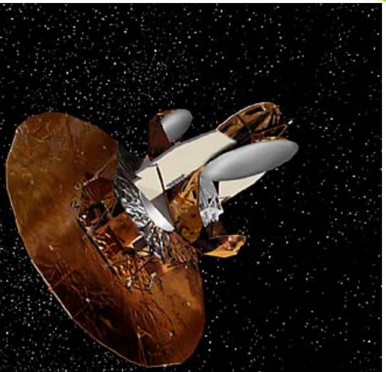
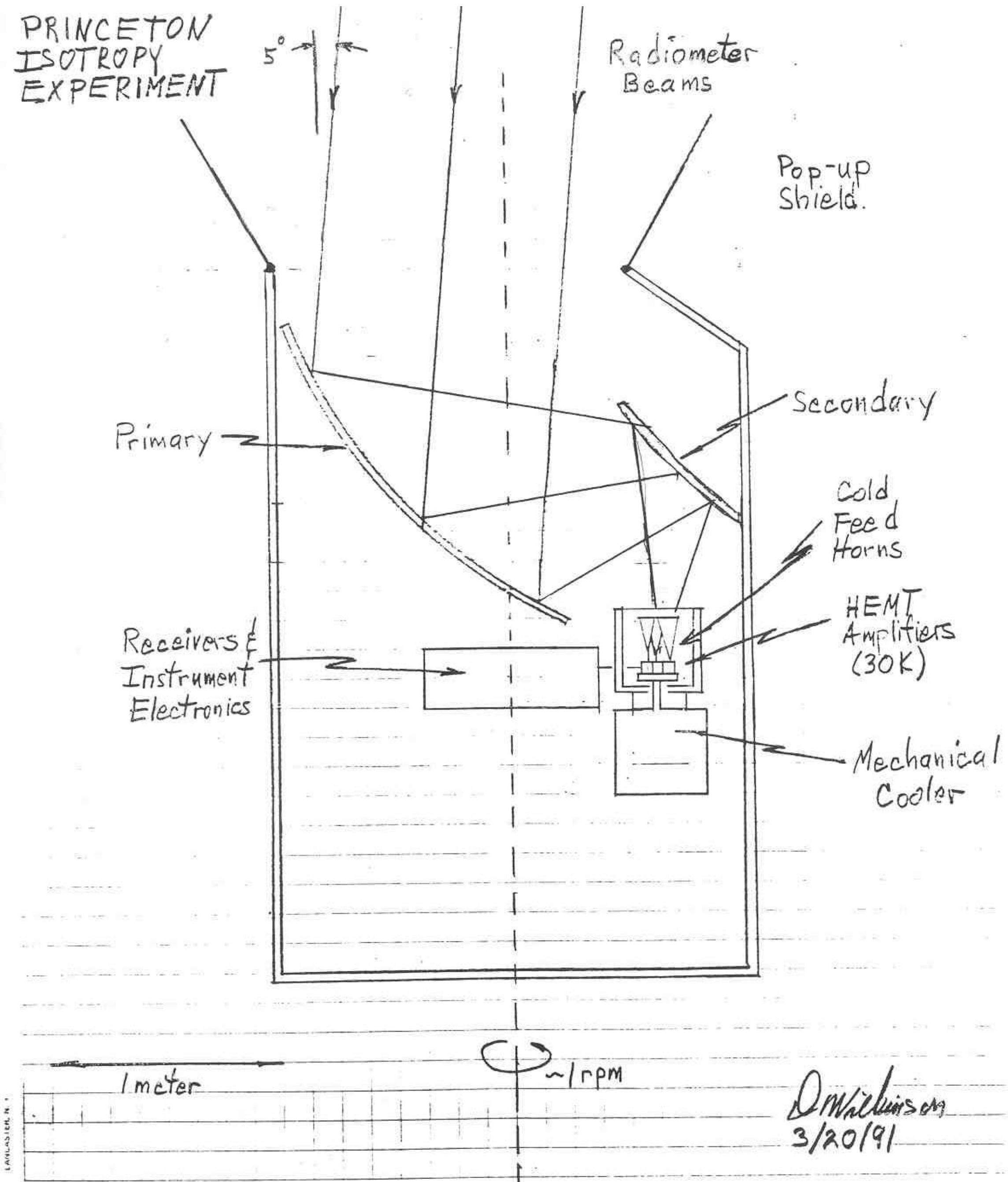
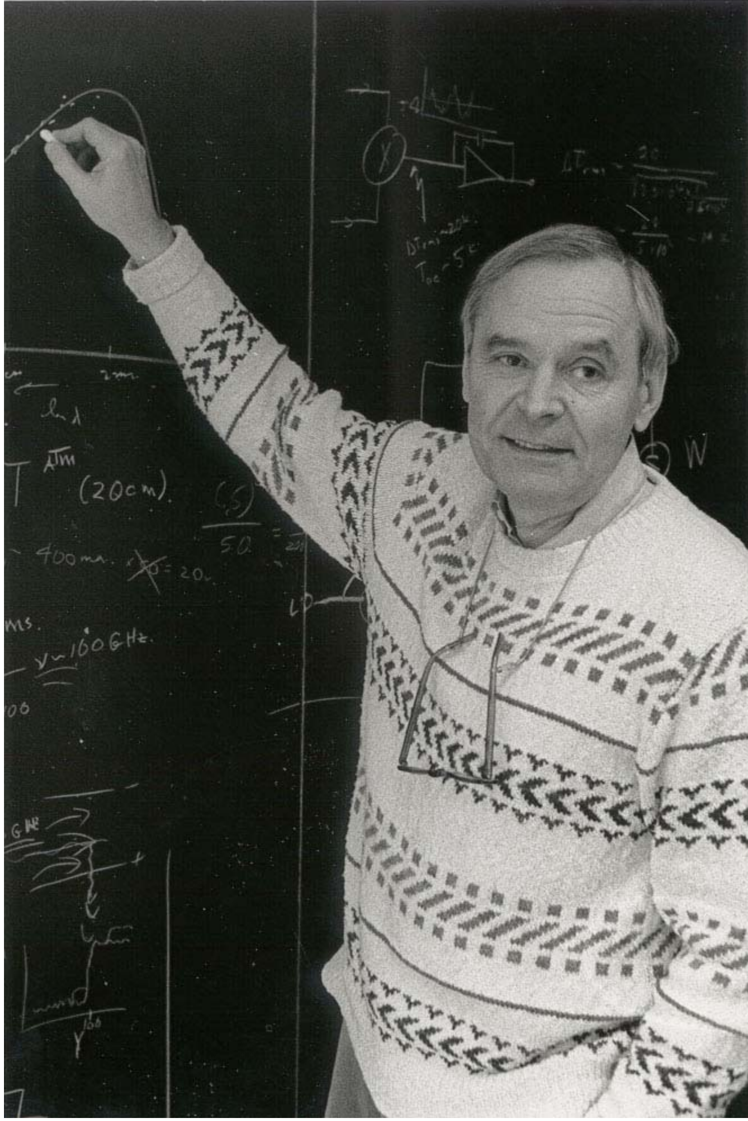
Wilkinson Microwave Anisotropy Probe

(and Future Directions)



L. Page, Texas@Stanford, 2004





Dave Wilkinson

(COBE announcement, 4/92)

WMAP

A partnership between NASA/GSFC and Princeton

Science Team:

NASA/GSFC

- Chuck Bennett (**PI**)
- Bob Hill
- Gary Hinshaw
- Al Kogut
- Michele Limon
- Nils Odegard
- Janet Weiland
- Ed Wollack

WMAP Movie

Brown

Greg Tucker

UCLA

- Ned Wright

UBC

Mark Halpern

Chicago

- Stephan Meyer
- Hiranya Peiris

CITA

Mike Nolta

UT Austin

Eiichiro Komatsu

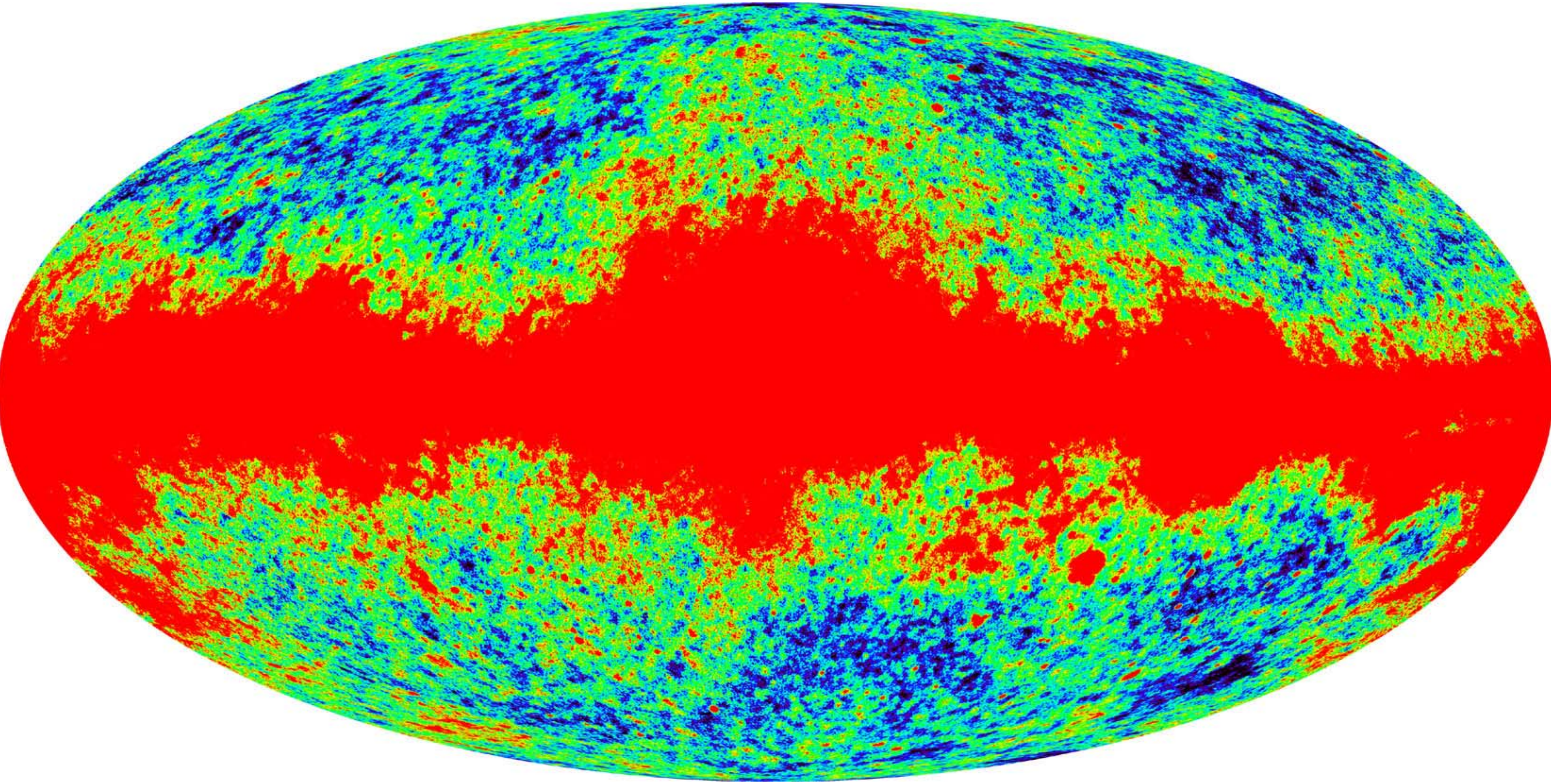
Penn

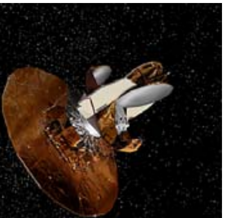
Licia Verde

Princeton

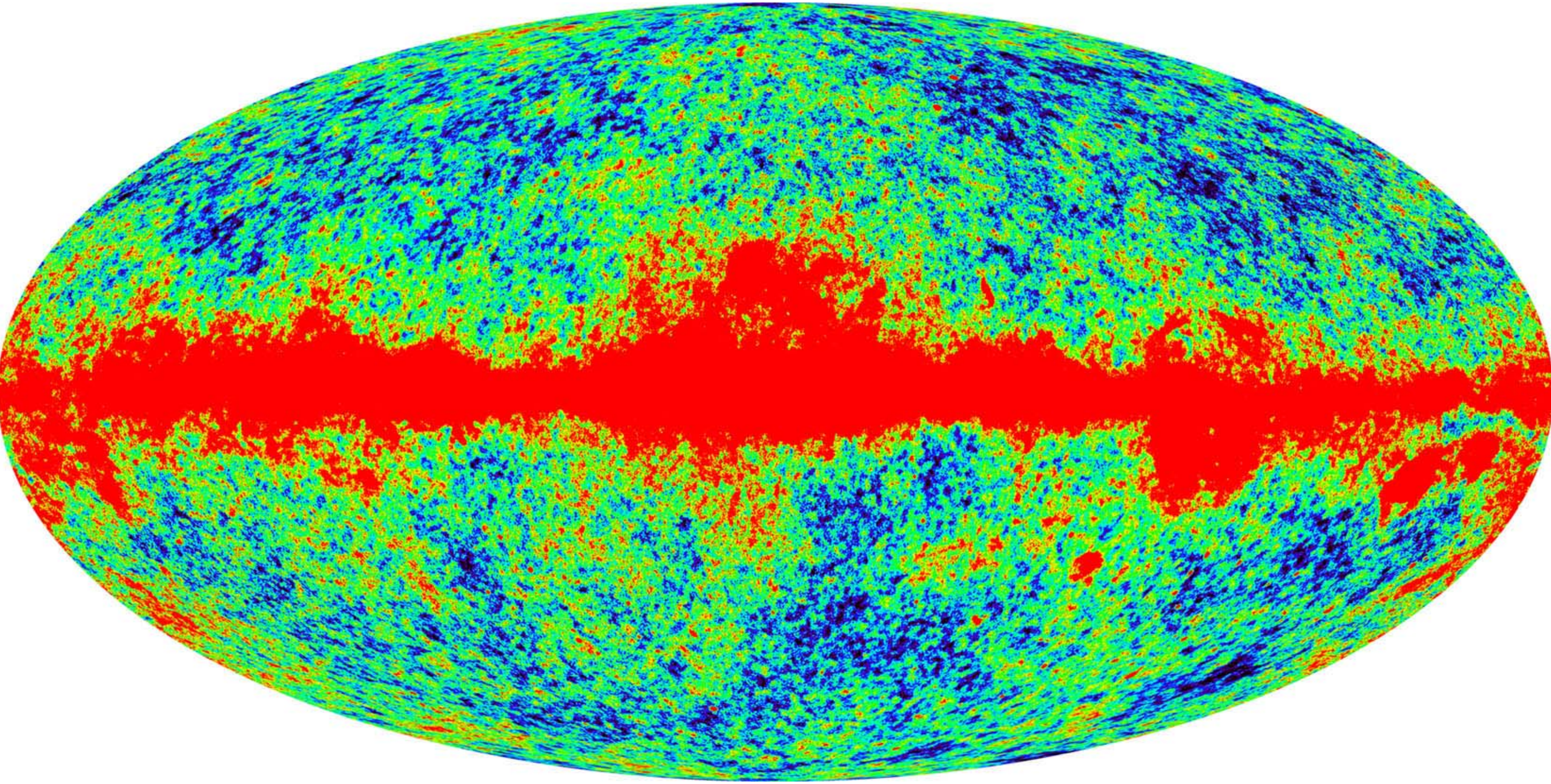
- Chris Barnes (Microsoft)
- Rachel Bean
- Olivier Dore
- Norm Jarosik
- Lyman Page
- David Spergel

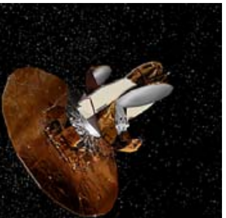
K - 22GHz



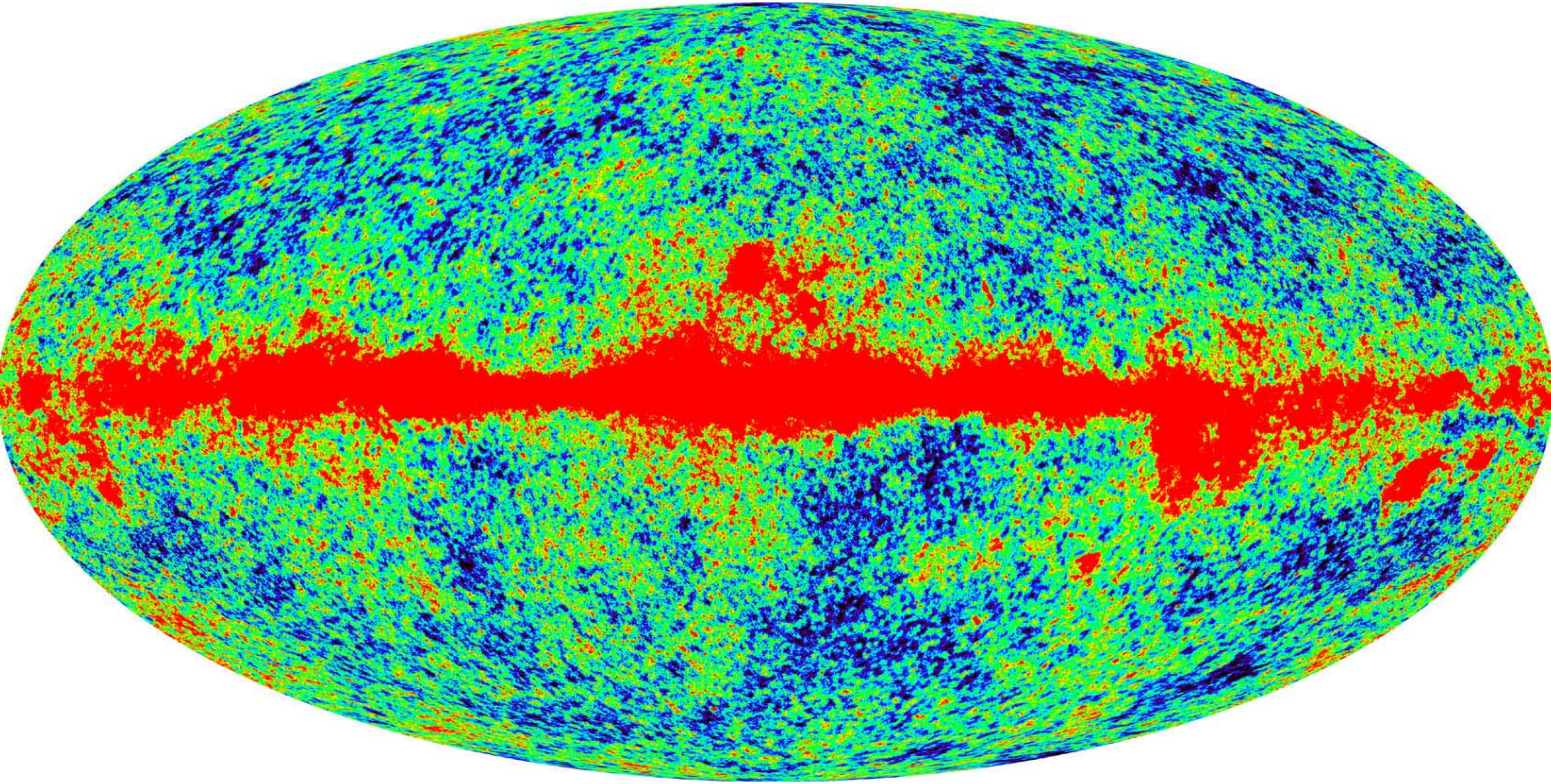


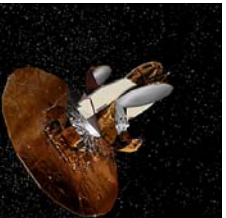
Ka - 33GHz



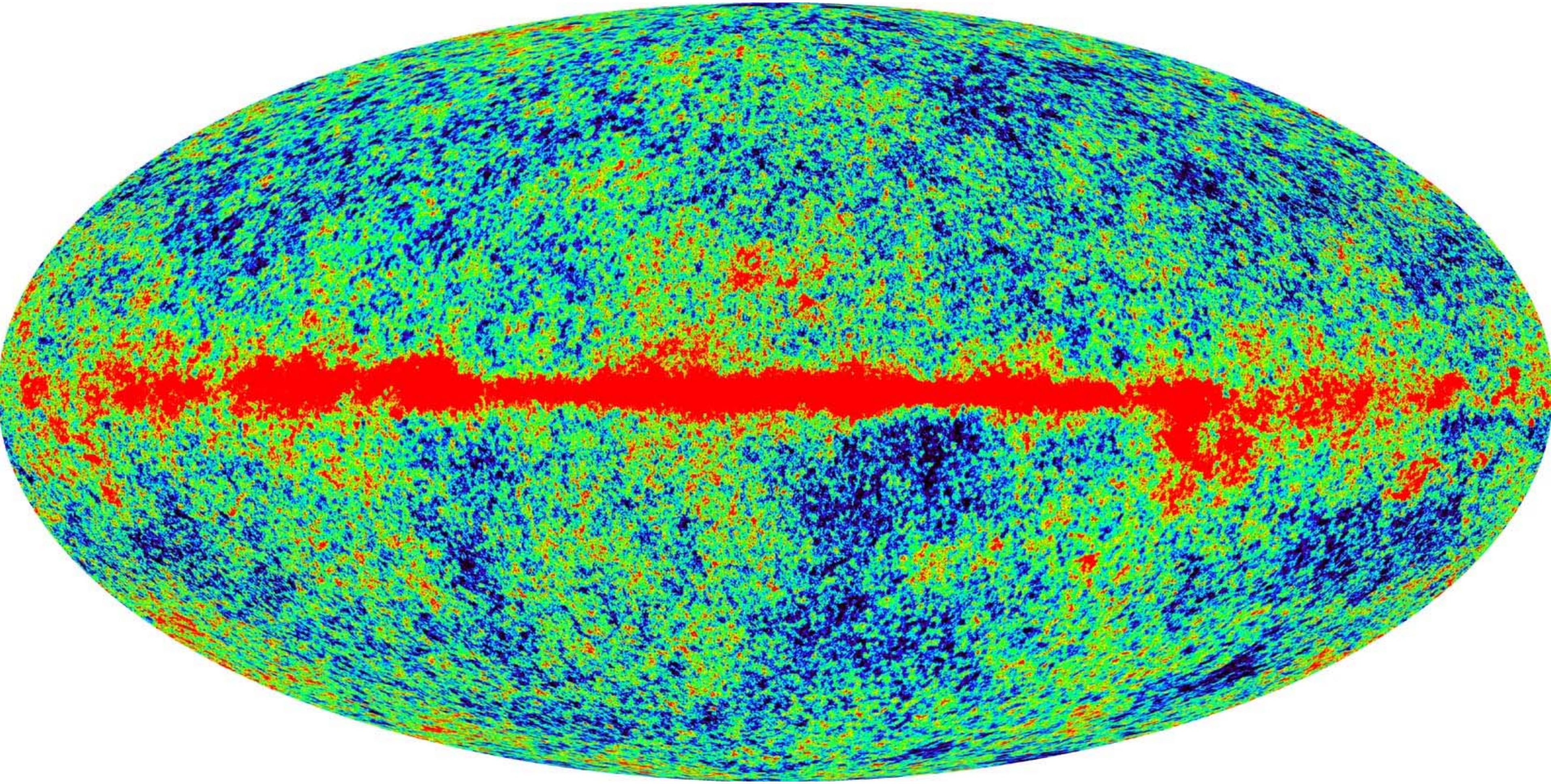


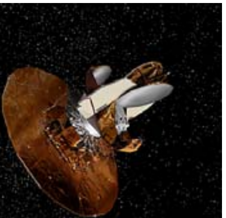
Q - 41GHz



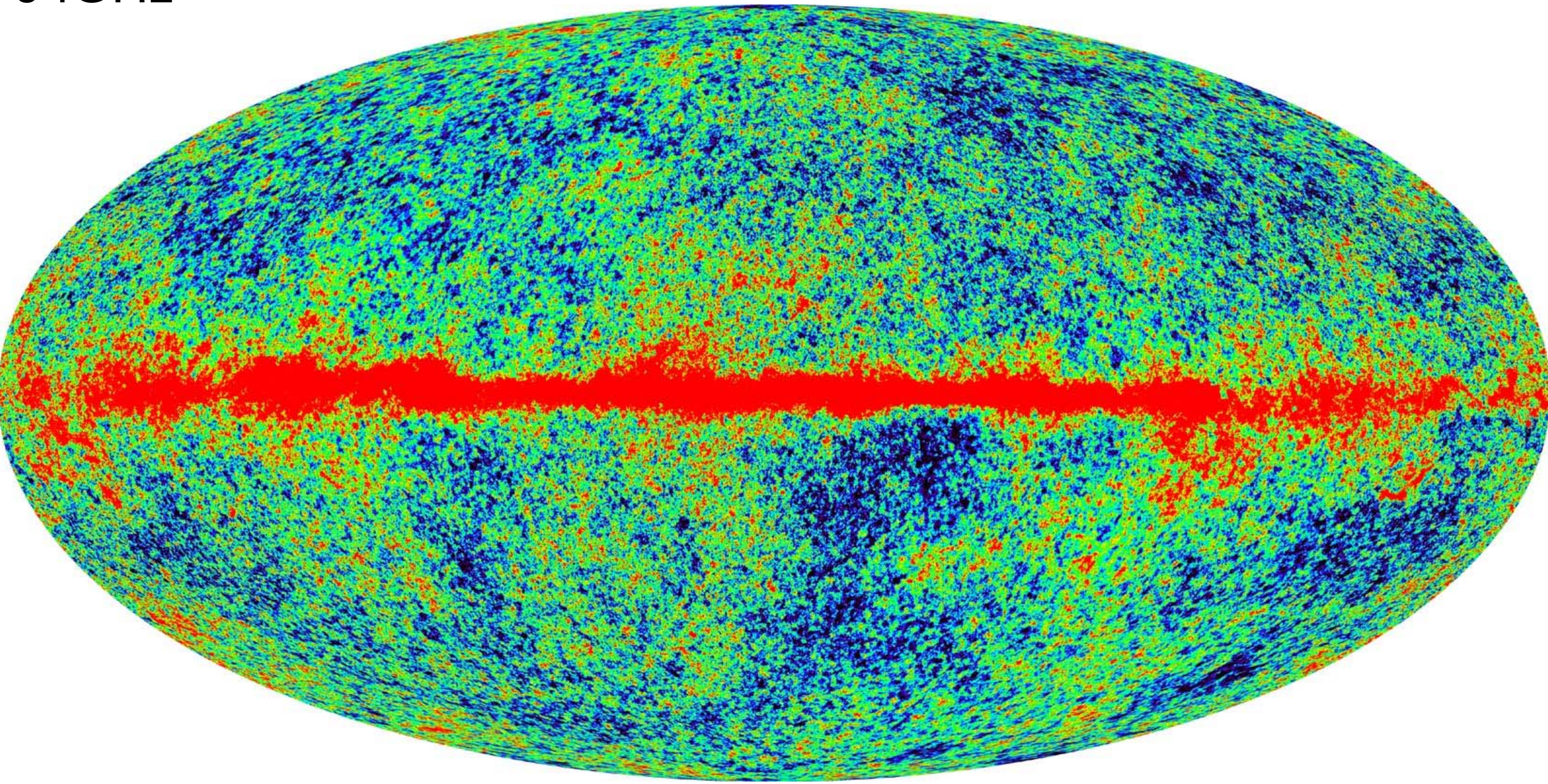


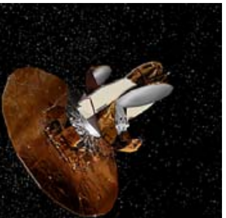
V - 61GHz

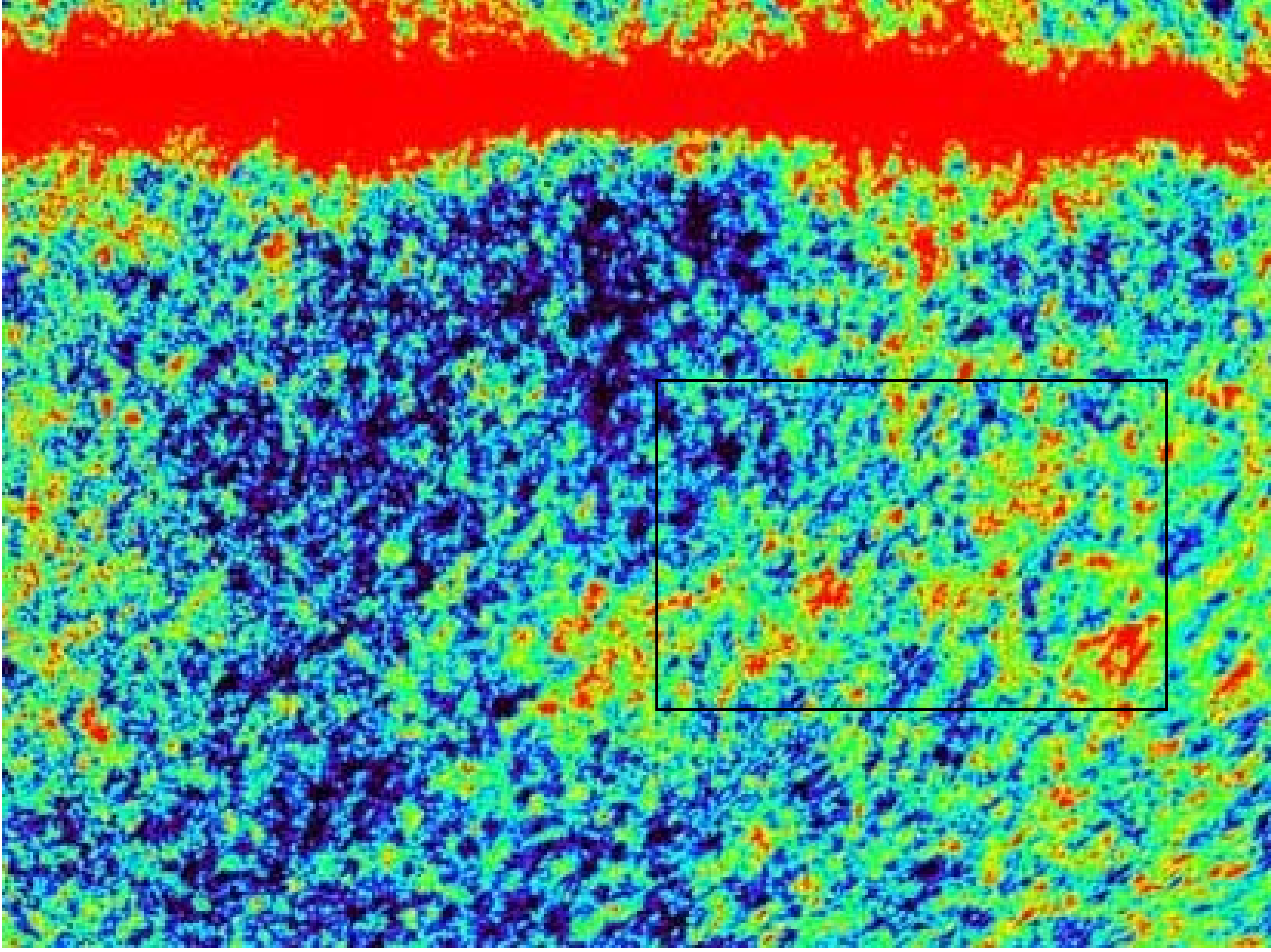


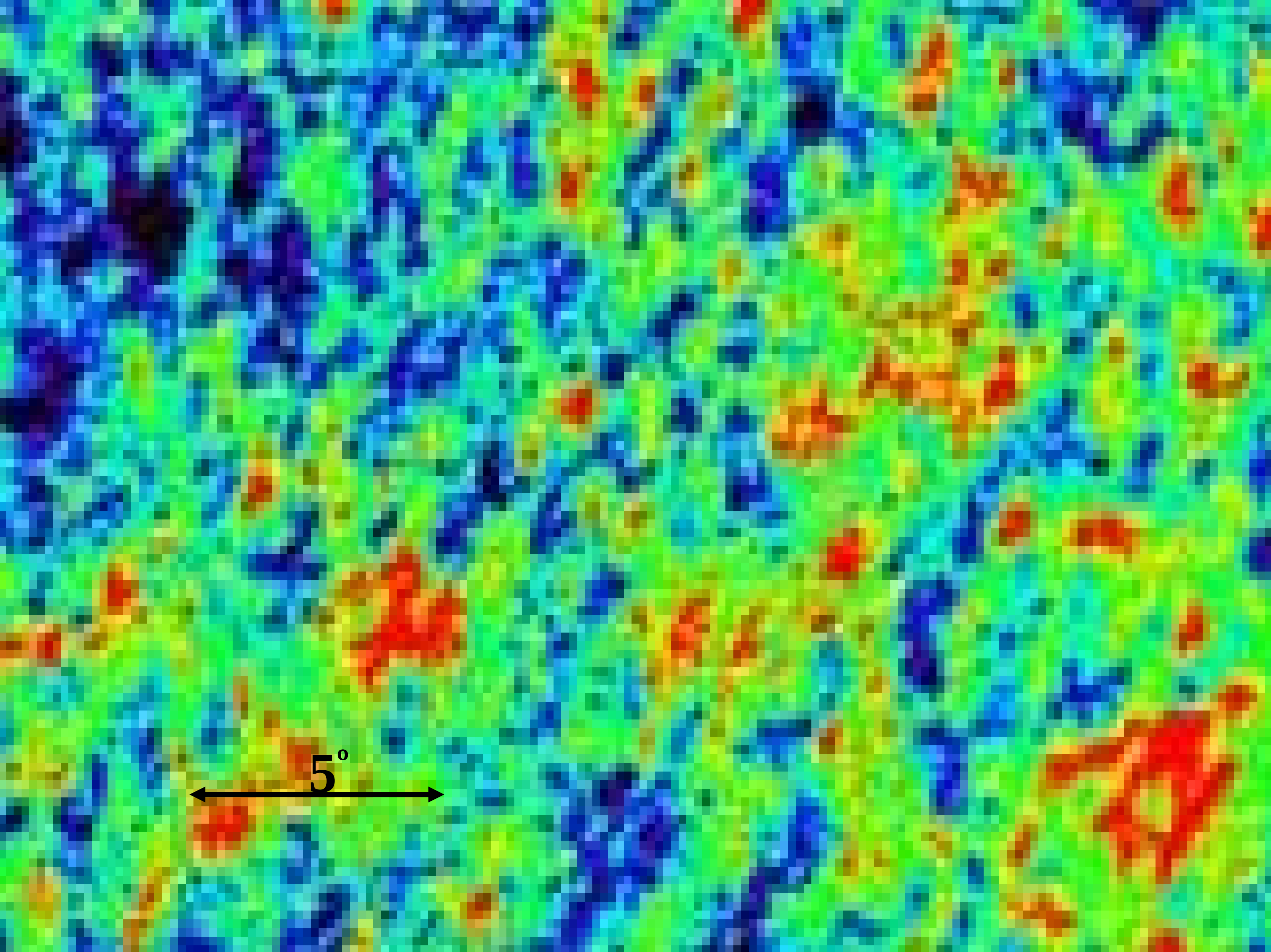


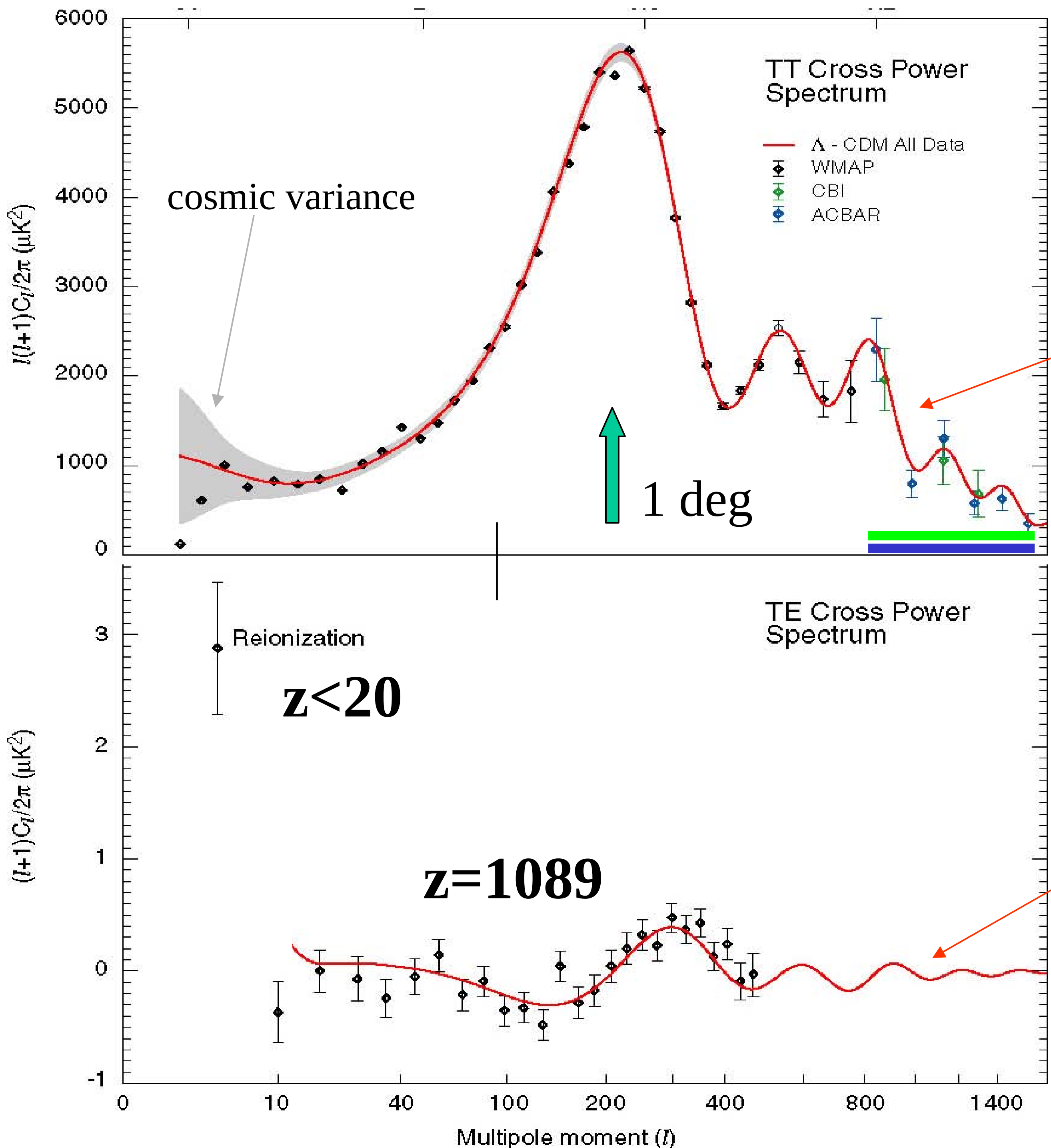
W -
94GHz








5°



Temperature

85% of sky

Best fit model

Temperature-polarization

Prediction
based on TT,
no free params.

Fundamental Findings

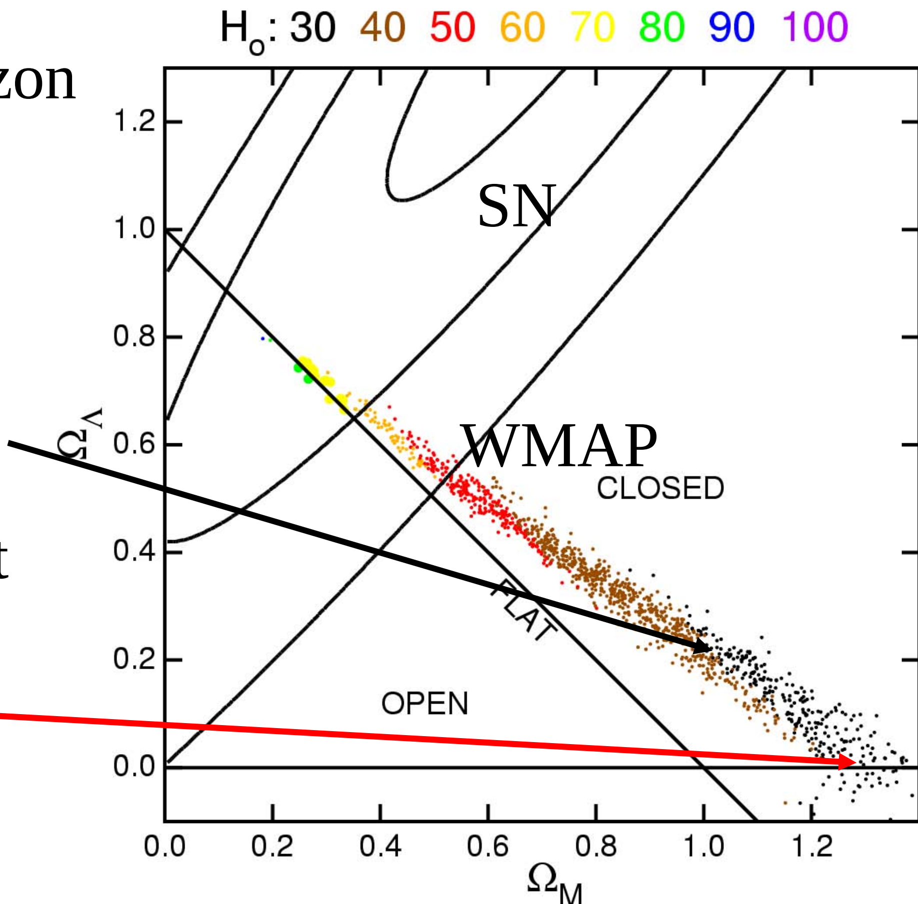
- A simple flat model with six parameters fits 1,000,000 data points remarkably well.

$$A,\ \Omega_b h^2, \Omega_m h^2, h, n_s, \tau$$

- We see there must be superhorizon *fluctuations* from the TE data.

- The Einstein-de Sitter model is disfavored by the WMAP CMB data at > 5 sigma.

- A closed model fits the data but requires H_0=33 km/sec, in conflict with other non-CMB data. WMAP/NVSS ISW disfavors this as well.



Next steps in constraining models of the 10^{-35} s universe.

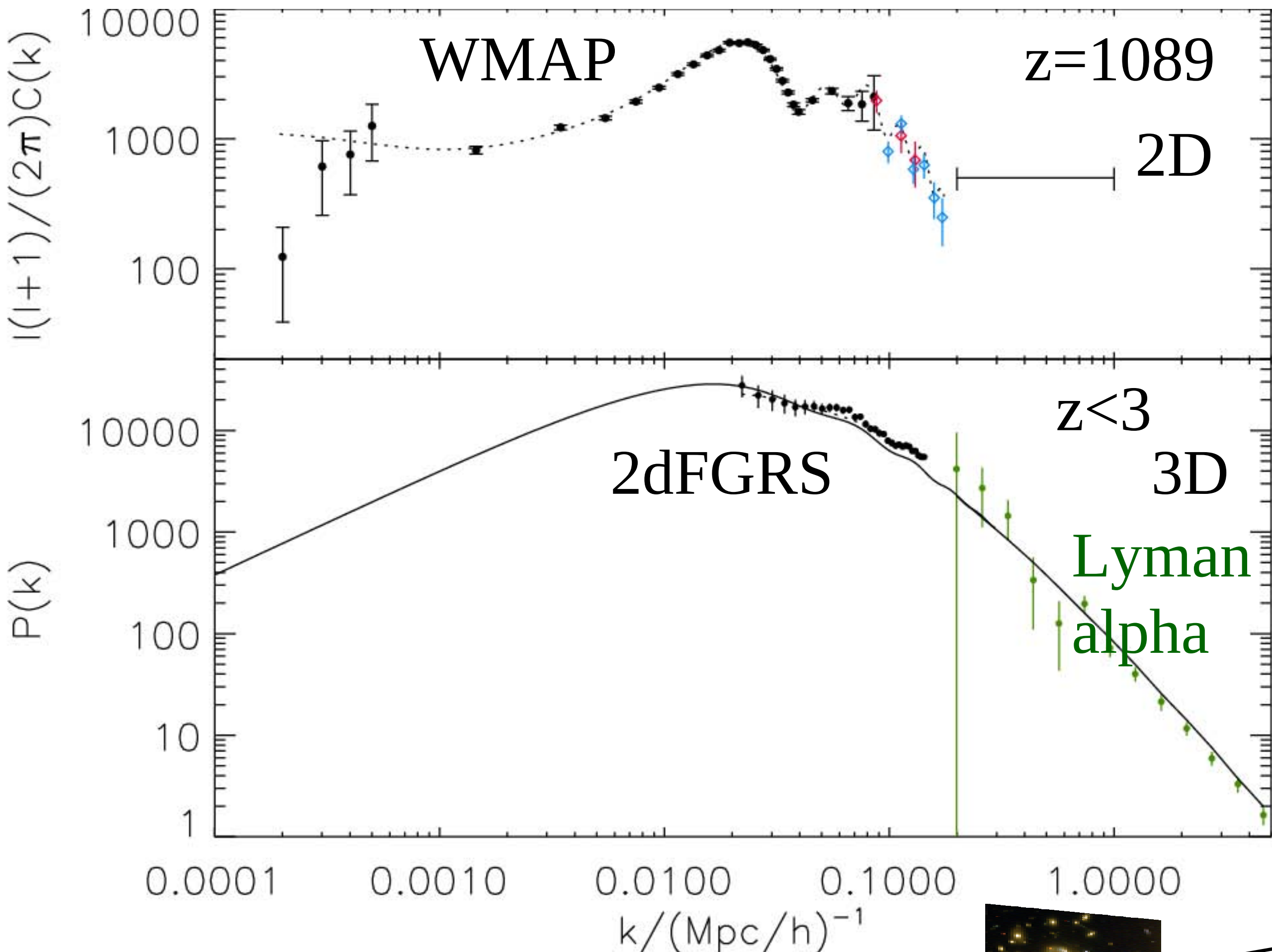
- Measure n_s and the running of the index.
- Measure or constrain r, the tensor to scalar index.

SDSS Movie

File too large

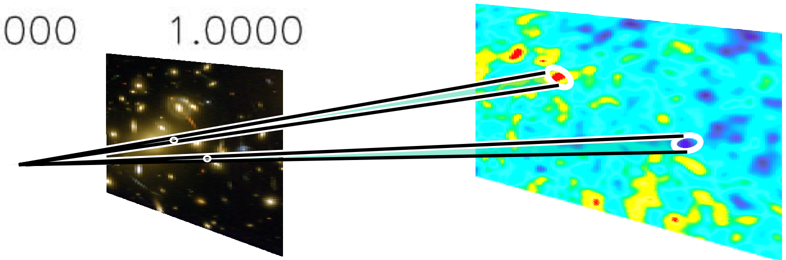
Mark Subbarao & SDSS Collaboration

The spectrum of scalar fluctuations.



Verde et al. 2003

and now SDSS as well.



The scalar index, n_s, with six parameters.

$$n_s = 0.99 \pm 0.04$$ WMAP

$$n_s = 0.98 \pm 0.03$$ +SDSS Tegmark *et al*. 2004

$$n_s = 0.97 \pm 0.02$$ +SDSS Galaxies and Lya

Seljak *et al*. 2004

Simple models of inflation predict:

$$n_s = 0.96 \pm 0.02$$

- **This is significant in that it is a clear departure from scale invariance.**
- **We expect n_s to 1% by 2008 from the CMB.**

Running of the scalar index.

In the two recent analyses of WMAP plus SDSS there is no evidence for running.

SDSS Galaxies

Tegmark *et al.* 2004

Galaxies and Lya

Seljak *et al.* 2004

An analysis of CBI+WMAP+LSS shows evidence of running at the 3-sigma level (-0.085+/-0.031) but the CBI team does not place a lot of weight on the result.

Readhead *et al.* 2004

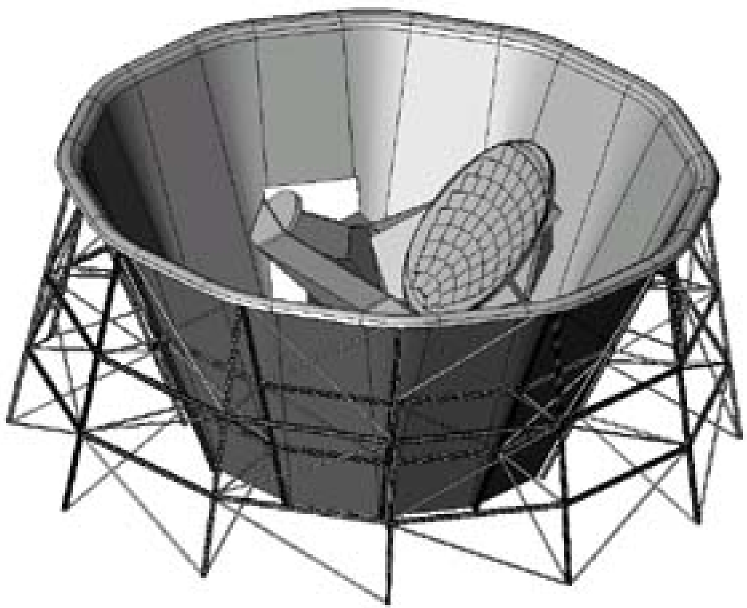
ACT

Science:

- ★Growth of structure
- ★Equation of state
- ★Neutrino mass
- ★Ionization history
- ★Inflation
- ★Power spectrum

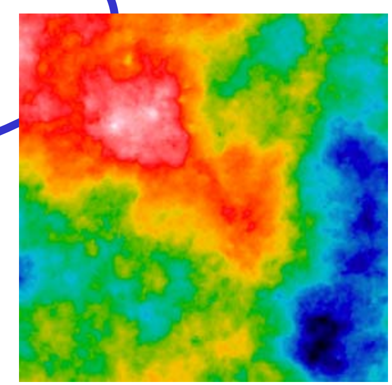
Observations:

- ★CMB: l>1000
- ★ Cluster (SZ, KSZ X-rays, & optical)
- ★ Diffuse SZ
- ★ OV
- ★ Lensing



X-ray

Optical



Theory

NSF Funded

ACT Collaboration

14 Universities, 3 Government Agencies, 6 Countries

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Phil Mauskopf

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- Britt Reichborn-Kjennerud (GS)
- Craig Peters (UG)
- Dan Harlow (UG)
- Ben Hooberman (UG)
- David Tam (UG)

CUNY

Martin Spergel

Haverford

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Bruce Partridge
- Ryan Sajac (UG)
- Sarah Burke (UG)

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- Jeff Wagg (GS)

KwaZulu-Natal (SA)

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Gareth Amery
- Ryan Warne (GS)

LLNL/SSL UCB

Ed Wishnow

NASA/GSFC

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Harvey Moseley
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Ed Wollack

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Gene Hilton
Kent Irwin
Carl Reintsema
Leila Vale
Yizi Xu (tech)

Collaboration cont.

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- Adam Hincks (GS)
- Josh Burton (UG)
- Lusanne Wang (UG)
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- Jess Reidel (UG)
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- Matthew Francis (GS)

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Ted Williams

Univ. of British Columbia

Mark Halpern
- Danica Marsden (UG)

Univ. de Catolica

Hernan Quintana

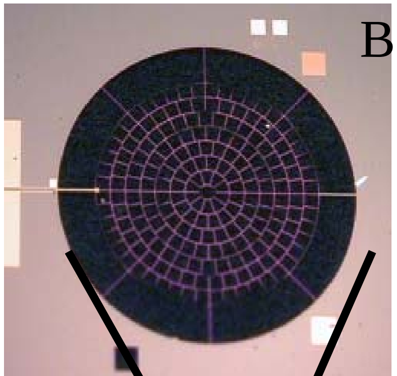
UMass

Grant Wilson

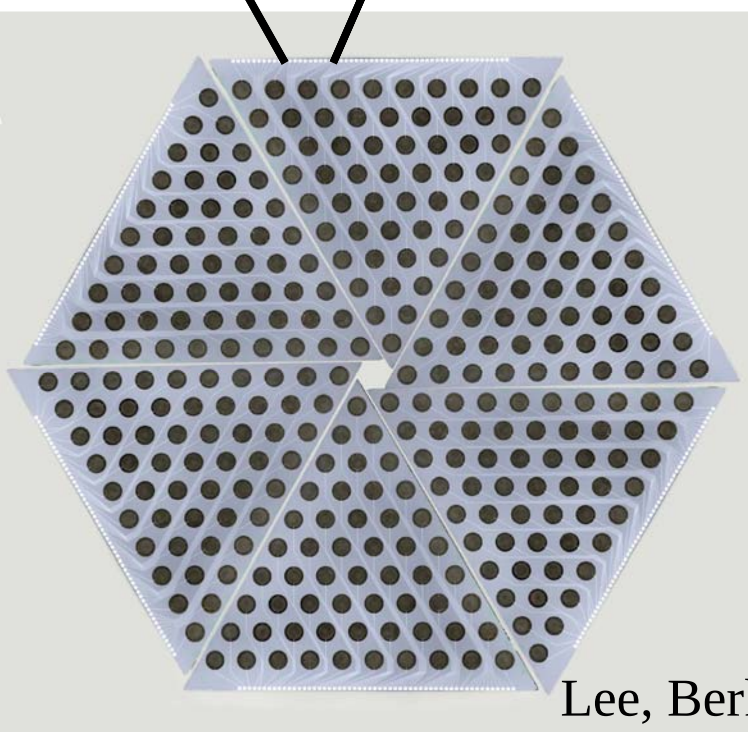
Univ. of Toronto

Barth Netterfield

Arrays of bolometers

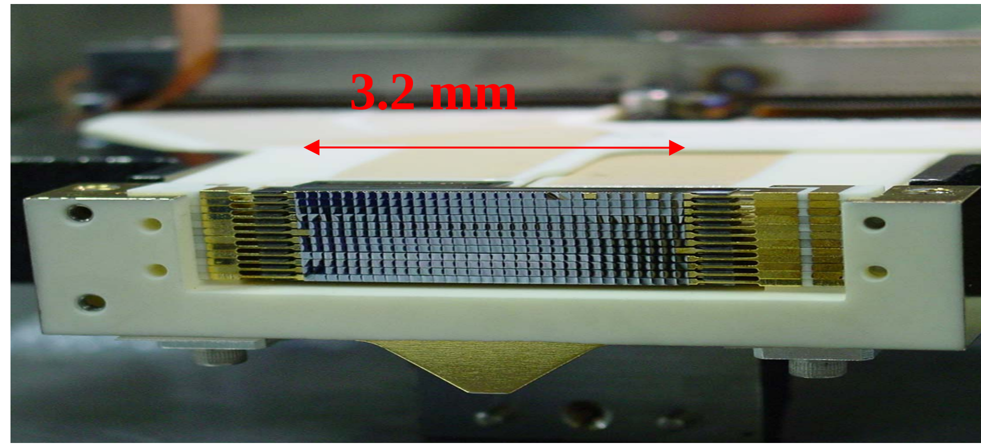


Bock, JPL/Caltech

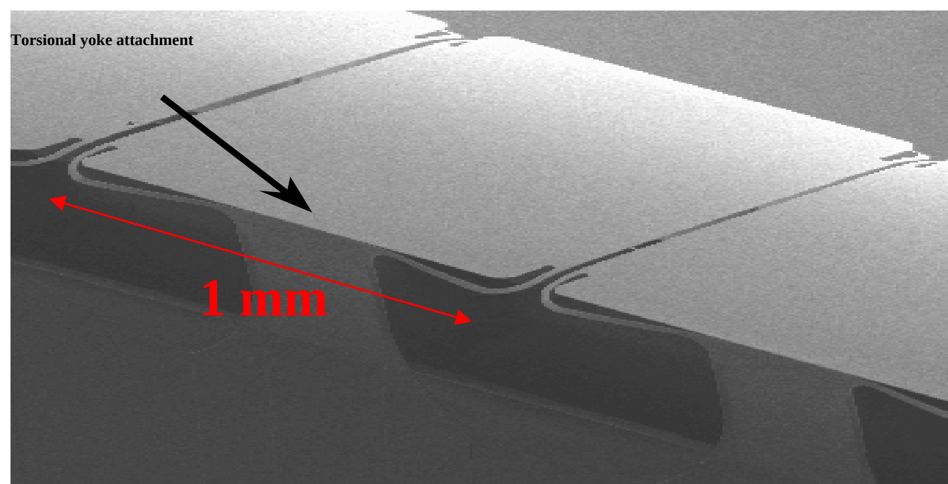


Lee, Berkeley

Moseley et al, NASA



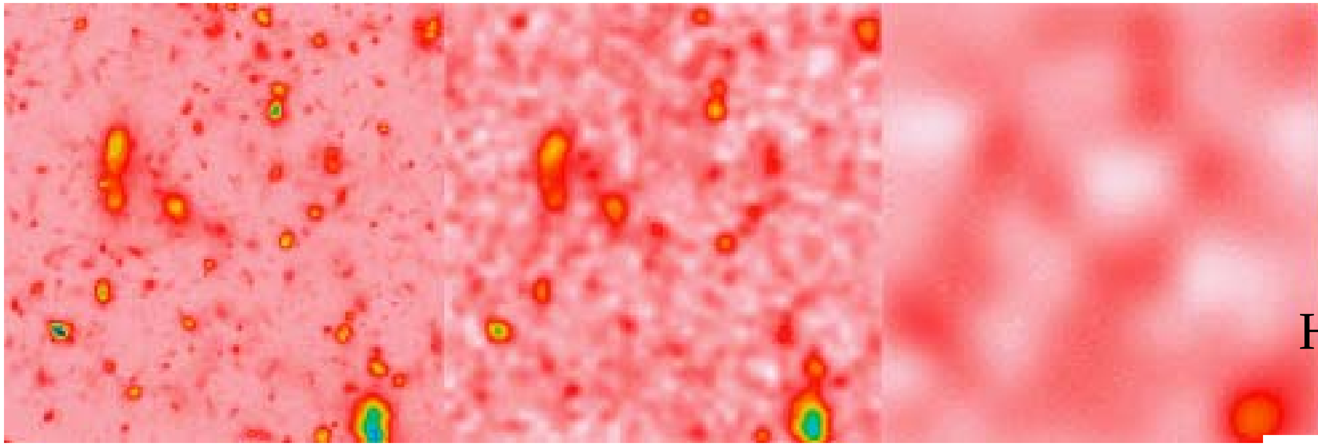
SHARC II 12x32 Popup Array
PI D. Dowell



One element of array

Simulations of mm-wave data.

1.4^0

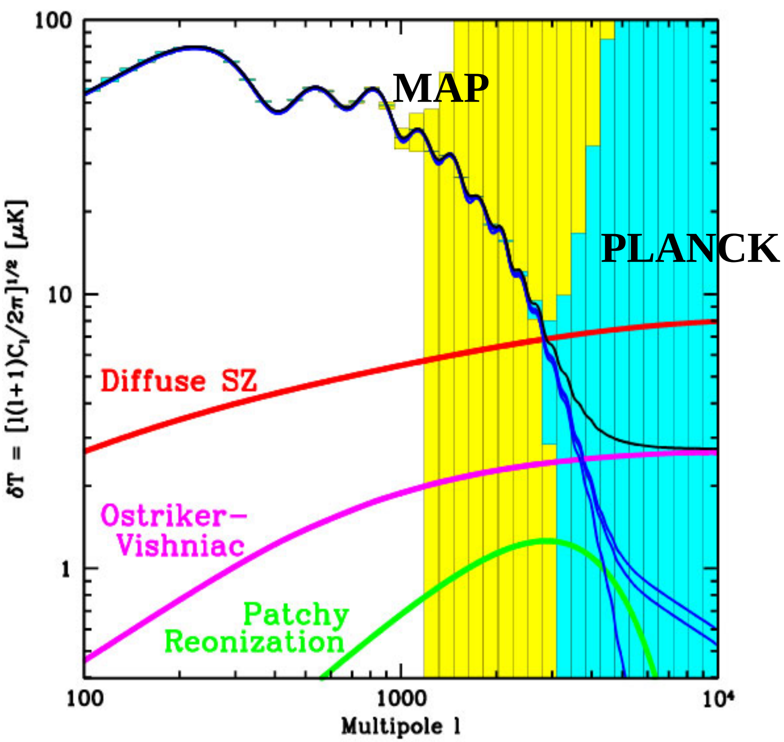


<1% Survey area

$\approx 2\%$ High quality area

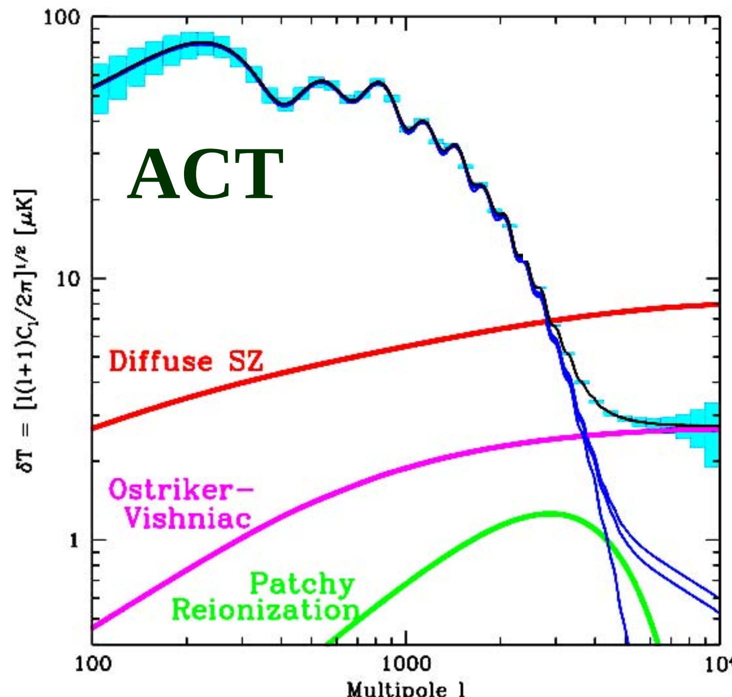
150 GHz **SZ Simulation** **MBAC on ACT** **PLANCK** Burwell/Seljak

1.7' beam



Statisitcal uncertainties

SPT and APEX too.



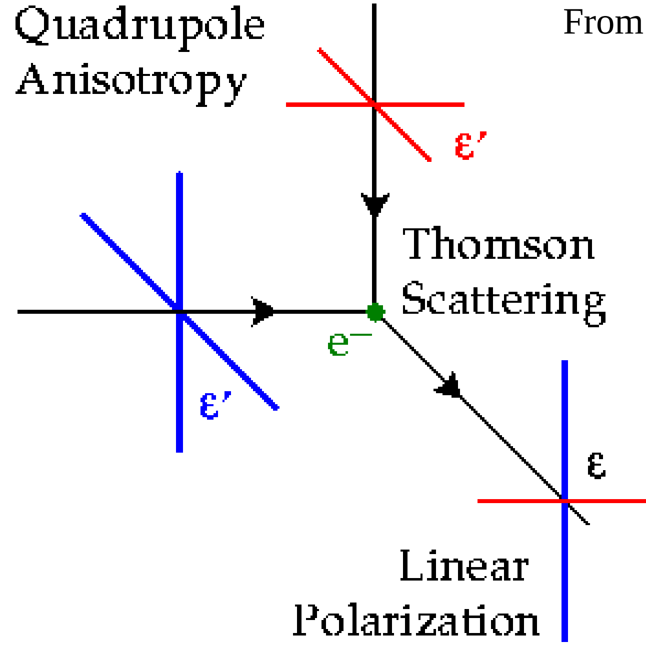
de Oliveira-Costa

CMB Polarization

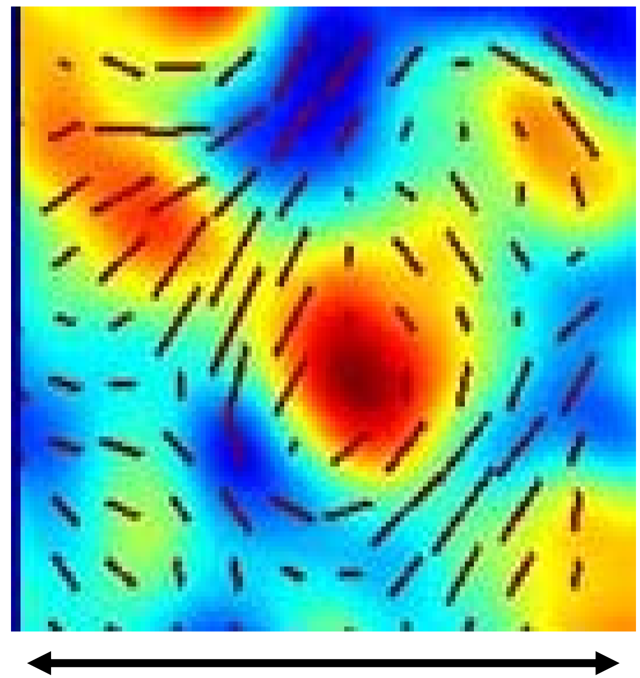
- Polarization of the CMB is produced by Thompson scattering of a quadrupolar radiation pattern.

- A component of the polarization is correlated with the temperature anisotropy.

- Whenever there are free electrons, the CMB is polarized.



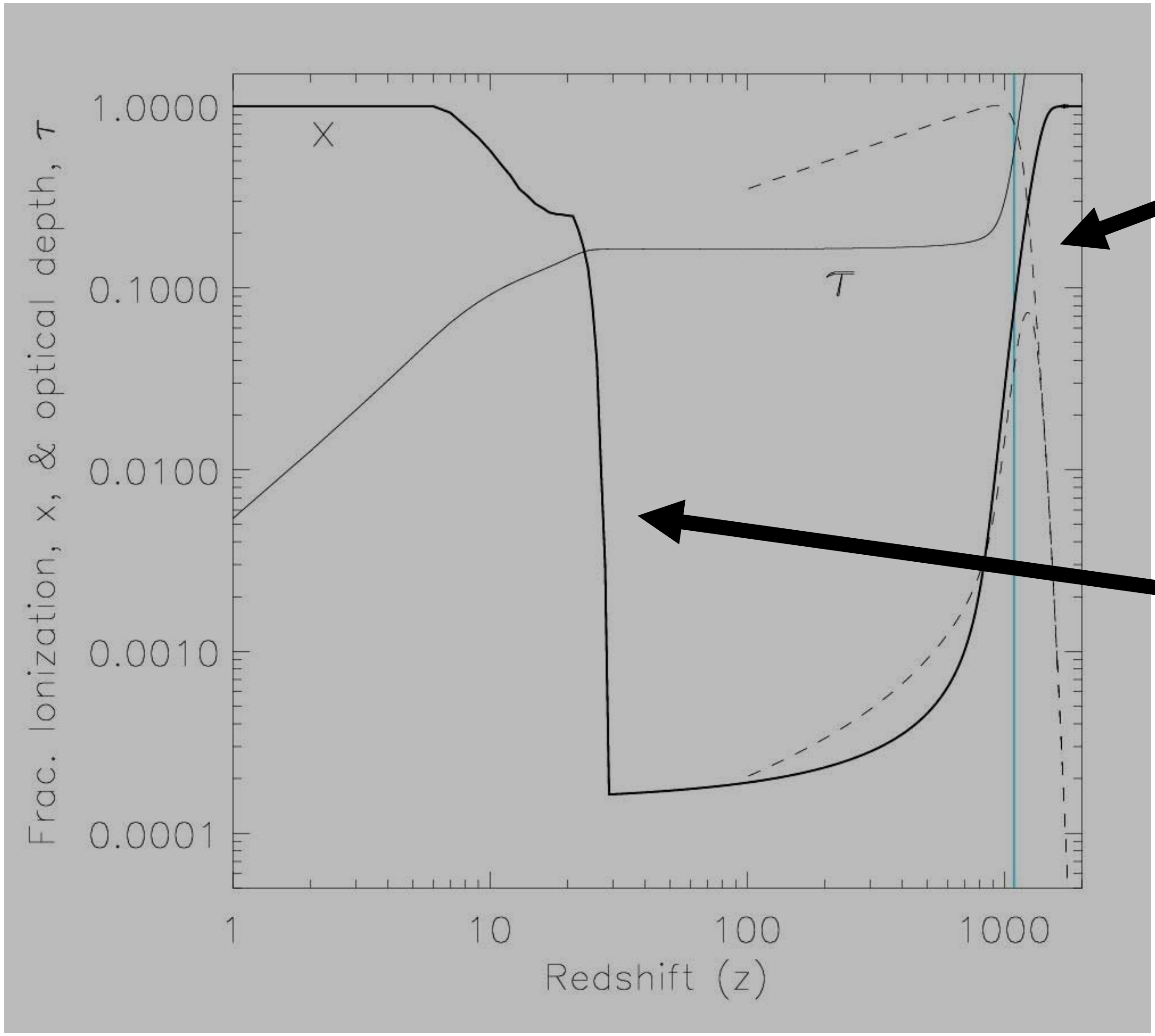
From Wayne Hu



2 deg

Seljak & Zaldarriaga

Ionization History of Universe



Polarization generated at decoupling surface.

Polarization generated by first stars turning on.

Types of Cosmological Perterbations

Scalars: $\frac{\delta\rho}{\rho}$, $\mathrm{P(k)} \propto k^{n_s}$

- Temperature
- E polarization

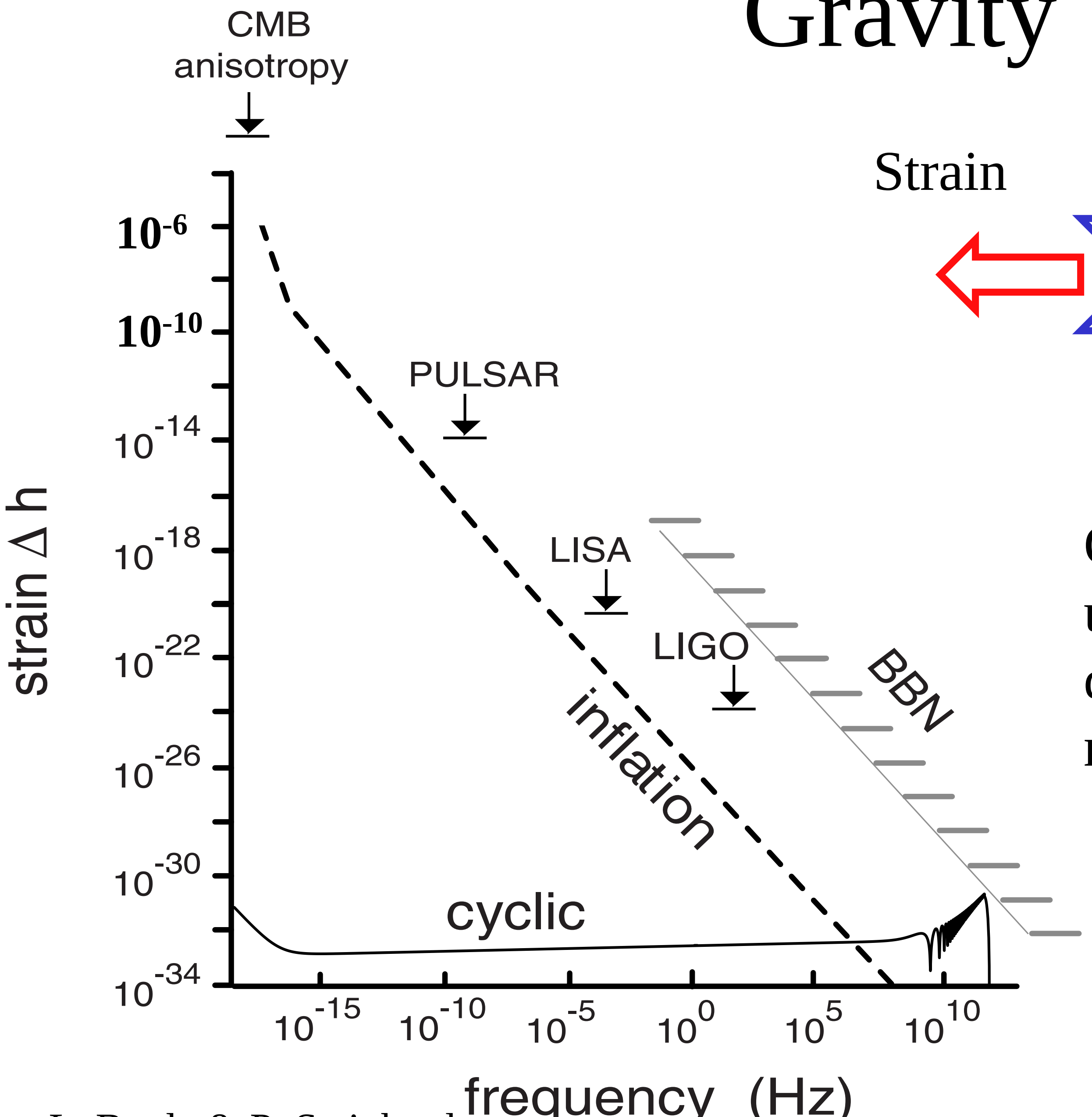
Tensors *h* (GW strain)

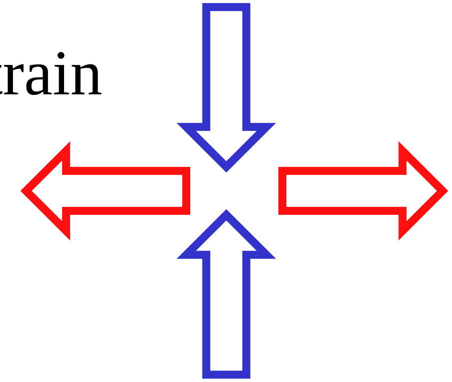
- Temperature
- E polarization
- B polarization

$$r = \frac{\mathrm{Var(Tensors)}}{\mathrm{Var(Scalars)}} \sim 0.27$$ (Maximum)

Khoury et al.

Gravity Waves





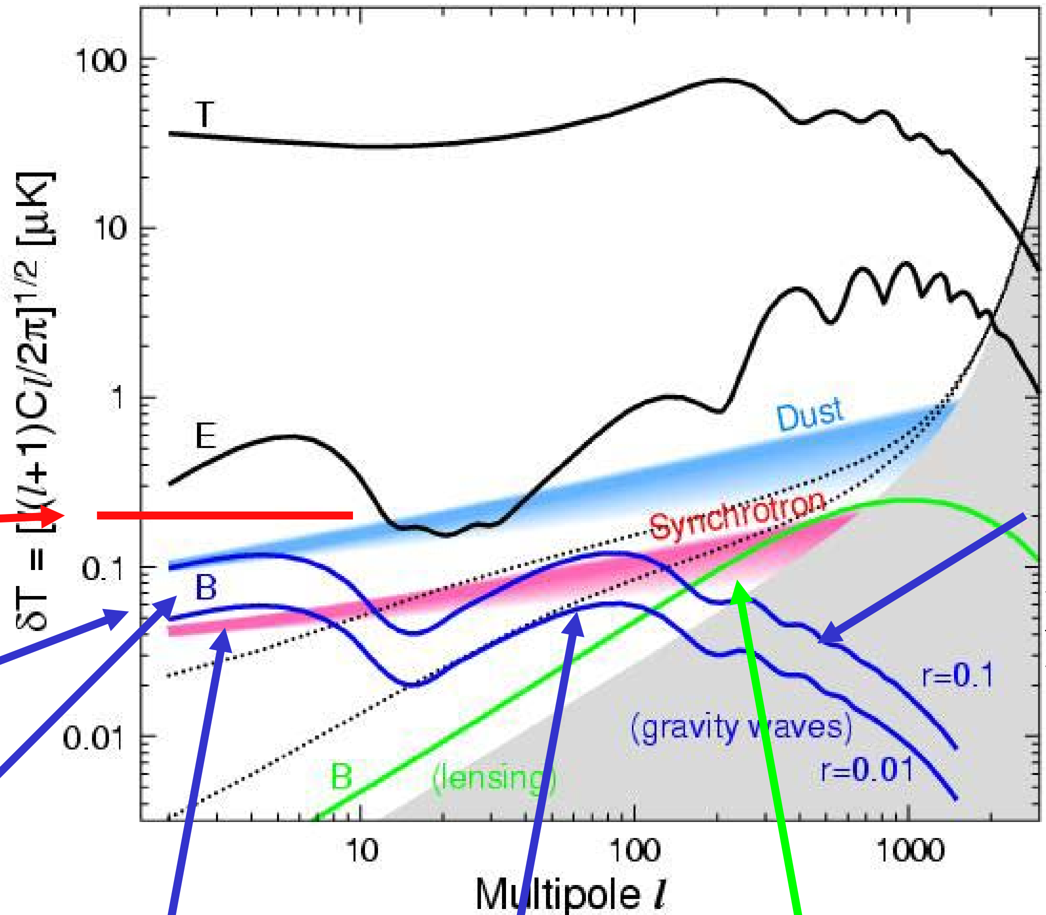
Over expanse of universe, one side is displaced 1000 ly with respect to the other.

From L. Boyle & P. Steinhardt

Polarization Spectrum

Test inflation & tau

Test T predictions



Current limit on tensors

B modes from tensors only.

G-waves decay once inside the horizon.

$$\delta T_l^B \propto r^{1/2} \propto E_{infla}^2$$

Reionization peak (z_r=20)

Horizon size at decoupling (z_{dec}=1089)

B modes from lensing of E modes.

On the Verge of Detecting r?

$$r \leq 0.84 \quad (95\%\ cl, \quad \mathrm{WMAP})$$ Spergel et al, 2003

$$r \leq 0.53 \quad (95\%\ cl, \quad \mathrm{WMAP} + \mathrm{2dF})$$ Spergel et al, 2003

$$r \leq 0.47 \quad (95\%\ cl, \quad \mathrm{WMAP} + \mathrm{SDSS})$$ Tegmark et al, 2004

$$r \leq 0.36 \quad (95\%\ cl, \quad \mathrm{WMAP} + \mathrm{SDSS} + \mathrm{Lya})$$ Seljak et al, 2004

- All come from the temperature anisotropy and will improve. Simple models of inflation are being leaned on!
- A possible 95% *cl* limit on r from TT is roughly 0.1.
  Kosowsky, '04
- The window for using B modes to detect r will open soon.

The tensor to scalar ratio is being constrained by the low *l* region of the TT spectrum.

When *r* is added to the mix of parameters (making 7), n_s rises to compensate. There is a n_s-*r* degeneracy*.

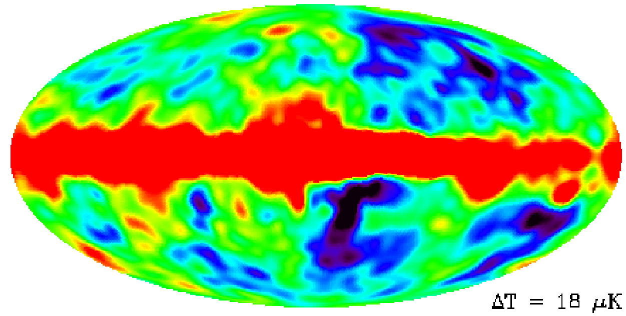
$r<0.84$	$n_s = 1.064^{+0.66}_{-0.059}$	WMAP
$r<0.47$	$n_s = 1.012^{+0.049}_{-0.036}$	WMAP+SDSS Tegmark *et al*
$r<0.38$	$n_s = 1.00 \pm 0.03$	WMAP+SDSS+Lya Seljak *et al*

This is starting to lean on *r*=0.27 for simple models of inflation.

*and tau, A too.

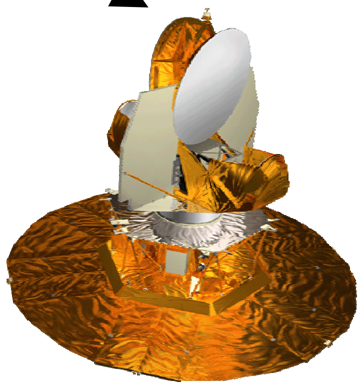
Sensitivity Advances

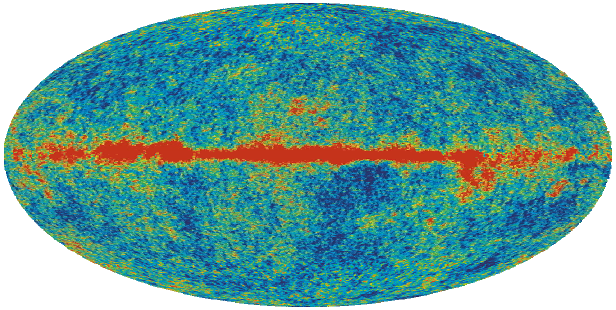
COBE



>x60

WMAP





>x20

Planck

>x50?

Inflation Probe

Galaxy Removed CMB Map