Precision Cosmology with Large Scale Structure

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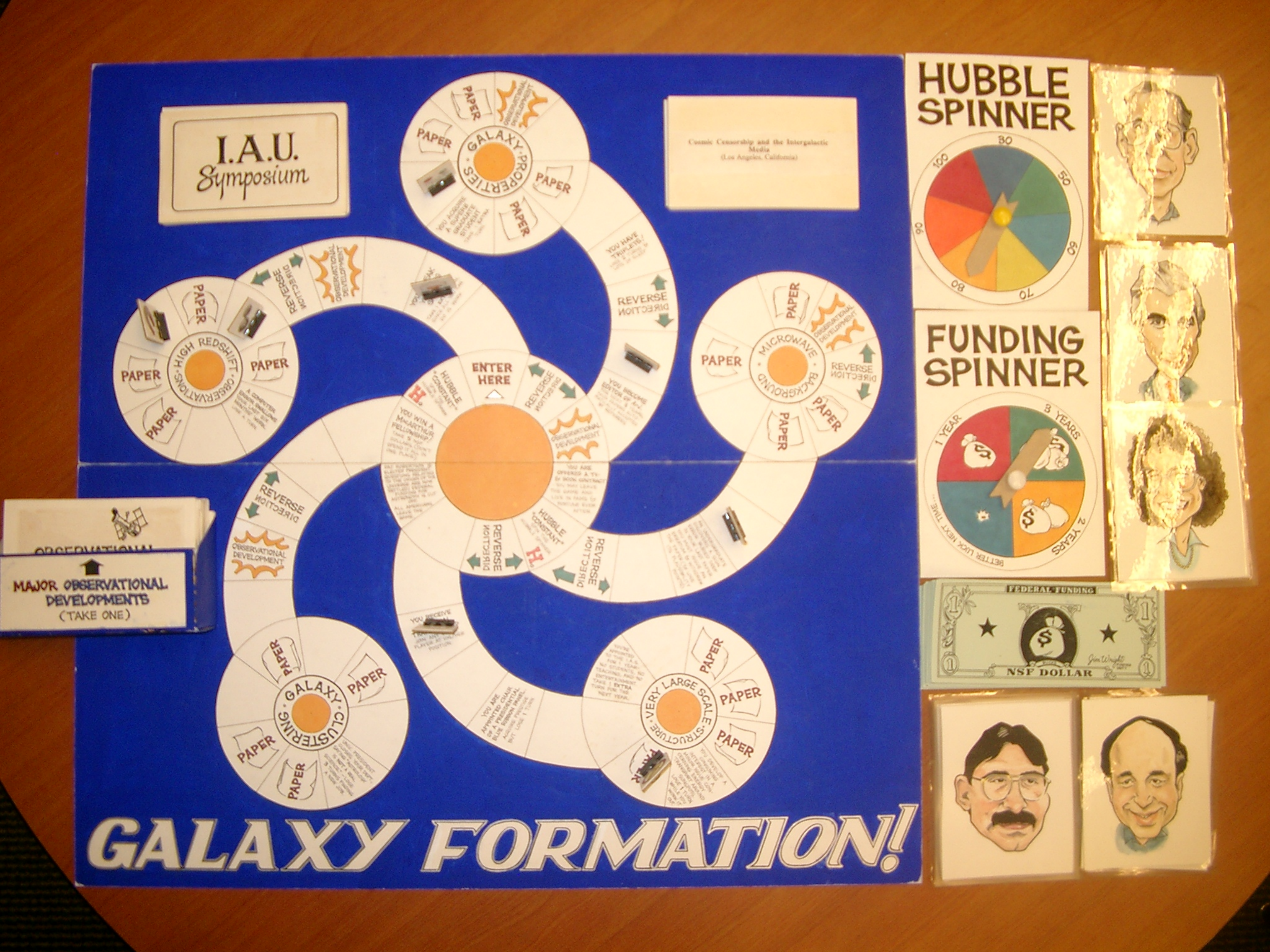
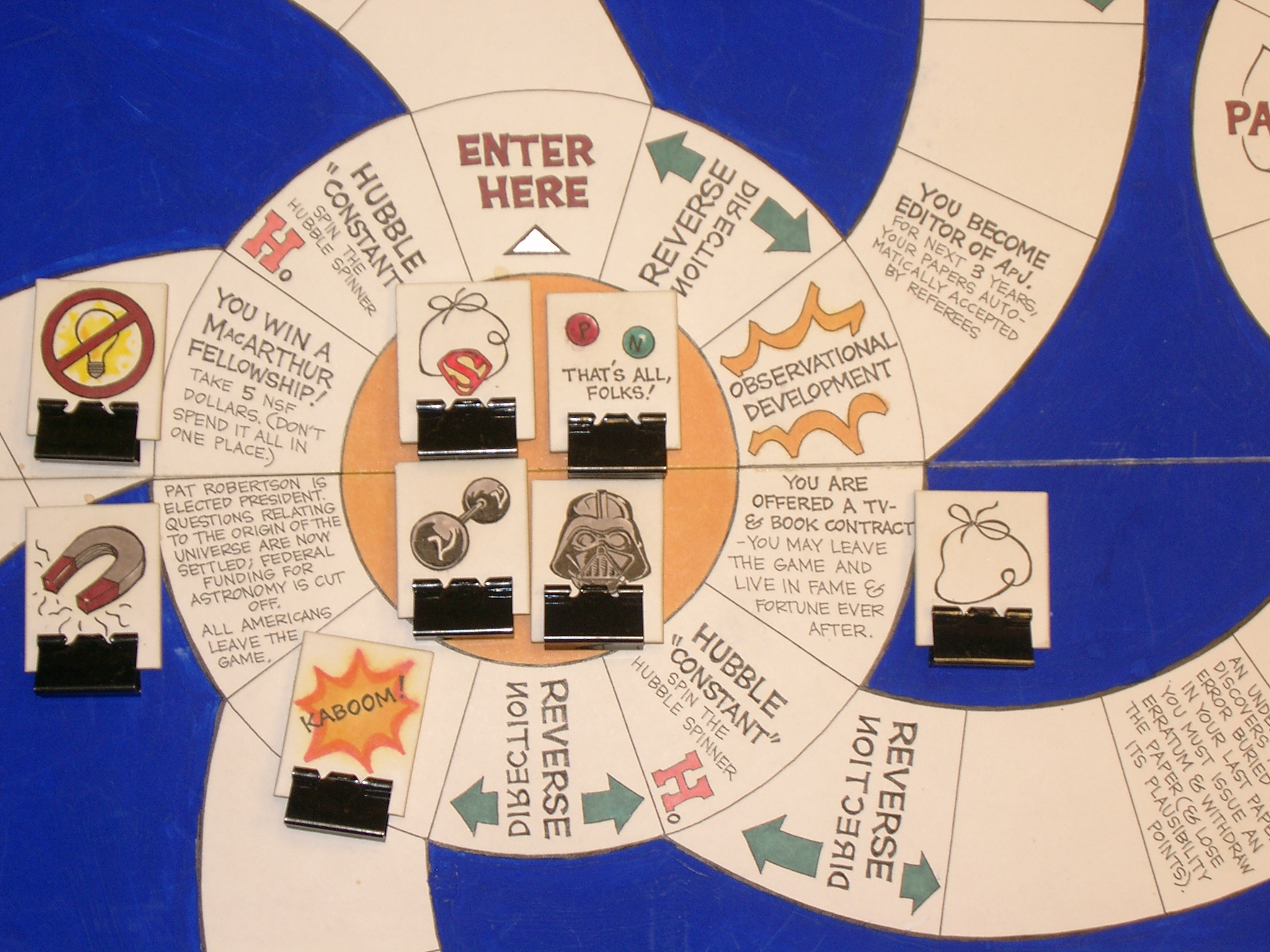

GALAXY FORMATION!
I.A.U. Symposium
Cosmic Censorship and the Intergalactic Media (Los Angeles, California)
GALAXY PROPERTIES
HIGH REDSHIFT OBSERVATIONS
MICROWAVE BACKGROUND
GALAXY CLUSTERING
VERY LARGE SCALE STRUCTURE
ENTER HERE
HUBBLE CONSTANT
YOU WIN A MacARTHUR FELLOWSHIP
YOU ARE OFFERED A TV
PAPER
REVERSE DIRECTION
OBSERVATIONAL DEVELOPMENT
MAJOR OBSERVATIONAL DEVELOPMENTS
(TAKE ONE)
HUBBLE SPINNER
30
50
60
70
80
90
100
FUNDING SPINNER
1 YEAR
3 YEARS
2 YEARS
BETTER LUCK NEXT TIME
FEDERAL FUNDING
NSF DOLLAR
1



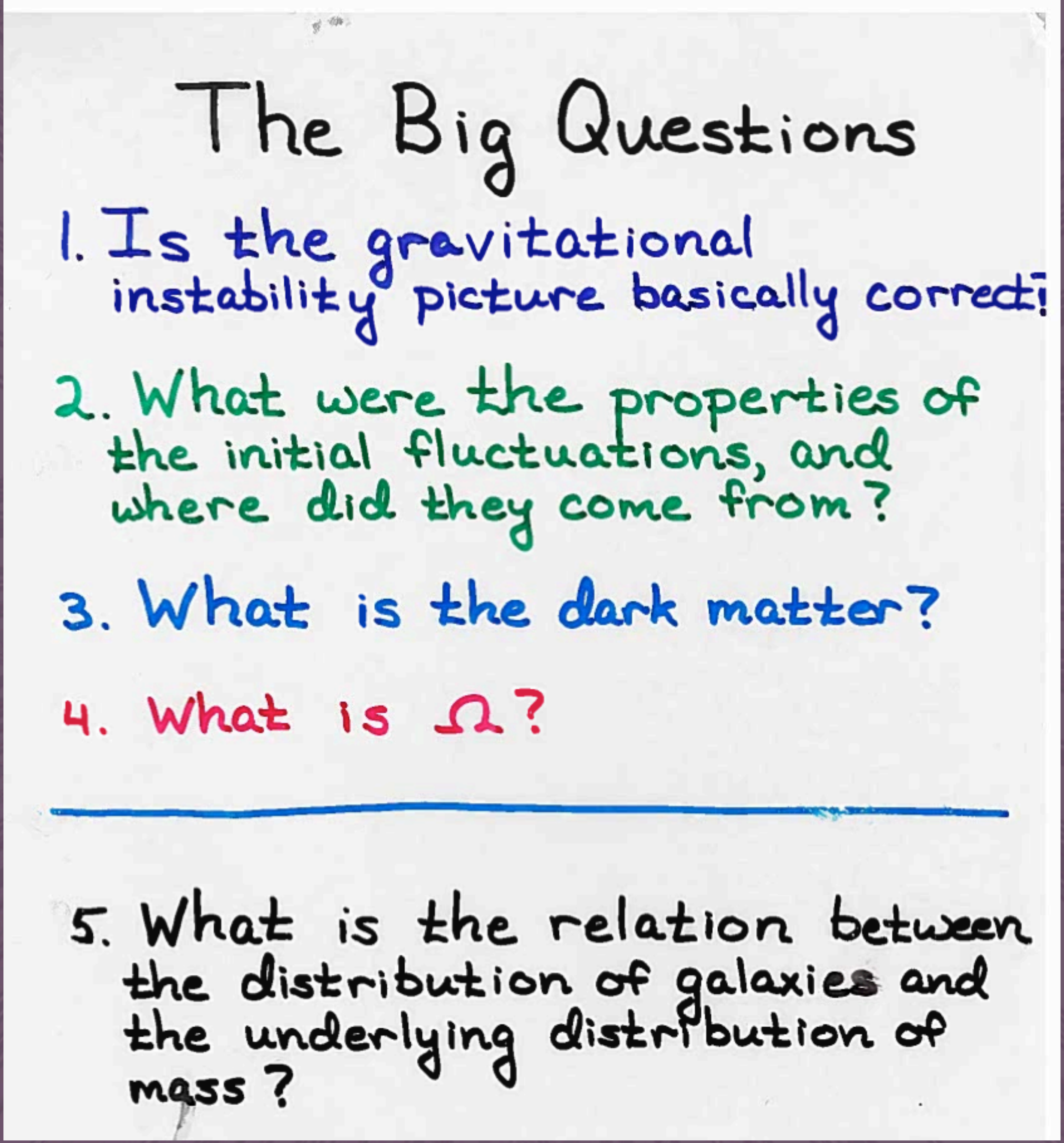
YOU BECOME EDITOR OF ApJ. FOR NEXT 3 YEARS, YOUR PAPERS AUTOMATICALLY ACCEPTED BY REFEREES

YOU WIN A MacARTHUR FELLOWSHIP! TAKE 5 NSF DOLLARS. (DON'T SPEND IT ALL IN ONE PLACE.)

PAT ROBERTSON IS ELECTED PRESIDENT. QUESTIONS RELATING TO THE ORIGIN OF THE UNIVERSE ARE NOW SETTLED; FEDERAL FUNDING FOR ASTRONOMY IS CUT OFF. ALL AMERICANS LEAVE THE GAME.

YOU ARE OFFERED A TV- & BOOK CONTRACT -YOU MAY LEAVE THE GAME AND LIVE IN FAME & FORTUNE EVER AFTER.

AN UNDE
DISCOVERS
ERROR BURIED
IN YOUR LAST PAP
YOU MUST ISSUE AN
ERRATUM & WITHDRAW
THE PAPER (& LOSE
ITS PLAUSIBILITY
POINTS).



The Big Questions

1. Is the gravitational instability picture basically correct
2. What were the properties of the initial fluctuations, and where did they come from?
3. What is the dark matter?
4. What is Ω?

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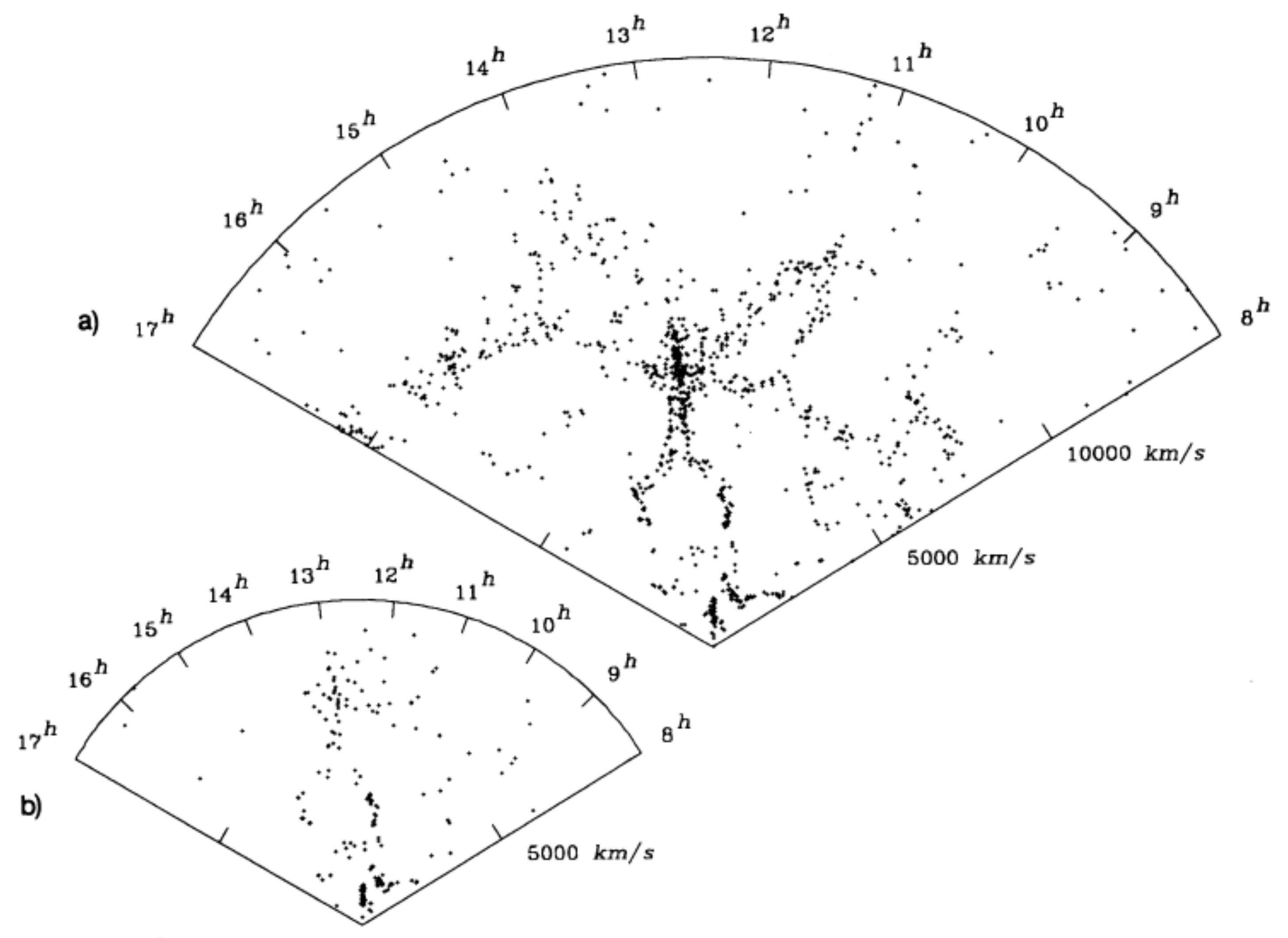
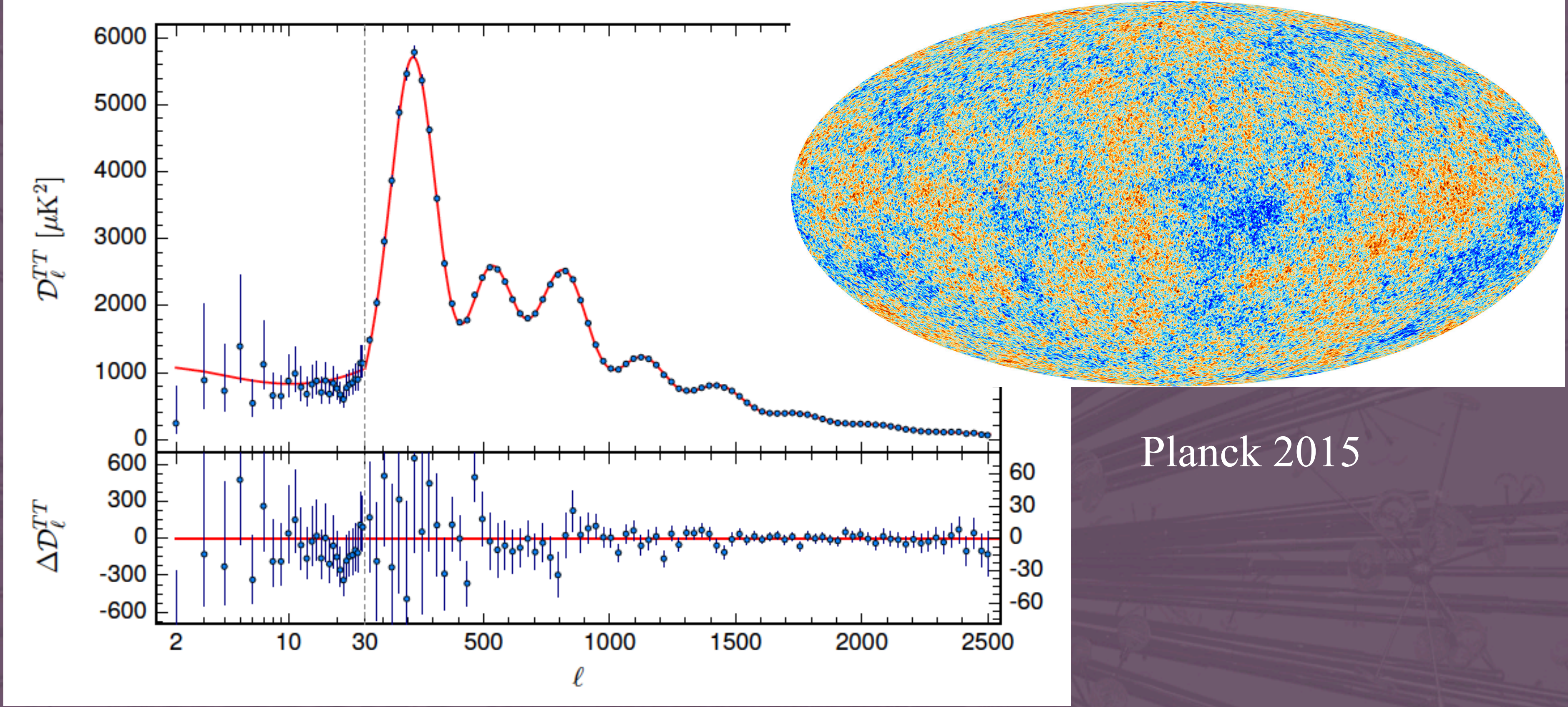
5. What is the relation between the distribution of galaxies and the underlying distribution of mass?

A SLICE OF THE UNIVERSE[1]

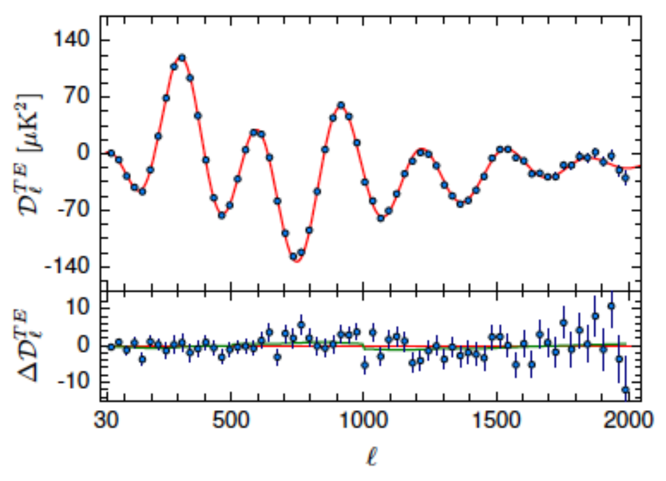
Valérie de Lapparent,[2,3] Margaret J. Geller,[2] and John P. Huchra[2]

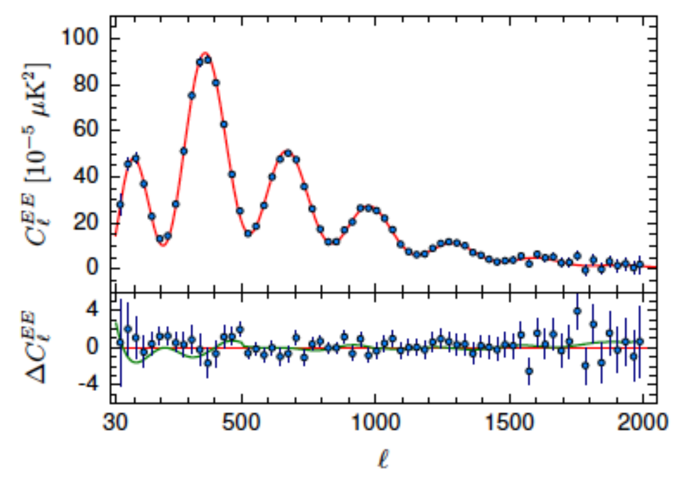
Received 1985 November 12; accepted 1985 December 5




6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

Planck 2015


140
70
0
-70
-140
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
-10
$\Delta\mathcal{D}_\ell^{TE}$
30
500
1000
1500
2000
ℓ


100
80
60
40
20
0
C_ℓ^{EE} [10^{-5} μK^2]
4
0
-4
ΔC_ℓ^{EE}
30
500
1000
1500
2000
ℓ

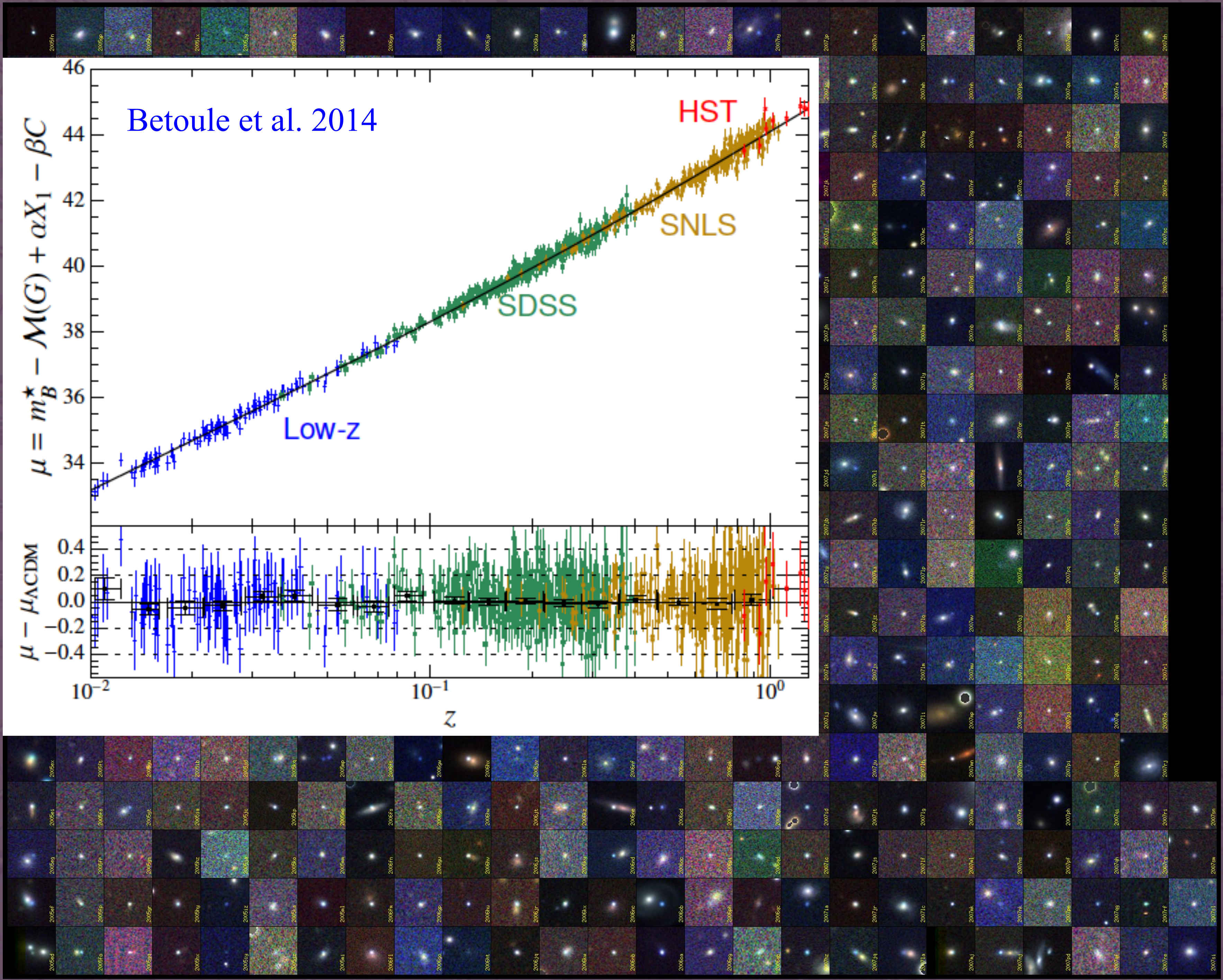
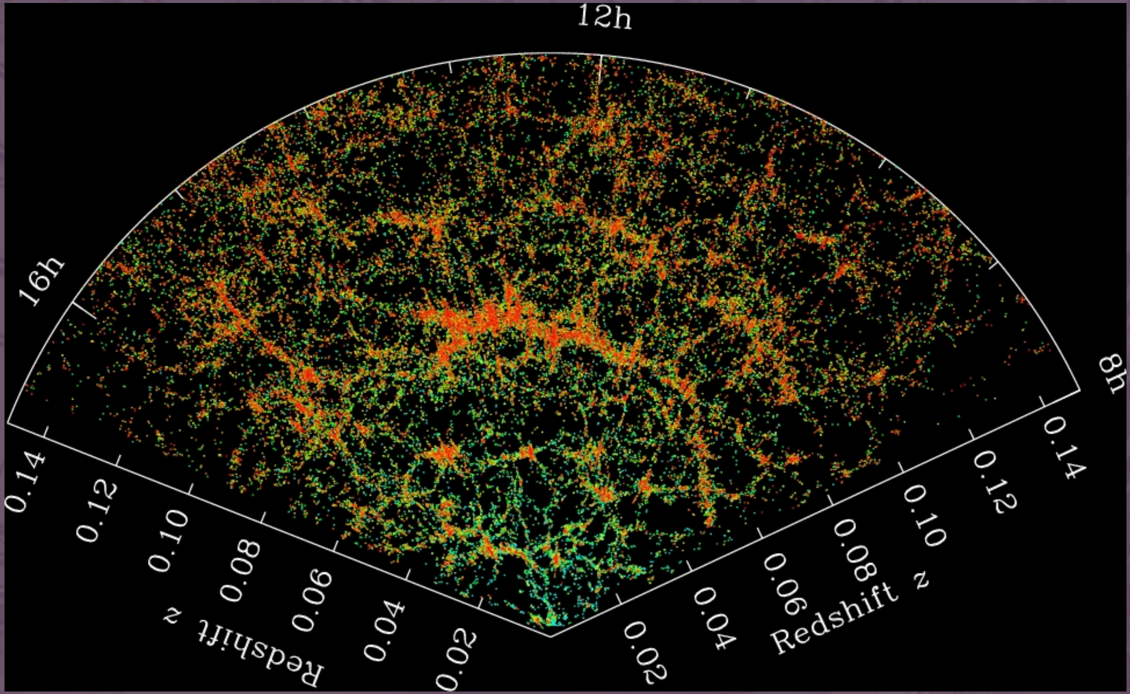
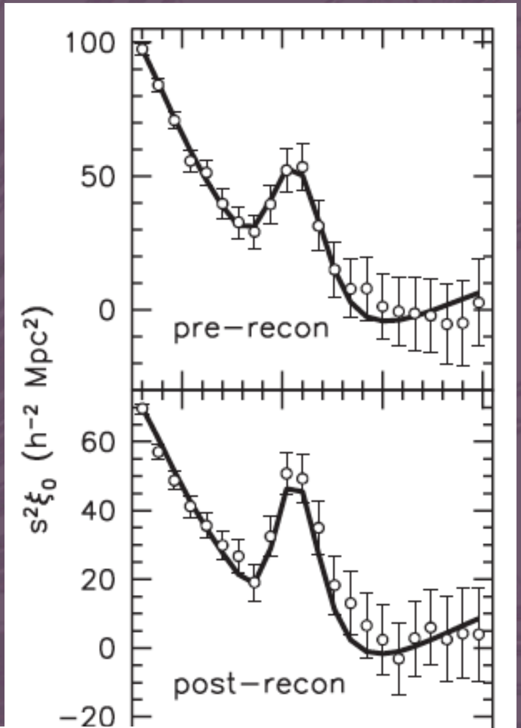
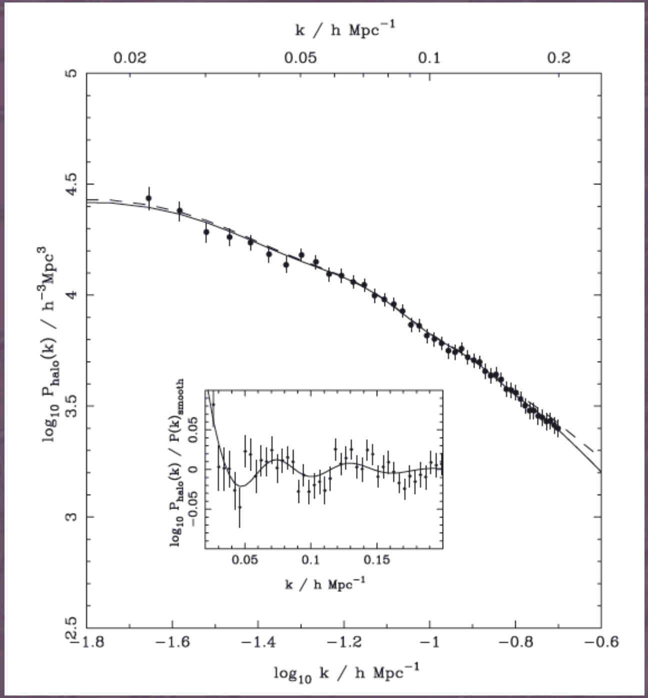
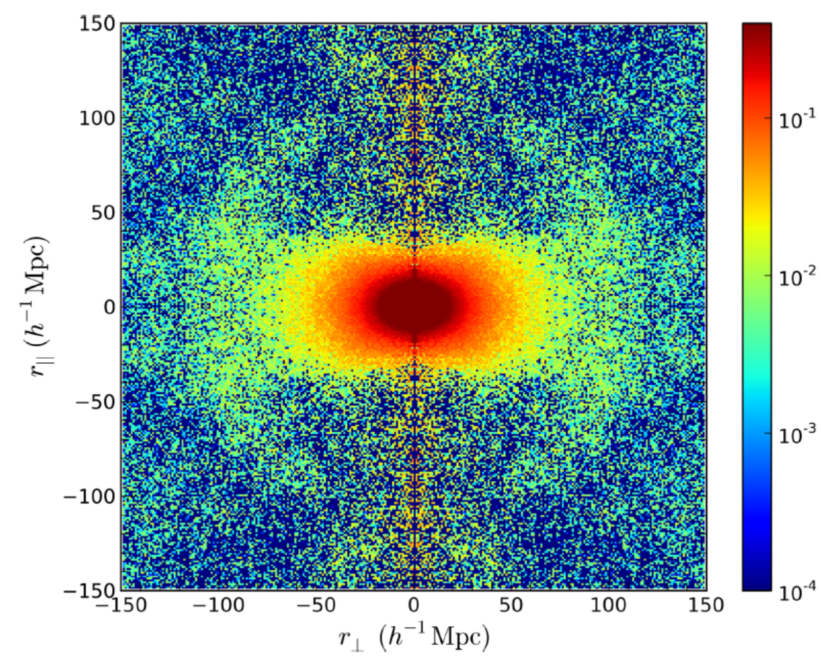


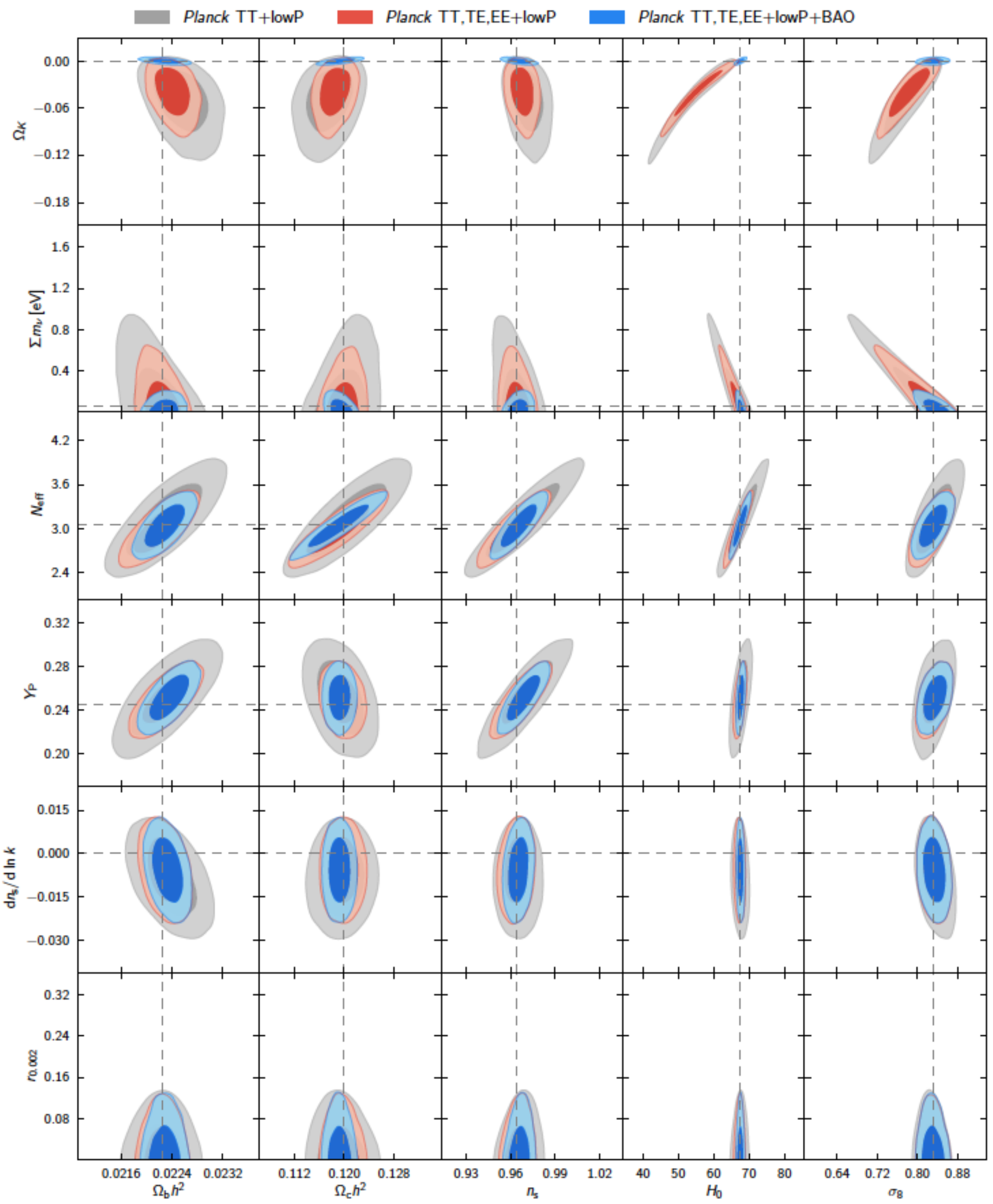
Figure: B. Dilday


12h
16h
8h
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

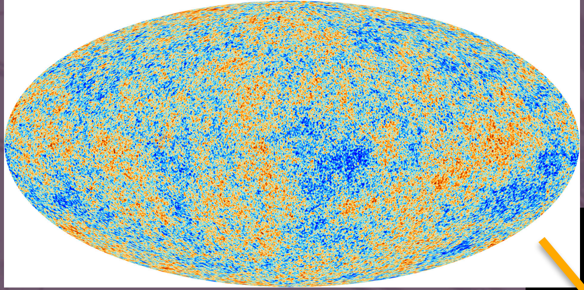

100
50
0
pre−recon
60
40
20
0
−20
post−recon
$s^2\xi_0$ (h^{-2} Mpc^2)
100
150
200
s (h^{-1} Mpc)

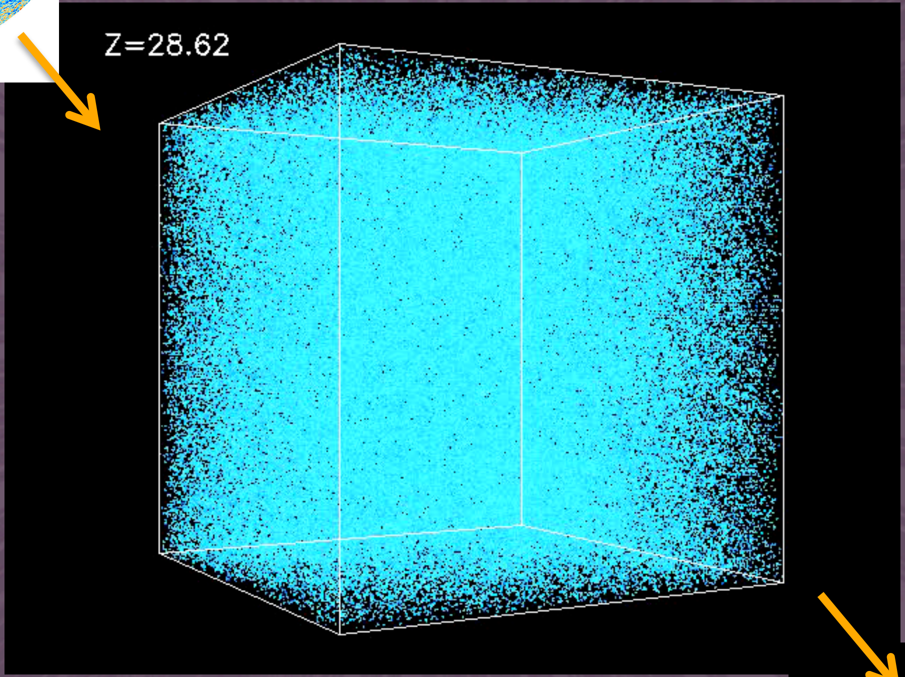

k / h Mpc^{-1}
0.02
0.05
0.1
0.2
5
4.5
4
3.5
3
2.5
$\log_{10}$ $P_{\rm halo}$(k) / h^{-3}Mpc^3
−1.8
−1.6
−1.4
−1.2
−1
−0.8
−0.6
$\log_{10}$ k / h Mpc^{-1}
0.05
0
−0.05
$\log_{10}$ $P_{\rm halo}$(k) / P(k)$_{\rm smooth}$
0.05
0.1
0.15
k / h Mpc^{-1}


150
100
50
0
−50
−100
−150
$r_{\parallel}$ (h^{-1}Mpc)
−150
−100
−50
0
50
100
150
$r_{\perp}$ (h^{-1}Mpc)
10^{-1}
10^{-2}
10^{-3}
10^{-4}


Planck TT+lowP
Planck TT,TE,EE+lowP
Planck TT,TE,EE+lowP+BAO
Ω_K
0.00
−0.06
−0.12
−0.18
Σm_ν [eV]
1.6
1.2
0.8
0.4
$N_{\rm eff}$
4.2
3.6
3.0
2.4
Y_P
0.32
0.28
0.24
0.20
$dn_s/d\ln k$
0.015
0.000
−0.015
−0.030
$r_{0.002}$
0.32
0.24
0.16
0.08
0.0216
0.0224
0.0232
$\Omega_b h^2$
0.112
0.120
0.128
$\Omega_c h^2$
0.93
0.96
0.99
1.02
n_s
40
50
60
70
80
H_0
0.64
0.72
0.80
0.88
σ_8

Testing modified gravity: does structure grow at the expected rate?

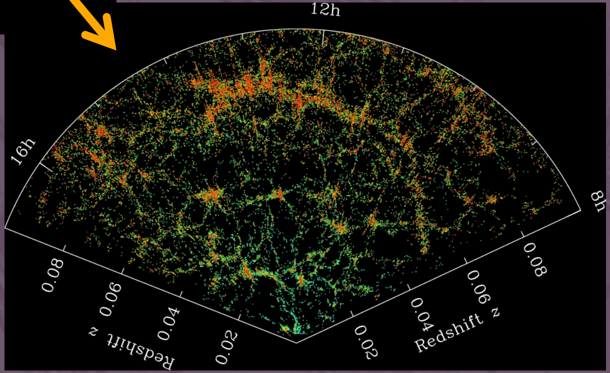




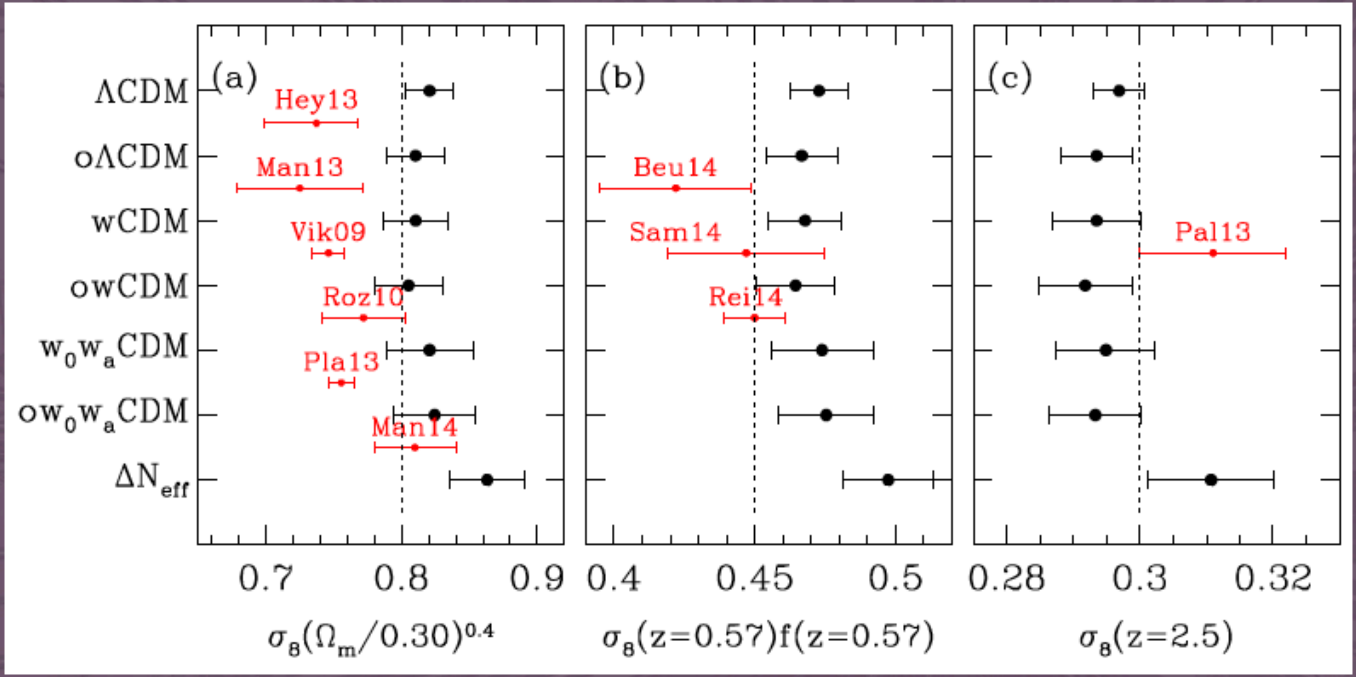
Simulation by
A. Kravtsov

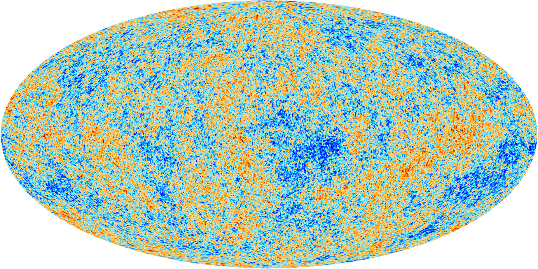
Growth rate of linear fluctuations:

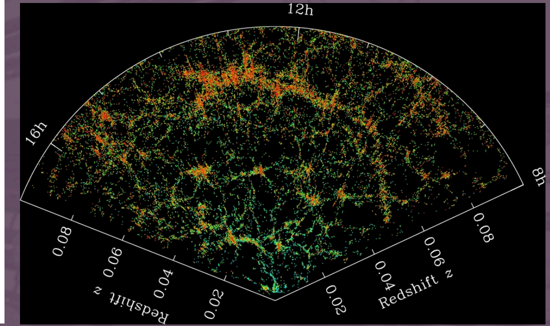
$$\frac{G(z)}{G_0} \approx \exp\left(-\int_0^z \frac{dz'}{1+z'}\left[\Omega_m(1+z)^3\frac{H_0^2}{H^2(z)}\right]^\gamma\right) \quad , \quad \gamma \approx 0.55$$



Trouble with gravity?



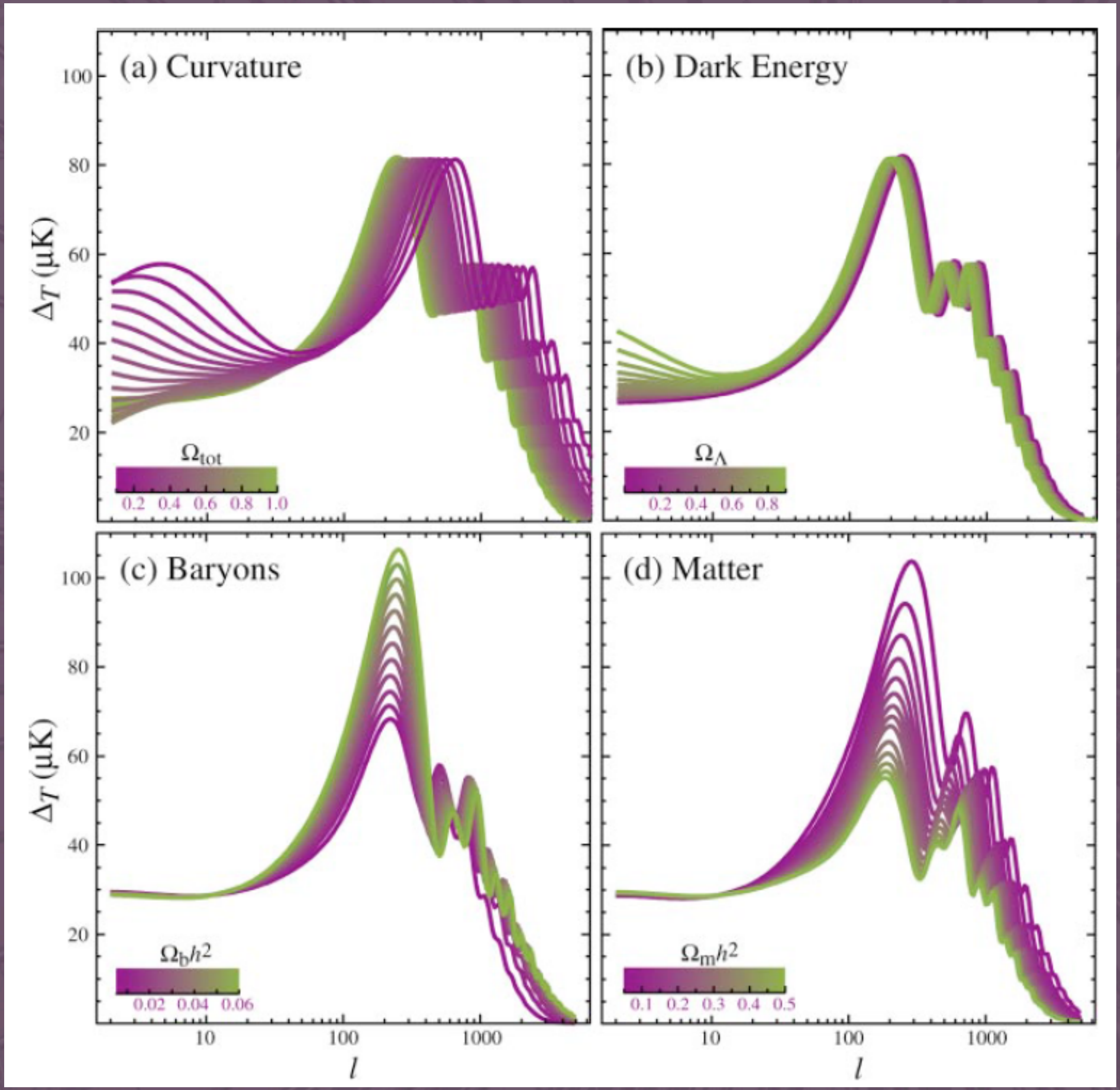




Black points: Predicted clustering amplitude in increasingly flexible dark energy models, constrained by BAO+SN+CMB.

Red points: Measurements from clusters, weak lensing, redshift-space distortions, Lyα forest power spectrum (vertical position arbitrary).

Extrapolating growth of cosmic structure from the CMB to today overpredicts most local measurements of dark matter clustering..



Hu & Dodelson 2002

See also http://space.mit.edu/home/tegmark/movies.html

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)}$$

$$\frac{u_\phi(z)}{u_\phi(z=0)} = \exp\left[3\int_0^z [1+w(z')]\frac{dz'}{1+z'}\right]$$

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

$$D_A(z) \approx D_C\left[1 + \frac{1}{6}\Omega_k\left(\frac{D_C}{c/H_0}\right)^2\right]$$

$$\ddot{G}_{\rm GR} + 2H(z)\dot{G}_{\rm GR} - \frac{3}{2}\Omega_m H_0^2(1+z)^3 G_{\rm GR} = 0$$

$$f_{\rm GR}(z) \equiv \frac{d\ln G_{\rm GR}}{d\ln a} \approx [\Omega_m(z)]^\gamma$$

$$\frac{G_{\rm GR}(z)}{G_{\rm GR}(z=0)} \approx \exp\left[-\int_0^z \frac{dz'}{1+z'}[\Omega_m(z')]^\gamma\right]$$

$$\gamma = 0.55 + 0.05[1 + w(z=1)]$$

$$\Omega_m(z) \equiv \frac{\rho_m(z)}{\rho_{\rm crit}(z)} = \Omega_m(1+z)^3\frac{H_0^2}{H^2(z)}$$

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)}$$

$$\frac{u_\phi(z)}{u_\phi(z=0)} = \exp\left[3\int_0^z [1+w(z')]\frac{dz'}{1+z'}\right]$$

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

$$D_A(z) \approx D_C\left[1+\frac{1}{6}\Omega_k\left(\frac{D_C}{c/H_0}\right)^2\right]$$

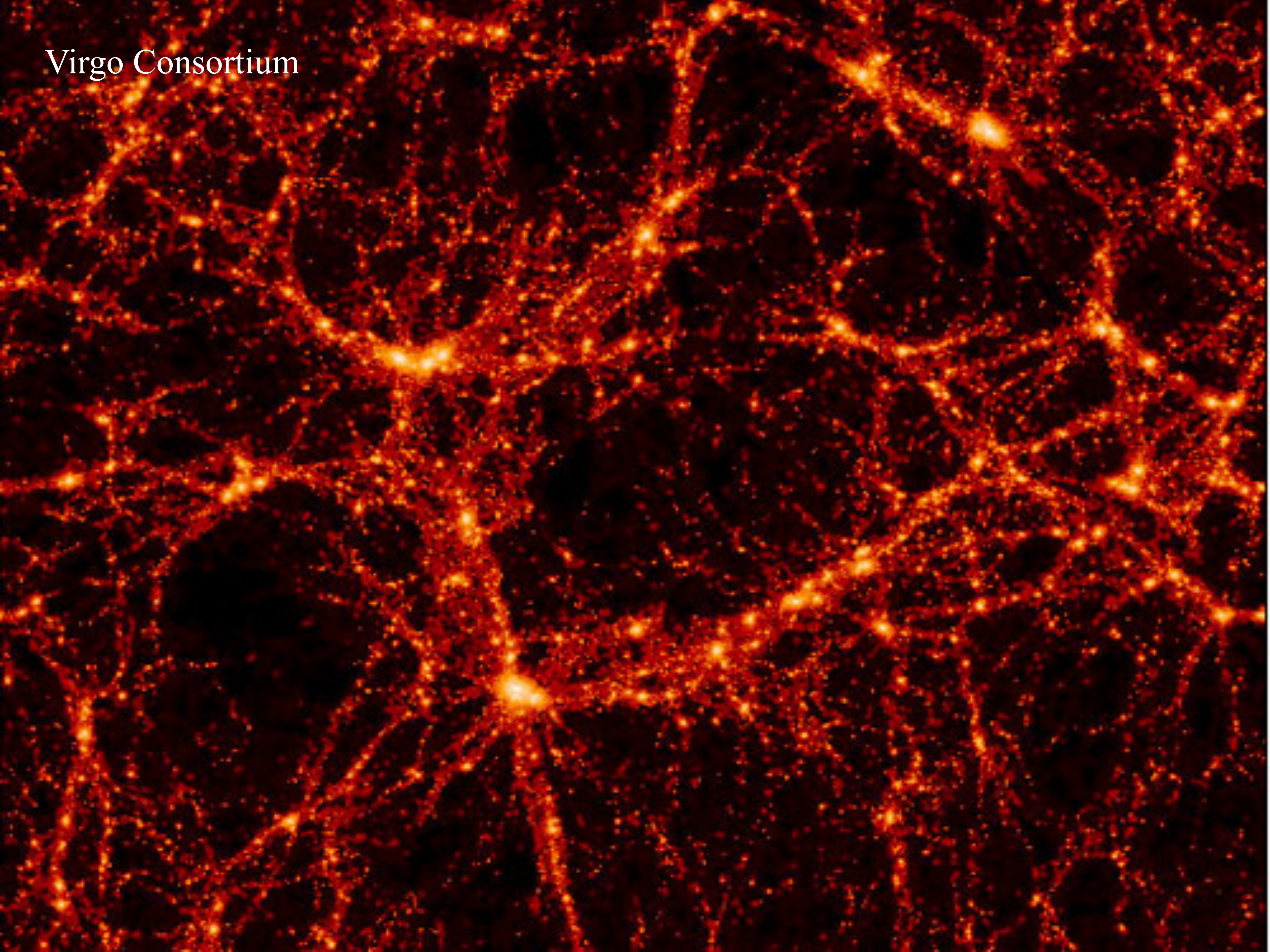
$$\ddot{G}_{\mathrm{GR}} + 2H(z)\dot{G}_{\mathrm{GR}} - \frac{3}{2}\Omega_m H_0^2(1+z)^3 G_{\mathrm{GR}} = 0$$

$$f_{\mathrm{GR}}(z) \equiv \frac{d\ln G_{\mathrm{GR}}}{d\ln a} \approx [\Omega_m(z)]^\gamma$$

$$\frac{G_{\mathrm{GR}}(z)}{G_{\mathrm{GR}}(z=0)} \approx \exp\left[-\int_0^z \frac{dz'}{1+z'}[\Omega_m(z')]^\gamma\right]$$

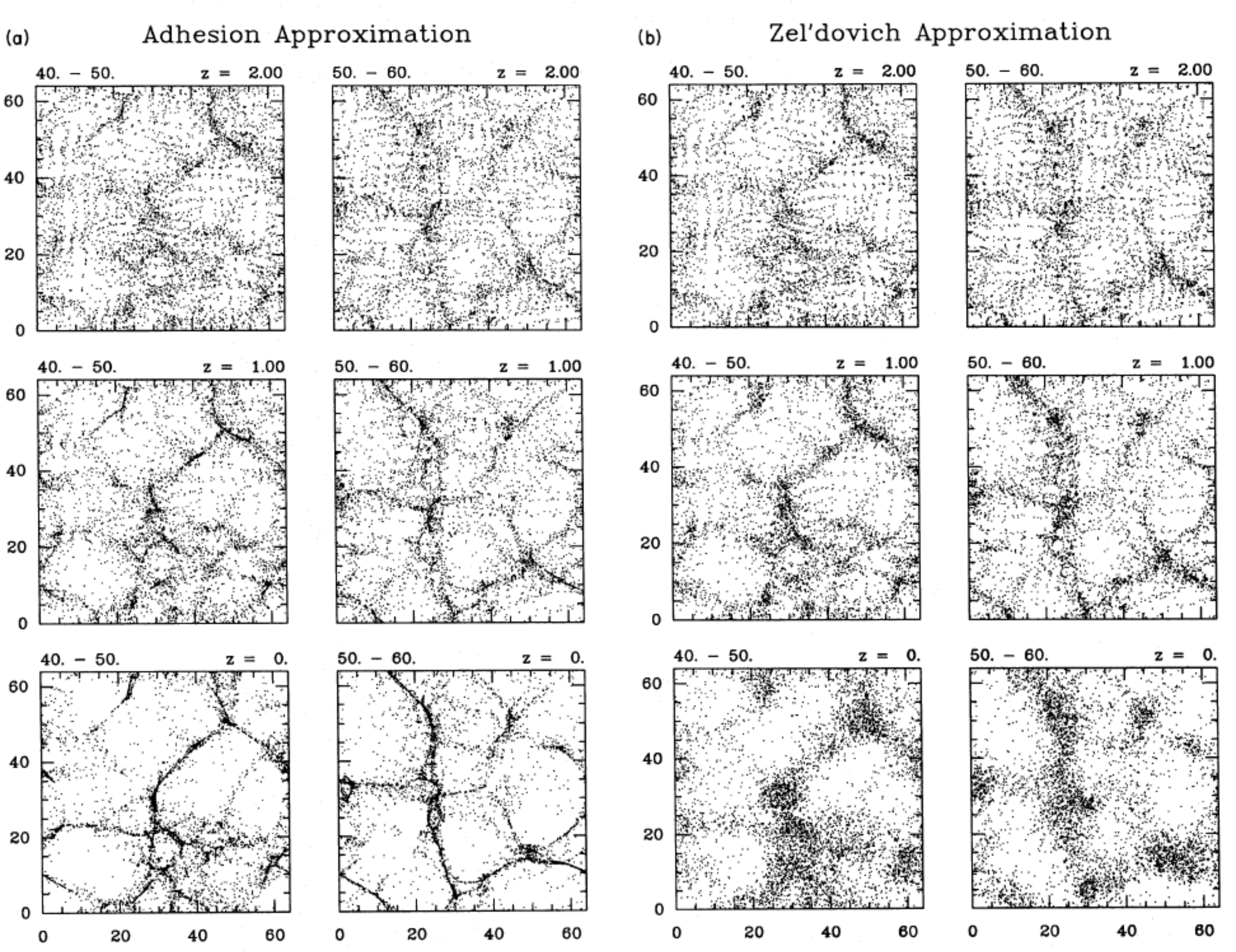
$$\gamma = 0.55 + 0.05[1+w(z=1)]$$

$$\Omega_m(z) \equiv \frac{\rho_m(z)}{\rho_{\mathrm{crit}}(z)} = \Omega_m(1+z)^3\frac{H_0^2}{H^2(z)}$$

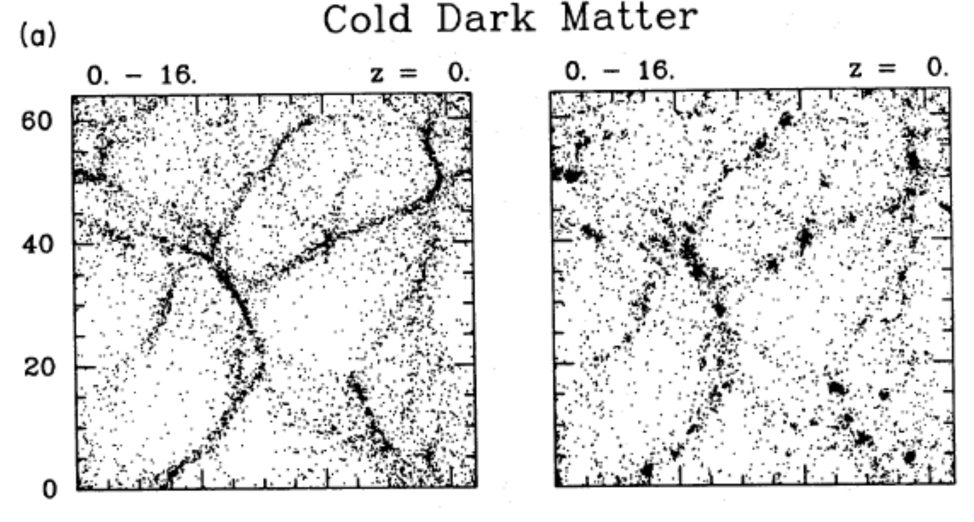


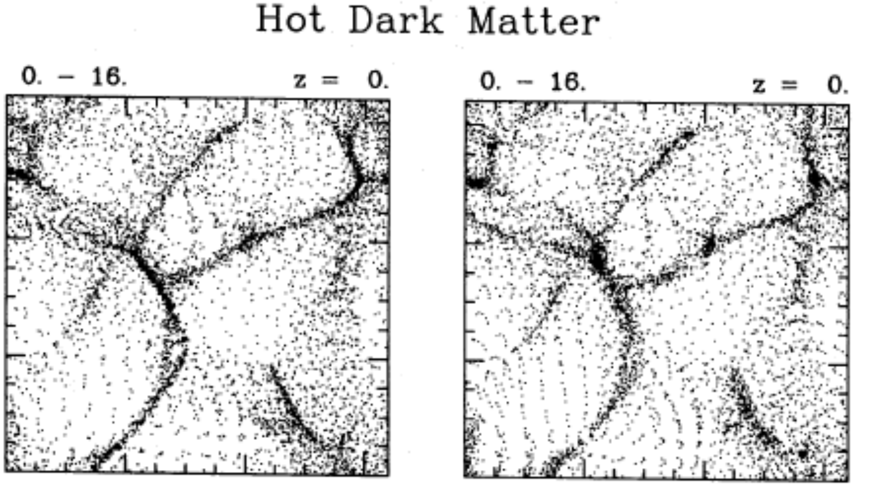
Virgo Consortium

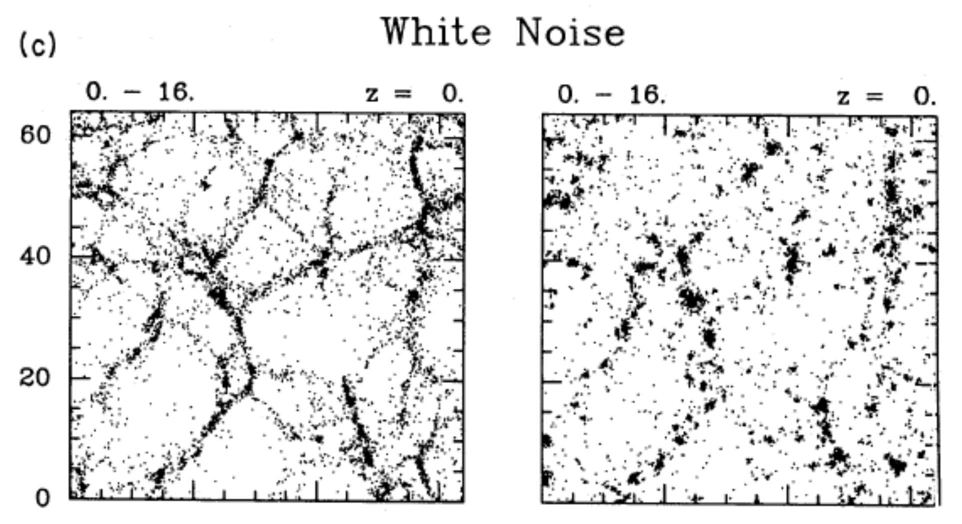
Weinberg & Gunn 1990
Large Scale Structure and the Adhesion Approximation

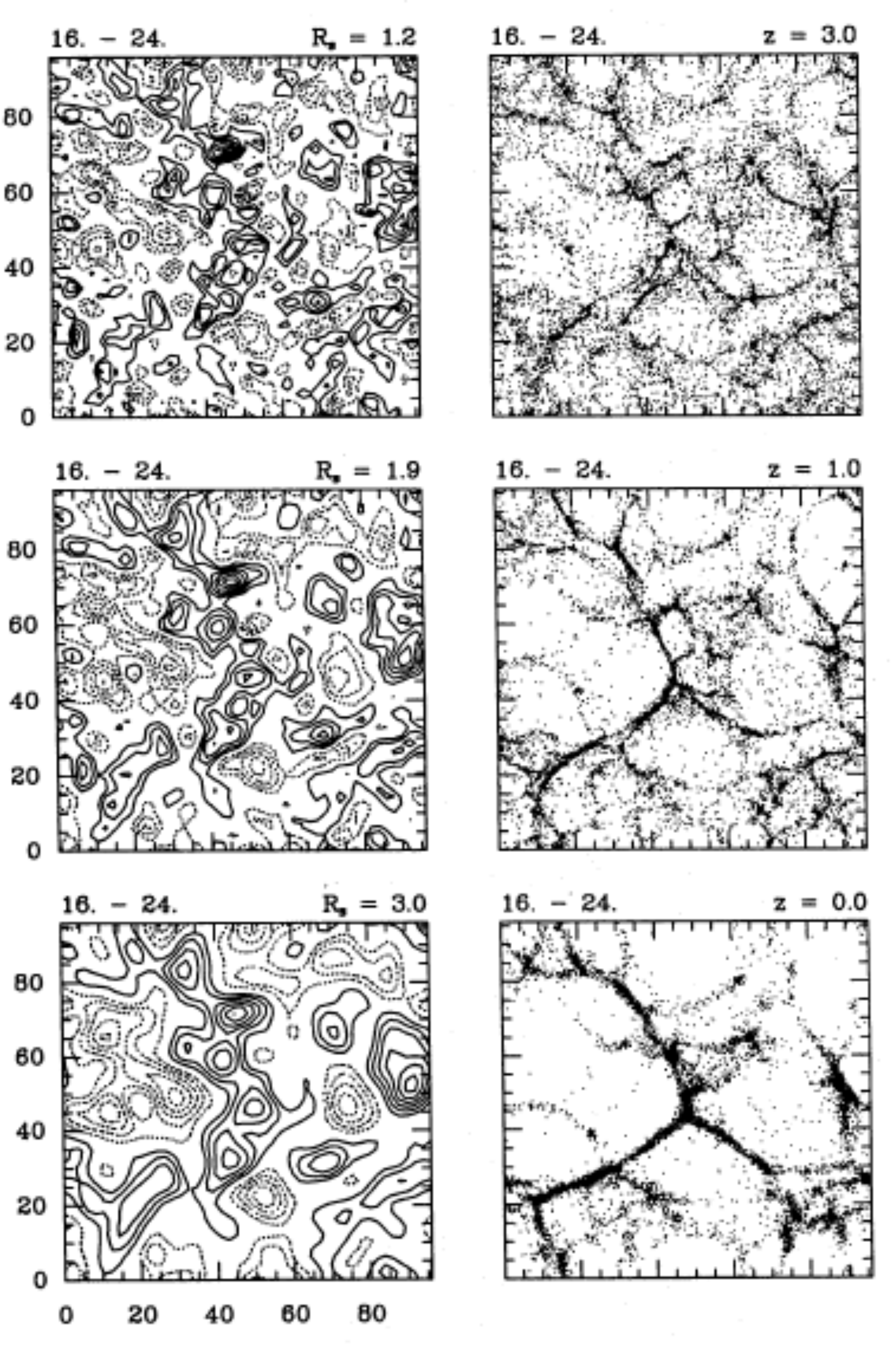


Adhesion vs. N-body

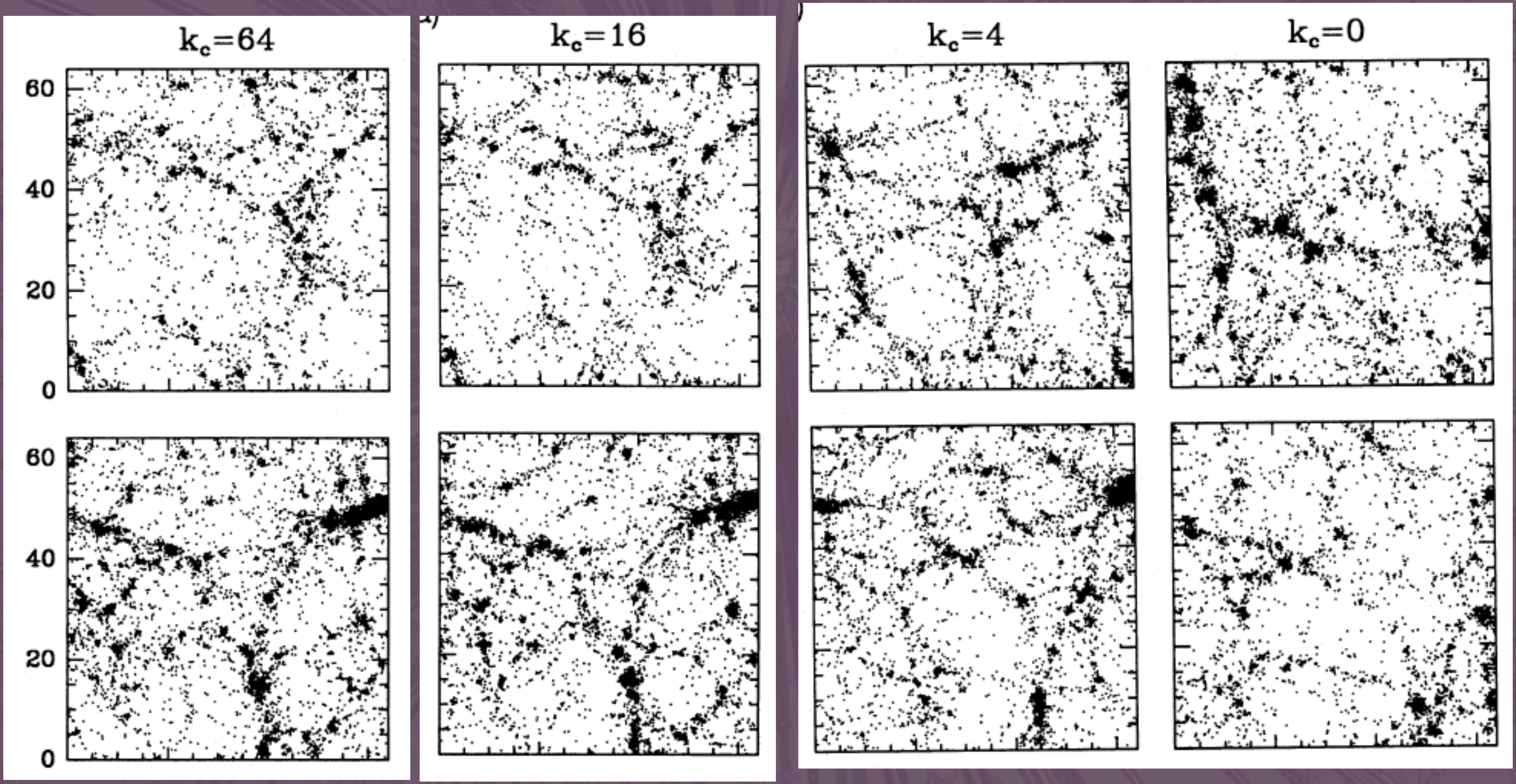


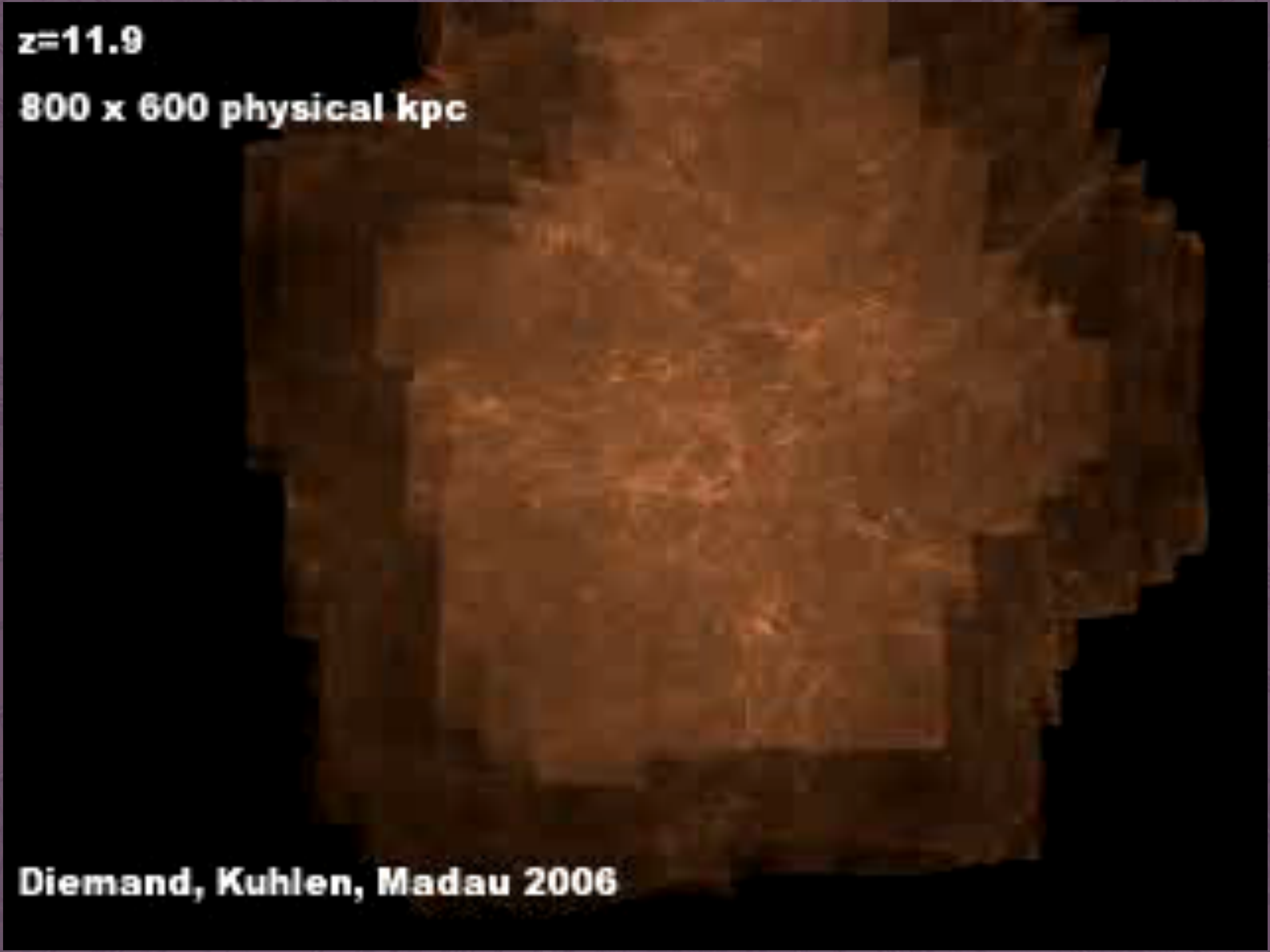




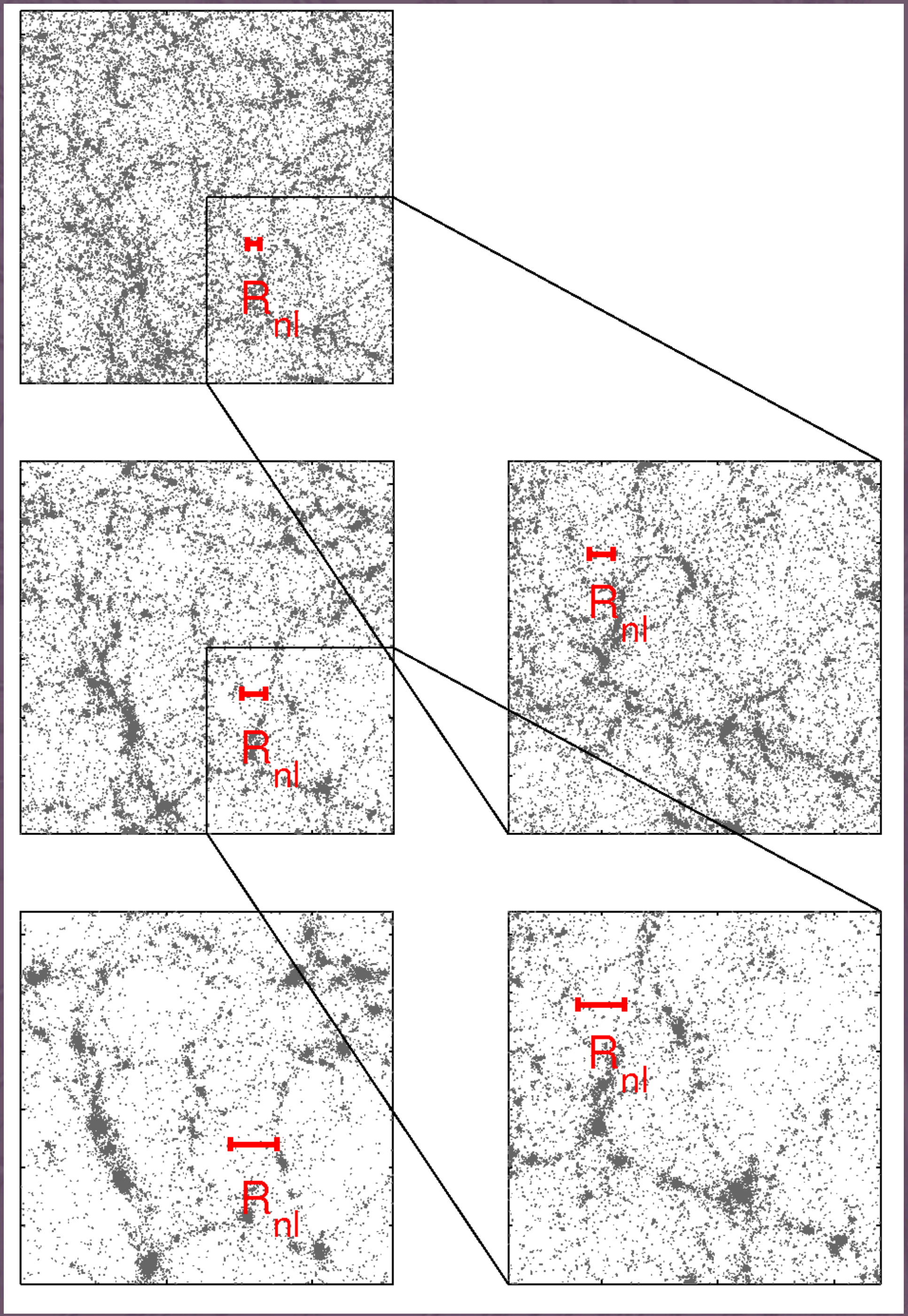

16. – 24.
R_s = 1.2
16. – 24.
z = 3.0
16. – 24.
R_s = 1.9
16. – 24.
z = 1.0
16. – 24.
R_s = 3.0
16. – 24.
z = 0.0
0
20
40
60
80

Little, Weinberg, & Park 1991
Primordial Fluctuations and Non-Linear Structure



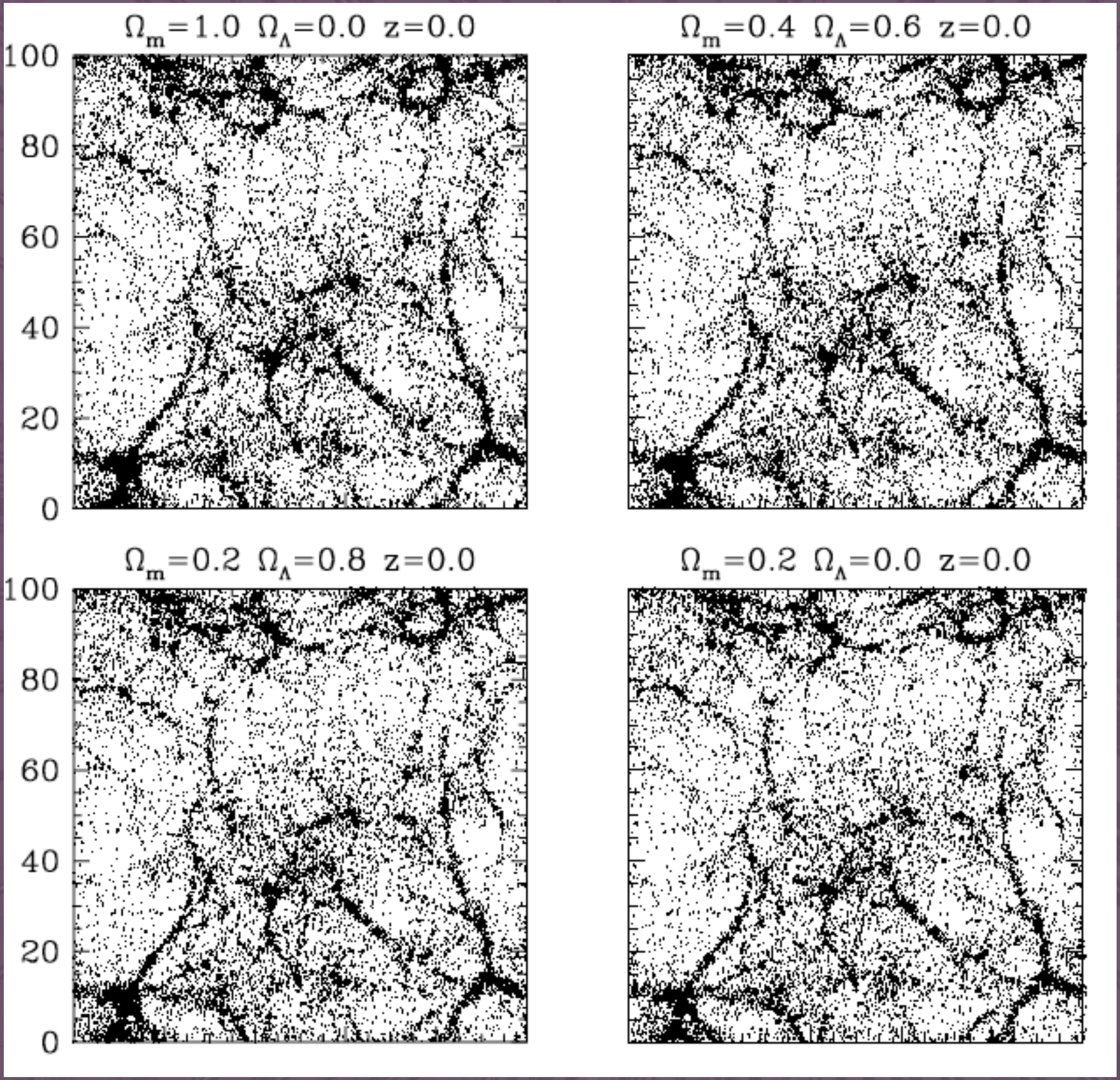


Diemand, Kuhlen, Madau 2006

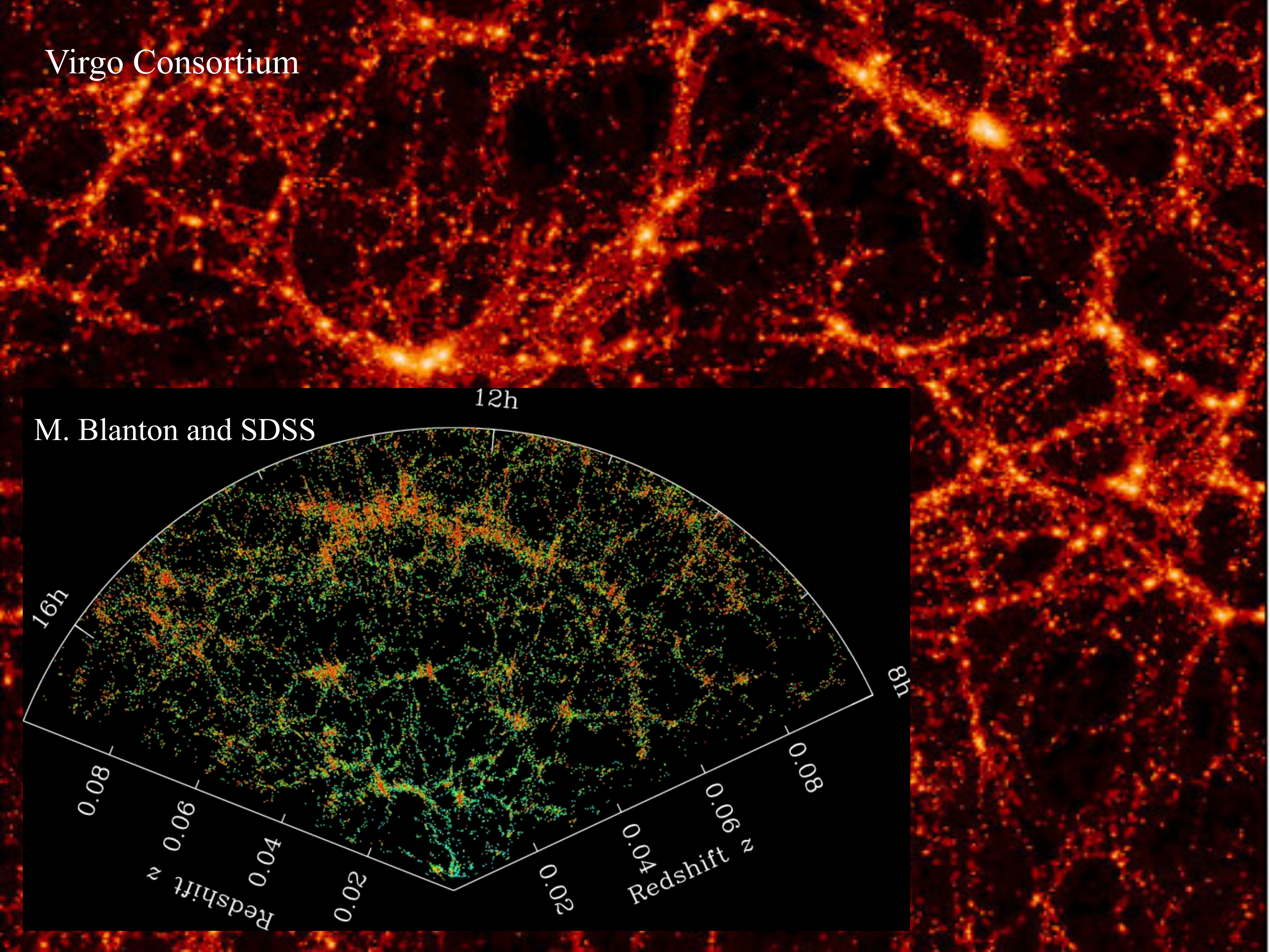


Self-similar clustering evolution
$P(k) \sim k^{-1}$
$\Omega_m = 1$

C. Orban, PhD thesis



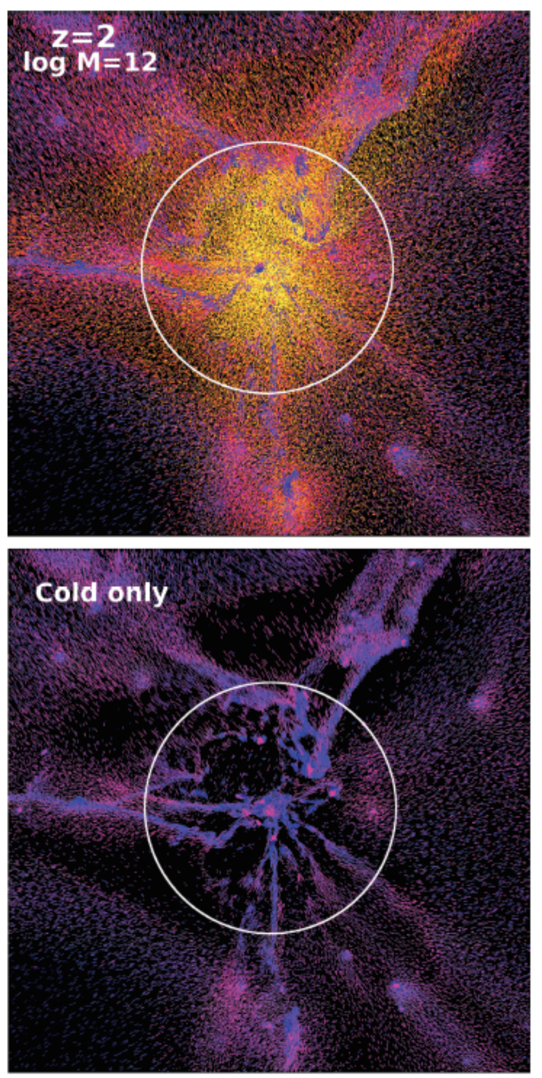
Zheng et al. 2002 N-body simulations evolved from same linear density field (to same σ_8) with different cosmological parameters.



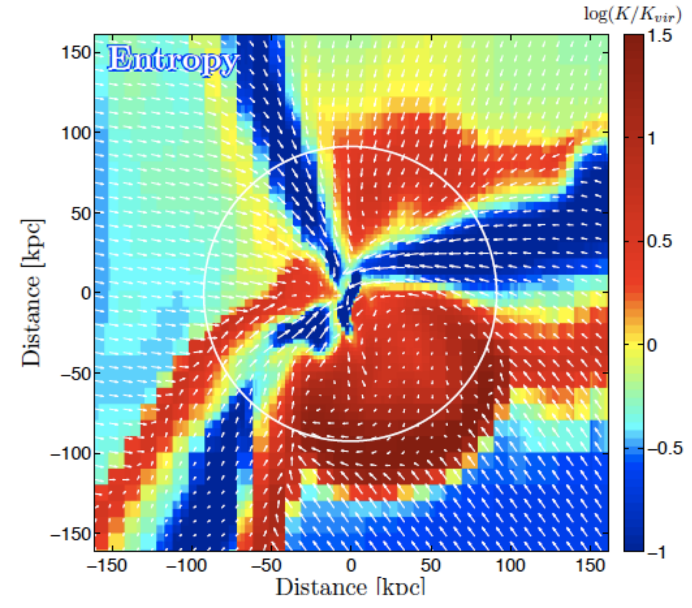
Virgo Consortium

M. Blanton and SDSS

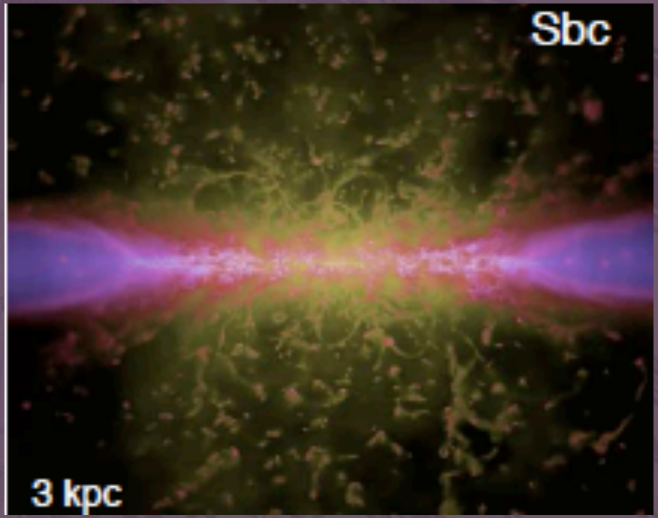
Keres et al. 2009



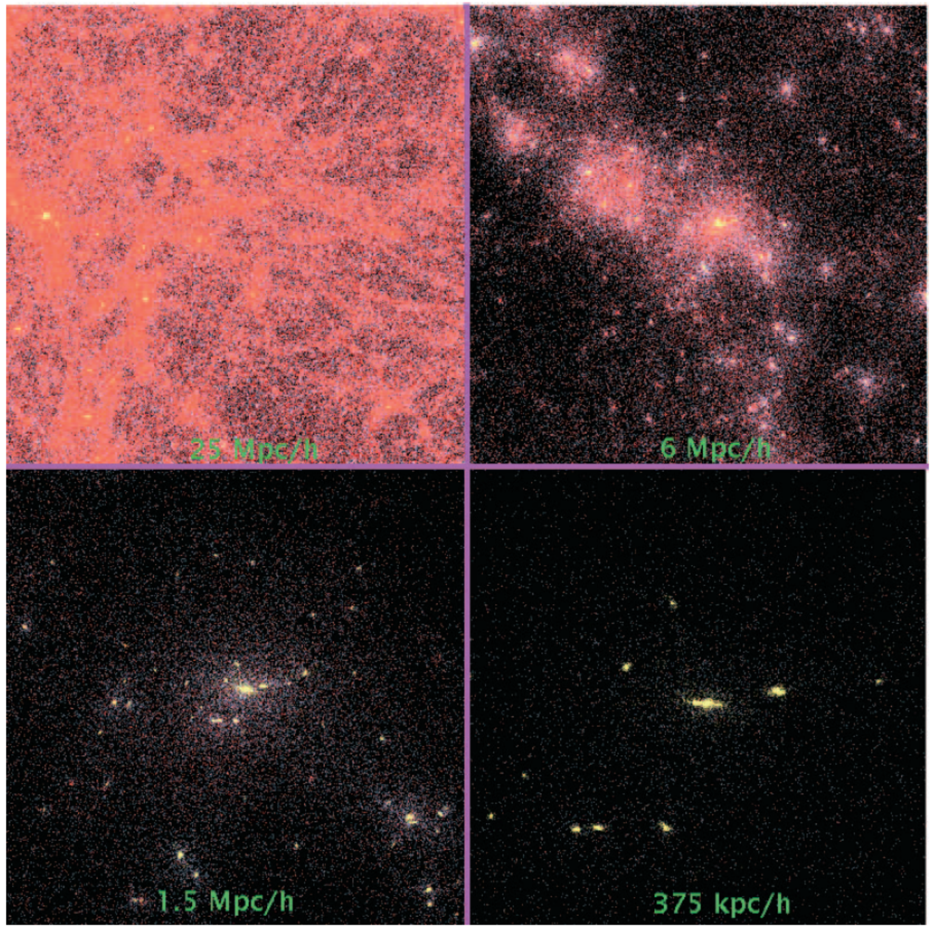
Dekel et al. 2009



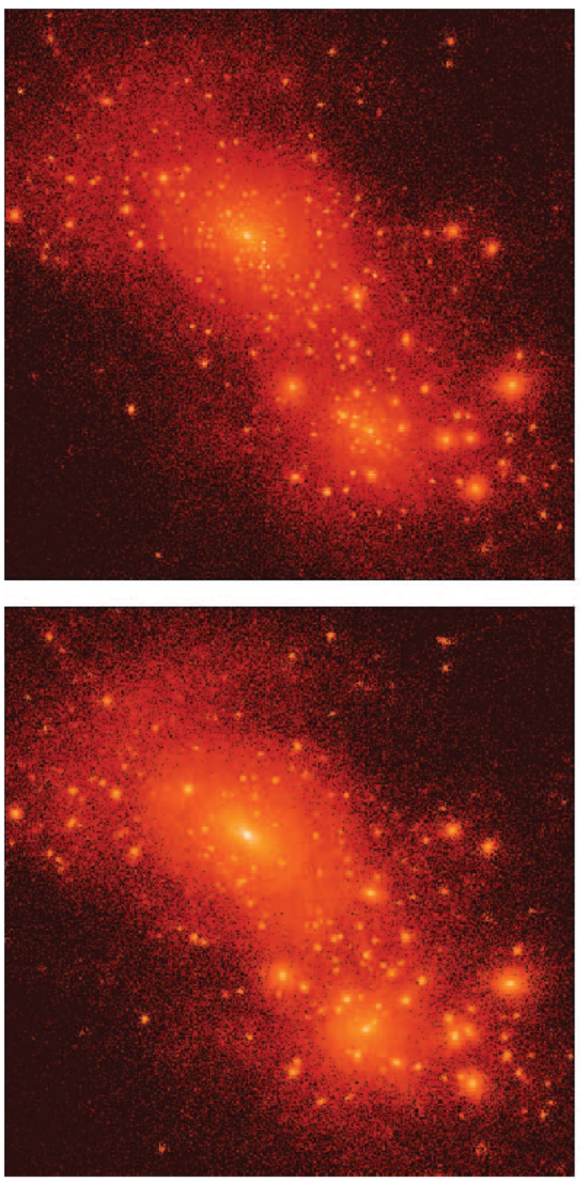
Hopkins et al. 2012



Weinberg et al. 2004
Galaxy distribution in hydro simulation



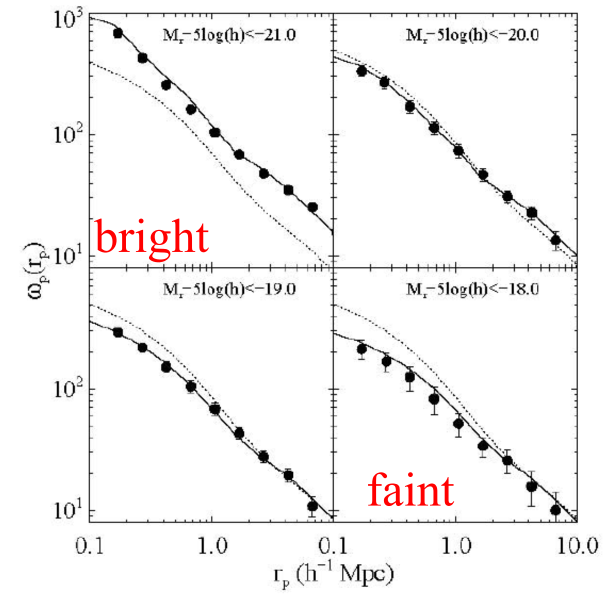
Weinberg et al. 2008
DM in hydro simulation vs.
N-body only



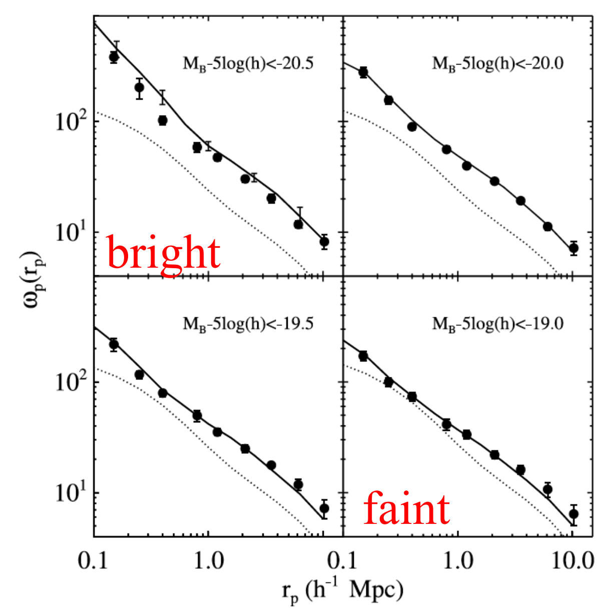
Conroy, Wechsler, & Kratvsov 2006

Abundance matching

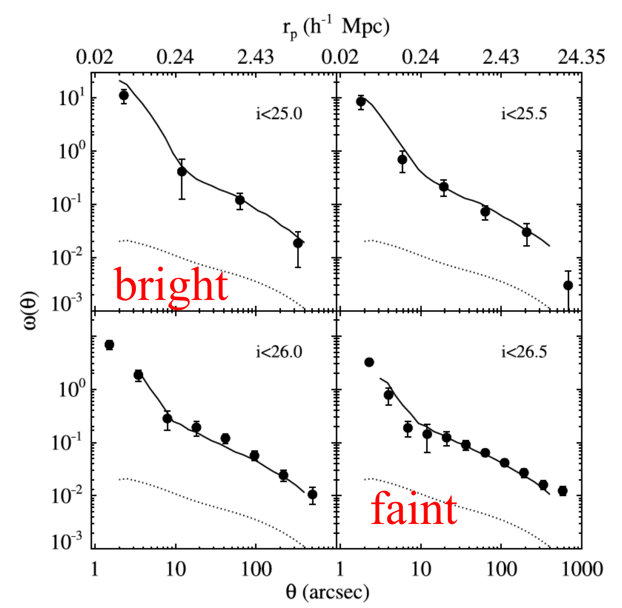
SDSS, z ~ 0



DEEP2, z ~ 1



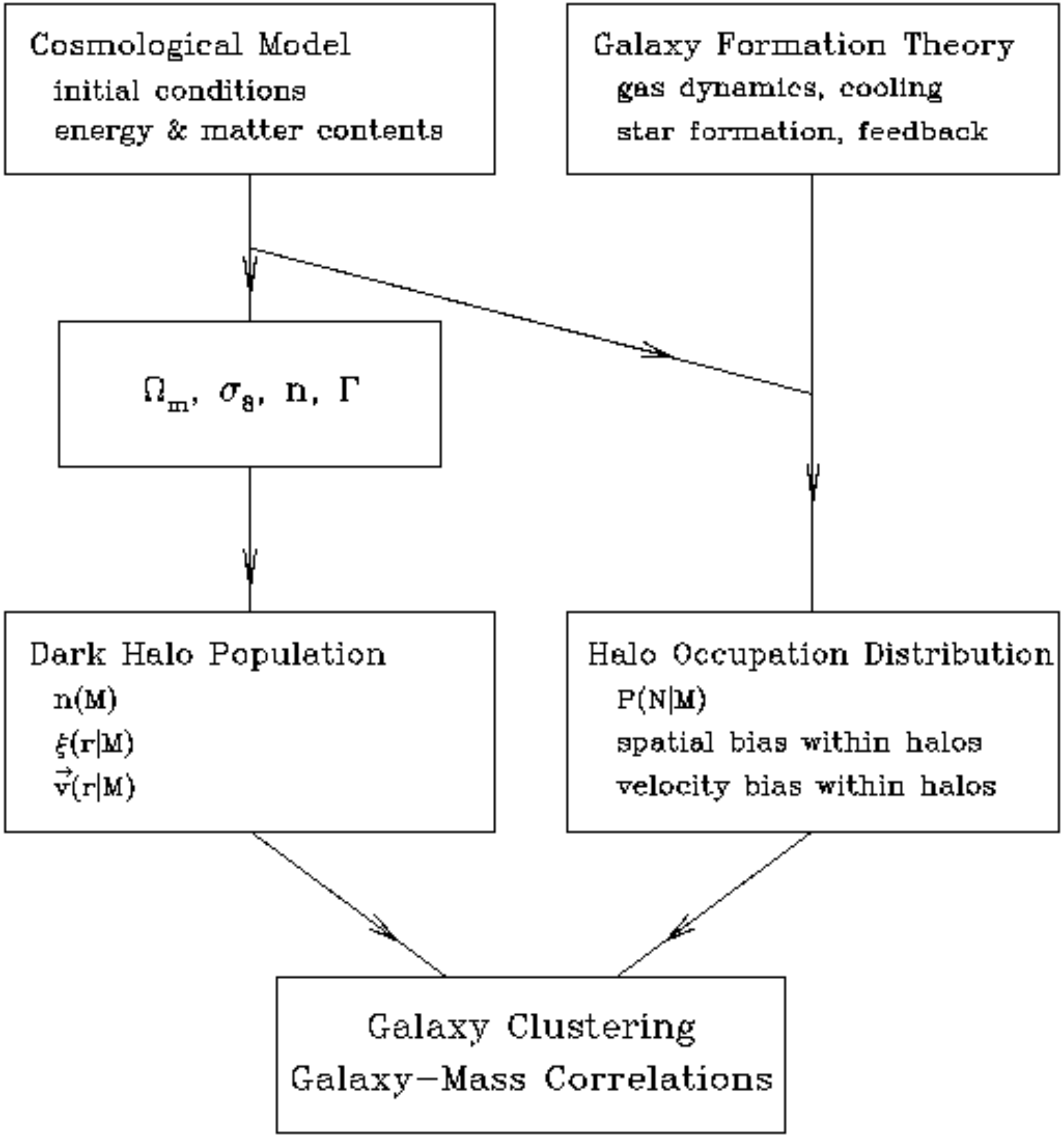
Subaru LBGs, z ~ 4



Projected correlation functions, dotted=DM, solid=SHAM, points=data

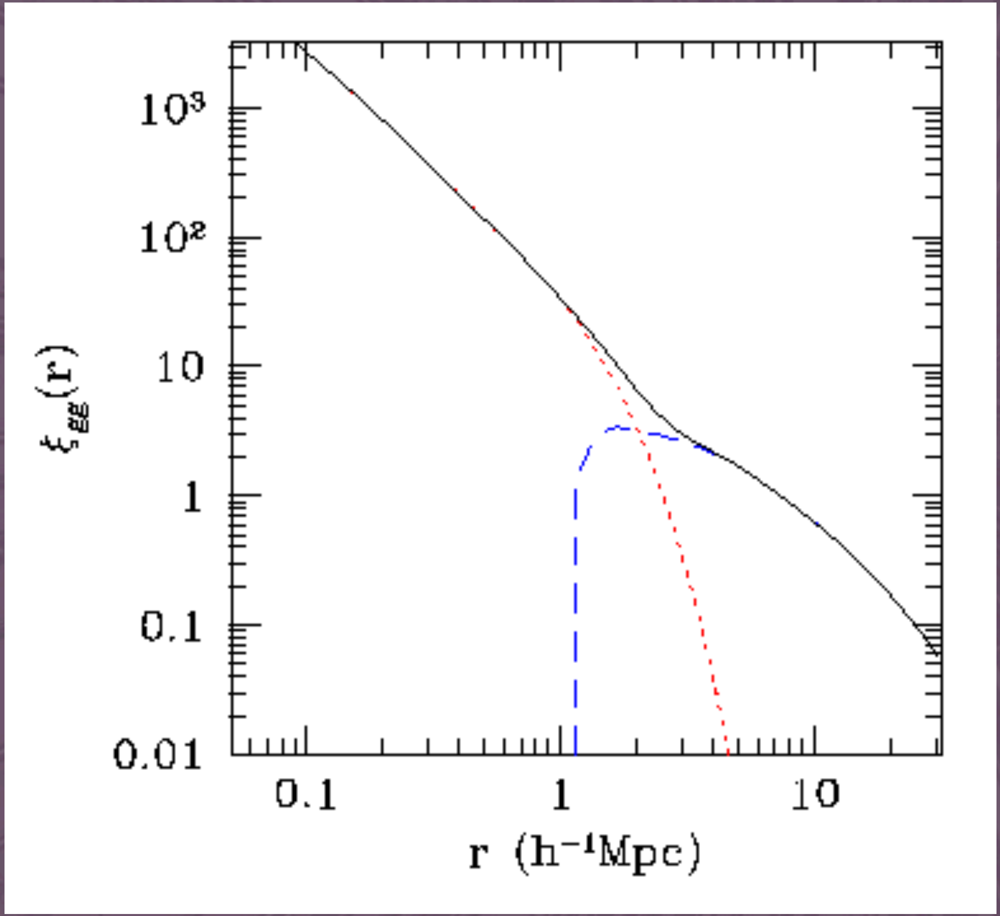
Zero-parameter model reproduces redshift and luminosity dependence over a remarkable range.

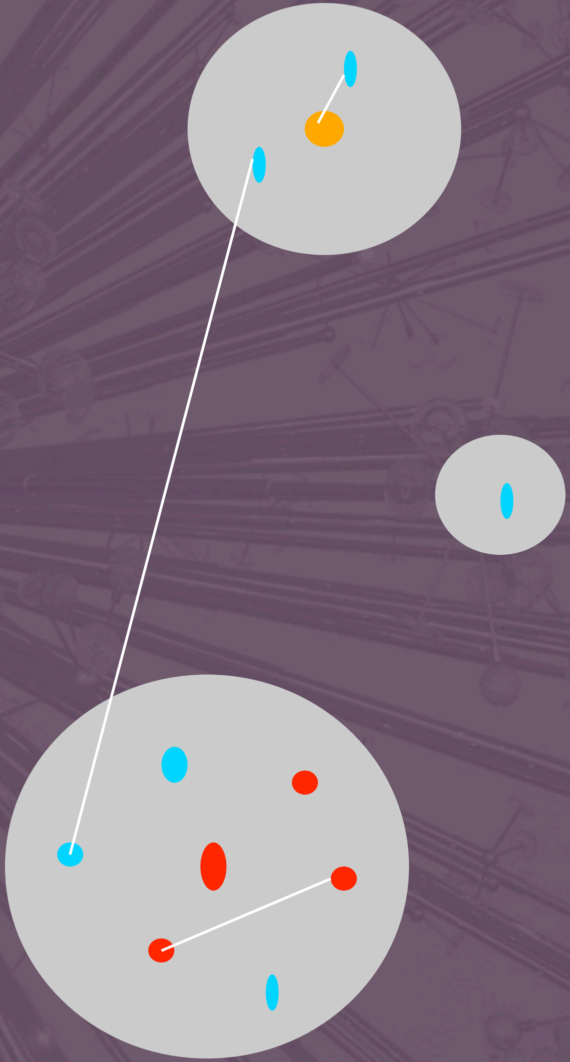
Booyah!



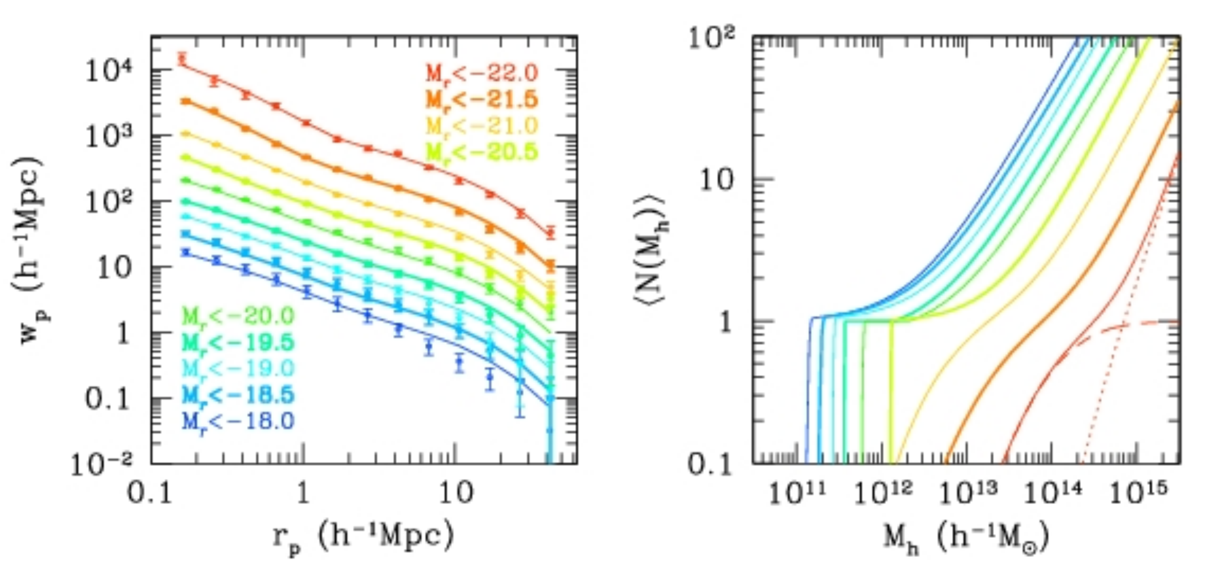
Durham 2001:
"A New Era in Cosmology"

Galaxy correlation function

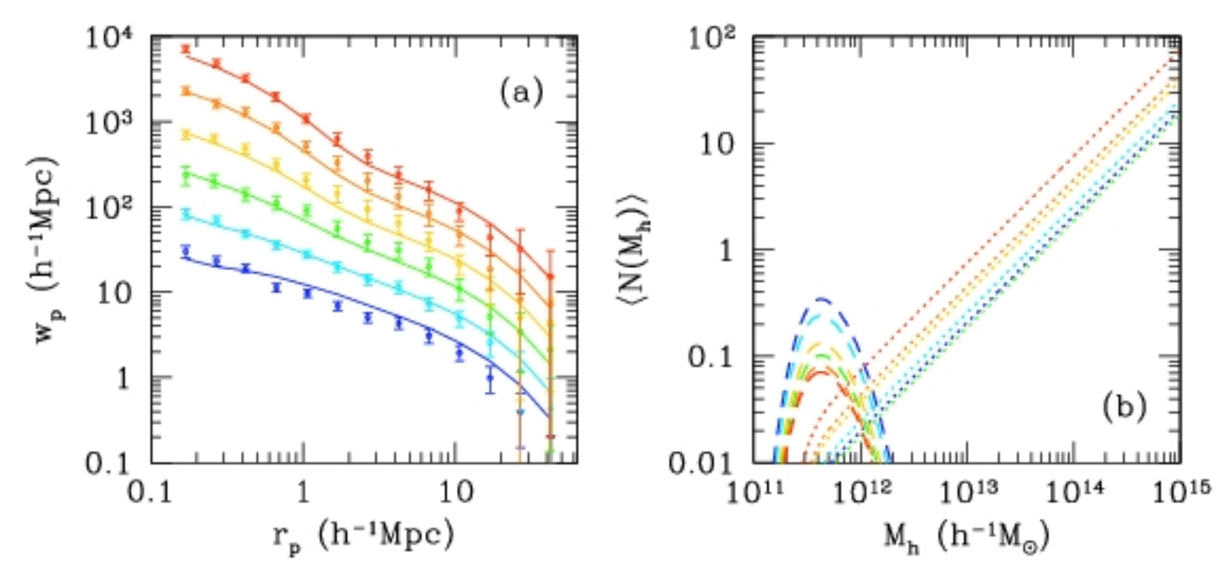




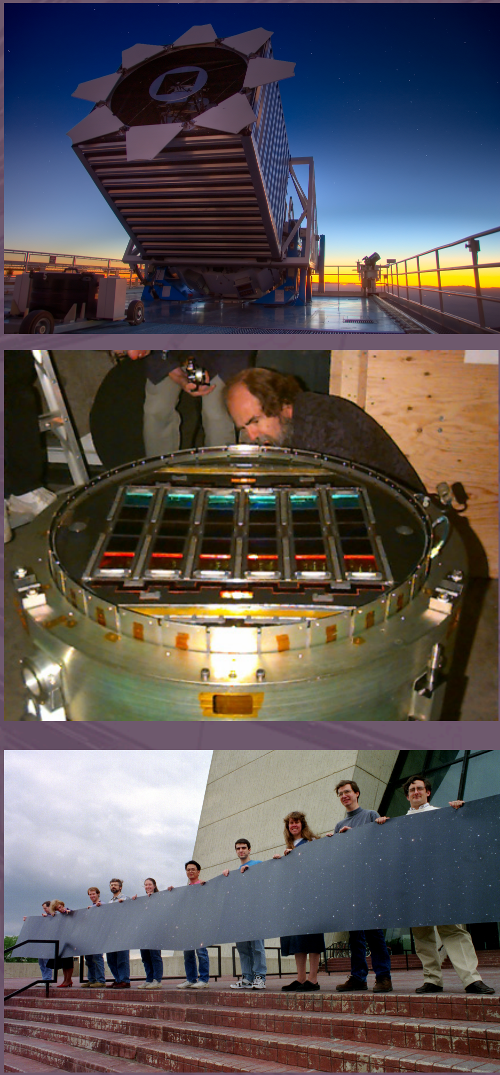
Zehavi, Zheng, Weinberg et al. 2011



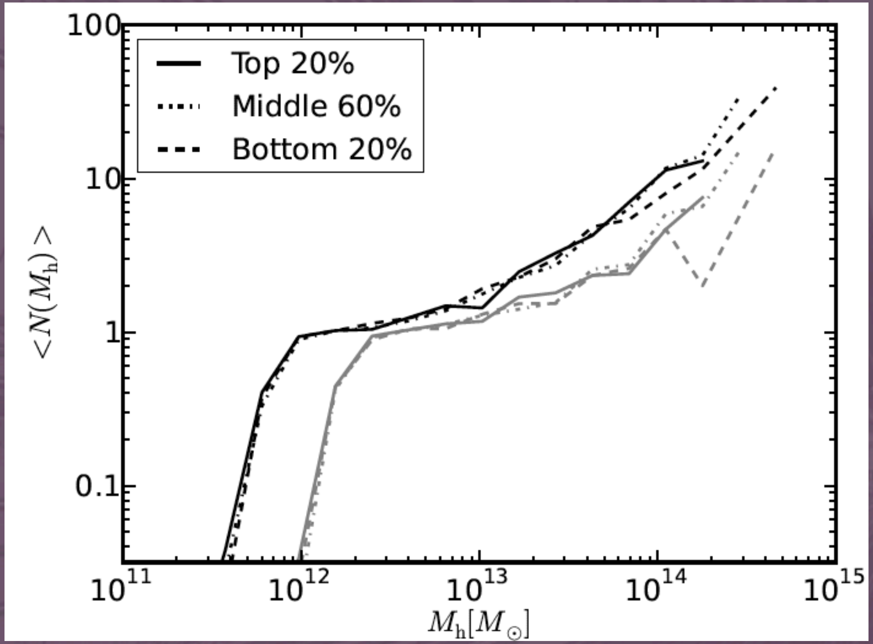
Luminosity Dependence



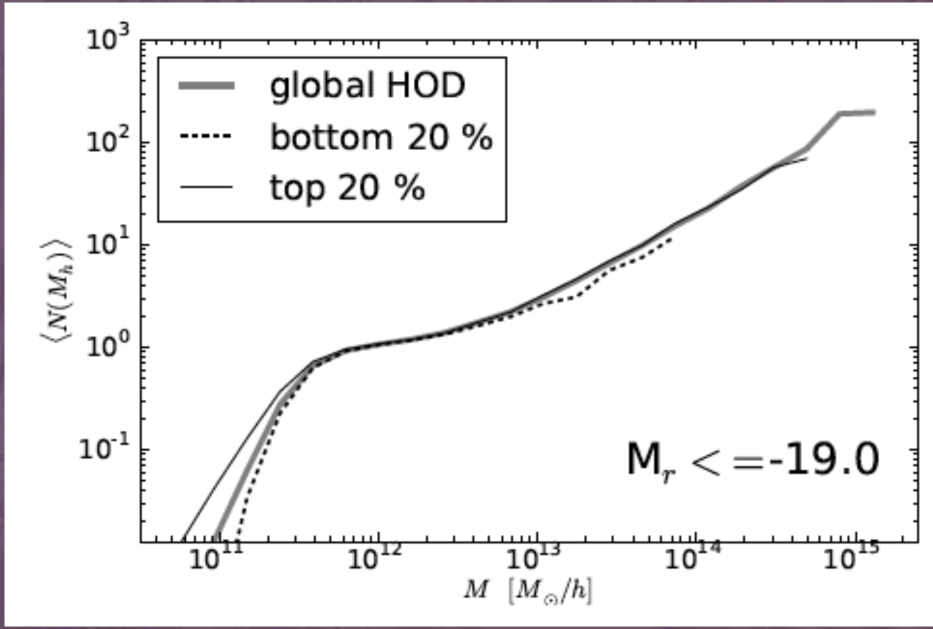
Color Dependence



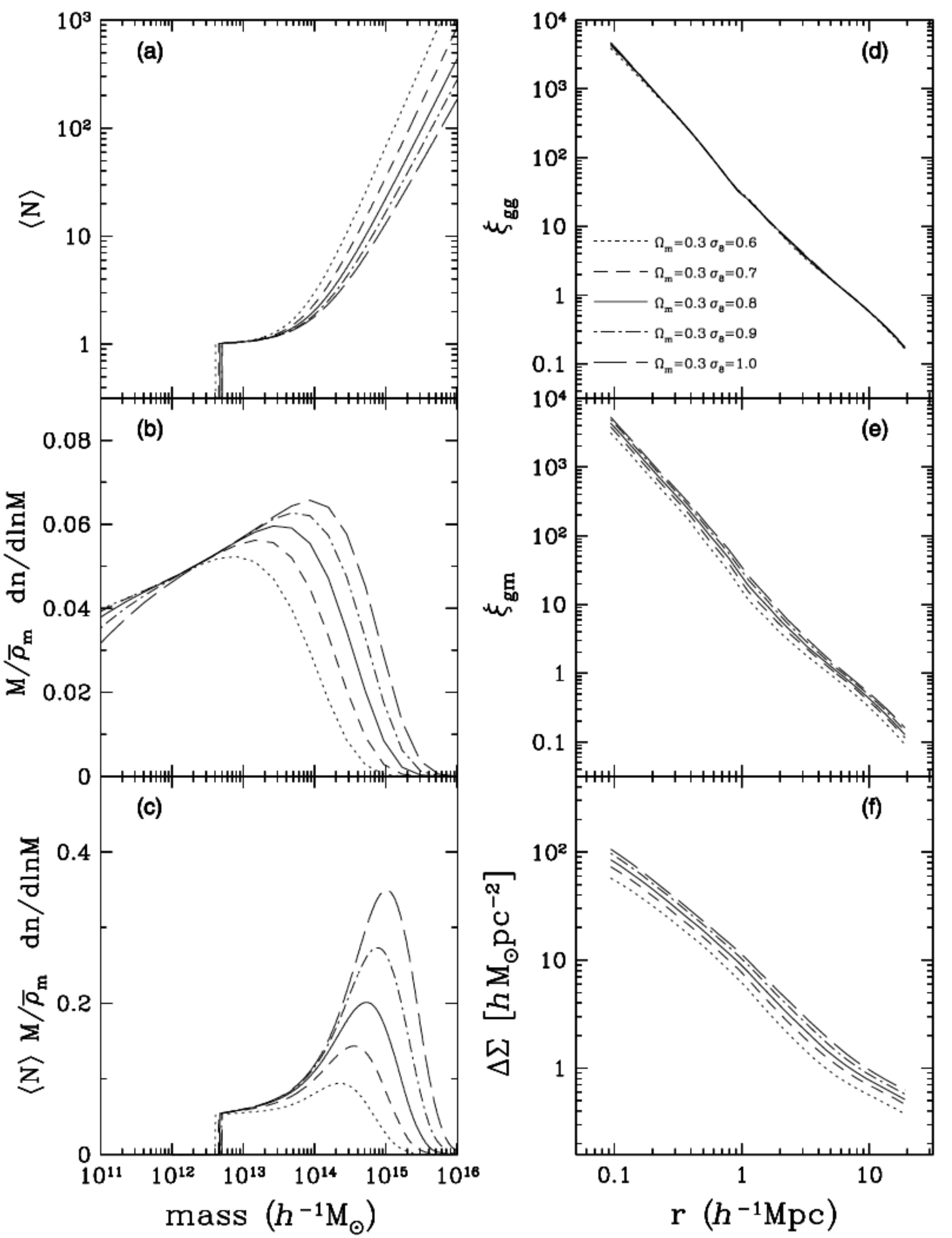
Google “SDSS At Night” to find this on YouTube



K. Mehta PhD thesis:
No environment dependence of HOD in hydro simulations of galaxy formation.



McEwen & Weinberg in prep:
Environment dependence of HOD in Hearin & Watson abundance matching galaxy catalogs.

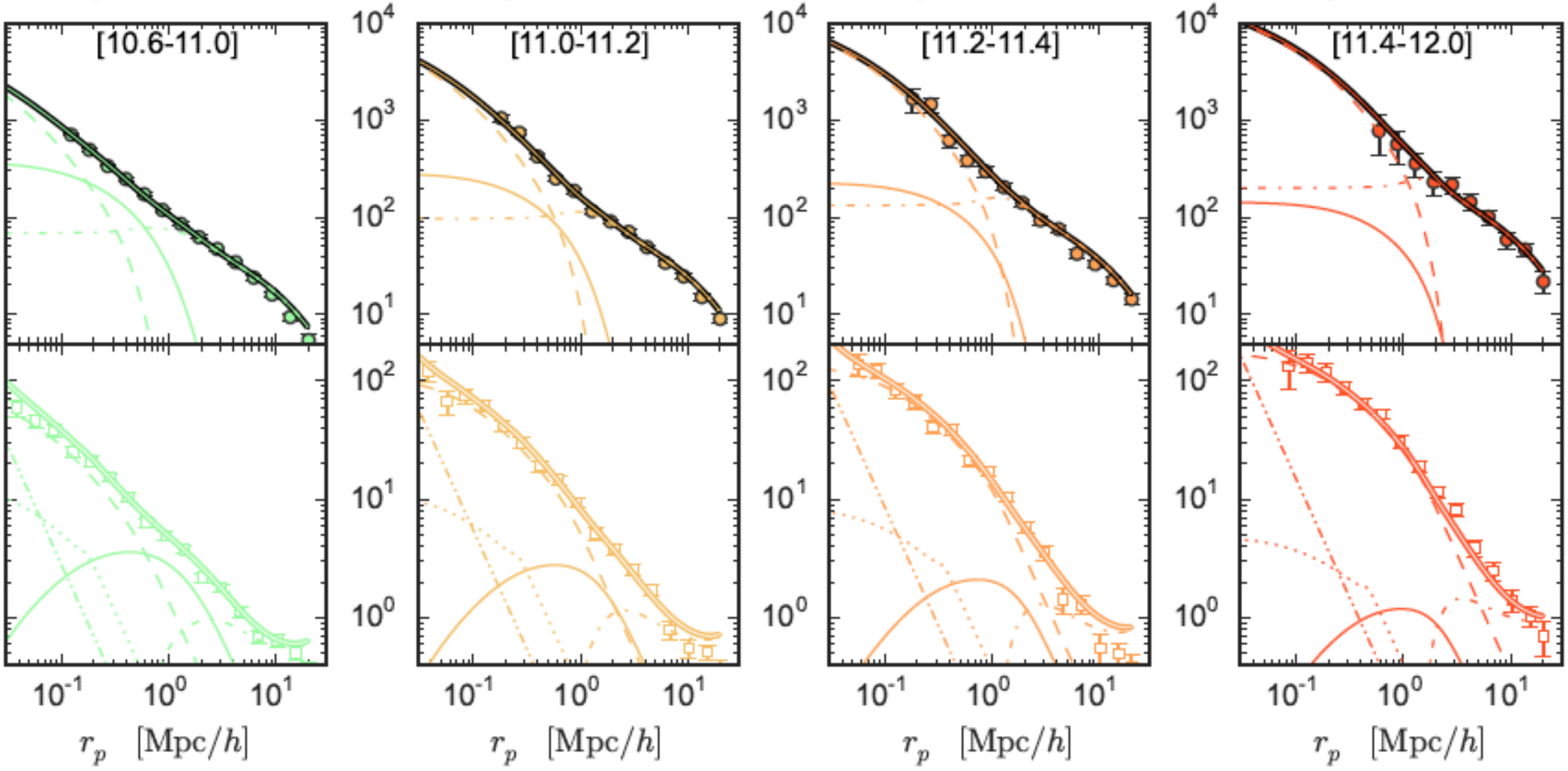


Yoo et al. 2006

HOD modeling of galaxy-galaxy lensing

With HOD chosen to match galaxy correlation function, GGL signal depends on σ_8 and Ω_m

Zu & Mandelbaum 2013
iHOD model vs. SDSS measurements
for $\sigma_8 = 0.77$ and $\Omega_m = 0.26$



Current cosmological data sets

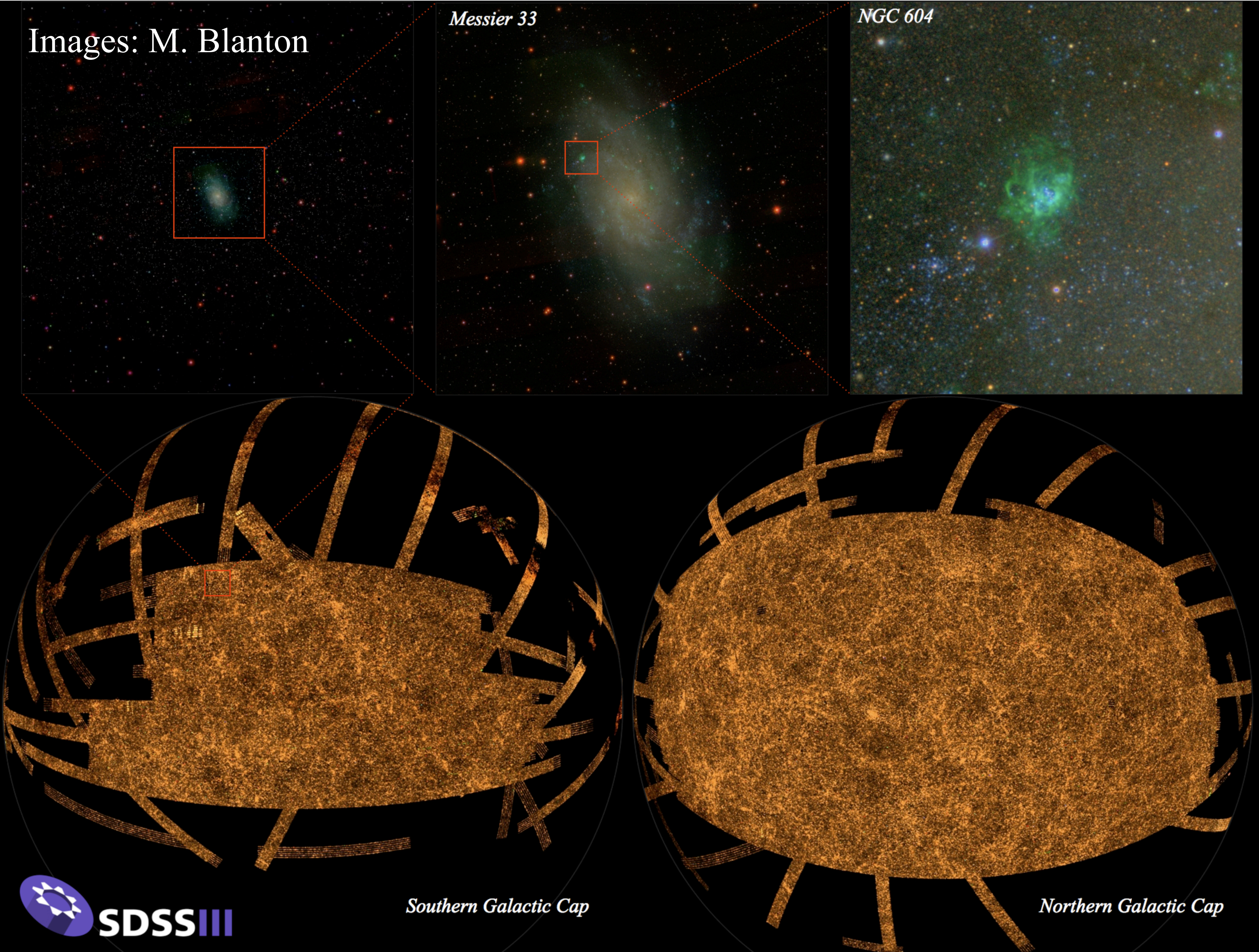
CMB: Planck (all sky), SPT and ACT (~ 0.01 – 0.1 sky)

Supernovae: Union 2.1 and JLA, both ~ 800 Type Ia SNe, z = 0 – 1.2

Imaging: SDSS (0.25 sky), Stripe 82 (0.005 sky), CFHTLens (0.005 sky), Pan-STARRS (0.75 sky)

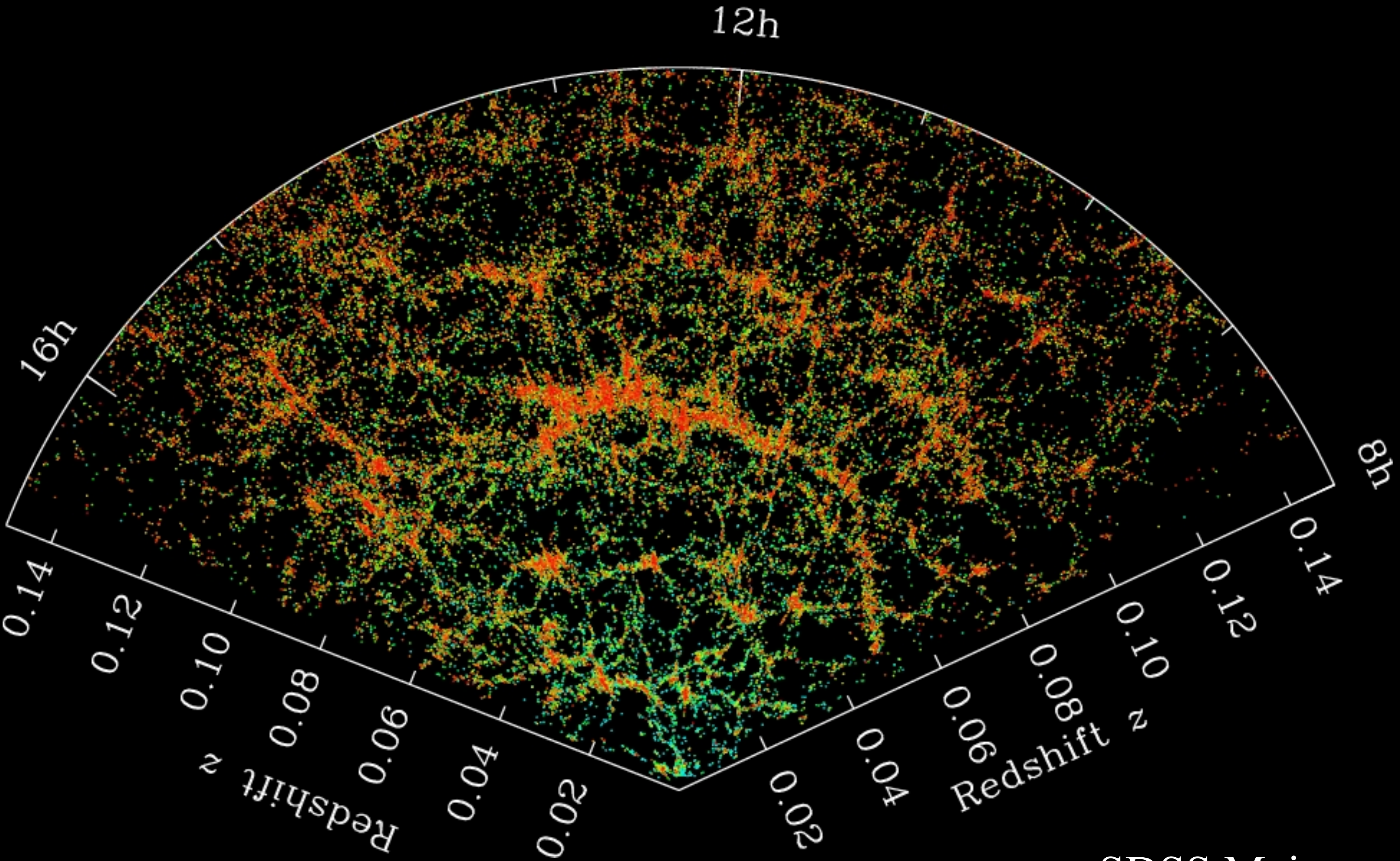
Spectroscopic:
SDSS-I/II: 1 million broadly selected galaxies z = 0-0.2,
10^5 luminous red galaxies (LRGs) z = 0.2 -0.45
SDSS-III BOSS: 1.5 million luminous galaxies, z = 0.2-0.7,
160,000 quasars at z = 2-4

Images: M. Blanton



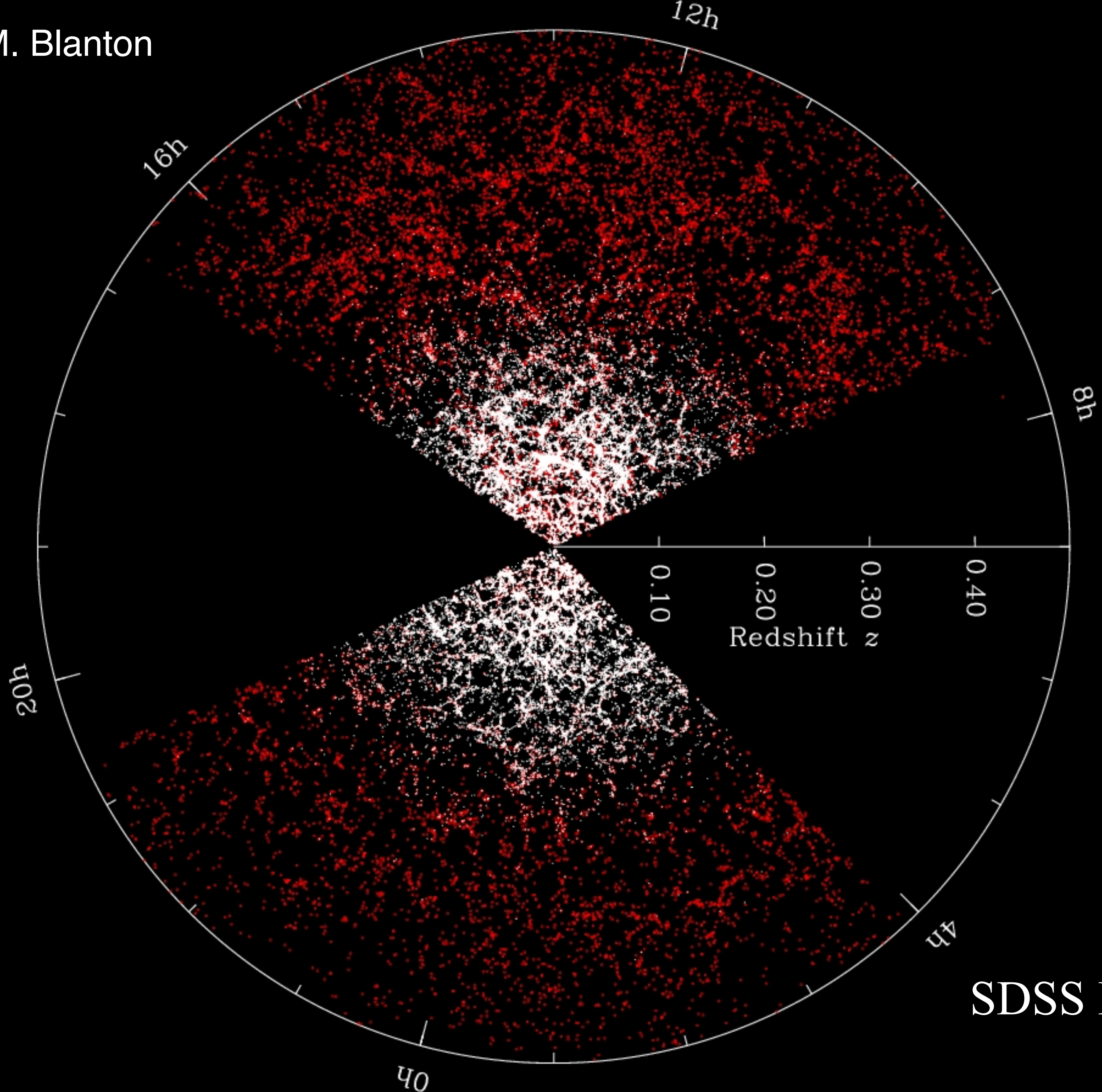
SDSS III

Figs by M. Blanton



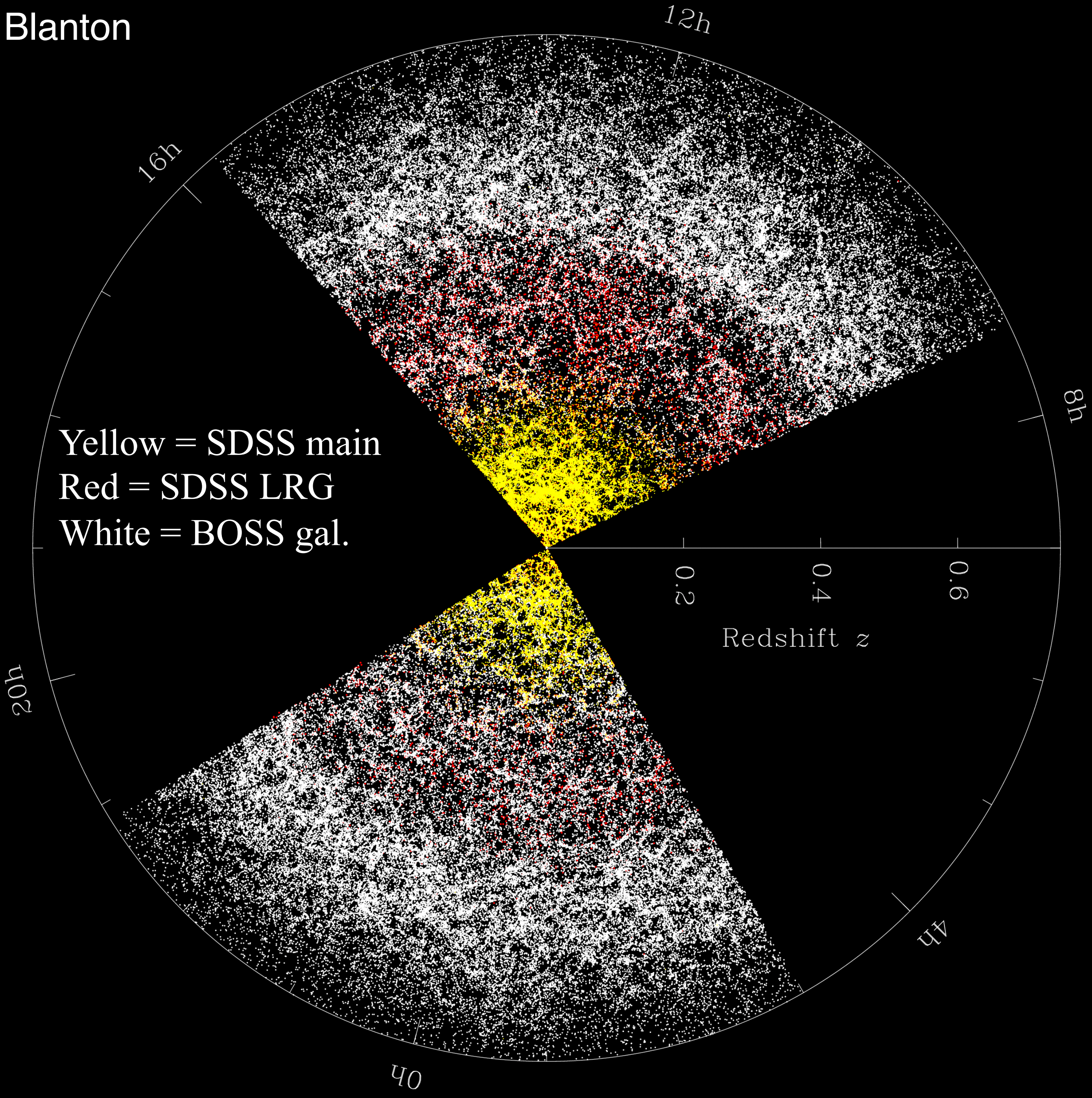
SDSS Main

Figs by M. Blanton

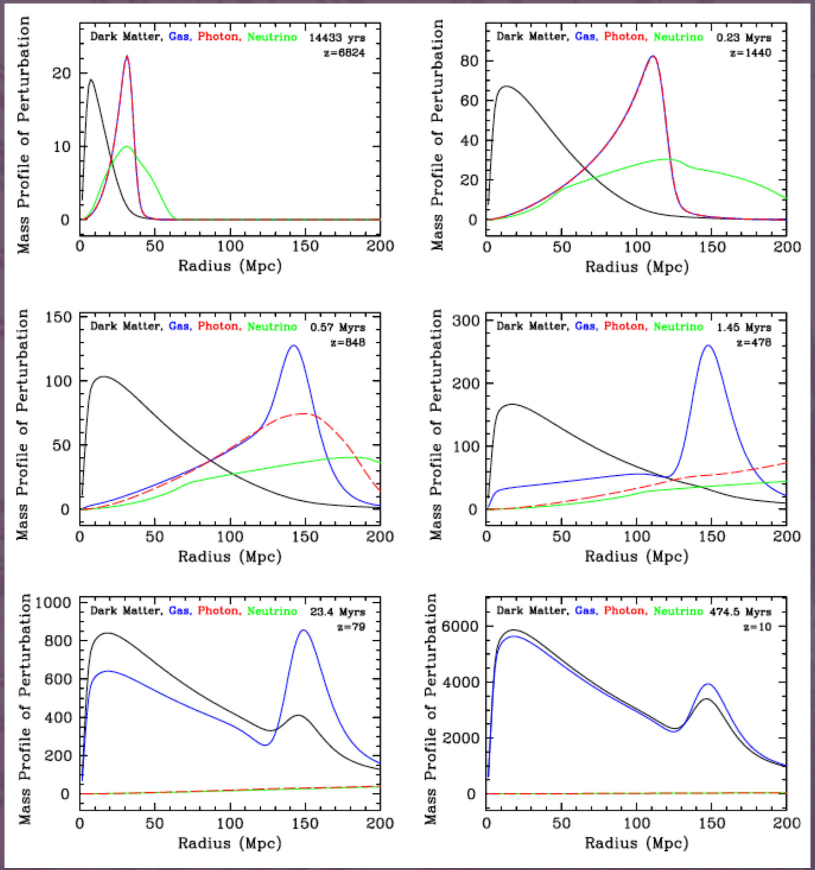


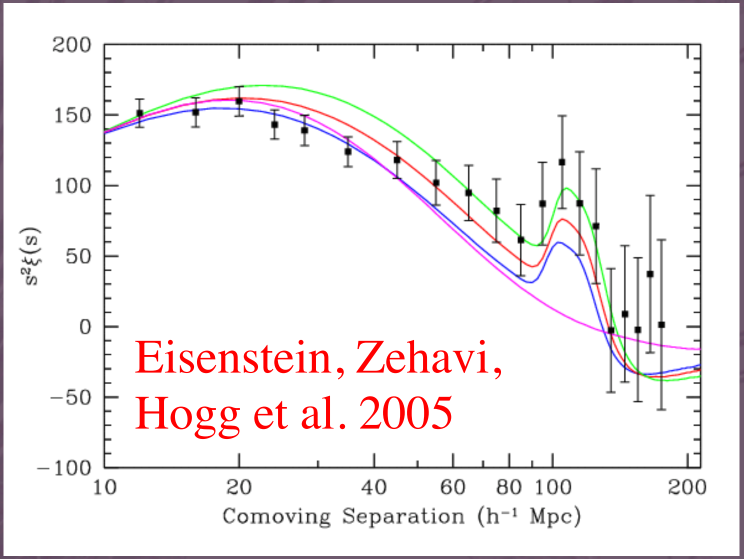
SDSS LRG

Figs by M. Blanton

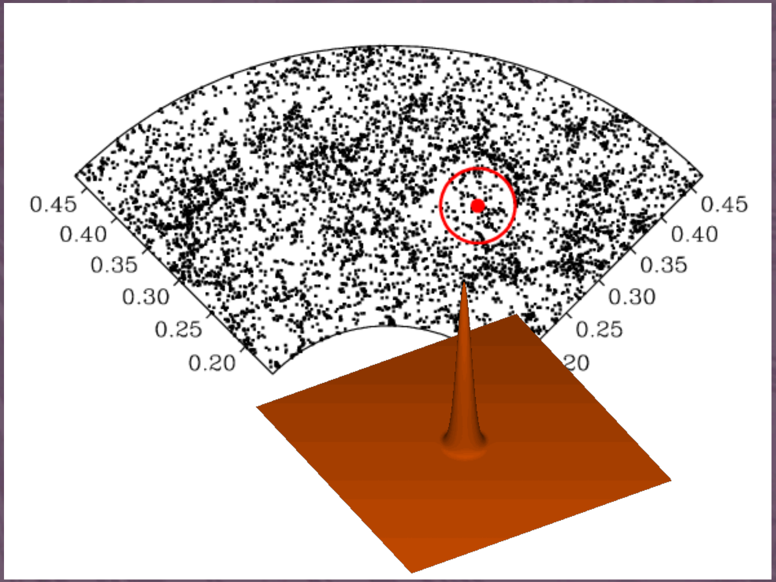


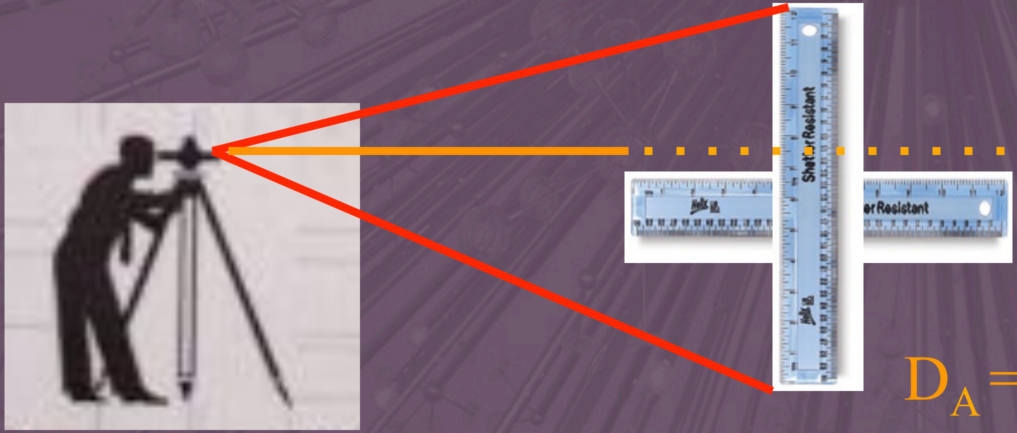
Yellow = SDSS main
Red = SDSS LRG
White = BOSS gal.



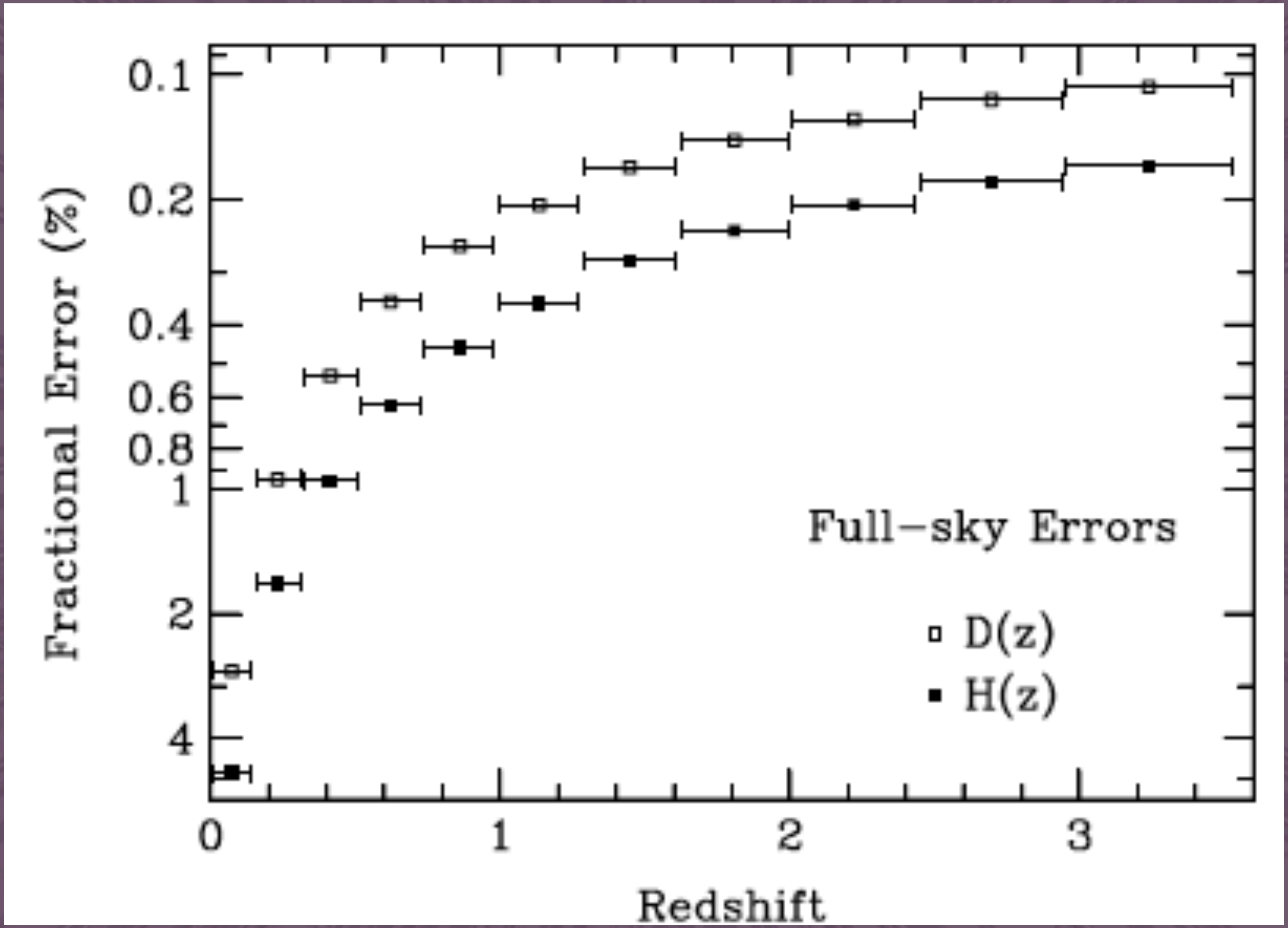


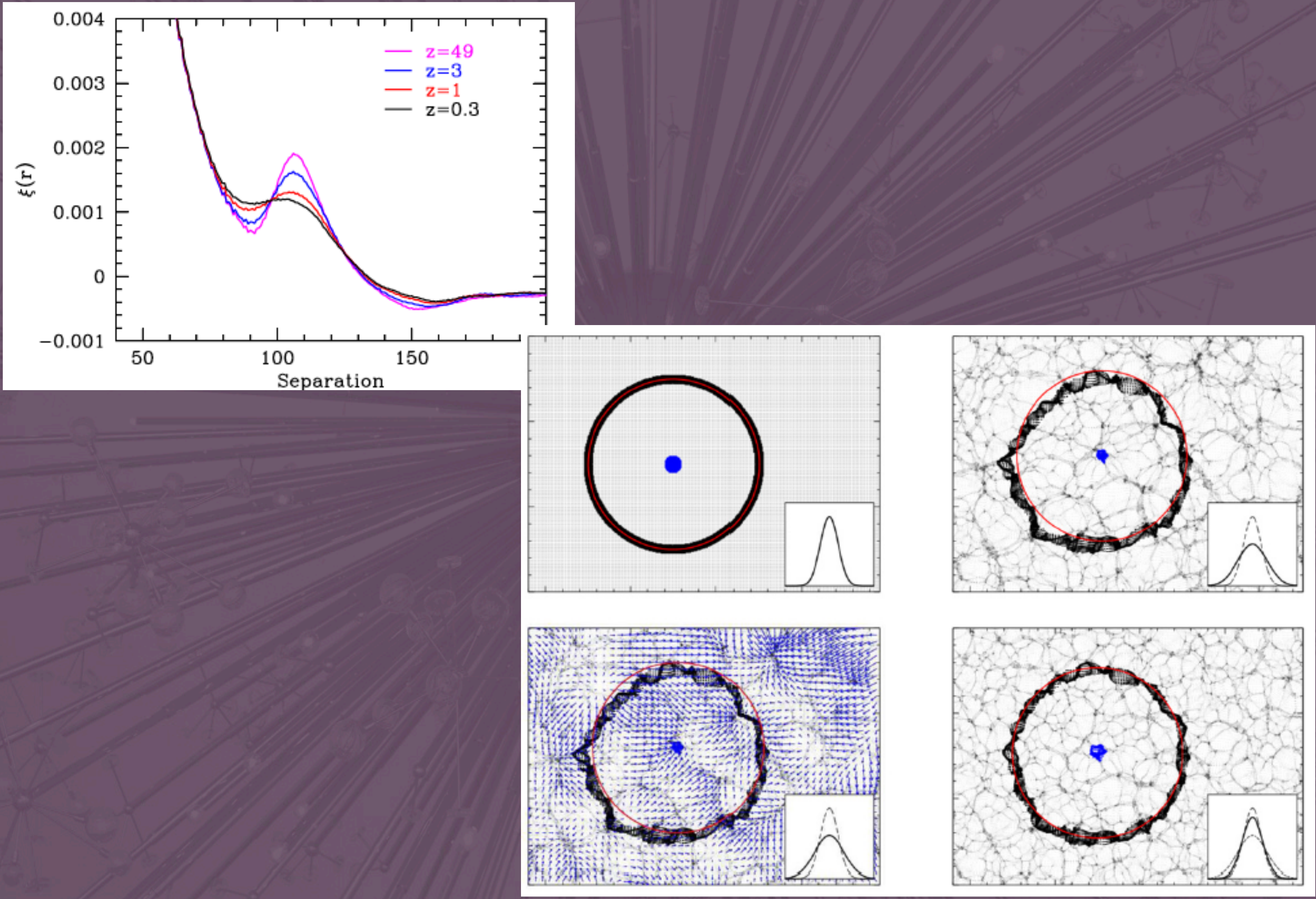
Eisenstein, Zehavi, Hogg et al. 2005

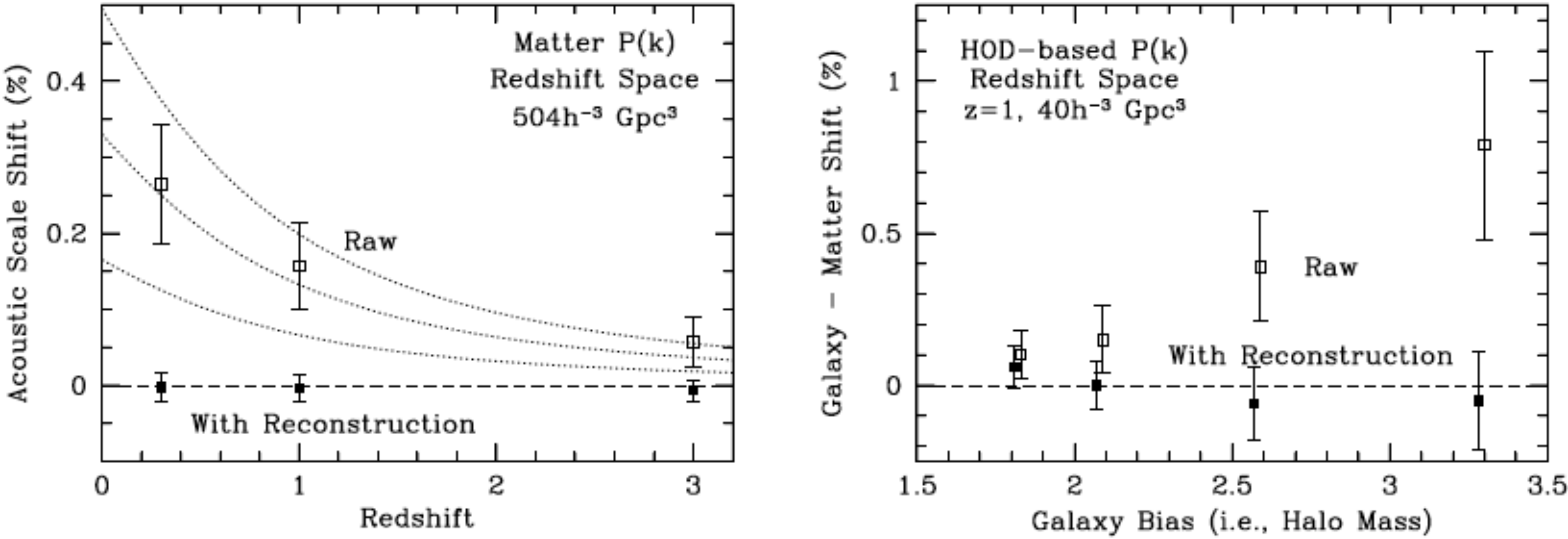




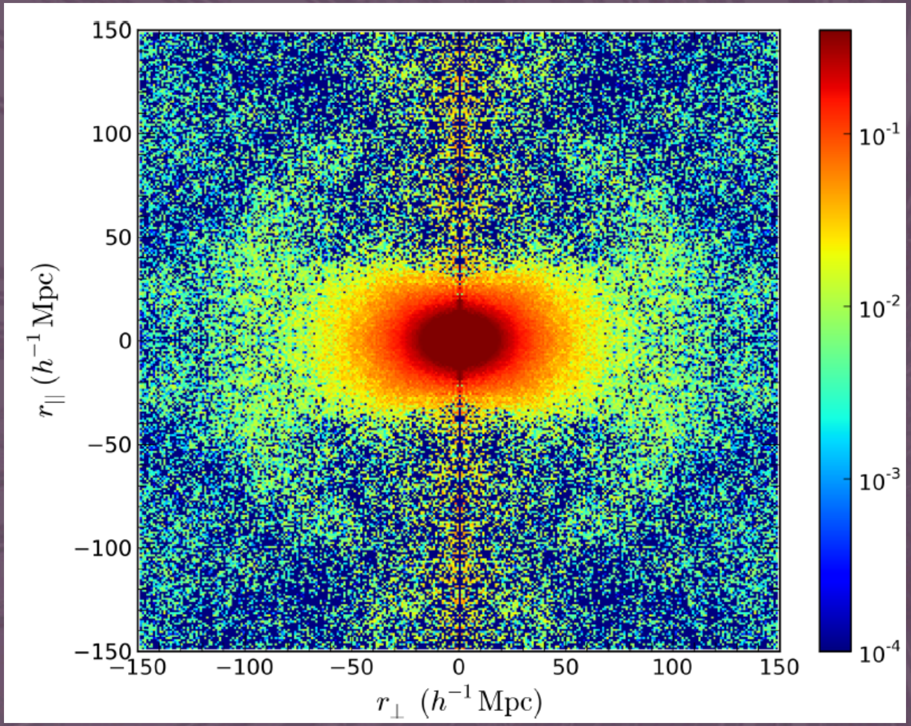
$D_A = L / \theta$; $H = c\,\Delta z / L$


0.1
0.2
0.4
0.6
0.8
1
2
4
Fractional Error (%)
0
1
2
3
Redshift
Full-sky Errors
□ D(z)
■ H(z)


0.004
0.003
0.002
0.001
0
−0.001
$\xi(r)$
50
100
150
Separation
z=49
z=3
z=1
z=0.3

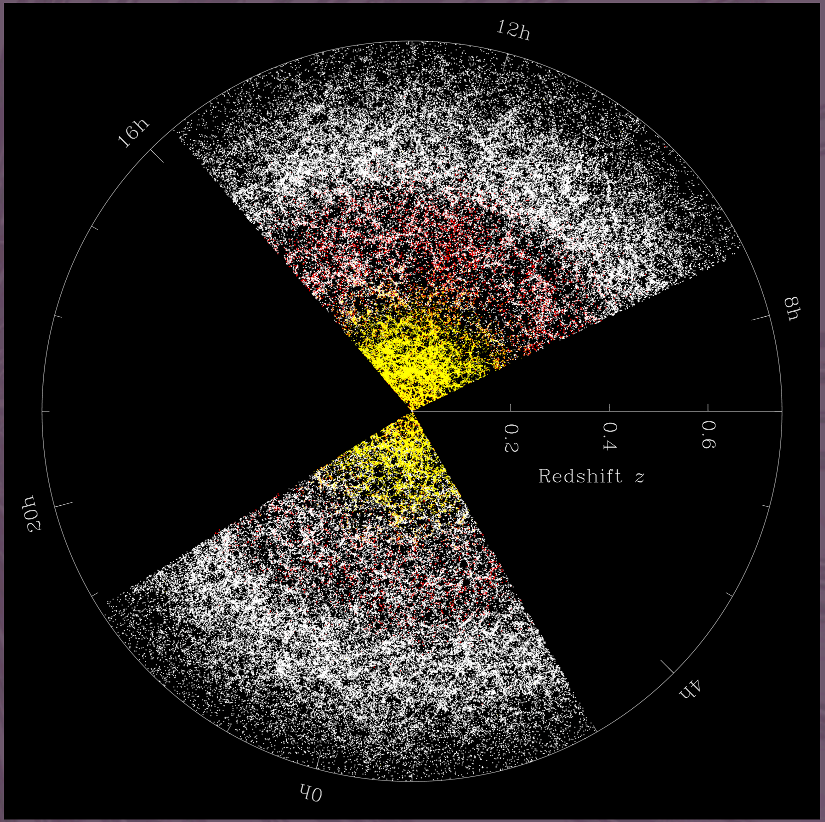

Matter P(k)
Redshift Space
504h⁻³ Gpc³
Raw
With Reconstruction
Acoustic Scale Shift (%)
0.4
0.2
0
0
1
2
3
Redshift
HOD−based P(k)
Redshift Space
z=1, 40h⁻³ Gpc³
Raw
With Reconstruction
Galaxy − Matter Shift (%)
1
0.5
0
1.5
2
2.5
3
3.5
Galaxy Bias (i.e., Halo Mass)

2-d galaxy correlation function:
Redshift-space distortion and the BAO ring.

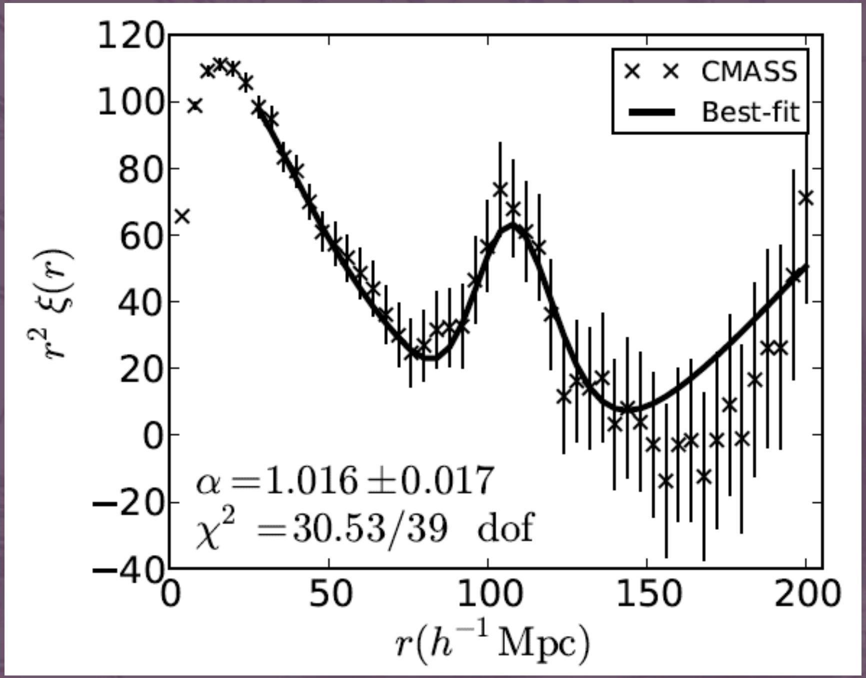


line-of-sight

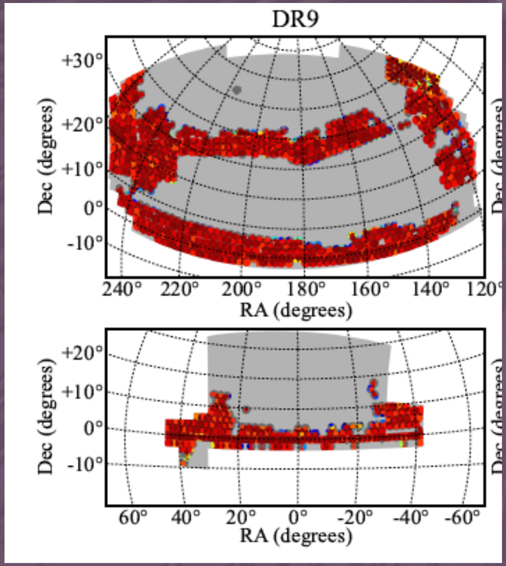
transverse

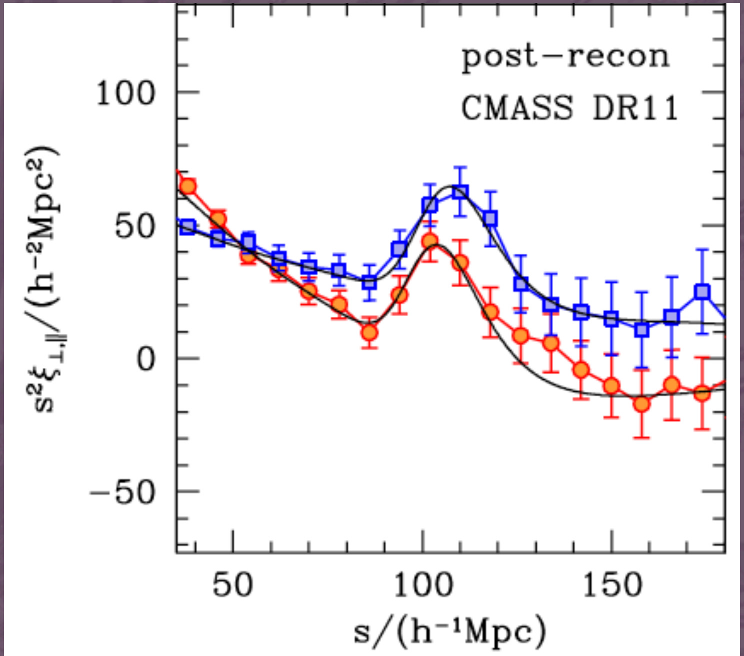


Samushia, Reid, White et al. 2014

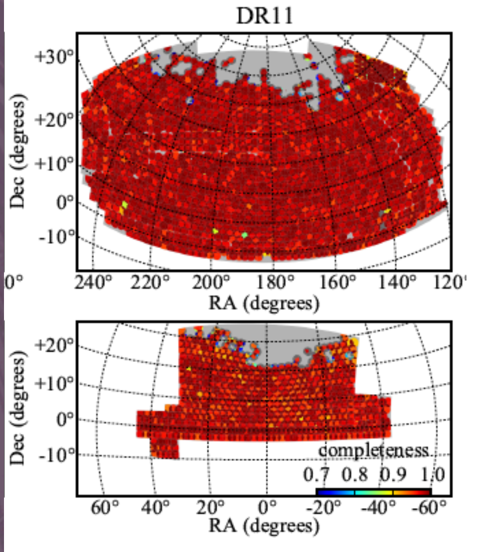


Anderson, Aubourg, Bailey et al. 2012:

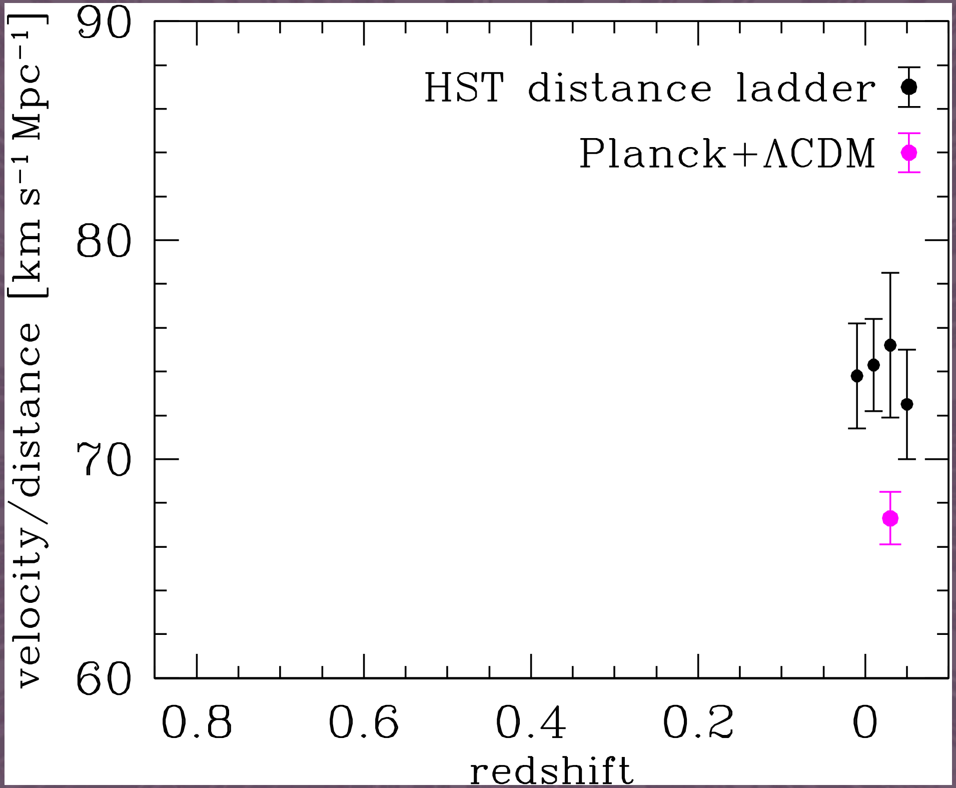




Anderson, Aubourg, Bailey et al. 2013



An "inverse distance ladder" measurement of H_0.

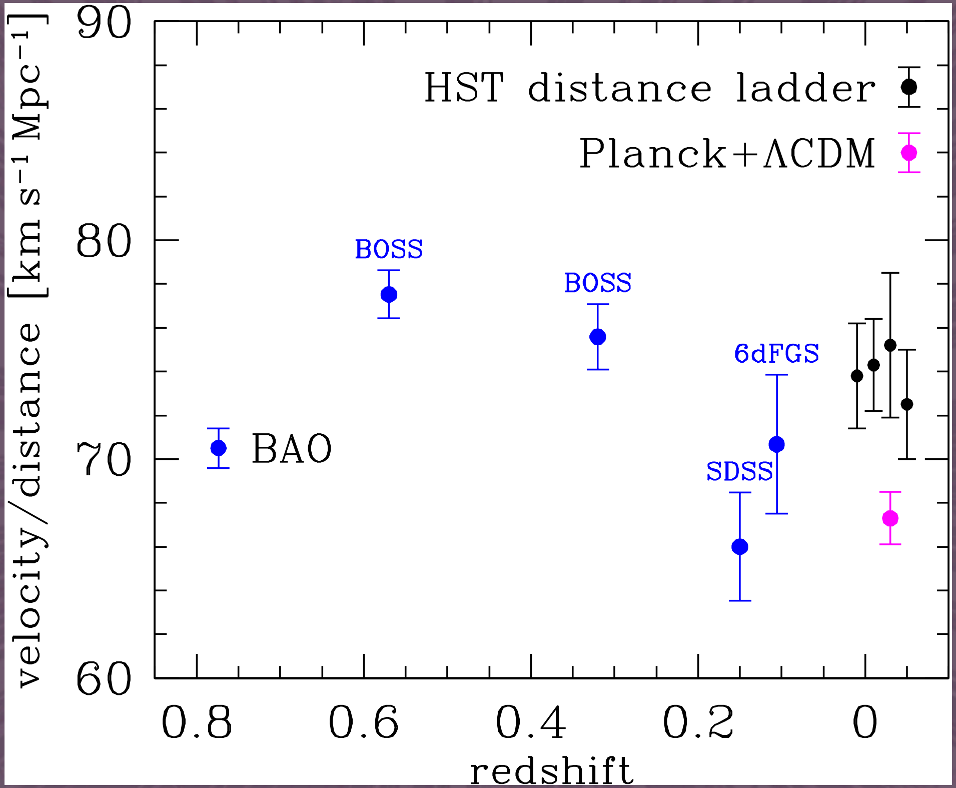


Significant (~ 2σ) discrepancy between direct distance-ladder (Cepheid + SNIa) measurements of H_0 and prediction of ΛCDM constrained by Planck.

An “inverse distance ladder” measurement of H_0.

$cz / D_M(z)$

converges to H_0 at $z = 0$



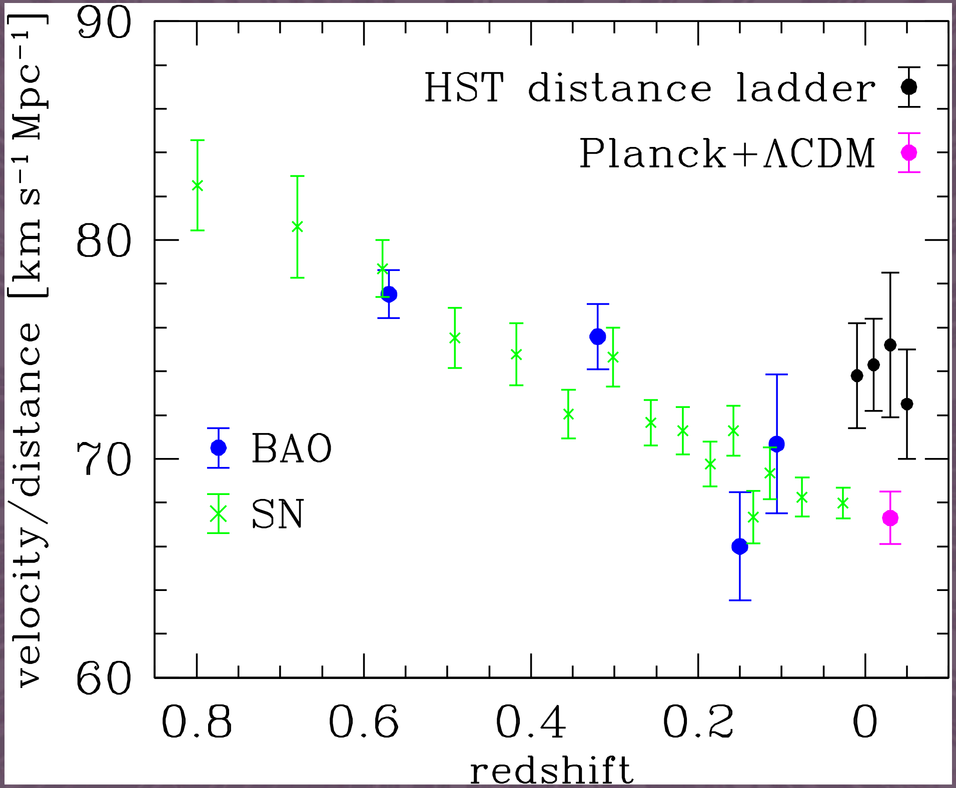
BAO distance measurements. Known in absolute units, to 0.4% Planck uncertainty.

Assumes standard *pre-recombination* physics, but no assumption about low-z dark energy behavior.

An “inverse distance ladder” measurement of H_0.

$cz / D_M(z)$

converges to H_0 at $z = 0$



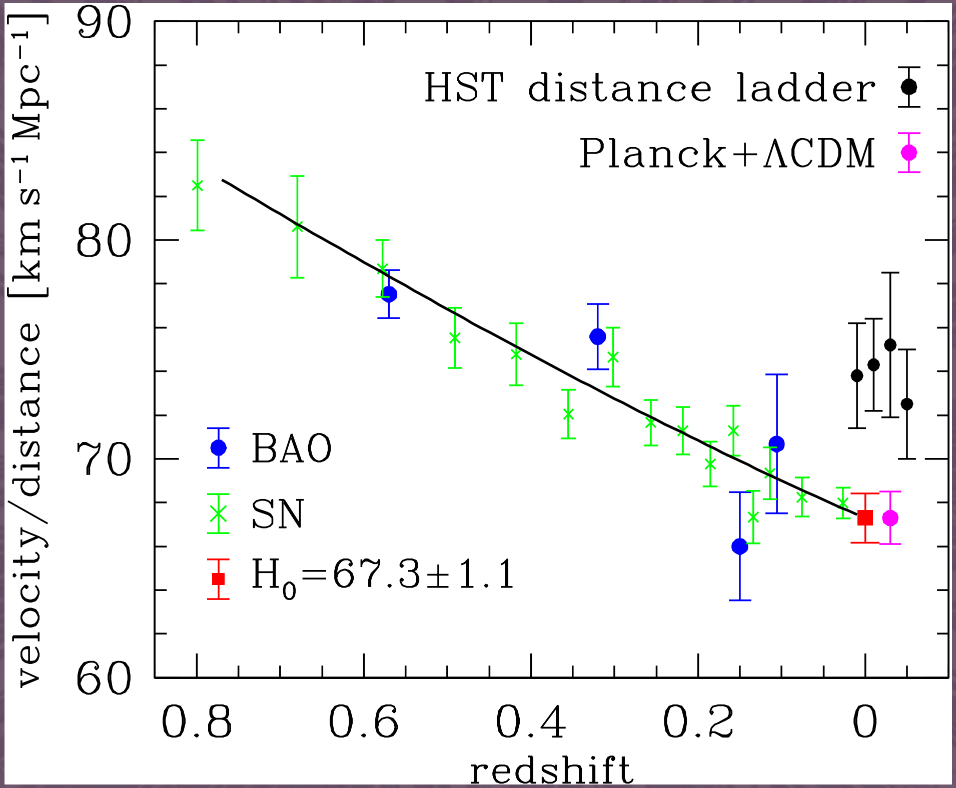
Normalize SNIa absolute magnitude scale to BAO distance scale.

Accurate *relative* SNIa distances transfer BAO measurements to $z = 0$.

An “inverse distance ladder” measurement of H_0.

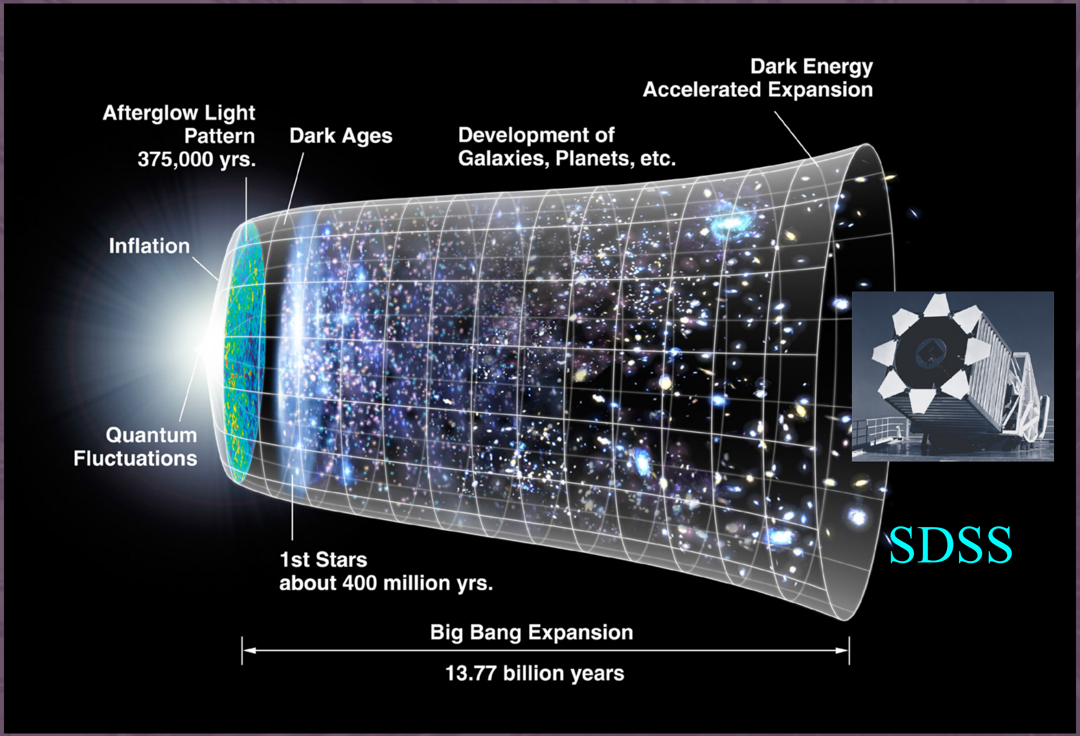
$cz / D_M(z)$

converges to H_0 at $z = 0$



Joint BAO + SN fit with extremely flexible dark energy model yields $H_0 = 67.3 \pm 1.1$ km s^{-1} Mpc^{-1}, a 1.7% measurement in excellent agreement with Planck + ΛCDM.

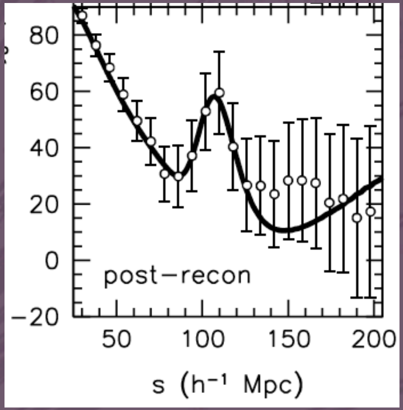
Higher H_0 requires changing r_d, hence pre-recombination physics.



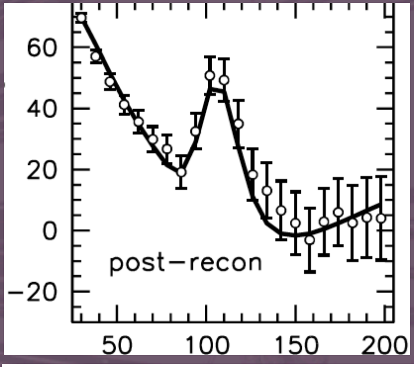
High-precision distance and expansion rate measurements over a wide range of redshift, with a common standard ruler.

Tighten the pressure on ΛCDM.

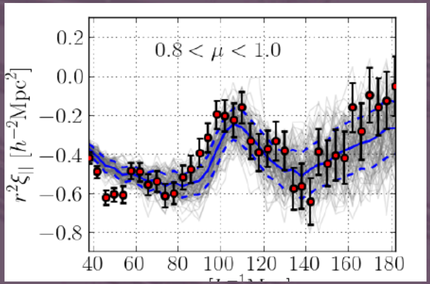
$Z = 0.32$



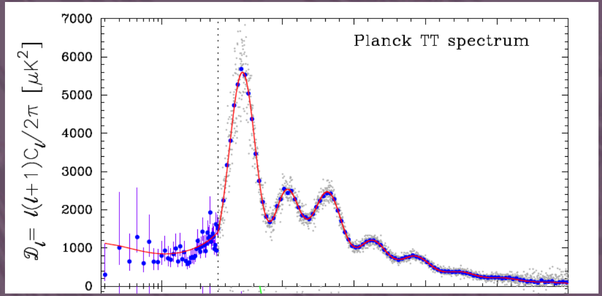
$Z = 0.57$



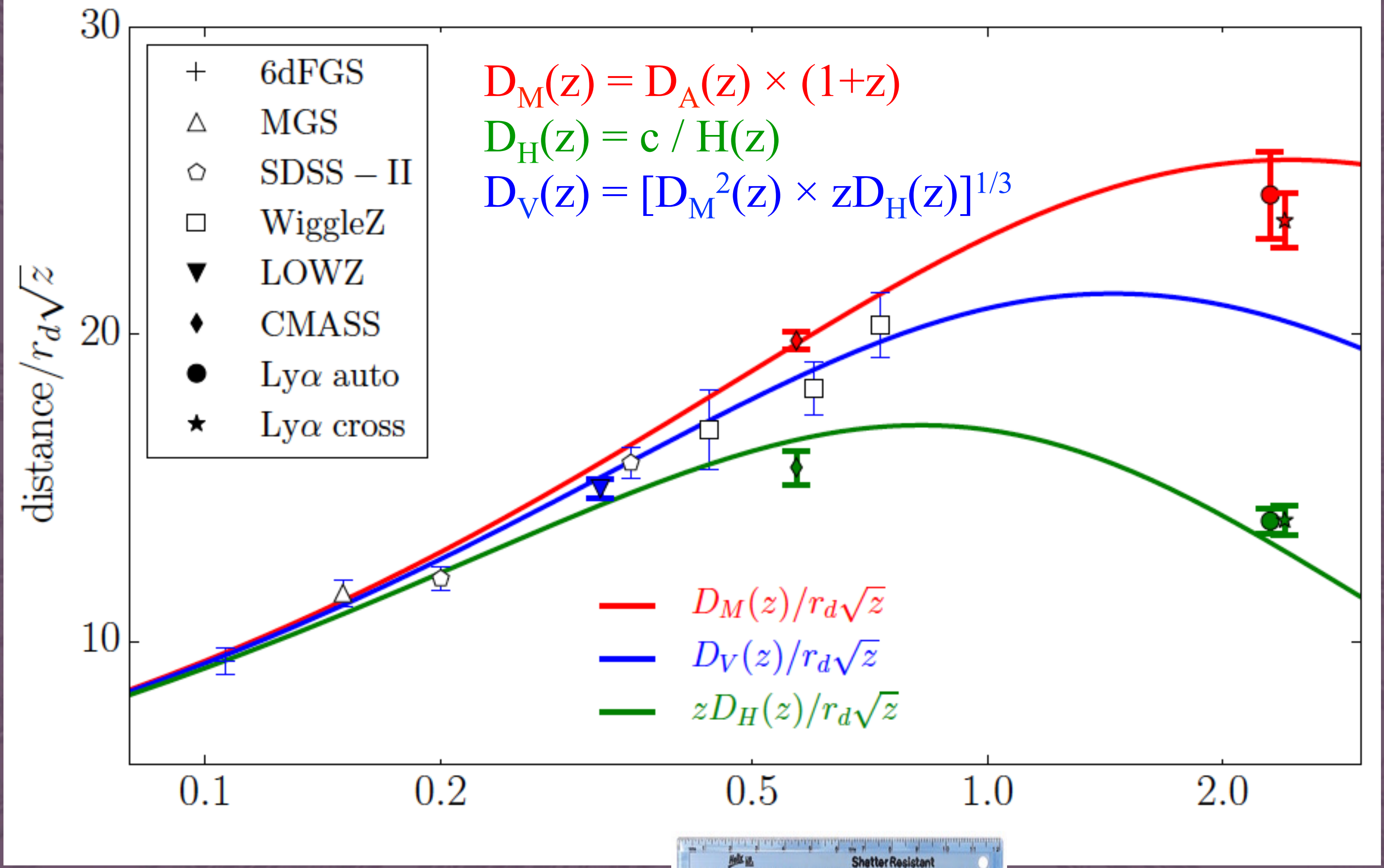
$Z = 2.34$



$Z = 1090$



BAO distance measurements vs. ΛCDM prediction



$D_M(z) = D_A(z) \times (1+z)$

$D_H(z) = c / H(z)$

$D_V(z) = [D_M^2(z) \times zD_H(z)]^{1/3}$

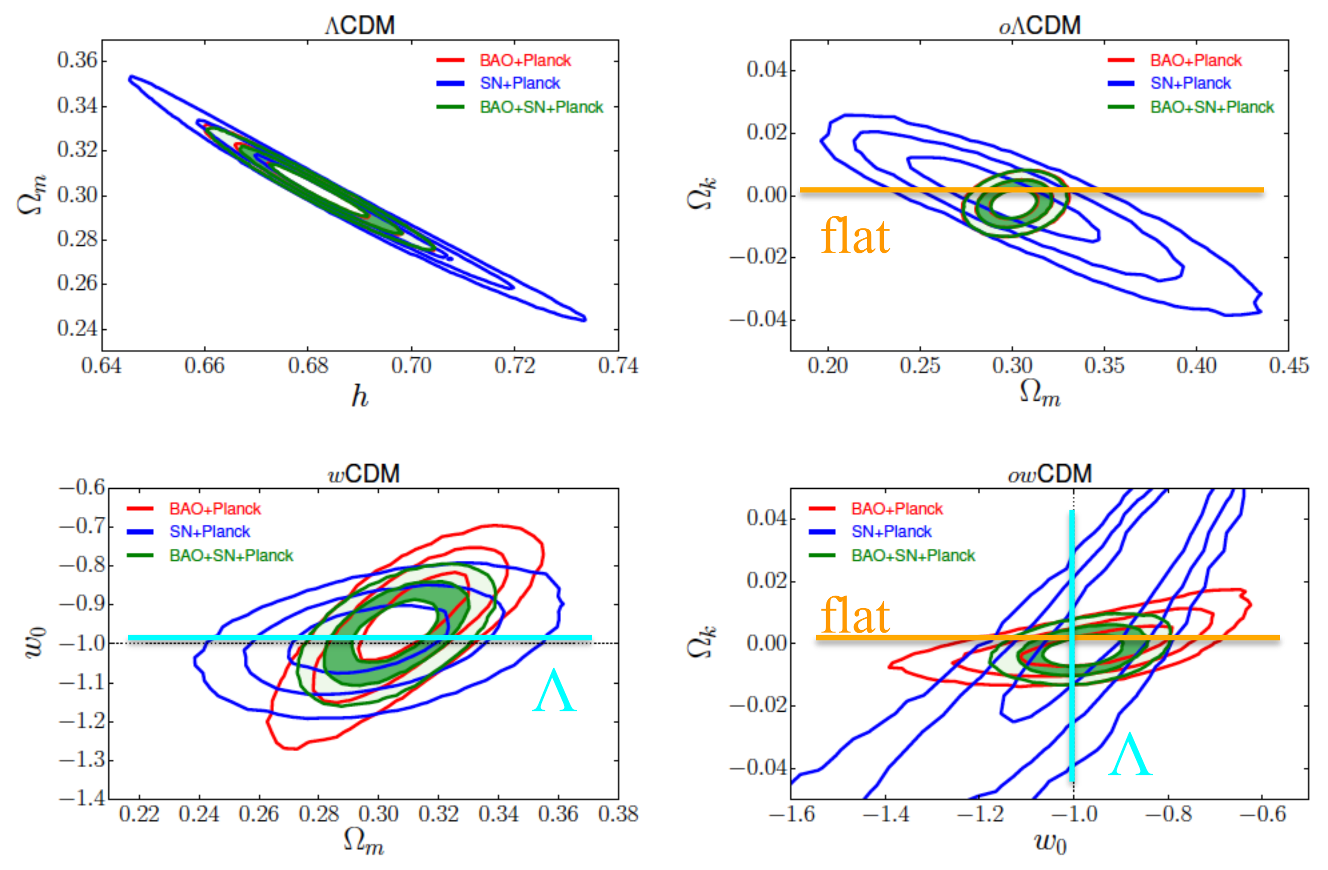
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \ ,$$

= 147.49 ± 0.59 Mpc (0.4%)

(Planck 2013, standard radiation background)

Joint constraints (BAO+SN+CMB) on cosmological parameters

Free Curvature

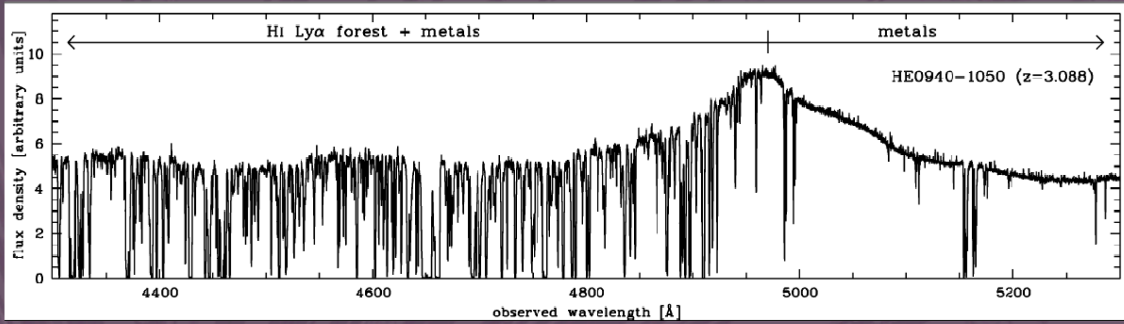


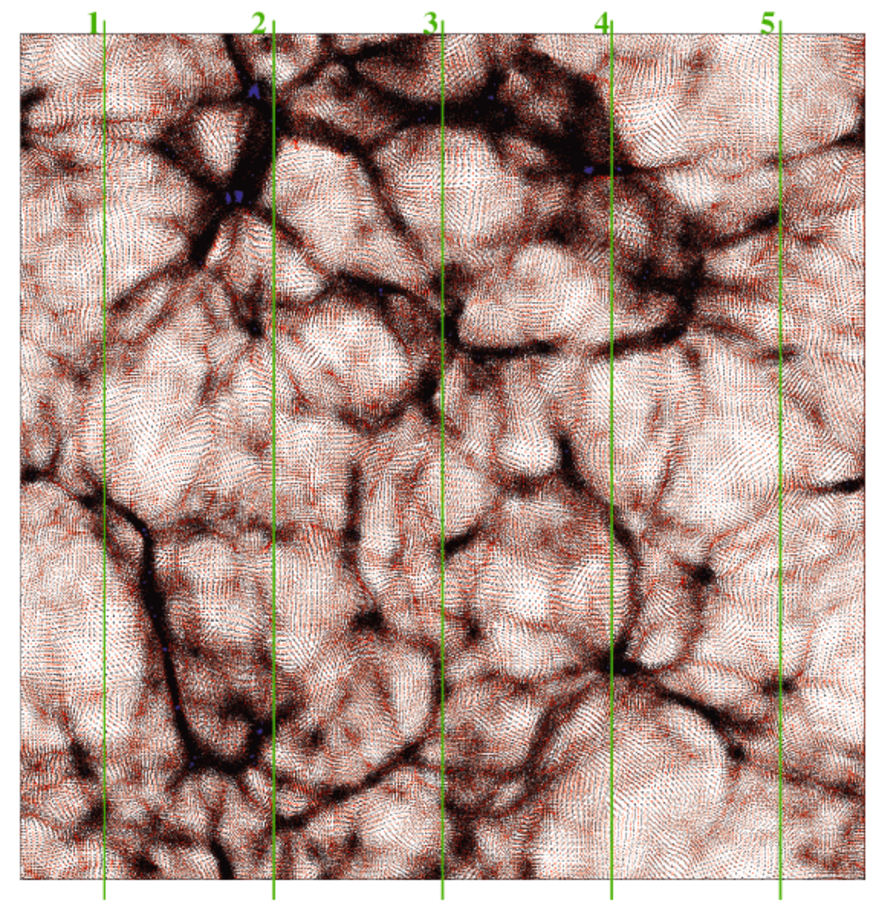
Free w

When fitting flexible models to the observed cosmic expansion history, a cosmological constant and a flat universe are always close to the best fit.

The Lyman-α Forest

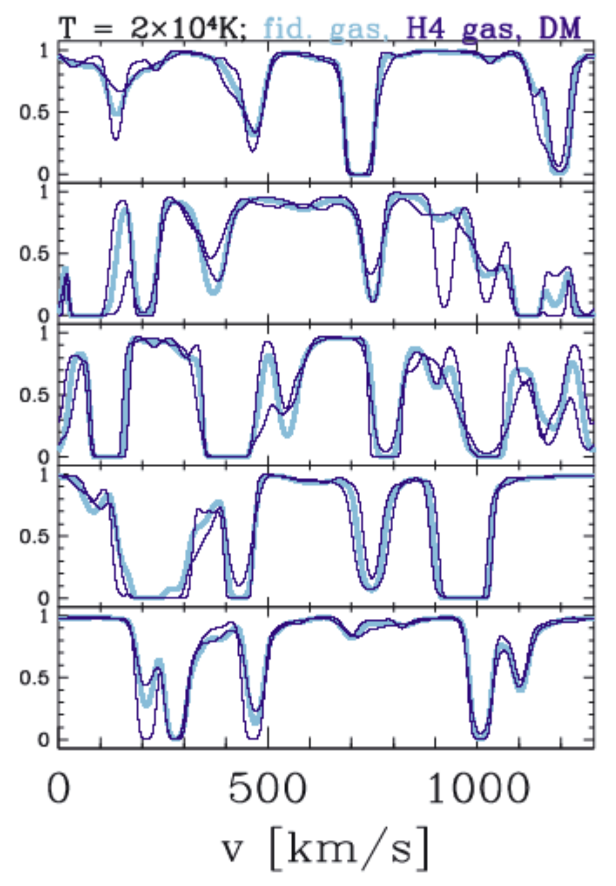
An observable tracer of high-redshift structure



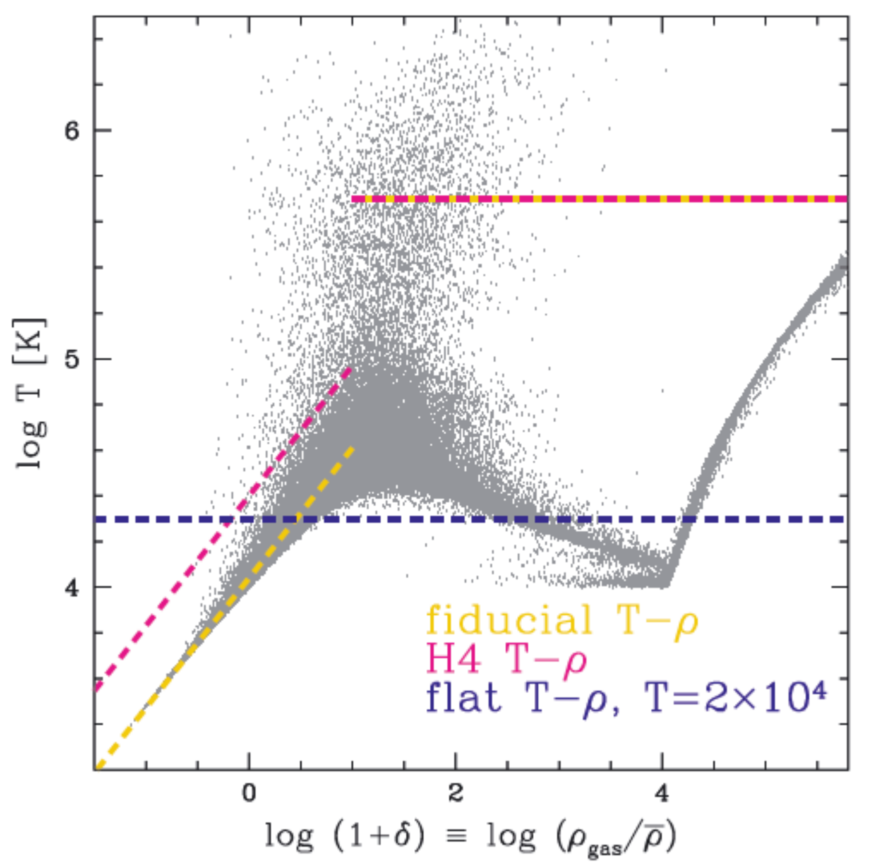


12.5 h^{-1} Mpc (comoving) at $z=3$

$F = e^{-\tau}$



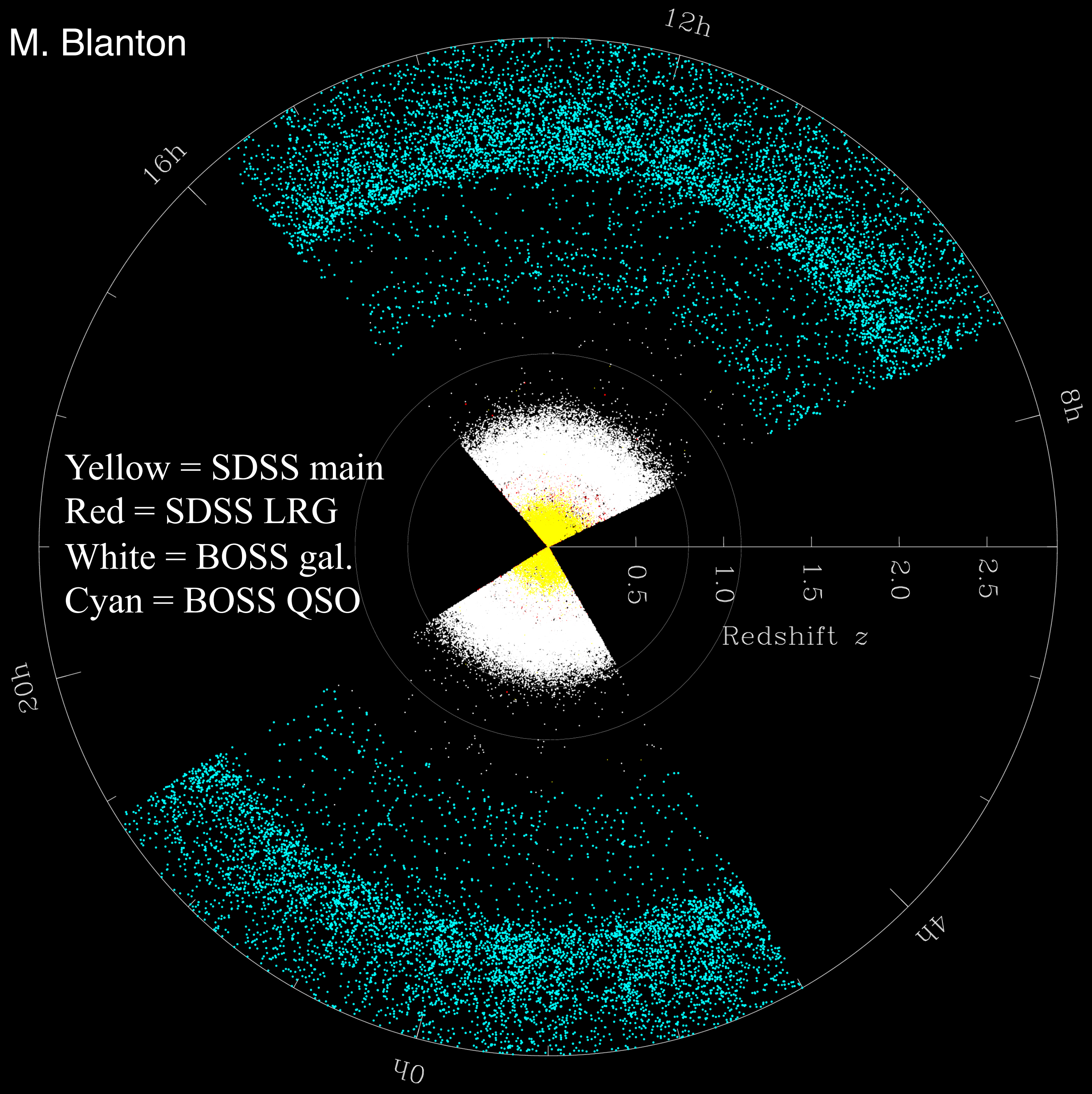
Peeples et al. 2010



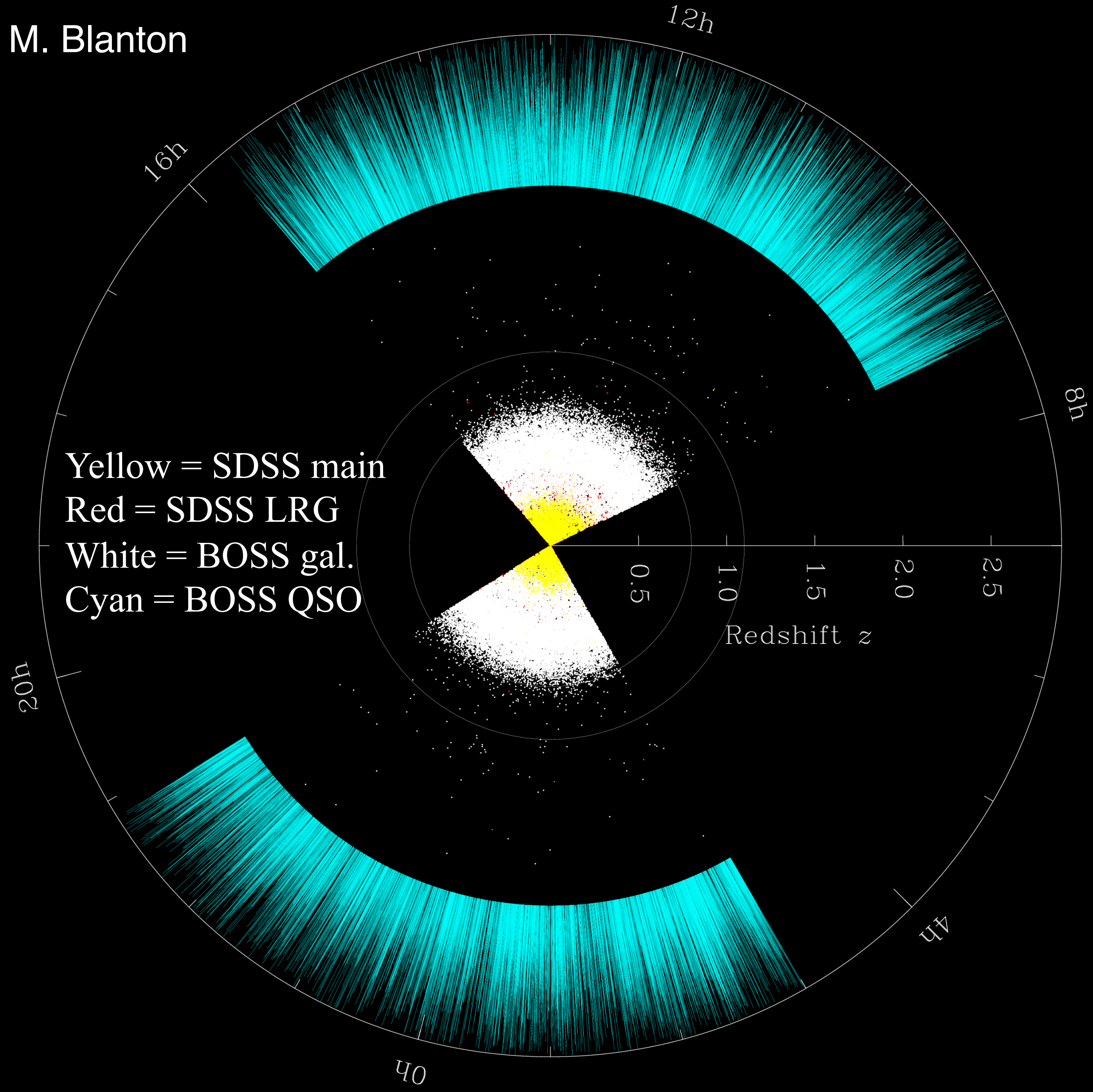
Peeples et al. 2010

$$\tau_{\mathrm{H\,I}} = 1.54 \times \left(\frac{T_0}{10^4\,\mathrm{K}}\right)^{-0.7} \left(\frac{10^{-12}\,\mathrm{s}^{-1}}{\Gamma_{\mathrm{UV}}}\right) \left(\frac{1+z}{1+3}\right)^{6} \left(\frac{0.7}{h}\right) \times \left(\frac{\Omega_{\mathrm{b},0}h^2}{0.021\,56}\right)^{2} \left[\frac{4.0927}{H(z)/H_0}\right] (1+\delta)^{2-0.7\alpha} \left[1 + \frac{1}{H(z)}\frac{\mathrm{d}V_{\mathrm{los}}}{\mathrm{d}x}\right]^{-1}. \tag{8}$$

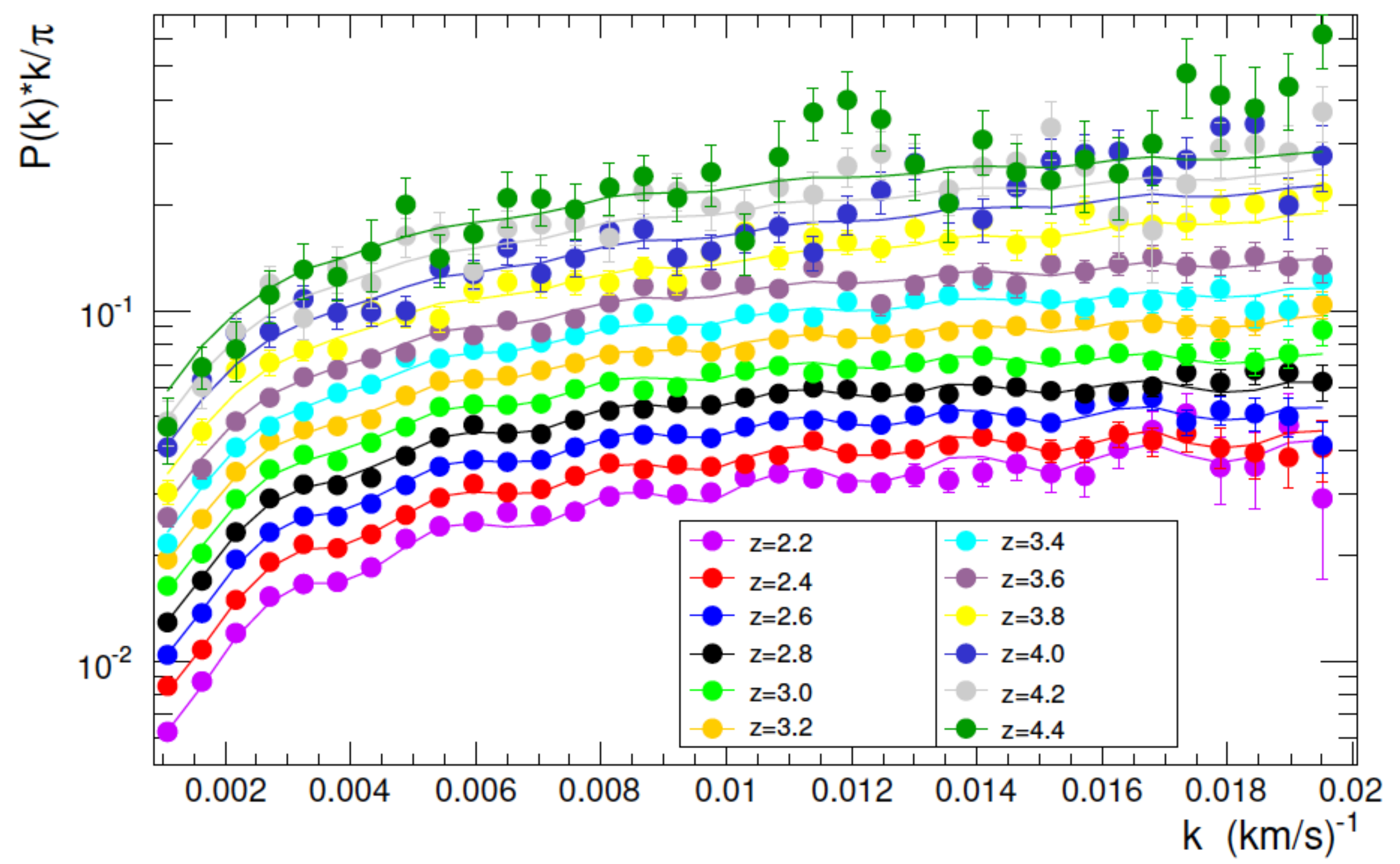
Figures: M. Blanton



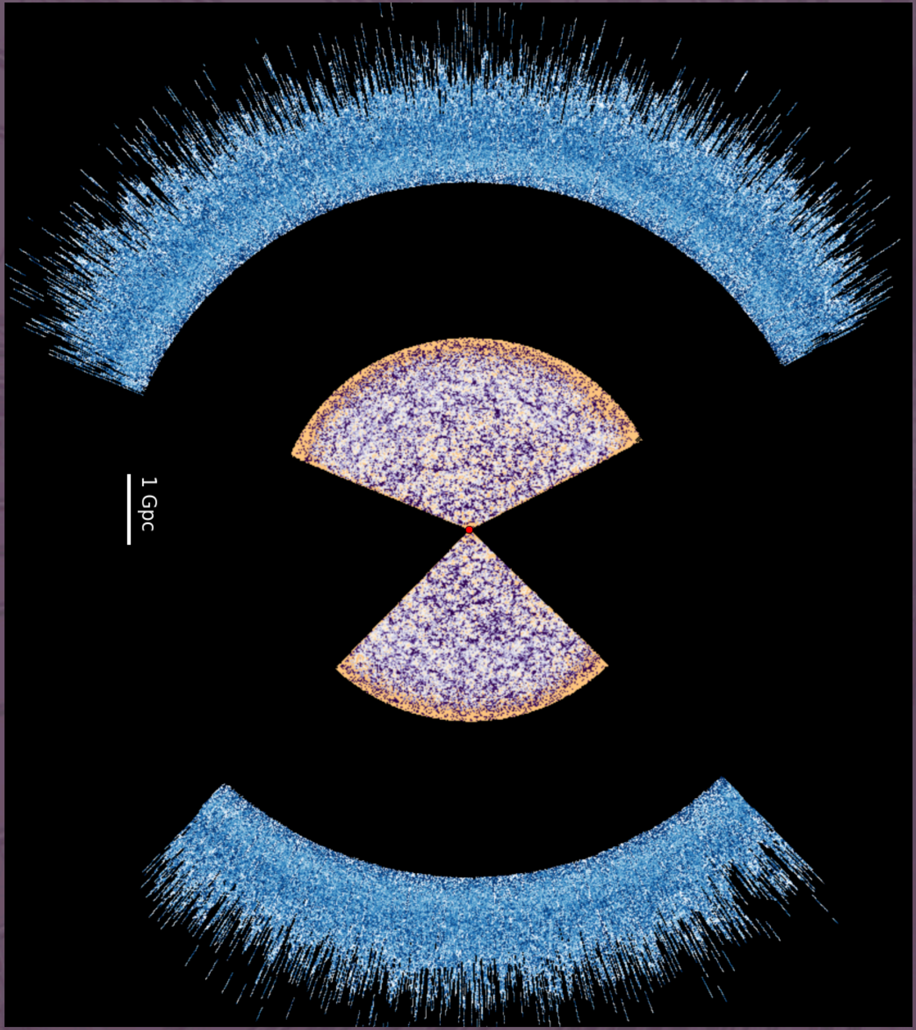
Figures: M. Blanton



Palanque-Delabrouille et al. 2015
BOSS 1-d Lyα forest power spectrum



3-d correlations in the Lyman-α forest



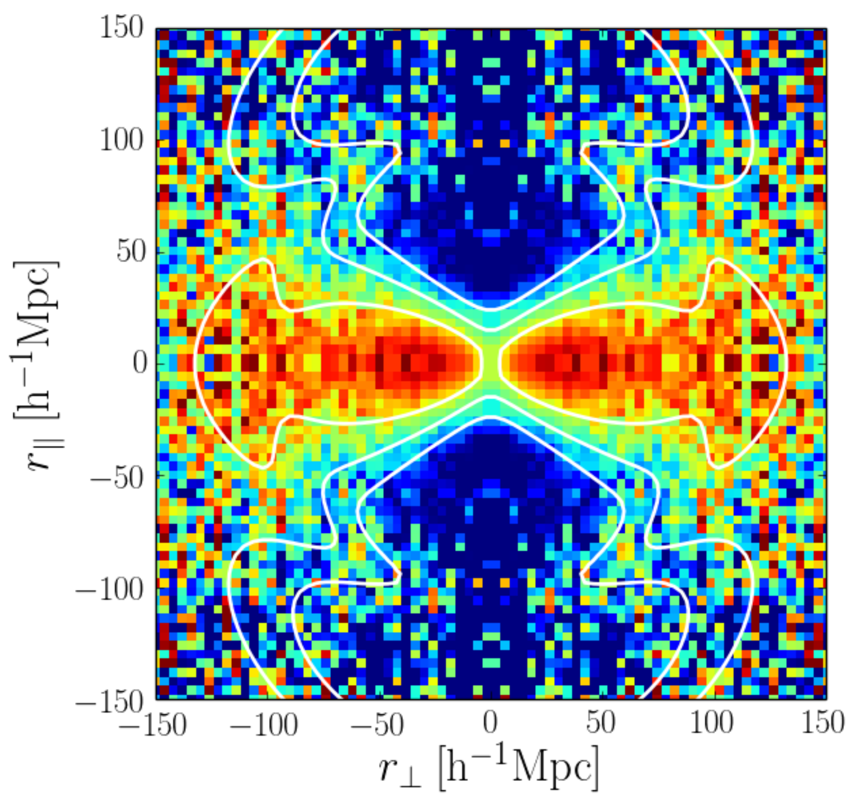
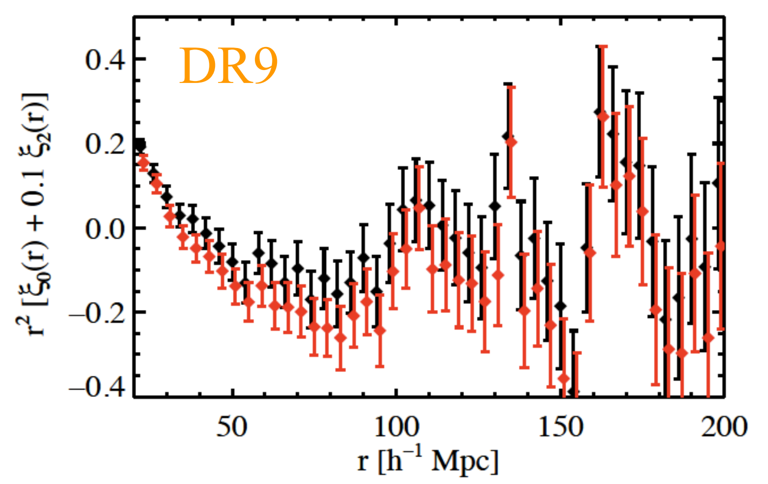


Figure: N. Busca

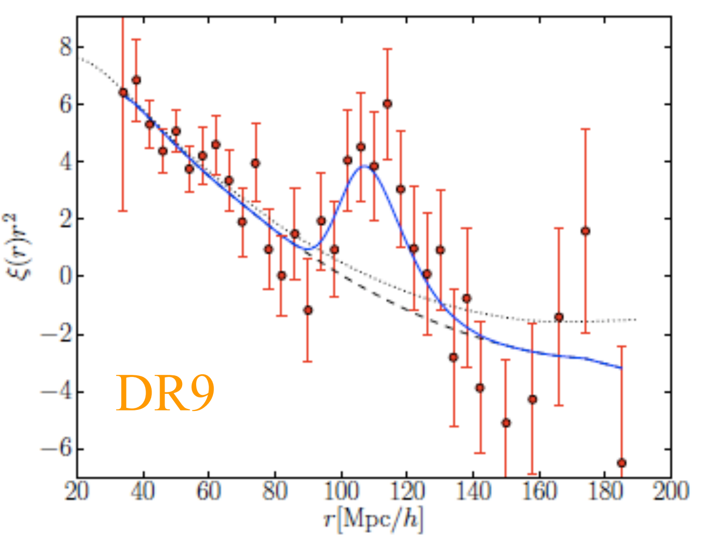
Figure: A. Slosar

BAO in the Lyman-α forest

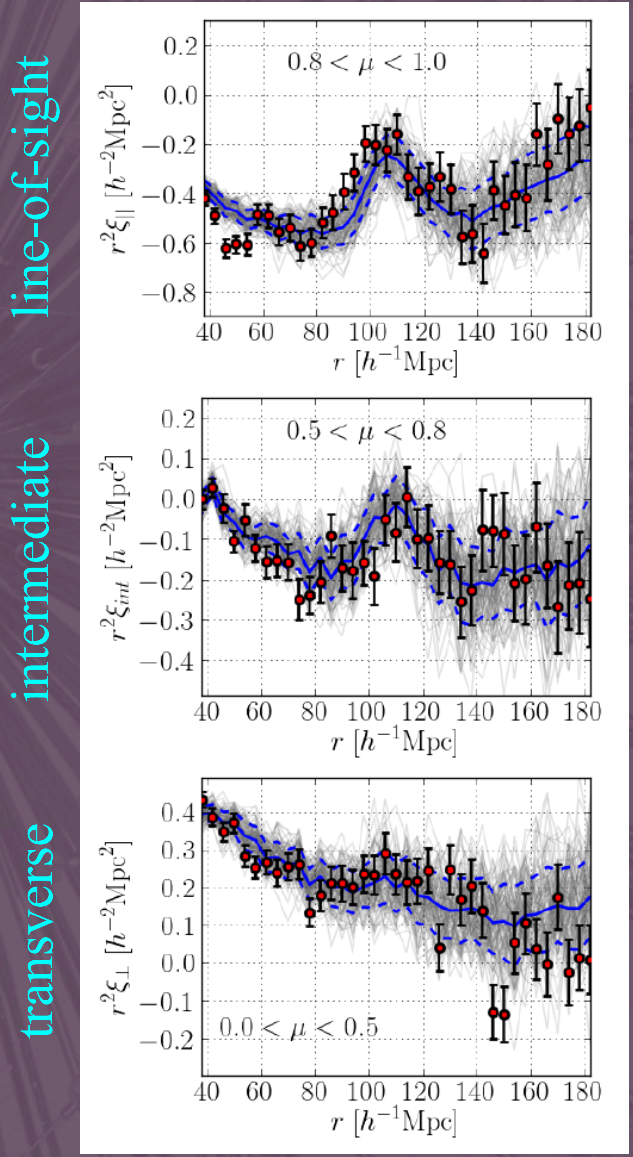
Busca, Delubac, Rich et al. 2013



Slosar, Irsic, Kirkby et al. 2013



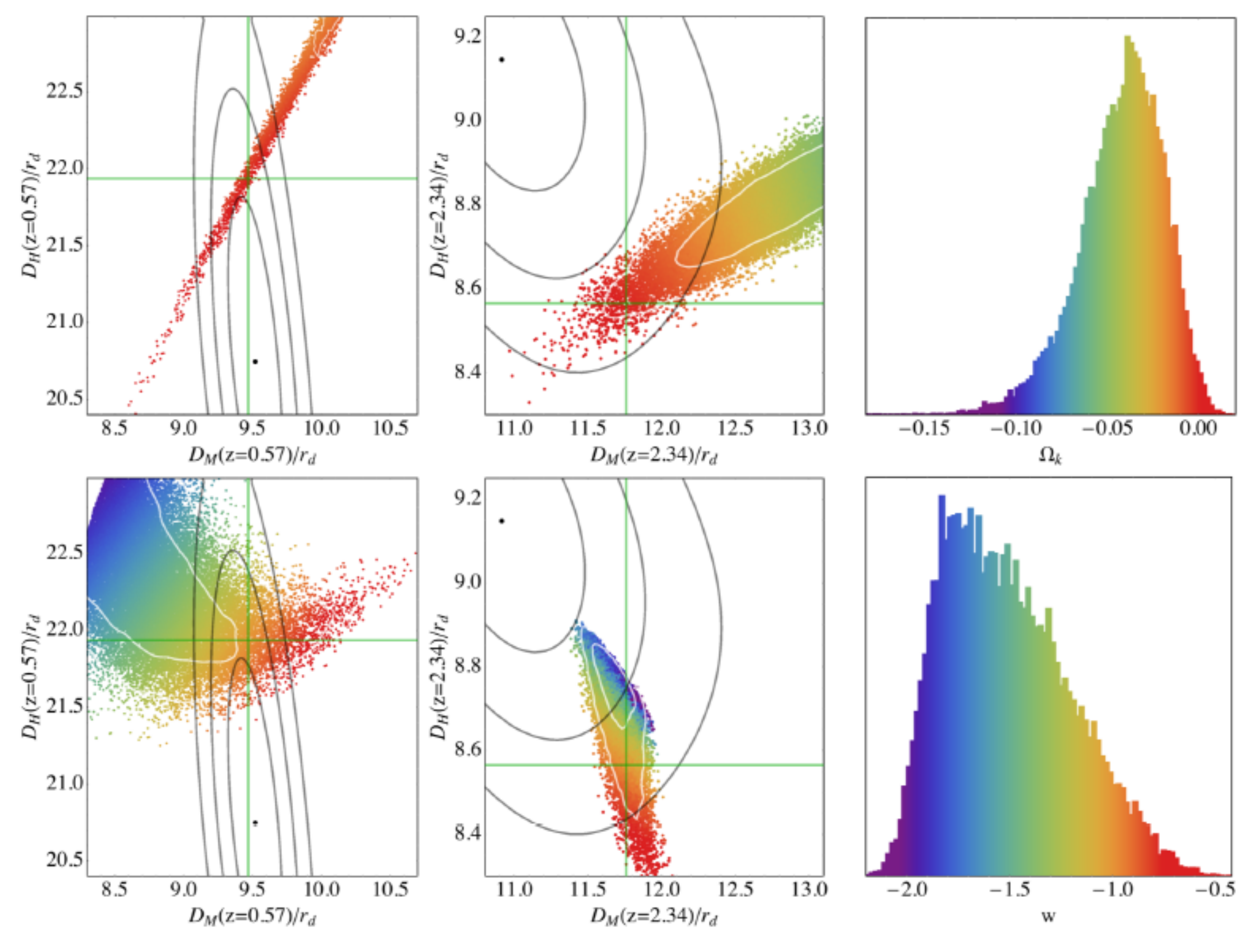
DR11: 2% distance scale at z=2.35



Delubac, Bautista, Busca et al. 2014 +
Font-Ribera, Kirkby, Busca et al. 2014

Tension with Lyα Forest

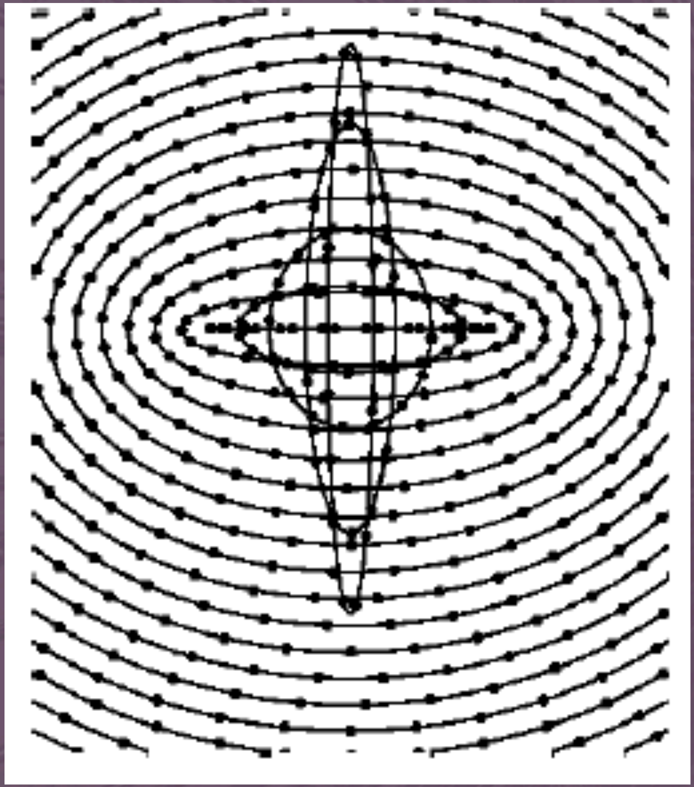
z=0.57, galaxies   z=2.3, Lyα   CMB only



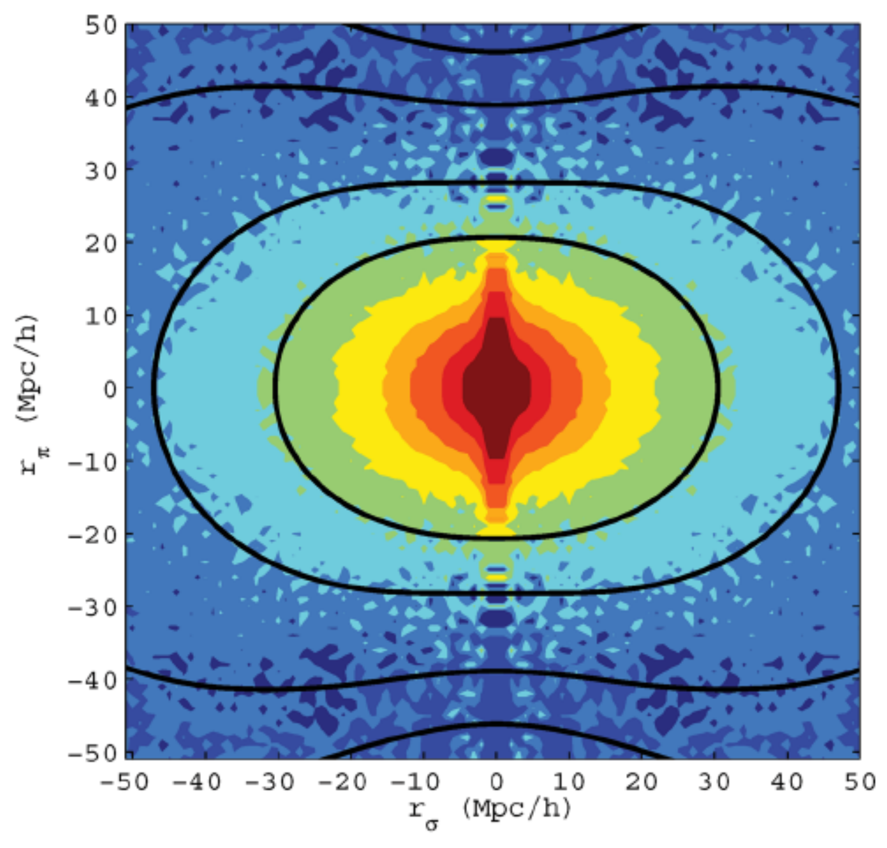
Models with non-zero curvature

Models with non-constant dark energy

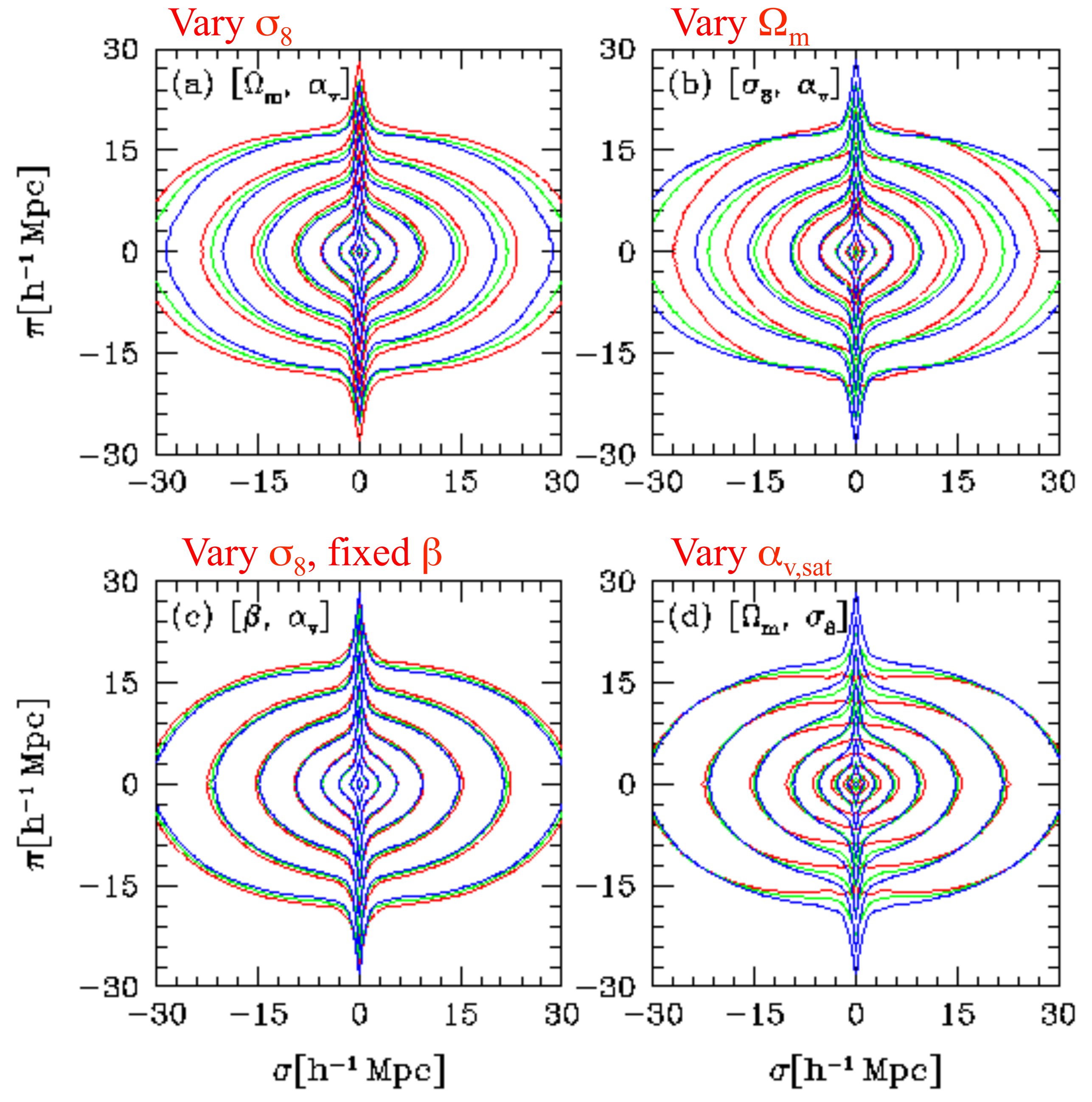
Constraints in (D_H, D_A) plane [expansion, distance]



Hamilton 1998 (after Kaiser 1987)



Reid et al. 2012, BOSS DR9



Vary σ_8

Vary Ω_m

Vary σ_8, fixed β

Vary $\alpha_{v,sat}$

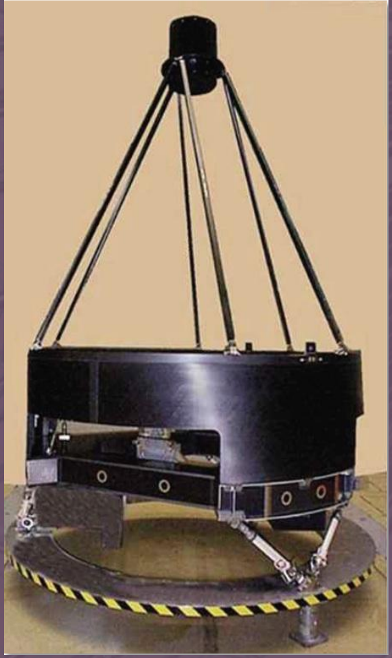
For large scales, degeneracy axis is $\beta \propto \sigma_8\,\Omega_m^{0.6}$, as predicted by linear theory.

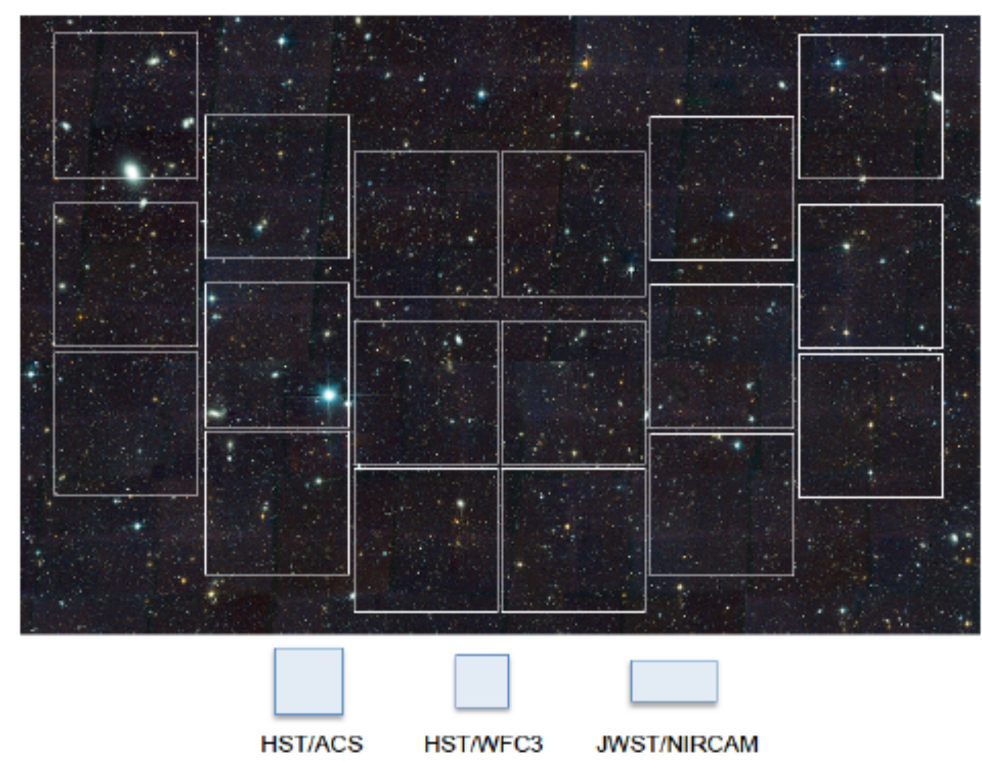
But small scale distortions have different dependence on Ω_m, σ_8, α_v.

Tinker et al. (2006)

Wide Field Infrared Survey Telescope (WFIRST)

- Top priority large space mission in Astro2010 decadal survey
- WFIRST-AFTA would use 2.4-m (Hubble-size) "hand me down" telescope
- Survey speed is hundreds-to-thousands × faster than HST or JWST
- ~ 400 million WL shapes, ~ 20 million galaxy redshifts
- Roughly speaking: doing at z=1what SDSS has done at z=0





WFIRST-AFTA Dark Energy Roadmap

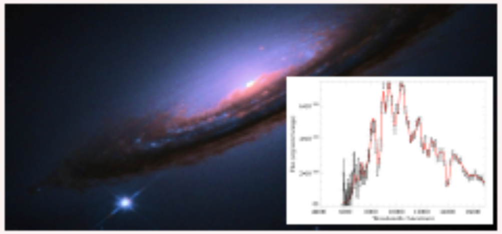
Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

↓

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

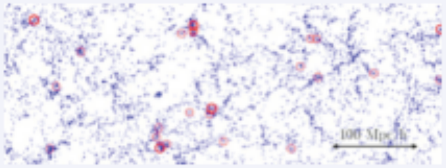
imaging: weak lensing shapes

380 million lensed galaxies
40,000 massive clusters

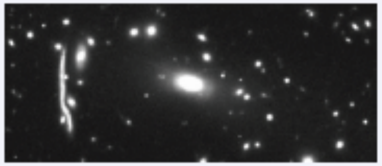
↓

standard ruler

distances	expansion rate
z = 1–2 to 0.5%	z = 1–2 to 0.9%
z = 2–3 to 1.3%	z = 2–3 to 2.1%



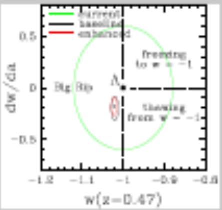
dark matter clustering
z < 1 to 0.21% (WL); 0.24% (CL)
z > 1 to 0.78% (WL); 0.88% (CL)
1.1% (RSD)



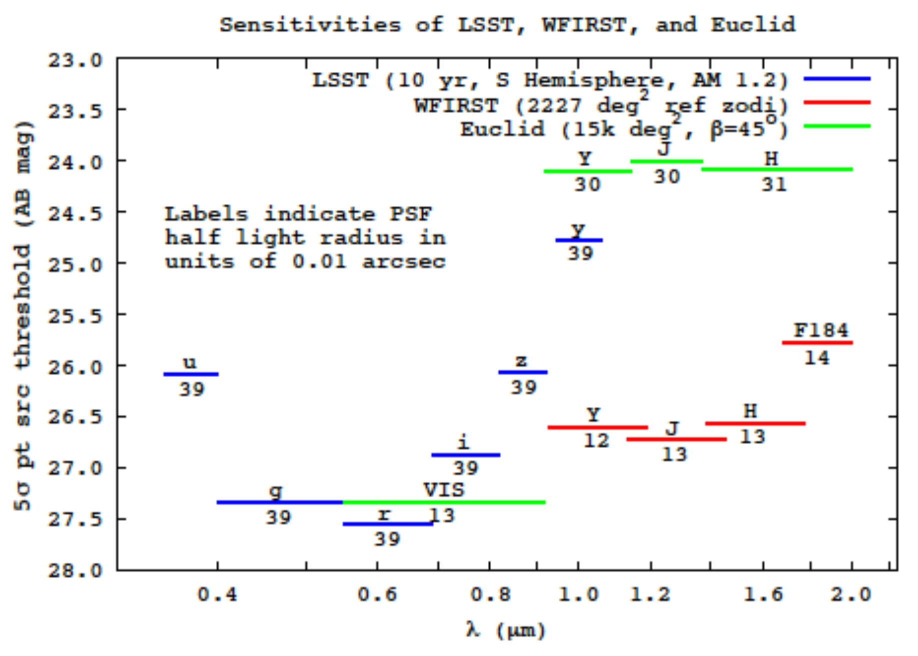
↓

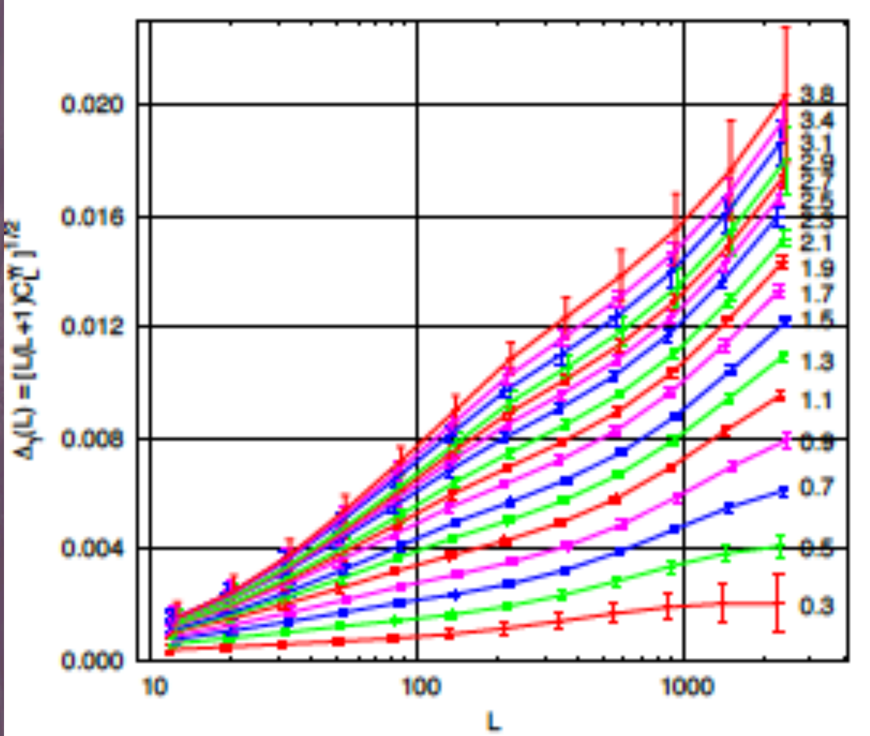
history of dark energy
+
deviations from GR

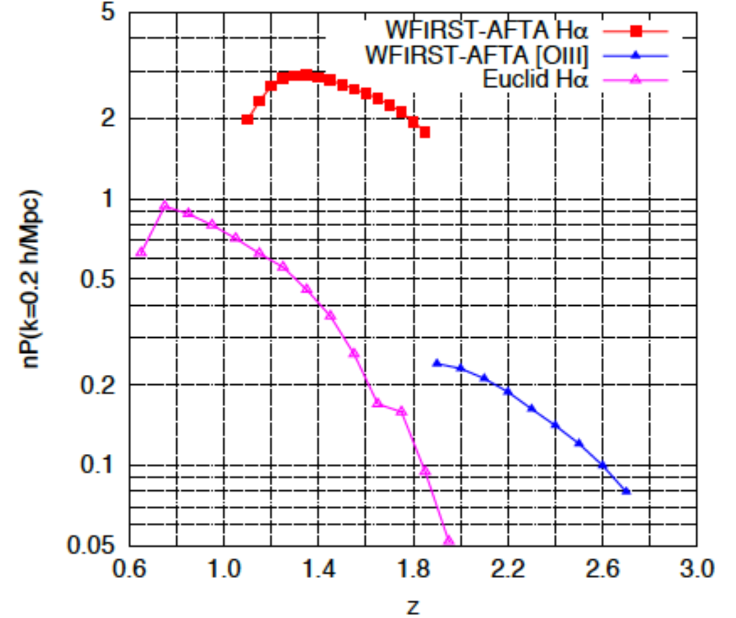
$w(z)$, $\Delta G(z)$, Φ_{REL}/Φ_{NREL}

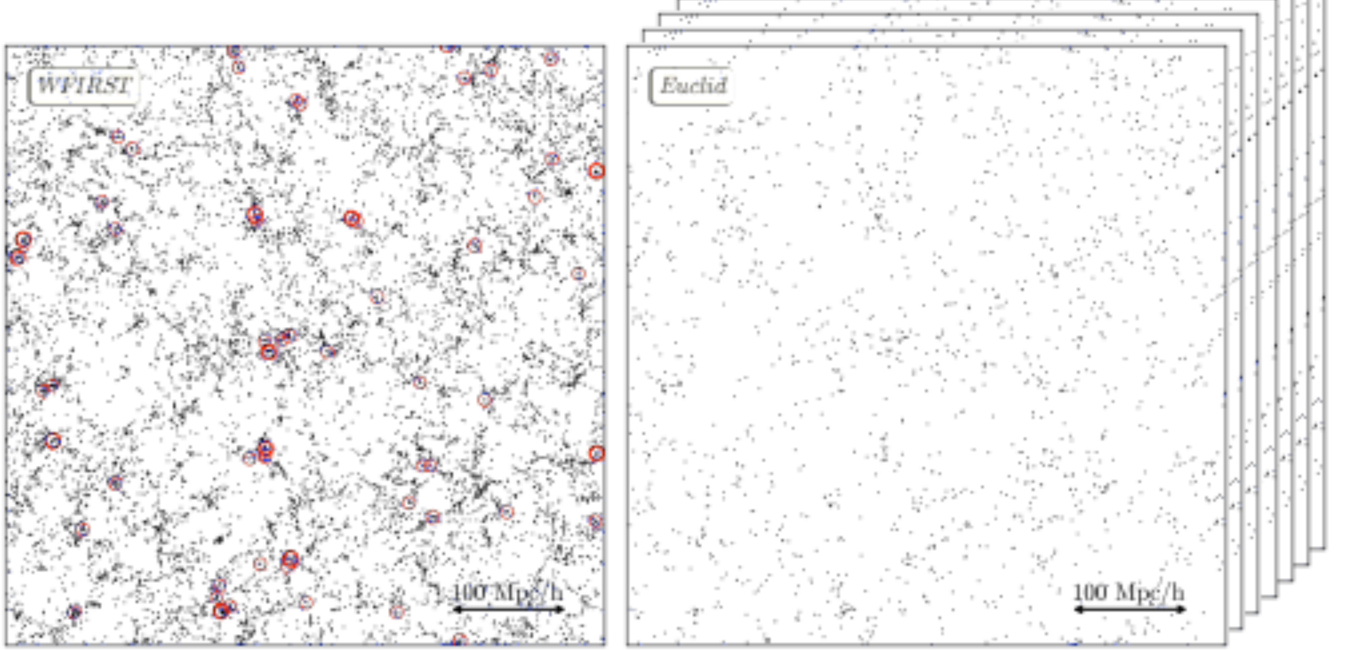


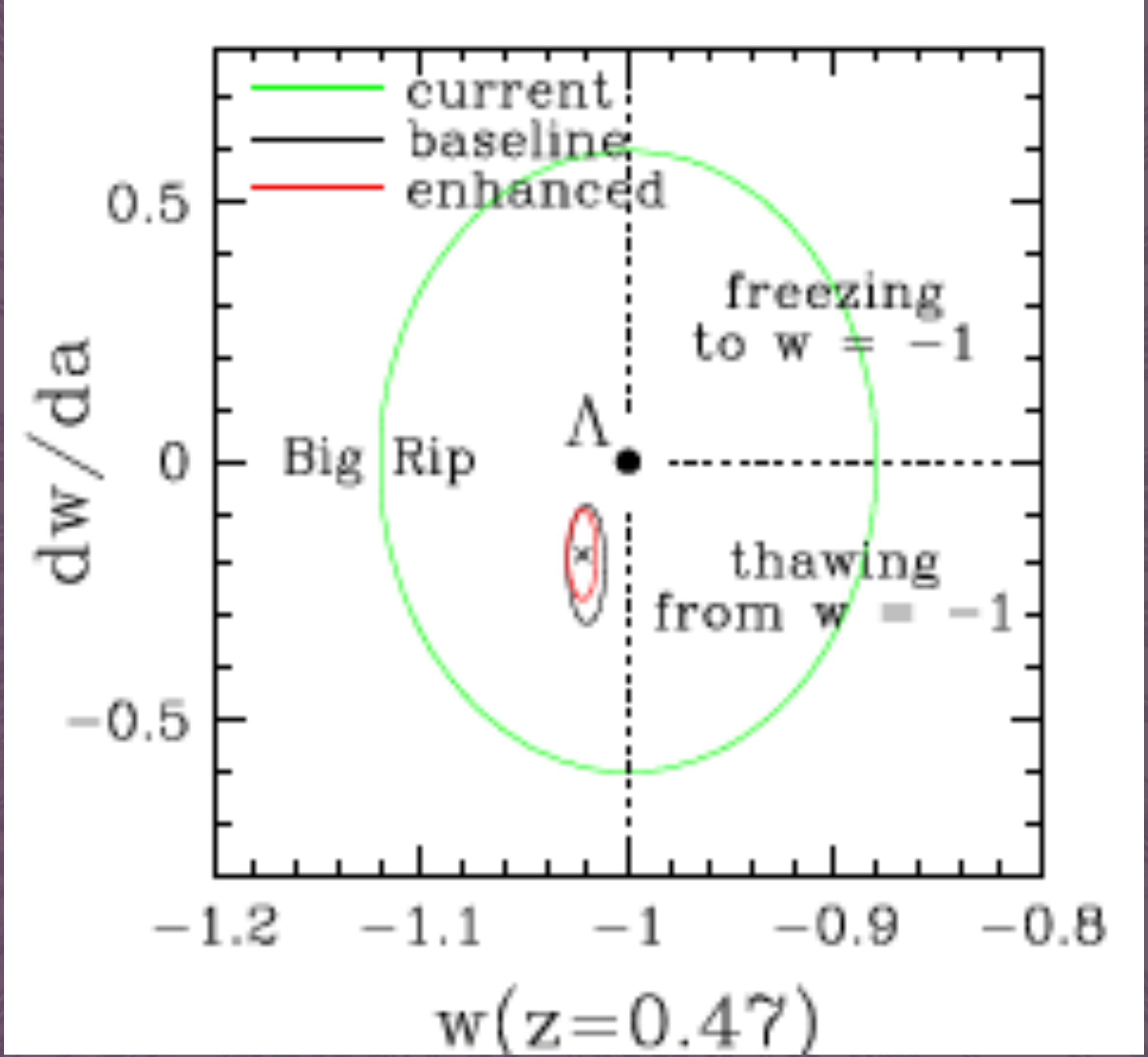
High-Latitude Survey (HLS): Imaging depth and WL precision






WFIRST-AFTA Hα
WFIRST-AFTA [OIII]
Euclid Hα
nP(k=0.2 h/Mpc)
5
2
1
0.5
0.2
0.1
0.05
0.6
1.0
1.4
1.8
2.2
2.6
3.0
z


WFIRST
Euclid
100 Mpc/h
100 Mpc/h


current
baseline
enhanced
0.5
0
−0.5
dw/da
freezing to w = −1
Λ
Big Rip
thawing from w = −1
−1.2
−1.1
−1
−0.9
−0.8
w(z=0.47)