Galaxy Clustering as a Cosmological Probe

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Tracing Cosmic Evolution With Clusters of Galaxies

Sesto, Italy, July 3, 2013

Cosmology from GC:

- Dark Energy
- Neutrino Mass
- Primordial Non-Gaussianity
- Inflation
- Dark Matter

DARK ENERGY

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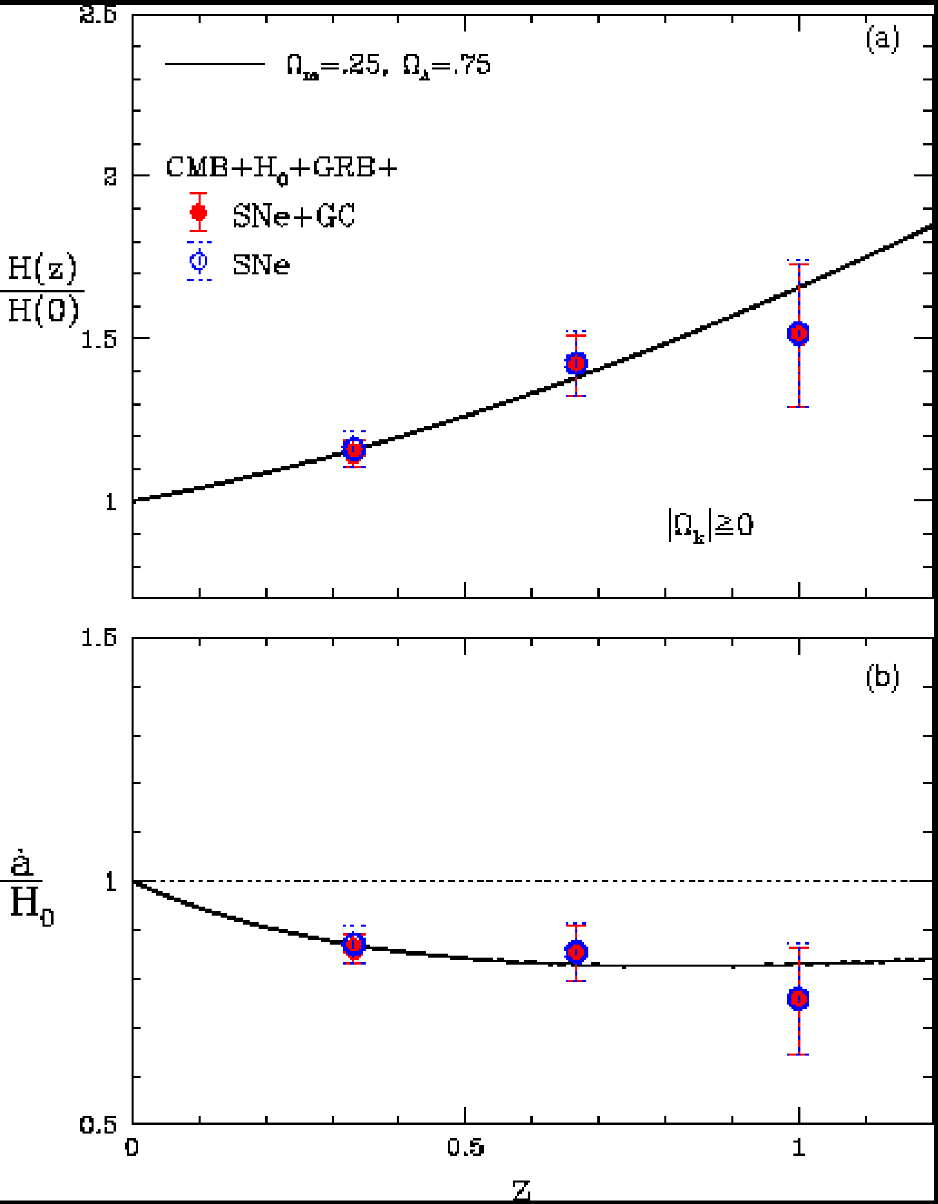


Wang, Chuang, & Mukherjee (2012)

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

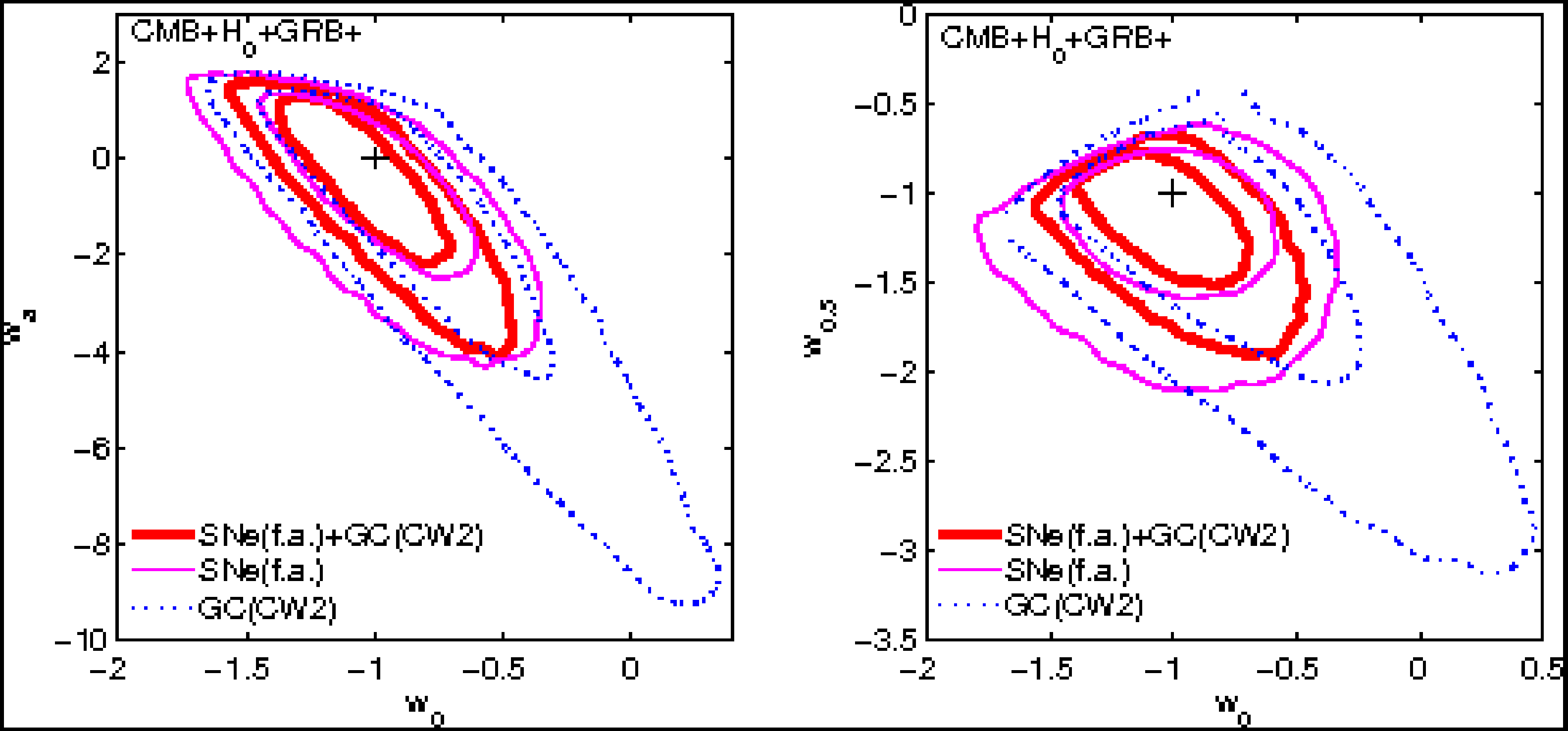
Hubble parameter:

$$H(z) = \frac{1}{a}\frac{da}{dt}$$

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

← Cosmic Acceleration:

$$\frac{d^2a}{dt^2} > 0$$



$w(z) = w_0+w_a(1-a)$; $w(z)=w_0(3a-2)+3w_{0.5}(1-a)$

$1+z = 1/a$; *z: cosmological redshift; a: cosmic scale factor*

CMB: WMAP7 (*Komatsu et al. 2011*)

H_0=73.8±2.4 km/s/Mpc (*Riess et al. 2011*)

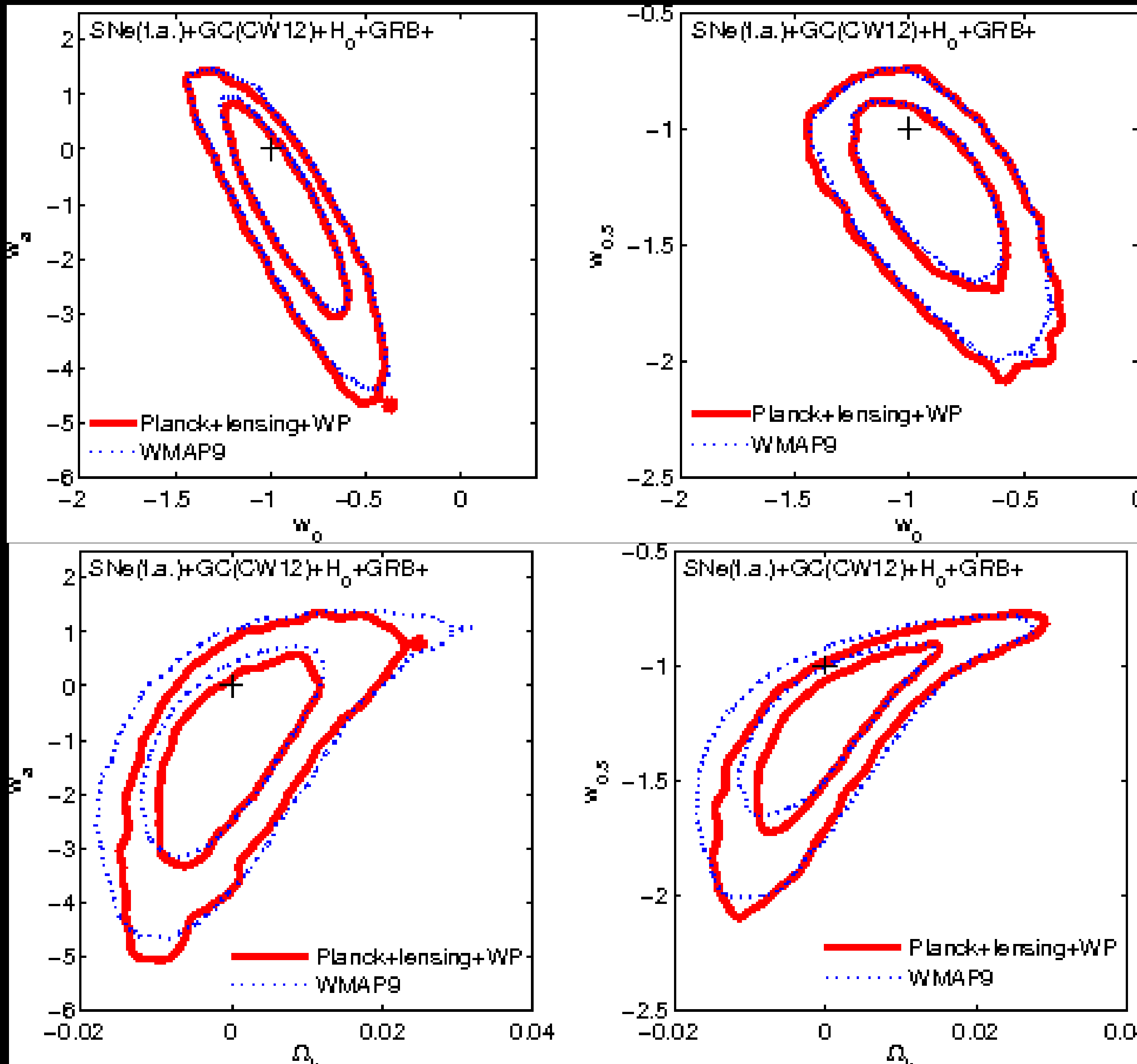
GRBs (*compiled by Wang 2008*)

SNe: 472 SNe Ia (compiled by *Conley et al. 2011*)

GC: [$H(z=0.35)$, $D_A(z=0.35)$] *from SDSS LRGs* (*Chuang & Wang 2011*)

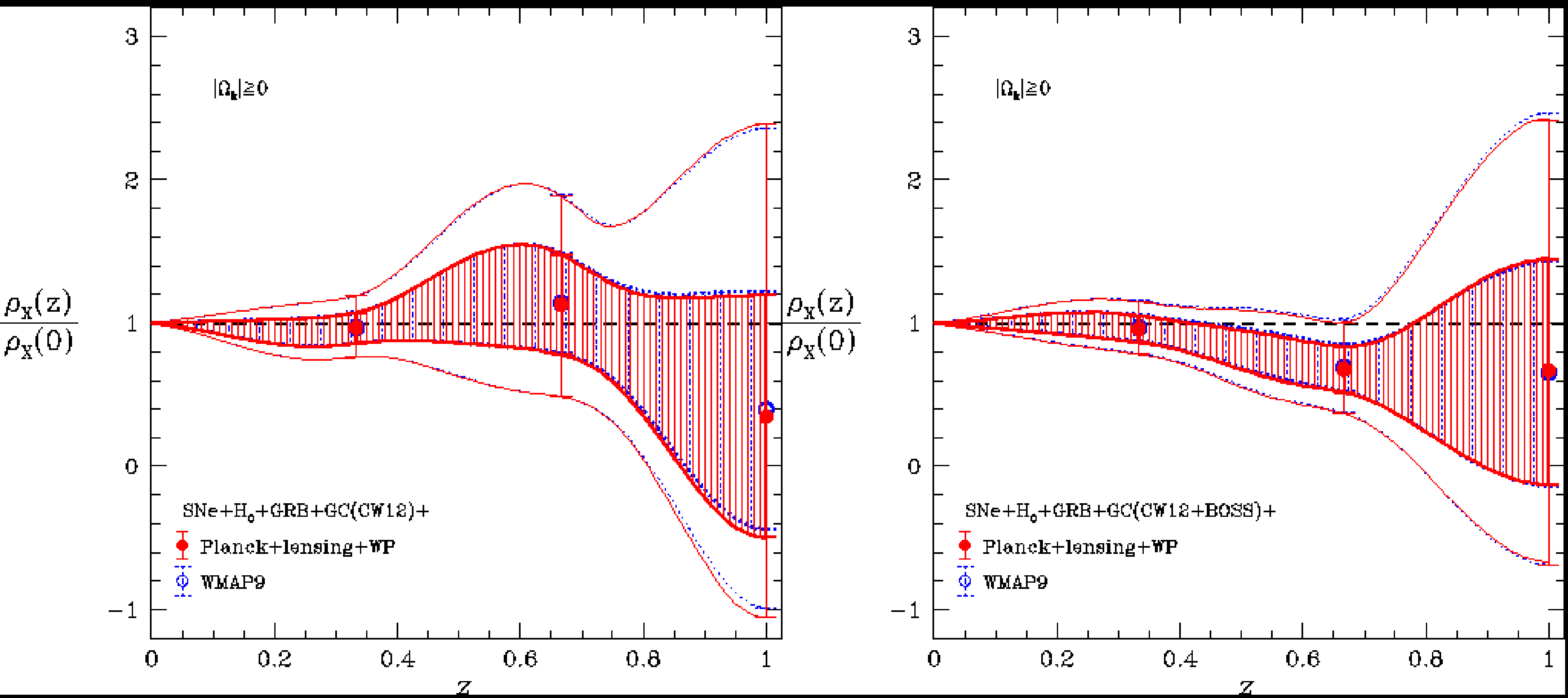
Wang, Chuang, & Mukherjee (2012)

Constraints on linear $w_X(z)$



Y. Wang, & S. Wang (2013)

Constraints on Dark Energy Density Function



Y. Wang, & S. Wang (2013)

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 ρ_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 $\boldsymbol{H(z)}$

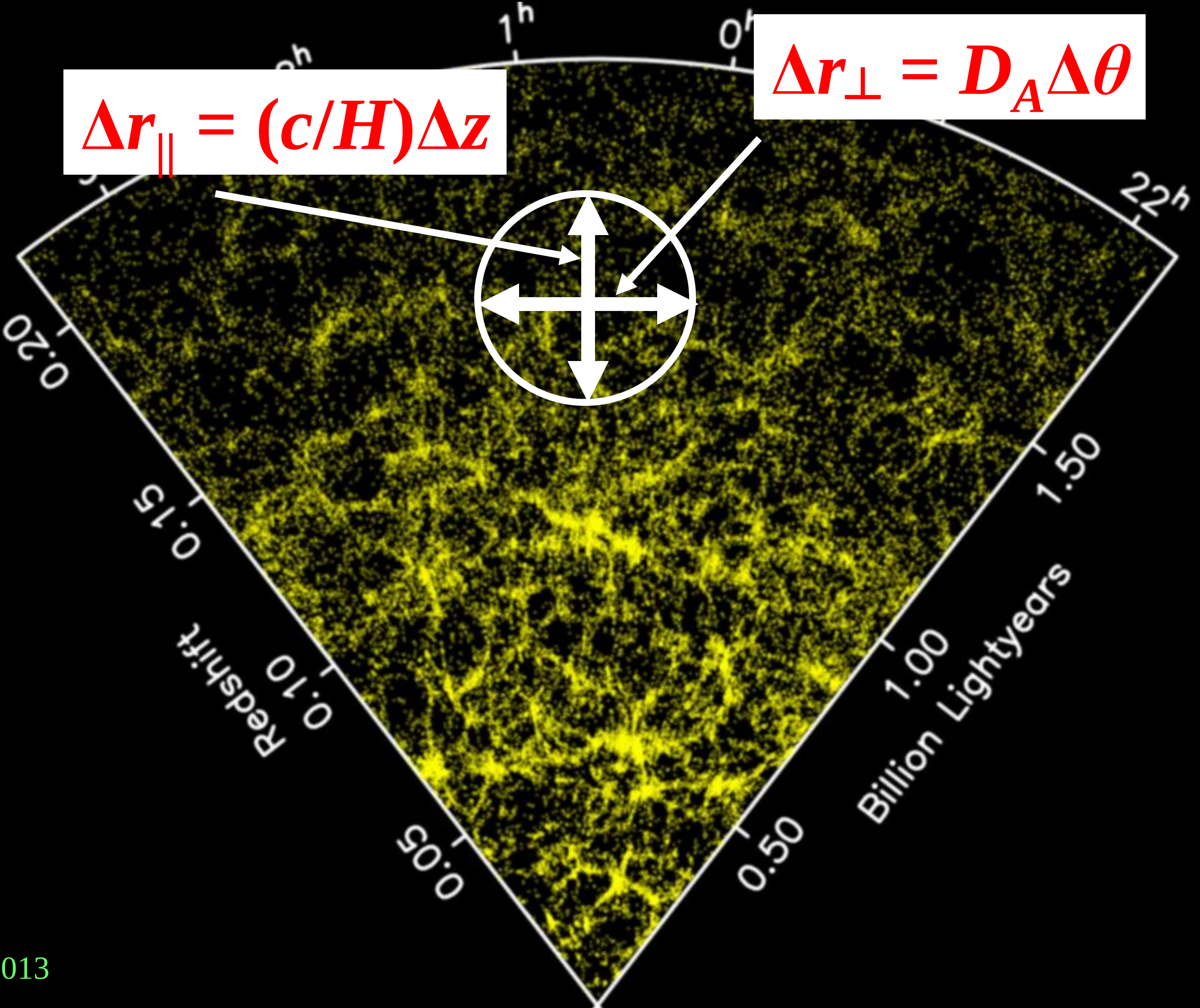
BAO as a Standard Ruler

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



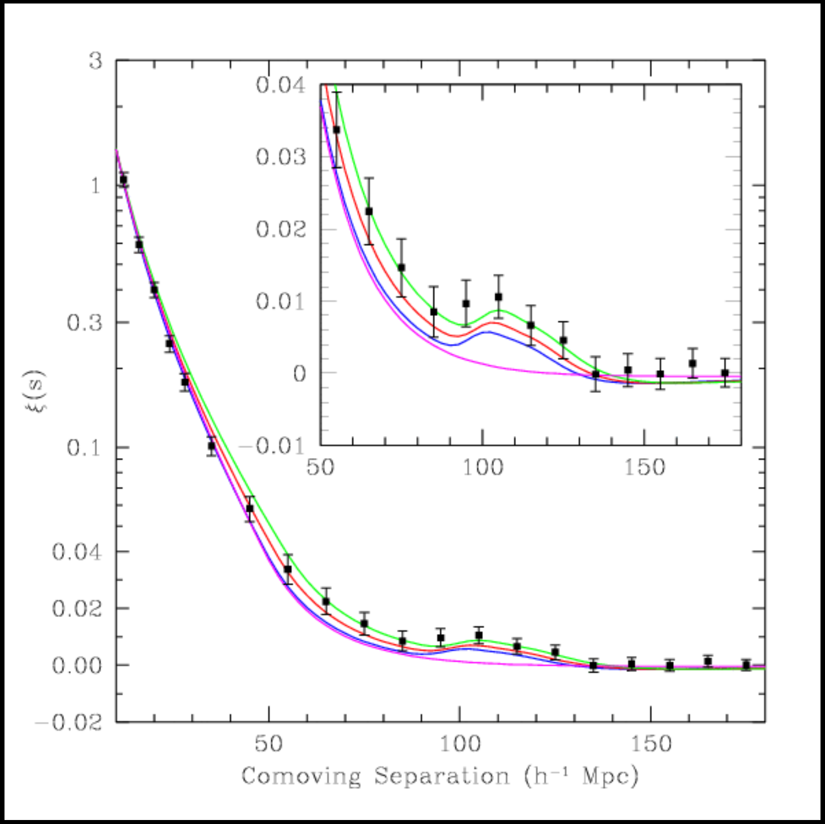
$$\Delta r_{||} = (c/H)\Delta z$$

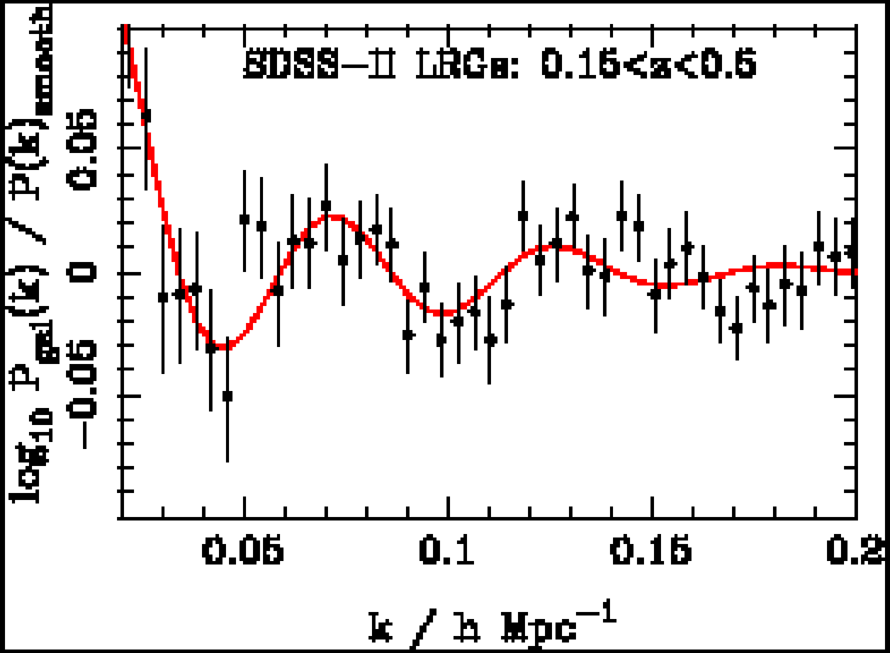
$$\Delta r_{\perp} = D_A \Delta\theta$$

Use Baryon Acoustic Oscillations to Probe Dark Energy

Galaxy 2-pt correlation function

Galaxy power spectrum





Eisenstein et al. (2005)

Percival et al. (2009)

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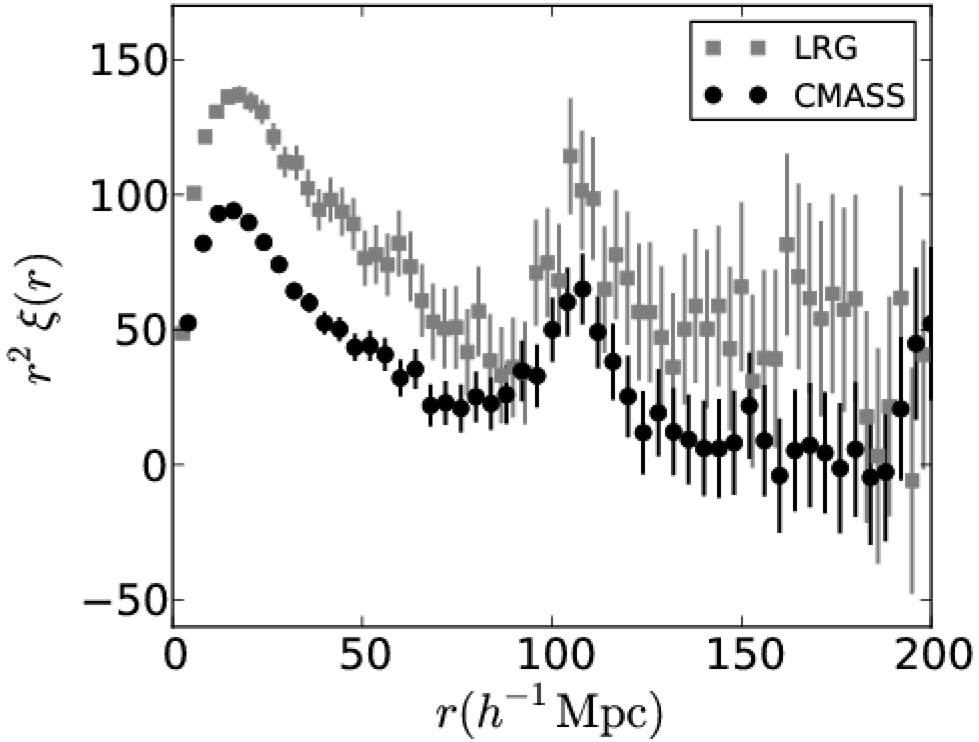
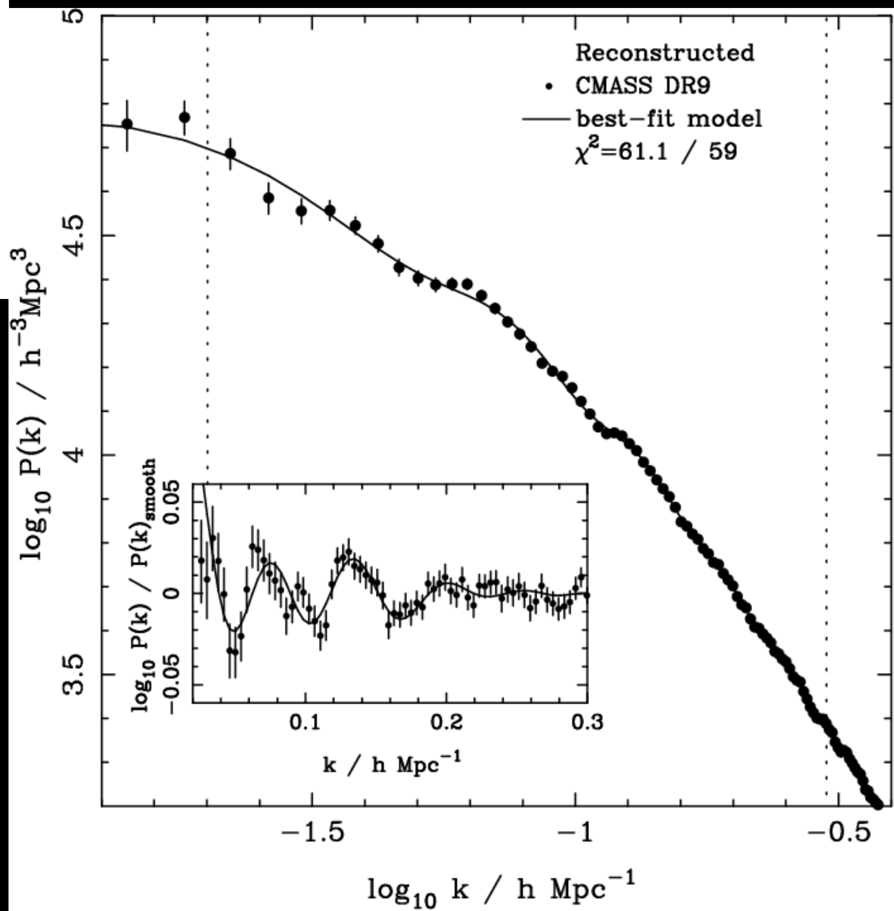
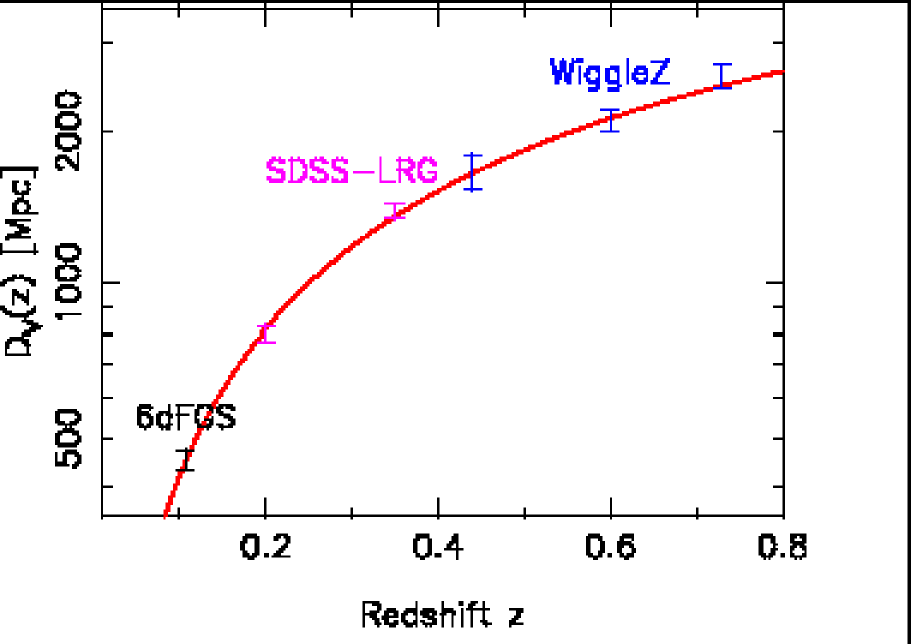
Results from SDSS III (BOSS)



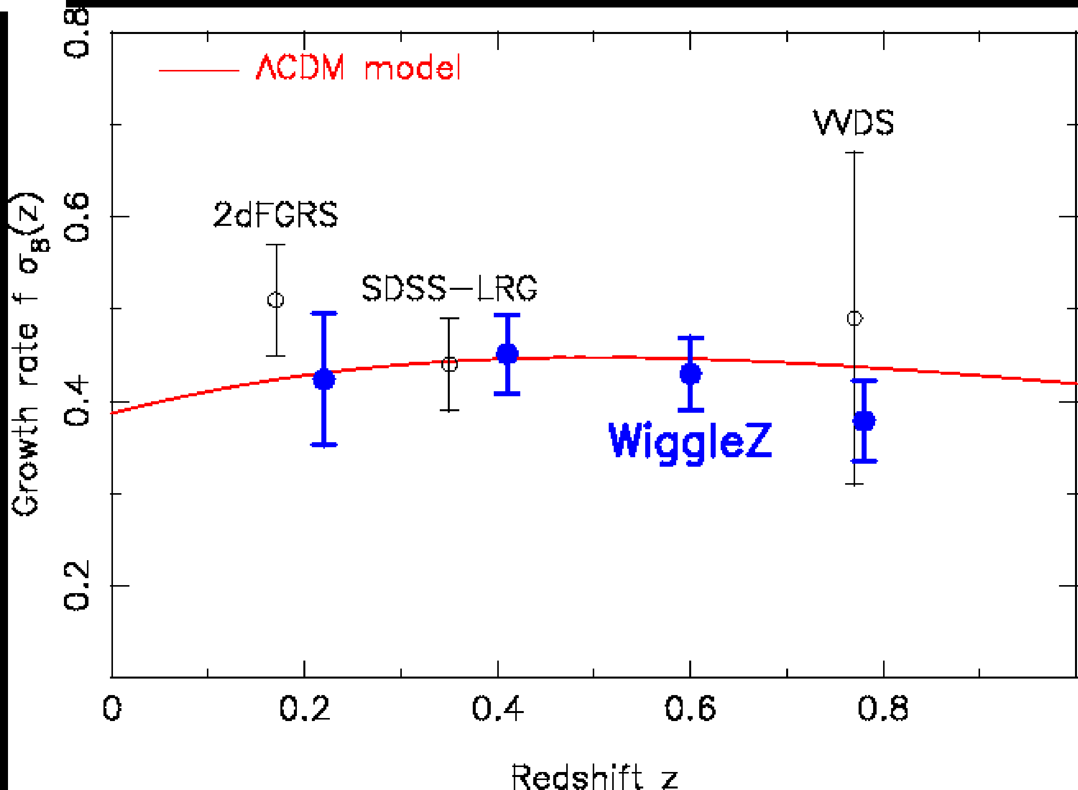


Spherically-averaged galaxy correlation function (top) and galaxy power spectrum (right).

Anderson et al. (2012)



Results from WiggleZ



Top: spherically averaged.

Right: background cosmology fixed.

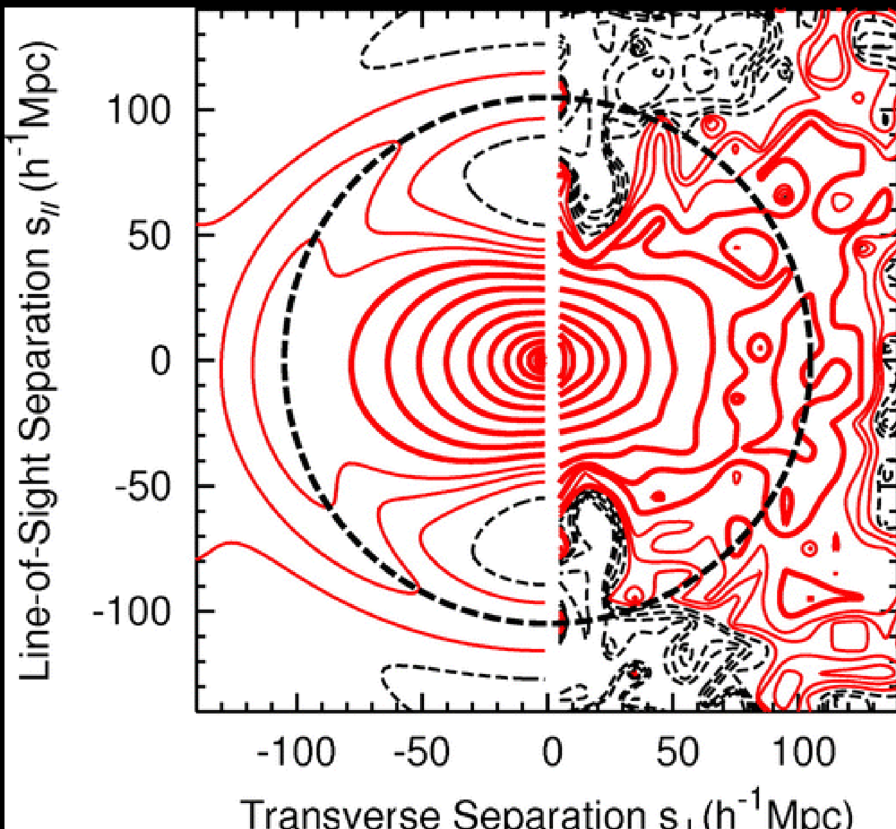
Blake et al. (2011ab)

GC/BAO Avantages & Challenges

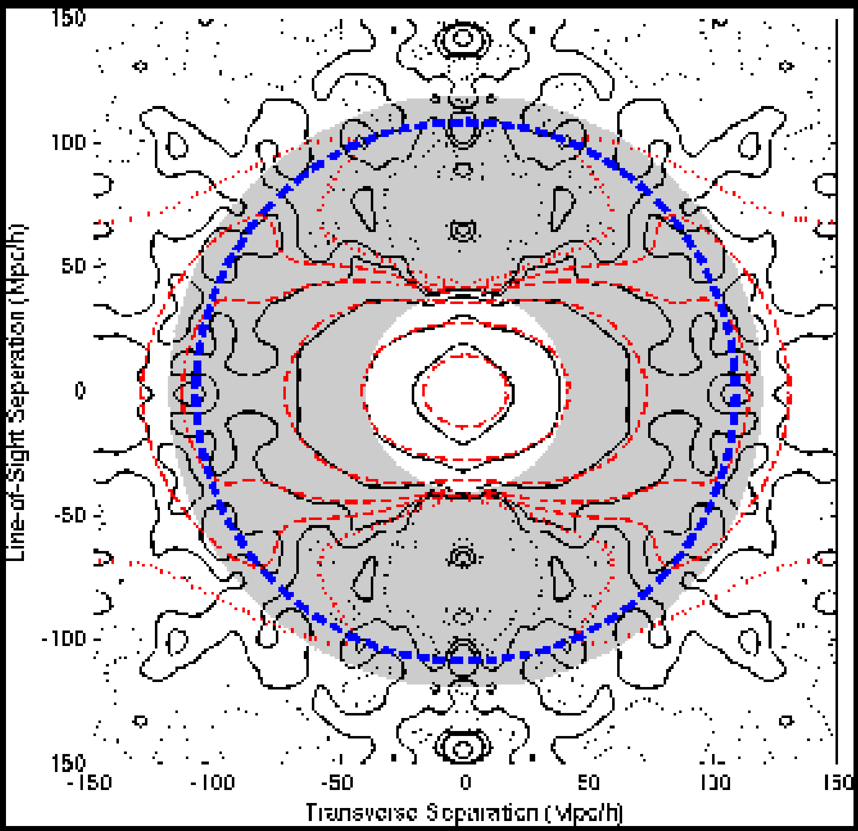
- Advantages:
  - Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).
  - Intrinsic systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling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

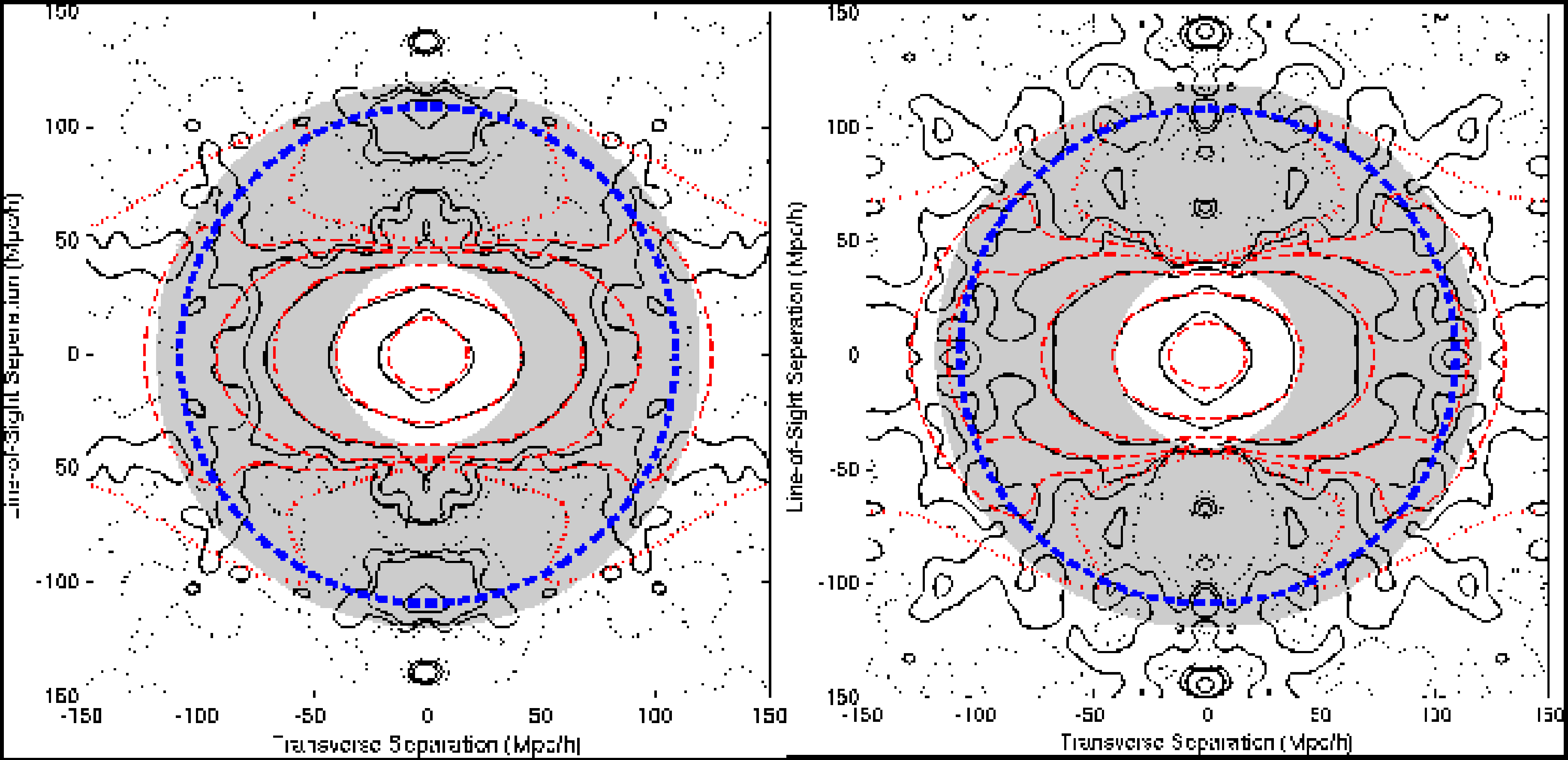


Chuang & Wang, arXiv:1102.2251, MNRAS, 426, 226 (2012)



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

LasDamas mock catalog | *SDSS LRG catalog*



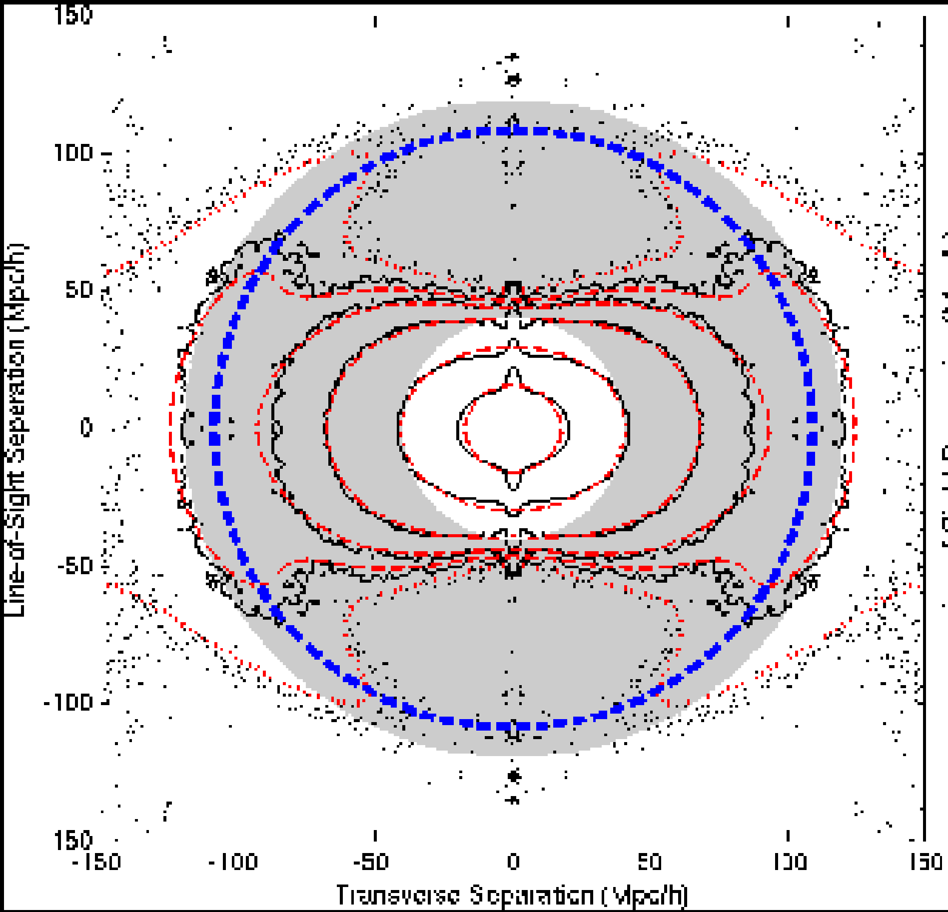
$x_h(z) = H(z)s = 0.04339 \pm 0.00178$ (4.1%); $x_d(z) = D_A(z)/s = 6.599 \pm 0.263$ (4.0%)

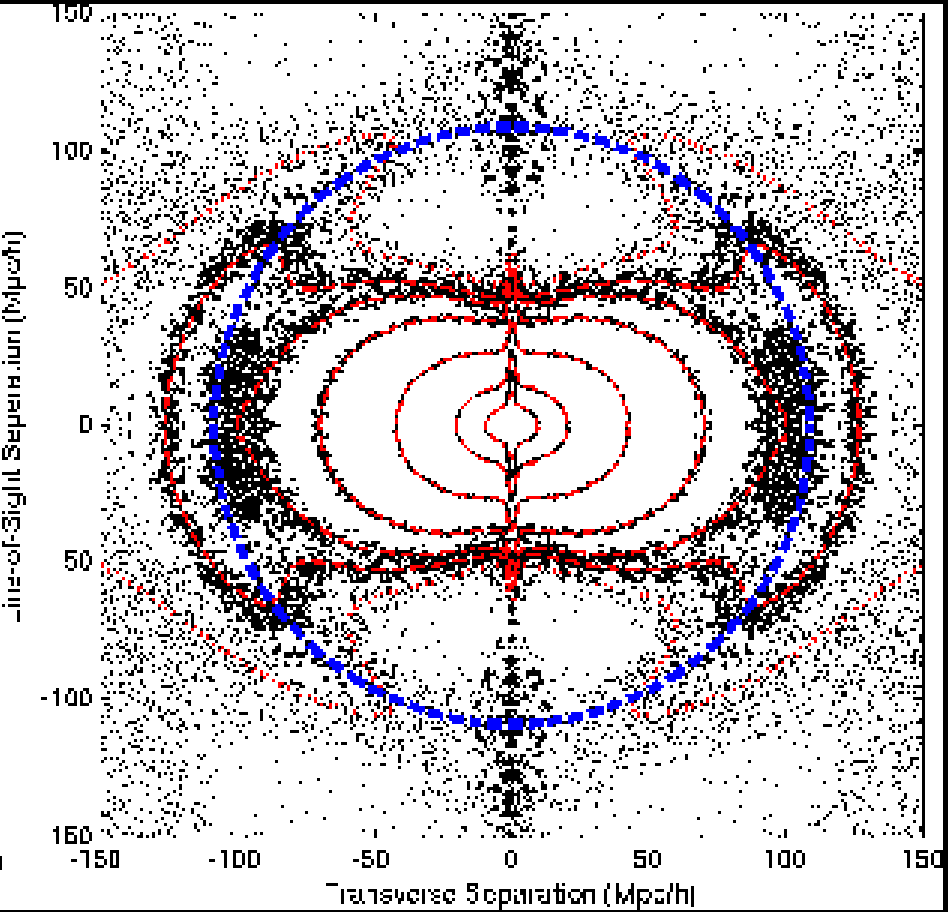
$r(x_h, x_d) = 0.0604$ (z=0.35, s: BAO scale, i.e., sound horizon at the drag epoch)

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

Evaluating the Modeling

Average of 160 LasDamas mock catalogs





Chuang & Wang, MNRAS, 426, 226 (2012) ***Chuang & Wang, arXiv:1209.0210***

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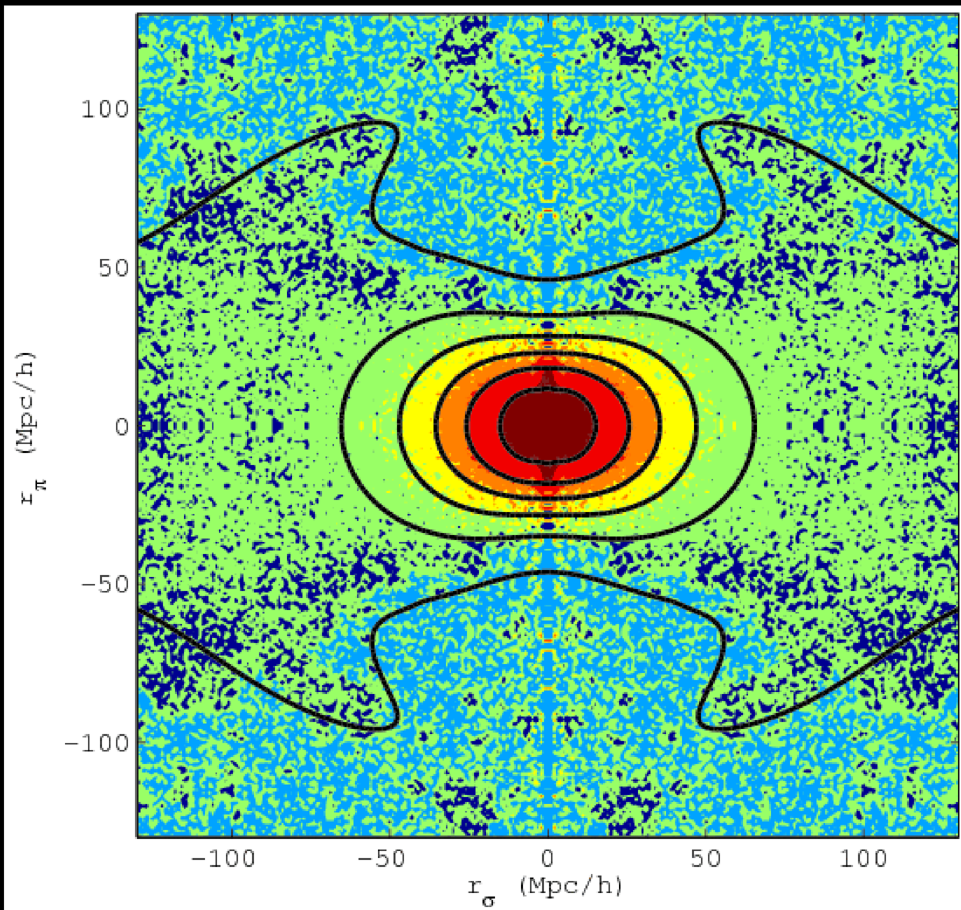
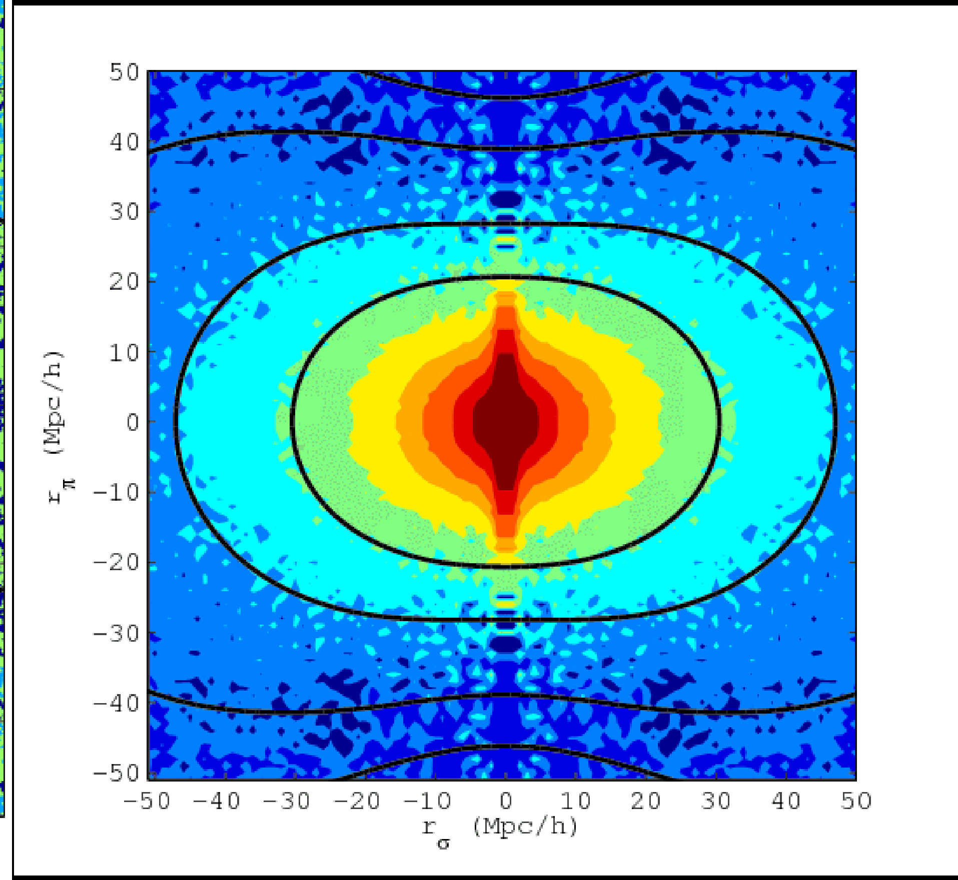
BOSS Results at z=0.57





Reid et al. (2012) measured H(z), D_A(z), f_g(z)σ_8(z) assuming WMAP7 priors

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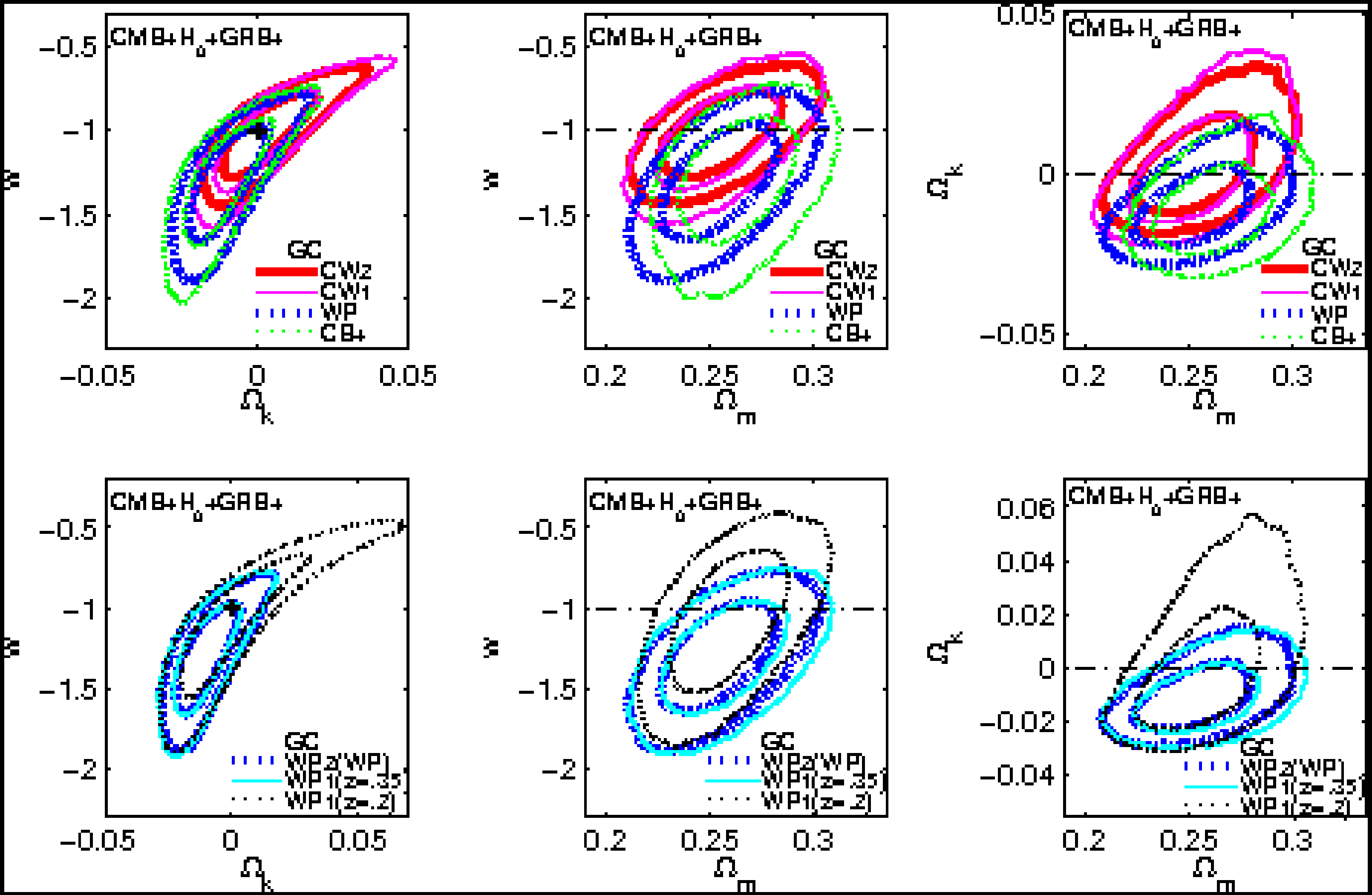
Latest BOSS Results (2013)
(converted to the same parameters at z=0.57)

Authors	Method	$H(z)r_s(z_d)/c$	$D_A(z)/r_s(z_d)$	Growth at z=0.57
Chuang et al.	Scaling of $\xi(\sigma,\pi)$ multipoles [Chuang & Wang (2012, 2013)]	0.0454 ±0.0031	8.95 ±0.27	$f\sigma_8$=0.428 ±0.069
Kazin et al.	Clustering wedges [Kazin et al. 2012]+ BAO reconstruction	0.0464 ±0.0031	9.05 ±0.27	marginalized
Sanchez et al.	Clustering wedges [Kazin et al. 2012]	0.0466 ±0.0021	9.04 ±0.25	marginalized
Anderson et al.	Averaging multipoles & clustering wedges+ BAO reconstruction [Xu et al. 2013; Kazin et al. 2012]	0.0474 ±0.0040	9.19 ±0.29	marginalzied

Different Analyses of GC/BAO



GC results from Chuang & Wang (2012) favor *w* = -1, while the results from some other groups favor *w* < -1. ***Wang, Chuang, & Mukherjee (2012)***

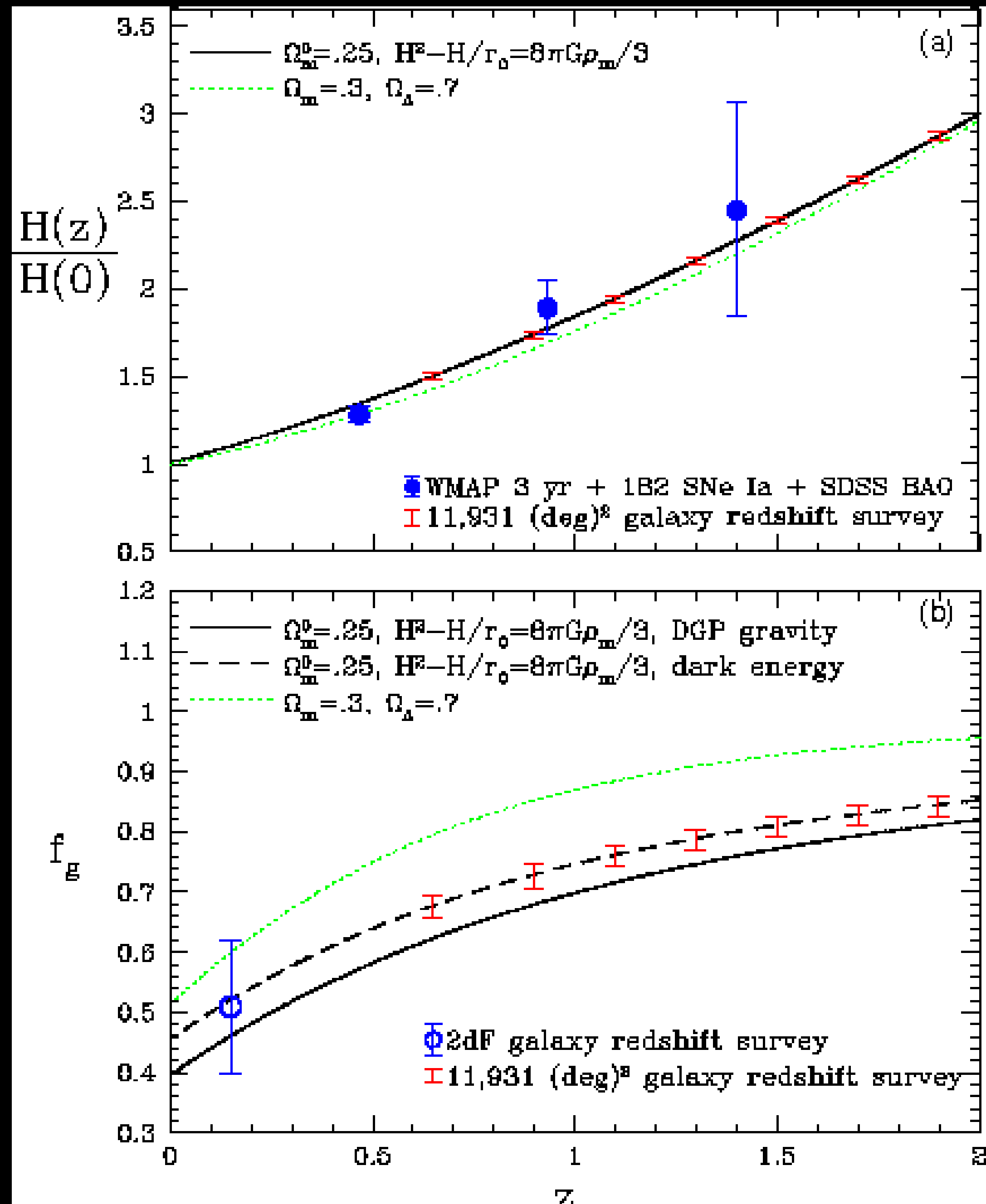
The Use of Galaxy Clustering to Differentiate Dark Energy & Modified Gravity

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

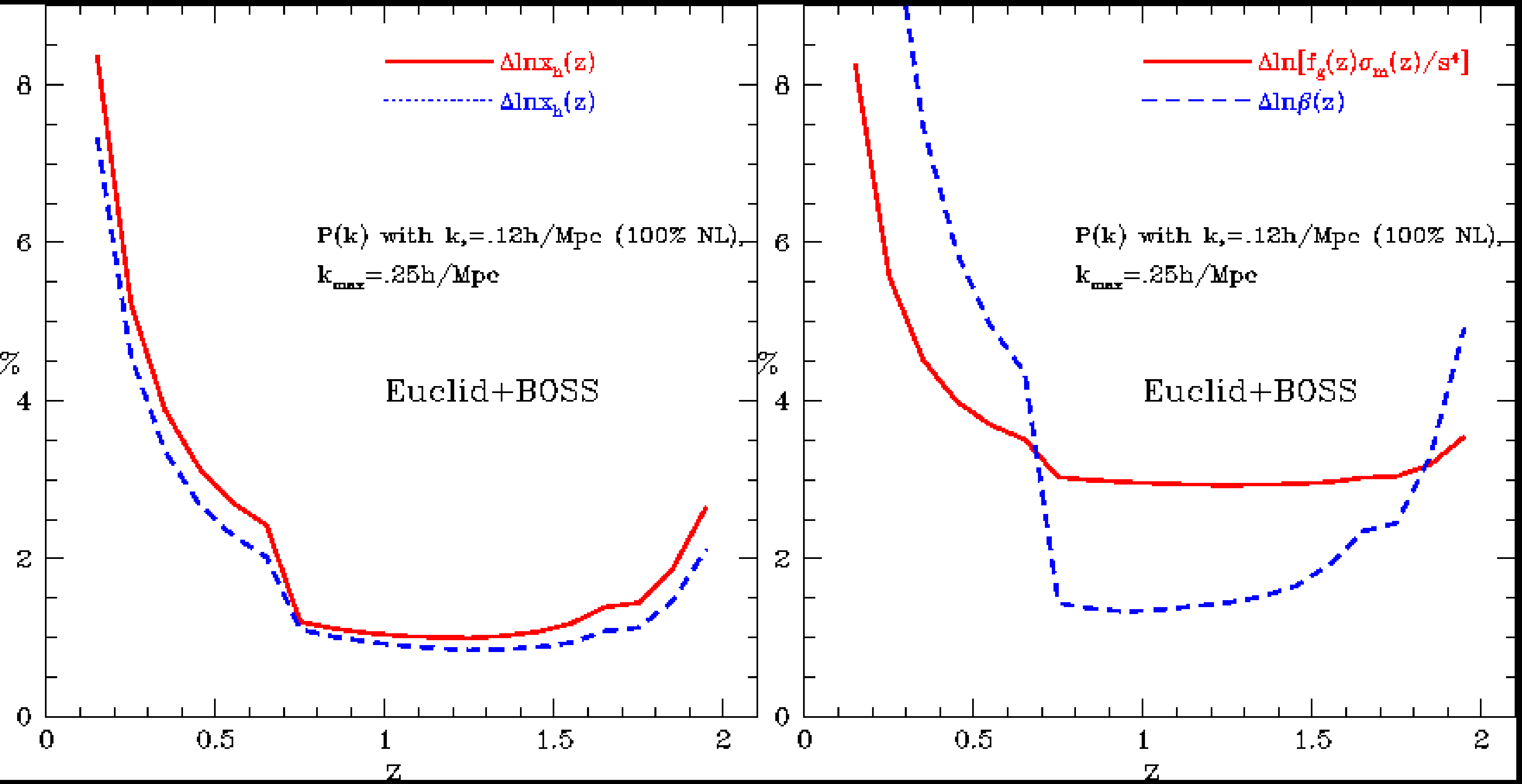
$[f_g=\mathrm{d}\ln\delta/\mathrm{d}\ln a]$

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

Wang (2008)



Euclid GC measurement of cosmic expansion & growth history



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NEUTRINO MASS

Neutrino mass ordering

The knowledge of $\Delta m_{21}^2 > 0$ and $|\Delta m_{31}^2|$ leads to the two possible schemes in Fig. 1. For masses much larger than the differences all neutrinos share in practice the same mass and then we say that they are degenerate.

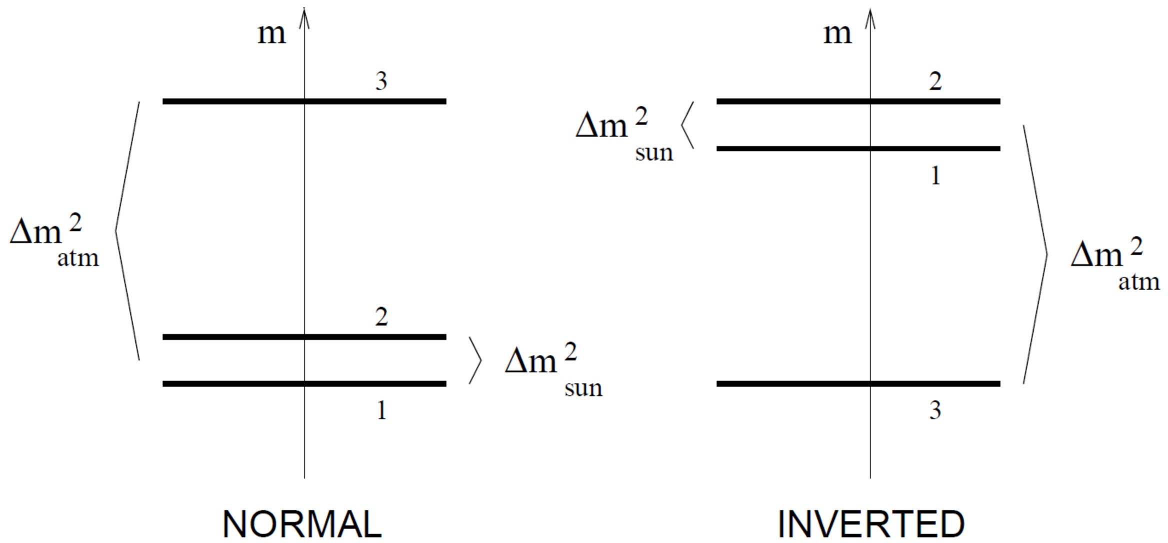

Fig. 1. The two neutrino schemes allowed if $\Delta m^2_{\rm atm} \gg \Delta m^2_{\rm sun}$: normal hierarchy (NH) and inverted hierarchy (IH).

Lesgourgues&Pastor (2006)

$\Delta m^2_{21} = m_2^2 - m_1^2$ and $\Delta m^2_{31} = m_3^2 - m_1^2$

solar

atmospheric

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Planck constraints on neutrinos

Planck Collaboration: Cosmological parameters

Parameter	*Planck*+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

ΛCDM+ν: Planck+lensing+WP+highL → M_ν<0.85 eV at 95% C.L. !!

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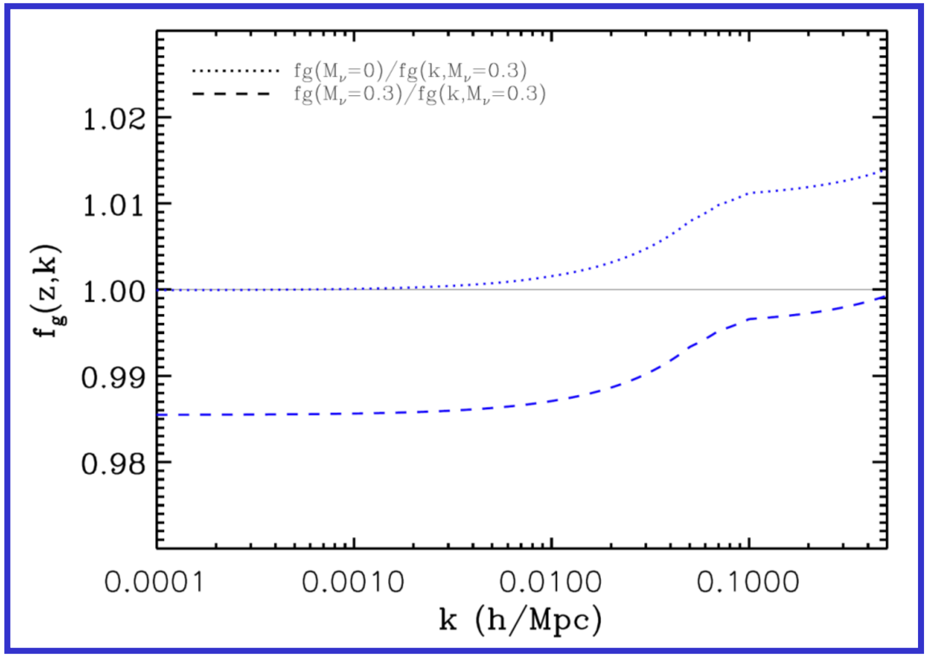
Constraints and forecasts from other probes

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
Lensing of CMB	0.85	0.2 – 0.05	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.9	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	0.1 – 0.006	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gadzooks [7]

Abazajian et al. 2011

Each of these probes faces technological, observational, and theoretical challenges

Effects of massive neutrinos on the scale-dependence of the linear growth



Kiakotou et al. 2007

$$f(z,k;f_\nu,w,\Omega_{\rm DE}) \approx \mu(k,f_\nu,\Omega_{DE})\Omega_m^\alpha(z)$$

$$\mu(k,f_\nu,\Omega_{DE}) = 1 - A(k)\Omega_{DE}f_\nu + B(k)f_\nu^2 - C(k)f_\nu^3$$

$$\frac{df_g}{d\ln a} = -f_g^2 - \left\{1 - \frac{1}{2}[\Omega_m(a) + (3w_{de}(a)+1)\Omega_{de}(a)]\right\} f_g + \frac{3}{2}\Omega_m(a)(1-f_\nu)$$

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Main results

Table 5: $\sigma(M_\nu)$ and $\sigma(N_{\rm eff})$ marginalised errors from LSS+CMB

			General cosmology			
fiducial→	M_ν=0.3 eV[a]	M_ν=0.2 eV[a]	M_ν=0.125 eV[b]	M_ν=0.125 eV[c]	M_ν=0.05 eV[b]	$N_{\rm eff}$=3.04[d]
slitless+BOSS+Planck	0.035	0.043	0.031	0.044	0.053	0.086
			ΛCDM cosmology			
slitless+BOSS+Planck	0.017	0.019	0.017	0.021	0.021	0.023

20%

[a]for degenerate spectrum: $m_1 \approx m_2 \approx m_3$; [b]for normal hierarchy: $m_3 \neq 0$, $m_1 \approx m_2 \approx 0$
[c]for inverted hierarchy: $m_1 \approx m_2$, $m_3 \approx 0$; [d]fiducial cosmology with massless neutrinos

Only 3 active neutrinos for M_ν errors

CC et al. 2011

If M_ν is > 0.1 eV, spectroscopic Euclid will be able to determine the neutrino mass scale independently of the model cosmology assumed. If M_ν is < 0.1 eV, the sum of neutrino masses, and in particular the minimum neutrino mass required by neutrino oscillations, can be measured in the context of a LCDM model. Galaxy-clustering from Euclid is competitive with future 3D shear photometric surveys.

*** Marginalized over Ω_k and (w_0, w_a)**

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Latest Neutrino Mass Constraints

- Σm_ν < 0.15 eV (95% C.L.), for flat Universe with w=-1, using WiggleZ+6dFGRS+SDSS(DR7&9) $D_V(z)$ measurments + Planck + WMAP Pol

  Riemer-Sorensen, Parkinson, Davis, astro-ph/1306.4153

- Σm_ν < 0.49 eV (95% C.L.), for flat Universe with constant w; Σm_ν < 0.35 eV (95% C.L.) for w=-1 & non-flat Universe, using SDSS (DR9) P(k) measurments + Planck (+lensing) + WMAP Pol

  Giusarma, de Putter, Ho, & Mena, astro-ph/1306.5544

PRIMORDIAL NON-GAUSSIANITY

Primordial Non-Gaussianity

- Paremtrizing local PNG:

$$\Phi(x,z)=\varphi(x,z) + f_{\mathrm{NL}}[\varphi^2(x,z)-\langle\varphi^2\rangle(z)] + g_{\mathrm{NL}}[\varphi^3(x,z)-3\langle\varphi^2\rangle(z)\,\varphi(x,z)\,]$$

  – Curvature perturbation [-grav. potential]
- Inflation models predict very nearly Gaussian primoridal fluctuations.
  – All single-field models → $f_{\mathrm{NL}}^{\mathrm{local}}$=0.02
  – Detection of f_{NL}>1 would rule out all single-field inflation models!

Komatsu 2012

- Review of PNG in CMB & LSS: Liguori et al. (2010)

Primordial Non-Gaussianity

- **Current constraints:**
  - **From GC+ISW: $-37 < f_{NL} < 25$ at 95% C.L.**
    (Giannantonio et al. 2013)
  - **Planck (2013): $f_{NL}=2.7\pm5.8$ (68% C.L.)**
- **Future forecasts (marginalized over DE & other parameters):**
  - **Euclid (GC+WL) + Planck: $\sigma(f_{NL})\sim3$**
    (Giannantonio et al. 2012)
  - **Euclid GC: $\sigma(f_{NL})\sim4$**
    (Amendola et al. 2012)

FUTURE PROSPECTS

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 (2014-2020):** 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 (2019-):** GRS over 15,000 sq deg of ELGs ($0.7<z<2$)
- **WFIRST (2022?-):** 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 2019
- 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

WFIRST

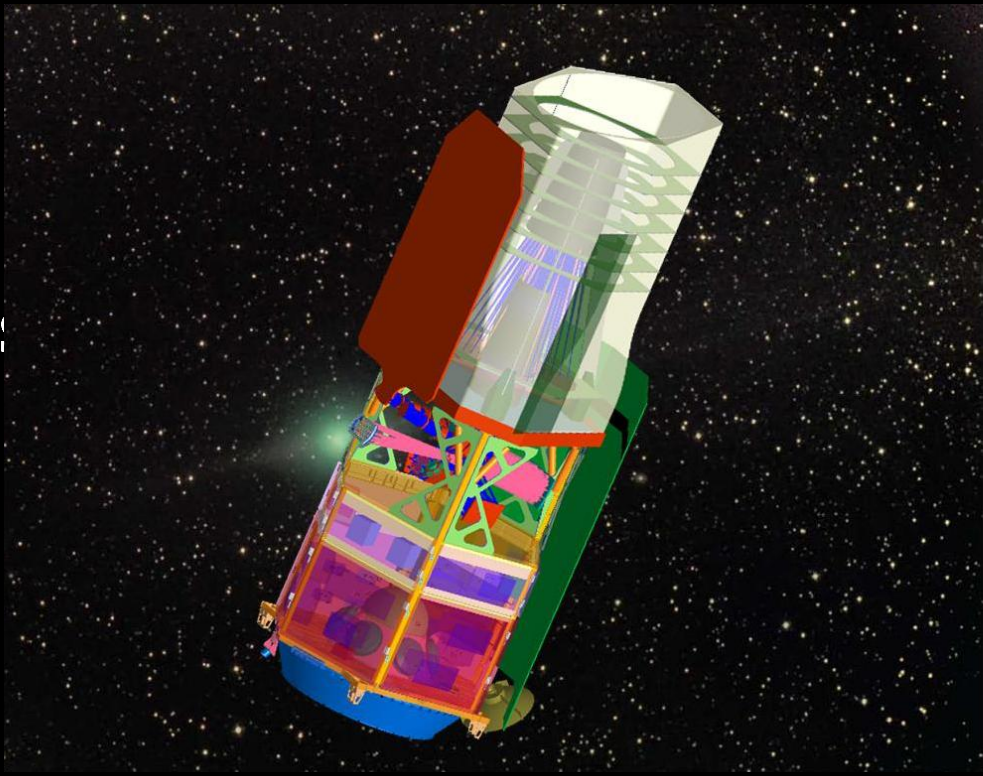
Wide-Field Infrared Survey Telescope

- **JDEM + MPF + NISS…**
- **2.4m from NRO**
- **Dark energy**

  + microlensing planets

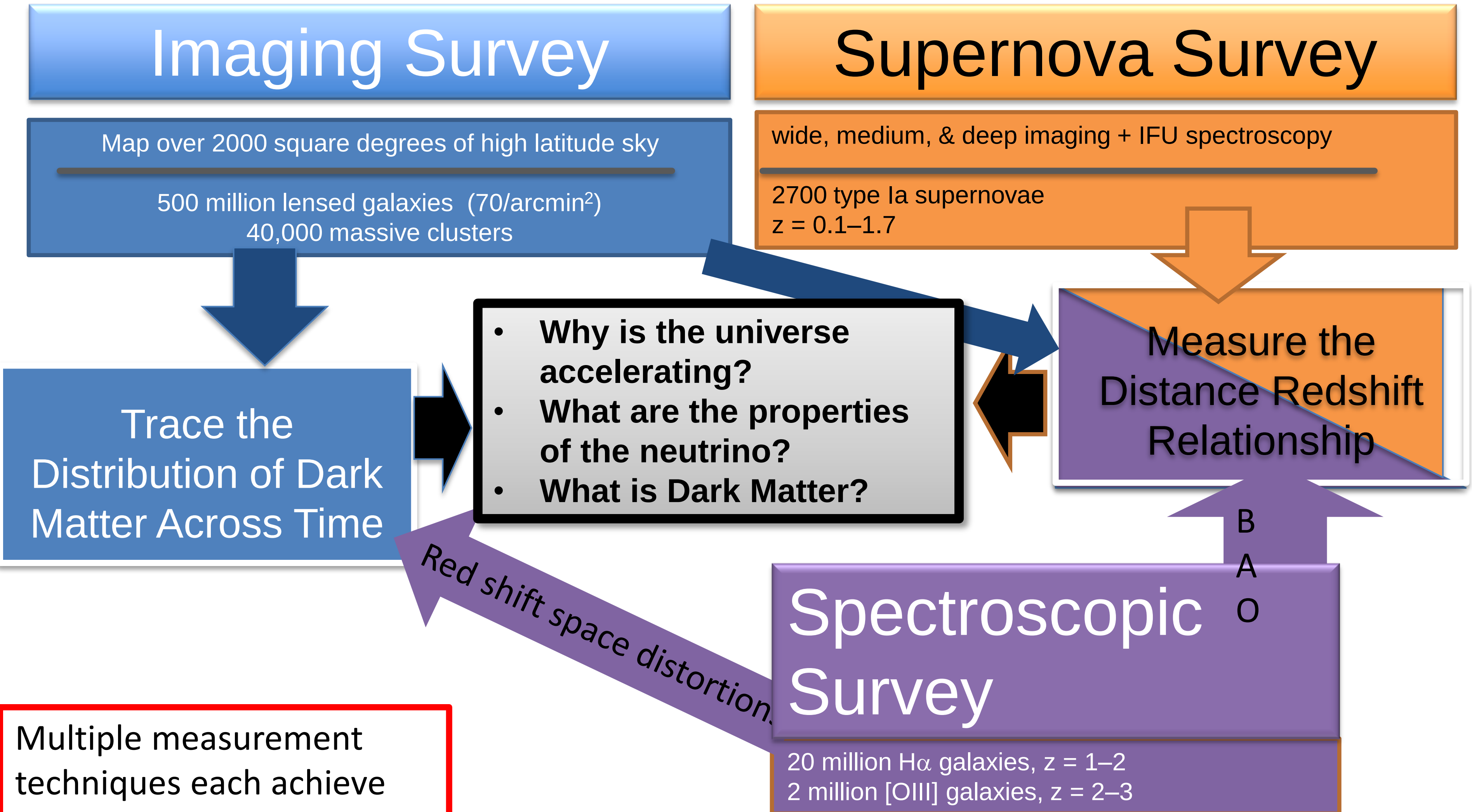
  + NIR survey

  + Guest Investigator
- **Launch date: 2022?**



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



Multiple measurement techniques each achieve 0.1-0.4% precision