Dark Energy

- J. Frieman: Overview 30
- A. Kim: Supernovae 30
- B. Jain: Weak Lensing 30
- M. White: Baryon Acoustic Oscillations 30

P5, SLAC, Feb. 22, 2008

Progress since last P5 Report

- BEPAC recommends JDEM as highest-priority for NASA's Beyond Einstein program: joint AO expected 2008
- DES recommended for CD2/3a approval
- LSST successful Conceptual Design Review
- ESA Cosmic Visions Program: DUNE, SPACE Concept Advisory Team studying possible merger

What is causing cosmic acceleration?

Dark Energy:

$$G_{\mu\nu} = 8\pi G[T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{dark energy})]$$

$$\text{DE equation of state}: \quad w = T_i^i / T_0^0 < -1/3$$

Gravity:

$$G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G T_{\mu\nu}(\text{matter})$$

Key Experimental Questions:

1. Is DE observationally distinguishable from a cosmological constant, for which $w = -1$?
2. Can we distinguish between gravity and dark energy?
   Combine distance with structure-growth probes
3. Does dark energy evolve: $w=w(z)$?

What is the nature of Dark Energy?

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

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

- and the growth of large-scale structure: $\frac{\delta\rho(a)}{\rho}$

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

$$\frac{dV}{dz d\Omega} = \frac{r^2(z)}{H(z)}$$

Four Primary Probes (DETF):

- Weak Lensing cosmic shear — Distance $r(z)$+growth
- Supernovae — Distance
- Baryon Acoustic Oscillations — Distance+$H(z)$
- Cluster counting — Distance+growth

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Model Assumptions

- Most current data analyses assume a simplified, two-parameter class of models:

$$\Omega_m, \Omega_{DE}, w(z) \;\Rightarrow\; \text{either}: \; \Omega_m, \Omega_{DE}(w=-1)$$
$$\text{or}: \; \Omega_m, \; w \text{ (constant)}, \text{ flat}: \; \Omega_m + \Omega_{DE} = 1$$

- Future experiments aim to constrain (at least) 4-parameter models:

$$\Omega_m, \Omega_{DE}, \; w(a) = w_0 + w_a(1-a)$$

- Higher-dimensional EOS parametrizations possible
- Other descriptions possible (e.g., kinematic)

Current Constraints on *Constant* Dark Energy Equation of State

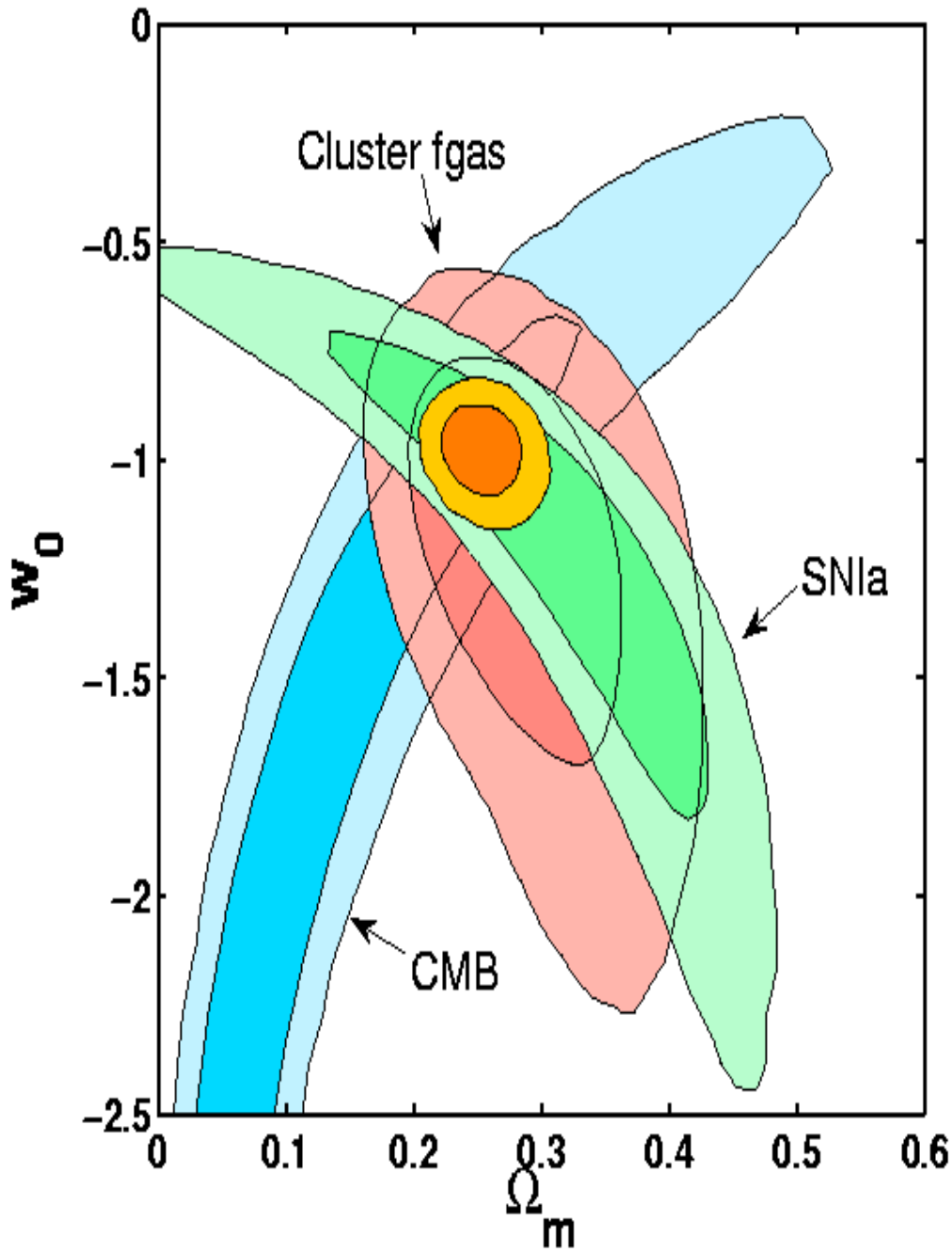
2-parameter model:

w, Ω_m

Data consistent with

w=−1±0.1

Allen et al 07



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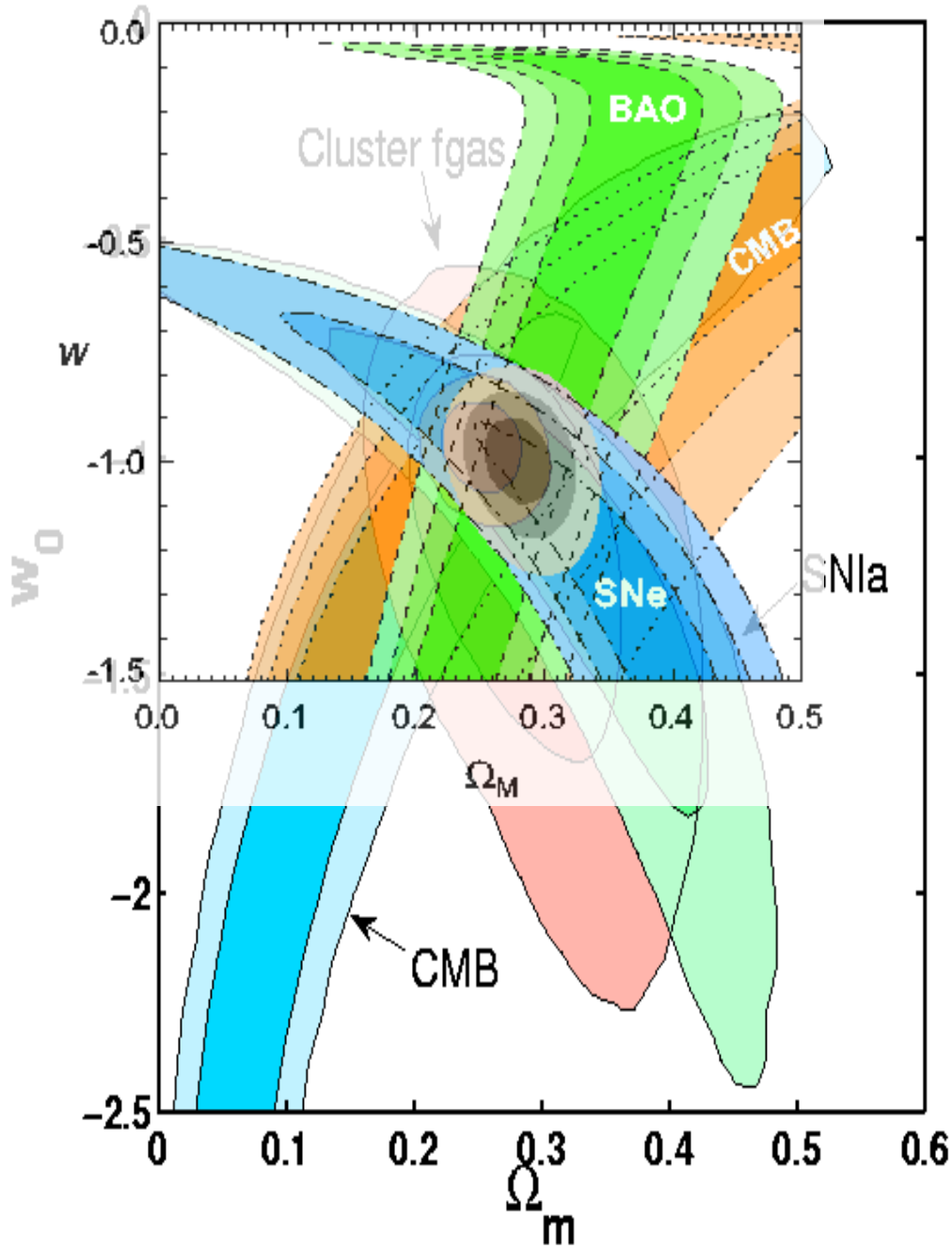
Kowalski et al 08



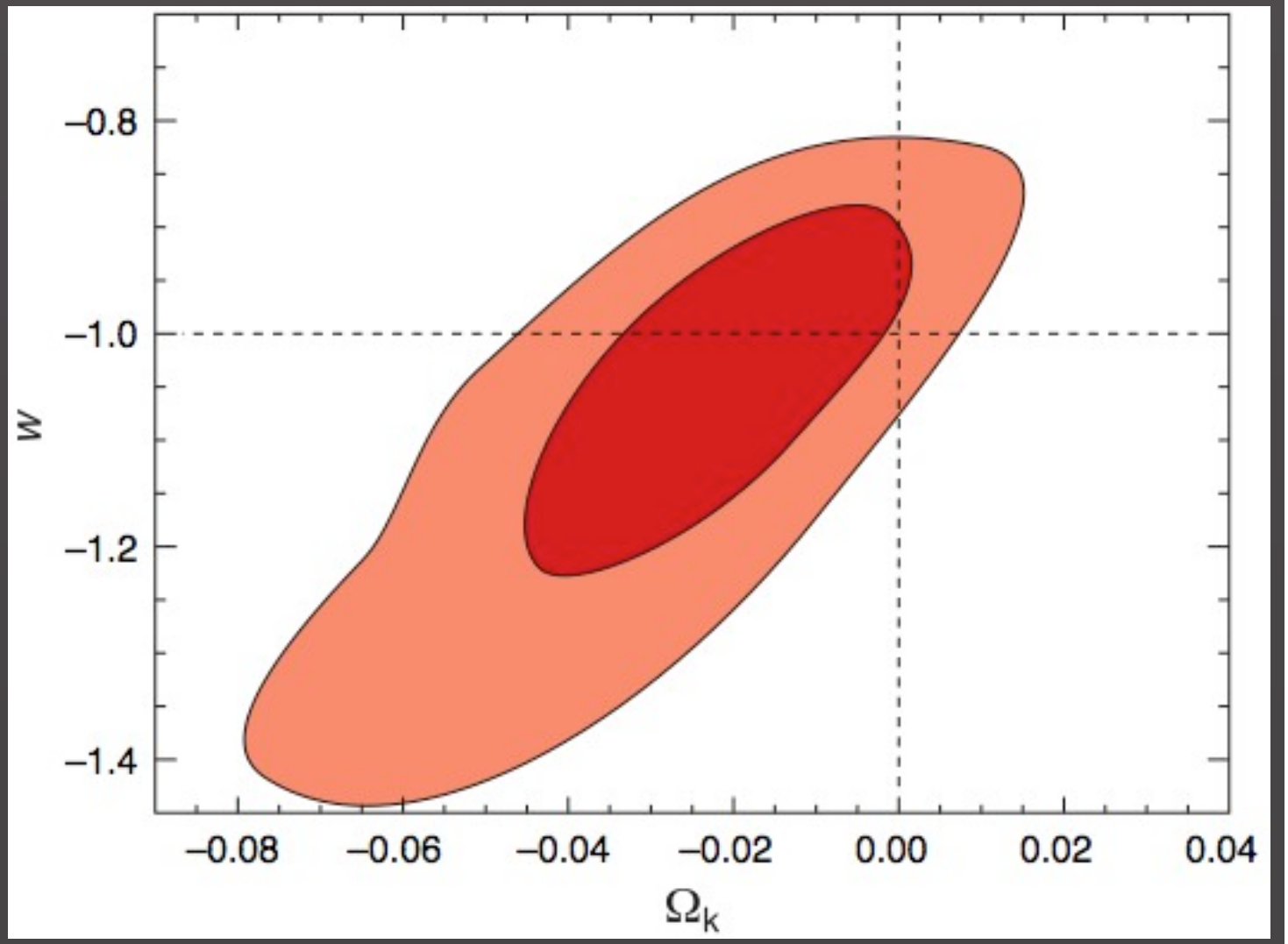
Curvature and Dark Energy

WMAP3+
SDSS+2dF+
SN

w(z)=constant
3-parameter
model:

$w,\ \Omega_m,\ \Omega_k$

Spergel etal 07

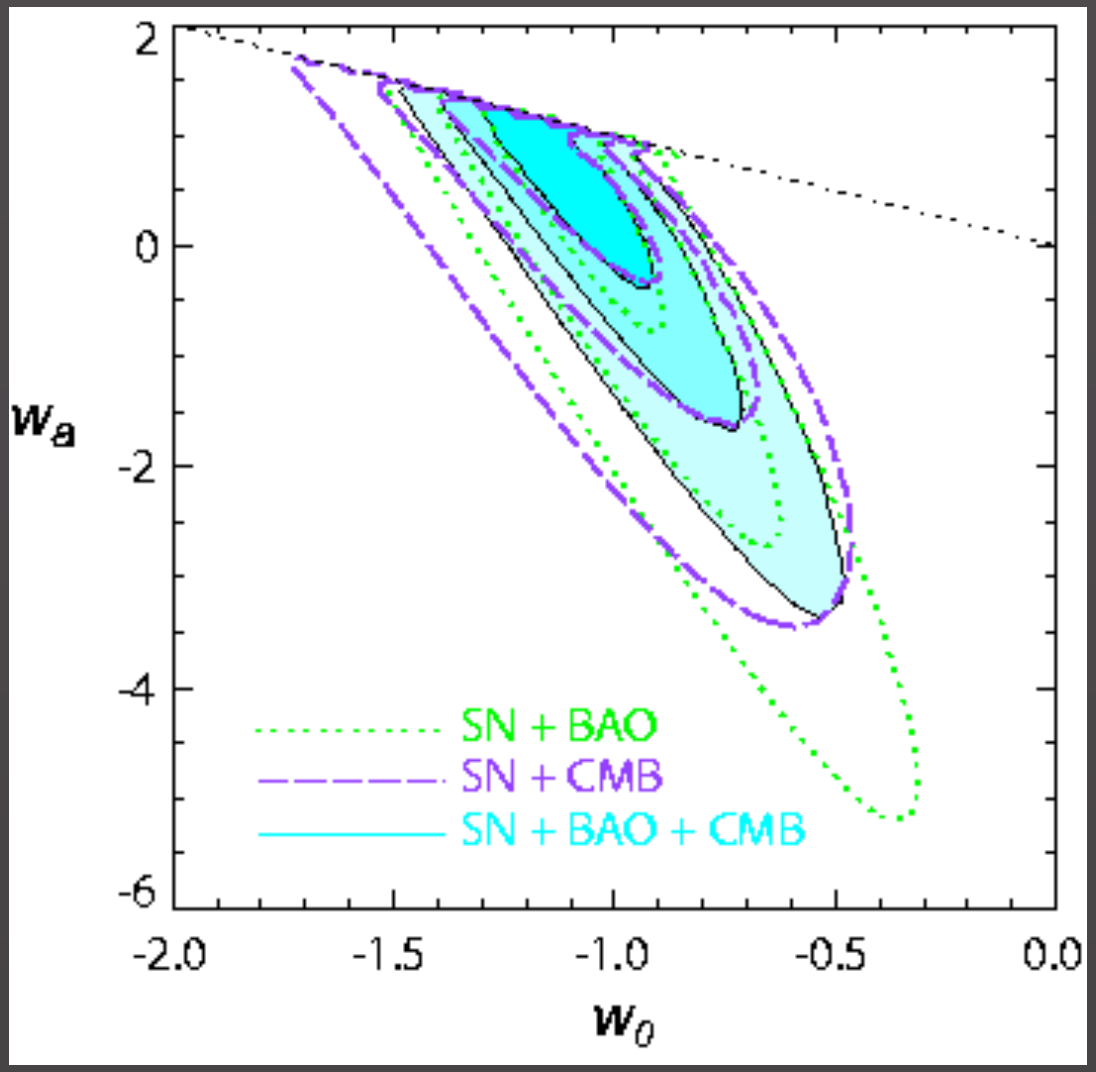


Much weaker current constraints on Time-varying Dark Energy

3-parameter model

$$w(z) = w_0 + w_a(1-a) + \ldots$$

marginalized over Ω_m



Assumes flat Universe

Kowalski et al 08

Dark Energy Task Force Report (2006)

- Defined Figure of Merit to compare expts and methods:

$$FoM \propto \frac{1}{\sigma(w_0)\sigma(w_a)}$$

- Highlighted 4 probes: SN, WL, BAO, CL

- Envisioned staged program of experiments:

  Stage II: on-going or funded as of 2006

  Stage III: intermediate in scale + time $\times 3$

  Stage IV: longer-term, larger scale $\times 10$

  LSST, JDEM

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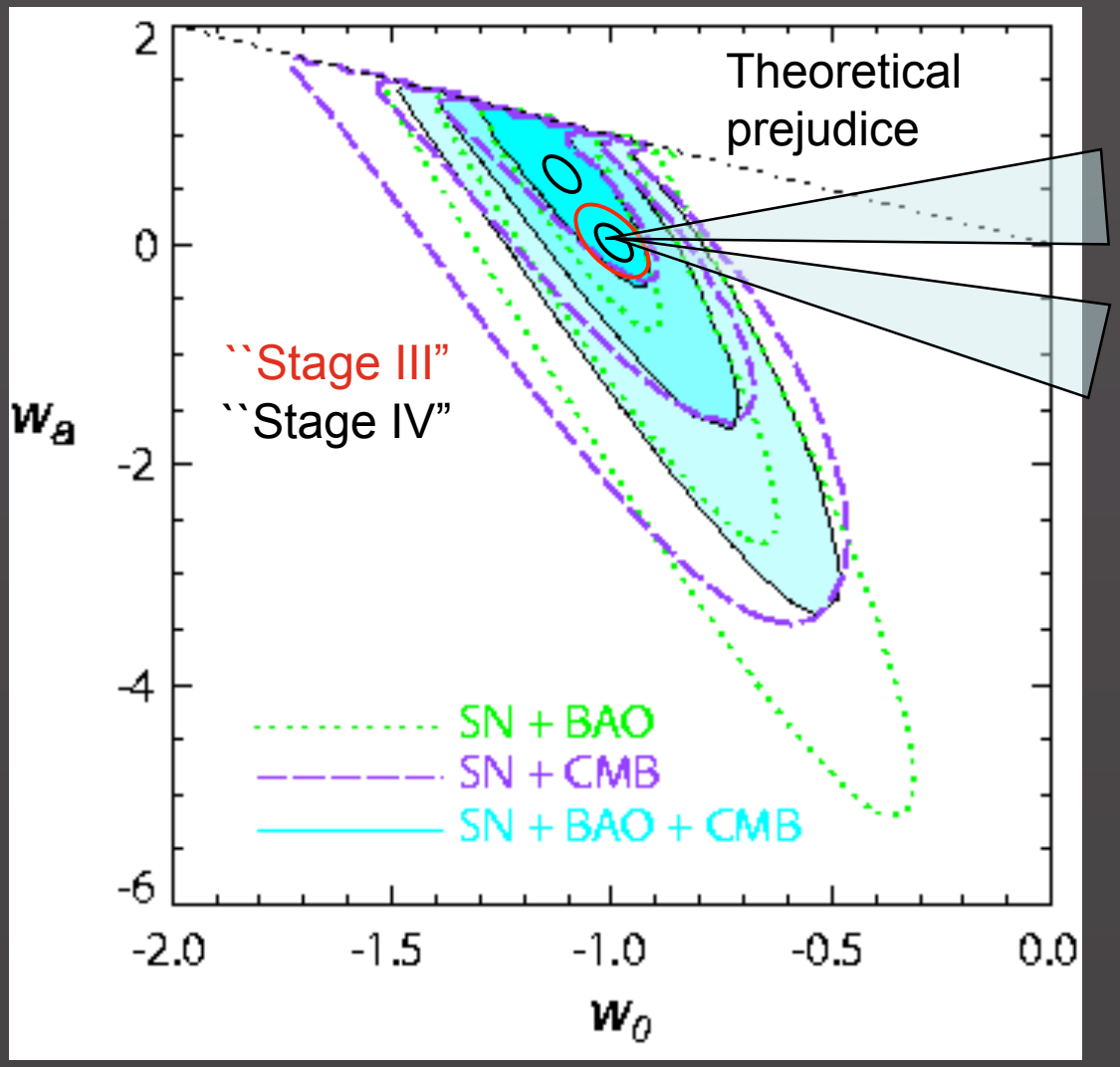


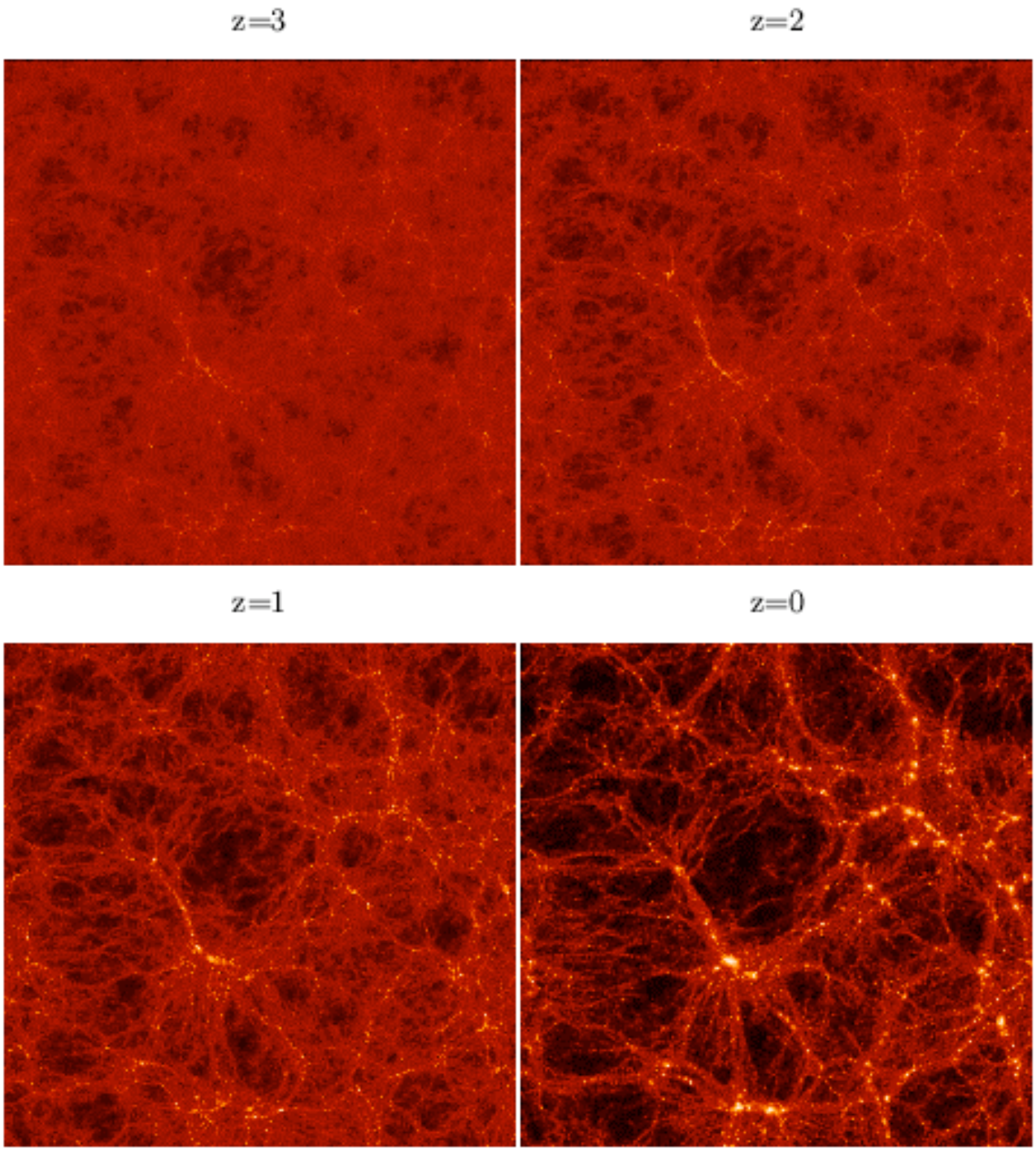
Kowalski et al 08

Growth of Large-scale Structure

Robustness of the paradigm recommends its use as a Dark Energy probe

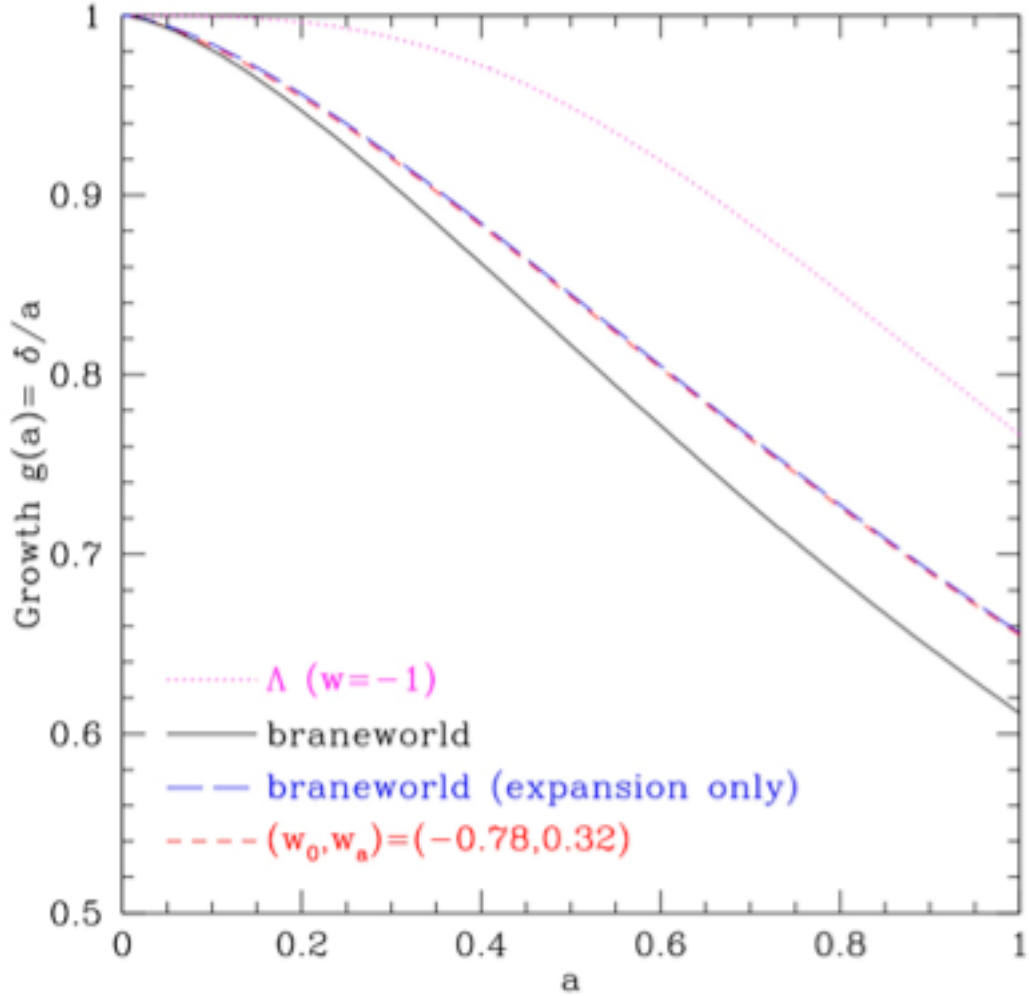
Price: additional cosmological and structure formation parameters

Bonus: additional structure formation parameters



Expansion History vs. Perturbation Growth

Growth of Perturbations probes *H(z)* and gravity modifications



Linder

$$g'' + [5 + \tfrac{1}{2}\tfrac{d\ln H^2}{d\ln a}]g'a^{-1} + [3 + \tfrac{1}{2}\tfrac{d\ln H^2}{d\ln a} - \tfrac{3}{2}G\,\Omega_m(a)]\,ga^{-2} = S(a)$$

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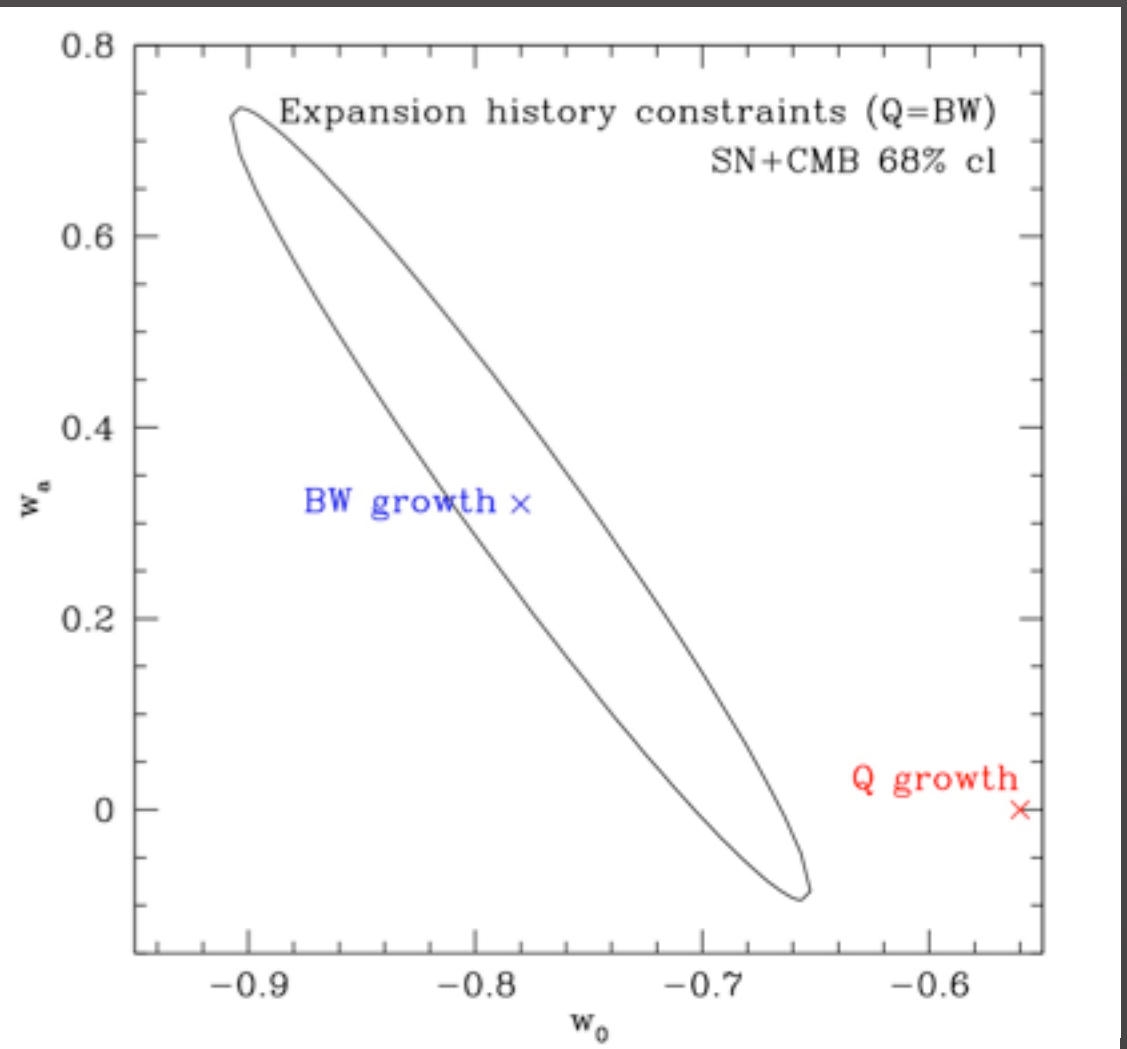

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Probing Dark Energy

Primary Techniques identified by the Dark Energy Task Force report:

- Supernovae
- Galaxy Clusters
- Weak Lensing
- Baryon Acoustic Oscillations

Multiple Techniques needed: complementary in systematics and in science reach

Caveat:
Representative list, not guaranteed to be complete or accurate

Table 3: Dark energy projects proposed or under construction. Stage refers to the DETF time-scale classification.

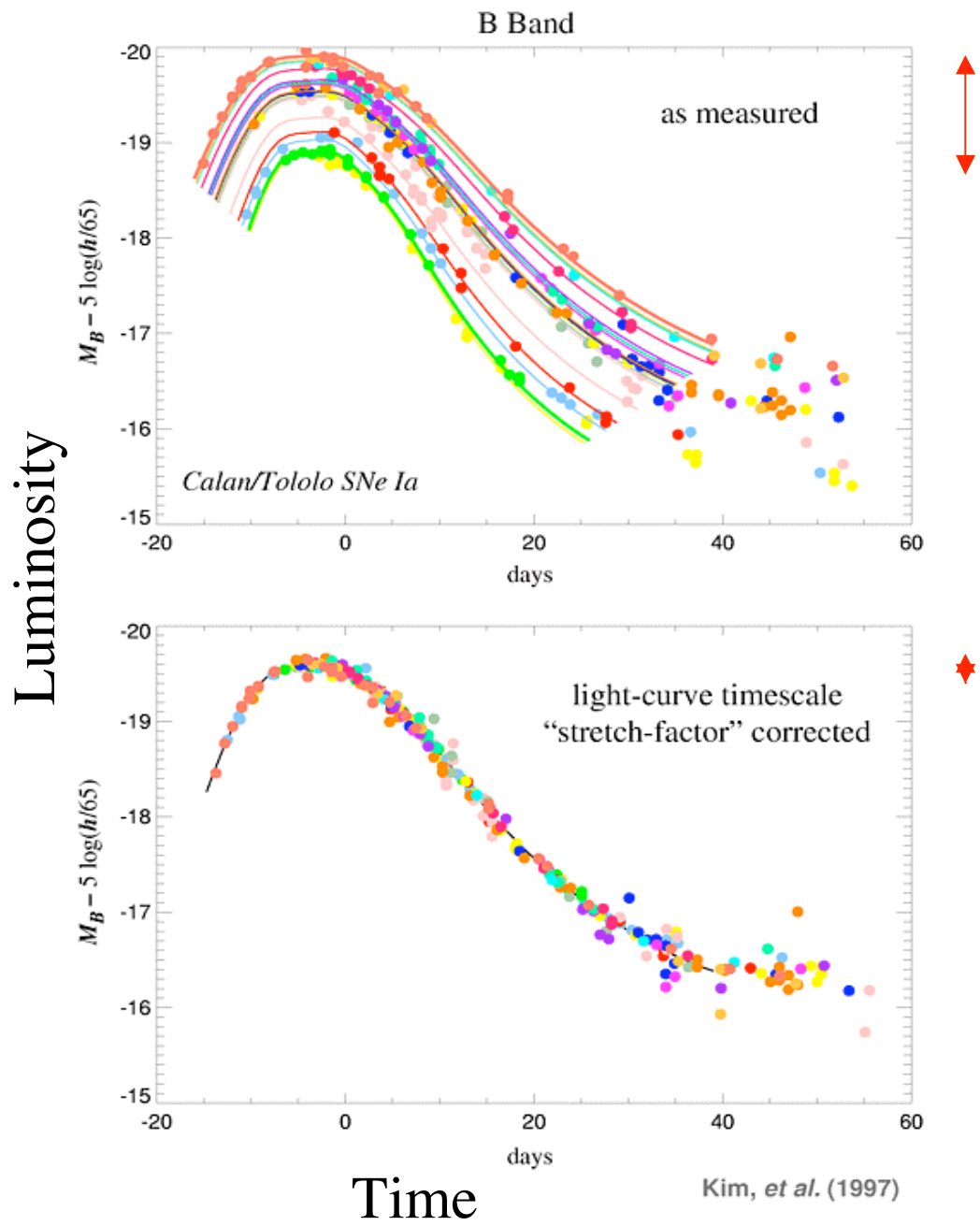
Survey	Description	Probes	Stage
Ground-based:			
ACT	SZ, 6-m	CL	II
APEX	SZ, 12-m	CL	II
SPT	SZ, 10-m	CL	II
VST	Optical imaging, 2.6-m	BAO,CL,WL	II
Pan-STARRS 1(4)	Optical imaging, 1.8-m($\times$4)	All	II(III)
DES	Optical imaging, 4-m	All	III
Hyper Suprime-Cam	Optical imaging, 8-m	WL,CL,BAO	III
ALPACA	Optical imaging, 8-m	SN, BAO, CL	III
LSST	Optical imaging, 6.8-m	All	IV
AAT WiggleZ	Spectroscopy, 4-m	BAO	II
HETDEX	Spectroscopy, 9.2-m	BAO	III
PAU	Multi-filter imaging, 2-3-m	BAO	III
SDSS BOSS	Spectroscopy, 2.5-m	BAO	III
WFMOS	Spectroscopy, 8-m	BAO	III
SKA	km^2 radio telescope	BAO, WL	IV
Space-based:			
JDEM Candidates			
ADEPT	Spectroscopy	BAO, SN	IV
DESTINY	Grism spectrophotometry	SN	IV
SNAP	Optical+NIR+spectro	SN, WL	IV
Proposed ESA Missions			
DUNE	Optical imaging	WL	
SPACE	Spectroscopy	BAO	
eROSITA	X-ray	CL	
CMB Space Probe			
Planck	SZ	CL	
Beyond Einstein Probe			
Constellation-X	X-ray	CL	IV

Type Ia SN
Peak Brightness
as calibrated
Standard Candle

Peak brightness
correlates with
decline rate

Variety of algorithms
for modeling these
correlations

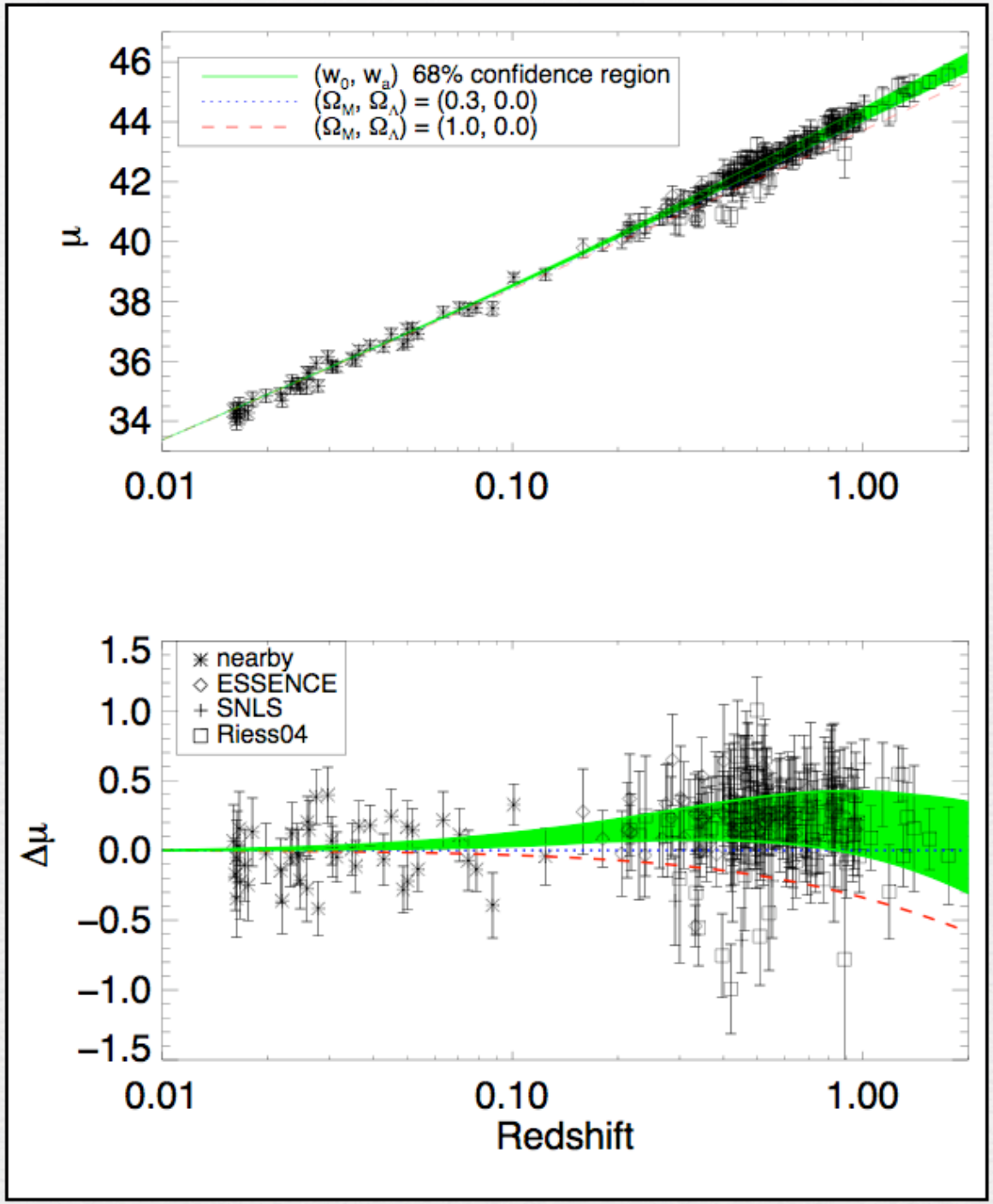
After correction,
σ~ 0.15 mag
(~7% distance error)



Global SNIa Hubble Diagram 2007

Hamuy 1996a,b
Riess 1998
Perlmutter 1999
Riess 1999
Riess 2001
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Clochiatti 2005
Astier 2006
Jha 2006

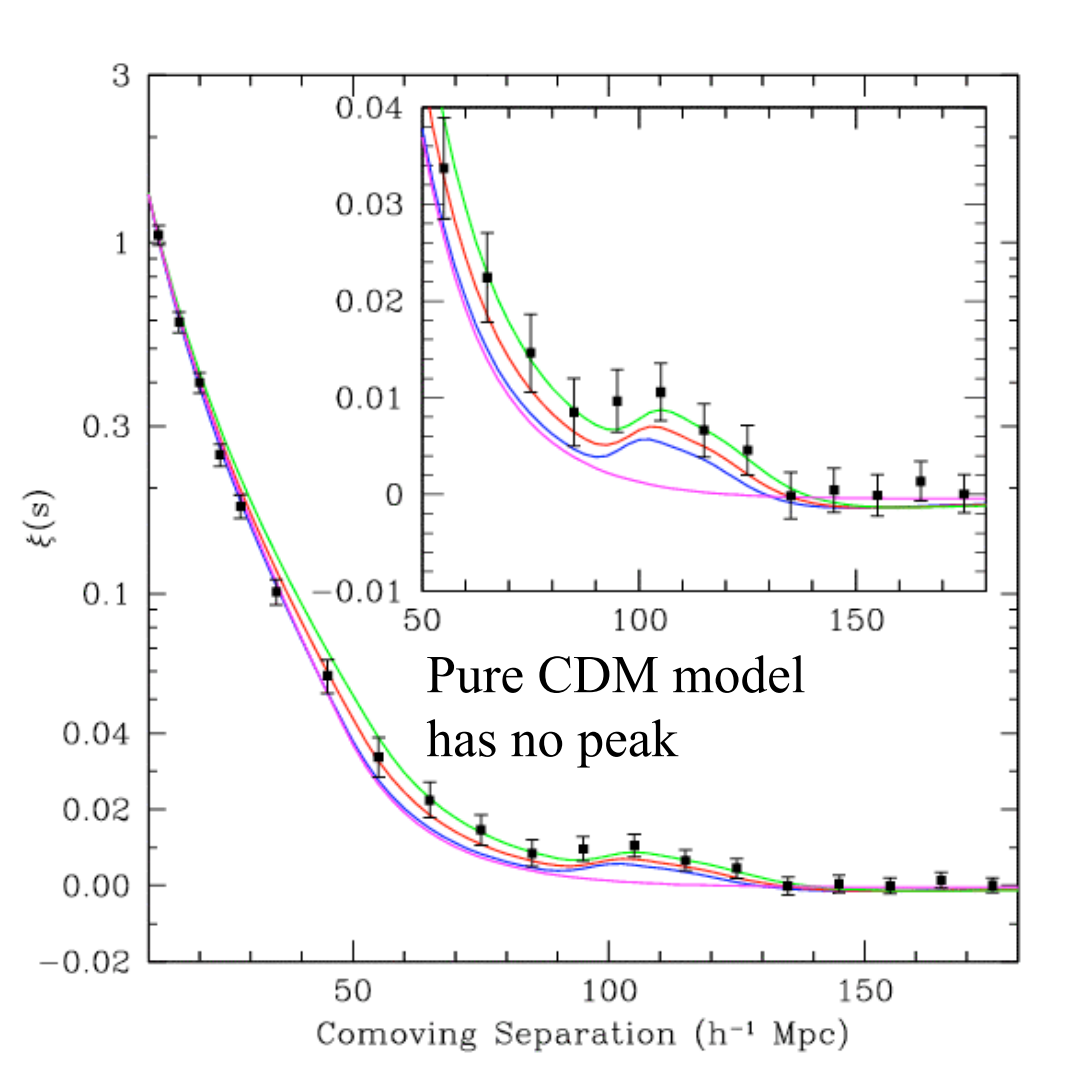
Wood-Vasey etal 07



Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function

$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$$



Baryon Acoustic Oscillations seen in Large-scale Structure

Eisenstein, etal 05

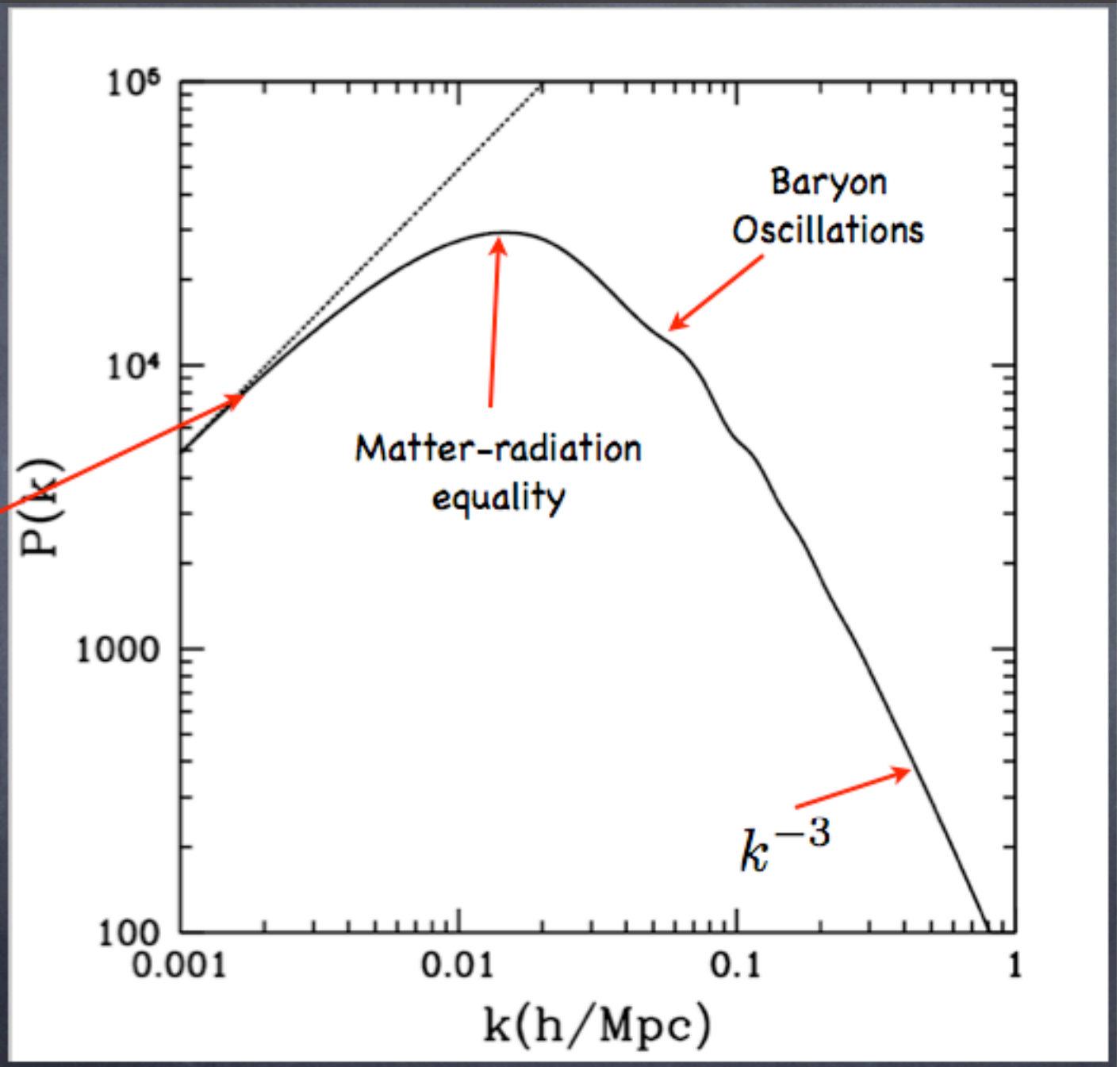
Cold Dark Matter Models

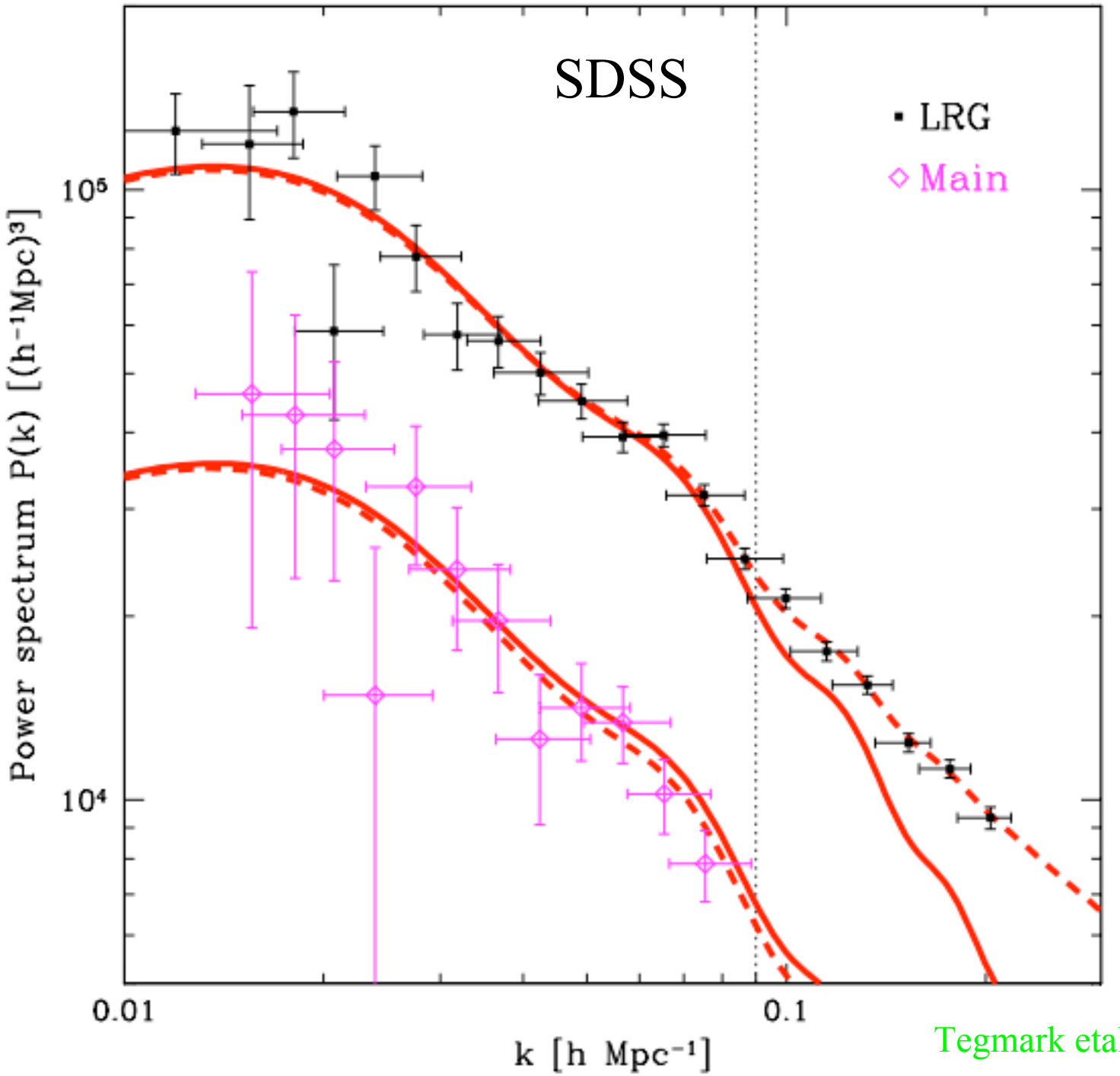
Power Spectrum of the Mass Density

Primordial

$$\delta(k) = \int d^3x \cdot e^{i\vec{k}\cdot\vec{x}} \frac{\delta\rho(x)}{\rho}$$

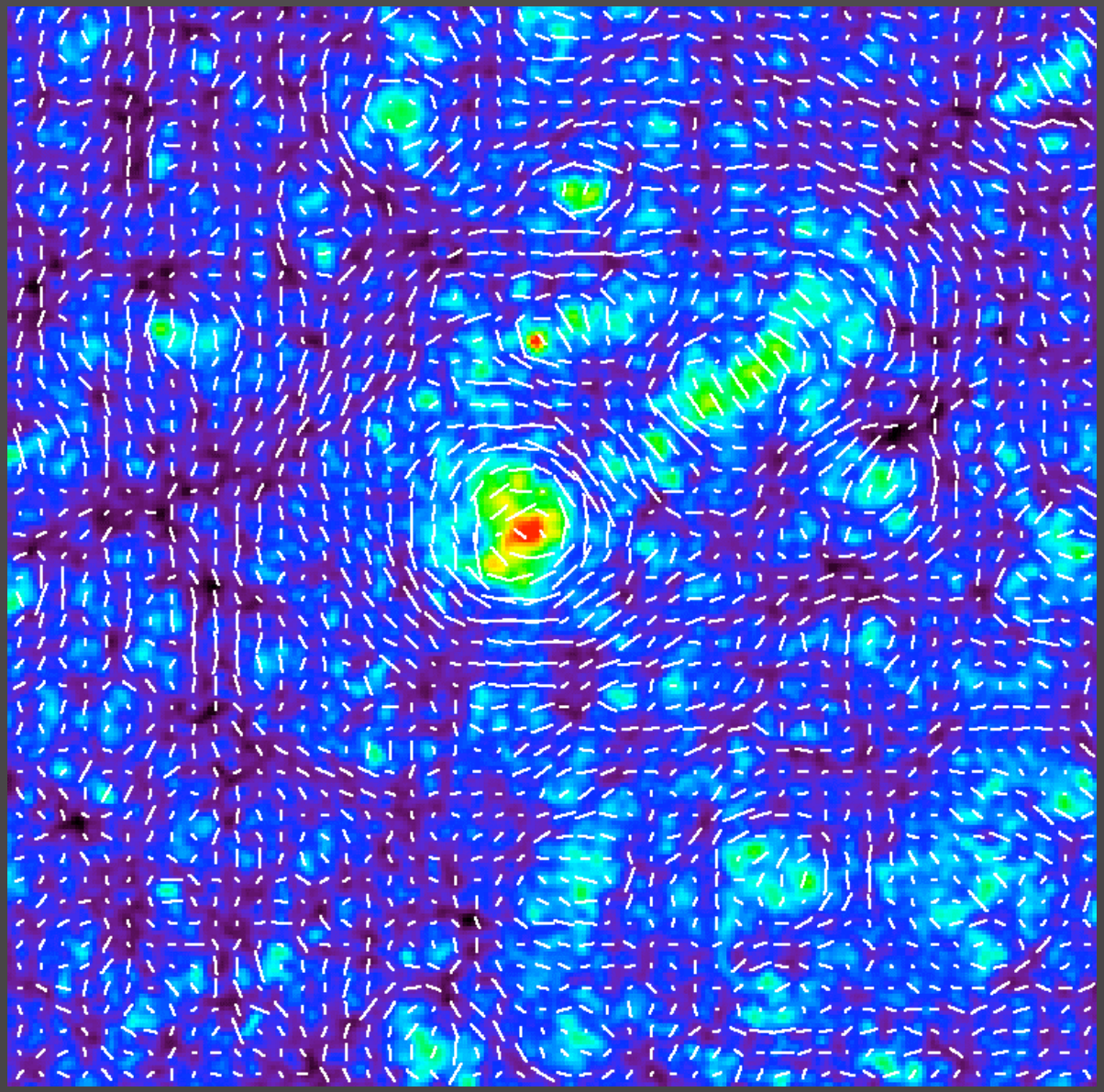
$$\langle \delta(k_1)\delta(k_2) \rangle = (2\pi)^3 P(k_1)\delta^3\left(\vec{k}_1 + \vec{k}_2\right)$$





Tegmark etal 06

Weak lensing: shear and mass



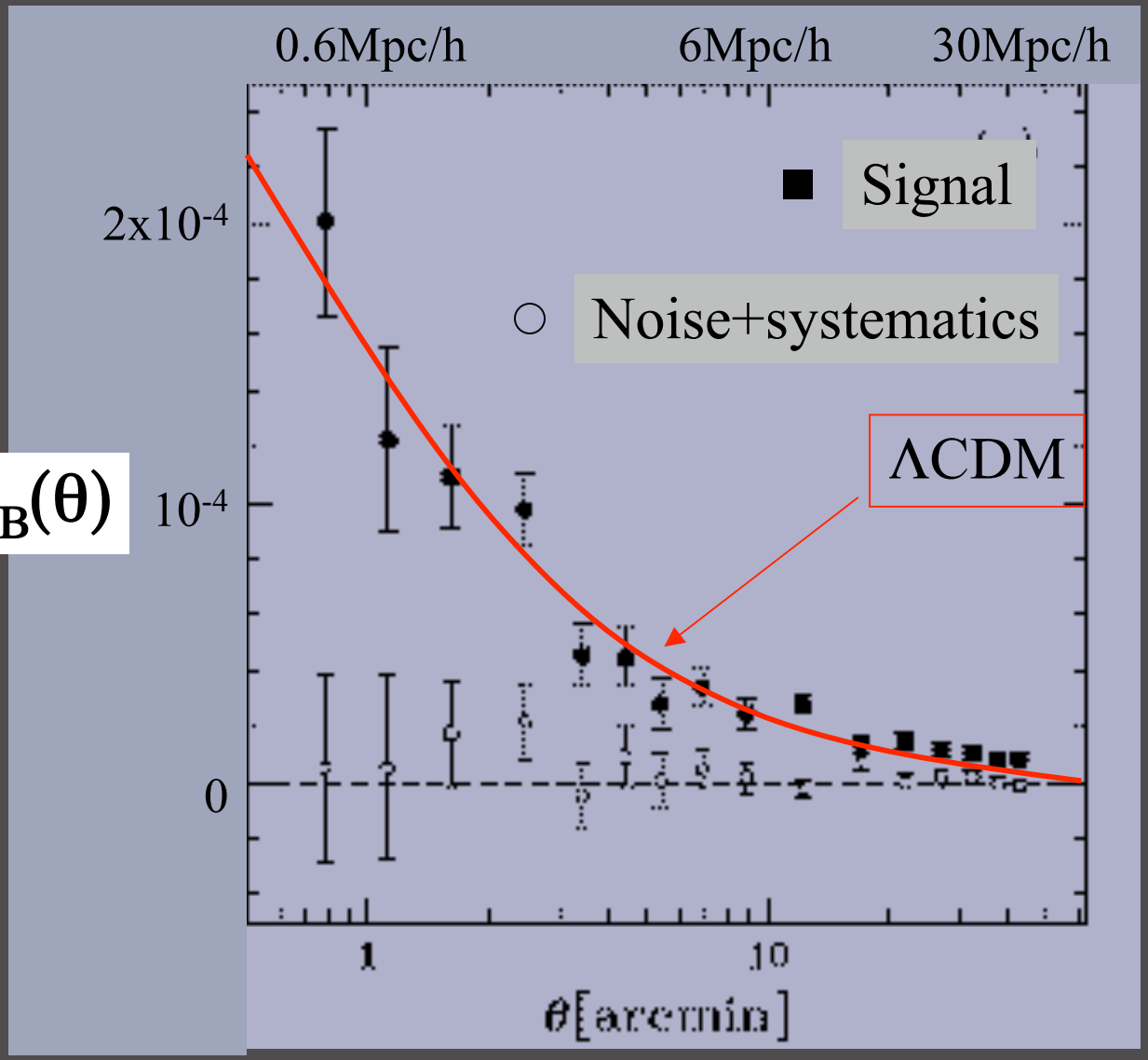
Jain

Cosmic Shear Correlations

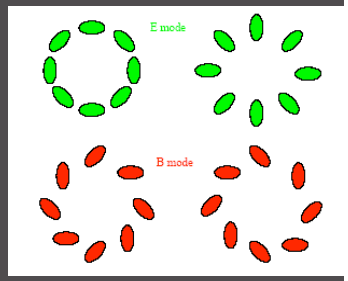
VIRMOS-Descart Survey

Shear Amplitude

$\xi_{E,B}(\theta)$



- 55 sq deg
- $z = 0.8$



Van Waerbeke etal 05

Clusters and Dark Energy

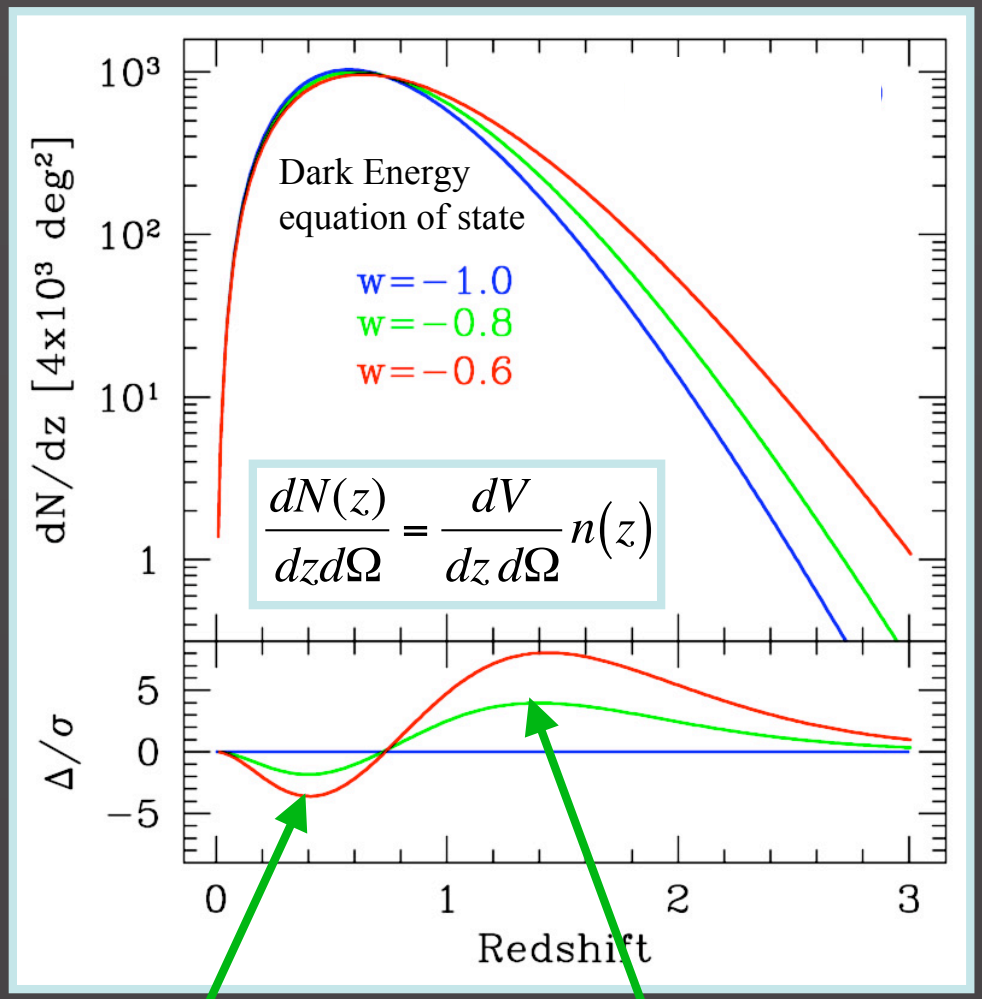
- Requirements
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy *O* that can be used as cluster mass estimate:

     $p(O|M,z)$

Primary systematic:

Uncertainty in bias & scatter of mass-observable relation

Number of clusters above observable mass threshold

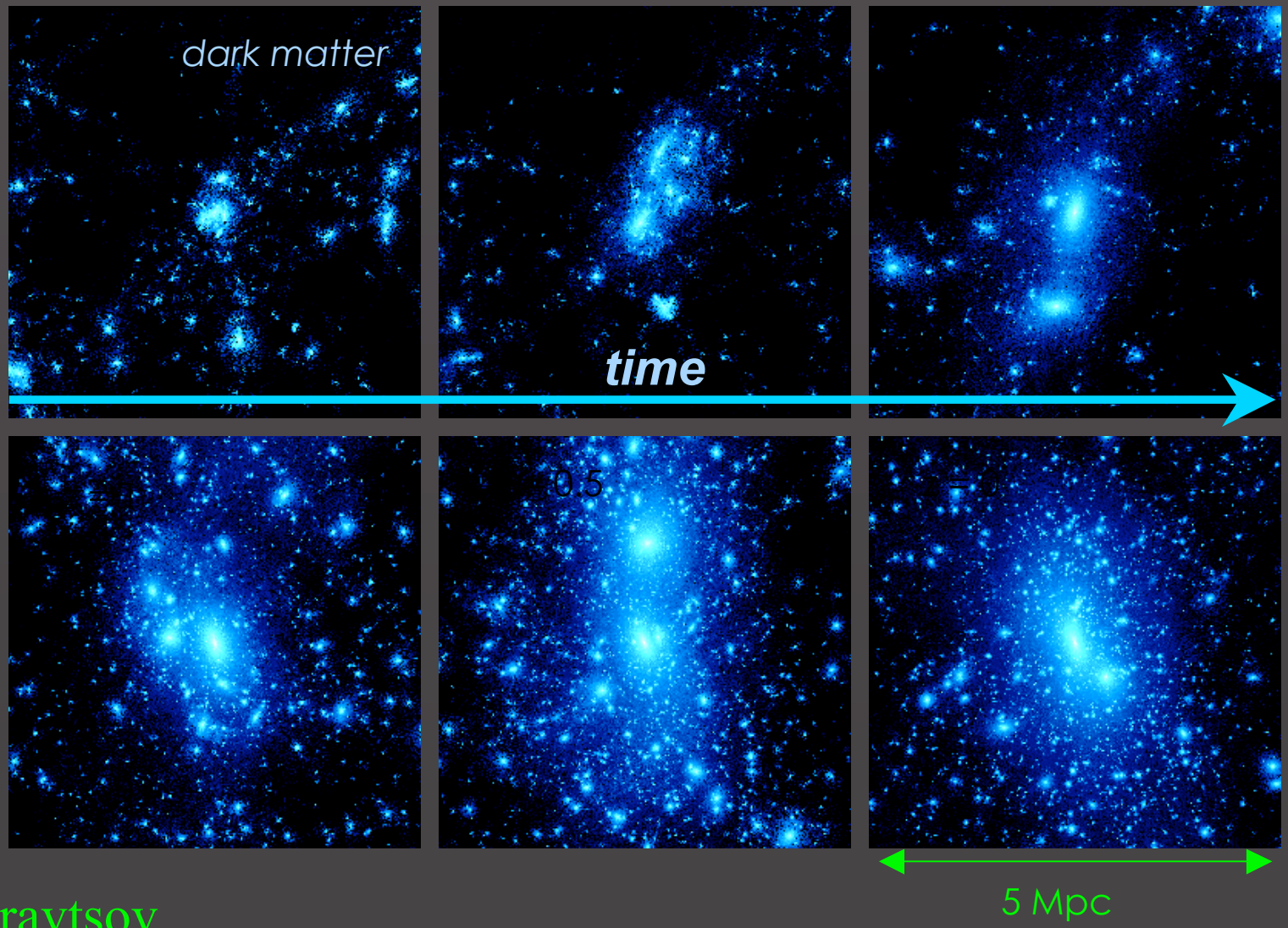


Volume (geometry)

Growth

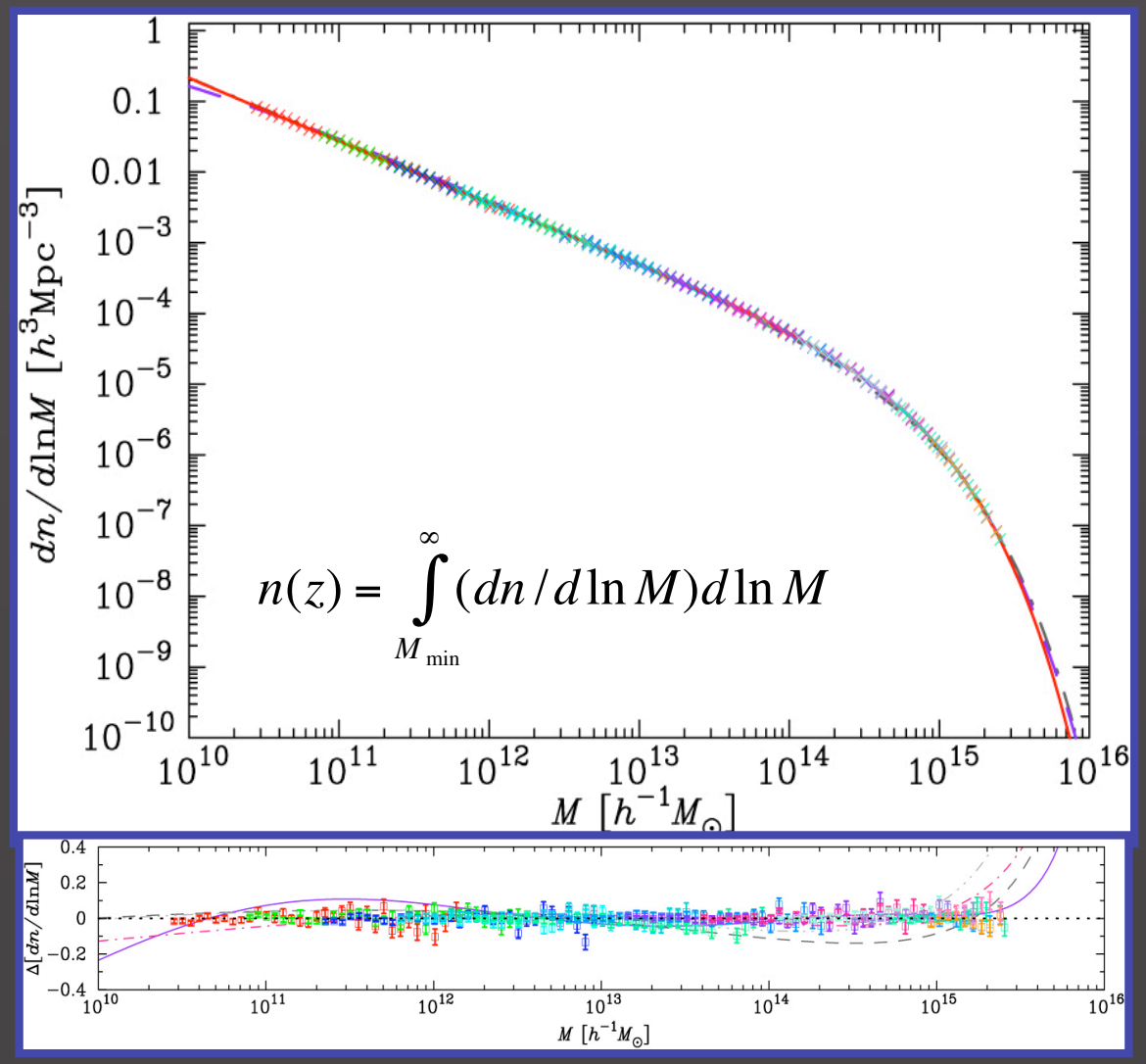
Mohr

Clusters form hierarchically



Kravtsov

Theoretical Abundance of Dark Matter Halos

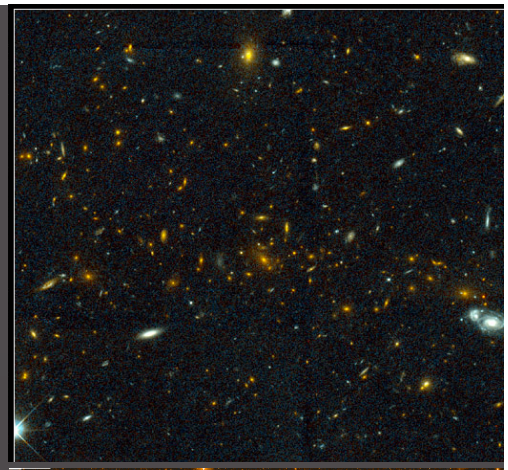


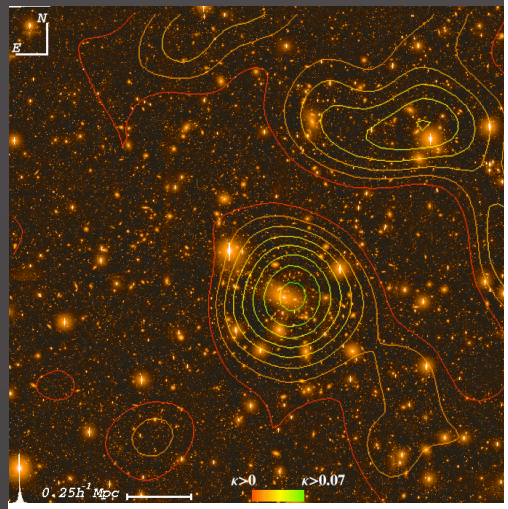
Warren etal

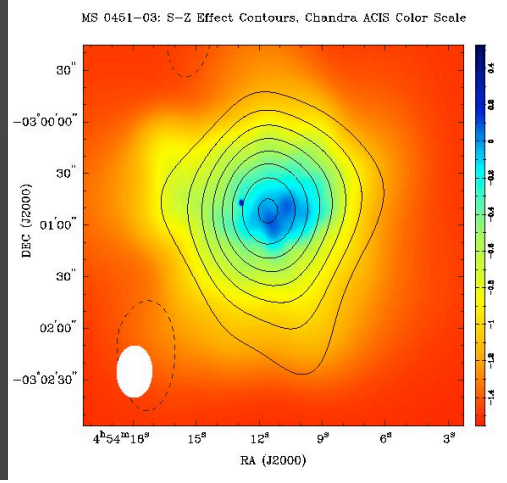
Cluster Selection

- 4 Techniques for Cluster Selection:
  - Optical galaxy concentration
  - Weak Lensing
  - Sunyaev-Zel'dovich effect (SZE)
  - X-ray

  - Cross-compare selection to control systematic errors



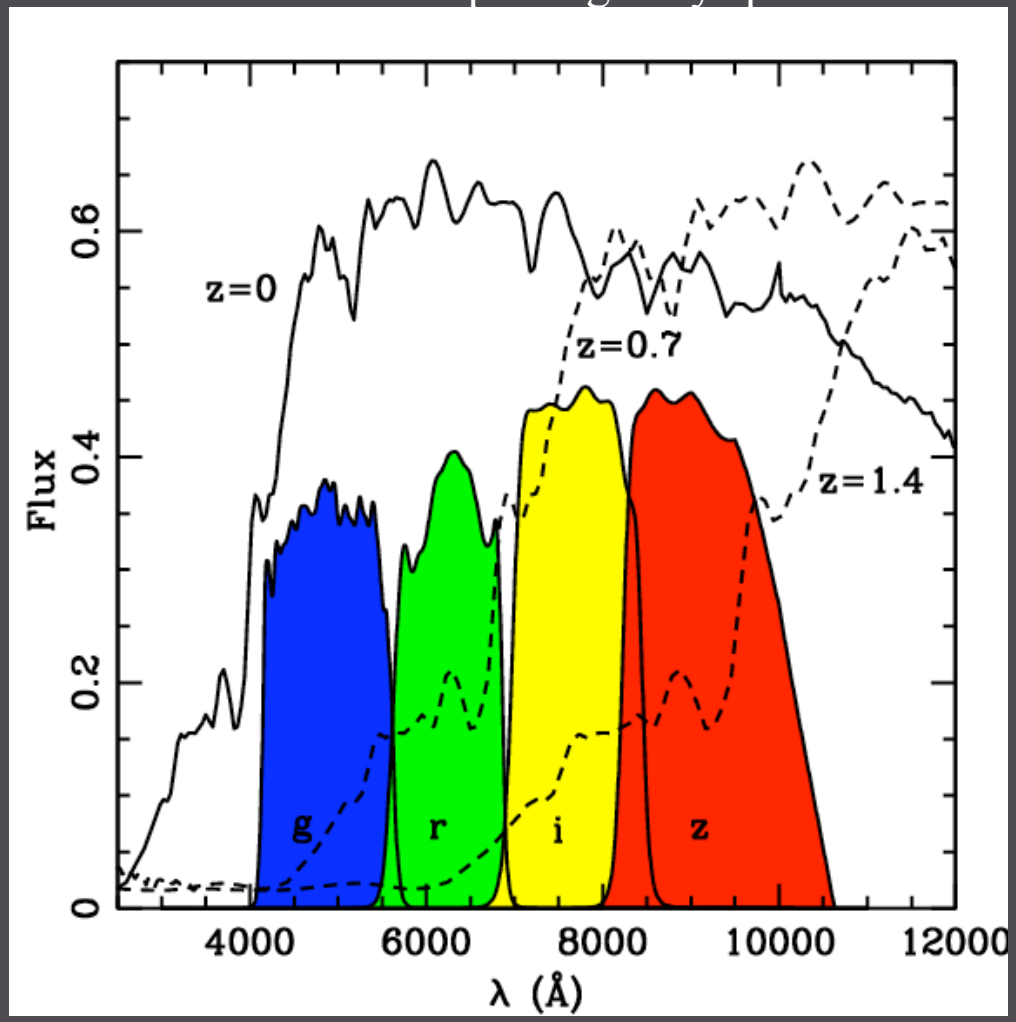




Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 A break
- Precision is sufficient for Dark Energy probes, *provided* error distributions well measured.
- Need deep spectroscopic galaxy samples to calibrate

Redshifted Elliptical galaxy spectrum



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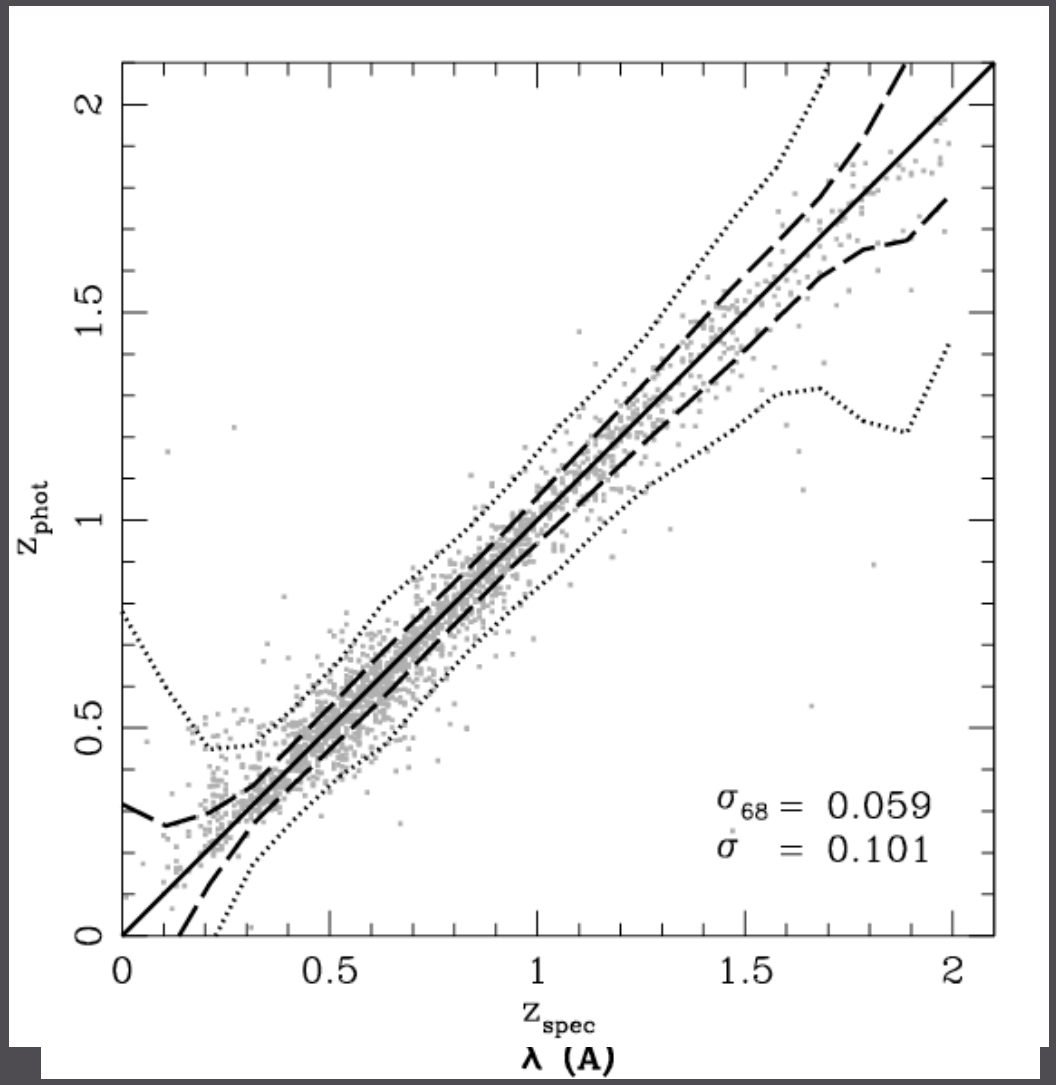


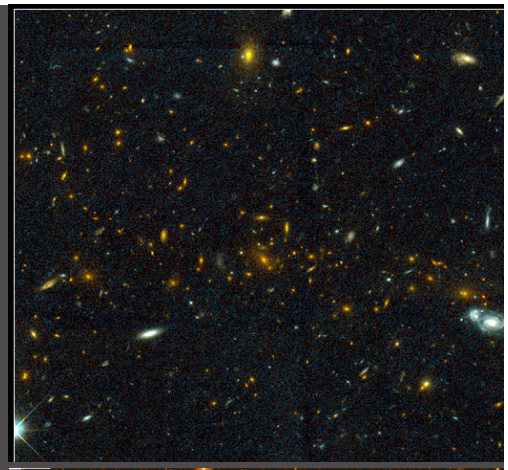
Cluster Mass Estimates

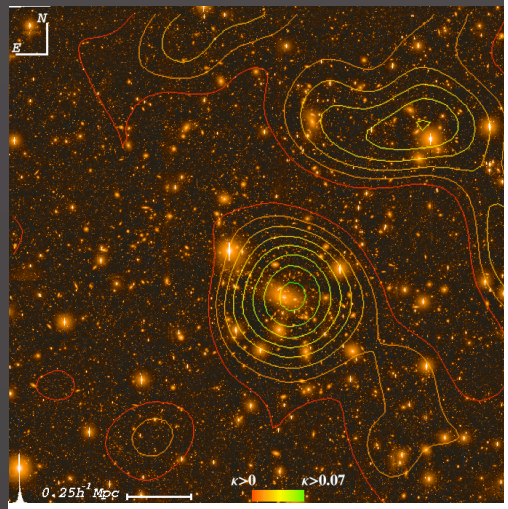
4 Techniques for Cluster Mass Estimation:

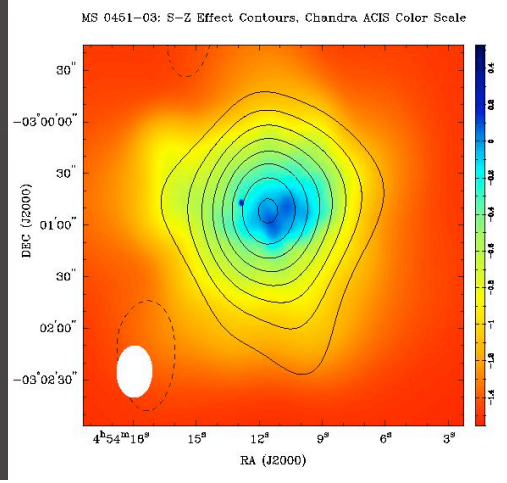
- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel'dovich effect (SZE)
- X-ray

- Cross-compare these techniques to reduce systematic errors
- Additional cross-checks:

  shape of mass function; cluster correlations

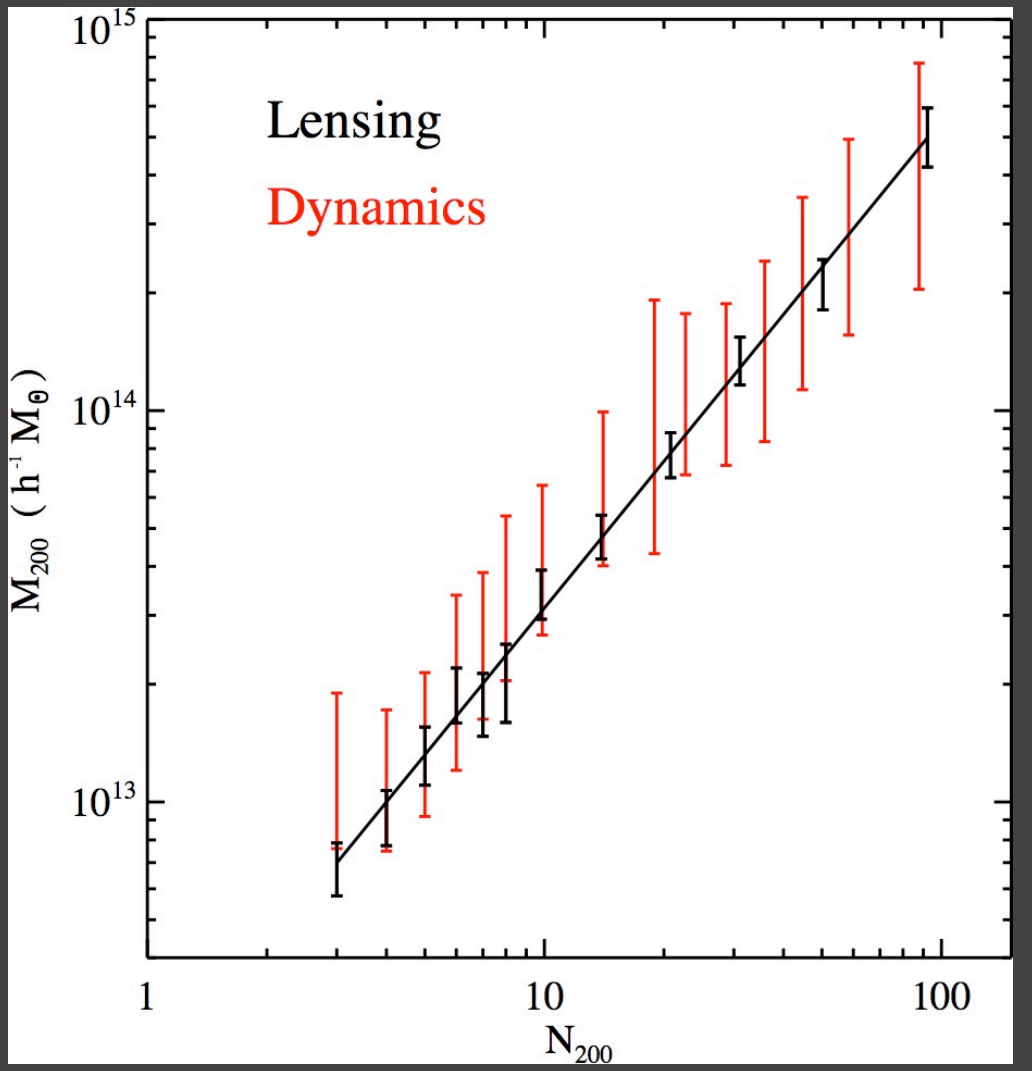






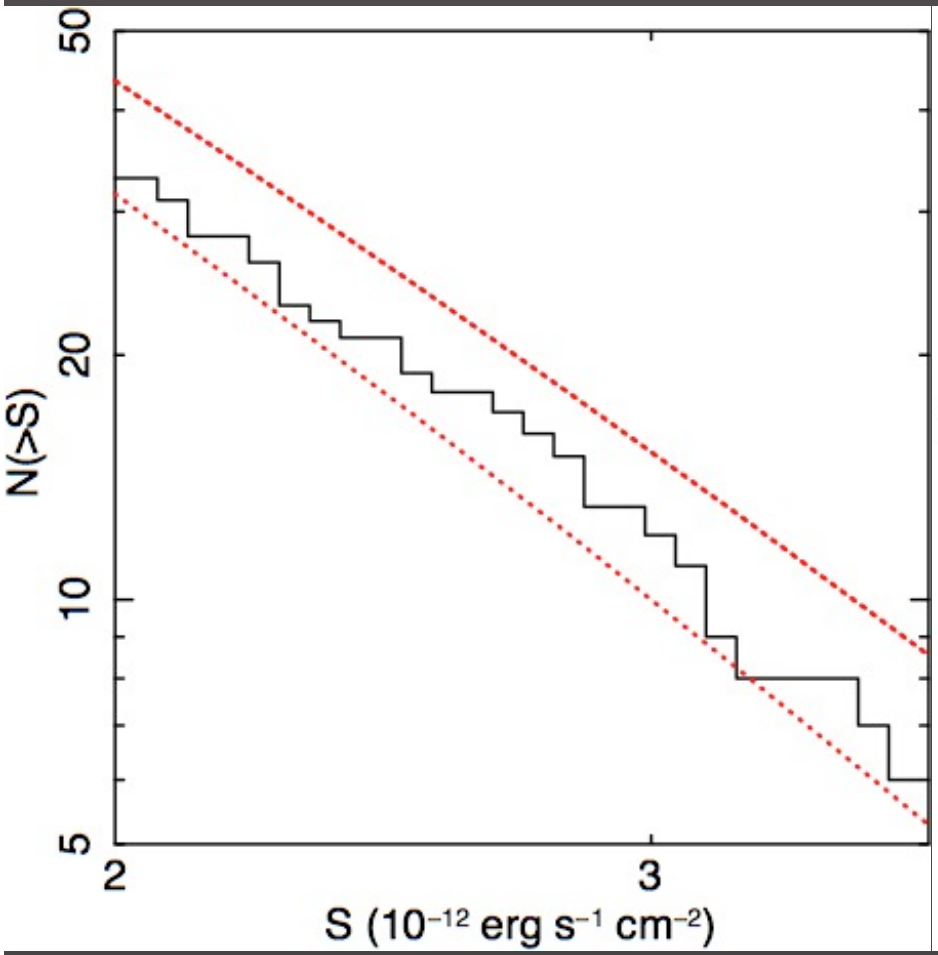
Calibrating the Cluster Mass-Observable Relation

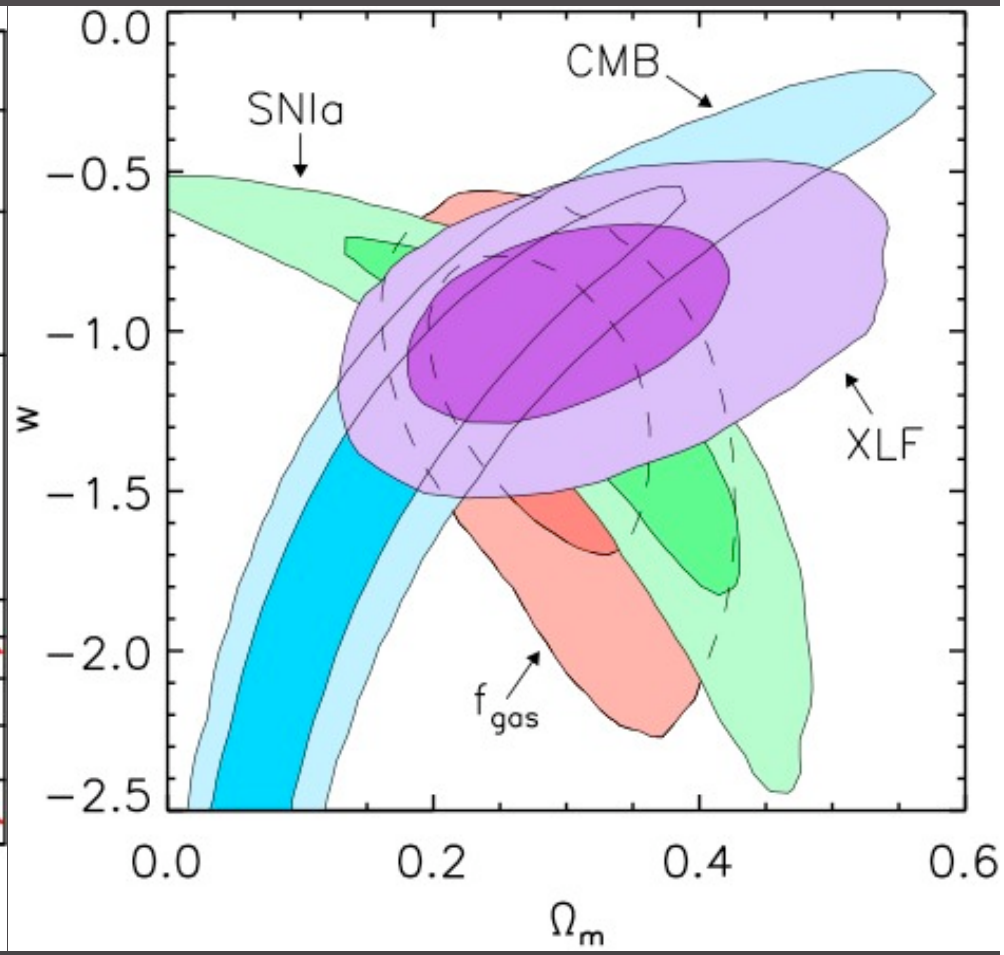
- Weak Lensing by stacked SDSS Clusters
- insensitive to projection effects
- Calibrate mass-richness



Johnston, Sheldon, etal 07

Current Constraints: X-ray clusters





Mantz, et al 2007

Systematic Errors

- Supernovae: uncertainties in dust and SN colors; selection biases; ``hidden" luminosity evolution; limited low-z sample for training & anchoring
- BAO: redshift distortions; galaxy bias; non-linearities; selection biases
- Weak Lensing: additive and multiplicative shear errors; photo-z systematics; small-scale non-linearity & baryonic efffects
- Clusters: scatter & bias in mass-observable relation; uncertainty in observable selection function; small-scale non-linearity & baryonic effects

Conclusions

• Excellent prospects for increasing the precision on Dark Energy parameters from a sequence of increasingly complex and ambitious experiments over the next 5-15 years

• Exploiting complementarity of multiple probes will be key: we don't know what the ultimate systematic error floors for each method will be. Combine geometric with structure-growth probes to help distinguish modified gravity from dark energy.

• What parameter precision is needed to stimulate theoretical progress? It depends in large part on what the answer is.