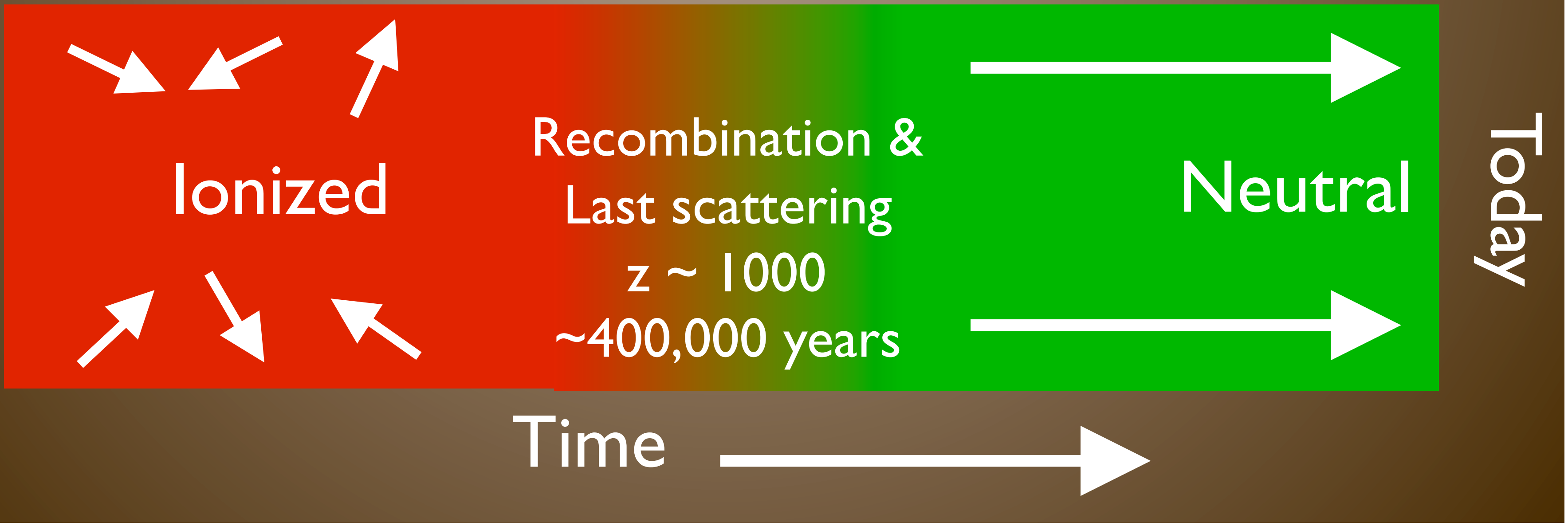
CMB: Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Photon-baryon perturbations oscillate as acoustic waves.

After recombination:

- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



Ionized

Recombination &
Last scattering
z ~ 1000
~400,000 years

Neutral

Today

Time

The cartoon

- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions.

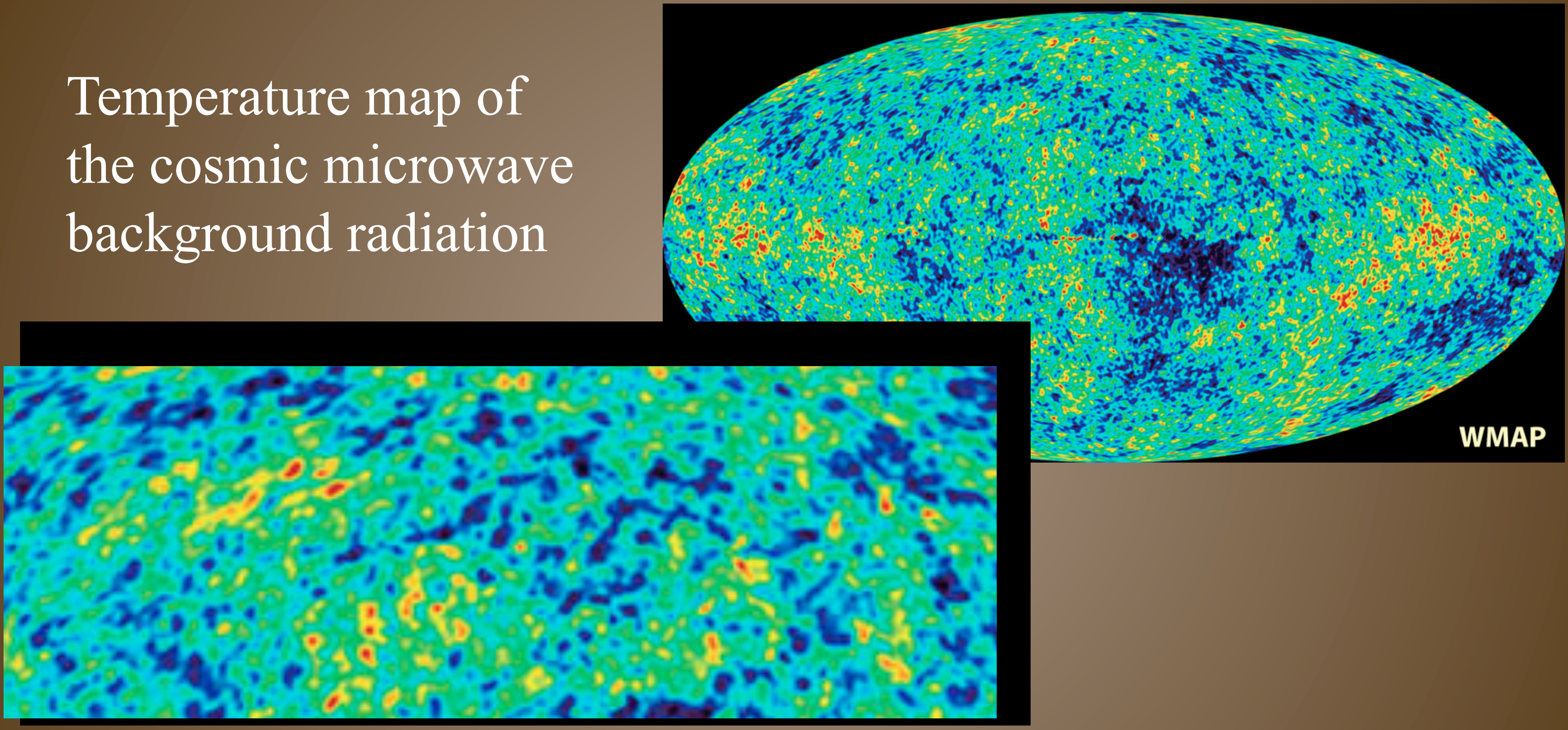
$$\frac{d}{d\tau}\left[m_{\rm eff}\frac{d\delta_b}{d\tau}\right]+\frac{k^2}{3}\delta_b=F[\Psi] \qquad m_{\rm eff}=1+3\rho_b/4\rho_\gamma$$

- These show up as temperature fluctuations in the CMB

$$\Delta T\sim\delta\rho_\gamma^{1/4}\sim A(k)\cos(kc_st) \qquad \text{[harmonic wave]}$$

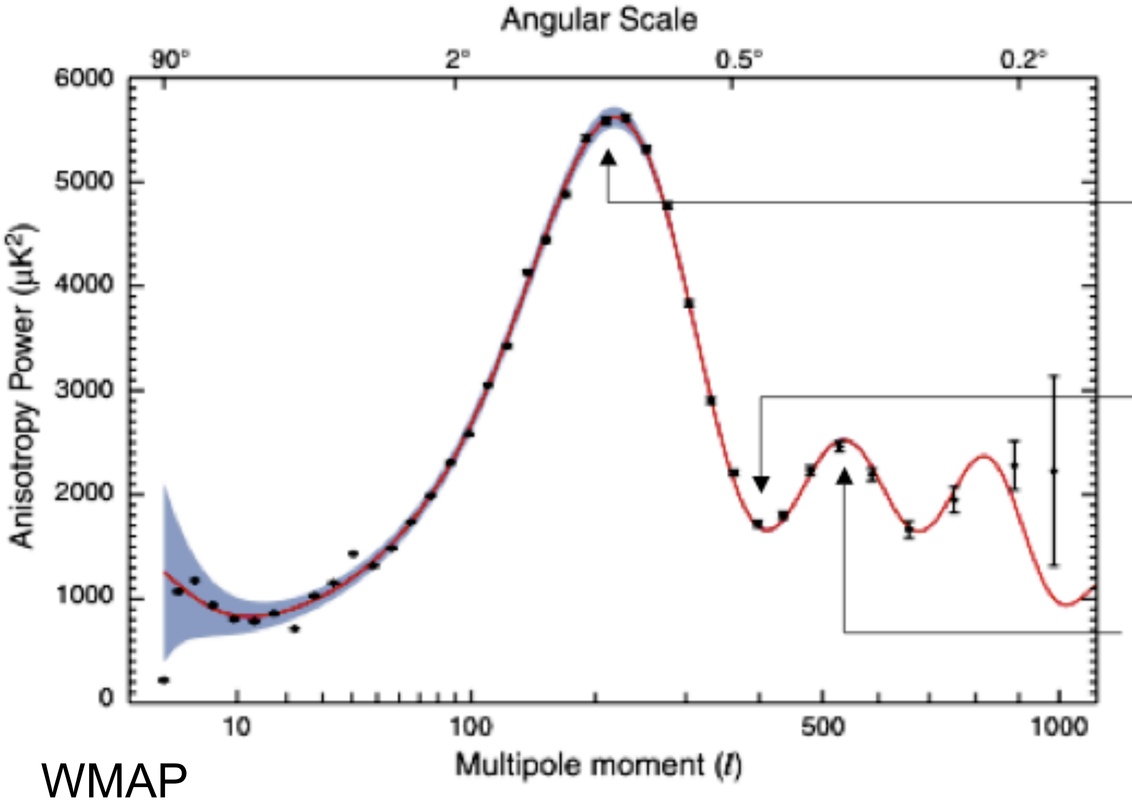
Acoustic Oscillations in the CMB

Temperature map of
the cosmic microwave
background radiation



- Although there are fluctuations on all scales, there is a characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves in the photon-baryon fluid can travel just before recombination: sound horizon ~ $c_s t_{ls}$

Acoustic oscillations seen!



WMAP

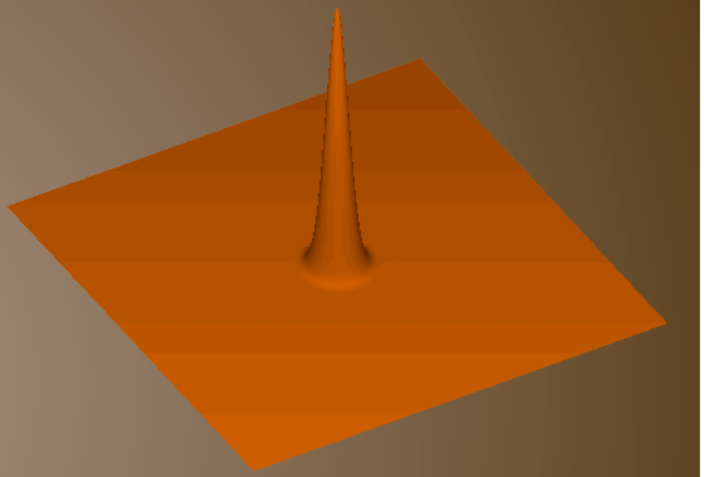
First "compression", at $kc_st_{ls}=\pi$. Density maxm, velocity null.

Velocity maximum

First "rarefaction" peak at $kc_st_{ls}=2\pi$

Acoustic scale is set by the *sound horizon* at last scattering: $s = c_s t_{ls}$

Sound Waves



- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.

Eisenstein

Sound horizon more carefully

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

Standard ruler

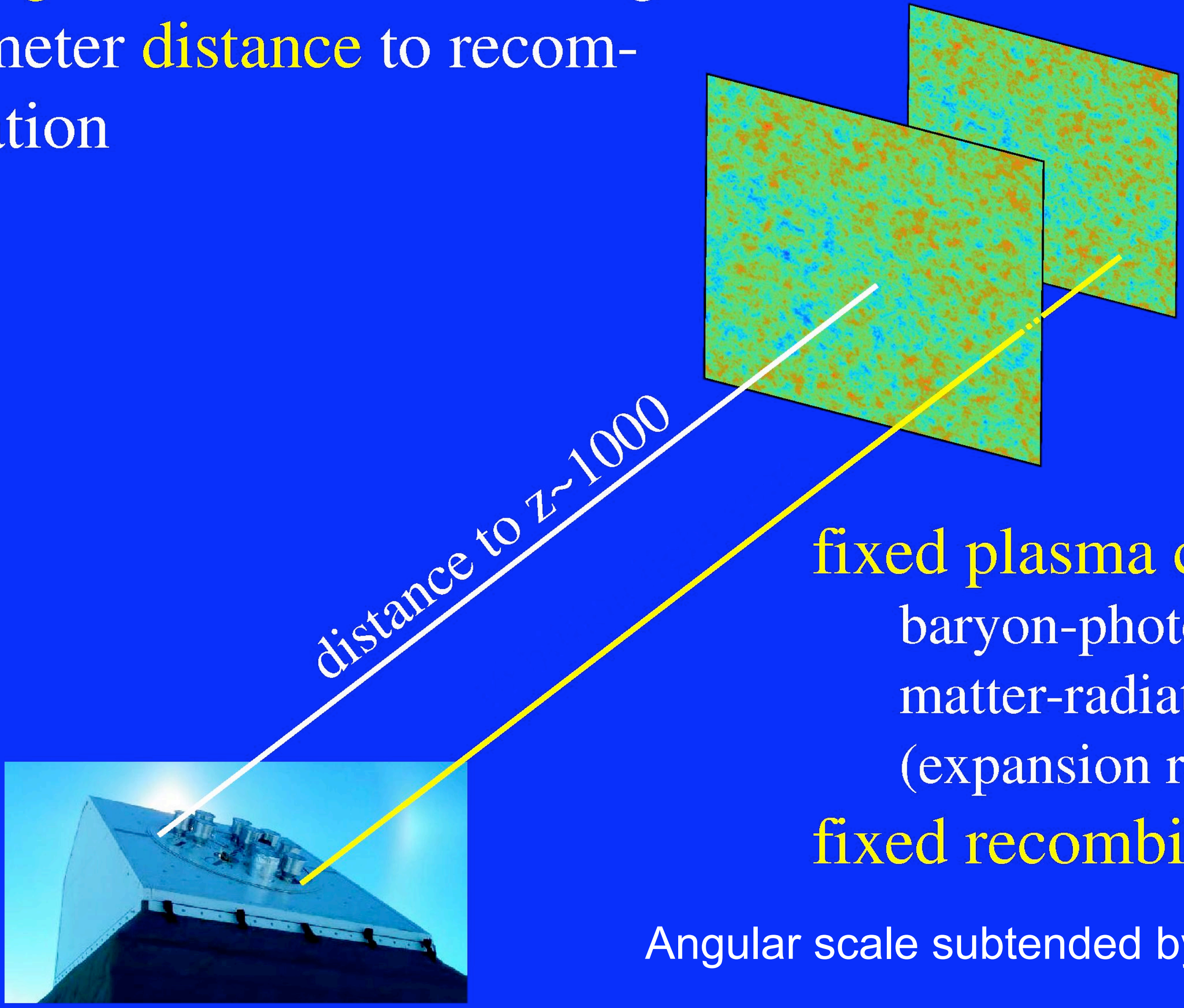
- Depends on
  - Epoch of recombination
  - Expansion of universe
  - Baryon-to-photon ratio (through c_s)

$$c_s = [3(1+3\rho_b/4\rho_\gamma)]^{-1/2}$$

Photon density is known exquisitely well from CMB spectrum.

CMB Angular Diameter Distance

- Temperature (and polarization) patterns shift in and out in angular scale with the angular diameter distance to recombination



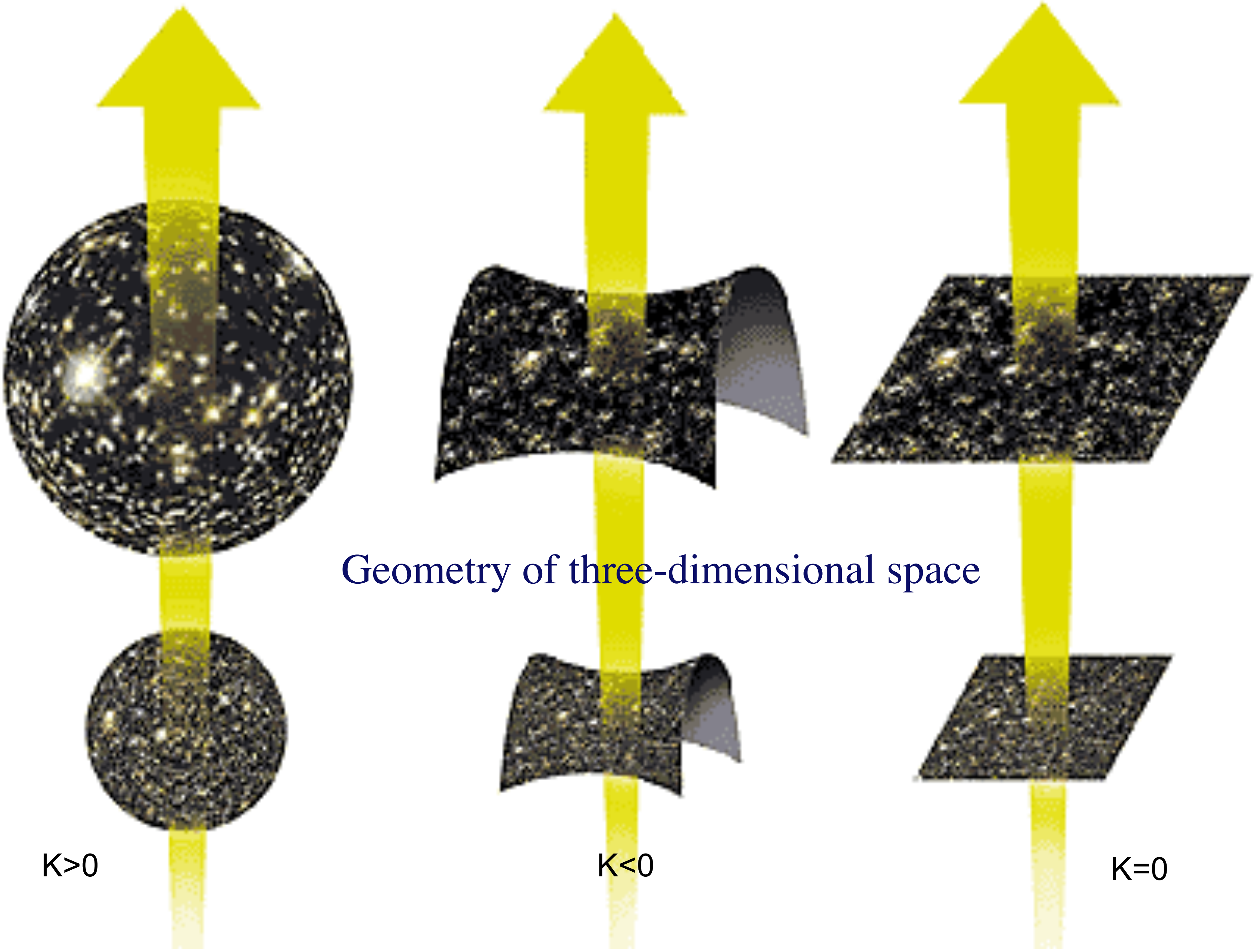
fixed plasma conditions

baryon-photon ratio: $\Omega_b h^2$
matter-radiation ratio: $\Omega_m h^2$
(expansion rate)

fixed recombination

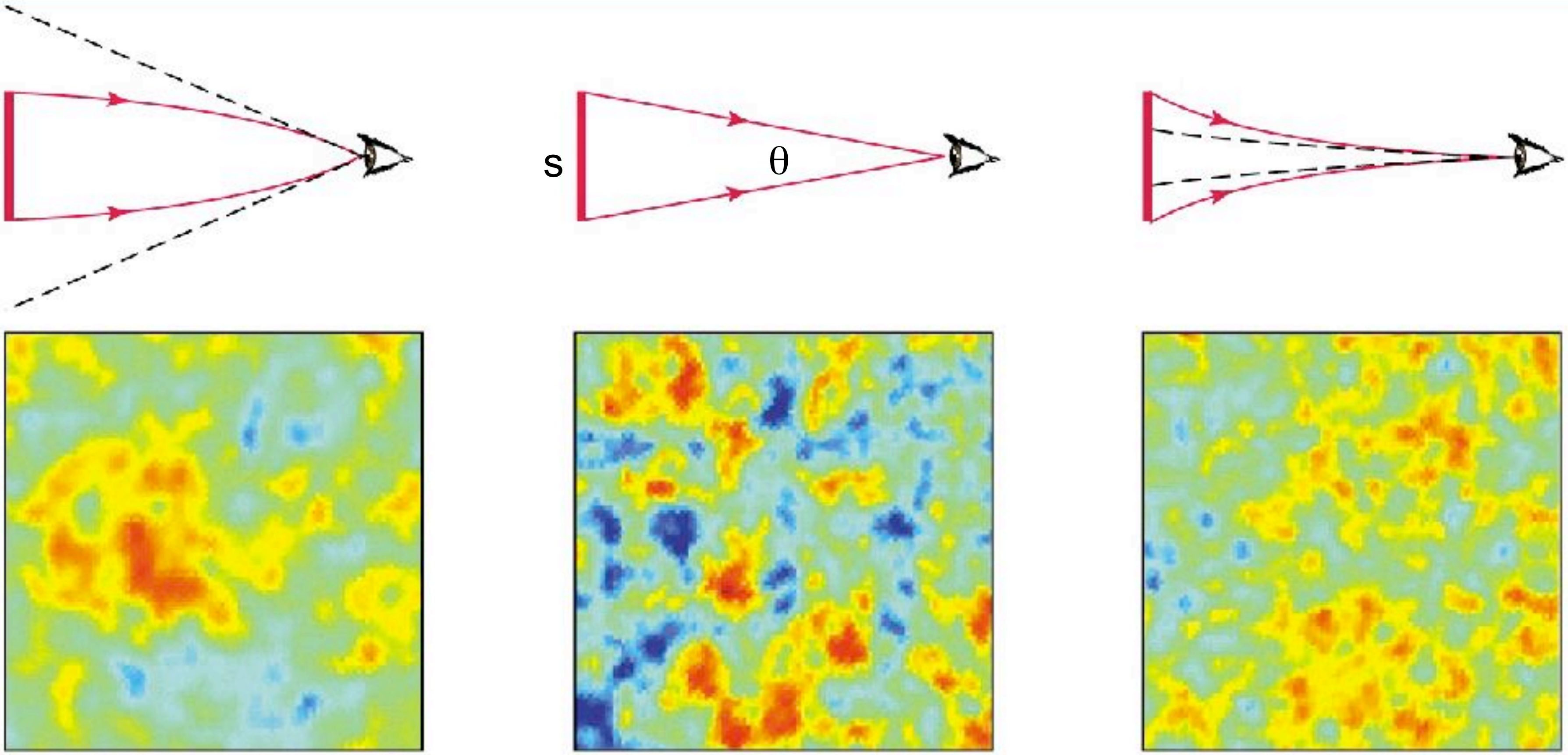
Hu

Angular scale subtended by *s*



Geometry of three-dimensional space

Seeing the Sound Horizon



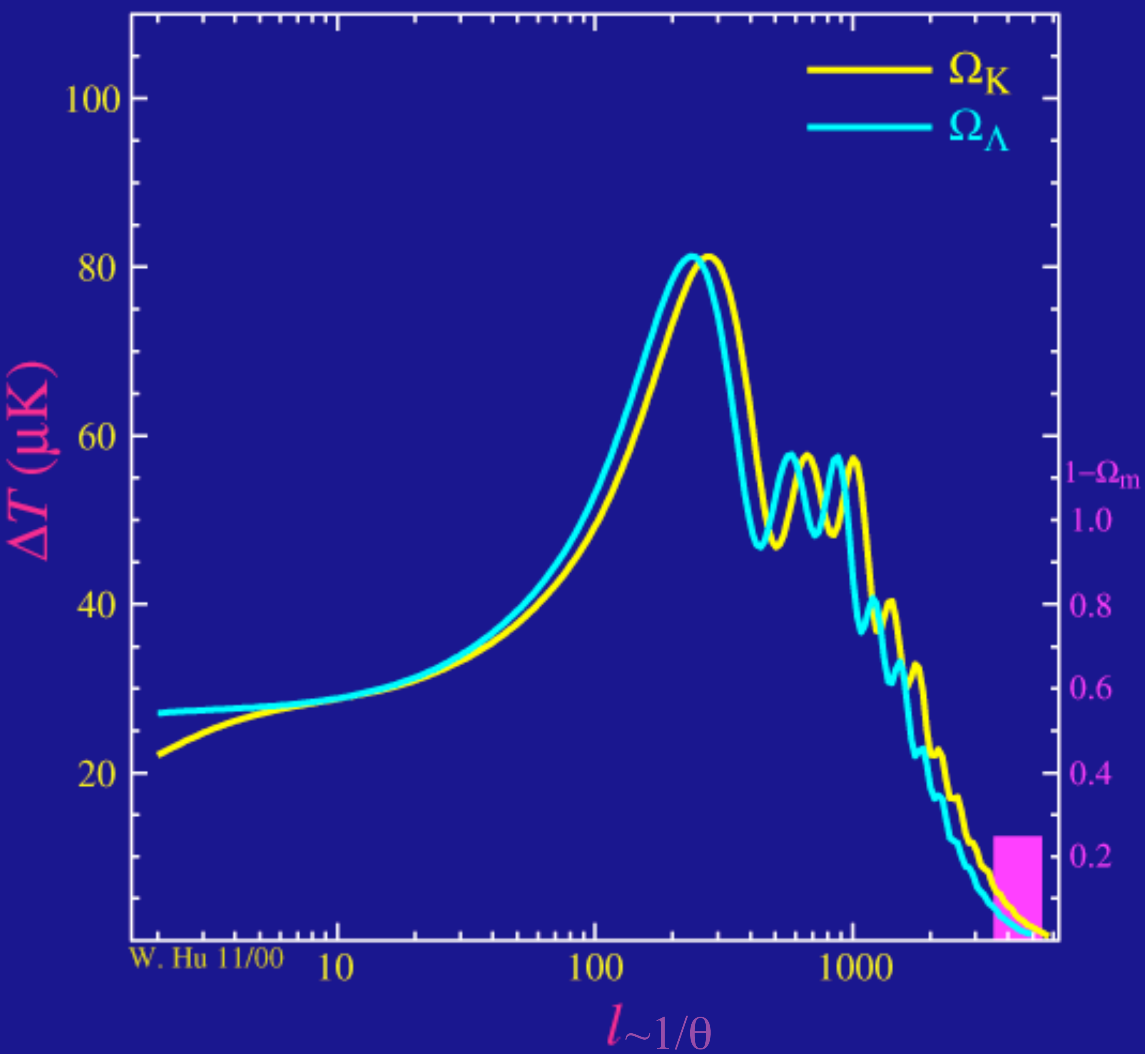
a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

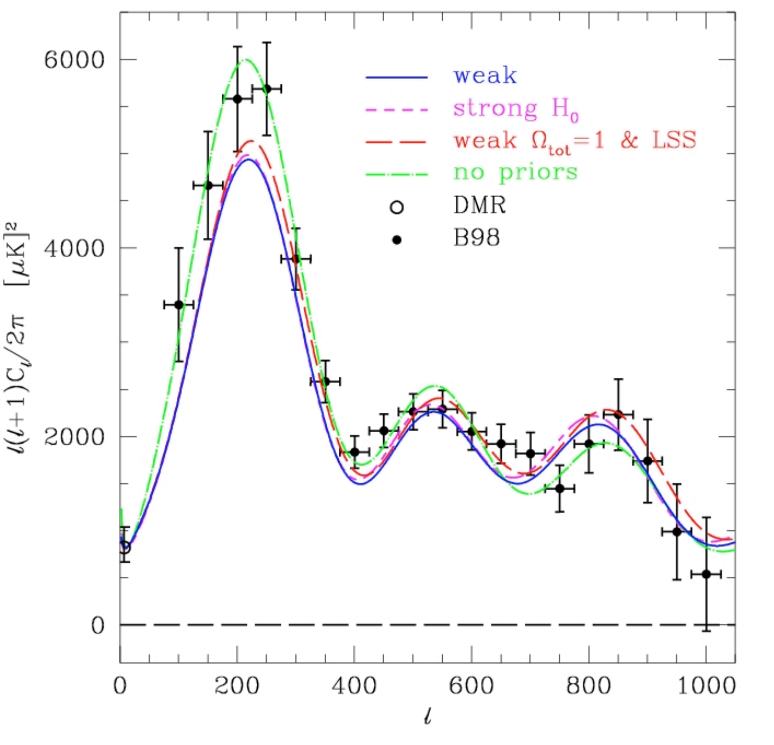
CMB Maps

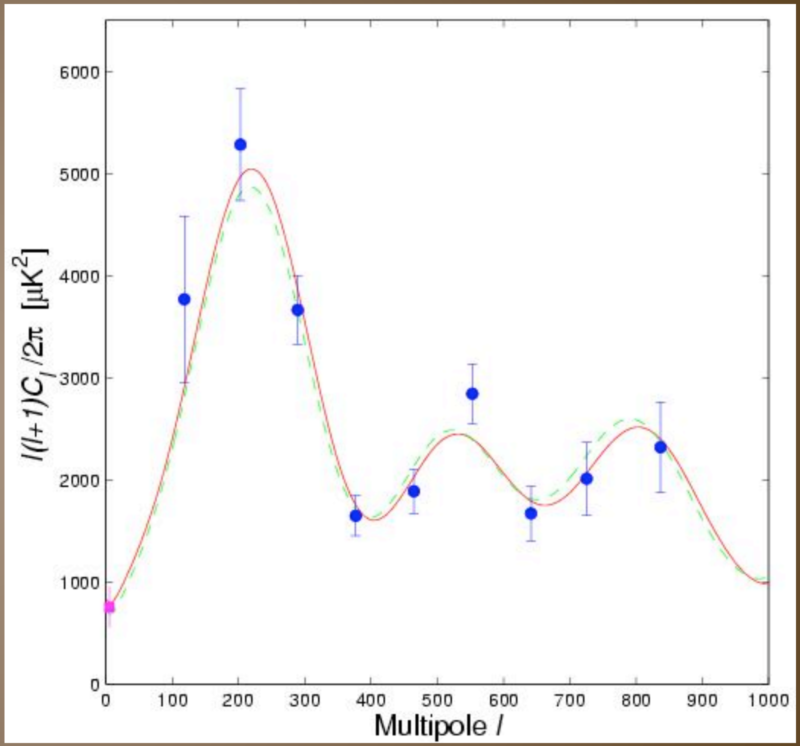
Angular positions of acoustic peaks probe spatial curvature of the Universe



Hu

Microwave Background Anisotropy Probes Spatial Curvature



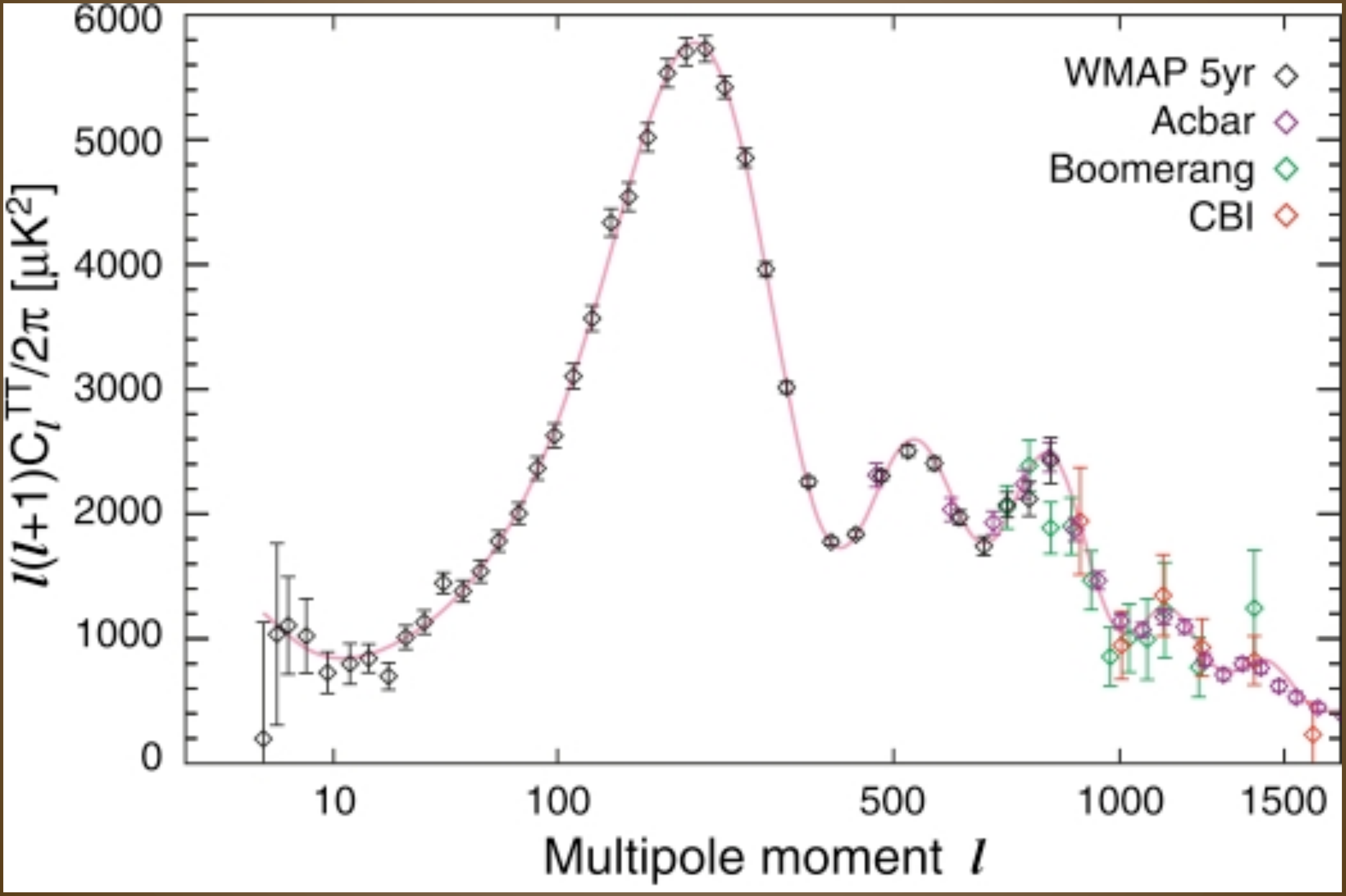


Boomerang (2001) Netterfield et al

DASI (2001) Pryke et al

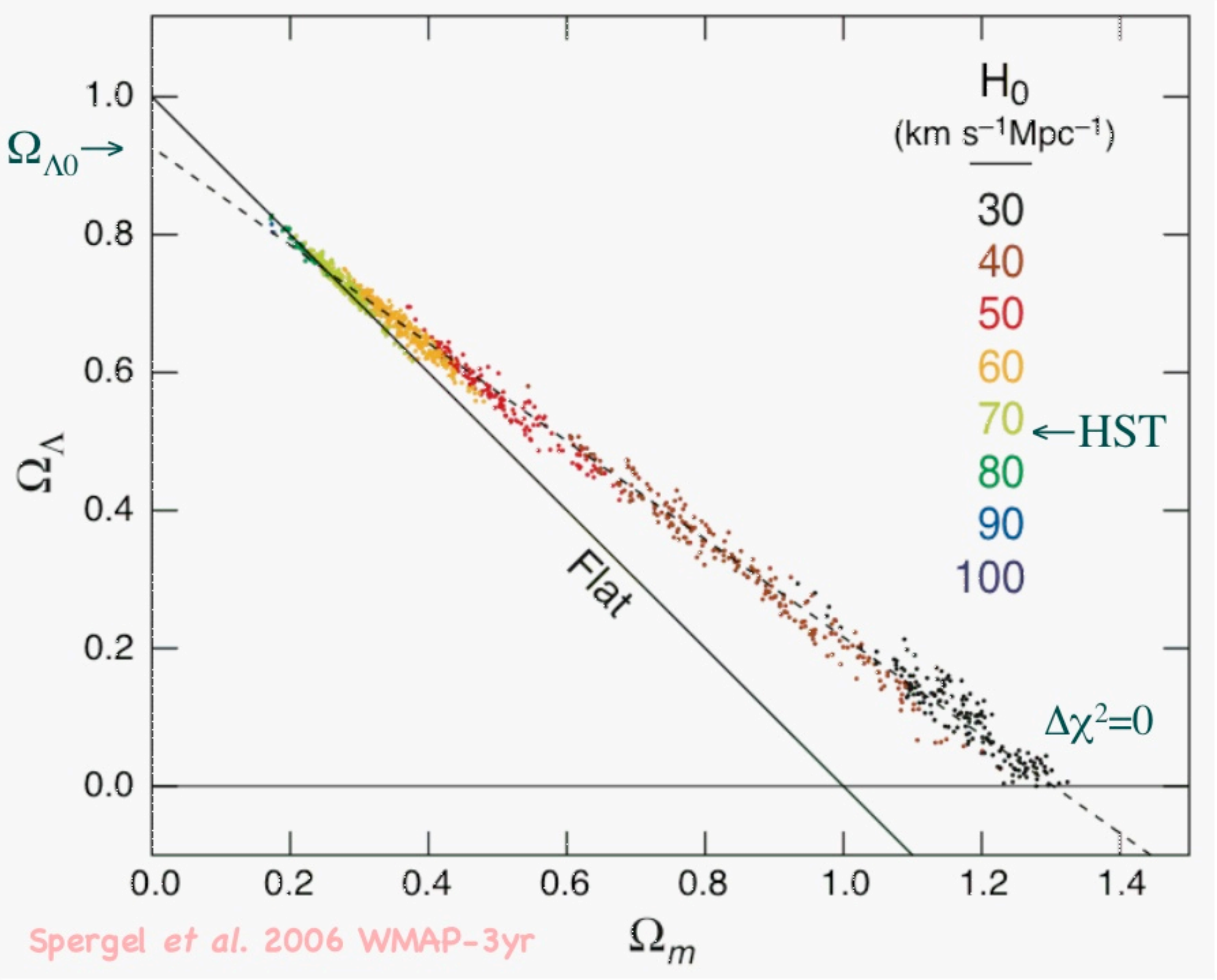
Data indicates nearly flat geometry *if* w =-1

CMB Results



6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi\ [\mu K^2]$
10
100
500
1000
1500
Multipole moment l
WMAP 5yr ◇
Acbar ◇
Boomerang ◇
CBI ◇

WMAP3 Results



$1-\Omega_0=-0.3+0.4\ \Omega_{\Lambda 0}\rightarrow$

$\leftarrow$HST

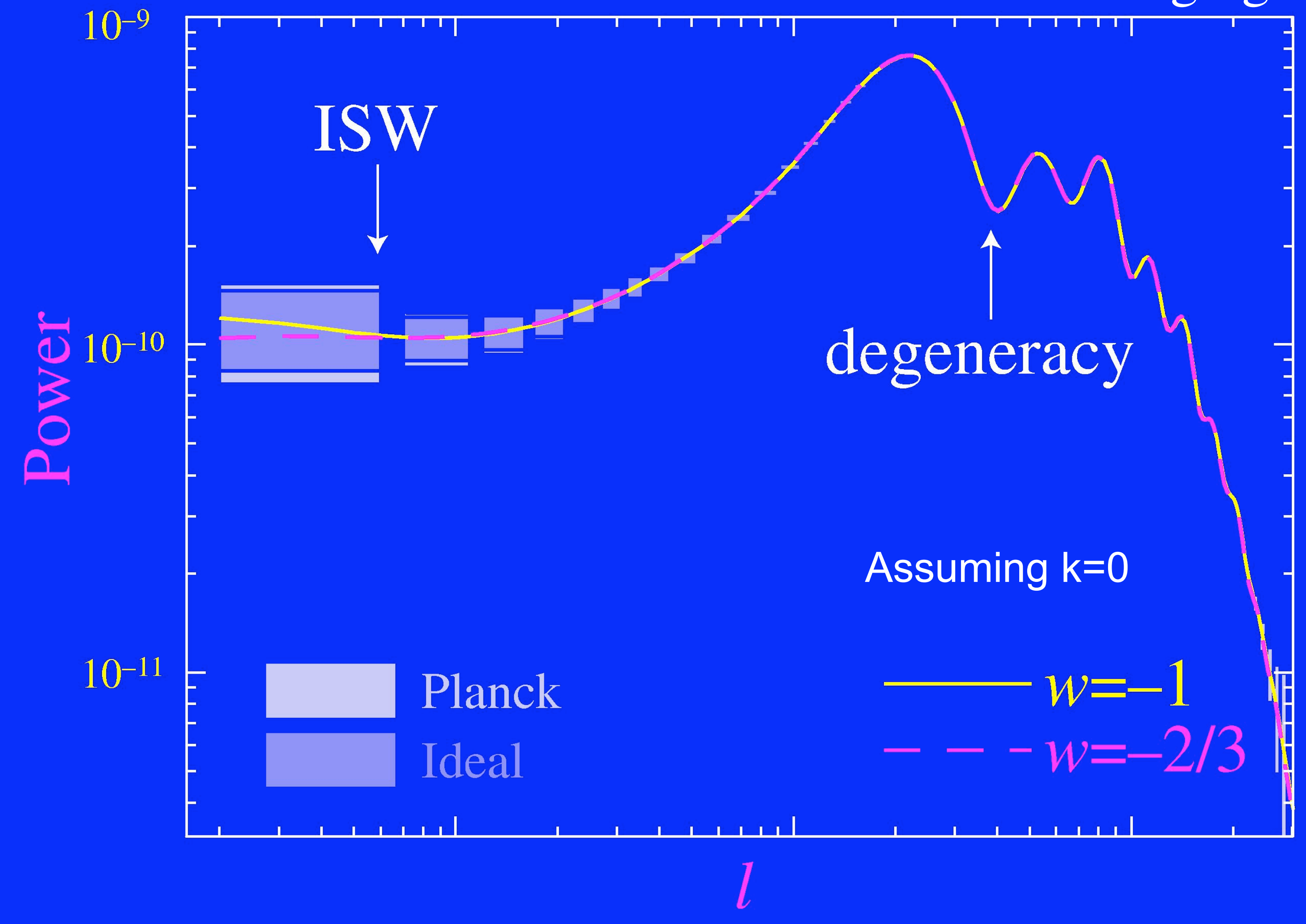
$\Delta\chi^2=0$

Spergel *et al.* 2006 WMAP-3yr

assuming w=-1

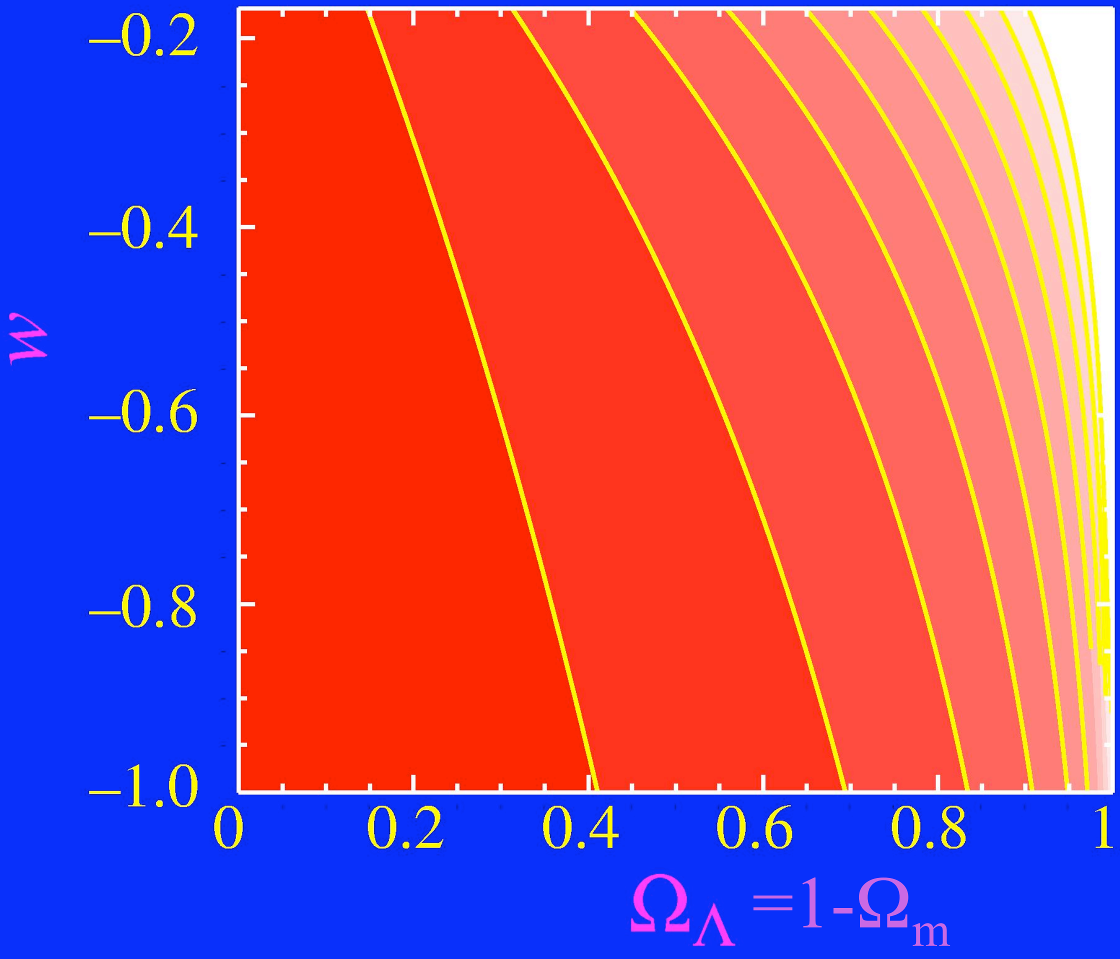
Degeneracy of the Peak Locations

- But raising the equation of state $w=p/\rho$ has the same effect as changing Ω_{DE}



Degeneracy of the Peak Locations

- Contours of angular diameter distance H_0D_A at constant $\Omega_b h^2$, $\Omega_m h^2$ (peak locations and morphology)



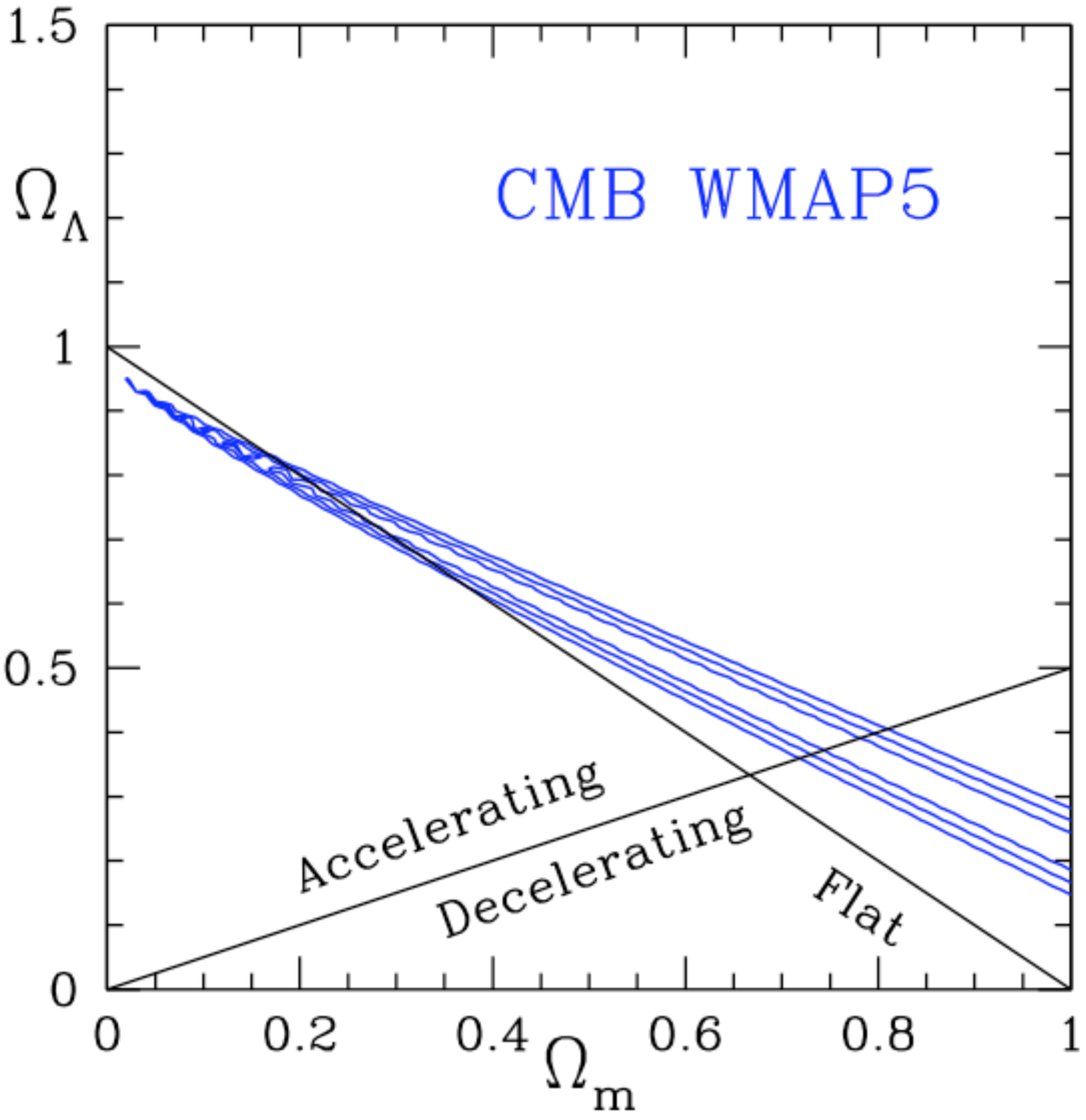
CMB shift parameter

CMB anisotropy constraint on Angular Diameter distance to last-scattering well approximated by:

$$R = \left(\Omega_m H_0^2\right)^{1/2} \int_0^{z_{LS}} \frac{dz}{H(z)} = 1.715 \pm 0.021$$

$$z_{LS} = 1089$$

WMAP5 results Komatsu etal 2008


CMB WMAP5
Ω_Λ
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
Ω_m
Accelerating
Decelerating
Flat

SALT MLCS

SDSS only:

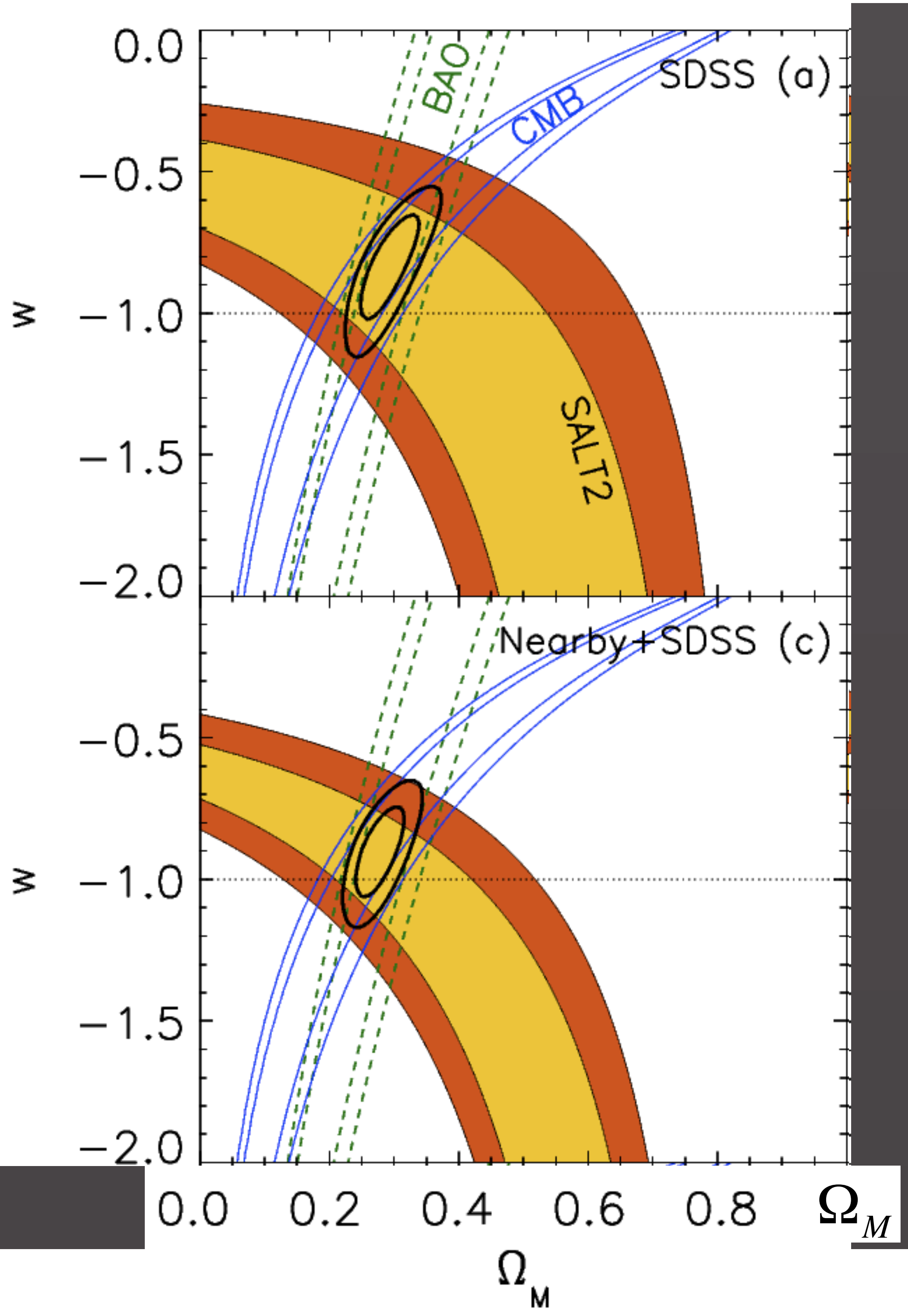
Nearby+SDSS:

MLCS

$w = -0.93 \pm 0.13(\mathrm{stat})^{+0.10}_{-0.32}(\mathrm{syst})$

SALT

$w = -0.92 \pm 0.11(\mathrm{stat})^{+0.07}_{-0.15}(\mathrm{syst})$



Standard rulers

- Suppose we had an object whose length (in *meters*) we knew as a function of cosmic epoch.
- By measuring the angle ($\Delta\theta$) subtended by this ruler ($\Delta\chi$) as a function of redshift we map out the angular diameter distance d_A

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)} \qquad d_A(z) = \frac{d_L(z)}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

- By measuring the redshift interval (Δz) associated with this distance we map out the Hubble parameter H(z)

$$c\Delta z = H(z)\ \Delta\chi$$

Sound horizon more carefully

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

$$s = \frac{1}{H_0\,\Omega_m^{1/2}} \int_0^{a_r} \frac{c_s}{(a+a_{\rm eq})^{1/2}}\,da$$

CMB calibration

- Not coincidentally the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB.

$$\begin{aligned} s &= 147.8 \pm 2.6 \text{ Mpc} \\ &= (4.56 \pm 0.08) \times 10^{24}\text{m} \end{aligned}$$

WMAP 3rd yr data

↑

Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum. (Planck will nail this!)

The Structure Formation Cookbook

1. Initial Conditions: A Theory for the Origin of Density Perturbations in the Early Universe $P_m(k) \sim k^n,\ n \sim 1$

   Primordial Inflation: initial spectrum of density perturbations

2. Cooking with Gravity: Growing Perturbations to Form Structure

   Set the Oven to Cold (or Hot or Warm) Dark Matter

   Season with a few Baryons and add Dark Energy $P_m(k) \sim T(k) k^n$

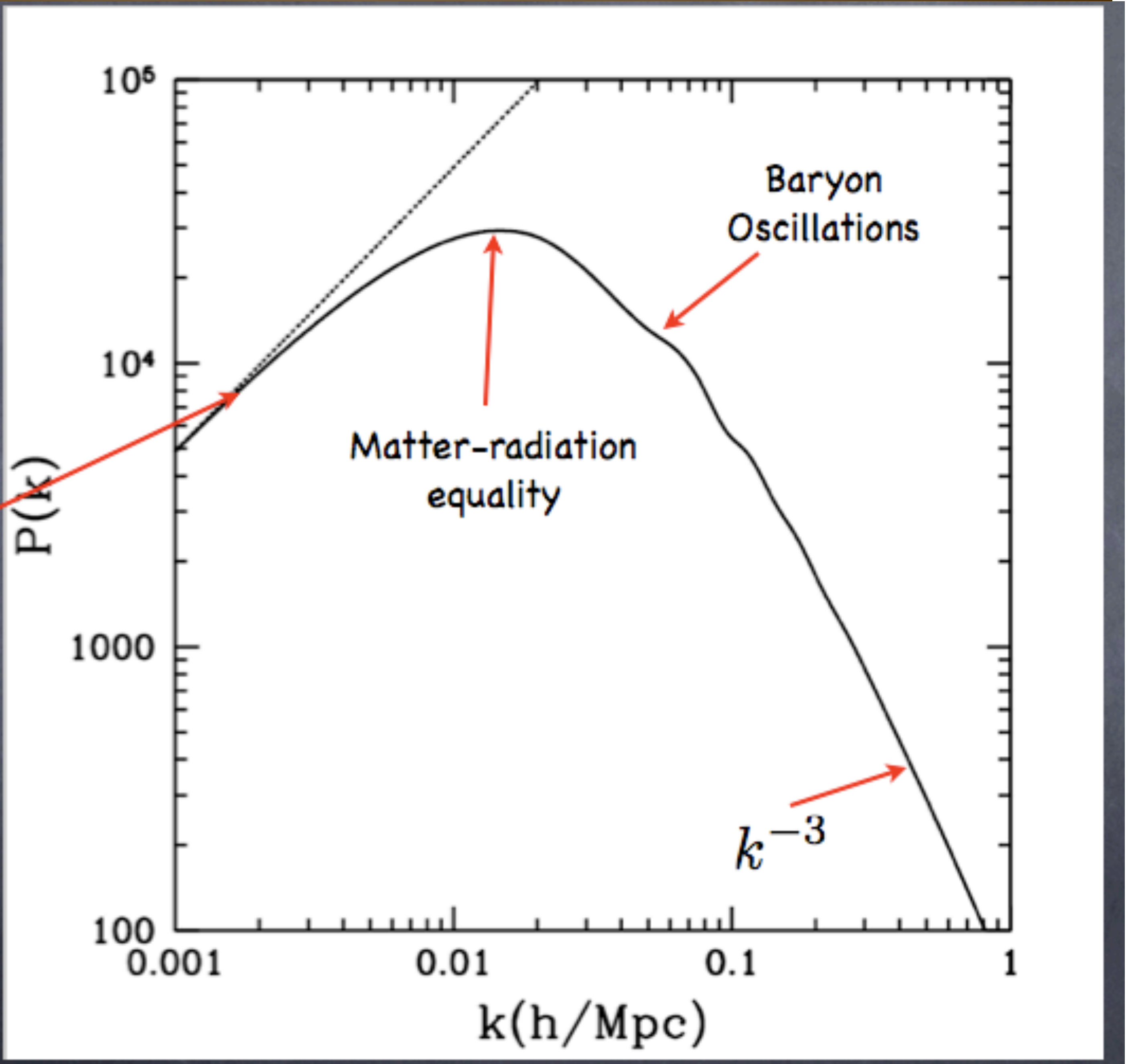
3. Let Cool for 13 Billion years $P_g(k) \sim b^2(k) T(k) k^n$

   Turn Gas into Stars

4. Tweak (1) and (2) until it tastes like the observed Universe.

Cold Dark Matter Models

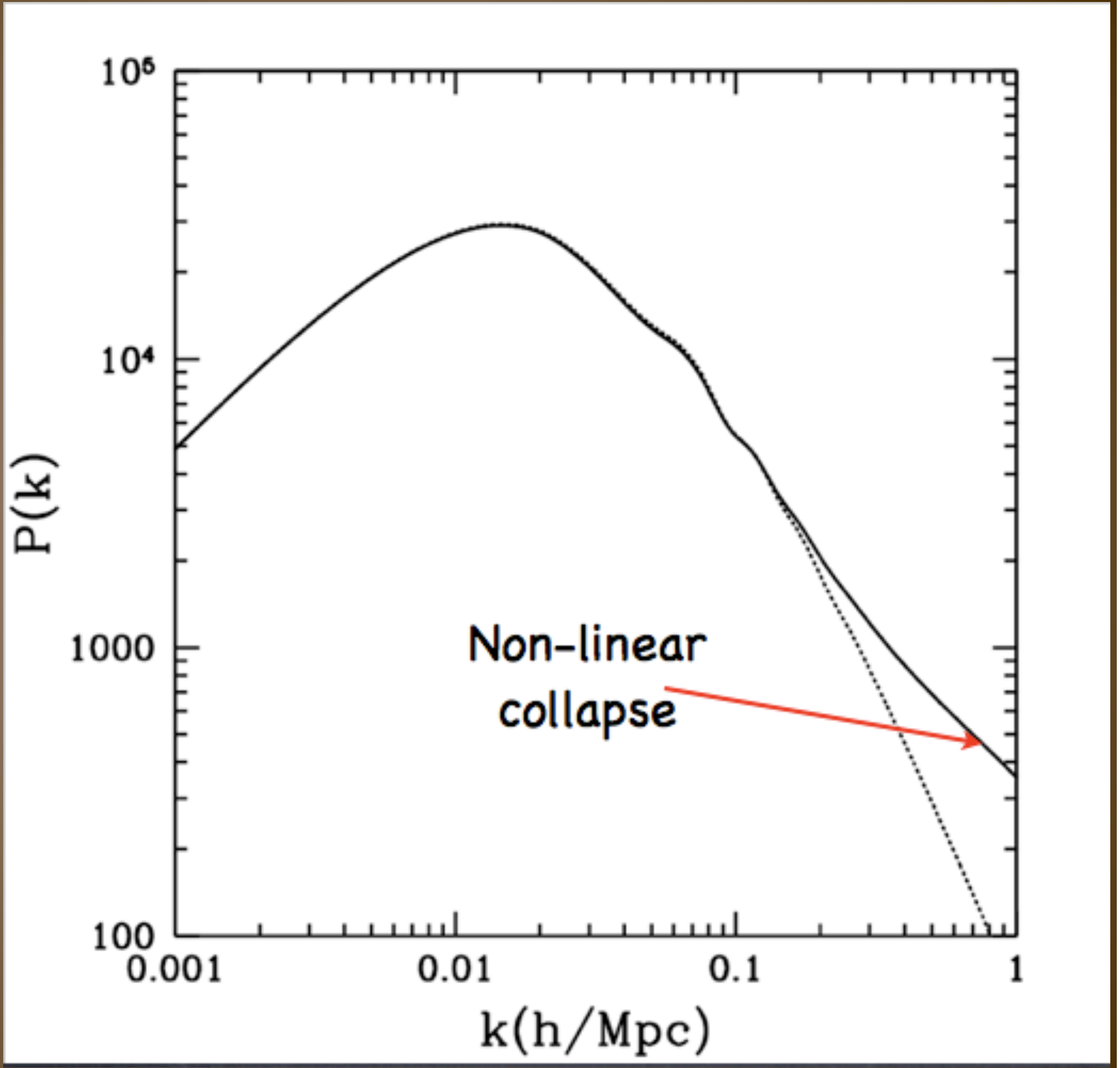
Power Spectrum of the Mass Density



Primordial

$$\delta(k) = \int d^3x \cdot e^{i\vec{k}\cdot\vec{x}} \frac{\delta\rho(x)}{\rho}$$

$$\langle \delta(k_1)\delta(k_2)\rangle = (2\pi)^3 P(k_1)\delta^3(\vec{k}_1 + \vec{k}_2)$$



Non-linear collapse

Cold Dark Matter Models

Theoretical
Power Spectrum
of the Mass Density

$$\delta(k) = \int d^3x \cdot e^{i\vec{k}\cdot\vec{x}} \frac{\delta\rho(x)}{\rho}$$

$$\langle \delta(k_1)\delta(k_2) \rangle = (2\pi)^3 P(k_1)\delta^3(\vec{k}_1 + \vec{k}_2)$$

Power spectrum measurements probe cosmological parameters

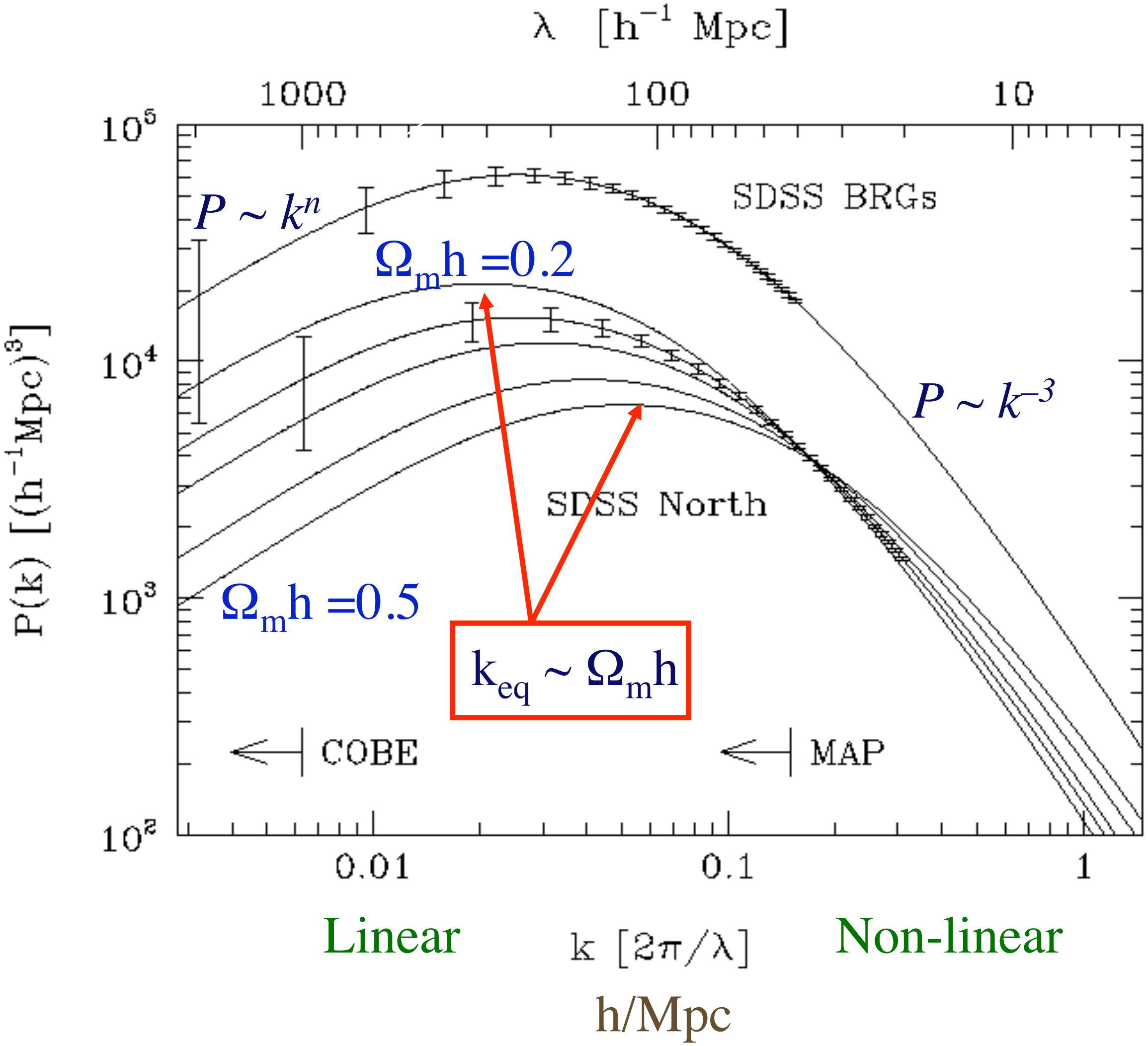
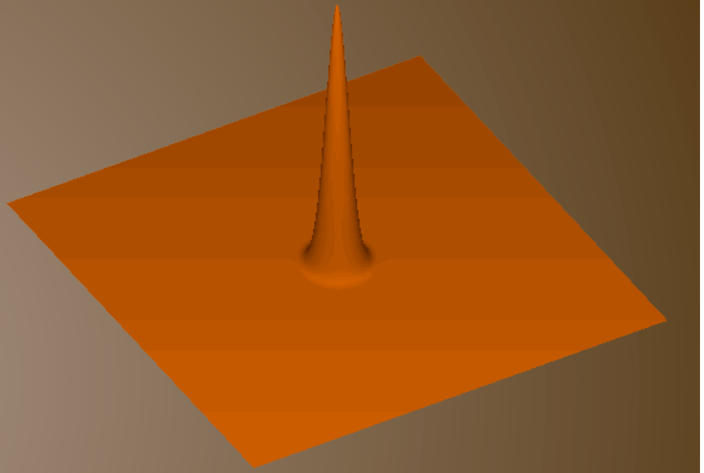
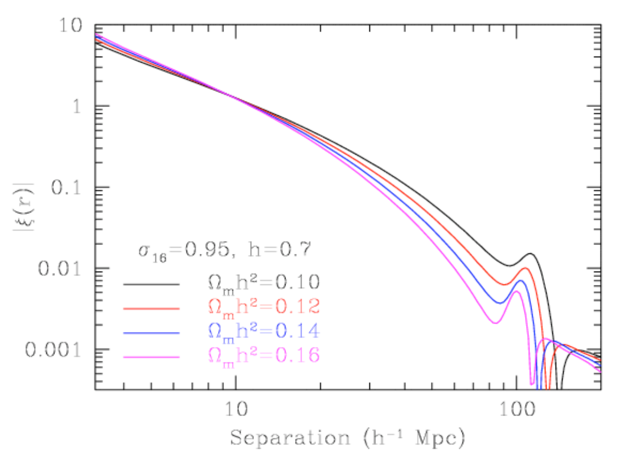


Fig. 3.— Predicted uncertainties in the power spectrum estimated from a volume-limited ($R_{max} = 500h^{-1}$ Mpc) sample of SDSS North and for the Bright Red Galaxy sample (upper set of error bars). These errors assume that the true power spectrum is that of an $\Omega h = 0.25$ CDM model and that the BRGs are more clustered than normal galaxies. Plotted for comparison to the SDSS North errors are CDM power spectra (normalized to $\sigma_8 = 1$) for a

Sound Waves again

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

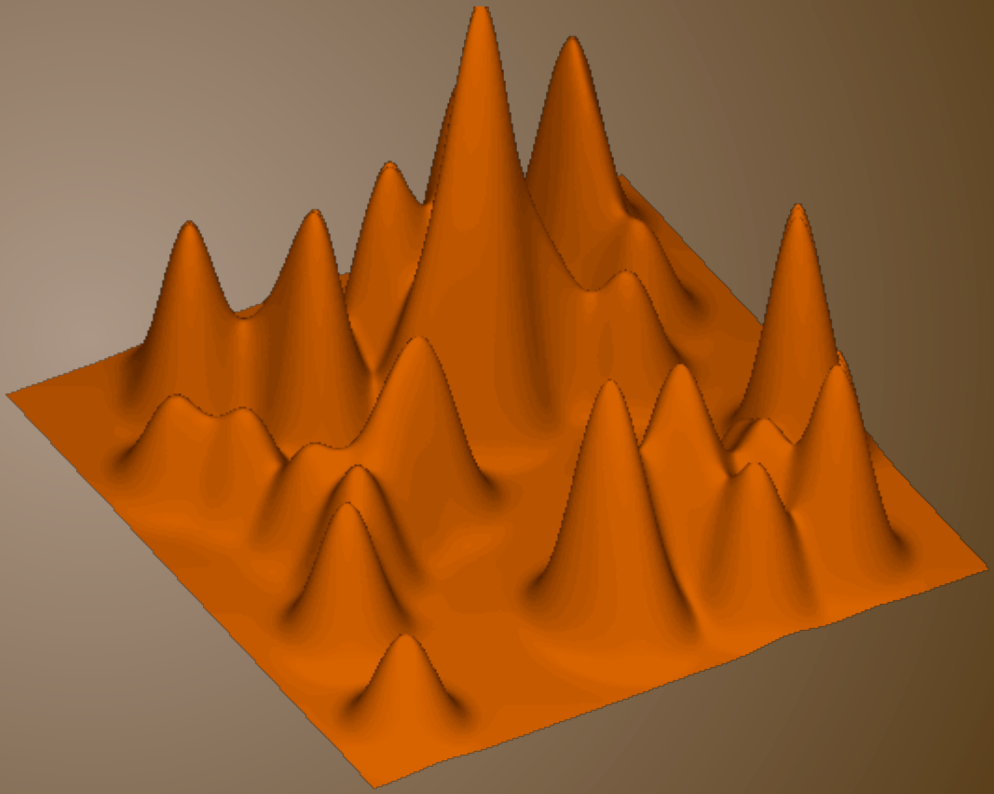




Eisenstein

A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bulls' eyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.



Origin of Baryon Acoustic Oscillations (BAO)

$$\dot{\vec{v}}_{\rm b} + \frac{\dot{a}}{a}\vec{v}_{\rm b} + \vec{\nabla}\Psi = \mathcal{C}$$

$$\mathcal{C} = \frac{1}{\rho_{\rm b}} \int \frac{d^3p}{(2\pi)^3} (-\vec{p})\, C[f_\gamma(\vec{p})]$$

Collision Term

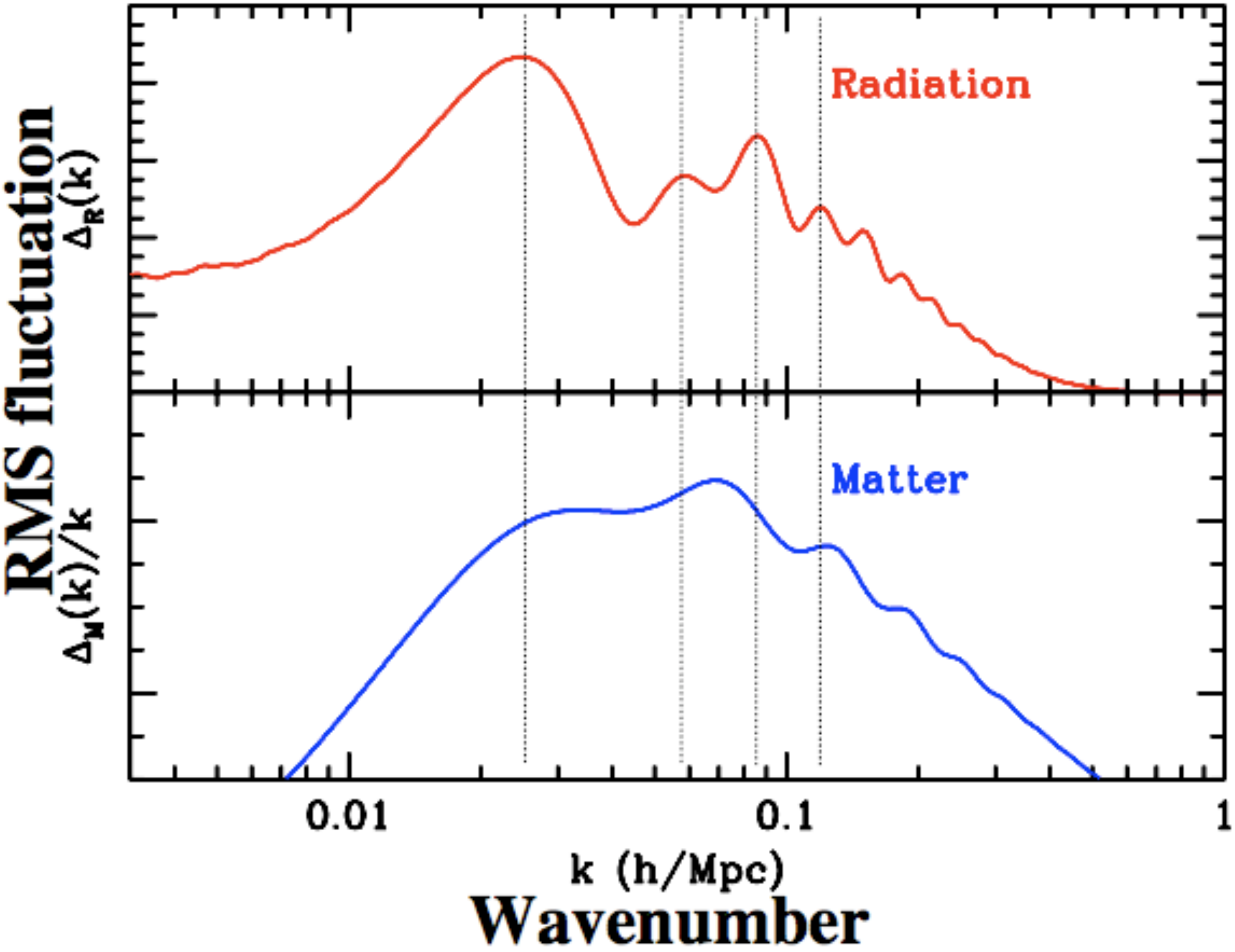
$$C[f_\gamma(\vec{p})] = -p\frac{\partial f_\gamma^{(0)}}{\partial p}\left(n_{\rm e}\sigma_T\right)\left(\Theta_0 - \Theta(\hat{p}) + \hat{p}\cdot\vec{v}_{\rm b}\right)$$

$$f_\gamma(\vec{p}) = \left[\exp\left\{\frac{p}{T(1+\Theta)}\right\} - 1\right]^{-1} \simeq f_\gamma^{(0)} - p\frac{\partial f_\gamma^{(0)}}{\partial p}\Theta$$

Baryon oscillations in *P(k)*

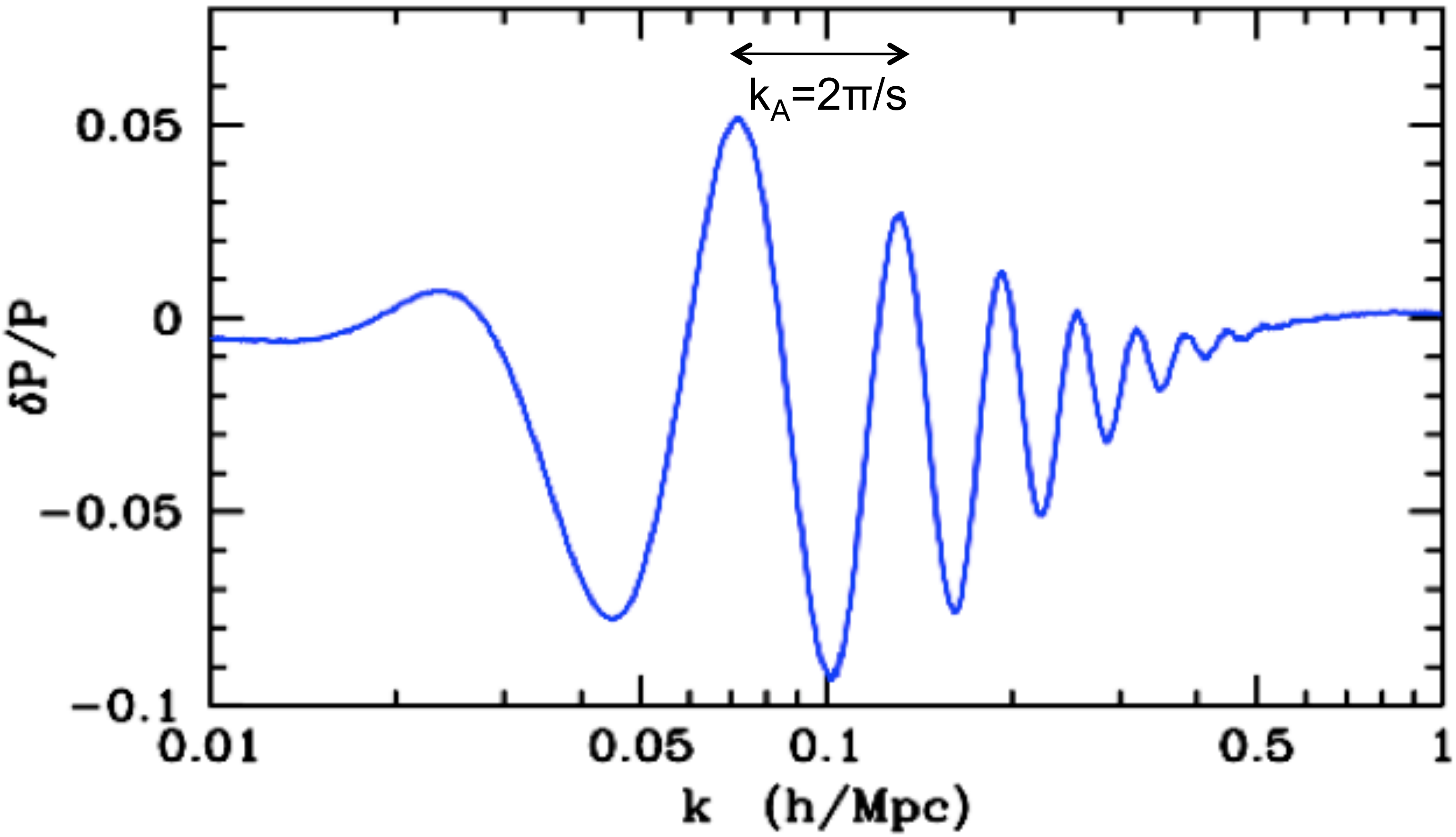
- Since the baryons contribute ~15% of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by *s*. sound horizon scale
- This leads to small oscillations in the matter power spectrum *P*(*k*).
  - No longer order unity, like in the CMB, now suppressed by $\Omega_b/\Omega_m \sim 0.1$

Baryon (acoustic) oscillations



Divide out the gross trend …

A damped, almost harmonic sequence of “wiggles” in the power spectrum of the mass perturbations of amplitude $O(10\%)$.



Simulation

The error due to sample variance on a power spectrum measurement, averaged over a radial bin in k-space of width Δk, is

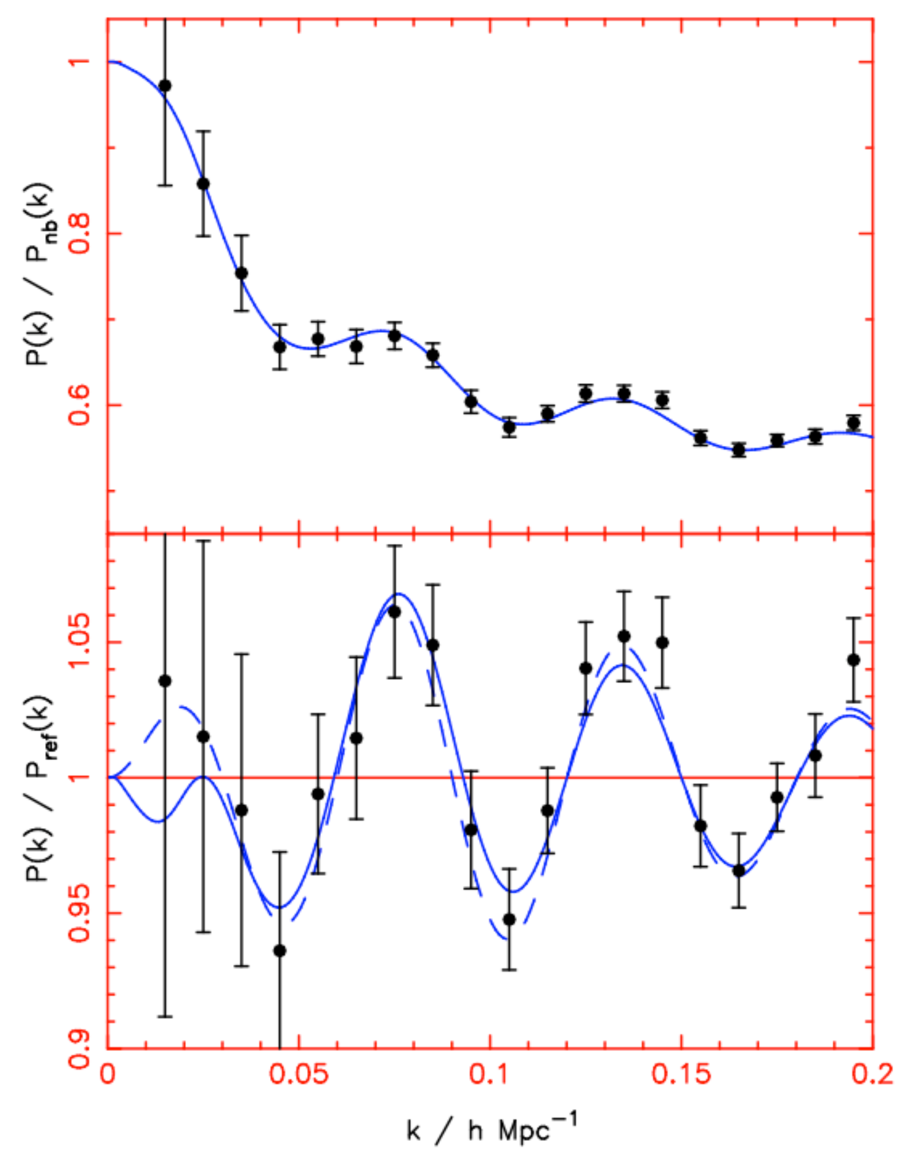
$$\left(\frac{\sigma_P}{P}\right)^2 = 2 \times \frac{(2\pi)^3}{V} \times \frac{1}{4\pi k^2 \Delta k} \qquad (2)$$

plus Poisson errors: multiply by $(1+1/nP)^2$

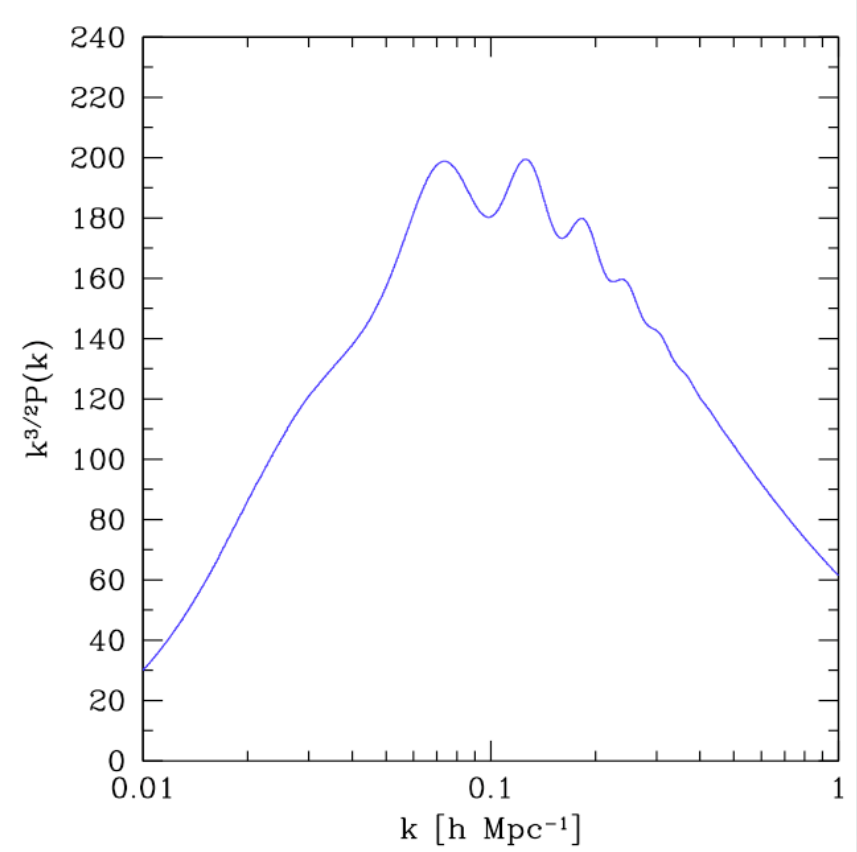
Assumes Gaussian errors (linear theory)

Fit with::

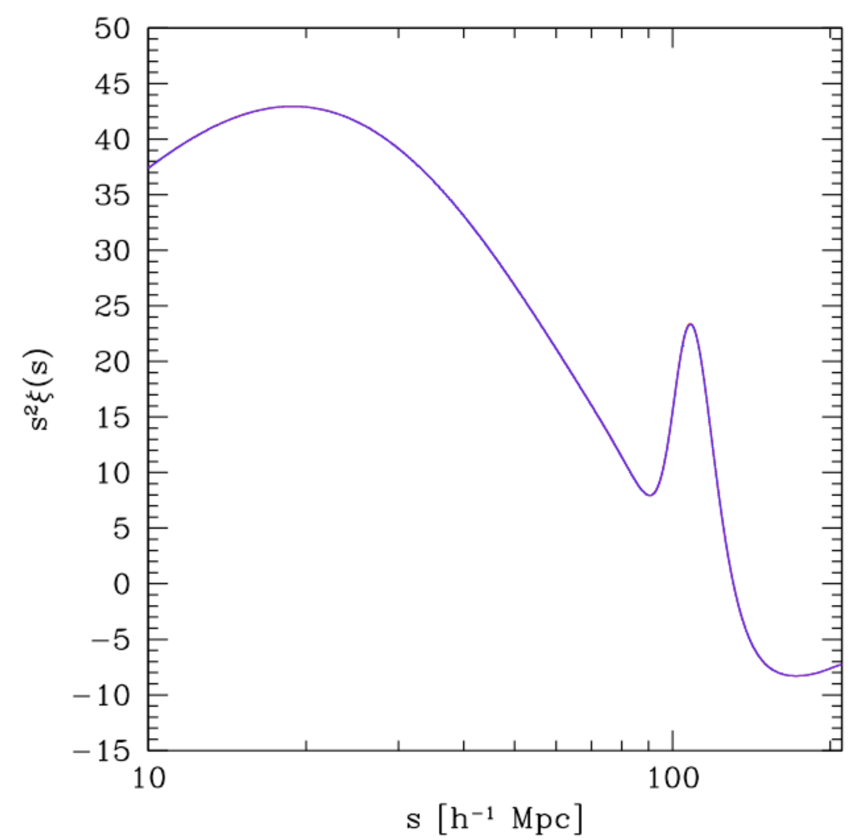
$$\frac{P(k)}{P_{\rm ref}} = 1 + A\,k\,\exp\left[-\left(\frac{k}{0.1\,h\,{\rm Mpc}^{-1}}\right)^{1.4}\right] \sin\left(\frac{2\pi k}{k_A}\right)$$



Power Spectrum



Correlation Function

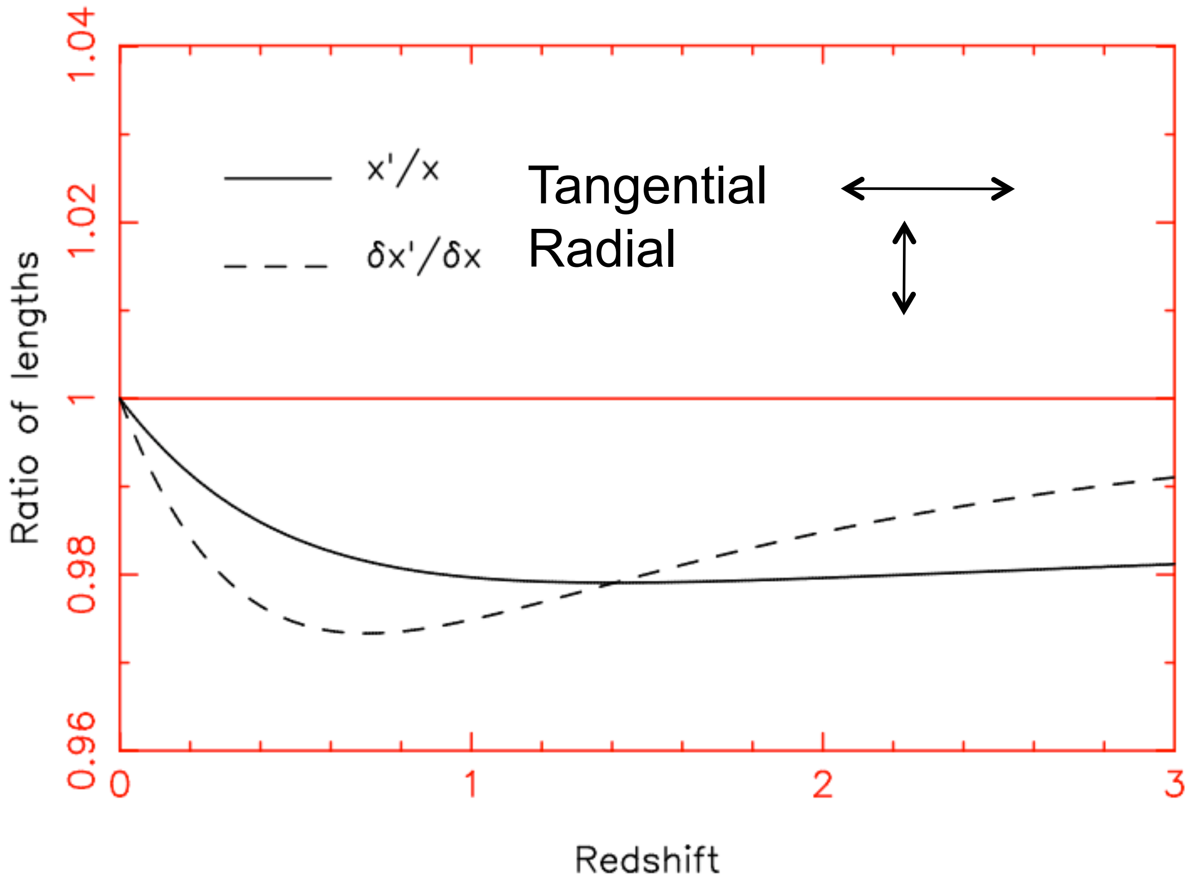


Measure redshifts and angular positions

Convert to comoving separation using redshift-distance relation

$$\frac{dx}{dz} = \frac{c}{H_0\,\Omega_m^{1/2}}\,\frac{1}{\sqrt{(1+z)^3 + (\Omega_m^{-1} - 1)(1+z)^{3(1+w)}}}$$

Dependence on *w*



Assuming constant Ω_m

Measure k_A to 1% plus known *s* yields *w* to ~5%

Fig. 5.— The length distortion of a rod as a function of redshift, supposing the true cosmology is $\Omega_m = 0.3$, $w_{true} = -1$ and the assumed cosmology is $\Omega'_m = 0.3$, $w_{ass} = -0.9$. The dashed and

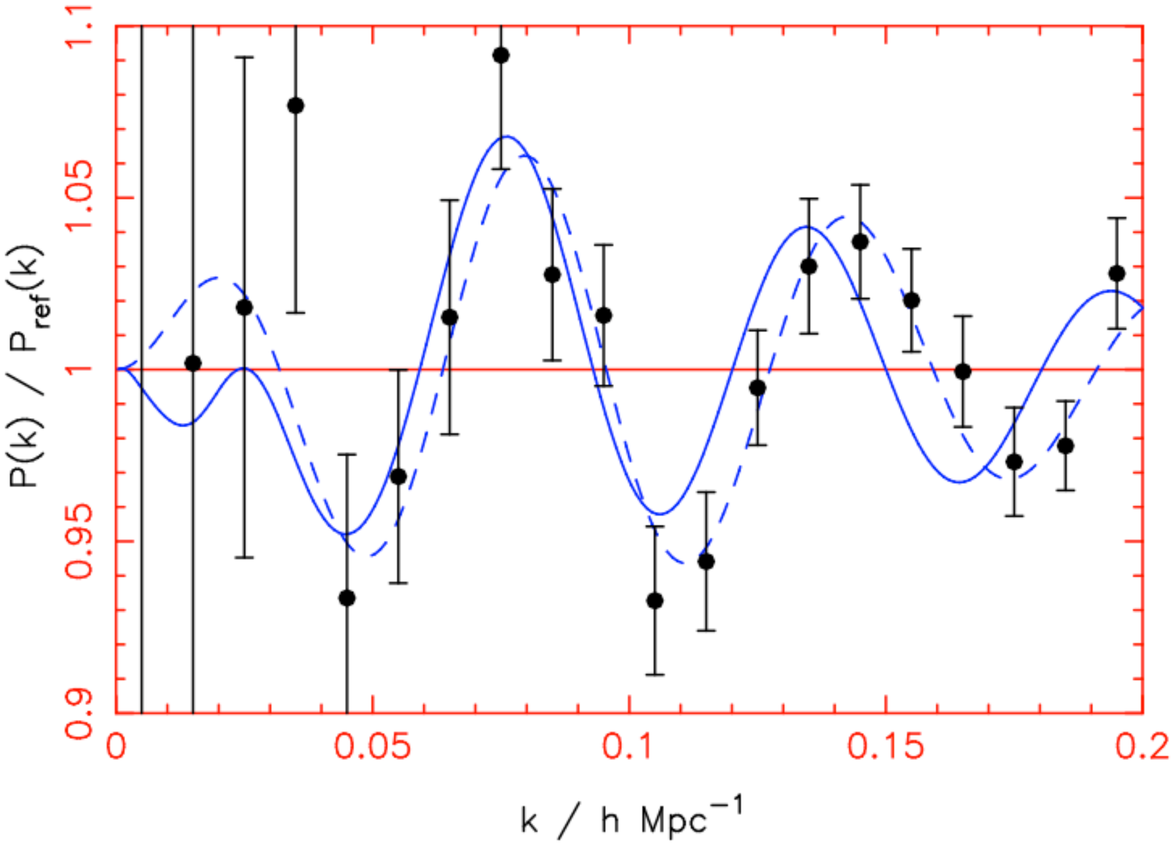
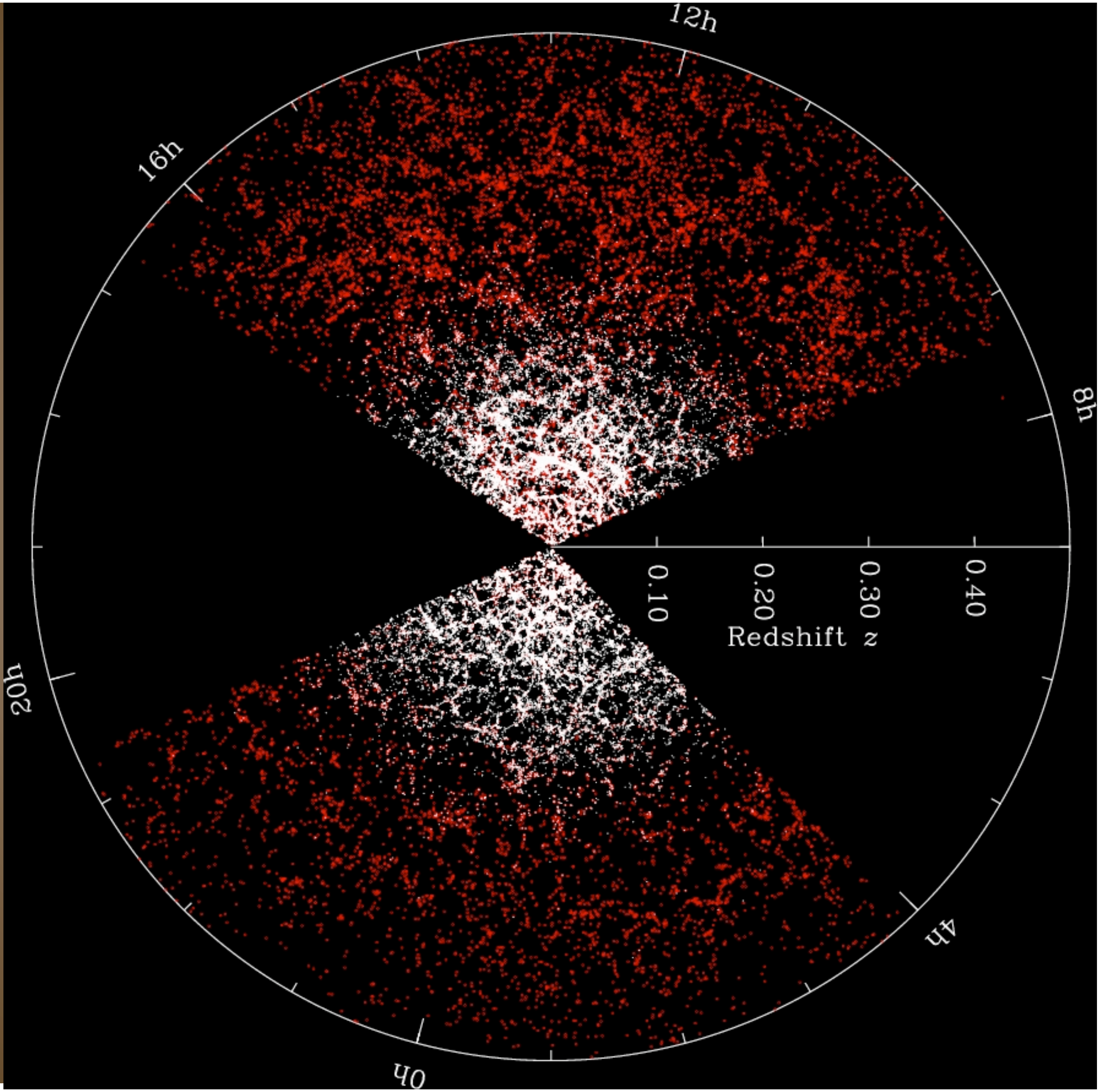


Fig. 6.— Power spectrum measurement for a simulated survey with the same parameters as Figure 2, except that the value $w = -0.8$ has been incorrectly assumed. The wavescale of the fitted function (the dashed line) is spuriously distorted

SDSS Galaxy Distribution

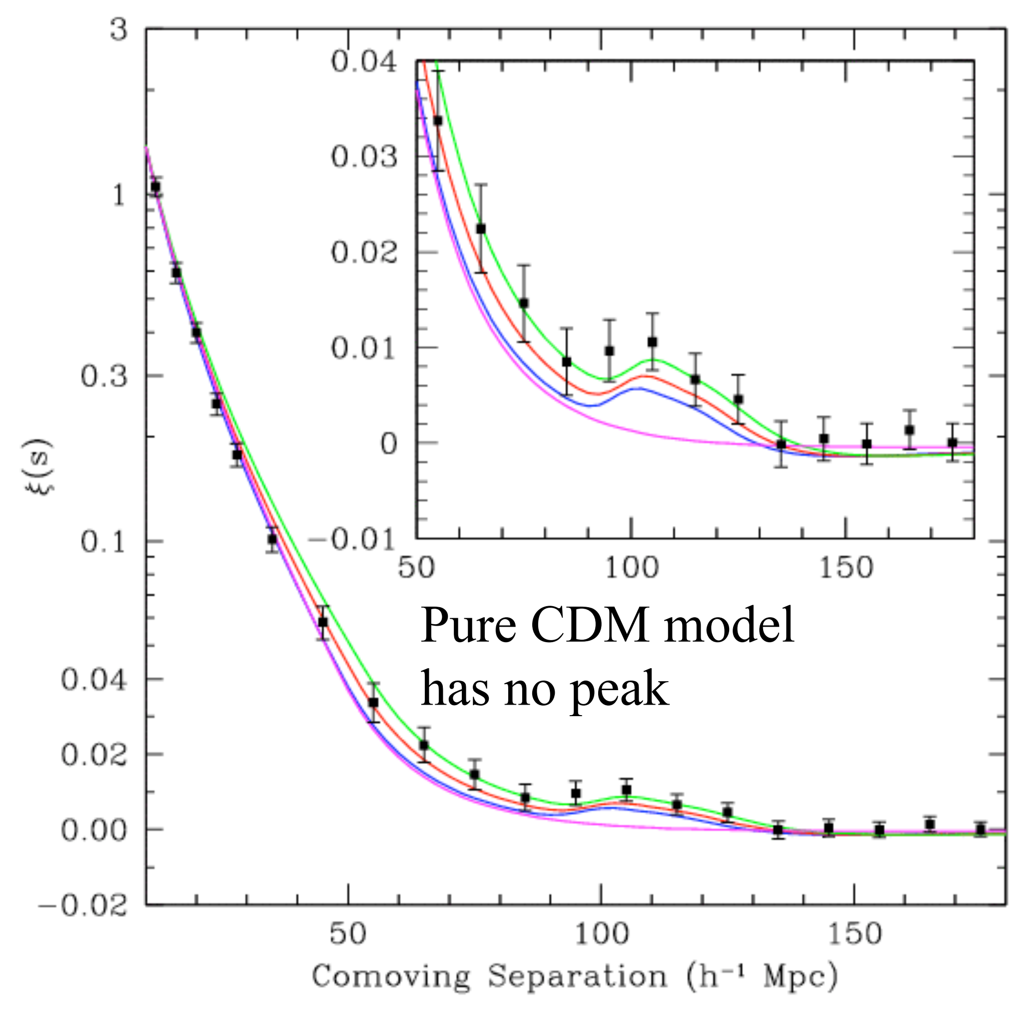
Luminous Red Galaxies



Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function

$$\xi(r) = \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \right\rangle$$



Pure CDM model has no peak

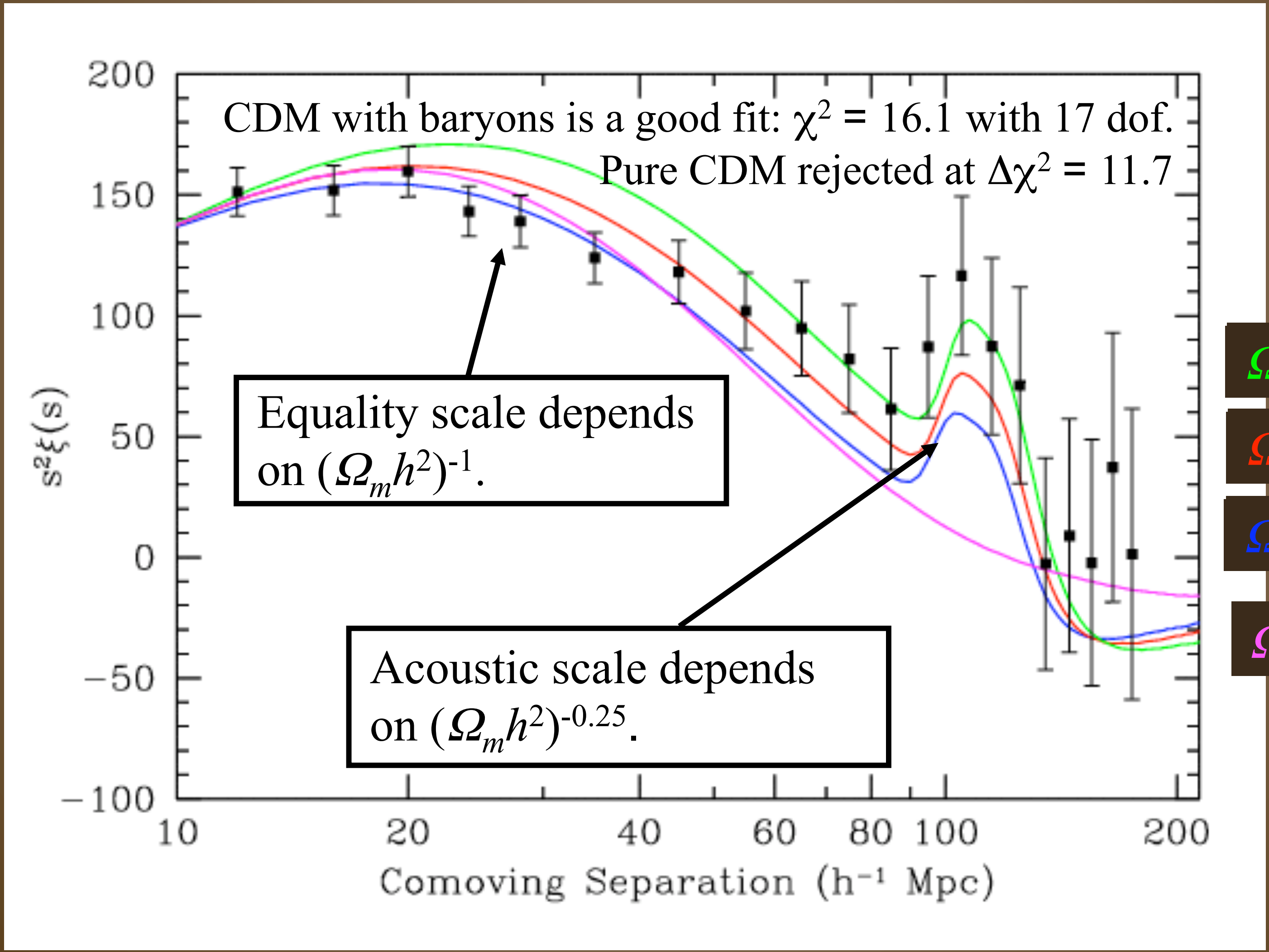
Baryon Acoustic Oscillations seen in Large-scale Structure

Warning: Correlated Error Bars

Eisenstein, etal

Model Comparison

Fixed $\Omega_b h^2=0.024$
$n_s=0.98$, flat



CDM with baryons is a good fit: χ^2 = 16.1 with 17 dof.
Pure CDM rejected at $\Delta\chi^2$ = 11.7

Equality scale depends on $(\Omega_m h^2)^{-1}$.

Acoustic scale depends on $(\Omega_m h^2)^{-0.25}$.

$\Omega_m h^2 = 0.12$

$\Omega_m h^2 = 0.13$

$\Omega_m h^2 = 0.14$

$\Omega_b h^2 = 0.00$

Constraints

Galaxy pair with separations $\Delta z,\ \Delta\theta$:

$\Delta r_c = c\Delta z / H(z)$ radial comoving separation

$\Delta r_c = \Delta\theta(1+z)d_A$ angular comoving separation

Spherically averaged correlation function probes

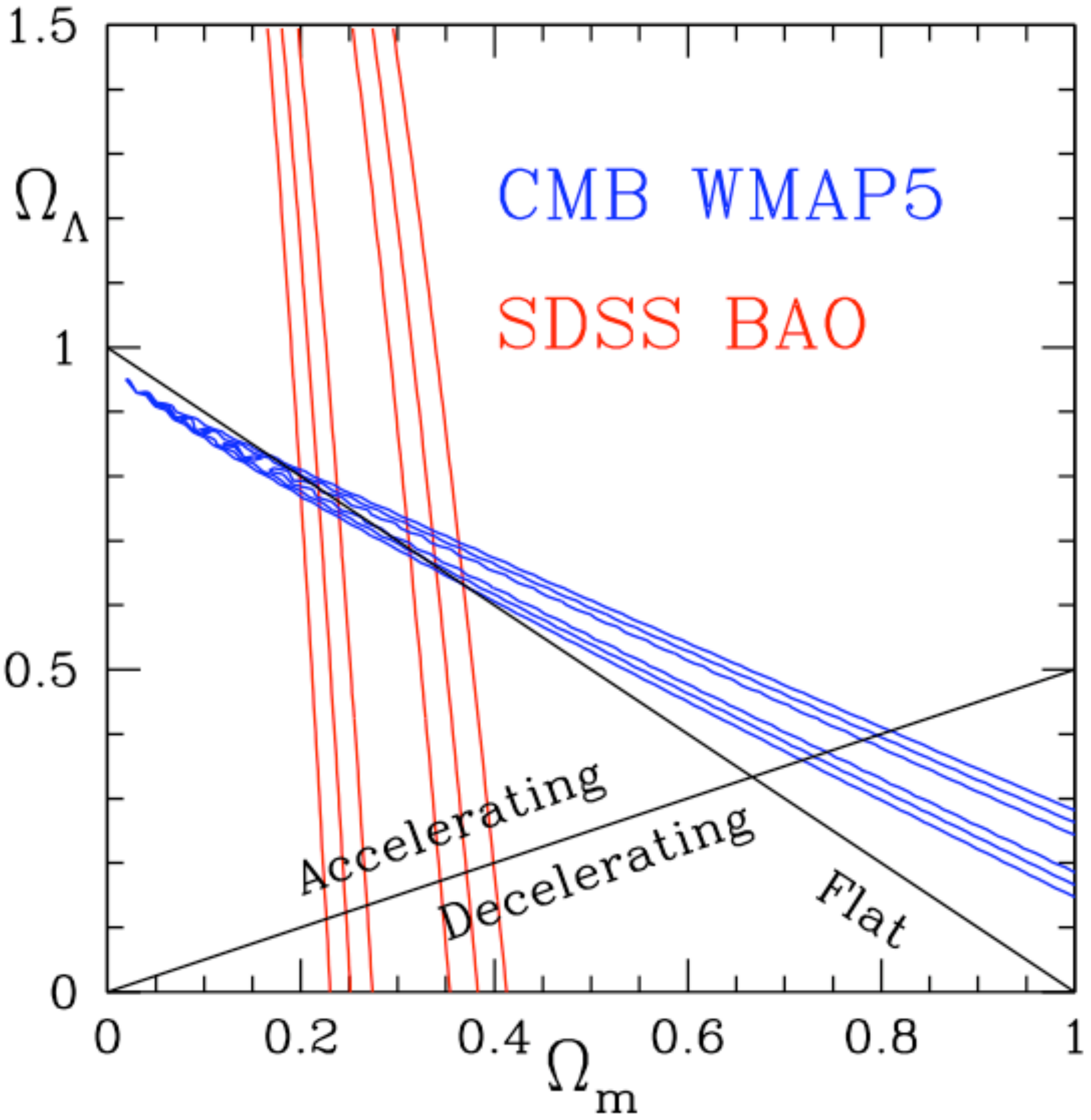
$$D_V(z) = \left[(1+z)^2 d_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

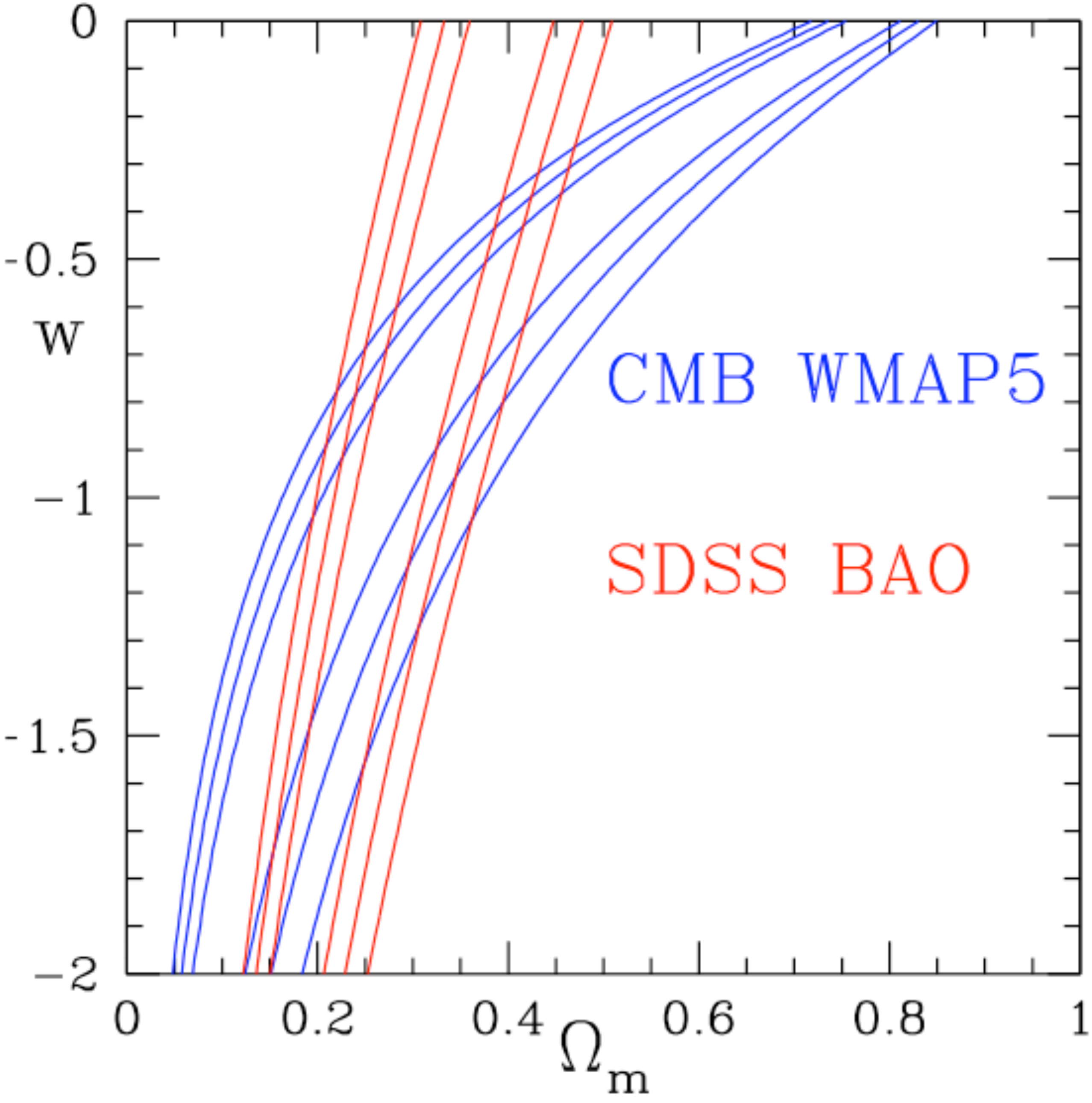
$$\text{SDSS}:\ D_V(z=0.35) = 1370 \pm 64\ \text{Mpc}$$

$$R_{0.35} = D_V(0.35)/d_A(z_{LS}) = 0.0979 \pm 0.0036$$

$$A = D_V(0.35)\frac{\sqrt{\Omega_m H_0^2}}{0.35c} = 0.469 \pm 0.017$$

Eisenstein etal 2005


1.5
1
0.5
0
Ω_Λ
0
0.2
0.4
0.6
0.8
1
Ω_m
CMB WMAP5
SDSS BAO
Accelerating
Decelerating
Flat


0
-0.5
w
−1
-1.5
−2
0
0.2
0.4
Ω_m
0.6
0.8
1
CMB WMAP5
SDSS BAO

MLCS
SALT

SDSS only:

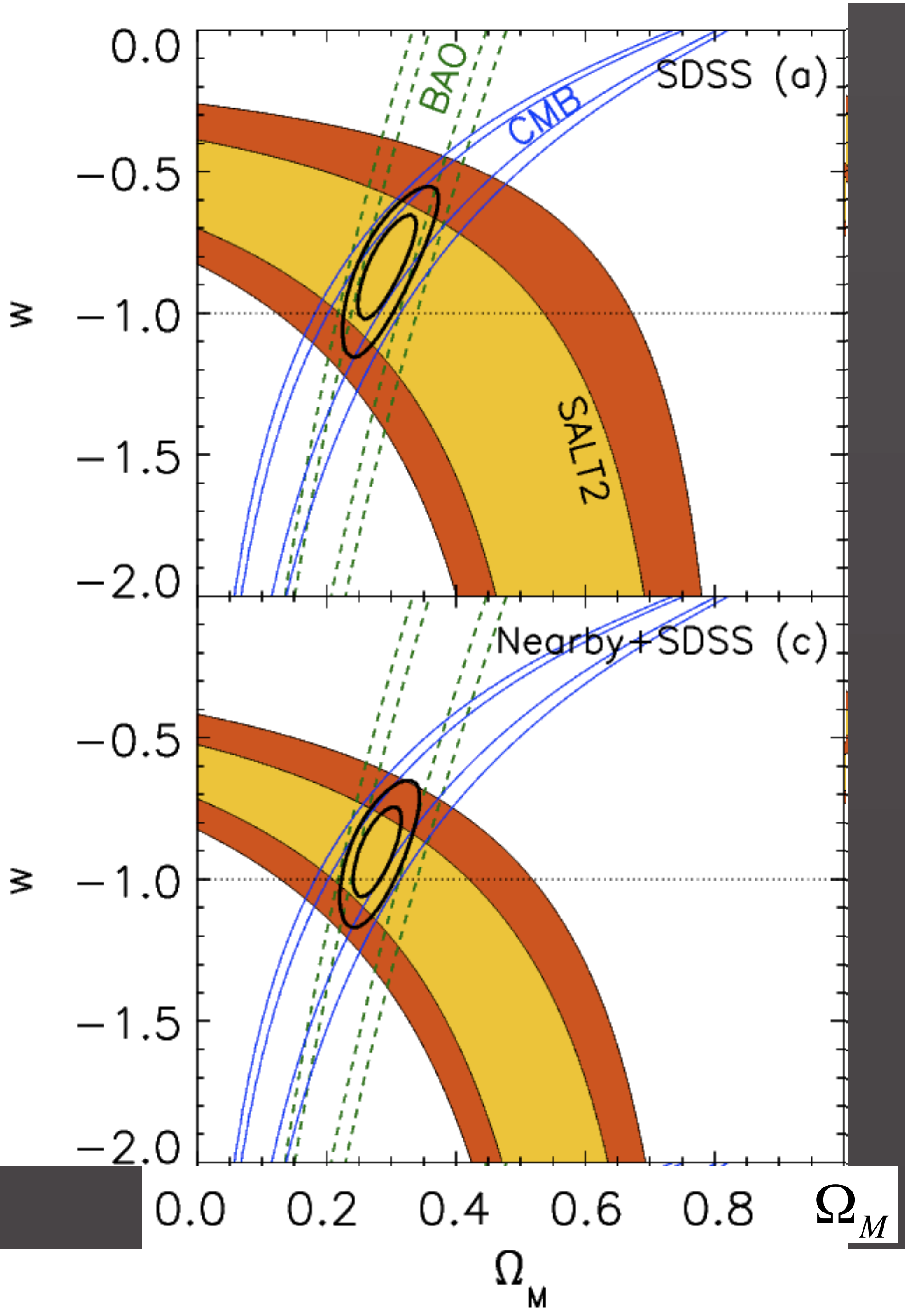
Nearby+SDSS:

MLCS

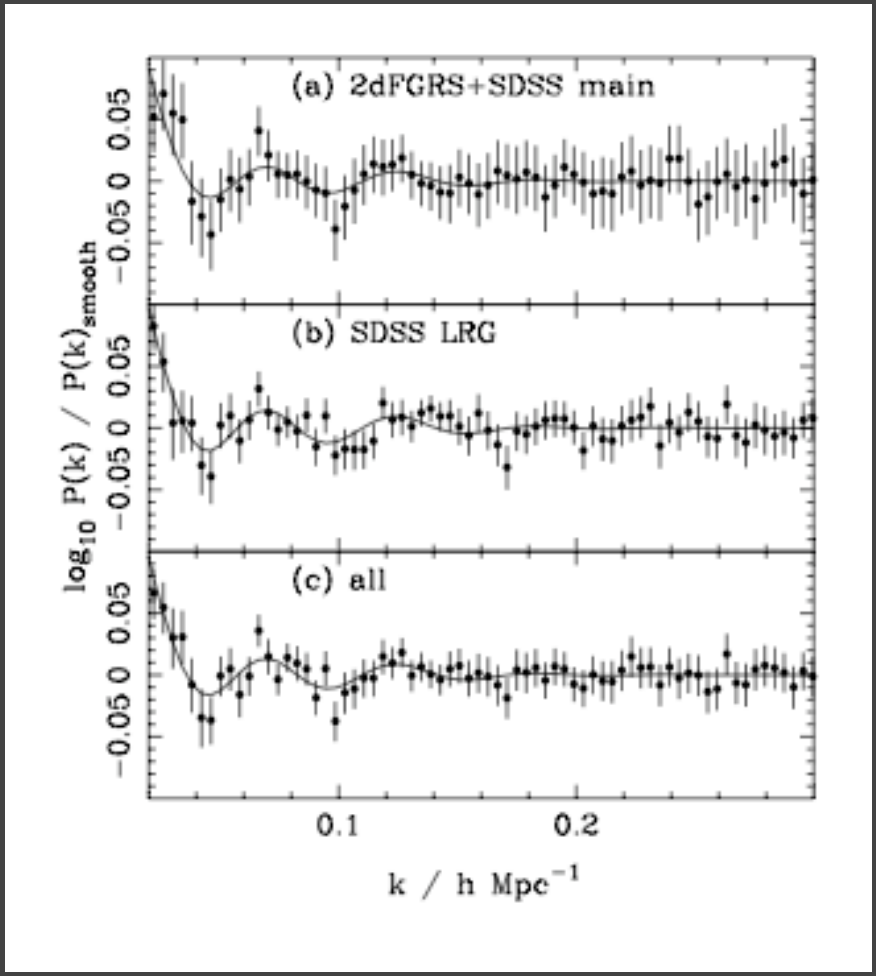
$w = -0.93 \pm 0.13(\mathrm{stat})^{+0.10}_{-0.32}(\mathrm{syst})$

SALT

$w = -0.92 \pm 0.11(\mathrm{stat})^{+0.07}_{-0.15}(\mathrm{syst})$



BAO from SDSS + 2dFGRS



BAO detected at low redshift
0<z<0.3 (effective redshift 0.2)
SDSS main + 2dFGRS

BAO detected at high redshift
0.15<z<0.5 (effective redshift 0.35)
SDSS LRGs

BAO from combined sample
(detected over the whole redshift range 0<z<0.5)
All SDSS + 2dFGRS

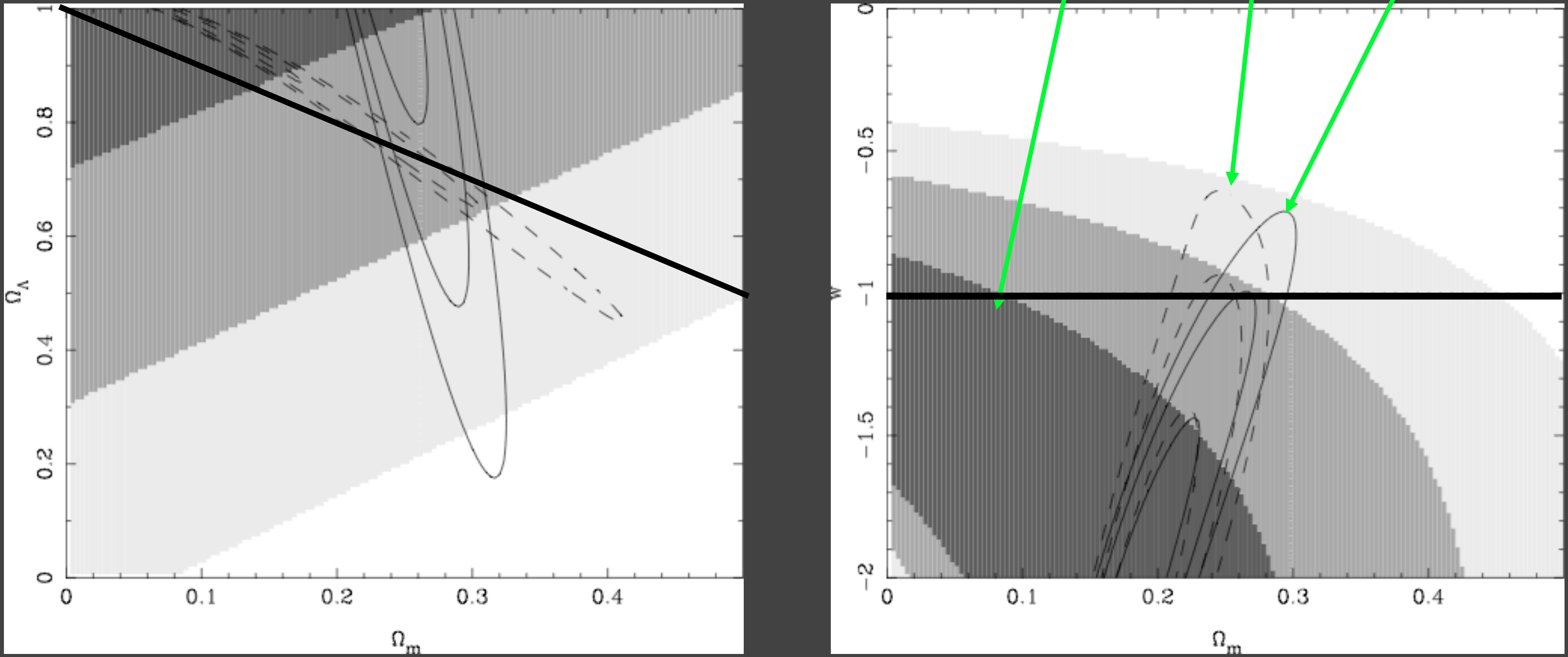
$$\frac{D_V(z=0.35)}{D_V(z=0.2)} = 1.812 \pm 0.060$$

Percival et al. 2007

Cosmological constraints: BAO

Consider two simple models:

1. ΛCDM
2. Flat, constant *w*



Constraint fitting s/D_V with model for s

Constraint including distance to CMB $d_A(z_{LS})/D_V$

Constraint from $D_V(0.35)/D_V(0.2)$

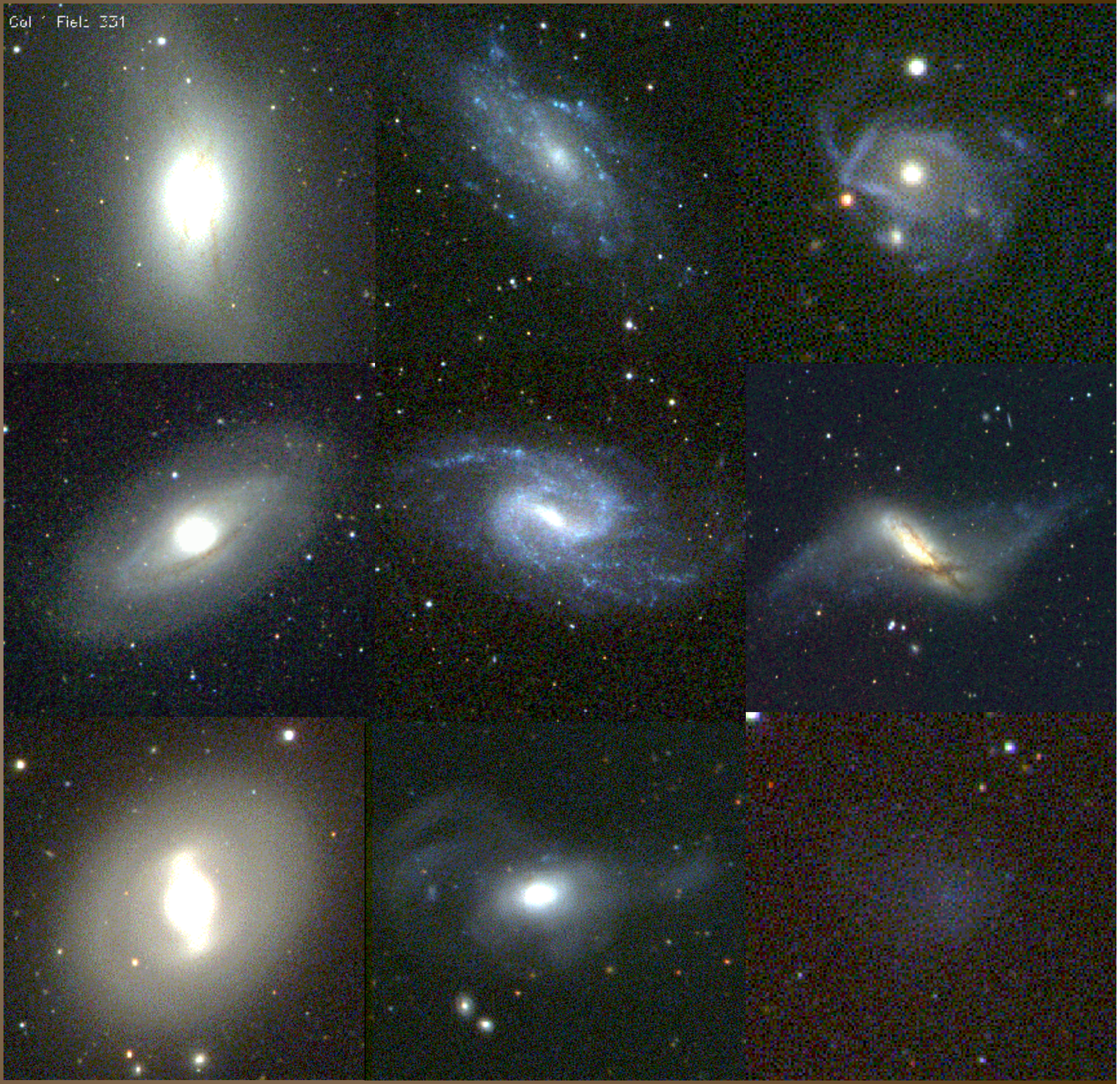
Percival et al. 2007

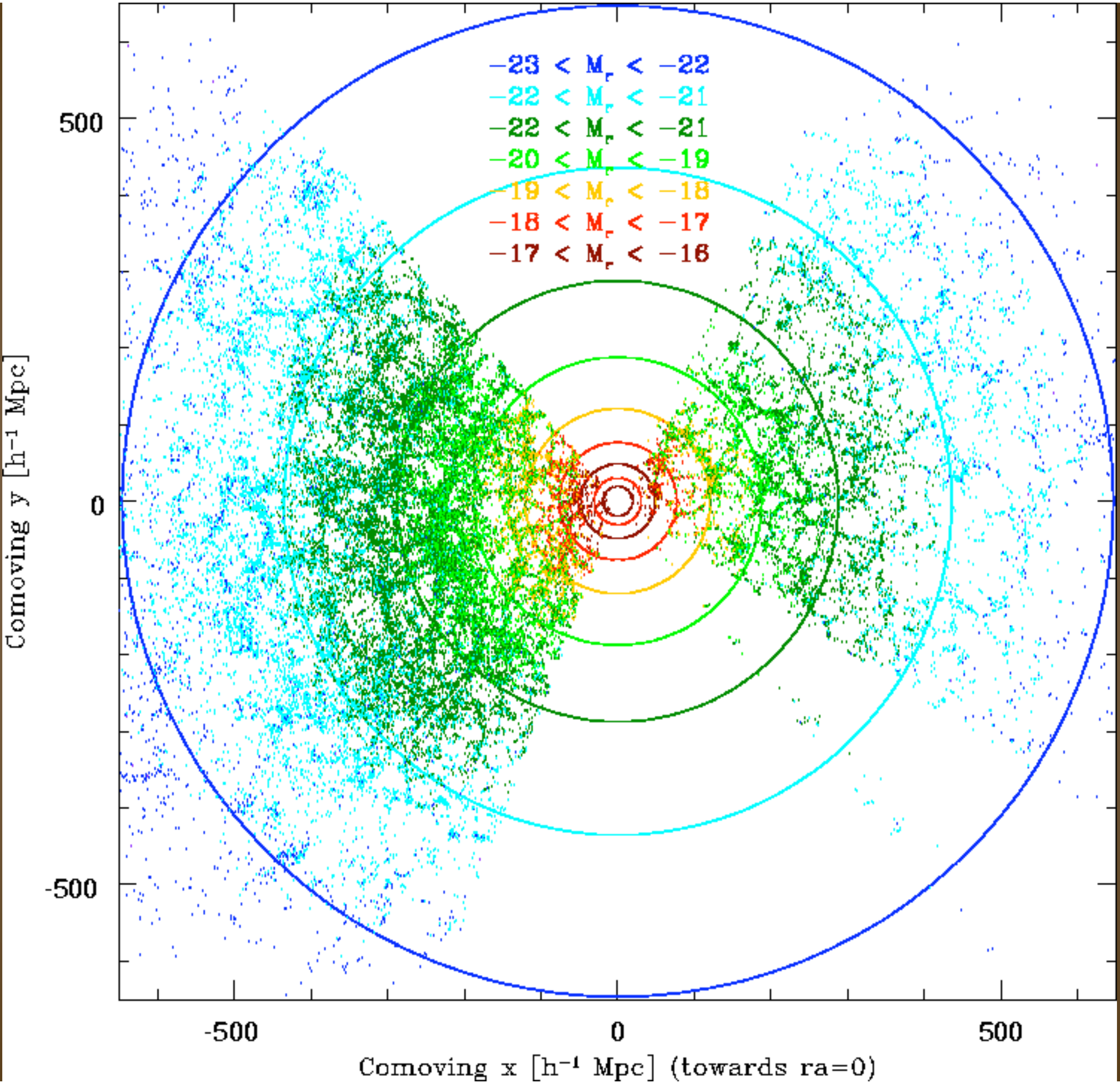
Galaxy Clustering varies with Galaxy Type

How are each of them related to the underlying Dark Matter distribution?

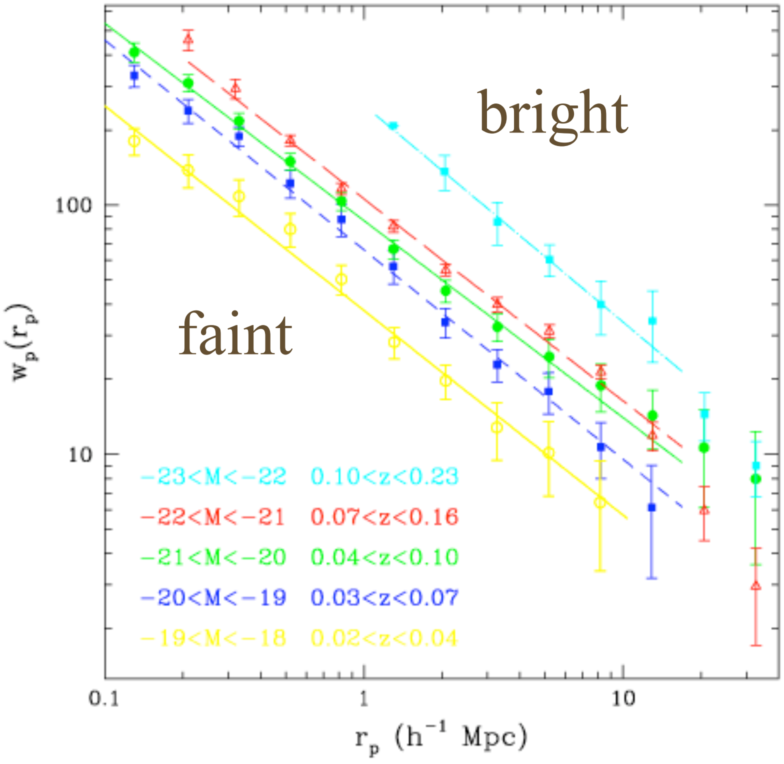
BIAS

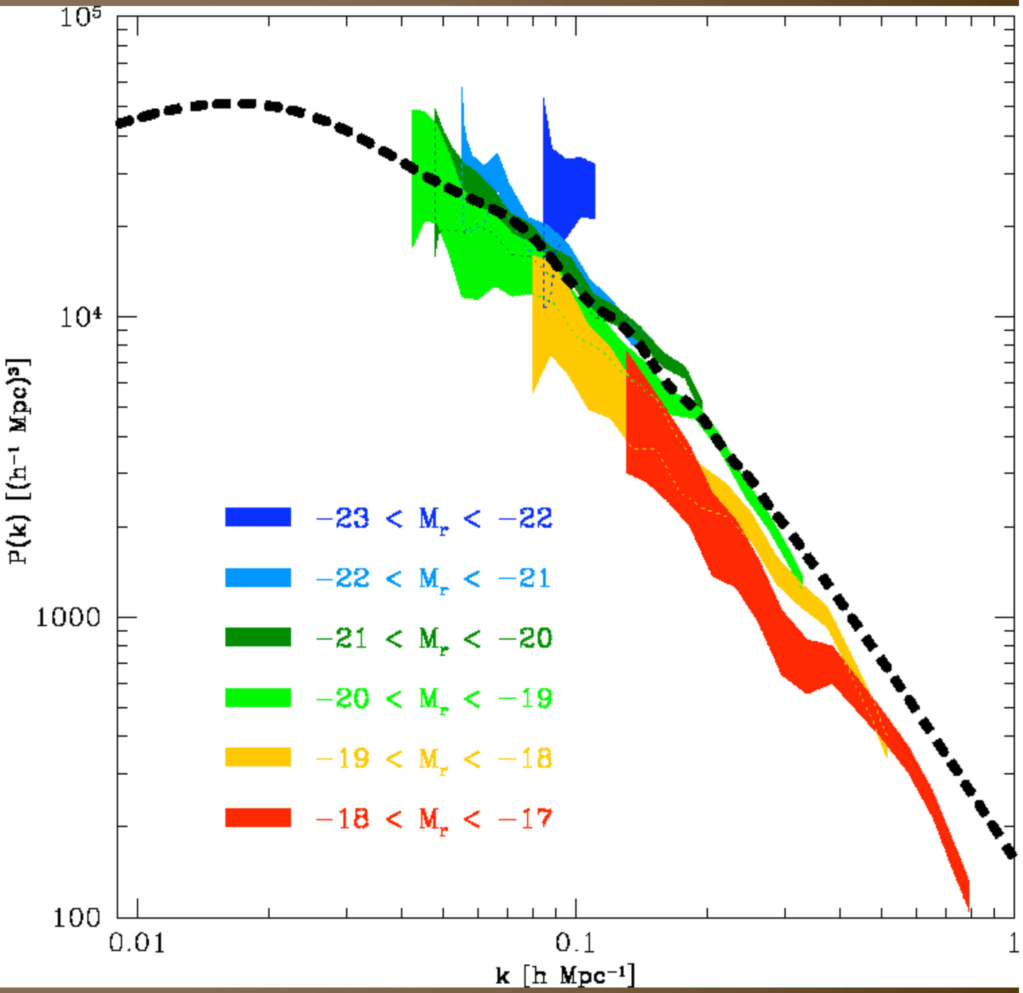
Caveat for inference of Cosmological Parameters from LSS




−23 < M_r < −22
−22 < M_r < −21
−22 < M_r < −21
−20 < M_r < −19
−19 < M_r < −18
−18 < M_r < −17
−17 < M_r < −16
500
0
-500
Comoving y [h⁻¹ Mpc]
-500
0
500
Comoving x [h⁻¹ Mpc] (towards ra=0)

Galaxy Clustering as a function of Galaxy Luminosity





Zehavi, etal

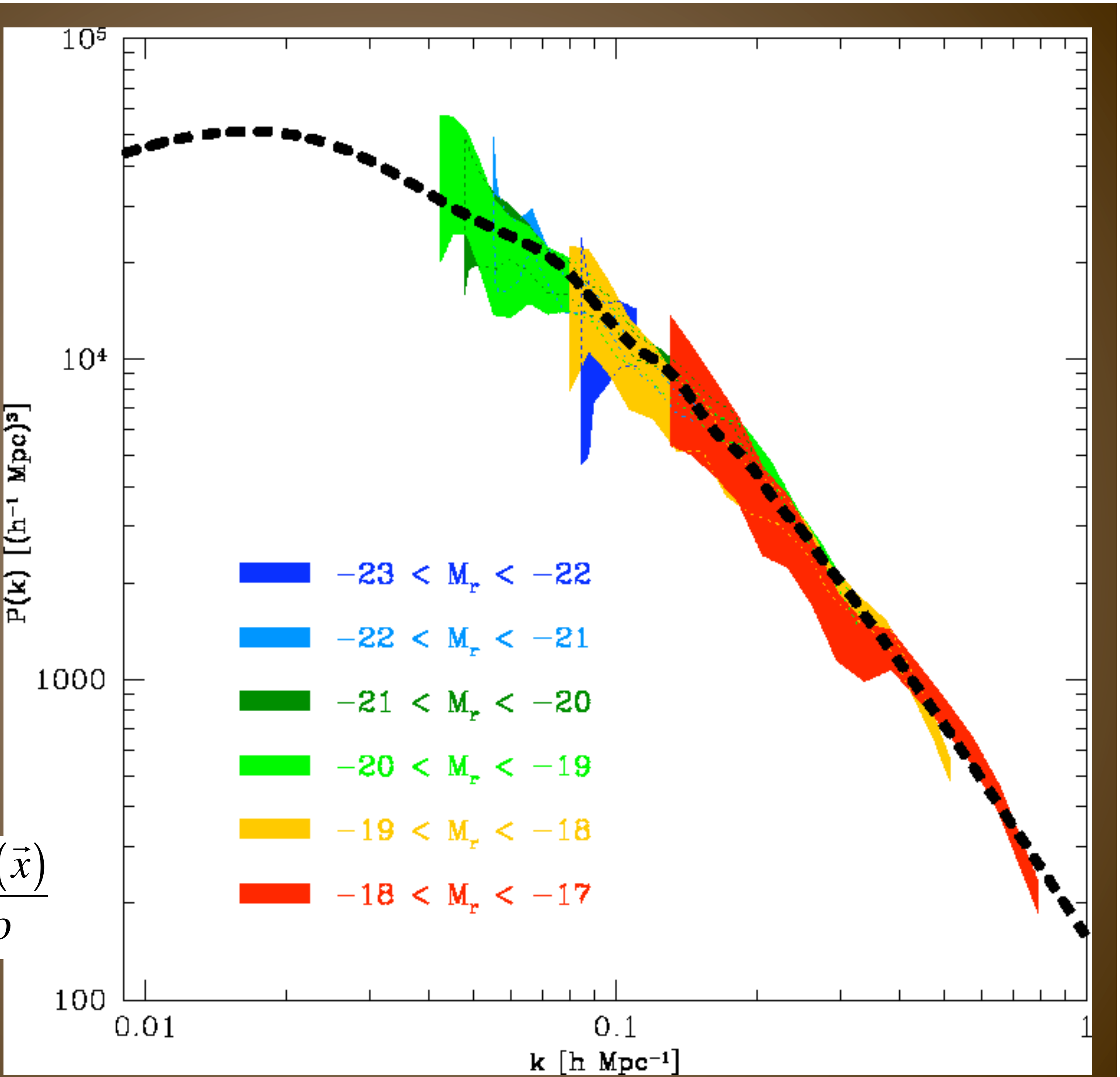
Tegmark, etal

Based on sample of ~200,000 galaxies

Correct For Luminosity Bias

Vertical Shift: Constant *Bias*

$$\frac{\delta n_{gal}(L,\vec{x})}{n_{gal}(L)} = b(L)\frac{\delta\rho(\vec{x})}{\rho}$$



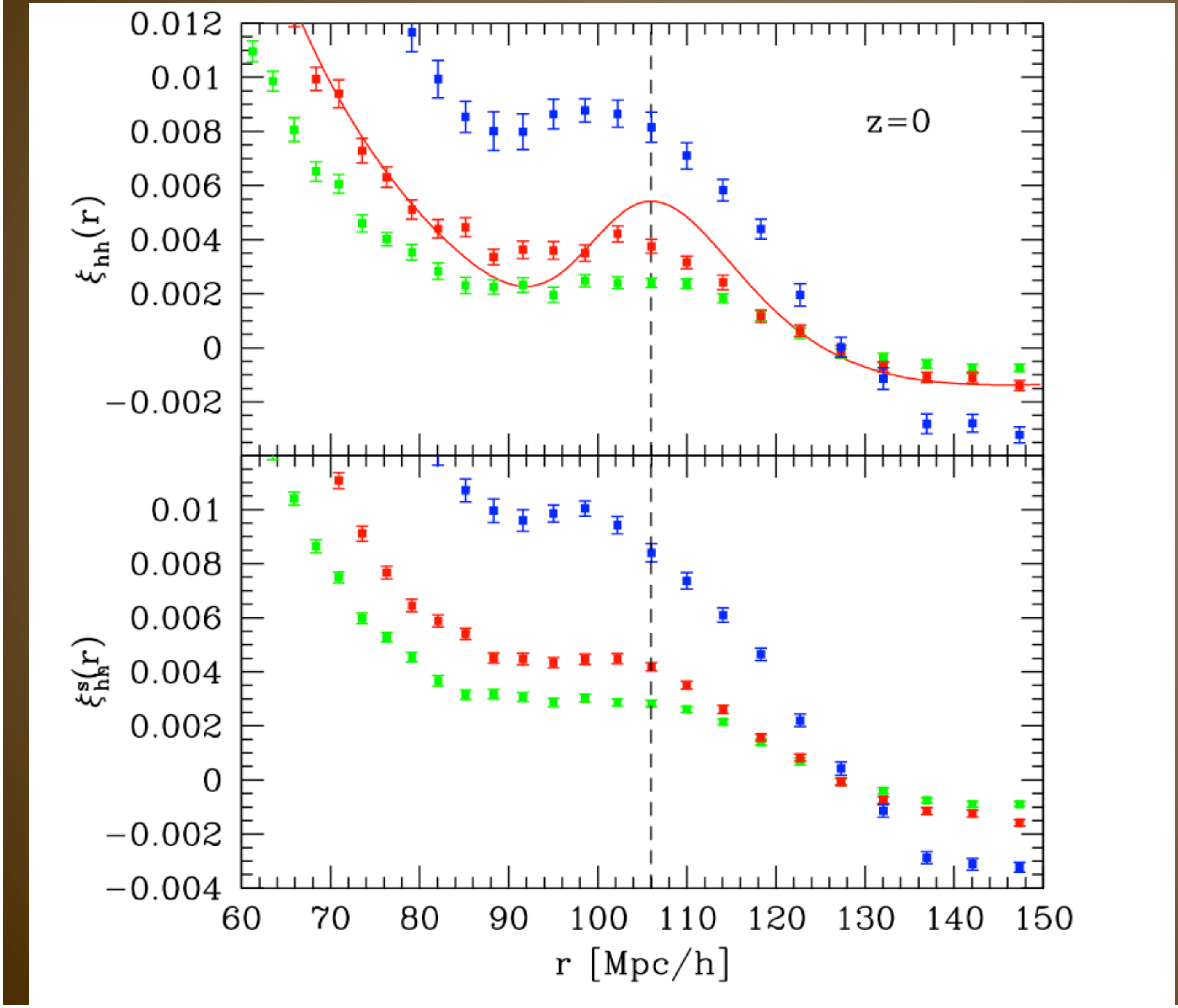
Systematic Issues for BAO

Effects of non-linearities on BAO signal

Modeling redshift distortions precisely

Effects of (non-linear) galaxy bias

Halos vs. Dark Matter



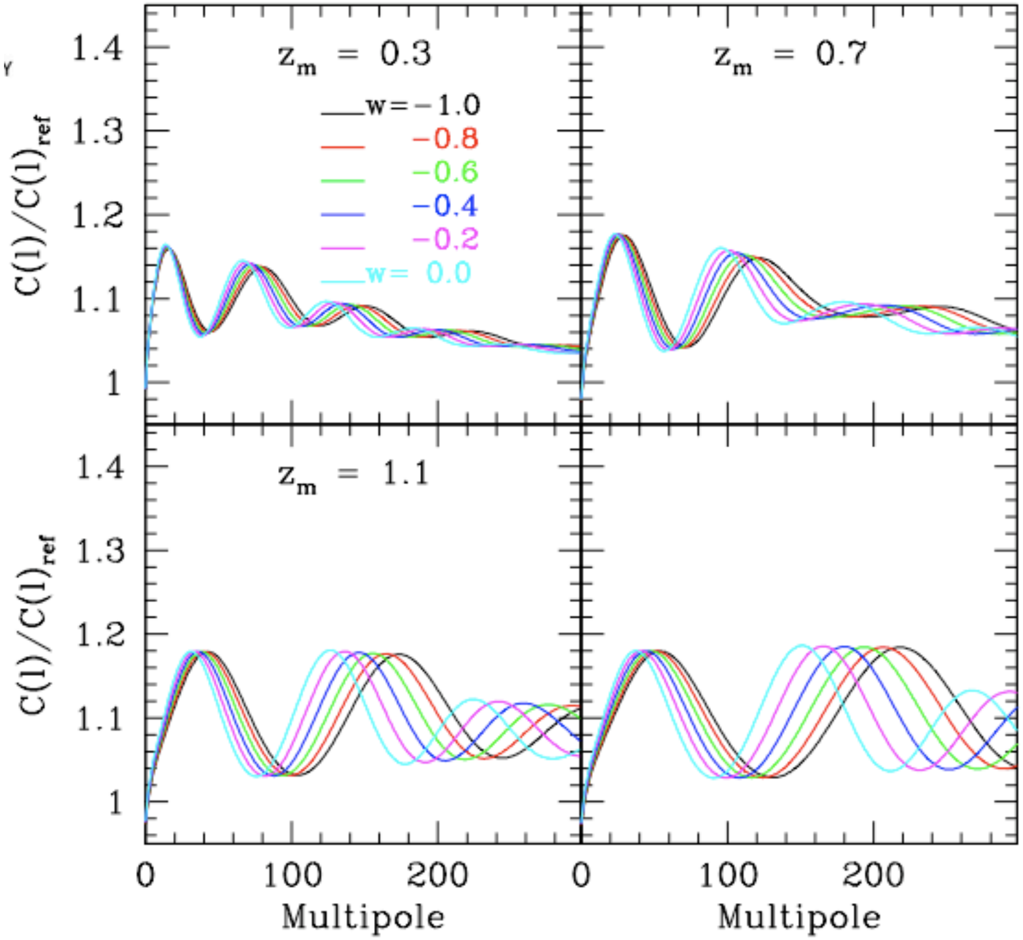
Real Space

Redshift Space

III. Baryon Acoustic Oscillations

Galaxy Angular Correlation Function in Photo-z bins

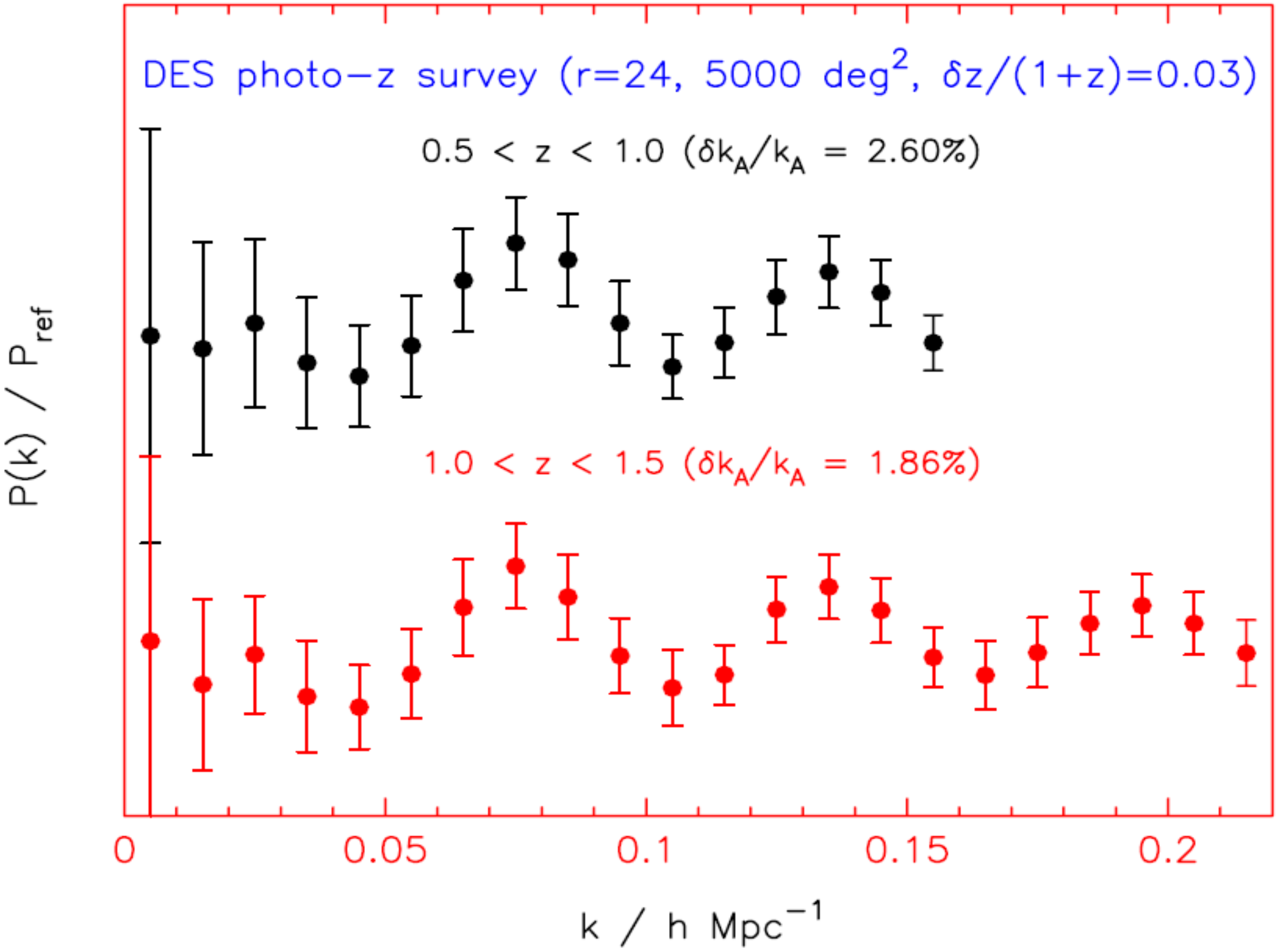
Systematics:
photo-z's,
correlated photometric errors,
non-linearity, scale-dependent bias



Fosalba & Gaztanaga

DARK ENERGY SURVEY

III. Baryon Acoustic Oscillations



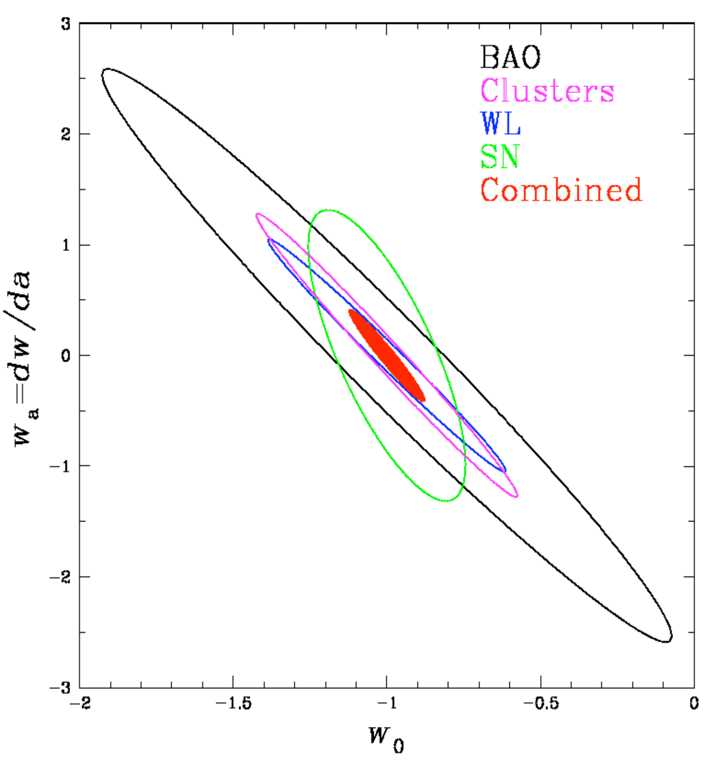
Blake & Bridle

DES Science Program

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - ~10,000 with SZE measurements from SPT
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Forecast Constraints on DE Equation of State

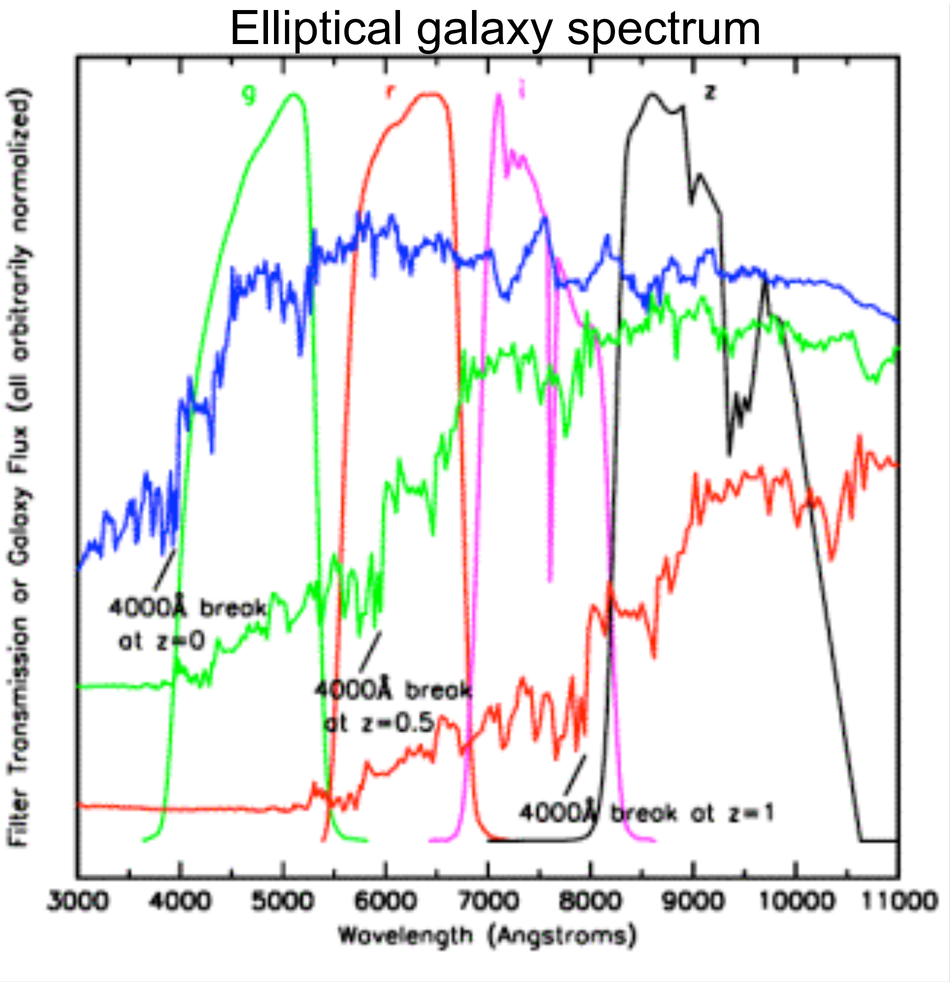


Photometric Redshifts

- Measure relative flux in multiple filters:
  track the 4000 A break

- Estimate individual galaxy redshifts with accuracy
  $\sigma(z) < 0.1$ (~0.02 for clusters)

- Precision is sufficient for Dark Energy probes, provided error distributions well measured.



Elliptical galaxy spectrum

Galaxy Photo-z Simulations

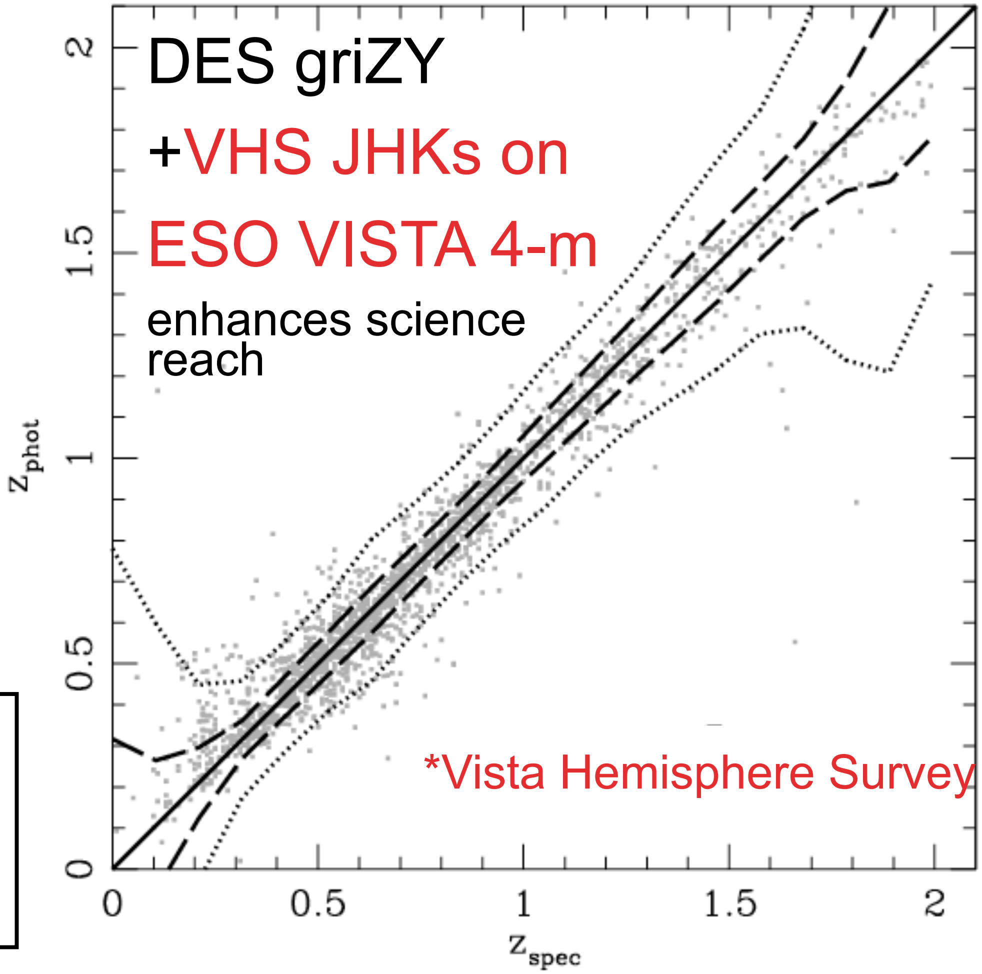
DES +VHS*

10σ Limiting Magnitudes

g	24.6		
r	24.1	J	20.3
i	24.0	H	19.4
Z	23.8	Ks	18.3
Y	21.6		

+2% photometric calibration error added in quadrature

Photo-z systematic errors under control using *existing* spectroscopic training sets to DES photometric depth: low-risk



DES griZY +VHS JHKs on ESO VISTA 4-m enhances science reach

*Vista Hemisphere Survey

+Developed improved Photo-z & Error Estimates and robust methods of outlier rejection

Oyaizu, Cunha, Lima, Frieman, Lin