Title: Dark Insights from Light - Cosmology and the CMB

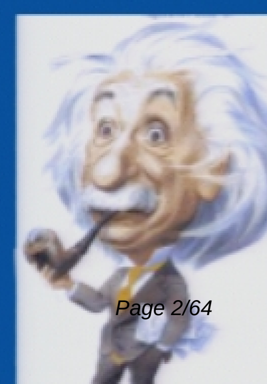
Date: Mar 07, 2005 11:00 AM

URL: http://pirsa.org/05030098

Abstract: The cosmic microwave background (CMB) is our most direct cosmological observable, encoding critical information about the evolution and development of the universe. The Wilkinson Microwave Anisotropy Probe (WMAP) has measured the angular power spectrum of the CMB temperature and temperature-polarization power spectra with unprecedented accuracy from its first year in flight. These recent observations along with developments in supernovae and galaxy surveys are generating critical challenges for theoretical physics, producing fundamental, intriguing questions in particle physics, cosmology and astrophysics that are as yet unresolved. We discuss in this seminar how the theoretical picture of the nature of dark matter and dark energy, and the origins of the universe, is being guided and modified by observations.

My aims for this talk

- To convince you of the importance of the CMB to cosmology
  - -It plays <u>the</u> central role observationally
- To give you an overview of some of the technical issues being faced
- To set the stage for the second year results from WMAP
  - -What you should be looking out for in any CMB release



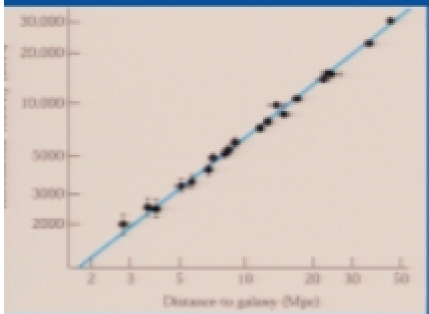
"Joy in looking and comprehending is nature's most beautiful gift."

Albert Einstein

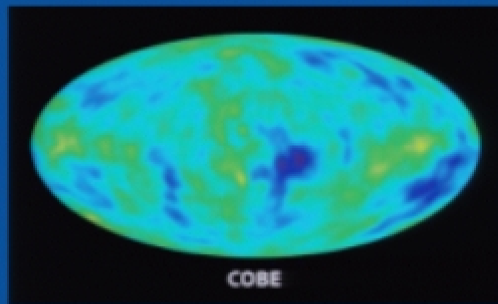
Outline of my talk

- A little cosmological context
- A Potted CMB
  - What is the CMB and why do we care?
- Getting at the CMB
  - Large scale CMB temperature measurements
  - CMB polarization
- Interpreting the CMB
  - Is there a cosmological standard model?
  - What is the nature of dark energy?
  - What is the nature of dark matter?
  - What is the nature of inflation?
- Conclusion

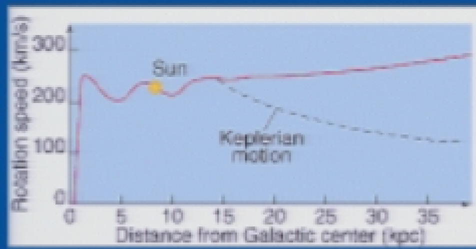
Observations have driven many key theoretical developments



An expanding universe



Homogeneity and isotropy on large scales



Galaxy outer rotation velocities

An accelerating universe

Hot Big Bang

Inflation

Dark matter

Dark energy

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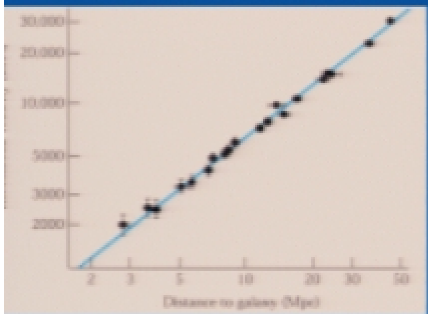

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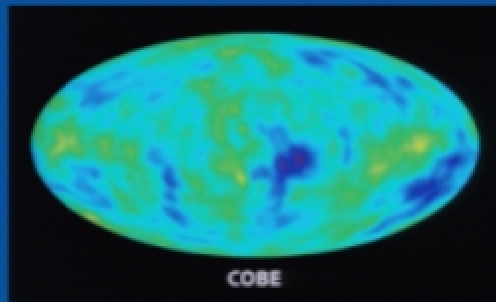

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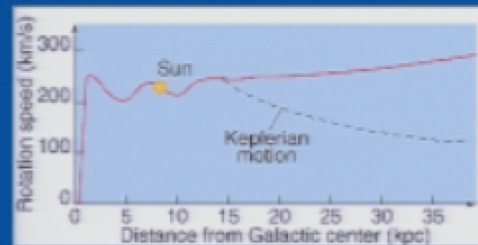

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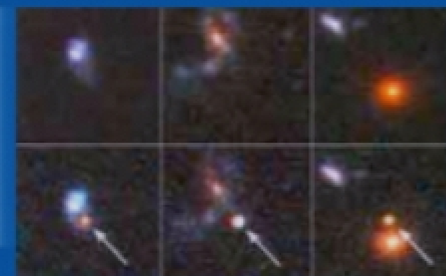

An accelerating universe

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Solutions create many unanswered questions in themselves!

What are the implications for 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?

Hints at significant progress!

- Describing the properties of the matter constituents
  - Photons, Baryons, Neutrinos, Dark matter, Dark Energy ...
- Chronicling many phases of cosmological history
  - Inflation, Baryogenesis, Recombination of atoms, Dark matter domination, Formation and growth of structure, Reionization, Dark Energy domination ...
- Quantifying the parameters to high precision

But complexity and uncertainty still ...

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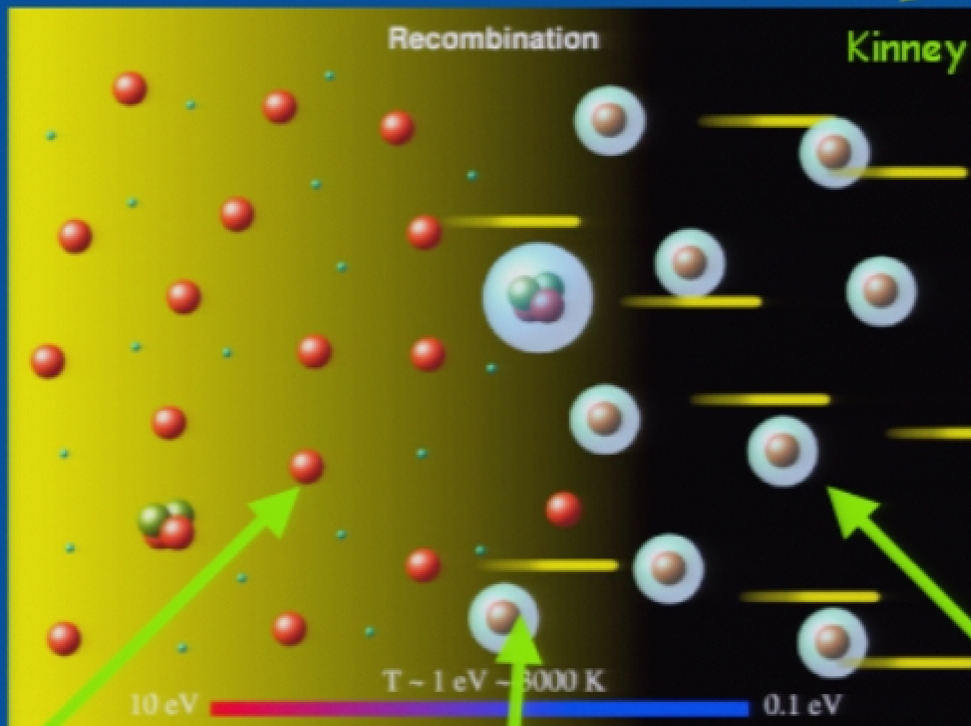
- Don't have fundamental theoretical descriptions for key matter components ...
  - e.g.Dark matter, Dark Energy
- Some processes are still mysteries, and have valid non-standard alternatives ...
  - e.g. the process of inflation, or dark energy domination
- Some parameters are known to a few percent, others are known only to a factor of 2 or an order of magnitude!
  - e.g. neutrino masses, the Hubble expansion factor, H_0

Future CMB measurements key to breaking uncertainties

The CMB is a near perfect primordial blackbody spectrum

Universe expanding and cooling over time...



<u>Optically opaque plasma</u>
photons interacting with
free charged particles
(protons and electrons)

2) <u>The 'last scattering' of photons</u>
~300,000 years after the Big Bang, e^-
and p^+ 're'combine into neutral atoms and
photons stop interacting with them.

3) <u>'Free Streaming' CMB</u>
Thermalized (blackbody) photons at
~6000K are diluted and redshifted by
universe's expansion to become a
~2.726K background we measure today.
(Vital support for the Big Bang Theory)

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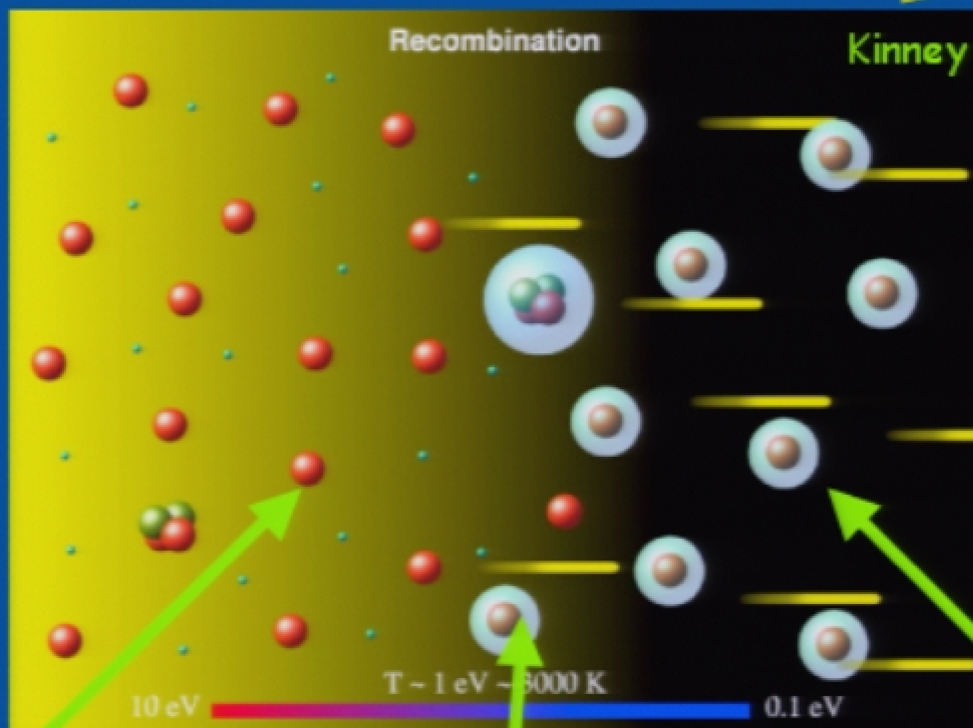

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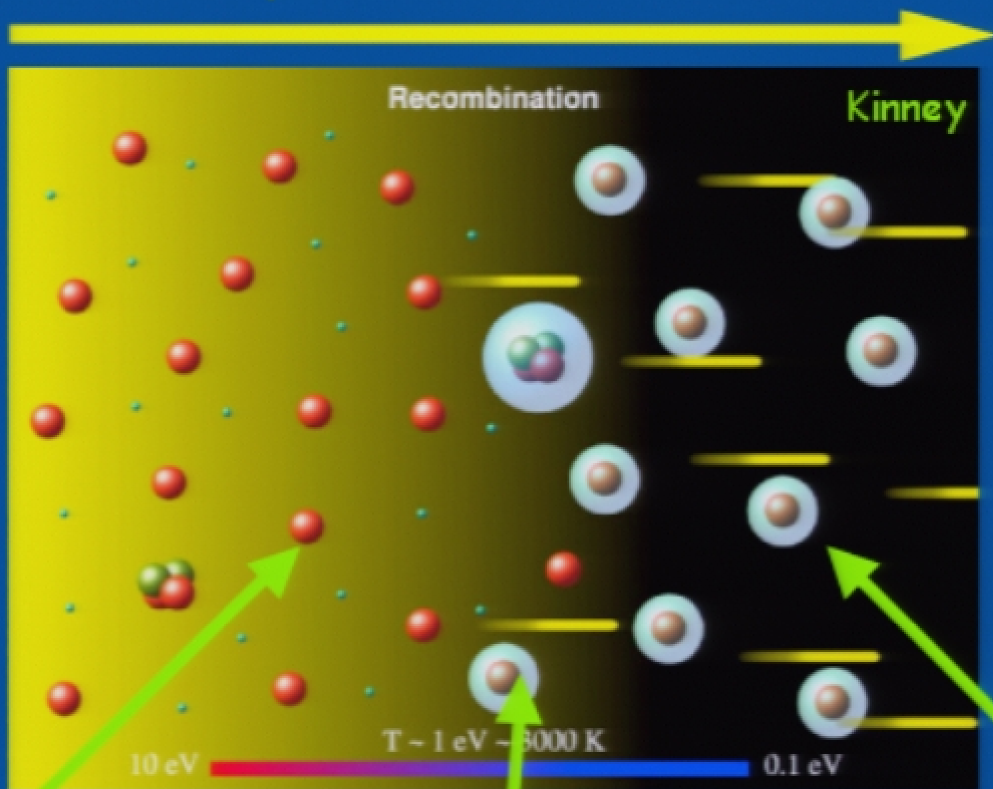

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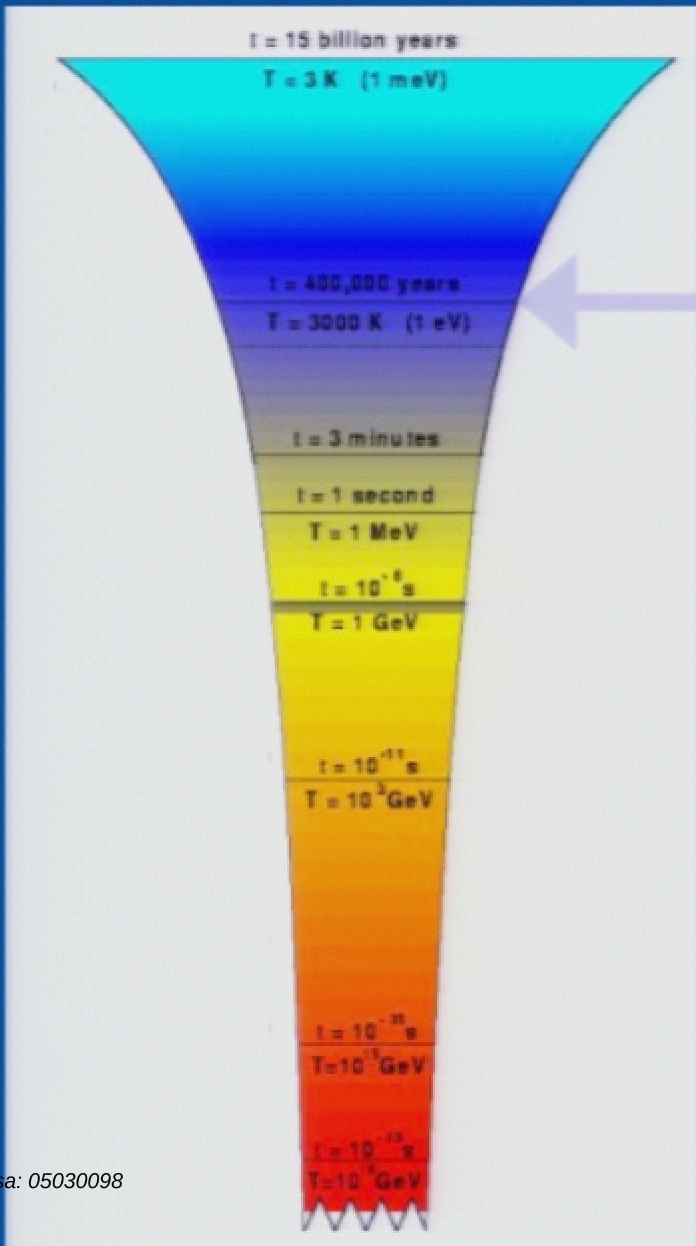
It is our oldest observable fossil from the early universe



Recombination

CMB

Nucleosynthesis

Quark-hadron phase transition

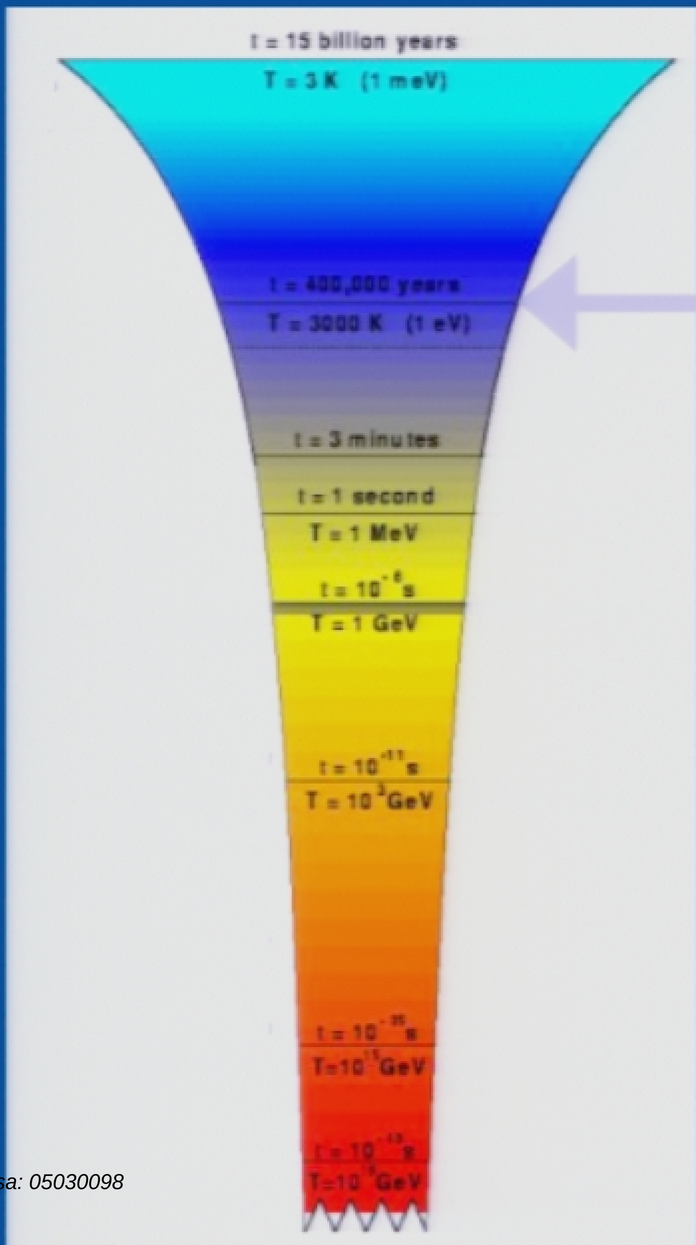
Processes during opaque era imprint in CMB fluctuations

Electroweak phase transition

Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects...

The information it holds is the cosmic equivalent of tree rings...



Dark Energy domination

Reionization

Galaxy formation

Recombination

Nucleosynthesis

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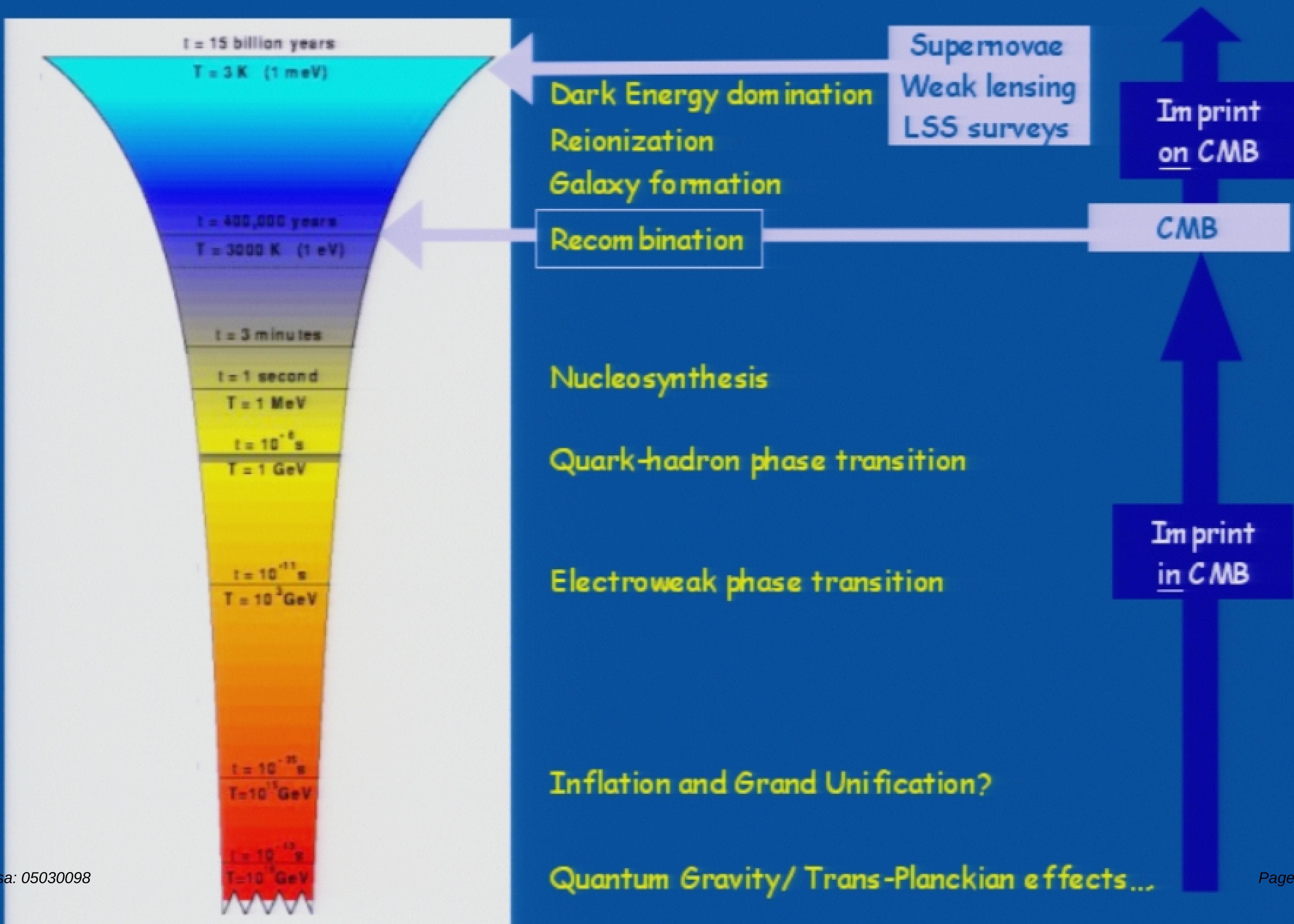
Processes following recombination imprint on CMB

CMB

Imprint in CMB

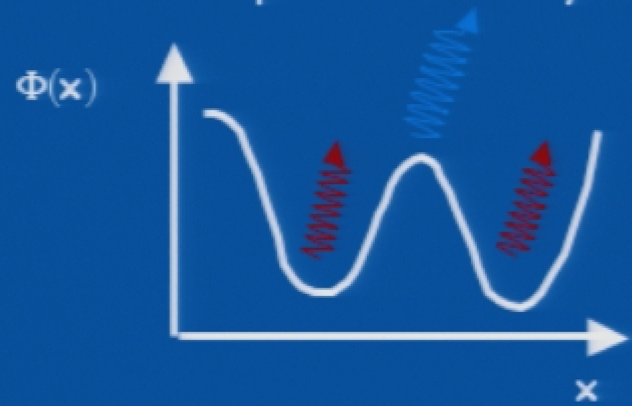
And allows important comparisons with observations from later epochs



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

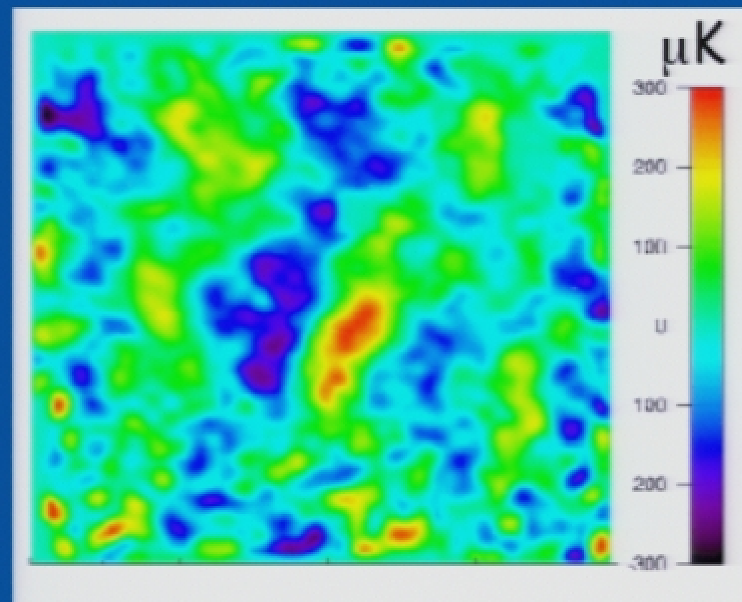


- Compton Scattering interactions in photon-electron/baryon fluid

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

  $\gamma \longleftrightarrow e^- \longleftrightarrow p^+$
  Compton scattering — Coulomb interaction

- ...Translate into fluctuations in the blackbody photon temperature $\Delta T_{CMB}(\mathbf{x})$ at ~1/100,000 level



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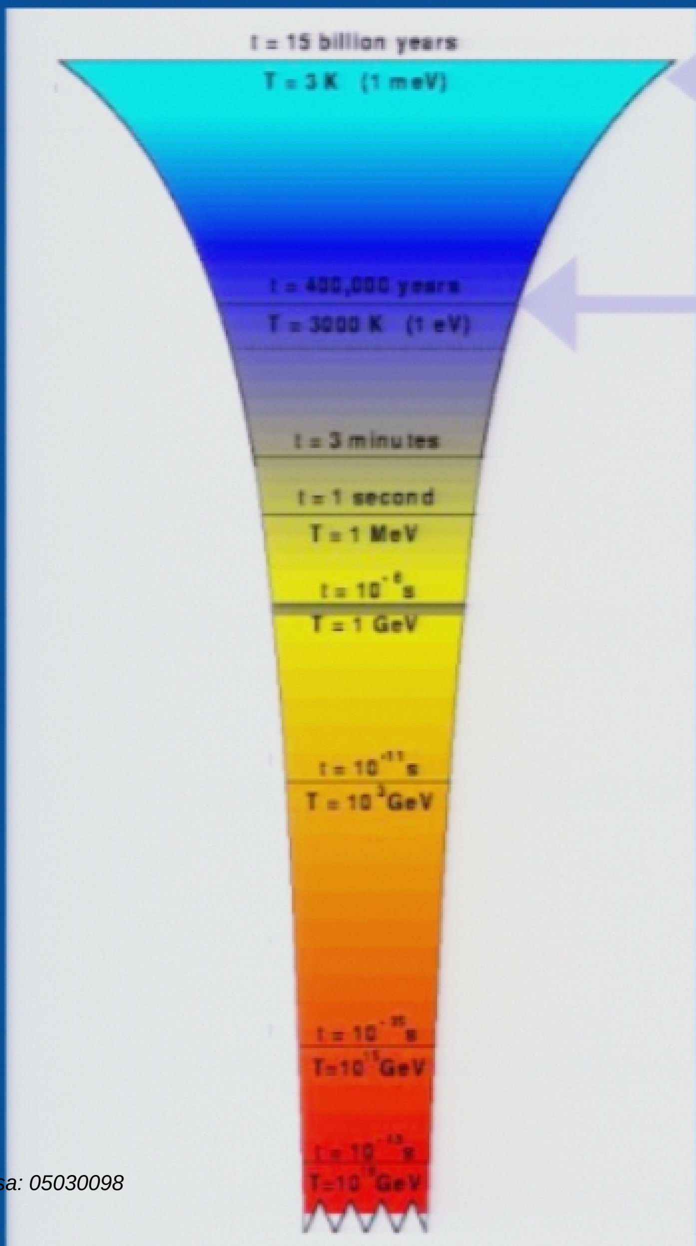

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Quark-hadron phase transition

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Inflation and Grand Unification?

Quantum Gravity/ Trans-Planckian effects...

Supernovae
Weak lensing
LSS surveys

Imprint on CMB

CMB

Imprint in CMB

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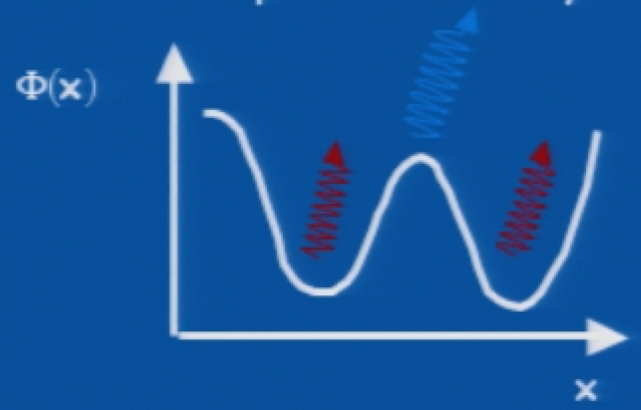

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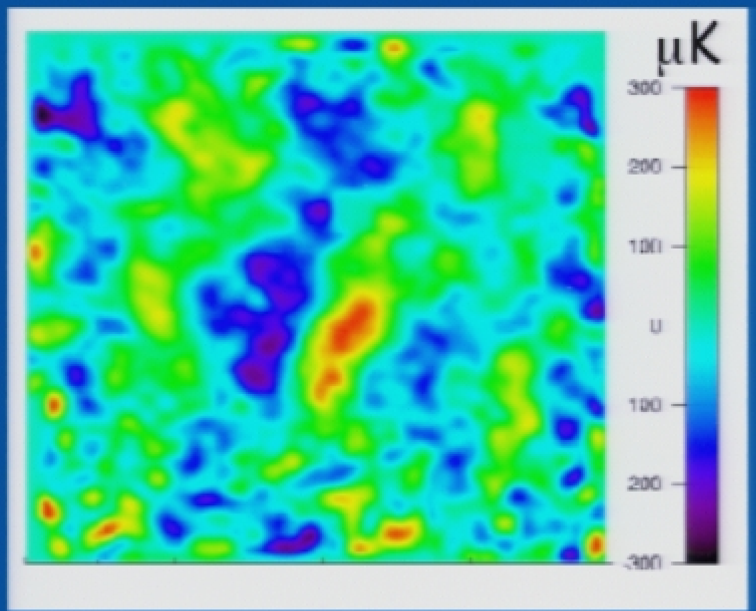

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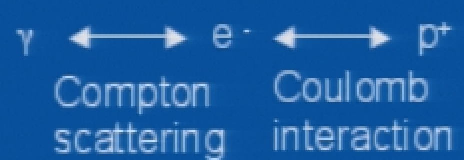
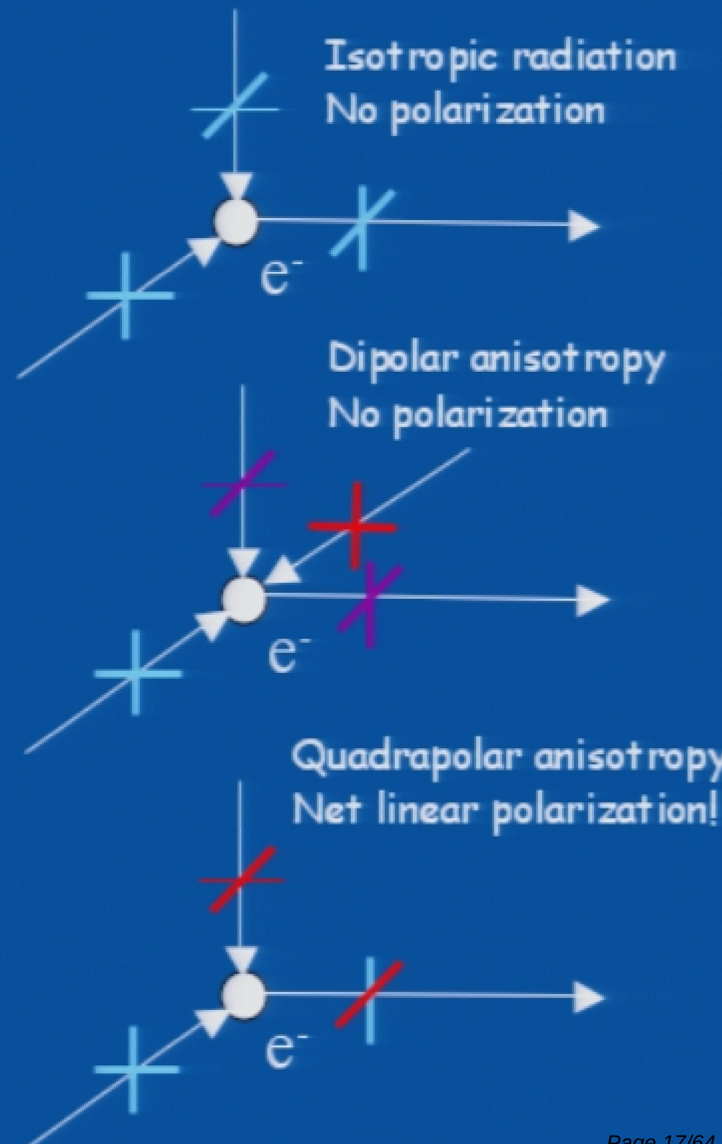


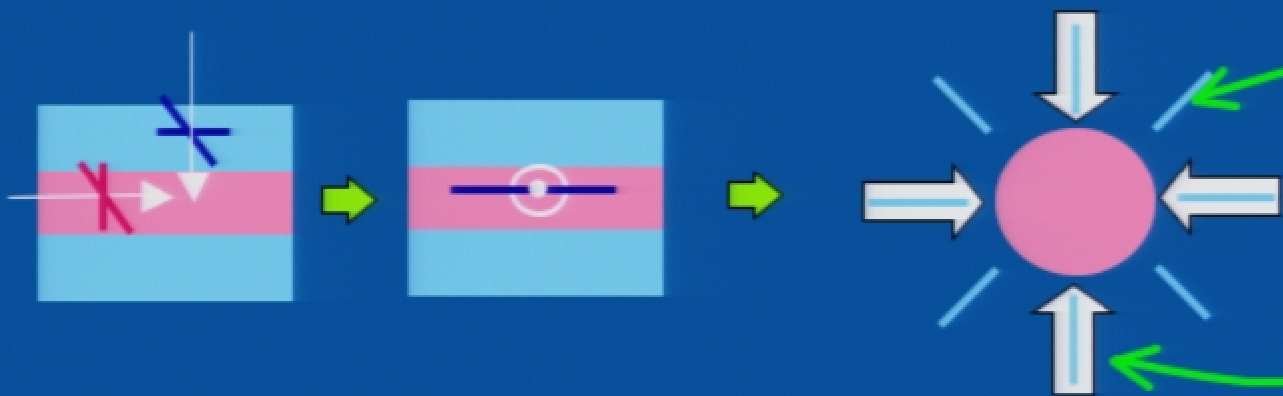
CMB scattering gives a 'twofer': Polarization fluctuations too!

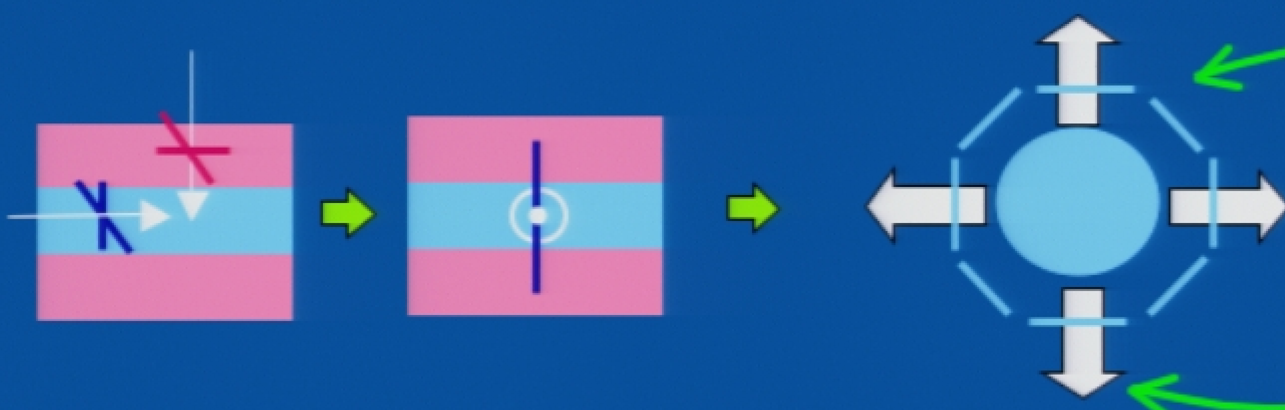
- CMB polarization created by Thomson scattering of photons with a non-zero quadrupole (l=2 spherical harmonic)
- Polarization gives a purer imprint of early universe than temperature
  - -Once electrons in atoms scattering processes stop
- Polarization only observed on scales below horizon scale at scattering
  - -small scale polarization at recombination z~1088
  - -Larger scale from reionization by the first stars z~25



Expect temperature and polarization signatures to be correlated

- For adiabatic fluctuations (where density fluctuations of radiation and matter are simply related) temperature fluctuations should have characteristic polarization patterns





- Polarization pattern correlated with velocity flow of matter from high density to low density areas rather than density itself which determines temperature fluctuation

  –Leads to prediction that polarization should π out of phase with temperature

CMB Polarization: Alternative descriptions

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

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

Polarization can be described using Stokes Parameters (Q,U) or using E/ B decomposition analogous to EM.

-E/B decomposition independent of axis choice and nicely divides underlying processes

Scalar perturbations only generate EE spectra

-EE polarization intimately matter density and therefore to CMB temperature

-Cross correlation tells us about direction of velocity flows at time of polarization production

Only tensor perturbations can generate both EE and BB

-BB provides insight into primordial gravity waves with little 'contamination' from scalar modes

-Due to fact that direction of field strength and its orientation need not be aligned/perpendicular

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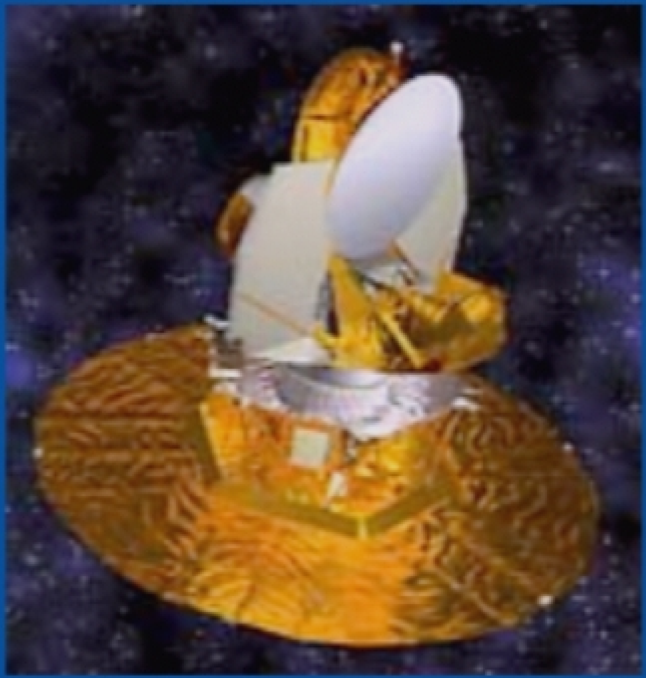
Large scale CMB: Wilkinson Microwave Anisotropy Probe

WMAP satellite

Collaboration between NASA Goddard and Princeton with other key members from UCLA, Brown, Chicago and UBC



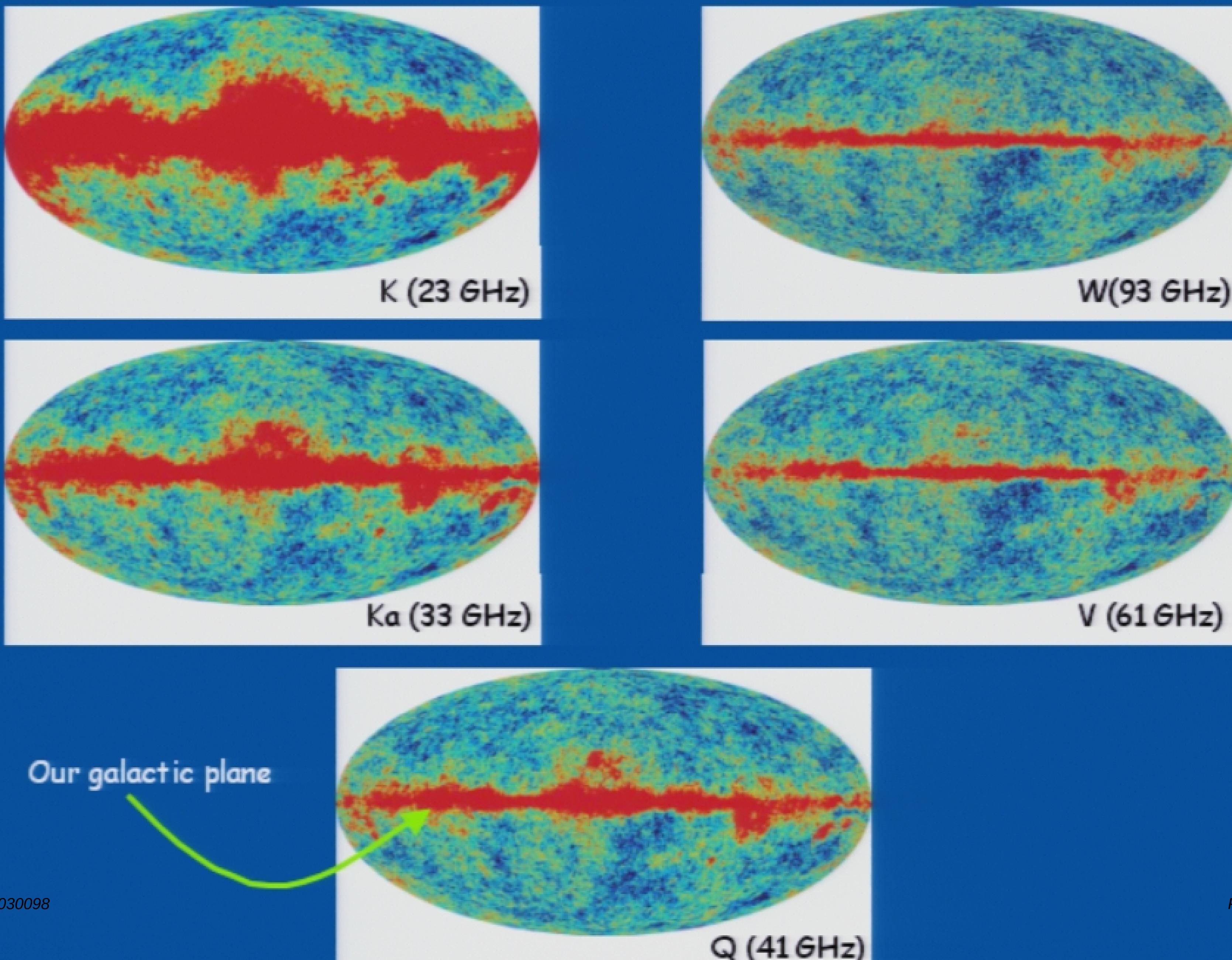
Launched June 2001

Reached L2 August 2001

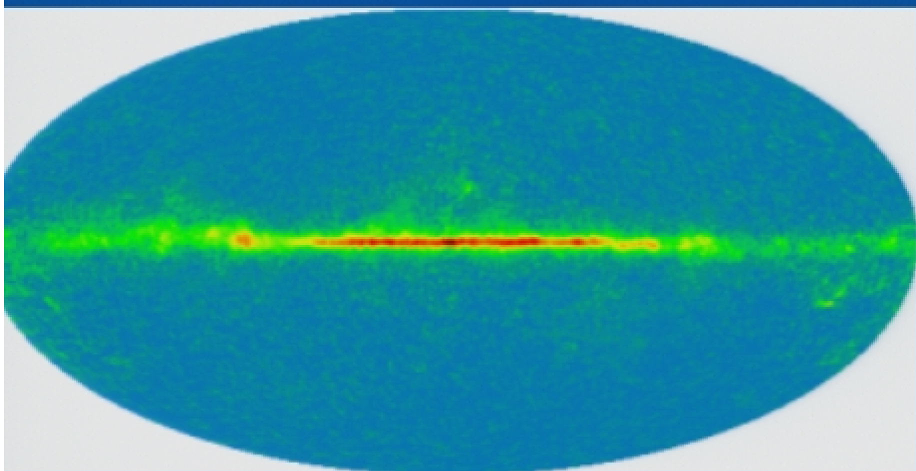
Now made 3 years of observations

2nd and 3rd year results out in 2005

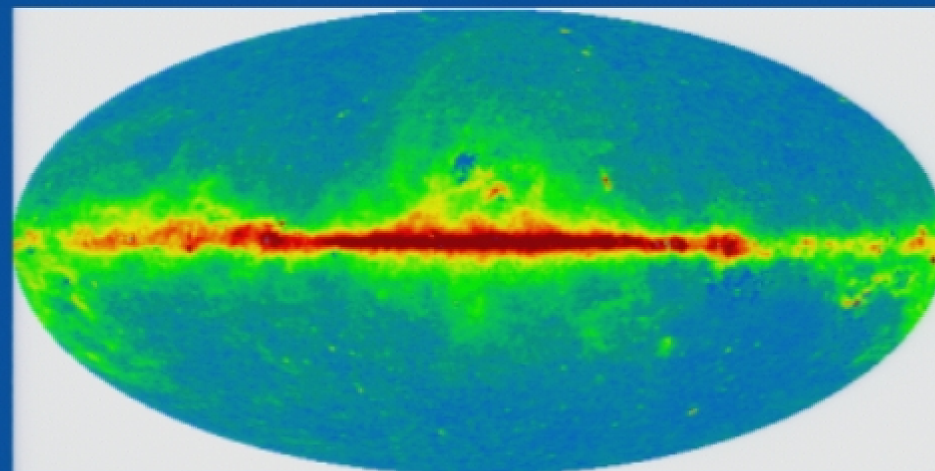
Measure CMB at multiple frequencies to minimize systematics



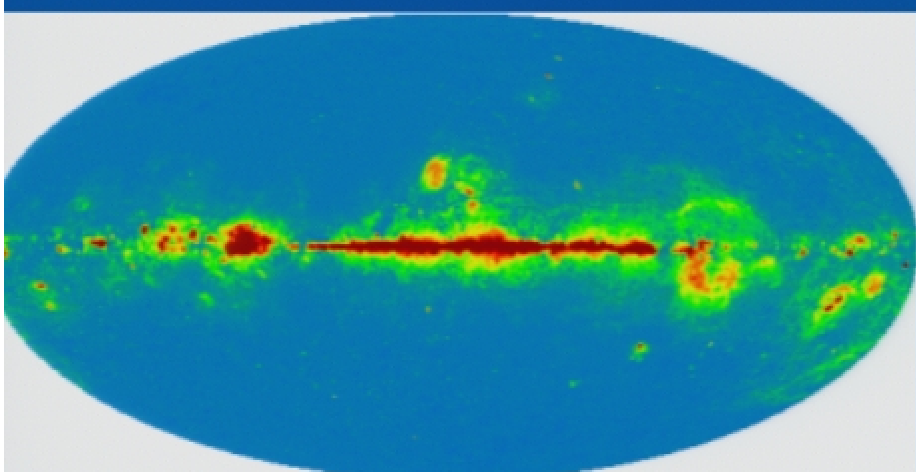
Derived galactic foreground maps are fascinating in themselves



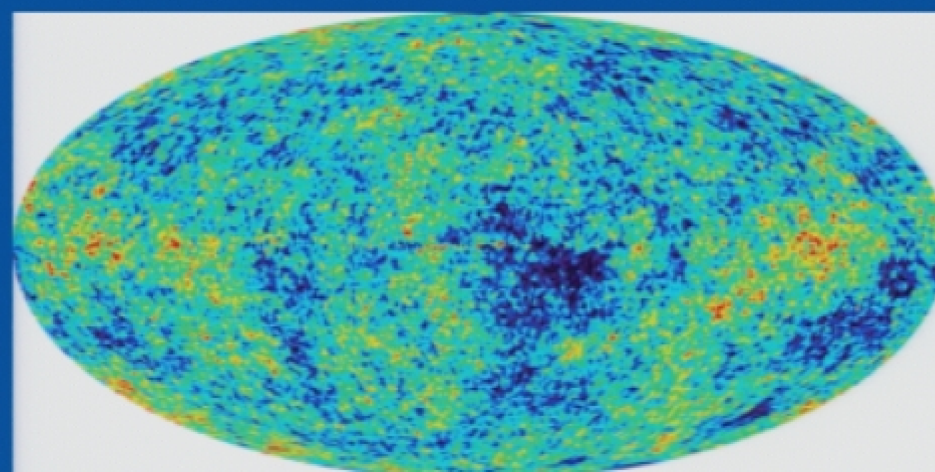
Thermal Dust map



Synchrotron map



Free-free map



CMB map

But (harshly) they are considered contaminants from now on in!

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 Gaussian random field all we need to describe the system is the 2 point 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")

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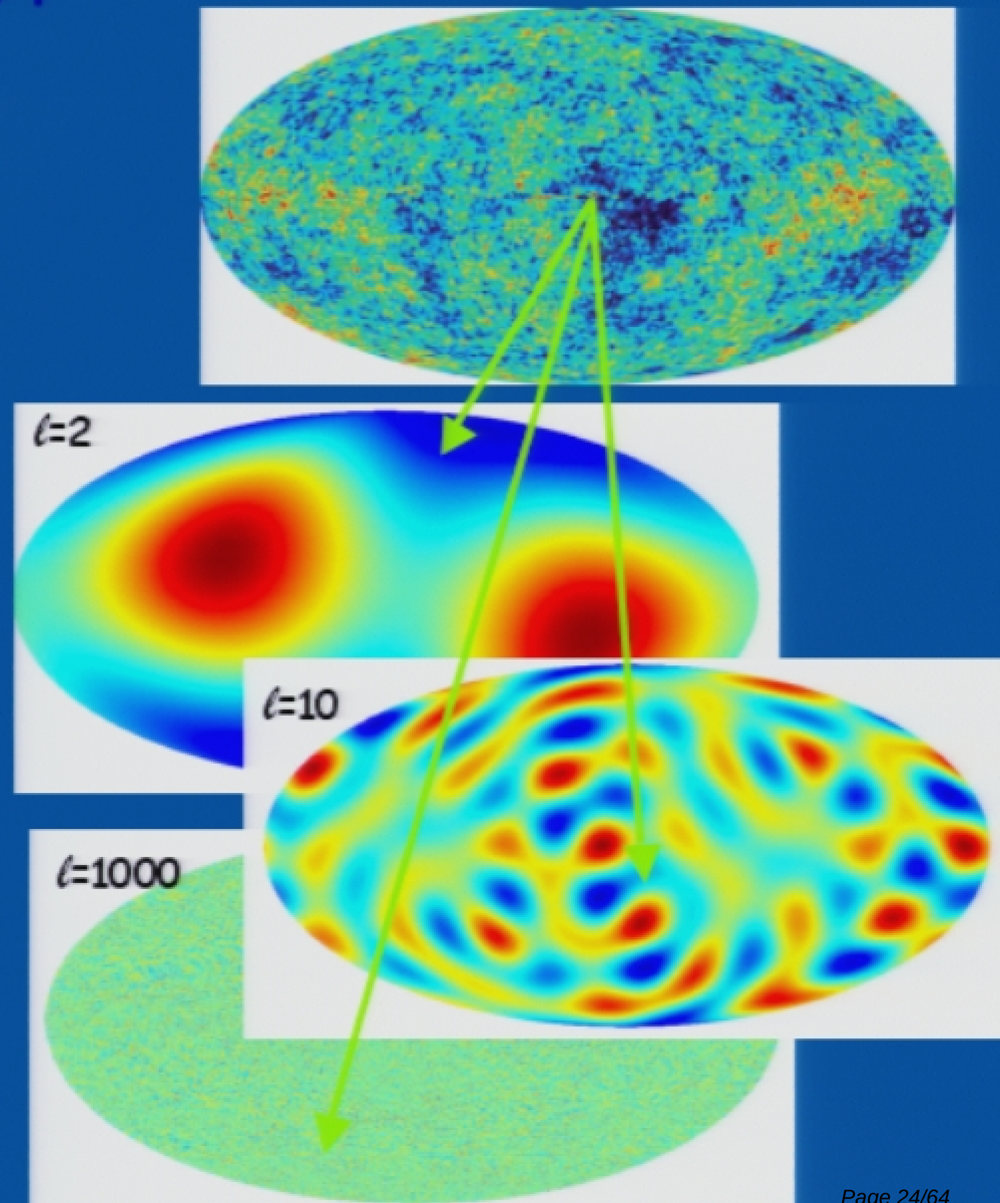

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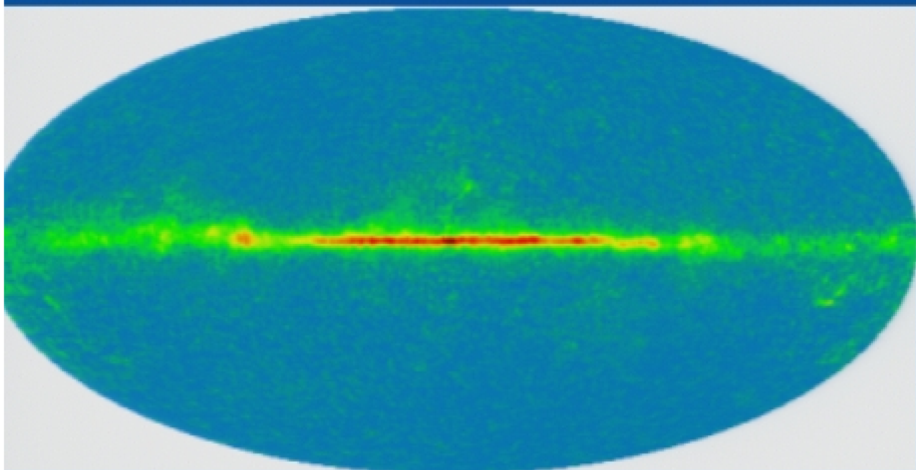

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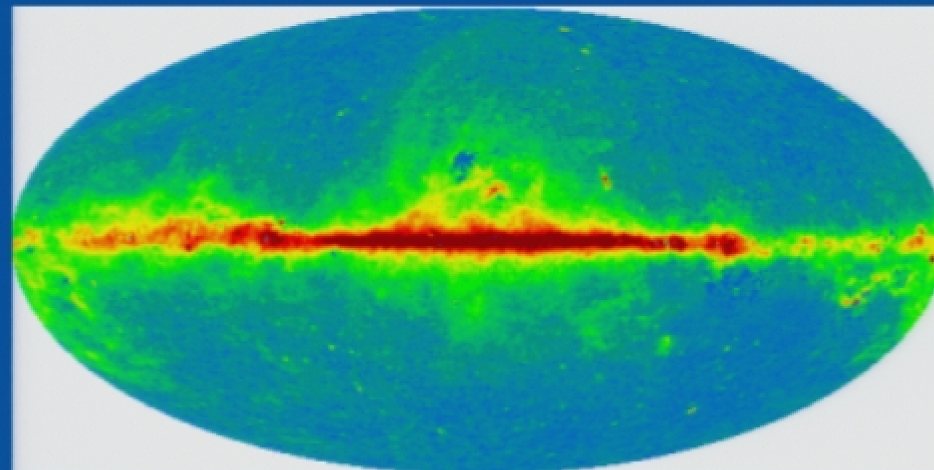

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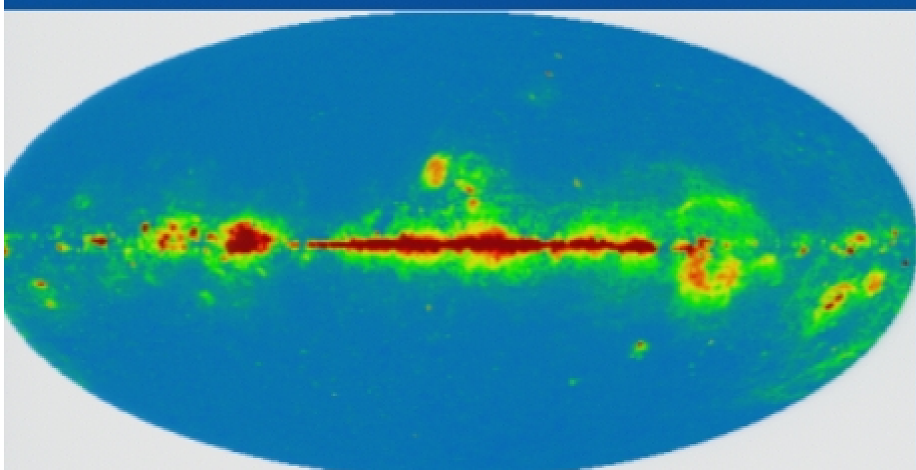

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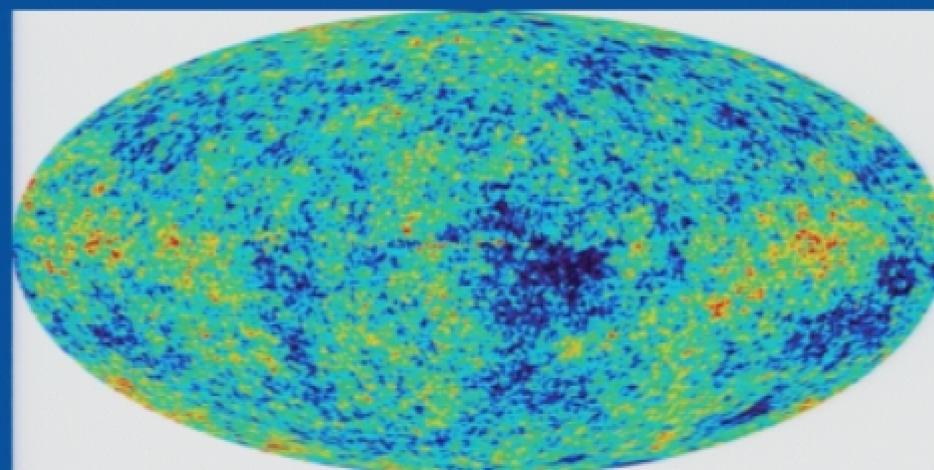

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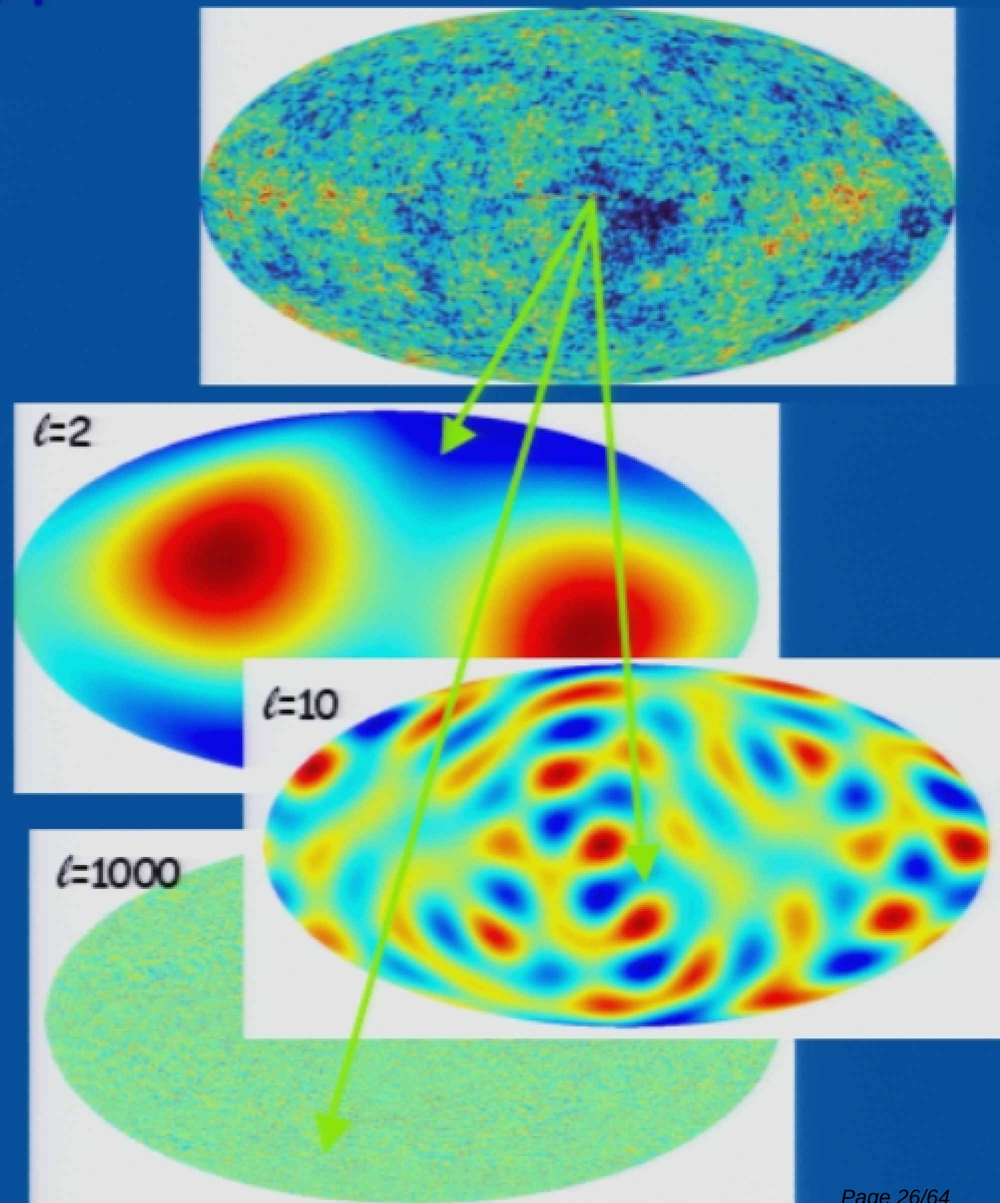

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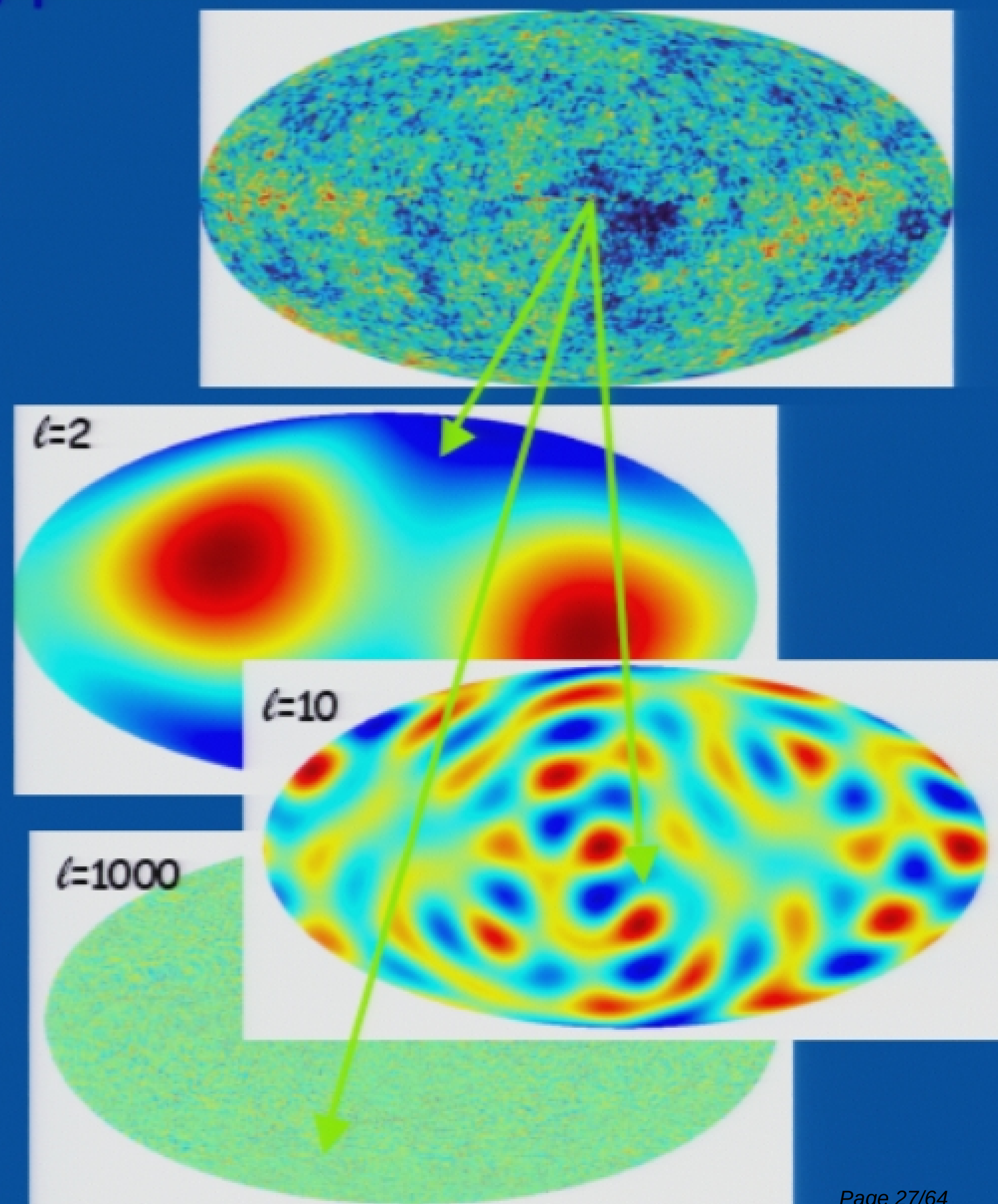

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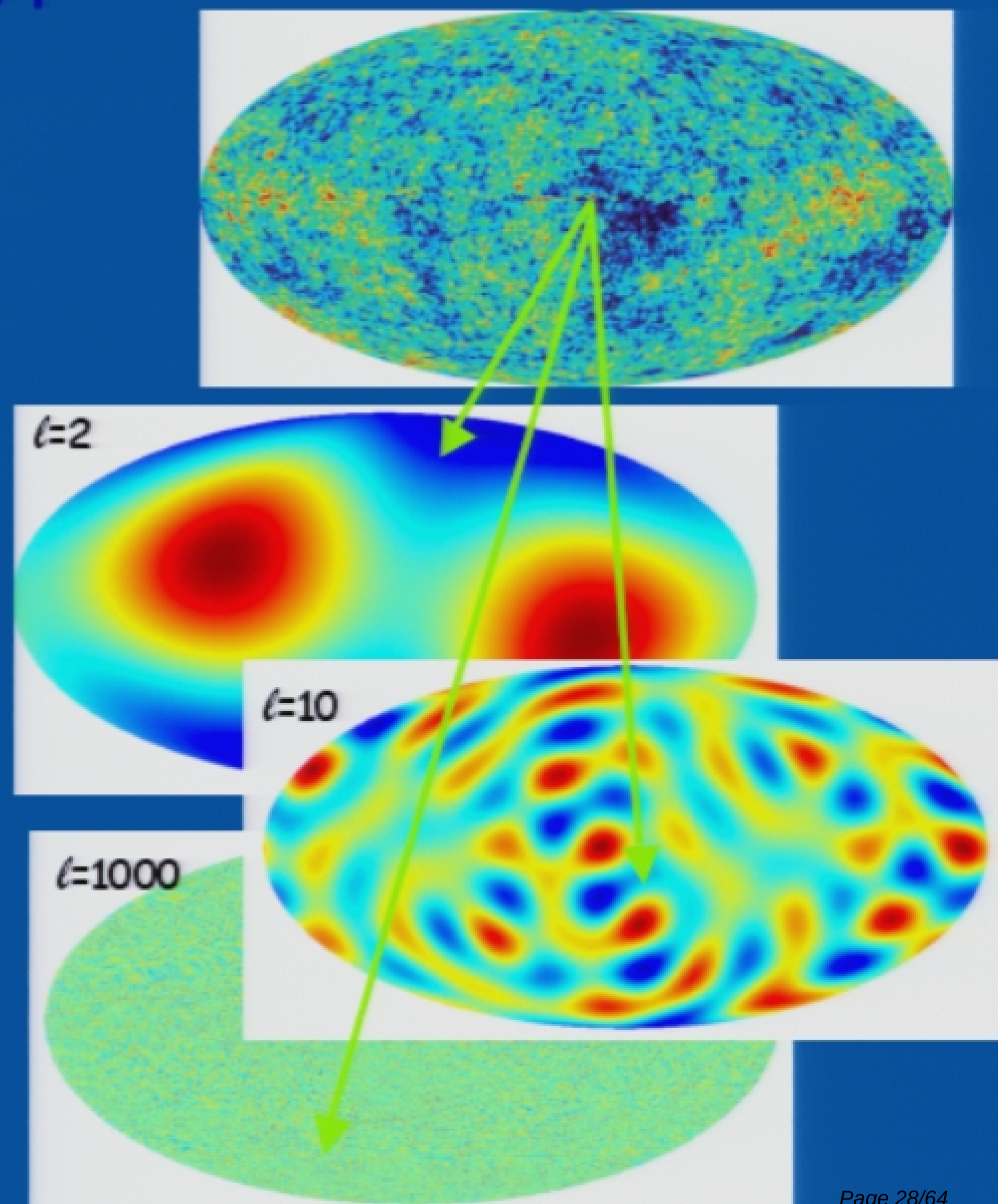

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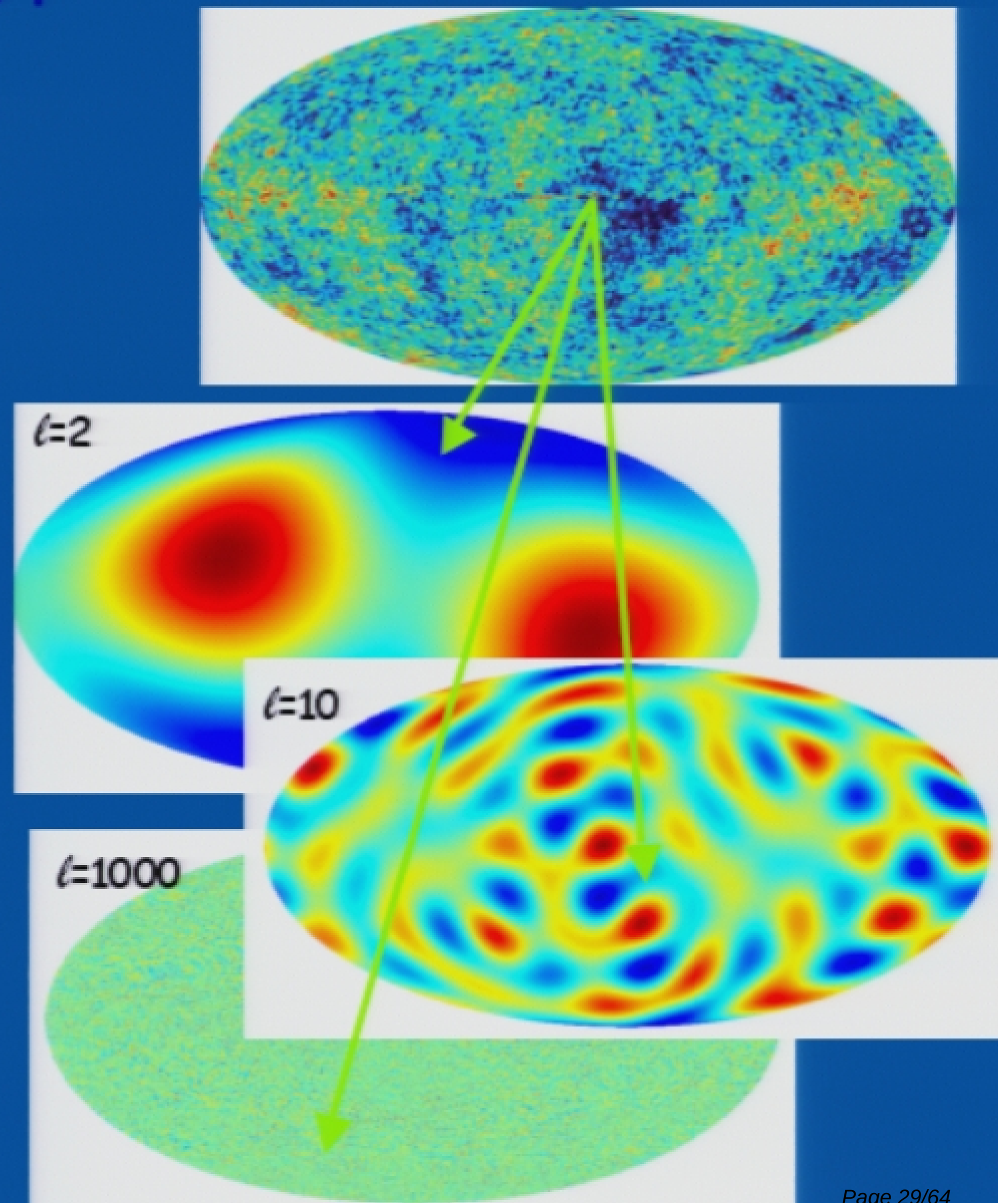
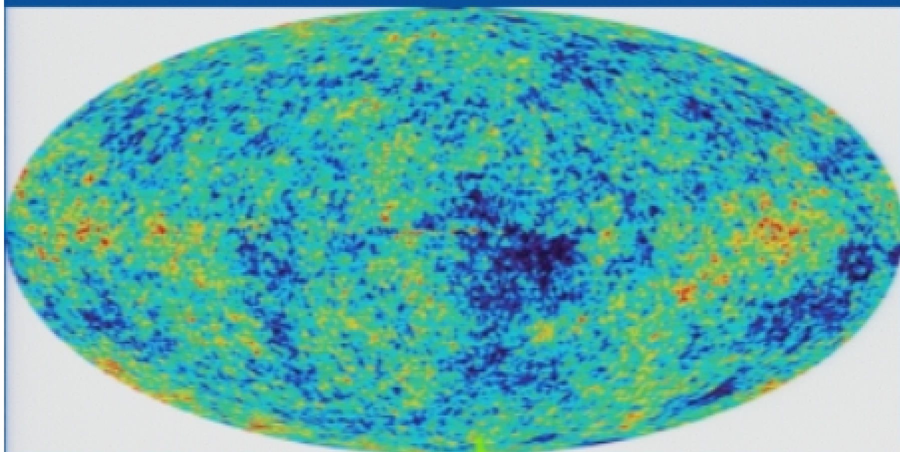
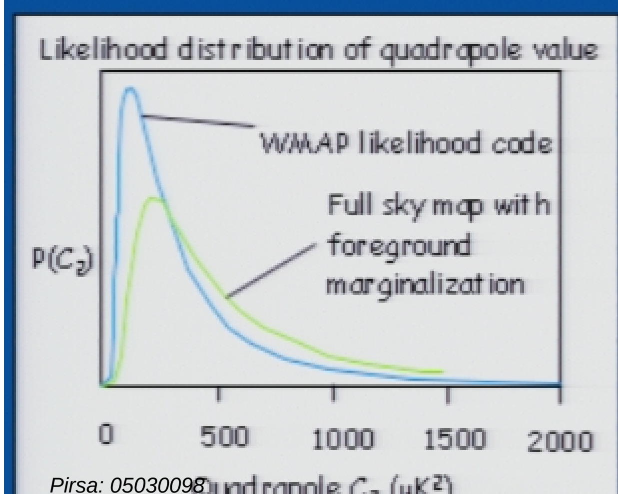


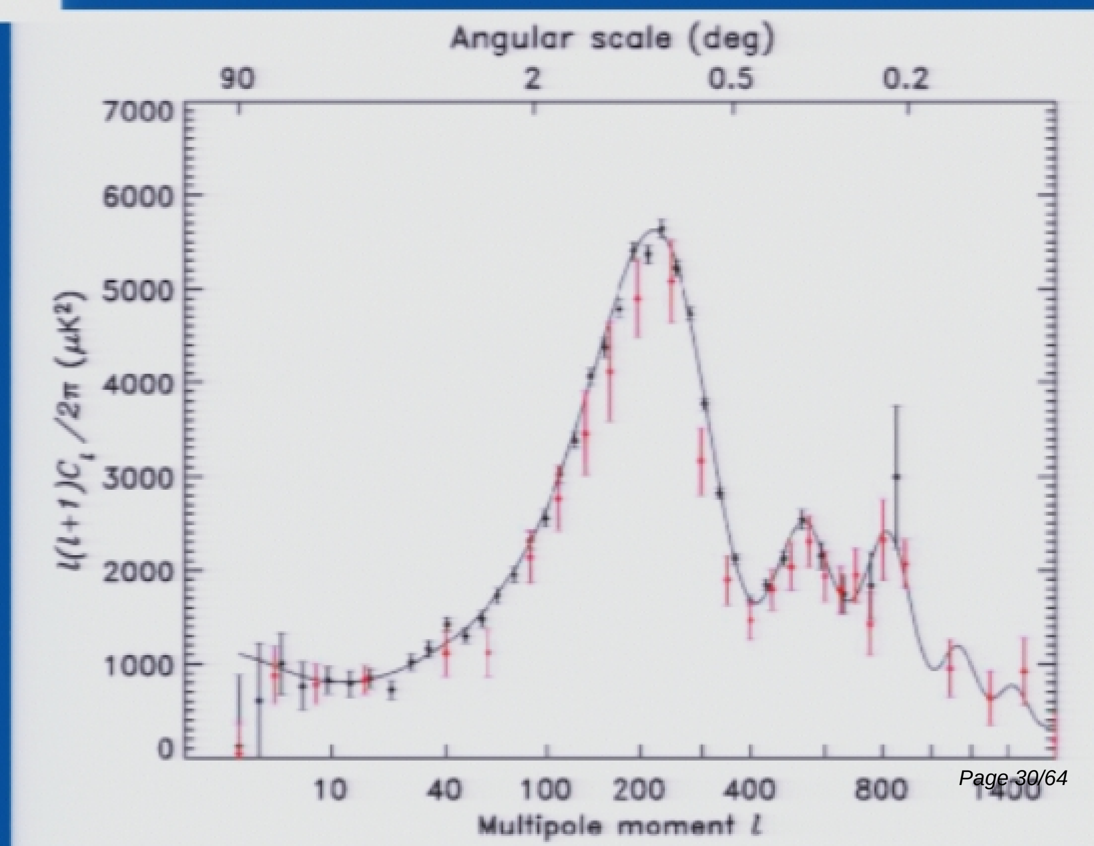
Spatial fluctuations transform into well-known power spectrum



- Estimator and masking/foreground marginalization dependent C_l spectrum



Slozar et al 2004



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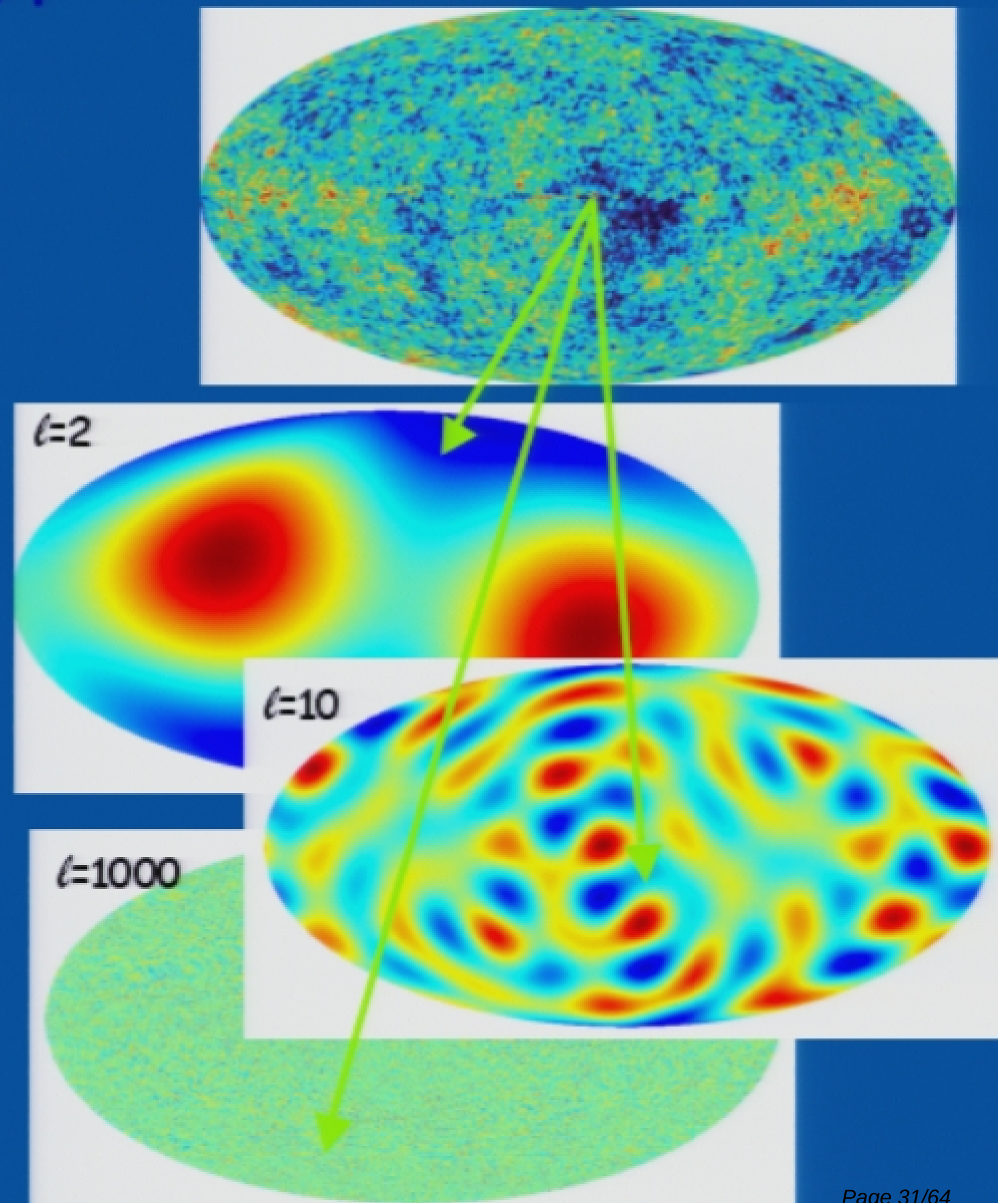

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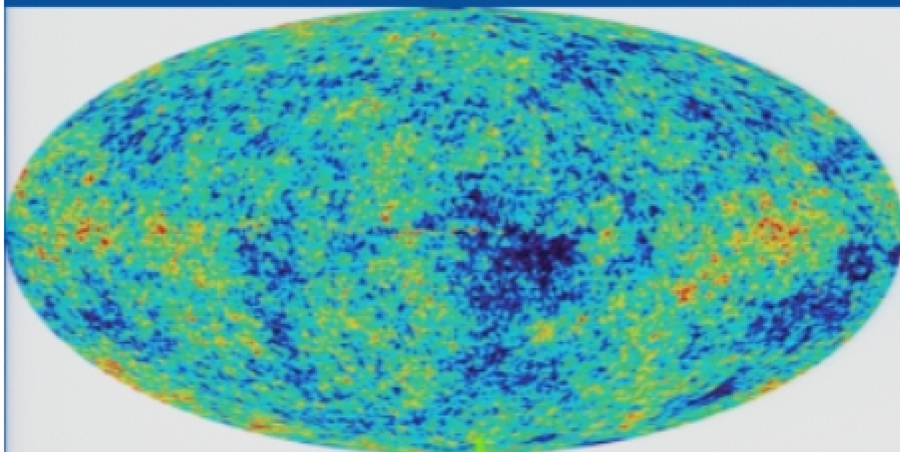
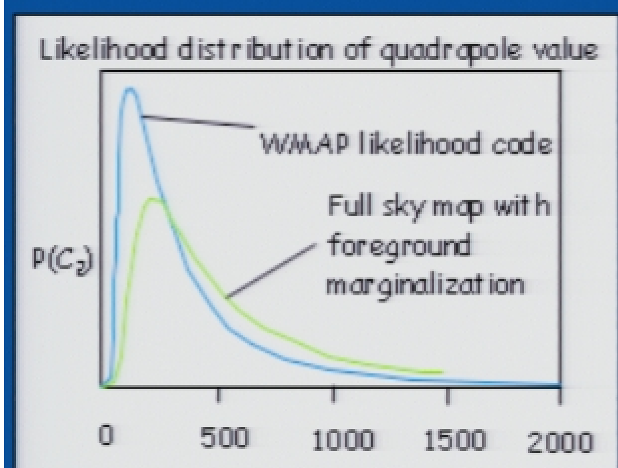
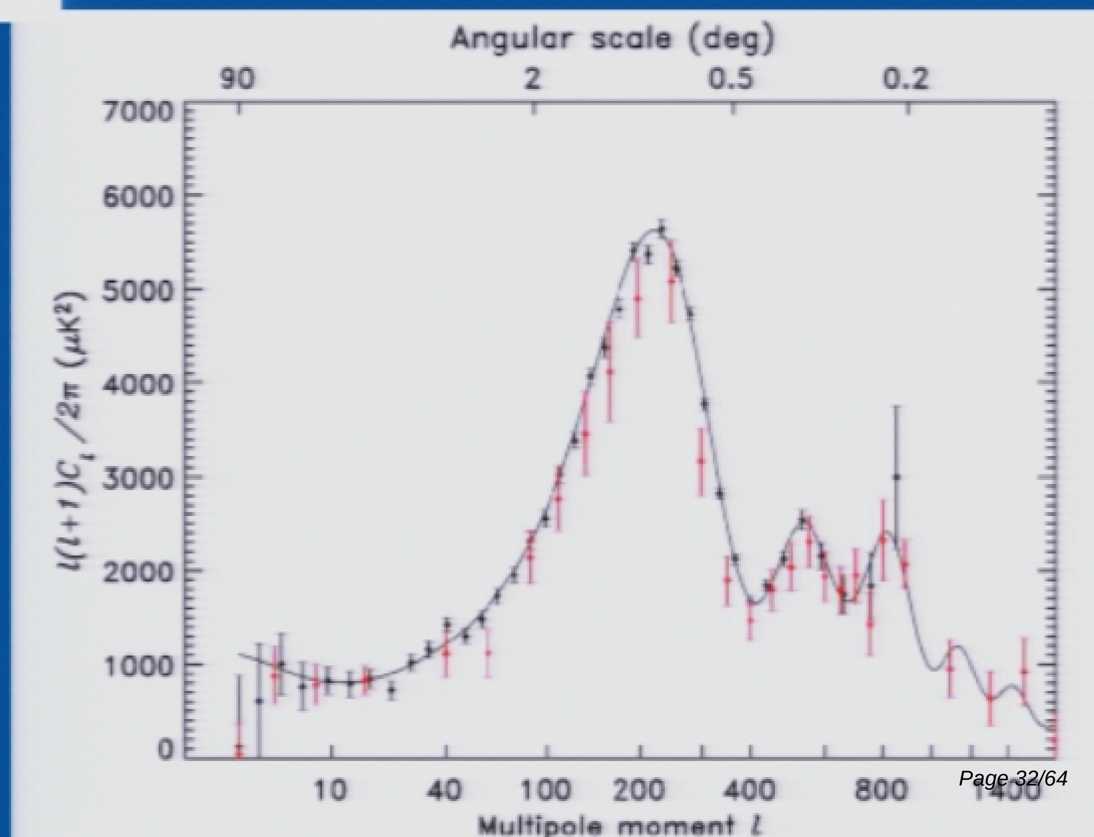


- Estimator and masking/foreground marginalization dependent C_l spectrum



Slozar et al 2004



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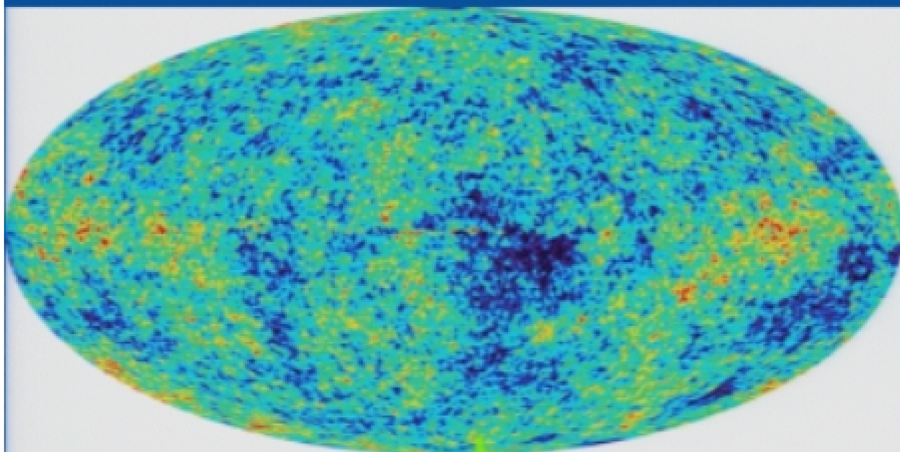

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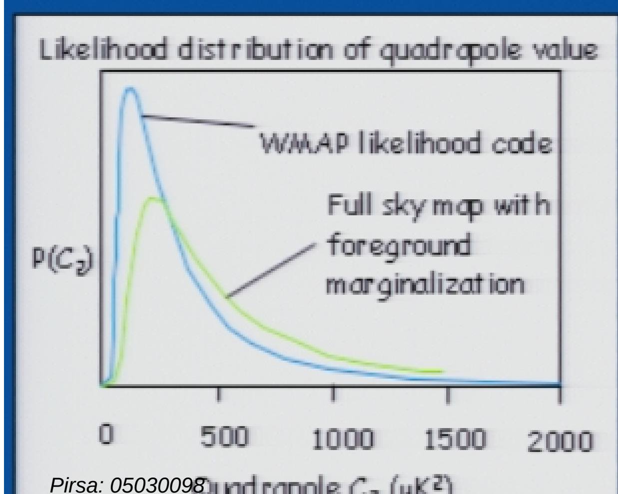
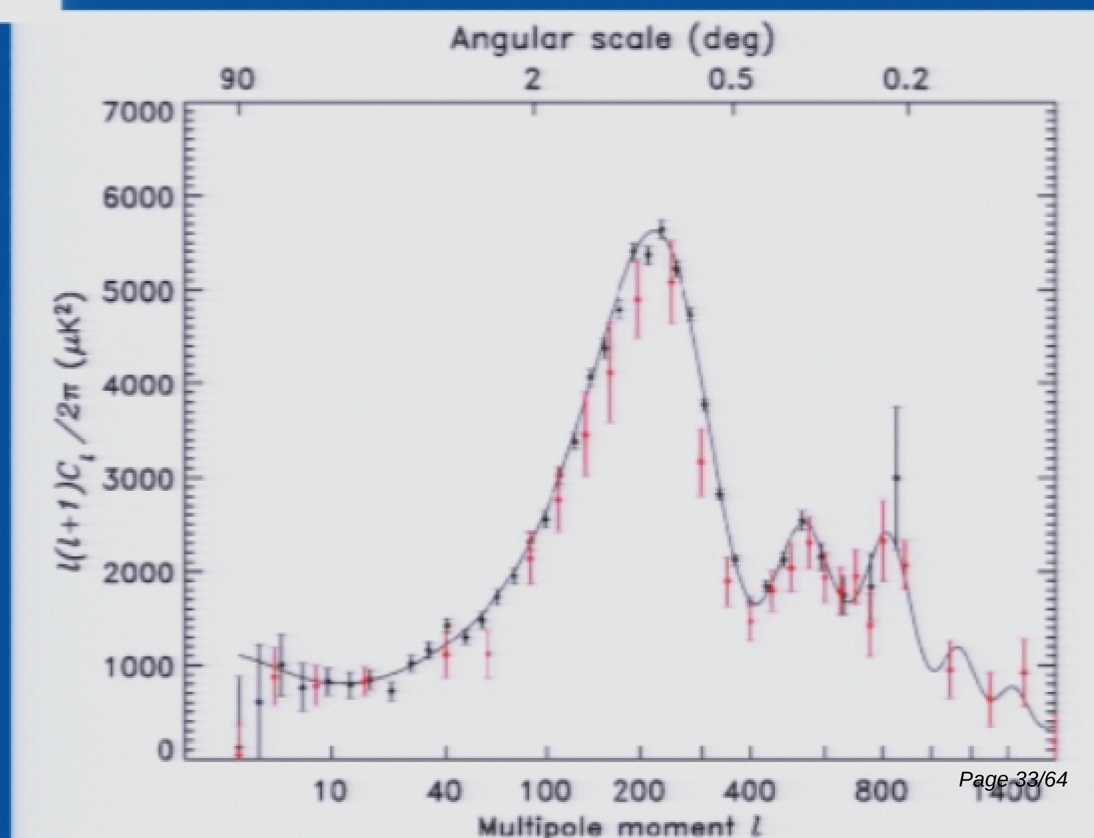


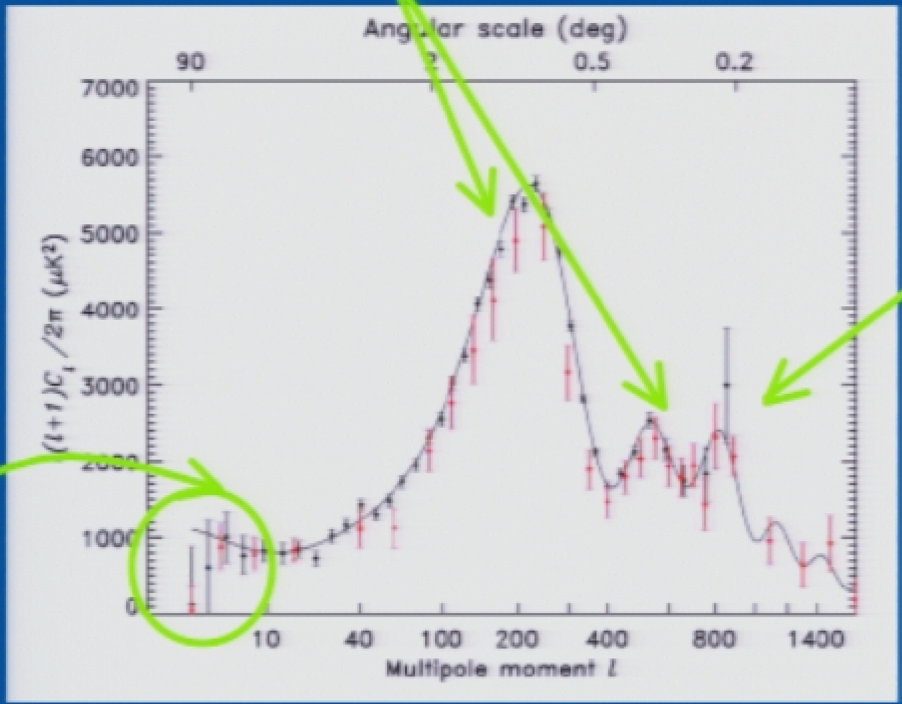
Slozar et al 2004



CMB Temperature fluctuations: An overview

Acoustic oscillations

- Photon- baryon fluid behavior at last scattering



Damping tail

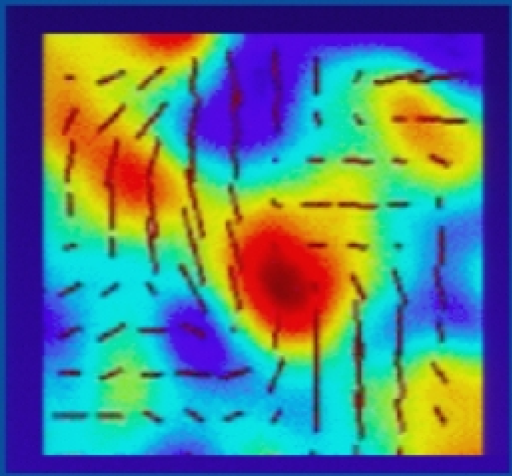
- Small scales affected by a range of scattering processes after recombination (Thermal and kinetic Sunyaev Zeldovich effects, etc.)

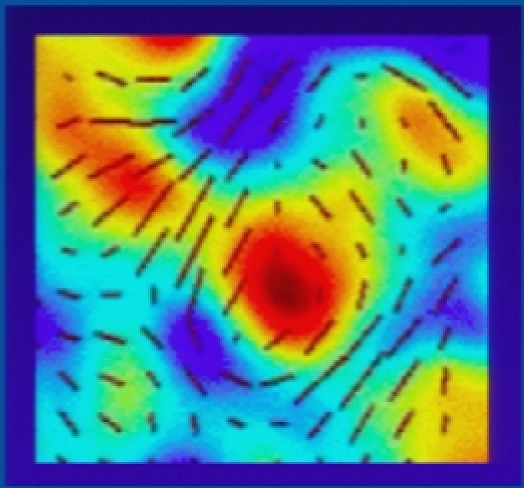
Largest scale modes

- Only just entering causal horizon recently, affected by universe's recent evolution
- Unaffected by small scale scattering processes
- Any low observed large scale power and intrinsic alignments hard to explain other than in cosmological context (except from biased statistical estimator or incorrect foreground removal)
- Limited number of measurable modes on the sky (inherent sampling uncertainty) "cosmic variance"

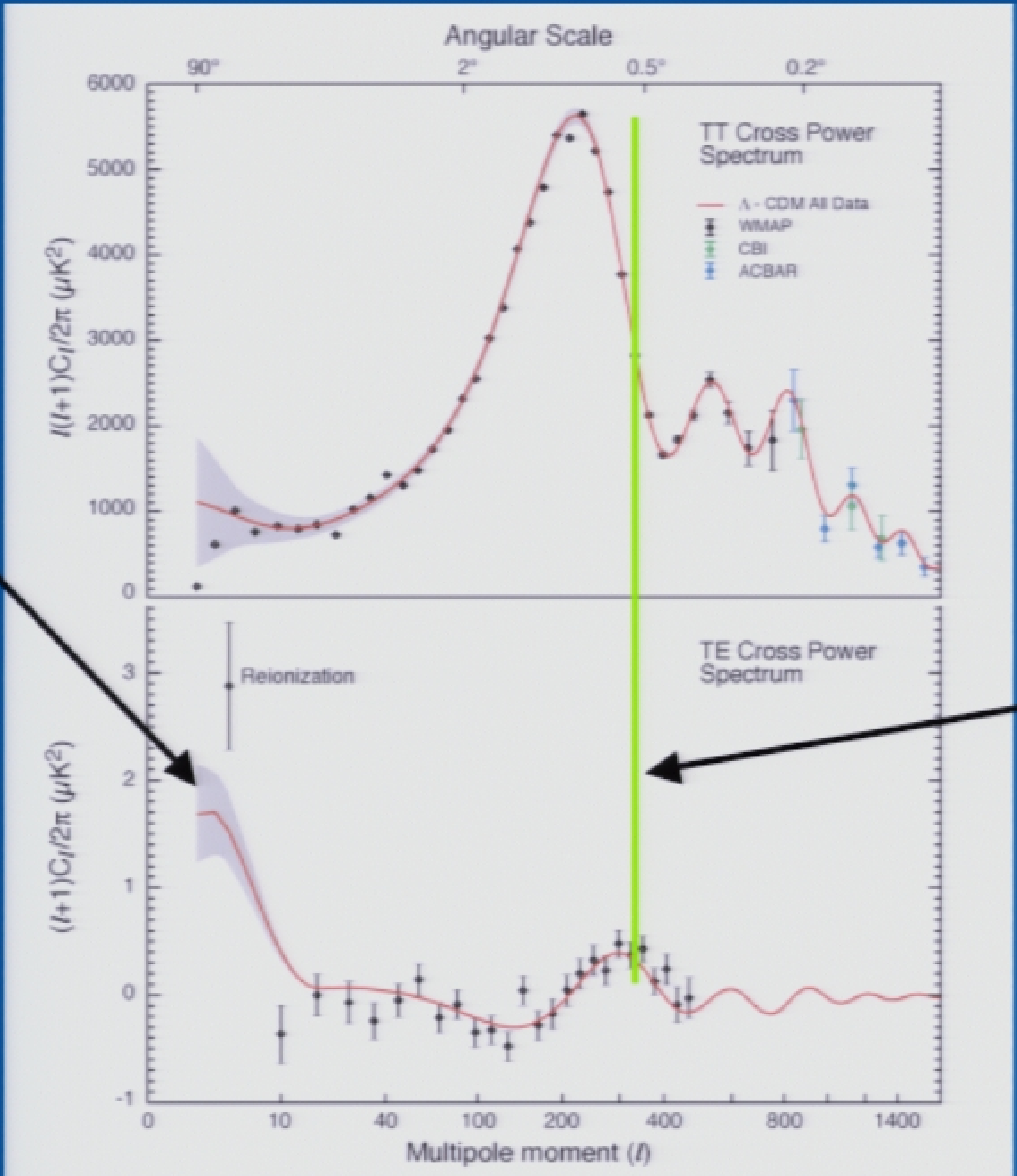
Polarization measurements many orders of magnitude smaller!

- Polarization signals are 10^2- 10^3 times smaller in power
  - -measuring ~1-10μK^2 in E/B vs a ~1000μK^2 in T
- Instrumental artifacts have to be known and understood to far greater precision
- Foreground maps are primitive
  - -Extrapolation of temperature based emission maps using polarization fractions
  - -Marginalization over uncertainties in spectrum as with low l spectrum
  - -Mask out high foreground contaminated areas (avoid issue altogether!)
- Theoretical predictions of no correlation between T and B, and E and B
  - -Useful null tests to deal with systematics





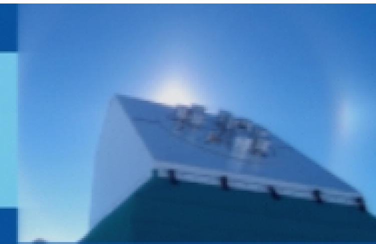
WMAP best measurement yet of TE correlation



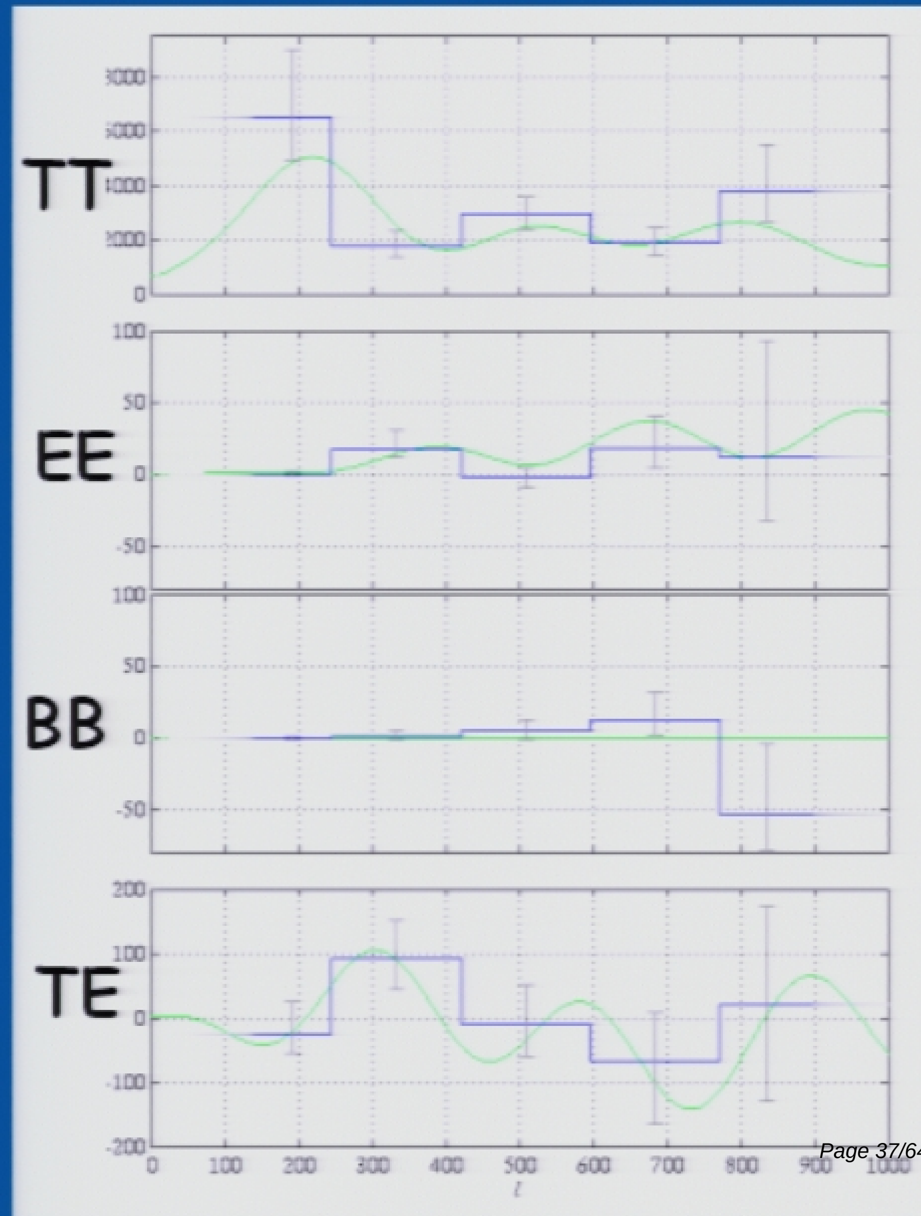
arge scale
larization from
ter scattering
poch from
ionization

TE correlation in agreement with π out of phase prediction for adiabatic fluctuations

DASI and CBI results from September 2005 give latest measurement of EE



- Represents 3 years of data from DASI interferometer experiment at the South Pole.
- Detected E modes at 6.3 σ with correlation consistent with TE spectra
- Measured B modes consistent with 0
- Detected TE cross correlation at 2.9 σ consistent with WMAP

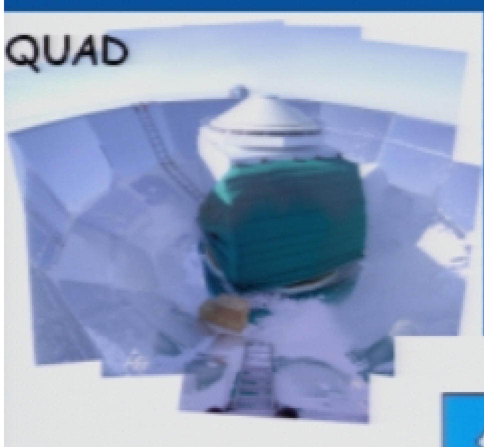


Leitch et al 2004

Good number of future surveys promise precision measurements of polarization spectra with wide ranging implications

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

Experiment	Location	Status
Polatron	Ground	Building
BICEP	Ground	Building
Quest	Ground	Building
Maxipol	Balloon	Building
Planck	L2	Building
Clover	Ground	Funded



POLARBEAR

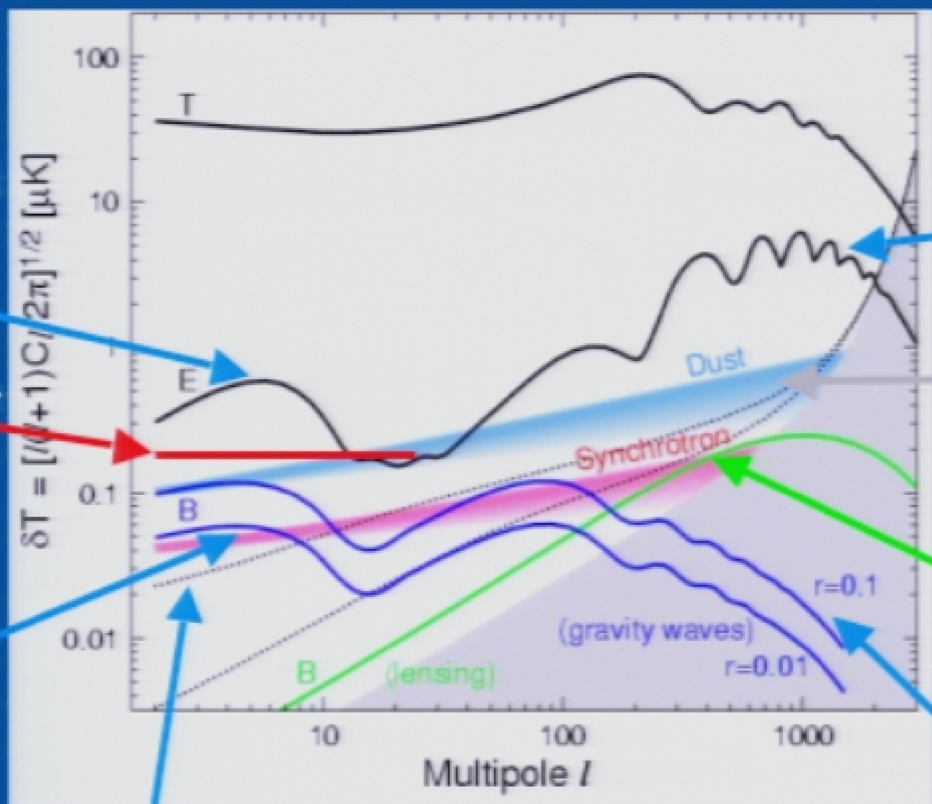
ClOVER

Good number of future surveys promise precision measurements of polarization spectra with wide ranging implications

Reionization peak (example z_r=20)

Current limit on tensors

B modes from tensors only



Temperature correlated recombination peaks

Learn a great deal about systematic effects and foregrounds

B modes from lensing of E modes should be able to cross correlate with LSS.

G- waves decay once inside the horizon.

Inflationary gravity wave signature

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

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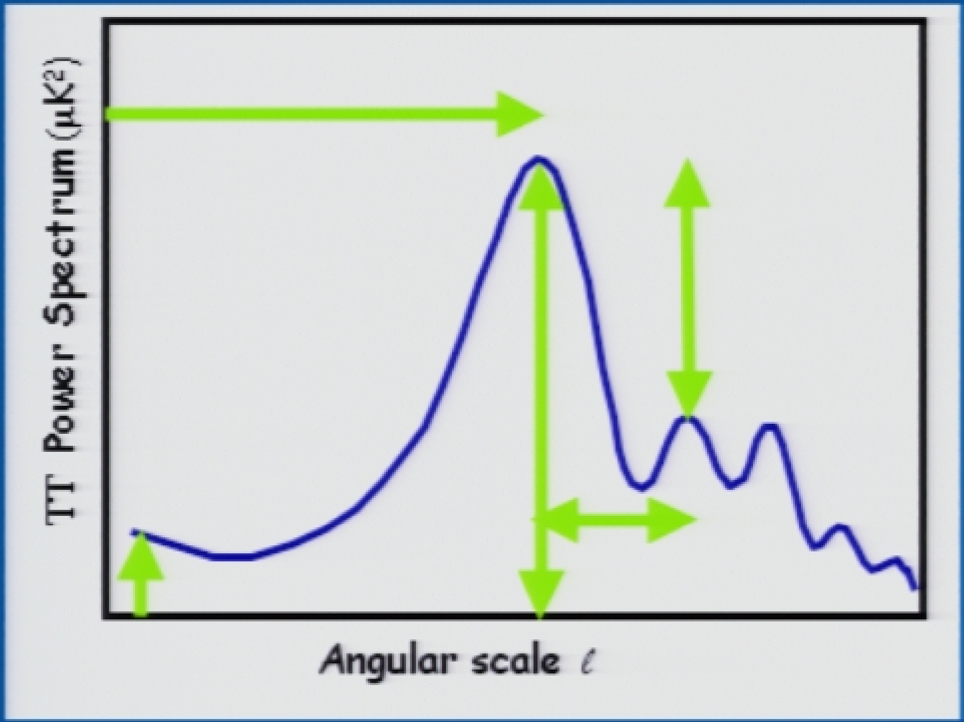
CMB peaks, troughs and plateaus constrain cosmology

- CMB TT key observables
  - -CMB First peak position
  - -Large scale power
  - -Peak to plateau ratio
  - -Second/ third peak to first peak ratio
  - -Second/ third peak spacing

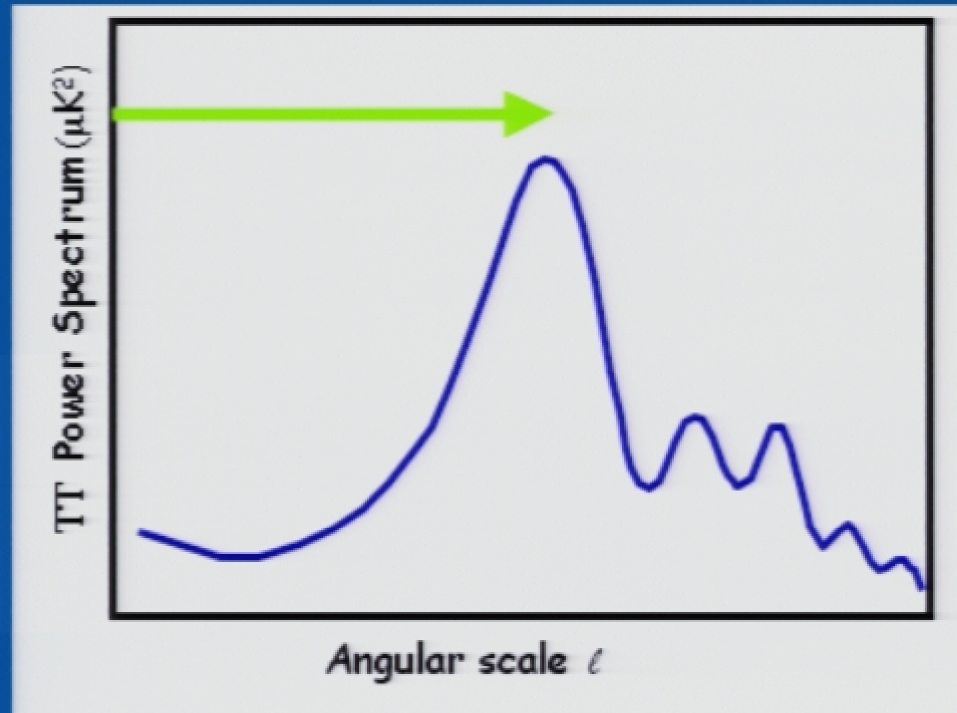


- Are translated into core cosmological parameters
  - -The expansion history (a,z): Hubble expansion factor H_0,
  - -The matter budget/ curvature : fractional energy densities($\Omega_X=\rho_X/\rho_{total}$)
  - - Primordial power spectrum : spectral tilt (n_s), and amplitude (A_s), running in the tilt ($dn_s/d\ln k$), tensor amplitude ($r = A_T/A_s$)
  - -Dark energy characteristics : w_0, $w(z)$, c_s^2?
  - -Ionization history : optical depth (τ), redshift of reionization(z_{rei})

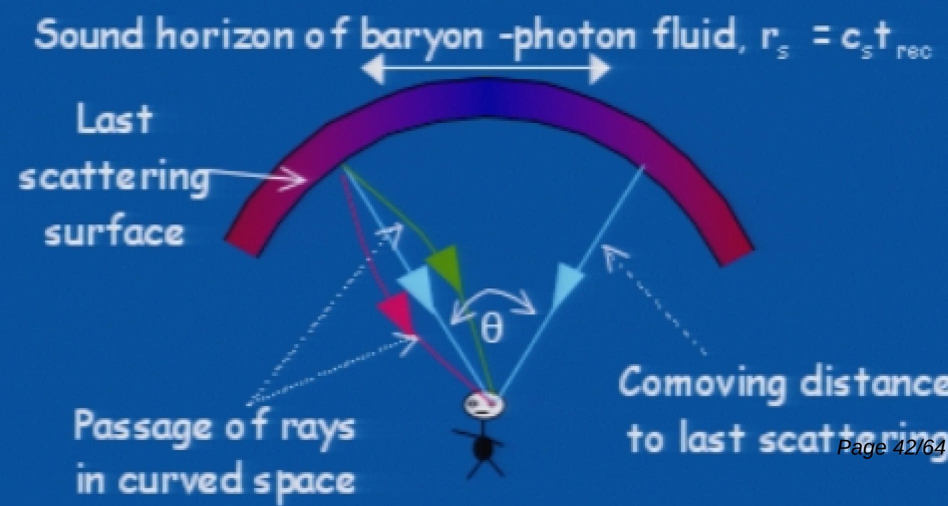
First peak position key constraint on the matter budget

- CMB First peak position determined by angular diameter distance to last scattering and the size of the sound horizon.
  - -Ratio of integrals over matter budget

$$\theta = \frac{\sqrt{3}\int_0^{a_{rec}} \left[\left(1+\frac{3\Omega_b}{4\Omega_\gamma}\right)\sum_i \Omega_i a^{(1-3w_i)}\right]^{-1/2} da}{\int_{a_{dec}}^{1} \left[\sum_i \Omega_i a^{(1-3w_i)}\right]^{-1/2} da}$$

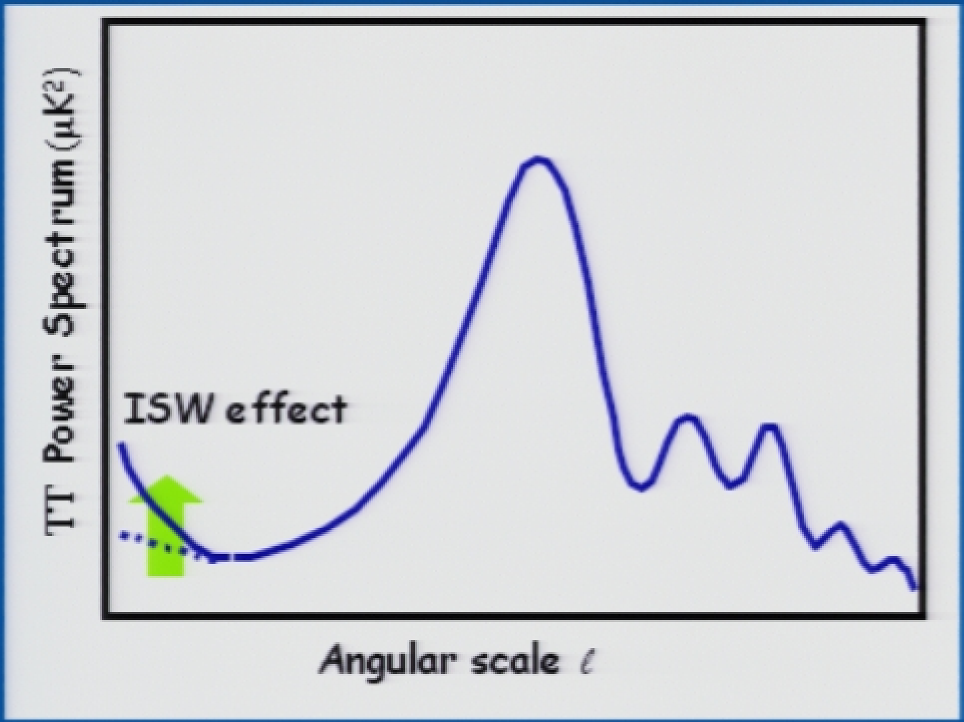


- Constrains Ω_m (CDM + baryons)
  - -Doesn't help distinguish baryons from CDM
- Geometrical degeneracy between Ω_Λ and Ω_K
  - -Broken by large scale behavior (see next)



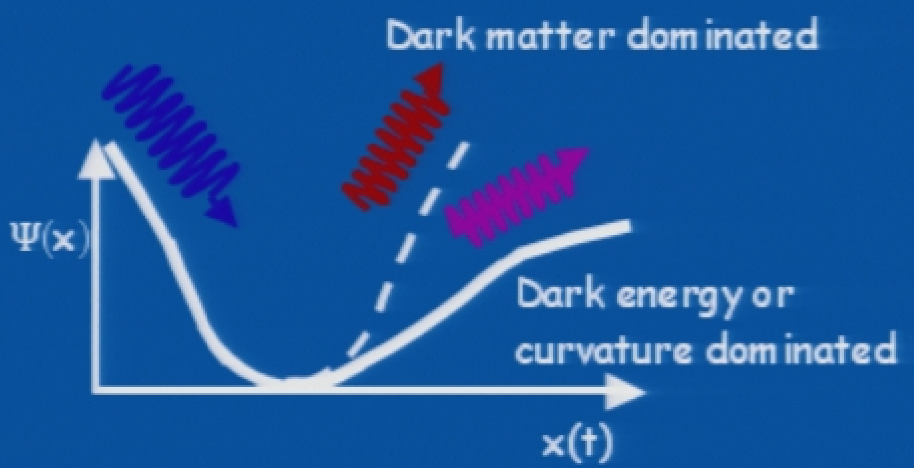
Dark energy domination induces large scale signature in CMB

- When dark energy or curvature dominates they act to suppress growth in the CDM and gravitational potential wells , Ψ



- late time Integrated Sach's Wolfe effect (ISW) in CMB photons results
  = Net blue shifting of photons as they traverse gravitational potential well of baryonic and dark matter on way.

- ISW important at large scales
  -Cancellation of effects on small scales

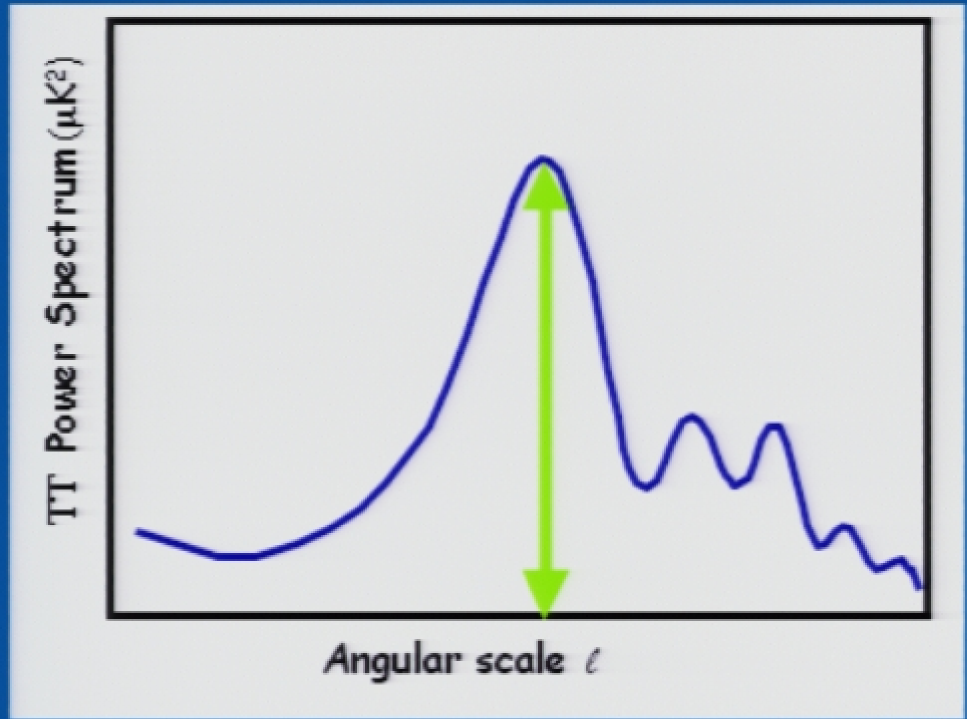


- ISW breaks geometrical degeneracy between curvature and dark energy
  -Curvature dominates earlier than dark energy therefore

- Tensor modes, and tilting/ running tilt in the spectrum can also affect large scales

First peak height important but sensitive to many effects

- **Baryons** + Increase gravitational well
  Drive growth in fluctuations
- **CDM** − Earlier matter domination
  Stops decaying potential in
  Radiation era (early ISW)
- **Tilt** + $C_l(n_s)/C_l(n_s=1) \sim (l/l_{pivot})^{n-1}$
- **Normalization** +
- **Optical depth** − Reionization scatters CMB
  $(1-\exp(-\tau))$ remain unscattered



- **Multiple degeneracies broken by:**
  - Measuring extra peaks (especially for baryons)
  - Combining with other datasets

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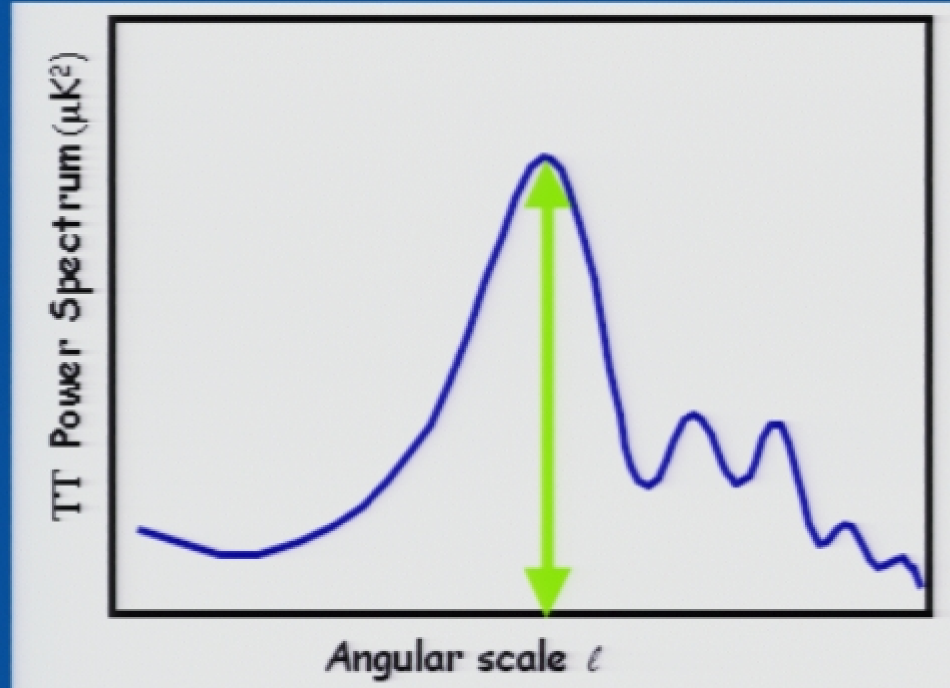
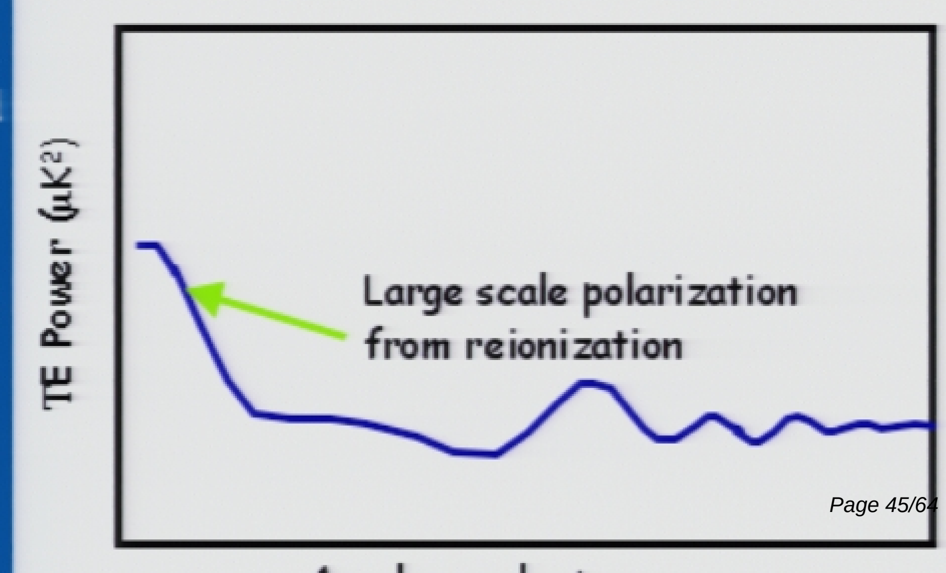
- **Multiple degeneracies broken by:**
  - Measuring extra peaks (especially baryons)
  - Combining with other datasets
  - Polarization (TE has already helped lots!)





CMB TT+ TE has provided a standard cosmological model

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

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

- The 6 parameter model fits essentially all current cosmological data: SDSS, 2dF, Lensing, HST, Ly-alpha,...

			WMAP	WMAP+CBI	WMAP+VSA
aryon density	$\Omega_b h^2$	$=$	0.024 ± 0.001	0.0232 ± 0.0012	0.0234 ± 0.0017
atter density	$\Omega_m h^2$	$=$	0.14 ± 0.02	0.136 ± 0.014	0.134 ± 0.015
ubble parameter	h	$=$	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.07
mplitude	A	$=$	0.9 ± 0.1	...	...
ptical depth	τ	$=$	0.17 ± 0.08	$0.152^{+0.023}_{-0.041}$	$0.14^{+0.14}_{-0.07}$
calar index	n_s	$=$	0.99 ± 0.04	0.98 ± 0.03	0.97 ± 0.04
			Spergel et al	Readhead et al	Rebolo et al

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The key dark energy questions (as I will talk about on Wednesday!)

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

Adjustment to gravity?

- Non-minimal couplings to gravity?

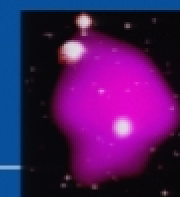
-Higher dimensional gravity?

Cosmological constant?

-Early phase transitions?

-Holographic?

-Anthropic?



Adjustment to matter?

-An 'exotic', dynamical matter component?

- 'Unified Dark Matter'?

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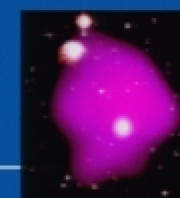

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CMB angular diameter distance gives a constraint on w

- Dark energy is a strange component who's energy density is not readily diluted by the universe's expansion

$$\rho \propto a^{-3(1+w)}\ ,\ w < -\frac{1}{3}$$

- It's equation of state (w) could be a purely geometrical effect or actually relate to intrinsic properties of a particle w=p/ρ (e.g. scalar field)

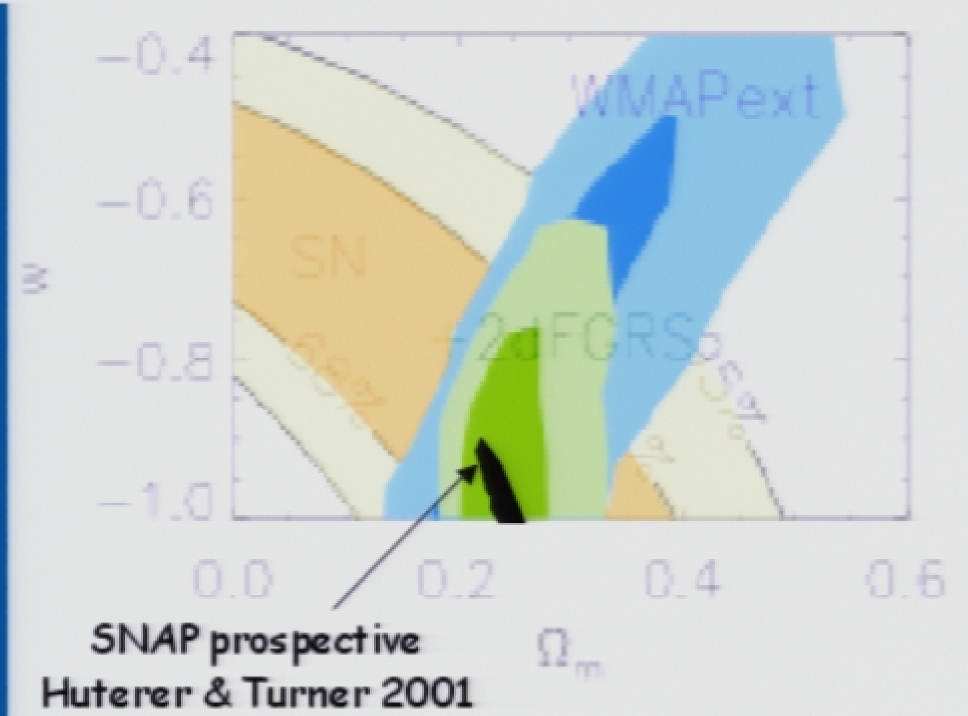
- Degeneracy in CMB angular diameter distance between w and Ω_M is complementary to that in supernovae from luminosity distance

- But need to remember CMB gives measure of *averaged, effective equation of state*

$$w_{eff} \sim \int_{a_i}^{a_f} \Omega_Q(a) w(a) da$$

-how do we combine its data with SN if w is evolving?

Combined constraints on constant equation of state



Spergel et al. 2003

What are the different constraints?

Probes of background expansion due to dark energy

- Late time probes of w(z)
  - Luminosity distance vs. z
  - Angular diameter distance vs. z
- Probes of an integrated 'w_{eff}'
  - Angular diameter distance to last scattering Bean & Melchiorri PRD 65 (2002)
  - Age of the universe

Probes of background and clustering of dark energy

- Late time probes of w(z) and $c_s^2(z)$
  - -Comoving volume * no. density vs. z Bean and Dore, PRD 68(2003)
  - -Shear convergence
  - -Late time ISW Bean & Dore PRD 69 (2003)

Early universe constraints on dark energy

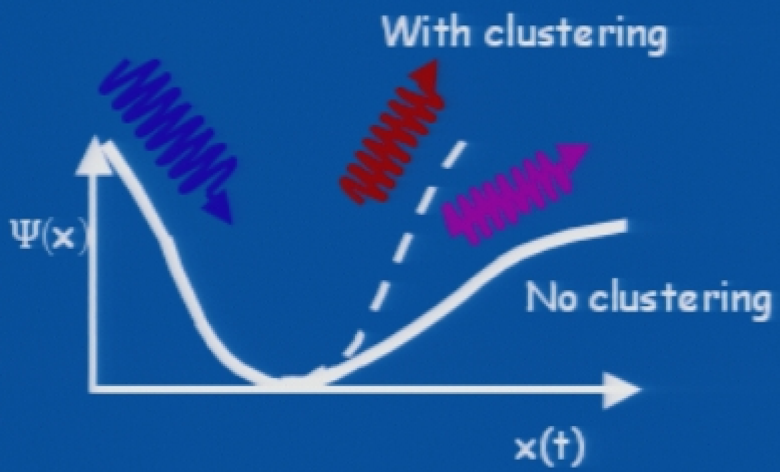
- Early time probes of $\Omega_Q(z)$
  - -N_{eff} Bean, Hansen, Melchiorri (2001)

Probes of the wacky nature of dark energy

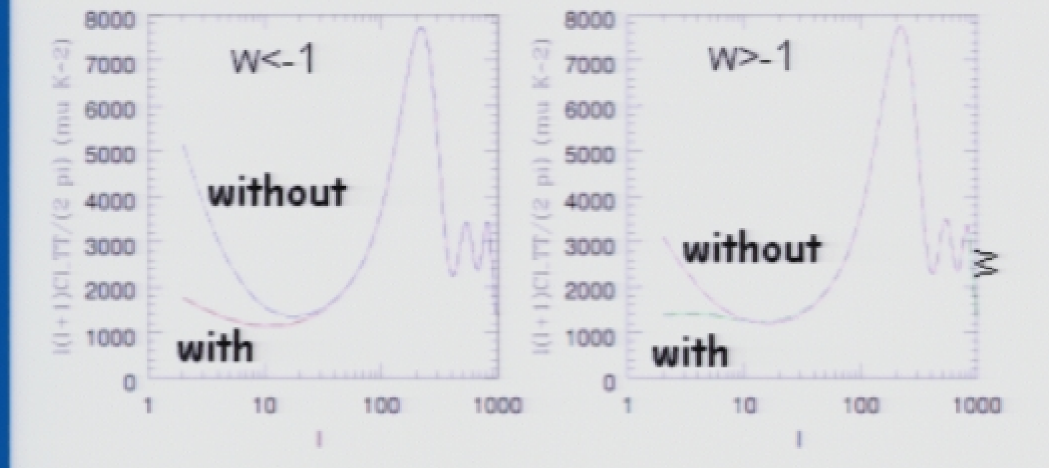
- Alternate probes of non-minimal couplings between dark energy and R/ matter or deviations from Einstein gravity
  - Varying alpha tests Martins et al (2002), Rocha et al (2004)
  - Equivalence principle tests
  - Deviation of solar system orbits

ISW important for learning about true nature of dark energy

If dark energy clusters, it acts to counter the suppression of CDM growth at late times, it has an effect on the ISW

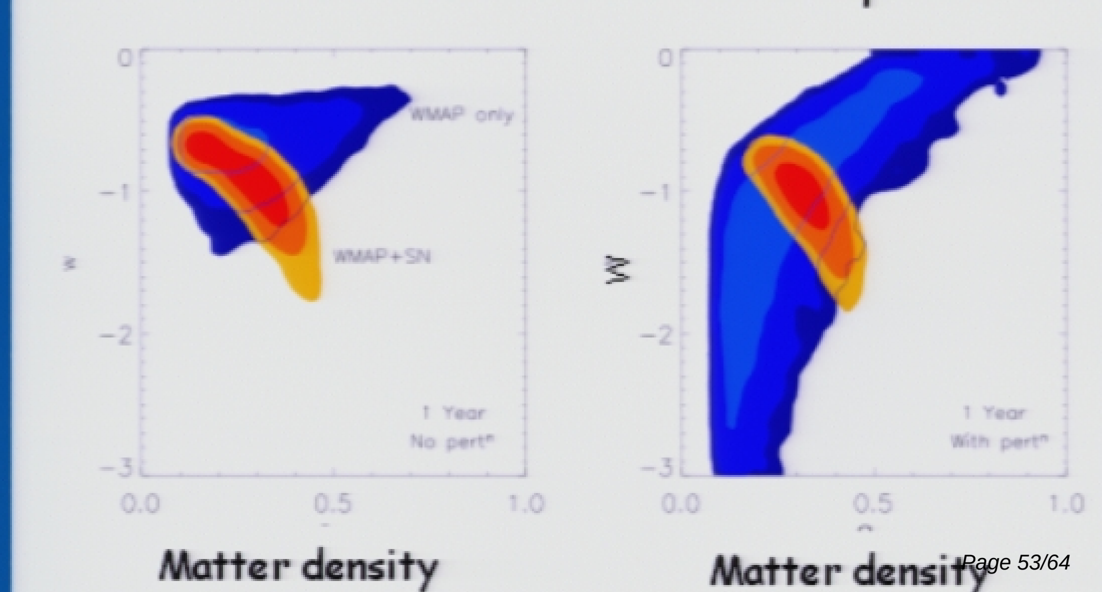


CMB spectra for DE models incl/excl perturbations



Dark energy clustering (Bean & Dore PRD 69 2003) and dark energy isocurvature modes mechanisms for low large-scale power

Constraints on w from CMB+ SN1a incl/excl perturbations



Prior assumption on clustering could be important in combining CMB with other data sets

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  - CMB polarization
- The power of the CMB - answering 4 key questions
  - Is there a cosmological standard model?
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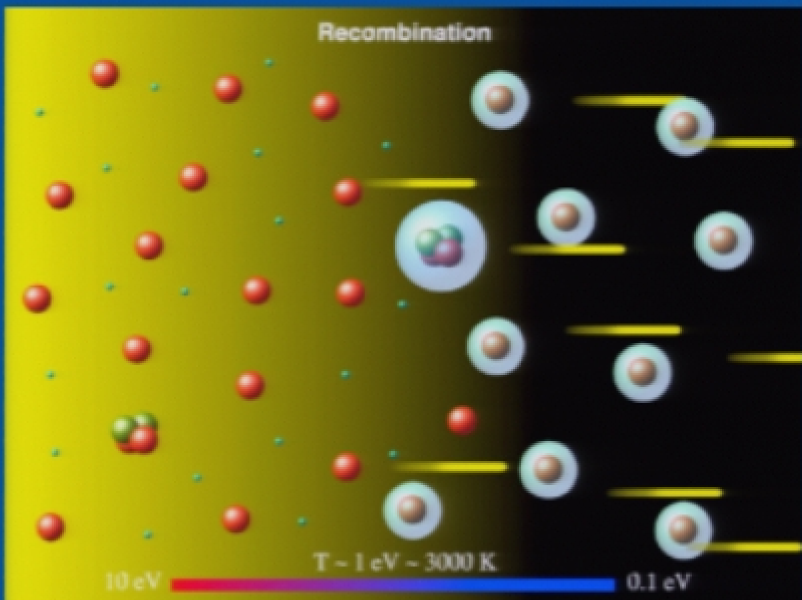
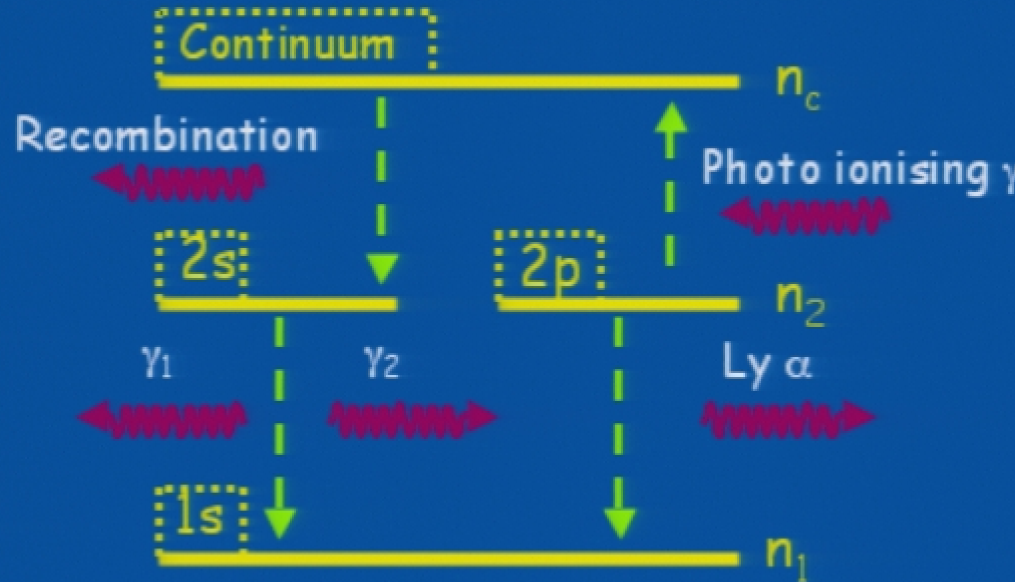
Recombination history as a dark matter probe



Kinney



$$-\frac{dx_e}{dt}\Big|_{std} = C\left[a_c n x_e^2 - b_c(1-x_e)\exp\left(-\frac{\Delta B}{k_B T}\right)\right]$$

et recombination rate

2 γ decay from meta-stable 2s

Recombination coeff over all n>1

Photo-ionization coeff over all n>1

Energy difference between n=1,2

Peebles, 1968

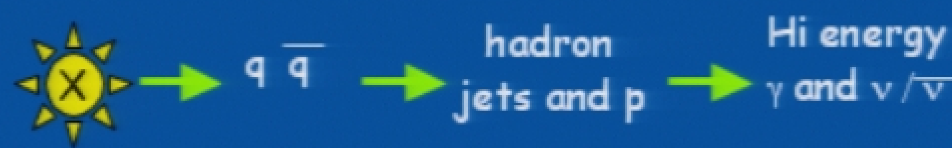
Beyond standard recombination : additional photon sources

- Adding ionizing and Ly α photons through particle decay
  - -Super heavy dark matter (SHDM) decay/annihilation
  - -black hole evaporation
  - -sterile neutrinos
  - -Radiation from cosmic strings ...

$$\frac{dn_\alpha}{dt} = \varepsilon_\alpha(z)H(z)n, \quad \frac{dn_i}{dt} = \varepsilon_i(z)H(z)n$$

$$-\frac{dx_e}{dt} = -\frac{dx_e}{dt}\Big|_{std} - C\varepsilon_i H - (1-C)\varepsilon_\alpha H$$

- Proposed mechanism for extra γ generation:
  - -SHDM decay with lifetime t_X
  - -Particle cascades generate lower energy γ
  - -These extra γ disrupt recombination



$$\frac{dn_X}{dt} = -\frac{n_X(t)}{\tau_X(n_X,t)}, \quad \varepsilon_X(t) = -\frac{n_X(t)}{H(t)\tau_X n_H}$$

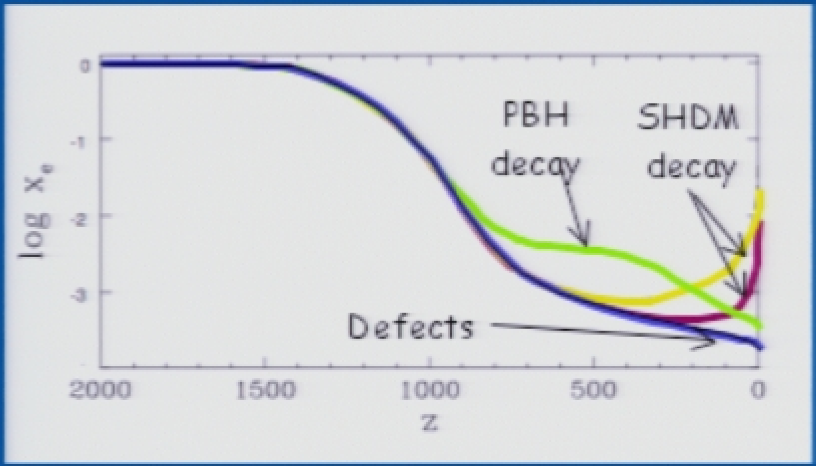
$$\gamma_{UHECR} + \gamma_{CMB} \rightarrow e^+ + e^-$$
$$e^-_{UHECR} + \gamma_{CMB} \rightarrow e^{-\prime} + \gamma'$$
$$p_{UHECR} + \gamma_{CMB} \rightarrow p' + e^+ + e^- + \gamma'$$

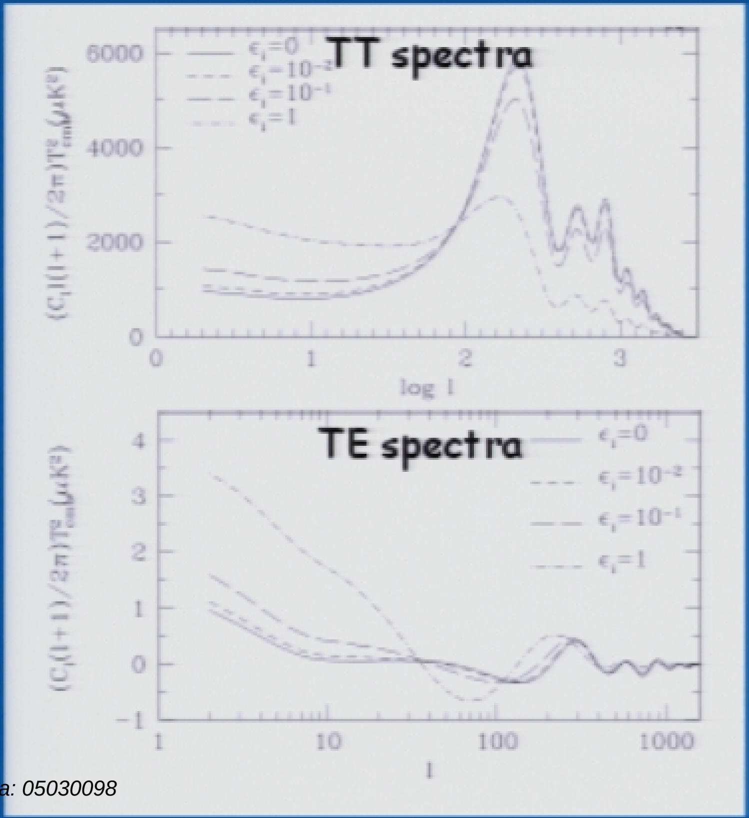
- Use EGRET measurements of high energy cosmic rays to place an upper limit on cascade energy injection rate today

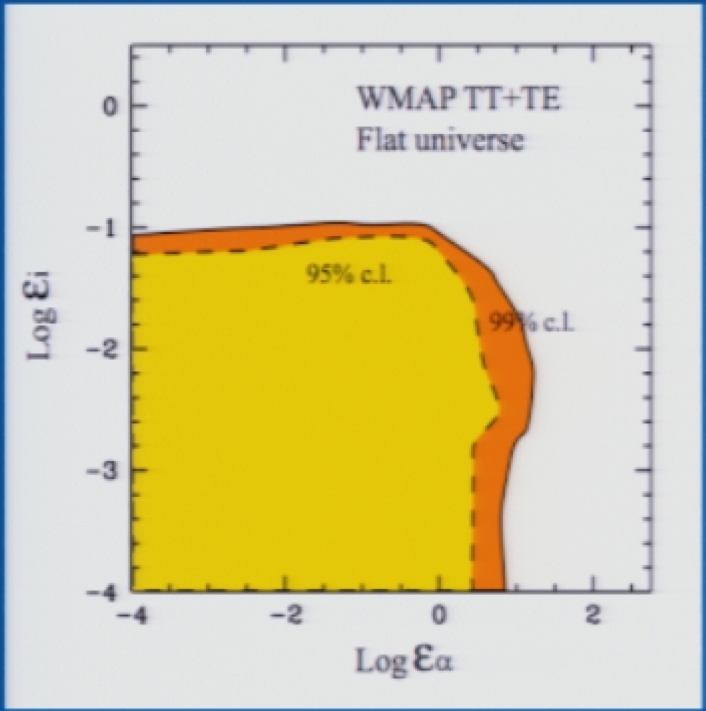
Naselsky astro-ph/0210034, Sigl hep-ph/0109202
Berezinsky et al. (1990) and Protheroe et al. (1995)

Beyond standard recombination : Current constraints from CMB

- Decay evolution is model dependent different evolutions for SHDM, for defects, and for PBHs
- Increased ionization fraction translates into temperature and polarization signatures in CMB



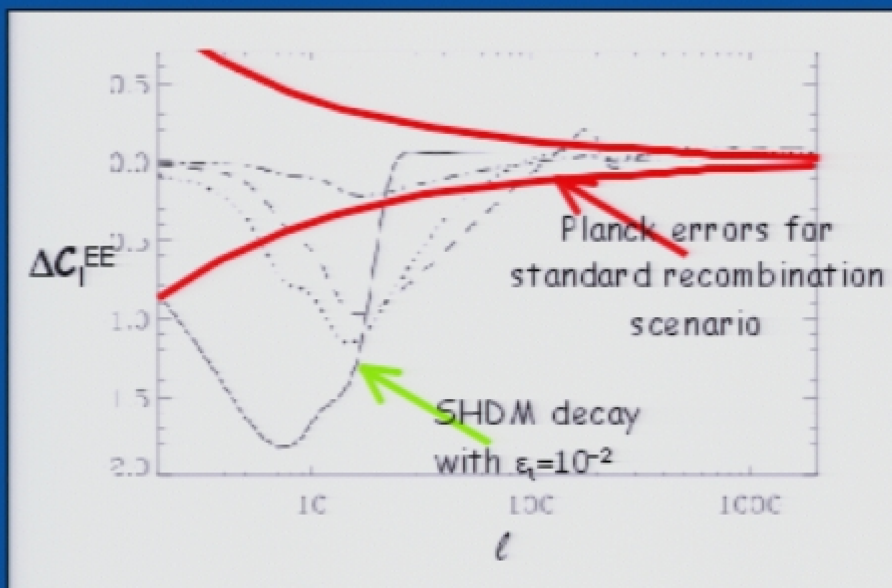




Bean, Melchiorri and Silk (2003)

Beyond standard recombination : Prospective constraints from CMB

- Constraints from EE polarization spectrum
  - enable cleaner inferences about ionization history to be made (Planck in particular will make model distinctions possible)



Naselsky astro-ph/0210034

- Potential for direct comparison of CMB in many frequencies
  - -Extract out dust, synchotron and free-free signatures explicitly to isolate residual extraneous signal.
  - -Residual diffuse background consistent with 100GeV annihilation with cross section $10^{-26}cm^3s^{-1}$ (Finkbeiner 2004)

Constraints on tilt and tensors consistent with inflation

- Tilt and tensor contributions entirely consistent with inflationary predictions
- The tensor to scalar ratio is being constrained by the low l region of the TT spectrum.

$$r = \frac{\Delta_T^2}{\Delta_S^2}$$

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

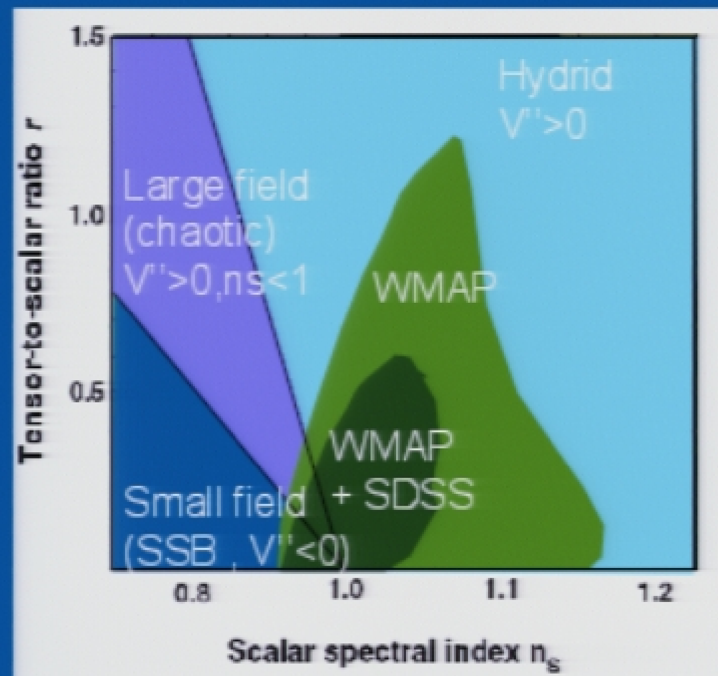
$$r < 0.84 \qquad n_s = 1.064^{+0.66}_{-0.059}$$

WMAP Tegmark et al

$$r < 0.38 \qquad n_s = 1.00 \pm 0.03$$

WMAP+SDSS+Lya Seljak et al

- Constraints are starting to lean on the r~0.27 for simple models of inflation ($\lambda\phi^4$ potentials).



Tegmark et al (2003)

- New data will break key degeneracies
  - -Polarization measurements will break n_s-τ,
  - -3rd peak/ SZ observations will break Ω_b - n_s

Is it time to start thinking beyond the n_s/r description?

Non-Gaussianity in the CMB

Think of inflaton field as a QHO with potential V

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left[\left(\frac{k}{a}\right)^2 + V''\right] = 0$$

$$\psi = \sum \alpha_n \psi_n \quad P(\phi) = |\psi|^2$$
$$\psi_n(\phi) = C_n H_n\left(\frac{\phi}{\sqrt{2}\sigma_0}\right)\exp\left(-\frac{\phi^2}{4\sigma_0^2}\right)$$
$$H_n(x) = (-1)^n e^{x^2}\frac{d^n}{dx^n}e^{-x^2}$$

Ground state, single field, inflaton has a gaussian distribution

$$|\psi_0|^2 \propto \exp\left(-\frac{\phi^2}{2\sigma_0^2}\right)$$

General inflationary spectrum includes higher energy states. This can be nicely described by an Edgeworth expansion, Contaldi, Bean and Magueijo 2000

-coefficients given by nth order cumulants, κ_n

$$(x) = \frac{e^{x^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}}\left[1 + \frac{\kappa_3}{12\sqrt{2}}H_3\left(\frac{x}{\sqrt{2}\sigma}\right) + \frac{\kappa_4}{96}H_4\left(\frac{x}{\sqrt{2}\sigma}\right) + \frac{\kappa_5}{480\sqrt{2}}H_5\left(\frac{x}{\sqrt{2}\sigma}\right) + \frac{\kappa_6+10\kappa_3^2}{4960}H_6\left(\frac{x}{\sqrt{2}\sigma}\right) + ..\right]$$

- Predicted non-Gaussian distribution dependent on coherent or incoherent superposition of wave function

Probability density for coherent superposition..

$$P(\phi) = \frac{e^{-\frac{\phi^2}{2\sigma_0^2}}}{\sqrt{2\pi}\sigma_0}\left[1 + \sum_{n\geq 1}\frac{2\Re(\alpha_n)}{(2^n n!)^{1/2}}H_n\left(\frac{\phi}{\sqrt{2}\sigma_0}\right)\right]$$

..And for an incoherent one

$$P(\phi) = \frac{e^{-\frac{\phi^2}{2\sigma_0^2}}}{\sqrt{2\pi}\sigma_0}\sum_{keven}\left(\sum_n \frac{b_k^{nn}|\alpha_n|^2}{2^n n!}\right)H_k\left(\frac{\phi}{\sqrt{2}\sigma_0}\right)$$

-κ_n coefficients relate to n^{th} (coherent) $n/2^{th}$ (incoherent) energy eigenstate

- NB *can't* generate inter-mode correlations however (an alternative non-Gaussian signature)
  - E.g. No bispectrum signal

Non-Gaussianity, primordial or not, actively sought in CMB

- Initial analyses indicated that the WMAP results were consistent with Gaussianity:

  -3-point tests are consistent up to known point source contribution (Komatsu et al., Gaztanaga & Wagg)

  -non-Gaussianities in COBE bispectrum do not appear in WMAP (Magueijo & Madeiros)

  -Topological tests (Minkowski functionals, genus) are also consistent (Komatsu et al., Colley & Gott)

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- Some recent analyses have pointed to possible inconsistencies e.g.:

  -Evidence that north ecliptic hemisphere has less large scale power than southern (Eriksen et al.)

  -A wavelet analysis shows evidence for non-Gaussianity in the southern Galactic hemisphere (Vielva et al.)

  -Some strange alignments seen in the quadrupole and octopole moments (Tegmark et al.) and see Moffat 2005

  -Multipole vector analysis indicates unexpected alignments at low l (Copi et al.) but see Land & Magueijo 2005

Are non-Gaussian signatures primordial? foreground contamination? contamination of the dataset (like it was in COBE) ?or just a lucky choice of statistical choice-after-the-fact?....

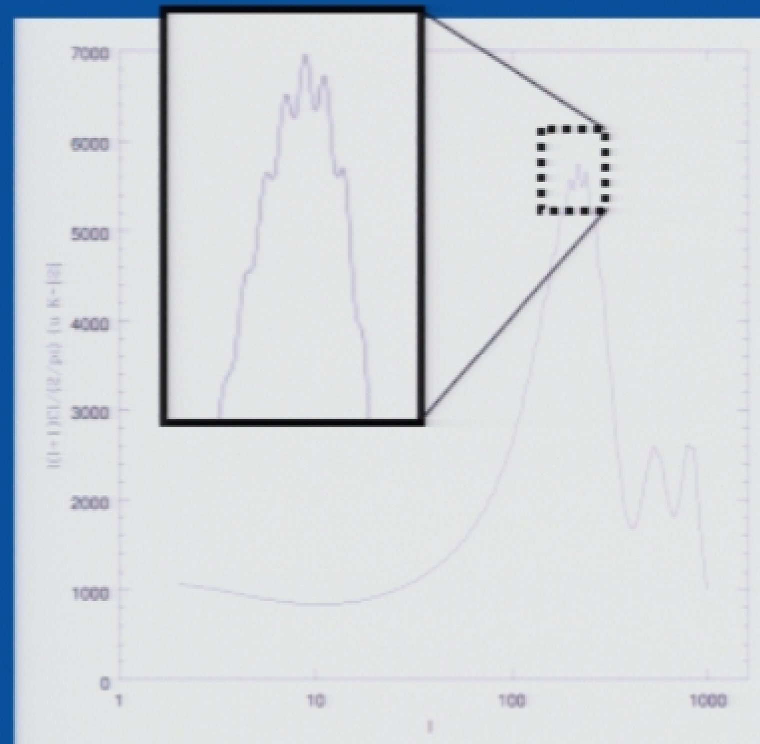
Warrants further investigation!

Too many bumps, wiggles, sags and alignments?

- χ^2 fit to large scale TT data is significantly improved by oscillatory feature in the primordial spectrum
  - mimic observed bumps and features l<250
  - Trans-Planckian ringing effect? Martin and Ringeval (2003)

But

- severe selection going on to fit data (parameter space is a hedgehog!)
- Only phenomenological approaches to TP so far
- Is the effect a more mundane systematic?



Based on model by Martin and Ringeval (2003)

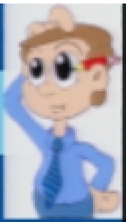
- Is the low quadrupole of primordial origin?
  - Evidence of a large running spectral index?
  - A large scale fundamental cut off? holographic?
  - Or is it a more recent effect e.g. dark energy clustering

Except

- maybe improved statistics reduce significance of this (from 1/700 to 1/20?) Efstathiou (2004))

Observations provide plenty of potential for theorists!

What have been saying?

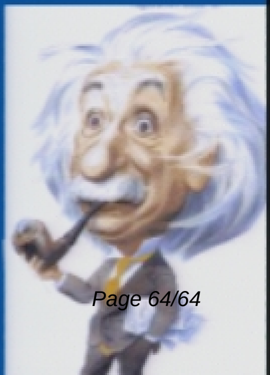


- The CMB will be a hive of industry in the next 10 years
  - -CMB experiments probing l>1000 for cosmological parameters and growth of structure.
  - -Precision polarization measurements testing inflation, optical depth, and looking for tensor modes

- WMAP has not only improved our understanding of the universe on a quantitative level (with the matter budget) but also qualitatively
  - - Evidence of significant late time scattering from reionization
  - - Evidence that the velocity flows at recombination were adiabatic
  - - ISW predictions consistent with a dark energy scenario

  And
  - - Tantalizing features in the data (wiggles and low quadrupole) fueling theoretical activity

- We have much more to learn from the CMB!
  - -Key insights into inflation, dark matter and dark energy



"If an idea does not appear absurd at first then there is no hope for it"
Albert Einstein