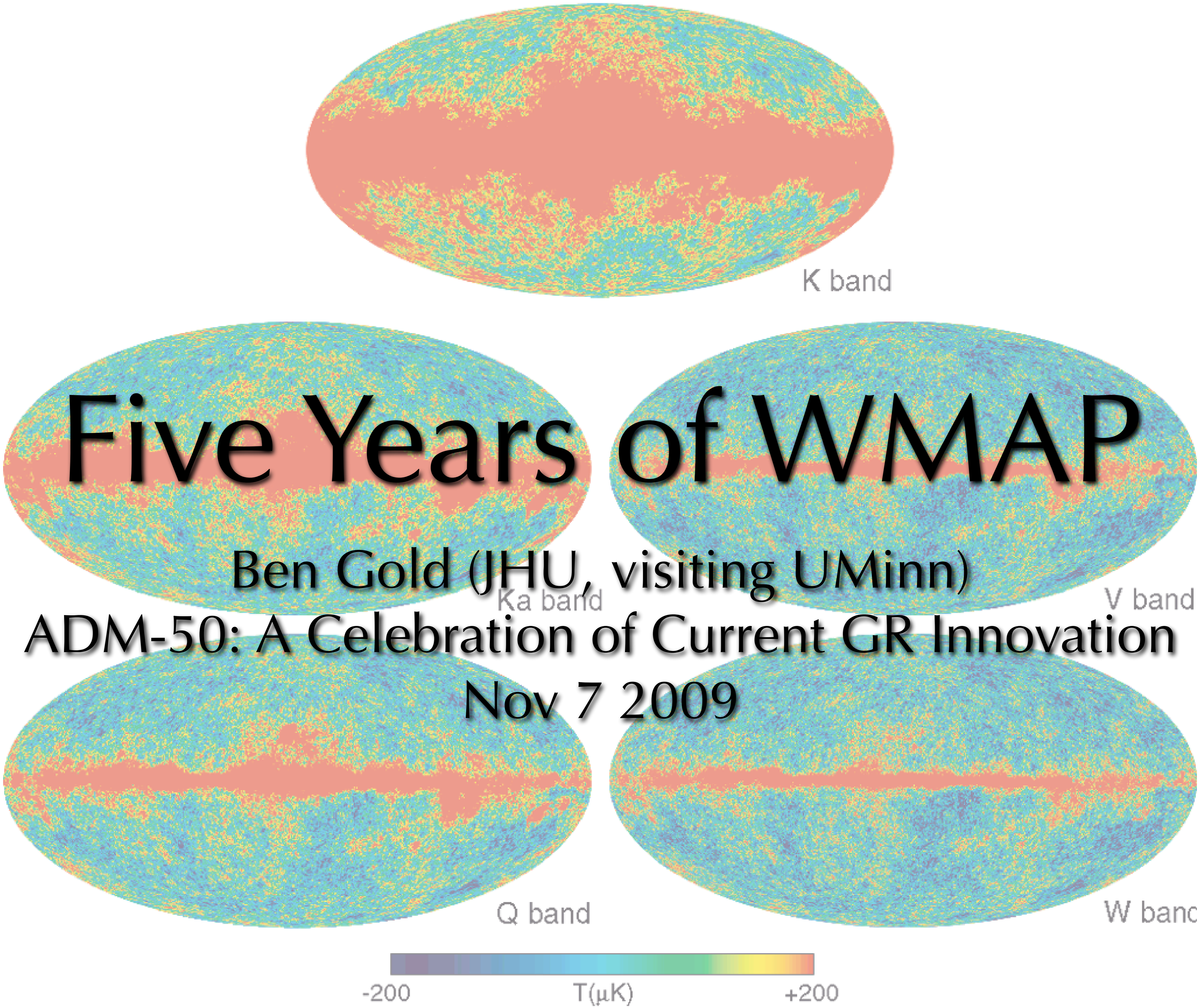
Five Years of WMAP

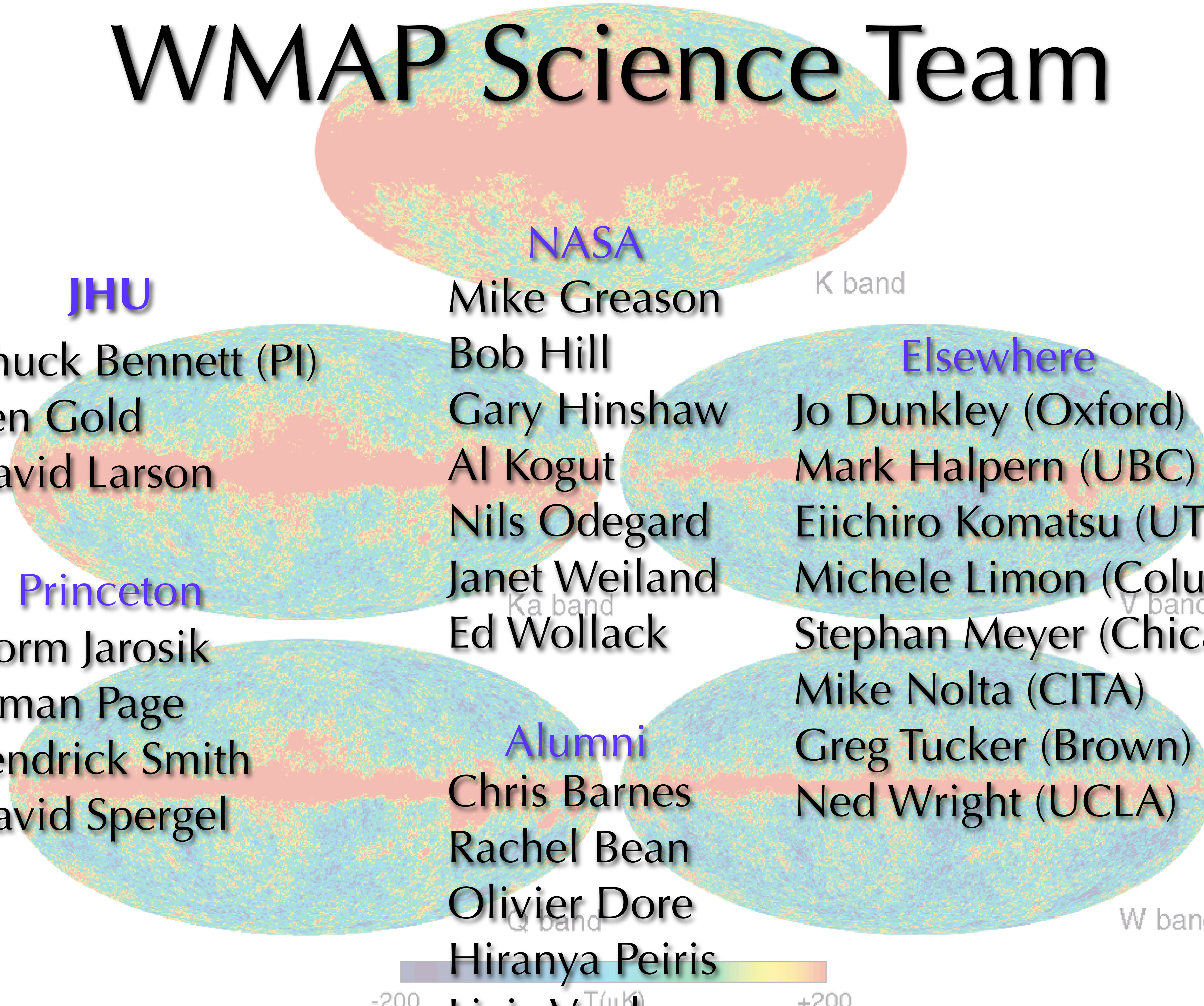
Ben Gold (JHU, visiting UMinn)

ADM-50: A Celebration of Current GR Innovation

Nov 7 2009



WMAP Science Team



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Ben Gold
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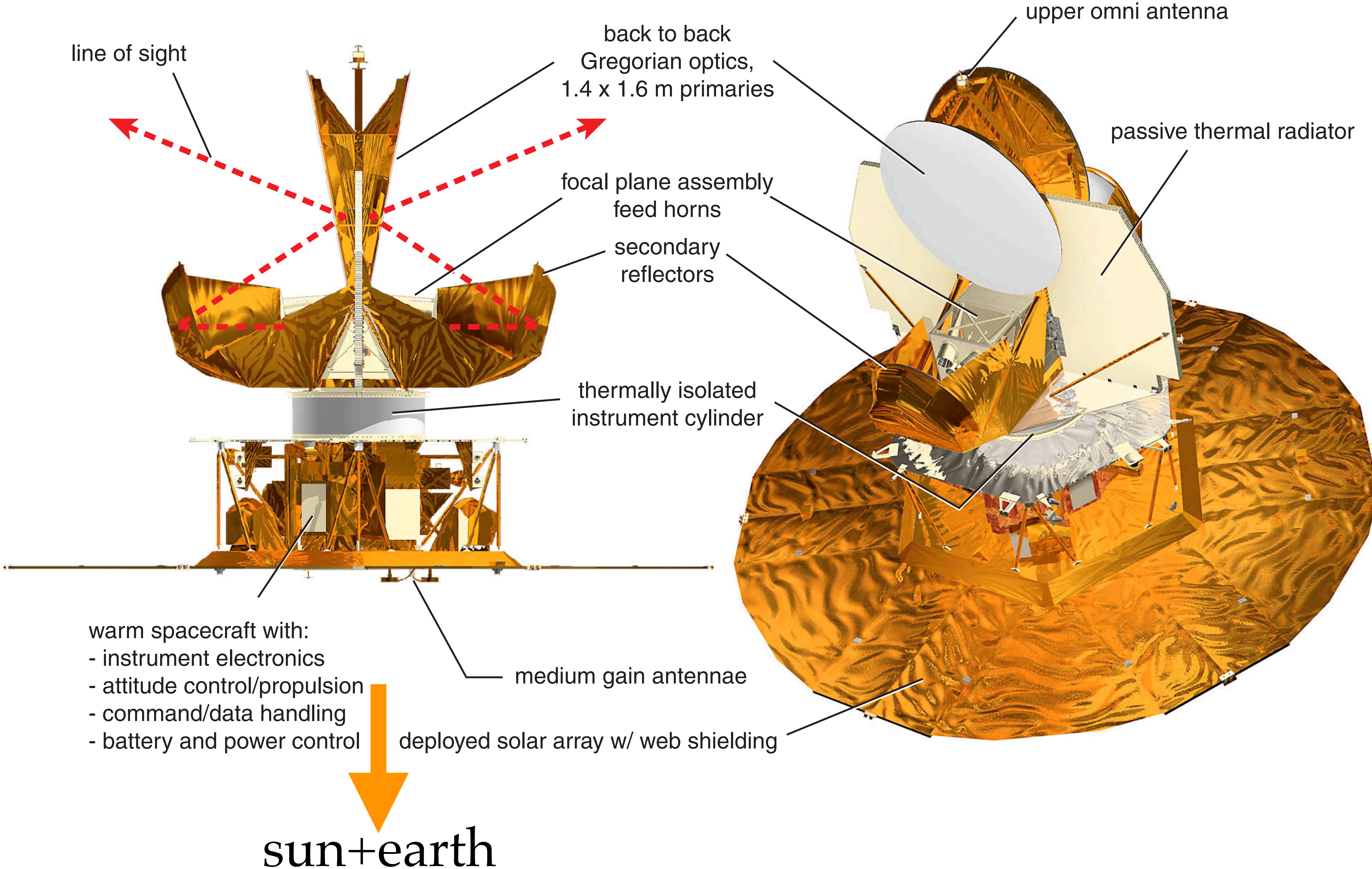
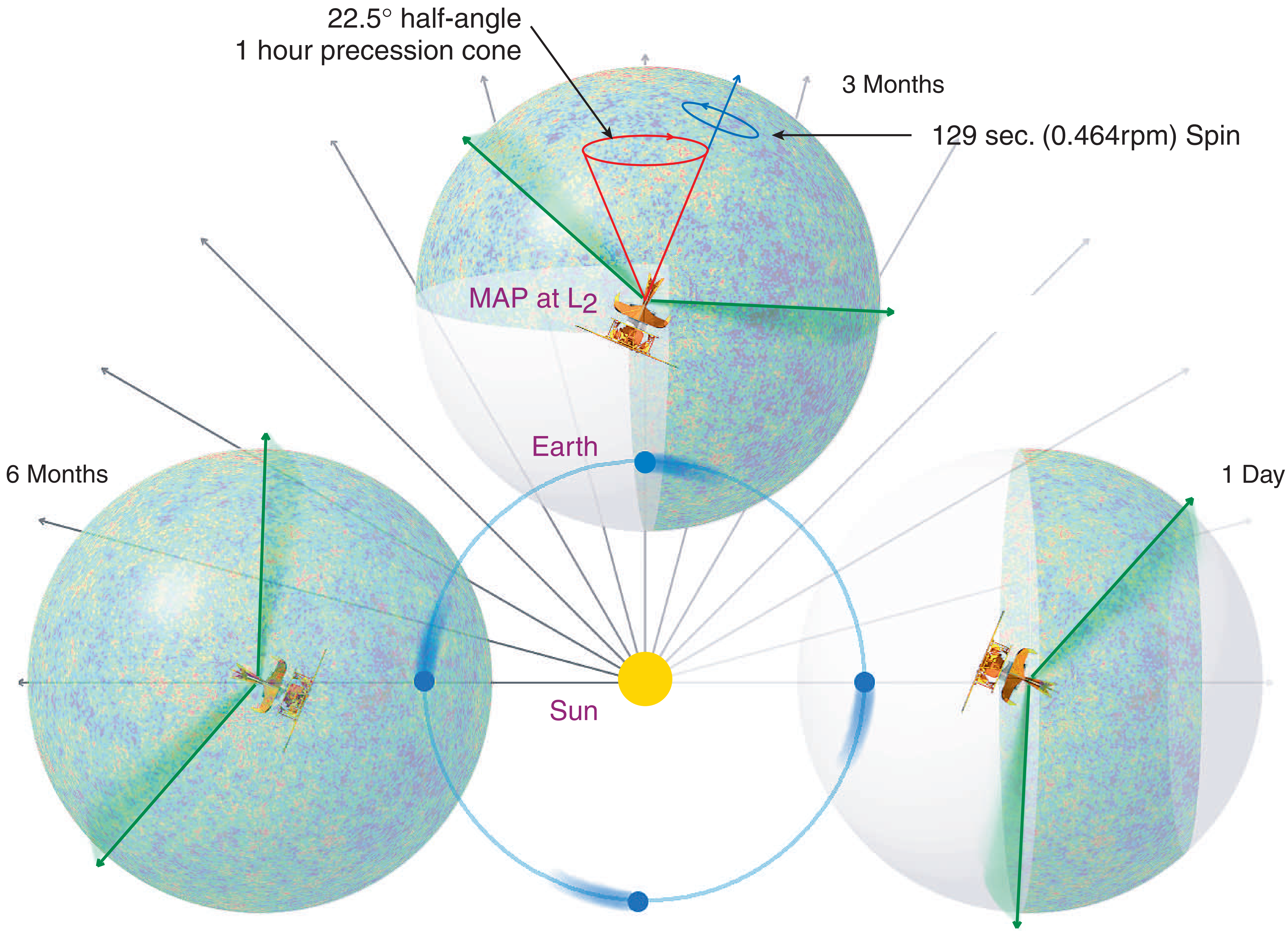
Eiichiro Komatsu (UT Austin)
Michele Limon (Columbia)
Stephan Meyer (Chicago)
Mike Nolta (CITA)
Greg Tucker (Brown)
Ned Wright (UCLA)

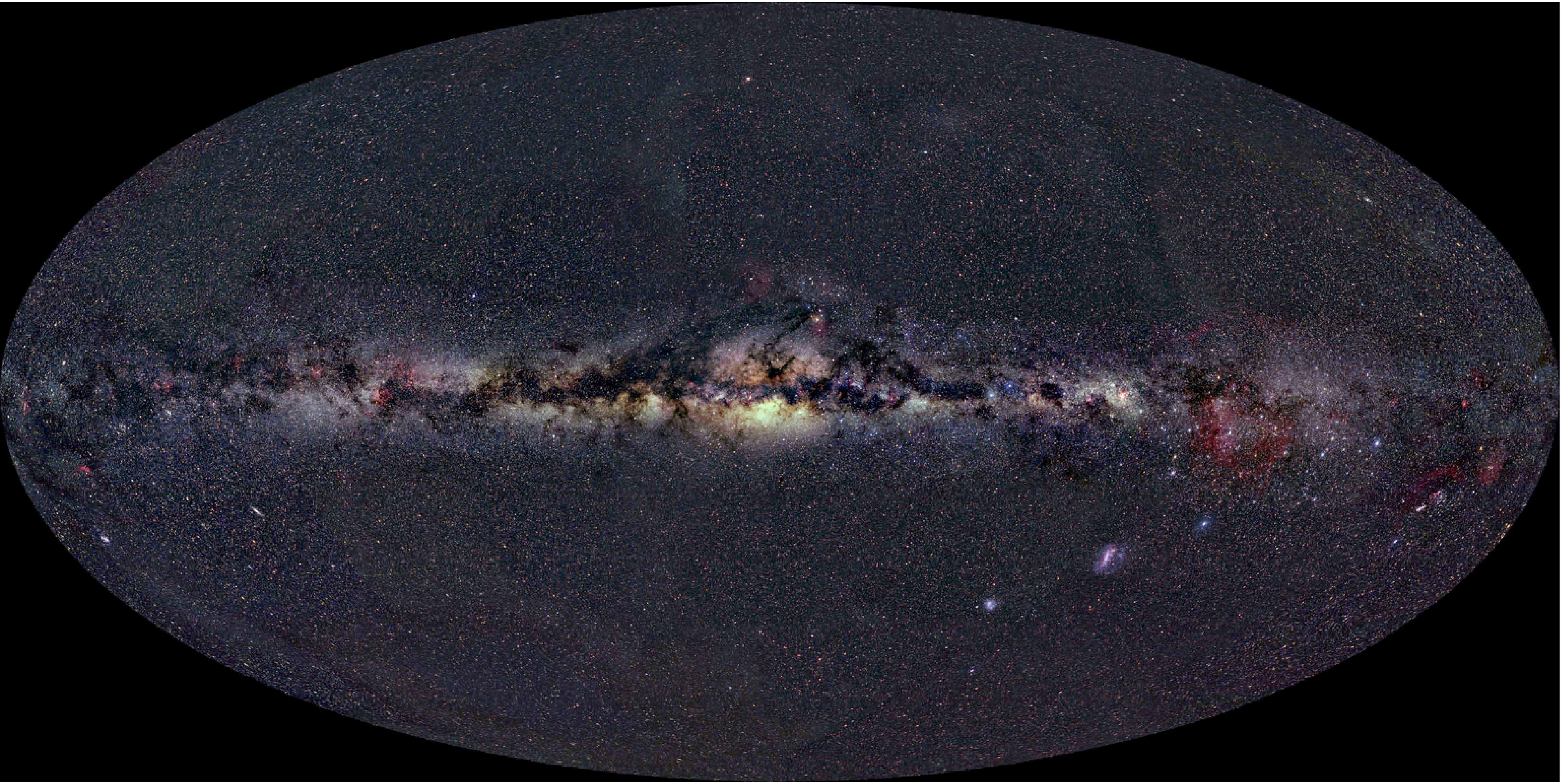
WMAP: a mm-wave differencing telescope



Scan pattern and sky coverage

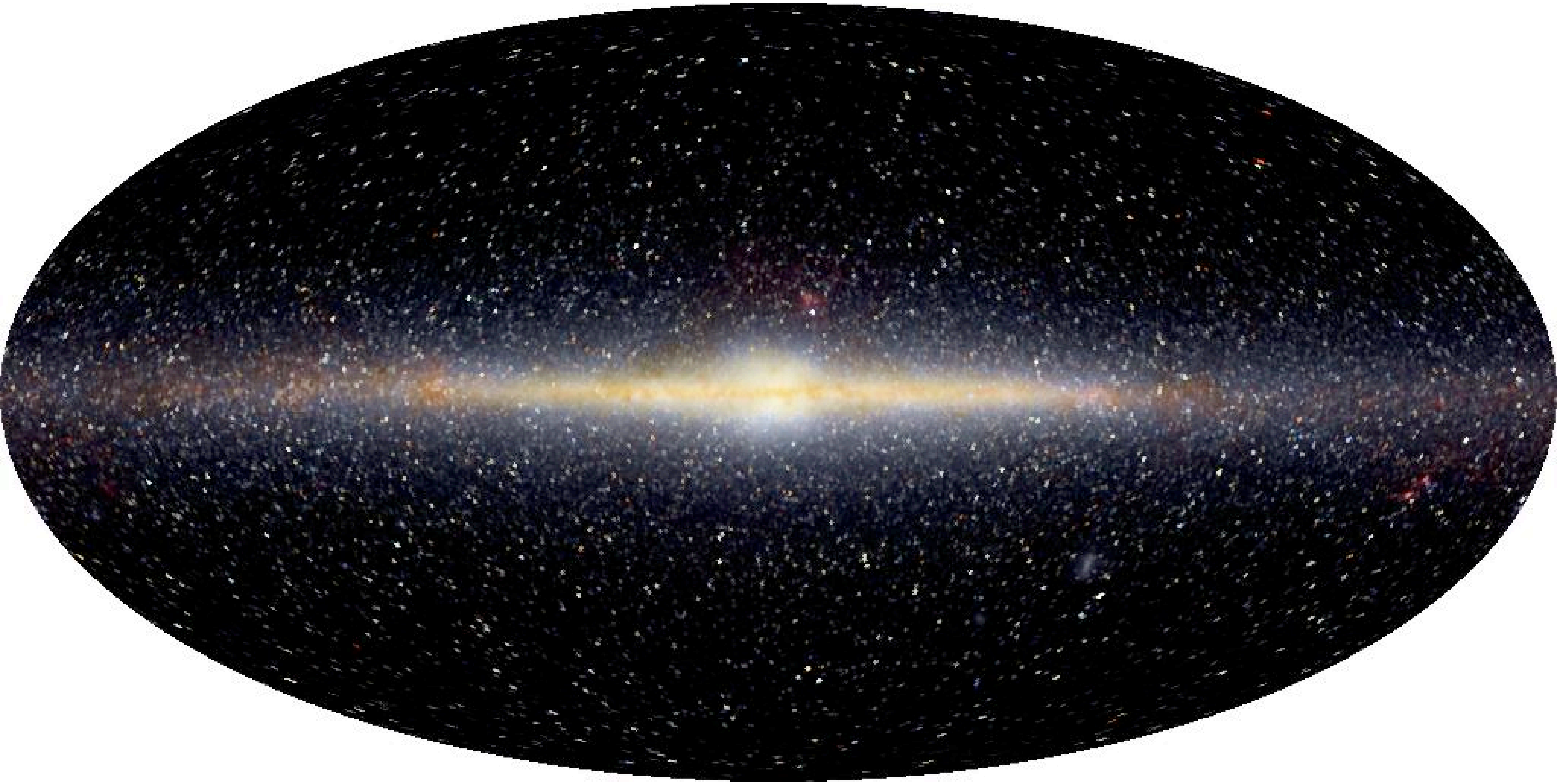


Why mm?



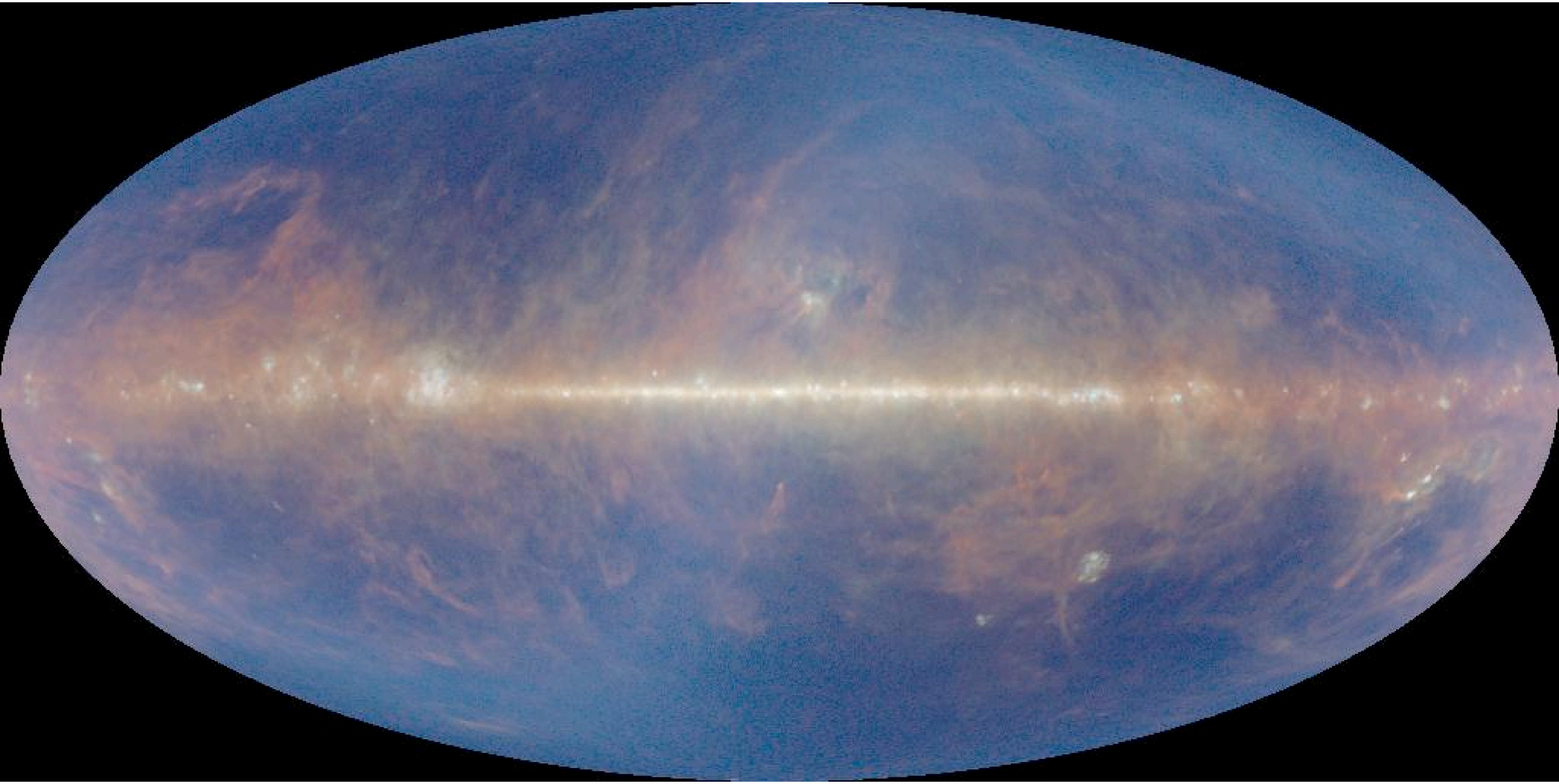
Axel Mellinger

Why mm?



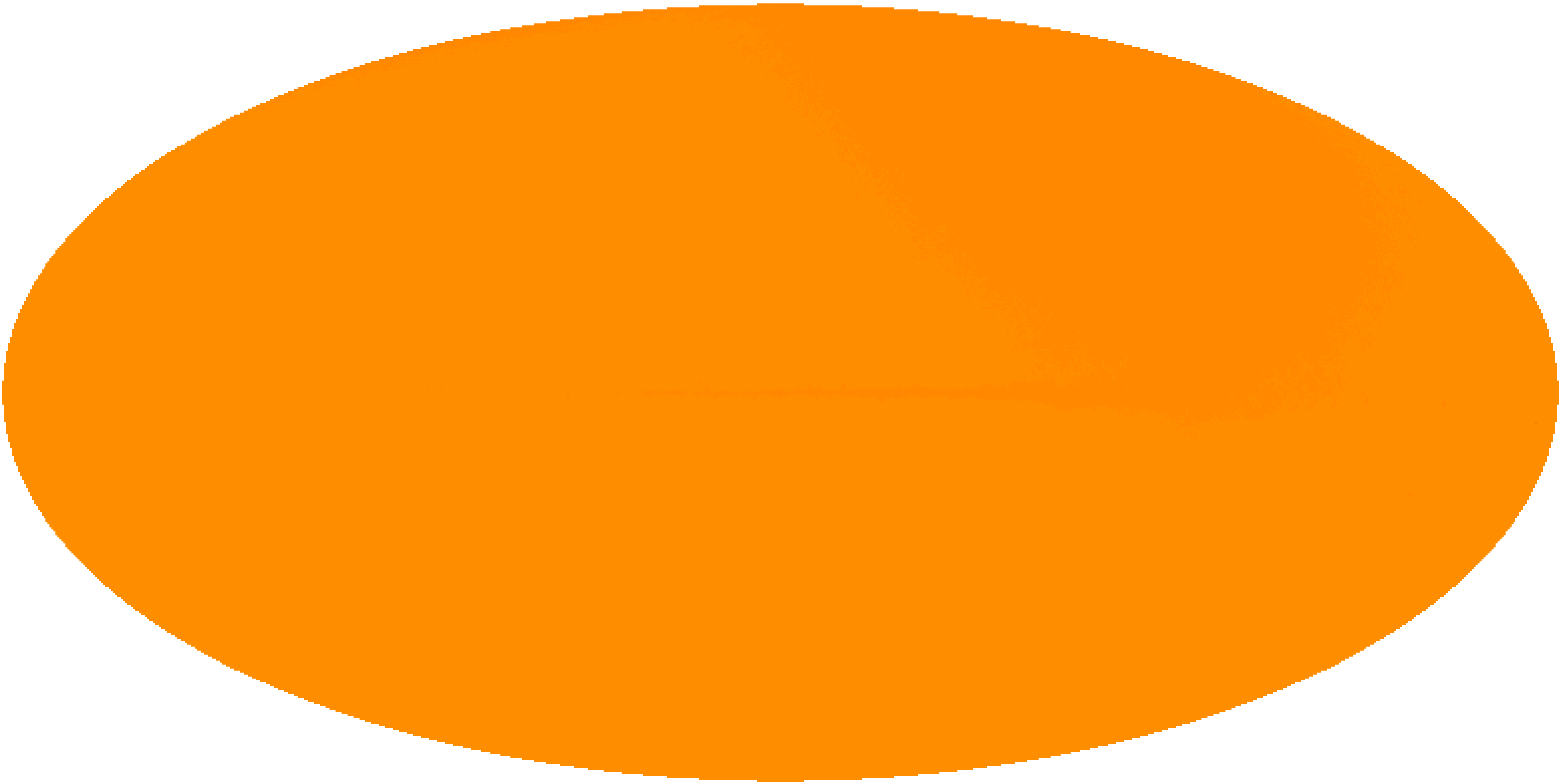
COBE DIRBE

Why mm?



COBE DIRBE

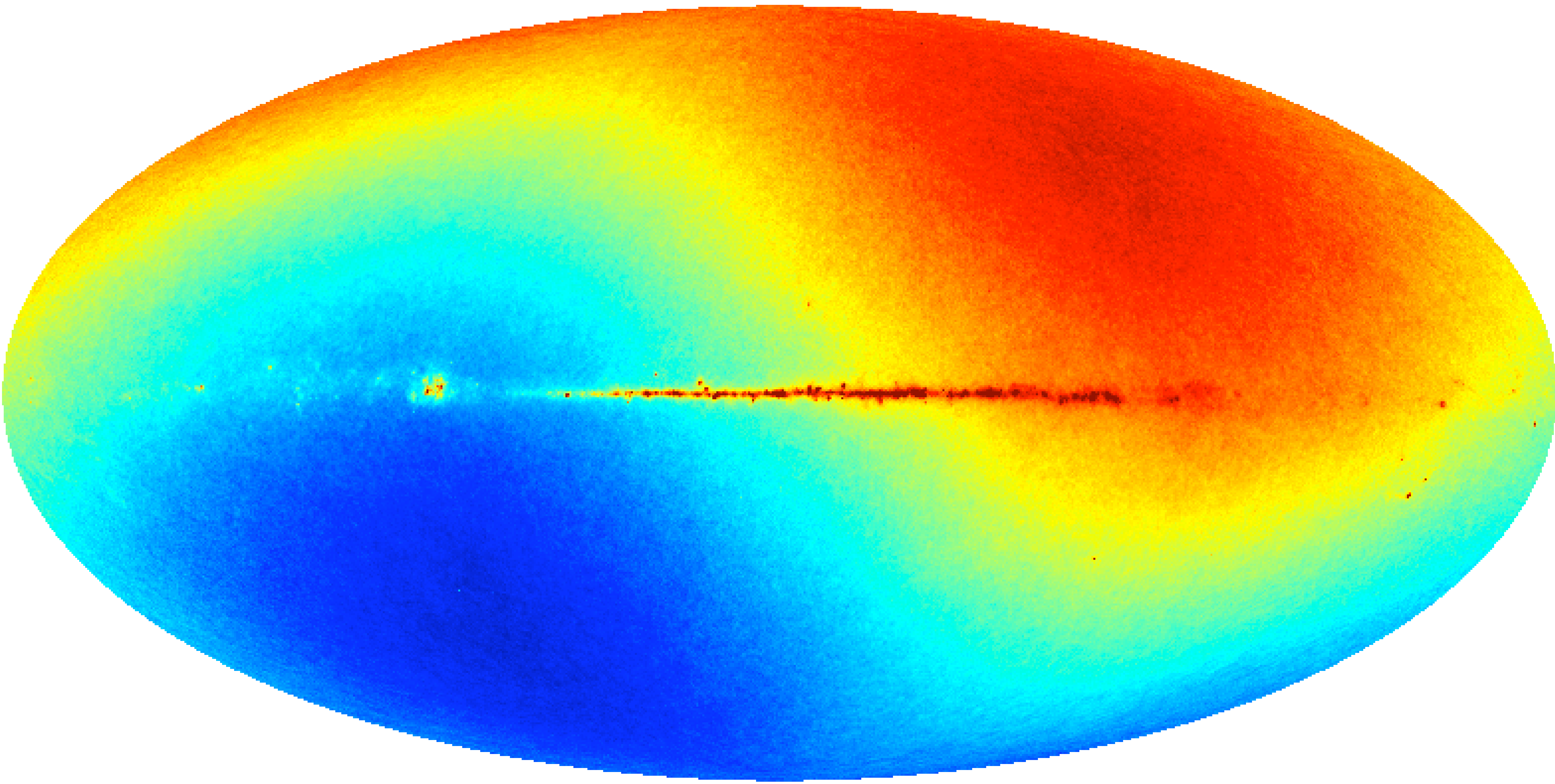
Why mm? Cosmic Microwave Background



COBE DMR+WMAP

0K to 3K

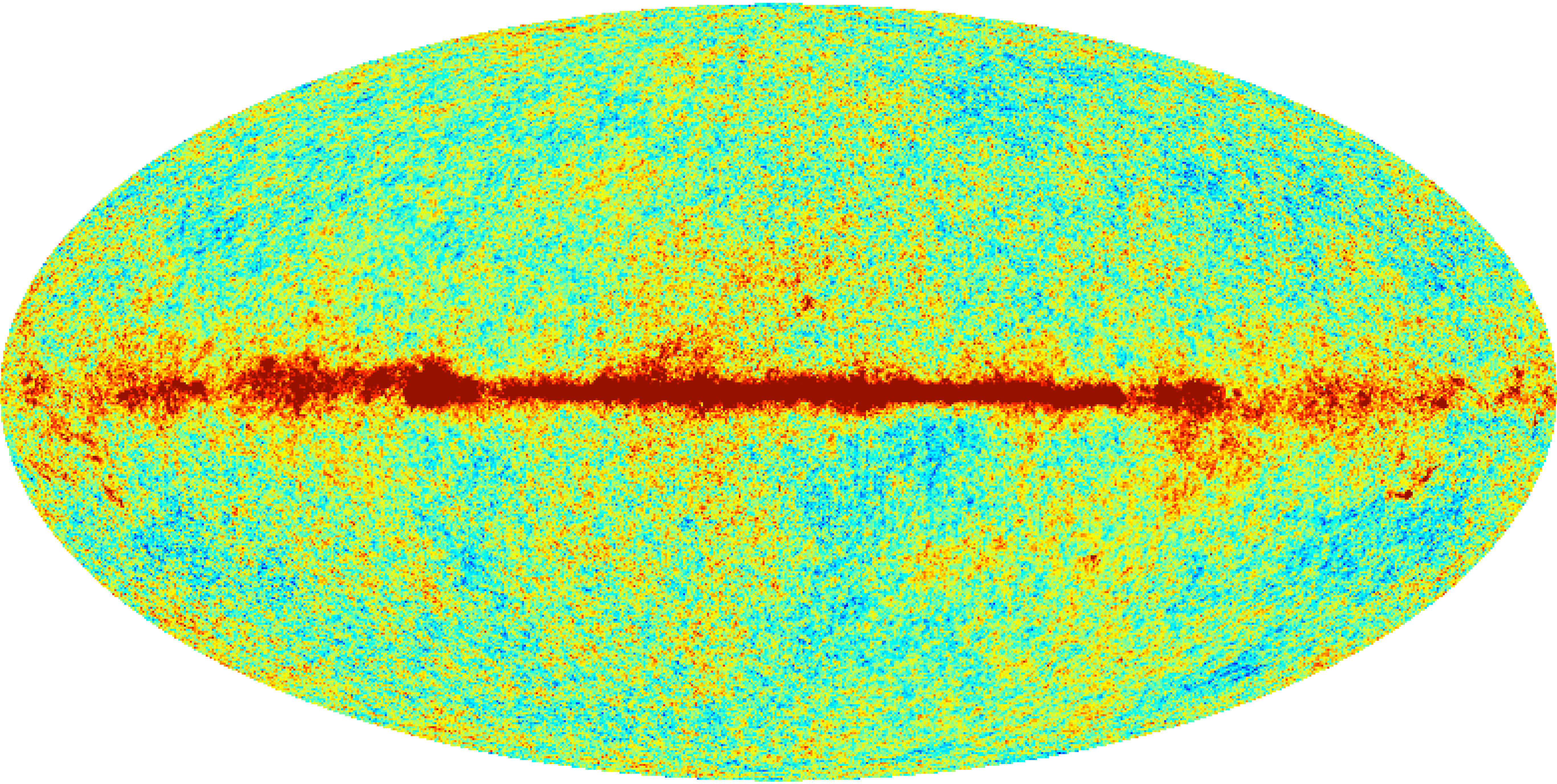
Why difference?



WMAP

-4mK to +4mK

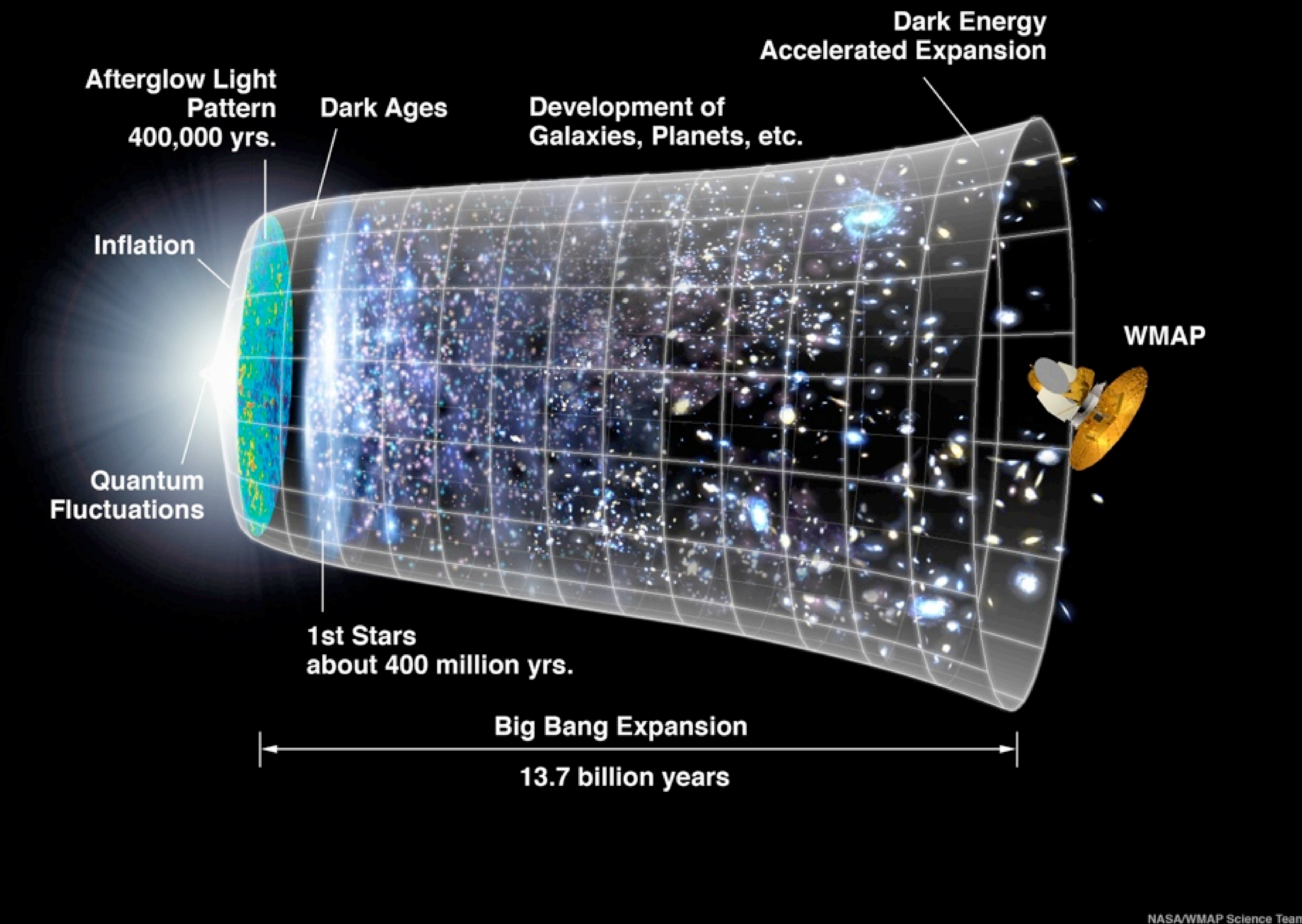
CMB fluctuations

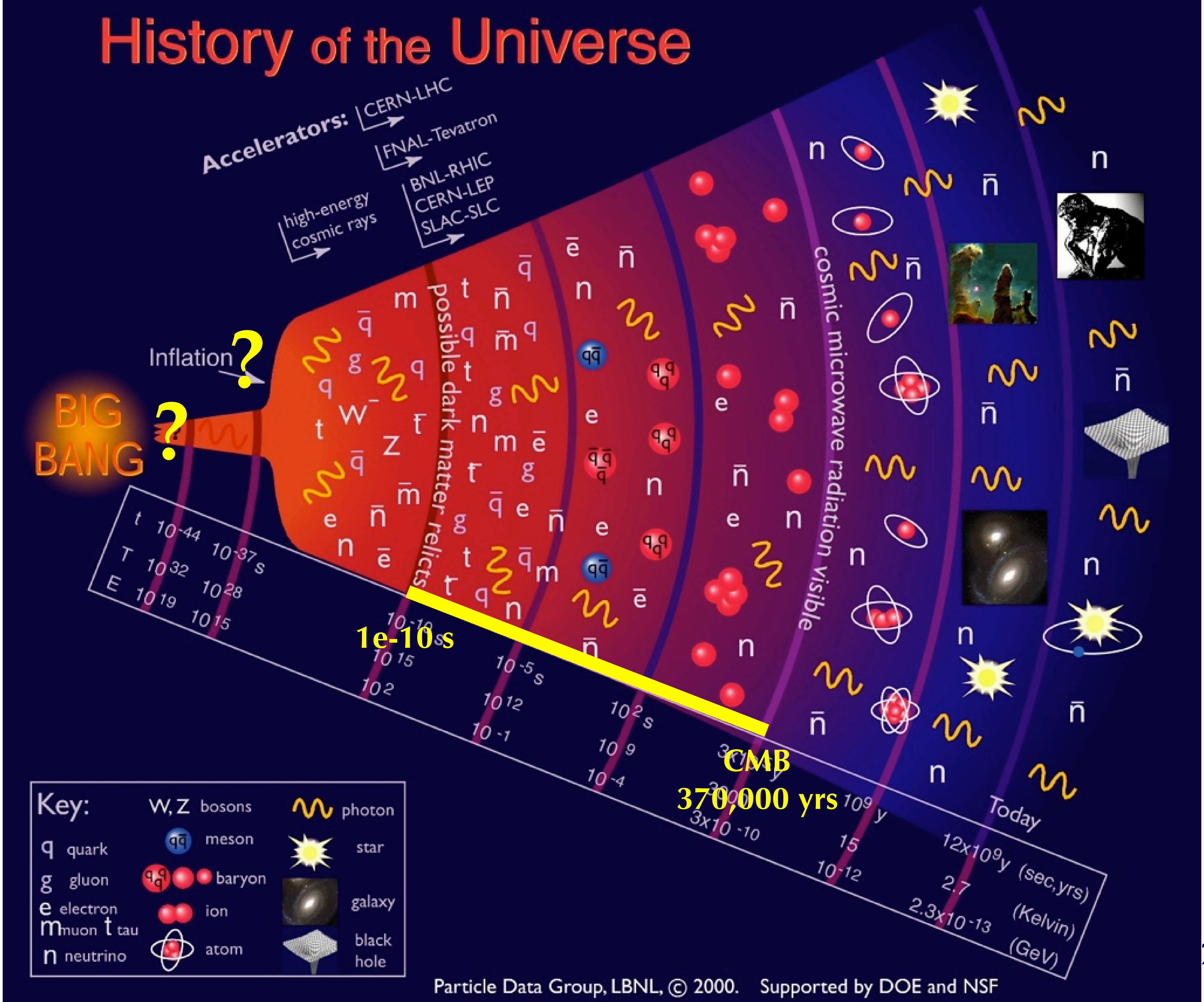


WMAP

-500μK to +500μK

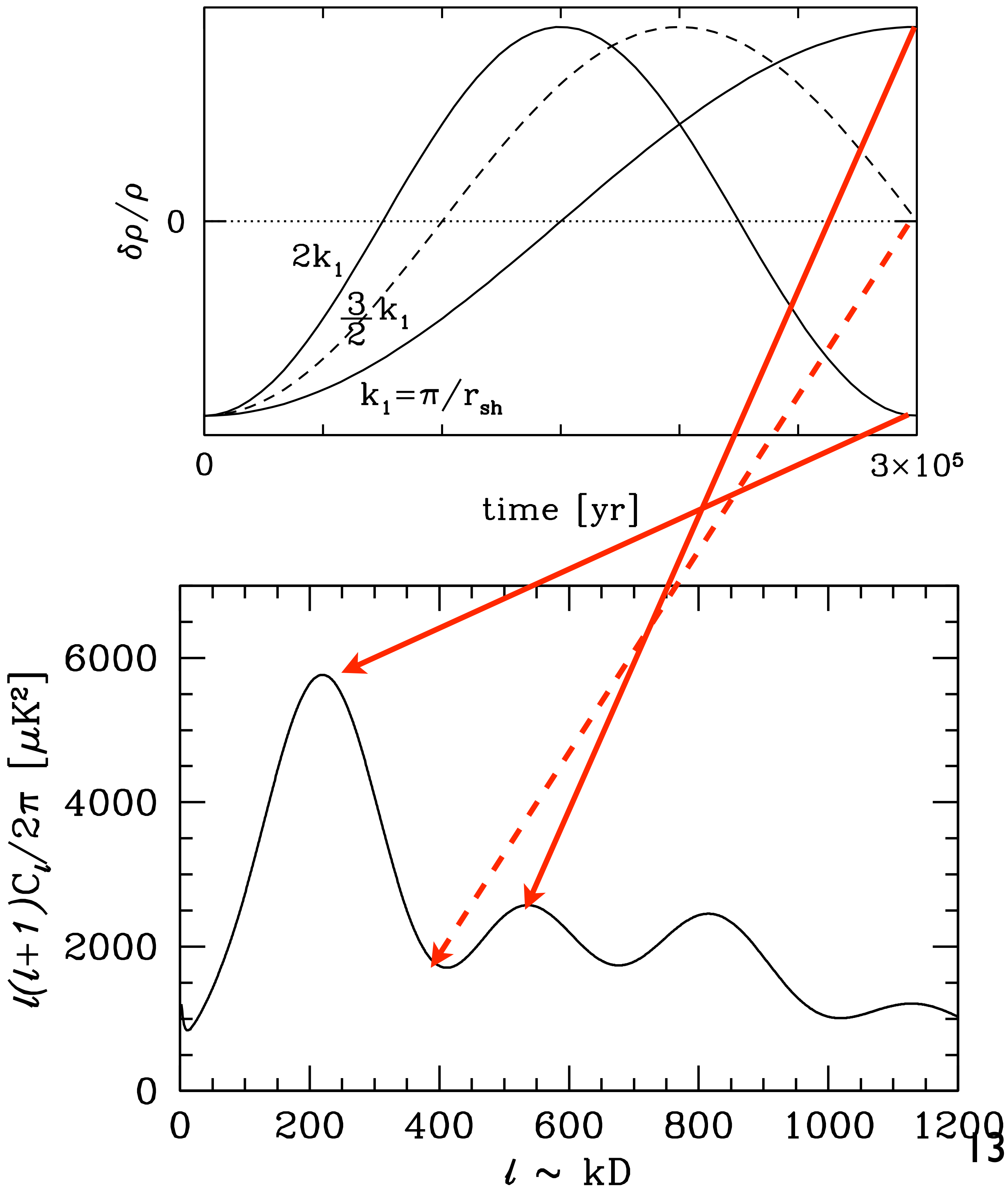
What does WMAP see?



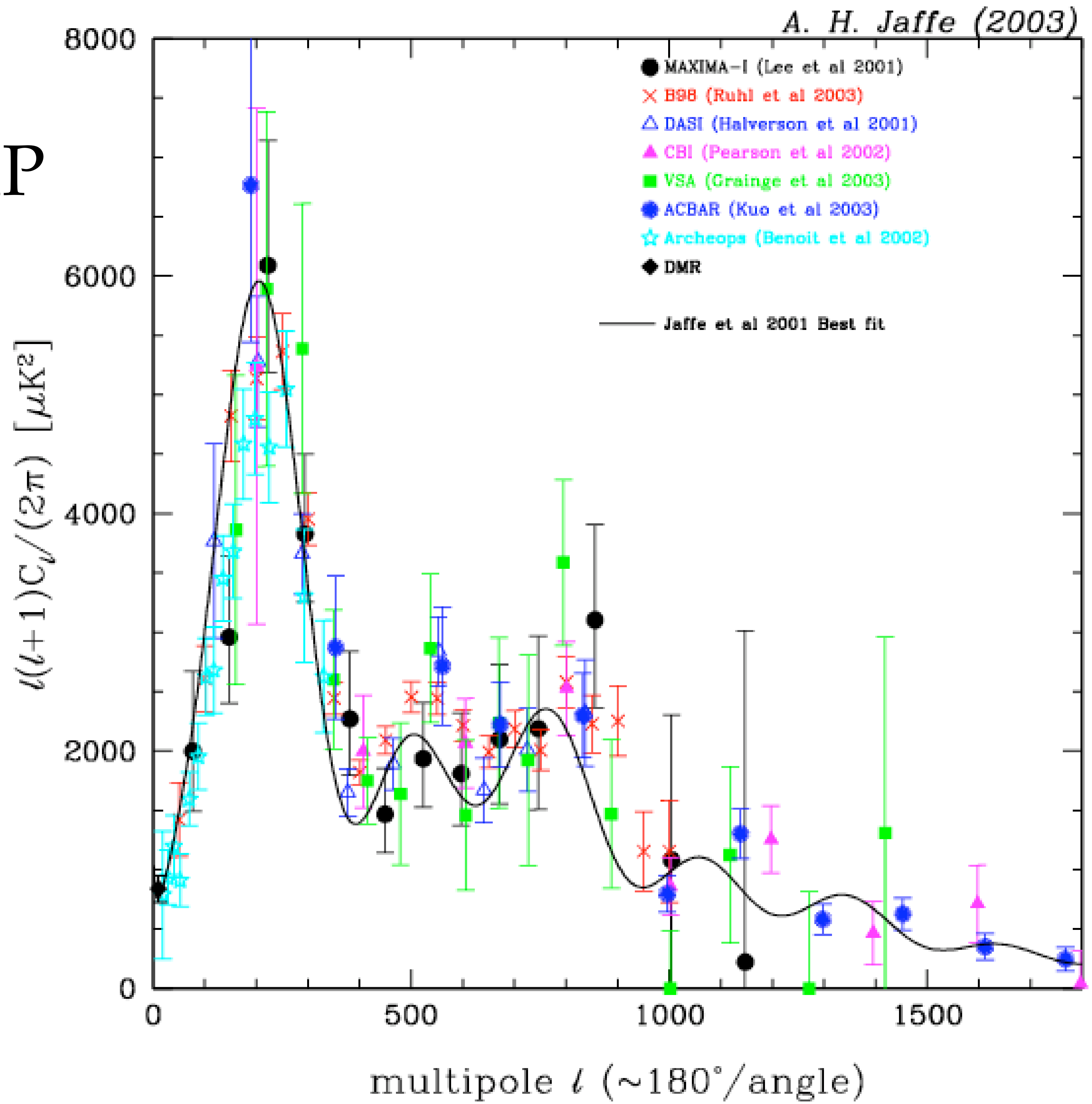

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
?
?
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
1e-10 s
CMB
370,000 yrs
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

CMB: Plasma Acoustic Oscillations

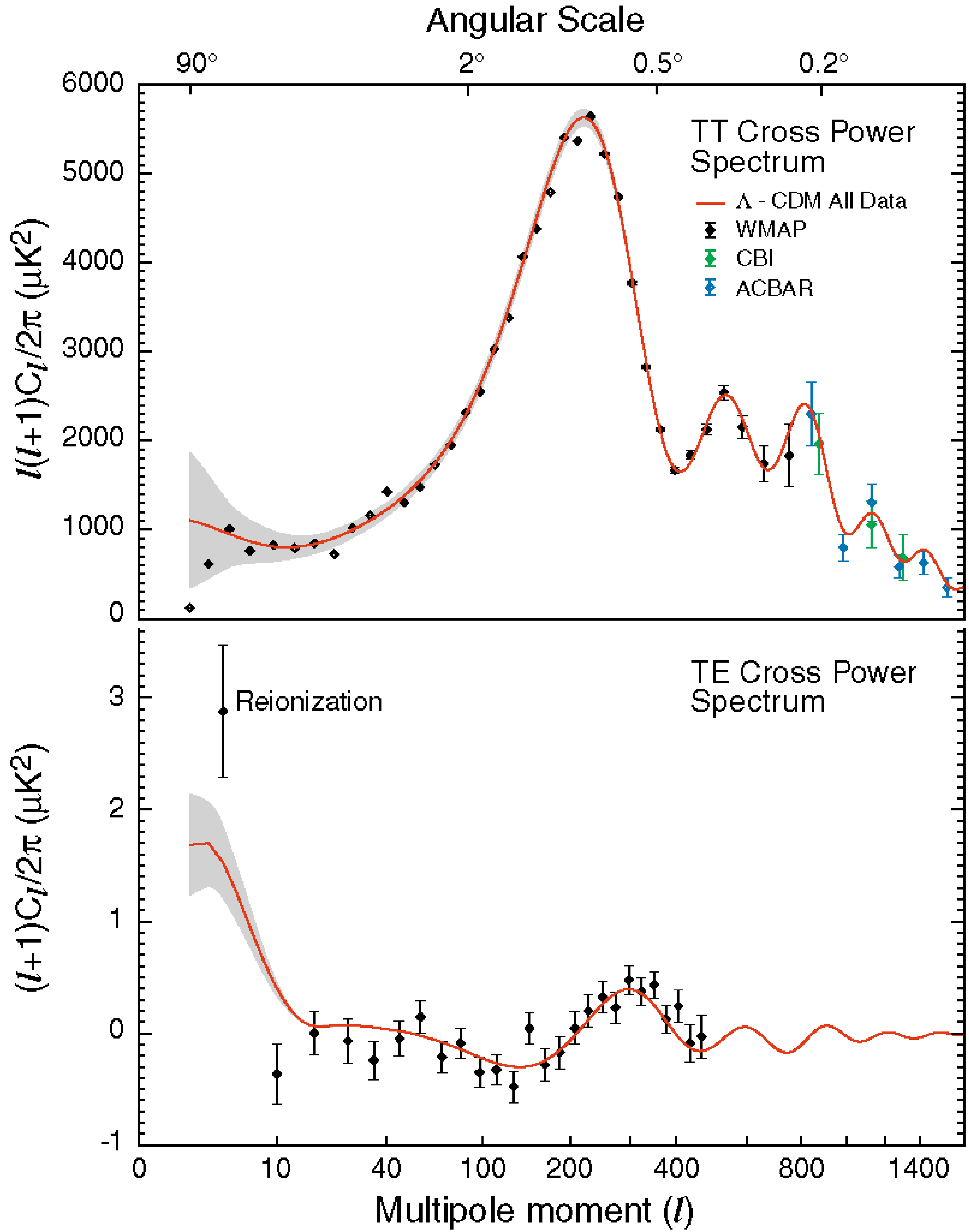
- perturbation theory on a FLRW background
- plasma physics at accessible energies
- result: acoustic waves
- phase is important



before WMAP

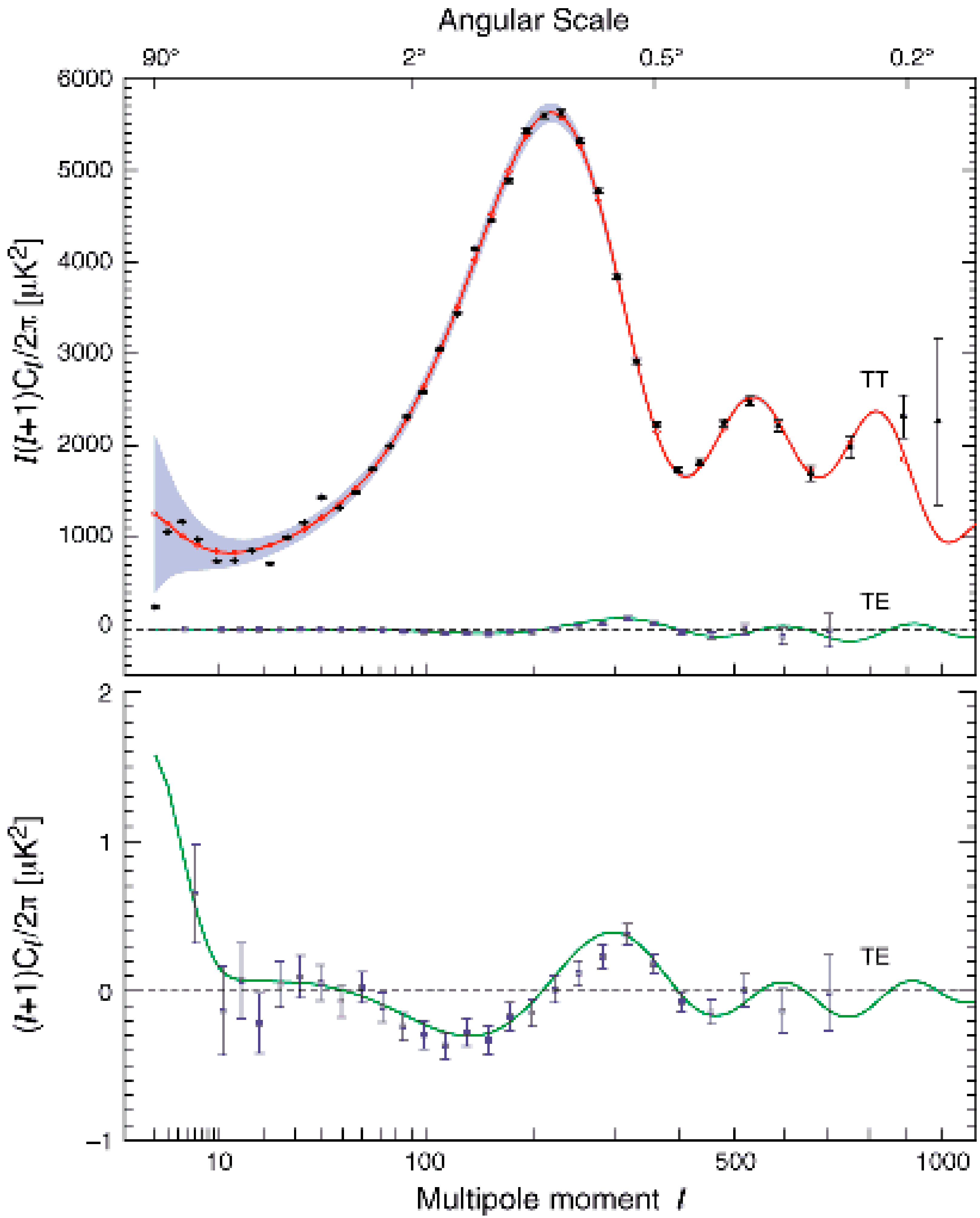

A. H. Jaffe (2003)
8000
6000
4000
2000
0
0
500
1000
1500
MAXIMA-I (Lee et al 2001)
B98 (Ruhl et al 2003)
DASI (Halverson et al 2001)
CBI (Pearson et al 2002)
VSA (Grainge et al 2003)
ACBAR (Kuo et al 2003)
Archeops (Benoit et al 2002)
DMR
Jaffe et al 2001 Best fit
$\ell(\ell+1)C_\ell/(2\pi)$ $[\mu K^2]$
multipole ℓ (~180°/angle)

1yr WMAP

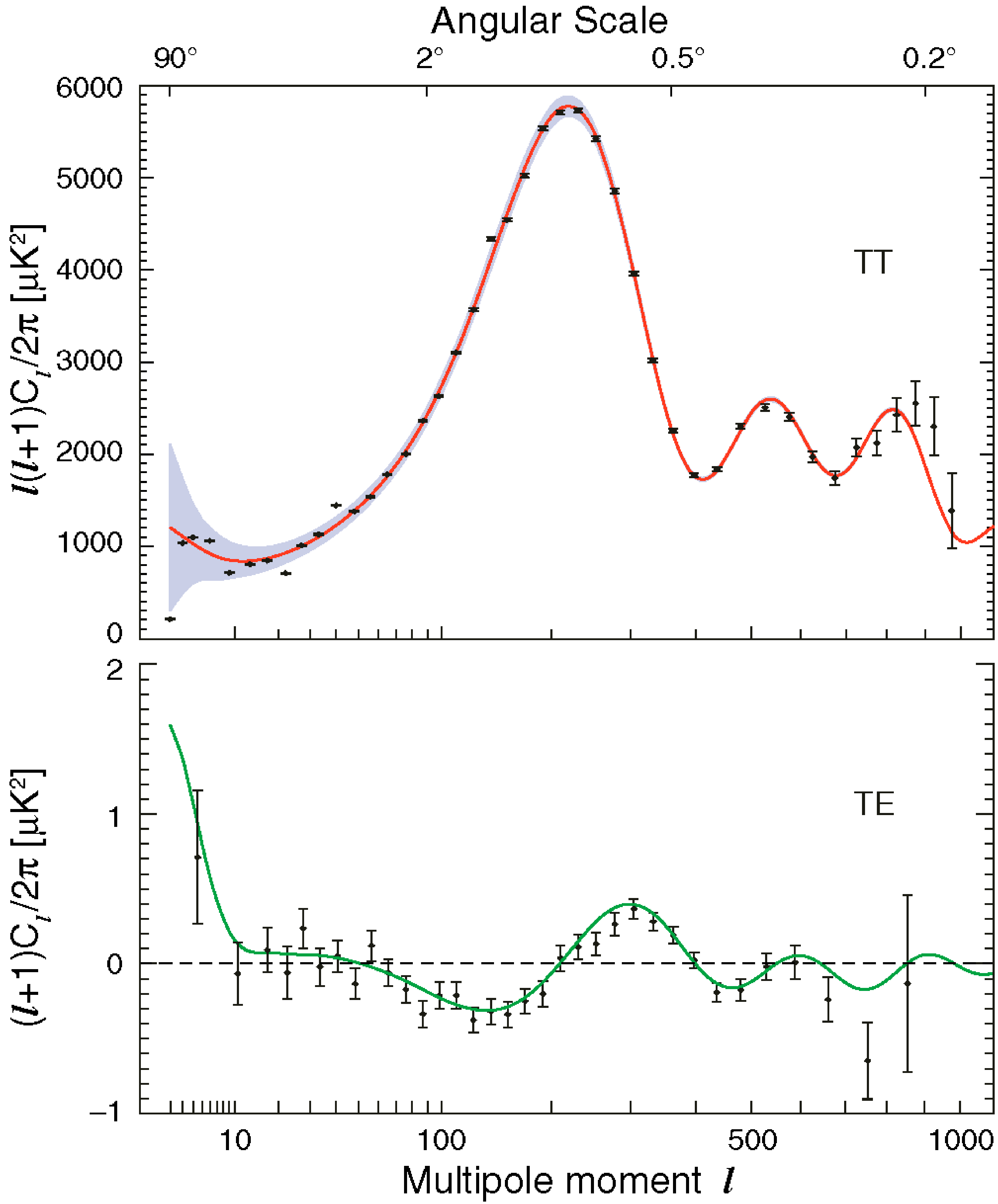


(CMB is 1% polarized, polarization is 180° out of phase, cross-correlation is thus 90° out of phase)

3yr WMAP


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
TT
TE
2
1
0
−1
$(l+1)C_l/2\pi$ [μK^2]
TE
10
100
500
1000
Multipole moment l

5yr WMAP

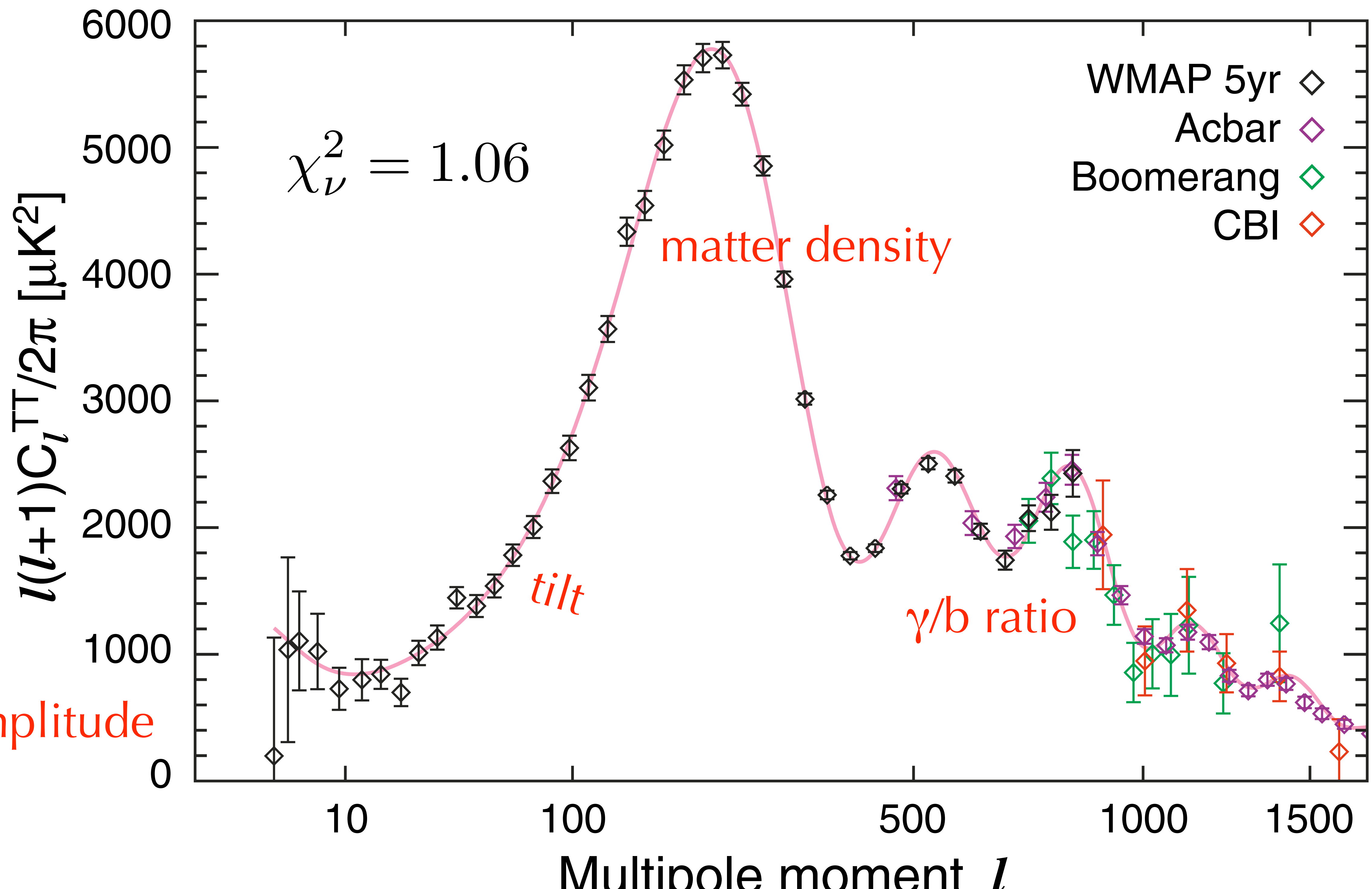

Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT
l(l+1)C_l/2π [μK²]
2
1
0
−1
TE
(l+1)C_l/2π [μK²]
10
100
500
1000
Multipole moment l

The Concordance Model

- Six parameter curve fits hundreds of independent data points!
- No need (yet) for other interesting parameters
- 2 initial conditions, 2 particle params, 1 astro param, 1 geometric param, plus upper limits/assumptions about others

	Parameter	5 Year Mean (WMAP only)	
γ/b ratio	$100\Omega_b h^2$	2.273 ± 0.062	**~¼ atom per m^3**
matter density	$\Omega_c h^2$	0.1099 ± 0.0062	**~1.2 GeV per m^3**
distance to LSS	Ω_Λ	0.742 ± 0.030	**~(1.8 meV)^4**
tilt	n_s	$0.963^{+0.014}_{-0.015}$	**potential shape**
pol'n bump	τ	0.087 ± 0.017	**~9% rescattered**
amplitude	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$	**potential shape**

The Concordance Model



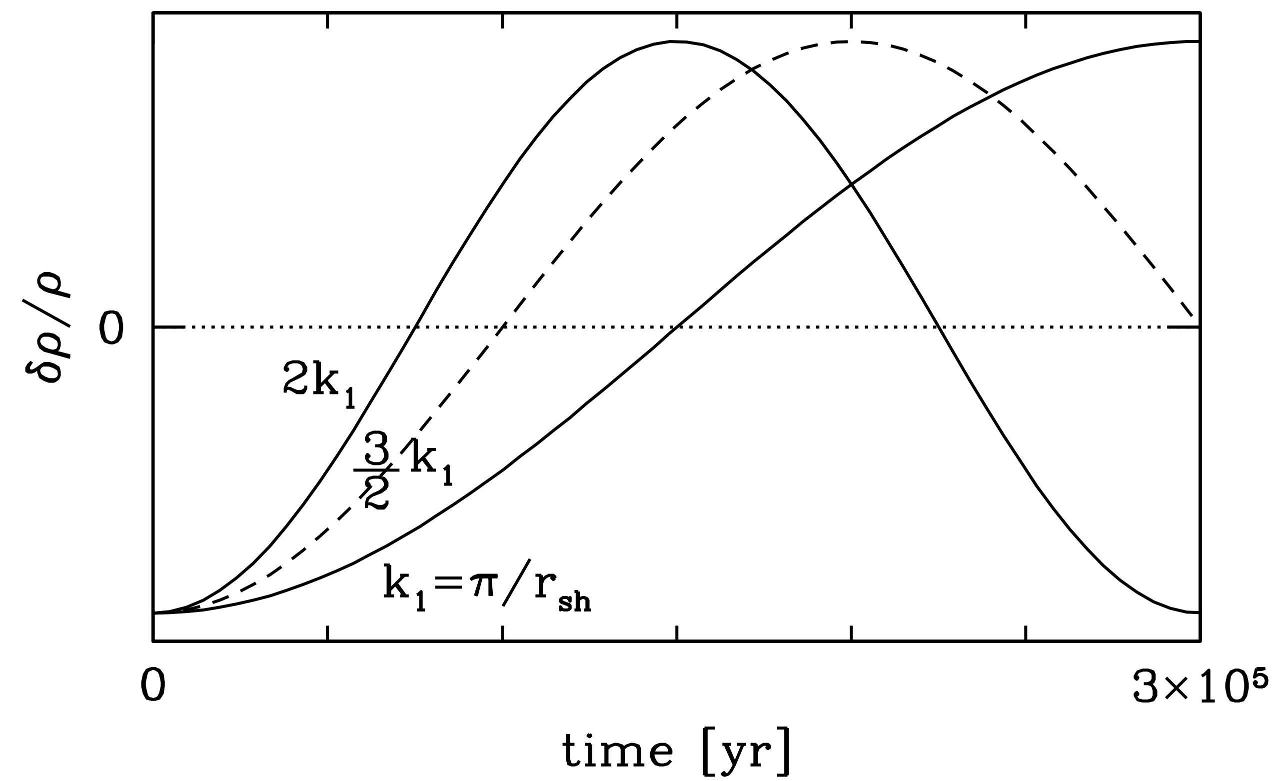
amplitude

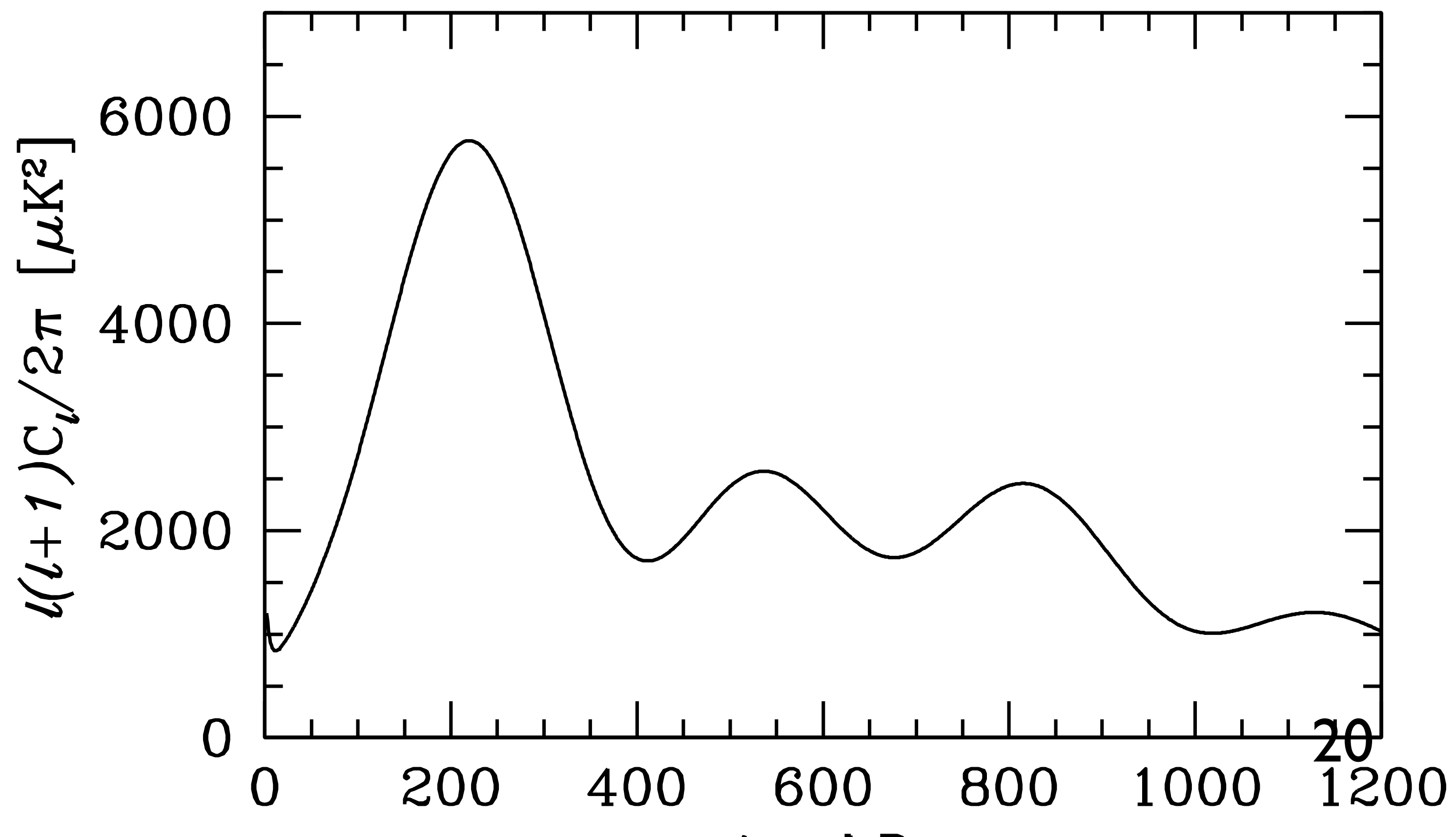
distance to LSS

What set the initial conditions?

- needs to produce density perturbations "in phase"
- needs to be roughly scale invariant
- would be nice to solve horizon and curvature problems
- might be nice to clean up weird relics (monopoles?)

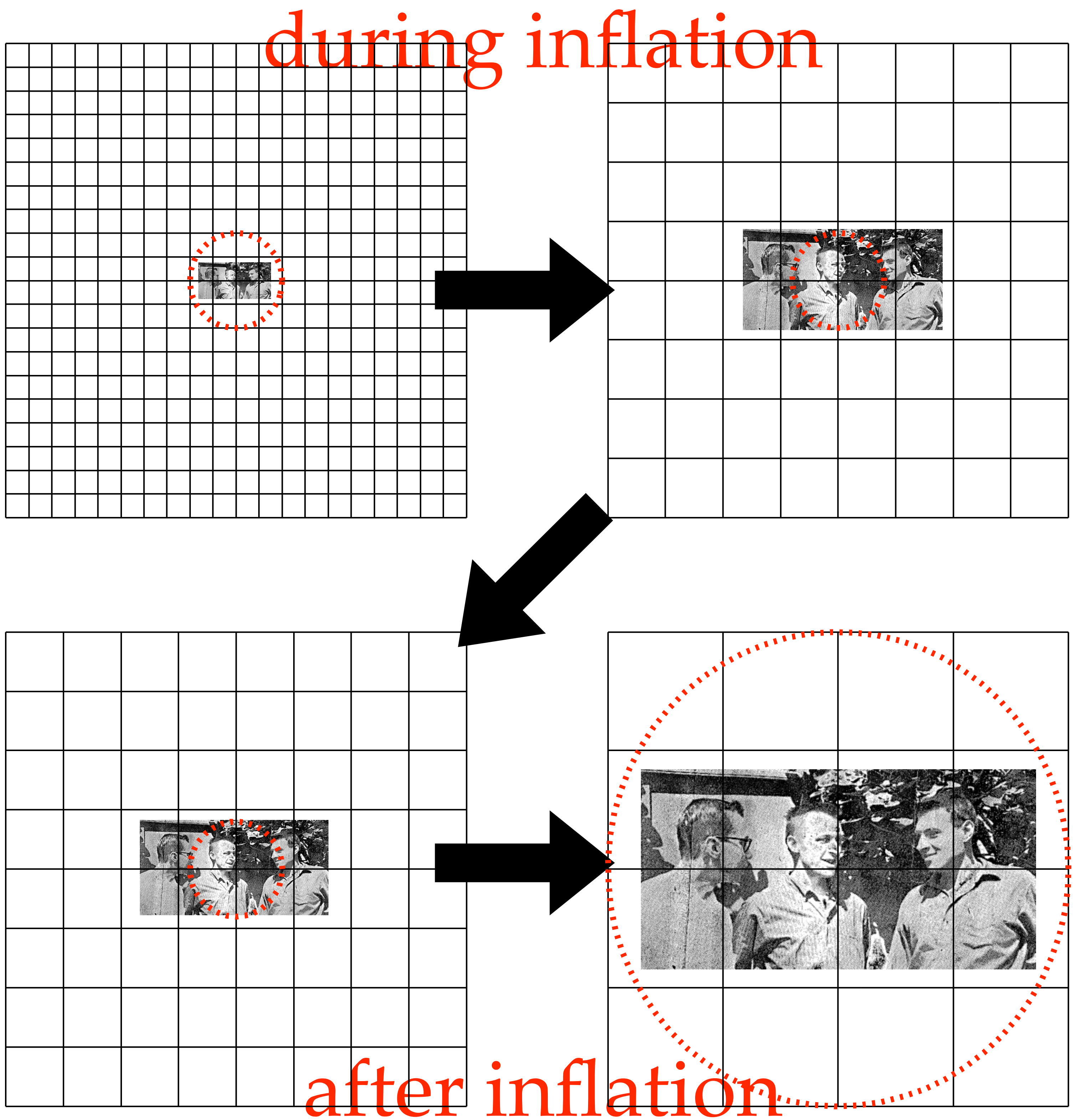
Inflation?





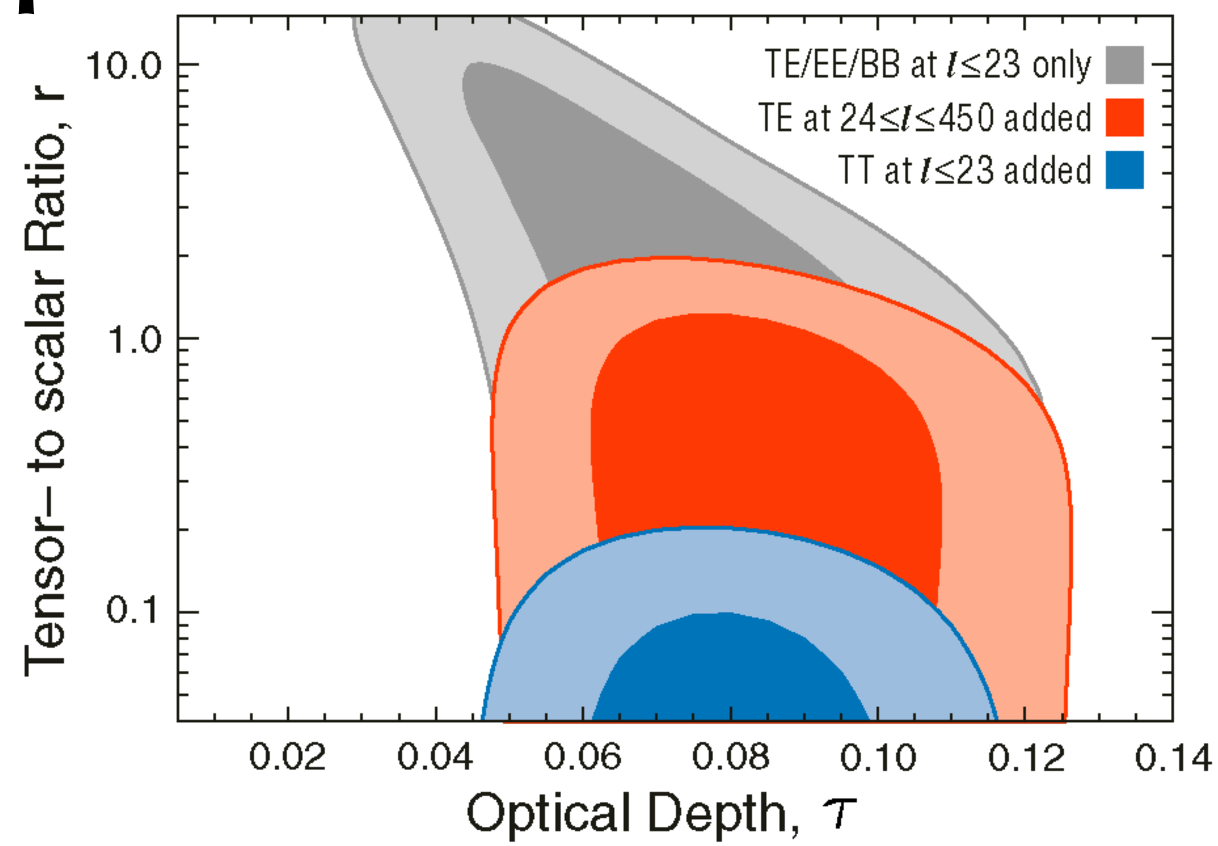
Inflation

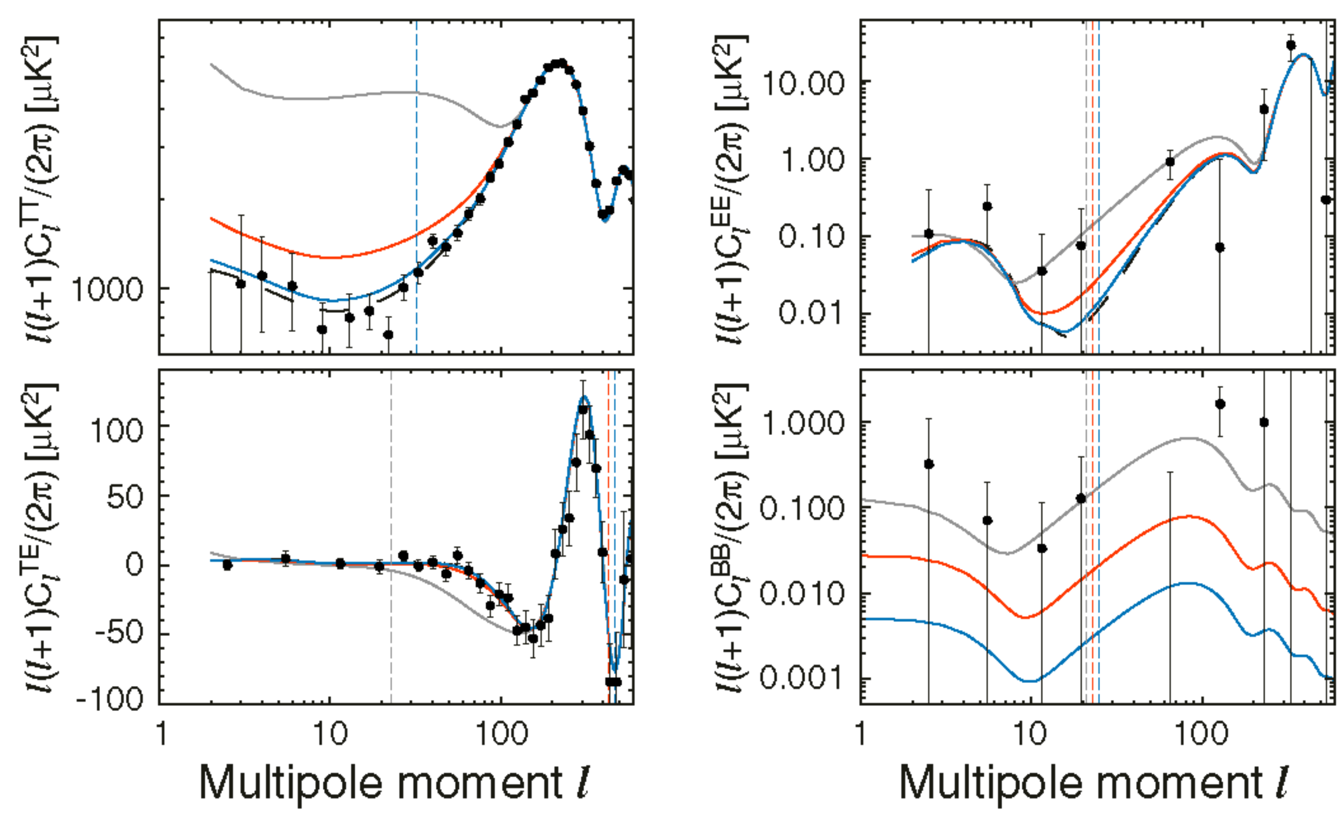
- early phase of accelerating expansion solves horizon, flatness, and relic issues
- for inflation to end, use a dynamical entity: a scalar field
- quantum fluctuations become initial density perturbations, with zero velocity
- there are more implications from this model!



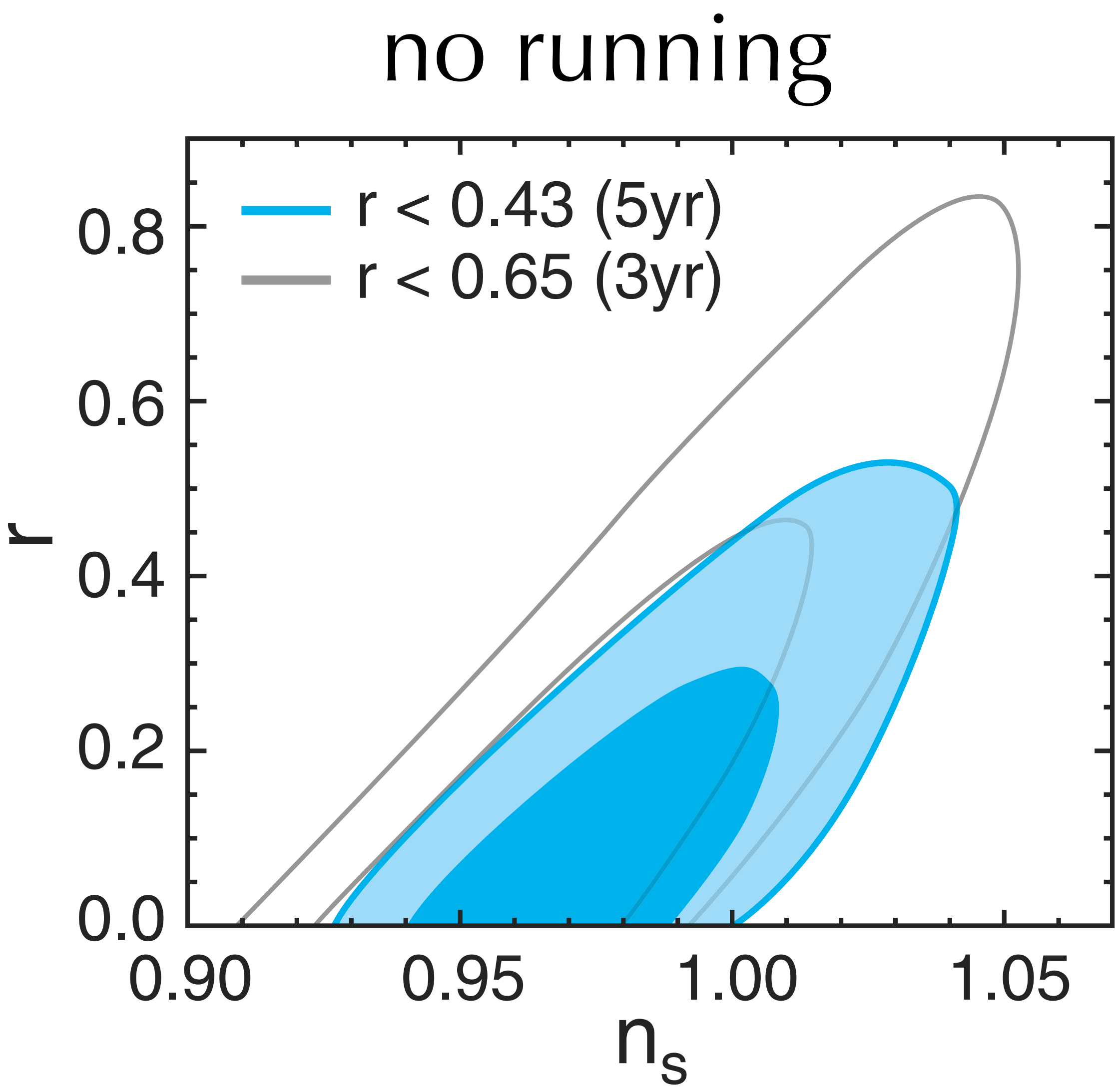
Inflation parameters

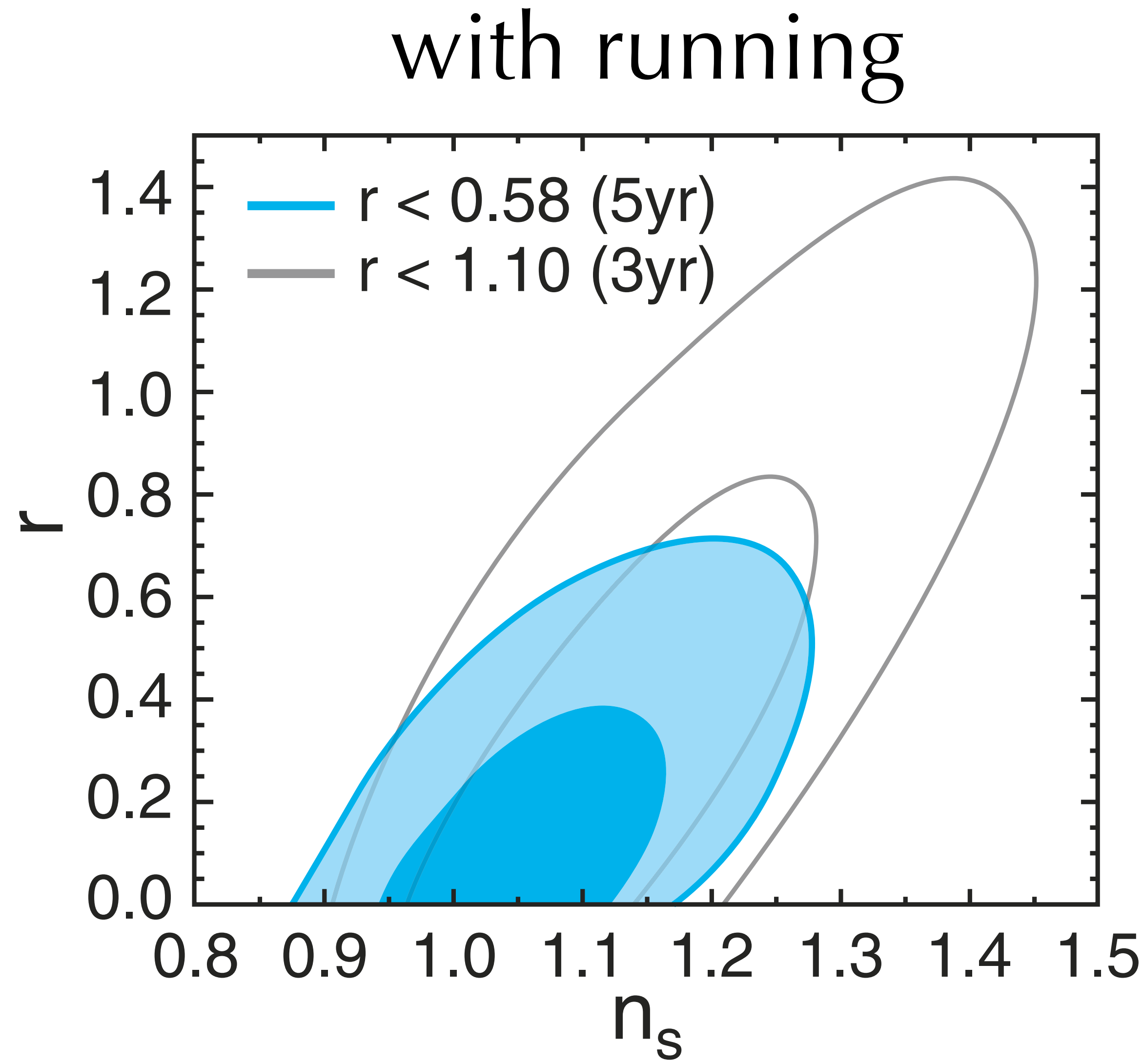
- gravity wave amplitude is proportional to energy scale of inflation
- large enough gravity waves cause large-scale density fluctuations themselves
- further constraints require polarization





Inflation parameters



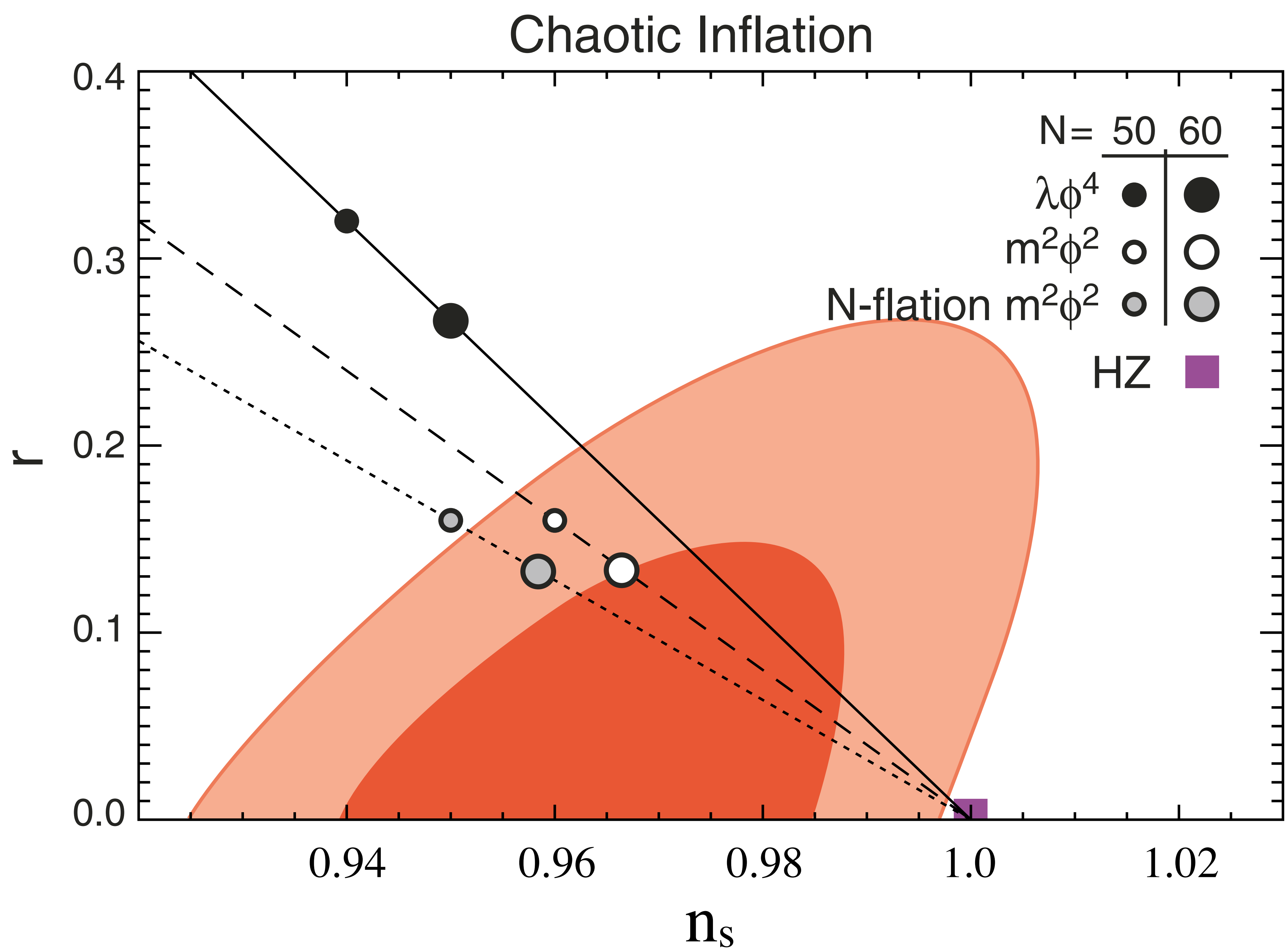


(WMAP only)

3yr to 5yr is not just $\sqrt{t}$!

Inflation parameters

- N < 70 for post-Planck inflation
- ϕ^4 very disfavored!
- r–n_S combo pushing on theory

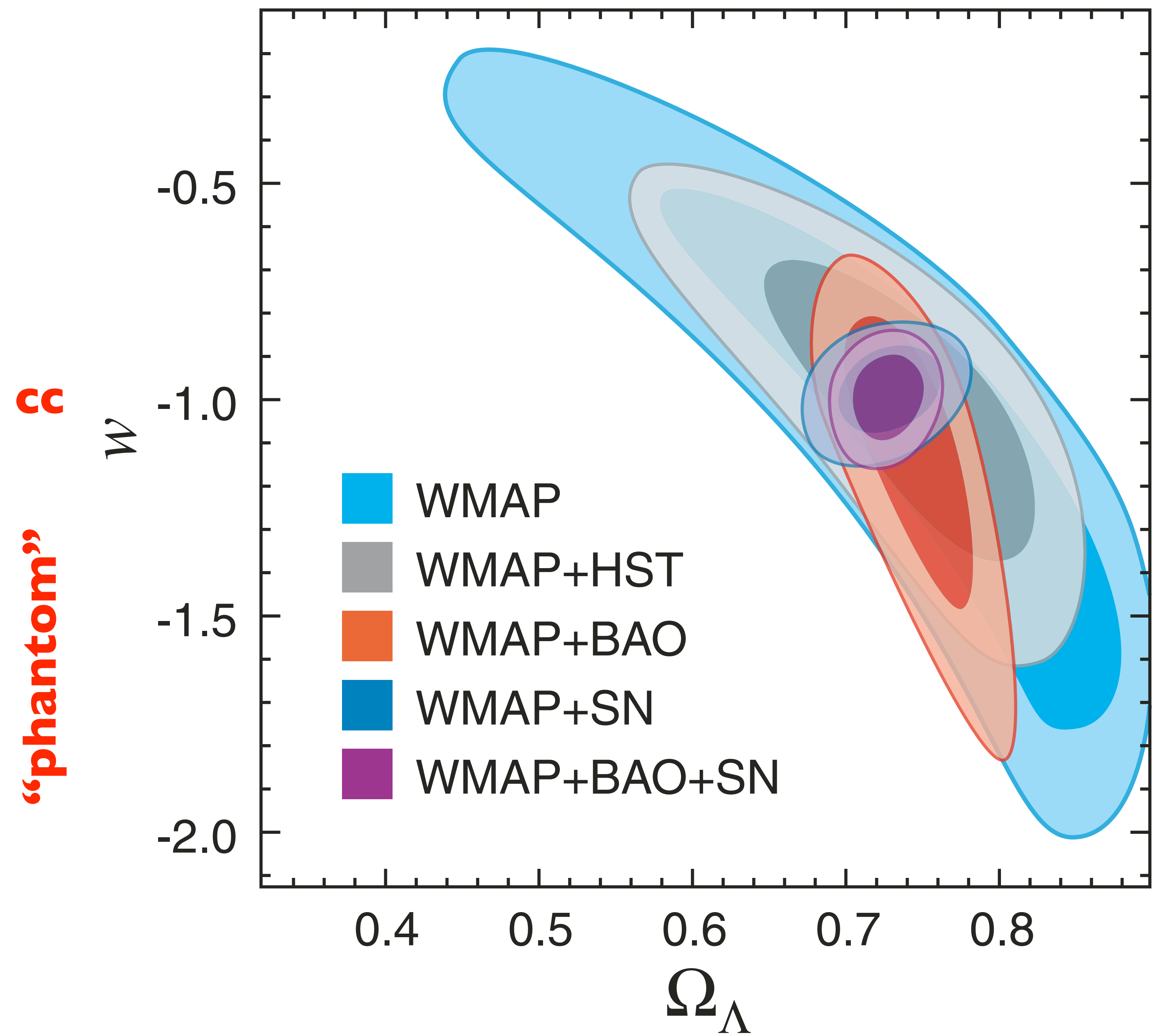


Beyond the concordance model

- tensor (gravitational wave) amplitude
- non-Λ dark energy
- scale-invariant scale-invariance (running of the index)
- axionic/other non-inflationary generation of perturbations
- neutrino mass

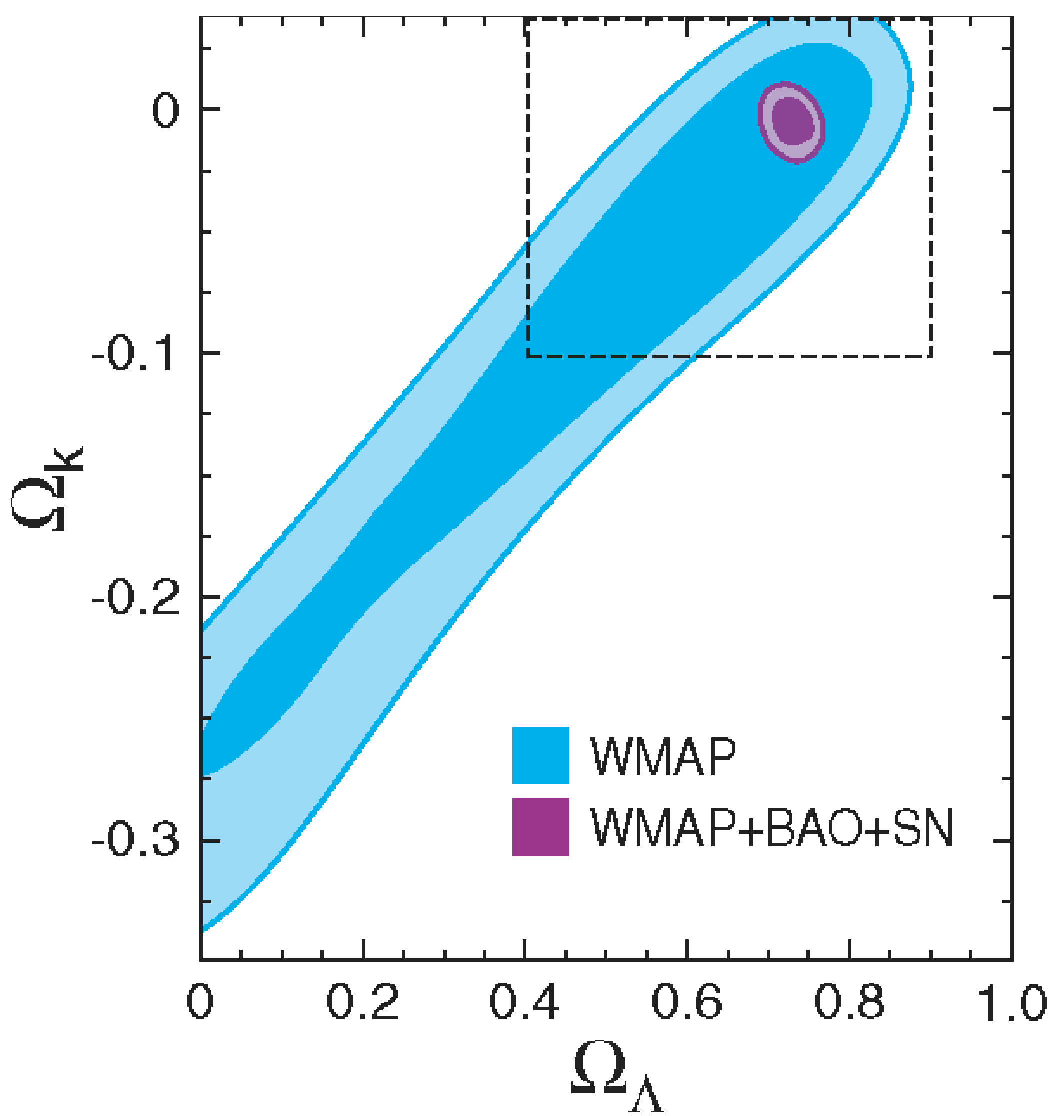
Non-Λ Dark energy

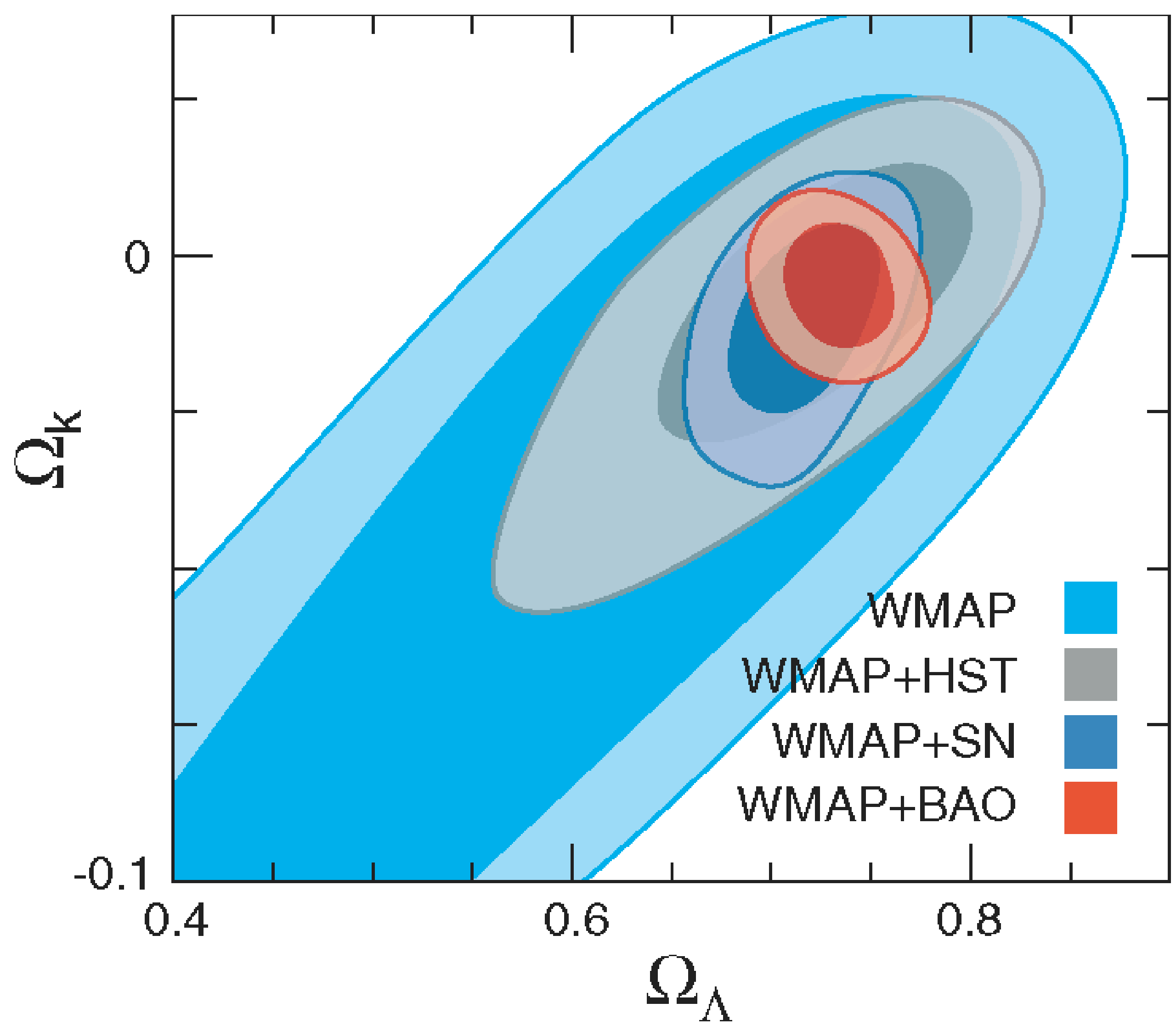
assume flatness



Dark energy

don't assume flatness

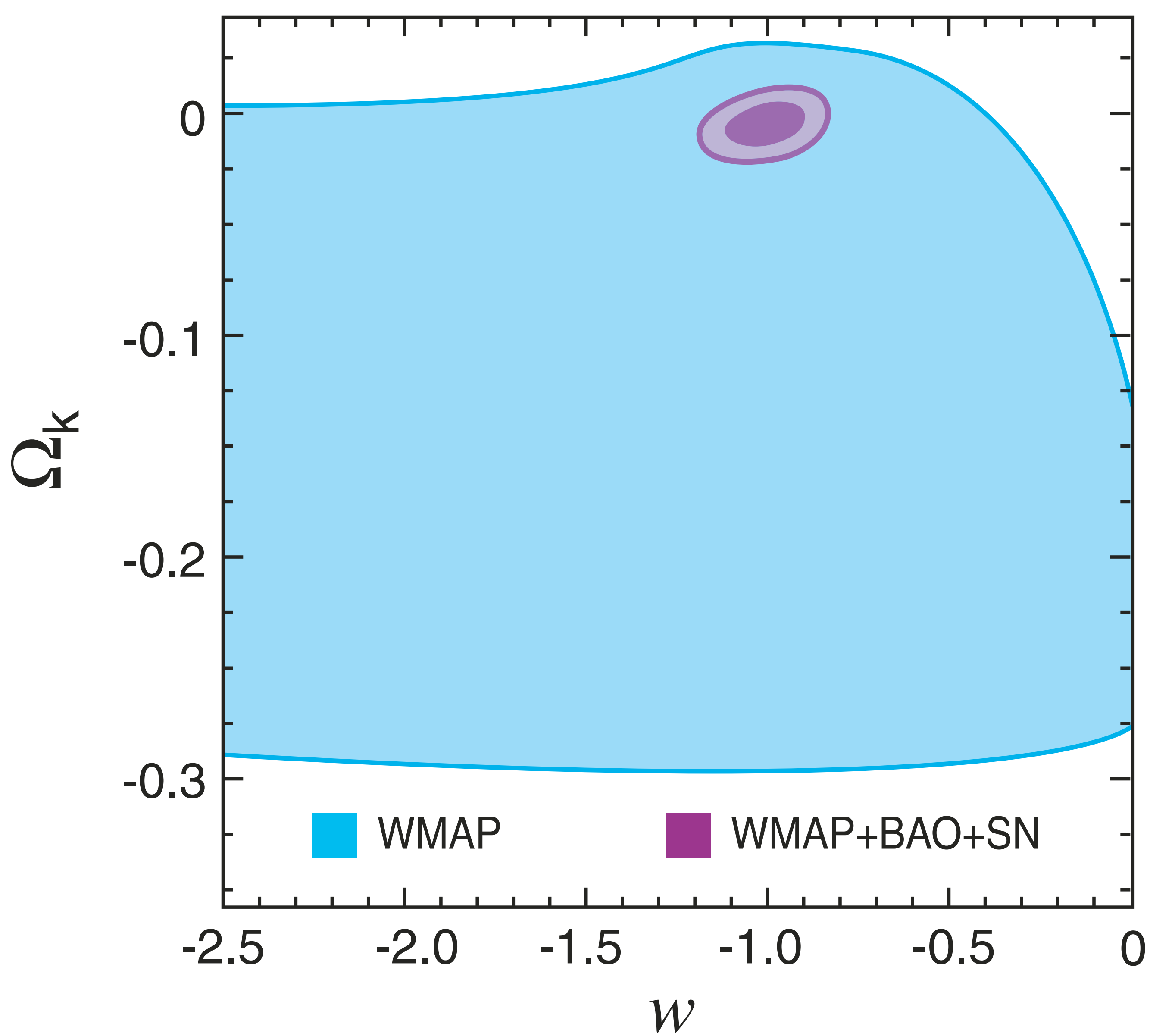


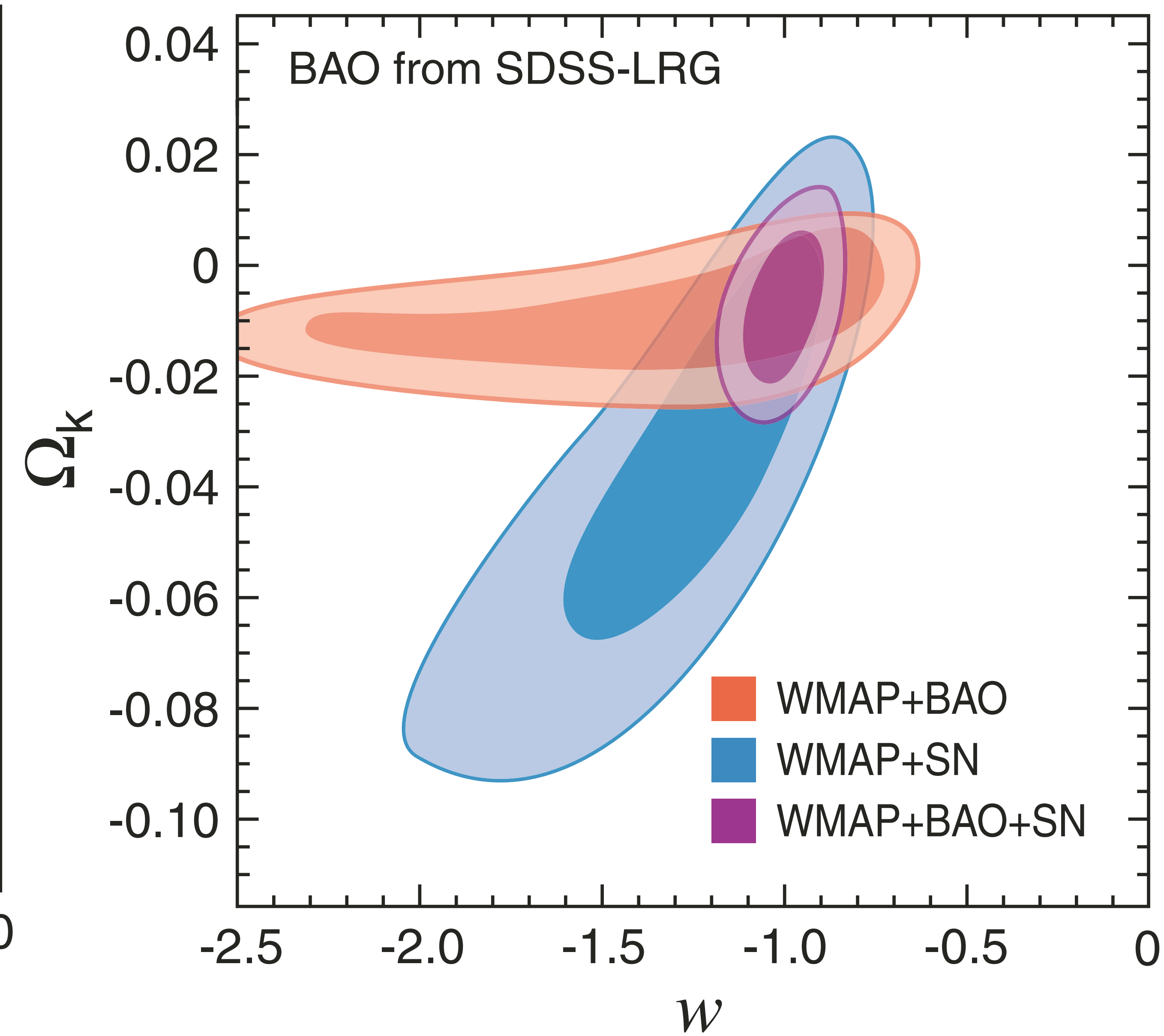


CMB alone constrains "geometry", combination of curvature and dark energy

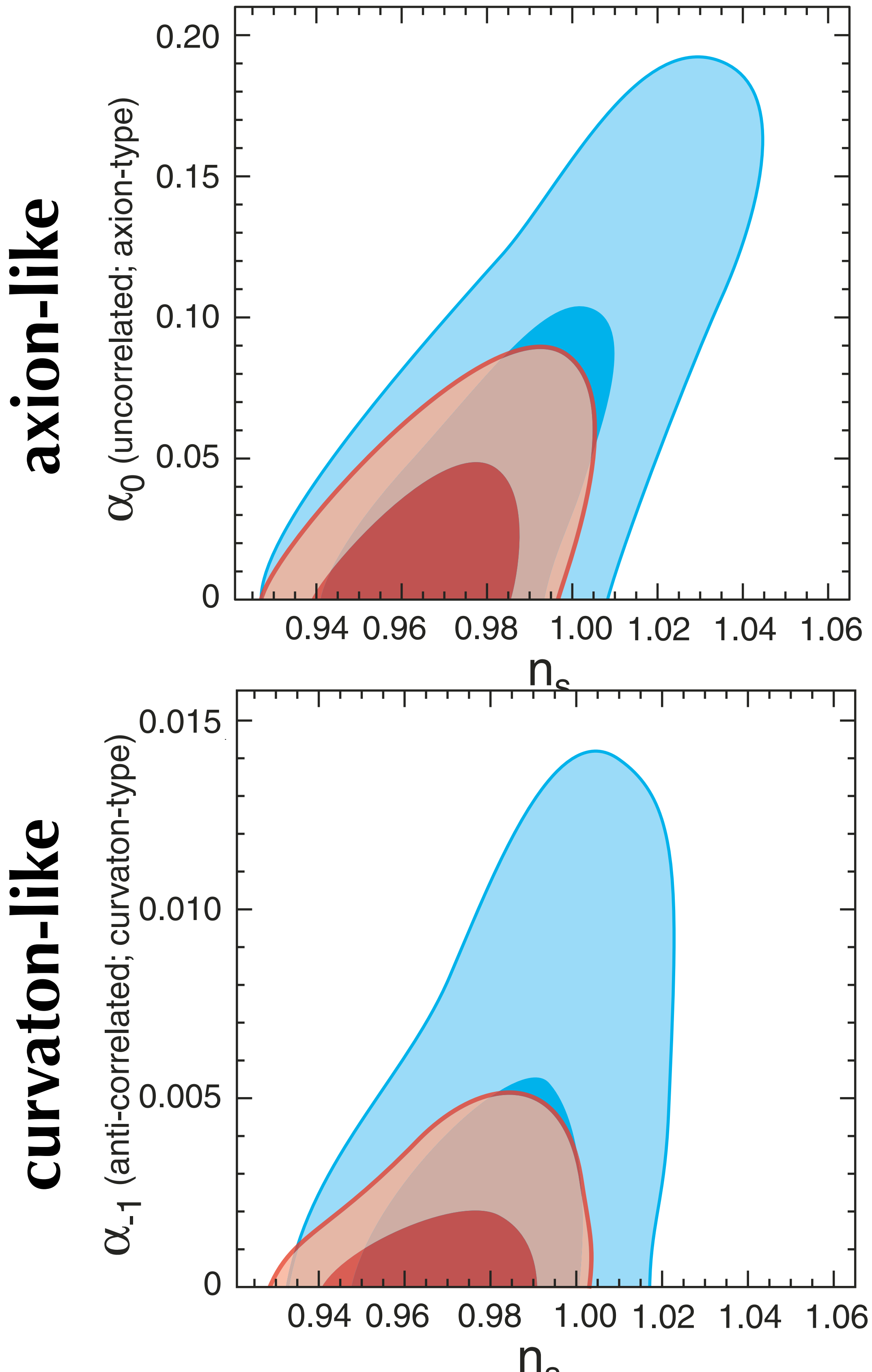
Non-Λ Dark energy

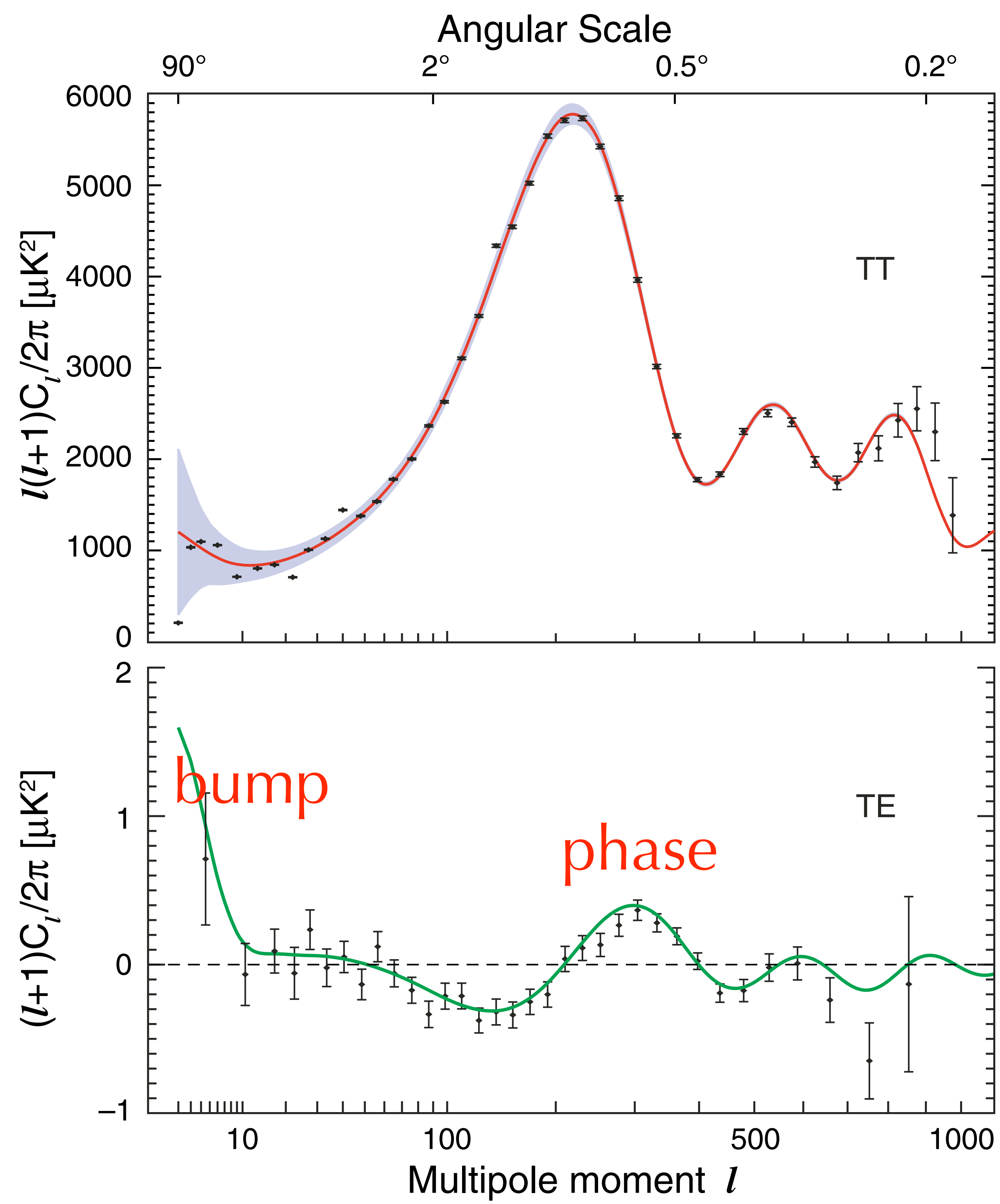
don't assume flatness





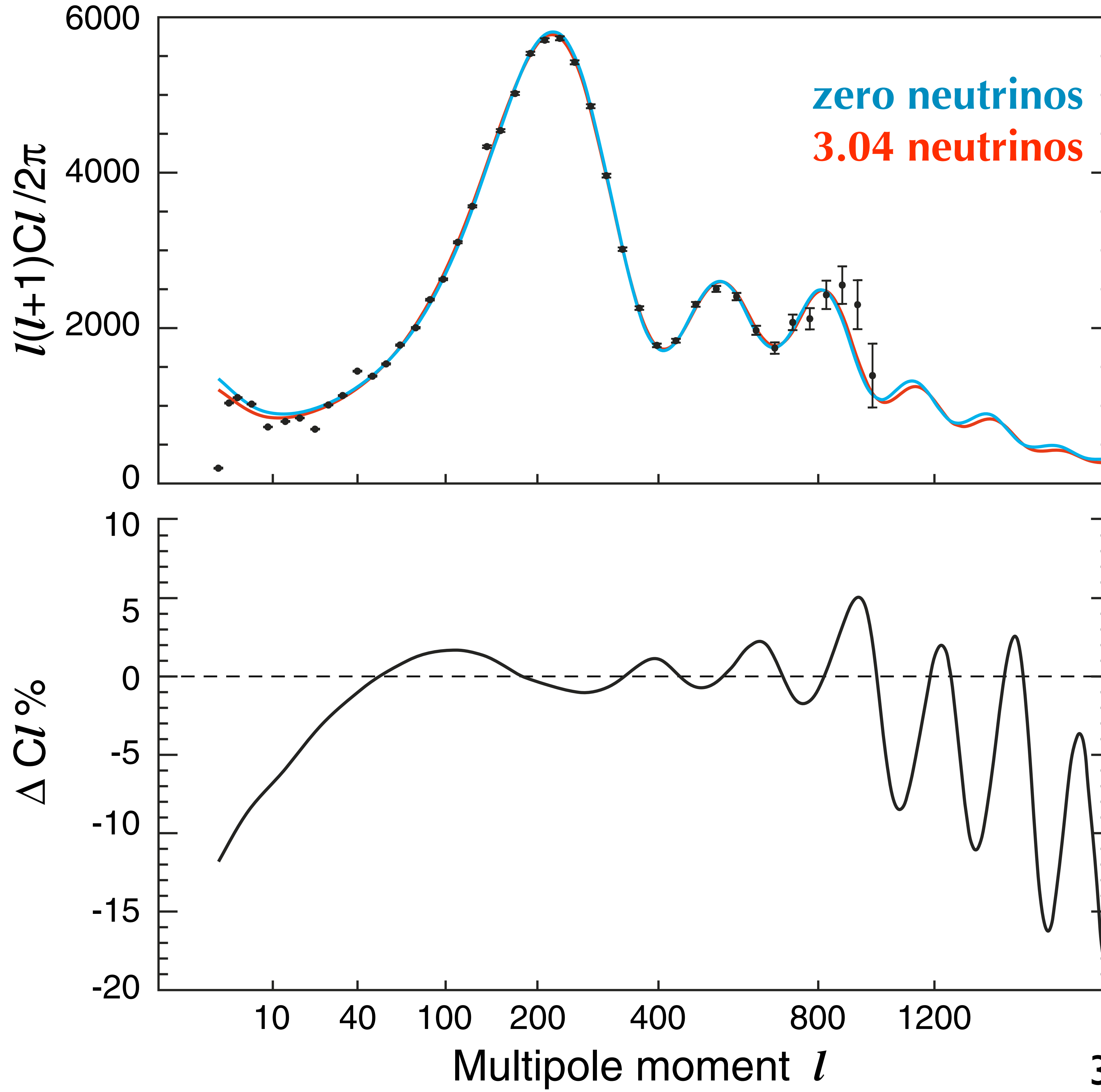
Alternative dark matter



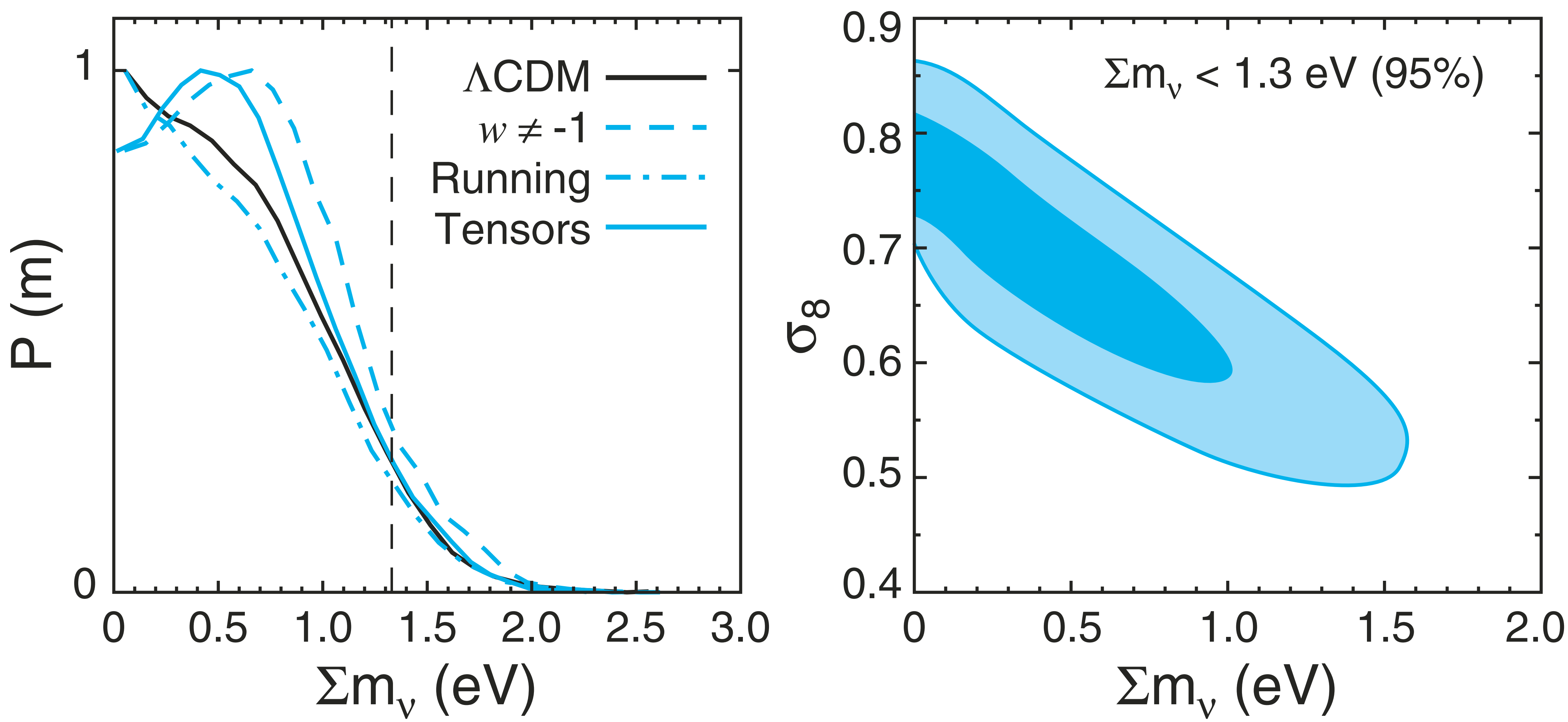


What if neutrinos weren't there?

- Neutrino background is cosmologically significant!
- $N_{eff} > 0$ with 99.5% confidence
- Limit comes primarily from the unique effects of a weakly interacting relativistic "fluid"
- Explaining the CMB without neutrinos would push χ^2 up 8.2, push $H_0 > 75$, and break concordance



Neutrino mass limits

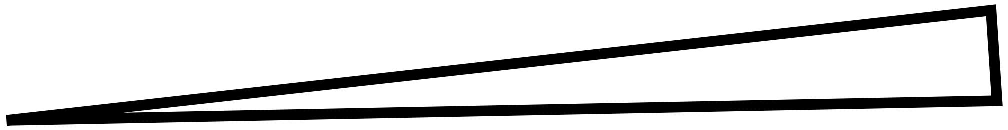


(WMAP only)

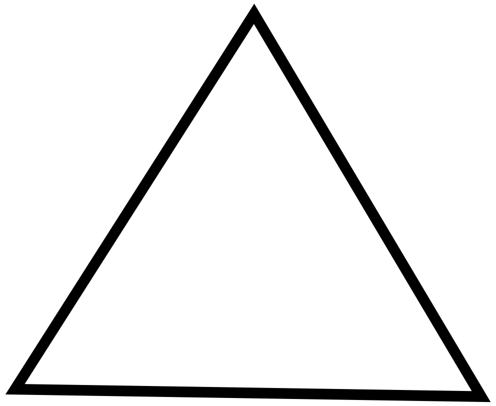
$\Sigma m_\nu < 0.67$ eV (with BAO)

Non-Gaussianity

("Gaussian" here means fluctuations at different wavenumbers are statistically independent)



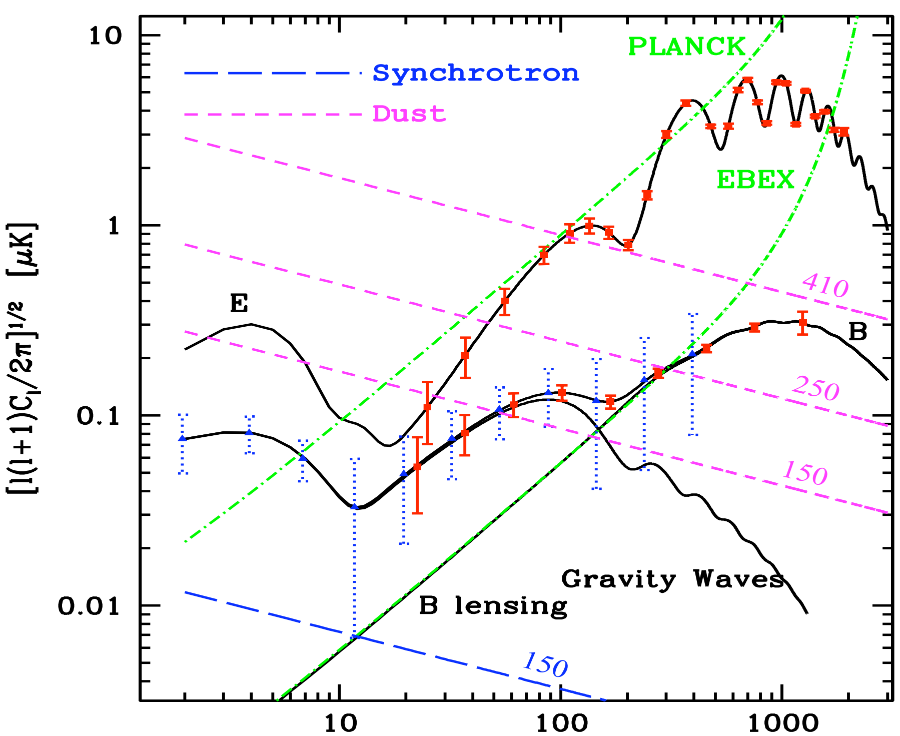
or



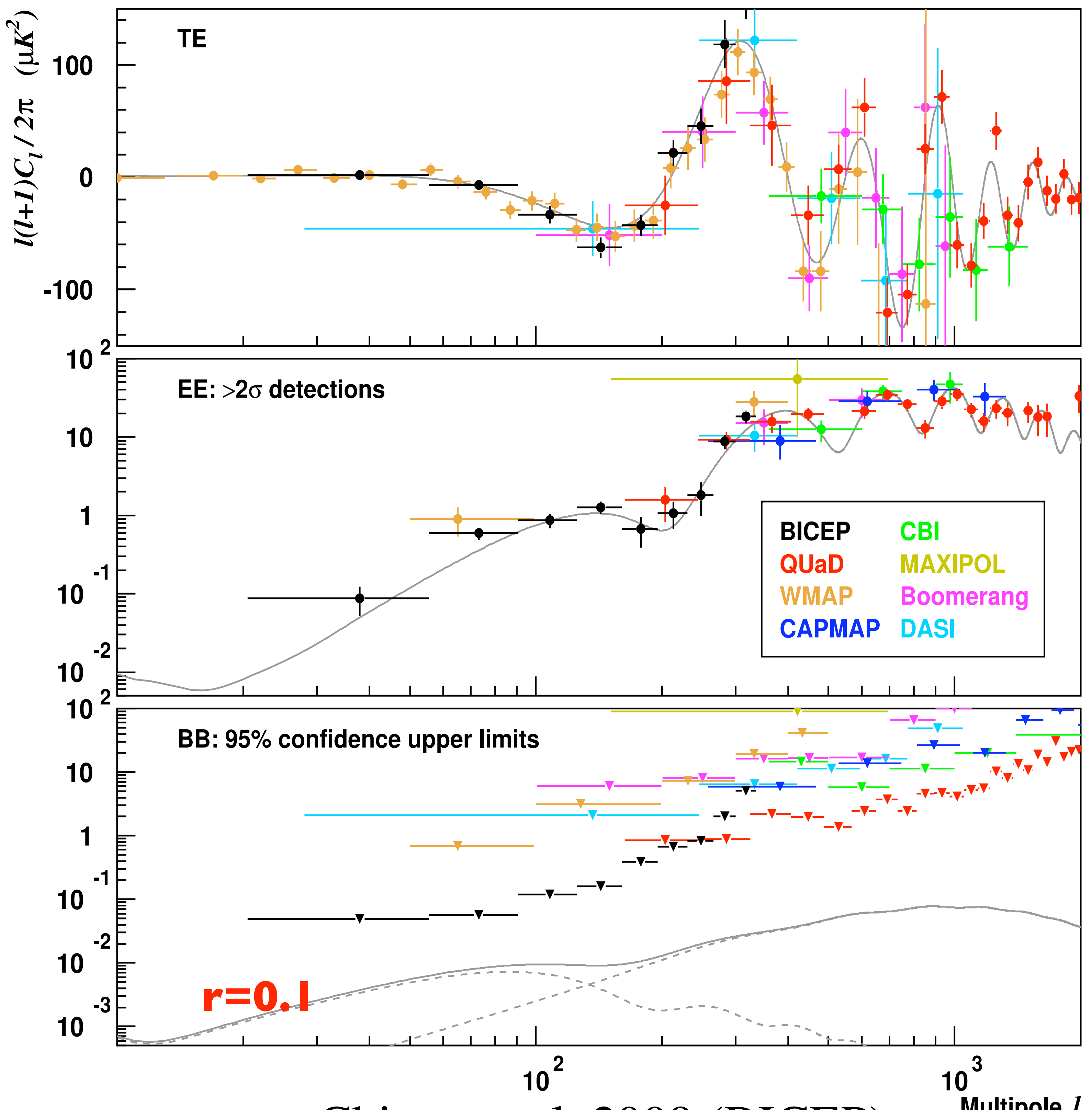
- CMB is a gaussian random field to 0.1%
- $-9 < f_{NL}$ (squeezed) < 111 (95% CL)
- $-151 < f_{NL}$ (equilateral) < 253 (95% CL)
- **$27 < f_{NL}$ (squeezed) < 147 (95% CL) [Yadav & Wandelt 2008]**
- **$-18 < f_{NL}$ (squeezed) < 80 (95% CL) [Curto et al. 2009]**
- limits improve rapidly as noise and foregrounds come down

Future

- WMAP: 7yr being analyzed, 8yr data for certain, more if funded
- Planck: in progress!
- polarization B-modes -> strong limits on tensor/scalar ratio

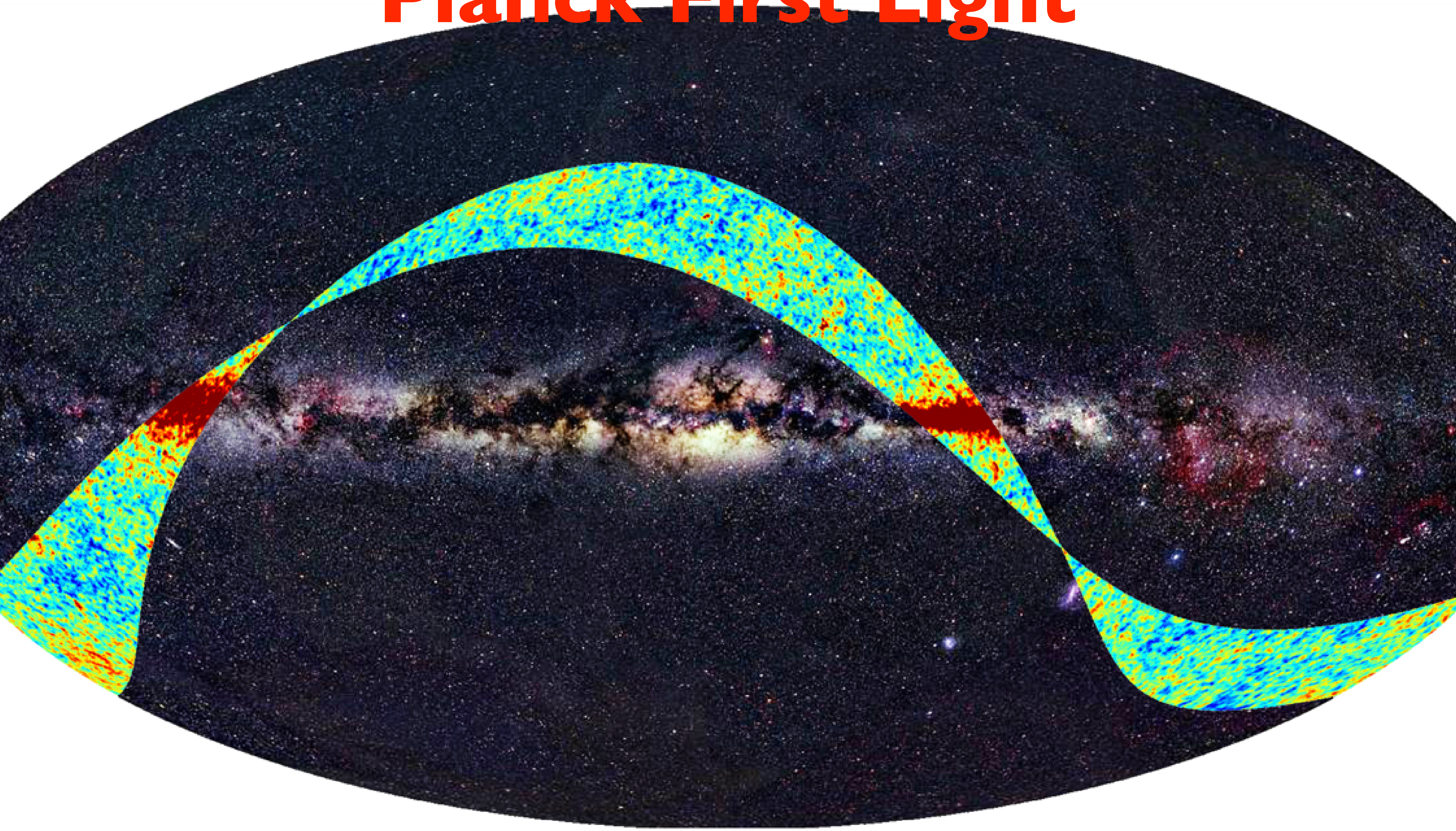


EBEx collaboration



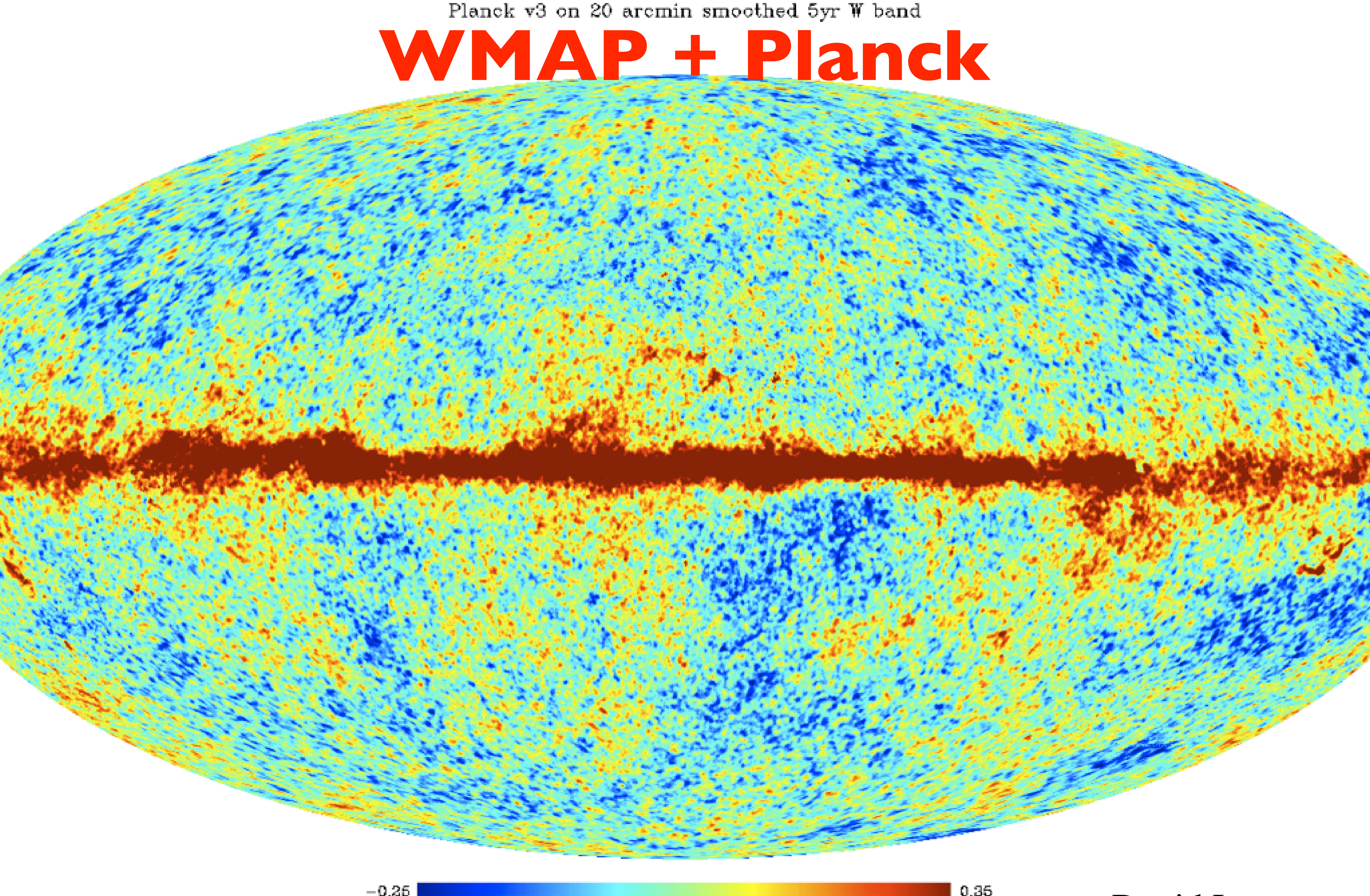
Chiang et al. 2009 (BICEP)

Planck First Light



ESA, LFI & HFI consortia,
background Axel Mellinger

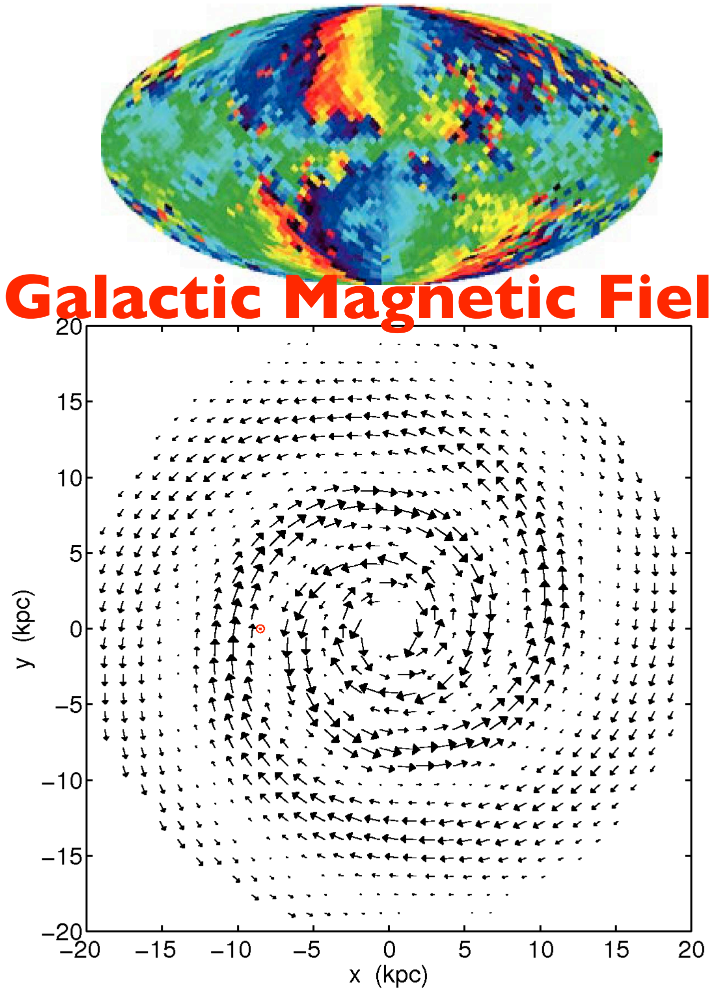
WMAP + Planck



courtesy David Larson

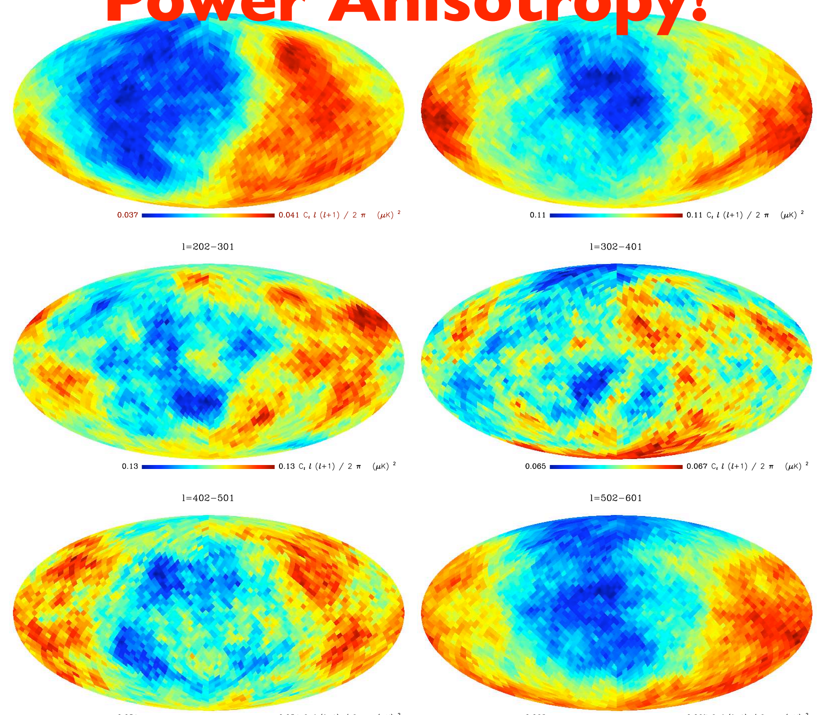
Other stuff

Galactic Magnetic Field



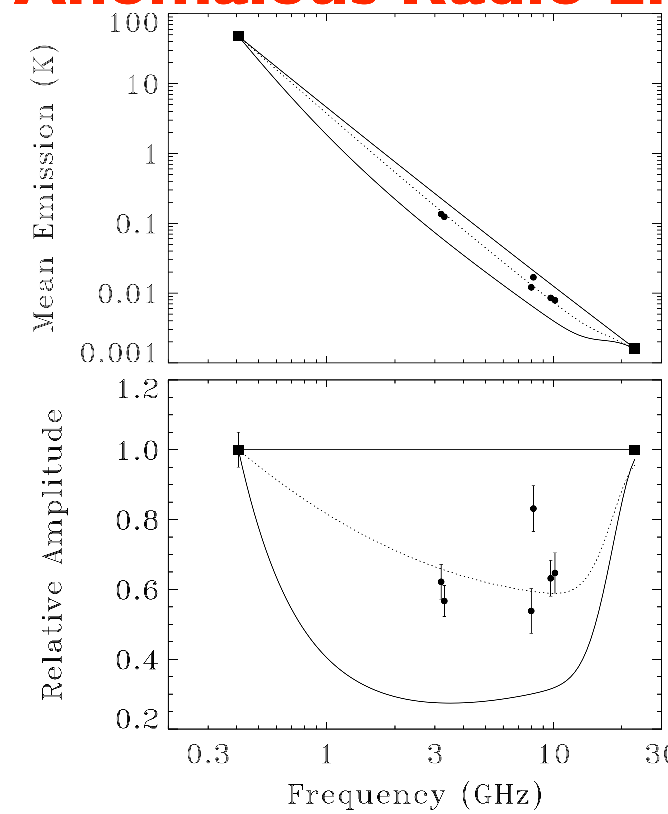
Jansson et al. (2009)

Power Anisotropy?



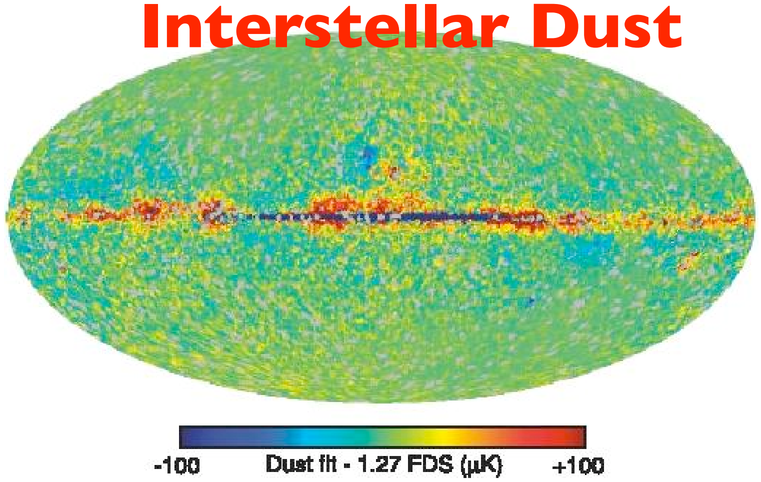
Hansen et al. (2009)

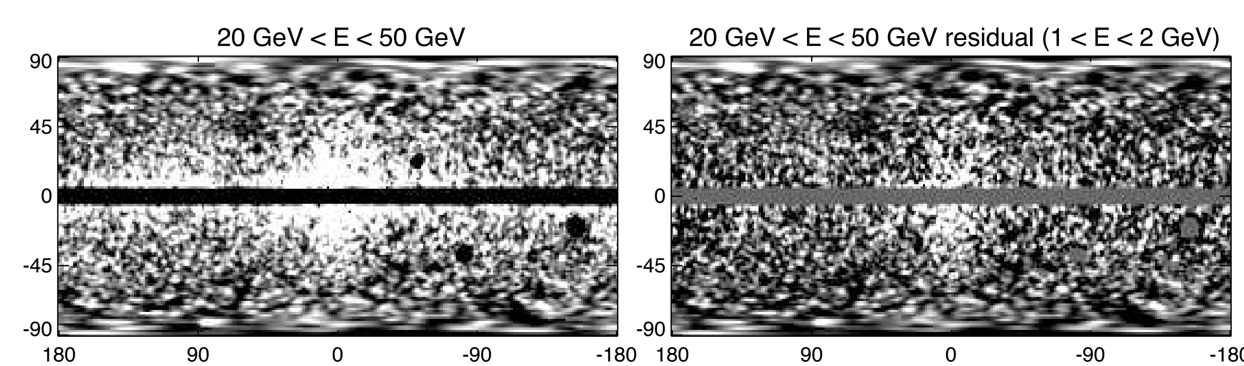
Anomalous Radio Emission?



Kogut et al. (2009)

Interstellar Dust





Dobler et al. (2009)