Dark Energy: Observations

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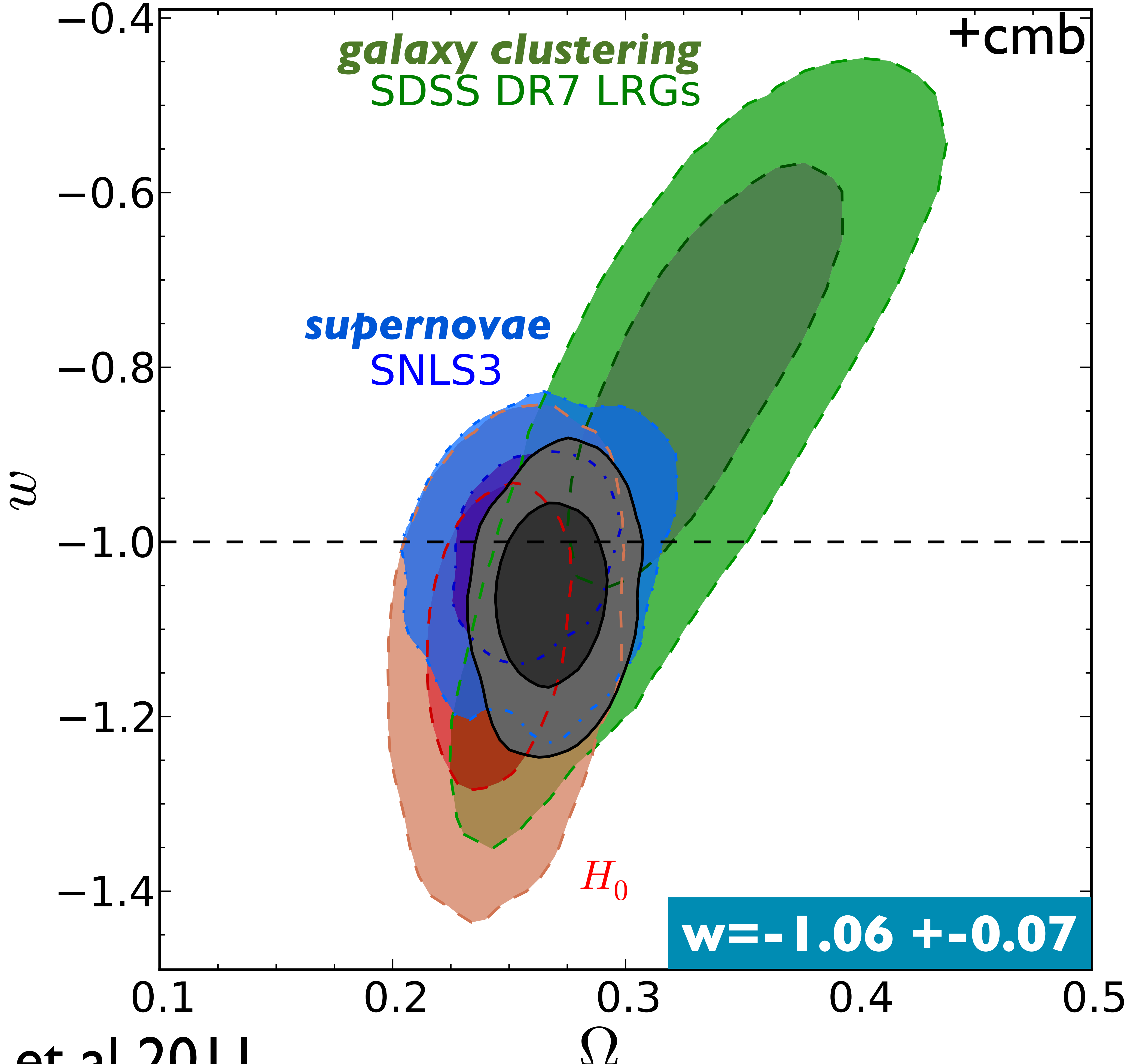
Outline

- How dark energy affects cosmological observables
  - a(t) => distances(z), growth of structure(z)
- Dark energy probes
  - cosmic microwave background
  - supernovae (type IA)
  - galaxy clustering
  - weak gravitational lensing
  - galaxy cluster number counts

Warning: not a comprehensive list of experiments!



Sullivan et al 2011

Energy Densities in Cosmology

$$H = H_o\sqrt{\Omega_m(1+z)^3 + \Omega_x(1+z)^{3(1+w)}}$$

d(ln a)/dt

matter

dark energy

a=1/(1+z)

scale factor

redshift

The expanding universe

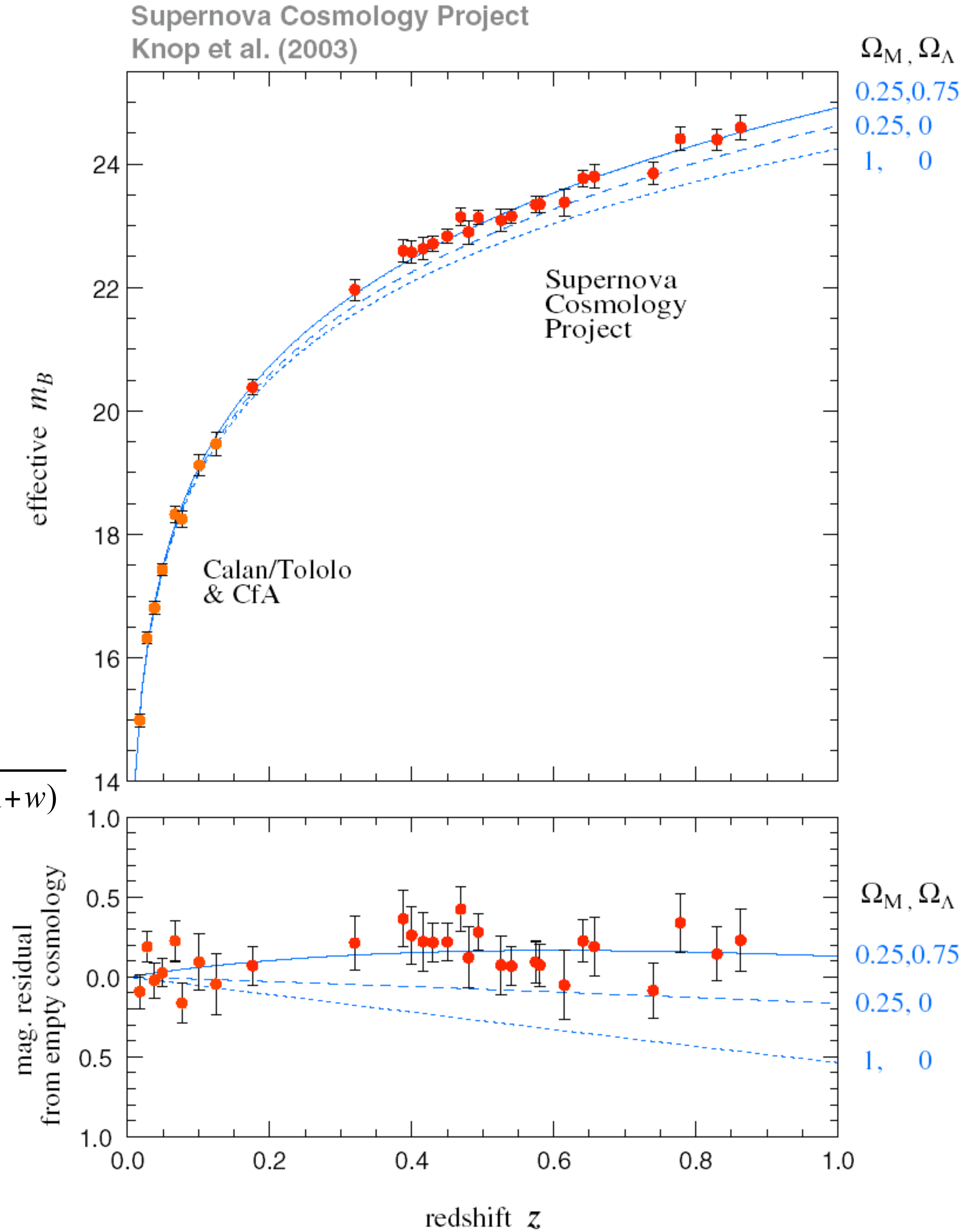
- spatially flat FRW: $dt^2=a^2(t)\ dr^2$
- mapping between comoving distance between points and time depends on expansion history

Dark Energy from Distances

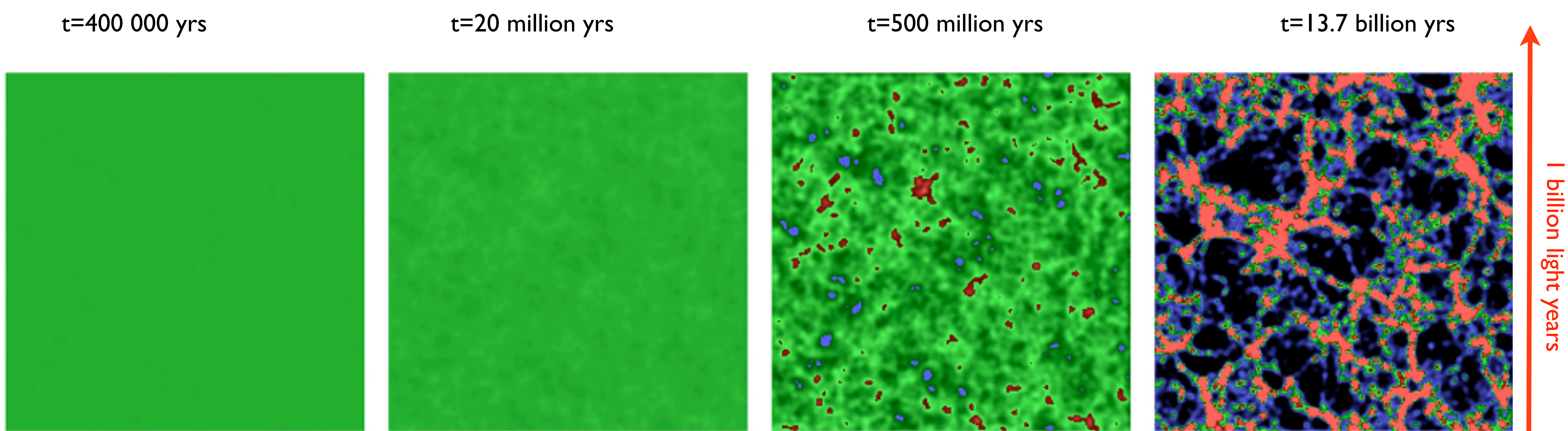
- distance sensitive to expansion rate

$$H = H_o\sqrt{\Omega_m(1+z)^3 + \Omega_x(1+z)^{3(1+w)}}$$

$$d_L = c(1+z)\int_0^z dz'\, H^{-1}(z')$$



Gravity at work



***simulated* density contrast at different times**

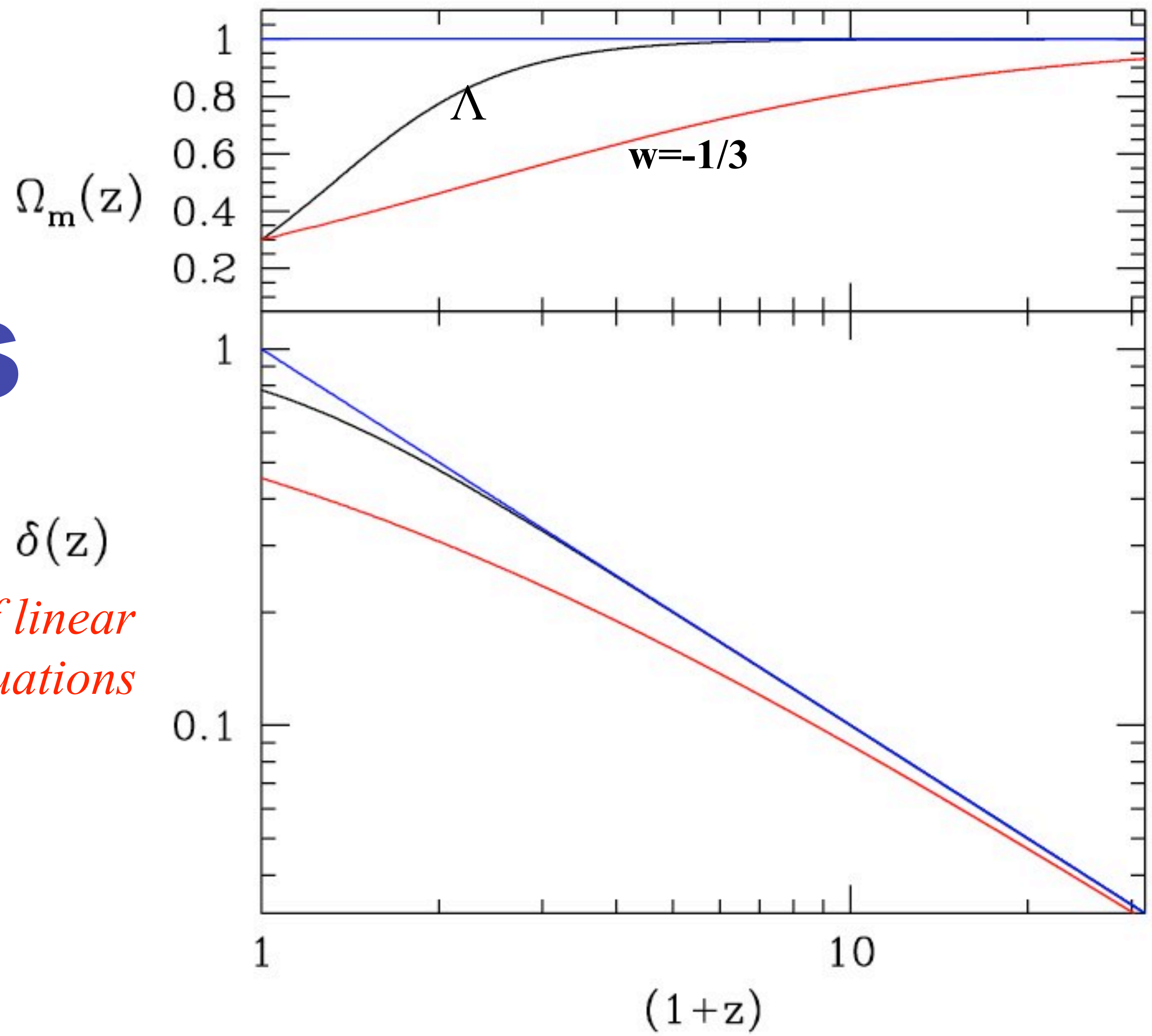
simulations carried out by the Virgo Supercomputing Consortium using computers based at Computing Centre of the Max-Planck Society in Garching and at the Edinburgh Parallel Computing Centre. The data are publicly available at www.mpa-garching.mpg.de/NumCos

$$\ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G\rho_o\delta$$

Dark Energy Studies with Growth Tests

- Growth of structure sensitive to expansion rate

Amplitude of linear density fluctuations

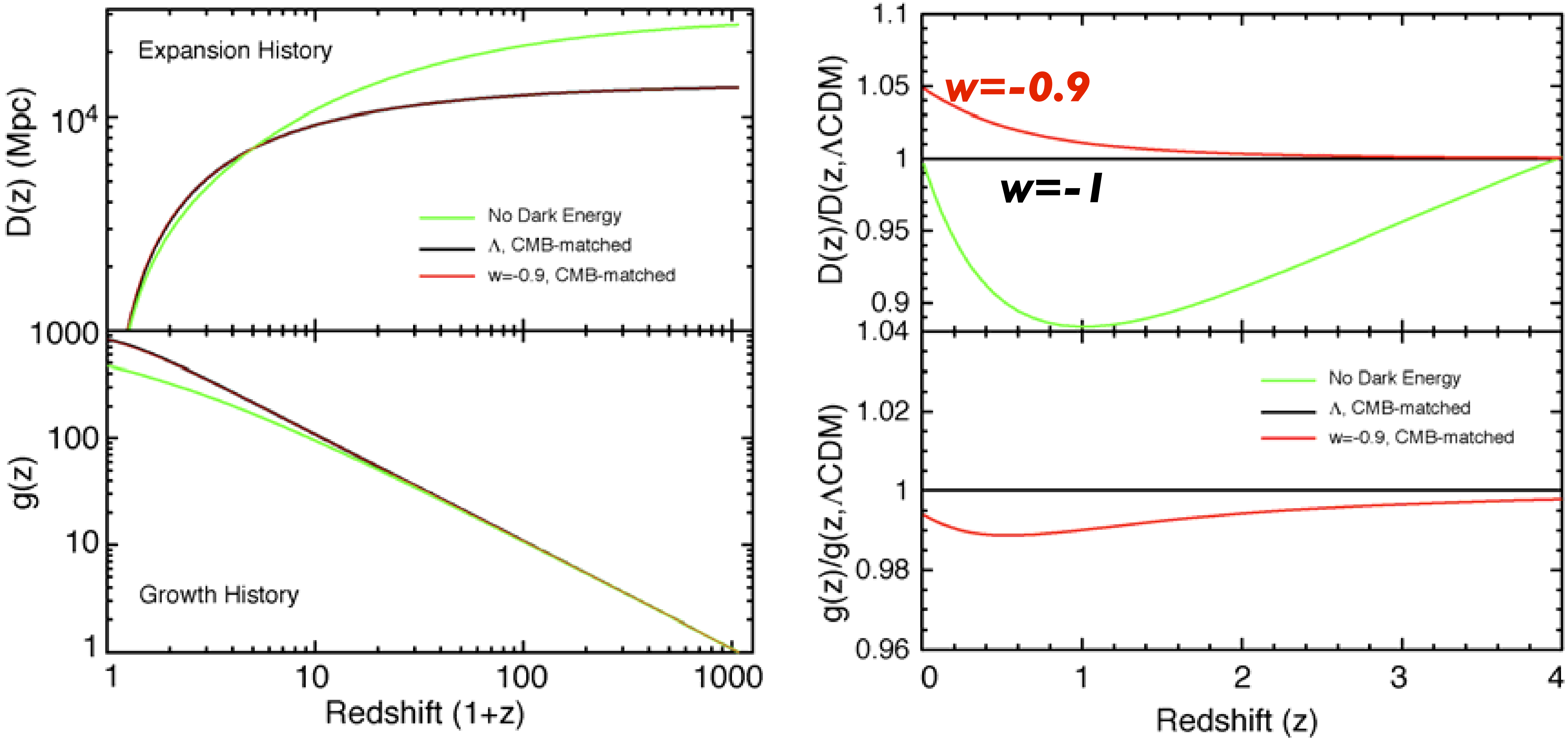


$$H(z) = H_o \sqrt{\Omega_m (1+z)^3 + \Omega_x (1+z)^{3(1+w)}}$$

Amplitude of density fluctuations in linear theory:

$$\ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G \rho_o \delta$$

Characterizing Dark Energy

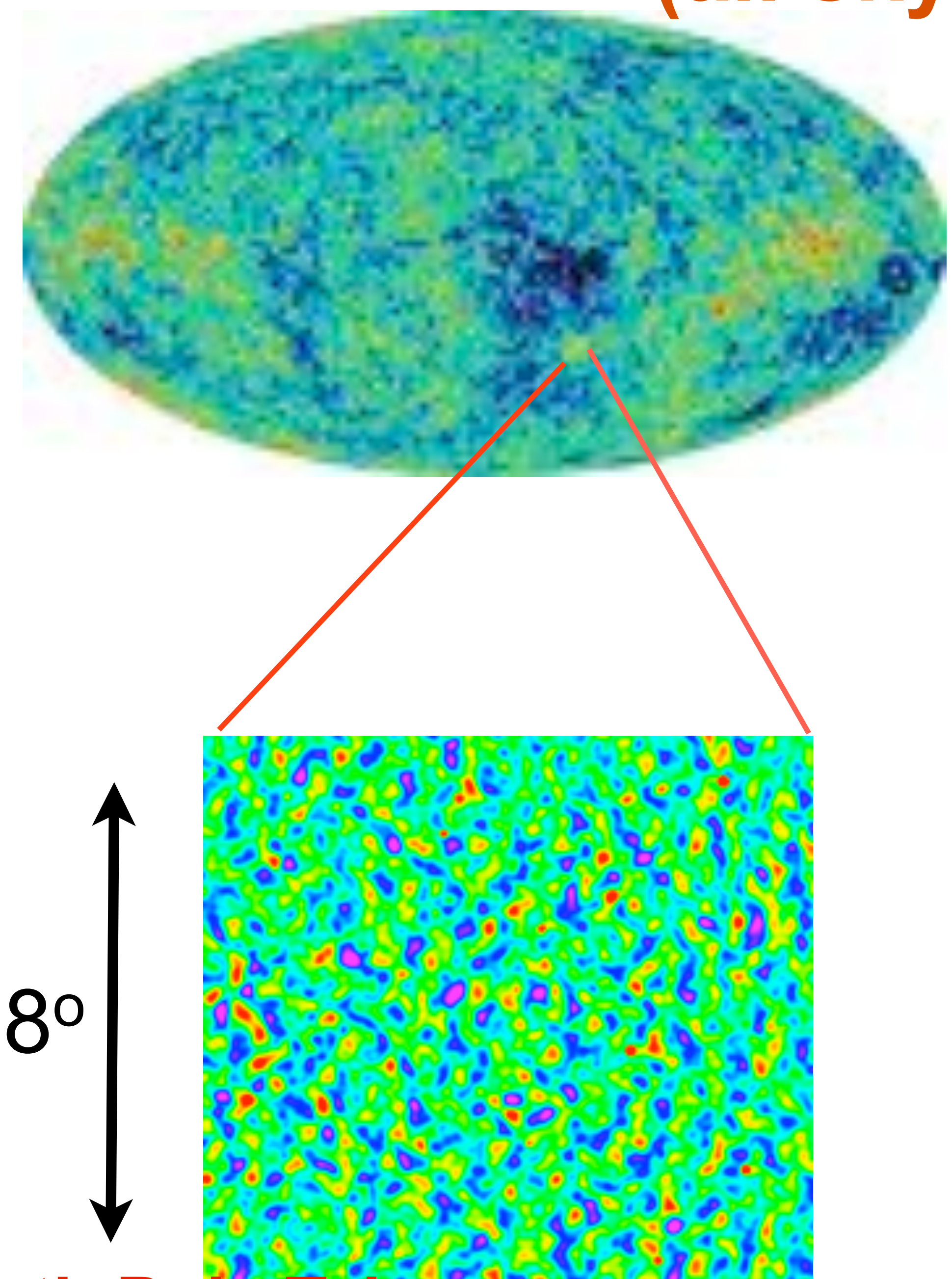


from Dark Energy Task Force report

Cosmic Microwave Background

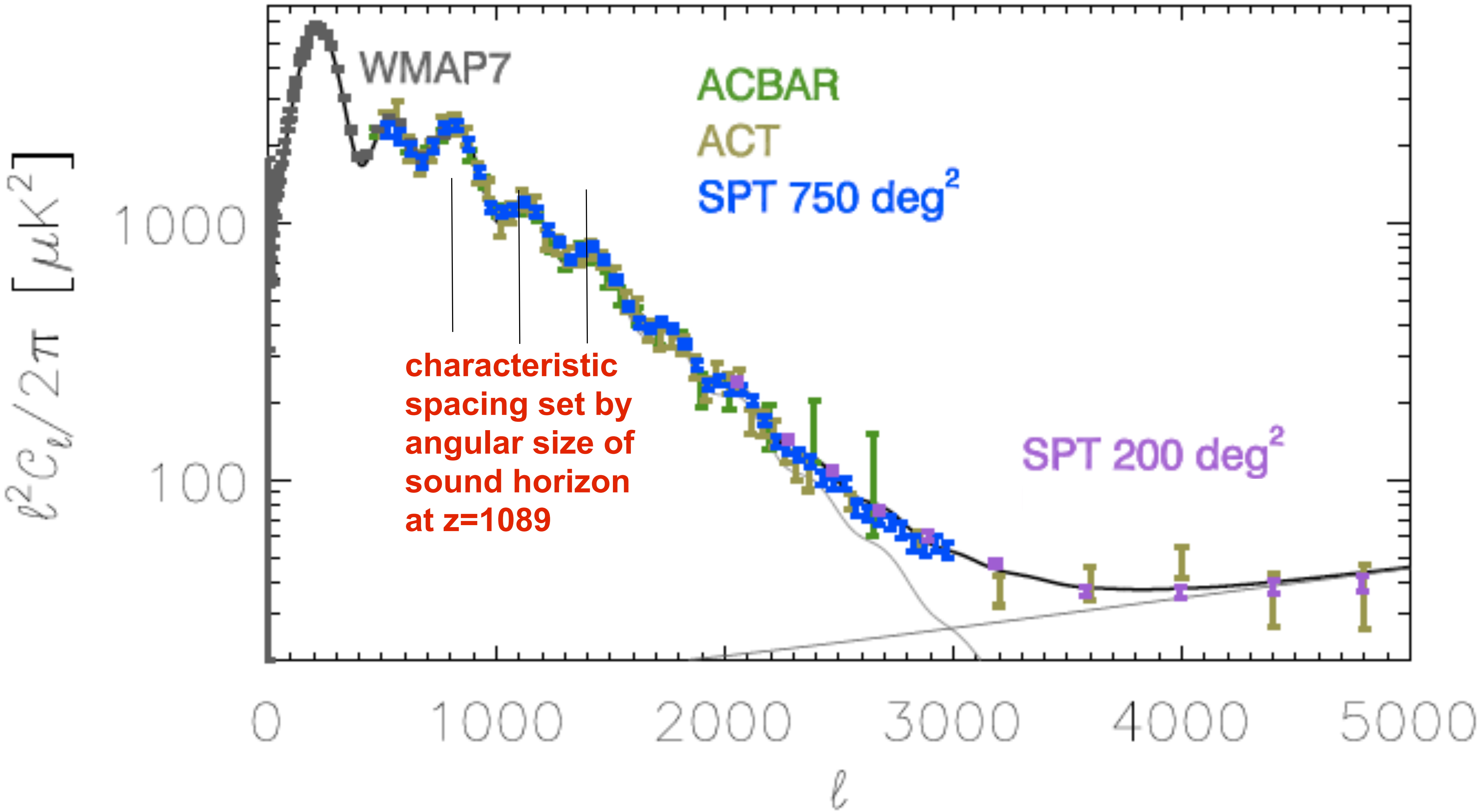
- acoustic scale (in cm) set by physics unrelated to dark energy
  - –angular scale depends on expansion history
- provides normalization of fluctuation amplitude at z~1100

WMAP (all sky)



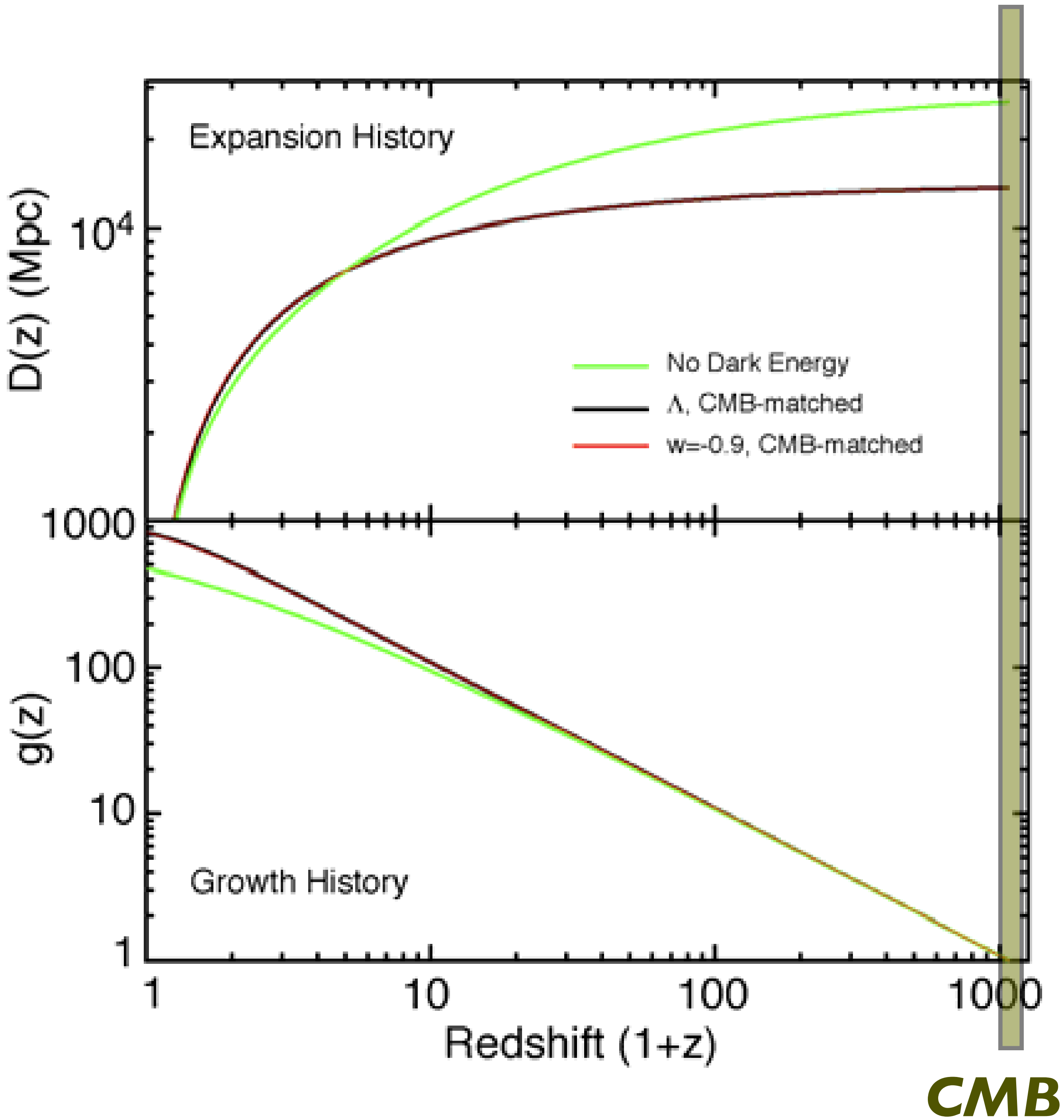
South Pole Telescope (total 2500 sq deg)

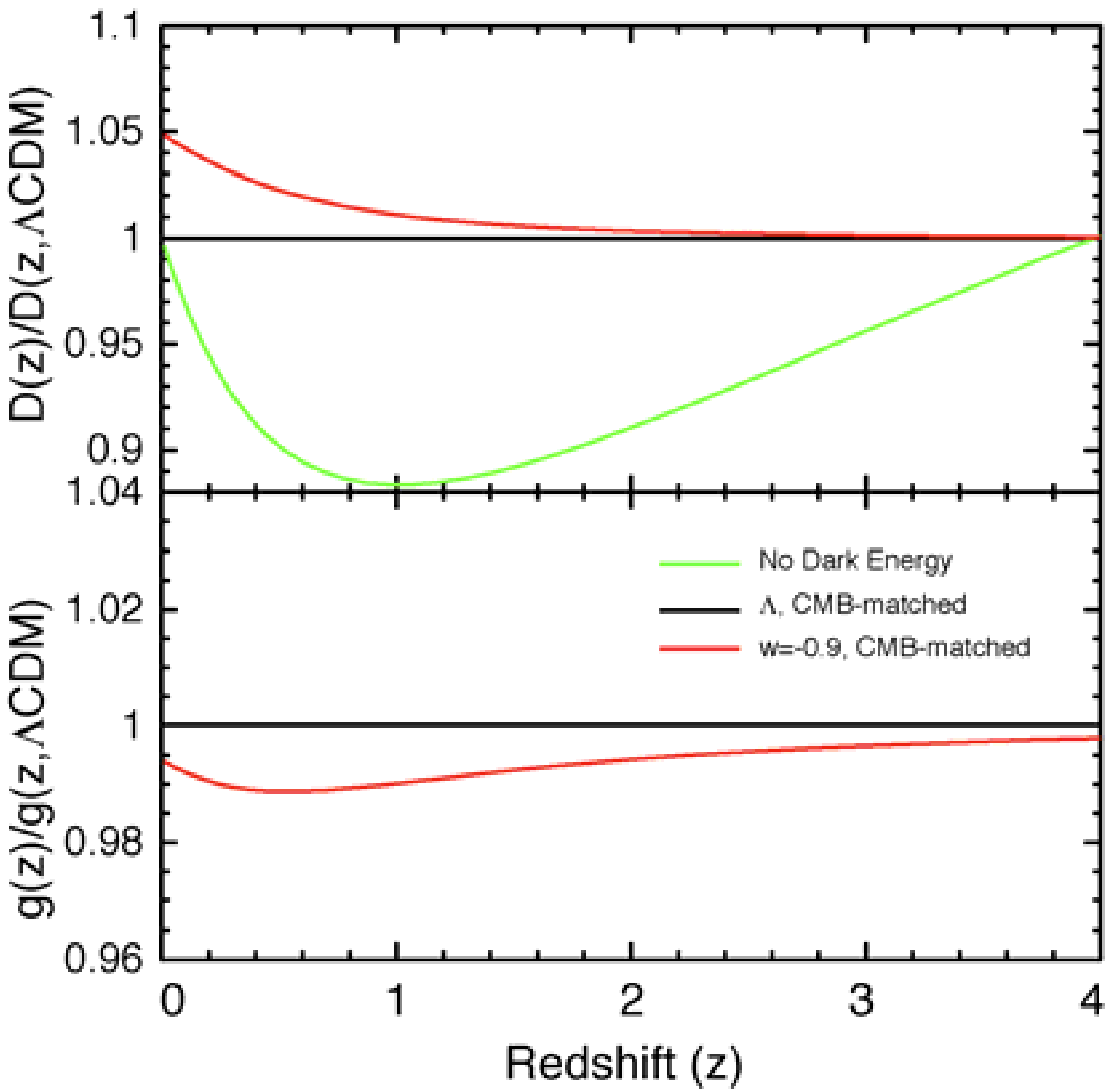
CMB Power Spectrum



SPT power spectra: Ryan Keisler; Christian Reichardt; Erik Shirokoff

Characterizing Dark Energy





from Dark Energy Task Force report

Exploding stars: Supernovae

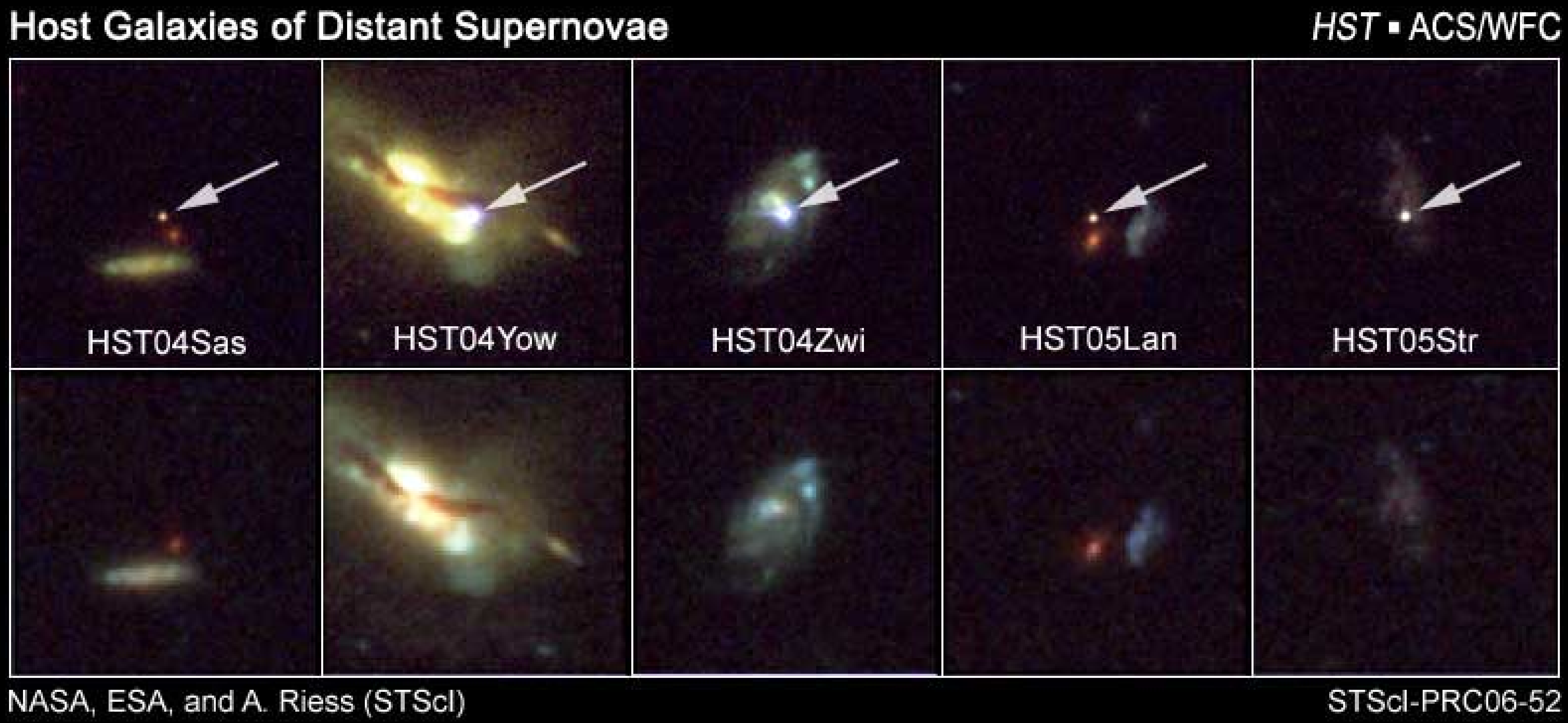
nearby (Type II)

It appears that some supernovae (IA) all have the same intrinsic brightness

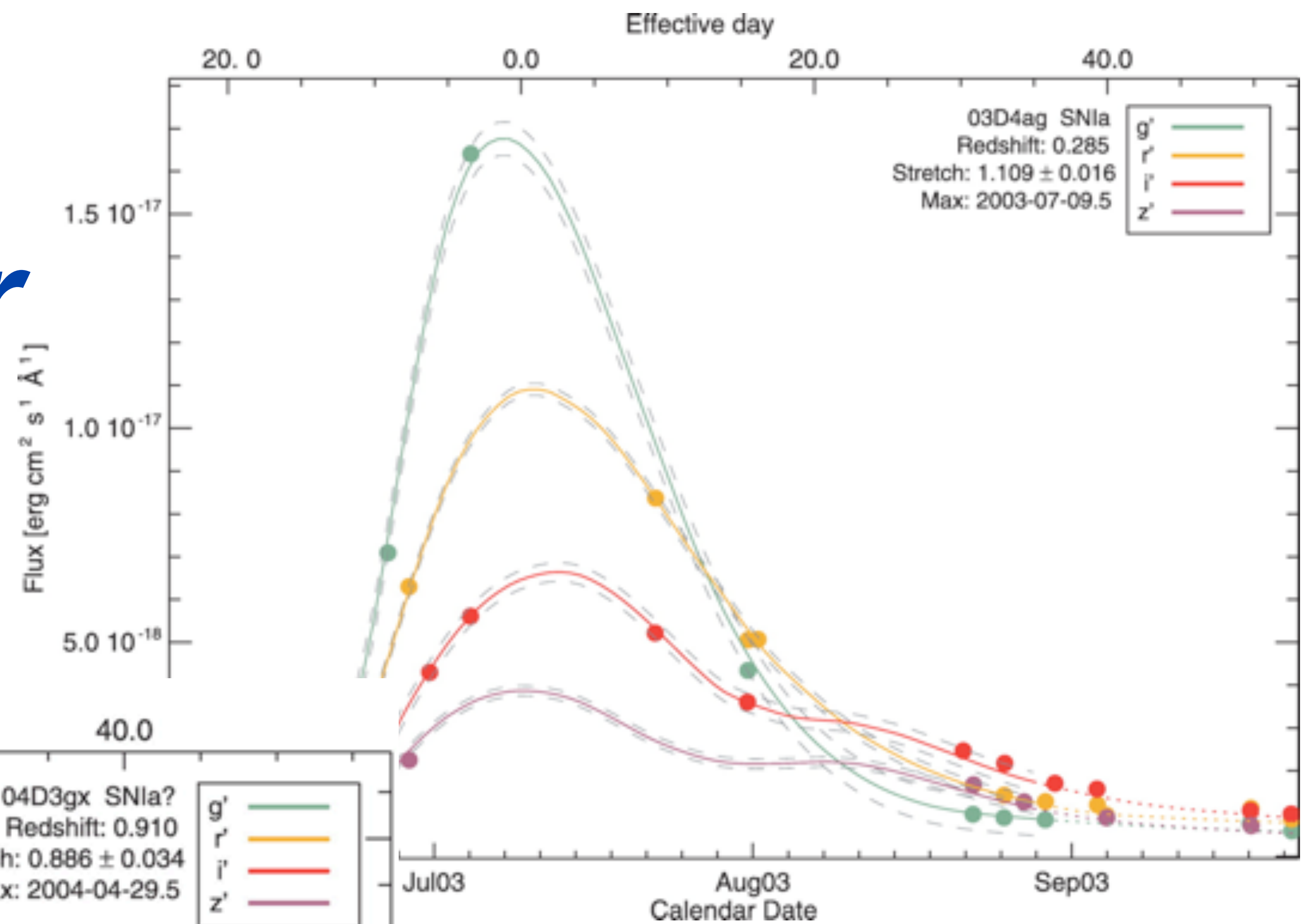
distant

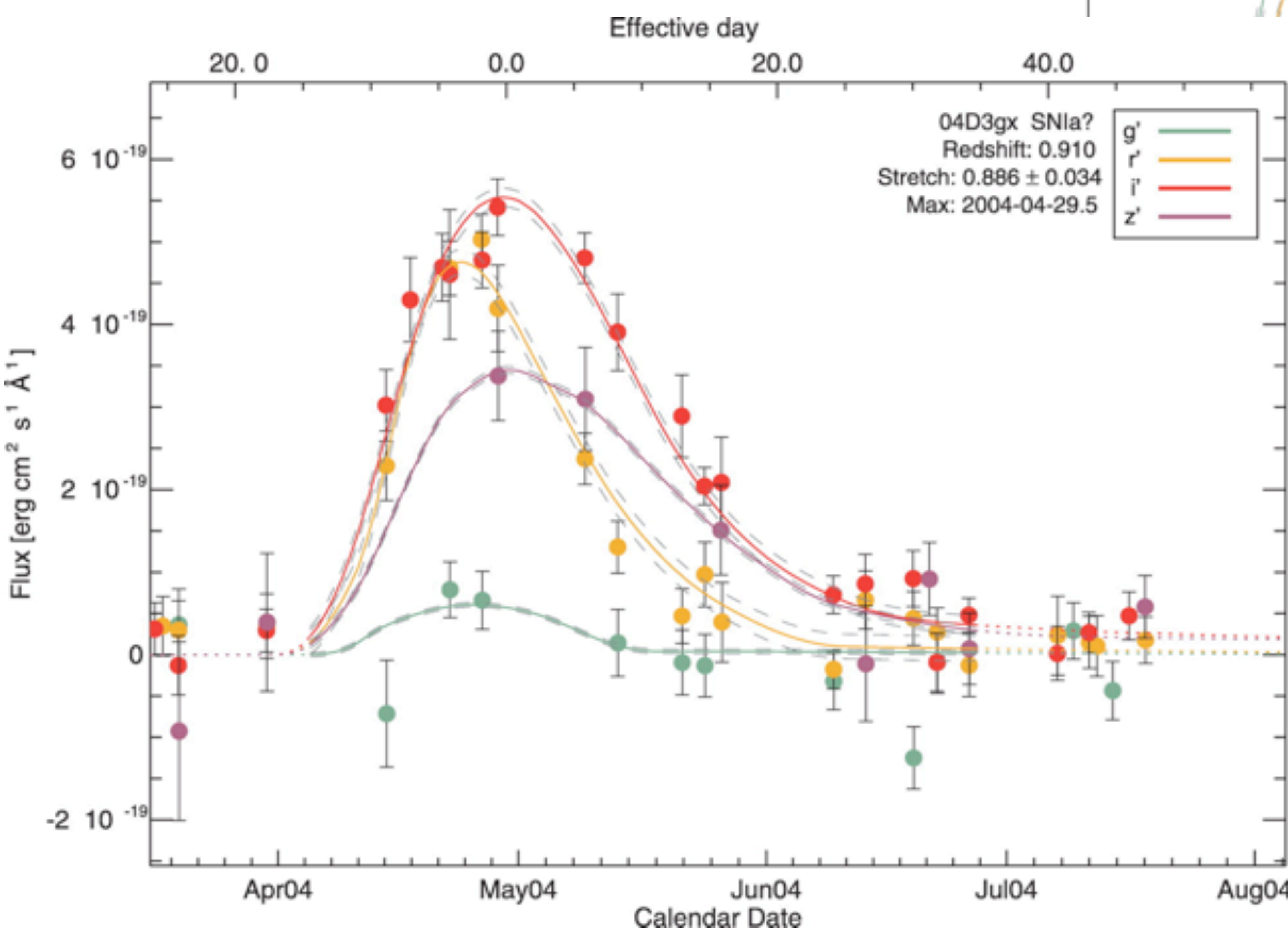
(Type IA)

Supernova!


Host Galaxies of Distant Supernovae
HST ▪ ACS/WFC
HST04Sas
HST04Yow
HST04Zwi
HST05Lan
HST05Str
NASA, ESA, and A. Riess (STScI)
STScI-PRC06-52

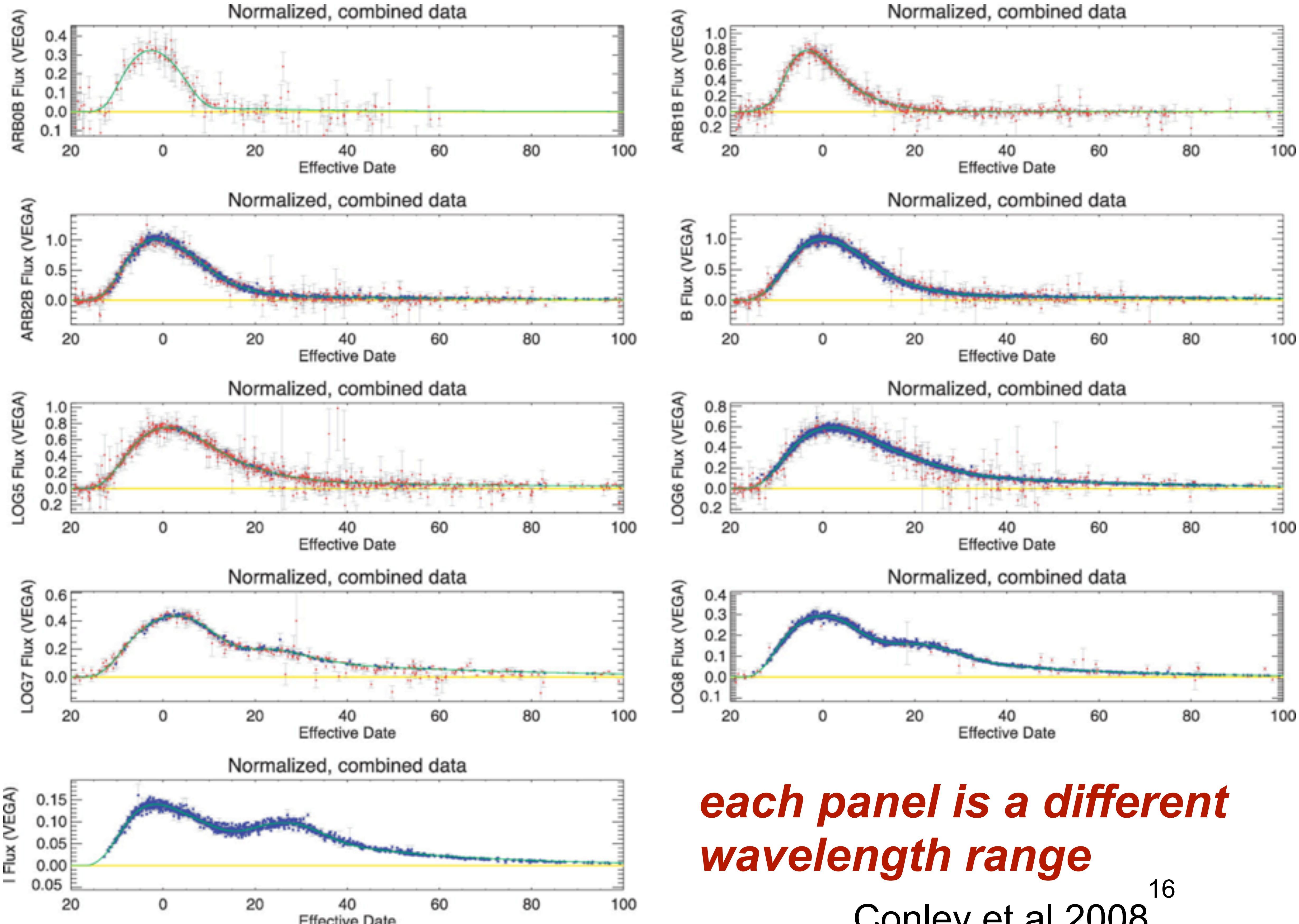
SNe Multi-color Light Curves





Conley et al 2008

Standardized Candles

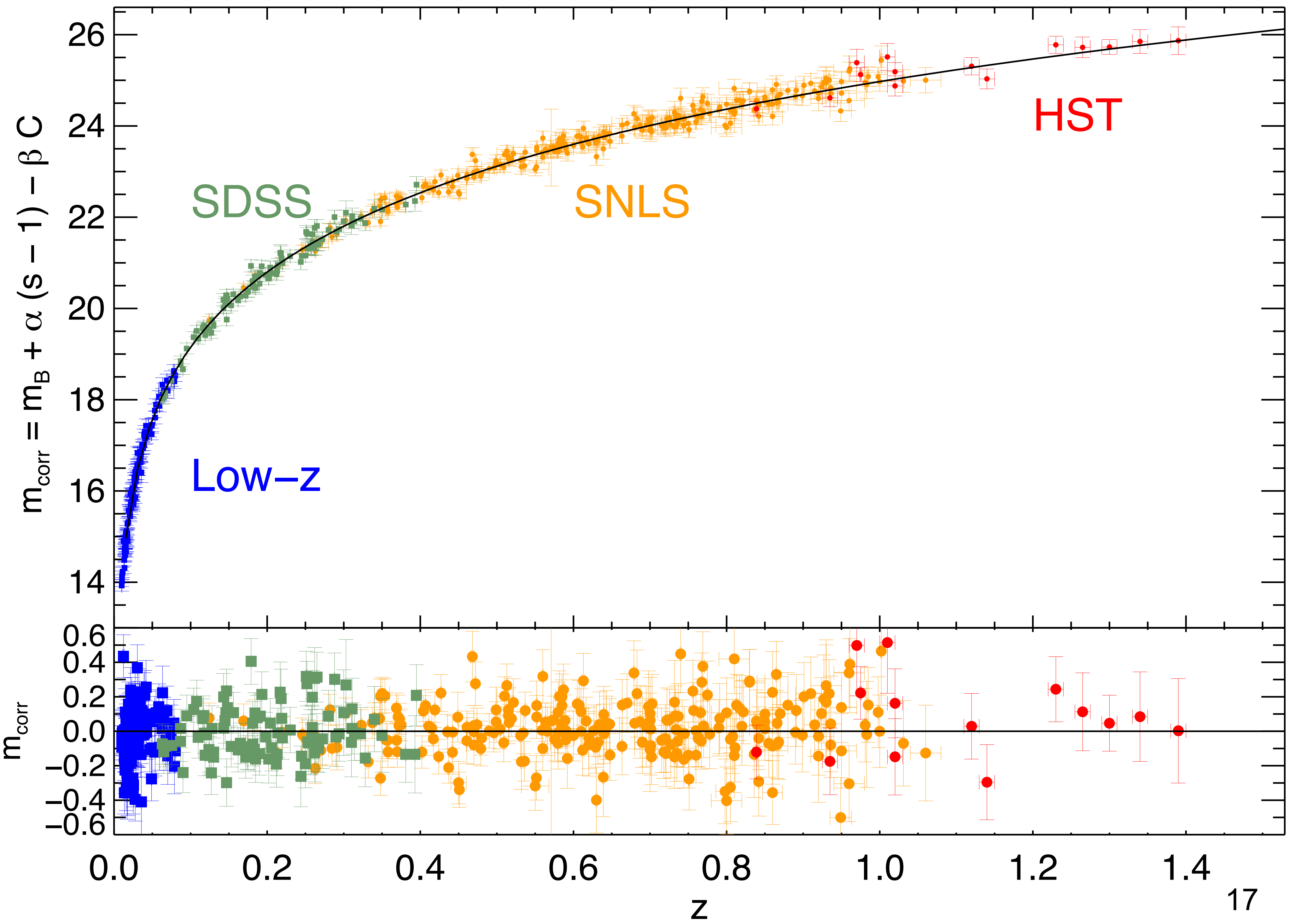


each panel is a different wavelength range

Conley et al 2008

SNe Hubble Diagram

5 log10(distance)

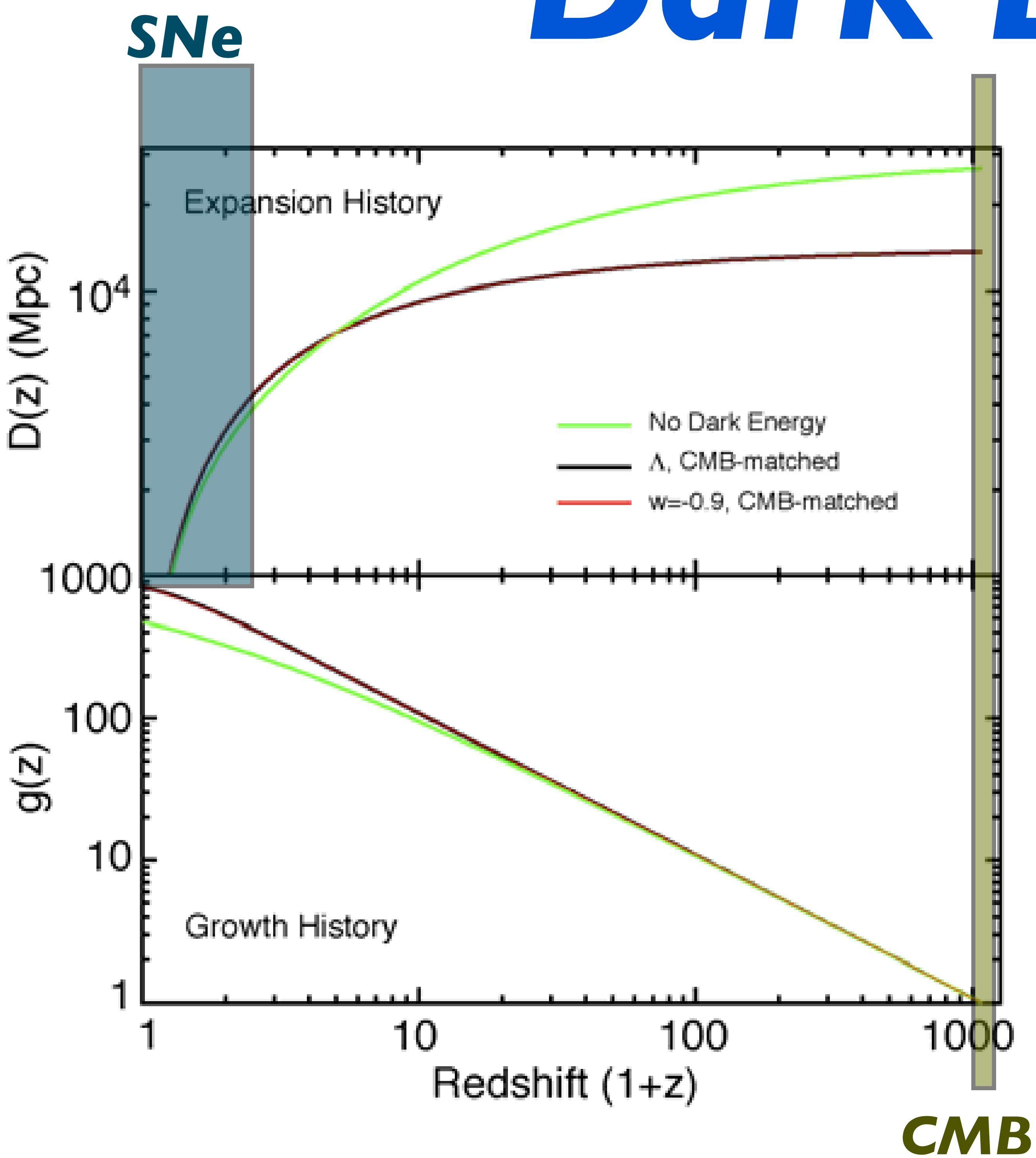


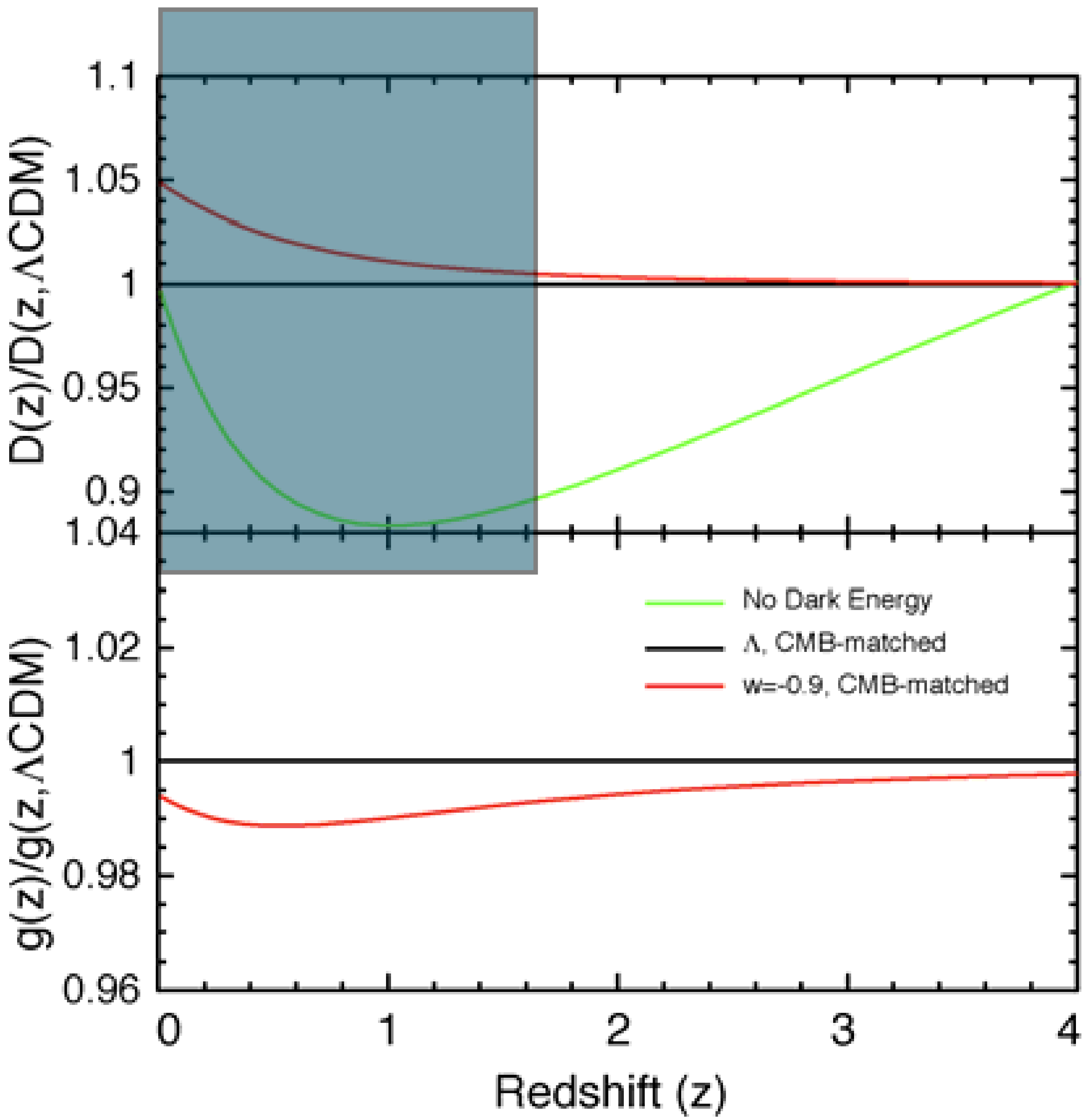
Conley et al 2011

Forecast & Wish List for SNe

- need more SNe both at low-z and at $z>1$
  - population studies to ensure that there isn't some evolution in either each SN or in the demographics of the SN population
- more colors would be nice (IR, UV?)
  - space-based? (WFIRST)
- a strong theoretical understanding of spectra & light curves would be reassuring

Characterizing Dark Energy

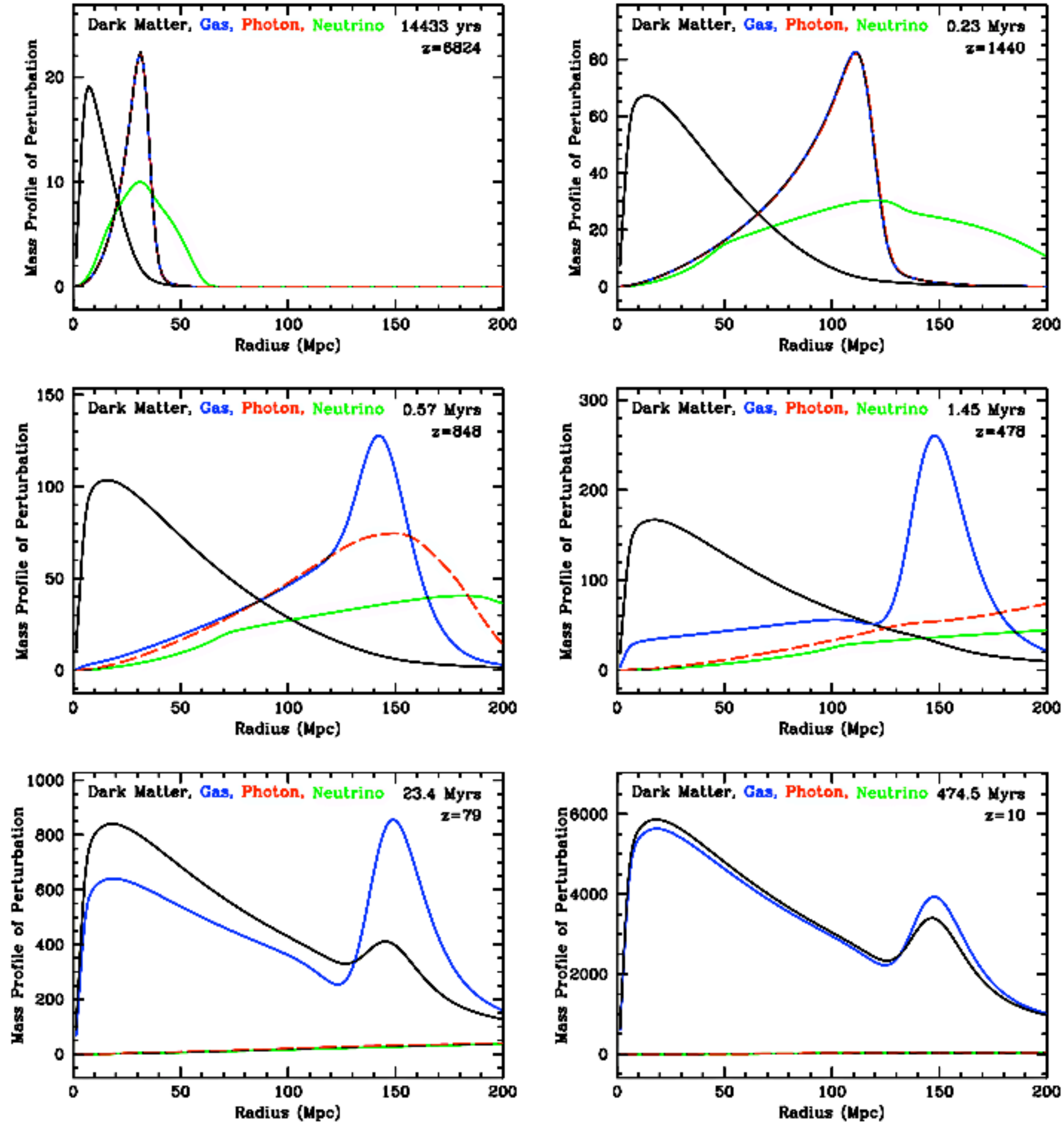




from Dark Energy Task Force report

BAO

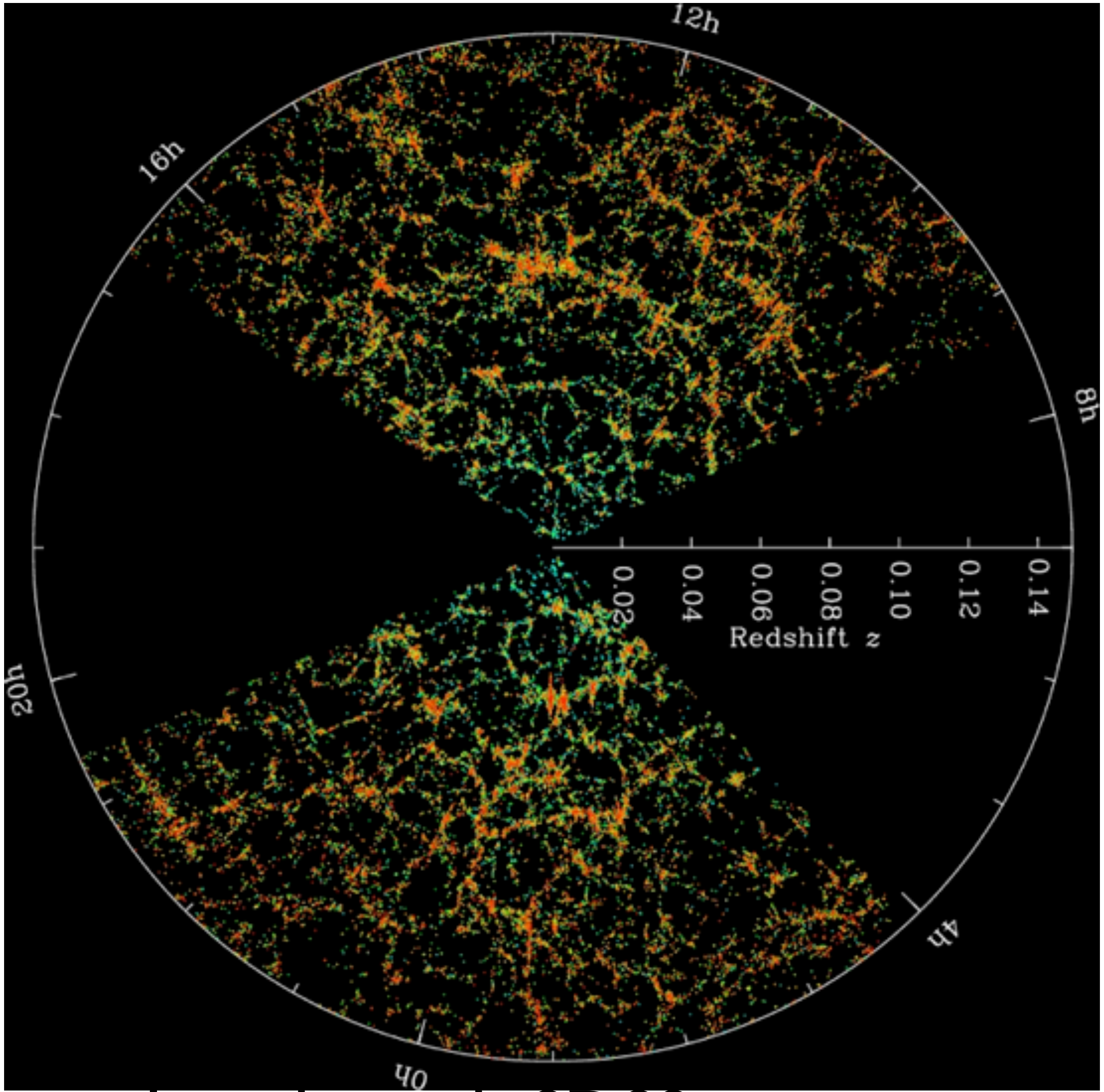
- Baryon Acoustic Oscillations leave imprint in matter distribution



Eisenstein, Seo & White 2006

Galaxy Clustering

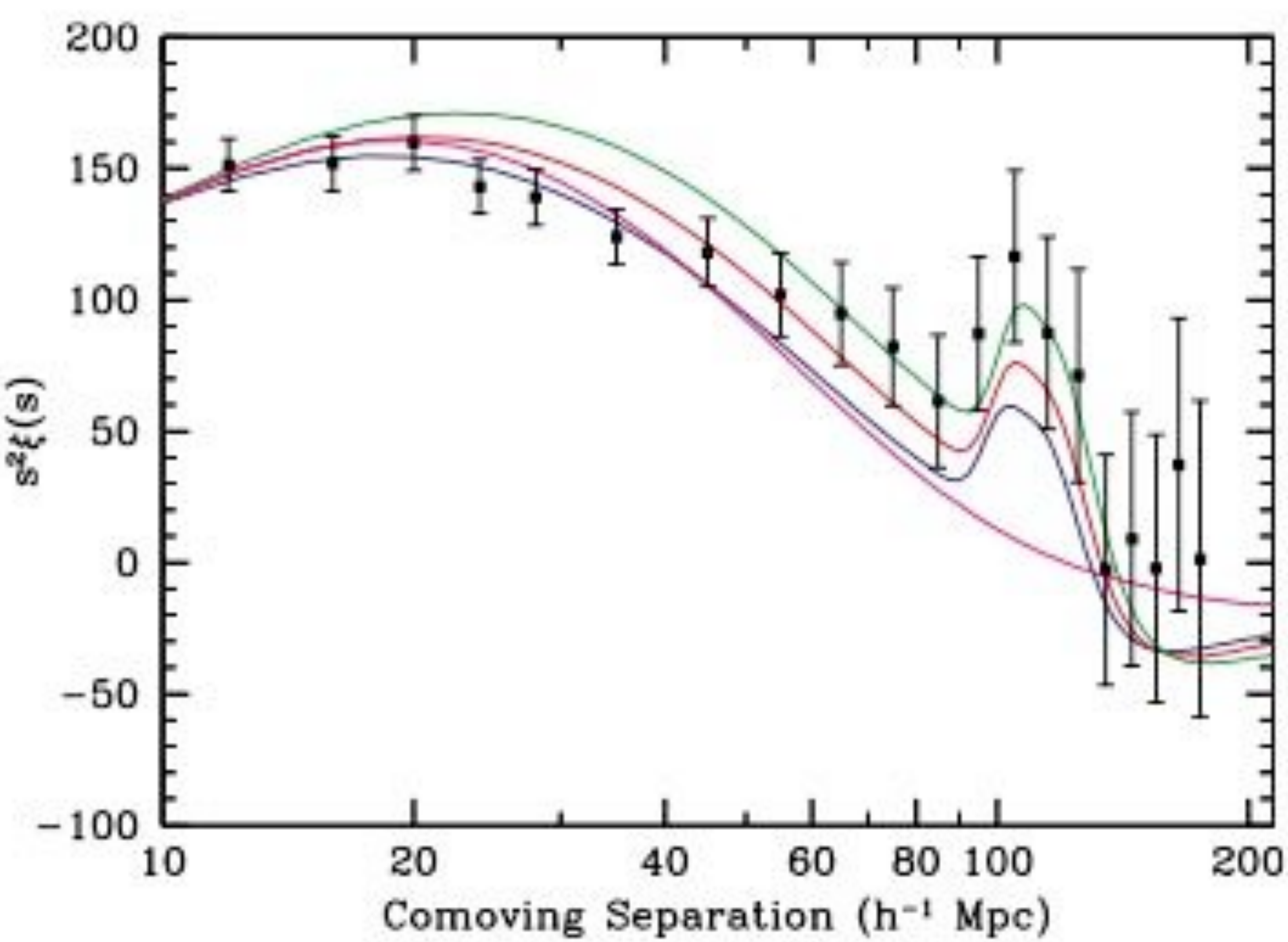
- galaxies are clustered
    - amplitude a bit tricky to use because galaxies live at peaks of density field (``biased”)
- BAO signature leads to boosted clustering on acoustic scale (~100 h^{-1}Mpc)



slice through SDSS survey

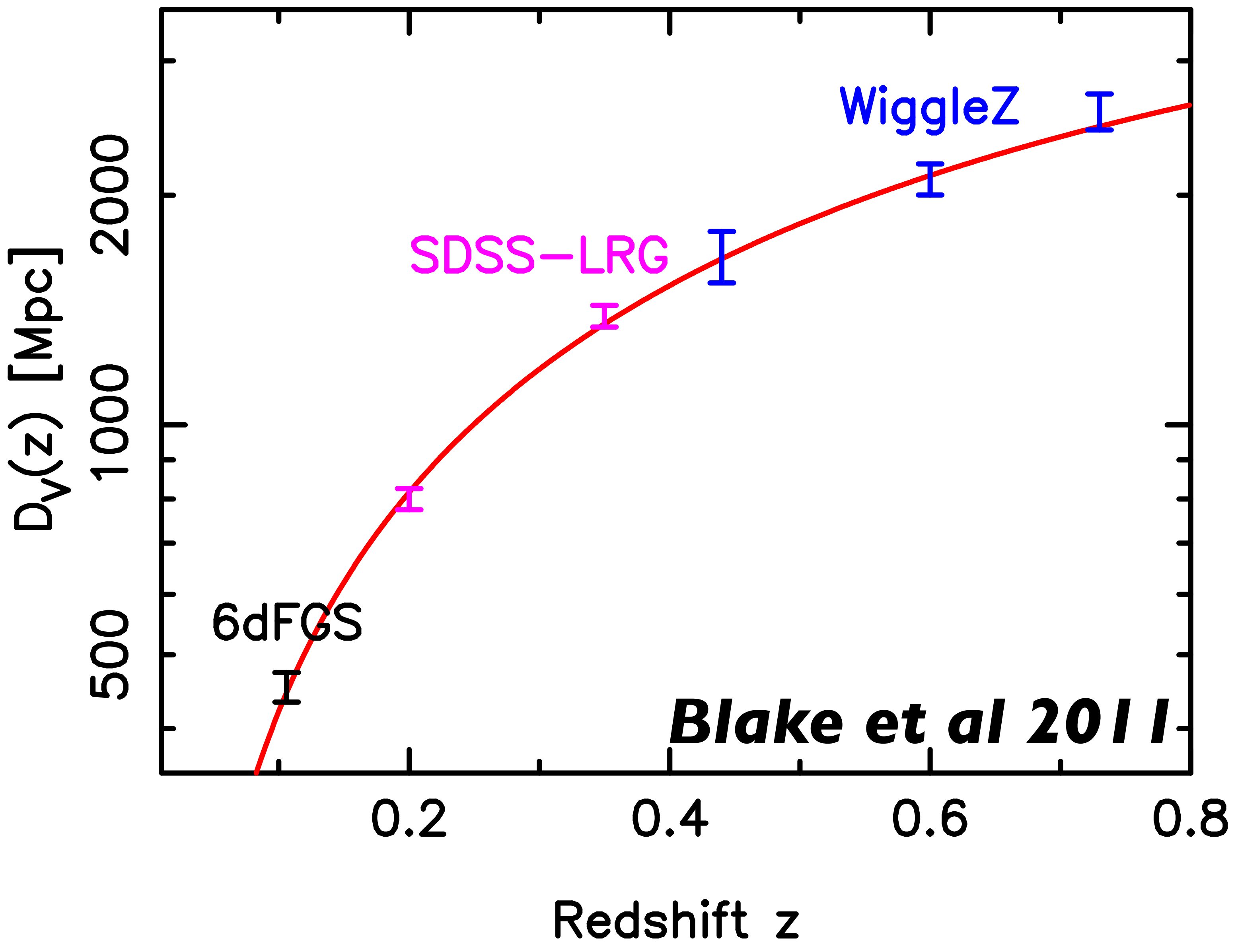
Baryon Oscillations imprinted in Galaxy Clustering

- first detected in Eisenstein et al 2005 using SDSS LRG sample (extends to z~0.5)
- actually detected in angular & radial clustering
  - ***standard ruler***



The BAO Hubble Diagram

- BAO measurements at different z allow a test of the distance-redshift relation



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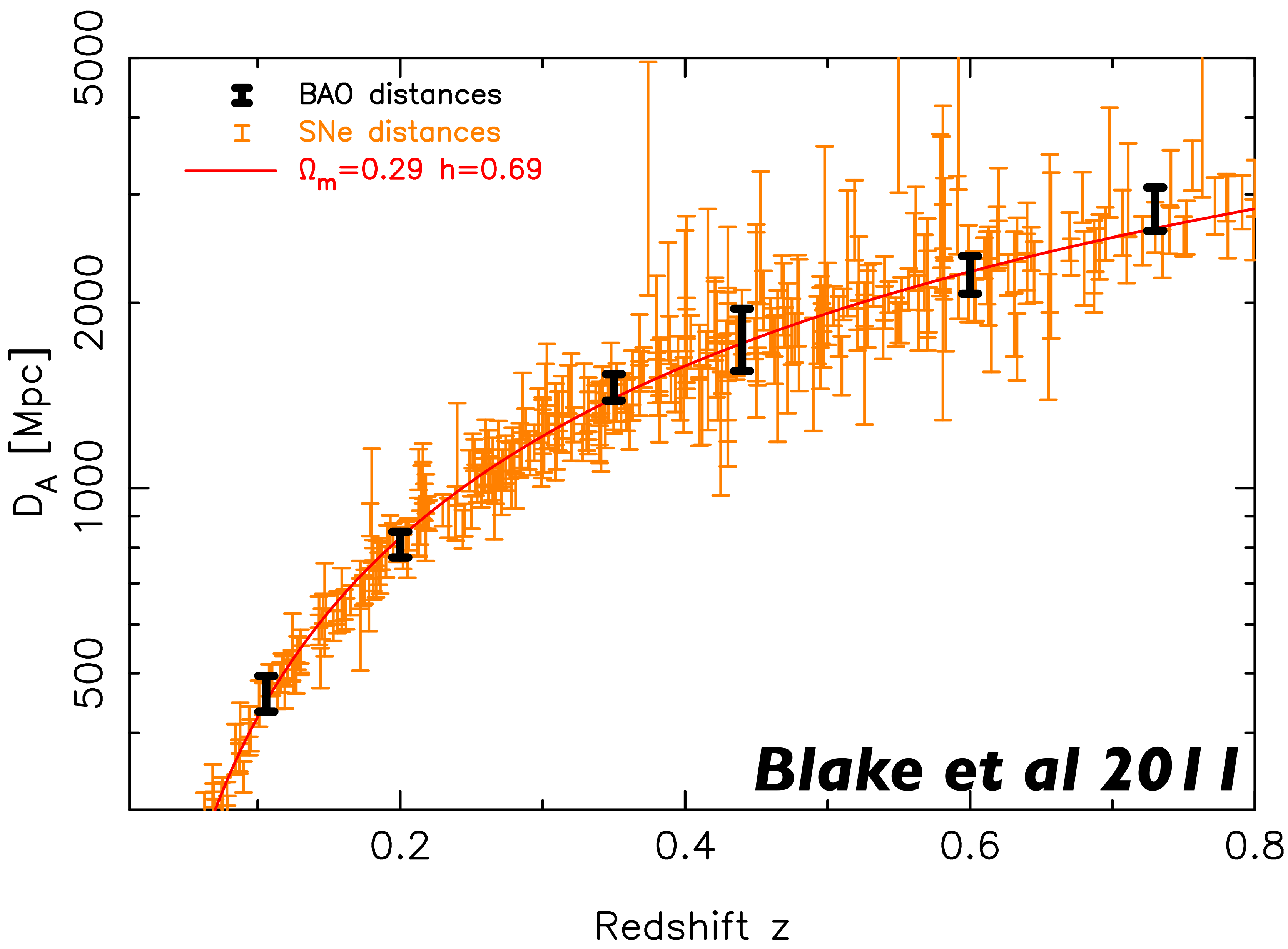
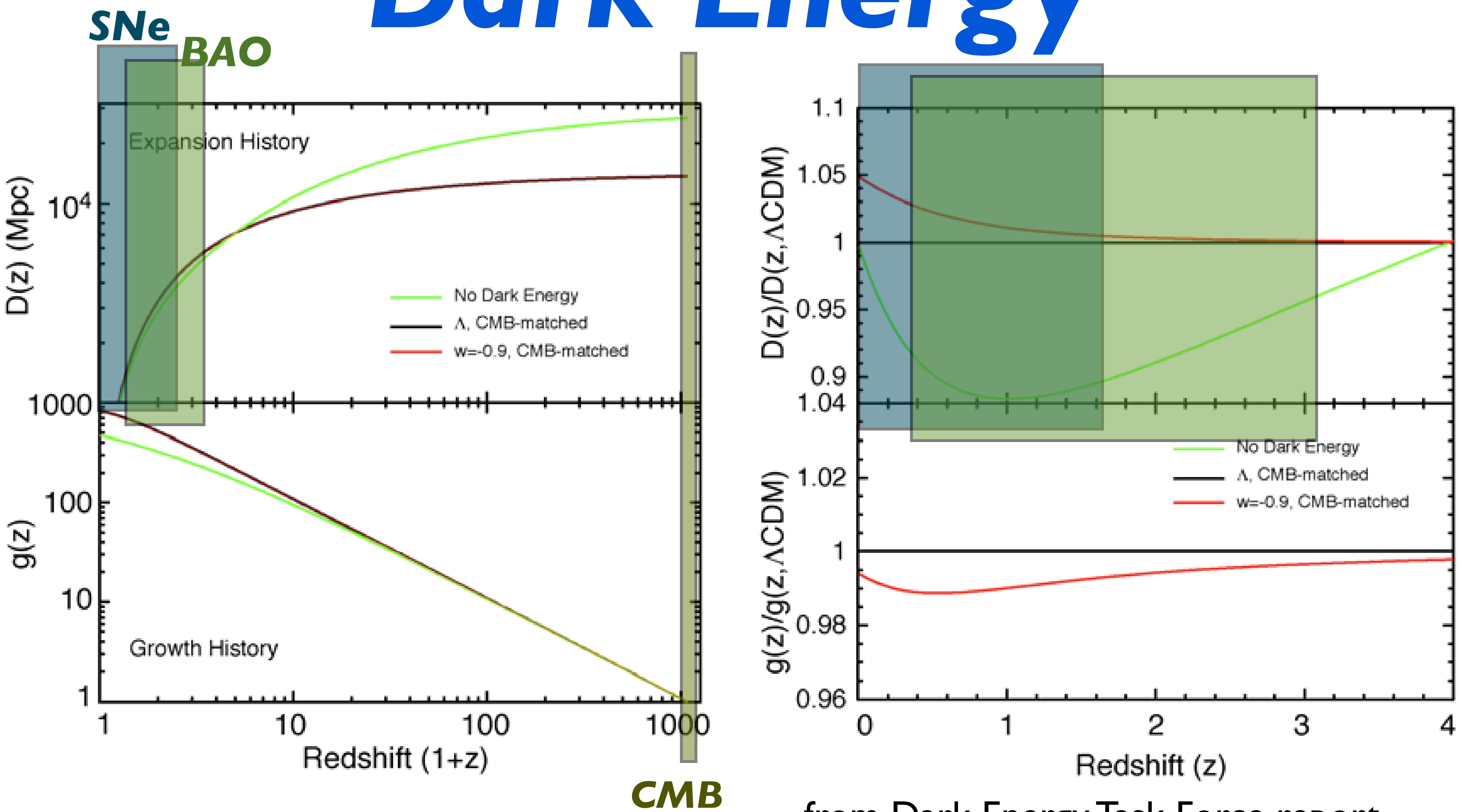


Forecast & Wish List for BAO

- minimal (but not completely negligible) non-linear physics
- mainly need more volume
    - **100 Mpc/h scale + 1% precision requires at least a few Gpc on a side surveys (cH_0^{-1}~3 Gpc/h)**
- lots of ideas & new surveys
    - e.g.., quasar absorption lines/optical galaxies (BigBoss); CHIME (21cm intensity mapping)

just my personal favorites, no offense to the many others...

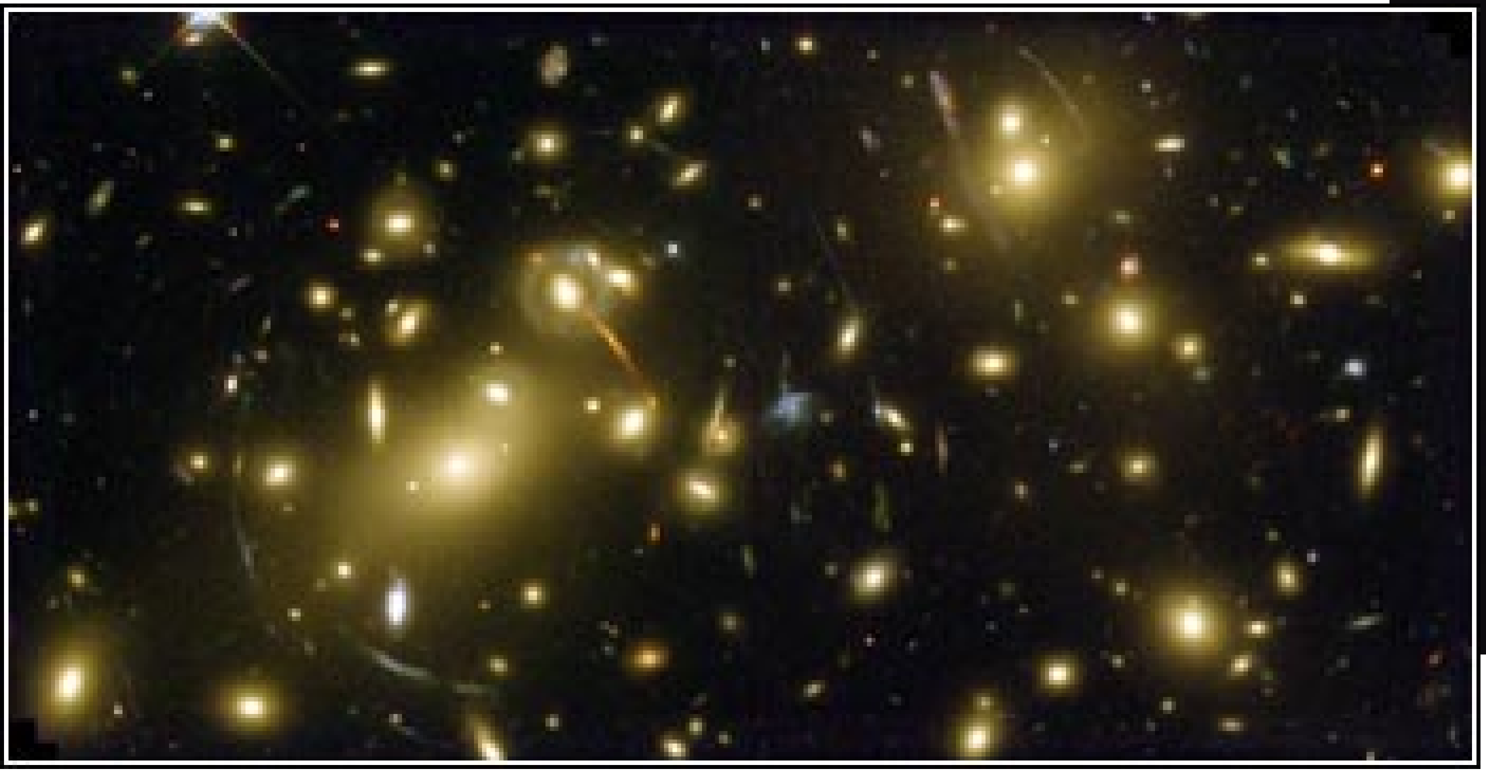
Characterizing Dark Energy

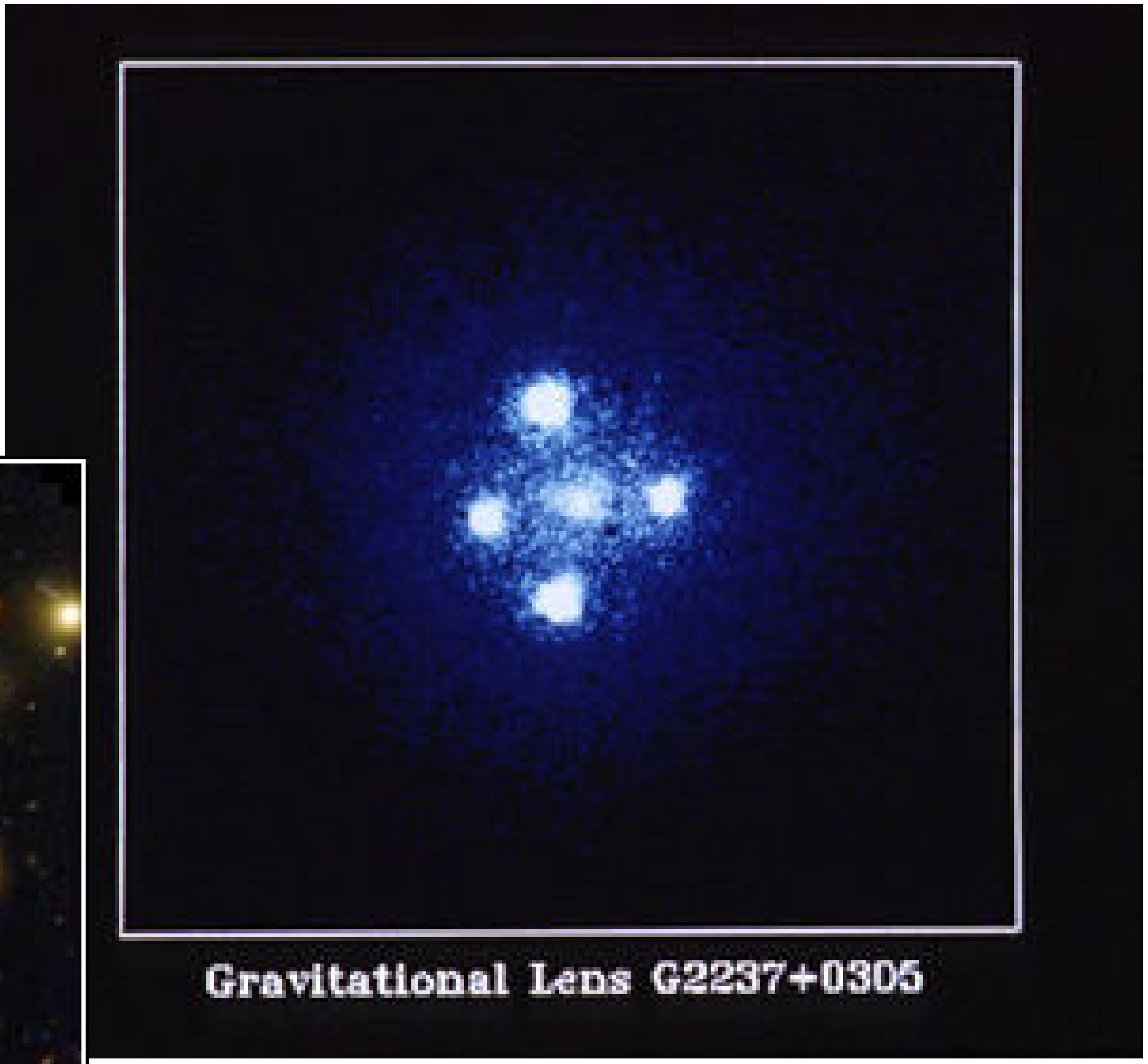


from Dark Energy Task Force report

Gravitational Lensing

- Distortion, multiple imaging of distant sources



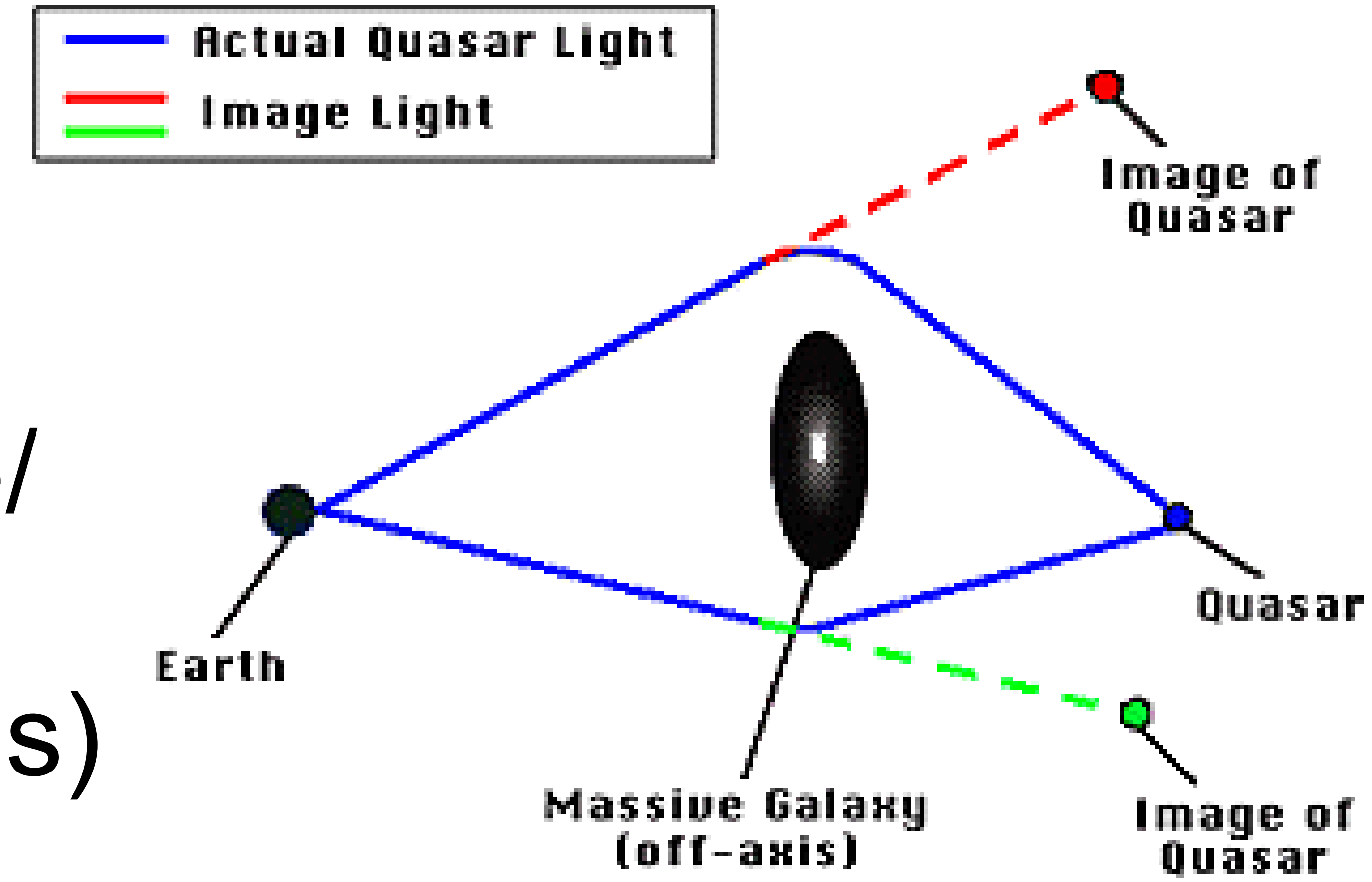


http://imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html

www.hubblesite.org

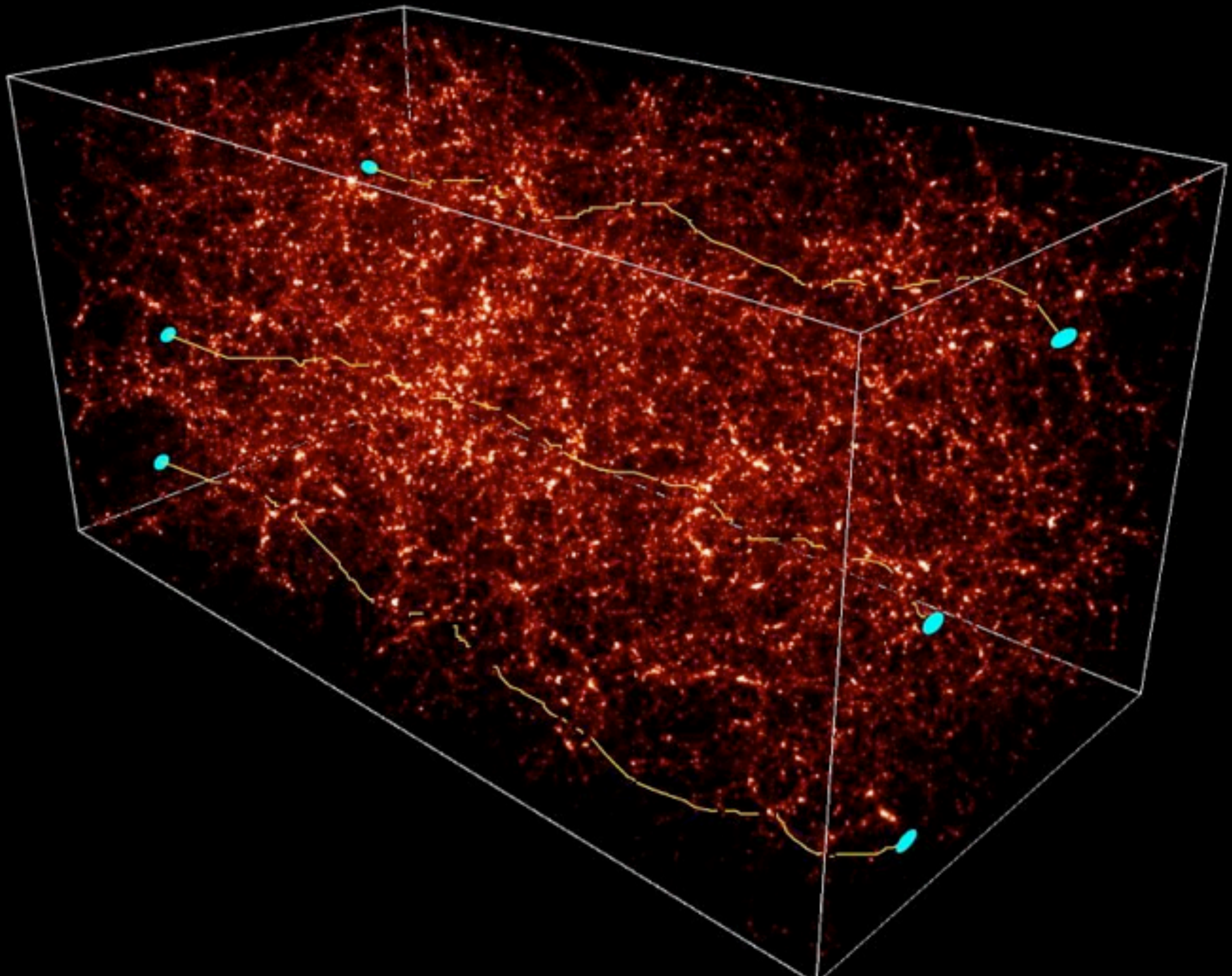
Gravitational Lensing

- Distortion, multiple imaging of distant sources
- amount of lensing depends on source/ lens/observer geometry (distances)



http://imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html

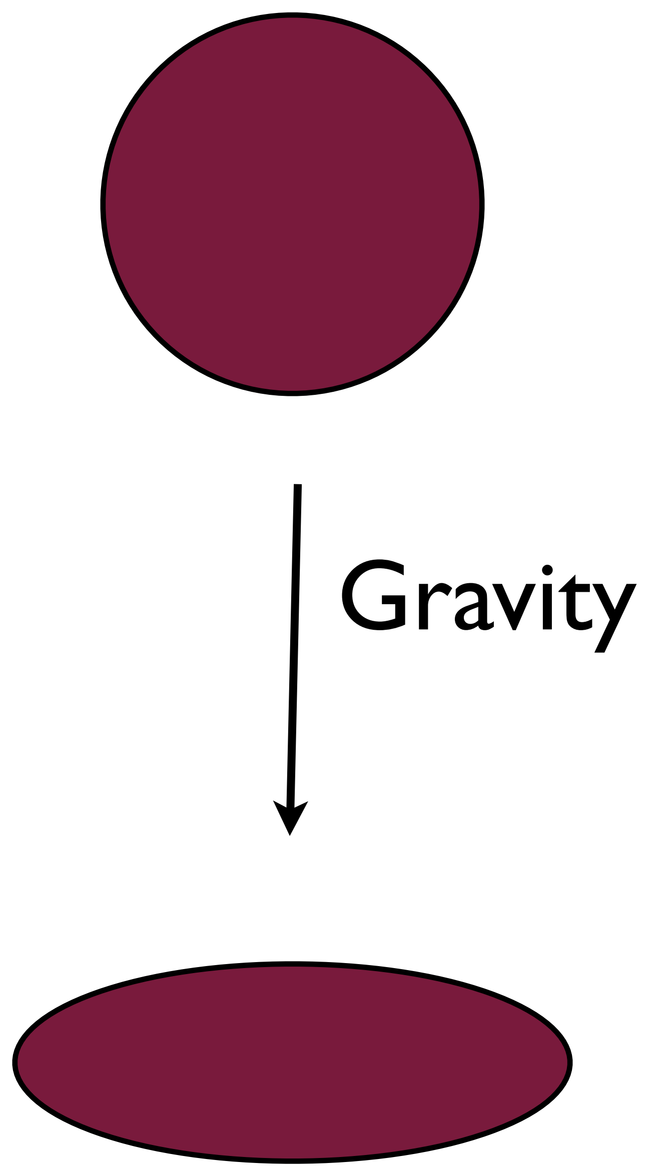
DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES



SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

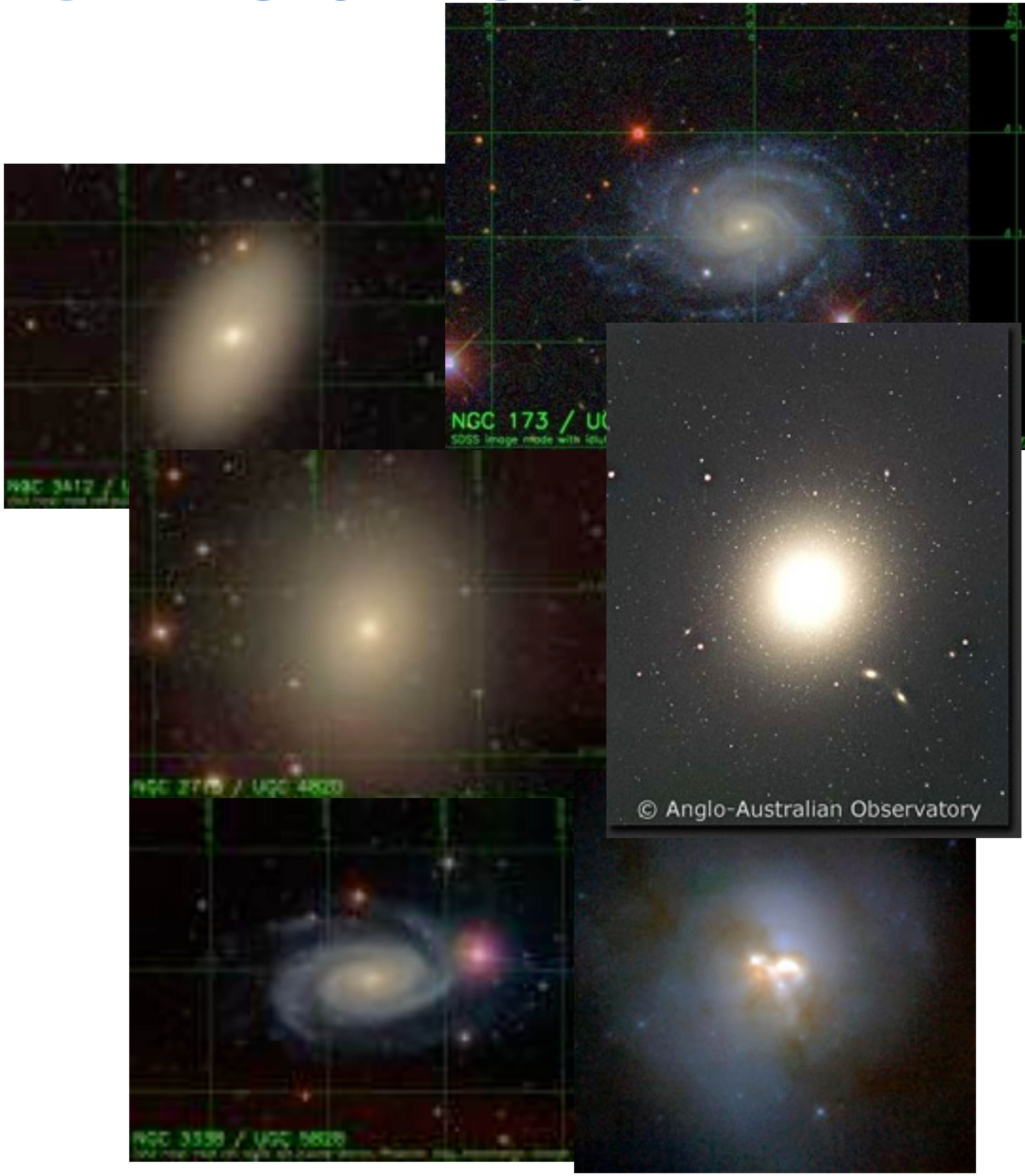
Weak Lensing

- gravitational potentials distort shapes by stretching, squeezing, shearing
- typical cosmic shear signal ~1%



Galaxies are not round

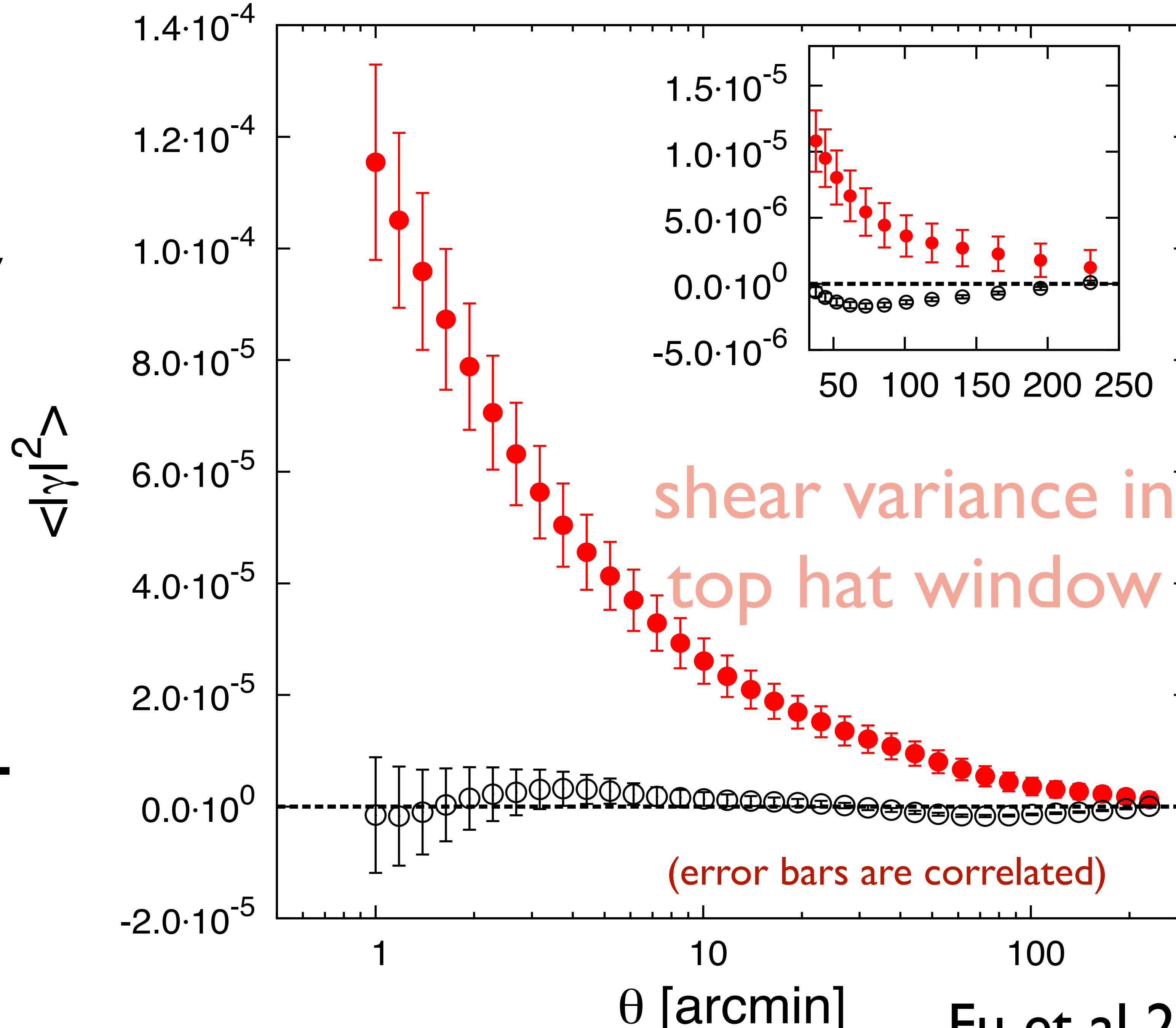
- individual galaxies have complex morphologies
- solution: average over many galaxies



Cosmic Shear Measurements

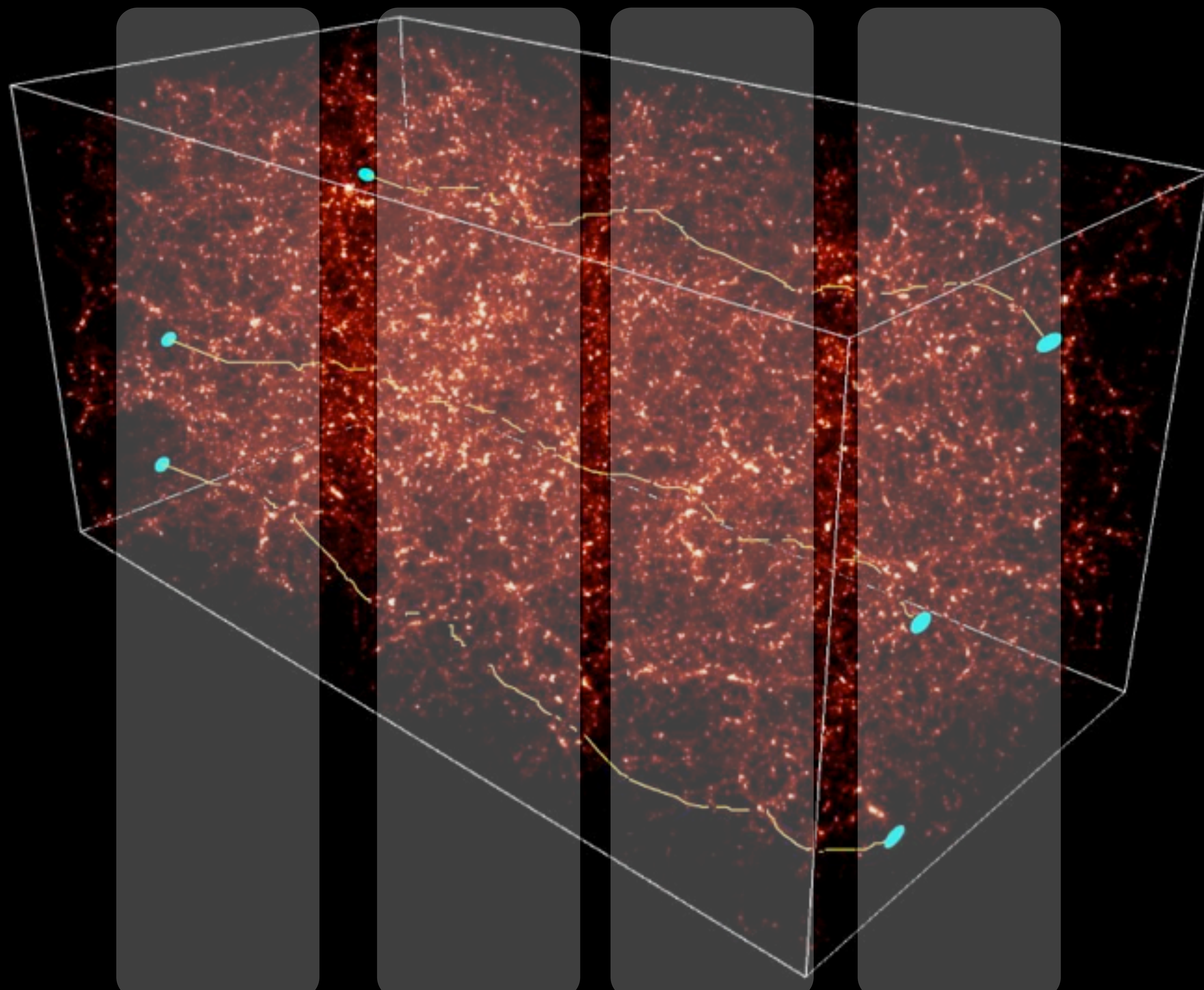
- very strong detections are now being made
- e.g., CFHTLS has published results from 57 sq deg of single-band ground-based imaging

CFHTLS



Fu et al 2008

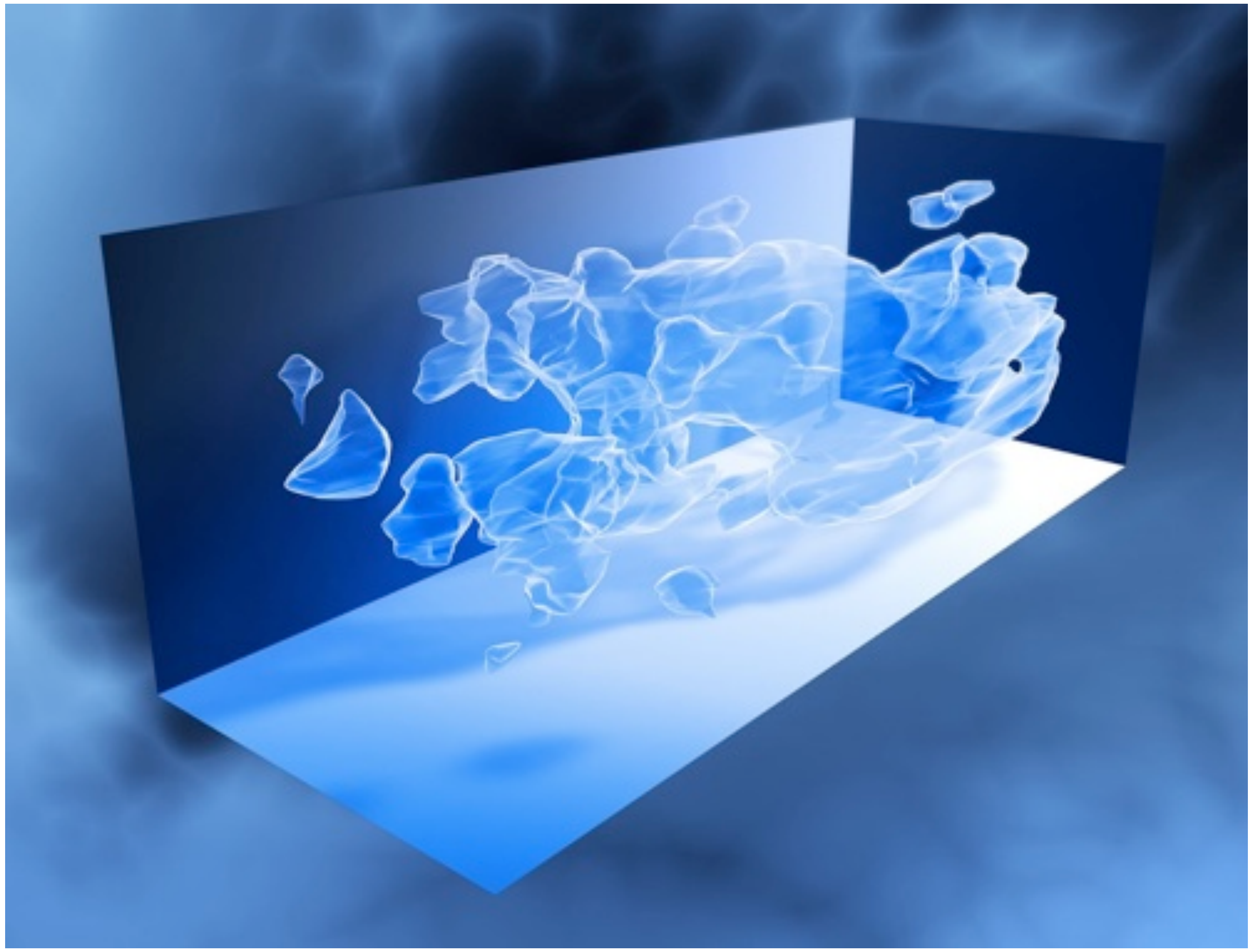
DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES



SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Weak lensing tomography

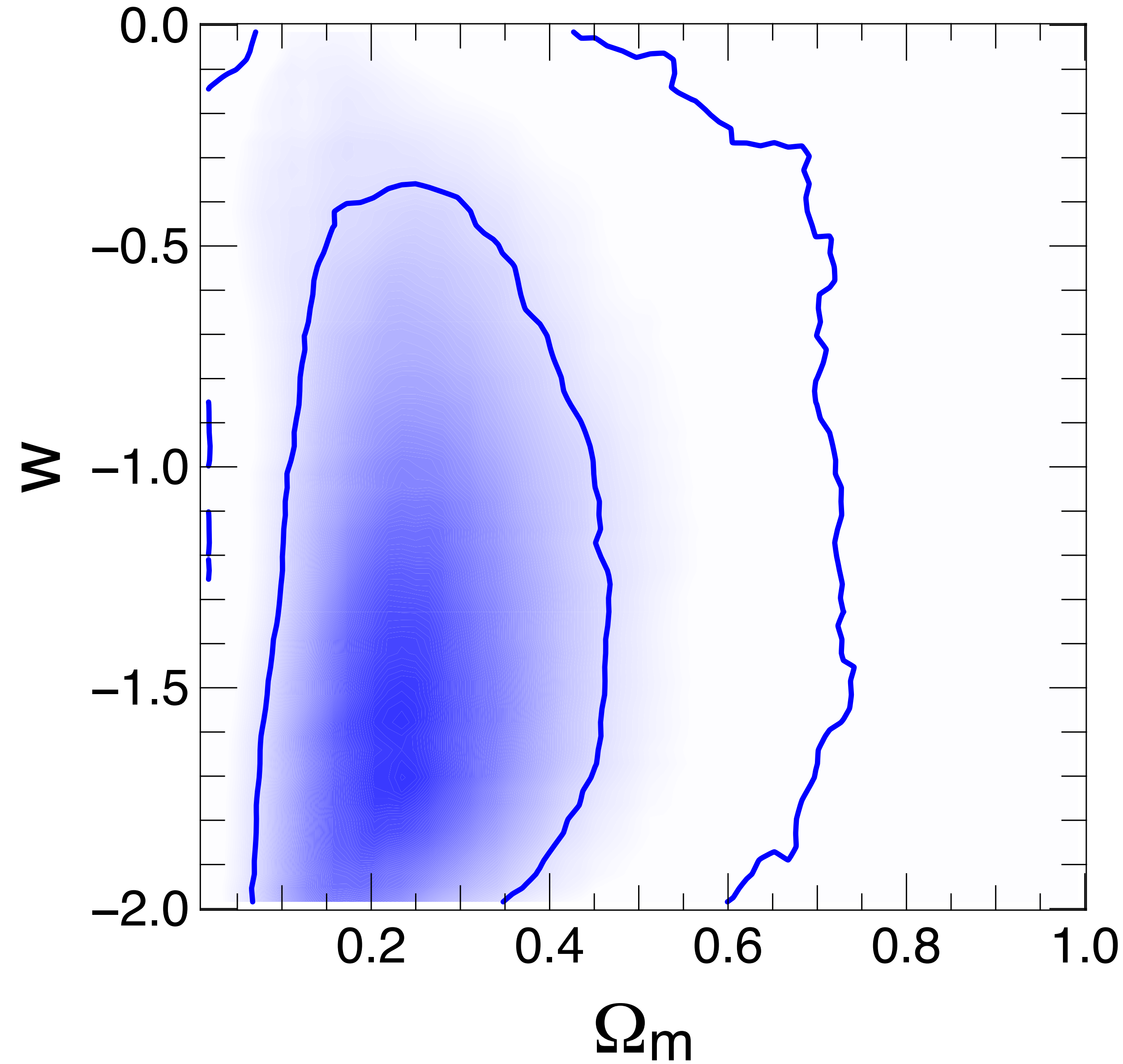
- using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
- mass, not galaxy, density means you can measure the time evolution of the density fluctuations
- recent results using Hubble over ~1 sq deg



Massey et al

Weak lensing tomography

- using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
- mass, not galaxy, density means you can measure the time evolution of the density fluctuations

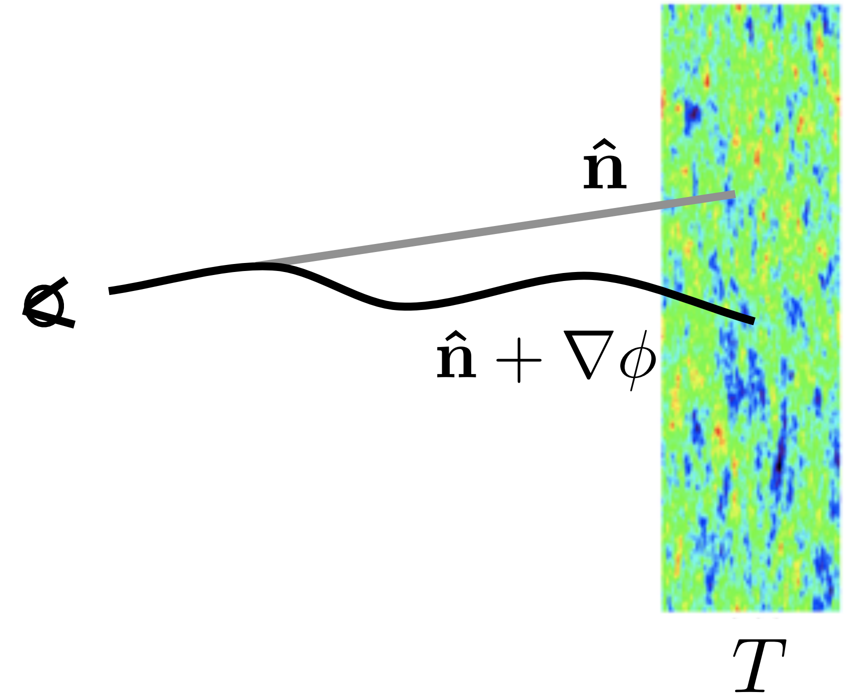


Schrabback et al 2010

CMB Lensing

Photons get shifted

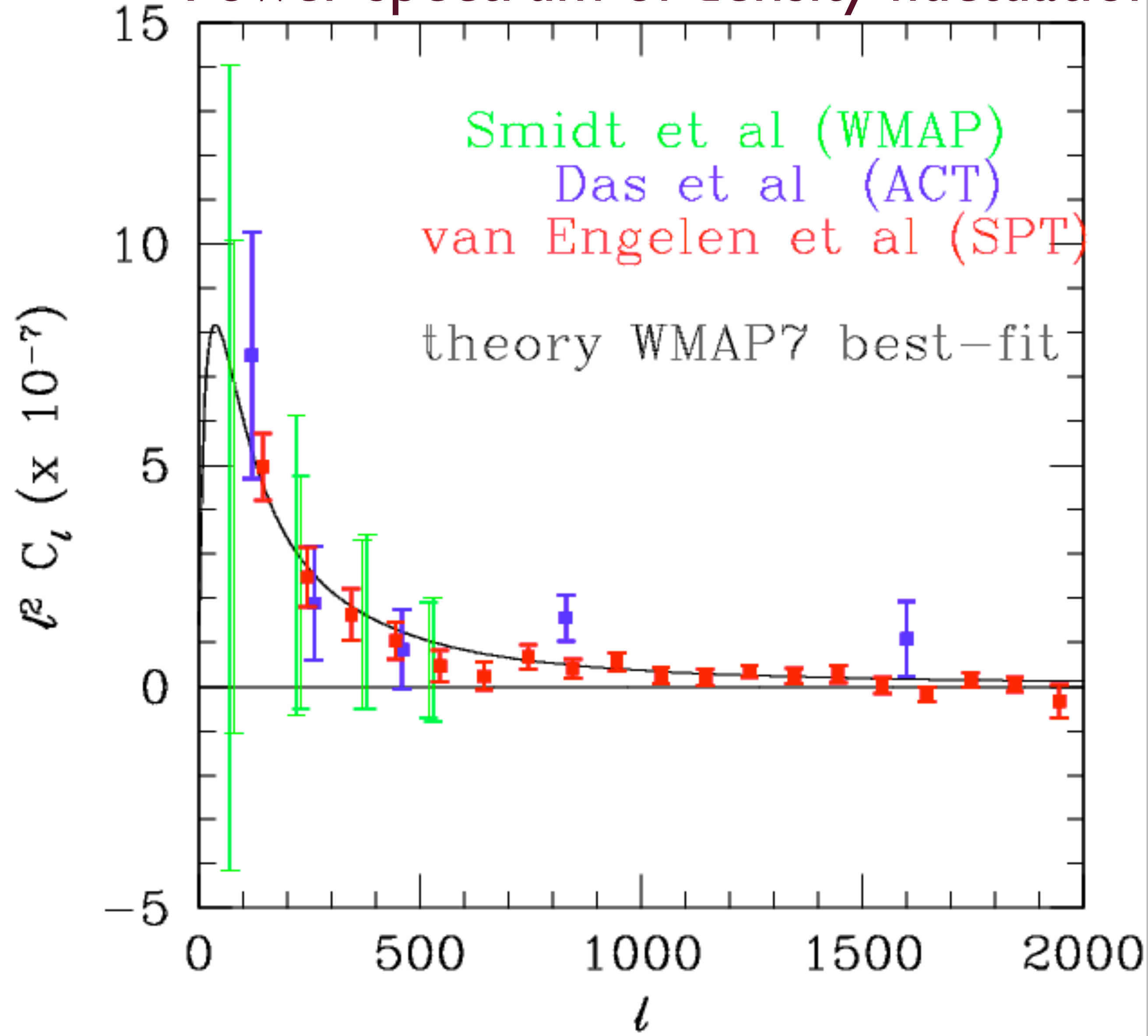
$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$



- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
  - At redshift which is (a) unique, (b) known, and (c) highest

strong detections now exist

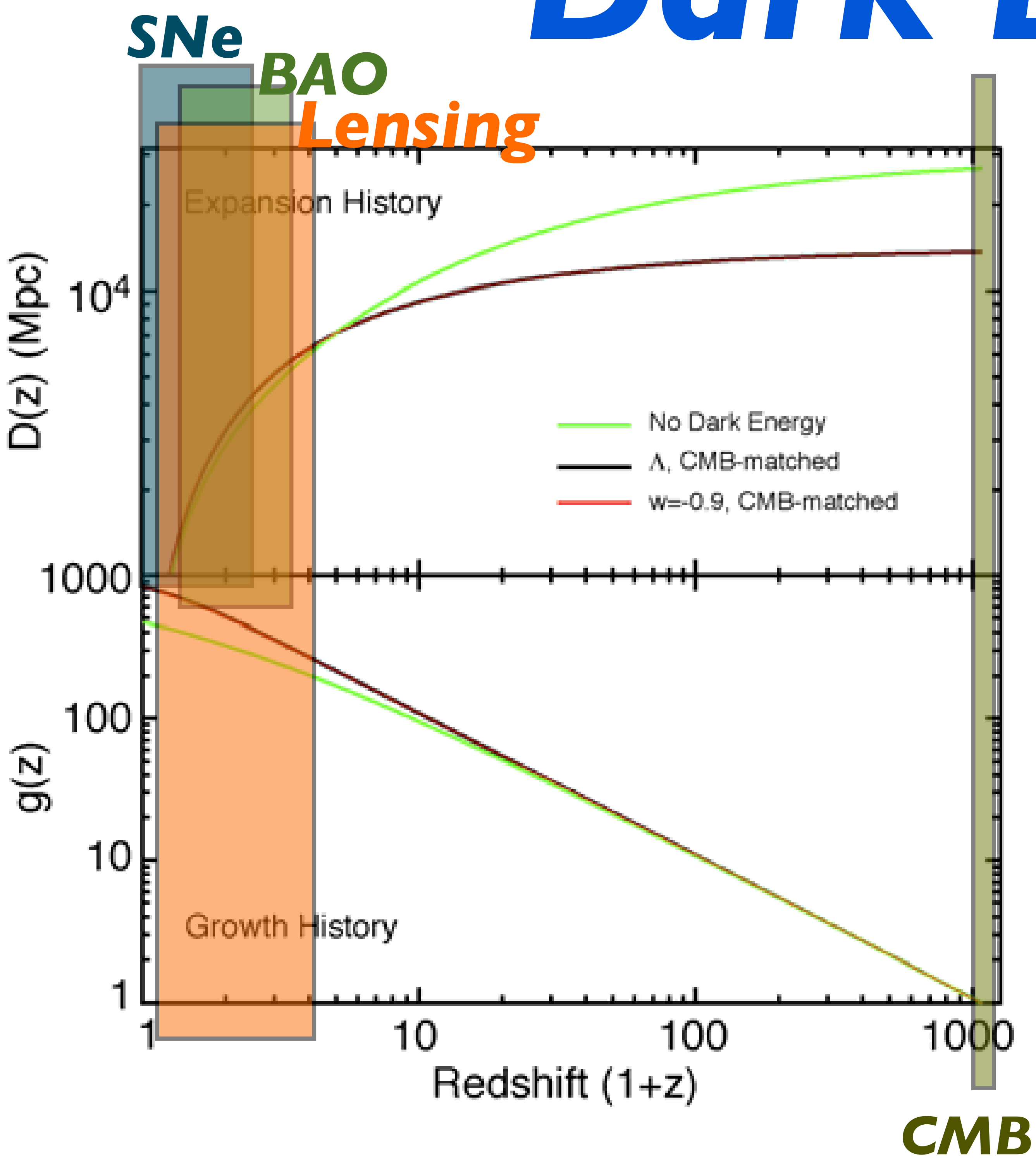
Power spectrum of density fluctuations

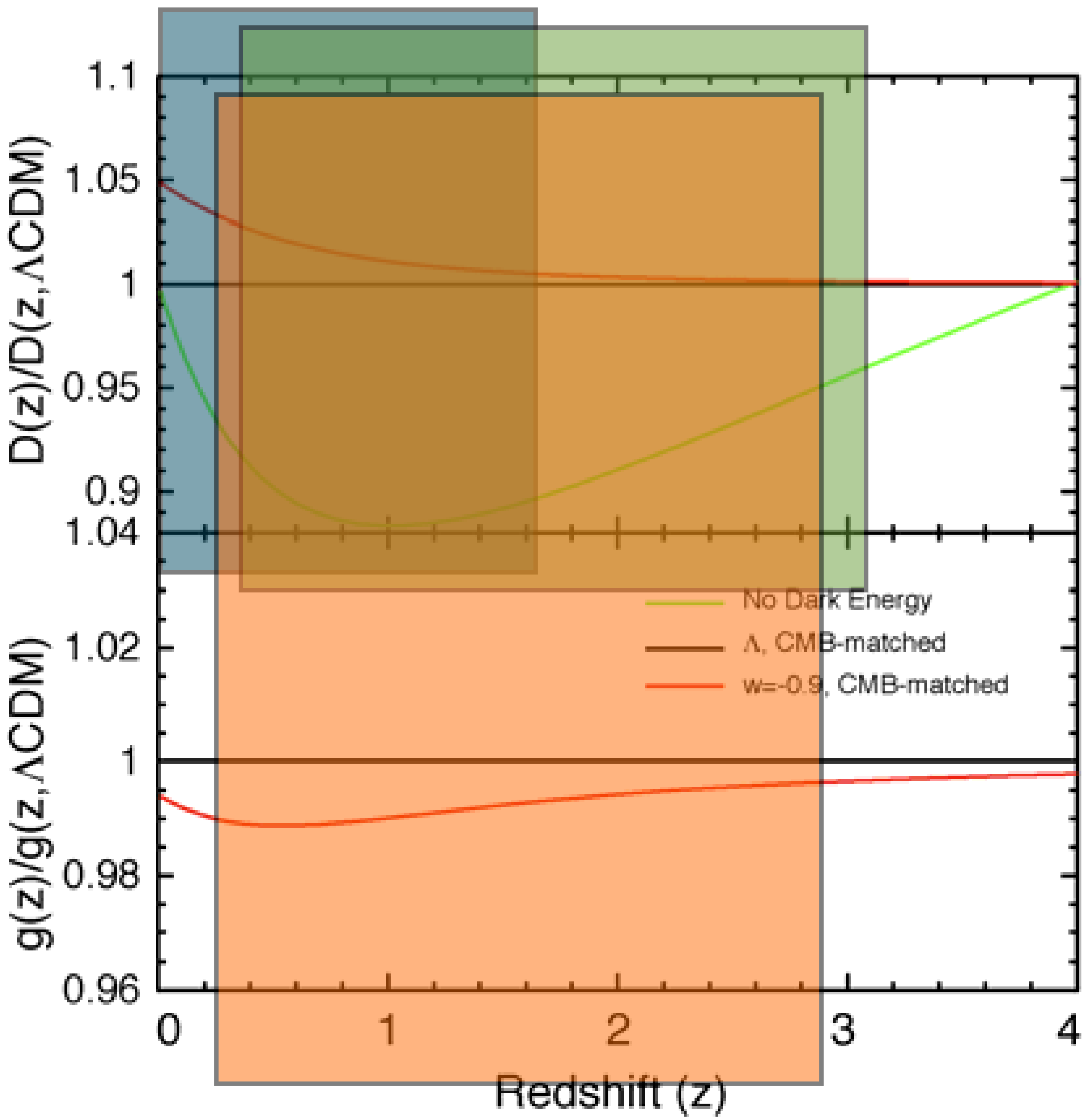


Forecast & Wish List for lensing

- cosmic shear requires large areas, good redshift discrimination, good telescope understanding
  - *space-based may be easier (high resolution, broad wavelength coverage, very dark sky)*
- large surveys coming soon: 1000s of square degrees of deep imaging (DES, Pan-Starrs, ...,LSST)

Characterizing Dark Energy



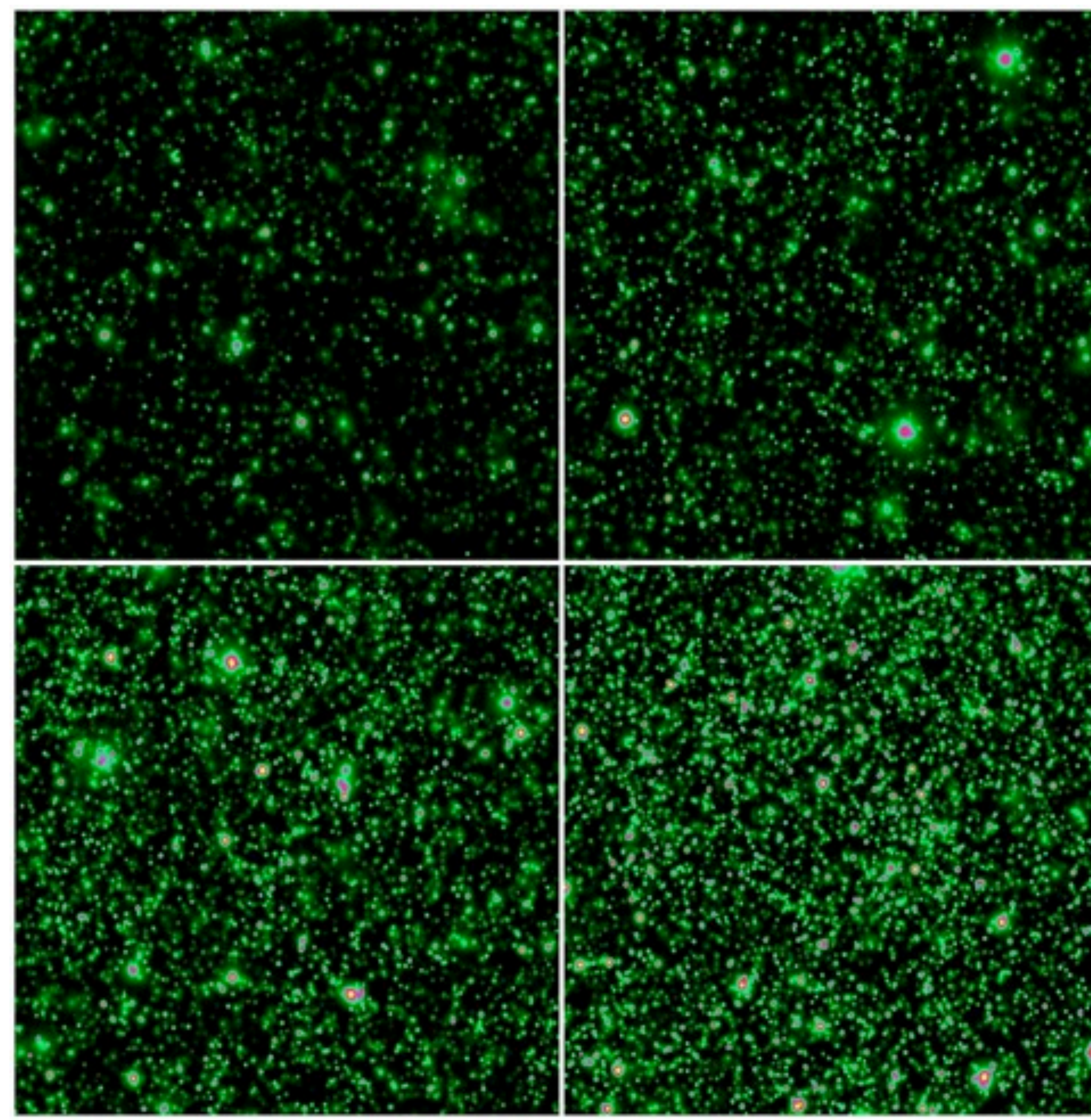


from Dark Energy Task Force report

Number counts of rare objects

- simulated 2x2 degree map showing projected thermal pressure
- number of most massive objects highly sensitive to amplitude of density fluctuations

-10% **ref fluctuation amplitude**



+10% **+20%**

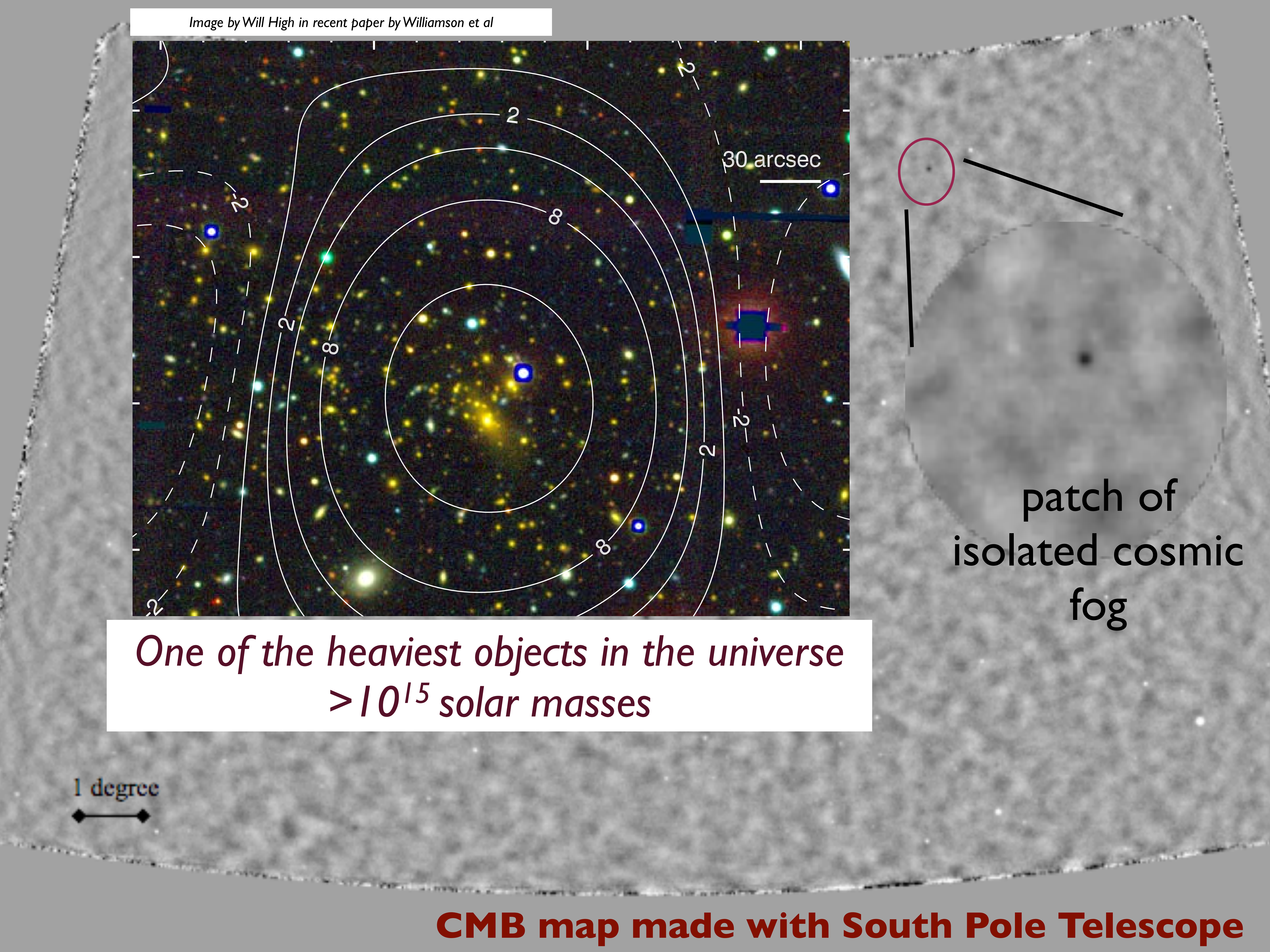
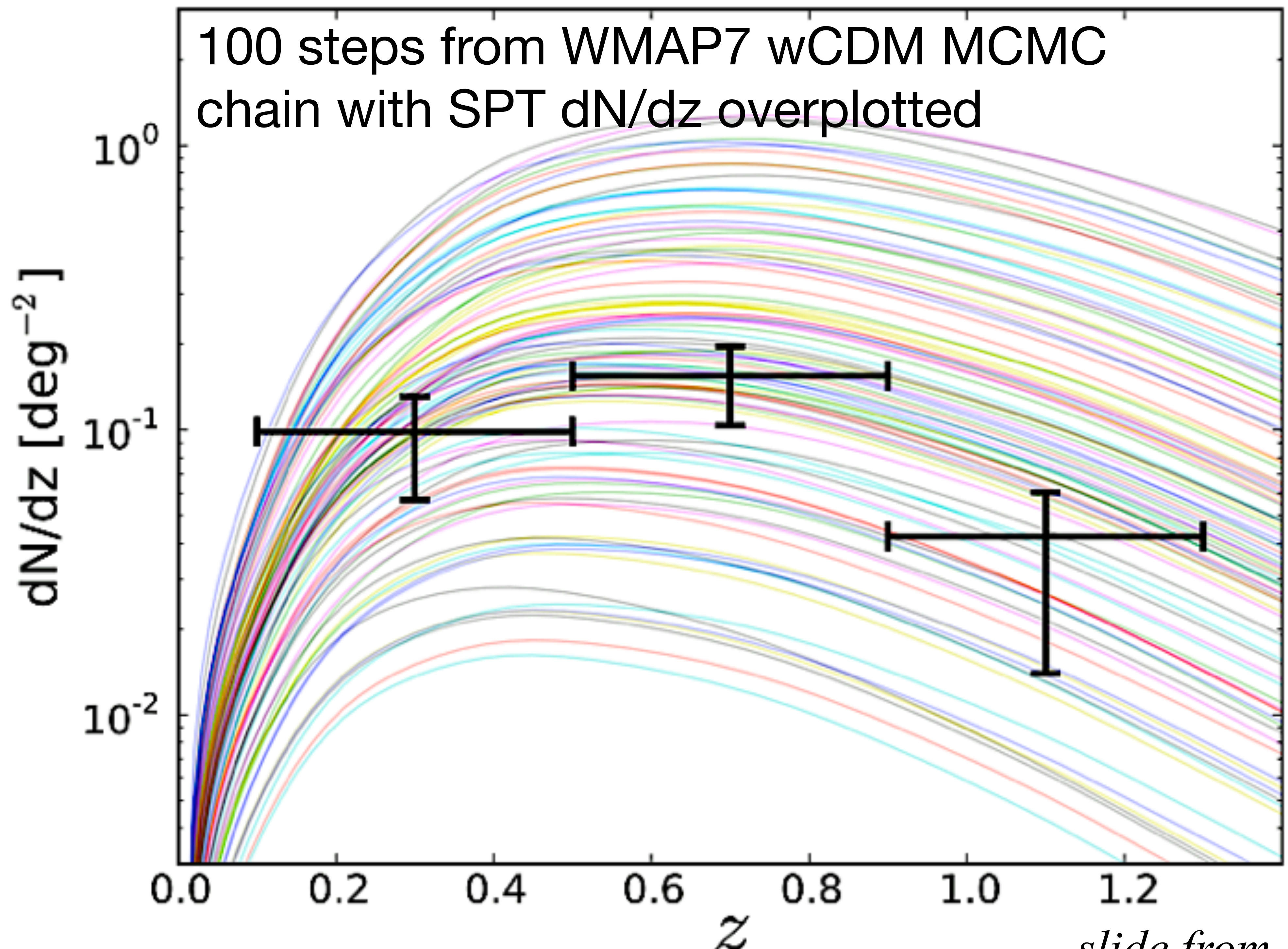


Image by Will High in recent paper by Williamson et al
30 arcsec
patch of isolated cosmic fog
One of the heaviest objects in the universe
$>10^{15}$ solar masses
1 degree
CMB map made with South Pole Telescope

Cluster dN/dz

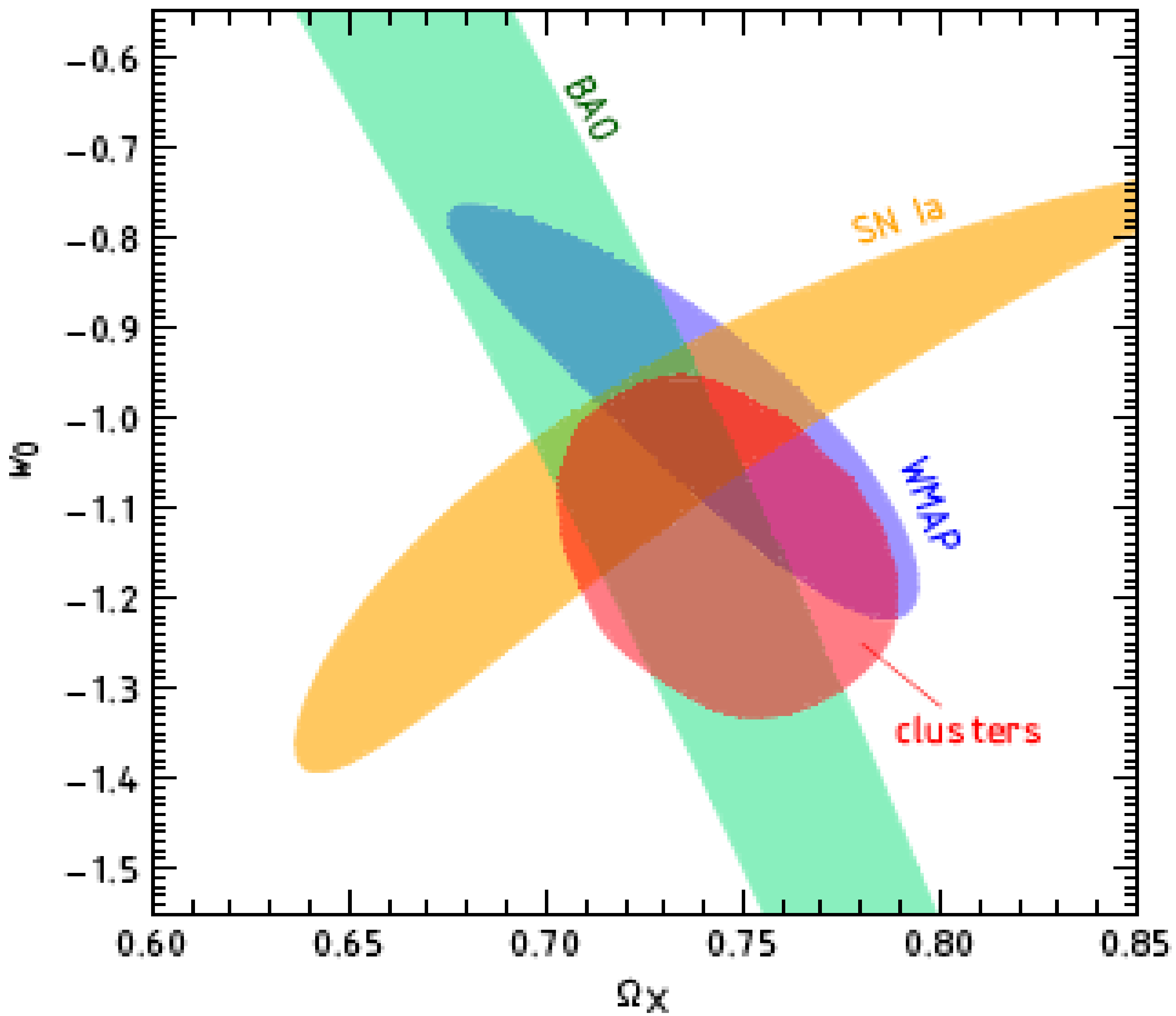
First SPT Cosmological result (Vanderlinde et al 2010), used SPT's first 21 clusters to constrain cosmology



slide from Brad Benson

Constraints on dark energy from X-ray selected galaxy clusters

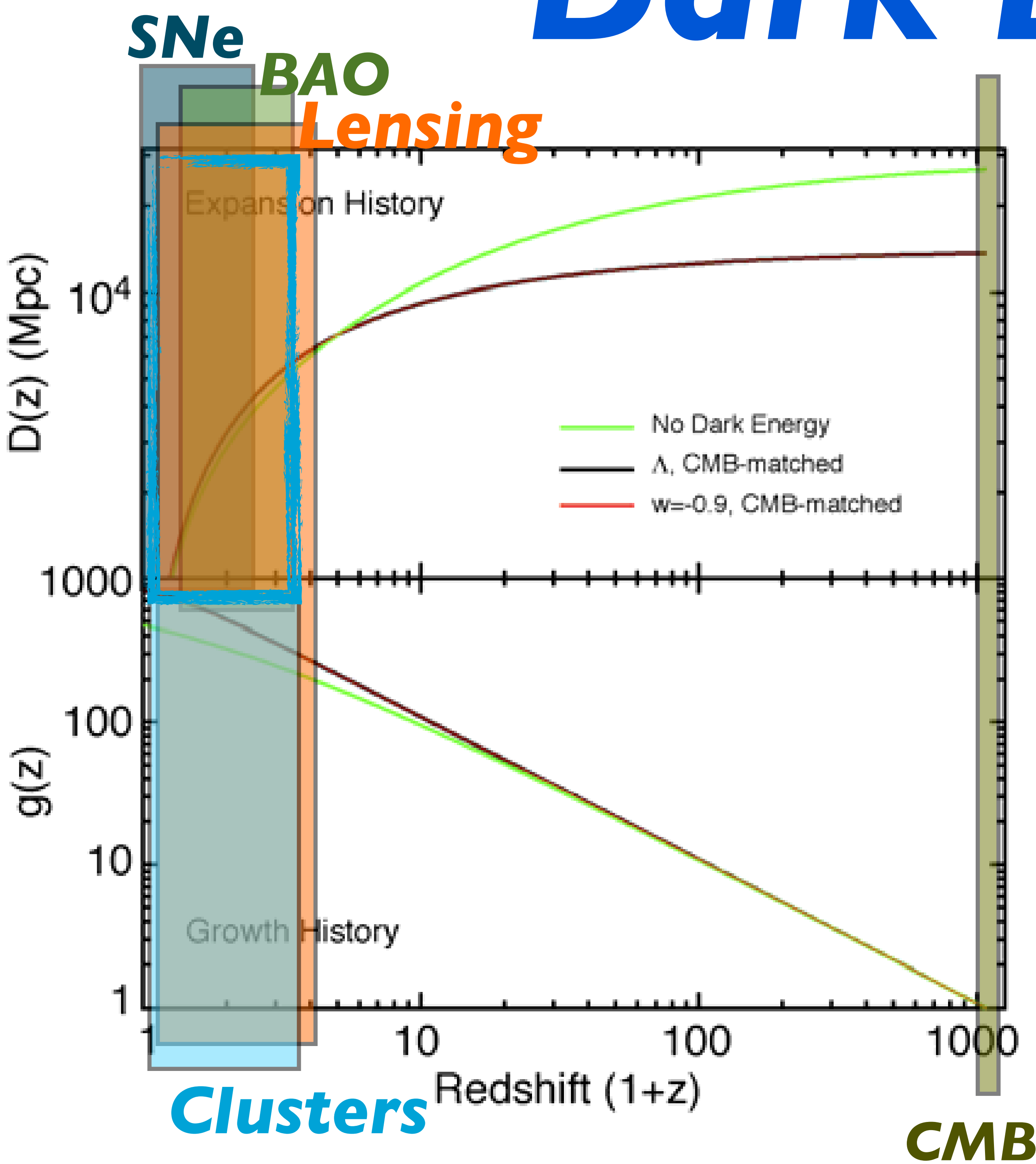
- Vikhlinin et al 2009 (see also Mantz et al)
- ~60 clusters at z<0.7

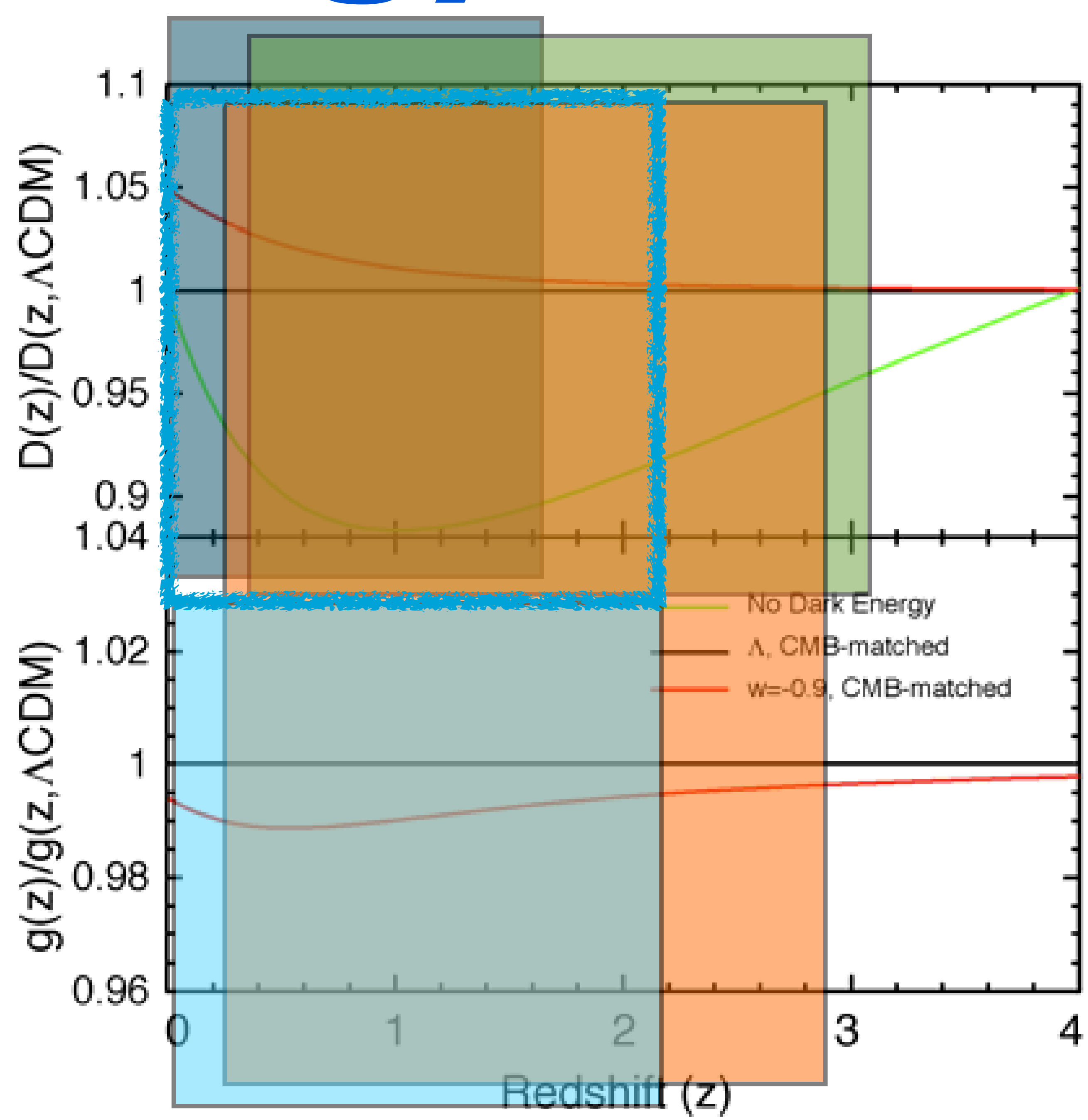


Forecast & Wish List for galaxy clusters

- need larger samples: 1% requires 1000s of clusters just to beat Poisson noise: eROSITA (X-ray), DES (optical)
- need strong validation campaign to ensure the sample properties are well-understood (i.e., make sure that the number of objects is changing, not the type of object that is being found)

Characterizing Dark Energy





from Dark Energy Task Force report

Summary

- dark energy is being observed in many different ways
  - first discovered through supernovae, but many independent cross-checks!
- distances & structure formation are two fundamentally different tests
- all methods have strengths and weaknesses but great promise for figuring out dark energy