Falsifying

Dark Energy Paradigms

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Outline

- Falsifiable Predictions of
  - ΛCDM
  - Smooth Dark Energy
- Confrontation with
  - Clusters of Galaxies
  - Cosmic Shear

- Collaborators

Tim Eifler
Dragan Huterer
Michael Mortonson
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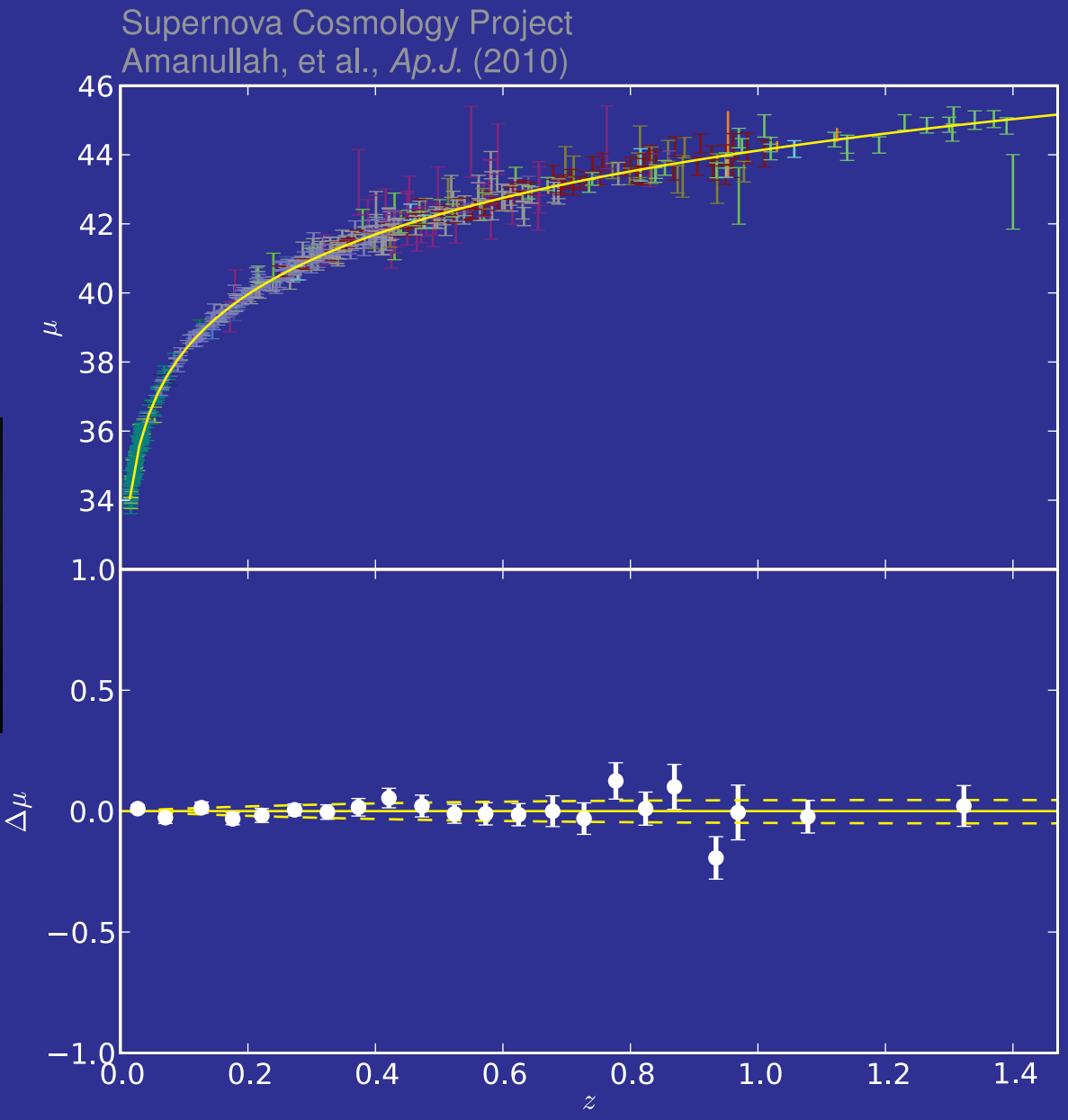
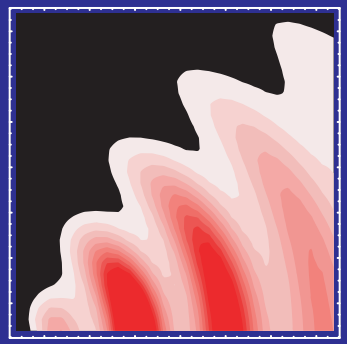
Falsifying ΛCDM

- Geometric measures of distance redshift from SN, CMB, BAO

Standard(izable)
Candle
Supernovae
Luminosity v Flux





Standard Ruler
Sound Horizon
v CMB, BAO angular
and redshift separation

Fixed Deceleration Epoch

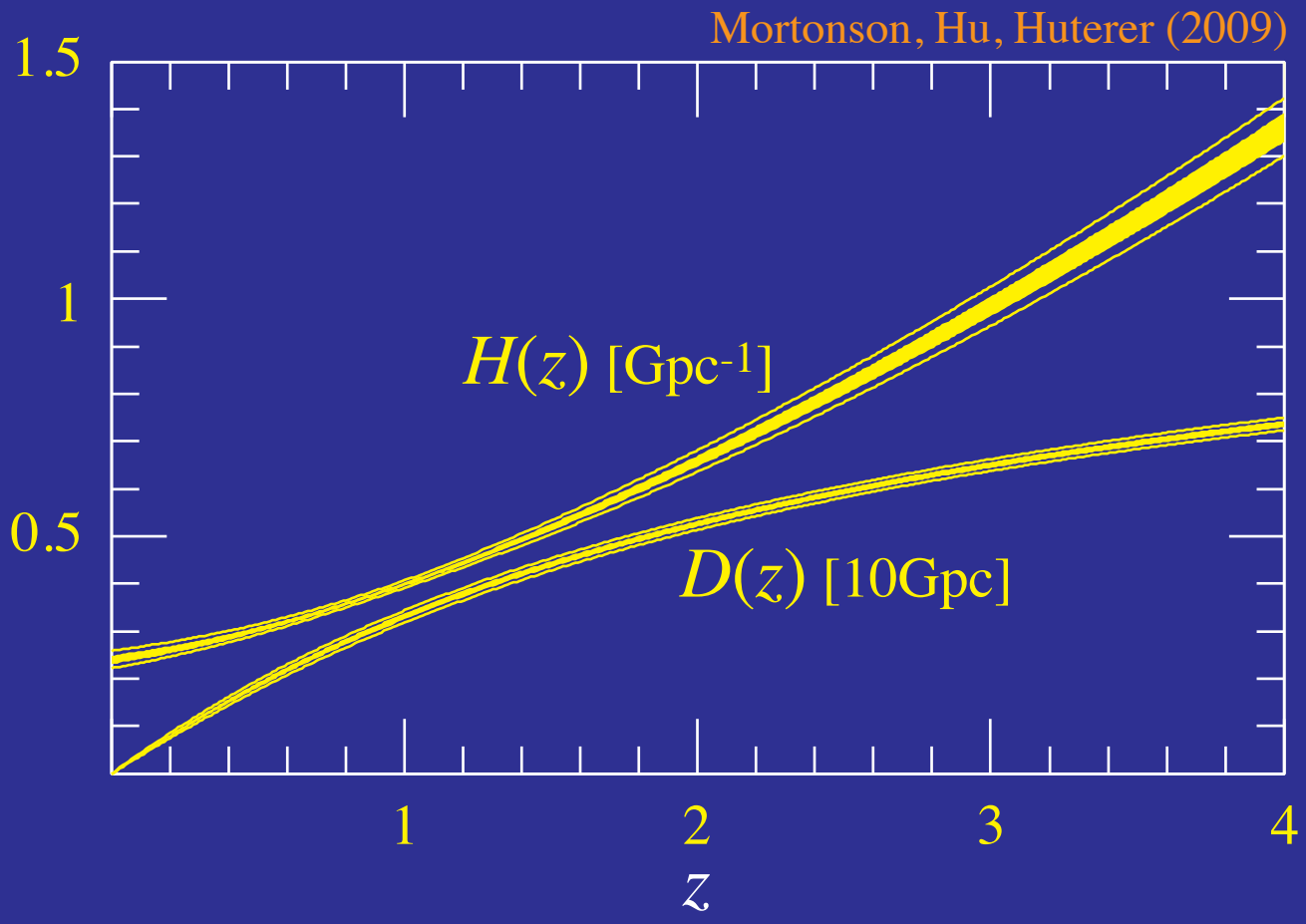
- CMB gives matter density assuming standard radiation content
- WMAP7: $\Omega_m h^2 = 0.133 \pm 0.006 \rightarrow 4.5\%$
- Distance to recombination D_* determined to $\frac{1}{4} 4.5\% \approx 1\%$
- Expansion rate during any redshift in the deceleration epoch determined to $\frac{1}{2} 4.5\%$
- Distance to any redshift in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- Volumes determined by a combination $dV = D_A^2 d\Omega dz / H(z)$
- Structure also determined by growth of fluctuations from z_*
- $\Omega_m h^2$ can be determined to $\sim 1\%$ from Planck.

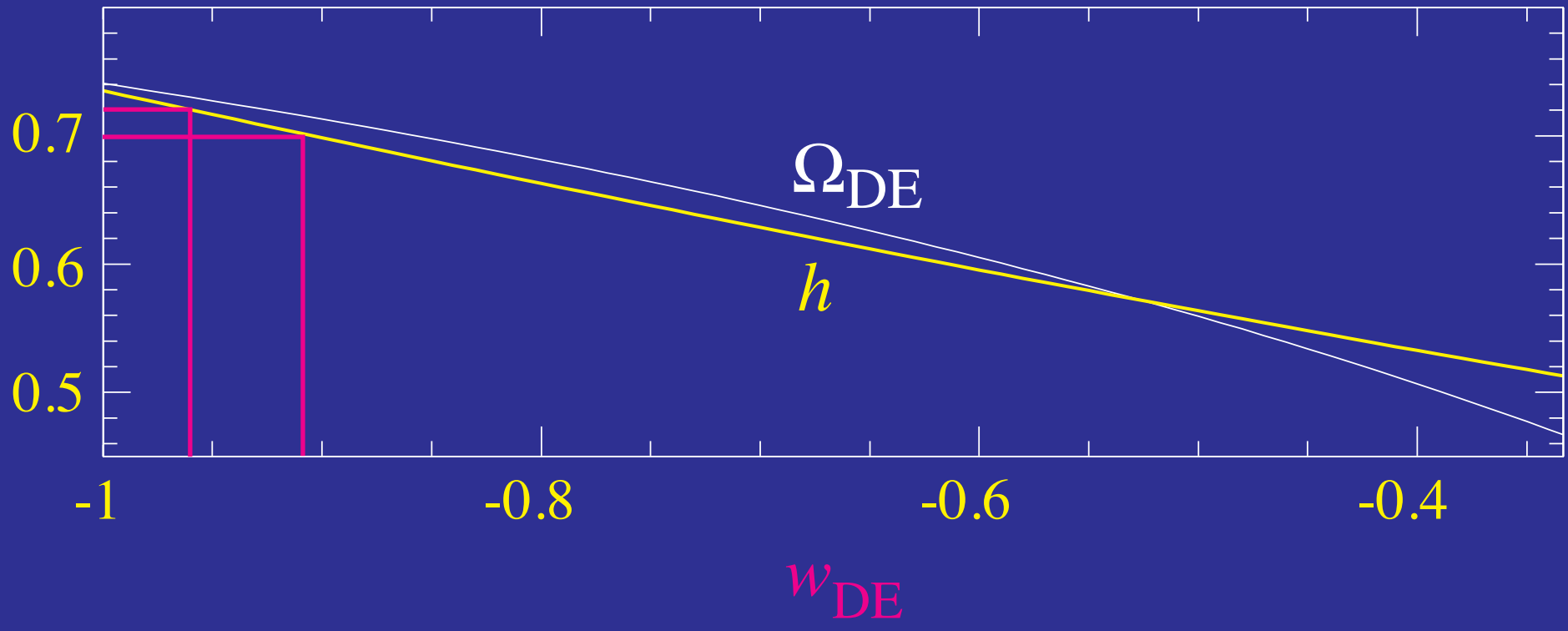
Flat ΛCDM

- CMB predicts expansion history and distance redshift relation at all redshifts to few percent precision
- Any violation falsifies flat ΛCDM
  (violation of flatness falsifies standard inflation)



H_0 = Dark Energy

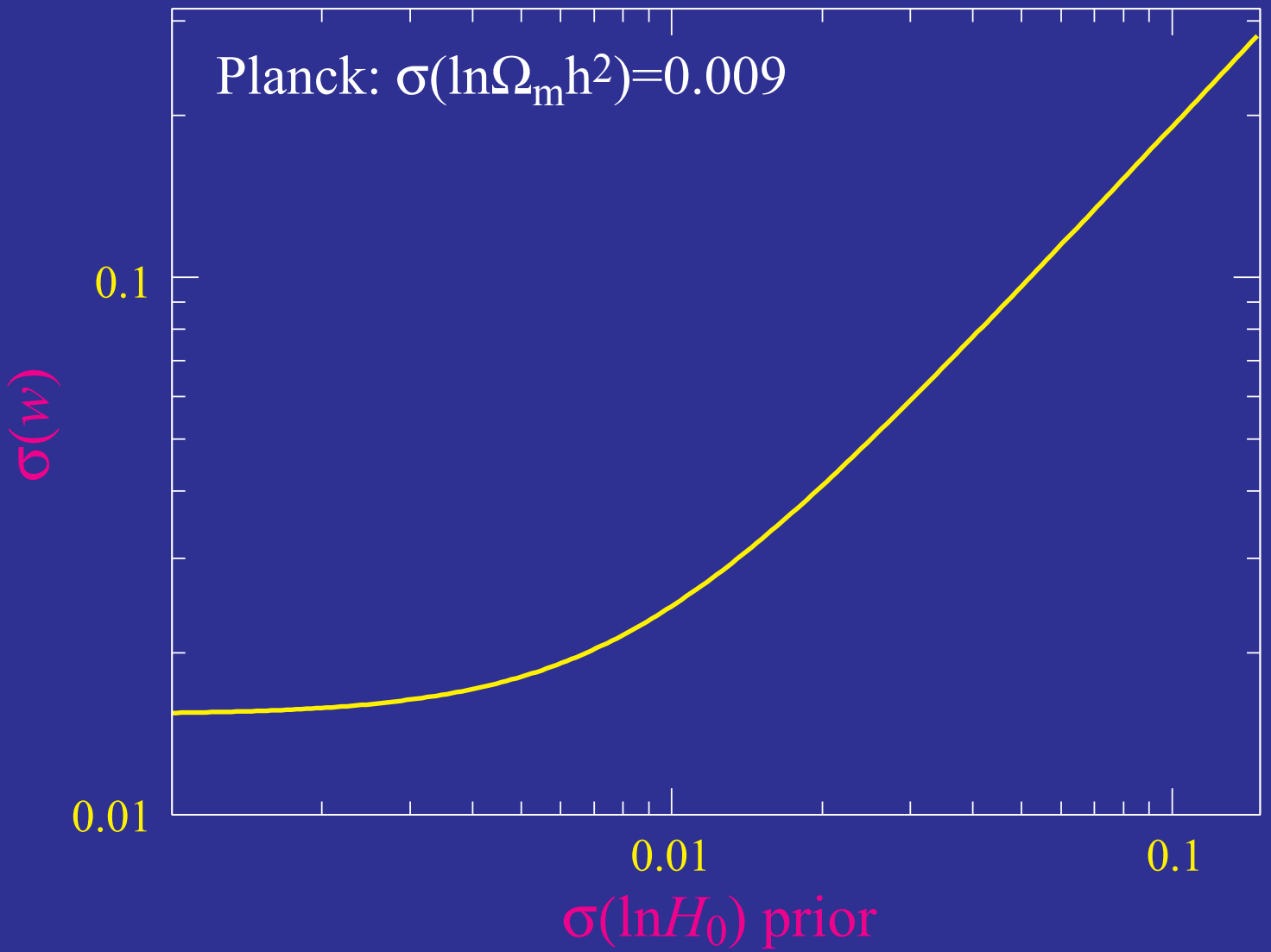
- Flat constant w dark energy model
- Determination of Hubble constant gives w to comparable precision



- For evolving w, equal precision on average or pivot w, equally useful for testing a cosmological constant
- If $w \geq -1$, then Hubble constant can only decrease

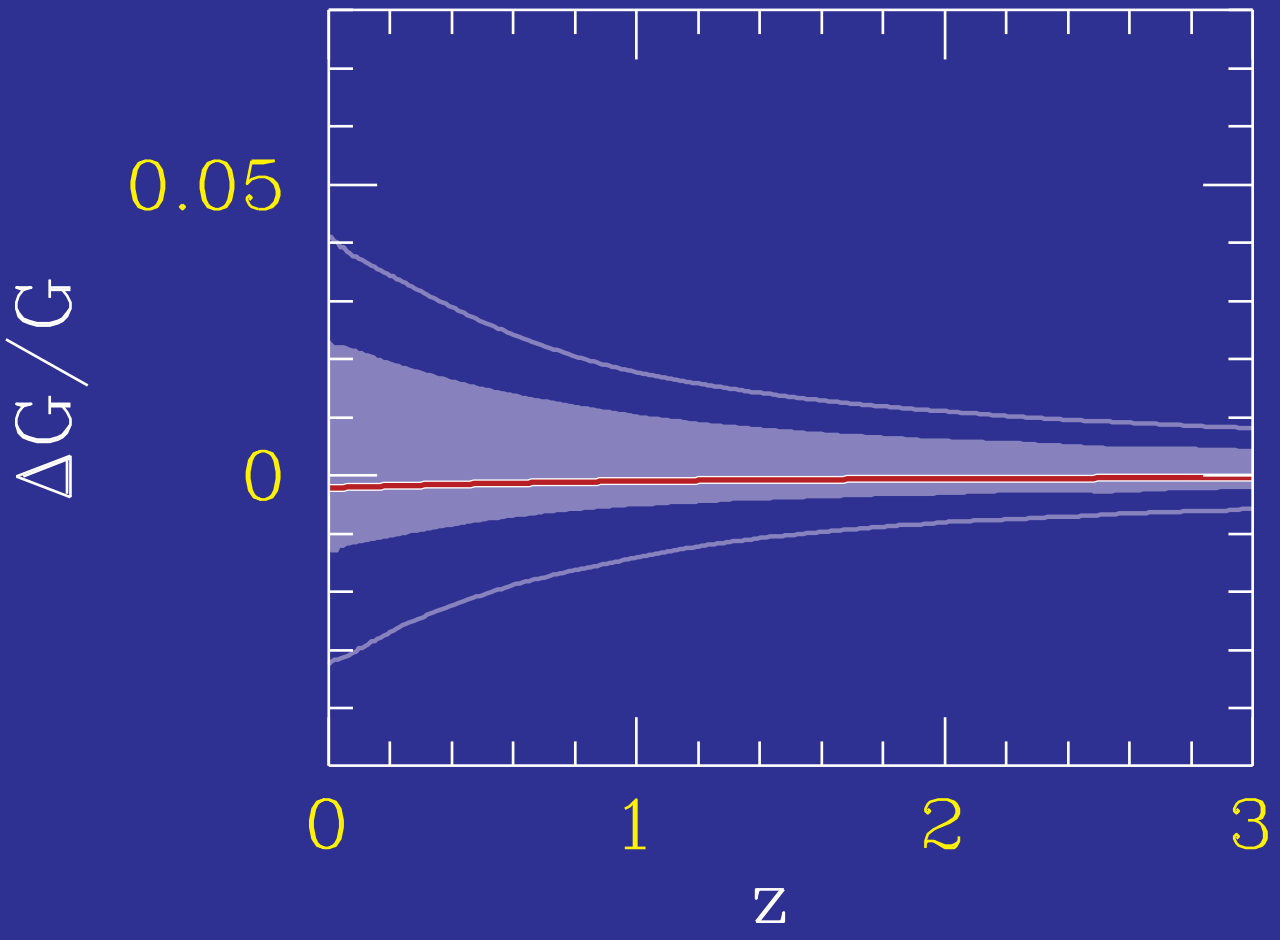
Forecasts for CMB+H_0

- To complement CMB observations with $\Omega_m h^2$ to 1%, an H_0 of ~1% enables constant w measurement to ~2% in a flat universe



Falsifying ΛCDM

- Λ slows growth of structure in highly predictive way



Cosmological Constant

Beyond ΛCDM

Smooth Dark Energy

- Scalar field dark energy has $\delta p = \delta\rho$ (in constant field gauge) – relativistic sound speed, no anisotropic stress
- Jeans stability implies that its energy density is spatially smooth compared with the matter below the sound horizon

$$\begin{aligned} ds^2 &= -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2 \\ \nabla^2\Phi &\propto \text{matter density fluctuation} \end{aligned}$$

- Anisotropic stress changes the amount of space curvature per unit dynamical mass: negligible for both matter and smooth dark energy

$$\nabla^2(\Phi+\Psi) \propto \text{anisotropic stress approx } 0$$

in contrast to modified gravity or force-law models

Falsifiability of Smooth Dark Energy

- With the smoothness assumption, dark energy only affects gravitational growth of structure through changing the expansion rate
- Hence geometric measurements of the expansion rate predict the growth of structure
  - Hubble Constant
  - Supernovae
  - Baryon Acoustic Oscillations
- Growth of structure measurements can therefore falsify the whole smooth dark energy paradigm
  - Cluster Abundance
  - Weak Lensing
  - Velocity Field (Redshift Space Distortion)

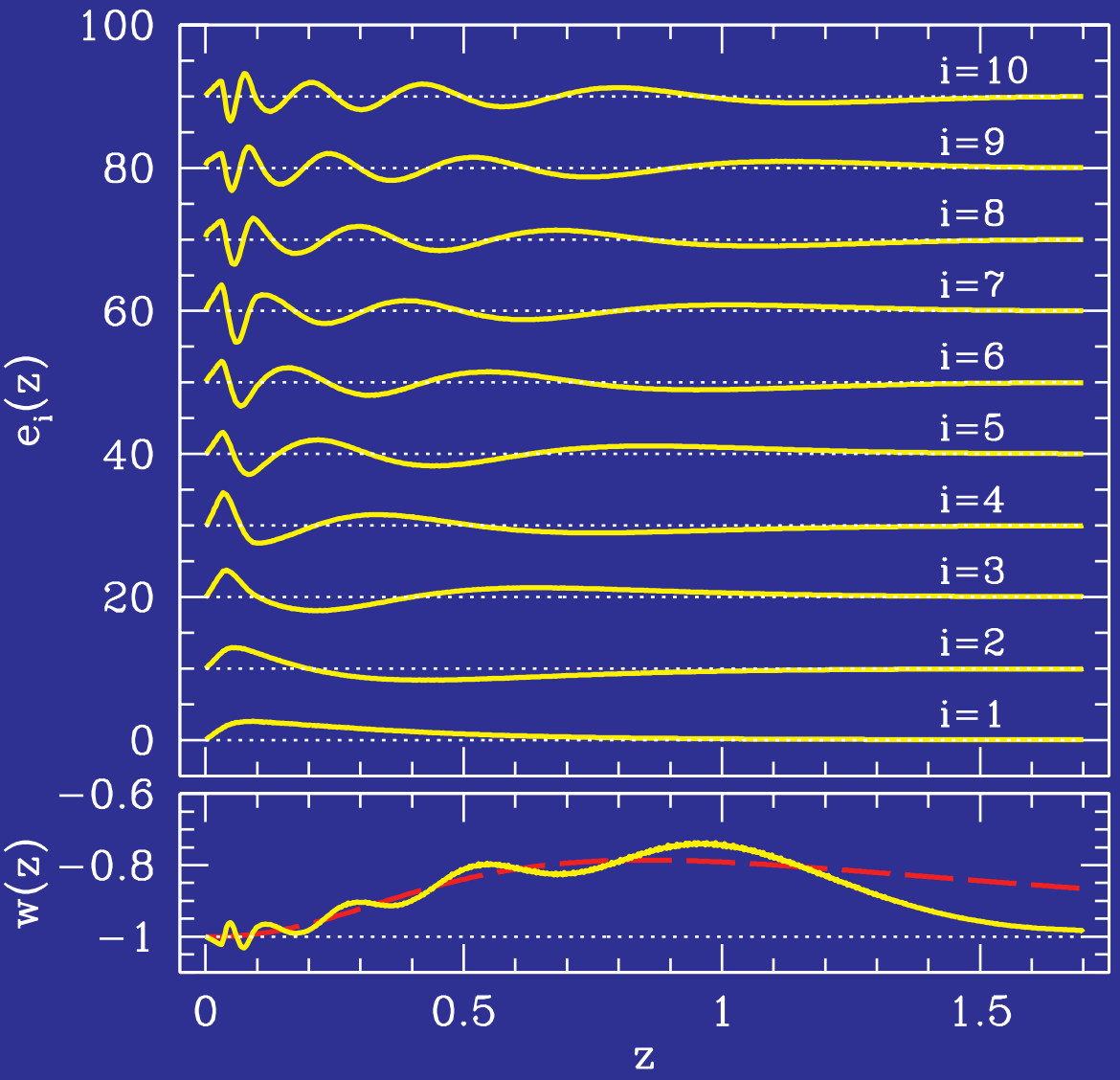
Why PCs

- Principal components are the eigenbasis of the projected or actual covariance matrix for a discrete representation of $f(x_i)$
- Rank ordered in observability and decorrelated linear combination

  Advantages:
  - Define according to Fisher projected covariance matrix – no a posteriori bias in looking for features
  - Efficient – can keep only observable modes and never requires MCMC over large correlated discrete space
  - Complete – can include as many modes as required to make basis observationally complete
  - Paradigm testing – rapidly explore all possible observational outcome of a given paradigm
  - Falsifiable predictions for other observables not yet measured

Equation of State PCs

- 10 PCs defined for StageIV (SNAP+Planck) define an observationally complete basis out to z=1.7

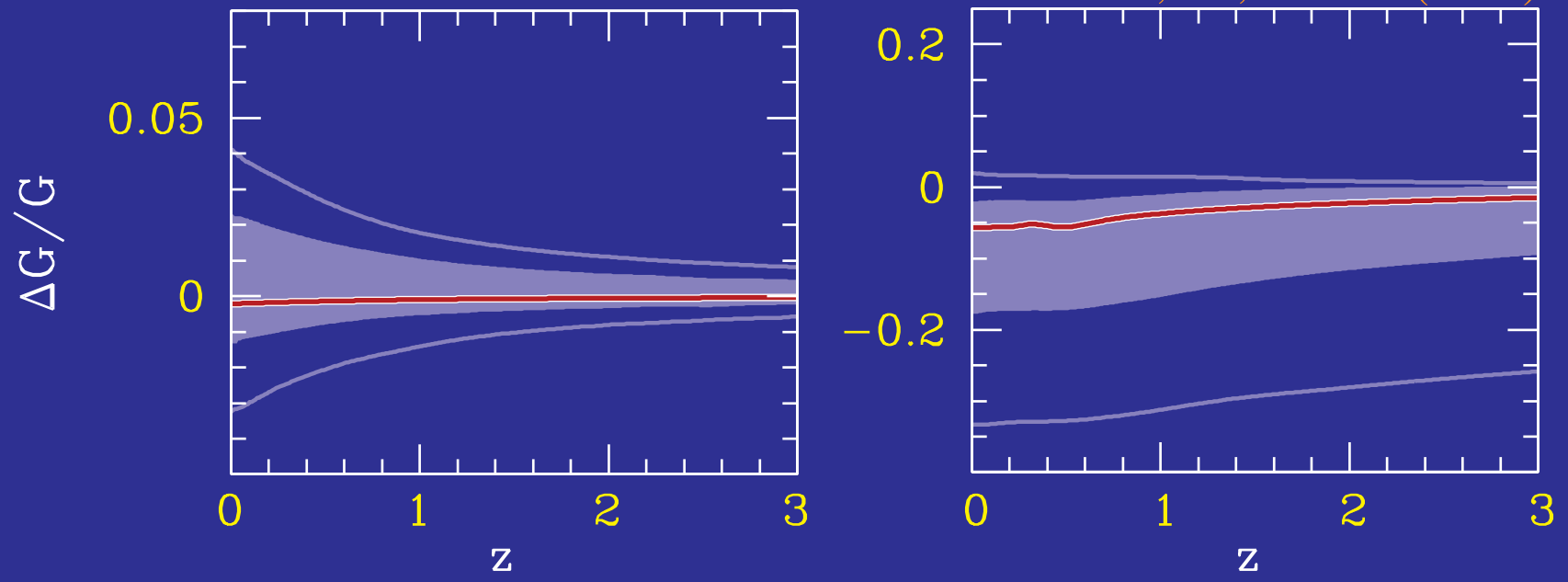


Mortonson, Huterer, Hu (2010)

Falsifying Quintessence

- Dark energy slows growth of structure in highly predictive way

Mortonson, Hu, Huterer (2009)



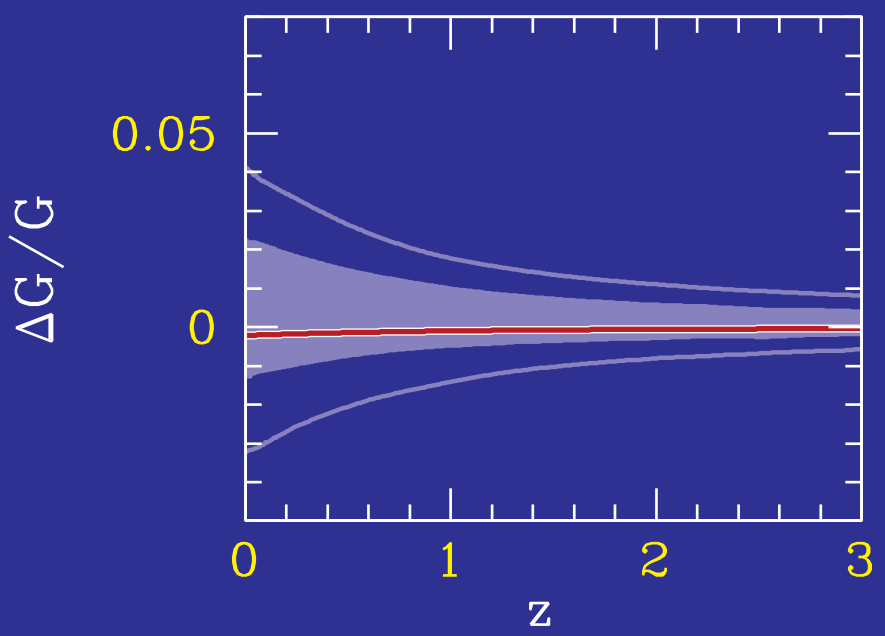
Cosmological Constant Quintessence

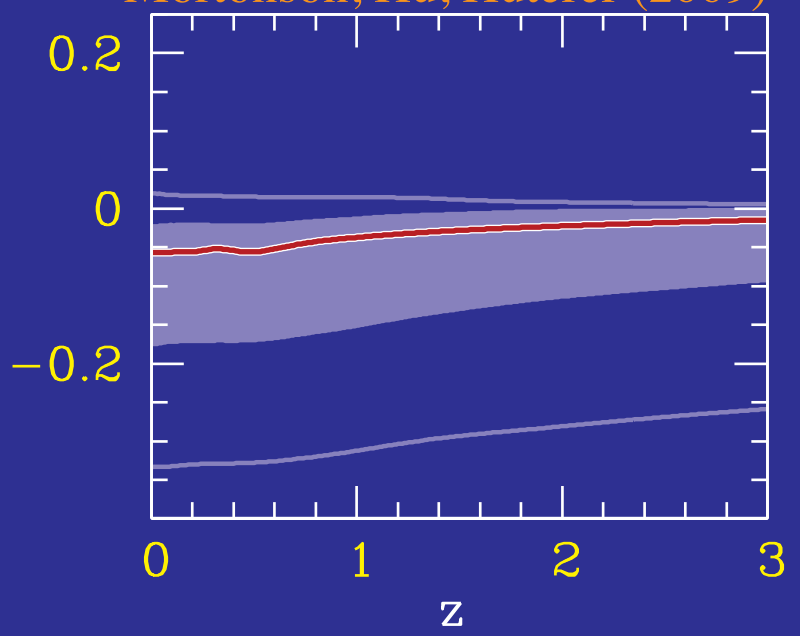
- Deviation significantly >2% rules out Λ with or without curvature
- Excess >2% rules out quintessence with or without curvature and early dark energy [as does >2% excess in H_0]

Dynamical Tests of Acceleration

- Dark energy slows growth of structure in highly predictive way

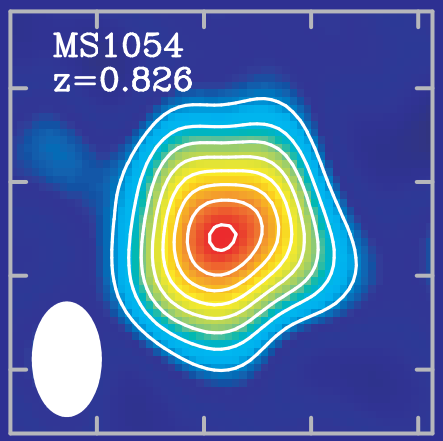
Mortonson, Hu, Huterer (2009)

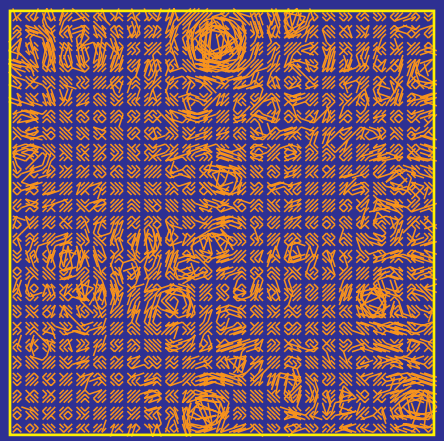


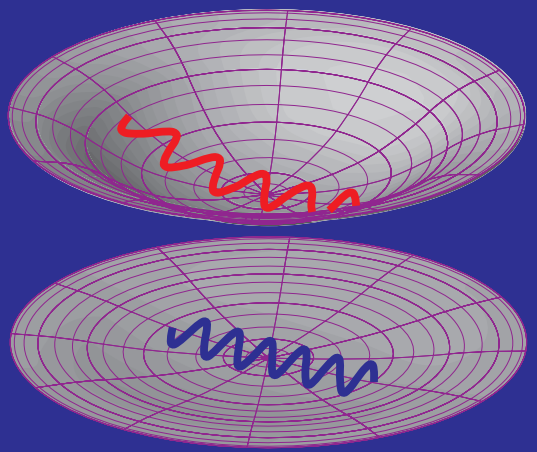


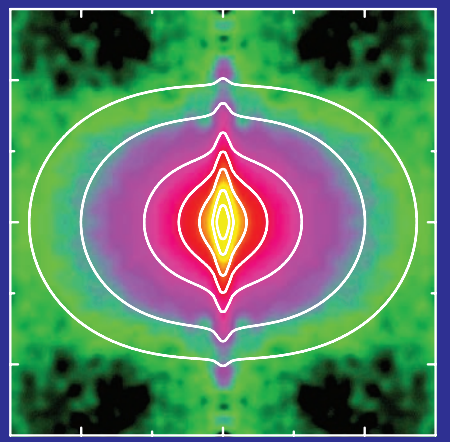
Cosmological Constant

Quintessence



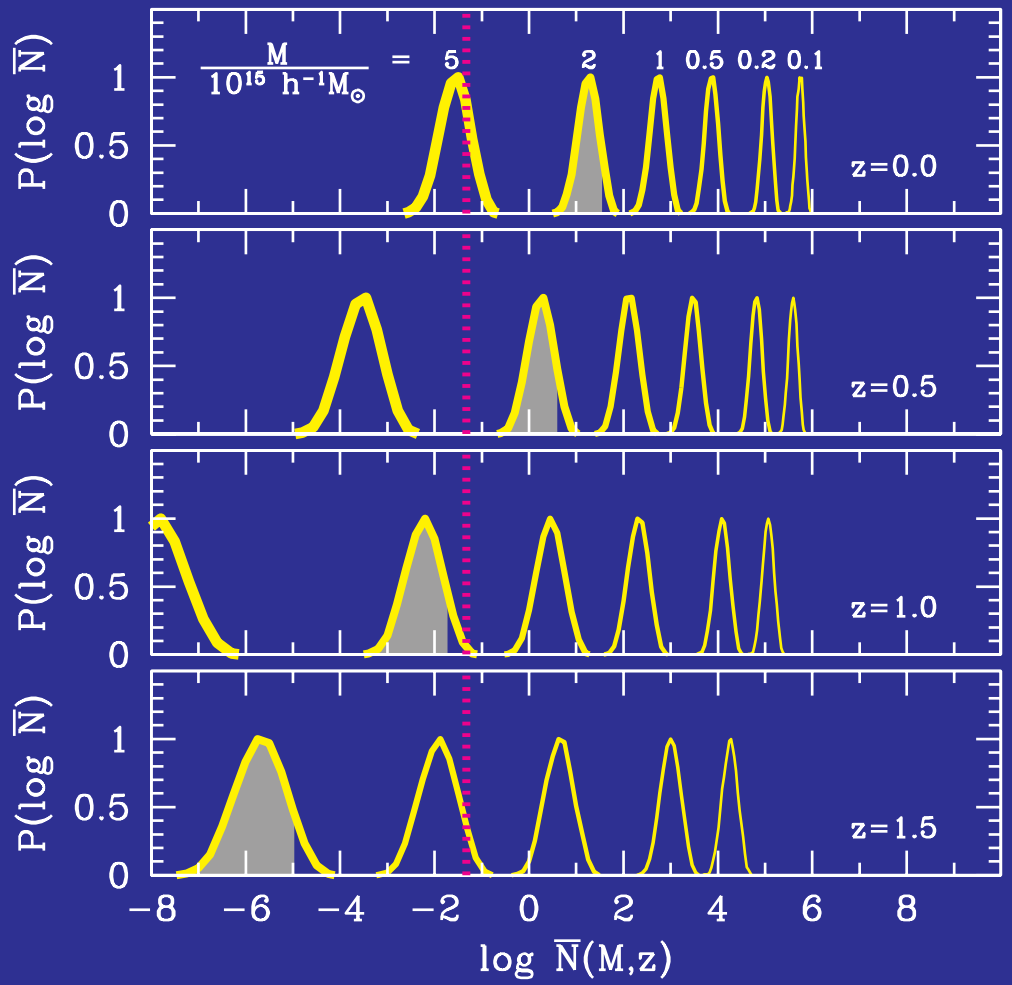






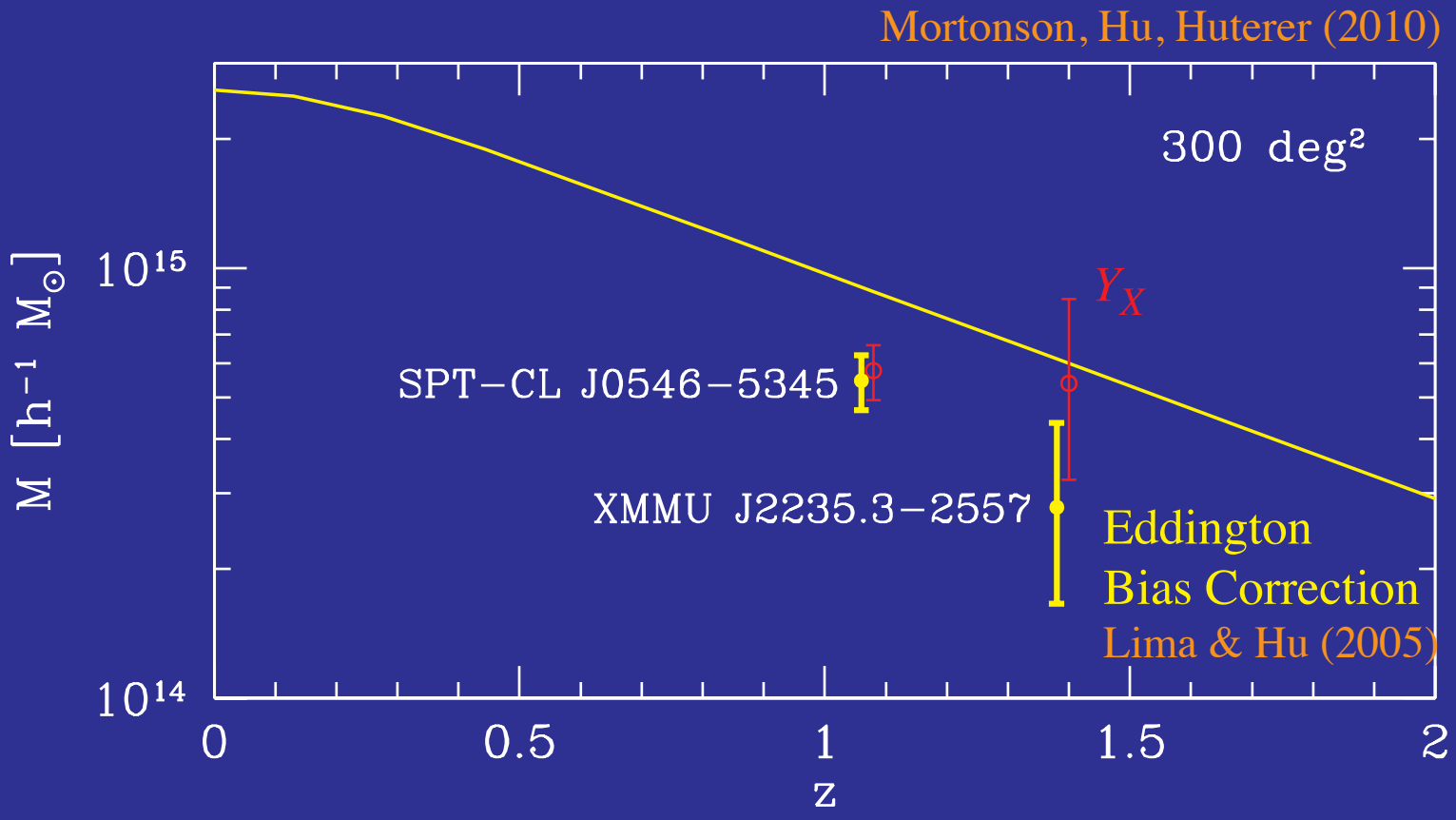
Elephantine Predictions

- Geometric constraints on the cosmological parameters of ΛCDM
- Convert to distributions for the predicted average number of clusters above a given mass and redshift



ΛCDM Falsified?

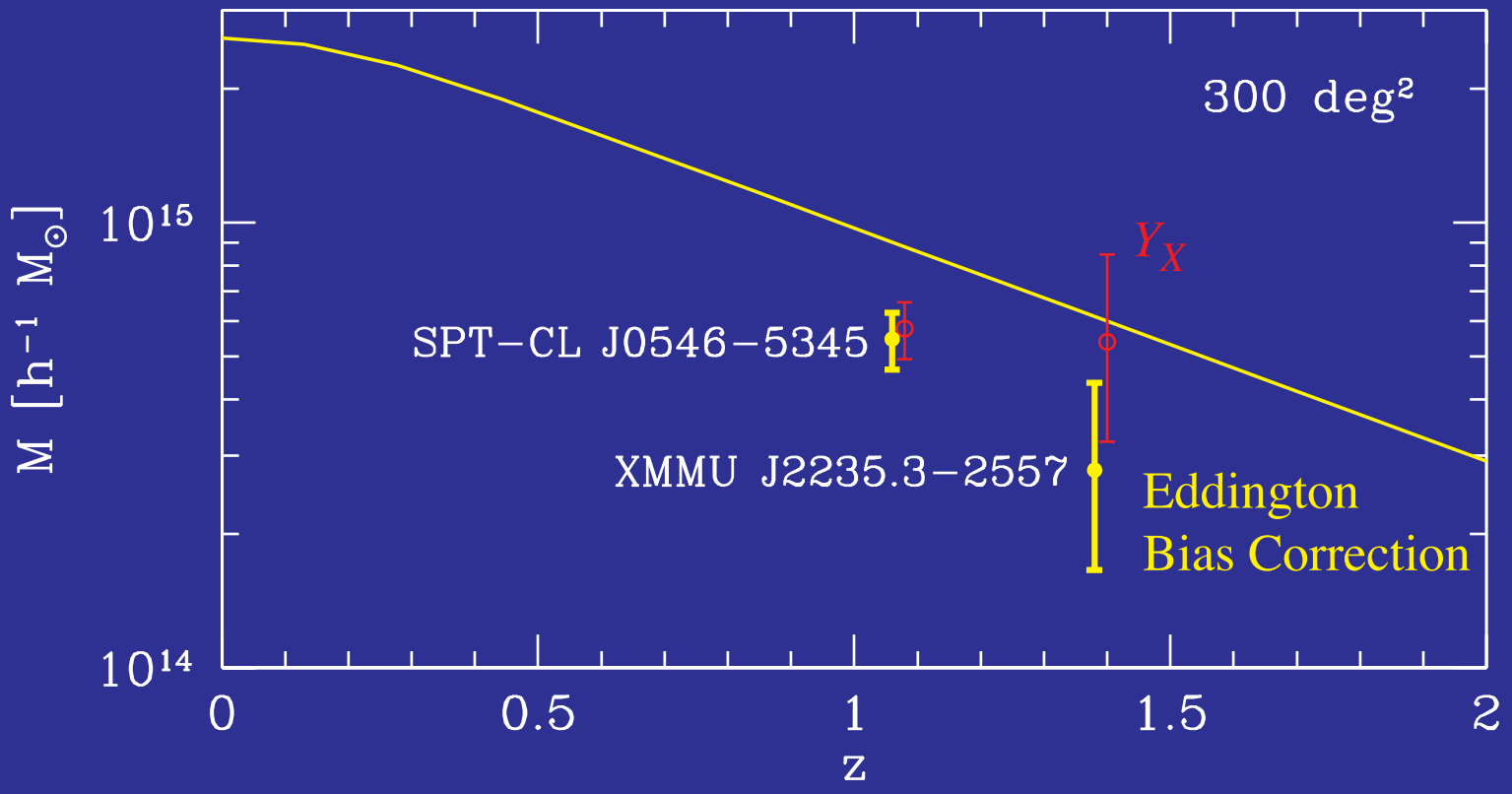
- 95% of ΛCDM parameter space predicts less than 1 cluster in 95% of samples of the survey area above the $M(z)$ curve
- No currently known high mass, high redshift cluster violates this bound



ΛCDM Falsified?

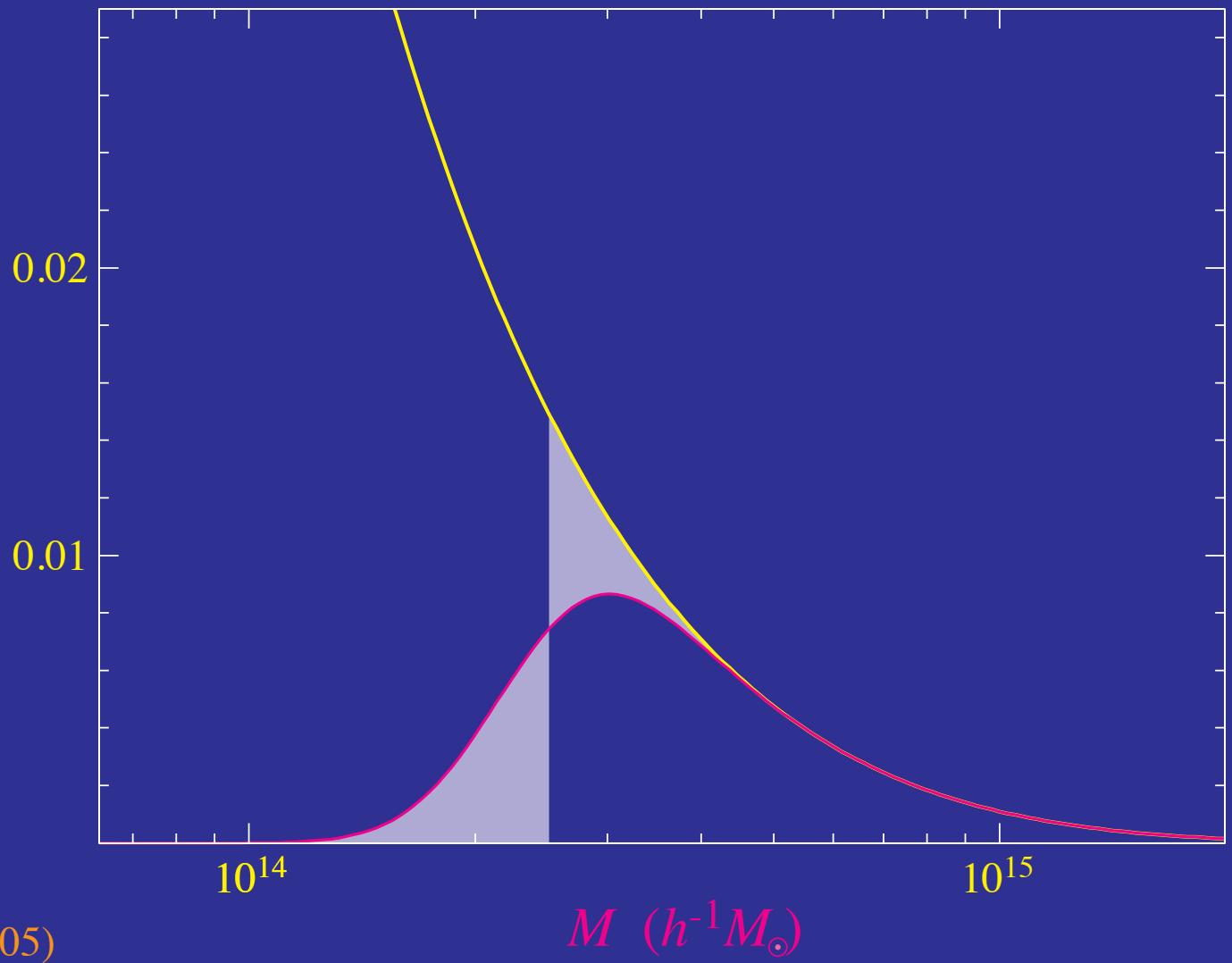
- 95% of ΛCDM parameter space predicts less than 1 cluster in 95% of samples of the survey area above the $M(z)$ curve
- Convenient fitting formulae for future elephants:
  http://background.uchicago.edu/abundance

Mortonson, Hu, Huterer (2010)



Number Bias

- For $>M_{\rm obs}$, scatter and steep mass function gives excess over $>M$
- Equate the number $>M_{\rm obs}$ to $>M_{\rm eff}$
- Not the same as best estimate of true mass given model!



Lima & Hu (2005)

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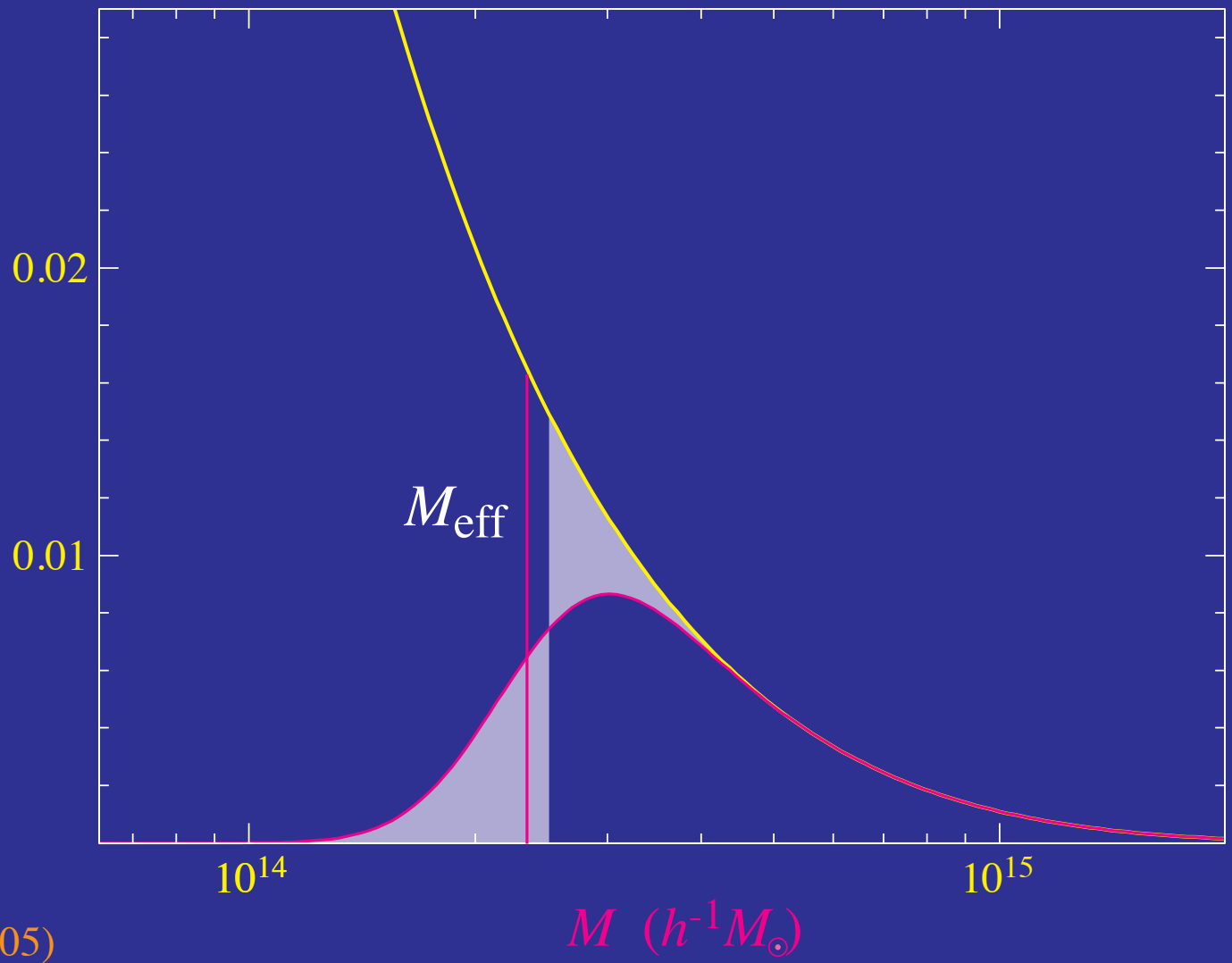
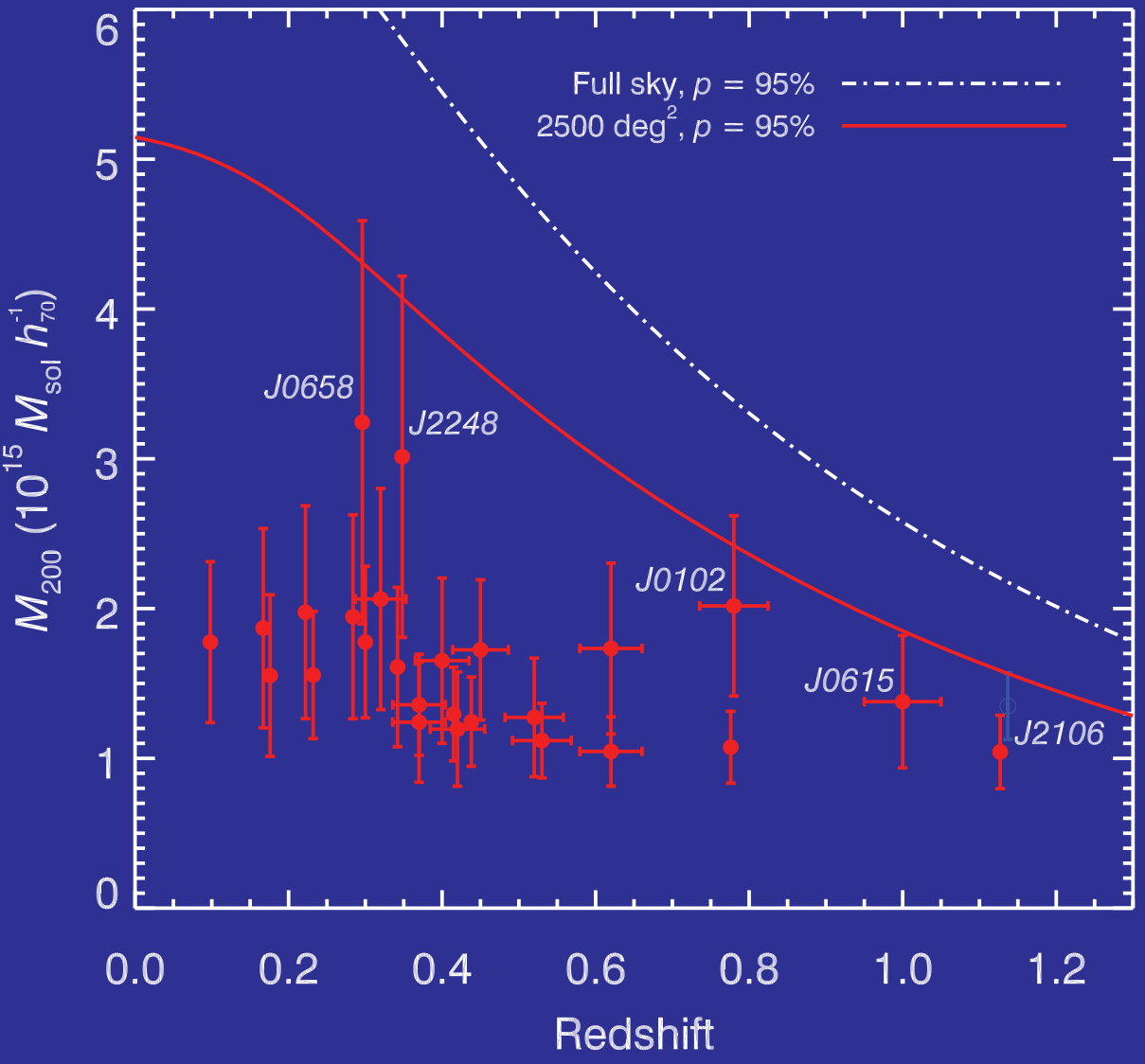


Lima & Hu (2005)

Pink Elephant Parade

- SPT catalogue on 2500 sq degrees

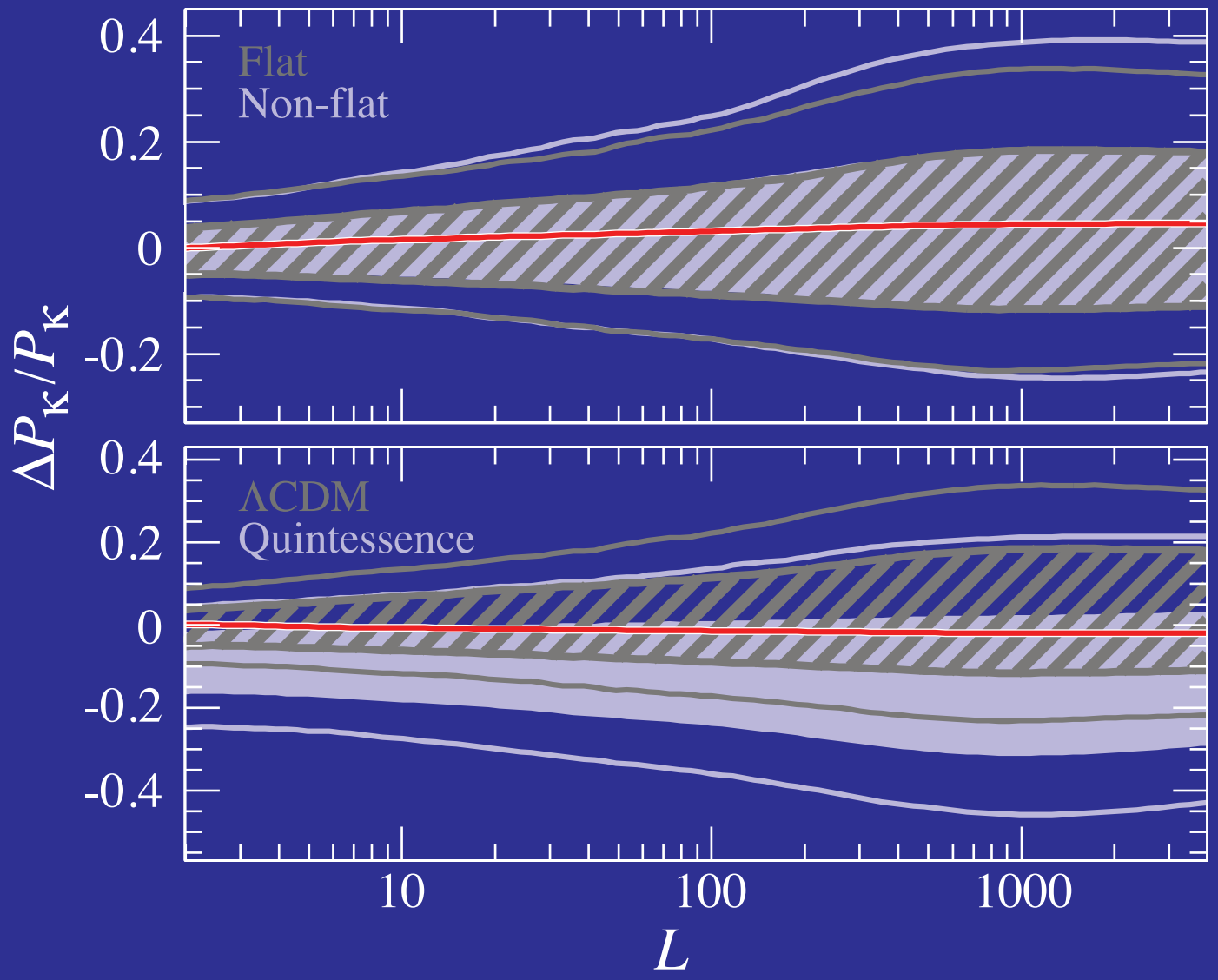
Williamson et al (2011)



Cosmic Shear Tests

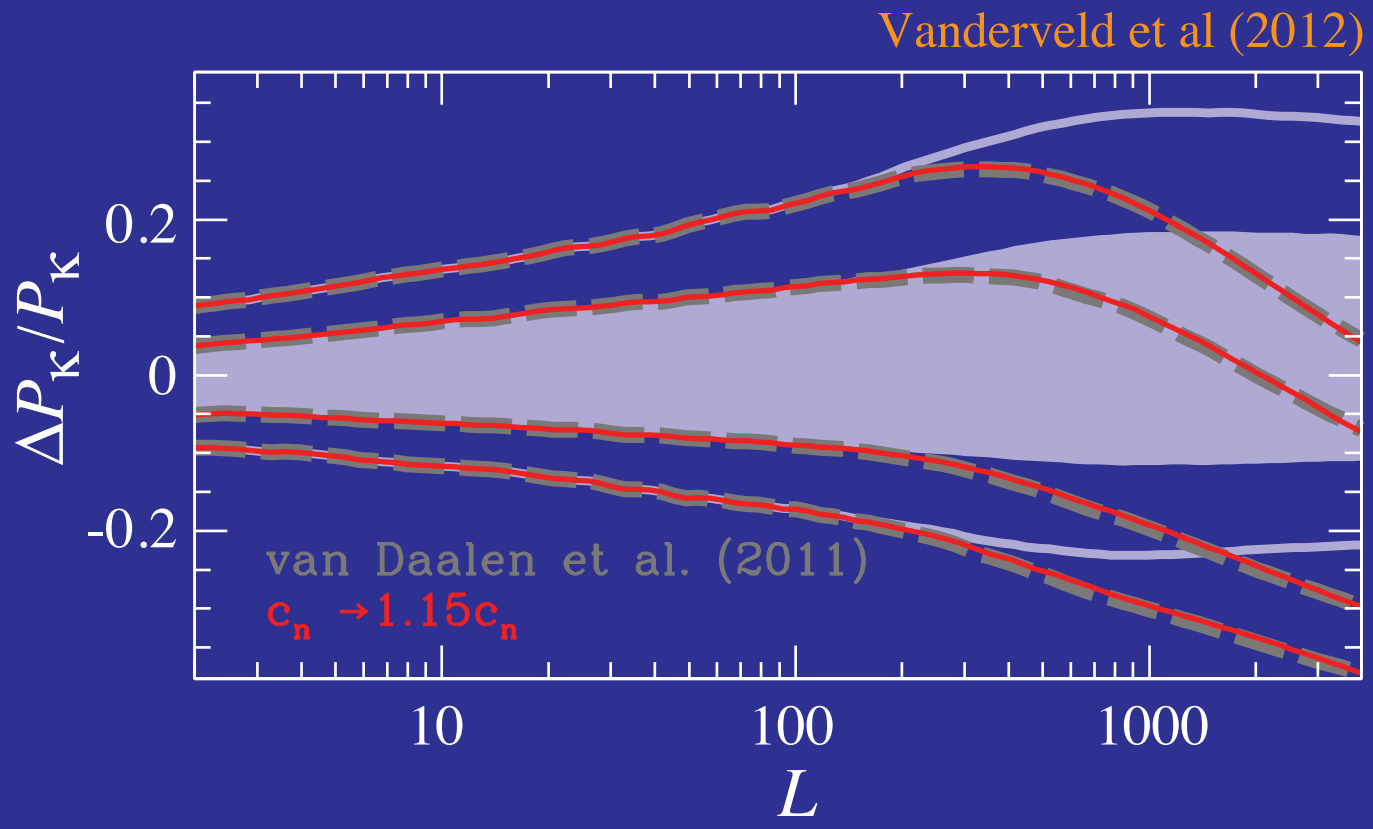
- Convergence power spectrum of CFHLT-like survey; currently consistent with ΛCDM

Vanderveld et al (2012)



Cosmic Shear Tests

- Systematics from baryonic feedback (e.g. AGN, cooling, star formation in clusters) comparable to statistical errors
- Calibration must be improved
- Residual uncertainties characterized by variations in Halofit parameters



Summary

- Flat ΛCDM is highly predictive and falsifiable
- Distance-redshift relation at all redshifts, including $z = 0$ and H_0 fixed at the few percent level largely from CMB
- Smooth dark energy predicts growth given distance-redshift
- Even including arbitrary $w(z)$ and uncertainties of current distance constraints, smooth dark energy make sharp predictions
- ΛCDM places firm upper bound on growth of structure for all quintessence models (smooth dark energy with $w \geq -1$)
- Observations of excess clusters or cosmic shear that falisfy ΛCDM also falsifies quintessence