CMB@60

Lessons Learned from WMAP

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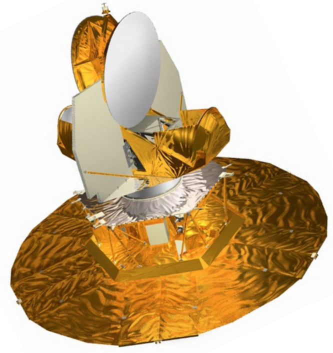

26 Science Team Members

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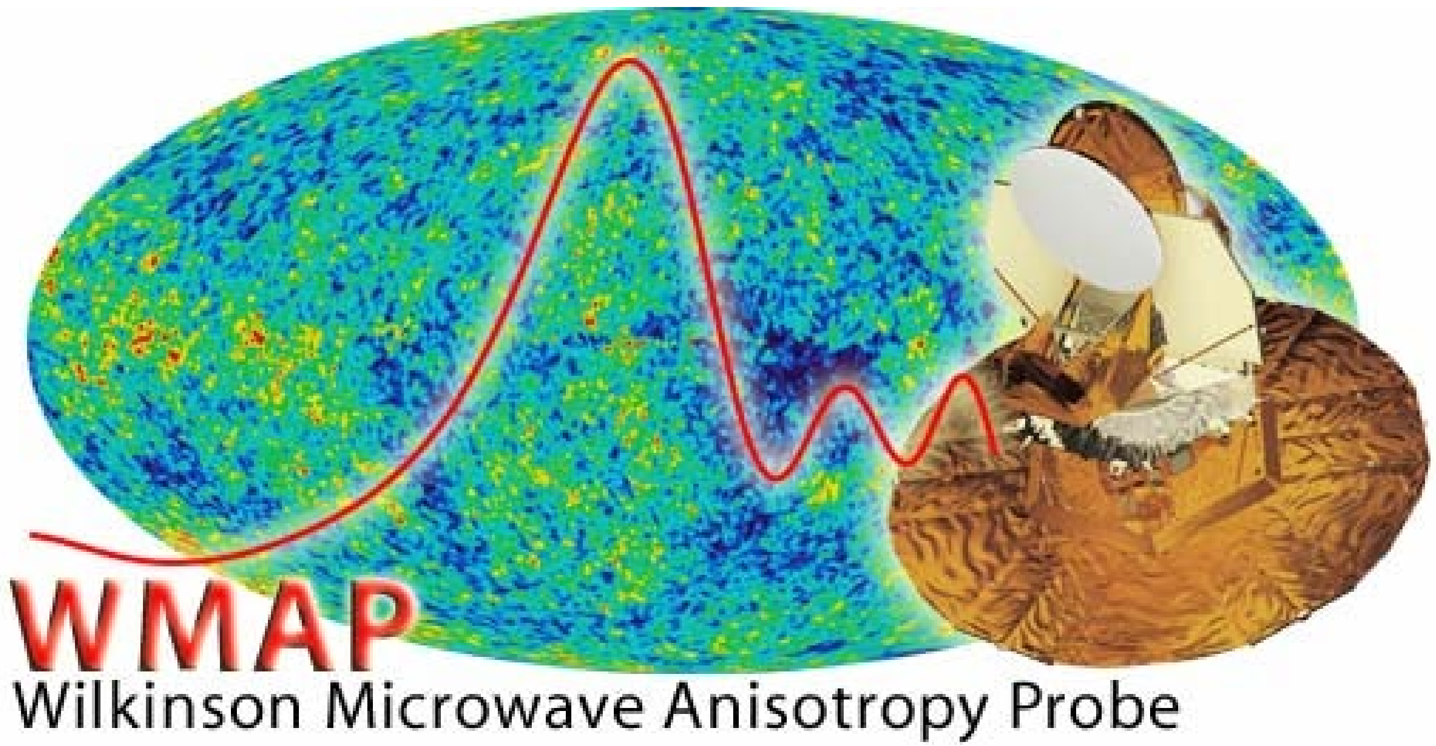


on original proposal (+Mather → JWST)

Key WMAP Event Dates

1995	Proposed to NASA
1996	Accepted by NASA
2001	Launched June 30 (5 years from acceptance to launch)
2003	Initial results in February
2010	Operations completed (9 years)
2012	Final papers submitted / published 2013 (before Planck results – i.e., no Planck feedback to WMAP results)

The Run-Up to WMAP

COBE DMR discovers anisotropy in 1992

>7° super-horizon

CMB community pushes sub-horizon measurements from space

No near-term launch opportunities

Convince NASA managers to create smaller Explorer mission lines

Held conference with scientists presenting various astrophysics ideas

NASA HQ agreed to smaller, faster science missions: SMEX and MIDEX programs

Announcement of Opportunity in 1995

IMAGE and “MAP” missions selected in 1996

“MAP” later became “WMAP”

Many in community doubtful of CMB to get the cosmological parameters

proposal covered the consequences of a lack of acoustic peaks!

The Run-Up to WMAP

Guiding principle for WMAP, as stated by Dave Wilkinson:

"I don't want to do everything.
I just want to do something, and to do it soon."

$70 M NASA MIDEX proposal cost cap enforced this approach

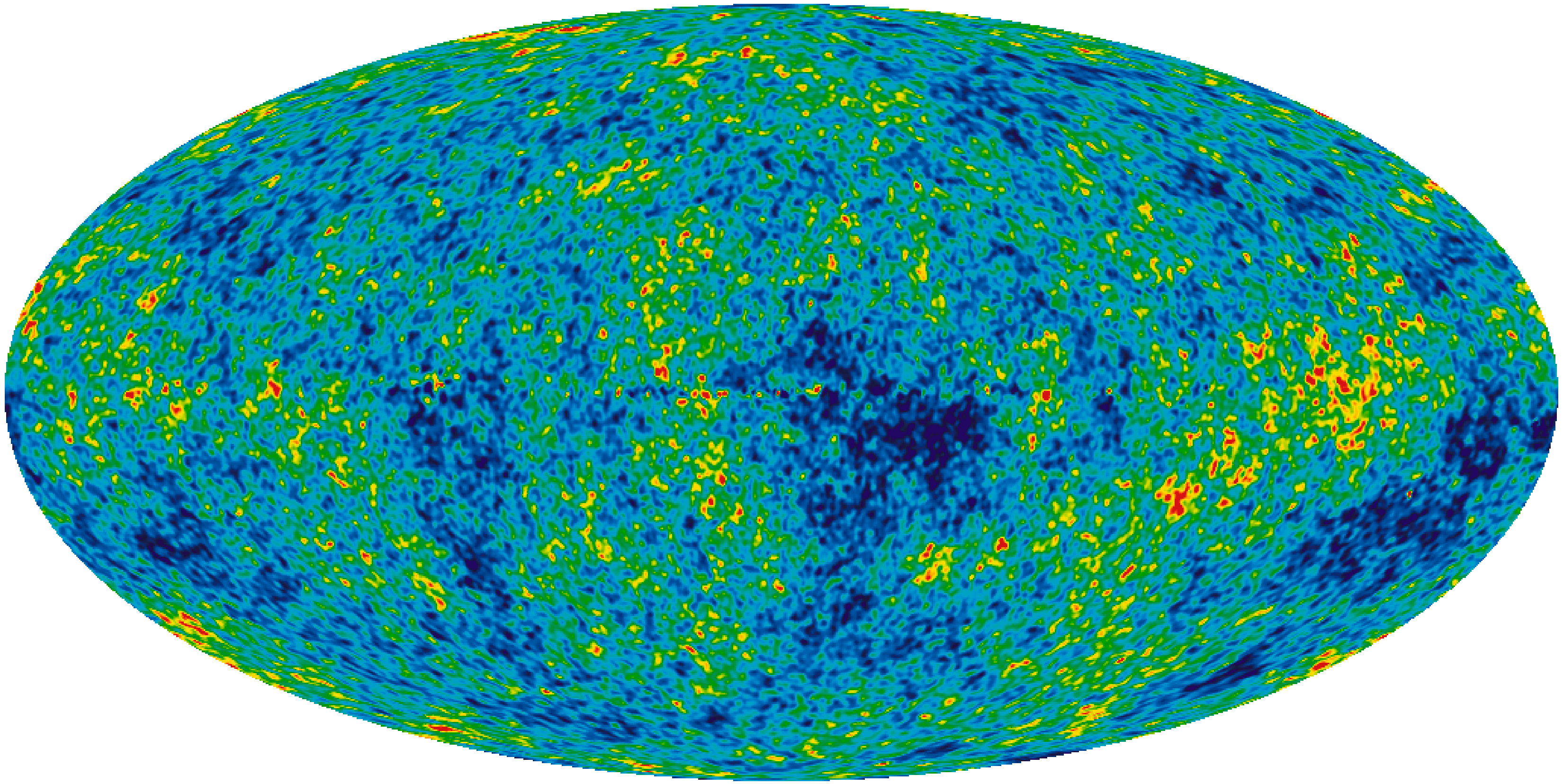
Concentrated on the largest angular scales as extremely difficult to do from the ground

Requirement: CV-limited first peak measurement

Ensured that 2nd peak would be very well-measured

Final result: CV-limited to $l < 457$ & signal-to-noise ratio >1 to $l < 946$

1st Full Sky Sub-horizon CMB Anisotropy map



(smoothed to 1°)

Some Other WMAP Firsts

- ✓ **1st simultaneous fit of all cosmological parameters**
- ✓ **Fluctuations measured: tested to be gaussian & adiabatic**
- ✓ **Inflation**

1st detection of a TE (anti)correlation on super-horizon scales

1st detection of n_s<1 (0.9608 ± 0.0080)

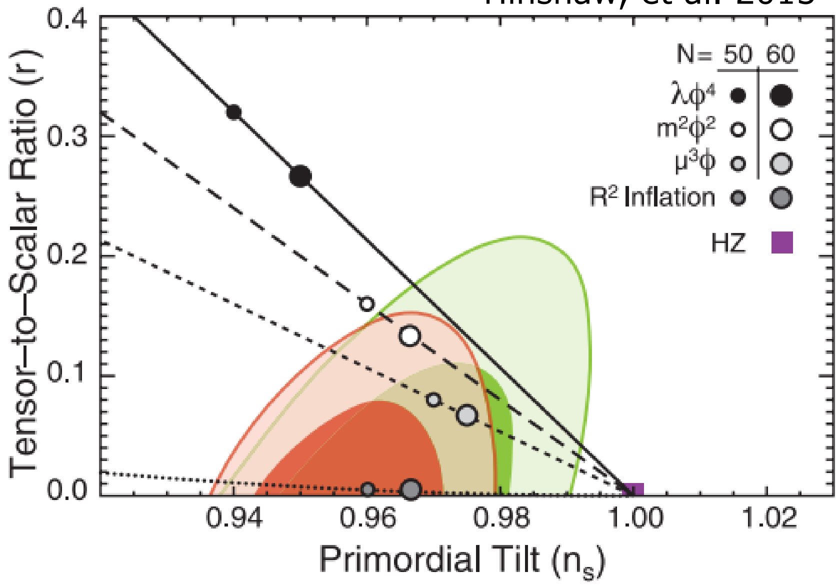
1st precision (sub-percent) detection of flatness

$$\Omega_k = -0.0027^{+0.0039}_{-0.0038}$$

1st time ruling out specific inflation models based on r & n_s

$r < 0.13$ (95% CL)

Hinshaw, et al. 2013



WMAP: 1st CMB neutrino solutions

<u>For WMAP+eCMB+BAO</u>

$$N_{\text{eff}} = 3.84 \pm 0.40$$

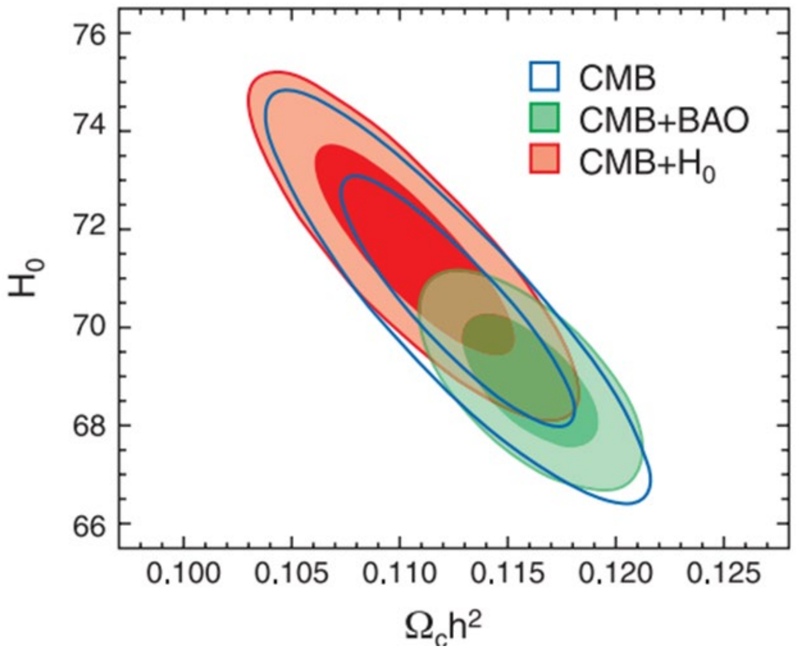
$$\Sigma m_\nu \text{ (eV)} < 0.44 \text{ (95\% CL)}$$

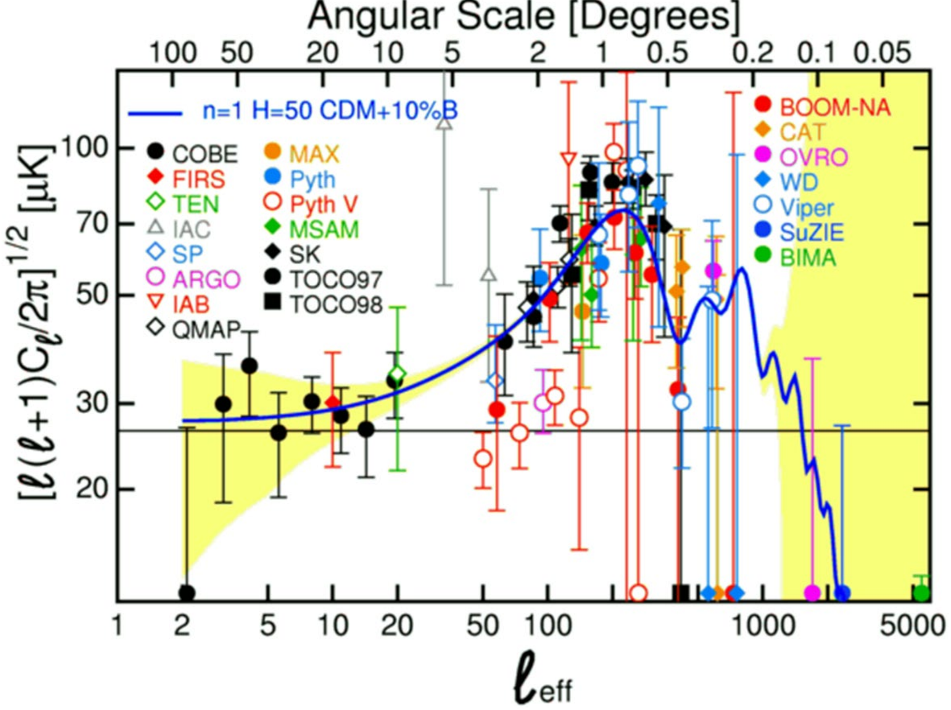
Hinshaw et al. 2013

Early Hints of Hubble Tension

Combining WMAP CMB with SNe pulled H_0 up
Combining WMAP CMB with BAO pulled H_0 down

SNe & BAO & CMB data are much improved today
➔ tension has become more significant

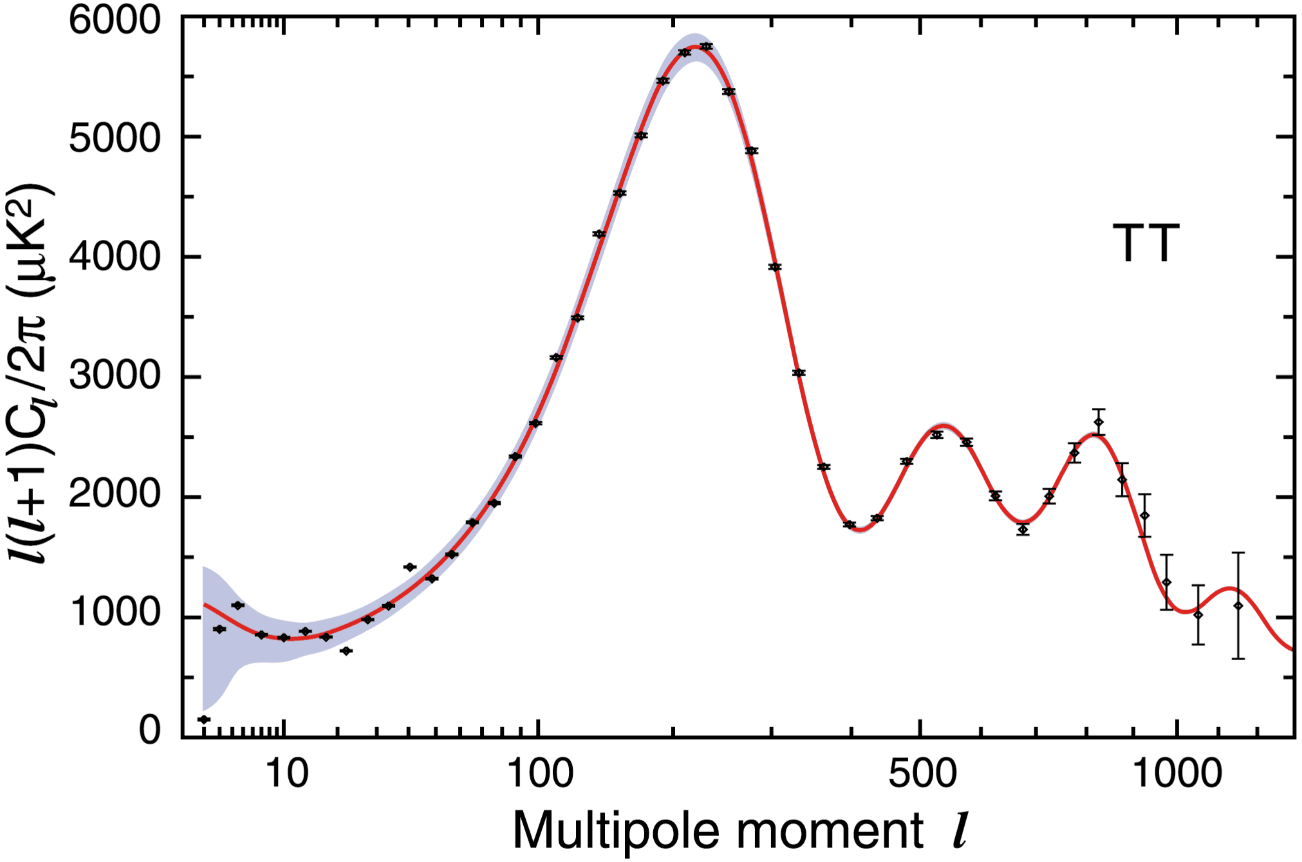


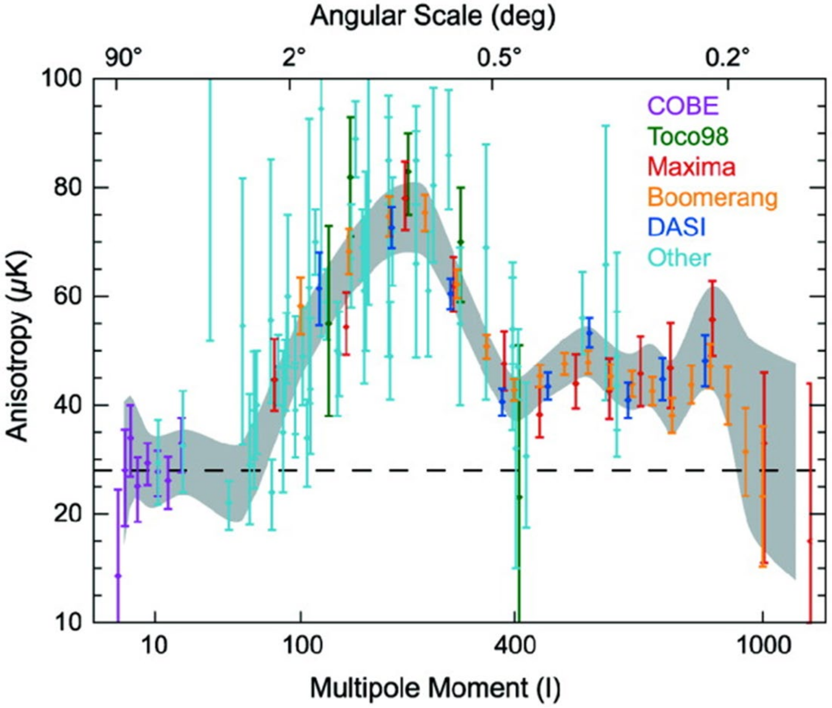


Ned Wright 3 Dec 1999

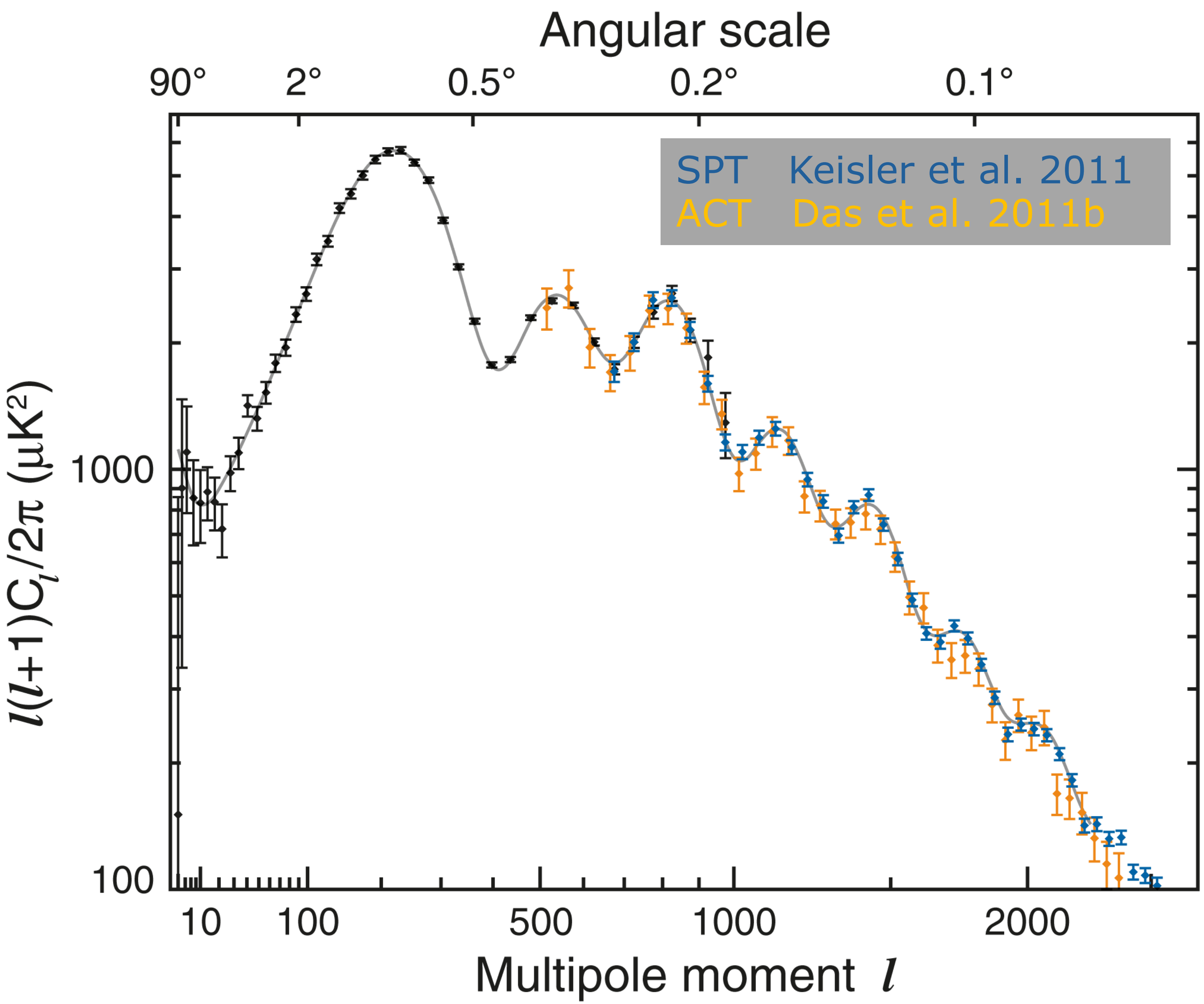
Model: n_s=1, H_0=50, CDM+10% baryons

Bennett et al. 2013, ApJS, 208, 20





Bennett et al. 2003, ApJ, 583, 1

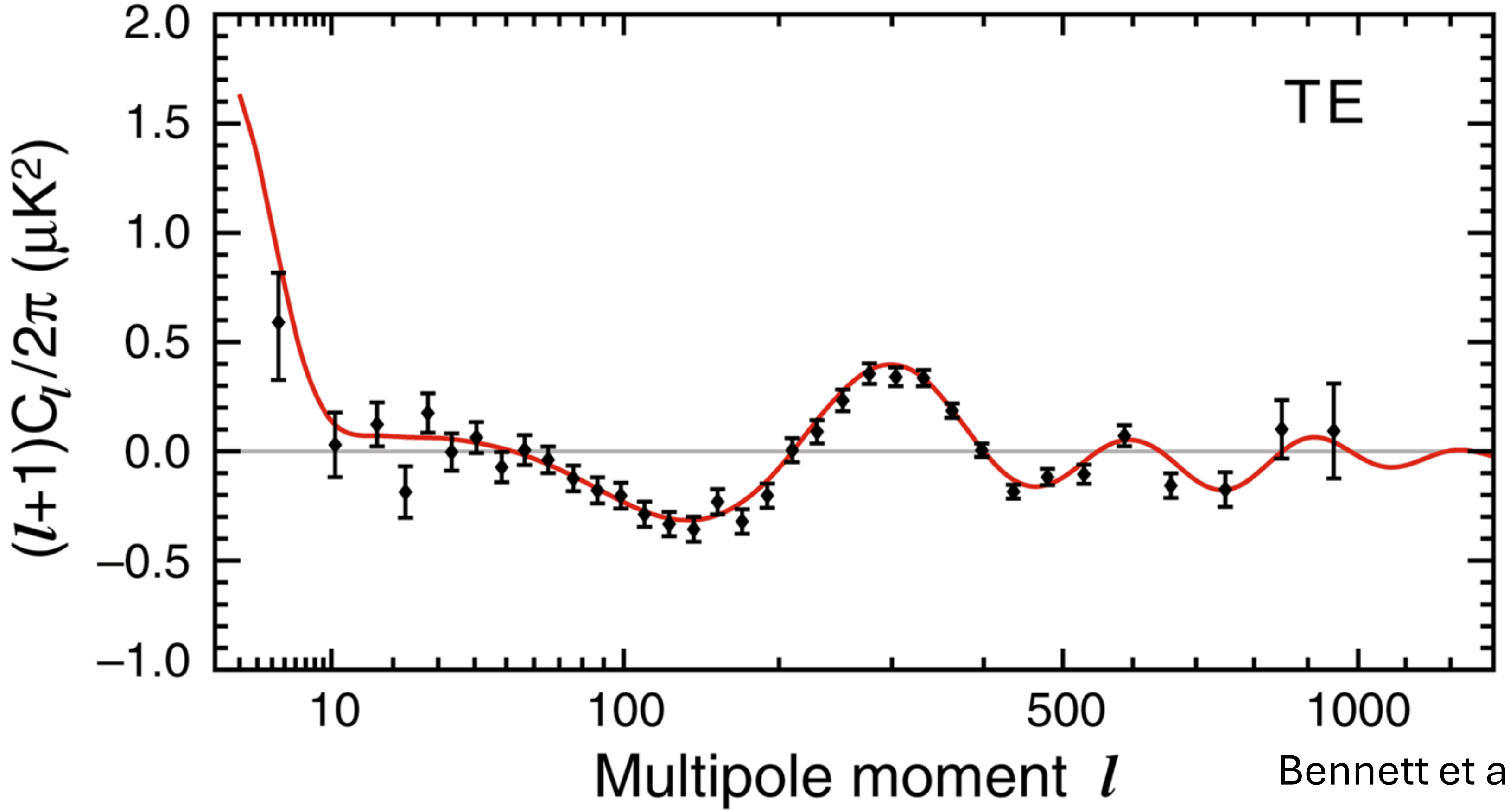


Hinshaw, et al. 2013
ApJS 208 19

Polarization

WMAP had no polarization requirements

No decisions allowed the information to be lost… neither was it optimized



Bennett et al. 2013, ApJS, 208, 20

Optical Depth, τ

- Before WMAP no CMB detections of τ

- Final WMAP determination using a sudden approximation

  $\tau = 0.081 \pm 0.012$ WMAP9+eCMB+BAO+H_0

- Residual foregrounds cleaned

  $\tau = 0.062 \pm 0.012$ WMAP9 (Ka,Q,V) + Planck 353 GHz

- Other examples:

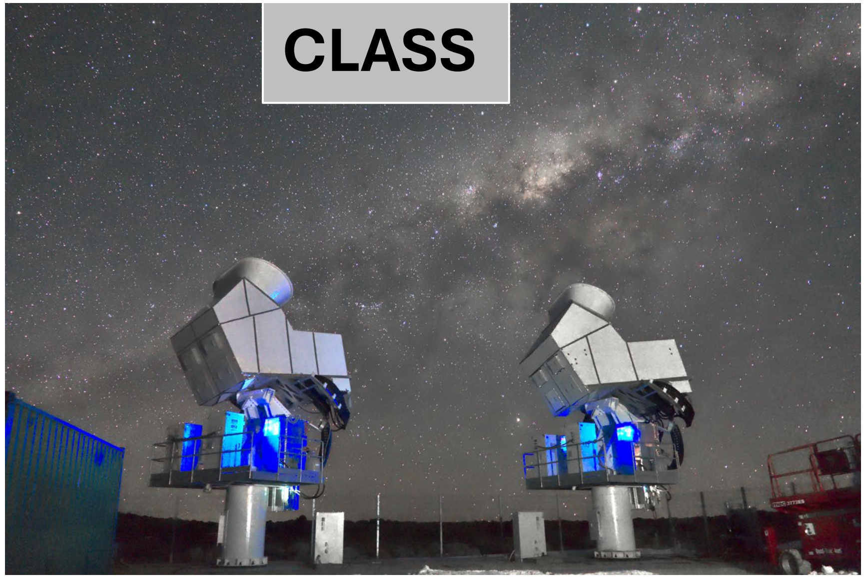
  0.063 ± 0.020 LFI 70 GHz Planck 2018 Legacy

  0.051 ± 0.009 HFI 100 X 143 Planck 2018 Legacy

$0.053^{+0.018}_{-0.019}$ CLASS (90 GHz) X Planck (100, 143 GHz)

NEW

Li, et al. , arXiv:2501.11904



Toby Marriage, PI

Lessons Learned

1) Power spectrum of mission sizes desirable: few large, many smaller
   - Smaller has benefits, especially for focused “physics” missions to get fast turn-around

2) WMAP had low “transaction costs”:
   - One country / One funding agency
   - Pre-determined known budget cap
   - Small coordinated team

3) Golden Rule of management
   - Lines of authority and lines of responsibility must be maximally common
   - Mostly true for WMAP

4) There is no substitute for experience
   - WMAP science team had deep experience with relevant hardware and experimental design – This was key!
     - extensively involved in spacecraft development, often guiding NASA engineers:
     - “*I never knew that scientists could be so helpful*”
   - Team members were selected for complementary roles based on their knowledge & capabilities
   - Small size means everyone on the team knew what everyone else is working on
     - all offer suggestions and constructive critiques

Lessons Learned

4) Computer processors, storage, and software improve rapidly

    Analyses, simulations, and modeling that could not previously be done are now easily possible

    Don't worry about future computer power – it will likely be better than you imagine for lower cost

5) CMB foregrounds have always been a limitation

    Multifrequency is a necessity (COBE DMR 3 bands, WMAP 5 bands, Planck 9 bands, LiteBIRD 15 bands)

    Deeper measurements require improved foreground removal

    No current models of foreground emission reflect the full complexity

6) Cosmology has benefitted greatly from independent and complementary measurements

7) Marginal tensions can be judged by their increase/decrease with time

    Hubble tension has significantly increased with additional data & improved analysis

    S_8 tension has abated

Questions

Is the ΛCDM model correct, or does it need modification?

- Did inflation happen? Which kind?
- Nature of dark energy? Λ or $w_0 w_a$? Why a tiny Λ? What $V(\varphi)$?
- Hubble tension? What is wrong?
- CMB anomalies?
- Neutrino masses?

  "The Neutrino Diet" – Lose more than you weigh! – Act now!

Cosmology has come a very long way in a short time.
We still have much to learn!