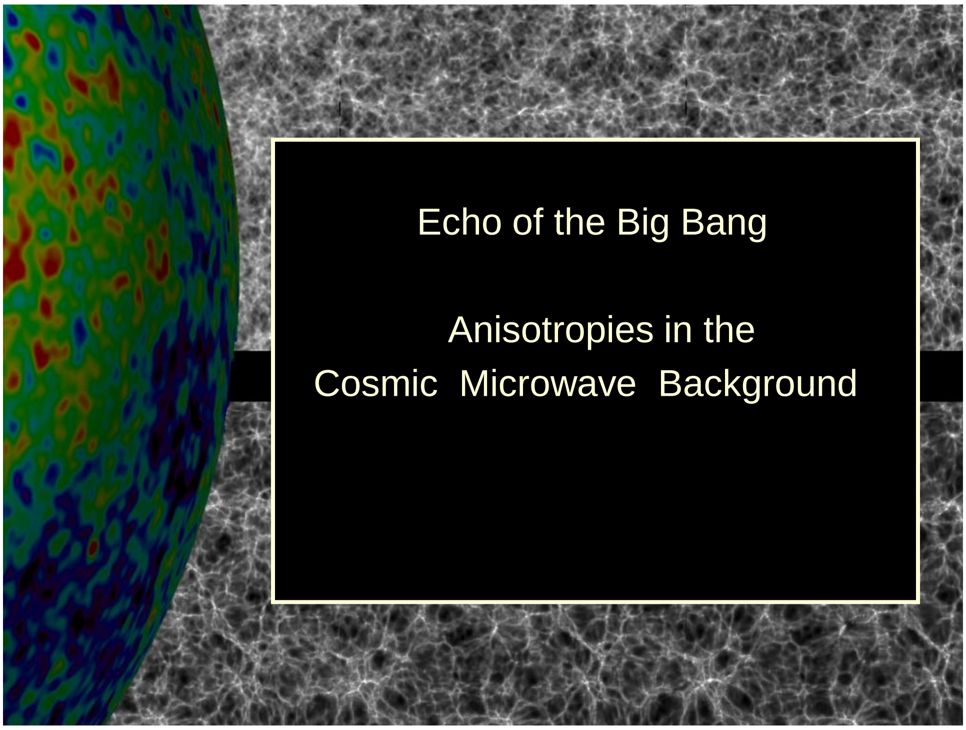
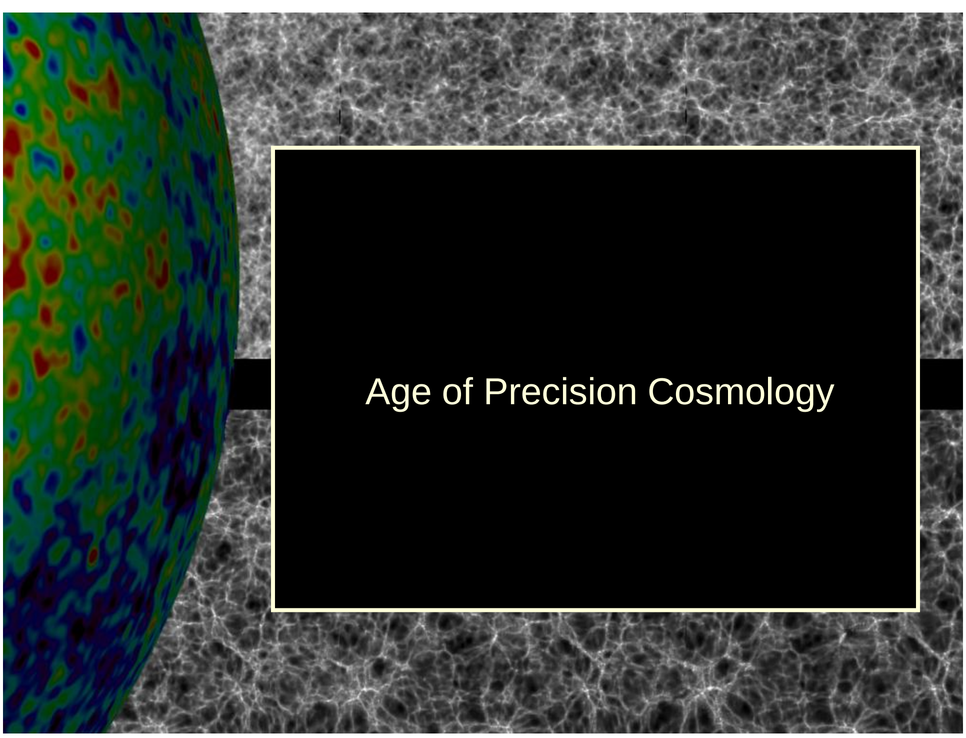
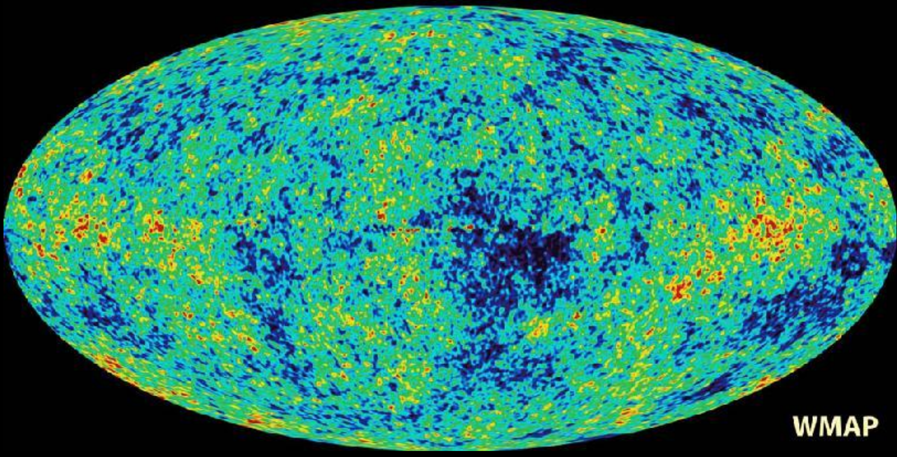

Echo of the Big Bang
Anisotropies in the
Cosmic Microwave Background


Age of Precision Cosmology

# Cosmic Microwave Background

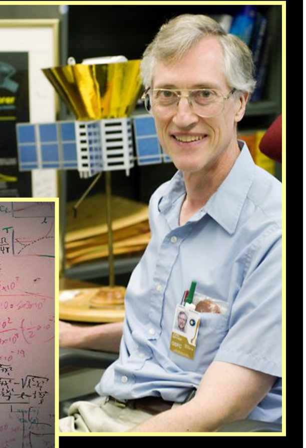


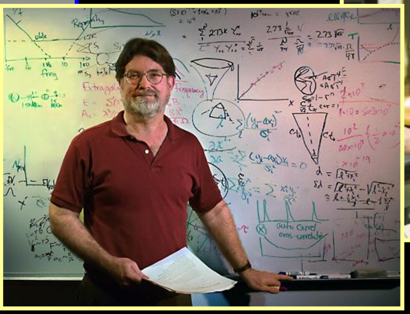

Echo of the Big Bang

# Nobelprijs Natuurkunde 2006

COBE (1992):

- John Mather
  - DIRBE: temperature, blackbody
- George Smoot
  - DMR: fluctuations, embryonic structure





# Cosmic Microwave Background: Some Facts

## Radiation Field of the Universe:

0) Discovered in 1965 (serendipitously) by Penzias & Wilson,

Nobelprize 1978 !!!!!

- Thermal radiation pervading throughout the whole Universe
- As yet it has a temperature of

$T_\gamma$=2.725 K

1) By far CMB photons represent the most abundant species in the Universe:

$n_\gamma \sim 415\ cm^{-3}$

- For comparison: $n_\gamma/n_B \sim 1.9 \times 10^9$ !!!! (second: cosmic neutrino's)
- Stellar photons: negligible !!!! (integrated over all stars at all times!)

# Cosmic Microwave Background: Some Facts

7) CMB highly (impressively) Isotropic:

- in each direction on the sky the radiation has almost exactly the same temperature/intensity
- temperature anisotropies VERY SMALL, in the order of

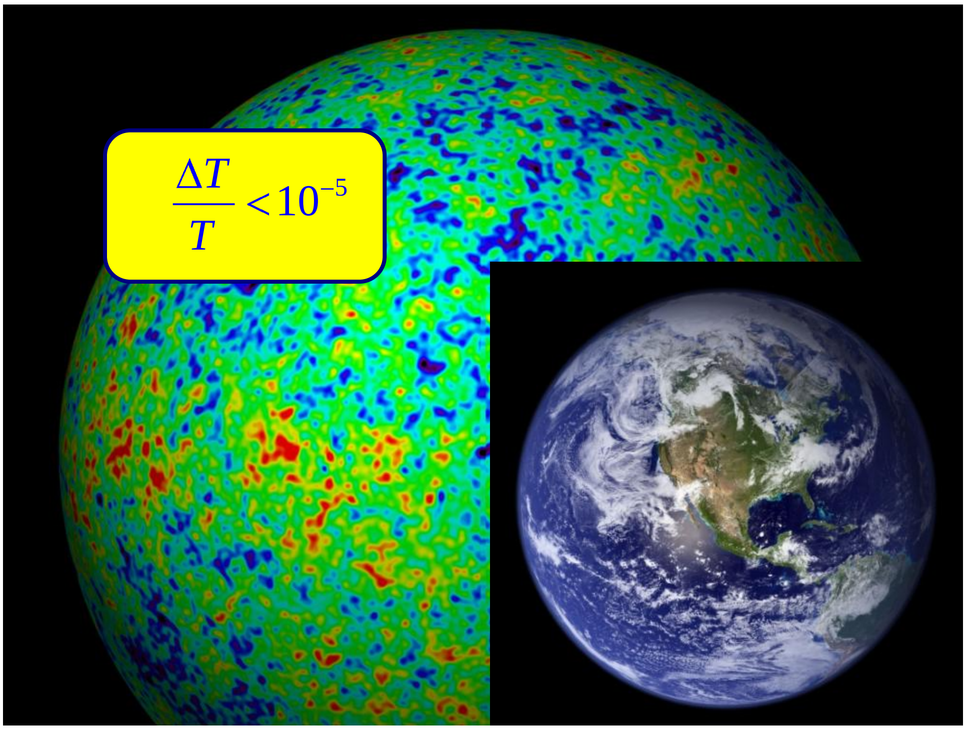
$$\frac{\Delta T}{T} < 10^{-5}$$

- for comparison:

Planet Earth's highest mountain would be in the order 10-25 m !!!!!!

8) The electromagnetic spectrum of the CMB PERFECTLY Thermal Blackbody (most accurately measured BB spectrum ever):

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$




# Cosmic Microwave Background: Some Facts

6) CMB photons Last Scattered

379,000 yrs. after Big Bang

at a redshift $z=1089$ (ie. expansion factor $a(t)=1/1089$)

7) Following the - Decoupling of Radiation and (Baryonic) Matter

- Recombination Hydrogen Atoms

(as protons and electrons combine)

8) At recombination T ~ 3000 K: the (CMB) sky would look red

Since then, gradual cooling of radiation through expansion Universe:

- cosmic redshift photons

9) The CMB photons created at much earlier epoch !!!

Last surge: positron-electron annihilation,

1 min. after Big Bang, redshift $z \sim 10^9$

# Cosmic Microwave Background

## COBE (1992):

Accurate measurement Planck spectrum CMB

First detection angular temperature perturbations ($\theta \sim 7^{o}$): Sachs-Wolfe effect

# Cosmic Microwave Background

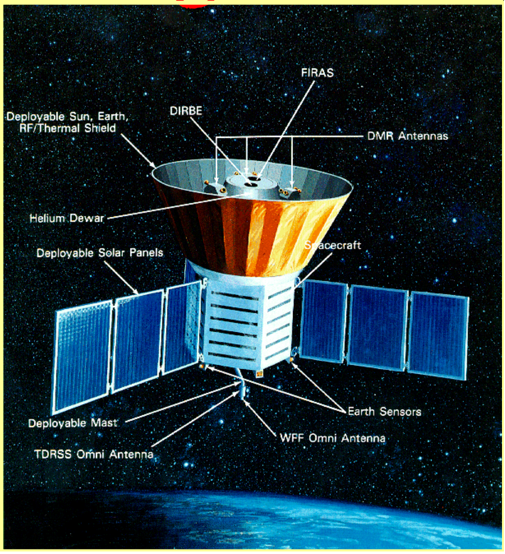
## COBE (1992):

Three instruments:

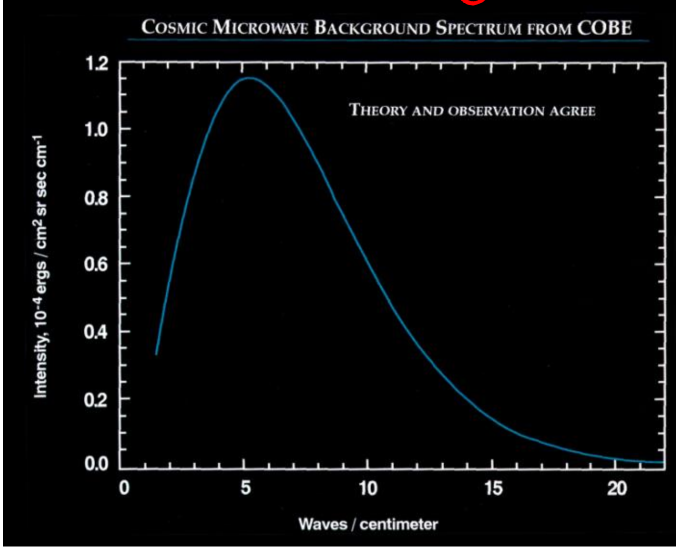
FIRAS: Mather
Far-Infrared Absolute Spectrophotometer

DIRBE: Hauser
Diffuse Infrared Background Experiment

DMR: Smoot
Differential Microwave Radiometer

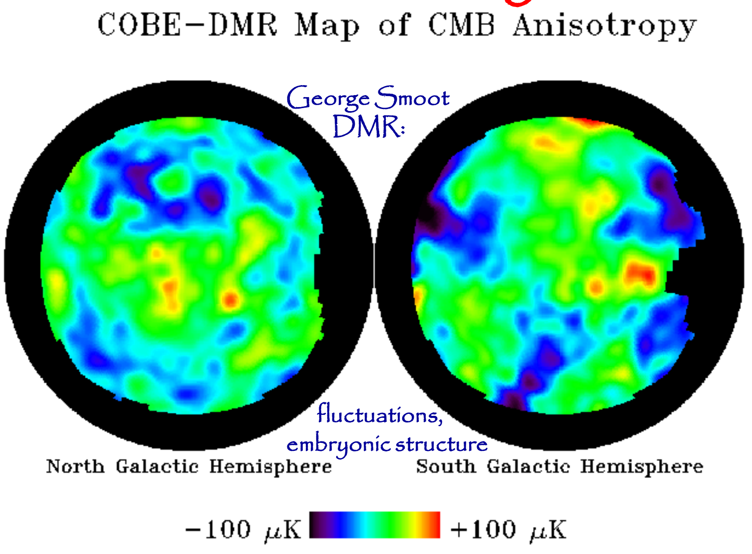


# Spectrum
# Blackbody Radiation

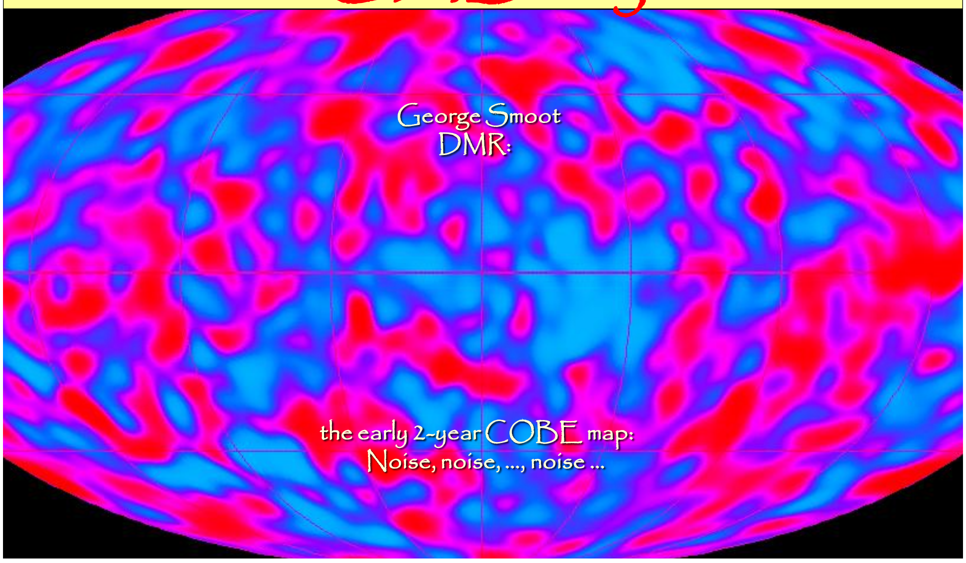


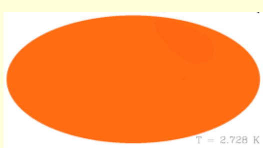

- John Mather
- COBE-DIRBE: temperature, blackbody
- Most accurately measured Black Body Spectrum Ever!!!!!

# Primordial Anisotropies
# CMB sky

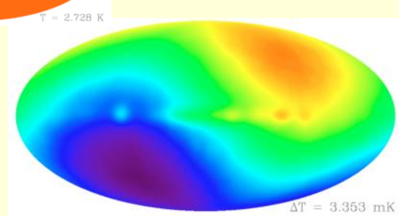


# Primordial Anisotropies CMB sky



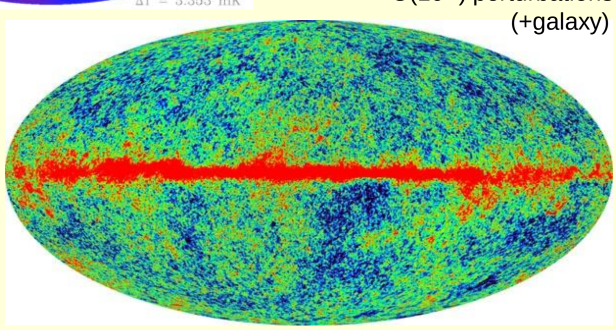




(almost) uniform 2.726K blackbody




Dipole (local motion)

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



Observations: the microwave sky today

Source: NASA/WMAP Science Team

# Key to the Universe

CMB Radiation, the cosmic radiation field of the Universe,

Cosmic Treasure Trove:

1) Direct probe of Thermal State of the early primordial Universe, the Universe before Decoupling:

   Ultimate Proof Reality of Hot Big Bang

2) Direct reflection of Primordial Structure of the Universe,

   the Embryonic State

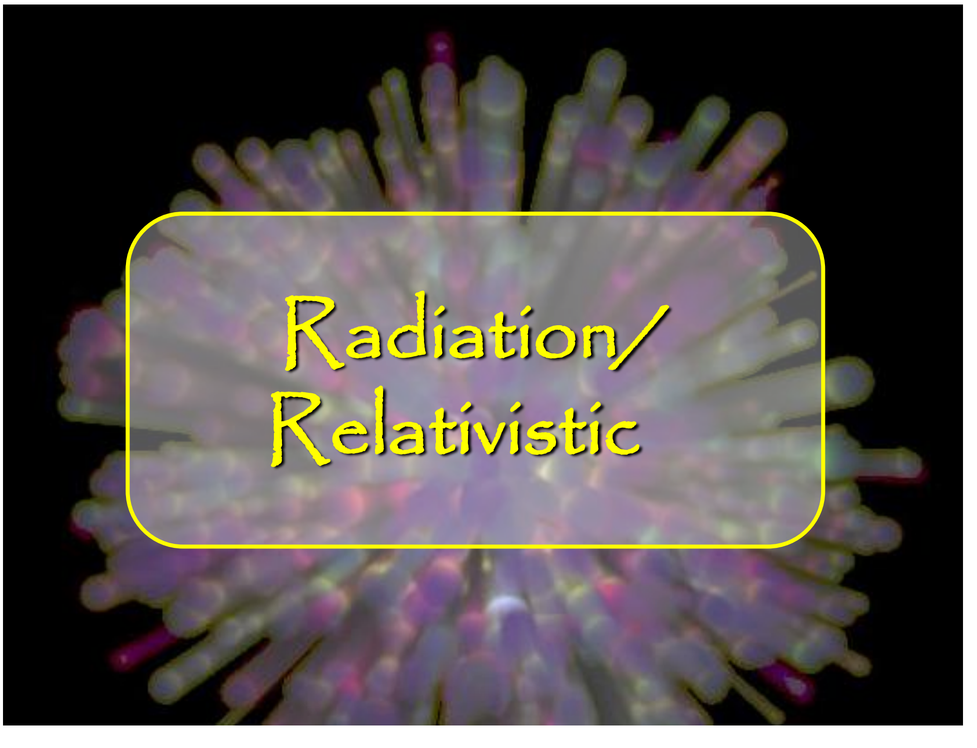
   of all Structure in today's Universe

3) Through its simplicity (linearity) the ultimate diagnostic tool for measuring the Universe:

   Cosmic Parameters

4) Link on early decisive hypothetical/theoretical ( $t \approx 10^{-36} - 10^{-34}$ sec )

   Inflationary Epoch



# Cosmic Radiation

Most ubiquitous, most pervasive, constituent of the Universe: Radiation.

- photons $\gamma$
- neutrinos $\nu$

Two major components of relativistic (massless) species:

# Cosmic Radiation

1) Number Density CMB photons:

$$n_\gamma(T) = \frac{8\pi}{c^3}\int_0^\infty \frac{\nu^2\,d\nu}{e^{h\nu/kT}-1} = 60.4\left(\frac{kT}{hc}\right)^3$$

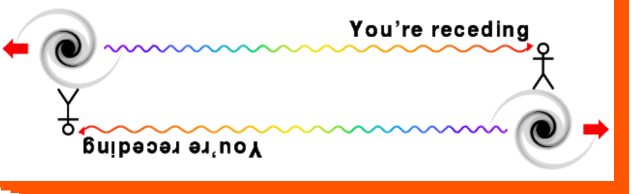
$$n_\gamma = 60.4\left(\frac{kT}{hc}\right)^3 \approx 410\,(1+z)^3\ \mathrm{cm}^{-3}$$

Present Number Density: ⇨ $n_\gamma \sim 410\,\mathrm{cm}^{-3}$

# Cosmic Redshift

$$1 + z = \frac{1}{a} \Longleftarrow \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})} \lambda_0 \end{cases}$$

$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$




# Cosmic Radiation

2) Number photons/neutrinos conserved

- photon number density $n_{rad} \propto a(t)^{-3}$

3) As a result of the cosmic expansion, wavelength of a photon redshifts:

- photon energy $\varepsilon_{rad} \propto a(t)^{-1}$

4) Energy Density Radiation evolves:

$$\rho_{rad} \propto a(t)^{-4} \propto (1+z)^4$$

# Cosmic Radiation

5) Energy Density ➡ at present negligible:

$$\Omega_{rad} \approx 10^{-5}$$

6) Dynamically increasingly important in early Universe, dominant over Matter before

$z > z_{eq}$ : $\rho_{\rm rad} > \rho_m$
$z < z_{eq}$ : $\rho_{\rm rad} < \rho_m$

⇩

$z > z_{eq}$ : $a(t) \propto t^{1/2}$
$z < z_{eq}$ : $a(t) \propto t^{2/3}$

**Equivalence Epoch**

$$1 + z_{eq} = 4.0 \times 10^4\ \Omega_m h^2$$

# Cosmic Radiation

7) In terms of Number Density,
Cosmic Photons have ALWAYS been dominant,
Most abundant species in the Universe. By FAR !!!!!!!!

$$n_B(z) = n_{B,0}\,(1+z)^3$$

$$n_\gamma(z) = n_{\gamma,0}\,(1+z)^3$$

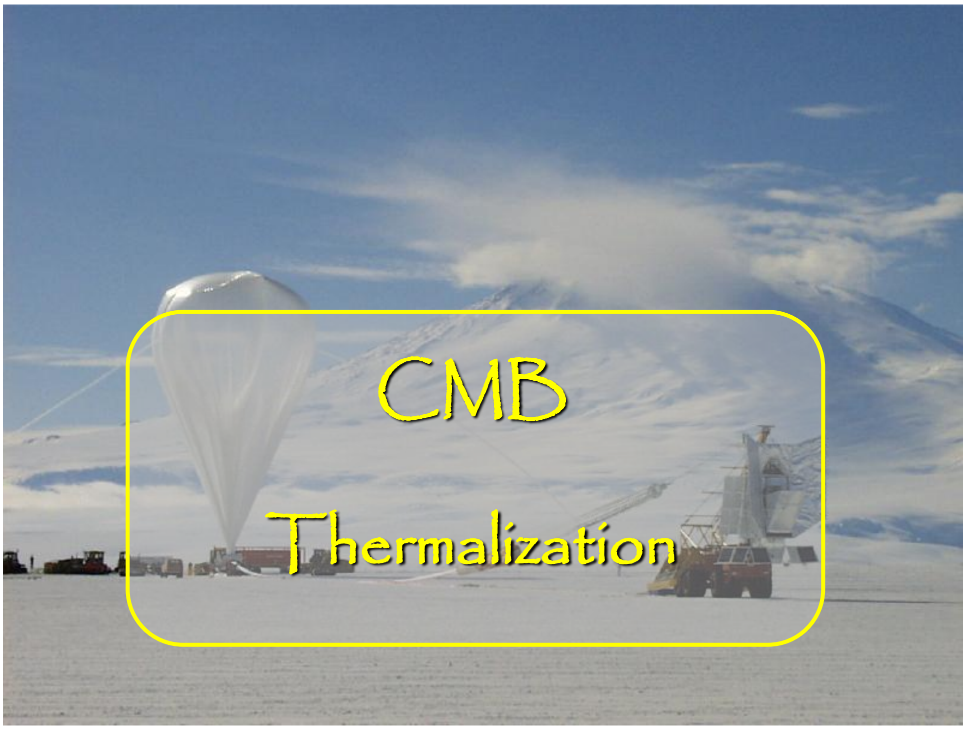
$$\Downarrow$$

$$\eta(z) \equiv \frac{n_B(z)}{n_\gamma(z)} = \frac{n_{B,0}}{n_{\gamma,0}} = \eta_0$$

5) Ratio Baryons to Photons
Entropy Universe

$$\frac{n_\gamma}{n_B} \approx 10^9$$

Fundamental Property !!!!!!
Universe very Peculiar Physical System




# Electron-Positron Annihilation

$T < 10^9$ K

$t \sim 1$ min, $z \sim 10^9$

At this redshift the majority of photons of the Cosmic Microwave Background are generated

- Before this redshift, electrons and photons are in thermal equilibrium. After the

$$e^+ + e^- \rightleftharpoons 2\gamma$$

temperature drops below $T \sim 10^9$ K, the electrons and positrons annihilate, leaving a sea of photons.

- As they absorb the total entropy $s$ of the $e^+$, $e^-$, $\gamma$ plasma, the photons acquire a temperature $T_\gamma >$ neutrino temperature $T_\nu$.

# Electron-Positron Annihilation

- At the onset certainly not thermally distributed energies
- Photons keep on being scattered back and forth until z ~ 1089, the epoch of recombination.
- Thermal equilibrium (blackbody spectrum) of photons reached within 2 months after their creation

Blackbody Spectrum produced through three scattering processes

- Compton scattering
- Free-free scattering
- Double Compton scattering

# CMB Thermalization

- Thermalization through three scattering processes
  - Compton scattering + dominant energy redistribution
  - Free-free scattering + creates new photons to
  - Double Compton scattering adjust spectrum to Planck
- While Compton scattering manages to redistribute the energy of the photons, it cannot adjust the number of photons. Free-free scattering and Double Compton scattering manage to do so ...
- But ...

  only before $z < 10^5$, after that the interaction times too long ....

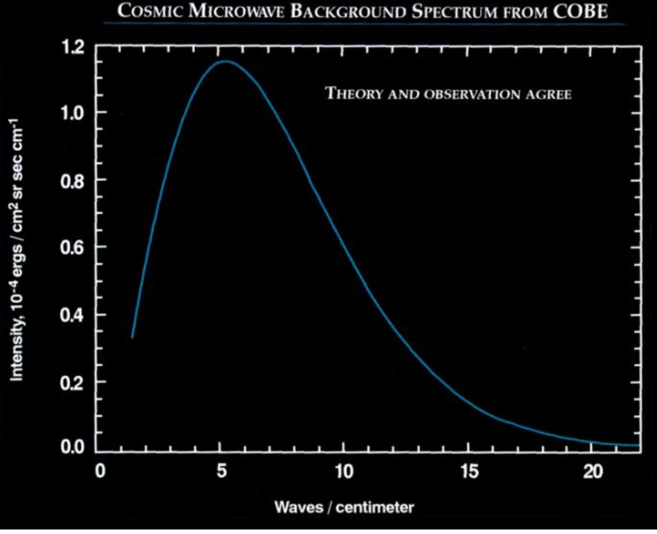
# CMB Thermalization

- Following this thermalization, a perfect blackbody photon spectrum has emerged:

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

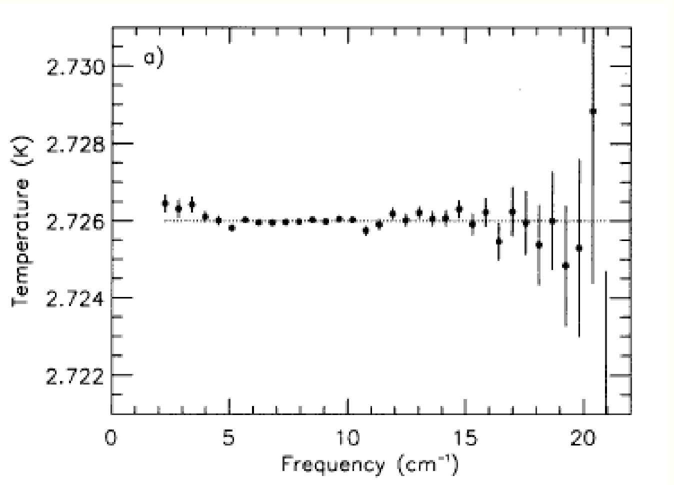
- This is the ULTIMATE proof of the HOT BIG BANG
- Note: after z ~ 105 till recombination, the interaction between electrons and photons exclusively by Thomson Scattering

# Spectrum Blackbody Radiation



# Spectrum
# Blackbody Radiation

Residuals wrt.
T=2.726 K




# Recombination & Decoupling

T ~ 3000 K

$z_{dec}$=1089 ($\Delta z_{dec}$=195); $t_{dec}$=379.000 yrs

- Before the "Recombination Epoch
  Radiation and Matter are tightly coupled through Thomson scattering.
- The events surrounding "recombination" exist of THREE major (coupled, yet different) processes:

| | |
|---|---|
| • Recombination | protons & electrons combine to H atoms |
| • Decoupling | photons & baryonic matter no longer interact |
| • Last scattering | meaning, photons have a last kick and go … |

# Recombination & Decoupling

T ~ 3000 K

$z_{dec}$=1089 ($\Delta z_{dec}$=195); $t_{dec}$=379.000 yrs

- Before this time, radiation and matter are tightly coupled through Thomson scattering:

$$e^- + \gamma \rightleftharpoons e^- + \gamma$$

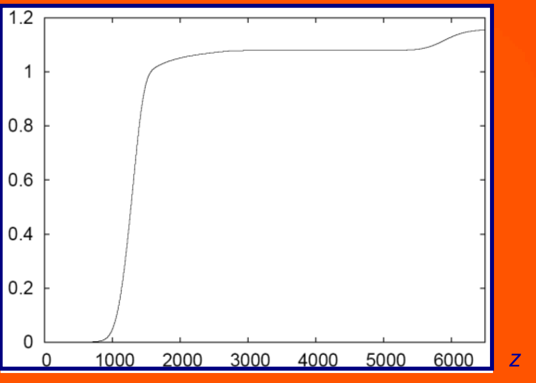
  Because of the continuing scattering of photons, the universe is a "fog".
- A radical change of this situation occurs once the temperature starts to drop below T~3000 K. and electrons. Thermodynamically it becomes favorable to form neutral (hydrogen) atoms H (because the photons can no longer destory the atoms):

$$p + e^- \rightleftharpoons \mathrm{H}$$

- This transition is usually marked by the word "recombination", somewhat of a misnomer, as of course hydrogen atoms combine just for the first time in cosmic history. It marks a radical transition point in the universe's history.

# Recombination history

$x_e = \frac{n_e}{n_H}$




As temperature changes:
- shifting ionization can be followed through Saha equation (note: on "wrong" premise of equilibrium)
- Recombination should happen at T ~ 4000 K
- But: far too many CMB photons, it is not equilibrium process !!!!!

# Recombination & Decoupling

- Note that the decoupling transition occurs rather sudden at T~3000 K, with a "cosmic photosphere" depth of only $\Delta z_{dec}$~195 (at z~1089).
- The cosmological situation is highly exceptional. Under more common circumstances the (re)combination transition would already have taken place at a temperature of T~$10^4$ K.
- Due to the enormous amount of photons in the universe, signified by the abnormally high cosmic entropy,

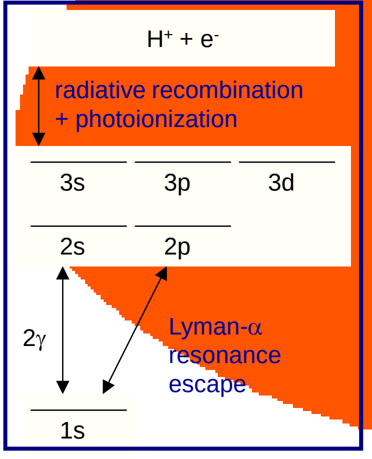
$$\frac{n_\gamma}{n_B} \approx 10^9$$

even long after the temperature dropped below T~ $10^4$ K there are still sufficient photons to keep the hydrogen ionized (i.e. there are still plenty of photons in the Wien part of the spectrum).
- Recombination therefore proceeds via a 2-step transition, not directly to the groundstate of hydrogen. The process is therefore dictated by the rate at which Lyα photons redshift out of the Lyα rest wavelenght. For $n_\gamma/n_B$~$10^9$ this occurs at

$$T \sim 3000\,\mathrm{K}$$

# Standard theory of H recombination

(Peebles 1968, Zel'dovich et al 1968)




Recombination Process
not entirely trivial:

- ground state could be reached via Lya transition (2P-1S)

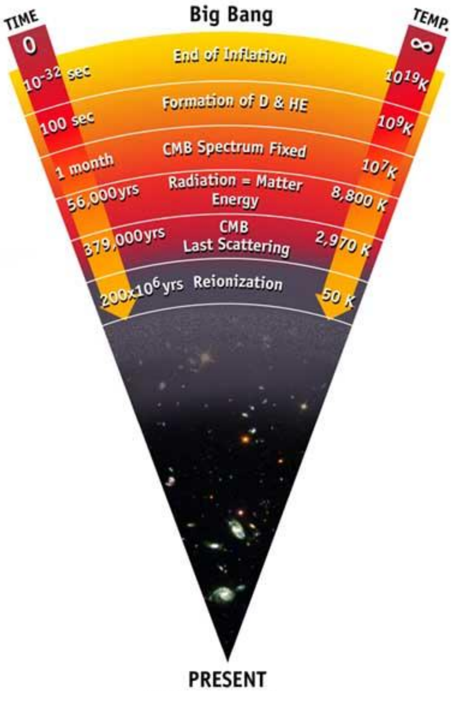
DOES NOT WORK !!!!

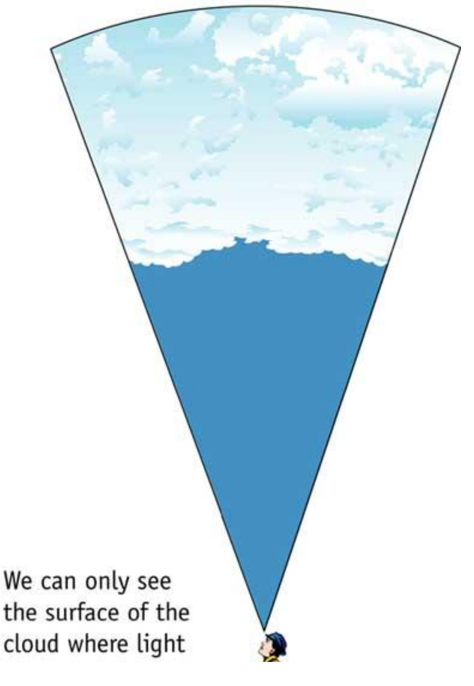
large abundance Lya → Ionization

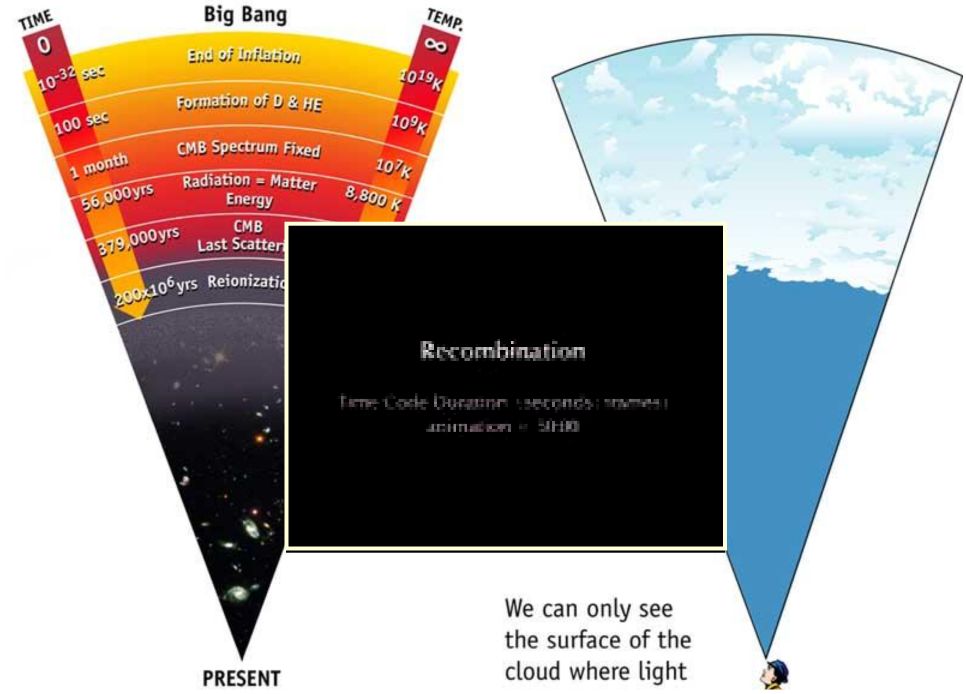
- Recombination in parts:
  forbidden transition = 2-photon emission:
  2S - 1S

- Takes 8.23 $s^{-1}$ → much slower than 'direct', and thus

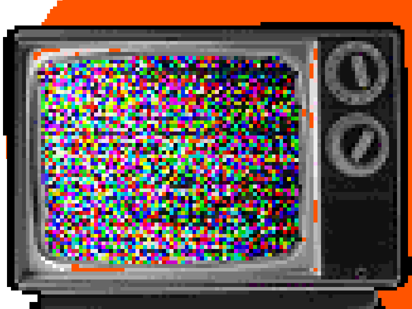
recombination occurs late ...
at T ~ 3000 K






# Cosmic Photons



**Note:**

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your tv set …

Courtesy: W. Hu

# Recombination & Decoupling

- In summary, the recombination transition and the related decoupling of matter and radiation defines one of the most crucial events in cosmology. In a rather sudden transition, the universe changes from

**Before $z_{dec}$, $z>z_{dec}$**

- universe fully ionized
- photons incessantly scattered
- pressure dominated by radiation:

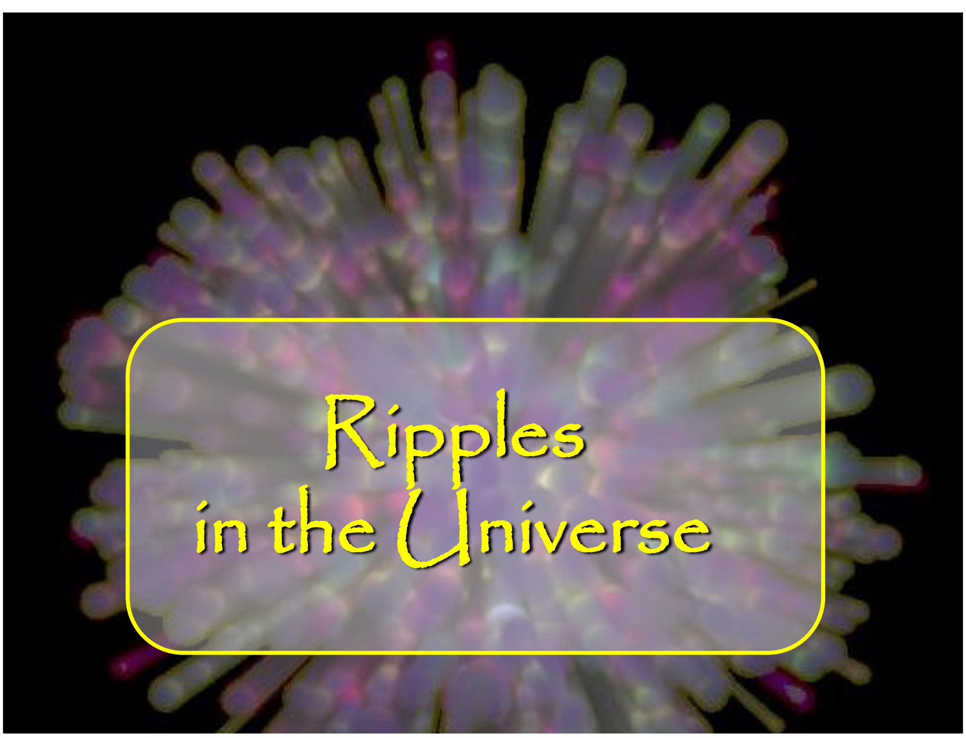
$$p = \frac{1}{3} a T^4$$

**After $z_{dec}$, $z<z_{dec}$**

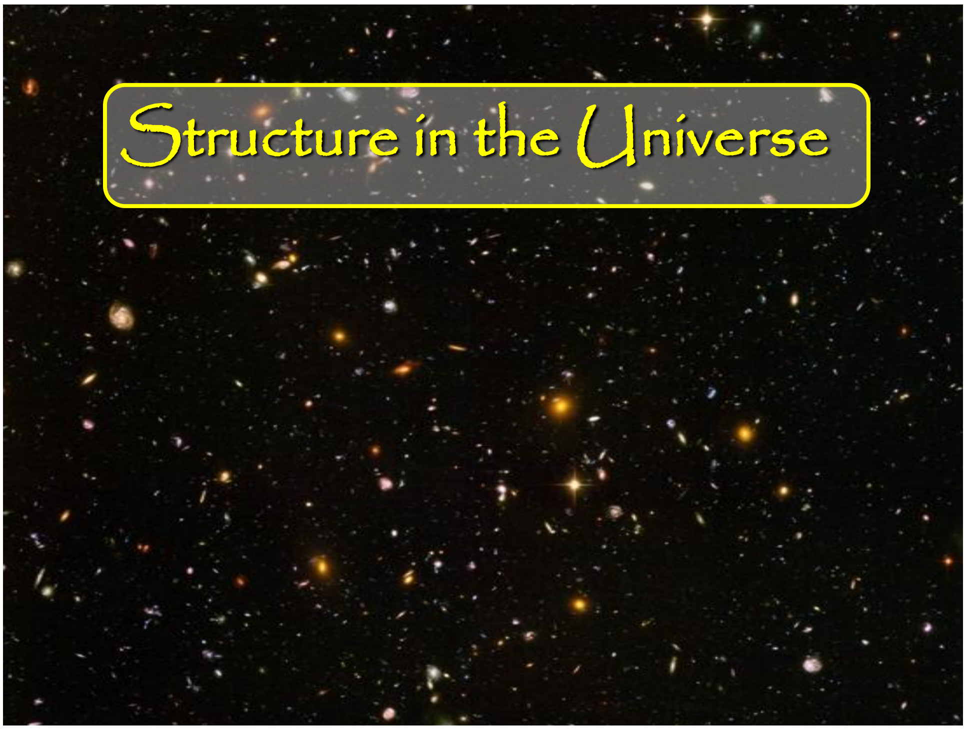
- universe practically neutral
- photons propagate freely
- pressure only by baryons:

$$p = n k T$$

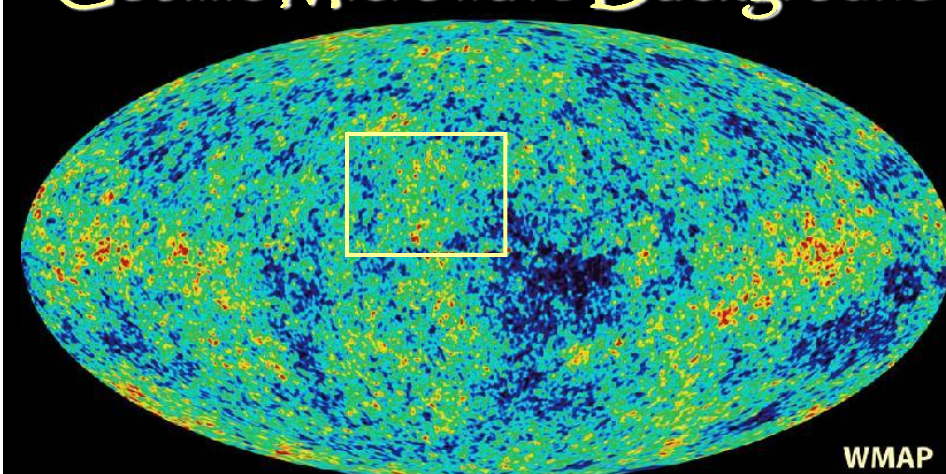
- (photon pressure negligible)



# Structure in the Universe



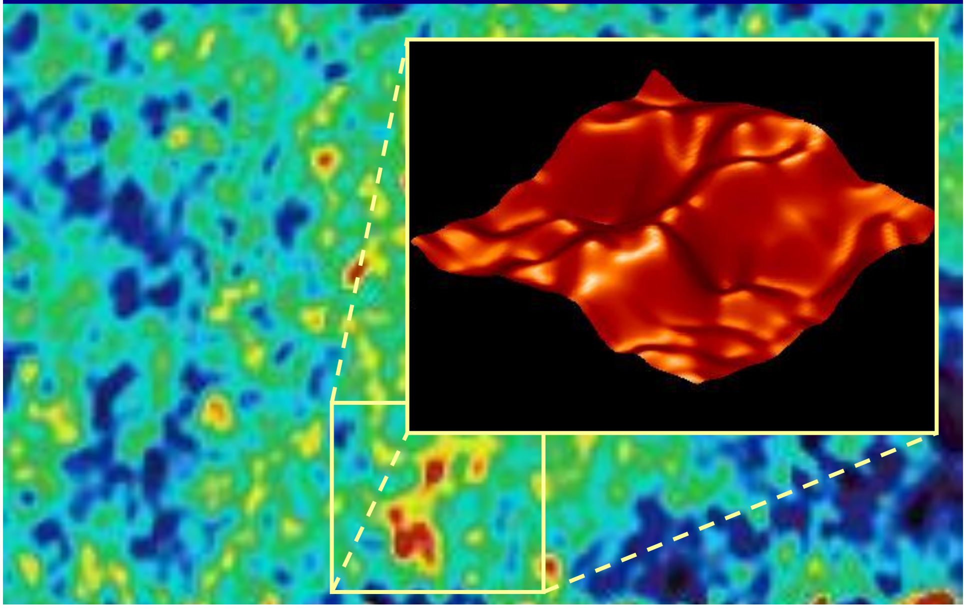
# Cosmic Microwave Background




Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

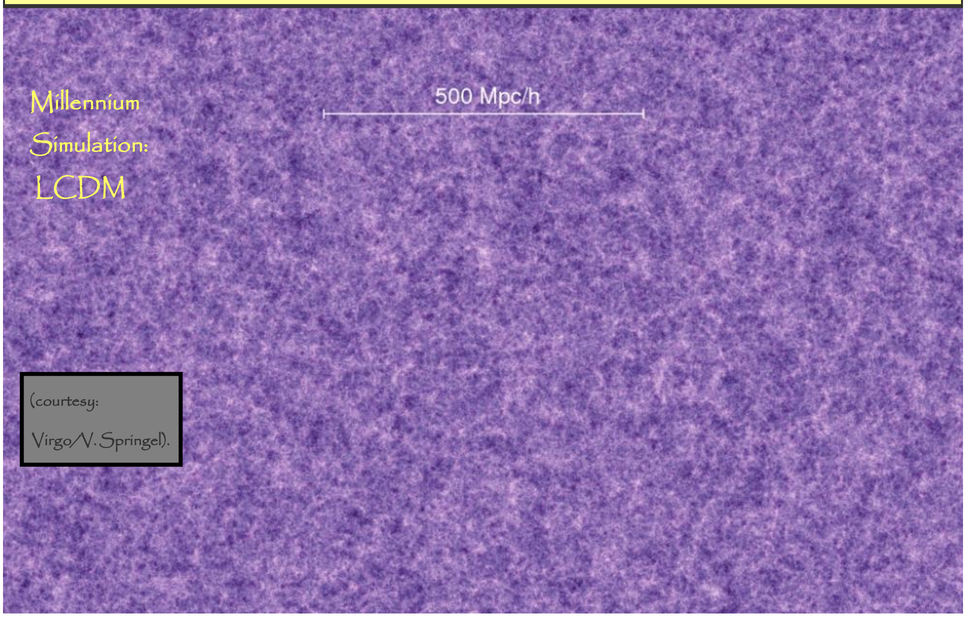
# Primordial Gaussian Perturbations



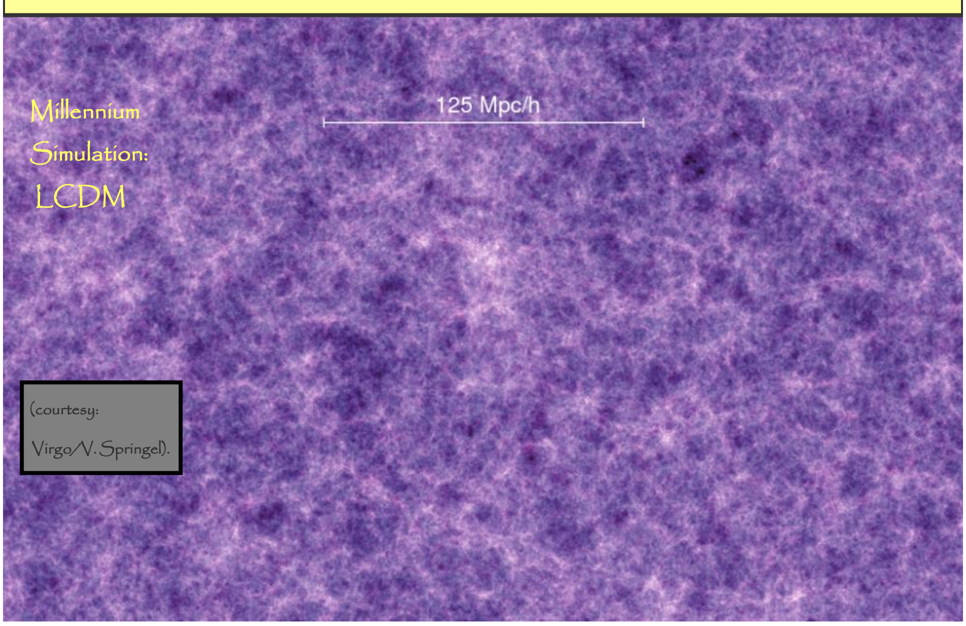
# Gravitational Instability


$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

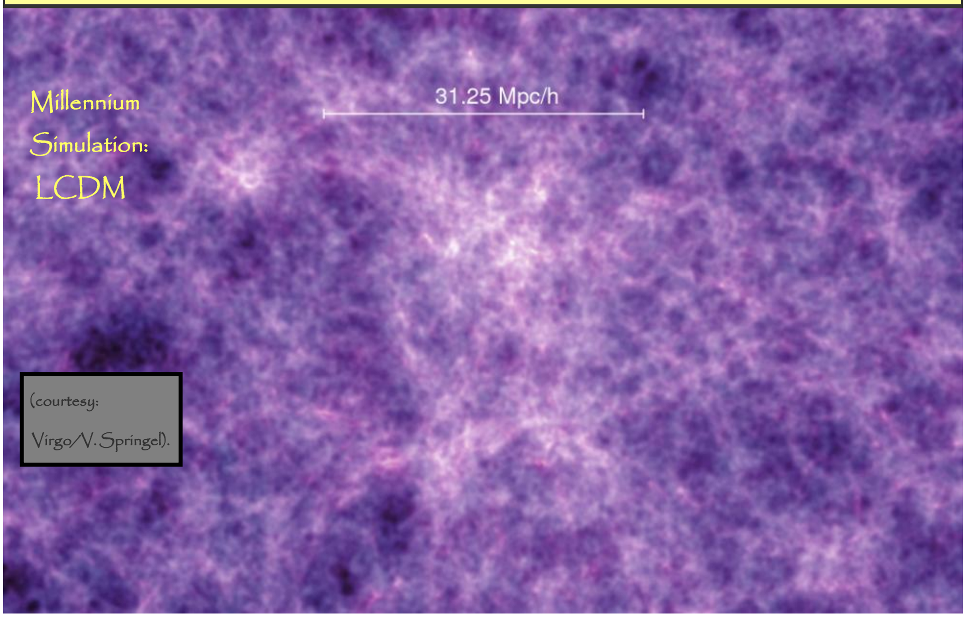
# Millennium Simulation



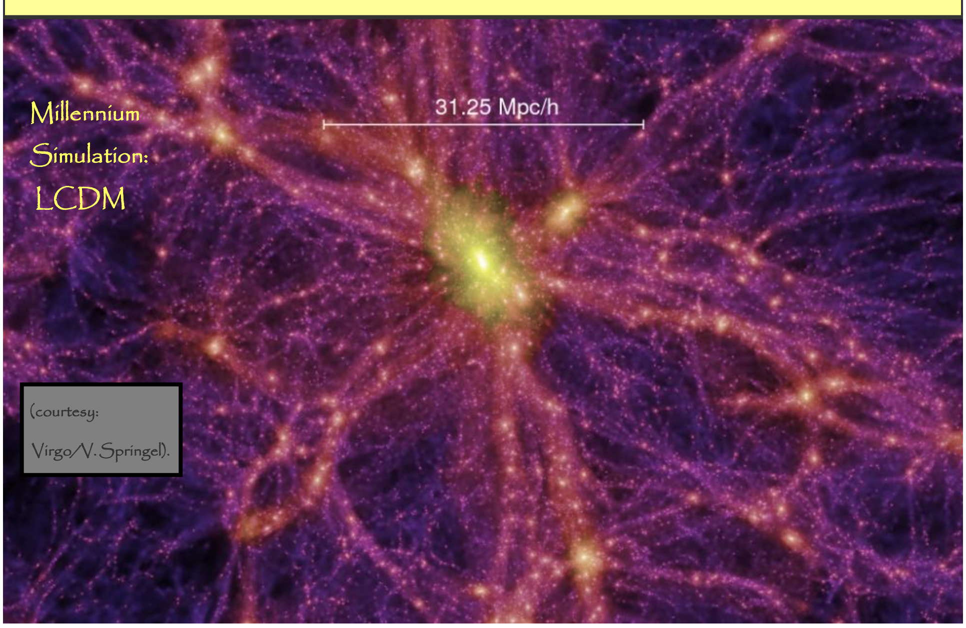

# Millennium Simulation



# Millennium Simulation




# Millennium Simulation



# Rippling Origins

# Inflationary Origins

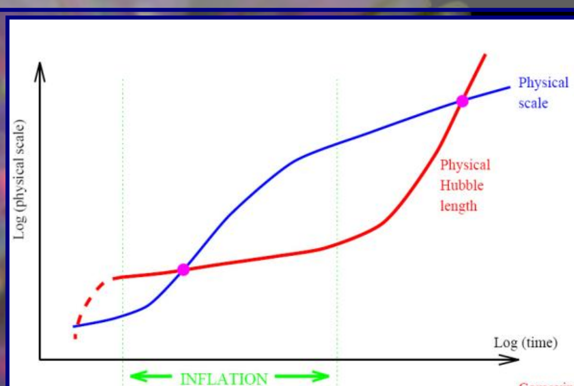
Inflationary Origin of Cosmic Structure:
- Primordial Quantum Noise (due to uncertainty principle)
- becomes seeds for structure today
- at inflation the fluct's expanded to superhorizon size

Predictions:

- Gaussian fluctuations
- Adiabatic fluctuations (radiation & matter equally perturbed)
- Near scale-free potential perturbations:

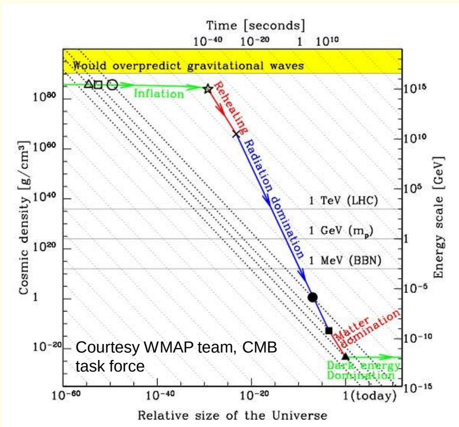
$P(k) \sim k^n$

$n \approx 0.96$



# The Standard Model

Over the past decade we have arrived at a Standard Cosmological




THE PILLARS OF INFLATION

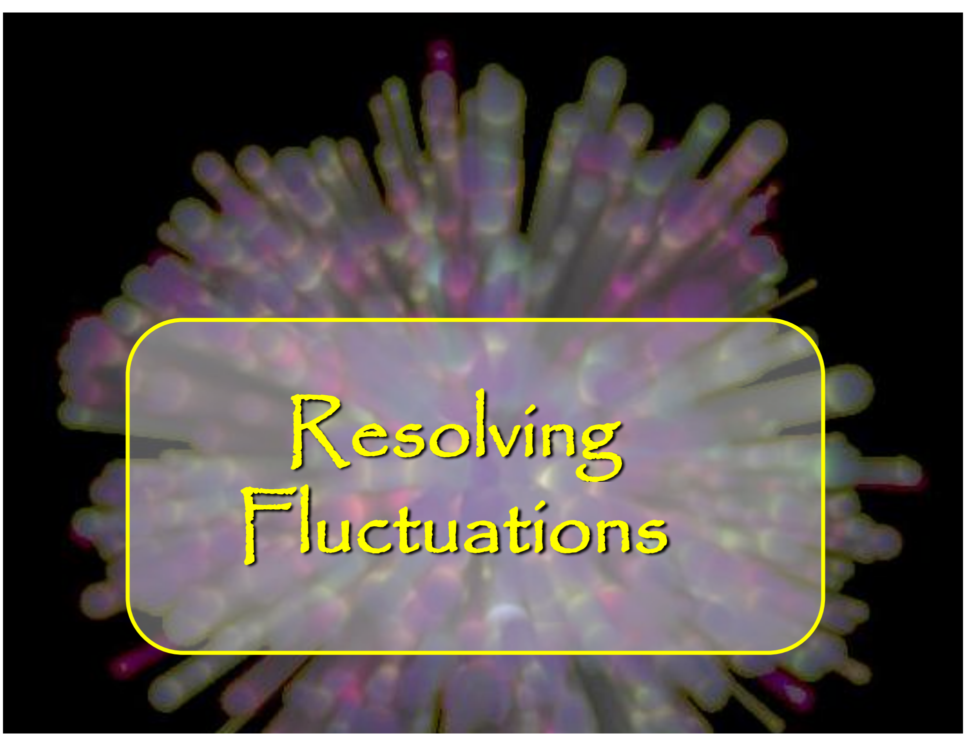
1) super-horizon (>2°) anisotropies
2) acoustic peaks and harmonic pattern (~1°)
3) damping tail (<10')
4) Gaussianity
5) secondary anisotropies
6) polarization
7) gravity waves

But … to test this we need to measure a signal which is 3x10[7] times weaker than the typical noise!

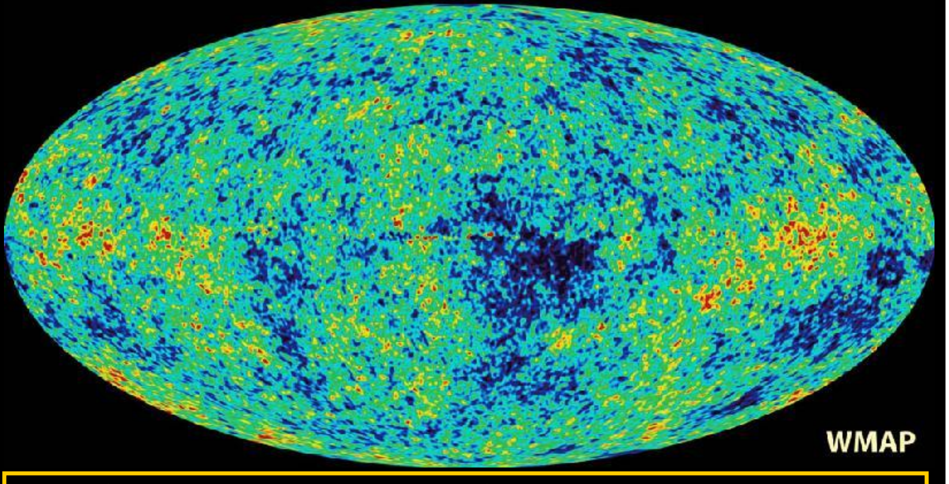
The (scalar) cosmological parameters:

| $\Omega_k$ | $\Omega_b$ | $\Omega_{cdm}$ | $n_s$ | $\Omega_\Lambda$ | $\Omega_m$ | h | $\tau$ |
|---|---|---|---|---|---|---|---|
| geometry of the universe | baryonic fraction protons, neutrons | cold dark matter not protons and neutrons | primordial fluctuation spectrum | dark energy negative pressure of space | matter fraction | Hubble Constant size & age of the universe | optical depth to last scattering of cmb |

51



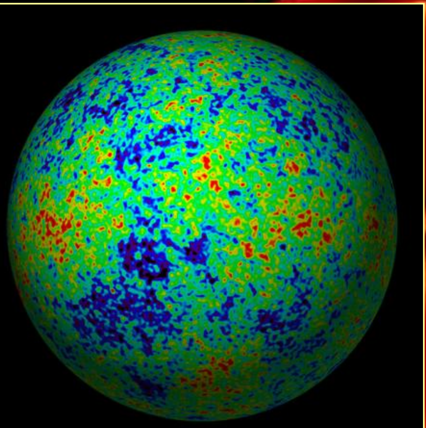
# Cosmic Microwave Background




Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

# Temperature Anisotropies

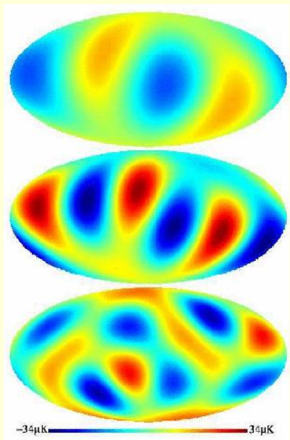


Temperature Perturbations in terms of Spherical Harmonics:

$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

# Temperature Anisotropies

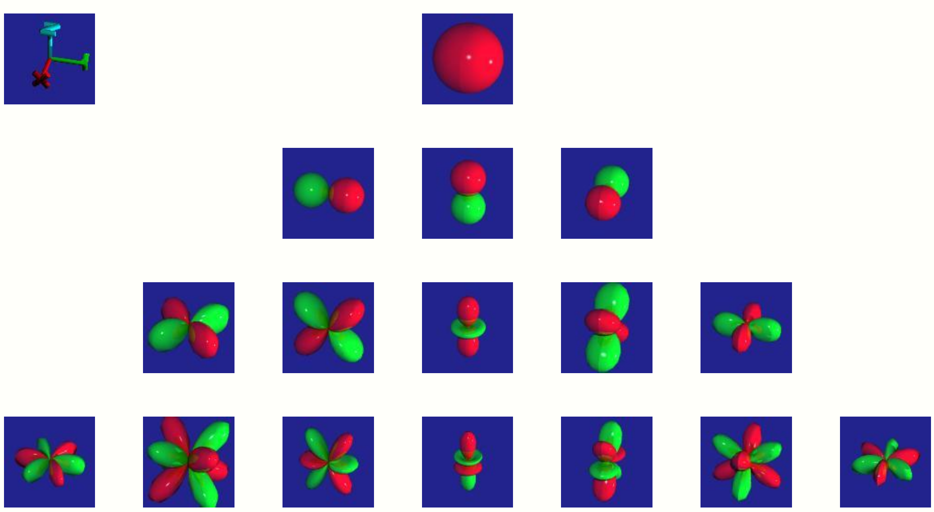



Temperature Perturbations in terms of Spherical Harmonics:

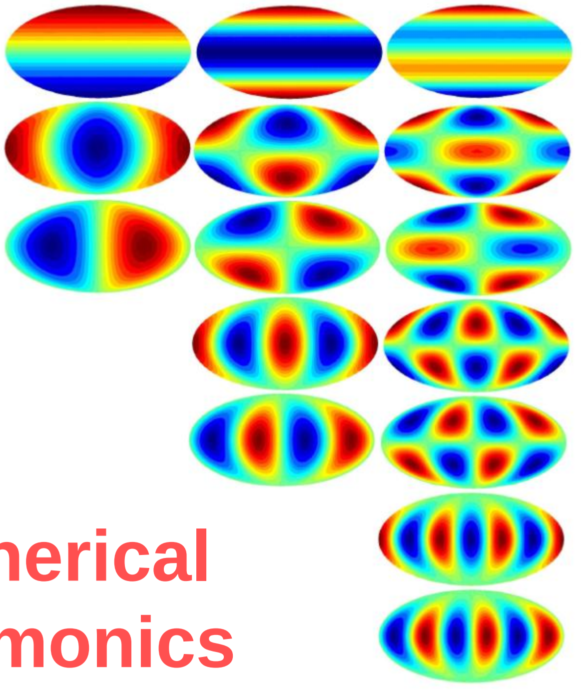
$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

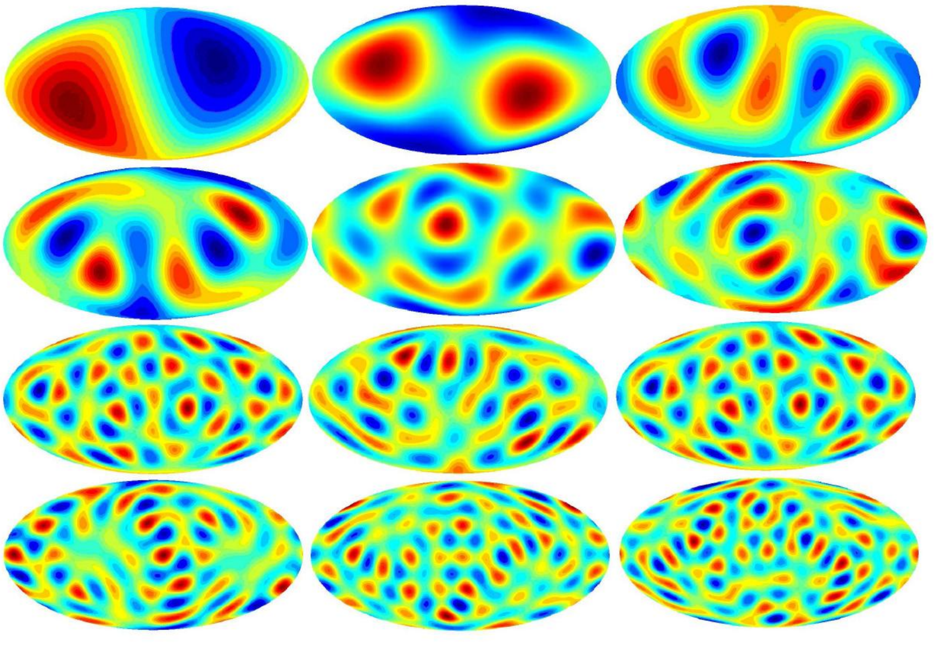
# Spherical Harmonics



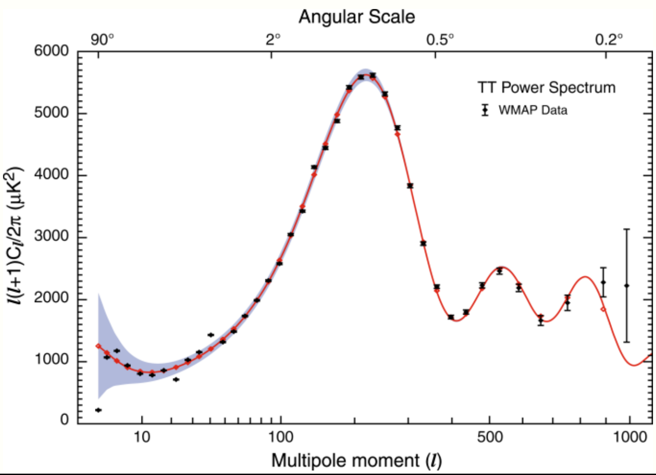
http://web.uniovi.es/qcg/harmonics/harmonics.html



# Spherical Harmonics



# CMB Power Spectrum



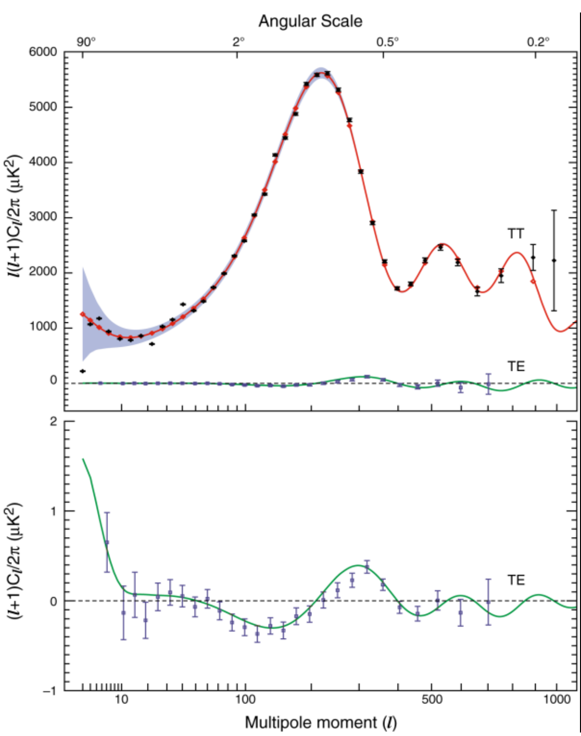

$$T(\theta,\phi)=\sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

Angular power spectrum

$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

$$C_l \propto l(l+1)$$

$$P(k) \propto k$$




CMB

Angular power spectrum

WMAP3

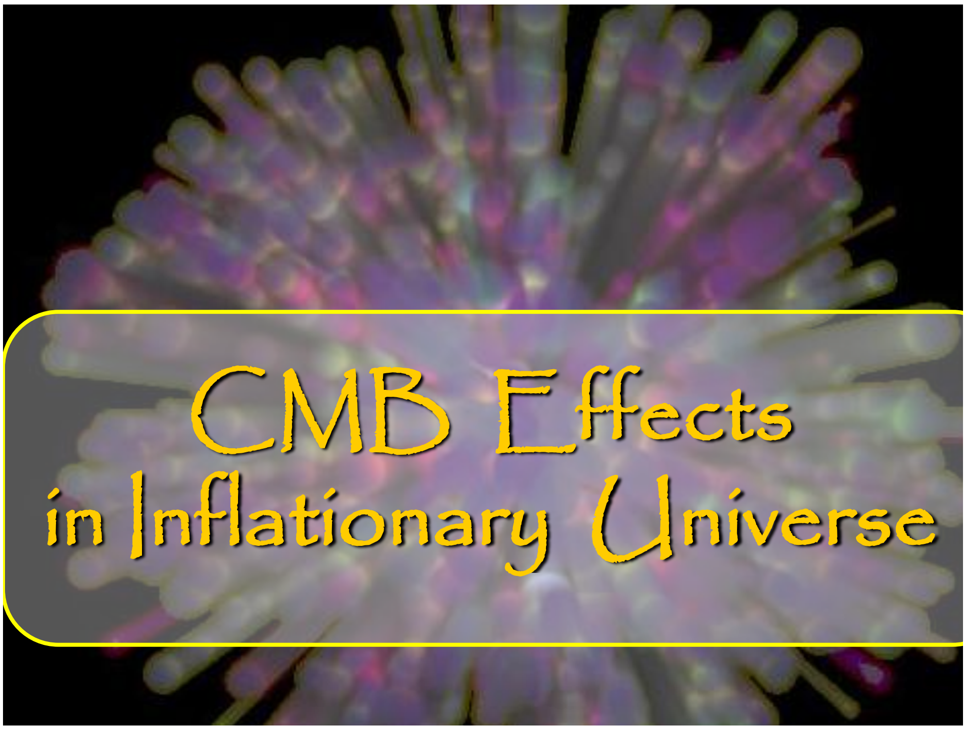
Temperature fluctuations

Temperature-Polarization

$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

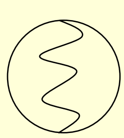
$$C_l \propto l(l+1)$$

$$P(k) \propto k$$



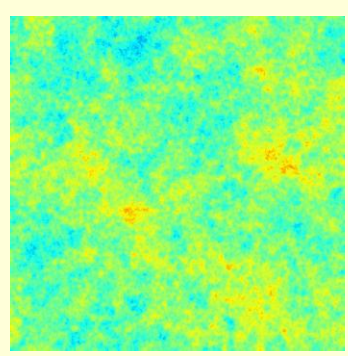

## Can we predict the primordial perturbations?

- Maybe..



**Quantum Mechanics**
"waves in a box" calculation
vacuum state, etc…

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

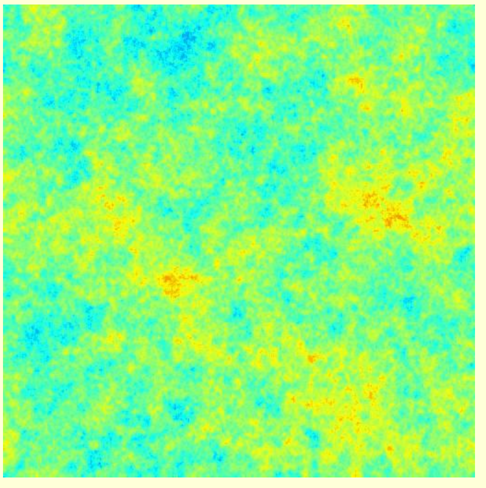


**After inflation**
Huge size, amplitude ~ $10^{-5}$

## Perturbation evolution – what we actually observe

CMB monopole source till 380 000 yrs (last scattering), linear in conformal time
scale invariant primordial adiabatic scalar spectrum

photon/baryon plasma + dark matter, neutrinos



Characteristic scales: sound wave travel distance; diffusion damping length

## Calculation of theoretical perturbation evolution

Perturbations O($10^{-5}$)

⇨ Simple linearized equations are very accurate (except small scales)

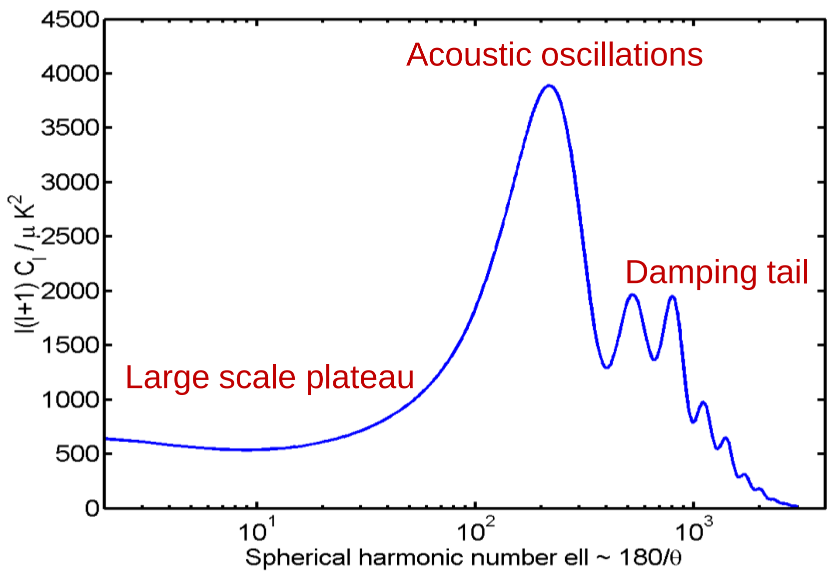
Can use real or Fourier space

Fourier modes evolve independently: simple to calculate accurately

**Physics Ingredients**

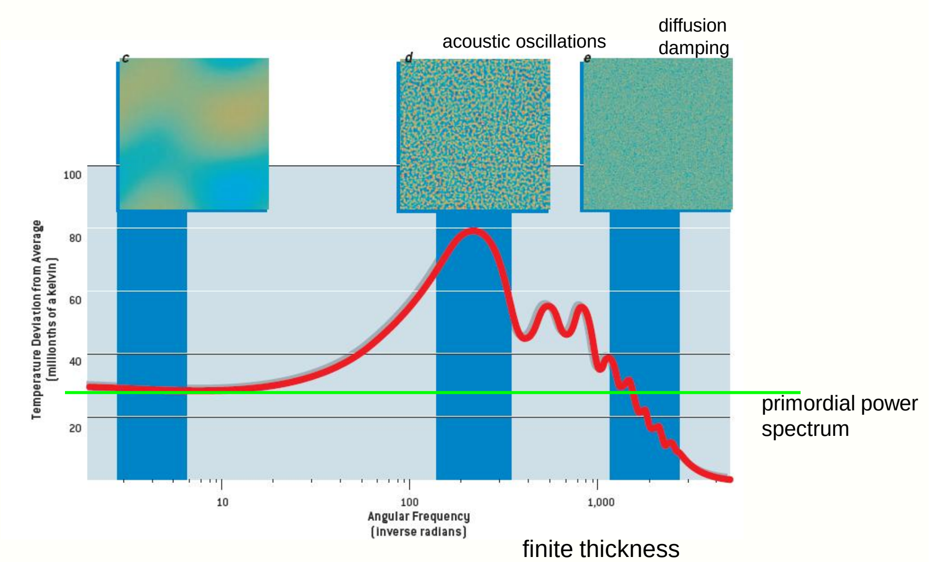
- Thomson scattering (non-relativistic electron-photon scattering)
  - tightly coupled before recombination: 'tight-coupling' approximation (baryons follow electrons because of very strong e-m coupling)
- Background recombination physics (Saha/full multi-level calculation)
- Linearized General Relativity
- Boltzmann equation (how angular distribution function evolves with scattering)

# CMB Power Spectrum: 3 Regimes




## CMB temperature power spectrum

Primordial perturbations + later physics




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

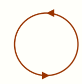
# Perturbation Modes

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

Scalar modes: Density perturbations, potential flows

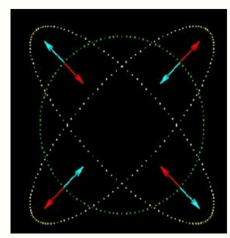
$\delta\rho, \nabla\delta\rho, etc$

Vector modes: Vortical perturbations



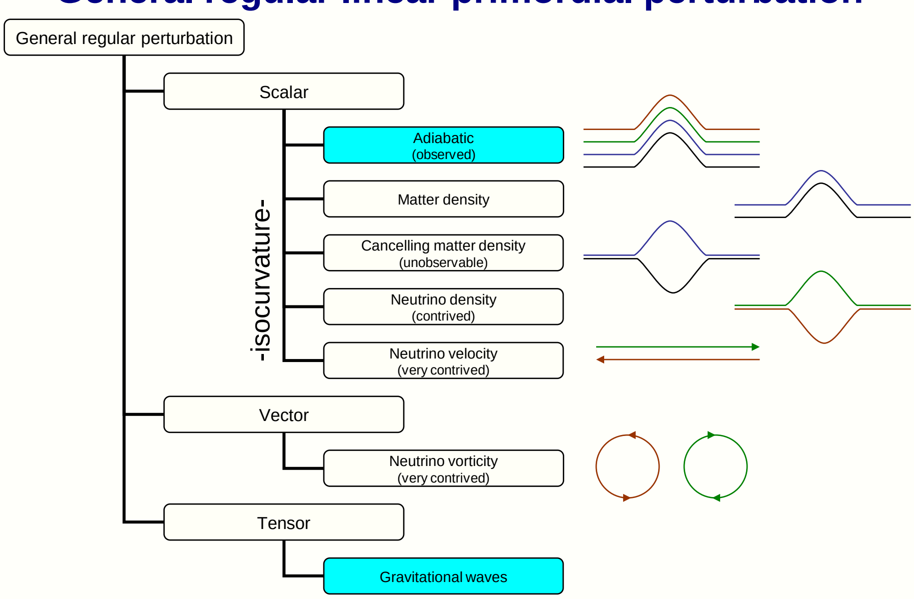
velocities, $v$ $\quad (\nabla \bullet v = 0)$

Tensor modes: Anisotropic space distortions
– gravitational waves



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

## General regular linear primordial perturbation




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

# CMB Anisotropy

$$\begin{aligned}\left(\frac{\delta T}{T}\right)_{\rm jour} &= -\int d\Phi + \int (\dot{\Phi}+\dot{\Psi})dt + \boldsymbol{v}_{\rm obs}\cdot\hat{\boldsymbol{n}} \\ &= \Phi(t_{\rm dec},\boldsymbol{x}_{\rm ls}) - \Phi(t_0,\boldsymbol{0}) + \int (\dot{\Phi}+\dot{\Psi})dt + \boldsymbol{v}_{\rm obs}\cdot\hat{\boldsymbol{n}} \\ &\overset{\Psi\approx\Phi}{=} \Phi(t_{\rm dec},\boldsymbol{x}_{\rm ls}) - \Phi(t_0,\boldsymbol{0}) + 2\int \dot{\Phi}dt + \boldsymbol{v}_{\rm obs}\cdot\hat{\boldsymbol{n}}\end{aligned}$$

$$\boxed{\left(\frac{\delta T}{T}\right)_{\rm obs} = \frac{1}{4}\delta_\gamma^N - \boldsymbol{v}^N\cdot\hat{\boldsymbol{n}} + \Phi(t_{\rm dec},\boldsymbol{x}_{\rm ls}) + 2\int \dot{\Phi}dt\,.}$$

# Sources of CMB anisotropy

**Sachs Wolfe:**
Potential wells at last scattering cause redshifting as photons climb out

**Photon density perturbations:**
Over-densities of photons look hotter

**Doppler:**
Velocity of photon/baryons at last scattering gives Doppler shift

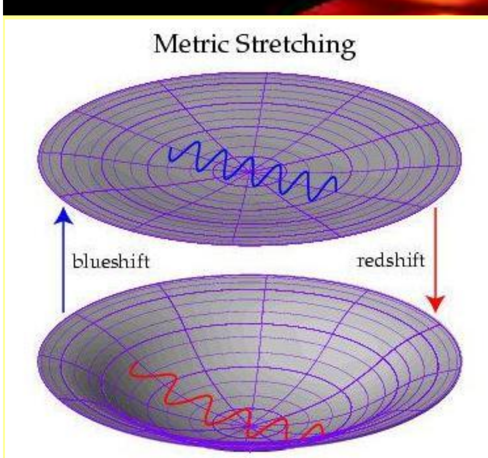
**Integrated Sachs Wolfe:**
Evolution of potential along photon line of sight:
net red- or blue-shift as photon climbs in an out of varying potential wells

**Others:**
Photon quadupole/polarization at last scattering, second-order effects, etc.

**Secondary Anisotropies**

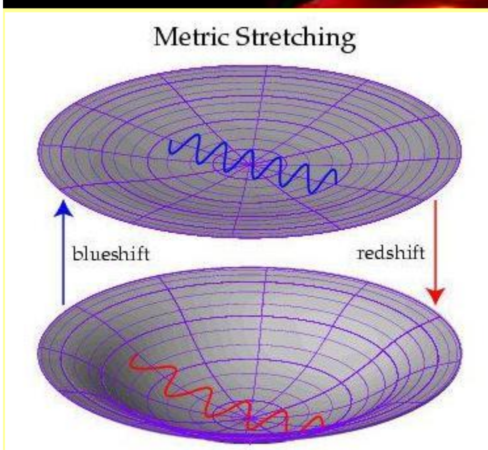
# Rippling the Photons: Sachs-Wolfe

# CMB Perturbations




- As a result of perturbations in
  Gravitational potential
  photons experience frequency shift
- While travelling through perturbation:
  - Gravitational Redshift +
  - (Relativistic) Time Dilation
- Combined effect:
  Sachs-Wolfe Effect

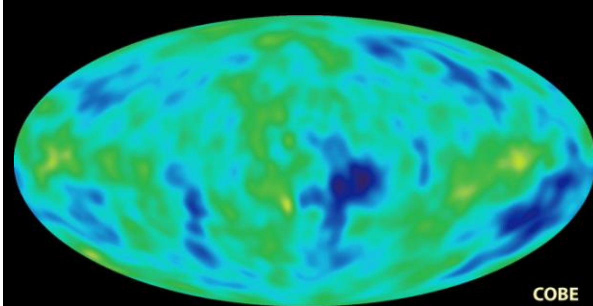
# Sachs-Wolfe Effect

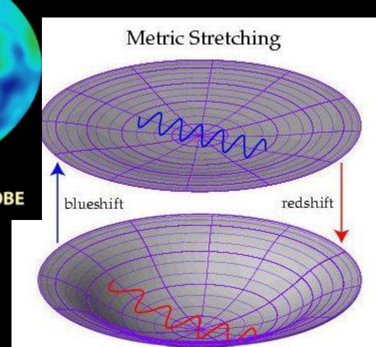



## Sachs-Wolfe Effect

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$

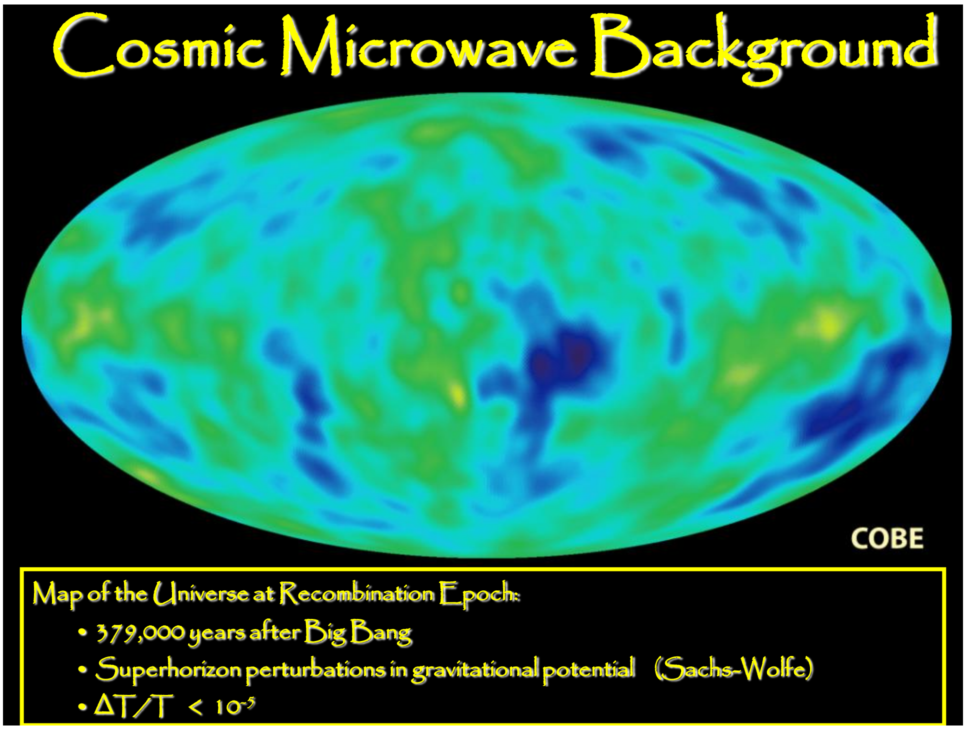
# Cosmic Microwave Background



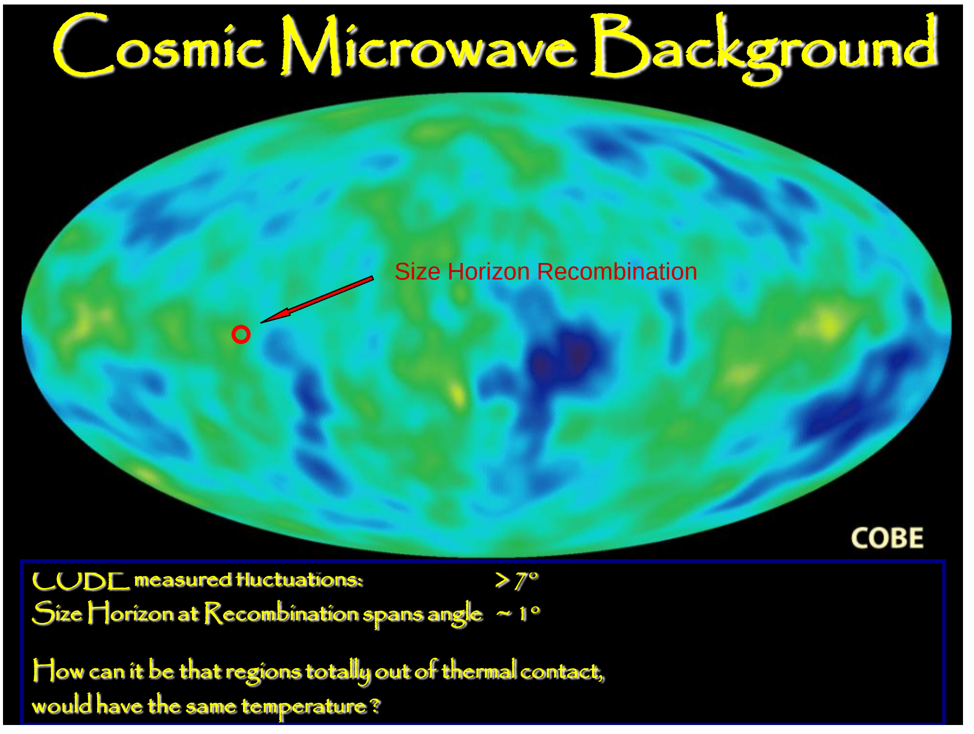



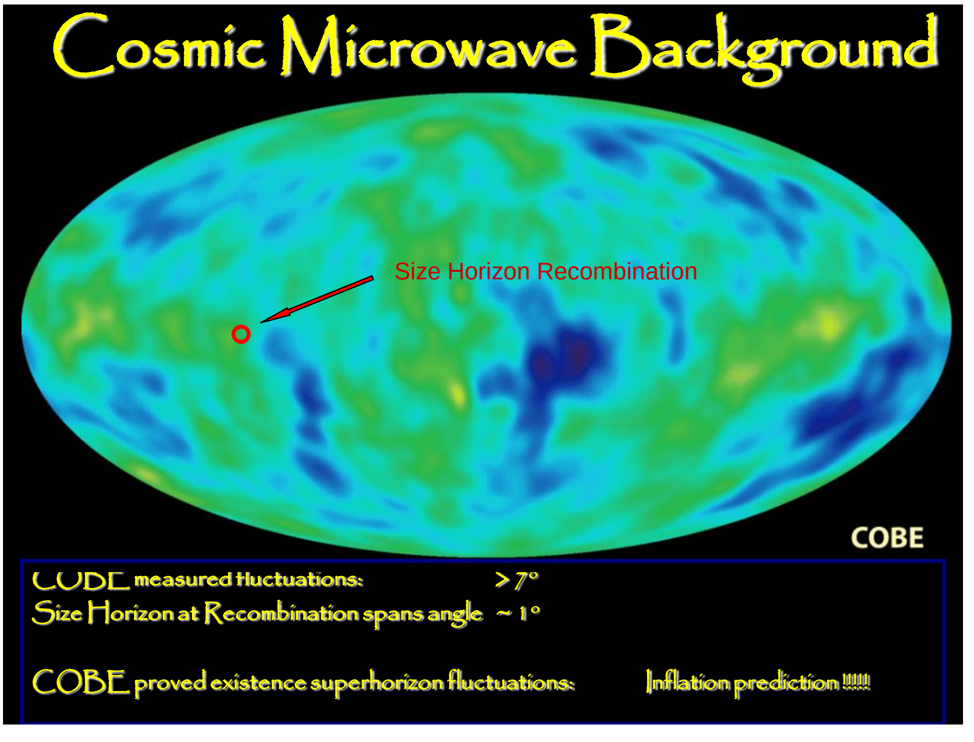

Map of the Universe at Recombination Epoch:

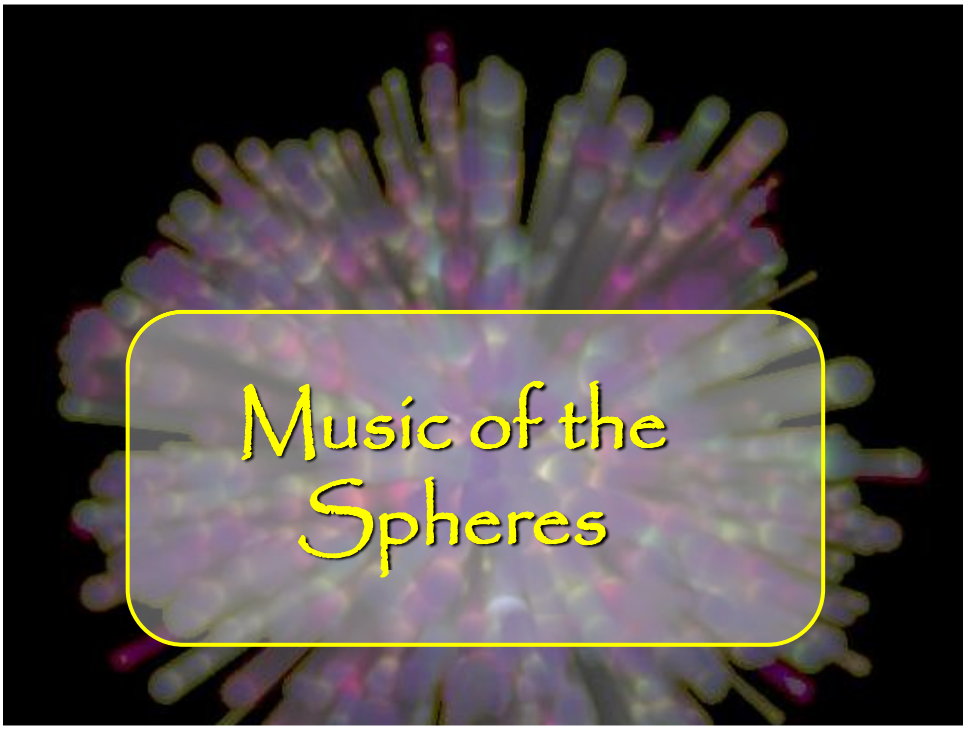
- 379,000 years after Big Bang
- Superhorizon perturbations in gravitational potential (Sachs-Wolfe)
- $\Delta T/T < 10^{-5}$

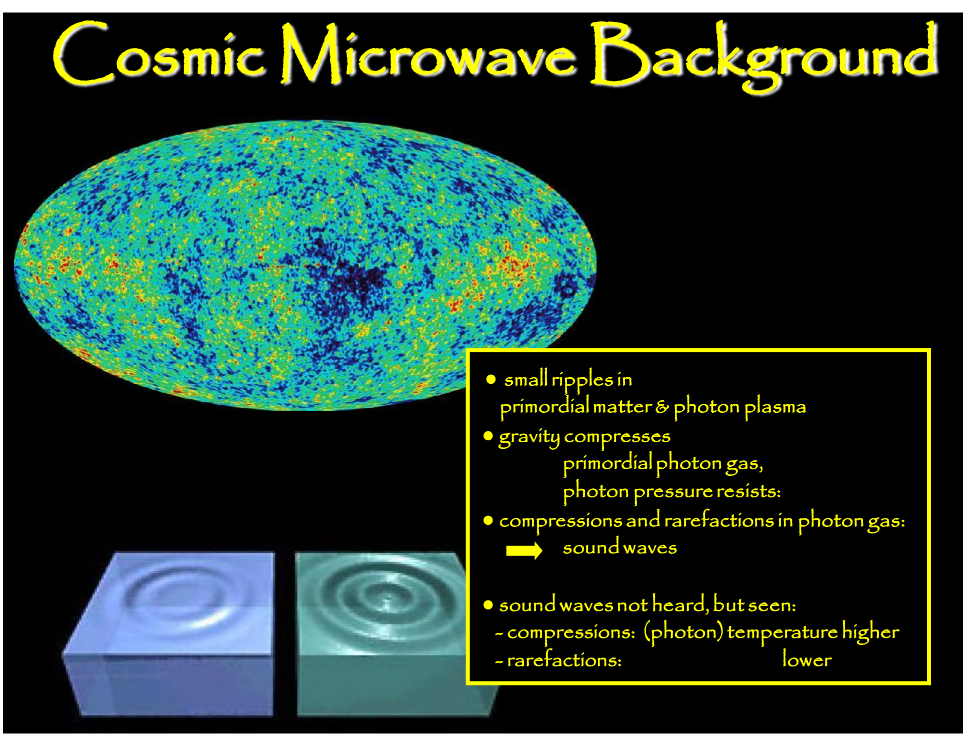

Cosmic Microwave Background
COBE
Map of the Universe at Recombination Epoch:
• 379,000 years after Big Bang
• Superhorizon perturbations in gravitational potential (Sachs-Wolfe)
• ΔT/T < 10⁻⁵


Horizon Problem Illustrated


Cosmic Microwave Background
Size Horizon Recombination
COBE
COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°
How can it be that regions totally out of thermal contact,
would have the same temperature ?

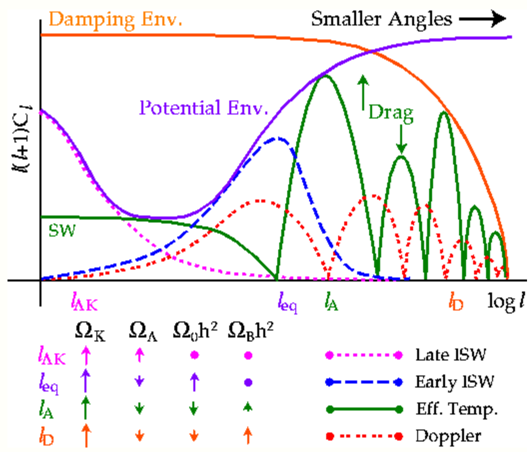

Cosmic Microwave Background
Size Horizon Recombination
COBE
COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°
COBE proved existence superhorizon fluctuations: Inflation prediction !!!!!


Music of the
Spheres


Cosmic Microwave Background
• small ripples in
primordial matter & photon plasma
• gravity compresses
primordial photon gas,
photon pressure resists:
• compressions and rarefactions in photon gas:
sound waves
• sound waves not heard, but seen:
- compressions: (photon) temperature higher
- rarefactions: lower

# The Angular Power Spectrum

- The CMB angular power spectrum is the sum of many individual physical effects
  - acoustic oscillations
  - (static) variations in potential (Sachs-Wolfe Effect)
  - baryon loading of oscillations
  - photon drag and damping
  - moving scatterers (Doppler)
  - time-varying gravitational potentials (ISW)
  - delayed recombination
  - late reionization




## Seeing Sound

For graphics & science see website Wayne Hu

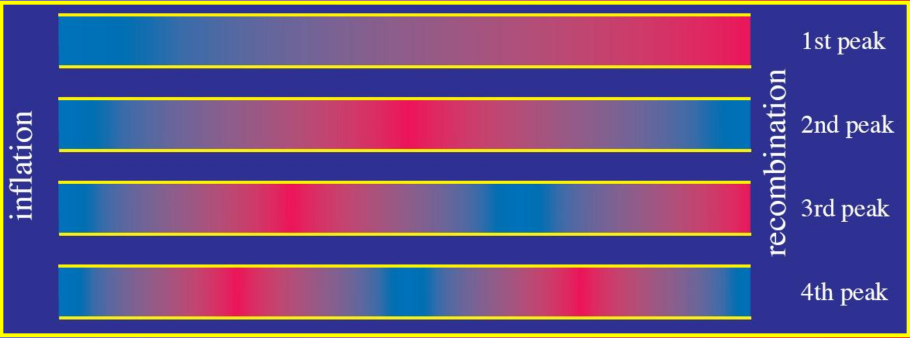
- Colliding electrons, protons and photons forms a plasma
- Acts like a gas
- Compressional disturbance propagates in the plasma through collisions

- Unlike sound in the air:
  - air molecules travel ≈ $10^{-5}$ cm before colliding
  - in primordial plasma, photons travel $10^4$ pc
- Unlike sound in the air:
  - we do not hear it but see it in the CMB
  - compression heats the gas resulting in a hot spot in the CMB

# Piper at the Gates of Dawn

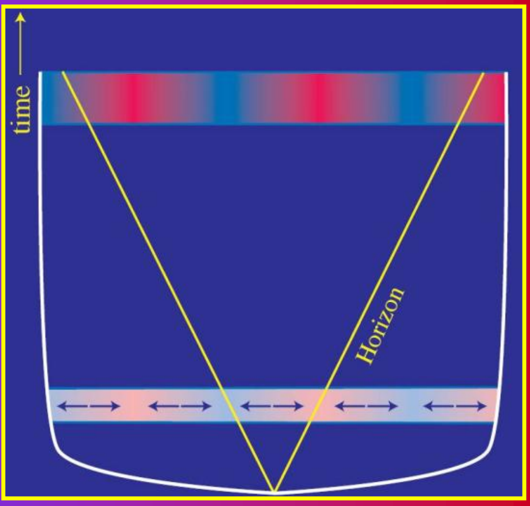
- Like blowing into a flute or an open pipe
- Spectrum of sound contains a

Fundamental frequency & Harmonic overtones




# Piper at the Gates of Dawn

- Inflation is the source of sound waves at the beginning of time
- Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement

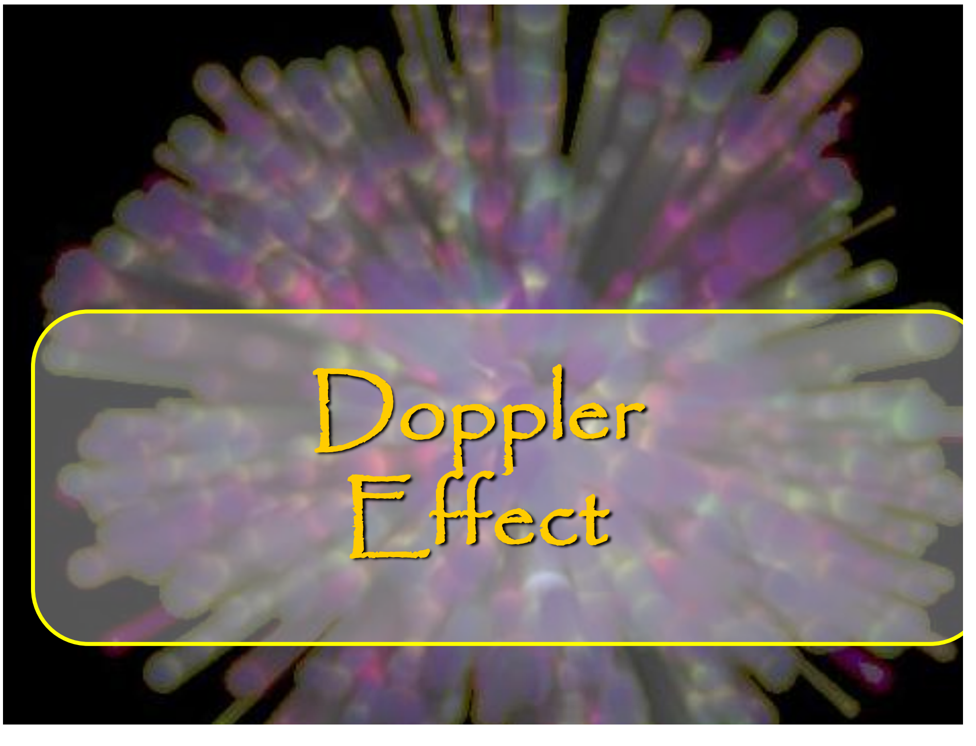


# Harmonic Signature

- Identify structure and composition of the Universe
  - through detailed examination of the pattern of overtones on the fundamental frequency
  - much like using them for a music instrument

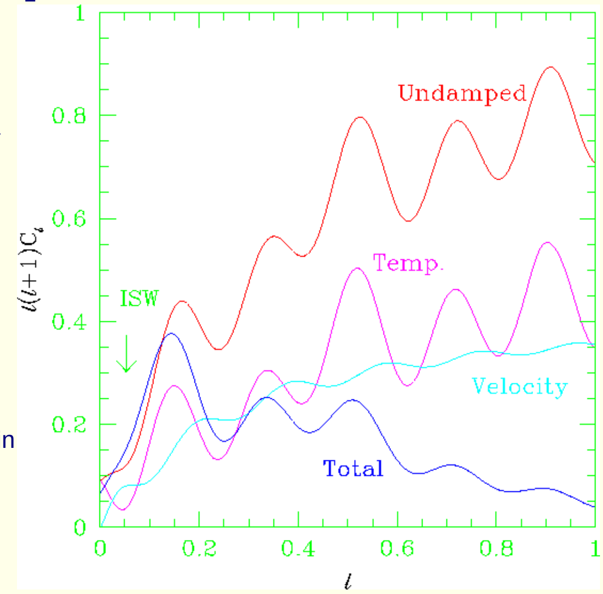
- Observed frequency spectrum consistent with inflationary origin:
  - spectrum of cosmic sound has harmonics at integer ratios of fundamental

- Without inflation, fluctuations should have been generated at intermediate times
- This would have destroyed the harmonic structure of the peaks (like drilling holes in an organ pipe)



# Doppler Effect

- Due to electron velocities
  - dipole at last scattering
- Out of phase with density fluctuations
  - 90 phase shift
  - sin($kc_S\eta$)
- Same size as potential effect
  - but decorrelated by projection onto sky
  - more important in reionized Universe and in polarization!




89

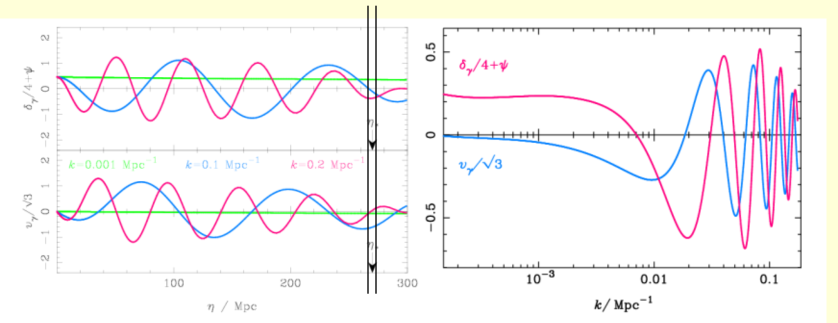
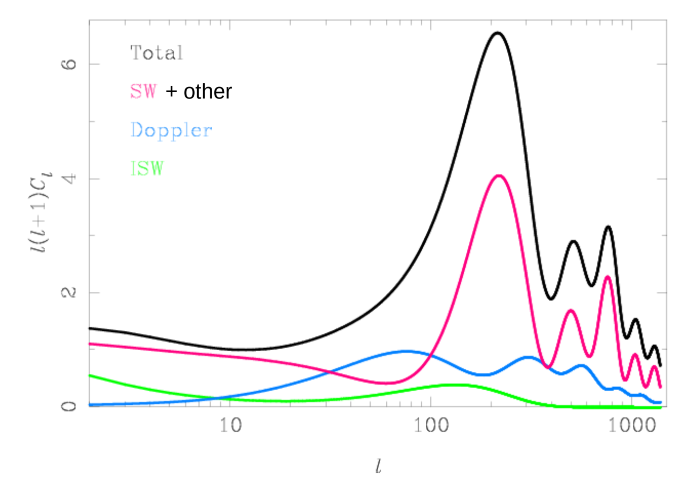



**Fig. 3.** Evolution of the combination $\delta_\gamma/4+\psi$ (top left) and the photon velocity $v_\gamma$ (bottom left) which determine the temperature anisotropies produced at last scattering (denoted by the arrow at $\eta_*$). Three modes are shown with wavenumbers $k = 0.001$, 0.1 and 0.2 Mpc$^{-1}$,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

Challinor: astro-ph/0403344

## Contributions to temperature $C_l$




Challinor: astro-ph/0403344

## CMB Checklist:
## primary predictions inflation-based cosmologies

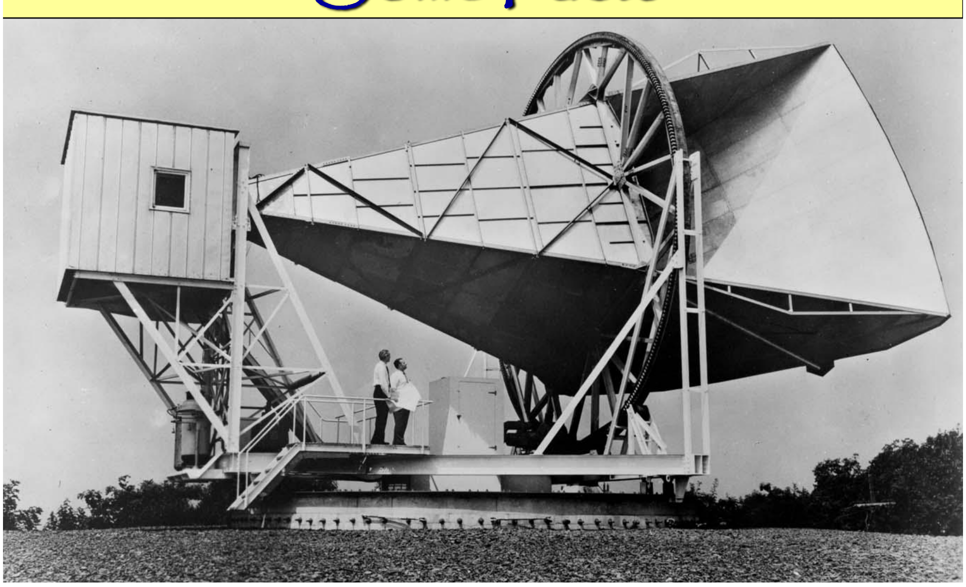
- acoustic oscillations below horizon scale
  - nearly harmonic series in sound horizon scale
  - signature of super-horizon fluctuations (horizon crossing starts clock)
  - even-odd peak heights baryon density controlled
  - a high third peak signature of dark matter at recombination
- nearly flat geometry
  - peak scales given by comoving distance to last scattering
- primordial plateau above horizon scale
  - signature of super-horizon potential fluctuations (Sachs-Wolfe)
  - nearly scale invariant with slight red tilt (n≈0.96) and small running
- damping of small-scale fluctuations
  - baryon-photon coupling plus delayed recombination (& reionization)

## CMB Checklist:
## Secondary predictions inflation-based cosmologies

- late-time dark energy domination
  - low $\ell$ ISW bump correlated with large scale structure (potentials)
- late-time non-linear structure formation
  - gravitational lensing of CMB
  - Sunyaev-Zeldovich effect from deep potential wells (clusters)
- late-time reionization
  - overall supression and tilt of primary CMB spectrum
  - Doppler and ionization modulation produces small-scale anisotropies

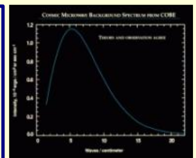
# CMB Observations

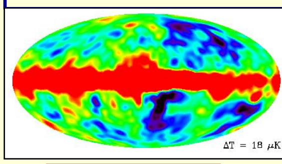
# Cosmic Microwave Background: Some Facts



# CMB Observations History

- Discovered 1965:
  - Penzias & Wilson
  - 2.7 K blackbody
    - Isotropic (<1%)
    - Relic of hot "big bang"
- 1970's and 1980's
  - 3 mK dipole (local Doppler)
  - $\delta T/T < 10^{-5}$ on arcminute






CMBPOL? maps out the B-modes?

E-mode Pol Observed DASI

2ndary Peaks DASI, Boom, Maxima

Definitive Map of Acoustic Peaks—WMAP

First Acoustic Peak – Boomerang Maxima, Toco

B-mode Pol Observed?? Polarbear?

CMB Discovery Penzias/Wilson

CMB
$10^{-5}$ large scale anisotropy
COBE DMR

Blackbody T=2.728 K

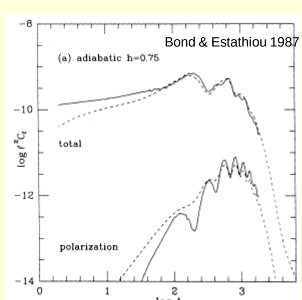
First observation of 2.3K in CN McKellar

CMB Dipole Smoot et al.

1941 | 1965 | 1975 | 1985 | 1995 | 2005 | 2015

# Search for Anisotropies in 1980s

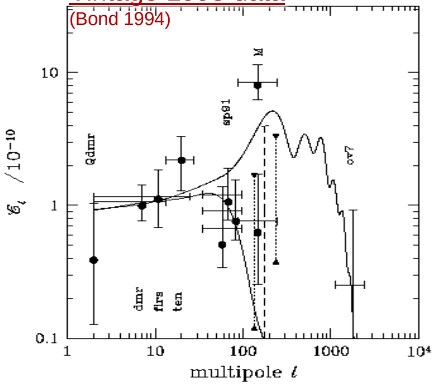
- Aside from dipole, only upper limits on anisotropy
  - Sensitivity limited by microwave technology
- Best limits on small (arcminute) angular scales
  - Uson & Wilkinson 1984; Readhead et al. 1989
    - $\Delta T/T < 2 \times 10^{-5}$ on 2'-7' scales
    - requires dark matter for reasonable $\Omega_0 > 0.2$
- Theory of CMB power spectra
  (e.g. Bond & Esthathiou 1987)



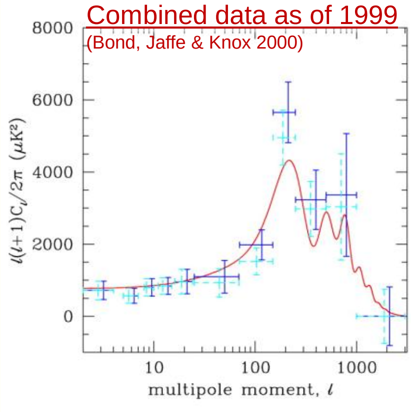
# CMB Observations 1990's

- Better receivers (e.g. HEMT) = first detections!
- COBE satellite:
  - FIRAS (spectrum), DMR (anisotropies)
- Ground and Balloon-based
- Hint of first peak detection!

Vintage 1993 data
(Bond 1994)

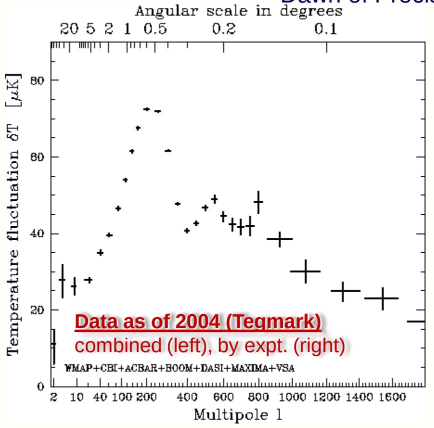



Combined data as of 1999
(Bond, Jaffe & Knox 2000)

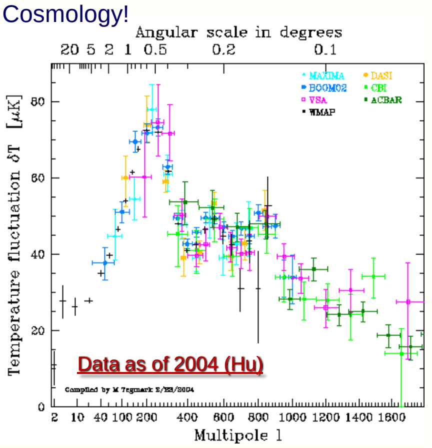



# Turn of the Century: 2000-

- Balloon results (Boomerang, Maxima);
- Interferometers (CBI, DASI, VSA);
- Satellites (WMAP)
  - Measurement of first 2-3 peaks and damping tail
  - Detection of E-mode polarization
  - Dawn of Precision Cosmology!



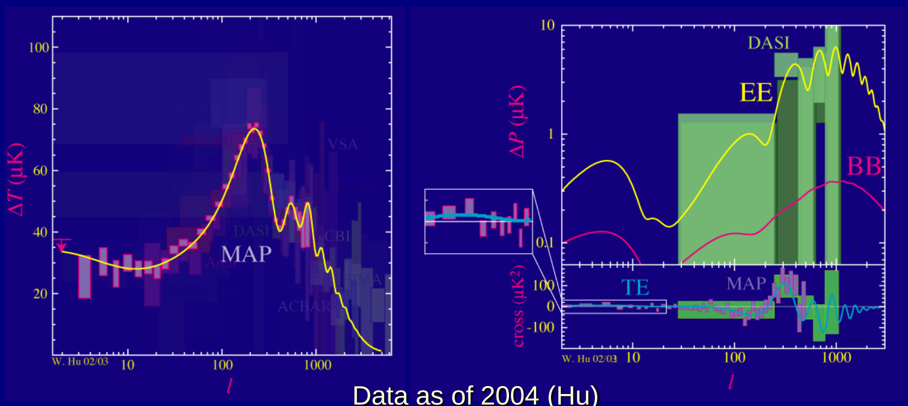

Data as of 2004 (Tegmark)
combined (left), by expt. (right)




Data as of 2004 (Hu)

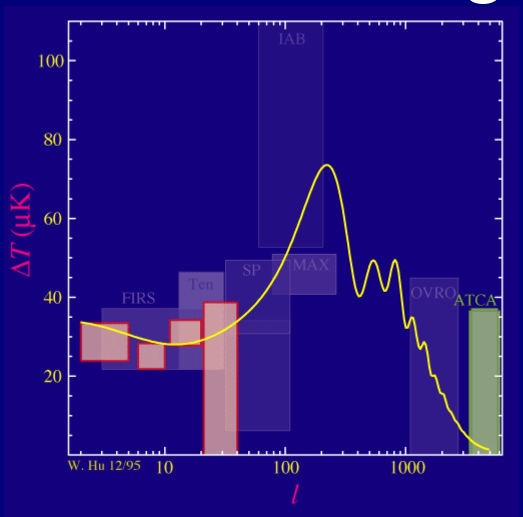
# Turn of the Century: 2000-

- Balloon results (Boomerang, Maxima);
- Interferometers (CBI, DASI, VSA);
- Satellites (WMAP)
  - Measurement of first 2-3 peaks and damping tail
  - Detection of E-mode polarization
  - Dawn of Precision Cosmology!

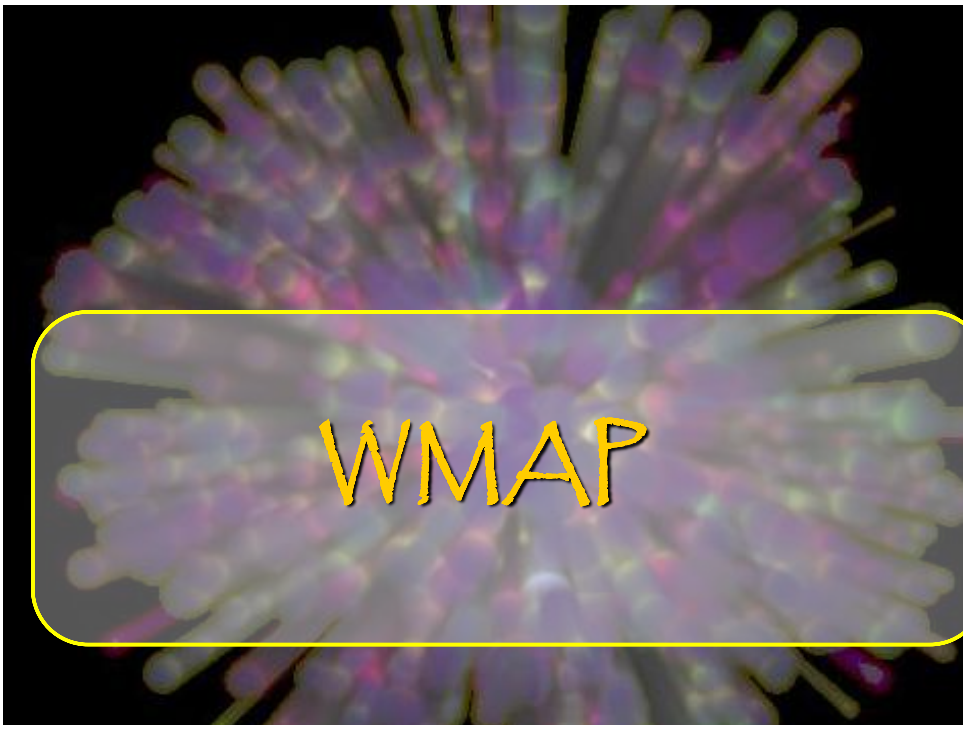



Data as of 2004 (Hu)

# The March of Progress

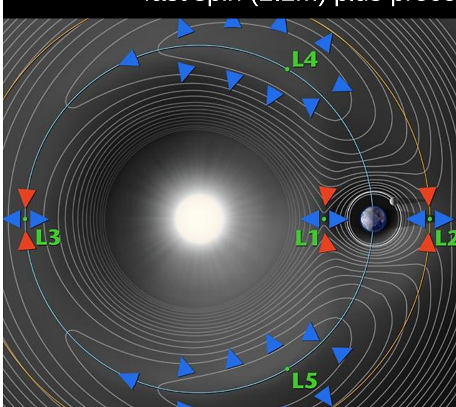



Continual improvements in observational technology and technique
ground, balloon, space




# the WMAP Mission

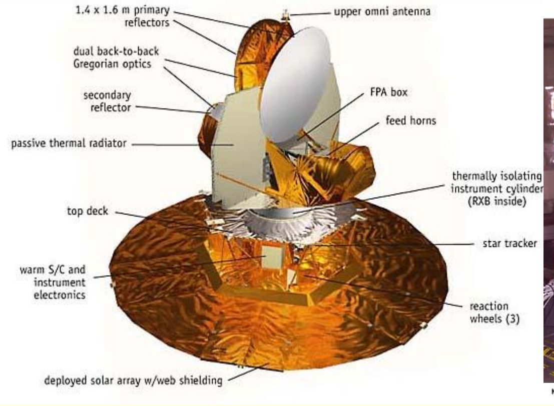
- Wilkinson Microwave Anisotropy Probe
  - proposed 1995
  - selected by NASA 1996
  - launched June 2001
  - at L2 point (Sun and Earth shielded), scan full sky in 1 year
  - fast spin (2.2m) plus precession (1hour), scan 30% sky in 1 day

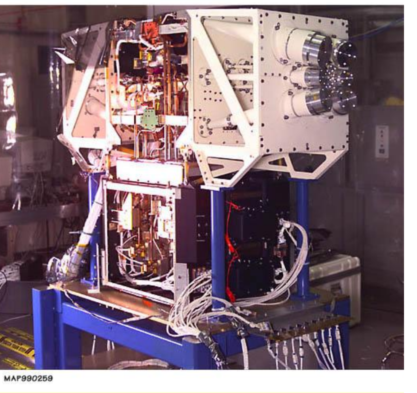



Courtesy WMAP Science Team *http://map.gsfc.nasa.gov*

# the WMAP Telescope

- 1.4m  1.6m Gregorian mirrors (0.3 – 0.7 resolution)
  - two telescopes pointed 140 apart on sky – differential radiometry
  - HEMT microwave radiometers (built by NRAO), orthogonal linear polarizations
  - 5 Bands: K (23GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)

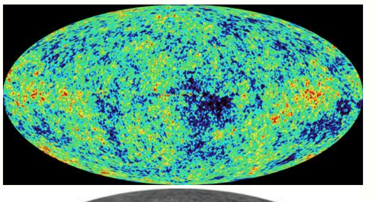


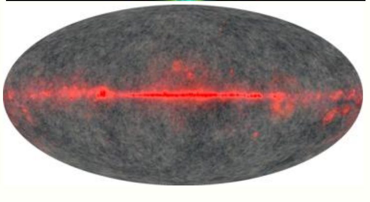




Courtesy WMAP Science Team *http://map.gsfc.nasa.gov*

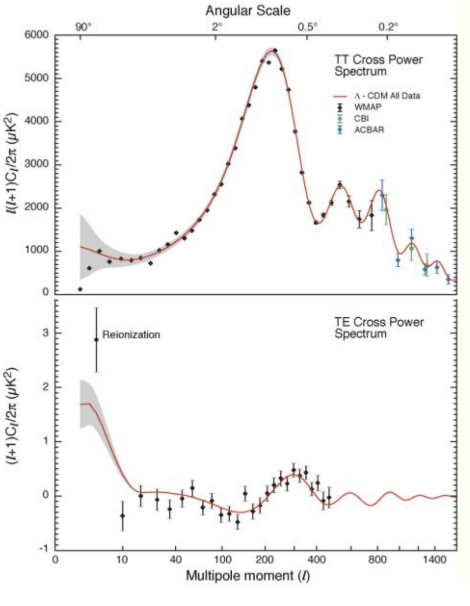
# WMAP 1-yr data release (2003)

- Bennett et al. (2003) ApJS, 148, 1
- TT spectrum
- TE spectrum
- ILC vs. 41/61/94GHz image





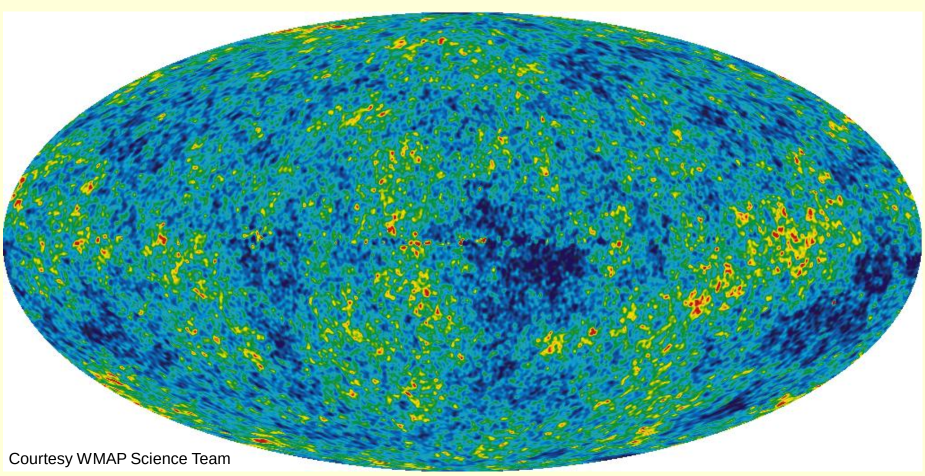
dipole subtracted -1➔ 1 mK



# WMAP Mission to 2006

- First year data release (2003)
  - first and second peaks in TT
  - low-ℓ anomalies & cold spots: geometry? foreground? variance?
  - first peak in TE polarization (but no EE or BB results reported)
  - confirmation of nearly flat Universe
  - consistent with scale-invarinat $n_{s\approx}1$, hint of running $\alpha_s$ (w/Ly$\alpha$)
  - high TE < 10 ➔ $\tau$=0.17 early reionization (z~20)
- Third year data release (2006)
  - rise to third peak (hint of lower $\sigma_8$ ~ 0.7)
  - better models for galactic (polarized) foregrounds!!!
  - EE & BB : lower $\tau$=0.09 standard reionization (z<10)
  - $n_{s\approx}0.95$  0.02, no hint of running $\alpha_s$ in WMAP alone

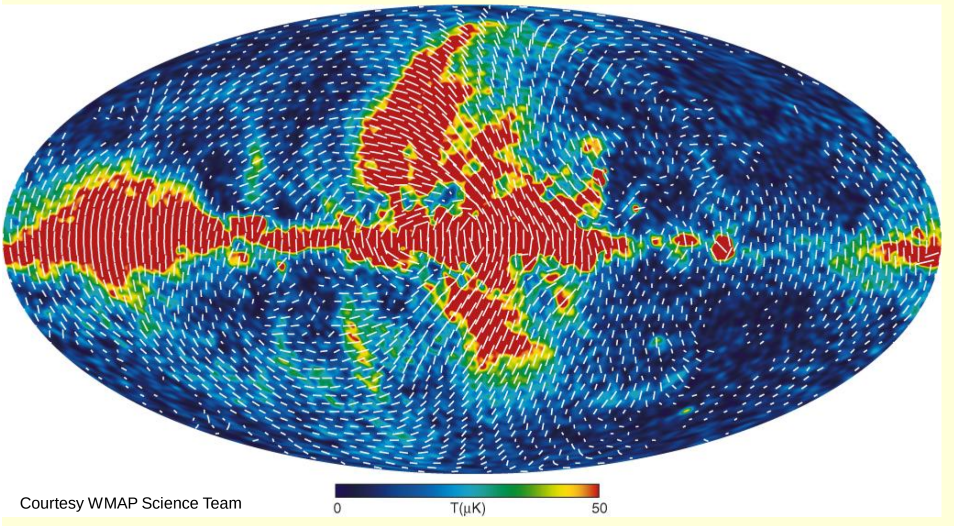
# WMAP 3 - ILC



Courtesy WMAP Science Team

WMAP 3yr internal linear combination (ILC) temperature map
(CMB -200 to 200 $\mu$K)

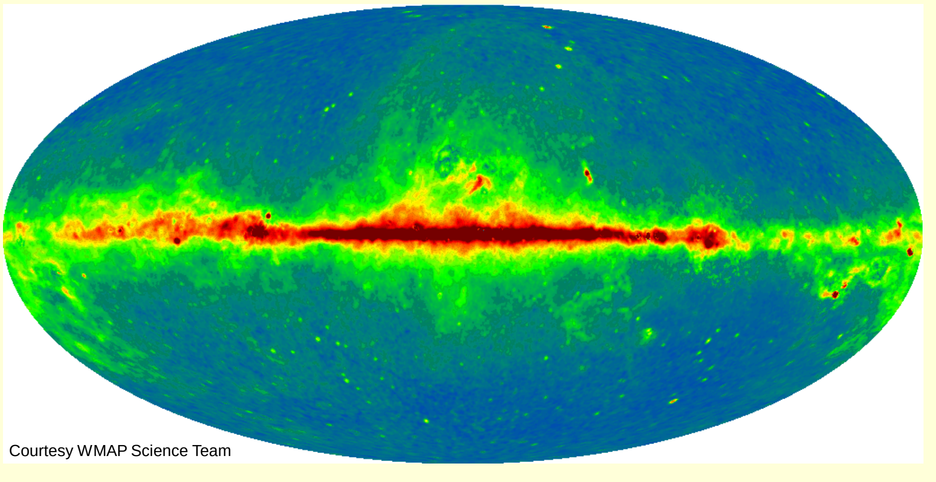
# WMAP 3 - polarization




WMAP 3-yr 22 GHz polarization map (galaxy)

(linear scale 0 to 50 μK)

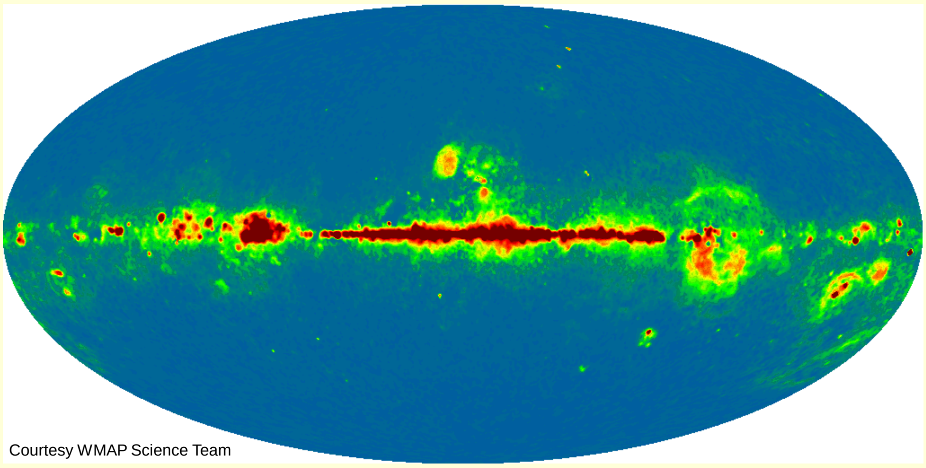
# WMAP 3 - synchrotron




WMAP 3-yr 23 GHz synchrotron map (galaxy)

(linear scale: -1 to 5 mK)

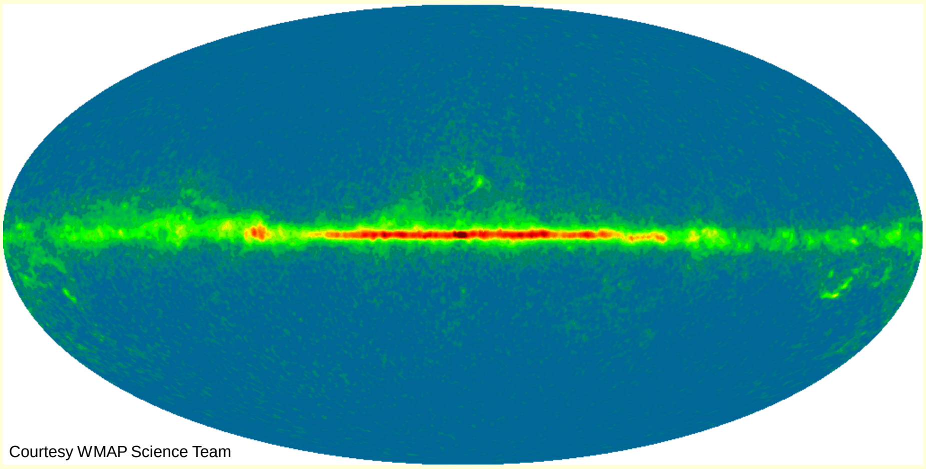
# WMAP 3 – free-fee




WMAP 3-yr 23 GHz free-free map (galaxy)

(linear scale: -1.0 to 4.7 mK)

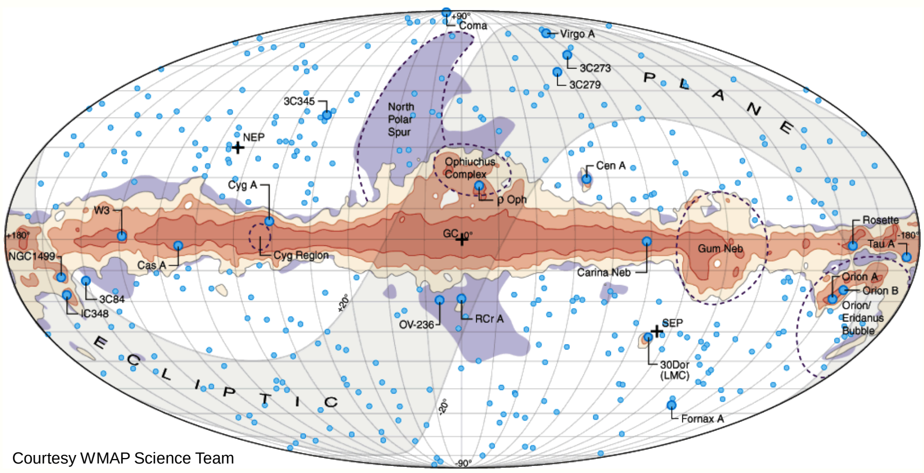
# WMAP 3 - dust




WMAP 3-yr 94 GHz dust map (galaxy)

(linear scale: -0.5 to 2.3 mK)

# WMAP 3 galaxy

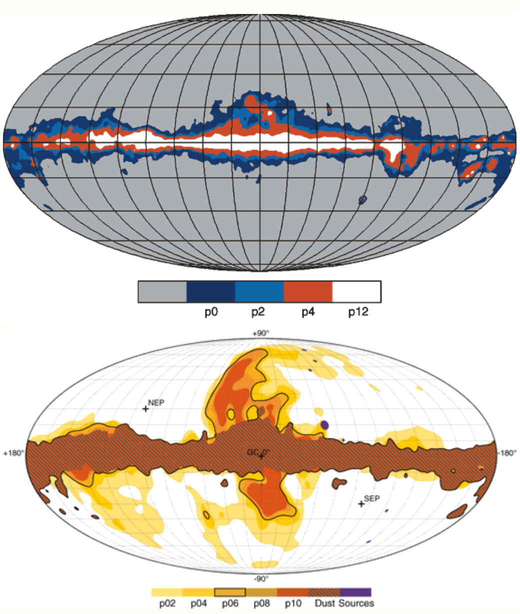



Courtesy WMAP Science Team

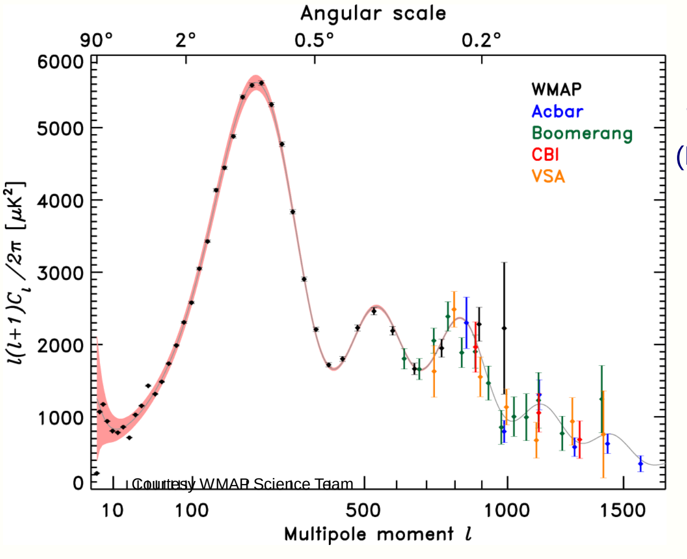
Galactic microwave map for orientation

# WMAP3 - masks

- To compute power spectrum and determine cosmological parameter constraints the WMAP team used galactic masks
  - top panel – the Kp2 mask was used for temperature data analysis. This was derived from the K-band (23GHz) total intensity image.
  - bottom panel – the P06 (black curve) was used for polarization analysis. The mask was derived from the K-band (23GHz) polarized 114intensity.

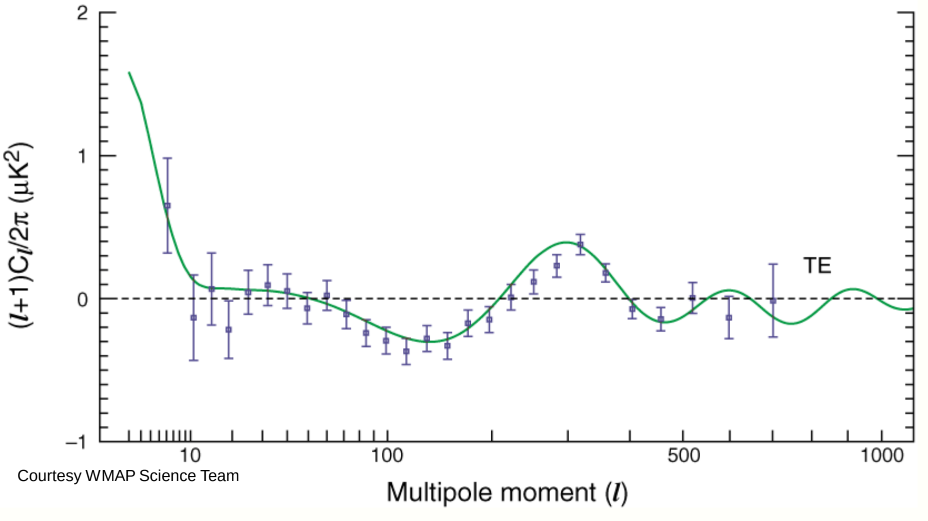


# WMAP 3 & additional experiments



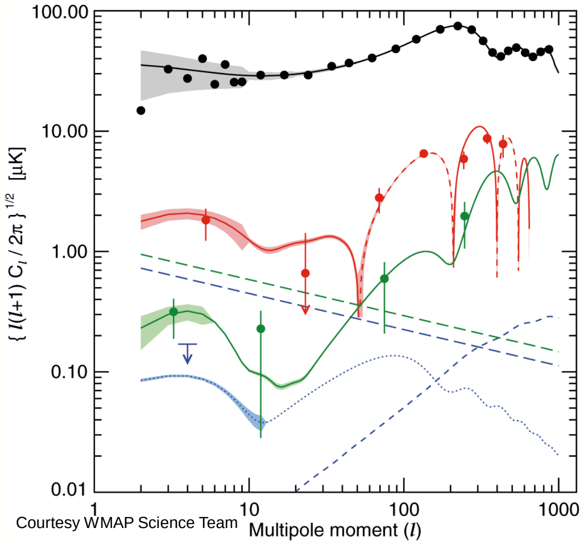

WMAP3
TT power spectrum
(Hinshaw et al. 2006)

# WMAP 3 – TE power spectrum




WMAP 3yr TE power spectrum (Hinshaw et al. 2006)

# WMAP 3 – TT/TE/EE spectrum

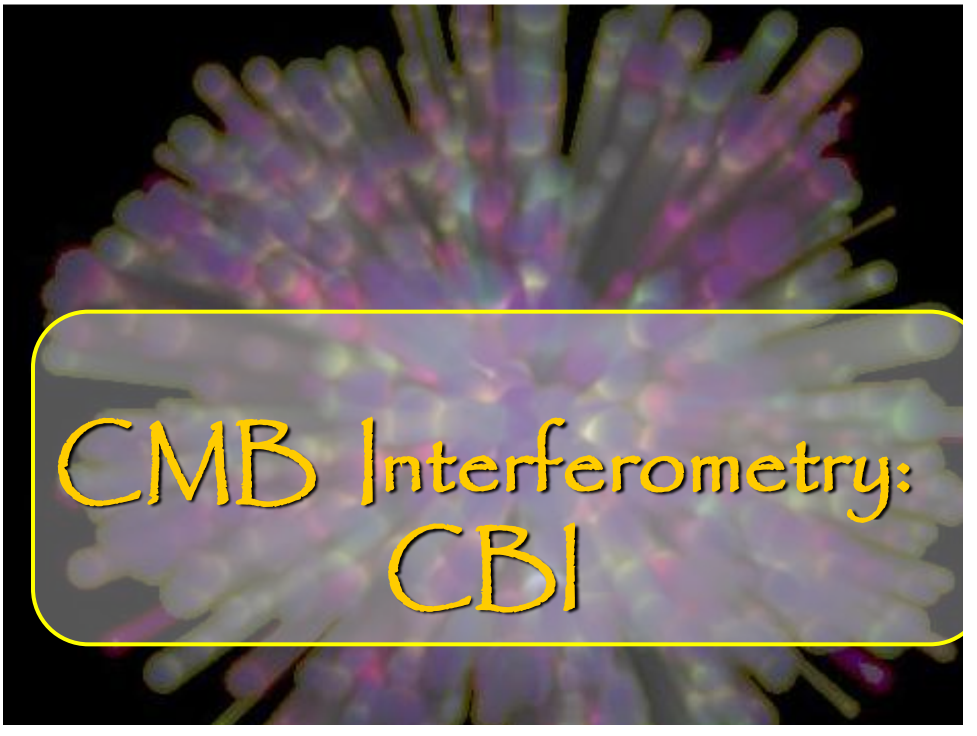



WMAP 3yr power spectra (Page et al. 2006)

# WMAP 3 Cosmological Parameters

| | | |
|---|---|---|
| $\Omega_c$ | = | $0.20^{+0.02}_{-0.04}$ |
| $\Omega_c h^2$ | = | $0.104^{+0.007}_{-0.010}$ |
| $\Omega_\Lambda$ | = | $0.76^{+0.04}_{-0.03}$ |
| $\Omega_m$ | = | $0.24^{+0.03}_{-0.04}$ |
| $\Omega_m h^2$ | = | $0.127^{+0.007}_{-0.009}$ |
| $\sigma_8$ | = | $0.74^{+0.05}_{-0.06}$ |
| $\sigma_8 \Omega_m^{0.6}$ | = | $0.31^{+0.04}_{-0.05}$ |
| $A_{SZ}$ | = | $0.99^{+0.92}_{-0.99}$ |
| $t_0$ | = | $13.7^{+0.1}_{-0.2}$ Gyr |
| $\tau$ | = | $0.088^{+0.028}_{-0.034}$ |
| $\theta_A$ | = | $0.595 \pm 0.002\ ^\circ$ |
| $z_{eq}$ | = | $3036^{+168}_{-250}$ |
| $z_r$ | = | $10.9^{+2.7}_{-2.3}$ |

| | | |
|---|---|---|
| $10^2 \Omega_b h^2$ | = | $2.23^{+0.07}_{-0.09}$ |
| $A$ | = | $0.68^{+0.04}_{-0.06}$ |
| $A_{0.002}$ | = | $0.80^{+0.04}_{-0.05}$ |
| $\Delta^2_{\mathcal{R}}$ | = | $(20^{+1}_{-2}) \times 10^{-10}$ |
| $\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$ | = | $(24^{+1}_{-2}) \times 10^{-10}$ |
| $h$ | = | $0.73^{+0.03}_{-0.04}$ |
| $H_0$ | = | $73^{+3}_{-4}$ km/s/Mpc |
| $\ell_A$ | = | $302.6^{+0.9}_{-1.4}$ |
| $n_s$ | = | $0.951^{+0.015}_{-0.019}$ |
| $n_s(0.002)$ | = | $0.951^{+0.015}_{-0.025}$ |
| $\Omega_b$ | = | $0.042^{+0.003}_{-0.005}$ |
| $\Omega_b h^2$ | = | $0.0223^{+0.0007}_{-0.0009}$ |




## The Cosmic Background Imager is…

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
  - reconfigurable
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Tnoise 8K, Tsys 15 K
- Single polarization (R or L)
  - U. Chicago polarizers < 2% leakage
- Analog correlators
  - 780 complex correlators
  - pol. product RR, LL, RL, or LR
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

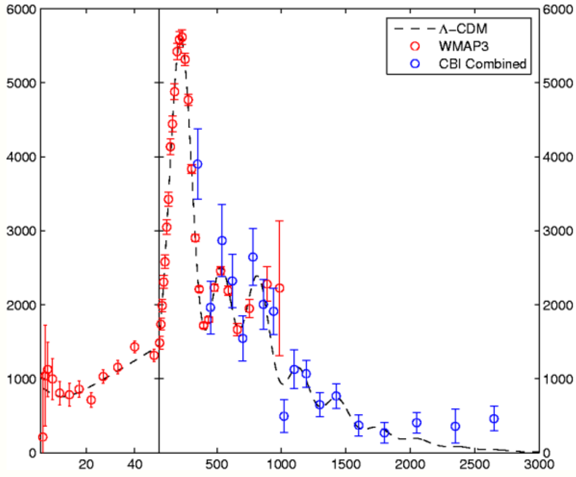
# CBI Temperature Observations

- Observed January 2000 to June 2002
  - extended configuration, reach higher ℓ

# CBI Polarization Program

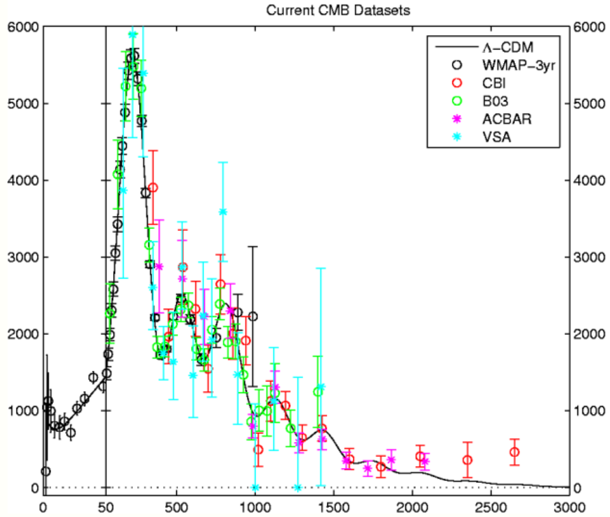
- Observed September 2002 to April 2005
  - compact configuration, maximum sensitivity

# CBI 2000-2005 Temperature



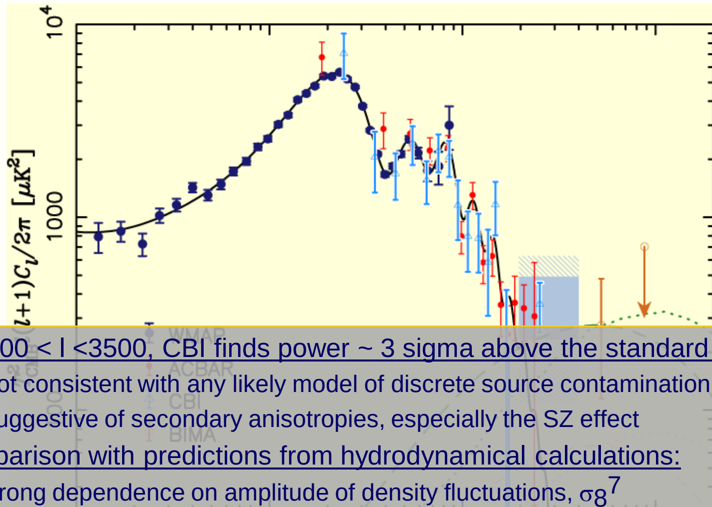

- Combined 2000-2001 and 2002-2005 mosaics
- 5th acoustic peak (barely) visible, plus excess!

# CBI 2000-2005 Temperature

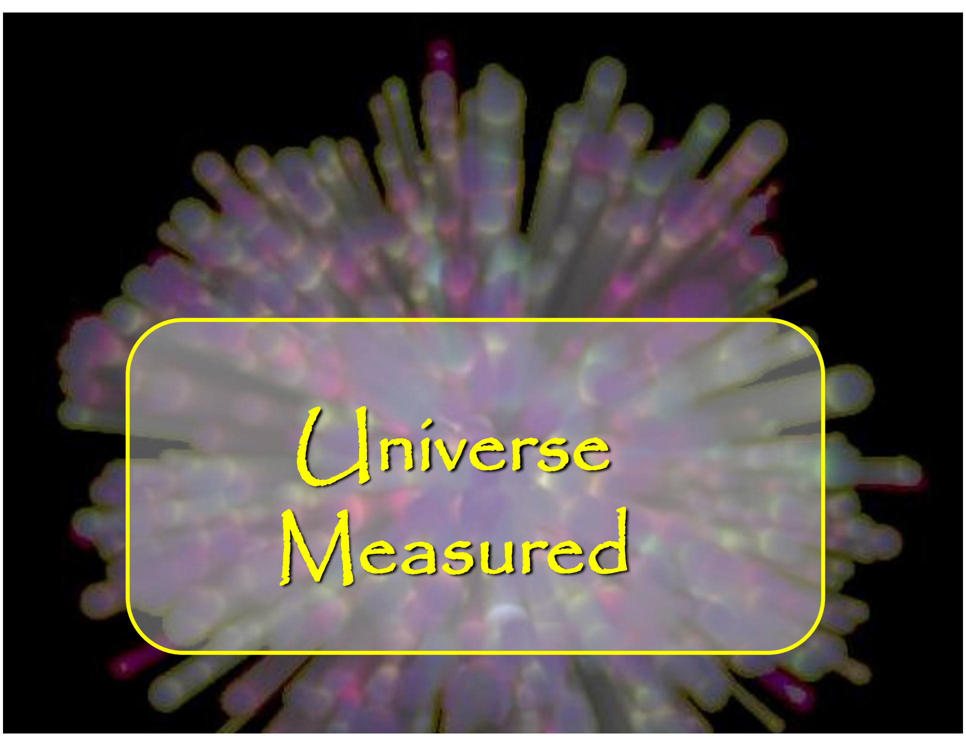



- also including new Boomerang (B03), plus VSA and ACBAR

# CBI Temperature high-ℓ excess




- At 2000 < l <3500, CBI finds power ~ 3 sigma above the standard models
  - Not consistent with any likely model of discrete source contamination
  - Suggestive of secondary anisotropies, especially the SZ effect
- Comparison with predictions from hydrodynamical calculations:
  - strong dependence on amplitude of density fluctuations, $\sigma_8{}^7$
  - CBI observed amplitude suggests $\sigma_8$~0.9-1.0
  - BUT, significant non-Gaussian corrections (dominated by nearby clusters)



# What can we learn from the CMB?

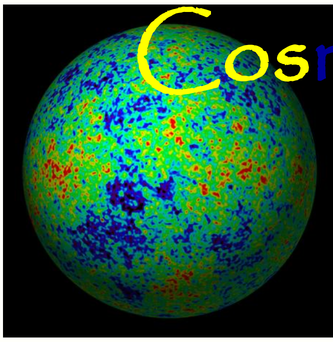
- Initial conditions
  What types of perturbations, power spectra, distribution function (Gaussian?);
  => learn about inflation or alternatives.
  (distribution of $\Delta T$; power as function of scale; polarization and correlation)
- What and how much stuff
  Matter densities ($\Omega_b$, $\Omega_{cdm}$);; neutrino mass
  (details of peak shapes, amount of small scale damping)
- Geometry and topology
  global curvature $\Omega_K$ of universe; topology
  (angular size of perturbations; repeated patterns in the sky)
- Evolution
  Expansion rate as function of time; reionization
  - Hubble constant $H_0$ ; dark energy evolution w = pressure/density
  (angular size of perturbations; *l* < 50 large scale power; polarizationr)
- Astrophysics
  S-Z effect (clusters), foregrounds, etc.

# Cosmological Parameters

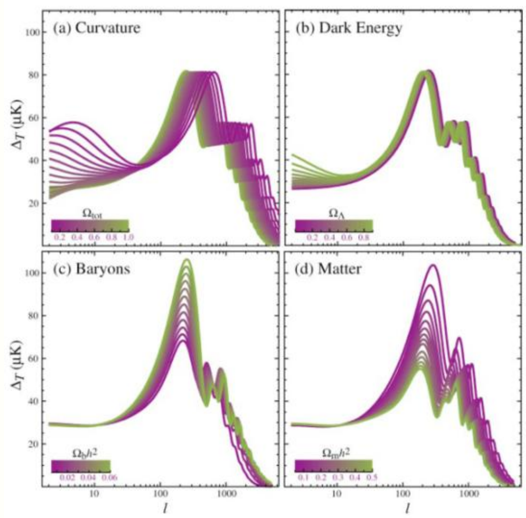
- Universe content:
  $\Omega_{\mathbf{b}}$, $\Omega_{\mathbf{DM}}$, $f_\nu$, $\Omega_{\Lambda,}$ w(z)
- Universe dynamics:
  $H_0$
- Clumpiness:
  $\sigma_8$, $n_s(k)$
- Primoridial gravity waves:
  $A_t$, $n_t$
- When the first stars formed:
  $z_{re}$
- Other: WDM, isocurvature, non-Gaussianity...


Each parameter has an effect on the CMB

# Cosmic Parameters

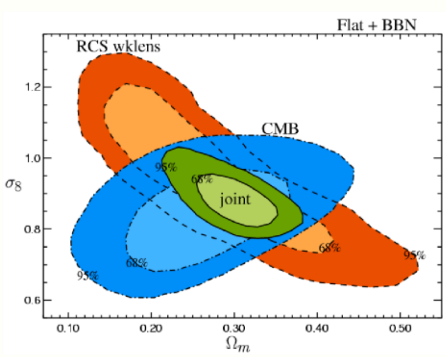


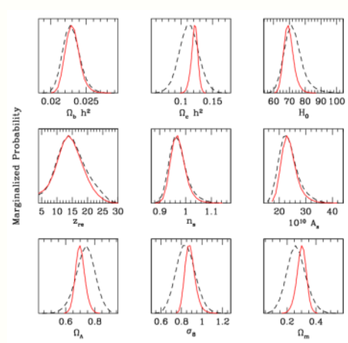
The WMAP CMB temperature power spectrum



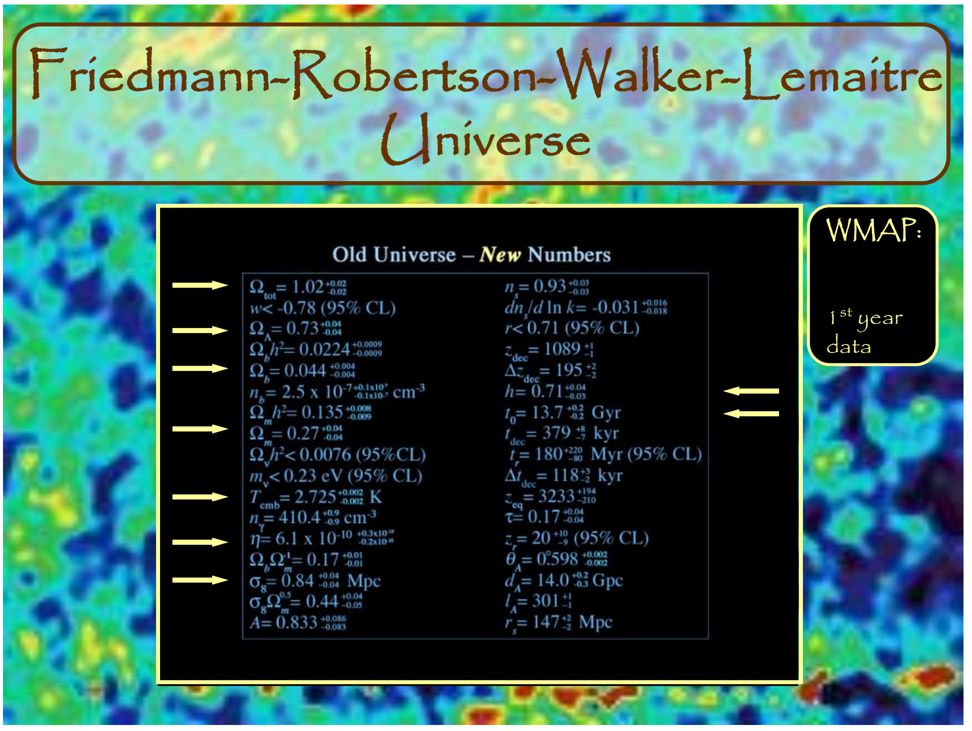

Plot number density of samples as function of parameters
Often better constraint by combining with other data

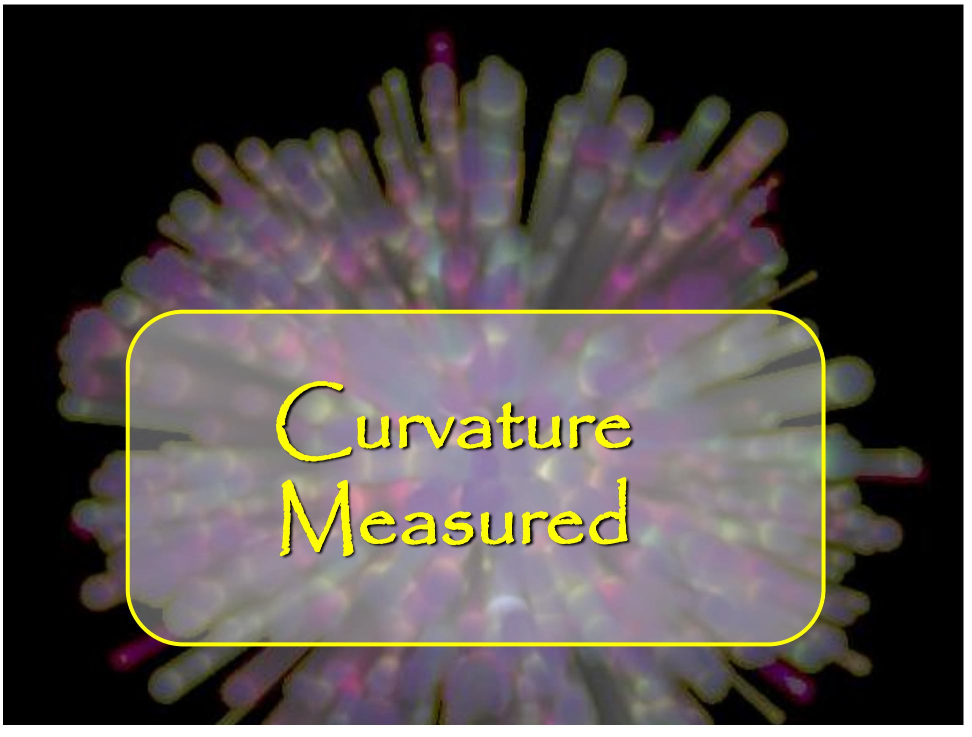
e.g. CMB+galaxy lensing +BBN prior



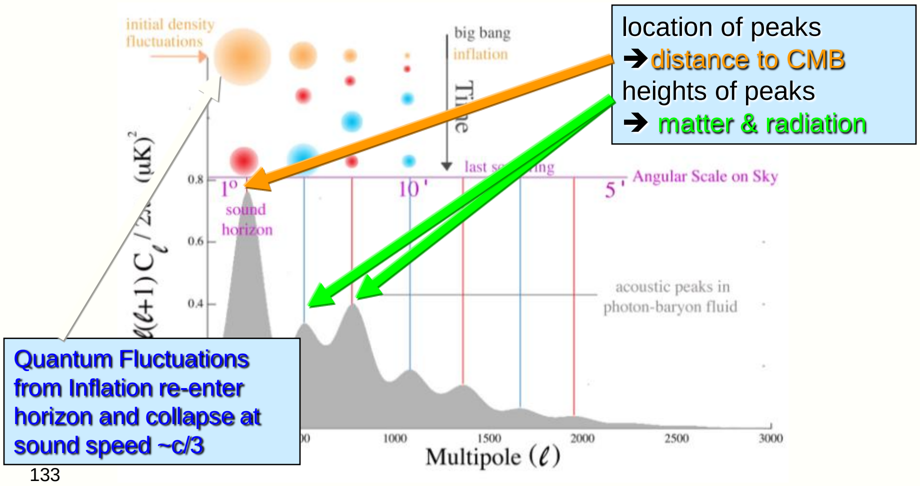

Contaldi, Hoekstra, Lewis: astro-ph/0302435


Friedmann-Robertson-Walker-Lemaitre Universe
WMAP:
1st year data
Old Universe – *New* Numbers
$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$
$w < -0.78$ (95% CL)
$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$
$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$
$\Omega_b = 0.044^{+0.004}_{-0.004}$
$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm$^{-3}$
$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
$\Omega_m = 0.27^{+0.04}_{-0.04}$
$\Omega_\nu h^2 < 0.0076$ (95%CL)
$m_\nu < 0.23$ eV (95% CL)
$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K
$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm$^{-3}$
$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$
$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$
$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc
$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$
$A = 0.833^{+0.086}_{-0.083}$
$n_s = 0.93^{+0.03}_{-0.03}$
$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
$r < 0.71$ (95% CL)
$z_{dec} = 1089^{+1}_{-1}$
$\Delta z_{dec} = 195^{+2}_{-2}$
$h = 0.71^{+0.04}_{-0.03}$
$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr
$t_{dec} = 379^{+8}_{-7}$ kyr
$t_r = 180^{+220}_{-80}$ Myr (95% CL)
$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
$z_{eq} = 3233^{+194}_{-210}$
$\tau = 0.17^{+0.04}_{-0.04}$
$z_r = 20^{+10}_{-9}$ (95% CL)
$\theta_A = 0.598^{\circ}{}^{+0.002}_{-0.002}$
$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
$l_A = 301^{+1}_{-1}$
$r_s = 147^{+2}_{-2}$ Mpc


Curvature Measured

# CMB Acoustic Peaks

- Compression driven by gravity, resisted by radiation
  ≈ seismic waves in the cosmic photosphere: $\cos(kc_s\eta)$




133

# Modulating Influences

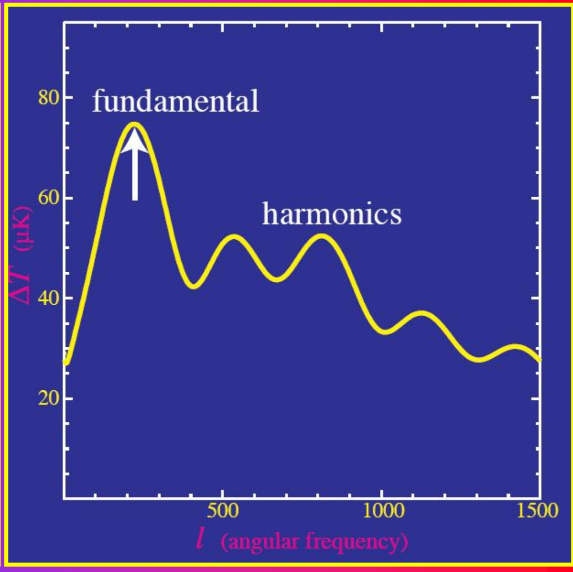
- Silk Damping:
  - photons diffuse out of matter perturbations
  - fluctuations with size < photon free-streaming length get suppressed
  - harmonic structure beyond third peak seriously damped
- Integrated Sachs-Wolfe effect:
  - damping/boosting temperature fluctuations due to decay/growth potential perturbations:
    - Early ISW: while still radiation-dominated, potential DM fluct's grow less, suppression of temp. fluct.
    - Late ISW: as Dark Energy takes over universe, potential wells decay (due to accelerated expansion)

# Harmonic Signature

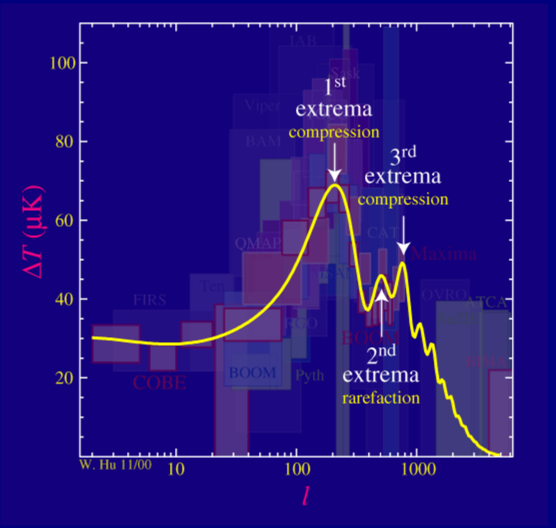
Spectrum cosmic sound:

-integer ratios fundamental

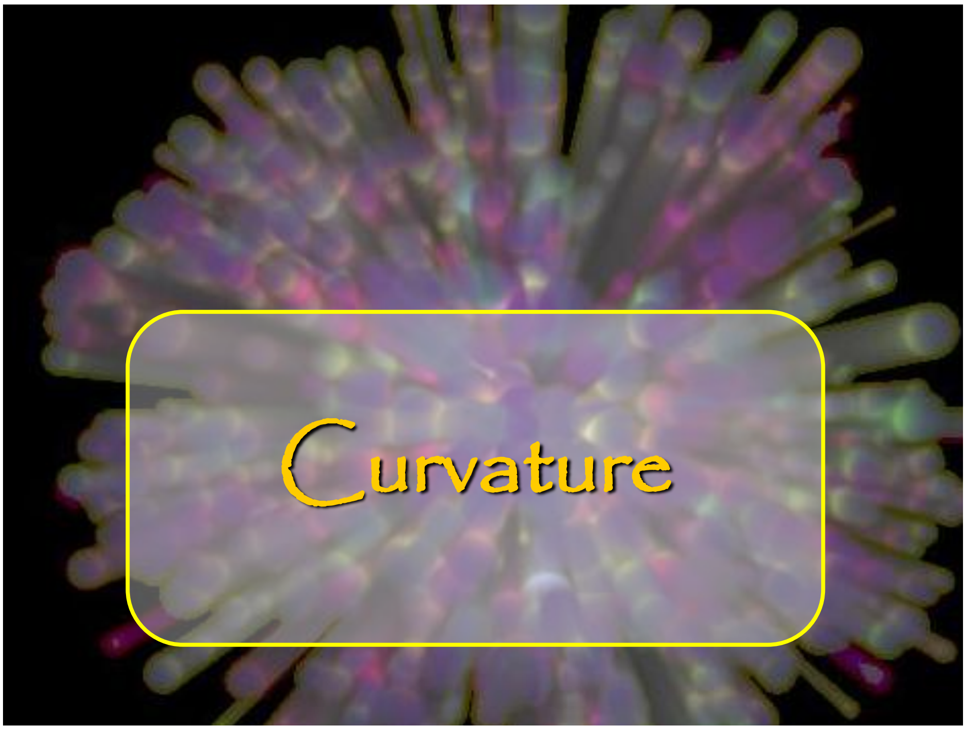
- competition between gravity vs. pressure: dependent on phase
- fundamental + odd mode: gravity along sonic motio
- even multiples: gravity fights sonic motion



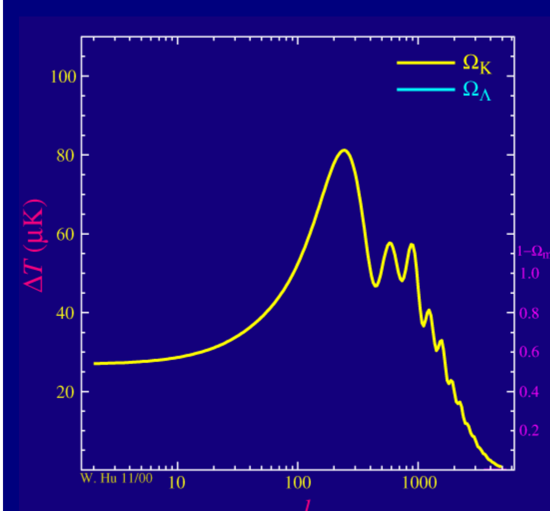

# CMB Acoustic Overtones




If we choose to follow a crest (overdensity) after horizon entry, the first acoustic peak is its first compression…




# Peaks and Curvature




Changing distance to $z$ =1100 shifts peak pattern

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

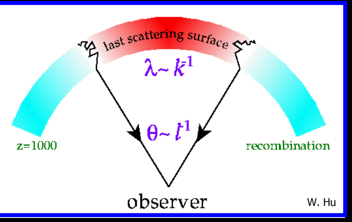
Courtesy Wayne Hu – *http://background.uchicago.edu*

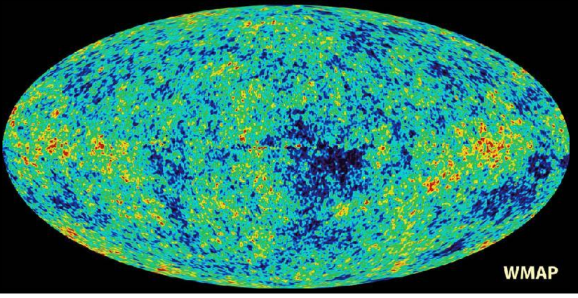
# Geometry of the Universe: Music of the Spheres

Measuring the Geometry of the Universe:

- Object with known physical size, at large cosmological distance
- Measure angular extent on sky
- Comparison yields light path

➡ *Geometry of space*




"Physical Object":

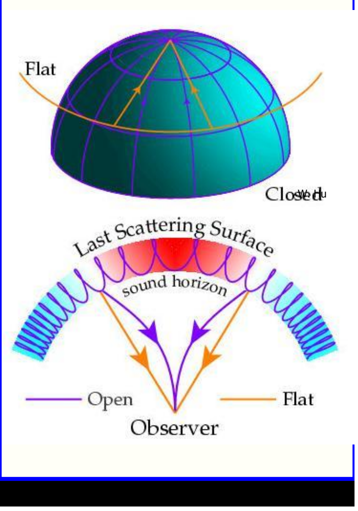
- Sound waves in primordial matter-radiation plasma: wavelength $\lambda_s$
- observable at surface of epoch recombination, at which photons were last scattered

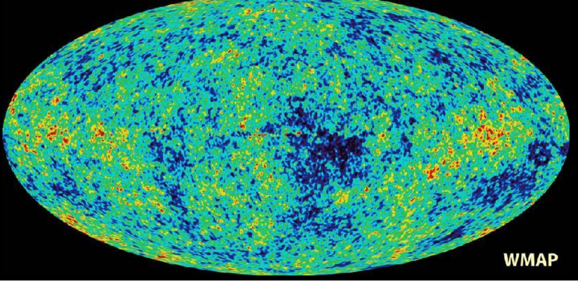
# Geometry of the Universe: Music of the Spheres

Measuring the Geometry of the Universe:

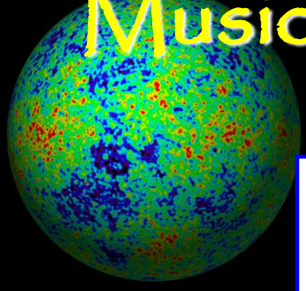
- Object with known physical size, at large cosmological distance
- Measure angular extent on sky
- Comparison yields light path

➡ *Geometry of space*



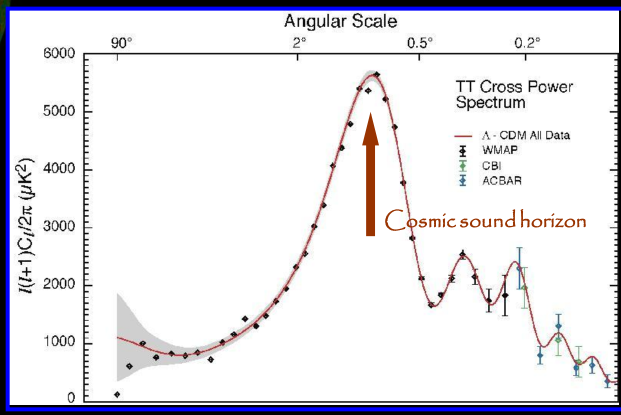



# Music of the Spheres



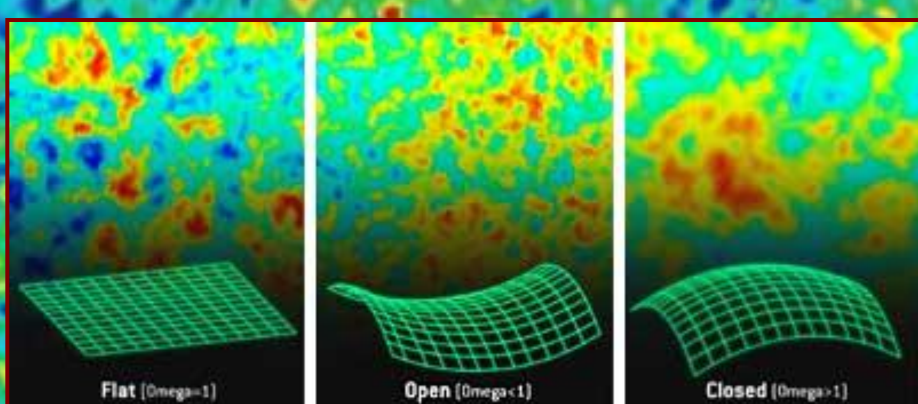
## The Cosmic Tonal Ladder

The WMAP CMB temperature power spectrum

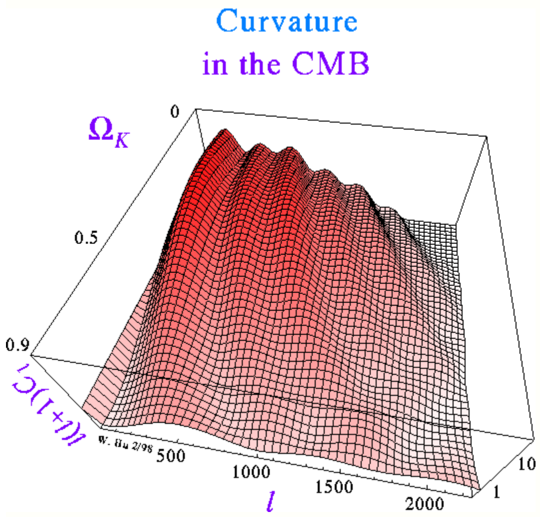



The Cosmic Microwave Background Temperature Anisotropies: the Embryonic Universe

# Friedmann-Robertson-Walker-Lemaitre Universe



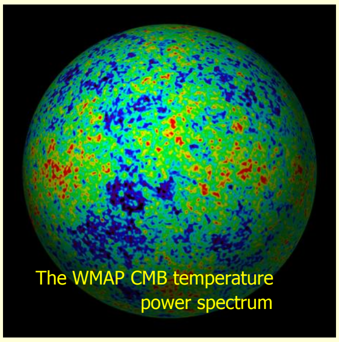
# Peaks and Curvature

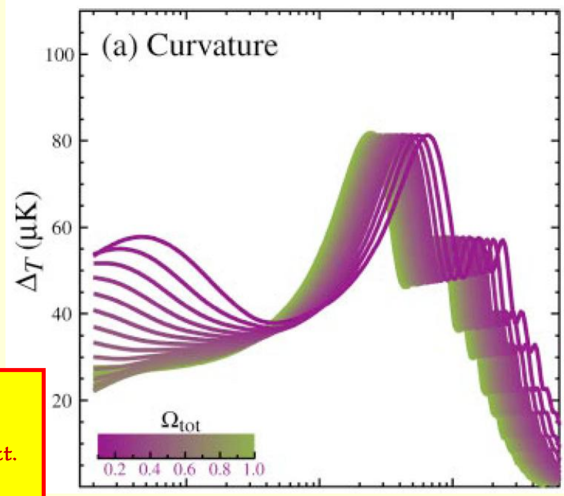



Changing distance to $z$ =1100 shifts peak pattern

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

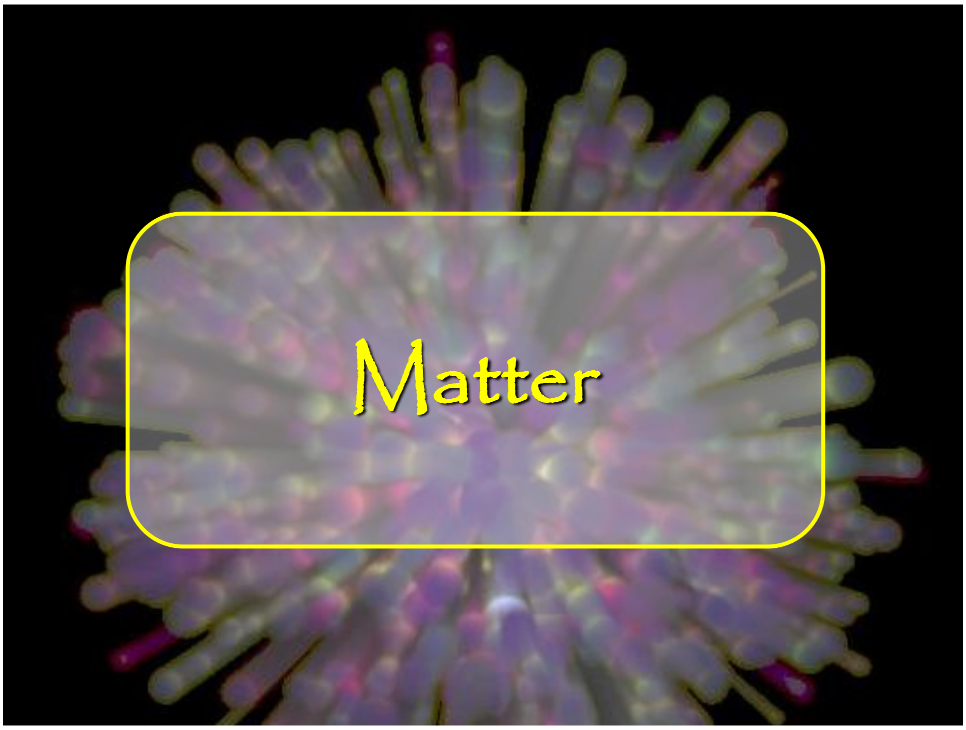
# Curvature: CMB



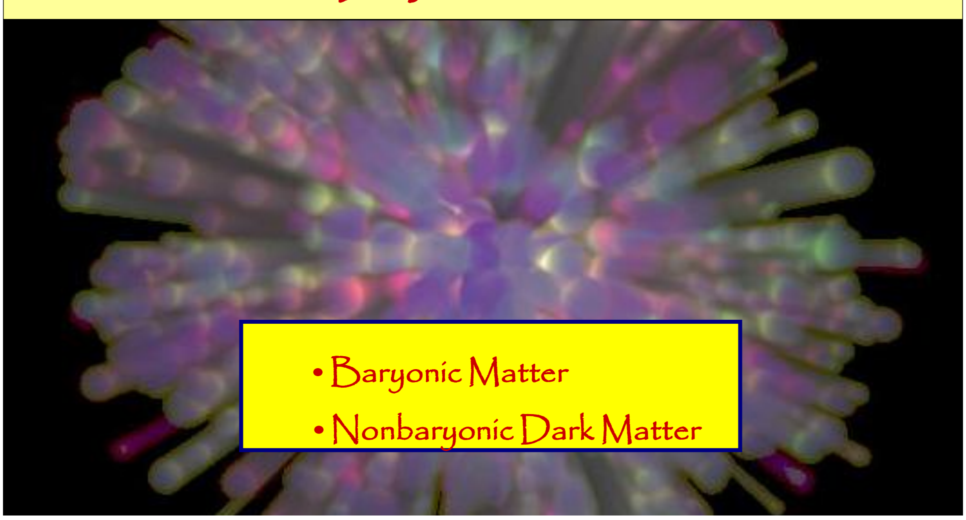



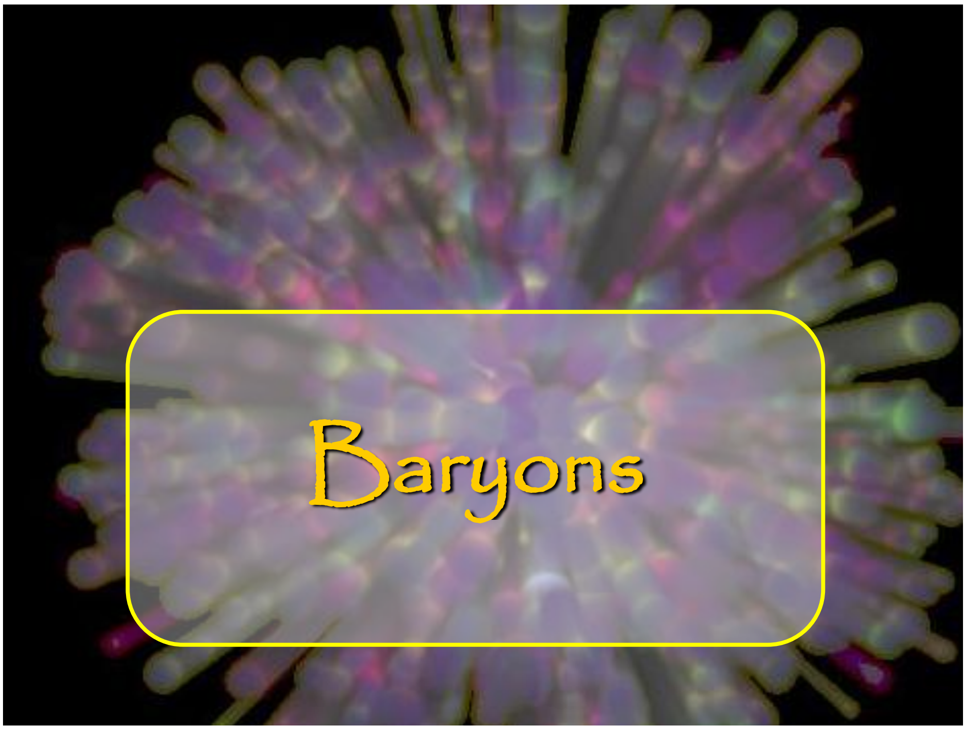

Curvature influences:

- angular scale of given physical fluct.
- evolution potential wells




# Cosmic Constituents: Matter



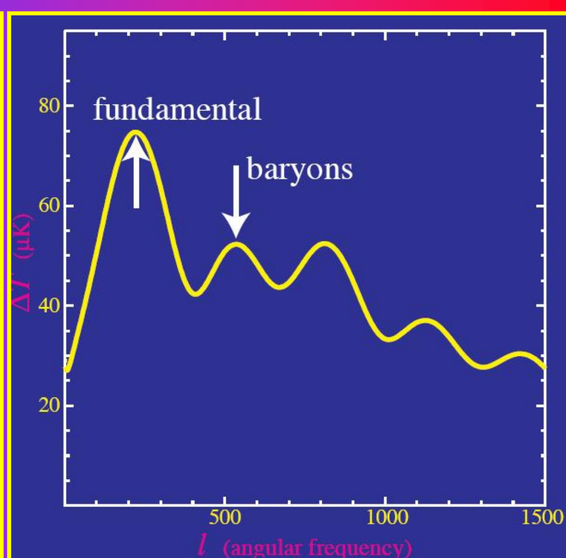



# Baryonic Matter

Baryonic Matter:

- Baryonic "drag" suppresses fluctuation

- low second peak: baryon density comparable to photon density



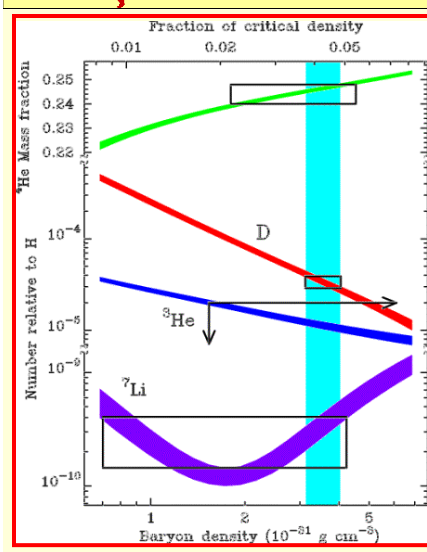
# Baryonic Matter

Note:

- STARS are but a fraction of the total amount of baryonic matter
- There is still a large amount of undetected baryonic matter:
  - hiding as warm Intergalactic Gas (WHIM) ?

| | | | | |
|---|---|---|---|---|
| 3 | baryon rest mass | | | $0.045 \pm 0.003$ |
| 3.1 | warm intergalactic plasma | | $0.040 \pm 0.003$ | |
| 3.1a | virialized regions of galaxies | $0.024 \pm 0.005$ | | |
| 3.1b | intergalactic | $0.016 \pm 0.005$ | | |
| 3.2 | intracluster plasma | | $0.0018 \pm 0.0007$ | |
| 3.3 | main sequence stars | spheroids and bulges | $0.0015 \pm 0.0004$ | |
| 3.4 | | disks and irregulars | $0.00055 \pm 0.00014$ | ← |
| 3.5 | white dwarfs | | $0.00036 \pm 0.00008$ | |
| 3.6 | neutron stars | | $0.00005 \pm 0.00002$ | |
| 3.7 | black holes | | $0.00007 \pm 0.00002$ | |
| 3.8 | substellar objects | | $0.00014 \pm 0.00007$ | |
| 3.9 | HI + HeI | | $0.00062 \pm 0.00010$ | |
| 3.10 | molecular gas | | $0.00016 \pm 0.00006$ | |
| 3.11 | planets | | $10^{-6}$ | |
| 3.12 | condensed matter | | $10^{-5.6\pm0.3}$ | |
| 3.13 | sequestered in massive black holes | | $10^{-5.4}(1+\epsilon_n)$ | |

# Baryonic Matter: primordial nucleosynthesis



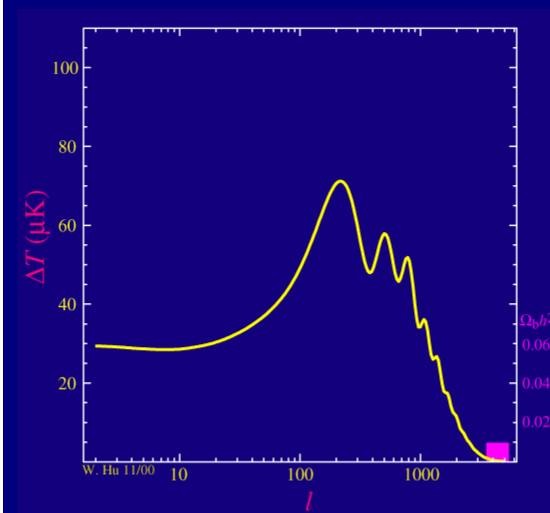

From measured light element abundances:

$$\eta \equiv \frac{n_B}{n_\gamma}$$

↓

$$0.005 \lesssim \Omega_b h^2 \lesssim 0.026$$

# Peaks and Baryons

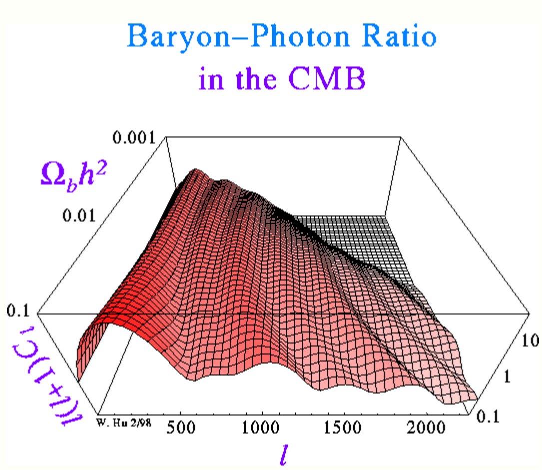



Changing baryon loading changes odd/even peaks

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

Courtesy Wayne Hu – *http://background.uchicago.edu*

# Peaks and Baryons

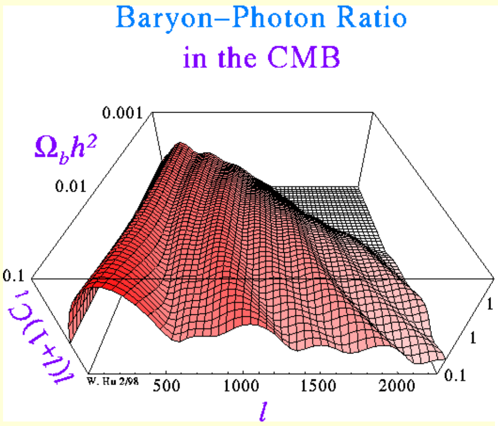



Changing baryon loading changes odd/even peaks

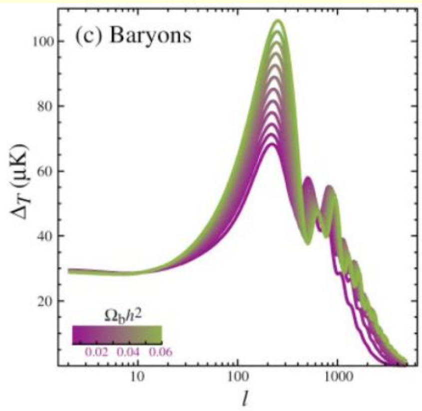
- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

152

# Baryonic Matter: CMB




Due to baryon drag in the primordial baryon-photon gas, 2nd peak in CMB spectrum is suppressed.




$$\Omega_b h^2 \approx 0.0224 \pm 0.0009$$
$$\Omega_b \approx 0.044 \pm 0.004$$

# Dark Matter

It is the nonbaryonic Matter that is responsible for the existence of Structure in the Universe !!!

If it had not been there: no substantial structure

# Nonbaryonic Dark Matter

Two major classes of Dark Matter:

MACHOs massive compact halo objects
- brown dwarfs
- stellar remnants (black holes, neutron stars)
- primordial black halos

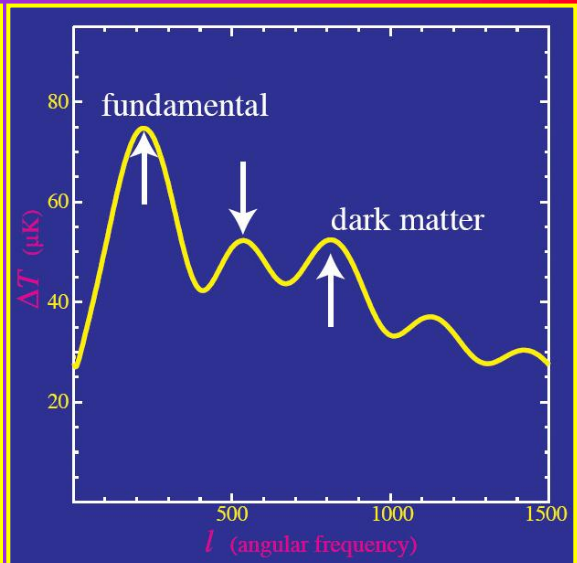
WIMPs weakly interacting massive particles:
- hot dark matter e.g. massive neutrinos
- cold dark matter axions, neutralinos
- warm dark matter

# Dark Matter

Dark Matter:

-Responsible for keeping up gravitational potential perturbations

- third peak:
  dark matter density



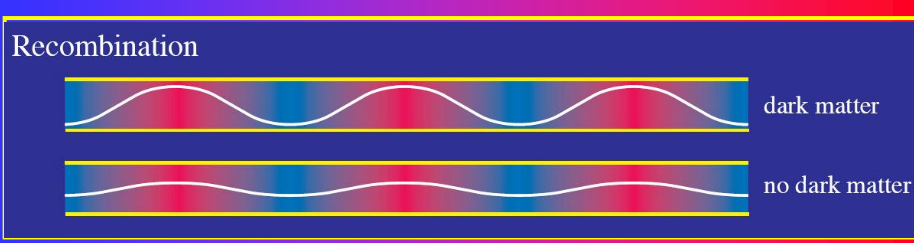

# Dark Matter

Dark Matter:

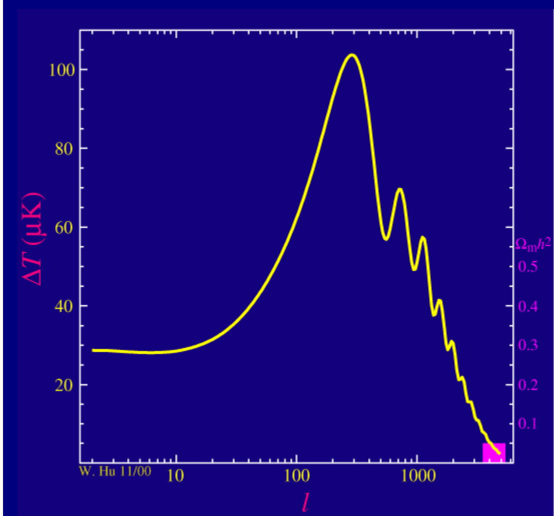
-Retains the gravitational potential,

- while baryonic matter oscillates as stable sound wave

- otherwise, decay gravitational potential



# Peaks and Matter

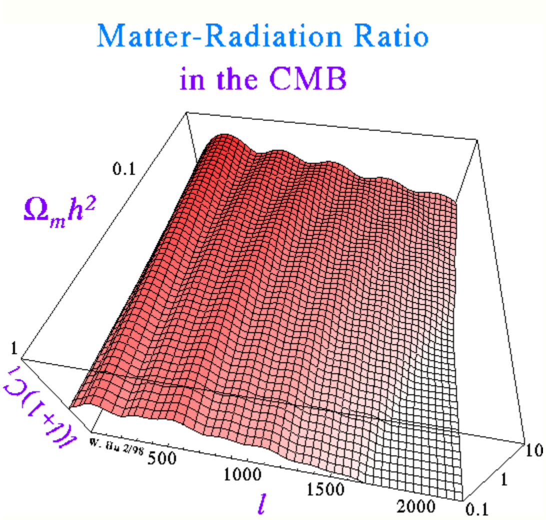



Changing dark matter density also changes peaks…

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

Courtesy Wayne Hu – *http://background.uchicago.edu*

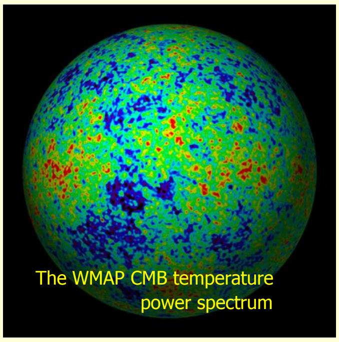
# Peaks and Matter



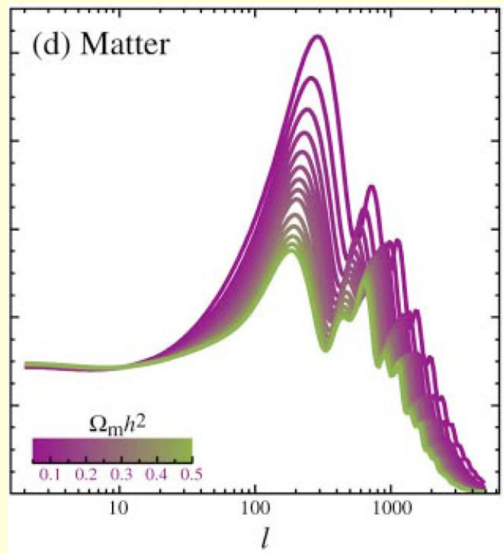

Changing dark matter density also changes peaks…

- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

# Matter: CMB




(Dark) Matter determines the depth of the potential wells, influencing the amplitude of the acoustic fluctuations



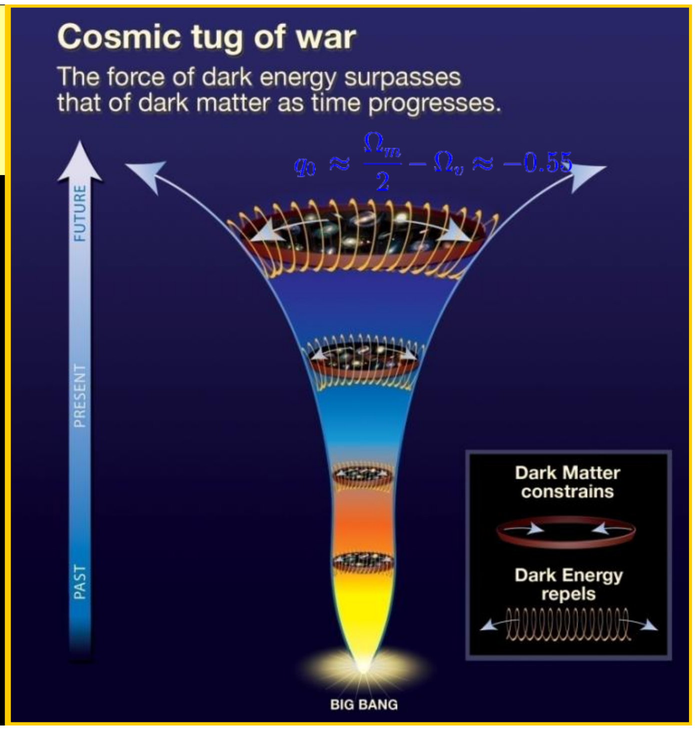

# Dark Energy/ Cosmological Constant

# Cosmic Acceleration

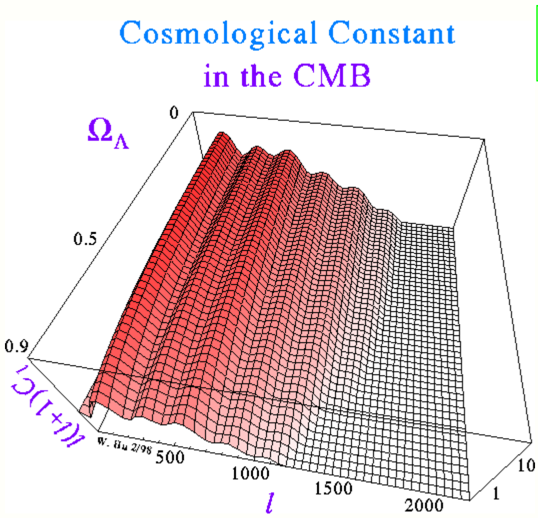
Our Universe

Present:
ACCELERATES

Past:
DECELERATED



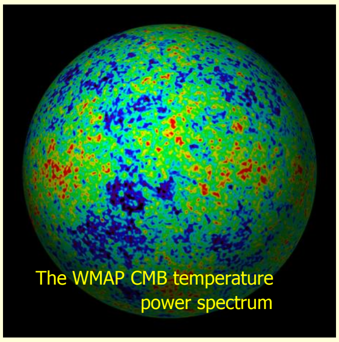

# Peaks and Lambda

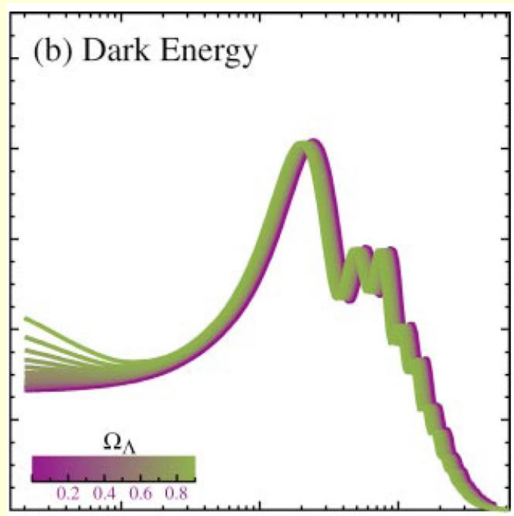



Changing dark energy (at fixed curvature) only slight change.

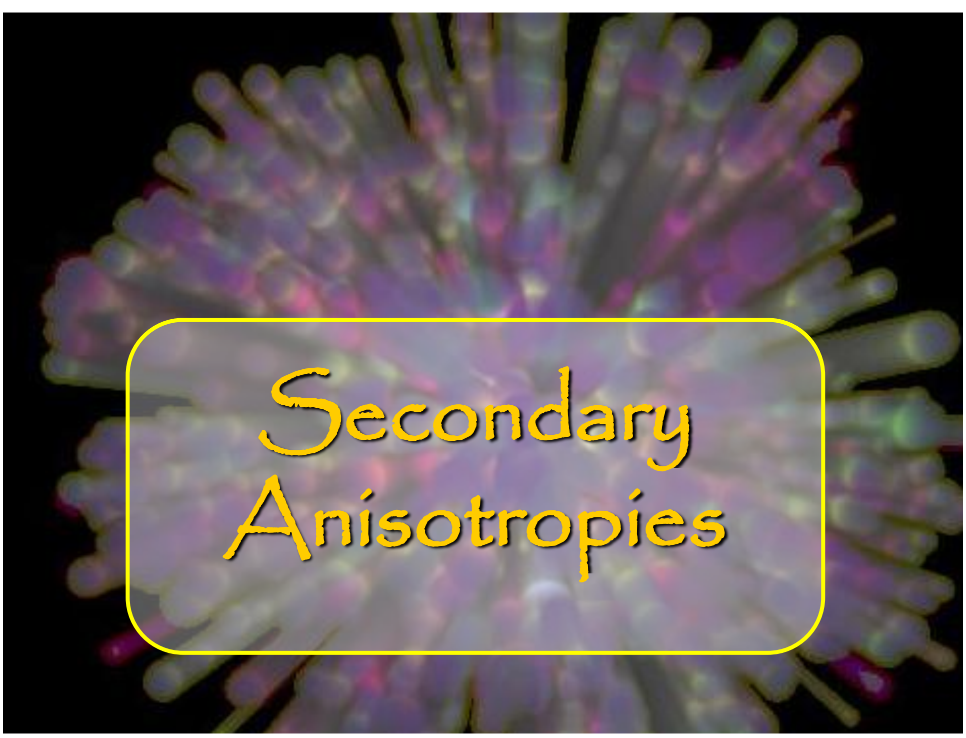
- Location and height of acoustic peaks
  - determine values of cosmological parameters
- Relevant parameters
  - curvature of Universe (e.g. open, flat, closed)
  - dark energy (e.g. cosmological constant)
  - amount of baryons (e.g. electrons & nucleons)
  - amount of matter (e.g. dark matter)

# Dark Energy: CMB

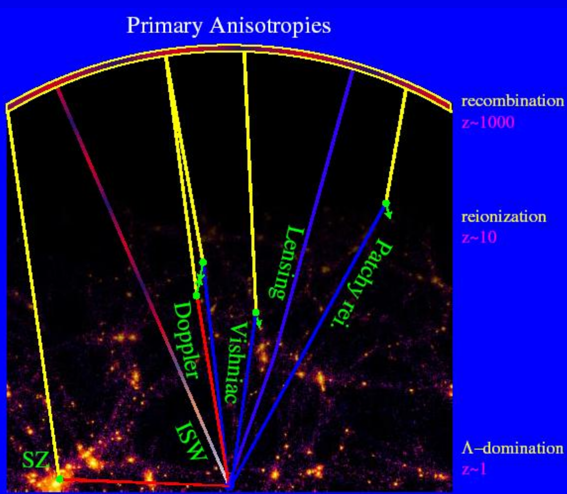



Dark Energy modifies evolution potential wells



# The CMB after Last Scattering

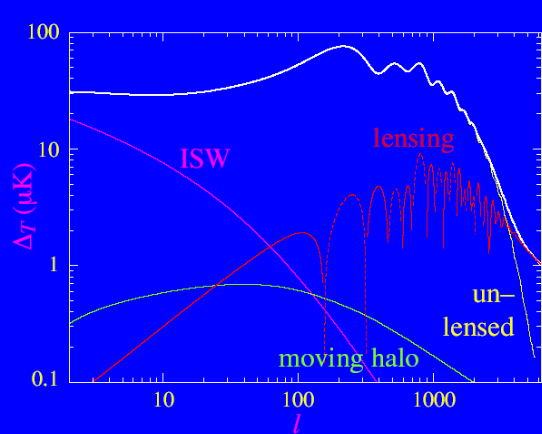



Secondary Anisotropies from propagation and late-time effects

Courtesy Wayne Hu – *http://background.uchicago.edu*

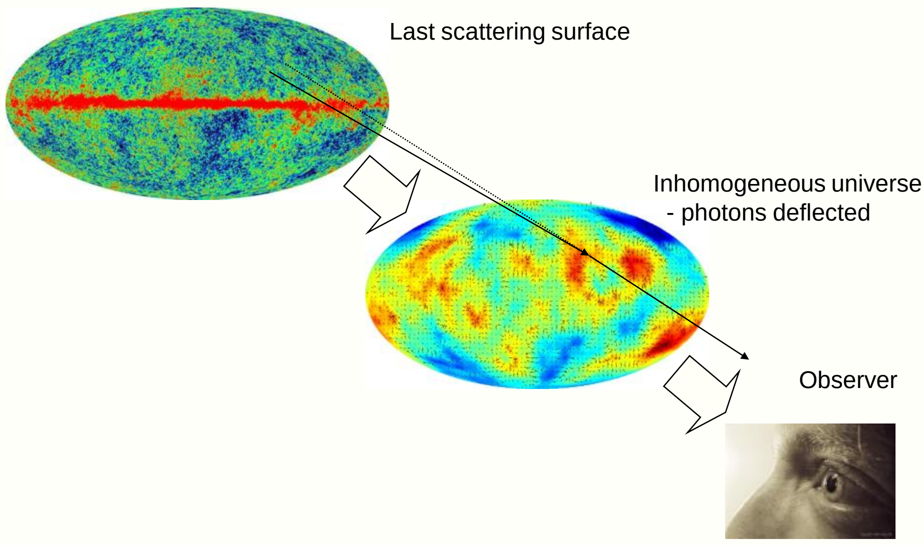
# Gravitational Secondaries

- Due to CMB photons passing through potential fluctuations (spatial and temporal)
- Includes:
  - Early ISW
    - (decay, matter-radiation transition at last scattering)
  - Late ISW
    - (decay, in open or lambda model)
  - Rees-Sciama
    - (growth, non-linear structures)
  - Tensors (gravity waves)
  - Lensing (spatial distortions)



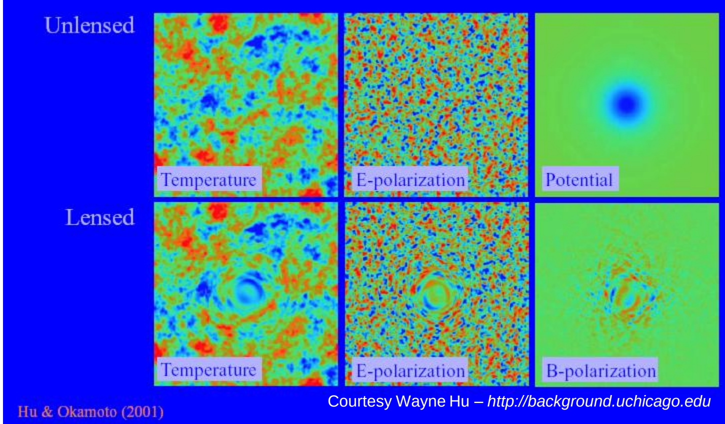

Courtesy Wayne Hu – *http://background.uchicago.edu*

# Weak lensing of the CMB




# CMB Lensing

- Distorts the background temperature and polarization
- Converts E to B polarization
- Can reconstruct from T,E,B on arcminute scales
- Can probe clusters

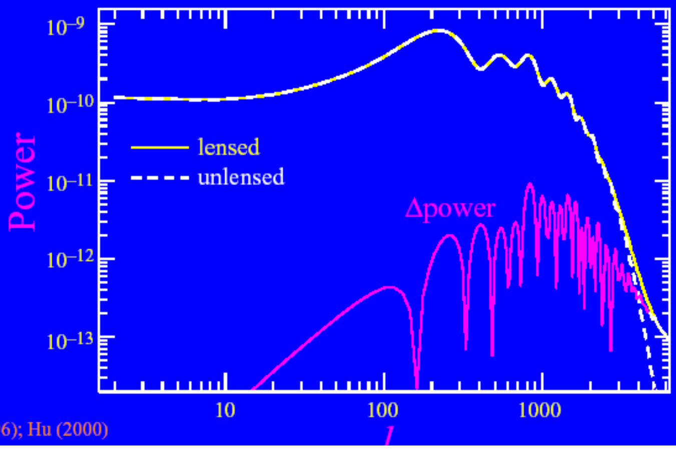



Courtesy Wayne Hu – *http://background.uchicago.edu*

# CMB Lensing

- Distorts the background temperature and polarization
- Converts E to B polarization
- Can reconstruct from T,E,B on arcminute scales
- Can probe clusters

Courtesy Wayne Hu – *http://background.uchicago.edu*



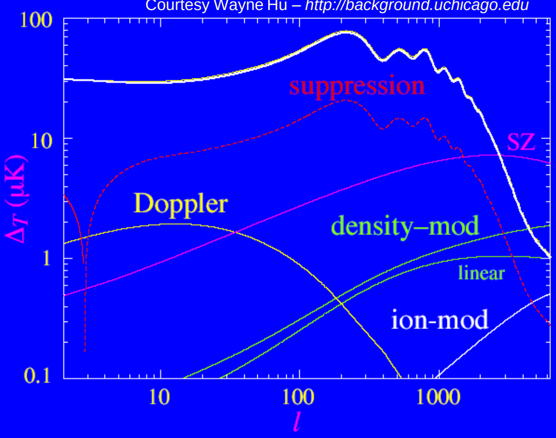

Seljak (1996); Hu (2000)

# Scattering Secondaries

Due to variations in:

- Density
  - Linear = Vishniac effect
  - Clusters = thermal Sunyaev-Zeldovich effect
- Velocity (Doppler)
  - Clusters = kinetic SZE
- Ionization fraction
  - Coherent reionization suppression
  - "Patchy" reionization

Courtesy Wayne Hu – *http://background.uchicago.edu*

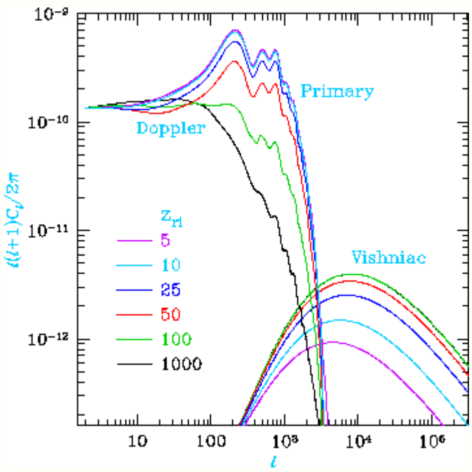



$$\frac{\Delta T}{T}(\hat{n}) = \int dx\,(n_e \sigma_T e^{-\tau})\,\hat{n}\cdot\mathbf{v}(\mathbf{x},z)$$

$$n_e = X_e n_p = \bar{X}_e \bar{n}_p (1 + \delta_x + \delta_b)$$

# Ostriker-Vishniac Effect

- Reionization + Structure
  - Linear regime
  - Second order (not cancelled)
  - Reionization supresses large angle fluctuations but generates small angle anisotropies




# Reionization

Late reionization reprocesses CMB photons

- Suppression of primary temperature anisotropies
  - as exp(-τ)
  - degenerate with amplitude and tilt of spectrum
- Enhancement of polarization
  - low ℓ modes E & B increased
- Second-order conversion of T into secondary anisotropy
  - not shown here
  - velocity modulated effects
  - high ℓ modes

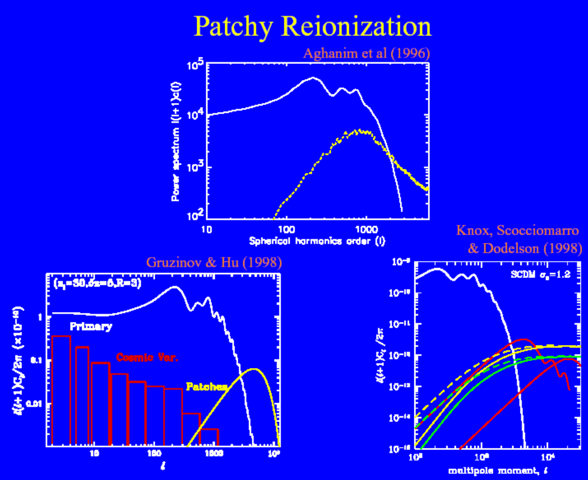
# Patchy Reionization

Structure in ionization

- Can distinguish between ionization histories
- Confusion, e.g. kSZ effec
- e.g. Santos et al. (030547

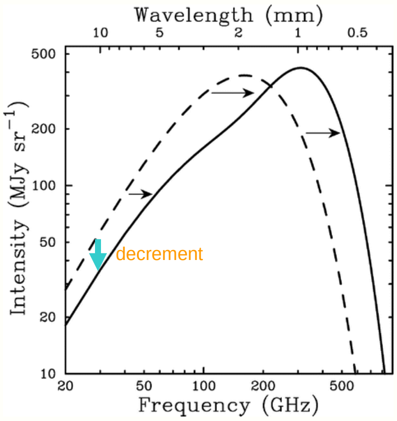
Effects similar

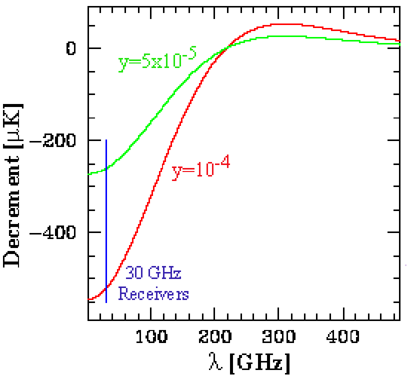
- kSZ, OV, PRel
- Different z's, use lensing?




# Sunyaev-Zel'dovich Effect

- Compton upscattering of CMB photons by keV electrons
- decrement in I below CMB thermal peak (increment above)
- negative extended sources (absorption against 3K CMB)
- massive clusters mK, but shallow profile $\theta^{-1} \rightarrow$ -exp(-v)




# SZE vs. X-rays

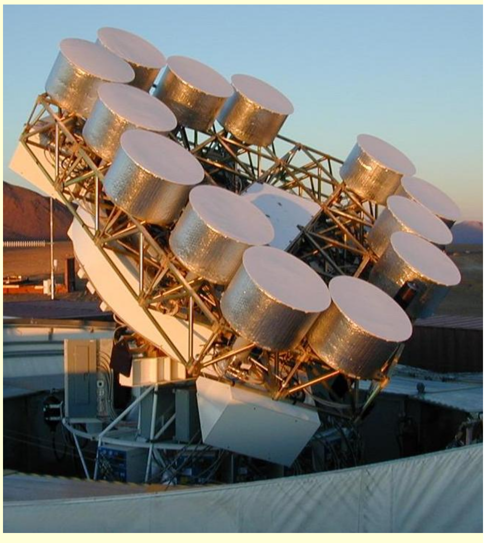
- gas density profiles: $n_e(r) = n_{e0}\left(1 + \frac{r^2}{r_0^2}\right)^{-3\beta/2}$
- X-ray surface brightness: $b_X(E) = \frac{1}{4\pi(1+z)^3}\int n_e^2(r)\Lambda(E, T_e)\,dl$
- SZE surface brightness: $\Delta I_{\rm SZE} \propto T_e \int n_e\,dl$
- exploit different dependence on parameters:
- use X-ray: $b_X \propto n_{e0}^2 \theta_0 D_A \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-3\beta+1/2}$

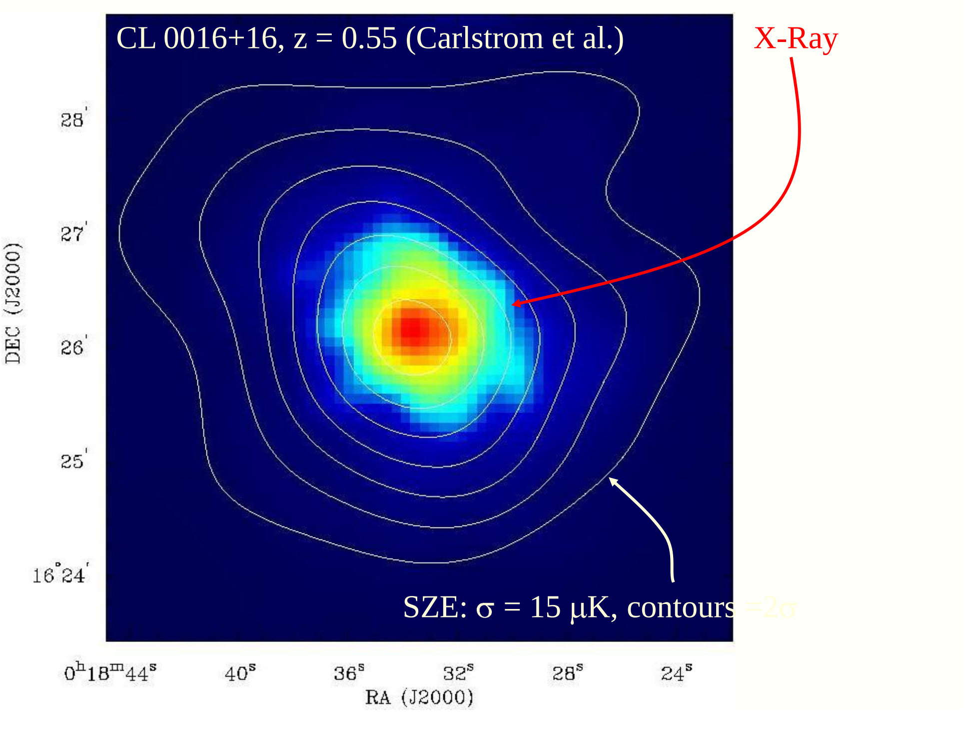
  $D_A \sim h^{-1}$  $n_{e0} \sim h^{1/2}$
- plug into SZE: $\Delta I_{\rm SZE} \propto T_e n_{e0} \theta_0 D_A \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}}$

  $\Delta I_{SZE} \sim h^{-1/2}$

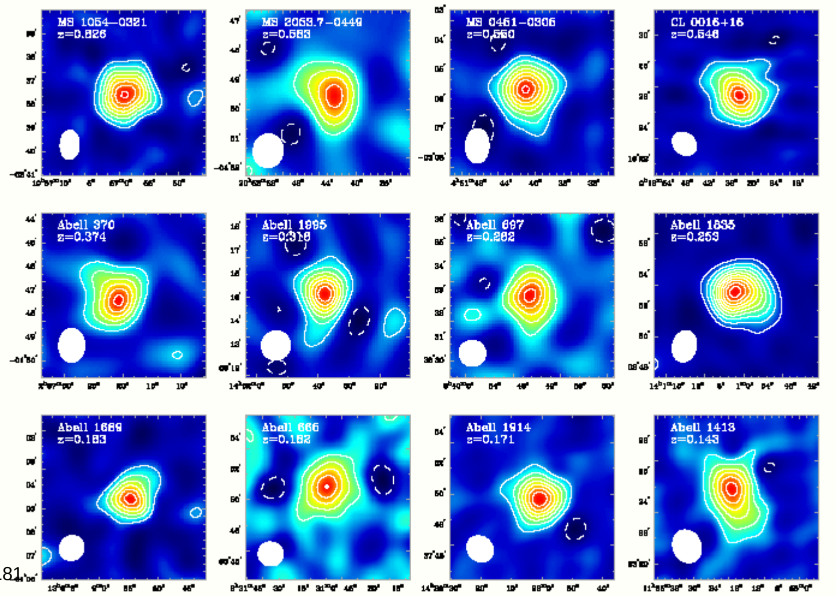
# CBI

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys 20 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin





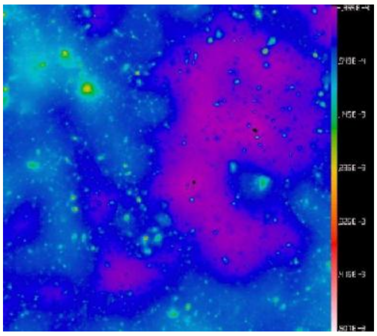
**Sample from 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03**

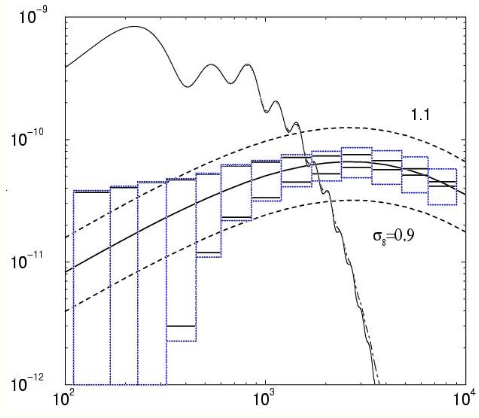



181

# Sunyaev-Zeldovich Effect (SZE)

- Spectral distortion of CMB
- Dominated by massive halos (galaxy clusters)
- Low-z clusters: ~ 20'-30'
- z=1: ~1' → expected dominant signal in CMB on small angular scales
- Amplitude highly sensitive to $\sigma_8$



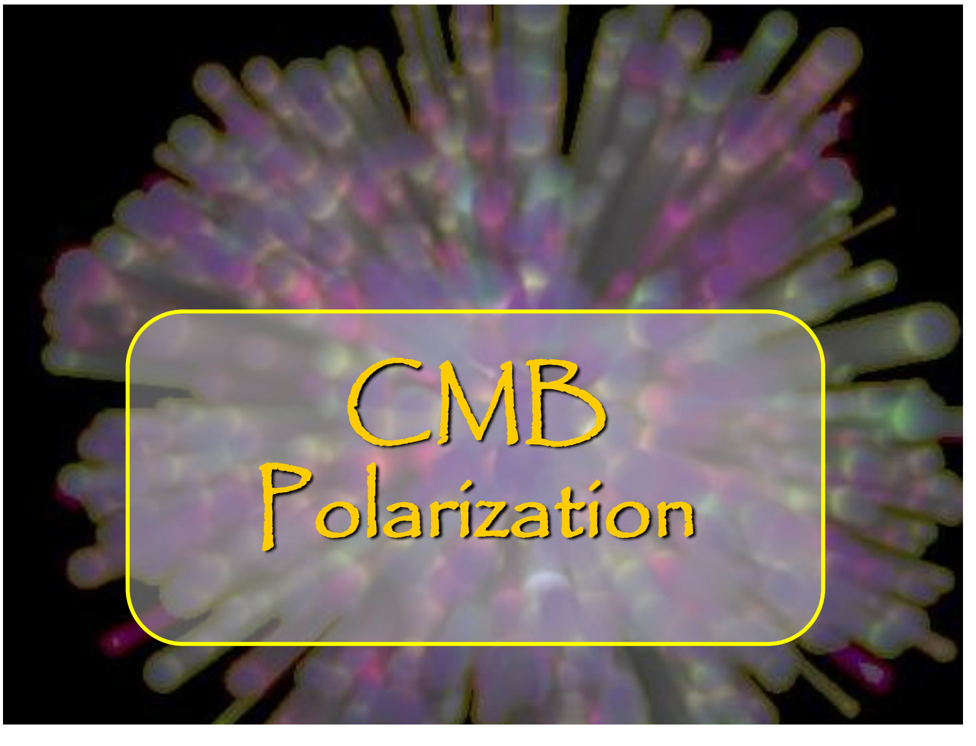



A. Cooray (astro-ph/0203048)

P. Zhang, U. Pen, & B. Wang (astro-ph/0201375)

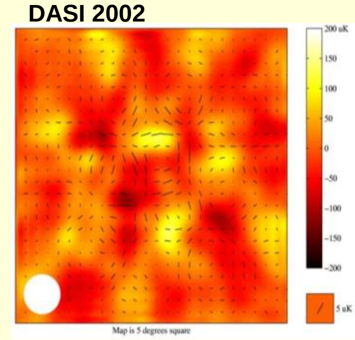
# Secondary Effects

- Sunyaev-Zel'dovich Effect
- Gravitational Lensing CMB
- Reionization: polarization
- Integrated Sachs-Wolfe Effect
- Rees-Sciama Effect
- Vishniac Effect
- ....



# Why measure CMB Polarization?

DASI 2002



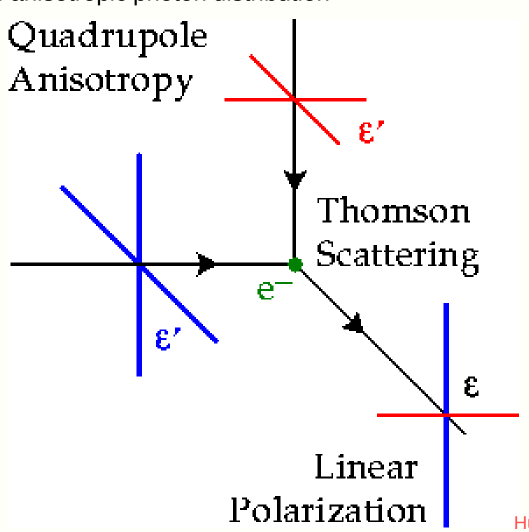

- scalar, vector & tensor fields carry more information than the temperature anisotropies alone.
- gives us more information about the acoustic peaks

→ measure cosmo parameters better

- measure the reionization epoch, which produces a large degeneracy in the Temp spectrum
- measure gravity wave amplitude… the smoking gun of inflationary models.

# CMB Polarization

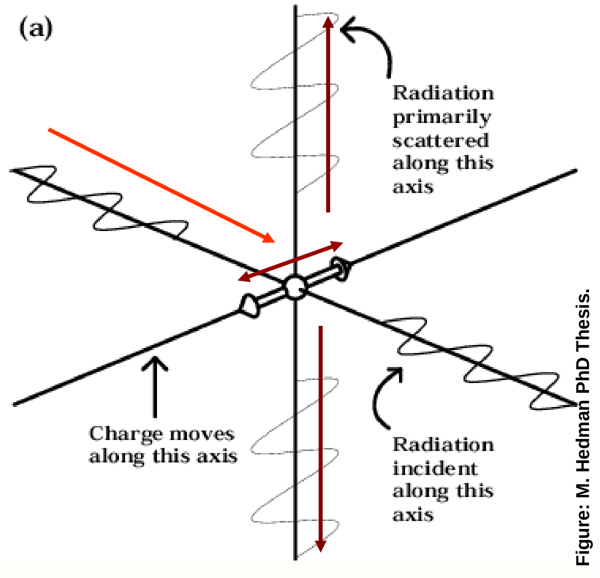
Generated during last scattering (and reionization) by Thomson scattering of anisotropic photon distribution




Hu astro-ph/9706147

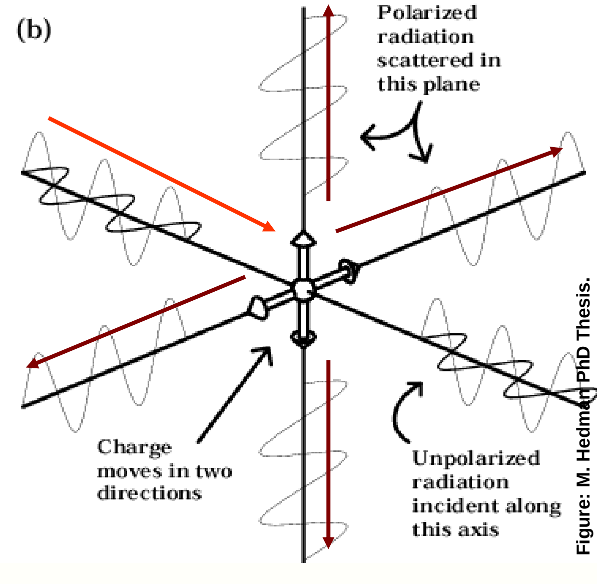
# Thomson Scattering & Polarization

- Incoming polarized light emerges polarized.




# Thomson Scattering & Polarization

- A plane wave undergoing Thomson scattering produces polarized light too.
- but if equal amounts of light coming from all directions, there is no net polarization.



# Thomson Scattering & Polarization

- Incoming polarized light emerges polarized.
- A plane wave undergoing Thomson scattering produces polarized light too.
- if we have equal amounts of light coming from all directions, there is no net polarization

- but if different intensities of quadrupole (unpolarized) light arrive from different directions, the net result is polarization. (10% of ΔT)

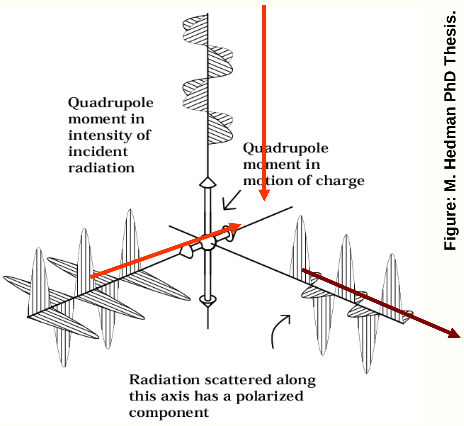



Figure: M. Hedman PhD Thesis.

# Thomson Scattering & Polarization

- Incoming polarized light emerges polarized.
- A plane wave undergoing Thomson scattering produces polarized light too.
- but if we have equal amounts of light coming from all directions, there is no net polarization.

- but if different intensities of quadrupole (unpolarized) light arrive from different directions, the net result is polarization. (10% of ΔT)

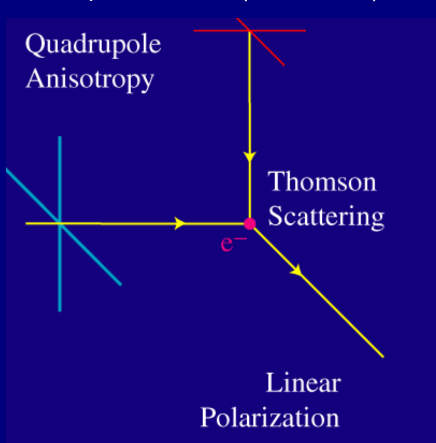
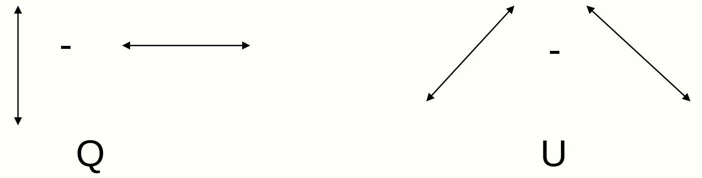



Figure: W. Hu doctored by G. Smoot

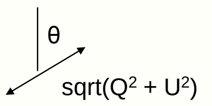
# Polarization: Stokes' Parameters




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

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

⇒ Spin-2 field Q + i U
or Rank 2 trace free symmetric tensor $P = \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}$




$\theta = ½ \tan^{-1} U/Q$

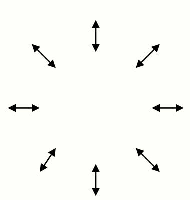
# E and B polarization

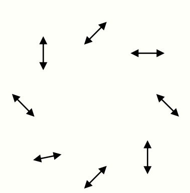
$$\mathcal{P}_{ab} = \nabla_{\langle a}\nabla_{b\rangle} P_E - \epsilon^c{}_{(a}\nabla_{b)}\nabla_c P_B$$

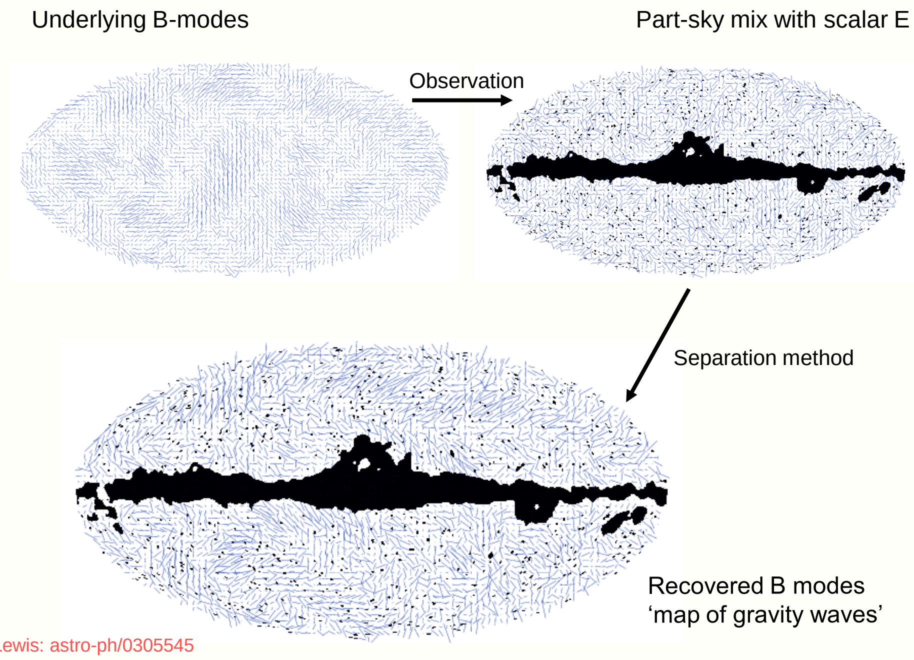
"gradient" modes
E polarization

"curl" modes
B polarization

e.g.








Lewis: astro-ph/0305545

# E and B harmonics

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

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

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

Harmonics are orthogonal over the full sky:

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

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

# CMB Polarization Signals

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

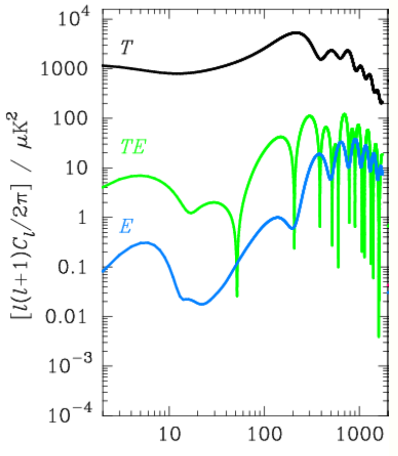
Average over possible realizations (statistically isotropic):

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

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

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

# Scalar adiabatic mode




E polarization only

correlation to temperature T-E

# Polarization CMB

Richest Source of Information on Primordial Universe:

Two modes:

E-mode: Doppler motions recombination
Reionization

B-mode: Gravitational Lensing
Primordial (Inflationary) Gravitational Waves

# CMB Polarization