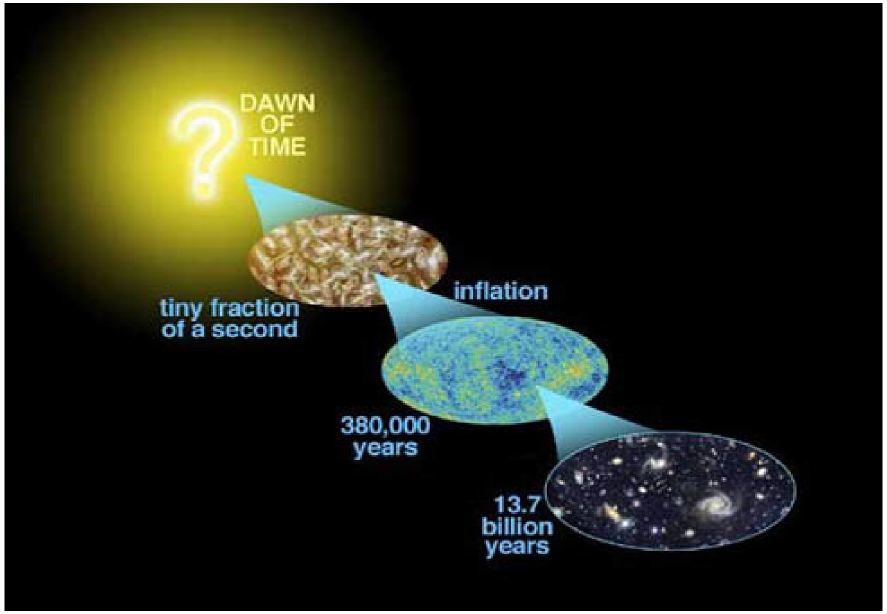
Plan of Lectures

1. Introduction to Standard Cosmology	Brief History of the Universe FRW cosmology Thermodynamics in the Expanding Universe
2. The Early Universe Phenomenology	Inflation Big Bang Nucleosynthesis Baryogenesis/Leptogenesis
3. CMB and Large Scale Structure of the Universe	Cosmic Microwave Backgrounds Baryon Acoustic Oscillations

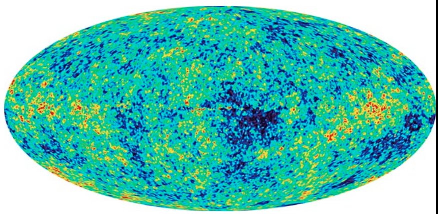
Outline

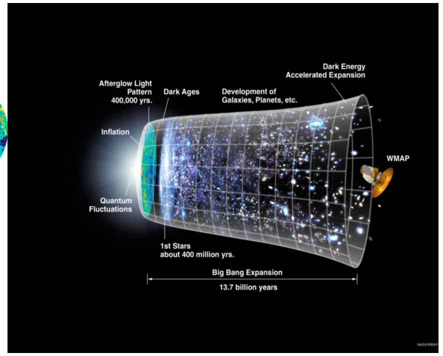


CMB and BAO

1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. Phase coherence
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations

CMB





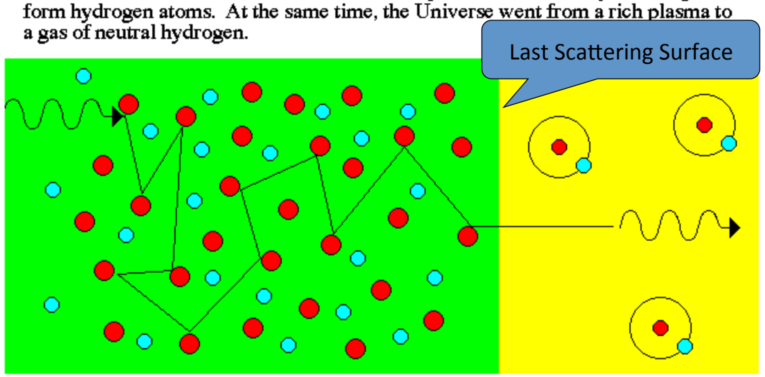
Cosmic Microwave Background

- Dominant component of current radiation energy
- Snapshot at 380,000 yrs after Big Bang (z~1100,T~0.1eV)

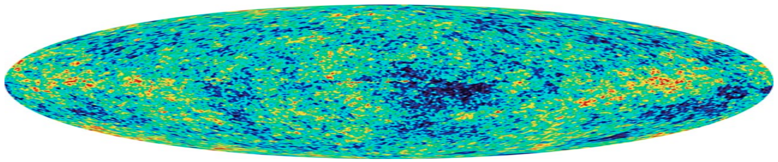
$$(n_\gamma \sim 410/cm^3, n_\nu \sim 340/cm^3, n_B \sim 2.5\times 10^{-7}/cm^3)$$

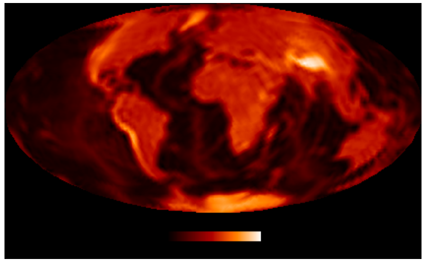
Last Scattering Epoch

As the Universe cooled, the free electrons and protons could finally bond togther to form hydrogen atoms. At the same time, the Universe went from a rich plasma to a gas of neutral hydrogen.

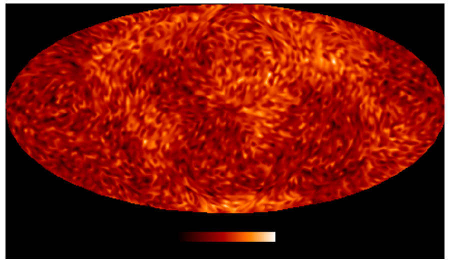


hydrogen plasma | atomic hydrogen

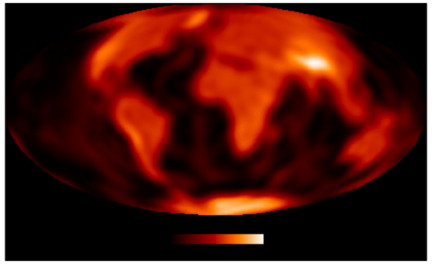




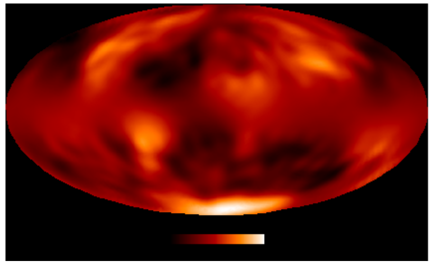
(World Map)



(With noise)



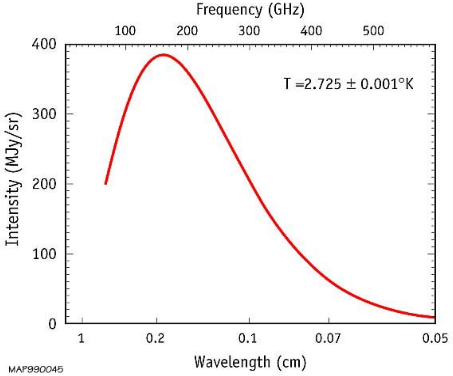
(7 degree resolution)

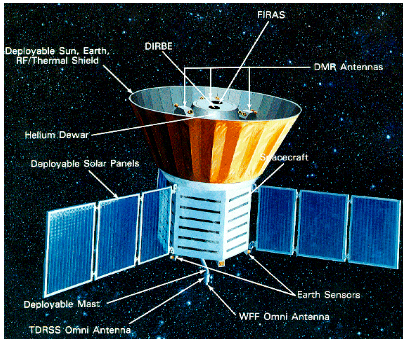


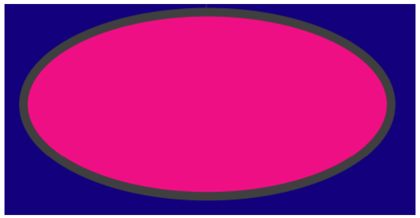
(Smoothed map to remove noises)

(taken from Wayne Hu's web page)

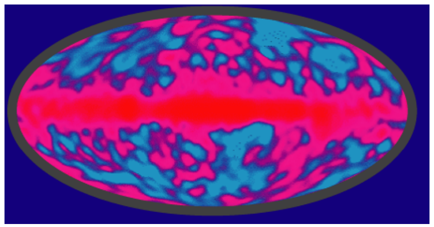
Spectrum of the Cosmic Microwave Background







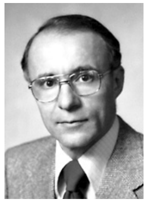
$\Delta T/T=10^{-3}$



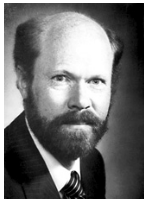
$\Delta T/T=10^{-5}$
(seeds structure formation of the Universe)

The Nobel Prize in Physics 1978

"for their discovery of cosmic microwave background radiation"



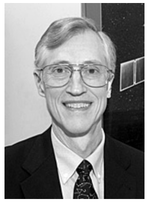
Arno Penzias



Robert Wilson

The Nobel Prize in Physics 2006

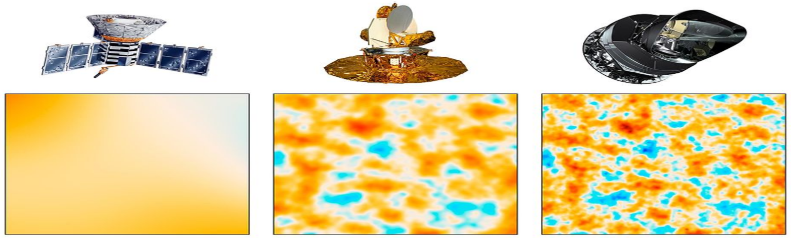
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



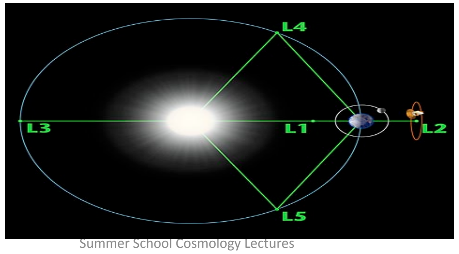
John C. Mather

George F. Smoot

COBE(launched 1989), WMAP(2001), Planck(2009)



COBE	WMAP	Planck
7 degree resolution	x 35 better	x 35 x 2.5 better



CMB and BAO

1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. Phase coherence
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations

$\boxed{C_l}$ CMB power spectrum

$$\boxed{\frac{\delta T}{T} = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}}$$

$$\langle a_{lm} \rangle = 0, \langle a_{lm} a^*_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l$$

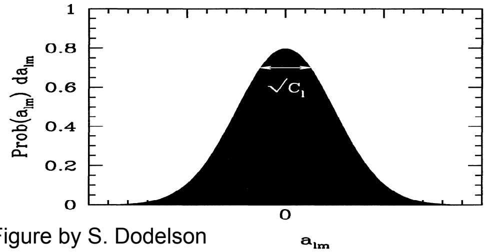


Figure by S. Dodelson

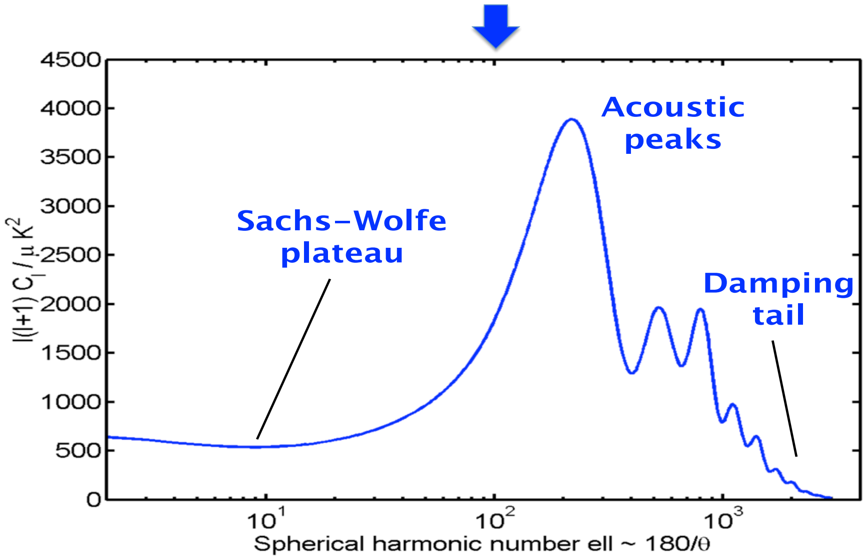
Variance of a_{lm}

$$\boxed{C_l = \frac{1}{2l+1} \sum_m \langle |a_{lm}|^2 \rangle}$$

$$\boxed{\left\langle \frac{\delta T(\hat{e}_1)}{T} \frac{\delta T(\hat{e}_2)}{T} \right\rangle = \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos\theta)}$$

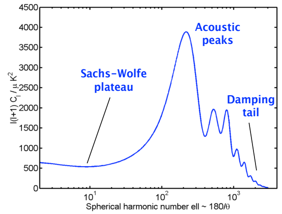
$$\boxed{P_l = \frac{4\pi}{2l+1} \sum_{m=-l}^{l} Y_{lm} Y^*_{lm}}$$

Horizon size at LSS (z~1100)~2 degrees (ell ~200)



Sachs-Wolf effect

CMB Photons get redshifted



$$\text{SWE}: C_l \sim \frac{4\pi}{25}\int_0^\infty \frac{dk}{k} P_R(k)\, j_l(kx)^2$$

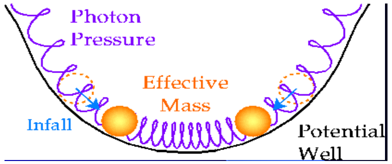
The primordial power spectrum $P_R(k) = A^2 k^{n-1}$

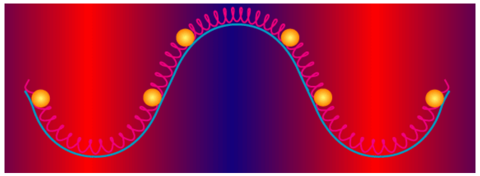
$n=1$ for the scale invaraint (Harrison-Zel'dovich) power spectrum

$$\int_0^\infty \frac{dk}{k} P_R(k)\, j_l(kx)^2 = \frac{1}{2l(l+1)} \Rightarrow \text{SWE}: \frac{l(l+1)}{2\pi} C_l = const$$

CMB Acoustic Oscillations

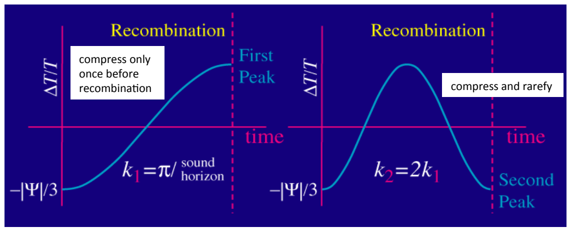
Harmonic oscillation of baryon-photon fluid.
Baryons falls into gravitational potential well against the radiation pressure

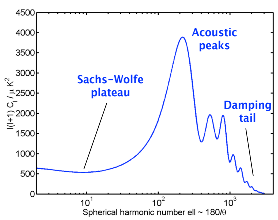




Temperature fluctuations at the bottom of potential well

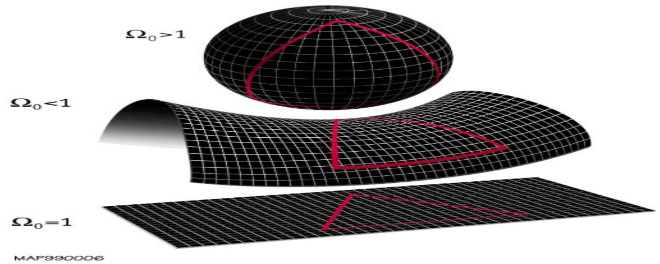
(figures from W. Hu)

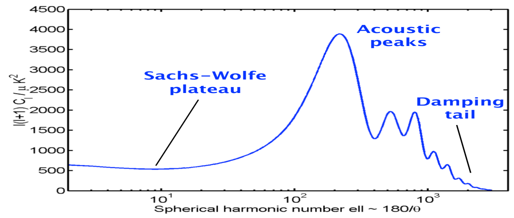


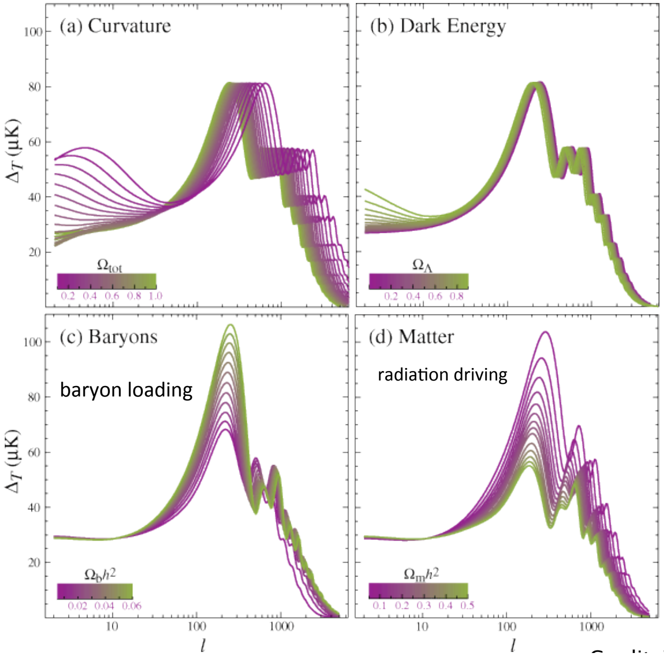


(NB: In CMB literature, "baryons" include electrons, e.g. "photon-baryon fluid")

How do the CMB power spectrum get affected by the cosmological parameters?



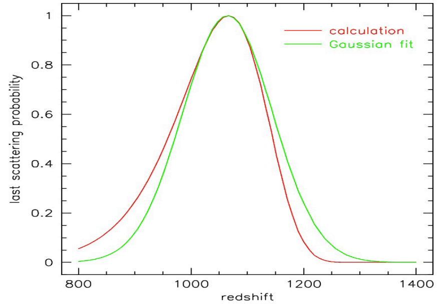




Hu&Dodelsor

Damping tail

Last scattering not instantaneous: ~ 10Mpc,Δz ~ 80



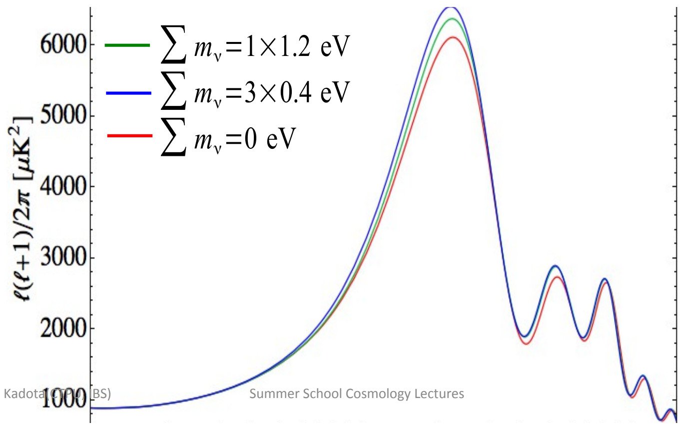
Fluctuations with the wave length comparable
to photon mean free path are damped

Silk damping (photon diffusion) at ell above about 2000

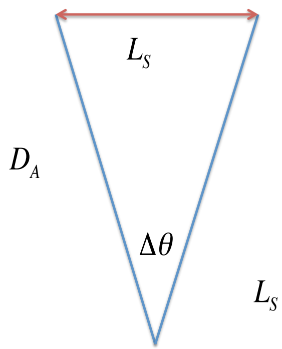
-Exercise: what are the effects of neutrinos on CMB?

-Exercise: calculate the sound horizon at z=1100
(the distance traveled by the sound wave $c_s dt$)

-Exercise: what are the effects of massive neutrinos on primary CMB?



-Exercise: calculate the sound horizon at z=1100: distance traveled by the sound wave $c_s dt$



$$\Delta\theta = \frac{L_S}{D_A} \sim 0.8^\circ$$

Reminder: Angular diameter distance d_A
In the flat Universe, it is just the physical distance.
d_A involves the integral of 1/H(z).

$$L_S \sim c_S(= c/\sqrt{3})t(z_R \approx 1100) \sim 100kpc$$

This horizon scale gets stretched to ~100 Mpc today (~100kpc*1100)

distance traveled by the sound wave $c_s dt$

$$x = 1+z \qquad c_S = c/\sqrt{3}$$

$$x_0 = \frac{\Omega_M}{\Omega_R} \sim 3500\left(\frac{\Omega_M}{0.3}\right)$$

$$L_S(t_R) = a(t_R)\int_0^{t_R}\frac{c_S dt}{a(t)} = \frac{c_S}{(1+z)}\int_{z_R}^{\infty}\frac{dz}{H(z)}$$

$$= \frac{c_S}{(1+z)H_0}\int_{z_R}^{\infty}\frac{dz}{\sqrt{\Omega_R(1+z)^4+\Omega_M(1+z)^3+\Omega_\Lambda+(1-\Omega_0)(1+z)^2}}$$

$$\sim \frac{c_S}{(1+z)H_0}\int_{z_R}^{\infty}\frac{dz}{\sqrt{\Omega_R(1+z)^4+\Omega_M(1+z)^3}}$$

$$= \frac{c_S}{(1+z)H_0}\int_{1+z_R}^{\infty}\frac{dx}{\sqrt{x^3(x+x_0)}} = \frac{c_S}{(1+z)H_0\sqrt{\Omega_R}}\left(-\frac{2}{x_0}\sqrt{1+\frac{x_0}{x}}\right)_{1+z}^{\infty}$$

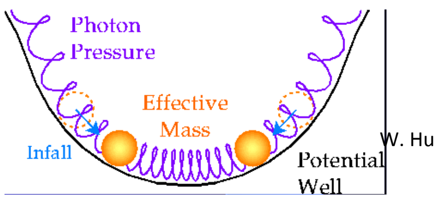
$$= 3.4\times 10^{-5}\frac{c}{H_0} \sim 110\frac{0.7}{h}\left(\frac{0.3}{\Omega_M}\right)^{1/2} kpc$$

This scale is stretched by 1+z=1100 to ~ 120 Mpc today

$$\theta = \frac{L_S(z)}{D_A(z)} = \frac{\int_{1+z}^{\infty}\frac{c_S dx}{H(x)}}{a_0\int_1^{1+z}\frac{c\,dx}{H(x)}} \sim 0.8^\circ$$

for the flat universe

$$\theta \sim \frac{r_s}{d_A}, r_s = 150Mpc(\sim 100Mpc/h)$$

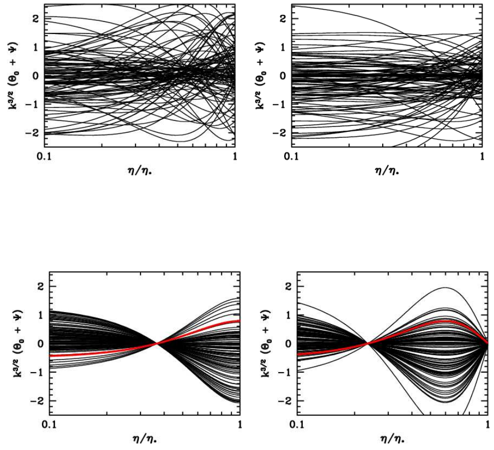


Sound horizon: the distance that sound can travel in baryon-photon fluid

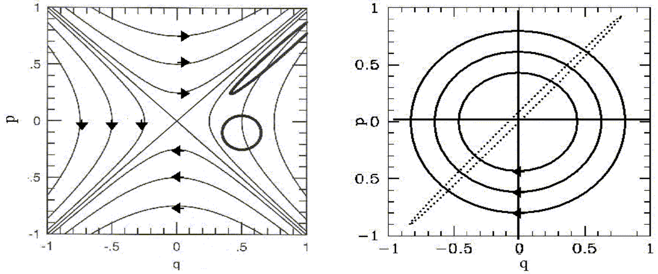
Harmonic oscillation of baryon-photon fluid.
Photon oscillation -> CMB
Baryon oscillation -> BAO imprinted into matter

CMB and BAO

1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. $\boxed{\text{Phase coherence}}$
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations



Cosmic Coherence

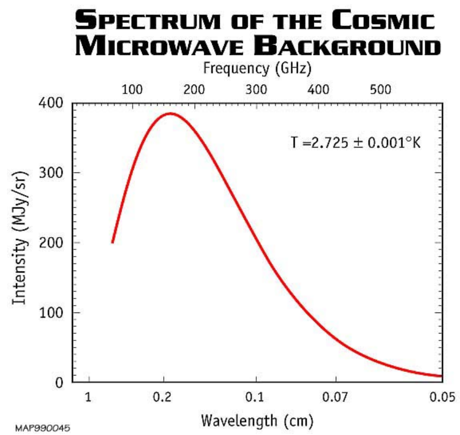


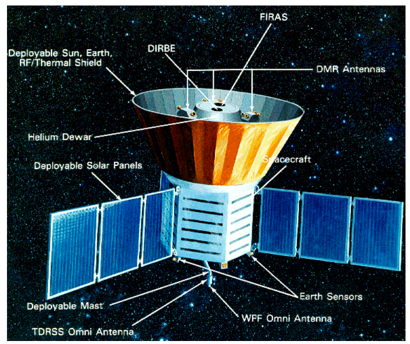
$$\ddot{q} = q \qquad\qquad \ddot{q} = -q$$

$$\ddot{\delta} - c_S^2 \nabla^2 \delta = F$$

CMB and BAO

1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. Phase coherence
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations

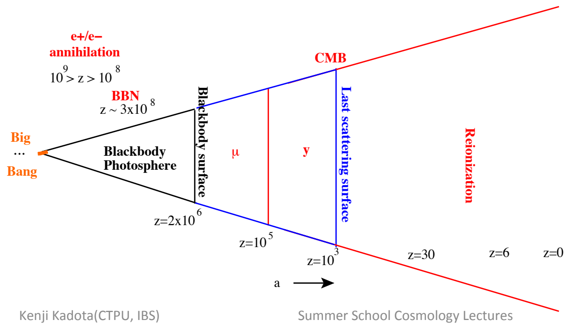




Thermal equilibrium:
Chemical equilibrium: Creation and destruction of photons
Kinetic equilibrium: Energy distribution by scattering

Radiative (double) Compton scattering: $e+\gamma \leftrightarrow e+\gamma+\gamma$
Bremsstrahlung: $e+N \leftrightarrow e+N+\gamma$
Compton scattering: $e+\gamma \leftrightarrow e+\gamma$

μ-type distortion: The number stays same but modifies the phase space distribution
y-type distortions: Kinematically decouple too, so it just adds energy shift

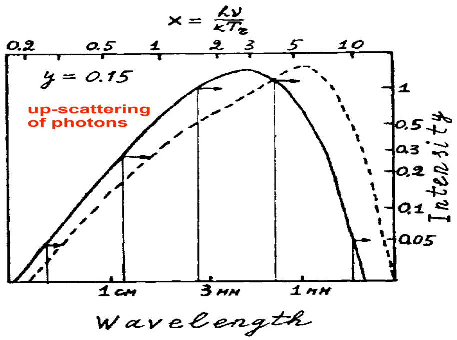


$$f = [e^{(E-\mu)/T} - 1]^{-1}$$

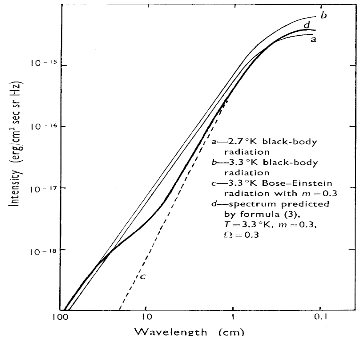
$$y \sim \sigma_T n_e k T_e$$

Khatri&Sunyaev'12

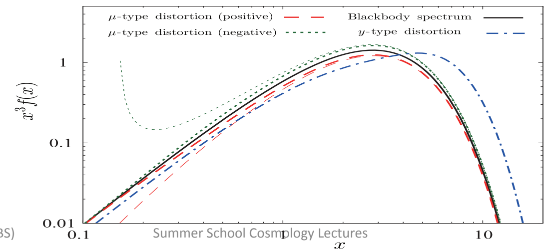
Figure 1. Important events in the history of the CMB spectrum and anisotropy formation in big bang cos-



Zeldovich, Sunyaev (1969)



Zeldovich, Sunyaev (1970)



Process	μ
electron-positron annihilation	10^{-178}
BBN tritium decay	2×10^{-15}
BBN ^{7}Be decay	10^{-16}
WIMP dark matter annihilation	$3\times10^{-9} f_\gamma \frac{10\mathrm{GeV}}{m_{\mathrm{WIMP}}}$
Silk damping	$10^{-8}-10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-2.7×10^{-9}

Khatri&Sunyaev'12

Table 1. Census of energy release and μ distortions in standard cosmological model. The negative distortion from adiabatic cooling of matter is shown in red.

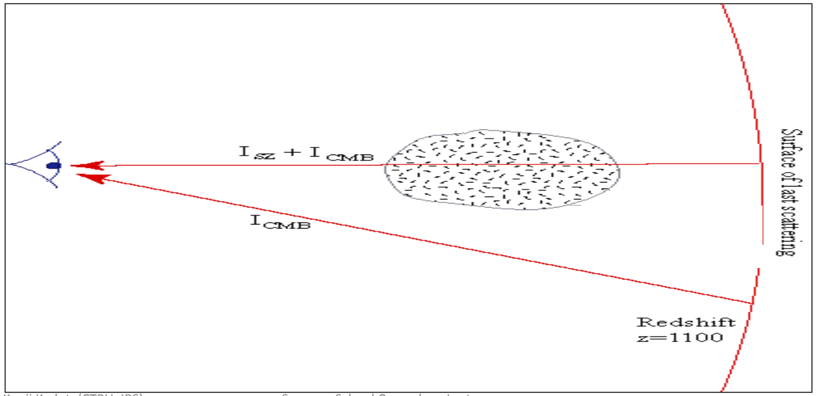
Process	y
WIMP dark matter annihilation	$6\times10^{-10} f_\gamma \frac{10\mathrm{GeV}}{m_{\mathrm{WIMP}}}$
Silk damping	$10^{-8}-10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-6×10^{-10}
Reionization	10^{-7}
Mixing of blackbodies: CMB $\ell \geq 2$ multipoles	8×10^{-10}

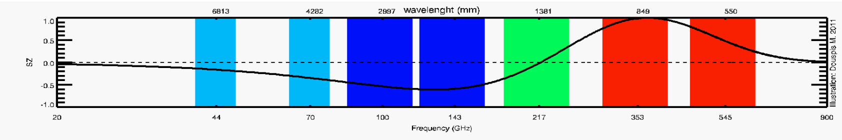
Table 2. Census of energy release and y distortions in standard cosmological model. We also give the value of y-type distortion expected from the mixing of blackbodies when averaging our CMB sky [53]. The negative distortion from adiabatic cooling of matter is shown in red. y type distortion is clearly dominated by the contributions, during and after reionization, from the intergalactic medium and clusters of galaxies, and the early Universe contributions are difficult to constrain.

Current limits $|\mu| < 9\times10^{-5}(95\%CL), y < 1.2\times10^{-5}(95\%CL)$

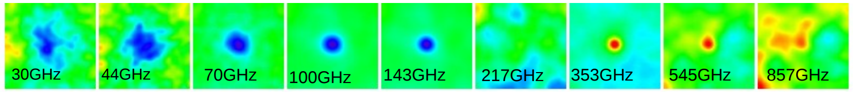
Suyaeve-Zel'dovich effect

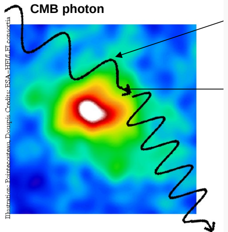
- Inverse Compton scattering: energy transfer from hot electrons(10^7-10^8K) to cool photons(3K)

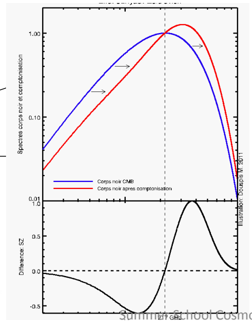


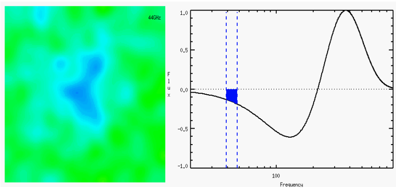


SZ Frequency dependence on stacks of clusters from *Planck*









Blind and simultaneous measurement of “positive” and “negative” SZ effect

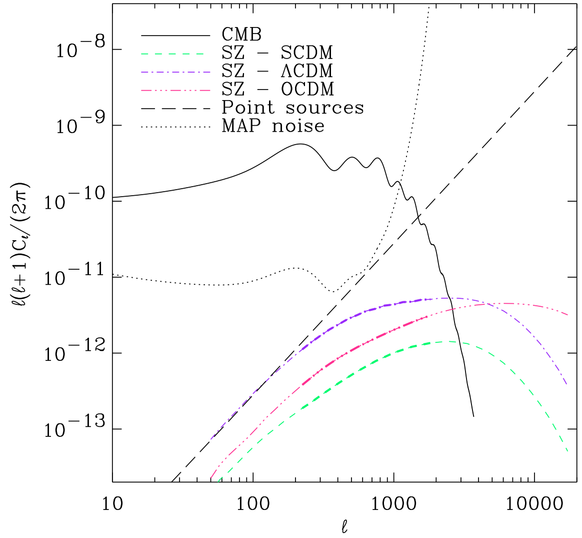
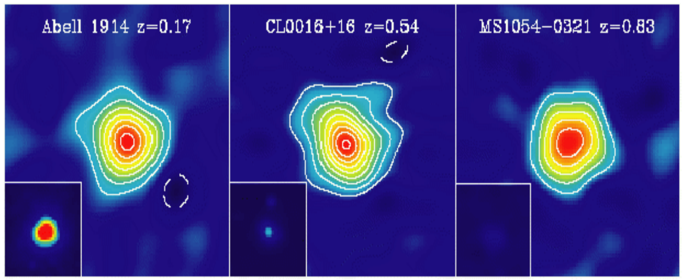


FIG. 8. Power spectrum of the SZ effect for each model in the RJ regime, as derived from the simulations. The approximate range of confidence ($200 < l < 2000$) is highlighted by thicker lines. The power spectra outside of this range should be taken as lower limits. For comparison, the primary CMB power spectrum is shown for the SCDM model. The 1σ uncertainty for the 94GHz map channel is shown, for a band average of $\Delta l = 10$. The power spectrum for the residual discrete sources (> 2Jy) for the 94 GHz MAP channel is also shown.

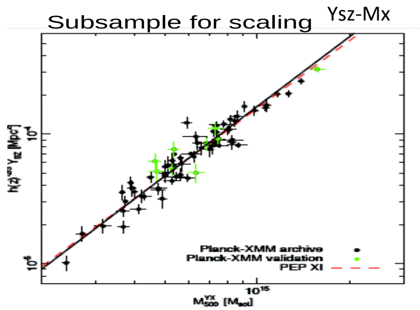
SZ- effect vs. X- ray emission

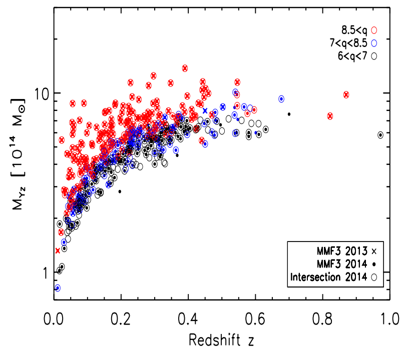
Differential surface brightness is independent of redshift.



Courtesy of J. Carlstrom et al.

e.g. Planck: A sample of 186
galaxy clusters of S/N>7.
1227 clusters&candidates
(683 previously known,
178 new clusters, 366 candidates)





1502.01597

CMB and BAO

1. CMB big picture

2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)

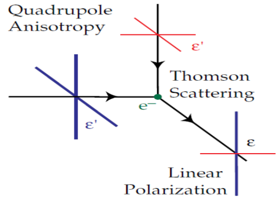
3. Phase coherence

4. CMB spectral distortion

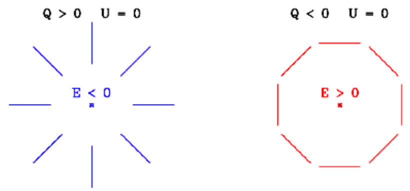
5. CMB Polarization

6. Matter power spectrum and Baryon Acoustic Oscillations

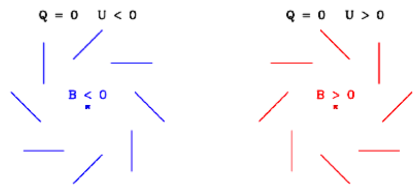
Polarization



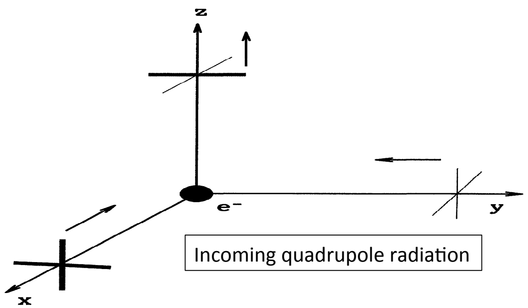
E-mode (curl-free, even under partiy)



B-mode (curl, odd under parityu)

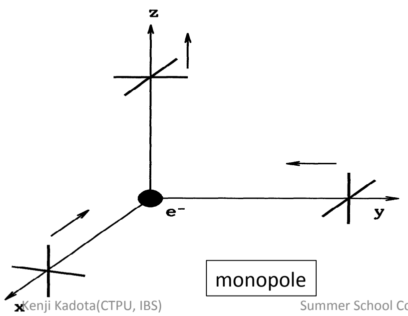


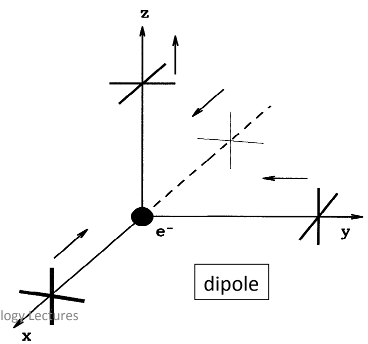
Scalar perturbation is parity even, leading to only E modes,
Tensor perturbations can produce both E and B modes

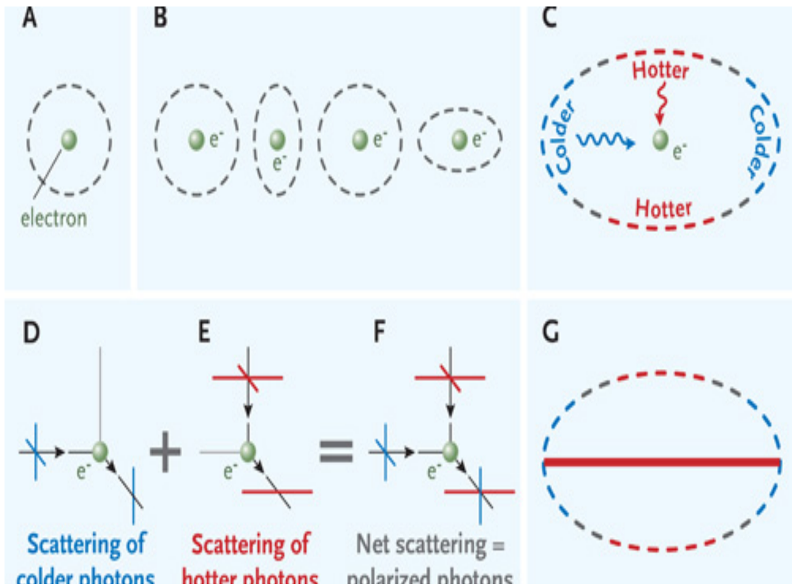


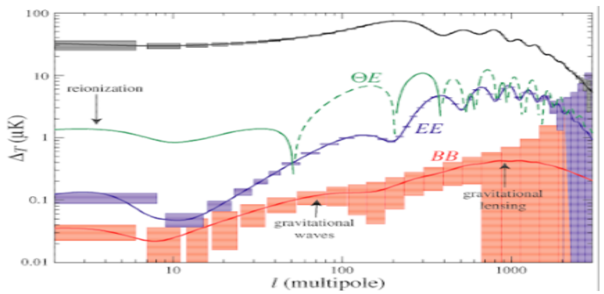
$$\frac{d\sigma_{thomson}}{d\Omega} \propto |\hat{\varepsilon} \bullet \hat{\varepsilon}'|$$

(figures from
Scott Dodelson)



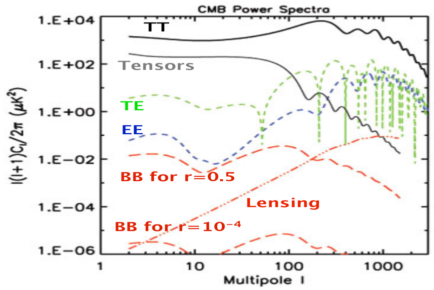


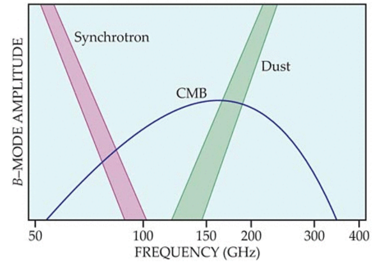




TB, EB vanishes because of the opposite parity
Negative TE cross correlation due to opposite phase

B mode

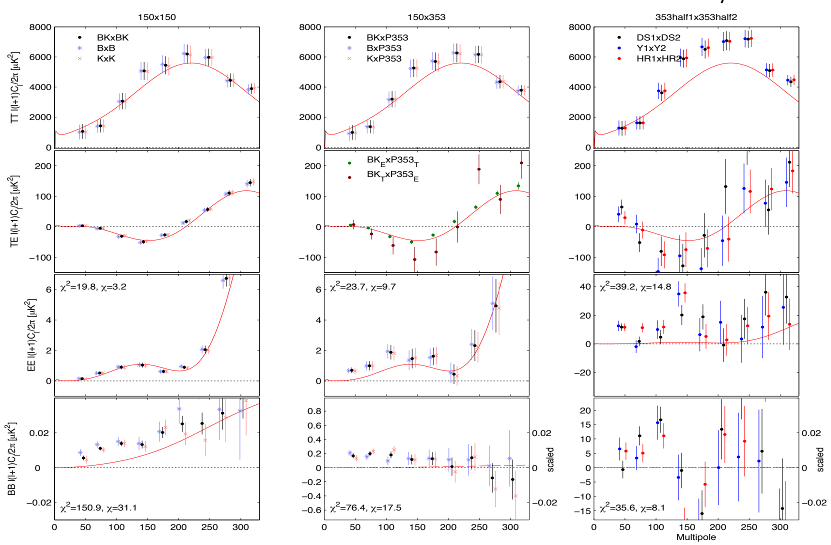




$$\boxed{\sqrt{l(l+1)C_B/2\pi} = 0.024(E_{\rm inf}/10^{16}GeV)\mu K}$$

Planck x Bicep x Keck (2015)

350 GHz should be dominated by the dust

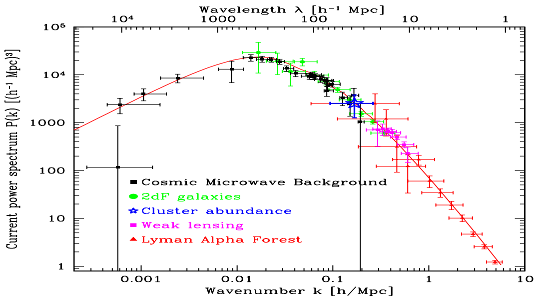


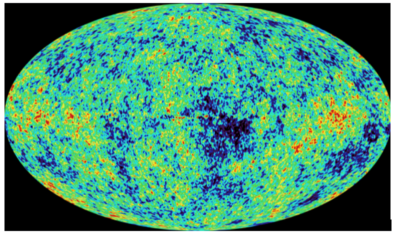
CMB and BAO

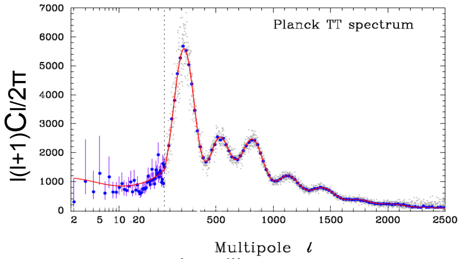
1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. Phase coherence
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations

Reminder: Two-point correlation function and power spectrum.

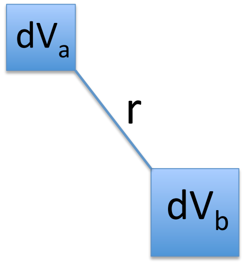
$P(\boldsymbol{k}): LSS$
$C(\boldsymbol{l}): CMB$







l ~ π/θ



Two point correlation function ξ

representing the excess in the joint probability.

Joint probability of finding a pair of object with a separation r

$$P(\boldsymbol{r}) = n_a n_b[1+\xi_{ab}(\boldsymbol{r})]dV_a dV_b$$

Its Fourier transform is the Power spectrum

$$P(\boldsymbol{k}) = \int d^3 r \xi(\boldsymbol{r}) e^{i\boldsymbol{k}\cdot\boldsymbol{r}}$$

representing the spread, or the variance, in the distribution.

$$\langle \delta(\boldsymbol{k})\delta(\boldsymbol{k}')\rangle = P(\boldsymbol{k})\delta^3(\boldsymbol{k}-\boldsymbol{k}')$$

$$\xi(\boldsymbol{r}) = \langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r})\rangle$$

e.g. Matter density fluctuation: in terms of the density contrast: $\delta = \frac{\rho-\bar{\rho}}{\bar{\rho}}$

Temperature fluctuation in terms of the temperature: $\delta = \frac{T-\bar{T}}{\bar{T}}$

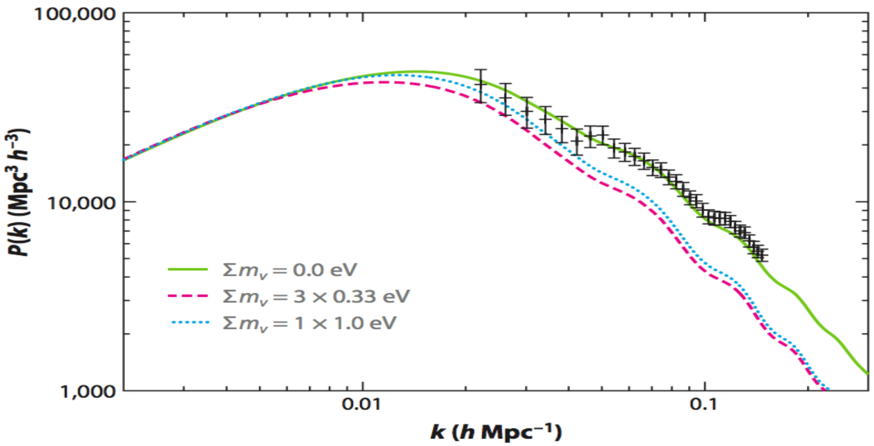
Galaxy distribution in terms of the number density: $\delta = \frac{n-\bar{n}}{\bar{n}}$

For the Gaussian statistics, two point correlations are all we need:

$\langle \delta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2)...\delta(\boldsymbol{k}_n)\rangle = 0$ for odd n

$\langle \delta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2)...\delta(\boldsymbol{k}_n)\rangle$ in terms of $P(k)$ for even n (Wick's theorem)

- Exercise: What are the effects of the neutrinos on matter power spectrum?



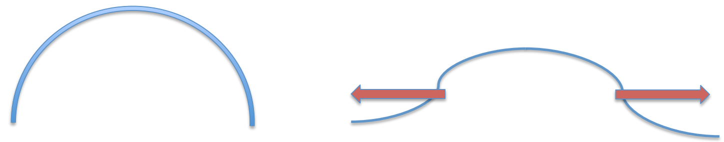
Free streaming scale

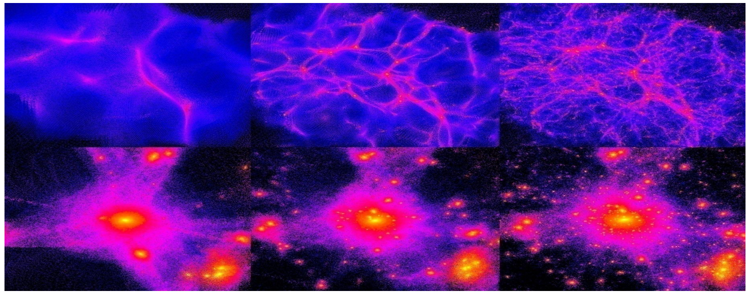
Free streaming length (c.f. Kolb and Turner)

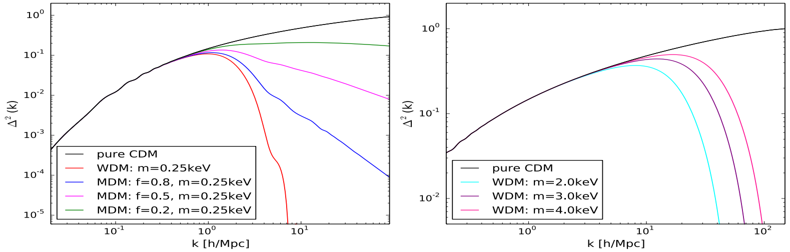
$$\lambda \equiv a(t_0)\int_{t_{dec}}^{t_0} dt v(t)/a(t) = a(t_0)a(t_{dec})v(t_{dec})\int_{t_{dec}}^{t_0} dt 1/a^2(t)$$

$$a \sim t^{1/2}, a \sim t^{2/3}$$

$$v(t_{dec}) \sim \sqrt{T(t_{dec})/m}$$

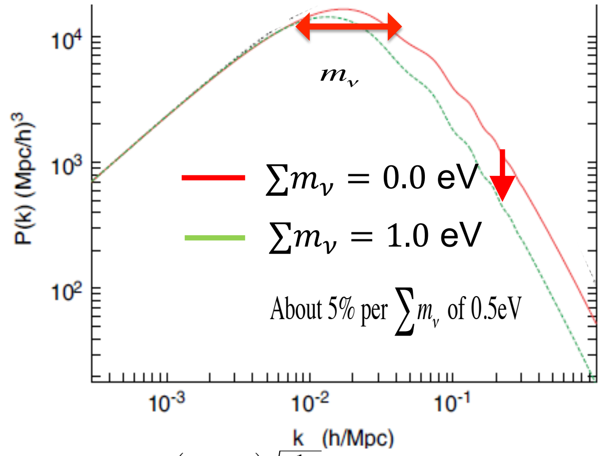






Schneider 1412.2133

Massive Neutrino effects on Large Scale Structure (c.f. Lesgourgues&Pastor 06)



$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

$$P \sim \langle \delta\delta \rangle$$

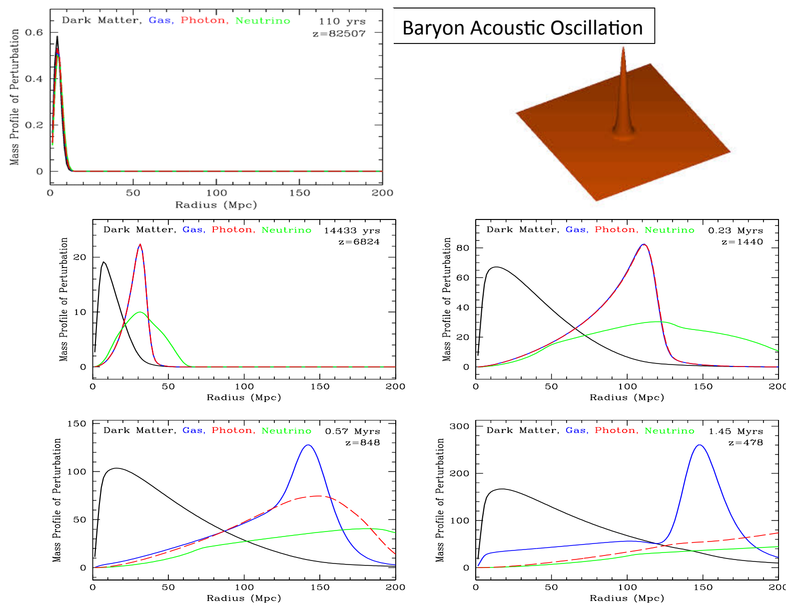
$$k_{fs} \sim 0.015/Mpc\left(\frac{m_\nu}{0.05eV}\right)\sqrt{\frac{1}{1+z}}$$

$$\delta \propto a^{1-3f_\nu/5}\,(f_\nu \equiv \Omega_\nu/\Omega_m)$$

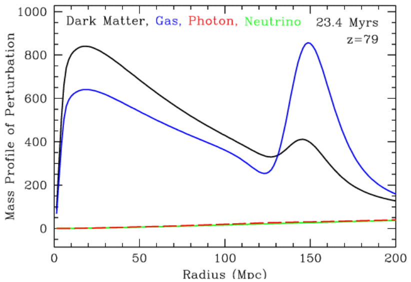
$$\frac{\Delta P}{P} \sim -8\frac{\Omega_\nu}{\Omega_m} \quad \text{(Hu et al 1998)}$$

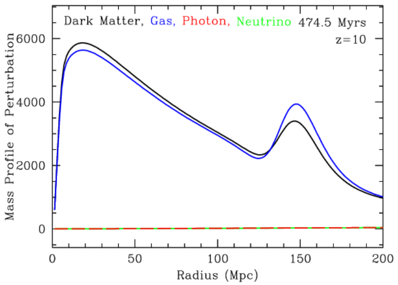
CMB and BAO

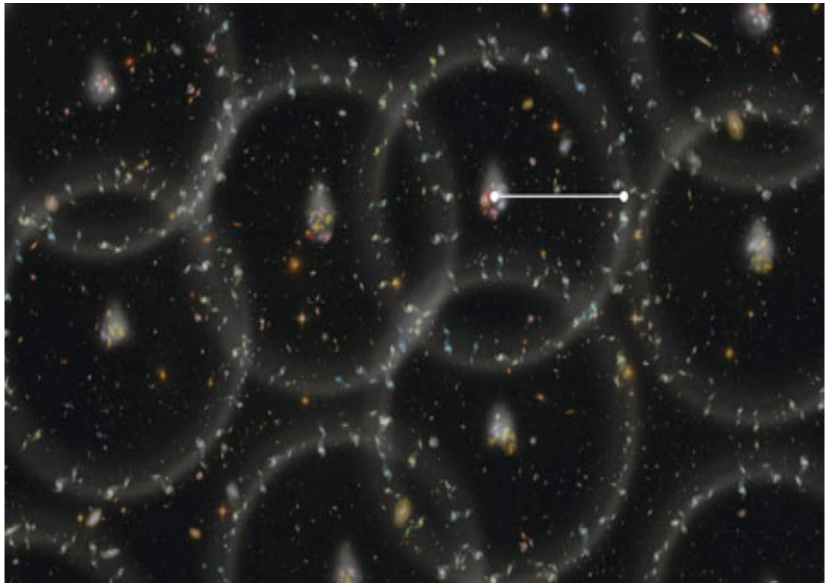
1. CMB big picture
2. CMB features
   (SW plateau, Acoustic oscillations, Silk damping)
3. Phase coherence
4. CMB spectral distortion
5. CMB Polarization
6. Matter power spectrum and Baryon Acoustic Oscillations



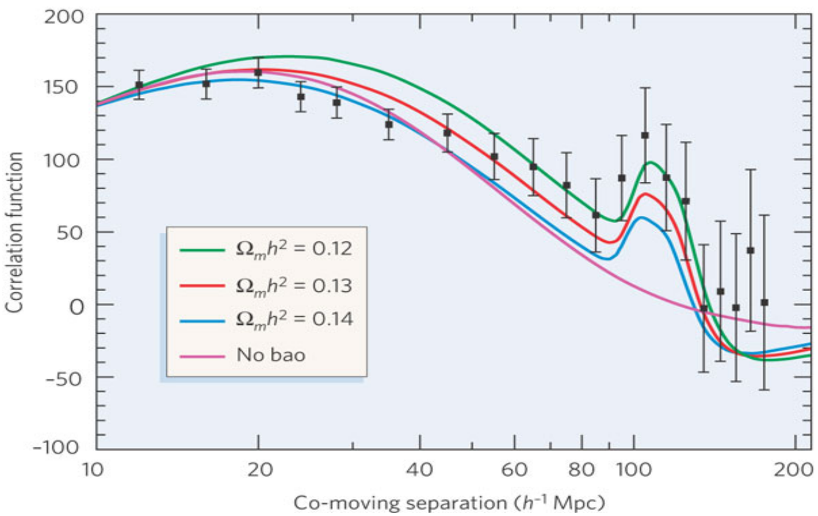
Eisenstein, Seo, White







http://www.skyandtelescope.com/



The amplitude depends on the baryon fraction, but the position is fixed by the sound horizon.
-> use this as a standard ruler.

Put this ruler of 150 Mpc (sound horizon size at LSS) at different redshifts, and measure the subtended angle.
-> We can map out the distance, and, consequently we can obtain H(z)

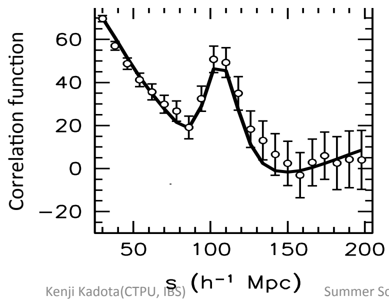
$$d_A = \text{physical size of ruler/subtended angle}$$

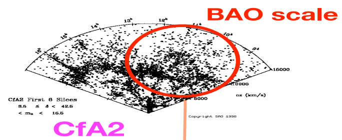
e.g.SDSS-III detects BAO precise enough to make 1% measurement of cosmological distance.
(Early surveys were too small. CfA2 could 'detect' BAO with 0.05 σ)

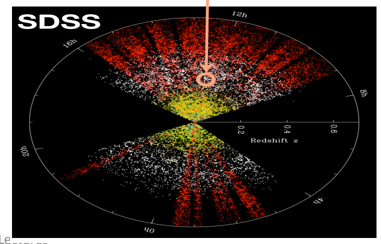
$\xi(\boldsymbol{r}) = \langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r})\rangle$

Galaxy distribution in terms of the number density $\delta = \frac{n_g - \overline{n_g}}{\overline{n_g}}$

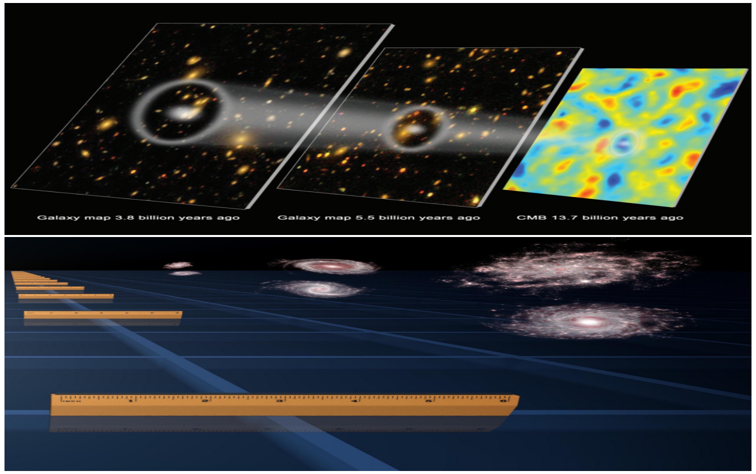
SDSSIII, Anderson et al (2013)







CMB alone suffers from degeneracies which can be broken by other observables.

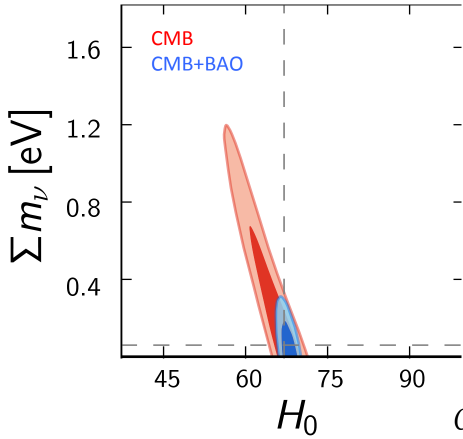


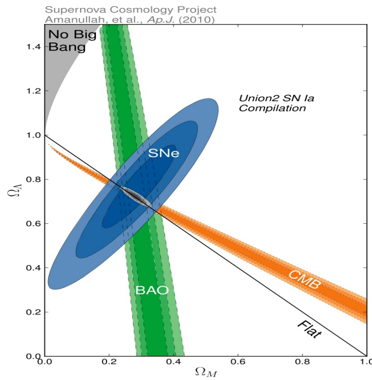
(figures from the Dark Energy Survey homepage)

H(z) from BAO helps! Standard ruler for cosmological distance measurement.

Currently: SDSS 1% distance measurement.
Future: DESI (Kitt Peak 4-m telescope, start~2018) 0.3% distance measurement.

CMB alone suffers from degeneracies which can be broken by other observables.





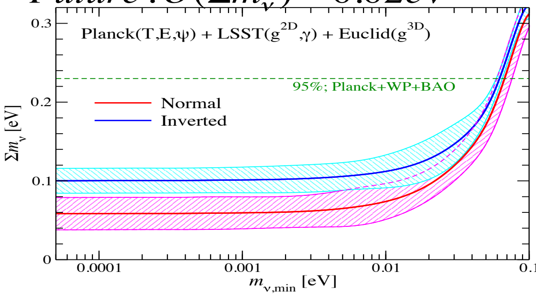
$CMB(Planck)$ $\sum m_\nu < 0.5eV$

$CMB + BAO$ $\sum m_\nu < 0.2eV$

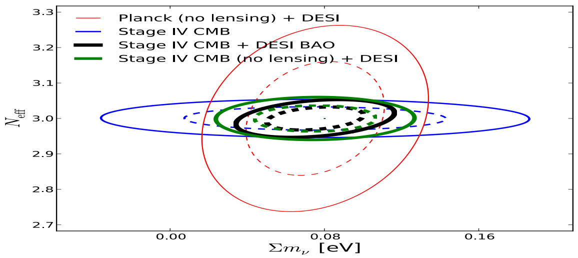
Putting all together: CMB + galaxy survey (including BAO, galaxy weak lensing, galaxy distribution)

$Current : \Sigma m_\nu < 0.17eV$ CMB+BAO(arXiv:1502.01589)

$Future : \sigma(\Sigma m_\nu) \sim 0.02eV$



Takeuchi and K.K. (2014)



Abazajian et al
1309.5383

To study further:

- Books (classics):

The Early Universe by E.W. Kolb and M.S. Turner, Addison-Wesley 1990

Modern Cosmology by Scott Dodelson, Academic Press 2003

Cosmological Physics by John Peacock, Cambridge University Press 1999

- Did not cover the cosmic perturbation production from inflation in the lectures:

Particle physics models of inflation and the cosmological density perturbation
David H. Lyth and Antonio Riotto. Physics Report 314 (1999)

- The Review of Particle Physics <http://pdg.lbl.gov/index.html>

which has many nice up-to-date review articles
(you can order a free hardcopy book from this link too)