WMAP 5-Year Results: Implications for Dark Energy

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WMAP 5-Year Papers

- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" 0803.0732
- **Hill et al.**, "*Beam Maps and Window Functions*" 0803.0570
- **Gold et al.**, "*Galactic Foreground Emission*" 0803.0715
- **Wright et al.**, "*Source Catalogue*" 0803.0577
- **Nolta et al.**, "*Angular Power Spectra*" 0803.0593
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" 0803.0586
- **Komatsu et al**., "*Cosmological Interpretation*" 0803.0547

WMAP 5-Year Science Team

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Special Thanks to **WMAP Graduates!**

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Need For Dark "Energy"

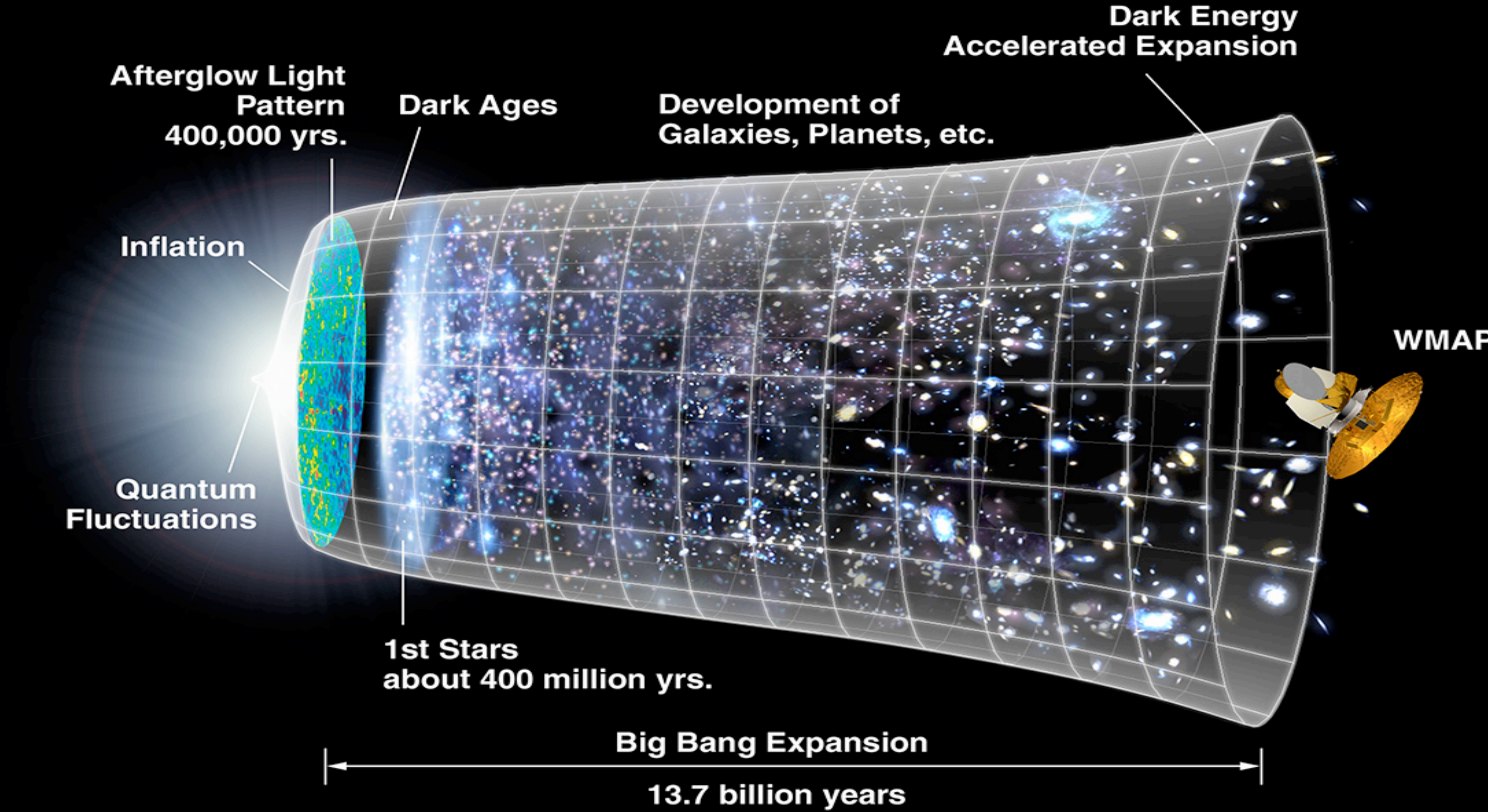
- First of all, DE does not even need to be energy.
- At present, *anything* that can explain the observed

  (1) **Luminosity Distances** (Type Ia supernovae)

  (2) **Angular Diameter Distances** (BAO, CMB)

  simultaneously is qualified for being called "Dark Energy."
- The candidates in the literature include: (a) energy, (b) modified gravity, and (c) extreme inhomogeneity.
- Measurements of the (3) **growth of structure** break degeneracy. (The best data right now is the X-ray clusters.)

Measuring Distances, H(z) & Growth of Structure



NASA/WMAP Science Team

WMAP5+BAO+SN

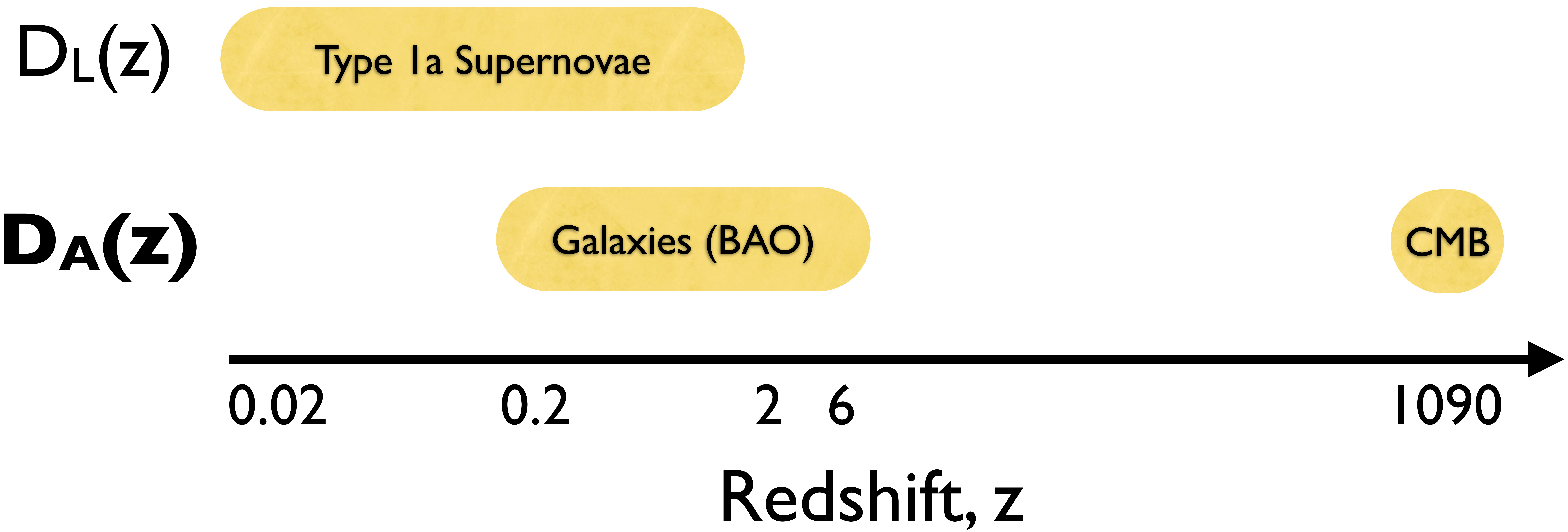
H(z): Current Knowledge

- $H^2(z) = H^2(0)[\Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_k(1+z)^2+\Omega_{de}(1+z)^{3(1+w)}]$
  - (expansion rate) H(0) = 70.5 ± 1.3 km/s/Mpc
  - (radiation) $\Omega_r = (8.4\pm0.3)\times10^{-5}$
  - (matter) $\Omega_m = 0.274\pm0.015$
  - (curvature) $\Omega_k < 0.008$ (95%CL)
  - (dark energy) $\Omega_{de} = 0.726\pm0.015$
  - (DE equation of state) $1+w = -0.006\pm0.068$

H(z) to Distances

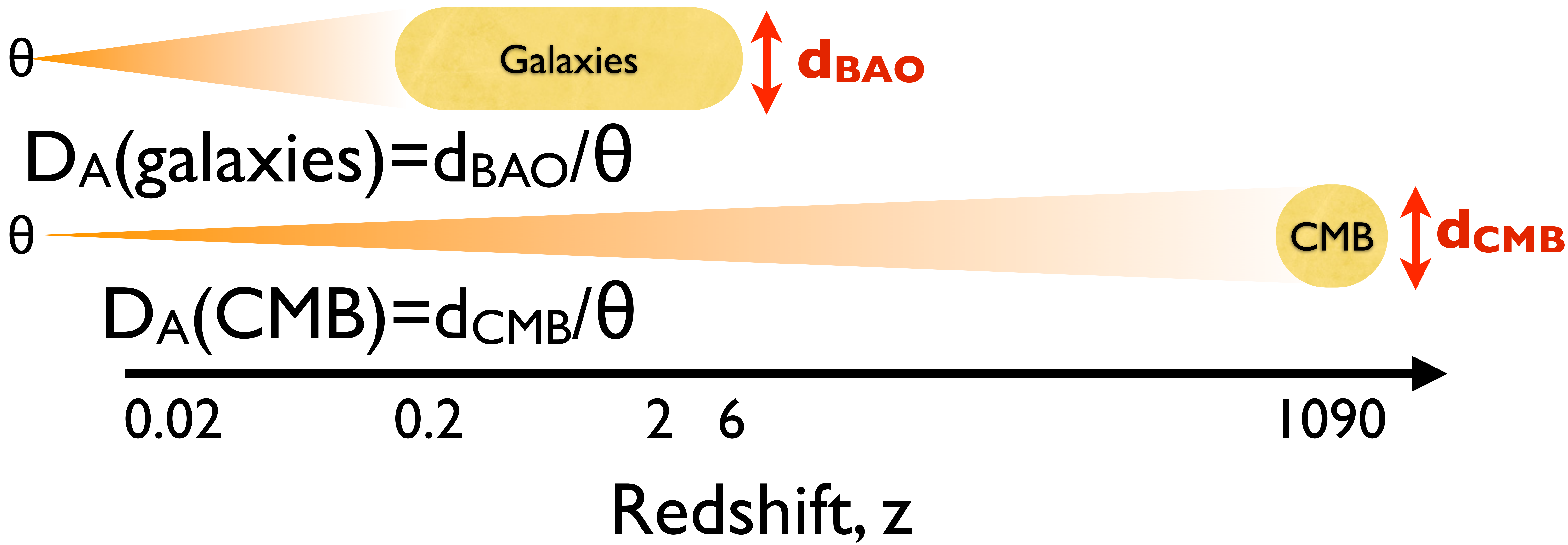
- Comoving Distance
  - $\chi(z) = c\int^z [dz'/H(z')]$
- Luminosity Distance
  - $D_L(z) = (1+z)\chi(z)[1-(k/6)\chi^2(z)/R^2+...]$
  - R=(curvature radius of the universe); k=(sign of curvature)
  - WMAP 5-year limit: $R>2\chi(\infty)$; justify the Taylor expansion
- Angular Diameter Distance
  - $D_A(z) = [\chi(z)/(1+z)][1-(k/6)\chi^2(z)/R^2+...]$

$$D_A(z) = (1+z)^{-2} D_L(z)$$



- To measure $D_A(z)$, we need to know the intrinsic size.
- What can we use as the *standard ruler*?

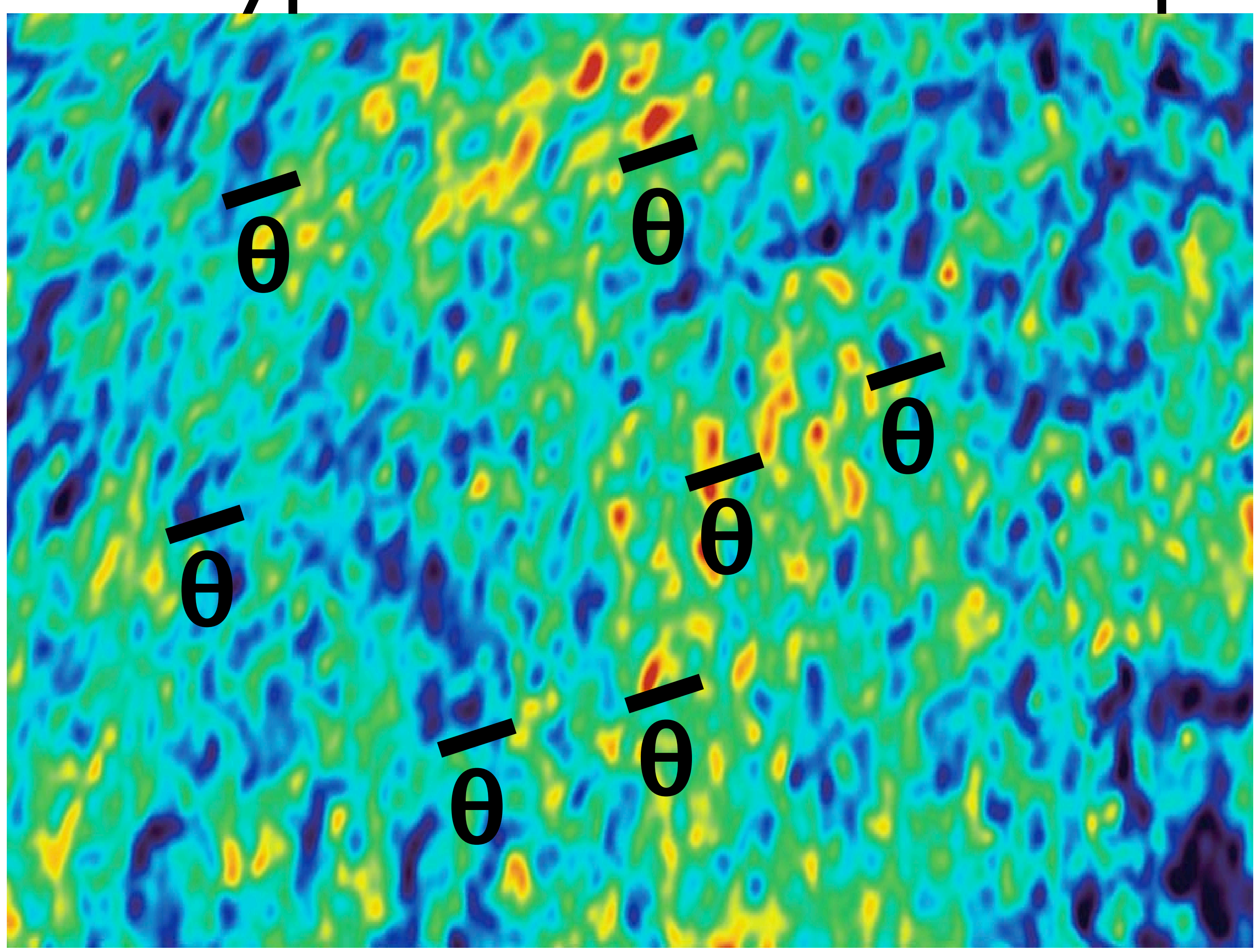
How Do We Measure $D_A(z)$?

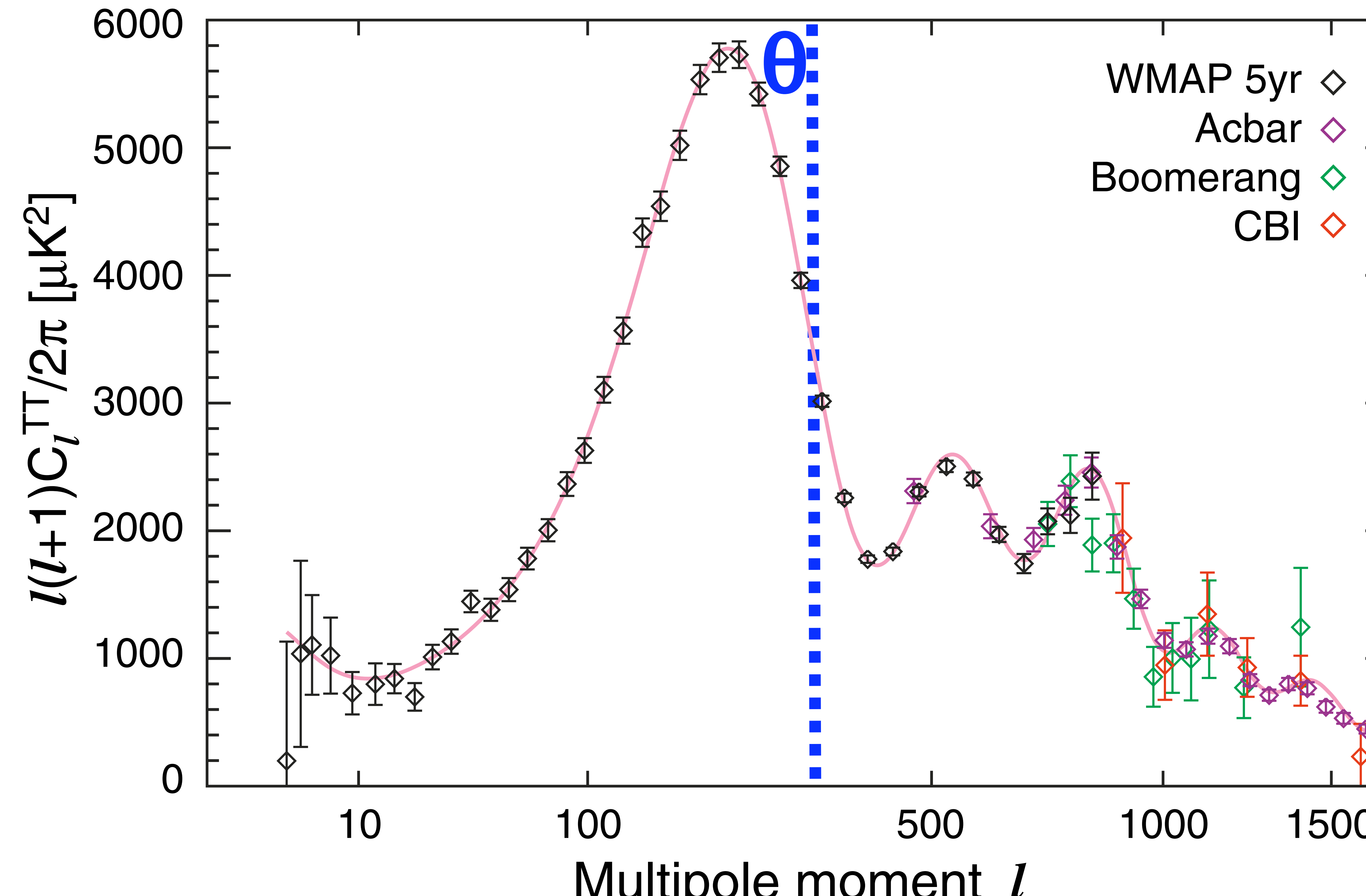


- If we know the intrinsic physical sizes, d, we can measure D_A. What determines d?

CMB as a Standard Ruler

θ~the typical size of hot/cold spots

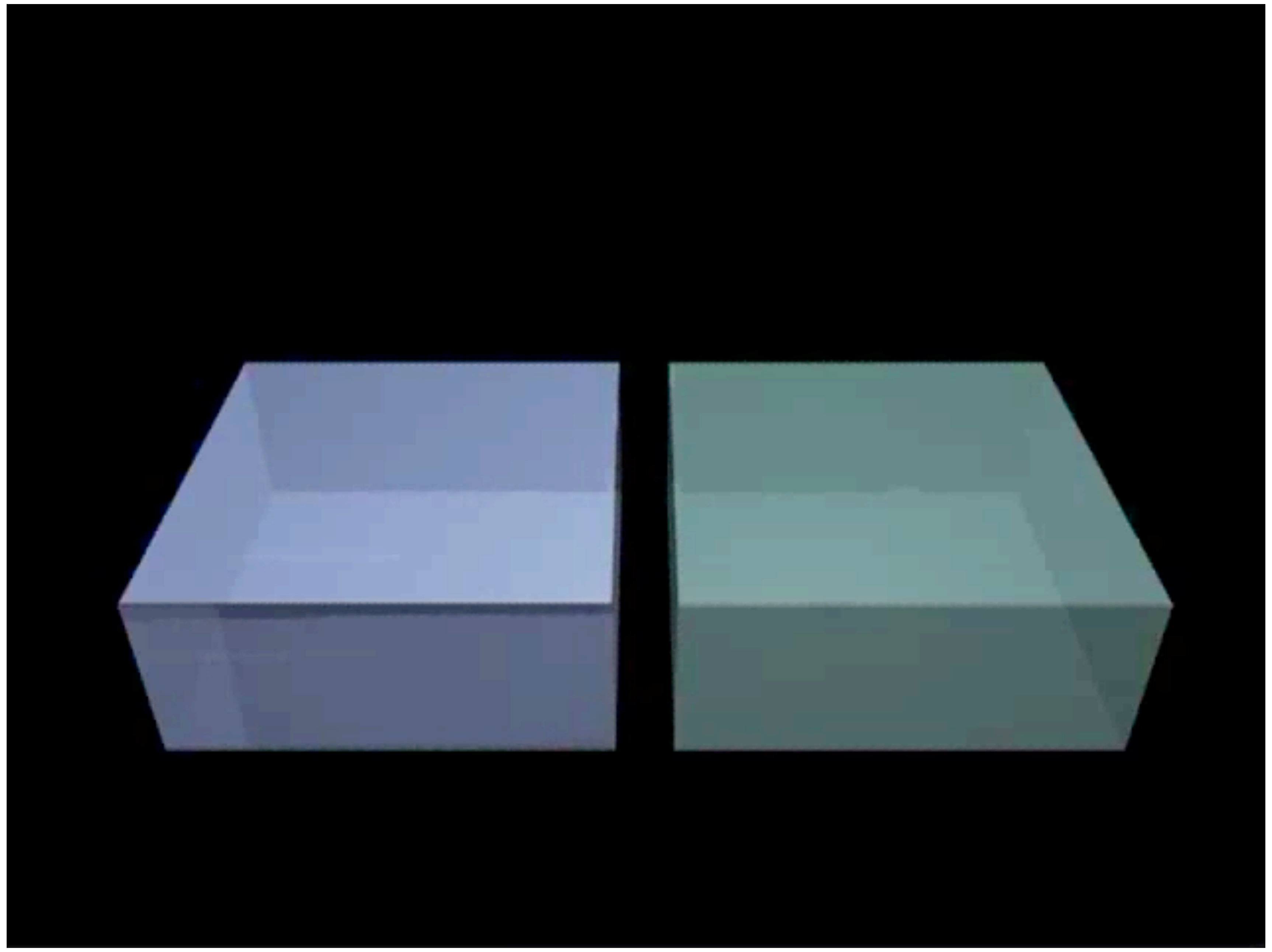


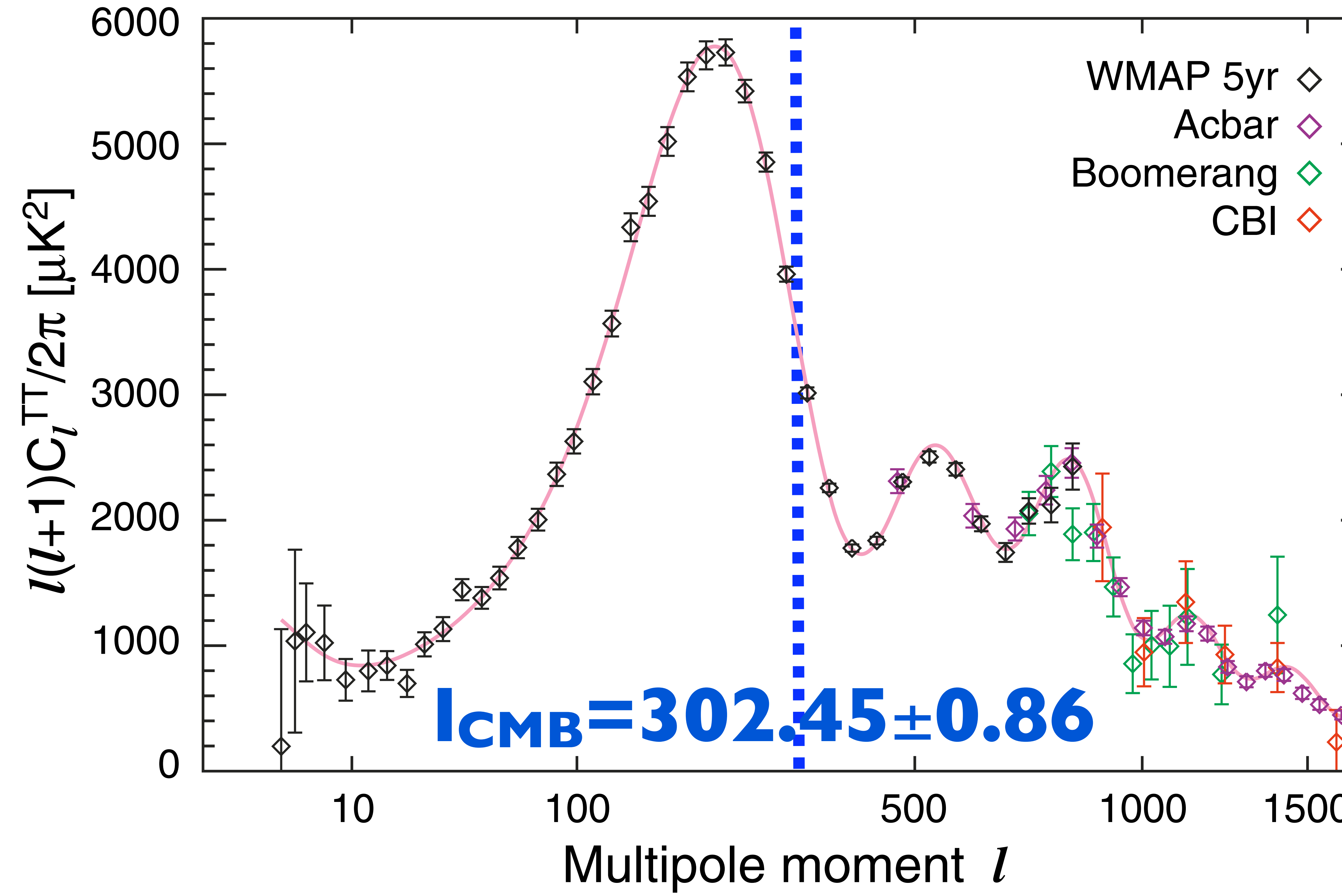


- The existence of typical spot size in image space yields oscillations in harmonic (Fourier) space. What determines the physical size of typical spots, **d_{CMB}**?

Sound Horizon

- The typical spot size, **d_{CMB}**, is determined by the **physical distance traveled by the sound wave** from the Big Bang to the decoupling of photons at z_{CMB}~1090 (t_{CMB}~380,000 years).
- The causal horizon (photon horizon) at t_{CMB} is given by
  - $d_H(t_{CMB})$ = $a(t_{CMB})$*Integrate[**c** dt/a(t), {t,0,t_{CMB}}].
- The **sound** horizon at t_{CMB} is given by
  - $d_s(t_{CMB})$ = $a(t_{CMB})$*Integrate[**c_s(t)** dt/a(t), {t,0,t_{CMB}}], where c_s(t) is the time-dependent **speed of sound of photon-baryon fluid**.

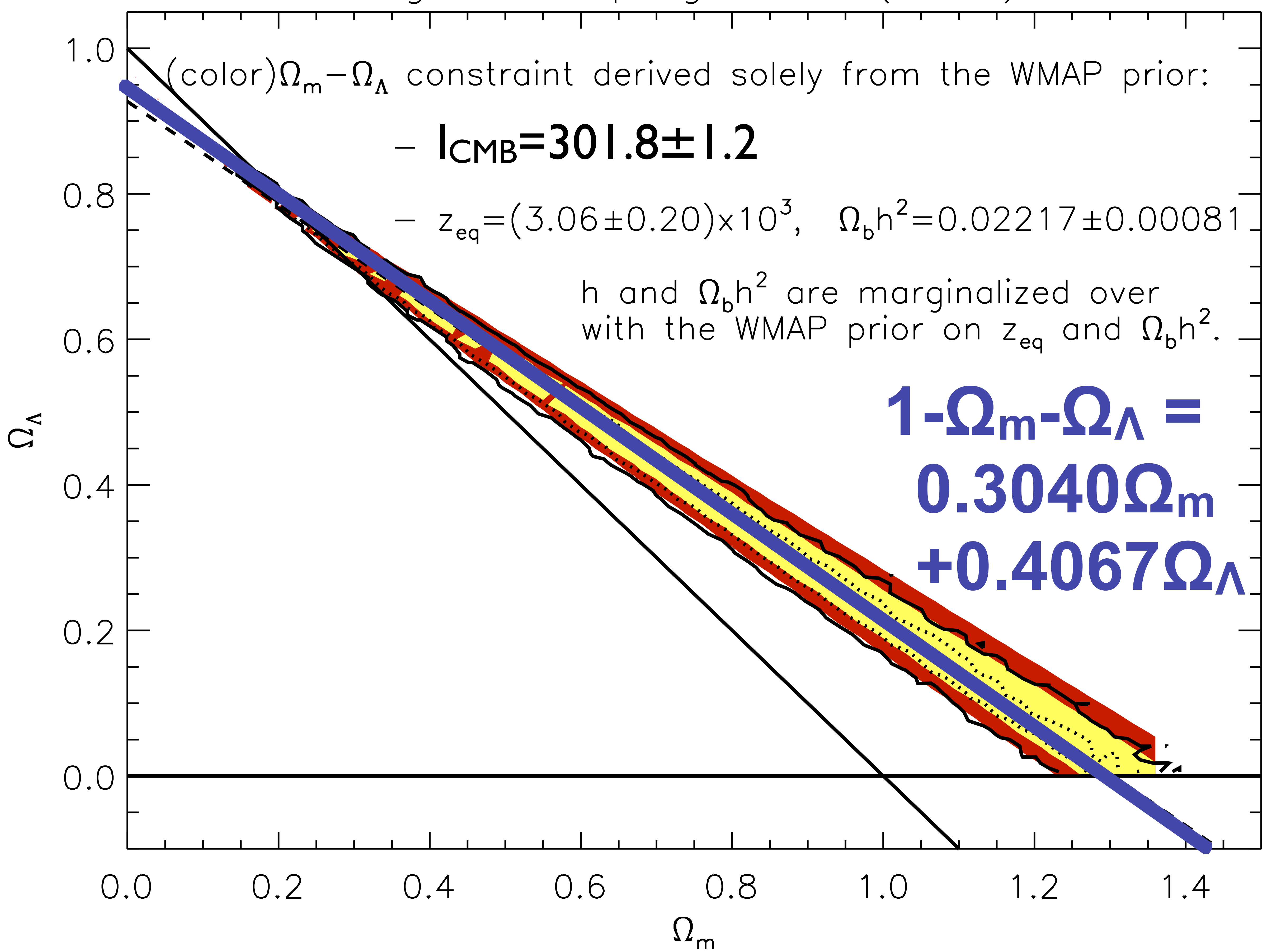




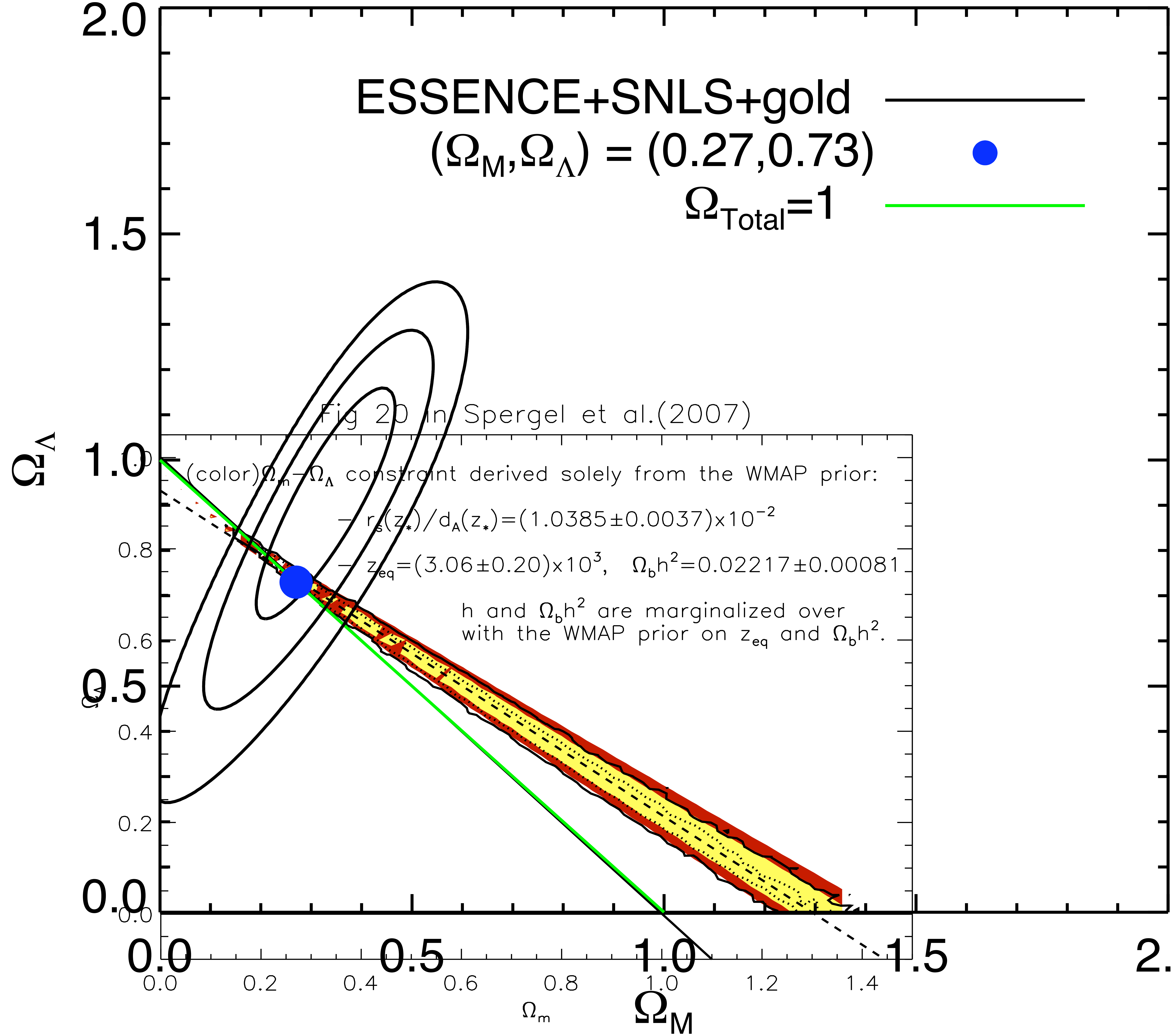
- The WMAP 5-year values:
  - $l_{CMB} = \pi/\theta = \pi D_A(z_{CMB})/d_s(z_{CMB}) = 302.45 \pm 0.86$
  - CMB data constrain the ratio, $\mathbf{D_A(z_{CMB})/d_s(z_{CMB})}$.
  - $r_s(z_{CMB}) = (1+z_{CMB}) d_s(z_{CMB}) = 146.8 \pm 1.8$ Mpc (comoving)

What $D_A(z_{CMB})/d_s(z_{CMB})$ Gives You (3-year example)

Fig 20 in Spergel et al.(2007)

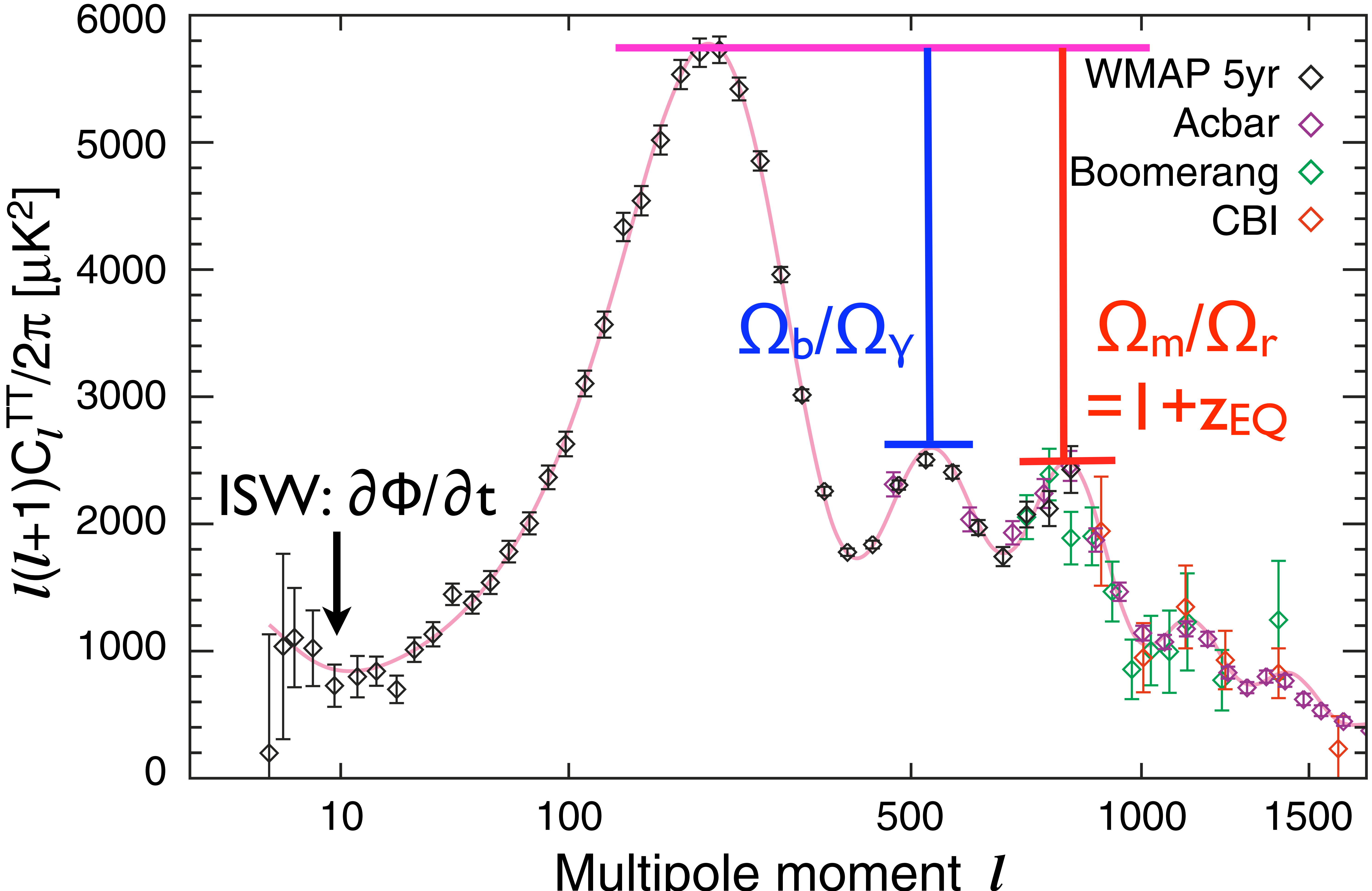


- Color: constraint from $l_{CMB}=\pi D_A(z_{CMB})/d_s(z_{CMB})$ with z_{EQ} & $\Omega_b h^2$.
- Black contours: Markov Chain from WMAP 3yr (Spergel et al. 2007)



ESSENCE+SNLS+gold
(ΩM,ΩΛ) = (0.27,0.73)
ΩTotal=1
Fig 20 in Spergel et al.(2007)
(color)Ωm–ΩΛ constraint derived solely from the WMAP prior:
— rs(z*)/dA(z*)=(1.0385±0.0037)×10−2
— zeq=(3.06±0.20)×10³, Ωbh²=0.02217±0.00081
h and Ωbh² are marginalized over
with the WMAP prior on zeq and Ωbh².
ΩΛ
ΩM
Ωm
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.2
1.4

Other Observables



- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- Low-l: Integrated Sachs Wolfe Effect (more talks later!)

Dark Energy From Distance Information Alone

- We provide a set of "WMAP distance priors" for testing various dark energy models.

Ω_b/Ω_γ
- Redshift of decoupling, z_*=1091.13 (Err=0.93)
- Acoustic scale, $l_A=\pi d_A(z_*)/r_s(z_*)$=302.45 (Err=0.86)

Ω_m/Ω_r
- Shift parameter, $R=\mathrm{sqrt}(\Omega_m H_0^2) d_A(z_*)$=1.721(Err=0.019)
- Full covariance between these three quantities are also provided.

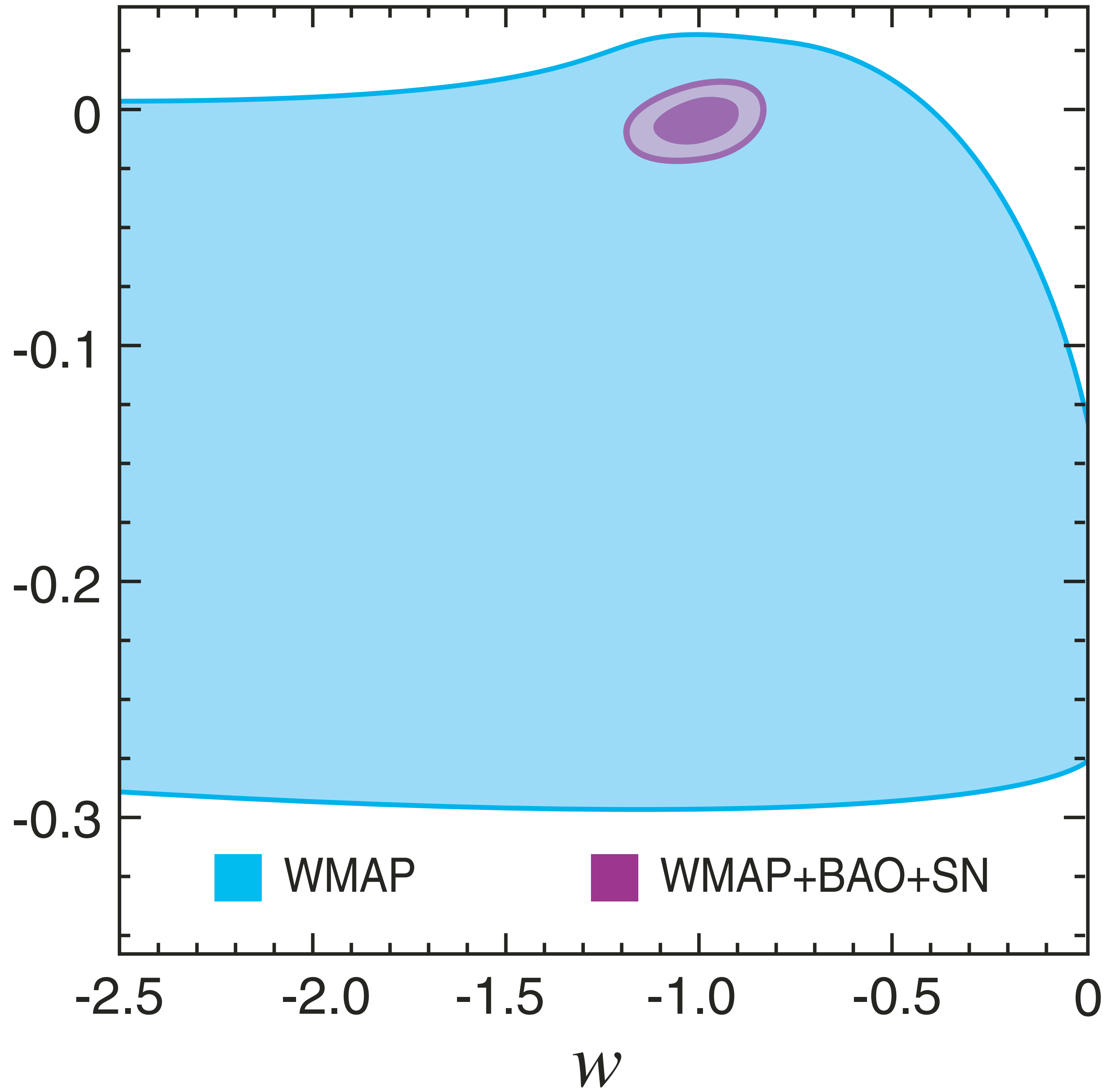
INVERSE COVARIANCE MATRIX FOR THE *WMAP* DISTANCE PRIORS

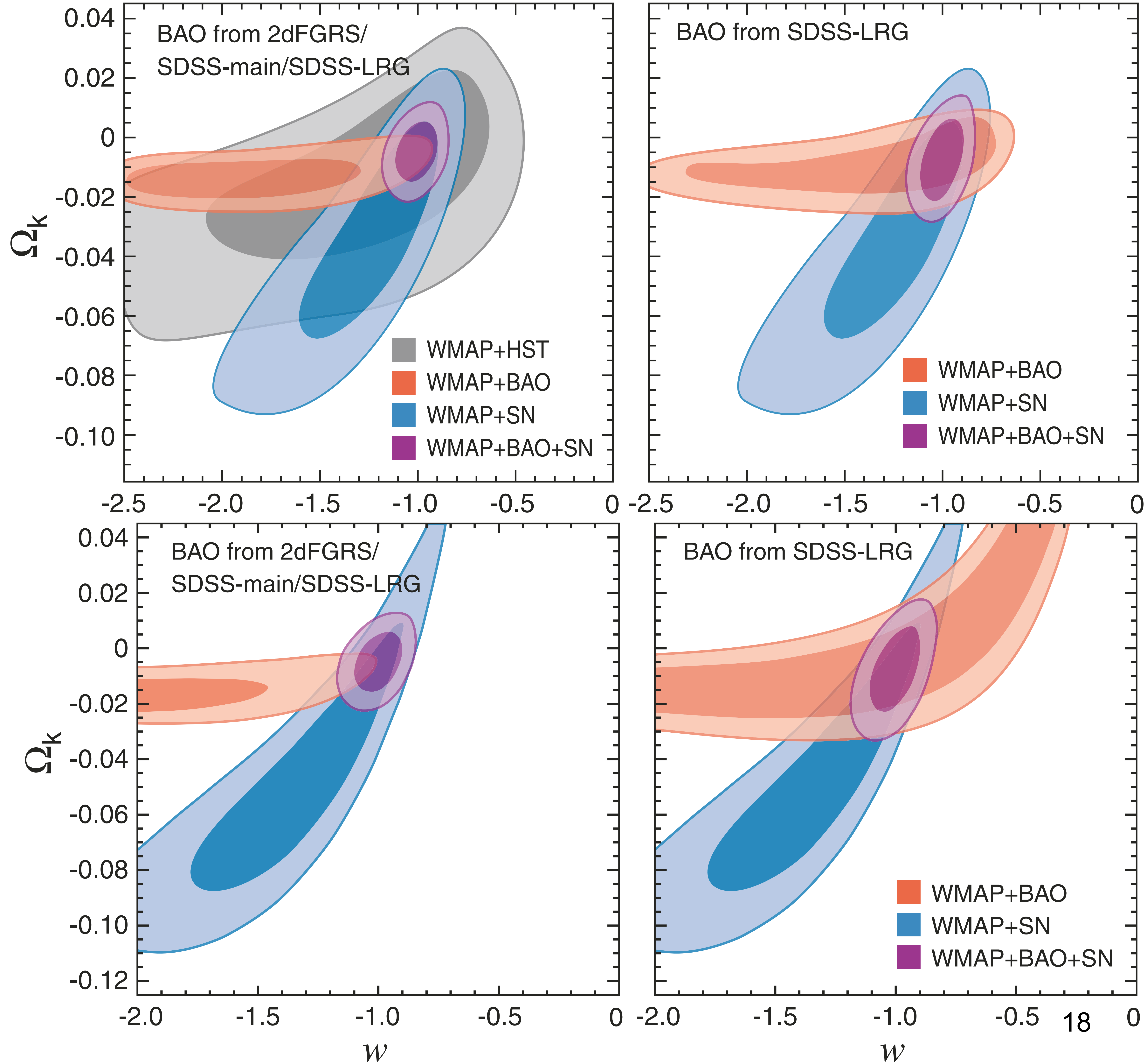
	$l_A(z_*)$	$R(z_*)$	z_*
$l_A(z_*)$	1.800	27.968	−1.103
$R(z_*)$		5667.577	−92.263
z_*			2.923

- WMAP 5-Year ML
  - z_*=1091.13
  - l_A=302.45
  - R=1.721
  - $100\Omega_b h^2$=2.2765

INVERSE COVARIANCE MATRIX FOR THE EXTENDED *WMAP* DISTANCE PRIORS. THE MAXIMUM LIKELIHOOD VALUE OF $\Omega_b h^2$ IS $100\Omega_b h^2 = 2.2765$.

	$l_A(z_*)$	$R(z_*)$	z_*	$100\Omega_b h^2$
$l_A(z_*)$	31.001	−5015.642	183.903	2337.977
$R(z_*)$		876807.166	−32046.750	−403818.837
z_*			1175.054	14812.579
$100\Omega_b h^2$				187191.186

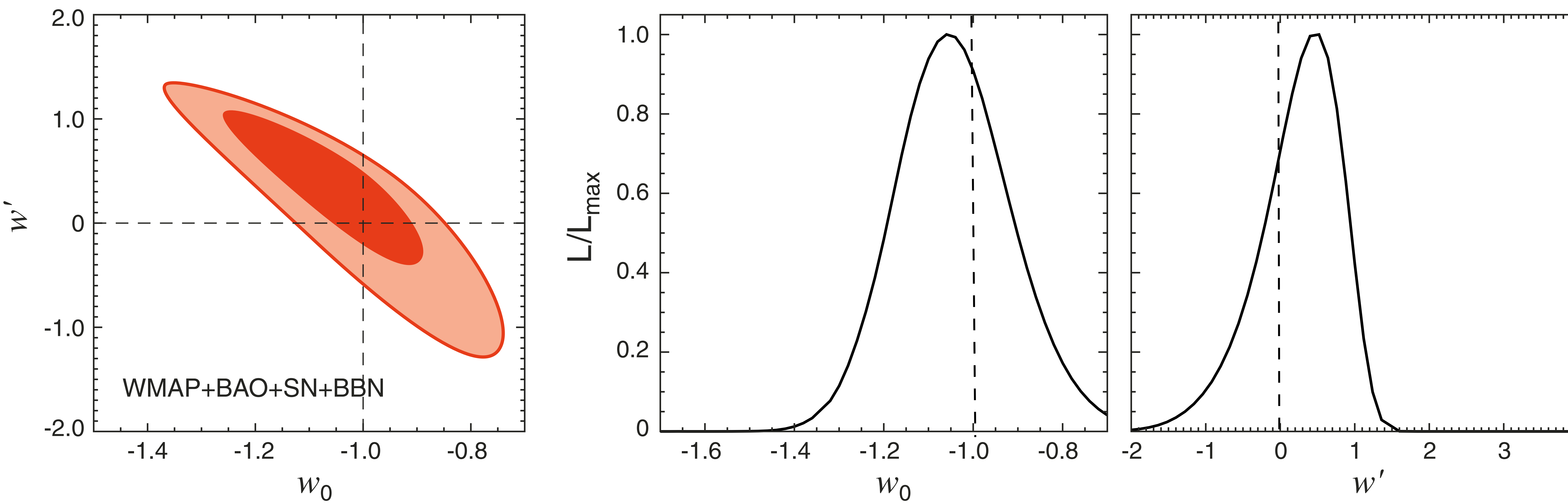




- Top
  - Full WMAP Data
- Bottom
  - WMAP Distance Priors

WMAP5+BAO+SN

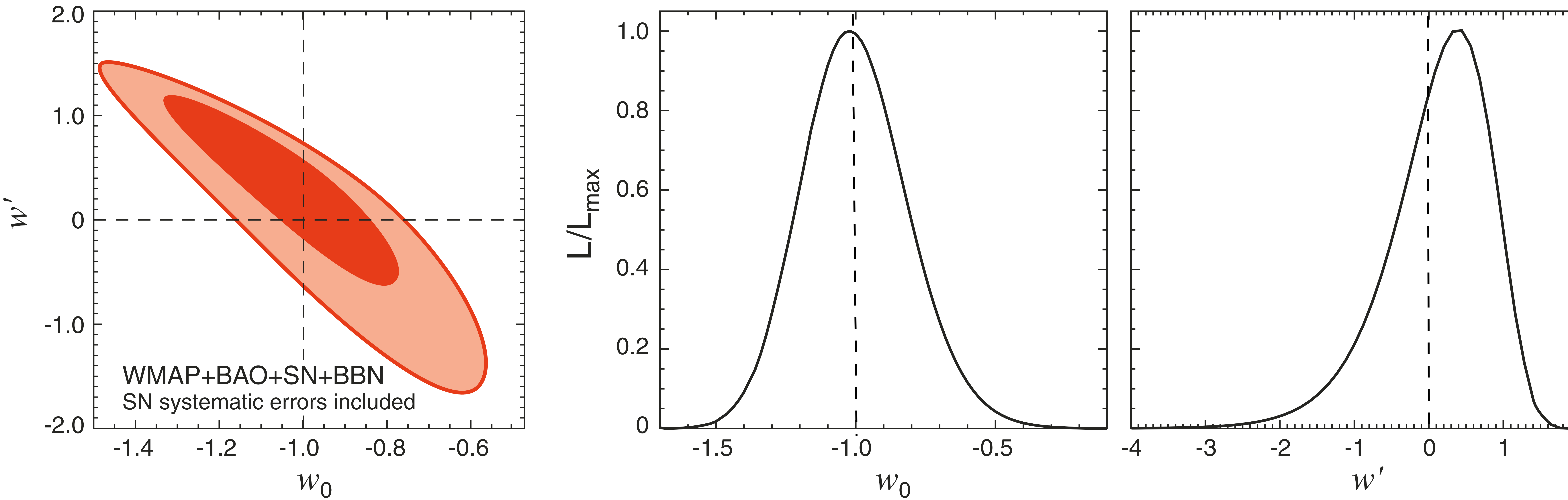
Dark Energy EOS: $w(z)=w_0+w'z/(1+z)$



- Dark energy is pretty consistent with cosmological constant: w_0=–1.04±0.13 & w'=0.24±0.55 (68%CL)

Dark Energy EOS: Including Sys. Err. in SN 1a

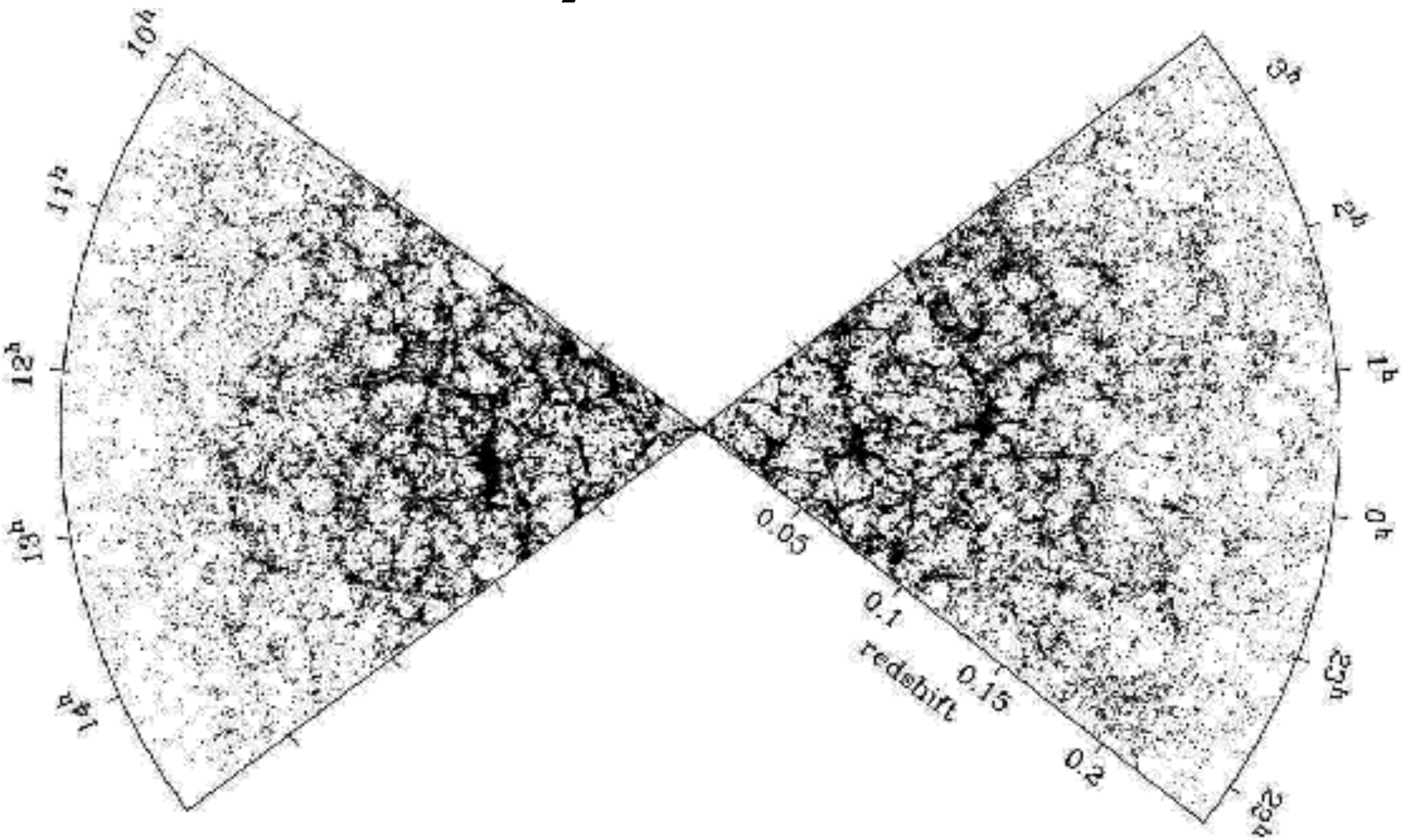
WMAP5+BAO+SN



- Dark energy is pretty consistent with cosmological constant: w_0=–1.00±0.19 & w'=0.11±0.70 (68%CL)

BAO in Galaxy Distribution

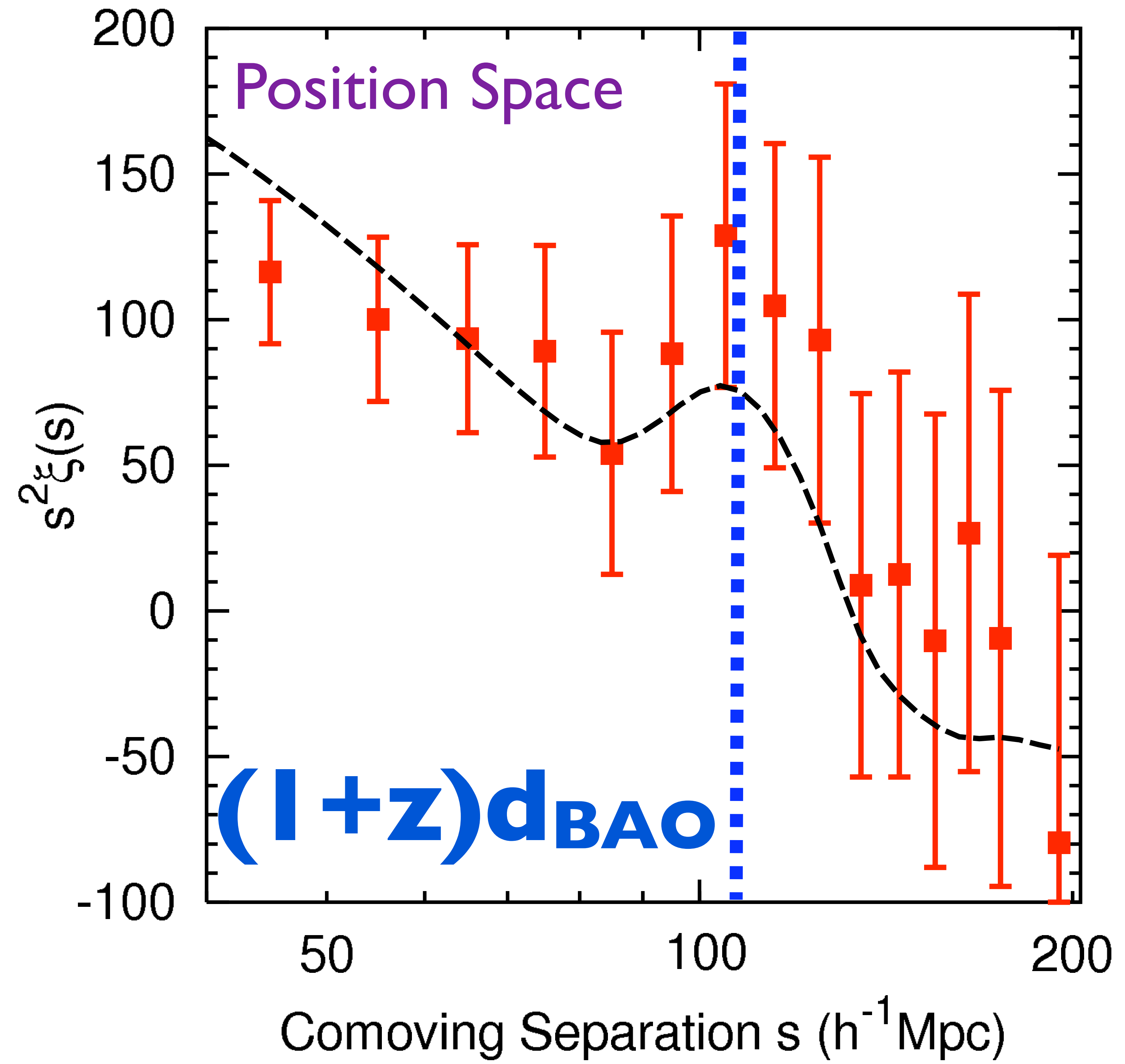
2dFGRS

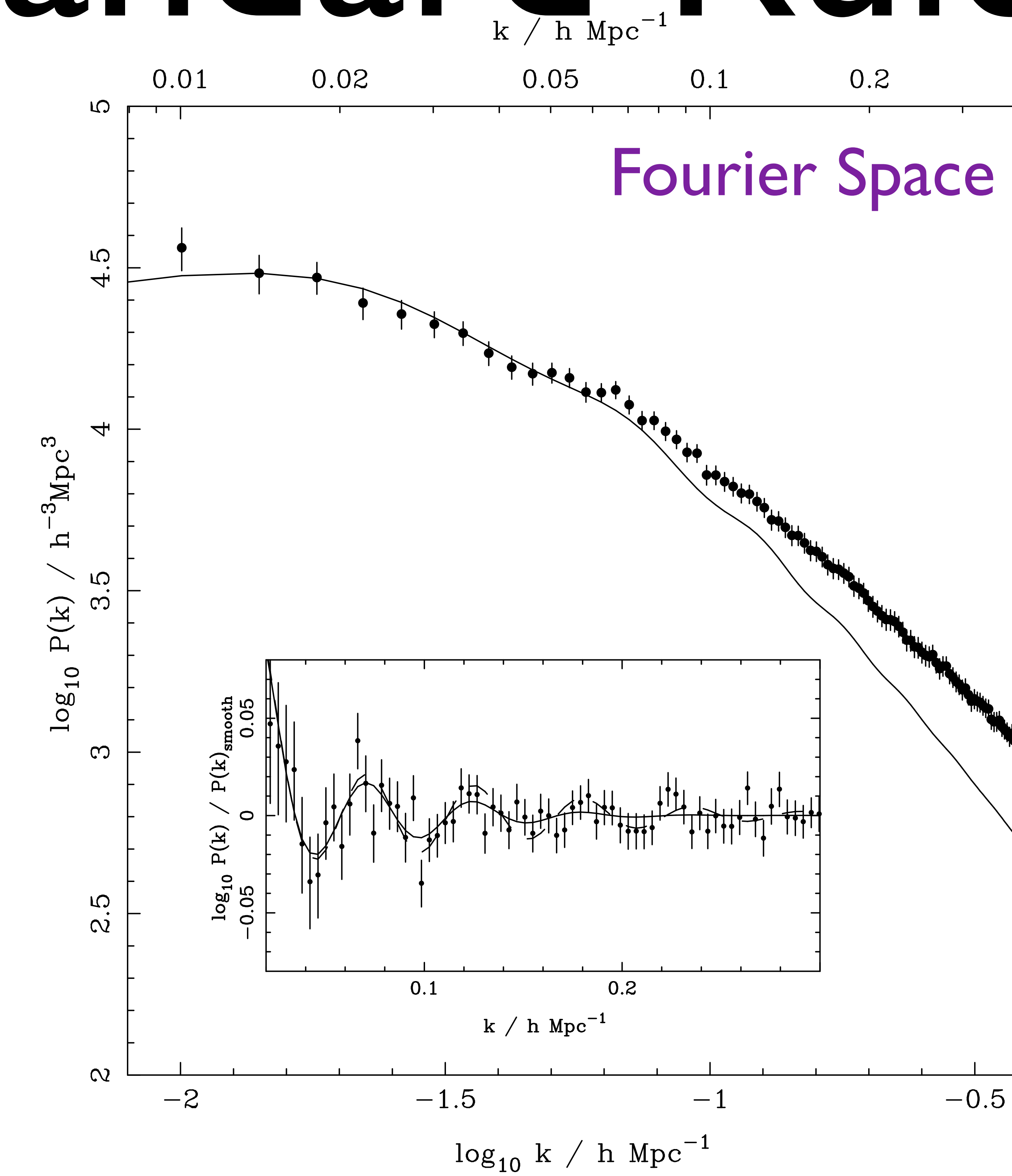


- The same acoustic oscillations should be hidden in this galaxy distribution...

BAO as a Standard Ruler

Okumura et al. (2007)





Percival et al. (2006)

- The existence of a localized clustering scale in the 2-point function yields oscillations in Fourier space. What determines the physical size of clustering, d_{BAO}?

Sound Horizon Again

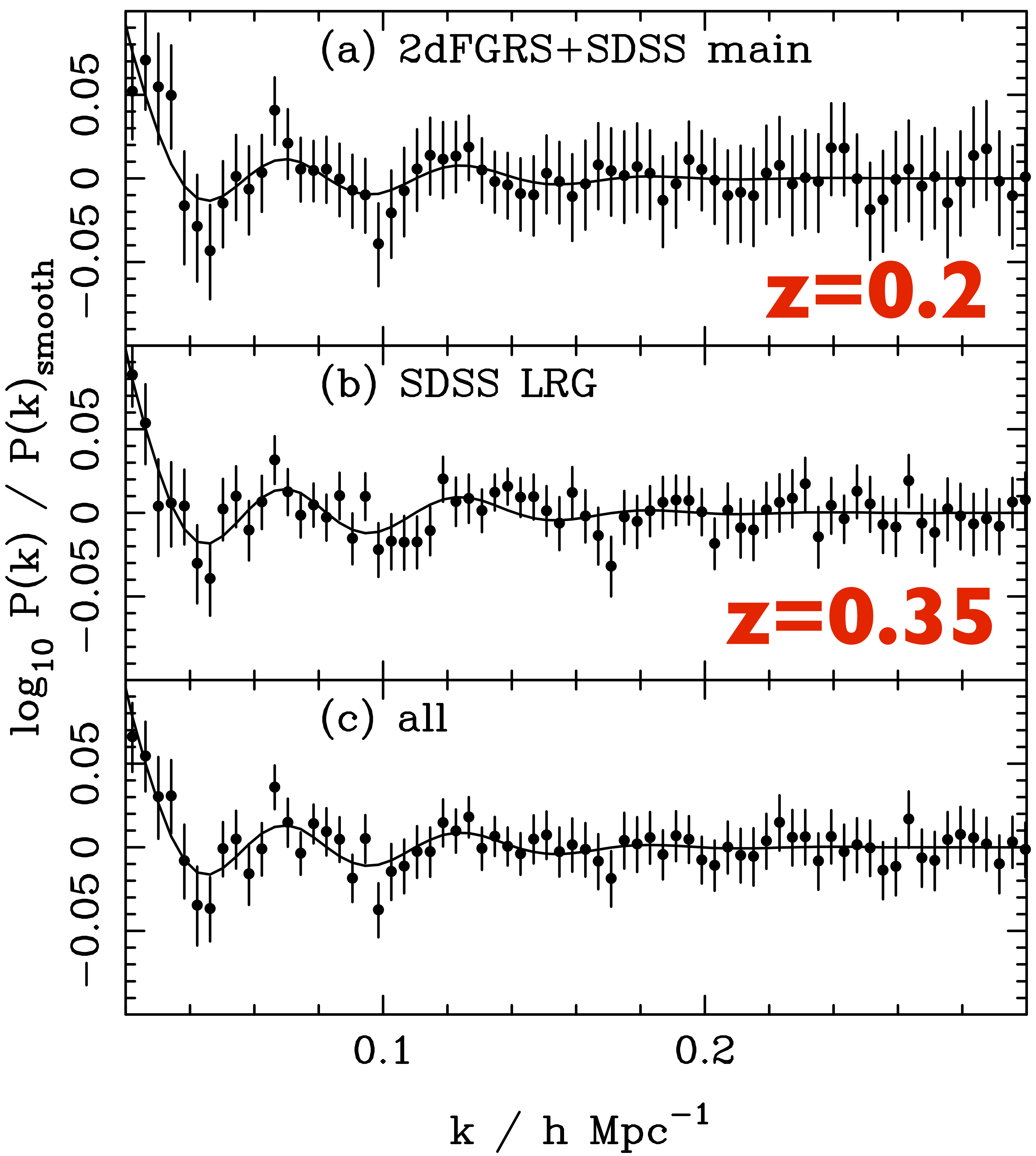
- The clustering scale, **d_{BAO}**, is given by the physical distance traveled by the sound wave from the Big Bang to the **decoupling of baryons** at $z_{BAO}=1020.5\pm1.6$ (c.f., $z_{CMB}=1091\pm1$).
- The baryons decoupled slightly later than CMB.
  - By the way, this is not universal in cosmology, but *accidentally* happens to be the case for our Universe.
  - If $3\rho_{baryon}/(4\rho_{photon}) = 0.64(\Omega_b h^2/0.022)(1090/(1+z_{CMB}))$ is greater than unity, $z_{BAO}>z_{CMB}$. Since our Universe happens to have $\Omega_b h^2=0.022$, $z_{BAO}<z_{CMB}$. (ie, $d_{BAO}>d_{CMB}$)

Standard Rulers in CMB & Matter

	Quantity	Eq.	5-year WMAP
CMB	z_*	(66)	1090.51 ± 0.95
CMB	$r_s(z_*)$	(6)	146.8 ± 1.8 Mpc
Matter	z_d	(3)	1020.5 ± 1.6
Matter	$r_s(z_d)$	(6)	153.3 ± 2.0 Mpc

- For flat LCDM, but very similar results for $w \neq -1$ and curvature$\neq 0$!

The Latest BAO Measurements



- 2dFGRS and SDSS main samples at z=0.2
- SDSS LRG samples at z=0.35
- These measurements constrain the ratio, **$D_A(z)/d_s(z_{BAO})$**.

Percival et al. (2007)

Not Just $D_A(z)$...

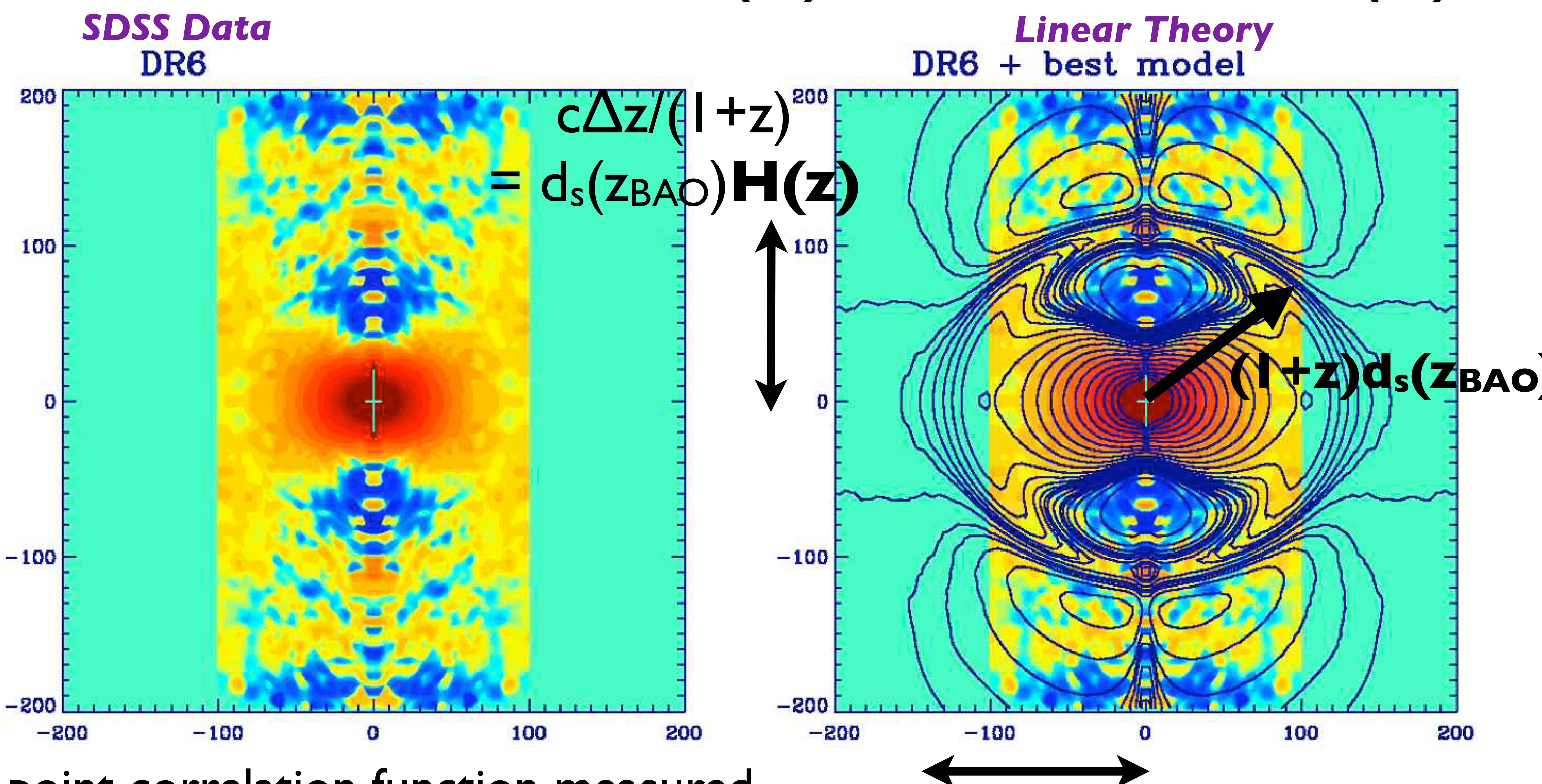
- A really nice thing about BAO at a given redshift is that it can be used to measure not only $D_A(z)$, but also the expansion rate, $H(z)$, directly, at **that** redshift.
  - BAO perpendicular to l.o.s

    $$\Rightarrow D_A(z) = d_s(z_{BAO})/\theta$$

  - BAO parallel to l.o.s

    $$\Rightarrow \mathbf{H(z) = c\Delta z/[(1+z)d_s(z_{BAO})]}$$

Transverse=$D_A(z)$; Radial=$H(z)$



$c\Delta z/(1+z)$

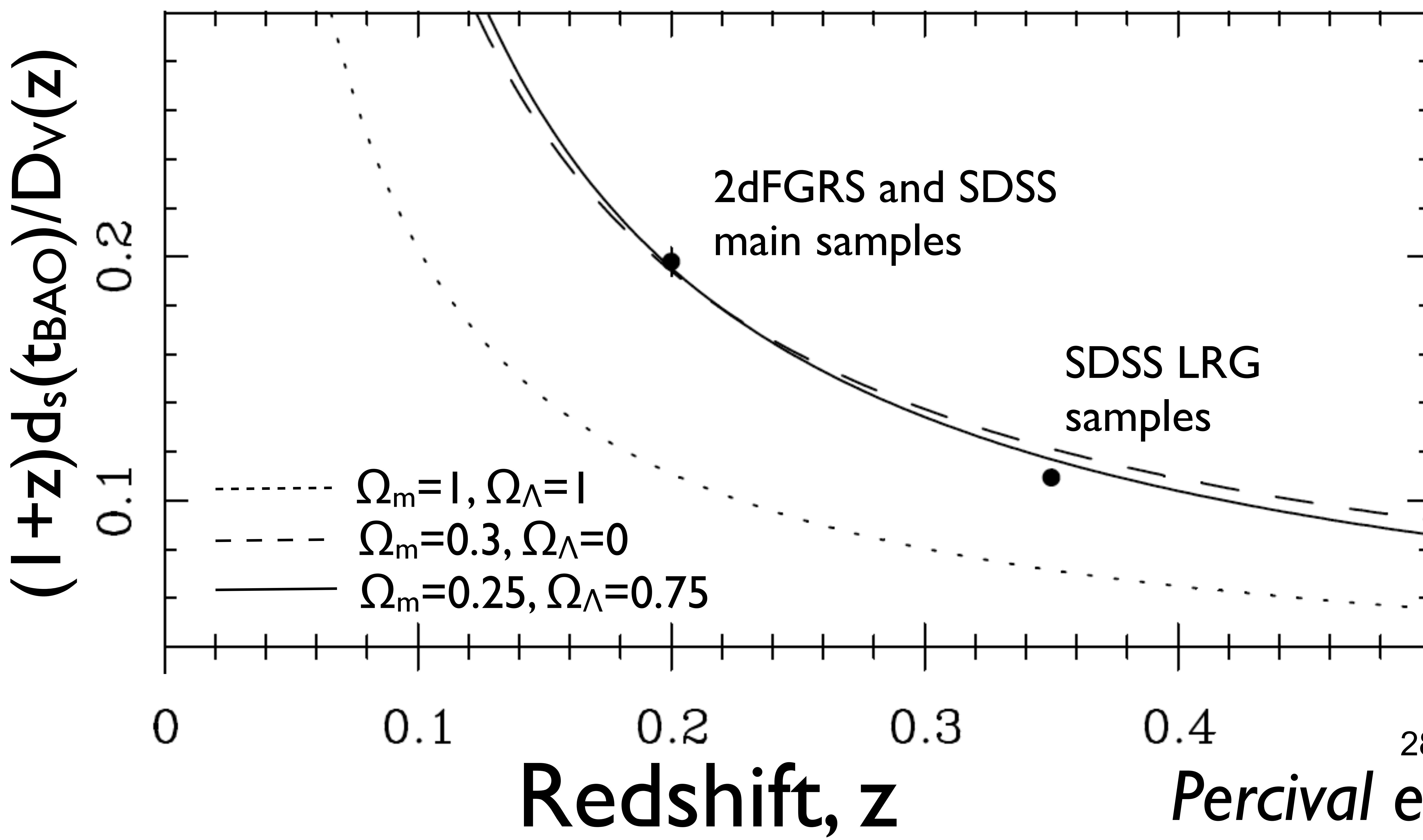
$= d_s(z_{BAO})\mathbf{H(z)}$

$\theta = d_s(z_{BAO})/\mathbf{D_A(z)}$

Two-point correlation function measured from the SDSS Luminous Red Galaxies (Gaztanaga, Cabre & Hui 2008)

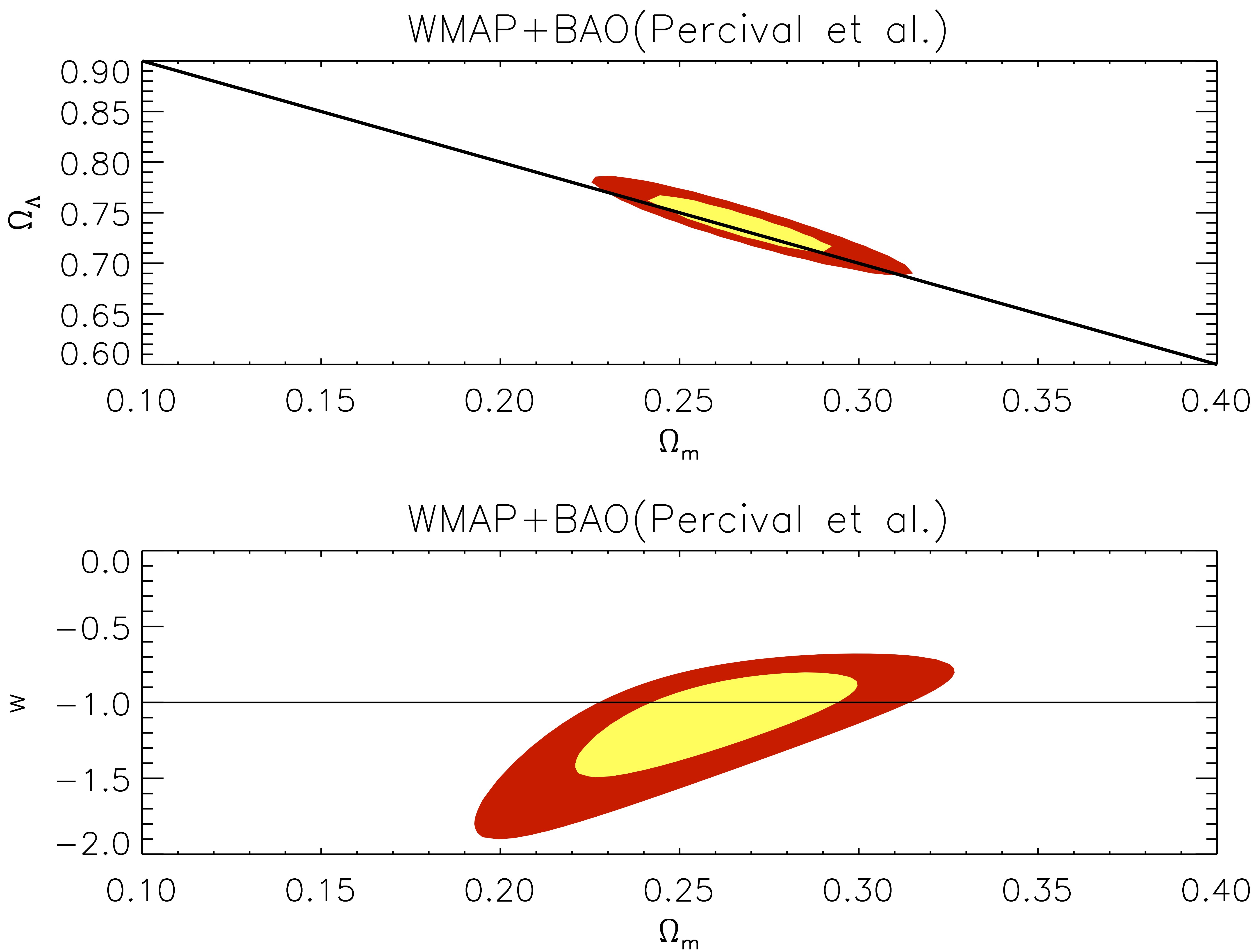
$$D_V(z) = \{(1+z)^2 D_A^2(z)[cz/H(z)]\}^{1/3}$$

Since the current data are not good enough to constrain $D_A(z)$ and $H(z)$ separately, a combination distance, **$D_V(z)$**, has been constrained.



Percival et al. (2007)

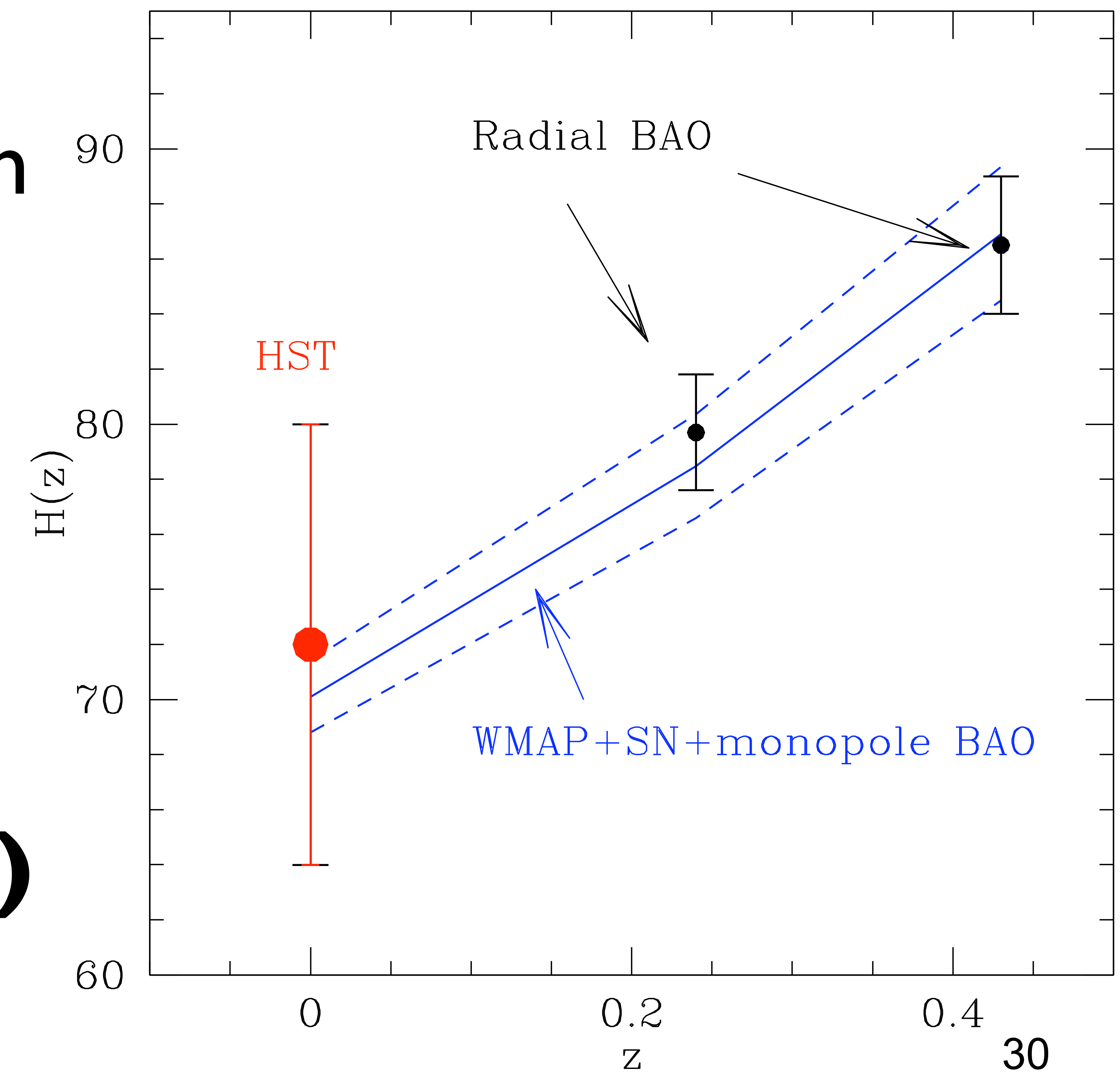
CMB + BAO => Curvature



- Both CMB and BAO are **absolute** distance indicators.
- Type Ia supernovae only measure relative distances.
- CMB+BAO is the winner for measuring spatial curvature.

H(z) also determined recently!

- SDSS DR6 data are now good enough to constrain H(z) from the 2-dimension correlation function *without spherical averaging*.
- Made possible by WMAP's measurement of **$r_s(z_{BAO})=(1+z_{BAO})d_s(z_{BAO})$ =153.3±2.0 Mpc** (comoving)

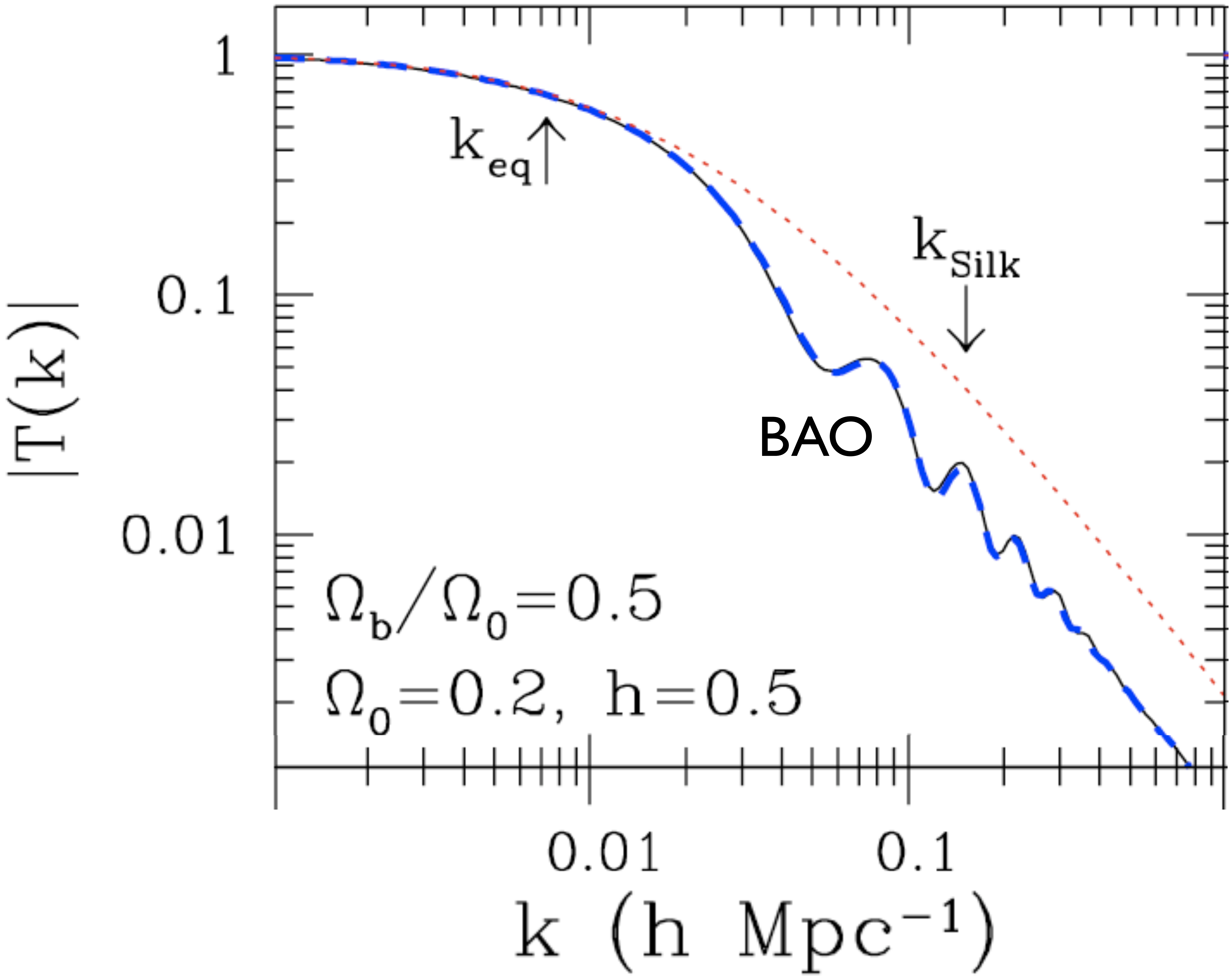


Gaztanaga, Cabre & Hui (2008)

Beyond BAO

- BAOs capture only a **fraction** of the information contained in the galaxy power spectrum!
- BAOs use the sound horizon size at z~1020 as the standard ruler.
- However, there are other standard rulers:
  - Horizon size at the matter-radiation equality epoch (z~3200)
  - Silk damping scale

Eisenstein & Hu (1998)



...and, these are all well known

- Cosmologists have been measuring k_{eq} over the last three decades.
- This was usually called the "Shape Parameter," denoted as Γ.
- Γ is proportional to k_{eq}/h, and:
  - The effect of the Silk damping is contained in the constant of proportionality.
  - Easier to measure than BAOs: the signal is much stronger.

WMAP & Standard Ruler

- **With WMAP 5-year data only,** the scales of the standard rulers have been determined accurately.
- Even when $w \neq -1$, $\Omega_k \neq 0$,

1.3%
  - $d_s(z_{BAO}) = 153.4^{+1.9}_{-2.0}$ Mpc ($z_{BAO}=1019.8 \pm 1.5$)

4.6%
  - $k_{eq}=(0.975^{+0.044}_{-0.045})\times10^{-2}$ Mpc^{-1} ($z_{eq}=3198^{+145}_{-146}$)

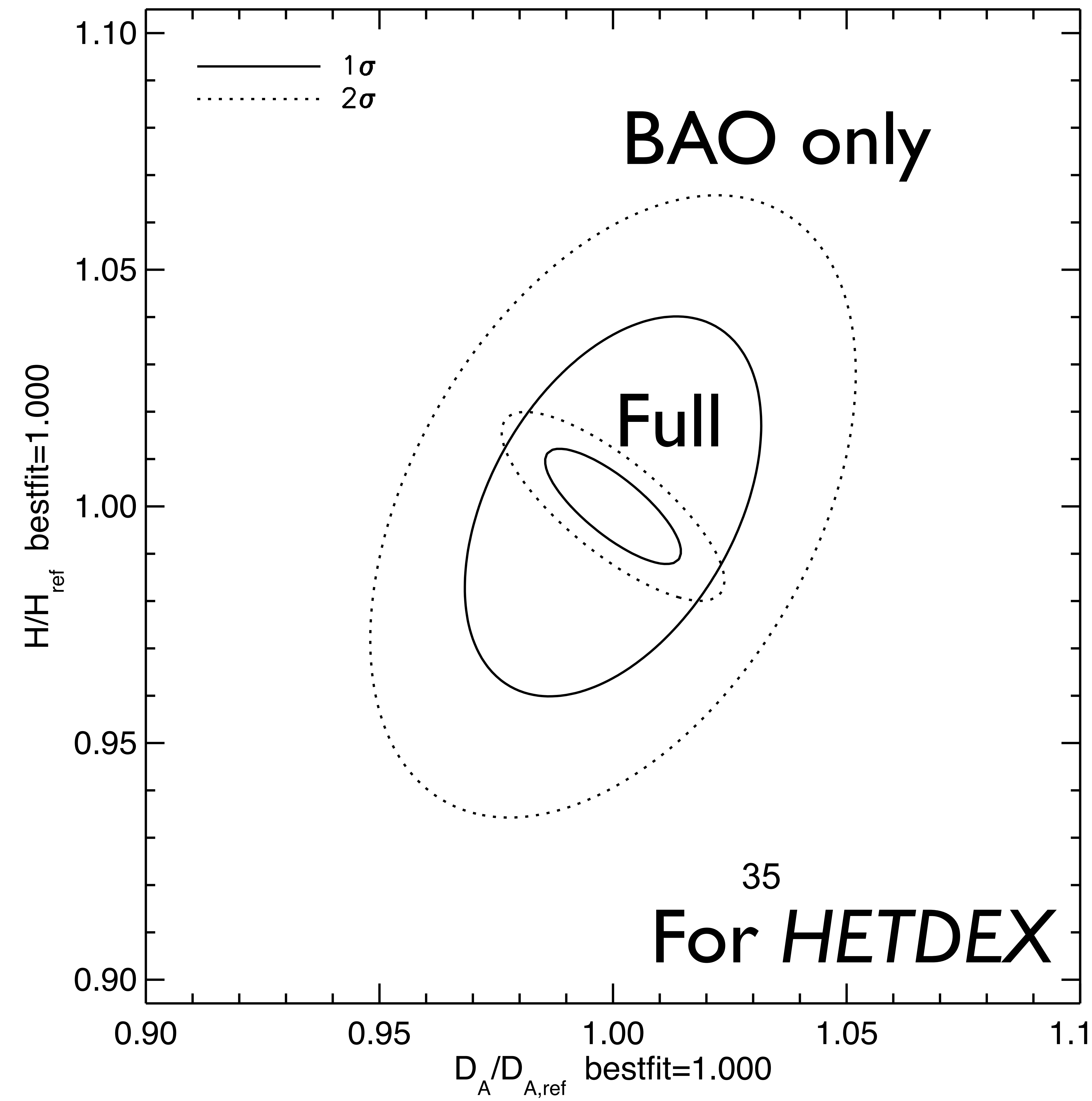
2.3%
  - $k_{silk}=(8.83 \pm 0.20)\times10^{-2}$ Mpc^{-1}

With Planck, they will be determined to higher precision.

Shoji, Jeong & Komatsu (2008)

BAO vs Full Modeling

- Full modeling improves upon the determinations of D_A & H by more than a factor of two.
- On the D_A-H plane, the size of the ellipse shrinks by more than a factor of four.



Why Not "GPS," Instead of "BAO"?

- JDEM says, "SN, WL, or BAO at minimum."
- It does not make sense to single out "BAO": the observable is the **galaxy power spectrum (GPS)**.
- To get BAO, we need to measure the galaxy power spectrum anyway.
- If we measure the galaxy power spectrum, why just focus on BAO? There is much more information!
- So, it would be better fro JDEM to say, perhaps, "use SN, WL, or GPS at minimum"?

WMAP Amplitude Prior

- WMAP measures the amplitude of curvature perturbations at z~1090. Let's call that R_k. The relation to the density fluctuation is

$$\delta_{m,\mathbf{k}}(z) = \frac{2k^3}{5H_0^2\Omega_m}\mathcal{R}_{\mathbf{k}}T(k)D(k,z)$$

- Variance of R_k has been constrained as:

Amplitude of curvature perturbations, $\mathcal{R}$, measured by *WMAP* at $k_{WMAP} = 0.02$ Mpc^{-1}

Model	$10^9 \times \Delta^2_{\mathcal{R}}(k_{WMAP})$
$\Omega_k = 0$ and $w = -1$	2.211 ± 0.083
$\Omega_k \neq 0$ and $w = -1$	2.212 ± 0.084
$\Omega_k = 0$ and $w \neq -1$	2.208 ± 0.087
$\Omega_k \neq 0$ and $w \neq -1$	2.210 ± 0.084
$\Omega_k = 0$, $w = -1$ and $m_\nu > 0$	2.212 ± 0.083
$\Omega_k = 0$, $w \neq -1$ and $m_\nu > 0$	2.218 ± 0.085
WMAP Normalization Prior	2.21 ± 0.09

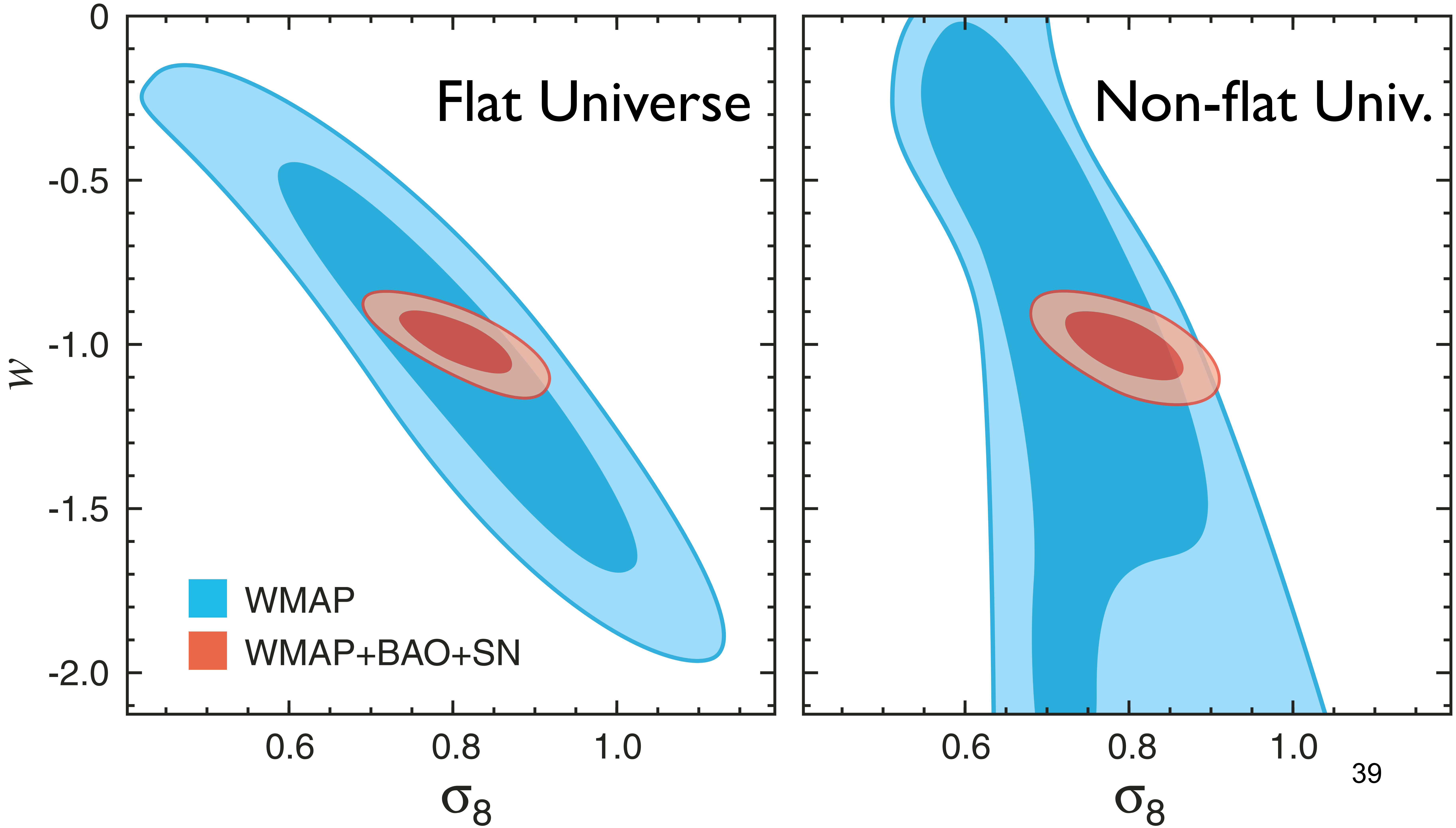
Then Solve This Diff. Equation...

Ignoring the mass of neutrinos and modifications to gravity, one can obtain the growth rate by solving the following differential equation (Wang & Steinhardt 1998; Linder & Jenkins 2003): **g(z)=(1+z)D(z)**

$$\frac{d^2g}{d\ln a^2}+\left[\frac{5}{2}+\frac{1}{2}\left(\Omega_k(a)-3w_{\rm eff}(a)\Omega_{de}(a)\right)\right]\frac{dg}{d\ln a}$$
$$+\left[2\Omega_k(a)+\frac{3}{2}(1-w_{\rm eff}(a))\Omega_{de}(a)\right]g(a)=0, \qquad (76)$$

- If you need a code for doing this, search for "**Cosmology Routine Library**" on Google

Degeneracy Between Amplitude at z=0 (σ_8) and w



Summary

- WMAP helps constrain the nature of DE by providing:
  - Angular diameter distance to $z_* \sim 1090$,
  - Amplitude of fluctuations at $z_* \sim 1090$, and
  - $\partial\Phi/\partial t$ at $z<1$ via the Integrated Sachs-Wolfe effect.
- WMAP also measures the sound horizon size for baryons, d_{BAO}, which is used by BAO experiments to constrain $D_A(z)$ and $H(z)$.
- Not just BAO! WMAP also provides the other standard rulers, k_{eq} and k_{silk}, with which the accuracy of $D_A(z)$ and $H(z)$ from galaxy surveys can be improved greatly.