Probing Cosmic Acceleration With Galaxy Clustering

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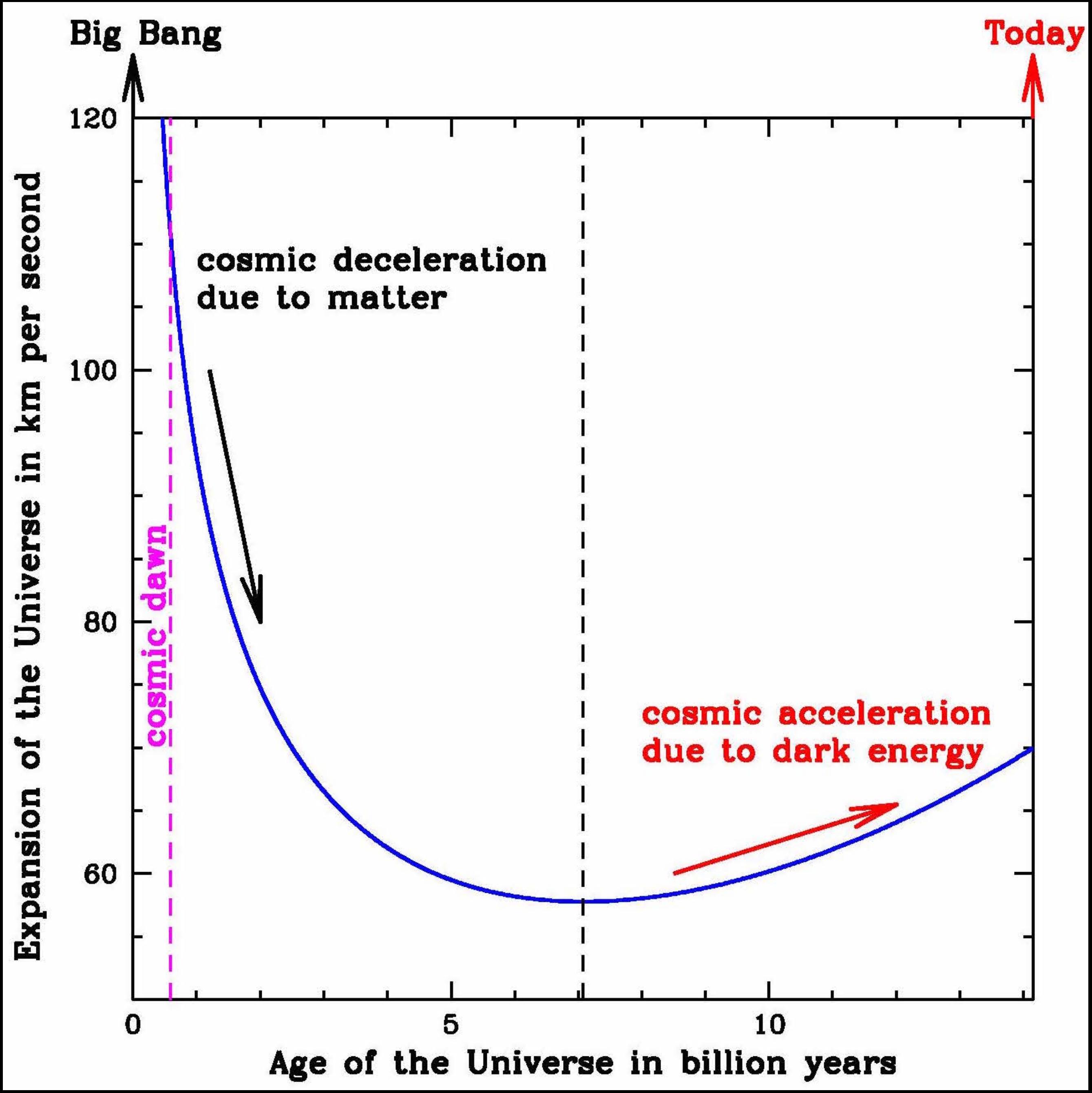
2015: The Spacetime Odyssey
Stockholm, June 2015



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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*)

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 $H(z)$

Measuring the Metric

In the conformal Newtonian gauge (the longitudinal gauge), the perturbed Robertson-Walker metric is given by

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

- 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

WL: probe $\phi+\psi$

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 $\boldsymbol{H(z)}$.

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

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

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

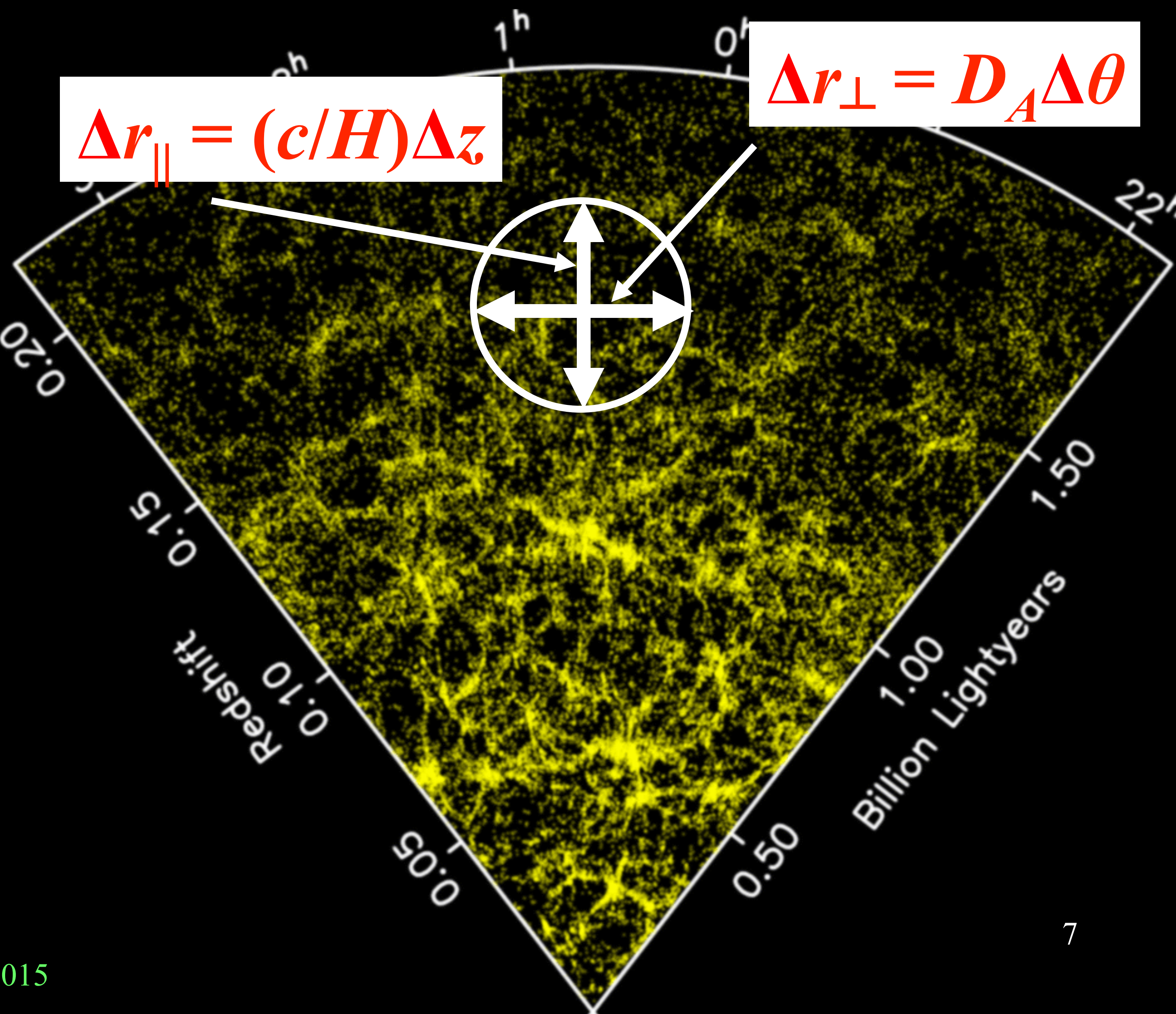
BAO as a Standard Ruler

Blake & Glazebrook 2003
Seo & Eisenstein 2003

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

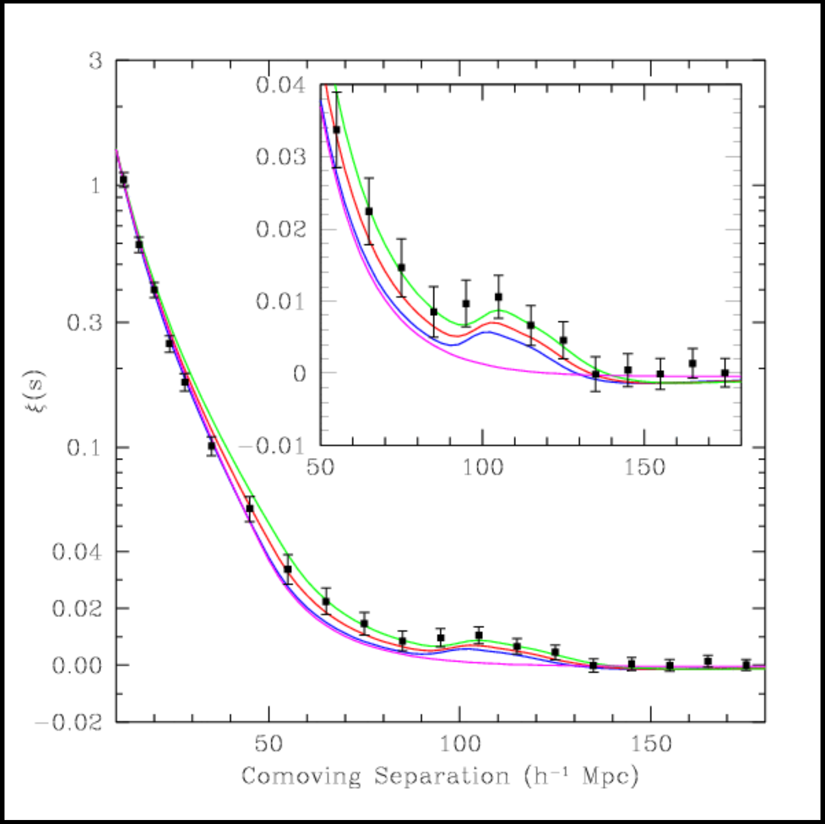
BAO "wavelength" in transverse direction in slices of z : $D_A(z)$

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



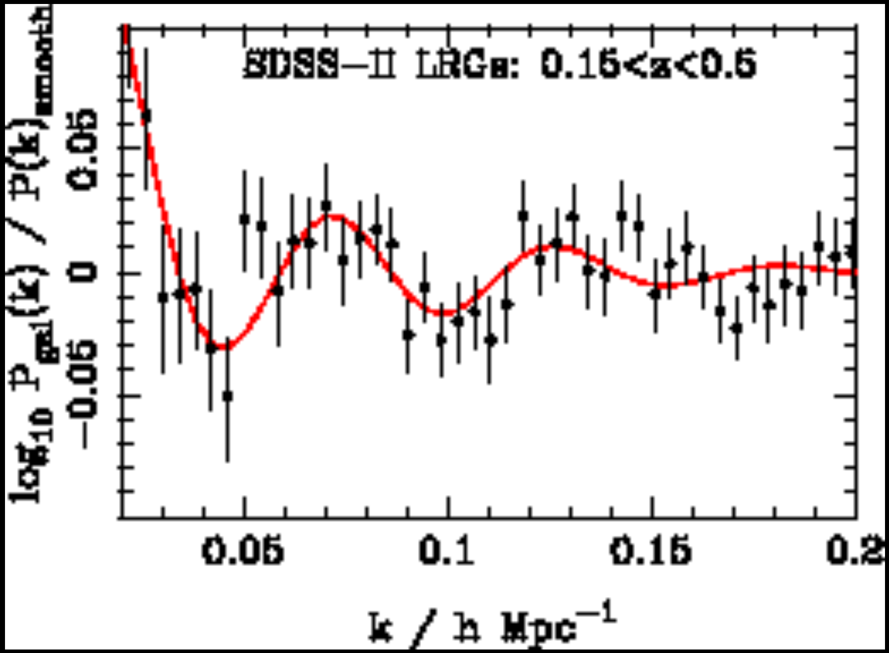
Use Baryon Acoustic Oscillations to Probe Dark Energy

Galaxy 2-pt correlation function

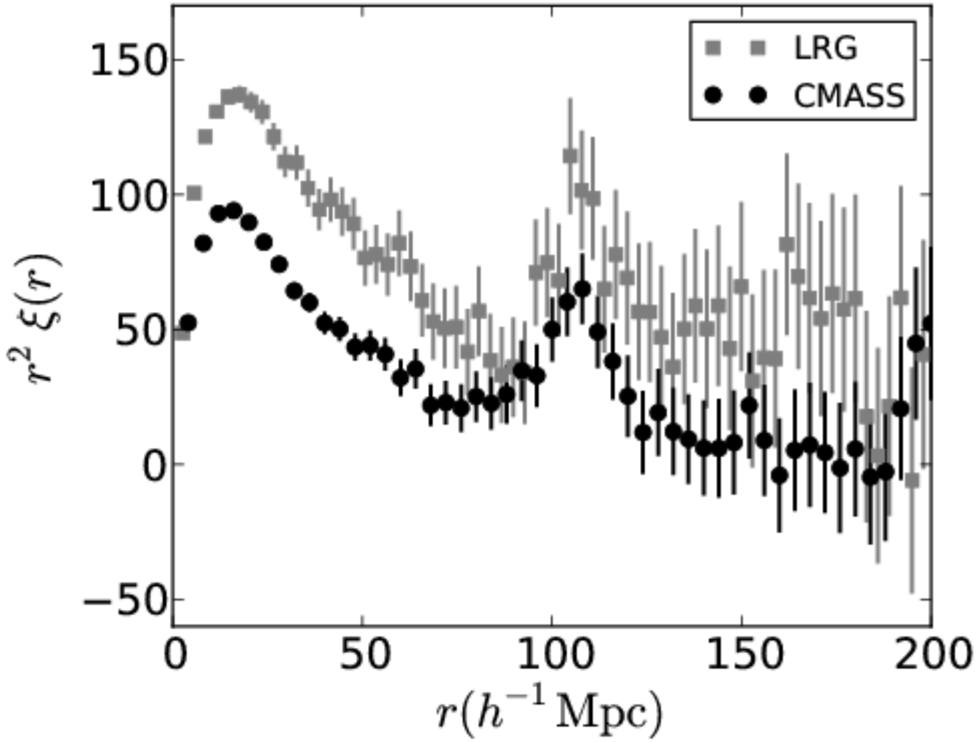


Eisenstein et al. (2005)

Galaxy power spectrum

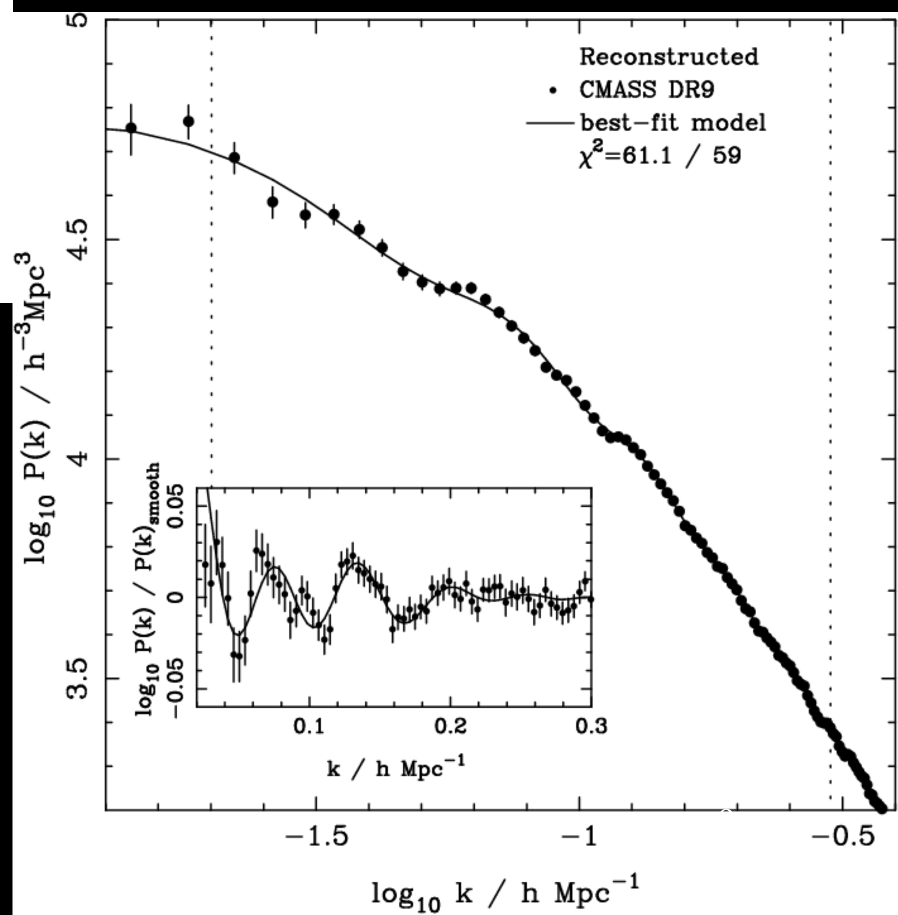


Percival et al. (2009)



Results from SDSS III (BOSS)

Anderson et al. (2012)



SDSS DR7 (LRG) vs DR9 (CMASS) spherically-averaged galaxy correlation function

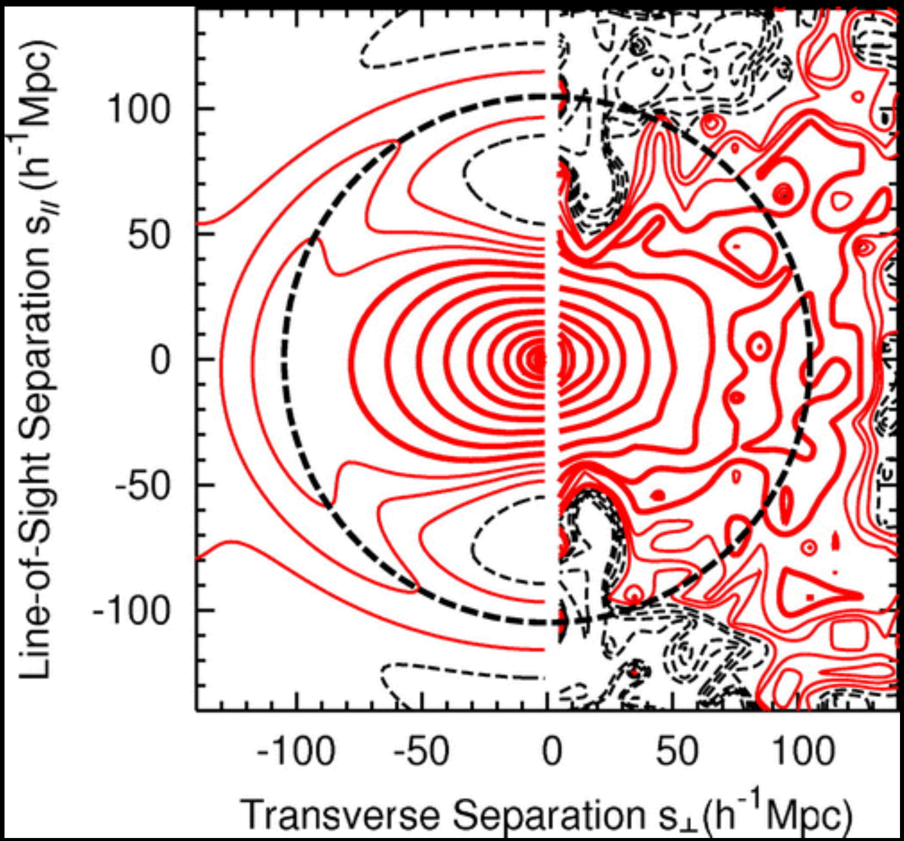
SDSS DR9 galaxy power spectrum

GC/BAO Avantages & Challenges

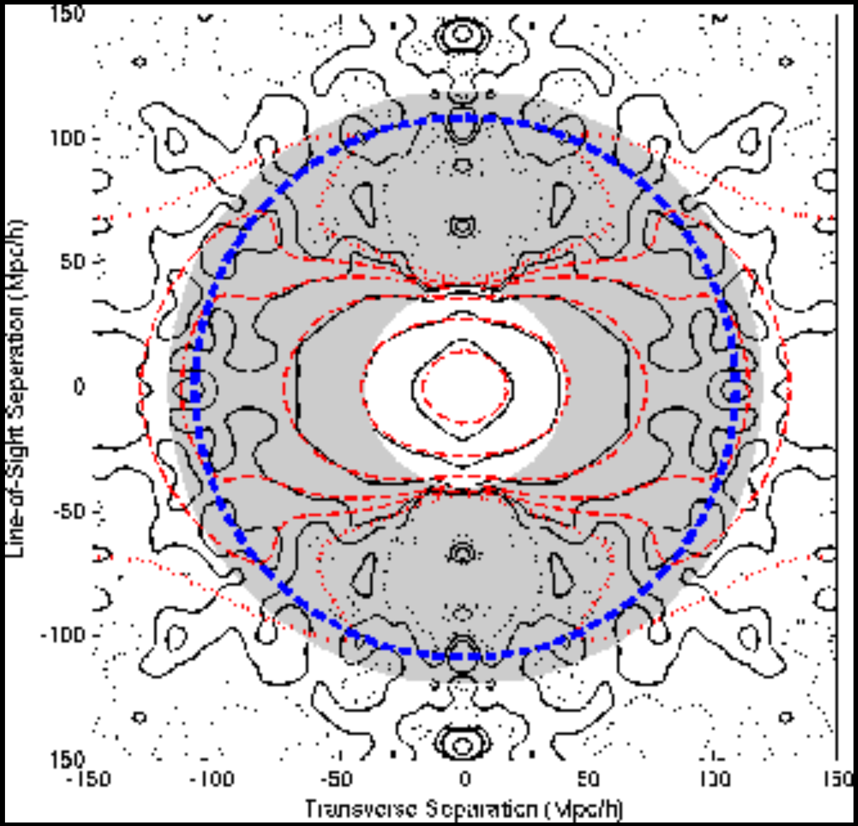
- Advantages:
  - Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).
  - Intrinsic systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling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

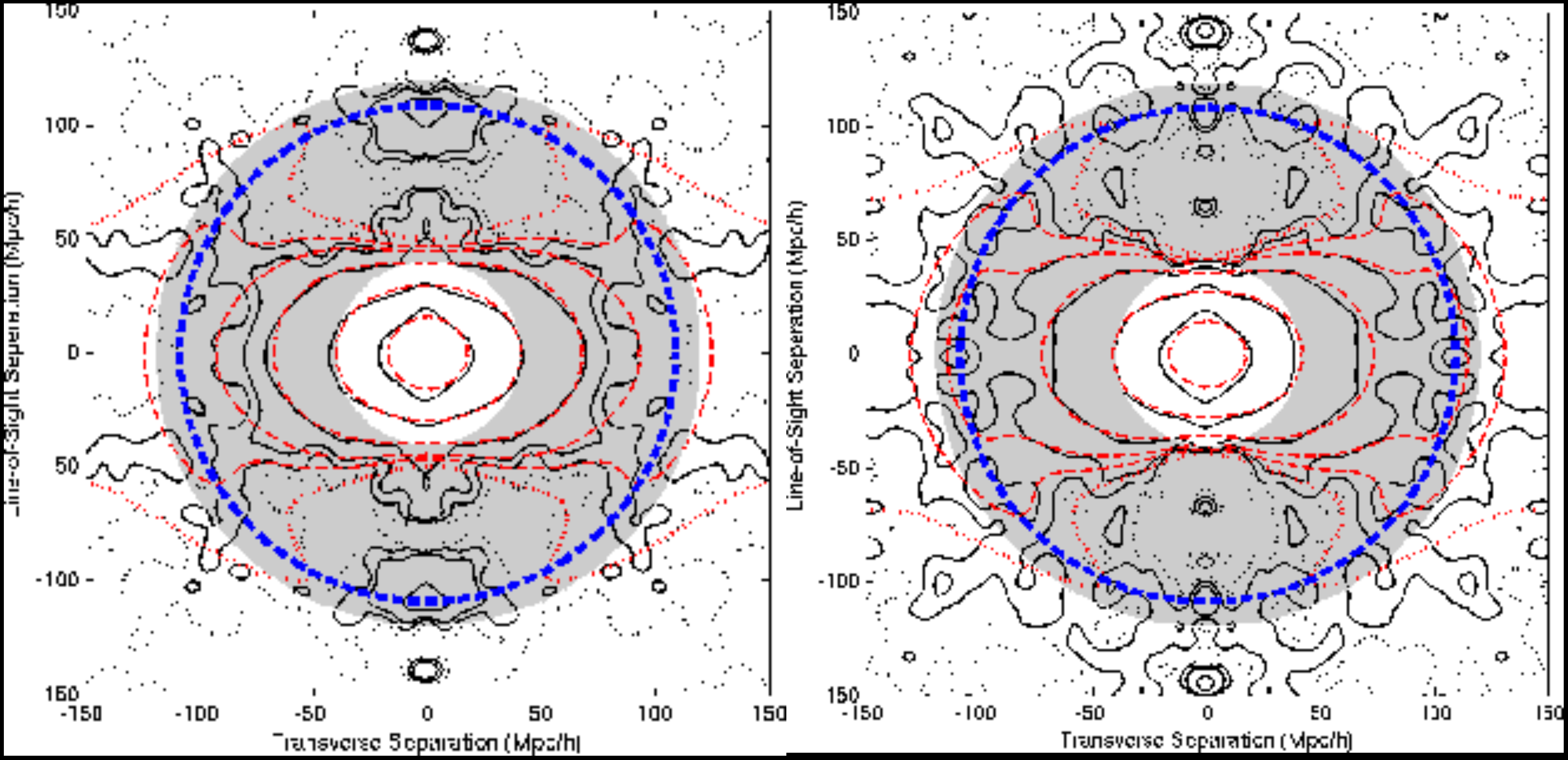


Chuang & Wang, arXiv:1102.2251, MNRAS, 426, 226 (2012)



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

LasDamas mock catalog *SDSS LRG catalog*

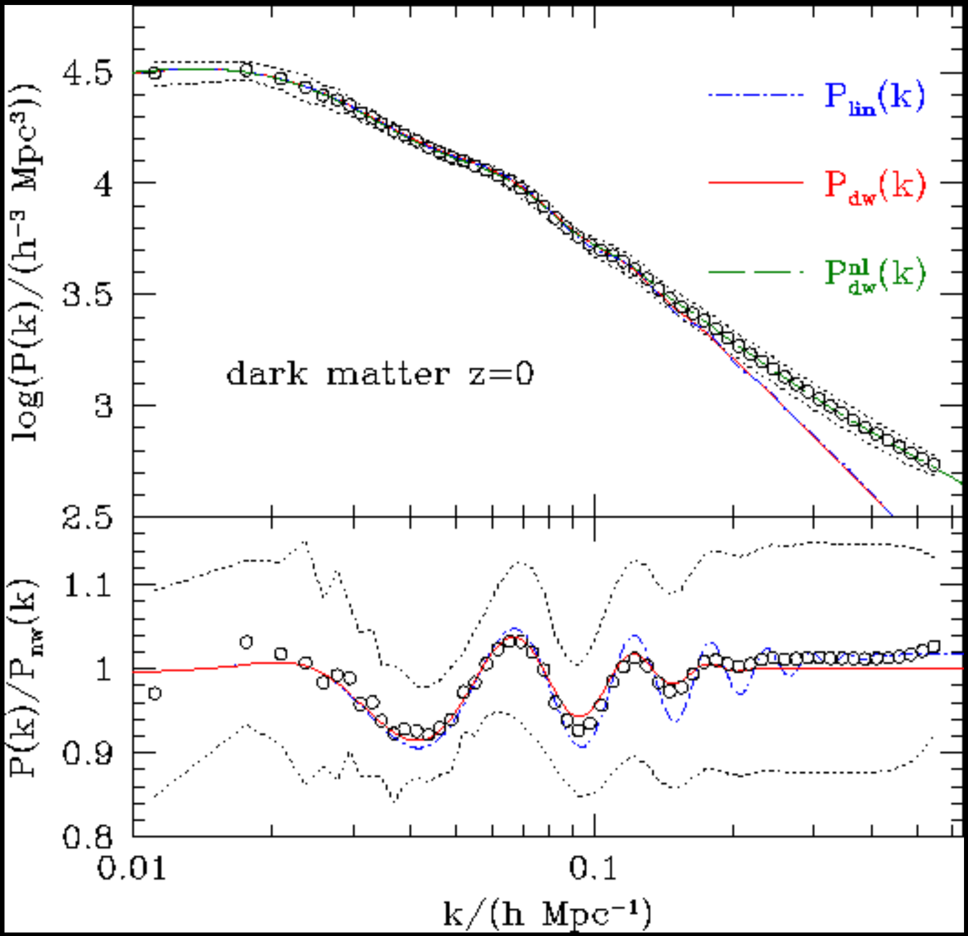


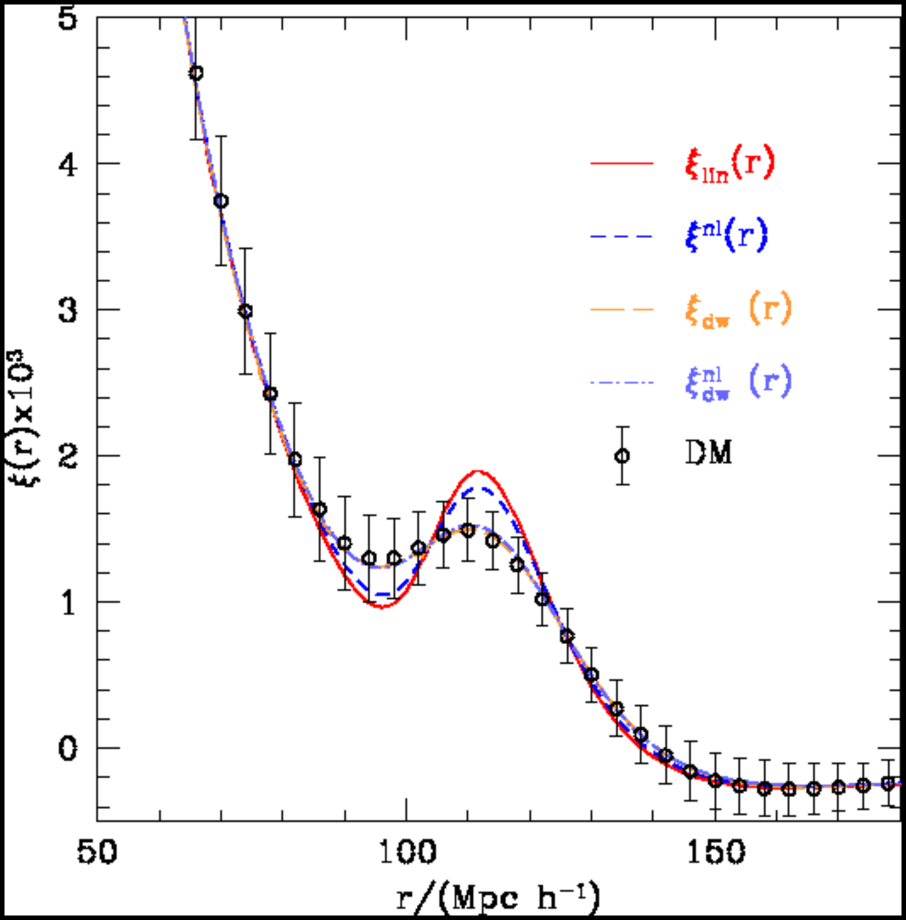
$x_h(z) = H(z)s = 0.04339 \pm 0.00178$ (4.1%); $x_d(z) = D_A(z)/s = 6.599 \pm 0.263$ (4.0%)

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

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

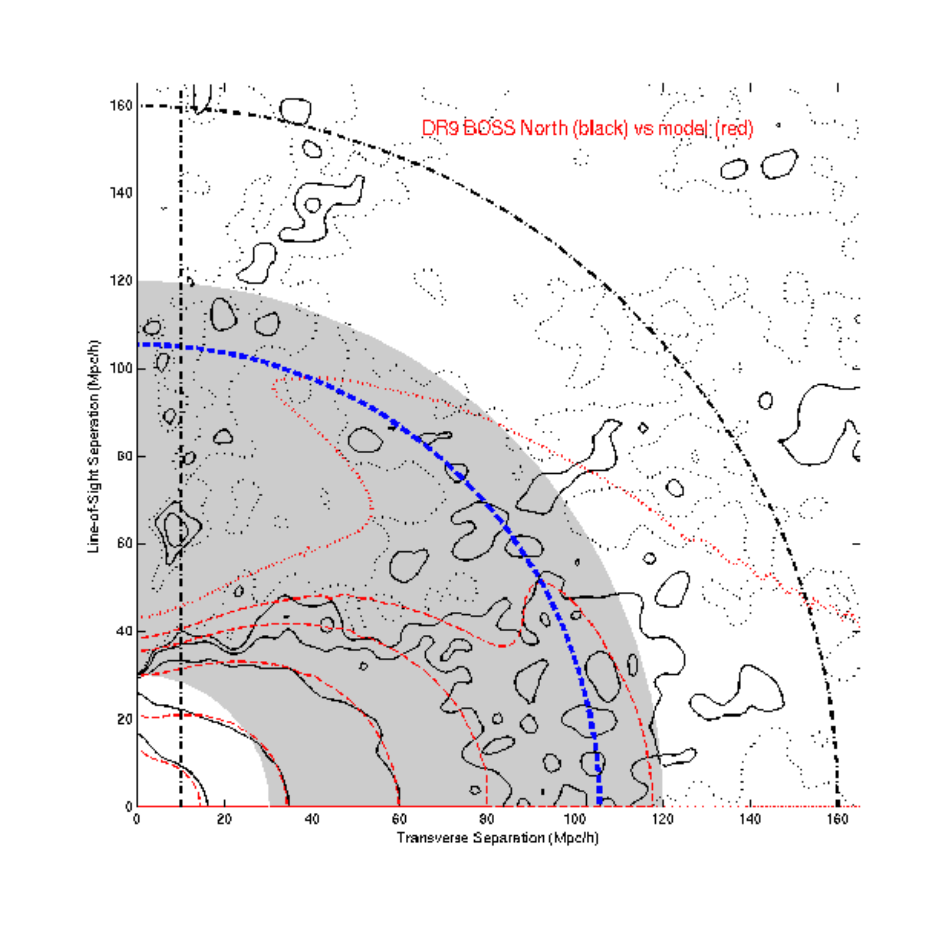
P(k) dewiggled model: validation by N-body simulations

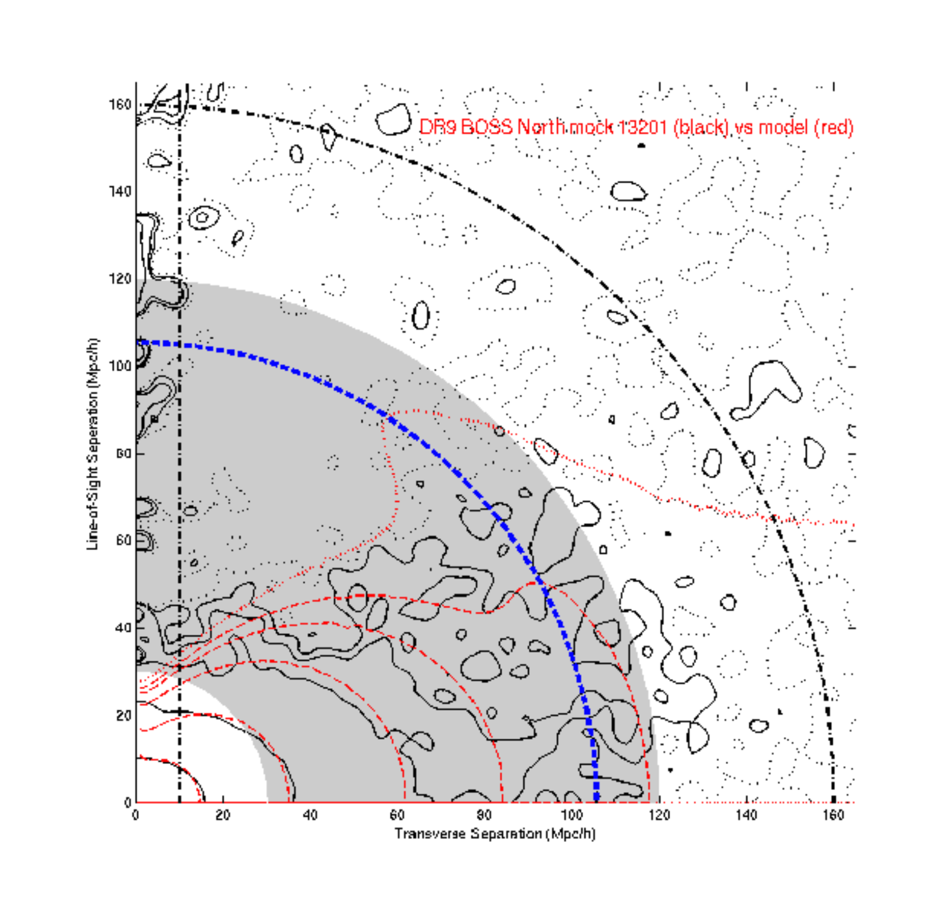




Sanchez, Baugh, & Angulo (2008)

DR9 North Data Vs. Mock

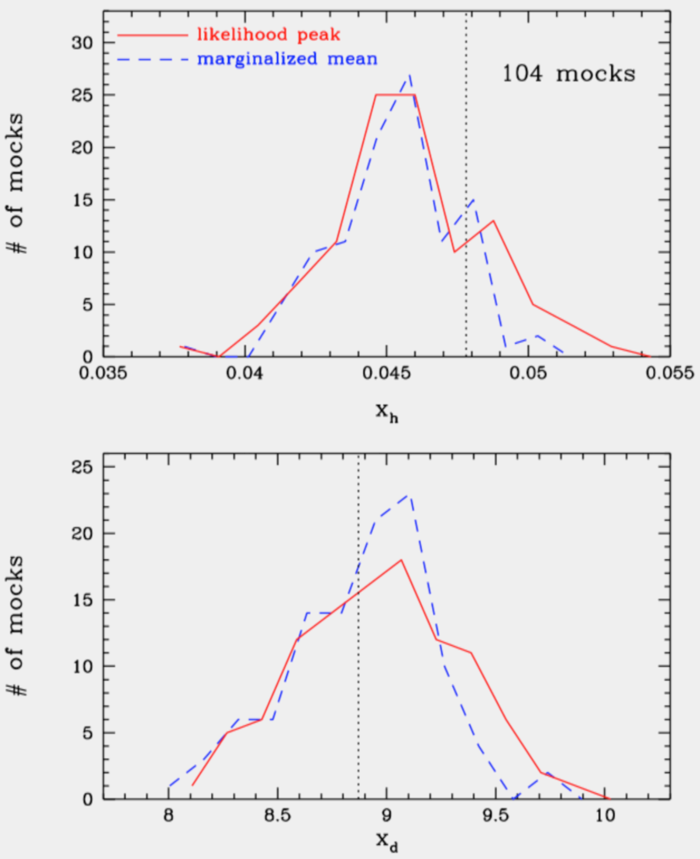




Scaling method applied to measuring H(z), $D_A(z)$, $f_g(z)$ using $\xi(\sigma,\pi)$.

Wang (2014)

Validation of Method

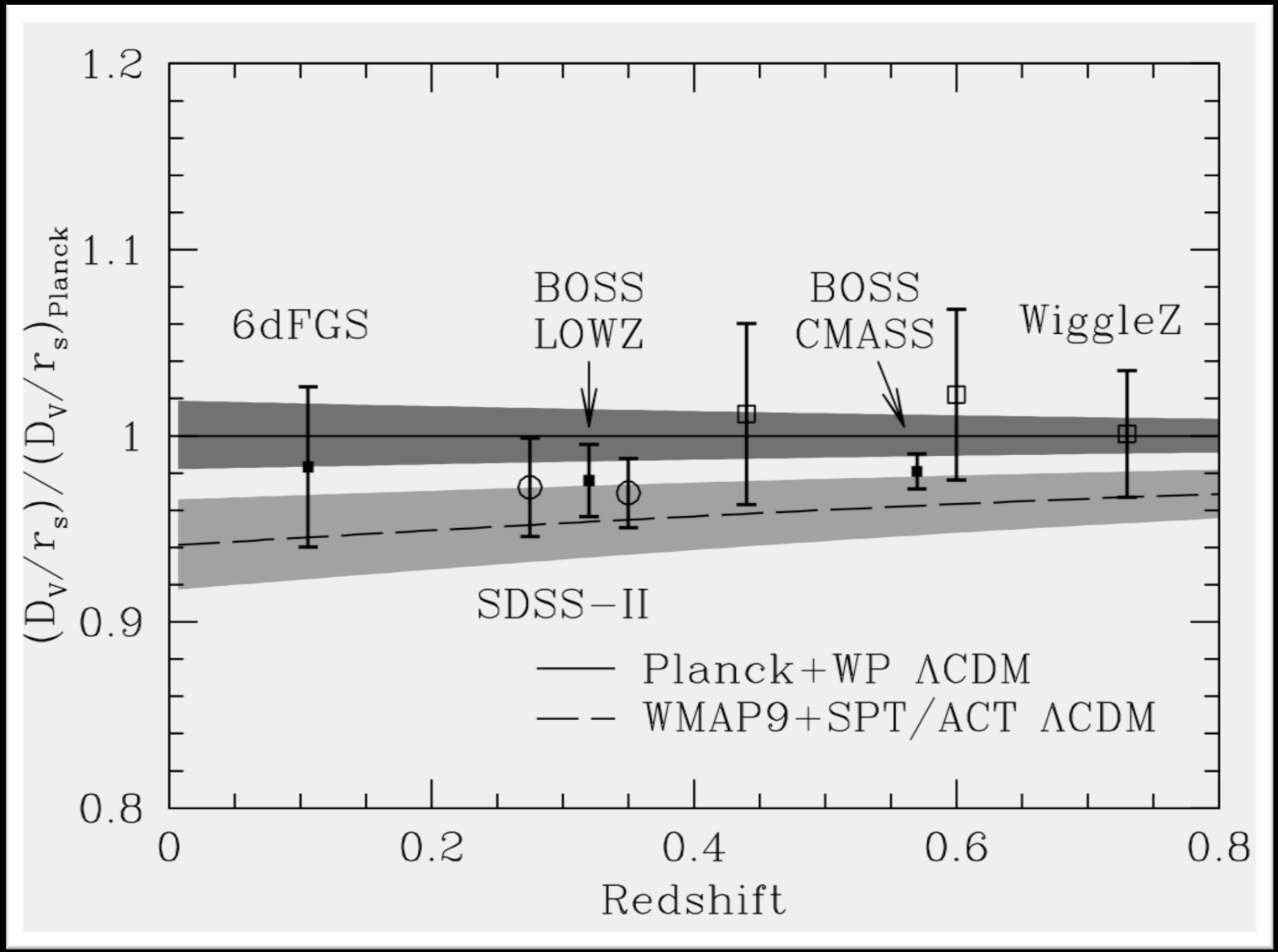


Wang (2014)

BOSS DR9 Results
(converted to the same parameters at z=0.57)

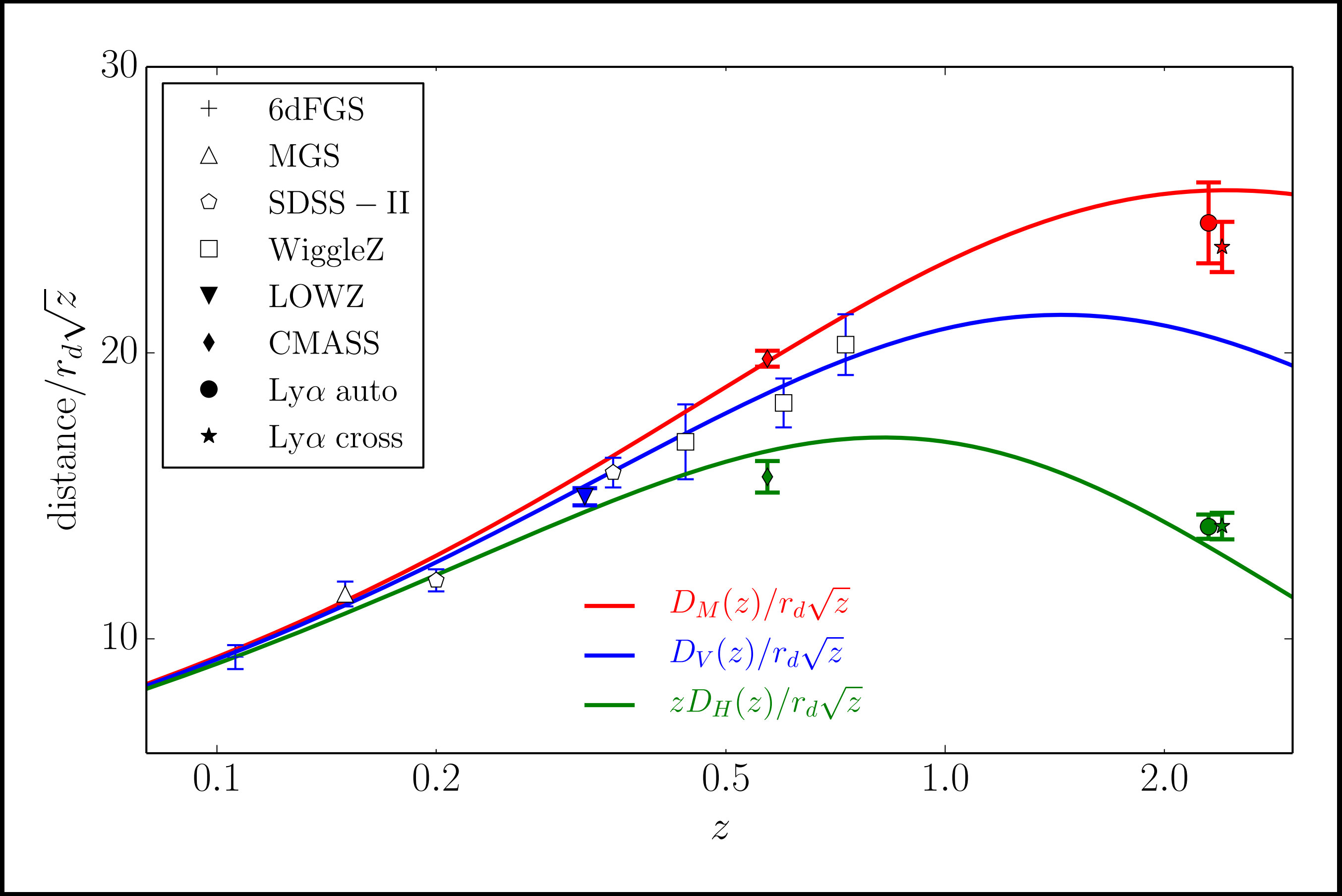
Authors	Method	$H(z)r_s(z_d)/c$	$D_A(z)/r_s(z_d)$	Growth at z=0.57
Chuang et al. (2013)	Scaling of $\xi(\sigma,\pi)$ multipoles	0.0454 ±0.0031	8.95 ±0.27	$f\sigma_8$=0.428 ±0.069
Kazin et al. (2013)	Clustering wedges+ BAO reconstruction	0.0464 ±0.0031	9.05 ±0.27	marginalized
Sanchez et al. (2013)	Clustering wedges	0.0466 ±0.0021	9.04 ±0.25	marginalized
Anderson et al. (2013)	Averaging multipoles & clustering wedges+ BAO reconstruction	0.0474 ±0.0040	9.19 ±0.29	Marginalzied
Wang (2014)	Scaling of $\xi(\sigma,\pi)$	0.0444 ±0.0019	9.01 ±0.23	$f_g\sigma_8$=0.474 ±0.075

BOSS DR11 vs. CMB



Anderson et al. (2014)

BOSS DR 11 (Nov 2014)



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

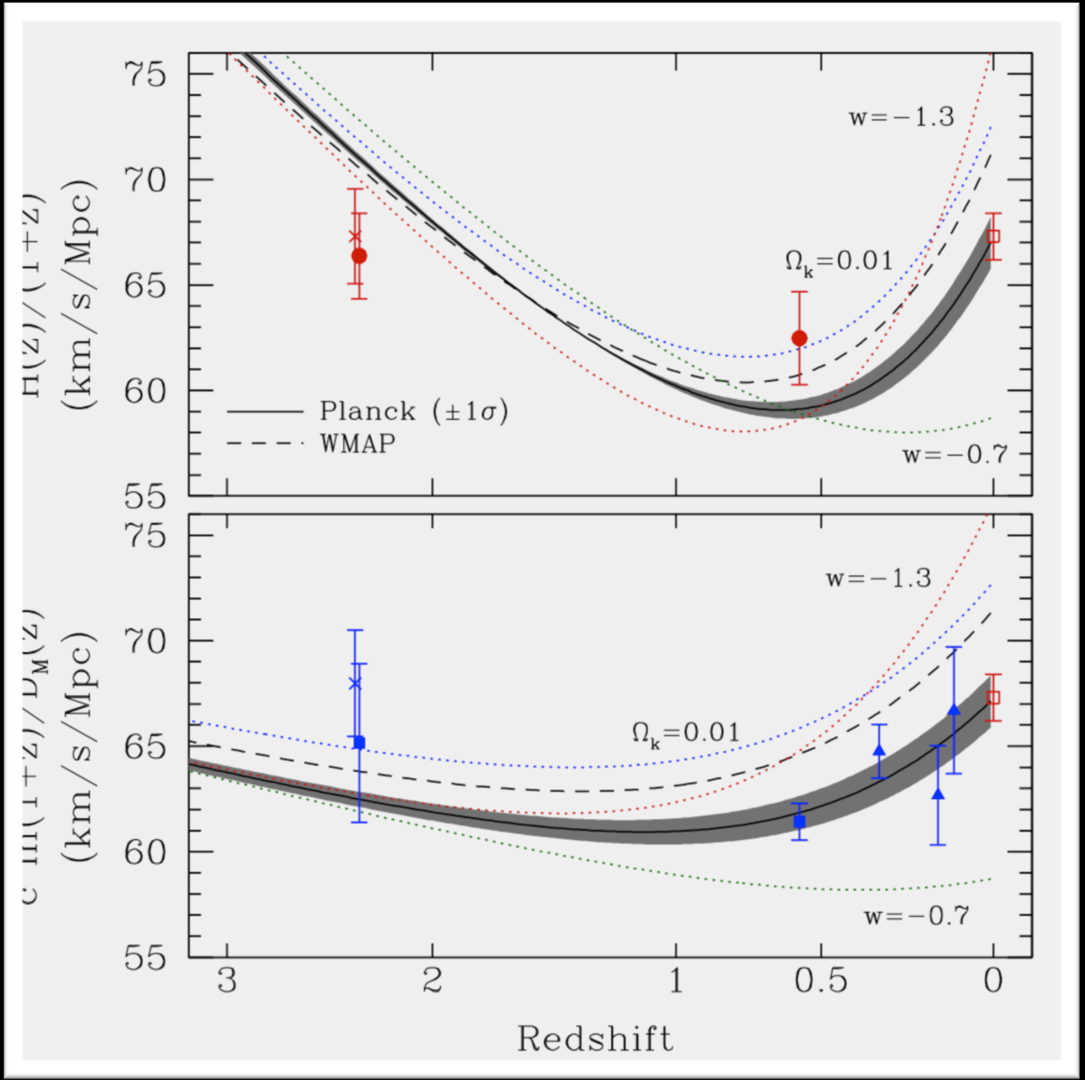
Aubourg et al. (2014)

BOSS DR 11

Aubourg et al. (2014)

Top: H(z)/(1+z)

Bottom: c ln(1+z)/r(z)



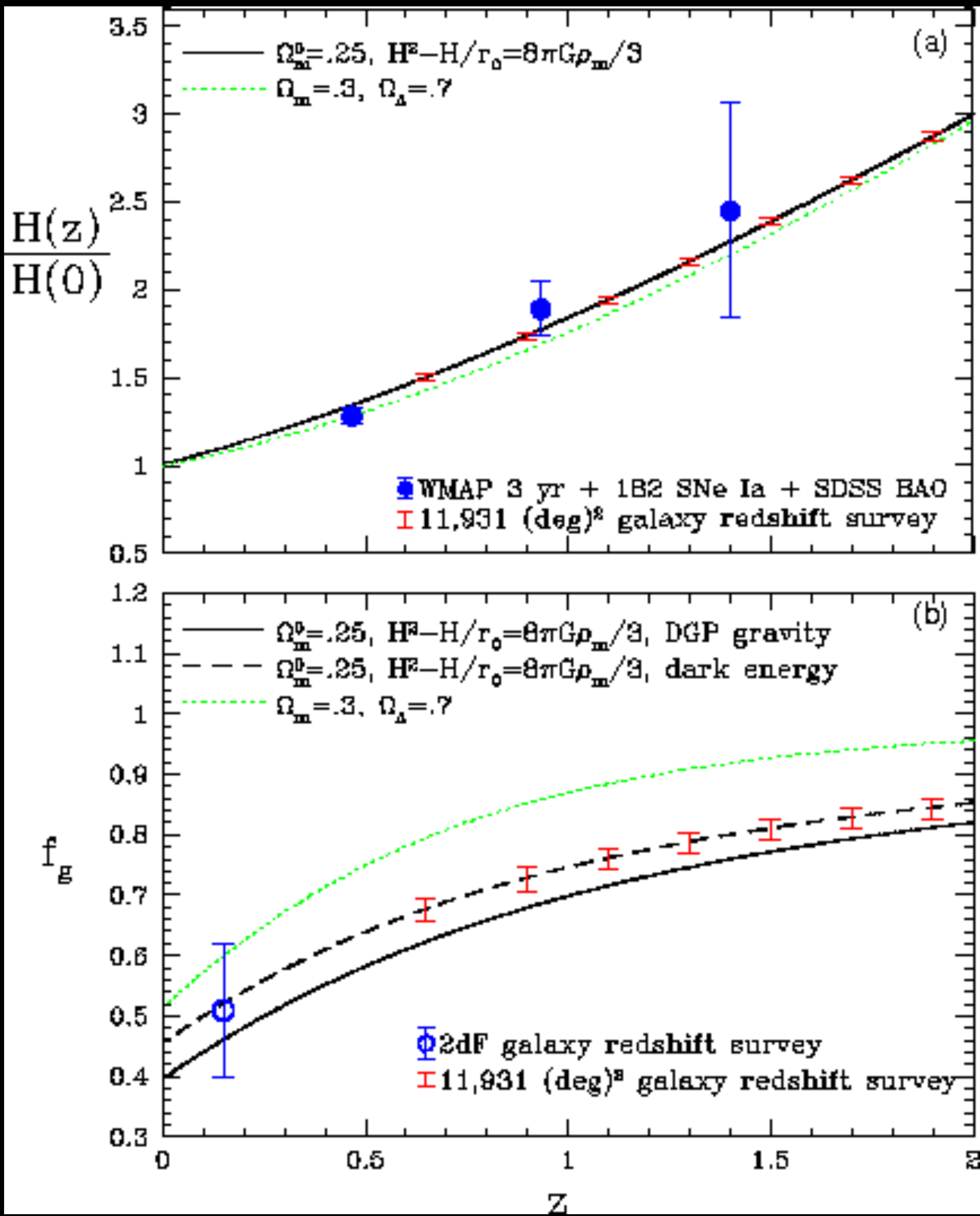
$[\Omega_m, H_0]$=[0.3183, 0.6704] (Planck 2013 -- used above); [0.308, 0.678] (Planck 2015)

Filled circles & squares/crosses: H(z) and r(z) from BOSS CMASS & LyαF auto-correlation, LyαF-quasar cross-correlation
Filled triangles (bottom panel): BOSS LOWZ and Main Galaxy Survey measurements of D_V (z) converted to r(z)

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

If dark energy & modified gravity models predict the same cosmic expansion history *H*(*z*), they would predict different cosmic large scale structure growth history $f_g(z)$.

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



Future Galaxy Redshift Surveys

(an incomplete list)

- **BOSS (2011-2014):** 10,000 sq deg GRS, $0.1<z<0.7$
- **Dark Energy Survey (2013-?):** photo-z, 5000 sq deg
- **HETDEX(2014-?):** 420 sq deg GRS, $1.9 < z < 3.5$
- **eBOSS (2015?-2021?):** GRS over 7,500 sq deg for LRGs ($0.5<z<1$), and over 15,000 sq deg for ELGs ($0.6<z<1$)
- **PFS (2018?-):** GRS of ELGs over 1400 sq deg ($0.6<z<2.4$)
- **DESI/BigBOSS (2018?-2022):** GRS over 14,000 sq deg for LRGs ($0.1<z<1.1$) and ELGs ($0.1<z<1.8$?)
- **LSST (2019?):** photo-z, 20,000 sq deg
- **Euclid (2020-):** GRS over 15,000 sq deg of ELGs ($0.7<z<2$)
- **WFIRST (2023?-):** GRS over ~2000 (?) sq deg of ELGs

Euclid

A geometrical probe of the universe selected for Cosmic Vision

= +

All-sky optical imaging for gravitational lensing

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

Euclid: a Space Mission to Map the Dark Universe

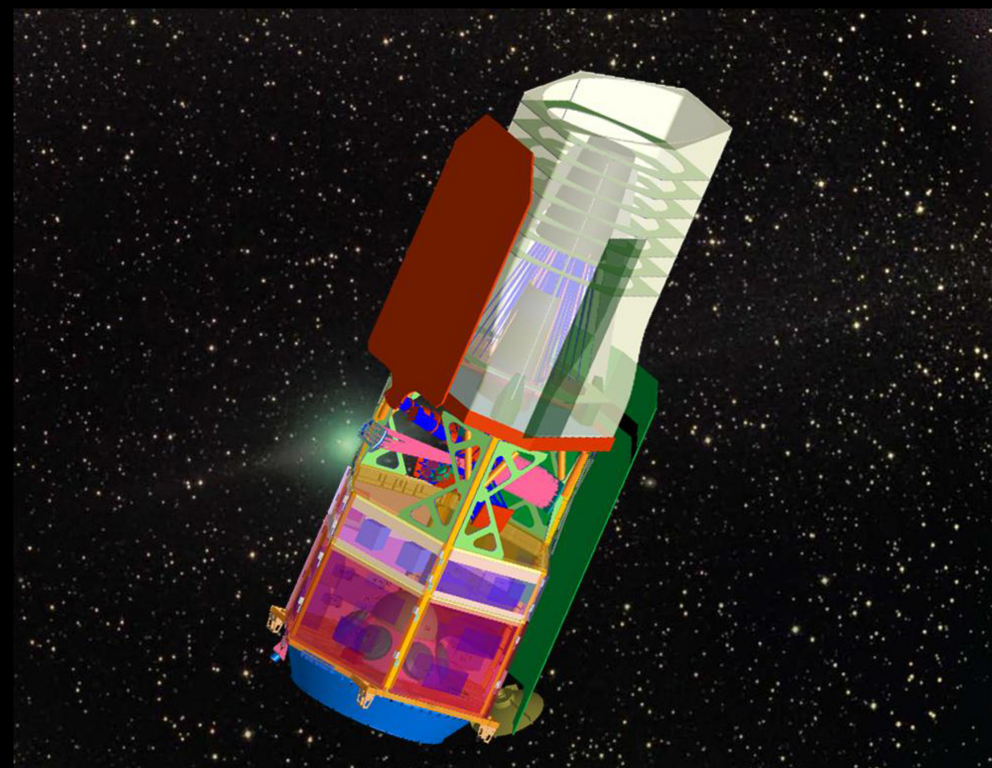
- ESA medium class mission to be launched in 2020
- Goal: Understand the origin of cosmic acceleration
- Telescope: 1.2m
- Imagers: Vis and NIR
- Spectrograph: slitless, NIR
- Launch vehicle: Soyuz ST-2.1B rocket
- Orbit: the L2 Lagrange point
- Mission duration: 6 years

Euclid GC measurement of cosmic expansion & growth history

Euclid 15,000 deg^2 spectroscopic survey of Hα emission line galaxies for ~0.7 < z < ~2 will measure $H(z)$ and $D_A(z)$ to ~1-2% accuracy in 0.1 redshift bins, and $f_g(z)$ to a few percent accuracy in the same redshift bins.

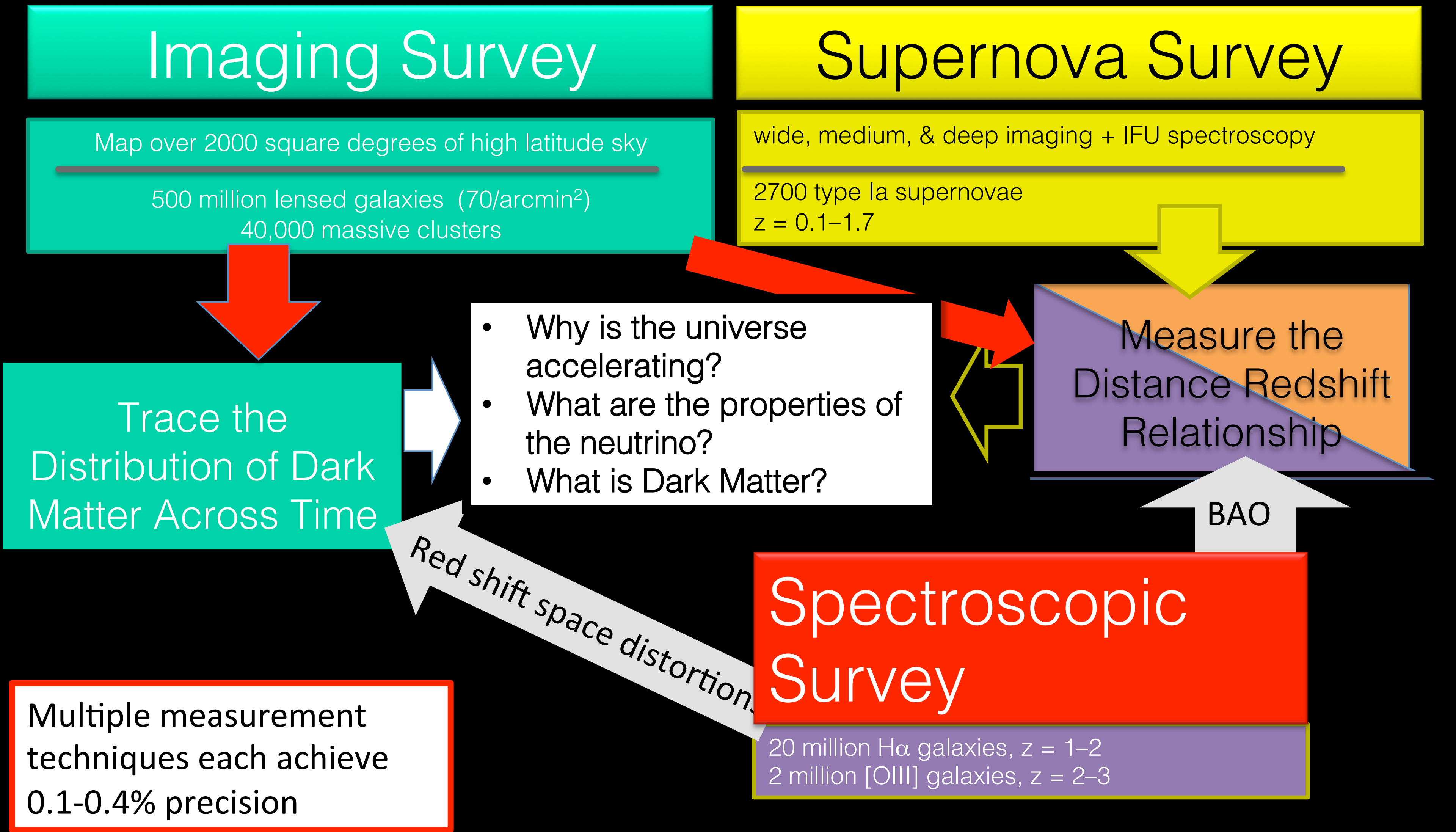
WFIRST
Wide-Field Infrared Survey Telescope

- JDEM + MPF + NISS…
- 2.4m from NRO
- Three pillars:
  - ⊙ Dark energy
    - Weak Lensing
    - Galaxy Clustering
    - Supernovae
  - ⊙ Exoplanet search
    - microlensing
    - coronograph
  - ⊙ Guest Observer Program
- Launch date: 2023?



Frontiers of Knowledge

As envisioned in NWNH, AFTA 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

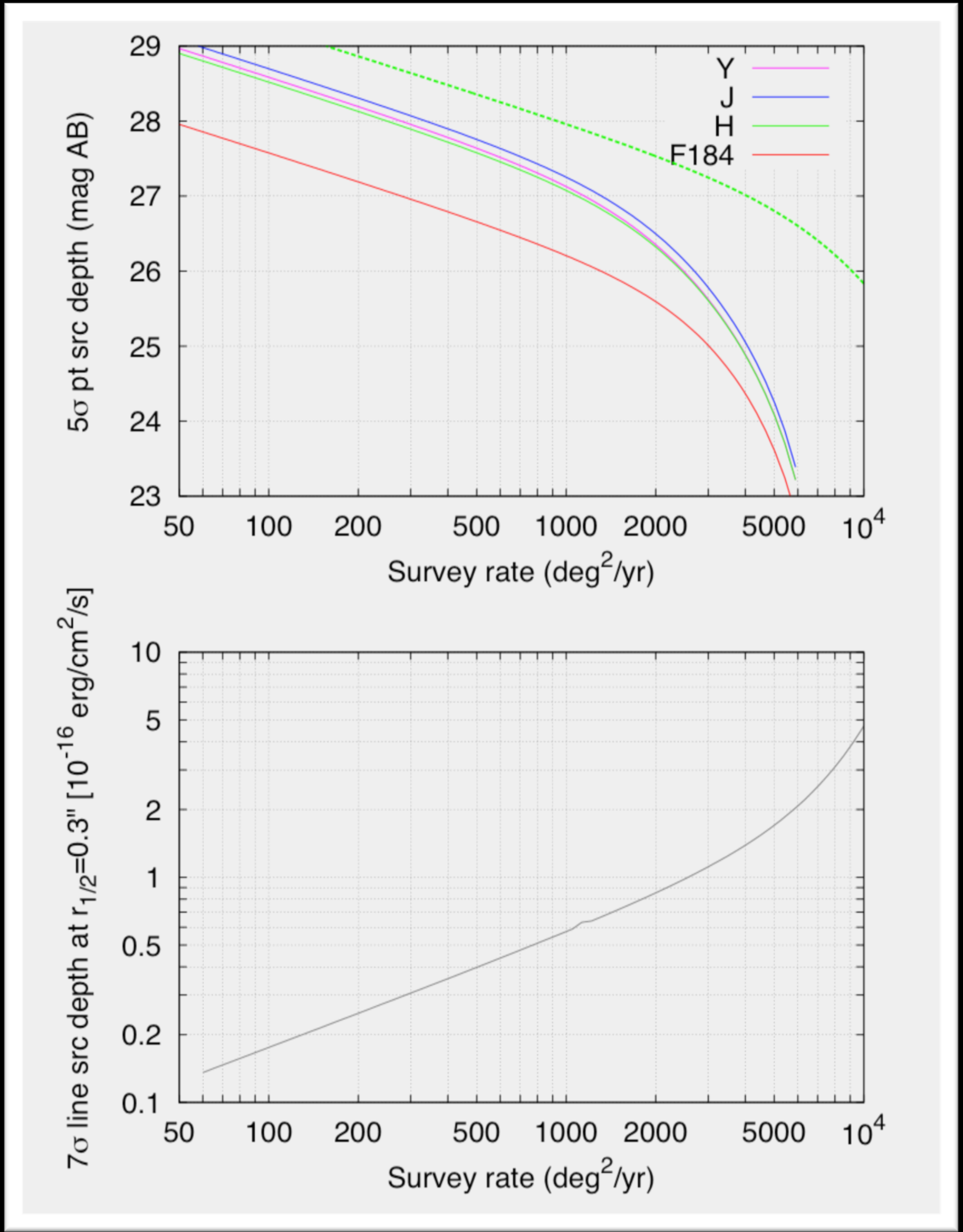


Flexibility and Power of WFIRST-AFTA

Weak lensing imaging survey

Spectroscopic galaxy redshift survey

(Figures from Chris Hirata)



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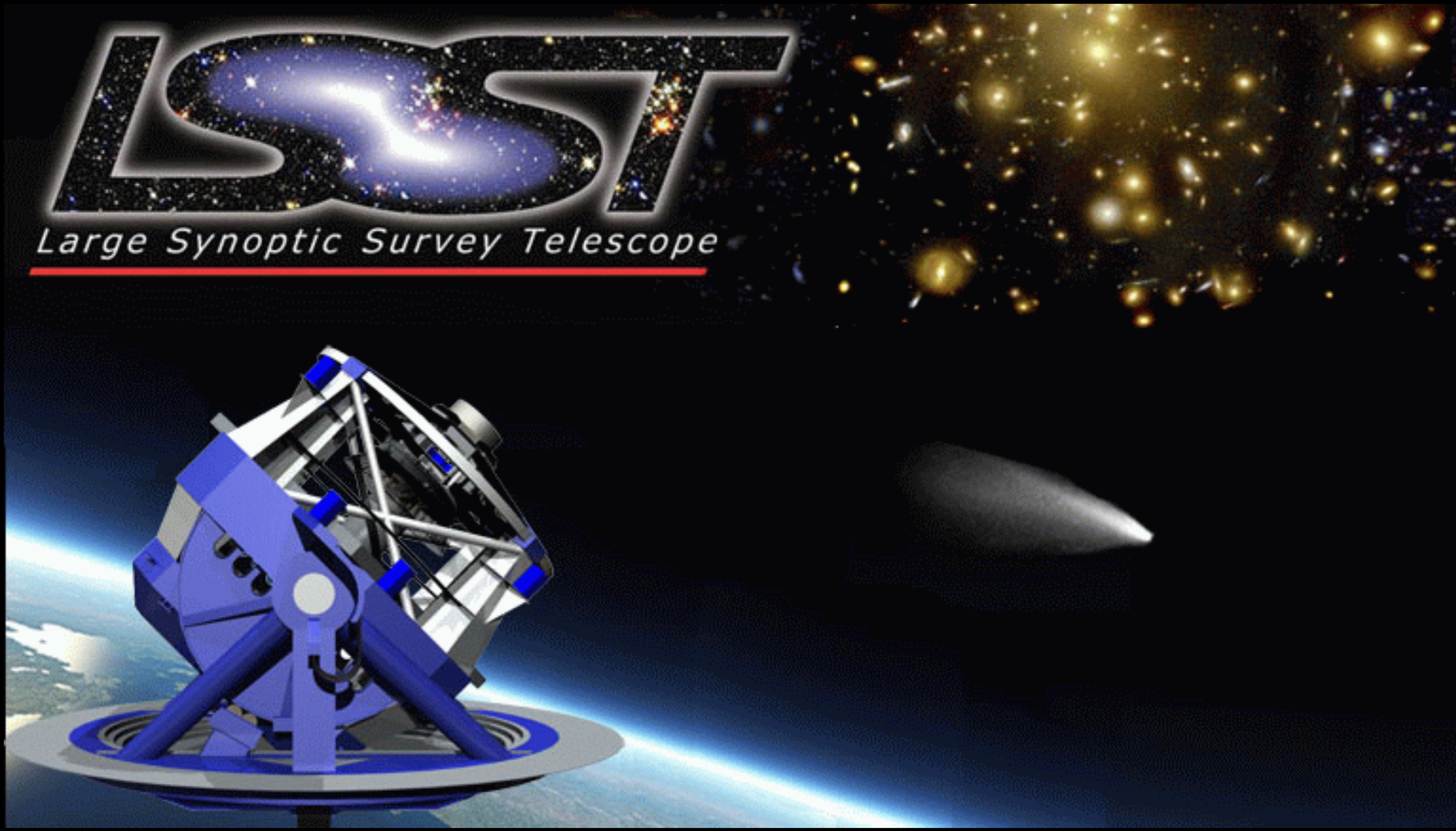

- 8.4m (6.5m clear aperture) telescope; FOV: 3.5 deg diameter; 0.3-1μm
- 10^6 SNe Ia y^{-1}, $z < 0.8$, 6 bands, $\Delta t = 4\text{-}7$d
- 20,000 sq deg WL & BAO with photo-z

Bright Future for Unraveling the Mystery of Cosmic Acceleration

Euclid

LSST
Large Synoptic Survey Telescope

WFIRST
Wide-Field Infrared Survey Telescope

Yun Wang, June 2015