Observational Approaches to Understanding Dark Energy

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Lepton and Photon 2007

Daegu, Korea

August 16, 2007

beware of the dark side …

Master Yoda

Outline

- How do we know dark energy exists?
- Observational methods for dark energy search
- Future prospects: recommendations by
  - the Dark Energy Task Force
  - ESA-ESO Working Group on Fundamental Cosmology

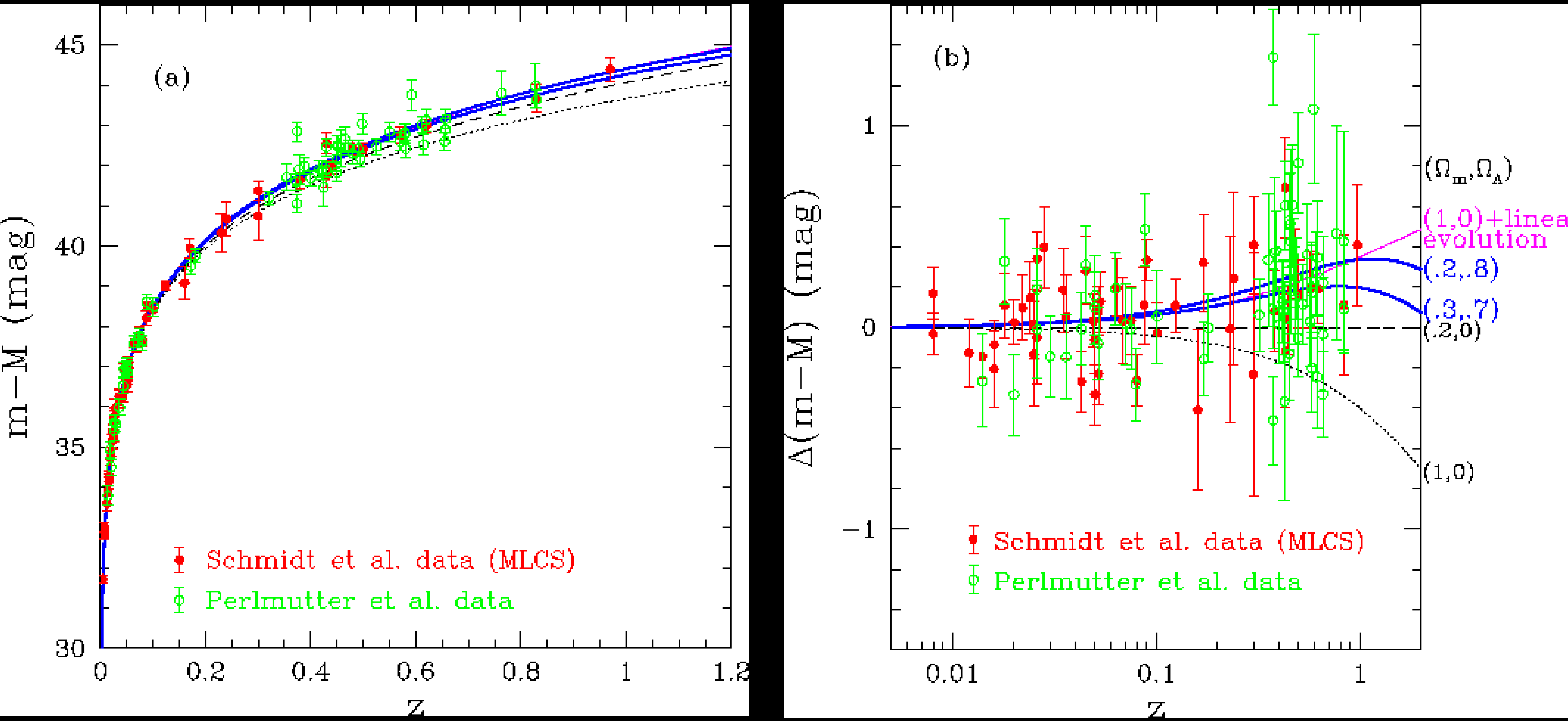
How do we know there is dark energy?

We infer its existence via its influence on the expansion history of the universe.

First Evidence for Dark Energy

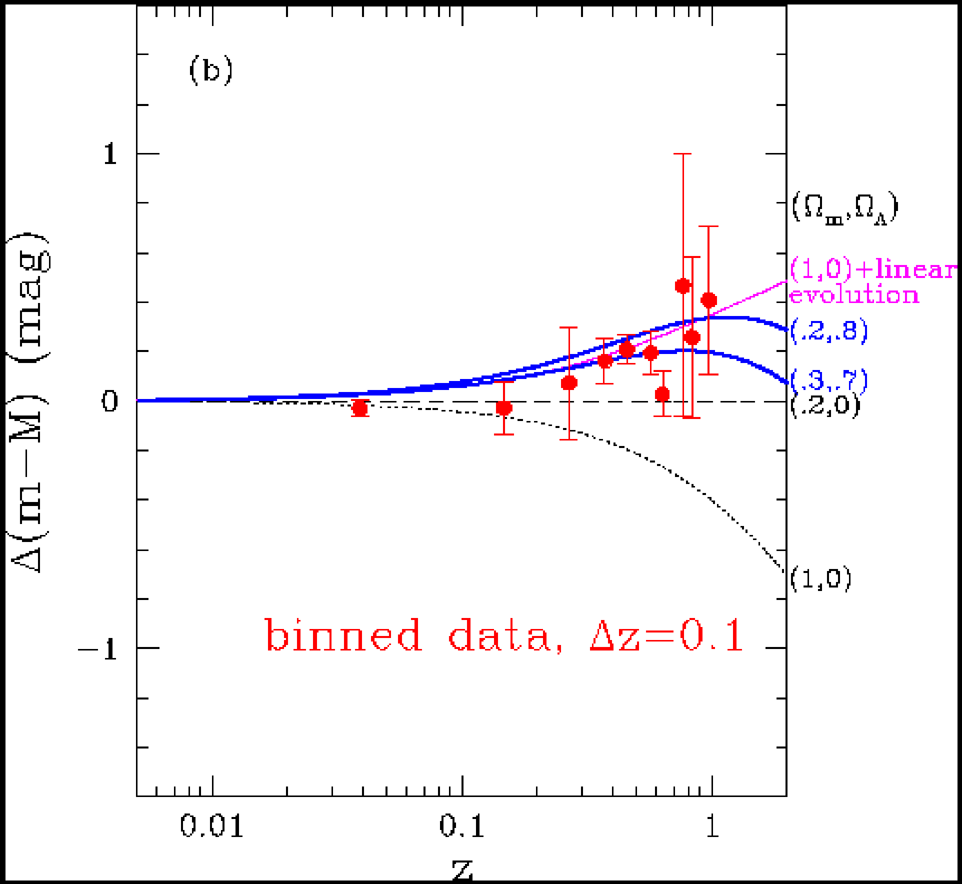
in the Hubble Diagrams of Supernovae [$d_L(z)$]

(Schmidt et al. 1998, Perlmutter et al. 1999)



Alternative Analysis of First Evidence

Flux-averaged and combined data of 92 SNe Ia from Schmidt et al. (1998) and Perlmutter et al. (1999). [***Wang 2000b, ApJ***]

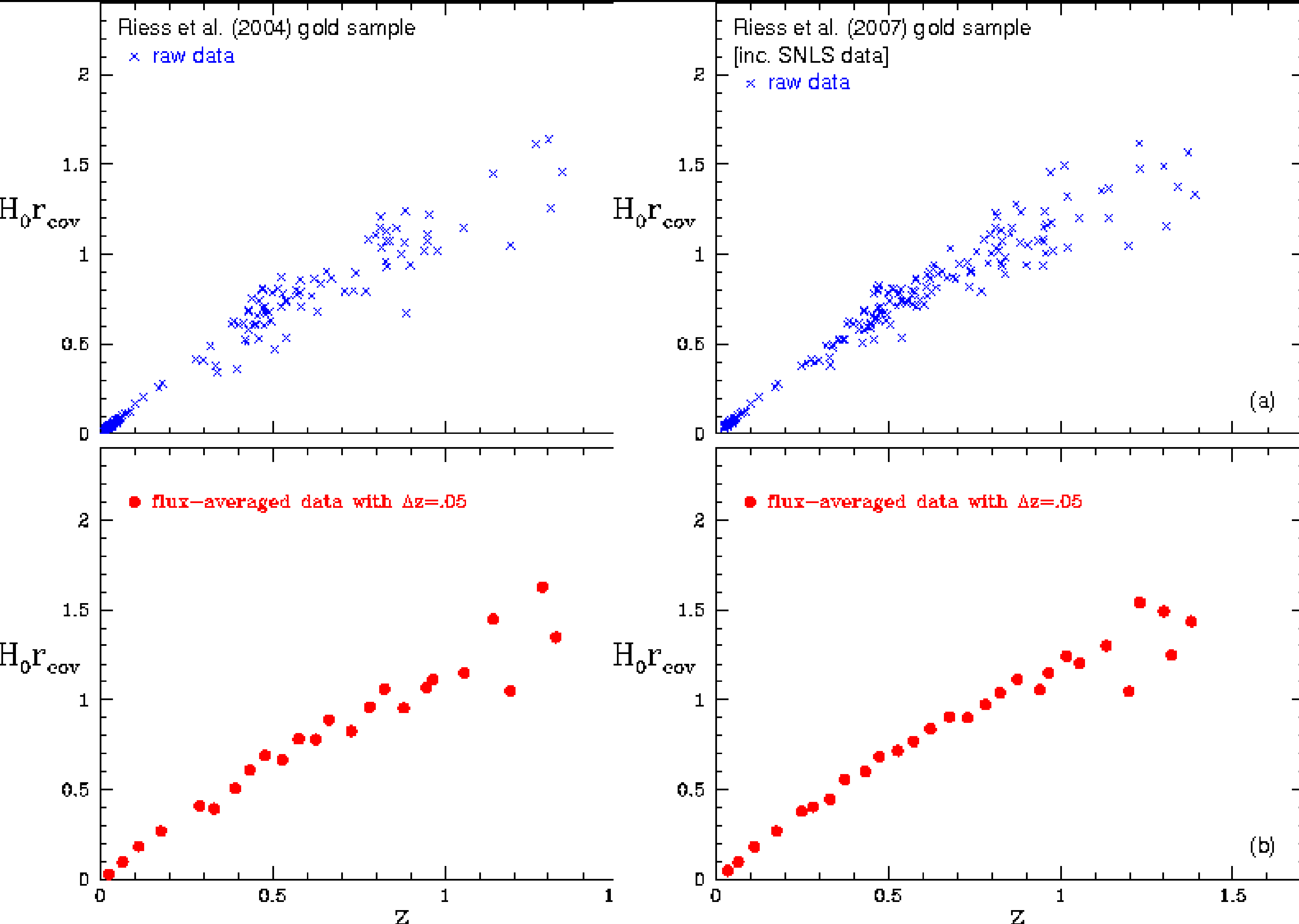


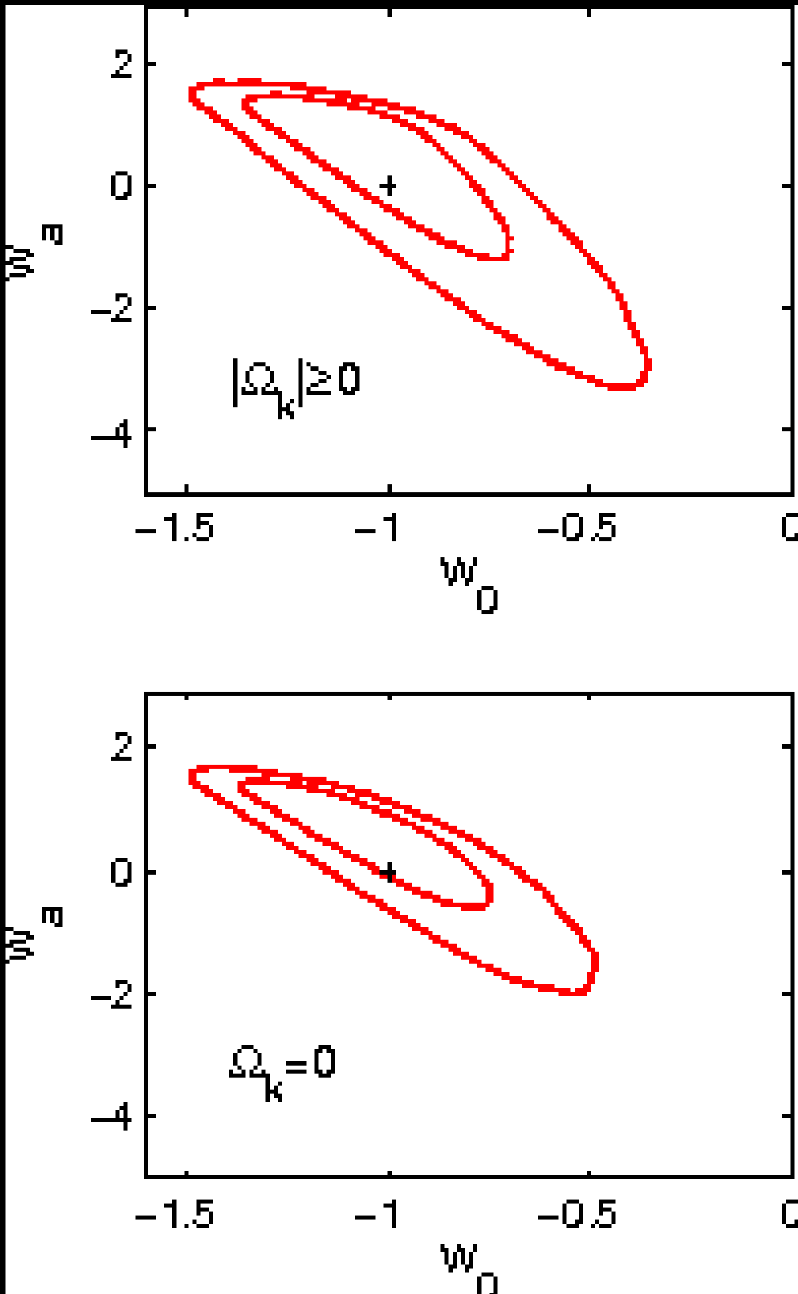
Deceleration parameter

$$q_0 = \Omega_m/2 - \Omega_\Lambda$$

Data favor $q_0 < 0$:
<u>cosmic acceleration</u>

Wang & Tegmark 2005





$$w(z) = w_0 + w_a(1-a)$$

$1+z = 1/a$

z: cosmological redshift

a: cosmic scale factor

WMAP3

+182 *SNe Ia (Riess et al. 2007, inc SNLS and nearby SNe)*

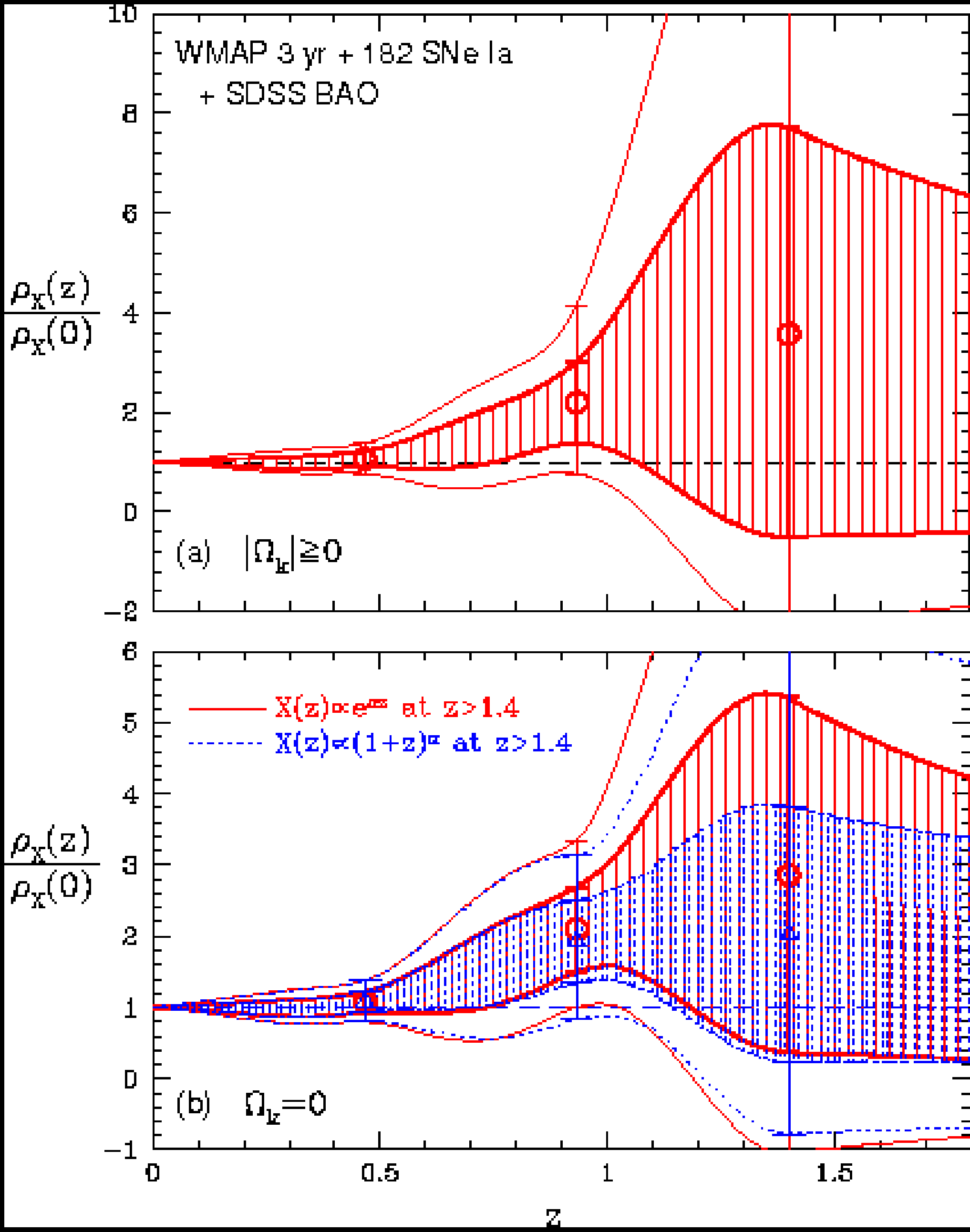
+*SDSS BAO*

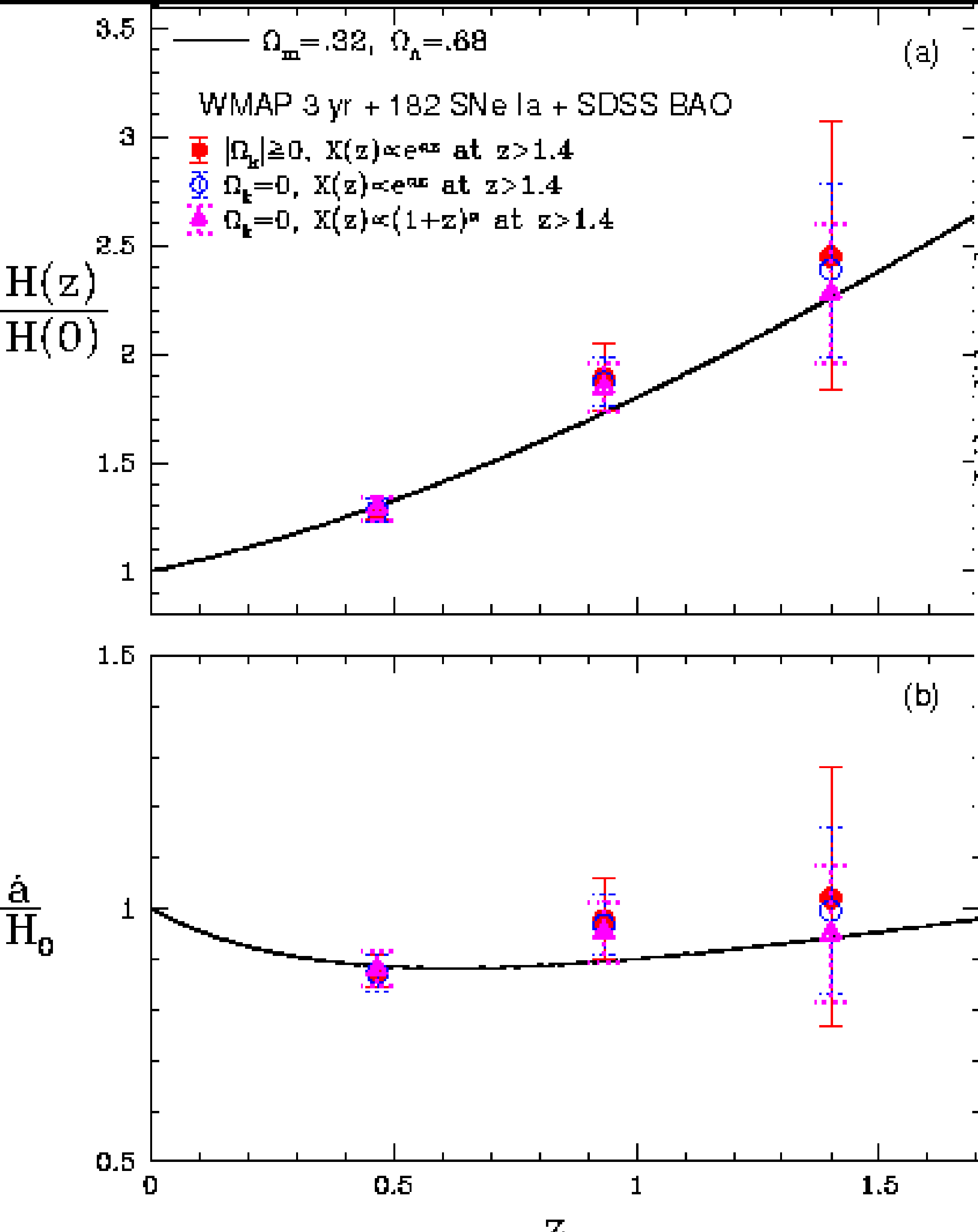
(Wang & Mukherjee 2007)

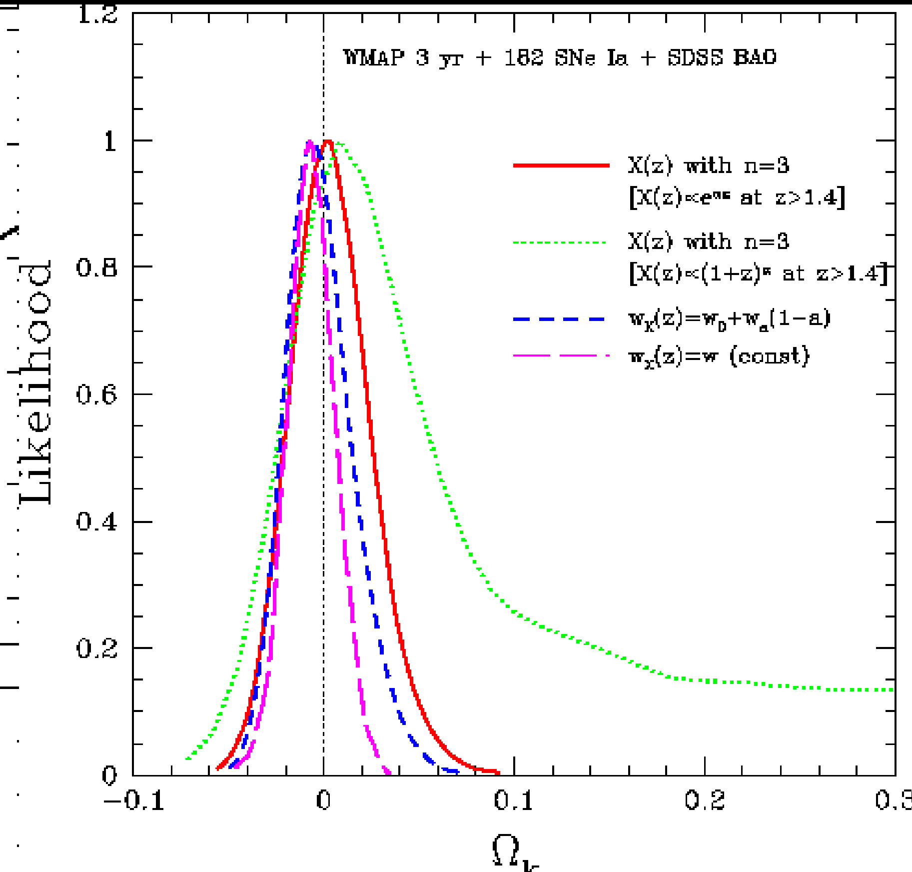
Model-independent constraints on dark energy

(as proposed by Wang & Garnavich 2001)

Wang & Mukherjee (2007)







Wang & Mukherjee (2007)

[See Wang & Tegmark (2005) for the method to derive uncorrelated estimate of $H(z)$ using SNe.]

$H(z) = [\mathrm{d}a/\mathrm{d}t]/a$

Some Candidates for Dark Energy

- **cosmological constant** *(Einstein 1917)*
- **quintessence** *(Freese, Adams, Frieman, Mottola 1987; Linde 1987; Peebles & Ratra 1988; Frieman et al. 1995; Caldwell, Dave, & Steinhardt 1998; Dodelson, Kaplinghat, & Stewart 2000)*
- **k-essence**: *(Armendariz-Picon, Mukhanov, & Steinhardt 2000)*
- **Modified Gravity**

Vacuum Metamorphosis *(Parker & Raval 1999)*

Modified Friedmann Equation *(Freese & Lewis 2002)*

Phantom DE from Quantum Effects *(Onemli & Woodard 2004)*

Backreaction of Cosmo. Perturbations *(Kolb, Matarrese, & Riotto 2005)*

How We Probe Dark Energy

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

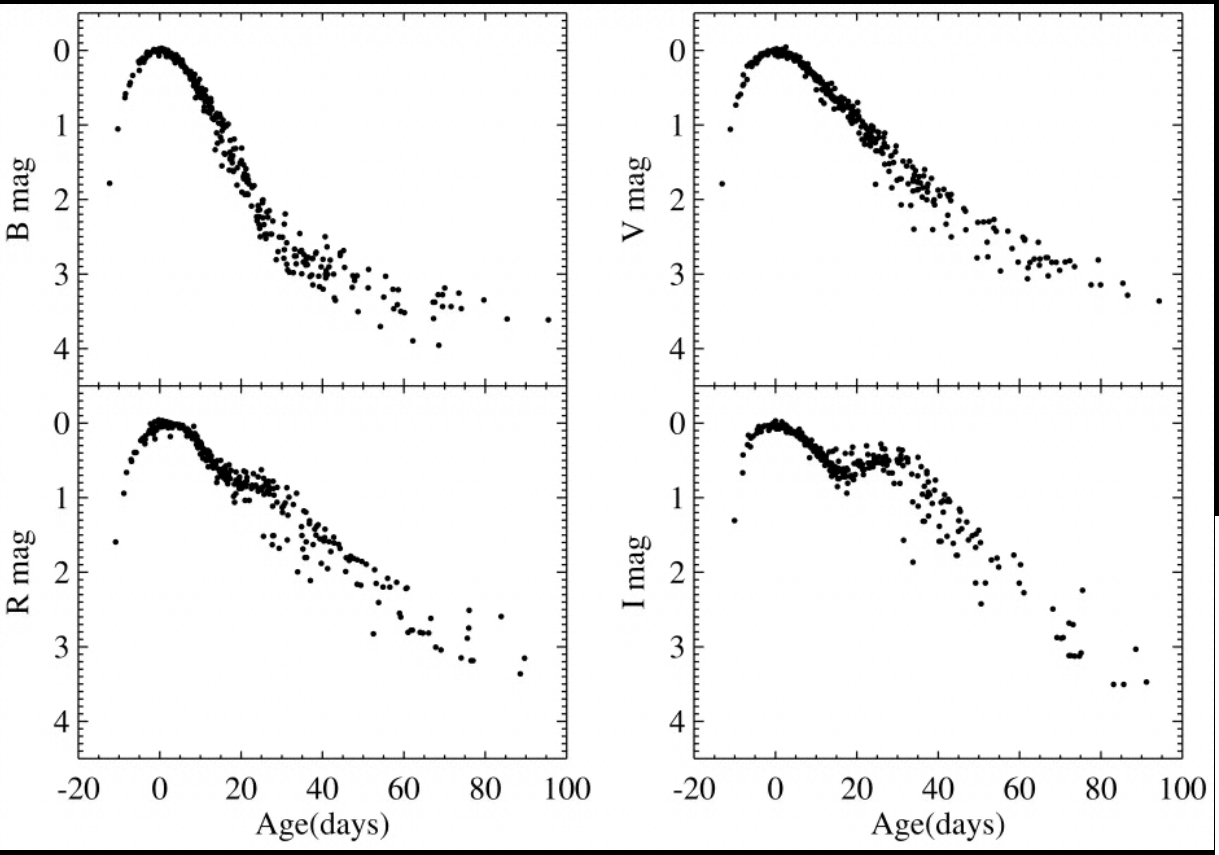
$$H^2(z) = 8\pi G[\rho_m(z) + \rho_r(z) + \rho_X(z)]/3 - k/a^2$$

- ***Growth history of cosmic large scale structure $G(z)$*** **tells us whether general relativity is modified**

Observational Methods for Dark Energy Search

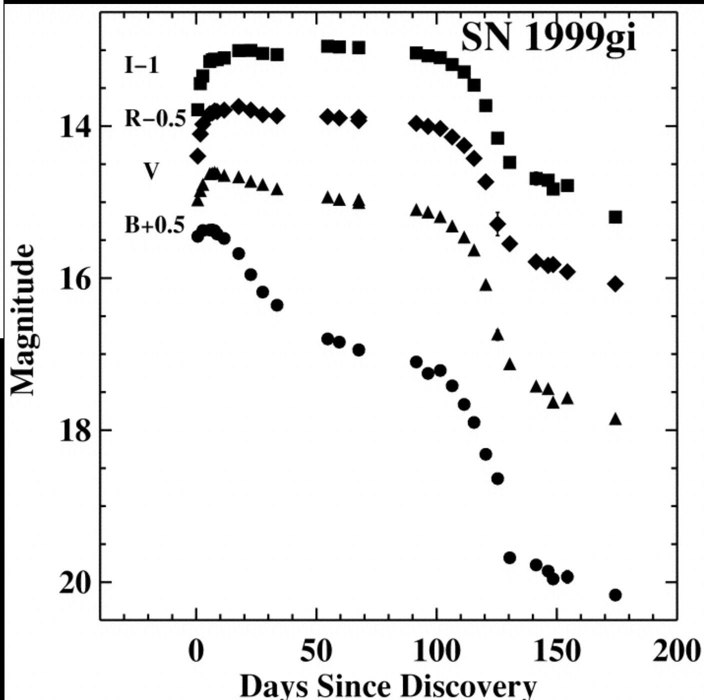
- ***SNe Ia (Standard Candles):***
  method through which DE has been discovered; independent of clustering of matter, probes $H(z)$
- ***Baryon Acoustic Oscillations (Standard Ruler):***
  calibrated by CMB, probes $H(z)$
- ***Weak Lensing Tomography and Cross-Correlation Cosmography:***
  probes clustering of matter $G(z)$, and $H(z)$
- ***Galaxy Cluster Statistics:***
  probes $H(z)$

Supernovae as Standard Candles



The SNe Ia lightcurves (left) are very different from that of SNe II (below).

Measuring the apparent peak brightness and the redshift of SNe Ia gives $d_L(z)$, hence $H(z)$



Yun Wang, LP07, 8/16/2007

Theoretical understanding of SNe Ia

Binary → C/O white dwarf at the Chandrasekher limit (~ 1.4 M_{Sun})

→ explosion

→ radioactive decay of ^{56}Ni and ^{56}Co: observed brightness

- **explosion: carbon burning begins as a turbulent deflagration, then makes a transition to a supersonic detonation**

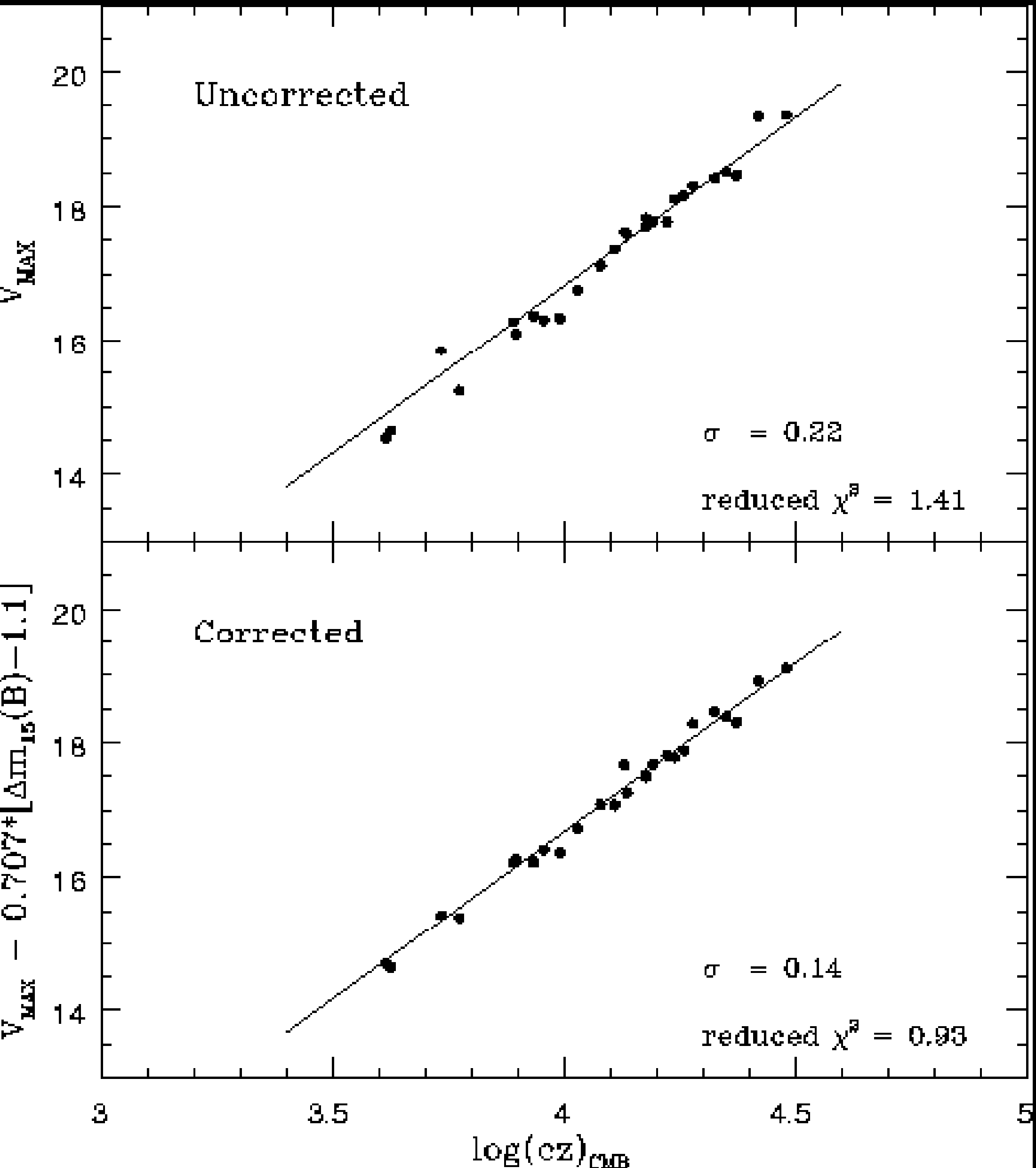
- **earlier transition:**

  ***cooler explosion* → less ^{56}Ni produced: dimmer SN Ia**

  ***lower opacity* → faster decline of the SN brightness**

Wheeler 2002 (resource letter)

Calibration of SNe Ia



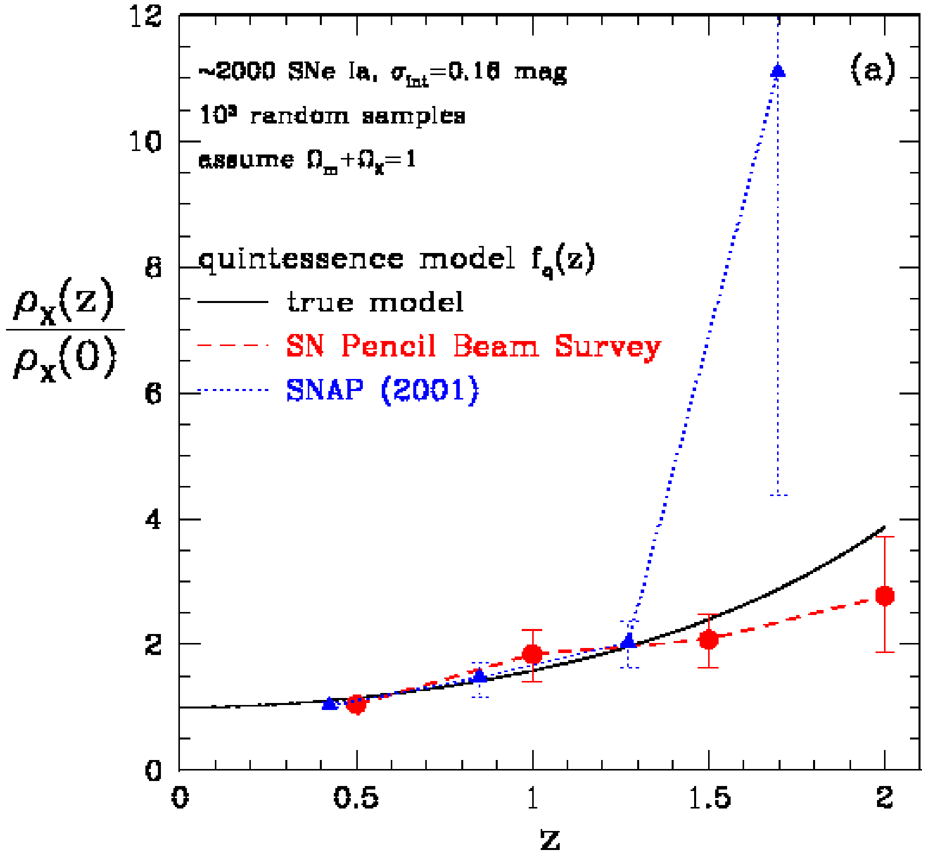
Phillips 1993
Riess, Press, & Kirshner 1995

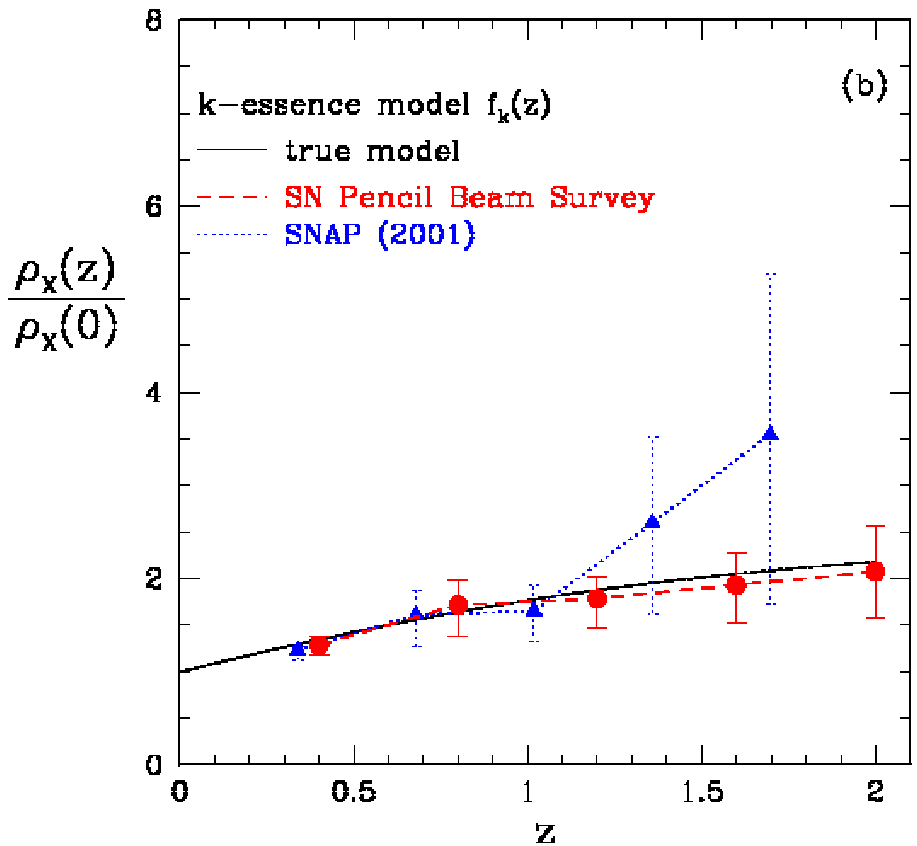
Brighter SNe Ia decline more slowly → make a correction to the brightness based on the decline rate.

26 SNe Ia with B_{max}-$V_{max} \leq 0.20$ from the Calan/Tololo sample [Hamuy et al. 1996, AJ, 112, 2398]

Getting the most distant SNe Ia:

critical for measuring the evolution in dark energy density:





Wang & Lovelave (2001)

SNe Ia as Cosmological Standard Candles

Systematic effects:

dust: can be constrained using multi-color data.

(Riess et al. 1998; Perlmutter et al. 1999)

gray dust: constrained by the cosmic far infrared background. *(Aguirre & Haiman 2000)*

gravitational lensing: its effects can be reduced by flux-averaging. *(Wang 2000; Wang, Holz, & Munshi 2002)*

SN Ia evolution (progenitor population drift):

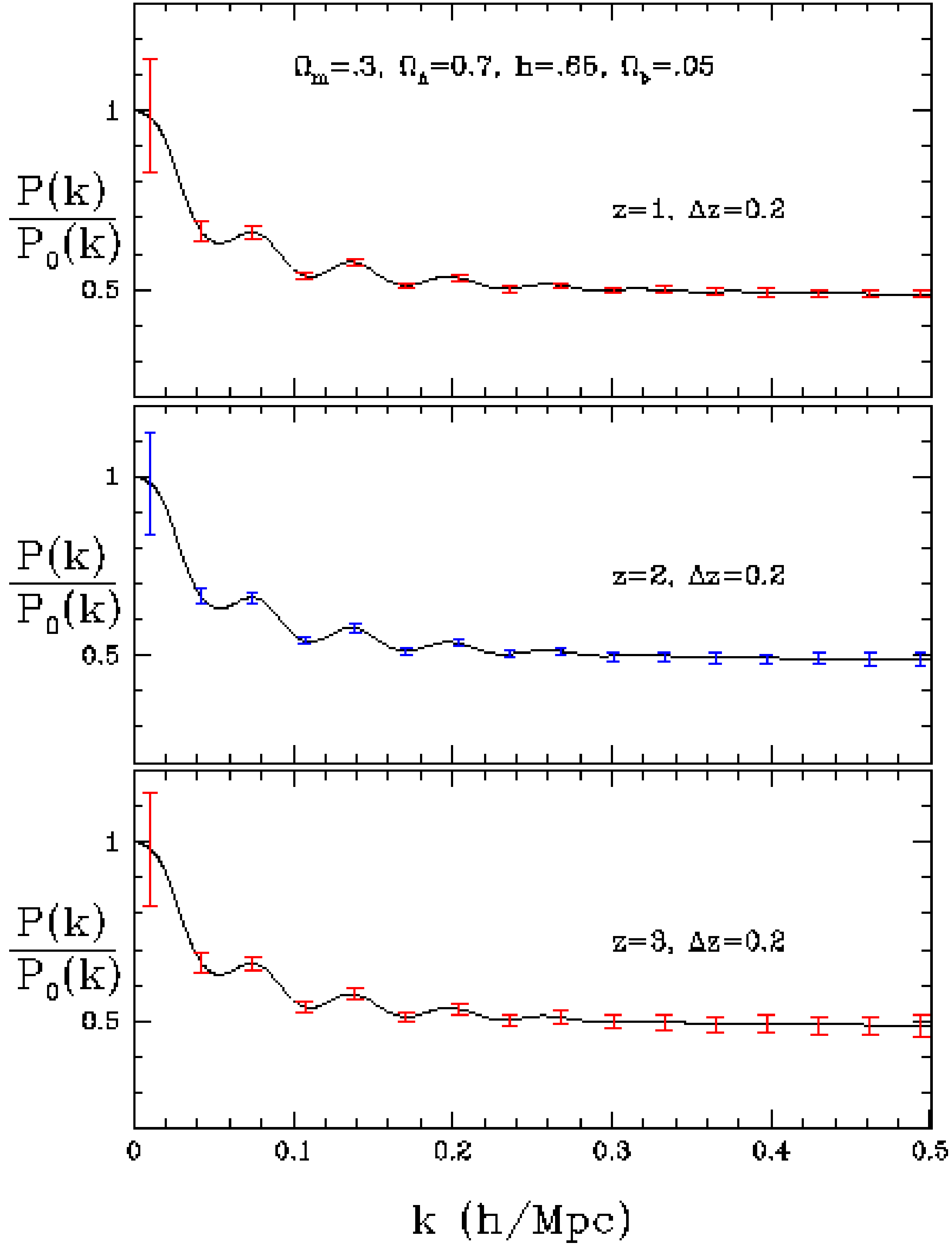
Once we obtain a large number of SNe Ia at high z ($z > 1$), we can disregard SN Ia events that have no counterparts at high z, and only compare like with like. *(Branch et al., astro-ph/0109070)*

Baryon acoustic oscillations as a standard ruler

Blake & Glazebrook 2003

Seo & Eisenstein 2003

Comparing the observed acoustic scale with its expected values gives us ***H*(*z*)** [radial direction] and ***D*$_A$(*z*)** [transverse direction]



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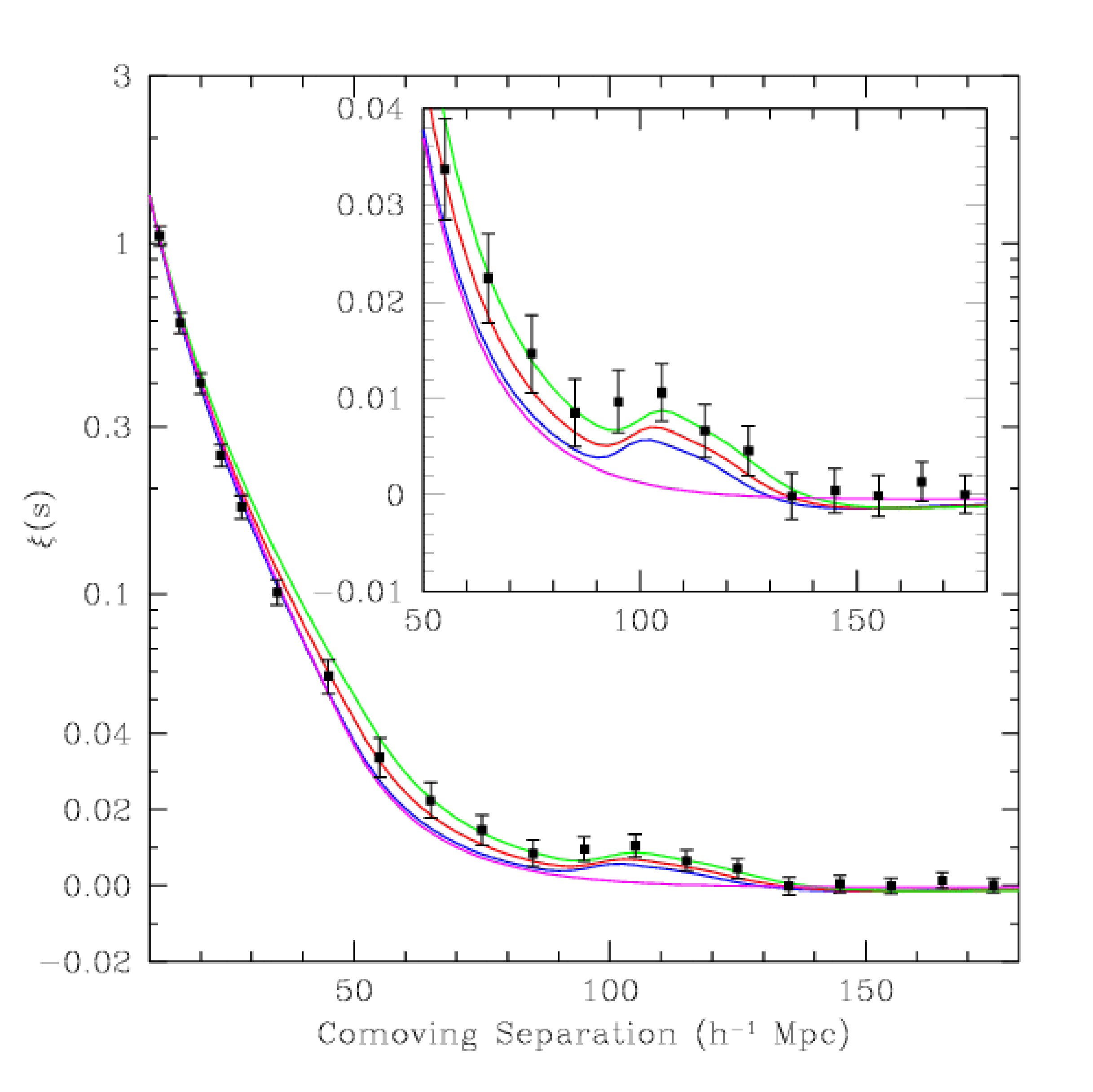
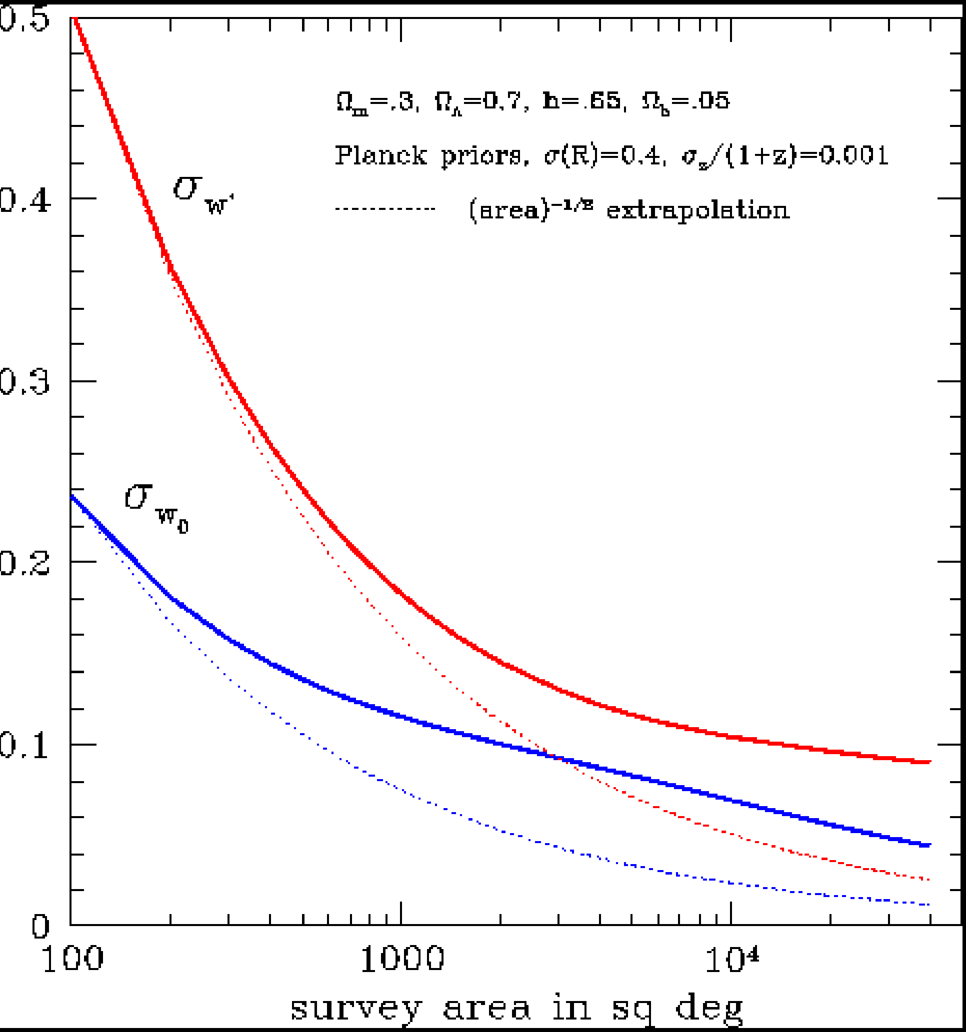
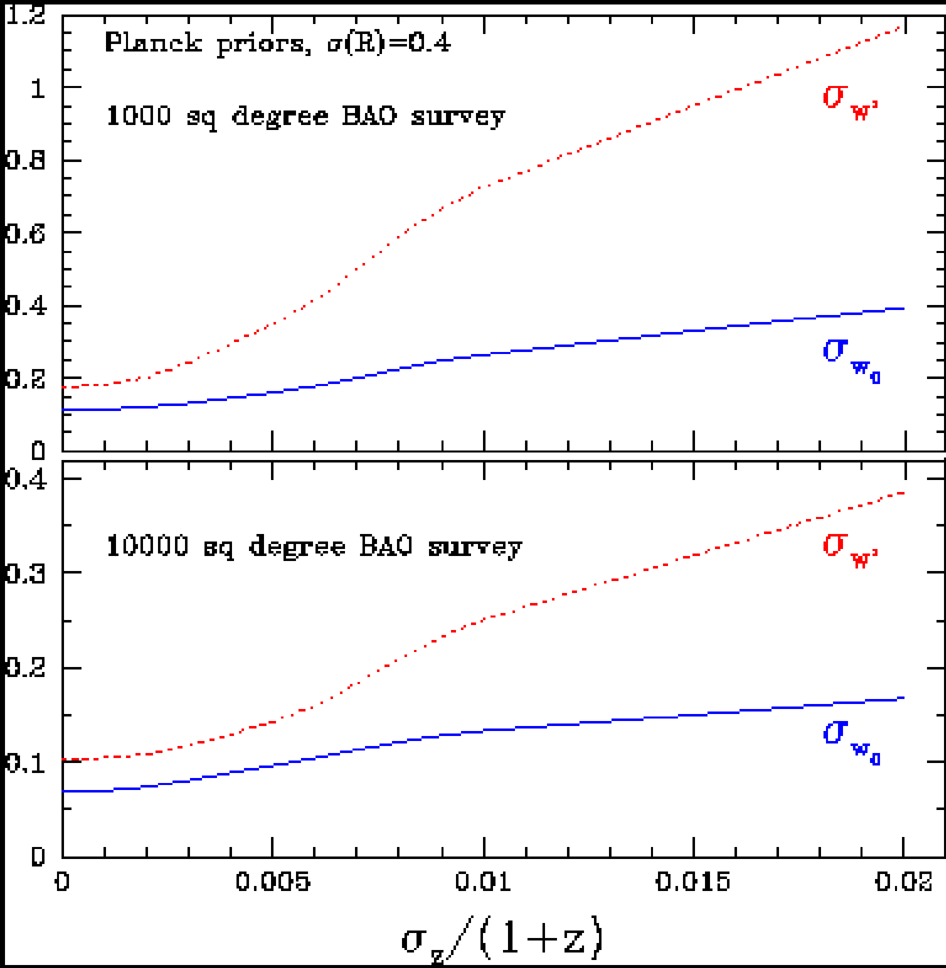
Detection of BAO in the SDSS data *[Eisenstein et al. 2005]*



DE eq. of state

$w(z)=w_0+w'z$





Wang 2006

BAO systematic effects

- Galaxy clustering bias
- Redshift space distortions
- Nonlinear gravitational clustering

Weak Lensing Tomography and Cross-Correlation Cosmography

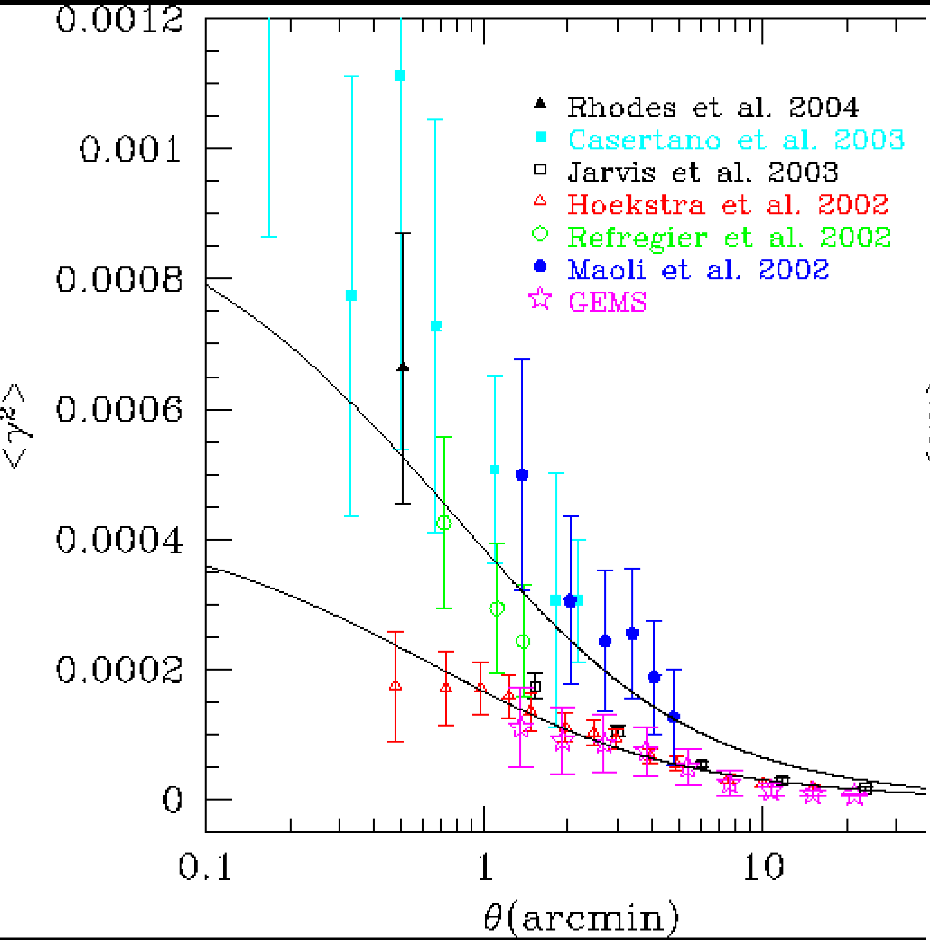
Gravitational Lens in Abell 2218 HST • WFPC2

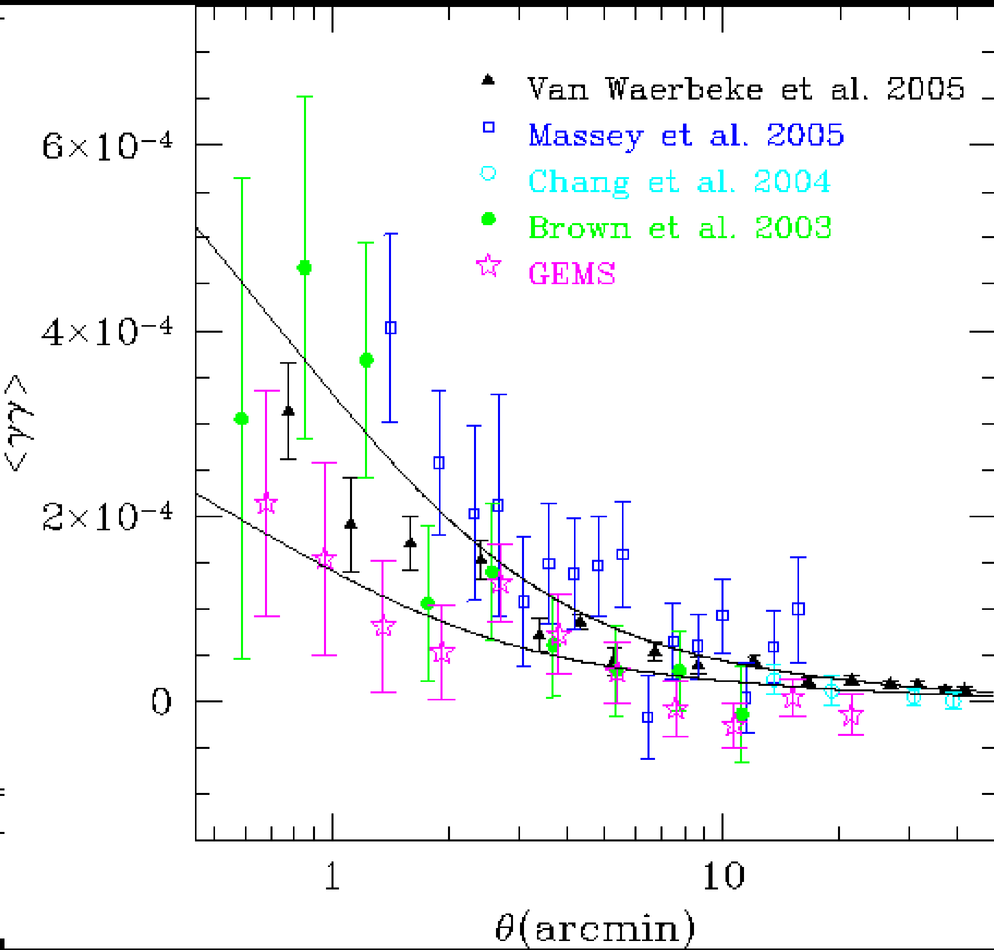
PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

- **Weak Lensing Tomography:** compare observed cosmic shear correlations with theoretical/numerical predictions to measure cosmic large scale structure growth history $G(z)$ and $H(z)$ *[Wittman et al. 2000]*

- **WL Cross-Correlation Cosmography** measure the relative shear signals of galaxies at different distances for the same foreground mass distribution: gives distance ratios $d_A(z_i)/d_A(z_j)$ that can be used to obtain cosmic expansion history $H(z)$ *[Jain & Taylor 2003]*

Measurements of cosmic shear (WL image distortions of a few percent)

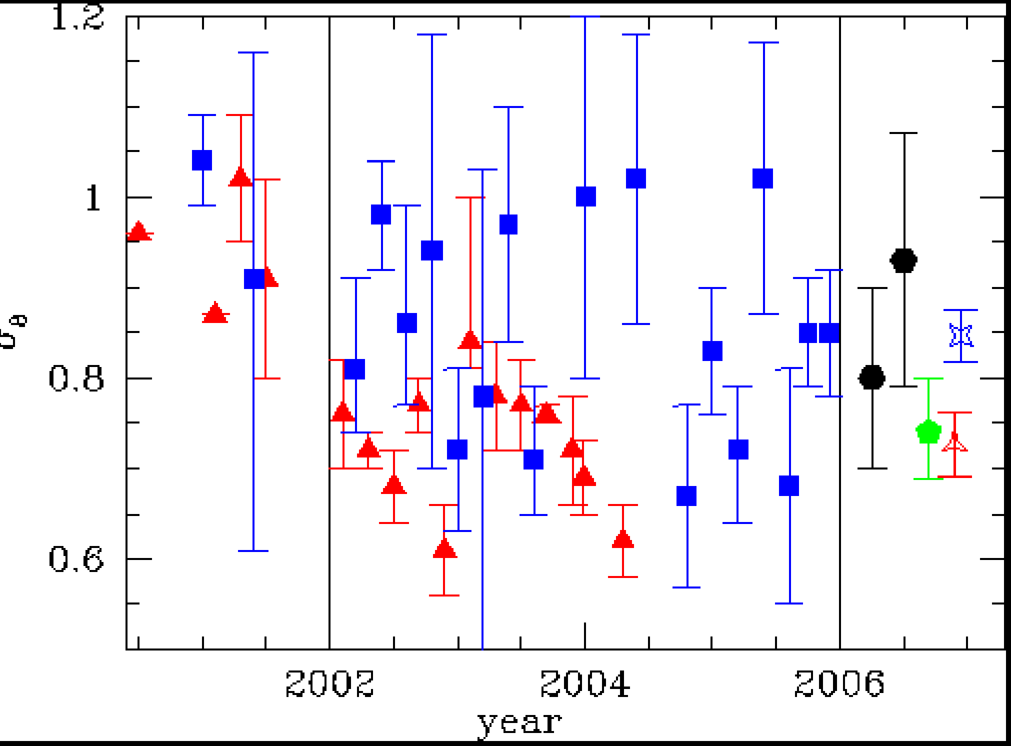


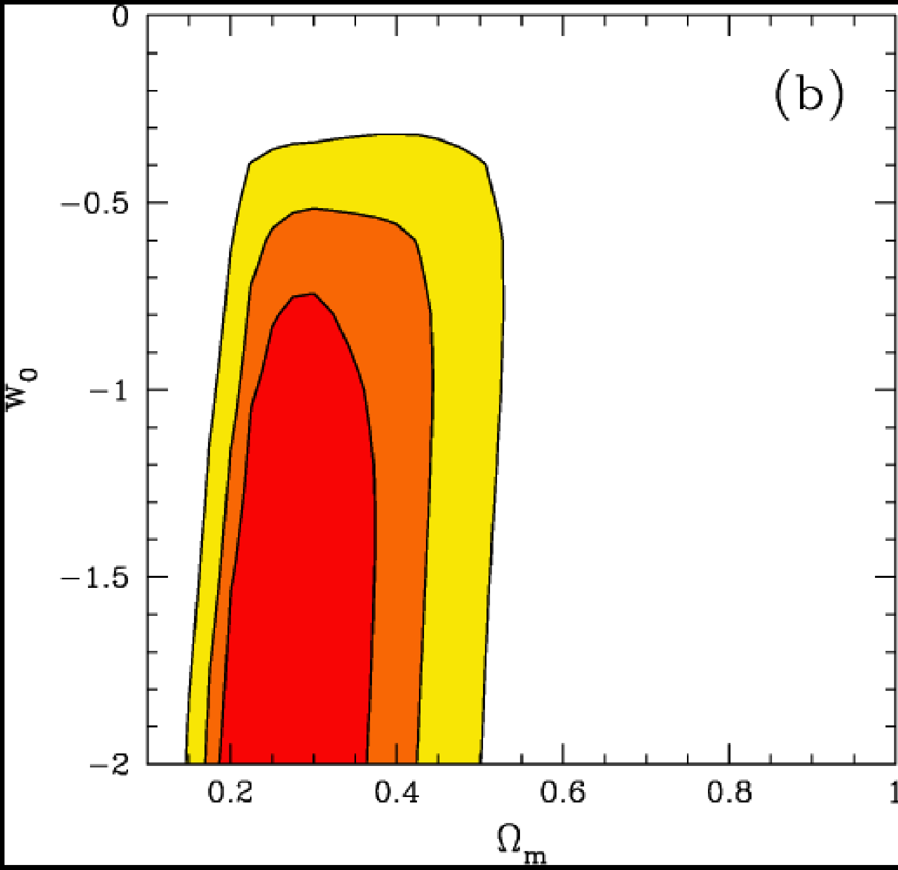


left:top-hat shear variance; right: total shear correlation function. σ_8=1 (upper); 0.7 (lower). z_m=1.

First conclusive detection of cosmic shear was made in 2000.

Cosmological parameter constraints from WL

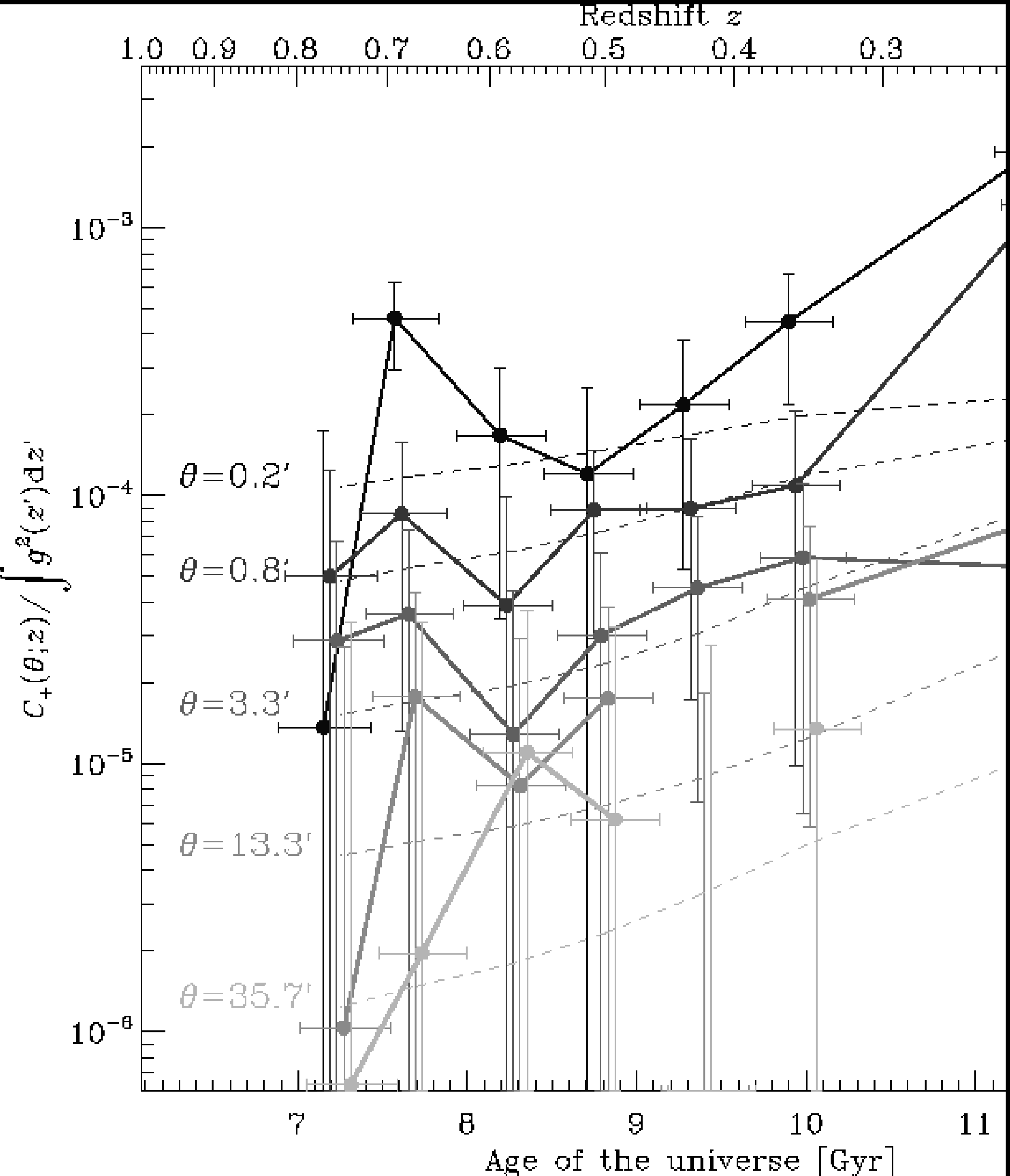




L: σ_8 from analysis of clusters of galaxies (red) and WL (other). *[Hetterscheidt et al. (2006)]*

R: DE constraints from CFHTLS Deep and Wide WL survey. *[Hoekstra et al. (2006)]*

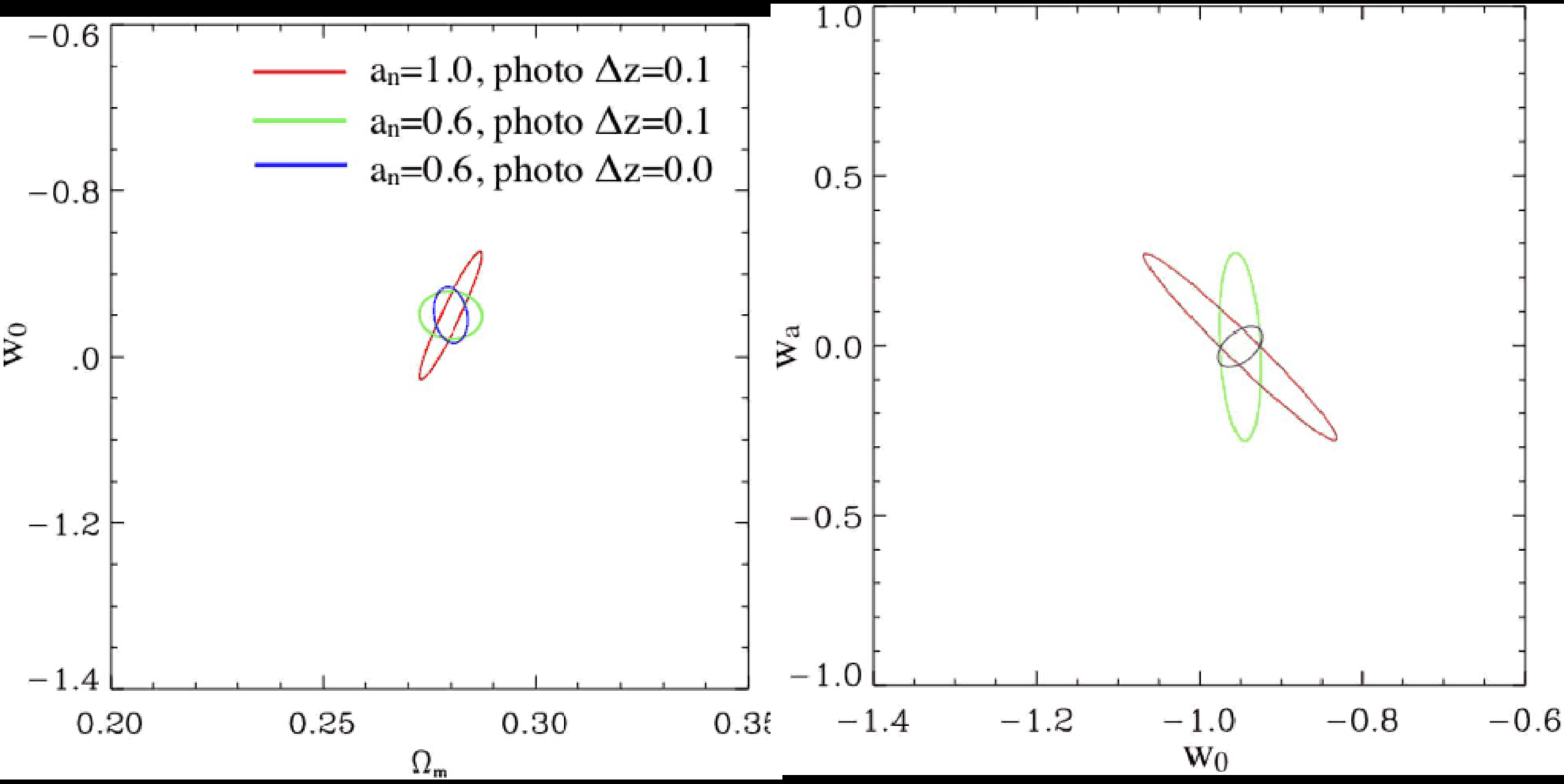
Growth history of structure from WL



Cosmic shear signal on fixed angular scales as a function of redshift.

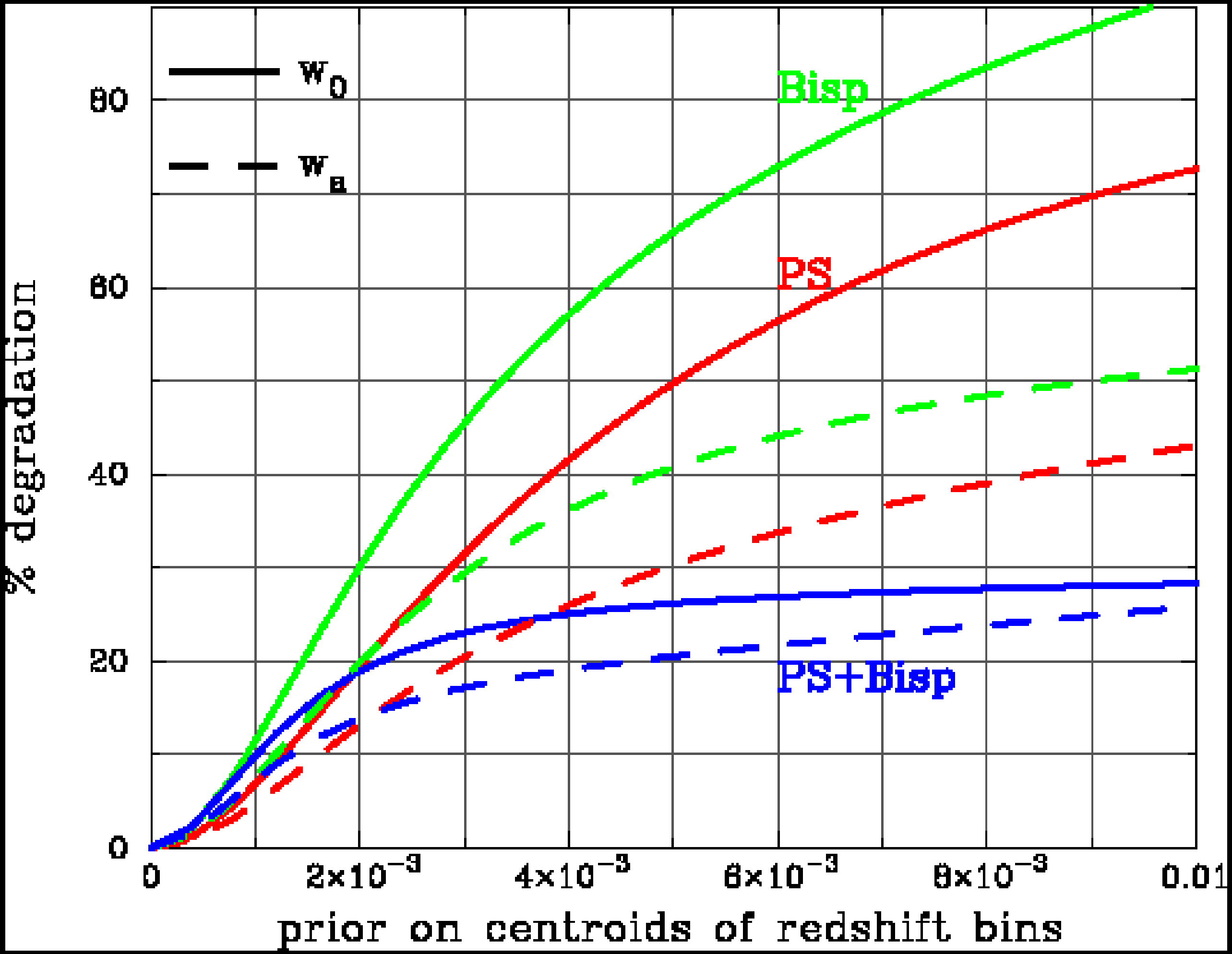
[Massey et al. (2007)]

Forecasting of DE constraints from WL



DUNE: 20,000 sq deg WL survey with z_m=1, 1 broad red band, photo-z from ground surveys [Refregier et al. (2006)]

DE constraints from WL depend on the accuracy of photometric redshifts



Huterer et al. (2006)

WL systematics effects

- Bias in photometric redshift distribution
- PSF correction
- Bias in selection of the galaxy sample
- Intrinsic distortion signal (intrinsic alignment of galaxies)

Clusters as DE probe

1) Use the cluster number density and its redshift distribution, as well as cluster distribution on large scales.

2) Use clusters as standard candles by assuming a constant cluster baryon fraction, or use combined X-ray and SZ measurements for absolute distance measurements.

- ***Large, well-defined and statistically complete samples of galaxy clusters are prerequisites.***

Clusters as DE probe

- Requirements for future surveys:
  - selecting clusters using data from X-ray satellite with high resolution and wide sky coverage
  - Multi-band optical and near-IR surveys to obtain photo-z's for clusters.
- **Systematic uncertainties:** uncertainty in the cluster mass estimates that are derived from observed properties, such as X-ray or optical luminosities and temperature.

Future Prospects:

Recommendations by

the Dark Energy Task Force *and* ESA-ESO Working Group on Fundamental Cosmology

DETF Definitions

- **DETF figure of merit**
  = 1/[area of error ellipse in the w_0-w_a plane]
- **DETF stages for DE probes:**
  - Stage I: Current knowledge
  - Stage II: Ongoing projects
  - Stage III: Near-term, medium-cost projects,
  - Stage IV: Long-term, high-cost projects (JDEM, LST, SKA)

DETF recommendations

- **Aggressive program** to explore DE as fully as possible.
- DE program with **multiple techniques** at every stage, at least one of these is a probe sensitive to the growth of cosmic structure in the form of galaxies and clusters of galaxies.
- DE program in **Stage III** designed to achieve at least **a factor of 3 gain over Stage II** in the figure of merit.
- DE program in **Stage IV** designed to achieve at least **a factor of 10 gain over Stage II** in the figure of merit.
- Continued research and development investment to **optimize JDEM, LST, and SKA** to address remaining technical questions and systematic-error risks.
- High priority for **near-term projects** to improve understanding of dominant **systematic effects** in DE measurements, and wherever possible, reduce them.
- **A coherent program of experiments** designed to meet the above coals and criteria.

ESA-ESO WG recommendations

- **Wide-field optical and near-IR imaging survey** [WL/CL]
  - ESA: satellite with high resolution wide-field optical and near-IR imaging
  - ESO: optical multi-color photometry from the ground
  - ESO: large spectroscopic survey (>100,000 redshifts over ~10,000 sq deg to calibration of photo-*z*'s)
- Secure access to an instrument with **capability for massive multiplexed deep spectroscopy** (several thousand simultaneous spectra over one sq deg) [BAO]
- A **supernova survey** with multi-color imaging to extend existing samples of z=0.5-1 SNe by an order of magnitude, and improve the local sample of SNe. [SNe]
- Use a European Extremely Large Telescope (ELT) to study SNe at z >1. [SNe]

Future Dark Energy Surveys
(an incomplete list)

- Essence (2002-2007): 200 SNe Ia, $0.2 < z < 0.7$, 3 bands, $\Delta t \sim 2d$
- Supernova Legacy Survey (2003-2008): 2000 SNe Ia to z=1
- CFHT Legacy (2003-2008): 2000 SNe Ia, 100's high z SNe, 3 bands, $\Delta t \sim 15d$
- ESO VISTA (2005?-?): few hundred SNe, $z < 0.5$
- Pan-STARRS (2006-?): all sky WL, 100's SNe y^{-1}, $z < 0.3$, 6 bands, $\Delta t = 10d$
- WiggleZ on AAT using AAOmega (2006-2009): 1000 deg^2 BAO, $0.5< z < 1$

- ALPACA (?): 50,000 SNe Ia per yr to z=0.8, $\Delta t = 1d$, 800 sq deg WL & BAO with photo-z
- Dark Energy Survey (?): cluster at $0.1<z<1.3$, 5000 sq deg WL, 2000 SNe at $0.3<z<0.8$
- HETDEX (?): 200 sq deg BAO, $1.8 < z < 3$.
- WFMOS on Subaru (?): 2000 sq deg BAO, $0.5<z<1.3$ and $2.5<z<3.5$

- LSST (2012?): 0.5-1 million SNe Ia y^{-1}, $z < 0.8$, > 2 bands, $\Delta t = 4\text{-}7d$; 20,000 sq deg WL & BAO with photo-z
- JDEM (2017?): several competing mission concepts [ADEPT, DESTINY, JEDI, SNAP]

How many methods should we use?

- The challenge to solving the DE mystery will not be the statistics of the data obtained, but the tight control of systematic effects inherent in the data.
- A combination of the three most promising methods (SNe, BAO, WL), each optimized by having its systematics minimized by design, provides the tightest control of systematics.

Conclusions

- **Unraveling the nature of DE is one of the most important problems in cosmology today. Current data (SNe Ia, CMB, and LSS) are consistent with a constant $\rho_X(z)$ at 68% confidence. However, the reconstructed $\rho_X(z)$ still has large uncertainties at $z > 0.5$.**
- **DE search methods' checklist:**

  1) Supernovae as standard candles;

  2) Baryon acoustic oscillations.

  3) Weak lensing tomography and cosmography.
- **A combination of different methods is required to achieve accurate and precise constraints on the time dependence of $\rho_X(z)$. This will have a fundamental impact on particle physics and cosmology, and strongly recommended by DETF and ESA-ESO working group on fundamental cosmology.**

Evidence for Dark Energy

Speeding up of cosmic expansion increases the distance between two galaxies (Milky Way and supernova host galaxy), which would lead to fainter than expected observed supernovae.

Observed supernovae are fainter than expected, so the expansion of the universe must have accelerated.

For convenience, the unknown cause for the observed acceleration of the cosmic expansion is dubbed dark energy.

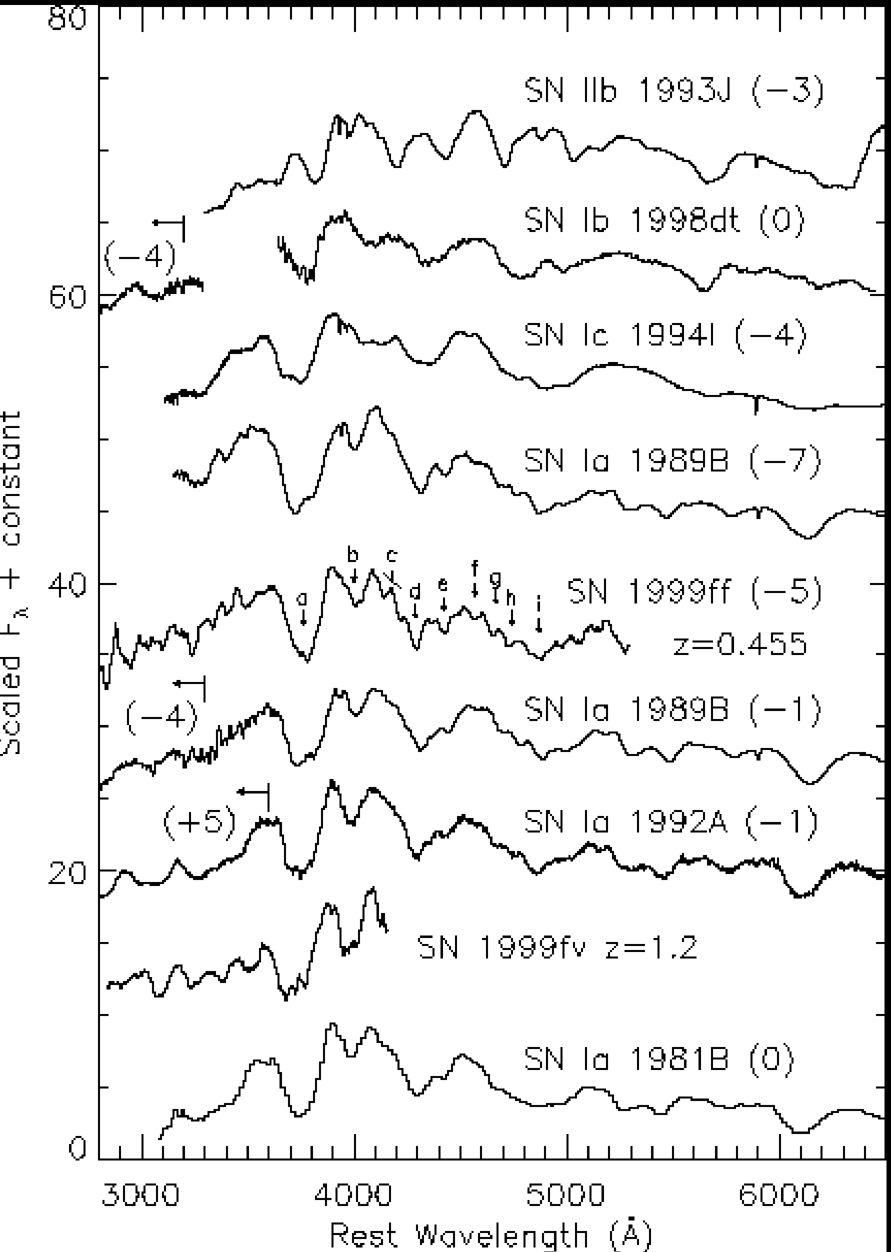
What is dark energy?

Two Possibilities:

(1) Unknown energy component

(2) Modification of Einstein’s theory of general relativity (a.k.a. Modified Gravity)

Spectral Signature of SNe Ia



Primary feature: Si II λ6355 at λ_{rest}=6150Å

Secondary feature: Si II λ4130 dip blueshfted to 4000Å

SN Ia 1999ff (z=0.455):

a: Ca II H and K absorption

b: Si II λ4130 dip blueshfted to 4000Å

c: blueward shoulder of Fe II λ4555

d: Fe II λ4555 and/or Mg II λ4481

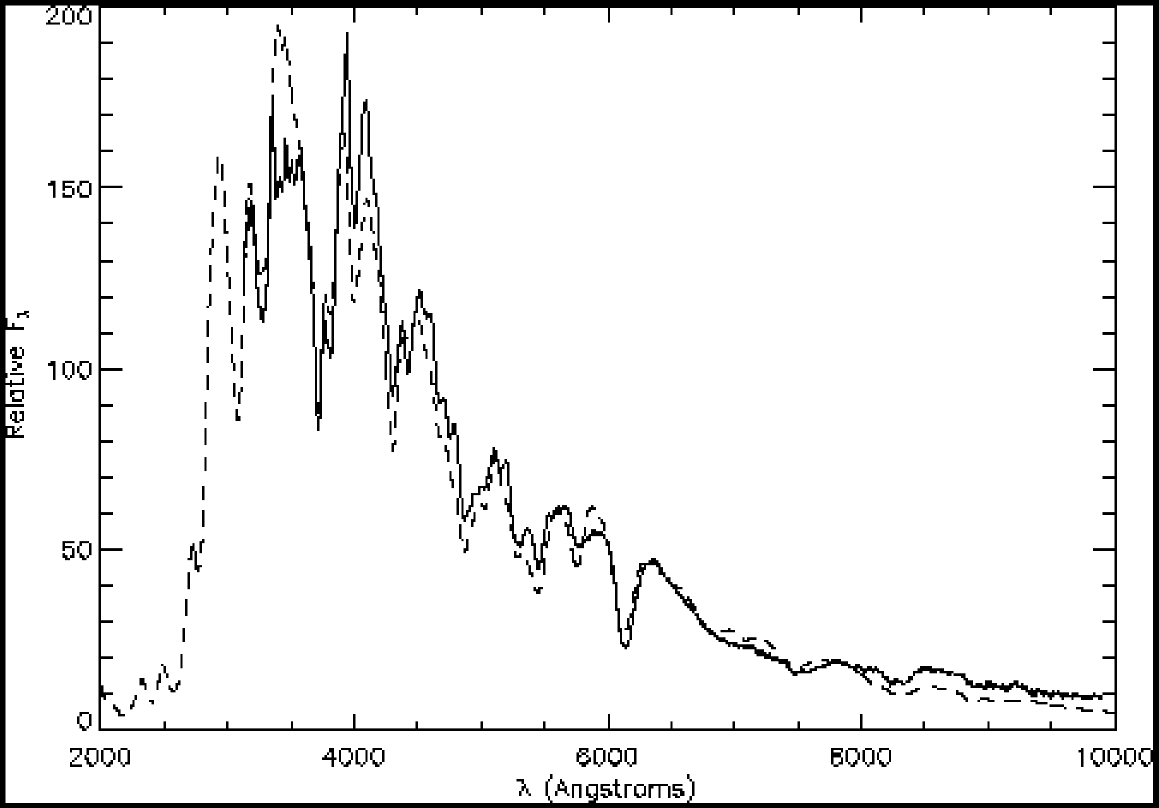
e: Si III λ4560

i: Si II λ5051

SN IIb 1993J: double peak centered just blueward of 4000Å, due to Ca II H and K absorption at 3980Å due to blueshufted Hδ, but not similar to Ia redward of 4100Å.

[Coil et al. 2000, ApJ, 544, L111]

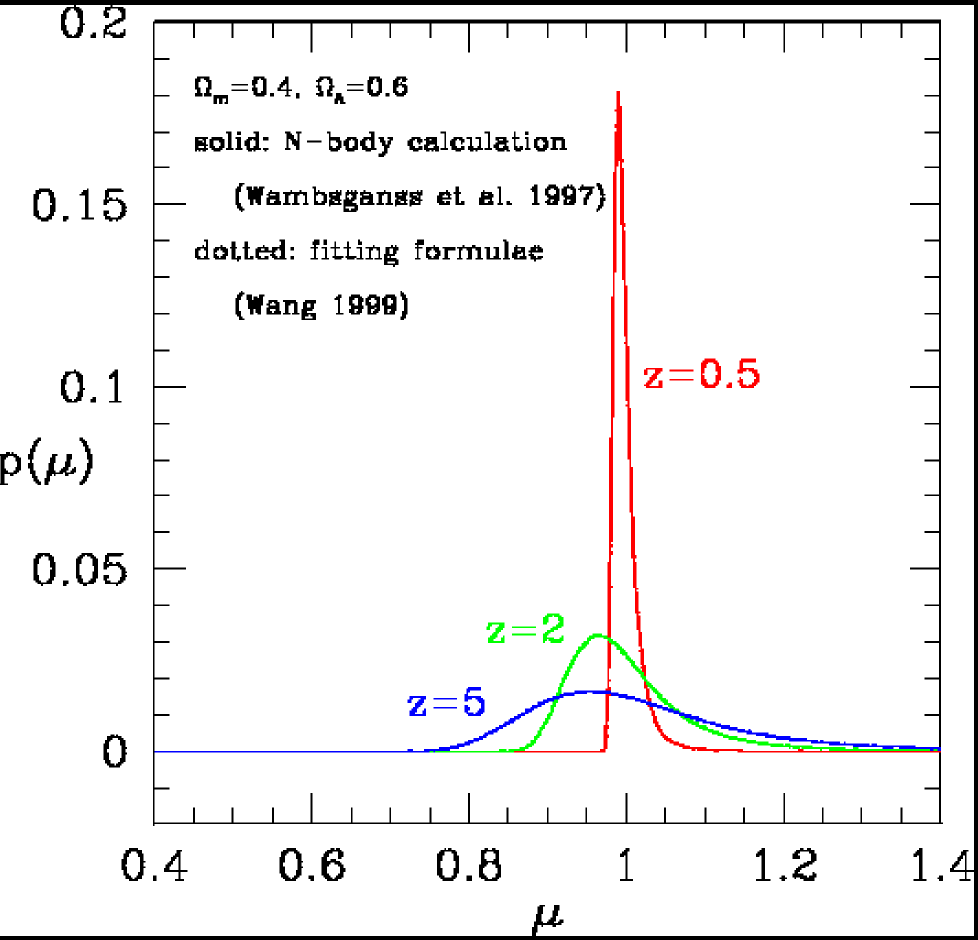
Understanding SN Ia Spectra



Solid: Type Ia SN 1994D, 3 days before maximum brightness

Dashed: a PHOENIX synthetic spectrum (Lentz, Baron, Branch, Hauschildt 2001, ApJ 557, 266)

Weak Lensing of SNe Ia



Kantowski, Vaughan, & Branch 1995
Frieman 1997
Wambsganss et al. 1997
Holz & Wald 1998
Metcalf & Silk 1999
Wang 1999

WL of SNe Ia can be modeled by a Universal Probability Distribution for Weak Lensing Magnification *(Wang, Holz, & Munshi 2002)*

The WL systematic of SNe Ia can be removed by flux averaging

(Wang 2000; Wang & Mukherjee 2003)

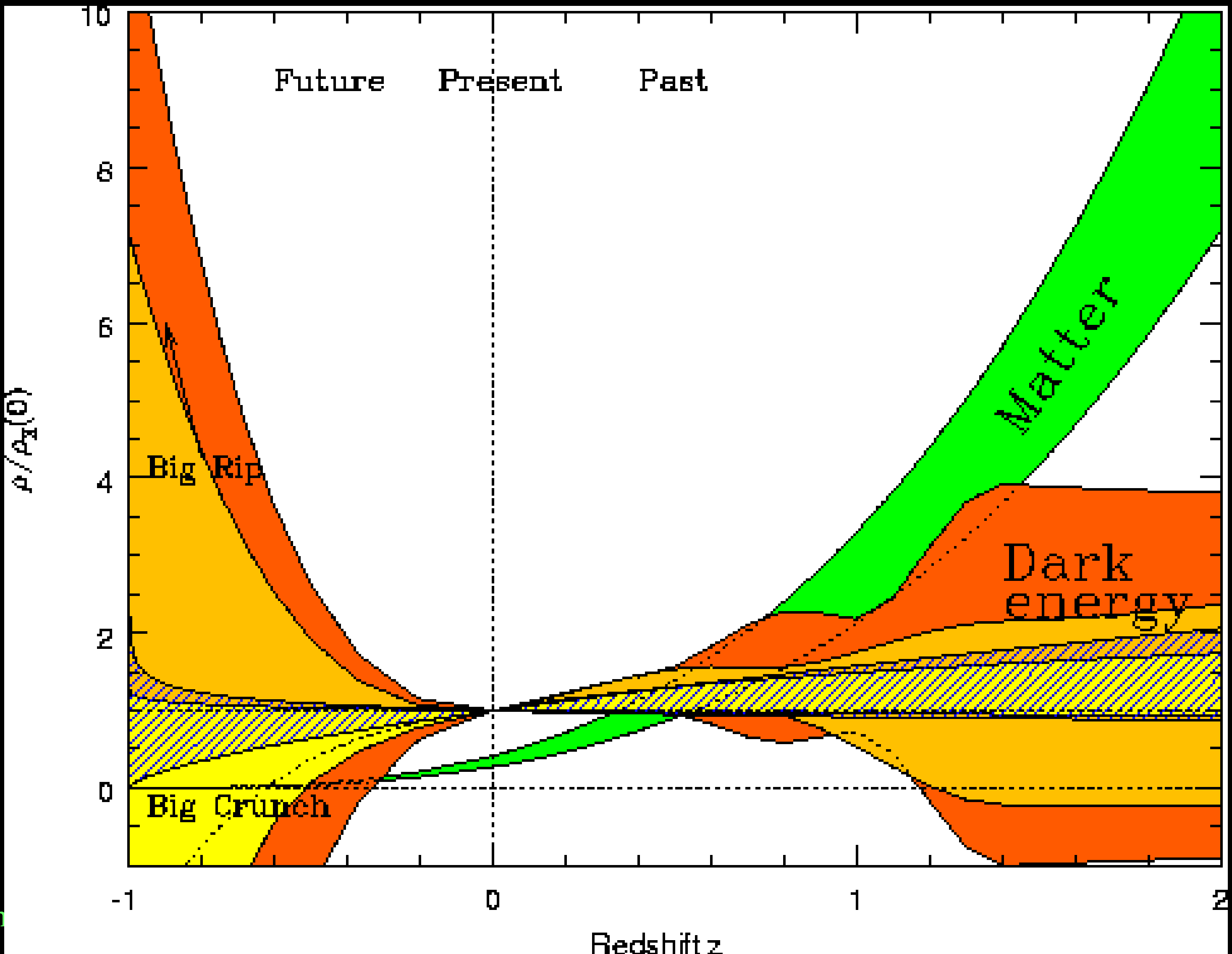
Ultra Deep Supernova Survey

To determine whether SNe Ia are good cosmological standard candles, we need to nail the systematic uncertainties (*luminosity evolution*, *gravitational lensing*, *dust*). This will require at least hundreds of SNe Ia at *z>1*. This can be easily accomplished by doing an ultra deep supernova survey using a dedicated telescope, which can be used for other things simultaneously (weak lensing, gamma ray burst afterglows, etc).

Wang 2000a, ApJ (astro-ph/9806185)

What is the fate of the universe?

Wang & Tegmark, PRL (2004)



Yun

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.**

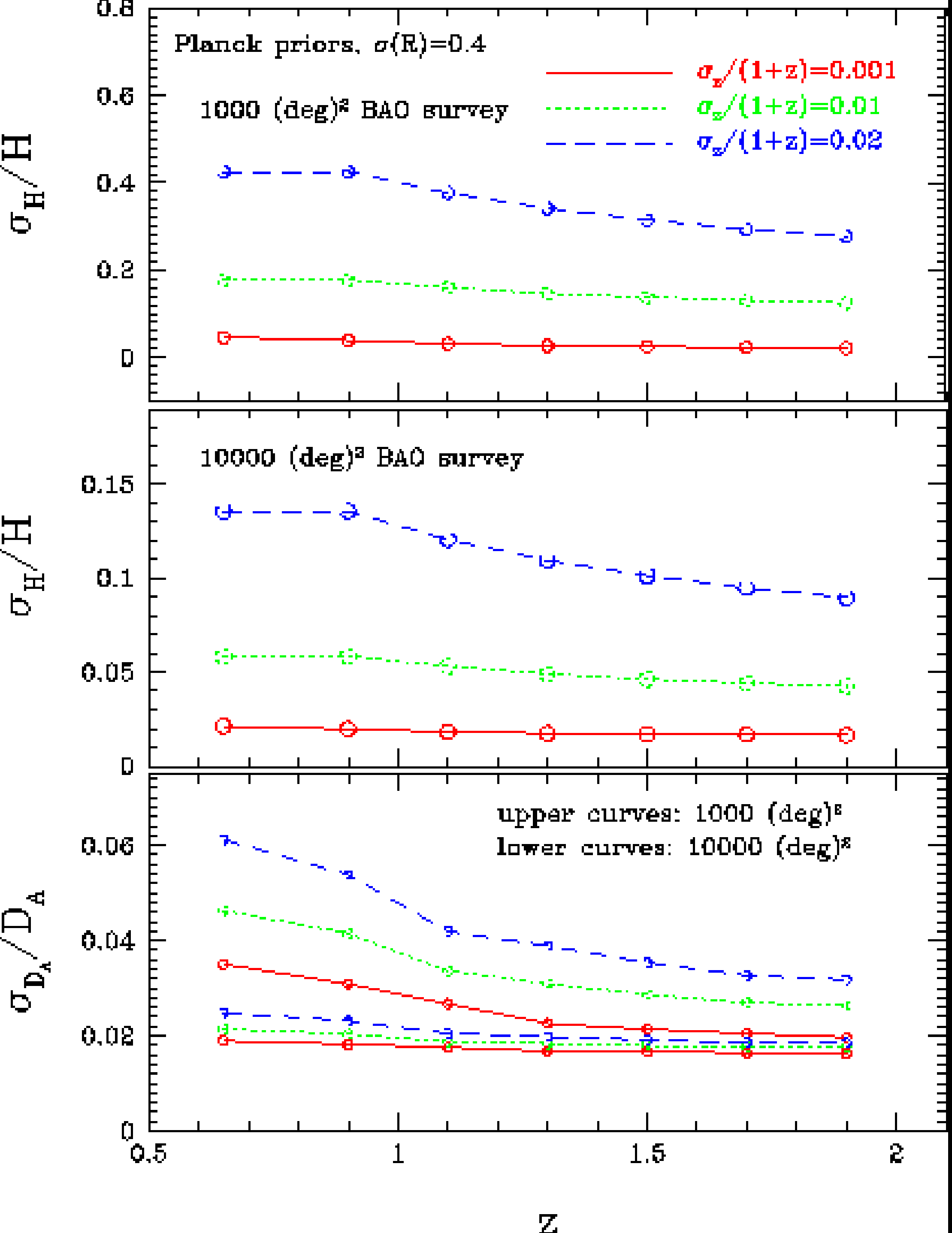
SNLS (SNe)+WMAP3+SDSS(BAO):

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%

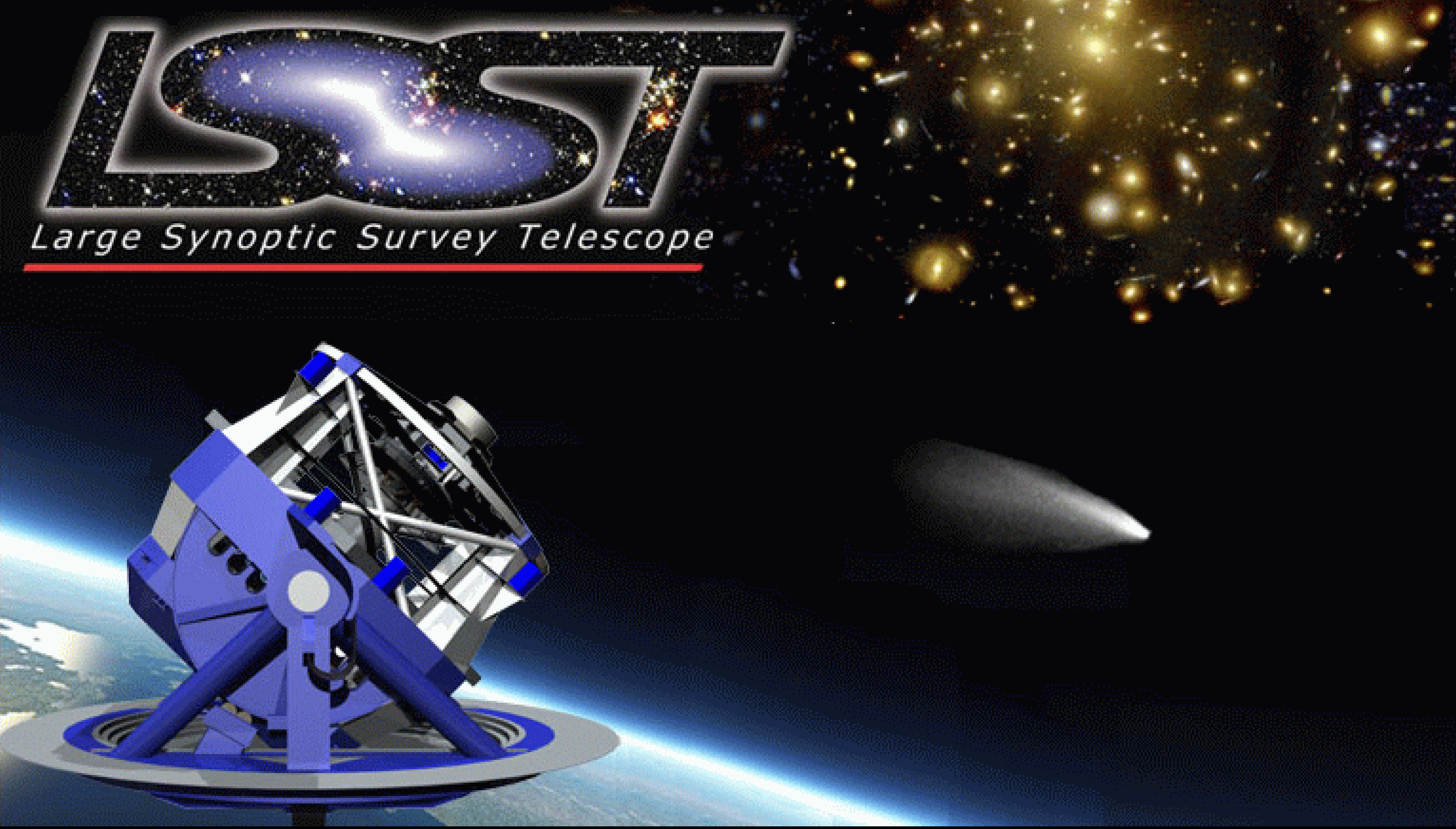
Liddle, Mukherjee, Parkinson, & Wang (2006)


Planck priors, σ(R)=0.4
1000 (deg)² BAO survey
σ_z/(1+z)=0.001
σ_z/(1+z)=0.01
σ_z/(1+z)=0.02
σ_H/H
10000 (deg)² BAO survey
σ_H/H
upper curves: 1000 (deg)²
lower curves: 10000 (deg)²
σ_DA/D_A
z

Wang 2006

ALPACA

- 8m liquid mirror telescope
- FOV: 2.5 deg diameter
- Imaging λ=0.3-1μm
- 50,000 SNe Ia per yr to z=0.8, 5 bands, Δt = 1d
- 800 sq deg WL & BAO with photo-z

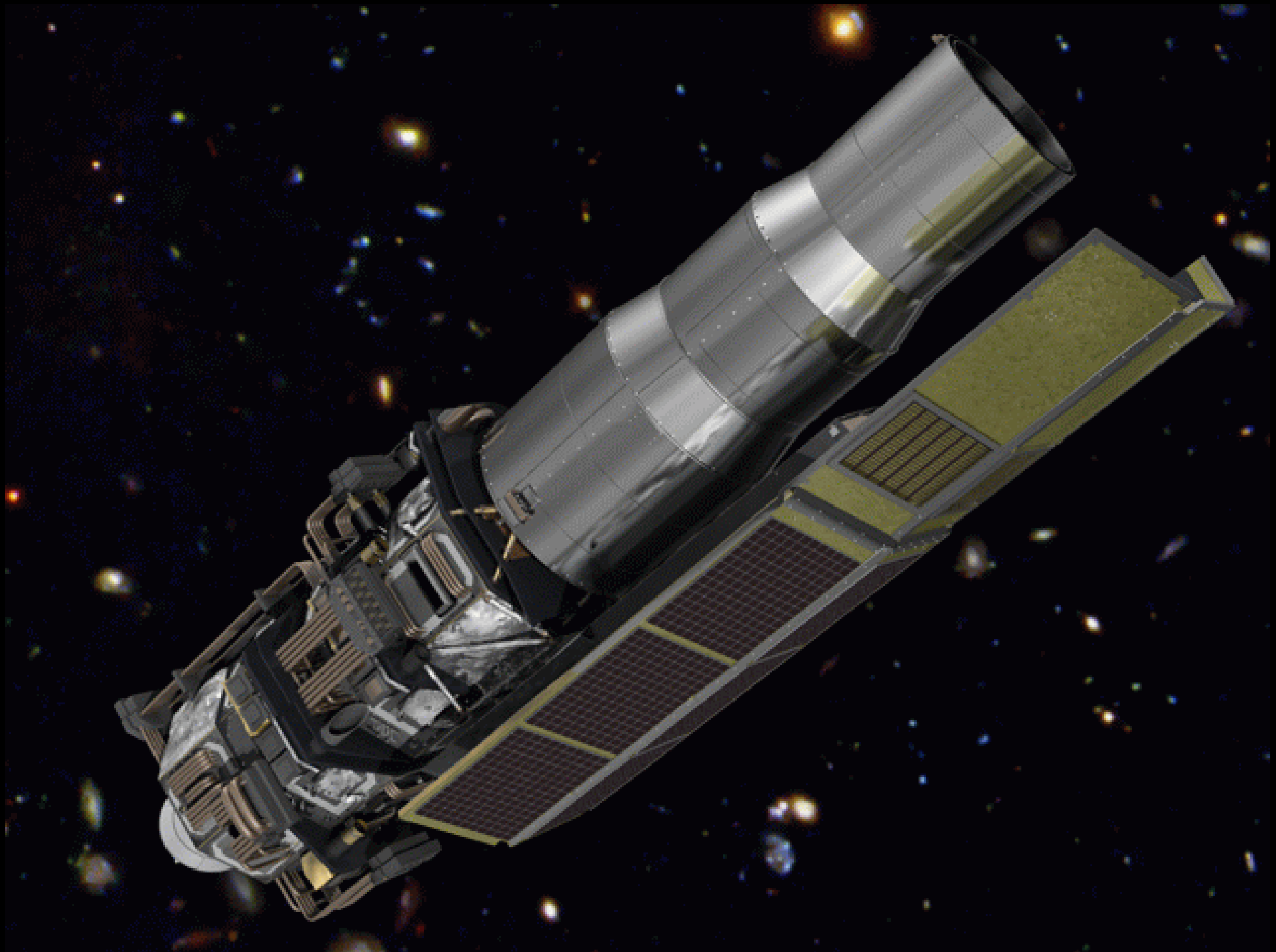


- 8.4m (6.5m clear aperture) telescope; FOV: 3.5 deg diameter; 0.3-1μm
- 10^6 SNe Ia y^{-1}, $z < 0.8$, 6 bands, $\Delta t = 7$d
- 20,000 sq deg WL & BAO with photo-z

Joint Efficient Dark-energy Investigation (JEDI):

a candidate implementation of JDEM

http://jedi.nhn.ou.edu/



JEDI Collaboration

PI: **Yun Wang** (U. of Oklahoma)
Deputy PI: **Edward Cheng** (Conceptual Analytics)

Scientific Steering Committee:
Arlin Crotts (Columbia), **Tom Roellig** (NASA Ames), **Ned Wright** (UCLA)

SN Lead: **Peter Garnavich** (Notre Dame), **Mark Phillips** (Carnegie Observatory)
WL Lead: **Ian Dell'Antonio** (Brown)
BAO Lead: **Leonidas Moustakas** (JPL)

Eddie Baron (U. of Oklahoma)
Stefano Casertano (Space Telescope Insti.)
Salman Habib (LANL)
Katrin Heitmann (LANL)
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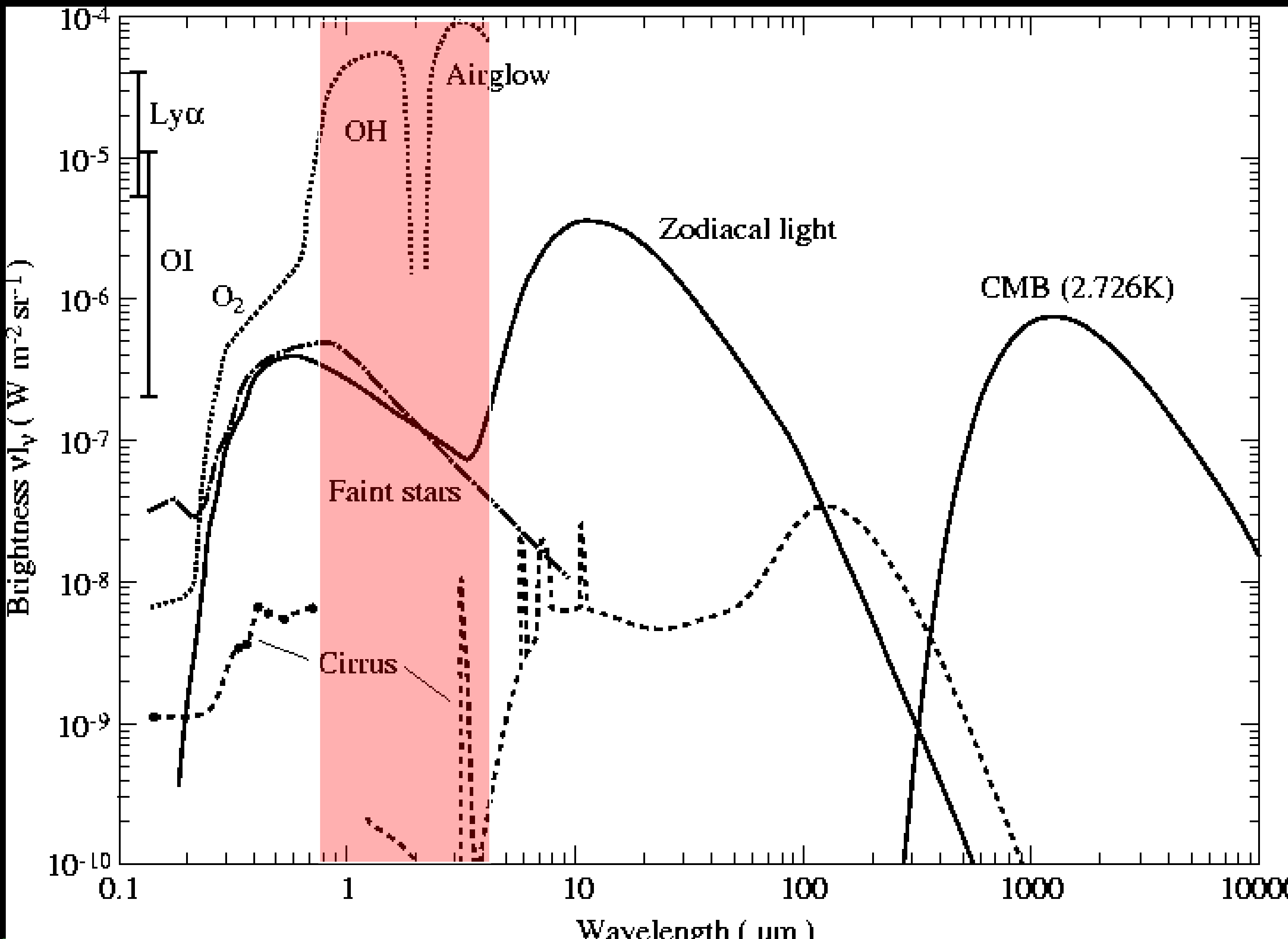
William Priedhorsky (LANL)
Volker Springel (Max Planck Insti.)
Jason Surace (Caltech)
Craig Wheeler (UT Austin)

JEDI: exploiting 0.8-4 μm "sweet spot"

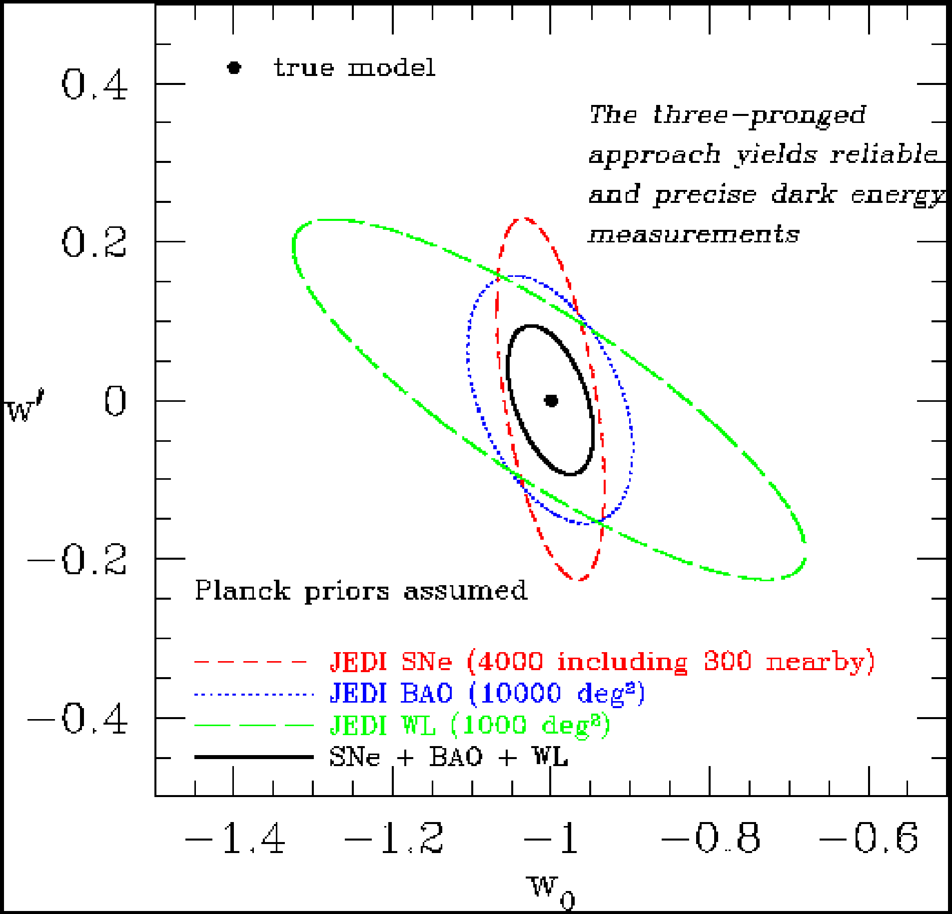
- lowest sky background region within ~0.3-100 μm wavelengths
- rest wavelengths in red/near-IR for redshifts 0 < z < 4



Background sky spectrum: Leinert 1998, A&AS, 127, 1

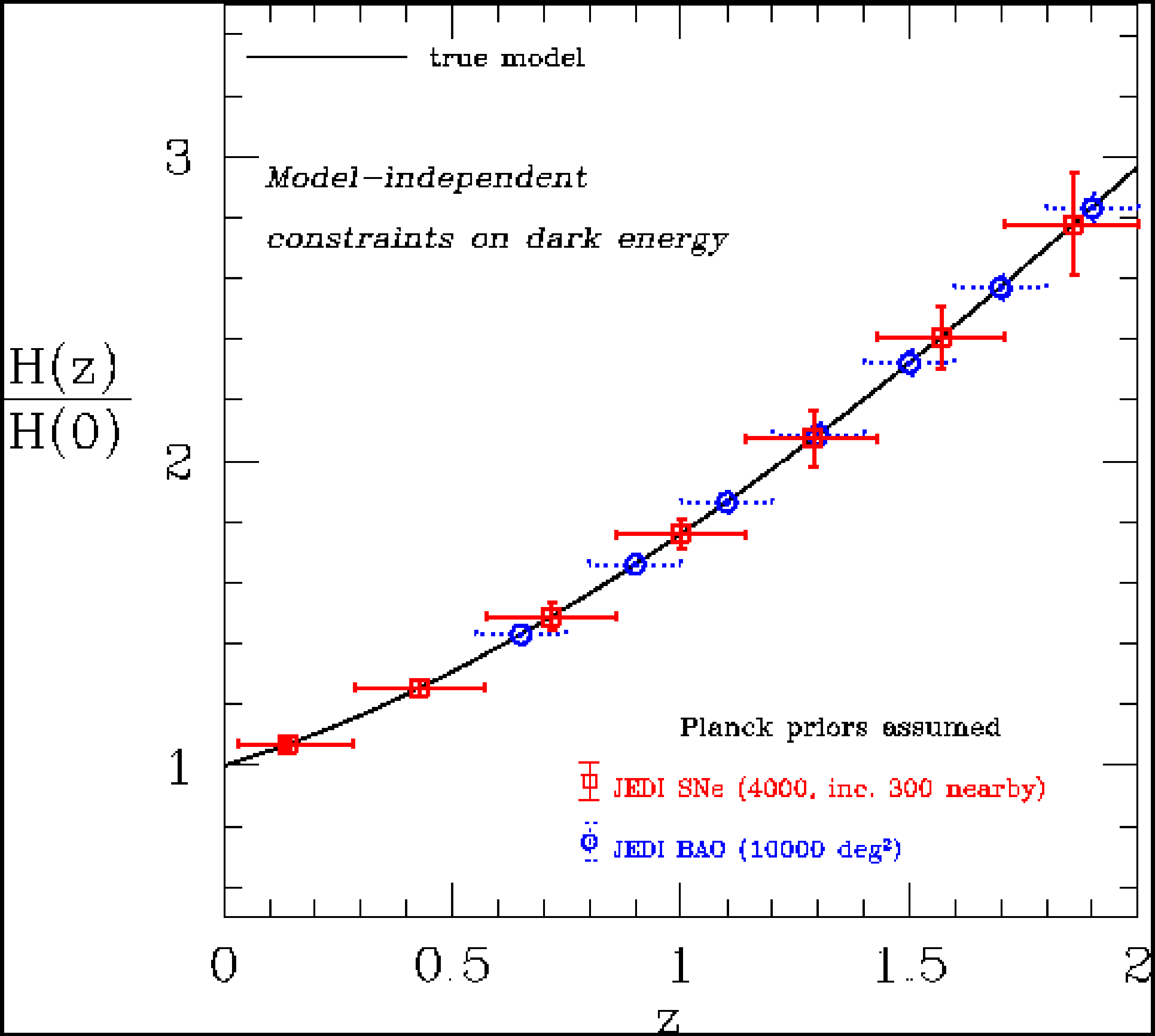
JEDI: the Power of Three Independent Methods

Supernovae as standard candles:
luminosity distances $d_L(z_i)$
Baryon acoustic oscillations as a standard ruler:
cosmic expansion rate $H(z_i)$
angular diameter distance $d_A(z_i)$
Weak lensing tomography and cosmography:
cosmic structure growth history $G(z)$; ratios of $d_A(z_i)/d_A(z_j)$



The three independent methods will provide a powerful cross check, and allow JEDI to place precise constraints on dark energy.

JEDI Measures H(z) to ≤ 2% accuracy using supernovae and baryon acoustic oscillations



Note that the errors go opposite ways in the two methods.

Wang et al., in preparation (2007)