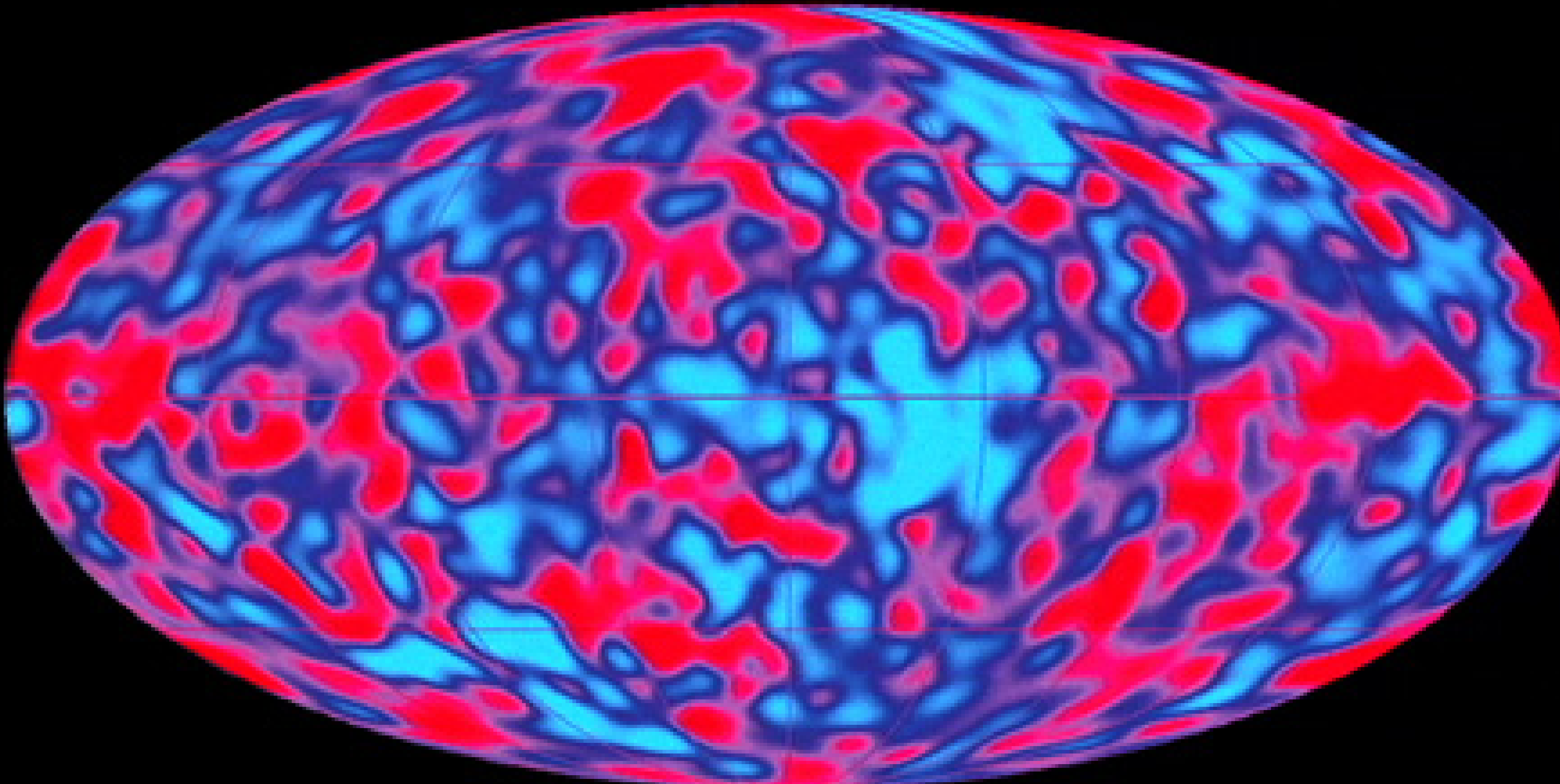
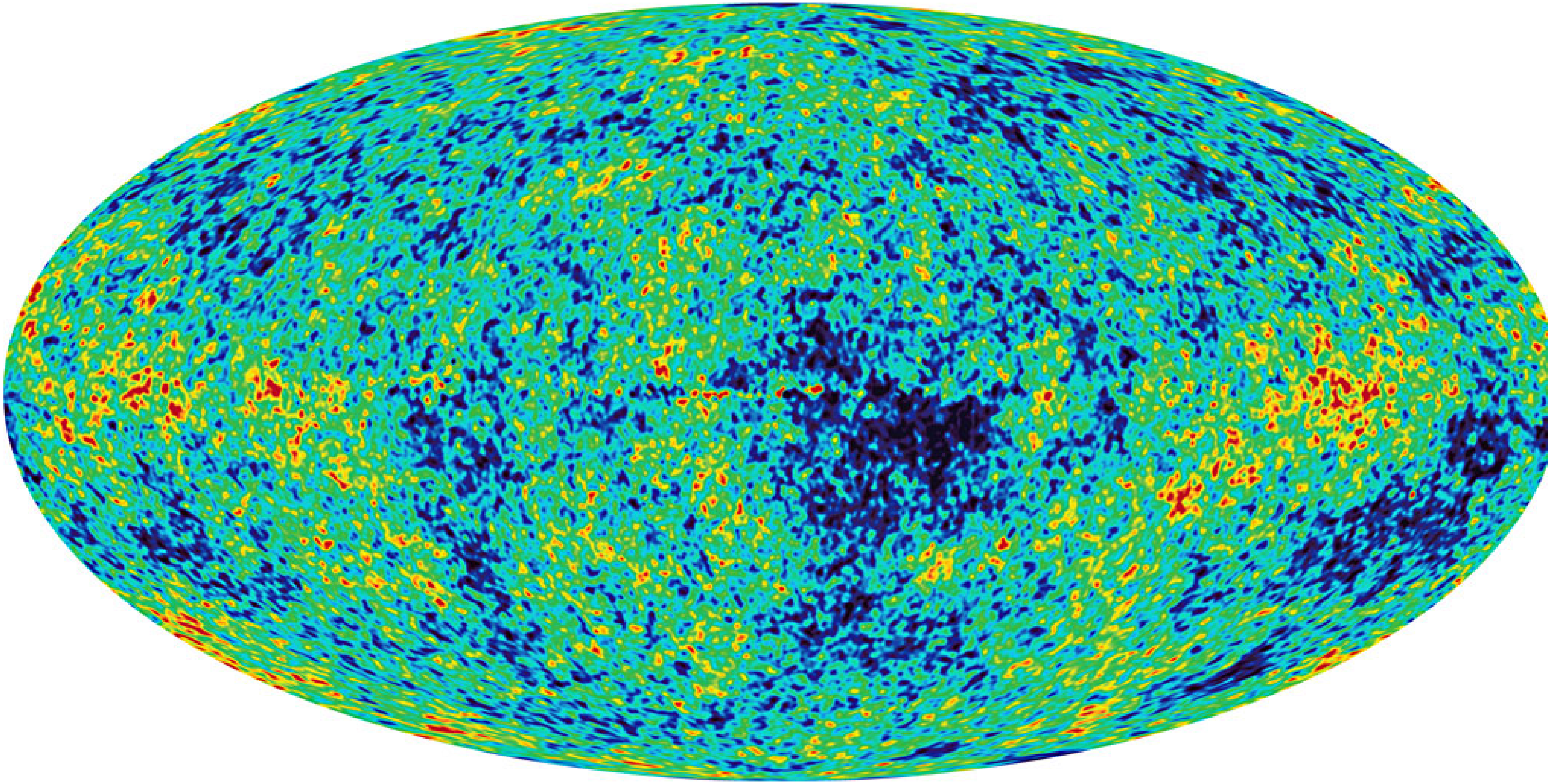
YETI, IPPP, Durham
January 8th 2015

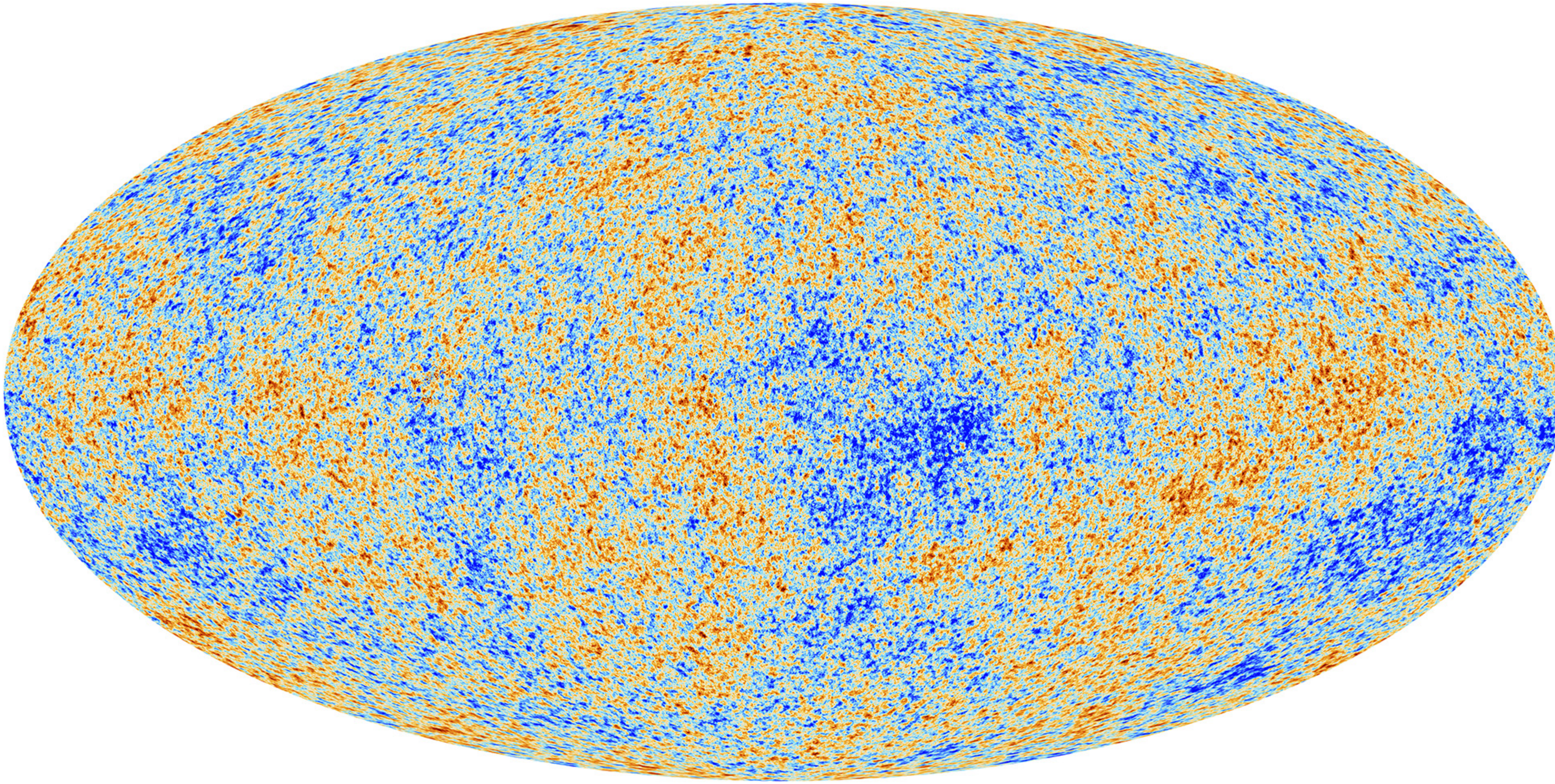
CMB:Theory

Peter Coles (Sussex)
(@telescoper)

with many thanks to Antony Lewis!







The Elephant in the Room

BICEP2

17 March 2014 Last updated at 14:46

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Cosmic inflation: 'Spectacular' discovery hailed

By Jonathan Amos
Science correspondent, BBC News

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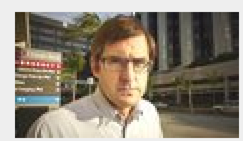

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Kylie Minogue on her pop c

8 January 2015

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Pages feed 20+

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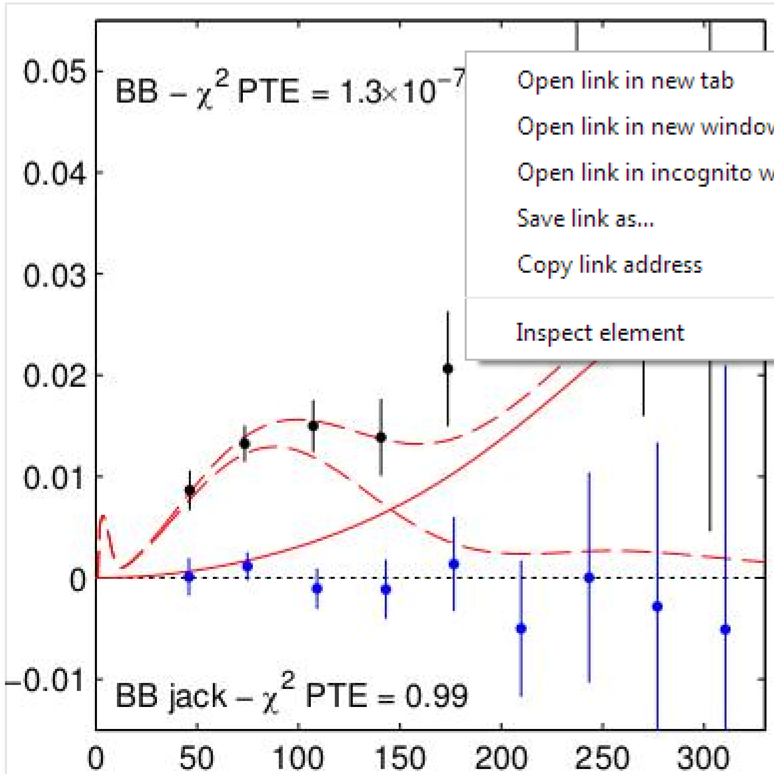
DEVELOPER

Create App...

the update) don't look very comforting. Even just a single value of 0.000 only has a probability of 14%, not leaving much room for the other low values in the table.



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You, Per Barth Lilje, Paolo Natoli and 5 others like this.

Julian Borrill See elsewhere - the 0.000 jackknife values are typos.
20 hours ago · Like

Hans Kristian Eriksen I know -- that's what "even after the update" refers to. That is, my point is that even in the new table there are 1 value of 0.000, 1 value of 0.002, 3 values of 0.004, 1 value of 0.008, 1 value of 0.010, 1 value of 0.022, 1 value of 0.024, 1 value of ... See More

ABOUT 853 me

Open group

853 members (852 new) · Invite by Em

+ Add people to Group

SUGGESTED GROUPS

Quantum Physics
28,803 members

Online Astronomy Society
Natasha Mendes and 3 other friends joined

Young @ CERN
2,601 members

Marketing for Scientists
Subhanjoy Mohanty and 8 other friends joined

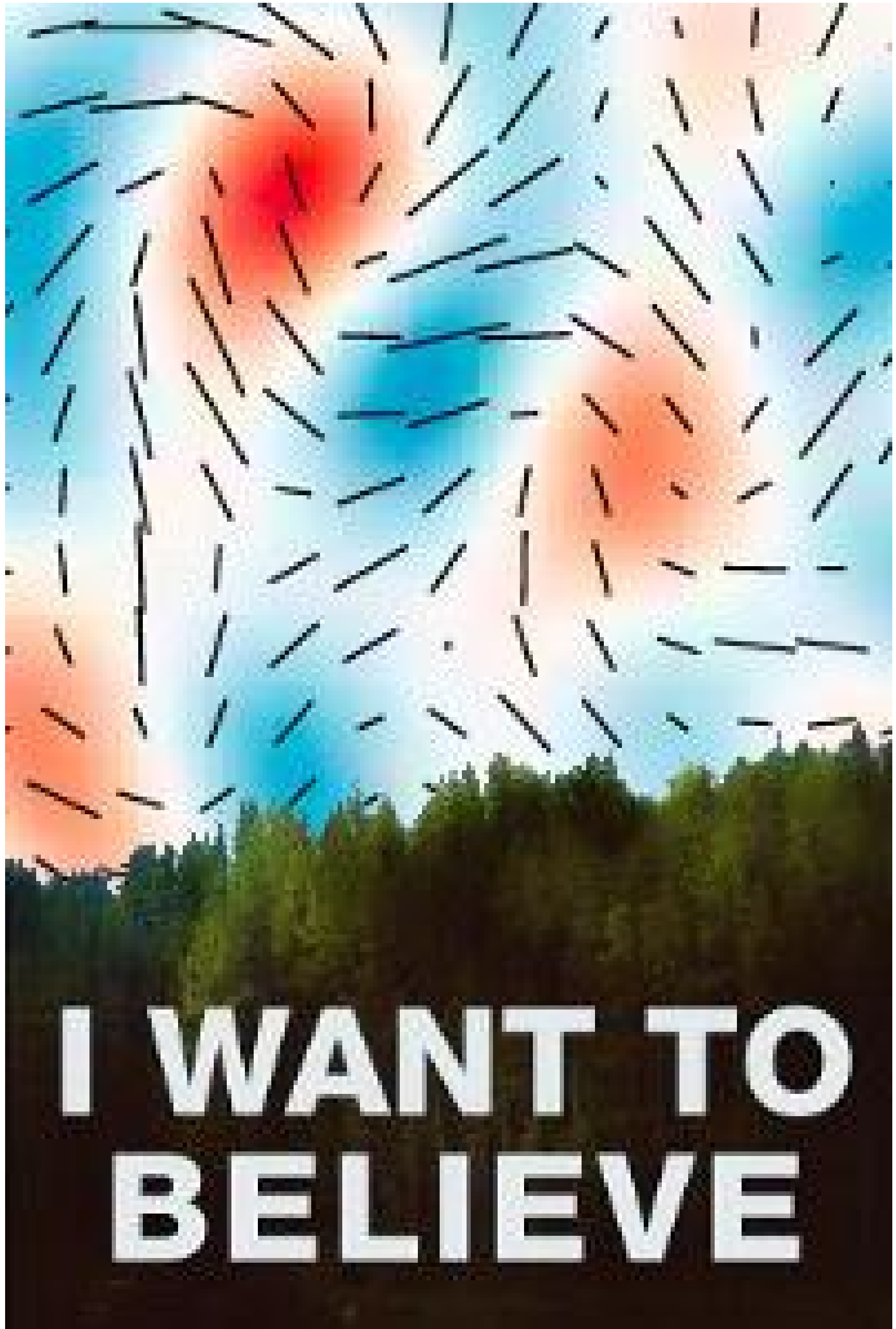
SUGGESTED MEMBERS

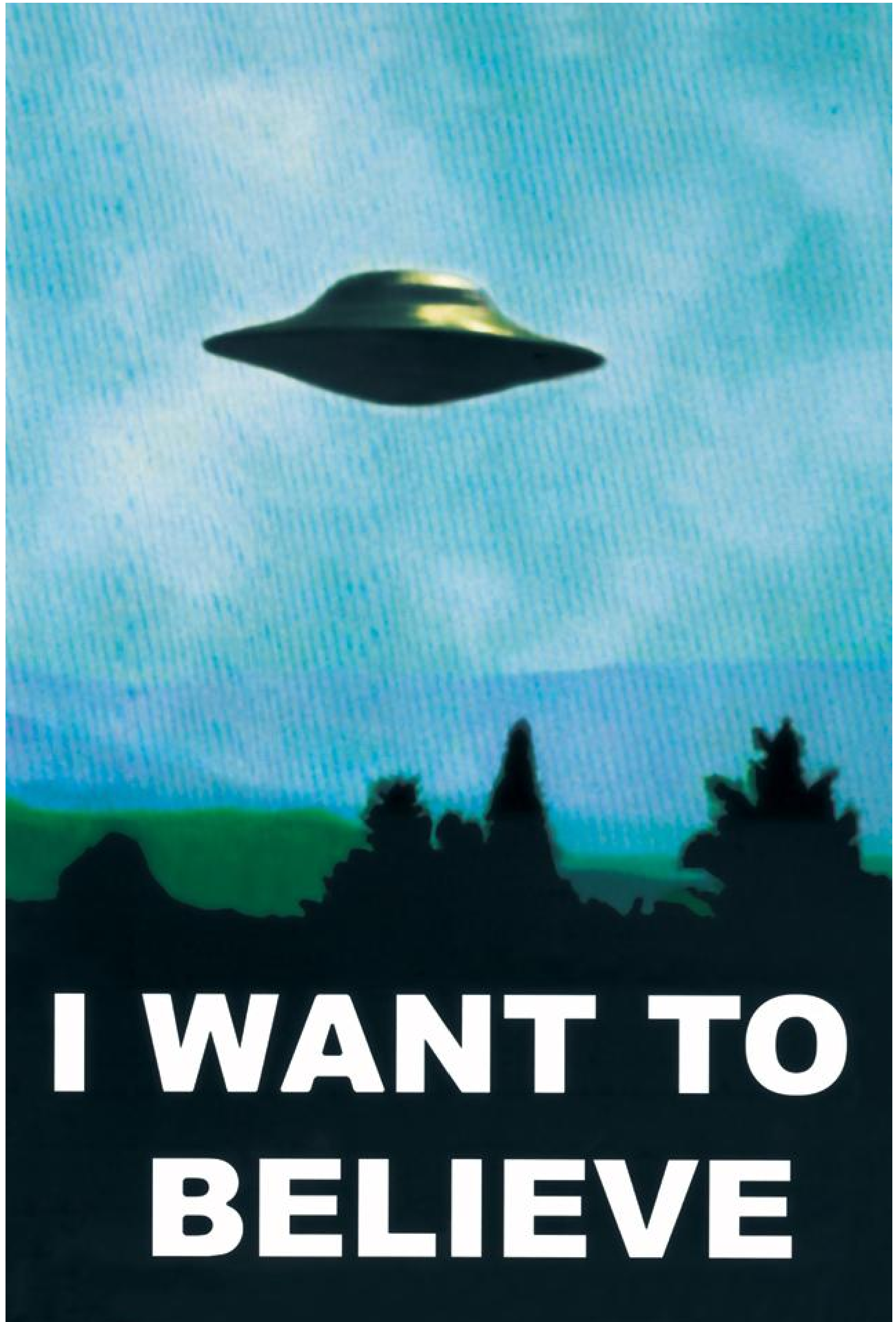
Martin Kilbinger

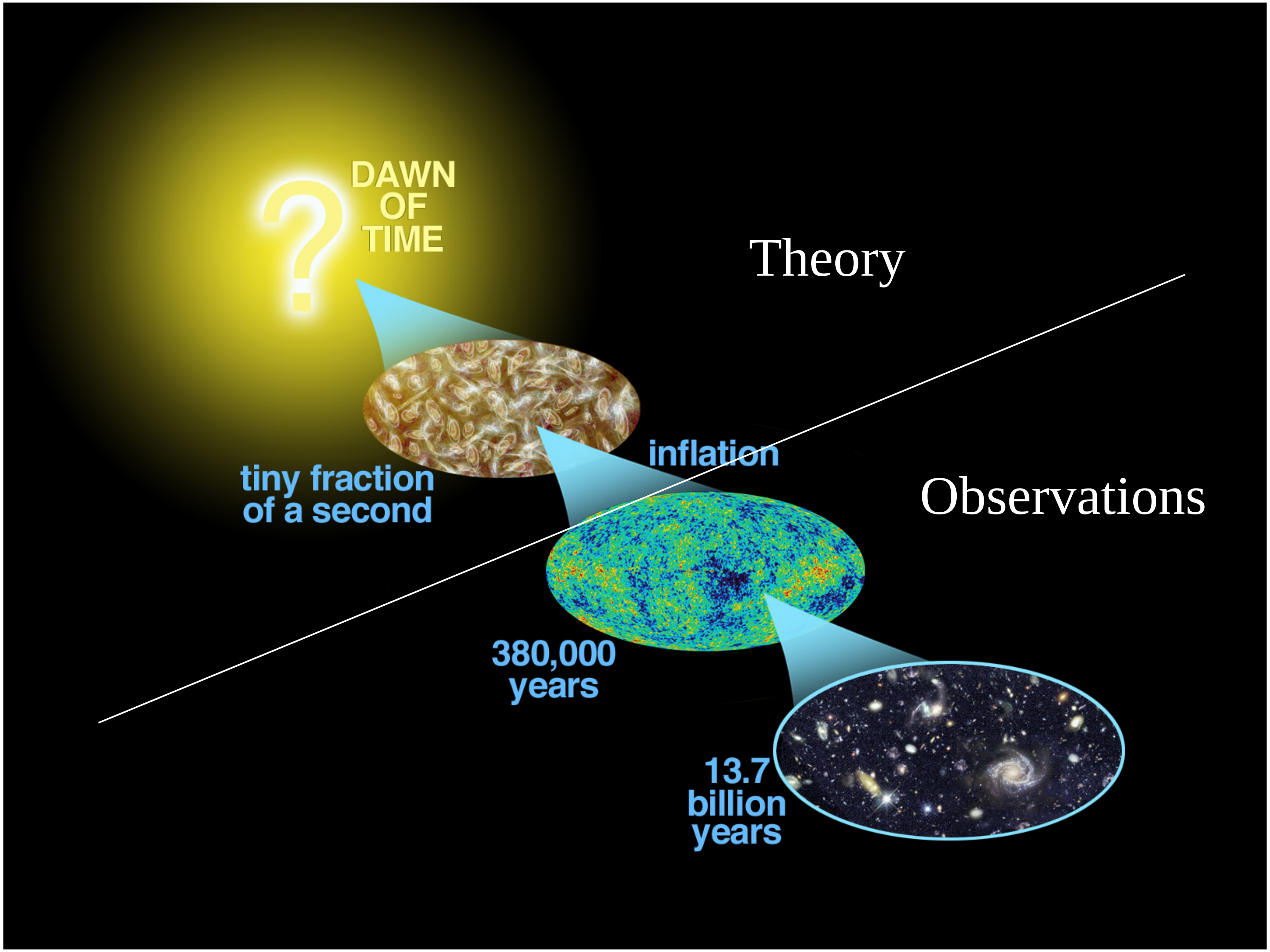
Fdnl Quest Inst

Paolo Salucci

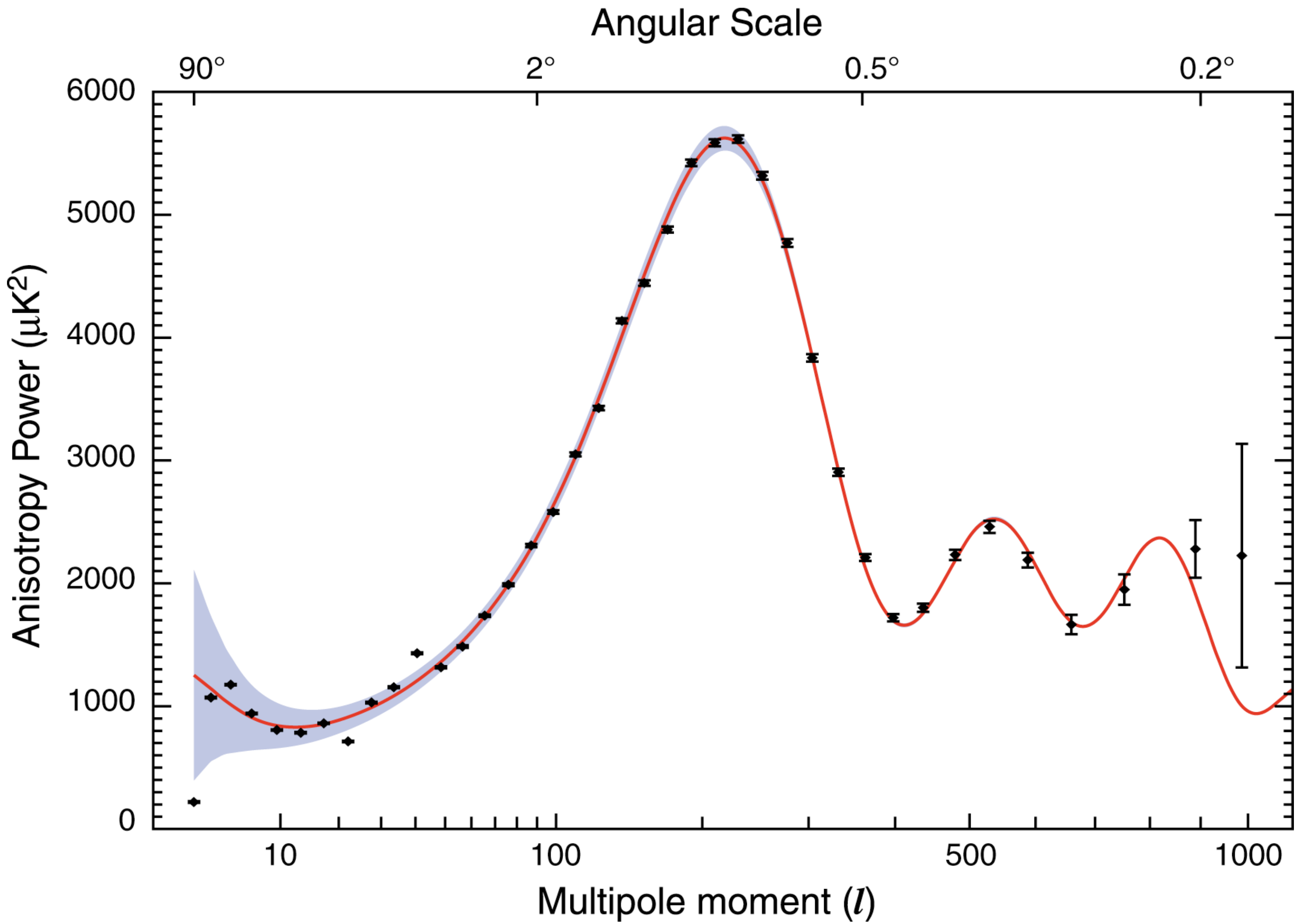
Edward Wright


I WANT TO
BELIEVE

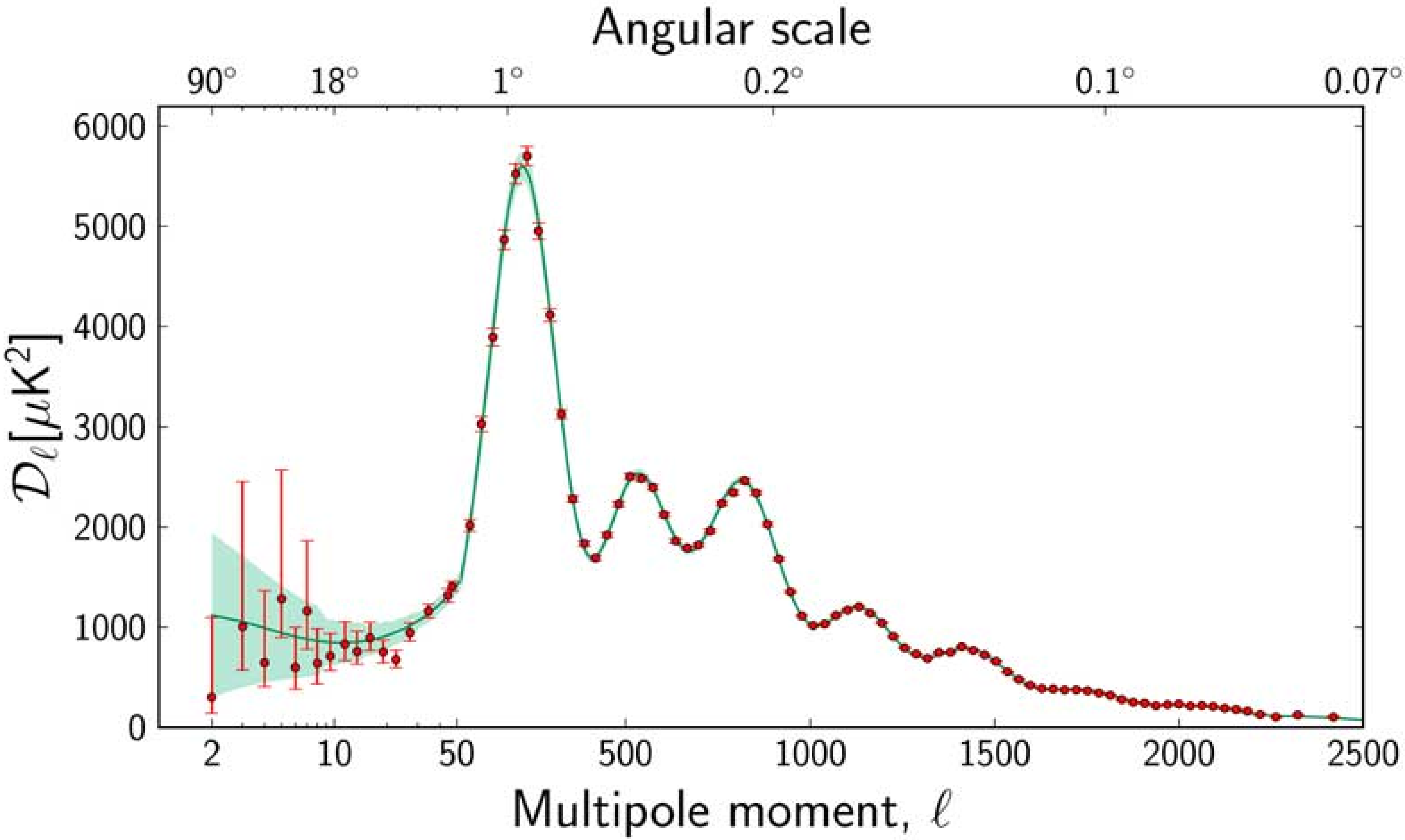

I WANT TO
BELIEVE



Source: NASA/WMAP Science Team



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)



Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Planck results: cosmological parameters

Main result: the standard 6-parameter ΛCDM model remains a good fit to CMB data.

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

Some interesting derived numbers:

H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$


BJ AB JP PC VI RvdW PK
H0 40 35 65 75 60 70 60
Ω0 0.2 1 0.35 0.2 1 0.3 0.2
Λ0 0 0 0 0 0 0.7 0
k −1 0 −1 −1 0 0 −1
t0 15 14 >9 12 18 14 16

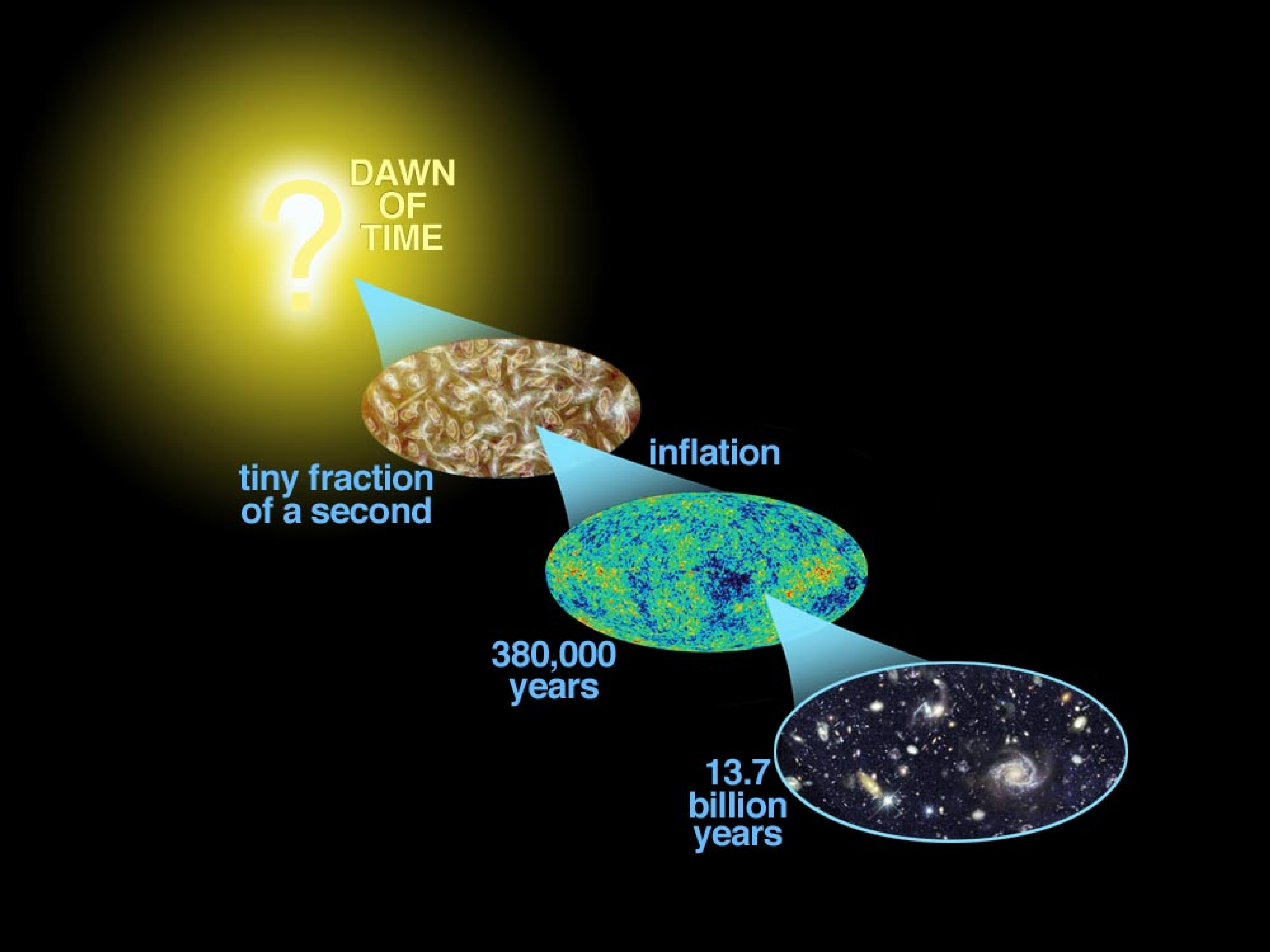
Precision Cosmology

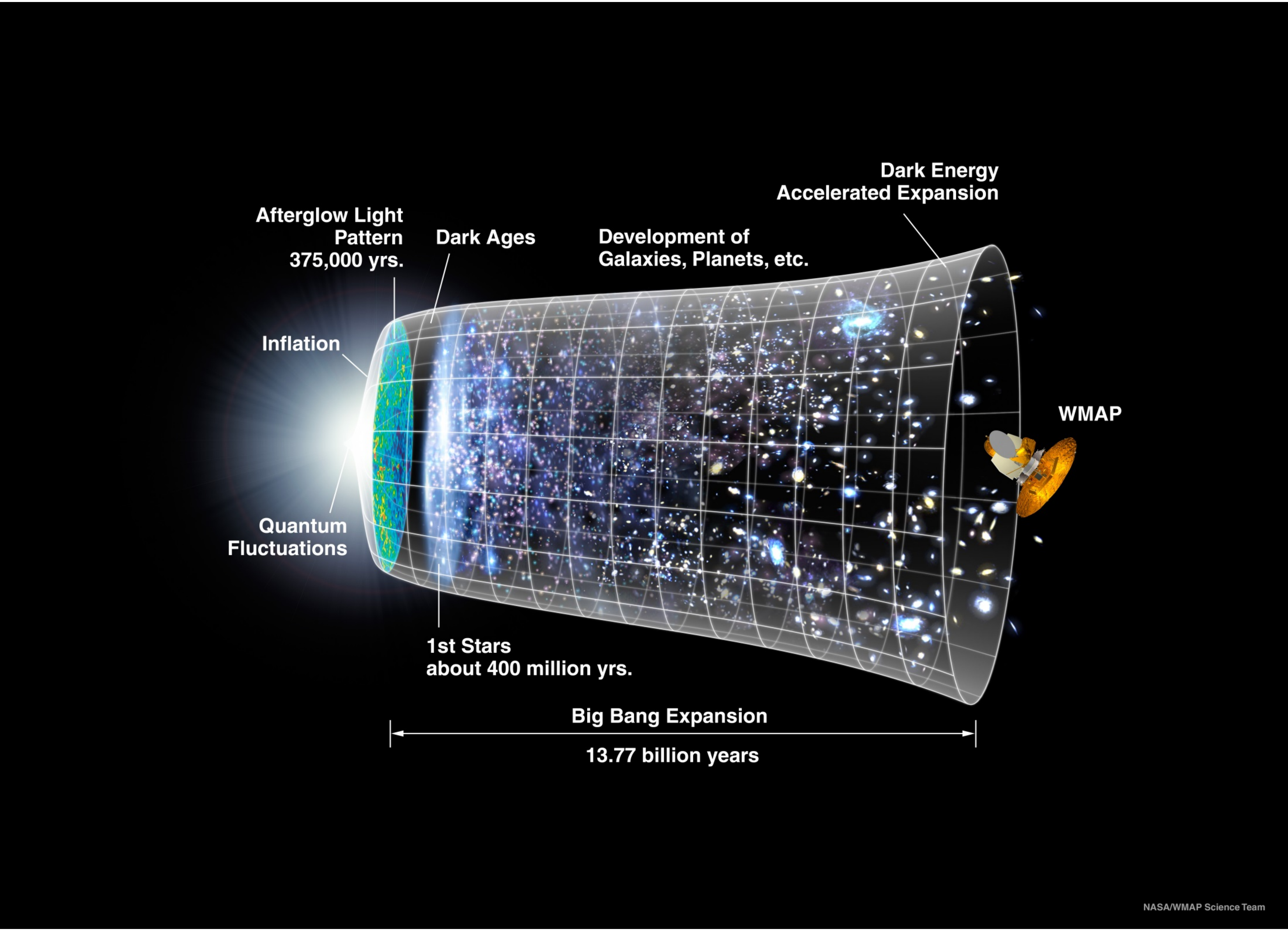
“…as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know.”


SAY “PRECISION
COSMOLOGY”
ONE MORE TIME…

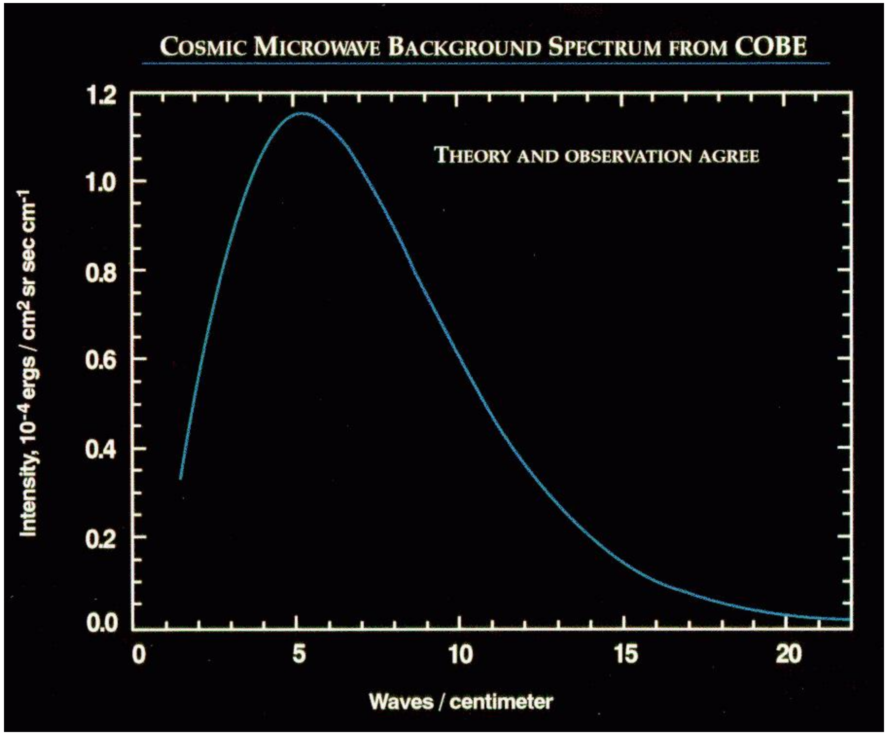
Outline

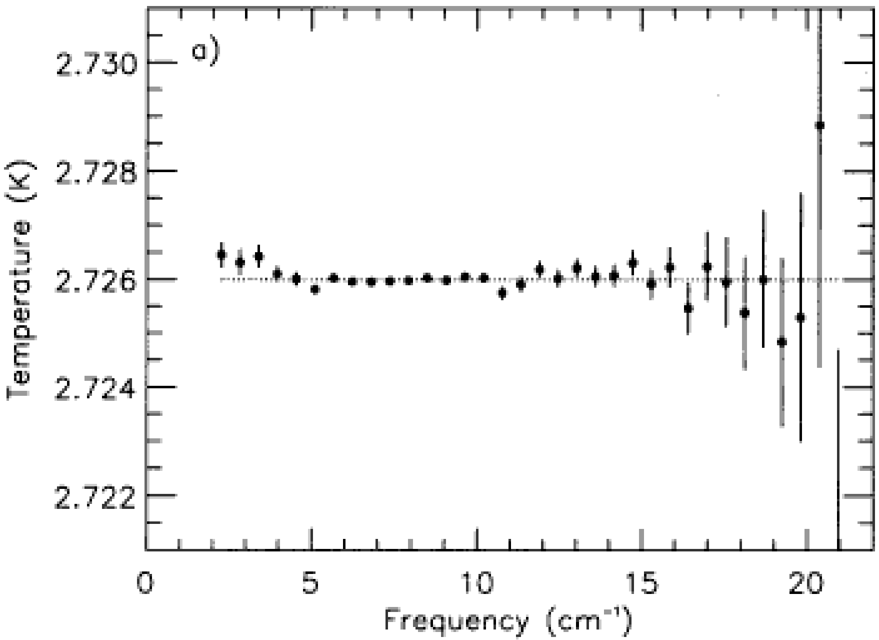
- Introduction and *basic* physics
- CMB temperature power spectrum and observables
- Beyond the power spectrum?
- Parameter estimation
- Primordial perturbations
- CMB Polarization: E and B modes
- CMB lensing (if time)


?
DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

Black body spectrum observed by COBE



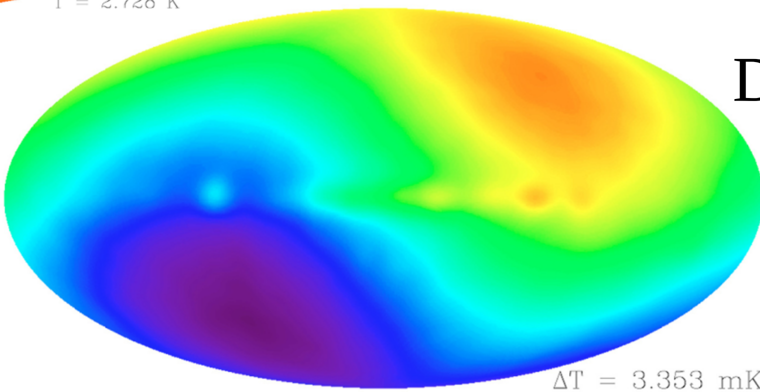


Residuals Mather et al 1994

close to thermal equilibrium:

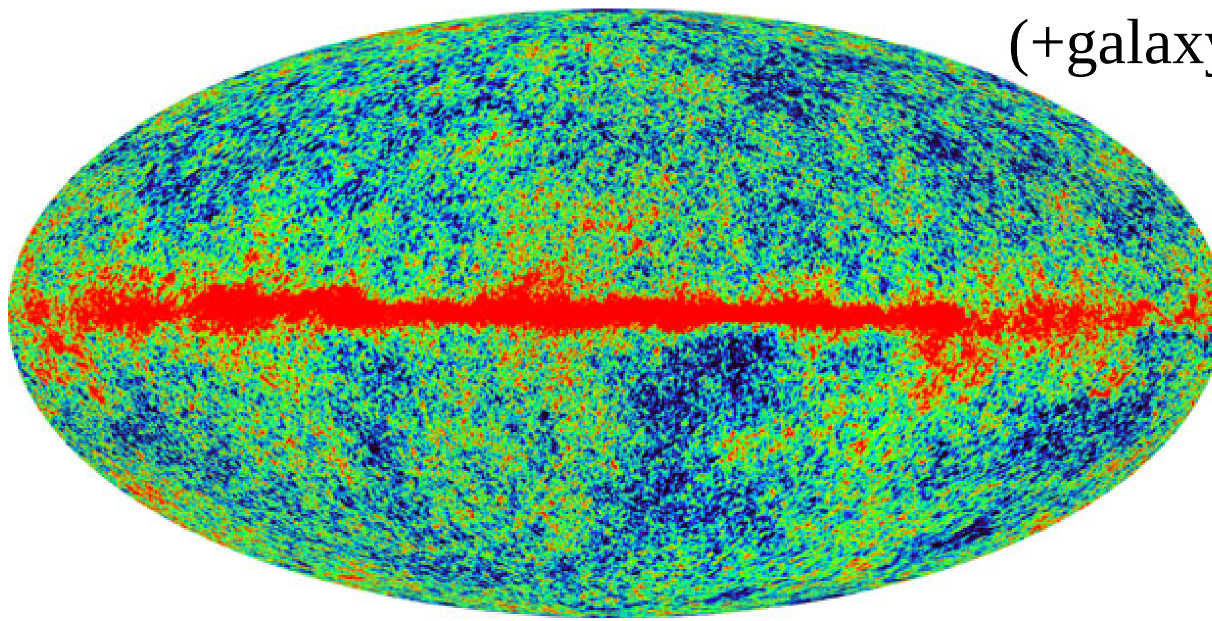
temperature today of 2.726K (~ 3000K at z ~ 1000 because ν ~ (1+z))

(almost) uniform 2.726K blackbody



Dipole (local motion)

$O(10^{-5})$ perturbations
(+galaxy)

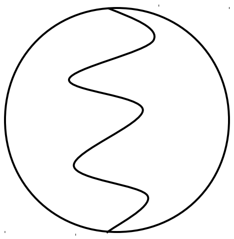


Observations:
the microwave
sky today

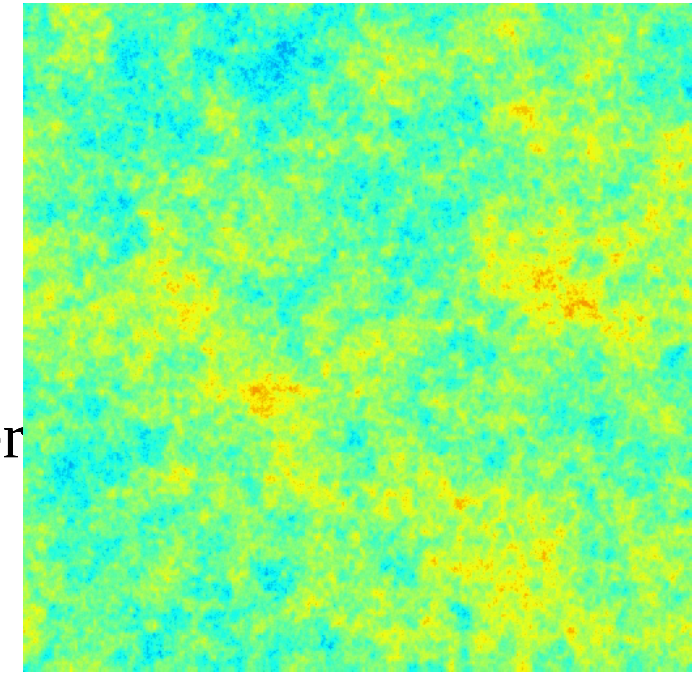
Source: NASA/WMAP Science Team

Can we predict the primordial perturbations?

- Maybe..



Inflation
make $>10^{30}$ times bigger



Quantum Mechanics
“waves in a box” calculation
vacuum state, etc…

After inflation
Huge size, amplitude $\sim 10^{-5}$

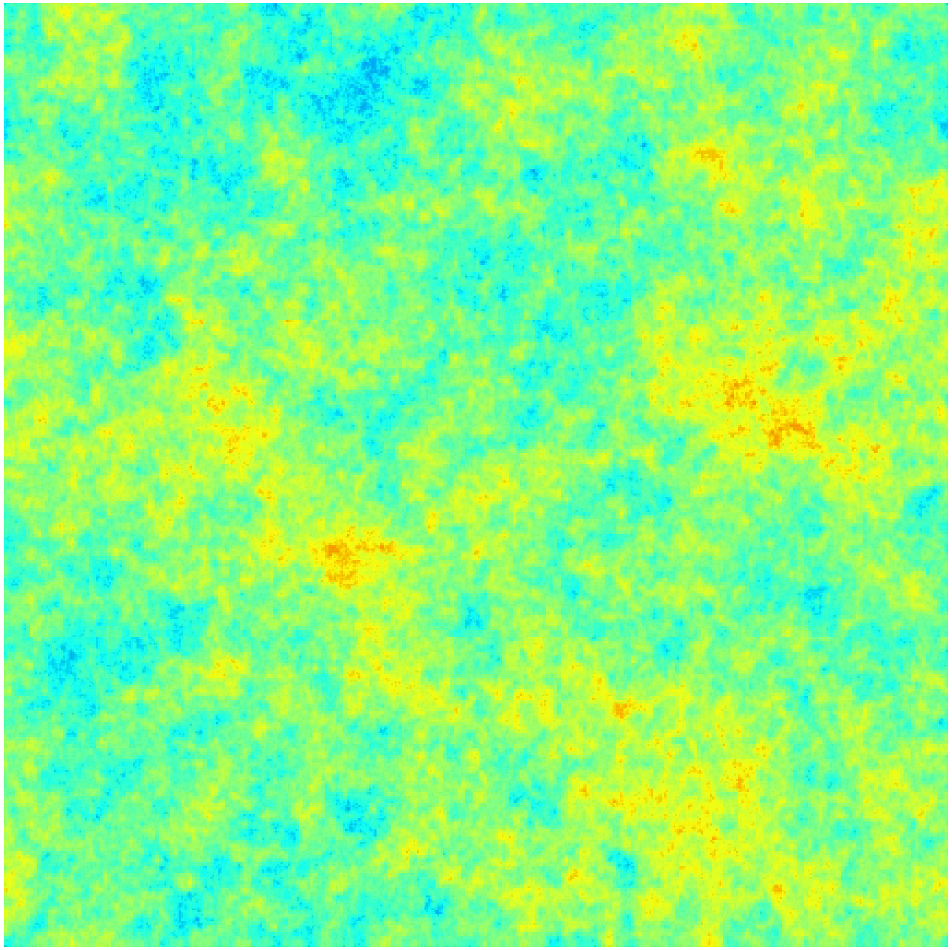

Oxford Crossword Dictionary
Concise Oxford English Dictionary
OXFORD
Oxford Thesaurus
OXFORD
Oxford English Dictionary
OXFORD
Oxford Dictionary & Thesaurus
OXFORD
Oxford Dictionary & Thesaurus
OXFORD
Oxford English Dictionary
OXFORD
Oxford English Dictionary
OXFORD
Oxford Dictionary

The Meaning of Inflation (OED)

1. The action of inflating or distending with air or gas
2. The condition of being inflated with air or gas, or being distended or swollen as if with air
3. The condition of being puffed up with vanity, pride or baseless notions
4. The quality of language or style when it is swollen with big or pompous words; turgidity, bombast

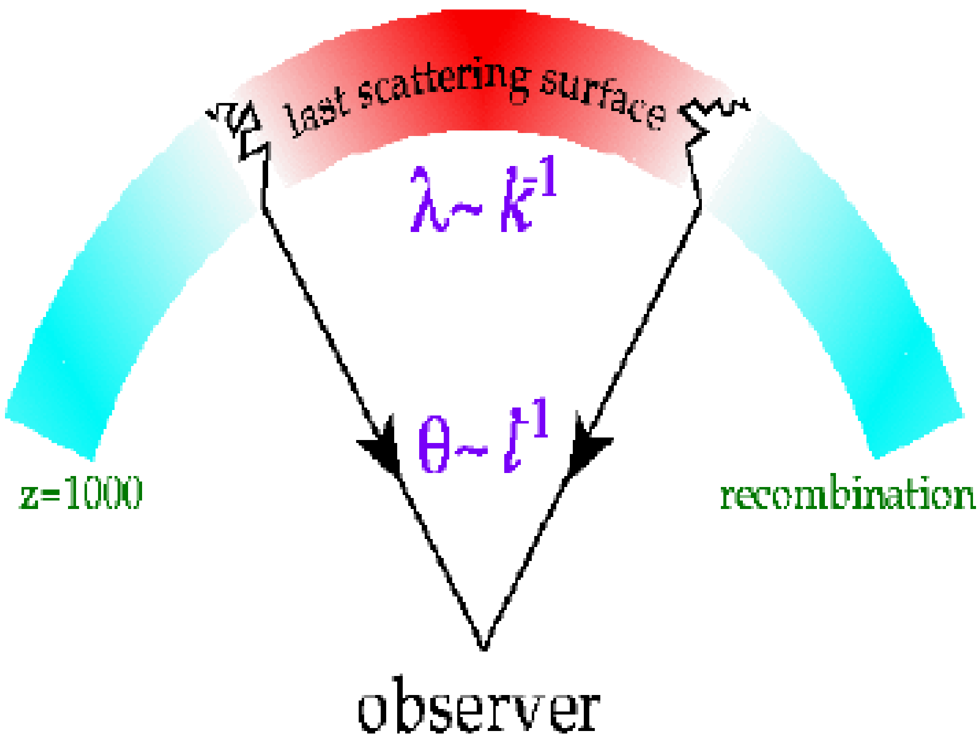
Perturbation evolution

photon/baryon plasma + dark matter, neutrinos



Characteristic scales: sound wave travel distance; diffusion damping length

Observed ΔT
as function of angle on the sky



Theory of perturbation evolution

Physics Ingredients

- **Linear Physics:** Perturbations ~ 10^{-5} so Fourier modes evolve independently
- **Thomson scattering** (non-relativistic electron-photon scattering)
  - tightly coupled before recombination: ‘tight-coupling’ approximation (baryons follow electrons because of very strong em coupling)
- **Background recombination physics** (full multi-level calculation)
- **Linearized General Relativity**
- **Boltzmann equation** (how angular distribution function evolves with scattering)

CMB power spectrum C_l

- Theory: Linear physics + Gaussian primordial fluctuations

$$a_{lm} = \int d\Omega \; \Delta T \; Y^*_{lm}$$

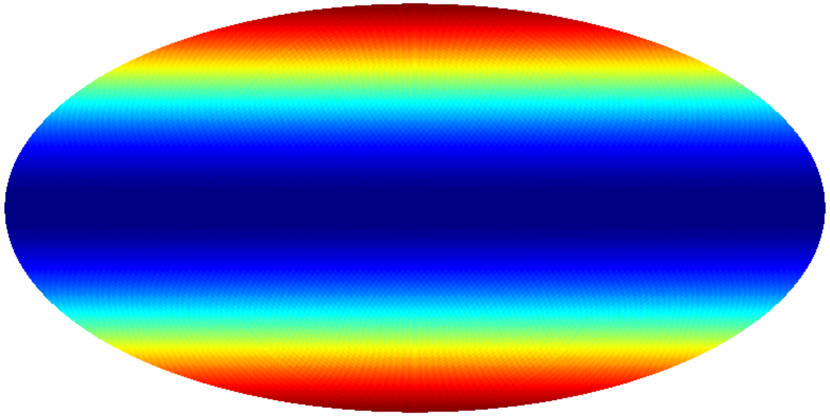
Theory prediction $C_l = \langle | a_{lm} |^2 \rangle$

- variance (average over all possible sky realizations)
- statistical isotropy implies independent of *m*

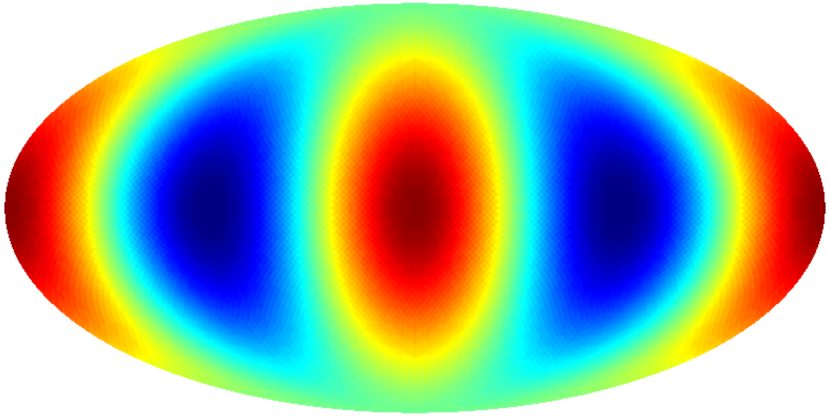
Initial conditions
+ cosmological parameters

linearized GR
+ Boltzmann equations → C_l

CMBFAST: cmbfast.org
CAMB: camb.info
CMBEASY: cmbeasy.org
COSMICS, etc..

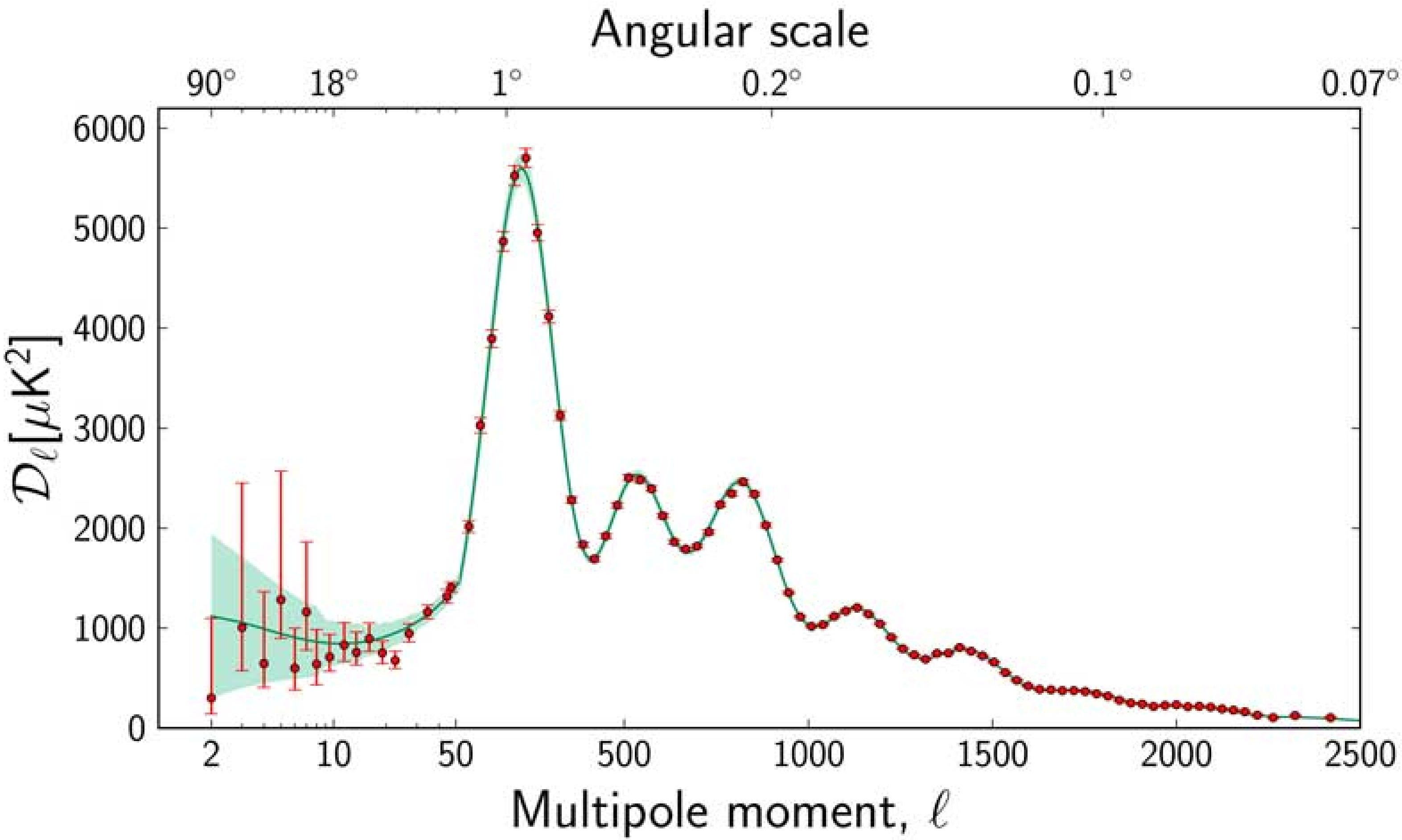


Zonal
(m=0)

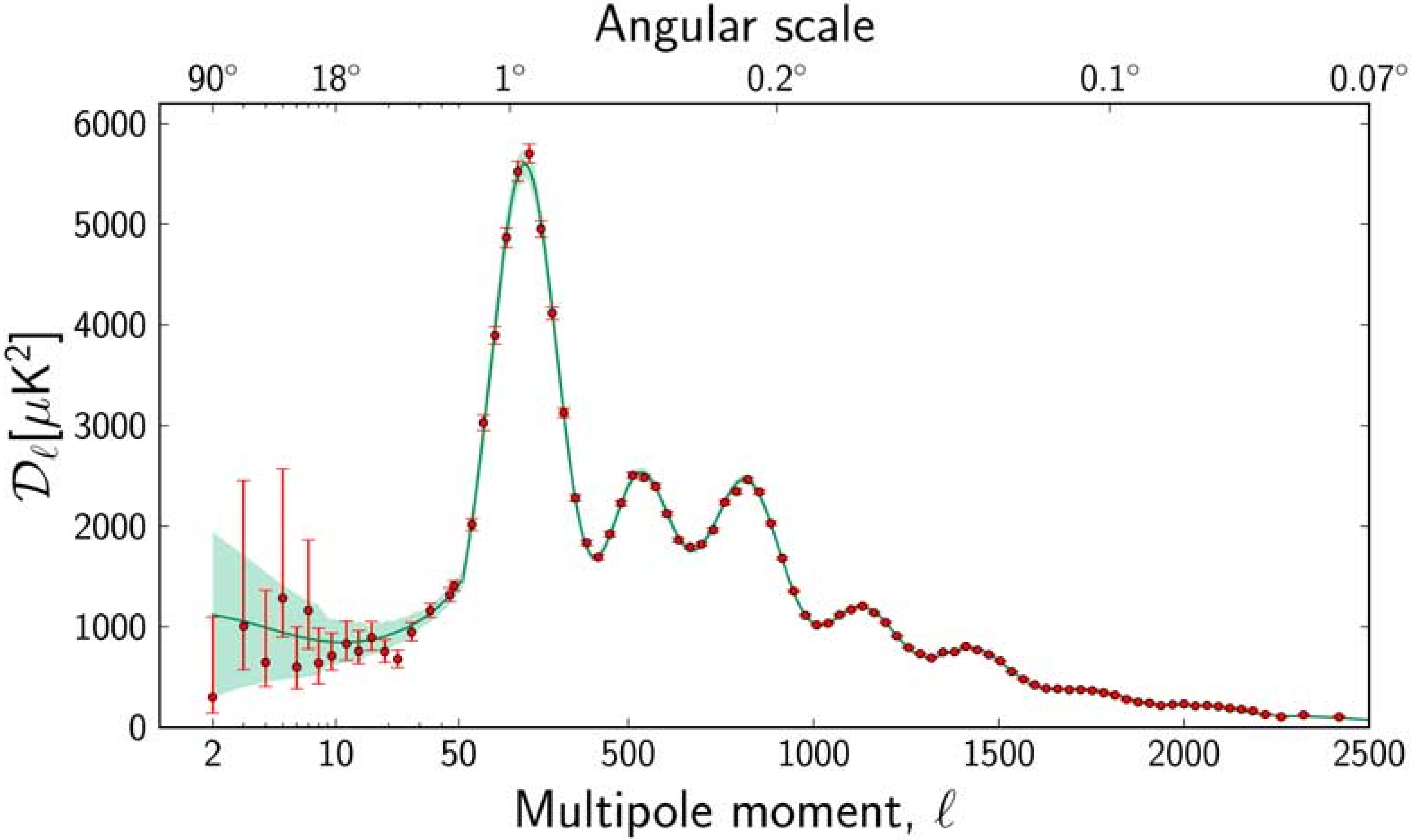


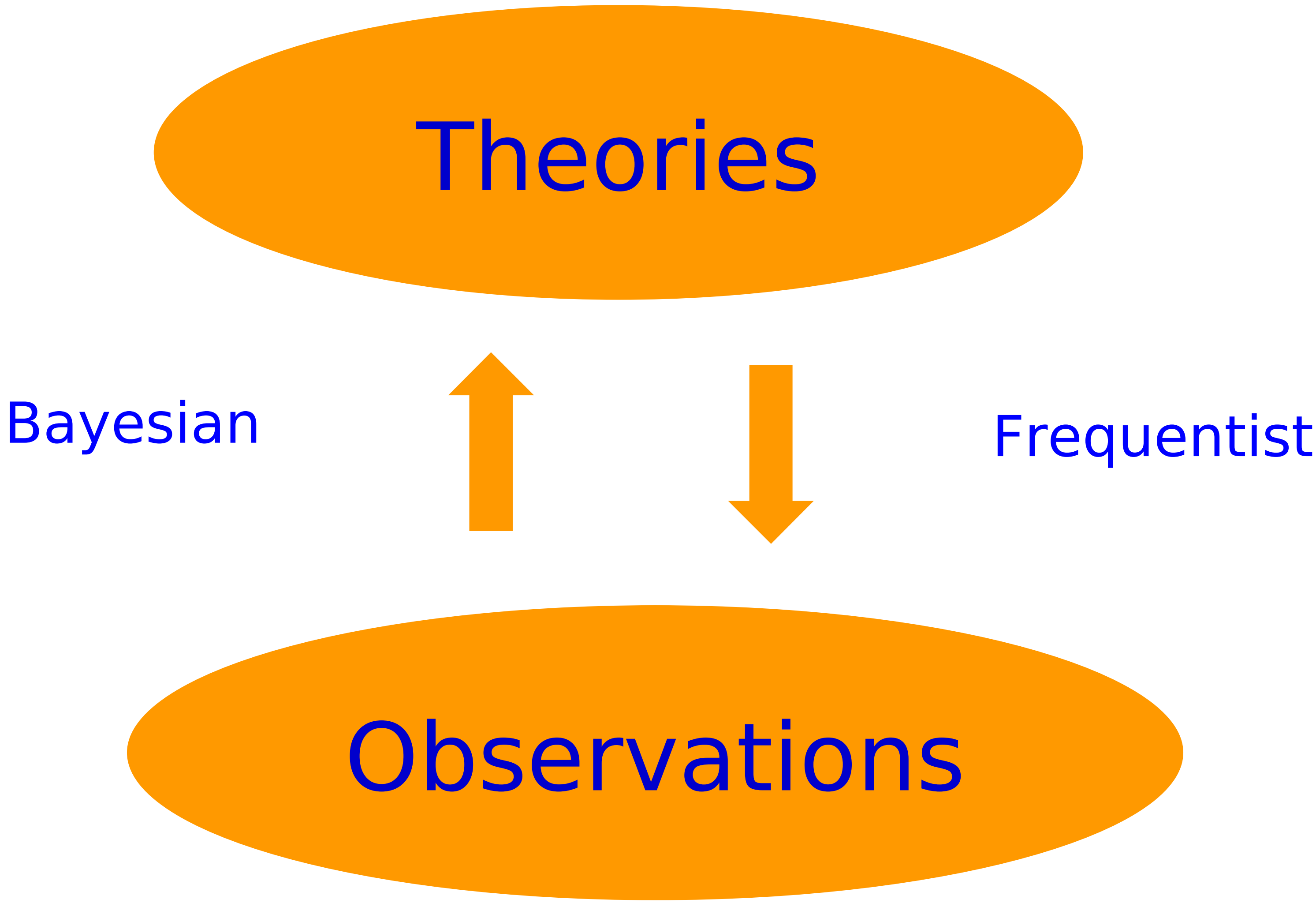
Sectoral
(m=l)

Parity Violation?



Digression !


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ



Theories
Bayesian
Frequentist
Observations

Cosmology is a massive exercise in data compression...

….but it is worth looking at the information that has been thrown away to check that it makes sense!

Beyond the Power Spectrum

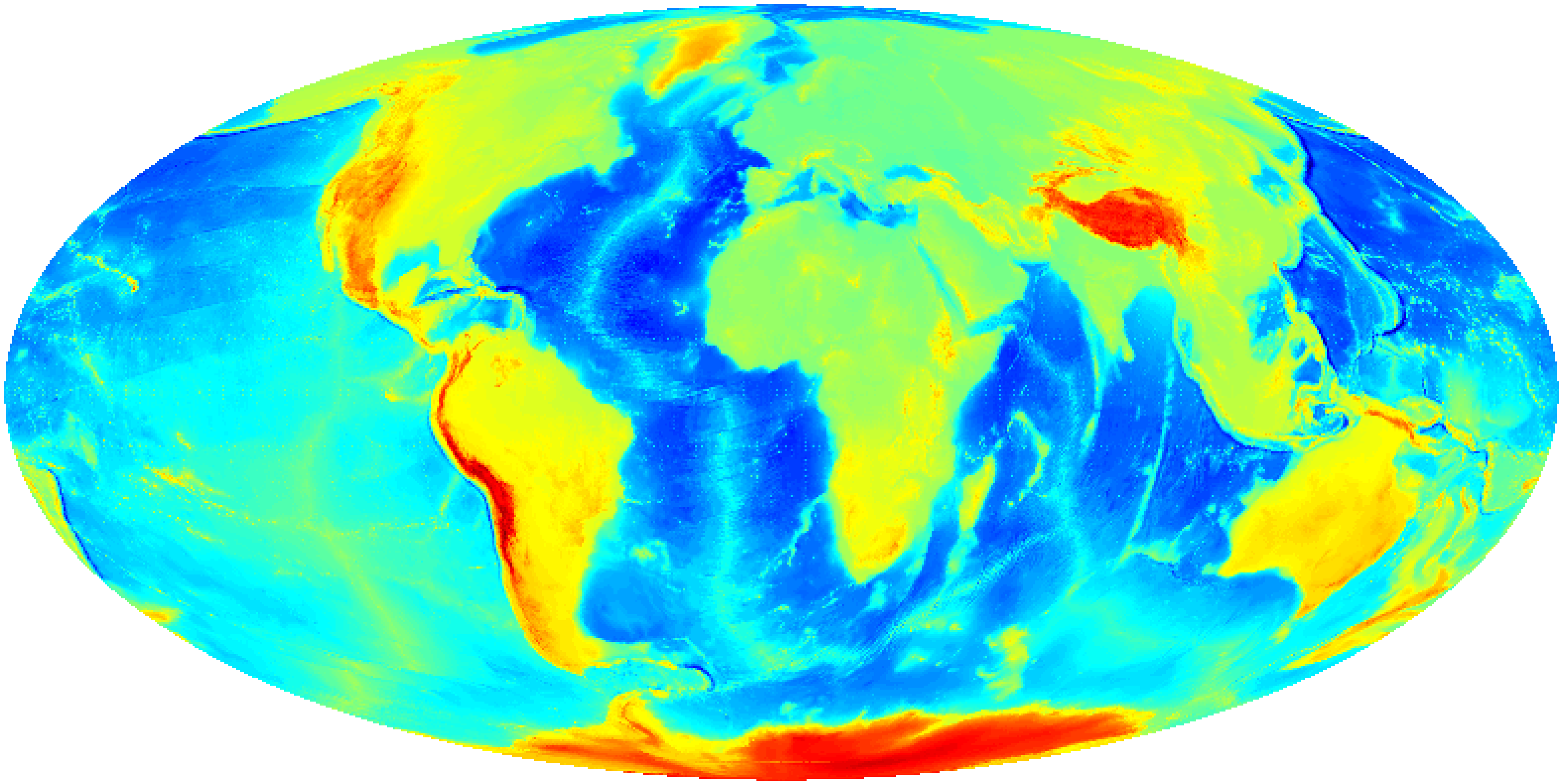
- So far what we have discovered is largely based on second-order statistics...
- This is fine as long as we don't throw away important clues...
- ..ie if the fluctuations are statistically homogeneous and istropic, and Gaussian..

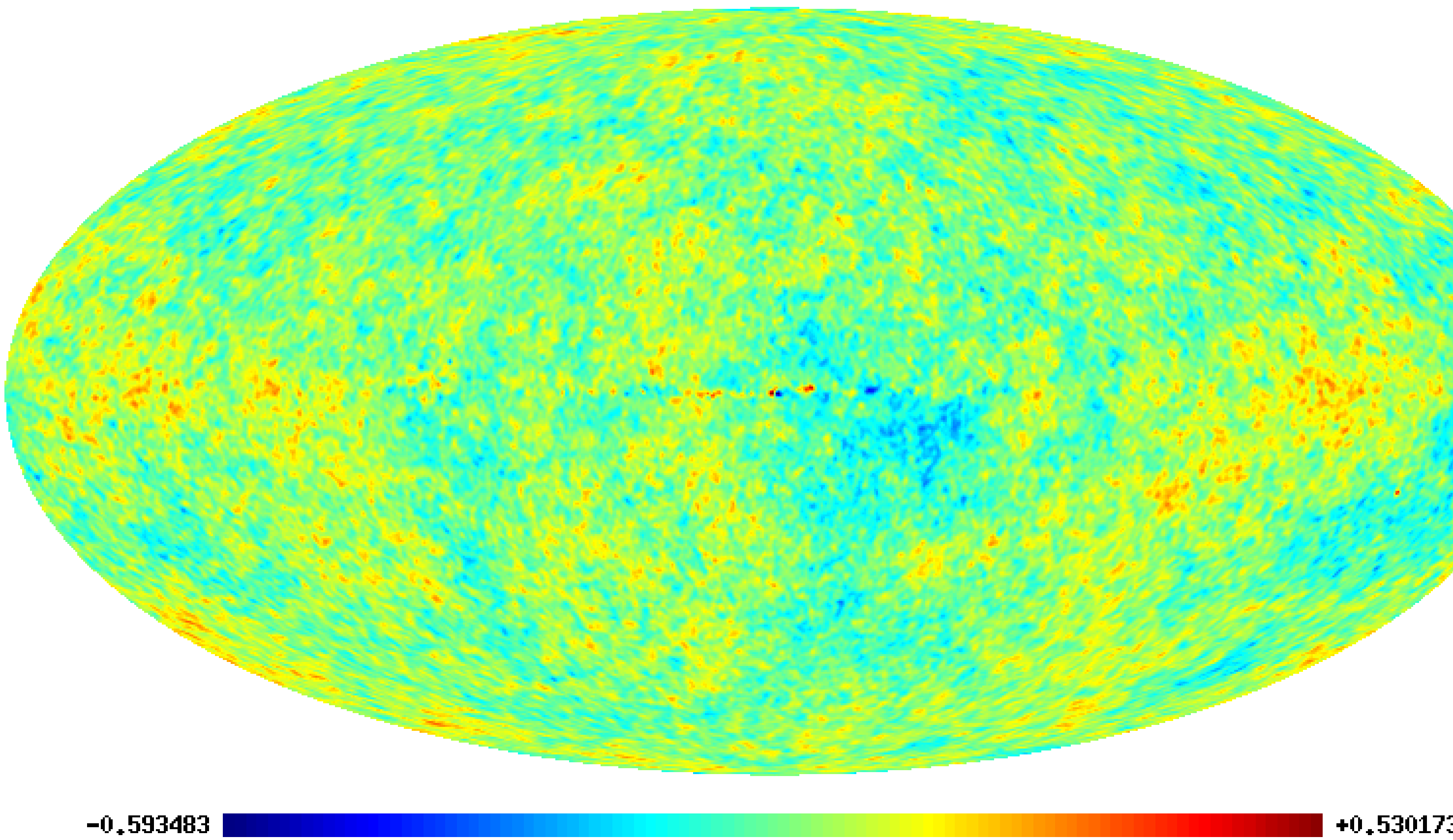
Weirdness in Phases

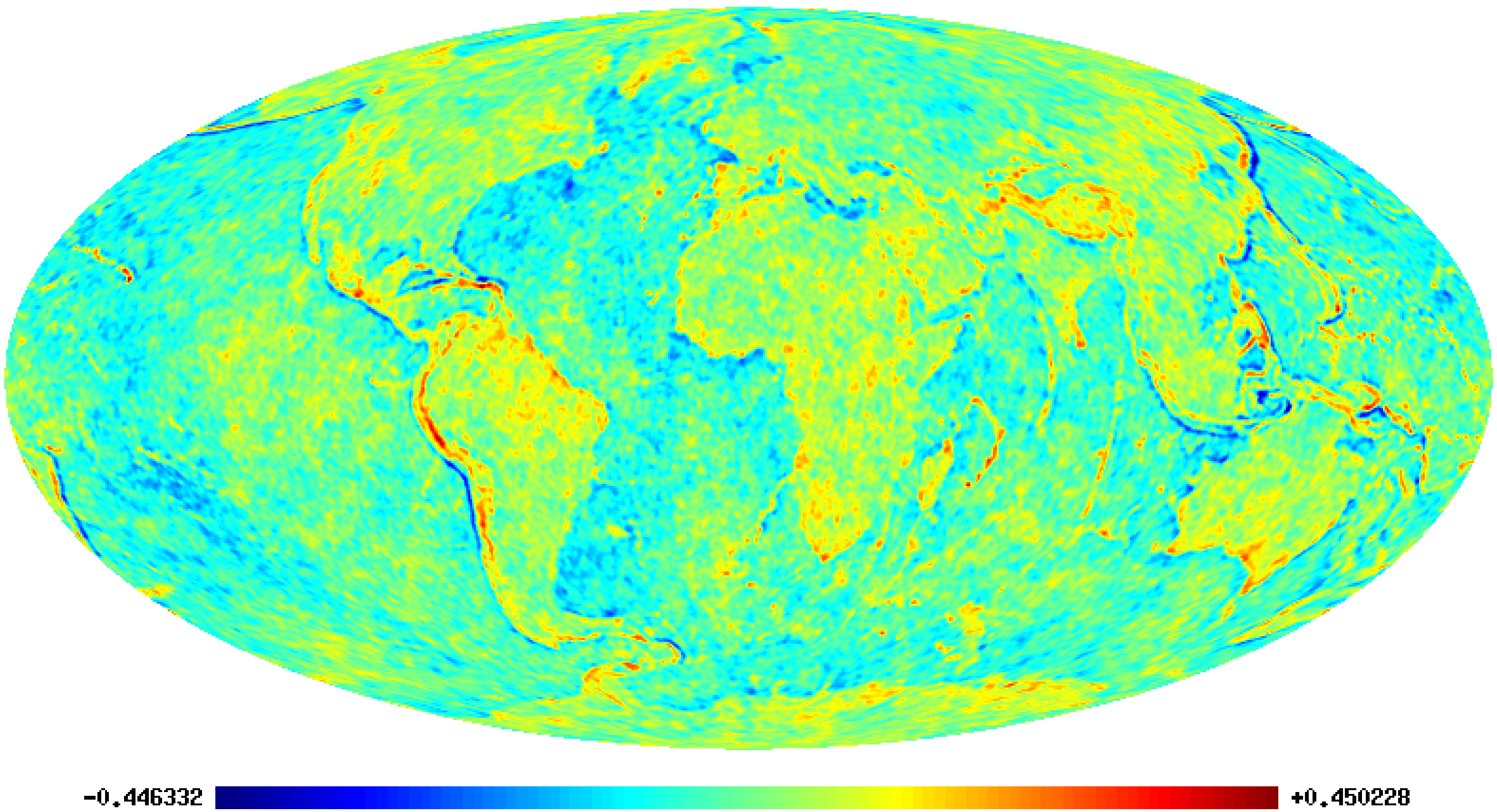
$$\frac{\Delta T(\theta,\varphi)}{T} = \sum\sum a_{l,m} Y_{lm}(\theta,\varphi)$$

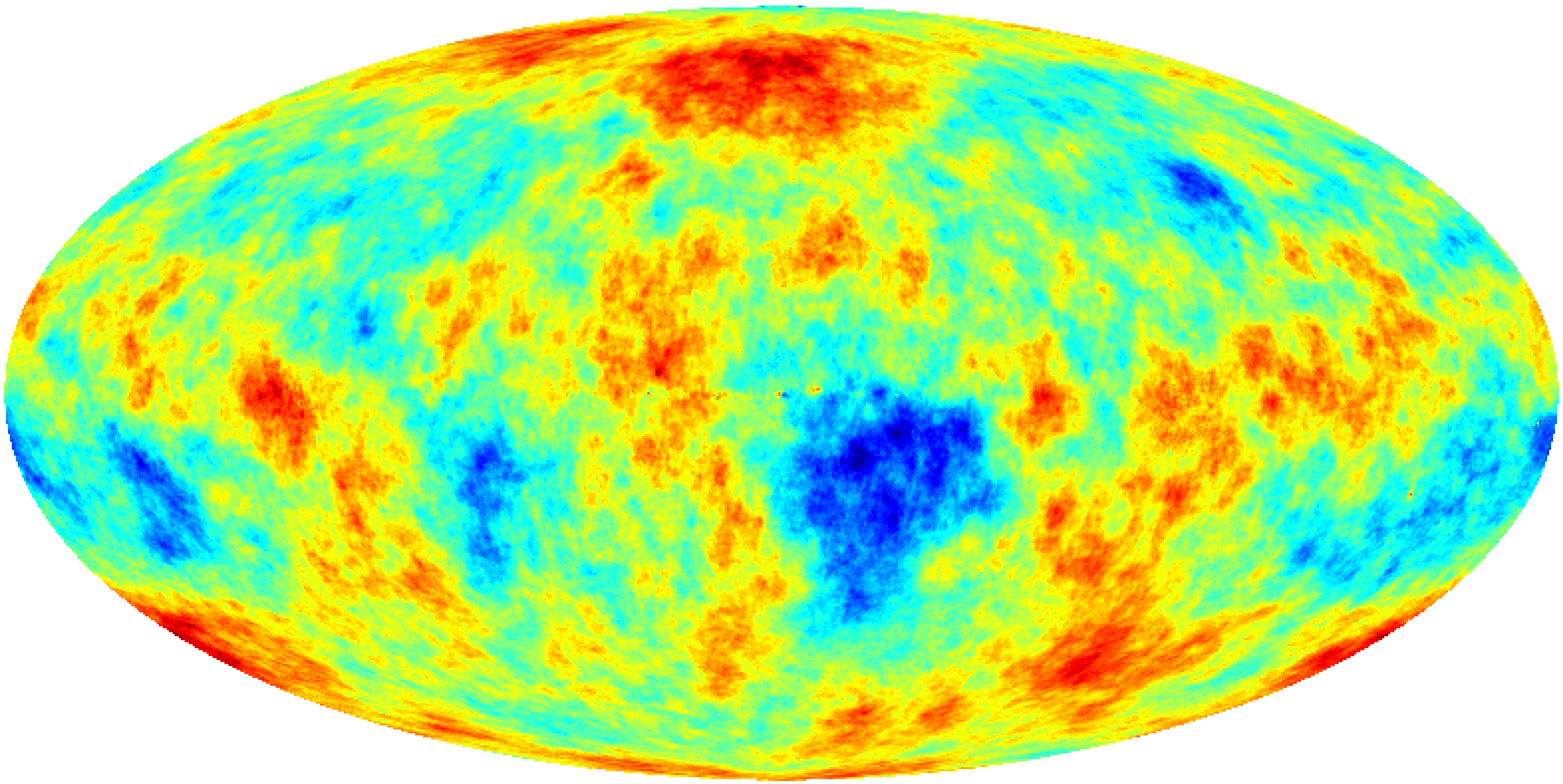
$$a_{l,m} = |a_{l,m}| \exp[i\phi_{l,m}]$$

For a homogeneous and isotropic Gaussian random field (on the sphere) the **phases** are independent and uniformly distributed. Non-random phases therefore indicate weirdness..




-0.593483
+0.530173


-0.446332
+0.450228

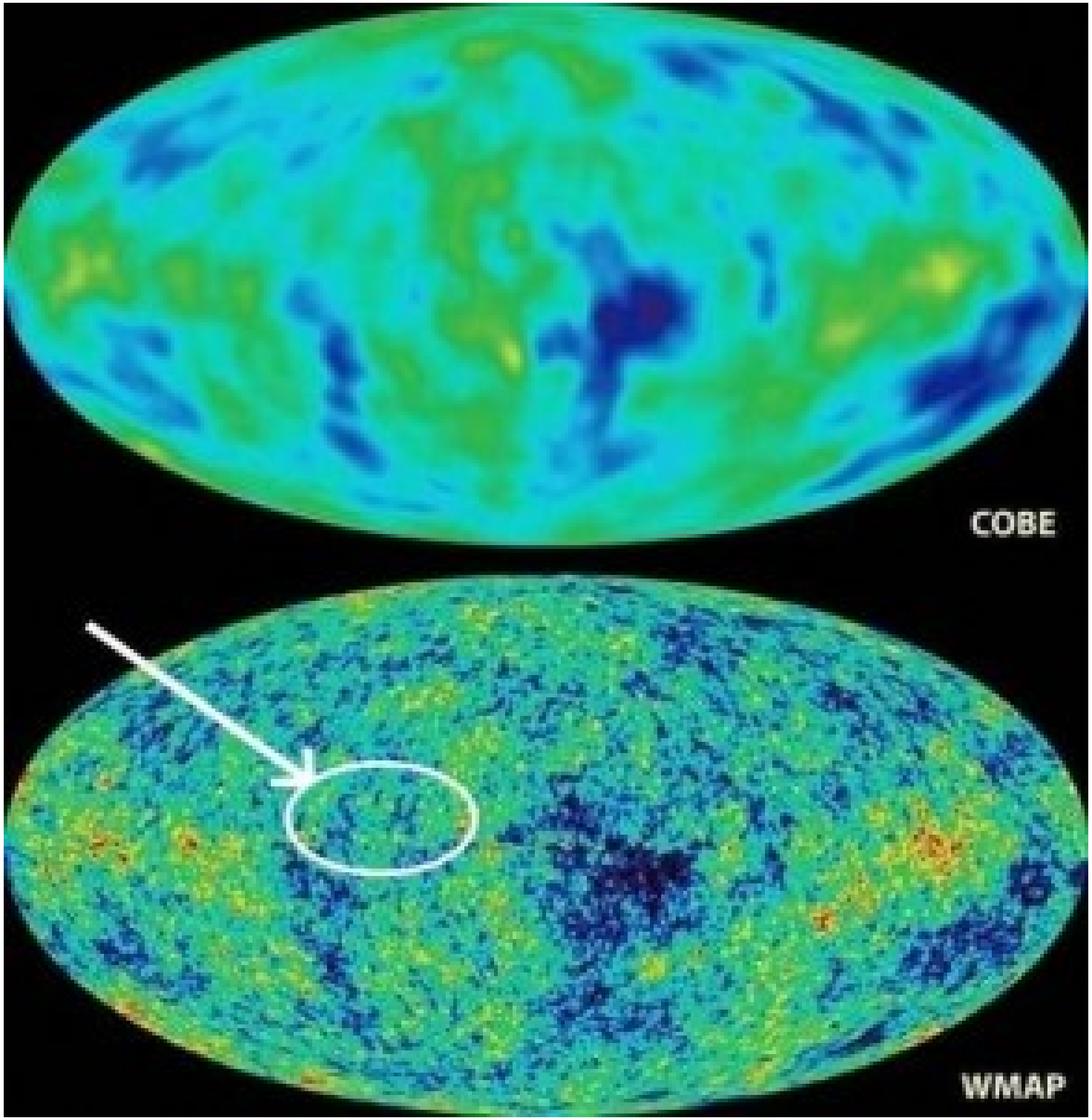


"If tortured sufficiently, data will confess to almost anything"

Fred Menger

Beware the Prosecutor's Fallacy!

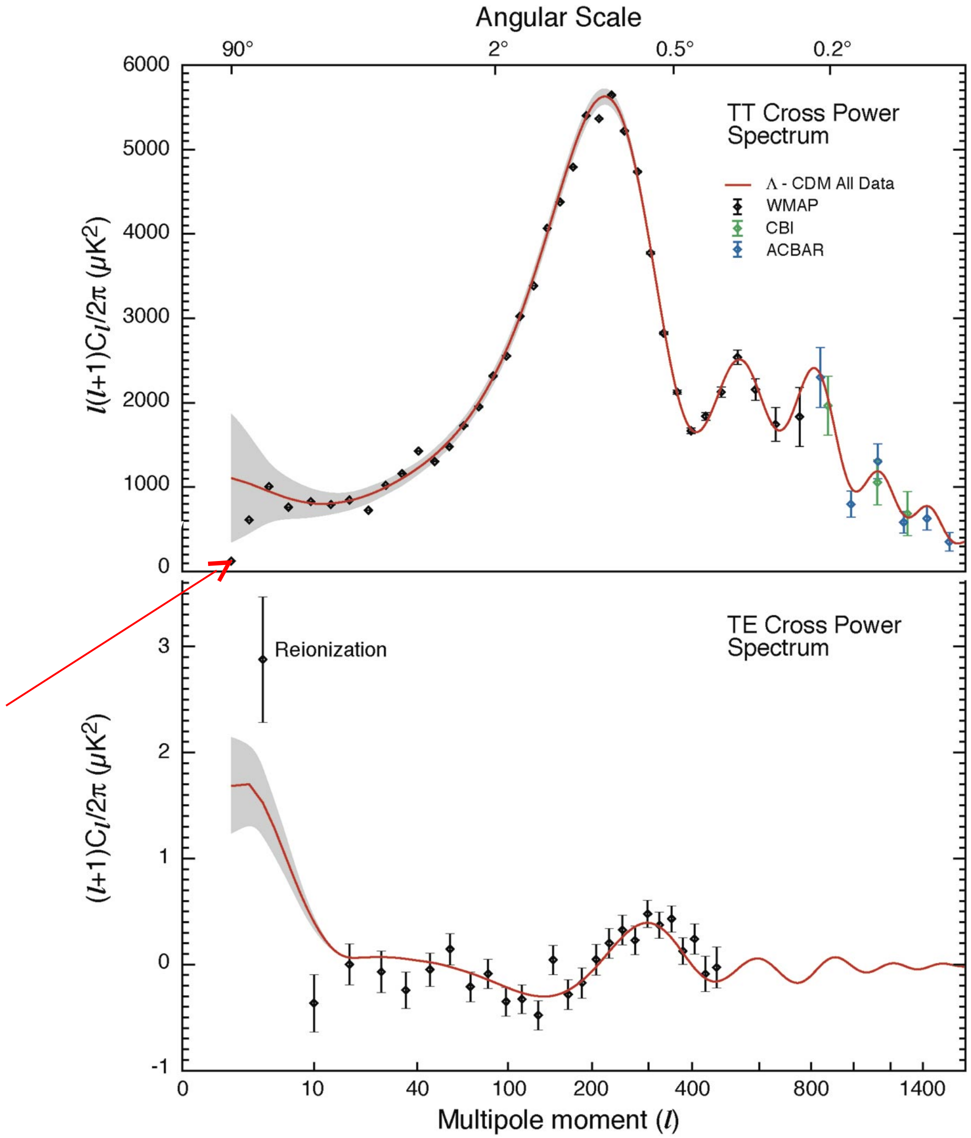
$$P(A|M) \neq P(M|A)$$


COBE
WMAP

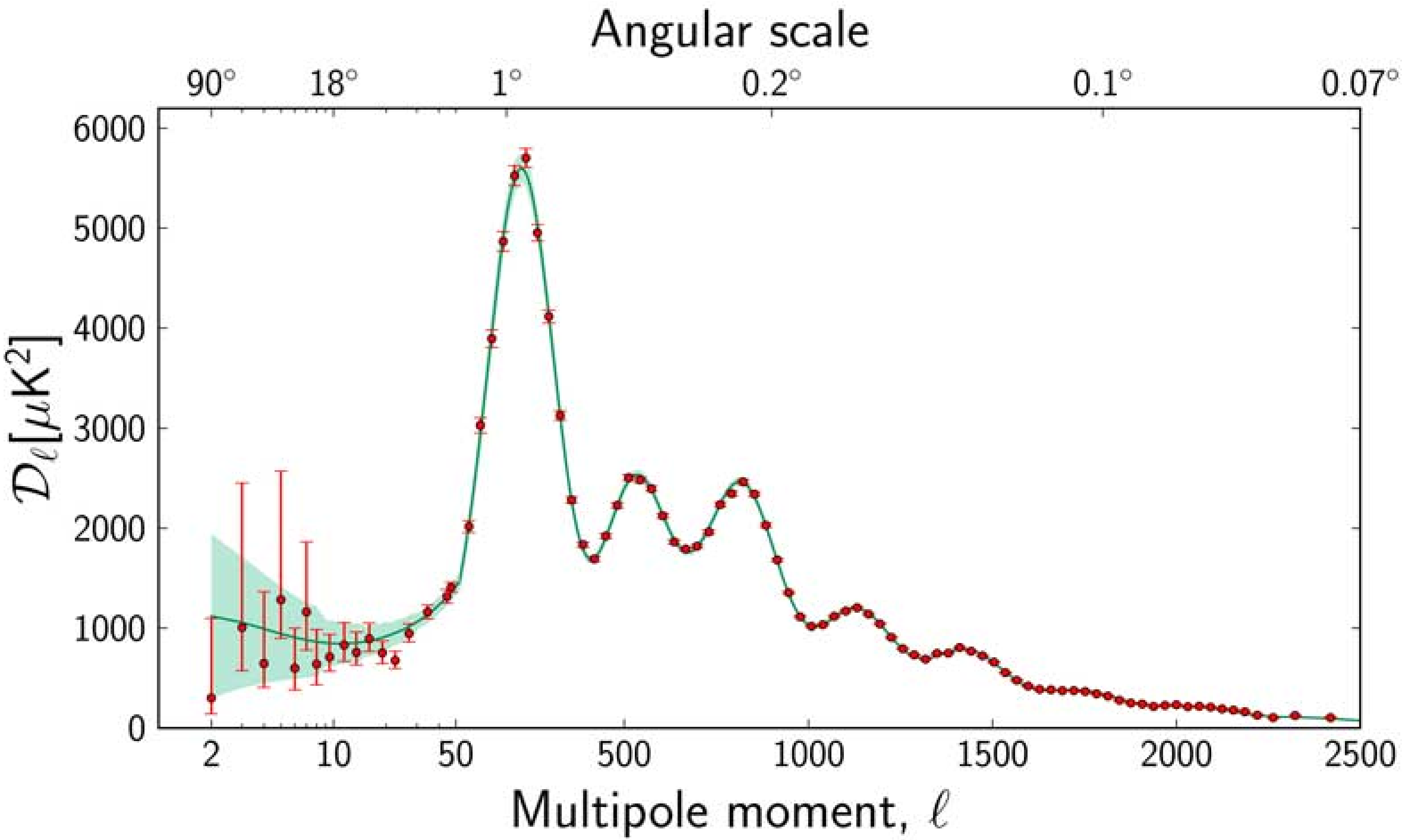
CMB Anomalies

- Type I – obvious problems with data (e.g. foregrounds)
- Type II – anisotropies and alignments (North-South, Axis of Evil..)
- Type III – localized features, e.g. “The Cold Spot”
- Type IV – Something else (even/odd multipoles, magnetic fields, ?)

Low Quadrupole?

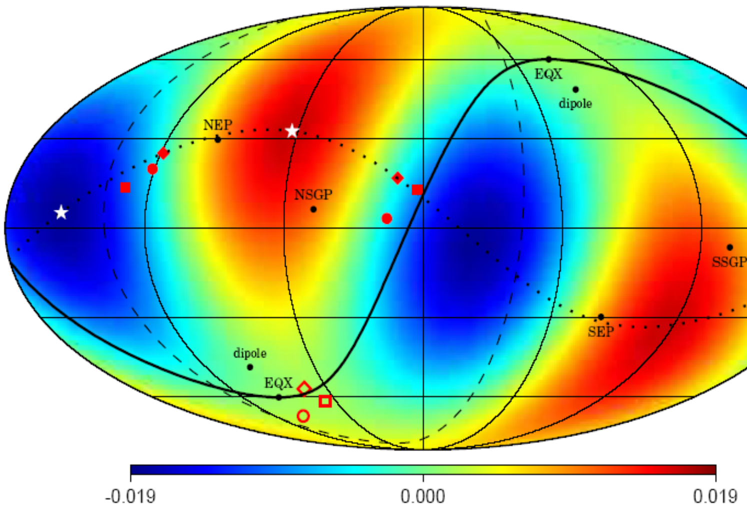


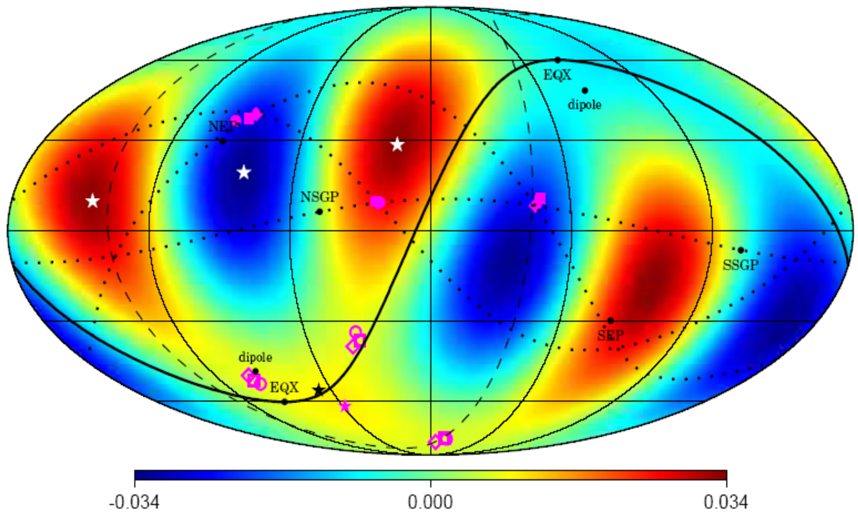
Parity Violation?



The Axle of Elvis

The Axis of Evil





(from Copi et al. 2005)

(from Hansen et al. 2004)

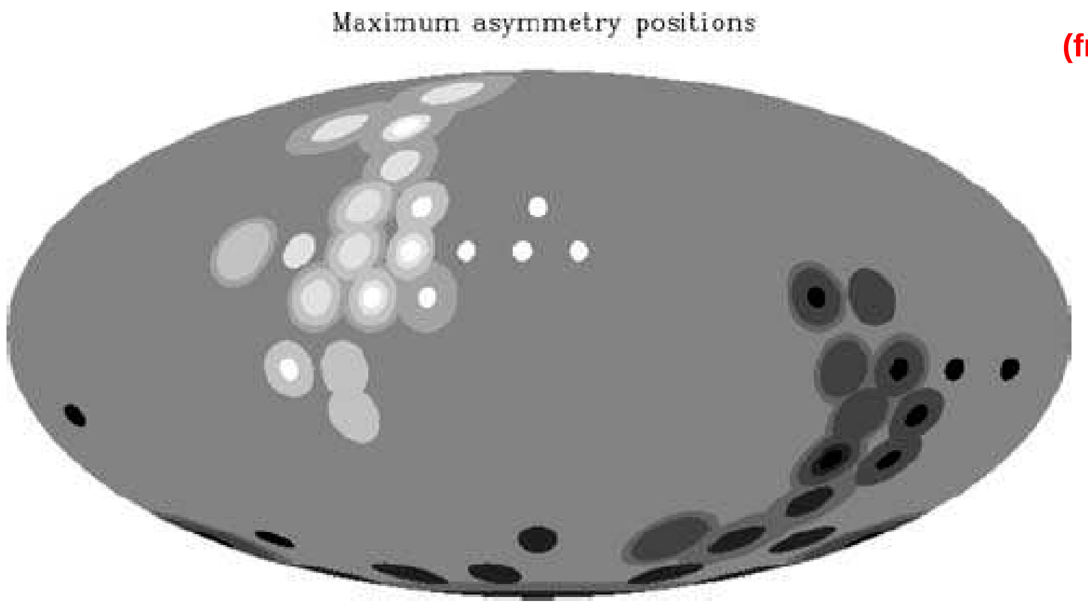
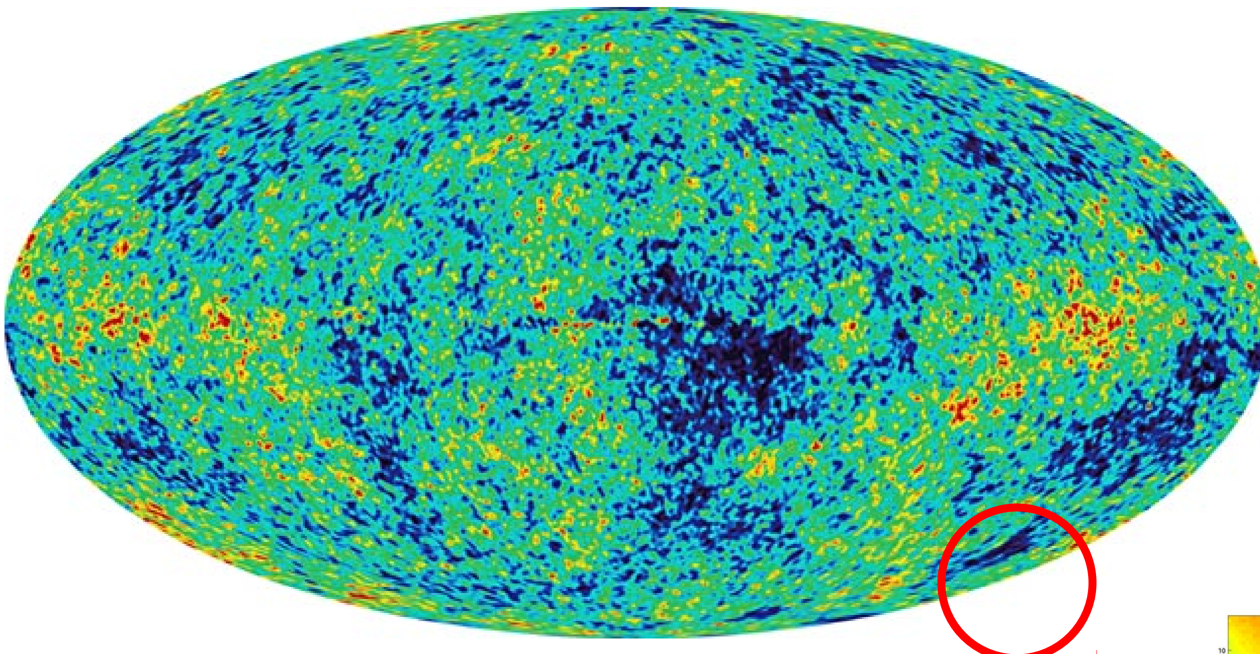
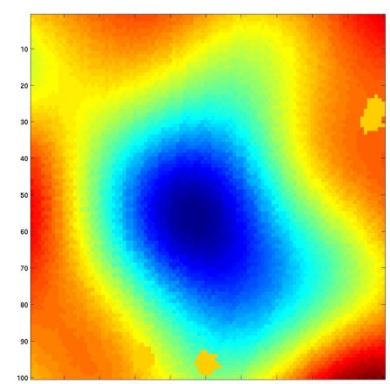
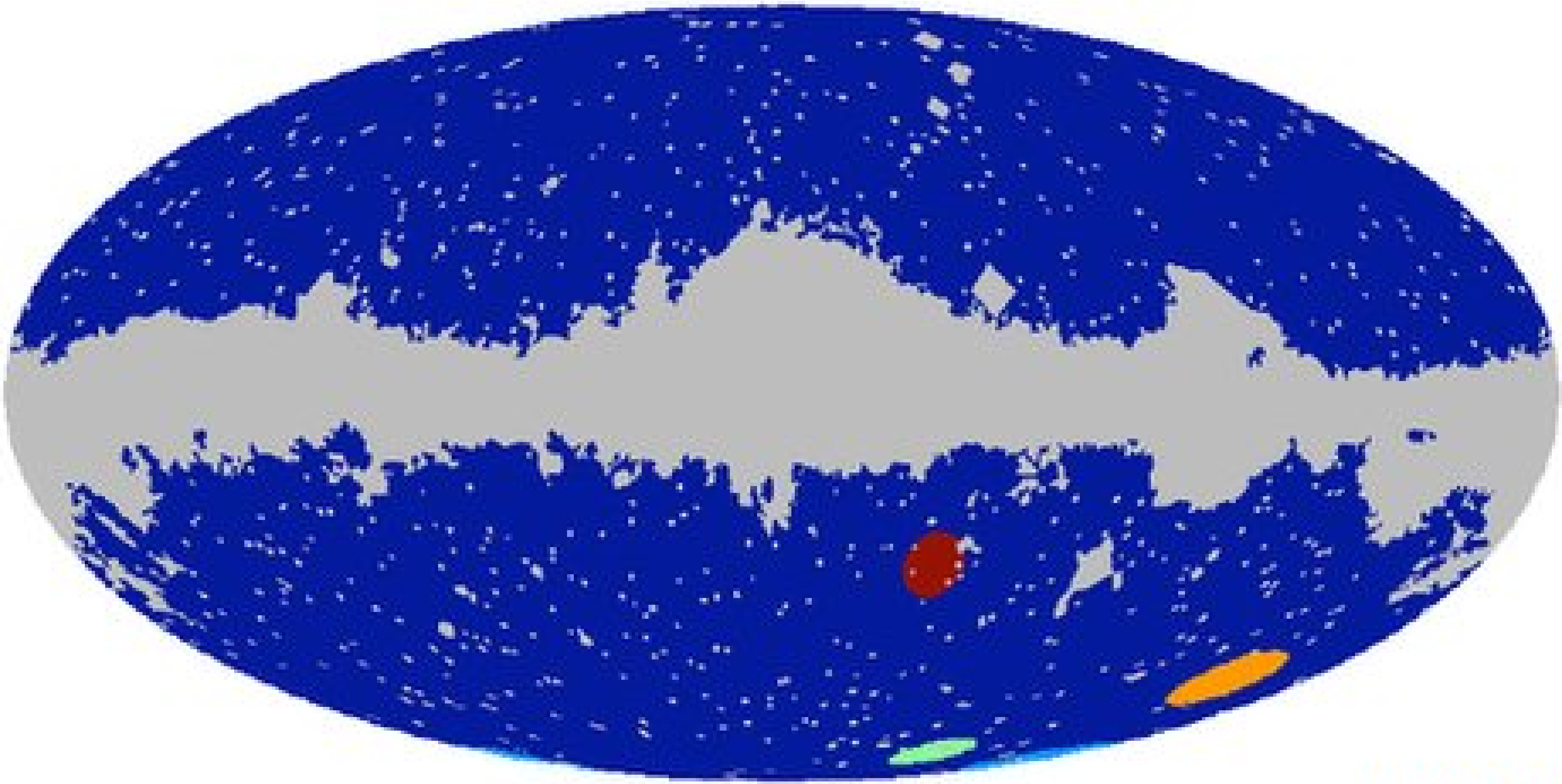


Figure 24. The discs show the positions of the hemispheres with the 10 highest (black discs) and 10 lowest (white discs) bin values. The power-spectrum bins considered were $\ell = 2$–40 (large discs), $\ell = 8$–40 (second-largest discs), $\ell = 5$–16 (second-smallest discs) and $\ell = 29$–40 (smallest discs).





10
20
30
40
50
60
70
80
90
100



FEENEY ET AL

Mon. Not. R. astr. Soc. (1988) **231,** 125–130

The hottest hotspot on the microwave sky

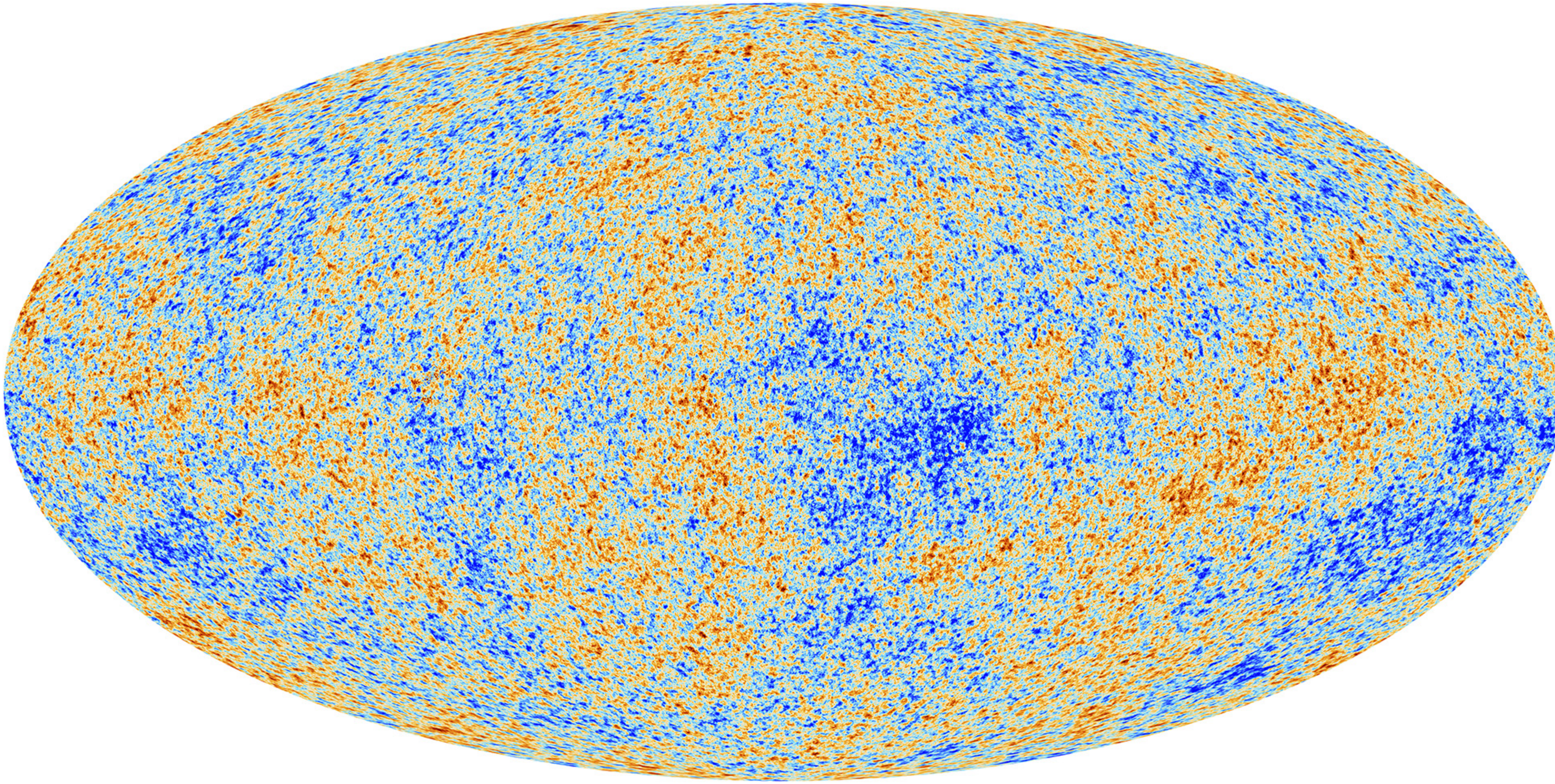
Peter Coles *Astronomy Centre, University of Sussex, Brighton BN1 9QH*

Accepted 1987 September 18. Received 1987 August 20; in original form 1987 July 13

Summary. Approximate confidence limits on the temperature of the hottest hotspot expected on the microwave sky are derived under the condition that the coherence angle of the temperature fluctuations is a very small fraction of the total sky. We apply the result to temperature anisotropies expected in galaxy formation models where the universe is dominated by cold dark matter and discuss its possible use for discriminating between high peaks in system noise and true sky fluctuations.

1 Introduction

Anisotropies of the cosmic microwave background provide one of the few direct tests of theories of galaxy formation. Theoreticians have predicted the rms amplitudes and covariance functions of the fluctuations produced by various models (Bond & Efstathiou 1984, Bond, Efstathiou & Silk 1981; Wilson & Silk 1980) and more recently, using techniques developed for the study of biased galaxy formation, have examined more detailed statistical properties of temperature fluctuations (Sazhin 1985; Zabotin & Nasel'skii 1985; Bond & Efstathiou 1987; Vittorio & Juszkiewicz 1987; Coles & Barrow 1987; Coles 1987, in preparation). For the most part, these analyses concentrate on *local* properties of the microwave sky such as the mean number density



A. There’s no problem at all with ΛCDM…

B. There are interesting indications…

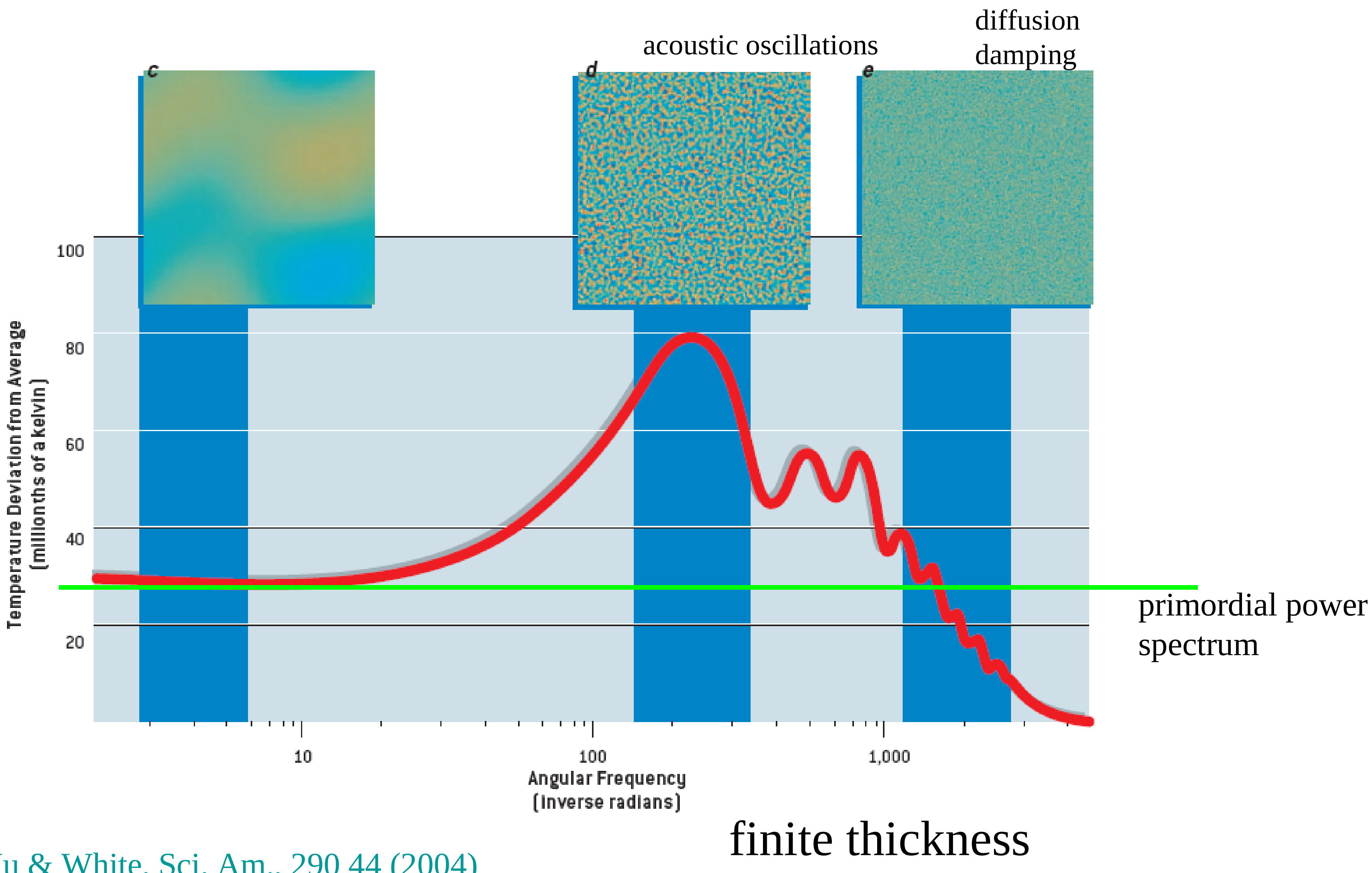
C. There’s definitely evidence of new physics

Sources of CMB anisotropy

Sachs Wolfe: Potential wells at last scattering cause redshifting as photons climb out
Photon density perturbations: Overdensities of photons look hotter
Doppler: Velocity of photon/baryons at last scattering gives Doppler shift
Integrated Sachs Wolfe: Evolution of potential along photon line of sight: net red- or blue-shift as photon climbs in an out of varying potential wells
Others: Photon quadupole/polarization at last scattering, second-order effects, etc.

CMB temperature power spectrum

Primordial perturbations + later physics



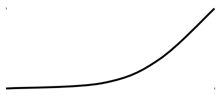
Hu & White, Sci. Am., 290 44 (2004)

Why The Wiggles?

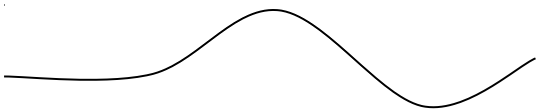
Think in k-space: modes of different size

•Co-moving Poisson equation: $(k/a)^2\ \Phi = \kappa\ \delta\rho\ /\ 2$
- potentials approx constant on super-horizon scales
- radiation domination $\rho \sim 1/a^4$

→ $\delta\rho/\rho \sim k^2 a^2\ \Phi$
→ since Φ ~ constant, super-horizon density perturbations grow $\sim a^2$



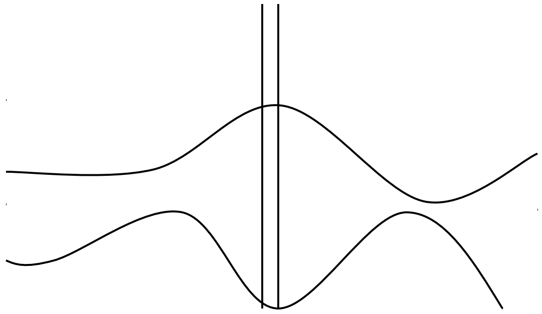
•After entering horizon pressure important: perturbation growth slows, then bounces back



→ series of acoustic oscillations (sound speed $\sim c/\sqrt{3}$)

•CMB anisotropy (mostly) from a surface at fixed redshift: phase of oscillation at time of last scattering depends on time since entering the horizon

→ k-dependent oscillation amplitude in the observed CMB



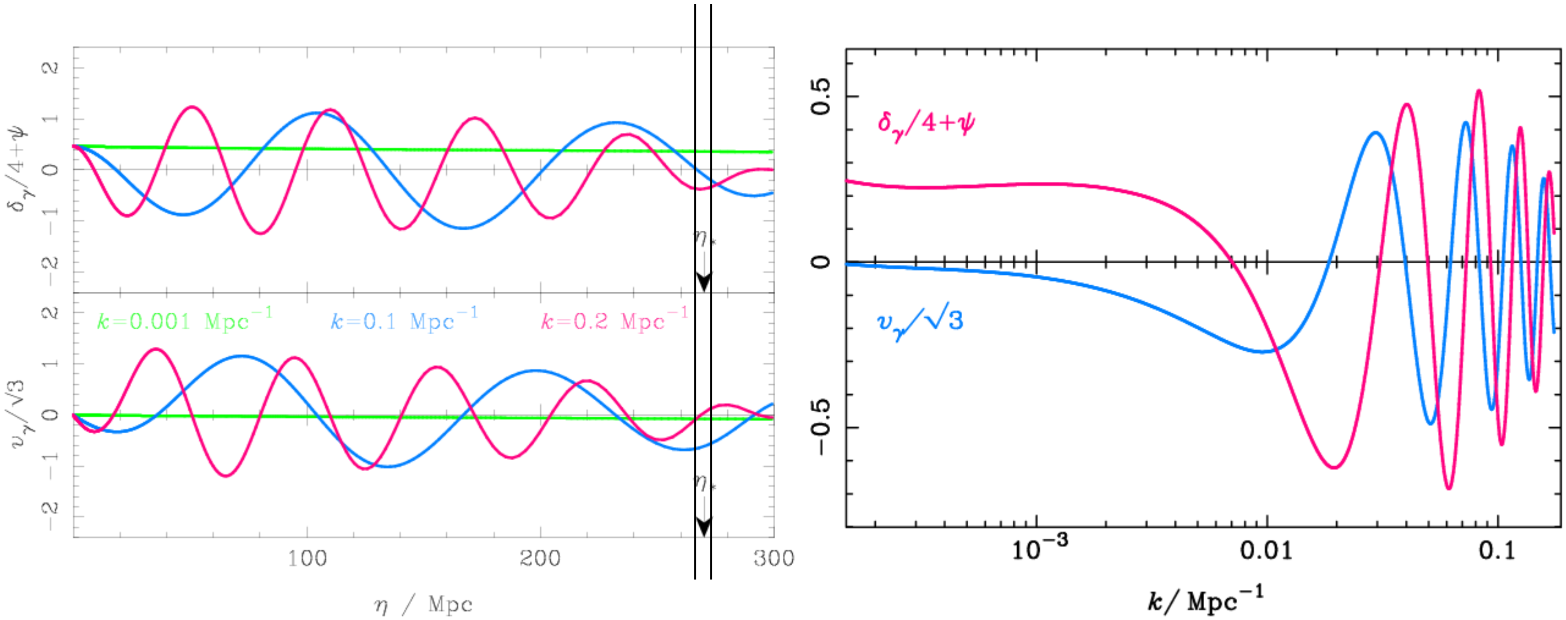
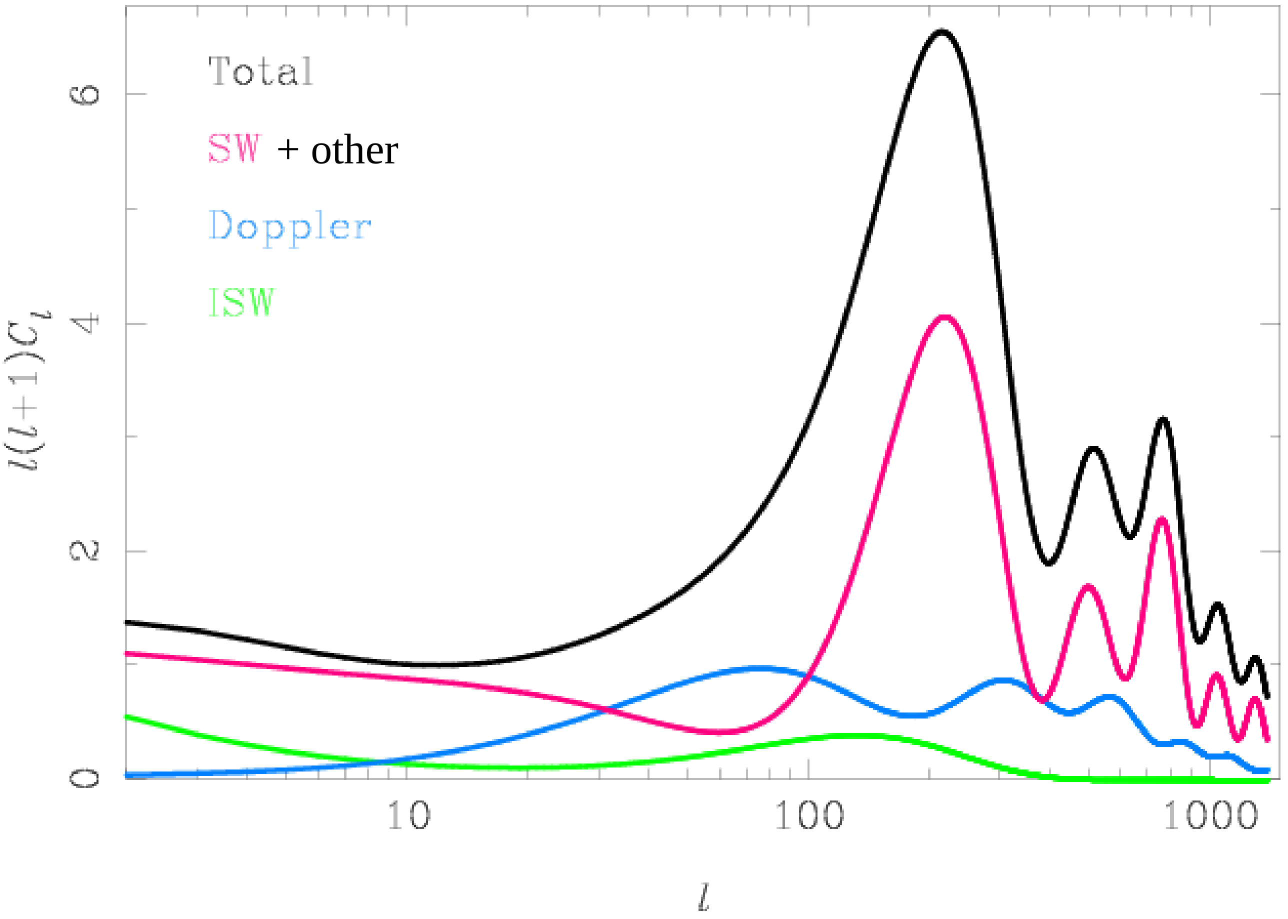


Fig. 3. Evolution of the combination $\delta_\gamma/4 + \psi$ (top left) and the photon velocity v_γ (bottom left) which determine the temperature anisotropies produced at last scattering (denoted by the arrow at η_*). Three modes are shown with wavenumbers $k = 0.001$, 0.1 and $0.2\,\mathrm{Mpc}^{-1}$, and the initial conditions are adiabatic. The fluctuations at the time of last scattering are shown as a function of linear scale in the right-hand plot.

Challinor: astro-ph/0403344

Contributions to temperature C_l



Challinor: astro-ph/0403344

What can we learn from the CMB?

- Initial conditions
  What types of perturbations, power spectra, distribution function (Gaussian?); => learn about inflation or alternatives.
  (distribution of ΔT; power as function of scale; polarization and correlation)

- What and how much stuff
  Matter densities (Ω_b, Ω_{cdm});$_{;}$ neutrino mass
  (details of peak shapes, amount of small scale damping)

- Geometry and topology
  global curvature Ω_K of universe; topology
  (angular size of perturbations; repeated patterns in the sky)

- Evolution
  Expansion rate as function of time; reionization
  - Hubble constant $H_{0\,;}$ dark energy evolution w = pressure/density
  (angular size of perturbations; *l* < 50 large scale power; polarizationr)

- Astrophysics
  S-Z effect (clusters), foregrounds, etc.

Cosmic Variance

Use estimator for variance: $C_l^{obs} = \frac{1}{2l+1} \sum_m |a_{lm}|^2$

Assume a_{lm} gaussian:

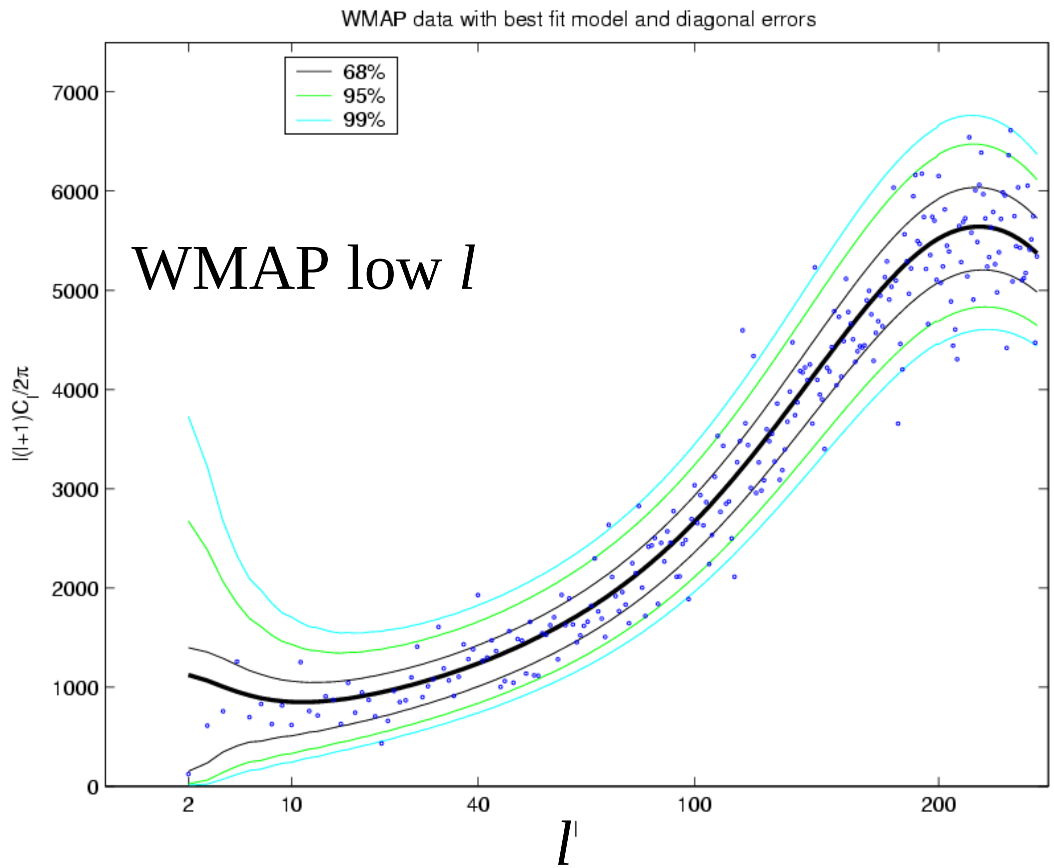
$C_l^{obs} \sim \chi^2$ with $2l+1$ d.o.f.

"Cosmic Variance"

$$\left\langle |\Delta C_l^{obs}|^2 \right\rangle \approx \frac{2C_l^2}{2l+1}$$

$P(C_l \,|\, C_l^{obs})$

- inverse gamma distribution (+ noise, sky cut, etc).



Parameter Estimation

- Can compute $P(\{\theta\} \mid \text{data}) = P(C_l(\{\theta\}) \mid c_l^{obs})$
- Often want marginalized constraints. e.g.

$$<\theta_1> = \int \theta_1 P(\theta_1\theta_2\theta_3 \ldots \theta_n \mid data)\, d\theta_1 d\theta_2 .. d\theta_n$$

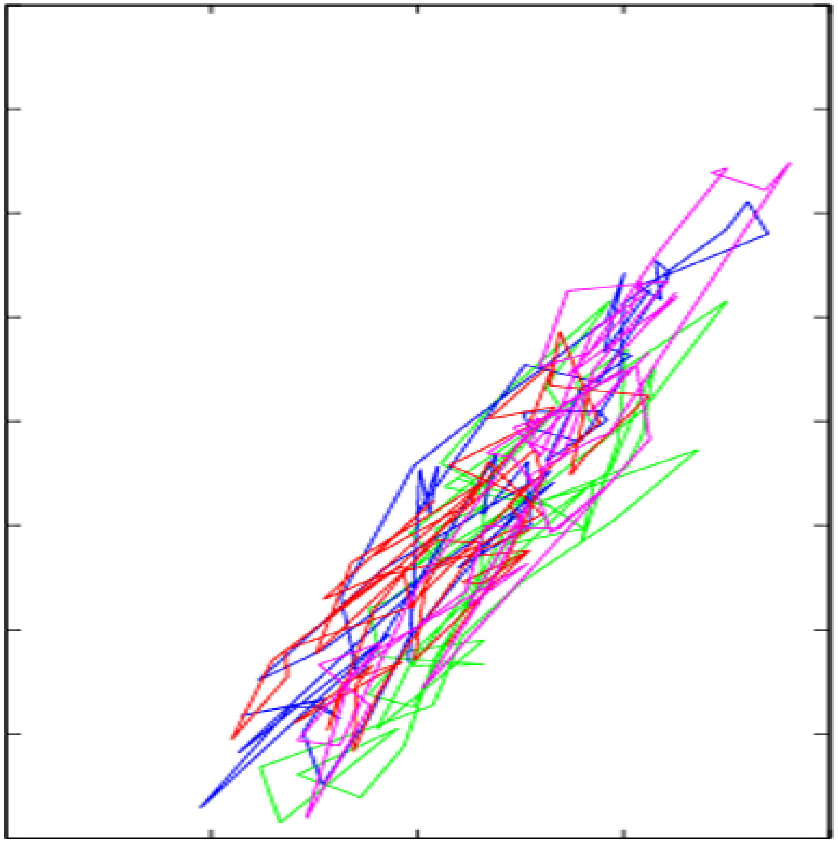
- BUT: Large *n* integrals very hard to compute!
- If we instead *sample* from $P(\{\theta\} \mid \text{data})$ then it is easy:

$$<\theta_1> \approx \frac{1}{N}\sum_i \theta_1^{(i)}$$

⇒ <u>Can easily learn everything we need from set of samples</u>

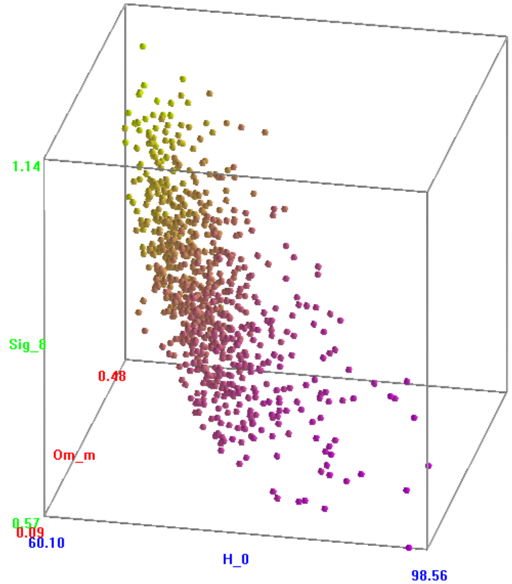
Markov Chain Monte Carlo sampling

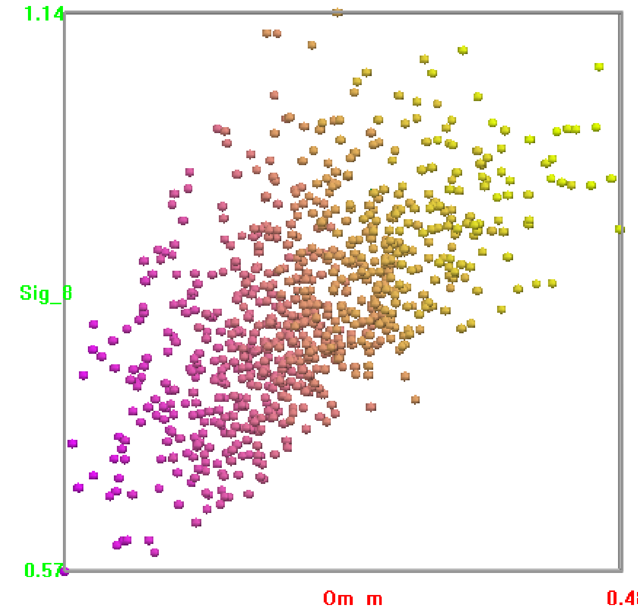
- Metropolis-Hastings algorithm
- Number density of samples proportional to probability density
- At its best scales linearly with number of parameters
  (as opposed to exponentially for brute integration)

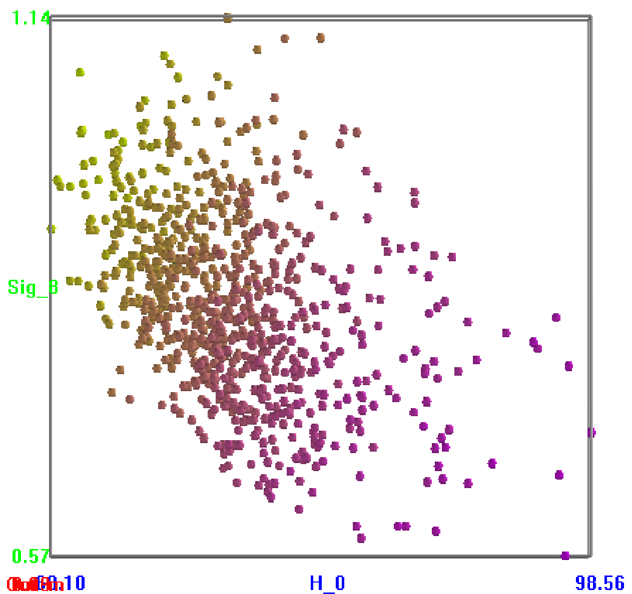


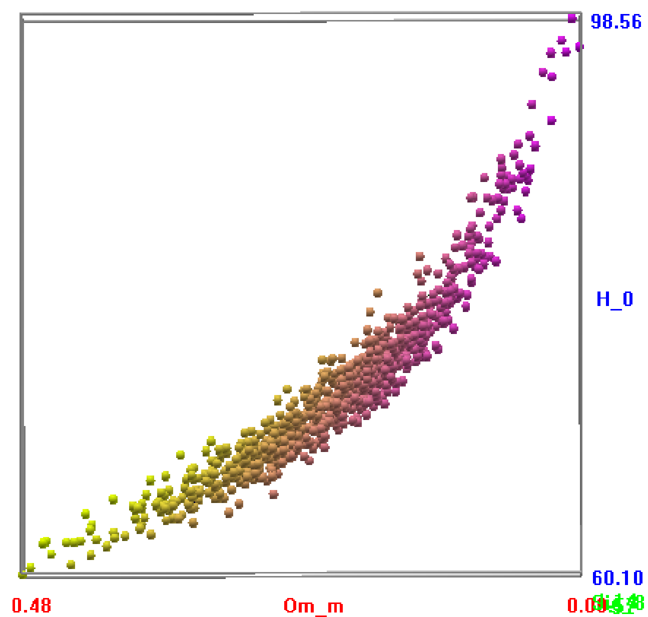
This is now standard method for parameter estimation. Public CosmoMC code available at http://cosmologist.info/cosmomc (Lewis, Bridle: astro-ph/0205436)

Samples in 6D parameter space







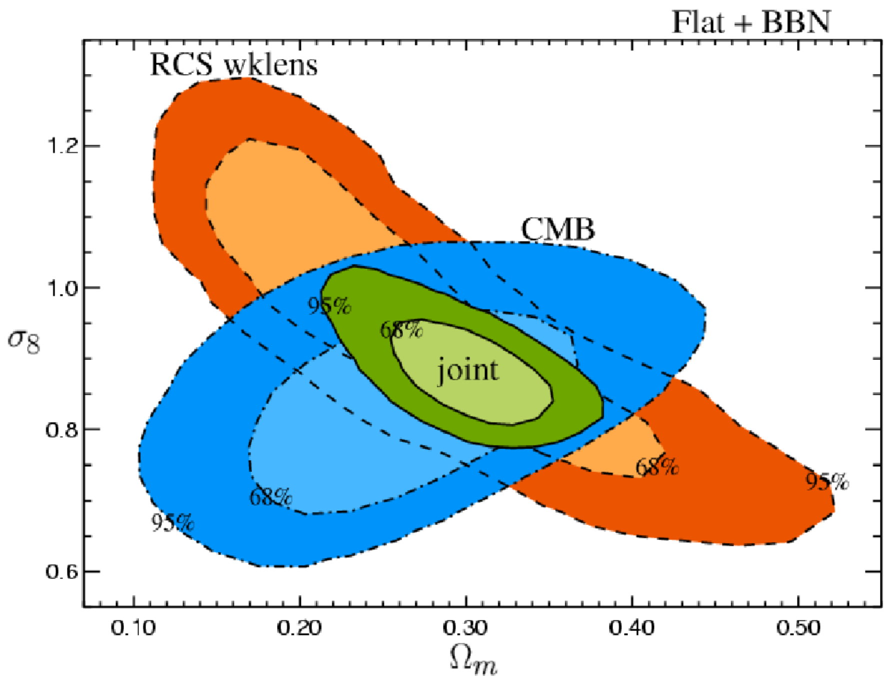


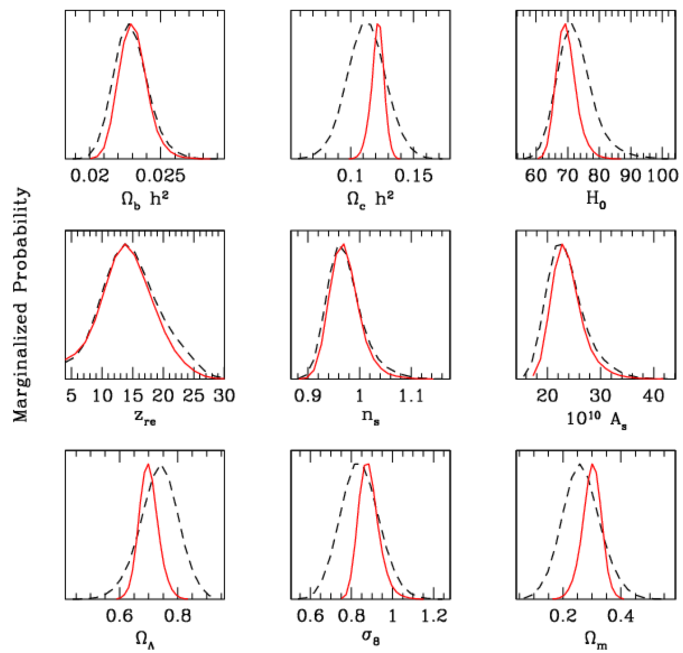
CMB data alone
color = optical depth

Plot number density of samples as function of parameters

Often better constraint by combining with other data

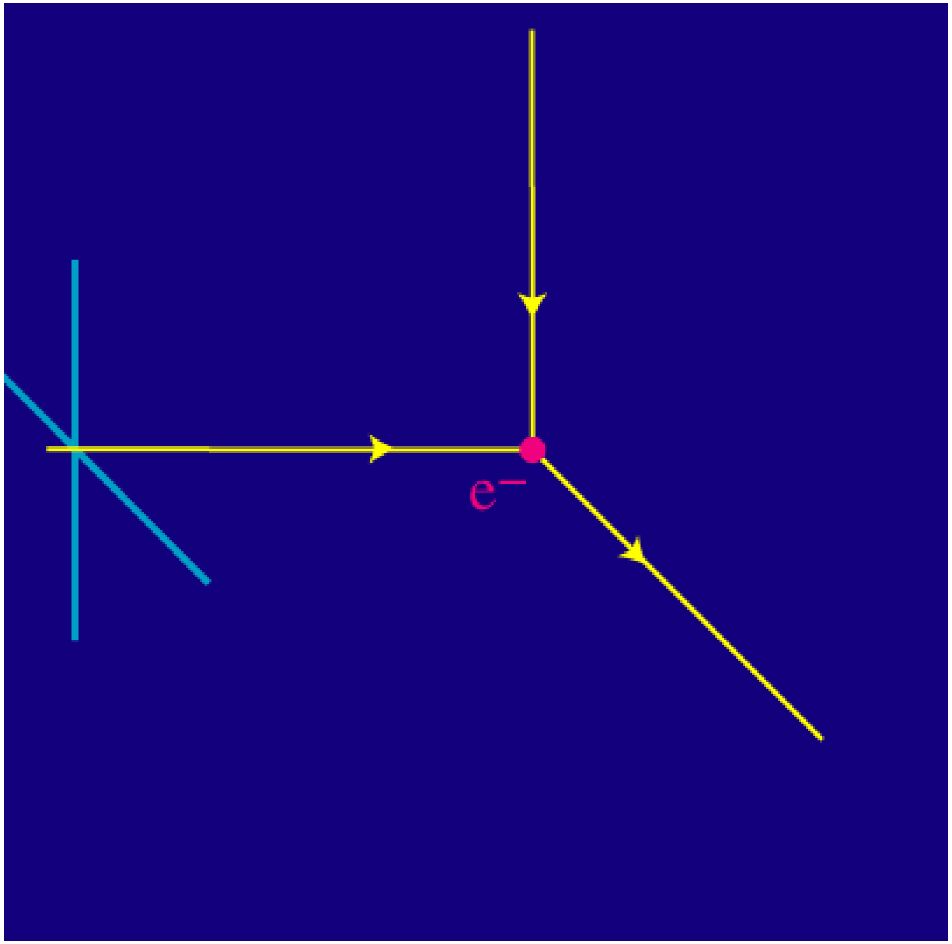
e.g. CMB+galaxy lensing +BBN prior





Contaldi, Hoekstra, Lewis: astro-ph/0302435

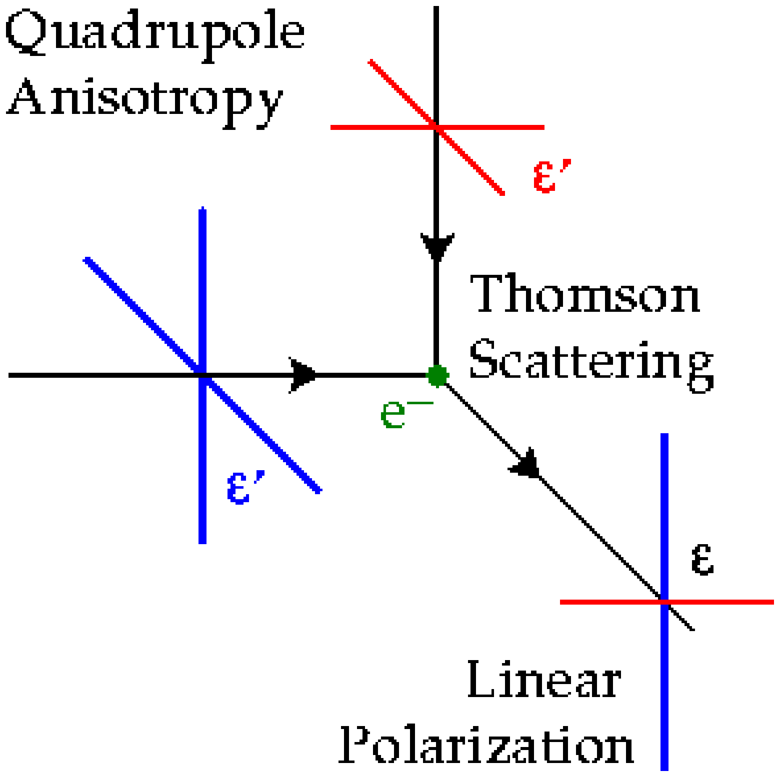
Thomson Scattering Polarization



W Hu

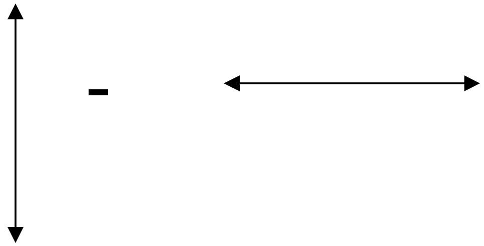
CMB Polarization

Generated during last scattering (and reionization) by Thomson scattering of anisotropic photon distribution

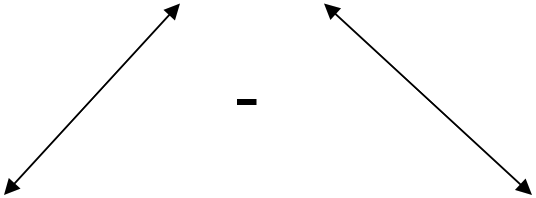


Hu astro-ph/9706147

Stokes' Parameters



Q



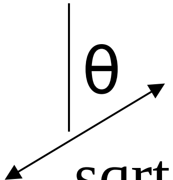
U

Q → -Q, U → -U under 90 degree rotation

Q → U, U → -Q under 45 degree rotation

Spin-2 field Q + i U
or Rank 2 trace free symmetric tens

$$P = \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}$$



sqrt($Q^2 + U^2$)

$\theta = \frac{1}{2} \tan^{-1} U/Q$

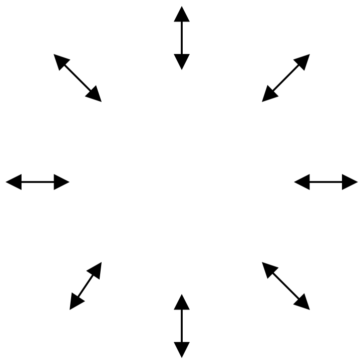
E and B polarization

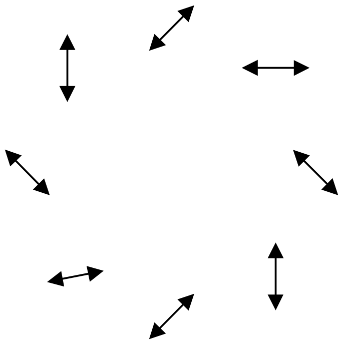
$$\mathcal{P}_{ab} = \nabla_{(a}\nabla_{b)}P_E - \epsilon^{c}{}_{(a}\nabla_{b)}\nabla_c P_B$$

"gradient" modes
E polarization

"curl" modes
B polarization

e.g.





E and B harmonics

- Expand scalar P_E and P_B in spherical harmonics
- Expand P_{ab} in tensor spherical harmonics

$$\mathcal{P}_{ab} = \frac{1}{\sqrt{2}} \sum_{lm} \left(E_{lm}\, Y^{G}_{(lm)ab} + B_{lm}\, Y^{C}_{(lm)ab} \right)$$

$$E_{lm} = \sqrt{2} \int_{4\pi} \mathrm{d}S\, Y^{G\,ab*}_{(lm)} \mathcal{P}_{ab} \qquad B_{lm} = \sqrt{2} \int_{4\pi} \mathrm{d}S\, Y^{C\,ab*}_{(lm)} \mathcal{P}_{ab}$$

Harmonics are orthogonal over the full sky:

E/B decomposition is exact and lossless on the full sky

Zaldarriaga, Seljak: astro-ph/9609170
Kamionkowski, Kosowsky, Stebbins: astro-ph/9611125

Primordial Perturbations

fluid at redshift < 10^9

- Photons

- Nearly massless neutrinos
  Free-streaming (no scattering) after neutrino decoupling at z ~ 10^9

- Baryons + electrons
  tightly coupled to photons by Thomson scattering

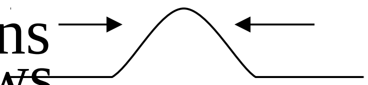
- Dark Matter
  Assume cold. Coupled only via gravity.

- Dark energy
  probably negligible early on

Perturbations O(10^{-5})

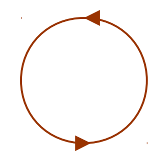
- Linear evolution
- Fourier k mode evolves independently
- Scalar, vector, tensor modes evolve independently
- Various linearly independent solutions

Scalar modes: Density perturbations, potential flows



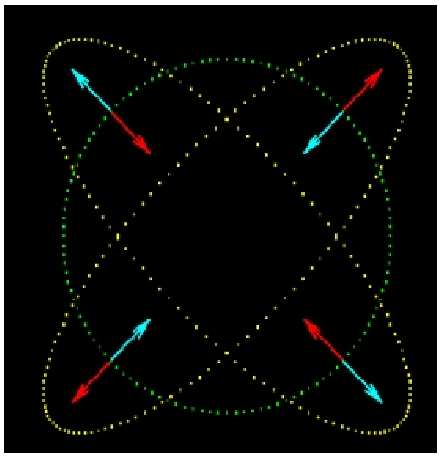
$\delta\rho, \nabla\delta\rho, etc$

Vector modes: Vortical perturbations



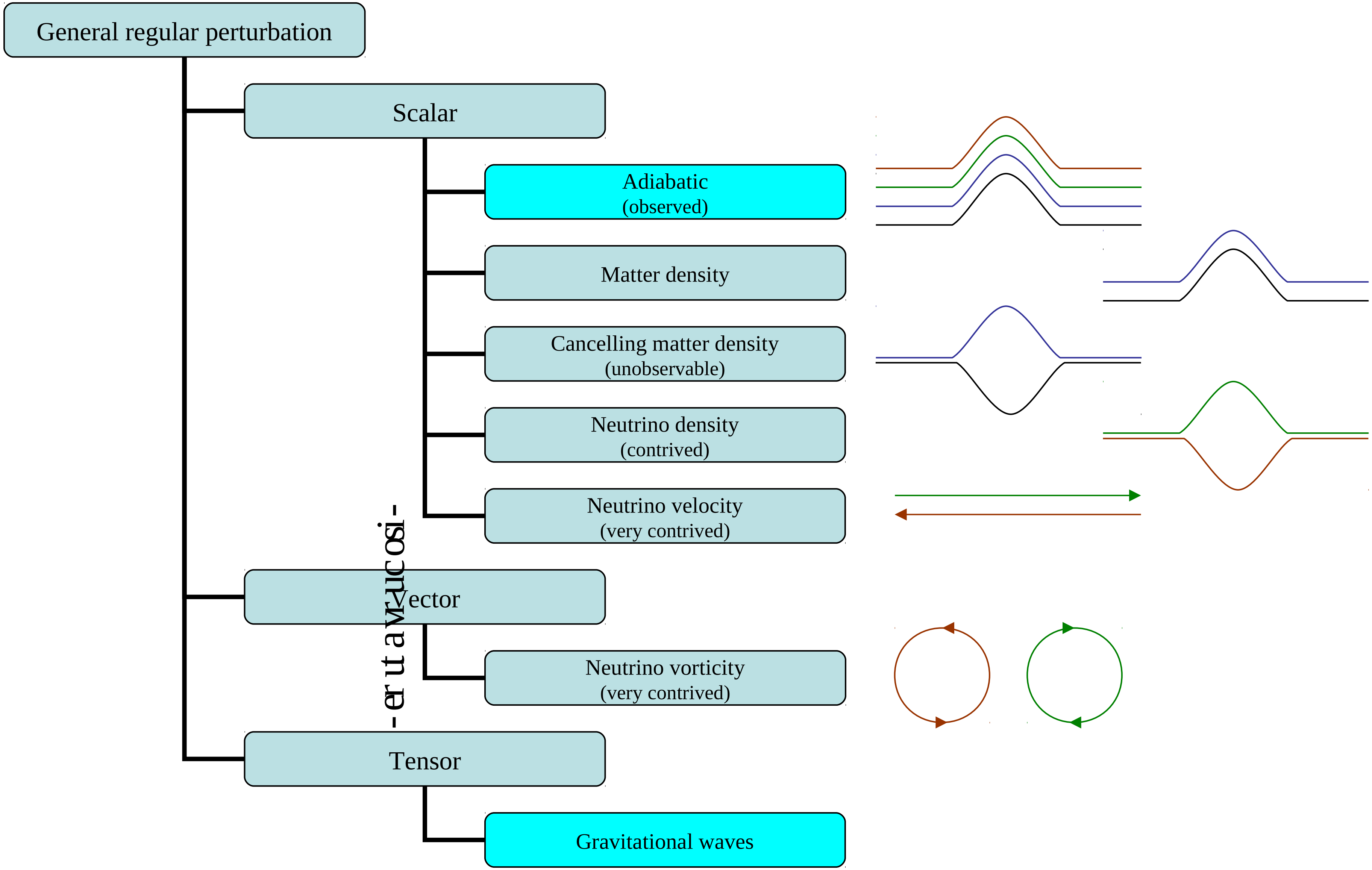
velocities, v $\quad (\nabla \bullet v = 0)$

Tensor modes: Anisotropic space distortions – gravitational waves



http://www.astro.cf.ac.uk/schools/6thFC2002/GravWaves/sld009.htm

General regular linear primordial perturbation



+ irregular modes, neutrino n-pole modes, n-Tensor modes Rebhan and Schwarz: gr-qc/9403032
+ other possible components, e.g. defects, magnetic fields, exotic stuff…

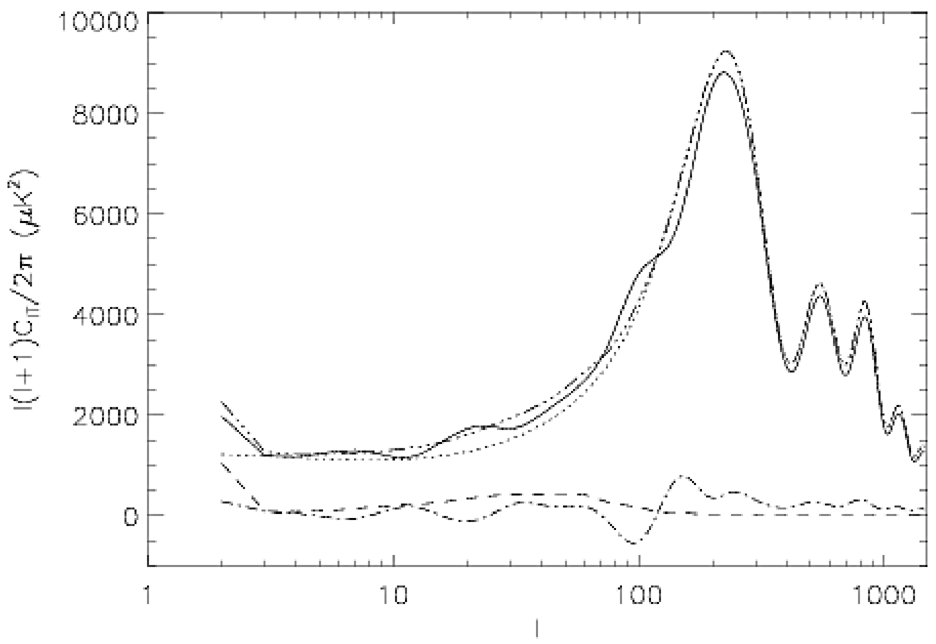
Decaying modes

- Generally ~ a^{-1}, a^{-2} or $a^{-1/2}$
- E.g. decaying vector modes unobservable at late times unless ridiculously large early on

Adiabatic decay ~ $a^{-1/2}$ after neutrino decoupling.

possibly observable if generated around or after neutrino decoupling

Otherwise have to be very large (non-linear?) at early times



Amendola, Finelli: astro-ph/0411273

CMB Polarization Signals

- E polarization from scalar, vector and tensor modes
- B polarization only from vector and tensor modes (curl grad = 0) + non-linear scalars

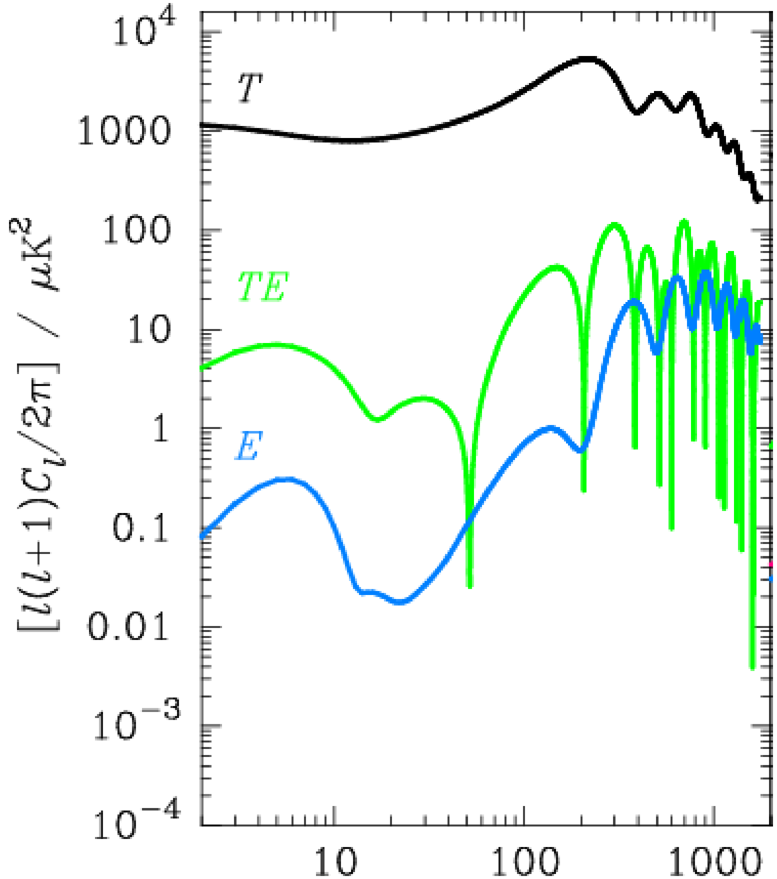
Average over possible realizations (statistically isotropic):

$$\langle E^*_{l'm'} E_{lm} \rangle = \delta_{l'l}\delta_{m'm} C_l^{EE} \qquad \langle B^*_{l'm'} B_{lm} \rangle = \delta_{l'l}\delta_{m'm} C_l^{BB}$$

Parity symmetric ensemble: $\langle E^*_{l'm'} B_{lm} \rangle = 0$

Power spectra contain all the useful information if the field is Gaussian

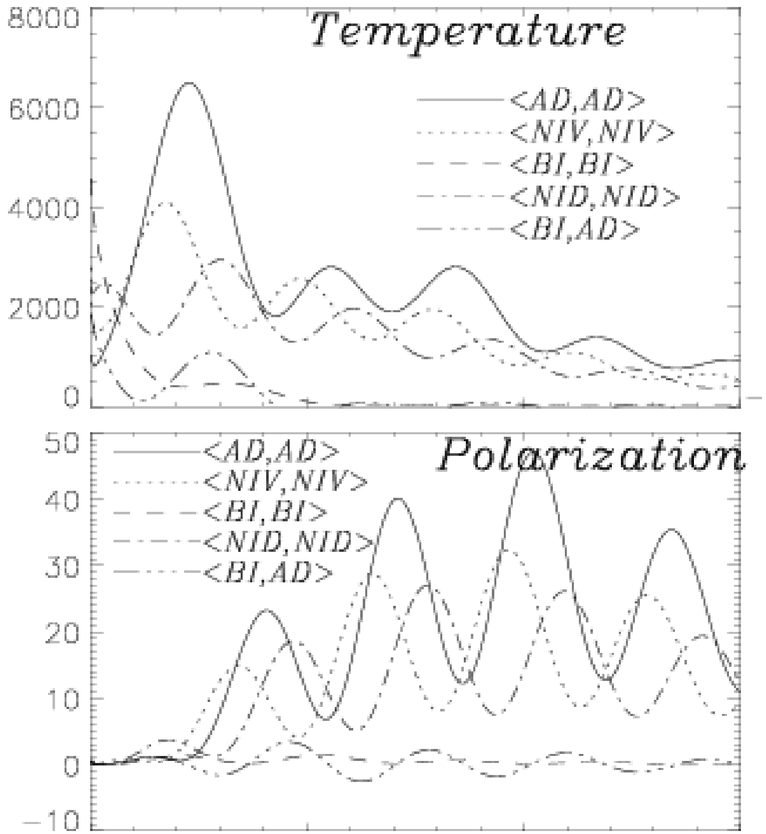
Scalar adiabatic mode



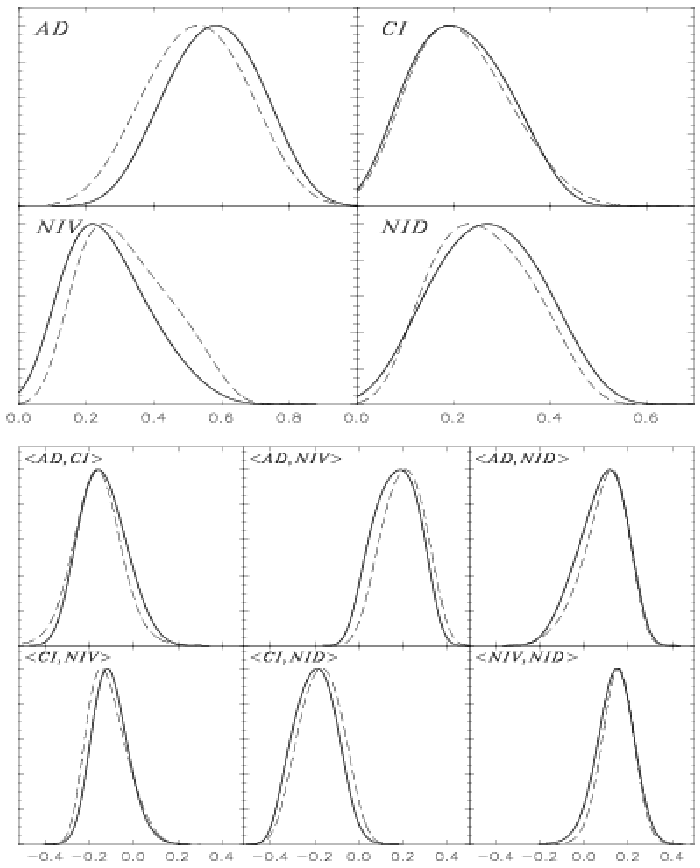
E polarization only

correlation to temperature T-E

General isocurvature models



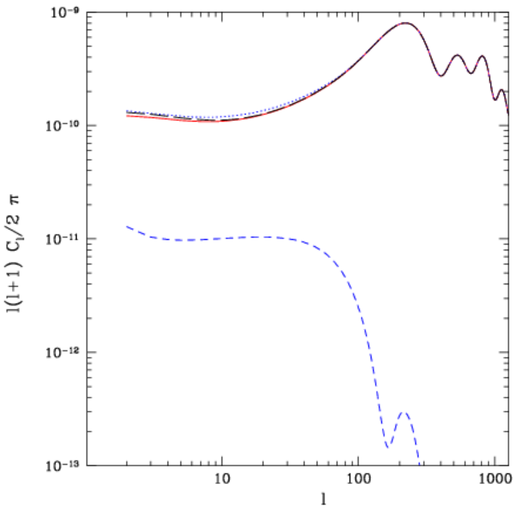
- General mixtures currently poorly constrained



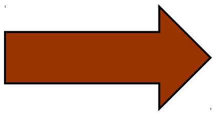
Bucher et al: astro-ph/0401417

Primordial Gravitational Waves (tensor modes)

- Well motivated by some inflationary models
  - Amplitude measures inflaton potential at horizon crossing
  - distinguish models of inflation
- Observation would rule out other models
  - ekpyrotic scenario predicts exponentially small amplitude
  - small also in many models of inflation, esp. two field e.g. curvaton
- Weakly constrained from CMB temperature anisotropy

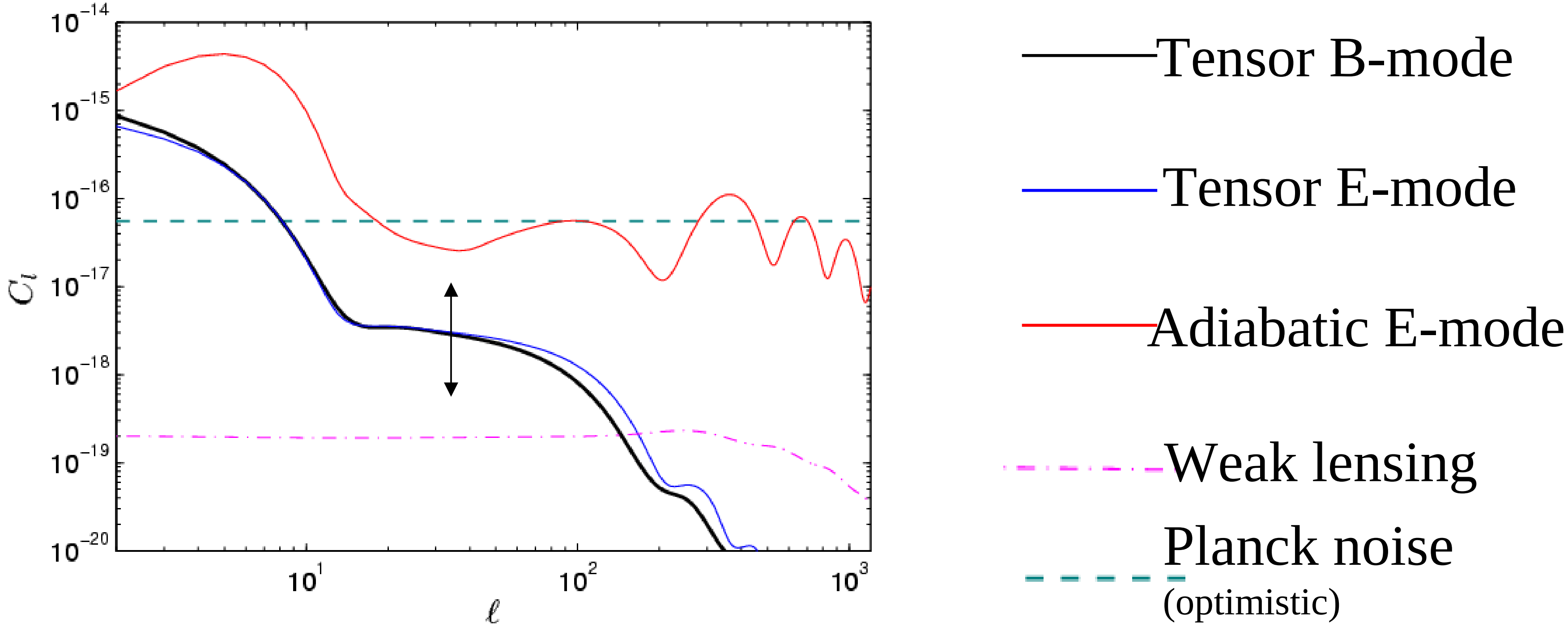


- cosmic variance limited to 10%
- degenerate with other parameters (tilt, reionization, etc)



Look at CMB polarization: 'B-mode' smoking gun

CMB polarization from primordial gravitational waves (tensors)



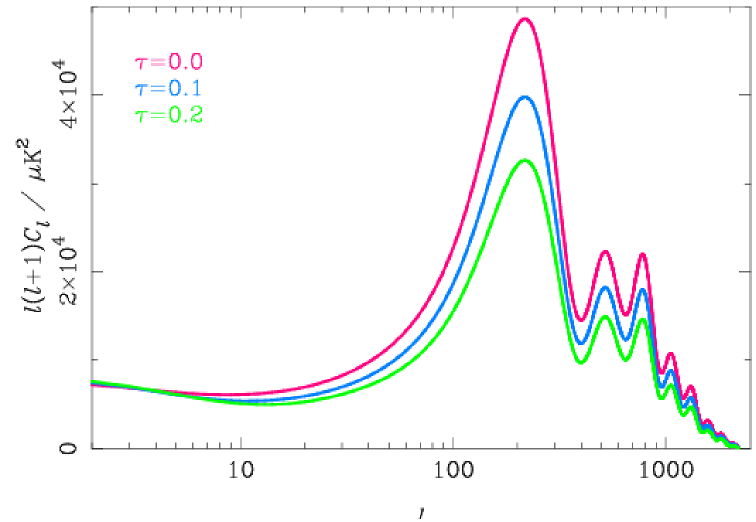
- Amplitude of tensors unknown
- Clear signal from B modes – there are none from scalar modes
- Tensor B is always small compared to adiabatic E

Seljak, Zaldarriaga: astro-ph/9609169

Reionization

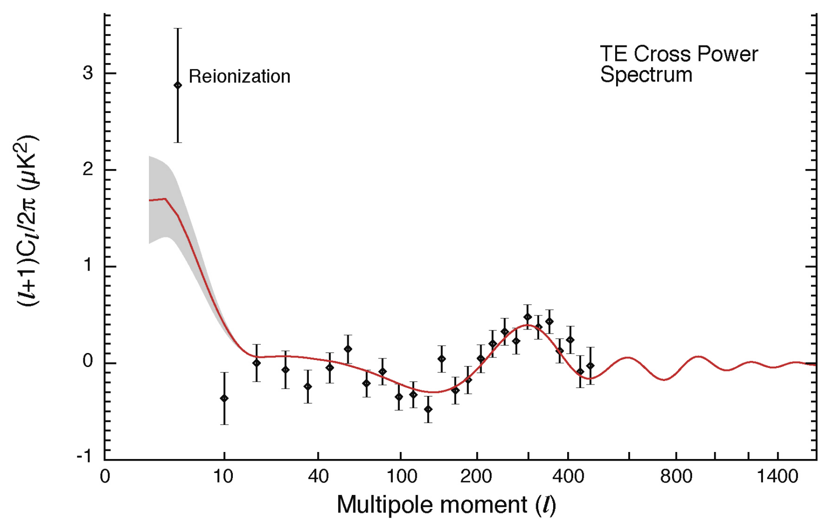
Ionization since z ~ 6-20 scatters CMB photons

Temperature signal similar to tensors



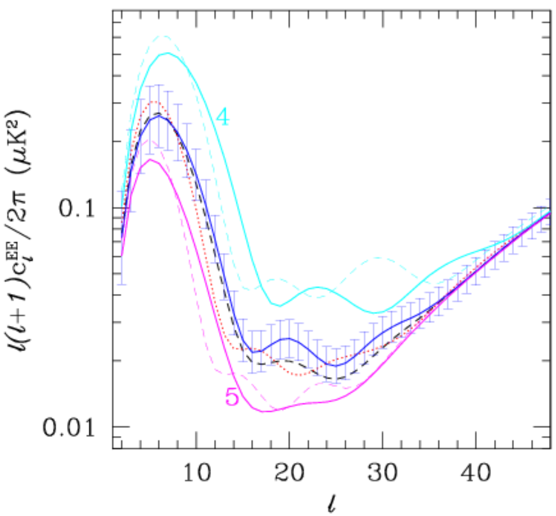
Quadrupole at reionization implies large scale polarization signal

Measure optical depth with T-E correlation

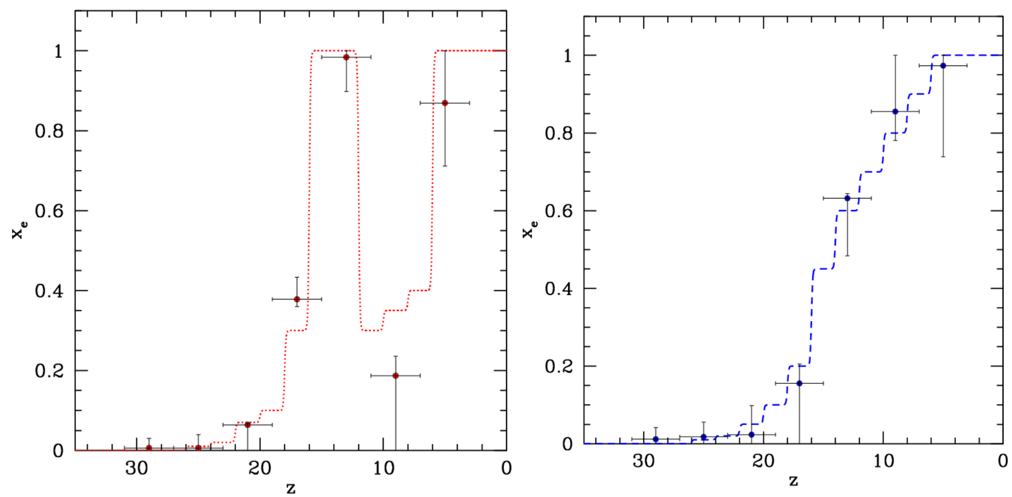


Cosmic variance limited data – resolve structure in EE power spectrum

<u>(Weakly) constrain ionization history</u>



Holder et al: astro-ph/0302404



Weller, Lewis, Battye (in prep)

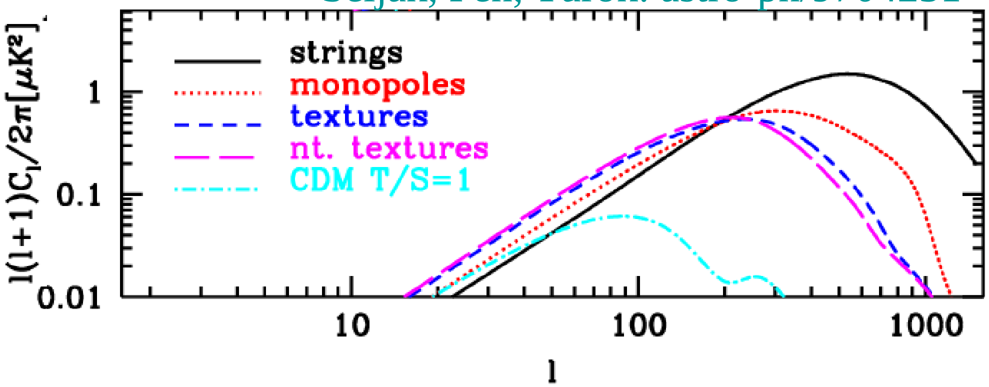
Other B-modes?

•Topological defects

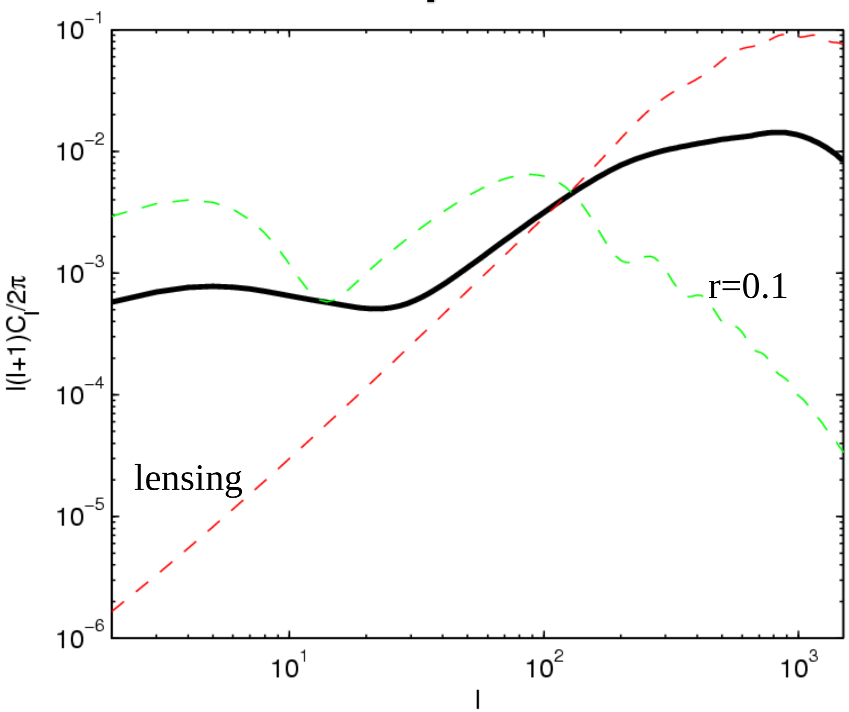
Non-Gaussian signals

global defects:

Seljak, Pen, Turok: astro-ph/9704231



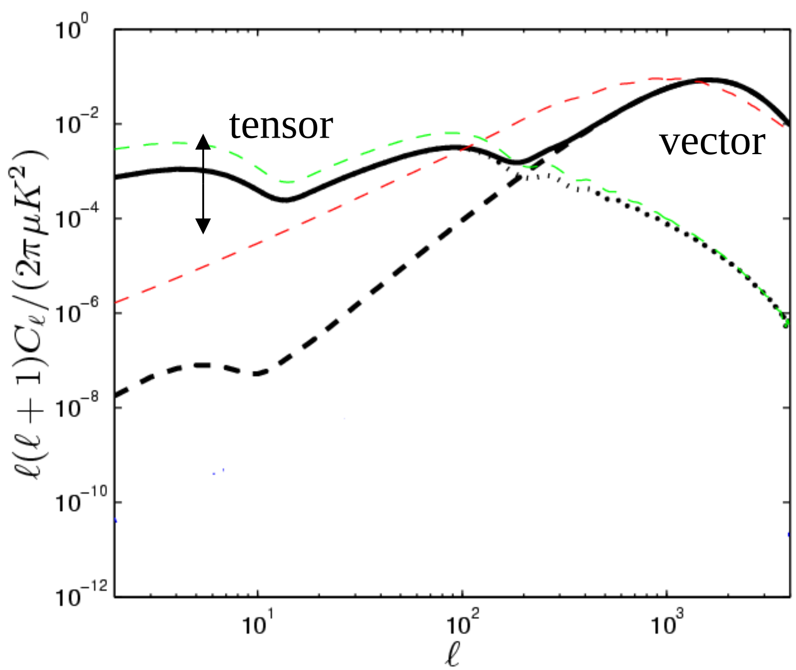
10% local strings from brane inflation:



Pogosian, Tye, Wasserman, Wyman: hep-th/0304188

Primordial magnetic fields

- motivation?



Tensor amplitude uncertain.

Non-Gaussian signal.

Check on galaxy/cluster evolution models.

the initial properties of the magnetic field. (c) Concerning studies of generation of cosmic microwave background (CMBR) anisotropies due to primordial magnetic fields of $B \sim 10^{-9}$ Gauss on $\gtrsim 10$ Mpc scales, such fields are not only impossible to generate in early causal magnetogenesis scenarios but also seemingly ruled out by distortions of the CMBR spectrum due to magnetic field dissipation on smaller scales and the overproduction of cluster magnetic fields. (d) The most promising detection

Banerjee and Jedamzik: astro-ph/0410032

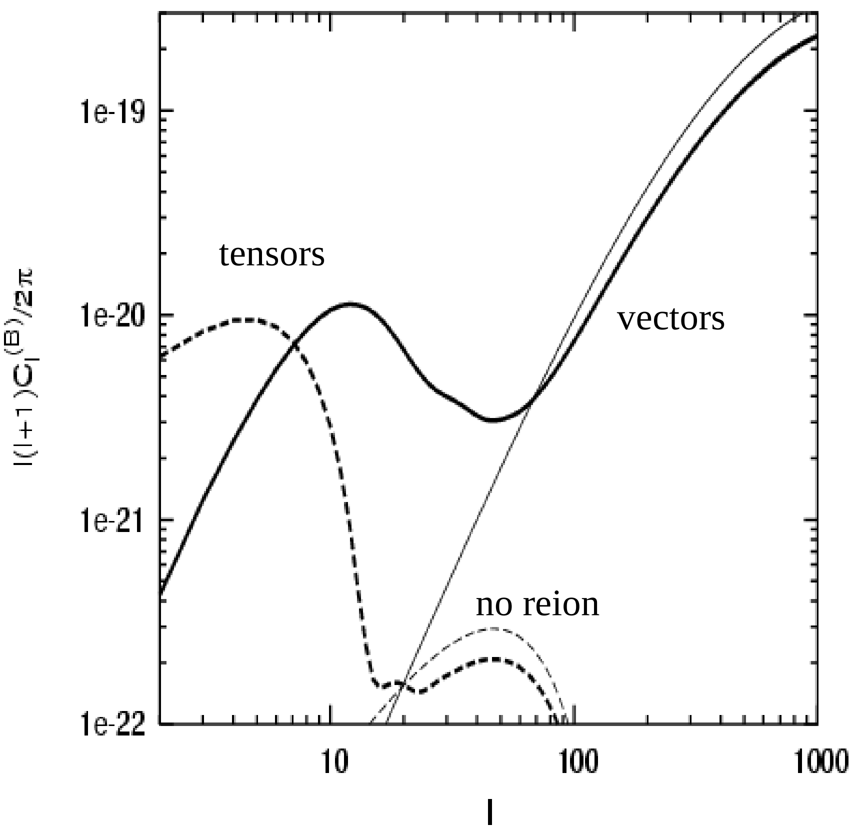
- Also Faraday rotation B-modes at low frequencies

Kosowsky, Loeb: astro-ph/9601055, Scoccola, Harari, Mollerach: astro-ph/0405396

- Small second order effects, e.g.

Second order vectors and tensors:

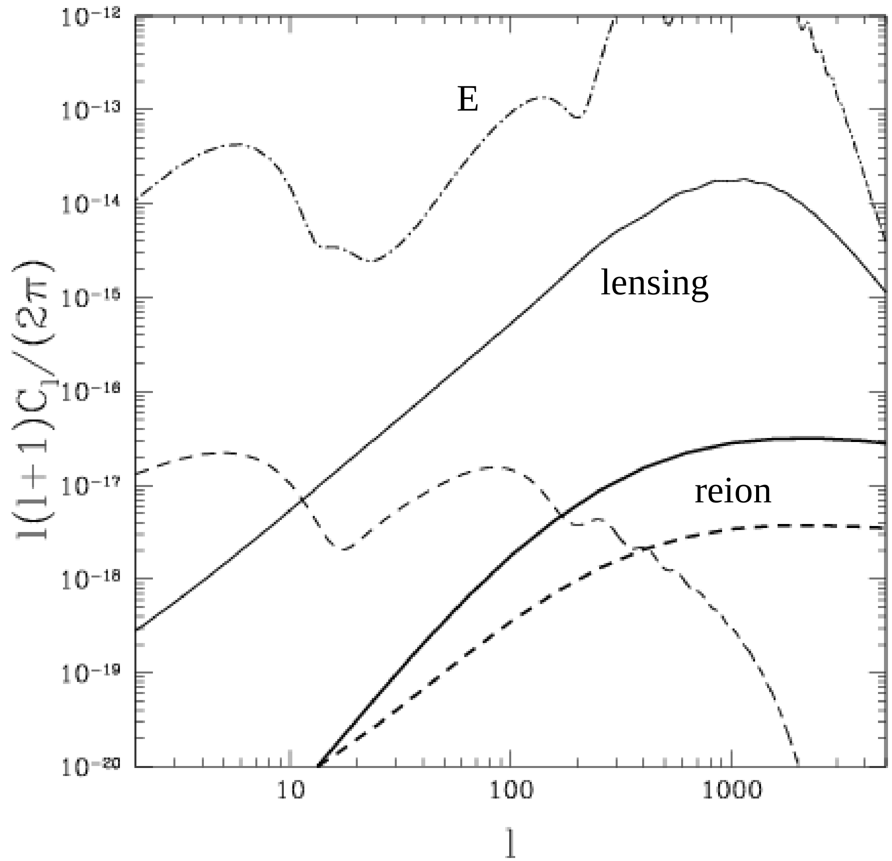
Mollerach, Harari, Matarrese: astro-ph/0310711



Inhomogeneous reionization

Santon, Cooray, Haiman, Knox, Ma:

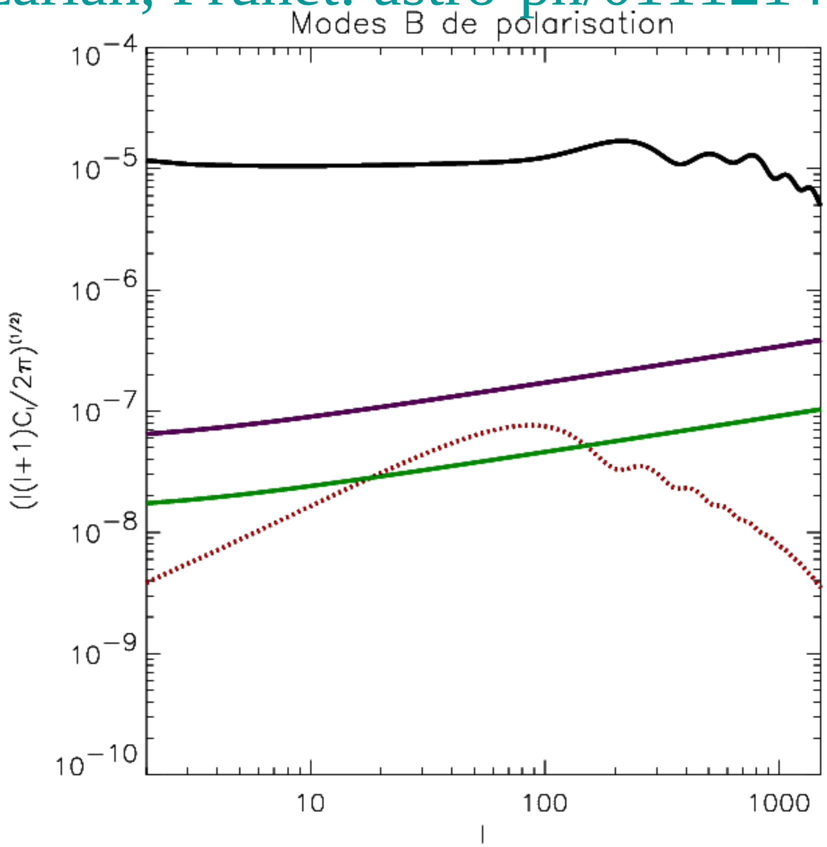
astro-ph/0305471; Hu: astro-ph/9907103



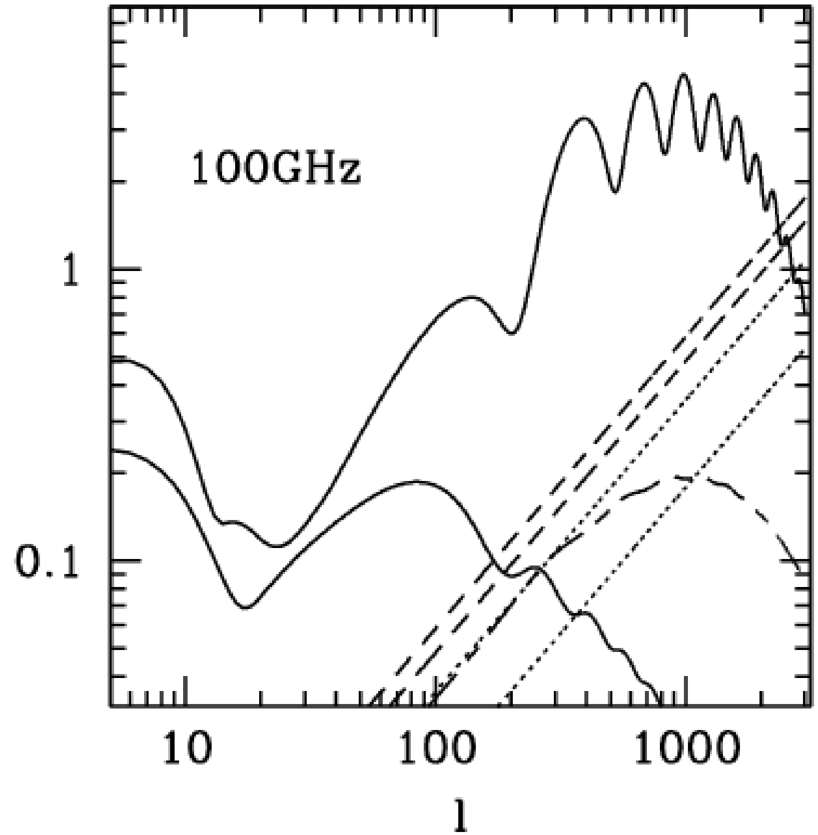
non-Gaussian

• Systematics and foregrounds, e.g.

Galactic dust (143 and 217 GHz):
Lazarian, Prunet: astro-ph/0111214



Extragalactic radio sources:
Tucci et al: astro-ph/0307073



B modes potentially a good diagnostic of foreground subtraction problems or systematics

Partial sky E/B separation problem

$$\mathcal{P}_{ab} = \nabla_{\langle a}\nabla_{b\rangle} P_E - \epsilon^{c}{}_{(a}\nabla_{b)}\nabla_c P_B$$

Pure E: $\nabla^a\nabla^b\mathcal{P}_{ab} = (\nabla^2 + 2)\nabla^2 P_E$

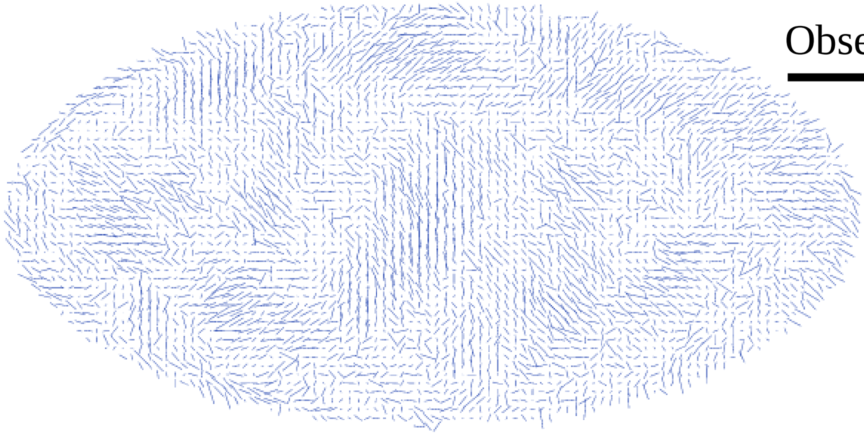
Pure B: $\epsilon^{b}{}_{c}\nabla^c\nabla^a\mathcal{P}_{ab} = (\nabla^2 + 2)\nabla^2 P_B$

Inversion non-trivial with boundaries

Likely important as reionization signal same scale as galactic cut

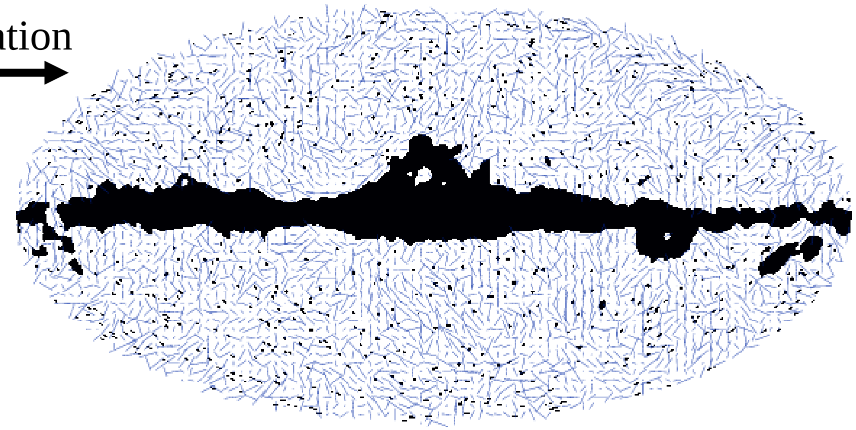
Use set of E/B/mixed harmonics that are orthogonal and complete
over the observed section of the sphere.
Project onto the `pure’ B modes to extract B.

Underlying B-modes

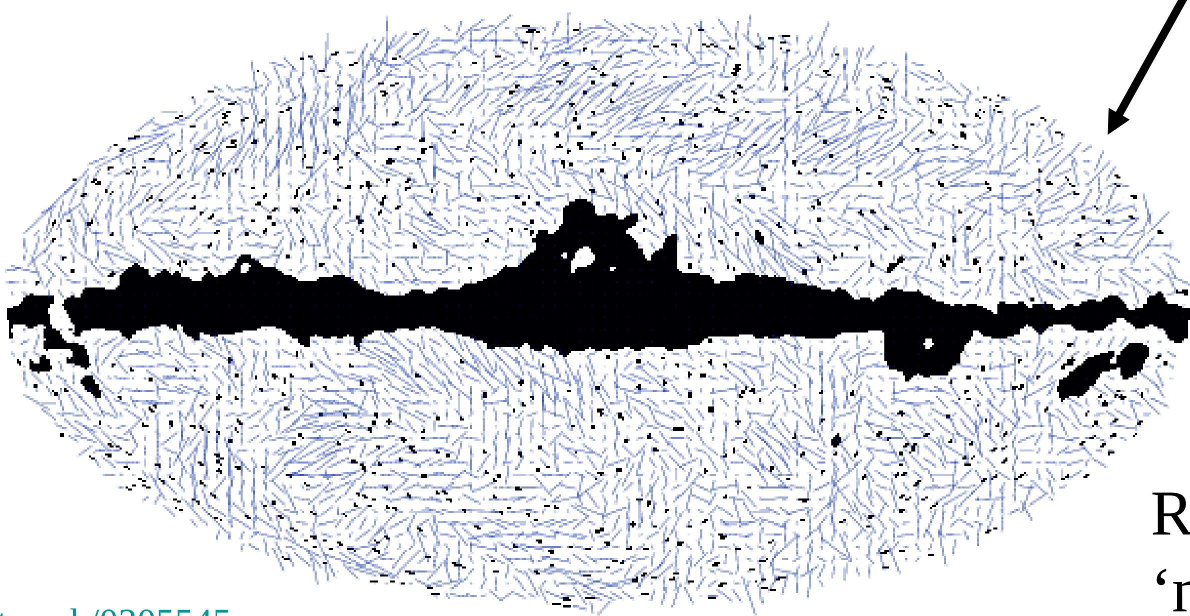


Observation

Part-sky mix with scalar E



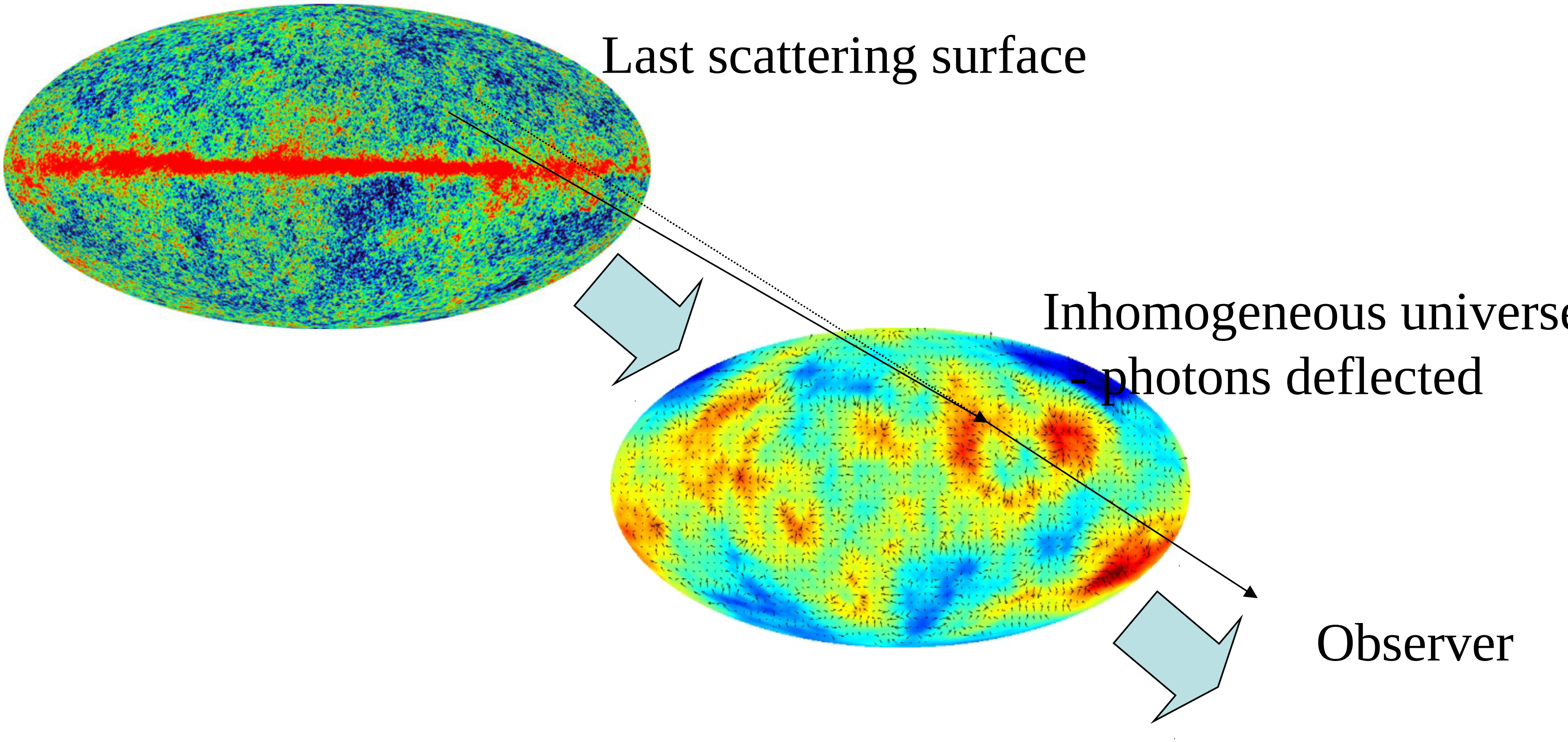
Separation method



Recovered B modes
'map of gravity

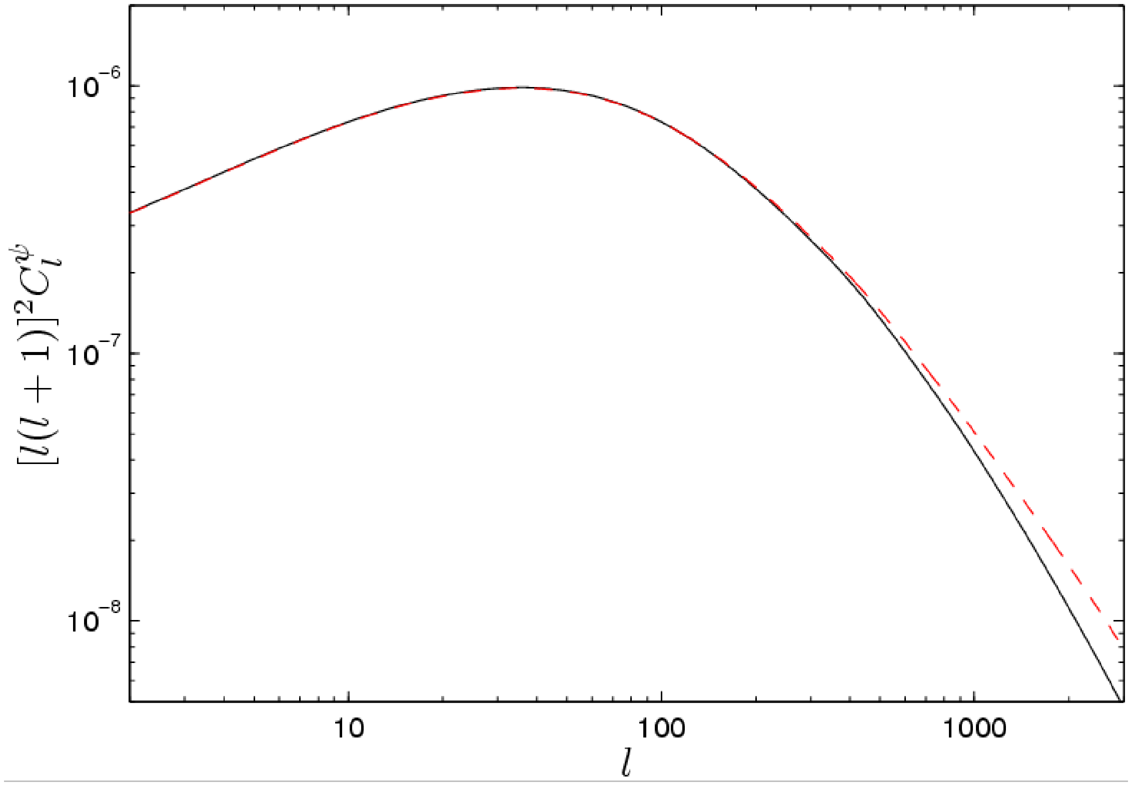
Lewis: astro-ph/0305545

Weak lensing of the CMB



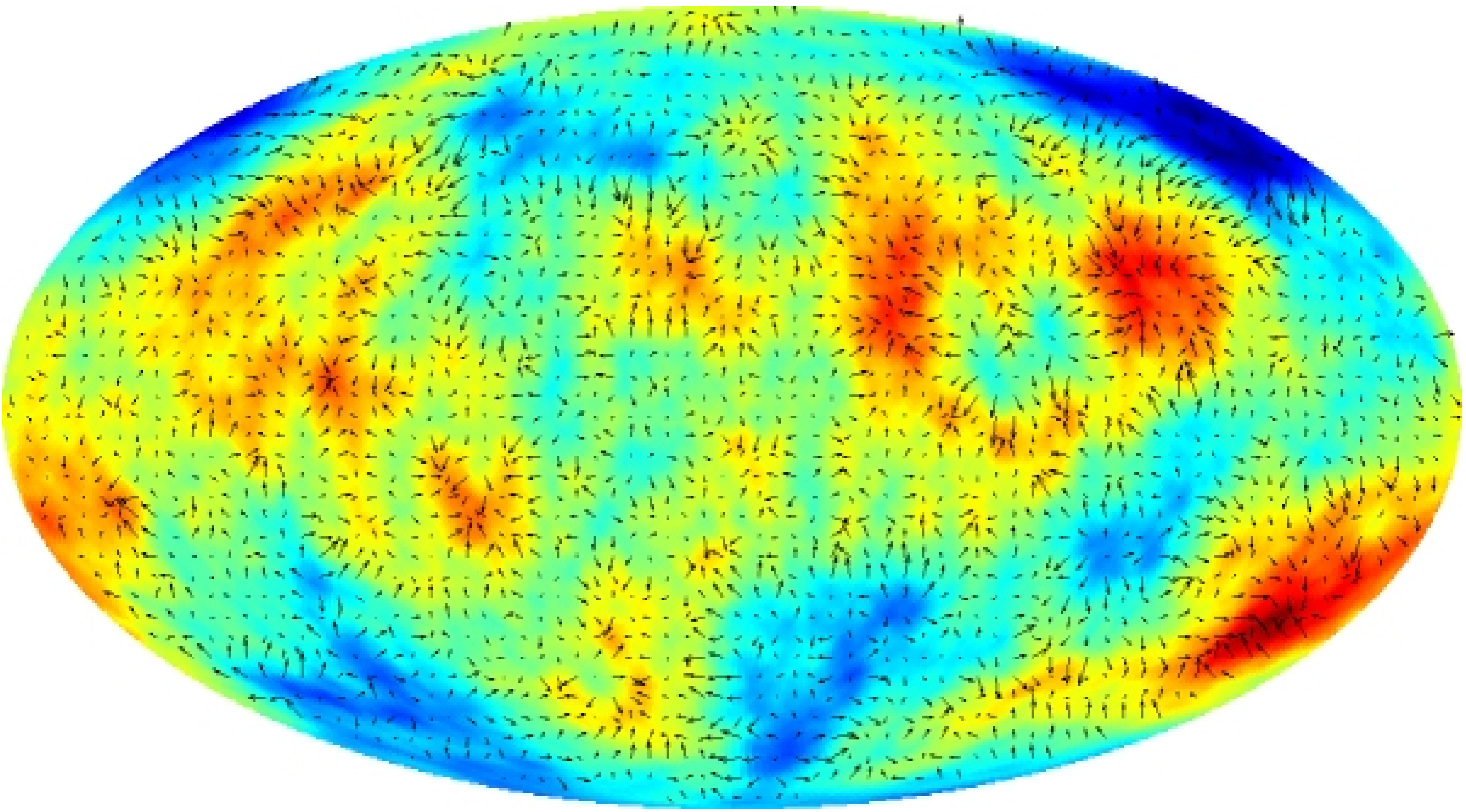
Lensing Potential

$$\bar{X}(\mathbf{n}) = X(\mathbf{n}') = X(\ \mathbf{n} + \nabla\psi(\mathbf{n})\ )$$



Deflections O(10^{-3}), but coherent on degree scales → important!

Lensing potential and deflection angles



- Changes power spectra
- Makes distribution non-Gaussian

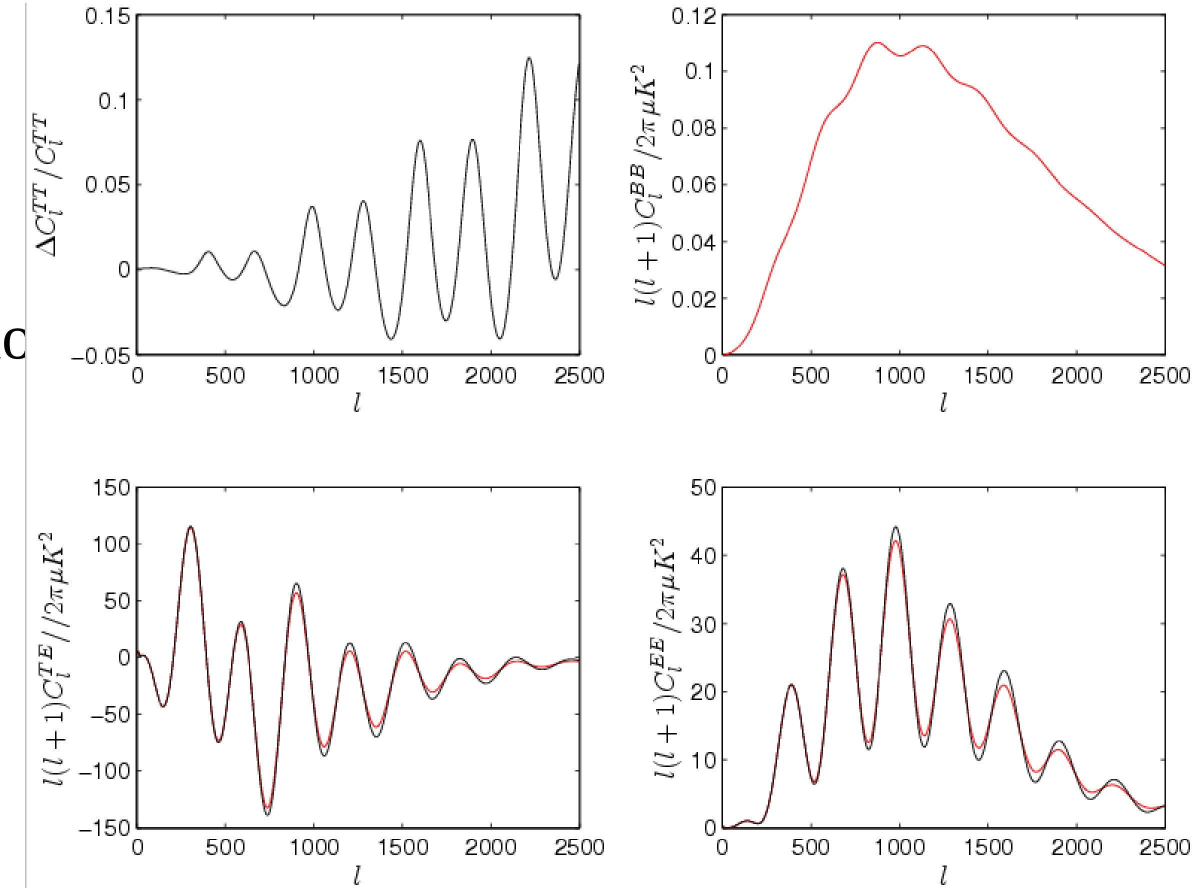
LensPix sky simulation code: http://cosmologist.info/lenspix

Lensed CMB power spectra

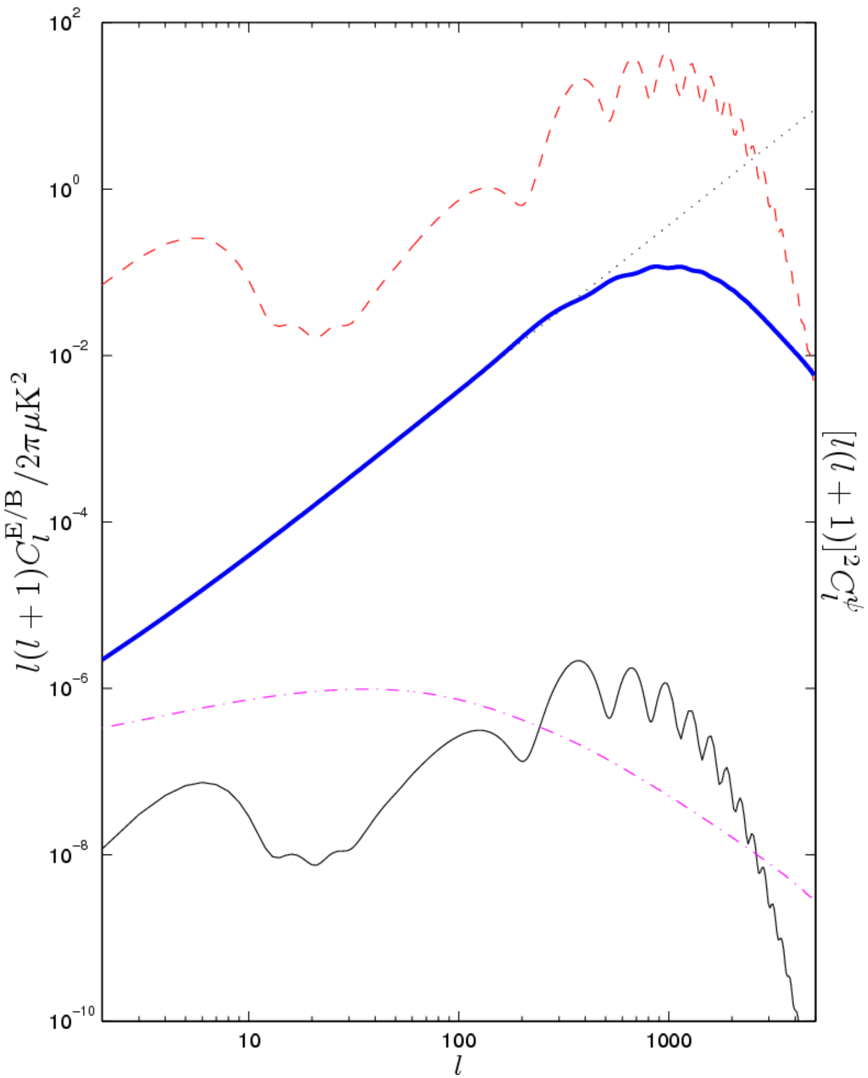
Few % on temperature

10% on TE/EE polarizatic

New lensed BB signal



Lensing of CMB polarization



Lewis, Challinor review in prep

Nearly white BB spectrum on large scales

Potential confusion with tensor modes

Lensing effect can be largely subtracted if only scalar modes + lensing present, but approximate and complicated (especially posterior statistics).

Hirata, Seljak : astro-ph/0306354, Okamoto, Hu: astro-ph/0301031

Other non-linear effects

- Thermal Sunyaev-Zeldovich
  Inverse Compton scattering from hot gas: frequency dependent signal
- Kinetic Sunyaev-Zeldovich (kSZ)
  Doppler from bulk motion of clusters; patchy reionization;
  (almost) frequency independent signal
- Ostriker-Vishniac (OV)
  same as kSZ but for early linear bulk motion
- Rees-Sciama
  Integrated Sachs-Wolfe from evolving non-linear potentials: frequency independent
- General second order
  includes all of the above + more

Conclusions

- CMB contains a lot of useful information!
- “Precision” Cosmology – many parameters constrained
- E-mode and TE measure optical depth, constraining models of reionization
- B-mode tells us about energy scale of inflation
- Weak Lensing can generate B-modes (already observed)