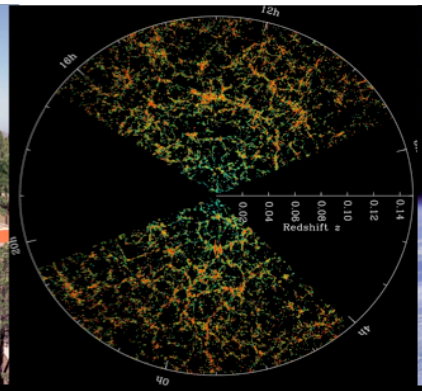
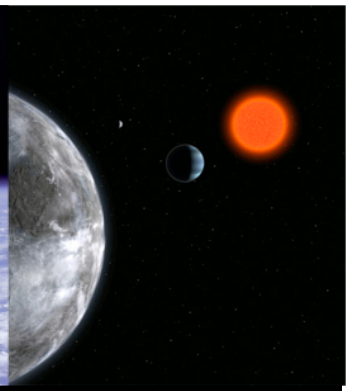
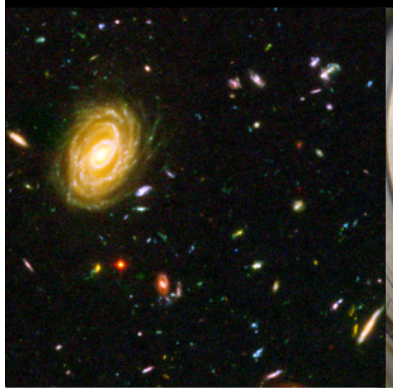
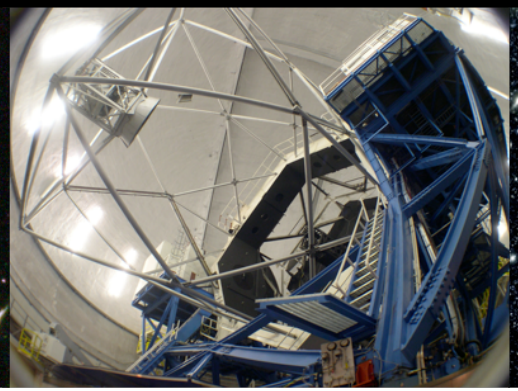




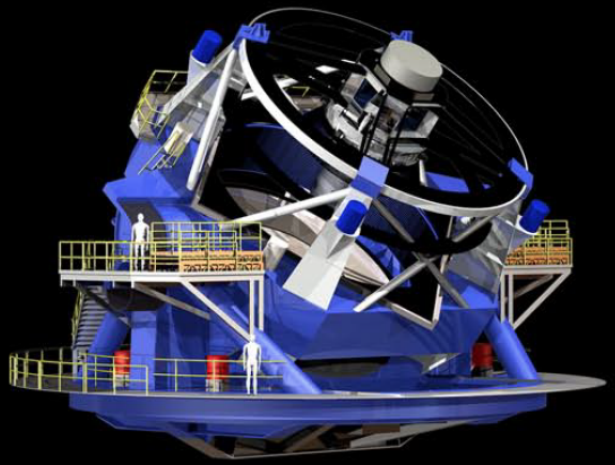
Cosmology and Surveys

Andrew Connolly
University of Washington

What occupies your time when you're not on a telecon…?

- LSST
  - Transient detection
  - Simulations of the LSST
- Photometric redshifts
  - Galaxy evolution
  - Large scale structure
  - Filter designs
- Scalable science
  - Machine learning applications
  - Data access and visualization
  - Google Sky



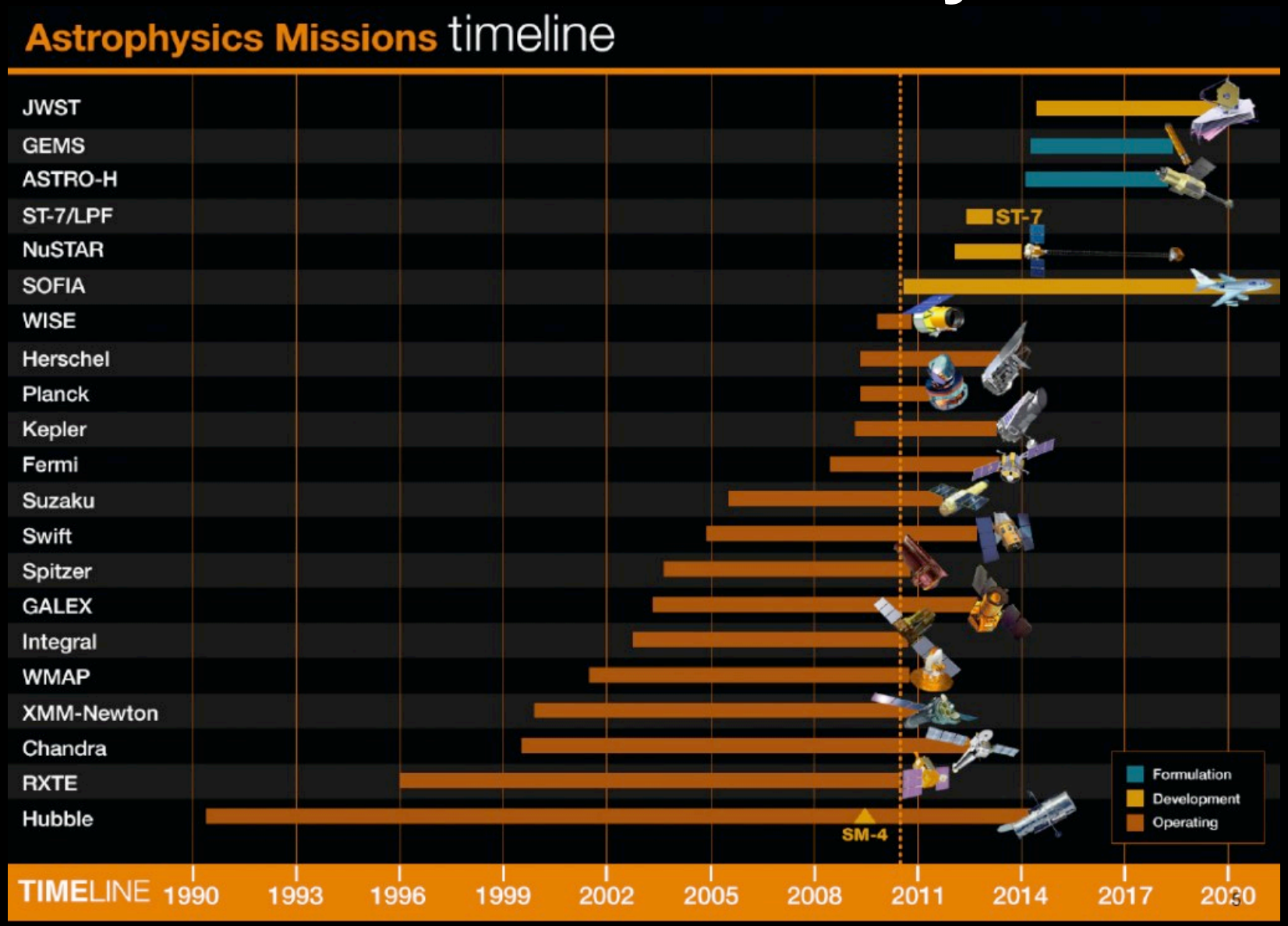
The evolution of data

Dinoj Surendran, Mark SubbaRao

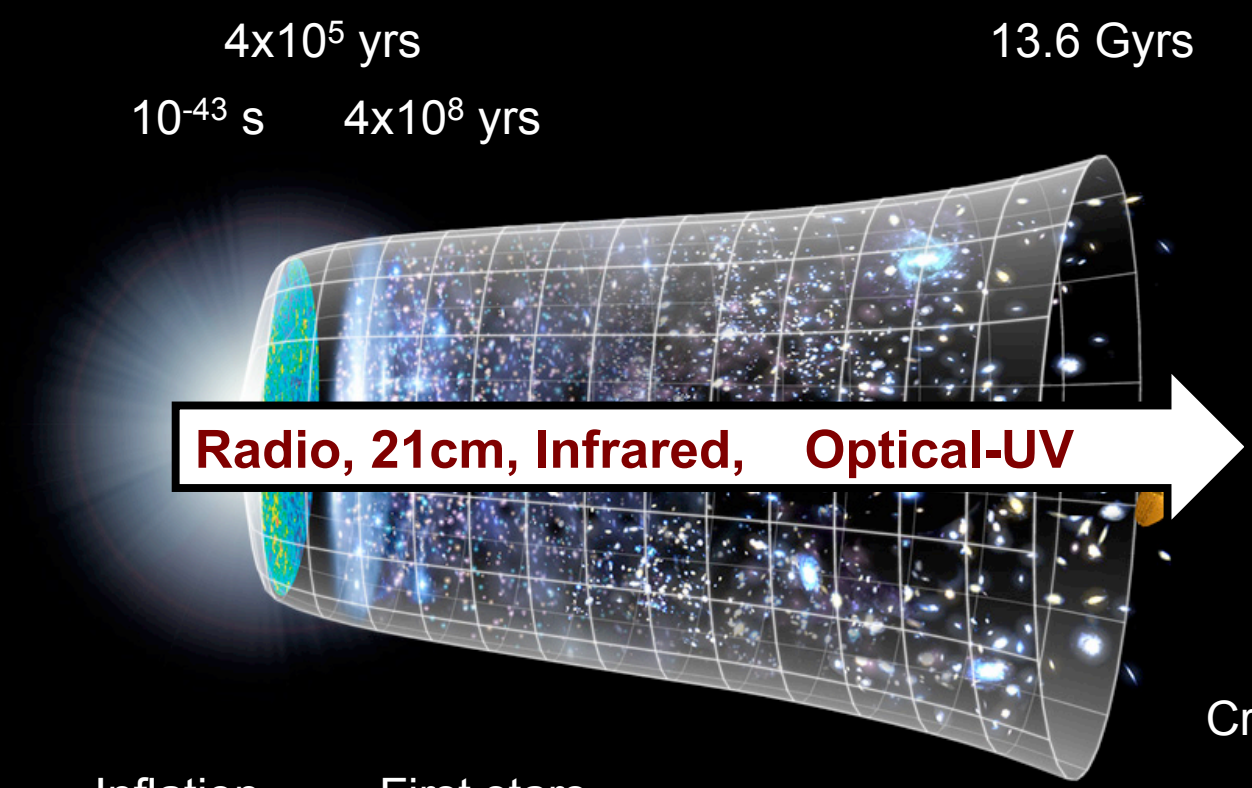
Structure of the lectures

1. Evolution of Cosmogony through Surveys
   - How has our understanding of cosmology evolved with time and how do surveys drive this understanding
2. What can we look forward to
   - In the era of survey astronomy what can we expect over the next decade
3. Statistics and Cosmology
   - How can we scale the science (and statistics) we want to undertake to the petascale surveys coming on line this decade

A decade of surveys



Growth of structure in the universe



Credit: WMAP

What are we trying to learn?

Scale factor

Curvature (-1,0,+1)

$$H^2(t) \equiv \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \left(\frac{8\pi}{3}\right)G\rho(t) - \frac{k}{a^2(t)}$$

Hubble parameter

Density

We live in an **isotropic** and **homogeneous** universe (averaged over large scales)

Goal is to measure the scale factor: a(t) or H(t)

In its more observer friendly form

Equation of state parameter

$$\frac{H^2(z)}{H_0^2} = \Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{DE,0}\exp\left[3\int(1+w(z))d\ln(1+z)\right] + \left(1-\Omega_0\right)\left(1+z\right)^2$$

Where density is in terms of the critical density – five Hydrogen atoms per cubic meter

$$\Omega_{X,0} = \rho_X(t_0)/\rho_{crit}$$

$$\rho_{crit} \equiv \frac{3H_0^2}{8\pi G} = 1.03\times10^{-29}\,\text{grams/cm}^3$$

$$H_0 = 70.4^{+1.3}_{-1.4}\,km/s/Mpc$$

To accomplish this we require redshift and distance

Redshift

$$1 + z = \frac{\lambda(t_2)}{\lambda(t_1)} = \frac{a(t_2)}{a(t_1)}$$

FRW Metric

$$ds^2 = c^2 dt^2 - a^2(t)\left[dr^2 + S_k^2(r)\left\{d\theta^2 + \sin^2\theta\, d\phi^2\right\}\right]$$

$$S_k(r) = \sinh(r),\ r,\ \sin(r) \qquad k = -1,\ 0,\ 1$$

Comoving distance

$$cdt = a\, dr \ \Rightarrow\ r = \int \frac{cdt}{a} = c\int \frac{da}{a^2 H(a)} = -c\int \frac{dz}{H(z)}$$

Surveys don't need to be large

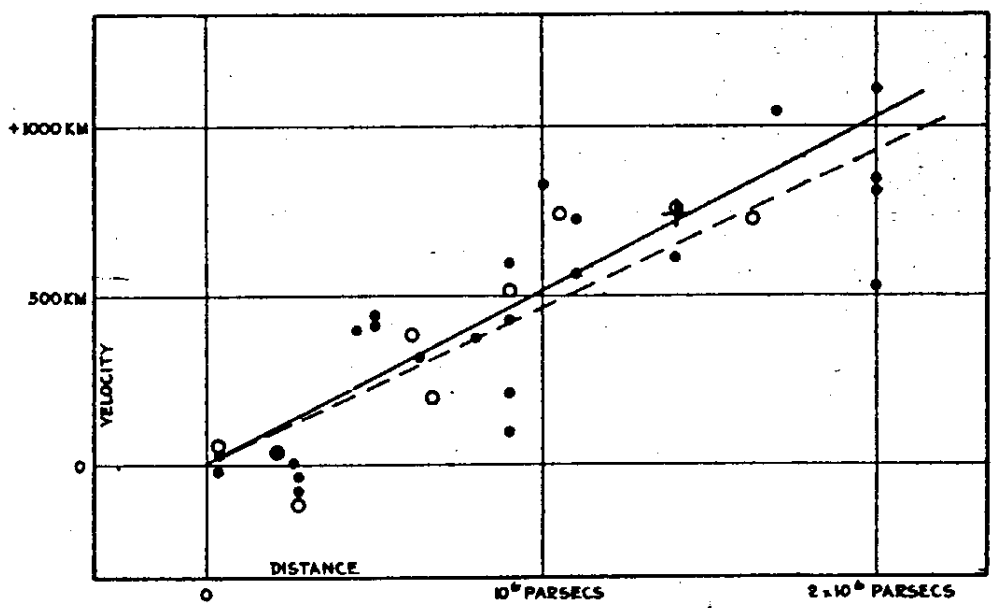
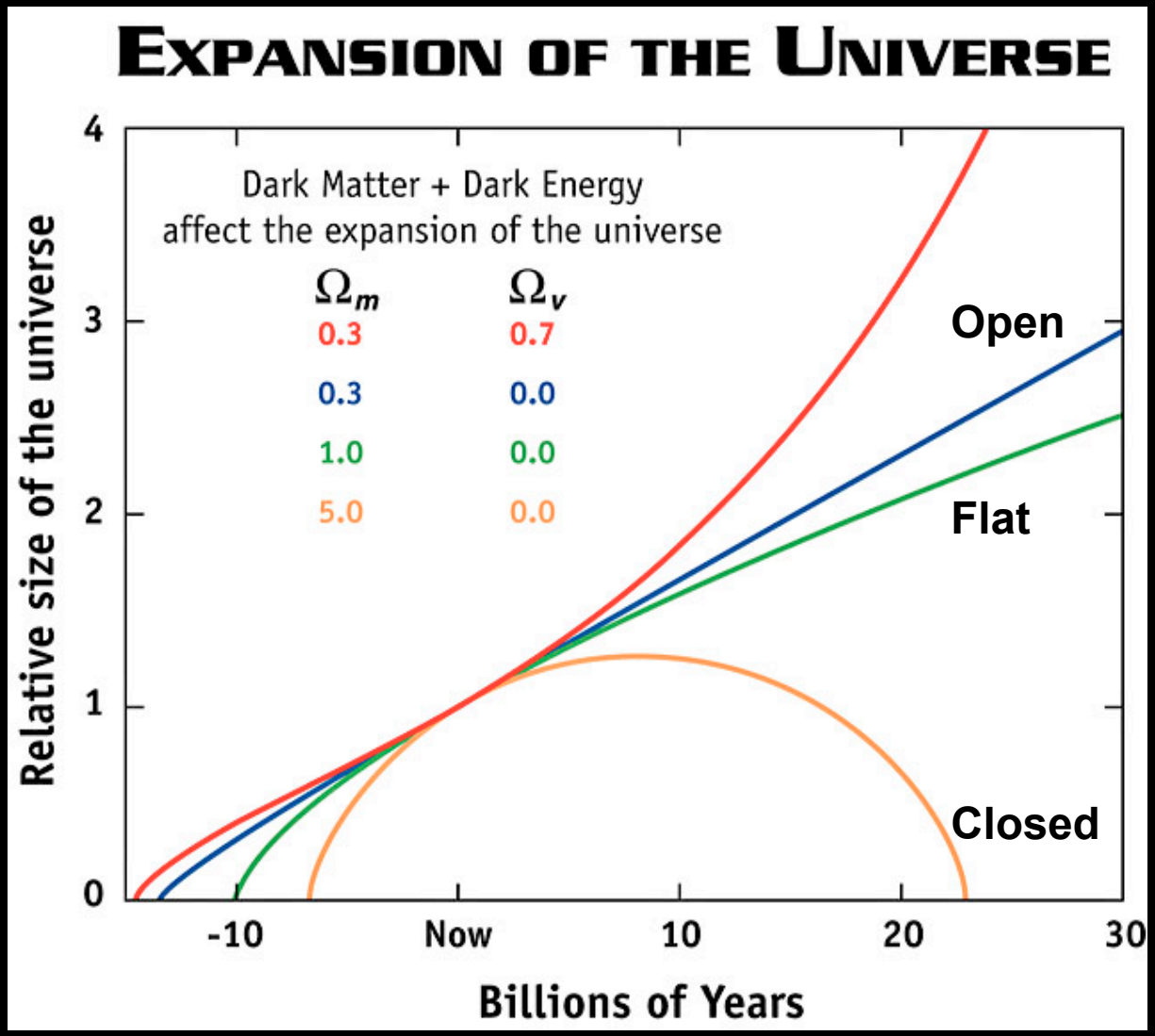


FIGURE 1

The present contribution concerns a correlation of empirical data of observation. The writers are constrained to describe the "apparent velocity-displacements" without venturing on the interpretation and its cosmologic significance. Further observations are desirable and will be carried on, although it seems probable that the

Hubble and Humason 1931

Evolution of a(t) through surveys



Research time

WMAP Team

Cosmology circa 1990

$$\frac{H^2(a)}{H_0^2} = \Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \left(1-\Omega_0\right)(1+z)^2$$

Theoretical preference for Ω_0=1 from inflation

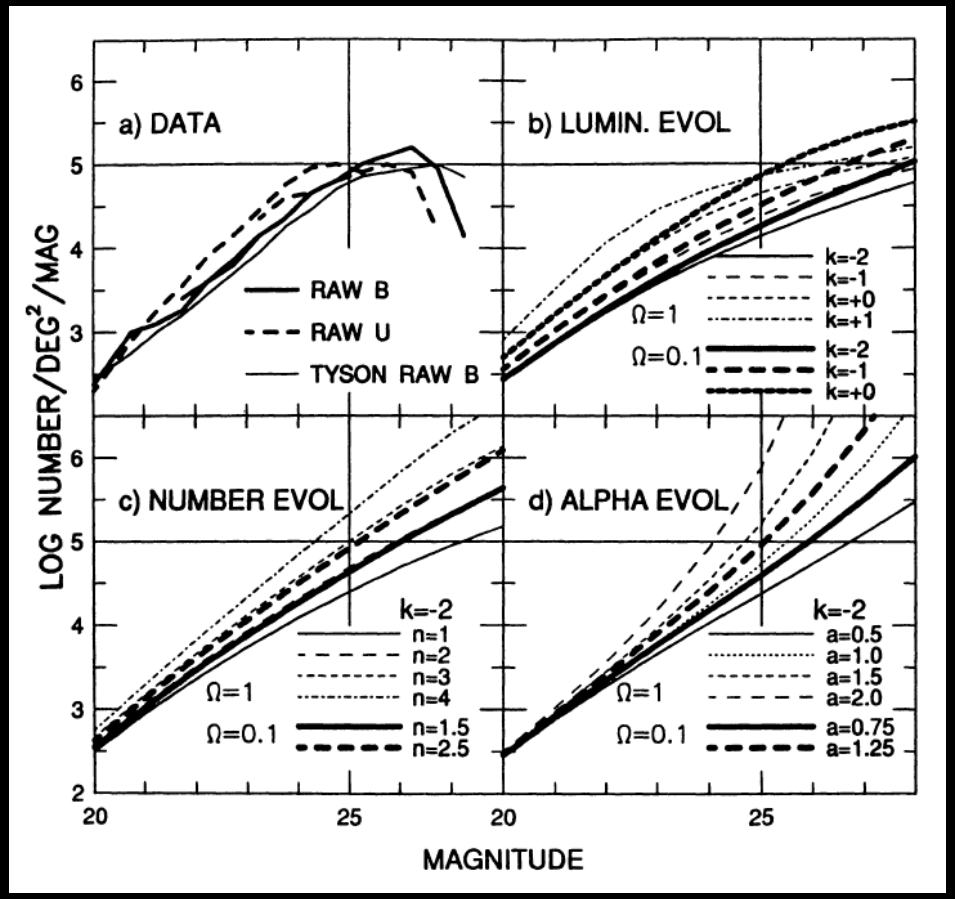
Observational preference for Ω_0=0.1 -- 0.3

$$H_0 = \frac{\dot{a}_0}{a_0}$$

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2}$$

Measuring H_0 and q_0 were the primary goals

Observational drivers



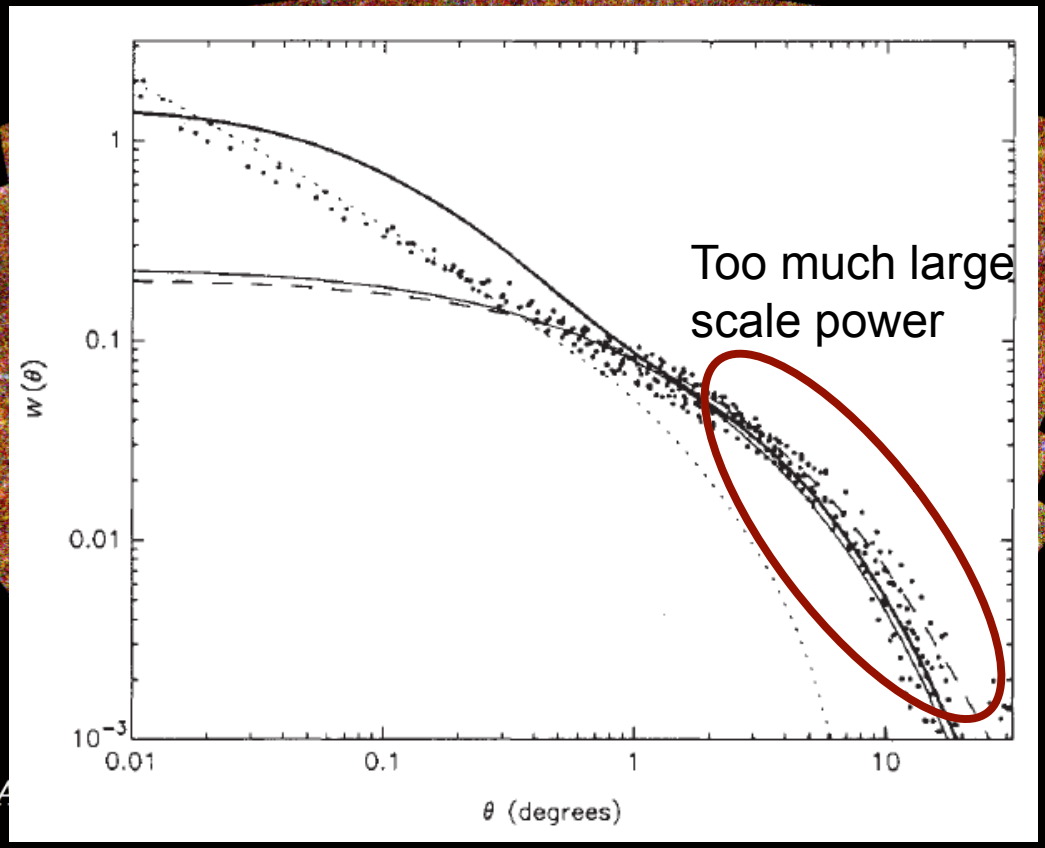
Koo 1990

Deep imaging data from CCDs and photographic plates

Open universe preferred for number counts and cluster abundances

Convolved with number, and luminosity evolution made interpretation complex

Observational drivers



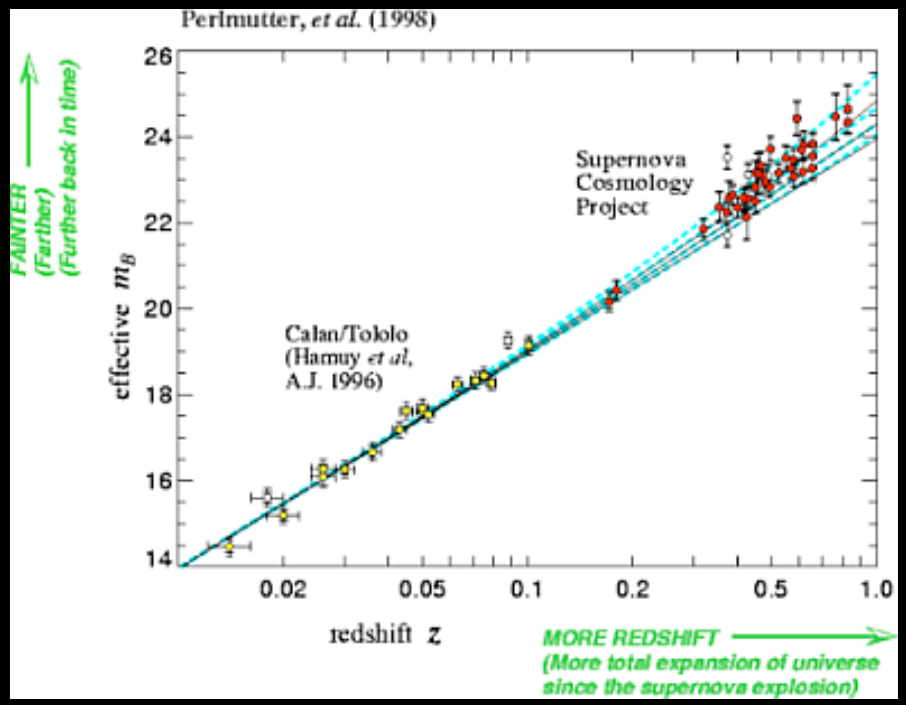
Efstathiou et al 1990

Evidence for Λ

Observations of too much large scale power

Suggests need for dynamically important energy density at late times

Cosmology circa 2000



Type Ia supernovae

- High-z supernova factory
- Supernova Cosmology Project
- SNe at z~0.5 are ~0.25 mag fainter than in an open Universe with same value of Ω_m
- Breakthrough because of the volume of the survey (guarantee follow-up of supernova candidates)
- Enabled by large format CCDs

Cosmology circa 2000

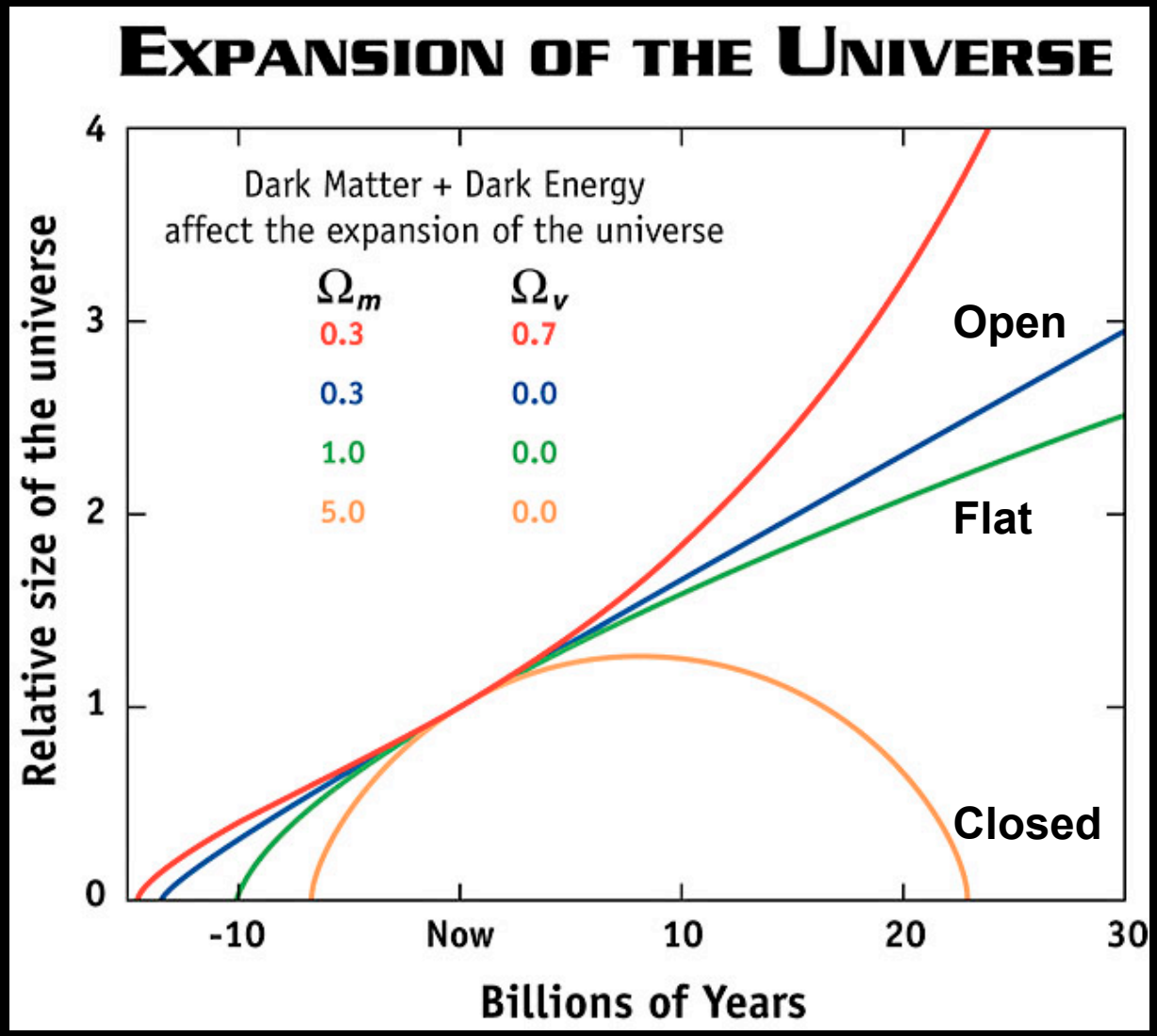
$$\frac{H^2(z)}{H_0^2} = \Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_\Lambda + \left(1-\Omega_0\right)(1+z)^2$$

No longer about geometry it is now about the equation of state of the energy density (w)

$$\Omega(z) = \sum_i \Omega_{i,0} z^{3(1+w_i)}$$

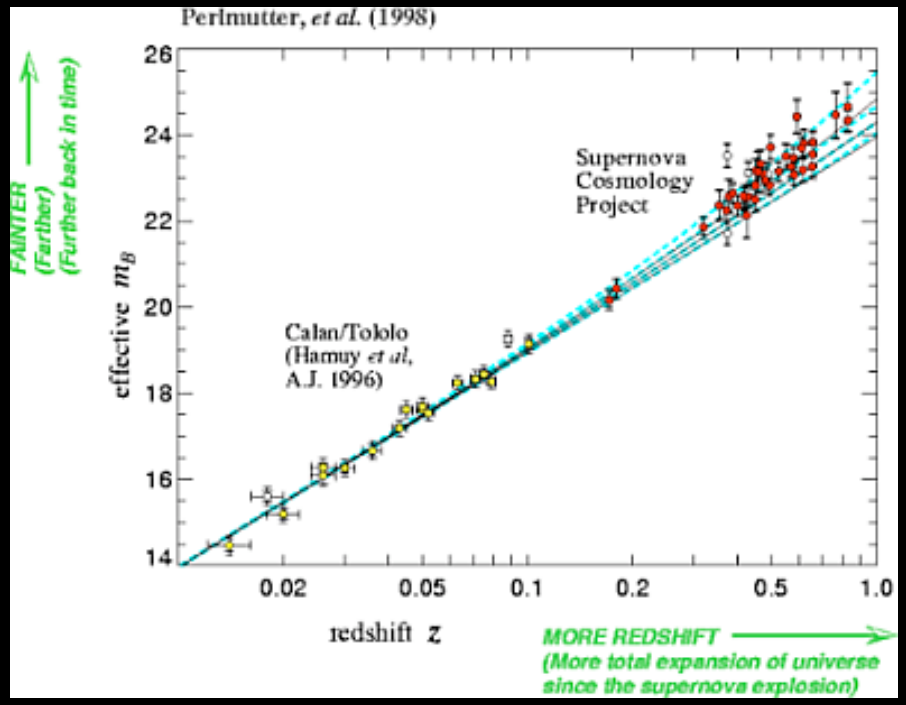
Introduction of precision cosmology (systematics are now a critical issue) and the age of Dark Energy

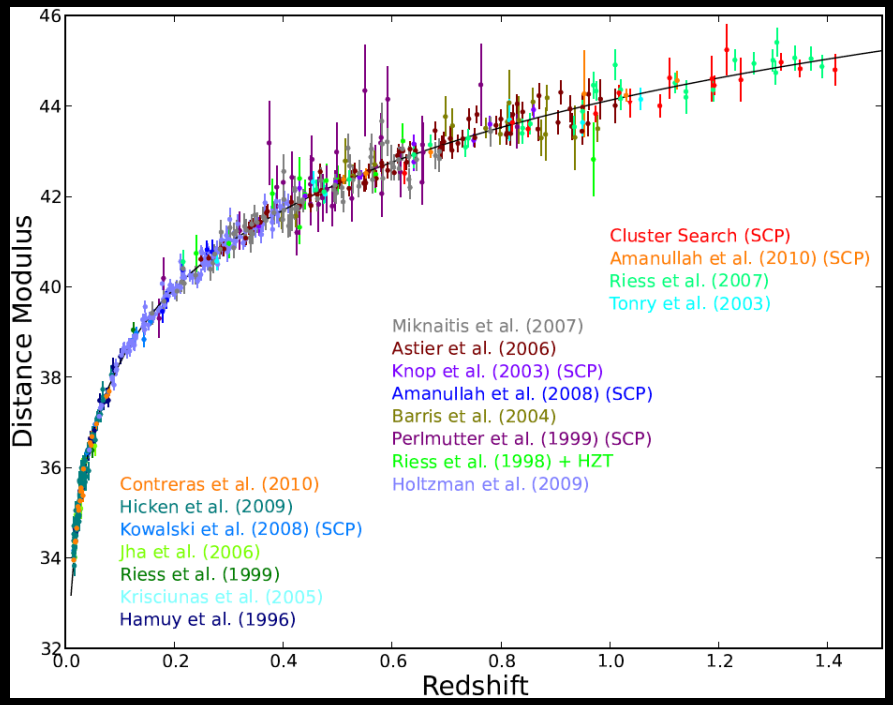
Evolution of a(t) through surveys



WMAP Team

Surveys still don't need to be large

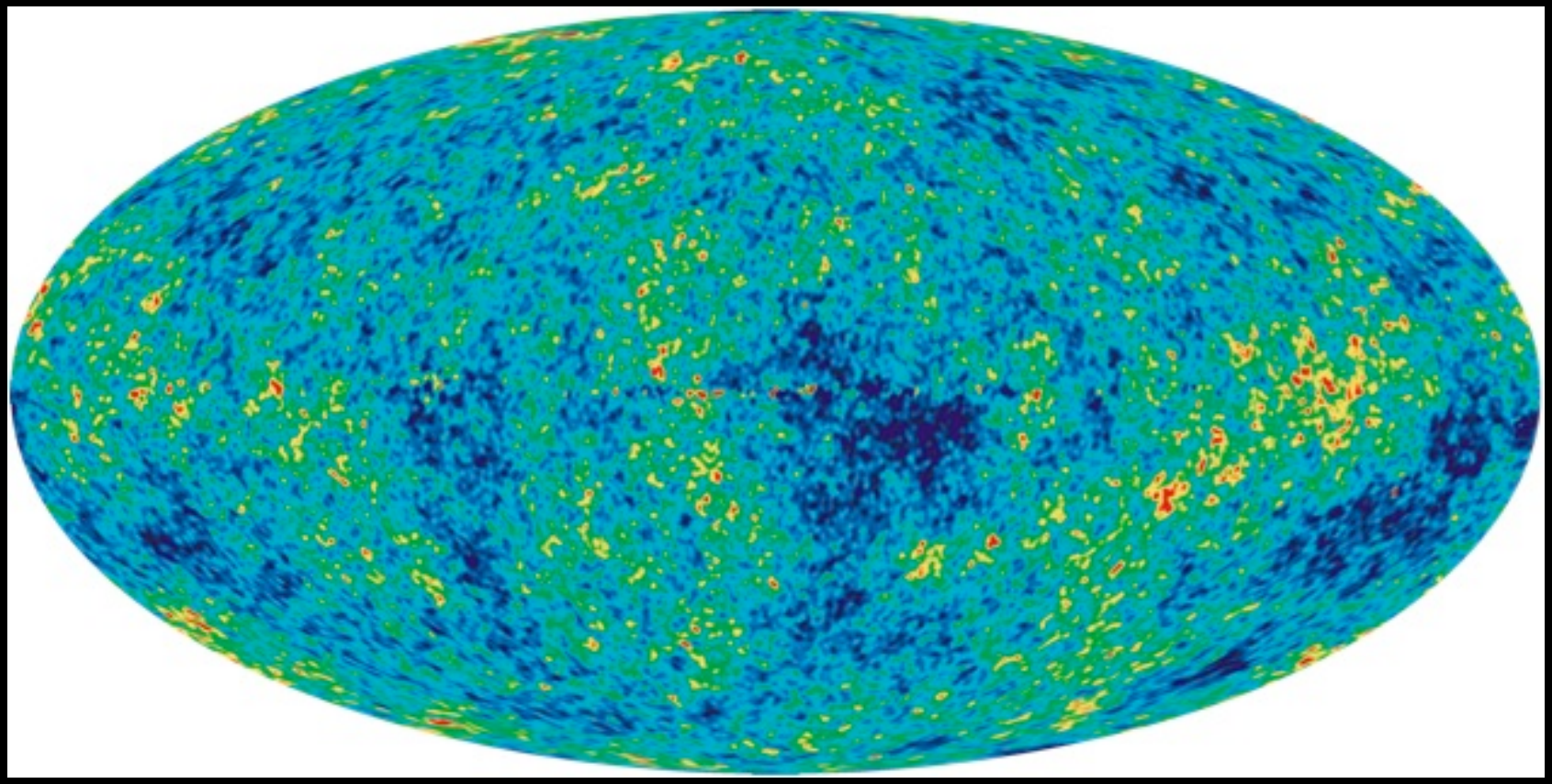




of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is

Perlmutter et al 1999

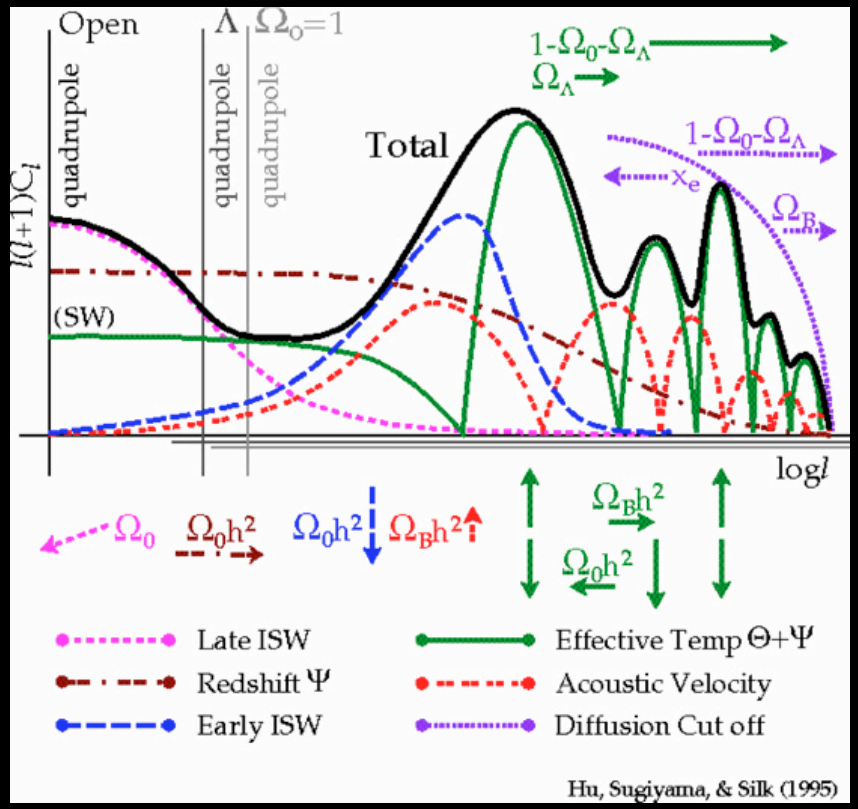
Cosmology circa 2010



Decade of CMB measurements: Boomerang,
Maxima discover the first peak in the CMB power spectrum

WMAP makes exquisite measurements of multiple peaks

Cosmology circa 2010



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

Cosmology circa 2010

WMAP Cosmological Parameters

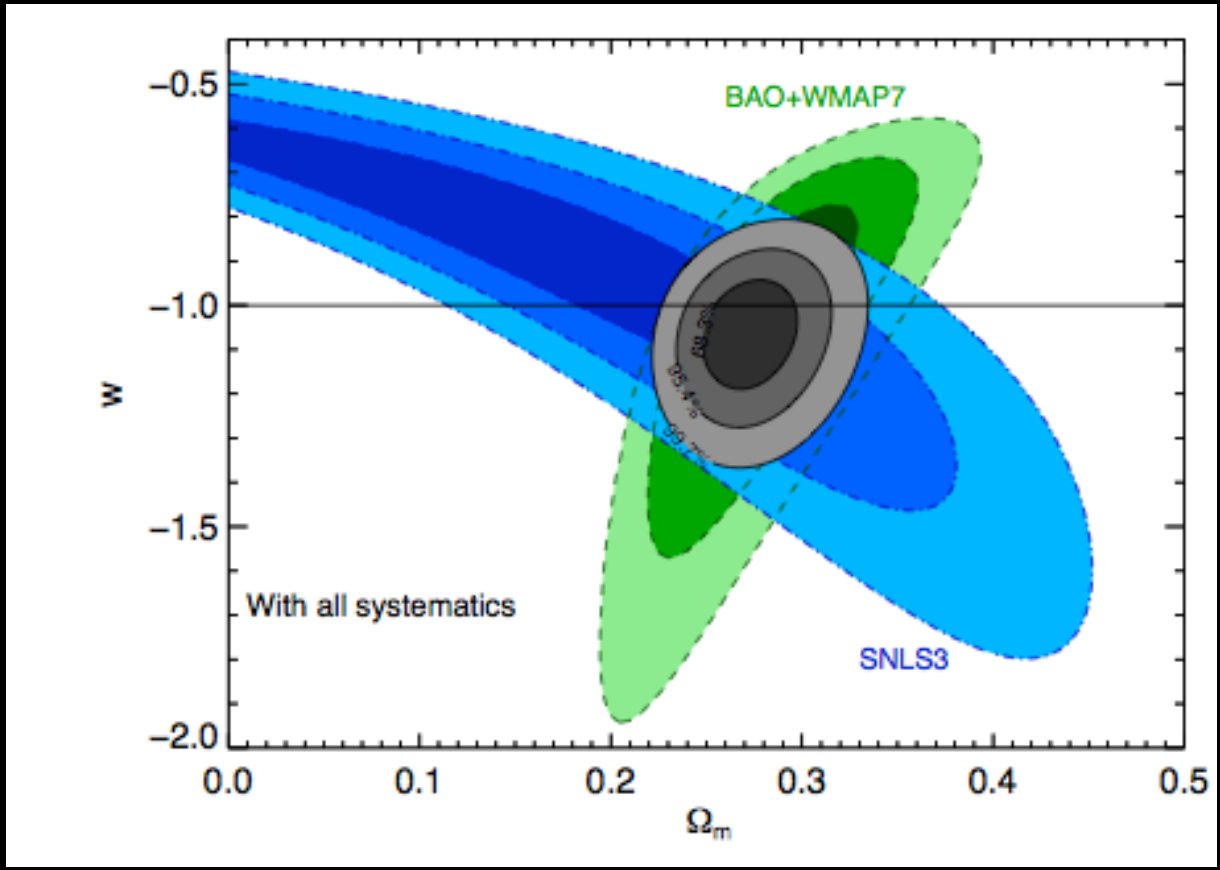
Model: lcdm+sz+lens

Data: wmap7

$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1-n_s$	0.037 ± 0.014
$1-n_s$	$0.0079 < 1-n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z=0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z=0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z=0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	0.5952 ± 0.0016 °	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

WMAP Team

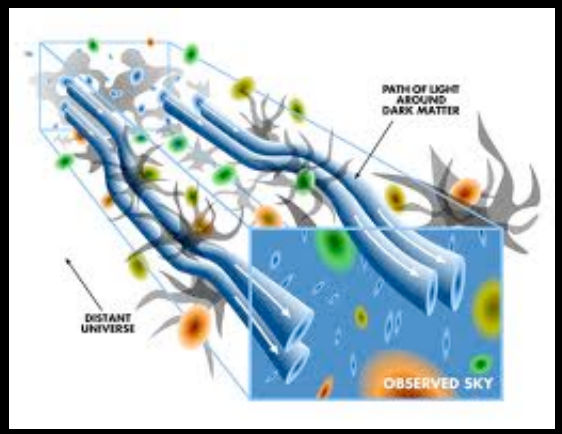
Cosmology circa 2010



Sullivan et al 2011

$$w(a) = w_0 + w_a(1 - a)$$

What are we measuring?



Gravitational weak lensing

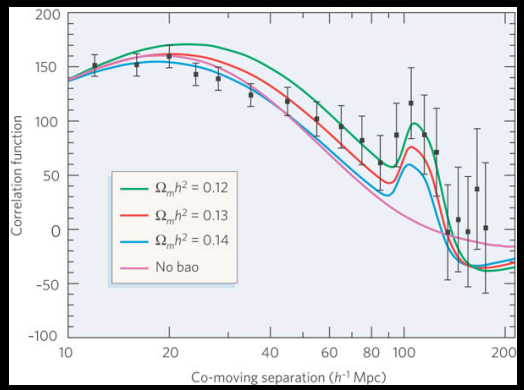
Angular diameter distance

Growth of structure

Clusters of galaxies

Volume element

Growth of structure



Baryon Acoustic oscillations

Angular diameter distance

Supernovae

Luminosity distance

Luminosity Distance

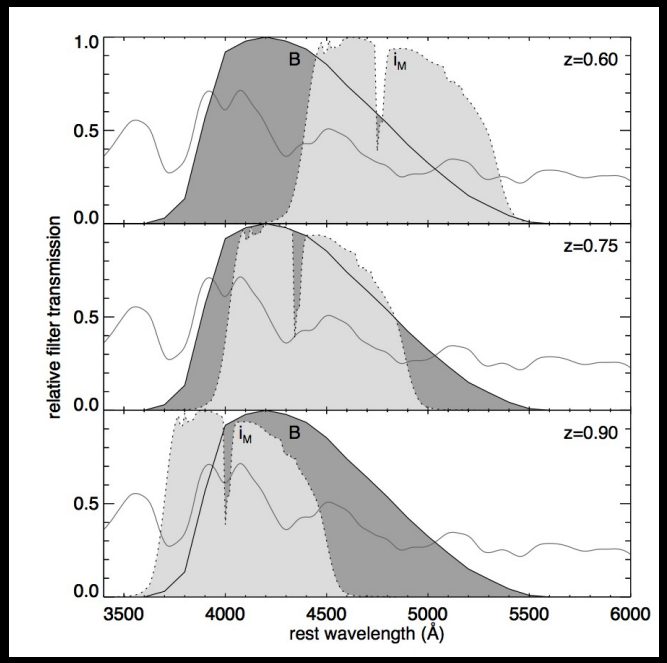
$$f = \frac{L}{4\pi d_L^2} \equiv \frac{L}{4\pi S_k(r)^2(1+z)^2}$$

For a bolometric source, luminosity distance relates the flux and luminosity assuming luminosity is emitted into solid angle dΩ and observed by a detector of a given area

1+z terms arise due to time dilation and redshifting of the photons

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

We rarely measure bolometric measures

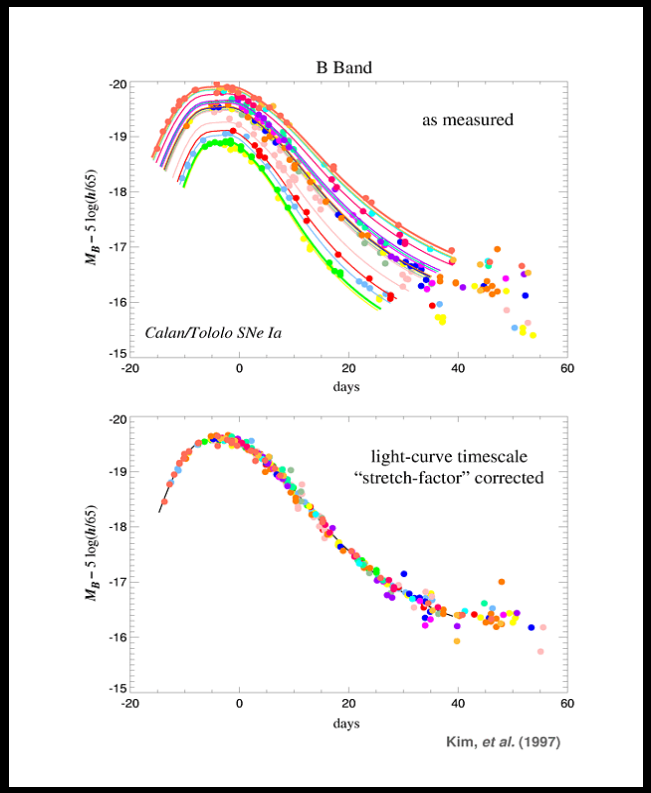


K-corrections

$$K_{QR} = -2.5\,\log_{10}\left[\frac{1}{[1+z]}\,\frac{\int \mathrm{d}\lambda_o\,\lambda_o\,L_\lambda\left(\frac{\lambda_o}{1+z}\right)\,R(\lambda_o)\,\int \mathrm{d}\lambda_e\,\lambda_e\,g_\lambda^Q(\lambda_e)\,Q(\lambda_e)}{\int \mathrm{d}\lambda_o\,\lambda_o\,g_\lambda^R(\lambda_o)\,R(\lambda_o)\,\int \mathrm{d}\lambda_e\,\lambda_e\,L_\lambda(\lambda_e)\,Q(\lambda_e)}\right]$$

Blanton and Roweis 2007

Standard Candles as distance indicators

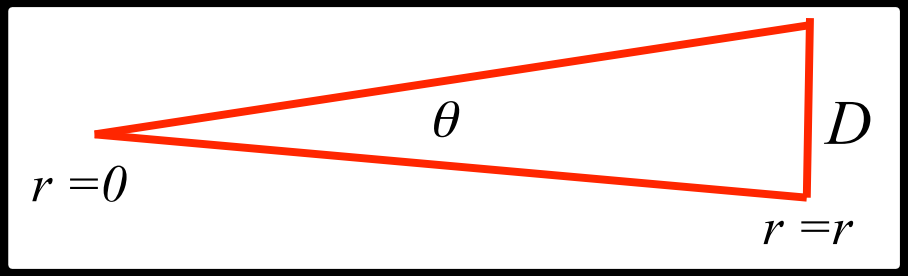


Measurement of the distance modulus

Combines luminosity distance, H_0, K-corrections, extinction, calibration of the photometric properies

$$m_i - M_j = 5\log[H_0 d_L(z,\Omega,w(z))] - 5\log H_0 + K_{ij}(z) + A_i + C$$

Angular Diameter Distance



Distance at which a source of proper size D subtends an angle θ

$$d_A \equiv \frac{D}{\theta} = a(t)S_k(r) = \frac{S_k(r)}{1+z}$$

$$d_A = \frac{d_L}{(1+z)^2}$$

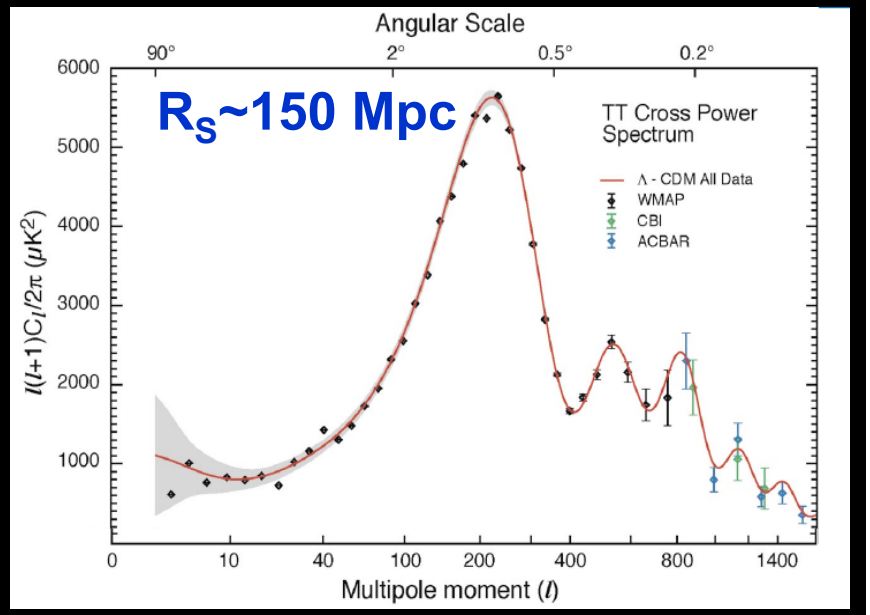
Standard rulers from the CMB onwards

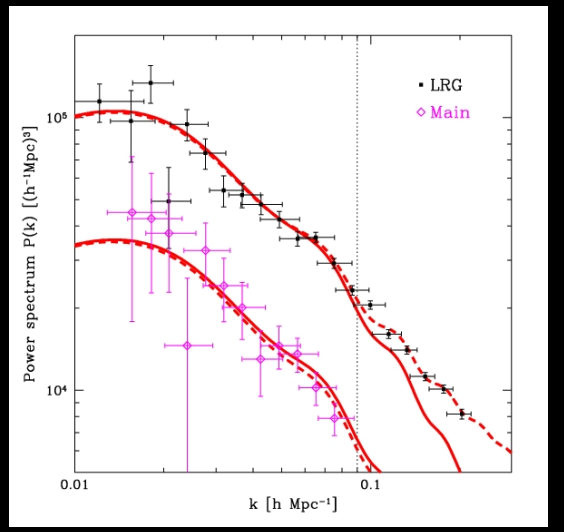
Baryon acoustic oscillations

Coupling between gas and photons in early universe causes perturbations in gas to oscillate as sound waves (travelling 57% of c)

Decoupling causes sound speed to plummet and waves stall at a radius of ~150Mpc

Overdensities imprinted on these scales



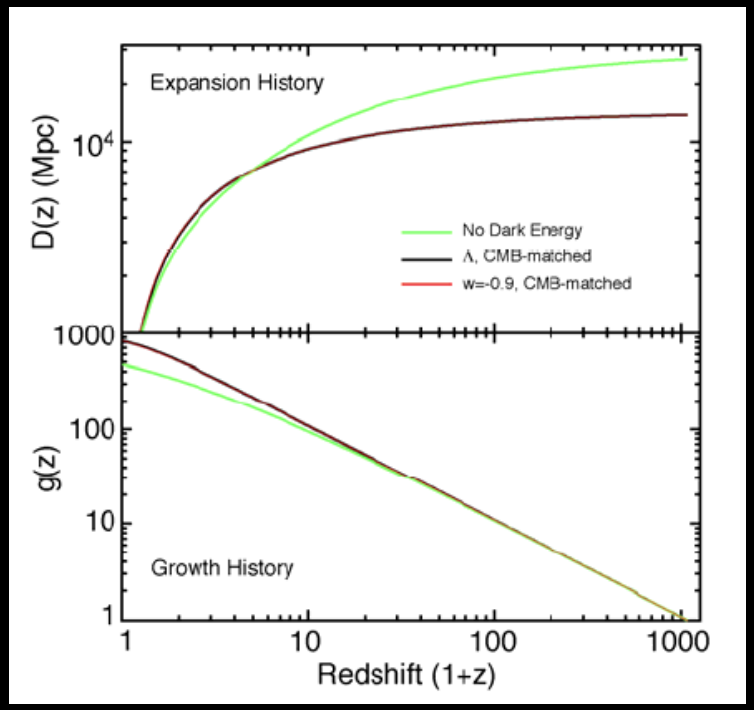


Eisenstein et al 2005

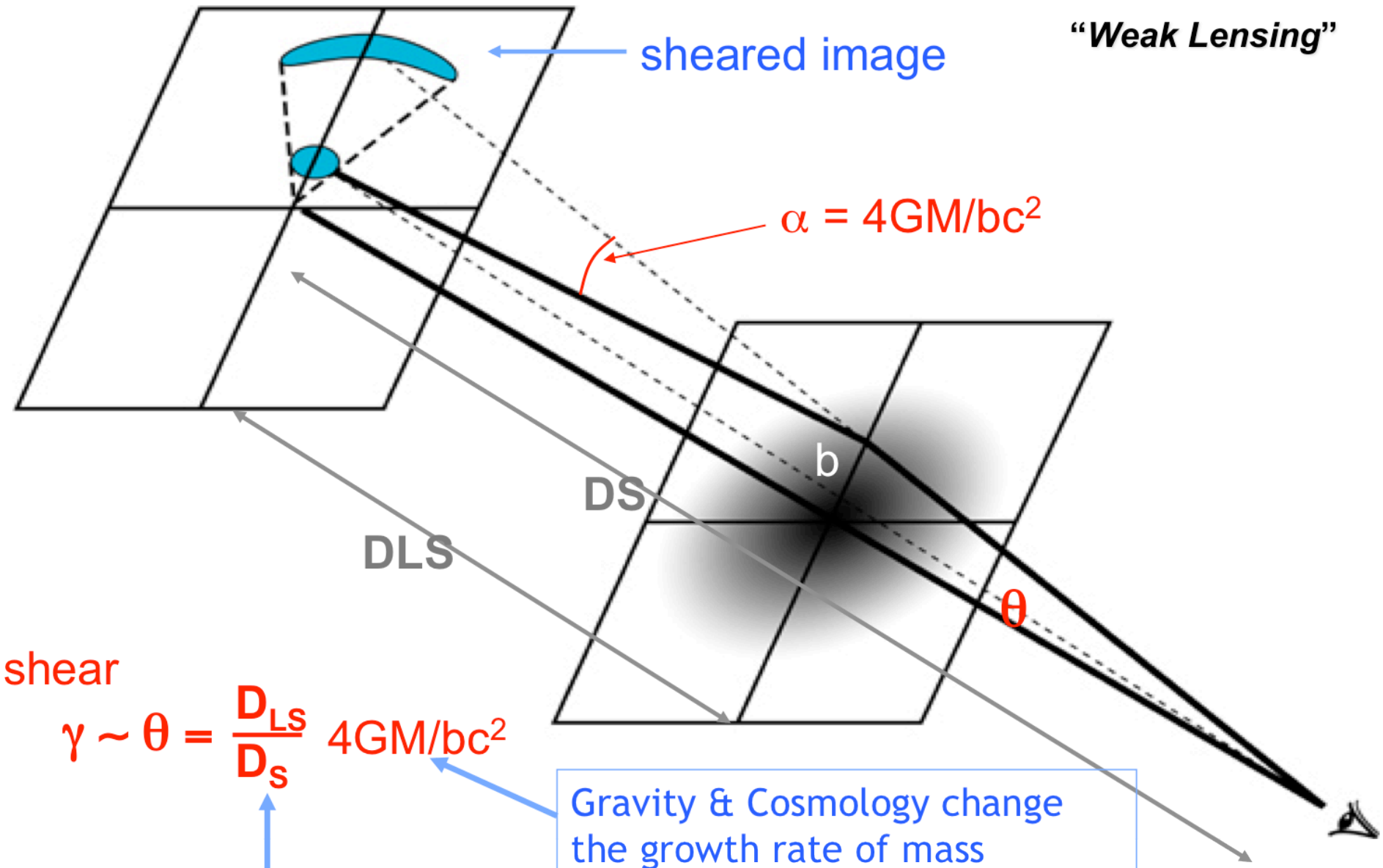
Evolution of the growth factor

$$\ddot{g} + 2H\dot{g} = \frac{3\Omega_m H_0^2}{2a^3} g$$

Expansion and growth of perturbations compete (expansion retards the exponential growth of overdensities)



Albrecht et al 2005



"*Weak Lensing*"

shear

$$\gamma \sim \theta = \frac{D_{LS}}{D_S} 4GM/bc^2$$

Gravity & Cosmology change the growth rate of mass structure

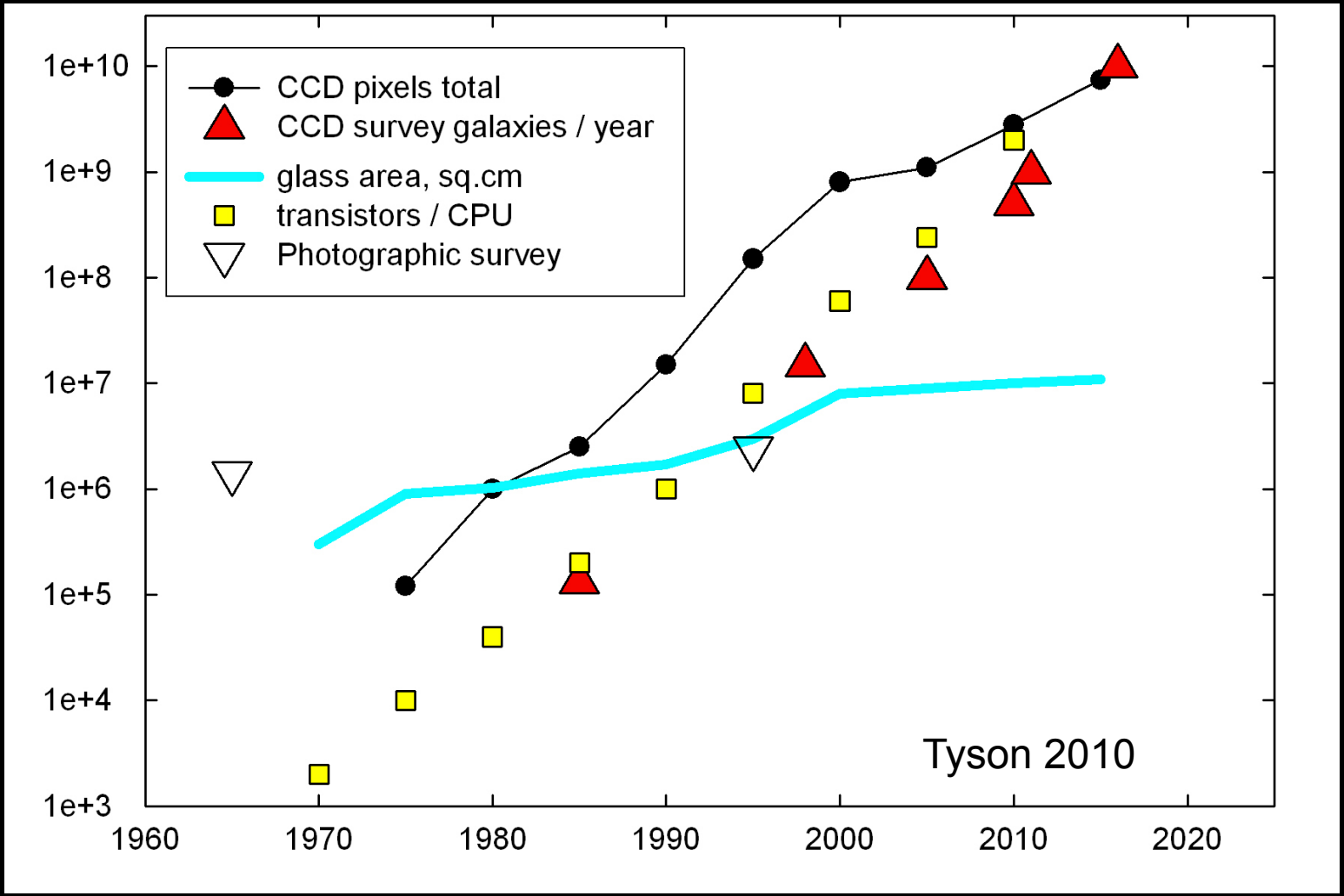
Cosmology changes geometric distance factors

Slide from G. Bernstein

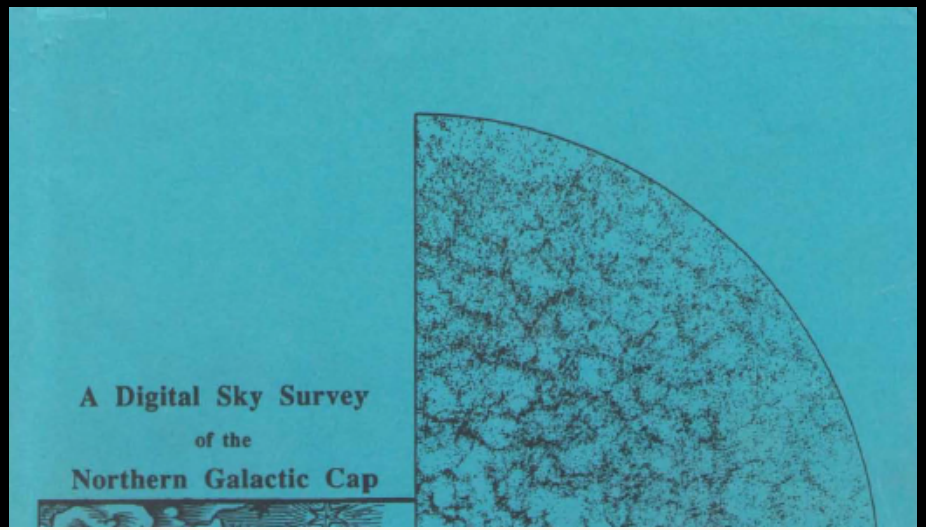
What should we take away?

- Introduced the multiple ways we will measure cosmological parameters in the next generation of surveys
- Seen how these measures will be dominated by calibration and systematics
  - Extinction (internal and Galactic)
  - Photometric zeropoints
  - Knowing the system response of the experiment
- Question becomes, what surveys do we need to characterize cosmology and how will we control their errors

Much of the progress in cosmology has been driven by surveys



Surveys are not always what they seem…



i. Proposal Abstract

This proposal describes a project which will produce a detailed digital photometric map of half the northern sky to about 23rd magnitude. This map will be used to select about a million galaxies and 100,000 quasars for which high-resolution spectra will be obtained with the same wide-field special-purpose telescope. The imaging survey will also be used to produce a catalog in four colors of all the detected objects, about 10^8 galaxies and a similar number of stars, and a million quasar candidates. The survey telescope will take about four years to build and test; the survey will then be completed over a five-year period.

The imaging data will be assembled into a high-resolution atlas of detected objects and a lower resolution map of the whole area and those two data sets and the spectra will be published in digital form and made available in a timely fashion to the entire community.

The survey will cost about $25M to complete, plus about 50 FTE-years of contributed faculty time. The funding and supporting institutions will commit $12.7M to the project. We therefore seek outside funding for a total of $12M, just under half the total cost for capital and operations.

Goals of the SDSS (1992)

- Large Scale Structure (5 pages)
  - Topology
  - Two point correlation function
- Clusters of galaxies (7 pages)
  - Topology
  - Cluster counts
- Galaxies (25 pages)
  - Luminosity functions, Low Surface Brightness Galaxies, Morphological properties
- QSOs (11 pages)
  - QSO selection, high redshift clustering,
- Stars (5 pages)
  - Halo stars, variables, proper motions, supernovae

SDSS Impact in terms of citation

- **"Cosmological parameters from SDSS and WMAP"**
  Tegmark et al 2004 1769 citations

- **"Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies"**
  Eisenstein et al 2005 1414 citations

- **"The Three-Dimensional Power Spectrum of Galaxies from the Sloan Digital Sky Survey"**
  Tegmark et al 2004 912 citations

- **"The Origin of the Mass-Metallicity Relation: Insights from 53,000 Star-forming Galaxies in the Sloan Digital Sky Survey"**
  Tremonti et al 2004 856 citations

- **"Composite Quasar Spectra from the Sloan Digital Sky Survey"**
  Vanden Berk et al 2001 619 citations

What drives survey design

- Statistical uncertainties
  - Shot noise: drives large n
  - Sample variance: drives large V
- Systematic errors
  - Absolute calibration: drives multiple visits (photometricity)
  - Relative calibration: drives offset pointings (reproducability)
- Analysis efficiency
  - Large n: drives compute resources
  - Complexity is the real challenge
- Theoretical considerations
  - Simulations exceed the volumes of galaxy surveys and have all of the same computational challenges