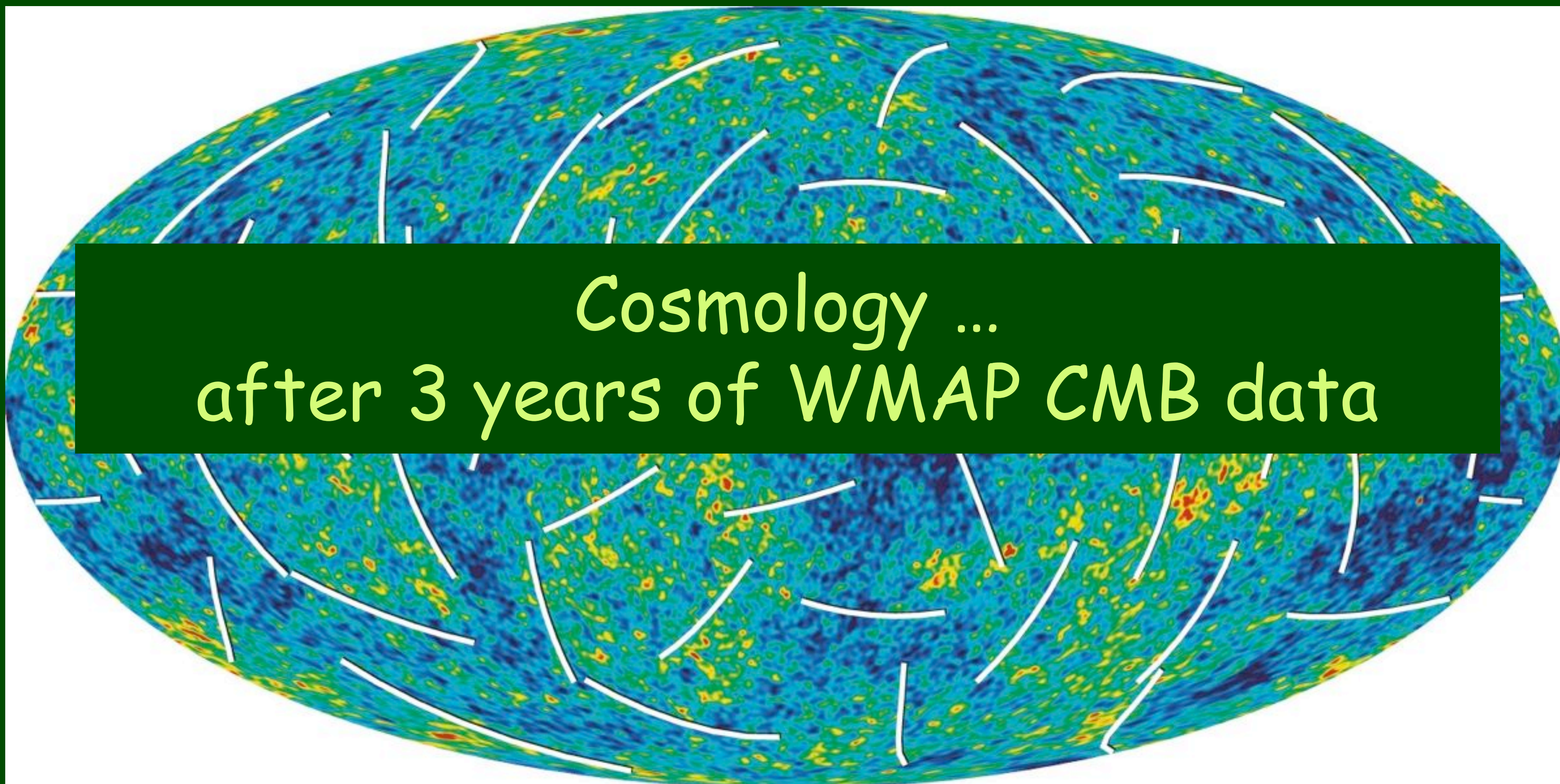
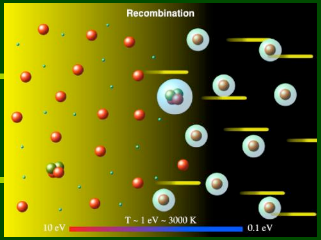


Cosmology …
after 3 years of WMAP CMB data

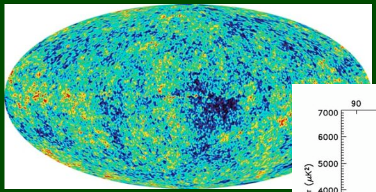
Rachel Bean
Cornell University

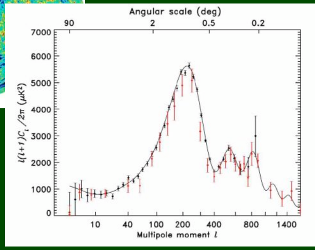
Plan

- o Introduction to CMB temperature and polarization

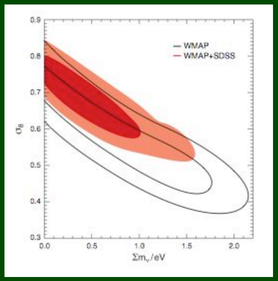


- o The maps and spectra



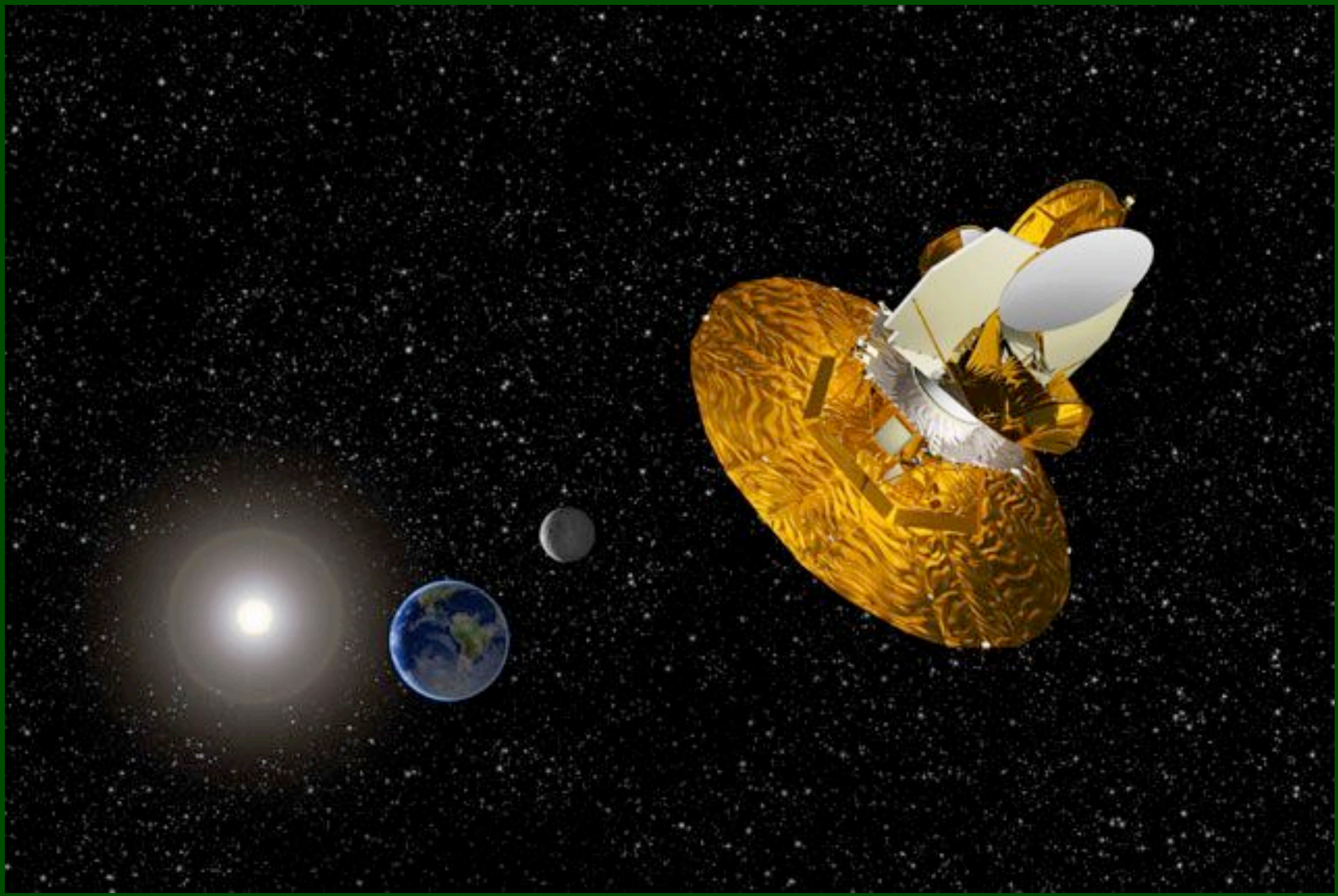


- o Cosmological implications



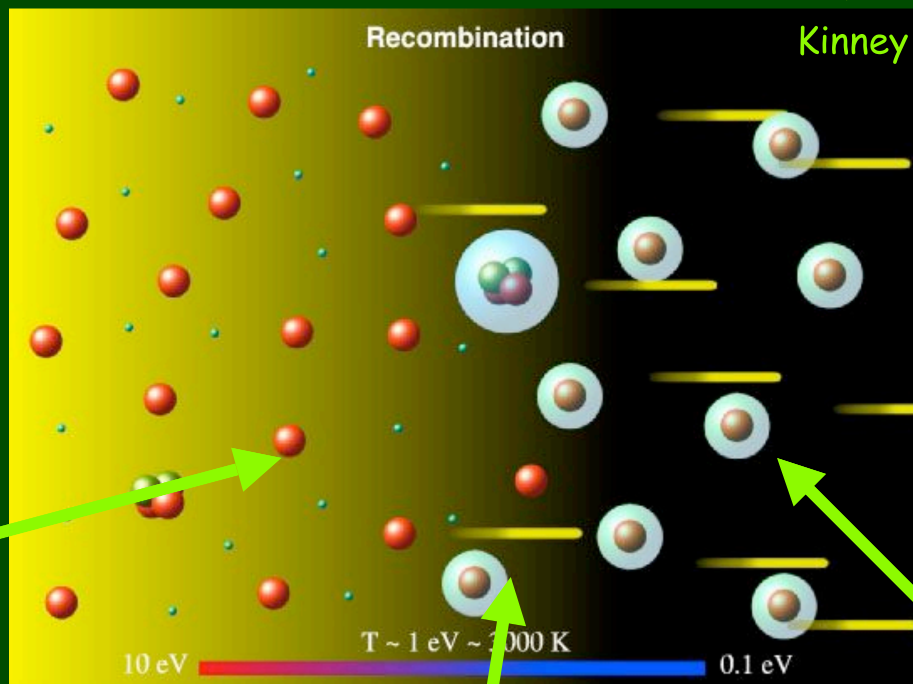
What is WMAP?

- NASA's `Wilkinson Microwave Anisotropy Probe'
- Satellite detecting primordial photons "cosmic microwave background"



CMB is a near perfect primordial blackbody spectrum

Universe expanding and cooling over time…

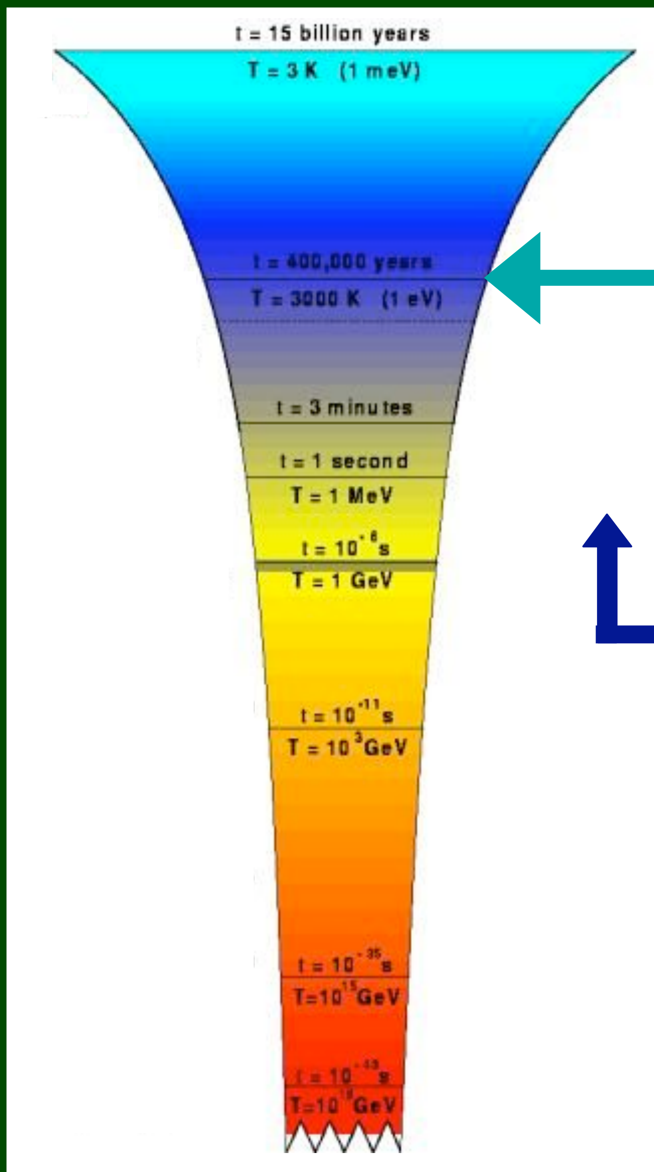


1) Optically opaque plasma

2) The 'last scattering' of photons ~400,000 years after the Big Bang,

3) 'Free Streaming' CMB Blackbody photons at ~3000K redshifted by universe's expansion -> ~2.726K today.

The oldest fossil from the early universe



Recombination

CMB

Nucleosynthesis

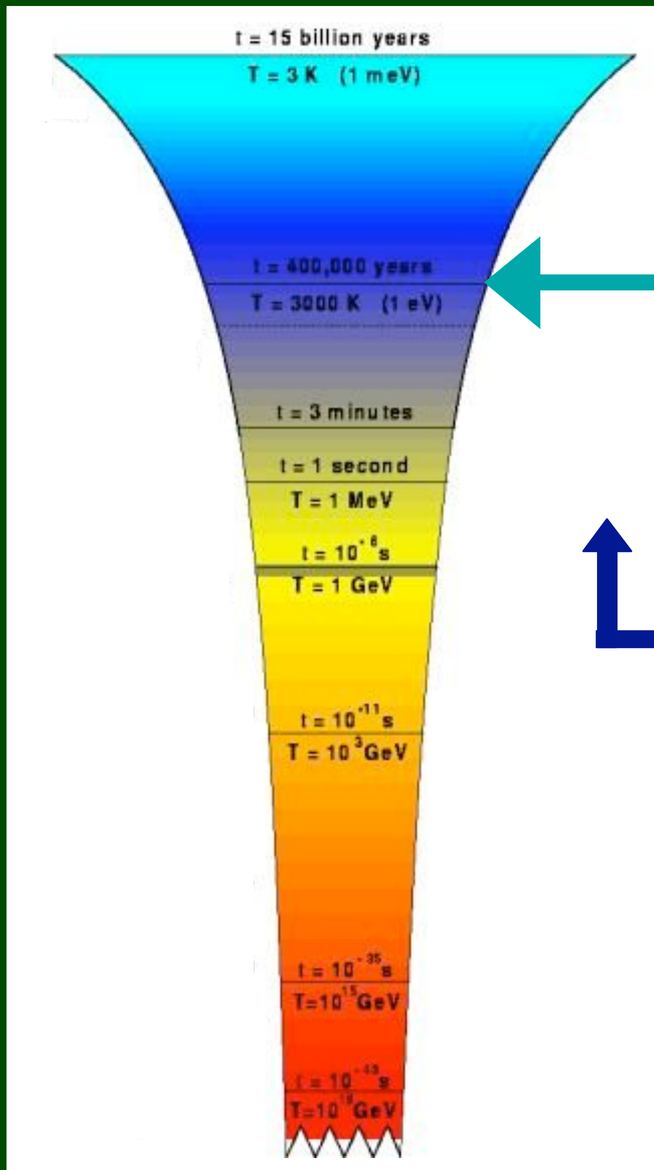
Testable in particle accelerators

Imprint in CMB

Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects....

The cosmic equivalent of tree rings...



Dark Energy domination

Reionization

Galaxy formation

Recombination

CMB

Imprint on CMB

Nucleosynthesis

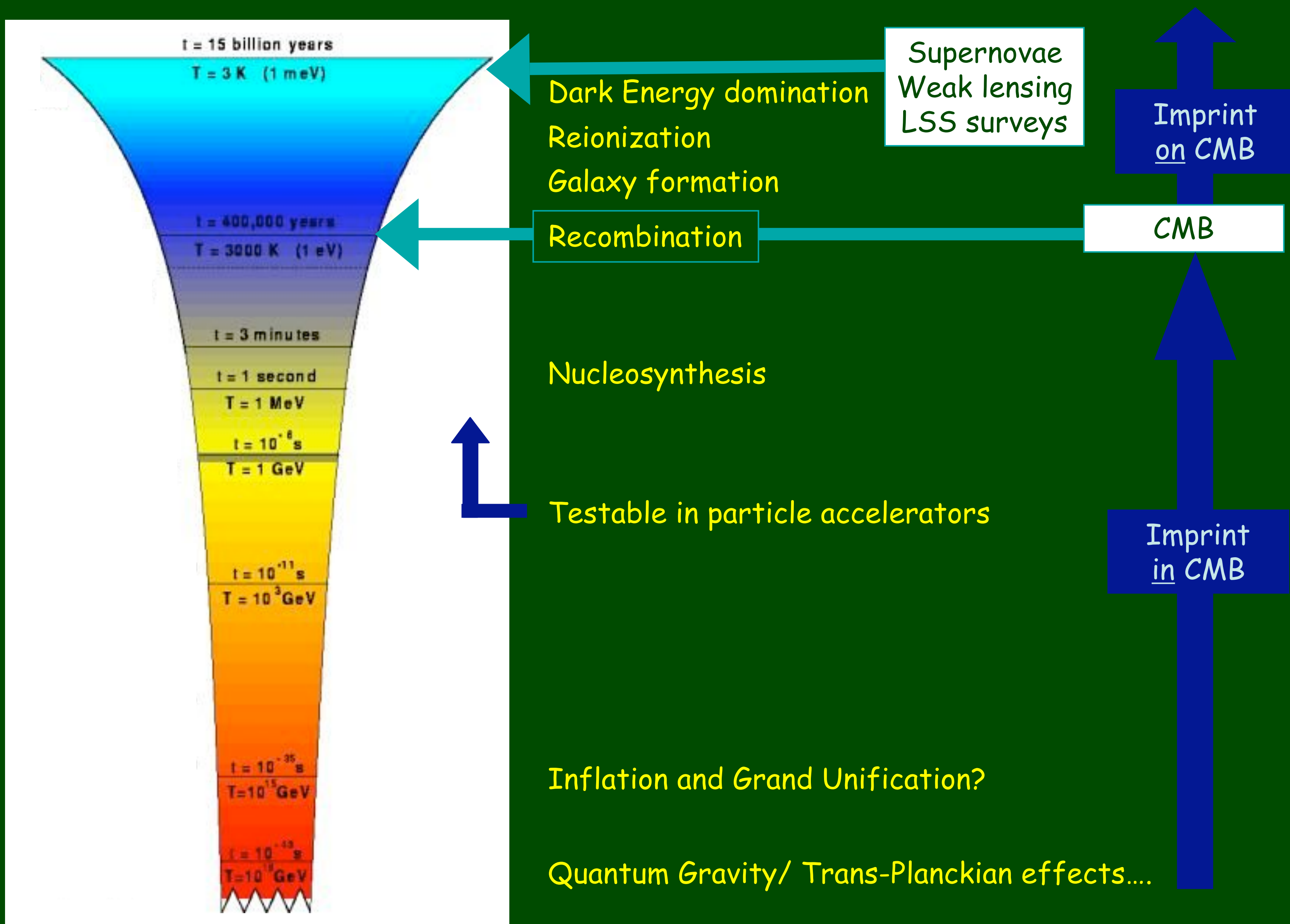
Testable in particle accelerators

Imprint in CMB

Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects....

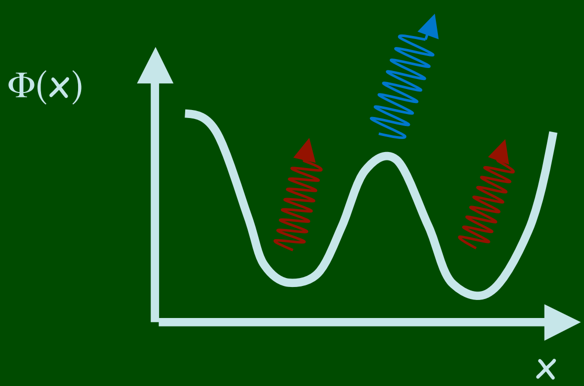
Important comparisons with later observations



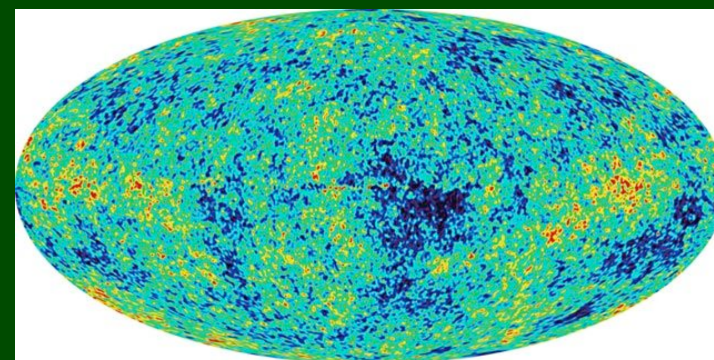
Imperfections in the CMB are what we are really interested in

- Photons escape from gravitational potential

Cold spots = high density
Hot spots = low density



- …Translate into fluctuations in the blackbody photon temp at ~1/100,000 level



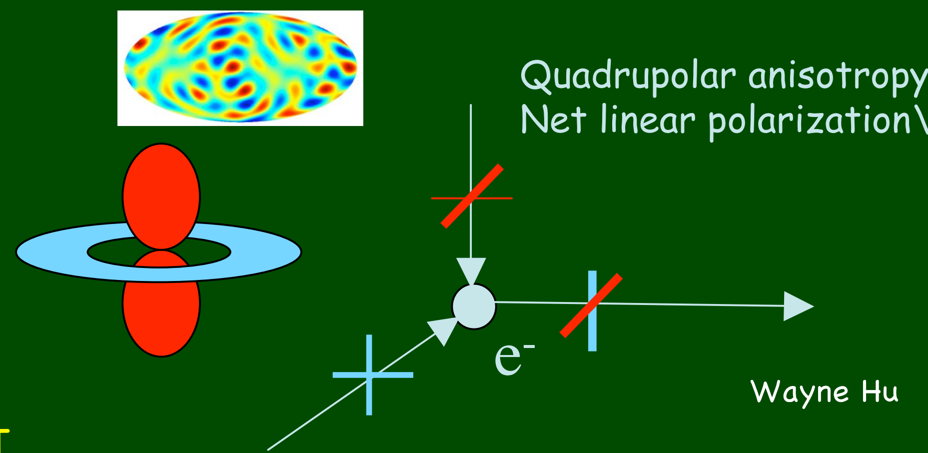
- Thomson scattering interactions in photon-electron/baryon fluid

characteristic scale $\lambda \sim c_s t_{rec}$

$\gamma \longleftrightarrow e^- \longleftrightarrow p^+$

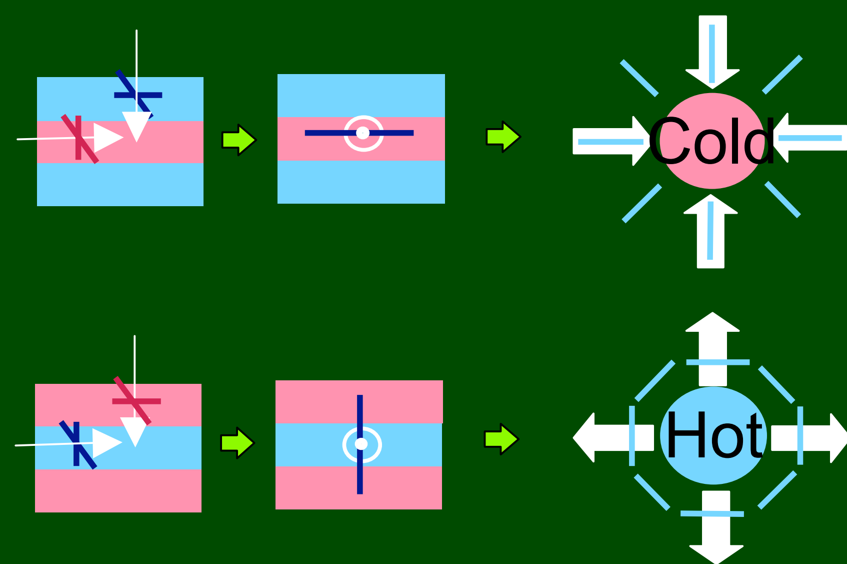
Compton scattering | Coulomb interaction

CMB scattering gives a "2 for 1": Polarization too!



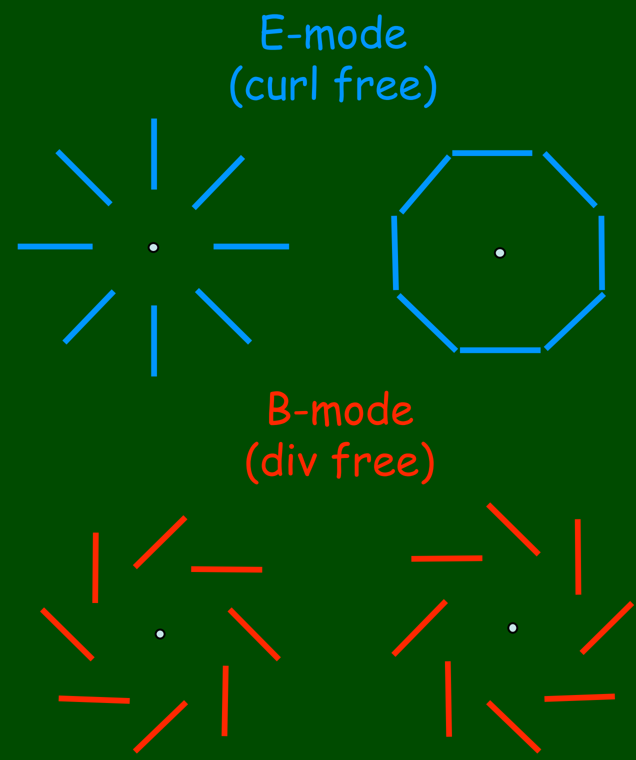
Wayne Hu

- Polarization created by Thomson scattering of photons
  - Quadrupolar T distribution
  - T and P correlated
- P a purer imprint of early universe than T
  - Once electrons in atoms, scattering processes stop
- P on scales below scattering horizon size
  - small scale polarization at recombination z~1088
  - Larger scale from reionization by the first stars z~25

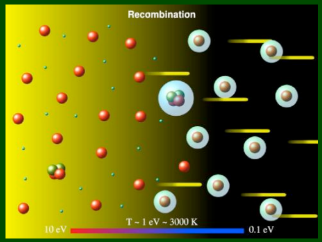


CMB Polarization: Alternative descriptions

- Polarization <=> Stokes Parameters (Q,U) <u>or</u> E/ B modes analogous to EM.
  - E/B rotationally invariant <u>and</u> nicely divides underlying processes
- Density (scalar) perturbations only generate EE
  - EE polarization <=> matter density & CMB temperature
- Metric (tensor) perturbations generate both EE and BB
  - BB insight into primordial gravity waves with little ‘contamination’ from scalar modes

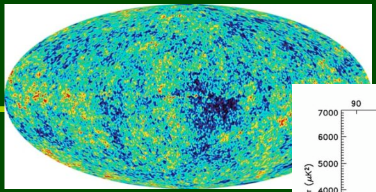


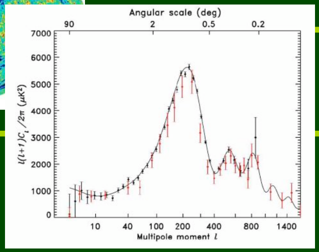
Plan



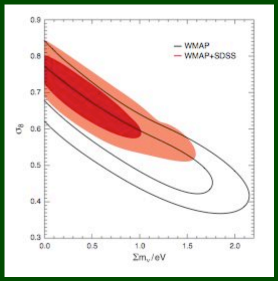
- o Introduction to CMB temperature and polarization

- o **The maps and spectra**

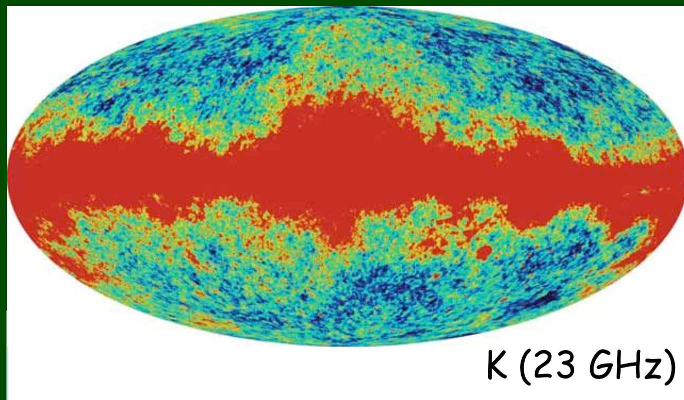


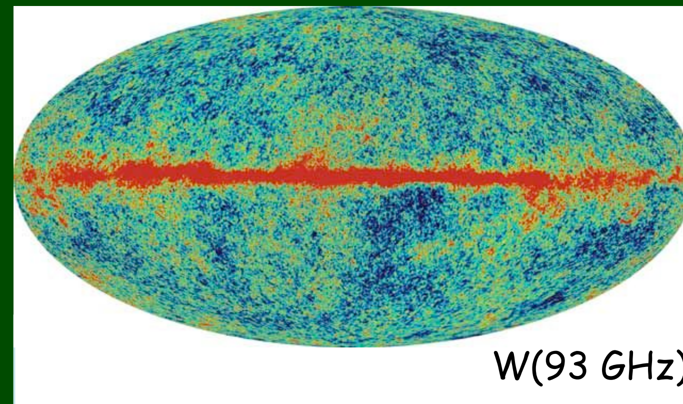


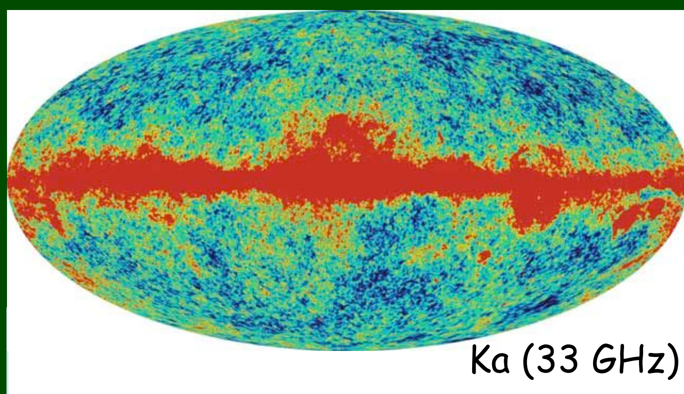
- o Cosmological implications

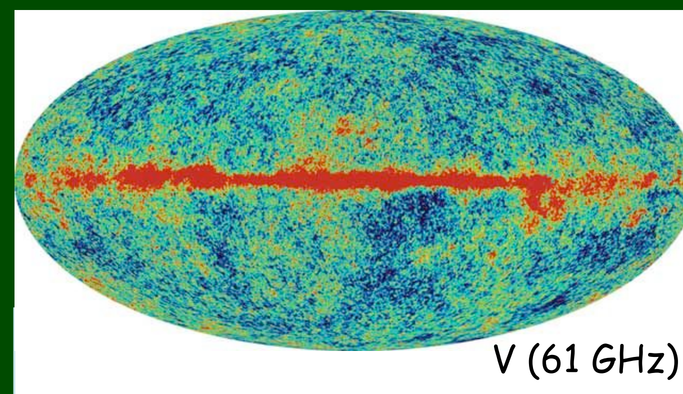


Measure CMB at multiple frequencies to minimize systematics

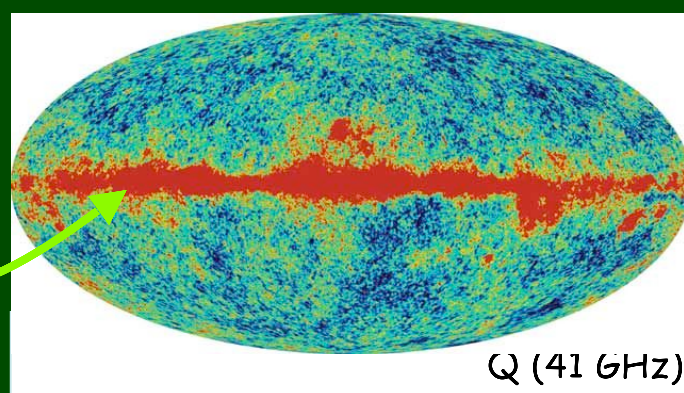




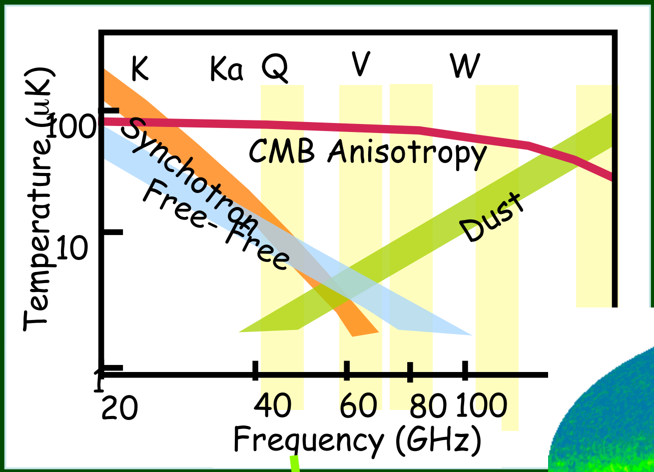


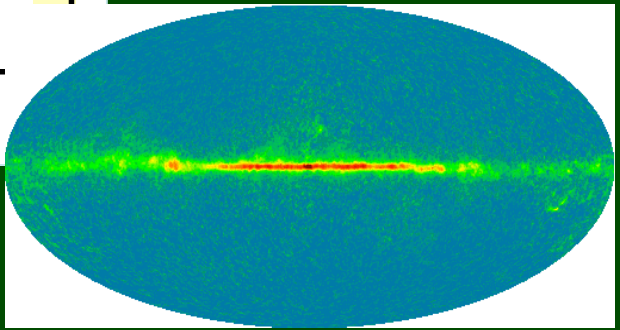


Our galactic plane

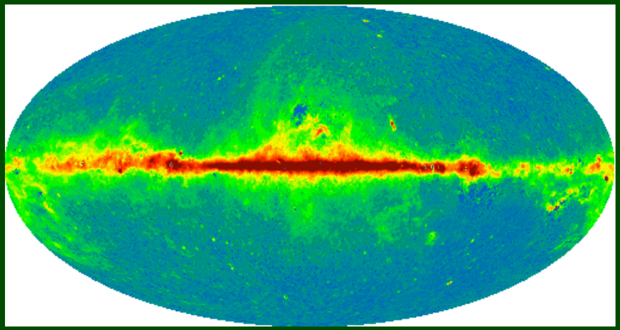


Multiple maps help extract galactic foregrounds

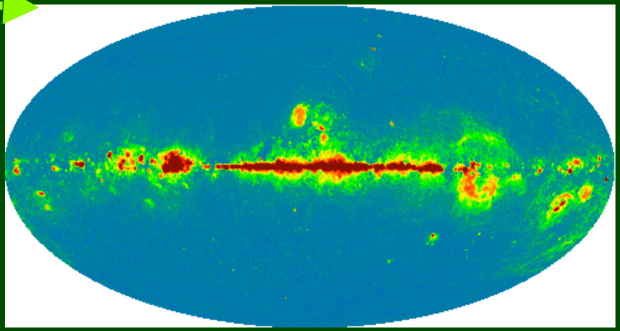




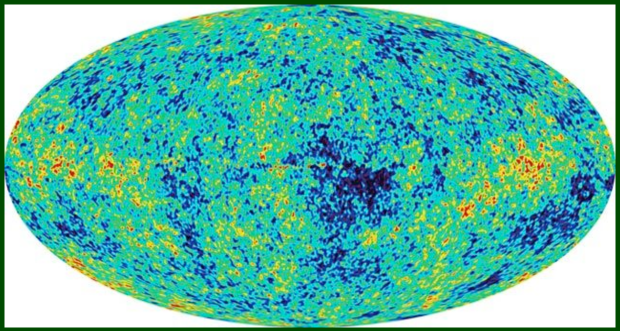
Thermal Dust map



Synchrotron map



Free-free map



CMB map

Harmonic analysis of the maps gives deeper insight into underlying processes

- Spherical harmonic decomposition of sky

$$\frac{\Delta T(p)}{T} = \sum_{lm} a_{lm} Y_{lm}(p)$$

- For a random field all we need to describe it is the correlation function

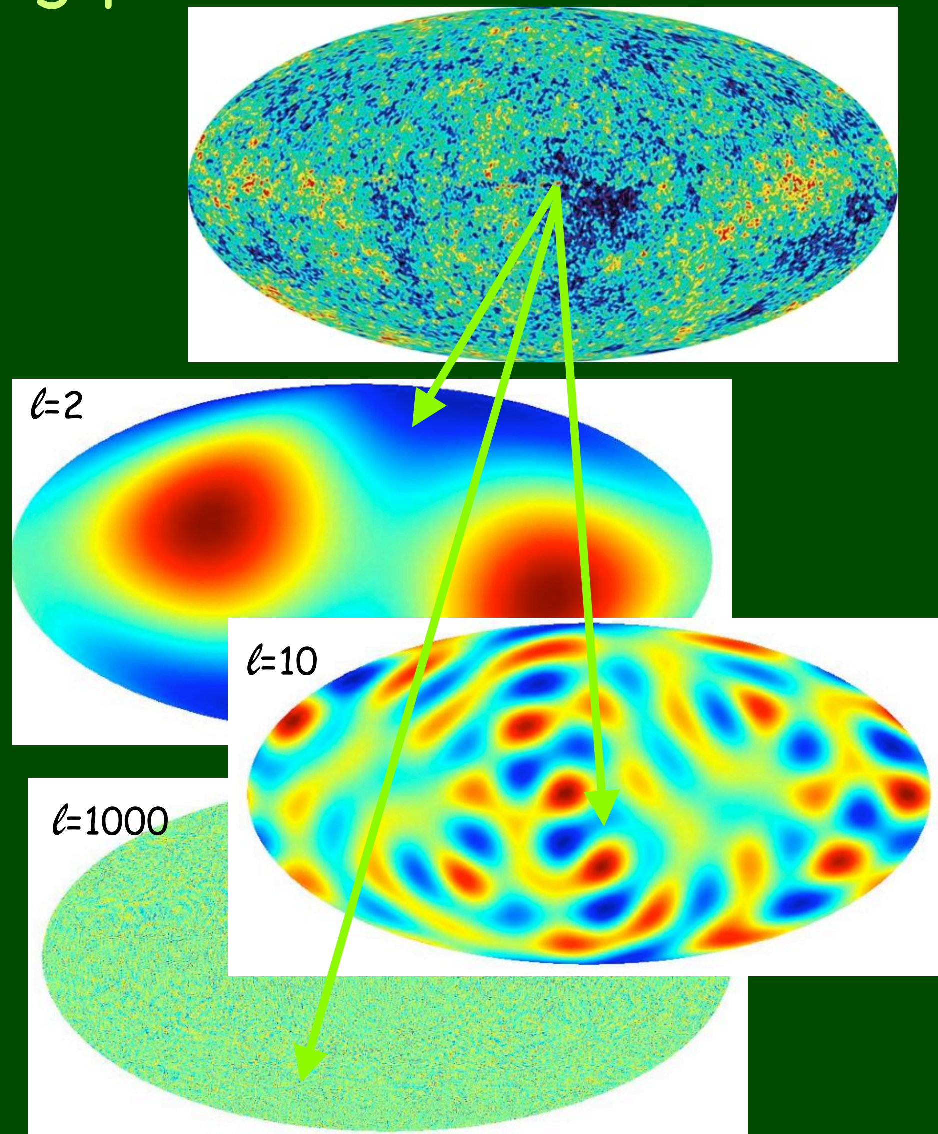
$$\langle a^*_{lm} a_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l$$

- Estimate C_l from sampling a_{lm} from the sky

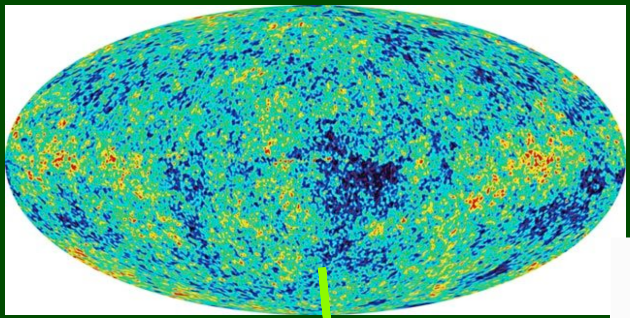
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

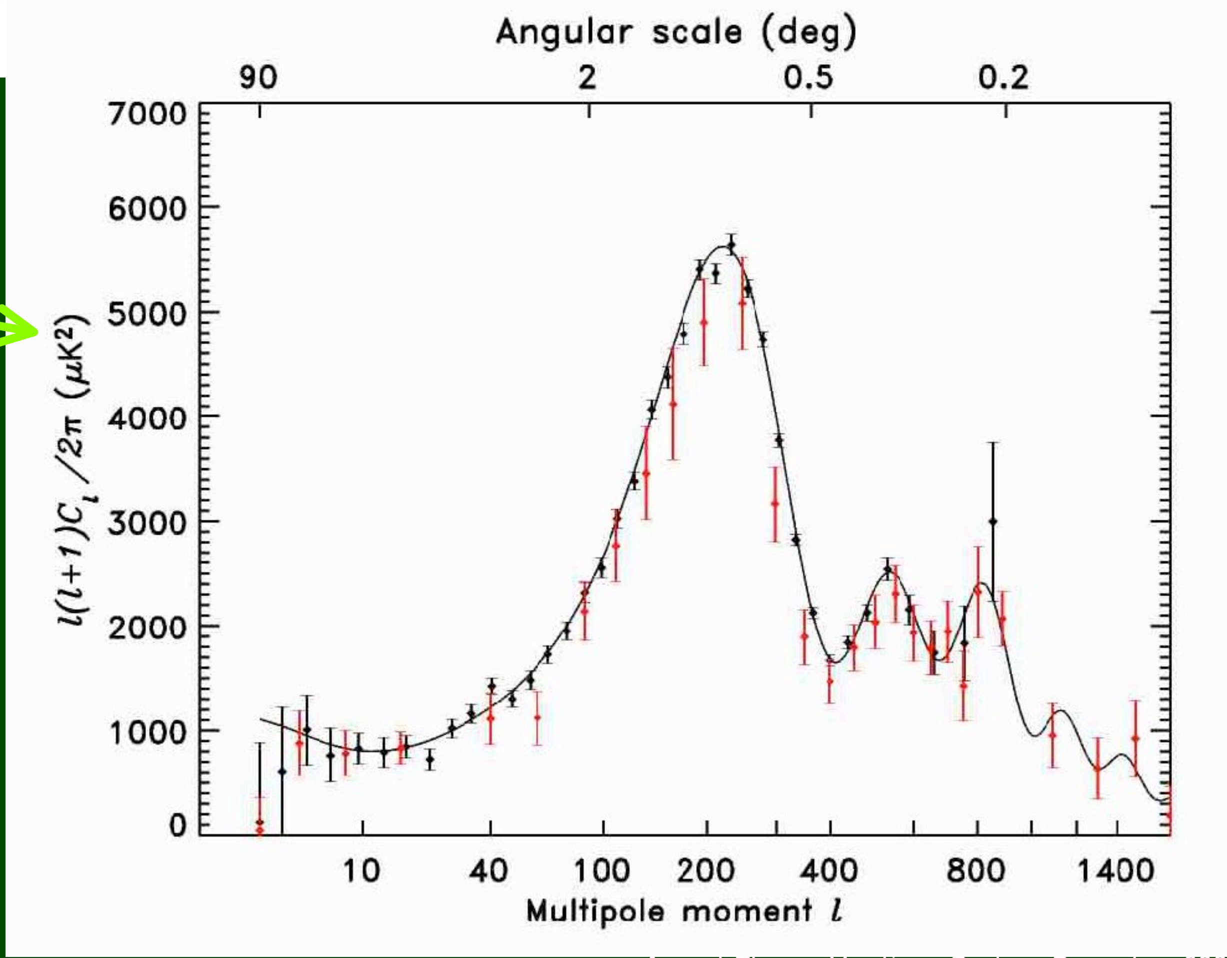
- Inherent sampling error associated with measurement ("cosmic variance")

$$\Delta C_l = \sqrt{\frac{2}{2l+1}} C_l$$



Spatial fluctuations transform into `angular power spectrum'

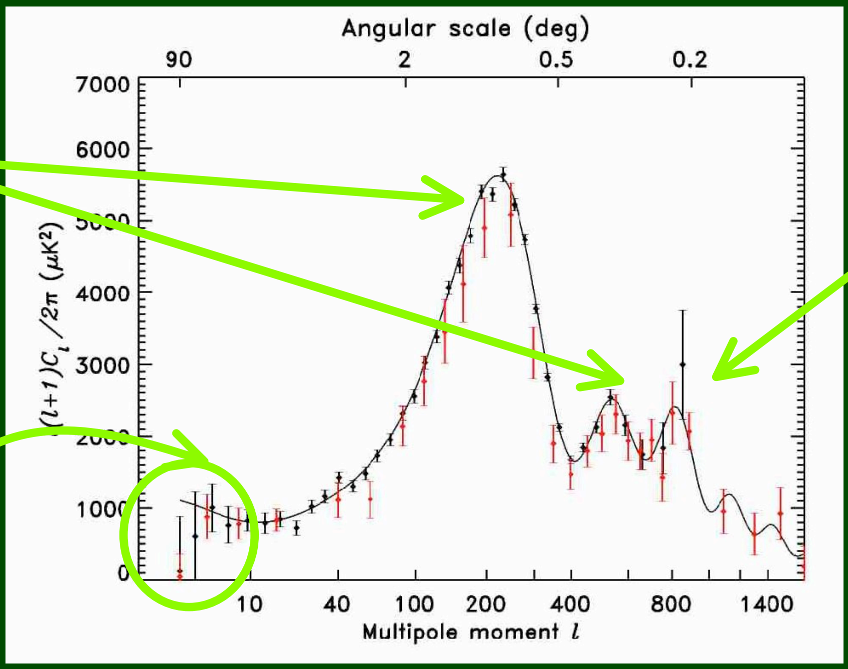




CMB Temperature fluctuations: An overview

Decreasing length scale

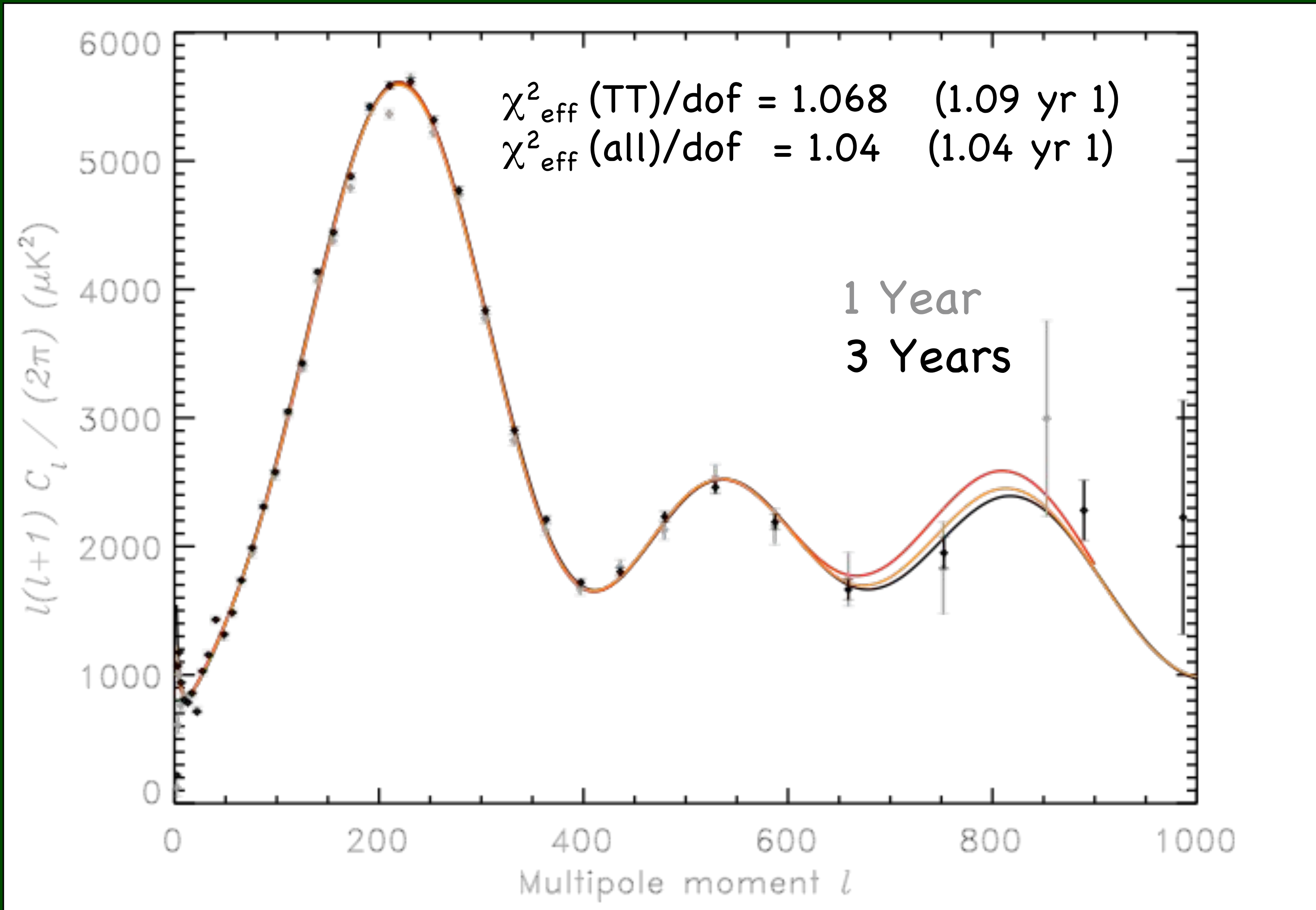
Acoustic oscillations
- Photon- baryon fluid at last scattering



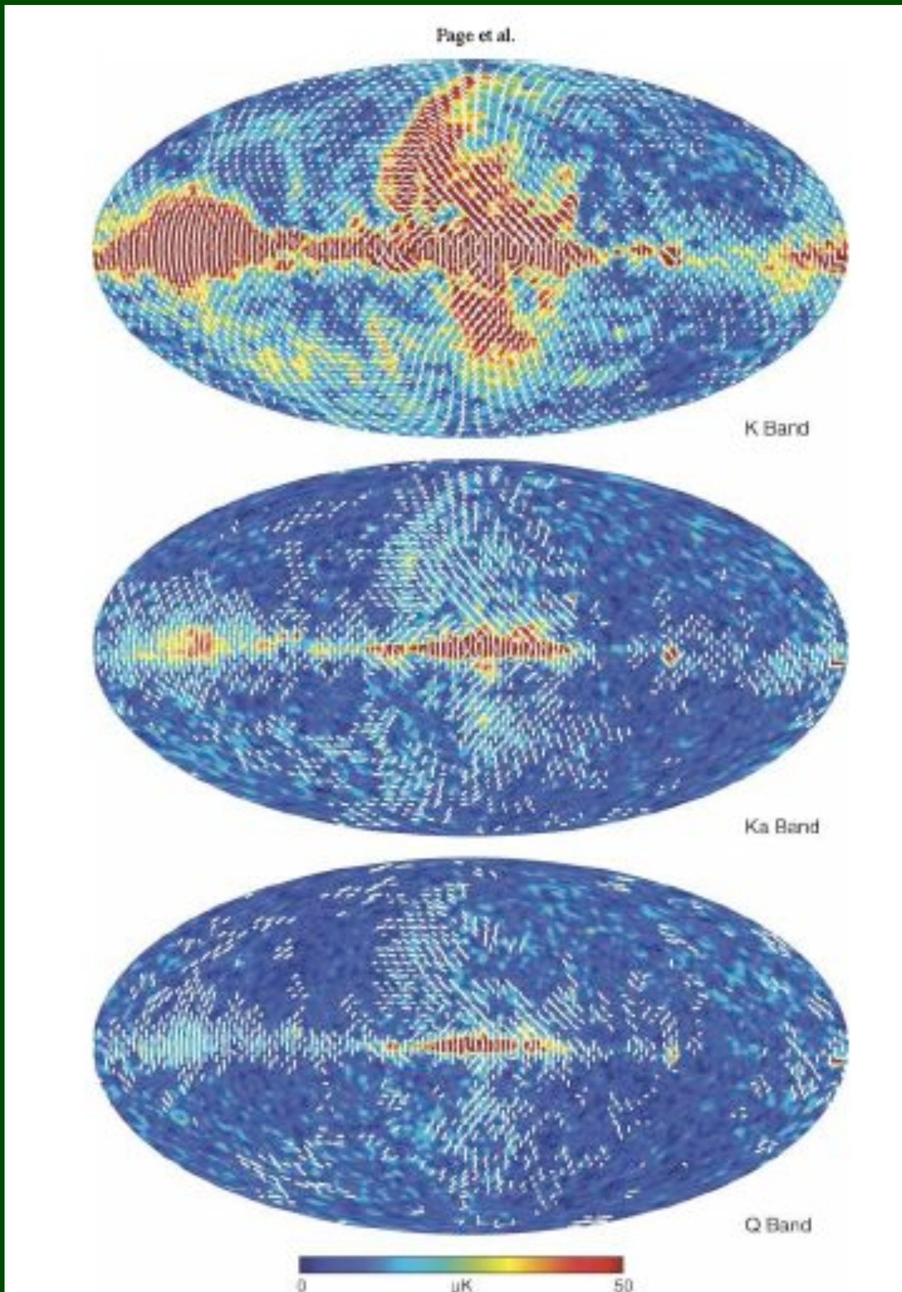
Small scales : Damping tail
- Scattering processes after recombination

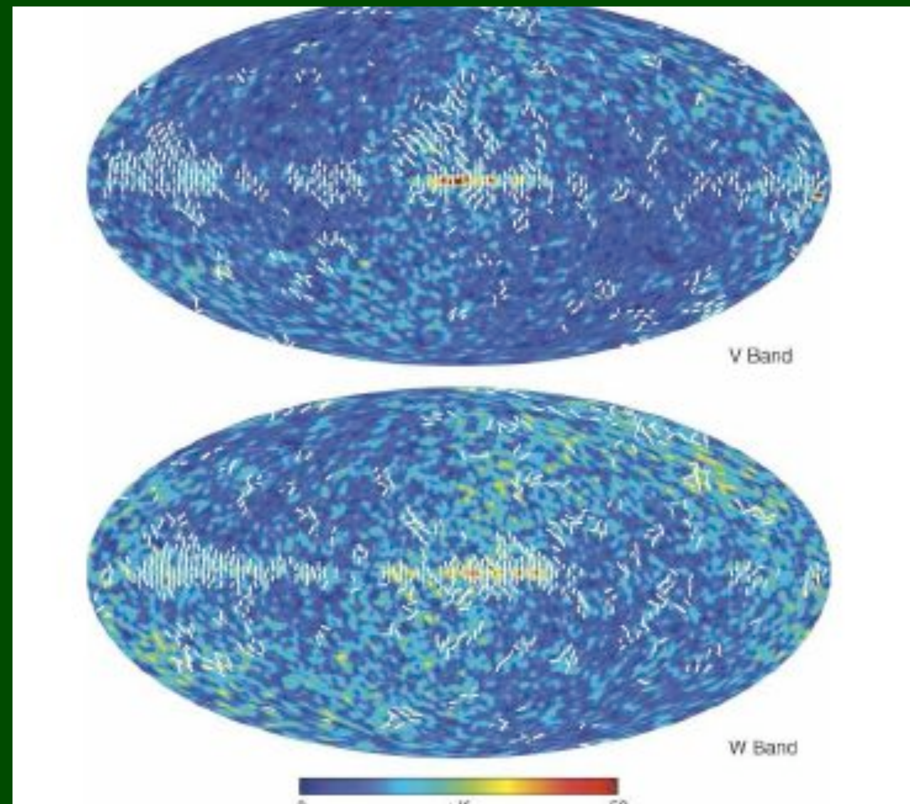
Largest scales
- Only just entering causal horizon recently, sensitive to universe's recent evolution
- Cosmological origins
- inherent sampling uncertainty "cosmic variance"

3 years of data vs 1 year: despite smaller error bars, the χ^2_{eff} improves



Polarization maps

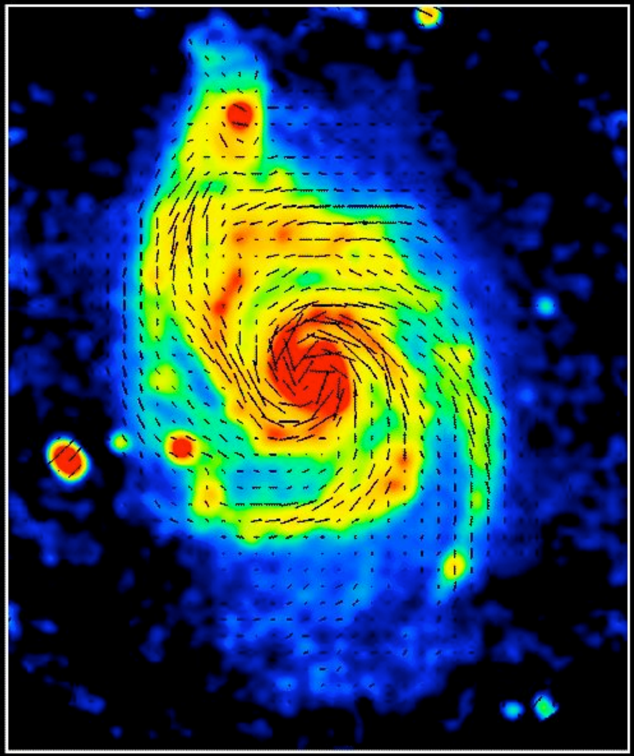




Polarized foregrounds - evidence of role of galactic magnetic field

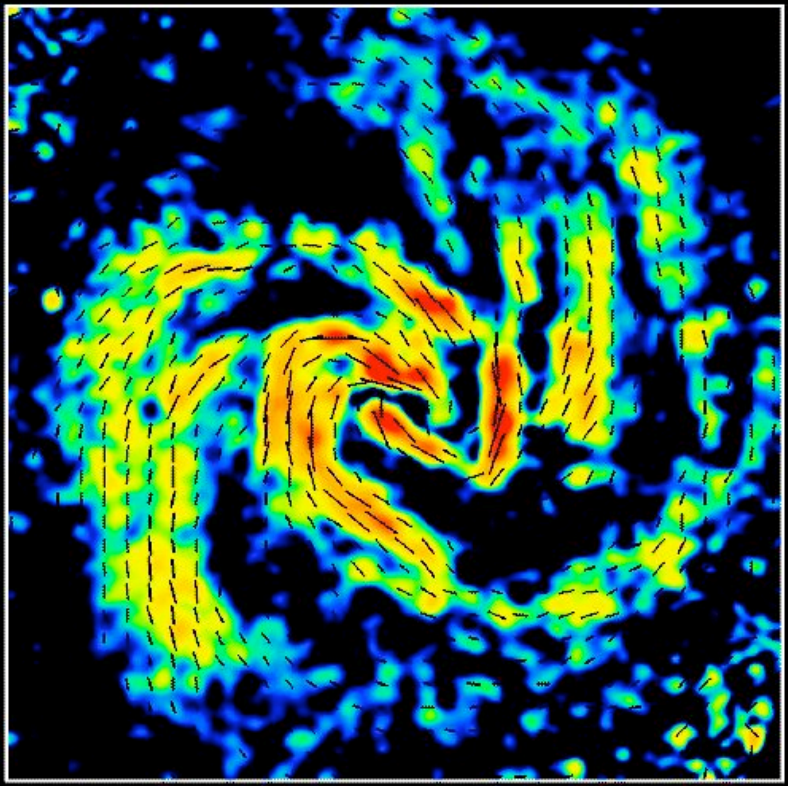
Magnetic Field Structure in external galaxies exhibit spiral structure

M51 6cm Total Int. + B-Vectors (VLA+Effelsberg)



Copyright: MPIfR Bonn (R.Beck, C.Horellou & N.Neininger)

M83 6cm Polarized Int. + B-Vectors (VLA+Effelsberg)



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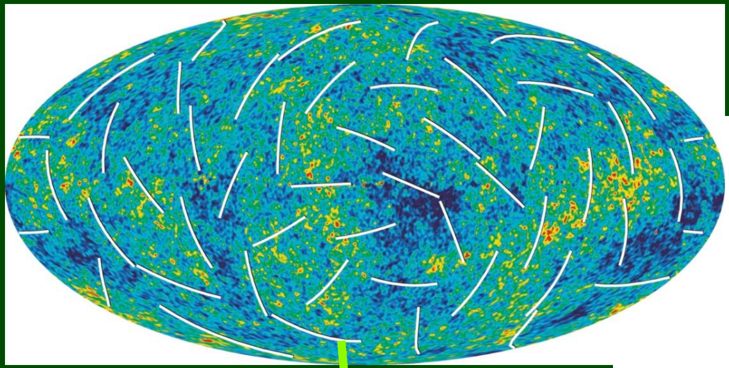
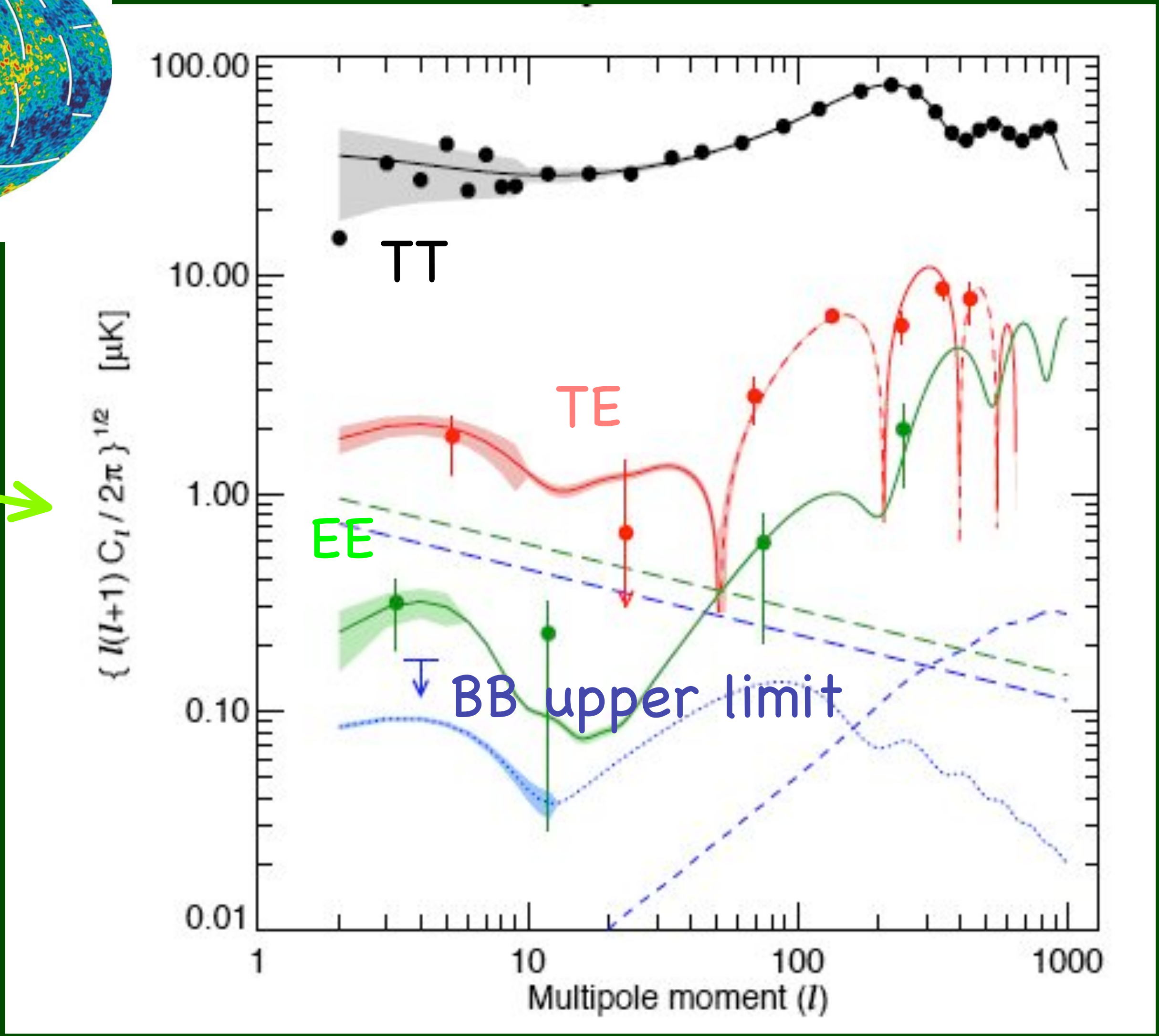
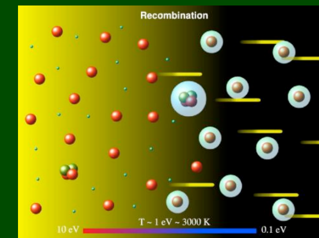
Summary of power spectrum results



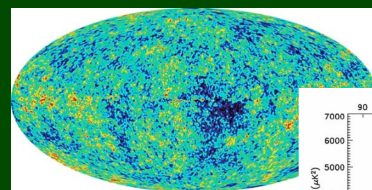


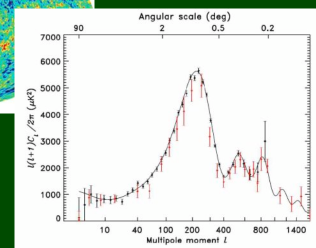
Plan



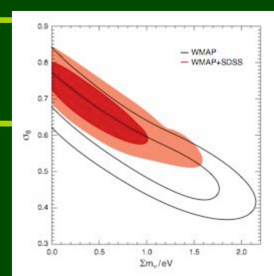
- o Introduction to CMB temperature and polarization

- o The maps and spectra

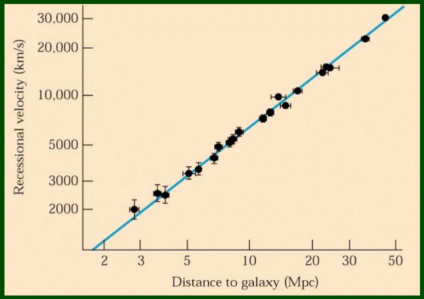




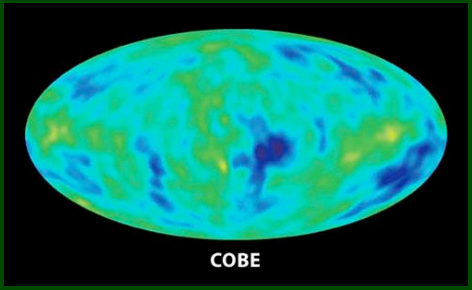
- o Cosmological implications



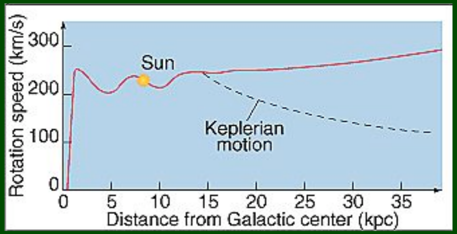
Observations have driven many key theoretical developments



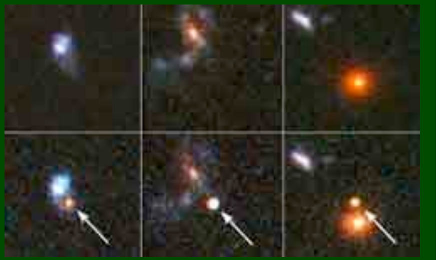
An expanding universe



Homogeneity and isotropy on large scales



Galaxy outer rotation velocities



An accelerating universe

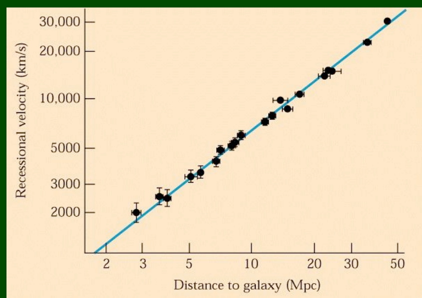
Hot Big Bang

Inflation

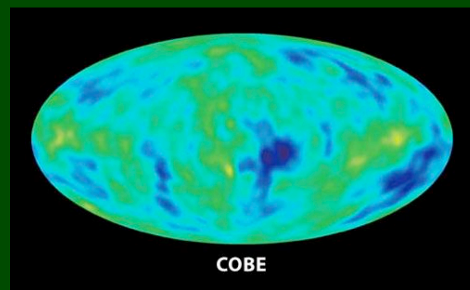
Dark matter

Dark energy

Observations have driven many key theoretical developments



An expanding universe



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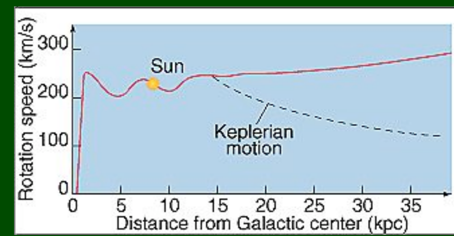


Galaxy outer rotation velocities

An accelerating universe

Hot Big Bang

Inflation

Dark matter

Dark energy

Solutions create many unanswered questions in themselves!

What are the implications for quantum (Planck) scale physics?

What causes inflation?

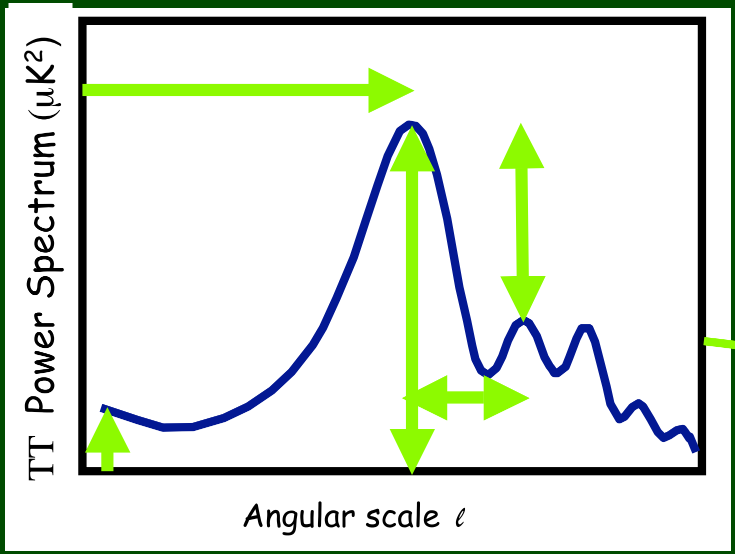
What is dark matter?

Can we find the dark matter in ground based experiments?

What is dark energy?

Are current and inflationary era expansion related?

CMB peaks, troughs and plateaus constrain cosmology

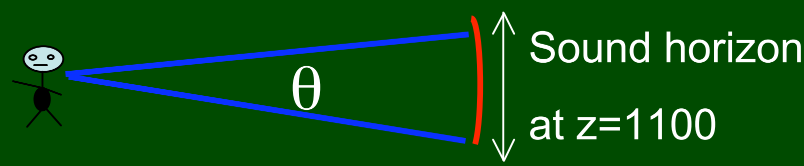


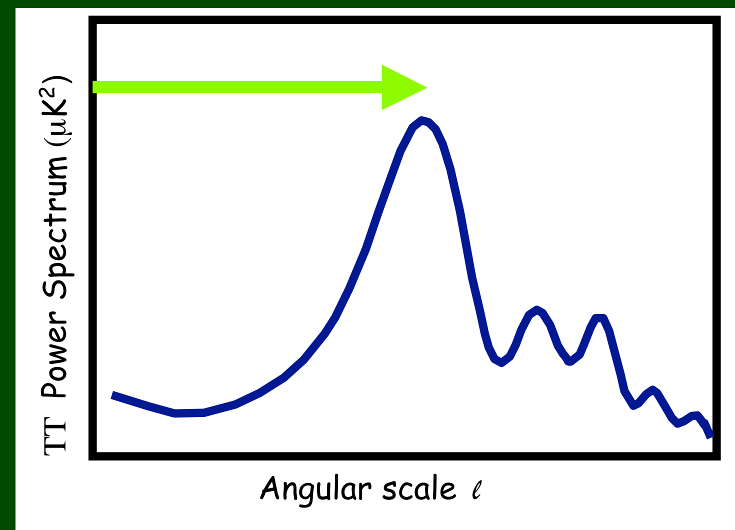
CMB spectrum features are translated into core cosmological parameters

The expansion history:	Hubble expansion factor H_0, $H(z)$
The matter content curvature :	fractional energy densities ($\Omega_X=\rho_X/\rho_{total}$)
Primordial power spectrum :	$P(k) = A\ k^{n-1}$, tensor to scalar ratio r
Dark energy characteristics :	equation of state, w=density/pressure
Ionization history :	optical depth (τ), redshift of reionization(z_{rei})

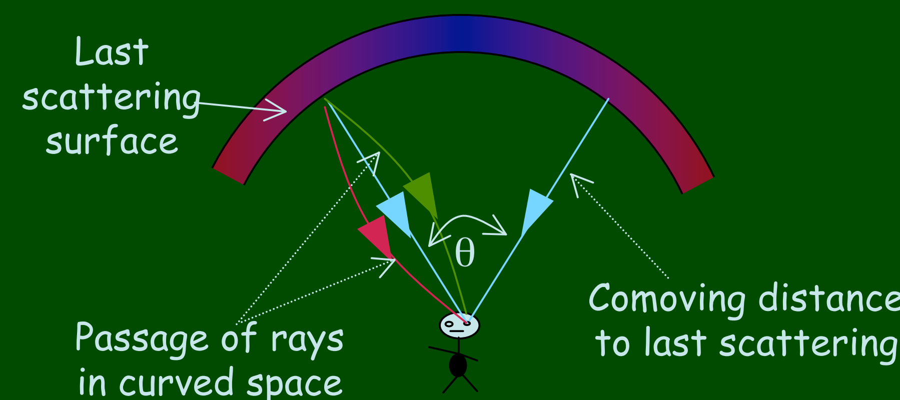
First peak position key constraint on the matter contents of the universe

- E.g. CMB First peak position – angular diameter distance to last scattering

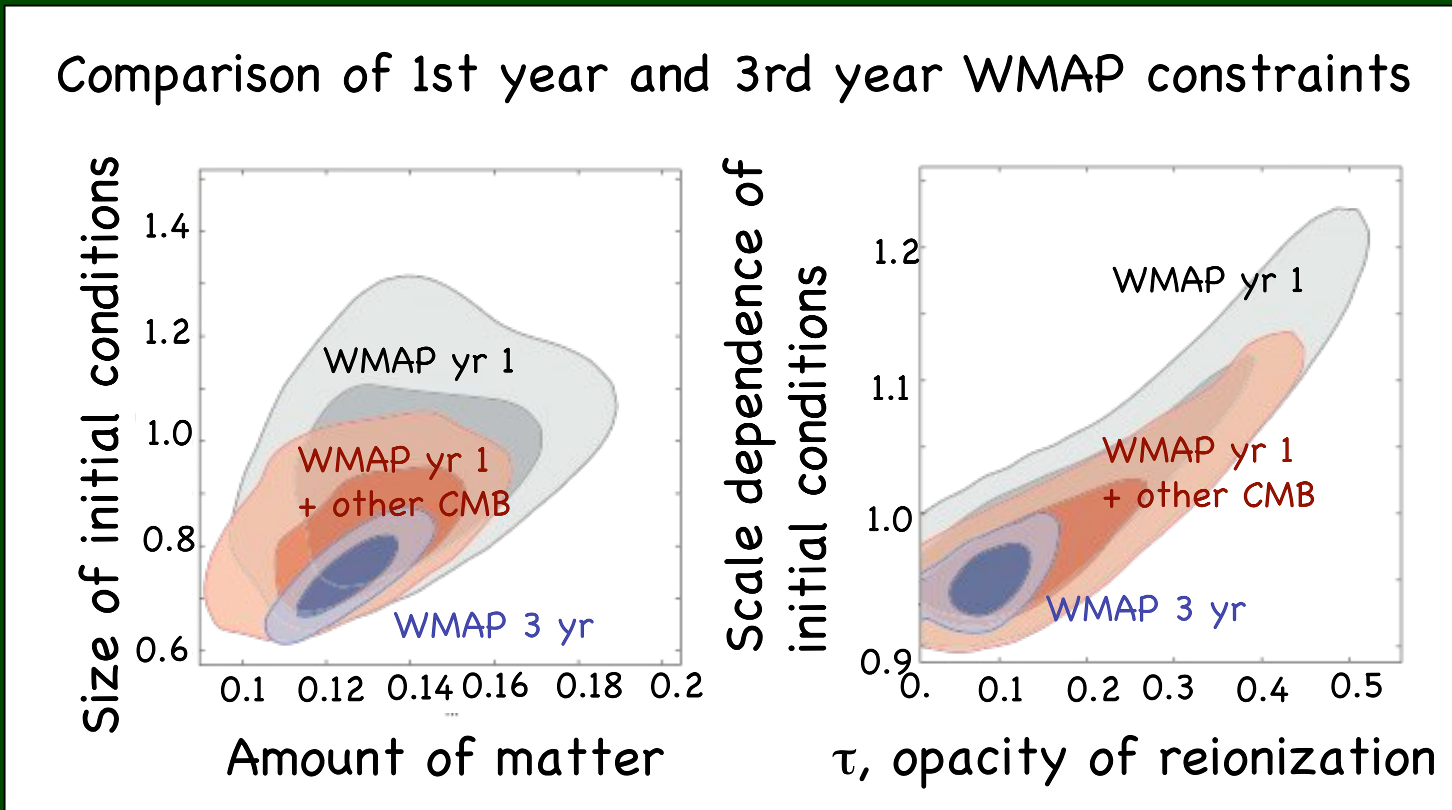




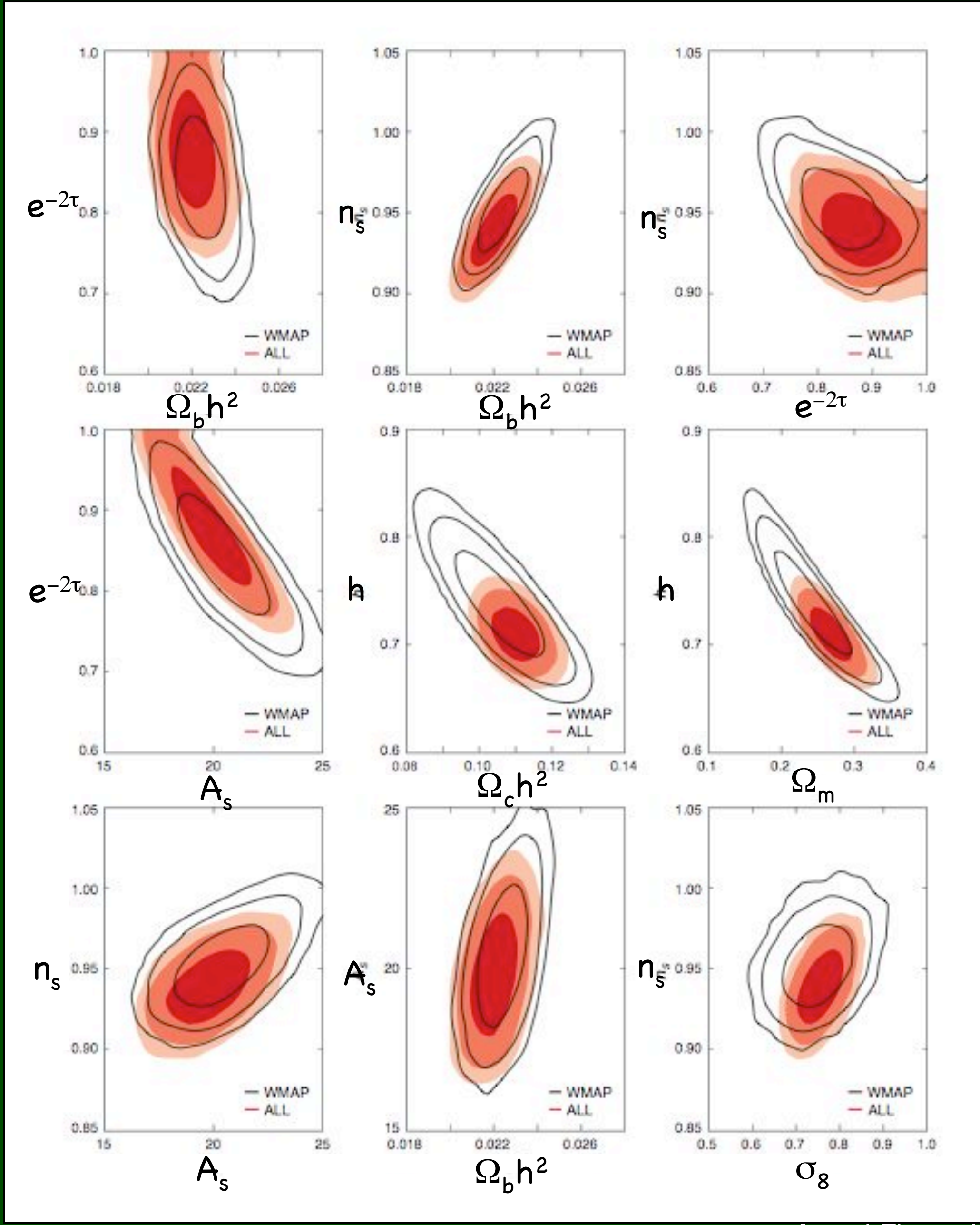
- Depends on matter content (expansion history)
- Depends on curvature
  - BUT Geometrical degeneracy
- Degeneracies BIG hurdle to get to theory
  - Polarization data helps break these!g



Improvement in Parameters from polarization measurement of reionization (τ)



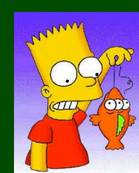
Improvement from additional complementary datasets

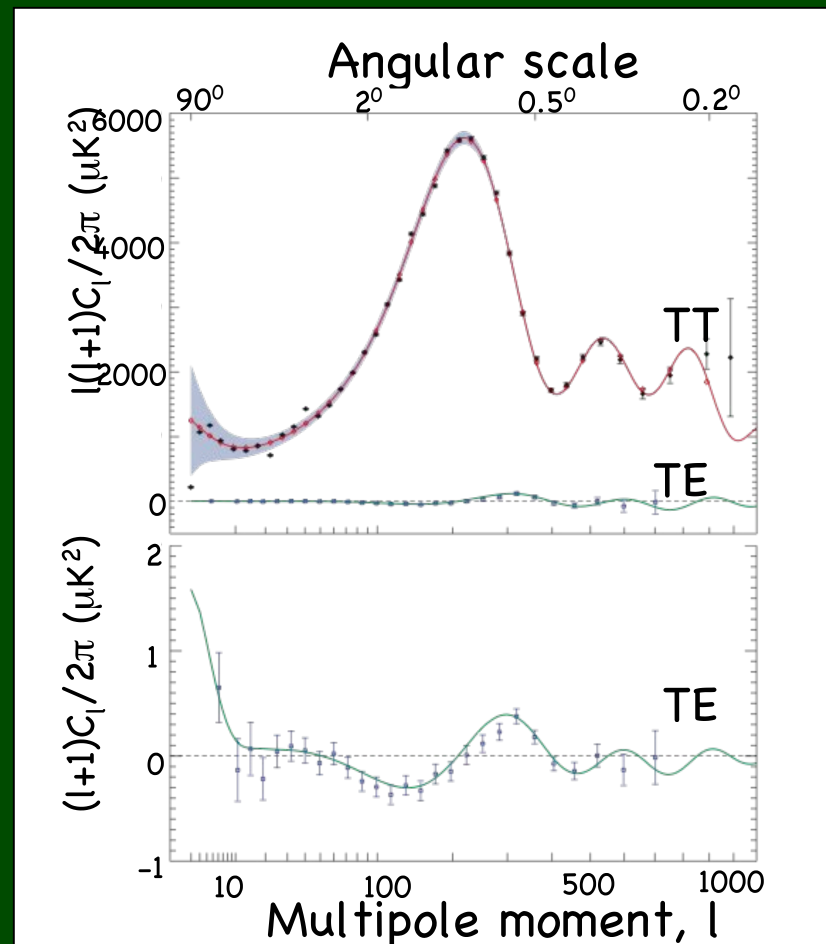


The simple 6 parameter cosmological model

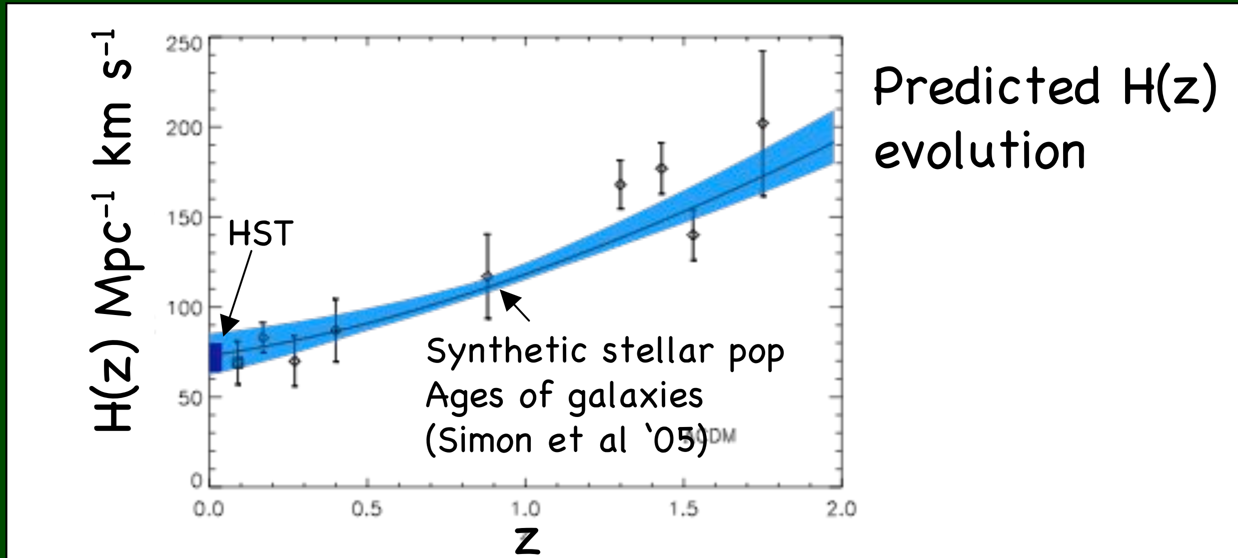
$\{\Omega_b h^2,\ \Omega_m h^2,\ h,\ \tau,\ n_s,\ A_s\}$: $\chi^2/\mathrm{dof} = 1.04$

- Run model forward in time
  - predict cosmological evolution
- Go backwards in time
  - to study early universe
- Constrain variants on simplest model
  - massive neutrinos
  - Dark energy models
  - Beyond power law inflation

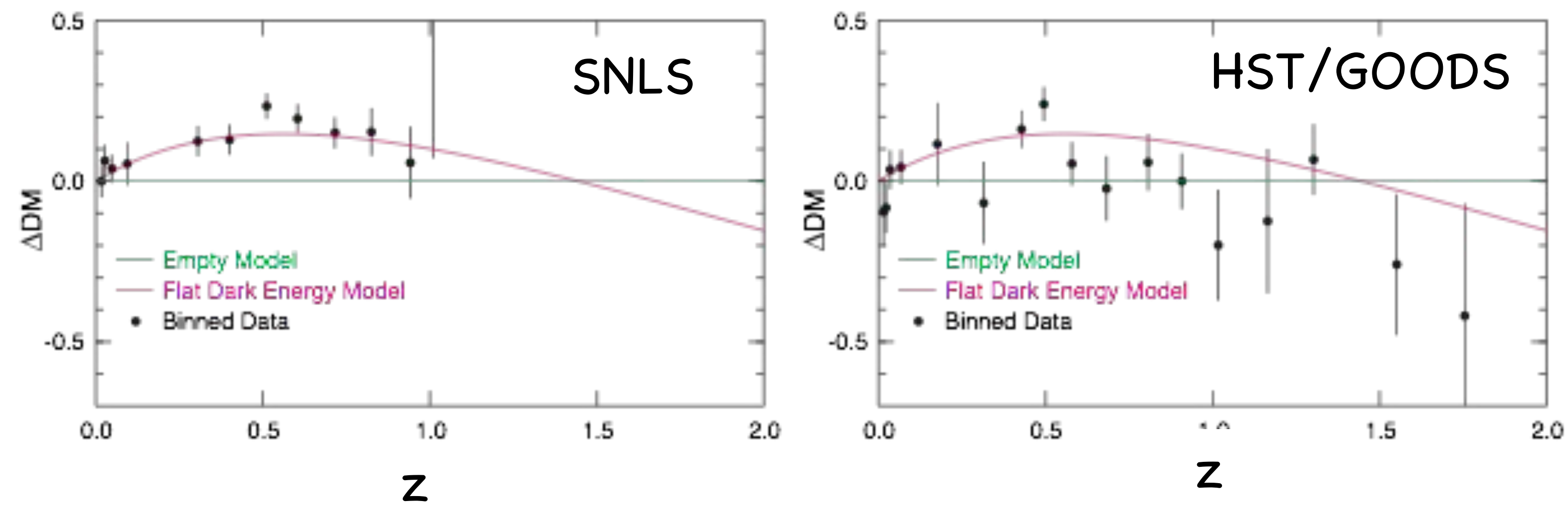




WMAP fits predict Hubble expansion H(z)

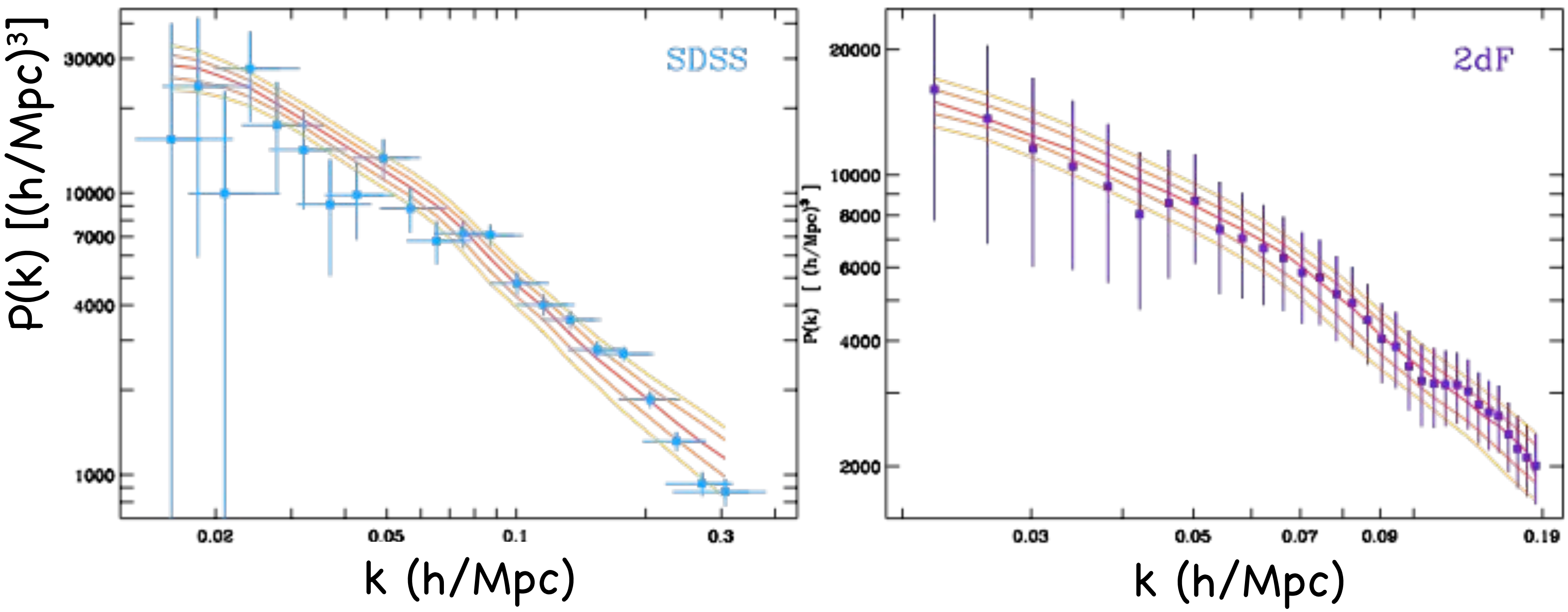


Luminosity distance prediction from WMAP alone



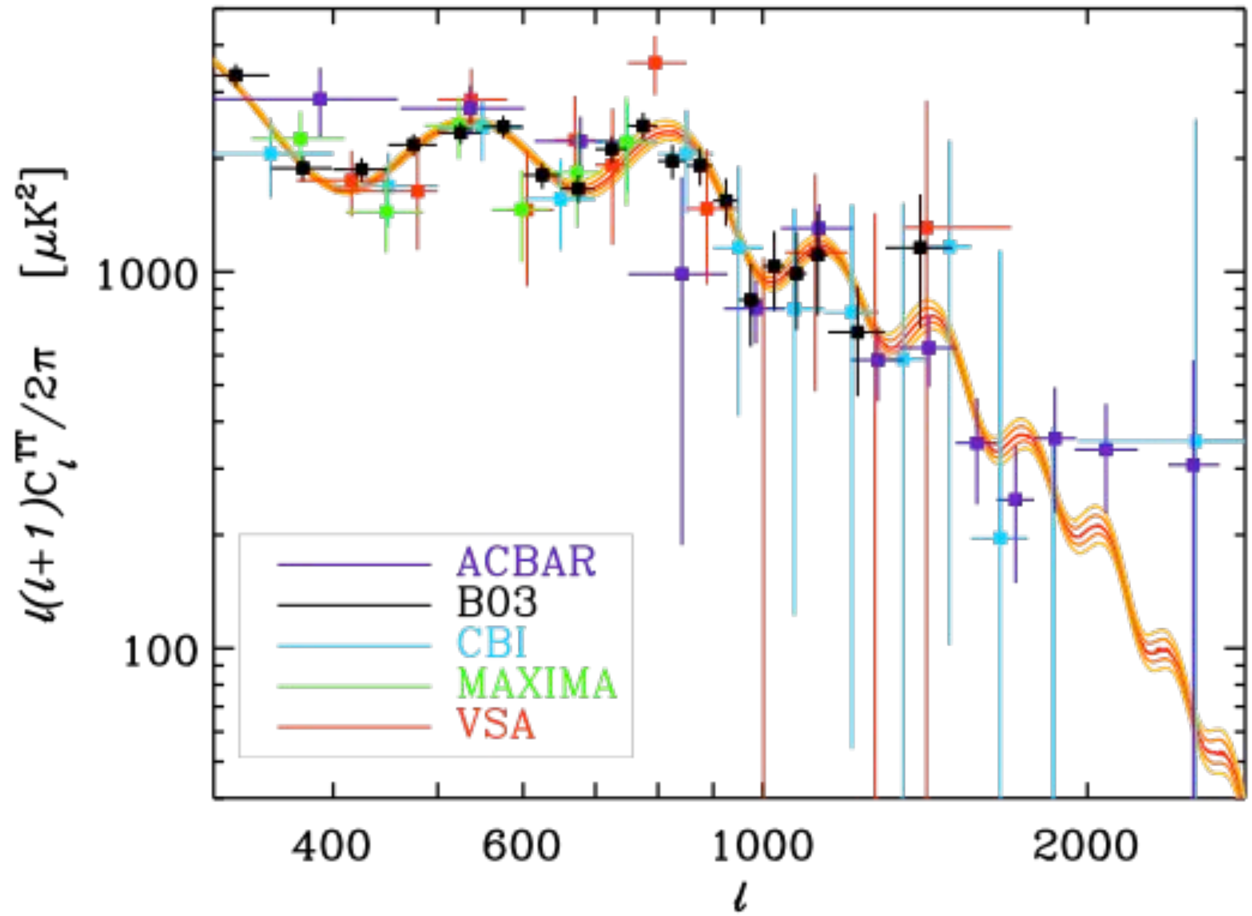
WMAP fits predict galaxy & mass distribution

Predicted P(k) for SDSS and 2dF galaxy surveys from WMAP alone



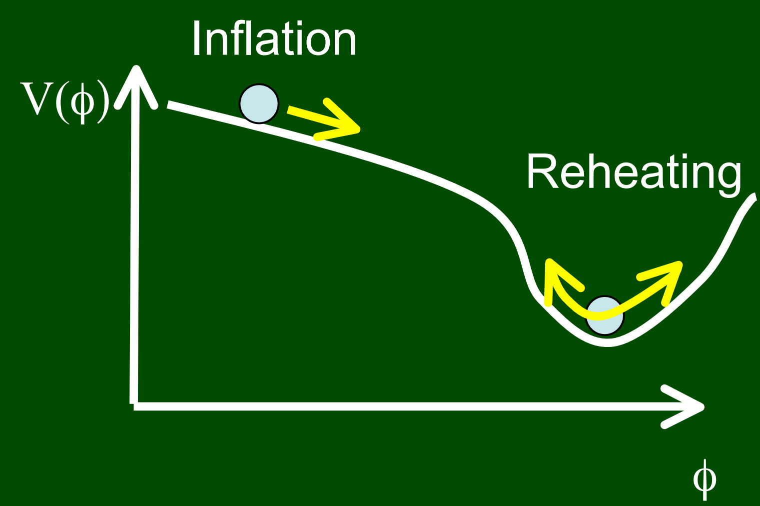
WMAP fits predict small scale CMB

Predicted small scale CMB spectrum from WMAP alone



Constraints on VERY early universe

- \`Inflation'
  - early period of accelerated expansion, just after the Big Bang
- Acceleration induced by slow roll of particle ϕ down a potential well $V(\phi)$
- Predicts …
  - No preferred scale $P(k) \sim k^{(n-1)}$ with $n-1 \sim 0$
  - Small tensor contribution $r=T/S$
  - Entropy conserving (adiabatic) fluctuations
- Acceleration causes Hubble horizon decrease
  - Stretches space -> spatial Flatness
  - Density fluctuations random (Gaussian)

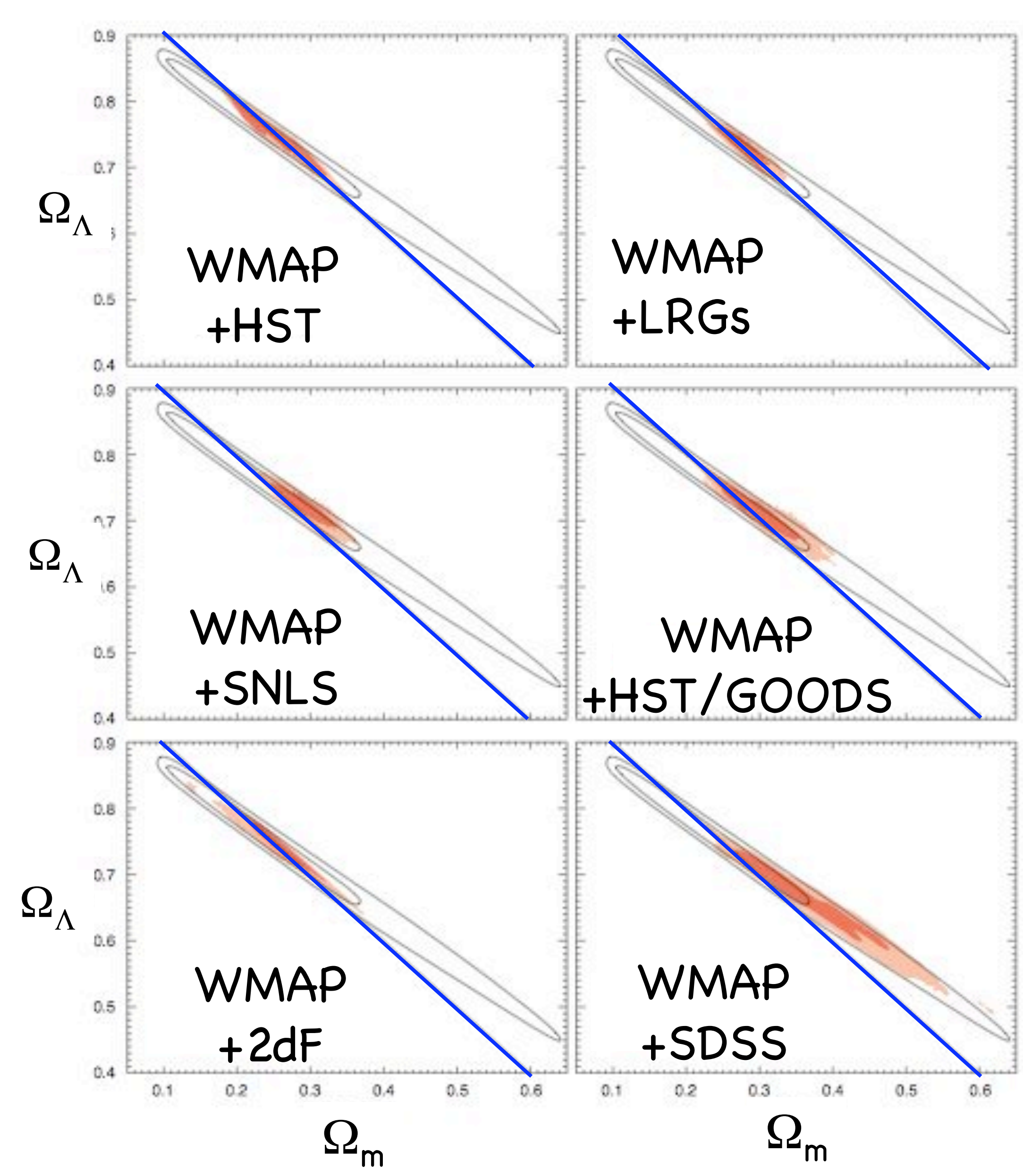


Constraints on geometry of the universe

CMB needs dark matter:
- alternative 10^{-54} less likely!

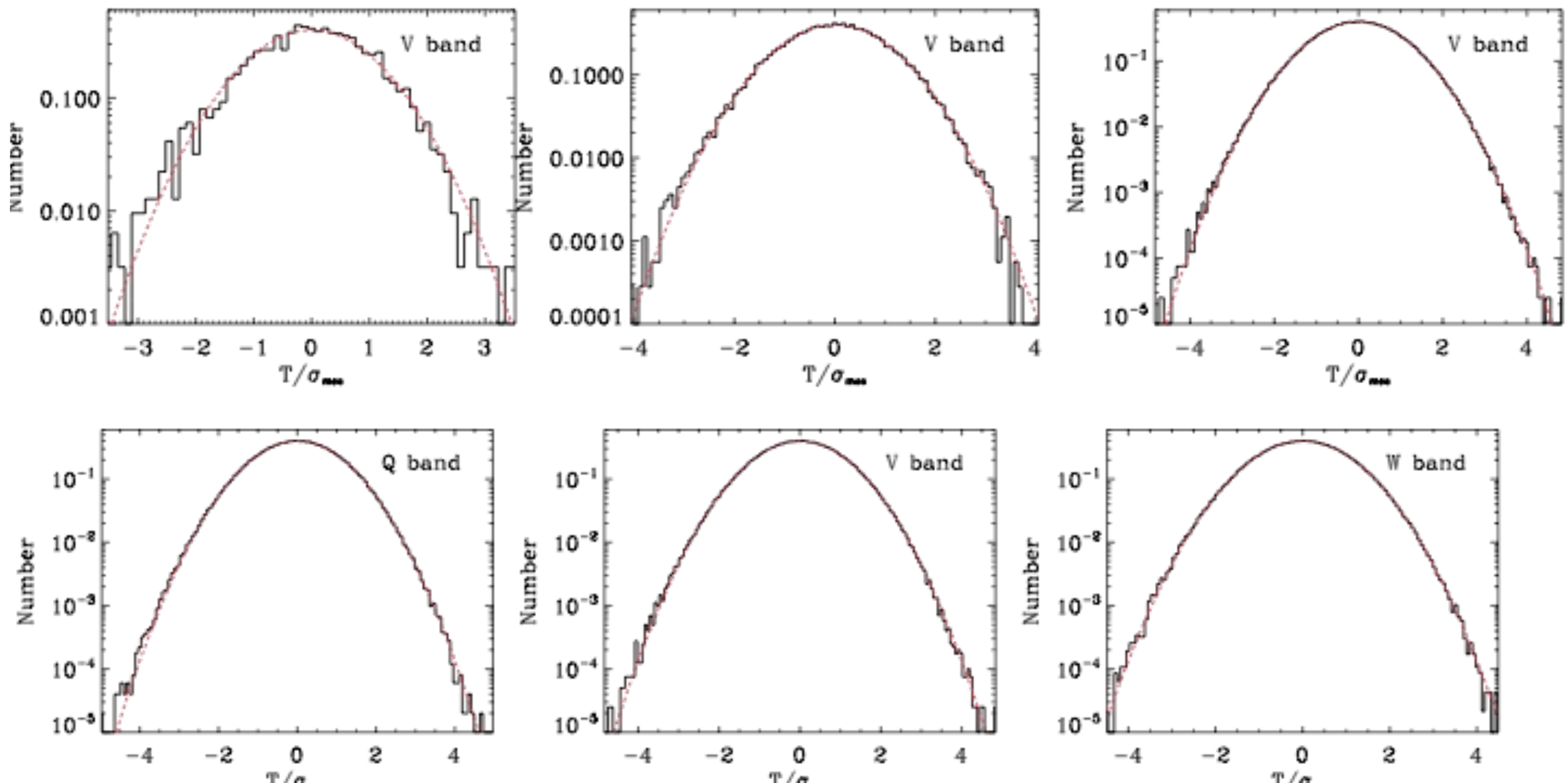
CMB doesn't need dark energy:
- Λ = 0 equally likely *but*
- Λ = 0 needs low expansion rate
(inconsistent with other observations)

WMAP+ other observations:
- Entirely consistent with flatness



Constraints on initial conditions: Gaussianity

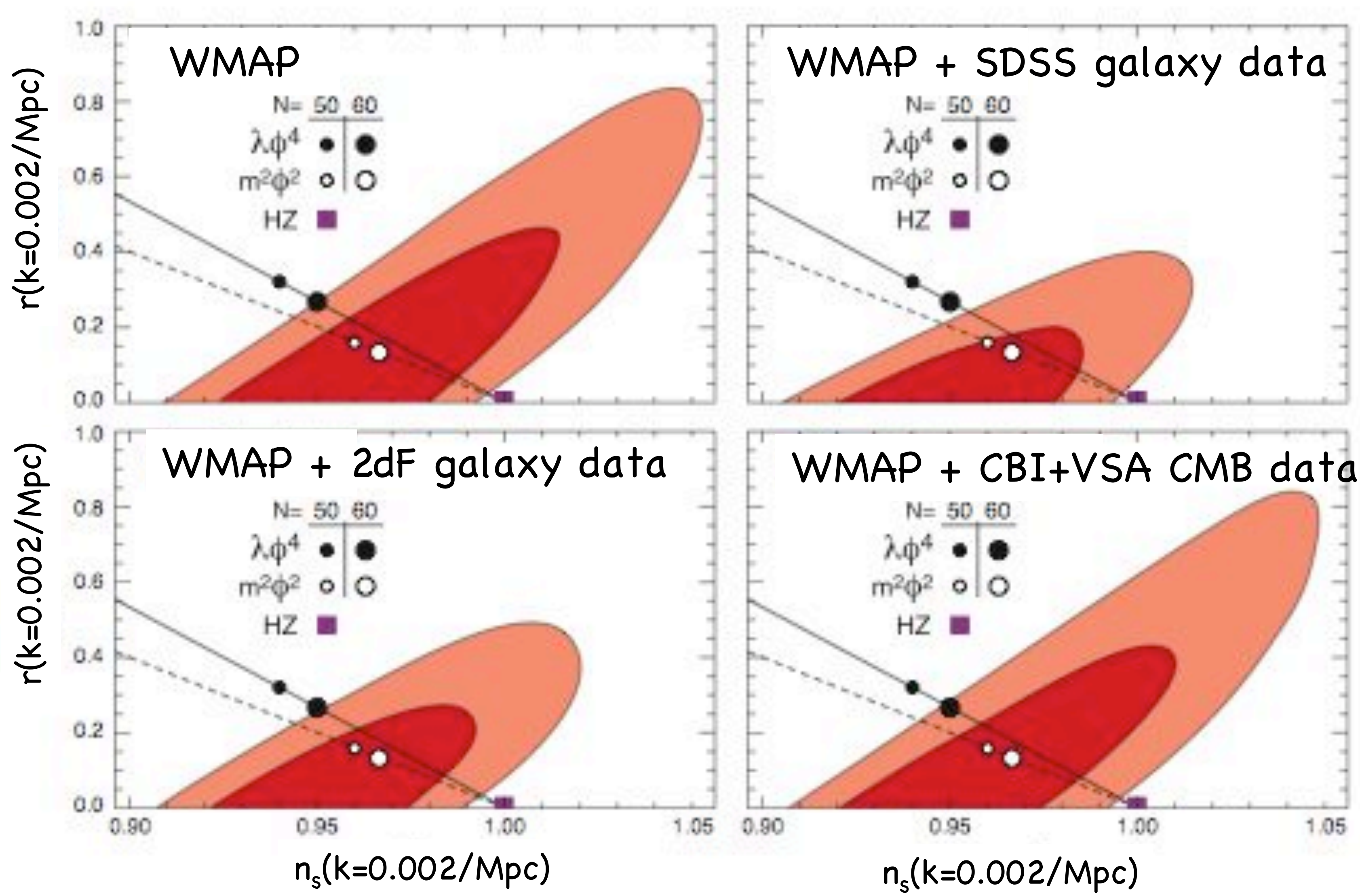
distribution of dT/T on the sky
(Npix = 3072, 12288, 786432)



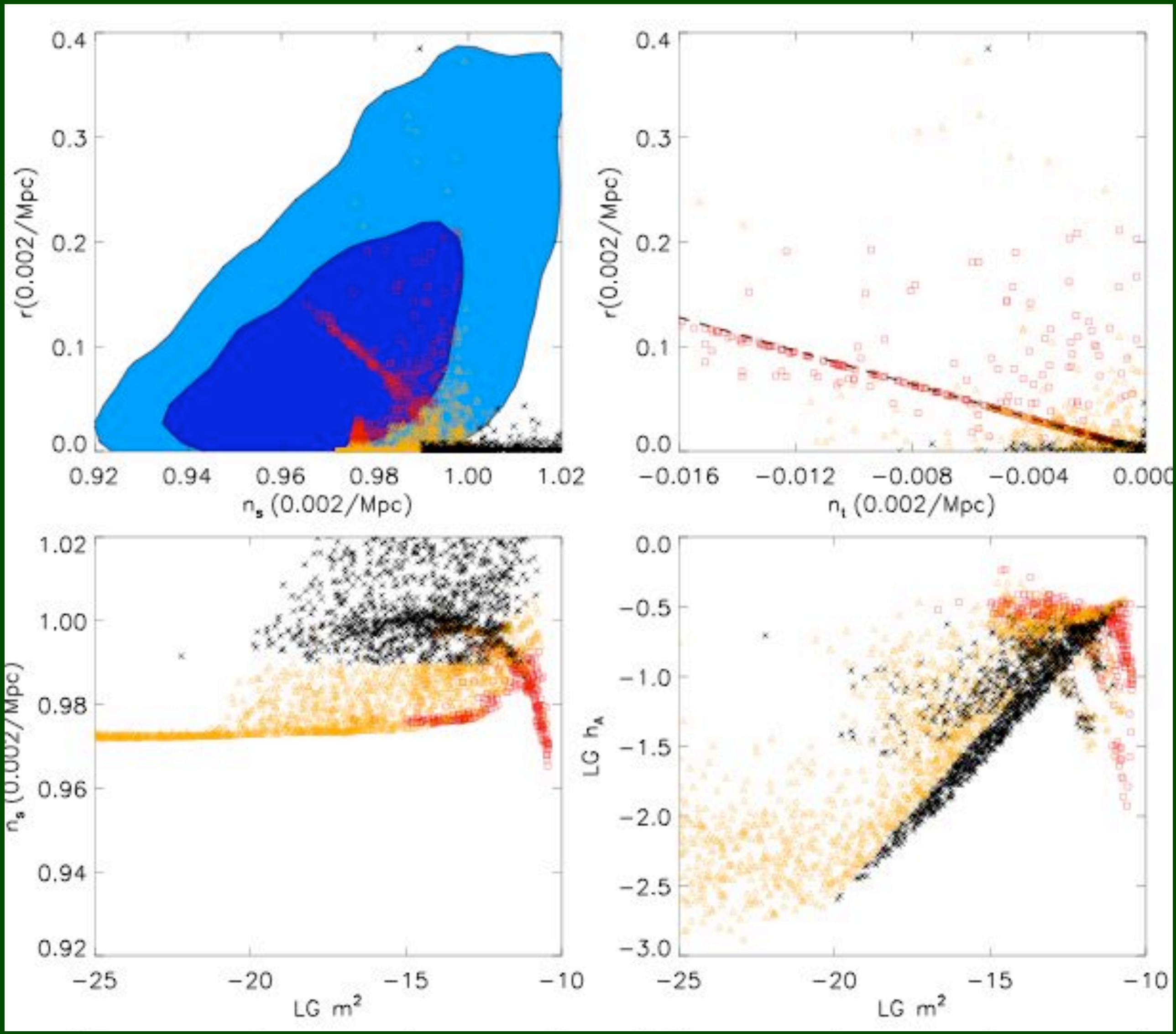
Still some interesting large scale correlations...

Constraints on initial conditions: power spectrum

Constraints on power law initial $P(k) \propto k^{n-1}$ + tensors, $r = A_T/A_S$



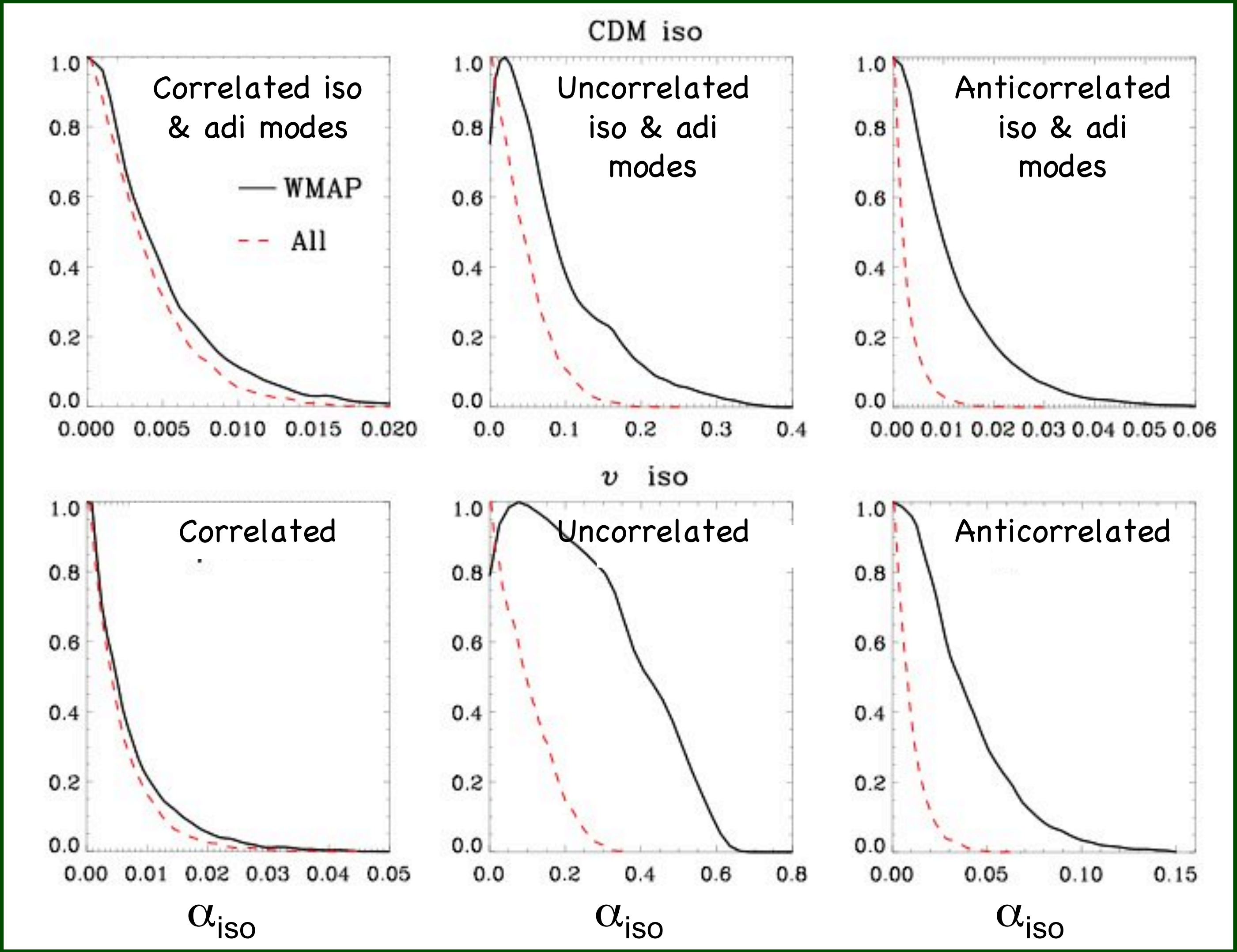
Constraints on initial conditions: slow roll inflation?



RB, Shandera, Tye, Xu (in prep)

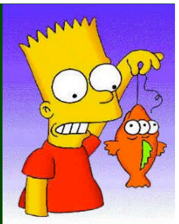
Constraints on initial conditions: adiabaticity

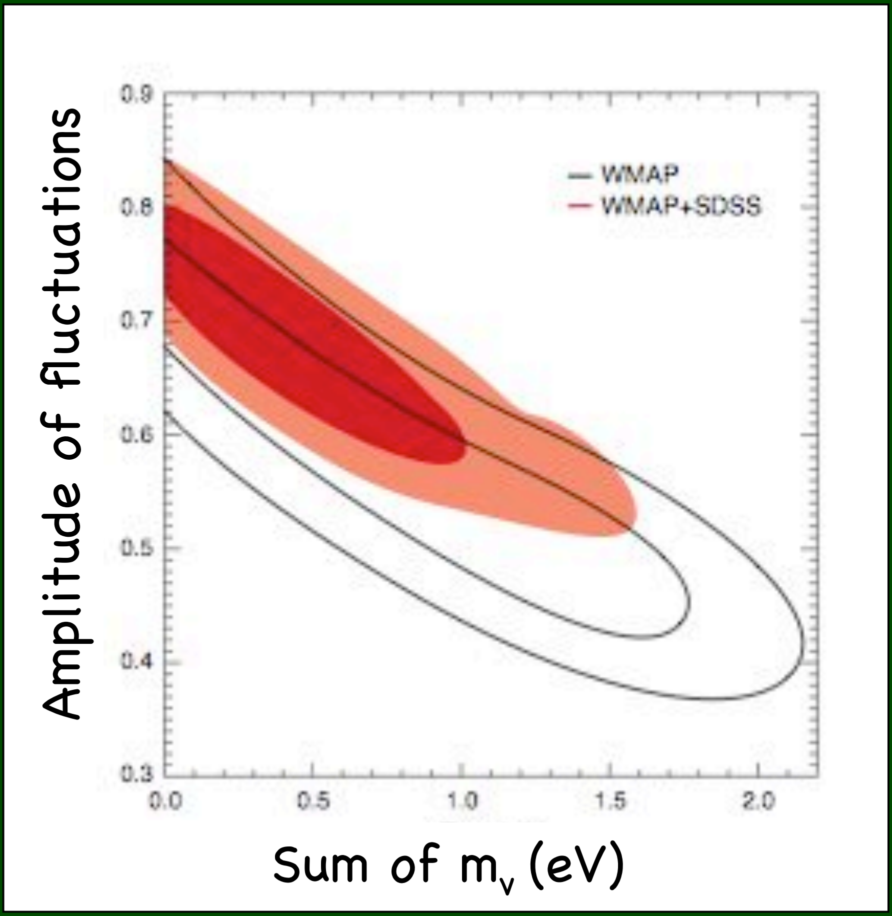
- No need for isocurvature perturbations



RB, Dunkley, Pierpaoli PRD 2006

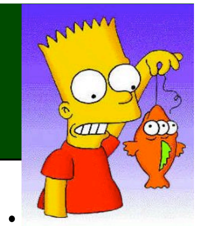
Beyond ΛCDM: Neutrino masses



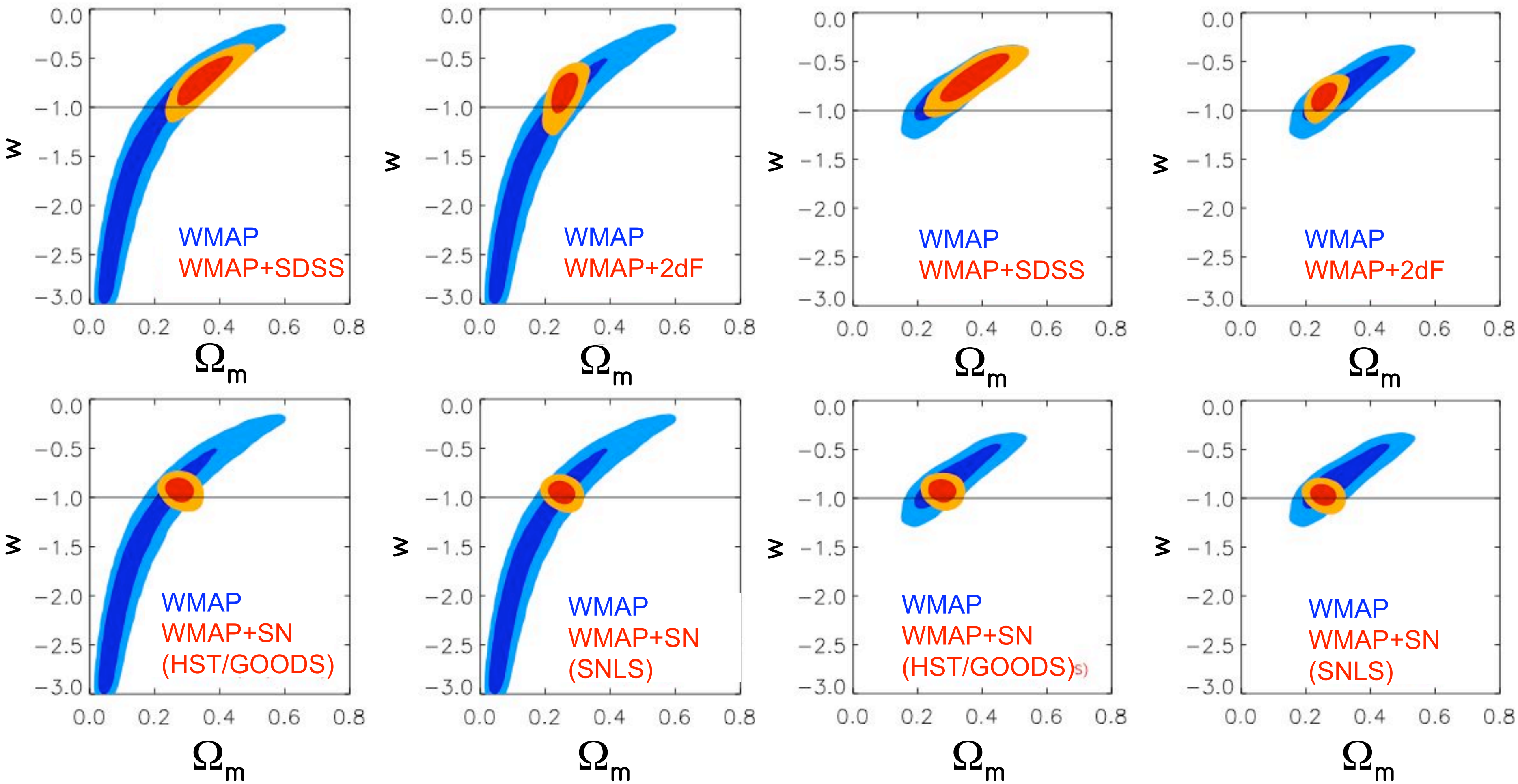


	Σm_ν (eV) 95% CL
WMAP only	1.8
WMAP+SDSS	1.3
WMAP+2dF	0.88
CMB +LSS + SN	0.66

Beyond ΛCDM: Dark Energy

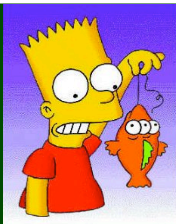


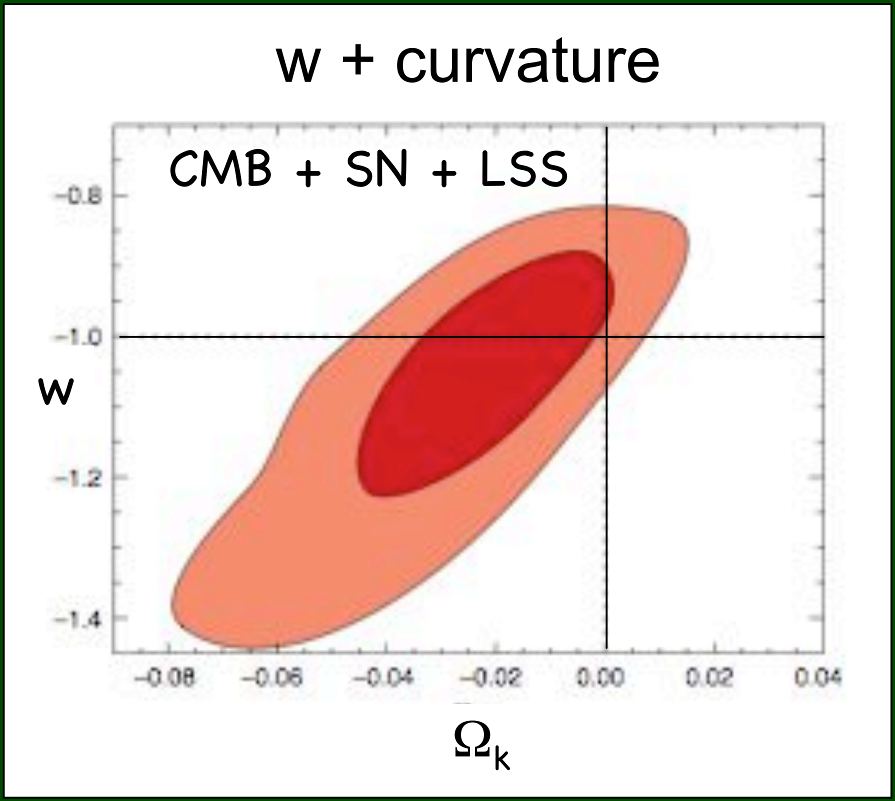
Clustering dark energy $c_s^2=1$ $w\neq-1$ | If fluctuations in DE negligible

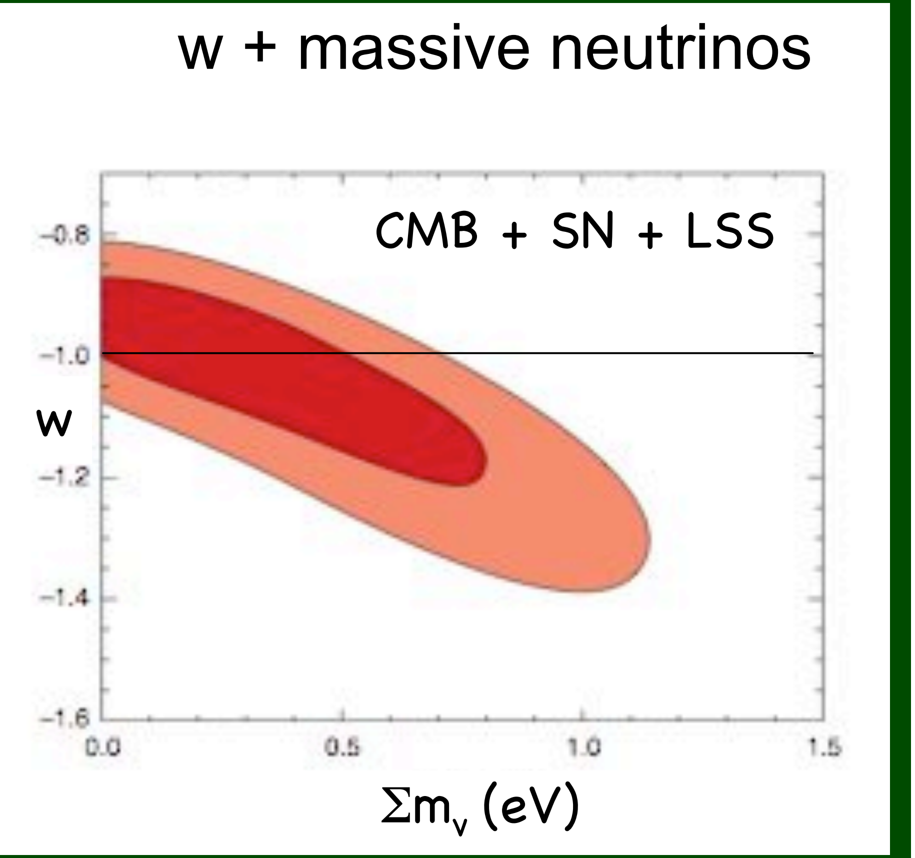


Sensitive to assumptions about clustering properties of Dark Energy

Beyond ΛCDM: Dark Energy Robust?

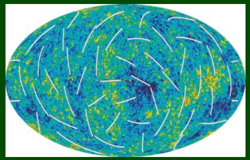






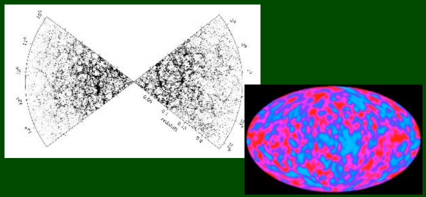
Conclusions

- WMAP now has full sky temperature and polarization maps



- Polarization maps important development for cosmology
  - Simple ΛCDM model survived its most rigorous test
  - Simplest inflationary models favored

- WMAP is a rich resource
  - combining/ correlating WMAP with complementary data
  - Foreground polarization templates for future surveys



- Future CMB from WMAP, and beyond, vital
  - Tensor modes: direct signature of inflation?
  - Role in investigations into dark matter/dark energy