Final results from the Sloan Digital Sky Survey: geometry of the universe and constraints on cosmological neutrinos

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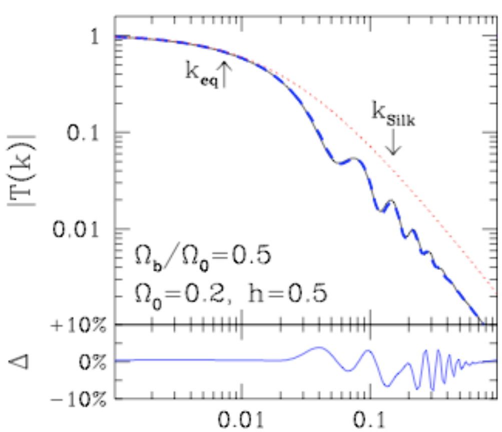
Outline

- Physics of Large Scale Structure (LSS): linear theory
- The “theory” of observing LSS
- SDSS DR7 BAO results: geometric constraints
- Modeling the DR7 Power Spectrum Shape
- Constraints on Cosmological Neutrinos

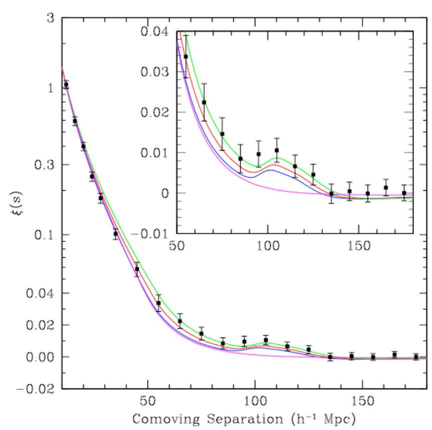
The Physics of LSS: CDM, baryons, photons, neutrinos I

$$P_{\mathrm{matter}}(k,z) = T^2(k)P_{\mathrm{prim}}(k)D^2(z)$$

- Primordial Perturbations: Gaussian and adiabatic $P_{\mathrm{prim}}(k) = A_0(k/k_0)^{n_s}$
- Transfer function T(k) describing physics at matter-radiation equality
  - depends only on $\Omega_m h^2$, $\Omega_b h^2$, $\Omega_r h^2 = \Omega_\gamma h^2(1+0.2271\ N_{\mathrm{eff}})$
  - horizon at matter-radiation equality $[k_{eq} = \Omega_m h^2(\Omega_r h^2/2)^{-1/2} \sim 0.01\ \mathrm{Mpc}^{-1}]$
  - sound horizon at the baryon drag epoch r_s
- All modes grow at the same rate during matter-domination: D(z)
- CMB peak height ratios give us $\Omega_b h^2$, $\Omega_m h^2/\Omega_r h^2 = 1+z_{eq}$



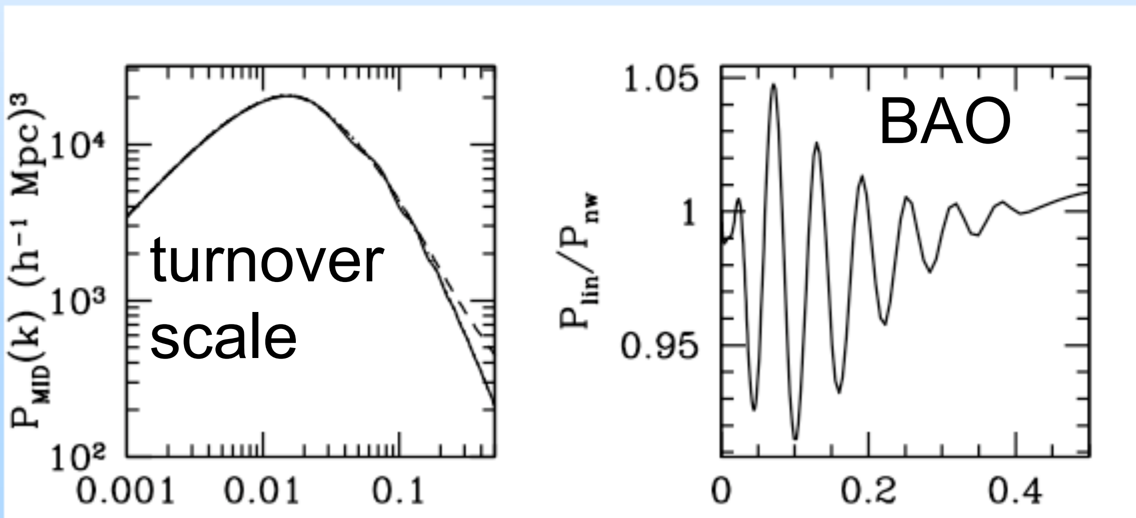
Eisenstein & Hu, 1998, ApJ, 496, 605



Eisenstein et al. 2005, ApJ, 633, 560

Physics of LSS: P(k) as a standard ruler

• WMAP5 almost fixes* the expected $P_{lin}(k)$ in **$\mathbf{Mpc^{-1}}$** through $\Omega_c h^2$ (6%) and $\Omega_b h^2$ (3%), independent of θ_{CMB} (and thus curvature and DE).

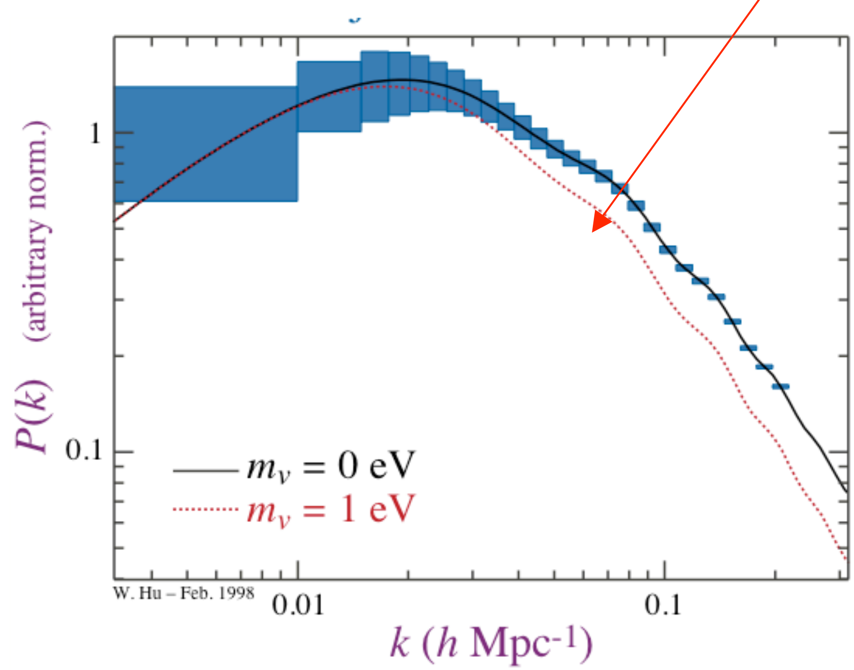


• In the minimal model (N_{eff} = 3.04, Σm_ν = 0), entire P(k) shape acts as a "std ruler" and provides an impressive consistency check -- same physics that generates the CMB at z=1100 also determines clustering at low z.

Physics of LSS: massive neutrinos

- Massive neutrinos $\Sigma\ m_\nu$ <~ 1 eV become non-relativistic AFTER recombination and suppress power on small scales

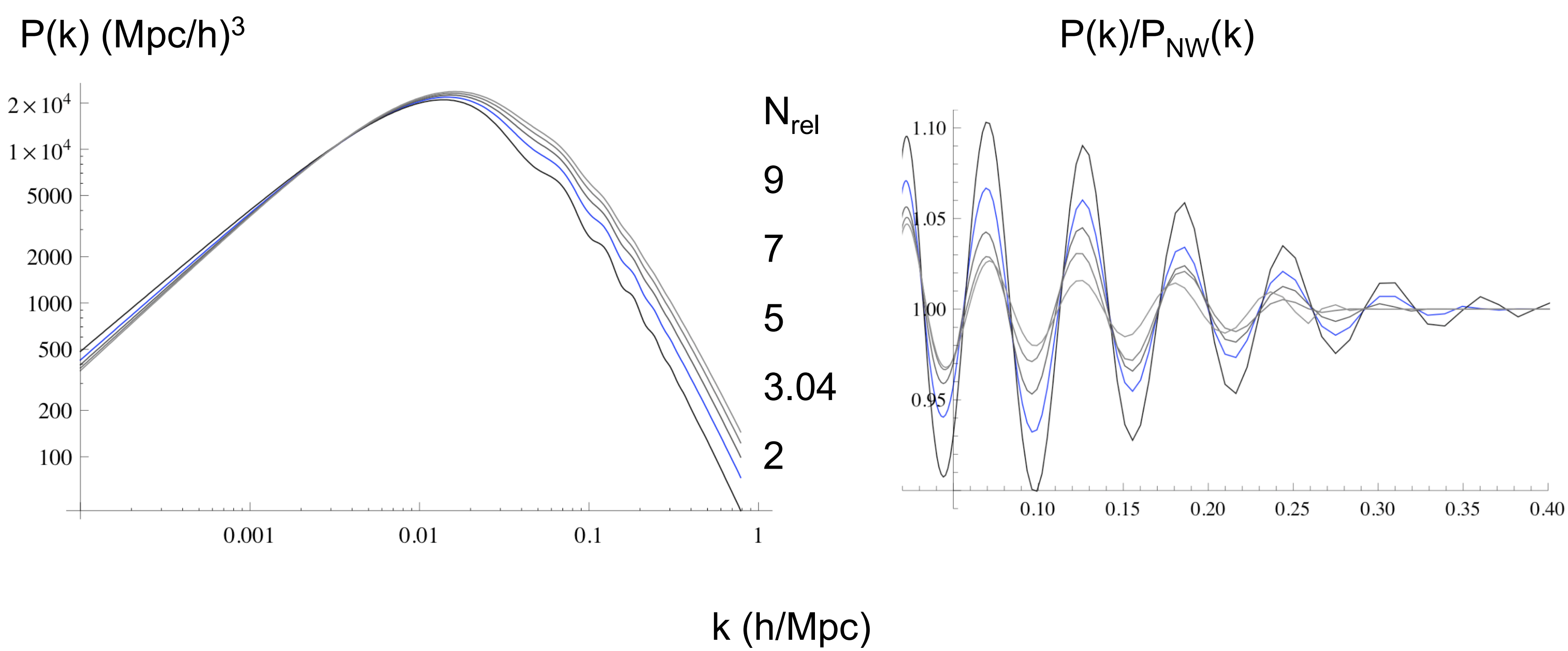
$$P_{\mathrm{matter}}(k, z) = T^2(k) P_{\mathrm{prim}}(k) D^2(z, k, \sum m_\nu)$$



Courtesy of W. Hu

Physics of LSS: relativistic species

- N_{rel} affects matter-radiation equality; degenerate with $\Omega_c h^2$ in WMAP
  (Not true for Planck!)
- Along WMAP degeneracy, both P(k) shape and the Ω_b/Ω_c change:



“Theory” of Observing LSS: Geometry

- We measure θ, φ, z; need a model to convert to co-moving coordinates.

- Transverse: $\chi(z) = \int_0^z \frac{c\,dz}{H(z)}$ Along LOS: $\Delta\chi(z) = \frac{c\,\Delta z}{H(z)}$

- Spherically averaged, isotropic pairs constrain

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

SDSS DR7 Results

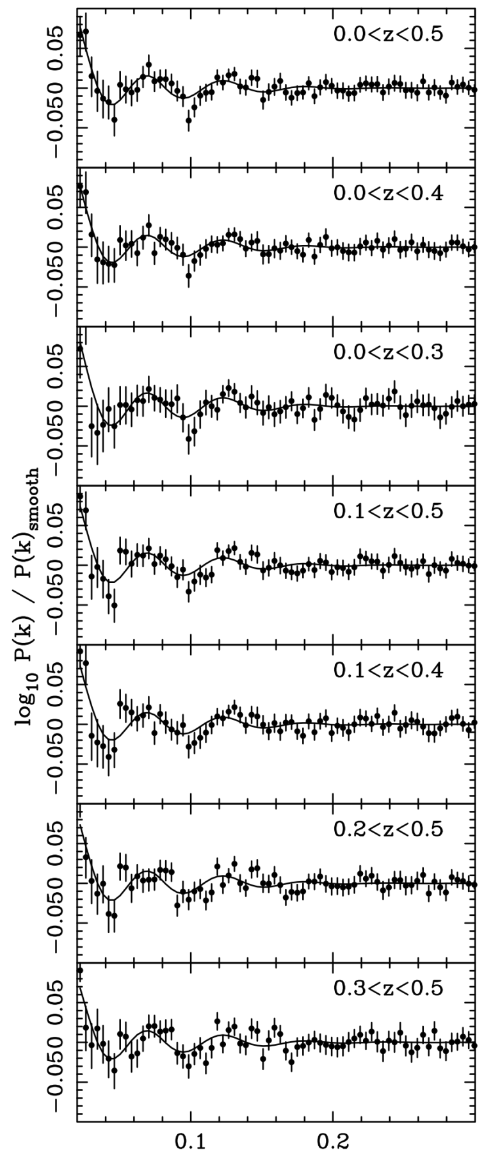
- BAOs only: arXiv:0907.1660
- LRG P(k): arXiv:0907.1659

BAO in SDSS DR7 + 2dFGRS power spectra

- Combine 2dFGRS, SDSS DR7 LRG and Main Galaxies
- Assume a fiducial distance-redshift relation and measure spherically-averaged P(k) in redshift slices
- Fit spectra with model comprising smooth fit × damped BAO
- To first order, isotropically distributed pairs depend on

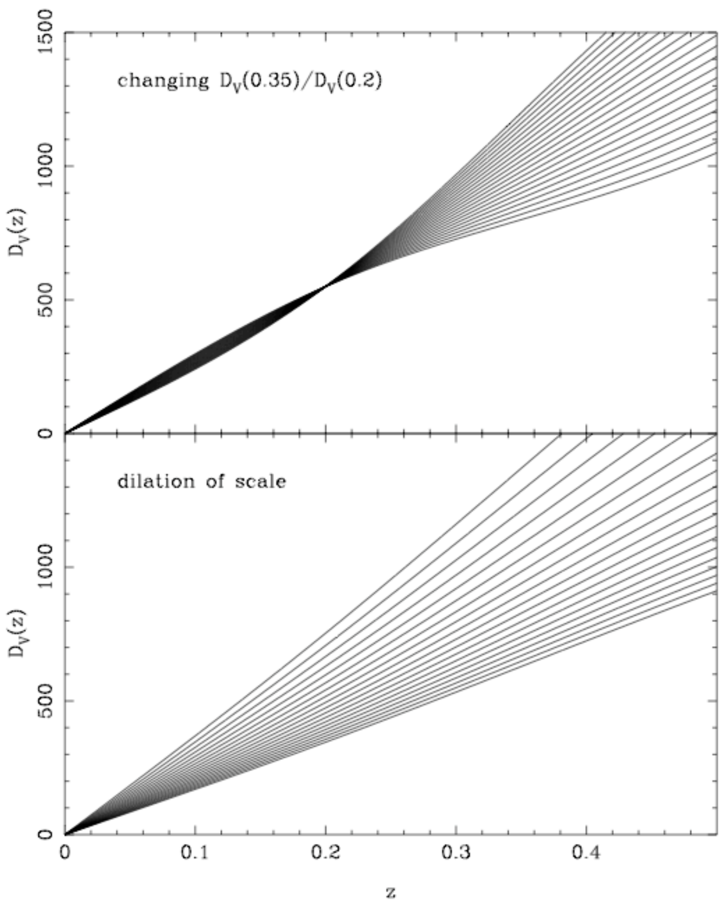
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

- Absorb cosmological dependence of the distance-redshift relation into the window function applied to the model P(k)
- Report model-independent constraint on $r_s/D_V(z_i)$



Percival, **BR**, et al. (2009, arXiv:0907.1660)

SDSS DR7 BAO results: modeling the distance-redshift relation



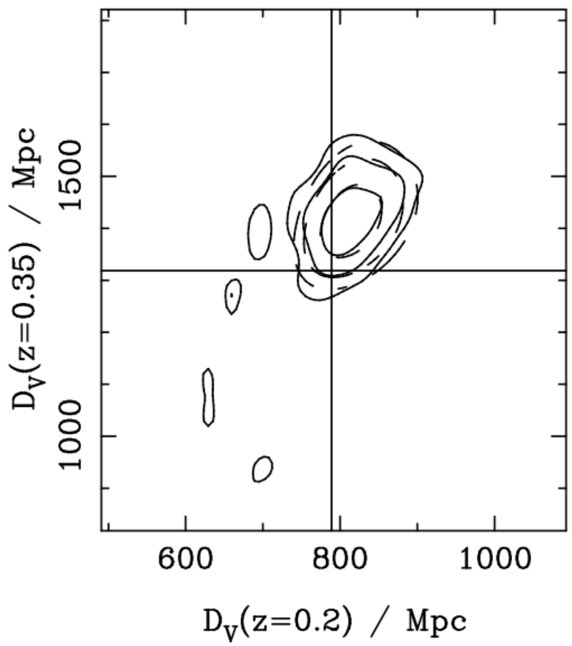
Parameterize distance-redshift relation by smooth fit: can then be used to constrain multiple sets of models with smooth distance-redshift relation

For SDSS+2dFGRS analysis, choose nodes at z=0.2 and z=0.35, for fit to D_V

$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Percival, **BR**, et al. (2009, arXiv:0907.1660)

BAO in SDSS DR7 + 2dFGRS power spectra



- results can be written as independent constraints on a distance measure to z=0.275 and a tilt around this

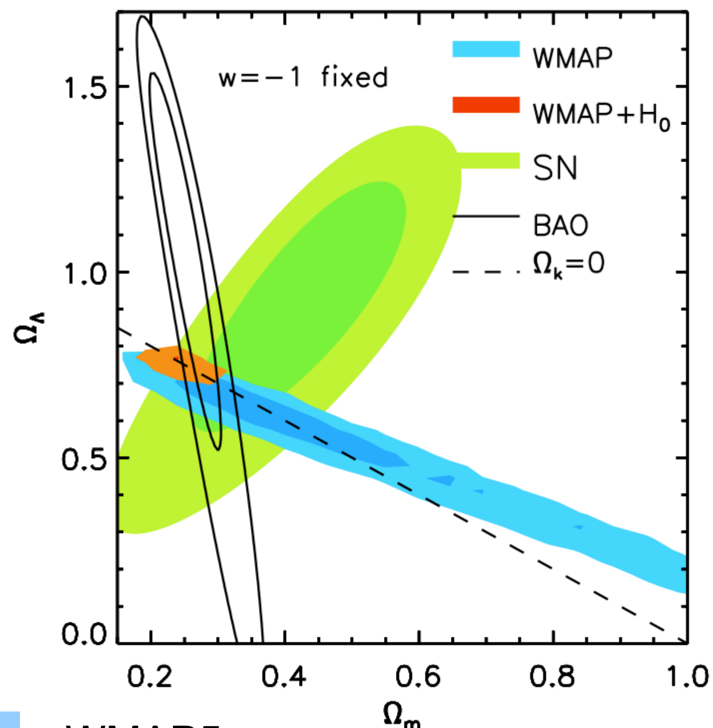
$$
\begin{aligned}
r_s(z_d)/D_V(0.275) &= 0.1390 \pm 0.0037 \quad (2.7\%) \\
D_V(0.37)/D_V(0.2) &= 1.736 \pm 0.065
\end{aligned}
$$

- consistent with ΛCDM models at 1.1σ when combined with WMAP5

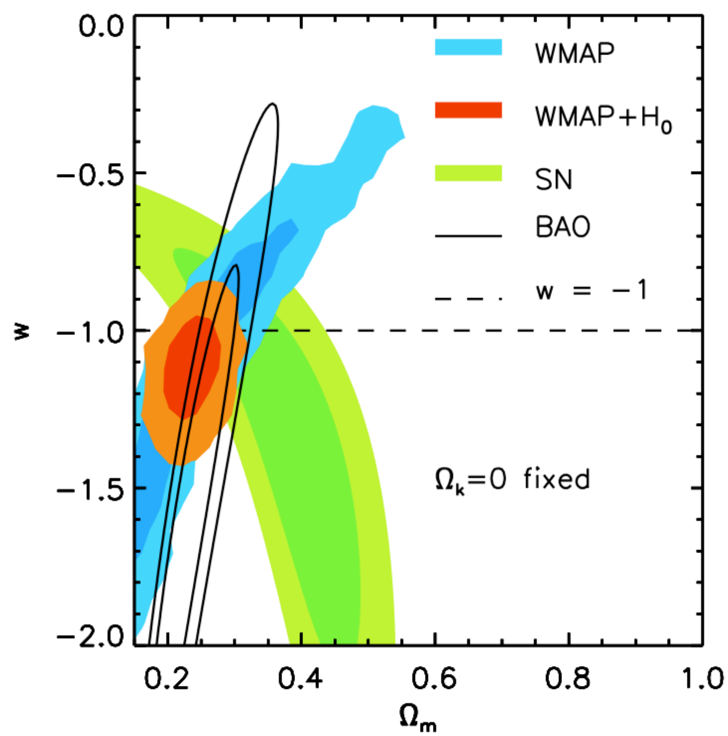
Percival, **BR**, et al. (2009, arXiv:0907.1660)

Cosmological Constraints

ΛCDM models with curvature



flat wCDM models



WMAP5

WMAP5+H_0 [Riess et et al. 2009]

Union supernovae

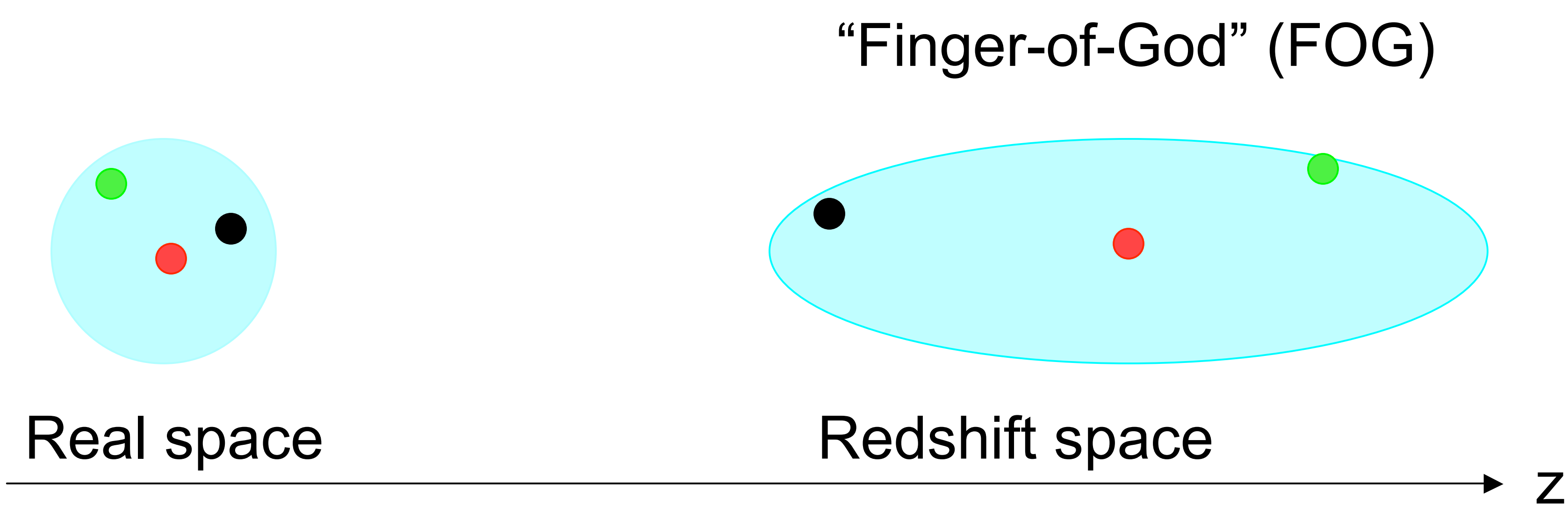
$r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

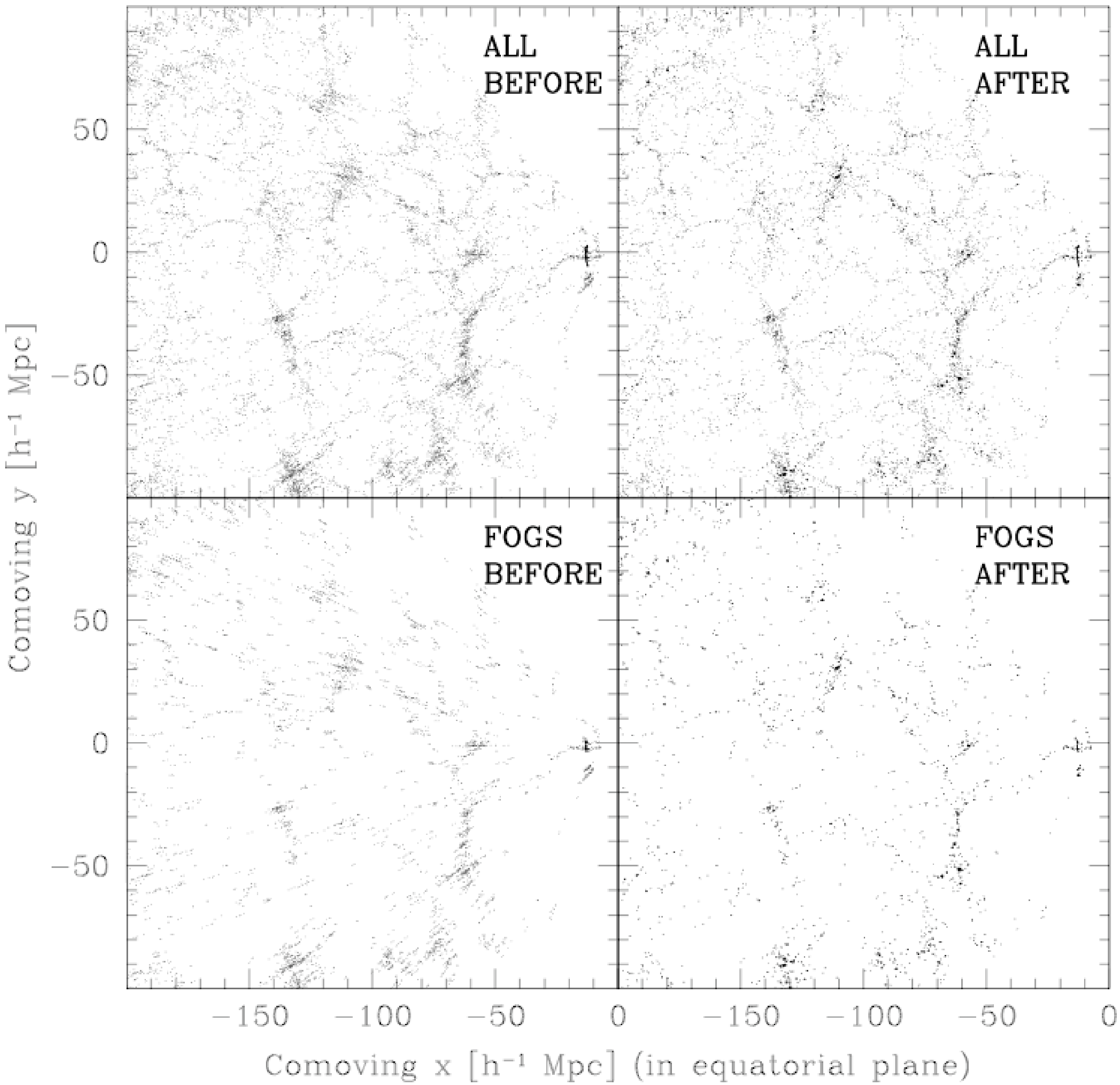
WMAP5+BAO ΛCDM:
$\Omega_m = 0.278 \pm 0.018$, $H_0 = 70.1 \pm 1.5$
WMAP5+BAO+SN wCDM + curvature:
$\Omega_{tot} = 1.006 \pm 0.008$, $w = -0.97 \pm 0.10$

Percival, **BR**, et al. (2009, arXiv:0907.1660)

Modeling $P_{gal}(k)$: Challenges

- density field goes nonlinear
- uncertainty in the mapping between galaxy and matter density fields
- galaxy positions observed in redshift space

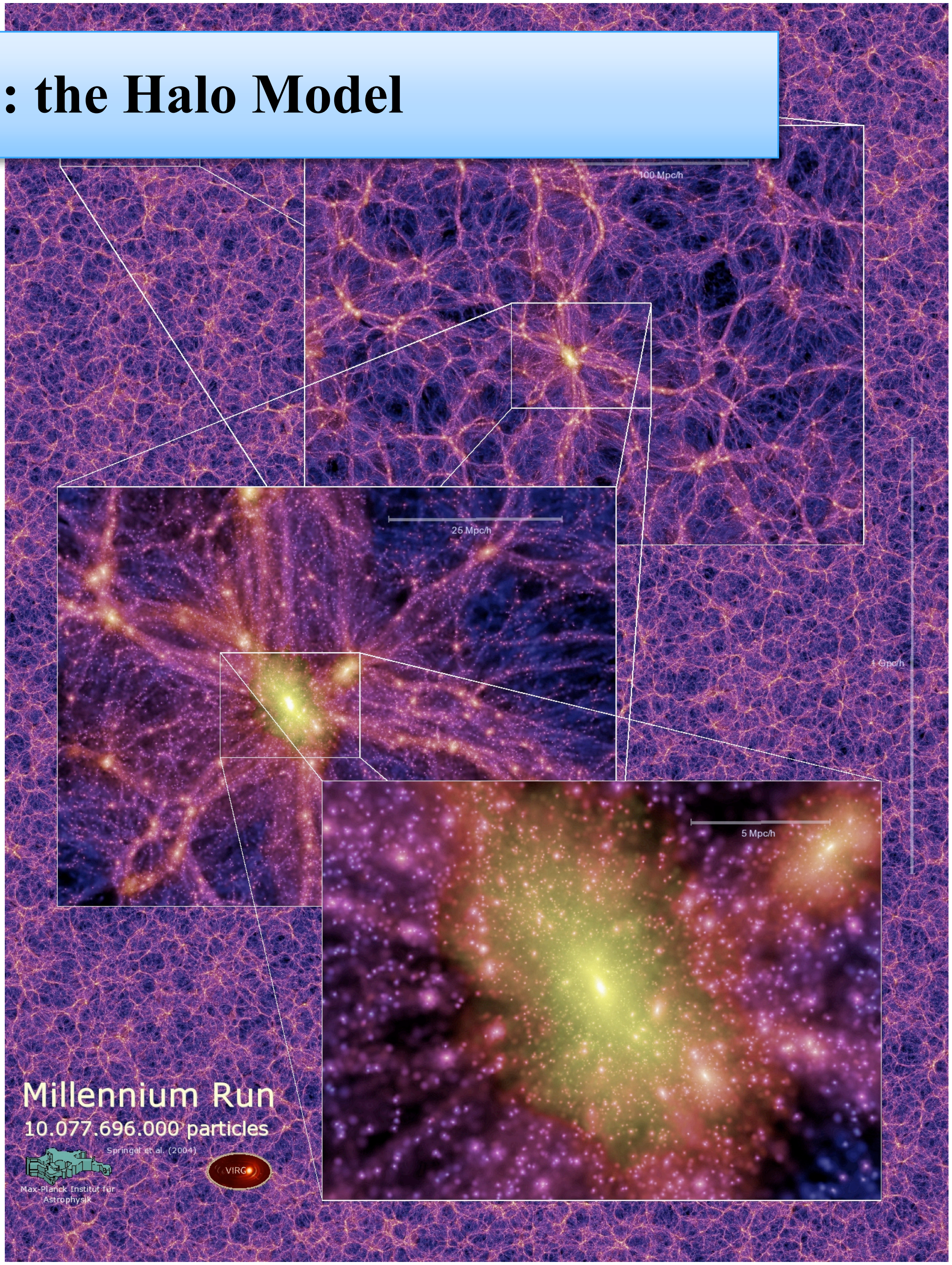




From:
Tegmark et al 04

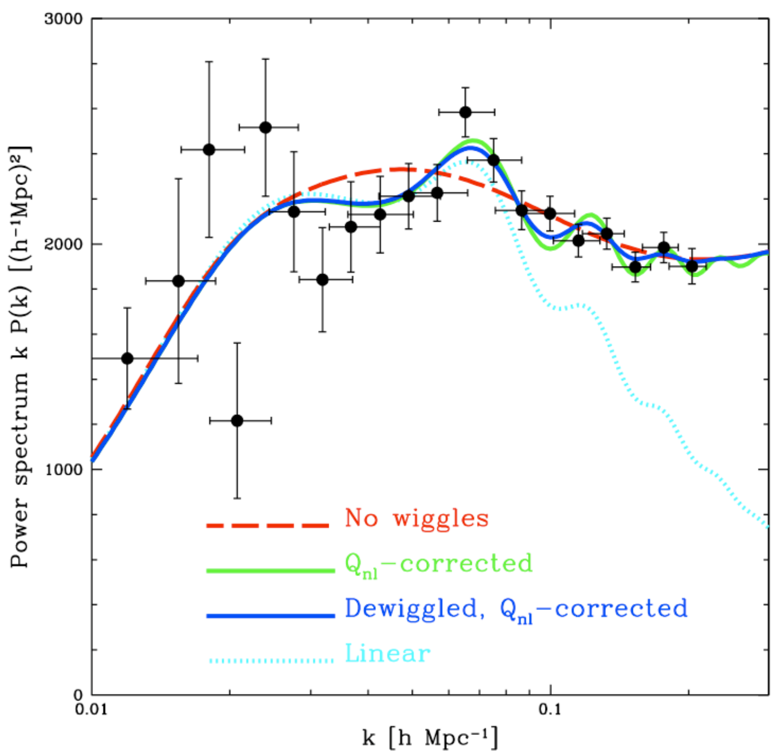
Interlude: the Halo Model

- Galaxy formation from first principles is HARD!
- Linear bias model insufficient!
  - $\delta_{gal} = b_{gal}\,\delta_m \longrightarrow P_{gal}(k) = b_{gal}^2\, P_m(k)$
- Halo Model Key Assumptions:
  - Galaxies only form/reside in halos
  - N-body simulations can determine the statistical properties of halos
  - Halo mass entirely determines key galaxy properties
- Provides a non-linear, cosmology-dependent model and framework in which to quantify systematic errors

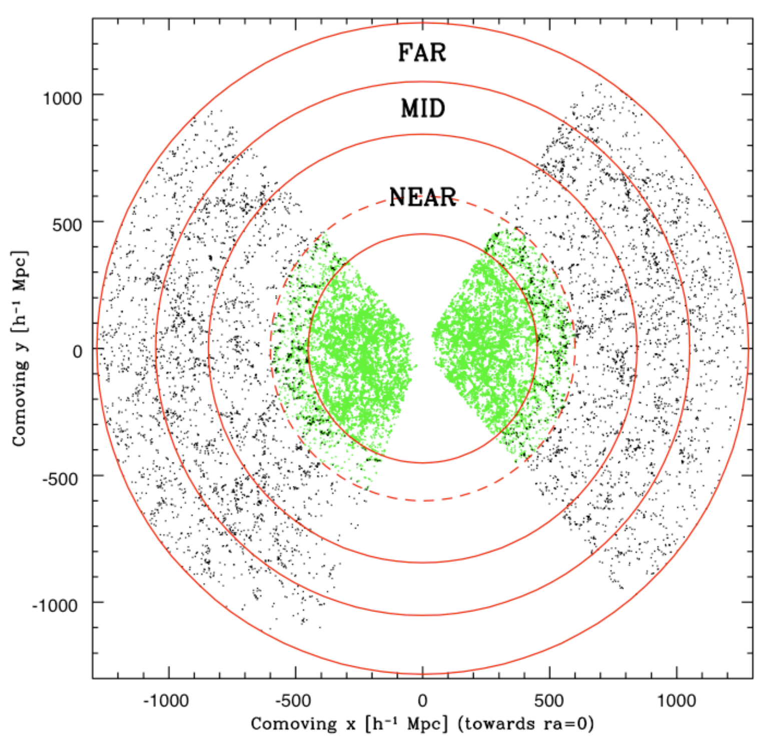


Luminous Red Galaxies

- DR5 analysis: huge deviations from $P_{lin}(k)$ -- WHY?



Tegmark et al. (2006, PRD 74 123507)

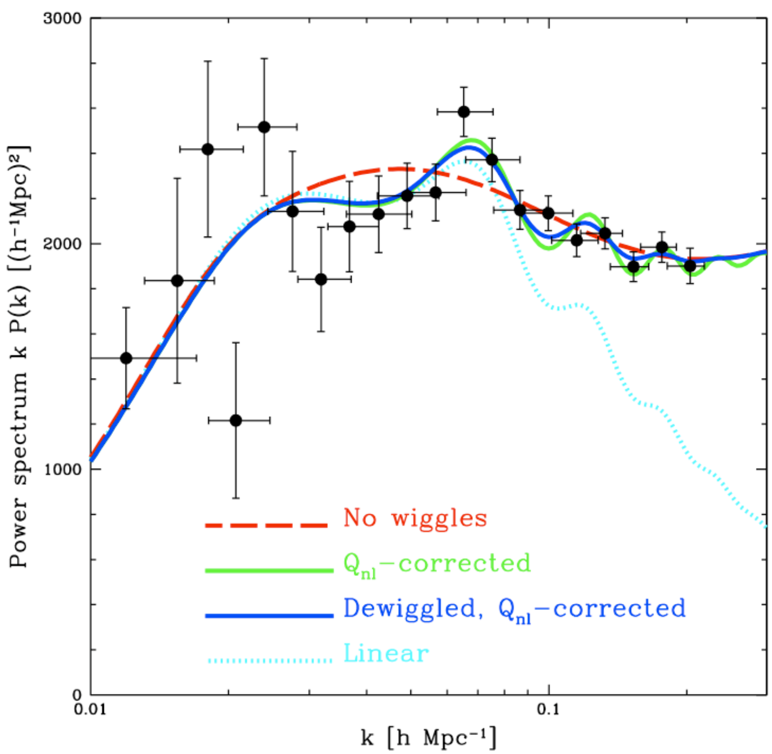


Tegmark et al. (2006, PRD 74 123507)

Luminous Red Galaxies

- DR5 analysis: huge deviations from $P_{lin}(k)$ -- WHY?

$$P_g(k) = P_{\mathrm{dewiggled}}(k) b^2 \frac{1 + Q_{nl} k^2}{1 + 1.4k}$$



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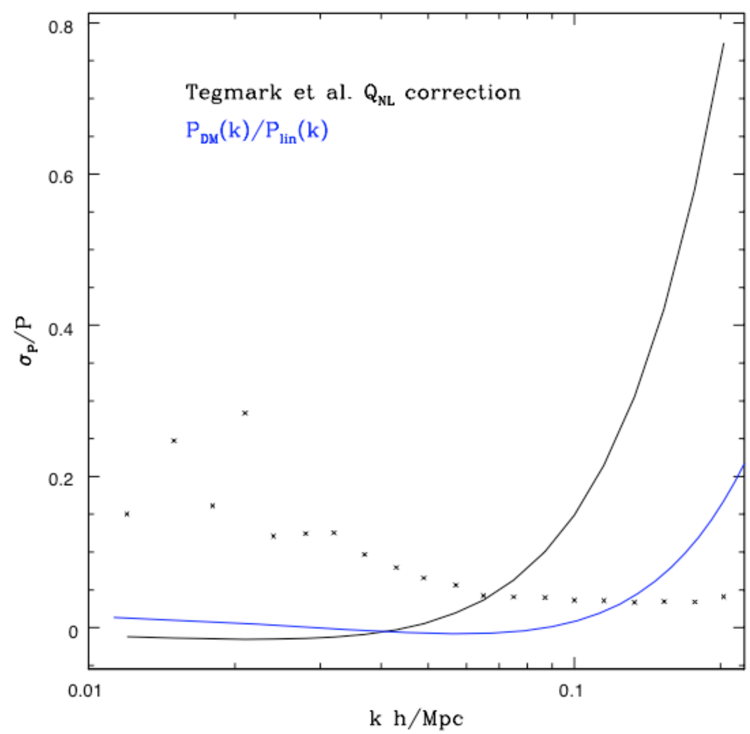


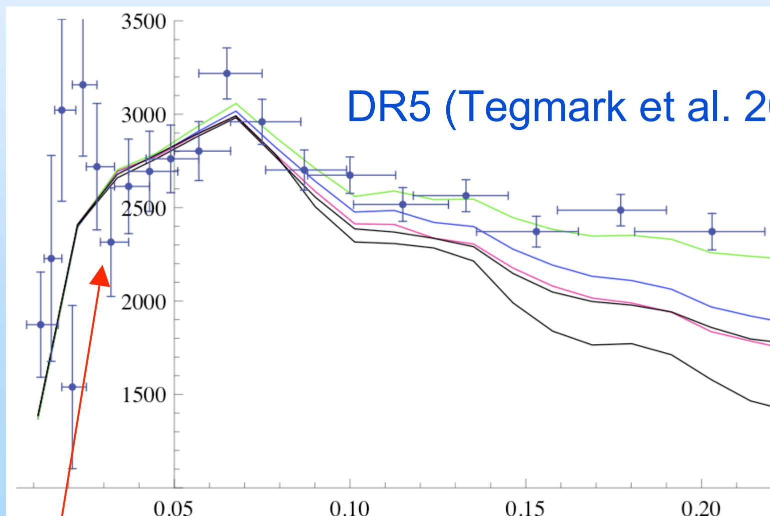
LRG Non-linearity: Answer in a nutshell

- nP ~ 1 to probe largest effective volume
  - shot noise correction important; on large scales, one-halo pairs contribute an excess shot noise
  - LRGs occupy massive halos $\longrightarrow$ large FOG features
- Large non-linear correction can be well-understood as the "one-halo" term after FOG compression, *even though only ~5% of LRGs are satellite galaxies!*
- Impact: Q_{NL} approach biases cosmological parameters and reduces statistical power of the sample

Reid, Spergel, Bode. (2009, ApJ 702, 249)

FOG treatment changes P(k) shape!

k*P(k) (Mpc/h)^2



DR5 (Tegmark et al. 2006)

Tegmark et al. 2006
FOG compression

No FOG compression

Reconstructed
halo density field

DM
IC

k (h/Mpc)

(Normalized to match on large scales)

Small deviations from linear theory should be predictable from small scale power!

Reid, Spergel, Bode. (2009, ApJ 702, 249)

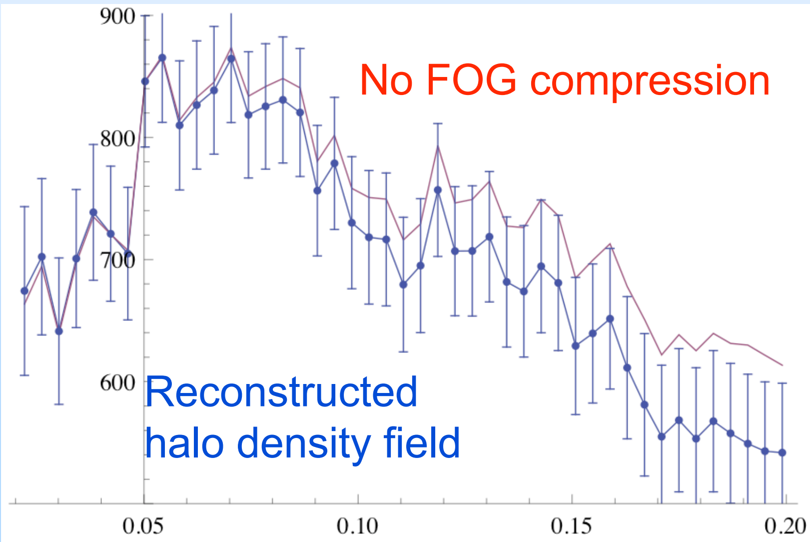
Calibrating halo density field reconstruction

- Basic ideas:
  - constrain galaxy bias on quasi-linear scales from measurements on small scales, where "one-halo" terms dominate
  - n_{LRG} small $\longrightarrow$ identify one-halo pairs with fidelity
- CiC group multiplicity function [measures the "one-halo" shot noise]
- Intra-group velocity distribution
- Calibrate errors on high-fidelity mock LRG catalogs
- Removes redshift evolution of P(k) shape

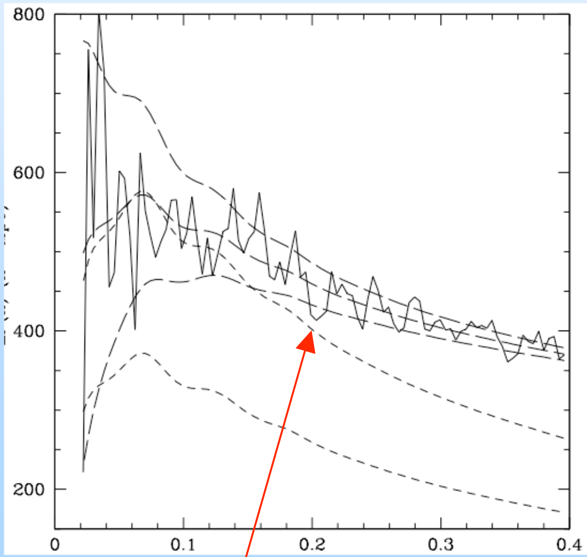
Reid et al. (2009, arXiv:0907.1659)

FOG treatment in DR7

k P(k) (Mpc/h)^2



ΔP(k) (Mpc/h)^3



k (h/Mpc)

Matches mocks + expected excess shot noise from fiber collisions with interlopers

Reid et al. (2009, arXiv:0907.1659)

Final model & Systematic Errors

$$P_{halo}(k, \mathbf{p}) = P_{damp}(k, \mathbf{p}) r_{DM,damp}(k, \mathbf{p}) r_{halo,DM}(k, \mathbf{p_{fid}}) F_{nuis}(k)$$

$$F_{nuis}(k) = b_0^2 \left(1 + a_1 \left(\frac{k}{k_\star}\right) + a_2 \left(\frac{k}{k_\star}\right)^2\right)$$

- This form of $F_{nuis}(k)$ describes
  - excess shot noise
  - slowly varying scale-dependent halo/galaxy bias
  - suppression from intra-halo velocities (**potentially largest systematic**)

Reid et al. (2009, arXiv:0907.1659)

DR7 P(k): What's new?

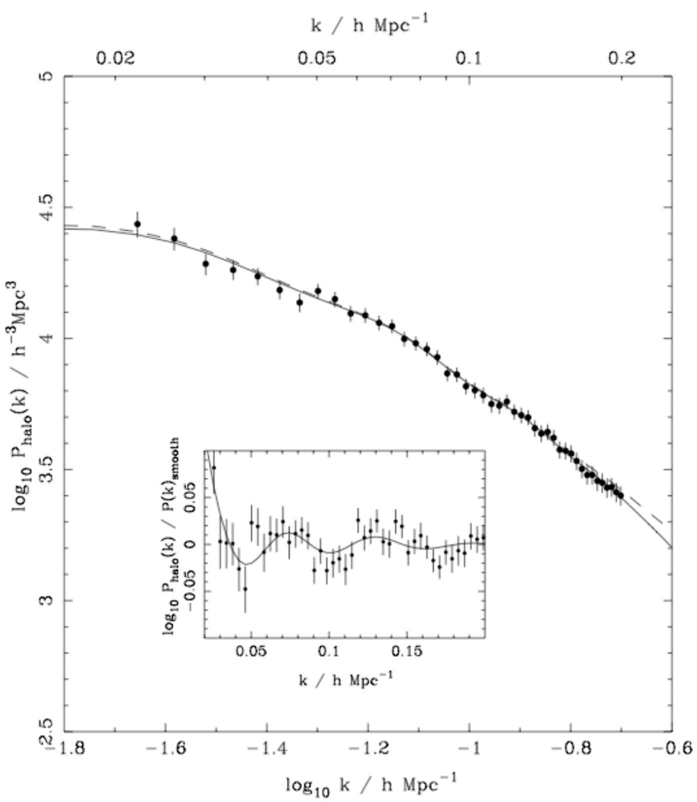
- Replace uncalibrated FOG compression algorithm with calibrated method to **reconstruct halo density field**
  - –Better tracer of underlying matter P(k)
- Replace heuristic nonlinear model (Tegmark et al. 2006 DR5) with cosmology-dependent, nonlinear model calibrated on accurate mock catalogs and with better understood, smaller modeling systematics
- What we gain:
  - –Increase k_{max} from 0.1 to 0.2 h/Mpc; 8x more modes!
  - –Simultaneously constrain k_{eq} and BAO scale
  - –Additional leverage on massive neutrino suppression of P(k)

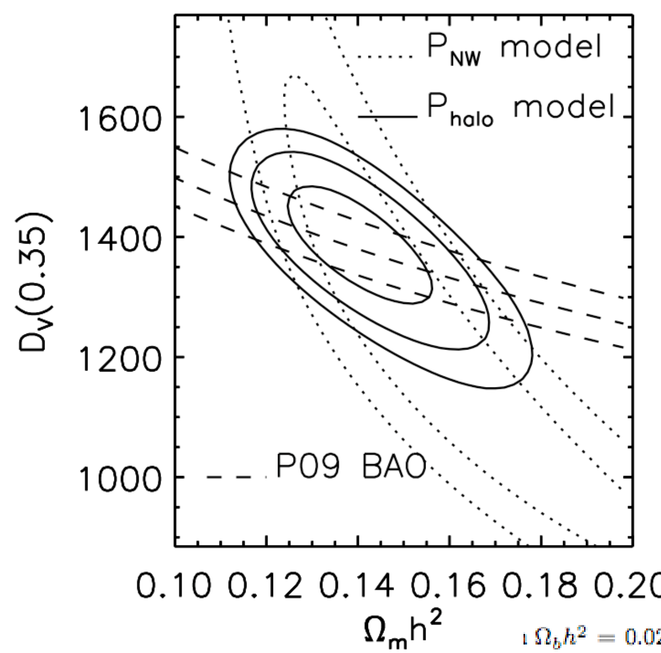
Reid et al. (2009, arXiv:0907.1659)

$P_{halo}(k)$ Results

- Constrains turnover ($\Omega_m h^2 D_V$) and BAO scale (r_s/D_V)

$$D_V(z) \quad = \quad \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)}\right]^{1/3}$$



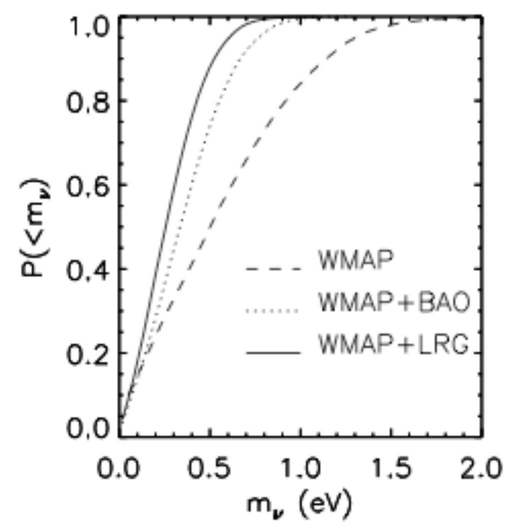


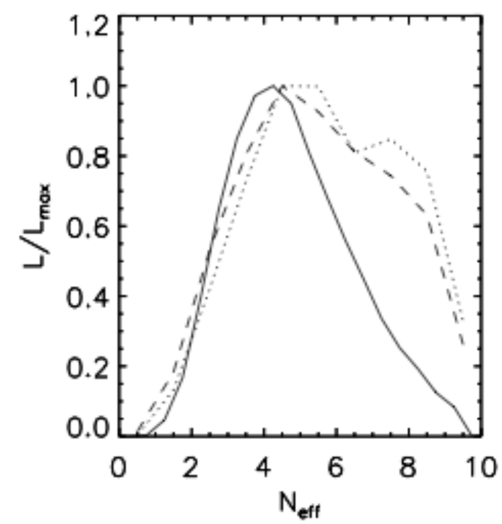
$\Omega_b h^2 = 0.02265$ and $n_s = 0.960$ fixed.

$\Omega_m h^2 (n_s/0.96)^{1.2} = 0.141 \pm 0.011$
$D_V(z=0.35) = 1380 \pm 67$ Mpc

WMAP+P_{halo}(k) Constraints: Neutrinos in ΛCDM

- P_{halo}(k) constraints tighter than P09 BAO-only
- Massive neutrinos suppress P(k)
  - WMAP5: $\Sigma\, m_\nu < 1.3$ eV (95% confidence)
  - WMAP5+LRG: $\Sigma\, m_\nu < 0.62$ eV
  - WMAP5+BAO: $\Sigma\, m_\nu < 0.78$ eV
- Effective number of relativistic species N_{rel} alters turnover and BAO scales differently
  - WMAP5: $N_{rel} = 3.046$ preferred to $N_{rel} = 0$ with > 99.5% confidence
  - WMAP5+LRG: $N_{rel} = 4.8 \pm 1.8$

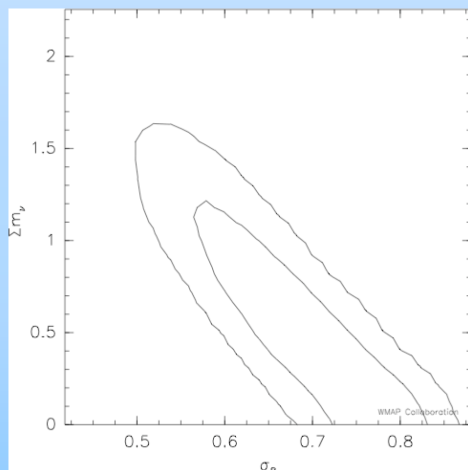


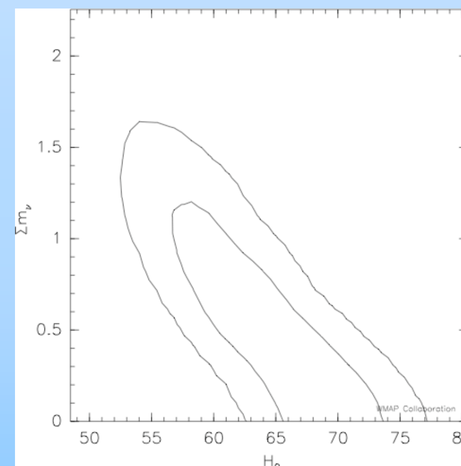


Reid et al. (2009, arXiv:0907.1659)

Robust Neutrino Constraints by Combining Low Redshift Observations with the CMB

- WMAP5 presents many constraints as +BAO+SN. Can other low redshift measurements improve neutrino constraints? Yes.
- SDSS maxBCG clusters constrain $\sigma_8\,(\Omega m/0.25)^{0.41} = 0.832 \pm 0.033$ [Rozo et al. 2009, arXiv:0902.3702]
- New H_0 constraint: 74.2 +/- 3.6 km/s/Mpc [Riess et al. 2009, ApJ 699, 539]

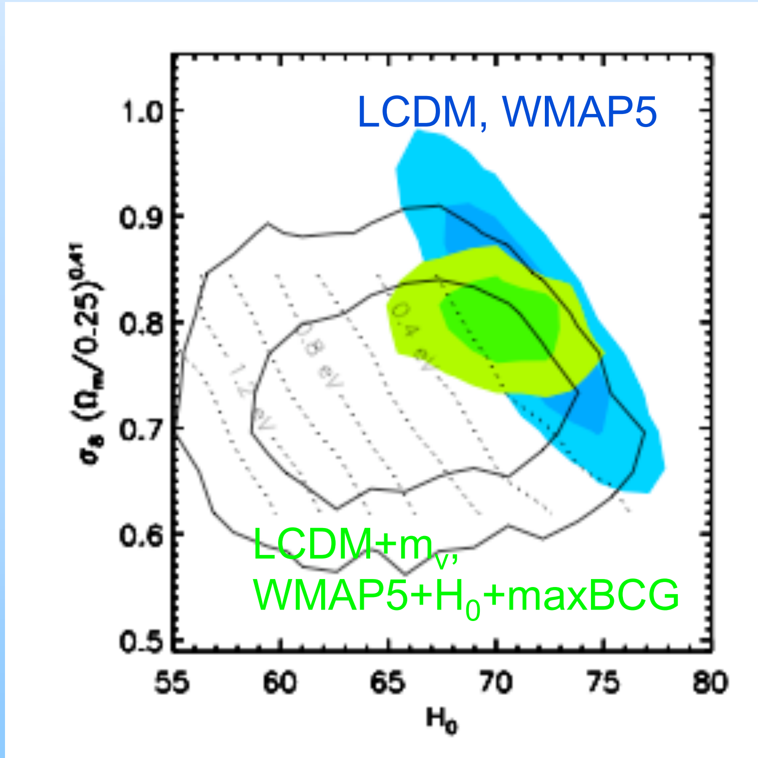


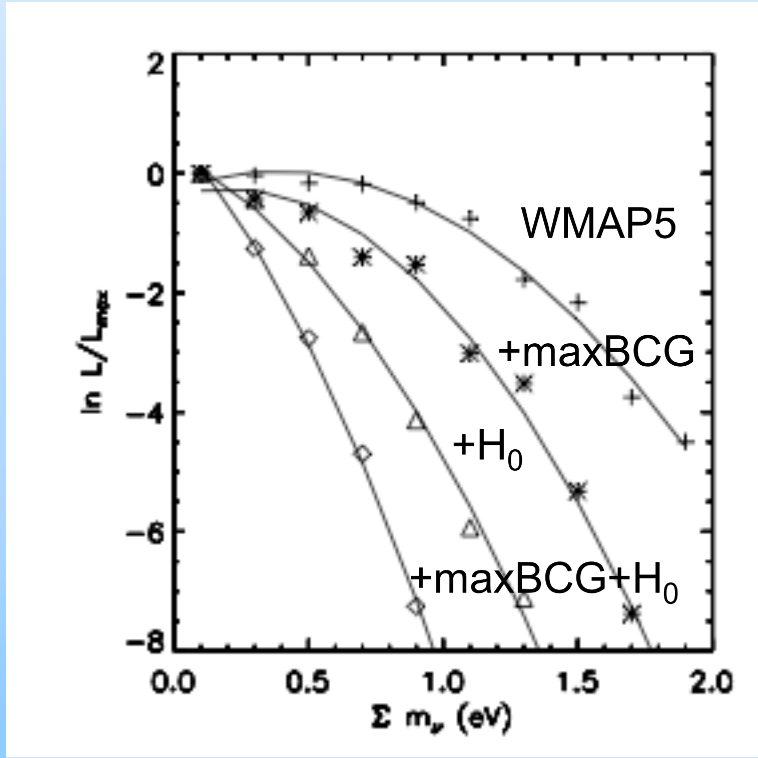


Reid et al. (2009, arXiv:0910.0008)

Neutrino Mass

- WMAP5+H_0+maxBCG: $\Sigma\, m_\nu < 0.4$ eV at 95% confidence, even with tensors or running of the spectral index
- Profile likelihood is “independent” of priors; gives comparable results

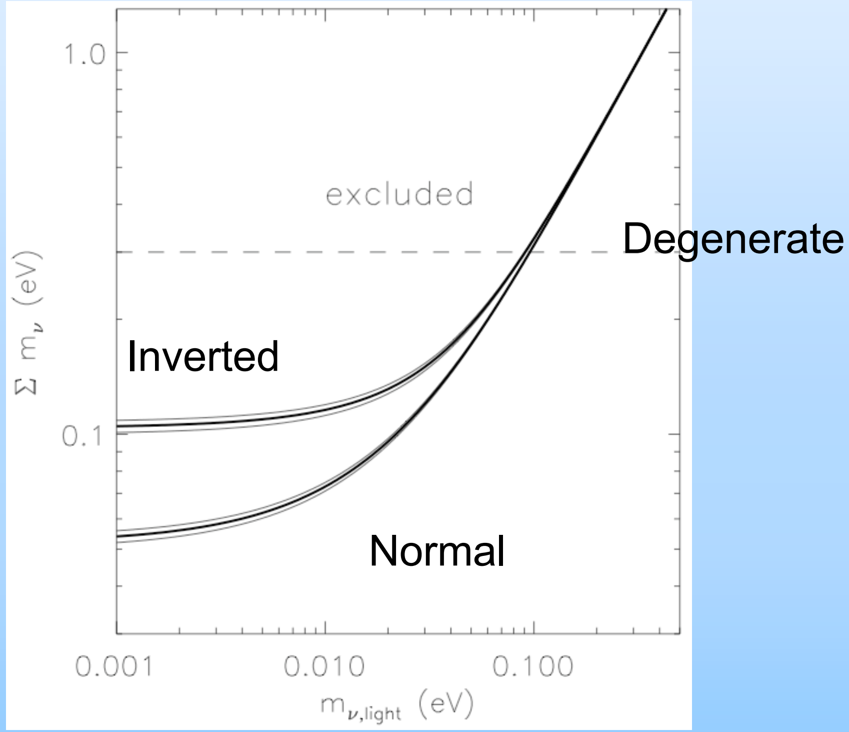




Reid et al. (2009, arXiv:0910.0008)

Neutrino Mass -- where do we stand?

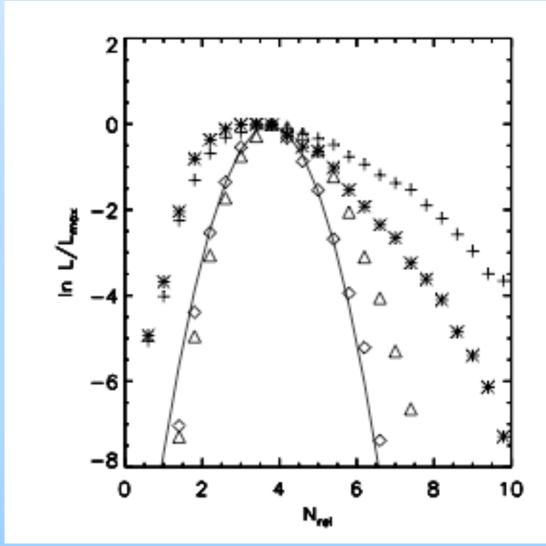
- Most optimistically, we are close to ruling out "degenerate" scenario

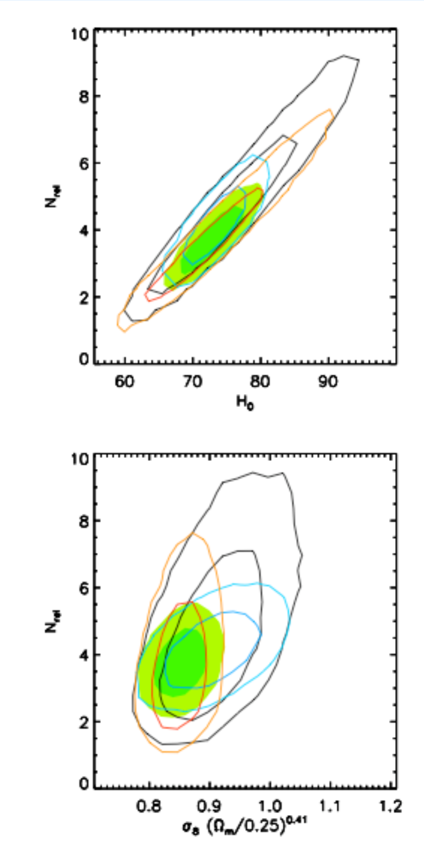


Reid et al. (2009, arXiv:0910.0008)

N_{rel} Results

- N_{rel} = 3.7 +/- 0.7 and profile likelihood becomes Gaussian with WMAP5+H_0+maxBCG combination



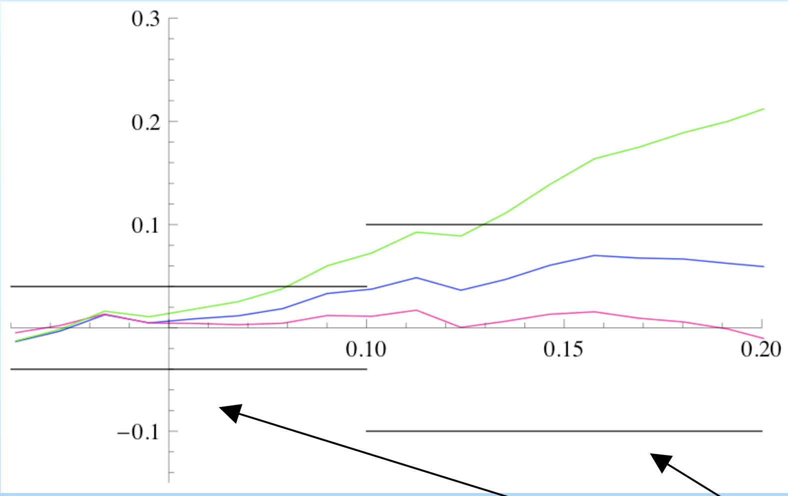


Reid et al. (2009, arXiv:0910.0008)

Conclusions

- BAOs provide tightest geometrical constraints
  - – consistent with ΛCDM models at 1.1σ when combined with WMAP5
  - – improved error analysis, n(z) modeling, etc.
- DR7 P(k) improvement: We use **reconstructed halo density field** in cosmological analysis
  - – Halo model provides a framework for quantifying systematic uncertainties
- Result: 8x more modes, improved neutrino constraints compared with BAO-only analysis
- Likelihood code available in new CosmoMC or here:
  - – http://lambda.gsfc.nasa.gov/toolbox/lrgdr/
- Shape information comes "for free" in a BAO survey!
- Neutrino Constraints substantially improved for data combination WMAP5+H_0+maxBCG

FOG treatment changes P(k) shape!



$P(k)/P_{DM}(k) - 1$

k (h/Mpc)

Tegmark et al. 2006
FOG compression

No FOG compression

Reconstructed
halo density field

Systematic error
bounds

Reid et al. (2009, arXiv:0907.1659)