Distances in cosmology

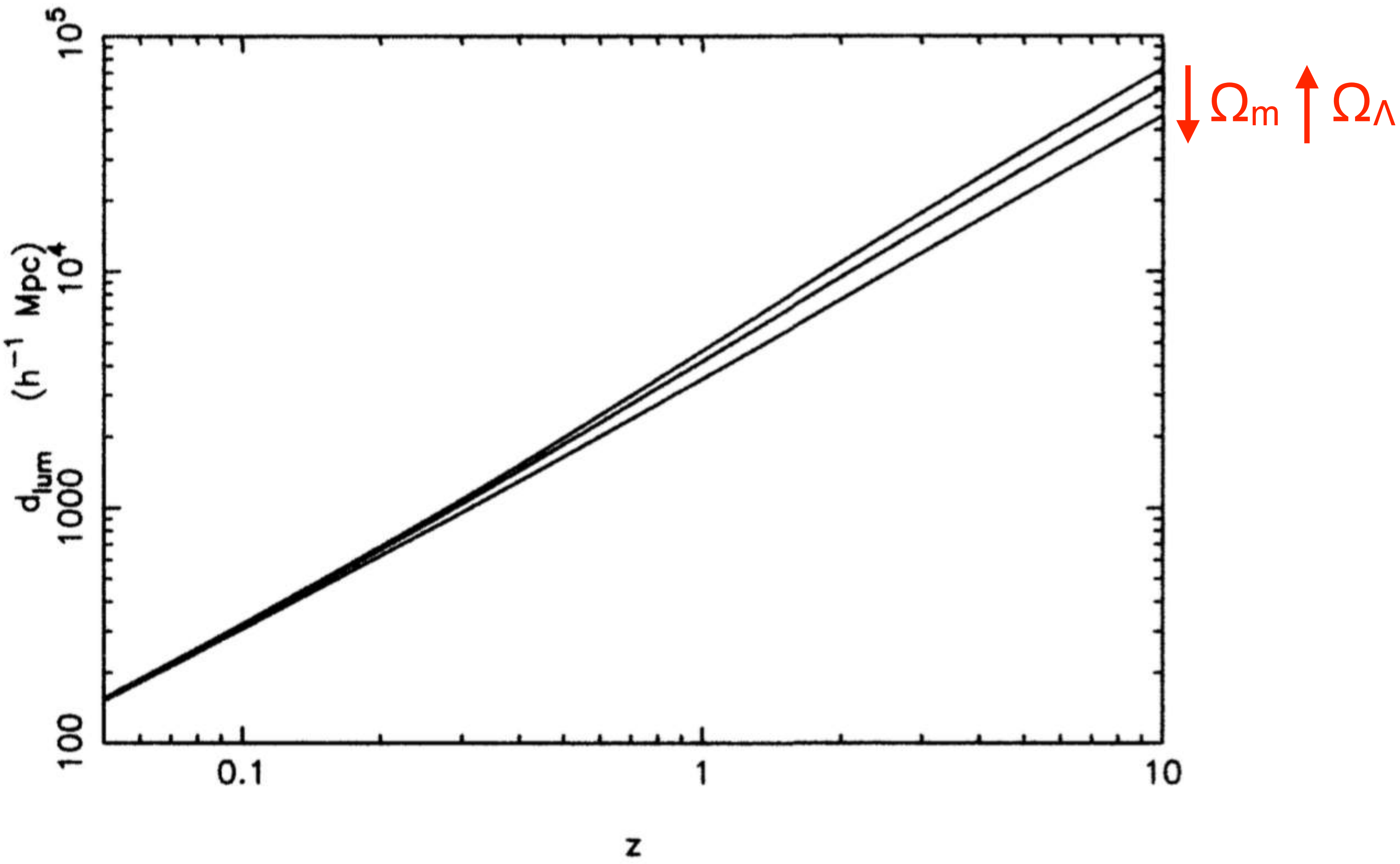


Figure A2.3 The luminosity distance as a function of redshift is plotted for three different spatially-flat cosmologies with a cosmological constant. From bottom to top, the lines are $\Omega_0 = 1, 0.5$ and 0.3 respectively. Notice how weak the dependence on cosmology is even to high redshift. It turns out that open Universe models with no cosmological constant have an even weaker dependence.

$(\Omega_0 = \Omega_{\mathrm{m},0})$

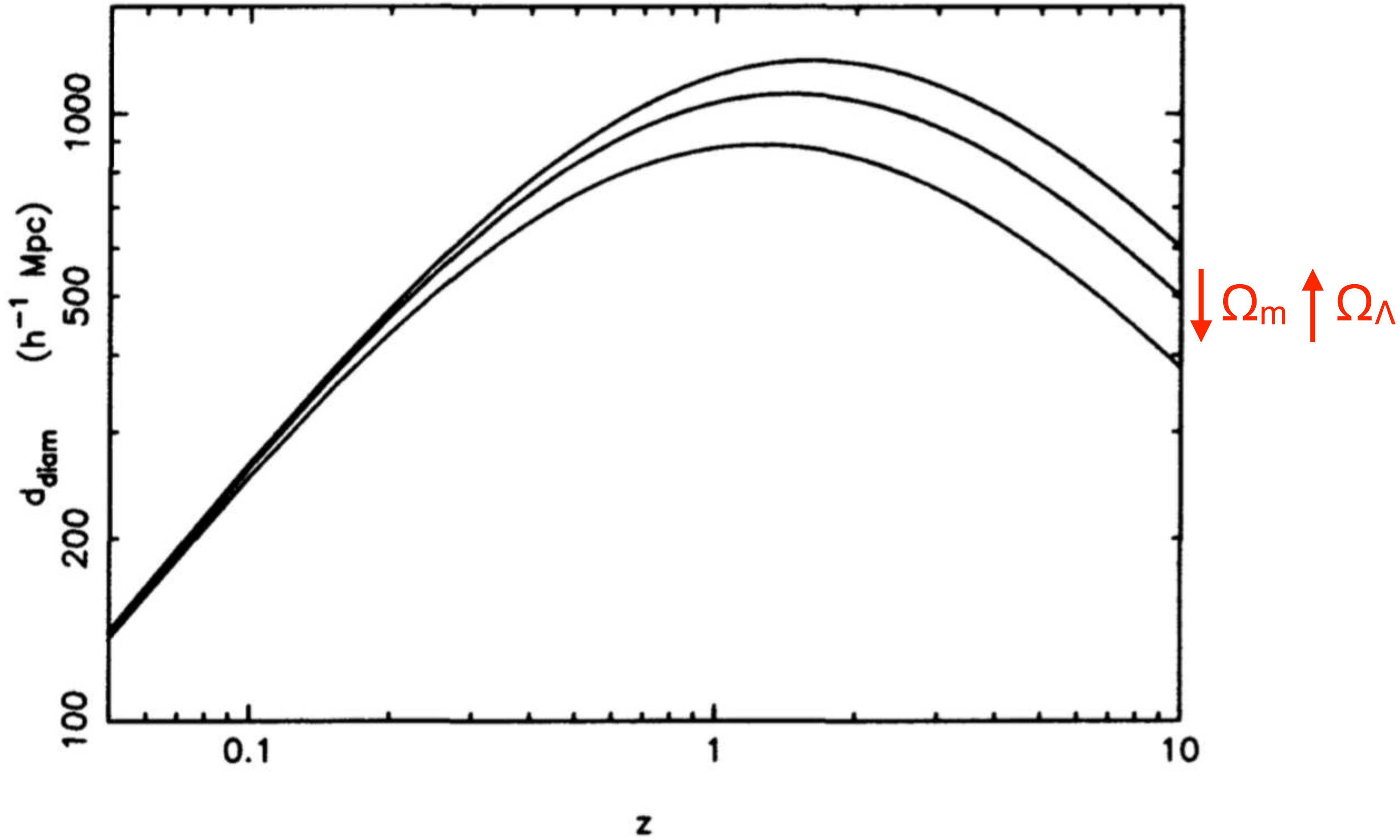


Figure A2.5 The angular diameter distance as a function of redshift is plotted for three different spatially-flat cosmologies with a cosmological constant. From bottom to top, the lines are $\Omega_0 = 1$, 0.5 and 0.3 respectively. For nearby objects $d_{\rm diam}$ and $d_{\rm lum}$ are very similar, but at large redshifts the angular diameter distance begins to decrease.

$(\Omega_0 = \Omega_{\rm m,0})$

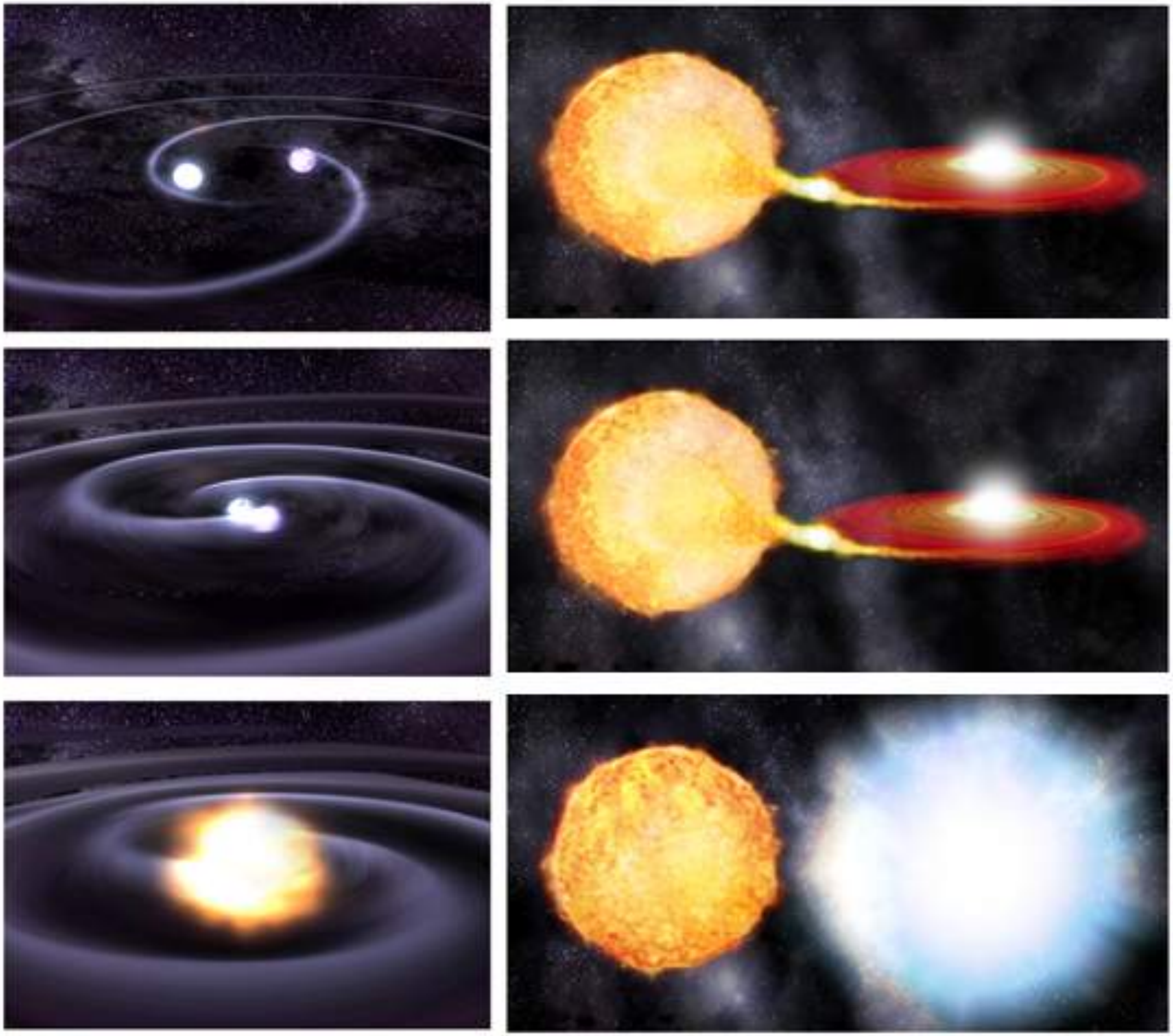
Evidence for cosmic acceleration from Type Ia SNe

Type Ia supernovae

- Observationally, SNe with no hydrogen lines in their spectrum
- Believed to occur when a white dwarf accretes material and exceeds the Chandrasekhar mass ~1.4 M_{sun}
  - single degenerate: ordinary star dumps material onto WD companion
  - double degenerate: two WDs merge

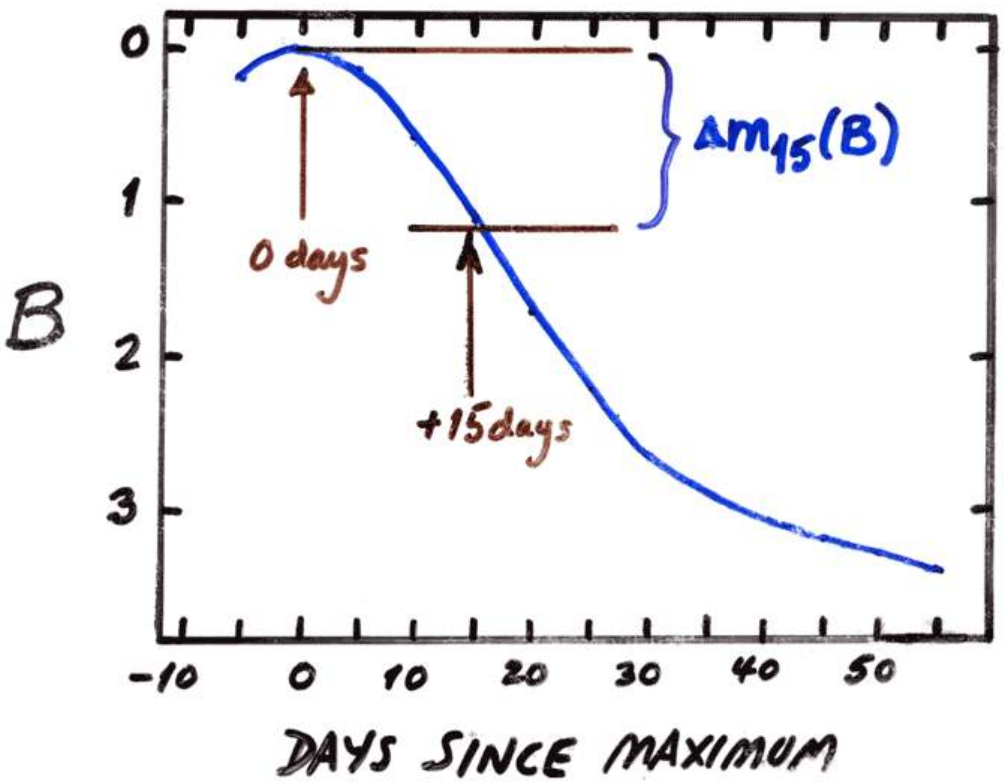
Type Ia SN in ‘Pinwheel' M101 galaxy

Double and single degenerate Type Ia scenarios



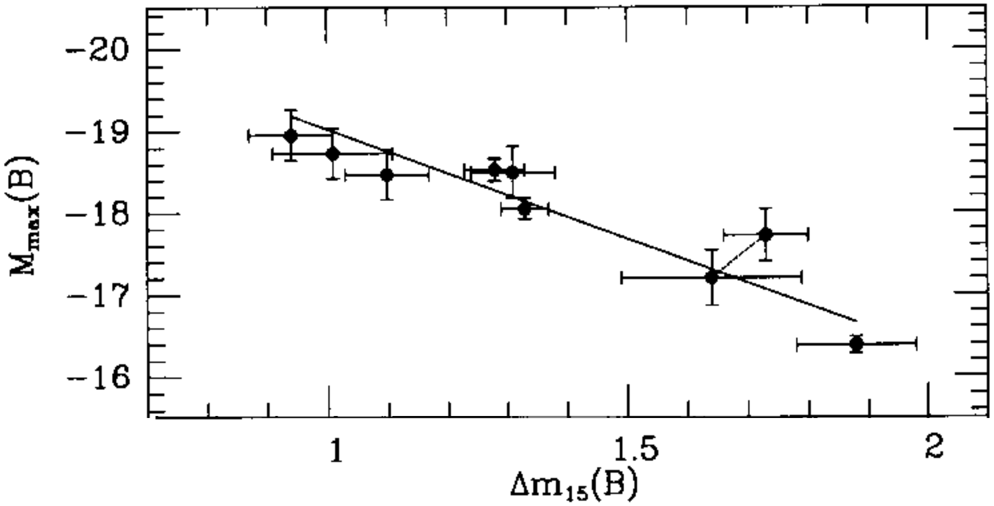
Type Ia supernovae as standard(izable) candles

- Shape of Type Ia light curves correlates tightly with peak absolute luminosity



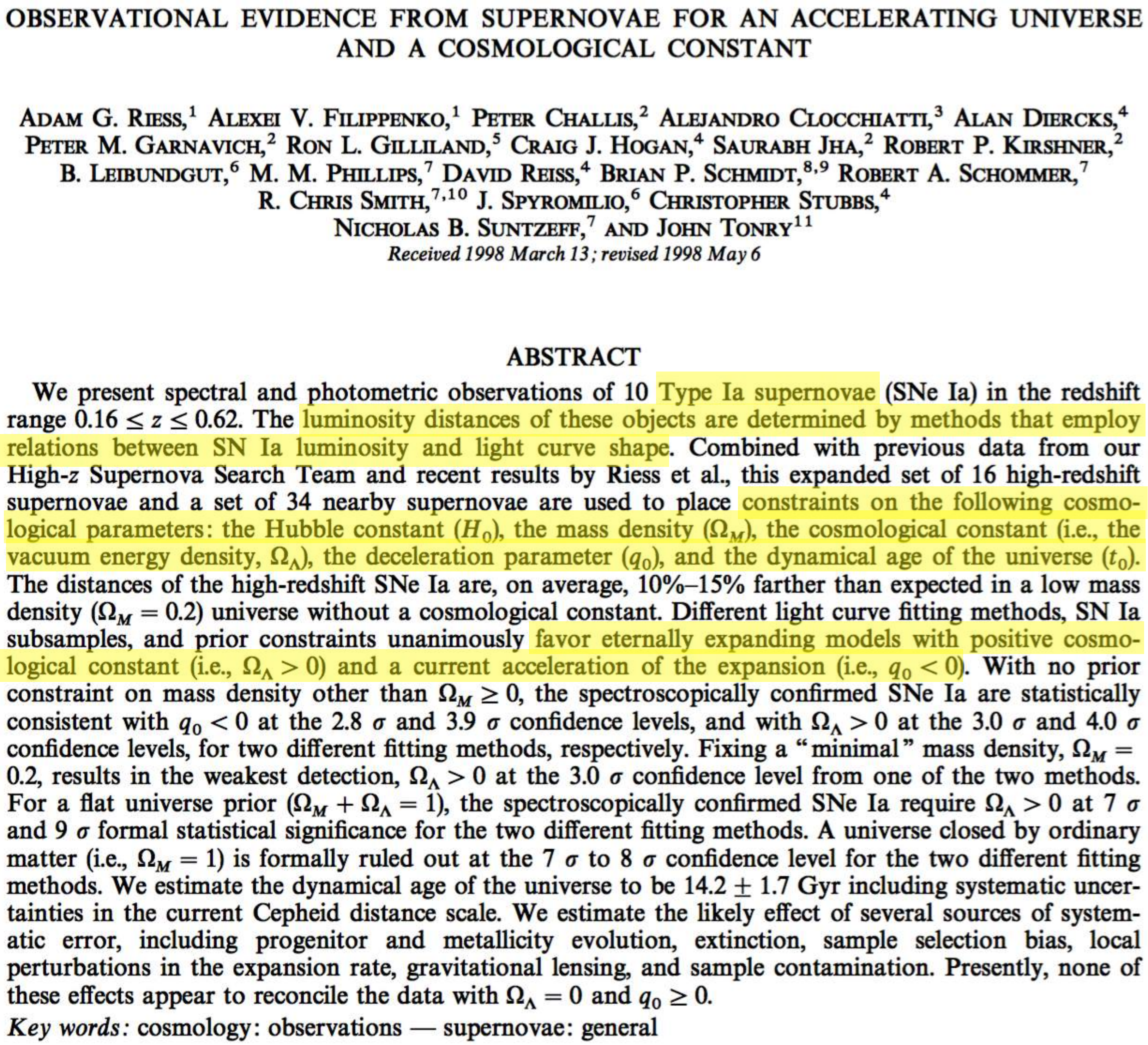
Absolute *B*-band mag.

- Phillips relation: most luminous Ia's have slower decline in first 15 days



Peak *B*-band mag.

Phillips 1993



OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2]
B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
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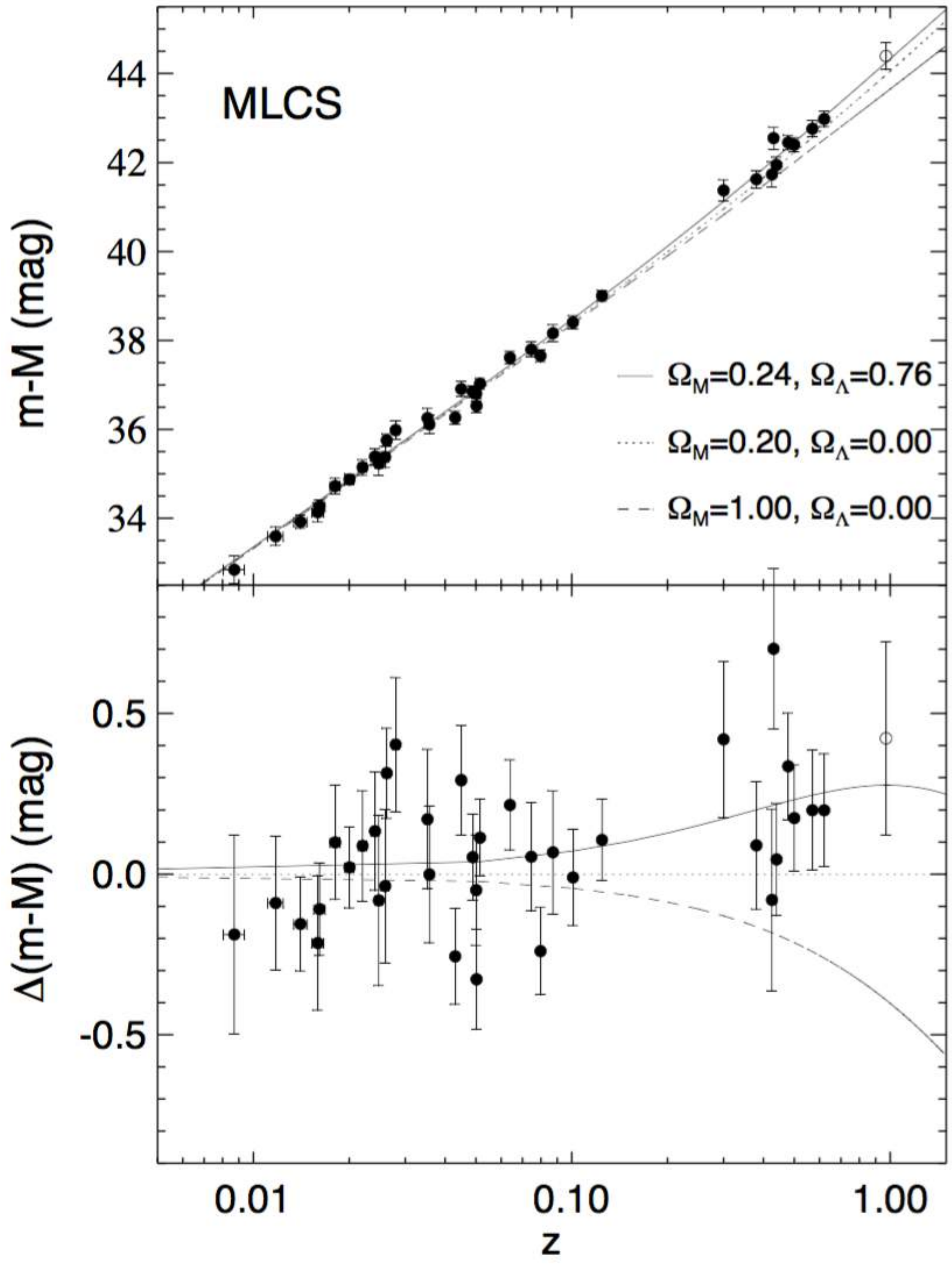
ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

parallel analysis by Perlmutter+99

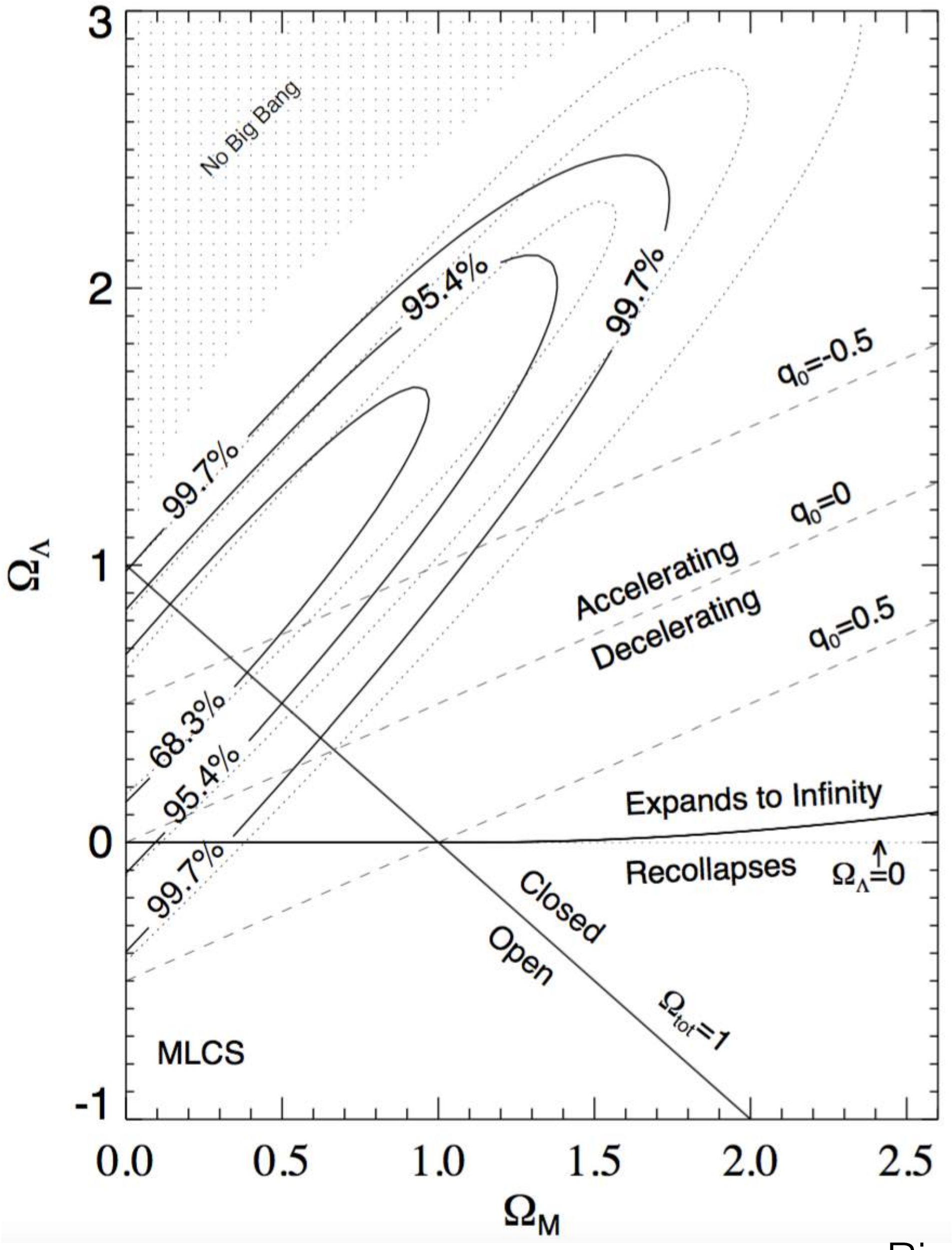
Based on high-redshift Type Ia Hubble diagram



Distance modulus=
5 log(d_{lum}/pc)-5

Riess+98 (see also Perlmutter+99)

Joint constraints on matter and cosmological constant densities from 1998 Type Ia supernovae



Riess+98 (see also Perlmutter+99)

The Nobel Prize in Physics 2011

Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

Photo: U. Montan

Brian P. Schmidt

Prize share: 1/4

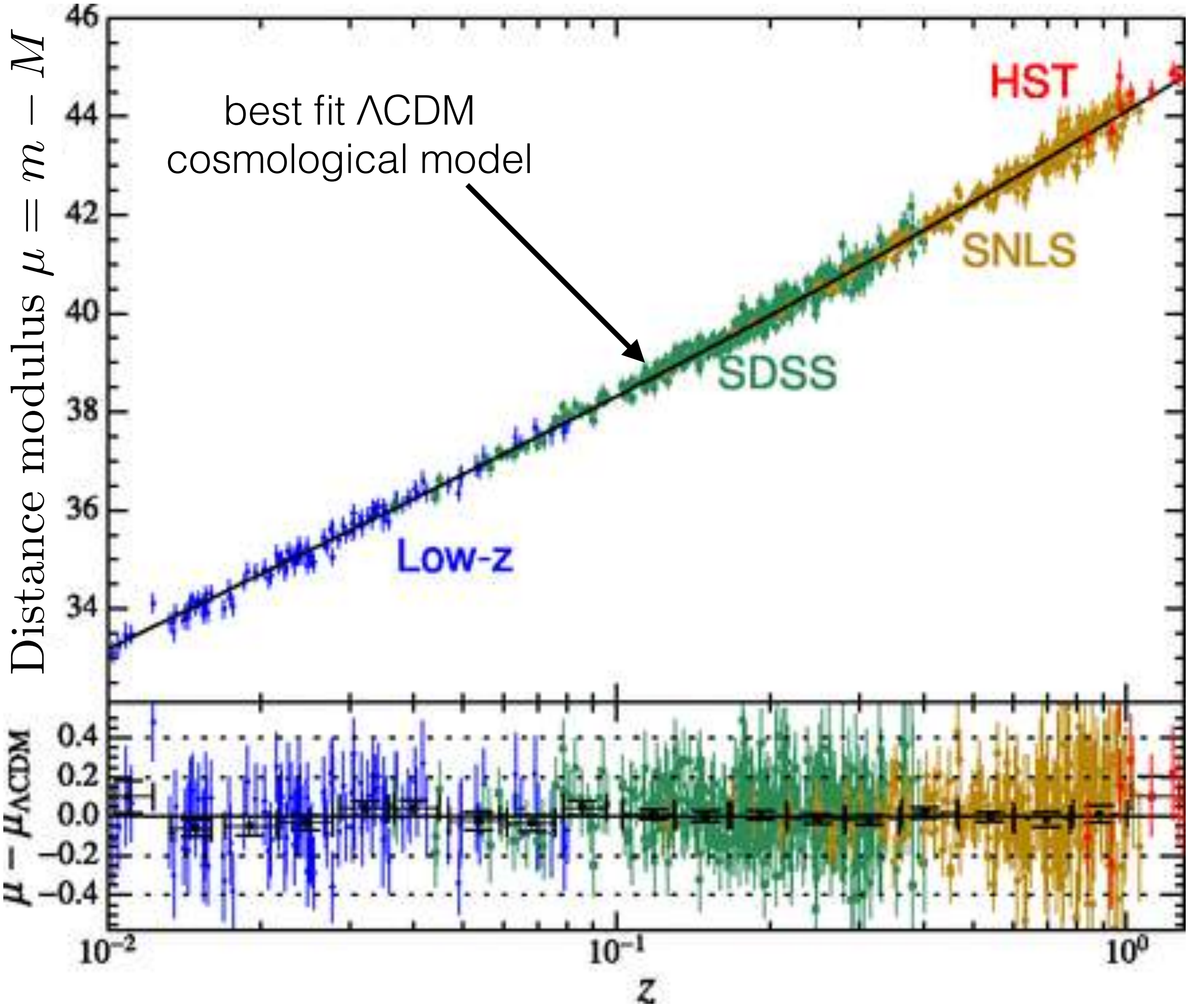
Photo: U. Montan

Adam G. Riess

Prize share: 1/4

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

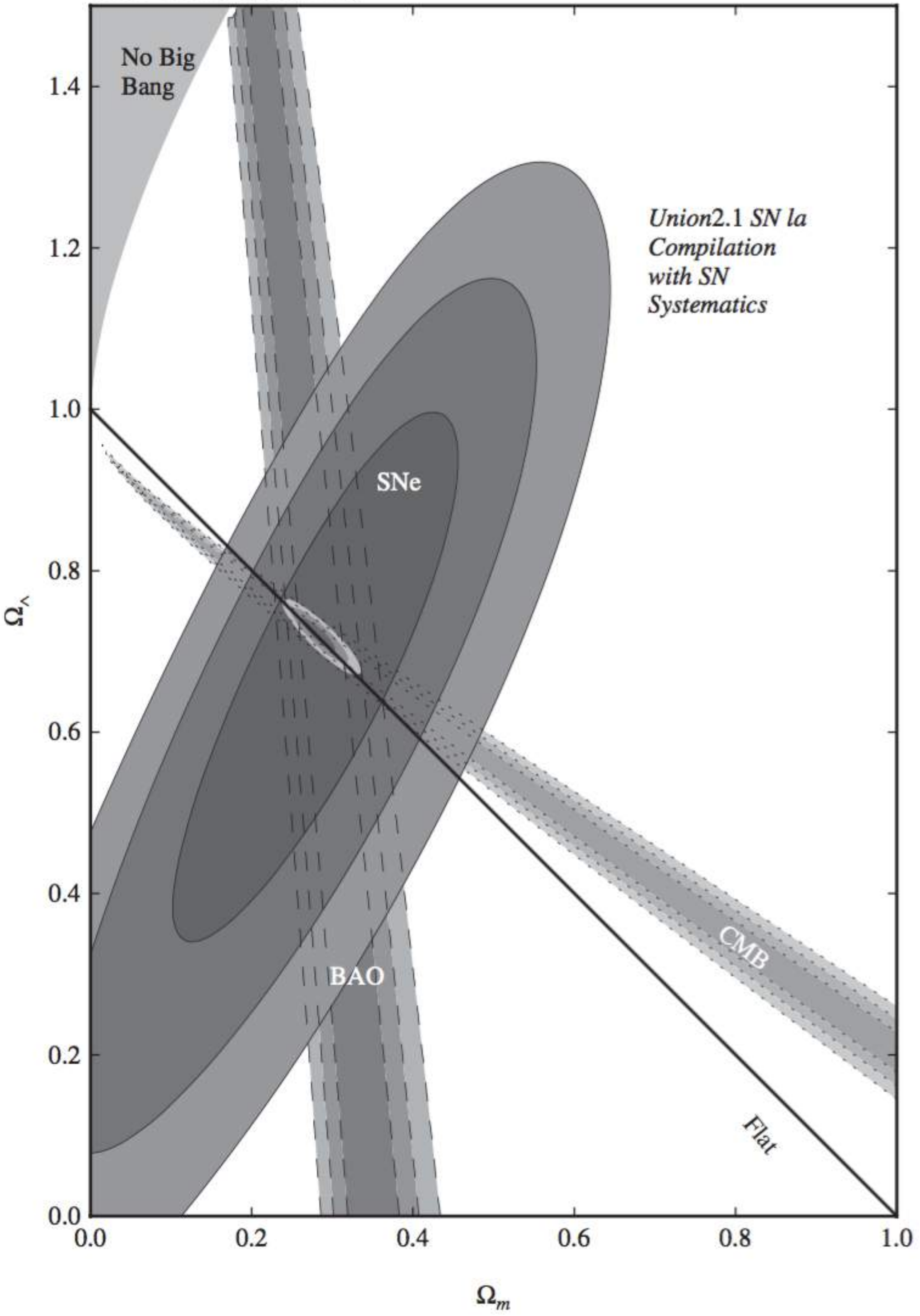
More recent SN Ia Hubble diagram



Betoule+14

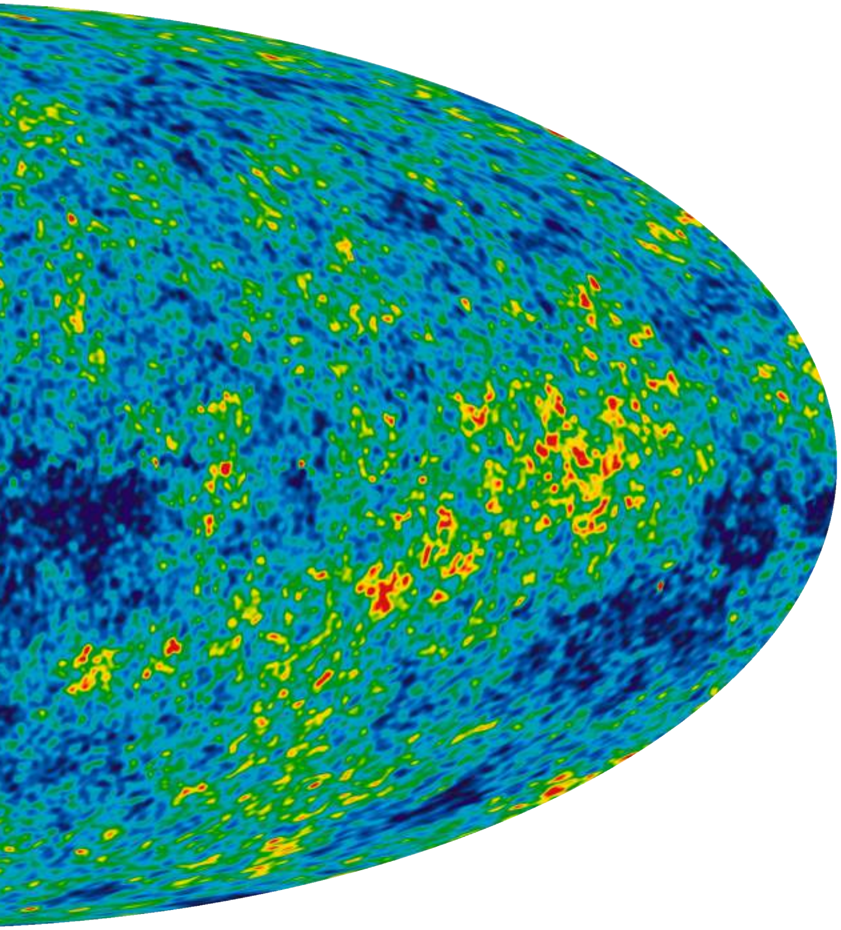
More recent joint constraints, combining SNe with complementary CMB and baryonic acoustic oscillation (BOA) data

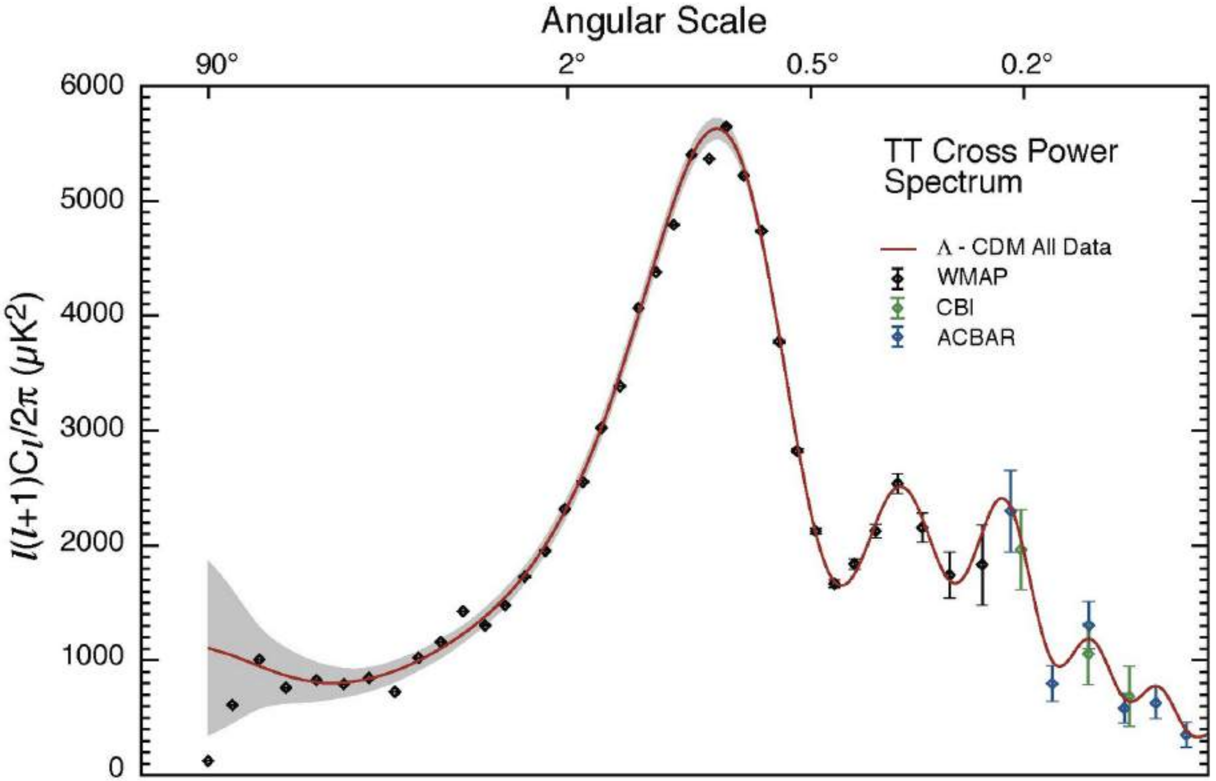
Supernova Cosmology Project
Suzuki et al., *Ap.J.* (2011)



Preview:
Using standard rulers for constraining cosmological parameters

CMB fluctuations have characteristic physical/angular scale — sound waves in early photon-baryon plasma

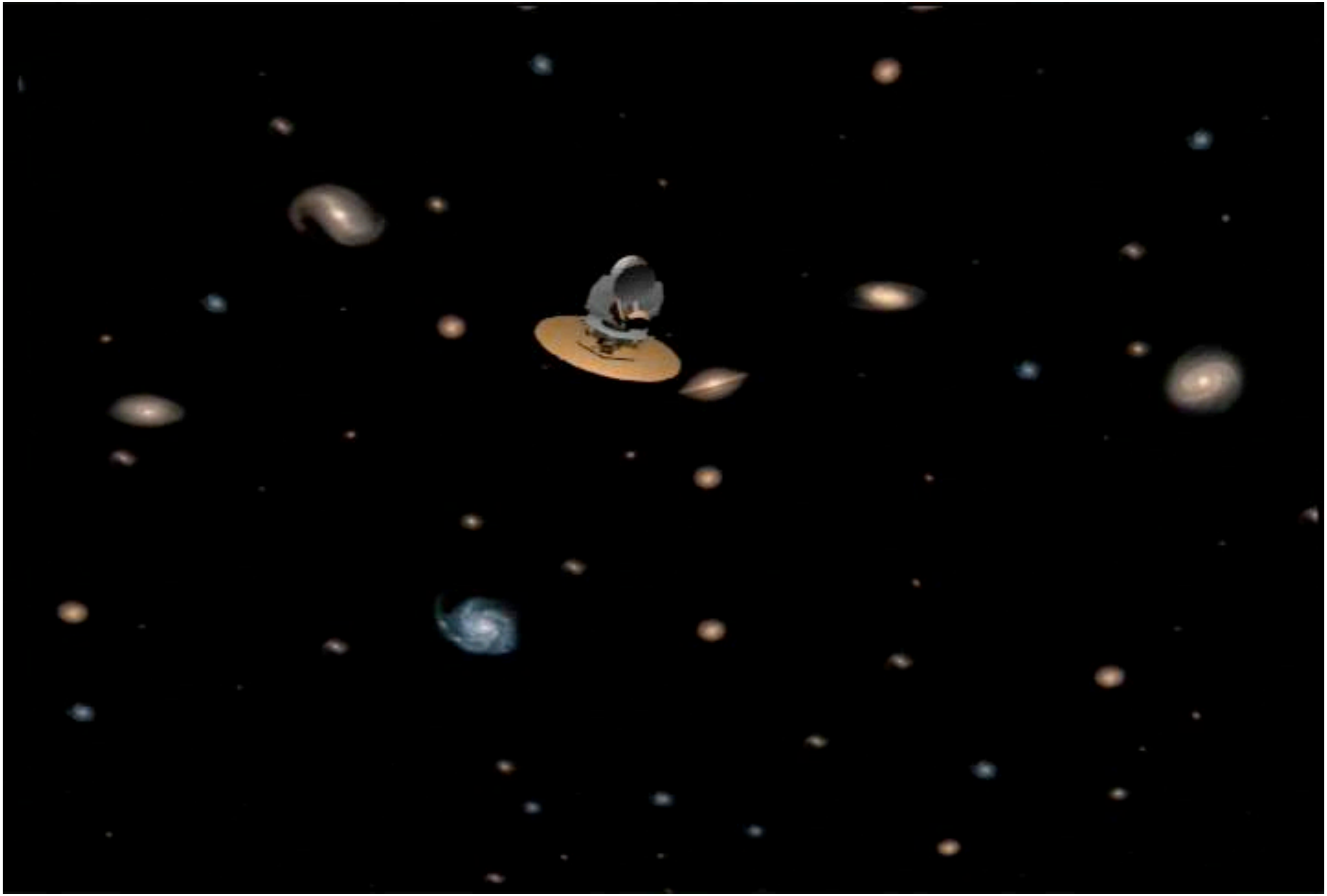




CMB power spectrum

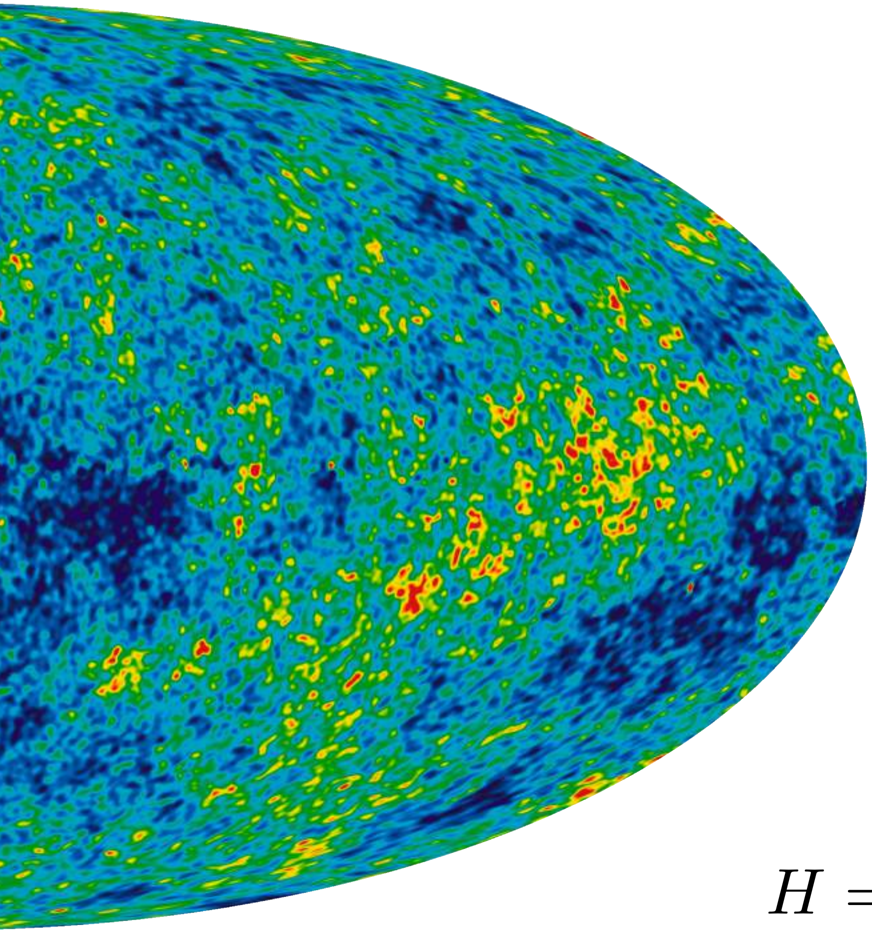
WMAP

Angular diameter distance constrains cosmic geometry



WMAP video

More details on measuring geometry using the CMB



From theory of CMB formation, know intrinsic physical size *l* and redshift *z* of anisotropies

Observations measure angular size *Θ*

→ solve for angular diameter distance

$$d_{\mathrm{A}}(z) = \frac{l}{\theta} = \frac{S_k(d_{\mathrm{com}}(z))}{1+z}$$

$$d_{\mathrm{com}}(z) = \int_{1/(1+z)}^{1} \frac{c\,da}{Ha^2}$$

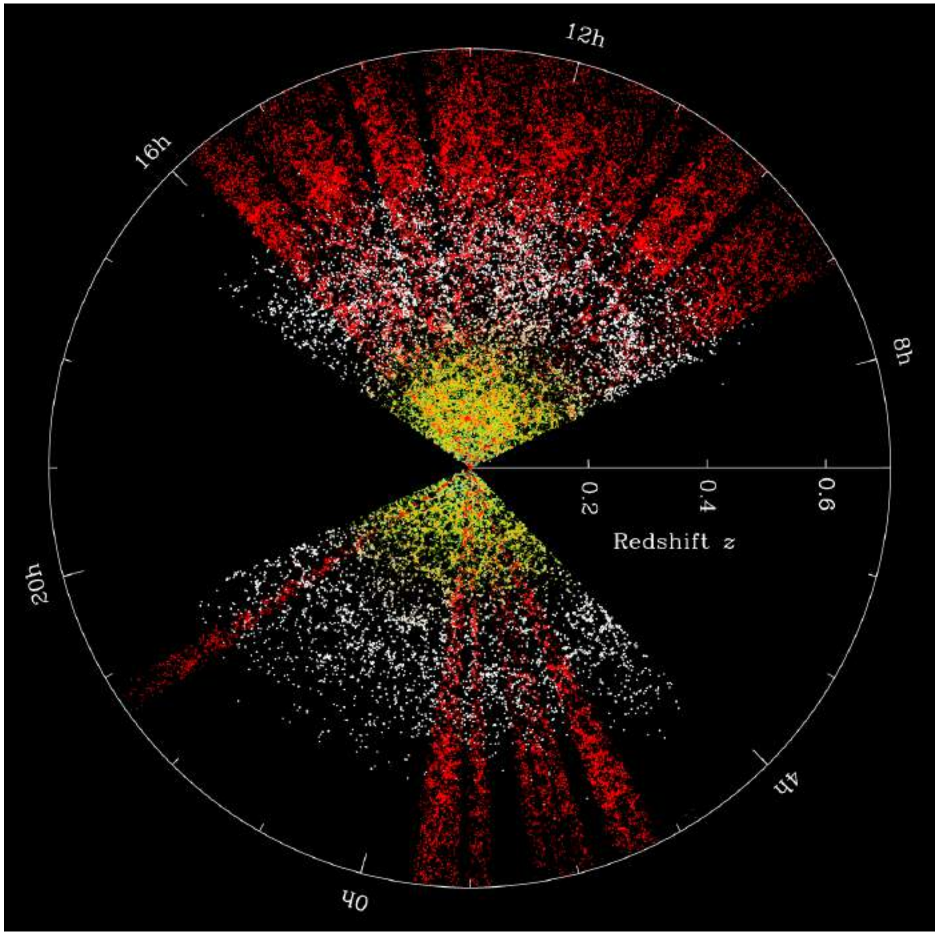
$$H = H_0(\Omega_{\mathrm{m}}a^{-3} + \Omega_\Lambda + \Omega_{\mathrm{rad}}a^{-4} + \Omega_k a^{-2})^{1/2}$$

Ω_{rad} accurately known from measurements of the CMB blackbody temperature

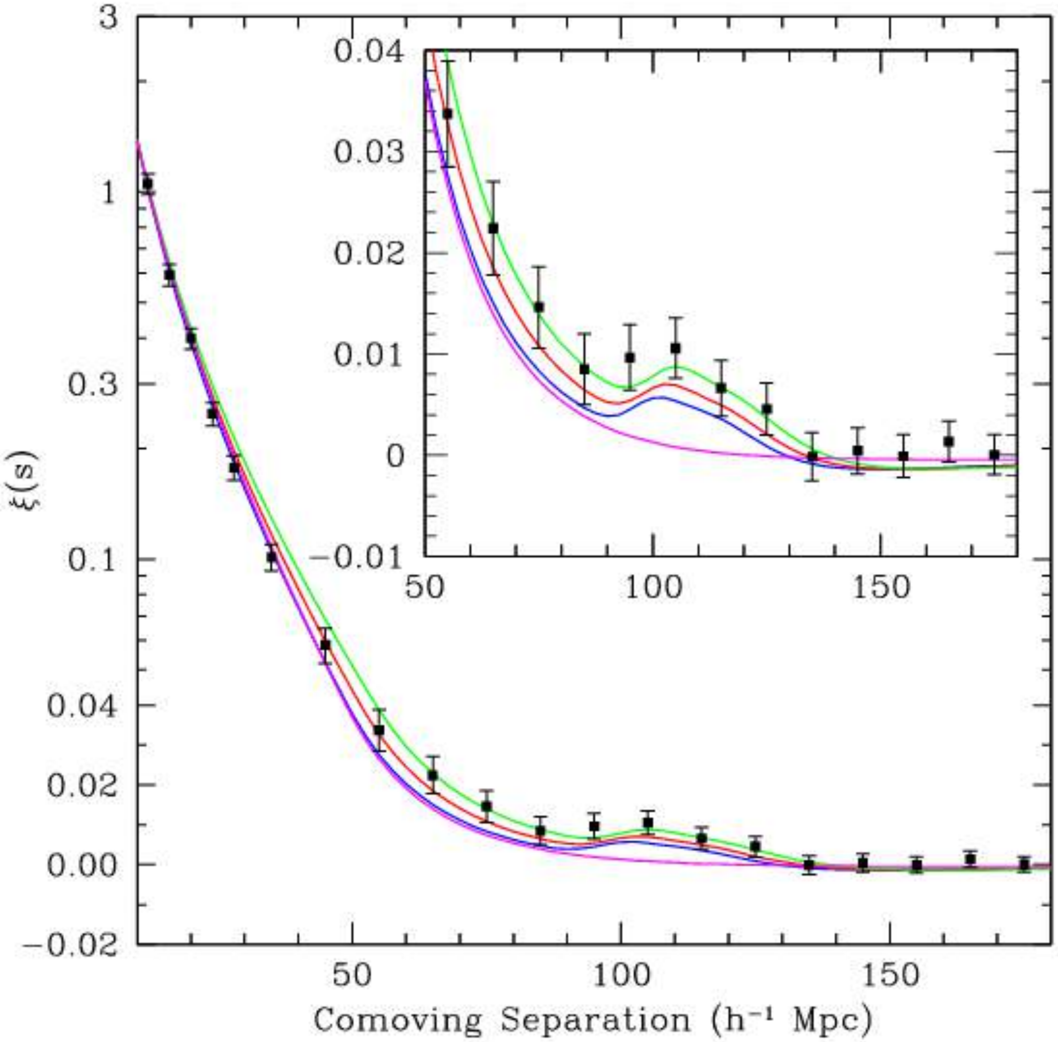
→ get joint constraint on Ω_{m}, Ω_Λ, Ω_{k} (actual constraints tighter because of additional information in details of CMB power spectrum, e.g. relative height of acoustic peaks)

CMB fluctuations grow into “baryonic acoustic oscillations” in the galaxy distribution (much lower *z*)

Baryonic Oscillation Spectroscopy Survey (BOSS) galaxy map

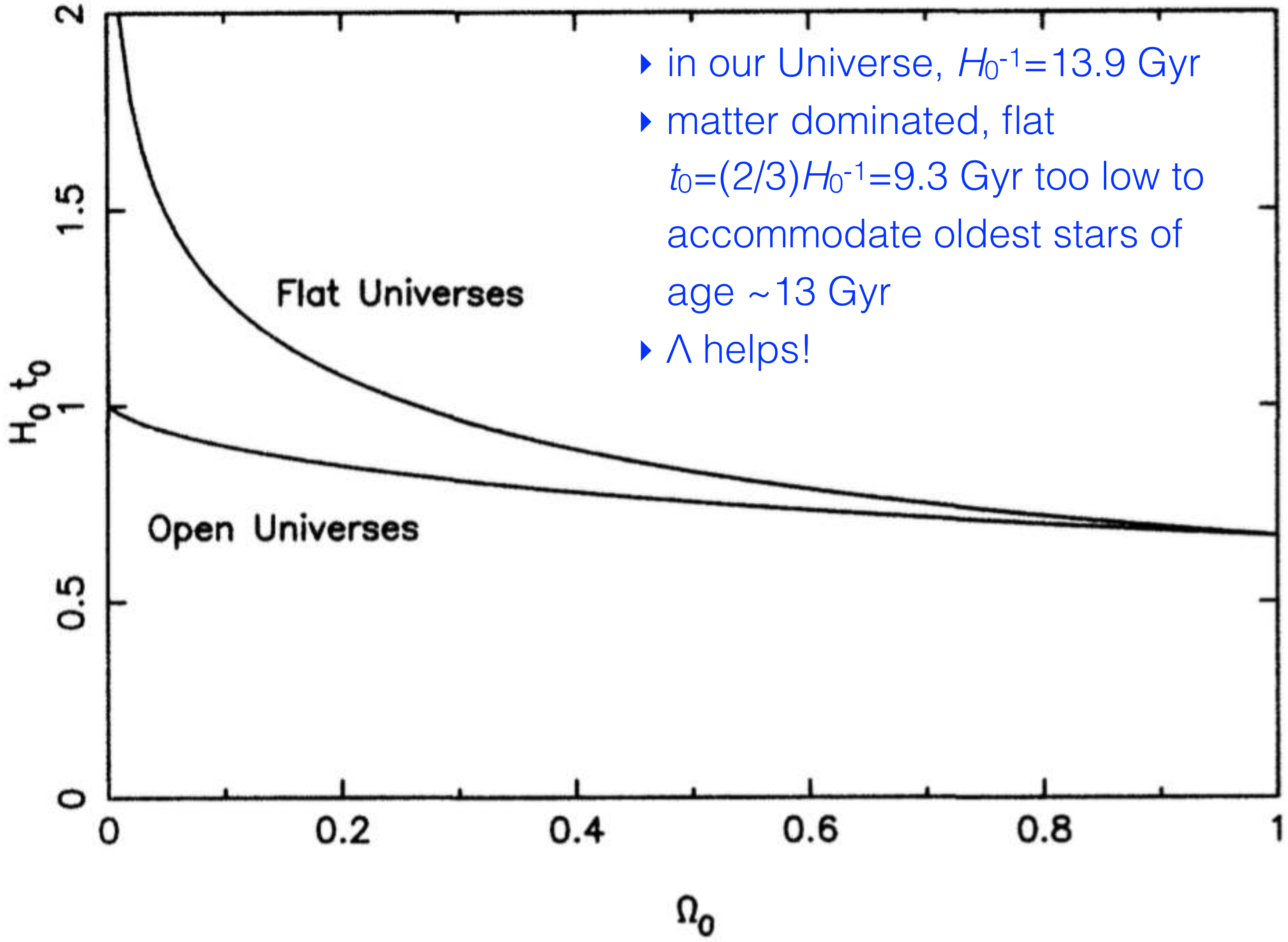


Luminous red galaxy (LRG) correlation function



Eisenstein+05

Age of the Universe



- in our Universe, H_0^{-1}=13.9 Gyr
- matter dominated, flat $t_0=(2/3)H_0^{-1}$=9.3 Gyr too low to accommodate oldest stars of age ~13 Gyr
- Λ helps!

Figure 8.1 Predicted ages as fractions of the Hubble time H_0^{-1}, for open Universes and for Universes with a flat geometry plus a cosmological constant. The prediction $H_0 t_0 = 2/3$ for critical density models is at the right-hand edge.

DISCOVERY OF HE 1523−0901, A STRONGLY *r*-PROCESS–ENHANCED METAL-POOR STAR WITH DETECTED URANIUM[1]

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Timothy C. Beers,[8] and Jaehyon Rhee[9,10]

Received 2006 November 21; accepted 2007 March 15; published 2007 April 11

ABSTRACT

We present age estimates for the newly discovered, very *r*-process–enhanced metal-poor star HE 1523−0901 ([Fe/H] = −2.95) based on the radioactive decay of Th *and* U. The bright (V = 11.1) giant was found among a sample of bright metal-poor stars selected from the Hamburg/ESO Survey. From an abundance analysis of a high-resolution (R = 75,000) VLT/UVES spectrum, we find HE 1523−0901 to be strongly overabundant in *r*-process elements ([*r*/Fe] = 1.8). The abundances of heavy neutron-capture elements ($Z > 56$) measured in HE 1523−0901 match the scaled solar *r*-process pattern extremely well. We detect the strongest optical U line at 3859.57 Å. For the first time, we are able to employ several different chronometers, such as the U/Th, U/Ir, Th/Eu, and Th/Os ratios to measure the age of a star. The weighted average age of HE 1523−0901 is 13.2 Gyr. Several sources of uncertainties are assessed in detail.

Subject headings: early universe — Galaxy: halo — nuclear reactions, nucleosynthesis, abundances —
stars: abundances — stars: individual (HE 1523−0901)

EOS and time evolution of dark energy

Observational constraints on *w* and w_a

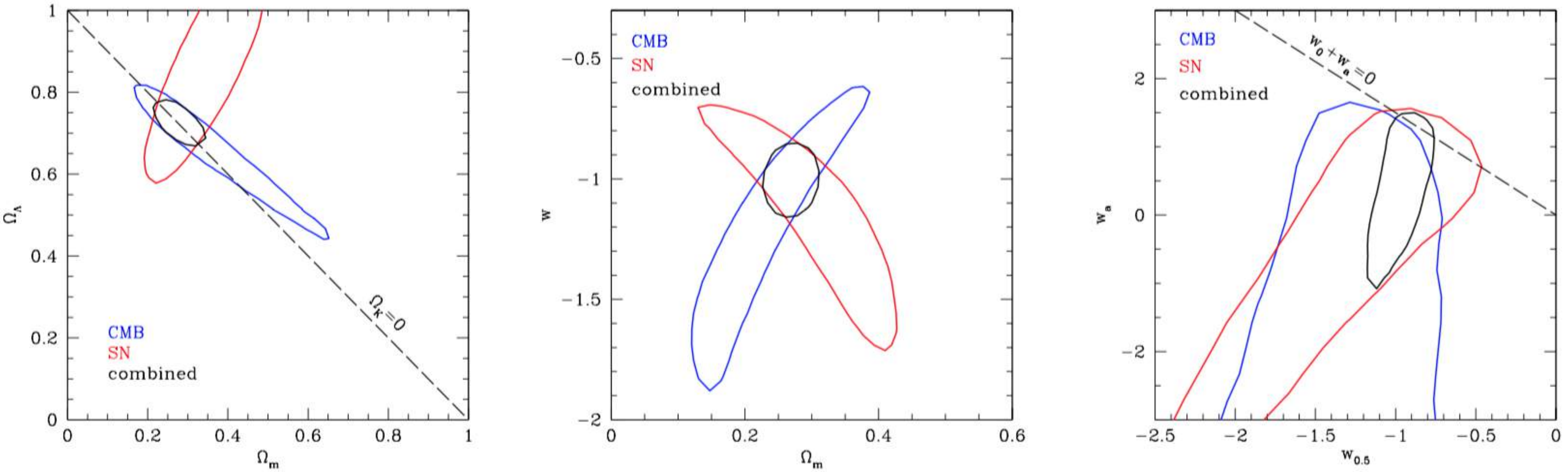


Figure 6 Constraints from WMAP7 CMB data, Union2 SN data, and the combination of the two, in (a) the $(\Omega_m, \Omega_\Lambda)$ plane assuming $w = -1$, (b) the (Ω_m, w) plane assuming $\Omega_k = 0$, and (c) the $(w_{0.5}, w_a)$ plane assuming $\Omega_k = 0$, where $w_{0.5}$ is the value of w at $z = 0.5$. Contours show 68% confidence intervals. In contrast to panels (a) and (b), the combined contour in (c) is tighter than one would guess from the overlap of the individual contours because the combined data set breaks degeneracies among other parameters that are marginalized over when inferring $w_{0.5}$ and w_a.

reasonable constraints that *w* ~ -1 (consistent with a cosmological constant)
but constraints are currently poor on the time evolution parameter w_a

Weinberg+13

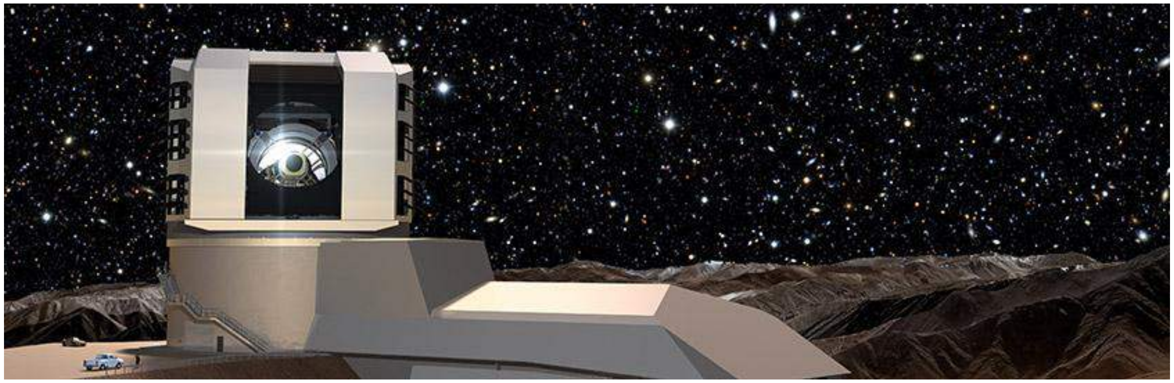
Some upcoming dark energy experiments

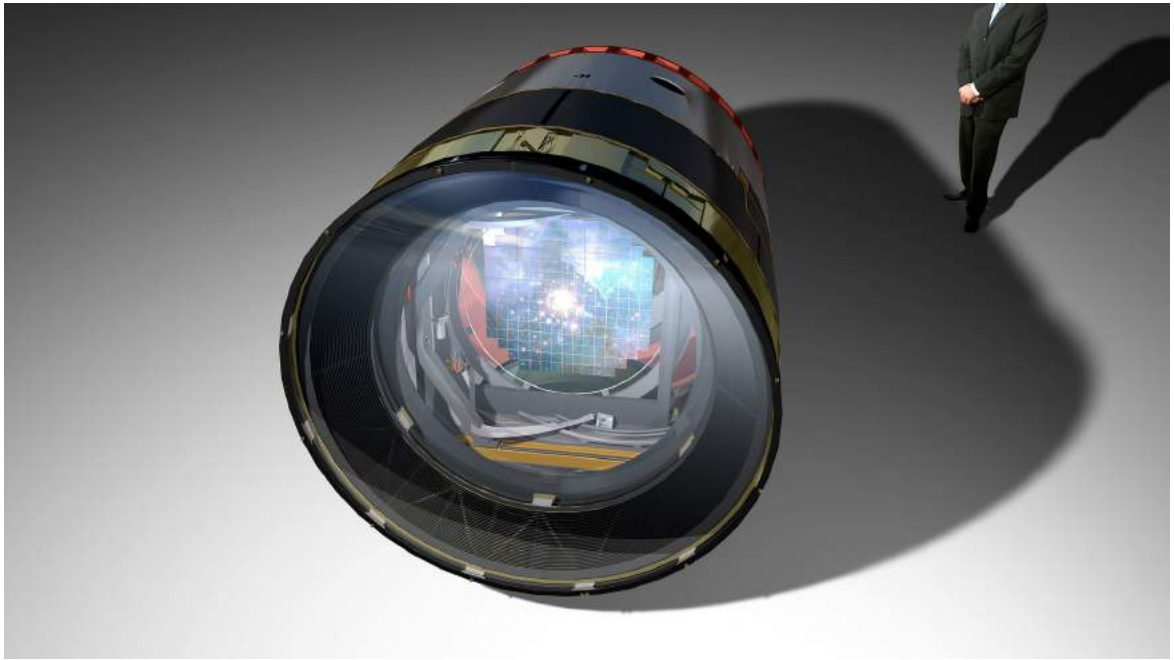
LSST

Large Synoptic Survey Telescope

- 8.4-m ground-based optical telescope in Cerro Pachón, Chile
- 3.5 degree diameter field of view (very wide — Moon is 0.5 degree across)
- 3.2 gigapixel camera (largest digital camera ever constructed)
- will record the entire visible sky twice each week
- over period of 10 years, 1,000 images of the entire sky
- 15 Tb of data per night
- unprecedented data stream will require advances in automated data processing using supercomputers to identify the most interesting signals

Under construction. First-light anticipated in 2019.

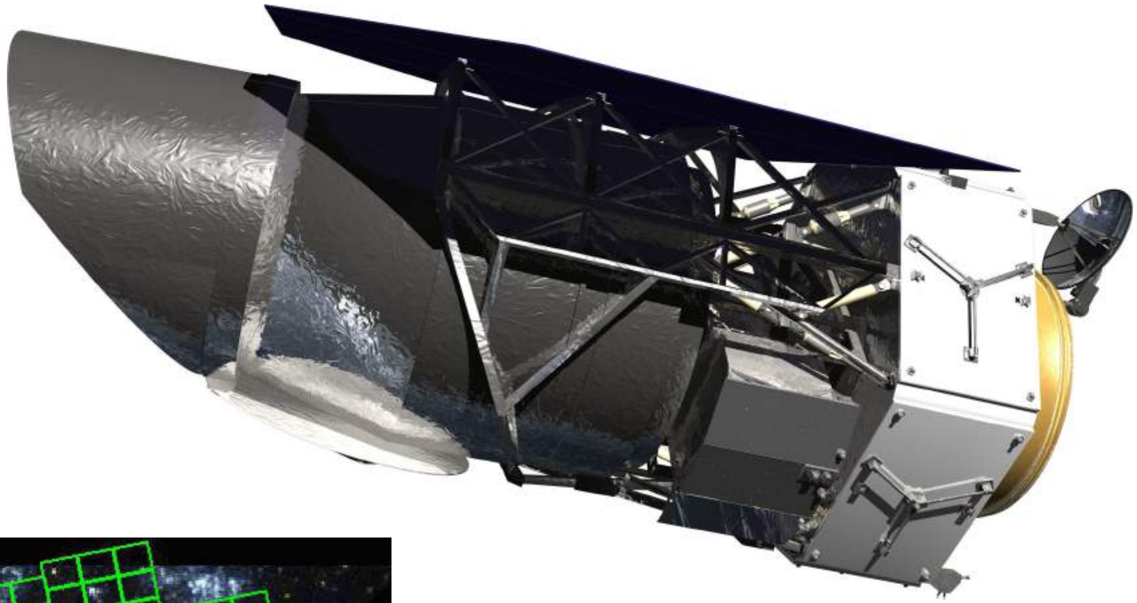




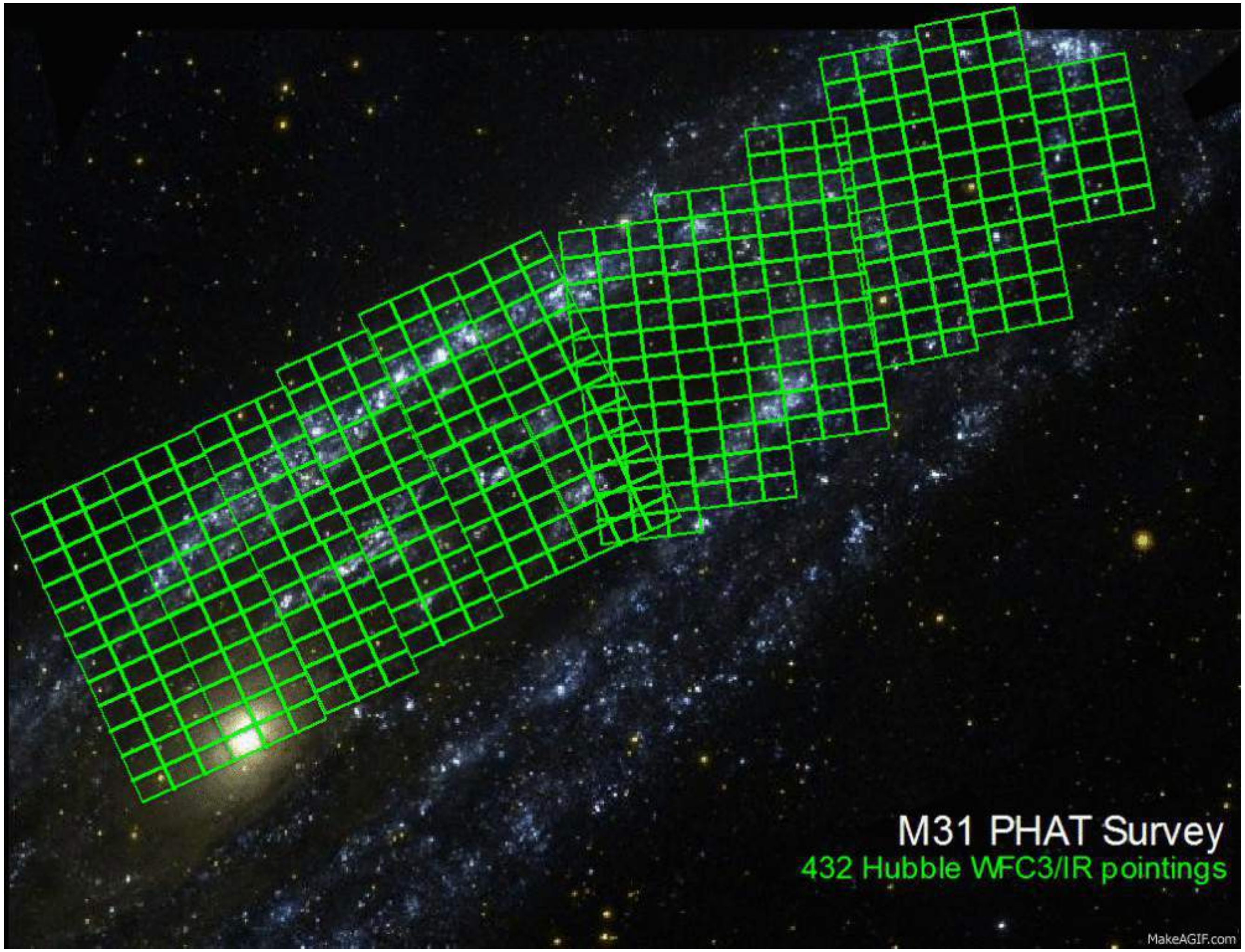
Wide-Field Infrared Survey Telescope

WFIRST

Astrophysics • Dark Energy • Exoplanets



Planned for mid-2020s launch by NASA



- 2.4-m space telescope (same diameter as Hubble) with much larger field of view
- 288 megapixel near-infrared camera
- will cover in 2 pointings what required >400 pointings with the Hubble Space Telescope (at similar resolution)
- one of the key goals is to discover a large number of Type Ia SNe to map out the expansion history of the Universe with greater precision
- also exoplanets (microlensing and direct imaging)