EUCLID

Baryon Acoustic Oscillations
Part I

Yun Wang (on behalf of
the Euclid collaboration)

ESTEC, November 17, 2009

Outline

- Introduction: BAO and galaxy clustering
- BAO as a standard ruler
- BAO as a robust dark energy probe
- Euclid galaxy redshift survey

The Origin of BAO

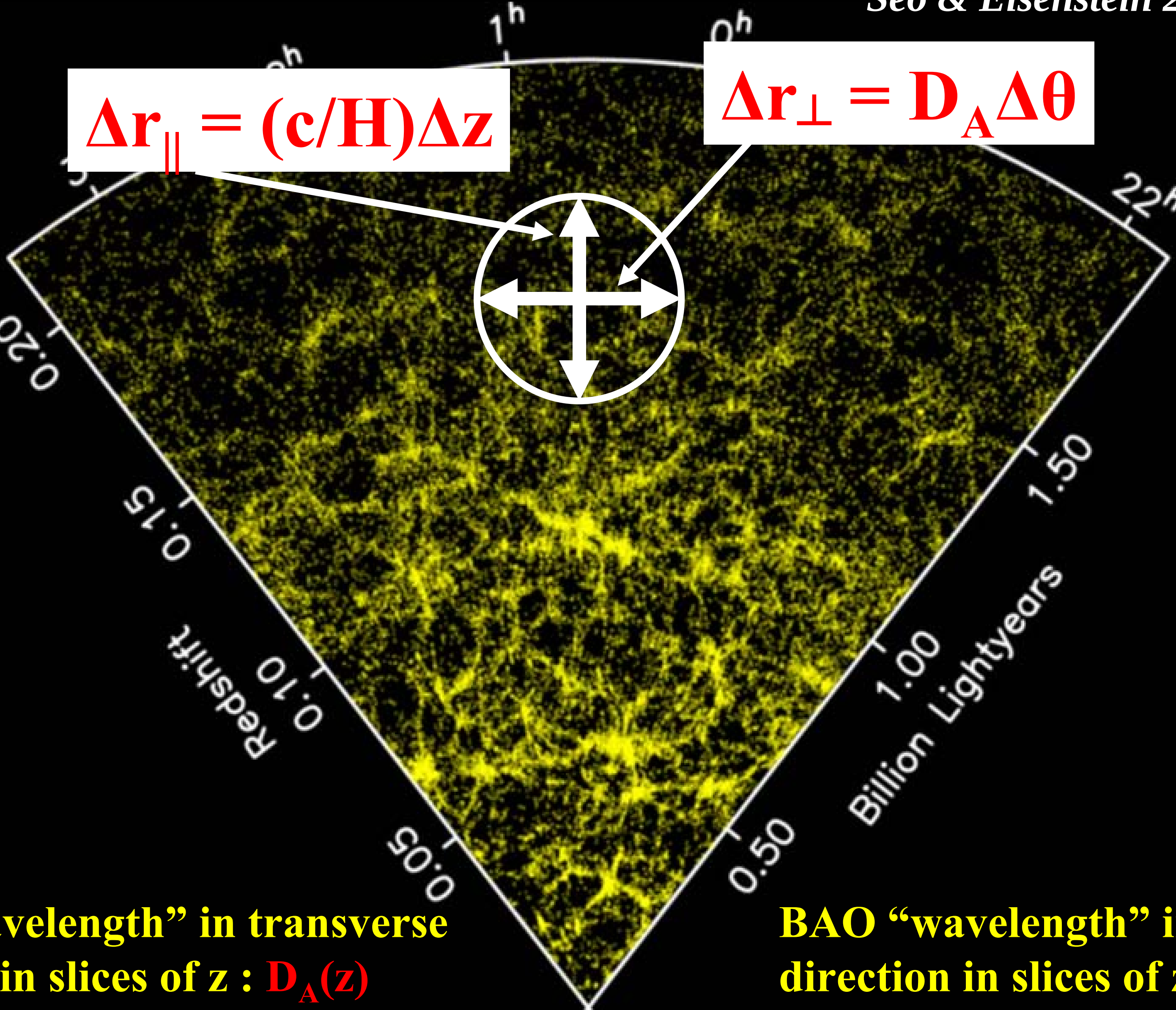
- At the last scattering of CMB photons, the acoustic oscillations in the photon-baryon fluid became frozen and imprinted on
  - CMB (acoustic peaks in the CMB)
  - Matter distribution (BAO in the galaxy power spectrum)
- The BAO scale is the sound horizon scale at the drag epoch, when photon pressure can no longer prevent gravitational instability in baryons (occurs slightly after photon-decoupling because Ω_b is small). WMAP 5 yr data give

$$s = 153.3 \pm 2.0 \text{ Mpc}, \quad z_d = 1020.5 \pm 1.6$$

(Komatsu et al. 2009)

Baryon acoustic oscillations as a standard ruler

Blake & Glazebrook 2003
Seo & Eisenstein 2003

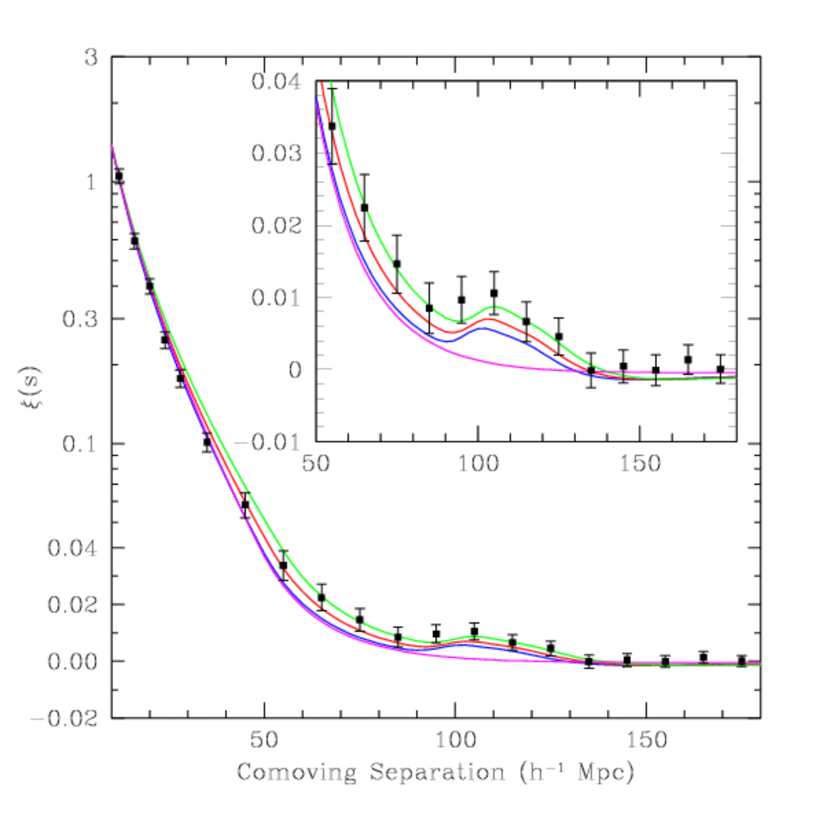


BAO "wavelength" in transverse direction in slices of z : $D_A(z)$

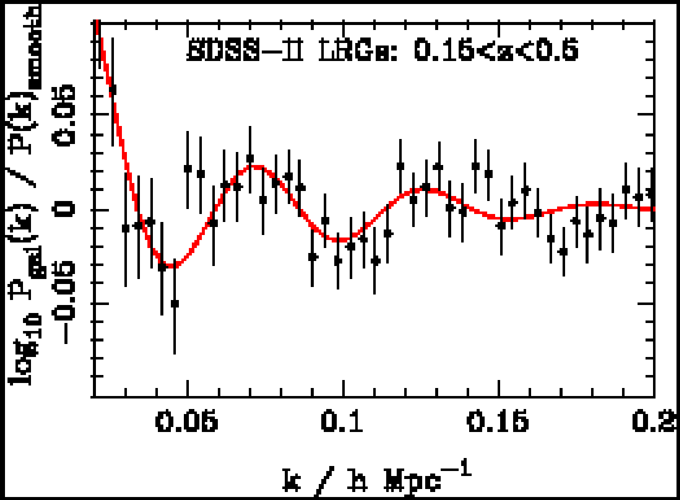
BAO "wavelength" in radial direction in slices of z : $H(z)$

Baryon acoustic oscillations have been measured:

Galaxy 2-pt correlation function



Galaxy power spectrum



Eisenstein et al. (2005)

Percival et al. (2009)

BAO as a Robust Dark Energy Probe

- The observational requirements are least demanding among all methods.
  - Redshifts and positions of galaxies are easy to measure.
- The systematic uncertainties are small (<<1%).
  - Improvements require only theoretical progress in numerical modeling of data.
  - Latest: BAO scale shift due to systematics < 0.3%, can be removed to <0.015% (NL & z-space distortions only, galaxy bias not yet included) *Seo et al. 2009, arXiv:0910.5005*

BAO Systematic Effects

- Galaxy clustering bias (how light traces mass)
  - Could be scale-dependent
  - Can be modeled numerically for a given galaxy sample selection *(Angulo et al. 2008)*
- Redshift space distortions (artifacts not present in real space)
  - Small scales: a smearing that can be easily modeled
  - Large scales: they boost BAO, and can be used to probe $f_g(z)$ *(Guzzo talk will give the details).*
- Nonlinear gravitational clustering (mode-coupling)
  - small scale information in P(k) destroyed by cosmic evolution due to mode-coupling (nonlinear modes); intermediate scale P(k) also altered in shape
  - Its effect can be reduced by

    (1) Density field reconstruction *(Eisenstein et al. 2007)*

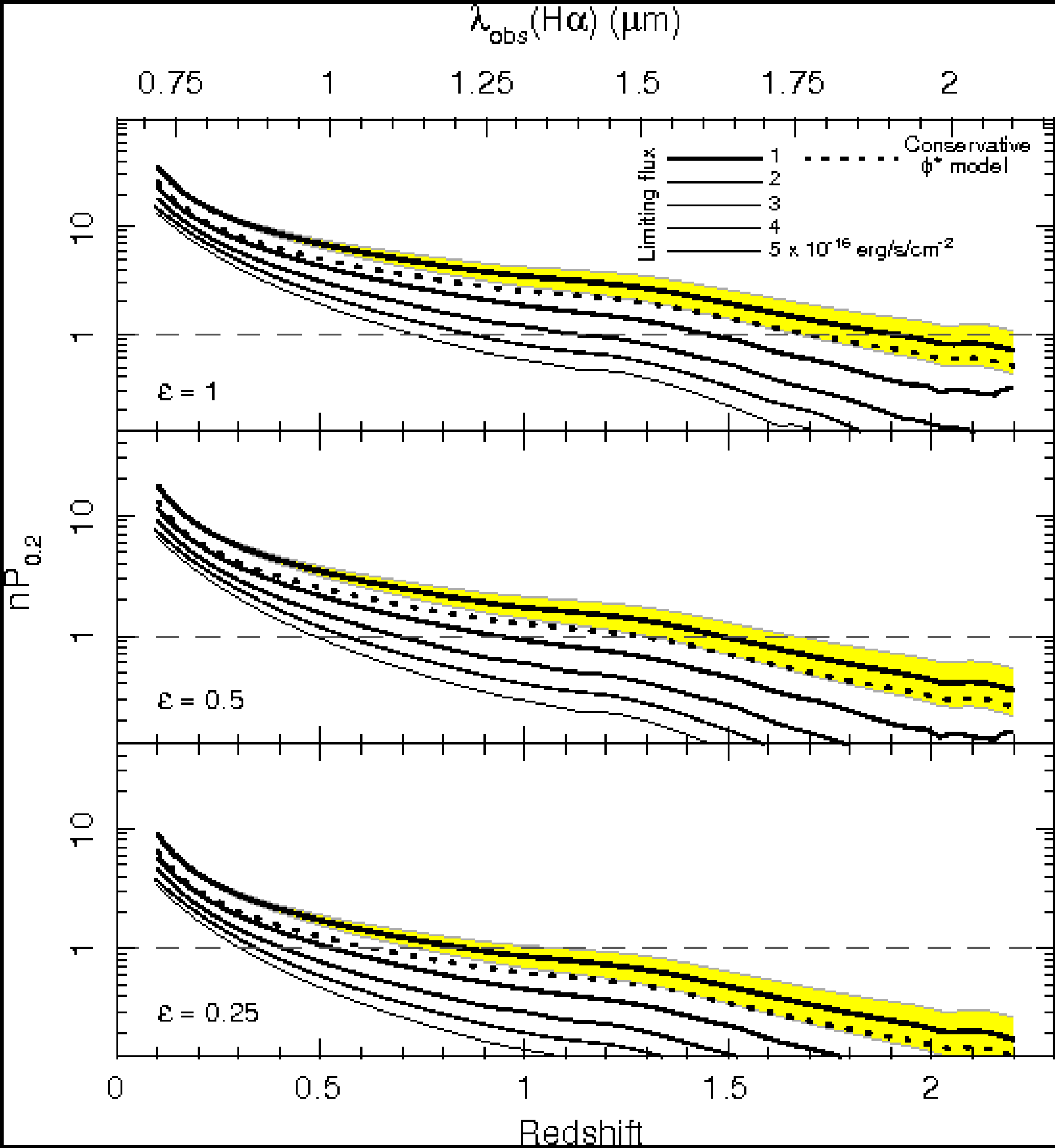
    (2) Extracting "wiggles only" constraints (discard P(k) shape info)

    (3) Full modeling of correlation function *(Sanchez et al. 2008)*

Euclid Galaxy Redshift Survey

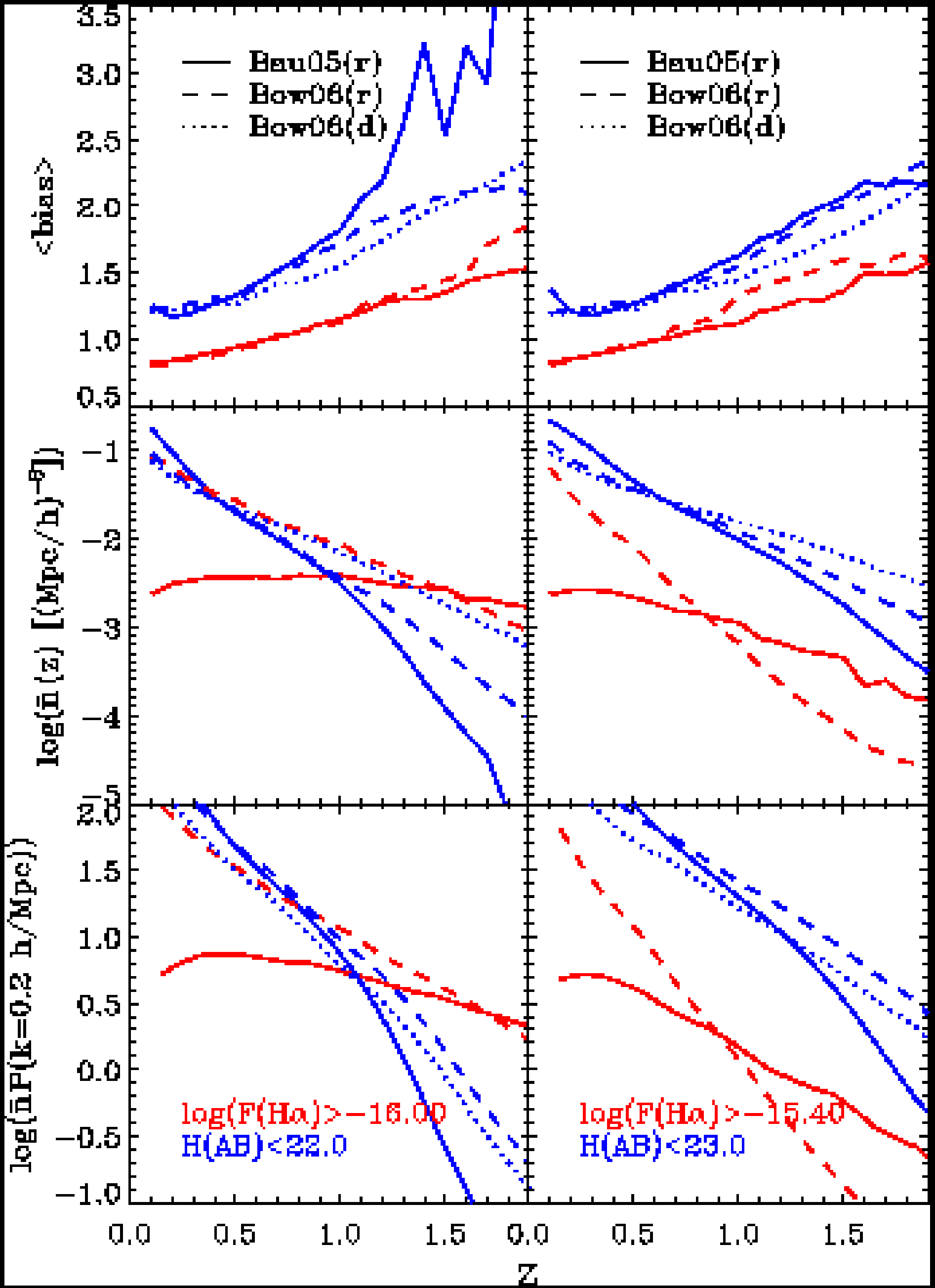
- empirical Hα emitter count
- bias from N-body simulations

Geach et al. 2009, arXiv:0911.0686
Orsi et al. 2009, arXiv:0911.0669



Euclid Galaxy Redshift Survey

DMD versus slitless



Orsi et al. 2009, arXiv:0911.0669

The End

How We Probe Dark Energy

- ***Cosmic expansion history $H(z)$*** **or DE density $\rho_X(z)$:**
  tells us whether DE is a cosmological constant

  $$H^2(z) = 8\pi G[\rho_m(z) + \rho_r(z) + \rho_X(z)]/3 - k(1+z)^2$$

- ***Cosmic large scale structure growth rate function $f_g(z)$, or growth history $G(z)$:***
  tells us whether general relativity is modified

  $$f_g(z)=\mathrm{dln}\delta/\mathrm{dln}a,\ G(z)=\delta(z)/\delta(0)$$

  $$\delta=[\rho_m-\langle\rho_m\rangle]/\langle\rho_m\rangle$$

Observational Methods for Dark Energy Search

- ***SNe Ia (Standard Candles):***
  method through which DE has been discovered; independent of clustering of matter, probes $H(z)$
- ***Baryon Acoustic Oscillations (Standard Ruler):***
  calibrated by CMB, probes $H(z)$. Redshift-space distortions from the same data probe growth rate $f_g(z)$.
- ***Weak Lensing Tomography and Cross-Correlation Cosmography:***
  probes a combination of growth factor $G(z)$ and $H(z)$
- ***Galaxy Cluster Statistics:***
  probes $H(z)$

The Drag Epoch

- The BAO scale is the sound horizon scale at the drag epoch, when photon pressure can no longer prevent gravitational instability in baryons.
  - Epoch of photon-decoupling: $\tau(z_*)=1$
  - Drag epoch: $\tau_b(z_d)=1$, $z_d<z_*$
  - The higher the baryon density, the earlier baryons can overcome photon pressure.
    - $R_b = (3\rho_b)/(4\rho_\gamma) = 31500\Omega_b h^2/[(1+z)(T_{CMB}/2.7K)^4]$
    - $z_d=z_*$ only if $R_b=1$
    - Our universe has low baryon density: $R_b(z_*)< 1$, thus $z_d<z_*$

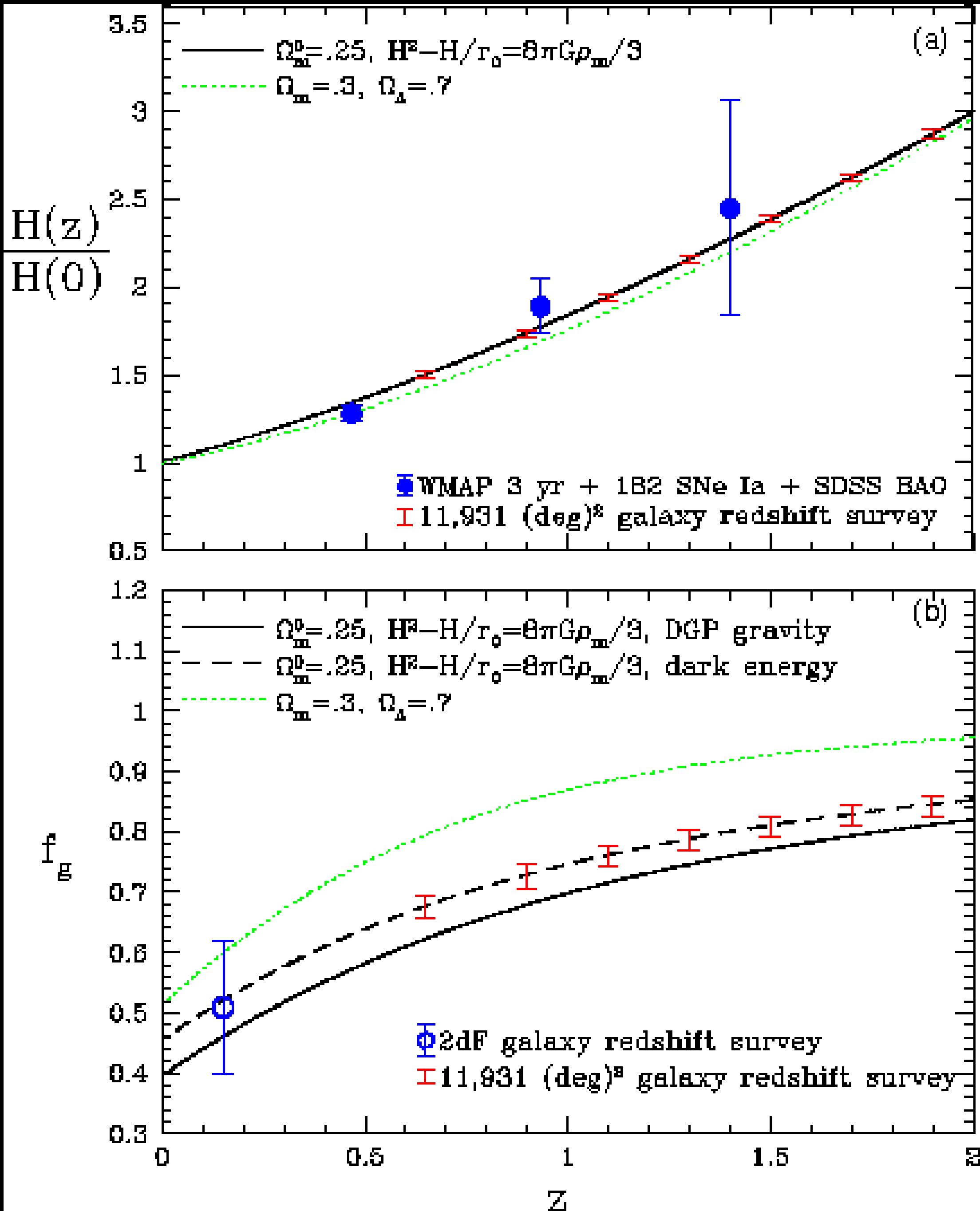
(Hu & Sugiyama 1996)

Differentiating dark energy and modified gravity

$f_g = d\ln\delta / d\ln a$

$\delta = (\rho_m - \langle\rho_m\rangle)/\langle\rho_m\rangle$

Wang (2008)



Model Selection Using Bayesian Evidence

Bayes theorem: $P(M|D)=P(D|M)P(M)/P(D)$

Bayesian edidence: $E=\int L(\theta)\Pr(\theta)d\theta$

:likelihood of the model given the data.

Jeffreys interpretational scale of $\Delta\ln E$ between two models:

- **$\Delta\ln E<1$: Not worth more than a bare mention.**
- **$1<\Delta\ln E<2.5$: Significant.**
- **$2.5<\Delta\ln E<5$: Strong to very strong.**
- **$5<\Delta\ln E$: Decisive.**

SNLS (SNe)+WMAP3+SDSS(BAO):

Compared to Λ, $\Delta\ln E$=-1.5 for constant w_X model

$\Delta\ln E$=-2.6 for $w_X(a)=w_0+w_a(1-a)$ model

Relative prob. of three models: 77%, 18%, 5%

Liddle, Mukherjee, Parkinson, & Wang (2006)