The Power
of the Galaxy Power Spectrum

Eric Linder

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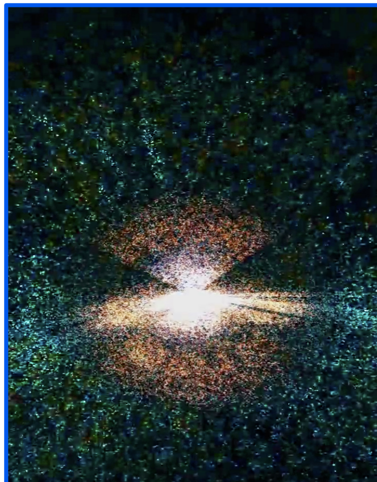
UC Berkeley & Berkeley Lab
Institute for the Early Universe, Korea

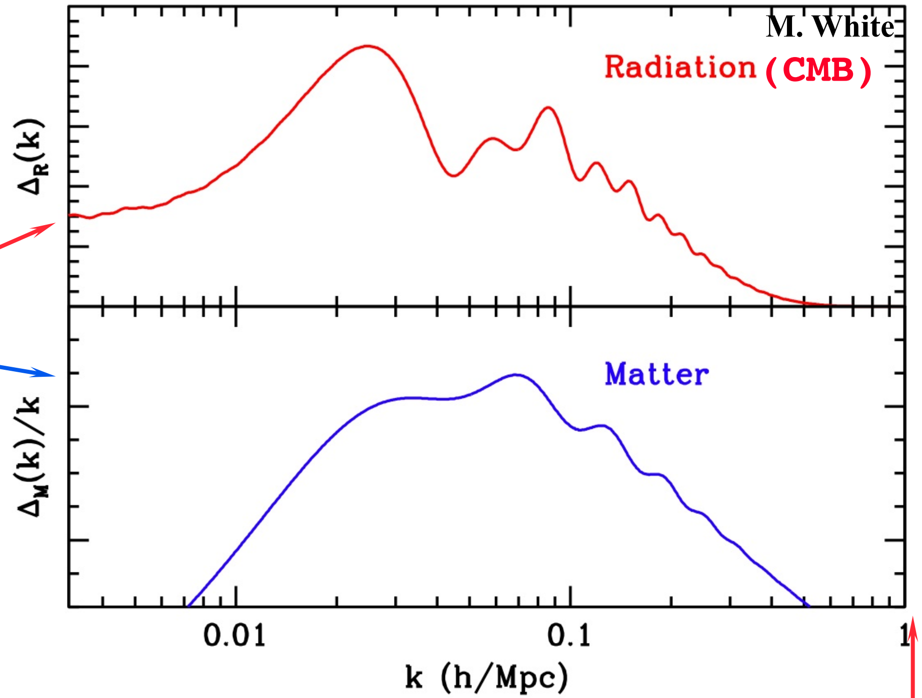


Baryon Acoustic Oscillations

In the beginning... **(well, 10-350,000 years after)**

It was hot. Normal matter was p^+,e^- – charged – interacting fervently with photons. This tightly coupled them, photon mfp << ct, and so they acted like a fluid. Density perturbations in one would cause perturbations in the other, but gravity was offset by pressure, so they couldn't grow - merely oscillated. Then swift decoupling so on the largest scales, set by the sound horizon, the perturbations were preserved.

The same primordial imprints in the *photon* field show up in *matter* density fluctuations.



Galaxy cluster size

***Baryon acoustic oscillations* = patterned distribution of galaxies on very large scales (~150 Mpc).**

Baryon Acoustic Oscillations

	Photons	Baryons
Name	CMB acoustic peaks	Baryon acoustic oscillations
Scale	1°	100 h^{-1} Mpc comoving
Base amplitude	5 x 10^{-5}	10^{-1}
Osc. amplitude	O(1)	5%
Detection	10^{15}/hand/sec	indirect: light from <10^{10} gal

Scale of oscillations informs re cosmic distances.

Angular separation → angular distance d(z)

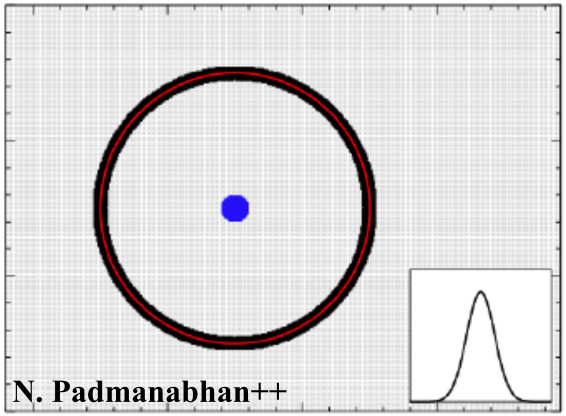
Radial distance in z → expansion rate H(z)

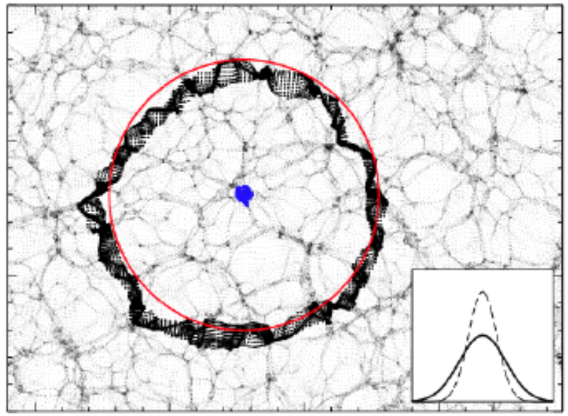
Cosmic volume surveys can measure d to <1%, H to <1.5%

BAO Systematics

Nonlinear, biasing effects distort BAO scale.

Not a pure geometric probe – depends on early evolution thru sound horizon (N_{eff}, Ω_{EDE}), late evolution thru gravity ($G_{eff}(k,z)$, coupling). Adds to, does not substitute for, supernova distances.



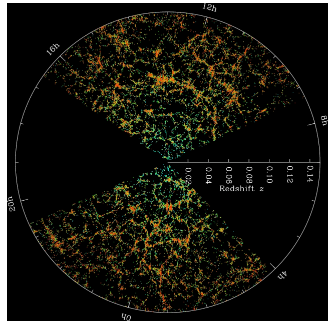


No such thing as pure BAO: velocity distortions always affect signal extraction (even if ignore).

Think in terms of full galaxy power spectrum.

Cosmic Structure

Galaxy 3D distribution or power spectrum contains information on:



- Growth - evolving amplitude
- Matter/radiation density, H - peak turnover
- Distances - baryon acoustic oscillations
- Growth rate - redshift space distortions
- Neutrino mass, non-Gaussianity, gravity, etc.

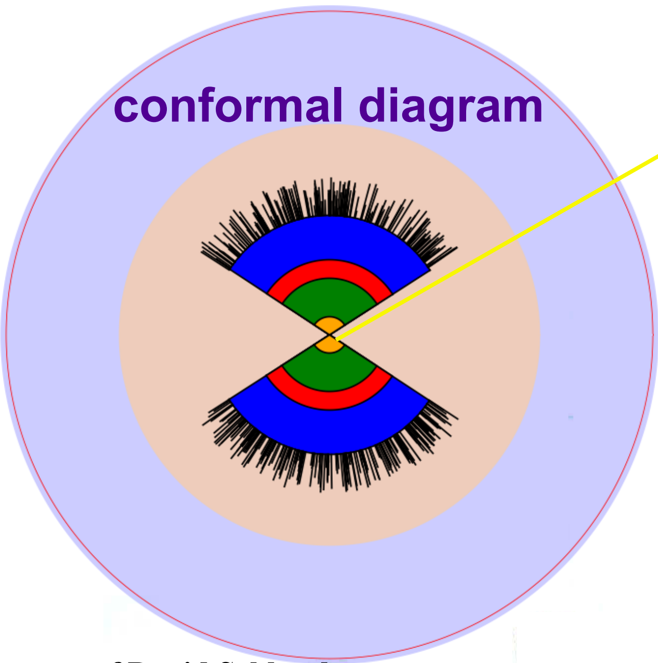
Data, Data, Data

As wonderful as the CMB is, it is 2-dimensional.
Number of information modes is *l(l+1)* or ~10 million.

BOSS (SDSS III) maps 400,000 linear modes.

N. Padmanabhan

WFIRST will map 15 million linear modes.



SDSS I, II, 2dF

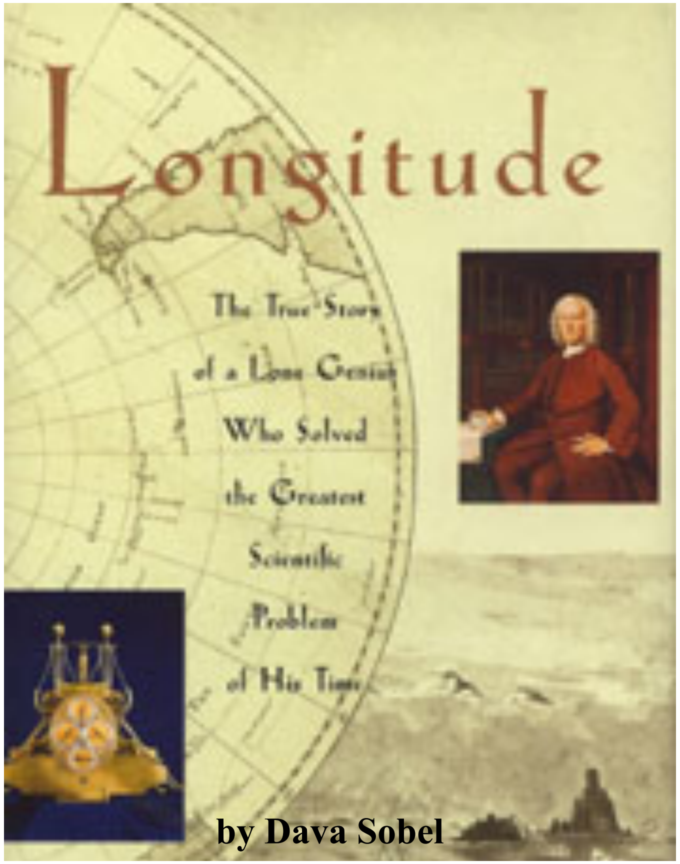
BOSS (SDSS III)

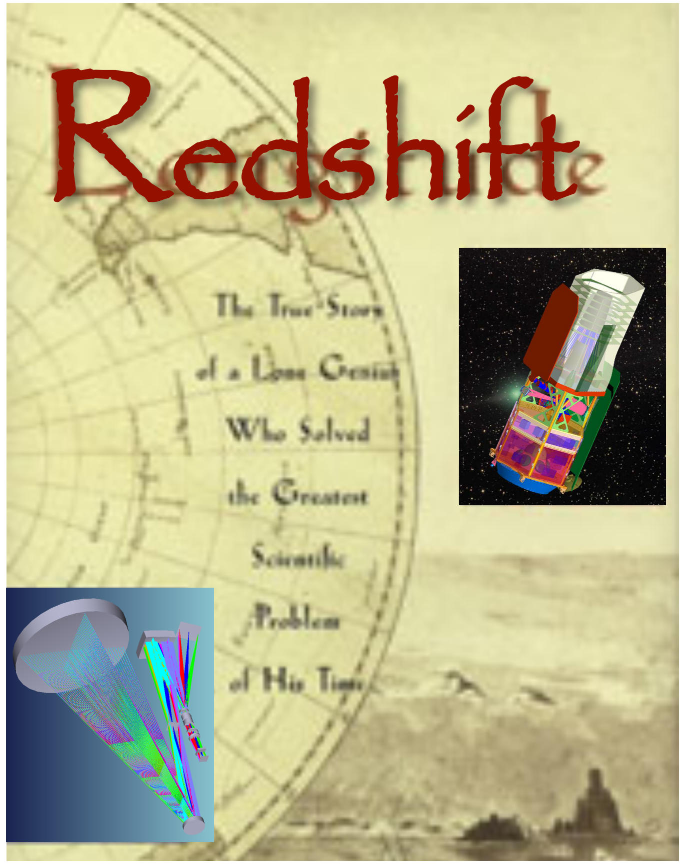
WFIRST
100 million galaxies
z=1-2

600,000 QSOs
z=1.8-3

courtesy of David Schlegel

“Greatest Scientific Problem”





Cosmological Revolution:

From 2D to 3D – CMB anisotropies to redshift surveys of density/velocity field.

BAO for Acceleration

Acceleration can be seen directly through redshift drift.

$$\dot{z} = H_0(1+z) - H(z)$$

McVittie/Sandage 1962

Europe wants to build a 40m telescope to stare at quasars for 10 years and measure z to 10^{-10}.

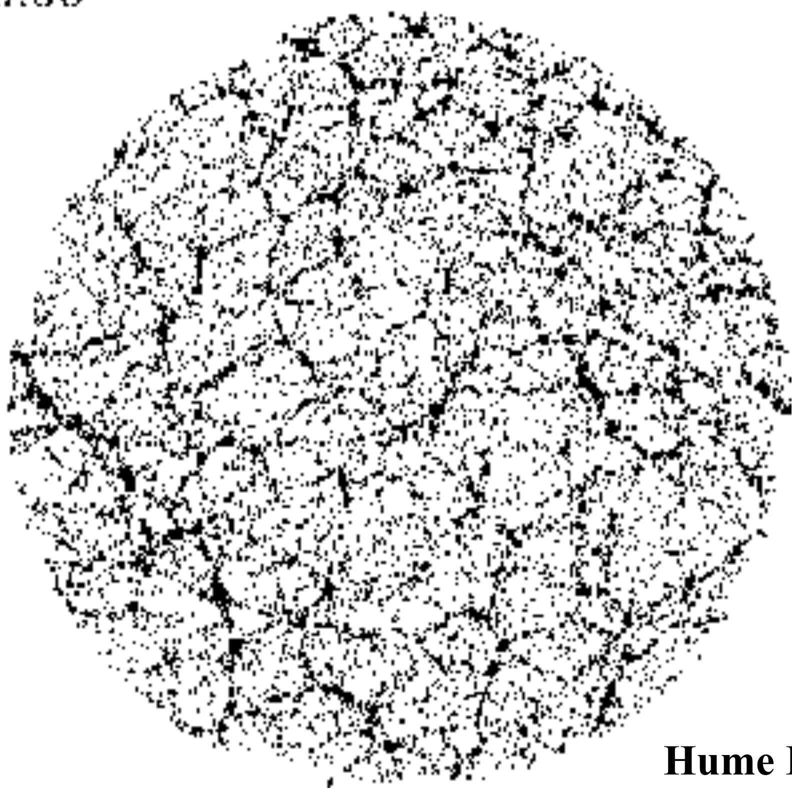
Instead, use radial BAO of galaxies 10^{10} years apart.

Technique	Equation	Nuisance	Sign
z Drift	$\dot{z}_2 - \dot{z}_1 = H_0(z_2 - z_1) - (H_2 - H_1)$	H_0	w < -1/3
radial BAO	$\mathrm{rBAO}_2 - \mathrm{rBAO}_1 = s(H_2 - H_1)$	s	w < -1

Redshift Space Distortions

Redshift space distortions (RSD) map velocity field along line of sight. Gets at growth rate f, one less integral than growth factor (like H vs d). See Weinberg talk

Ω_m = 0.00



Hume Feldman

$$f = \frac{d \ln D}{d \ln a} \sim \Omega_m(a)^{\gamma}$$

gravitational growth index γ

[GR γ=0.55]

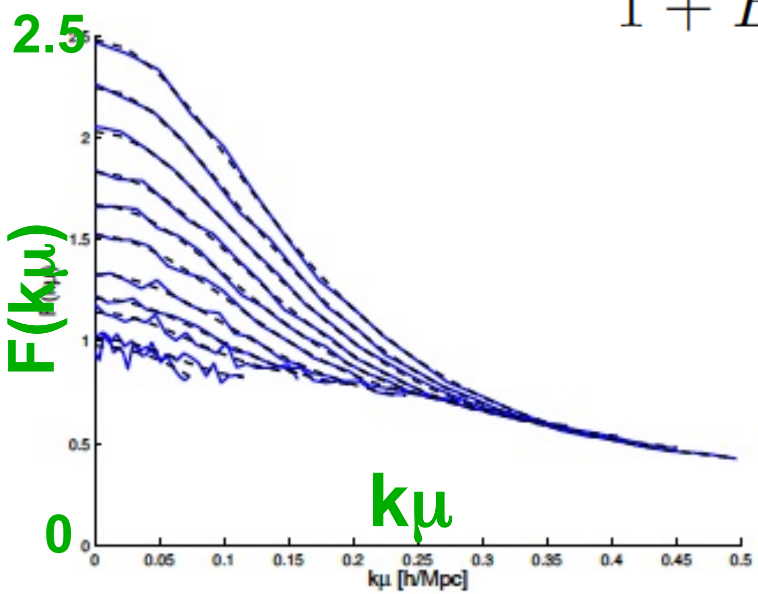
Redshift Space Distortions

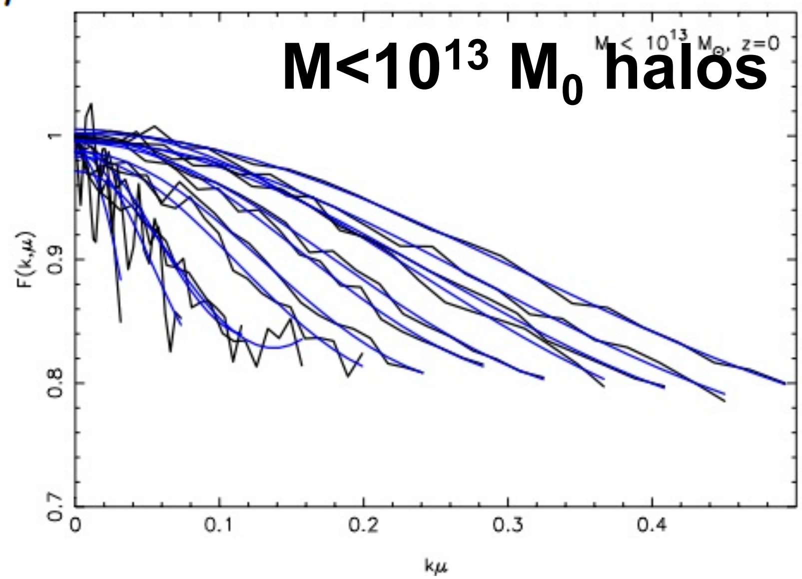
$$P_{gg}(k,z) = (b + f\mu^2)^2\, P_{\delta\delta}(k,z)$$ **Kaiser formula inaccurate**

Accurate RSD reconstruction Kwan, Lewis, Linder 2011

$P^{true}(k,\mu) = F(k\mu)\, P^{form}(k,\mu)$

$$F(k\mu) = \frac{A}{1 + Bk^2\mu^2} + Ck^2\mu^2$$





Accurate for both dark matter and biased halos.

Also see Okumura, Seljak, McDonald, Desjacques 2011 ; Okumura & Jing 2011

Testing Growth vs Expansion

Comparing cosmic expansion history vs. cosmic growth history is one of the major tests of the cosmological framework.

If do not simultaneously fit then deviation in one biases the other, e.g. looks like non-GR or non-Λ.

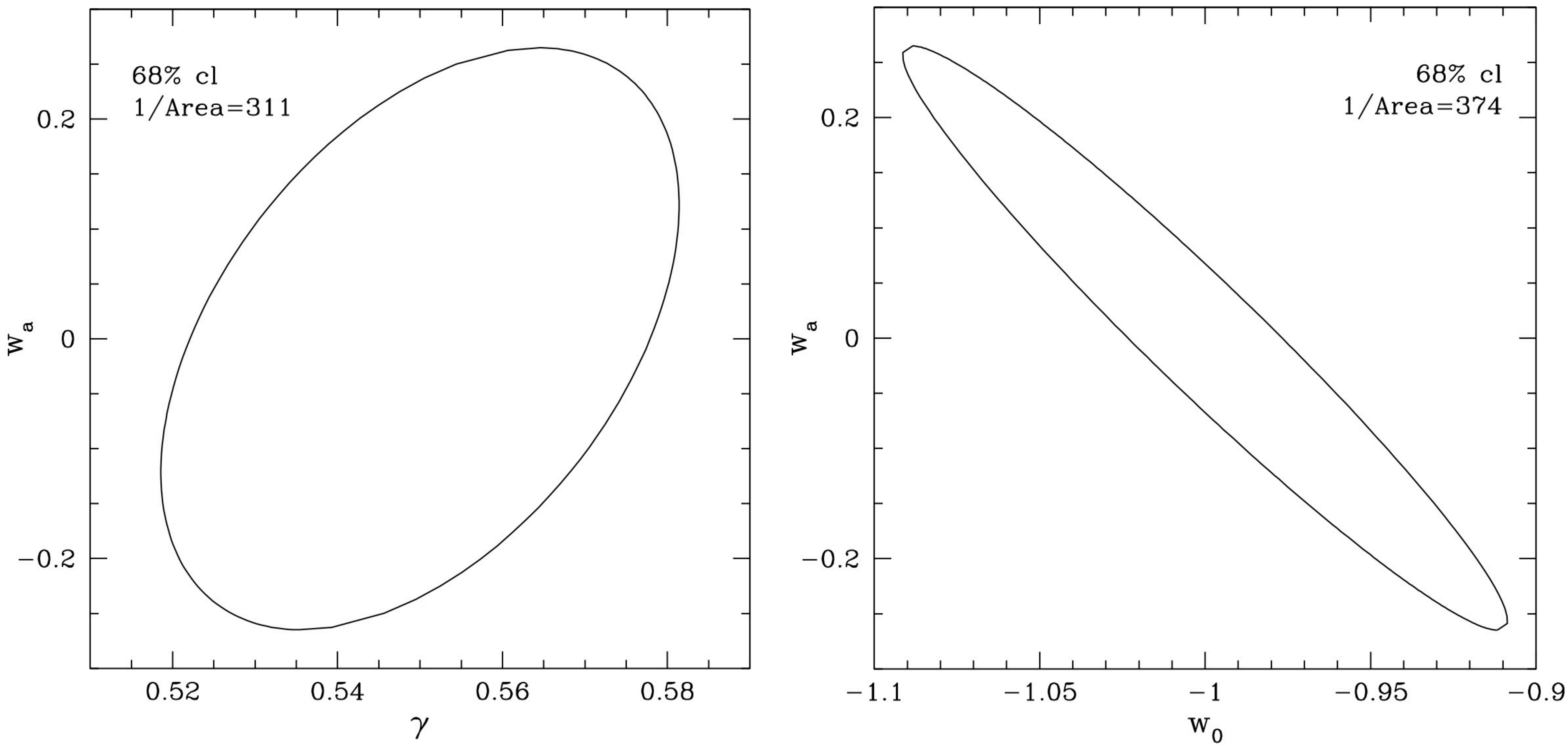
Separate out the expansion influence on the growth – gravitational growth index γ.

Growth rate depends on expansion and gravity.

$$f(z)\,\sigma_8(z) = {\Omega_m}^{\gamma}\, e^{\int d\ln a\, {\Omega_m}^{\gamma}}$$

Gravity and Growth

Joint fit of both acceleration and gravity, with little degeneracy: σ(γ)=0.021, correlation |r|<0.46



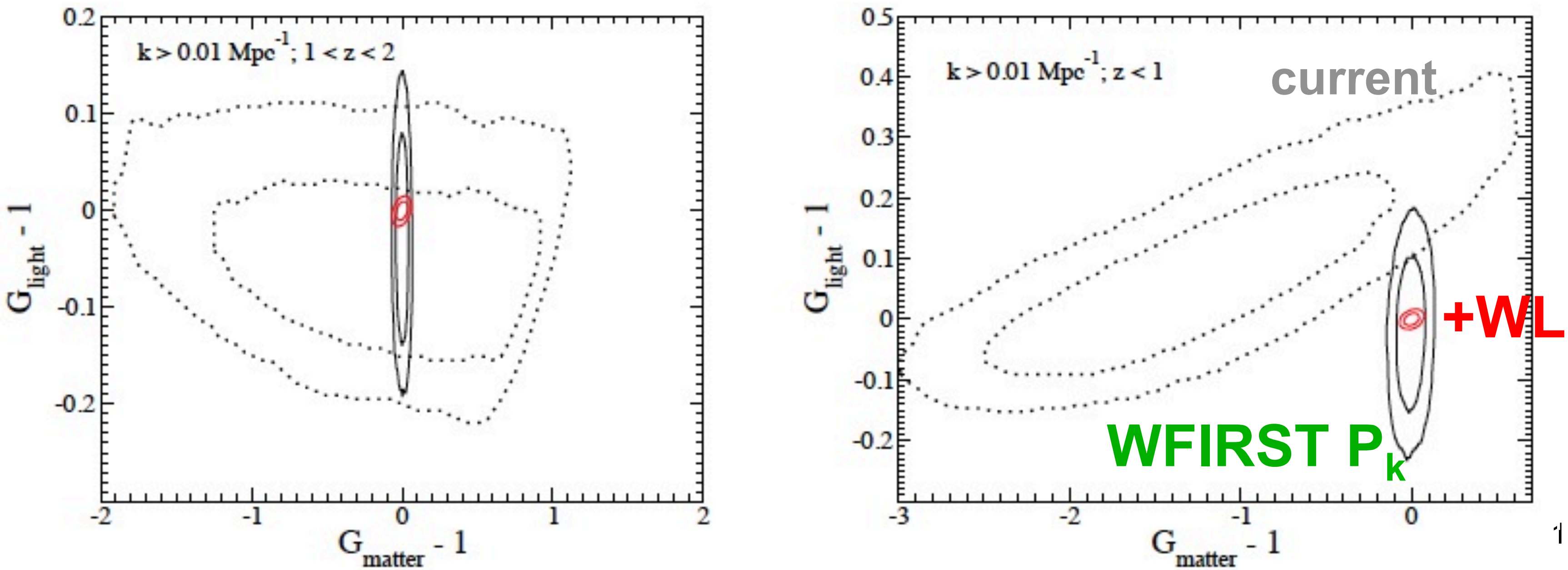
Gravity thru Time and Space

Test GR thru time and scale evolution; tie to observations through modified Poisson equations:

$$\nabla^2(\phi+\psi) = 8\pi G_N\, a^2\, \delta\rho \times G_{\rm light}$$
$$\nabla^2\psi = 4\pi G_N\, a^2\, \delta\rho \times G_{\rm matter}$$

G_{light} **tests how light responds to gravity (lensing).**

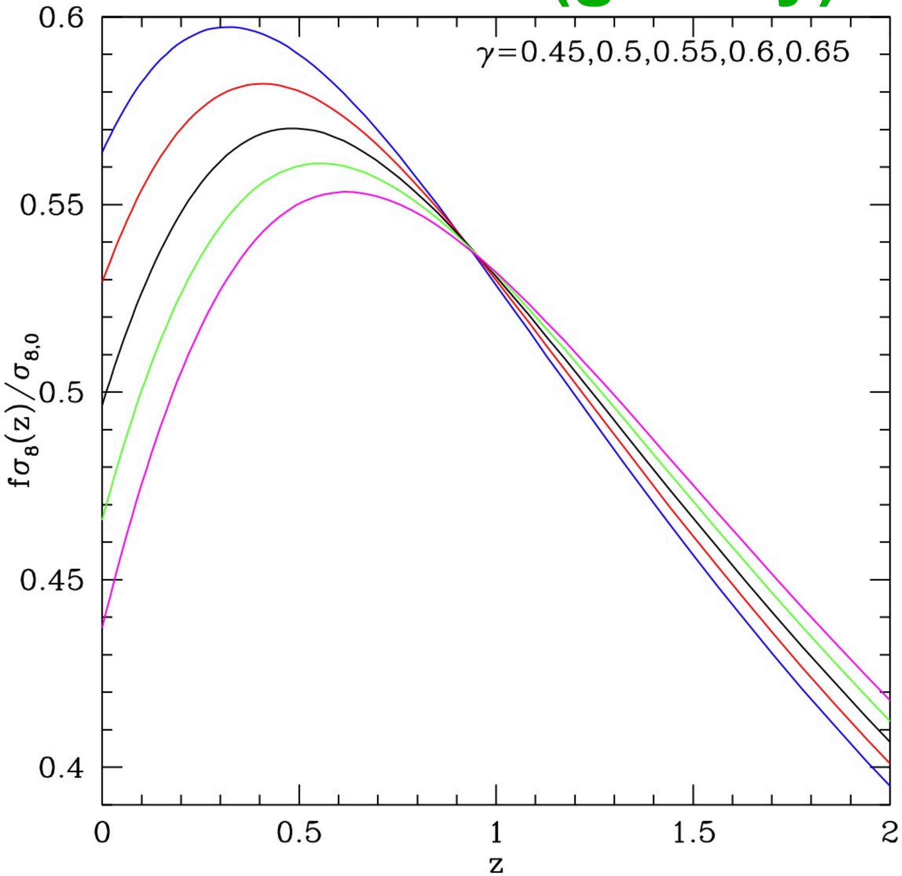
G_{matter} **tests how matter responds to gravity (growth; γ).**



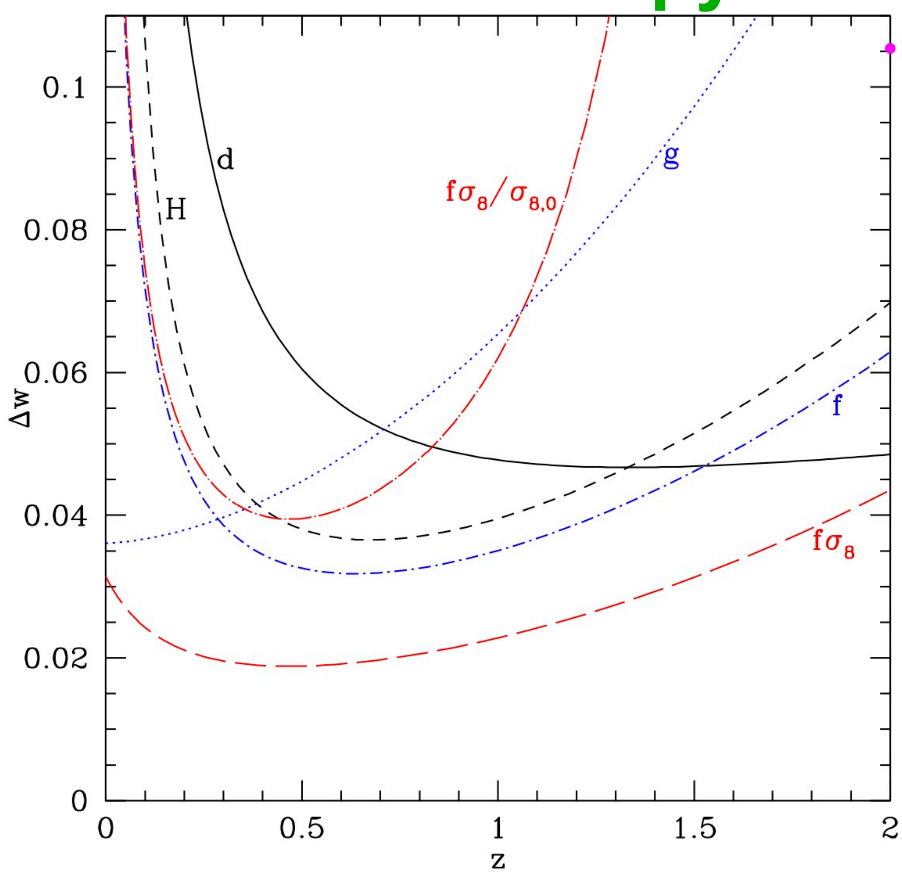
Discovery Space

Galaxy power spectrum has information on many scales, at many redshifts.

Growth rate(gravity)



DE Anisotropy



Summary

WFIRST galaxy redshift survey has **great promise** to probe gravity and expansion and growth jointly.

Such data is **needed** to uncover the origin of cosmic acceleration and new physics.

P_k also measures m_ν, non-Gaussianity, inflation.

Design survey to **complement** ground based P_k and other probes.