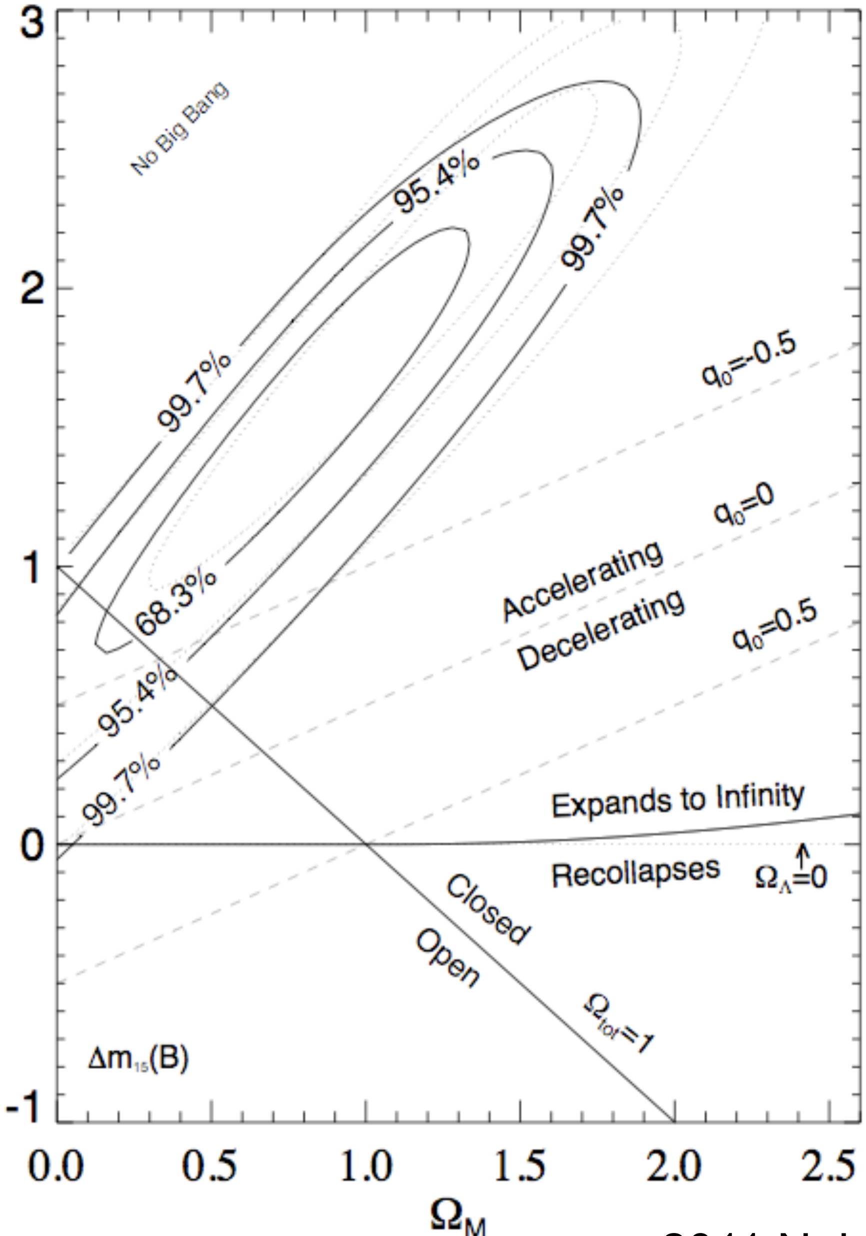
Dark Energy Observations

Josh Frieman

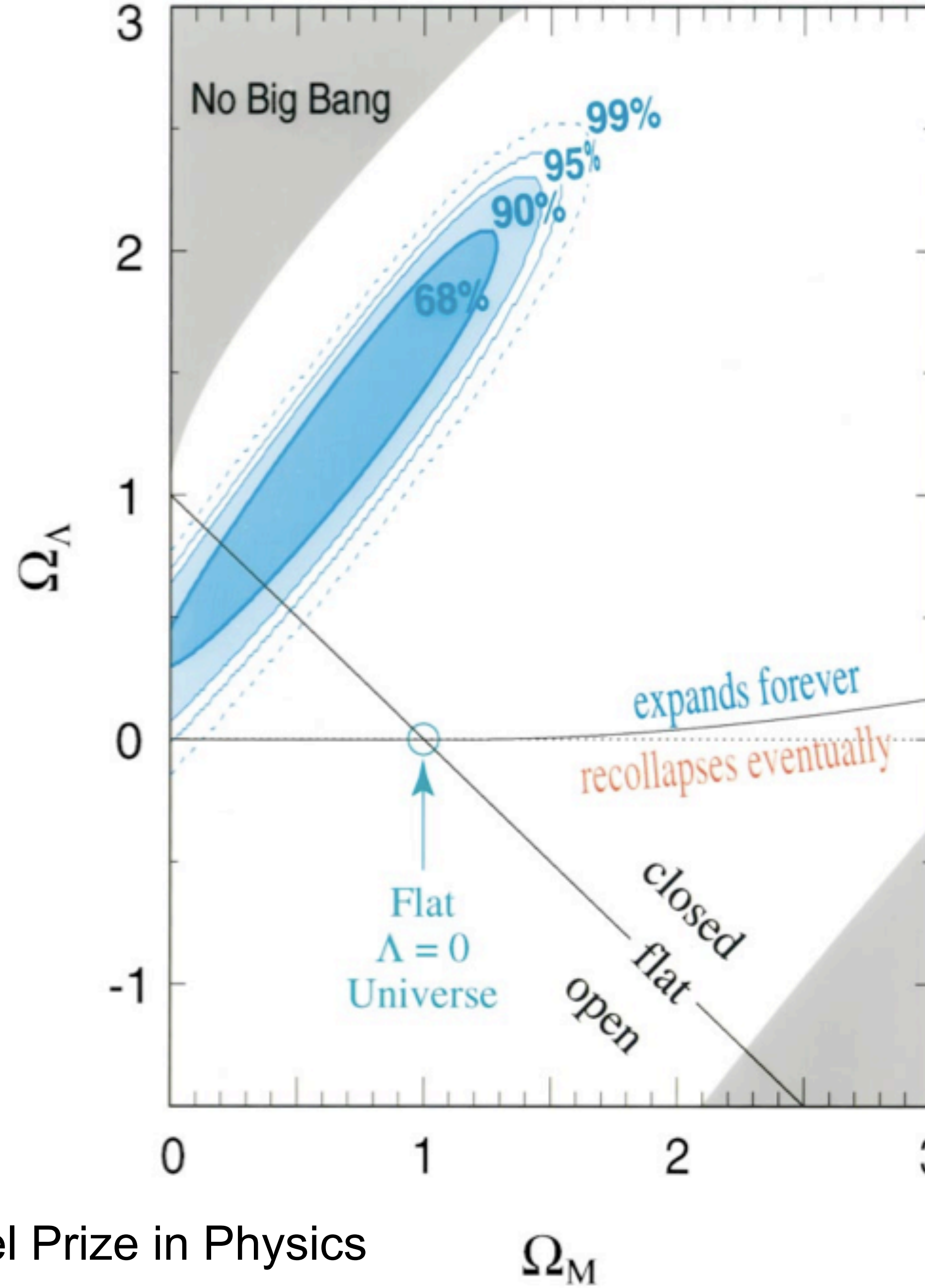
DES Project Director
Fermilab and the University of Chicago

Science with a Wide-Field Infrared Telescope in Space
Pasadena, February 2012

Riess et al. (1998, AJ)



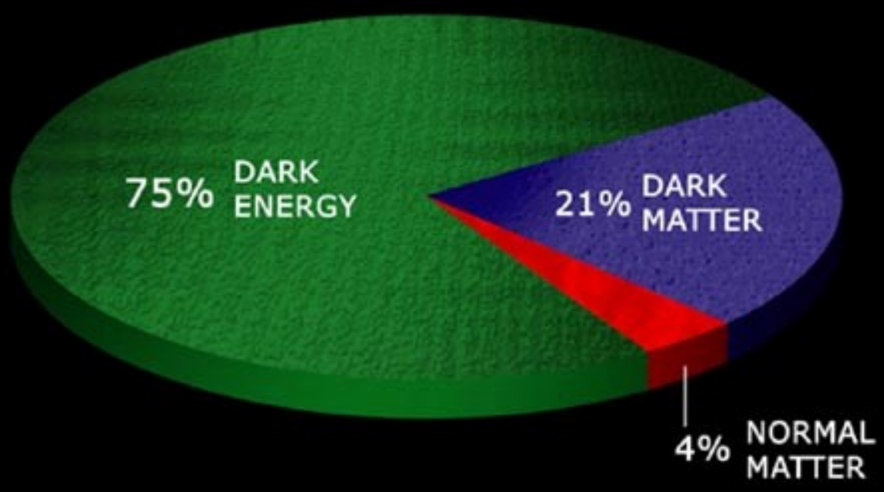
Perlmutter et al. (1999, ApJ)



2011 Nobel Prize in Physics

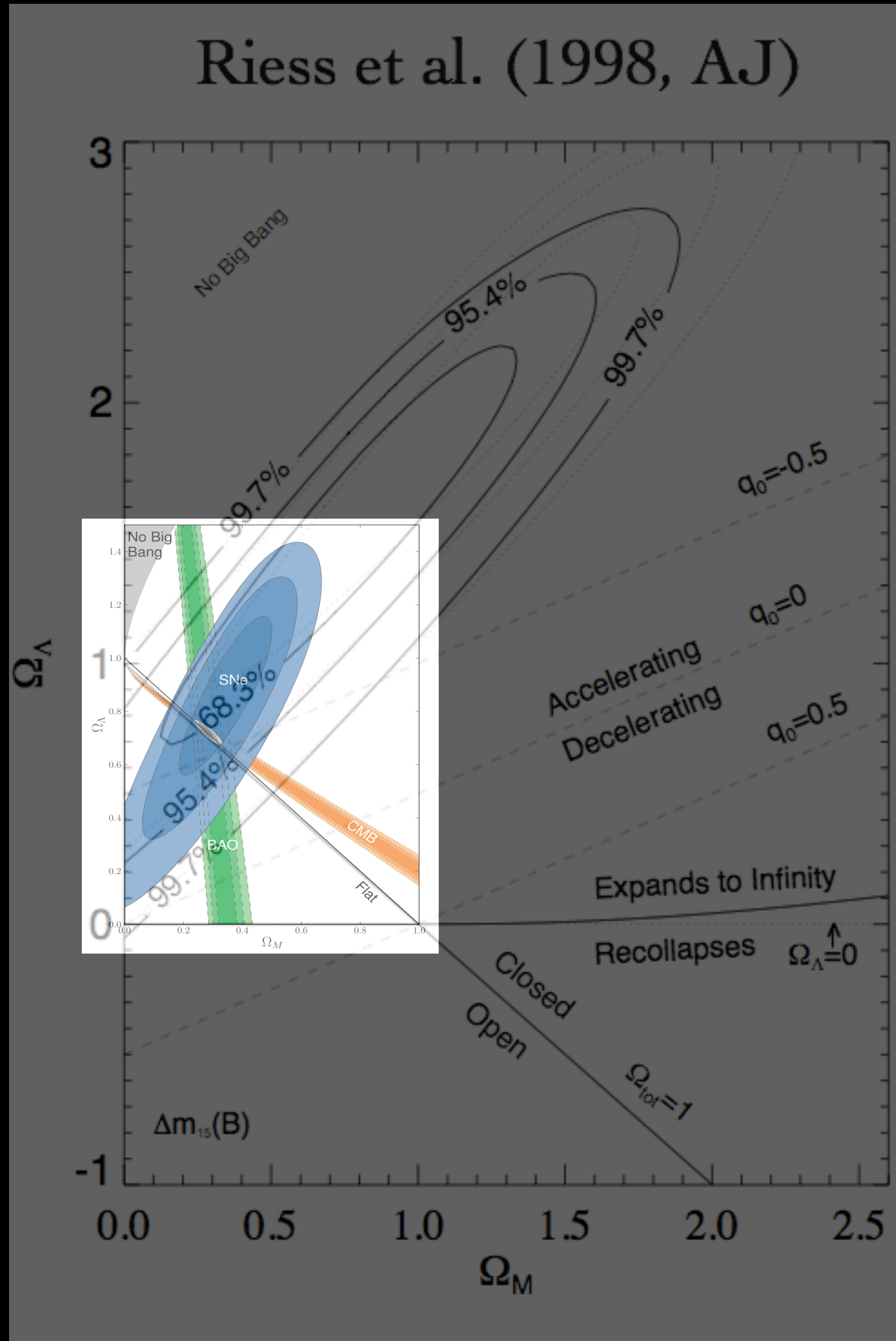
Dark Energy

- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - What is the DE equation of state parameter *w*?



Real Progress over the last 14 years

But these questions remain

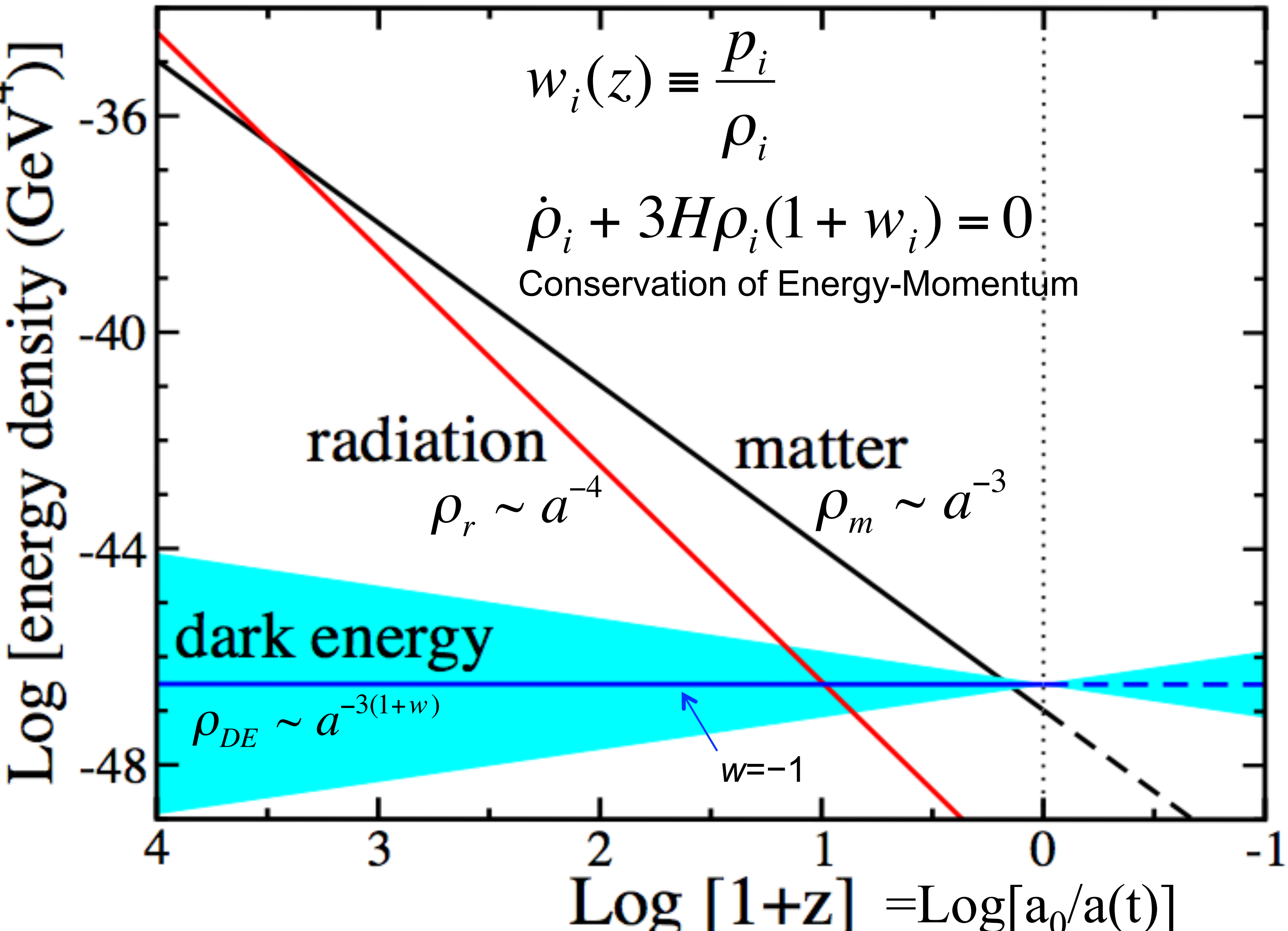


Supernovae

Baryon Acoustic Oscillations

Cosmic Microwave Background

Equation of State parameter *w* determines Cosmic Evolution



Theory?

- No consensus model for Dark Energy
- Theoretical prejudice in favor of cosmological constant (vacuum energy) with $w=-1$ was wrong once (Cf. inflation): that isn't a strong argument for it being correct now
- Cosmological constant problem (why is vacuum energy density not 120 orders of magnitude larger?) is not necessarily informative for model-building
- Some alternatives to Λ (Cf. quintessence) rely on notion that a very light degree of freedom can take ~current Hubble time to reach its ground state.

Scalar Field as Dark Energy (inspired by inflation)

- Dark Energy could be due to a very light scalar field, slowly evolving in a potential, $V(\varphi)$:

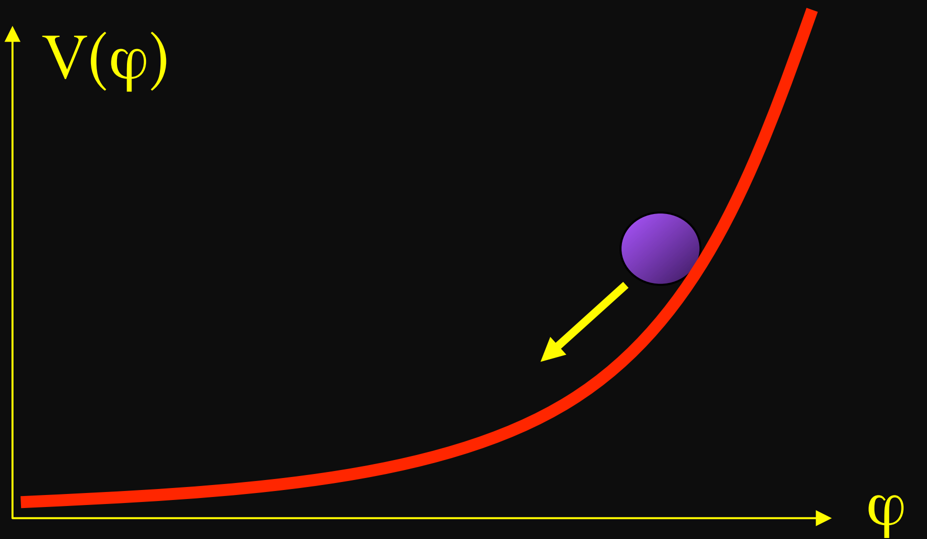
$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV}{d\varphi} = 0$$

- Density & pressure:

$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

- Slow roll:

$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Rightarrow P < 0$$
$$w < 0 \text{ and time-dependent}$$



Time-dependence of *w* can distinguish models

What can we probe?

- Probe dark energy through the history of the expansion rate:

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_{DE}\exp\left[3\int(1+w(z))d\ln(1+z)\right] + \left(1-\Omega_m-\Omega_{DE}\right)(1+z)^2$$

- and the growth of large-scale structure: $\frac{\delta\rho}{\rho}(z;\Omega_m,\Omega_{DE},w(z),...)$

- Distances are indirect proxies for *H(z)*:

  (Form of *F* depends on spatial curvature)

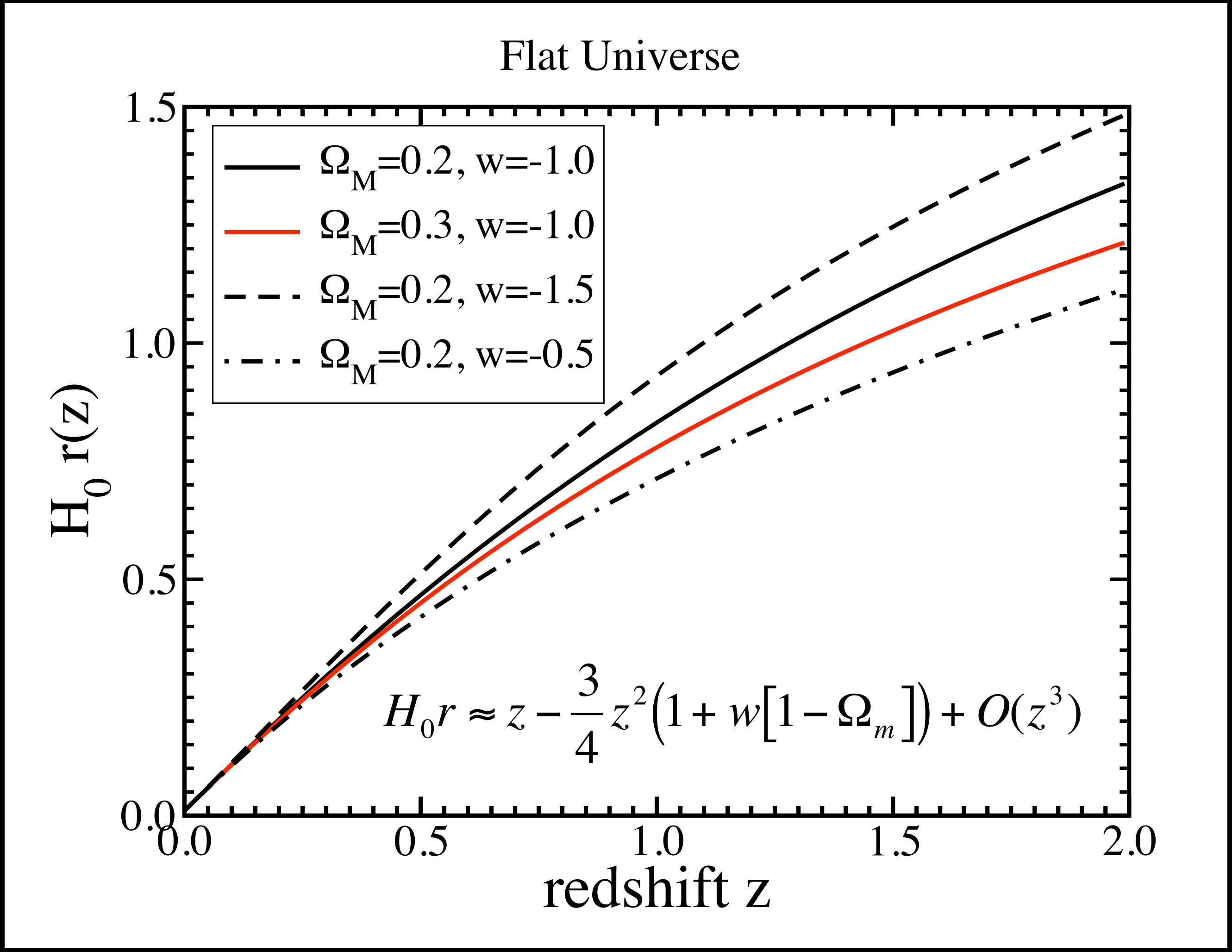
$$r(z) = F\left[\int\frac{dz}{H(z)}\right]$$

$$d_L(z) = (1+z)r(z)$$

$$d_A(z) = (1+z)^{-1}r(z)$$

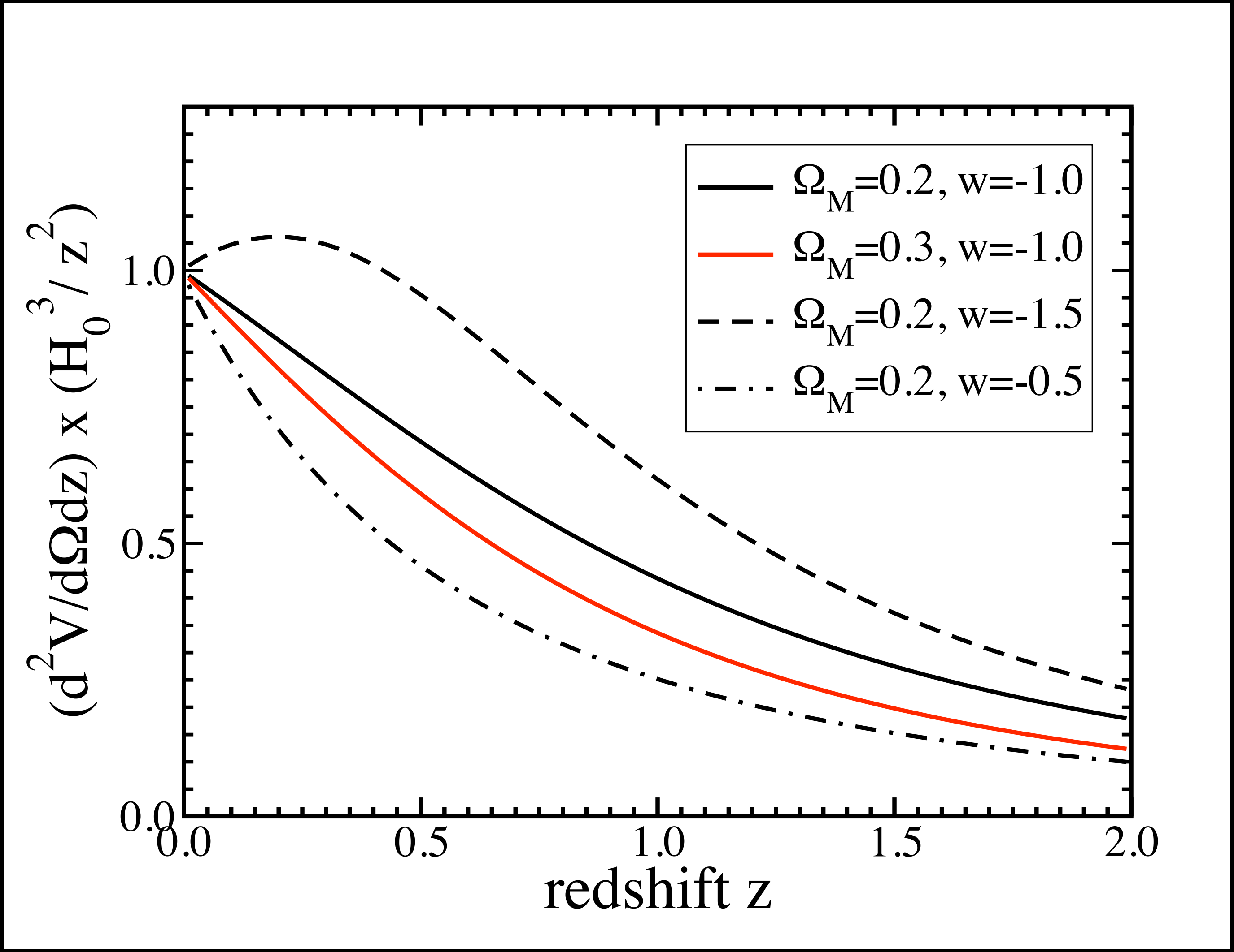
$$\frac{d^2V}{dzd\Omega} = \frac{r^2(z)}{H(z)}$$

Coordinate Distance



Percent-level determination of *w* requires percent-level distance estimates

Volume Element



Raising *w* at fixed Ω_m decreases volume

Growth of Density Perturbations

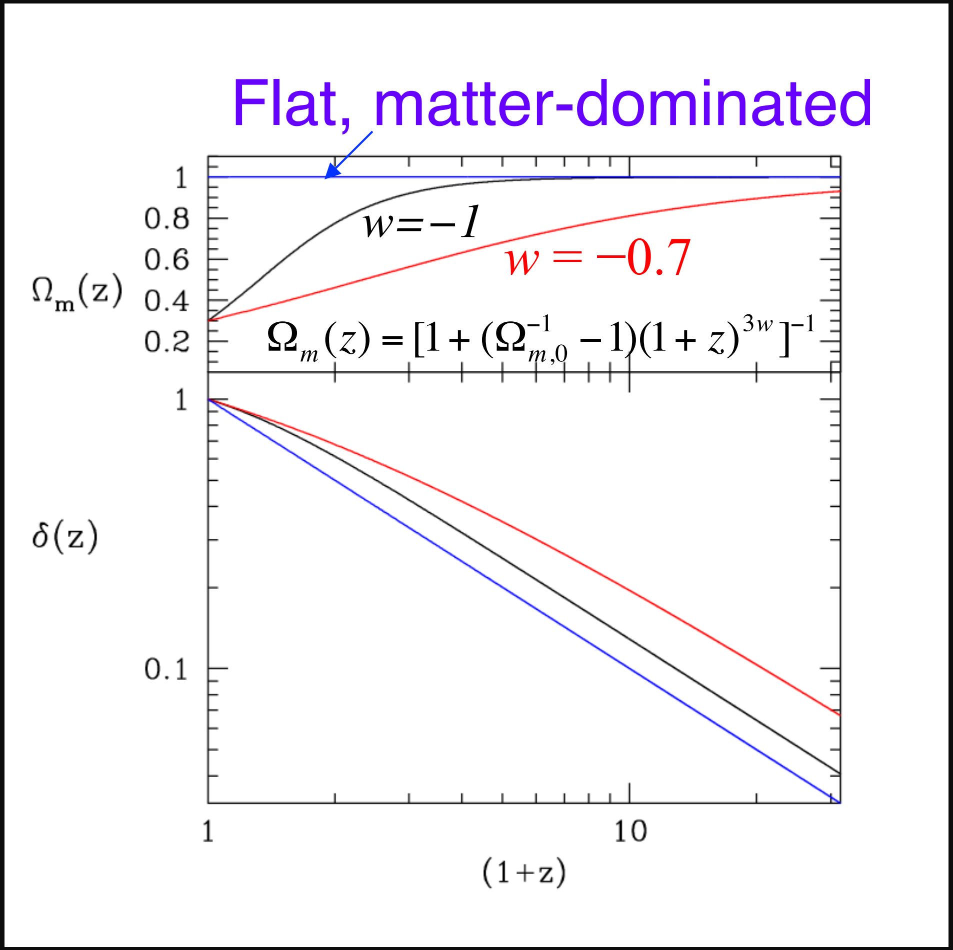
Linear growth of perturbations:

$$\delta_m(x,t) \equiv \frac{\rho_m(x,t) - \bar{\rho}_m(t)}{\bar{\rho}_m(t)}$$

$$\ddot{\delta}_m + 2H(t)\dot{\delta}_m - \frac{3}{2}\Omega_m(t)H^2(t)\delta_m = 0$$

Damping due to expansion

Growth due to gravitational instability



Raising *w* at fixed Ω_{DE}: decreases net growth of density perturbations, requires higher amplitude of structure at early times

Testing General Relativity

- Metric for perturbed FRW Universe:

$$ds^2 = -[1 + 2\Psi(\vec{x},t)]dt^2 + a^2(t)[1 - 2\Phi(\vec{x},t)][d\chi^2 + r^2(\chi)d\Omega^2],$$

- Poisson equation for Modified Gravity:

$$k^2\Psi = 4\pi G a^2 \mu(a,k)\bar{\rho}\delta(k,a)$$

- Growth of Perturbations:

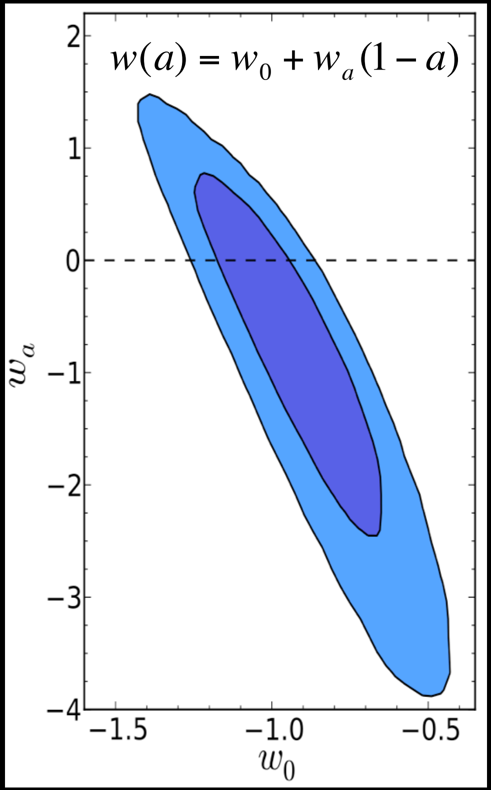
$$\ddot{\delta}(a,k) + 2H(a)\dot{\delta}(a,k) - \frac{k^2}{a^2}\Psi = 0$$

- GR: $\Psi = \Phi$ (no anisotropic stress), $\mu=1$, $d\ln\delta/d\ln a = \Omega_m^{0.6}$
- Weak Lensing: $\alpha = \nabla_\perp(\Phi + \Psi)$
- Need to probe growth $\delta(a)$ and $H(a)$.

Probes of Dark Energy

- Galaxy Clusters
  - Counts of Dark Matter Halos
  - Clusters as Proxies for Massive Halos
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Correlated Galaxy Shape measurements
  - Sensitive to growth of structure and geometry
- Large-scale Structure
  - Baryon Acoustic Oscillations: feature at ~150 Mpc
    - Sensitive to geometry
  - Redshift-space Distortions due to Peculiar Velocities
    - Sensitive to growth of structure
- Supernovae
  - Hubble diagram
  - Sensitive to geometry

Current Constraints on Equation of State

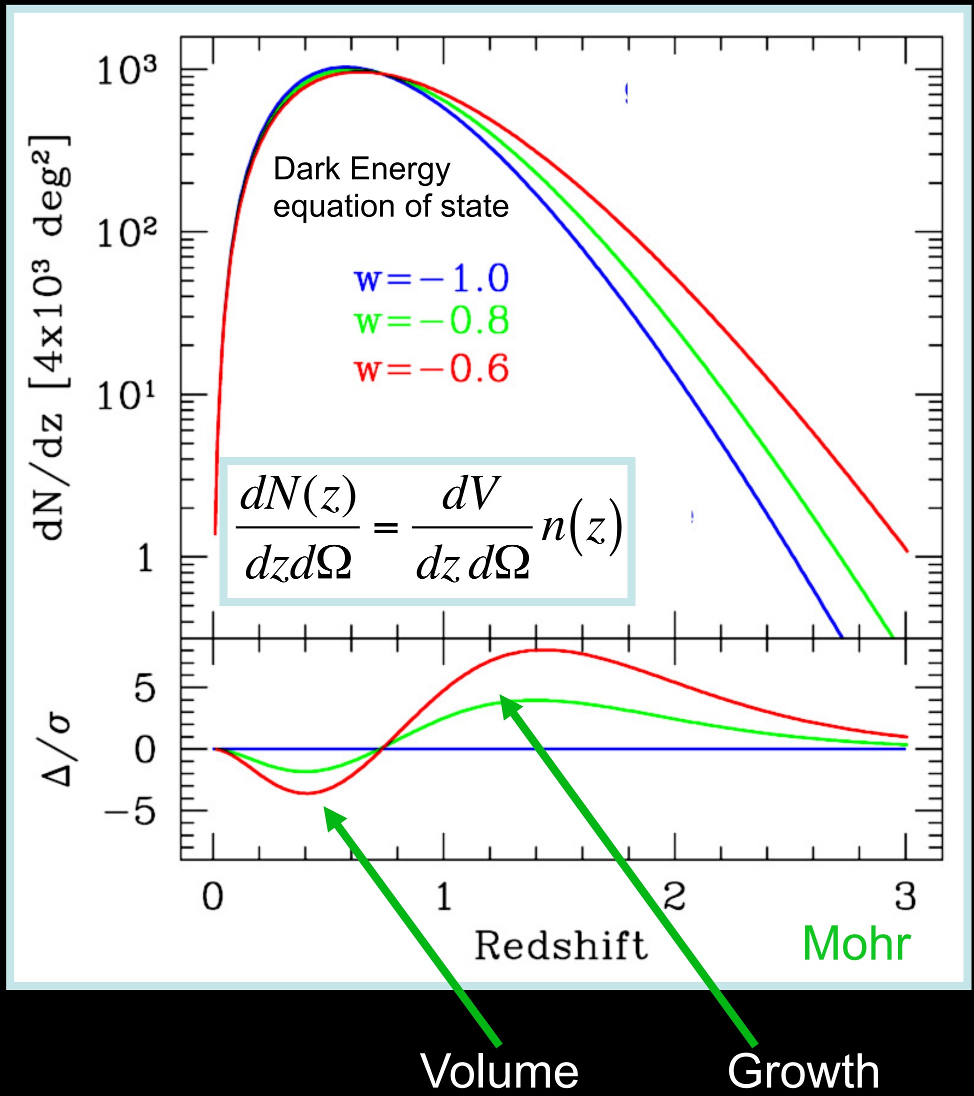


Sullivan, etal

I. Clusters

- Dark Halo abundance predicted by N-body simulations
- Clusters are proxies for massive halos and can be identified optically to redshifts z>1
- Galaxy colors provide photometric redshift estimates for each cluster
- Observable proxies for cluster mass: optical richness, SZ flux decrement, weak lensing mass, X-ray flux
- Cluster spatial correlations help calibrate mass estimates
- Challenge: determine mass (*M*)-observable (*O*) relation *g(O|M,z)* with sufficient precision

Number of clusters above mass threshold



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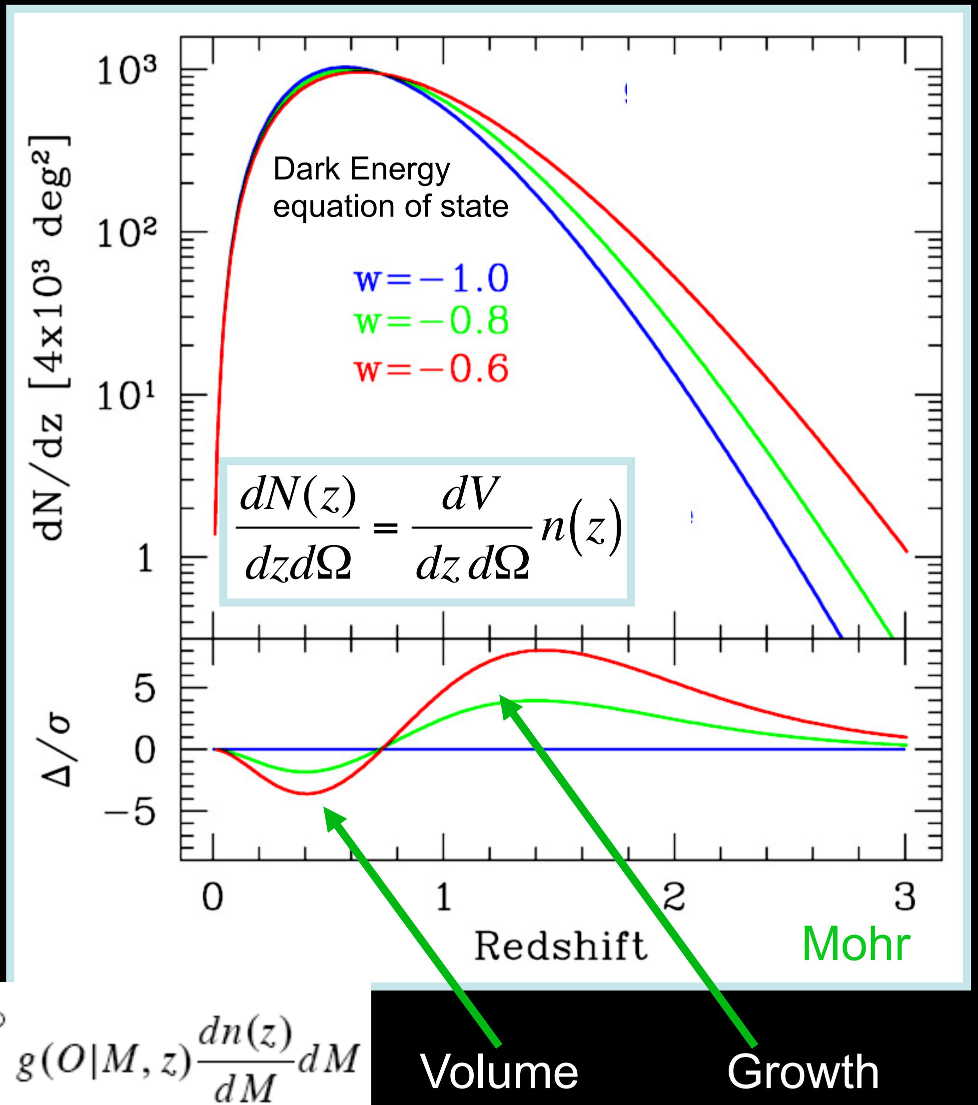
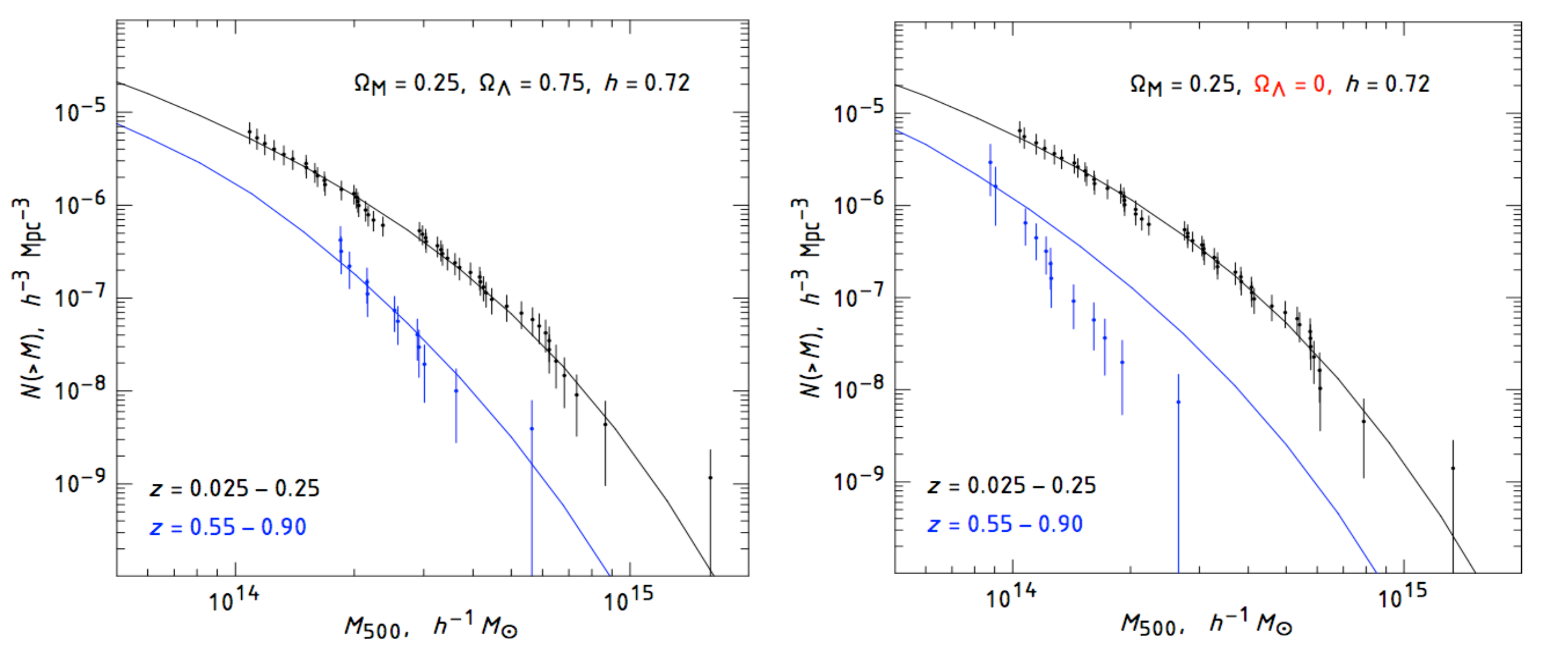


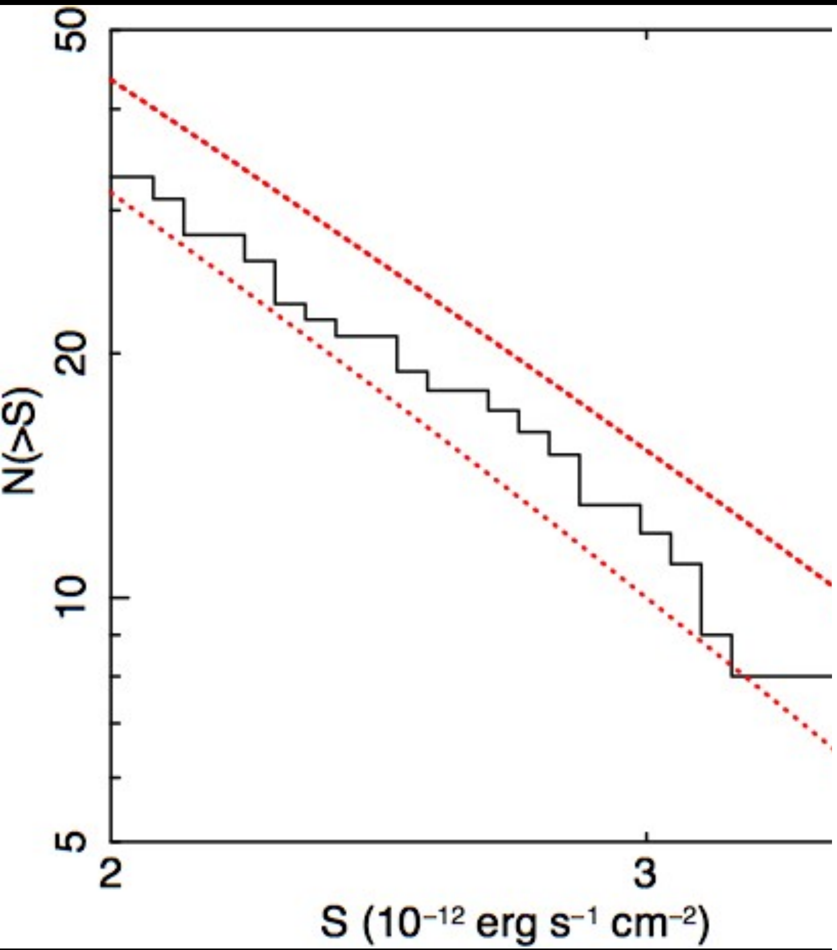
$$\frac{d^2N(z)}{dz\,d\Omega} = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_{O_{min}}^{\infty} f(O,z)\,dO \int_0^{\infty} g(O|M,z) \frac{dn(z)}{dM} dM$$

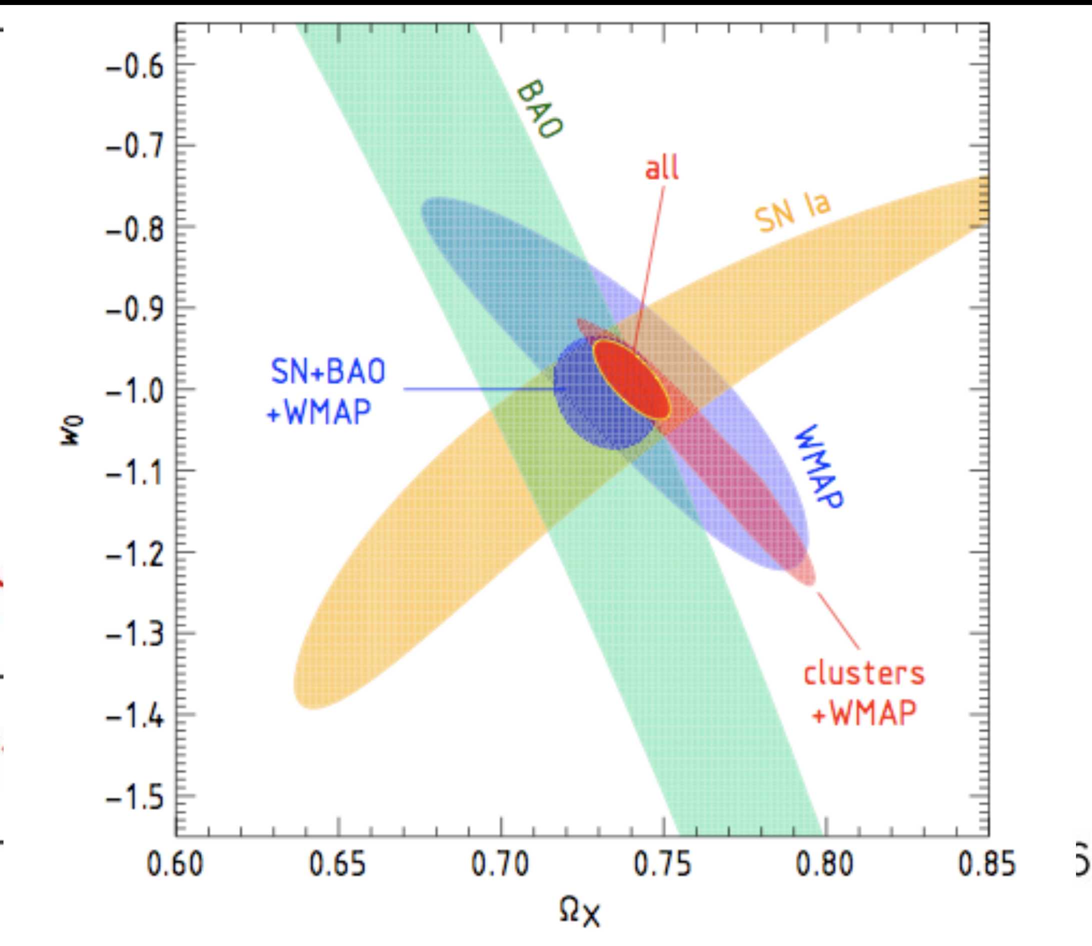
Constraints from X-ray Clusters



Vikhlinin etal

Constraints from X-ray clusters

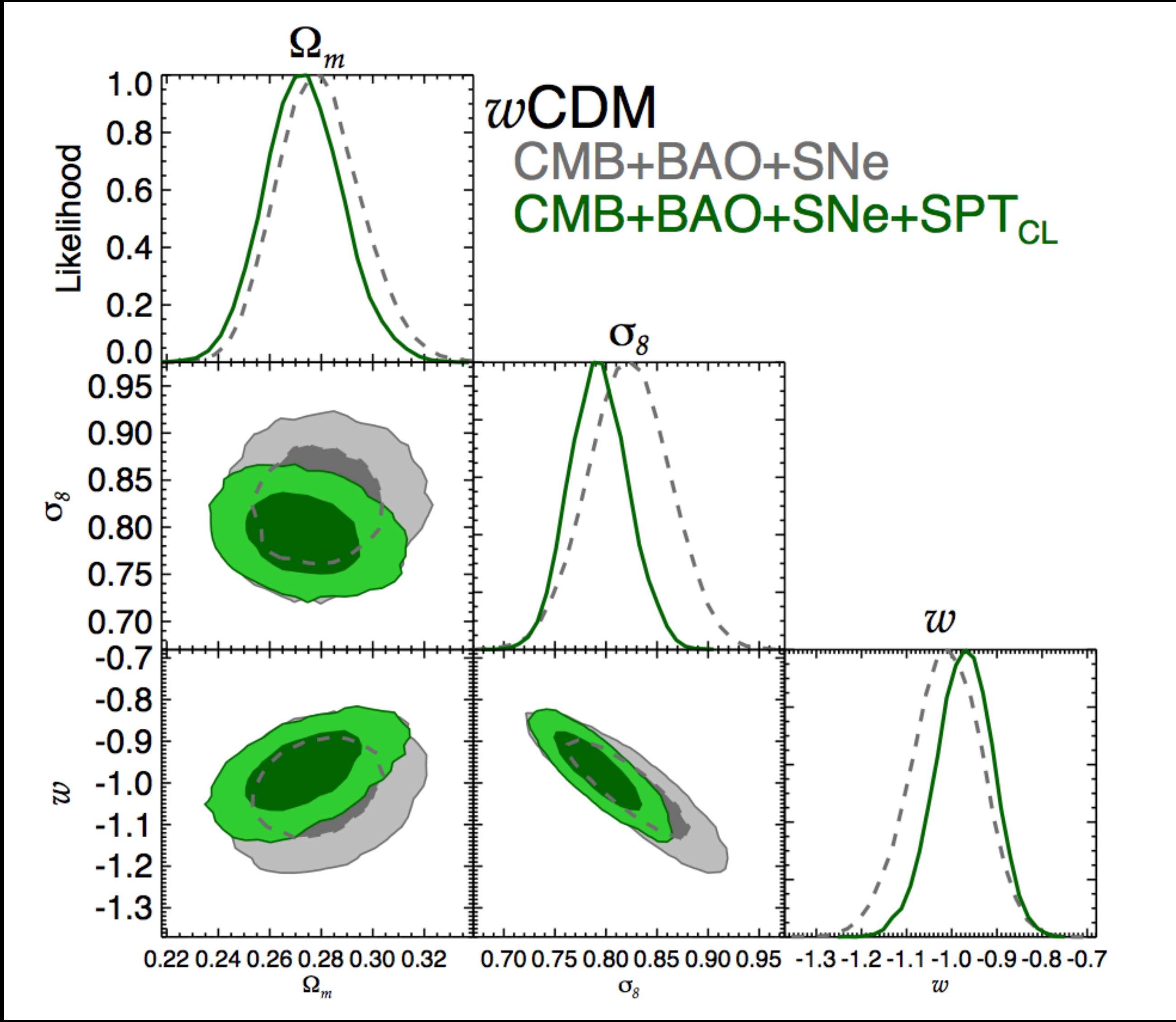




Mantz, et al 2007

Vikhlinin, et al 2008

X-ray+Sunyaev-Zel'dovich

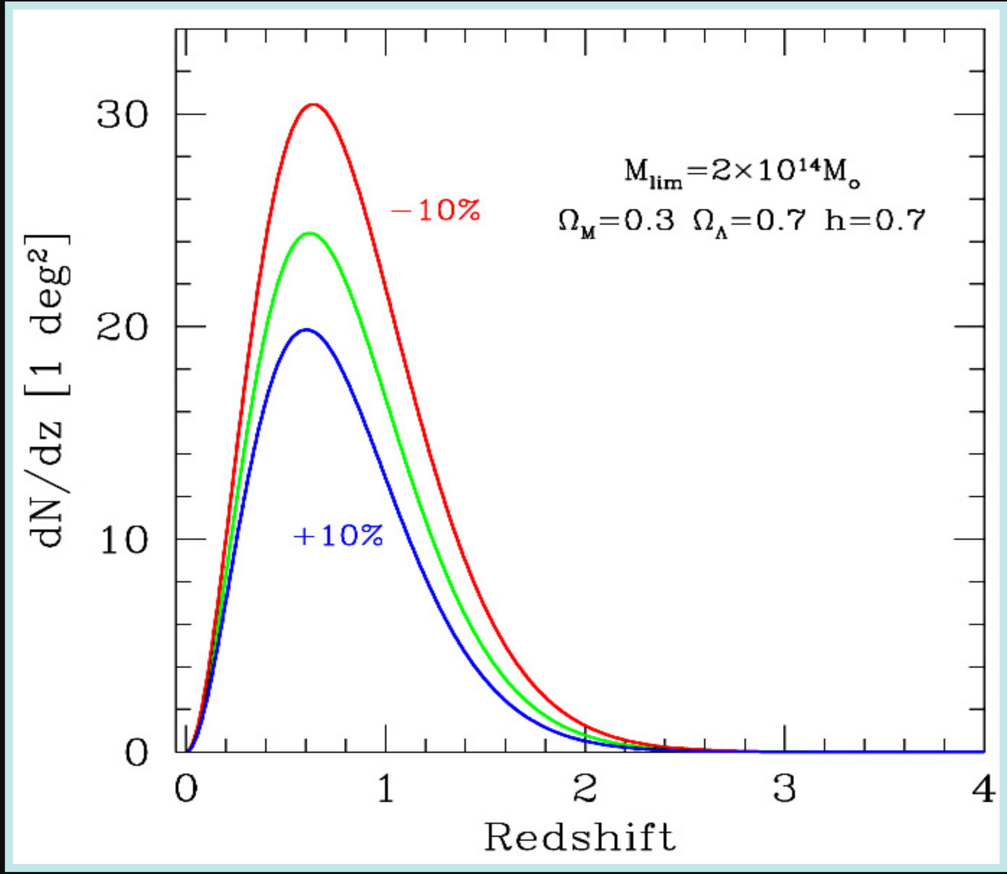


Benson, etal

South Pole Telescope

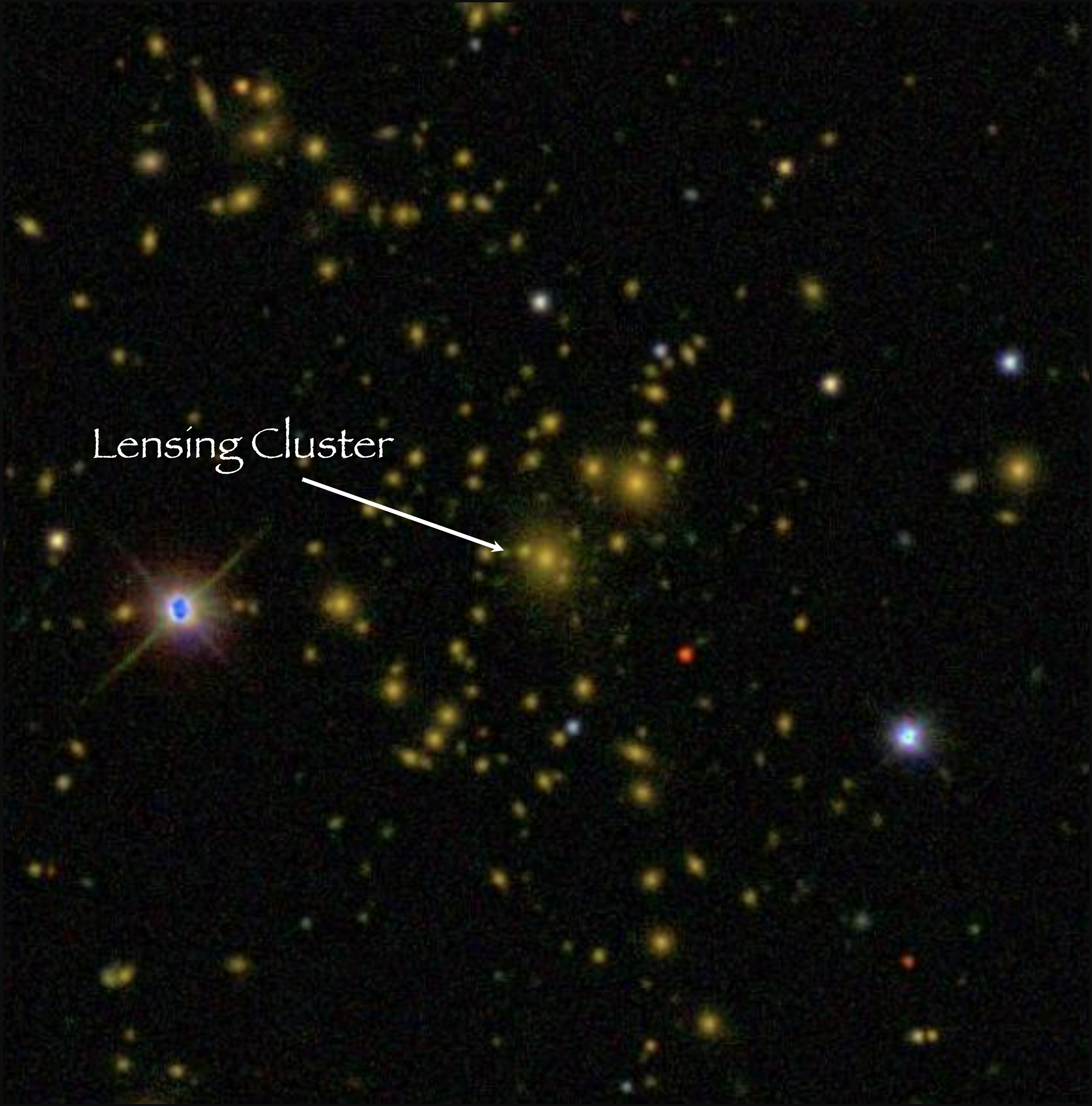
Uncertainty in Mass-Observable Relation

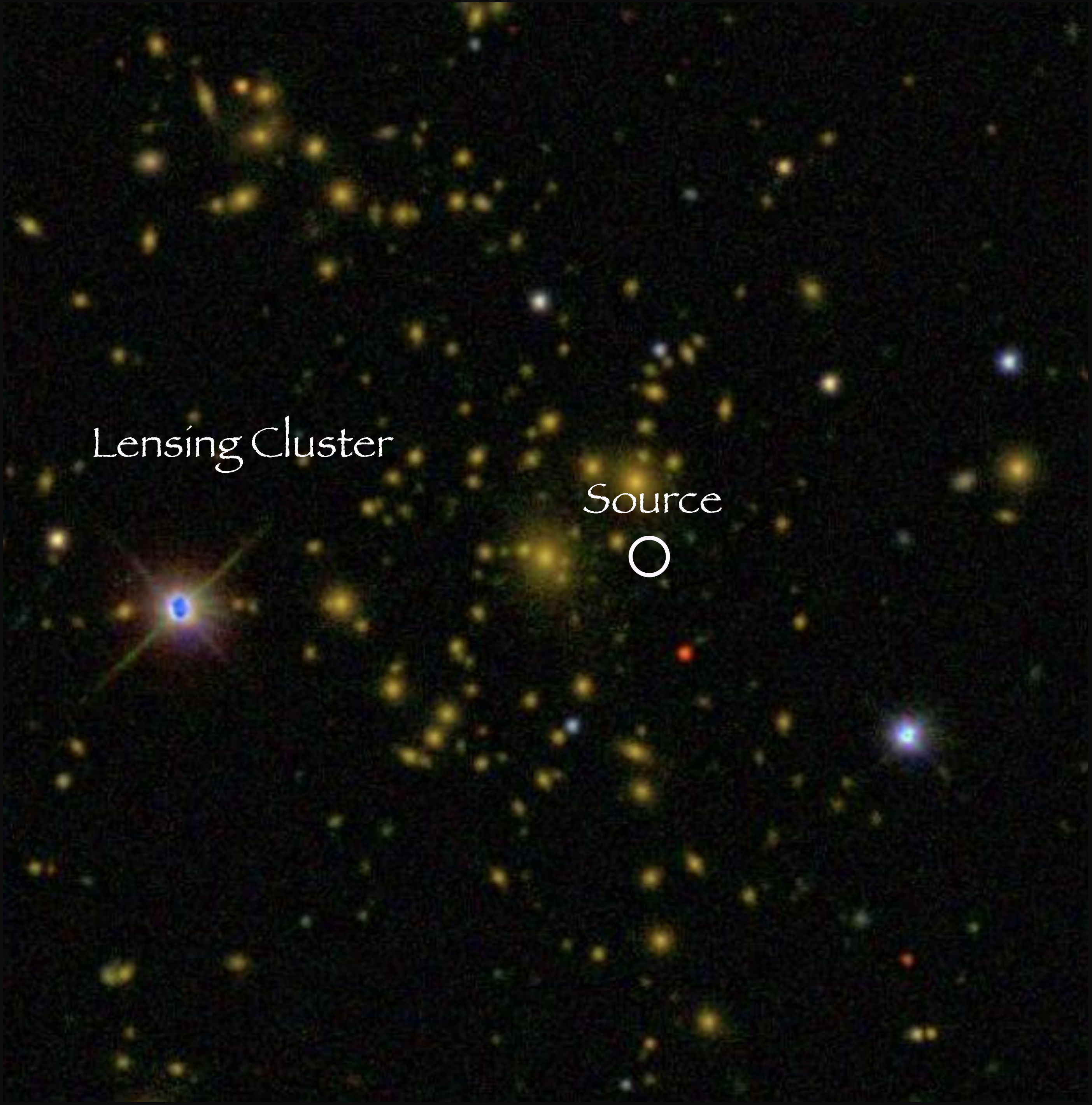
Sensitivity to Mass Threshold

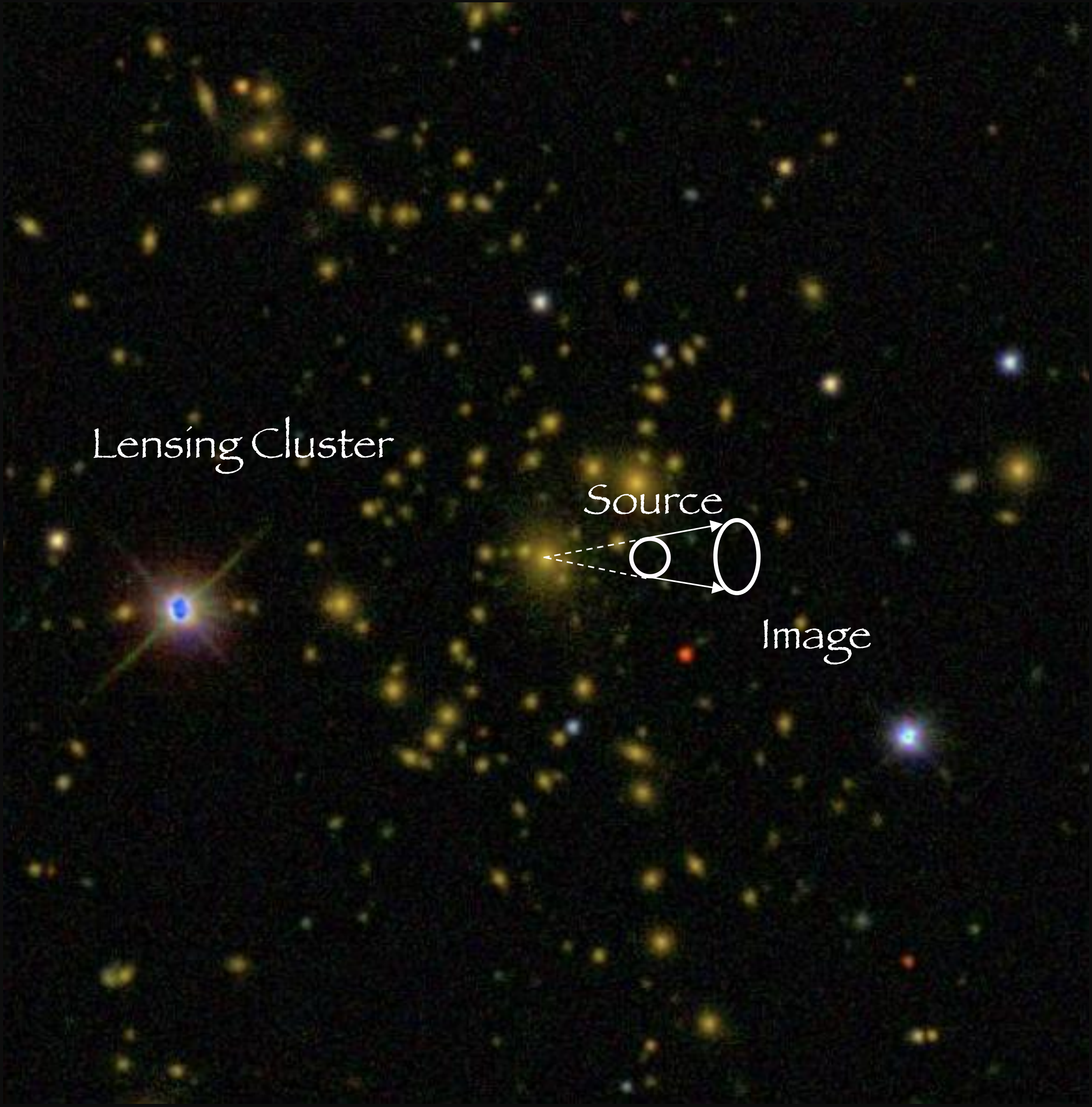


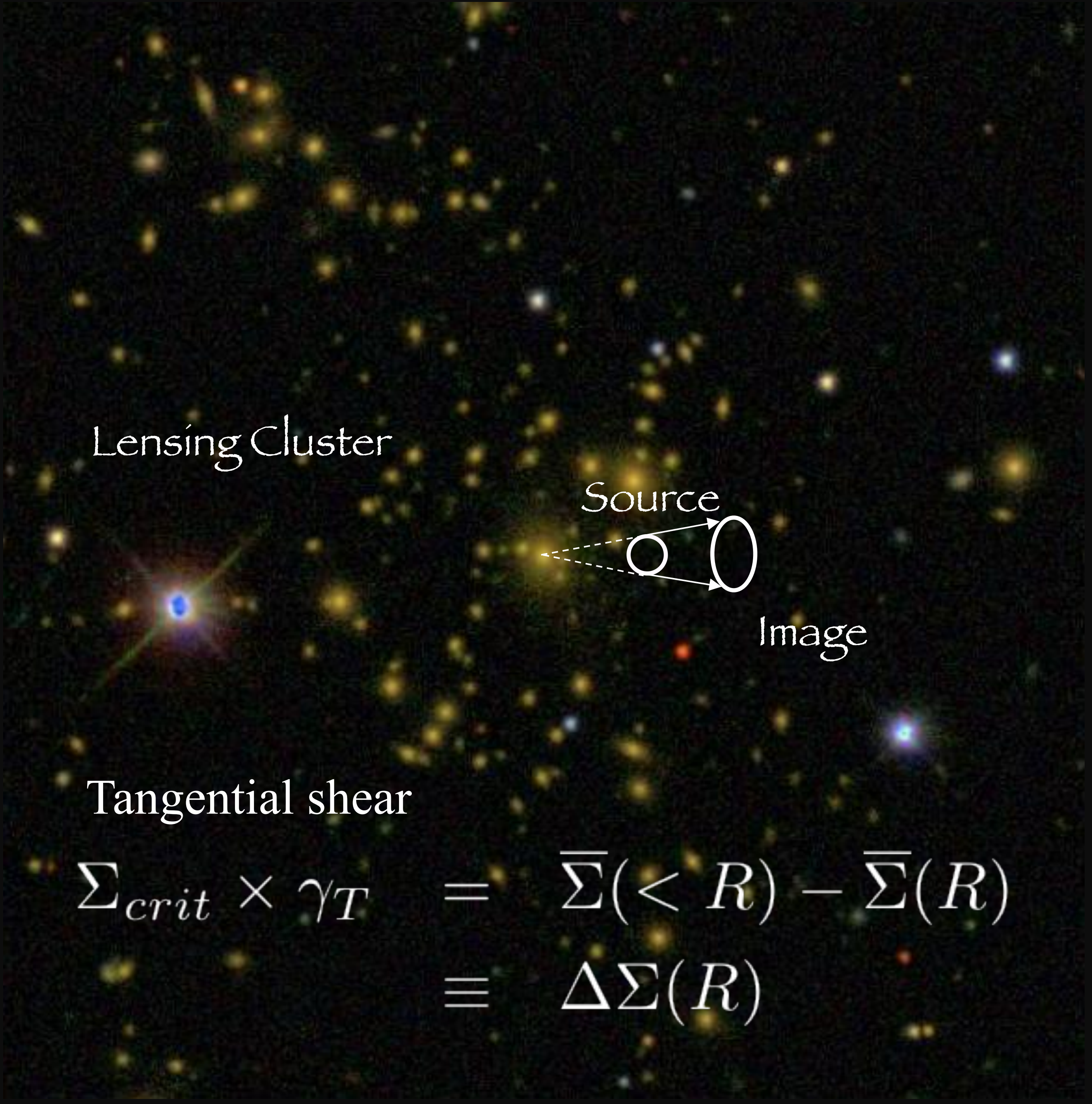
$$\frac{dN(z)}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM \frac{dn(M,z)}{dM} f(M)$$

Mass threshold


Lensing Cluster

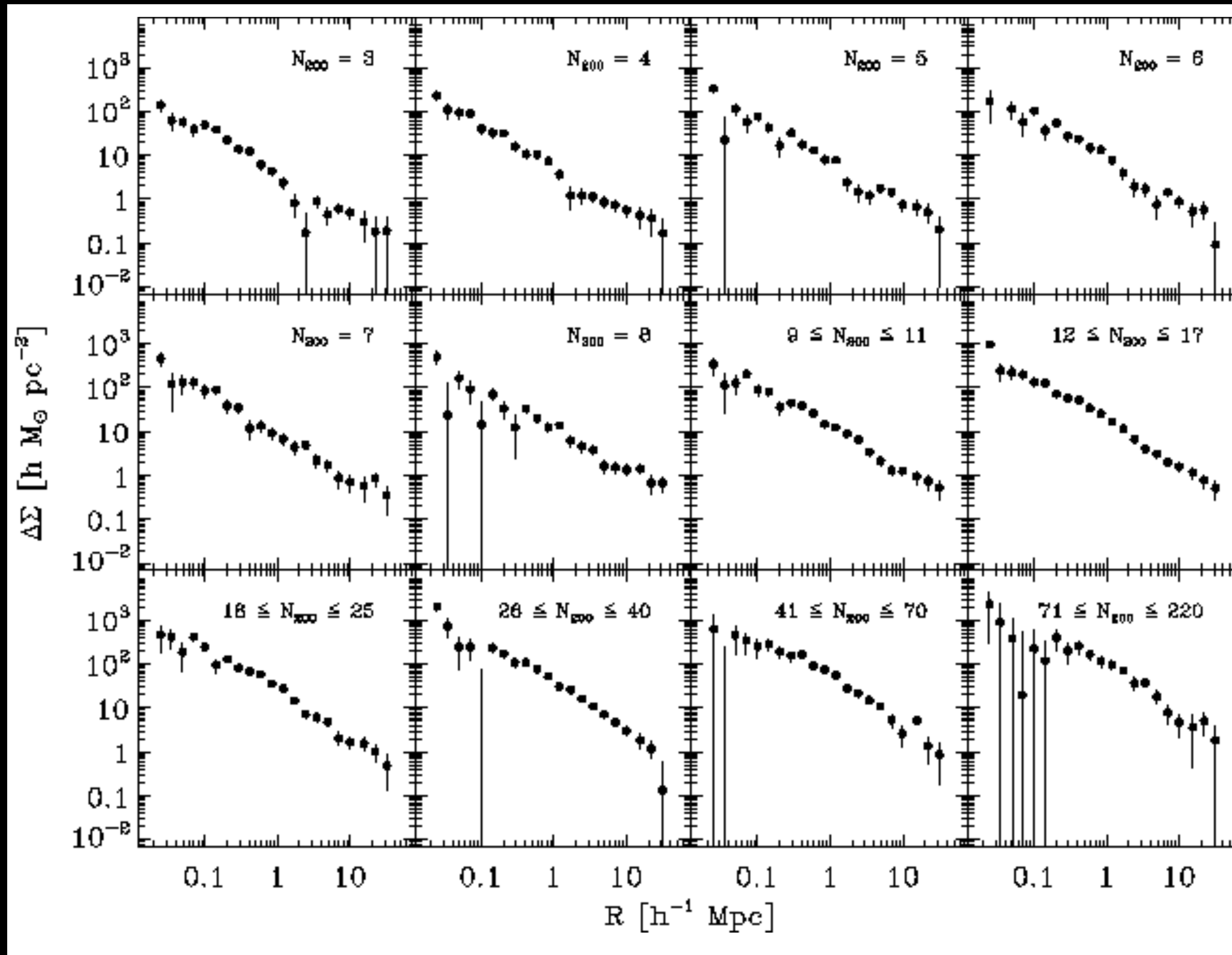

Lensing Cluster
Source


Lensing Cluster
Source
Image


Lensing Cluster
Source
Image
Tangential shear
$$\Sigma_{crit} \times \gamma_T = \overline{\Sigma}(< R) - \overline{\Sigma}(R) \equiv \Delta\Sigma(R)$$

Statistical Weak Lensing by Galaxy Clusters

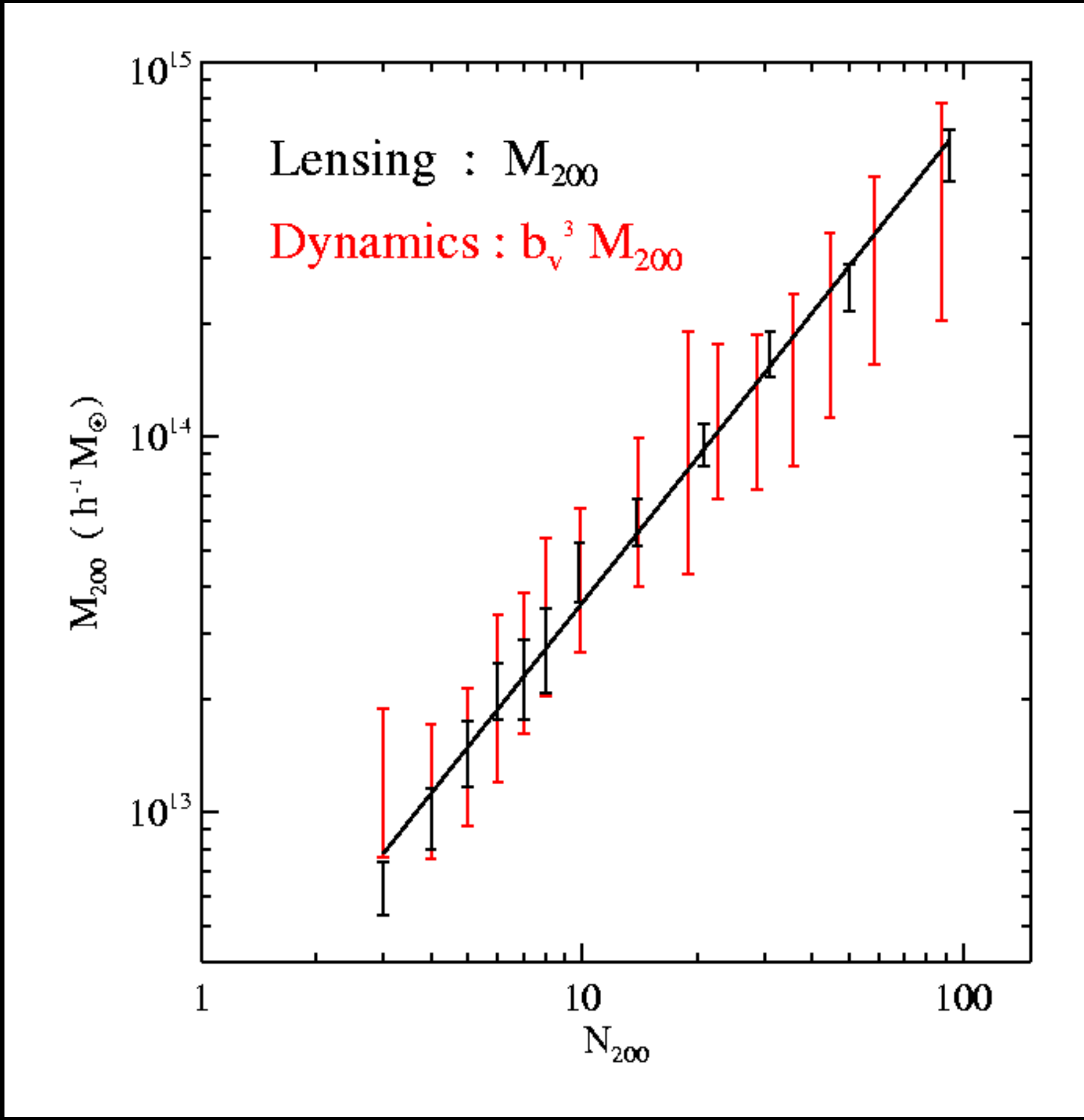
Mean Tangential Shear Profile in Optical Richness (N_{gal}) Bins to 30 h^{-1}Mpc



Sheldon, Johnston, etal SDSS

Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

Cluster Mass vs. Number of red galaxies they contain (richness)



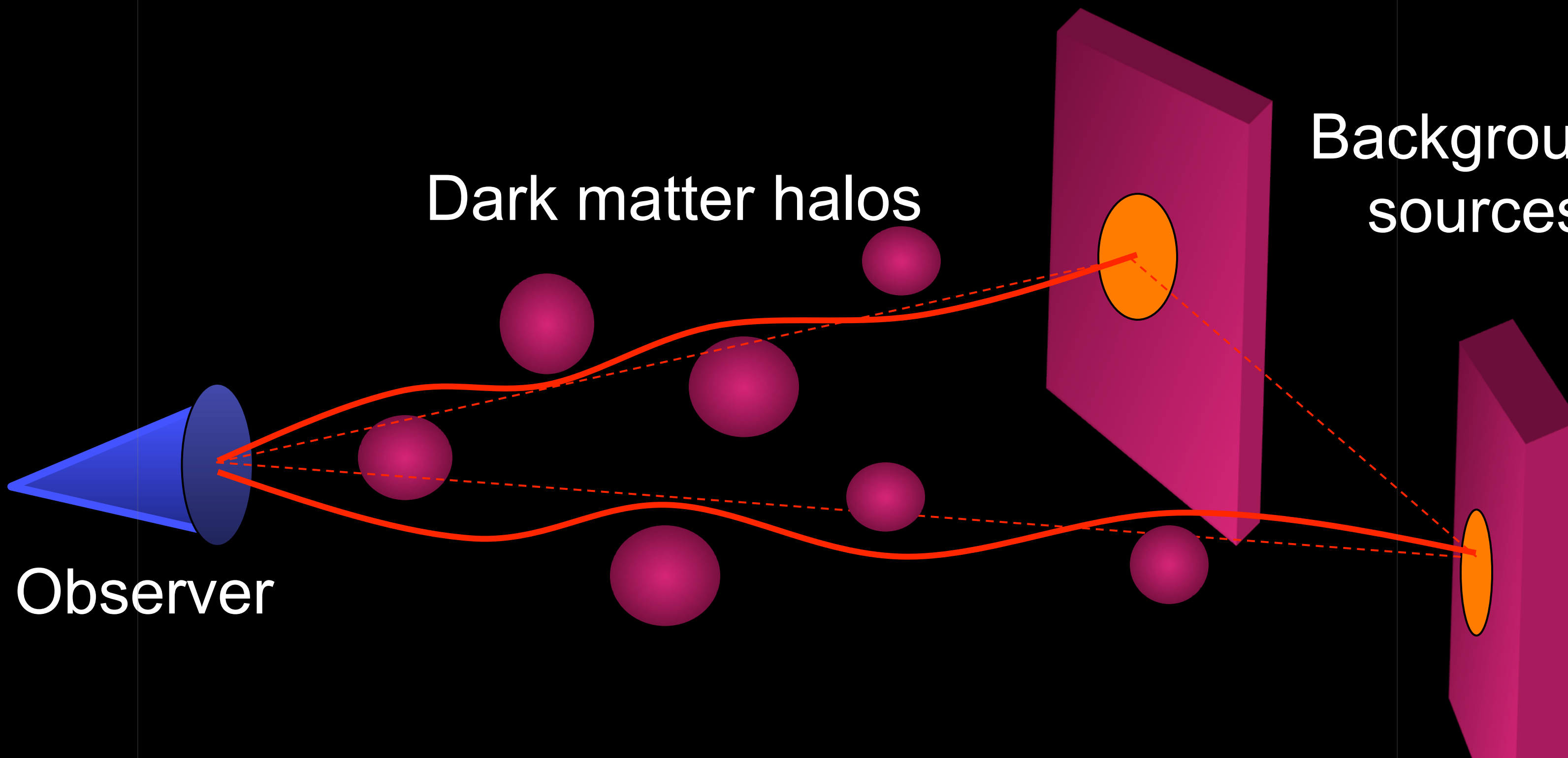
Johnston, Sheldon, etal

Statistical Lensing controls projection effects of individual cluster mass estimates

Improved red-sequence richness estimator reduces scatter in mass vs optical richness to ~20-30%

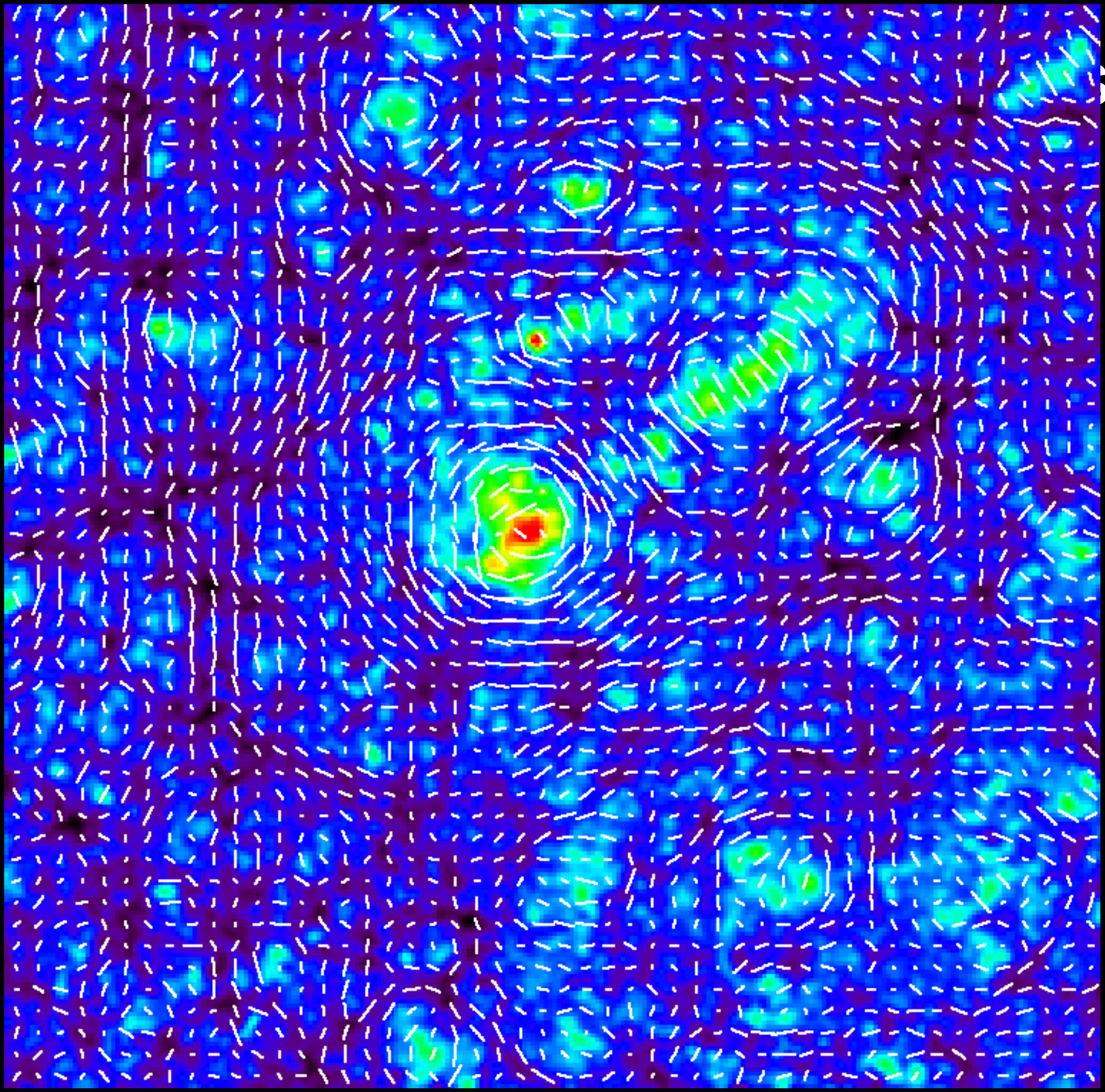
Rykoff etal

II. Weak Lensing: Cosmic Shear



- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

Weak Lensing Mass and Shear



Takada

Weak Lensing Tomography

- Shear-shear & galaxy-shear correlations probe distances & growth rate of perturbations: angular power spectrum

$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

- Galaxy correlations determine galaxy bias priors
- Statistical errors on shear-shear correlations:

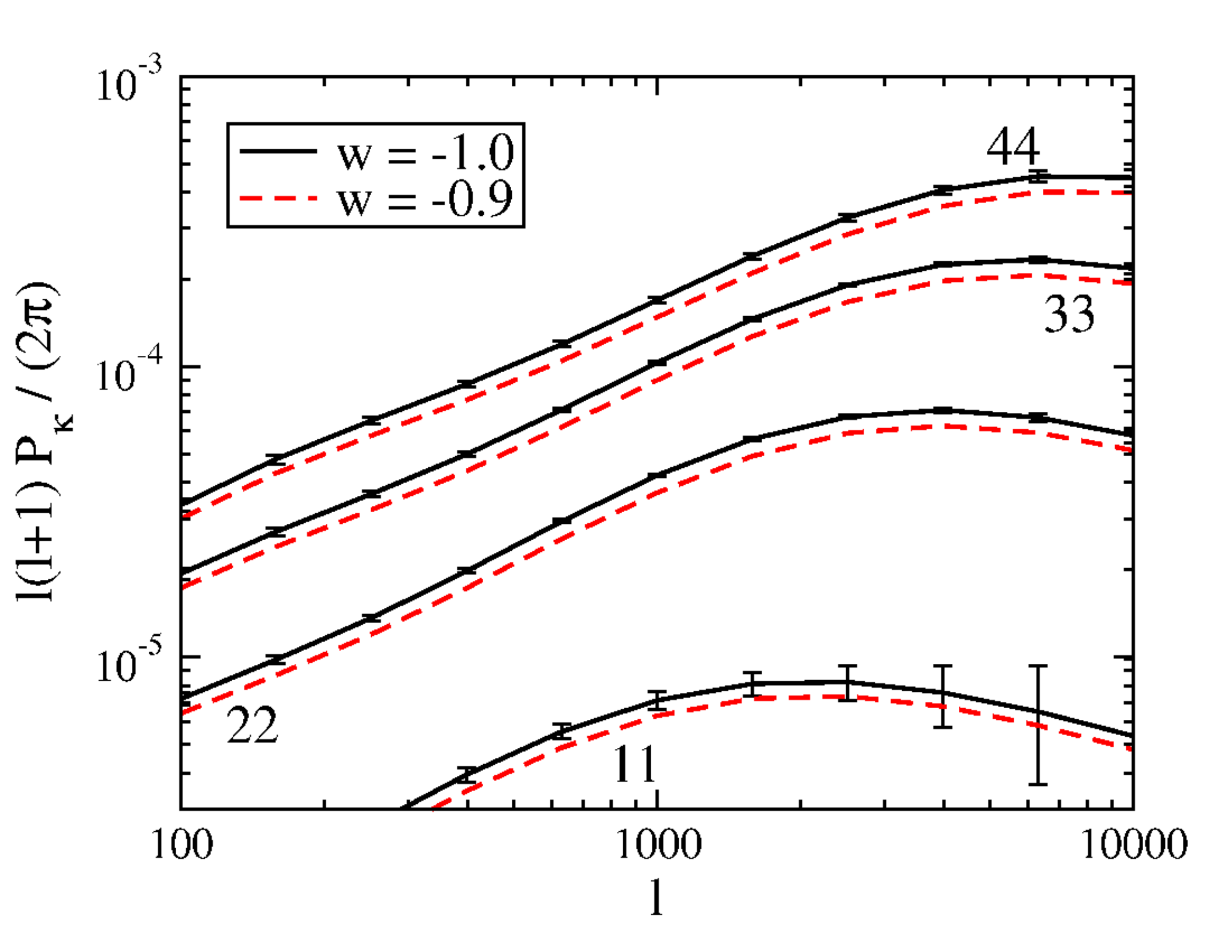
$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell + 1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

cosmic variance   shape noise

- Requirements: Sky area, depth, image quality & <u>stability</u>

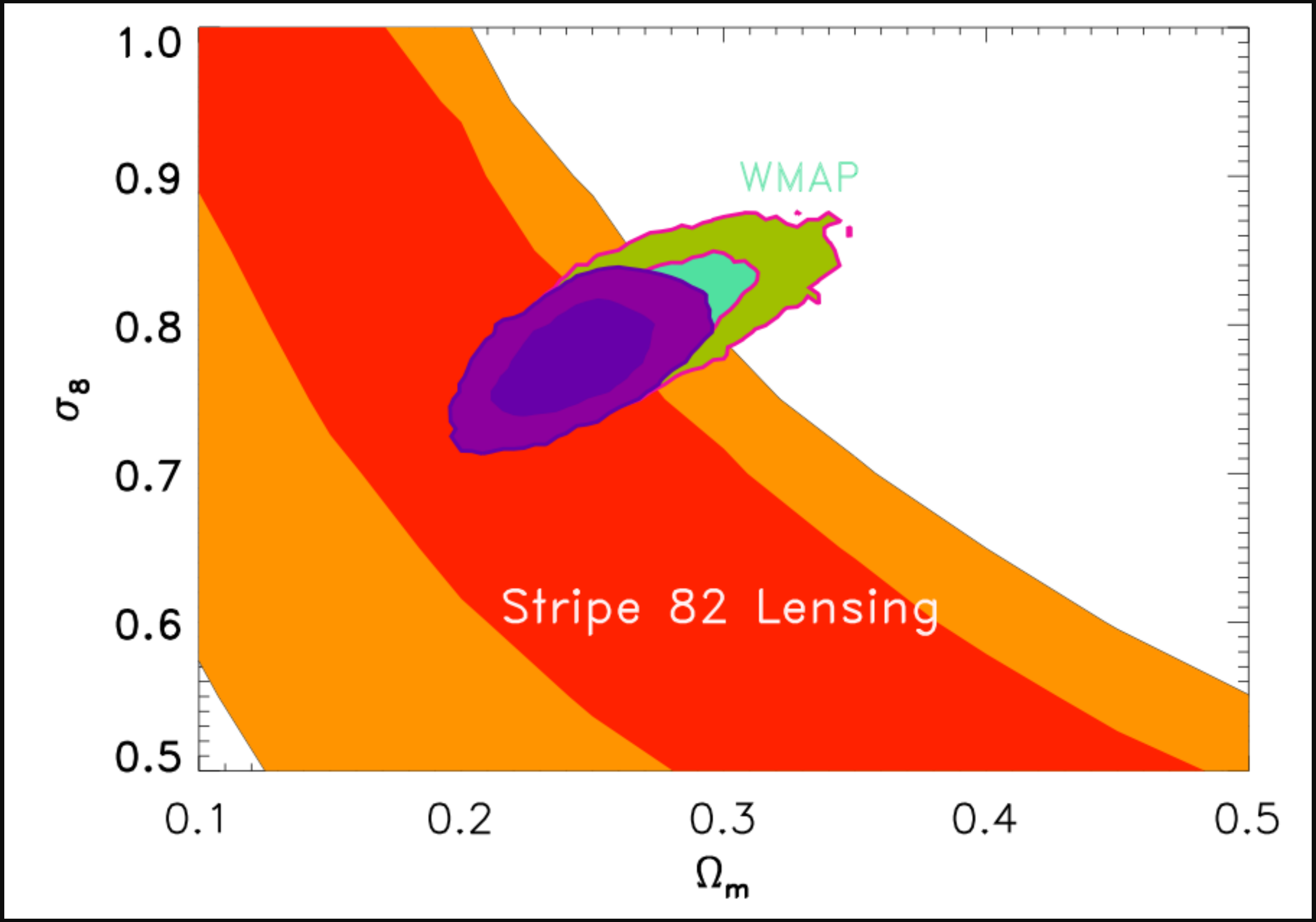
Weak Lensing Tomography

- Measure shapes for millions of source galaxies in photo-z bins
- Shear-shear & galaxy-shear correlations probe distances & growth rate of perturbations



Huterer

Weak Lensing Results



SDSS results: Lin, etal, Huff, etal

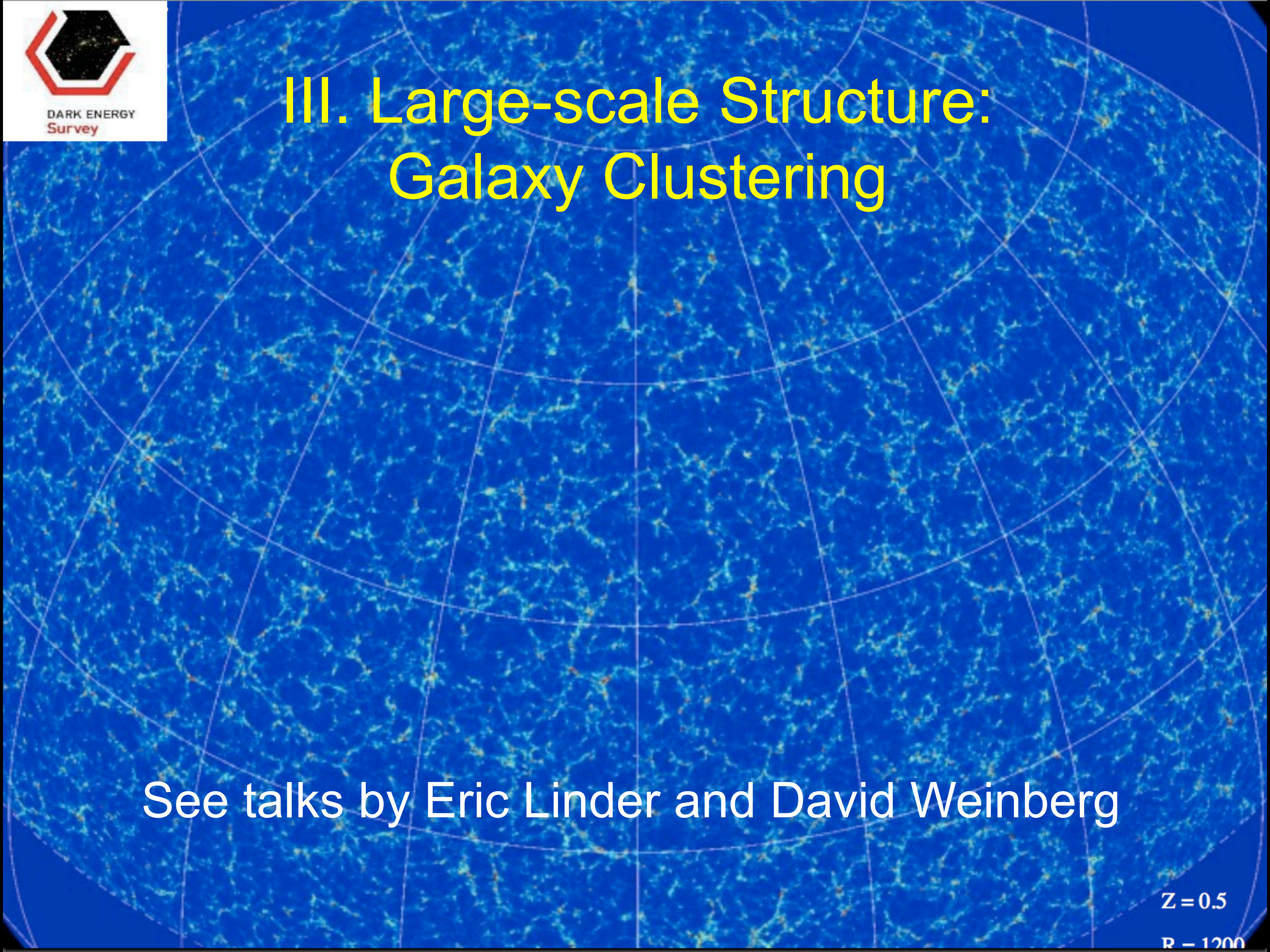
Weak Lensing Systematics

- Shear calibration errors
- PSF anisotropy correction errors
- Intrinsic alignments
- Photometric redshift errors
- Baryonic effects on small-scale mass power spectrum

- See talks by Chris Hirata, Rachel Bean

DARK ENERGY Survey

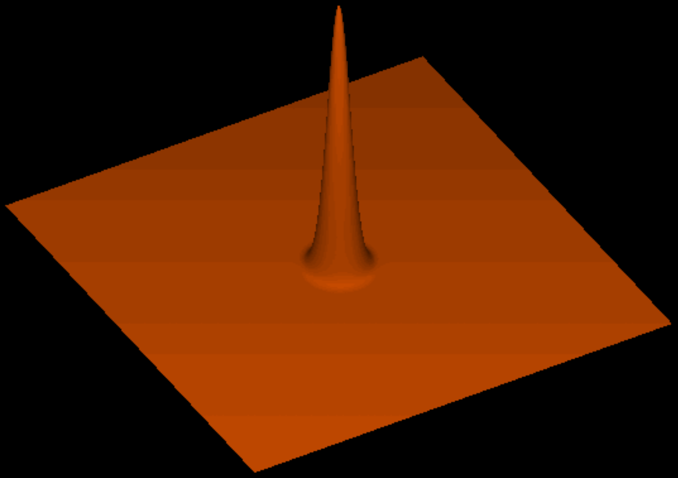
III. Large-scale Structure: Galaxy Clustering

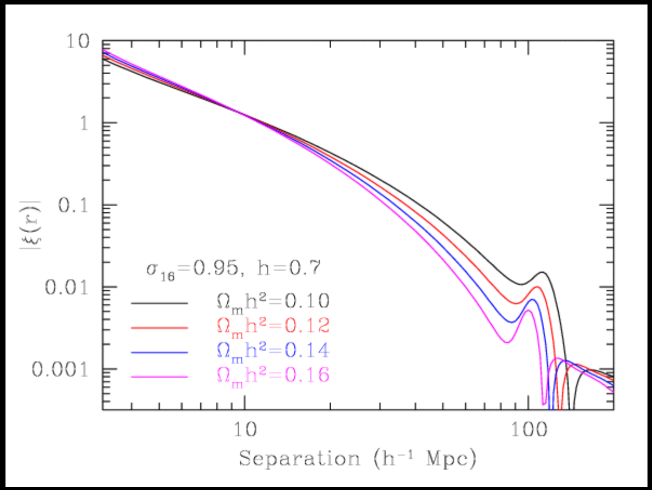


See talks by Eric Linder and David Weinberg

Baryon Acoustic Oscillations

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

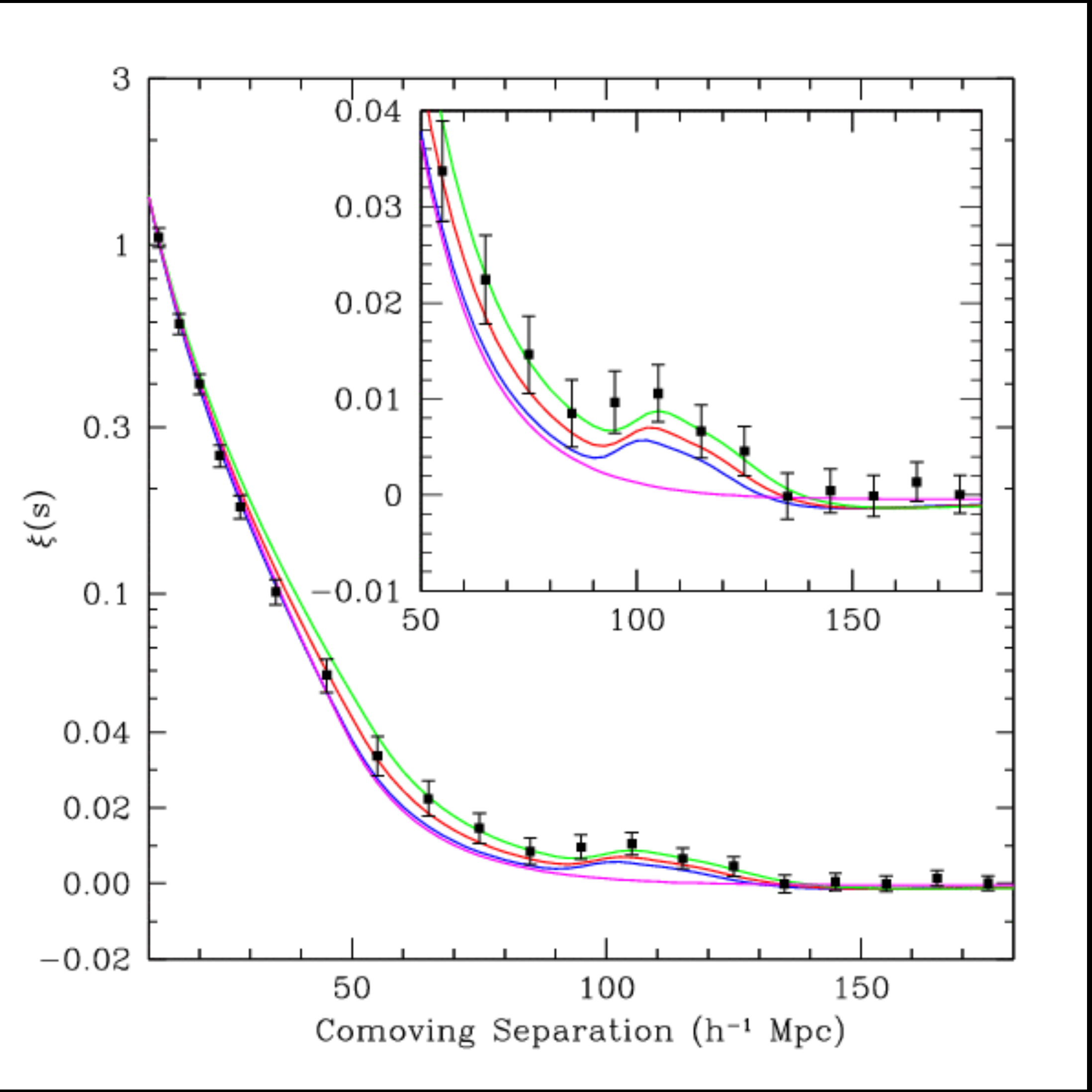




Eisenstein

Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function



Baryon Acoustic Oscillations seen in Large-scale Structure

Warning: Correlated Error Bars

Eisenstein, etal

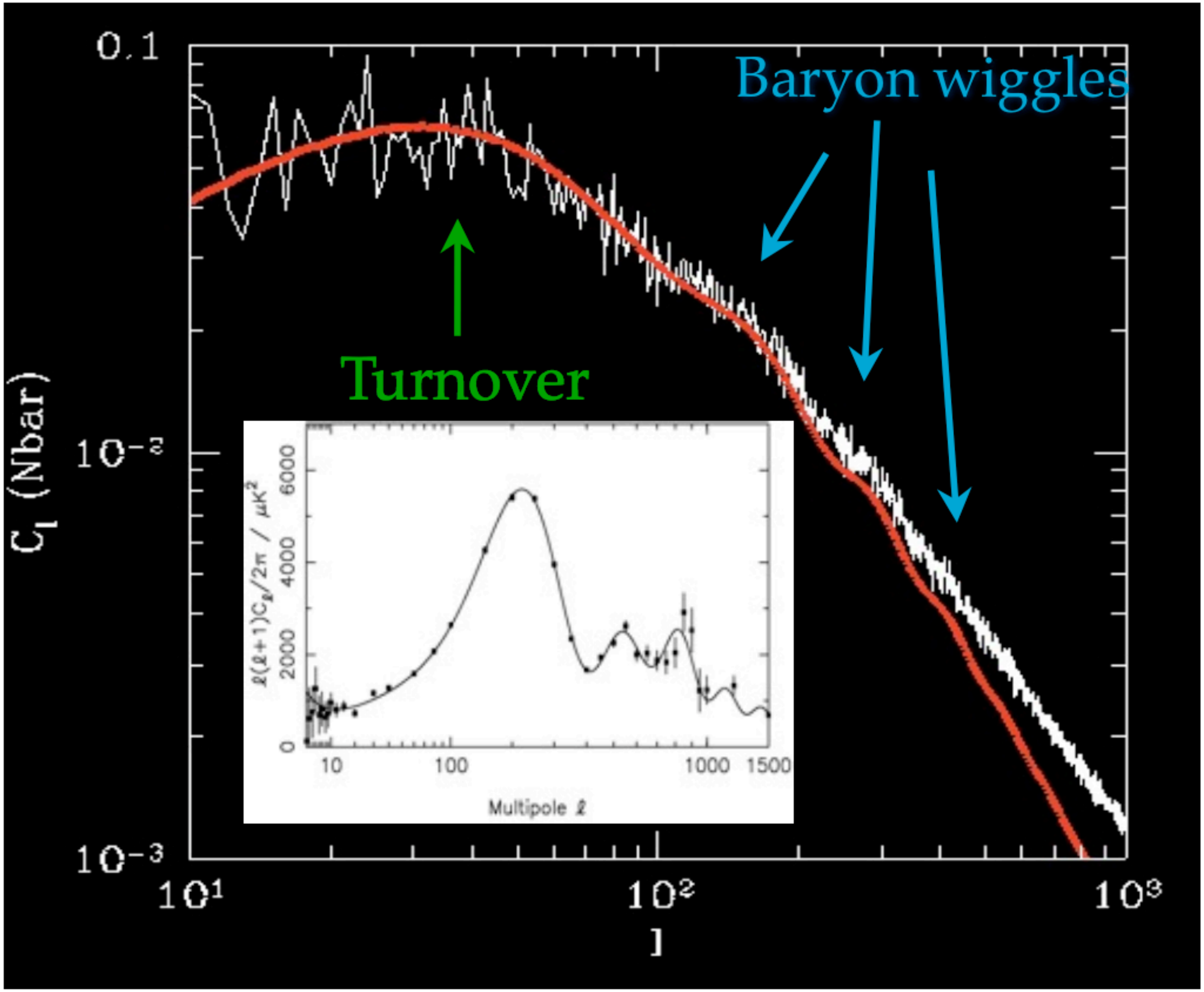
Angular Spectrum

For single redshift slice:

z =0.9-1.0

Out of MICE Simulation

www.ice.cat/mice



Measurements can provide both with:

1. BAO scale (DM & Baryon density)
2. distance to BAO scale (DE)

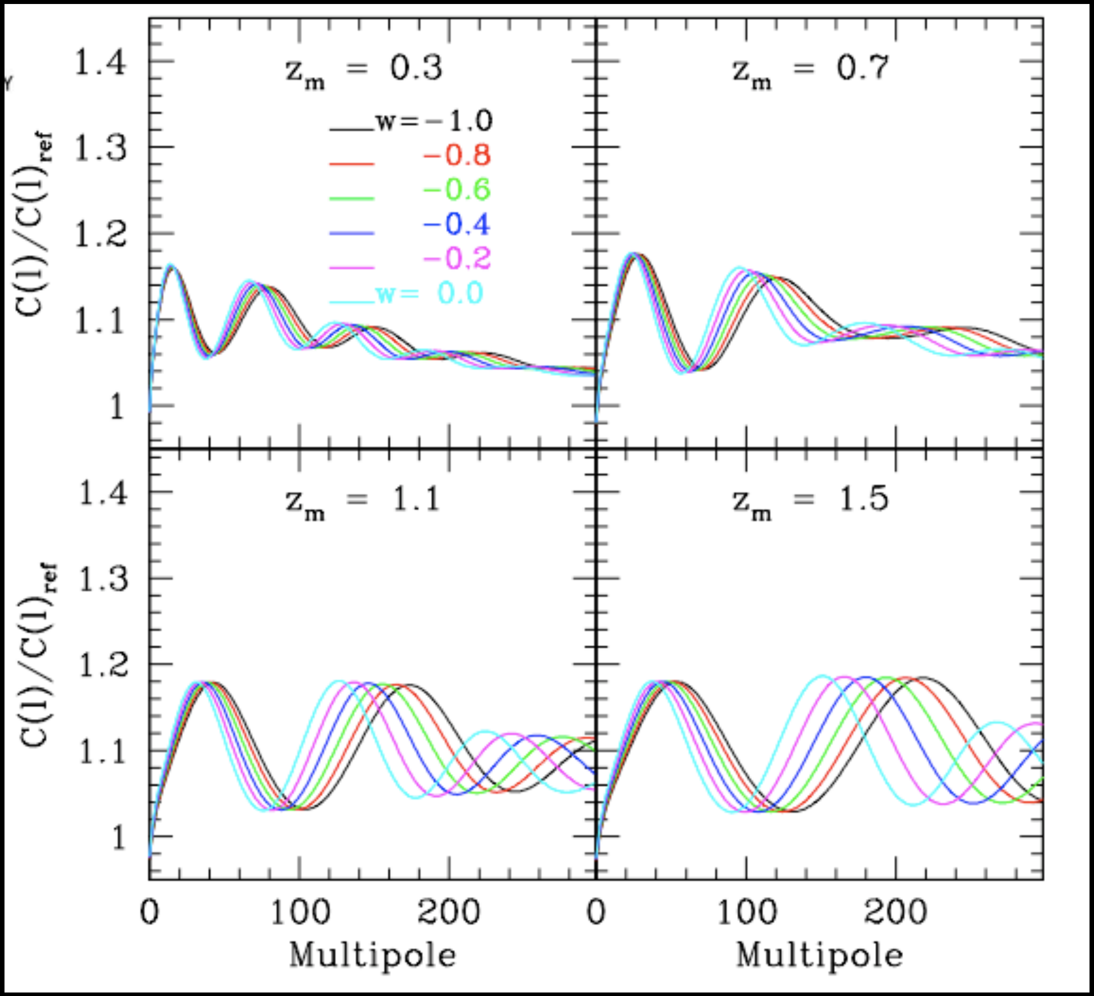
$$c\Delta z_{BAO} = r_{BAO} H(z) \qquad \Delta\theta_{BAO} = \frac{r_{BAO}}{d_A(z)}$$

Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins (relative to model without BAO)

Photometric surveys provide angular measure

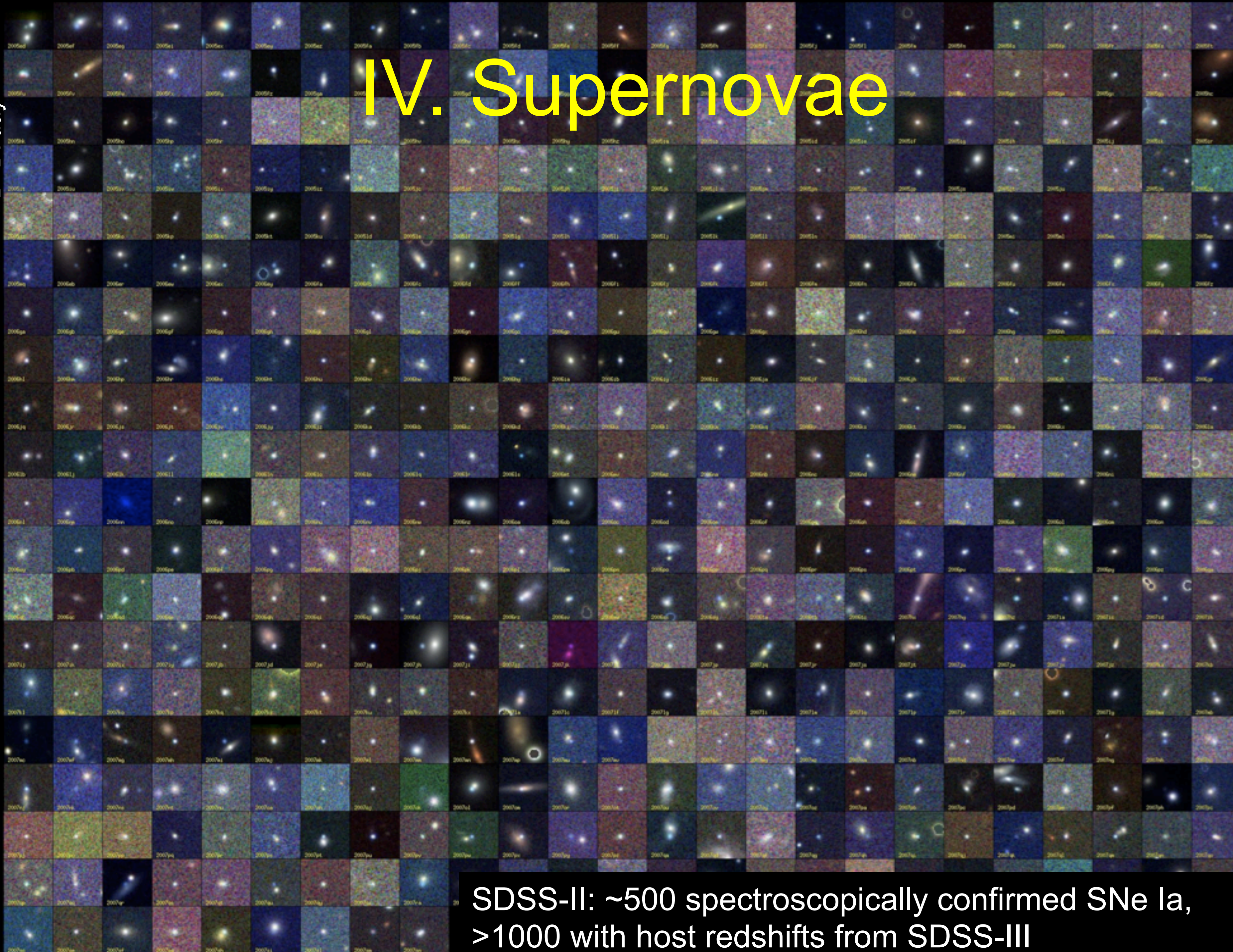
Radial modes require spectroscopy



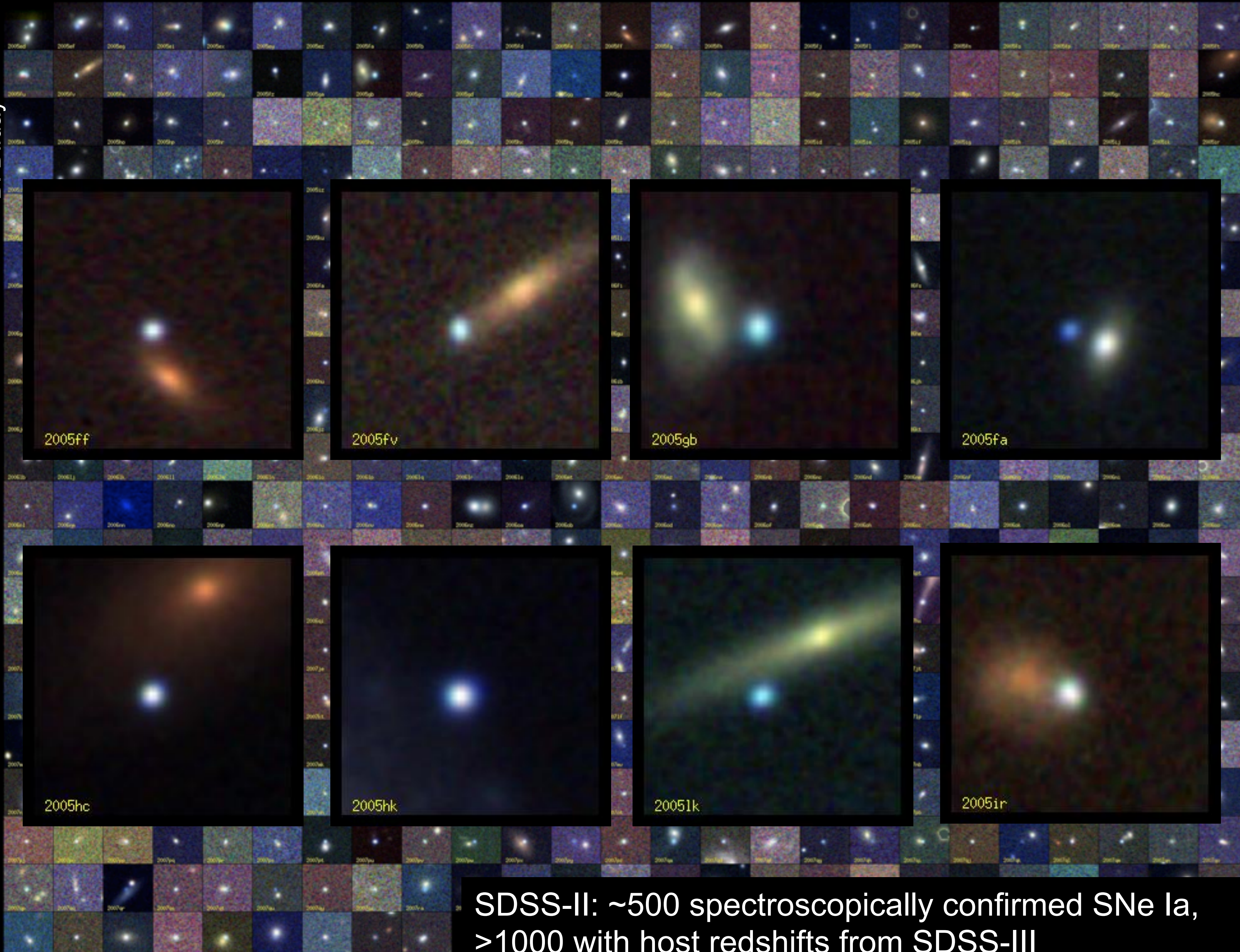
Fosalba & Gaztanaga

IV. Supernovae

B. Dilday



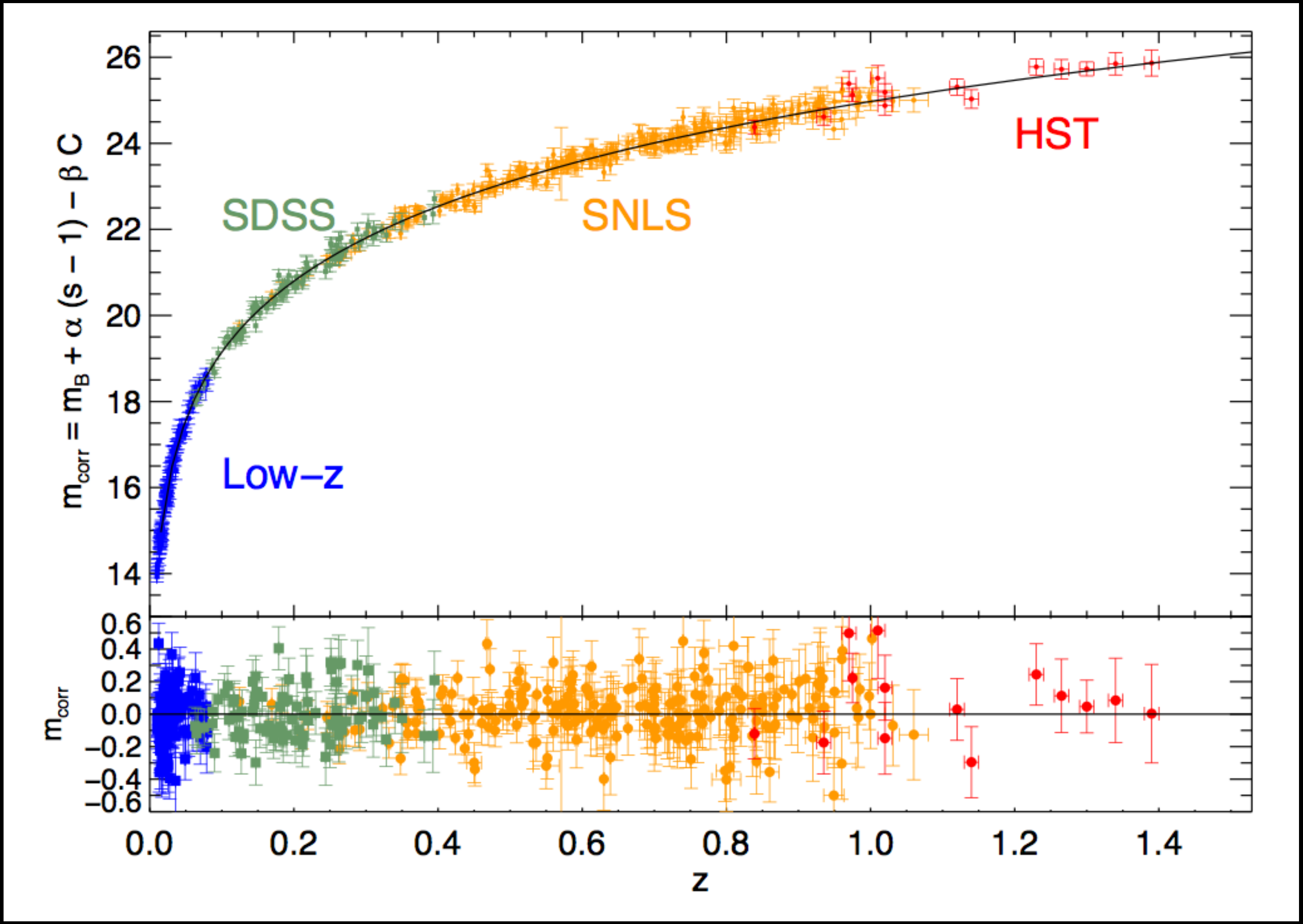
SDSS-II: ~500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III



B. Dilday

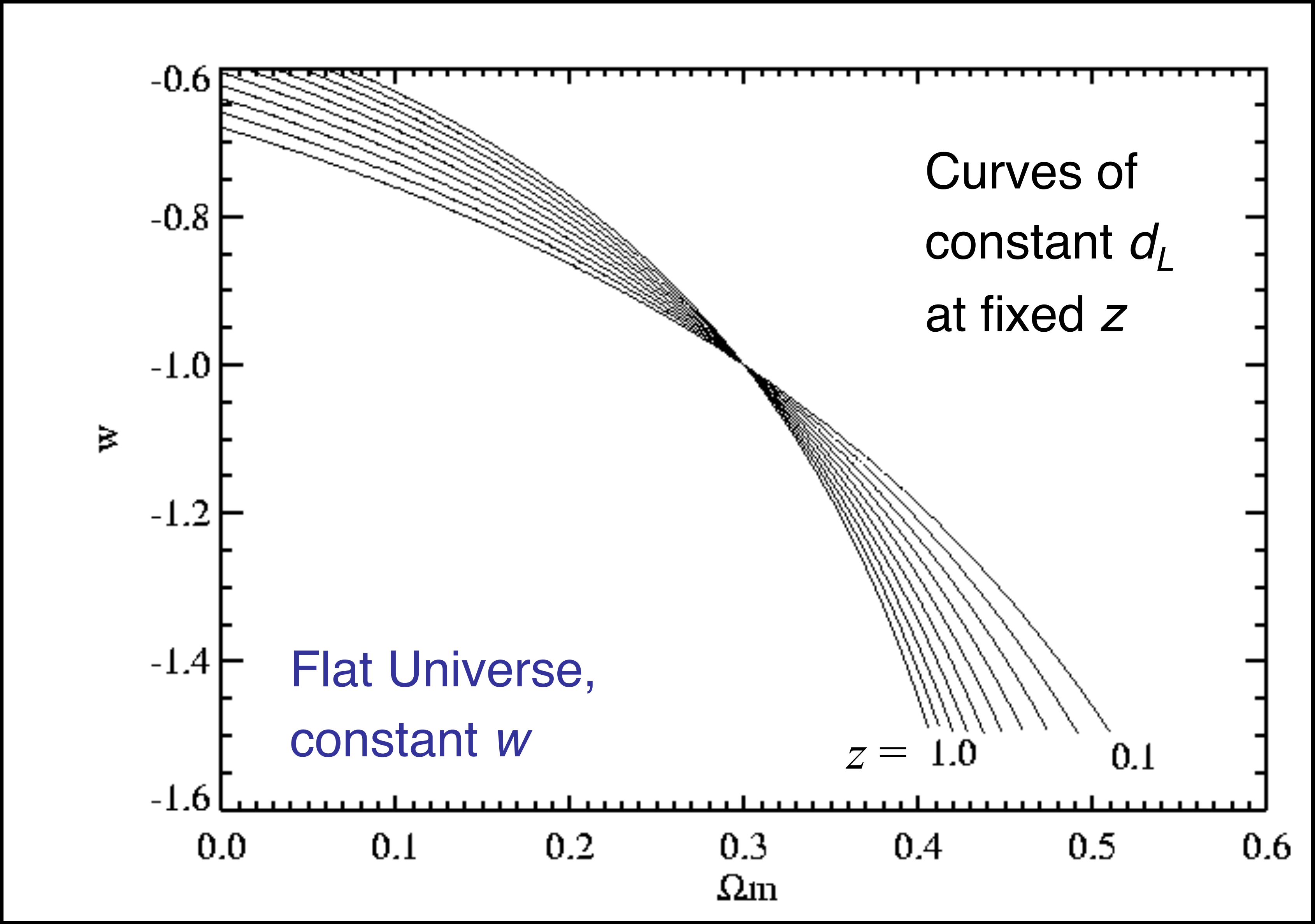
SDSS-II: ~500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III

Supernova Hubble Diagram

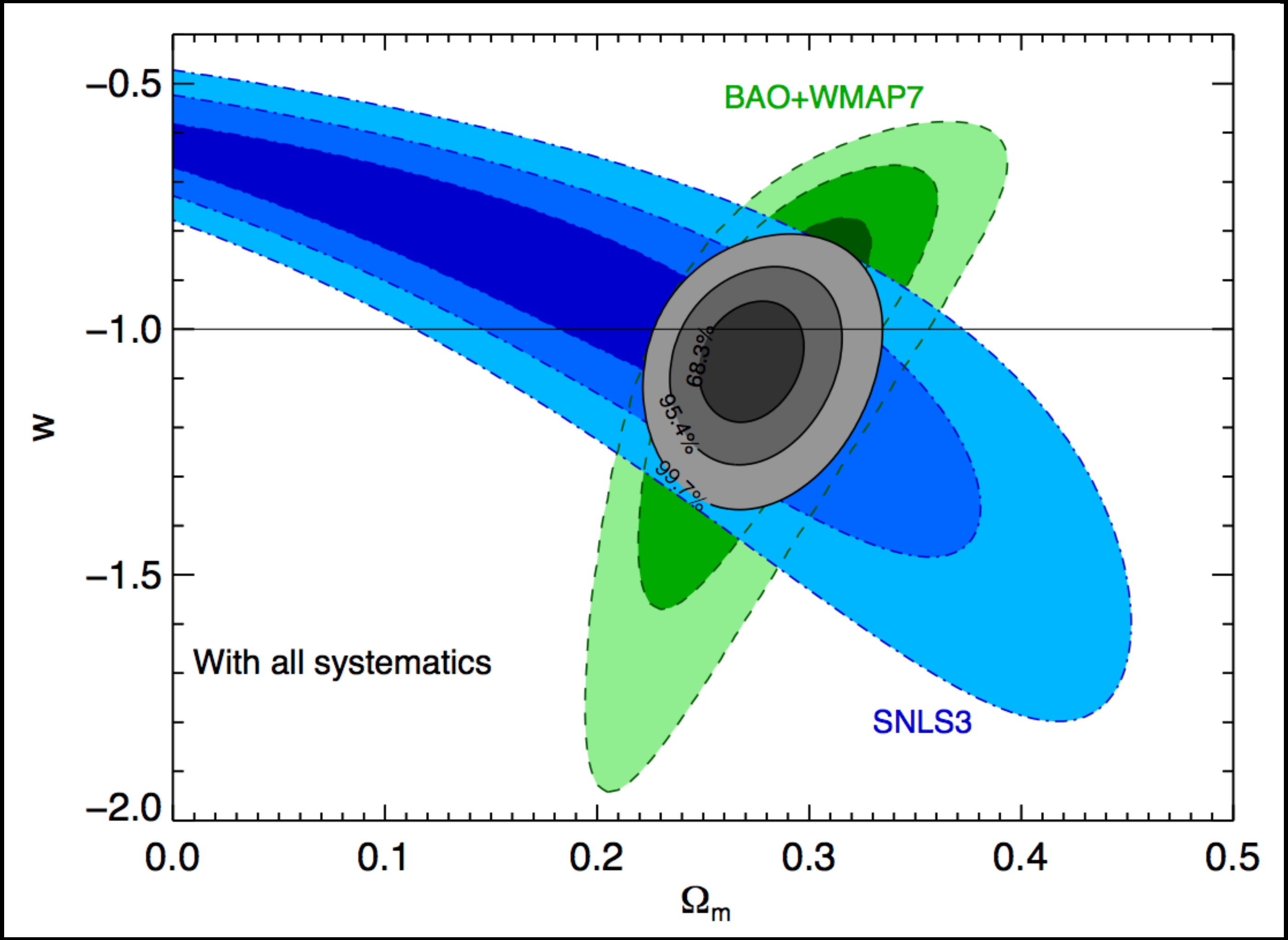


Conley, etal

Luminosity Distance



Supernova Results

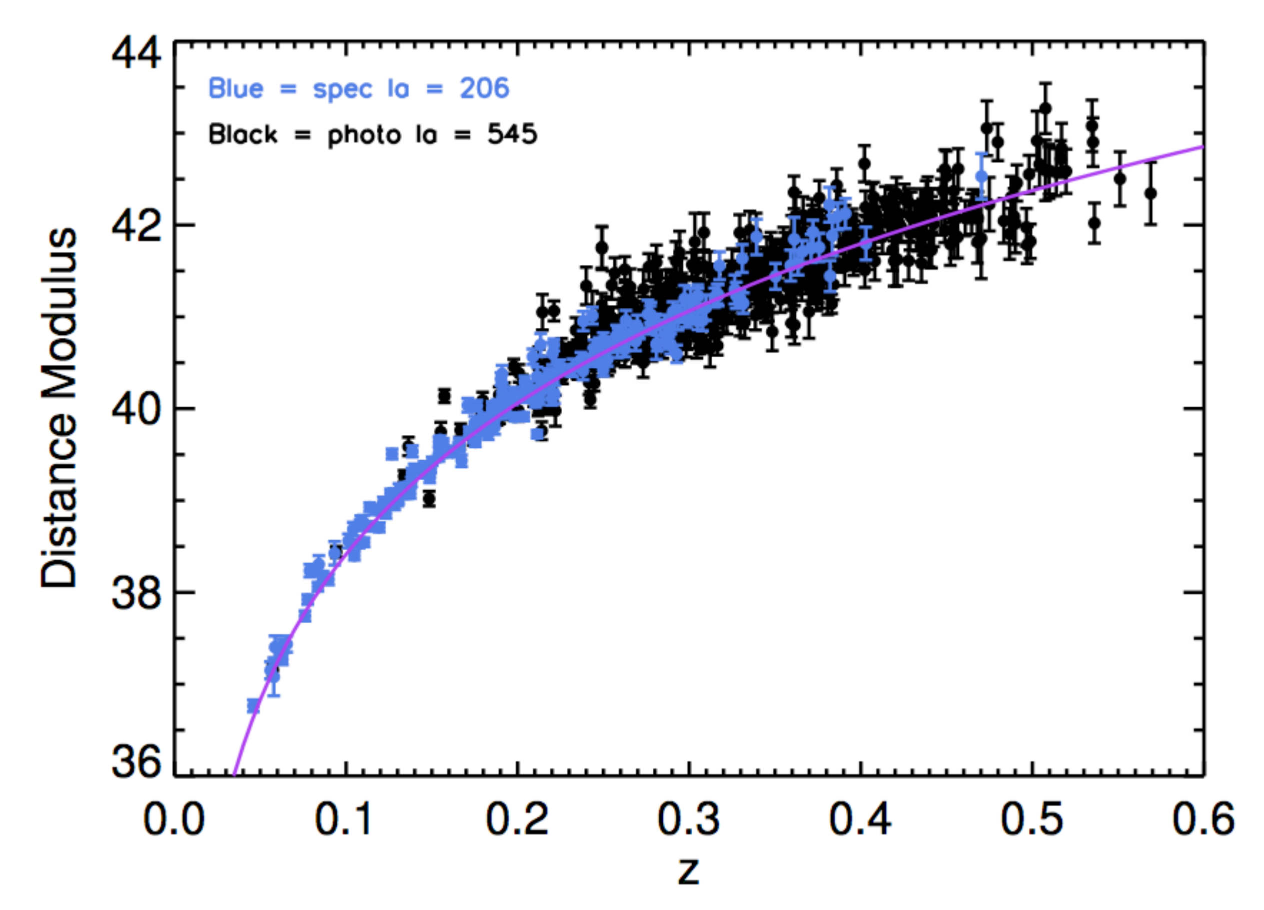


Systematics: phot. calibration, host-galaxy correlations, extinction, selection bias, …

Sullivan, etal

Photometric SN Cosmology: Ground-based Future

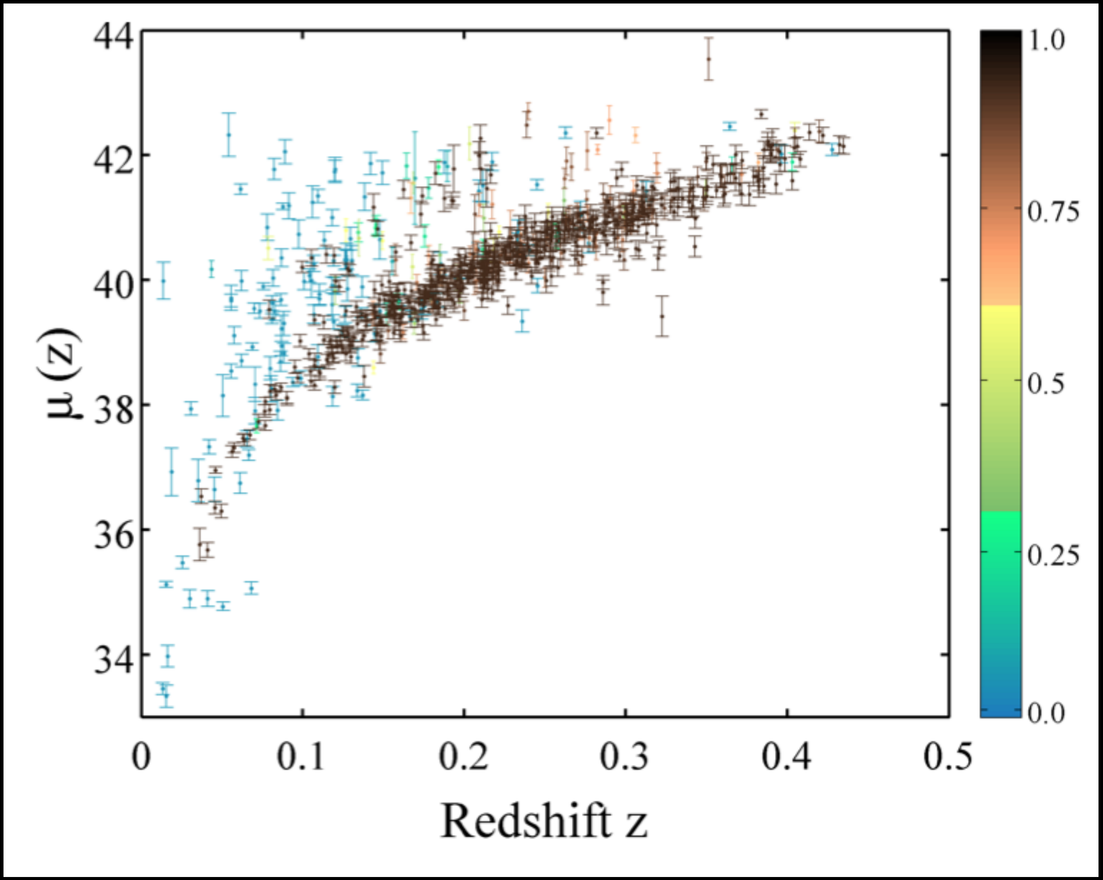
- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts measured by BOSS



Campbell, etal

Photometric SN Cosmology: Ground-based Future

- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts measured by BOSS, including classification probability: contamination issues



Hlozek, etal

Dark Energy Surveys

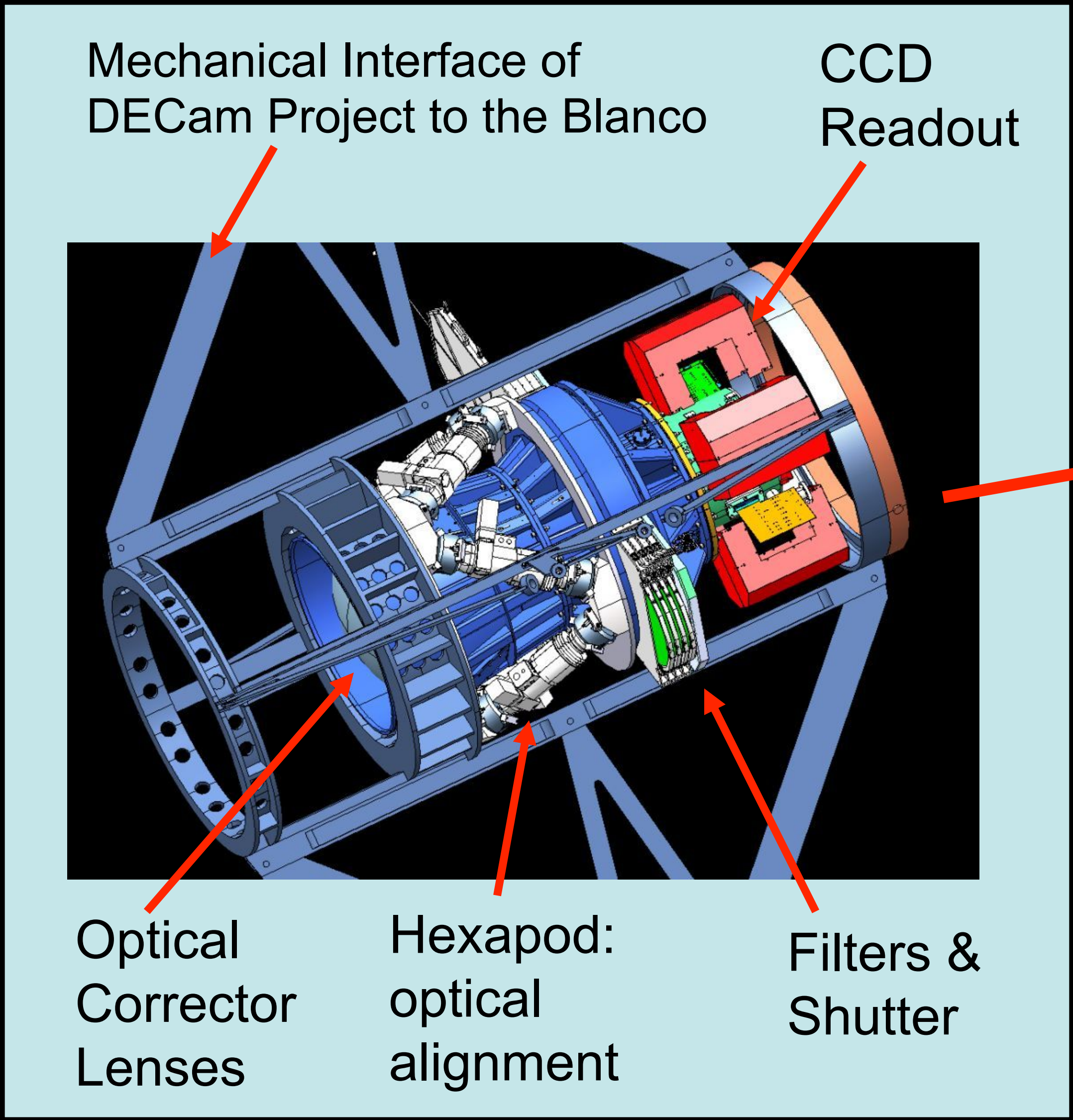
#Galaxies Cost

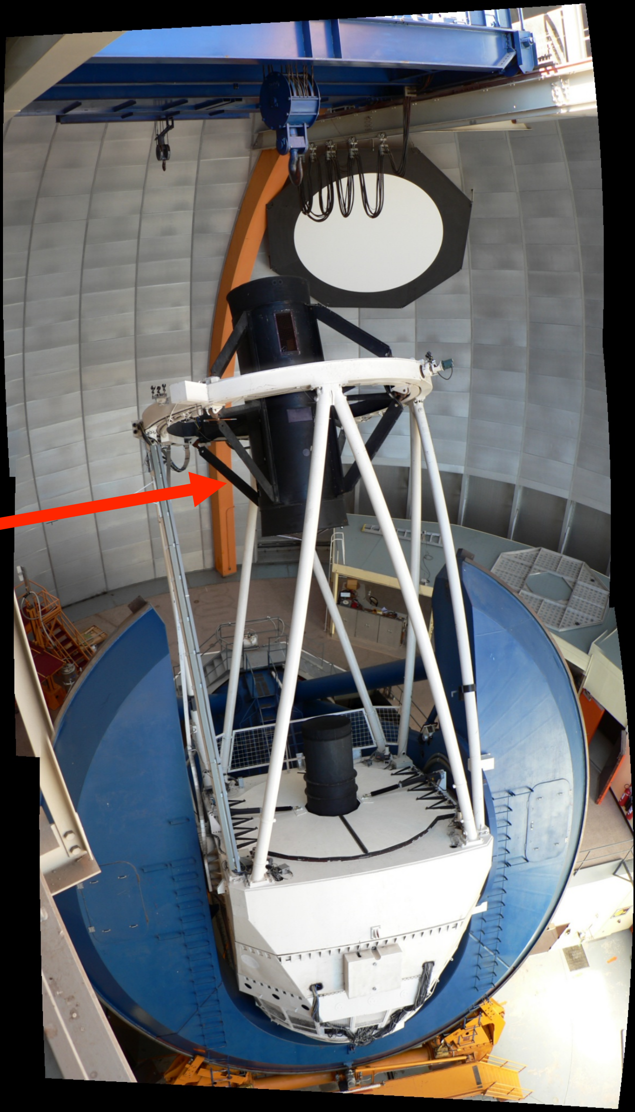
- Spectroscopic:
  - BOSS/SDSS-III (2008-14):
    - SDSS 2.5m: 1.5M LRGs to z<0.7, 150,000 QSOs for Lya at z=2.5 for BAO (1M 50M)
  - WiggleZ (completed):
    - AAO 4m: 240K ELGs to z~1 for BAO
  - Future possibilities: eBOSS (SDSS-IV), Sumire PFS (Subaru), BigBOSS (KP 4m), DESpec (CTIO 4m),… (10M 50-100M)
- Photometric:
  - PanSTARRS (1.8m), DES (4m), HSC (8m) (300M 50M)
  - Future: LSST (8.4m) (2B 600M)
- Both:
  - Space: Euclid, WFIRST (2B ~1.5B)

•X-ray:
- •XMM, Chandra
- •eROSITA

•SZ:
- •ACT,SPT, Planck

Dark Energy Camera



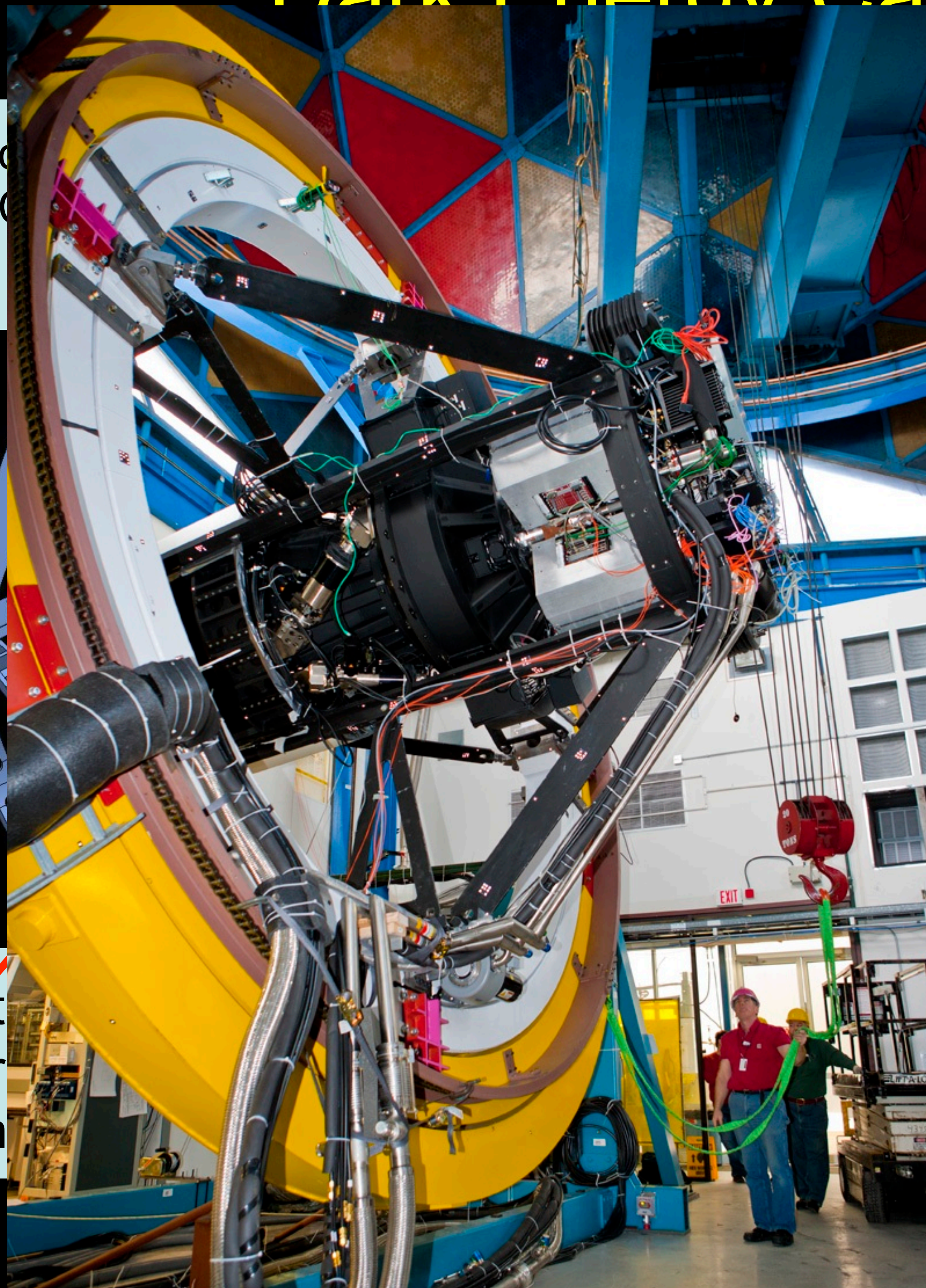


570-Megapixel imager
5000 s.d. grizy survey to 24th mag

Dark Energy Camera

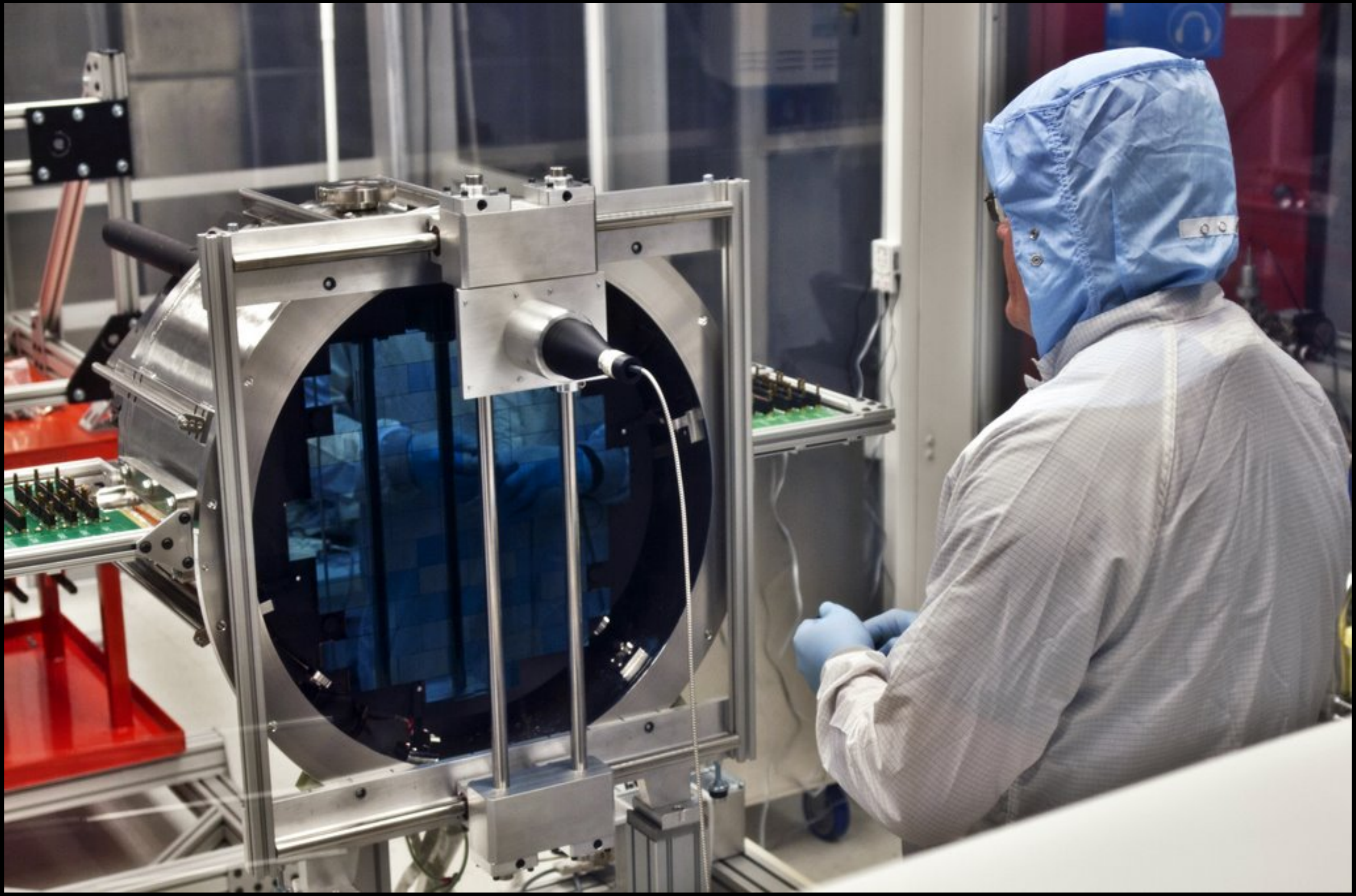
Mec
DEC

Opt
Cor
Len



DECam mounted on
Telescope Simulator
at Fermilab in early 2011

DECam at CTIO

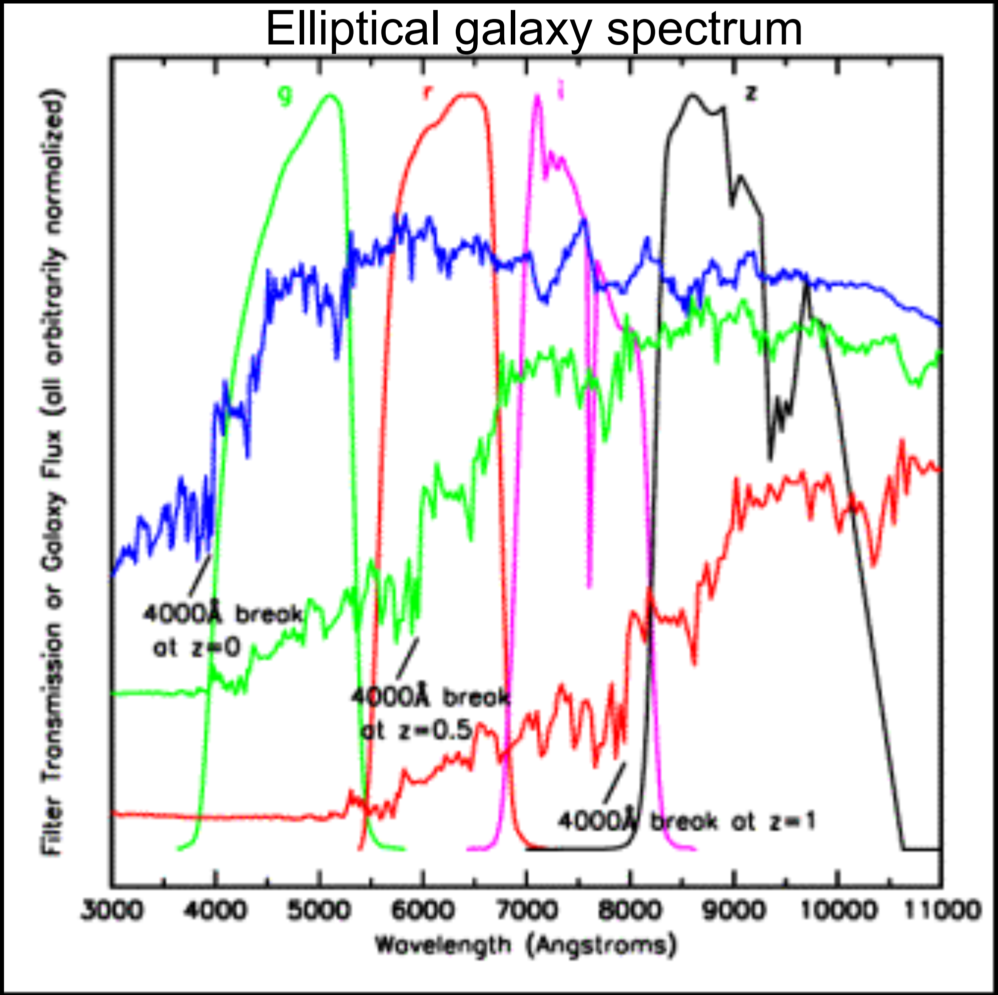


DECam ready for Installation

- Blanco shuts down for DECam installation Feb. 20
- DES starts late 2012

Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, *provided* error distributions well measured.
- Challenge: spectroscopic training & validation sets to flux limit of imaging survey (24th mag DES, 25.5 LSST)



Galaxy Photo-z Simulations

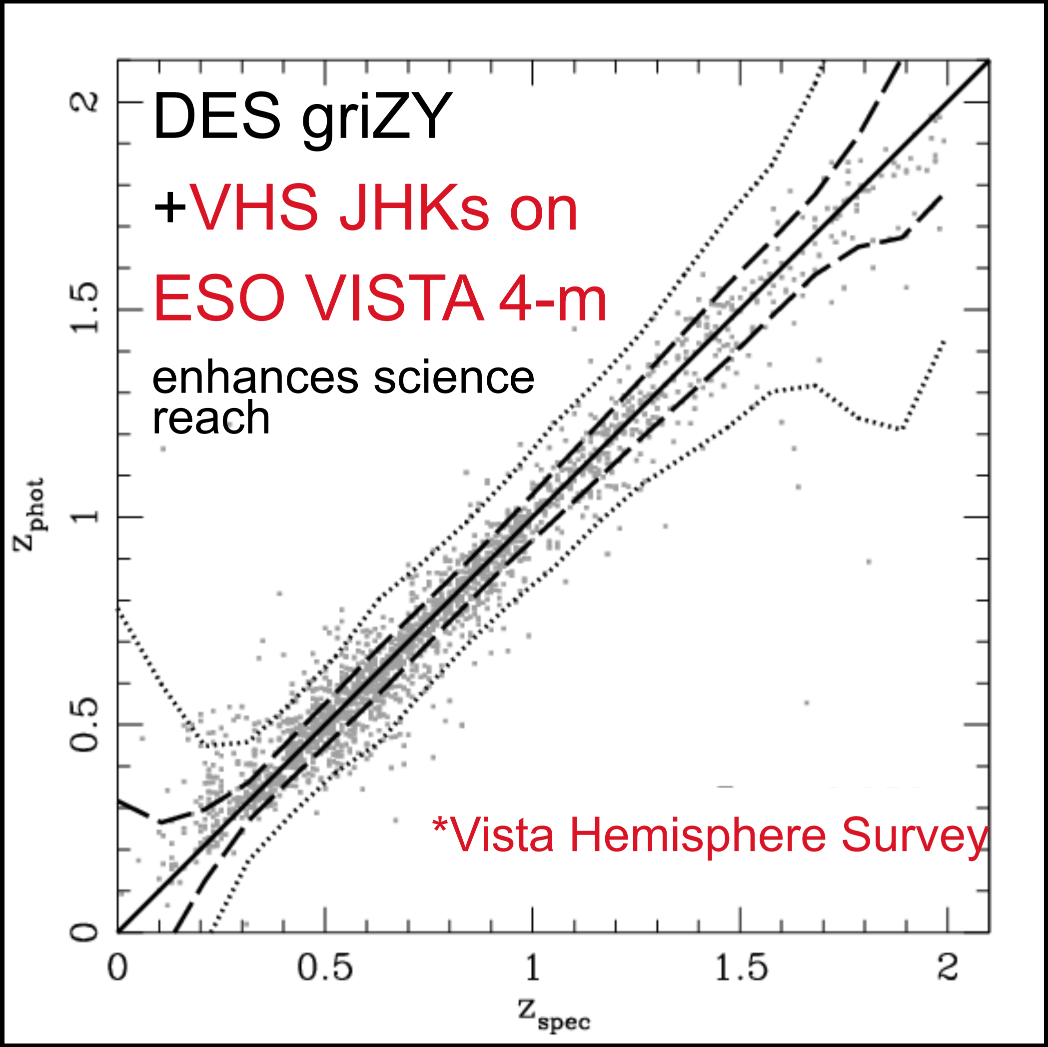
DES +VHS*

10σ Limiting Magnitudes

g	24.6		
r	24.1		
i	24.0	J	20.3
z	23.8	H	19.4
Y	21.6	Ks	18.3

+2% photometric calibration error added in quadrature

NIR imaging reduces photo-z errors at z>1



Dark Energy Program: Complementarity of Ground & Space

- Ground offers:
- Wide area coverage (long mission times)
- *Optical* multi-band surveys, photo-z's for NIR space surveys
- Adequate for imaging to m~25 and z~1
- Space advantages:
- Infrared → High-redshift → larger volumes → reduced cosmic errors
- Deeper, pristine imaging (small, stable PSF)
- Optical+NIR: powerful & necessary for photo-z's
- Potentially substantial gains from coordinating operations and data analysis from ground+space surveys