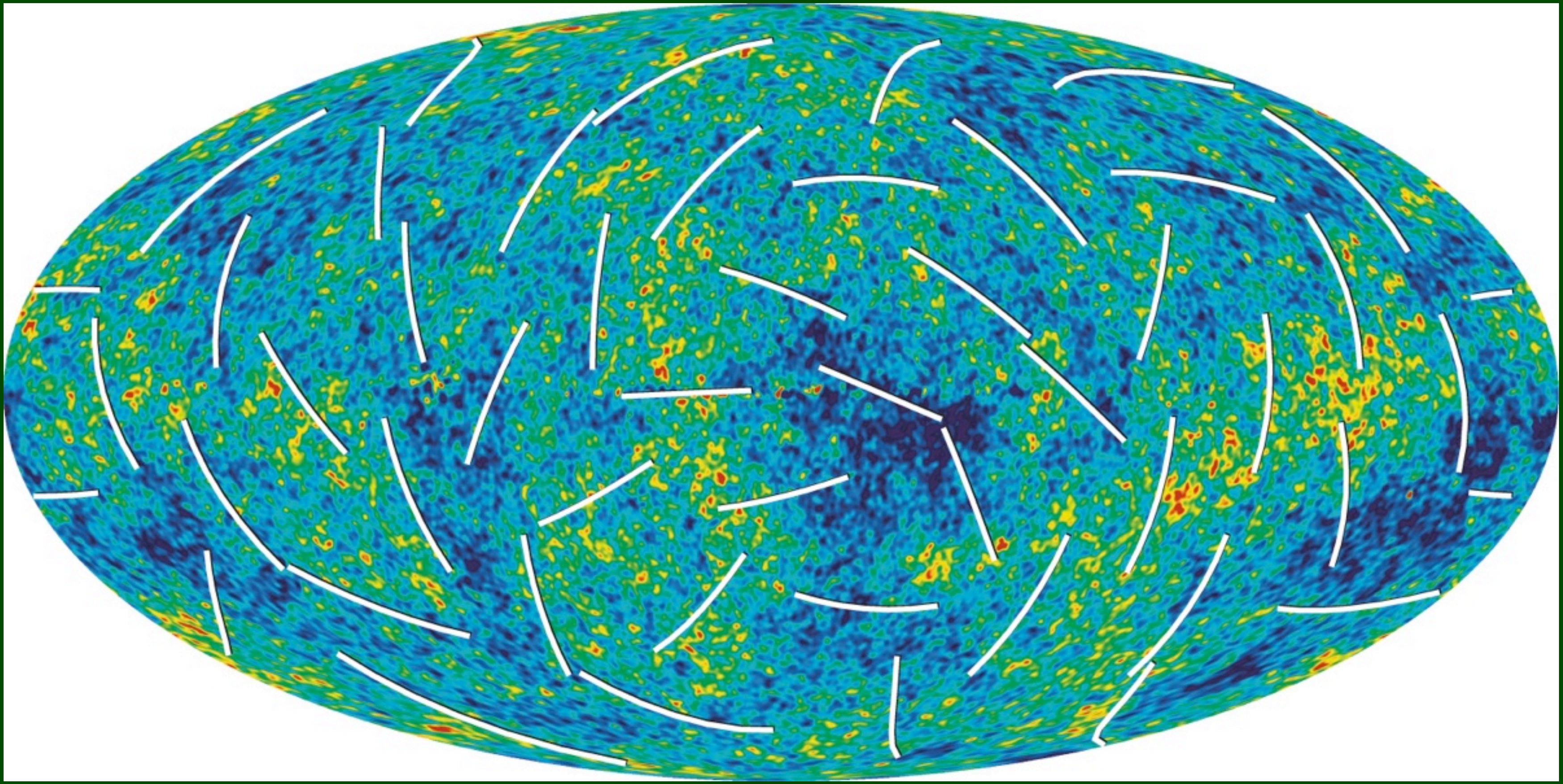
Cosmology from WMAP and Beyond



Rachel Bean

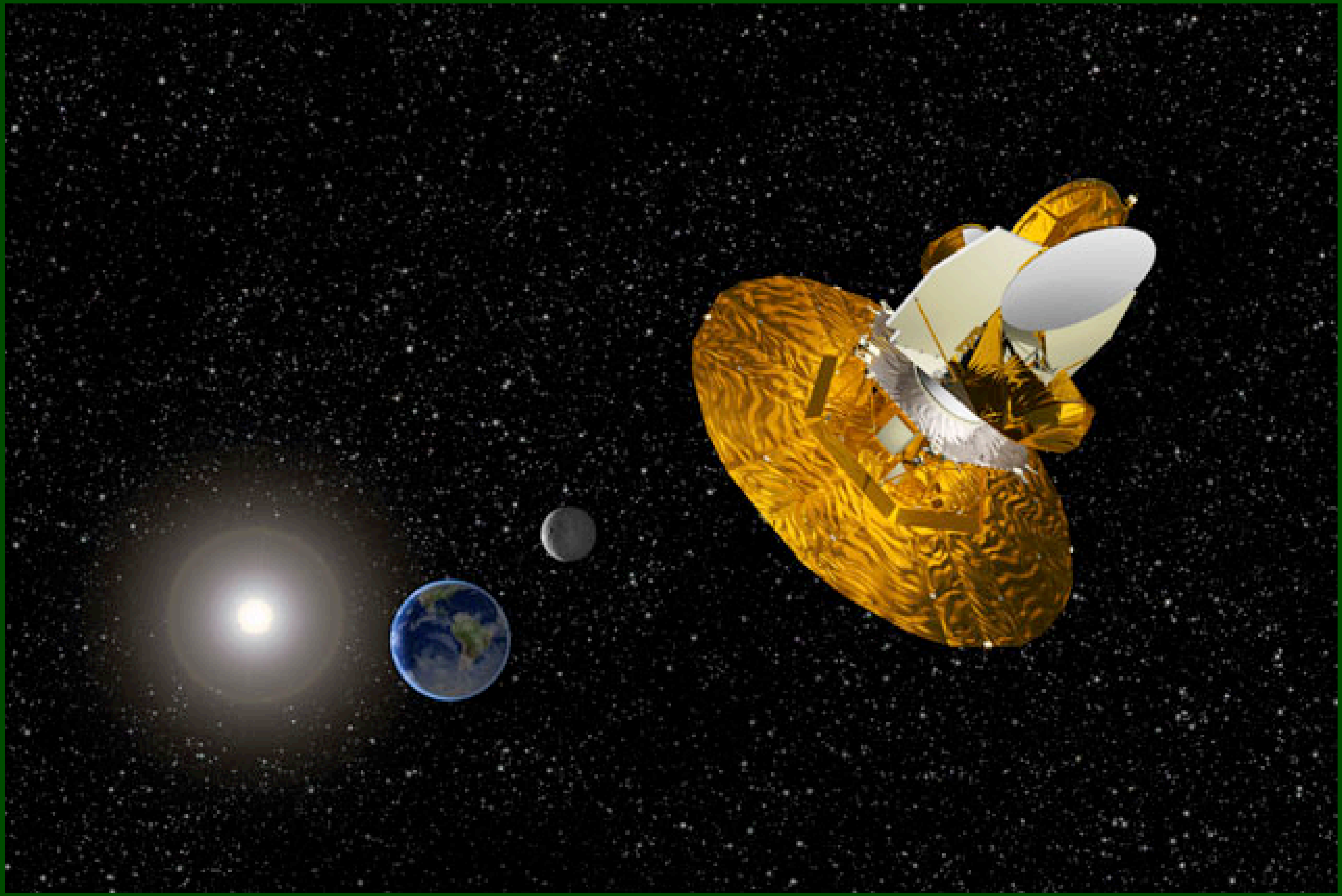
Fermilab 26th May 2006

Plan

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

What is WMAP?

- Satellite detecting primordial photons "cosmic microwave background"



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What is new with WMAP?

- 3 times more data
- Polarization maps
- More accurate understanding of the instrument

-> New cosmological implications

What Took So Long?

- Our detected polarization signal is weak
  - we have errors below 200 nanoKelvin

- Making a convincing detection of large-scale polarization required understanding:
  - the experimental systematics,
  - modeling the interplay between noise and scan strategy and
  - understanding galactic emission

What is New?

- Improved Gain (instrument responsivity) Model
- Improved Beam Model and more accurate treatment of sidelobes
- Improved Noise Model (uses real data rather than sims)
- Improved Foreground Model
- Finer pixelization
- Exact treatment of likelihood for large scale temperature and polarization

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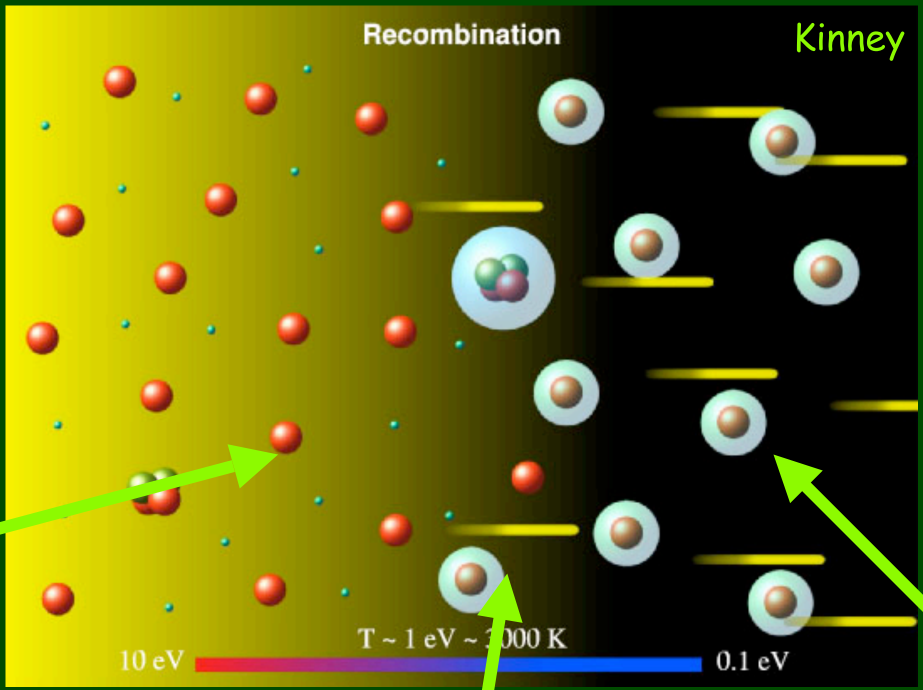
CMB is a near perfect primordial blackbody spectrum

Universe expanding and cooling over time...

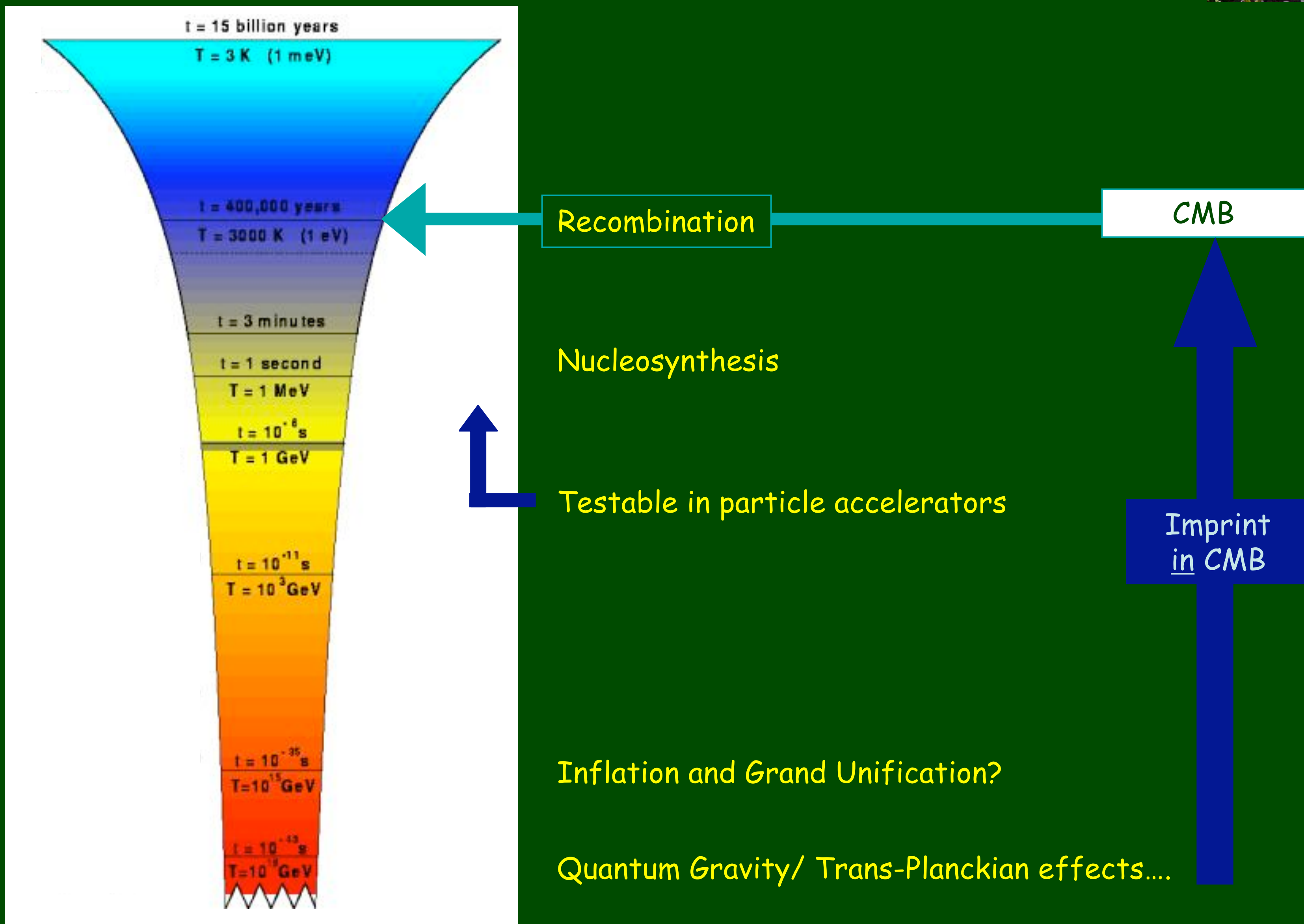


1) Optically opaque plasma

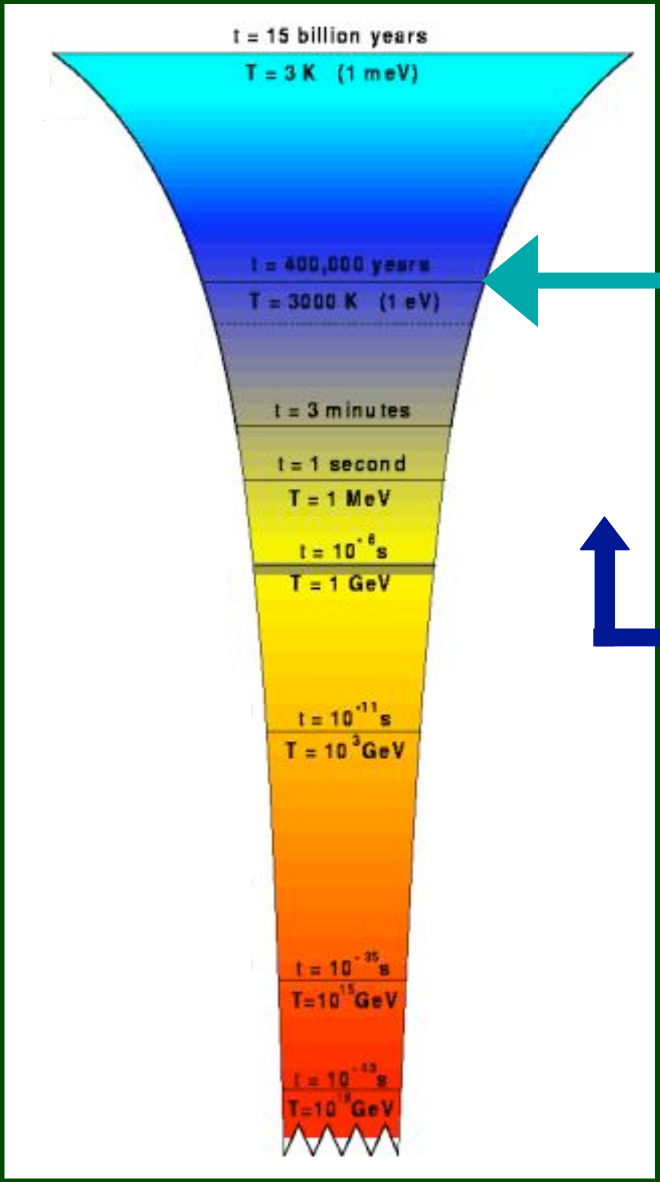
2) The 'last scattering' of photons ~400,000 years after the Big Bang,

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

The oldest fossil from the early universe



The cosmic equivalent of tree rings…



Dark Energy domination

Reionization

Galaxy formation

Recombination

Nucleosynthesis

Testable in particle accelerators

Inflation and Grand Unification?

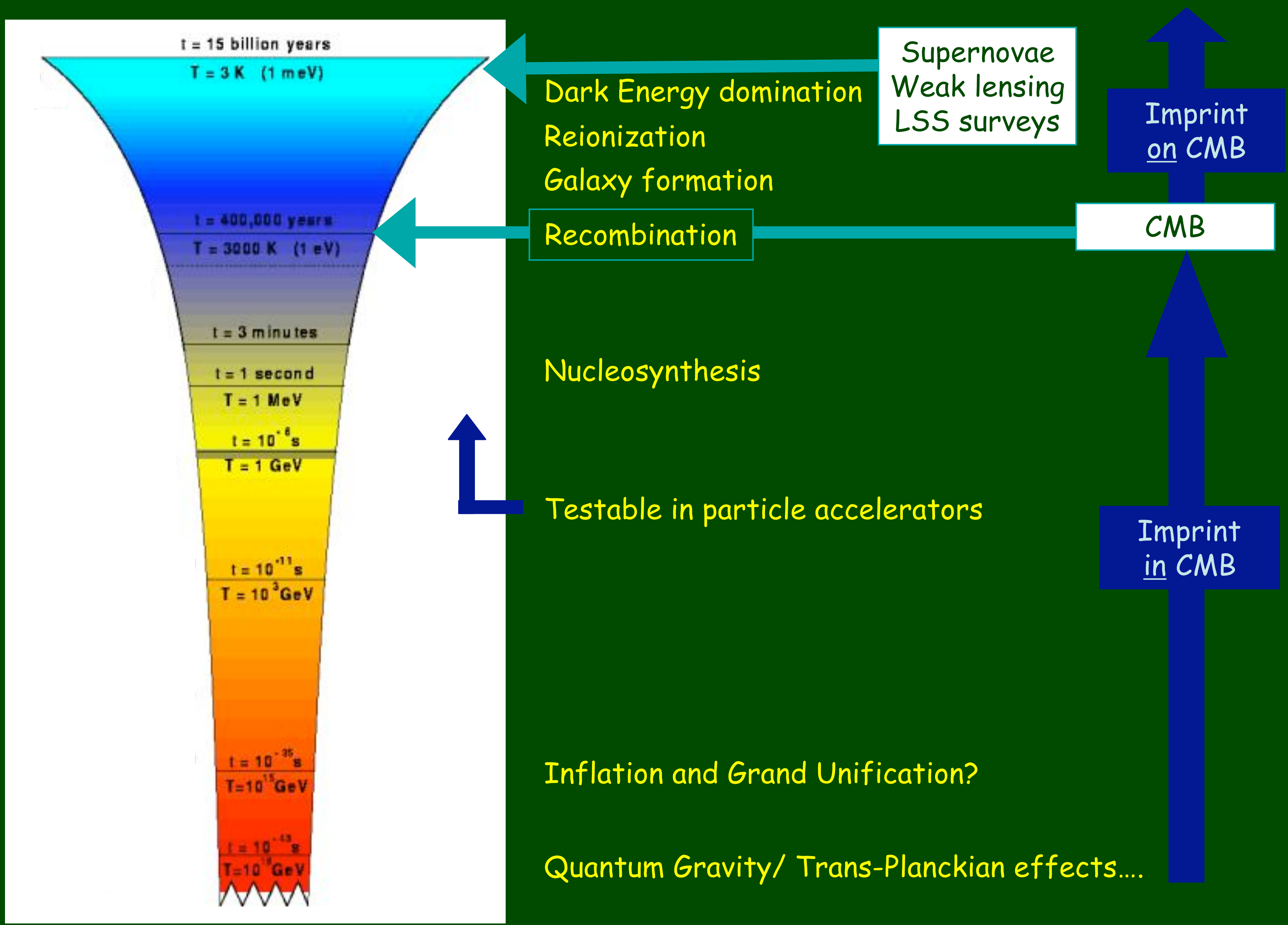
Quantum Gravity/ Trans-Planckian effects….

Imprint on CMB

CMB

Imprint in CMB

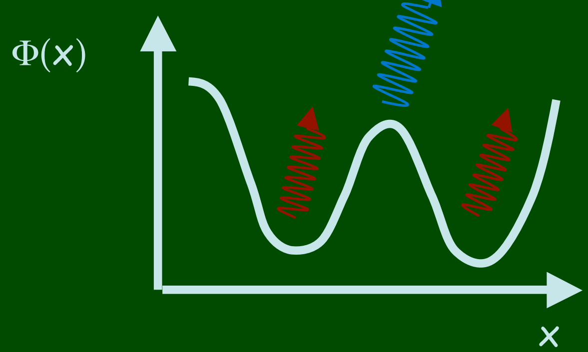
Important comparisons with later observations



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



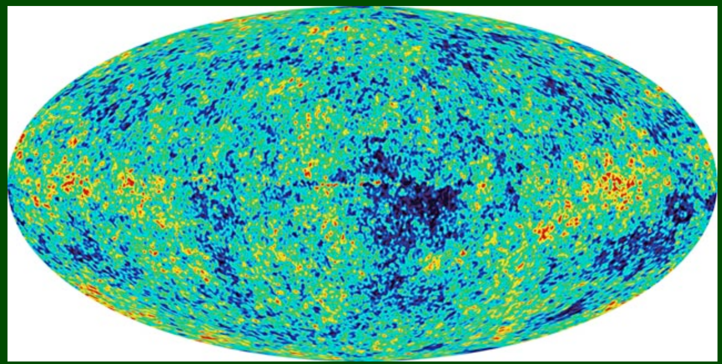
- Compton Scattering interactions in photon-electron/baryon fluid

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

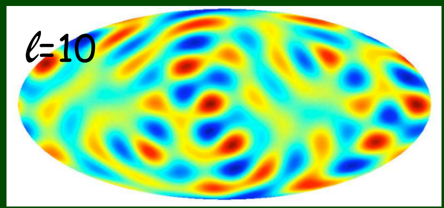
$\gamma \longleftrightarrow e^- \longleftrightarrow p^+$

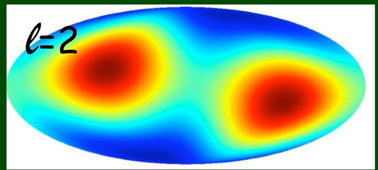
Compton scattering | Coulomb interaction

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



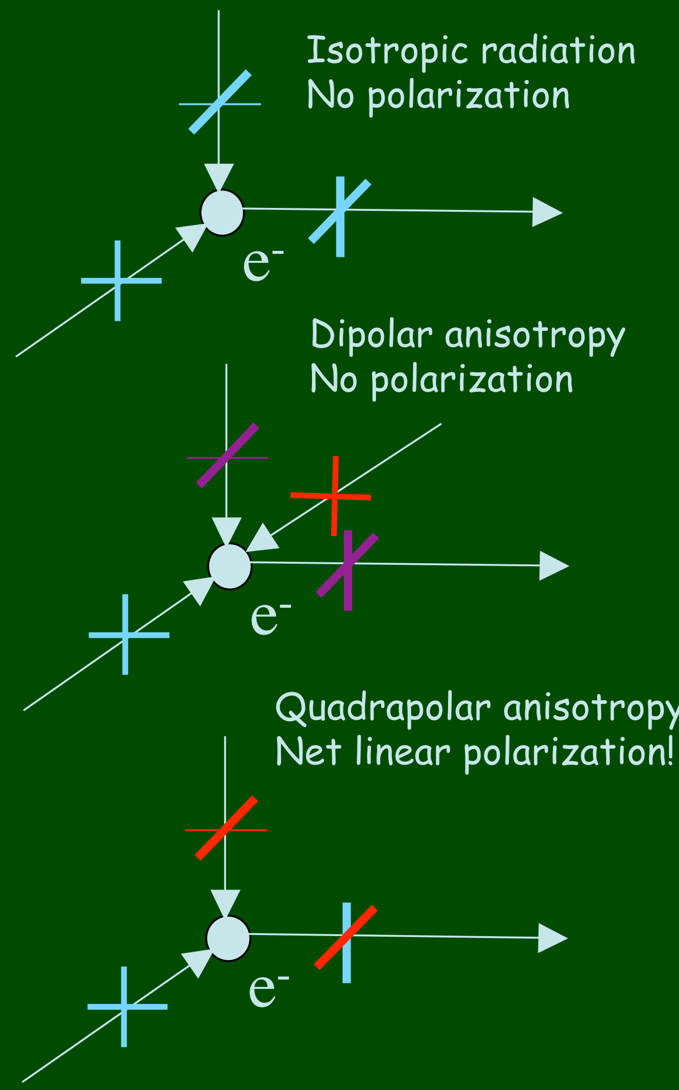
- Decompose into spherical modes on sky (ℓ ~ 1/angle).
  - Contribution of each mode -> Power spectrum





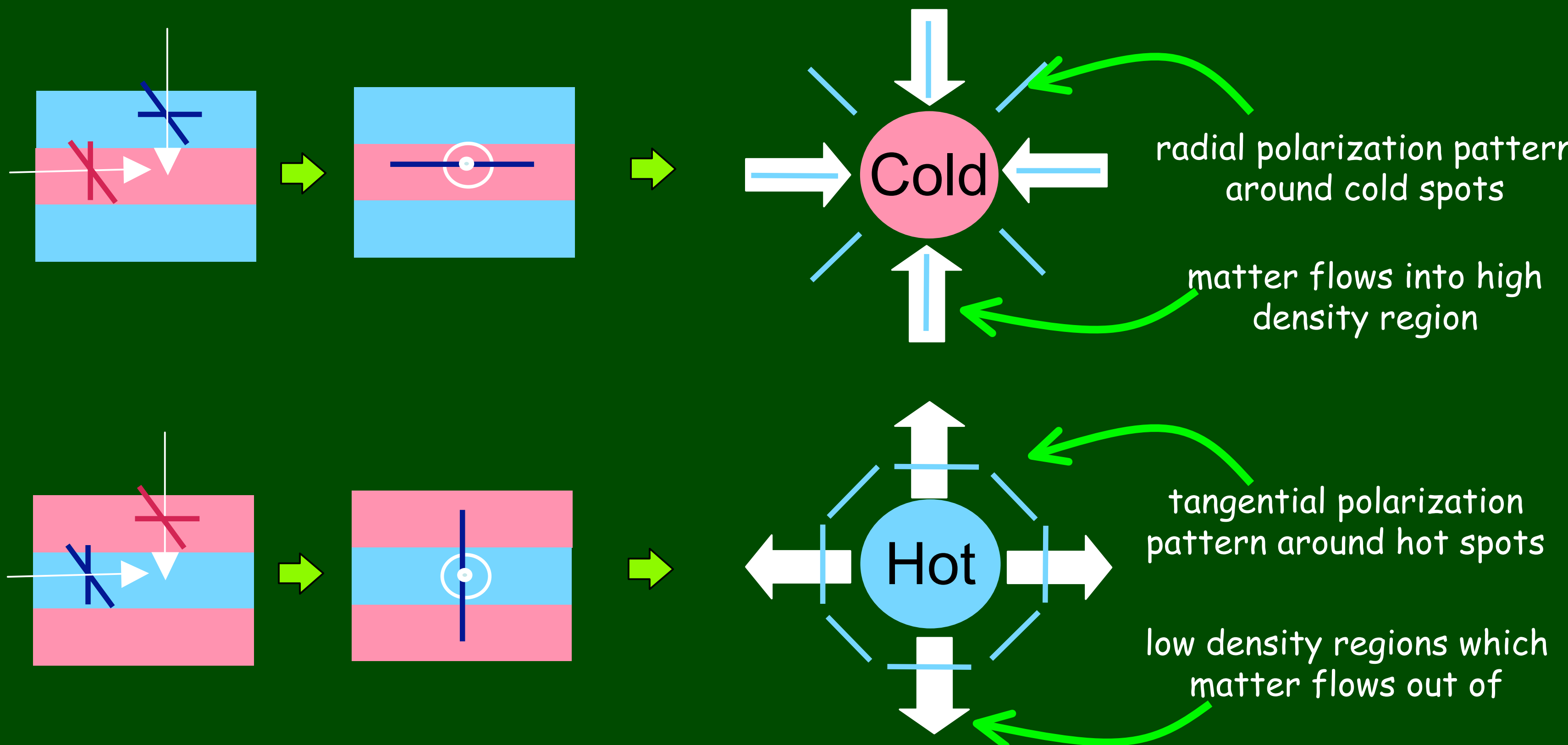
CMB scattering gives a "2 for 1": Polarization too!

- 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

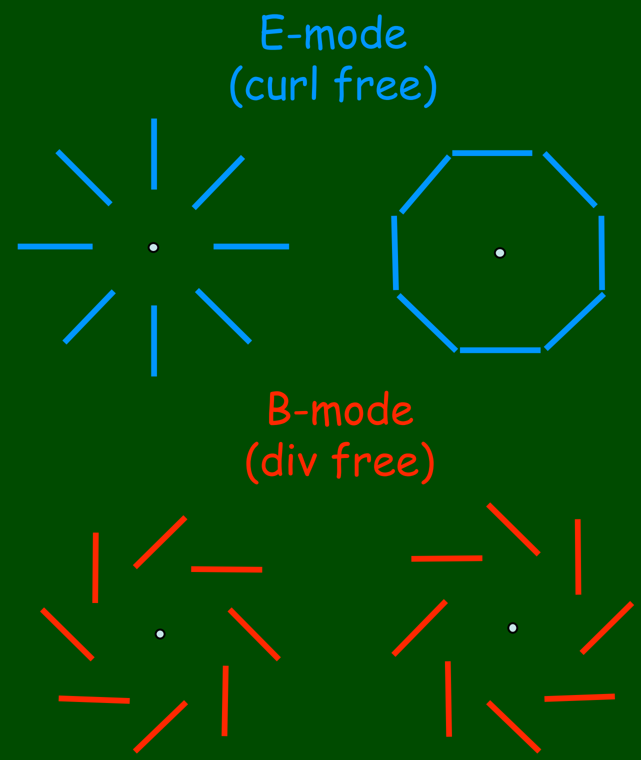
Temperature & polarization patterns correlated



- 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 rotationally invariant and nicely divides underlying processes
- 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



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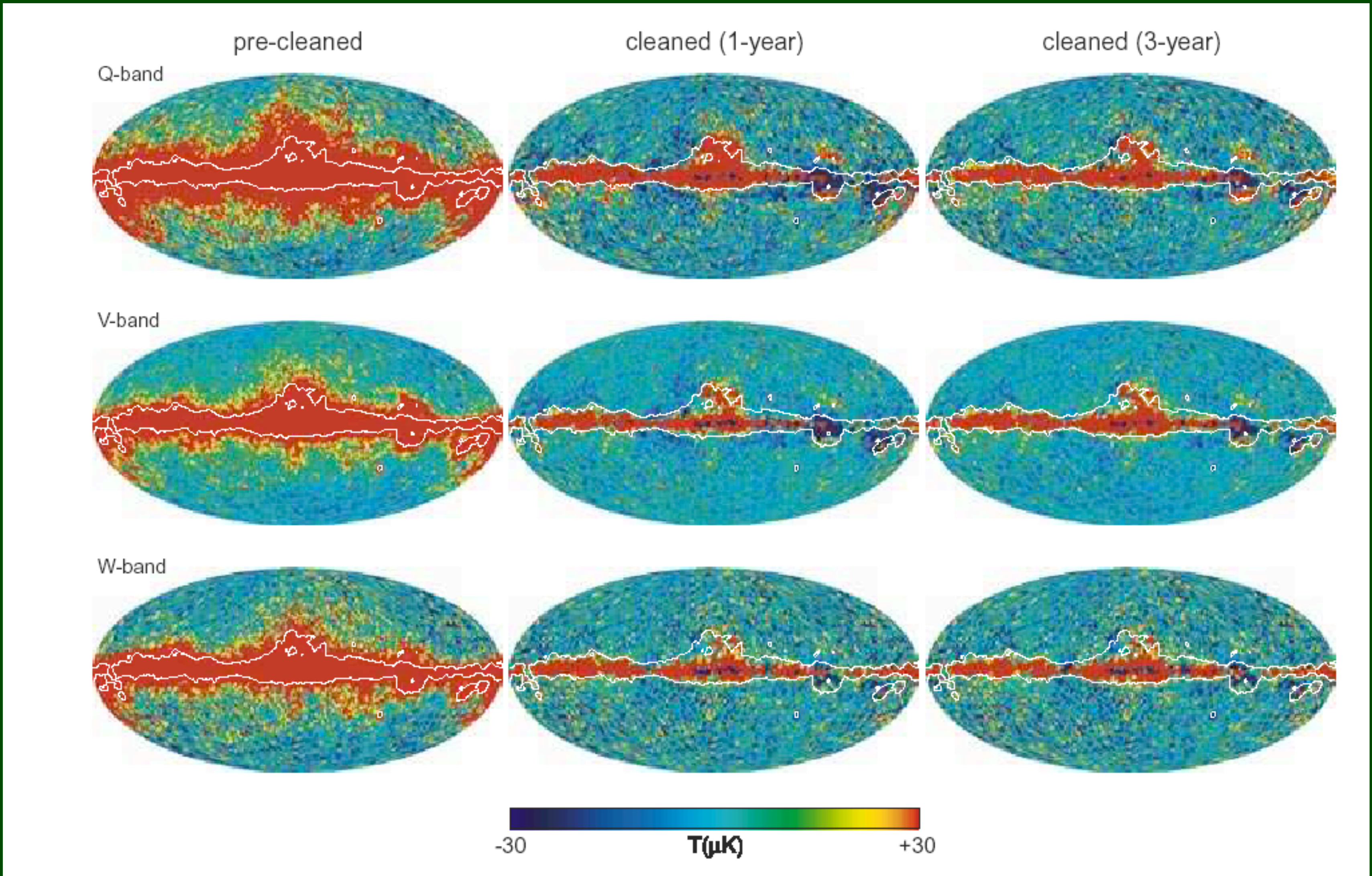
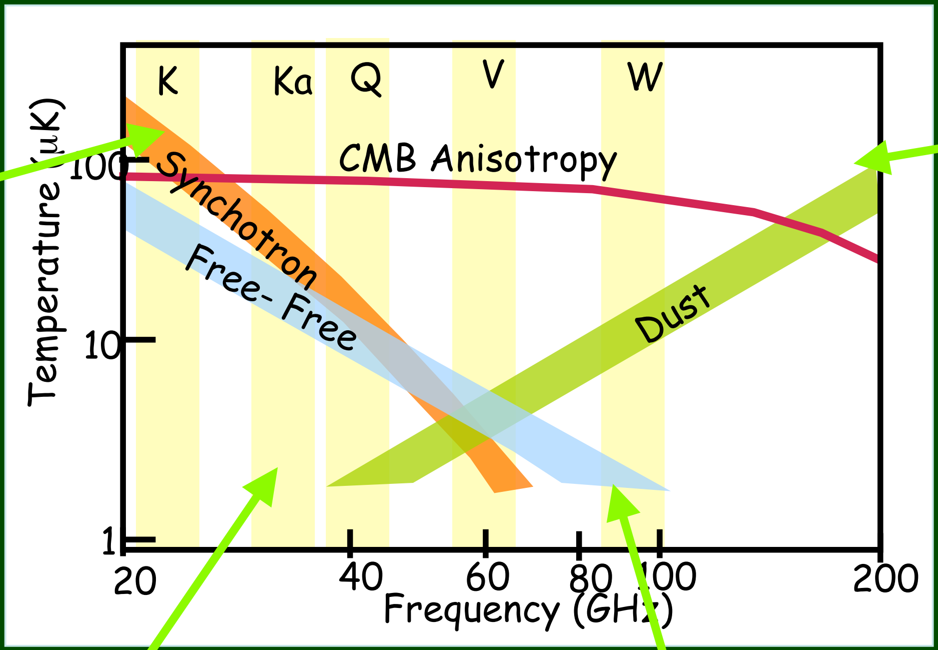
Temperature maps



Multiple maps help extract CMB from galactic contaminants



Synchroton emission

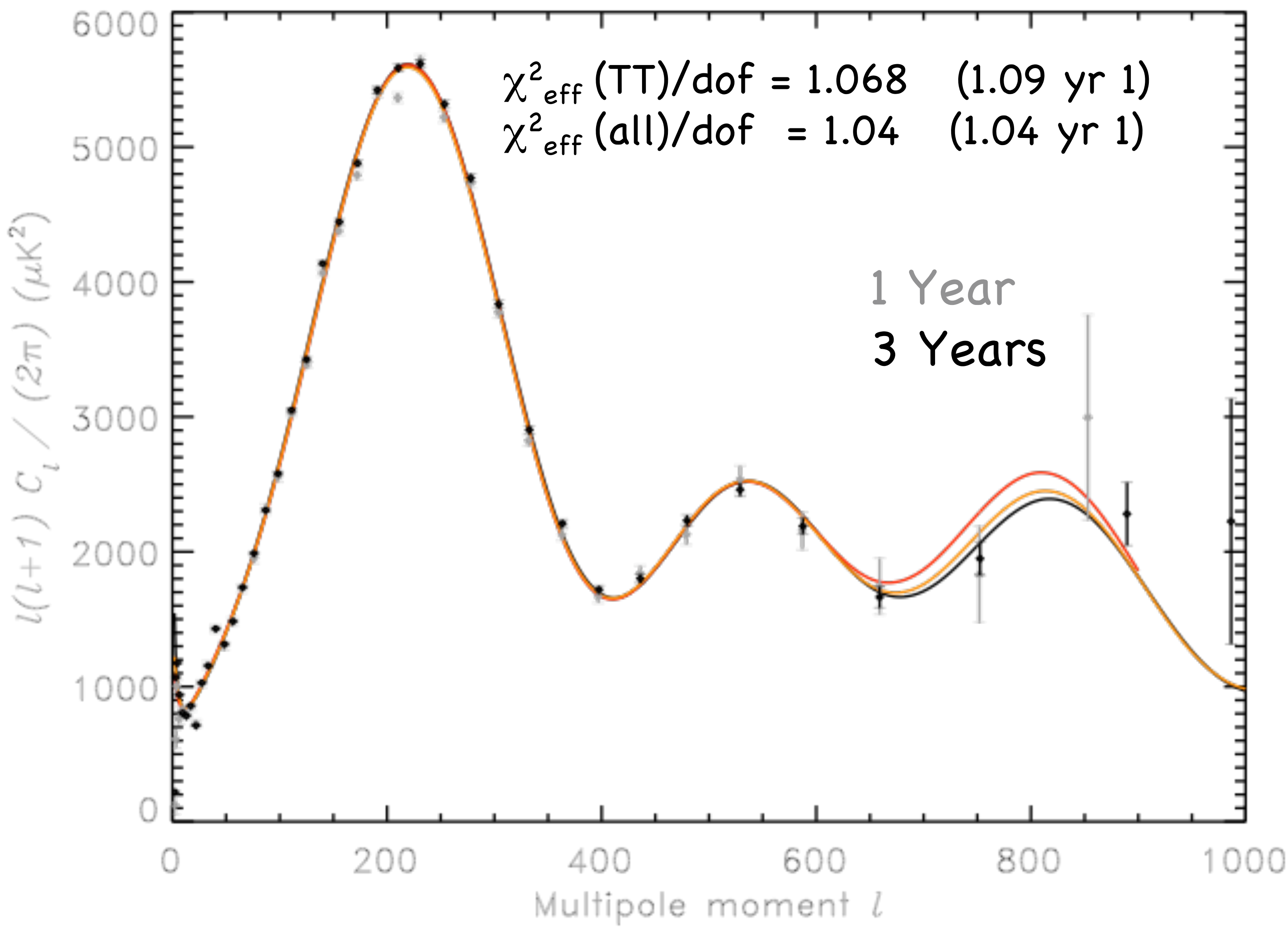
Thermal Dust

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

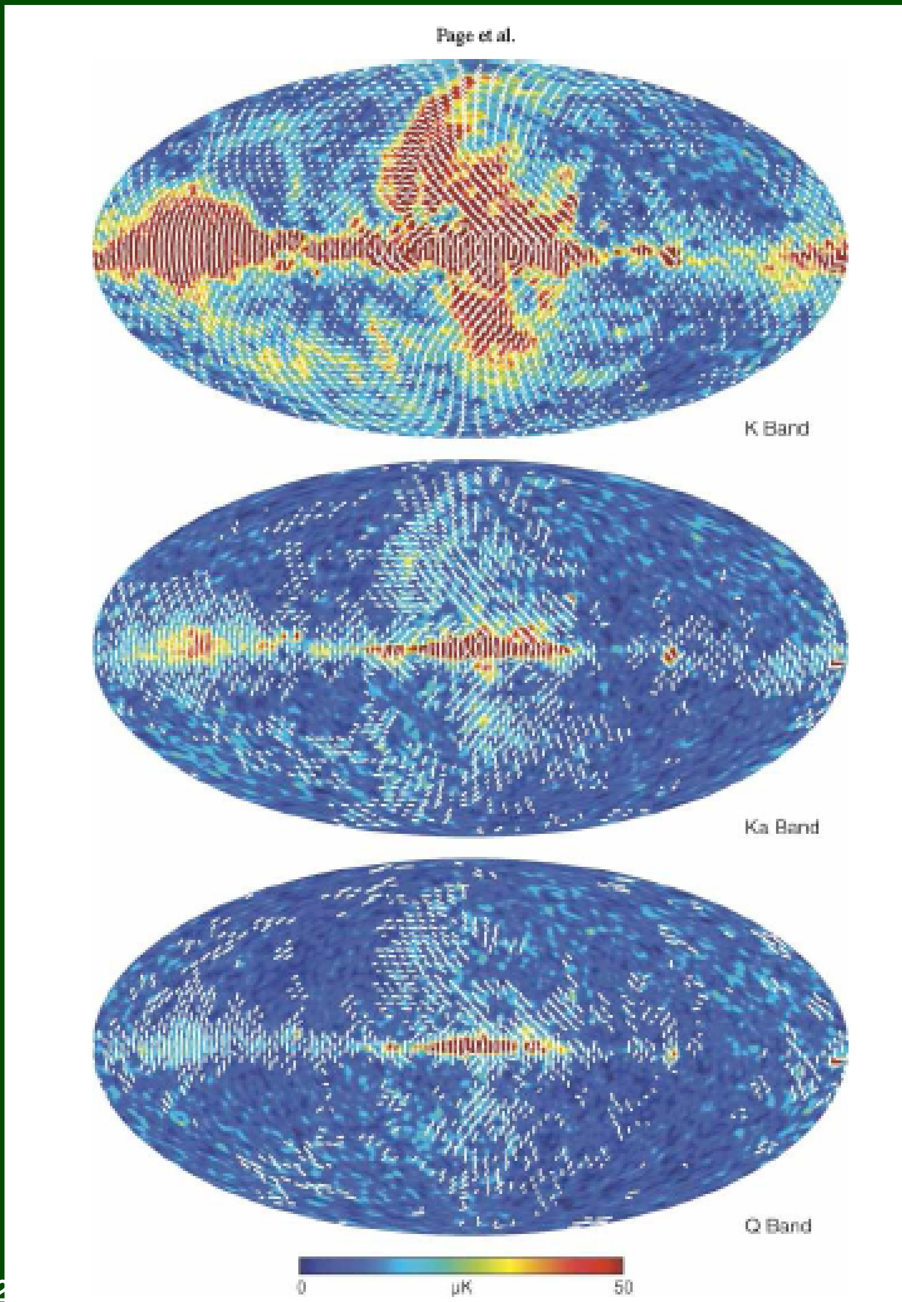
Free- free emission
-Electron-ion scattering

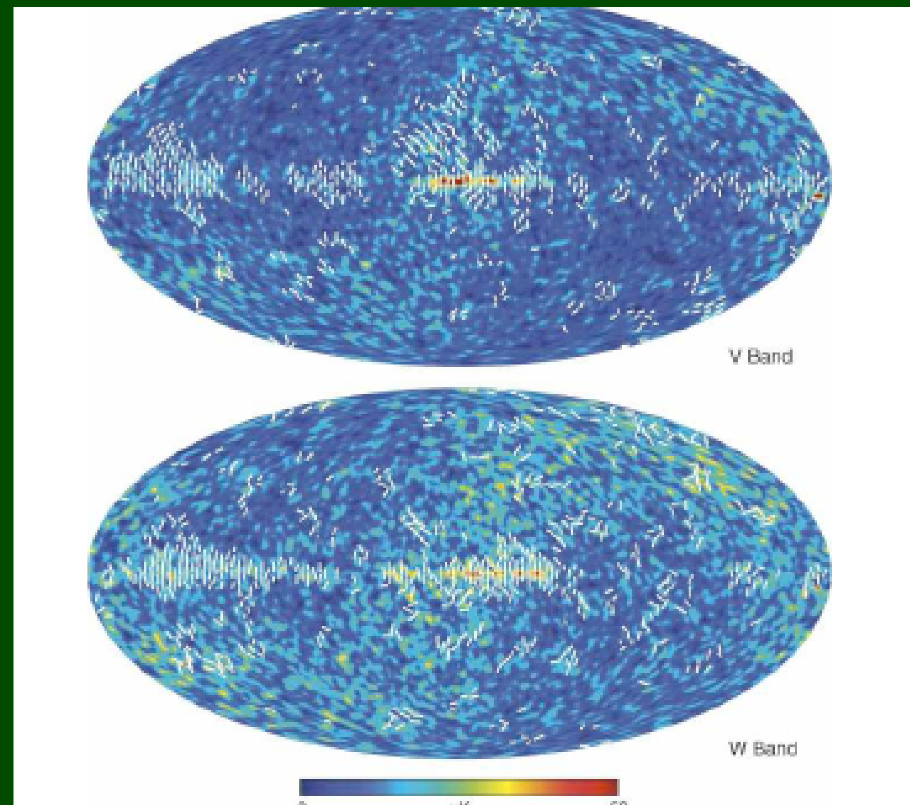
As well as remove other systematics e.g. 1/f noise from detectors

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



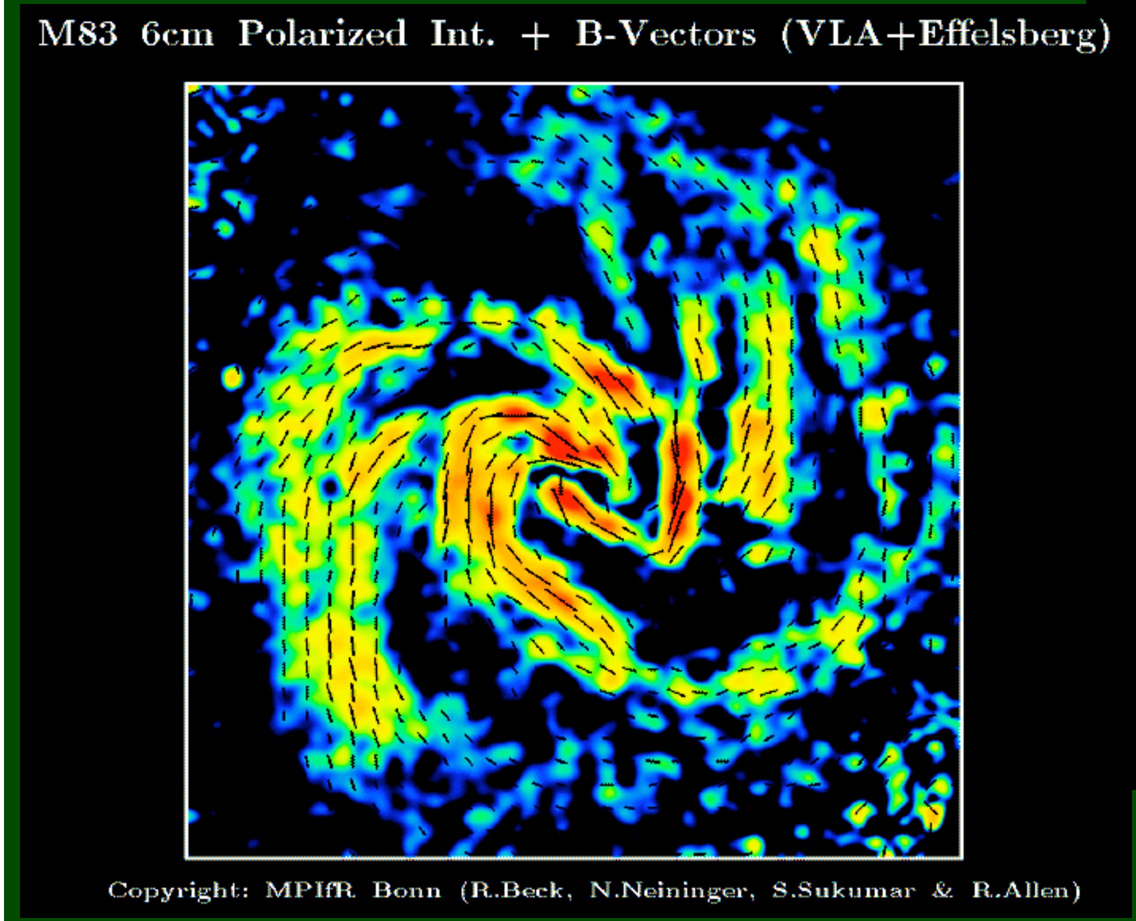
Polarization maps

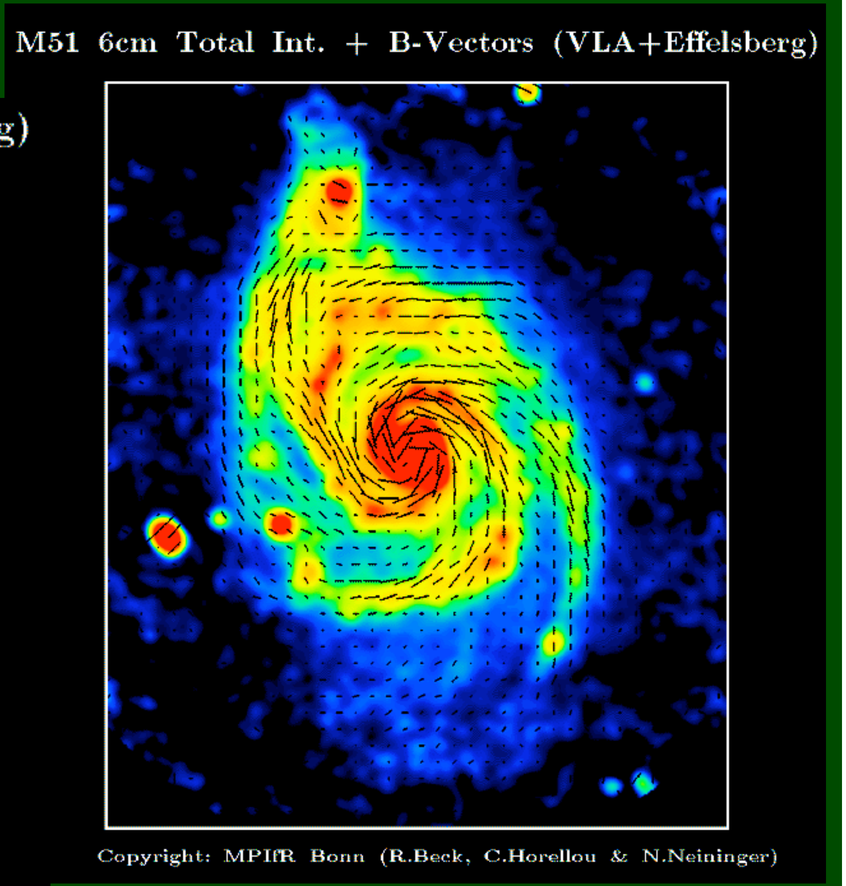




Polarized foregrounds - evidence of role of galactic magnetic field

Magnetic Field Structure in external galaxies exhibit spiral structure





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

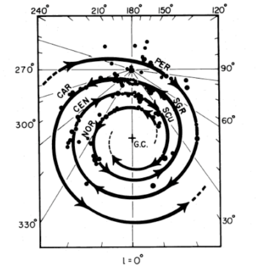
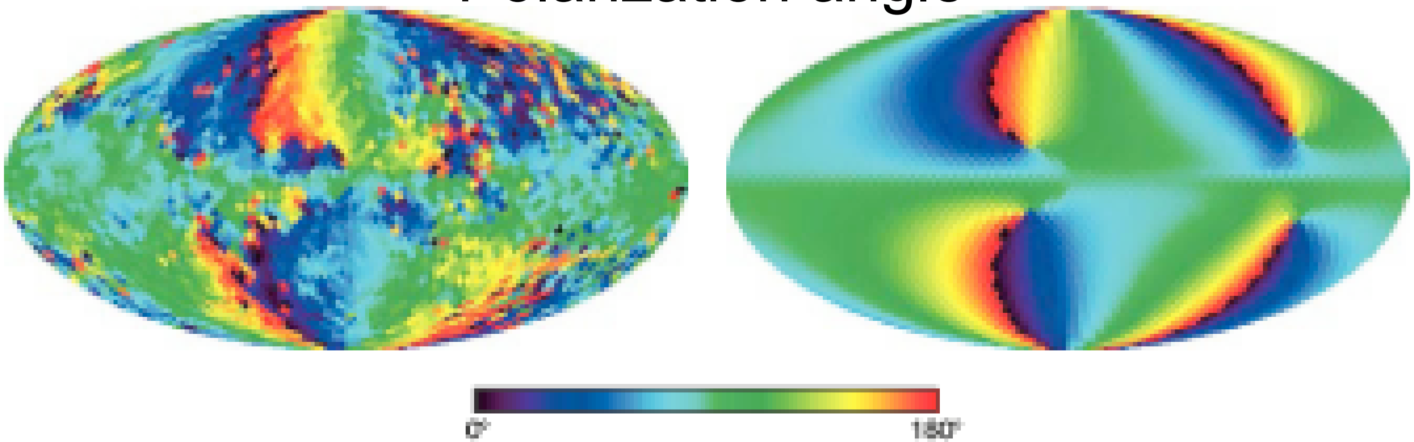
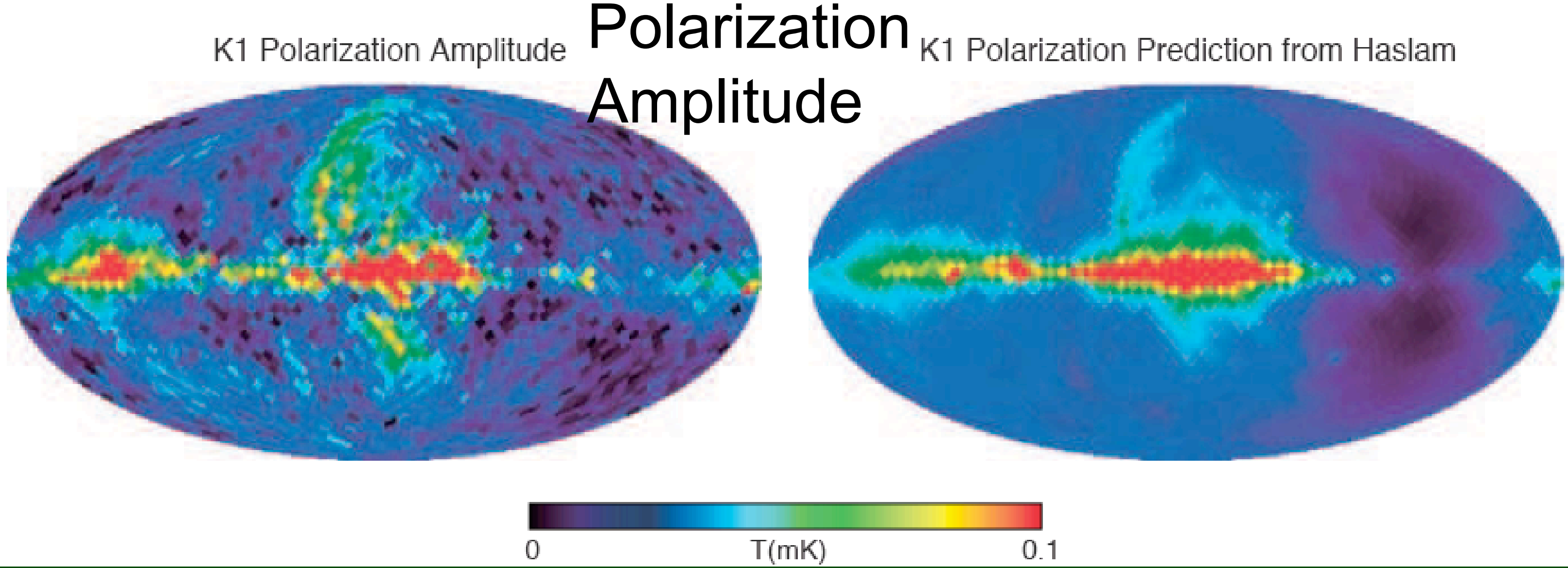


FIG. 4.—Possible, two-armed, bisymmetric spirals (*thick lines*) fitted to the distribution of H II regions (*filled circles*) given by Georgelin and Georgelin (1976). The arrows indicate the direction of magnetic field as inferred from Figs. 2 and 3.

Polarization angle



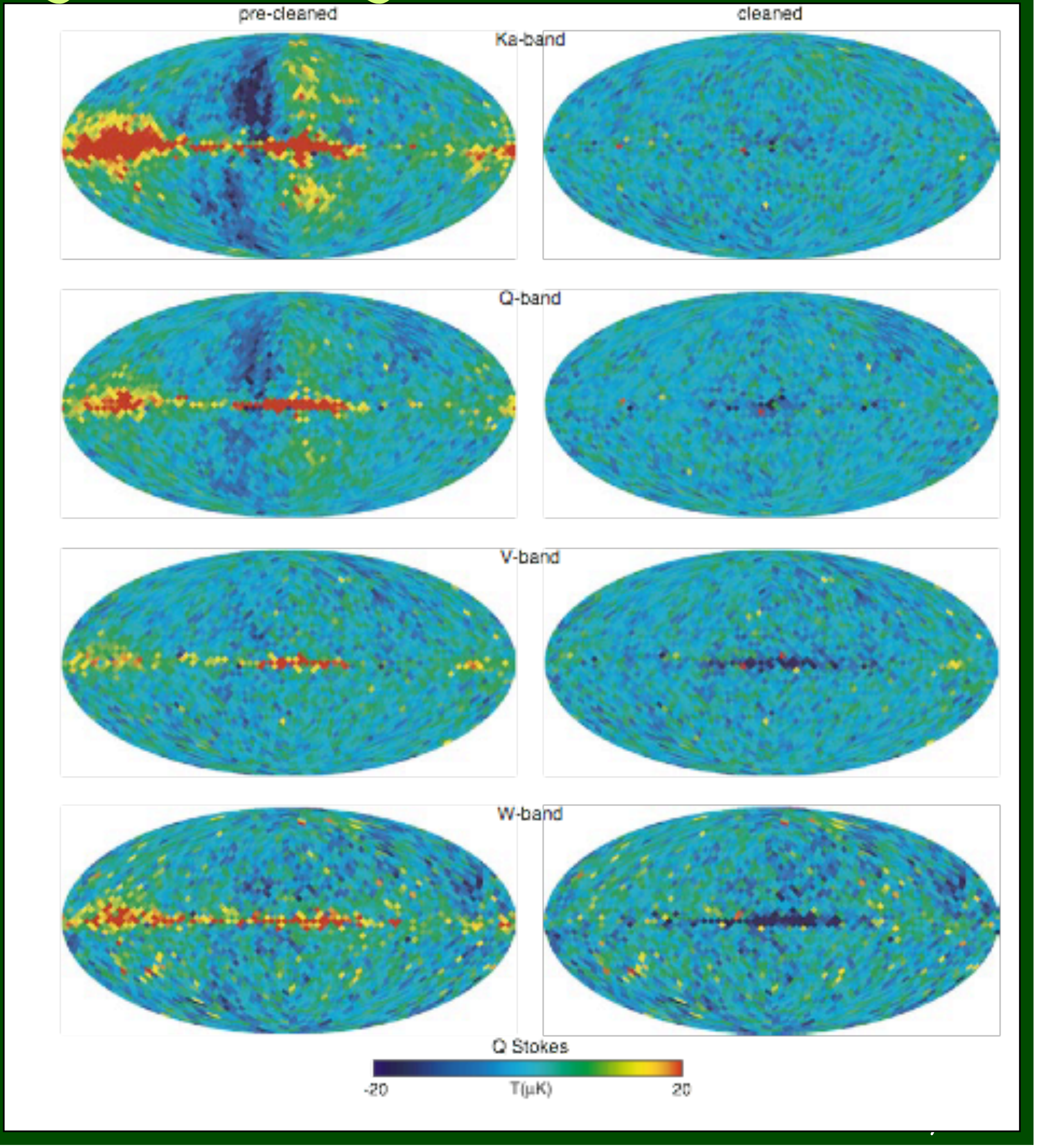
Polarization Amplitude



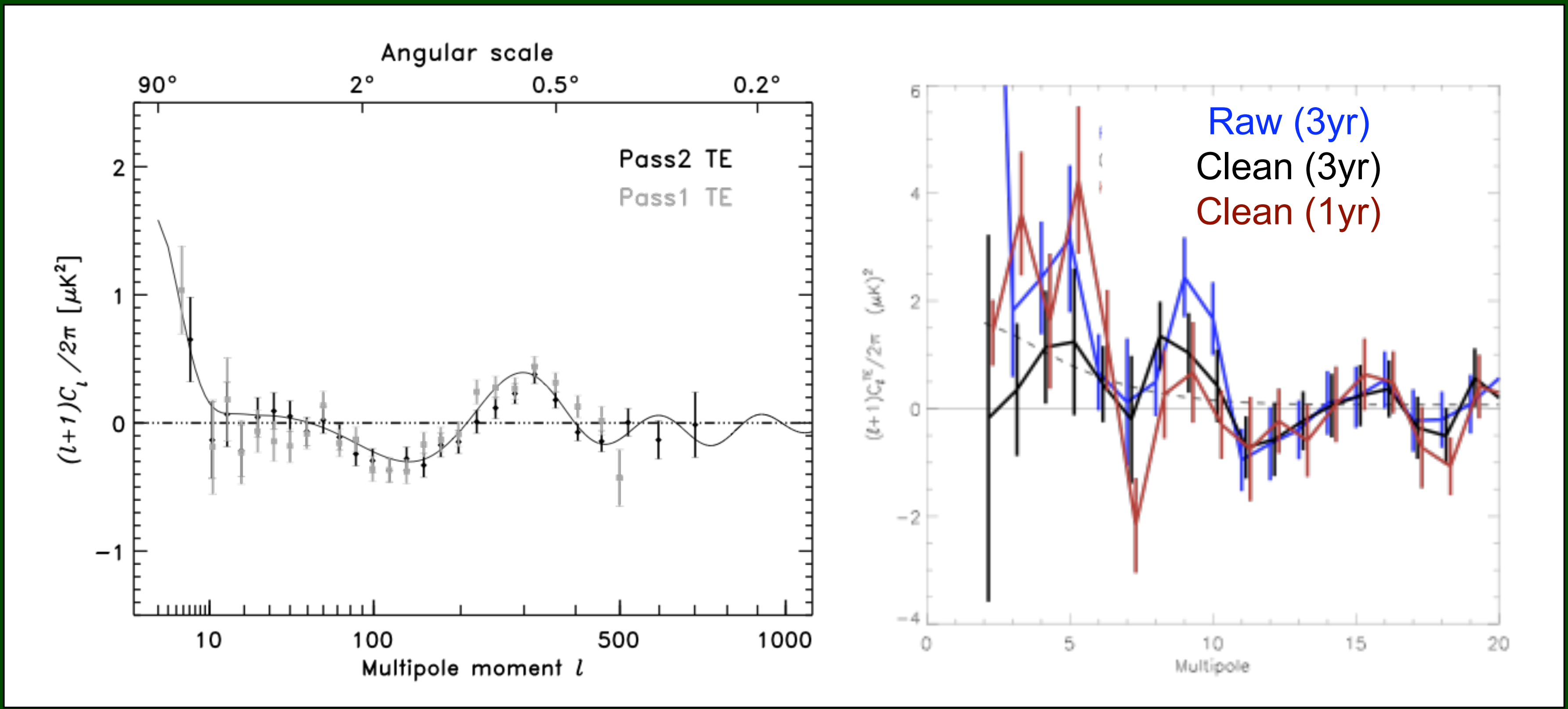
'Cleaning' out foregrounds

- K band data (synchrotron profile - galaxy magnetic field)
  + ILC dust map
  + starlight polarization (polarized dust) data
  used as a template to clean maps

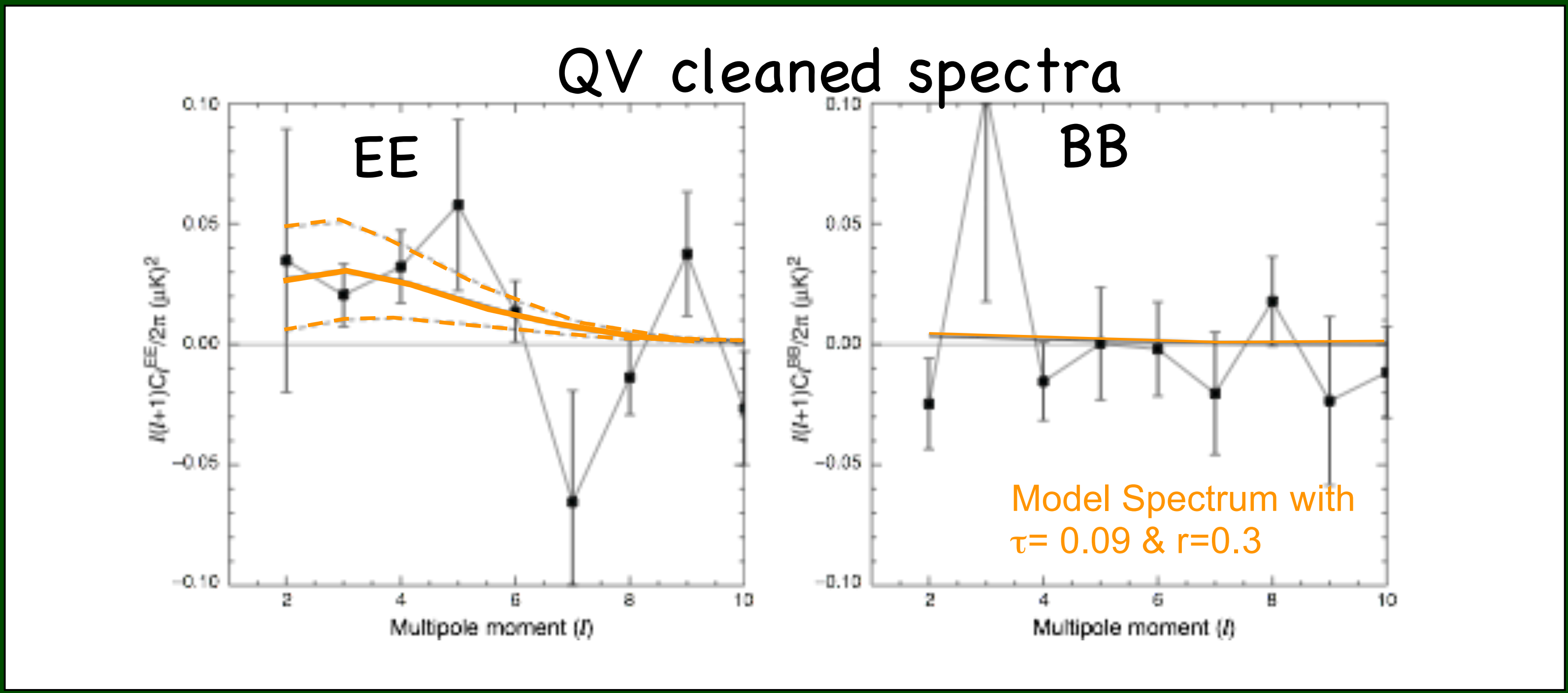
- Many people interested in galactic polarization (see Page et al) but from now on treat as contamination & look at cosmology!



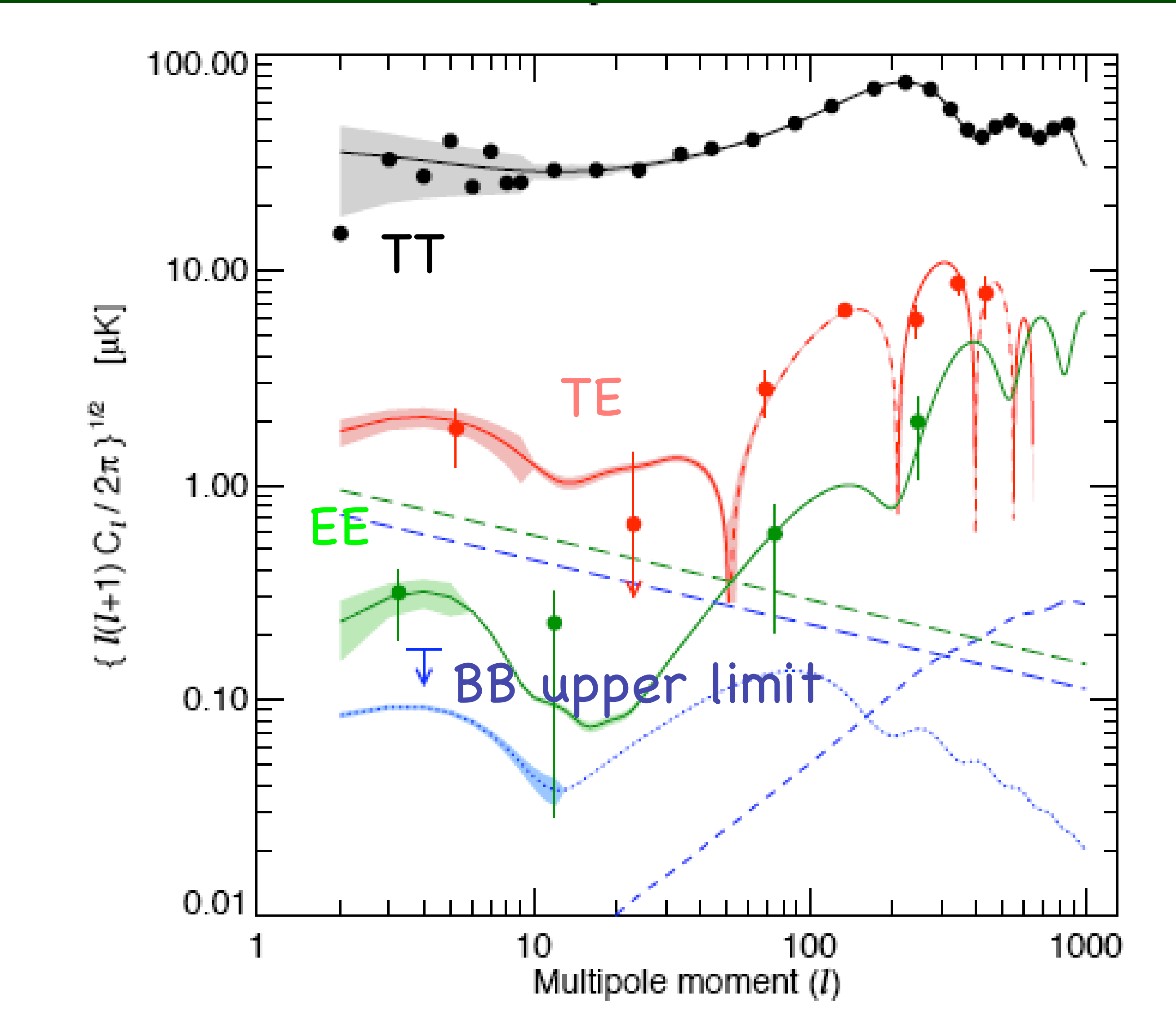
Better foreground model increased some TE errors (especially l = 2 and l=4)



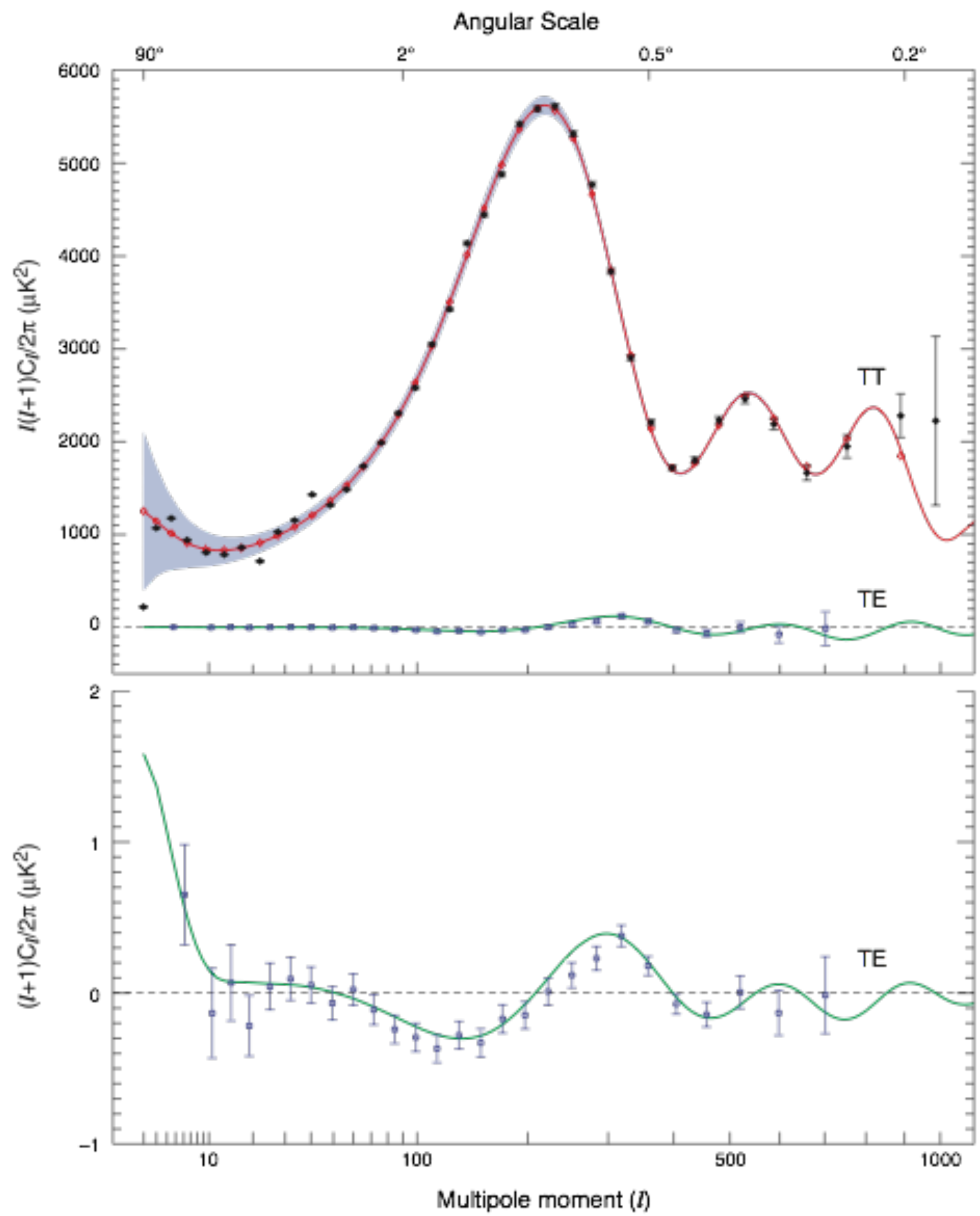
Large scale EE/BB polarization measurements



Summary of power spectrum results



Binned TT and TE spectra



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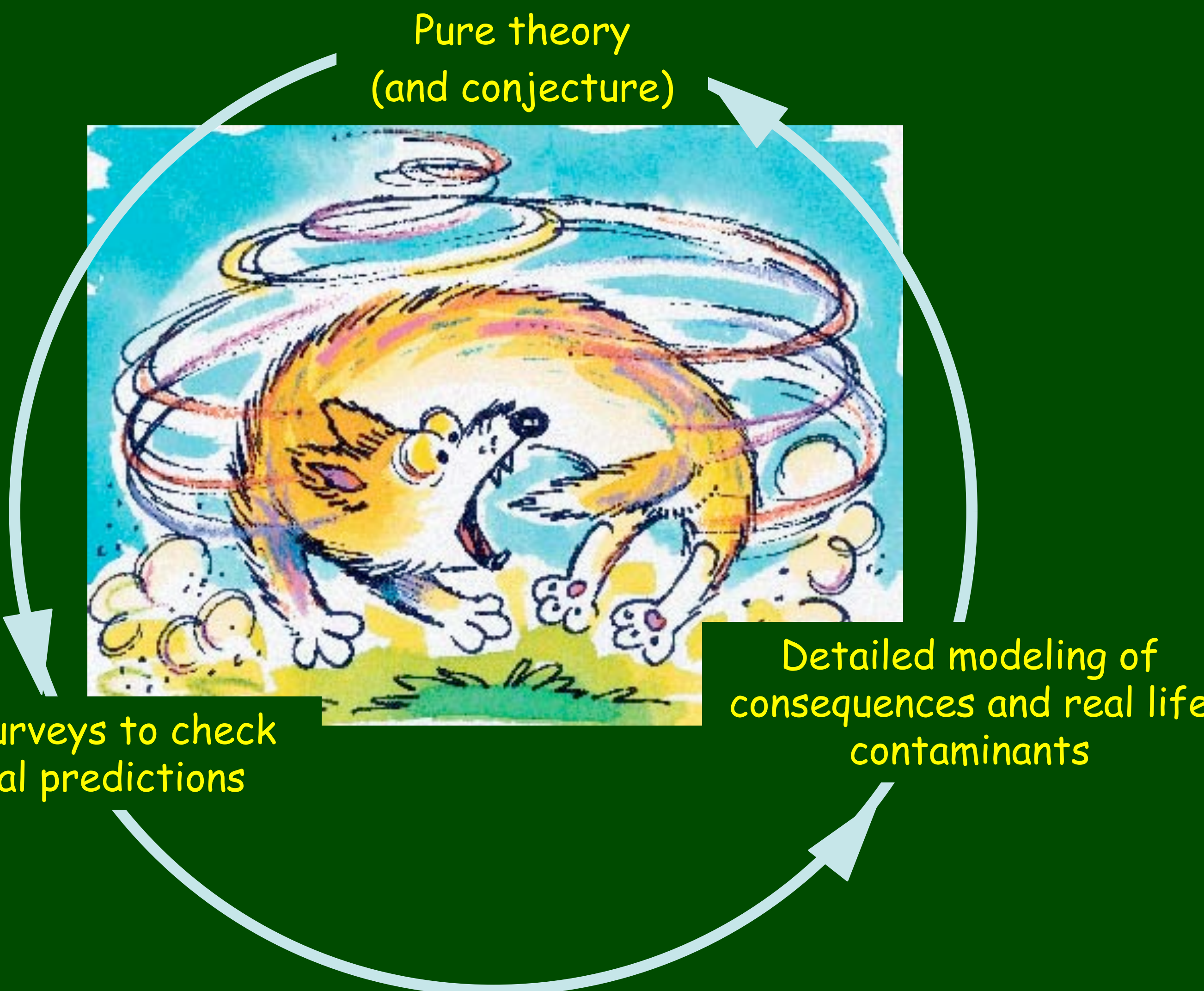
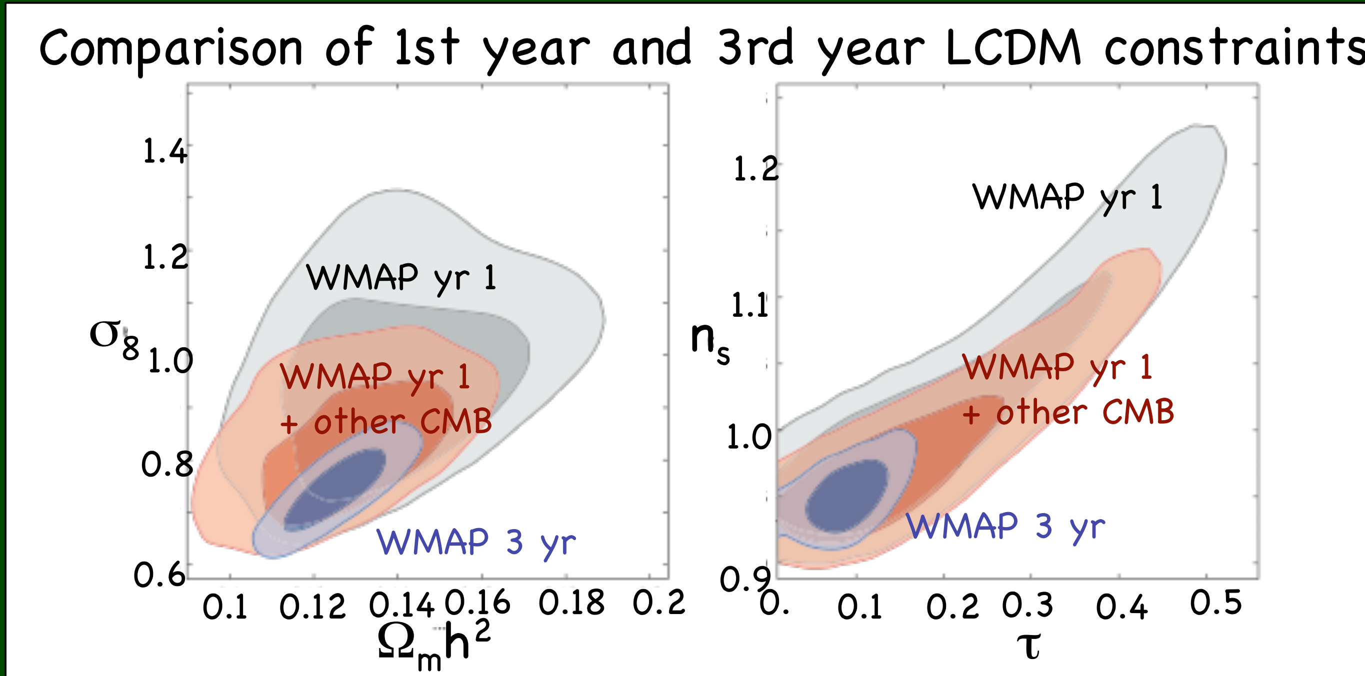
Cosmological discovery is an iterative process...

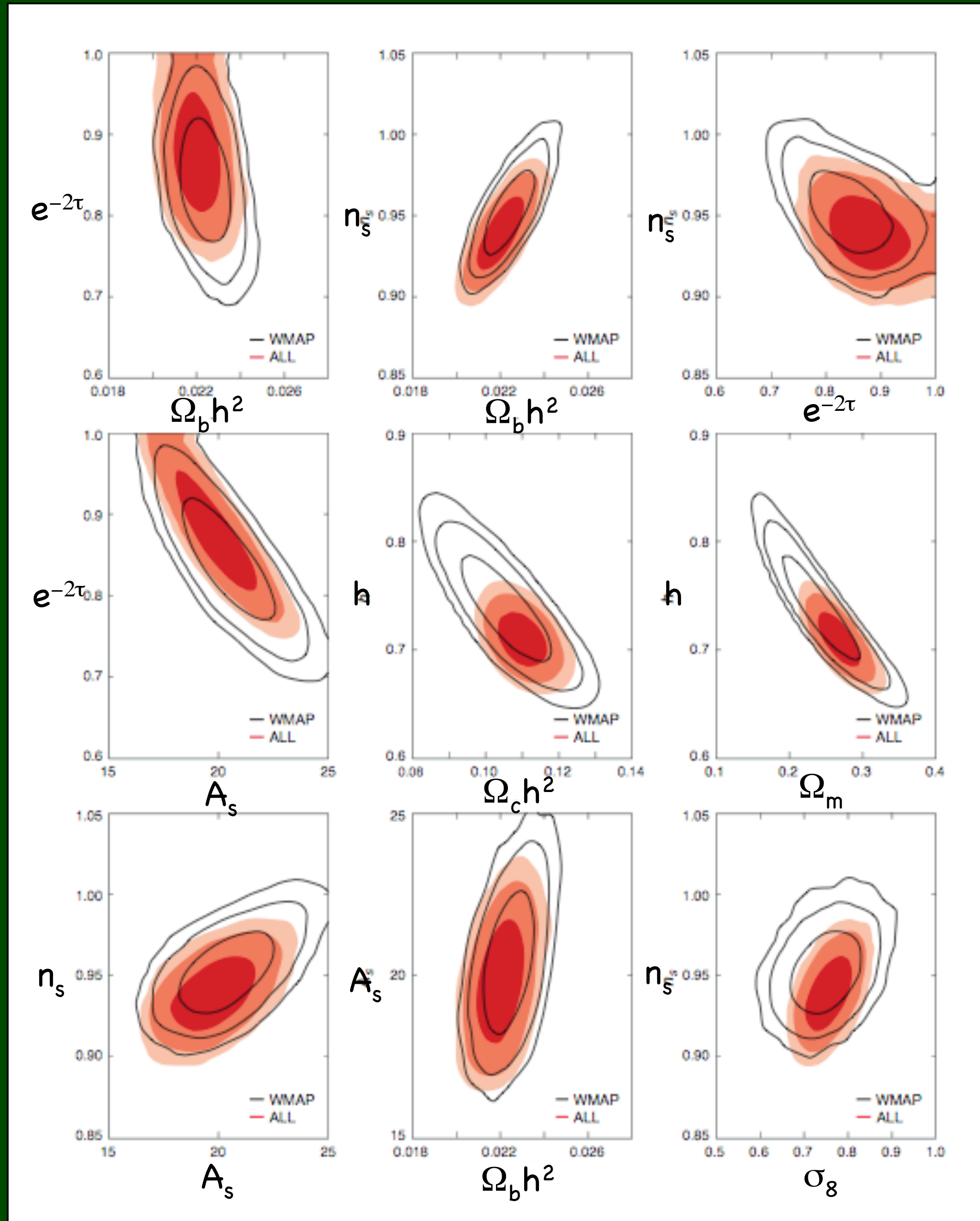


Improvement in Parameters from EE tau measurement

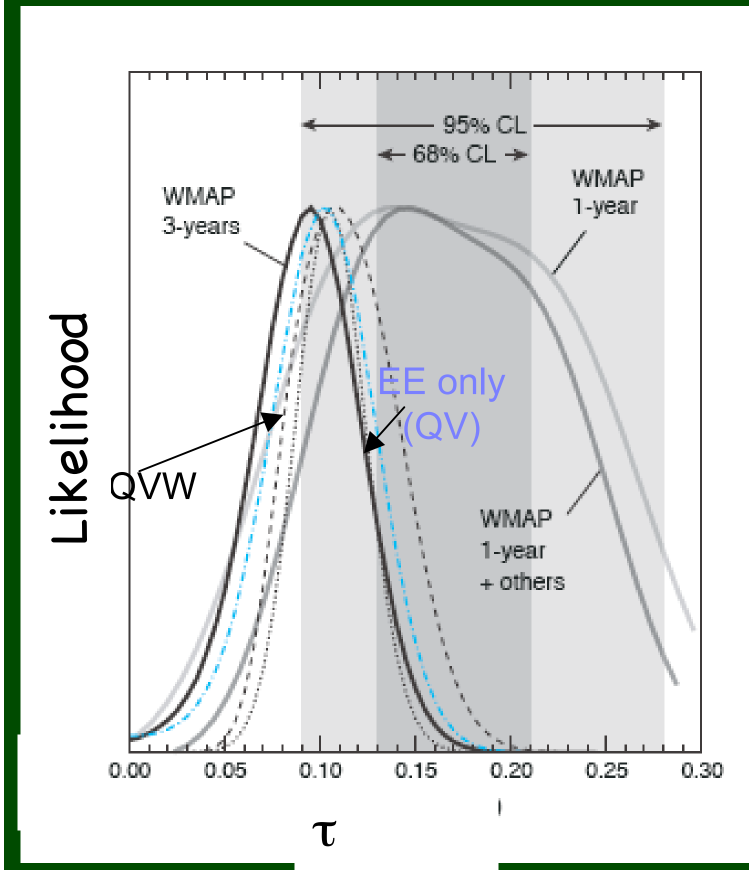


Parameter	First Year Mean	WMAPext Mean	Three Year Mean	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.30	2.21	2.22
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	0.145	0.138	0.128
H_0	72^{+5}_{-5}	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

LCDM: WMAP and WMAP+others

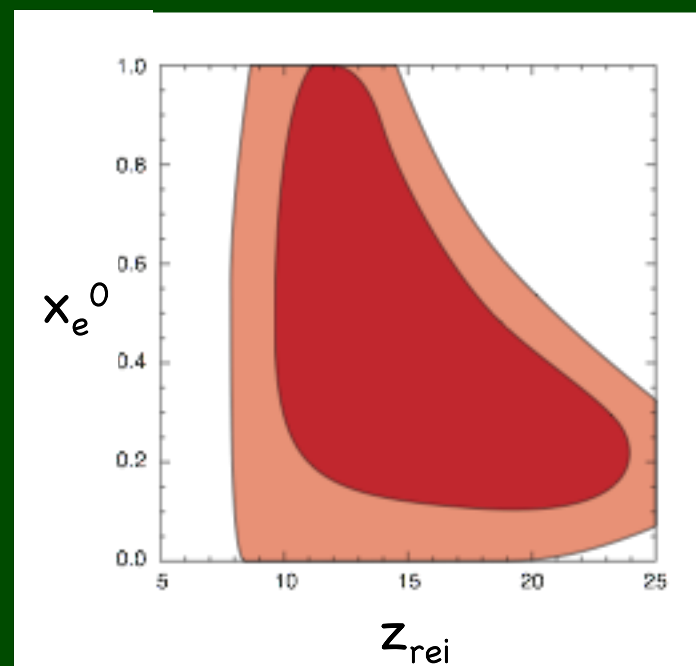


Likelihood Analysis of Optical Depth



- Exact likelihood treatment that includes both TE and EE data works directly with maps
- $\tau = 0 \Rightarrow \Delta\chi^2_{eff} = +8$ 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)



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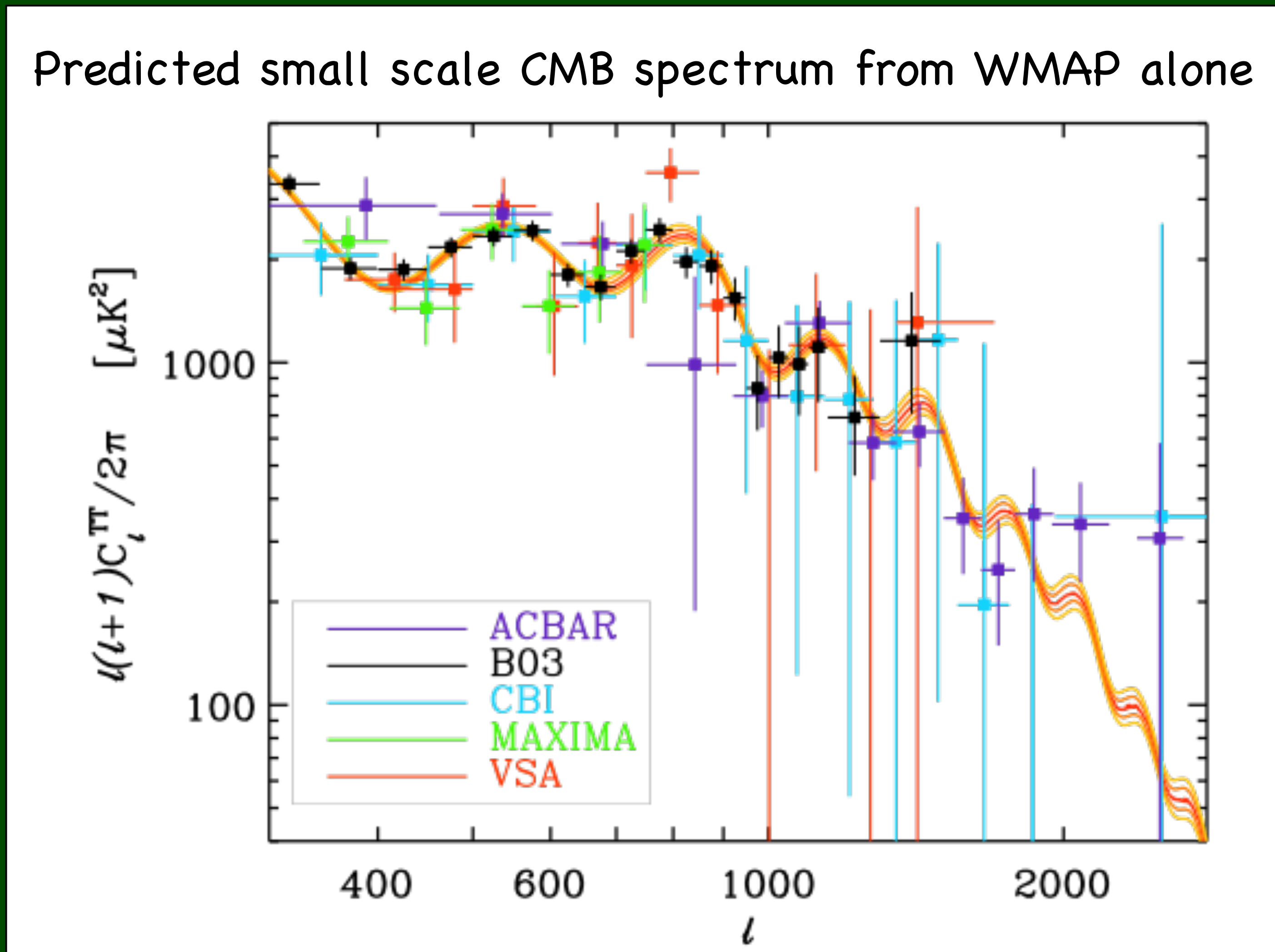
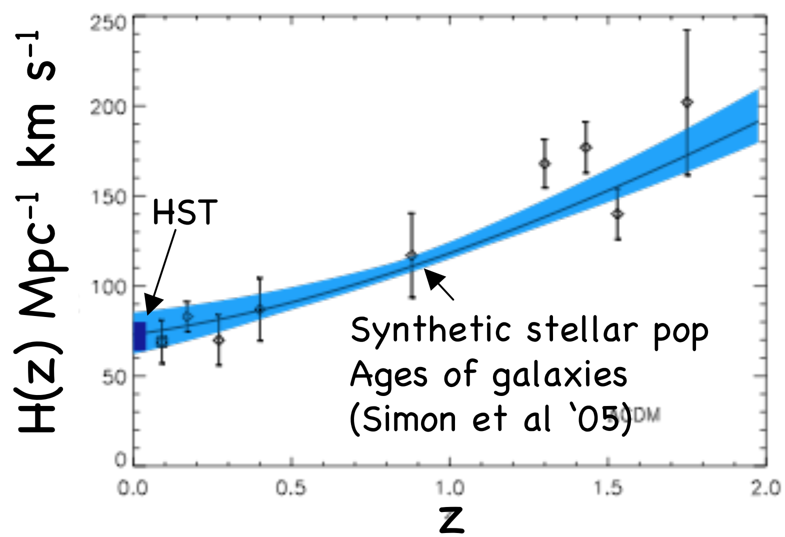
WMAP fits predict small scale CMB

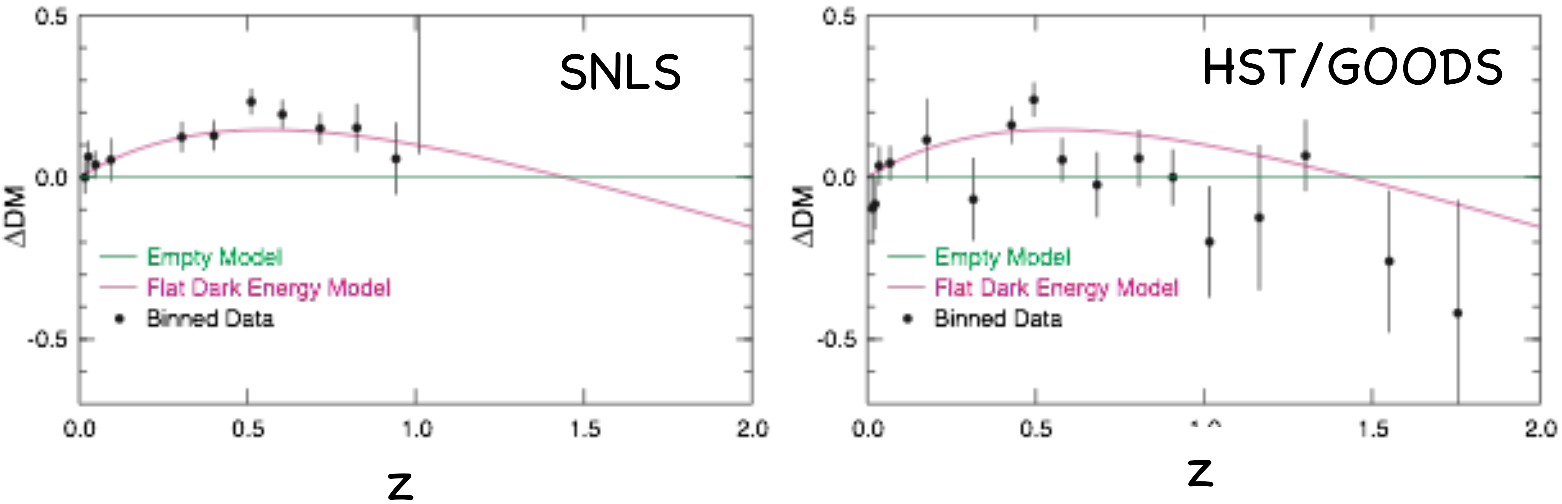


WMAP fits predict H(z)

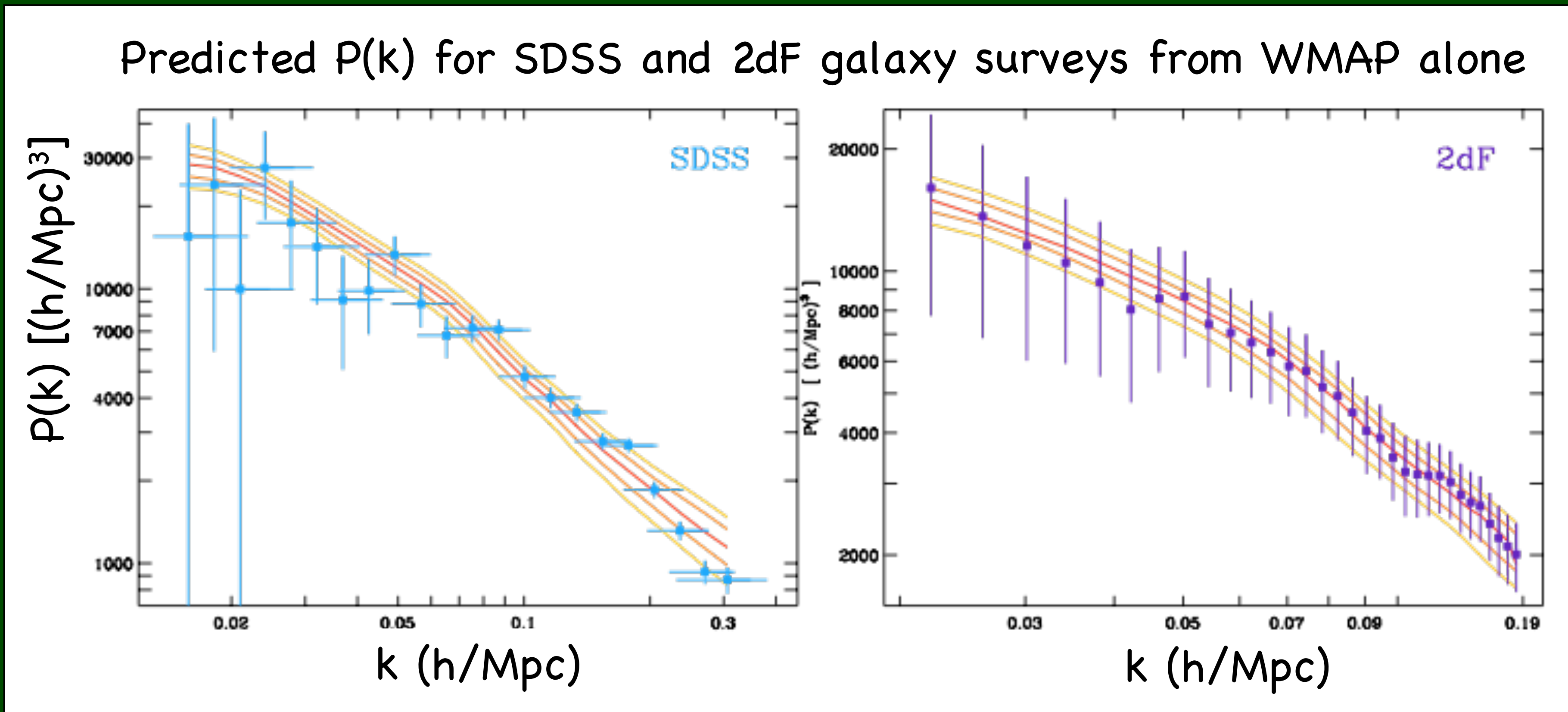


Predicted H(z) evolution

Luminosity distance prediction from WMAP alone



WMAP fits predict galaxy and mass distribution



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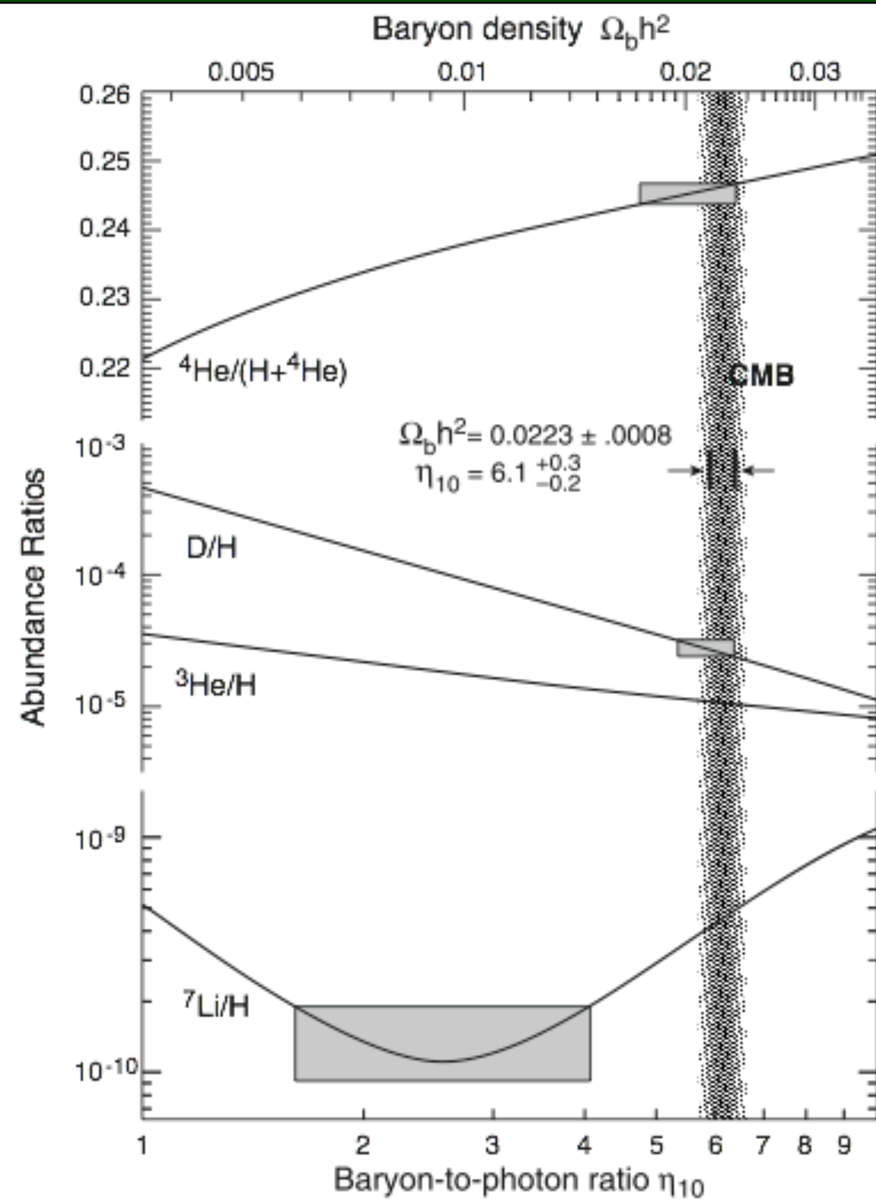
WMAP fits predict primordial abundances

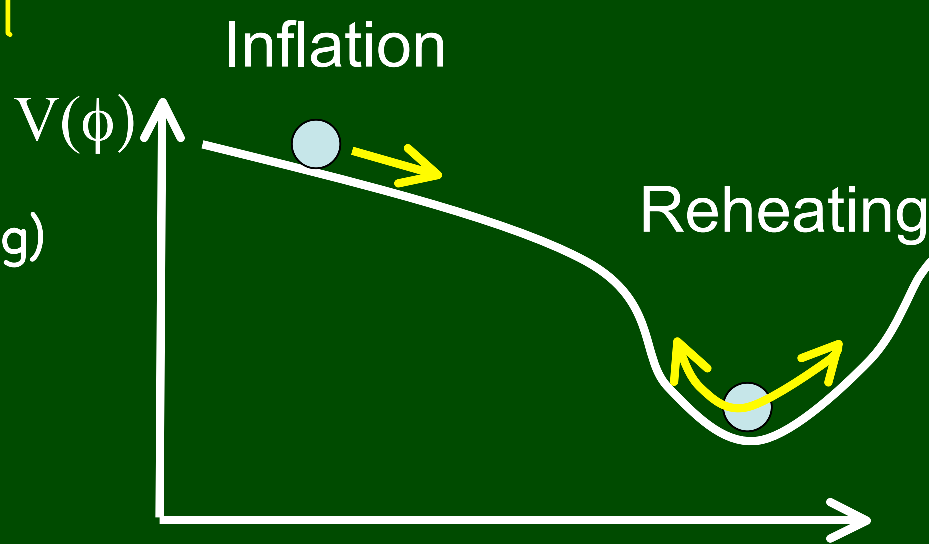
	CMB-based BBN prediction	Observed Value
$10^5 y_D^{FIT}$	$2.58^{+0.14}_{-0.13}$	1.6 - 4.0
$10^5 y_3$	$1.05 \pm 0.03 \pm 0.03$ (syst.)	$< 1.1 \pm 0.2$
Y_P	$0.24815 \pm 0.00033 \pm 0.0006$(syst.)	0.232 - 0.258
[Li]	2.64 ± 0.03	2.2 - 2.4

(Steigman et al 2005)



Predictions of inflation

- Acceleration induced by slow roll down scalar potential
  - Near scale invariant tilt
  - Scale variation in tilt (running) second order
  - 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 in scalar frozen outside horizon

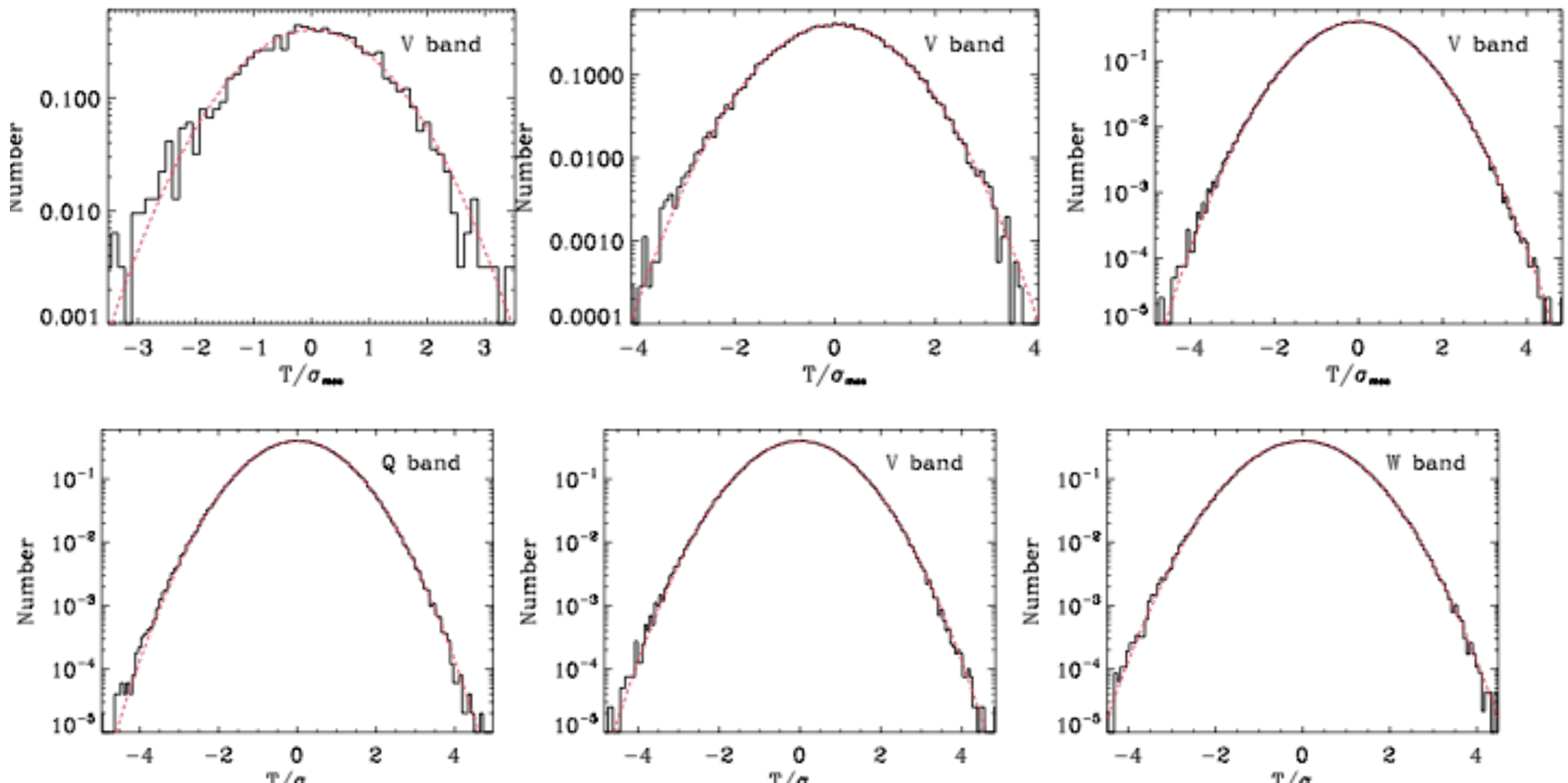
$$\eta = \frac{m_p^2}{8\pi}\frac{V''}{V} \ll 1$$

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

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

Looking Pretty Gaussian....

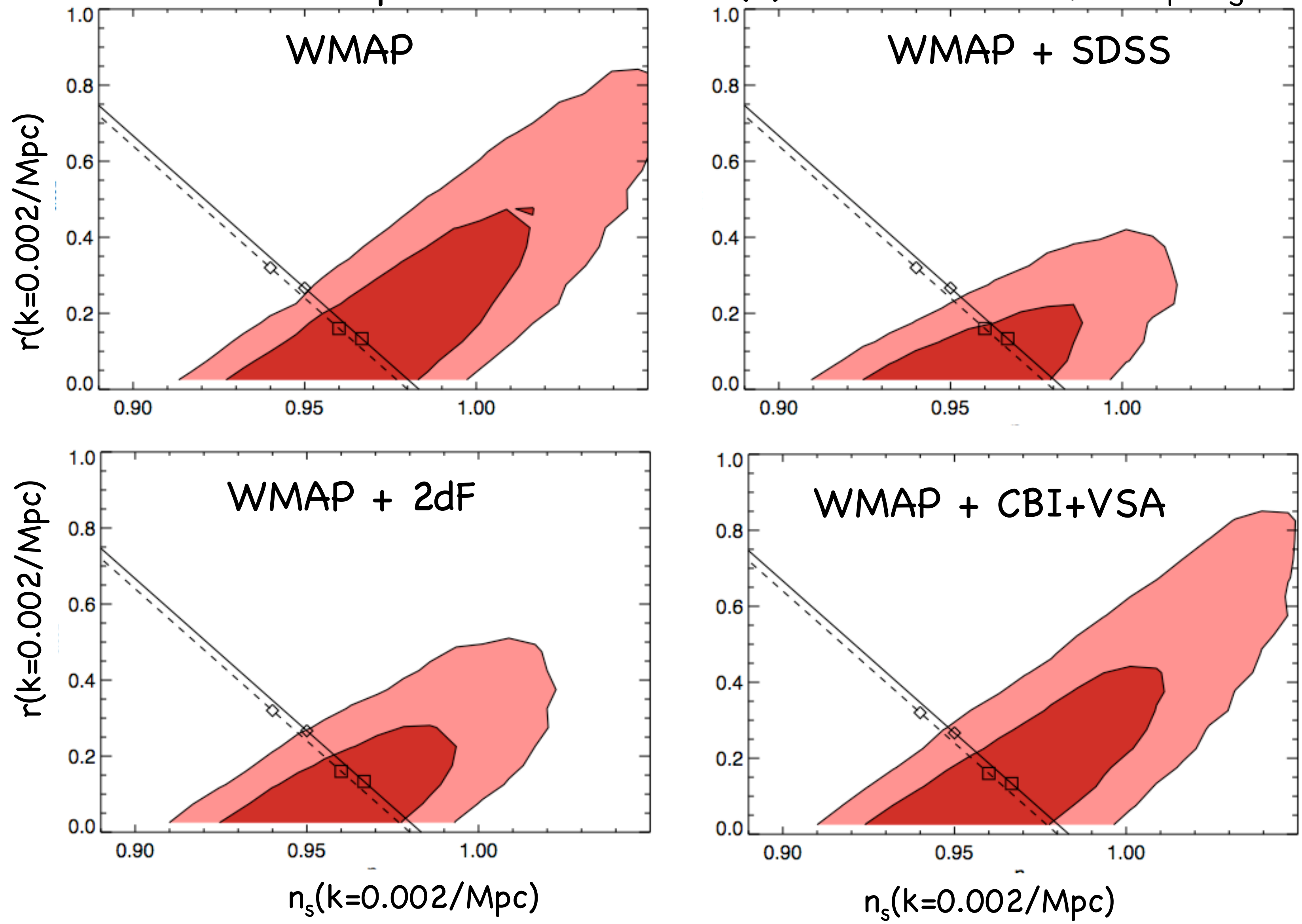
One point distribution function
(Npix = 3072, 12288, 786432)



Still some interesting large scale correlations...

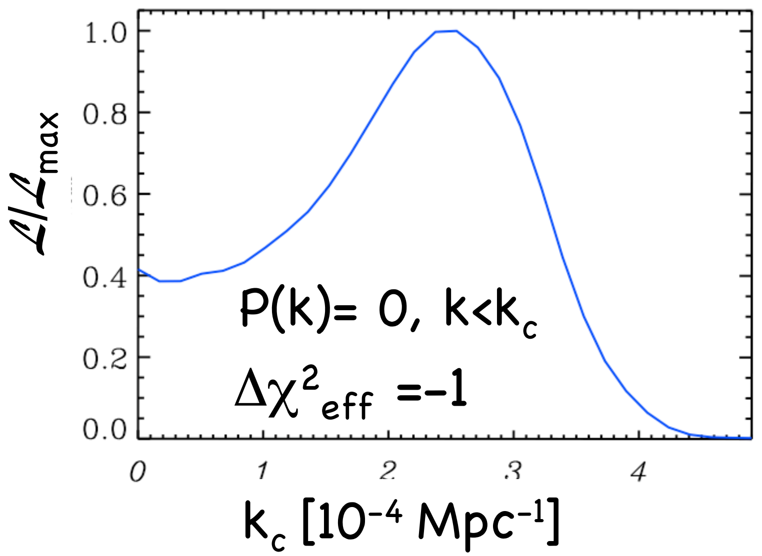
WMAP and Initial Conditions : constraining inflation

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



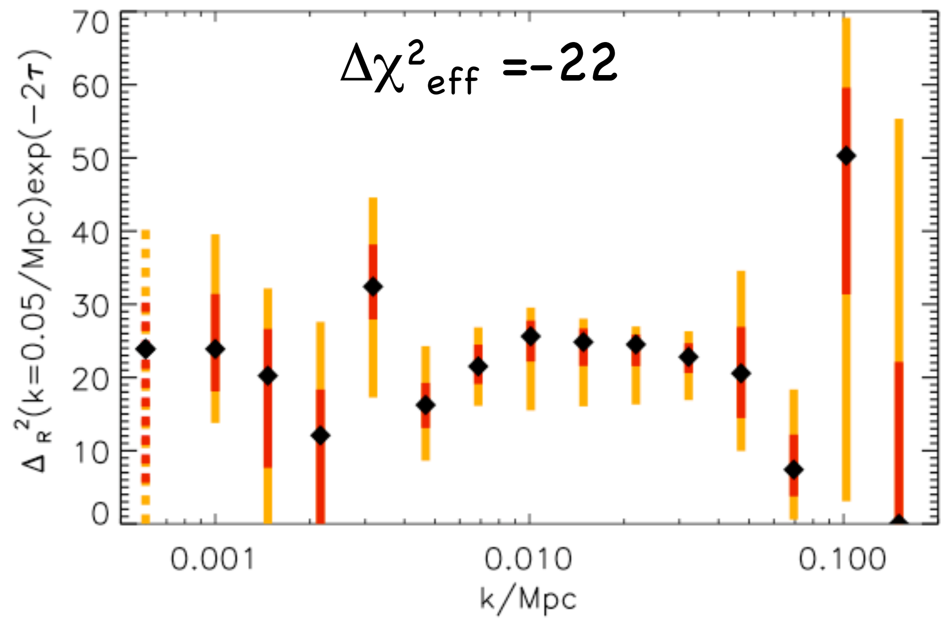
Alternative power spectrum models

Sharp k cutoff in initial spectrum



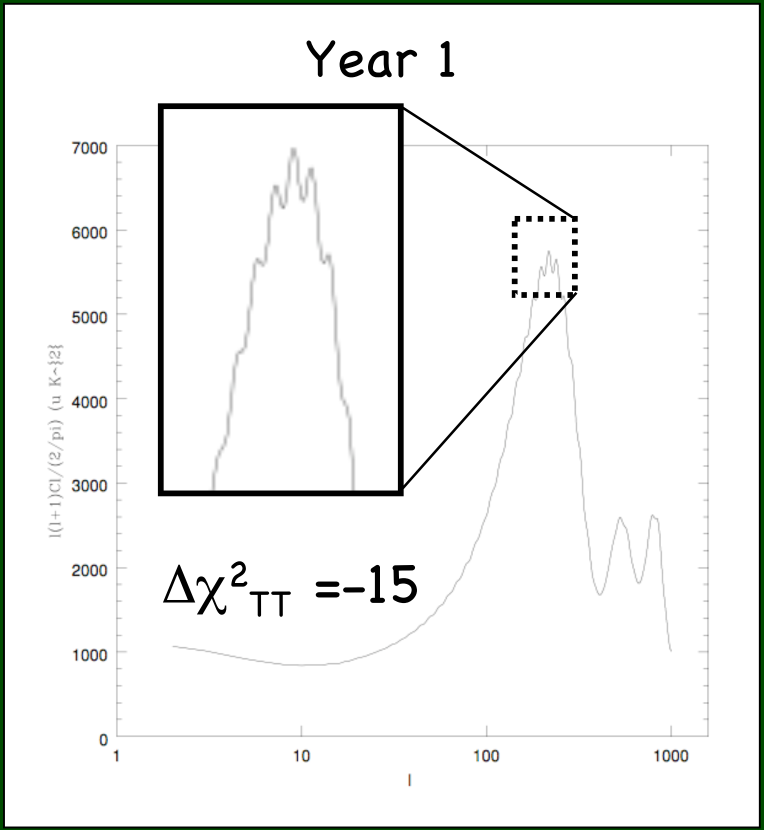
Improvement in fit by suppressing large scale power small,

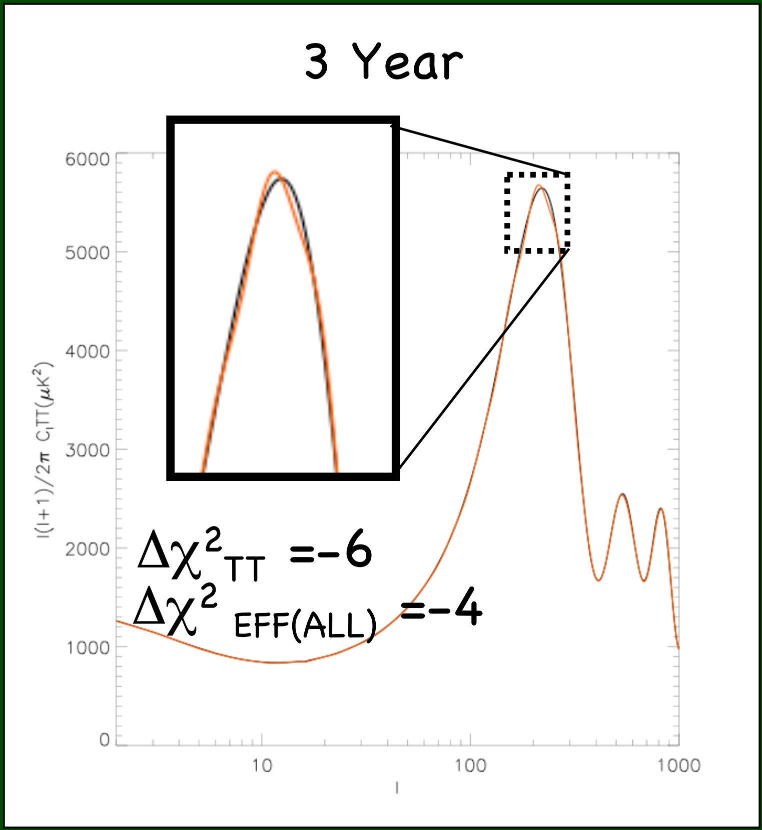
Reconstruction of P(k) in 15 k bins

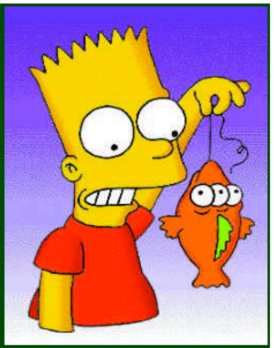


P(k) reconstruction consistent with power law P(k)

'Bumps and wiggles' reduced







Based on model by Martin and Ringeval (2003)

Other pure cos(k) and cos(lg k) modulations produce similar improvements: $\Delta\chi^2_{eff(ALL)}$ =-5 and -9.5 for 2 extra parameters

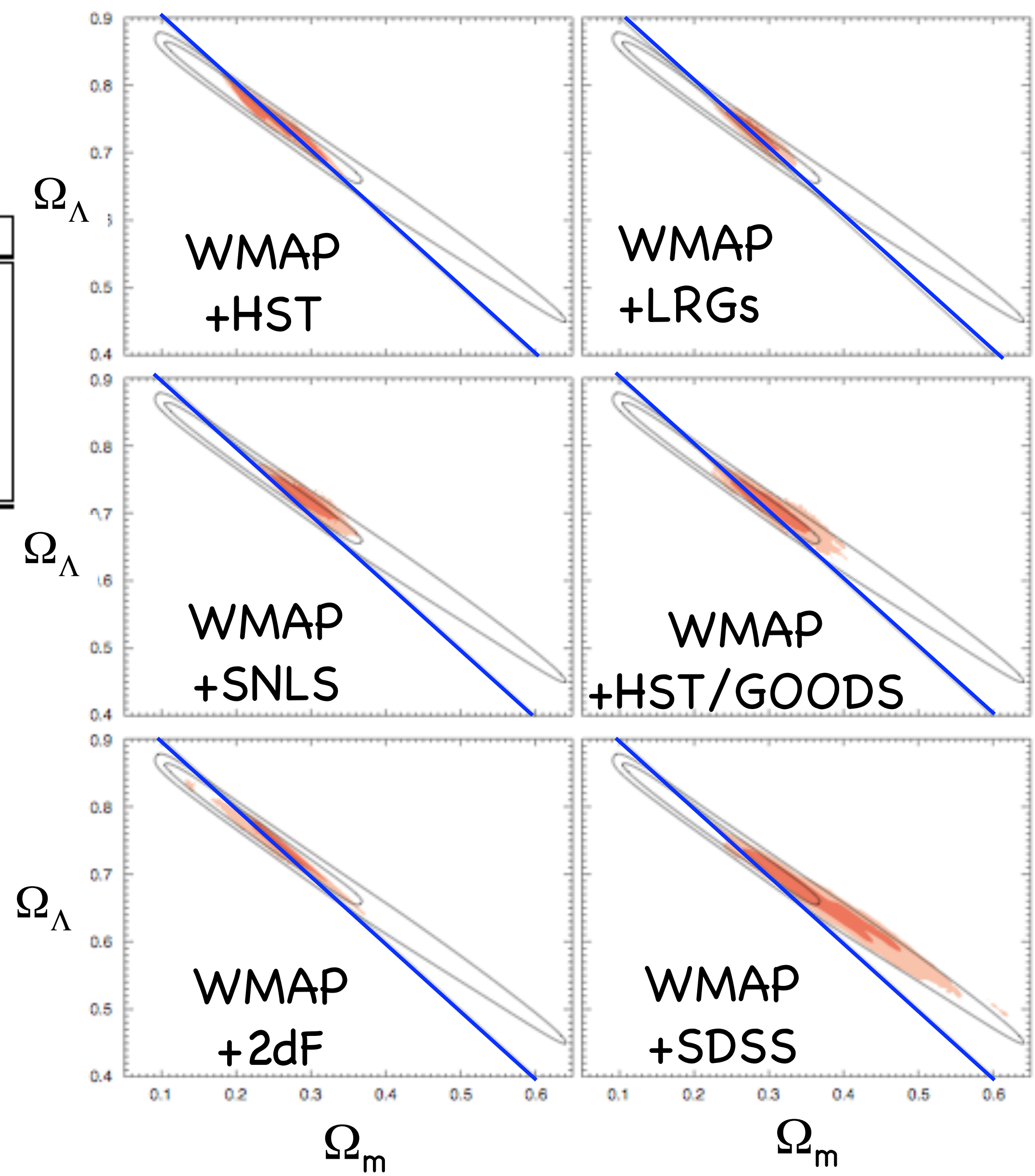
Geometry of the universe

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)



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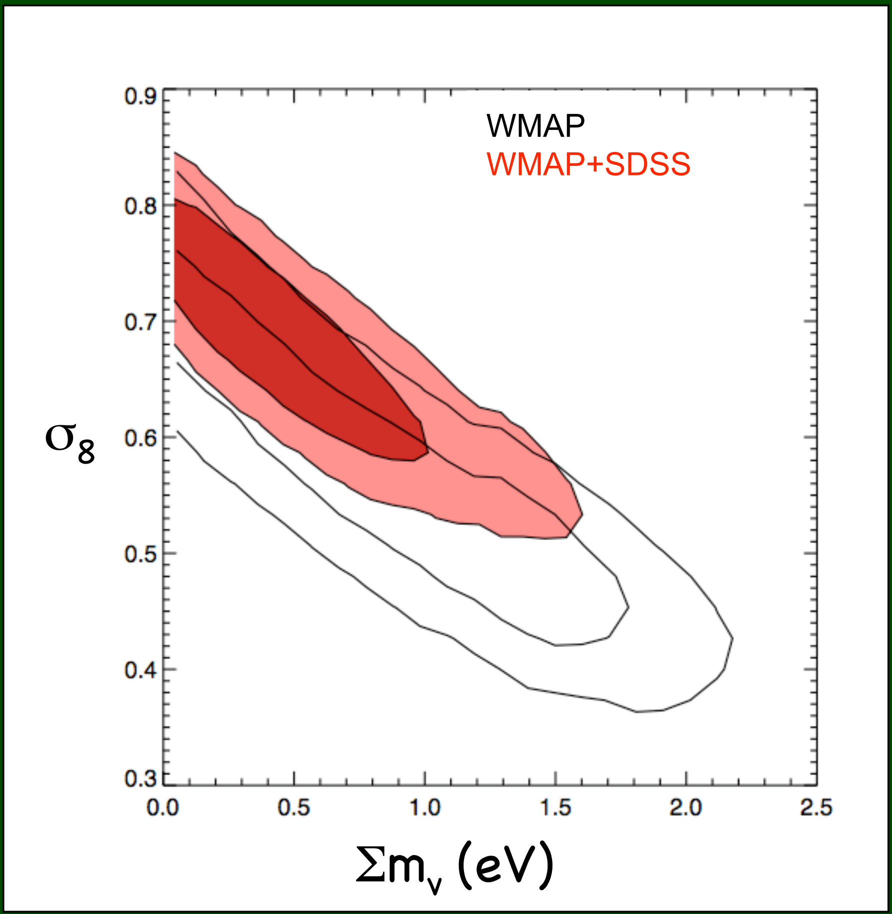
- Beyond WMAP

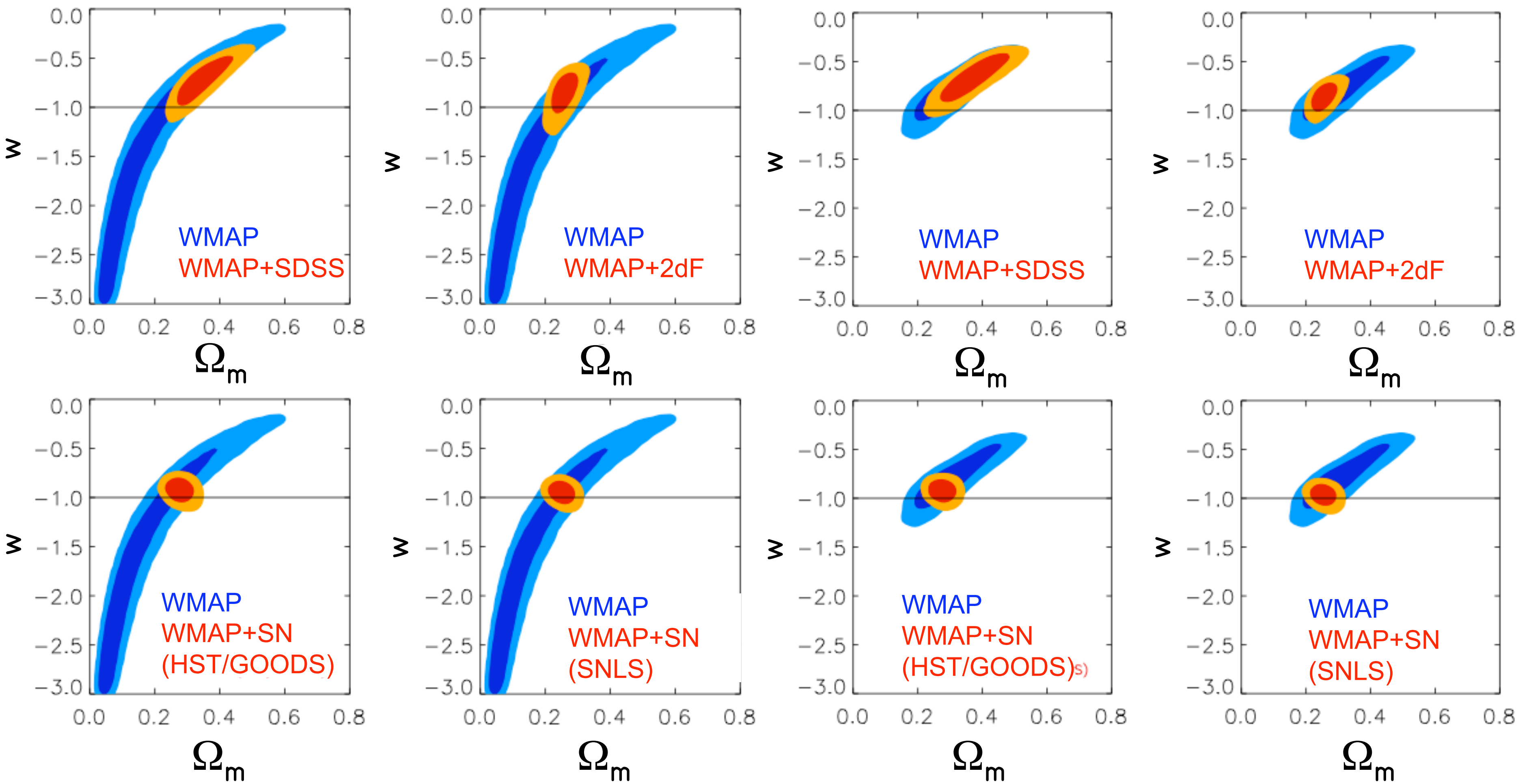
Massive neutrinos



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

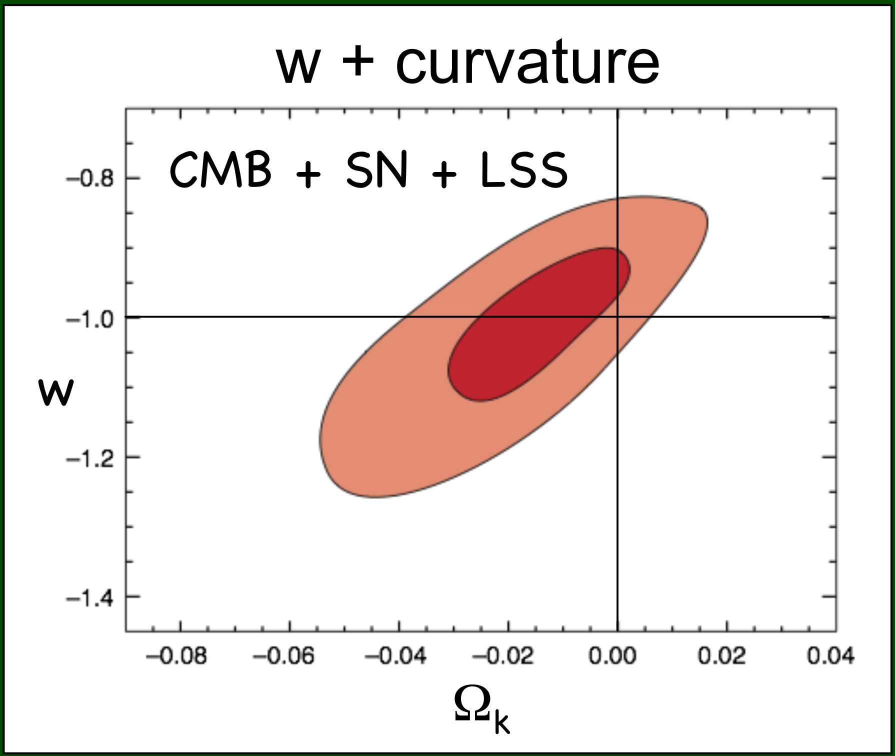
Dark Energy

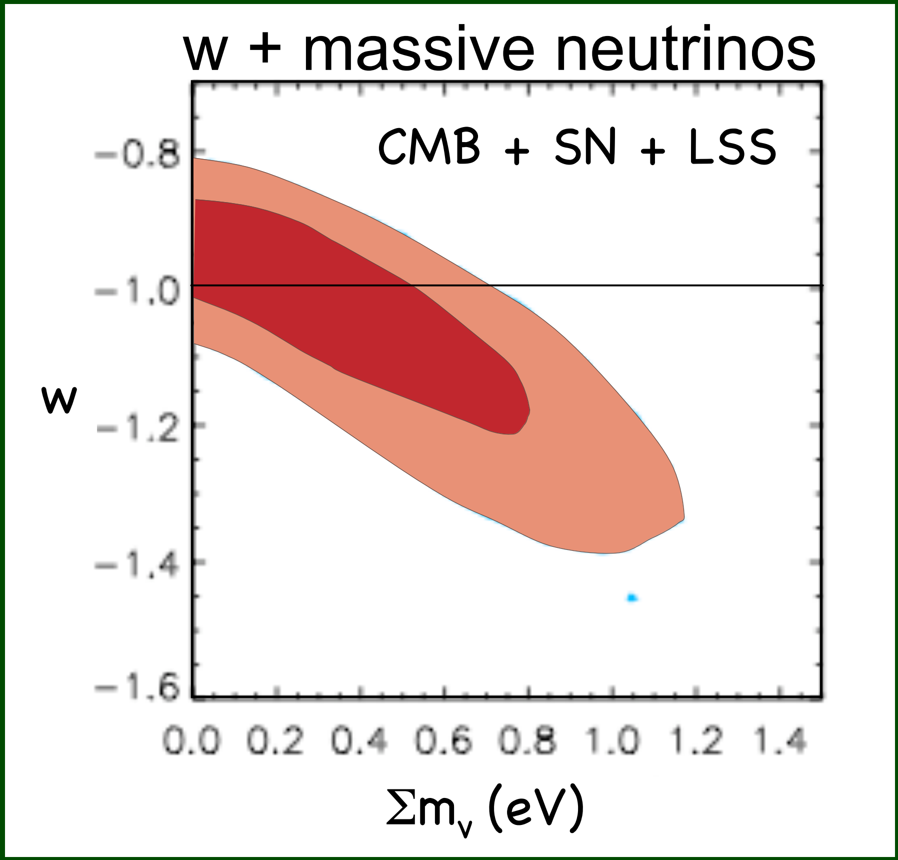
Clustering dark energy $c_s^2=1$ $w\neq-1$ If fluctuations in DE negligible



Sensitive to assumptions about clustering properties of Dark Energy

Robustness of dark energy constraints....

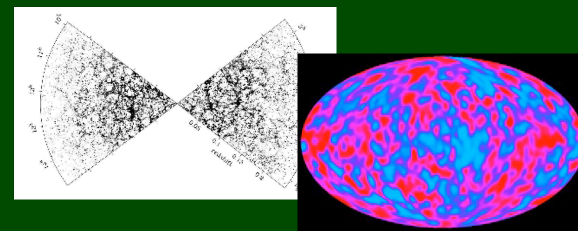




Talk plan

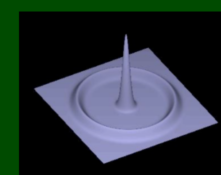
- Overview
- Introduction to CMB temperature and polarization
- The maps and spectra
- Cosmological implications
- Beyond WMAP

Beyond WMAP : Applying WMAP to new tasks

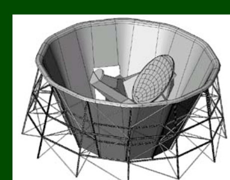


- Cross-correlation with structure :
  - Workshop over the last 2 days has shown the great potential of this
  - Exciting opportunities to probe dark energy, reionization …

- Complementary cosmological experiments
  - Crucial complementary parameter constraints from precise understanding of physics at last scattering

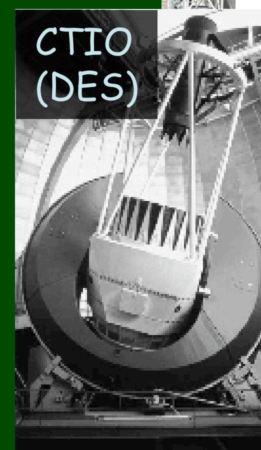


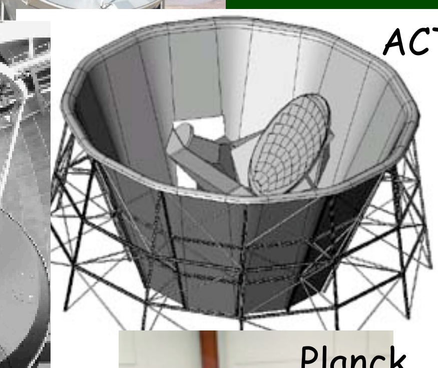
- Future CMB experiments:
  - Mapping the foregrounds
  - Calibration

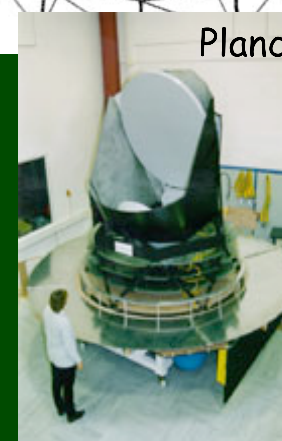


Small scale CMB / SZ surveys
Implications for dark matter/ dark energy research

- 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 …



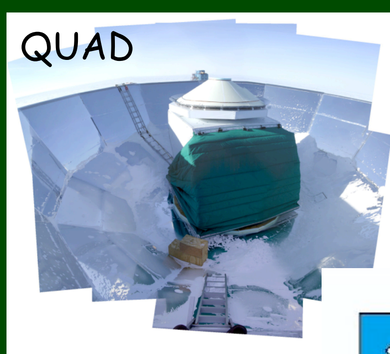




CMB polarization large and small scale: Primordial gravity waves & CMB lensing …

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



Conclusions

- WMAP now has full sky temperature and polarization maps
  - Distinct polarization signature of reionization with z~ 11 has reduced cosmological parameter degeneracies
  - Simple cosmological model has survived its most rigorous test
  - Data favors red spectral index (with values consistent with simple inflationary models) over Harrison-Zeldovich Peebles spectrum
- Rich cosmological prospects from combining WMAP with complementary data
- Very exciting future with experiments beyond WMAP