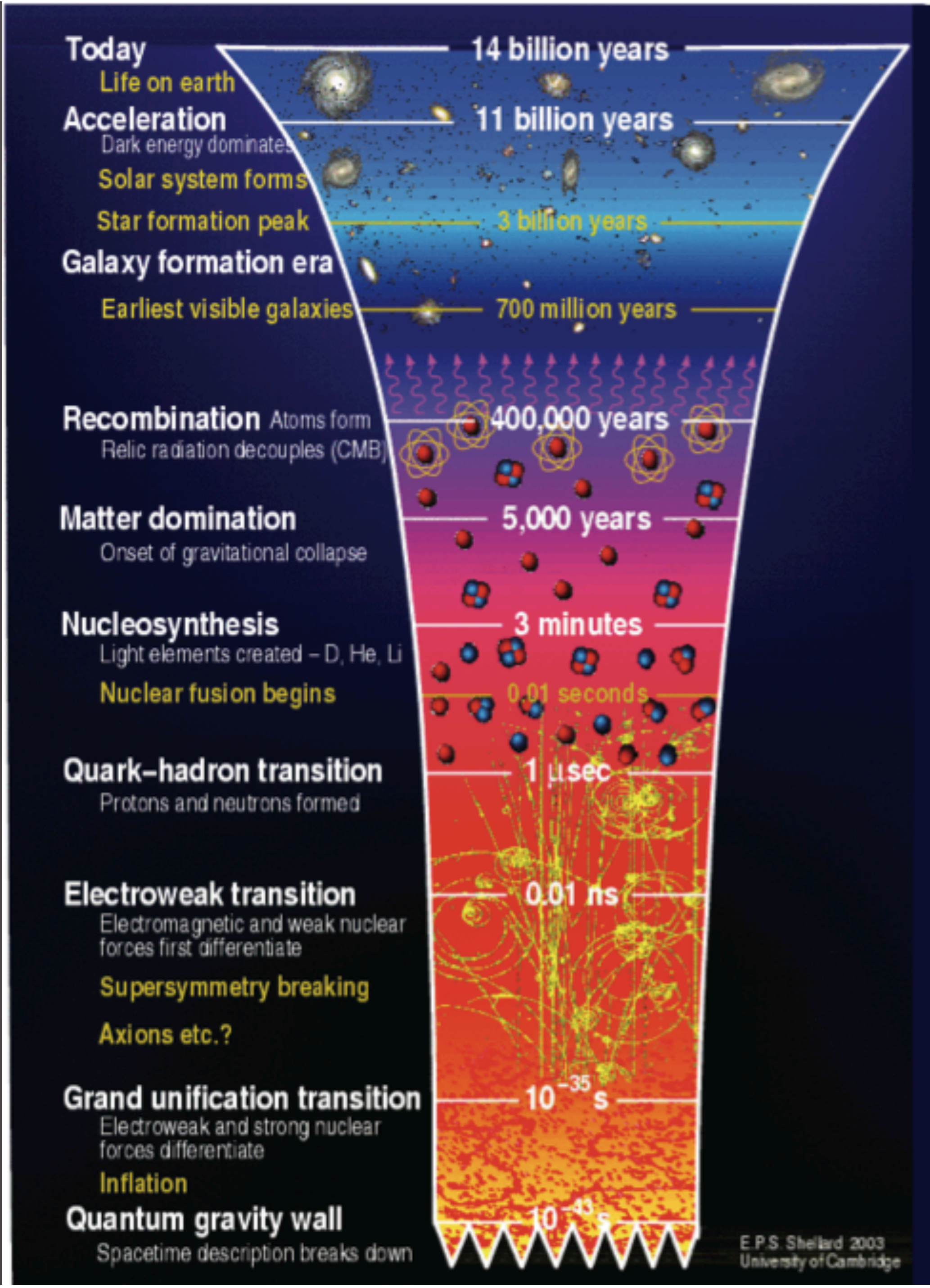
Cosmology

Josh Frieman

Fermilab & The University of Chicago

APS Division of Particles & Fields

Wayne State U., July 2009


Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
Quark–hadron transition
Protons and neutrons formed
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
0.01 seconds
1 µsec
0.01 ns
10^{-35} s
10^{-43} s
E.P.S. Shellard 2003
University of Cambridge

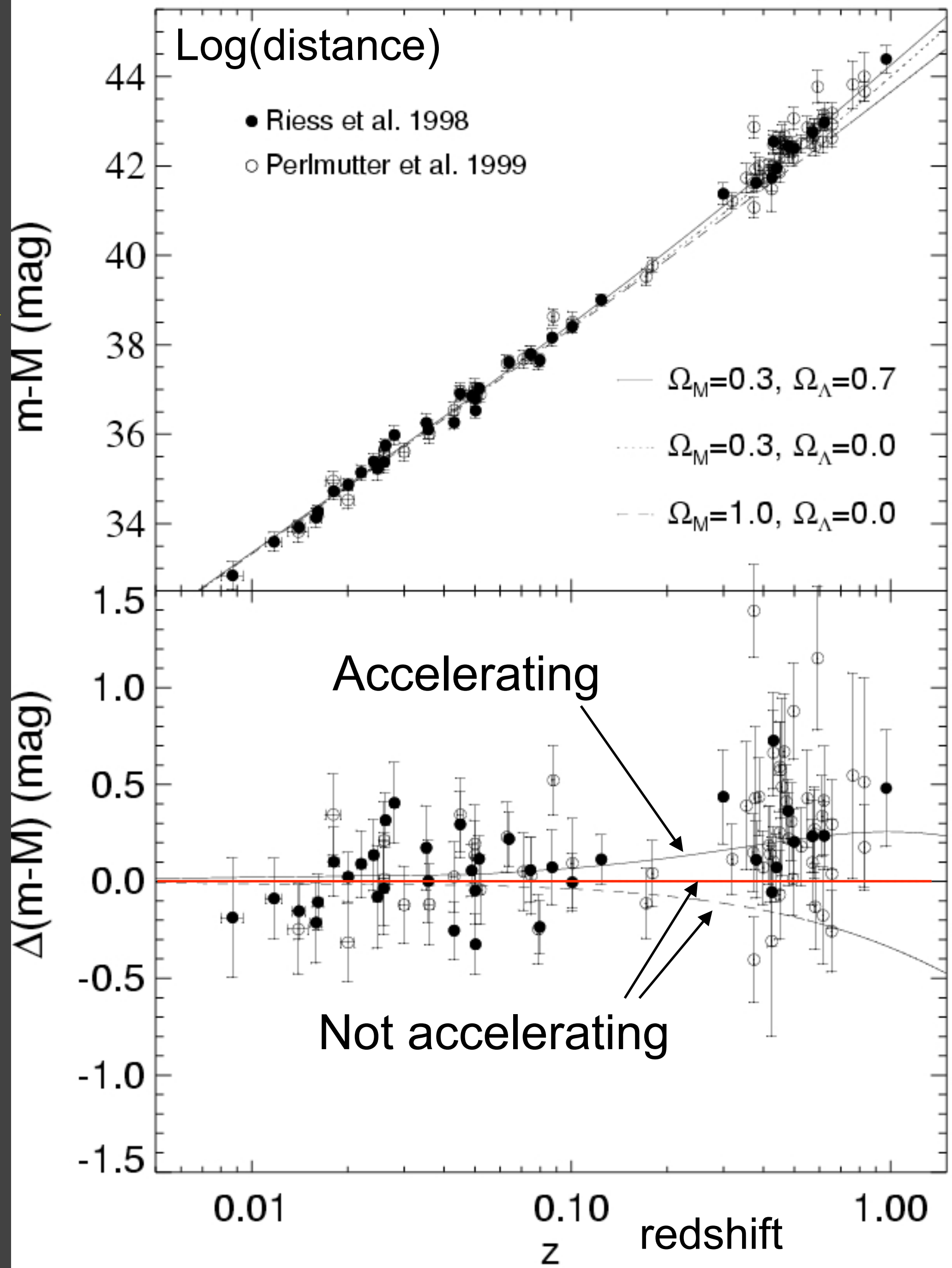
Key Questions

- Why is the expansion of the Universe accelerating?
- What is the Dark Matter?

  (covered by Golwala and Pierce yesterday)
- Was there an epoch of primordial acceleration (inflation)? What was the origin of cosmic structure?
- How did galaxies and large-scale structure form?

See also parallel sessions on Cosmology

Discovery of Cosmic Acceleration from High-redshift Supernovae



Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

$\Omega_\Lambda = 0.7$

$\Omega_\Lambda = 0.$

$\Omega_m = 1.$

What causes Cosmic Acceleration?

Three possibilities:

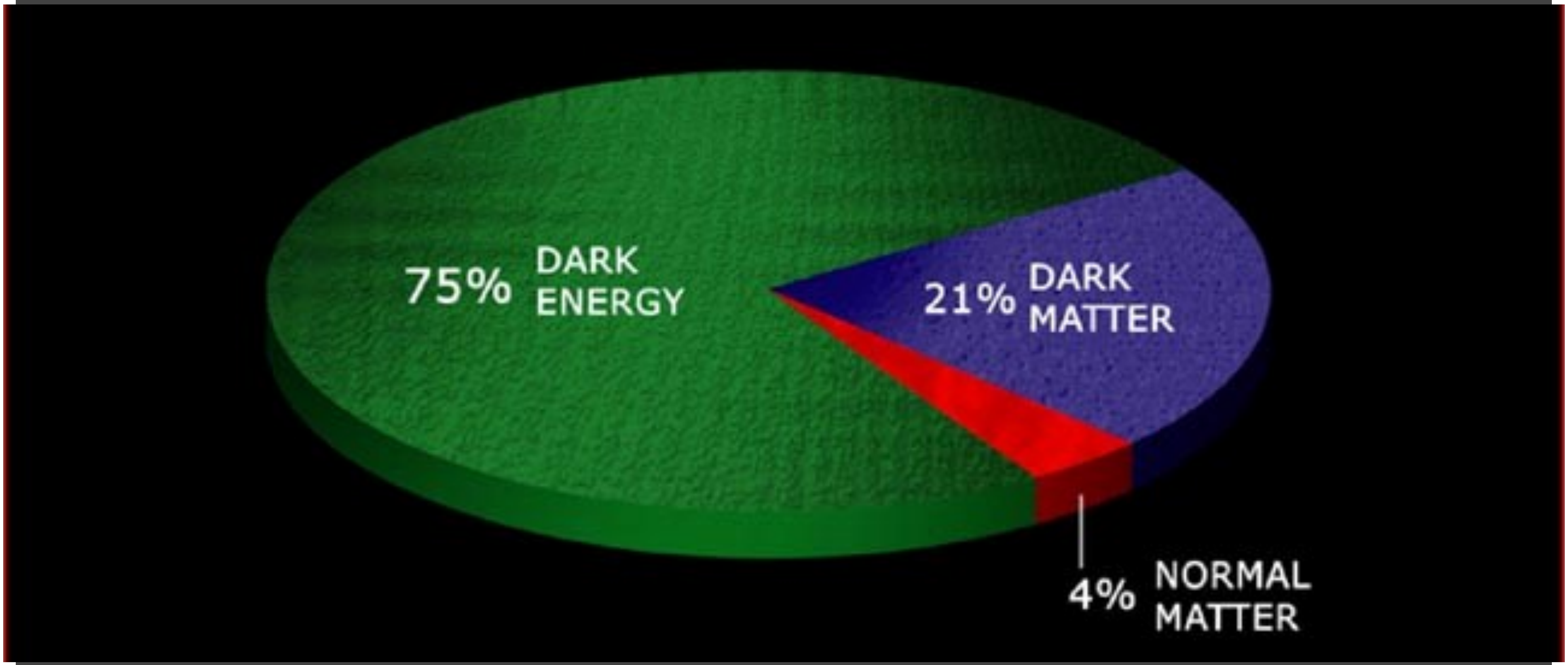
1. The Universe is filled with a negative-pressure component that gives rise to `gravitational repulsion':

   Dark Energy

2. Einstein's theory of General Relativity (gravity) is wrong on cosmic distance scales.

3. The Universe is inhomogeneous and only apparently accelerating, due to large-scale structure.

Components of the Universe



Cosmological Dynamics

Cosmic
Scale factor
a(t)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \rho_i\left(1+3w_i\right)$$

Friedmann
Equation

Equation of state parameter $w_i = p_i / \rho_i c^2$

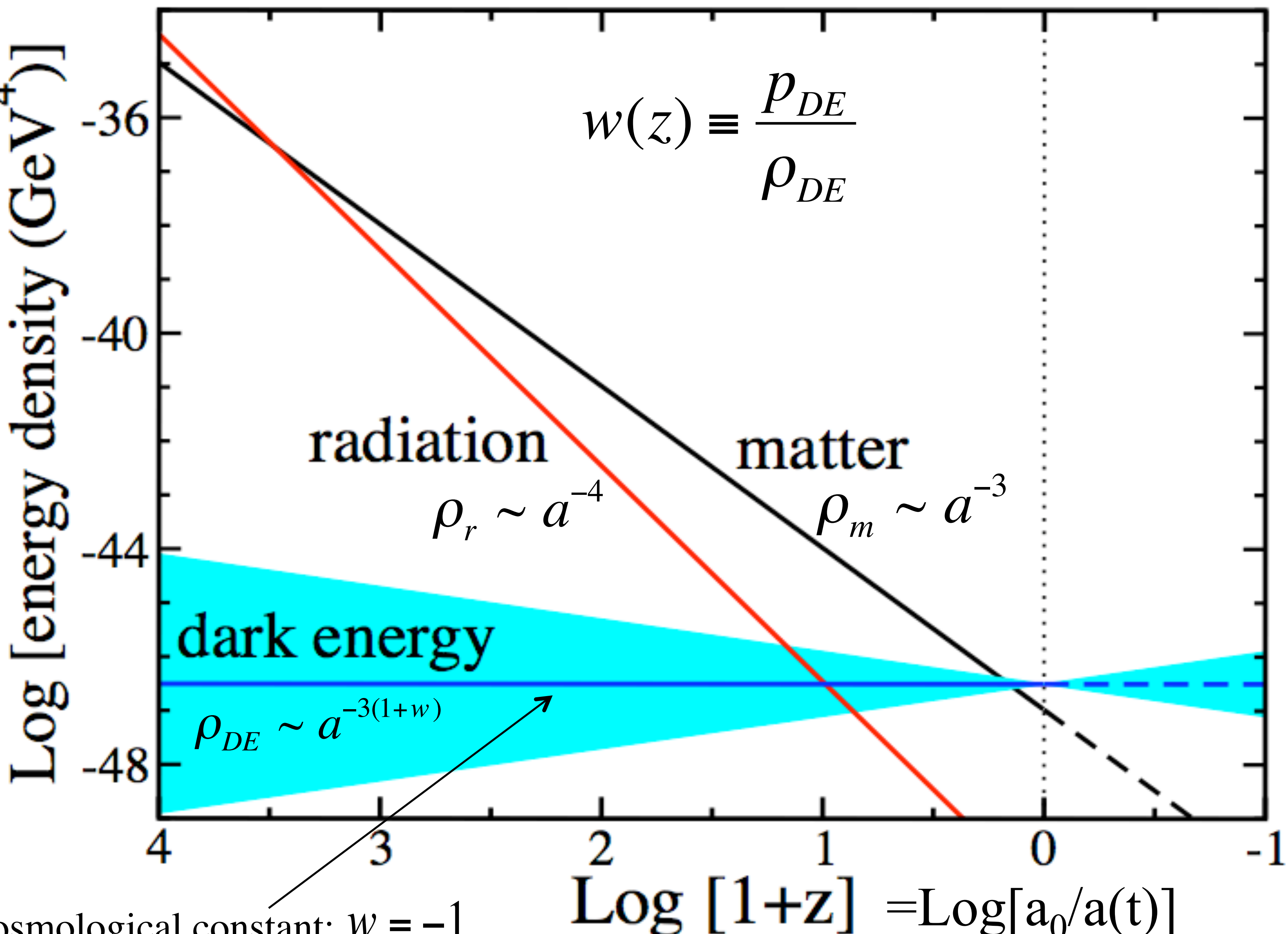
For acceleration, $w_i < -1/3$ in dominant component

Cosmological constant Λ: $w = -1$

Two simple Dark Energy models to constrain:

1. Λ: $w = -1$
2. Spatially flat Universe with $w =$ constant

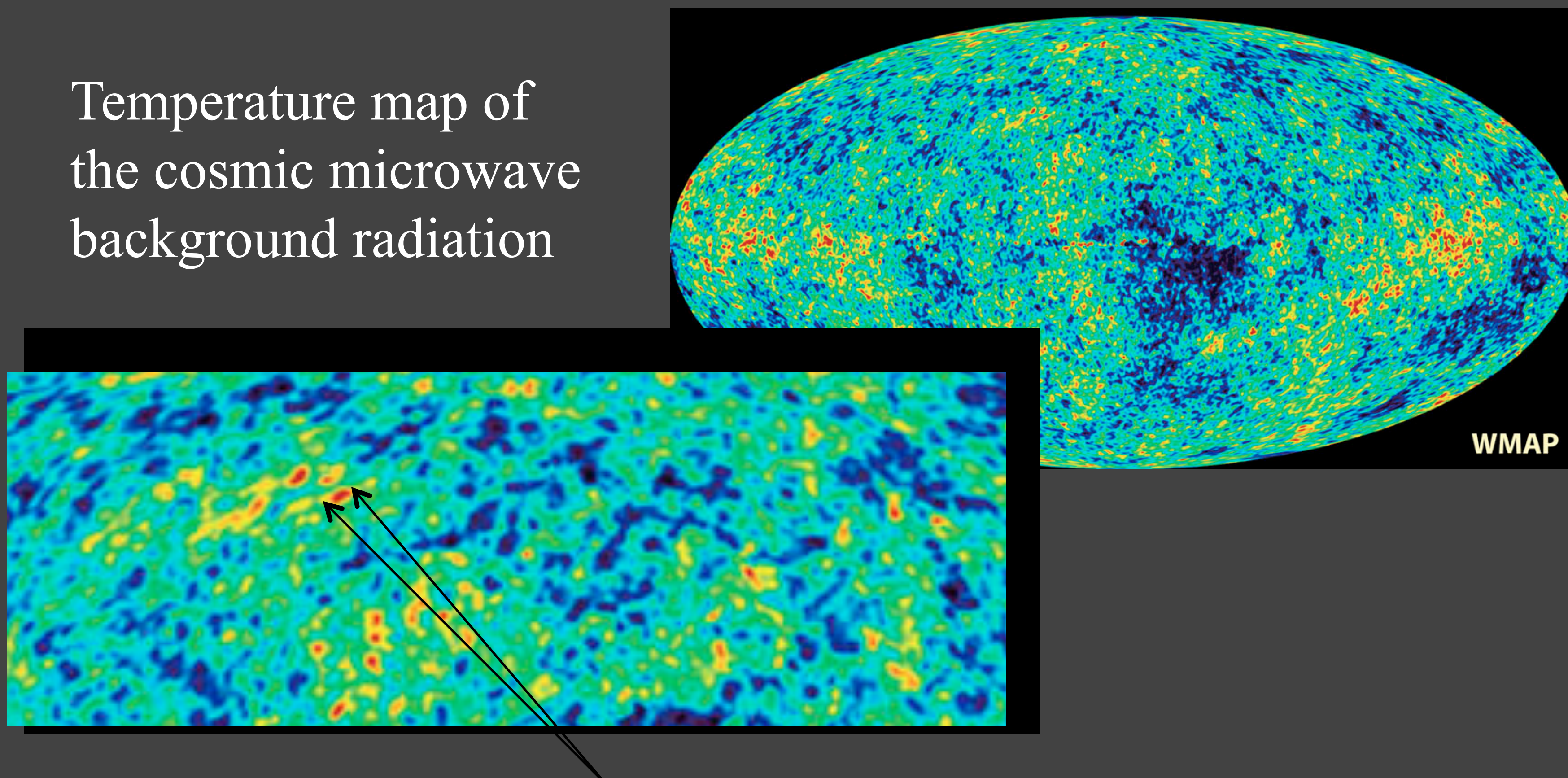
Dark Energy Equation of State parameter *w* determines Cosmic Evolution



Cosmological constant: $w = -1$

Cosmic Microwave Background

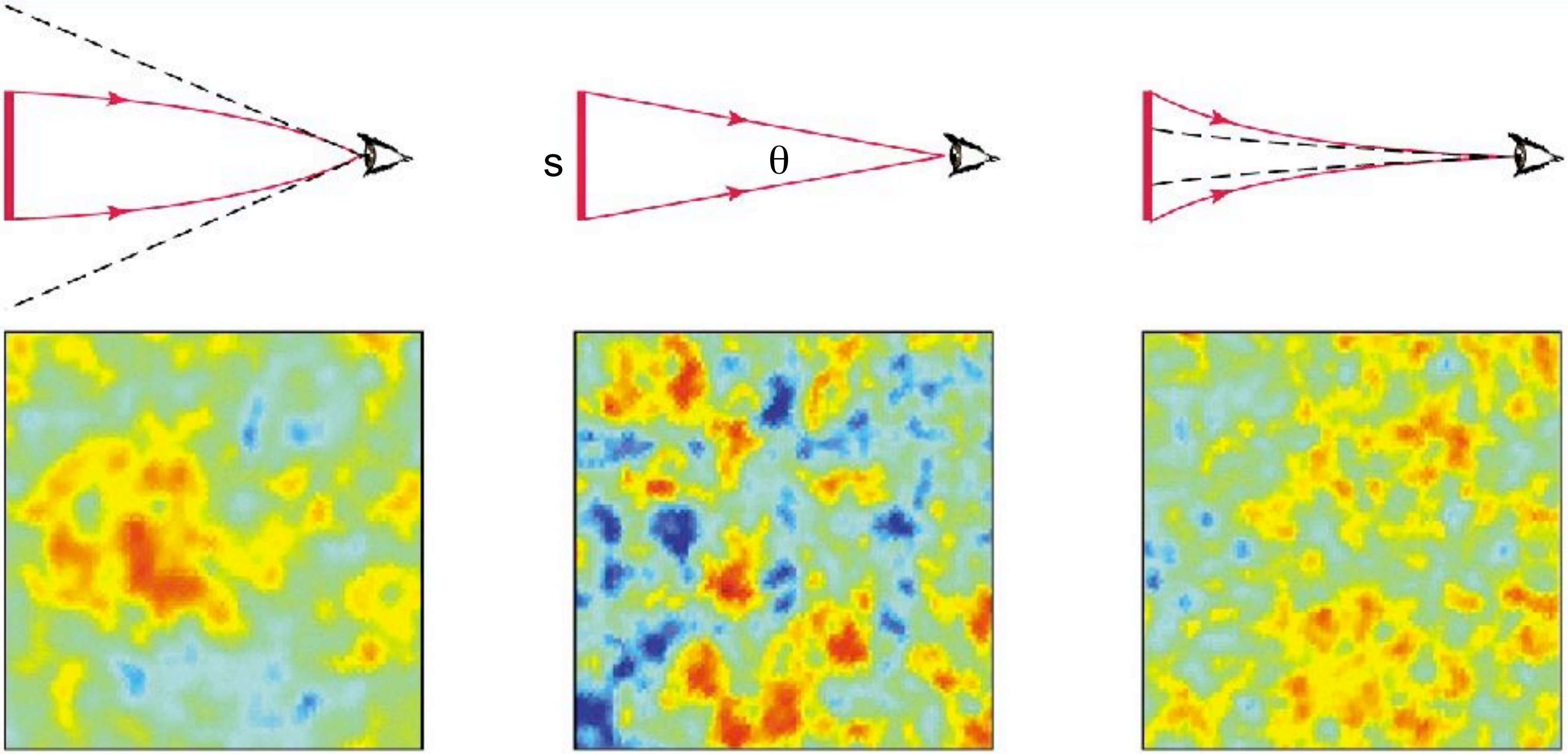
Temperature map of the cosmic microwave background radiation



- Characteristic angular scale, ~ 1 degree on the sky, set by the distance that sound waves in the ionized photon-baryon fluid can travel just before Hydrogen recombination t_{ls}~400,000 yrs after the Big Bang:

sound horizon $s \sim c_s t_{ls} \sim 150$ Mpc

Seeing the Sound Horizon



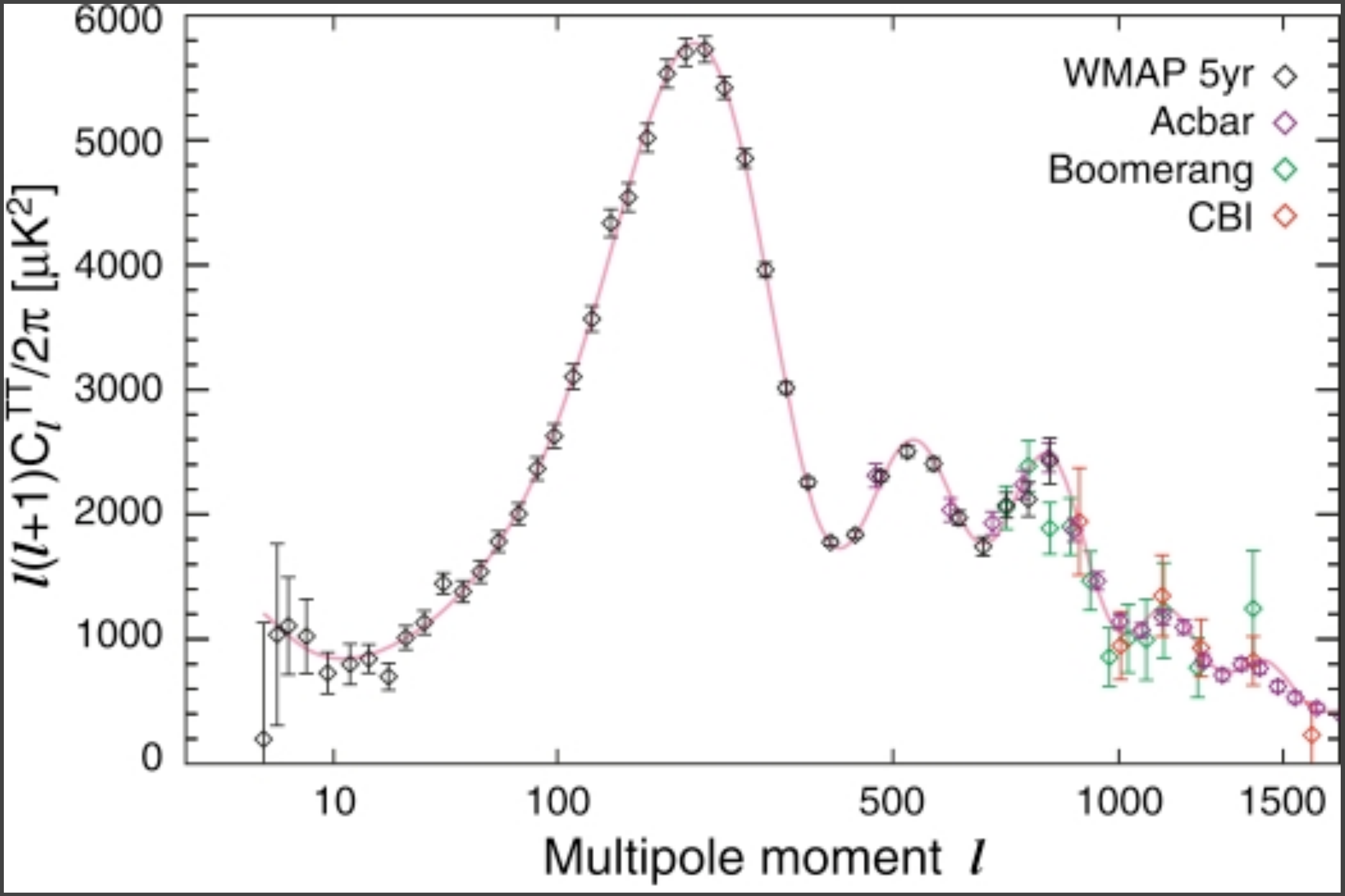
a If universe is closed, “hot spots” appear larger than actual size

b If universe is flat, “hot spots” appear actual size

c If universe is open, “hot spots” appear smaller than actual size

CMB Maps

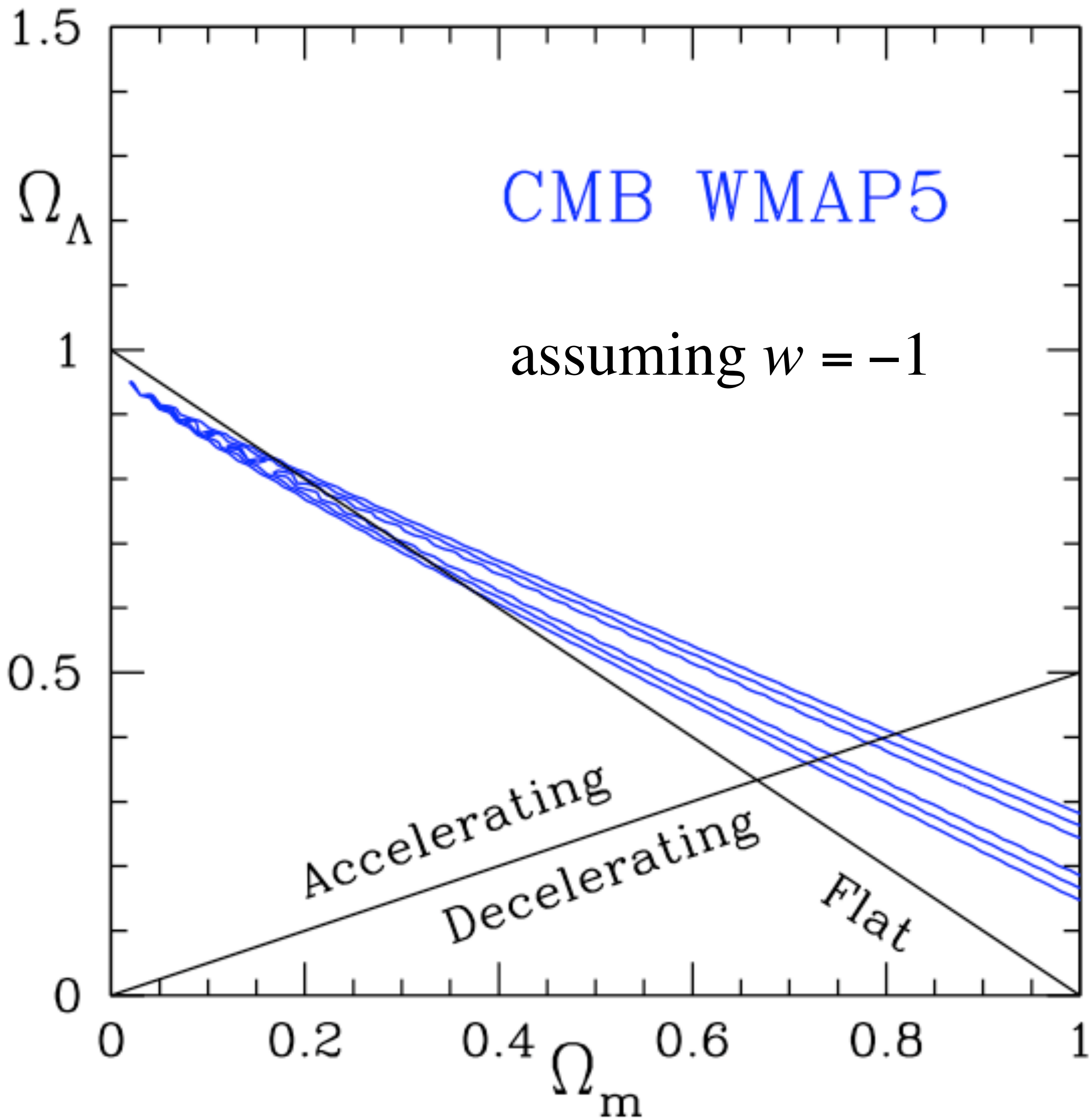
Current CMB Results

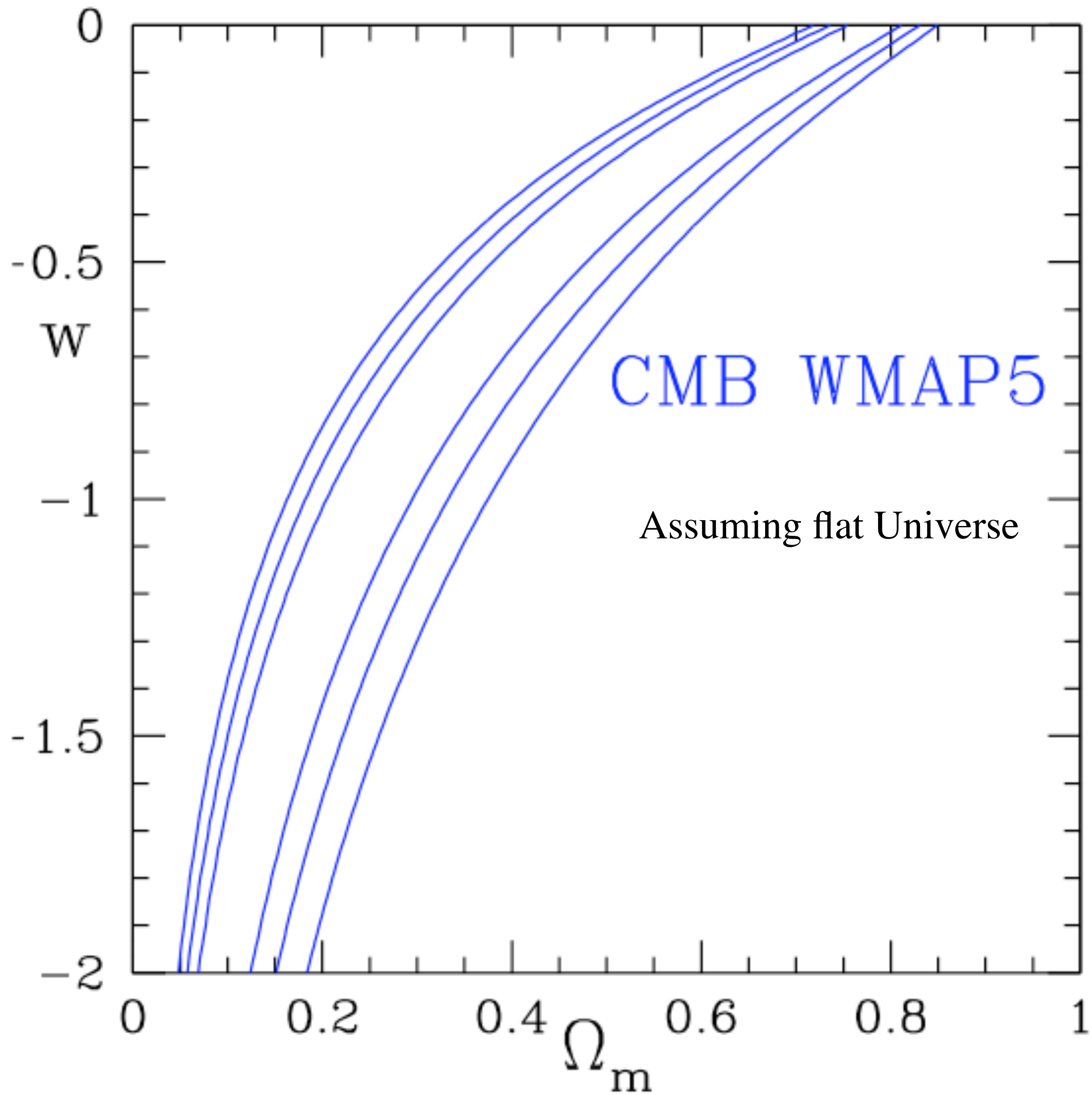


Dunkley etal

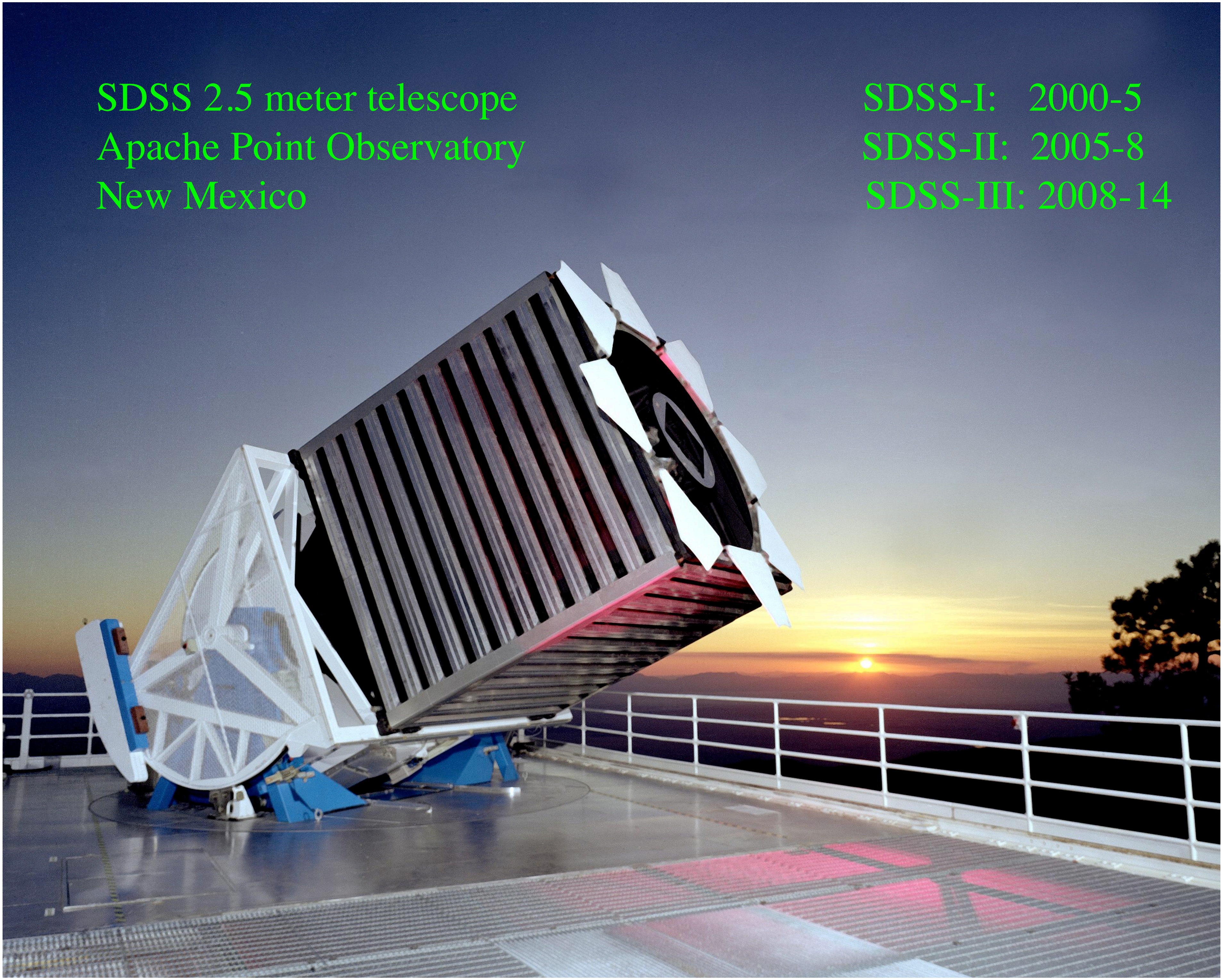
CMB Temperature anisotropy angular power spectrum

May 2009: Planck satellite launched & working

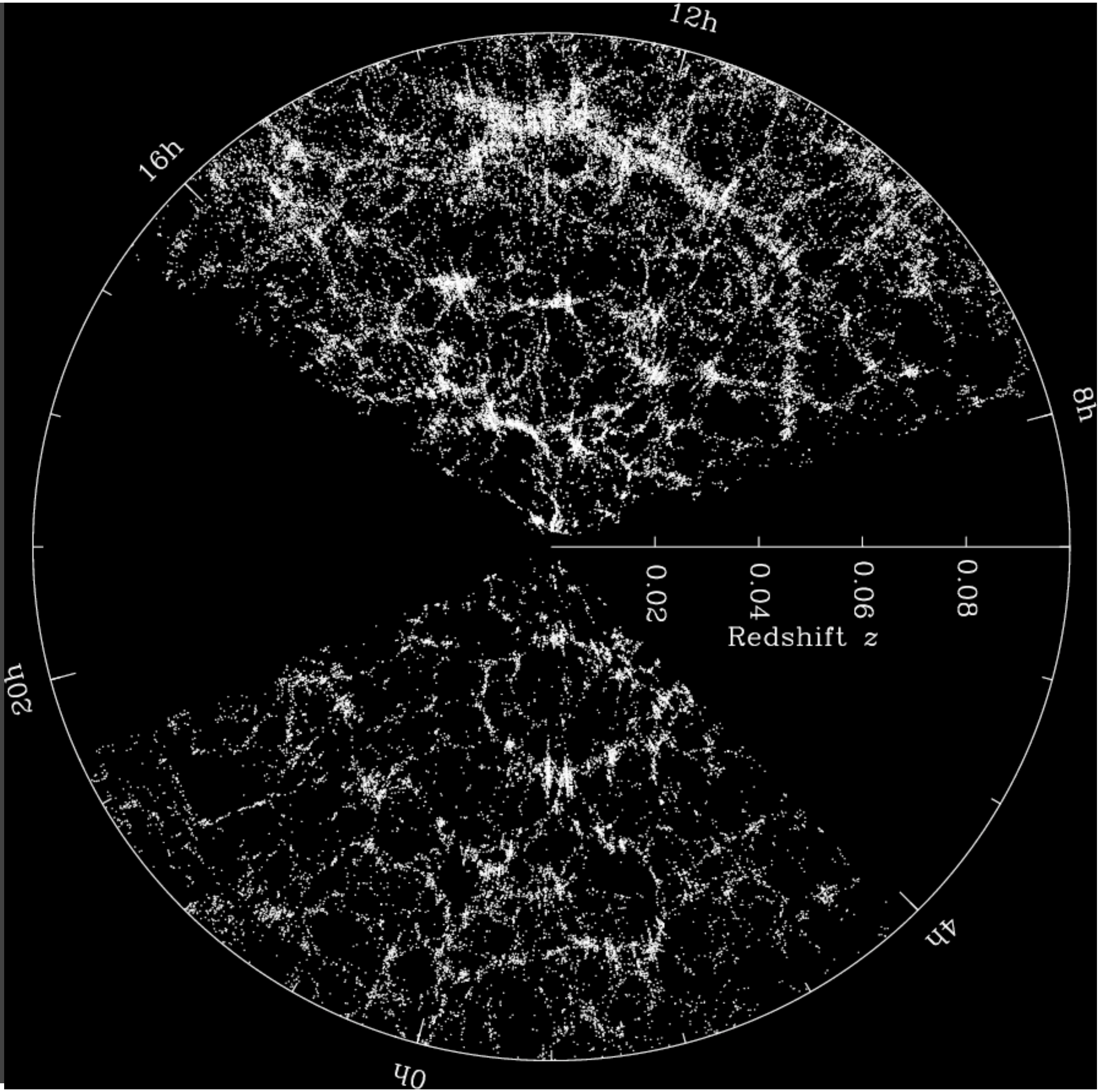

CMB WMAP5
assuming $w = -1$
Ω_Λ
Ω_m
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
Accelerating
Decelerating
Flat



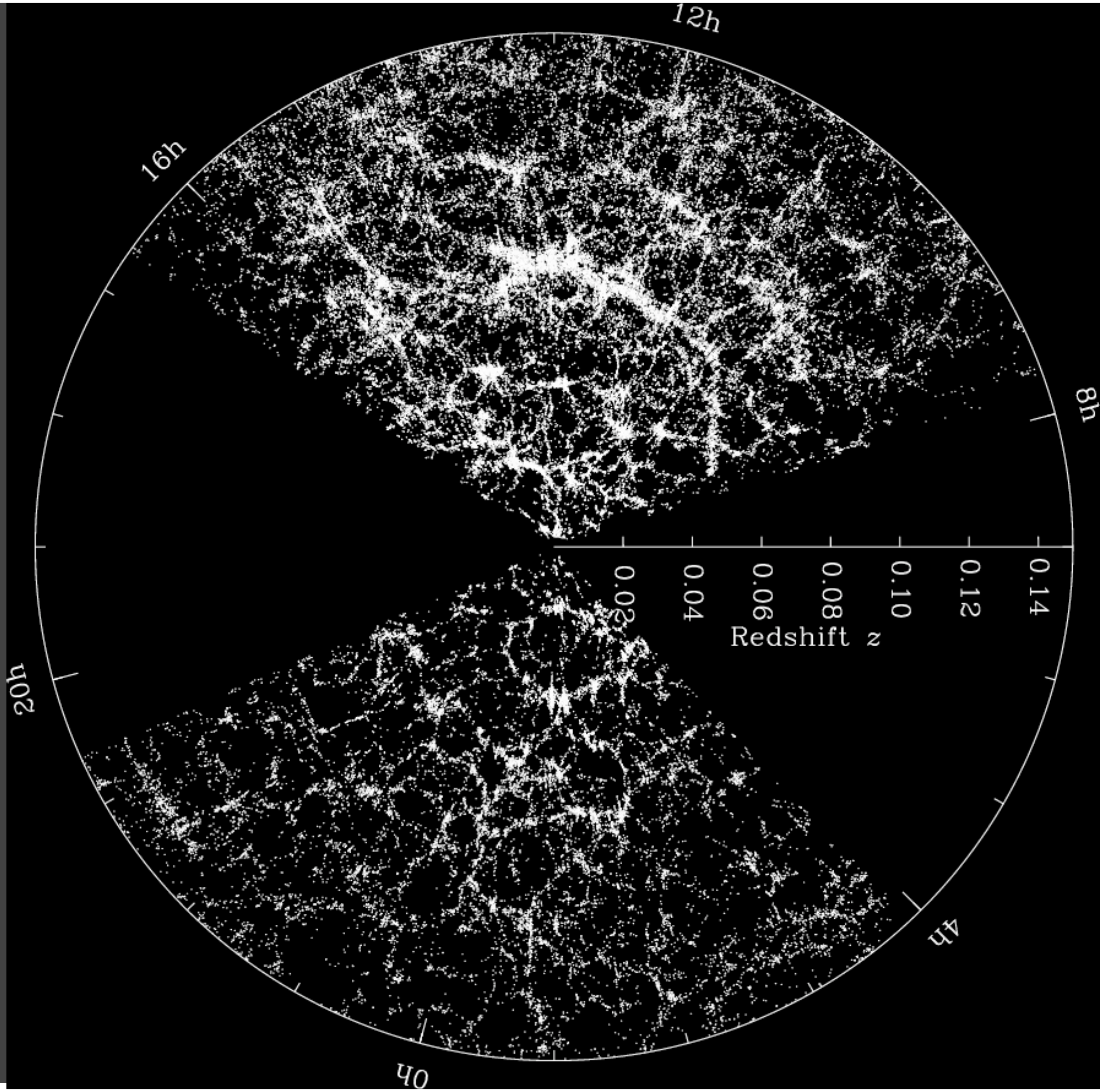
CMB WMAP5
Assuming flat Universe
w
0
-0.5
−1
-1.5
−2
0
0.2
0.4
0.6
0.8
1
Ω_m


SDSS 2.5 meter telescope
Apache Point Observatory
New Mexico
SDSS-I: 2000-5
SDSS-II: 2005-8
SDSS-III: 2008-14

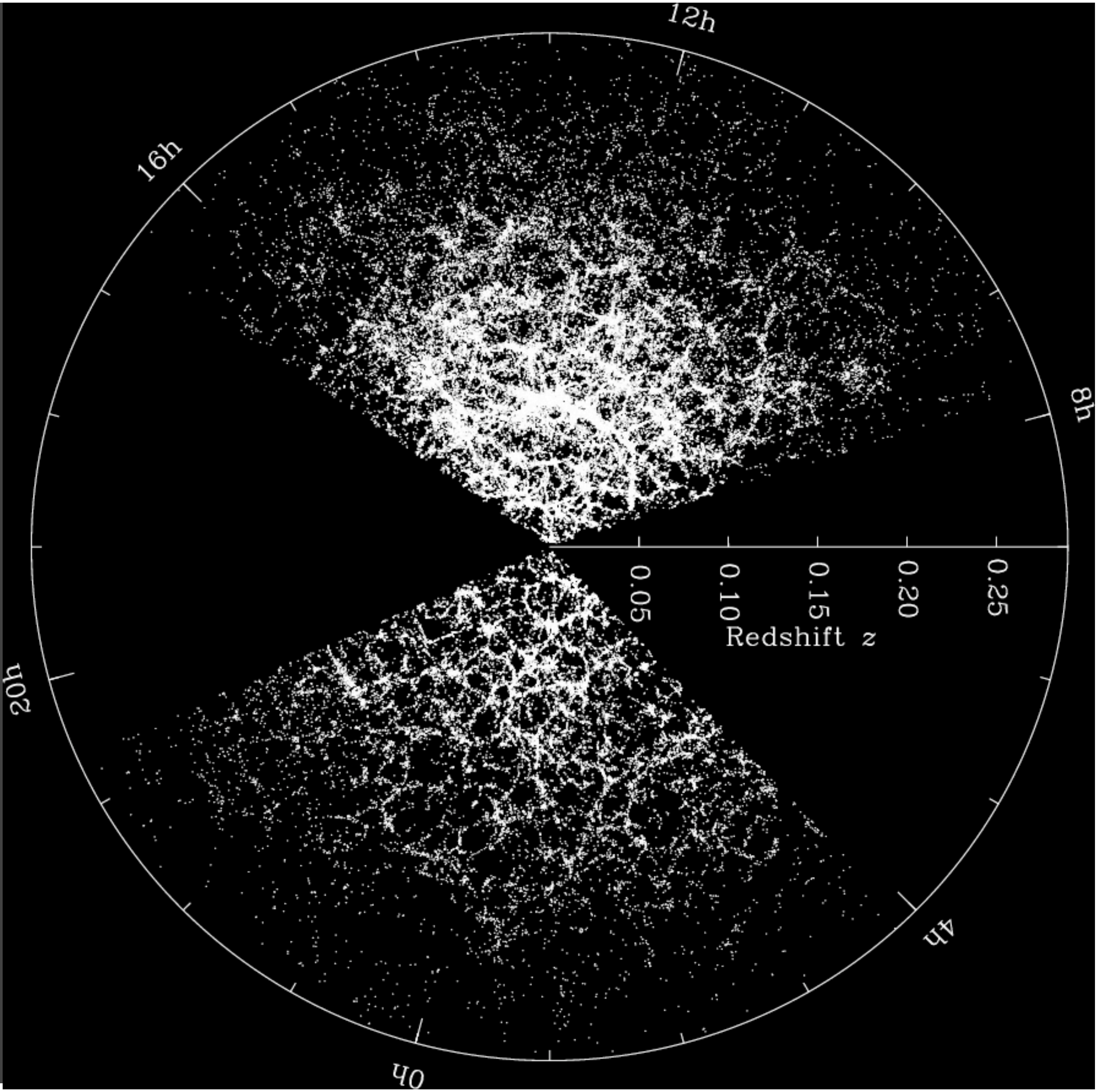
SDSS
Galaxy
Distribution



SDSS Galaxy Distribution



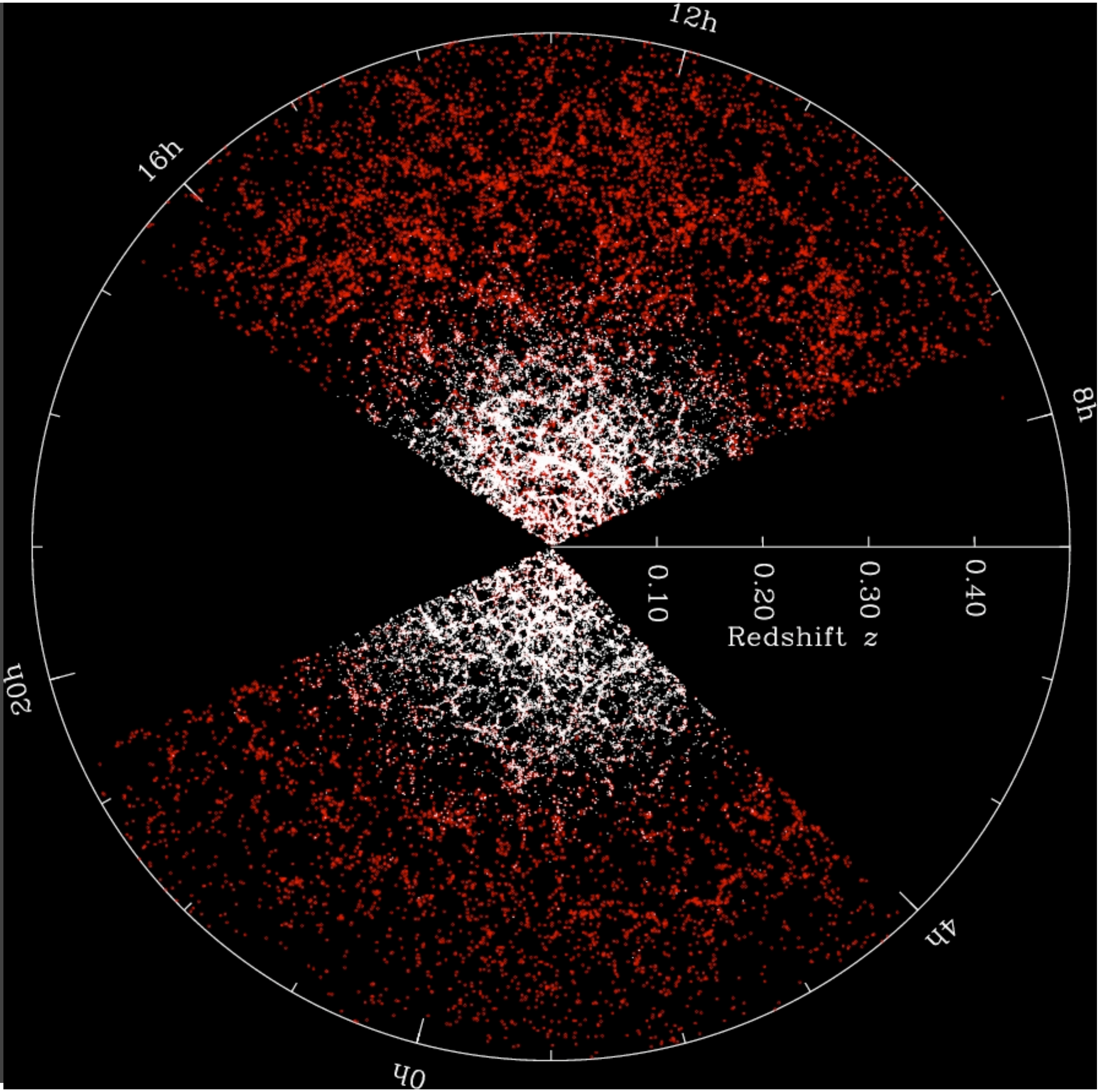
SDSS Galaxy Distribution



SDSS
Galaxy
Distribution

Luminous
Red
Galaxies

Their distribution also shows imprint of the sound horizon

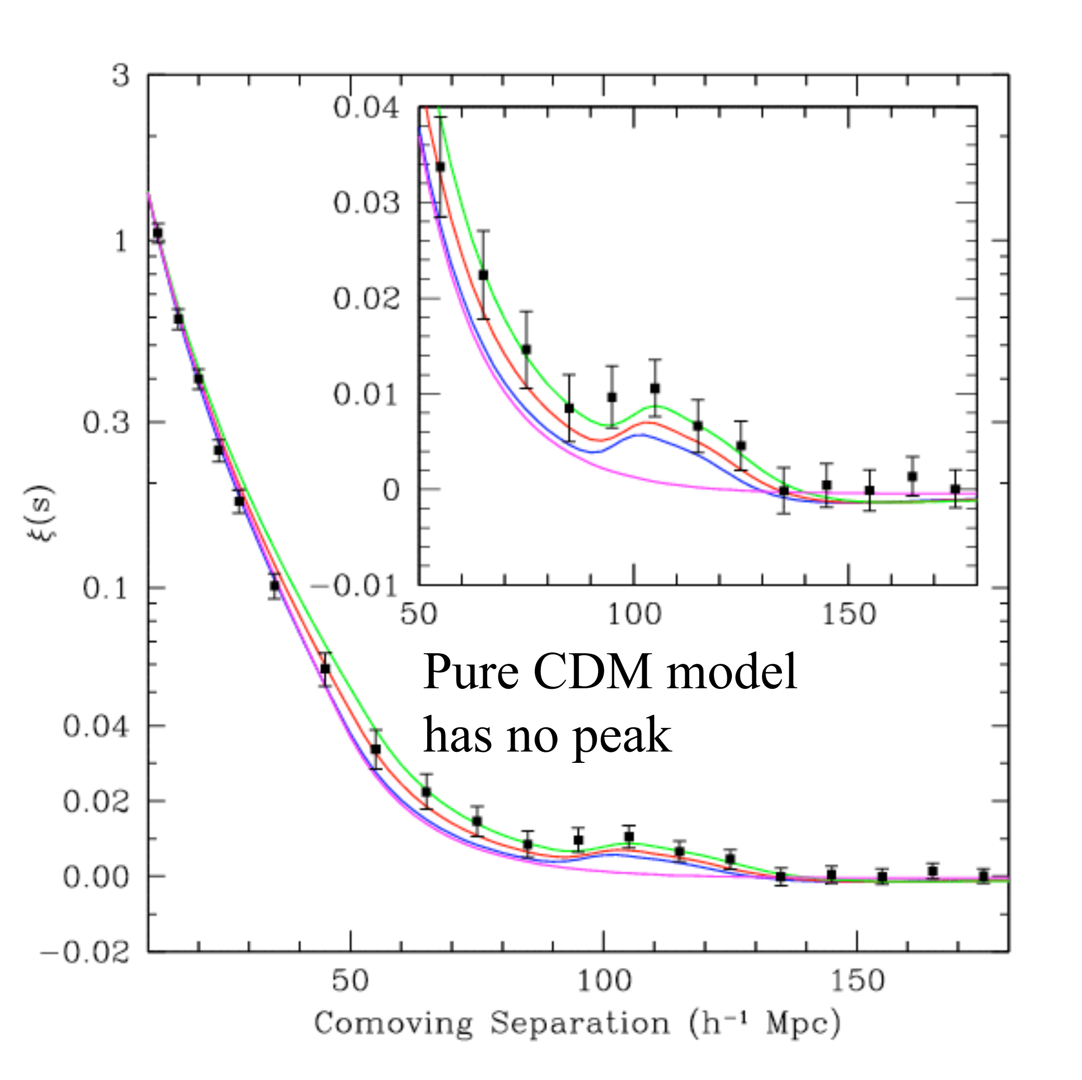


Large-scale Correlations of SDSS Luminous Red Galaxies

Redshift-space Correlation Function

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

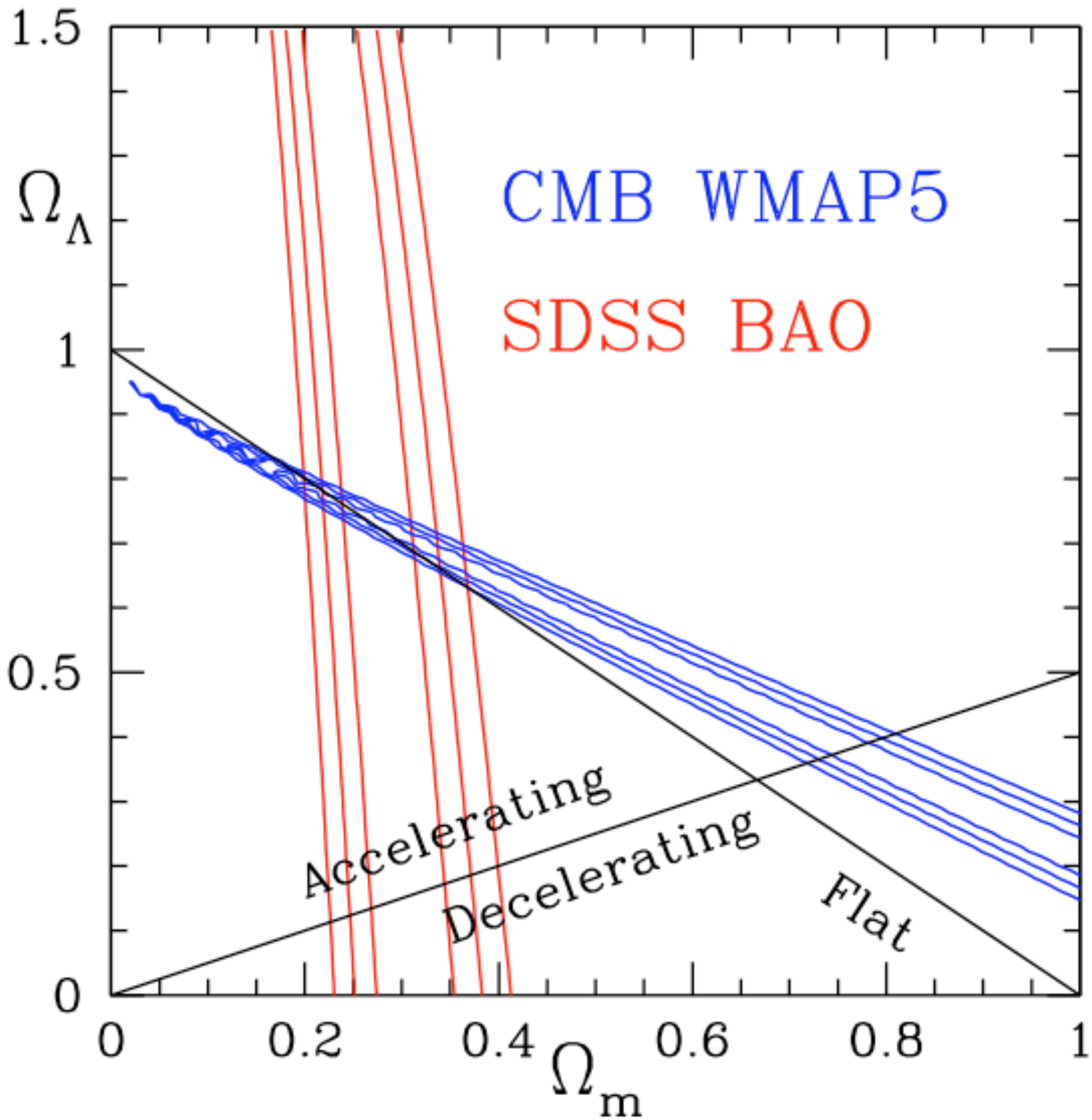
Warning: Correlated Error Bars

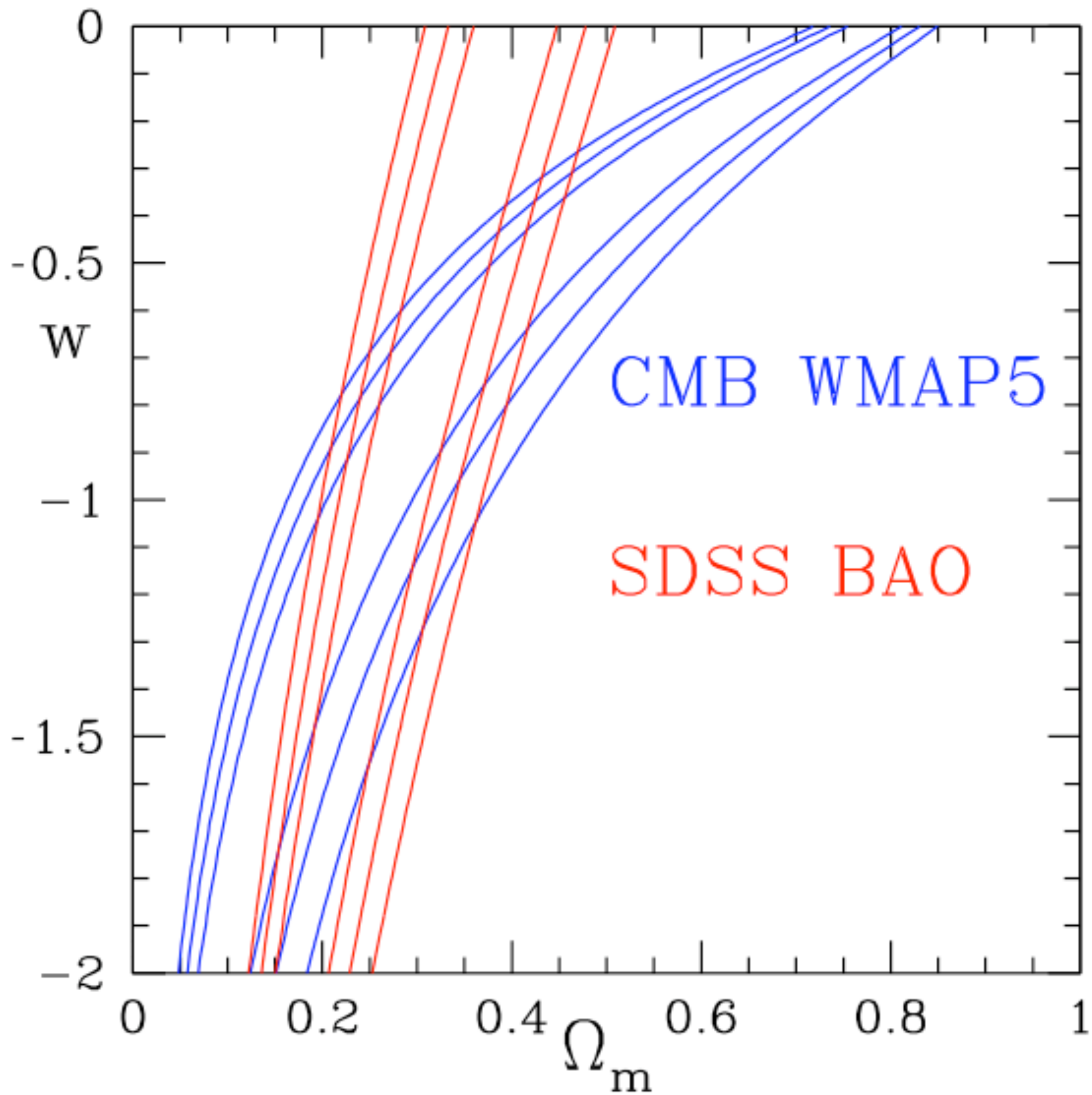


Baryon Acoustic Oscillations seen in Large-scale Structure:

mean distance to galaxies at z~0.35

Eisenstein, etal 2005


CMB WMAP5
SDSS BAO
Accelerating
Decelerating
Flat
1.5
1
0.5
0
0.2
0.4
0.6
0.8
Ω_Λ
Ω_m


0
-0.5
w
−1
-1.5
−2
0
0.2
0.4
0.6
0.8
1
Ω_m
CMB WMAP5
SDSS BAO

Supernova Legacy Survey (2003-2008)

- ~400+ distant SNe Ia to measure *w*
- Used CFHT/“Megacam”
- 36 CCDs with good blue response
- 4 filters *griz* for good K-corrections and color measurement
- Spectroscopic follow-up on 8-10m
- Astier etal (2006): published results based on ~70 SNLS SNe Ia (+Low-z) from 1st season

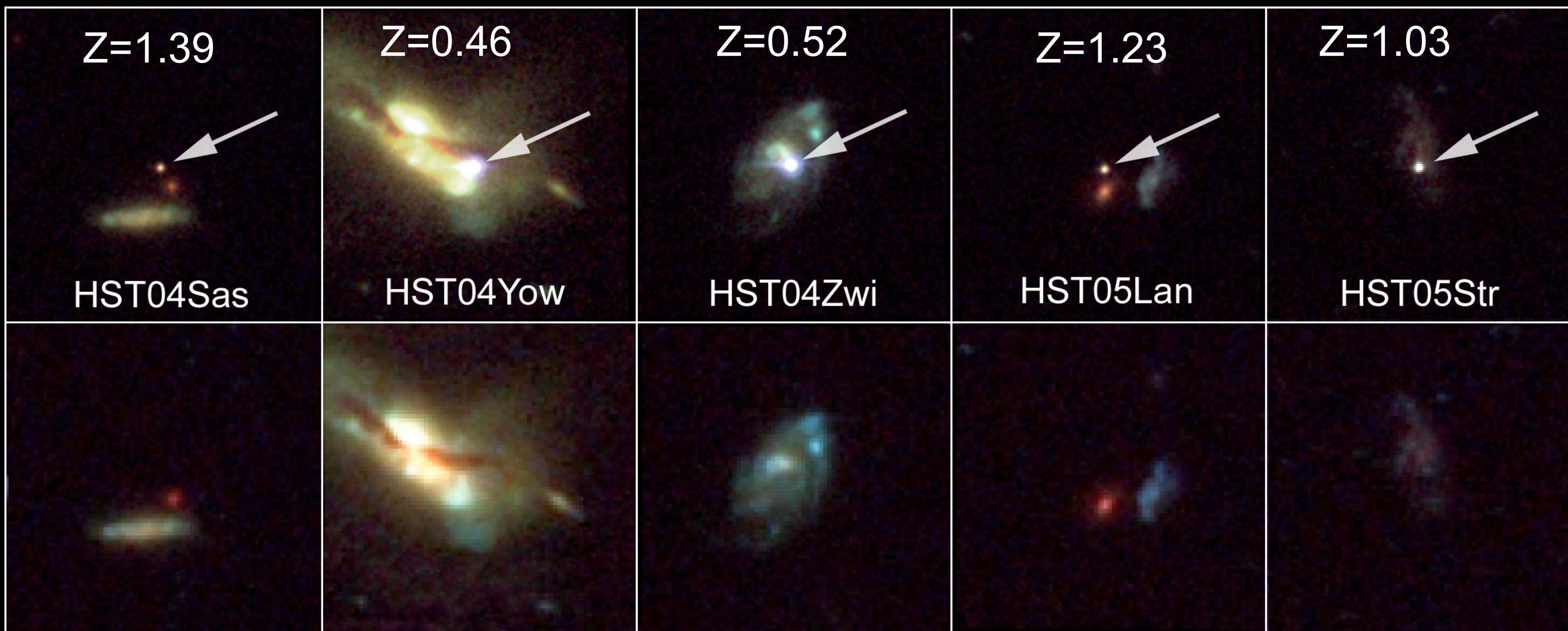
Megaprime Mosaic
CCD camera

The ESSENCE Survey

- Determine w to 10% or w!=-1
- 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, $0.2<z<0.8$

Wood-Vasey, etal (2007), Miknaitis, etal (2007): results from ~60 ESSENCE SNe (+Low-z)

Higher-z SNe Ia from HST

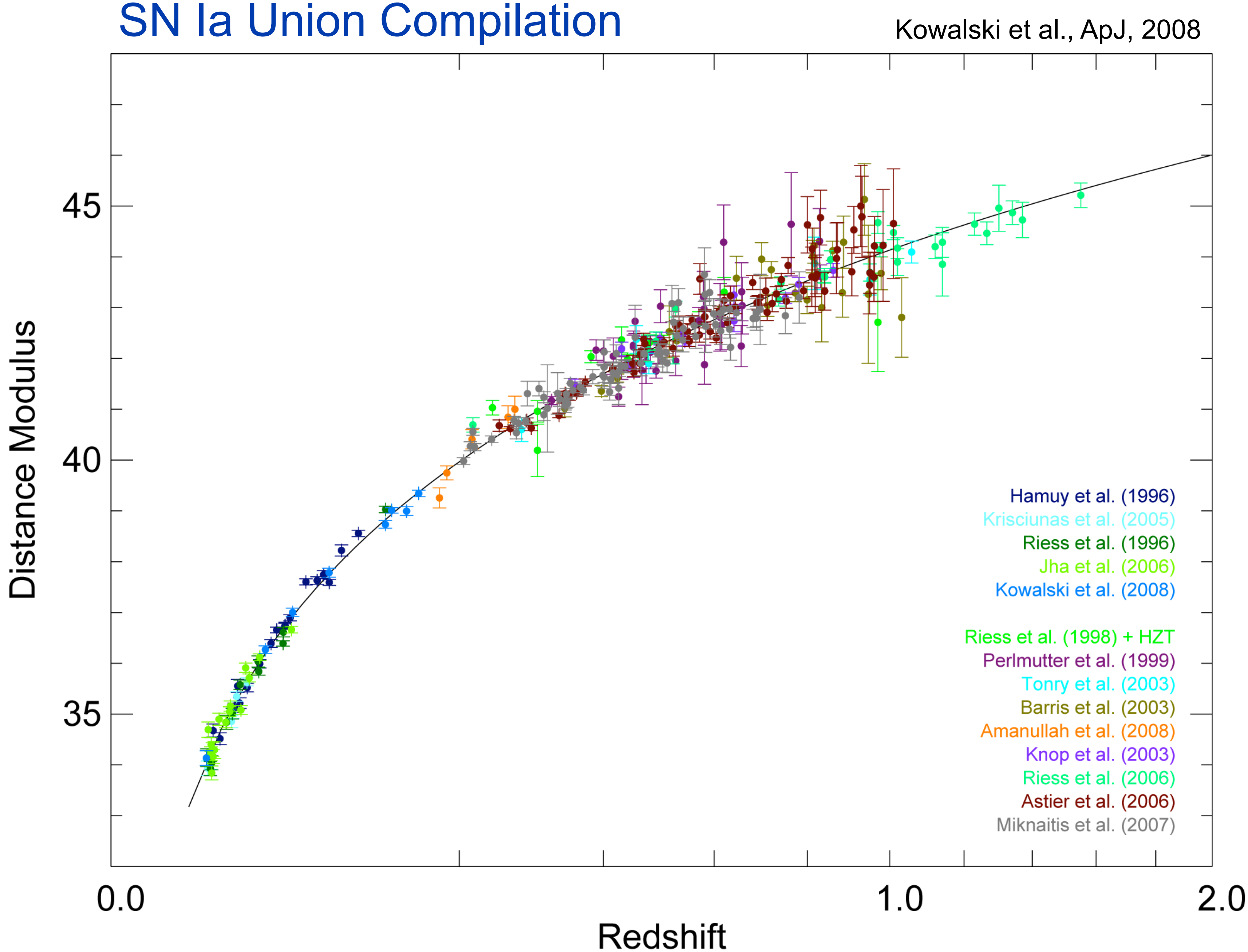


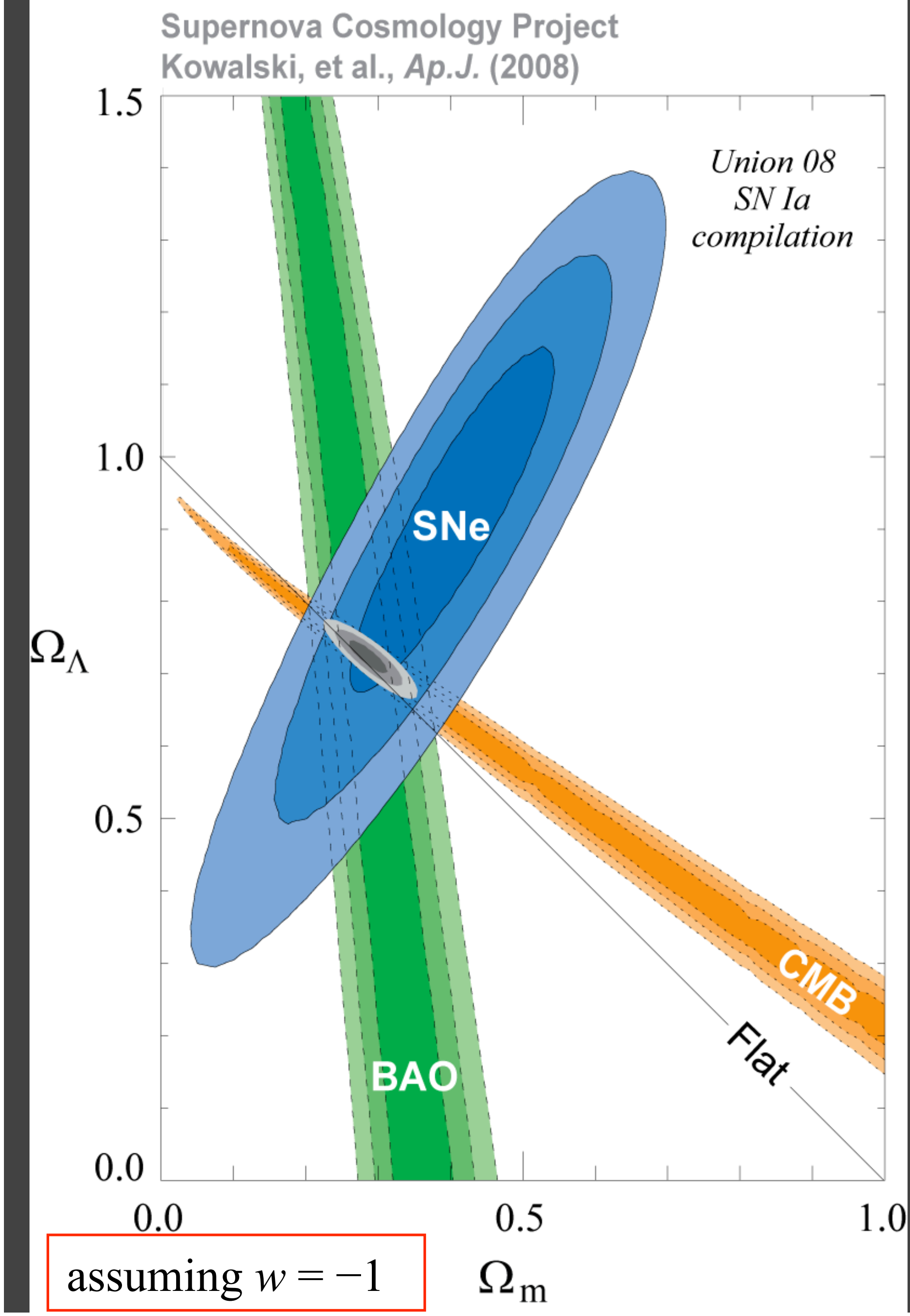
Host Galaxies of Distant Supernovae
Hubble Space Telescope ▪ Advanced Camera for Surveys

50 SNe Ia, 25 at z>1

Riess, etal

Supernova Cosmology Project
SN Ia Union Compilation





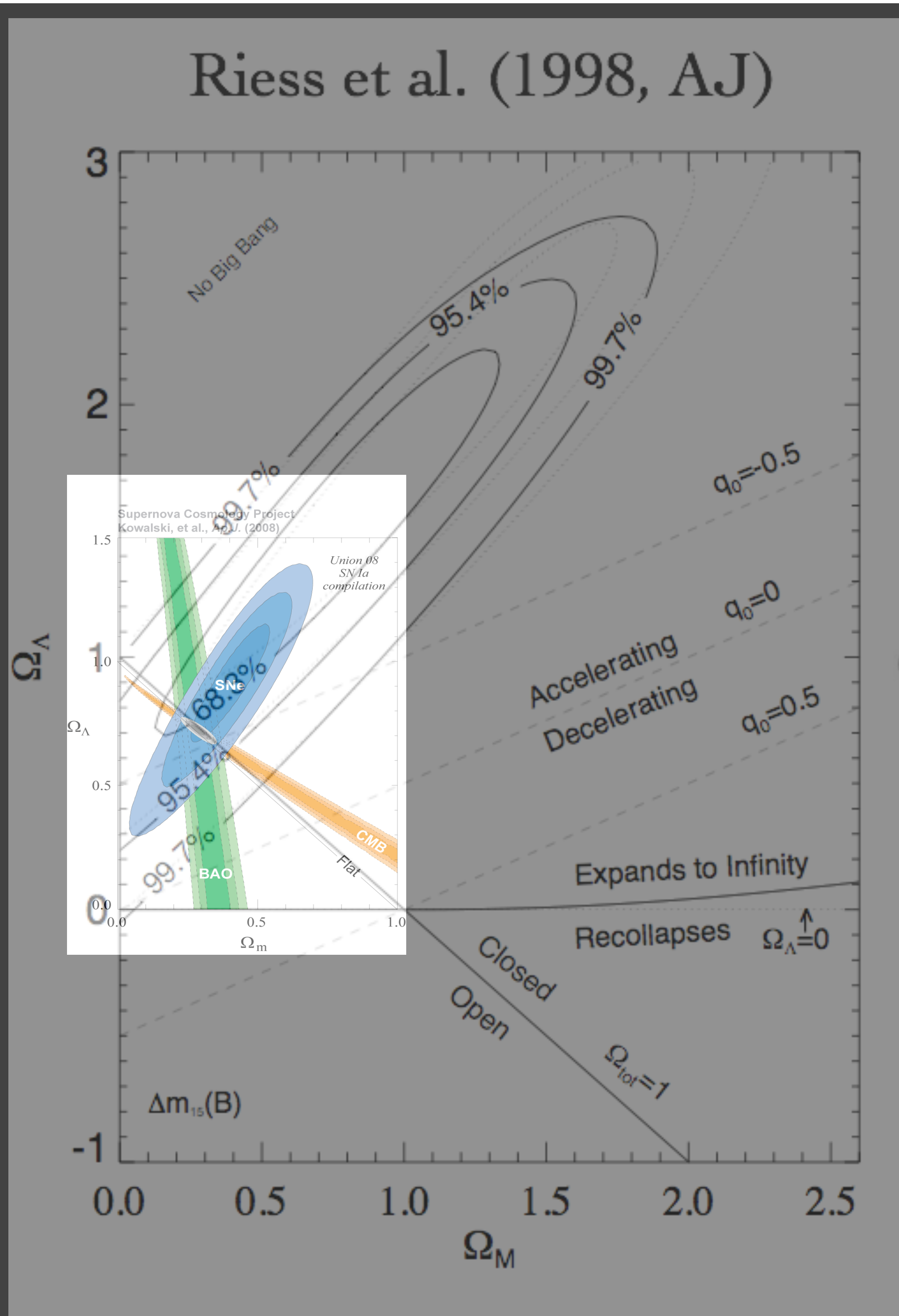
assuming $w = -1$

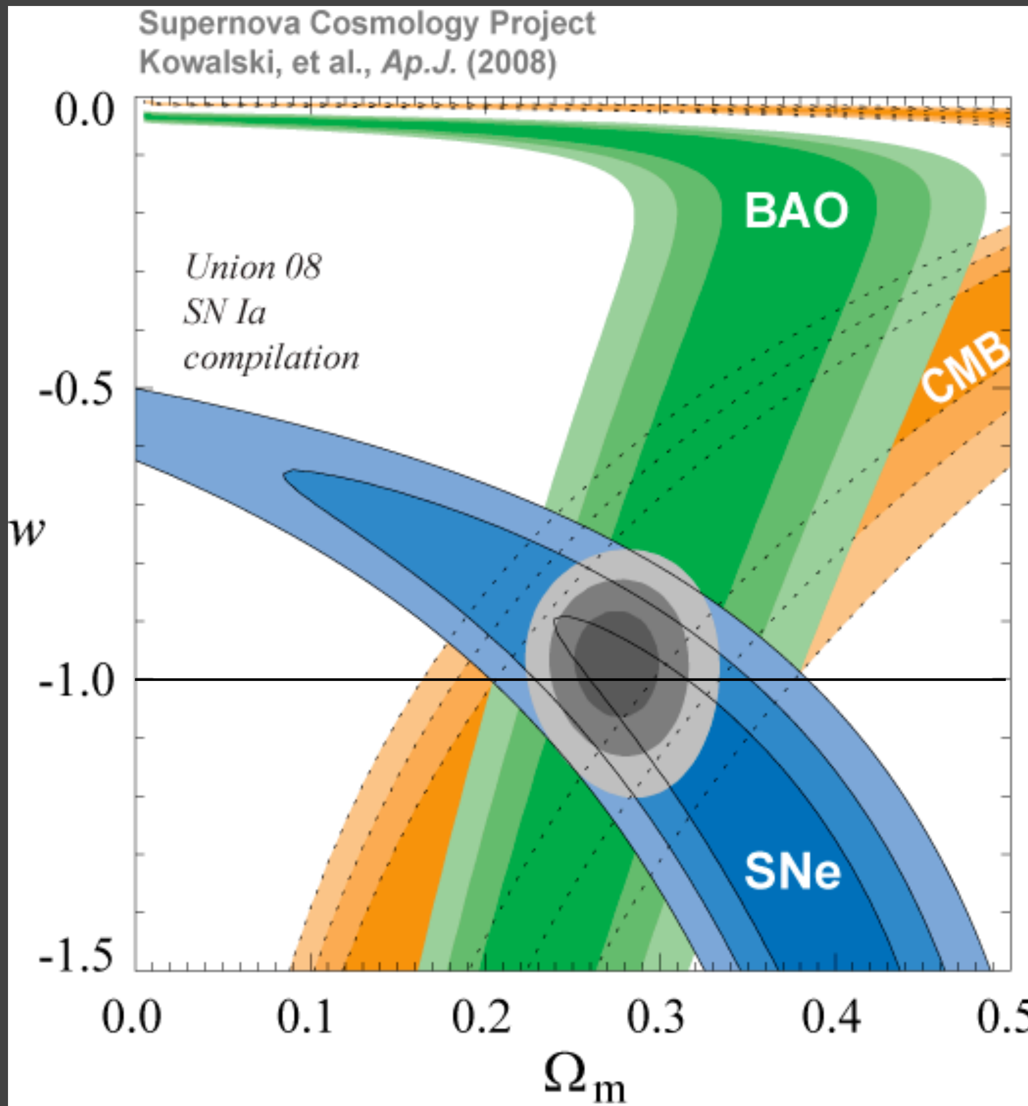
Recent Dark Energy Constraints

Improved SN constraints

Inclusion of constraints from Cosmic Microwave Background Anisotropy (WMAP) and Large-scale Structure (Baryon Acoustic Oscillations, SDSS)

Only statistical errors shown

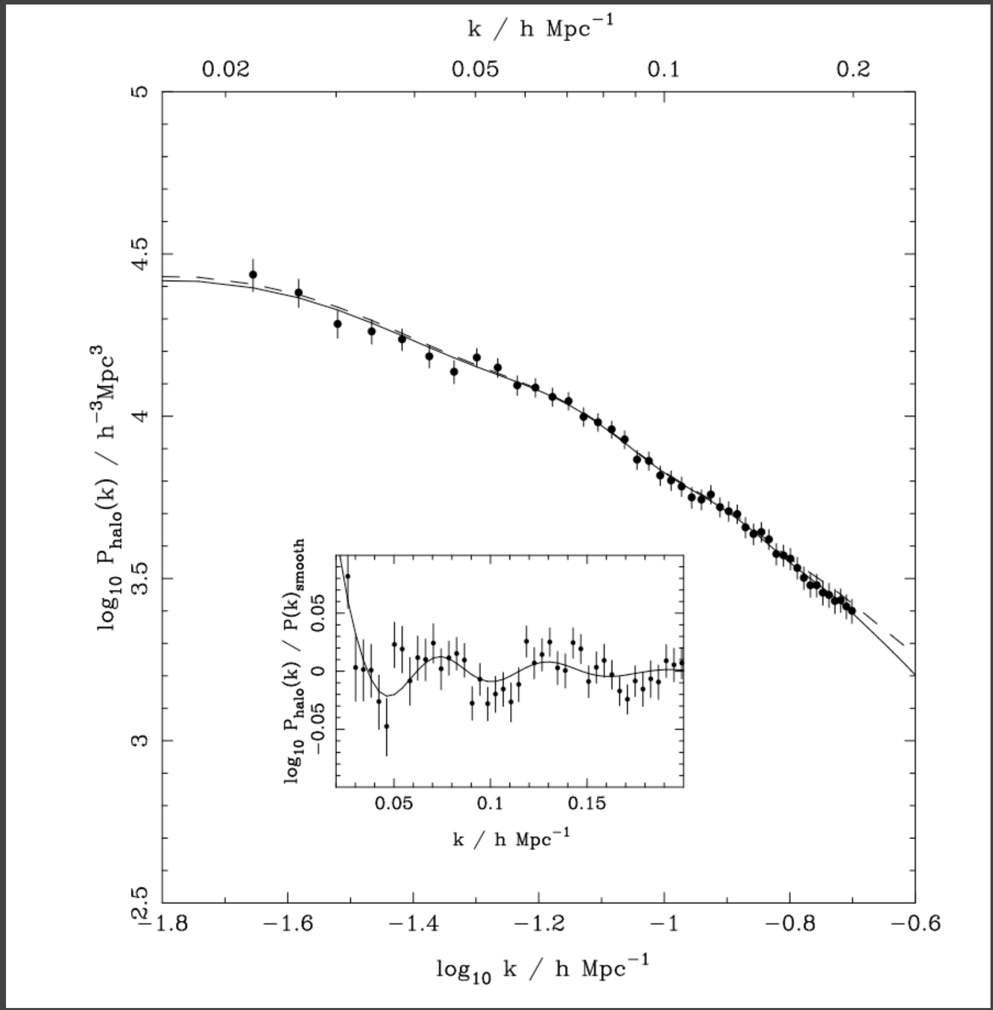

Riess et al. (1998, AJ)
No Big Bang
95.4%
99.7%
68.3%
q0=-0.5
q0=0
q0=0.5
Accelerating
Decelerating
Expands to Infinity
Recollapses
ΩΛ=0
Closed
Open
Ωtot=1
Δm15(B)
ΩΛ
ΩM
Supernova Cosmology Project
Kowalski, et al., Ap.J. (2008)
Union 08
SN Ia
compilation
SNe
BAO
CMB
Flat
Ωm



assuming flat Univ. and constant *w*

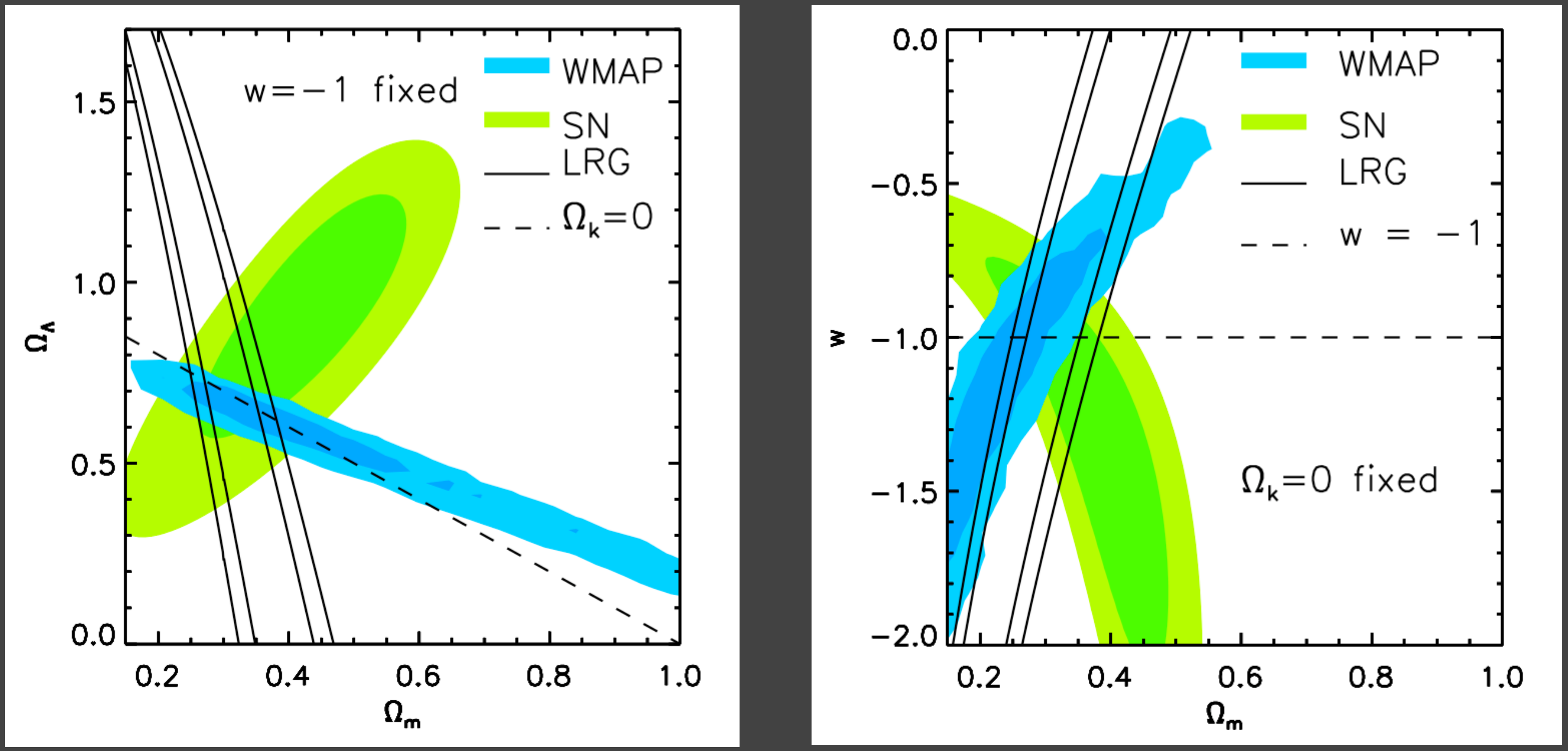
Only statistical errors shown

SDSS DR7 BAO Results

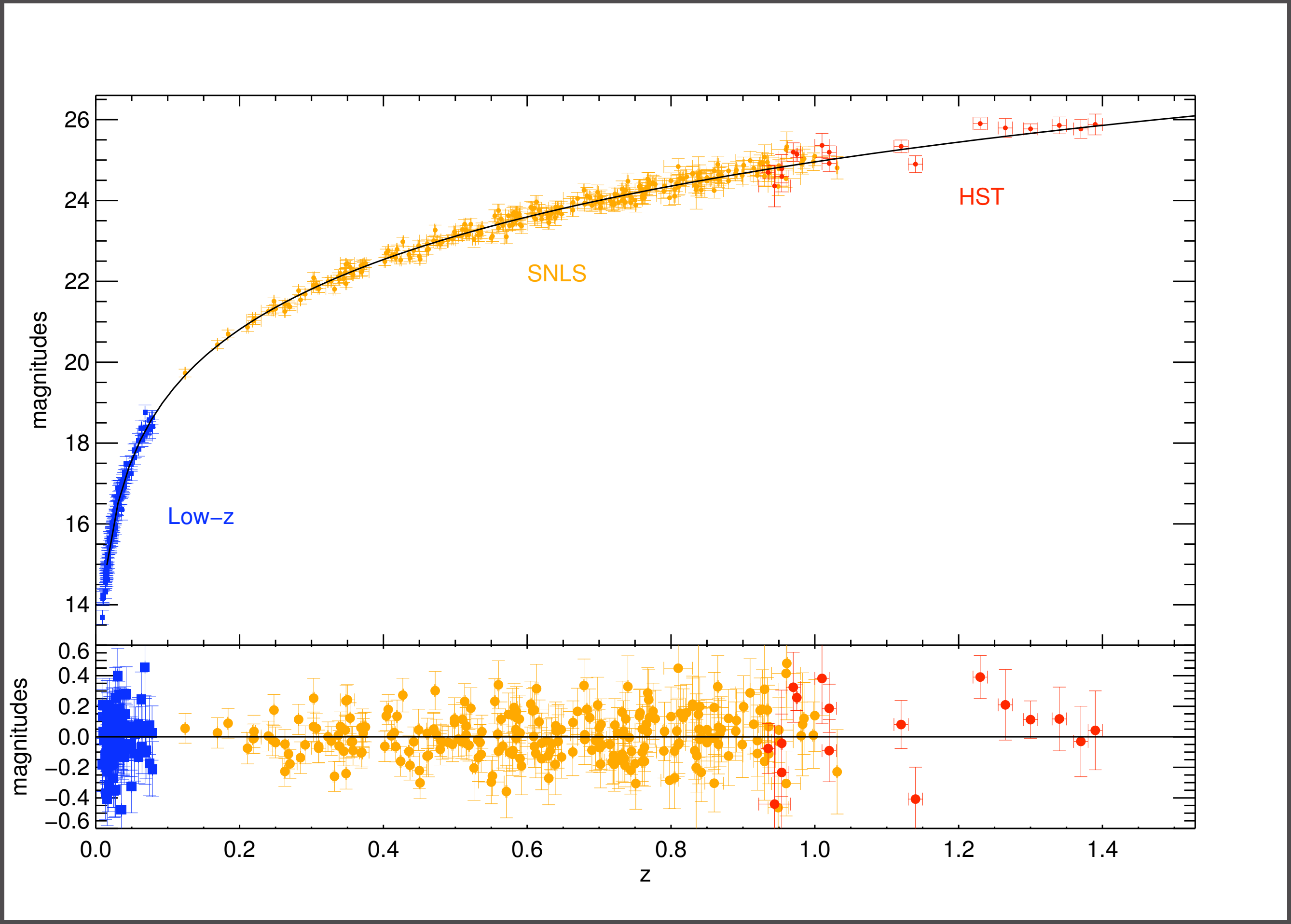


Percival, etal (2009); Reid, etal (2009)

SDSS DR7 BAO Results



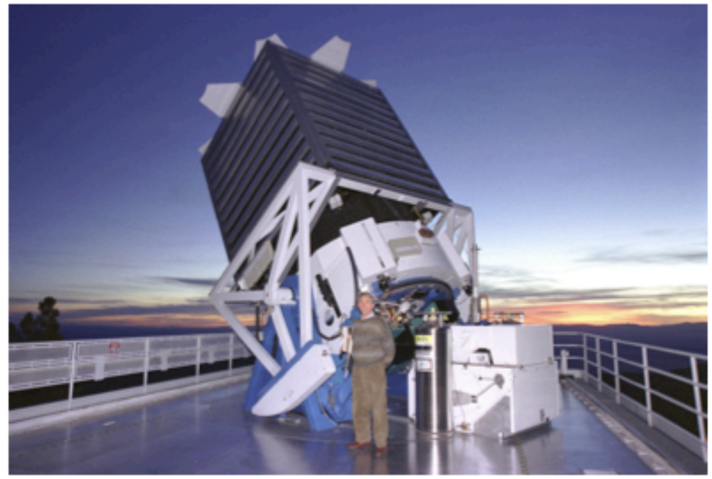
SNLS Preliminary 3rd year Hubble Diagram

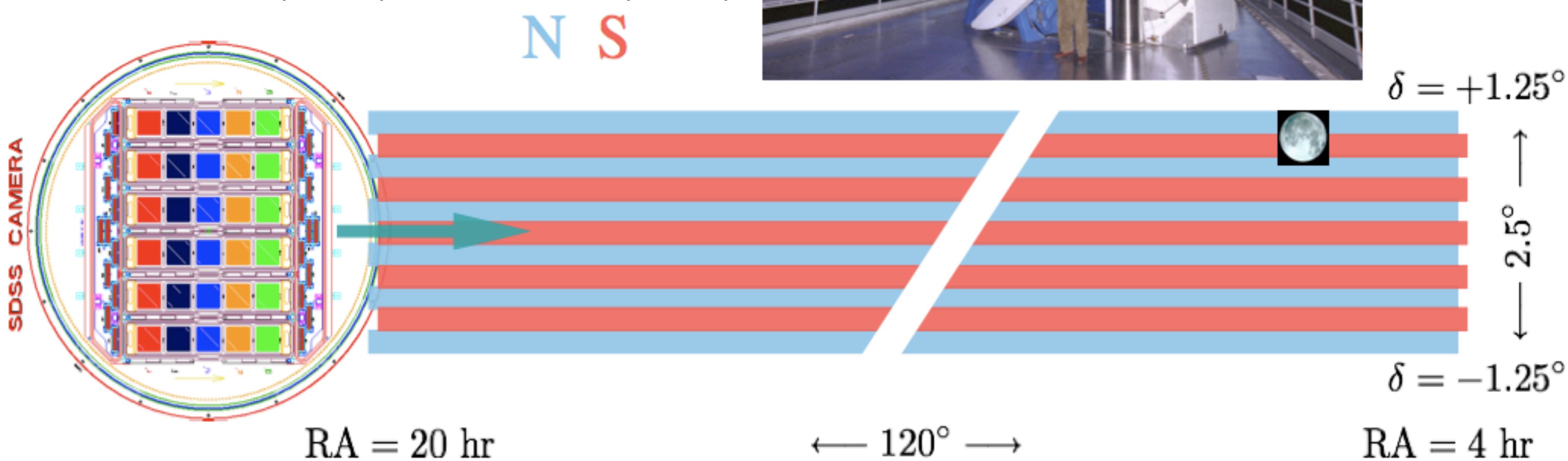


- Conley et al (2009): results with ~252 SNLS SNe (to be submitted)
- Independent analyses with 2 light-curve fitters: SALT2, SiFTO

SDSS-II SN Survey

Frieman, et al (2008); Sako, et al (2008)

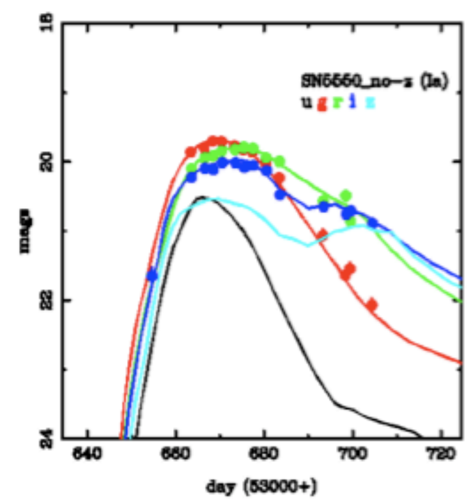


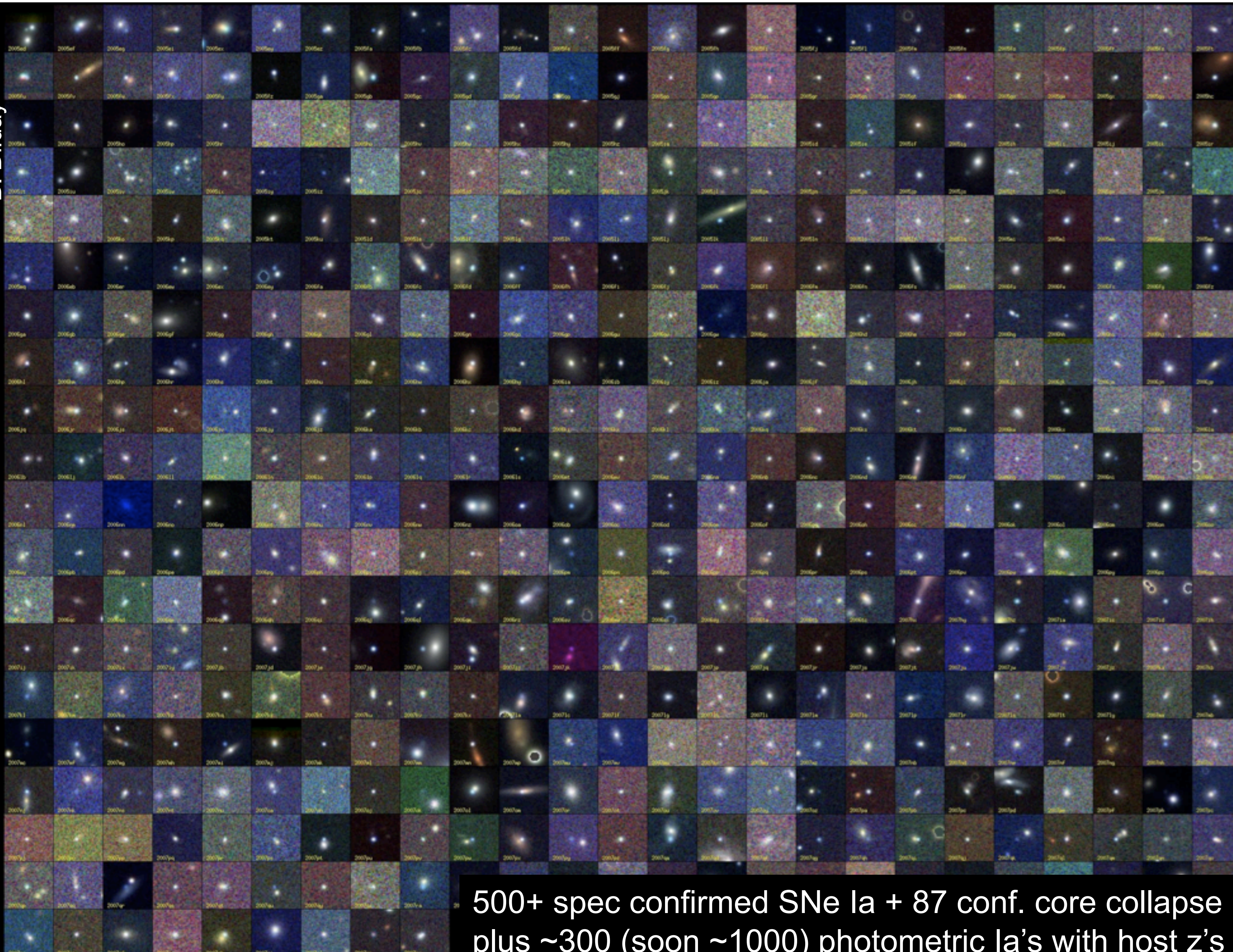


Use the SDSS 2.5m telescope

- September 1 - November 30 of 2005-2007
- Scan 300 square degrees every 2 days
- Obtain densely sampled multi-color light curves
- Results today from 2005 season

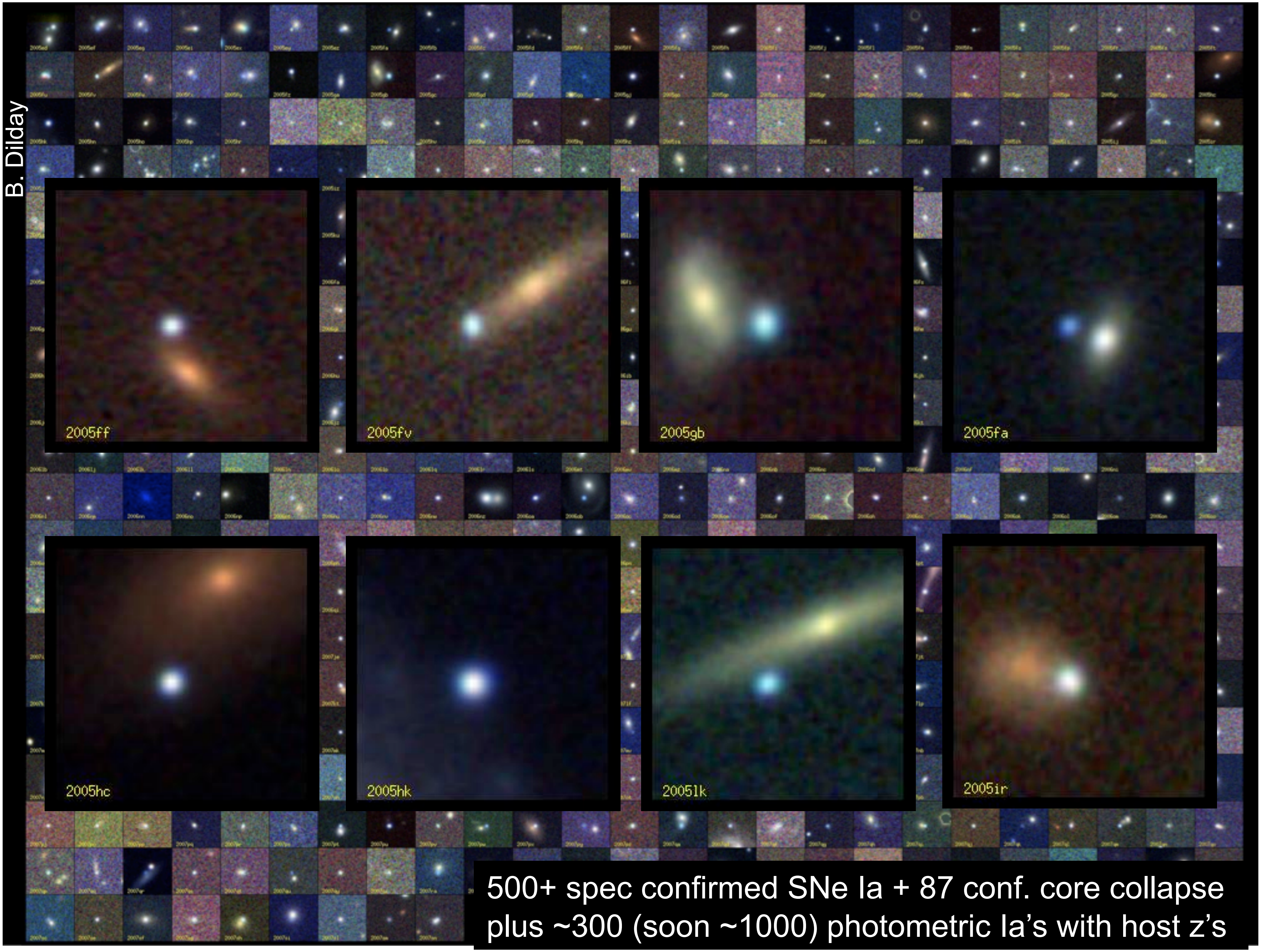
Kessler, et al 09; Lampeitl et al 09; Sollerman et al 09





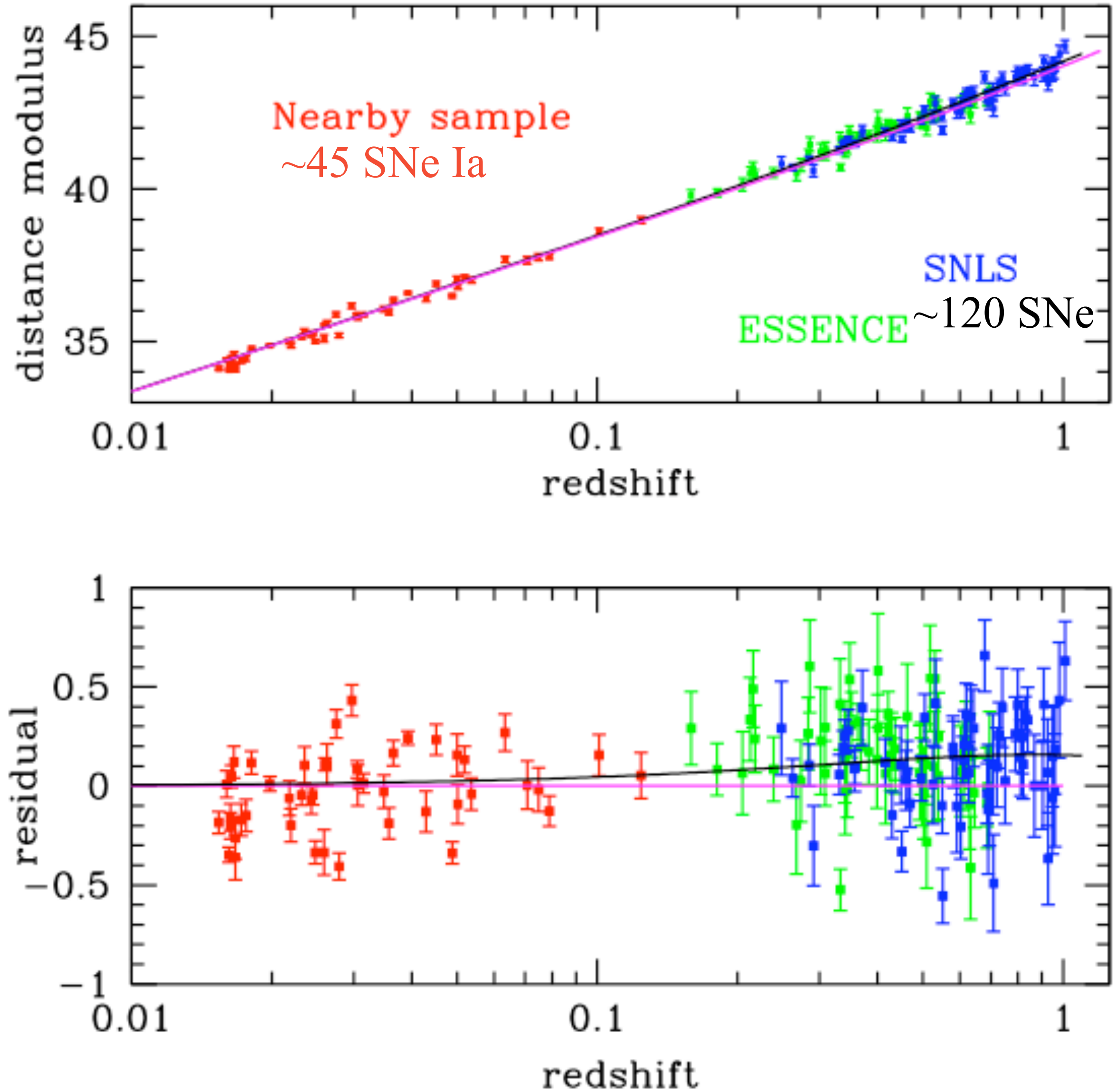
B. Dilday

500+ spec confirmed SNe Ia + 87 conf. core collapse
plus ~300 (soon ~1000) photometric Ia's with host z's



500+ spec confirmed SNe Ia + 87 conf. core collapse
plus ~300 (soon ~1000) photometric Ia’s with host z’s

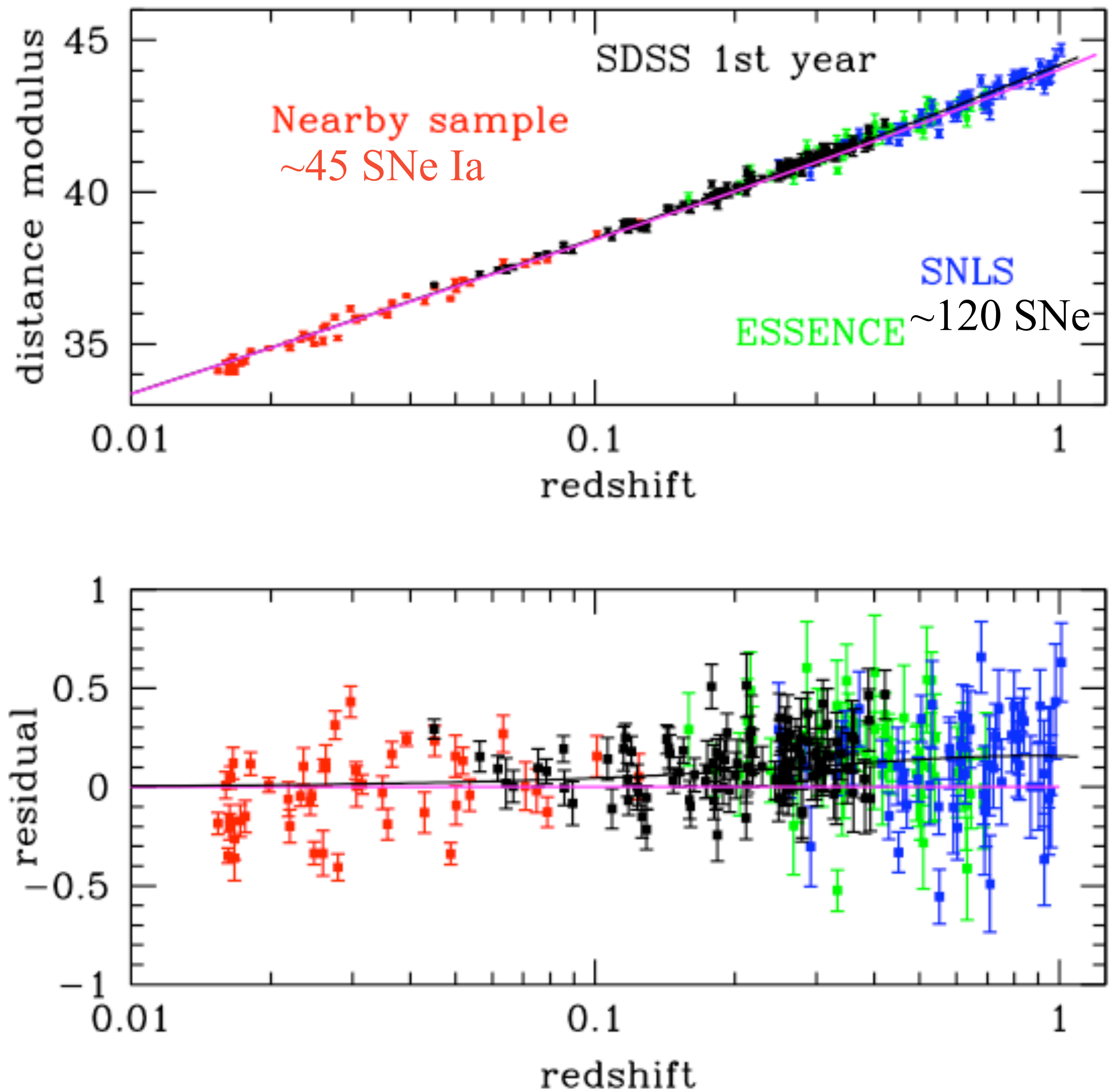
Hubble Diagram



Hubble Diagram with SDSS SNe

103 SNe Ia from first season that pass stringent light-curve quality cuts

Kessler etal (2009)
Lampeitl etal (2009)
Sollerman etal (2009)



SALT MLCS

SDSS only:

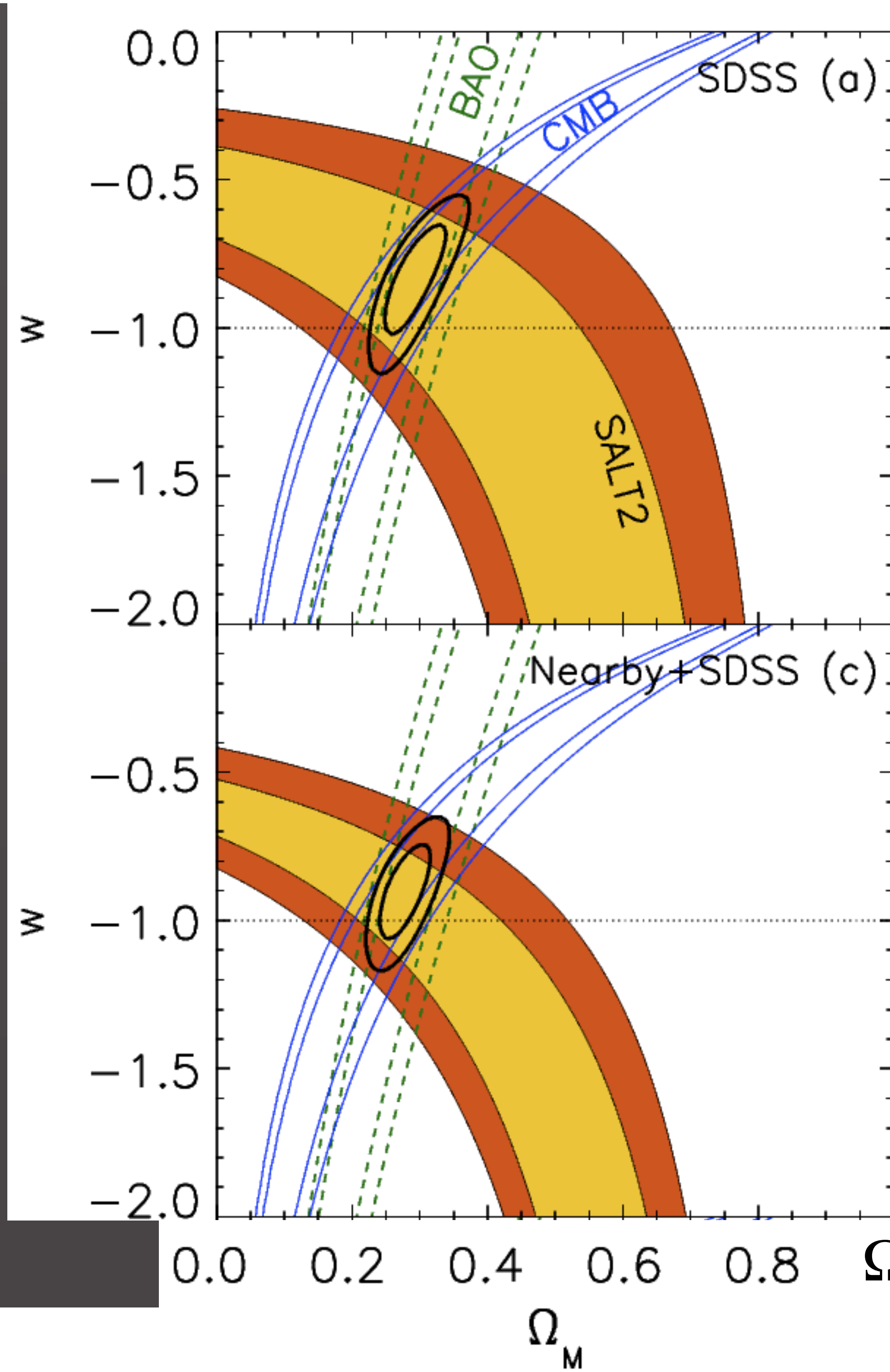
Nearby+SDSS:

MLCS

$w = -0.93 \pm 0.13(\text{stat})^{+0.10}_{-0.32}(\text{syst})$

SALT

$w = -0.92 \pm 0.11(\text{stat})^{+0.07}_{-0.15}(\text{syst})$



Ω_M

SALT MLCS

Nearby+SDSS:

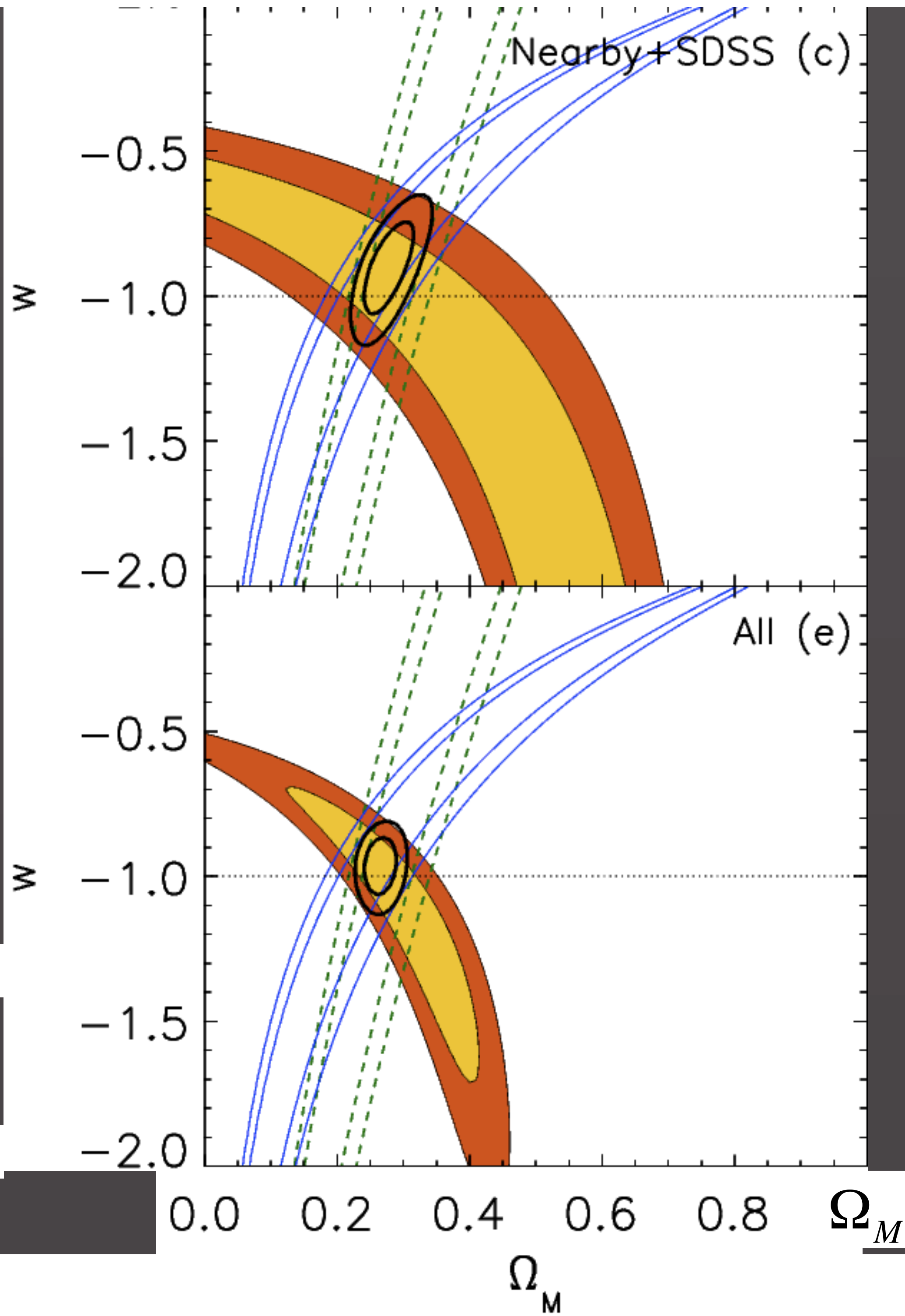
Nearby+SDSS+SNLS
+ESSENCE+HST:

MLCS

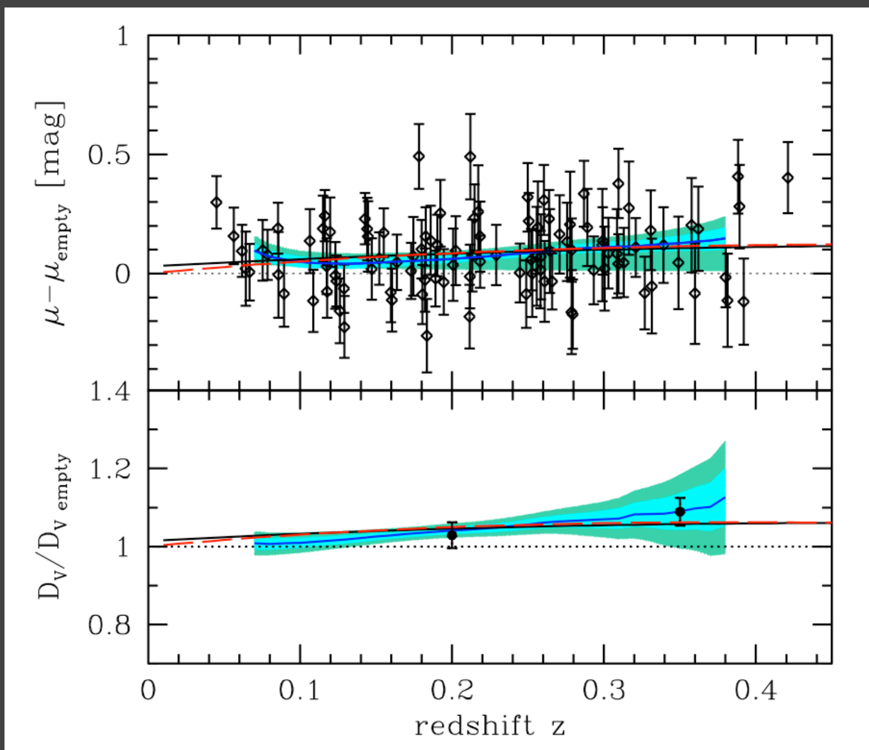
$w = -0.76 \pm 0.07(\text{stat}) \pm 0.12(\text{syst})$

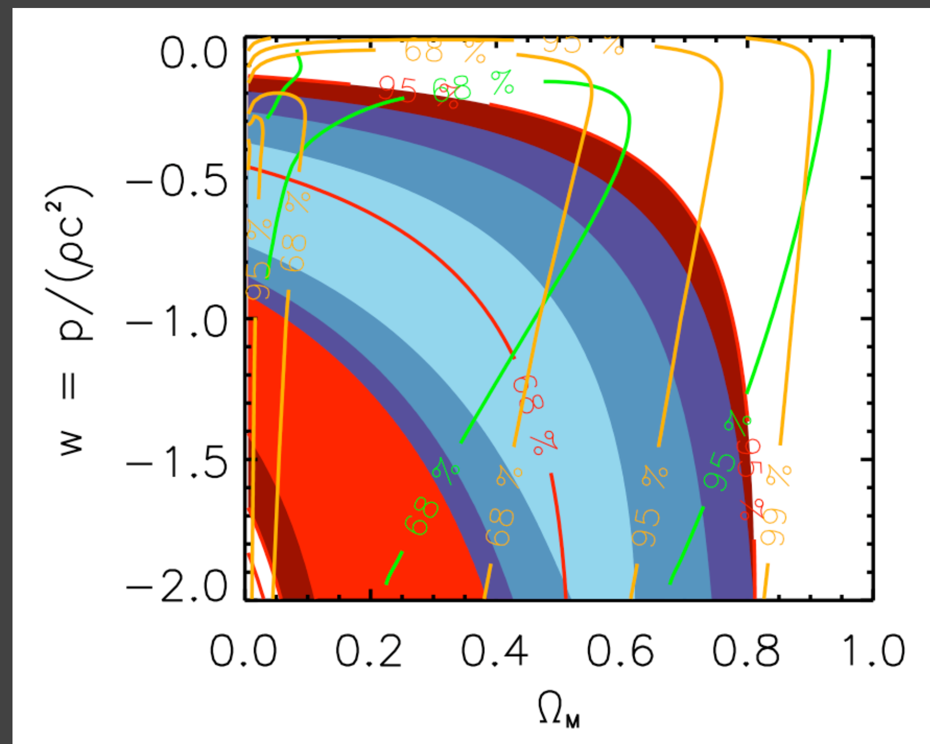
SALT

$w = -0.96 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})$



SDSS DR7 BAO+SN Results

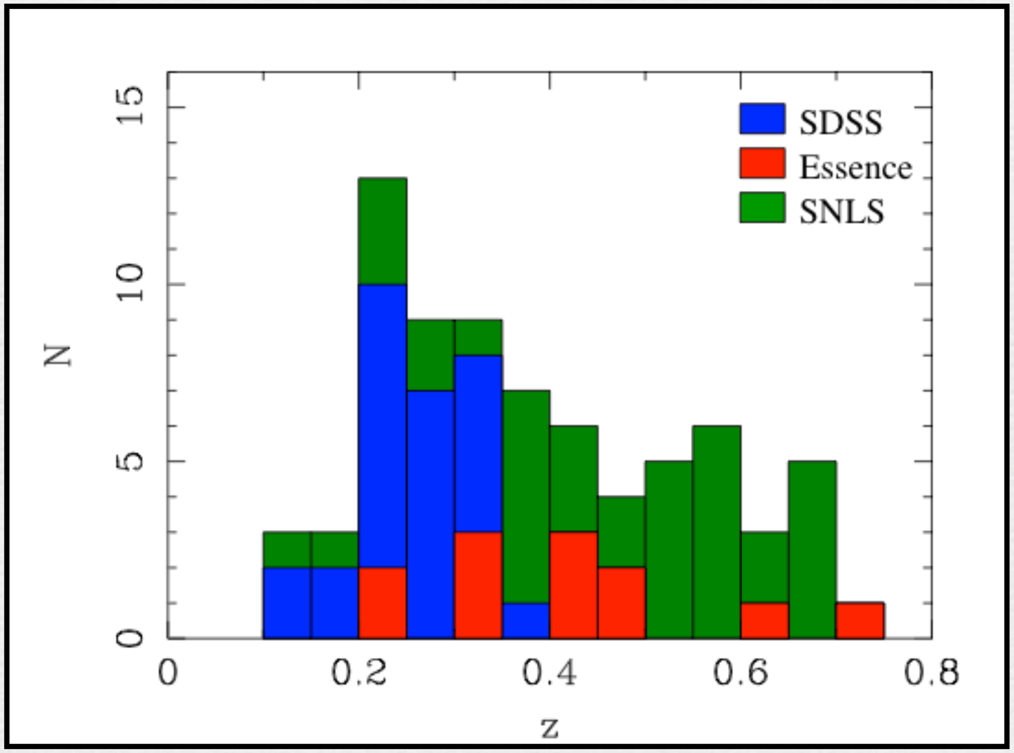




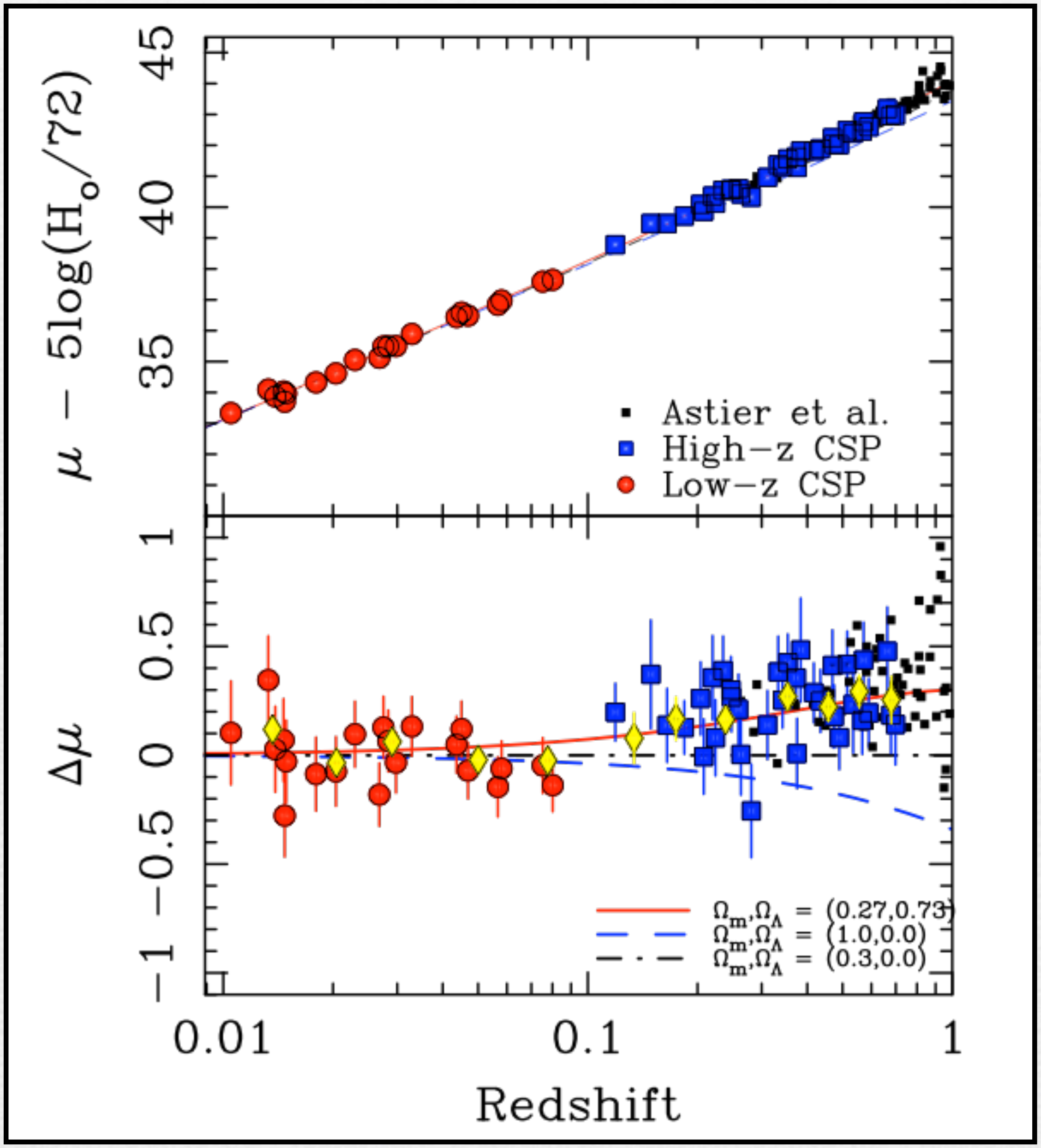
Consistency of BAO and SN Distances

Carnegie Supernova Project

- Goal: ~75 SN Ia in redshift range 0.2 - 0.7
- Photometry in near-infrared bands (Y + J) using Magellan 6.5m
- Gives rest-frame i-band flux near max.
- Reduce systematics due to dust extinction.
- Augment with optical +NIR observations at low-redshift



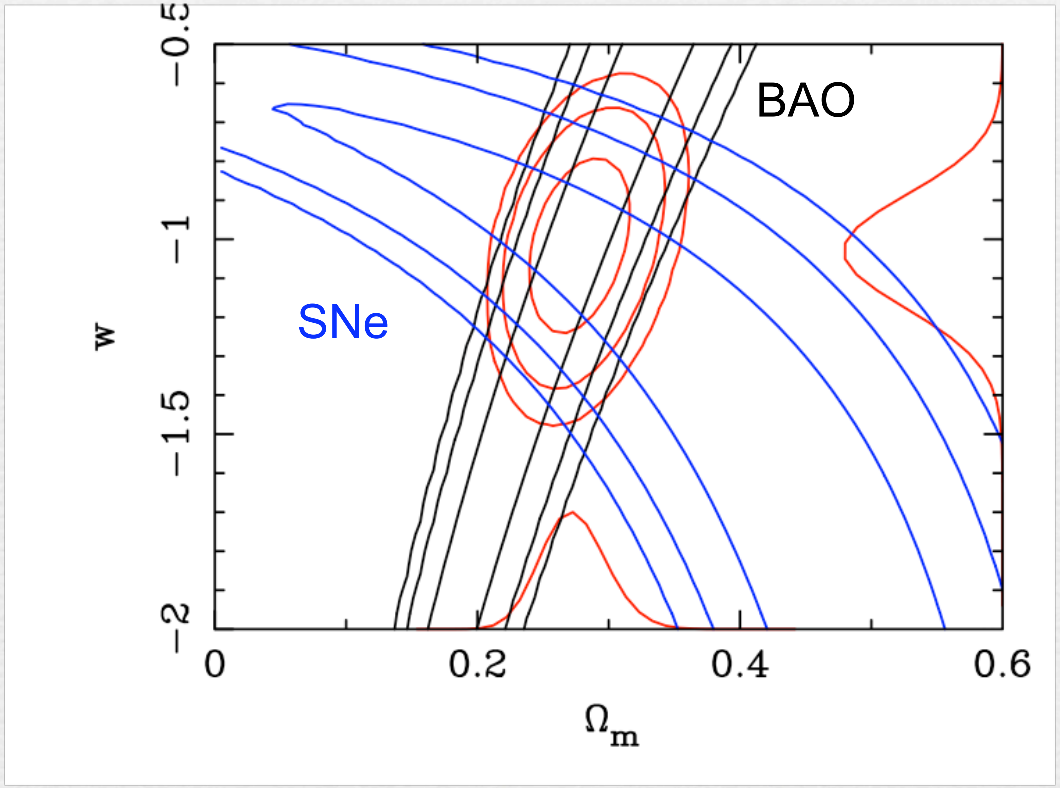
First Rest-frame i-band Hubble Diagram to z=0.7



Freedman et al. (2009)

CSP Dark Energy Constraints

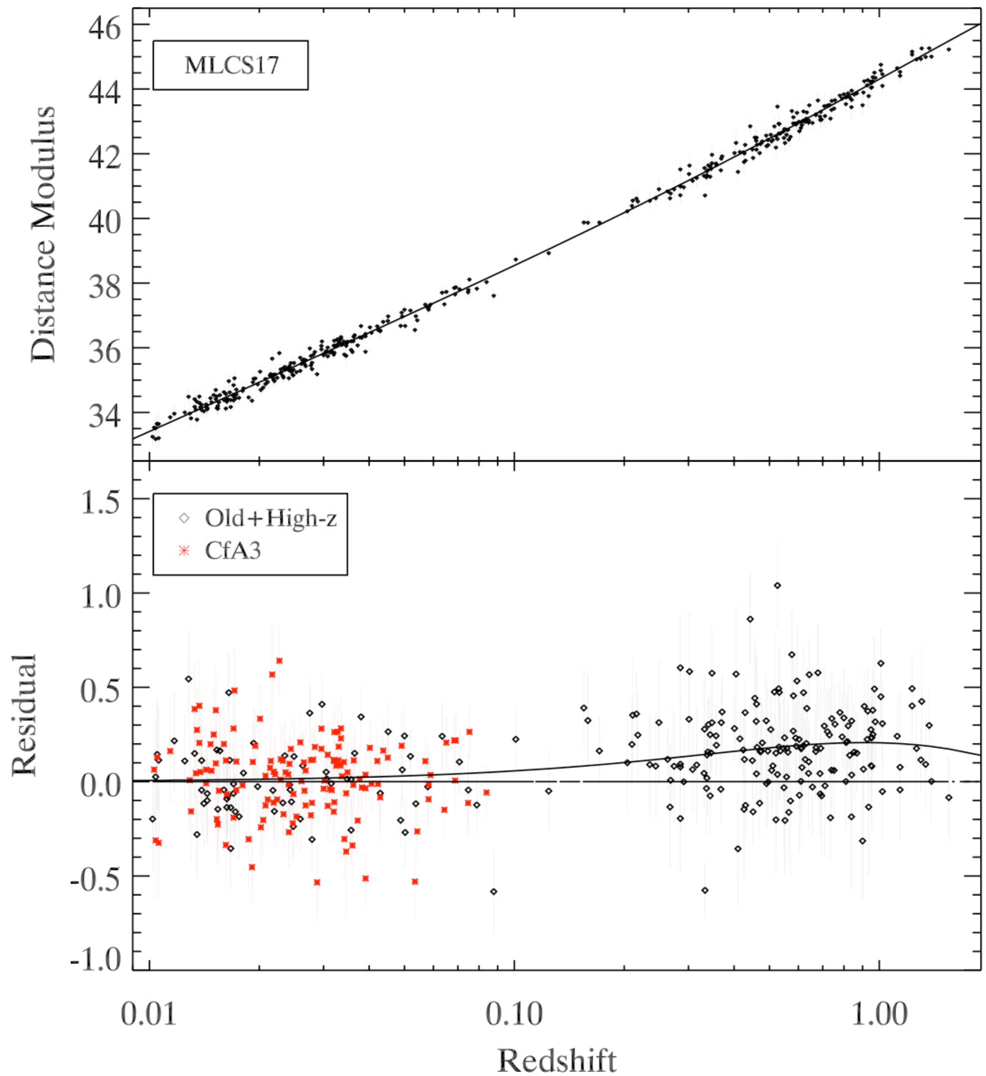
Freedman et al. (2009)



w = -1.05 ± 0.13(stat)±0.09(sys)

(assuming k=0 and BAO)

CfA3: New Distances at Low Redshift



Low:

CfA3

187 new low-z light curves

(Hicken et al 2009a,b)

High:

ESSENCE

SNLS

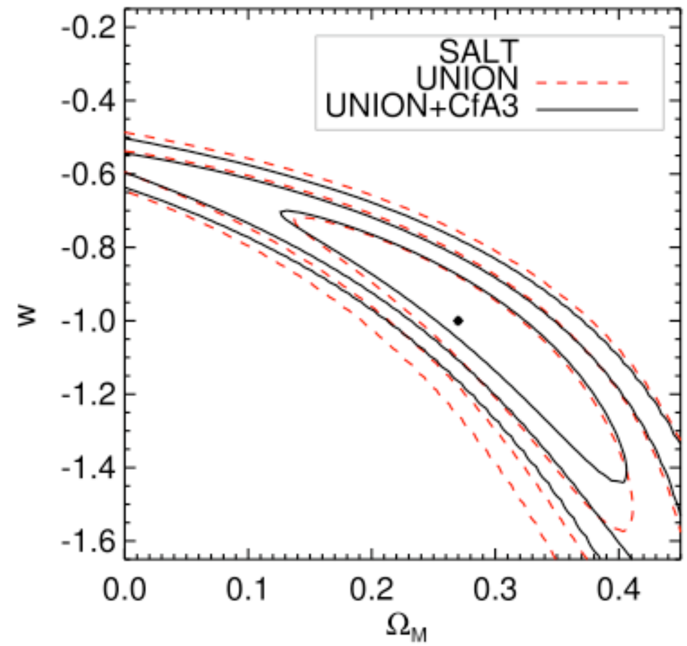
Higher-Z

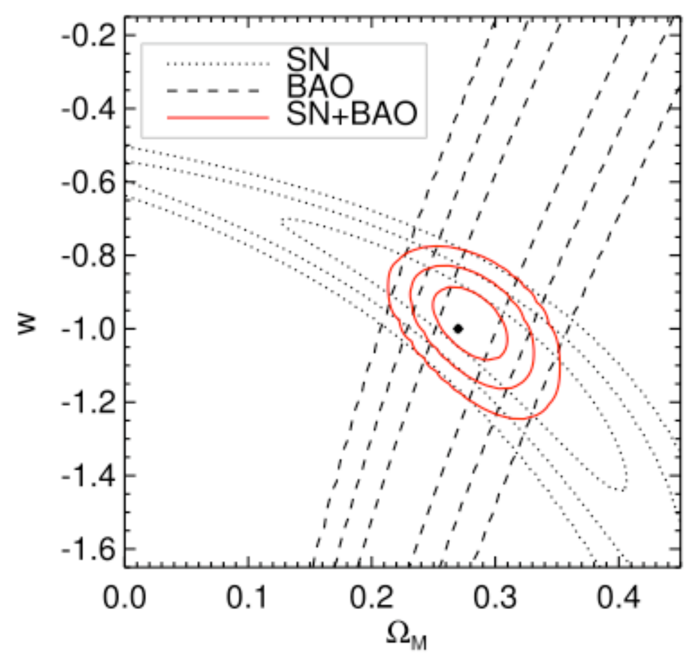
Dark Energy Constraints

Find best-fit dust parameter R_V=1.7 by minimizing scatter in the Hubble diagram

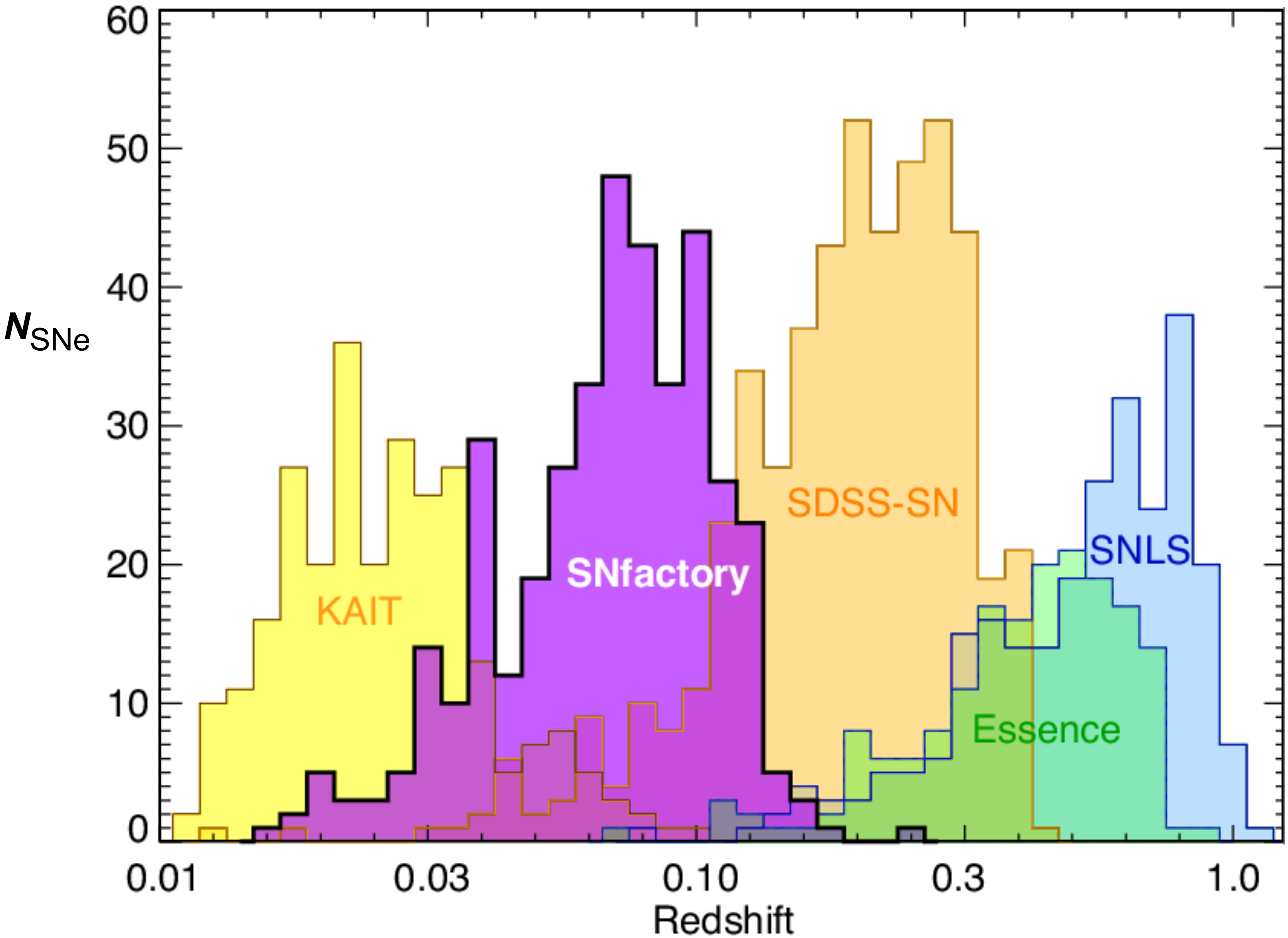
Similar R_V result from CSP Low-z

Hicken etal





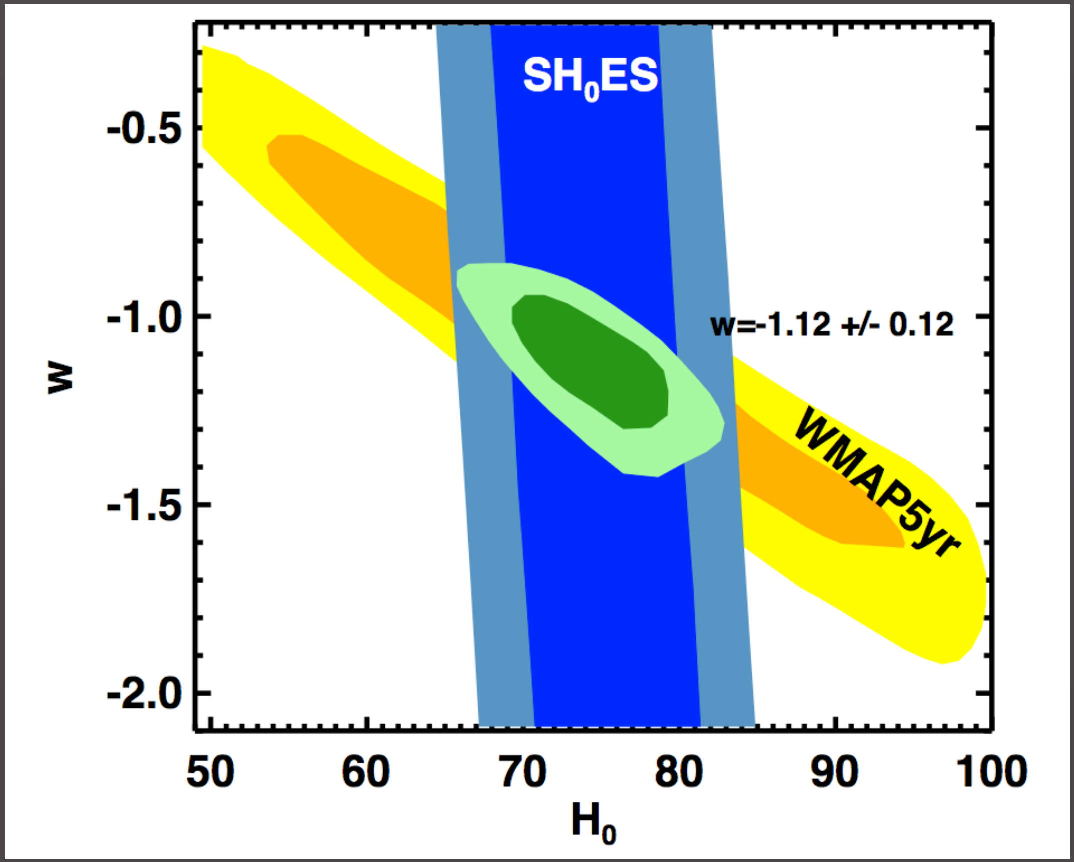
Number of Type Ia
Supernova Discoveries



Systematic Errors (and Controls)

- Dust and SN color variation (multi-λ, NIR, high S/N)
- Selection effects (artificial SNe, Monte Carlo simulations)
- Population evolution (SN properties vs host environment)
- Photometric calibration (system calibration (lasers, etc) & cross-calibration of systems)
- Sample purity (spectroscopy)
- All (subdivide large samples to cross-check)
- Clear pathway to progress

Improved Measurement of H_0



Riess, etal 2009

HST Distances to 240 Cepheid variable stars in 6 SN Ia host galaxies

$$H_0 = 74.2 \pm 3.6 \text{ km/sec/Mpc}$$

Clusters and Dark Energy

1. Volume depends on history of expansion rate
2. *n(z)* depends on growth rate of LSS

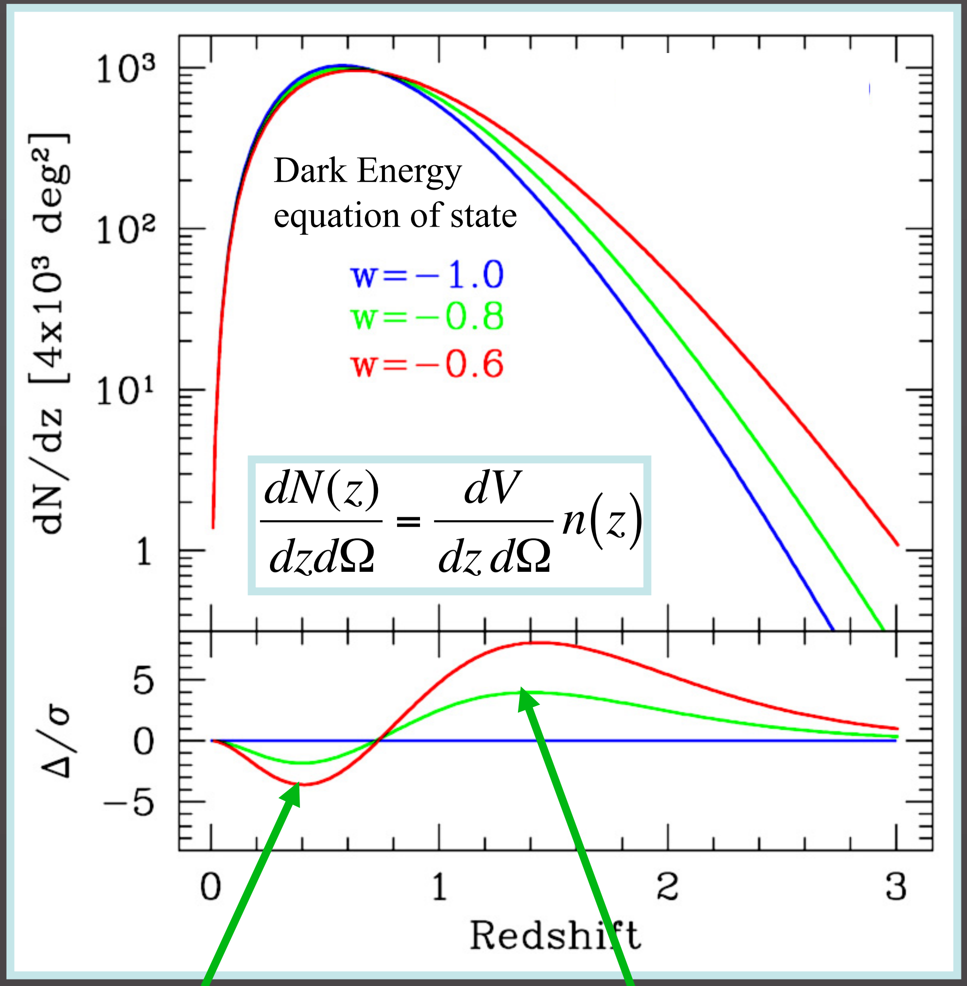
Need observable proxy *O* that can be used as cluster mass estimate:

$p(O|M,z)$

Primary systematic:

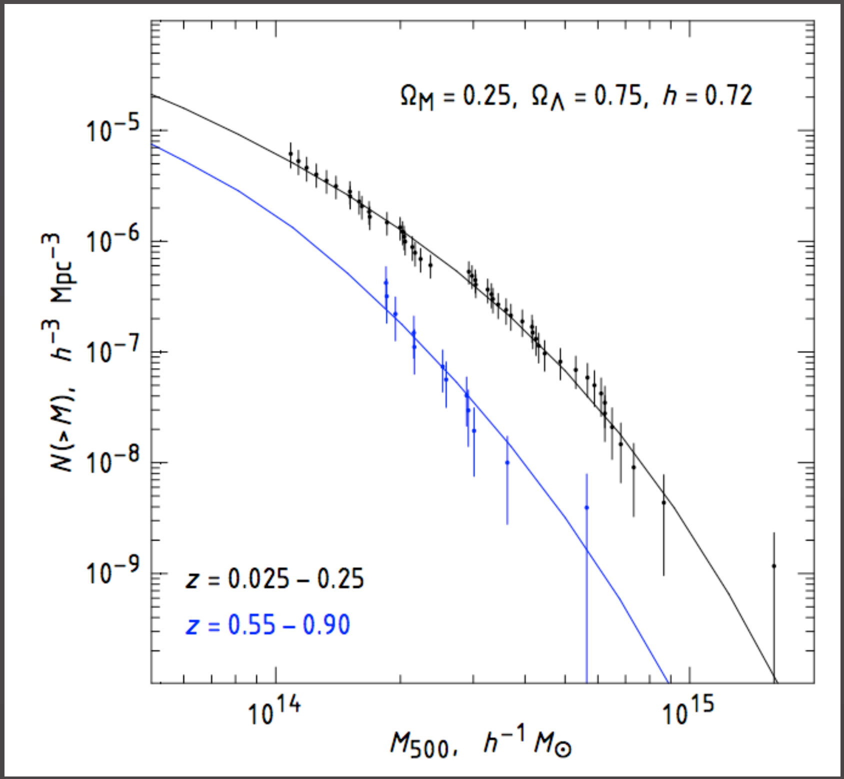
Uncertainty in bias & scatter of mass-observable relation

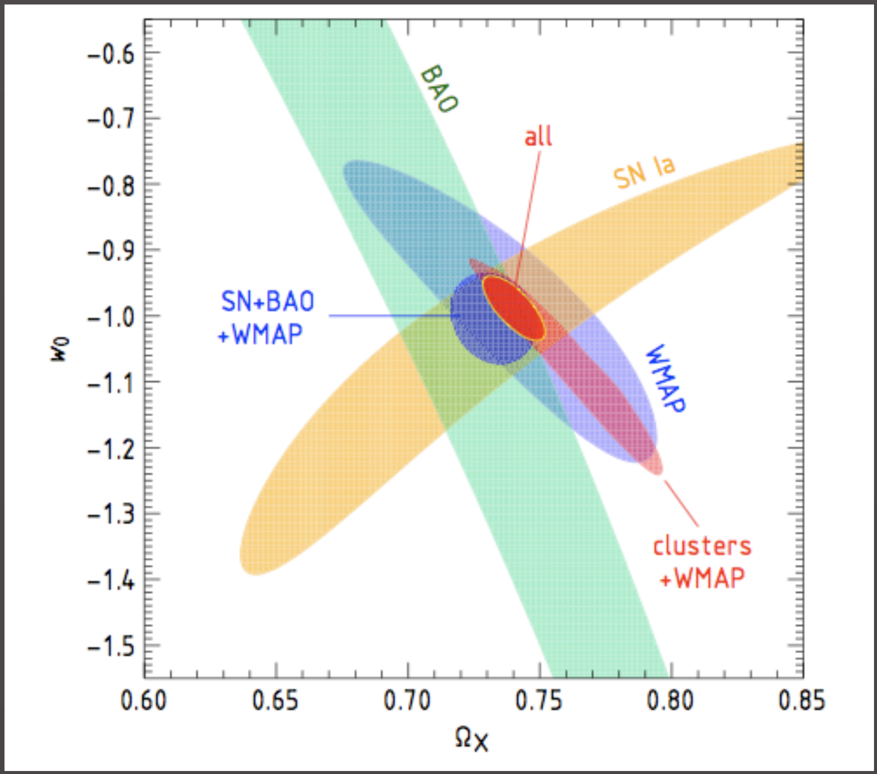
Number of clusters above observable mass threshold



Mohr

Chandra/ROSAT X-ray Cluster Results





Vikhlinin etal 2009

The Dark Energy Survey

- Study Dark Energy using 4 complementary* techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Baryon Acoustic Oscillations
  - IV. Supernovae

- Two multiband surveys:
  - 5000 deg^2 g, r, i, z, Y
  - smaller area repeat (SNe)

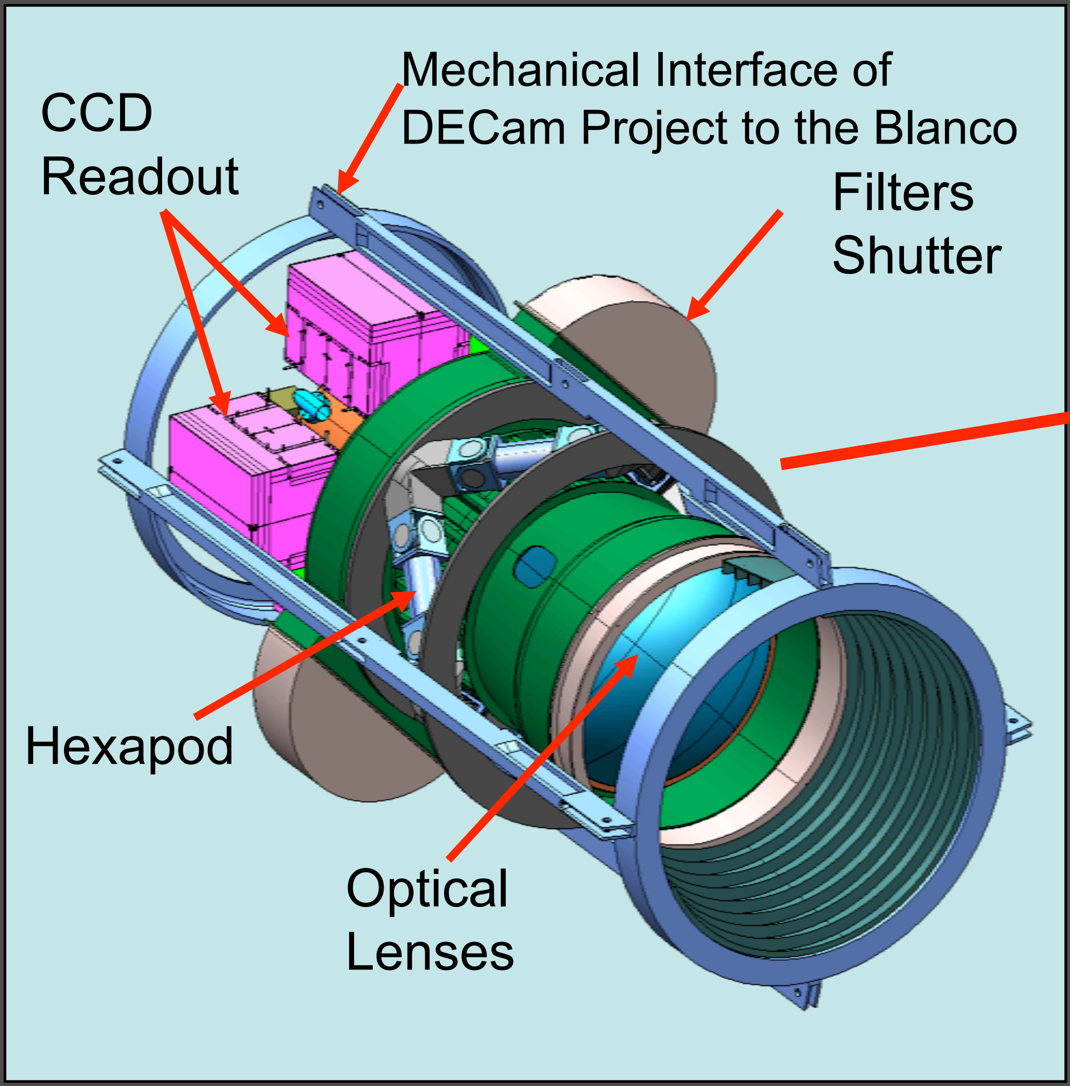
- Build new 3 deg^2 camera and Data management sytem
  - Survey 2011-2016 (525 nights)
  - Response to NOAO AO

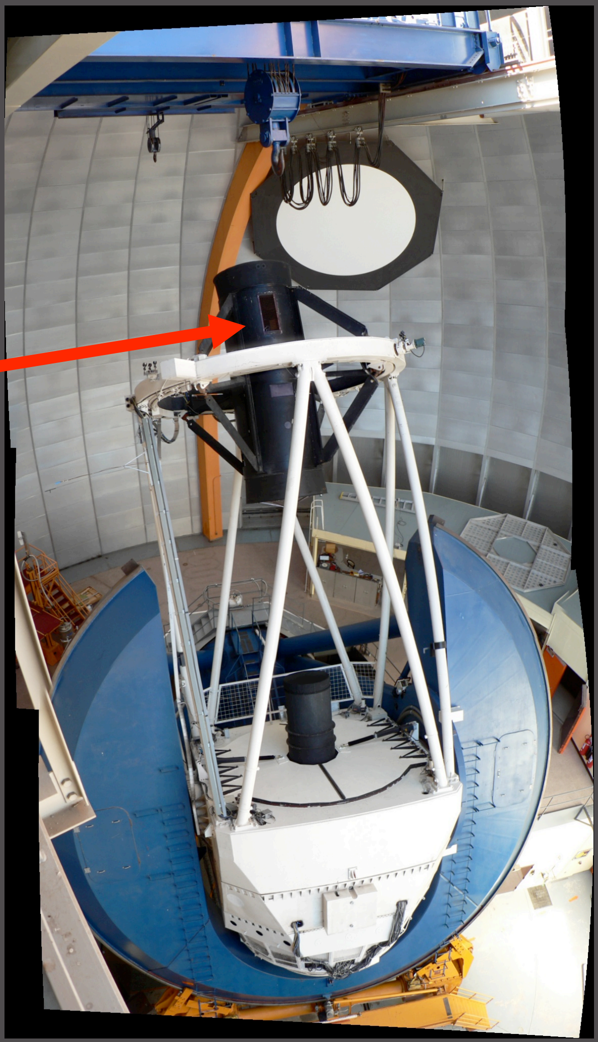
Blanco 4-meter at CTIO

*in systematics & in cosmological parameter degeneracies

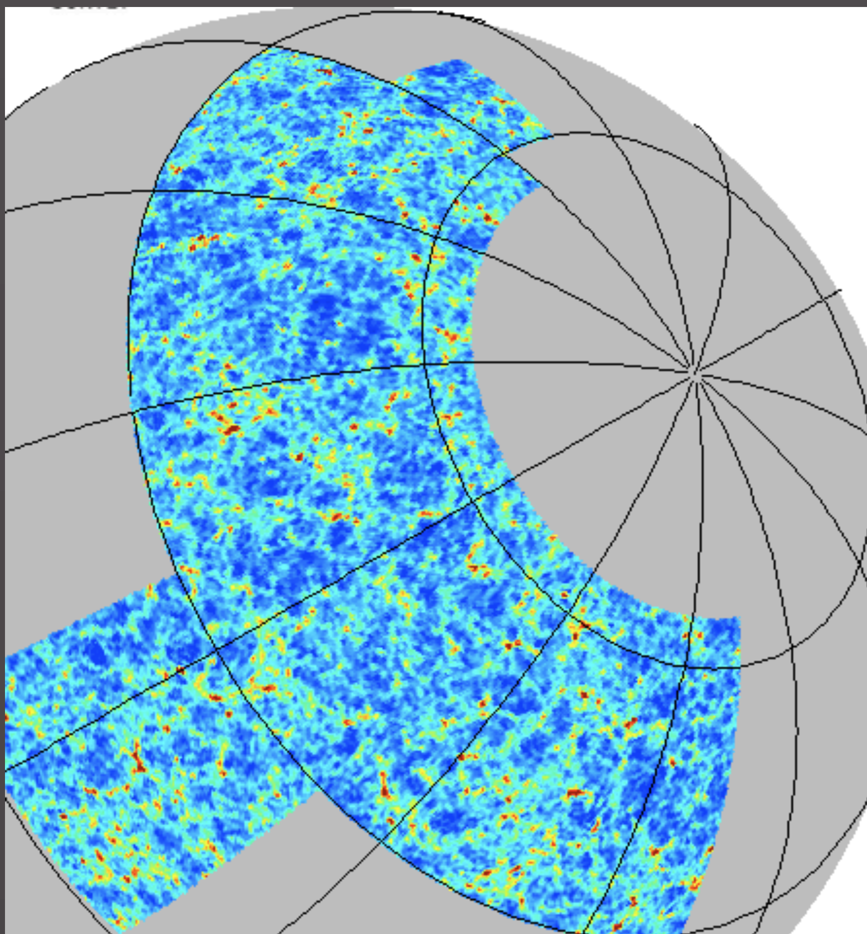
*geometric+structure growth: test Dark Energy vs. Gravity

DES Instrument: DECam



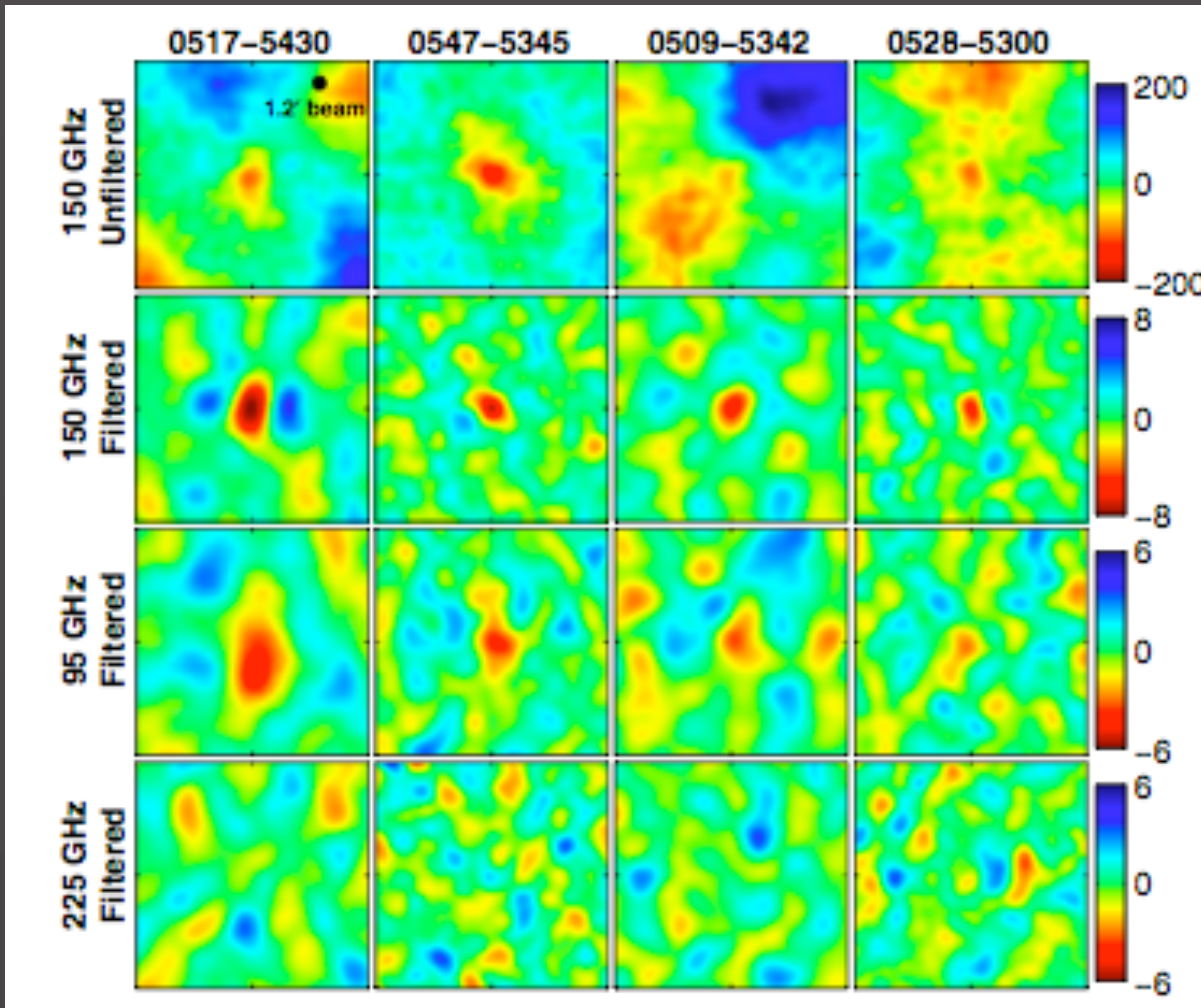


Synergy with South Pole Telescope



SPT will carry out Sunyaev-Zel'dovich (SZ) survey of clusters over most of the DES survey area

First SZ-discovered Galaxy Clusters

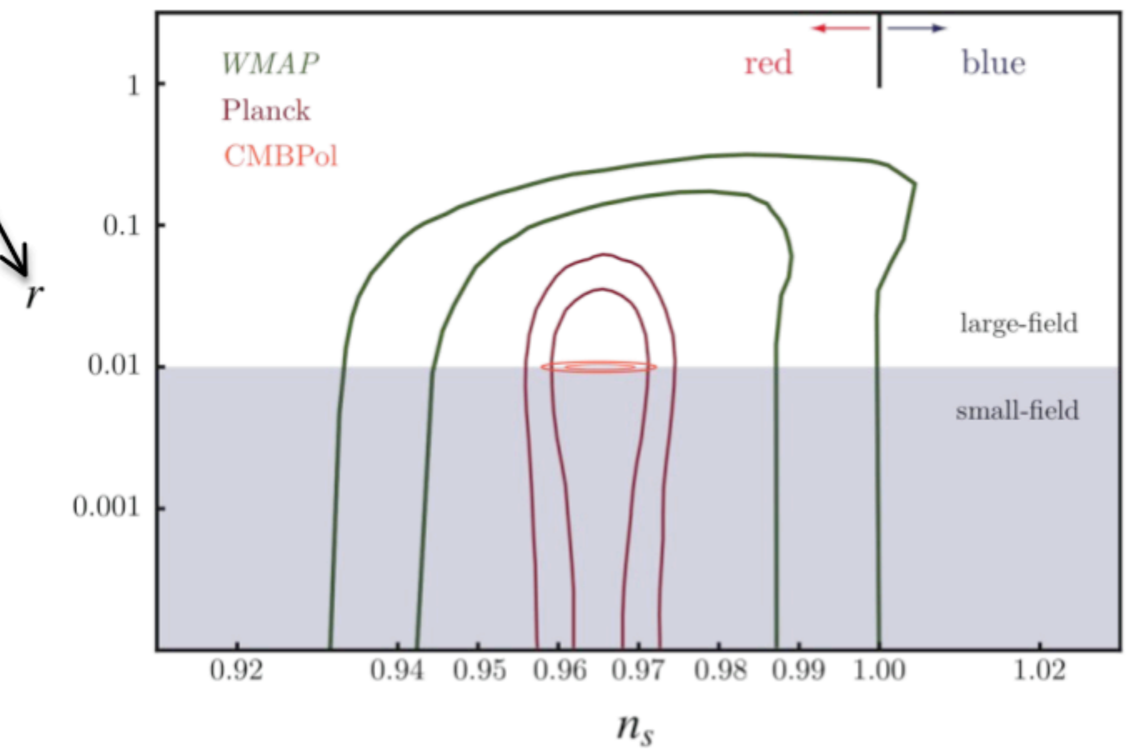


Staniszewski et al (2009)   South Pole Telescope

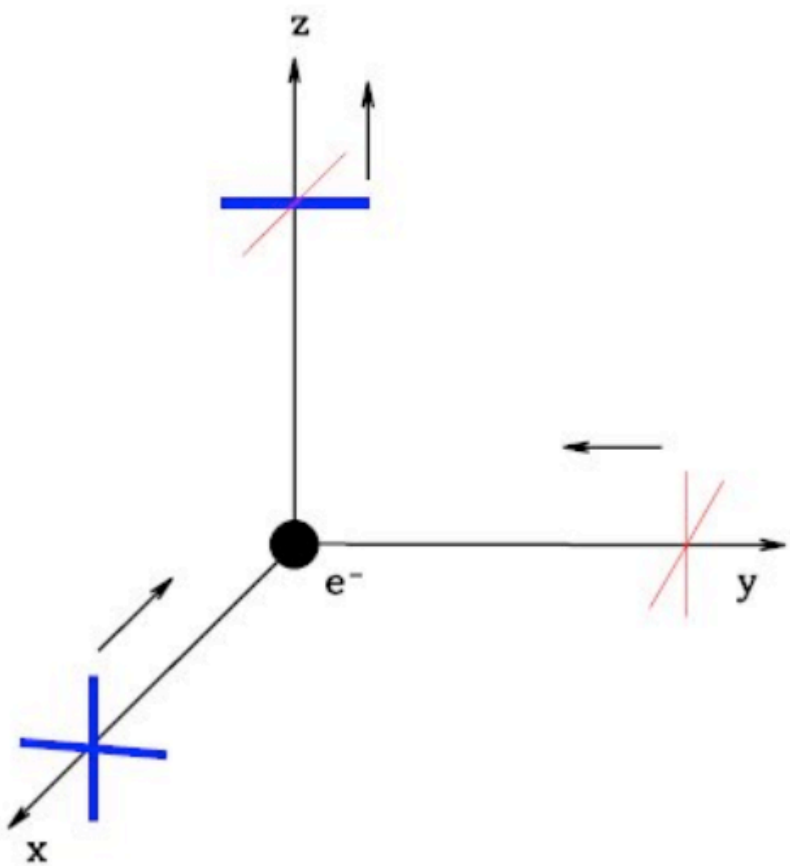
Gravitational Wave amplitude pins down physics driving Inflation

$$V^{1/4} = 1.06 \times 10^{16}\ \mathrm{GeV} \left(\frac{r_*}{0.01}\right)^{1/4}$$

Ratio of Tensor/Scalar Amplitudes



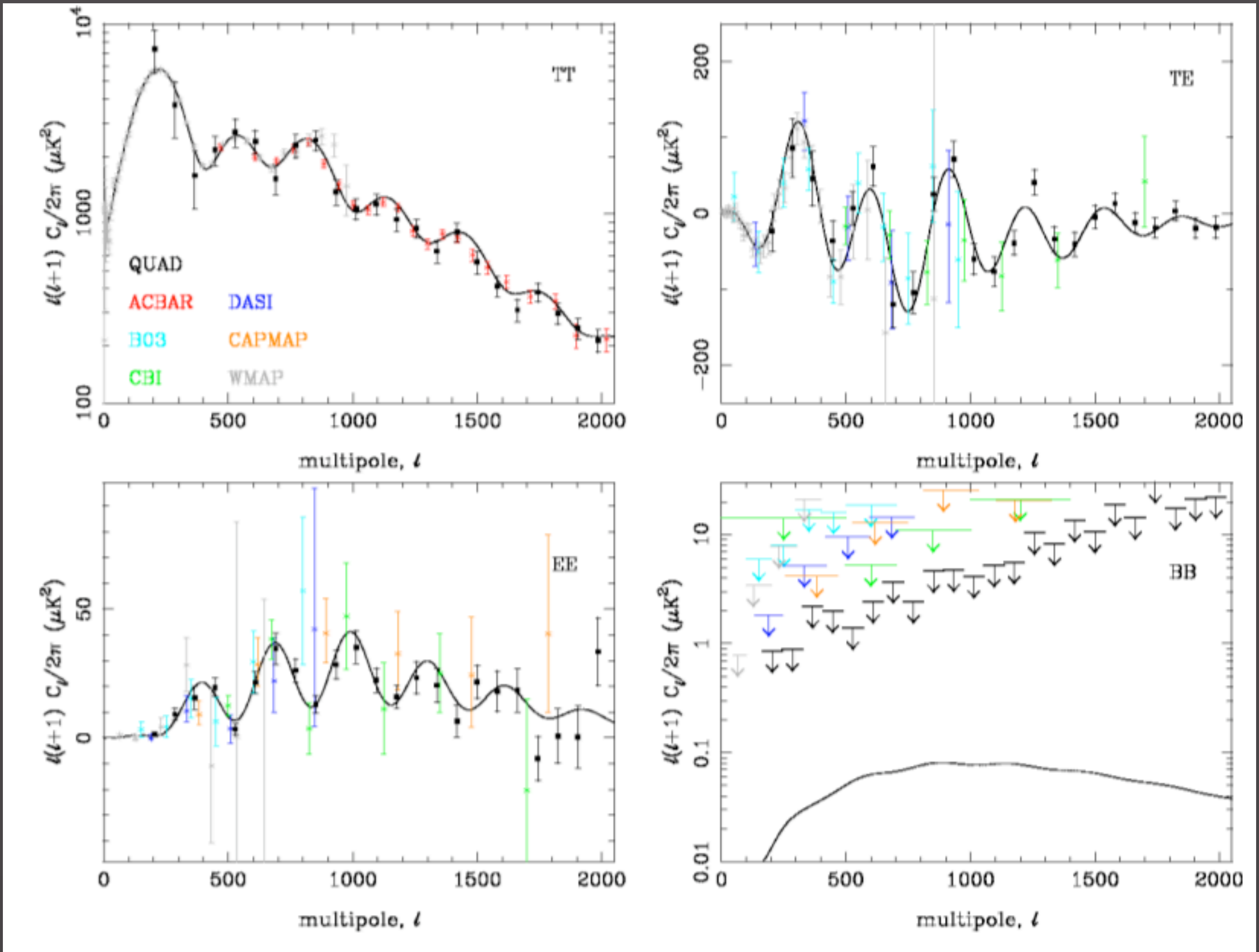
To detect Gravitational Waves, Measure CMB Polarization



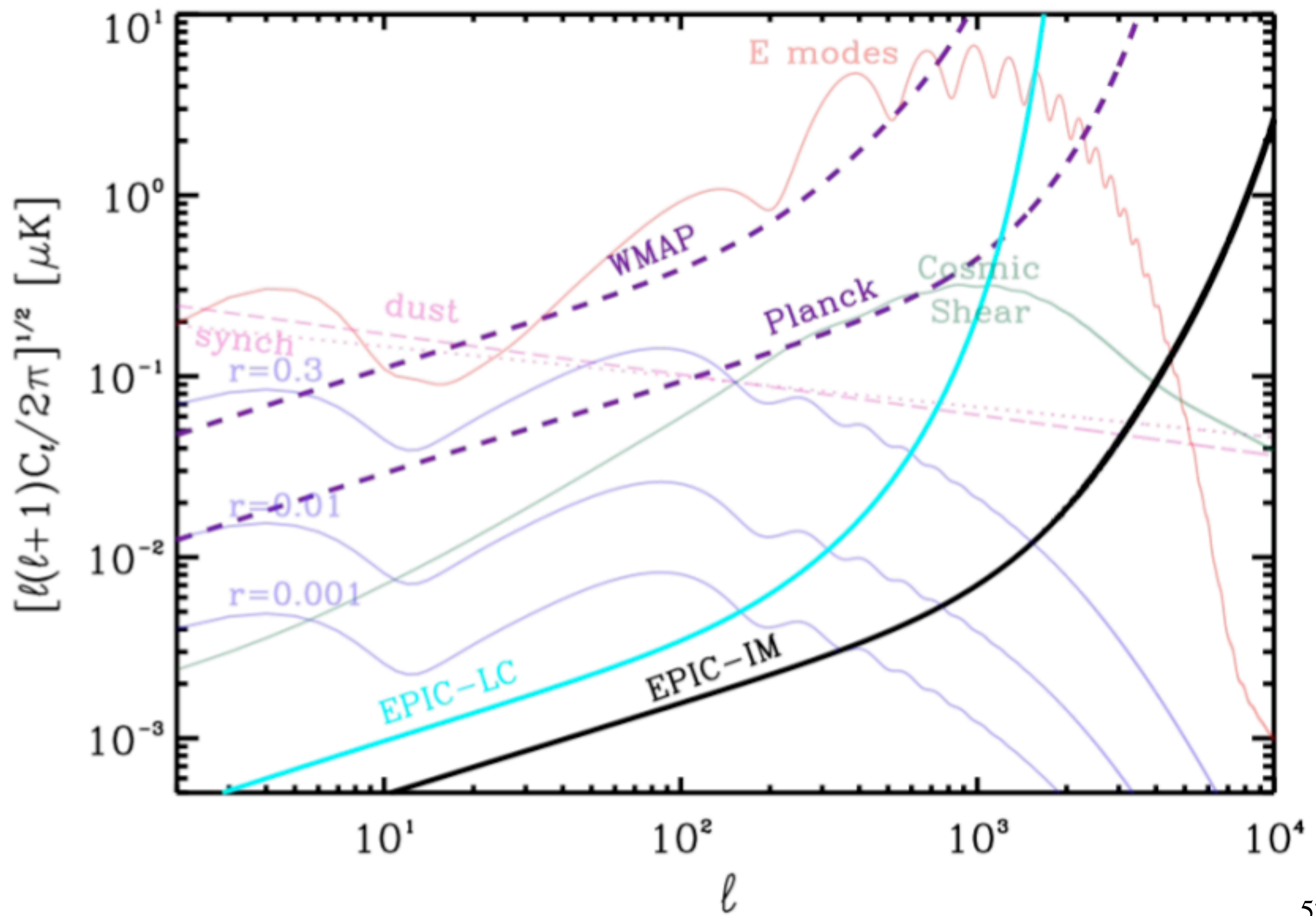
Compton scattering of unpolarized anisotropic radiation produces polarization

- Require Quadrupole (small before *t=400,000* yrs)
- Require Compton scattering (rare after *t=400,000* yrs)
- Signals factor of 10 smaller than temperature anisotropies

Recent CMB Results

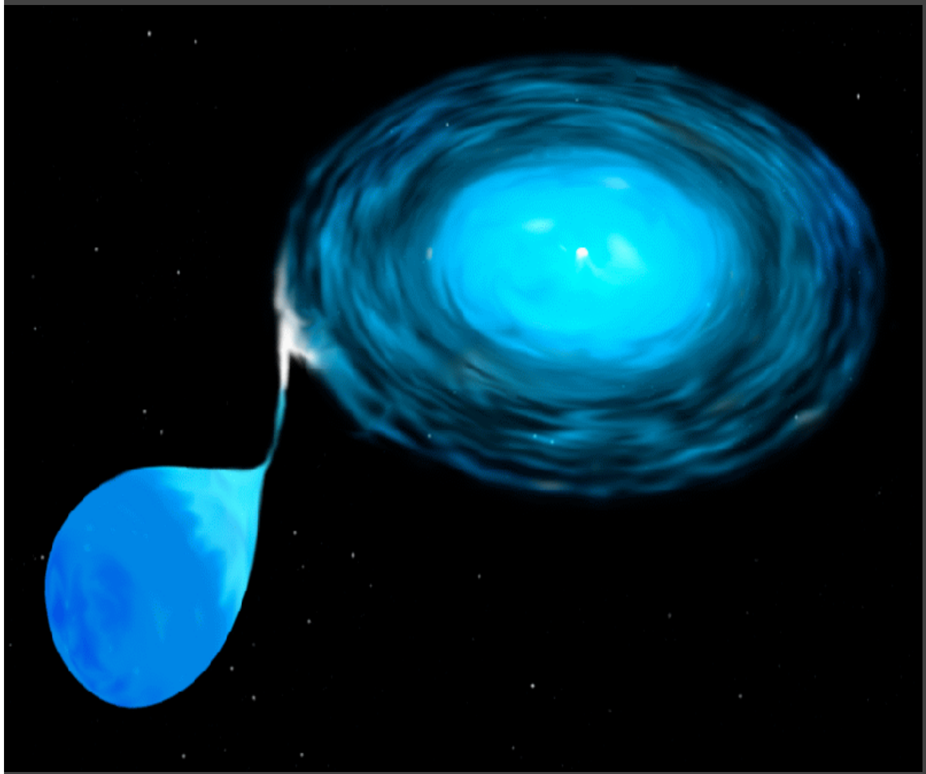


Satellite sensitivity



Extra Slides

Understanding Type Ia Supernovae



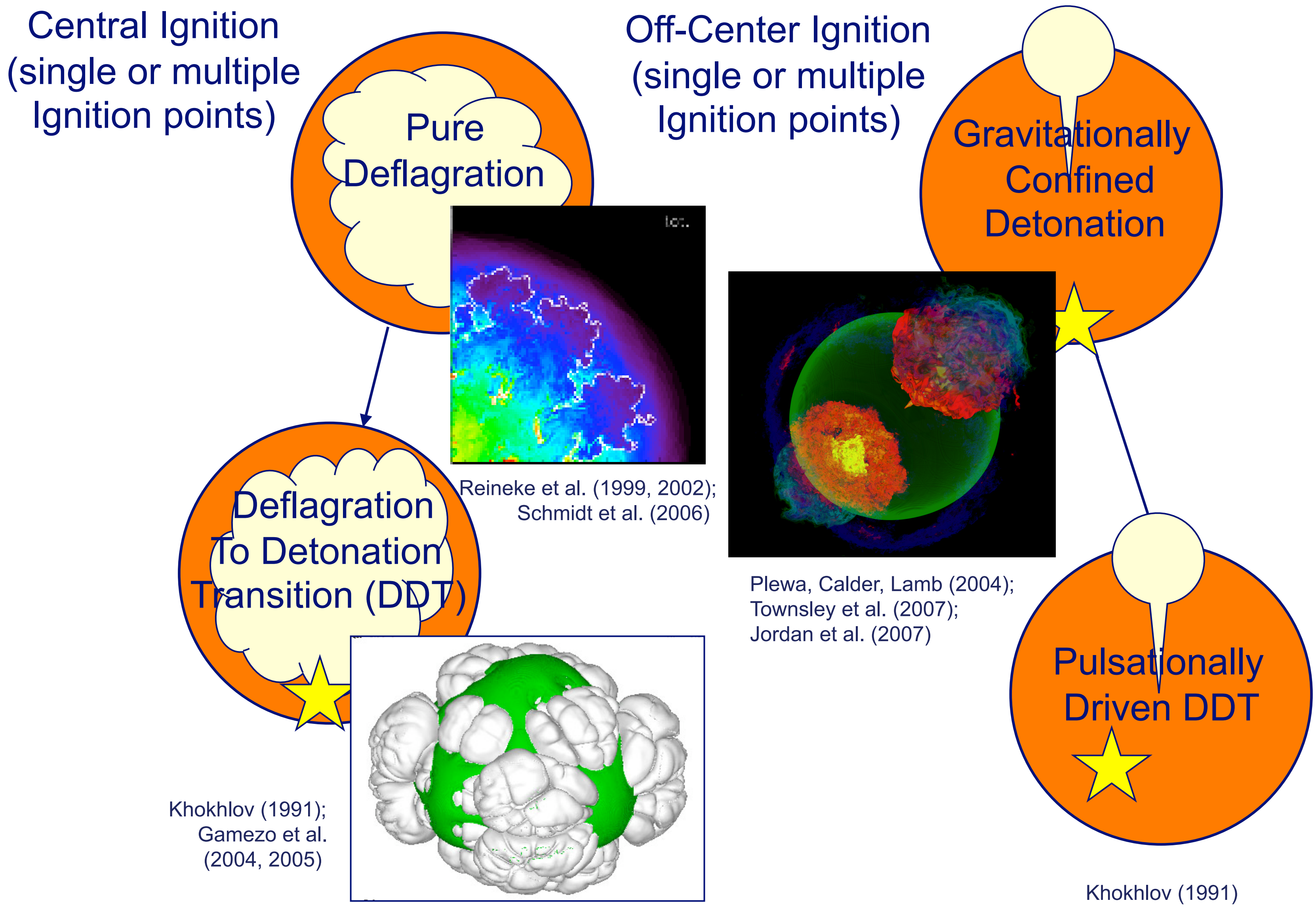
Thermonuclear explosions of White Dwarf stars

White Dwarf accretes mass from or merges with a companion star, growing to a critical mass~$1.4M_{sun}$

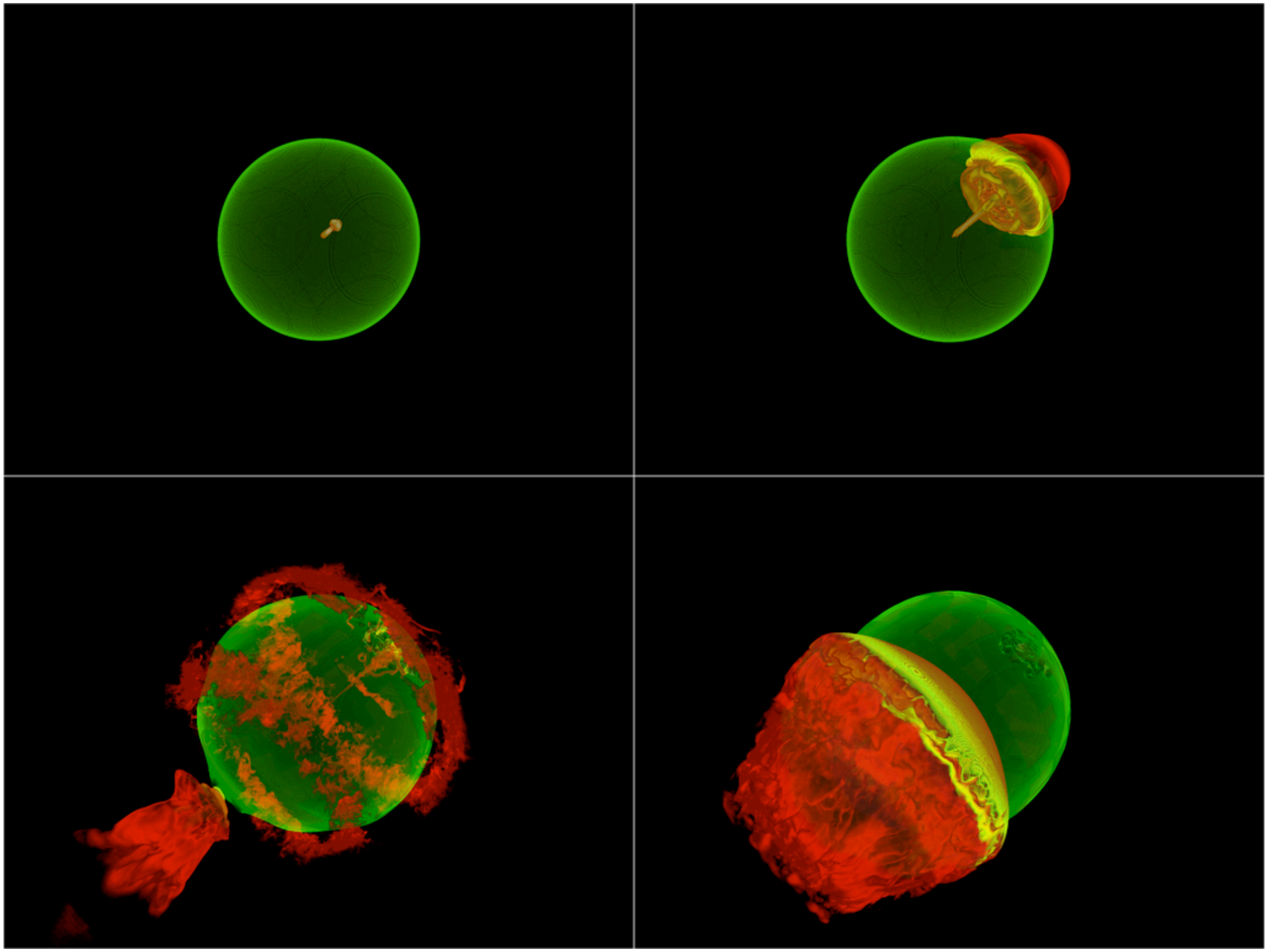
A violent explosion is triggered at or near the center, and the star is completely incinerated within seconds

In the core of the star, light elements are burned in fusion reactions to form Nickel. The radioactive decay of Nickel and Cobalt makes it shine for a couple of months

Four Current Models of Type Ia Supernovae

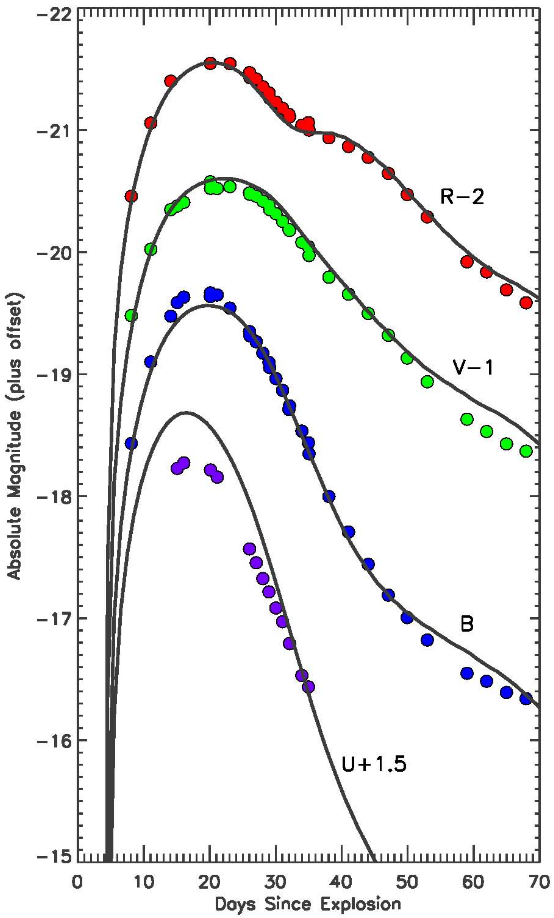


3D Simulations of GCD Model for Single-Bubble Initial Conditions



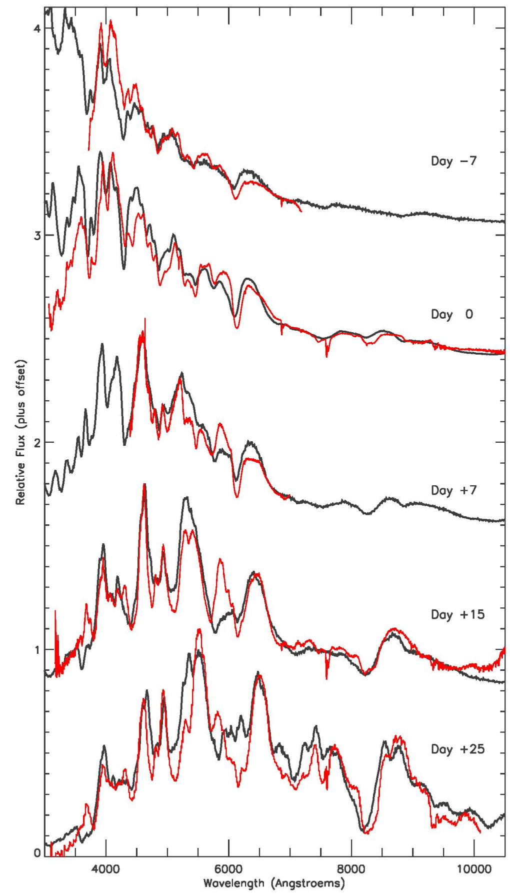
Jordan et al. (2008)

Comparison of Predicted and Observed Light Curves and Spectra



Comparison of U, V, B, R light curves predicted by GCD model and obs. of Type Ia Supernova SN 2001el

Kasen & Plewa (2006)



Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D

Moving into an era where comparisons of high-fidelity, 3D, whole-star stimulations and high-quality observations will allow us to discriminate among proposed explosion mechanisms