Dark Energy Review

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Cosmology Summer School
Canary Islands, September 18, 2017

Outline

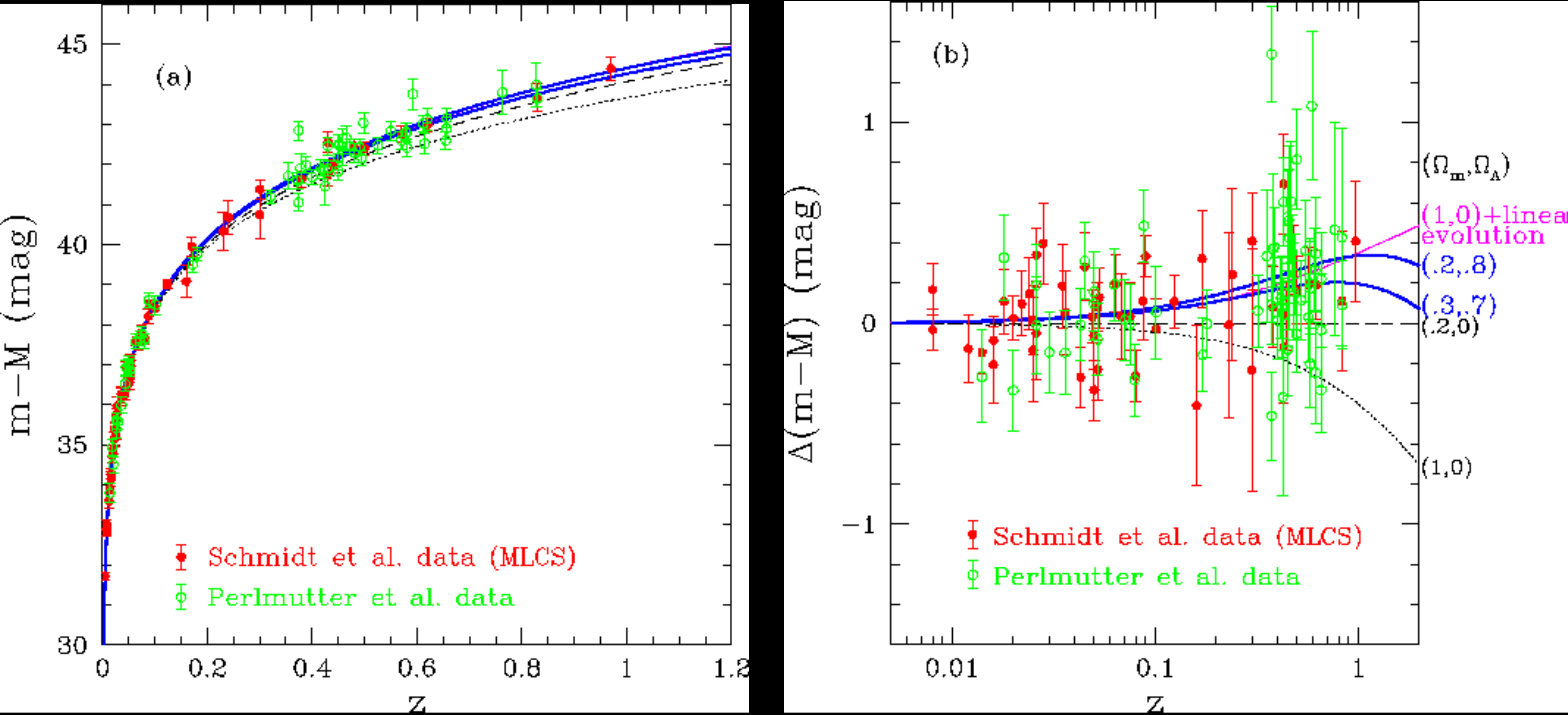
- How do we know that dark energy exists?
- What are the possible explanations for dark energy?
- How do we probe the nature of dark energy using observational data?
  - Supernovae as dark energy probe
  - Galaxy clustering as dark energy probe
  - Weak lensing as dark energy probe
- Future Prospects

How do we know that dark energy exists?

First Evidence for Dark Energy in the Hubble Diagrams of Supernovae [$d_L(z)$]

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

faint



bright

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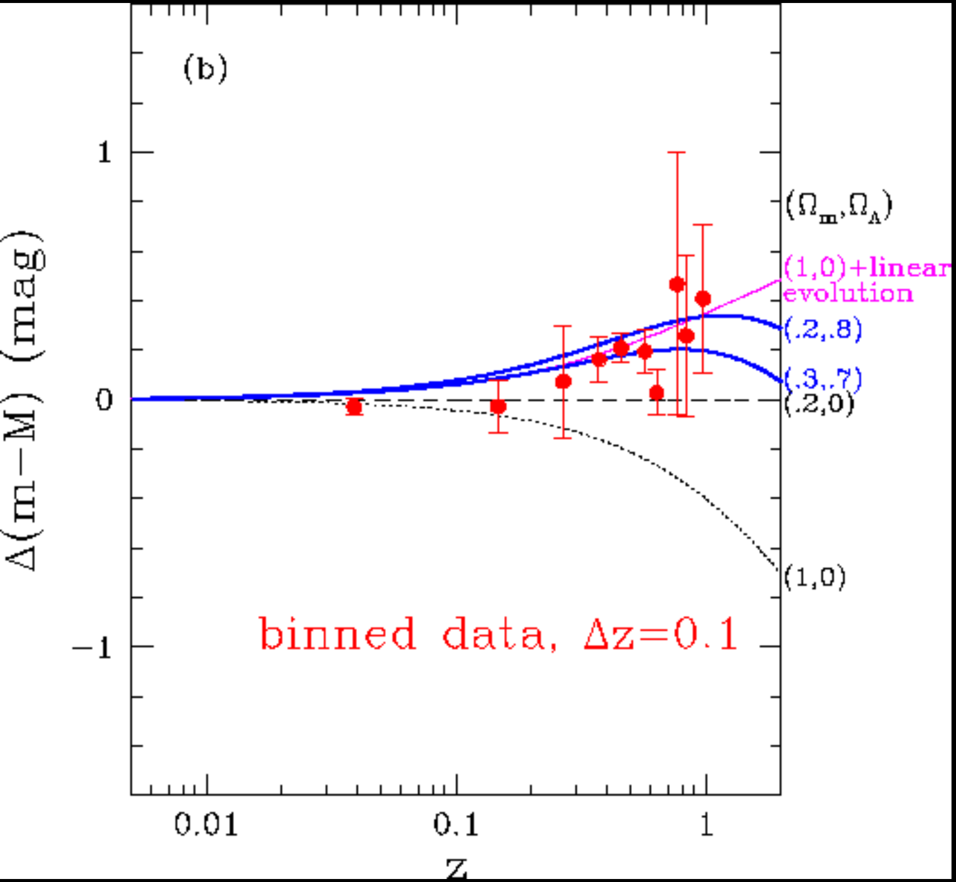
Alternative Analysis of First Evidence

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

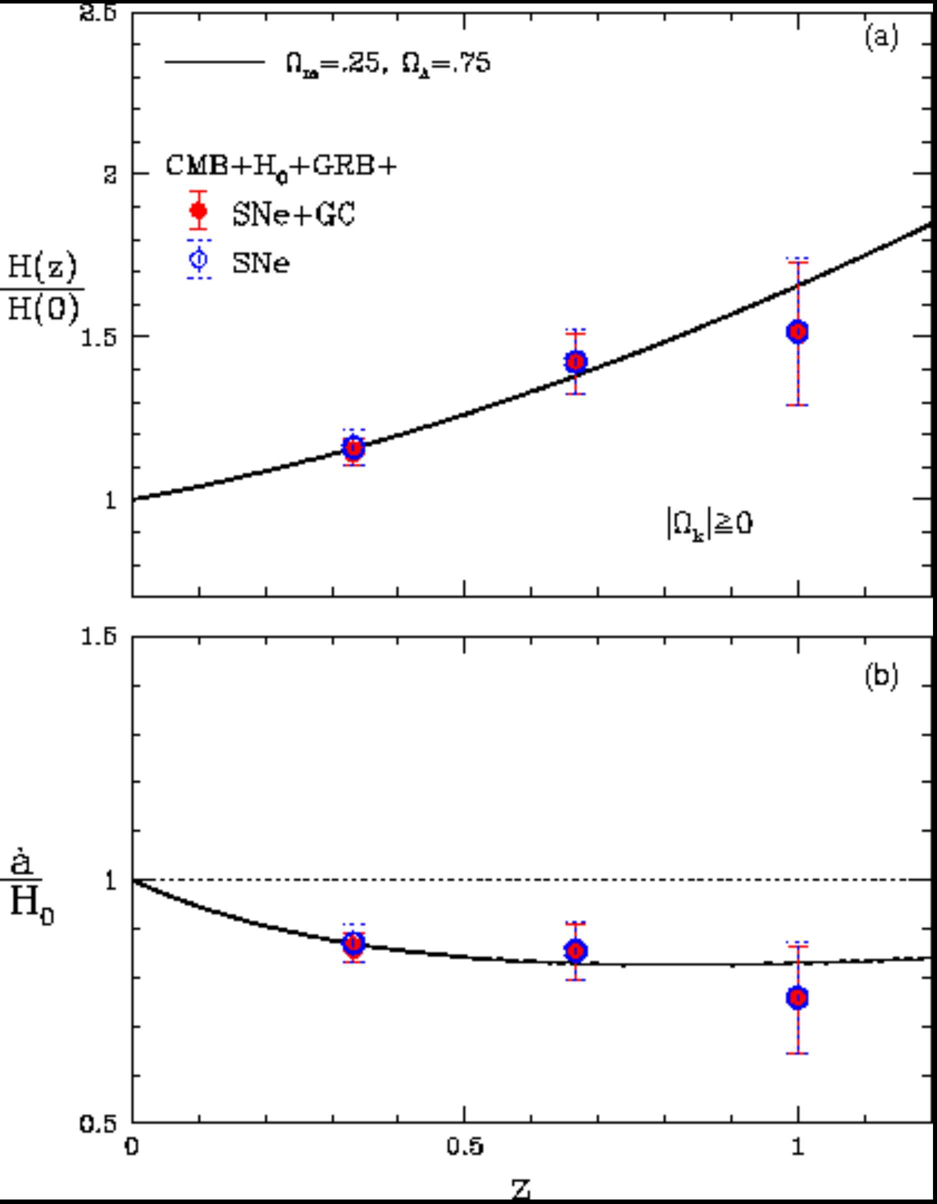


Deceleration parameter

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

Data favor $q_0 < 0$:

cosmic acceleration



Wang, Chuang, & Mukherjee (2012)

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

Hubble parameter:

$$H(z)=\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t}$$

a*(*t*): *cosmic scale factor

← Cosmic Acceleration:

$$\frac{\mathrm{d}^2a}{\mathrm{d}t^2}>0$$

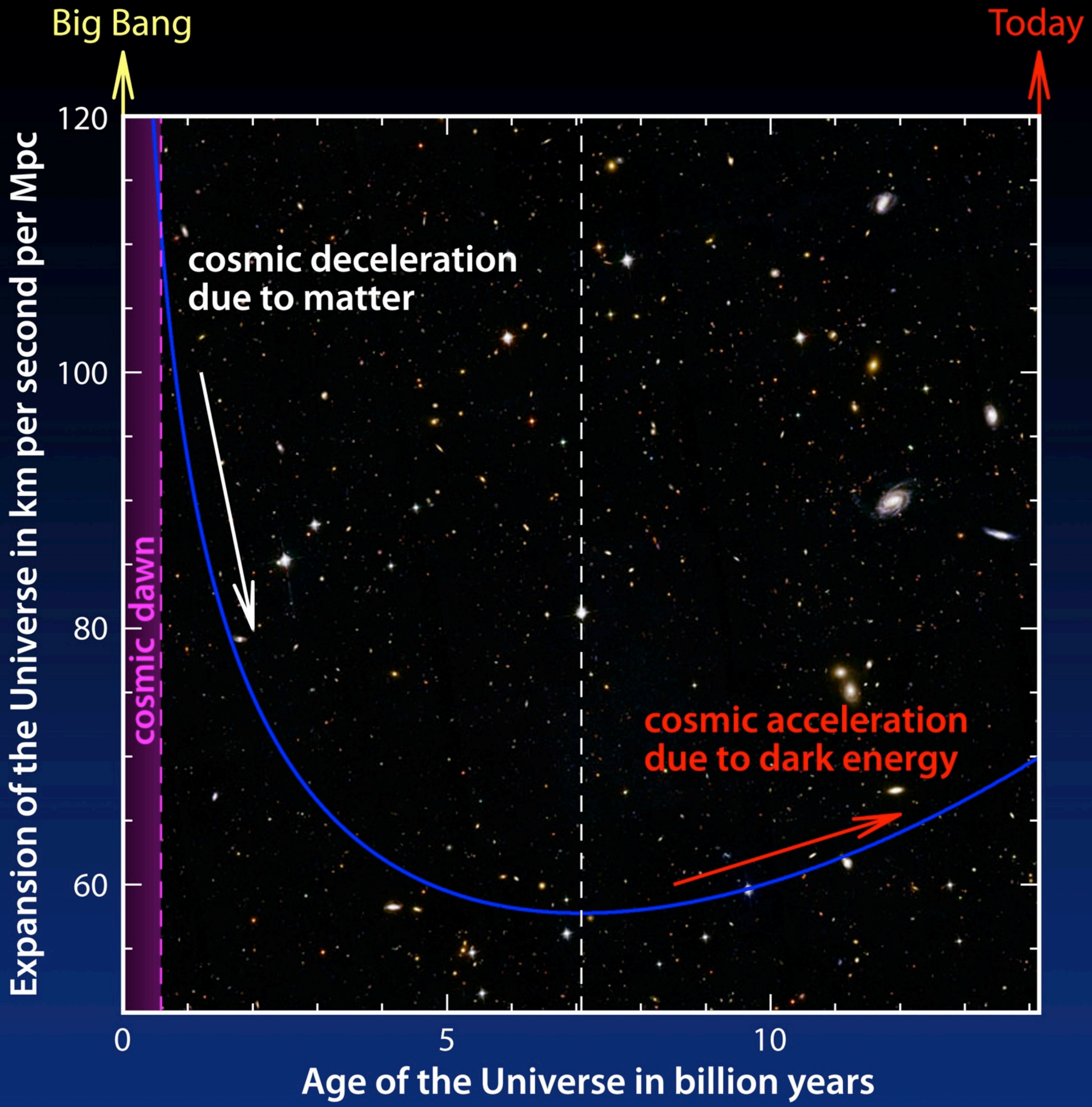
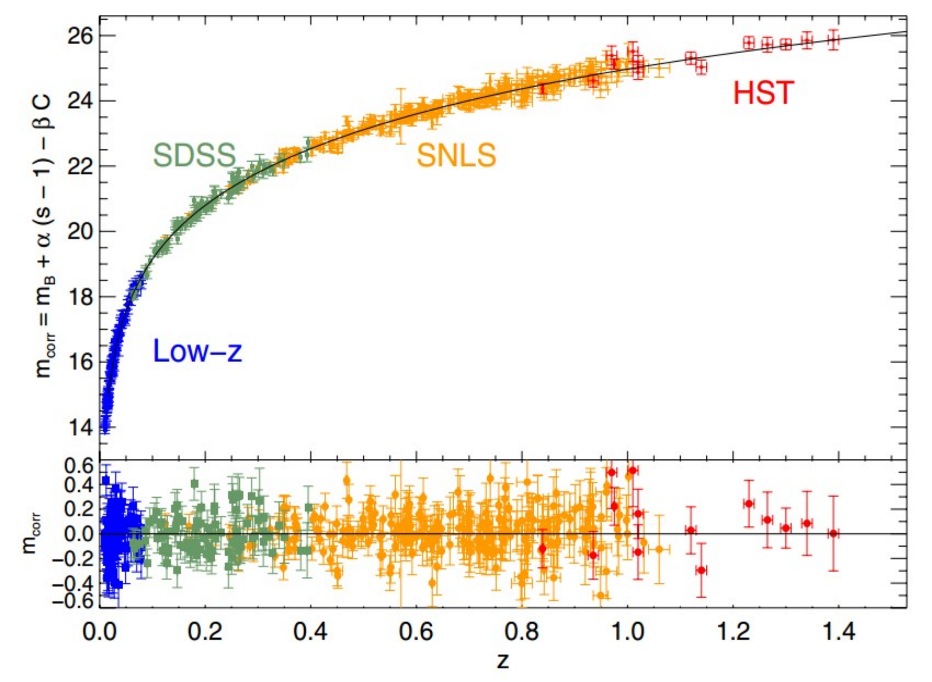


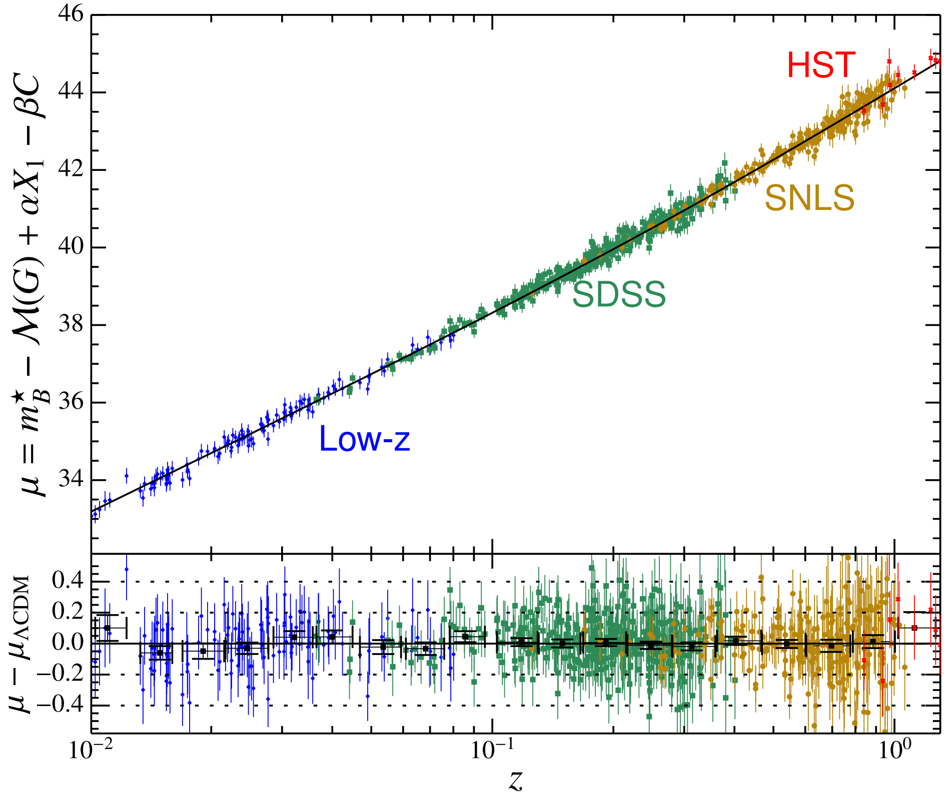
Figure by Yun Wang and Tim Pyle

Evidence for cosmic acceleration has strengthened with time

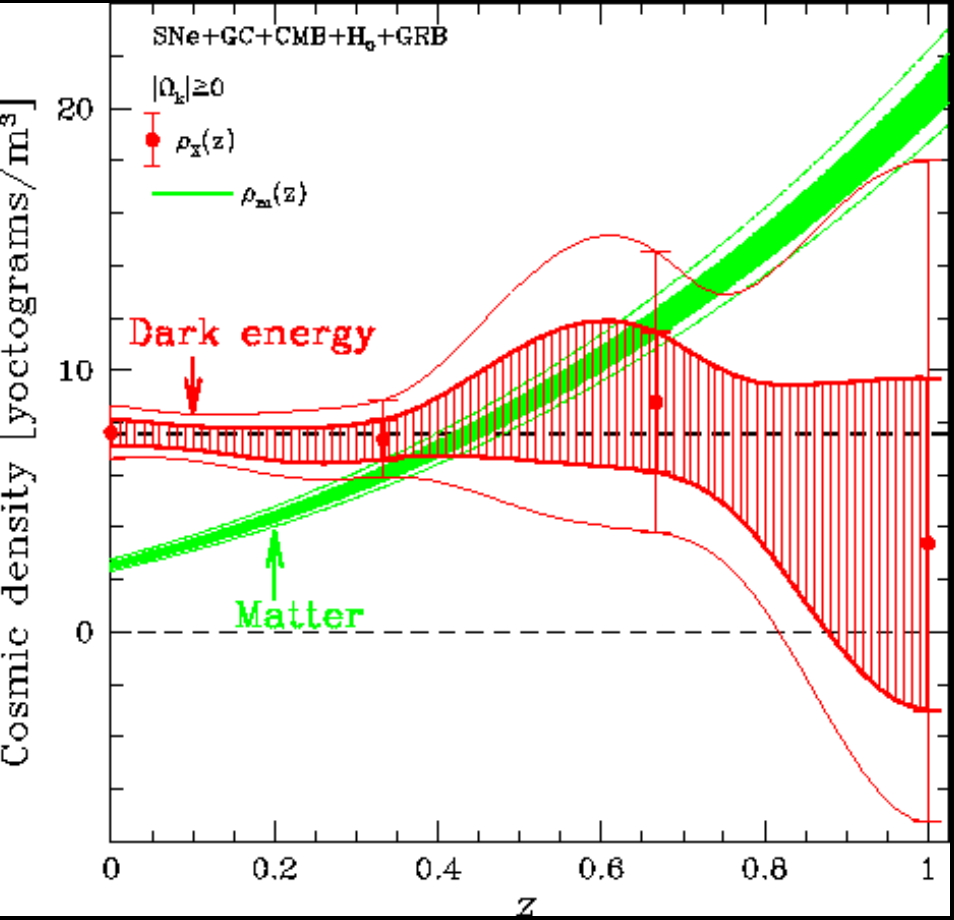
Hubble diagram of 472 SNe Ia compiled by Conley et al. (2011)



Hubble diagram of 740 SNe Ia compiled by Betoule et al. (2014) [JLA set]

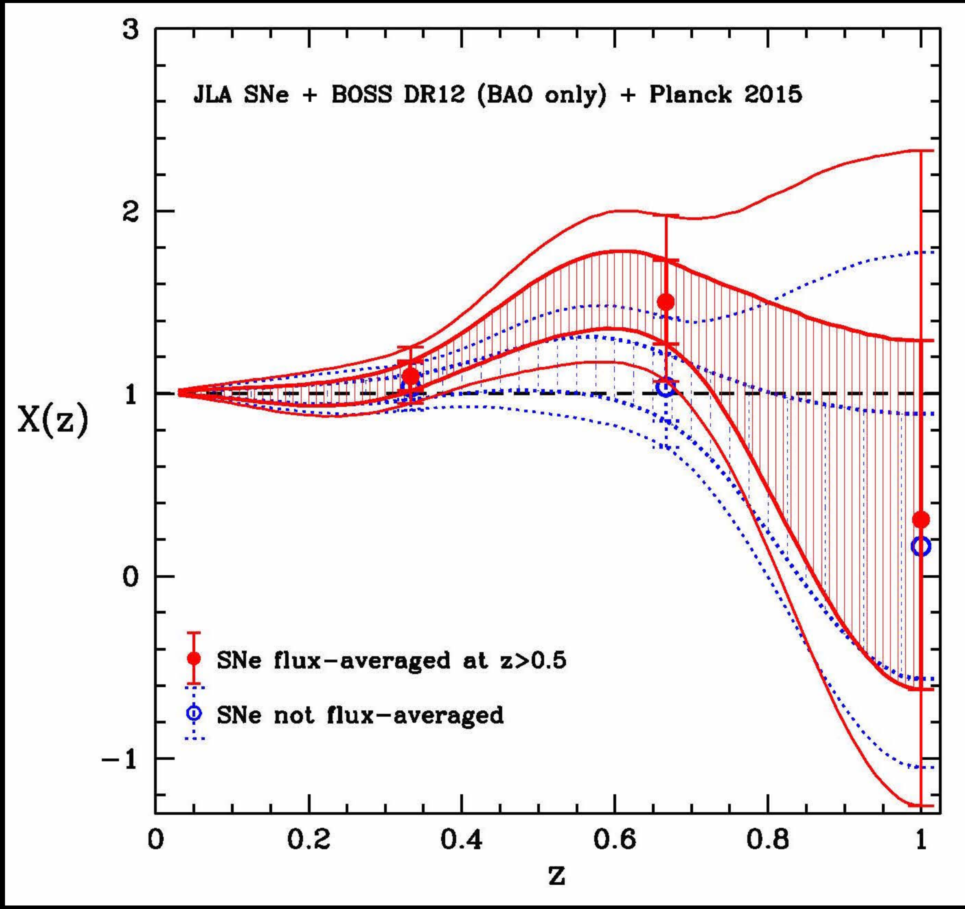


Model-independent constraints on dark energy



1 yoctogram=10^{-24}g

Wang, Chuang, & Mukherjee (2012)

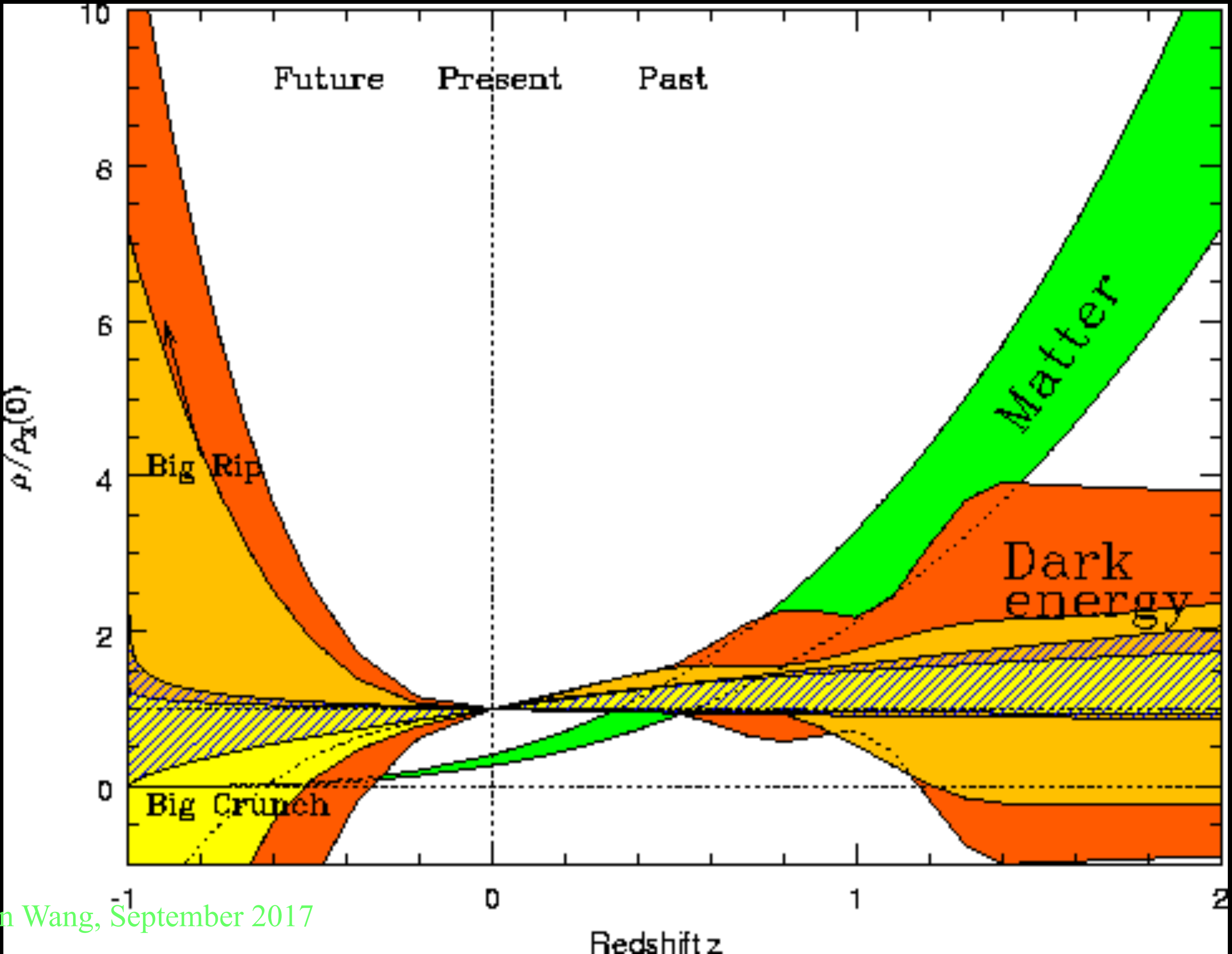


$X(z)=\rho_X(z)/\rho_X(0)$

Wang & Dai, PRD (2016)

What is the fate of the universe?

Wang & Tegmark, PRL (2004)



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What are the possible explanations for dark energy?

Cosmic Expansion Rate

Robertson-Walker Metric:

$$ds^2 = -c^2 dt^2 + a^2(t)[dr^2/(1-kr^2) + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2]$$

Einstein's Equation:

$$R_{\mu\nu} - g_{\mu\nu} R/2 = 8\pi G T_{\mu\nu}$$

- **The metric tensor is defined by** $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$
- **The energy-momentum tensor** $T_{\mu\nu}$ **for a perfect fluid with pressure p amd density ρ and four-velocity** U^μ**:** $T^\mu{}_\nu = p g^\mu{}_\nu + (p+\rho) U^\mu U_\nu$

Robertson-Walker metric + 0-0 component of Einstein's equation gives the **Friedmann equation**:

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

$$H(z) = [da(t)/dt]/a(t)$$

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Adding Dark Energy to the Cosmological Model

- Modify the Einstein Equation:
  - Change the right-hand-side by adding a new energy component: dark energy models
  - Change the left-hand-side by modifying the metric: modified gravity models

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 *(Sahni & Habib 1998; 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)*
  Emergent Gravity (*Padmanabhan 2009***)**

Example of a Dark Energy Model

Wang, Kratochvil, Linde, & Shmakova 2004, JCAP, 12, 006

- The doomsday model:

$$V(\phi)=V_0(1+\alpha\phi)$$

in which the universe collapses rather quickly after it stops expanding.

- $\rho_\phi=(d\phi/dt)^2/2+V(\phi)$, $p=(d\phi/dt)^2/2-V(\phi)$

Observational data [SN Ia + CMB + 2dF] constrain the collapse time of the universe from today to be > 42 (24) gigayears at 68% (95%) confidence.

Example of a Modified Gravity Model

- The DGP gravity model:
  - A brane embedded in a five-dimensional Minkowski bulk

    (Dvali, Gabadadze, & Porrati 2000)
  - Gravity is modified, which changes the growth rate of cosmic large scale structure
  - Simple example; already ruled out by observations

How do we probe the nature of dark energy using observational data?

Distance-Redshift Relations

- **Comoving distance (a.k.a. coordinate distance)**

$$r(z) = c\left|\Omega_k\right|^{-1/2} \mathrm{sinn}\left[\left|\Omega_k\right|^{1/2} \int_0^z \frac{dz'}{H(z')}\right]$$

$\Omega_k=-k/H_0^2$, sinn(x)=sin(x), x, sinh(x) for $\Omega_k<0$, $\Omega_k=0$, $\Omega_k>0$

- **Luminosity distance**

$$d_\mathrm{L}(z)=(1+z)r(z)$$

- **Angular diameter distance**

$$d_\mathrm{A}(z)=r(z)/(1+z)$$

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Growth Rate of Cosmic Large Scale Structure

- For a given $H(z)=H_0E(z)$, assuming the validity of general relativity

$$D''(\tau)+2E(z)D'(\tau)-\frac{3}{2}\Omega_m(1+z)^3D=0$$

$$\tau = H_0\, t$$

The linear growth rate $f_g = (d \ln D/d \ln a)$

- We can predict the observable $f_g(z)$ given the measured $H(z)$, if gravity is not modified

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 [growth rate $f_g(z)$ or growth factor $G(z)$]***

  tells us whether general relativity is modified, given $H(z)$

Dark Energy Equation of State

- Equation of state $w = p/\rho$
  - Matter: $p = 0$ ($w = 0$)
  - Radiation: $p = \rho/3$ ($w = 1/3$)
  - Dark energy: $p = w_X(z)\ \rho$

    Cosmological constant: $p = -\rho$ ($w = -1$)

Measure ρ_X Instead of w_X

Wang & Freese 2006

- ρ_X is on the same footing as Ω_m
- given w_X, one must integrate to obtain ρ_X:

$$\frac{\rho_X(z)}{\rho_X(0)} = \exp\left\{3\int_0^z dz' \frac{1+w_X(z')}{1+z'}\right\}$$

- **What we really want to know is:**
  does $\rho_X(z)$ change with time?

Testing Gravity: Measuring the Metric

Robertson-Walker Metric describes a homogeneous, isotropic, and expanding universe; it is perturbed in the presence of inhomogeneous matter distribution in the Universe. In the conformal Newtonian gauge (the longitudinal gauge), we have

the perturbed Robertson-Walker metric:

$$ds^2 = a^2(\tau)[-(1+2\phi)d\tau^2 + (1-2\psi)\gamma_{ij}dx_i dx_j]$$

- Applicable only for scalar mode of the metric perturbations
- ϕ: the gravitational potential in the Newtonian limit
- γ_{ij}: the three-metric for a space of constant spatial curvature
- **General relativity: $\psi = \phi$**

WL: probe $\phi+\psi$ (light rays follow geodesics, i.e., $ds = 0$)

GC/RSD: probes ϕ (peculiar velocities follow gradients of the Newtonian potential)

Observational Probes of Dark Energy

- **SNe Ia (Standard Candles):** method used in DE discovery, independent of clustering of matter, probes $H(z)$.

- **Galaxy Clustering (including Baryon Acoustic Oscillations as Standard Ruler):** BAO is calibrated by CMB, probes $H(z)$; redshift-space distortions probe $f_g(z)$.

- **Weak Lensing Tomography and Cross-Correlation Cosmography:** probe a combination of $G(z)$ and $H(z)$.

- **Galaxy Cluster Statistics:** probes a combination of $H(z)$ **and** $G(z)$

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/RSD, WL), each optimized by having its systematics minimized by design, provides the tightest control of systematics.

Evaluating Dark Energy Projects: the Dark Energy Task Force FoM

Albrecht et al. (2006)

- **DETF figure of merit**
  = 1/[area of 95% C.L. w_0-w_a error ellipse],
  for **$w_X(a) = w_0+(1-a)w_a$**

- **Pivot Value of a:**
  At $a=a_p$, $w_p= w_0 + (1-a_p)w_a$.
  Making $\langle\delta w_p \delta w_a\rangle=0$ gives $1-a_p= -\langle\delta w_0 \delta w_a\rangle / \langle\delta w_a^2\rangle$:
  DETF FoM = $1/[6.17\pi\sigma(w_a)\sigma(w_p)]$

- **$\mathrm{FoM}_r = 1/[\sigma(w_a)\sigma(w_p)]$**

- **a_p is different for each survey, thus w_p refers to a different property of DE in each survey.**

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Dark Energy Figure-of-Merit Generalized and Simplied

- Generalized FoM for parameters $\{f_i\}$:

  $\mathrm{FoM}_r = 1/[\det \mathrm{Cov}(f_1, f_2, f_3, \ldots)]^{1/2}$
- Can be easily applied to both real and simulated data
- Reduces to the DETF FoM for Gaussian-distributed errors for w_0 and w_a [for $w_X(z)=w_0+w_a(1-a)$]:

  $\mathrm{FoM}_r = 1/[\det \mathrm{Cov}(w_0 w_a)]^{1/2} = 1/[\sigma(w_a)\sigma(w_p)]$

  Wang (2008) DETF

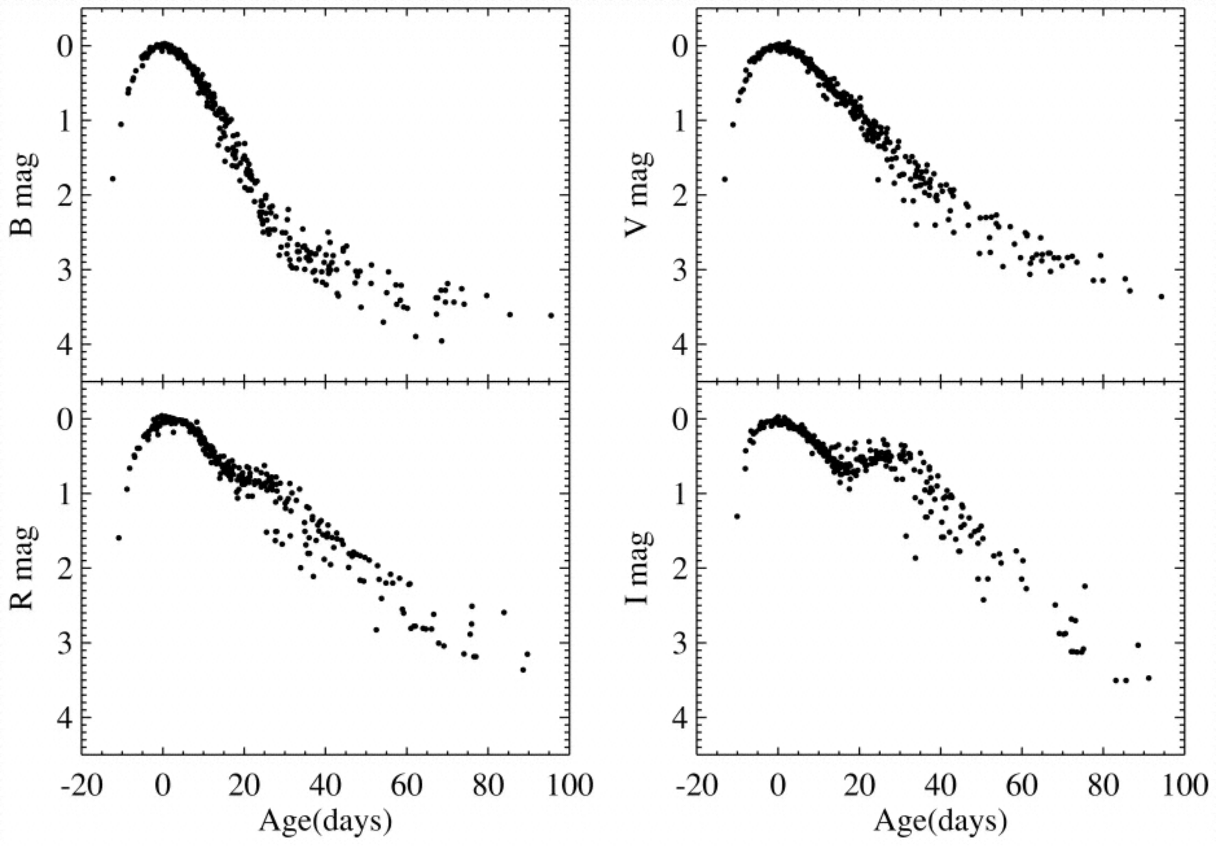
- 2 parameter parametrization of $w_X(z)$:

  $w_0 = w_X(z = 0)$ and $w_{0.5} = w_X(z = 0.5)$ are much less correlated than w_0 and w_a

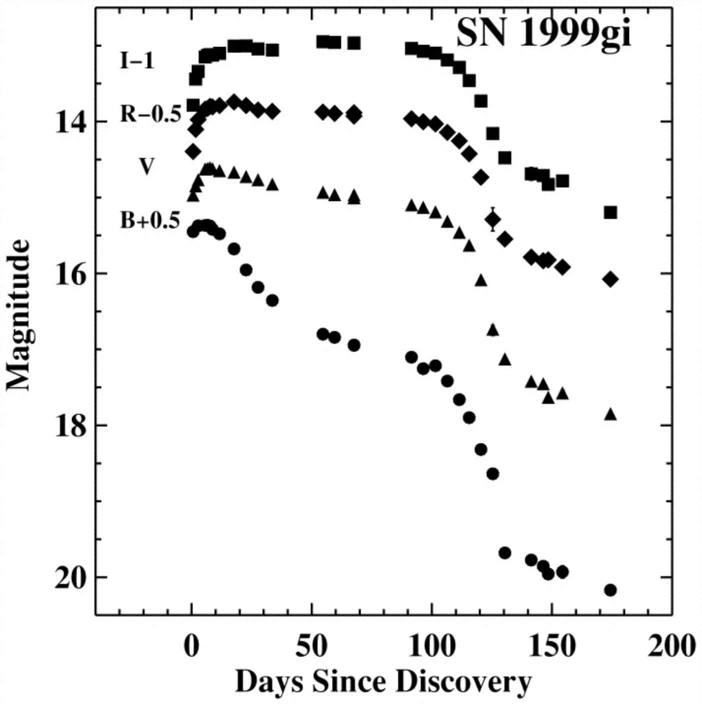
Wang (2008)

Supernovae as Dark Energy Probe

Supernovae as Standard Candles



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



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

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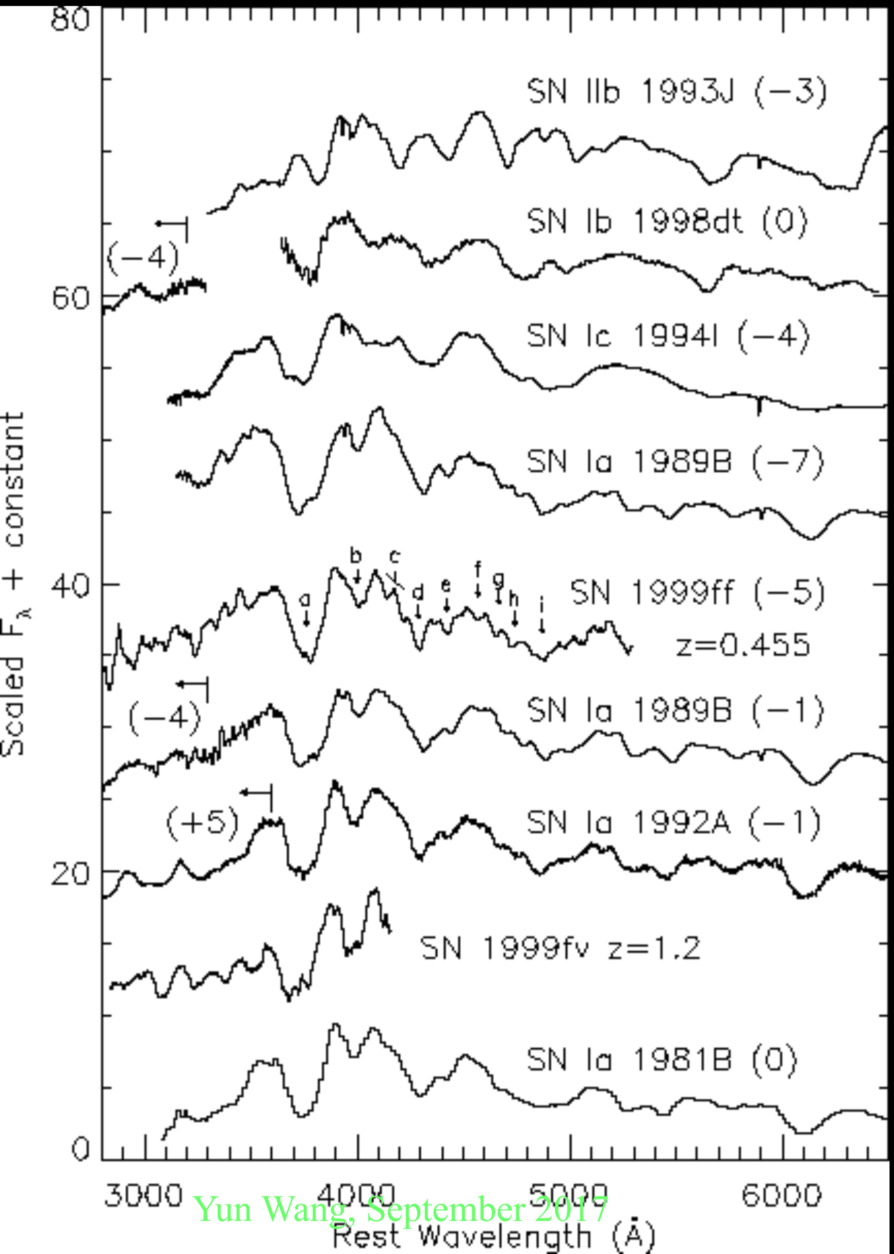
Spectral Signature of SNe Ia



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

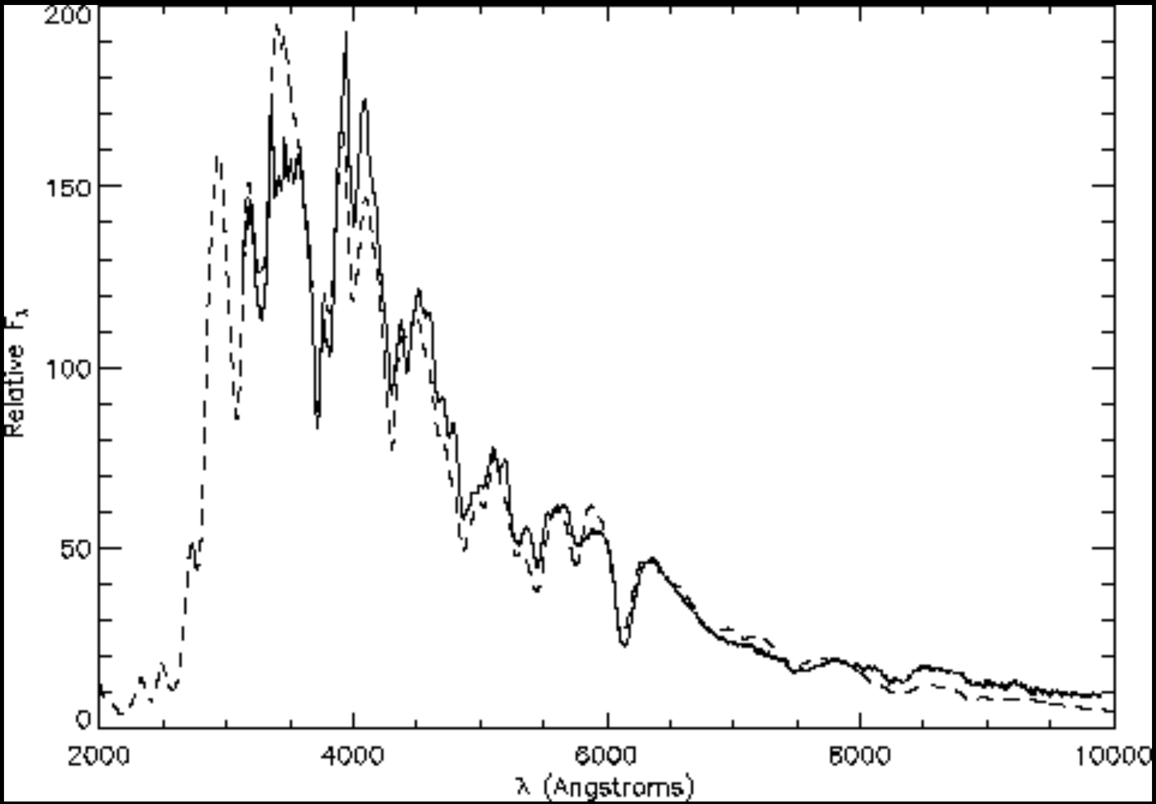
e: Si III λ4560

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)

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)

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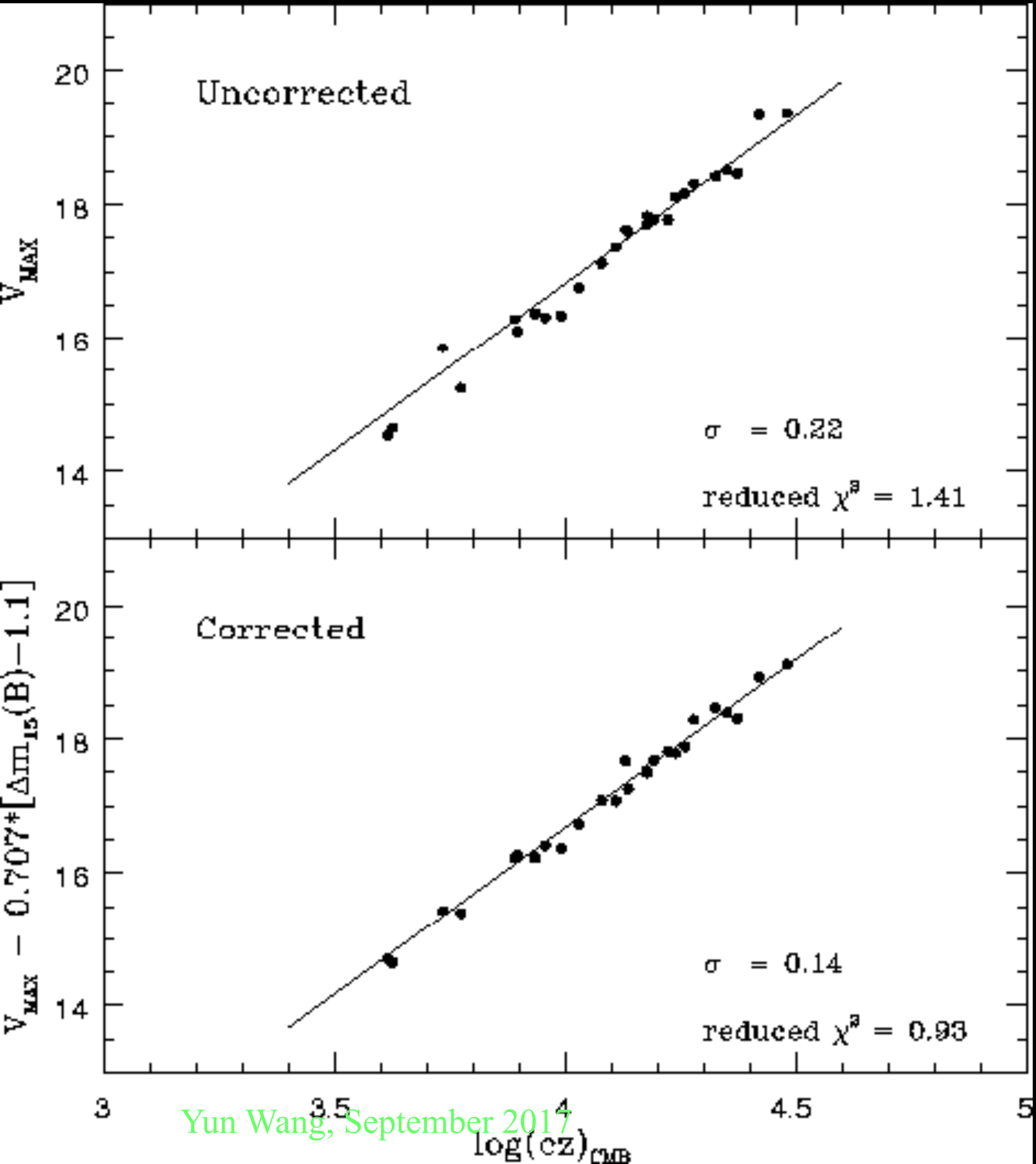
Calibration of SNe Ia

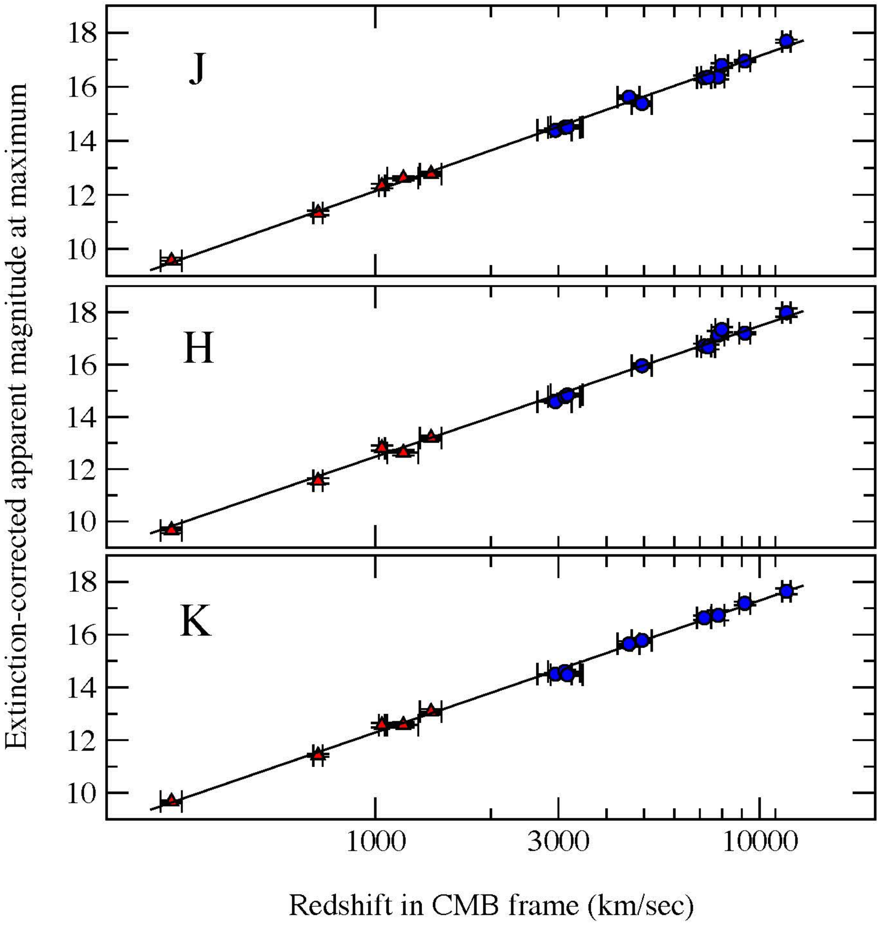
Phillips 1993
Riess, Press, & Kirshner 1995



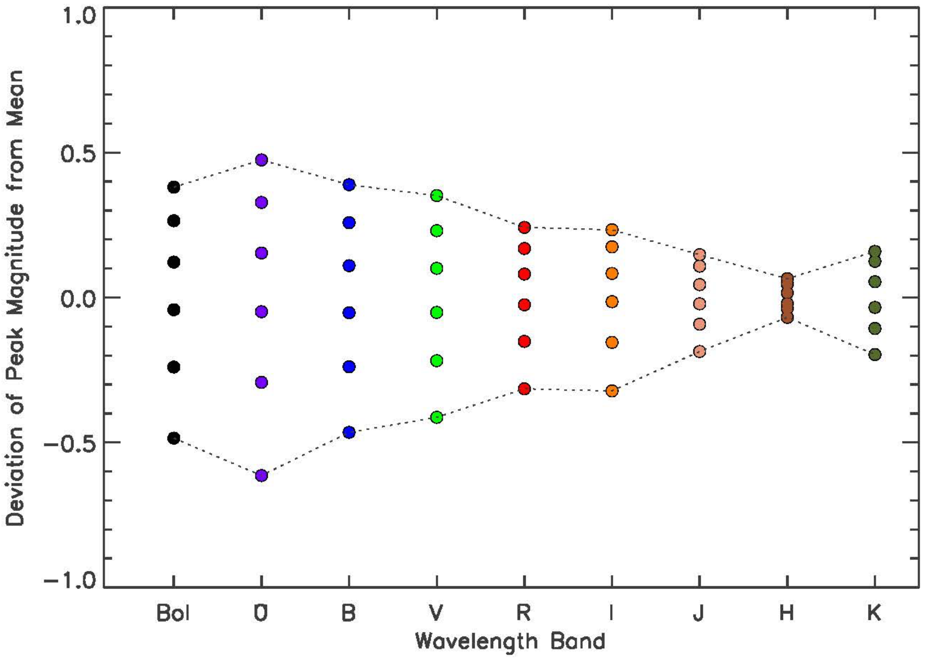
Brighter SNe Ia decline more slowly → make a correction to the brightness based on the decline rate.

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

SNe Ia are better standard candles in the NIR



SNe Ia corrected for dust extinction, but *not* for lightcurve width, from Krisciunas, Phillips, & Suntzeff (2004)



Radiative transfer calculations by Kasen (2006)

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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)

Photometric calibration:

See next slides.

Calibration Uncertainties

- Calibration dominates the systematic uncertainties.

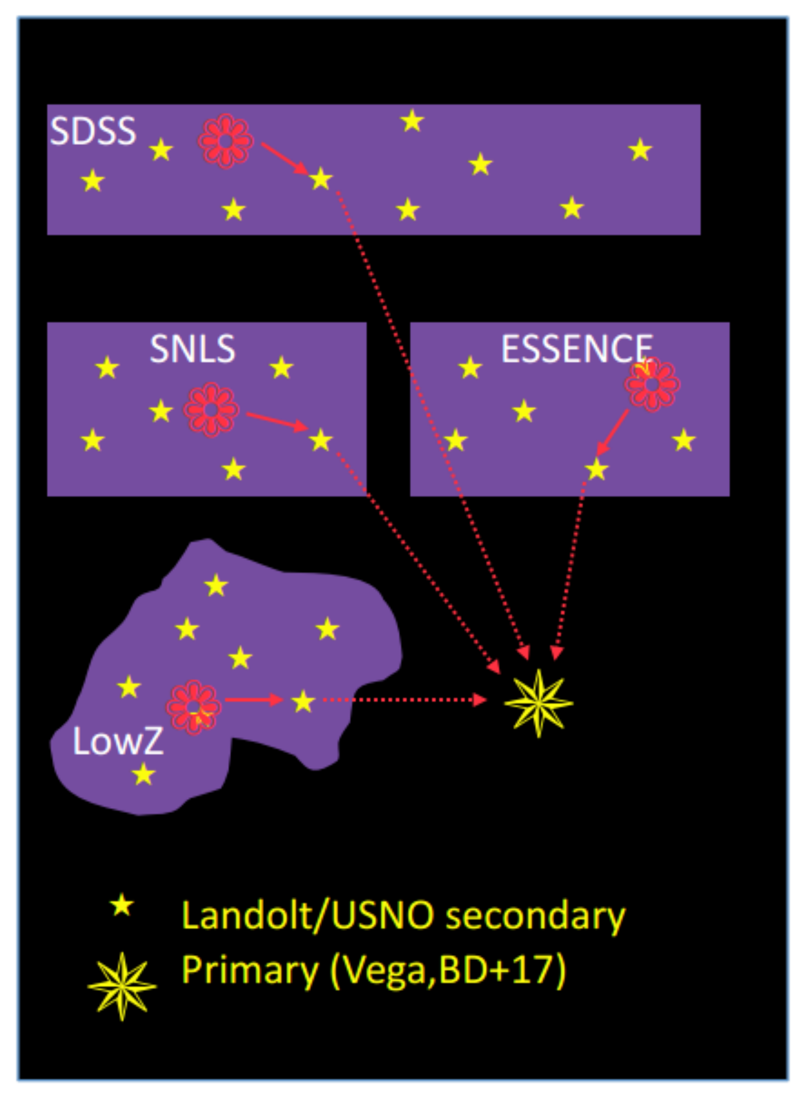
- Calibration consists of two steps:

1. Observations are standardized onto some photometric system
   → zero-point uncertainty
2. They are converted from the standard system into relative fluxes
   → calibration uncertainty

- Other calibration related uncertainties:

--- Filter transmission is not uniform over focal plane
--- Filter transmission can change with time
--- Model for atmosphere transmission

Based on slides from Mi Dai



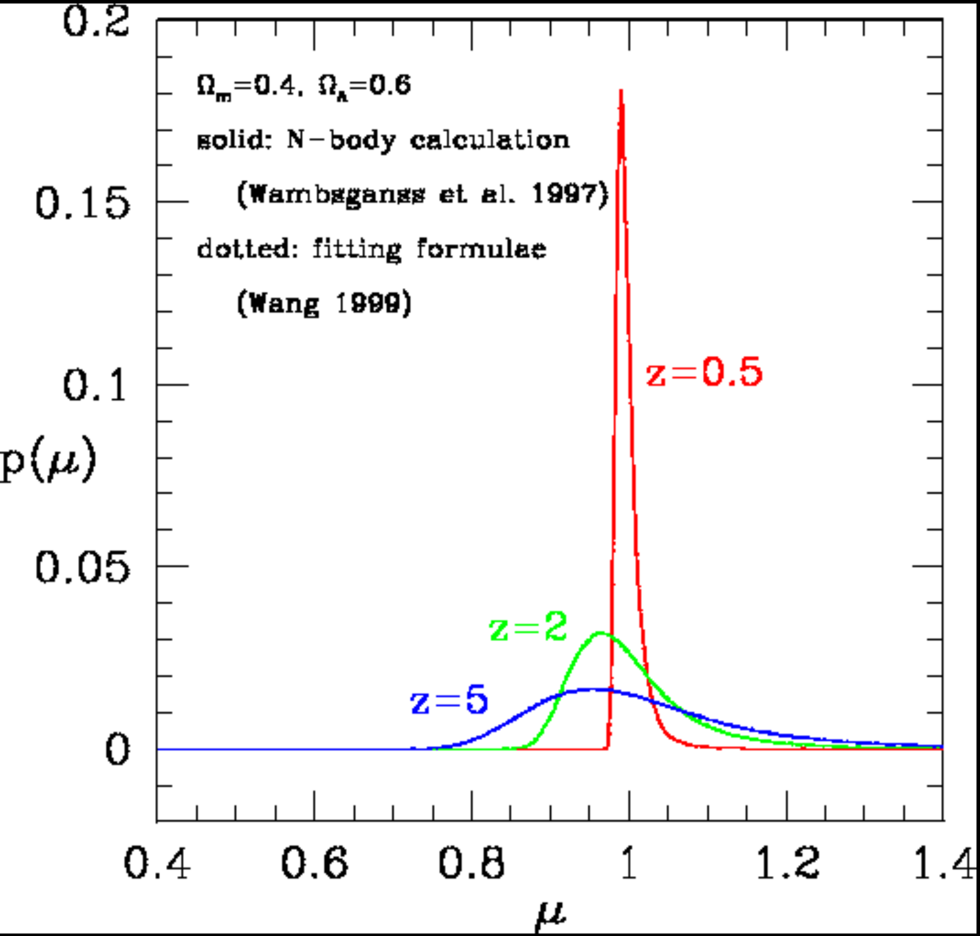
Kessler (2012)

Many of the important calibration systematic effects are related to the necessity of cross-calibrating SNLS data to the current low-z sample on the Landolt system.

Significantly improved low- and intermediate-z samples should become available in the next few years to help improve calibration.

Based on slides from Mi Dai

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

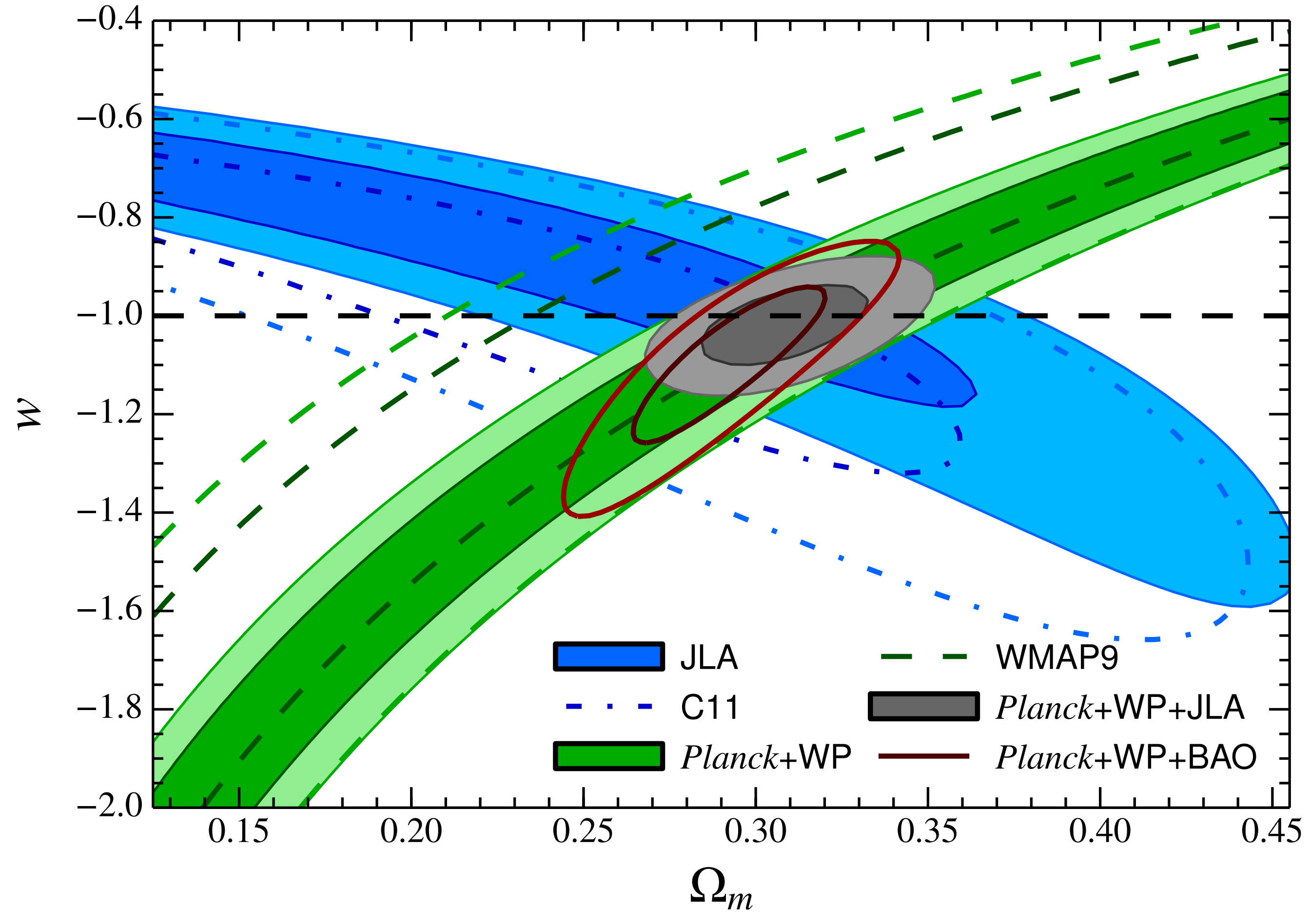
(Wang 2000; Wang & Mukherjee 2003)

If p(μ) can be measured from data, it can be used to probe cosmology.

(Wang in LSST Science Book)

Complementarity of SN Ia Data to Other Data

Flat Universe constraints from JLA SN data set



Betoule et al. (2014)

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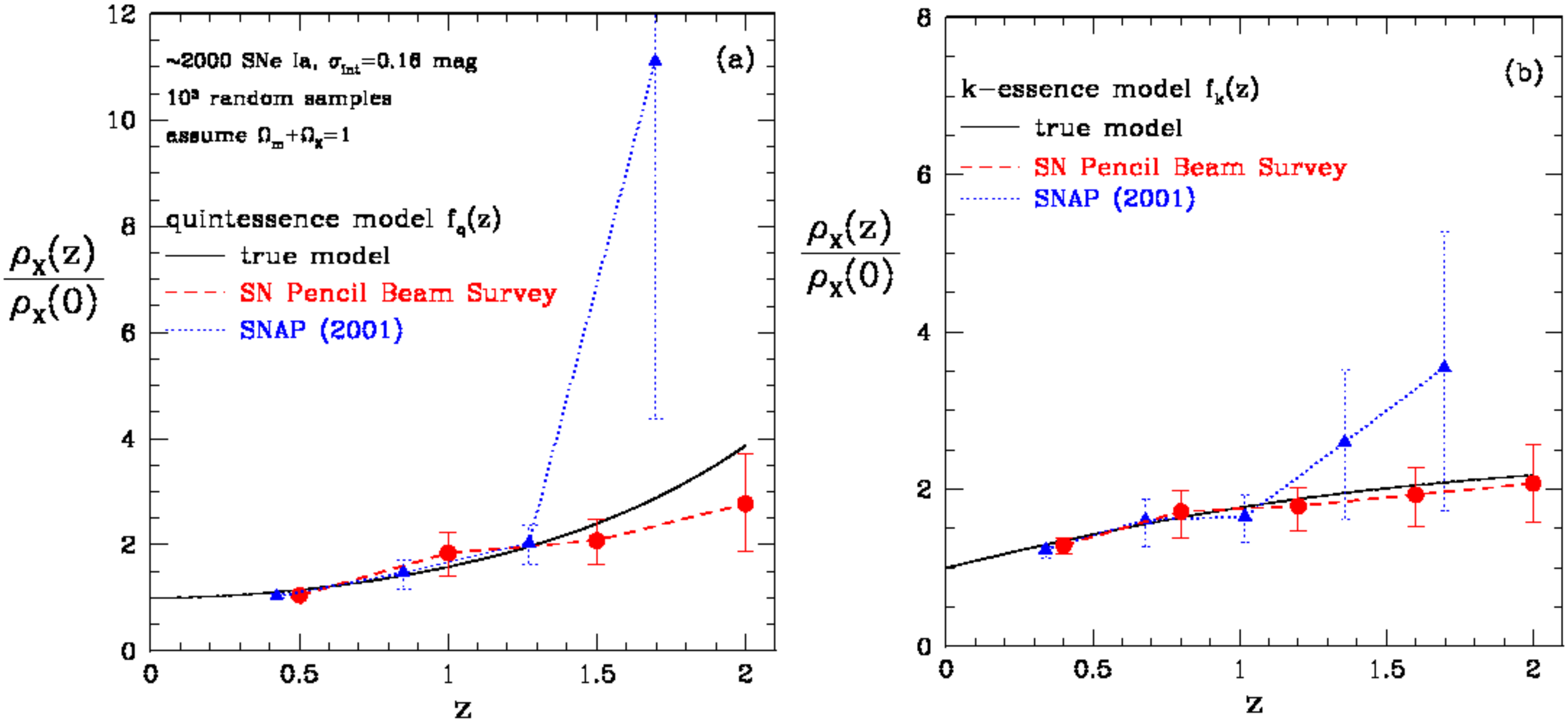
Getting the most distant SNe Ia:

critical for measuring the evolution in dark energy density:



Wang & Lovelave (2001)

Galaxy Clustering as Dark Energy Probe
(see also Percival's plenary lecture)

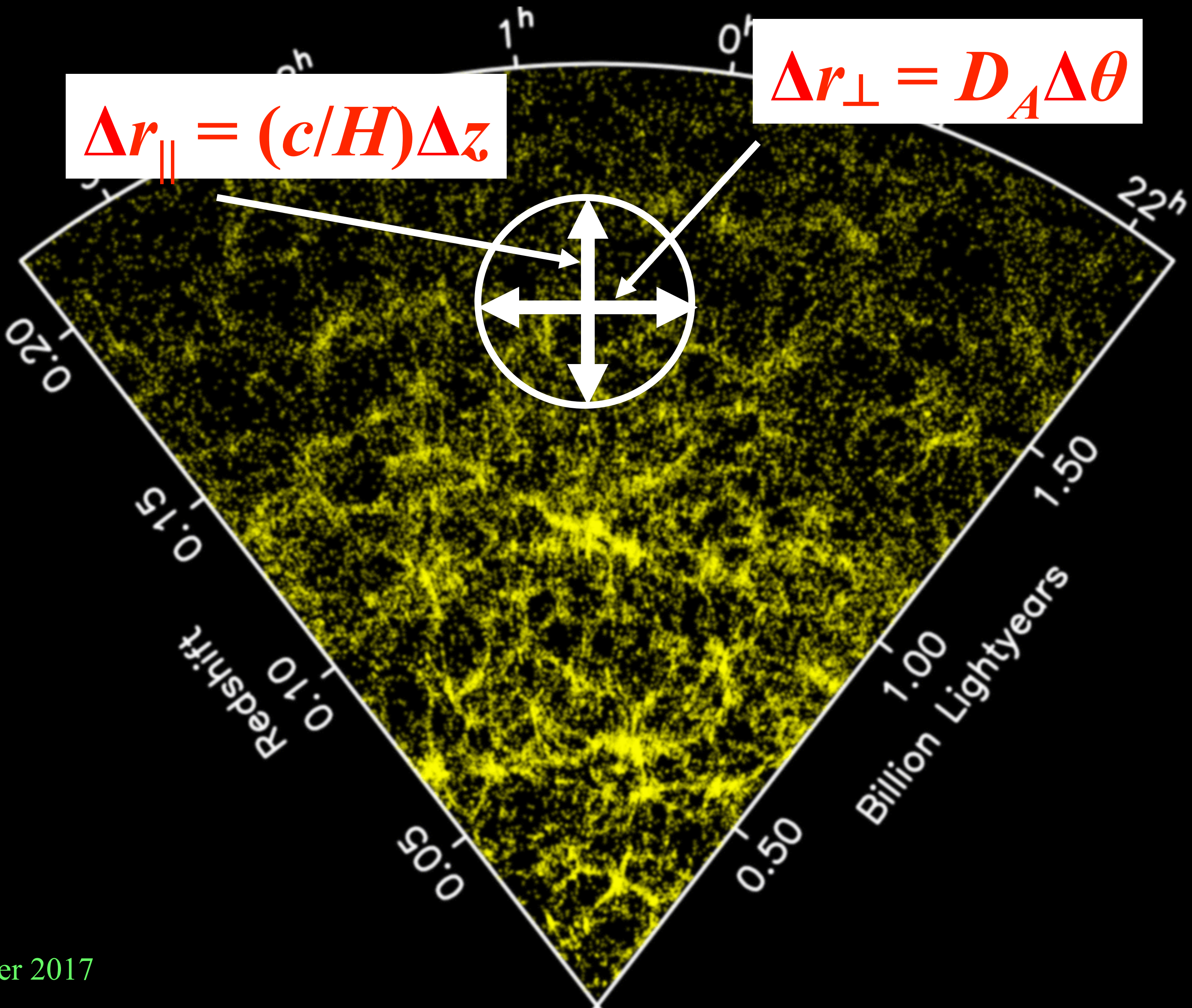
BAO as a Standard Ruler

Blake & Glazebrook 2003
Seo & Eisenstein 2003

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

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

BAO systematics:
- →Bias
- →Redshift-space distortions
- →Nonlinear effects



$\Delta r_{\parallel} = (c/H)\Delta z$

$\Delta r_{\perp} = D_A \Delta\theta$

The Origin of Baryon Acoustic Oscillations

- 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, *s*, is the sound horizon scale at the drag epoch
  - WMAP: measured *s* to ~ 1%
  - Planck: measued *s* to ~ 0.3%

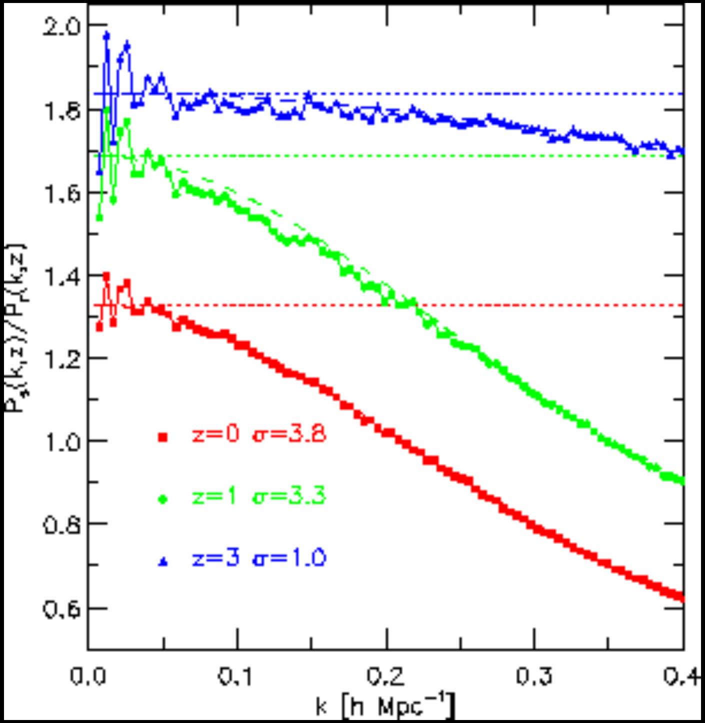
The Drag Epoch

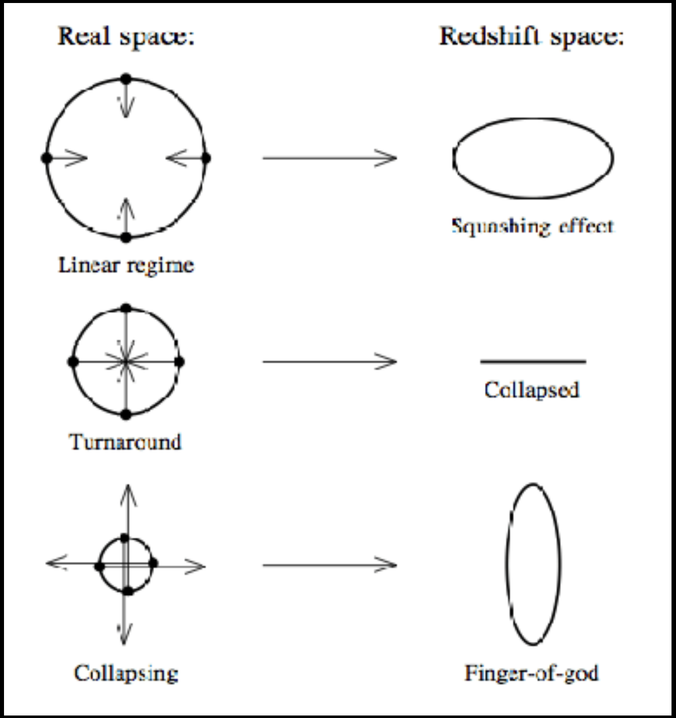
- The BAO scale is the sound horizon scale at the drag epoch, when photon pressure can no longer prevent gravitational instability in baryons.
  - Epoch of photon-decoupling: $\tau(z_*)=1$
  - Drag epoch: $\tau_b(z_d)=1$, $z_d<z_*$
  - The higher the baryon density, the earlier baryons can overcome photon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

(Hu & Sugiyama 1996)

BAO Systematic Effect: Redshift-Space Distortions

- Artifacts not present in real space
  - **Large scales: coherent bulk flows (out of voids and into overdense regions). These boost BAO; can be used to probe growth rate $f_g(z)$**
  - Small scales: smearing due to galaxy random motion ("Finger of God" effect)

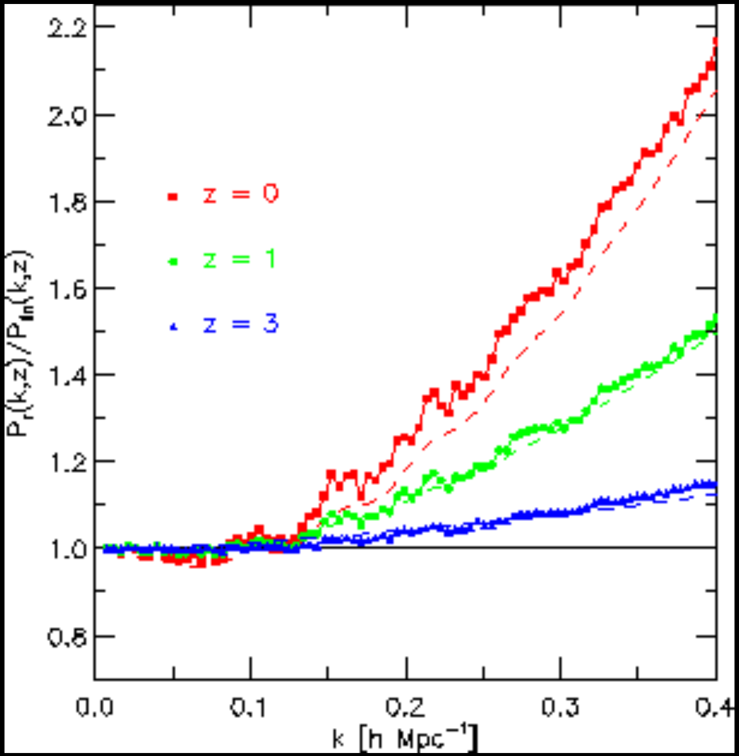




Left: Ratio of redshift-space and real-space power spectra. Horizontal lines: coherent bulk flows only. Dashed lines: model (Angulo et al. 2008)

BAO Systematic Effect: Nonlinear Gravitational Clustering

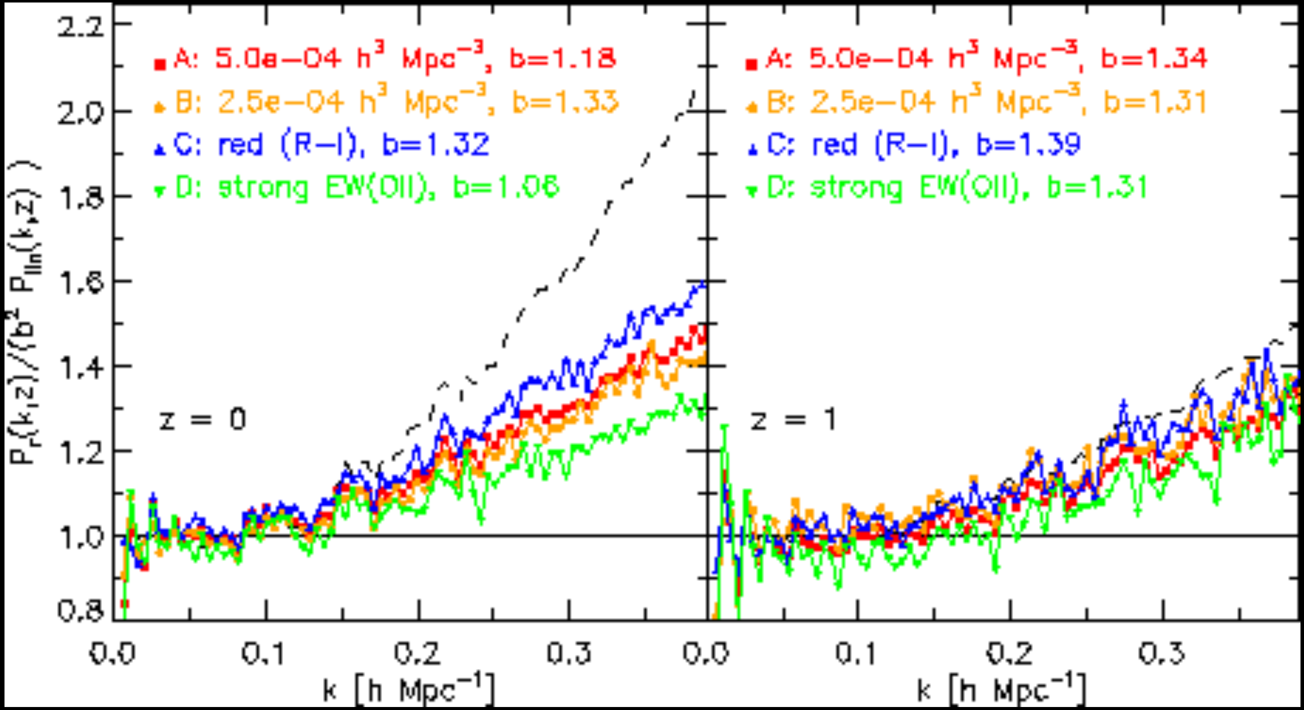
- On the very large scales, density perturbations $\boldsymbol{\delta}_k$ are small, thus their evolution is linear (no mode-coupling between different ***k*** modes).
- On BAO scales, there is mode-coupling between different ***k*** modes:
  - Small scale information in $P(k)=|\delta_k|^2$ destroyed by cosmic evolution due to mode-coupling; 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)



Ratio of nonlinear and linear P(k)
Horizontal line: no nonlinearity
Dashed lines: model
Dark matter only
(Augulo et al. 2008)

BAO Systematic Effect: Galaxy Clustering Bias

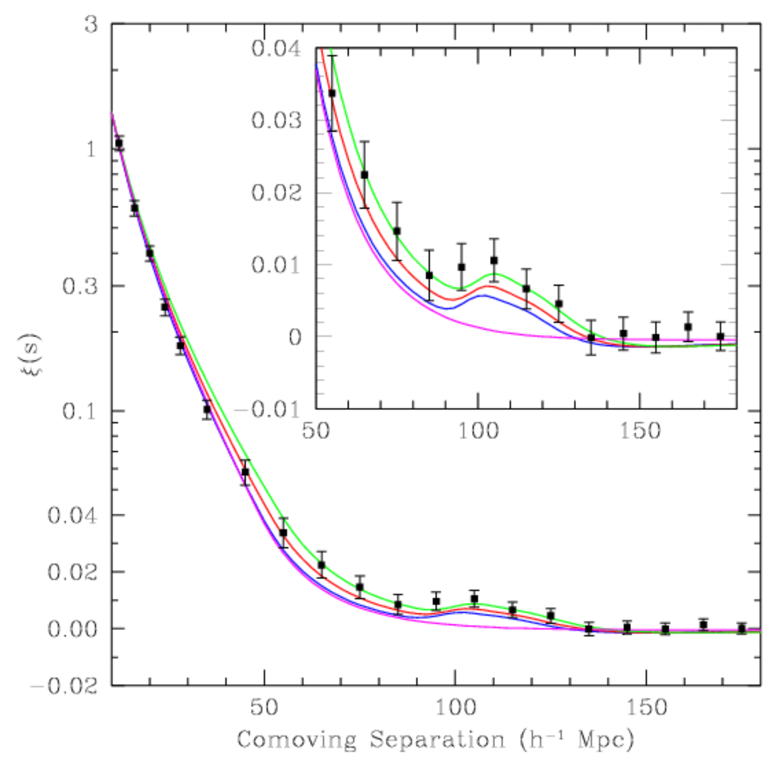
- How galaxies trace mass distribution
  - Could be scale-dependent
  - Only modeled numerically for a given galaxy sample selection (Angulo et al. 2008)



Ratio of galaxy power spectrum over linear matter power spectrum
Horizontal lines: no scale dependence in bias. Dashed lines: model

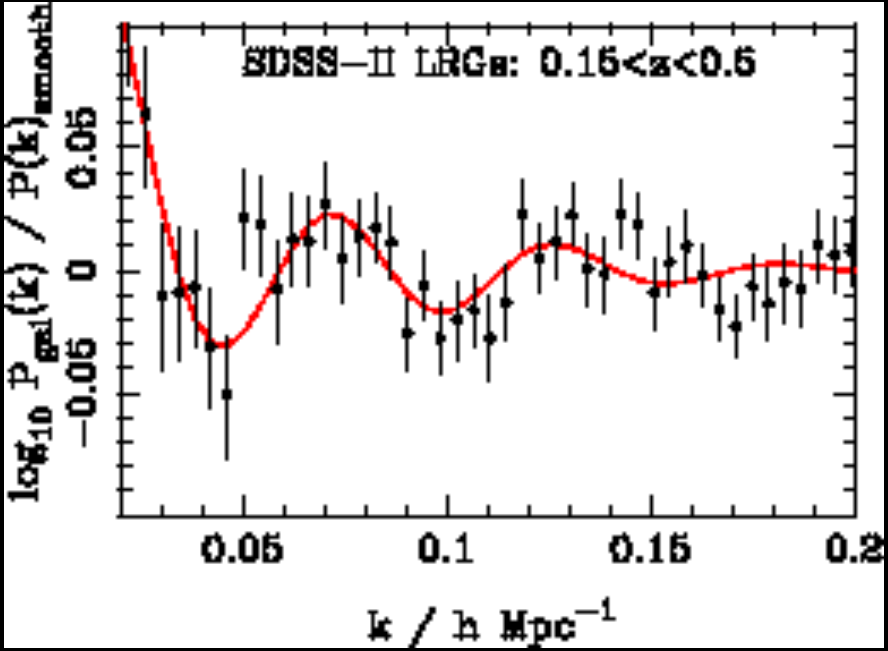
Baryon Acoustic Oscillation Measurements

Galaxy 2-pt correlation function



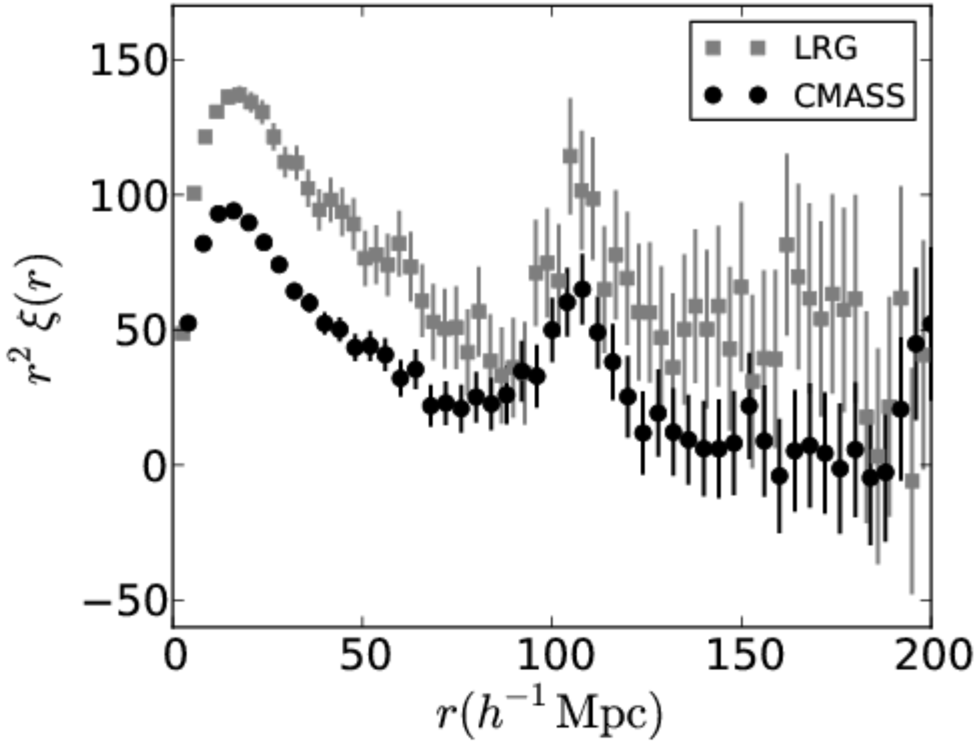
Eisenstein et al. (2005)

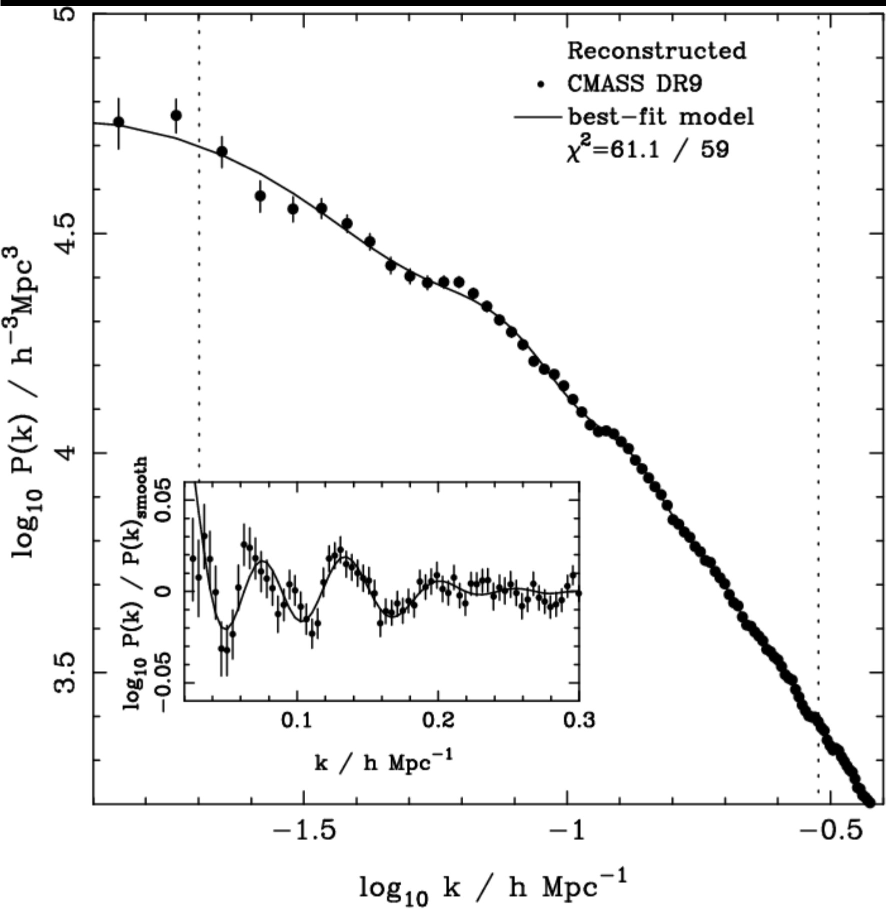
Galaxy power spectrum



Percival et al. (2009)

Results from SDSS III (BOSS)





Top: DR7 vs DR9, spherically-averaged galaxy correlation function

Right: DR9 galaxy power spectrum

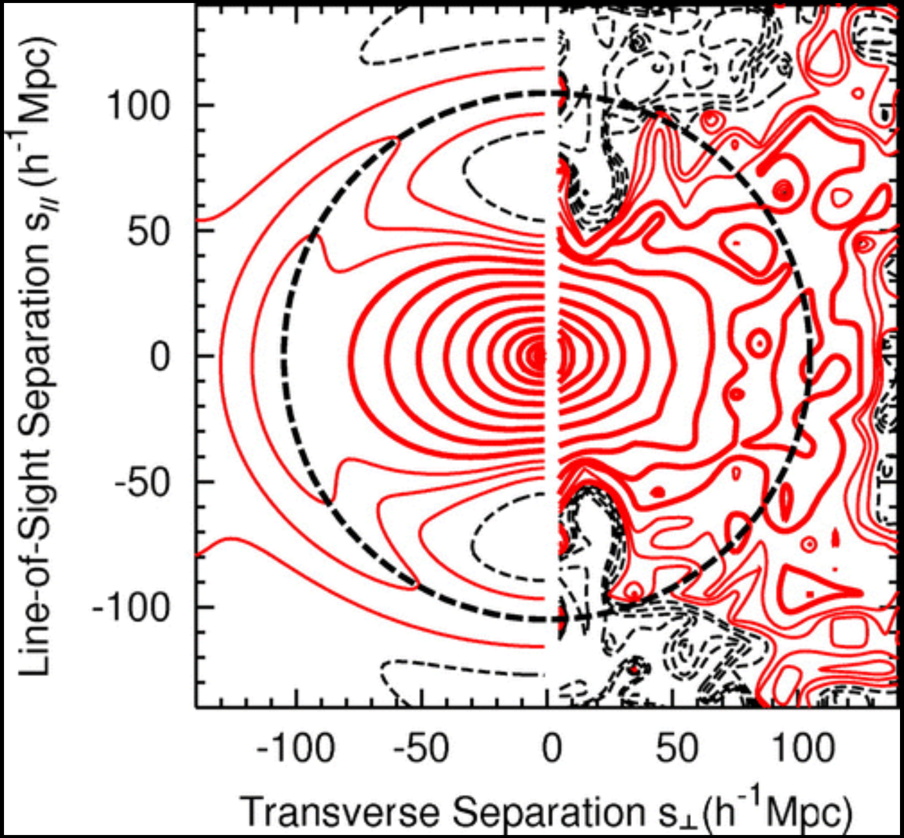
Anderson et al. (2012)

GC/BAO Avantages & Challenges

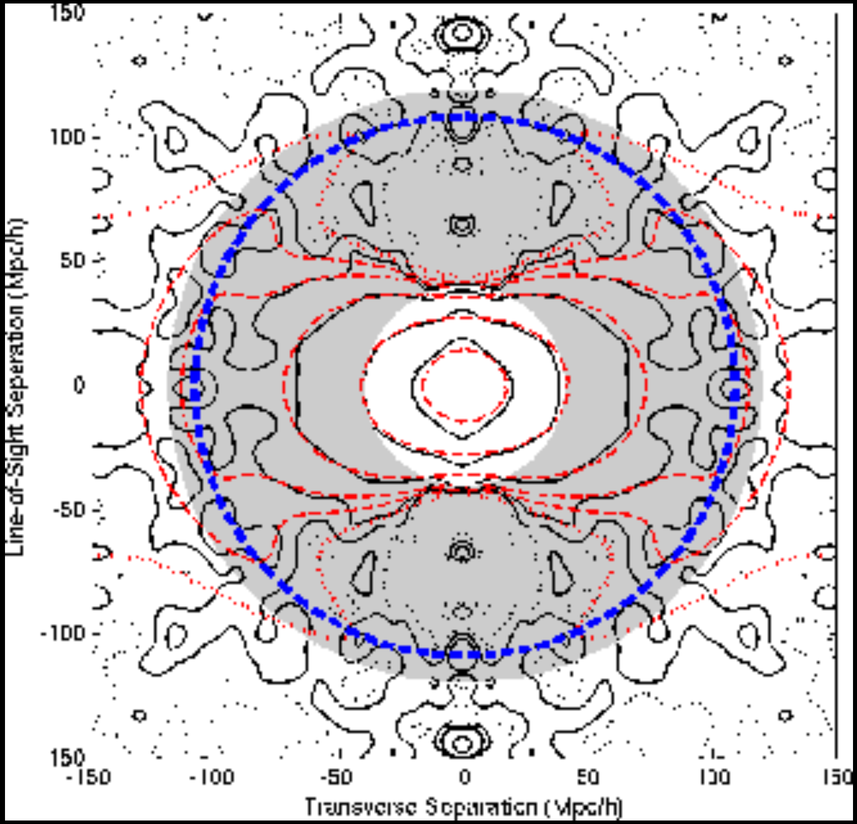
- Advantages:
  - Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).
  - Intrinsic systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling of data.
- Challenges:
  - Full modeling of systematic uncertainties
  - Translate forecasted performance into reality

Challenge in 2D: Proper Modeling of SDSS Data

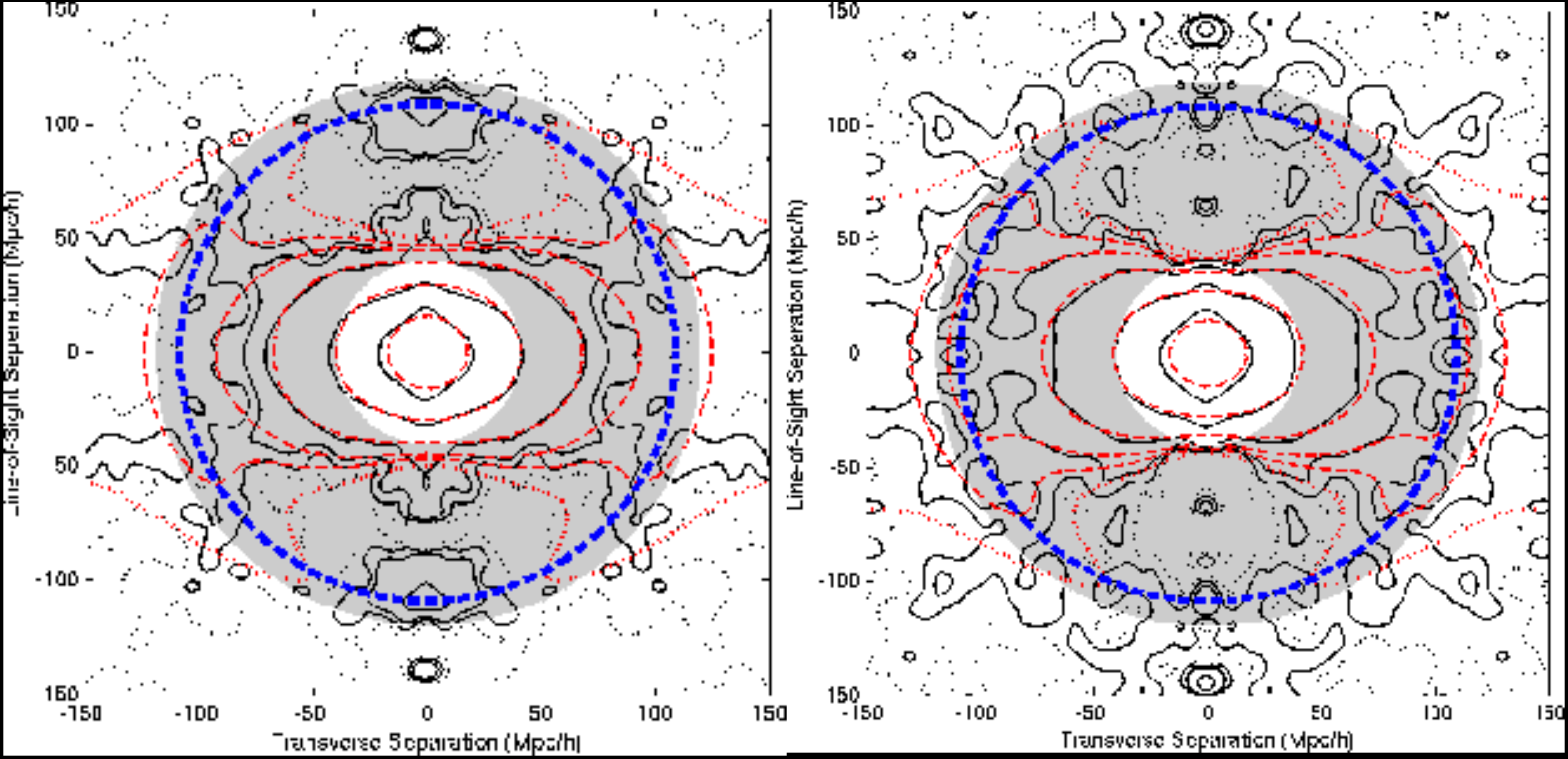
Okumura et al. (2008)



Chuang & Wang, arXiv:1102.2251, MNRAS, 426, 226 (2012)



First Measurements of $H(z)$ & $D_A(z)$ from Data



$x_h(z) = H(z)s = 0.04339 \pm 0.00178$ (4.1%); $x_d(z) = D_A(z)/s = 6.599 \pm 0.263$ (4.0%)

$r(x_h, x_d) = 0.0604$ ($z=0.35$, s: BAO scale, i.e., sound horizon at the drag epoch)

Chuang & Wang, MNRAS, 426, 226 (2012)

The Scaling Approach

$$\chi^2 \equiv \sum_{i,j=1}^{N_{bins}} \left[\xi_{th}(\mathbf{s}_i) - \xi_{obs}(\mathbf{s}_i)\right] C_{ij}^{-1} \left[\xi_{th}(\mathbf{s}_j) - \xi_{obs}(\mathbf{s}_j)\right]$$

$$\Delta\theta = \frac{\sigma}{D_A(z)} = \frac{\sigma_{fid}}{D_A^{fid}(z)}$$

$$\Delta z = H(z)\pi = H^{fid}(z)\pi_{fid},$$

$$(\sigma, \pi) = \left(\frac{D_A(z)}{D_A^{fid}(z)}\sigma_{fid}, \frac{H^{fid}(z)}{H(z)}\pi_{fid}\right). \qquad (30)$$

This means that the measured 2DCF's assuming an arbitrary model and the fiducial model are related as follows:

$$\xi_{obs}(\sigma, \pi) = T\left(\xi_{obs}^{fid}(\sigma_{fid}, \pi_{fid})\right), \qquad (31)$$

with T denoting the mapping given by Eq.(30).

$$\chi^2 \equiv \sum_{i,j=1}^{N_{bins}} \left\{T^{-1}\left[\xi_{th}(\mathbf{s}_i)\right] - \xi_{obs}^{fid}(\mathbf{s}_i)\right\} C_{fid,ij}^{-1} \cdot \cdot \left\{T^{-1}\left[\xi_{th}(\mathbf{s}_j)\right] - \xi_{obs}^{fid}(\mathbf{s}_j)\right\},$$

The model is mapped to the fiducial frame coordinates, and scaled by a volume factor:

$$V_{fac} = \frac{H(z)}{H^{fid}(z)}\left(\frac{D_A^{fid}(z)}{D_A(z)}\right)^2.$$

Chuang & Wang (2012)

The P(k) dewiggled model

$$P_g(k_{ref}, \mu_{ref}) = \frac{\frac{H(z)}{H(z)_{ref}}}{\left[\frac{D_A(z)}{D^{ref}_A(z)}\right]^2} b^2 \frac{(1+\beta\mu^2)^2}{1+\frac{1}{2}k^2\mu^2\sigma^2_{r,p}} P_{dw}(k, \mu, z) e^{-k^2\mu^2\sigma^2_{r,z}} + P_{shot}$$

$$P_{dw}(k, \mu, z) = G^2(z) P_0 k^{n_s} T^2_{dw}(k, \mu, z)$$

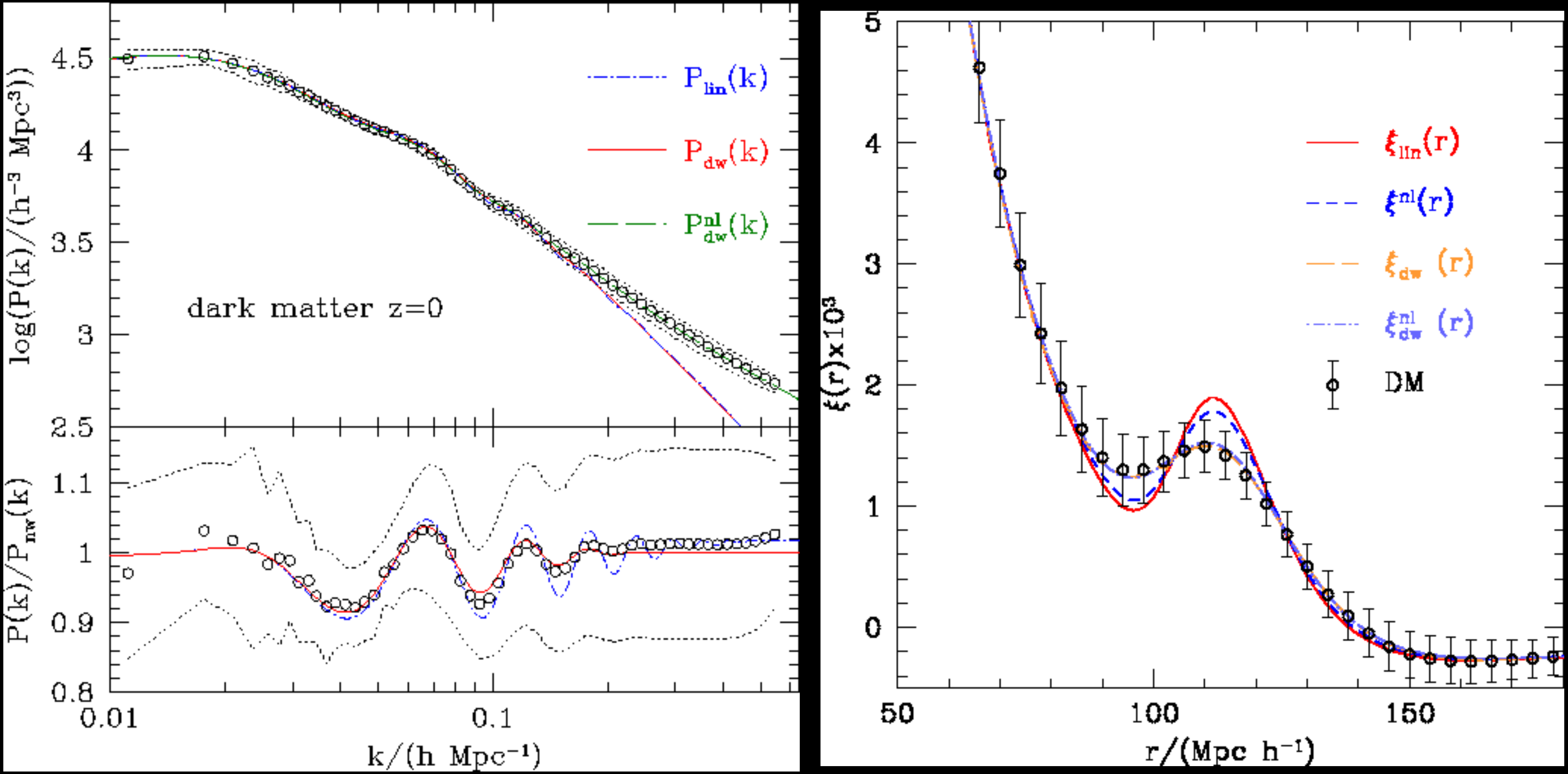
$$T^2_{dw}(k, \mu, z) = \mathrm{T}^2(\mathrm{k})\, e^{-\frac{g_\mu k^2}{2k_*^2}} + \mathrm{T}^2_{\mathrm{nw}}(\mathrm{k})\left[1 - e^{-\frac{g_\mu k^2}{2k_*^2}}\right]$$

$$g_\mu(\boldsymbol{k}, z) = G^2(z)\{1 - \mu^2 + \mu^2[1 + f_g(z)]^2\}$$

T(k): linear matter transfer function
T_{nw}(k): zero baryon CDM transfer function (Eisenstein & Hu 1998)

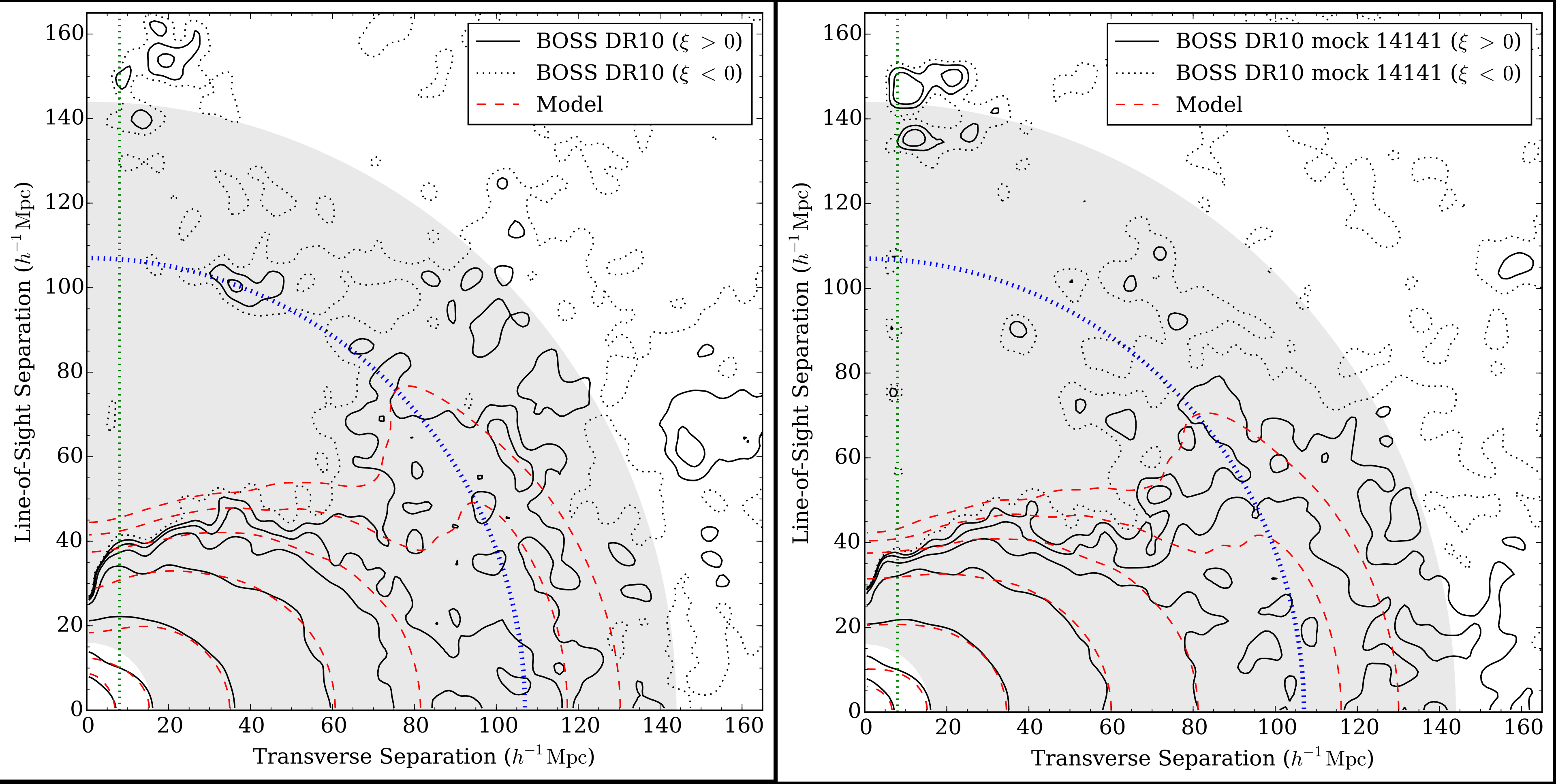
Eisenstein, Seo, & White (2007)

P(k) dewiggled model: validation by N-body simulations



Sanchez, Baugh, & Angulo (2008)

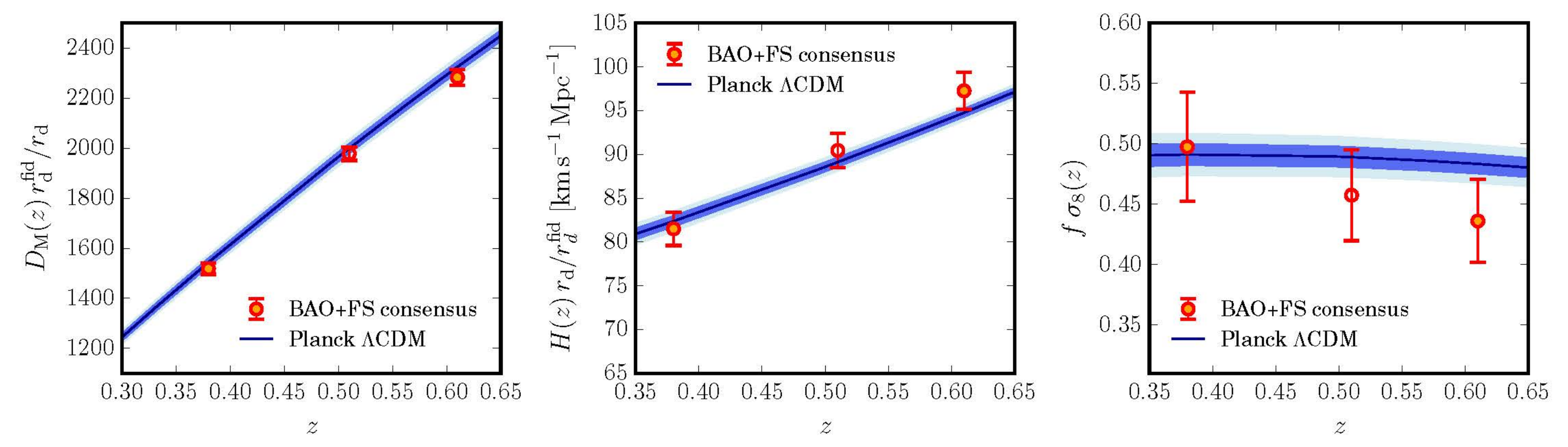
BOSS DR10 Data Vs. Mock



Scaling method (with improved RSD modeling) applied to measuring $H(z)$, $D_A(z)$, $f_g(z)$ using $\xi(\sigma,\pi)$. *Wang (2017)*

Yun Wang, September 2017

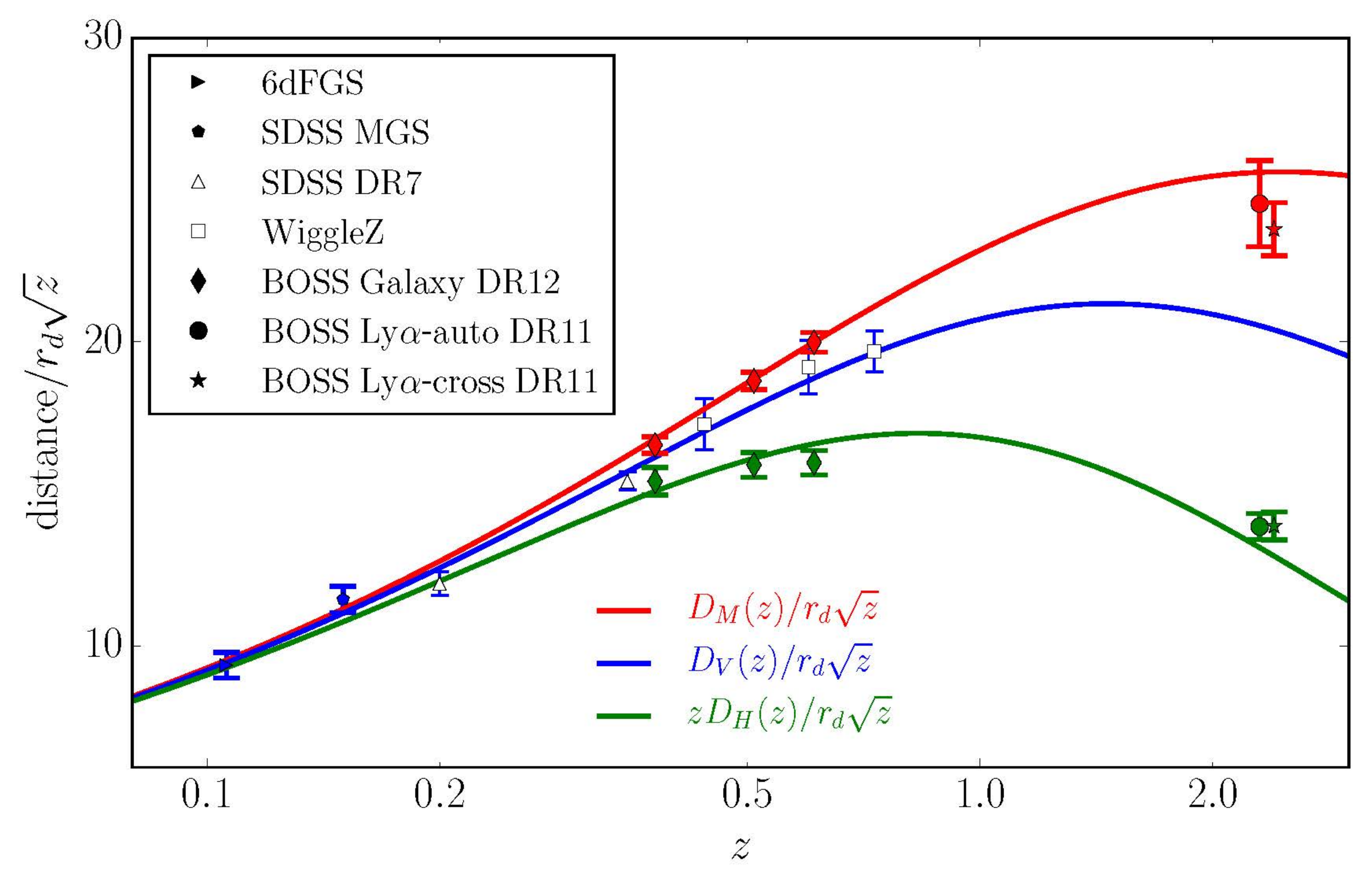
BOSS Final Results (DR12)



FS: full shape. *Alam et al. (2017)*

- Tension with CMB data, especially at $z_{eff} = 0.61$
- The H(z) and D_A(z) measurements at z=0.32 and z=0.57 are consistent with BOSS DR11 results.
- The growth rate measurements appear sensitive to model assumptions.

Summary of Distance Measurements



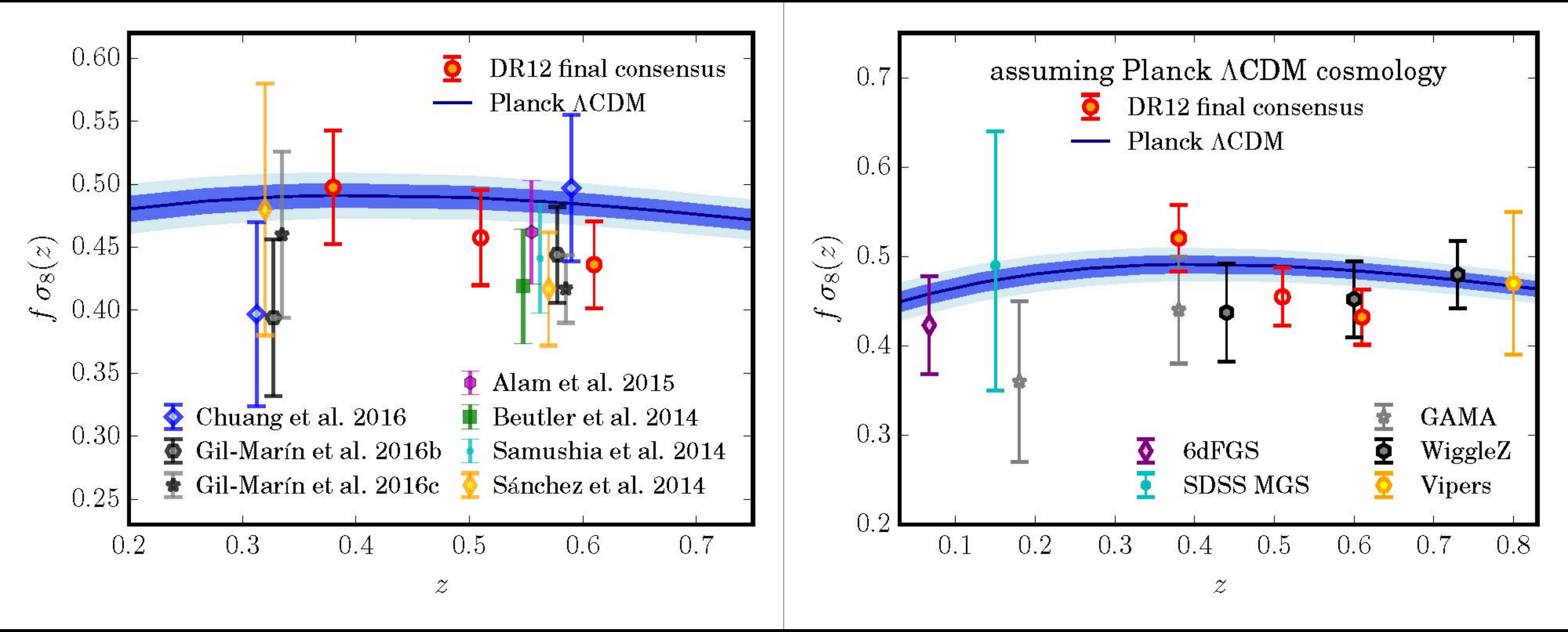
Curves: flat ΛCDM.

D_M=r(z); D_H=c/H(z); D_V=[r^2(z) cz/H(z)]$^{1/3}$: volume averaged distance

Alam et al. (2017)

Summary of Growth Rate Measurments

Alam et al. (2017)

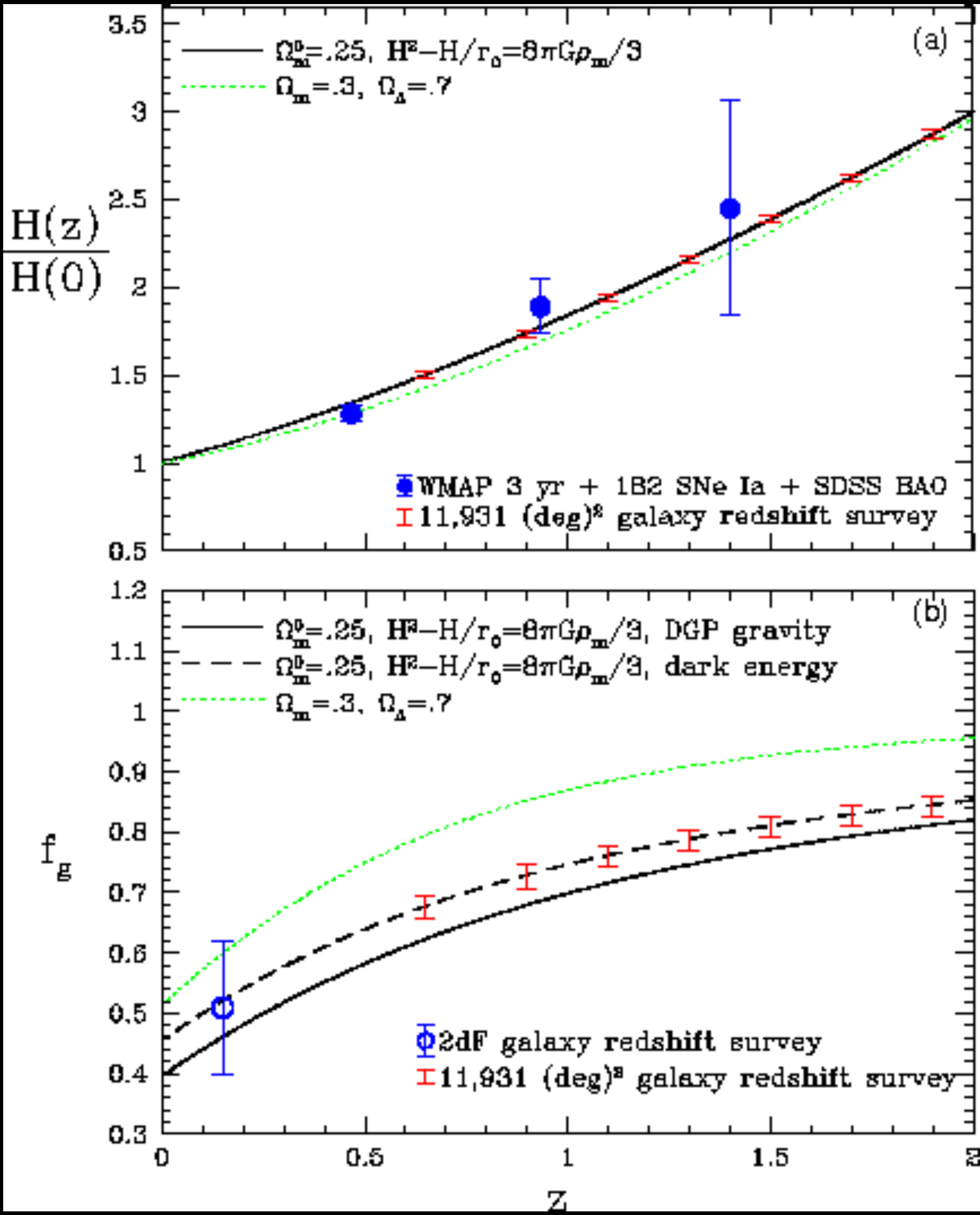


Left panel shows different results obtained using the same data, with different model assumptions.

The Use of Galaxy Clustering to Differentiate Dark Energy & Modified Gravity

Measuring redshift-space distortions $\beta(z)$ and bias $b(z)$ allows us to measure $f_g(z)=\beta(z)b(z)$

$[f_g=\mathrm{dln}\delta/\mathrm{dln}a]$



$H(z)$ and $f_g(z)$ allow us to differentiate dark energy and modified gravity.

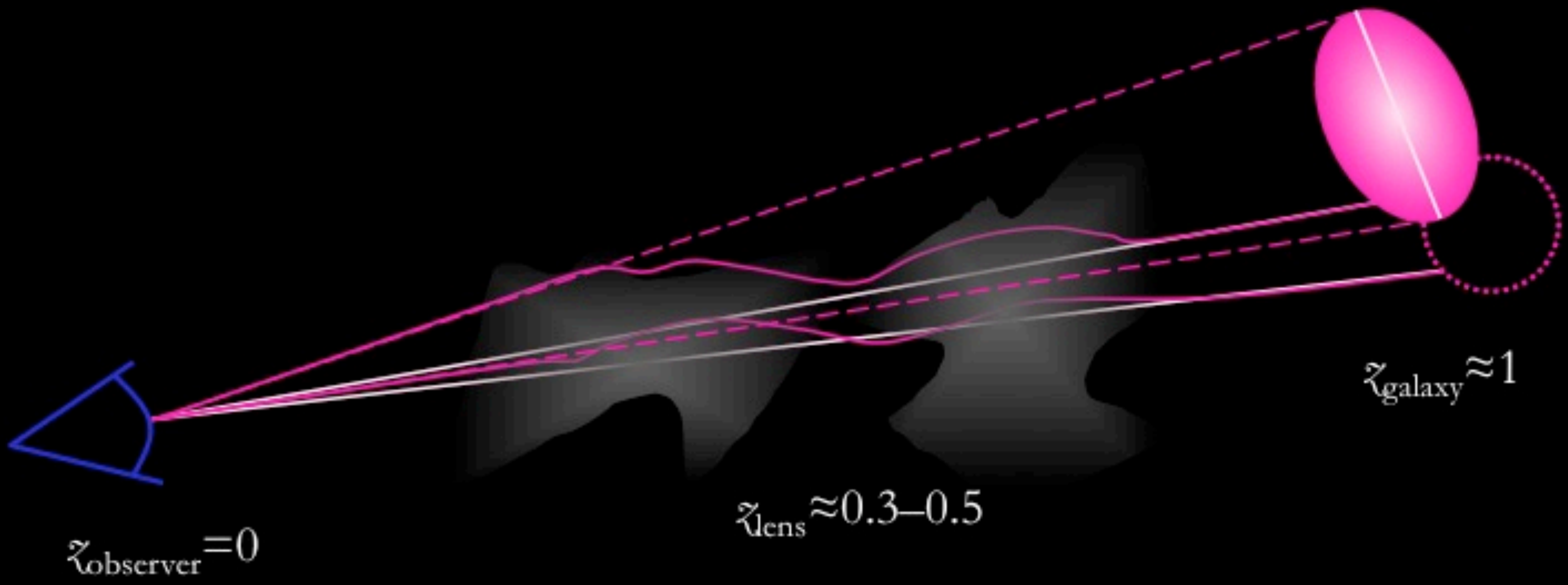
Wang (2008)

Weak Lensing as Dark Energy Probe (see Metcalf's focused lecture)

Yun Wang, September 2017

Weak Gravitational Lensing

Weak lensing effect cannot be measured from any individual galaxy. Must be measured statistically over many galaxies



If there is any intervening large-scale structure, light follows the distorted path (exaggerated). Background images are magnified and sheared by ~2%, mapping a circle into an ellipse. Like glass lenses, gravitational lenses are most effective when placed half way between the source and the observer.

(Illustration by Jason Rhodes)

Weak Lensing Observed

Gravitational Lens in Abell 2218 HST · WFPC2

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

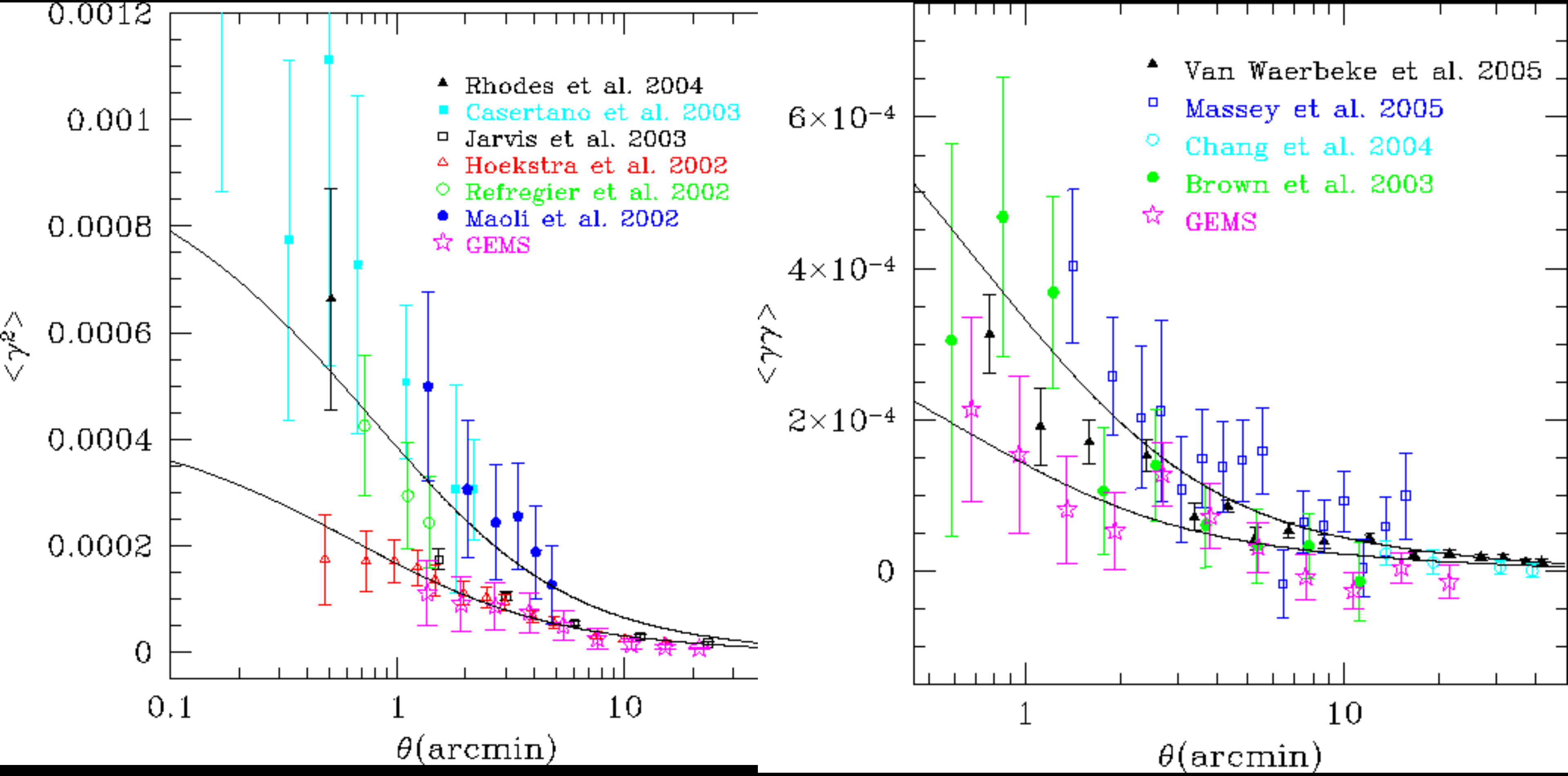
- **Weak Lensing Tomography:** compare observed cosmic shear correlations with theoretical/numerical predictions to measure cosmic large scale structure growth history $G(z)$ and $H(z)$ *[Wittman et al. 2000]*

- **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]*

WL systematics effects

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

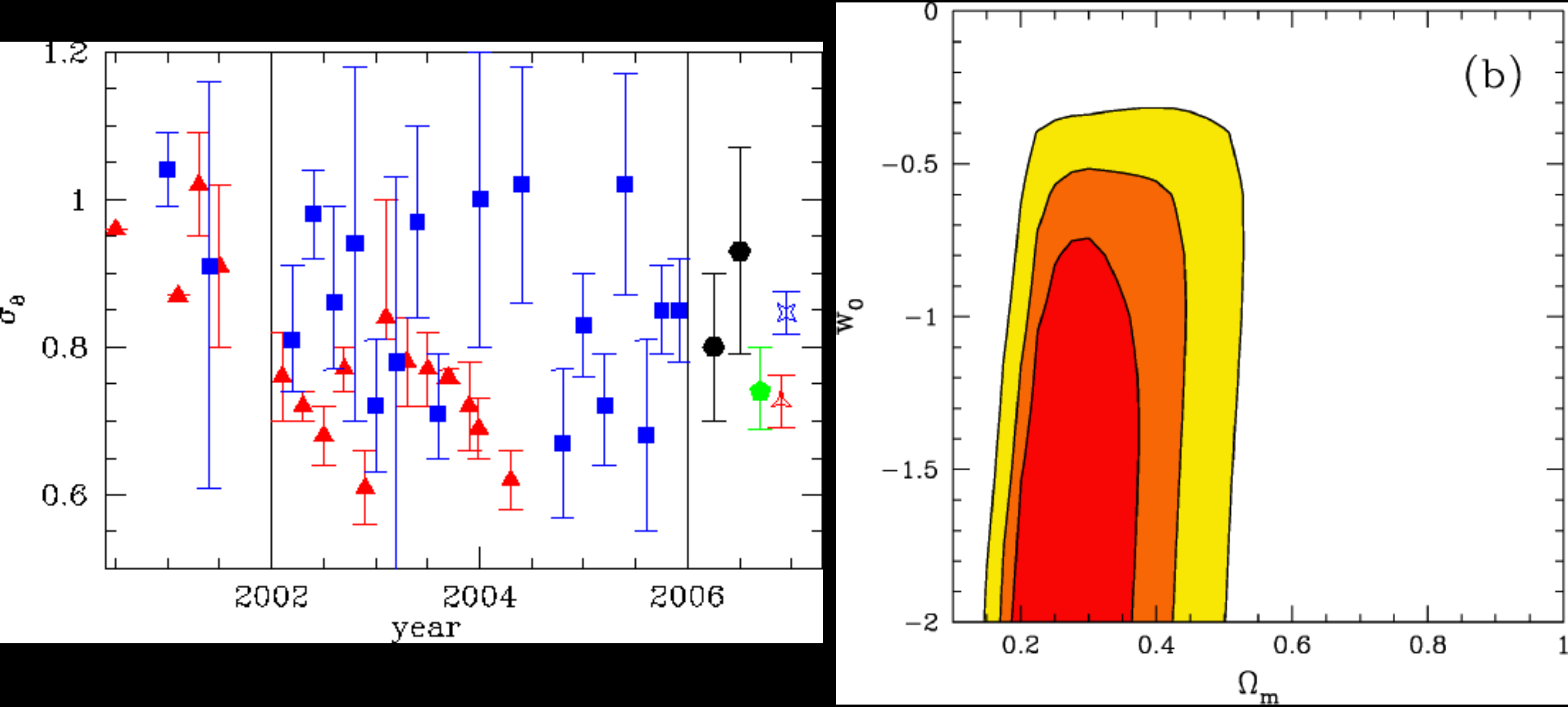
Measurements of cosmic shear (WL image distortions of a few percent)



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.

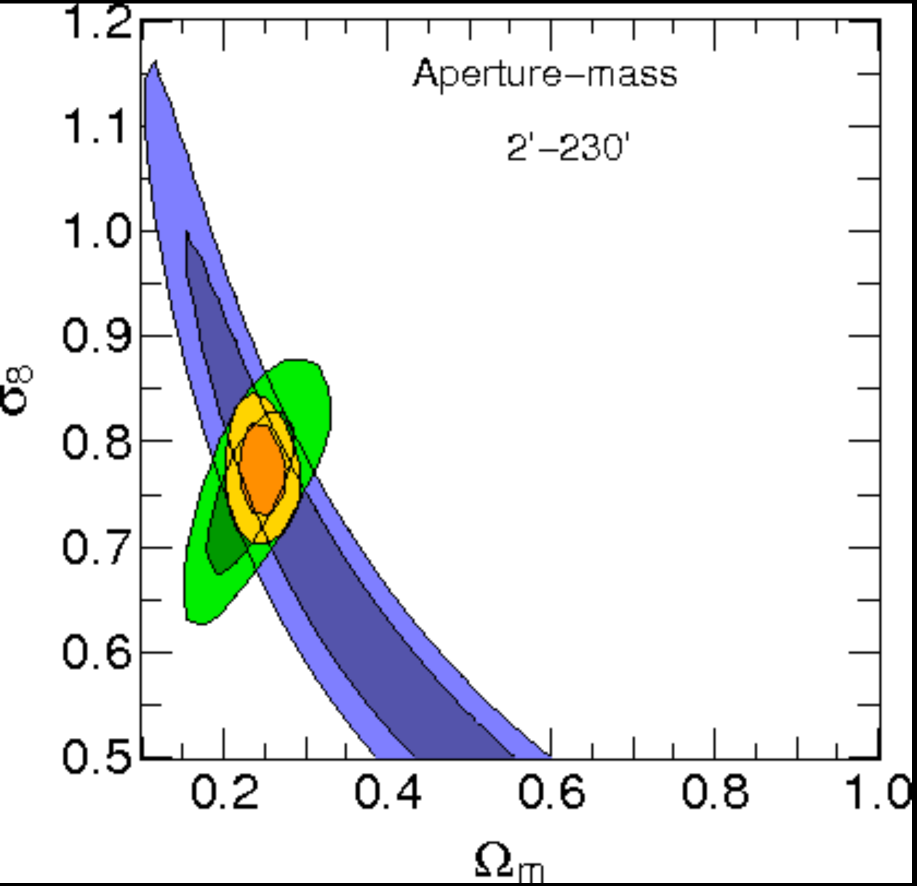
Cosmological parameter constraints from WL

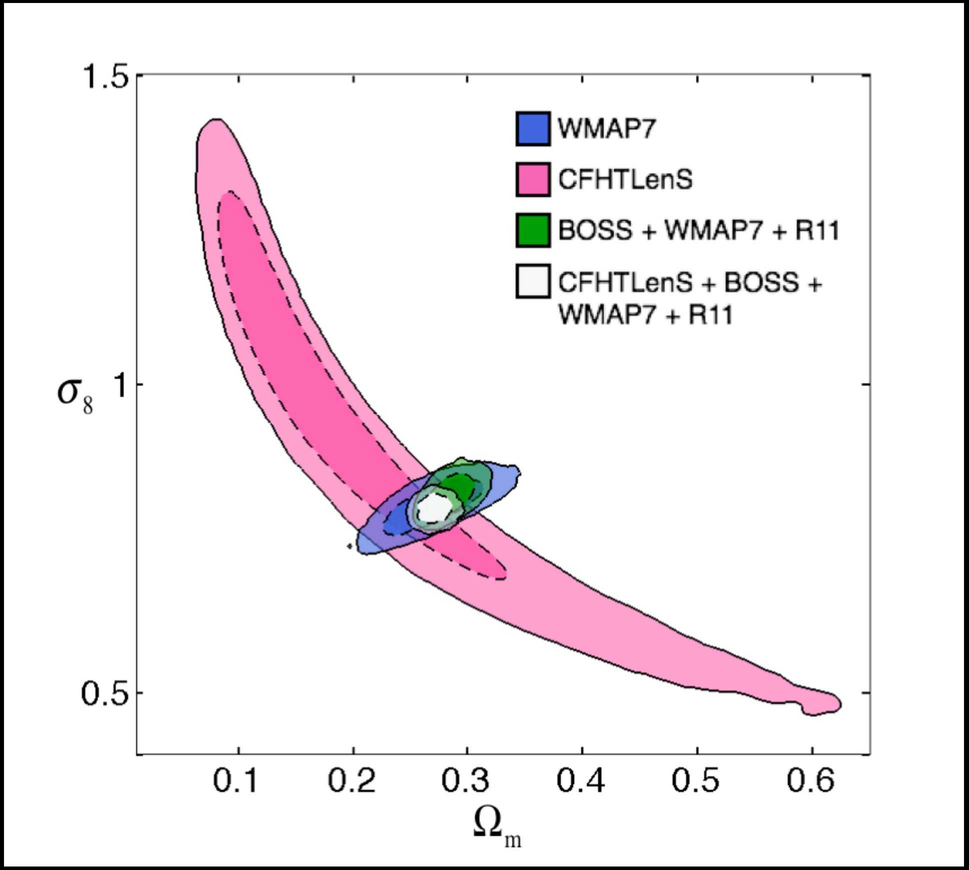


L: σ_8 from analysis of clusters of galaxies (red) and WL (other). *[Hetterscheidt et al. (2006)]*

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

Complementarity between WL and CMB





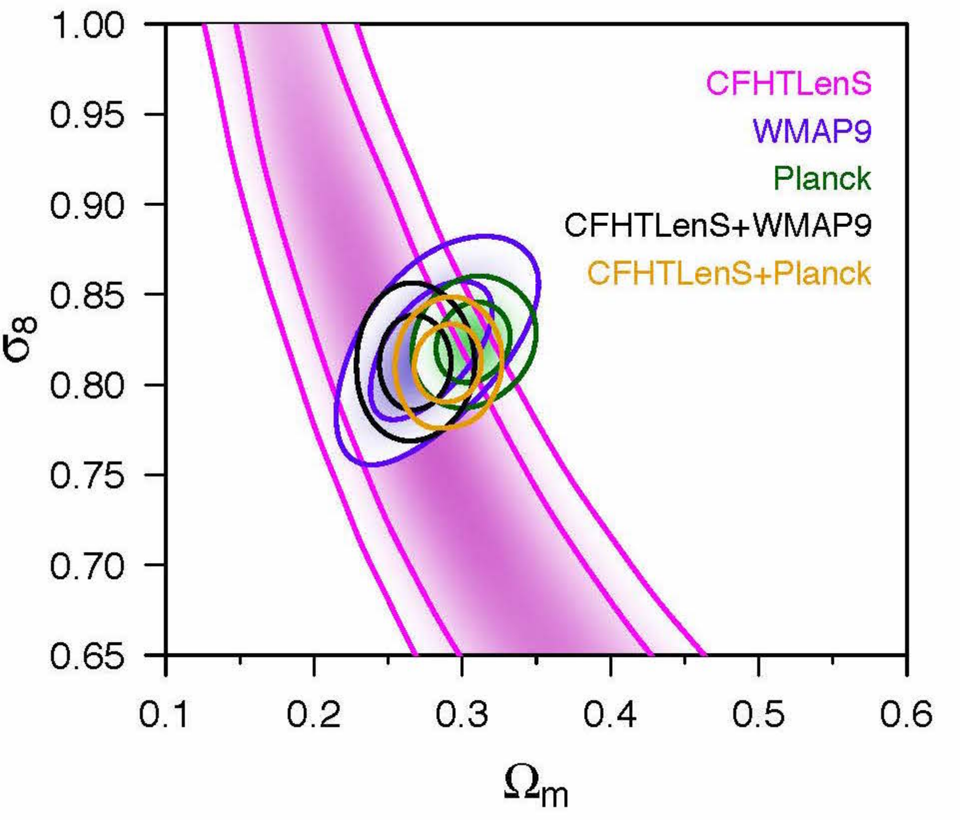
CFHTLS data

Fu et al. (2008) [WMAP3]

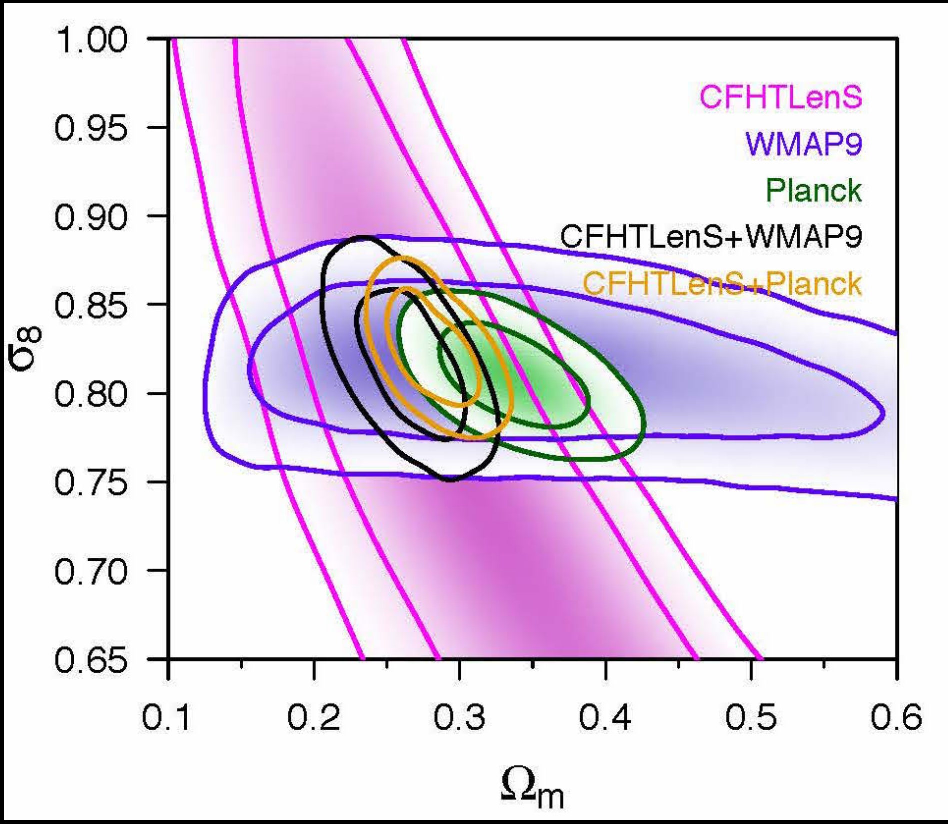
Heymans et al. (2013) [WMAP7]

Effect of assuming a flat Universe

Flat Universe



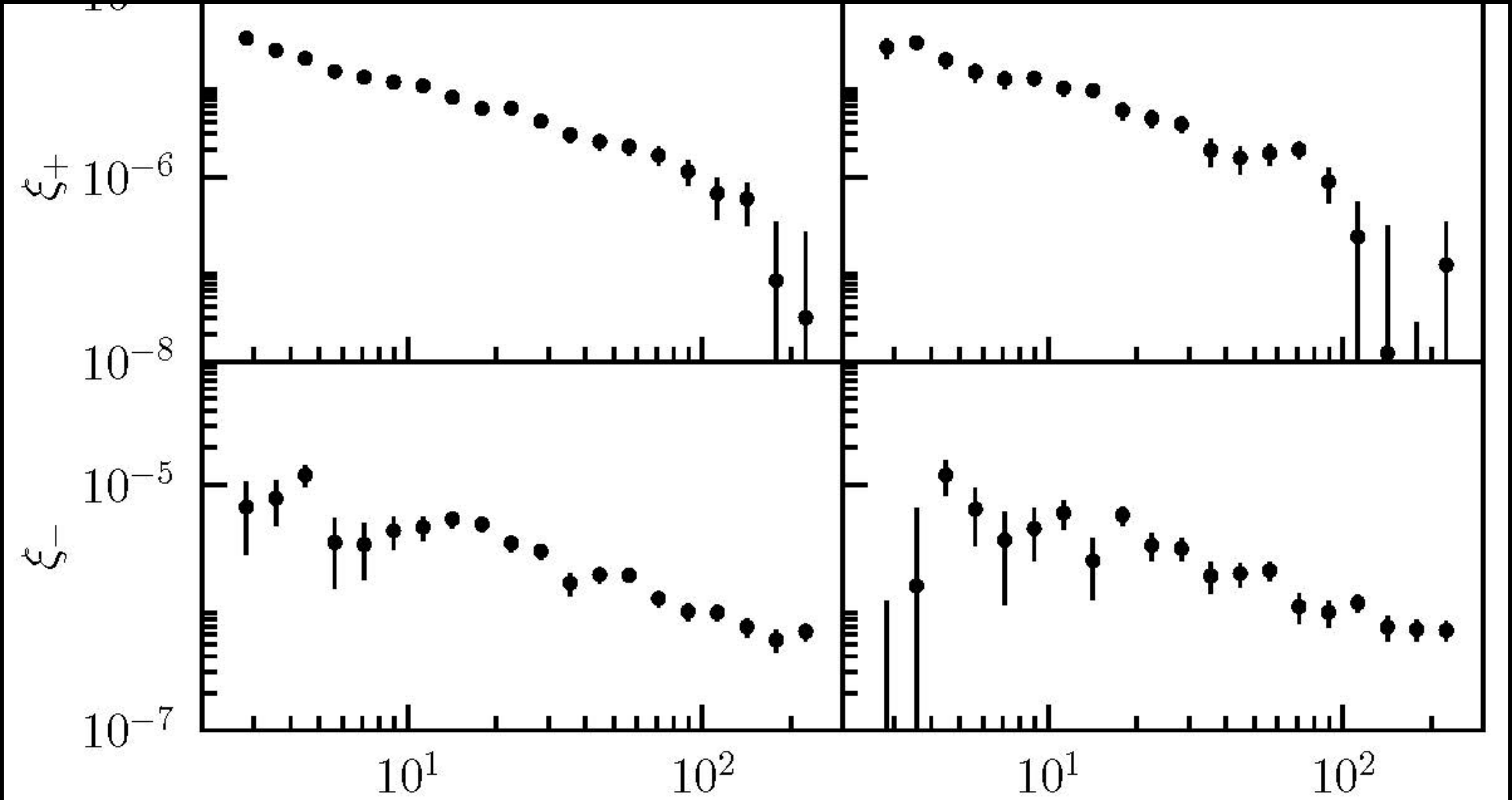
Non-flat Universe



CFHTLenS Results

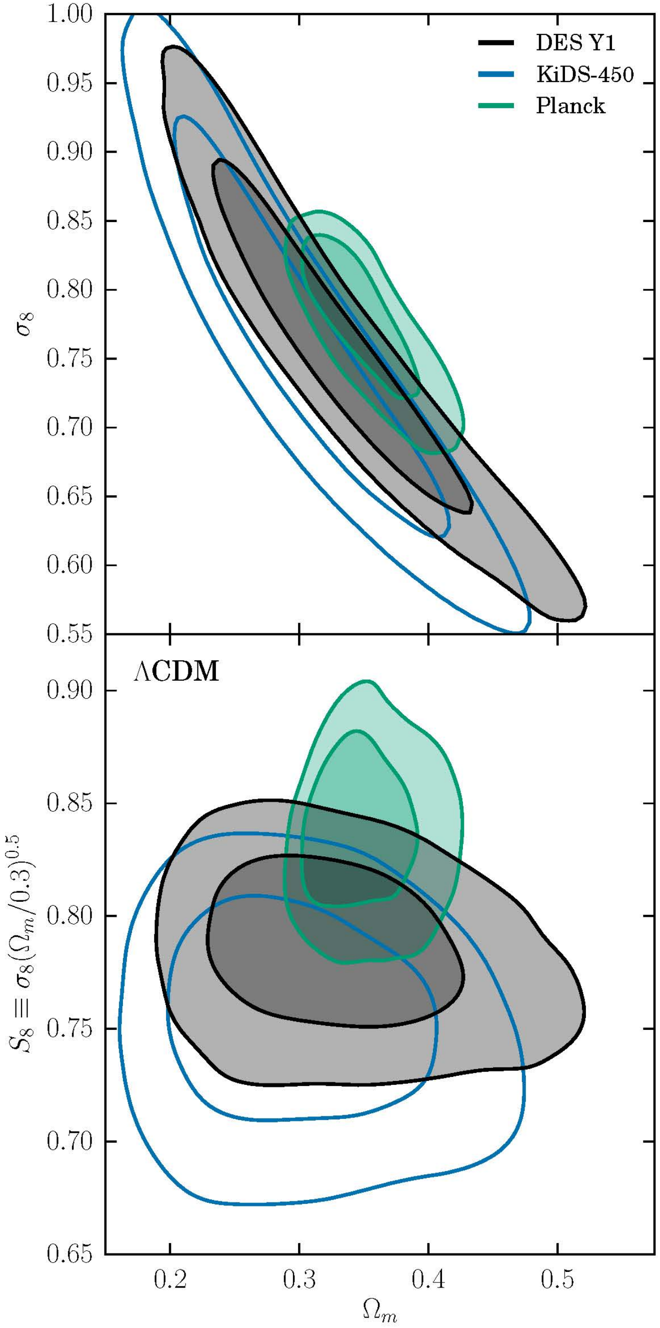
Fu et al. (2014)

DES Year 1 Results (2017)

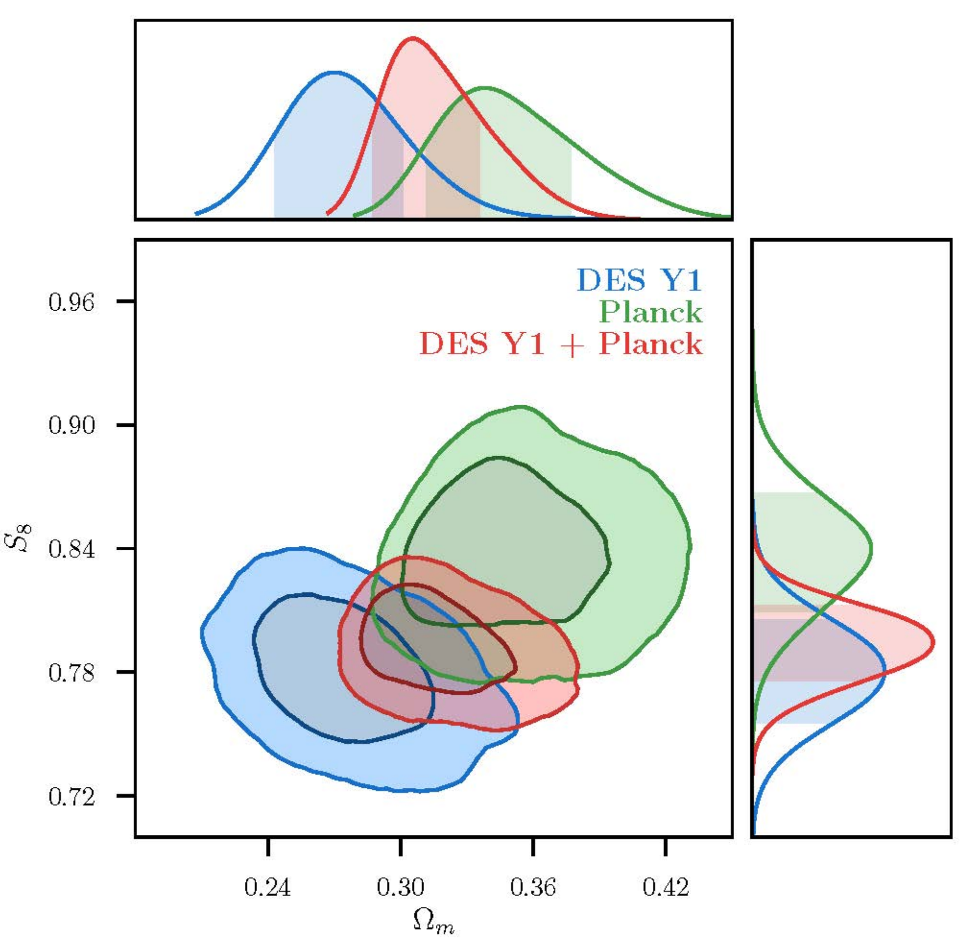


The measured non-tomographic shear correlation function ξ± for the DES Y1 shape catalogs (1786 sq deg). *Troxel et al. (2017)*

DES Year 1 Results

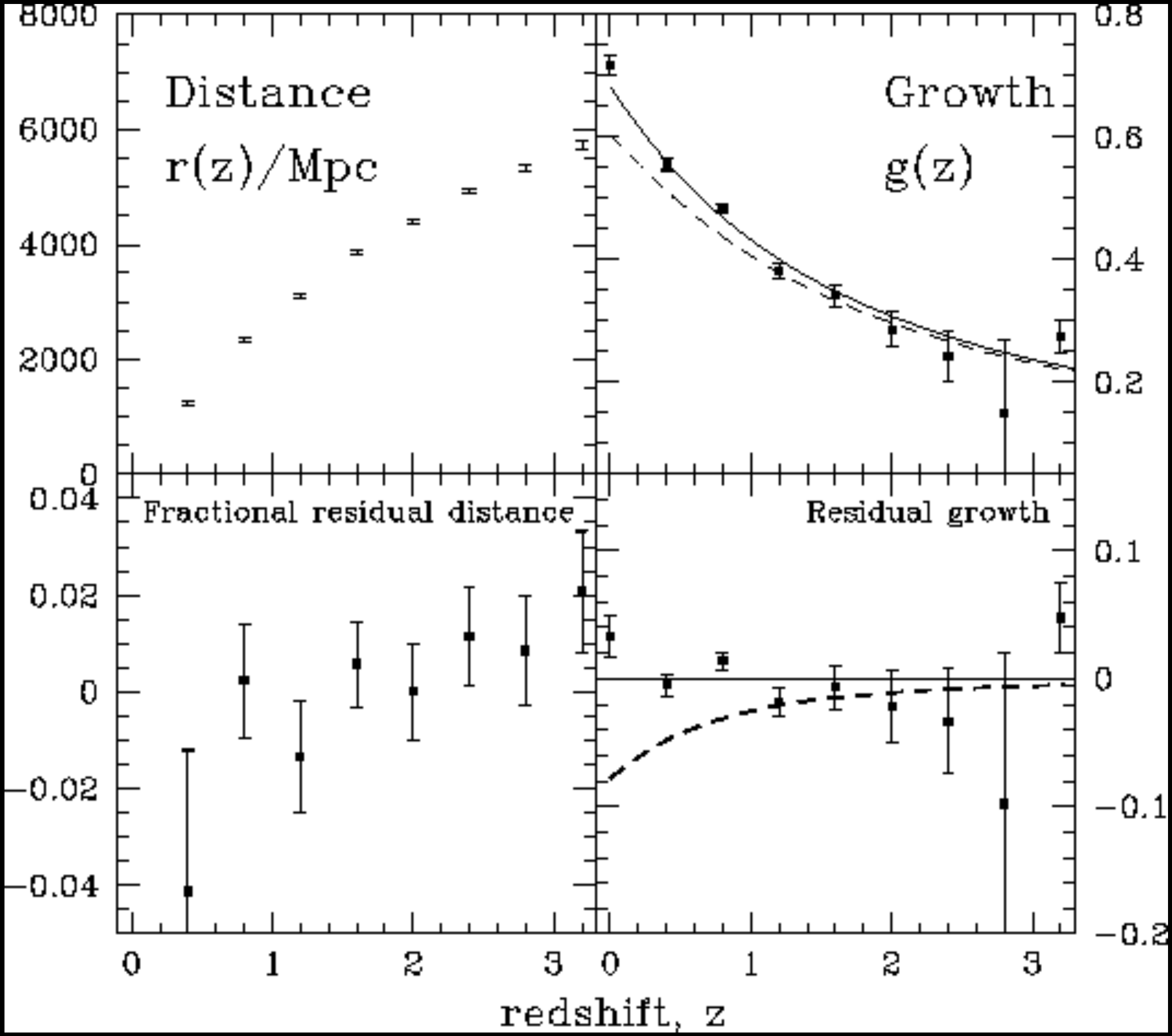


Flat Universe with w_X = -1 assumed.



Left: Cosmic shear constraints (Troxel et al. 2017)
Right: Constraints from the three combined probes ($\xi_\pm$, $w(\theta) + \gamma_t$) in DES Y1 (Abbott et al. 2017)

WL forecasts for a LSST-like survey



Knox, Song, & Tyson (2006)

Clusters as Dark Energy Probe

Yun Wang, September 2017

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.

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.***

Future Prospects

Future Dark Energy Surveys
(an incomplete list)

Galaxy Redshift Surveys:

•**HETDEX(2014-?):** 420 sq deg GRS, $1.9 < z < 3.5$

•**eBOSS (2014-2020):** GRS over 7,500 sq deg for LRGs ($0.6<z<0.8$), and over 1500 sq deg for [OII] ELGs ($0.6<z<1$)

•**PFS (2018?-):** GRS of ELGs over 1400 sq deg ($0.6<z<2.4$)

•**DESI (2018?-2022):** GRS over 14,000 sq deg for ELGs (cosmic variance limited at $z=1.4$)

•**Euclid (2020-):** GRS over 15,000 sq deg of ELGs ($0.9<z<1.8$)

•**WFIRST (2025-):** GRS over ~2200 sq deg of ELGs ($1<z<3$)

Weak Lensing Imaging Surveys:

•**DES (2013-?):** optical WL over 5000 sq deg ($i=24$)

•**Euclid (2020-):** NIR WL over 15,000 sq deg ($R+I+Z=24.5$, $H=24$)

•**LSST (2023-?):** optical WL over 18,000 sq deg ($r=24.5$)

•**WFIRST (2025-):** NIR WL over 2200 sq deg ($H\sim26.5$)

Supernovae Surveys:

•**DES (2013-?):** ~3000 at $z<0.8$

•**LSST (2023-?):** ~50,000 at $z<0.8$

•**WFIRST (2025-):** 2700 SNe Ia with $0.1<z<1.7$

Yun Wang, September 2017

Euclid

A geometrical probe of the universe selected for Cosmic Vision

Euclid = DUNE + SPACE

DUNE: All-sky optical imaging for gravitational lensing

SPACE: All-sky near-IR spectra to H=22 for BAO

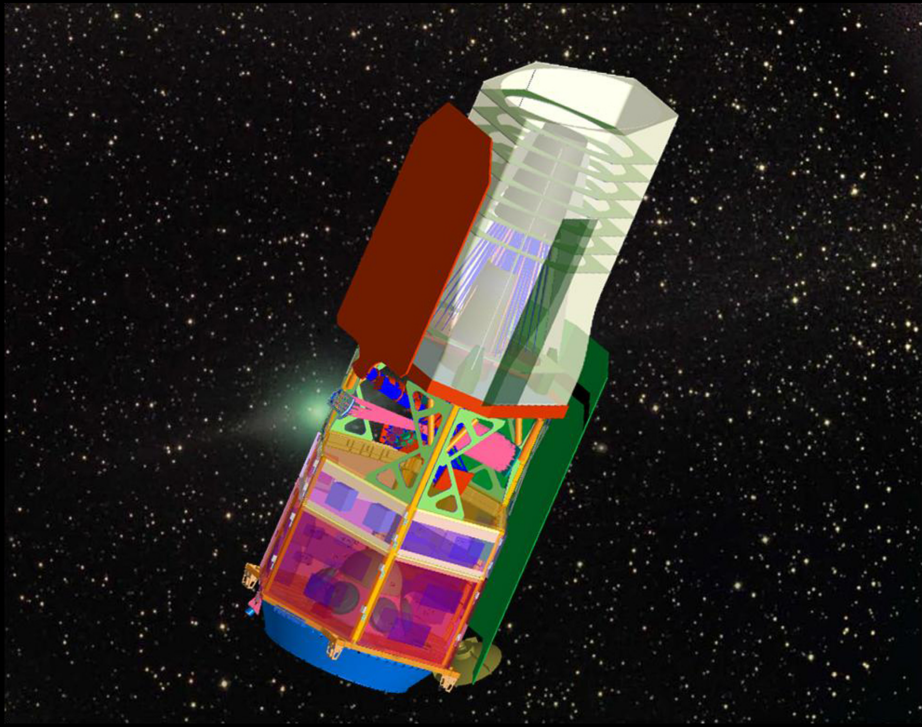
Euclid: a Space Mission to Map the Dark Universe

- ESA medium class mission to be launched in 2020
- Goal: Understand the origin of cosmic acceleration
- Telescope: 1.2m
- Imagers: Vis and NIR
- Spectrograph: slitless, NIR
- Launch vehicle: Soyuz ST-2.1B rocket
- Orbit: the L2 Lagrange point
- Mission duration: 6 years
- **See Percival's plenary lecture for more about Euclid**

WFIRST

Wide-Field Infrared Survey Telescope

- JDEM + MPF + NISS…
- 2.4m from NRO
- 100x the Hubble Field of View at the same sensitivity and resolution
- Dark energy
  + microlensing planets
  + NIR survey
  + Guest Investigator
- Launch date: ~2025



Euclid vs. WFIRST Comparison

Euclid: 1.2m aperture, launch in ~2020, DE science driven
WFIRST: 2.4m aperture, launch in ~2025, DE + planets driven

Galaxy Redshift Surveys:

	Depth/ erg/s/cm^2	Area/ (deg)^2	Redshift range	FoV/ (deg)^2	Spectral dispersion	Pixel scale (arcsec/pix)	Detectors
Euclid	2×10^{-16}	15,000	0.9-1.8	0.55	13.4 Å/pix	0.3	H2RG
WFIRST	10^{-16}	2,200	1-2	0.281	10.85 Å/pix	0.11	H4RG

Weak Lensing Surveys:

	Filters	Depth	Area/ (deg)^2	FoV/ (deg)^2	PSF/ arcsec	Pixel scale (arcsec/pix)	Detectors
Euclid	R+I+Z	24.5	15,000	0.55	0.16	0.101	CCD
WFIRST	Y, J, H, F184	~26.5	2,200	0.281	0.12-0.14	0.11	H4RG

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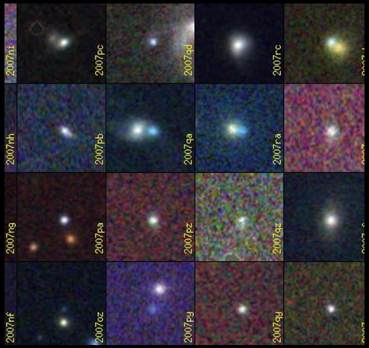
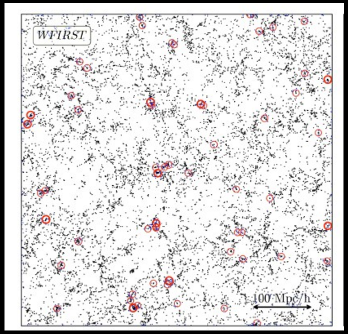
Slide from David Weinberg

Dark Energy with WFIRST



The ultimate supernova cosmology experiment
Unique in precision, redshift range, control of measurement and astrophysical systematics.

The best controlled weak lensing experiment Unique in depth, detail, and control of measurement and astrophysical systematics.



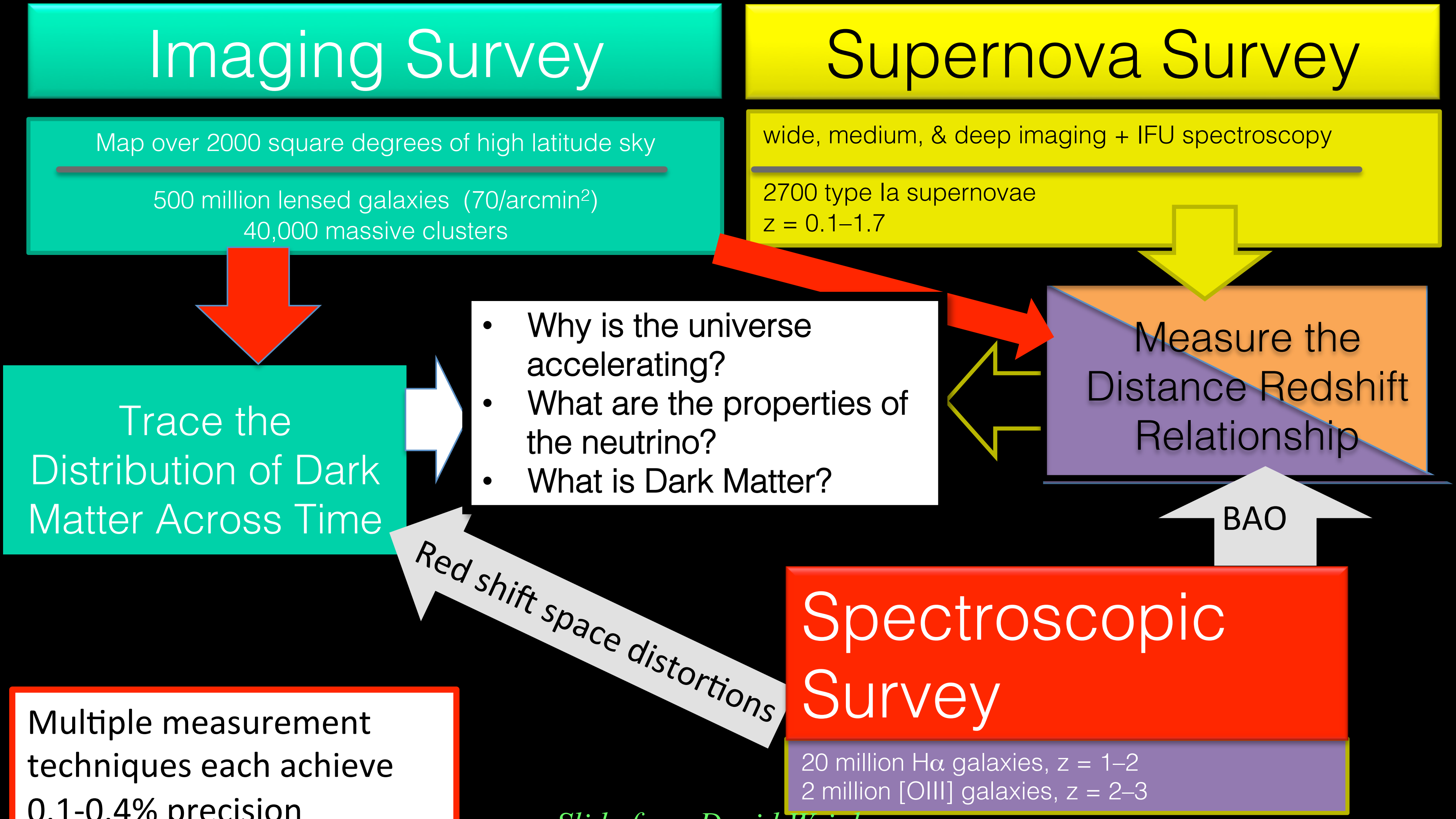
The densest large scale map of structure at $z = 1$-2
Only WFIRST can map this redshift range at the density needed to reveal details of structure.

Per unit time, WFIRST is most powerful supernova, weak lensing, and $z = 1$-2 spectroscopic facility.

Yun Wang, September 2017

Frontiers of Knowledge

As envisioned in NWNH, WFIRST uses multiple approaches to measure the growth rate of structure and the geometry of the universe to exquisite precision. These measurements will address the central questions of cosmology



Imaging Survey

Map over 2000 square degrees of high latitude sky

500 million lensed galaxies (70/arcmin^2)
40,000 massive clusters

Supernova Survey

wide, medium, & deep imaging + IFU spectroscopy

2700 type Ia supernovae
$z = 0.1–1.7$

Trace the Distribution of Dark Matter Across Time

- Why is the universe accelerating?
- What are the properties of the neutrino?
- What is Dark Matter?

Measure the Distance Redshift Relationship

BAO

Red shift space distortions

Spectroscopic Survey

20 million $H\alpha$ galaxies, $z = 1–2$
2 million [OIII] galaxies, $z = 2–3$

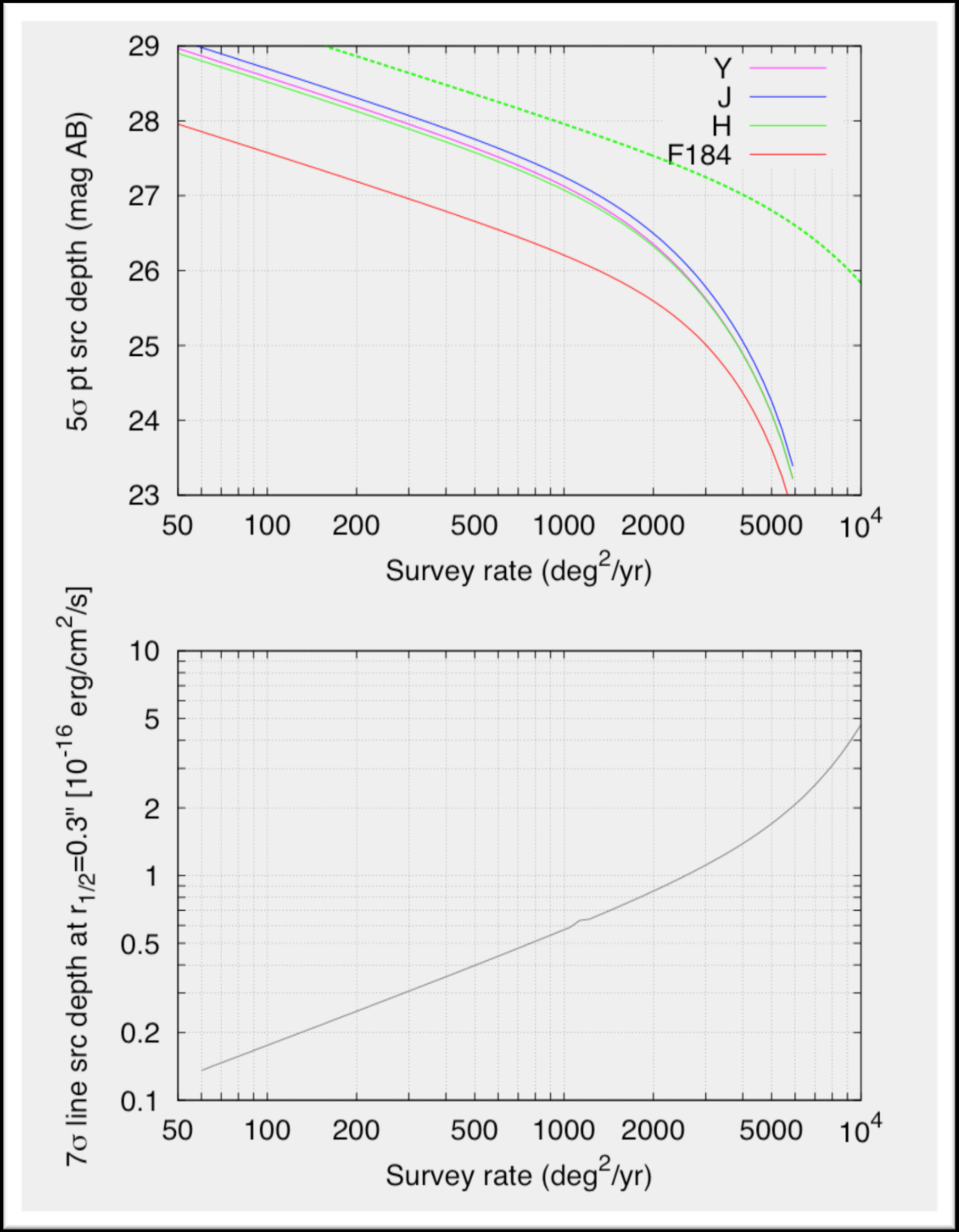
Multiple measurement techniques each achieve 0.1-0.4% precision

Slide from David Weinberg

Flexibility and Power of WFIRST

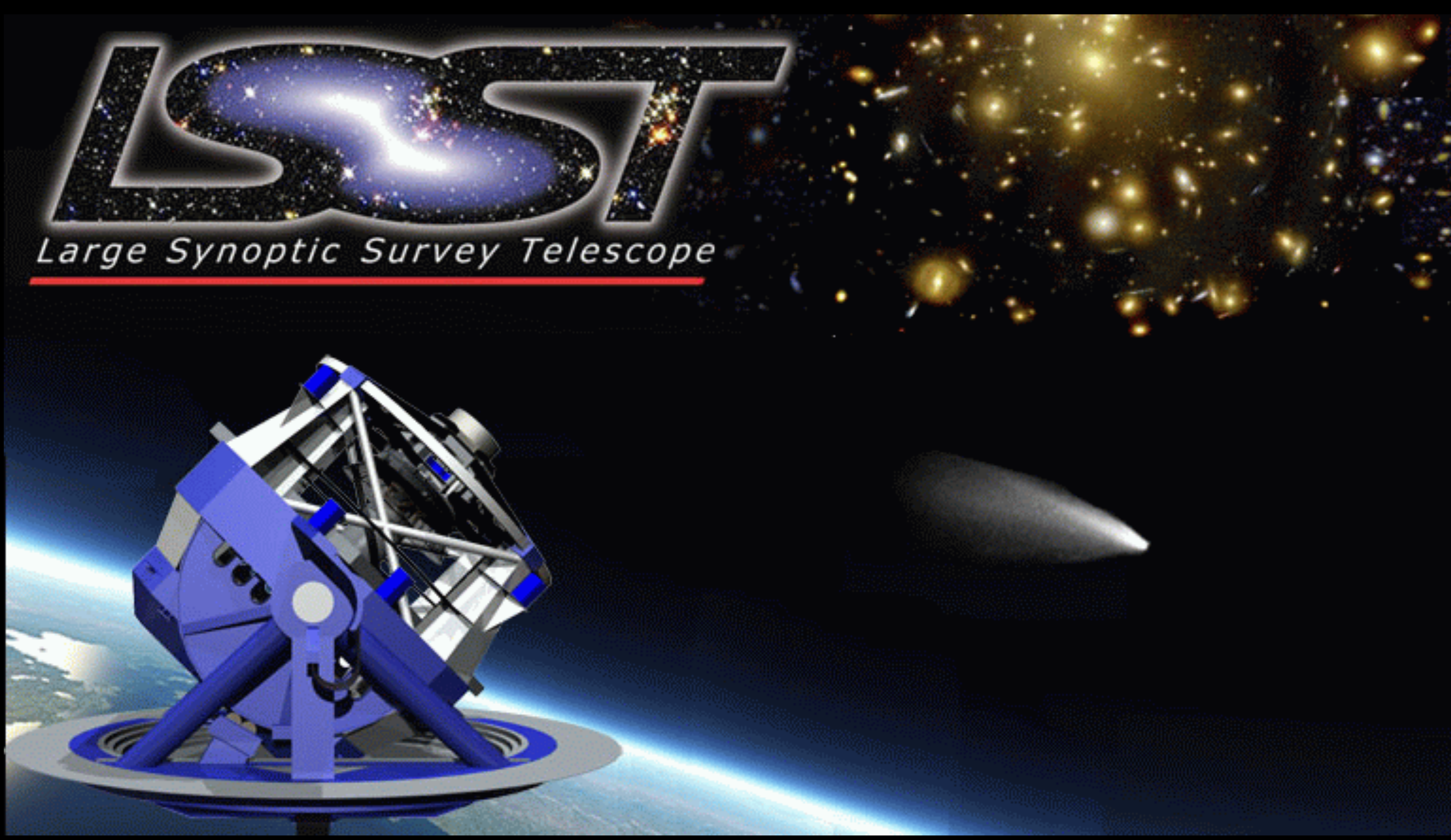
Weak lensing imaging survey

Spectroscopic galaxy redshift survey



(Figure from Chris Hirata)

Yun Wang, September 2017



- 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, $\Delta t = 4$-7d
- 20,000 sq deg WL & BAO with photo-z

References for Students

- *Dark Energy*, by Yun Wang, Wiley-VCH (2010)
- *Observational probes of cosmic acceleration*, by David Weinberg et al., Physics Reports, 530, 87 (2013)