Last scattering surface of neutrinos

Cosmic Neutrino Last Scattering Surface

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Neutrinos decoupled from the rest of the cosmic plasma when the Universe was less than one second old, far earlier than the photons, which decoupled at $t = 380\,000$ years. Surprisingly, though, the last scattering surface of massive neutrinos is much closer to us than that of the photons. Here we calculate the properties of the last scattering surfaces of the three species of neutrinos.

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face of the cosmic microwave background (CMB). Neutrinos last scatter when the temperature of the universe was a few MeV and the universe was less than a second old, while the photons in the CMB last scattered much later when the temperature was 1/3 eV at $t = 380,000$ years, so it is natural to assume that the neutrino LSS is further away than that of the CMB. Calculating how

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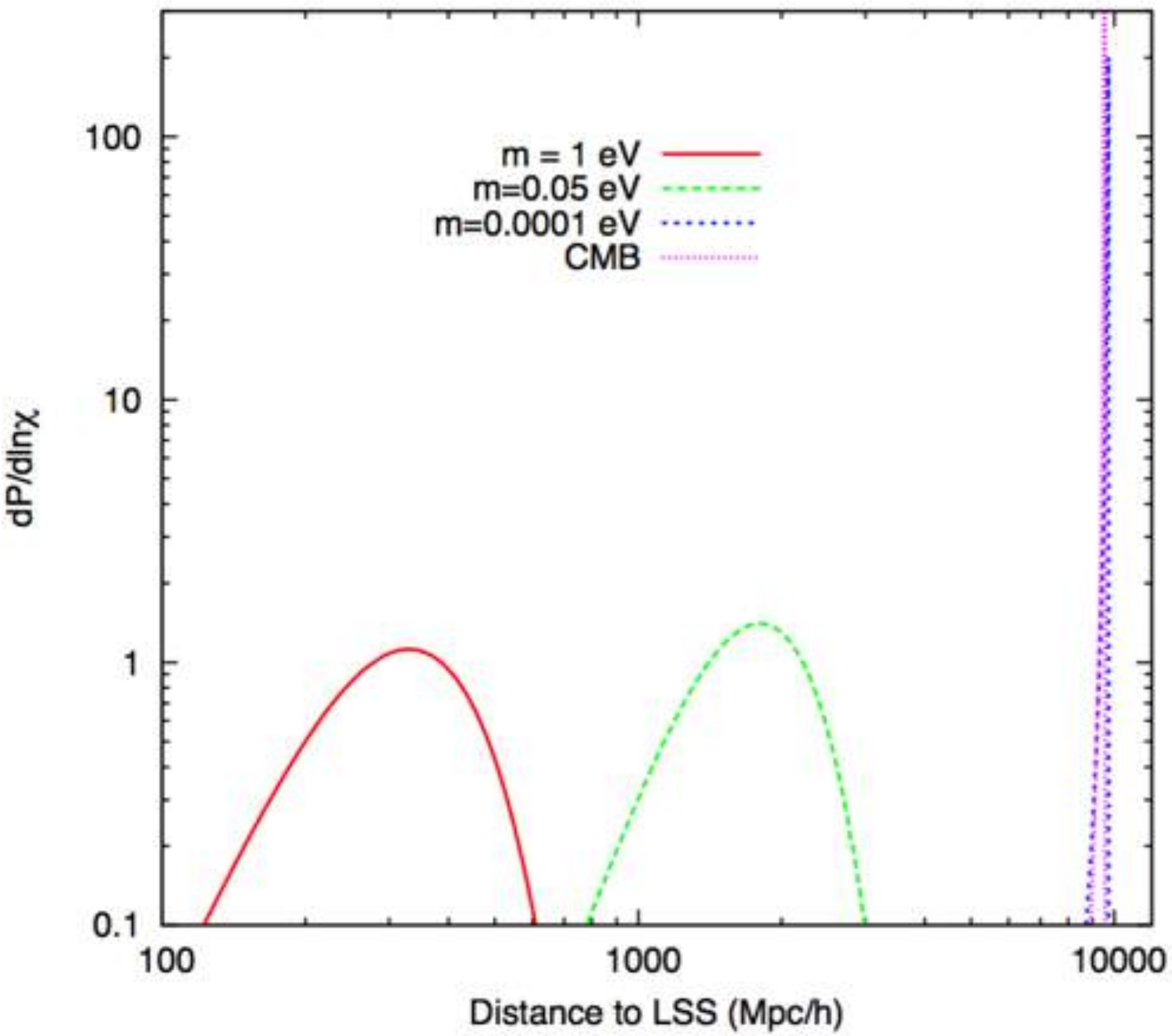


FIG. 2: The probability that a neutrino with mass m last scatters at a given comoving distance from us (the visibility function). Massive neutrinos travel more slowly than massless neutrinos so arrive here from much closer distances. Also shown is the last scattering surface of the cosmic microwave background, virtually indistinguishable from that of an $m_\nu = 10^{-4}$ eV neutrino.

Dodelson+09

Distances in cosmology

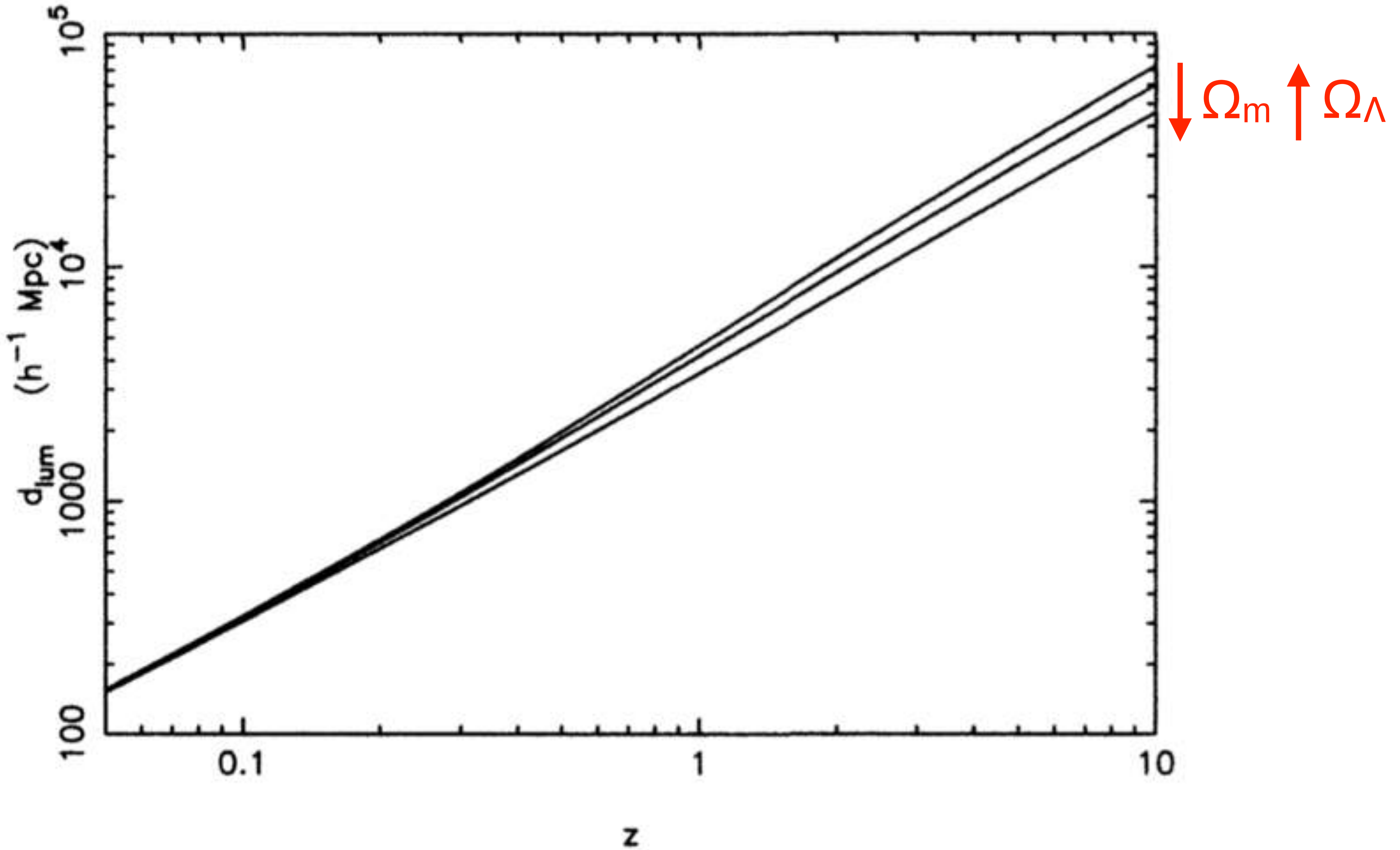


Figure A2.3 The luminosity distance as a function of redshift is plotted for three different spatially-flat cosmologies with a cosmological constant. From bottom to top, the lines are $\Omega_0 = 1$, 0.5 and 0.3 respectively. Notice how weak the dependence on cosmology is even to high redshift. It turns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

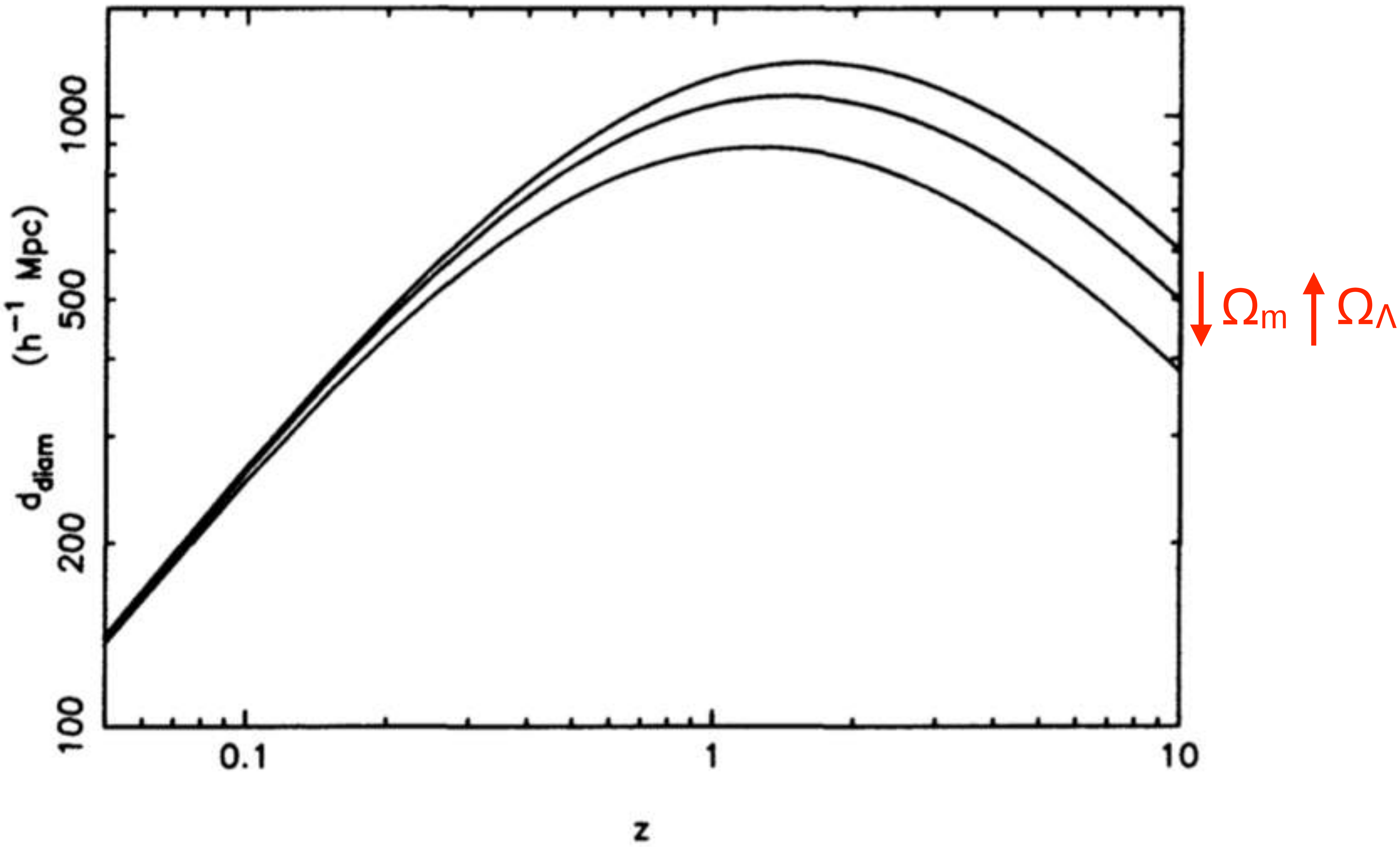


Figure A2.5 The angular diameter distance as a function of redshift is plotted for three different spatially-flat cosmologies with a cosmological constant. From bottom to top, the lines are $\Omega_0 = 1$, 0.5 and 0.3 respectively. For nearby objects $d_{\rm diam}$ and $d_{\rm lum}$ are very similar,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

Evidence for cosmic acceleration from Type Ia SNe

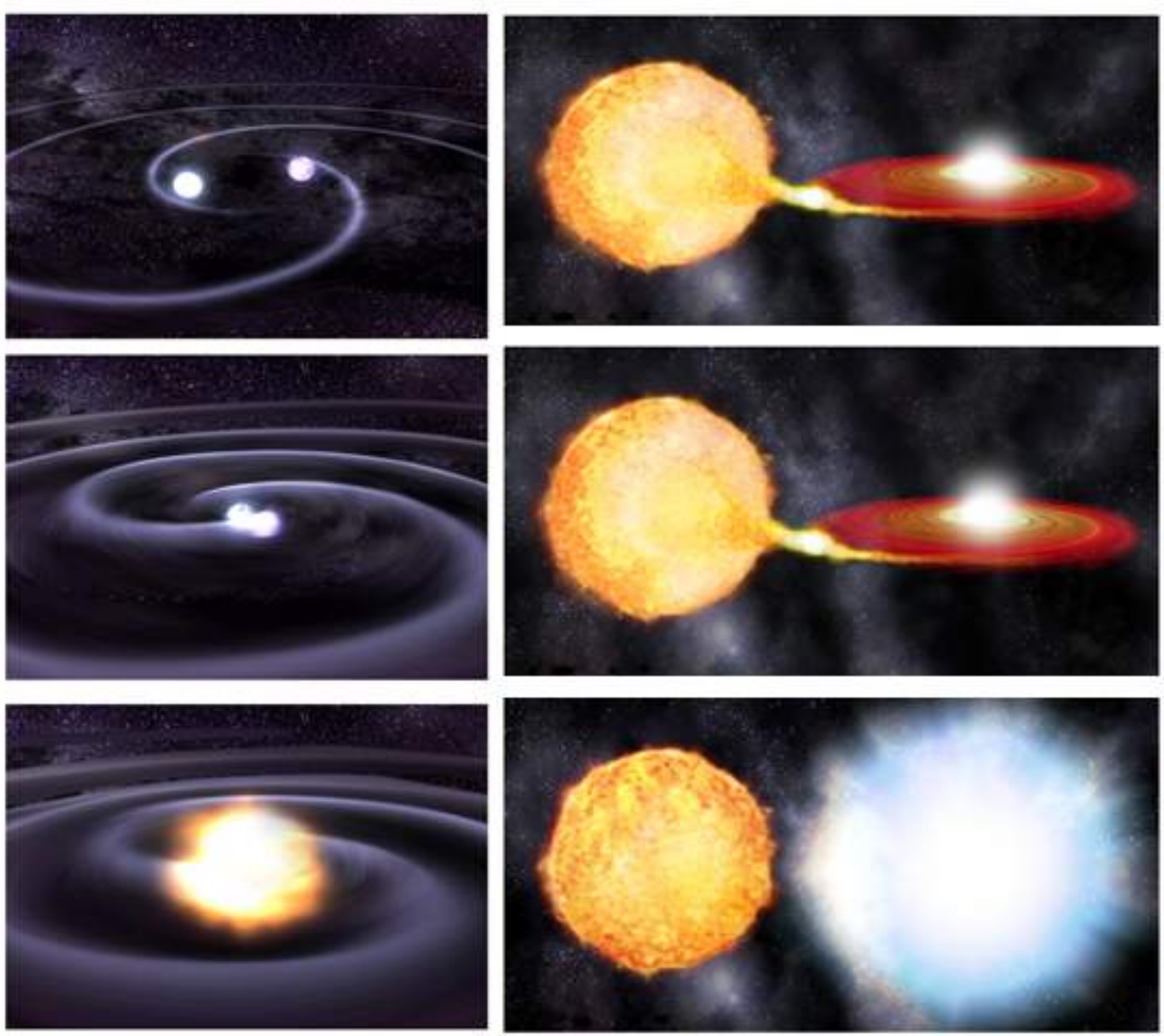
Type Ia supernovae

- 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

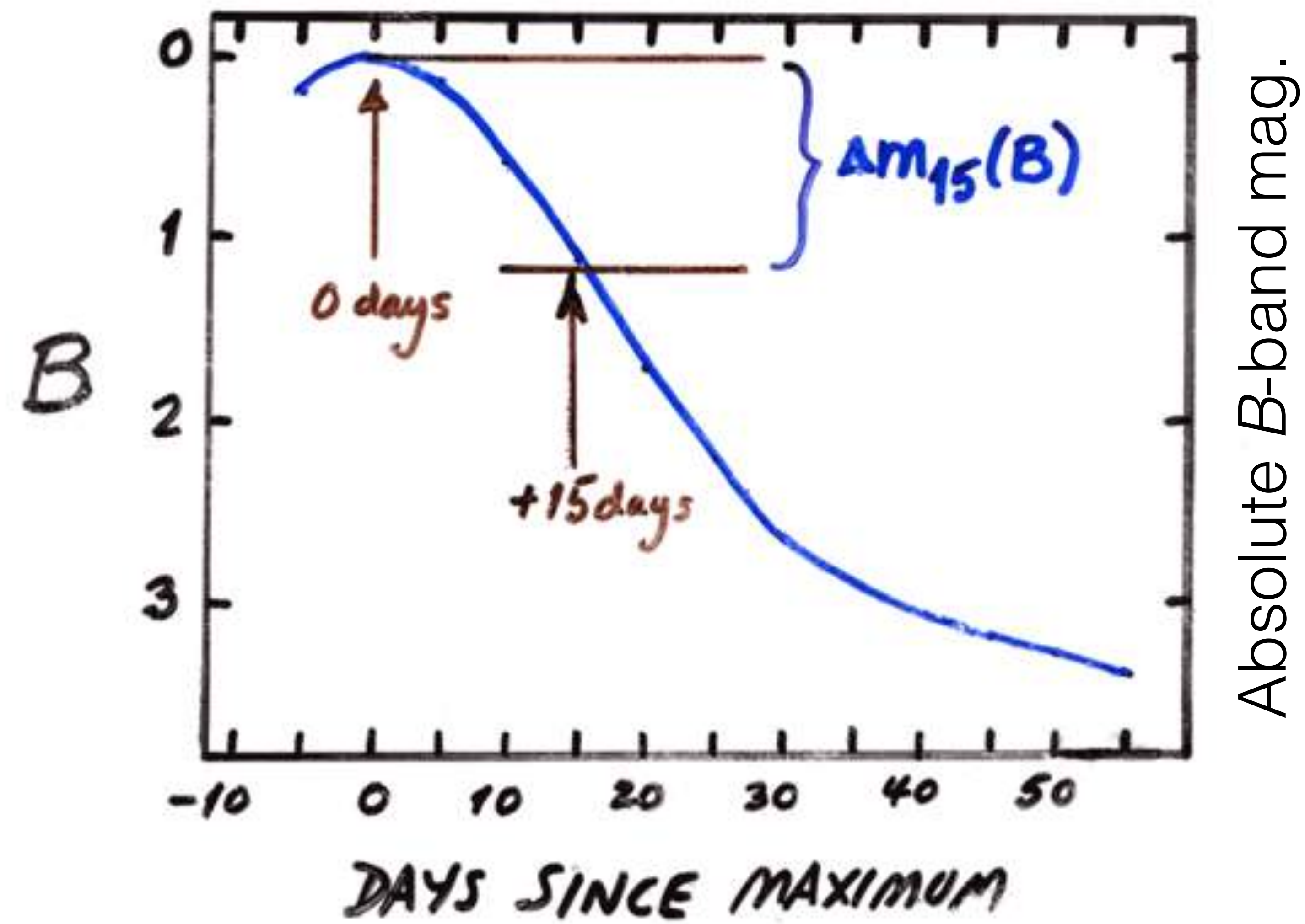
Type Ia SN in 'Pinwheel' M101 galaxy

Double and single degenerate Type Ia scenarios

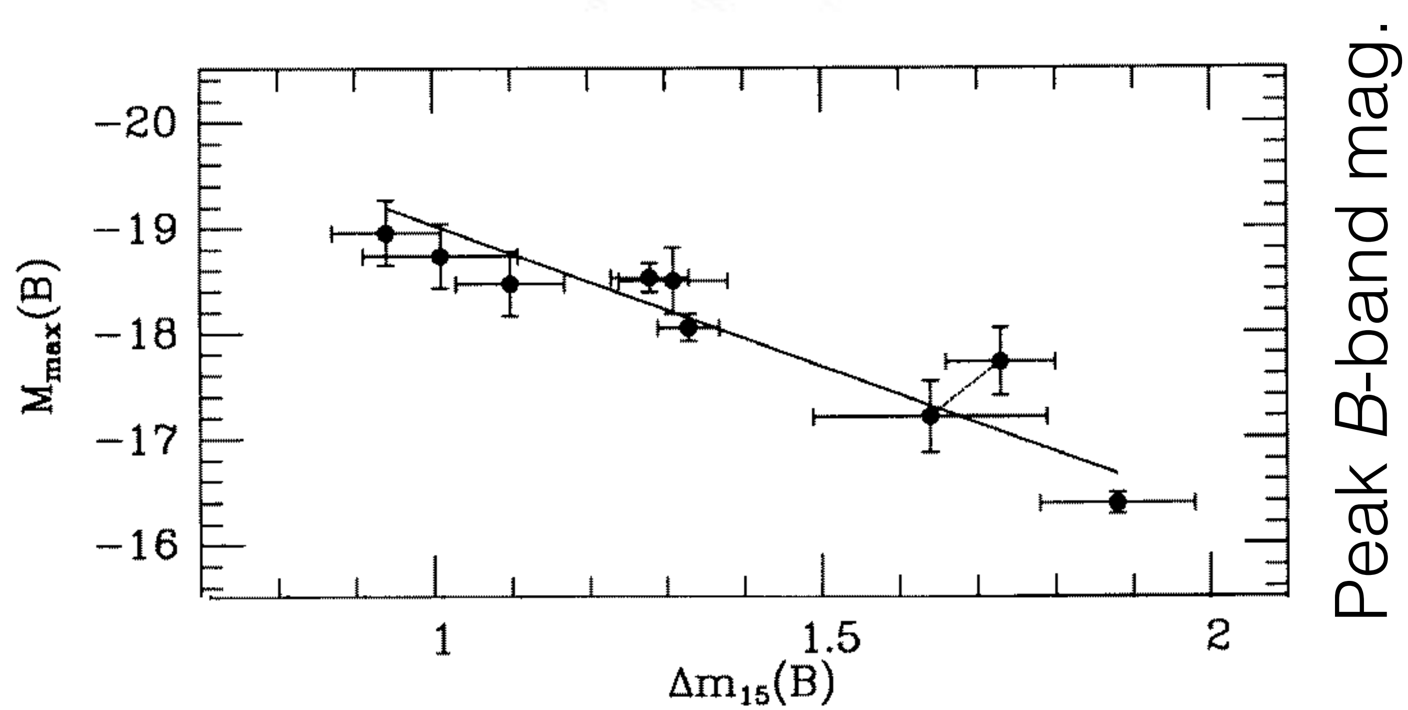


Type Ia supernovae as standard(izable) candles

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



- Phillips relation



Phillips 1993

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

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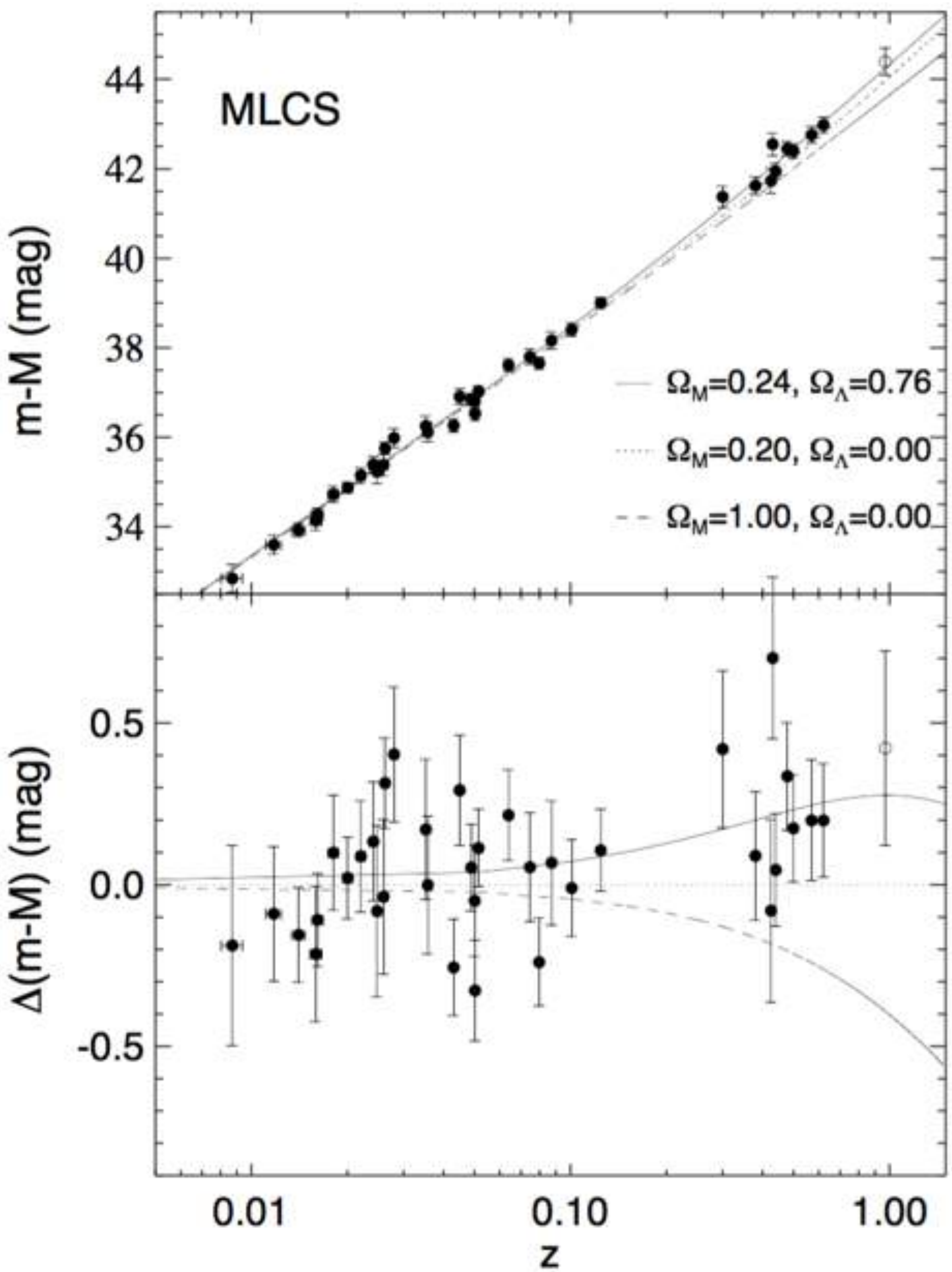
ABSTRACT

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

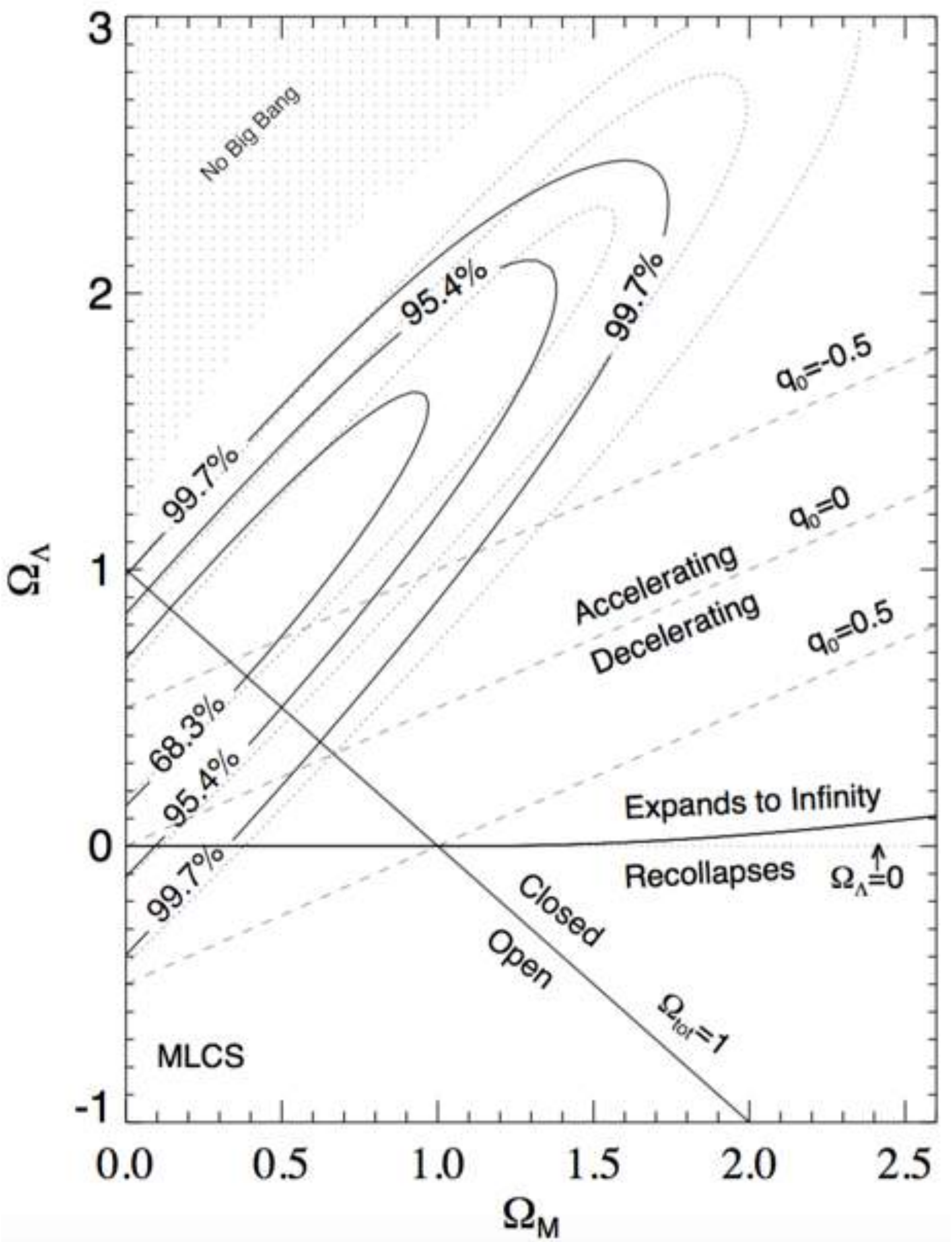
Original evidence for cosmic acceleration based on high-redshift Type Ia Hubble diagram



Distance modulus= 5 log($d_{\rm lum}$)-5

Riess+98 (see also Perlmutter+99)

Constraints on matter and cosmological constant cosmic 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

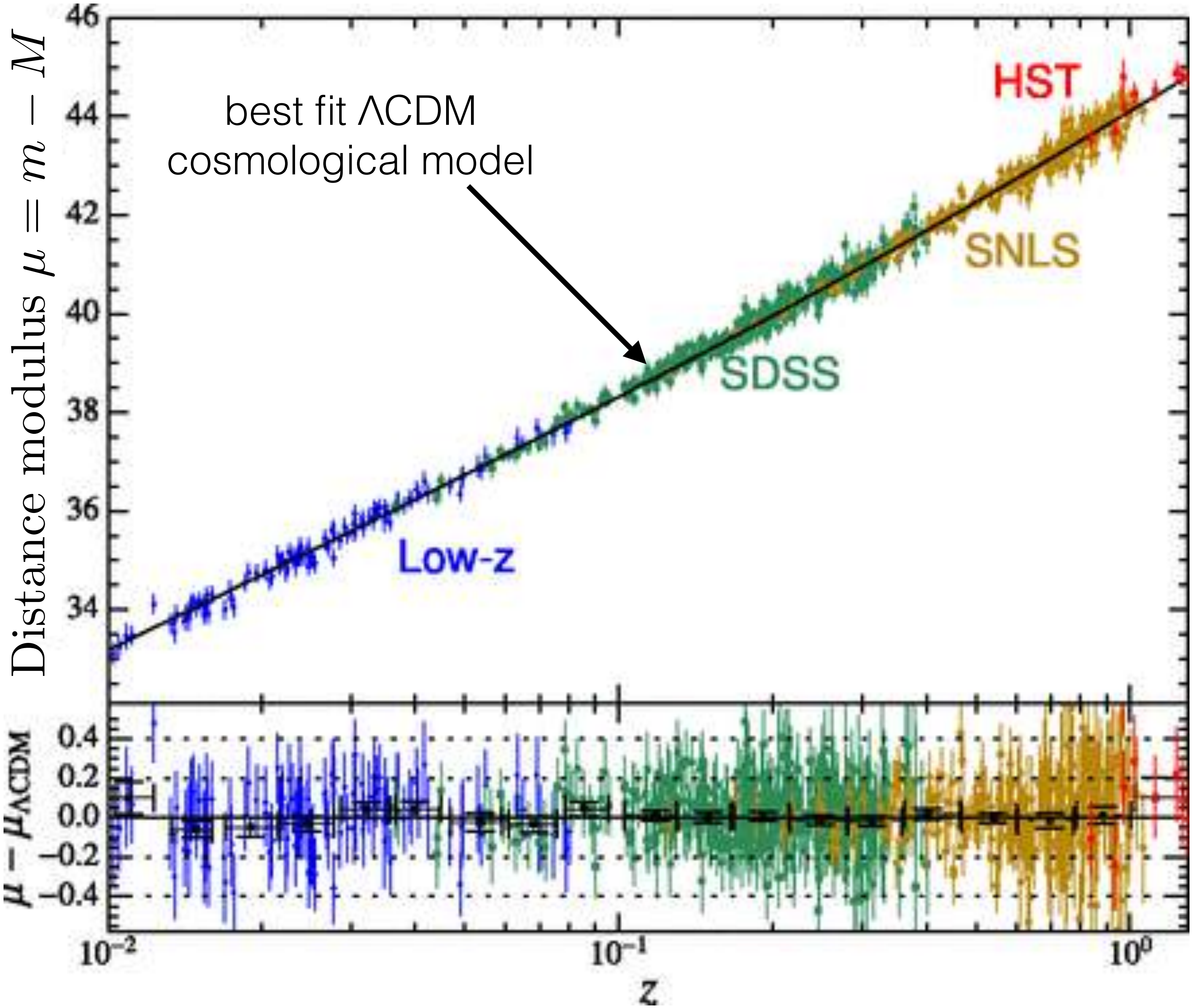
Photo: U. Montan

Adam G. Riess

Prize share: 1/4

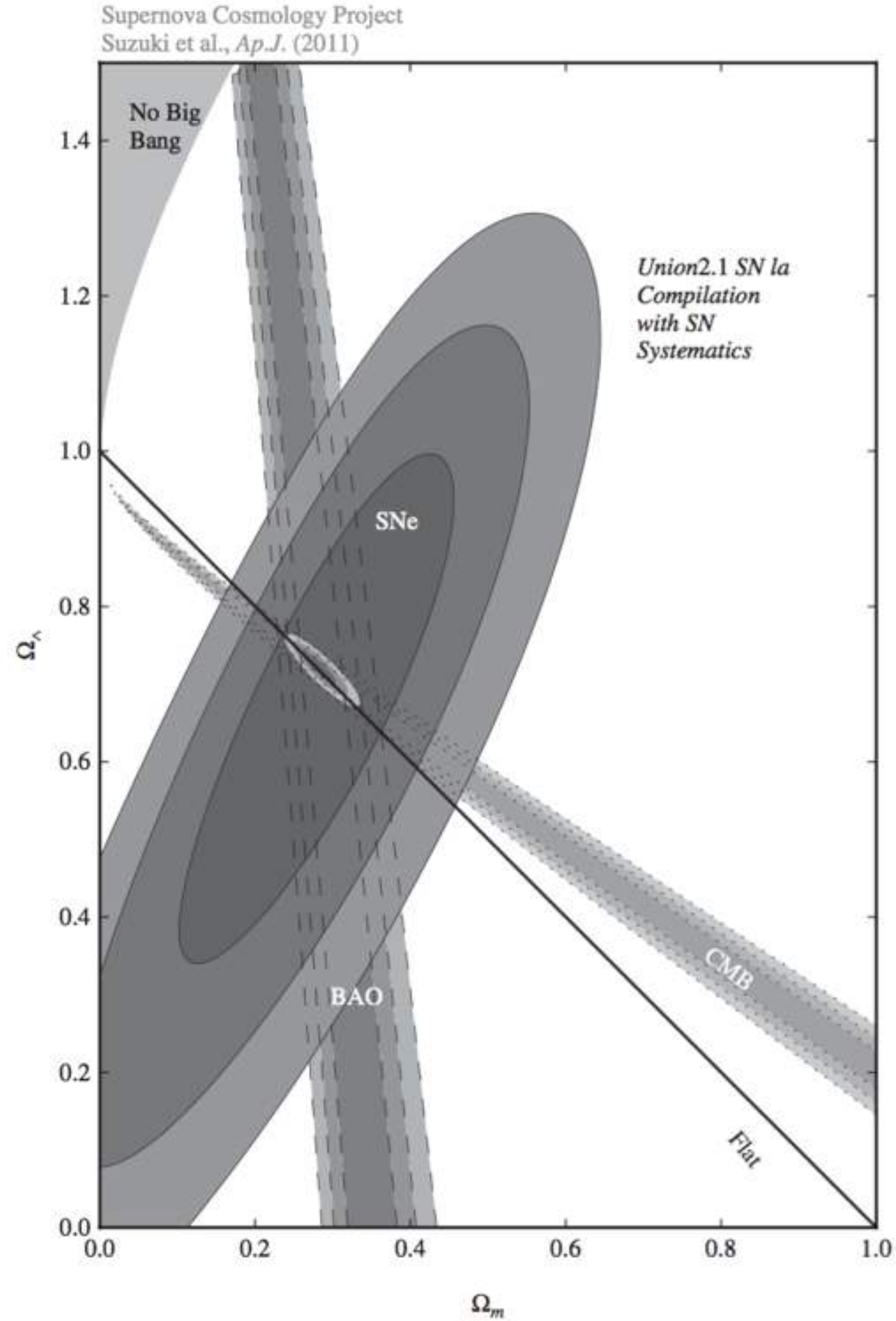
The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Recent supernova Hubble diagram



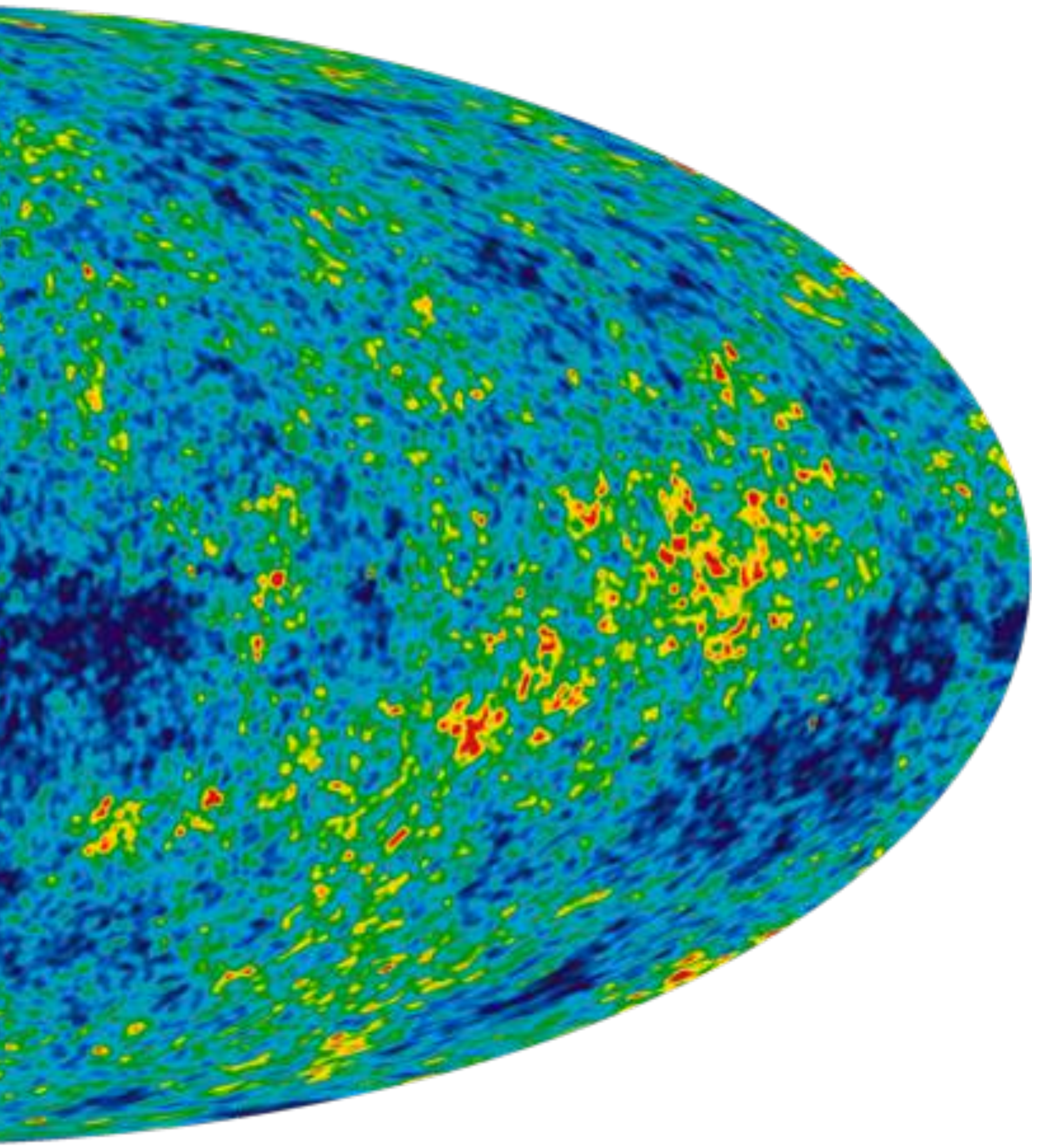
Betoule+14

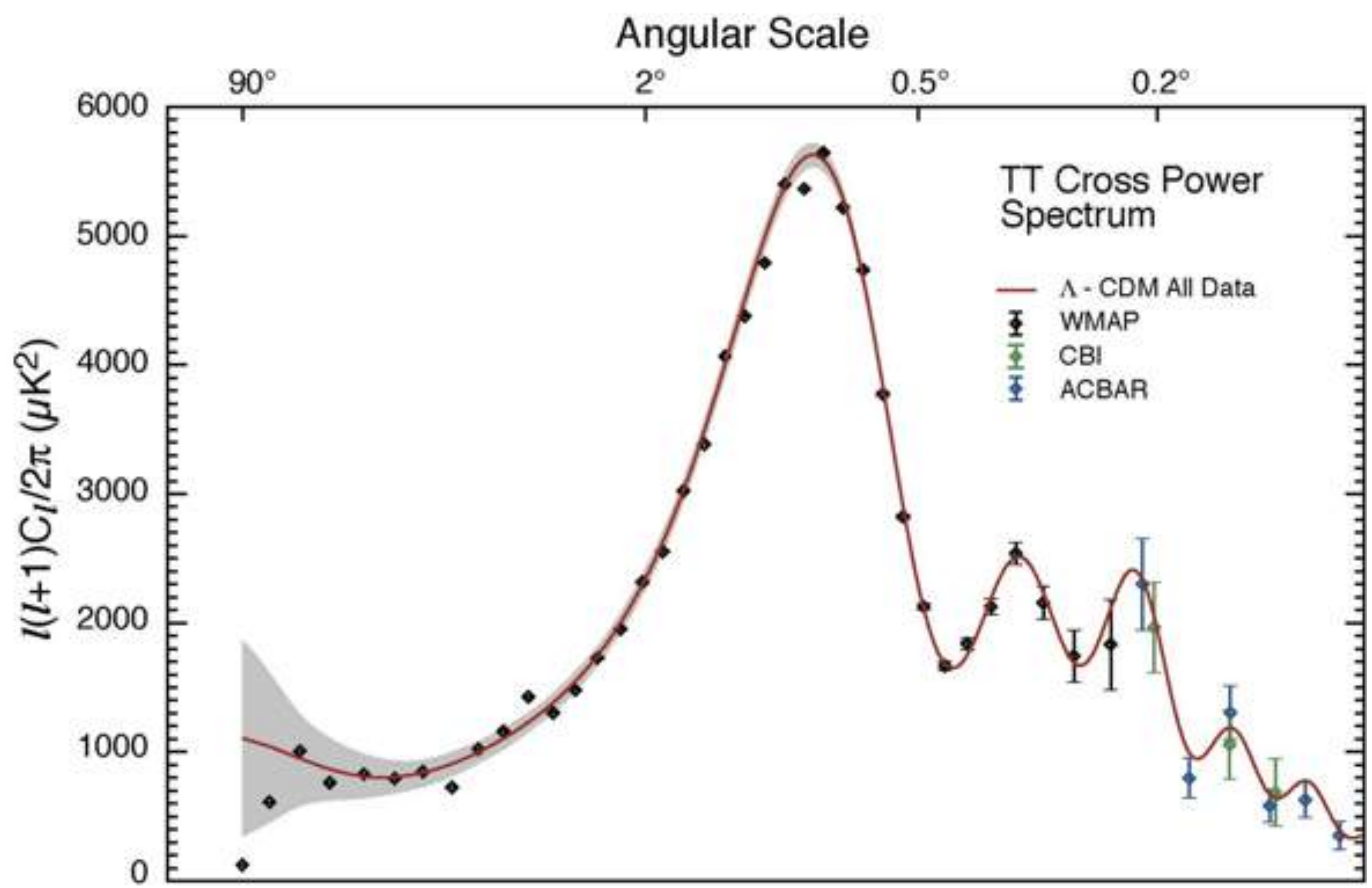
More recent constraints, combining SNe with complementary CMB and baryonic acoustic oscillation (BOA) data



Preview:
Using standard rulers for constraining cosmological parameters

CMB fluctuations have characteristic spatial scale ~1 degree — sound waves in early photon-baryon plasma



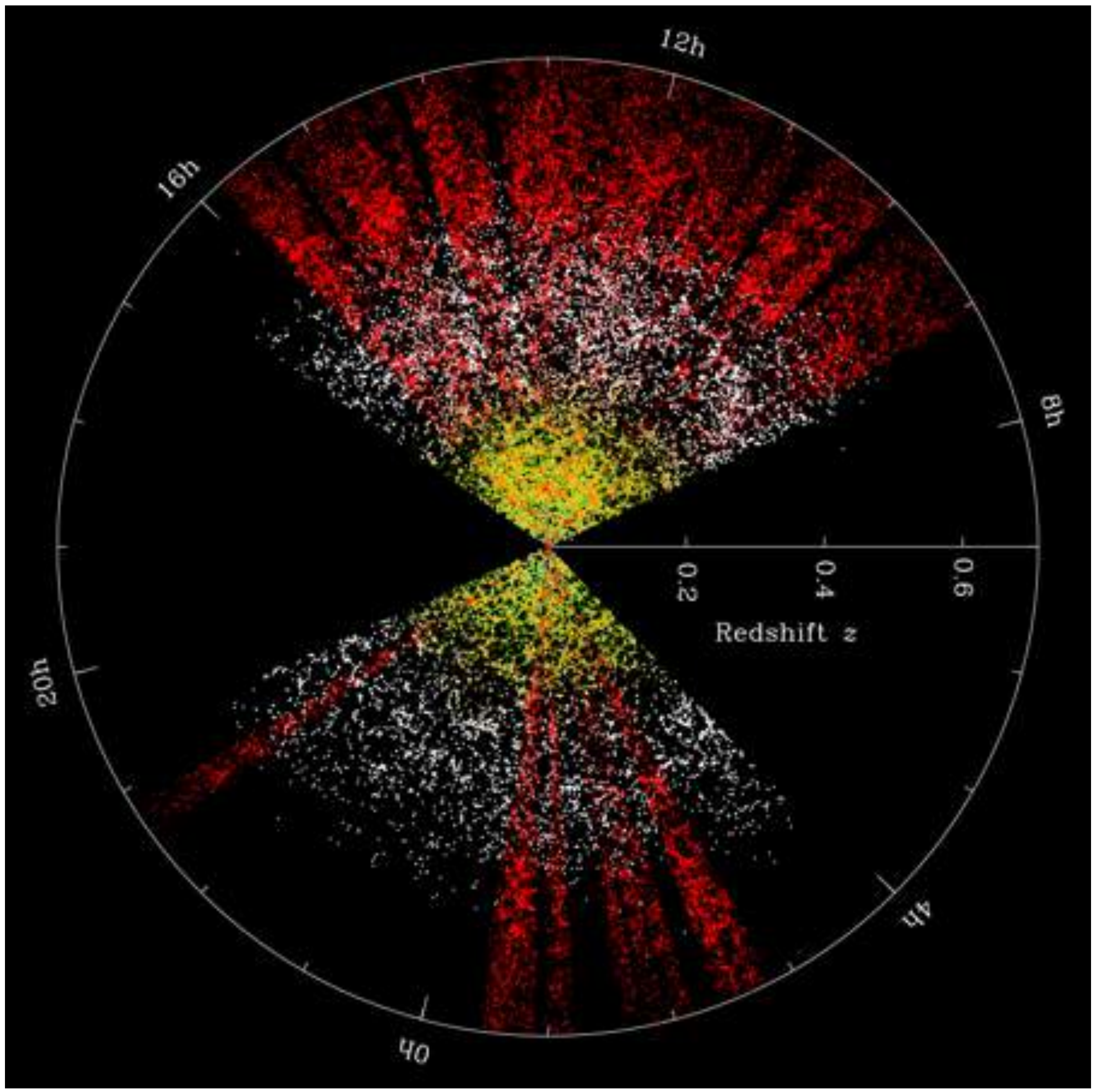


CMB power spectrum

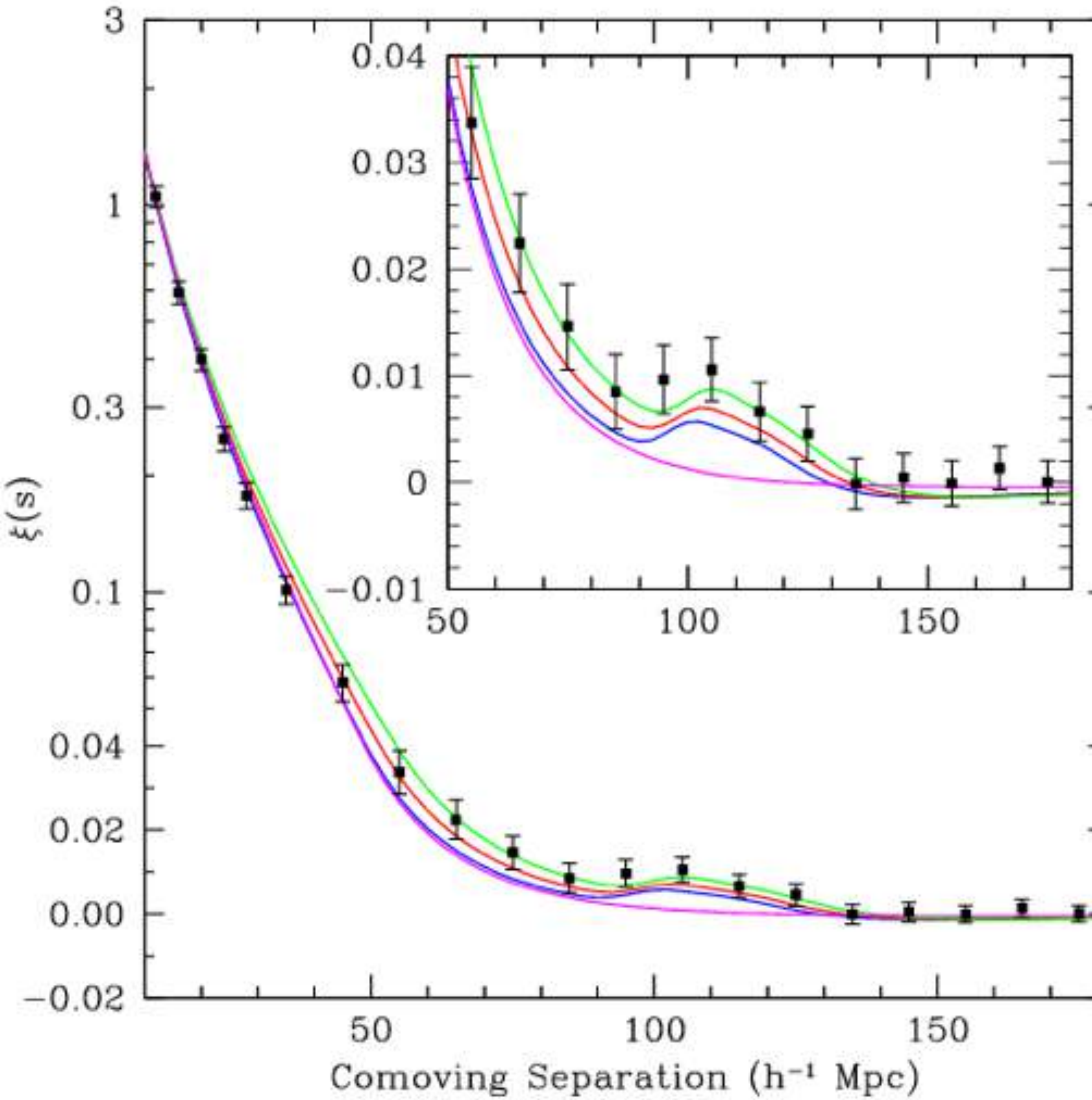
WMAP

CMB fluctuations grow into “baryonic acoustic oscillations” in the galaxy distribution

Baryonic Oscillation Spectroscopy Survey (BOSS) galaxy map



Luminous red galaxy (LRG) correlation function



Eisenstein+05

EOS and time evolution of dark energy

Observational constraints on w and w_a

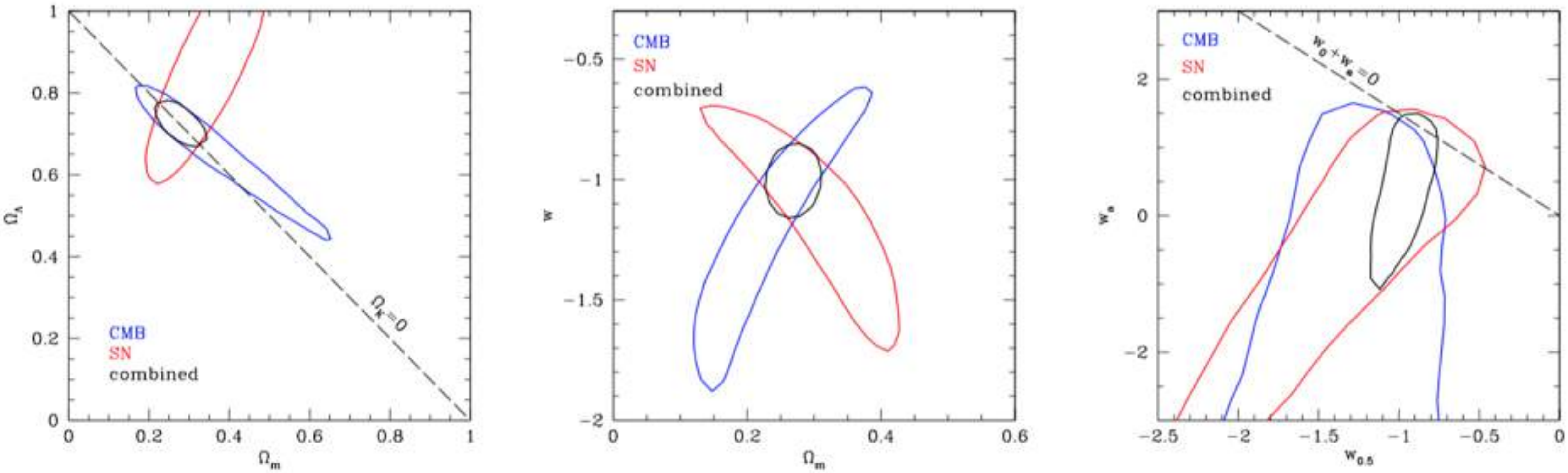


Figure 6 Constraints from WMAP7 CMB data, Union2 SN data, and the combination of the two, in (a) the $(\Omega_m, \Omega_\Lambda)$ plane assuming $w = -1$, (b) the (Ω_m, w) plane assuming $\Omega_k = 0$, and (c) the $(w_{0.5}, w_a)$ plane assuming $\Omega_k = 0$, where $w_{0.5}$ is the value of w at $z = 0.5$. 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.

Weinberg+13

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!

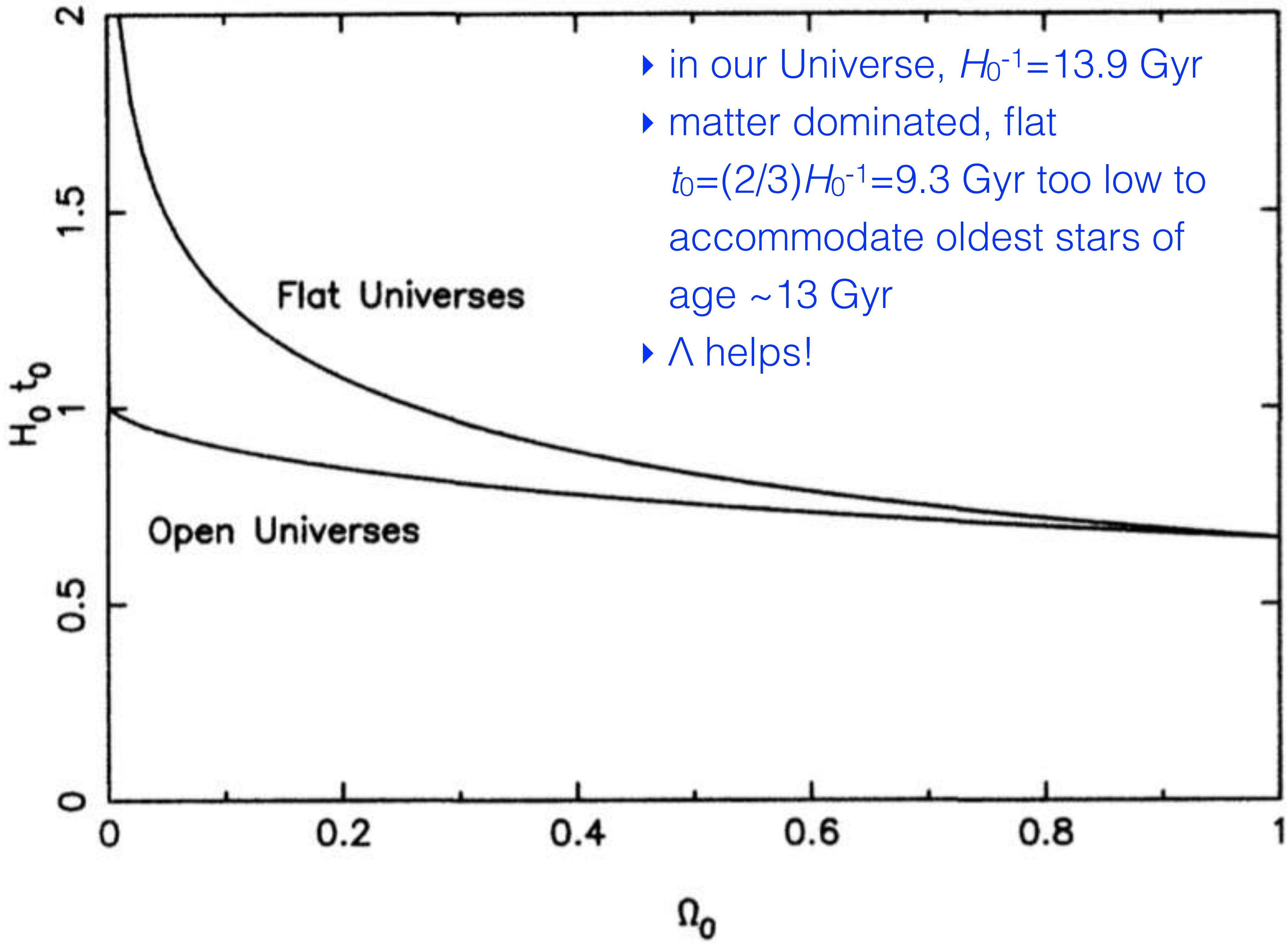


Figure 8.1 Predicted ages as fractions of the Hubble time H_0^{-1}, for open Universes and for Universes with a flat geometry plus a cosmological constant. The prediction $H_0 t_0 = 2/3$ for critical density models is at the right-hand edge.

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

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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)

Appendix: Perlmutter+'s discovery of cosmic acceleration

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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(THE SUPERNOVA COSMOLOGY PROJECT)
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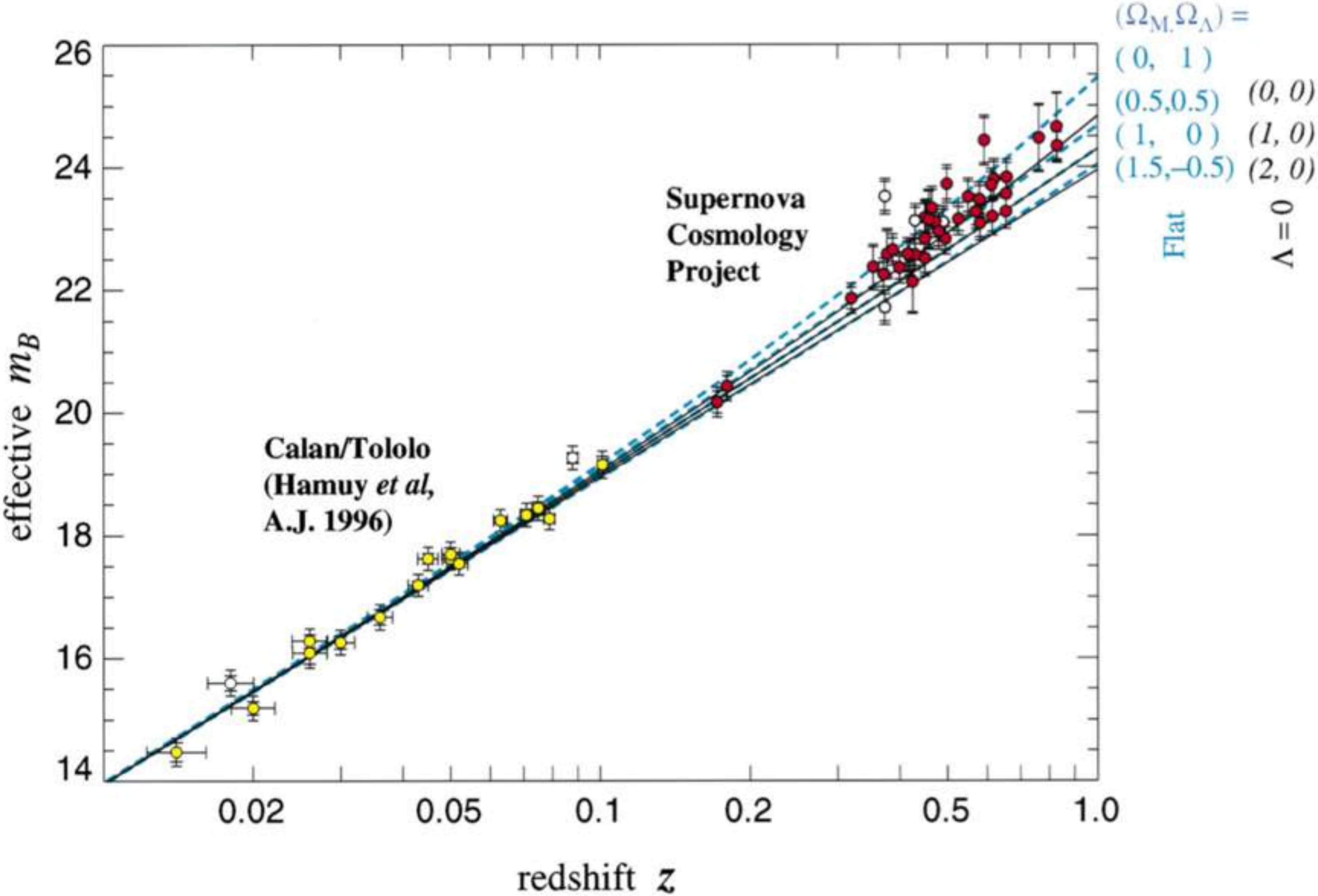
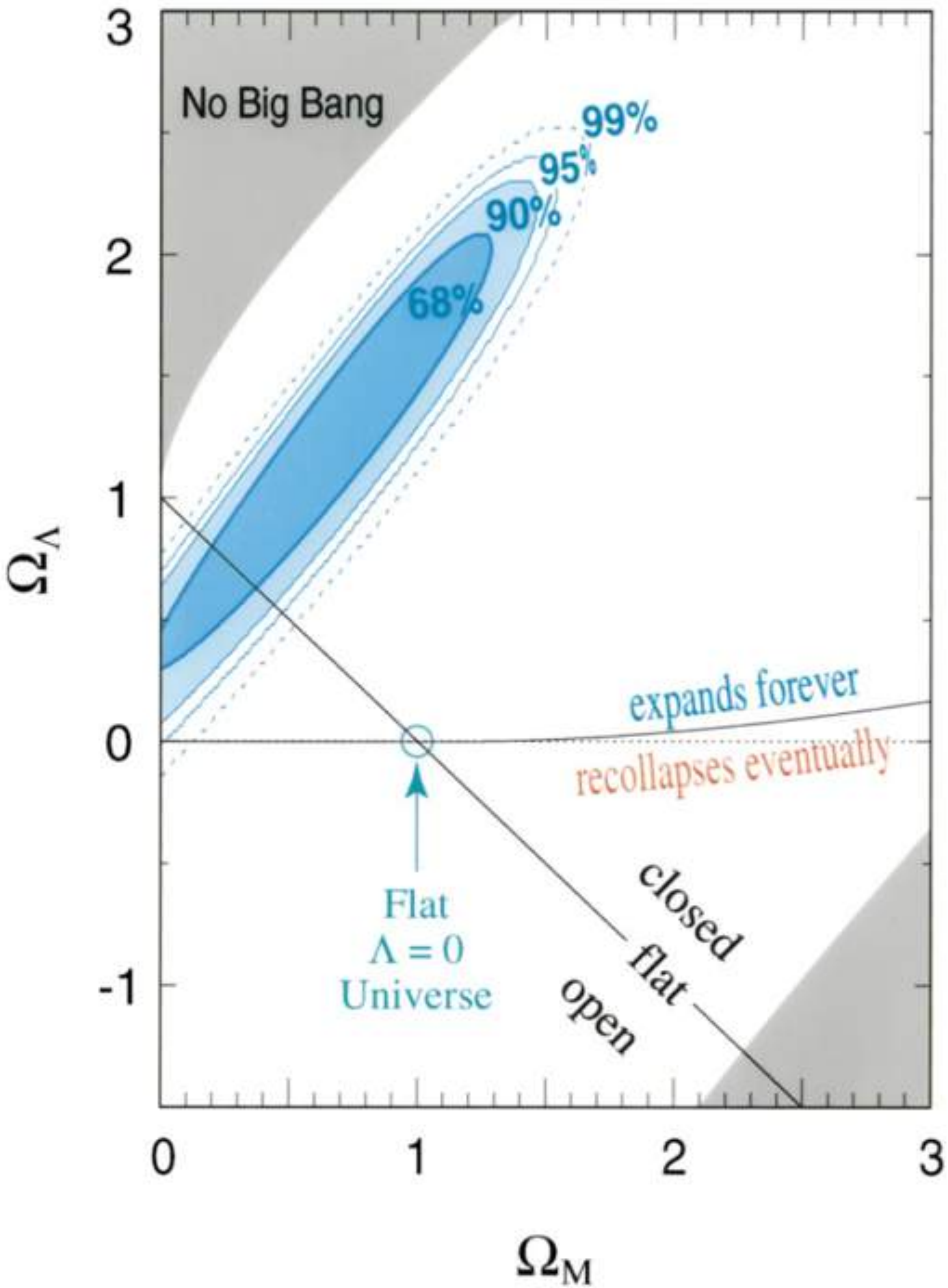
ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region 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 $t_0^{\rm flat} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of statistical tests to check for possible systematic errors and biases. We find no significant differences in either the host reddening distribution or Malmquist bias between the low-redshift Calán/Tololo sample and our high-redshift sample. Excluding those few supernovae that are outliers in color excess or fit residual does not significantly change the results. The conclusions are also robust whether or not a width-luminosity relation is used to standardize the supernova peak magnitudes. We discuss and constrain, where possible, hypothetical alternatives to a cosmological constant.

Subject headings: cosmology: observations — distance scale — supernovae: general

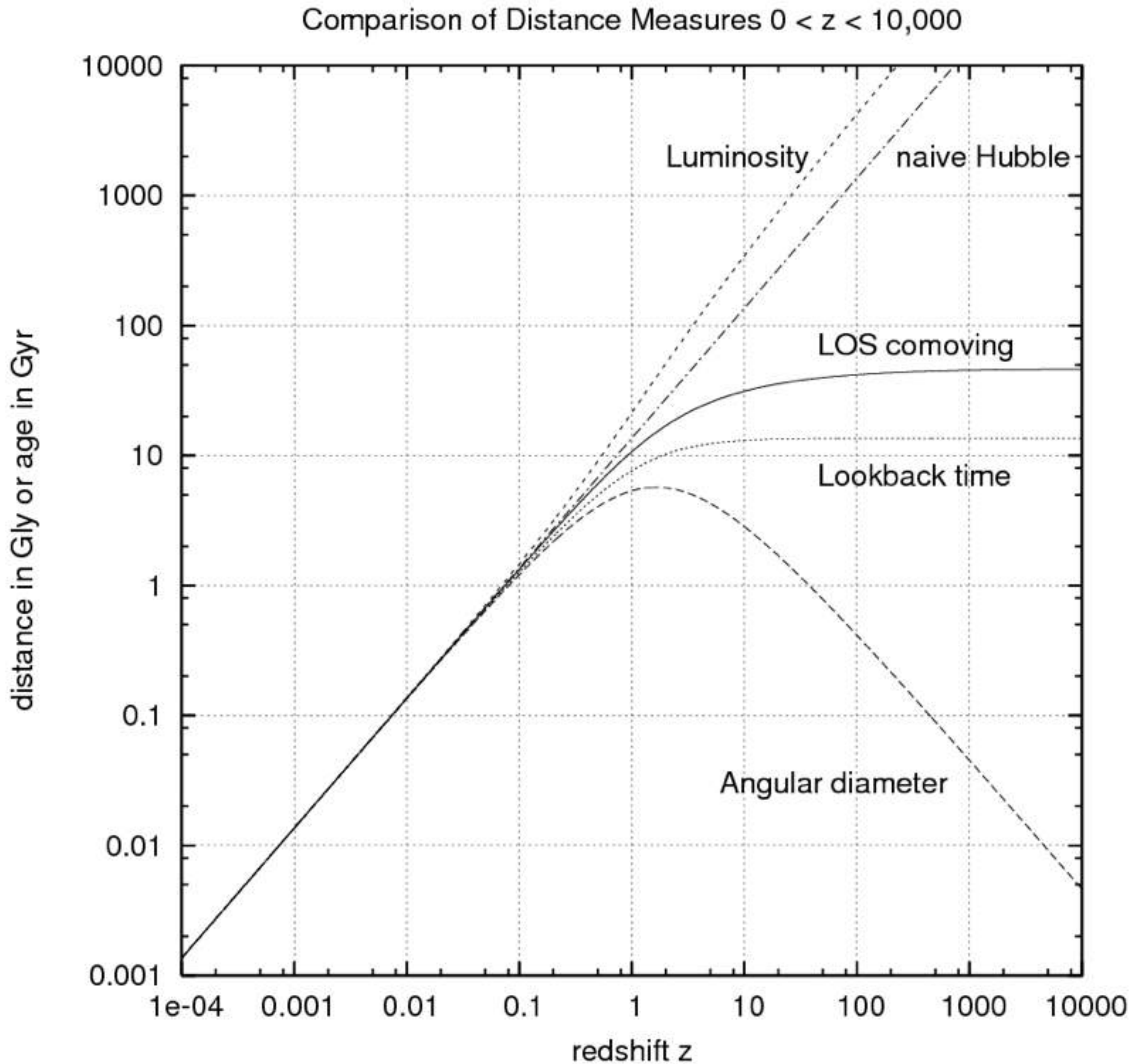


Perlmutter+99



Perlmutter+99

Extra slides


Comparison of Distance Measures 0 < z < 10,000
Luminosity
naive Hubble
LOS comoving
Lookback time
Angular diameter
distance in Gly or age in Gyr
redshift z
10000
1000
100
10
1
0.1
0.01
0.001
1e-04
0.001
0.01
0.1
1
10
100
1000
10000