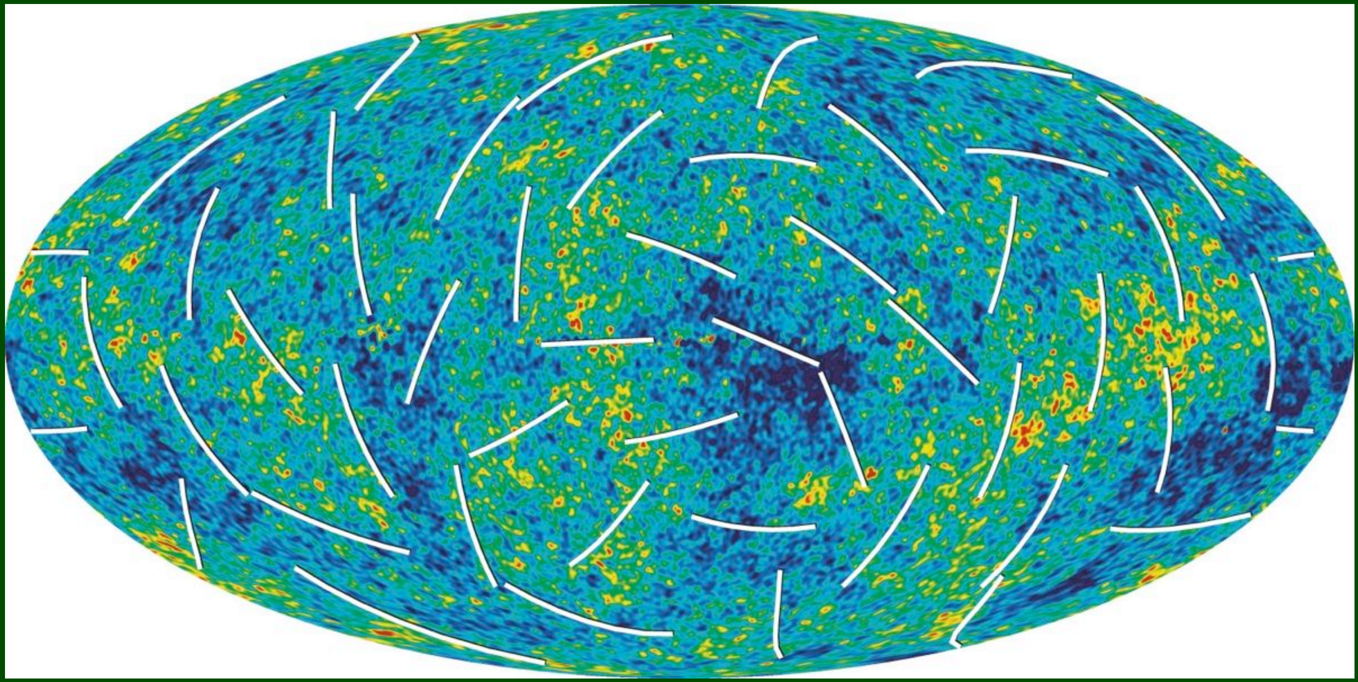
The WMAP results and cosmology



Rachel Bean
Cornell University

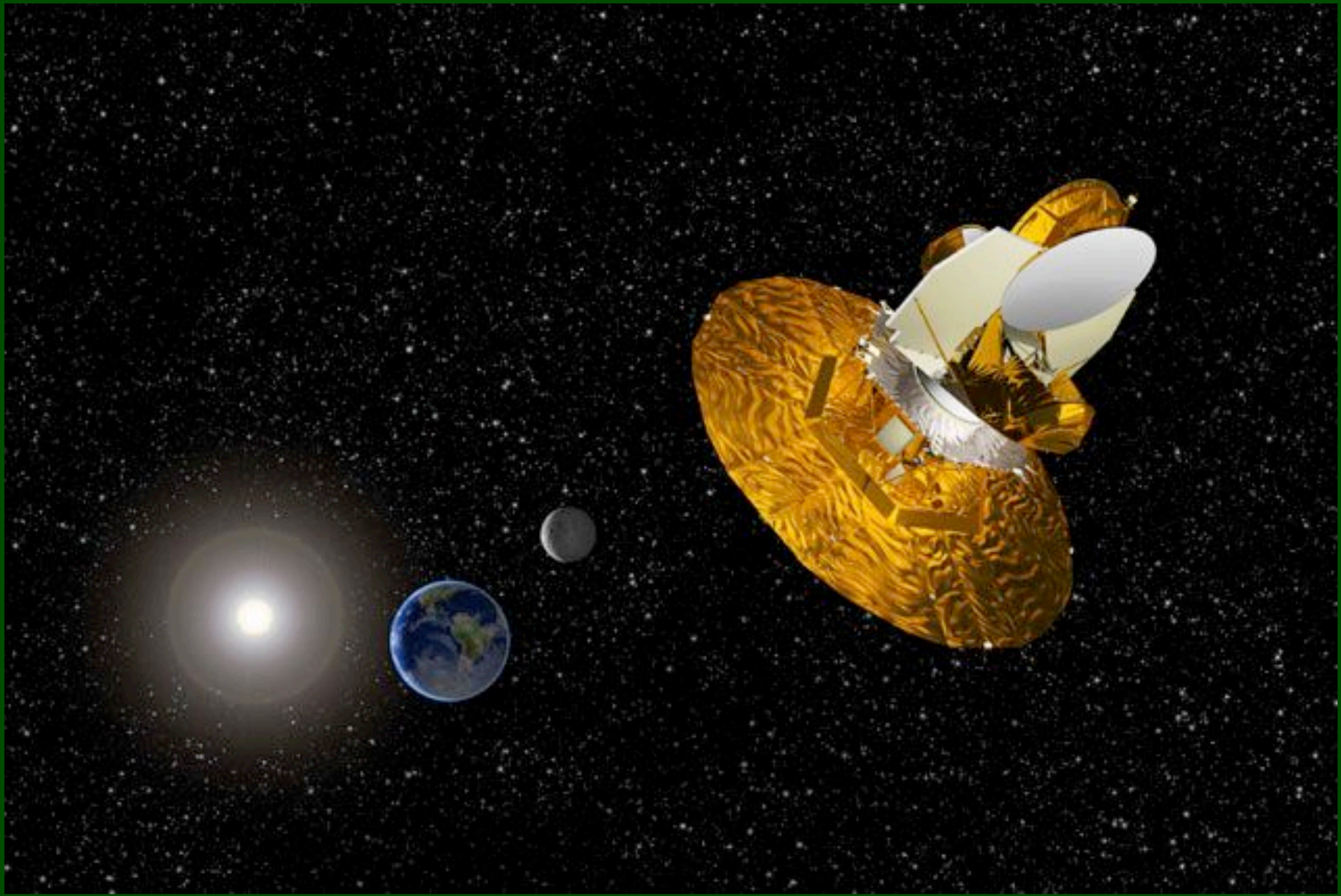
SLAC Summer Institute July 19th 2006

Plan

- Overview
- Introduction to CMB temperature and polarization
- The maps and spectra
- Cosmological implications

What is WMAP?

- Satellite detecting primordial photons "cosmic microwave background"



Science Team

C. Barnes (Princeton)
R. Bean (Cornell)
C. Bennett (JHU)
O. Dore (CITA)
M. Halpern (UBC)
R. Hill (GSFC)
G. Hinshaw (GSFC)
N. Jarosik (Princeton)
A. Kogut (GSFC)
E. Komatsu (Texas)
M. Limon (GSFC)
S. Meyer (Chicago)
H. Peiris (Chicago)
M. Nolta (CITA)
N. Odegard (GSFC)
L. Page (Princeton)
D. Spergel (Princeton)
G. Tucker (Brown)
L. Verde (Penn)
J. Weiland (GSFC)
E. Wollack (GSFC)

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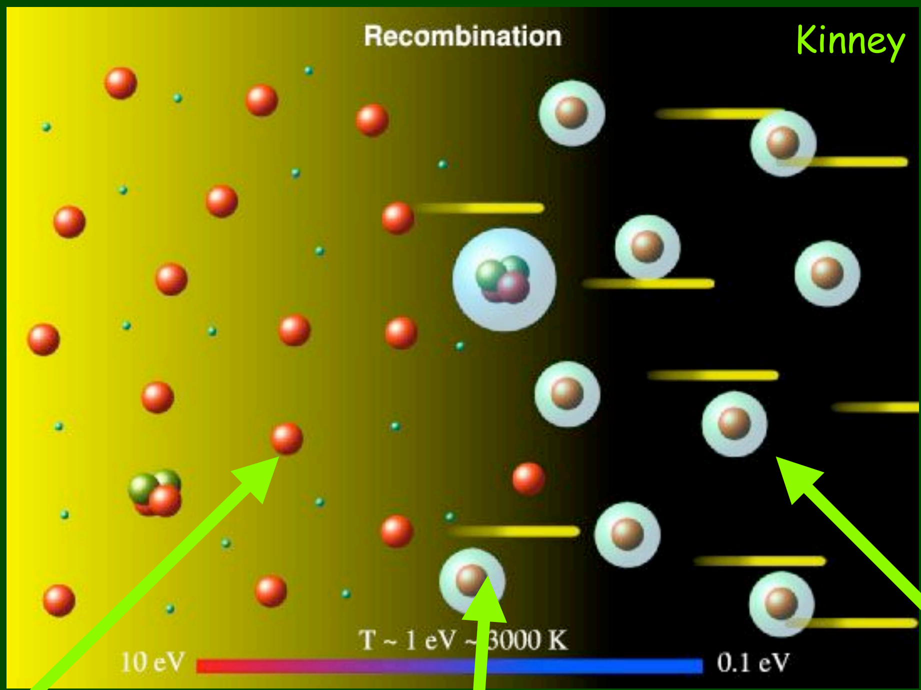
CMB is a near perfect primordial blackbody spectrum

Universe expanding and cooling over time…

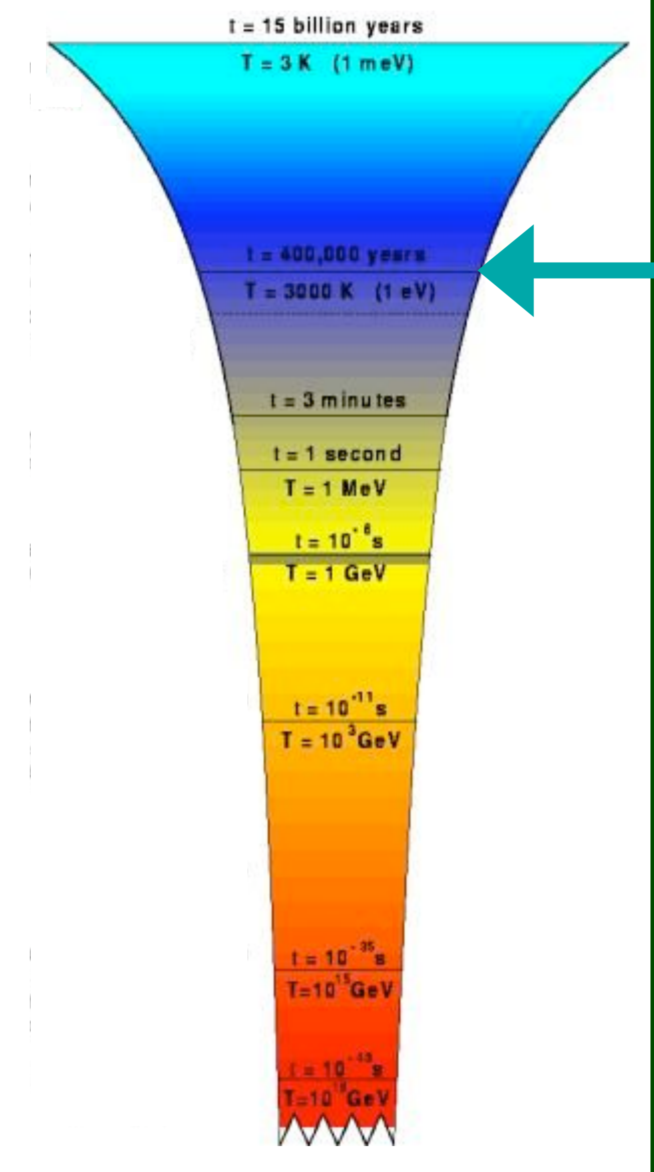


1) Optically opaque plasma
photons scattering off electrons

2) The 'last scattering' of photons
~300,000 years after the Big Bang, neutral atoms form and photons stop interacting with them.

3) 'Free Streaming' CMB
Thermalized (blackbody) photons at ~6000K diluted and redshifted by universe's expansion -> ~2.726K background we measure today.

The oldest fossil from the early universe



Recombination

CMB

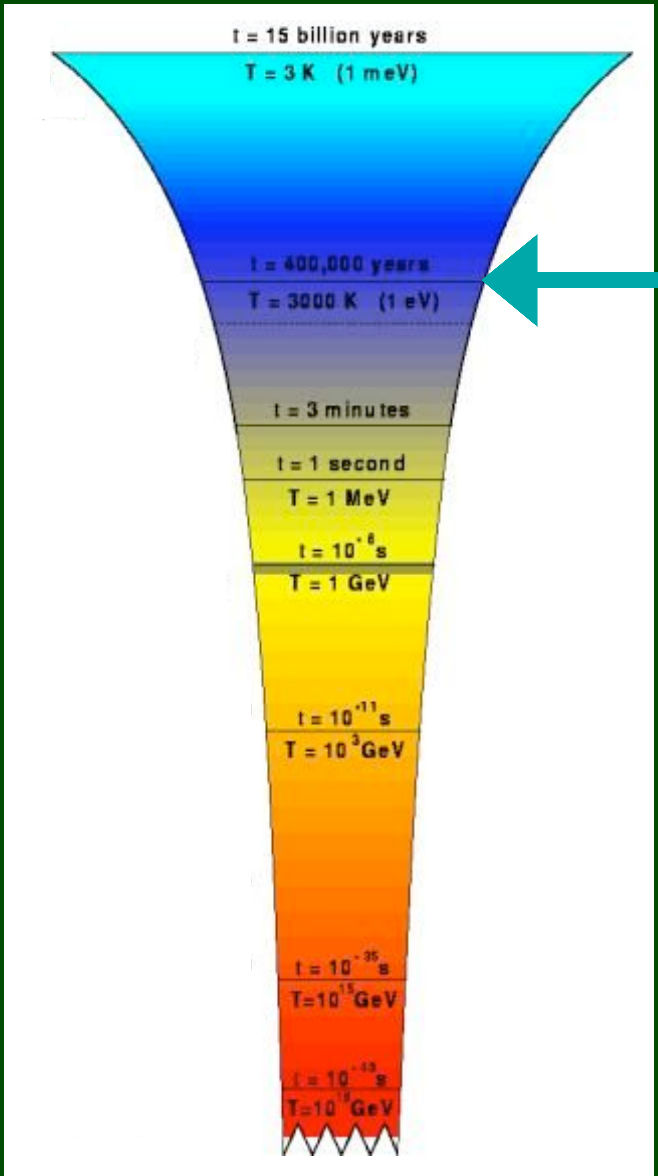
Nucleosynthesis

Processes during opaque era imprint in CMB fluctuations

Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects….

The cosmic equivalent of tree rings…



Dark Energy domination

Reionization

Galaxy formation

Recombination

Nucleosynthesis

Inflation and Grand Unification?

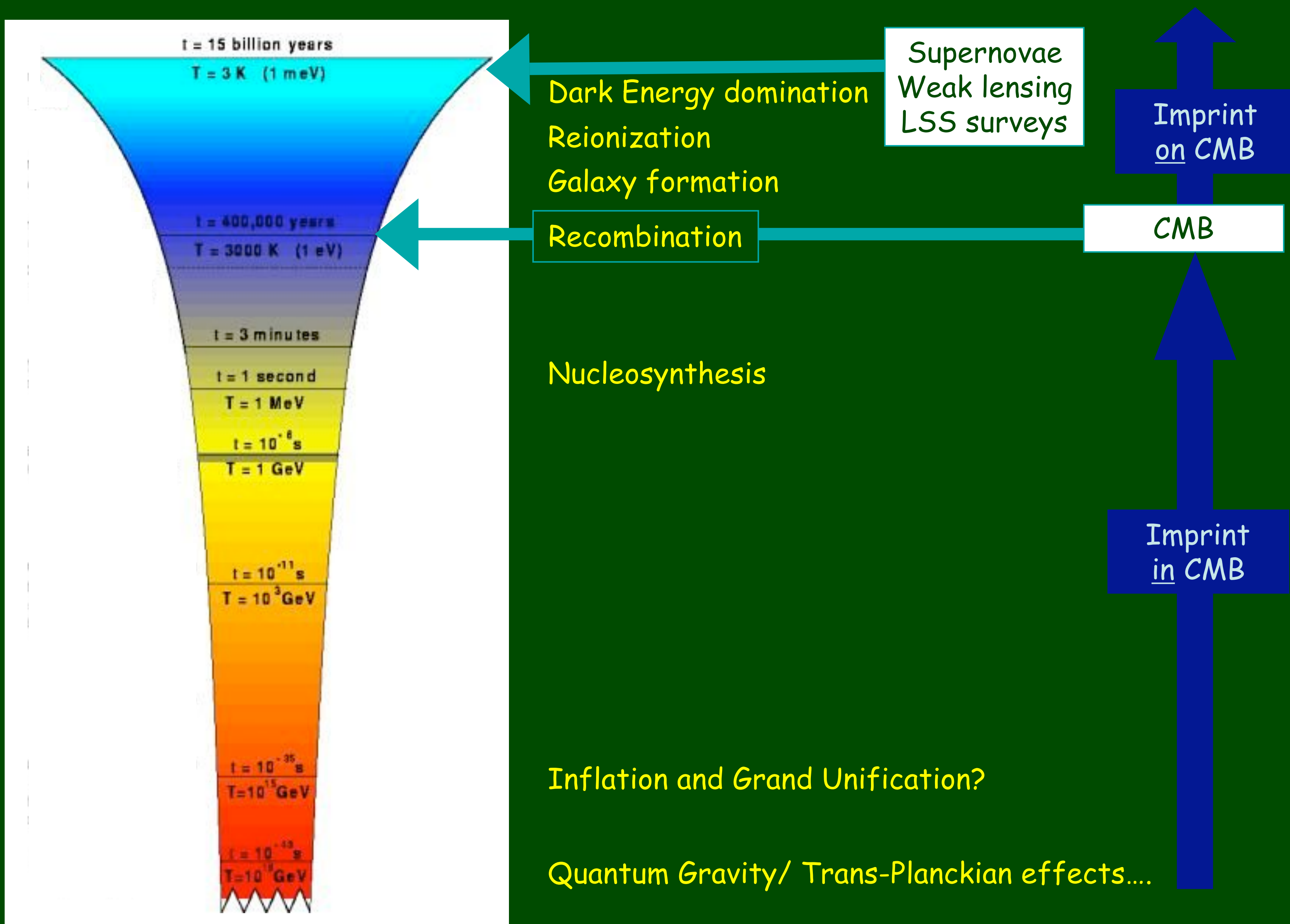
Quantum Gravity/ Trans-Planckian effects….

Processes following recombination imprint on CMB

CMB

Imprint in CMB

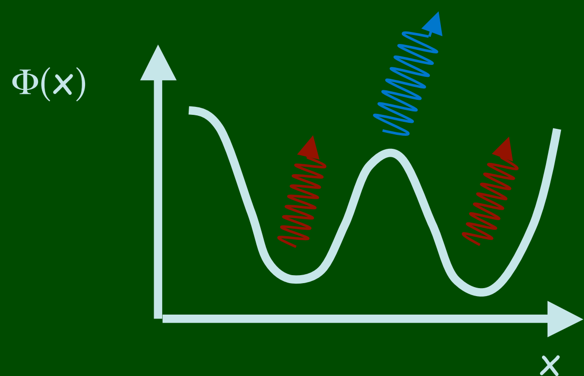
Important comparisons with later observations



Imperfections in the CMB are what we are really interested in

- Escape of photons from evolving gravitational potential wells at last scattering,

Cold spots = high density
Hot spots = low density



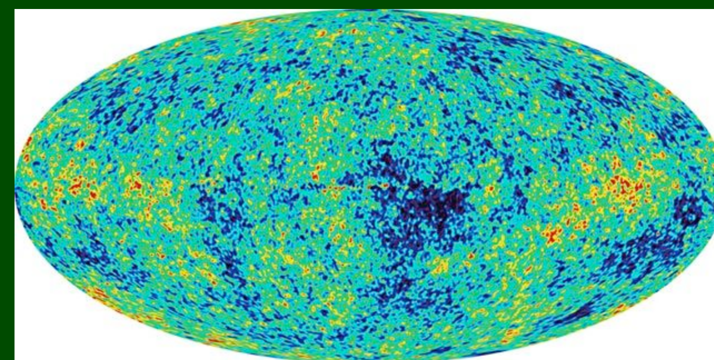
- Thomson Scattering interactions in photon-electron/baryon fluid

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

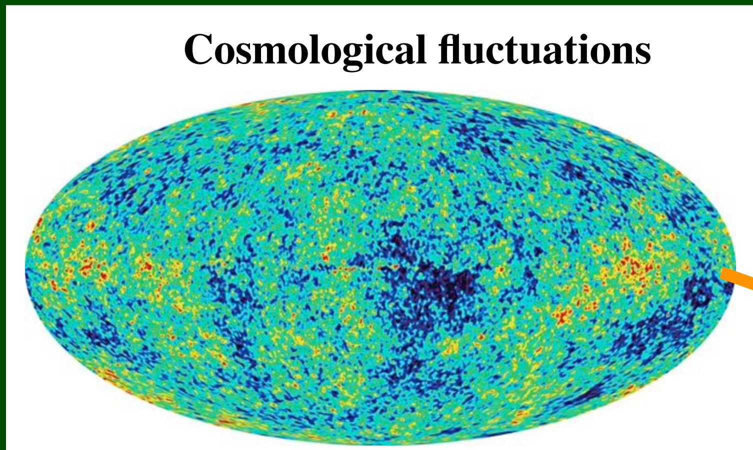
  $\gamma \longleftrightarrow e^- \longleftrightarrow p^+$

  Compton scattering — Coulomb interaction

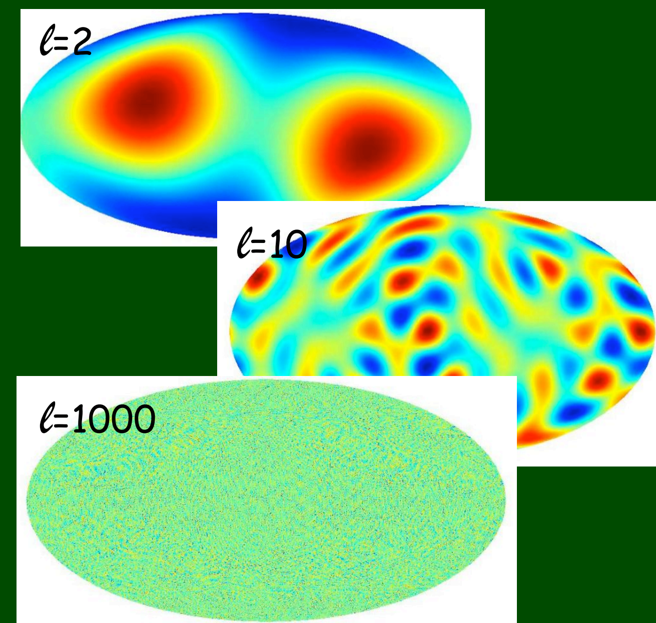
- …Translate into fluctuations in the blackbody photon temp at ~1/100,000 level

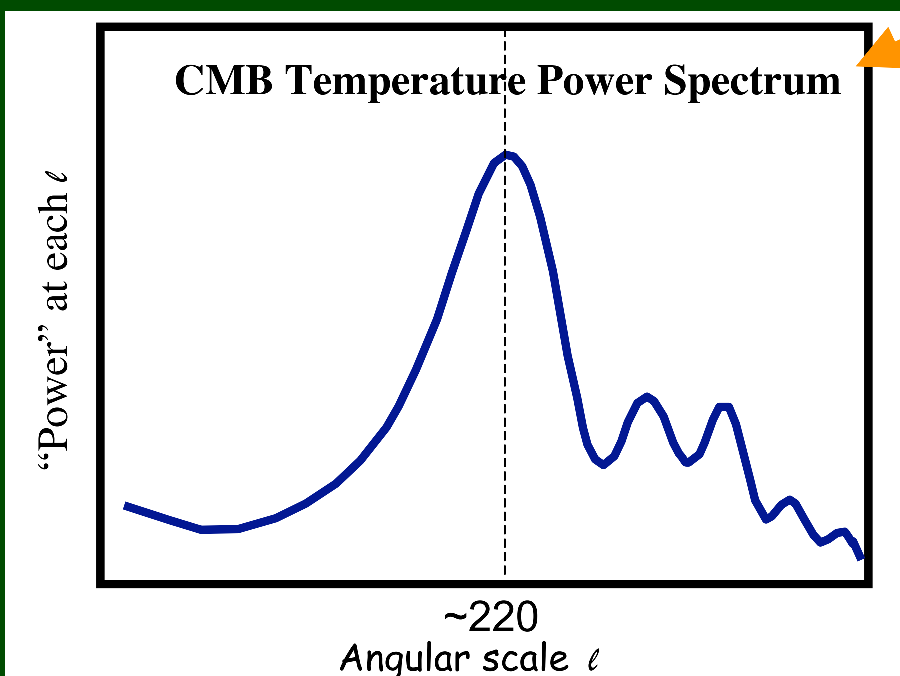


CMB "Power Spectrum"



- Decompose map into functions with fluctuations on different angular scales (denoted by ℓ)





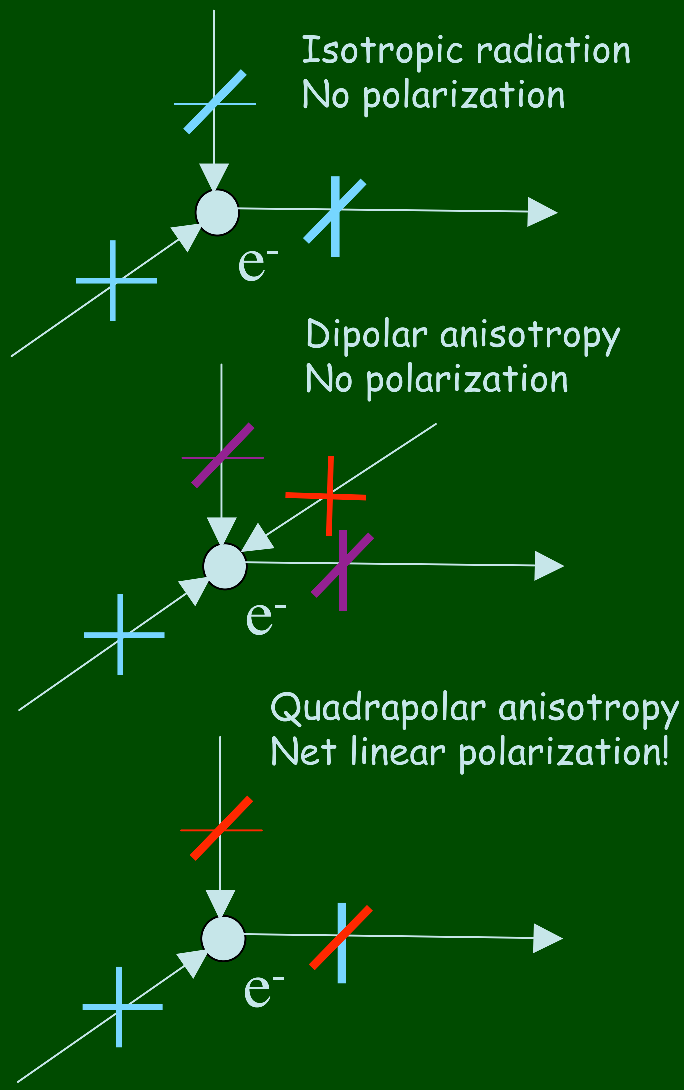
- Plot a graph of the weight (importance) each function has in the map
  - "the Power spectrum"

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

- Polarization created by Thomson scattering of photons with a non-zero quadrupole (l=2 spherical harmonic)

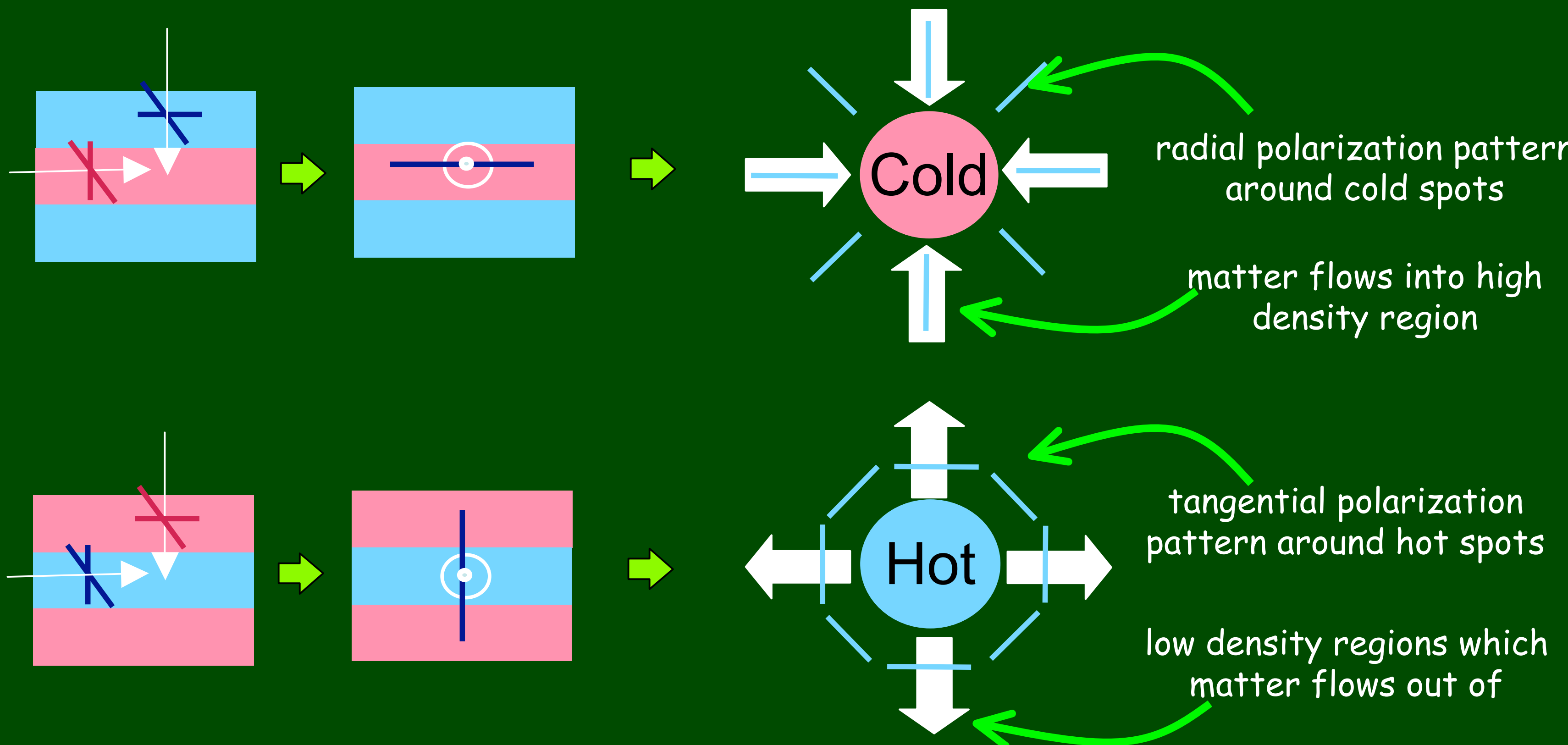
- Polarization gives a purer imprint of early universe than temperature
  - Once electrons in atoms scattering processes stop

- Polarization on scales below horizon scale at scattering
  - small scale polarization at recombination z~1088
  - Larger scale from reionization by the first stars z~25



Based on Wayne Hu's figures

Temperature & polarization patterns correlated



- Polarization pattern <-> velocity flow of matter from high to low density
  - Predicts polarization should π out of phase with temperature

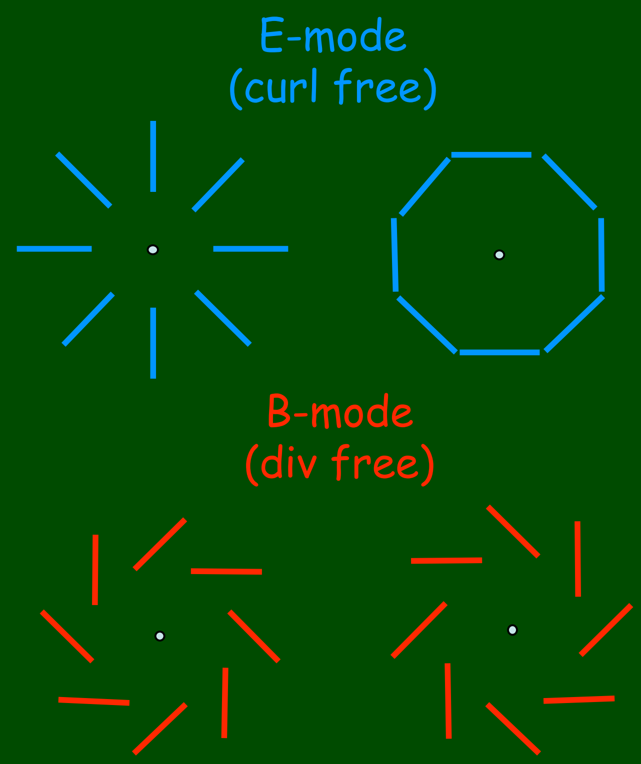
CMB Polarization: Alternative descriptions

- Polarization <=> Stokes Parameters (Q,U) or E/ B modes analogous to EM.
  - E/B independent of axis choice and nicely divides underlying processes

$$I_{ij} = \begin{pmatrix} T+Q & U \\ U & T-Q \end{pmatrix}$$

$$E(\hat{n}) = Q(\hat{n})cos(2\phi) + U sin(2\phi)$$
$$B(\hat{n}) = -Q(\hat{n})sin(2\phi) + U cos(2\phi)$$

- Scalar perturbations only generate EE
  - EE polarization <=> matter density & CMB temperature
- Only tensor perturbations can generate both EE and BB
  - BB insight into primordial gravity waves with little 'contamination' from scalar modes



Plan

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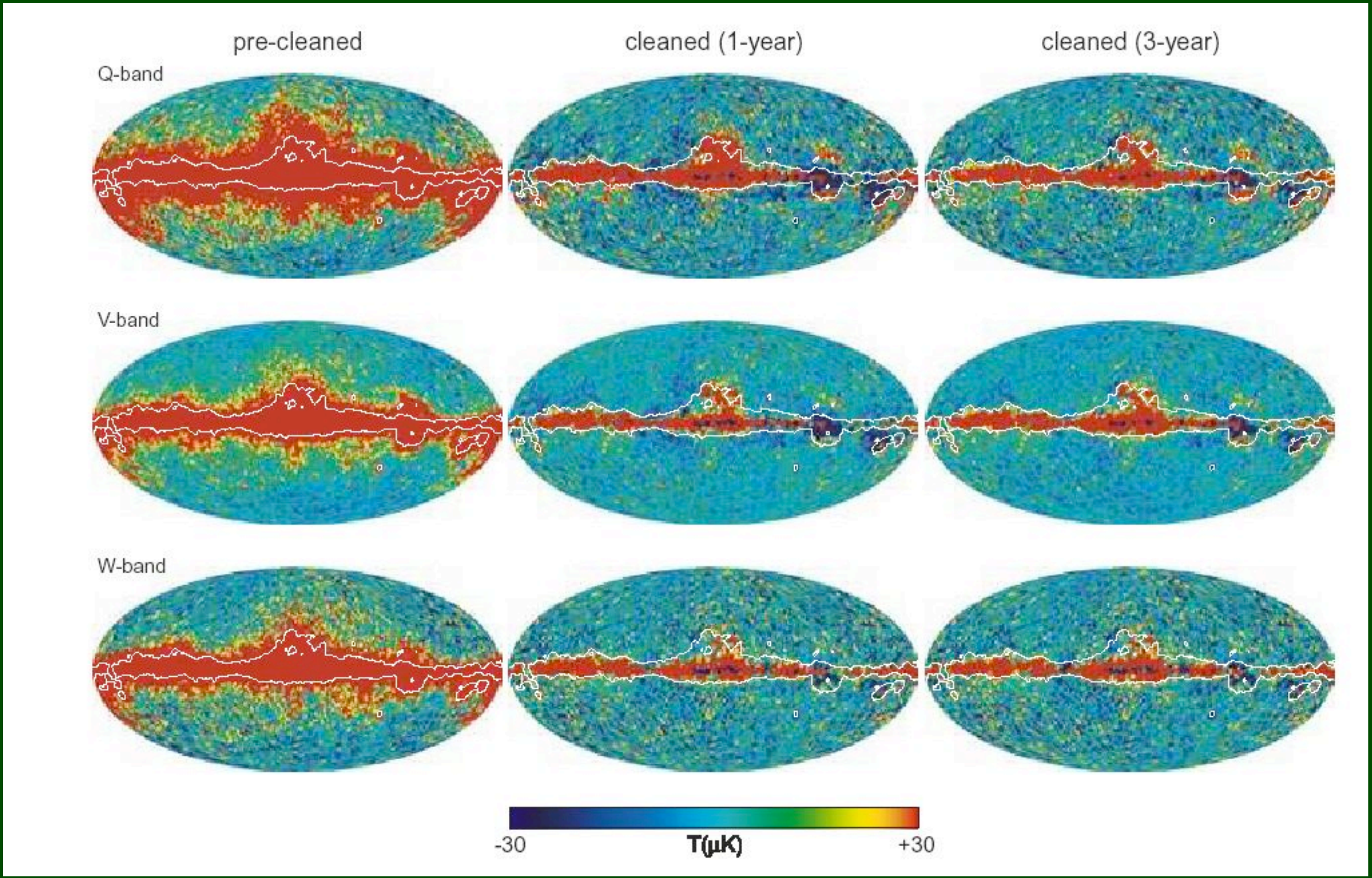
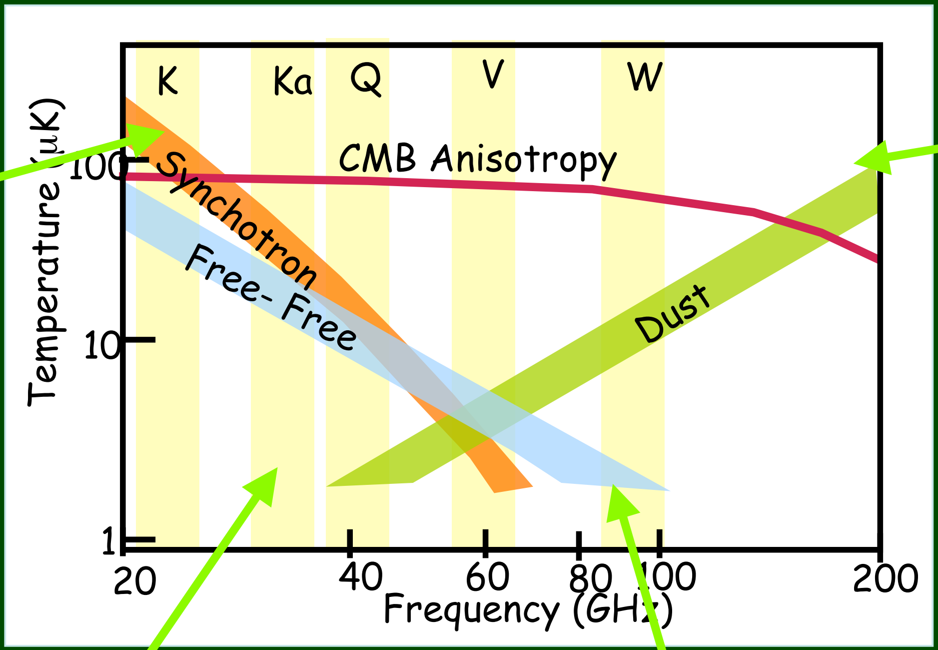
Temperature maps



Multiple maps help extract CMB from galactic contaminants



Synchroton emission
- Acceleration of cosmic ray electrons in magnetic fields of type 1b and type 2 SN remnants and from diffuse μG magnetic field in the galaxy
- Complicated frequency and source dependence, rough dependence~ $\nu^{-2.5} - \nu^{-3.1}$

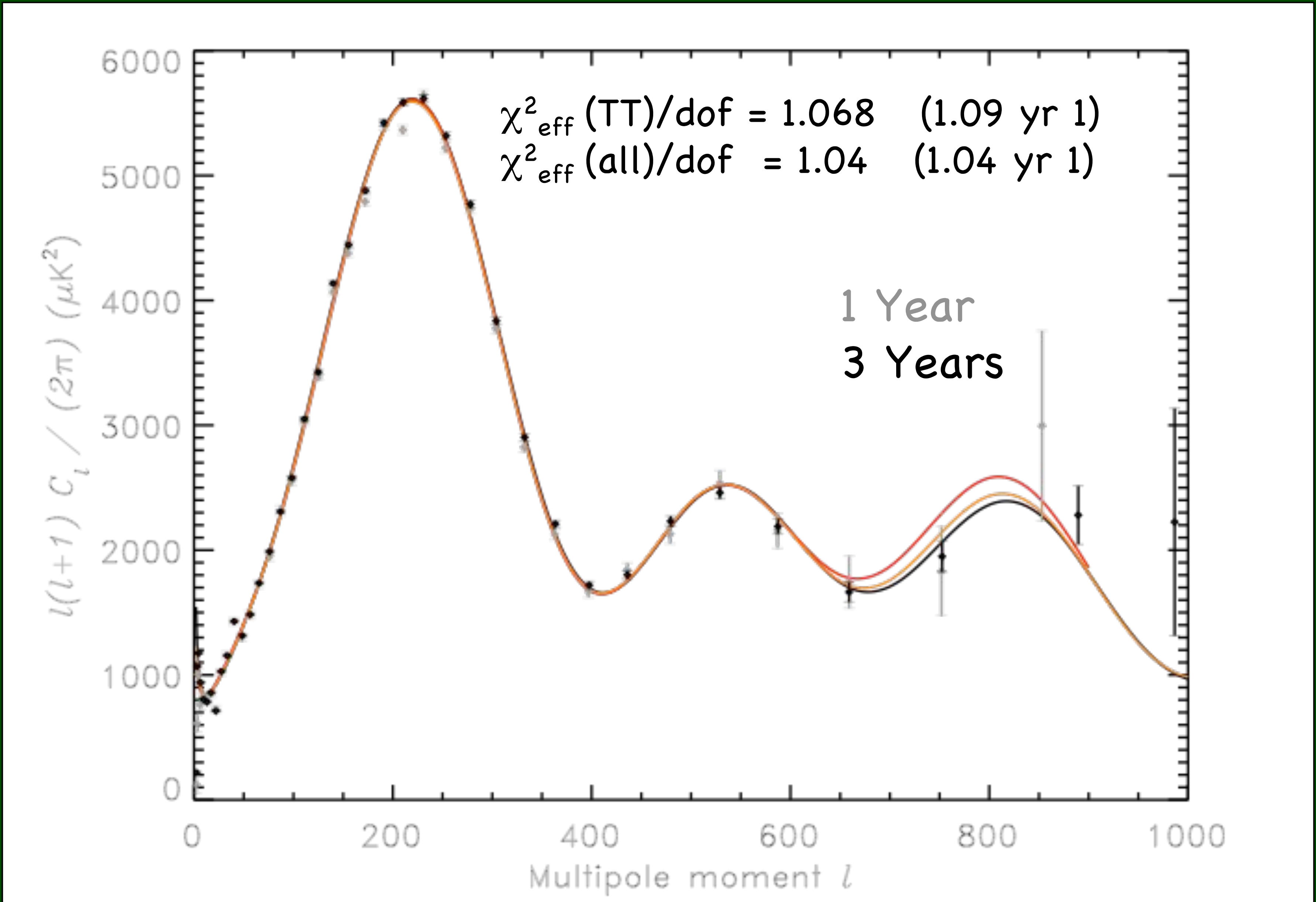
Thermal Dust
IR maps from COBE, IRAS and extrapolate ~ $\nu^{1.6}$

Spinning dust grains?
No detections reported
Expect strict cutoff ~40GHz

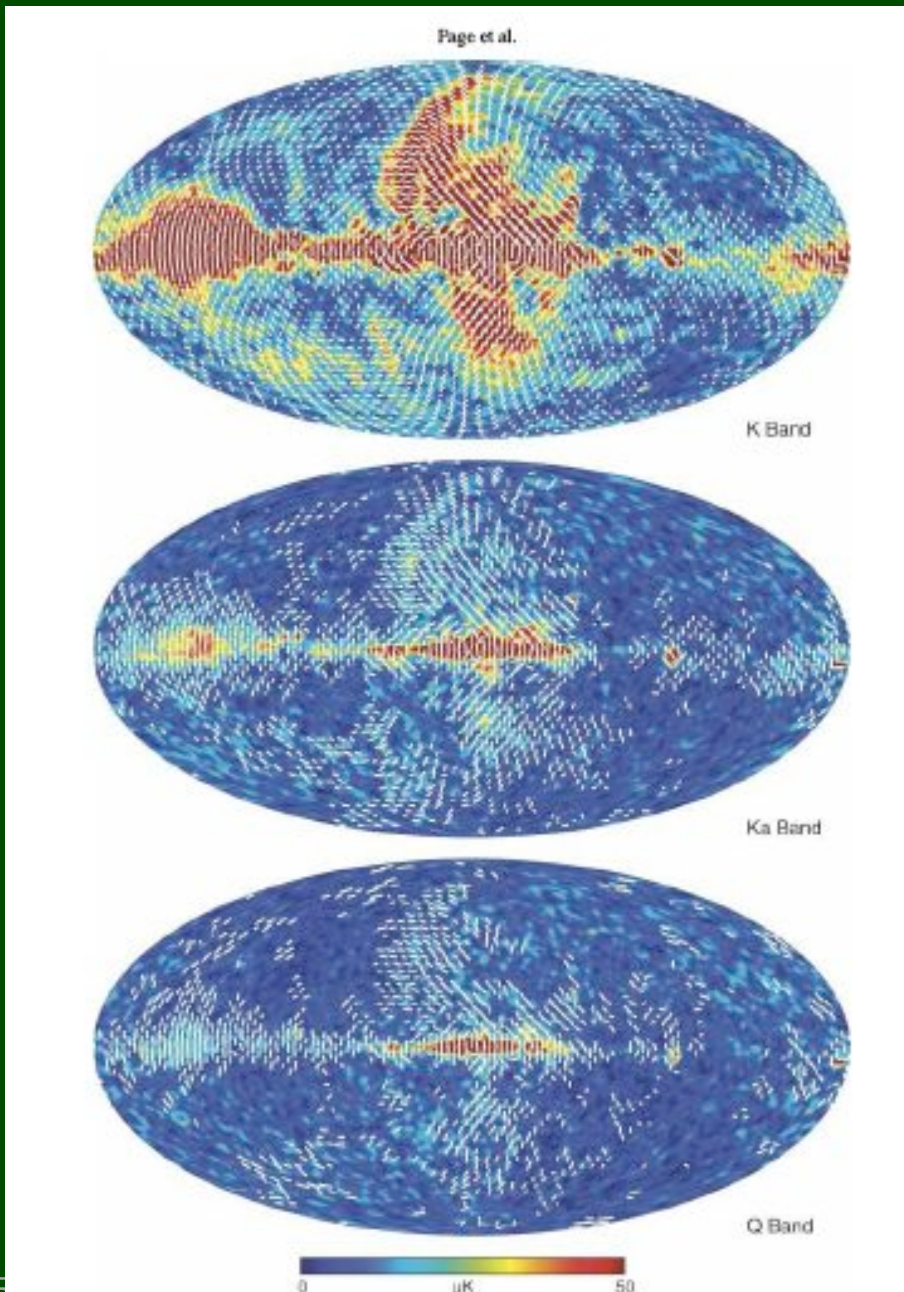
Free- free emission
-Electron-ion scattering ~ $\nu^{-2.15}$
-Use large scale Hα (H n=3->2) maps to estimate spatial contribution

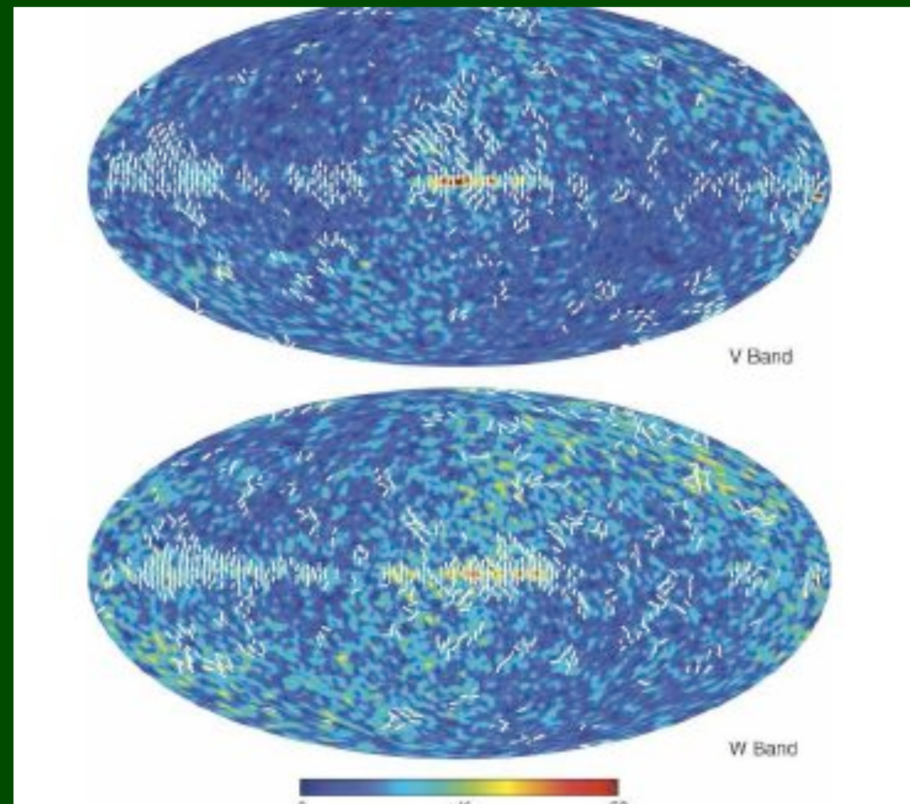
As well as remove other systematics e.g. 1/f noise from detectors

Despite smaller error bars, the χ^2_{eff} improves



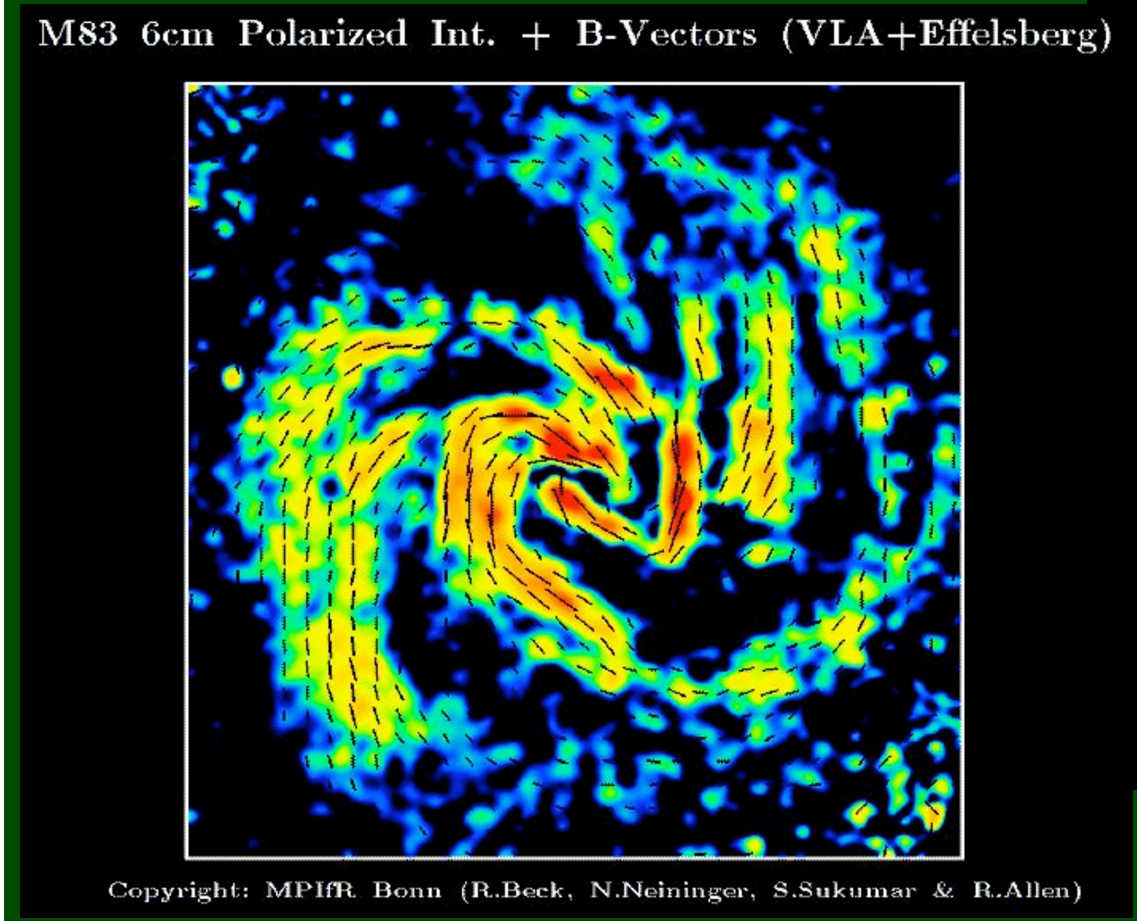
Polarization maps

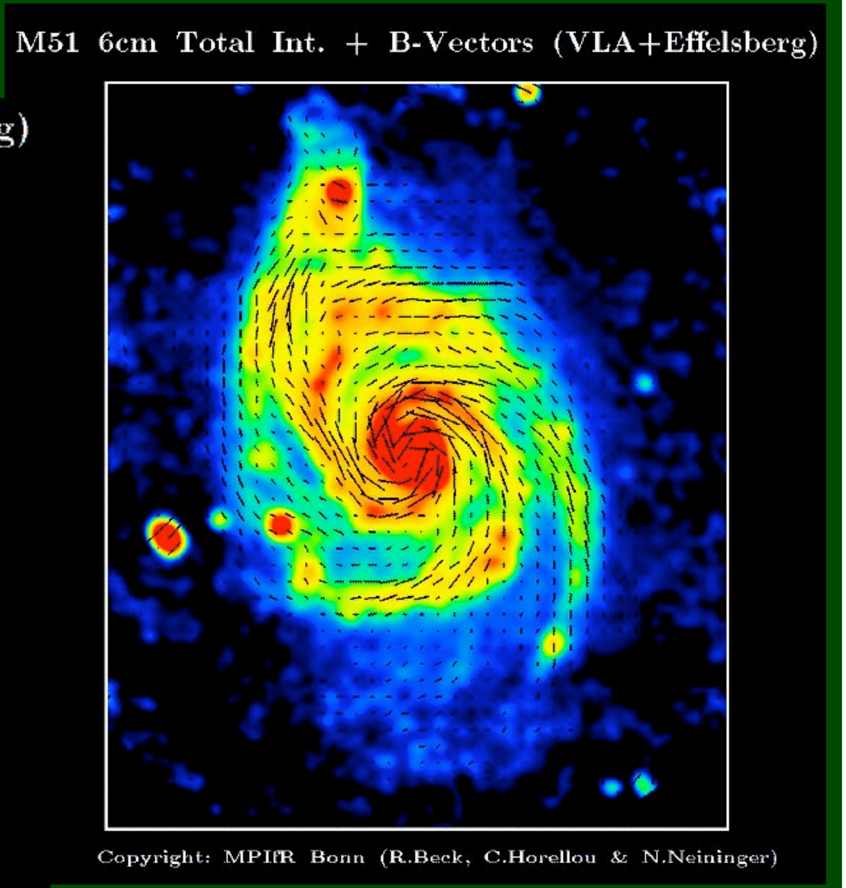




Polarized foregrounds - evidence of role of galactic magnetic field

Magnetic Field Structure in external galaxies exhibit spiral structure





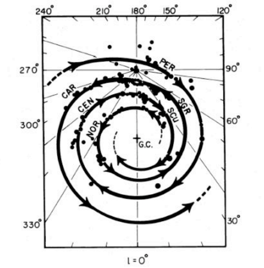
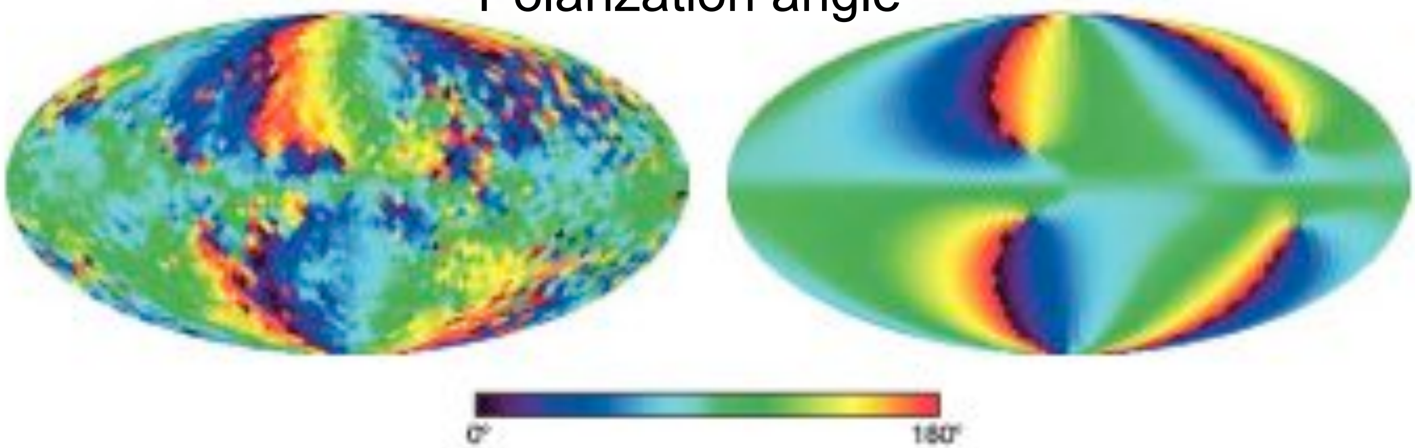


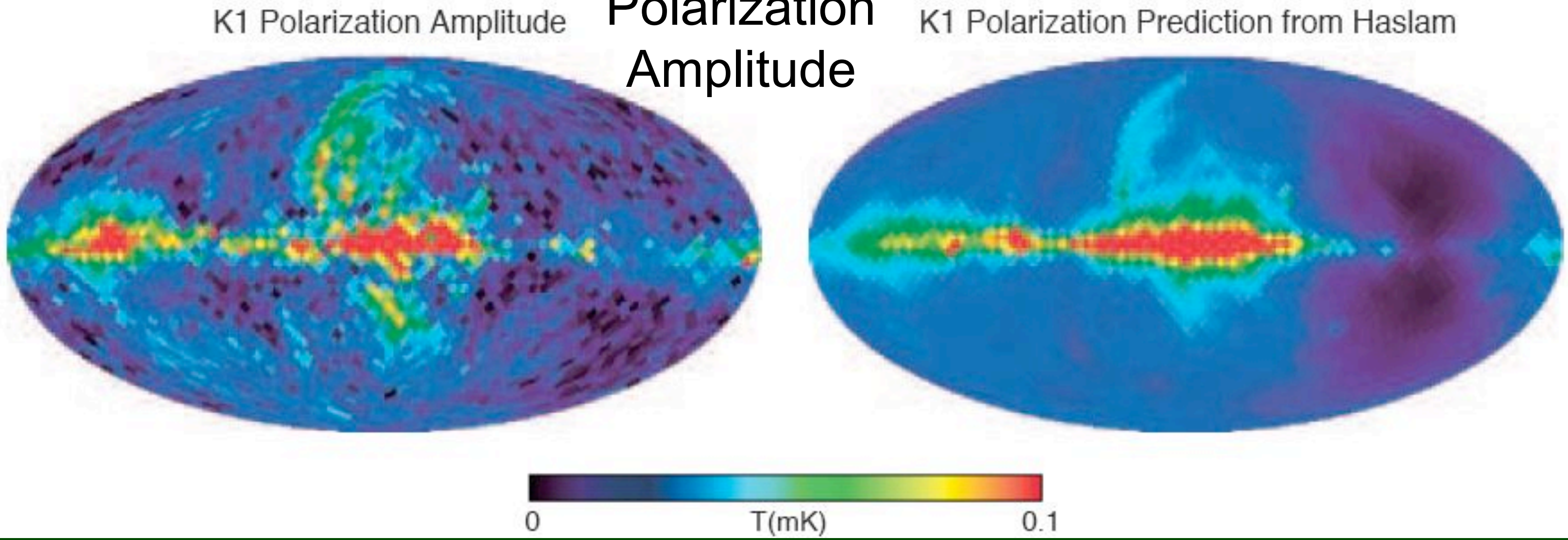
FIG. 4.—Possible, two-armed, bisymmetric spirals (*thick lines*) fitted to the distribution of H II regions (*filled circles*) given by Georgelin and Georgelin (1976). The arrows indicate the direction of magnetic field as inferred from Figs. 2 and 3.

Same bisymmetric spiral pattern is a good global fit to the field structure

Polarization angle



Polarization Amplitude



'Cleaning' out foregrounds

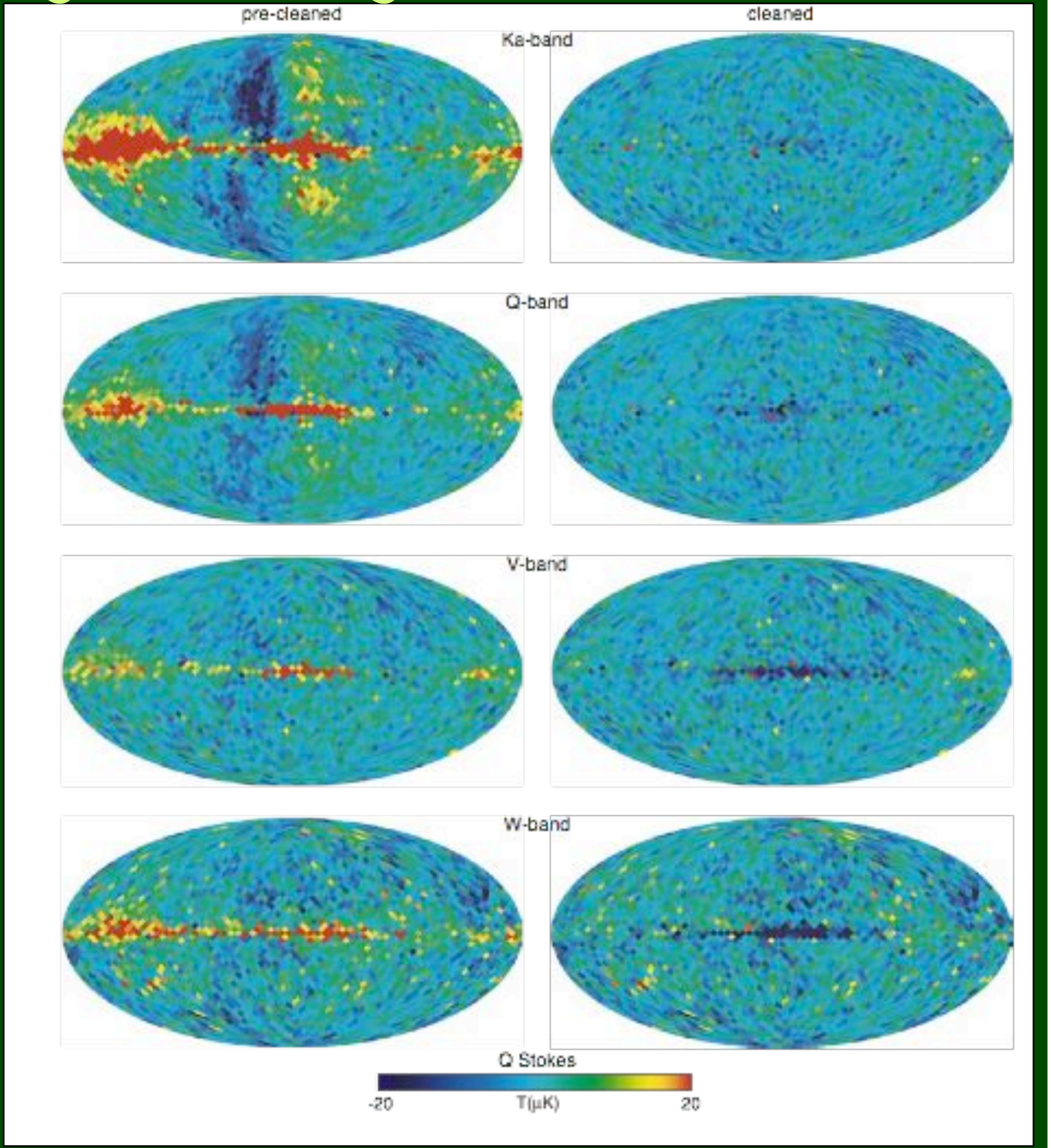
- Low frequency (K band) synchrotron profile of galaxy magnetic field

  + Multi-frequency dust map and starlight polarization measurements

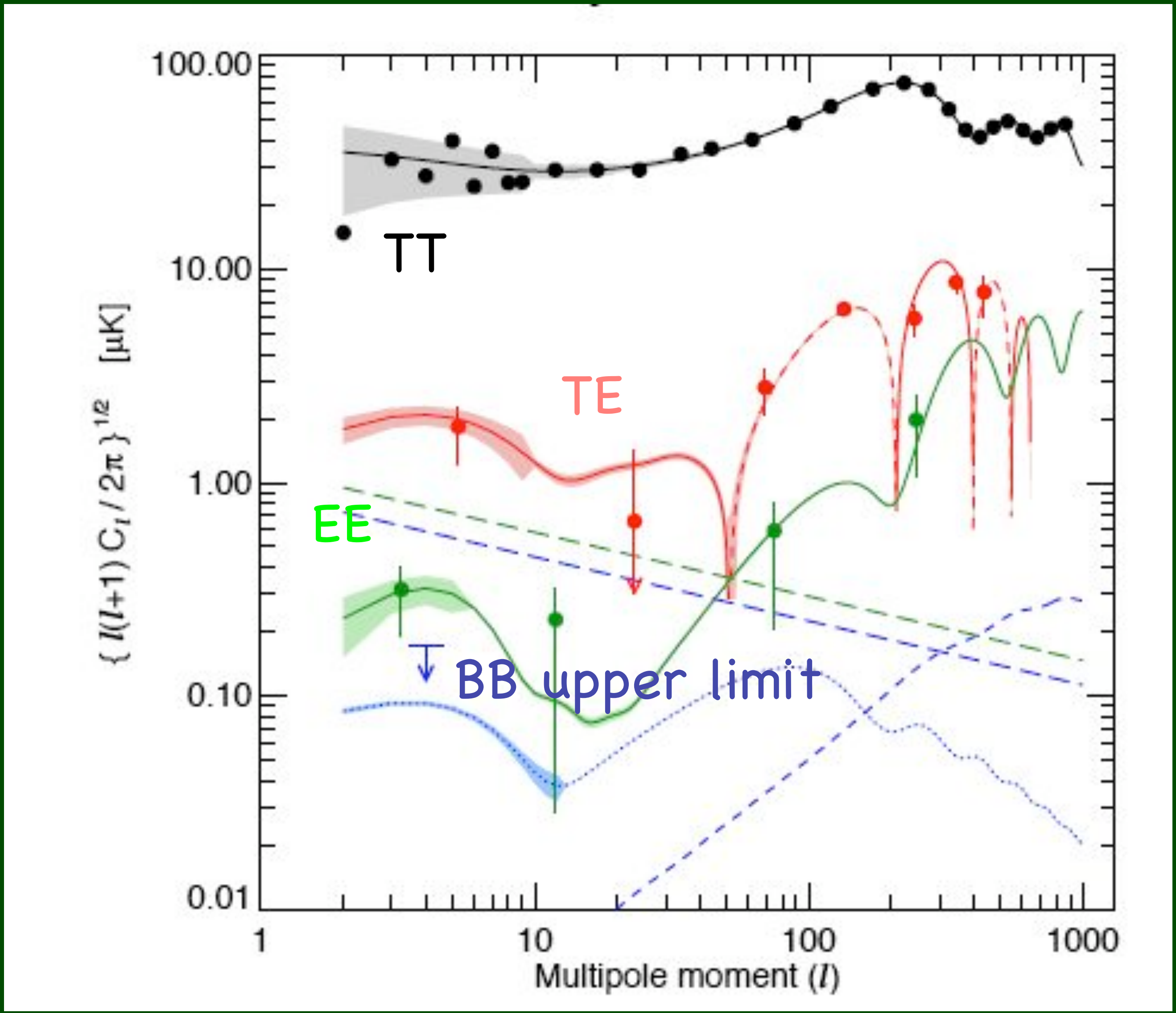
  =a template to clean maps

- Many people interested in galactic polarization

- but for cosmologists they are contamination!



Summary of power spectrum results



Talk plan

- Overview
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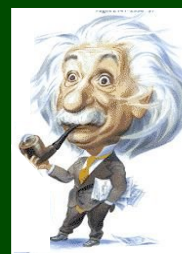
Cosmological input assumptions

- GR using Einstein's equations

$$G_{\mu\nu} = \frac{8\pi G T_{\mu\nu}}{c^4}$$



- Homogeneity and isotropy using Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3P)$$

- Initial conditions from inflation
  - More later
- Atomic processes at recombination
  - Thomson scattering
  - Atomic transitions
- Explicit properties of matter/space
  - Standard particle model
  - Cold Dark matter
  - Cosmological constant
  - Spatial flatness ….

"The least questioned assumptions are often the most questionable" Pierre Paul Broca

Cosmological Inference and Degeneracy

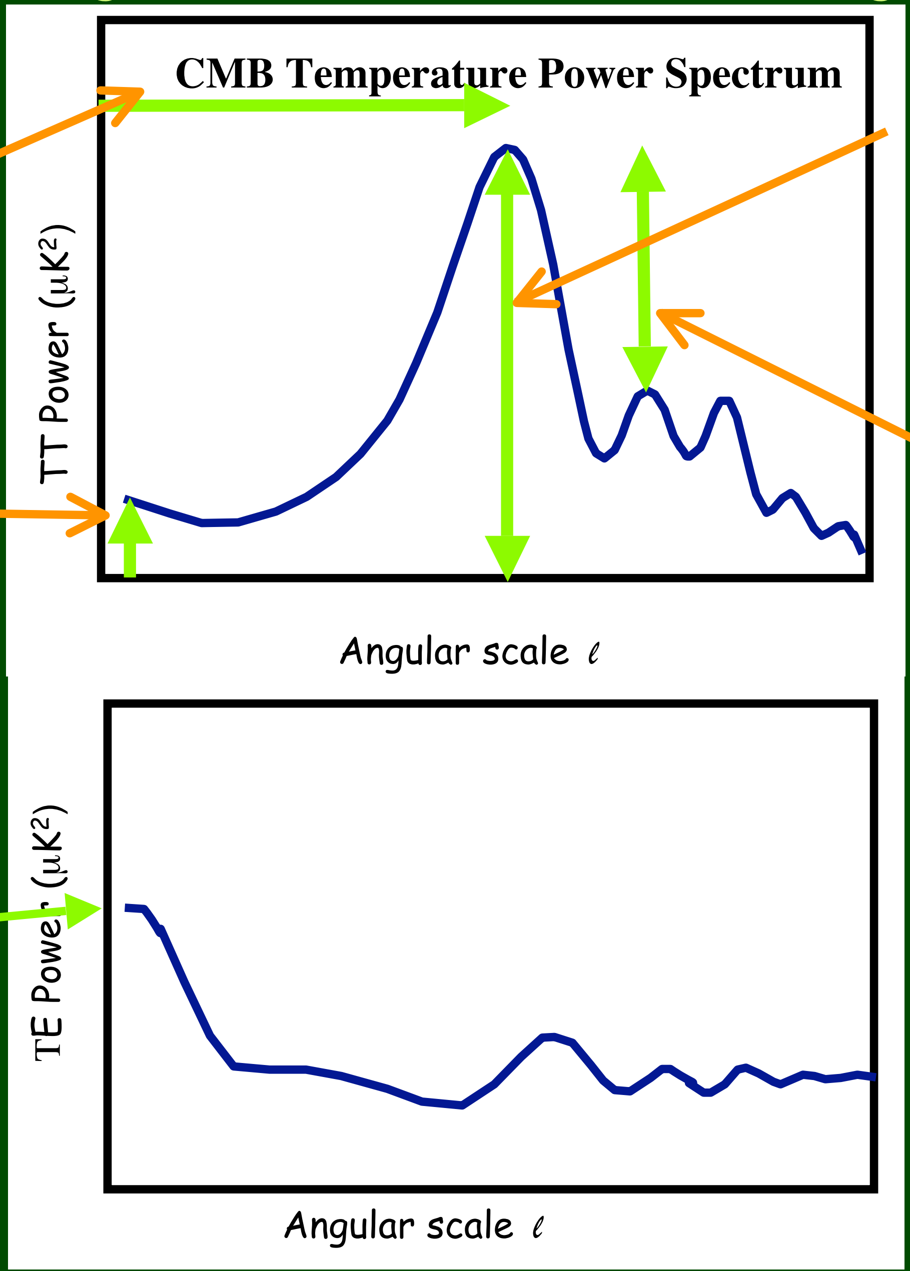
Universe's relative size today to when CMB was formed (Ω_m, Ω_Λ, h)

Geometry of the universe (Ω_k)

Dark Energy (Ω_Λ)

Initial conditions n_s

Large scale polarization from reionization



Matter to radiation ratio Ω_m/Ω_γ

Baryon fraction $\Omega_b h^2$

Reionization τ

Initial conditions n_s,A_s

Baryon fraction $\Omega_b h^2$

Initial conditions n_s

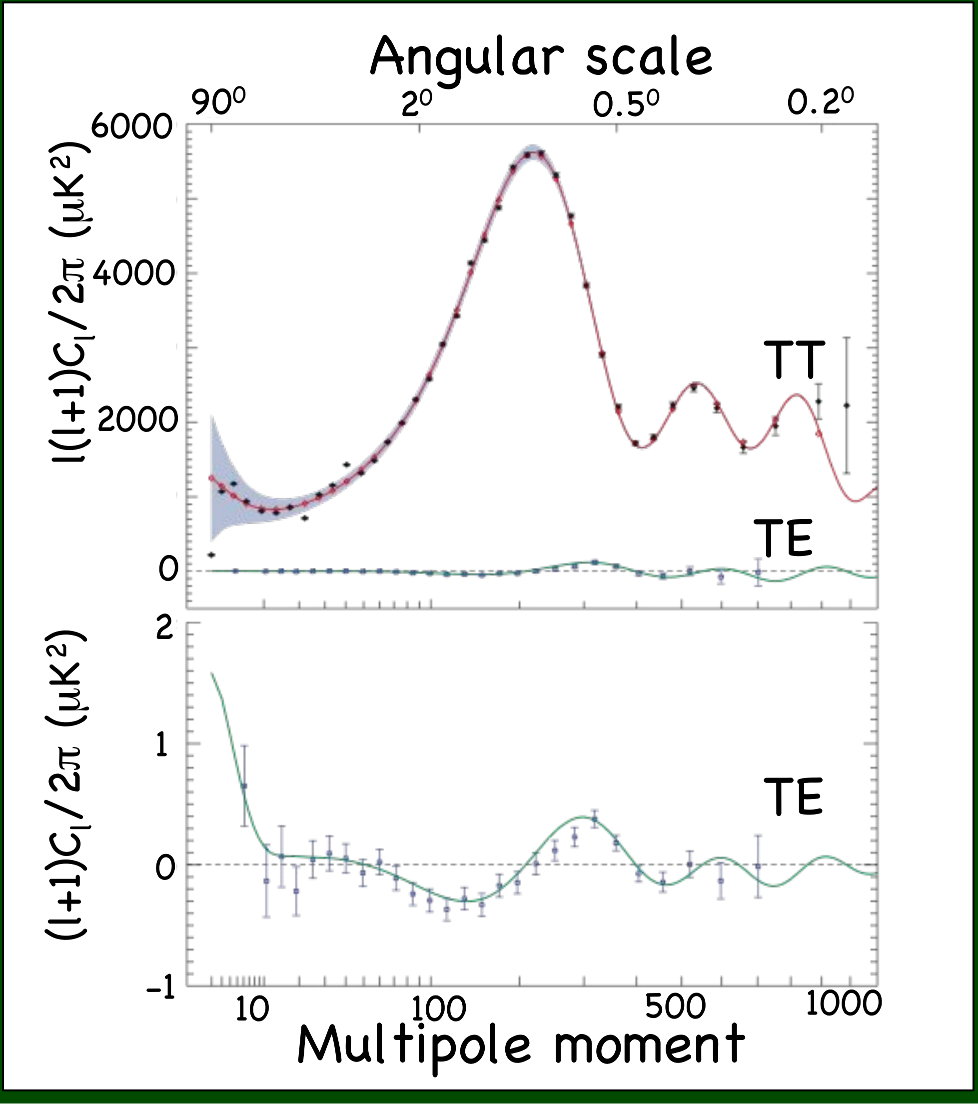
Wayne Hu's website

Summary

A simple cosmological model with only 6 parameters fits the WMAP data

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

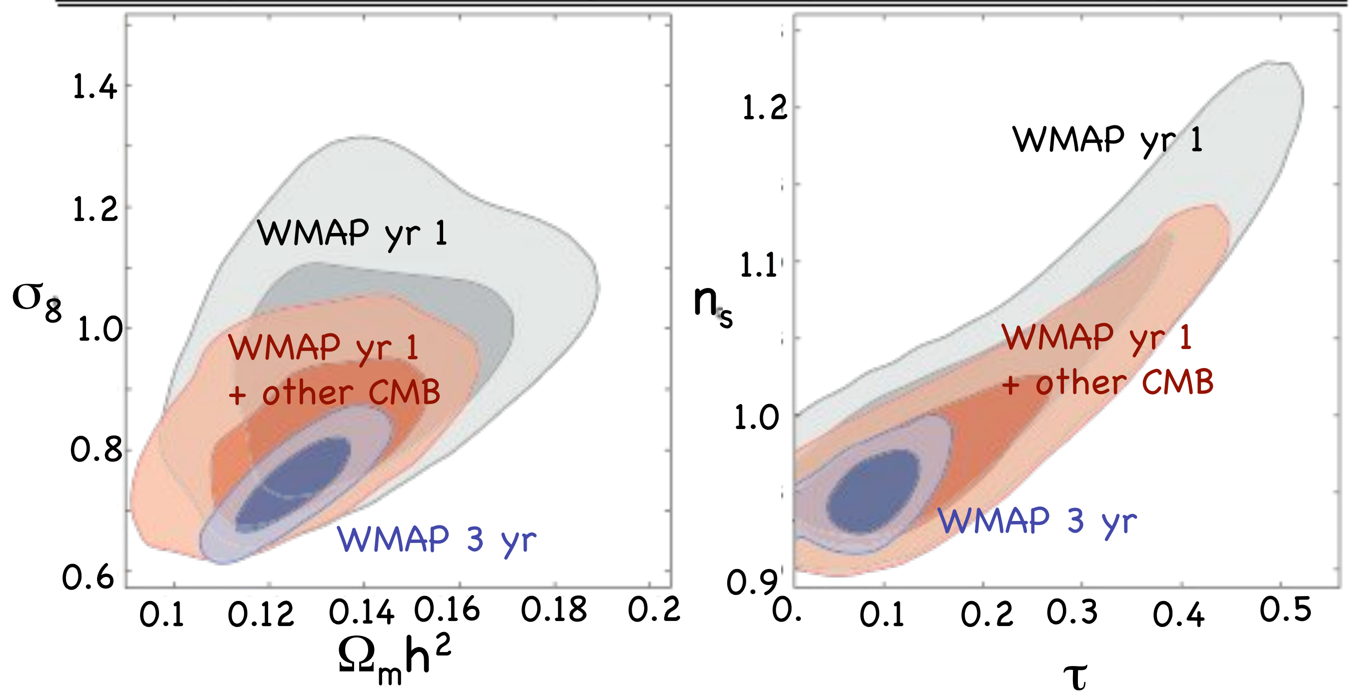
- Run model forward in time
  - predict cosmological evolution
- Go backwards in time
  - to study early universe
- Constrain variants on simplest model
  - open universe,
  - massive neutrinos
  - Dark energy models
  - Beyond power law inflation



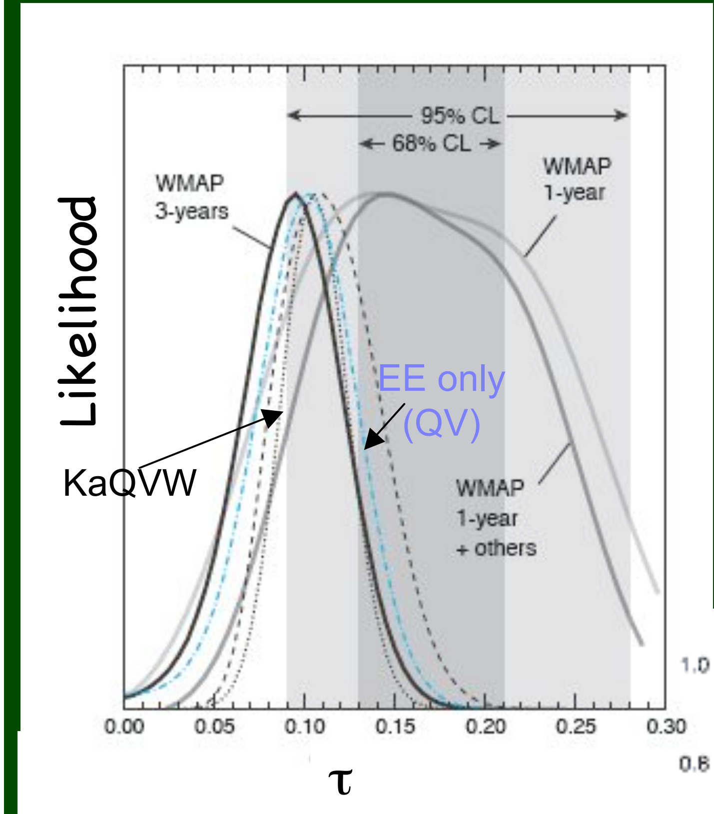
Improvement in Parameters

Comparison of 1st year and 3rd year LCDM constraints

Parameter	First Year Mean	WMAPext Mean	Three Year Mean	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.30	2.21	2.22
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	0.145	0.138	0.128
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}	68	71	73
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029	0.10	0.10	0.092
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017	0.97	0.96	0.958
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035	0.32	0.27	0.24
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05	0.88	0.82	0.77

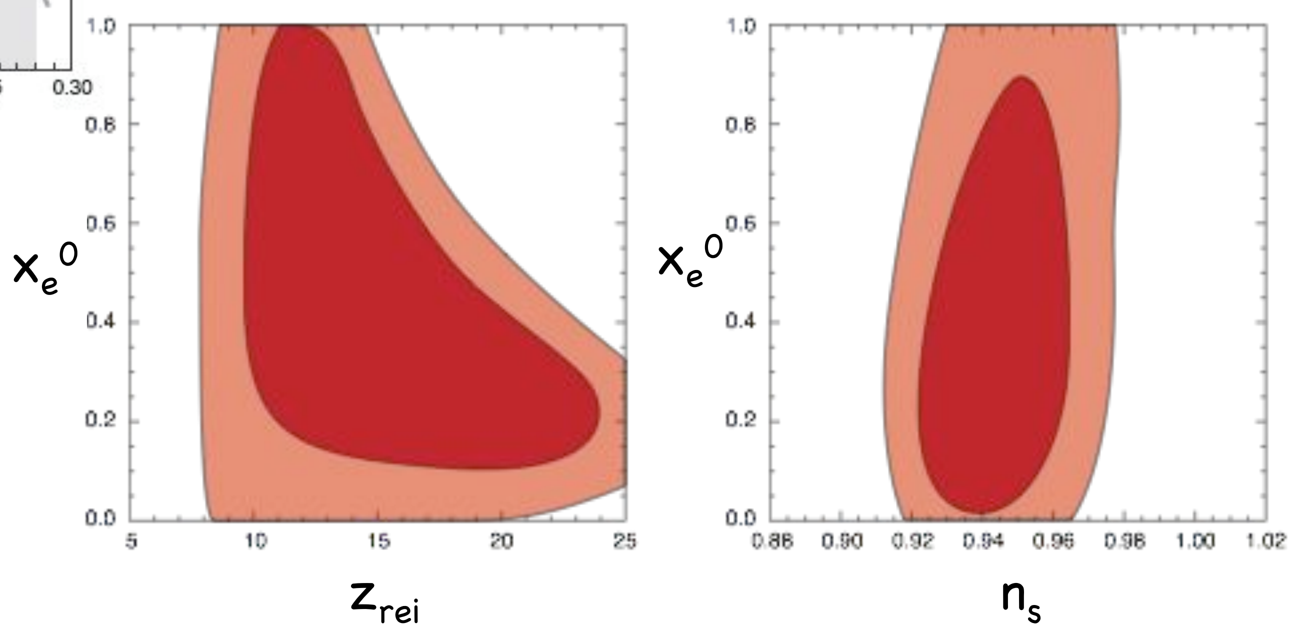


Likelihood Analysis of Optical Depth

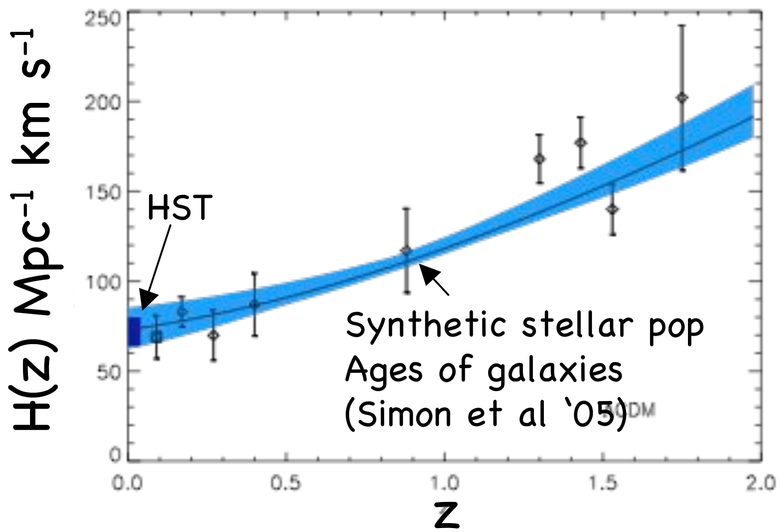


- Polarization data alone gives important information about reionization
  - $\tau = 0 \Rightarrow \Delta\chi^2_{eff} = +8$ vs bestfit $\tau > 0$
- More years of data will yield more insights into reionization e.g. 2 step process?
  - $x_e = 1$ for $z<7$
  - $x_e = x_e^0$ for $7<z<z_{rei}$

  $\Rightarrow 0.057<\tau<0.17$ (1σ)

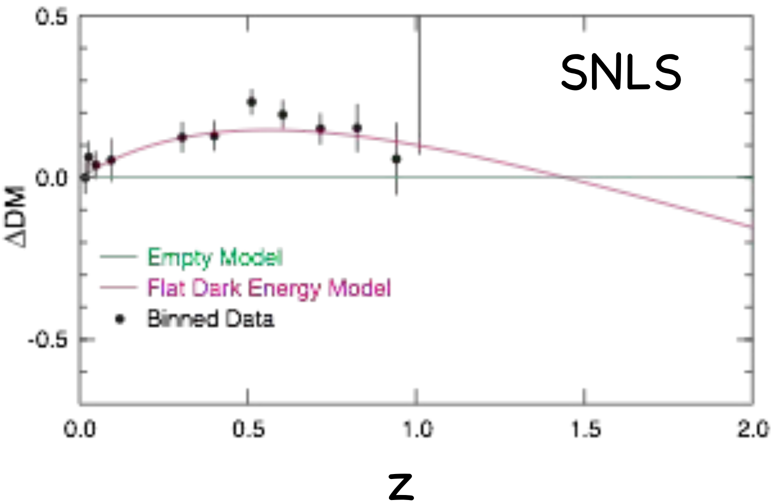


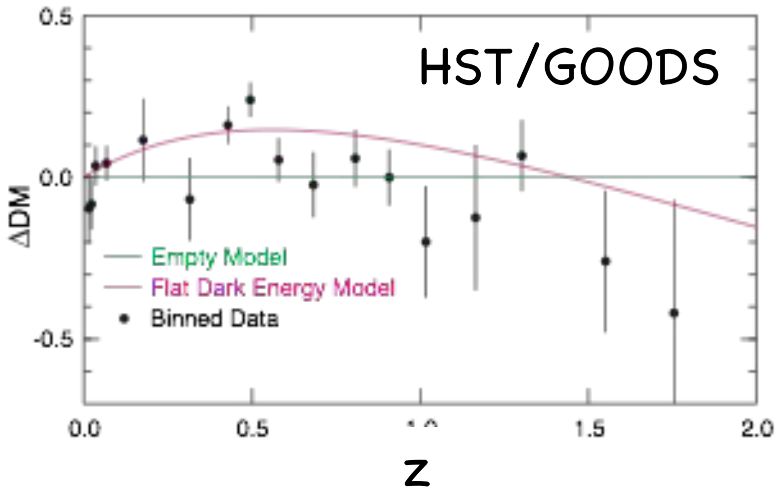
WMAP fits predict H(z)



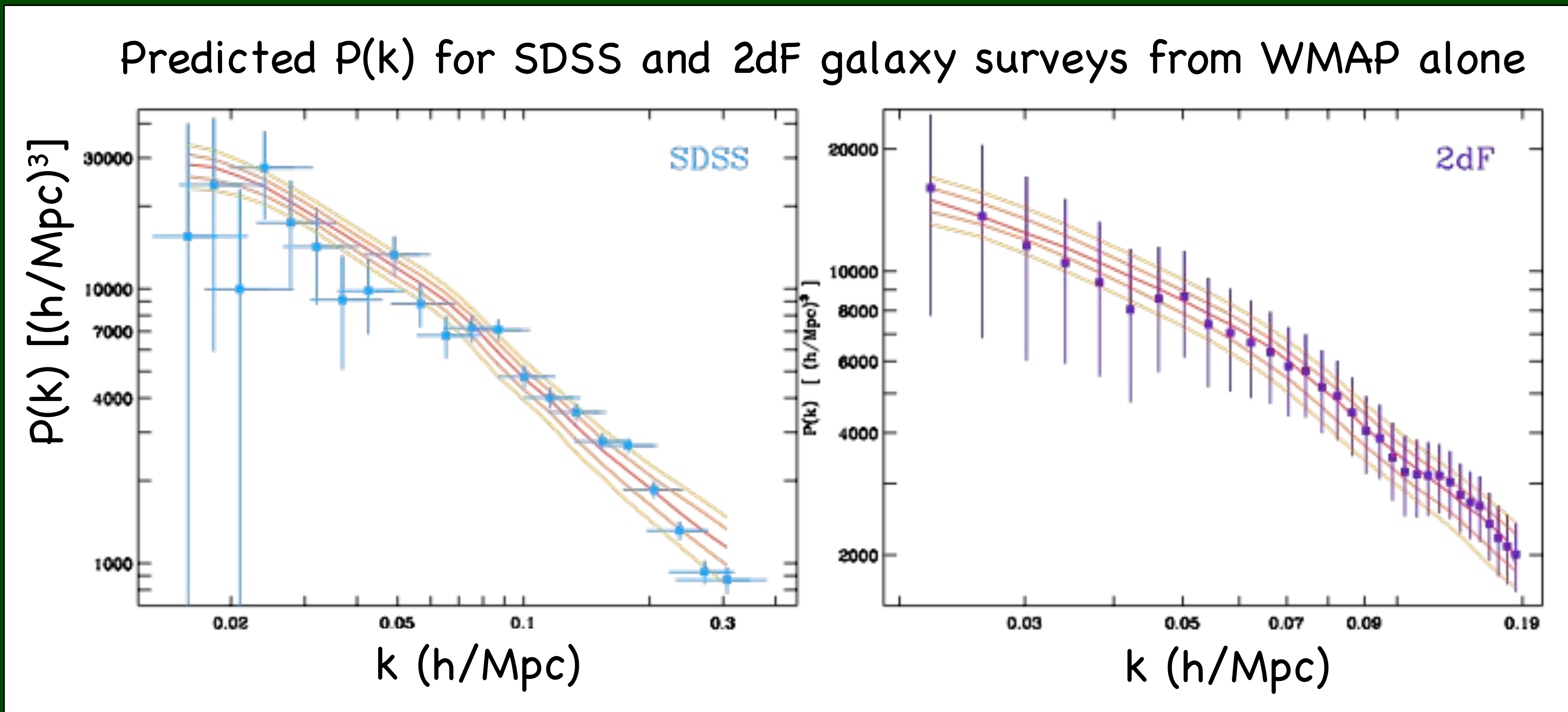
Predicted H(z) evolution

Luminosity distance prediction from WMAP alone





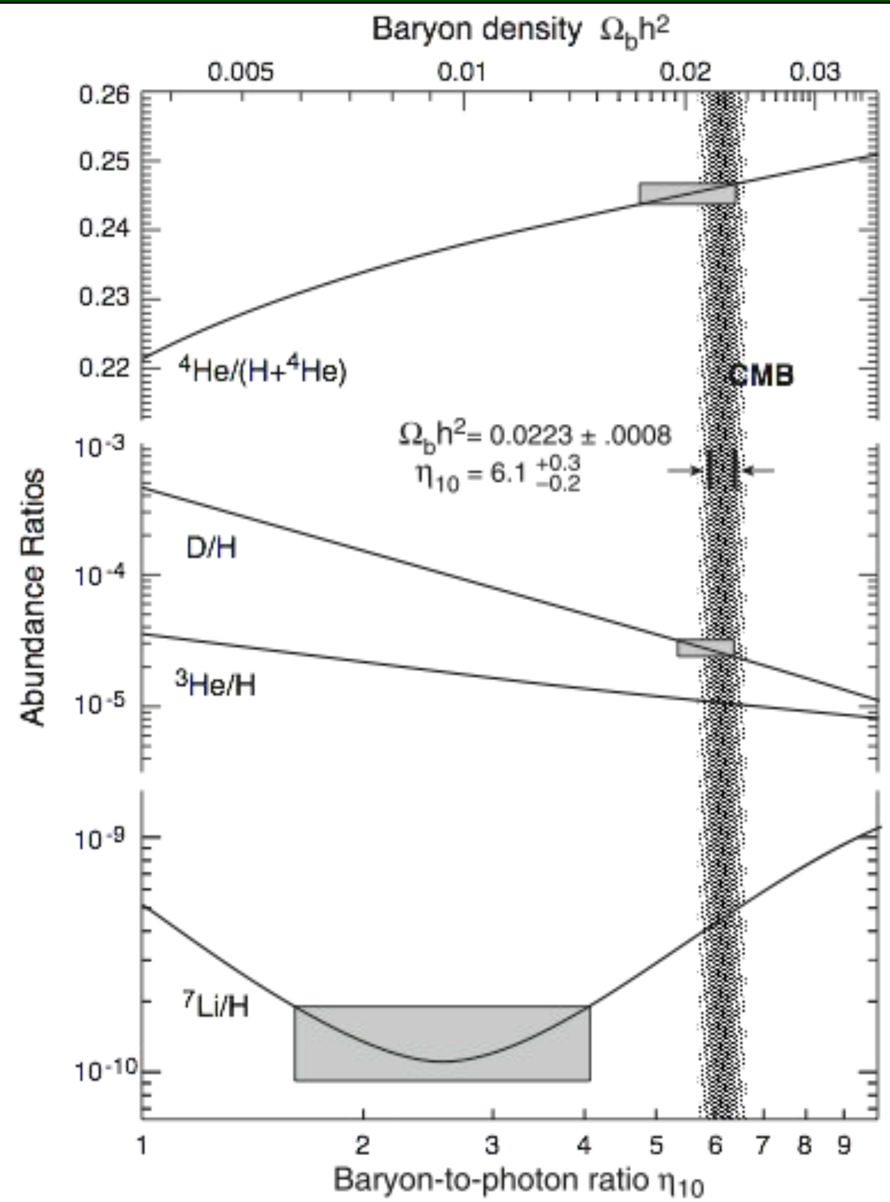
WMAP fits predict galaxy and mass distribution



WMAP fits predict primordial abundances

	CMB-based BBN prediction	Observed Value
$10^5 y_D^{FIT}$	$2.58^{+0.14}_{-0.13}$	1.6 - 4.0
$10^5 y_3$	$1.05 \pm 0.03 \pm 0.03$ (syst.)	$< 1.1 \pm 0.2$
Y_P	$0.24815 \pm 0.00033 \pm 0.0006$(syst.)	0.232 - 0.258
[Li]	2.64 ± 0.03	2.2 - 2.4

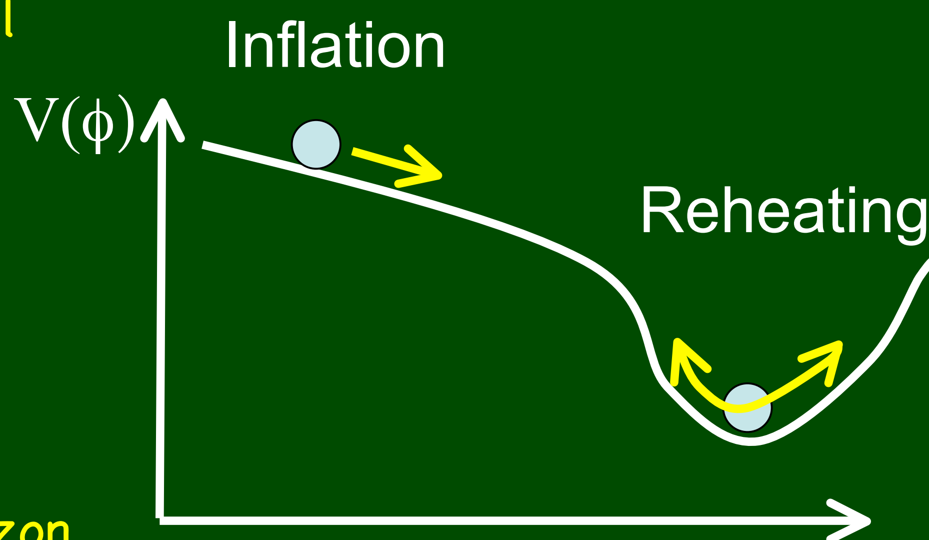
(Steigman et al 2005)



Predictions of inflation

- Acceleration induced by slow roll down scalar potential
  - Near scale invariant tilt
  - Small but non-zero tensor contribution r=T/S

- Acceleration causes Hubble horizon decreases
  - Flatness is an attractor
  - Density fluctuations seeded by Gaussian quantum fluctuations



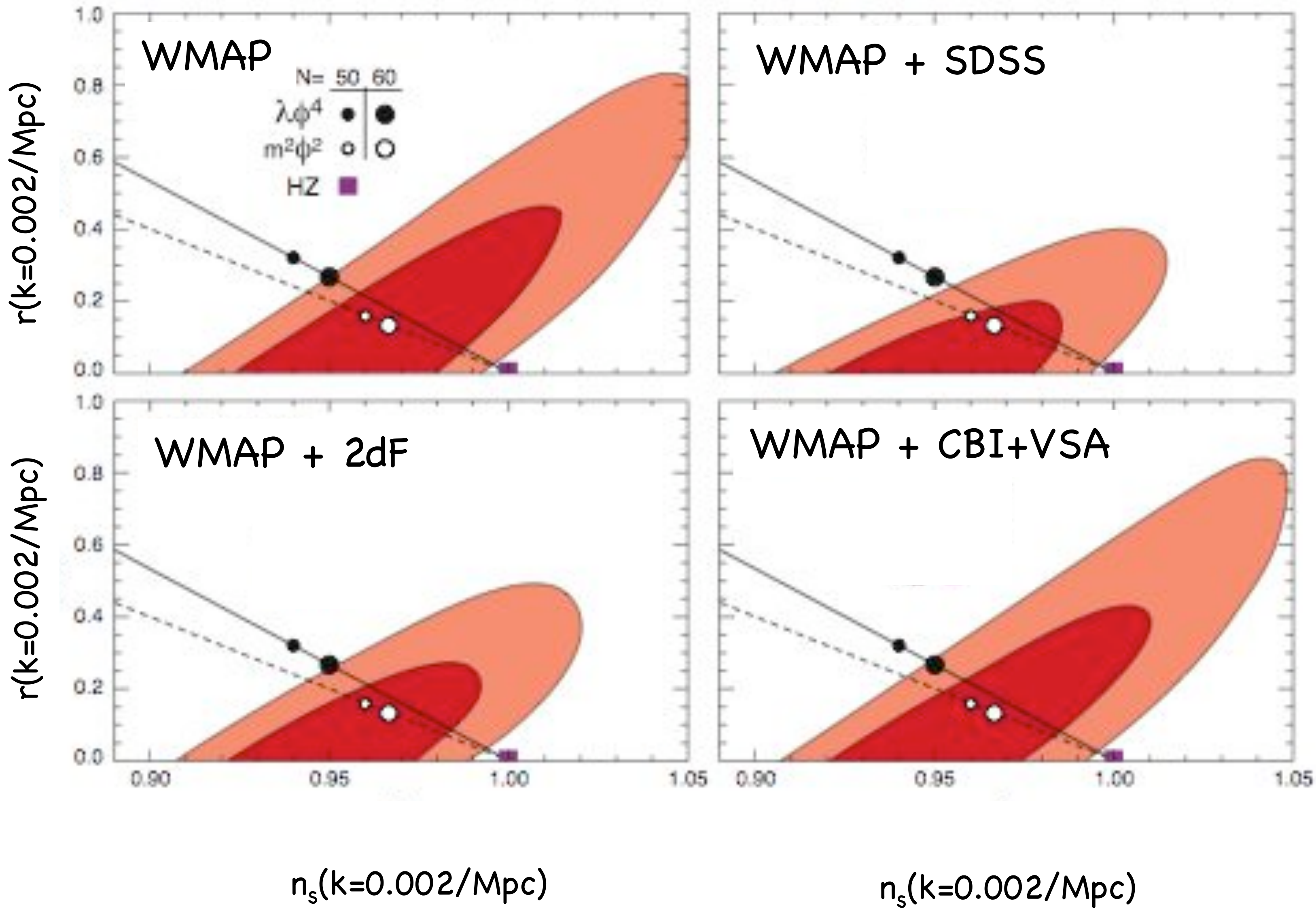
$$\eta = \frac{m_p^2}{8\pi}\frac{V''}{V} \ll 1$$

$$\varepsilon = \frac{m_p^2}{16\pi}\frac{V'^2}{V^2} \ll 1$$

$$n_s = 1 - 6\varepsilon + 2\eta$$

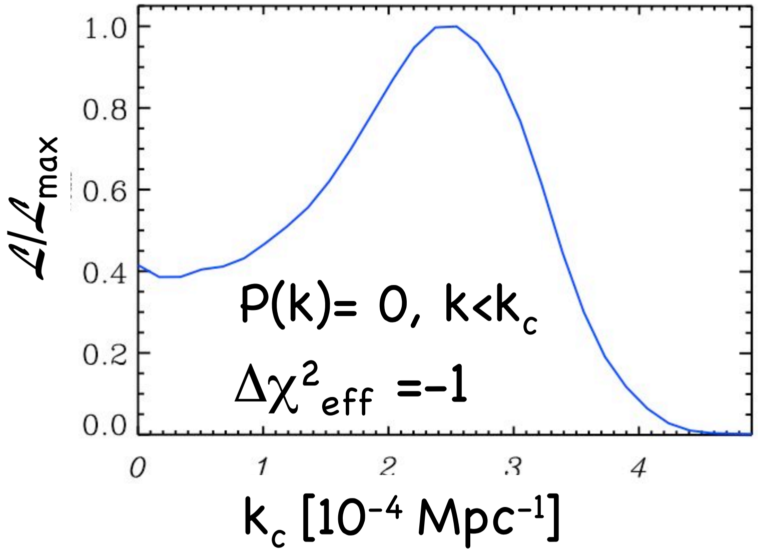
WMAP and Initial Conditions : constraining inflation

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



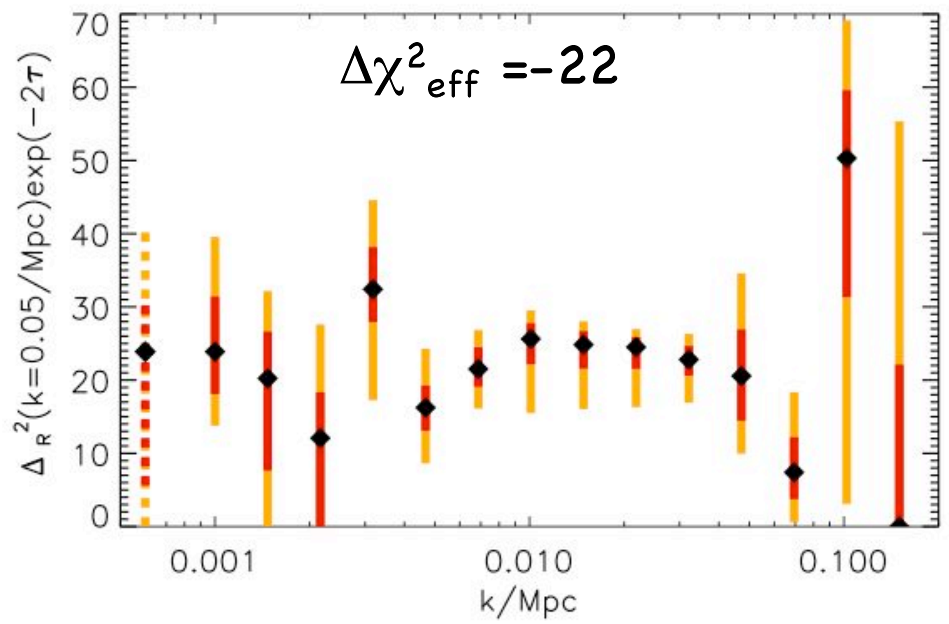
Alternative power spectrum models

Sharp k cutoff in initial spectrum



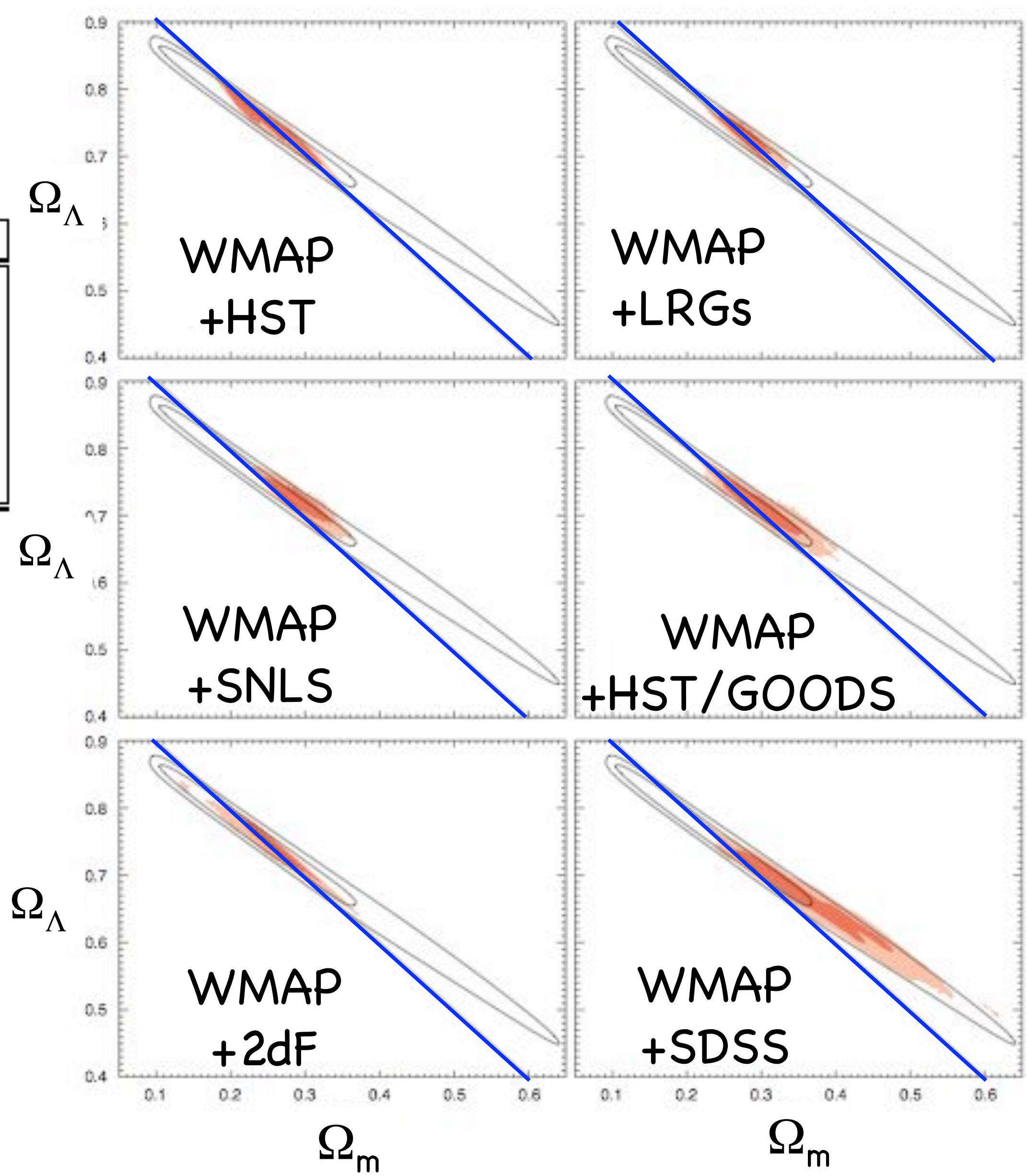
Improvements again small, power law P(k) fits the data well

Reconstruction of P(k) in 15 k bins



Geometry of the universe

Data Set	Ω_K	Ω_Λ
WMAP + $h = 0.72 \pm 0.08$	$-0.003^{+0.013}_{-0.017}$	$0.758^{+0.035}_{-0.058}$
WMAP + SDSS	$-0.037^{+0.022}_{-0.014}$	$0.650^{+0.058}_{-0.045}$
WMAP + 2dFGRS	$-0.0057^{+0.0085}_{-0.0064}$	0.739 ± 0.028
WMAP + SDSS LRG	$-0.008^{+0.011}_{-0.015}$	$0.729^{+0.021}_{-0.026}$
WMAP + SNLS	$-0.015^{+0.021}_{-0.016}$	$0.719^{+0.023}_{-0.028}$
WMAP + SNGold	$-0.017^{+0.020}_{-0.019}$	$0.703^{+0.036}_{-0.032}$

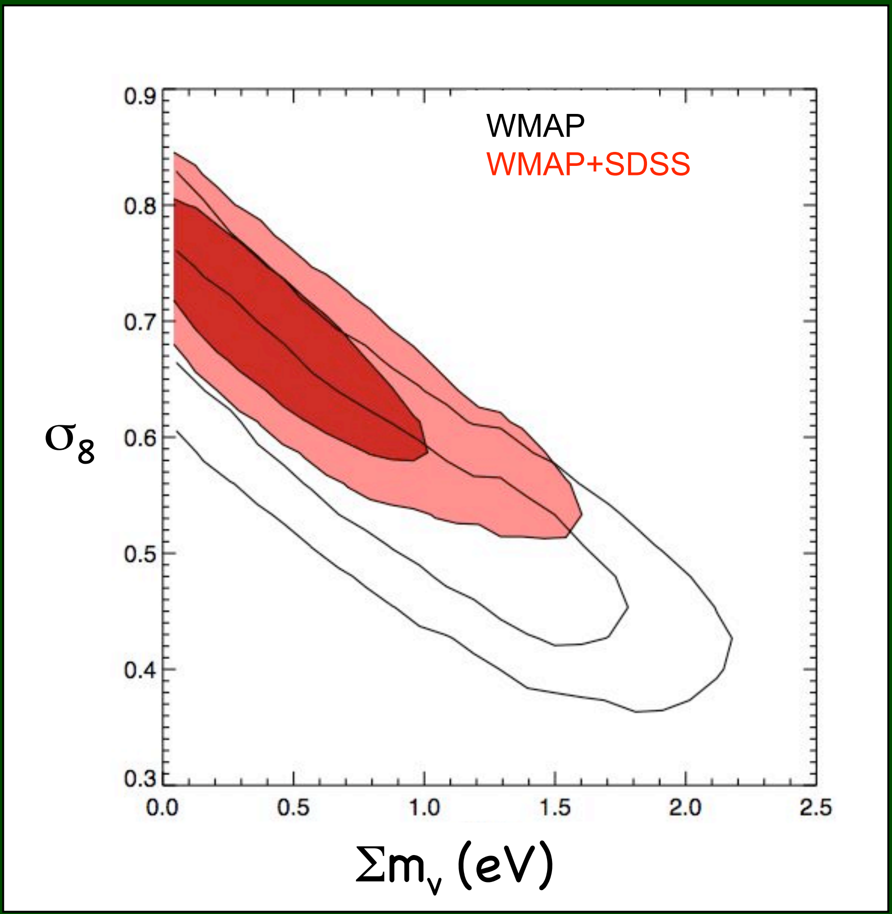


WMAP only

No CDM $\Delta\chi^2_{eff}$ =+248

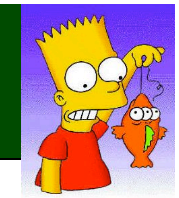
No Λ $\Delta\chi^2_{eff}$ =0 (H_0~30)

Massive neutrinos

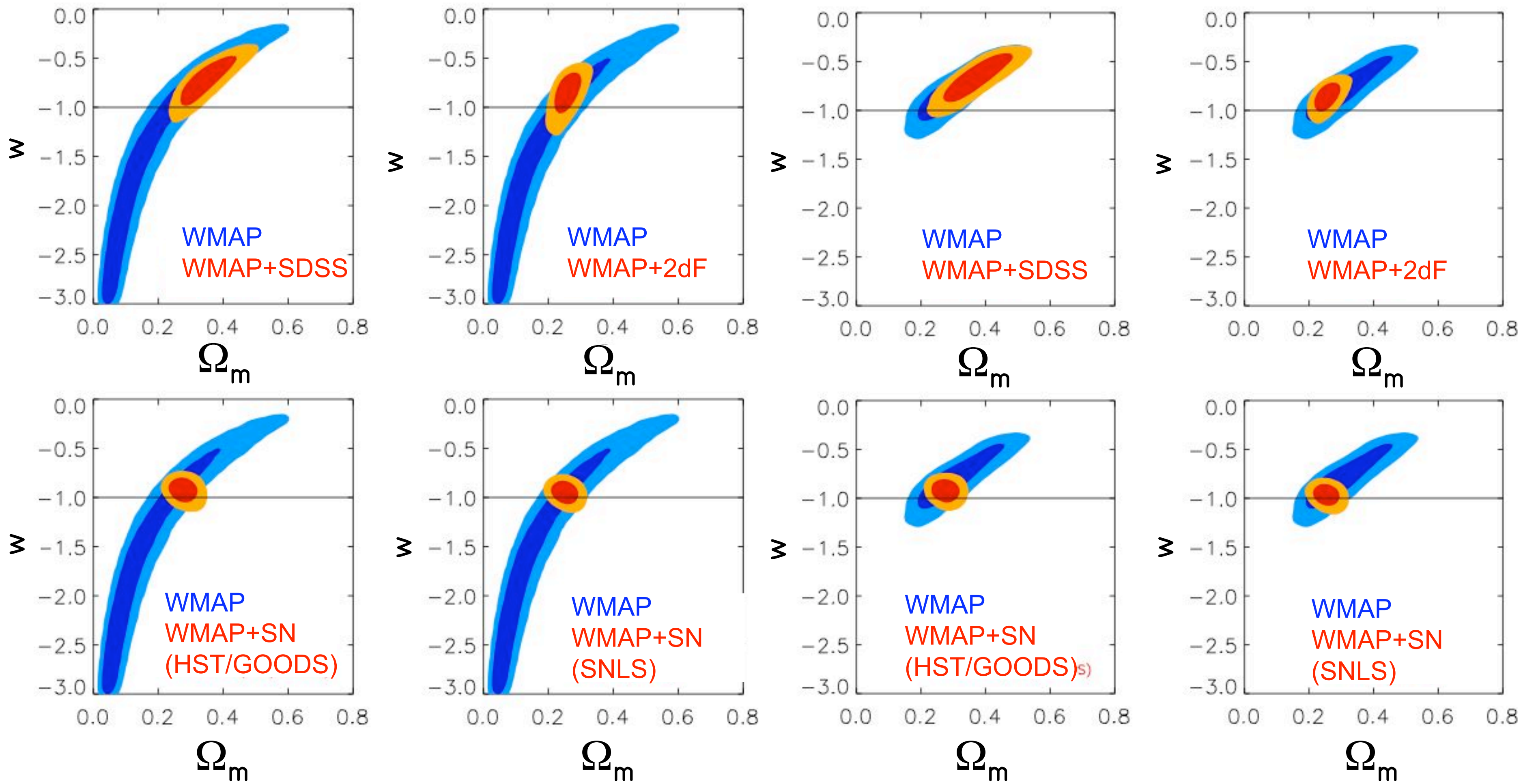


	Σm_ν (eV) 95% CL
WMAP only	2.0
WMAP+SDSS	0.93
WMAP+2dF	0.90
CMB +LSS + SN	0.68

Dark Energy

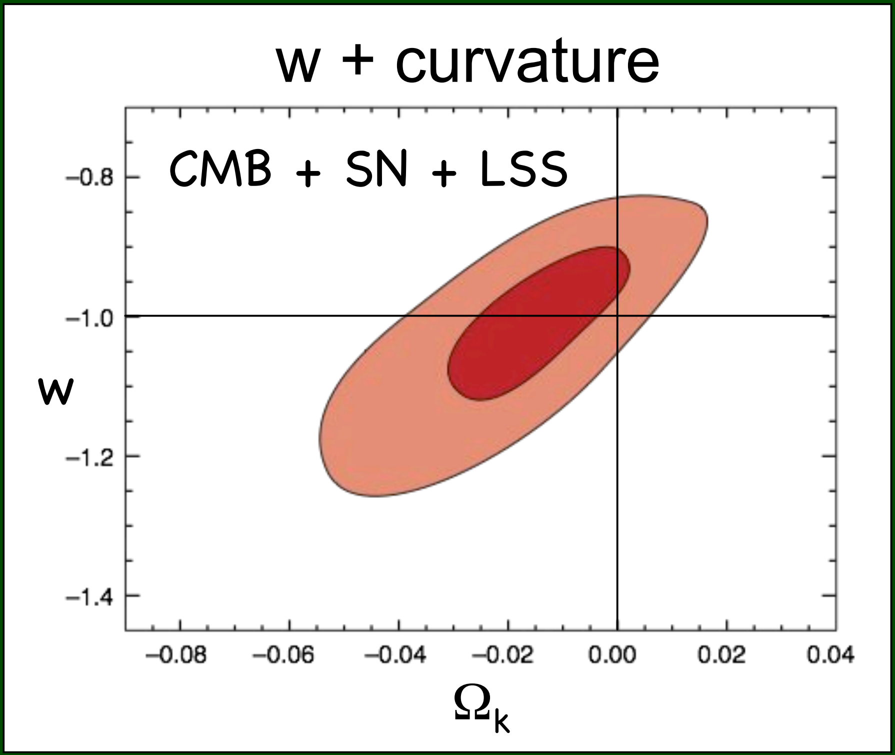


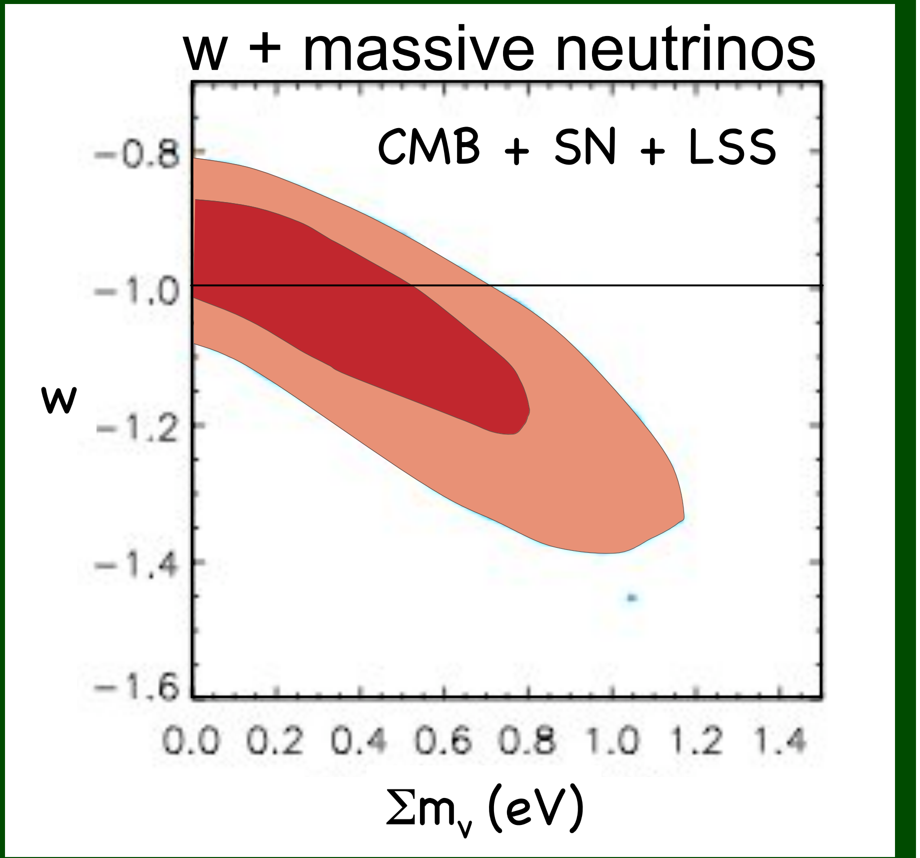
Clustering dark energy $c_s^2=1$ $w\neq-1$ | Ignoring fluctuations in DE



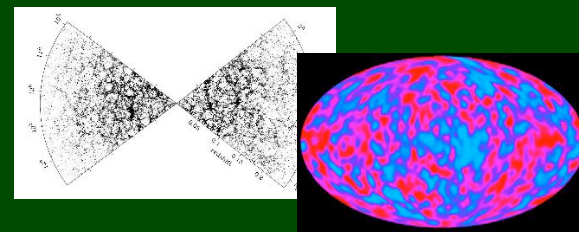
Sensitive to assumptions about clustering properties of Dark Energy

Robustness of dark energy constraints....

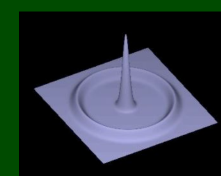




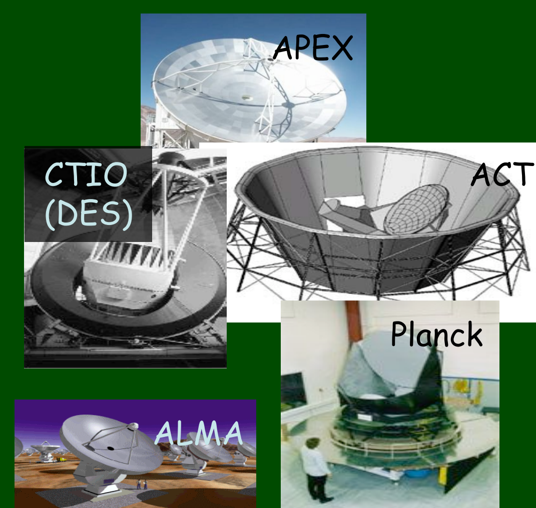
Beyond WMAP : Applying WMAP to new tasks



- Cross-correlation with structure :
  - Exciting opportunities to probe dark energy, reionization …
- Complementary cosmological experiments
  - Crucial complementary parameter constraints from precise understanding of physics at last scattering

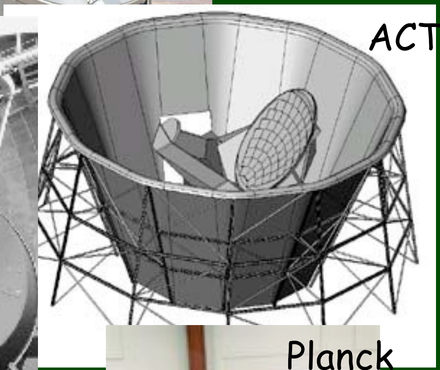


- Future CMB experiments:
  - Mapping the foregrounds
  - Calibration



Small scale CMB / SZ surveys
Implications for dark matter/ dark energy research

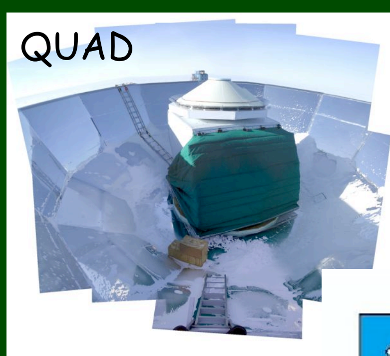
- Ground based e.g.:
  - -SZA ~100 clusters, 12 sqdeg, z~1, 2004
  - -APEX ~1000, 200sqdeg, 2005
  - -ACT ~1000 clusters, 100 sqdeg, z~1.4, early 2006, photometric support from SALT
  - -SPT ~10,000 clusters, 4,000 sqdeg, z~1.2, 2007, photometric support from DES
- Satellite :
  - Planck, ~ 15,000 clusters, z~1, 2007
- And others …



CMB polarization large and small scale: Primordial gravity waves & CMB lensing …

Experiment	Location	Status
PIQUE	Ground	Observing
WMAP	L2	Observing
DASI	Ground	Observing
CBI	Ground	Observing
QUAD	Ground	Observing
Amiba	Ground	Building

Experiment	Location	Status
EBEX	Balloon	Building
BICEP	Ground	Observing
Quest	Ground	Building
Maxipol	Balloon	Analyzing
Planck	L2	Building
Clover	Ground	Funded

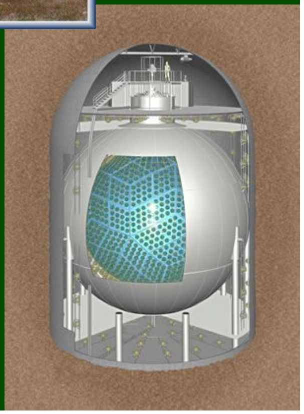


POLARBEAR

ClOVER

Ground based DIRECT detections vital counterpart

- Astrophysical sources detected on earth
  - Temper and test indirect observations
- Dark matter searches
  - CDSM - Soudan Mine, Minessota , US
  - UKDMC Boulby Salt Mine, Yorkshire ,UK
  - DAMA Gran Sasso underground lab, Italy
- LHC
  - Beyond the standard model
  - Existence of extra dimensions
  - Do scalar particles exist?



Conclusions

- WMAP now has full sky temperature and polarization maps
  - Polarization reionization signature breaks cosmological degeneracies
  - Simple ΛCDM cosmological model has survived its most rigorous test
  - Starting to constrain inflationary parameter space

- Rich prospects from combining/ correlating WMAP with other complementary data

- Future CMB polarization experiments promise of the universe when it was a trillionth of a second old

- Direct measurement on earth of dark matter particles / extra dimensions and a scalar particle will play a crucial role in progressing theoretical understanding