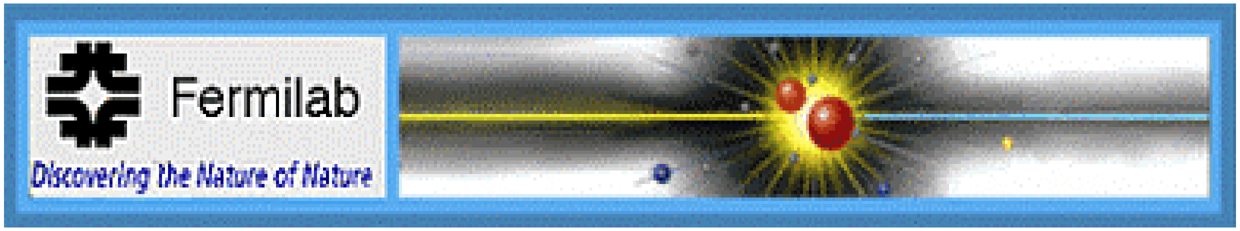
Complementary Probes of Dark Energy

Josh Frieman



Snowmass 2001

- The History of 20^{th} Century Cosmology is littered with `detections' of Λ which later evaporated.

- Man (and woman) cannot live by Supernovae alone.

- The implications of Dark Energy are so profound that the SNe Ia results must be confirmed/extended by multiple independent methods with:

  * different systematic errors
  * different cosmological parameter degeneracies

- The Cosmic Microwave Background is not a panacea: it has limited sensitivity to Dark Energy.

Key Issues

- Is there Dark Energy?

  Will the SNe results hold up?

- What is the nature of the Dark Energy?

  Is it Λ or something else?

- How does $w = p_X/\rho_X$ evolve?

  Dark Energy dynamics → Theory

Physical Effects of Dark Energy

Dark Energy affects expansion rate of the Universe:

$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_X)$$

$$H(z)^2 = H_0^2 \Big[\Omega_M (1+z)^3 + \Omega_X \exp[3 \int_0^z (1+w(x)) d\ln(1+x)]\Big]$$

Huterer & Turner

Dark Energy may also interact: long-range forces

Carroll

Physical Observables: probing DE

1. Luminosity distance vs. redshift: $d_L(z)$ $m(z)$

   Standard candles: SNe Ia

2. Angular diameter distance vs. z: $d_A(z)$

   Alcock-Paczynski test: Ly-alpha forest; redshift correlations

3. Number counts vs. redshift: $N(M,z)$

   probes:

   *Comoving Volume element $dV/dzd\Omega$

   *Growth rate of density perturbations $\delta(z)$

   Counts of galaxy halos and of clusters; QSO lensing

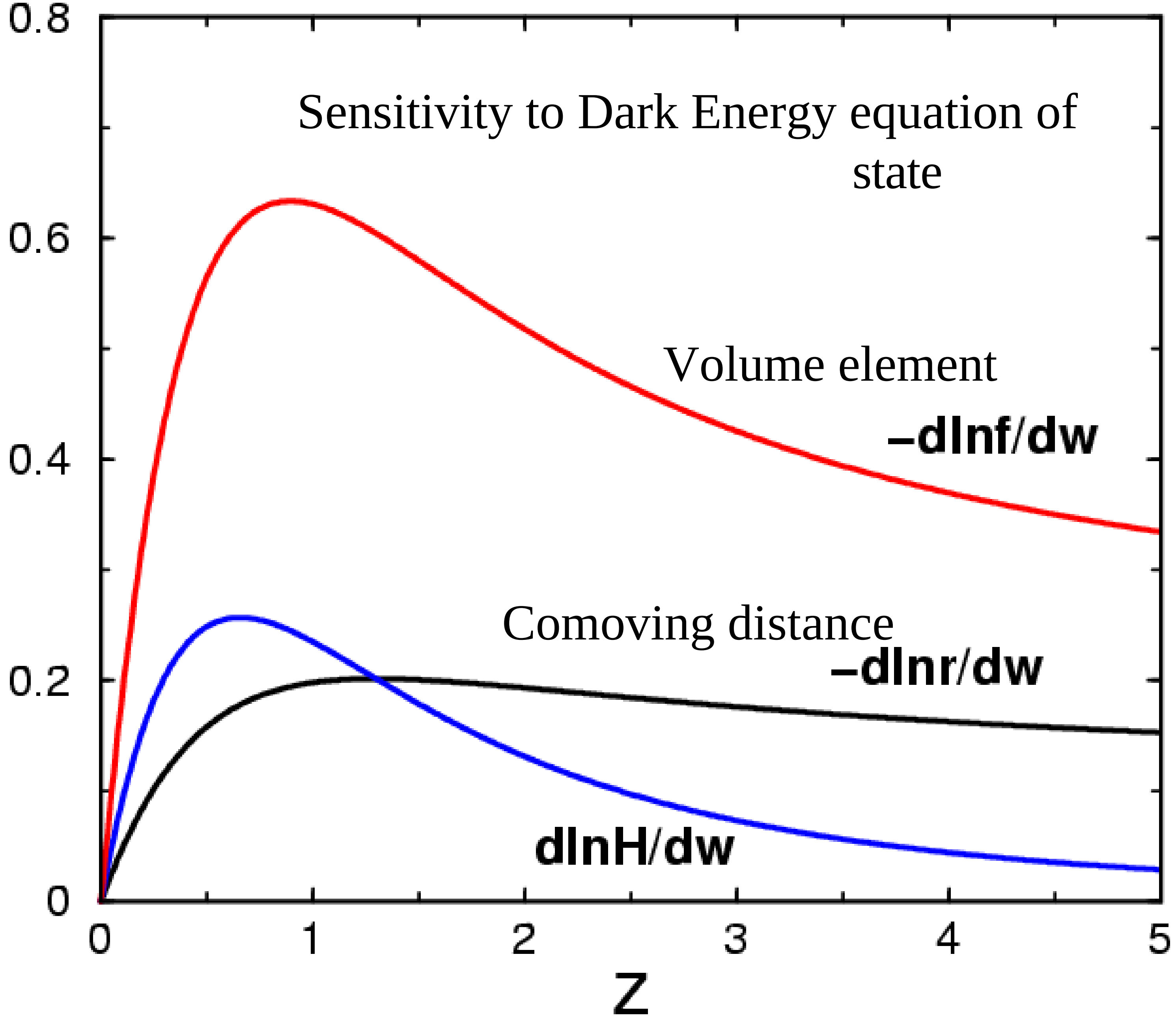
Comoving Distance: $r(z) = \int dx/H(x)$

In a flat Universe:

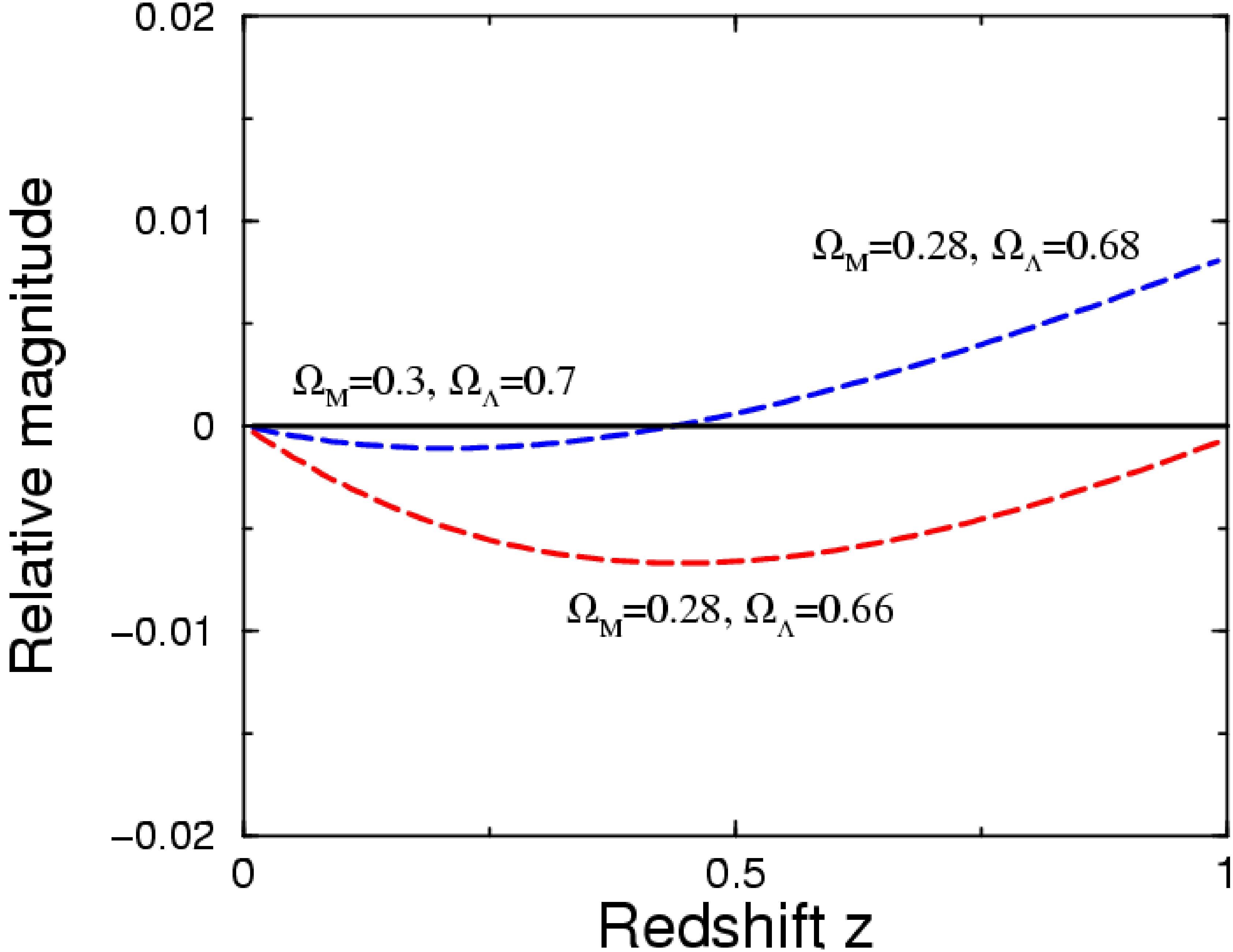
Luminosity Distance: $d_L(z) = r(z)(1+z)$

Angular diameter Distance: $d_A(z) = r(z)/(1+z)$

Comoving Volume Element: $dV/dzd\Omega = r^2(z)/H(z)$



Huterer & Turner

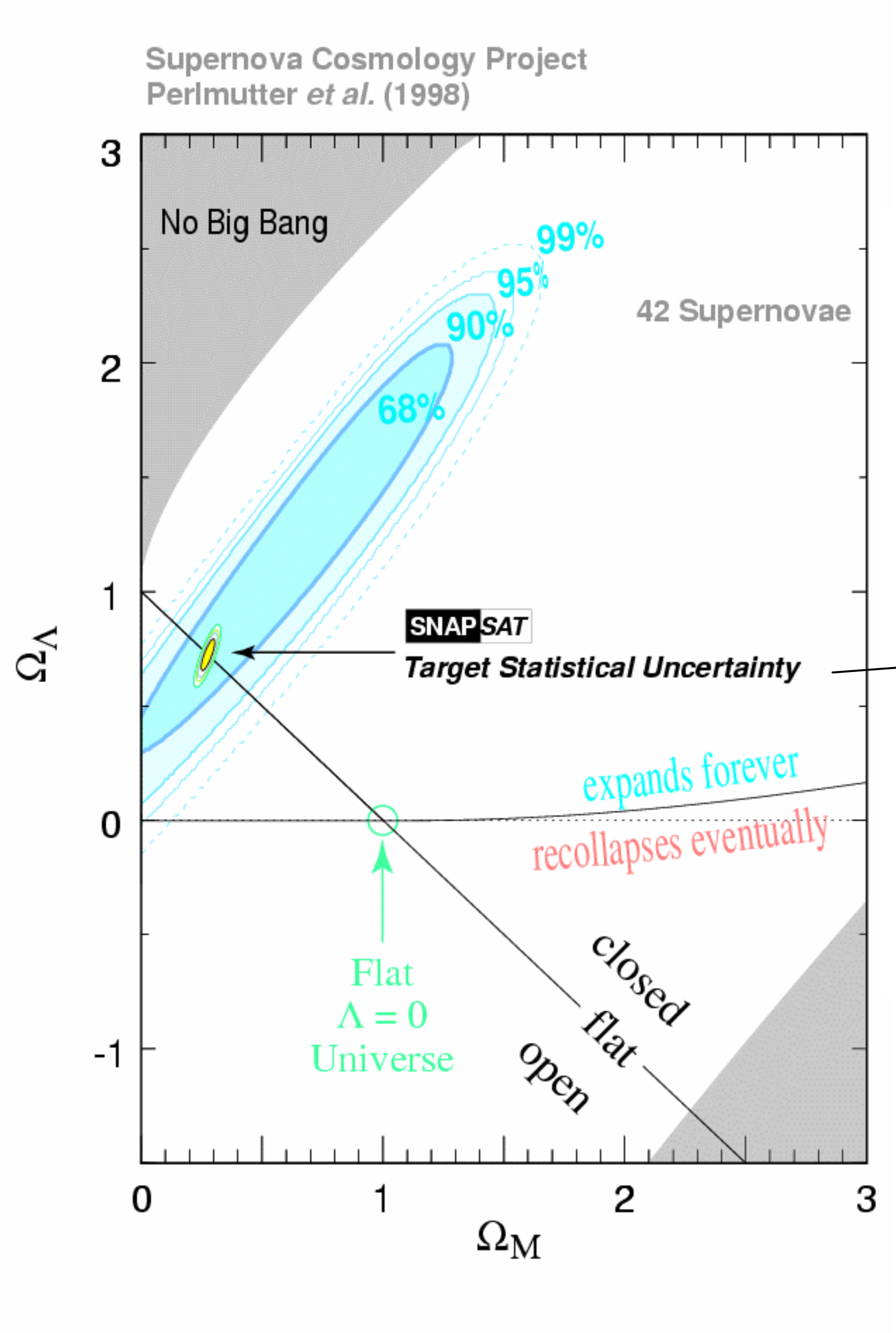


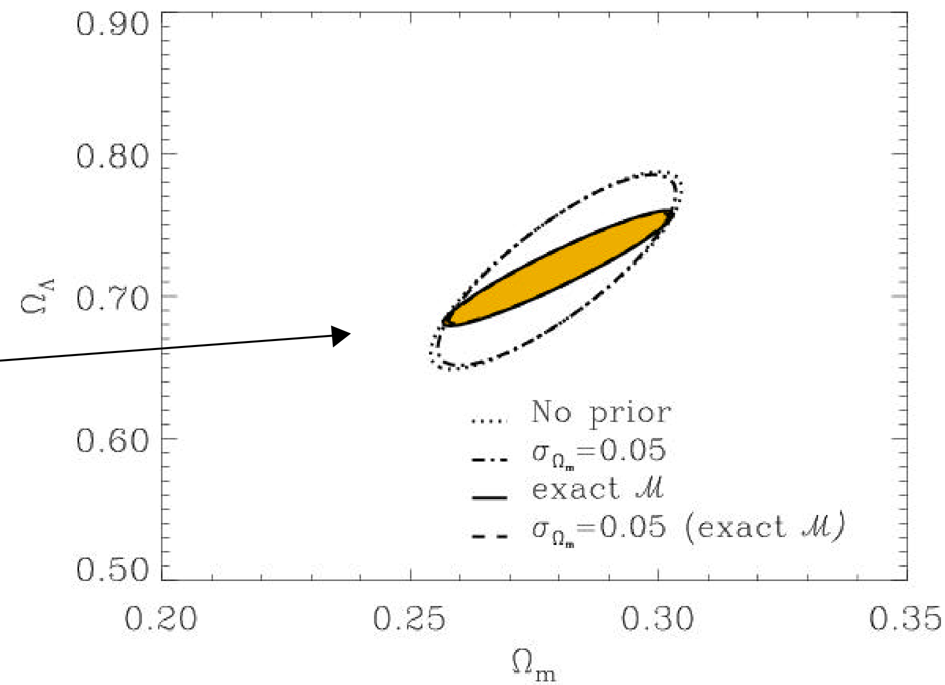
0.02
0.01
0
−0.01
−0.02
0
0.5
1
Relative magnitude
Redshift z
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.28, Ω_Λ=0.68
Ω_M=0.28, Ω_Λ=0.66

Warning

Constraint contours depend on priors assumed for other cosmological parameters

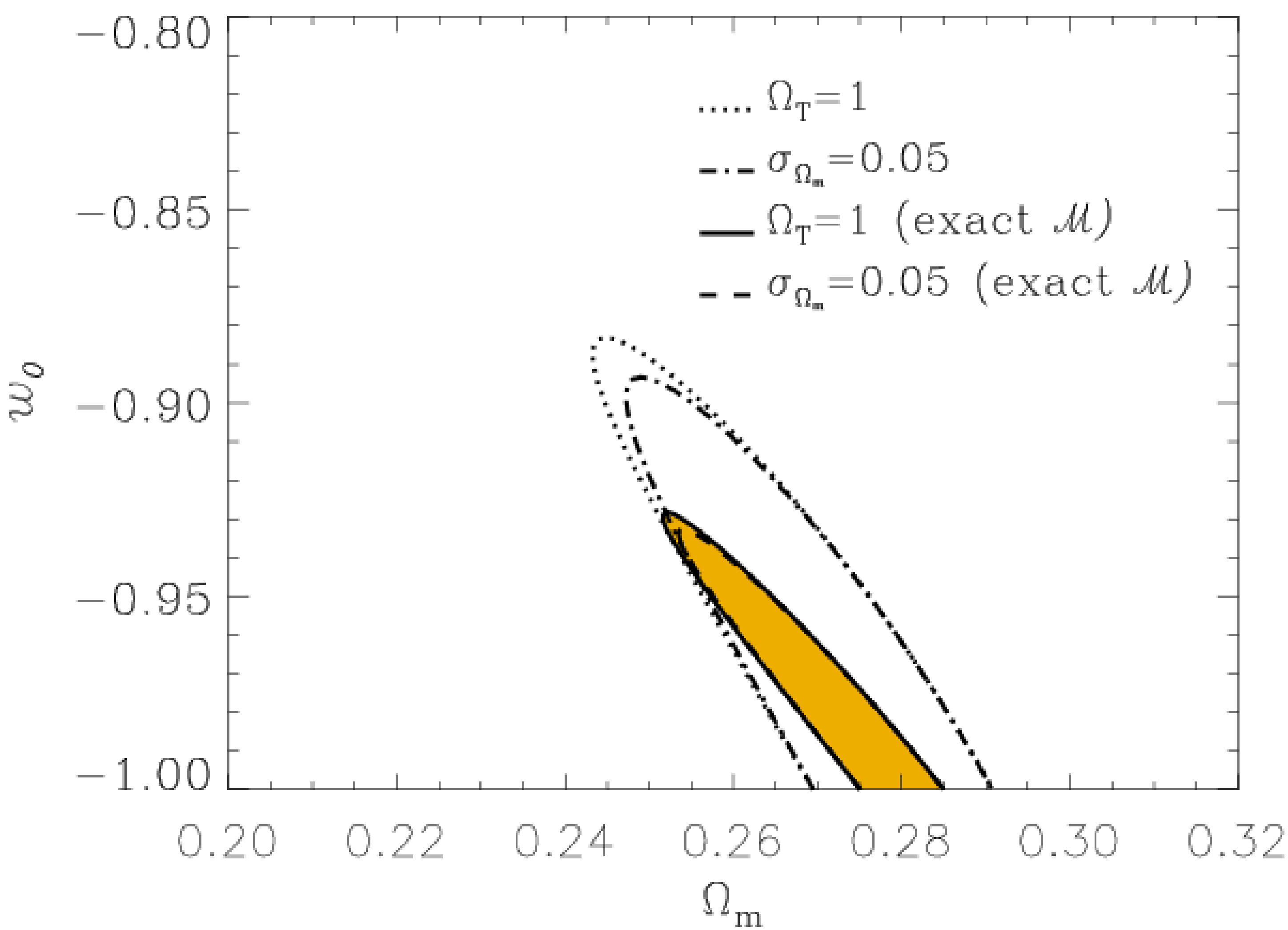
Conclusions depend on projected state of knowledge/ignorance



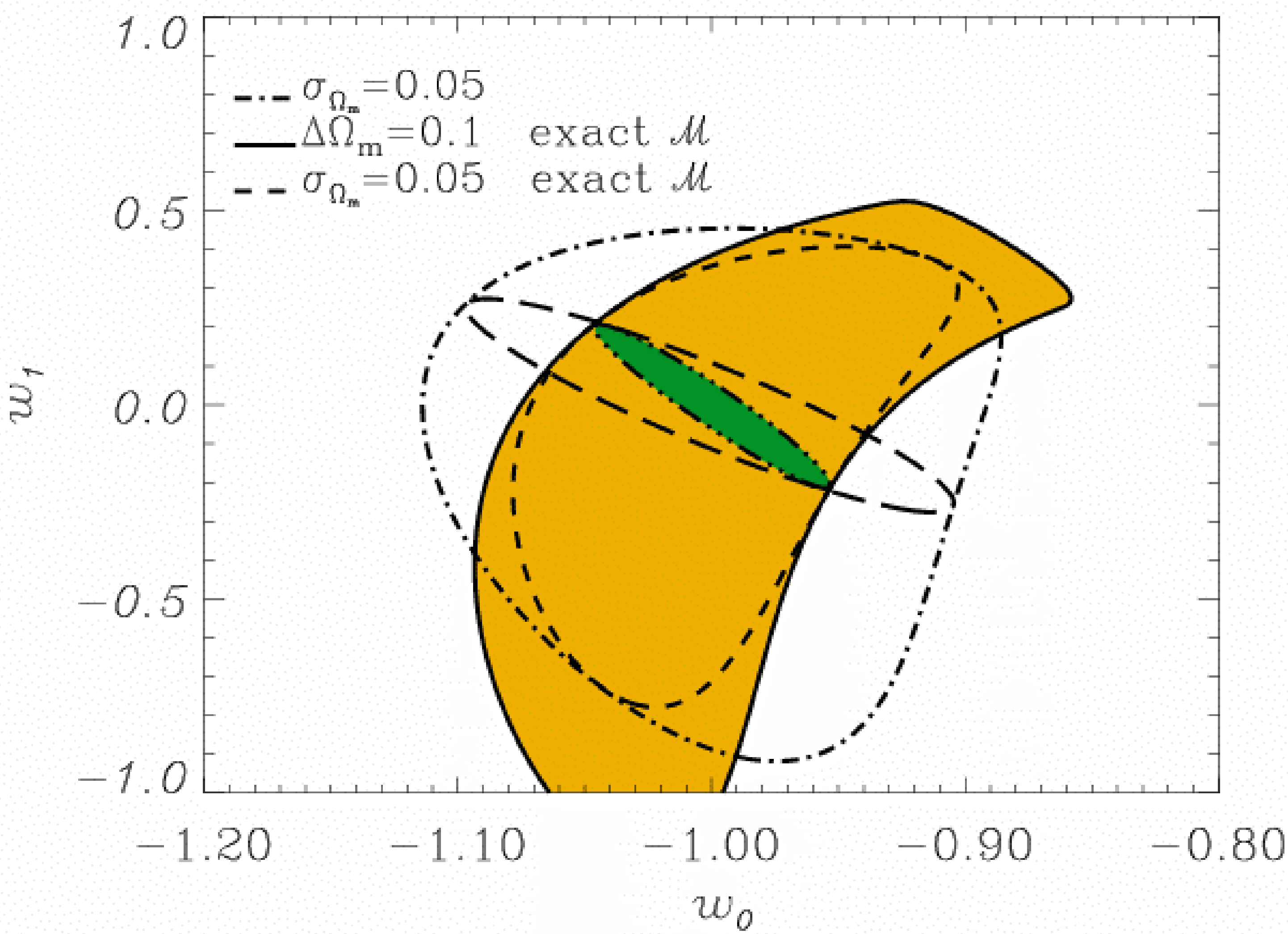


Goliath, etal

Projected SNAP Sensitivity to DE Equation of State



SNAP Sensitivity to Varying DE Equation of State



$$w = w_0 + w_1 z + \ldots$$

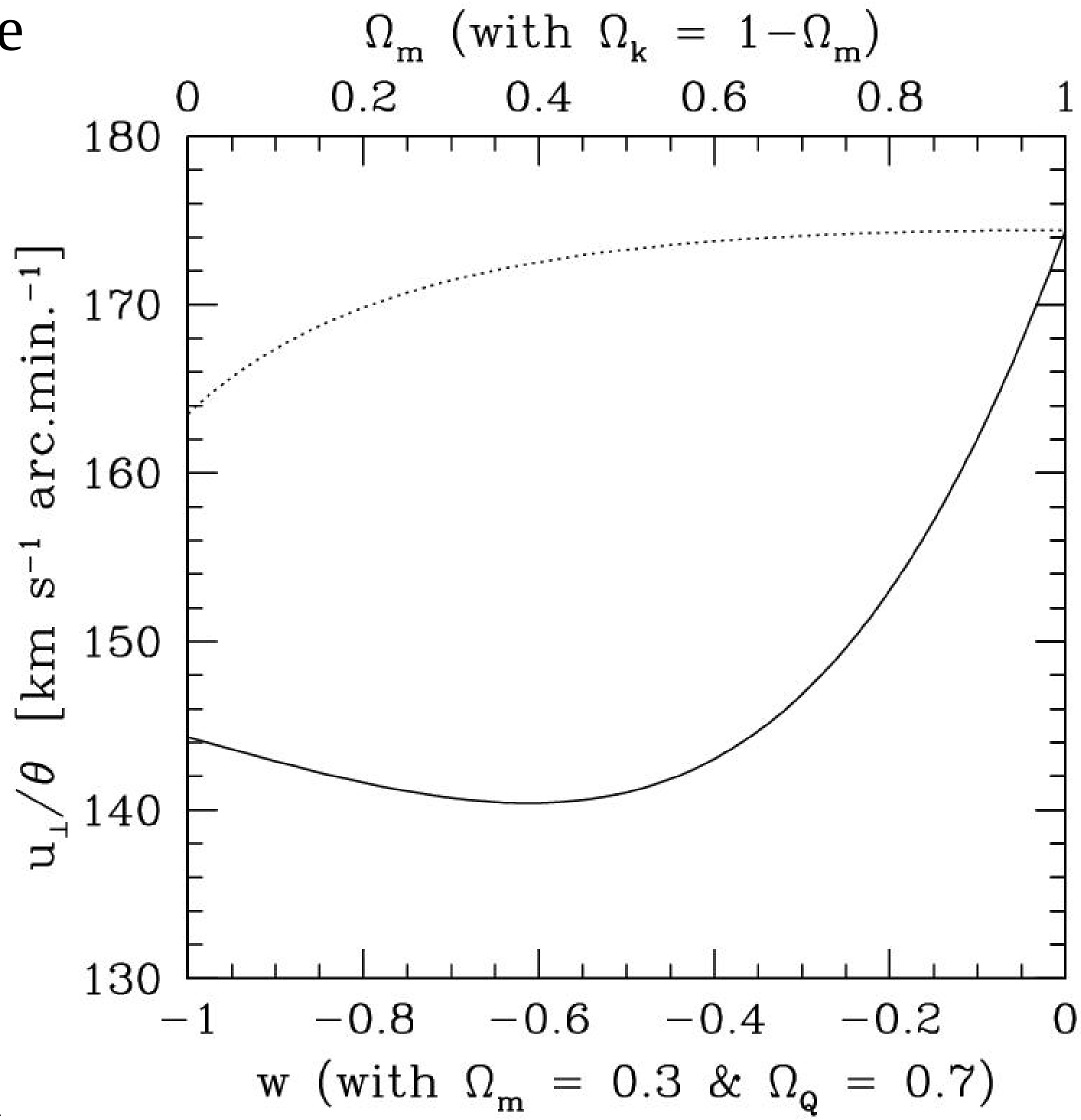
Angular Diameter Distance

$$u_\perp(\theta) = \frac{\bar{H}}{1+\bar{z}} D_A(\bar{z})\theta$$

Transverse extent

Angular size

Intrinsically isotropic clustering: radial and transverse sizes are equal



Hui, Stebbins, Burles

Lyman-alpha forest: absorbing gas along LOS to distant Quasars

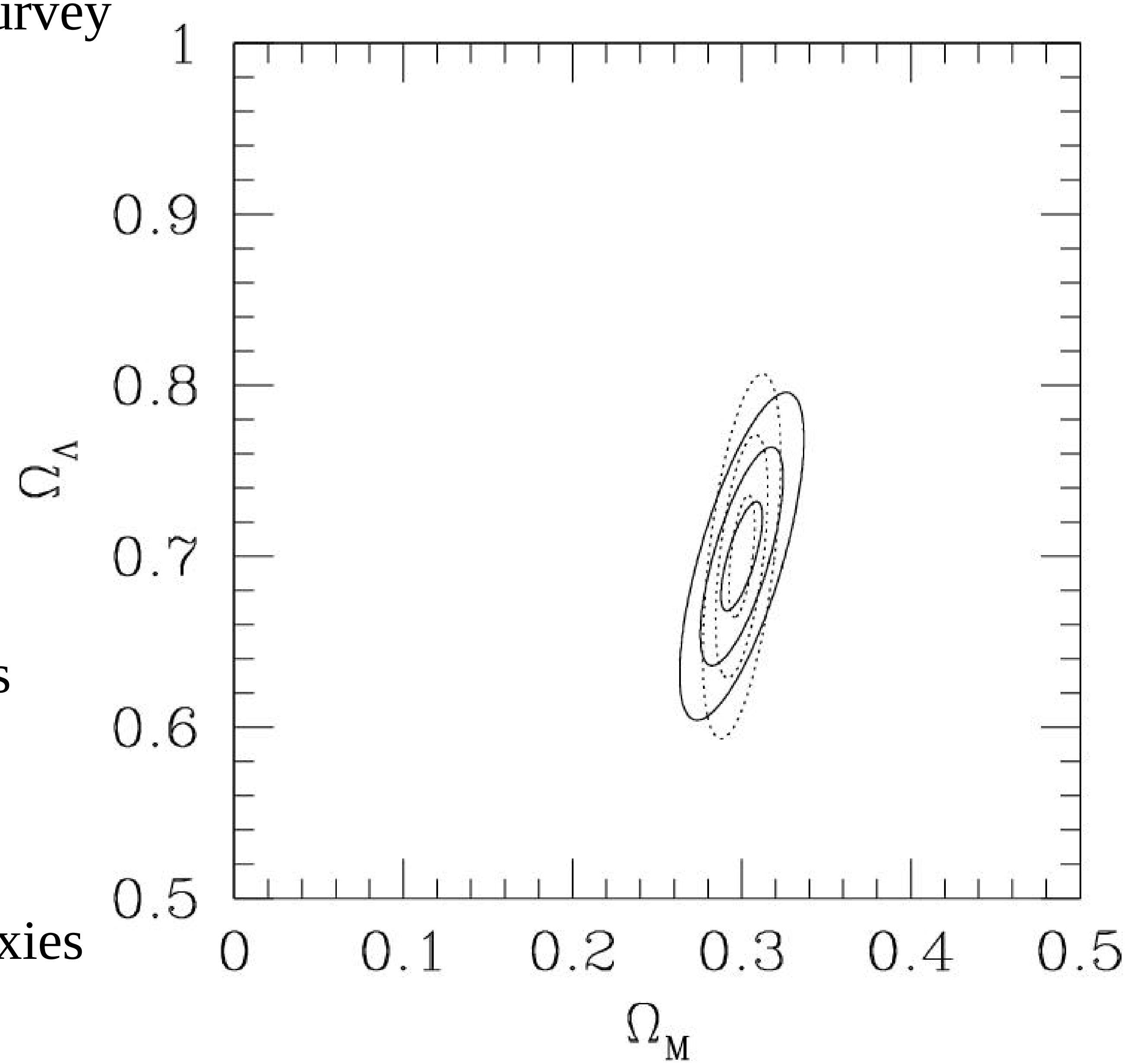
Clustering along line of sight

$$P^f_{||}(k_{||}) = \int_{k_{||}}^{\infty} \tilde{P}^f(k_{||}, k) k \frac{dk}{2\pi}$$

$$P^f_{\times}(k_{||}, \theta) = \int_{k_{||}}^{\infty} \tilde{P}^f(k_{||}, k) J_0[k_{\perp} \underline{u_{\perp}(\theta)}] k \frac{dk}{2\pi}$$

Cross-correlations between nearby lines of sight

Sloan Digital Sky Survey

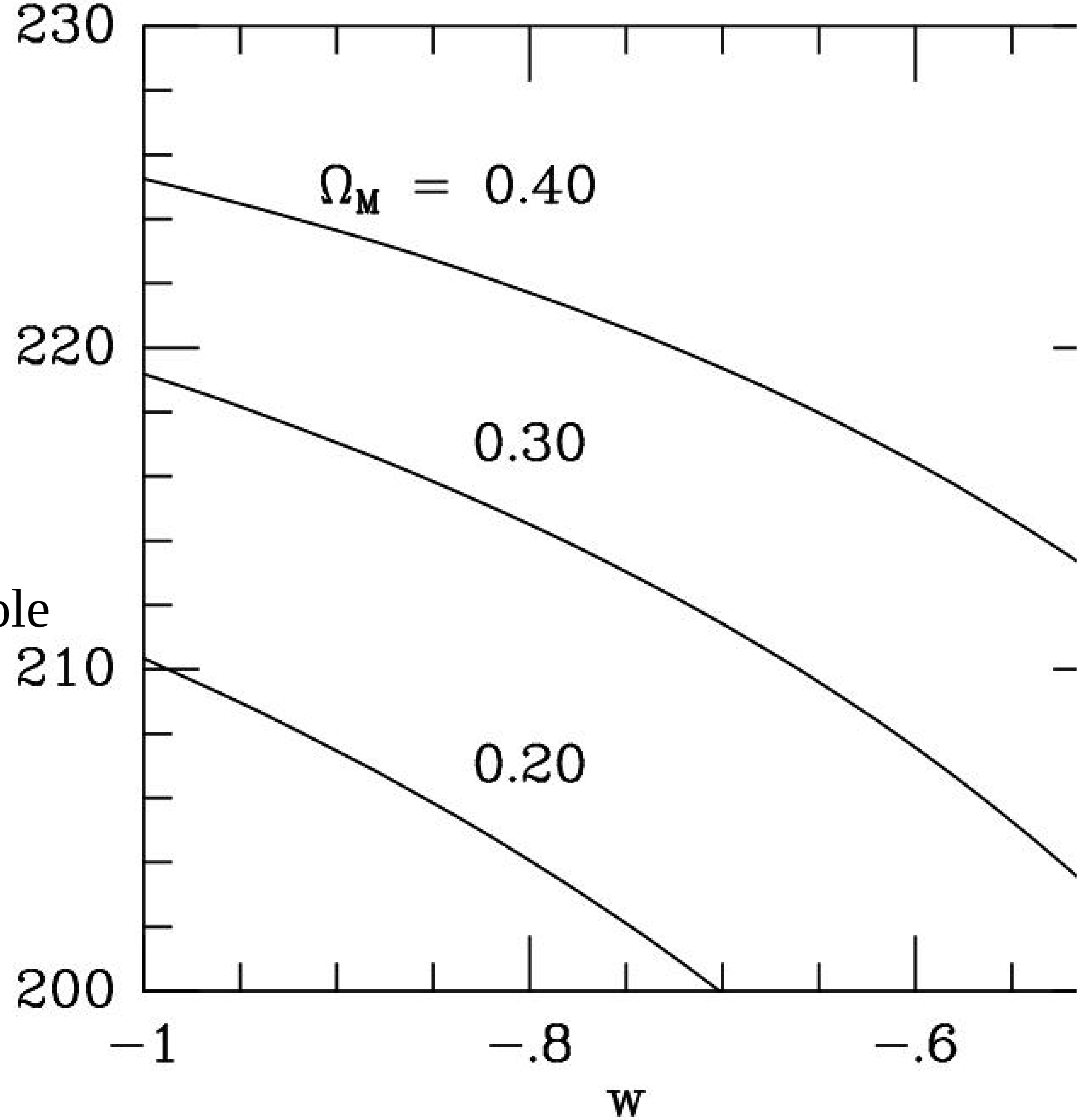


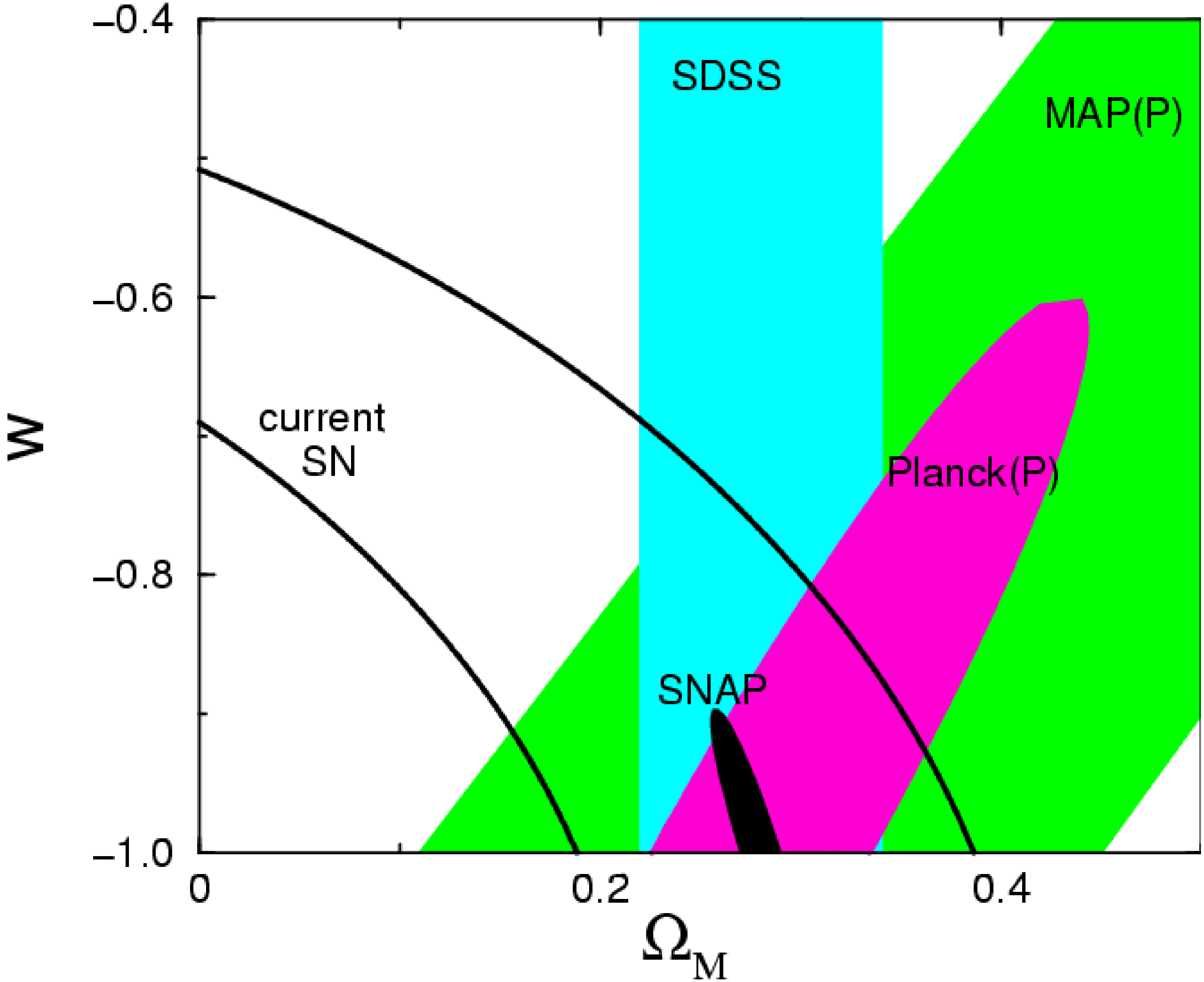
Projected constraints from redshift space clustering of 100,000 Luminous Red Galaxies ($z \sim 0.4$)

Matsubara & Szalay

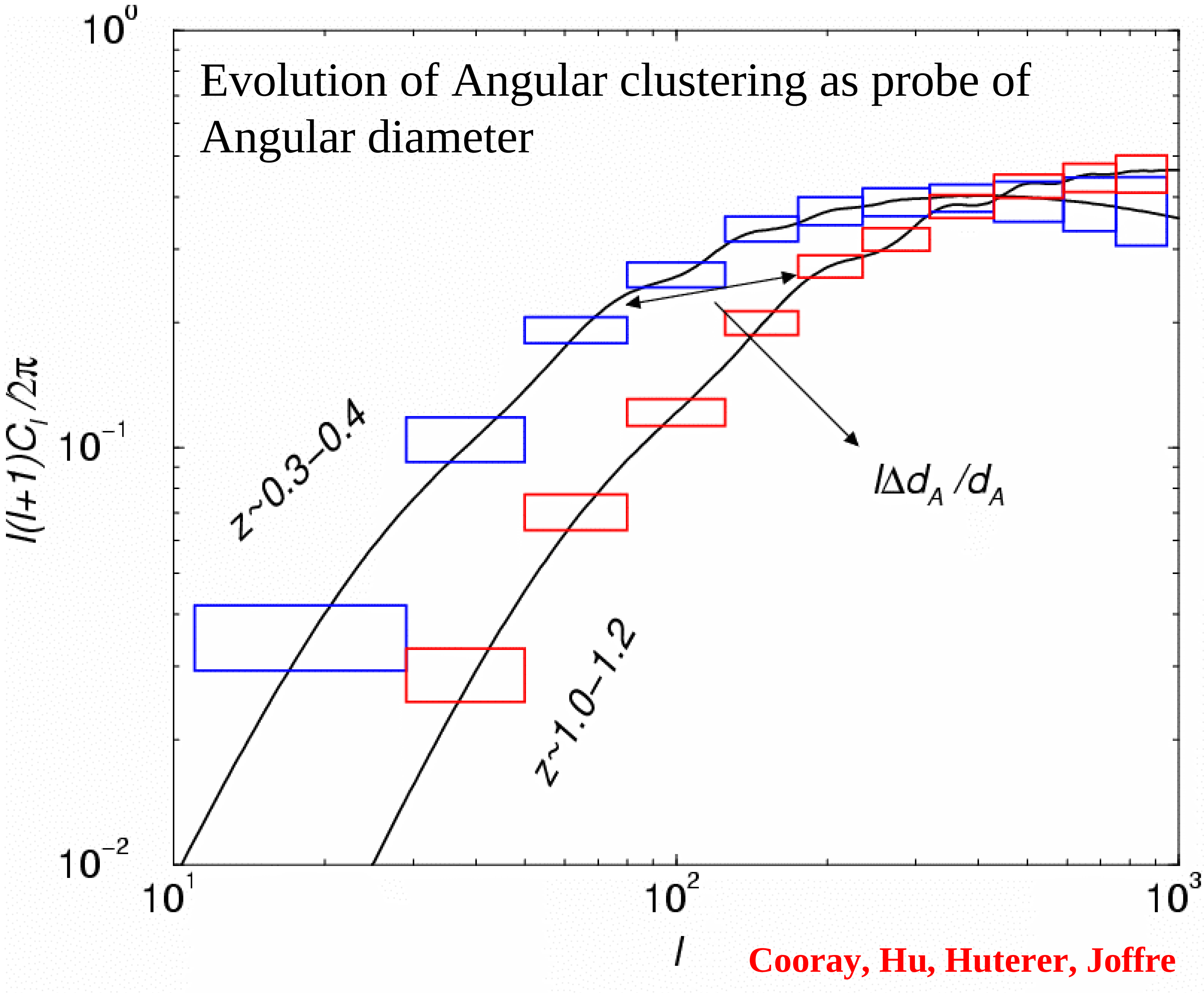
CMB Anisotropy:

Angular diameter
Distance to last
Scattering surface



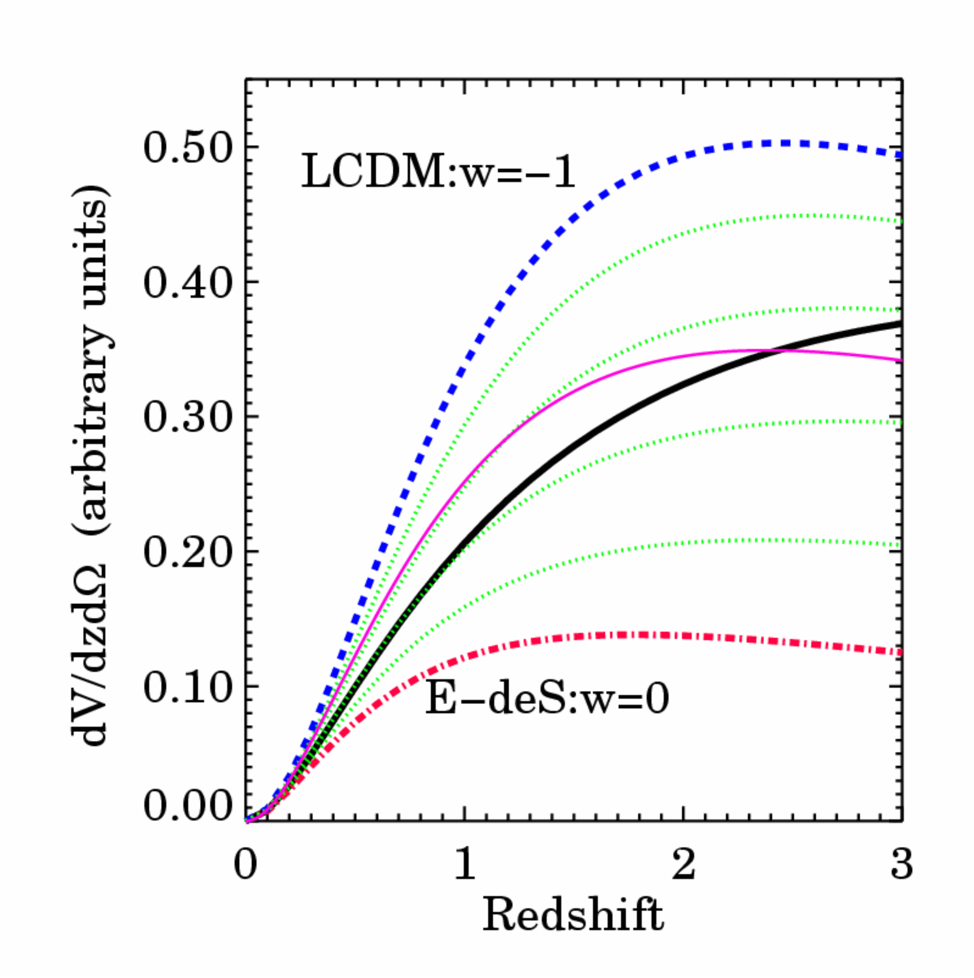


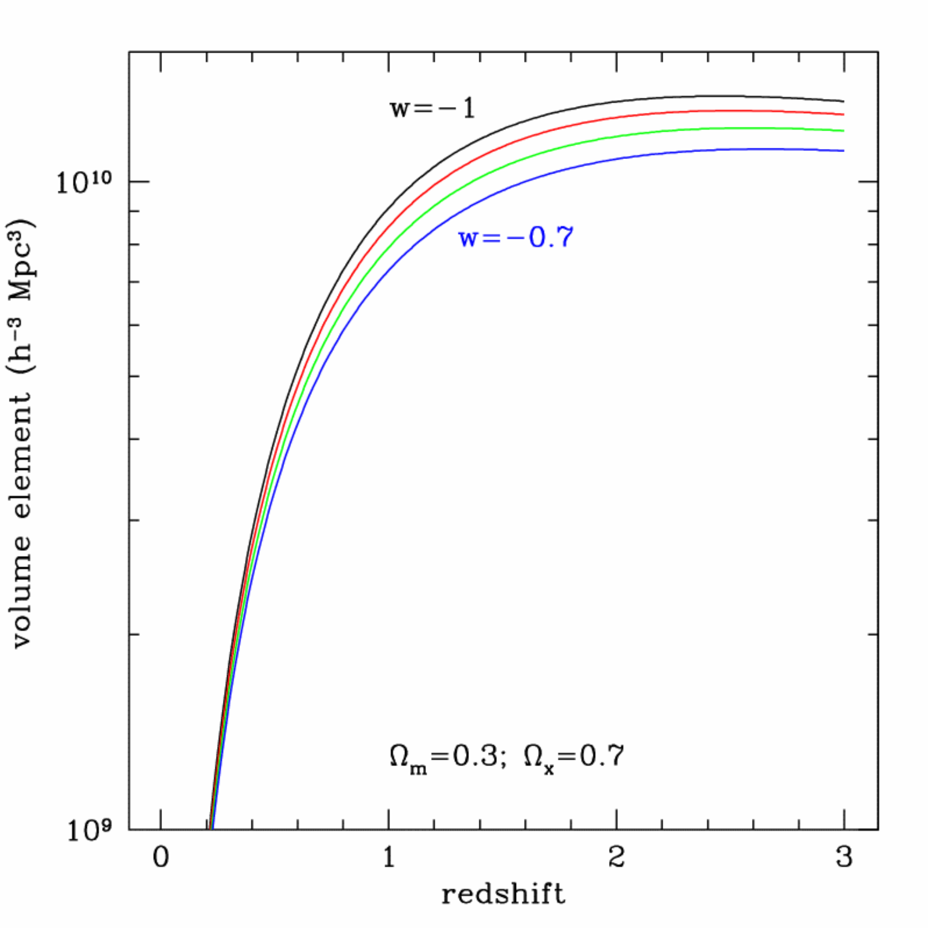
−0.4
−0.6
−0.8
−1.0
0
0.2
0.4
w
Ω_M
SDSS
MAP(P)
current
SN
Planck(P)
SNAP



Evolution of Angular clustering as probe of Angular diameter
10^0
10^{-1}
10^{-2}
$l(l+1)C_l/2\pi$
10^1
10^2
10^3
l
z~0.3–0.4
z~1.0–1.2
$l\Delta d_A/d_A$
Cooray, Hu, Huterer, Joffre

Volume Element as a function of w

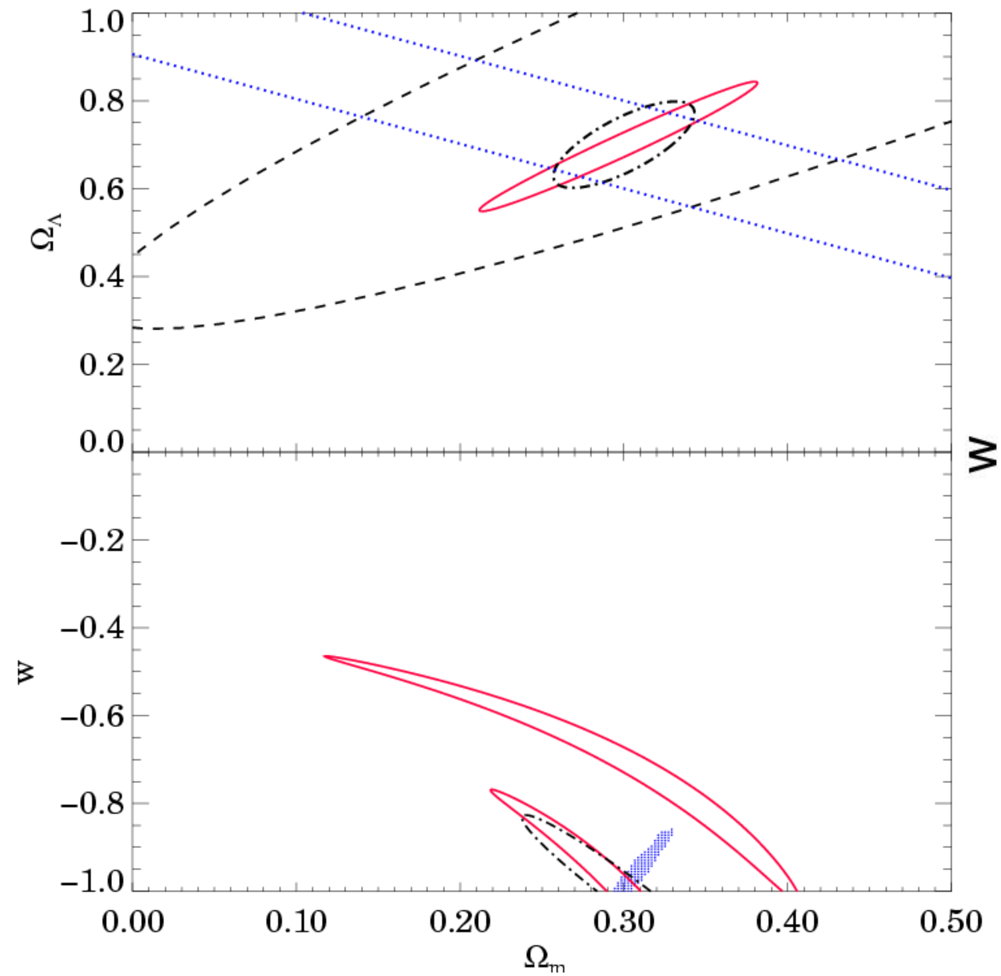


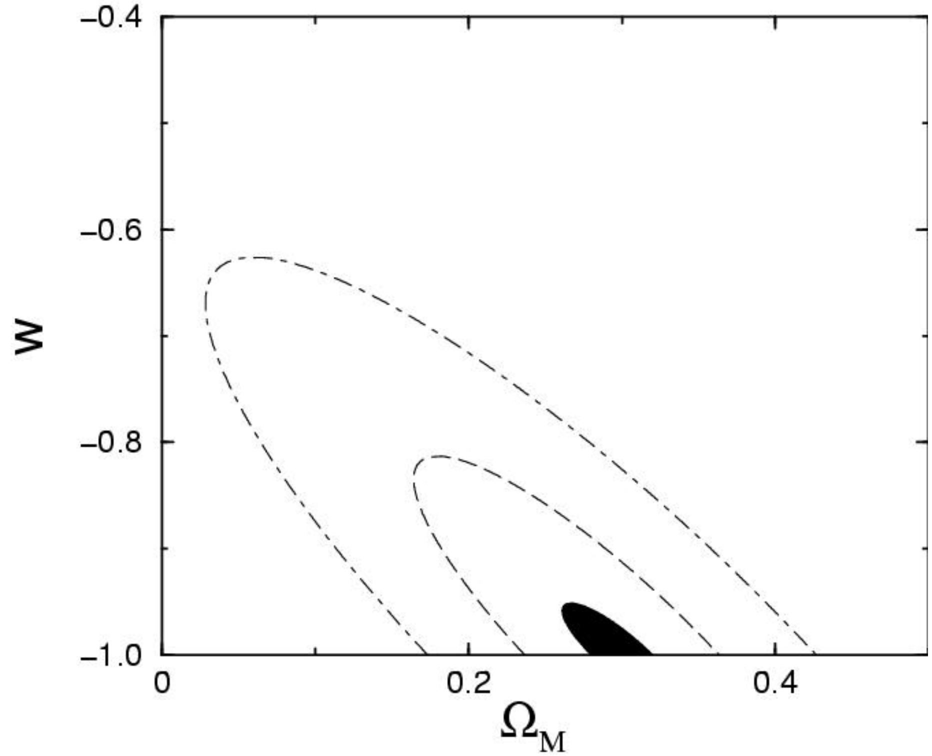


Dark Energy → More volume at moderate redshift

Counting Galaxy Dark Matter Halos with the DEEP Redshift Survey

10,000 galaxies at z ~ 1 with measured linewidths (rotation speeds)



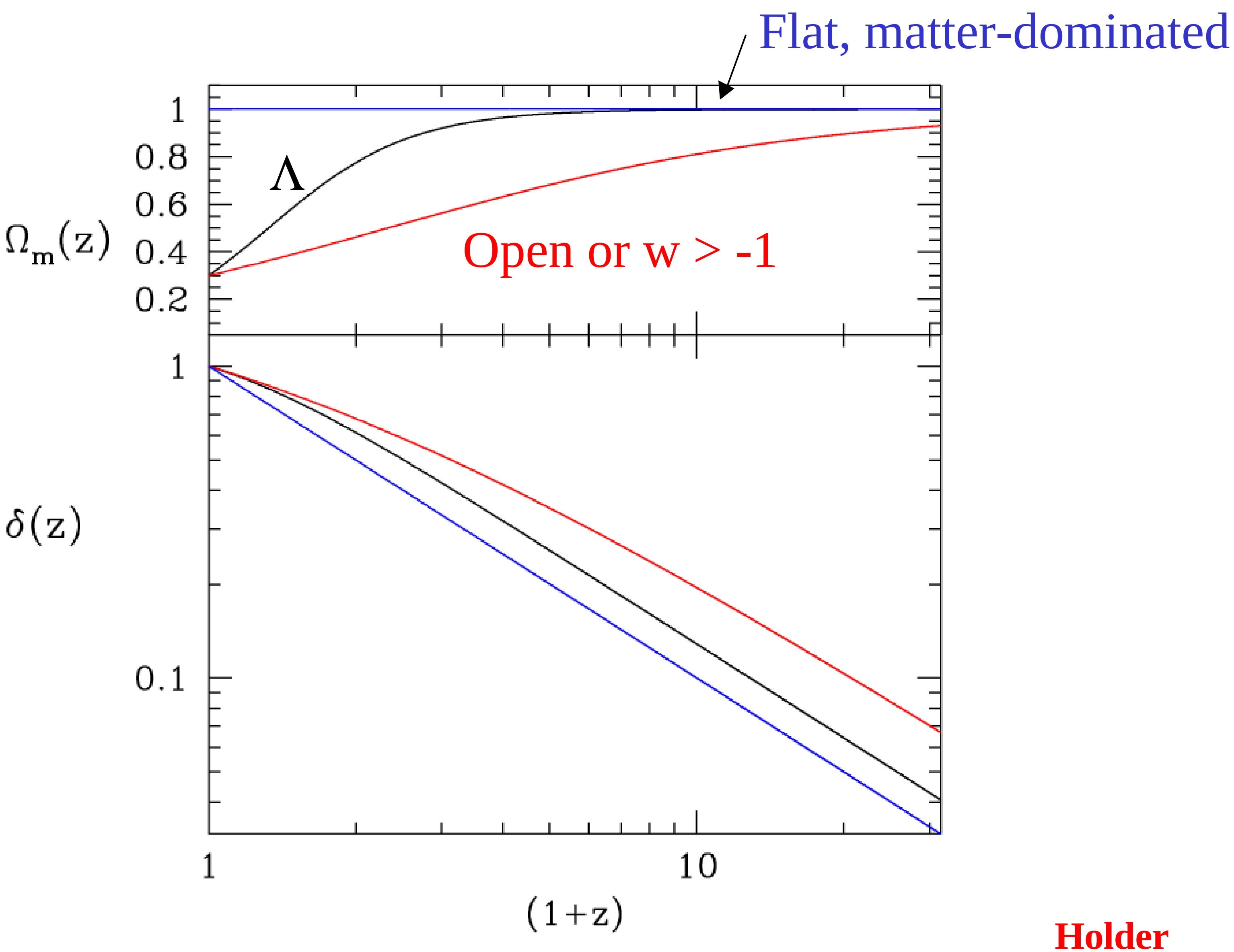


NB: must probe Dark matter-dominated regions

Newman & Davis

Huterer & Turner

Growth of Density Perturbations



Holder

Counting Clusters of Galaxies

Sunyaev Zel'dovich effect

X-ray emission from cluster gas

Weak Lensing

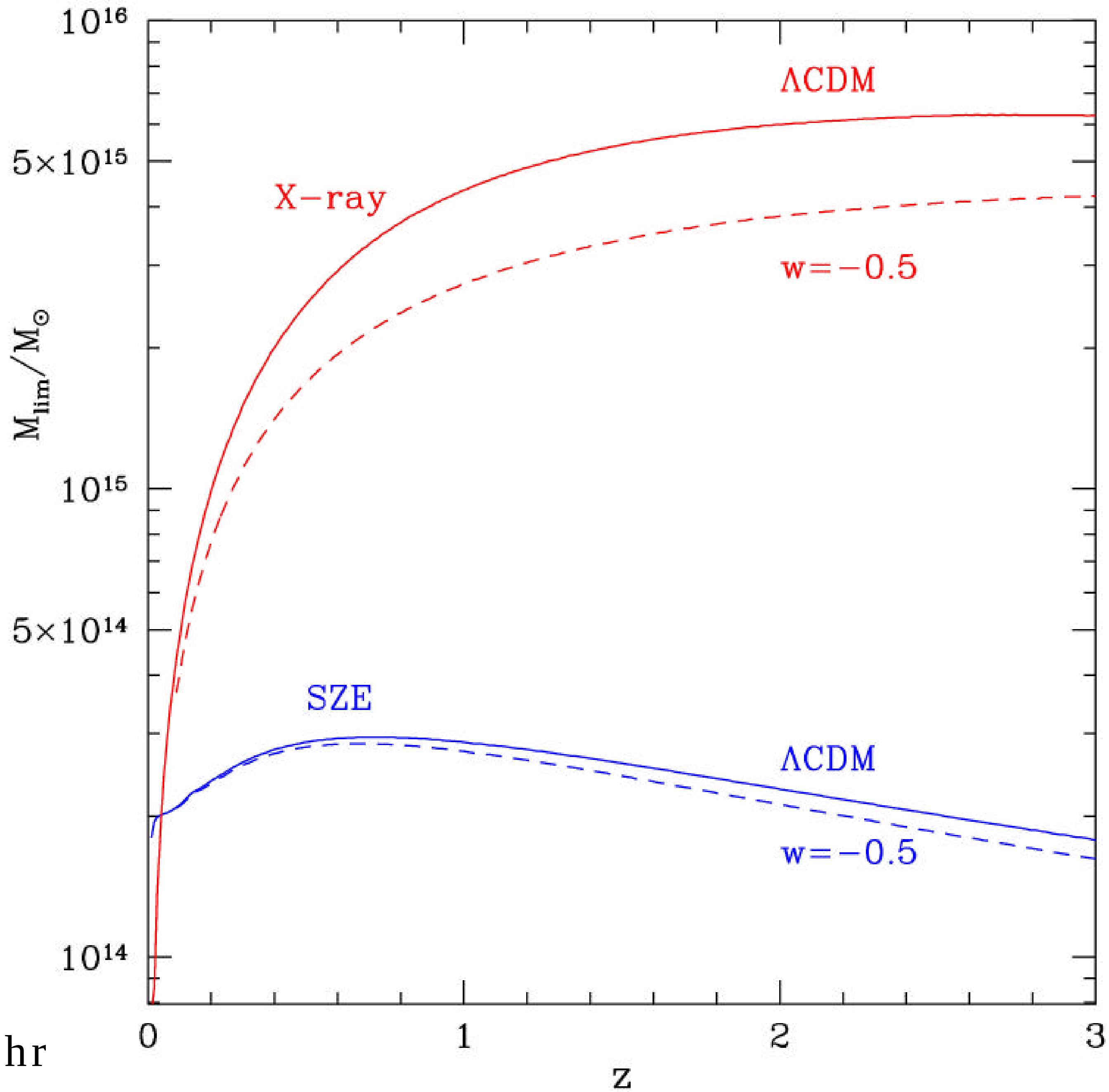
$$\frac{dN}{dz\,d\Omega}(z) = \left[\frac{dV}{dz\,d\Omega}(z)\int_{M_{\min}(z)}^{\infty} dM\,\frac{dn}{dM}\right]$$

Simulations:

$$\frac{dn}{dM}(z, M) = 0.315\frac{\rho_0}{M}\frac{1}{\sigma_M}\frac{d\sigma_M}{dM}\exp\left[-|0.61 - \log(D_z\sigma_M)|^{3.8}\right]$$

growth factor

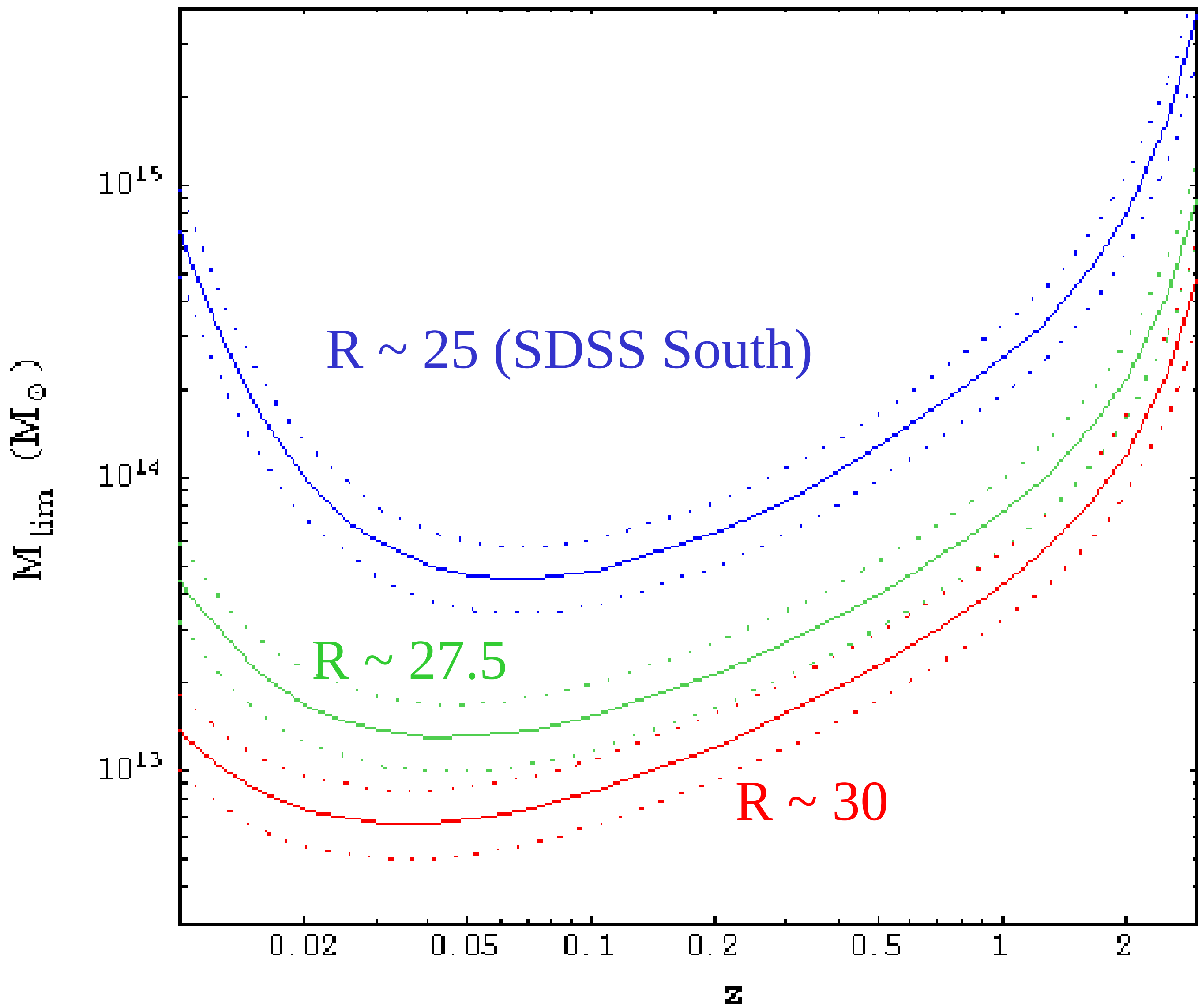
Detection Mass thresholds



Haiman, Holder, Mohr

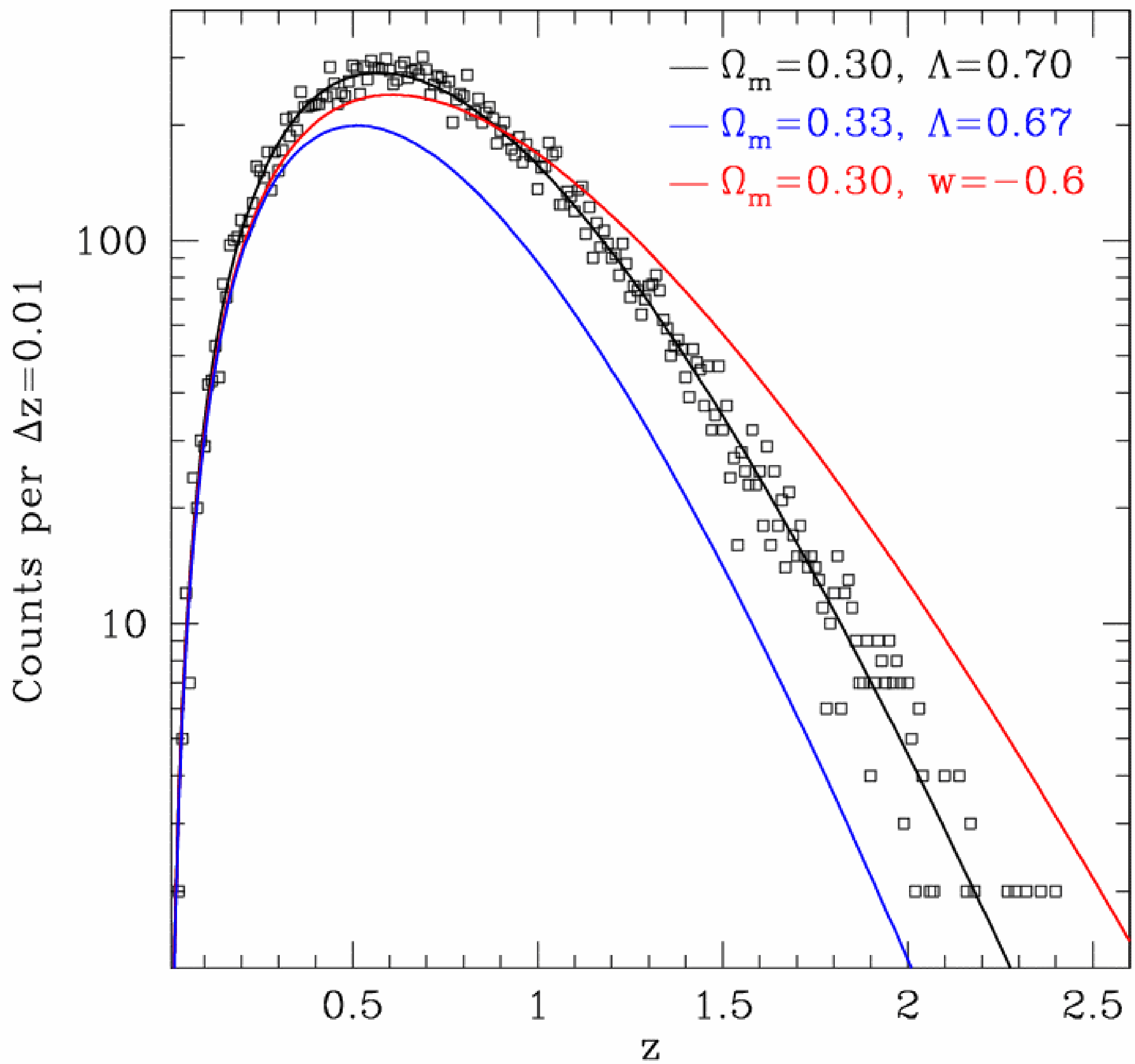
Weak Lensing:

Optical
Multi-band
Surveys of
Varying
Depth



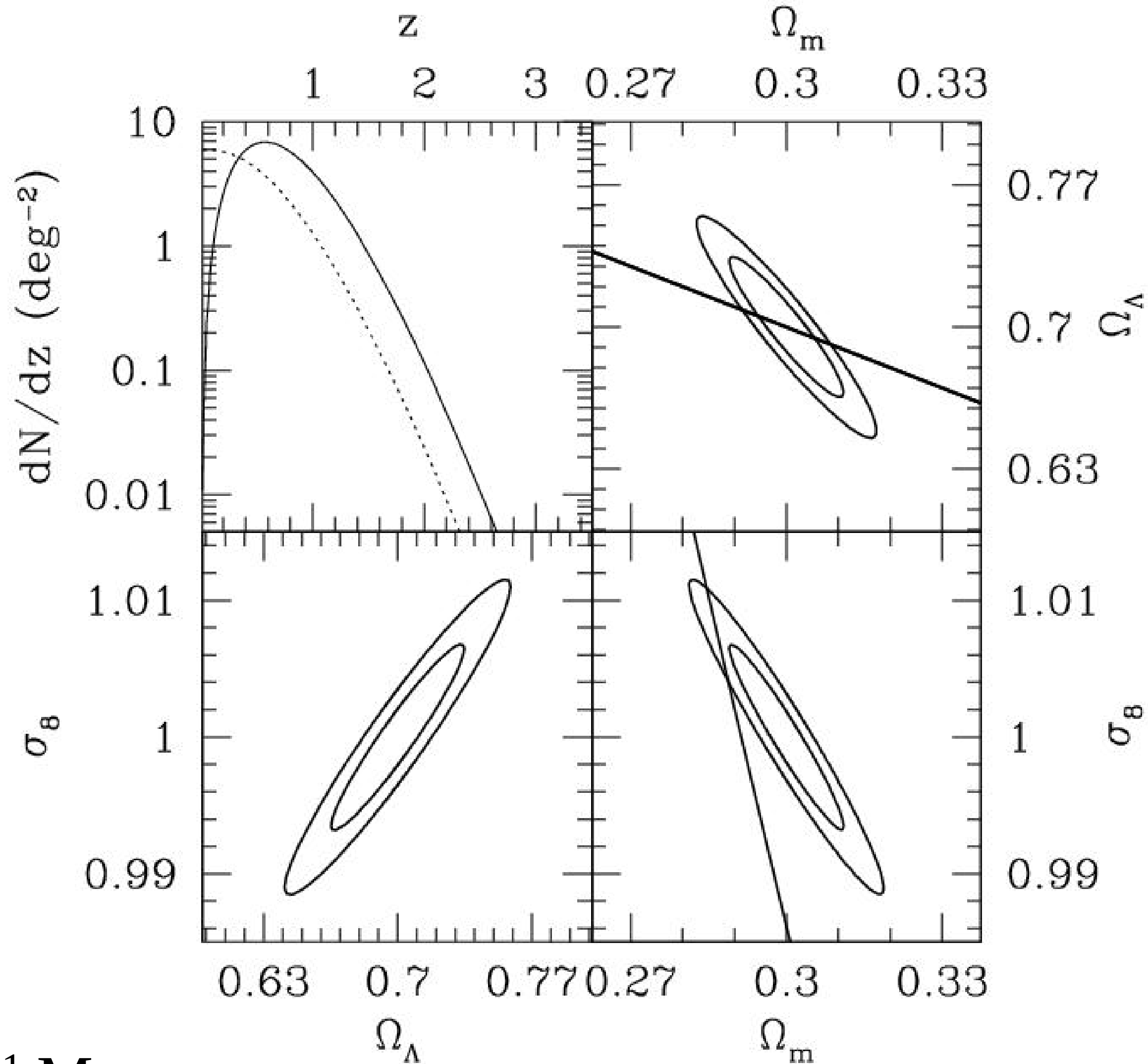
Joffre, Frieman

Expected Cluster Counts in a Deep, wide Sunyaev Zel'dovich Survey



Holder, Carlstrom, etal

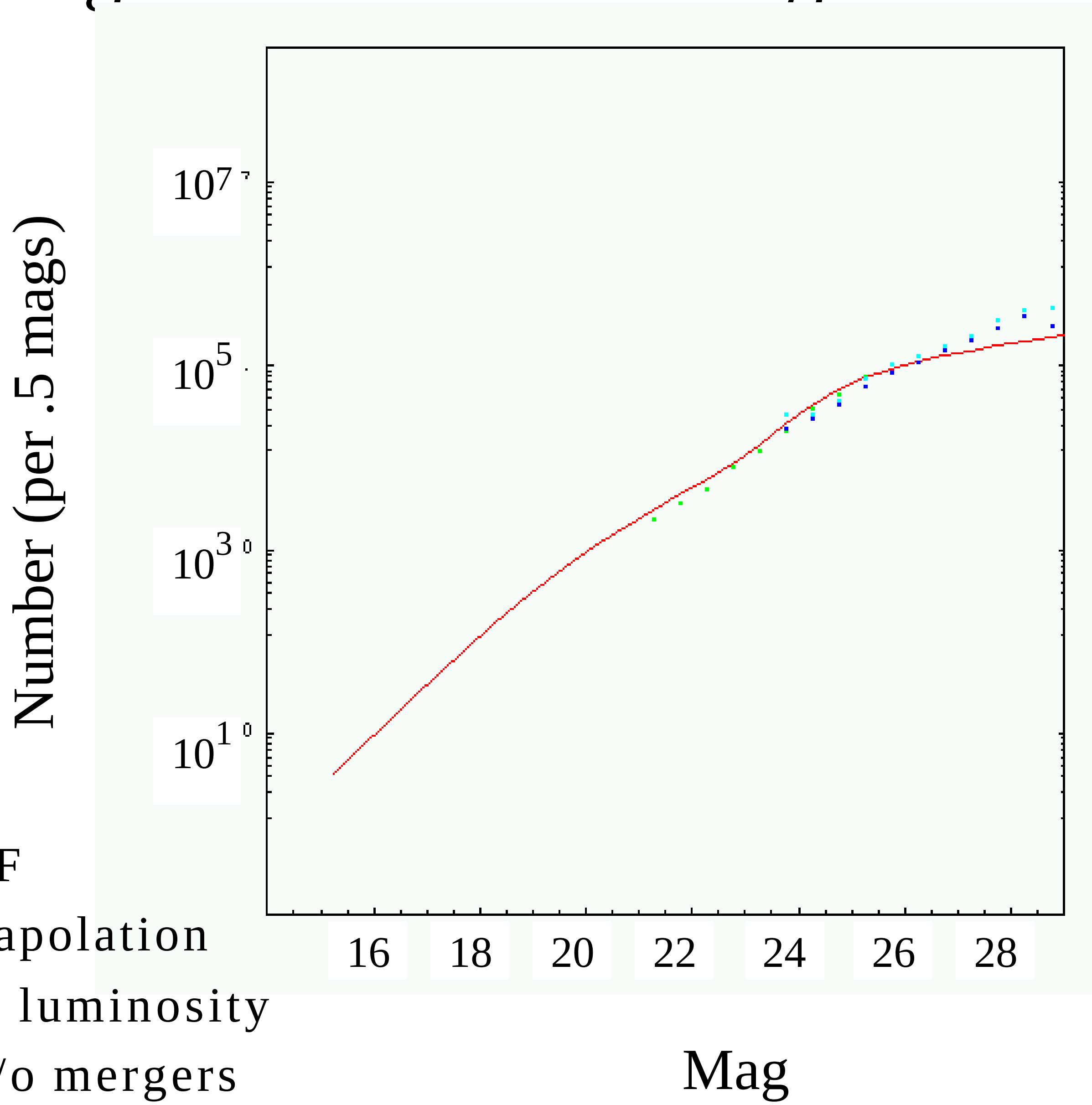
Constraints from
a 4000 sq. deg.
SZE Survey



$M_{lim} = 2.5 \times 10^{14}\ h^{-1}\ M_{sun}$

Holder, Haiman, Mohr

Weak Lensing:Number Cts of Background Galaxies



Points: HDF

Curve: extrapolation

From SDSS luminosity

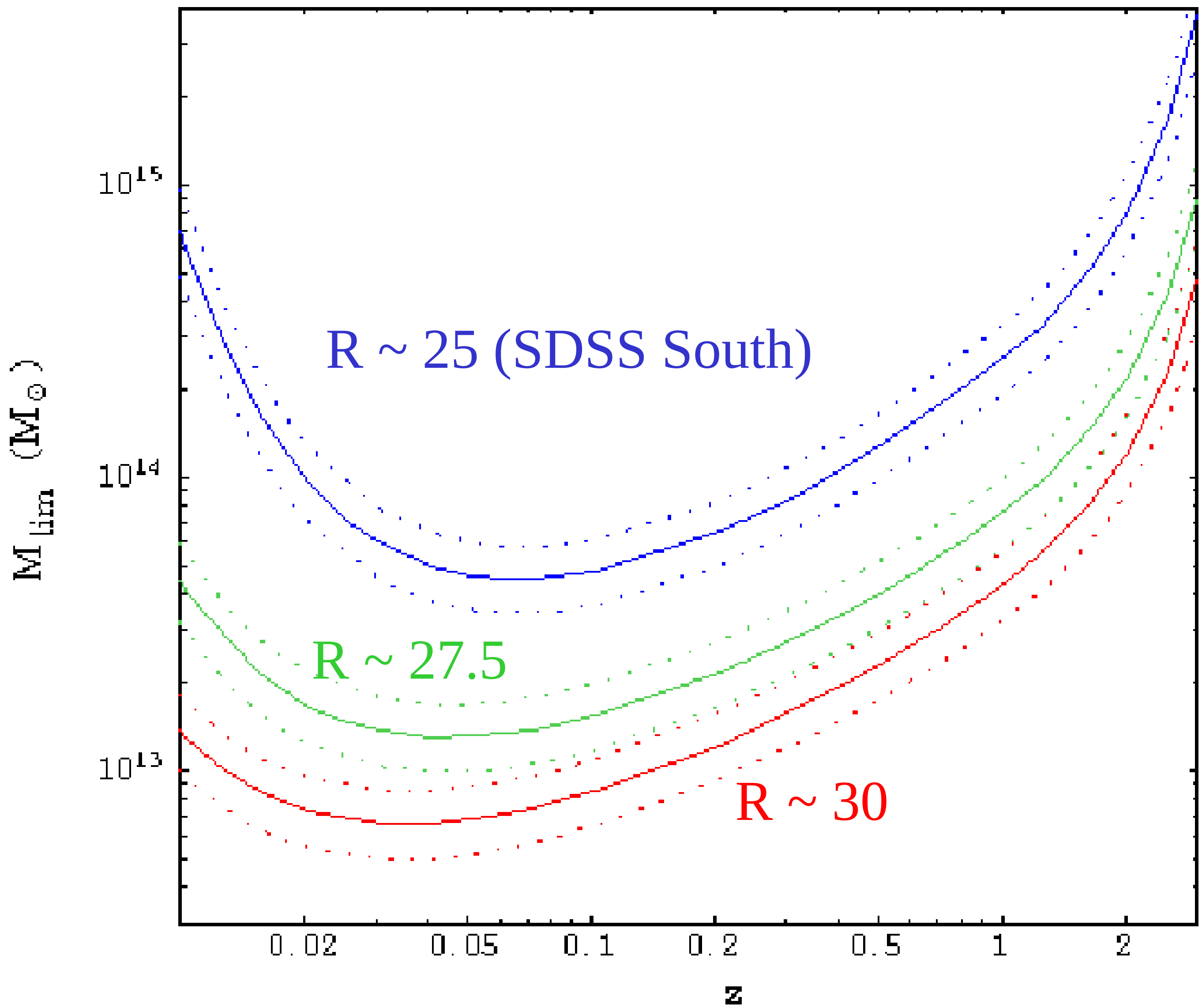
Function w/o mergers

Weak Lensing

S/N > 5 for aperture mass

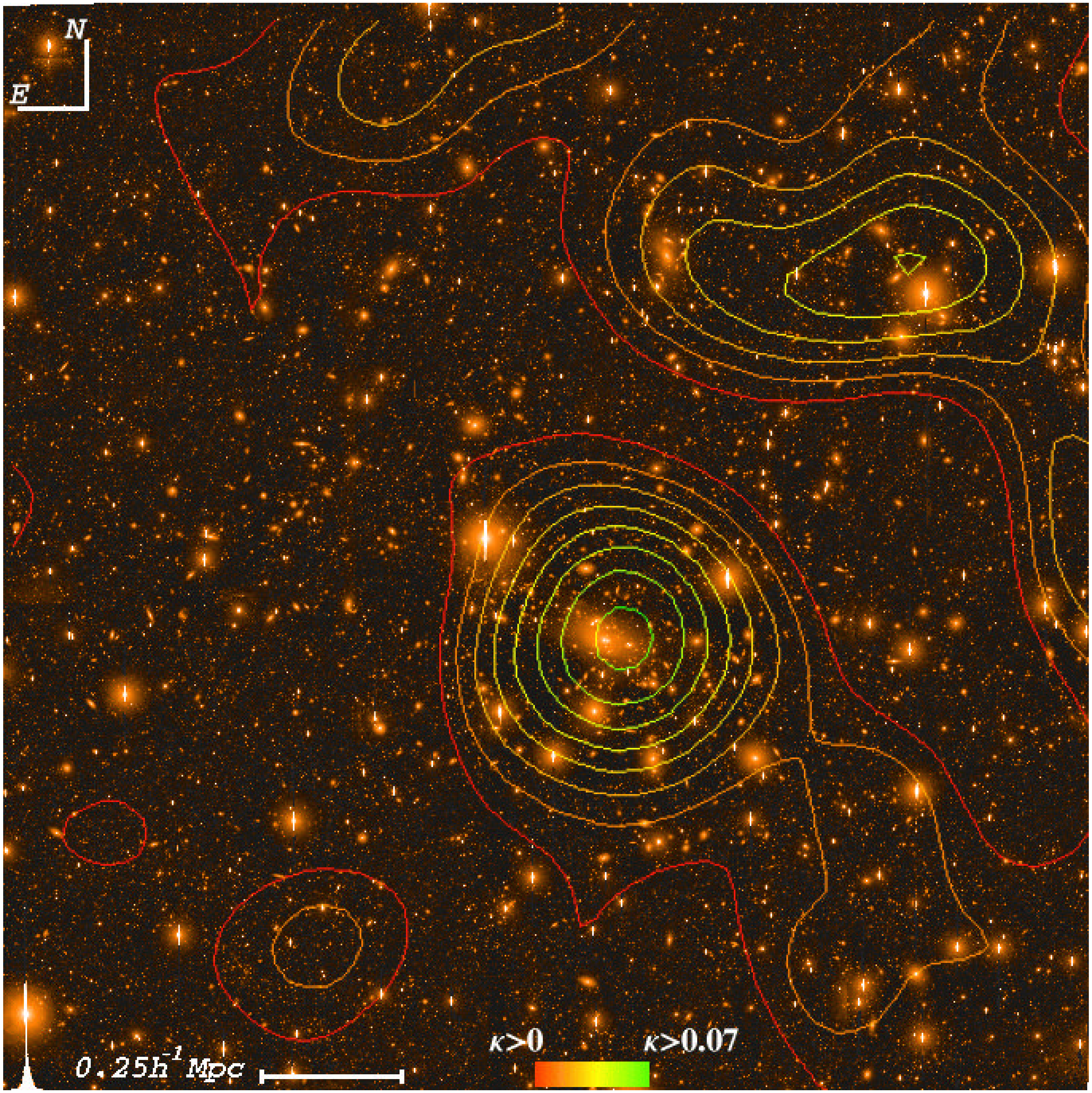
Assume NFW Profiles

Conservative on Number counts



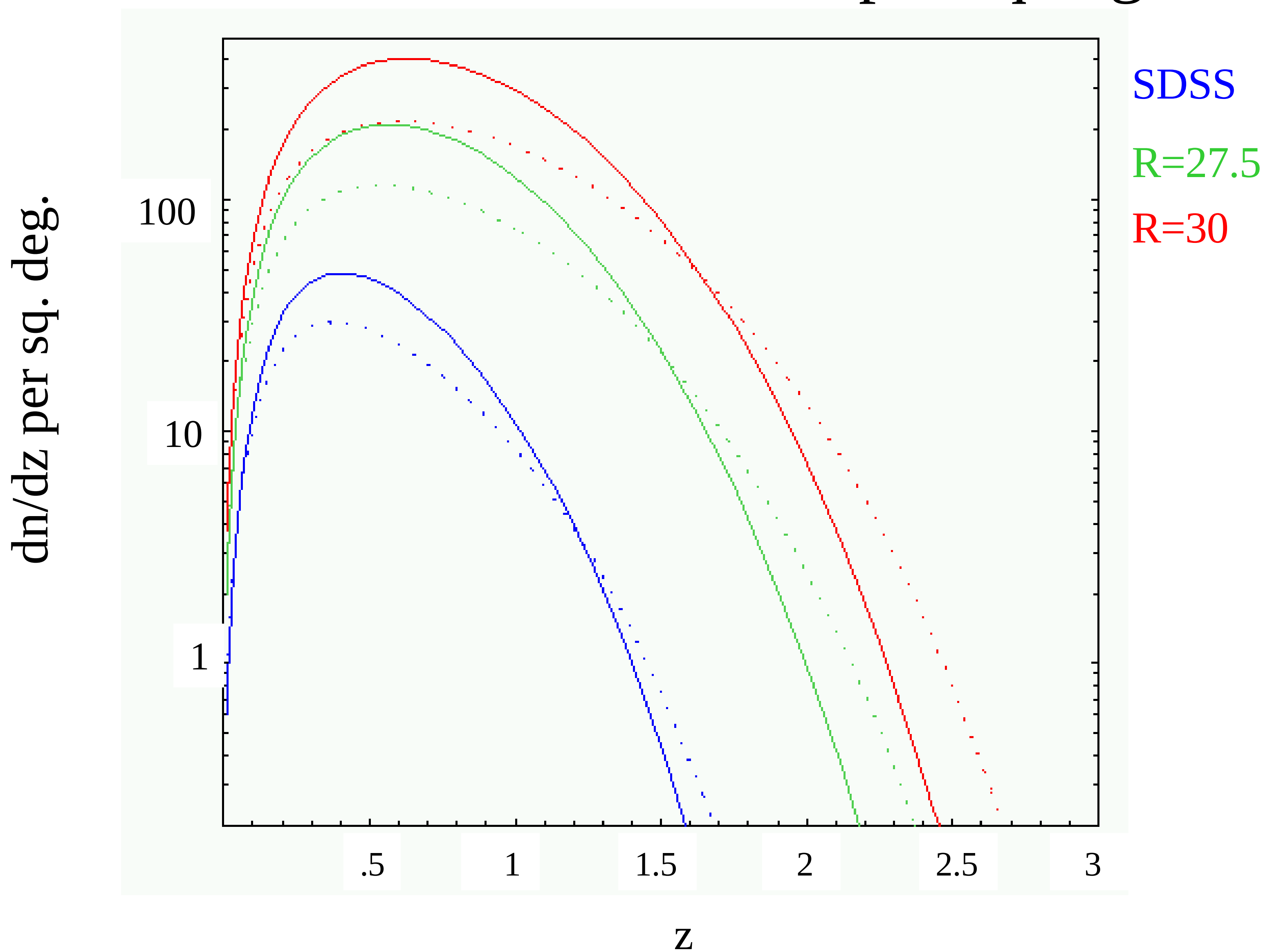
Abell 3667

z = 0.05

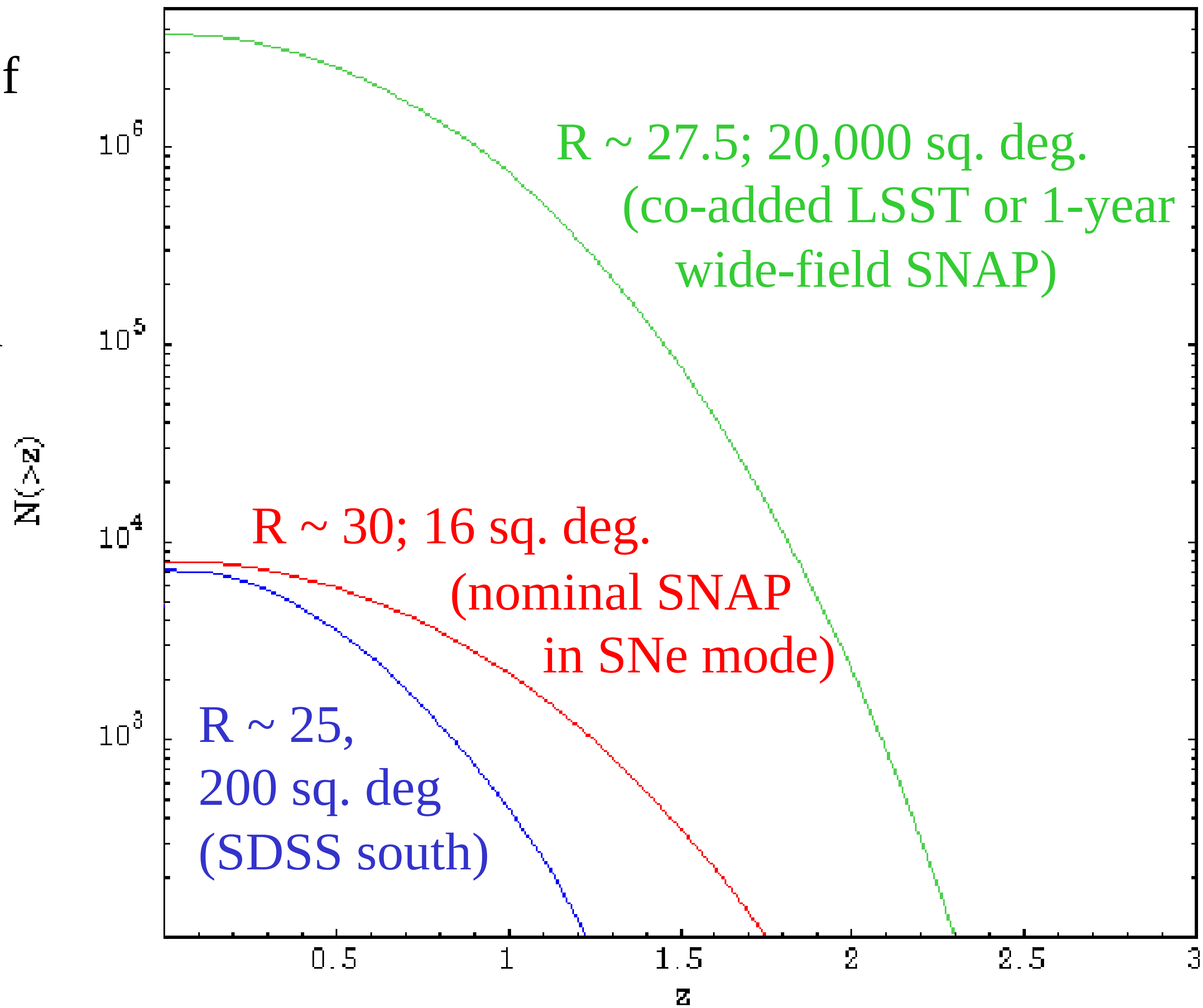


Joffre, etal

WL Detected Clusters dn/dz per sq.deg.

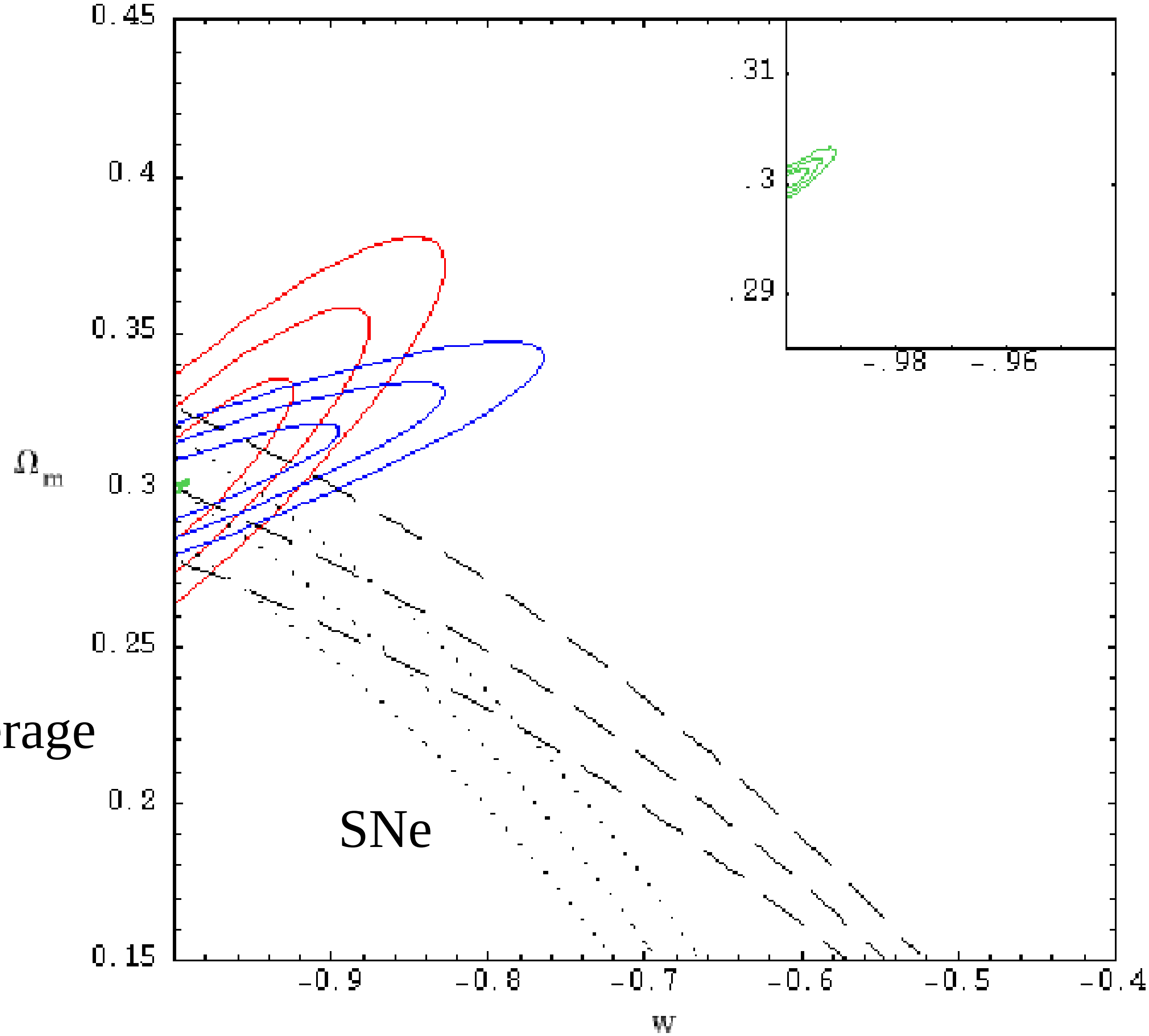


Number of Clusters detected above Threshold



Here,
$\sigma_8 = 1$
(will marginalize over)

Projected Constraints From Cluster Weak Lensing

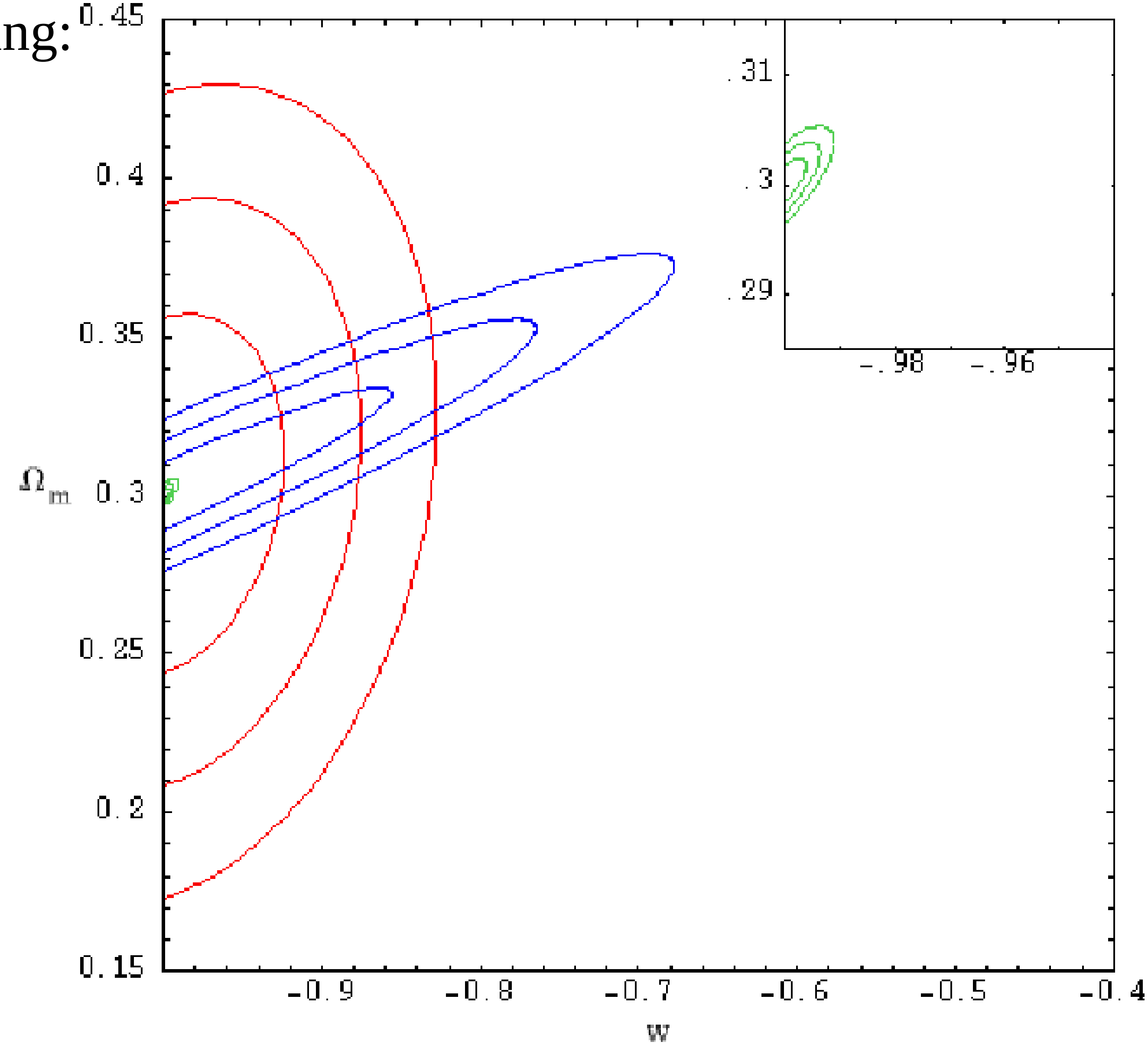


Large sky coverage is critical

Cluster Weak Lensing:

Bring in Da Noise,
Bring in Da Funk

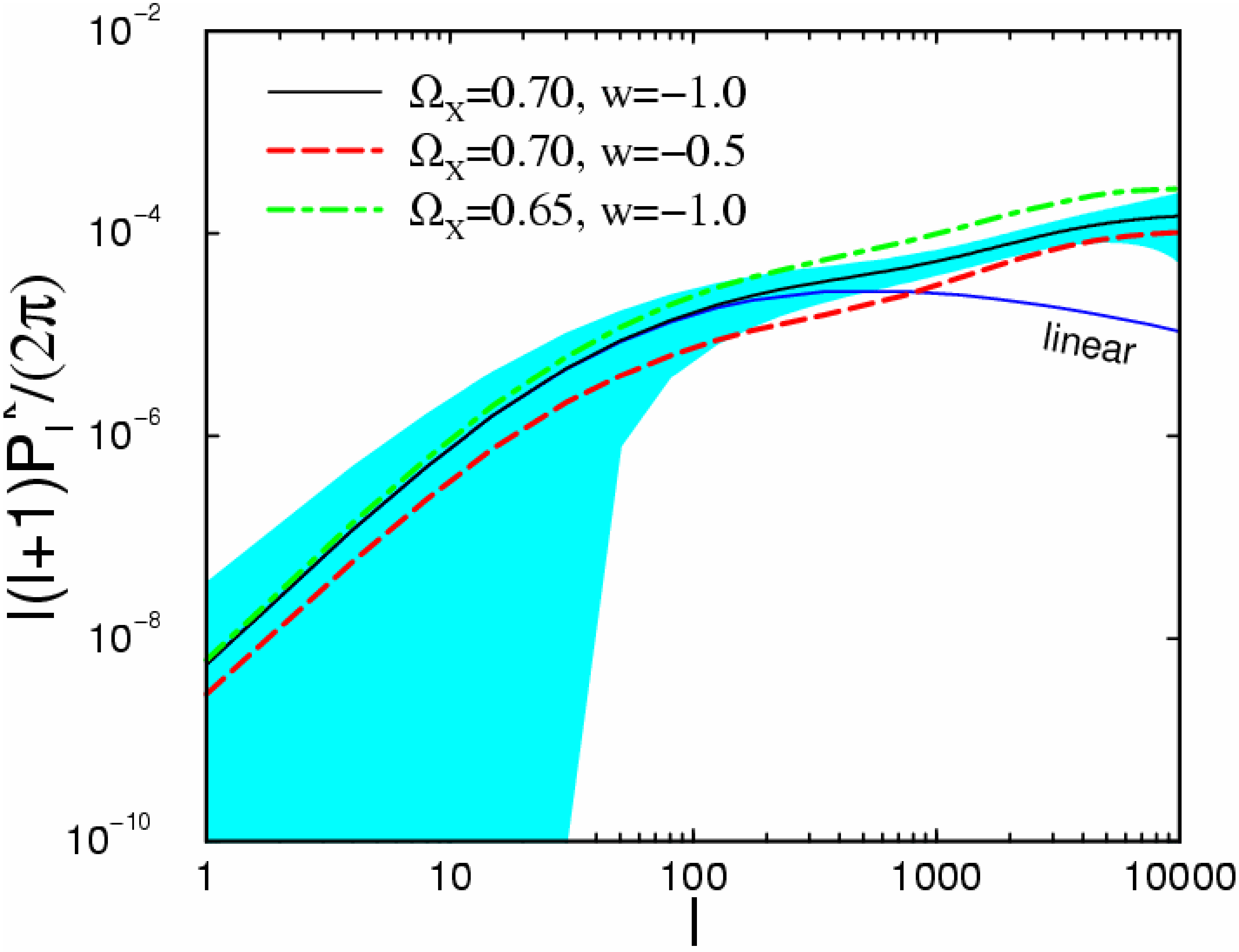
(account for:
projection effects
→Fuzziness in
Mass limit,
also
variations in
NFW concentration
parameter)



Note: there is more information to be used than N(z)

Weak Lensing: Large-scale shear

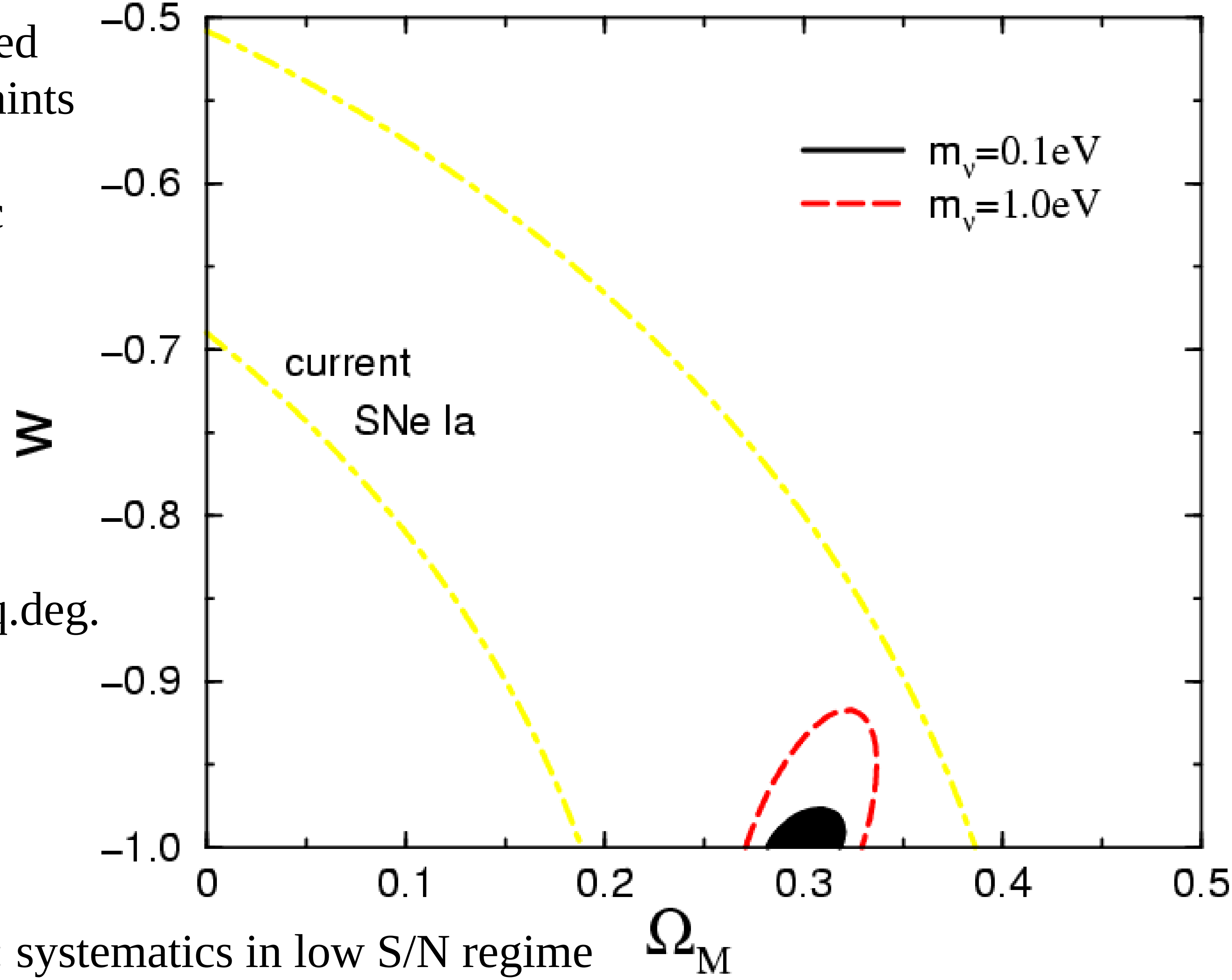
Convergence
Power
Spectrum



1000 sq. deg.
to R ~ 27

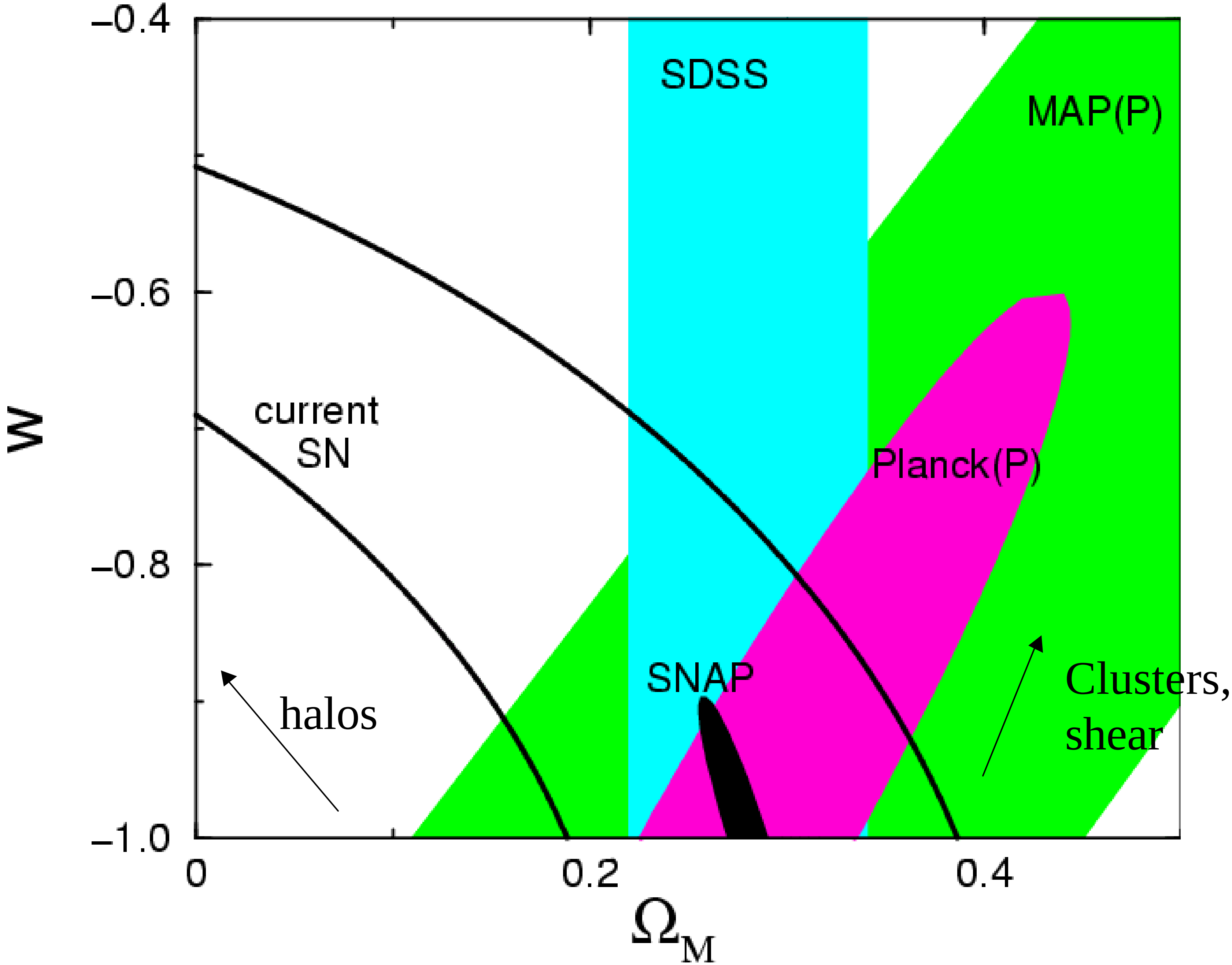
Huterer

Projected Constraints From Cosmic Shear



1000 sq.deg.
R ~ 27

Caveat: systematics in low S/N regime



−0.4
−0.6
−0.8
−1.0
w
0
0.2
0.4
Ω_M
SDSS
MAP(P)
current
SN
Planck(P)
SNAP
halos
Clusters,
shear

Conclusions

Multiple probes of Dark Energy, including SNe, should mature over the next 5-10 years

Independent confirmation of Dark Energy is within sight

Good prospects for independent
constraints on the nature of the Dark Energy, with varying systematics and nearly `orthogonal' parameter degeneracies