# Beyond BAO: Redshift-Space Anisotropy in the WFIRST Galaxy Redshift Survey

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Based partly on *Observational Probes of Cosmic Acceleration*

by DHW, Michael Mortonson, Daniel Eisenstein, Chris Hirata, Adam Riess, and Eduardo Rozo
arxiv:1201.2434, for *Physics Reports*

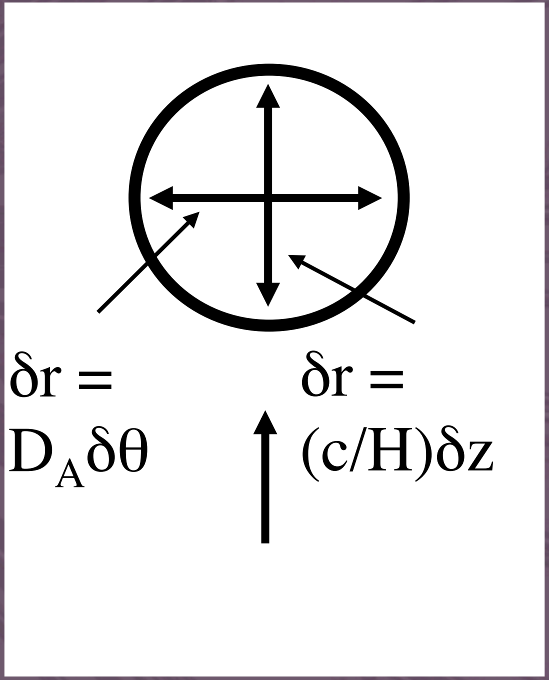
# Why is the universe accelerating?

1. Is cosmic expansion accelerating because of a breakdown of GR on cosmological scales or because of a new energy component that exerts repulsive gravity within GR?
2. If the latter, is the energy density of this component constant in space and time, consistent with fundamental vacuum energy?

General approach: Measure the expansion history and structure growth history with the highest achievable precision over a wide range of redshifts.

Four main ways a WFIRST-like redshift survey can constrain cosmic acceleration:

BAO: Constrains $D_A(z)$ and $H(z)$. Robust – likely to be limited by statistics rather than systematics.



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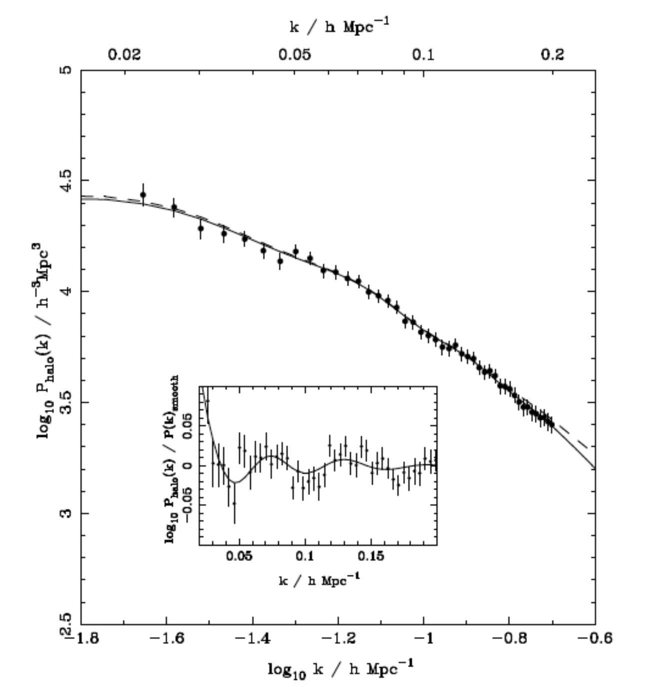


Reid et al. 2010, SDSS DR7

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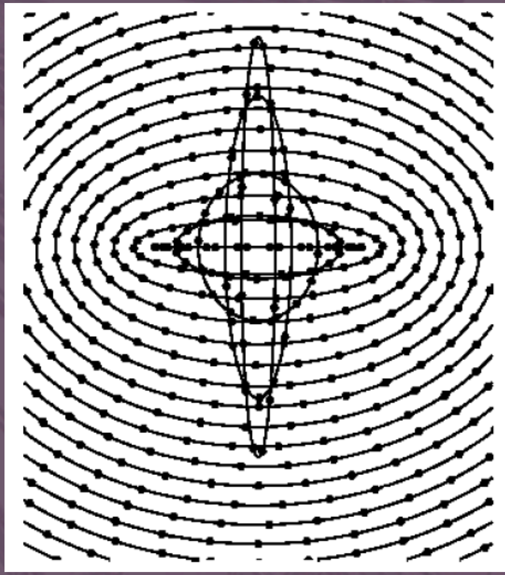

Kaiser 1987, Hamilton 1998

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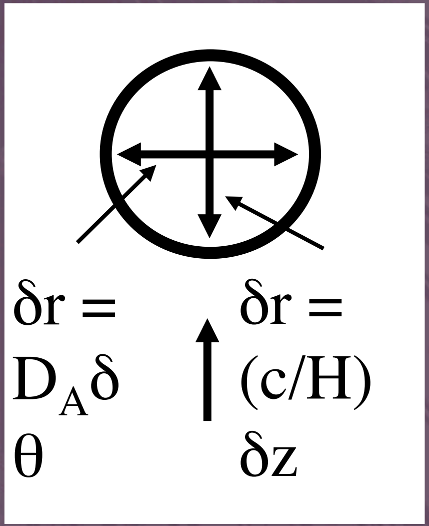
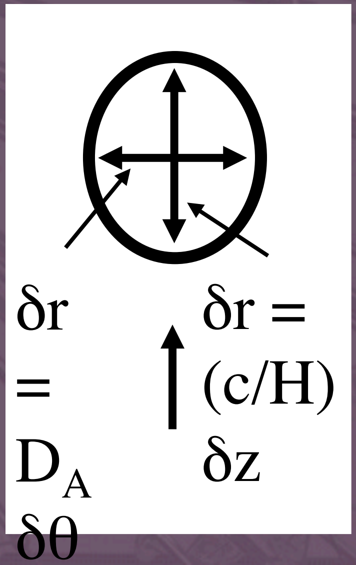
Alcock-Paczynksi (AP) test:



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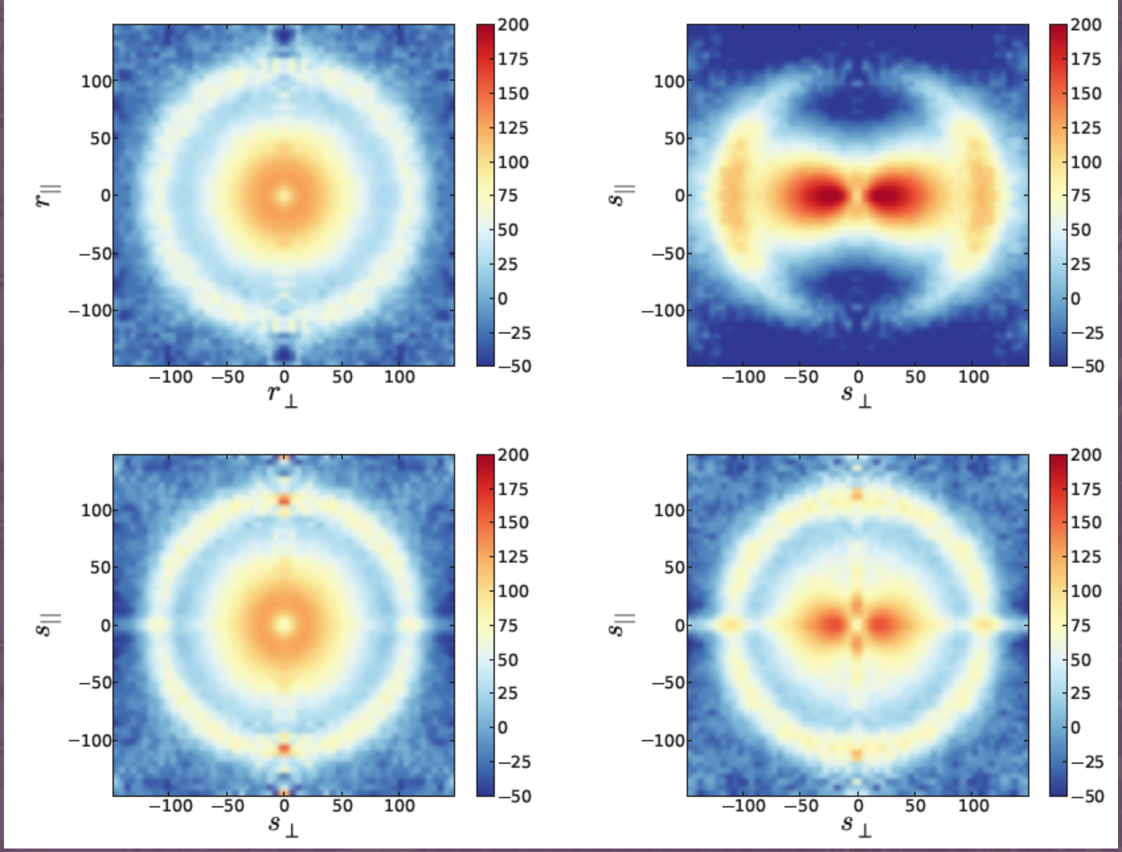
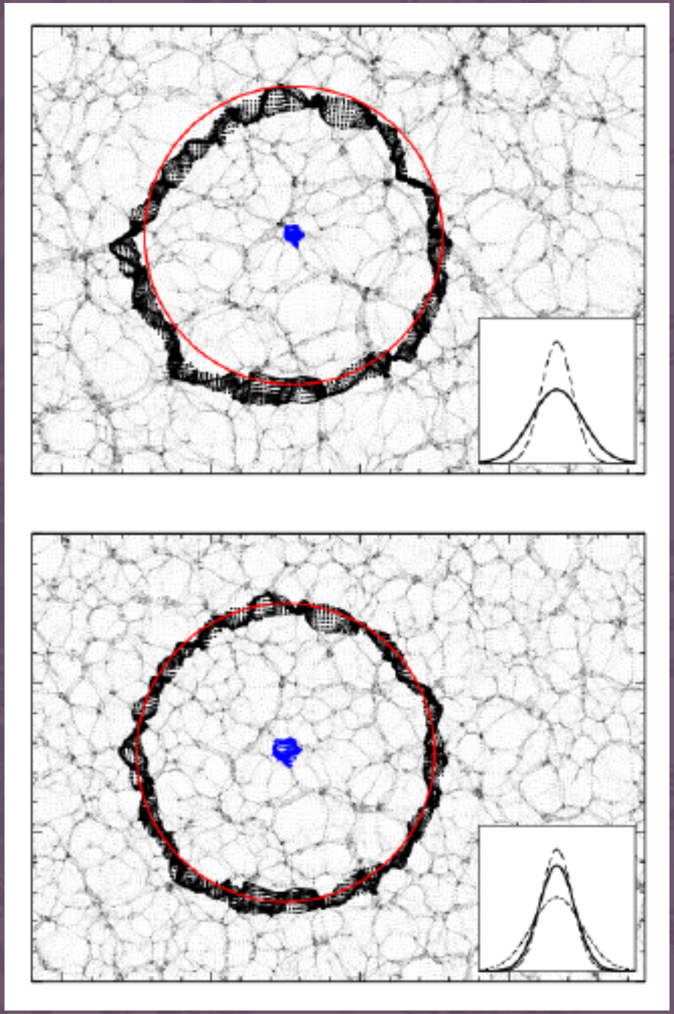
AP test: Demanding statistical isotropy of structure constrains $H(z) D_A(z)$. Potentially large gains if measured at smaller scale than BAO. Can transfer BAO/SN measures of $D_A(z)$ to $H(z)$, improving dark energy sensitivity.

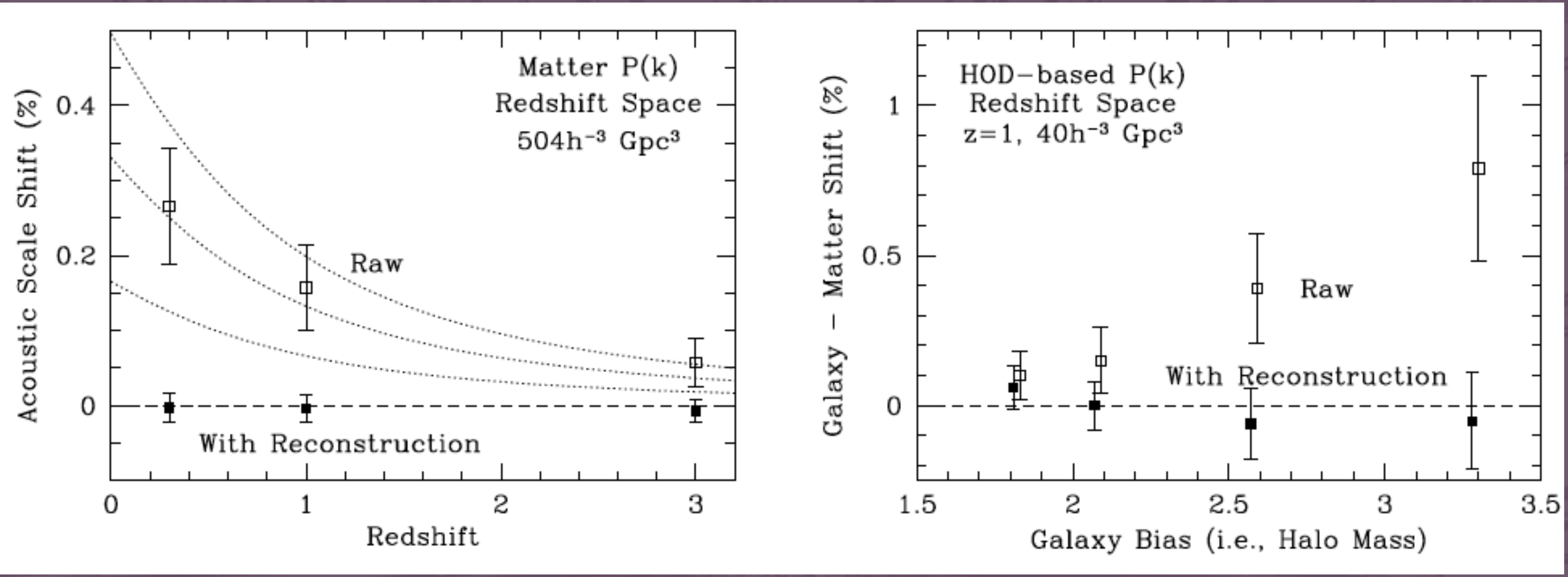
RSD (the peculiar velocity part) is a systematic for AP.





BAO reconstruction sharpens acoustic peak and removes non-linear shift by "running gravity backwards" to (approximately) recover linear density field.

Figs from Padmanabhan et al. 2012.



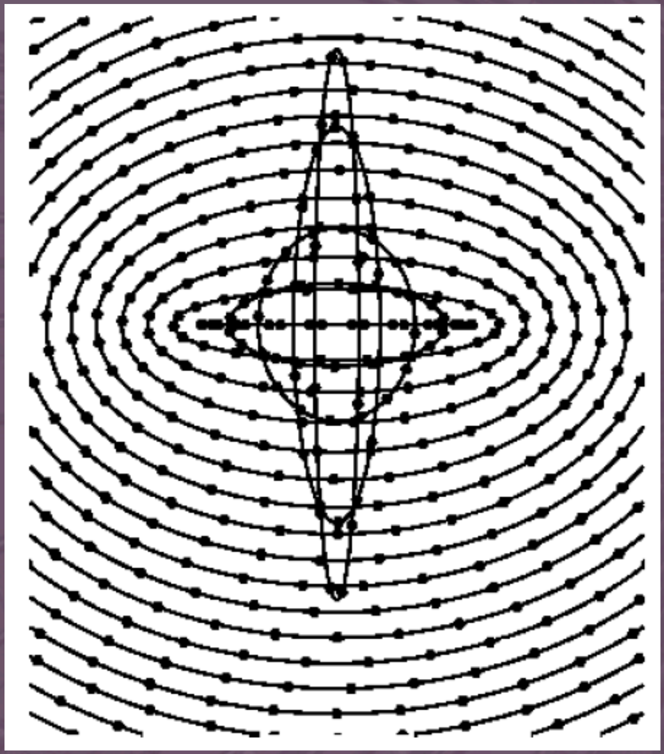

BAO robustness: Current simulations imply 0.1 – 0.3% shifts of acoustic scale from non-linear evolution, somewhat larger for highly biased tracers. Reconstruction removes shift at level of 0.1% or better.

Figs originally from Seo et al. (2010) and Mehta et al. (2011).

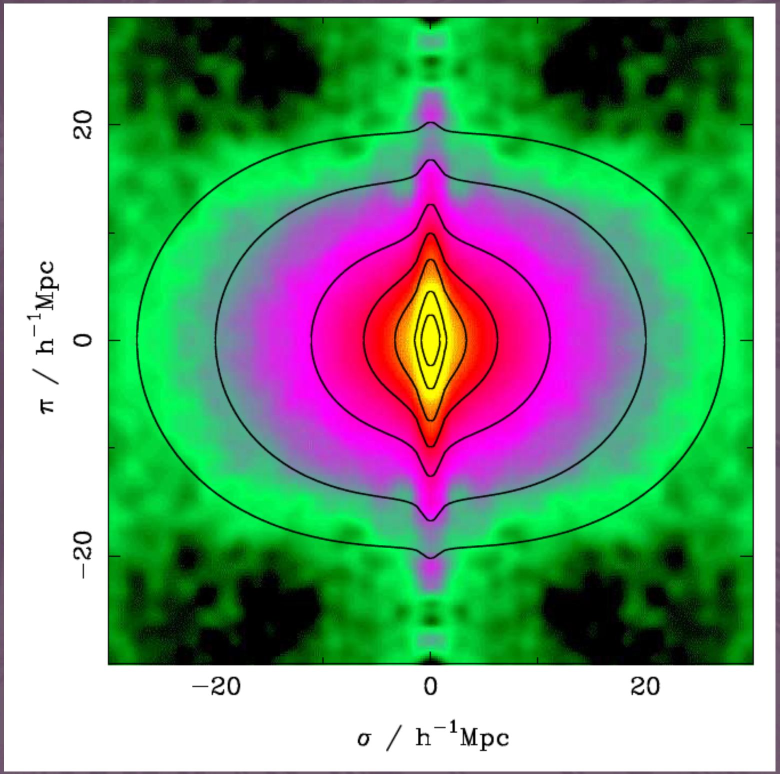
# Peculiar Velocity Distortions

Coherent peculiar velocities compress large scale overdensities along the line of sight.

Incoherent velocity dispersions in collapsed structures stretch them along the line of sight, producing "fingers of God."



Hamilton 1998 (Kaiser 1987)




Peacock et al. 2001, 2dFGRS

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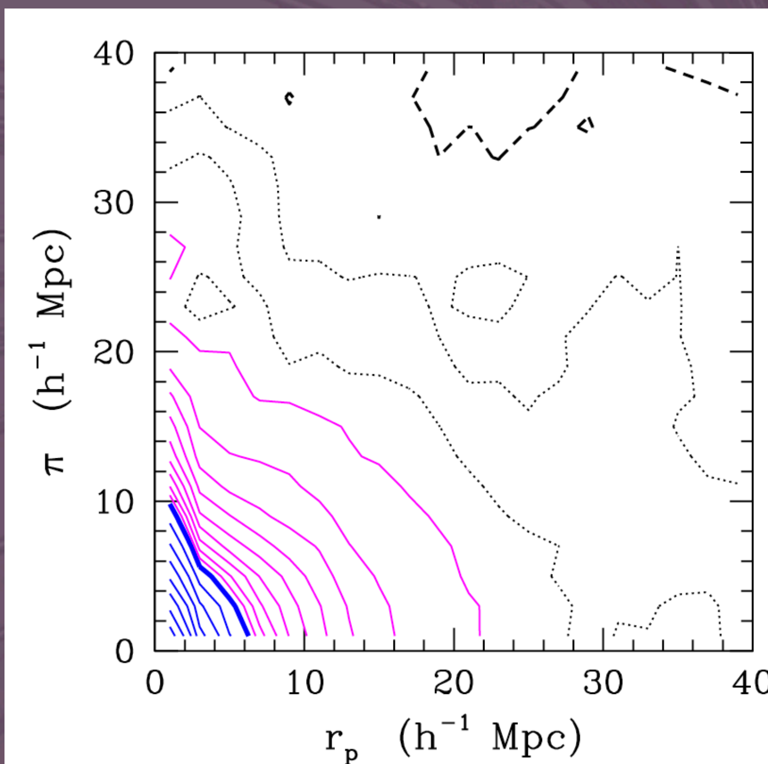
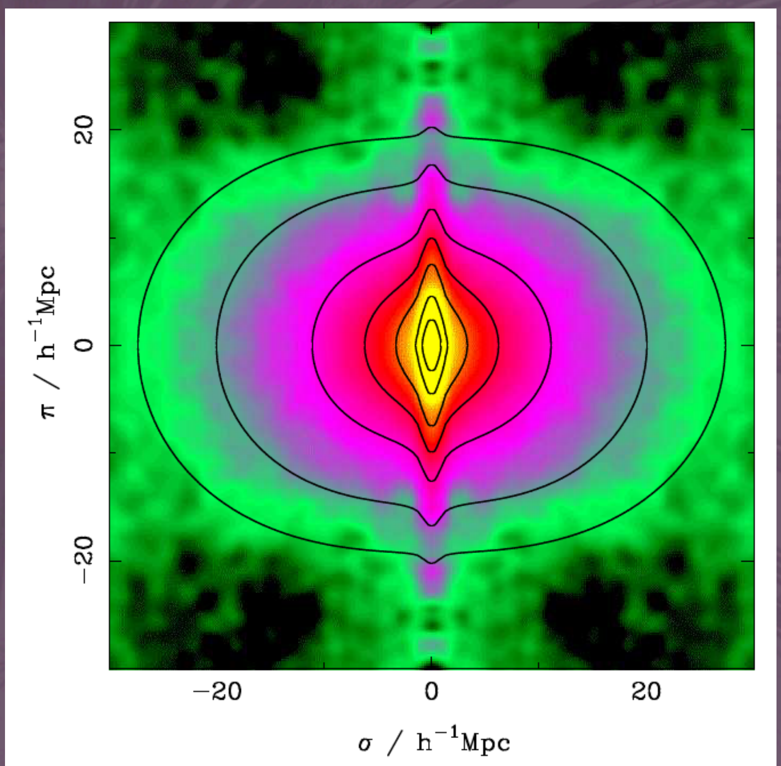



Zehavi et al. 2011, SDSS DR7

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In General Relativity, large scale fluctuations grow in proportion to linear growth factor G(z):

$$\frac{G(z)}{G_0} \approx \exp\left( - \int_0^z \frac{dz'}{1+z'} \left[ \Omega_m (1+z)^3 \frac{H_0^2}{H^2(z)} \right]^\gamma \right) \ , \quad \gamma \approx 0.55$$

Logarithmic growth rate dlnG/dlna = $f(z) \approx [\Omega_m(z)]^\gamma$

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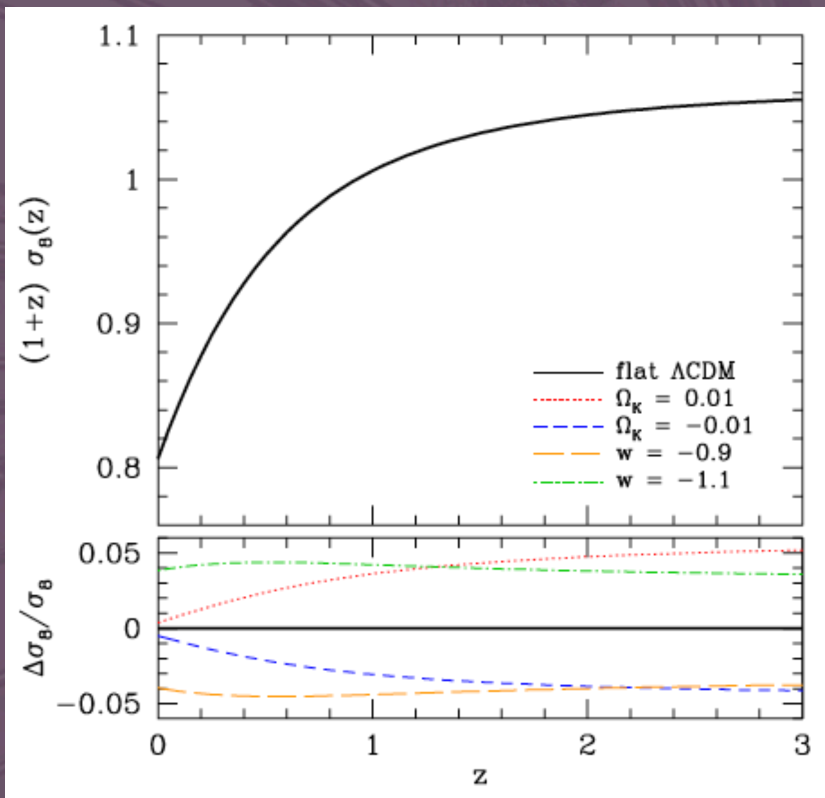
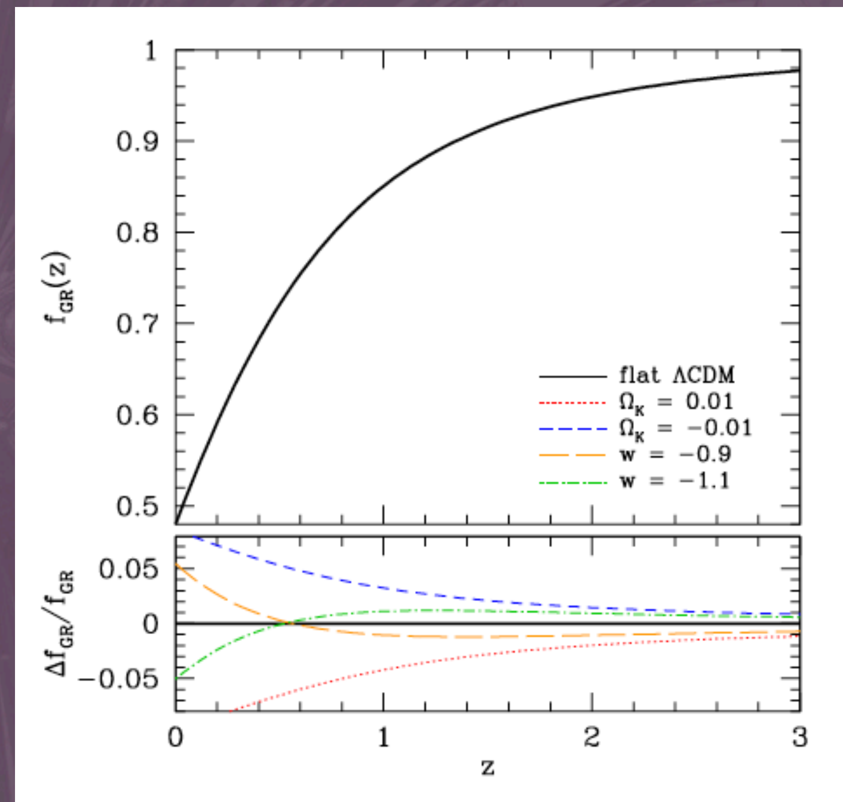



Matter fluctuation amplitude

$\sigma\ (R = 8h^{-1}\ \mathrm{Mpc}) = \sigma_8$

Logarithmic growth rate

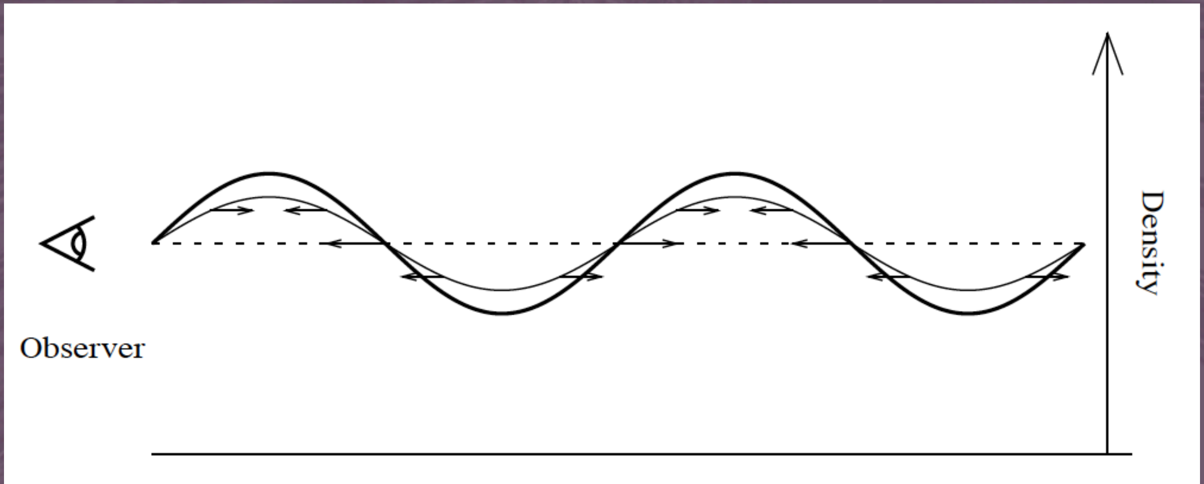
Linear perturbation theory (Kaiser 1987) for single Fourier mode:

$$\Delta_{g,s} = [b_g + f(z)\mu^2]\,\Delta_{m,r} \quad ; \quad \mu = \cos \mathbf{k} \bullet \mathbf{l}$$

making the power spectrum

$$P_{g,s}(k,\mu) = [b_g + f(z)\mu^2]^2\, P_m(k) \times \exp(-k^2\mu^2\sigma_v^{\,2})$$

where small scale random velocities are incoherent, dispersion $\sigma_v$.




Hamilton 1998

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- Use μ-dependence of $P_{g,s}(k,\mu)$ to back out $\sigma_8(z)f(z)$.
- Small scale velocities treated via "nuisance parameters."

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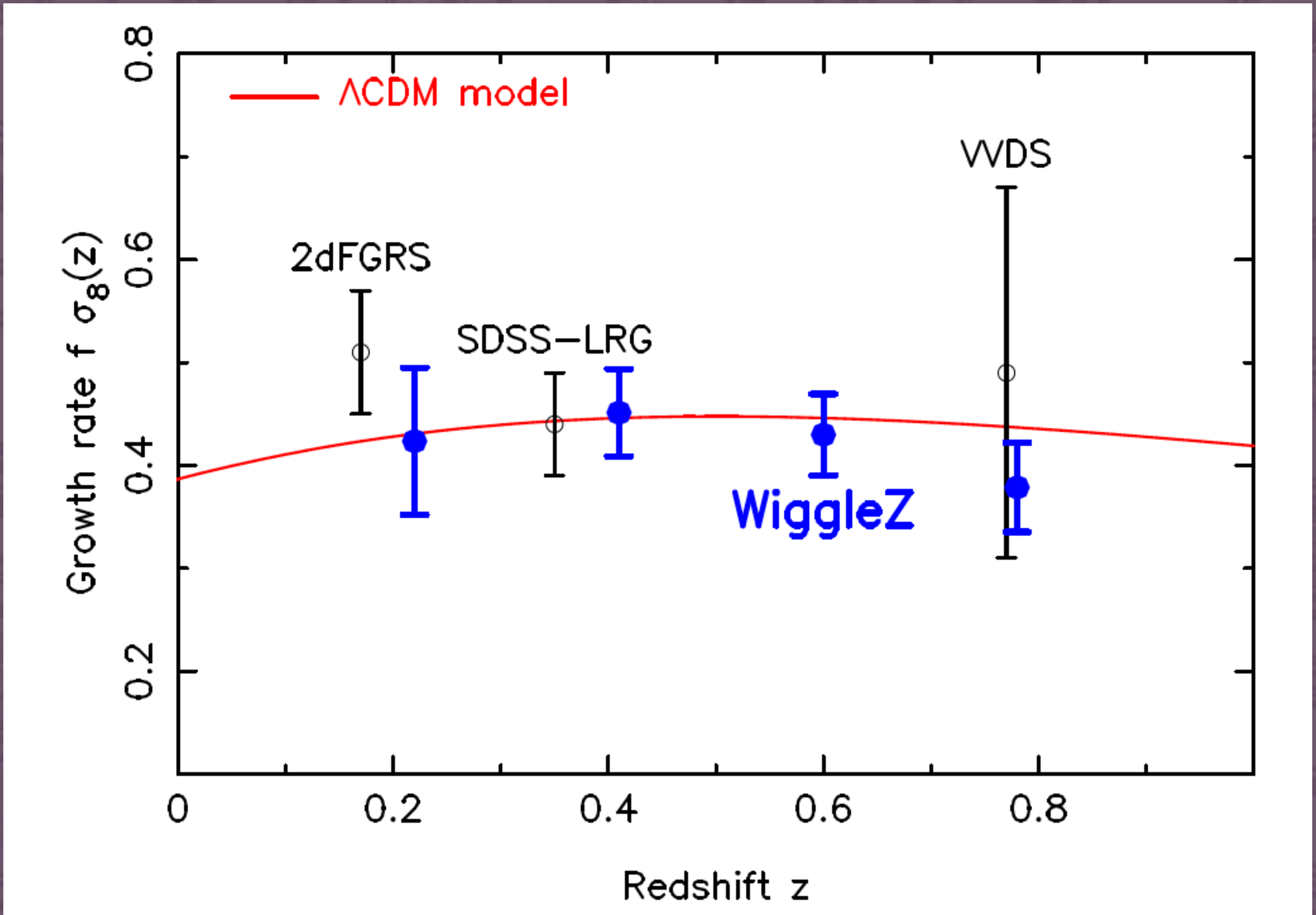
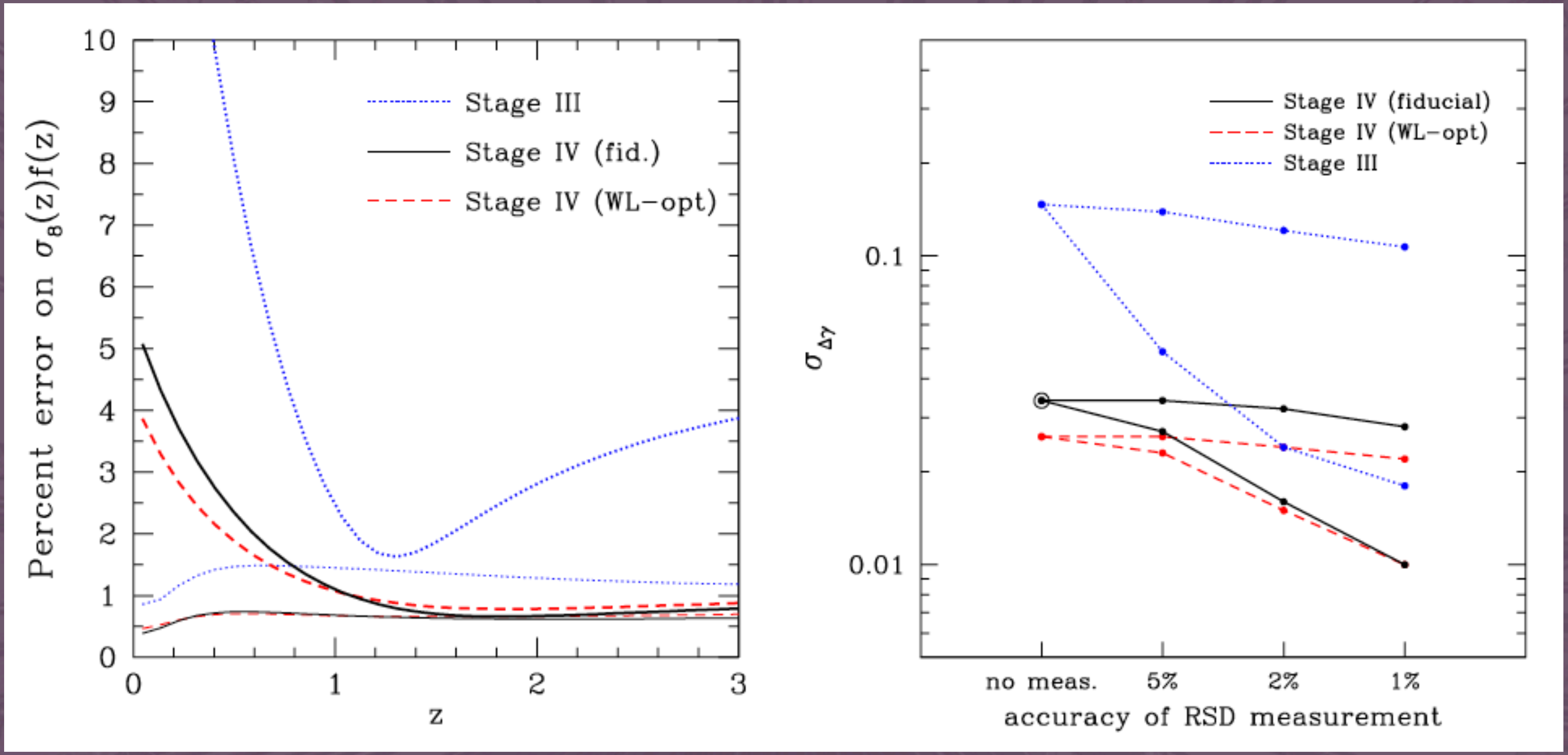
- Use $\mu$-dependence of $P_{g,s}(k,\mu)$ to back out $\sigma_8(z)f(z)$.
- Small scale velocities treated via "nuisance parameters."
- Cross-correlation of tracer populations of different $b_g$ yields additional, mode-by-mode leverage (McDonald & Seljak 2008).
- Recent papers (Bernstein & Cai 2011; Gaztanaga et al 2011) suggest that overlapping WL and spectroscopic surveys can yield significantly better constraints than non-overlapping surveys.
- In essence, WL by redshift survey galaxies calibrates absolute scale of $b_g$. Expected gain is quite dependent on details of surveys.

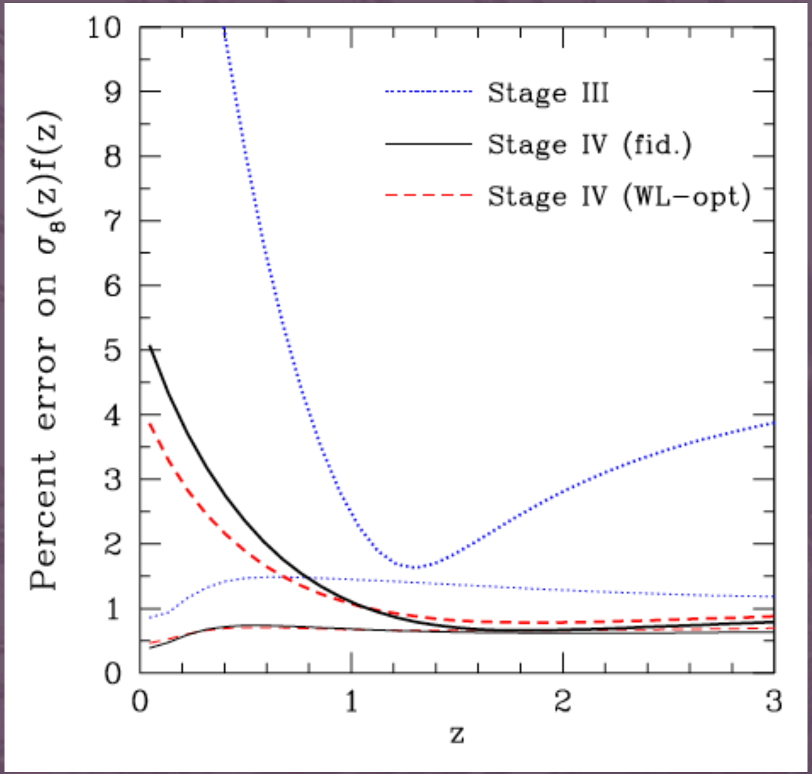


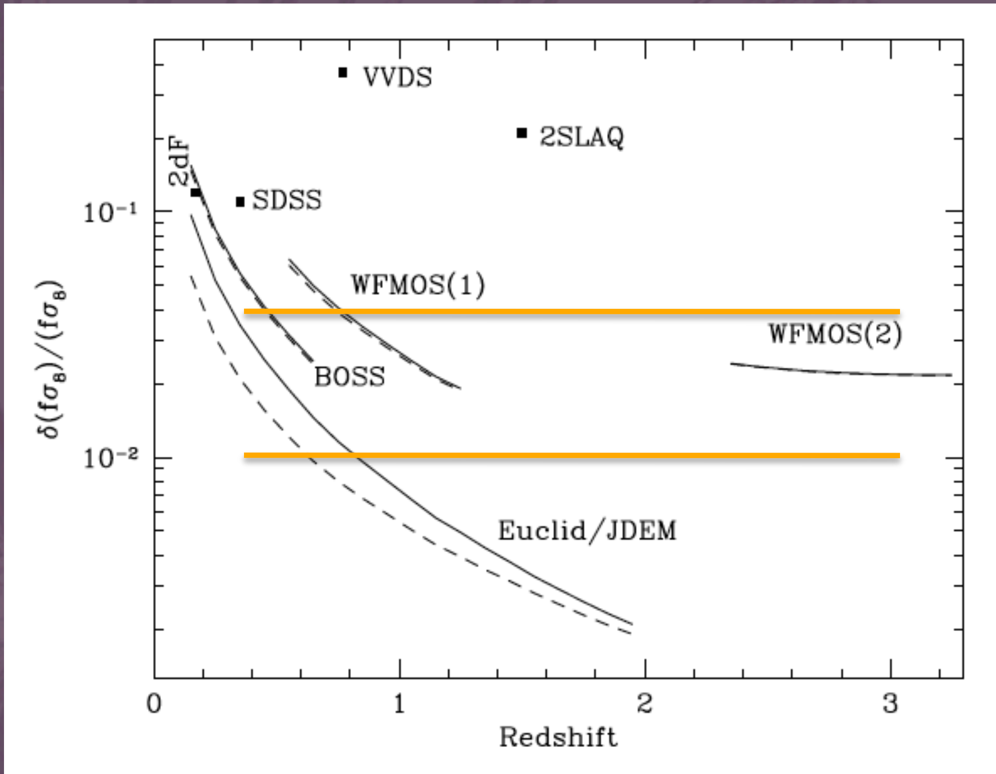

Blake et al. 2011




Thick black curve: Forecast errors on RSD observable from fiducial Stage IV CMB+SN+BAO+WL program, assuming $w_0$-$w_a$ and allowing GR deviations.

Improvement in $\Delta\gamma$ constraint from adding RSD measurement at z=0.2 (top) or z=1 (bottom).

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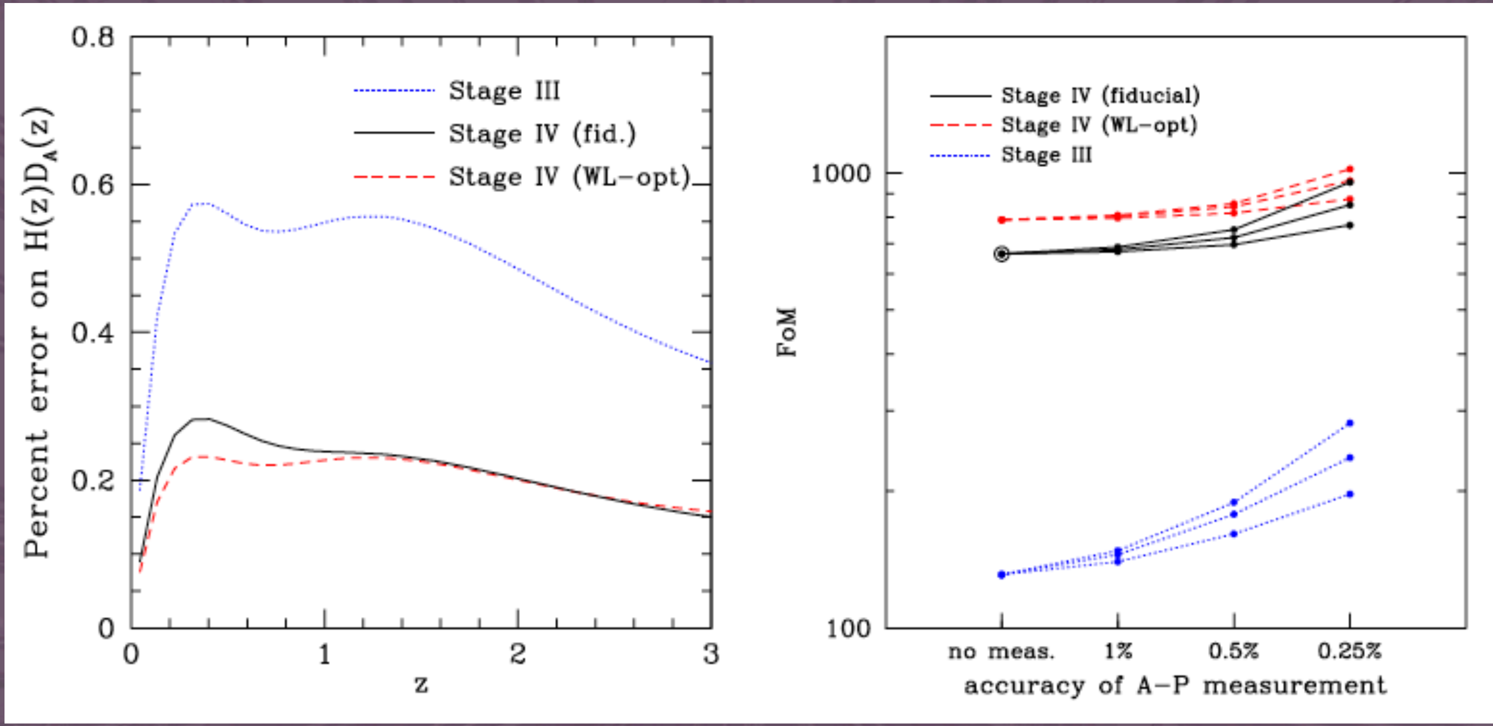
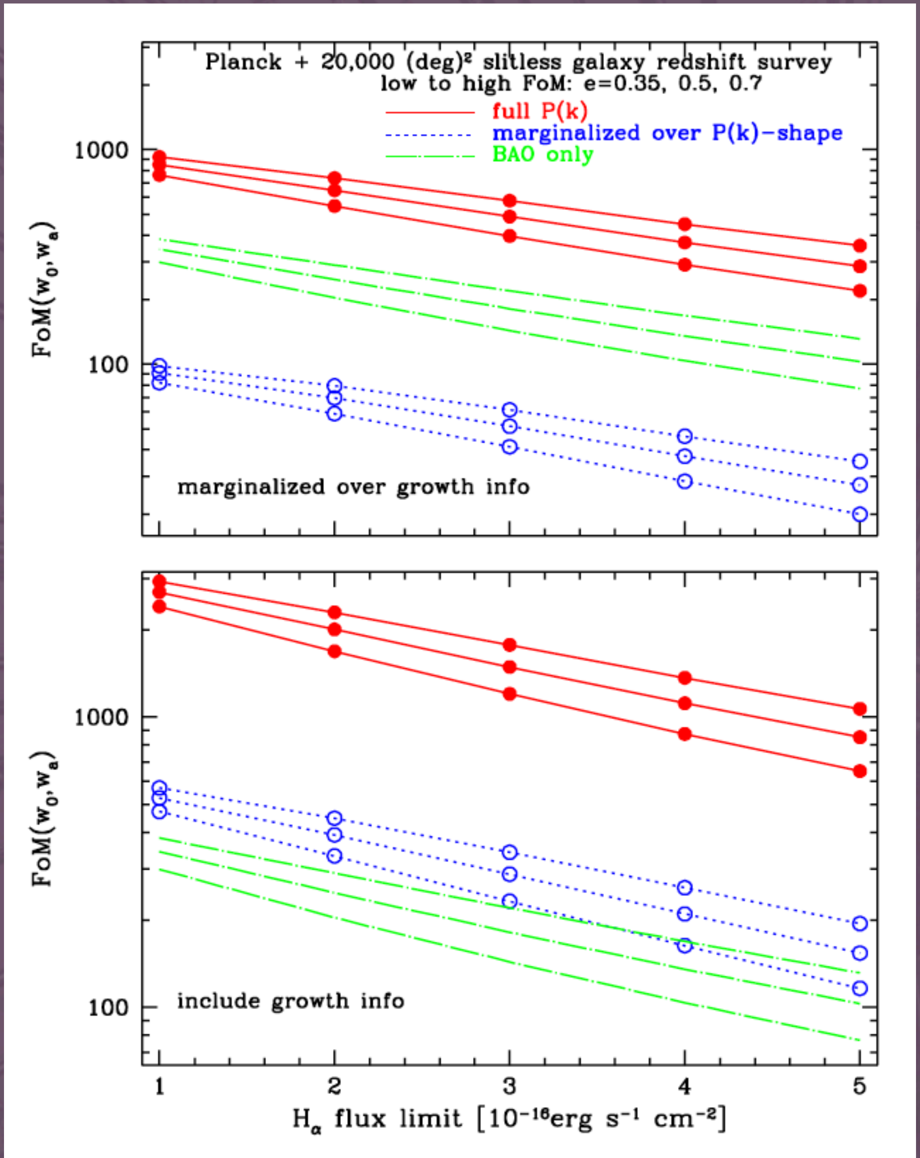
RSD performance forecasts by Percival, Song, & White 2008




- Alcock-Paczynski observable $H(z)D_A(z)$ already predicted to sub-percent accuracy by Stage III CMB+SN+BAO+WL.
- But attainable precision is very high in principle, depending on how small a scale one can work to.
- Modeling of peculiar velocity RSD is the main systematic.
- AP has direct power and converts BAO $D_A(z)$ to $H(z)$.




DETF FoM forecasts for Euclid/WFIRST-like survey:
full P(k) including RSD and AP
vs.
BAO-only

Not assuming GR

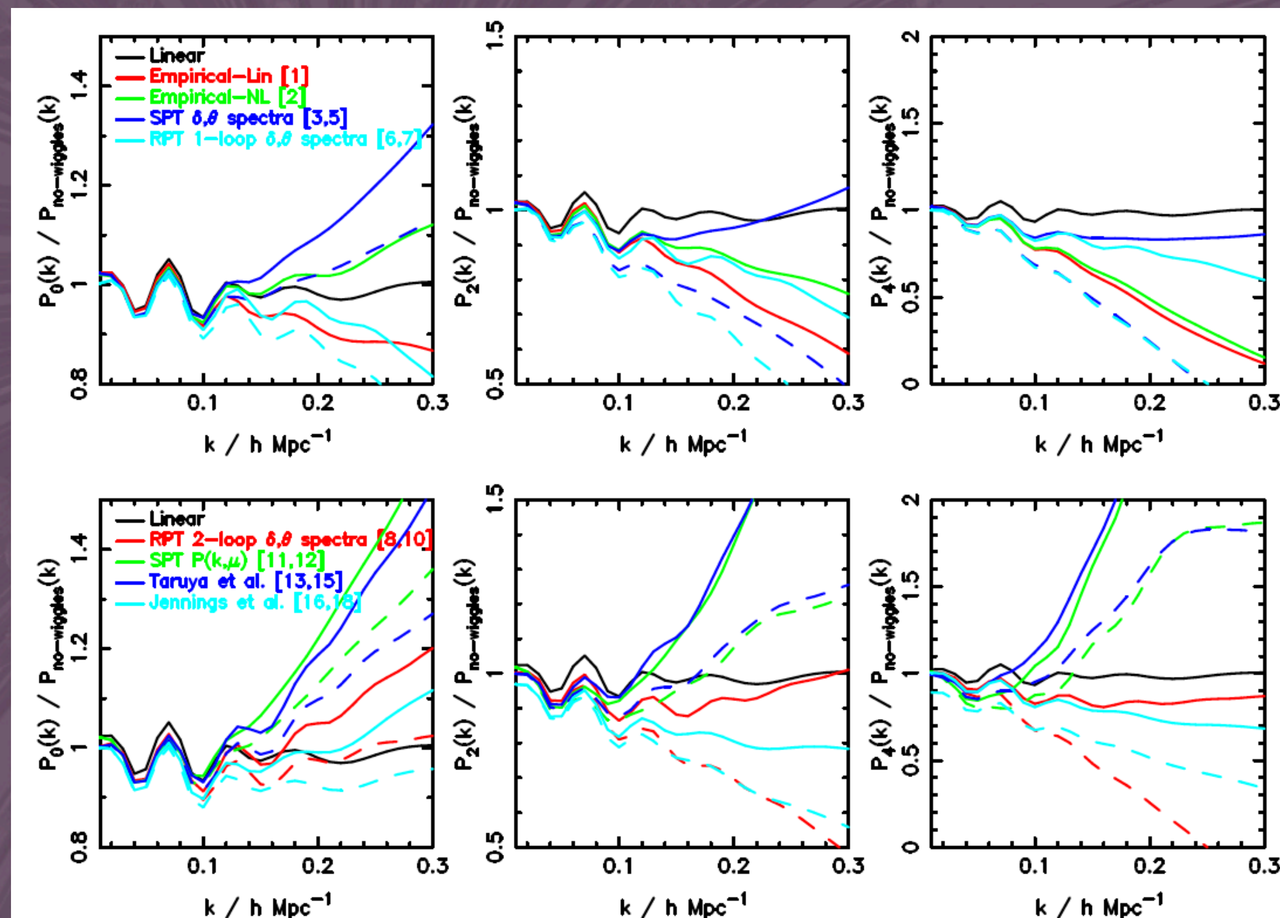
Assuming GR, note change of vertical axis.

Y. Wang, W. Percival, et al. 2010

# The theoretical challenge:

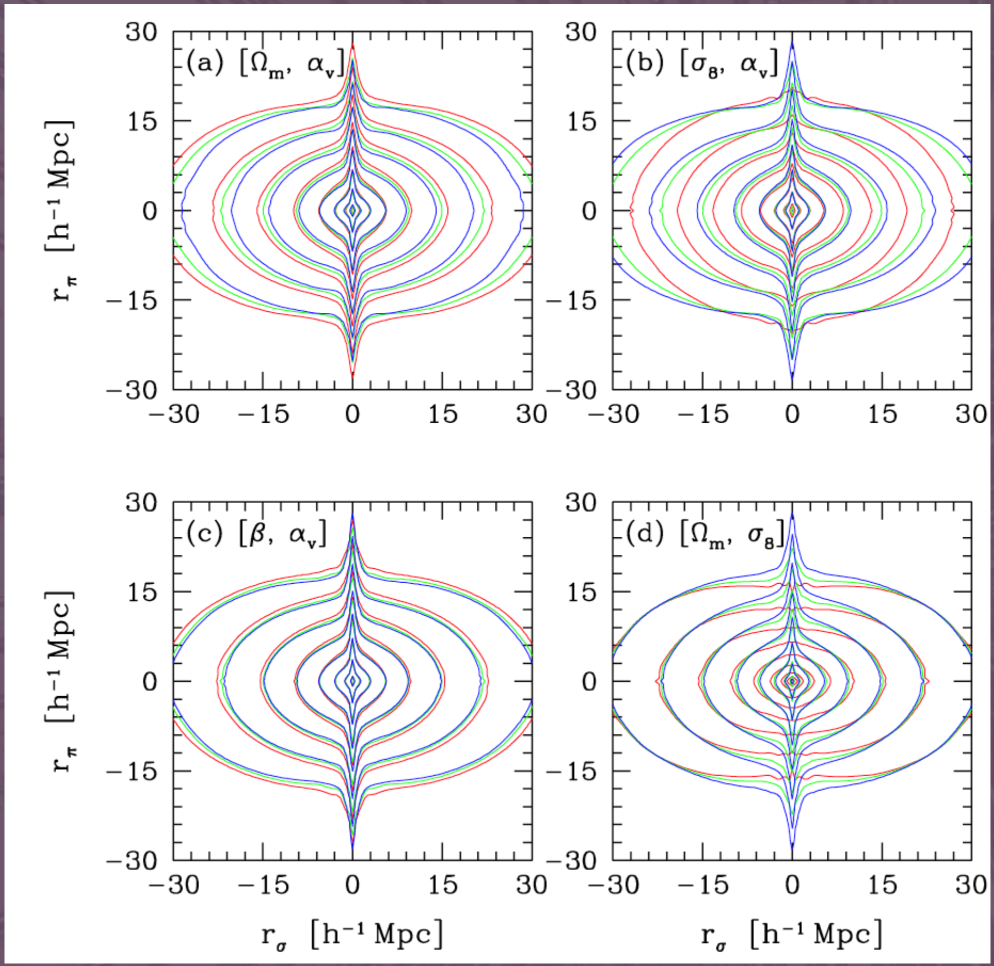
Develop models of peculiar velocity distortions that work to moderately non-linear scales and are accurate enough to exploit high statistical precision.

One approach: perturbation theory plus perturbative description of galaxy bias.




Blake et al. 2011

Tinker, Weinberg, & Zheng 2006



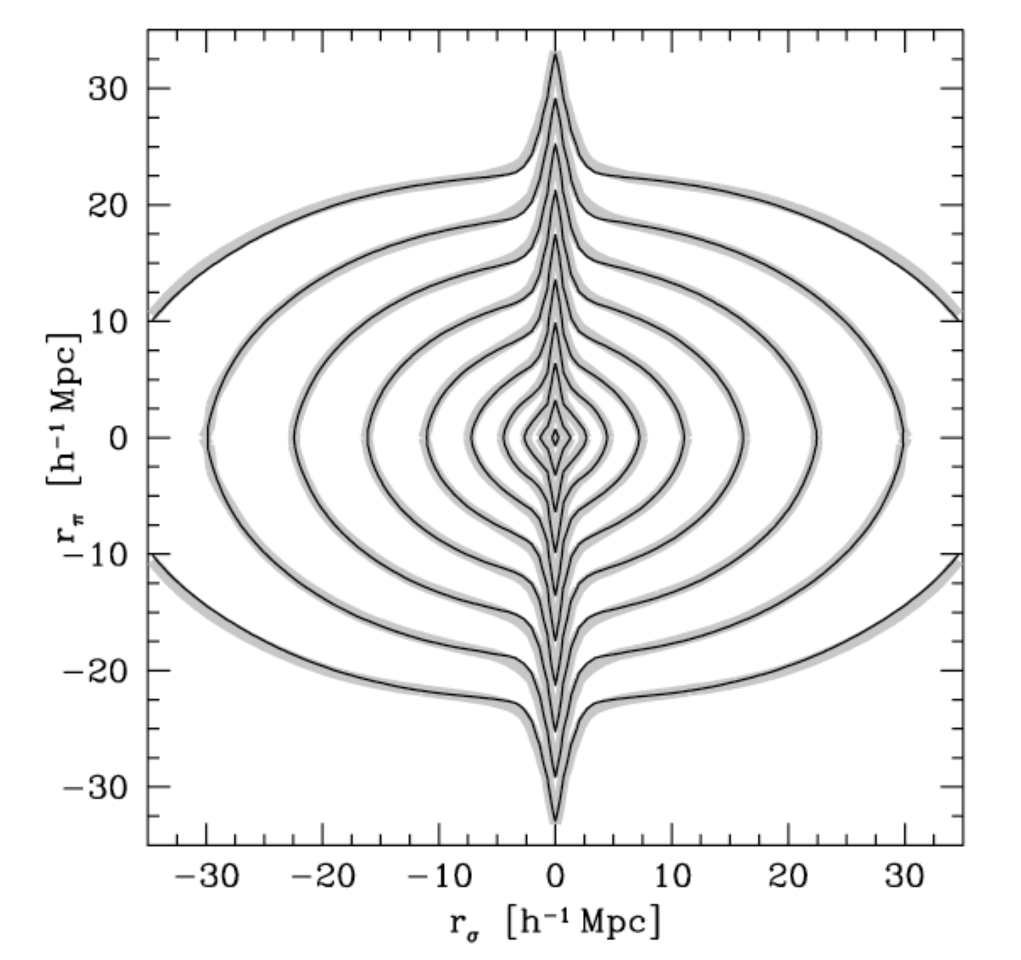

Another approach: Model galaxy bias with halo occupation distribution (HOD), predict with N-body simulations.

Marginalize over HOD parameters, including velocity bias.

Use small scale information to constrain model, break degeneracies. Not just a "nuisance."

Top left: Varying $\sigma_8$ only.
Top right: Varying $\Omega_m$ only.
Bottom right: Varying galaxy velocity dispersion bias.

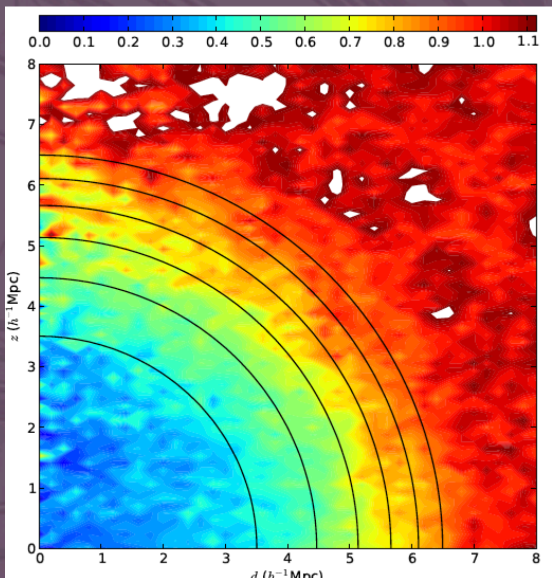
Tinker 2007



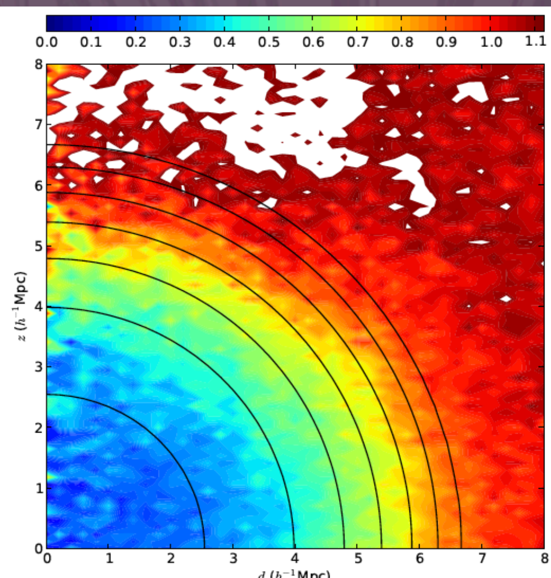

Tinker's (2007) analytic model describes HOD N-body results accurately. But it's fairly complicated, with elements calibrated on simulations.

Reid & White (2010) describe a similar but simpler approach, which may prove accurate enough on large scales.

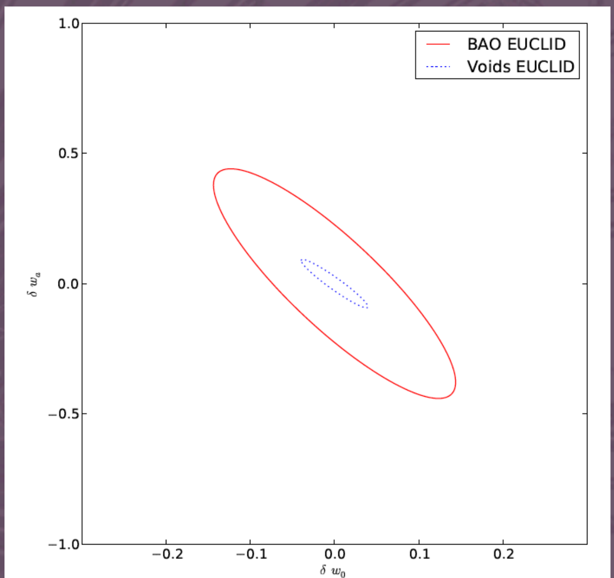
# Voids for Alcock-Paczynski?




Stacked void density profile: real space



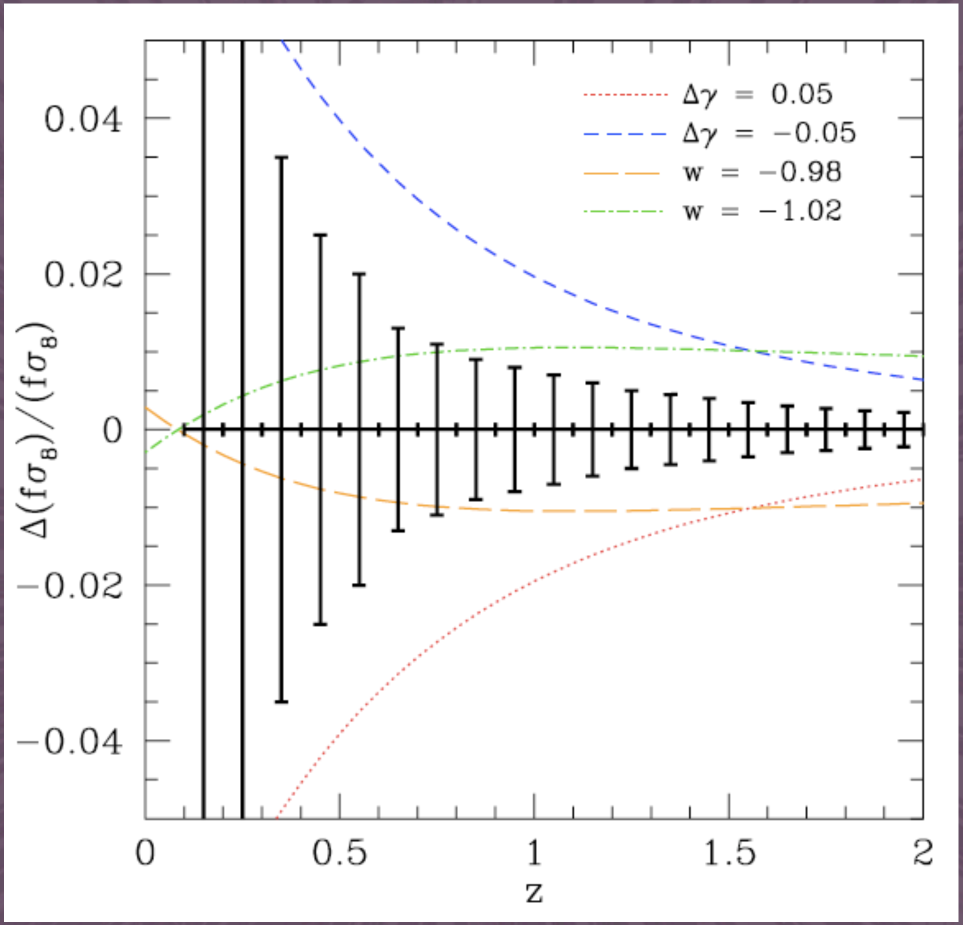

Stacked void density profile: redshift space




Euclid forecast

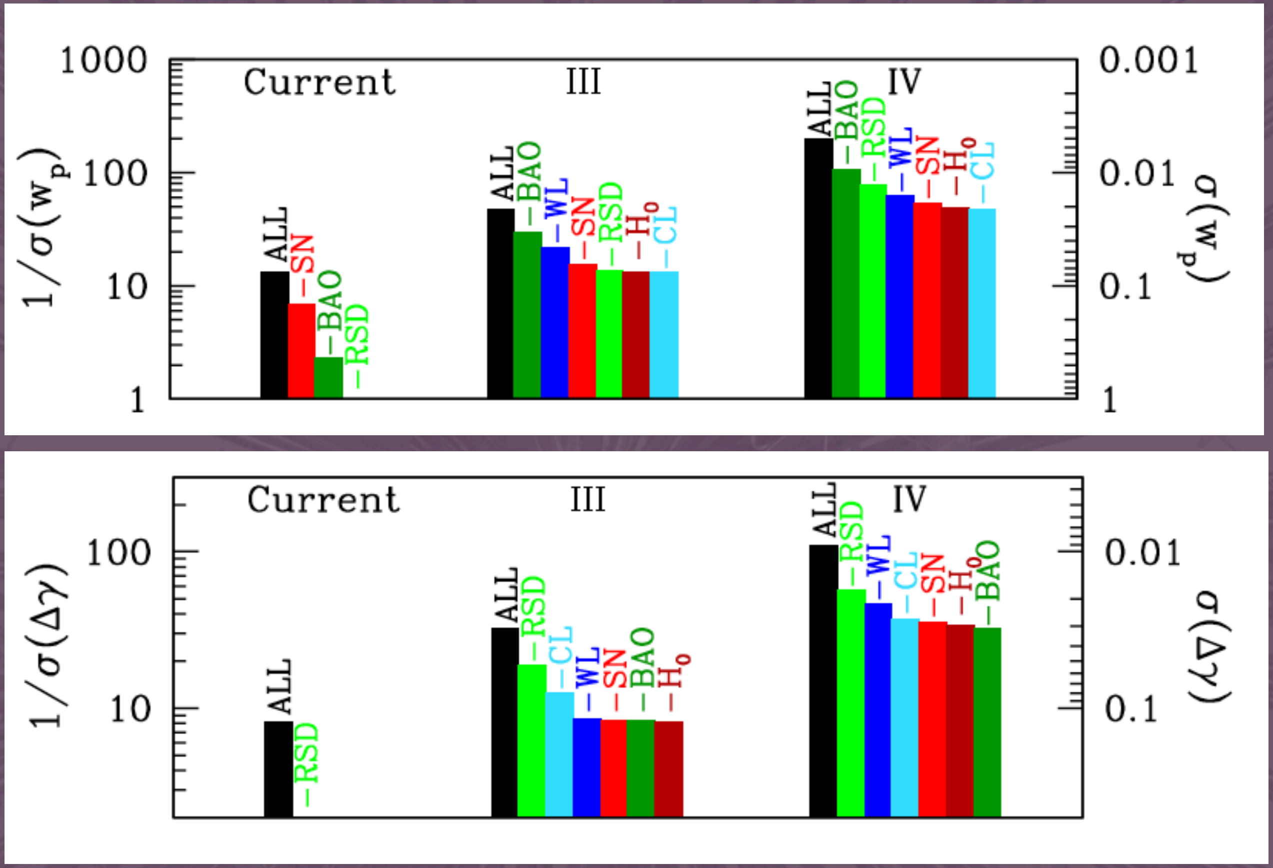
Lavaux & Wandelt (2010, 2011) propose using average shape of voids to implement AP test (see also Ryden 1995).
Scale well below BAO scale, so statistics much better.
Avoids high velocity dispersion regions, peculiar velocity correction might be insensitive to uncertain details.

Figure: M. Mortonson




Model dependence vs. forecast errors for JDEM/Euclid RSD from Percival et al. 2008

# Forecast errors from a notional 6-probe program (+ CMB)




Acceleration review, fig. by M. Mortonson

Probes dropped in order of leverage. Note *potentially* powerful contribution from redshift-space distortions (RSD).

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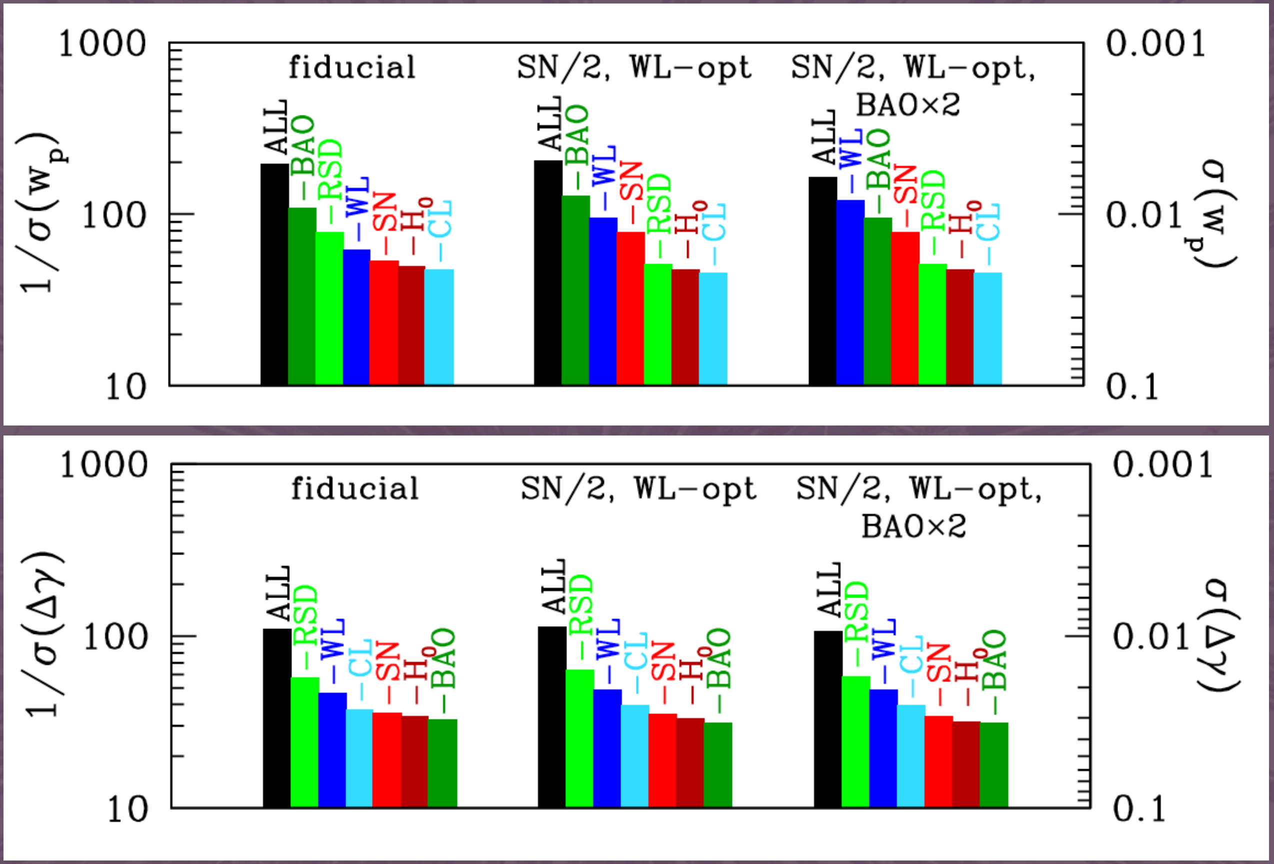


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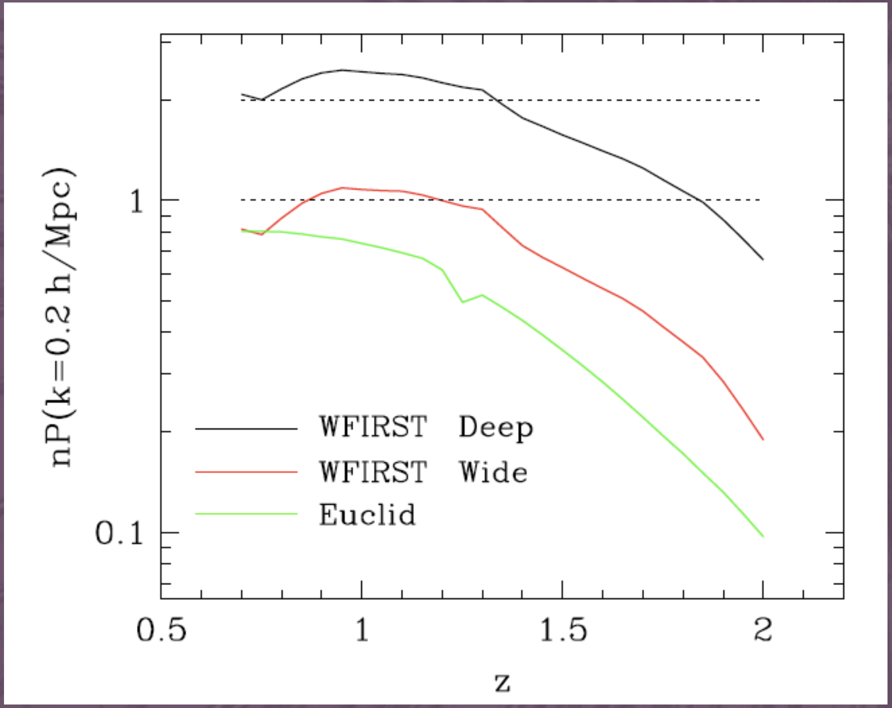
Effective volume of a survey for power-spectrum measurement at wavenumber k is

$V_{eff}(k) = V_0\,[nP / (1 + nP)]^2 \quad \approx \; (nP)^2\, V_0$ for $nP << 1$.

n = mean space density, P = power amplitude at k

$V_{eff} = 0.25\, V_0$ for nP=1, $V_0 = 0.44$ for nP=2




- Euclid is shot-noise dominated at all z.
- WFIRST-wide is shot-noise dominated at z > 1.4.
- WFIRST-deep is close to sample variance limited.
- But $nP \geq 2$ probably better criterion than $nP \geq 1$.

Based on calculations by C. Hirata

We are rightly concerned about systematic uncertainties, including the "unknown unknowns."

But the history of cosmological surveys shows that analysis methods can advance dramatically between when they are proposed and when they are producing data.

The questions of interest can also change in this interval.

Cosmological studies with WFIRST are reasonably likely to outperform our forecasts, perhaps by a large factor.

# Conclusions

- RSD can be a powerful constraint on growth of structure, competitive with or stronger than WL.
- AP on small scales could greatly improve constraints on expansion history.
- Realizing these gains requires substantial theoretical advances to control modeling uncertainties.
- Euclid and WFIRST-wide surveys are still well below sampling variance limit over much of their volume. Additional factors (reconstruction, RSD modeling) probably favor higher nP, though this has not really been investigated.
- The potential return from the WFIRST redshift survey is high, maybe much larger than that from BAO alone.

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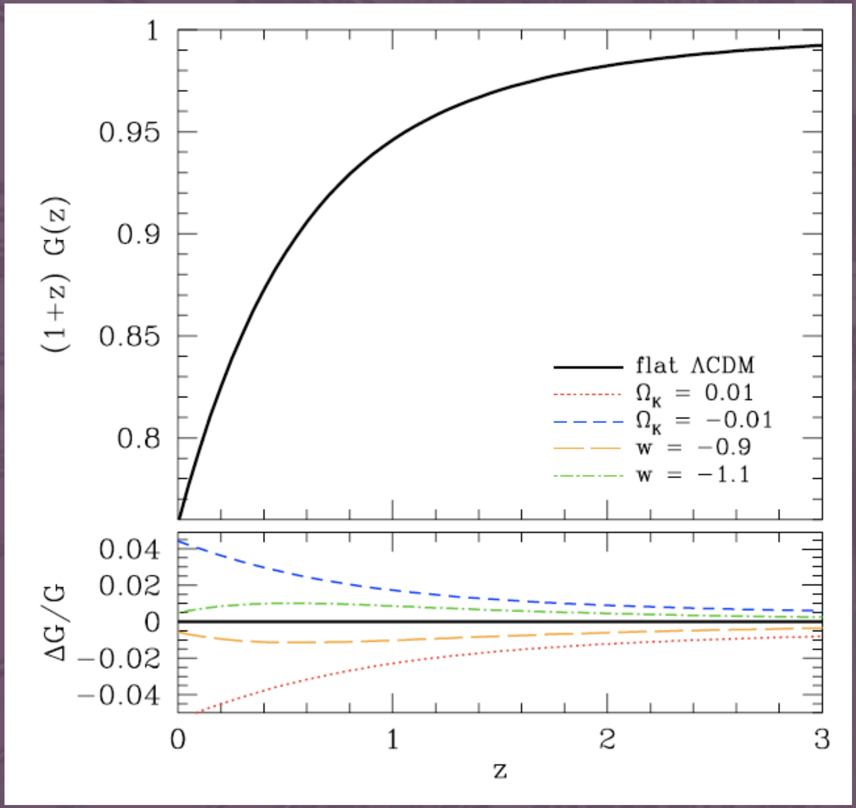
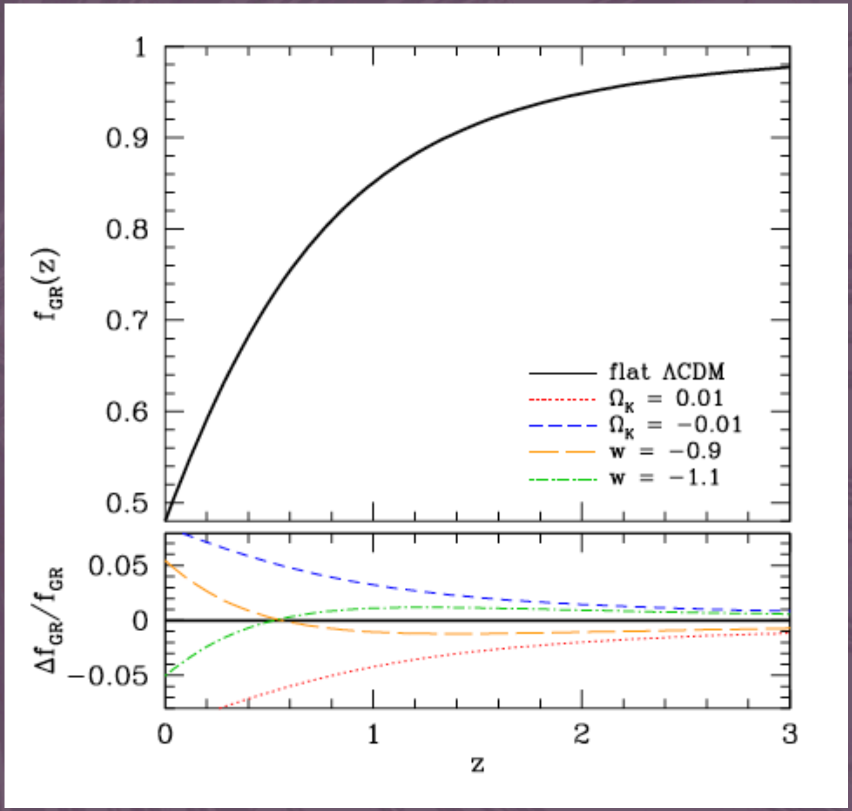
Logarithmic growth rate $d\ln G/d\ln a = f(z) \approx [\Omega_m(z)]^\gamma$




Linear growth factor

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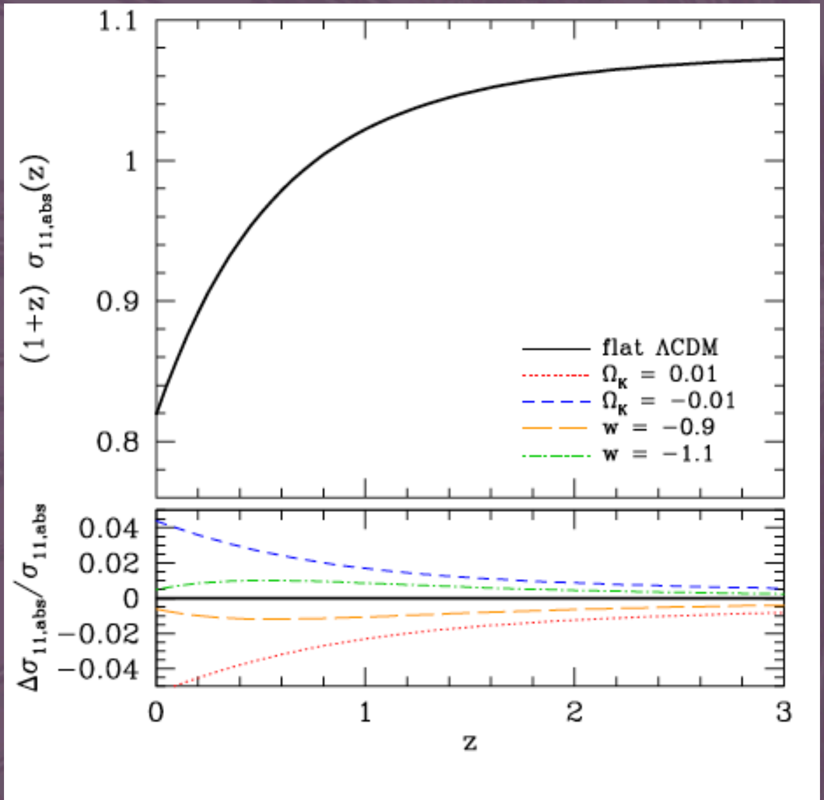
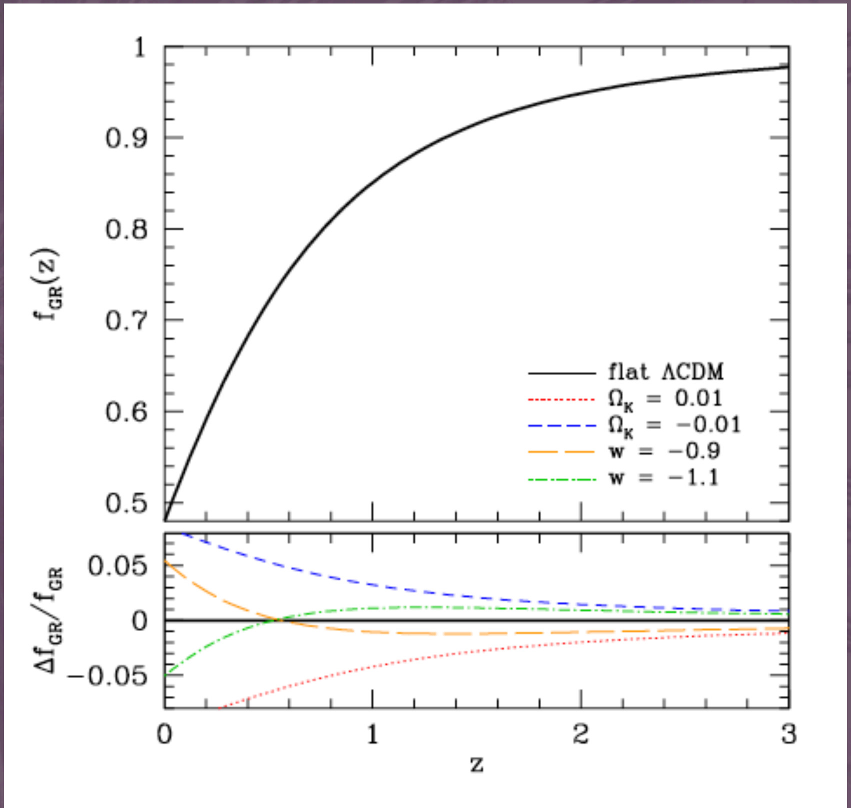



Matter fluctuation amplitude

$\sigma$ (R = 11 Mpc) = $\sigma_{11,abs}$




Logarithmic growth rate