cluster counts
  - QUaD [2.6m] (SP) – CMB polarization
  - QUIET [2m,7m] (Chile) – B-modes from ground
  - Atacama 25-meter (Chile) – FIR/sub-mm
  - SPIDER [2m] (Balloon) – B-modes from LDB





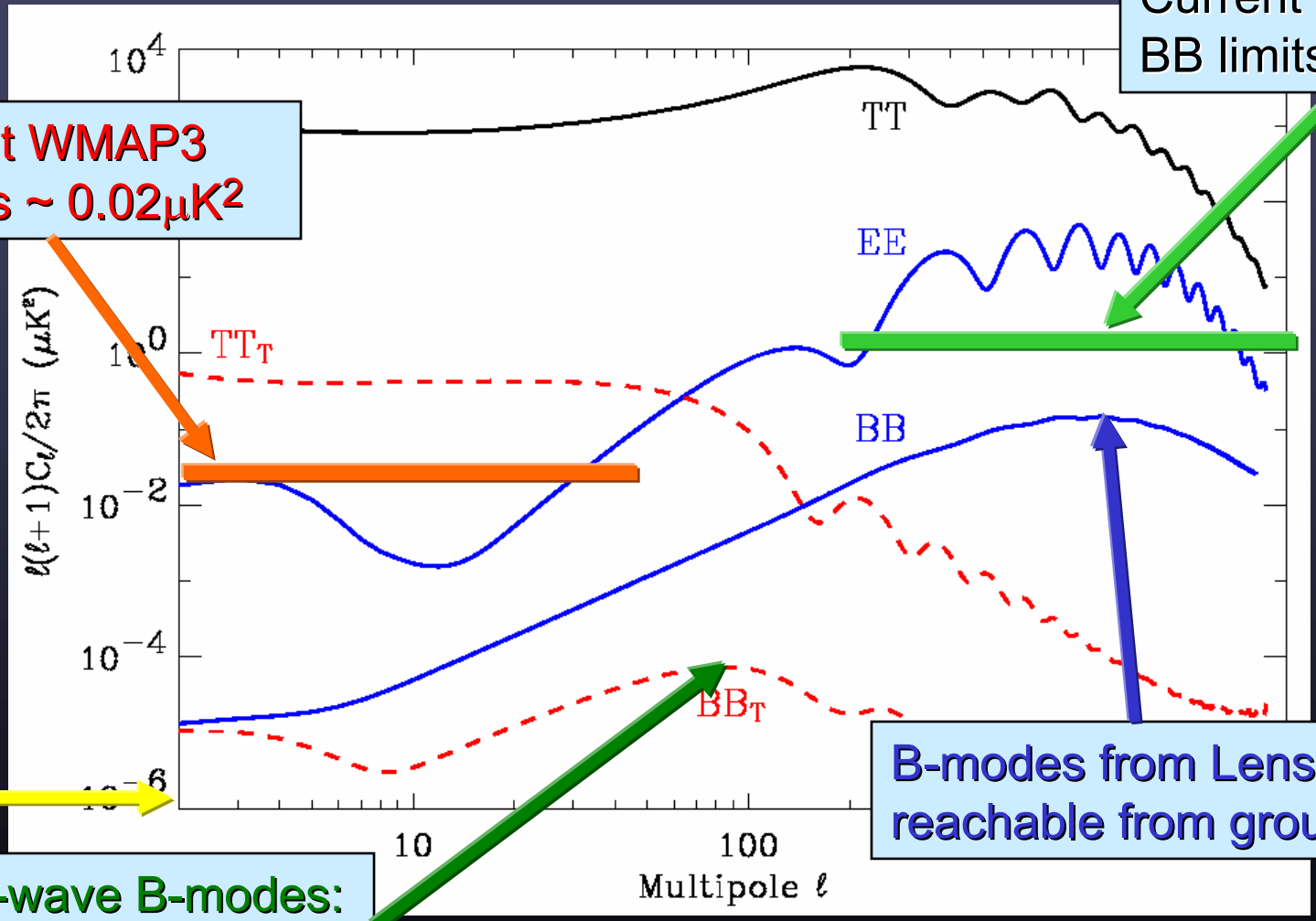






CMB Power Spectrum Goals

- EE and BB (lensing, inflation)



Current CBI+DASI
BB limits ~ 1μK²

Current WMAP3
BB rms ~ 0.02μK²

1 nK!

B-modes from Lensing:
reachable from ground.

Gravity-wave B-modes:
for T/S=0.001

The Next Generation: beyond 2010

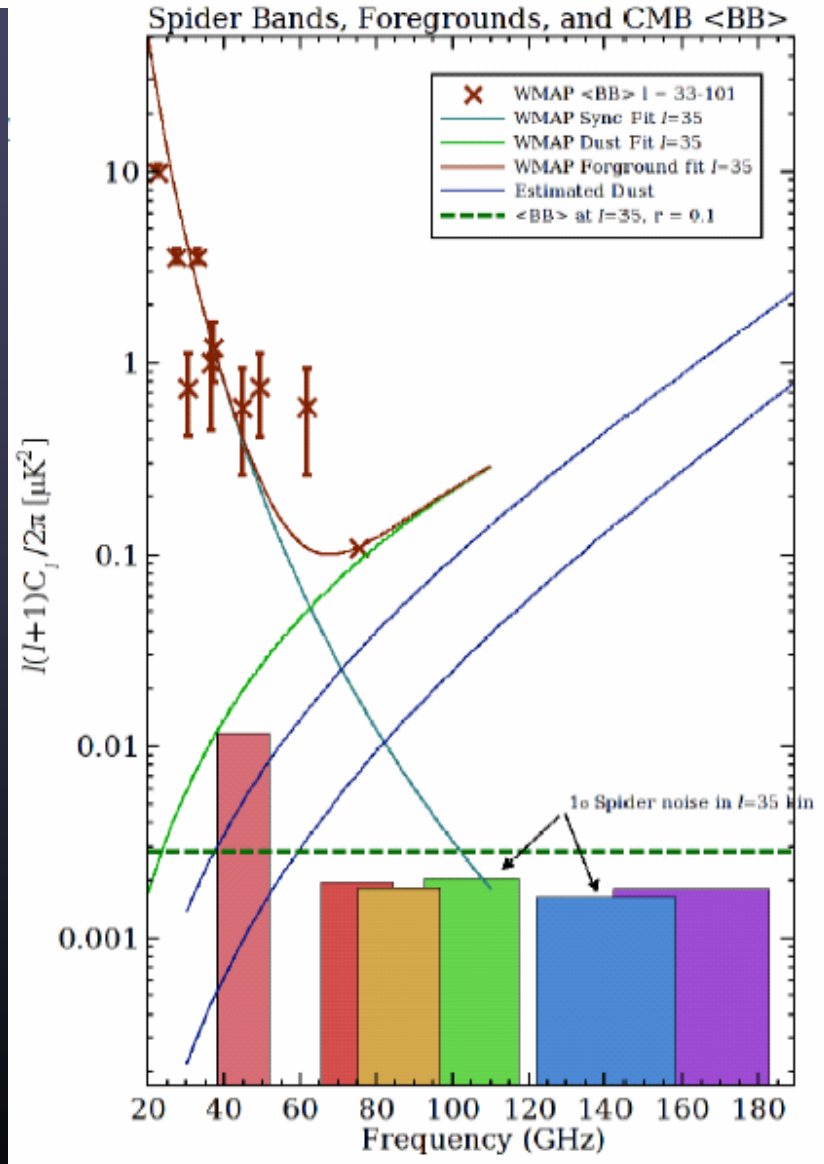
Beyond 2010 – the players??

- CMB – still the cleanest probe
  - working towards CMBpol (r<0.01 territory)
  - how well will we know the foregrounds?
  - are big bolometer cameras the answer?
- Large Scale Structure
  - DETF Stage IV surveys
  - cluster (SZ and O/IR, maybe Xray) census to z=3?
  - what about radio?
- Other
  - the era of Gravity Wave Observatories (LISA, pulsars)!
  - will we know H_0 to 1%?
  - will we know the density profile of galaxies in inner core?
  - particle physics beyond LHC?
  - will string theory make better sense?

The CMB Foreground Challenge

- Further progress in CMB astronomy will require the understanding and removal of foreground emission (solar system, galactic, extra-galactic) to unprecedented levels (10-100 nK)
  - Note – at 1cm in one square arcmin :
    1μK ~ 1μJy
- To image the CMB at these levels one images the entire Universe between *z*=0 and *z*=1000!

  = Whole Universe Imaging
- This is in full polarization…
- Frequencies from 20 GHz – 900 GHz!
- Looking at continuum, but beware of line contamination at these levels.



Plot from Barth Netterfield's talk at Irvine, March 2006
http://www.physics.uci.edu/CMB/

Aside: a CMB Mega-Array?

- CBI, DASI, & VSA have demonstrated the utility of interferometry for CMB (particularly for polarization)
- sensitivity limited by number of elements
  - detectors near quantum limit, need more throughput
  - would need 100-1000 elements →10^4 – 10^6 "pixels" (10-110x DASI)
- would require massive wide-band correlators
  - development of "inexpensive" large-scale correlators
  - already being explored for other next generation big arrays (ATA,SKA)
- would be competing against bolometer & MMIC arrays
  - but systematics cleaner → complementary!
- risky & expensive, but worth exploring…
  - detailed cost analysis: will NOT be a ~ $10M experiment
  - leverage off other next generation radio array development…

Towards the next Decadal Review

- What will radio astronomy be doing for cosmology?
  - CMB studies are cm and mm-wave radio astronomy!
    - CMB & foreground studes are large multi-band sky surveys
  - Fundamental distance scale work still important
  - Growth of structure in universe probes cosmology
- How do we tie our facilities into the Big Questions?
  - What observations can we do for CMB foregrounds? (surveys)
    - sub-mJy source pops, 1-20 GHz sky surveys (we are behind SDSS)
  - Will SKA fulfill DETF needs? (is HI the focus?)
  - Will we have sensitive VLBI capability beyond 2010? (underrated)
    - how far can we push astrometry? VLBI is a truly unique capability
- What do we do besides our big facilities?
  - radio instrumentalists being trained in small CMB & URO groups
  - technology crossover (FPAs, correlators)
  - support for theory, analysis, algorithm work

If we do nothing else…

- provide complete Sky Surveys
  - NVSS & FIRST a good start, but 10 years old now
  - these are used all the time by wide range of astronomers!
  - but reliability is an issue
- we want
  - 1-20 GHz at 1” or better, good fidelity, sub-mJy
  - especially low-surface brightness sensitivity, to 5’
    - can combine with “CMB” images at larger scales
  - 30MHz-1 GHz in key bands, e.g. HI to ???Mpc
  - a grand radio atlas: radio part of a “Google Sky”

shame on us if we don’t provide this basic service