Cosmology with Supernovae

Bruno Leibundgut

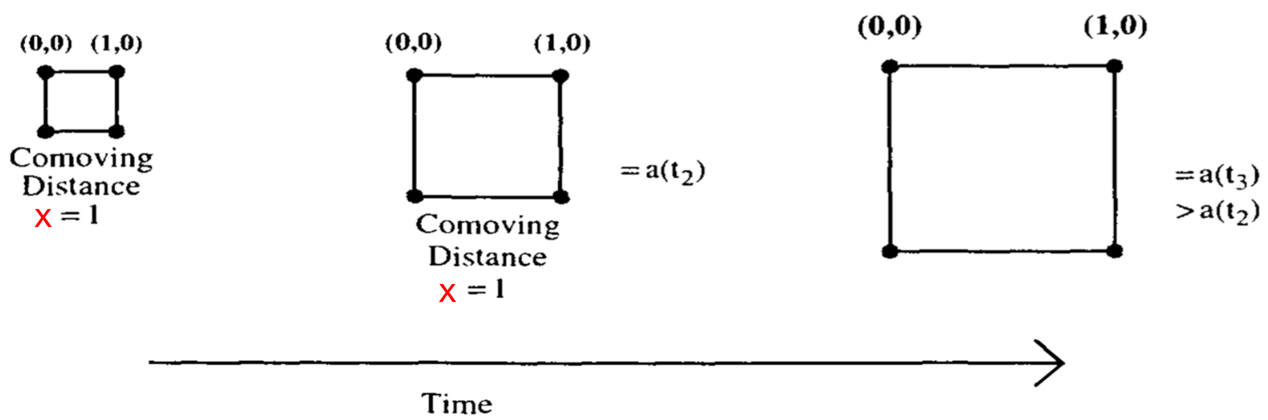
Cosmology with Supernovae

- Fundamentals
  - Observables
  - Theory
- Supernovae as distance indicators
  - Tests of General Relativity
    - Time dilation
    - Distance duality
  - Hubble Constant H_0
  - Mapping the expansion history $(q_0, \Omega_M, \Omega_\Lambda)$

Cosmic Distances

Separate the observed distances $r(t)$ into the expansion factor $a(t)$ and the fixed part x (called *comoving* distance)

$$r(t) = a(t)x$$

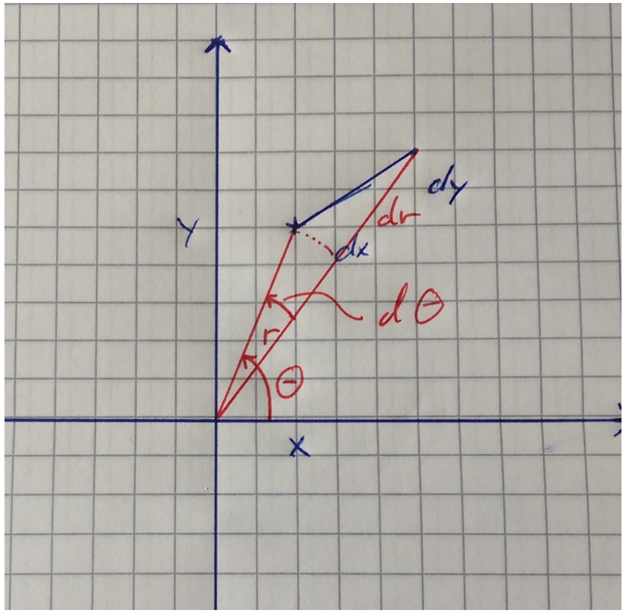


Calculating Distances

Simple example of distances in flat space:

- Coordinates x and y
  - Distance: $dl^2 = dx^2 + dy^2$ *(Cartesian)*
- Coordinates r and θ
  - Distance: $dl^2 = dr^2 + r^2\, d\theta^2$
- In general:

$$dl^2 = \sum_{i,j=1,2} g_{ij} dx^i\, dx^j$$



Cosmic Distances

In 4 dimensions

– (time as the 0th coordinate) this becomes

$$ds^2 = \sum_{\mu,\nu=0}^{3} g_{\mu\nu} dx^\mu dx^\nu = g_{\mu\nu} dx^\mu dx^\nu$$

using the (Einstein summation) convention where repeated indices are summed

or explicitly:

– Minkowski (flat) space

$$ds^2 = (cdt \quad dx \quad dy \quad dz) \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cdt \\ dx \\ dy \\ dz \end{pmatrix}$$

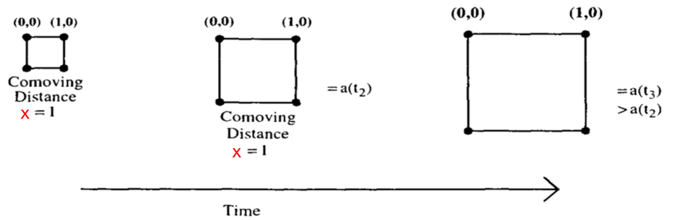
Calculating Distances

Expanding universe with scale parameter $a(t)$

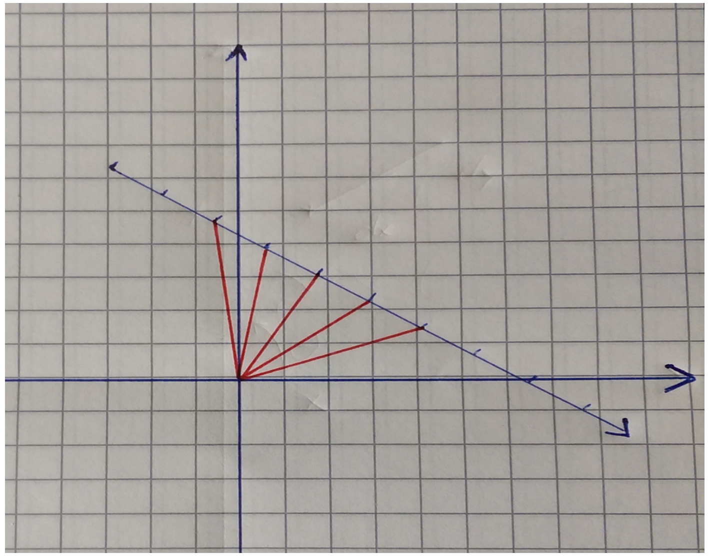
$$ds^2 = (cdt \quad dx \quad dy \quad dz)\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2(t) & 0 & 0 \\ 0 & 0 & a^2(t) & 0 \\ 0 & 0 & 0 & a^2(t) \end{pmatrix}\begin{pmatrix} cdt \\ dx \\ dy \\ dz \end{pmatrix}$$

➔ Lemaître-Friedmann-Robertson-Walker (FRW) metric for an isotropic and homogeneous universe

ds^2 is proper space and the metric $g_{\mu\nu}$ is the conversion from the coordinates dx^μ



Geodesic and Coordinate Transformation



Simple case:

– Minkowski space (flat):

– movement of a force-free particle (geodesic):

$$\frac{d^2x^i}{dt^2} = 0, with\ x^i = (x, y)$$ (Cartesian coordinates)

– How does this look like in polar coordinates?

$$x'^i = (r, \Theta) \implies \frac{d^2x^i}{dt^2} \neq 0 \text{ !!!}$$

An everyday $r\theta z$ system

Geodesic

General equation of a freely moving particle

$$\frac{d^2x'^l}{dt^2} + \Gamma^l_{jk}\frac{dx'^k}{dt}\frac{dx'^j}{dt} = 0$$

- Note the affine connection (Christoffel Symbol) $\Gamma^l_{jk} = 0$ for Cartesian coordinates


$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$
A. EINSTEIN

Recap Einstein Equations

- Gravity is the dominant force in the universe → General Relativity
- Need the most general form of the metric → transformations between coordinate systems
  - find 'invariant' parameters
- Equation of motion for a force-free particle ($\ddot{x} = 0$) in GR leads to affine connections → Christoffel symbols
- Putting this together with the geometry and the energy content → Einstein Equations

Lemaître Robertson Walker Metric

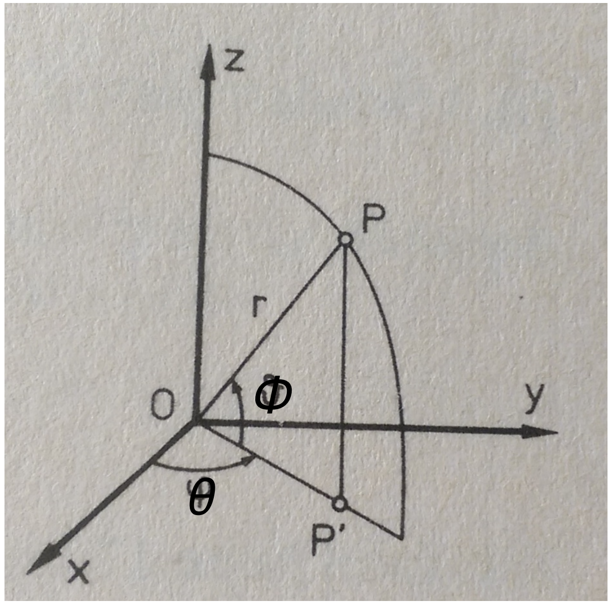
Assumes homogeneity and isotropy

Line element in polar metric has angular and radial components

$$ds^2 = -c^2dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta d\phi^2\right]$$

$$g_{00} = -1; \quad g_{rr} = \frac{a^2(t)}{1-kr^2};$$

$$g_{\theta\theta} = a^2(t)r^2; \quad g_{\phi\phi} = a^2(t)r^2\sin^2\theta$$



Light ray coming towards us

No angular dependence, hence

$$cdt = \pm a(t) \frac{dx}{\sqrt{1 - kx^2}}$$

and integrated

$$s = a \int_0^x \frac{dx}{\sqrt{1 - kx^2}} = aS(x)$$

with

$$S(x) = \begin{cases} \arcsin(x) & k = 1 \\ x & k = 0 \\ \operatorname{arcsinh}(x) & k = -1 \end{cases}$$

Strange Consequences

- k=1
  - closed universe
  - distances increase and then decrease again with increasing x
- k=0
  - ‘critical’ universe
  - expands forever
- k=-1
  - open universe
  - expands forever

The Energy-Momentum Tensor

Use the form for the 'perfect fluid'

$$T^{\mu\nu} = \begin{pmatrix} \rho c^2 & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Einstein's Field Equation

The (time) evolution of the scale factor depends only on the time-time component of the Einstein equation:

$$R_{00} - \frac{1}{2} g_{00} R = \frac{8\pi G}{c^4} T_{00}$$

- $T_{00} = \rho c^2$ *(energy density)*
- time part $R_{00} - \frac{1}{2} g_{00} R = \frac{3}{c^2} \left(\frac{\dot{a}}{a}\right)^2$

Friedmann Equation

Time evolution of the scale factor is described through the time part of the Einstein equations

Assume a metric for a homogeneous and isotropic universe (metric is diagonal in polar coordinates) and a perfect fluid

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G}{3}\rho(t)$$

Friedmann Equation

Put the various densities into the Friedmann equation

$$\frac{\dot{a}^2}{a^2} = H^2 = \frac{8\pi G}{3}\rho(t) - \frac{k}{a^2} = \frac{8\pi G}{3}\left(\rho_M + \rho_\gamma + \rho_{vac}\right) - \frac{k}{a^2}$$

Use the critical density $\rho_{crit} = \frac{3H_0^2}{8\pi G} \approx 2 \cdot 10^{-29}\ g\ cm^{-3}$ (flat universe), define the ratio to the critical density $\Omega = \frac{\rho}{\rho_{crit}}$

Most compact form of Friedmann equation

$$1 = \Omega_M + \Omega_\gamma + \Omega_{vac} + \Omega_k$$

with $\Omega_k = -\frac{k}{a^2 H^2}$

Dependence on Scale Parameter

For the different contents there were different dependencies for the scale parameter

$$\rho_M \propto a^{-3} \quad \rho_\gamma \propto a^{-4} \quad \rho_{vac} = const$$

Combining this with the critical densities we can write the density as

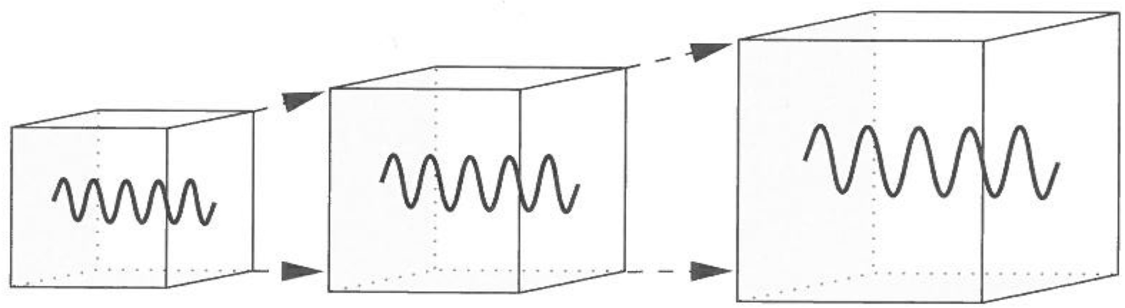
$$\rho = \frac{3H_0^2}{8\pi G}\left[\Omega_M\left(\frac{a_0}{a}\right)^3 + \Omega_\gamma\left(\frac{a_0}{a}\right)^4 + \Omega_\Lambda + \Omega_k\left(\frac{a_0}{a}\right)^2\right]$$

and the Friedmann equation

$$H^2 = H_0^2\left[\Omega_M(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda + \Omega_k(1+z)^2\right]$$

Redshift

Redshift is directly related to the ratio of the scales between emission and absorption of a photon



This is remarkably simple as a measurement in a spectrum tells the scale changes

Cosmological Redshift

For two different times we get

$$\frac{dt_1}{a(t_1)} = \frac{dt_2}{a(t_2)}$$

– i.e. the time scales with the scale parameter

If the time intervals dt are interpreted as oscillation periods, e.g. of a photon, then

$$\frac{dt_1}{dt_2} = \frac{\nu_2}{\nu_1} = \frac{a(t_1)}{a(t_2)} = \frac{1}{1+z}$$

with z as the redshift between the two times

Energy-Momentum Tensor

- The time (00) component of the Einstein equations is

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3p)$$

- As long as pressure and density are positive the universe decelerates $\ddot{a} < 0$.
- Acceleration requires $\rho c^2 + 3p < 0$ or $\omega < -\frac{1}{3}$.

Energy-Momentum Tensor

- A general form is an equation of state $p = \omega \rho c^2$. ω is the equation of state parameter.
- Inserting this into the conservation equation gives $\frac{\dot{\rho}}{\rho} = -3(1+\omega)\frac{\dot{a}}{a}$ which integrates to $\log(\rho) = -3(1+\omega)\log(a) + const.$
- Exponentiating yields $\rho \propto a^{-3(1+\omega)}$

Matter

- The pressure in matter is negligible compared to the mass content (think mc^2) and hence $\omega = \mathbf{0}$
- Thus $\rho_M \propto a^{-3}$
- Inserting this in the Friedmann equation for a flat universe (k=0) provides the time dependence of the scale factor

$$a(t) \propto t^{2/3}$$

Radiation

- Radiation decreases with the volume (i.e. number of photons), but has one additional factor due to the redshift $\omega = \frac{1}{3}$ and hence $\rho_\gamma \propto a^{-4}$
- The time dependence here is now
$$a(t) \propto \sqrt{t}$$

Vacuum energy

- A special case is $\rho_\Lambda = const.$
- In this case the density is associated to the vacuum
- Now the scale factor grows exponentially

$$a(t) \propto e^{Ht}$$

With the equation of state parameter ω

General luminosity distance

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_k|}} S\left\{\sqrt{|\Omega_k|}\int_0^z \left[\Omega_k(1+z')^2 + \sum_i \Omega_i(1+z')^{3(1+\omega_i)}\right]^{-\frac{1}{2}} dz'\right\}$$

– with $\Omega_k = 1 - \sum_i \Omega_i$ and $\omega_i = \frac{p_i}{\rho_i c^2}$

- $\omega_M = 0$ (matter)
- $\omega_\gamma = ⅓$ (radiation)
- $\omega_\Lambda = -1$ (cosmological constant)

Synopsis

- Gravity → Einstein Equations
  - ’Contents’ → Energy-momentum tensor
    - perfect fluid, density, pressure
    - dependence on different contents
      - matter, radiation, vacuum, curvature
  - FRW metric (isotropy, homogeneity) → different curvature models
- Time evolution → Friedmann Equation
  - Hubble constant
- Redshift → related to scale factor

Lookback Time

Consider

$$H = \frac{\dot{a}}{a} = \frac{\mathrm{da}}{\mathrm{dt}}\frac{1}{\mathrm{a}} = \mathrm{dt}\ln\left(\frac{\mathrm{a(t)}}{\mathrm{a_0}}\right) = \frac{1}{\mathrm{dt}}\ \ln\left(\frac{1}{1+\mathrm{z}}\right) = -\frac{1}{1+\mathrm{z}}\frac{\mathrm{dz}}{\mathrm{dt}}$$

Inserting into the Friedmann equation we find the equation for the time interval

$$dt = \frac{-dz}{H_0(1+z)\sqrt{\Omega_M(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda + \Omega_k(1+z)^2}}$$

and integrating

$$t_0 - t_1 = \frac{1}{H_0}\int_0^{z_1} \frac{dz}{(1+z)\sqrt{\Omega_M(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda + \Omega_k(1+z)^2}}$$

Age in a matter dominated universe ($t_1 = 0, z = \infty$)

$$t_{0,M} = \frac{1}{H_0}\int_0^\infty \frac{dz}{(1+z)^{5/2}} = \frac{2}{3H_0} \quad \text{and} \quad t_{0,\gamma} = \frac{1}{2H_0}$$

Cosmic Distances

We can now also express the luminosity distance $D_L = a_0 x_1 (1+z)$ in these terms

- from the metric for a light ray coming towards us we have $\frac{dr}{cdt} = \frac{\sqrt{1-kx^2}}{a(t)}$ which turns into $\frac{\mathrm{a}_0}{\mathrm{c}} \frac{dx}{\sqrt{1-kx^2}} = (1+z)dt$
- after integration we have (using dt from above) $\frac{a_0}{c} \int_0^{x_1} \frac{dx}{\sqrt{1-kx^2}} = \int_0^{z_1} \frac{dz}{H_0 \sqrt{\Omega_{matter}(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_\Lambda + \Omega_k (1+z)^2}}$
- solutions of the left side are $\frac{a_0}{c} \times \begin{cases} \frac{\arcsin(x_1\sqrt{k})}{\sqrt{k}} & k > 0 \\ x_1 & k = 0 \\ \frac{\operatorname{arcsinh}(x_1\sqrt{-k})}{\sqrt{-k}} & k < 0 \end{cases}$

Luminosity Distance

Putting this together with the appropriate trigonometric functions gives

$$D_L = a_0 x_1 (1+z) = \frac{c(1+z)}{H_0\sqrt{|\Omega_k|}} S\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\gamma(1+z')^4+\Omega_\Lambda+\Omega_k(1+z')^2}}\right)$$

with $S(y) = \begin{cases} \sin(y) & k > 0 \\ y & k = 0 \\ \sinh(y) & k < 0 \end{cases}$

Luminosity distance as a function of today's measurements (H_0, Ω's) and the redshift z

Luminosity Distance

- The rate of the photon arrivals is reduced by a factor $\frac{a(t_1)}{a(t_0)} = \frac{1}{1+z}$ and the energy of the photons ($E = h\nu$) is also reduced by a factor $(1+z)$ (remember luminosity L is energy per time)

$$l = \frac{L}{4\pi x_1^2 a^2(t_0)(1+z)^2}$$

- Set $D_L = x_1 a(t_0)(1+z)$ and we recover the equation for the luminosity distance $l = \frac{L}{4\pi D_L^2}$

Angular size distance

– A different method is to measure the angle of a distant object of known size $D_A = \frac{l}{\theta}$

(here l is the size of the object; θ the observed angle)

– Inspection of the metric (here we only need the $g_{\theta\theta}$ part), which gives $l = x_1 a(t_1)\theta$ and inserting this in the equation above yields $D_A = x_1 a(t_1)$ and with $\frac{a(t_1)}{a(t_0)} = \frac{1}{1+z}$ we find $\frac{D_L}{D_A} = (1+z)^2$.

Distance Duality

This is quite remarkable for high redshifts

- the physical distances differ for the same redshift!
- an object for which we could measure the angular size distance and the luminosity distance would give a different number of Mpc!
- a direct consequence of general relativity

$$\frac{D_L}{D_A} = (1+z)^2$$

z	$\frac{D_L}{D_A}$
0.1	1.21
0.15	1.32
0.2	1.44
0.25	1.56
0.3	1.69
0.35	1.82

Distance Duality

- Now measured in several systems
  - galaxy clusters
    - Sunyaev-Zeldovich effect
    - gravitational lenses
- Type II Supernovae
  - use two different methods to the same object
  - Expanding Photosphere Method
    - equates luminosity distance with angular size distance
  - Standardizable Candle Method
    - pure luminosity distance

Expansion of the Universe

Luminosity distance in an isotropic, homogeneous universe as a Taylor expansion

$$D_L = \frac{cz}{H_0}\left\{1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 \pm \frac{c^2}{H_0^2 R^2}\right]z^2 + O(z^3)\right\}$$

Hubble's Law deceleration jerk/equation of state

$$H_0 = \frac{\dot{a}}{a} \qquad q_0 = -\frac{\ddot{a}}{a}H_0^{-2} \qquad j_0 = \frac{\dddot{a}}{a}H_0^{-3}$$

Local Universe ($z \ll 1$)

Hubble Law

$$D = \frac{v}{H_0} = \frac{cz}{H_0}$$

Luminosity distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$

Distance modulus

$$m - M = 5\log(D_L) - 5$$

Distance in units of pc

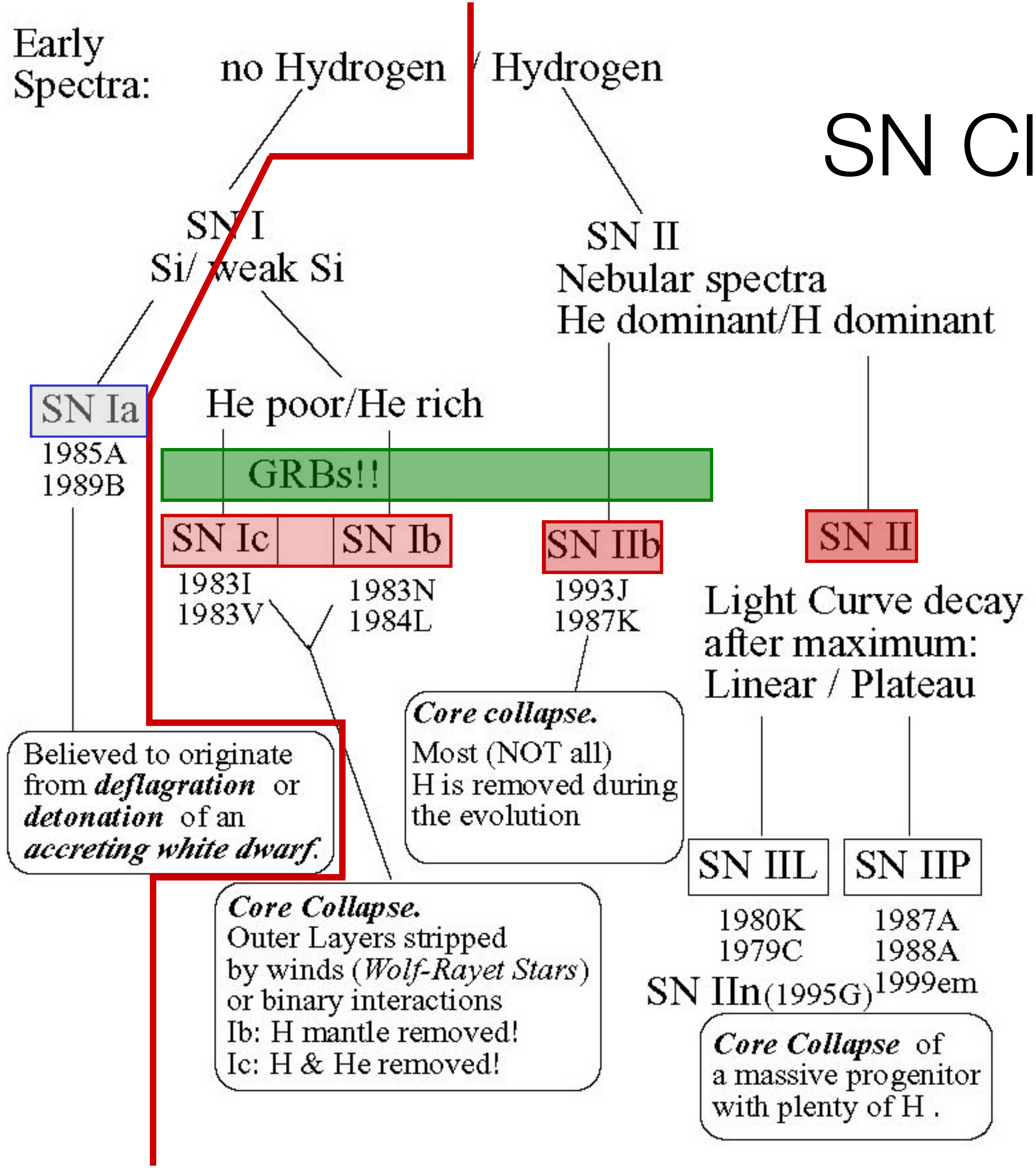
Hubble Constant

- Measure cosmic expansion velocity per unit scale length

$$H_0 = \frac{v}{D_L} \text{ (units: } km\ s^{-1}\ Mpc^{-1}\text{)}$$

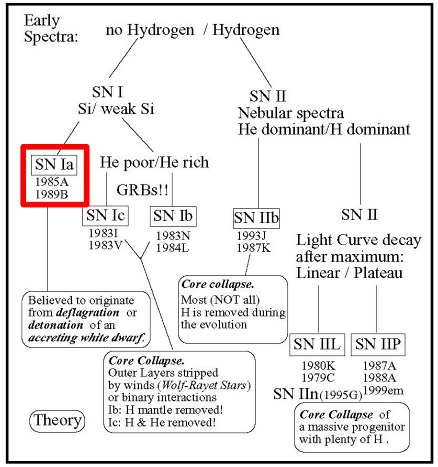
- Ignore higher-order cosmological effects
  – de/acceleration
- Spectroscopy → redshift → velocity
- Photometry → brightness → distance

SN Classification



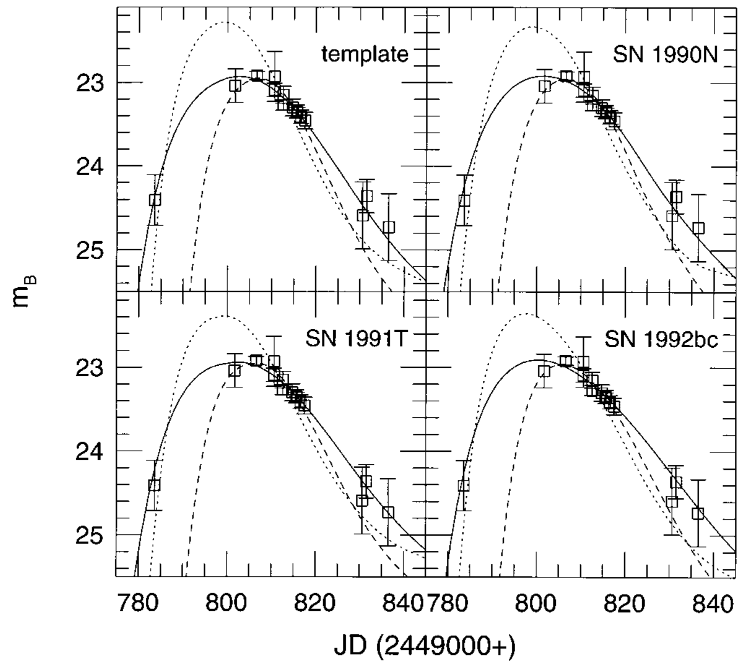
Bruno Leibundgut

Time Dilation in SNe Ia

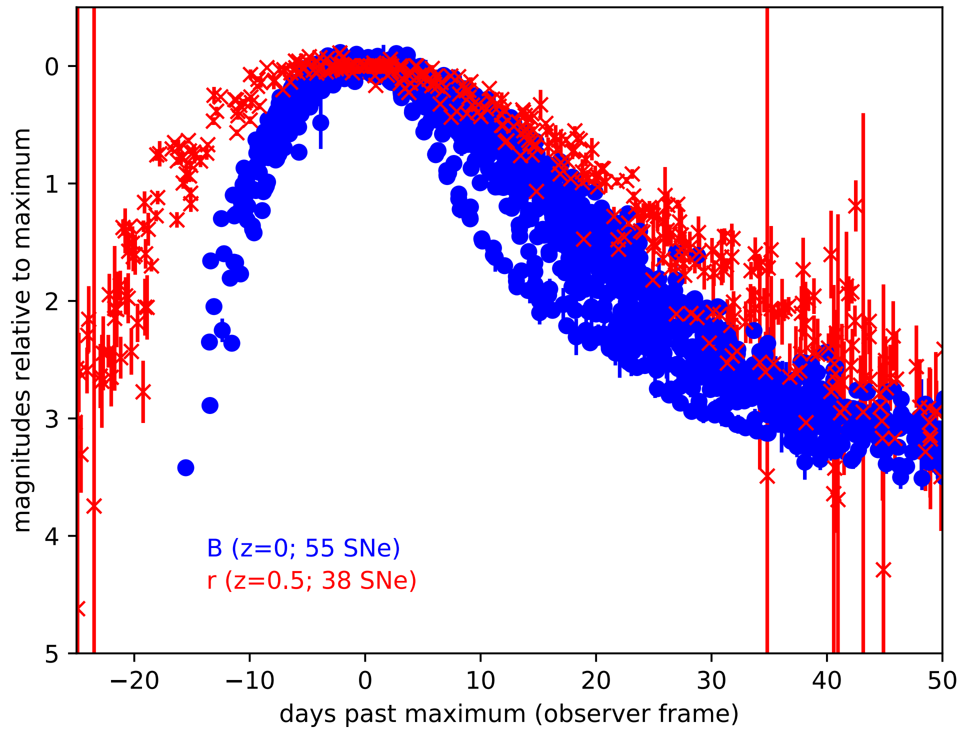


Uniform light curve shapes in a given filter

➔ Distant supernovae should show a 'slower' light curve

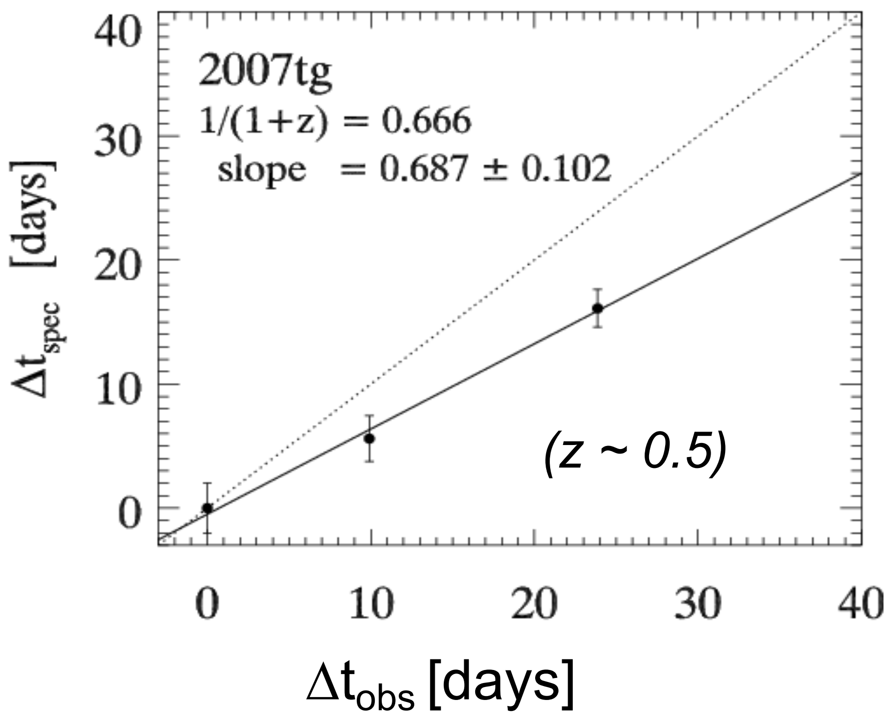


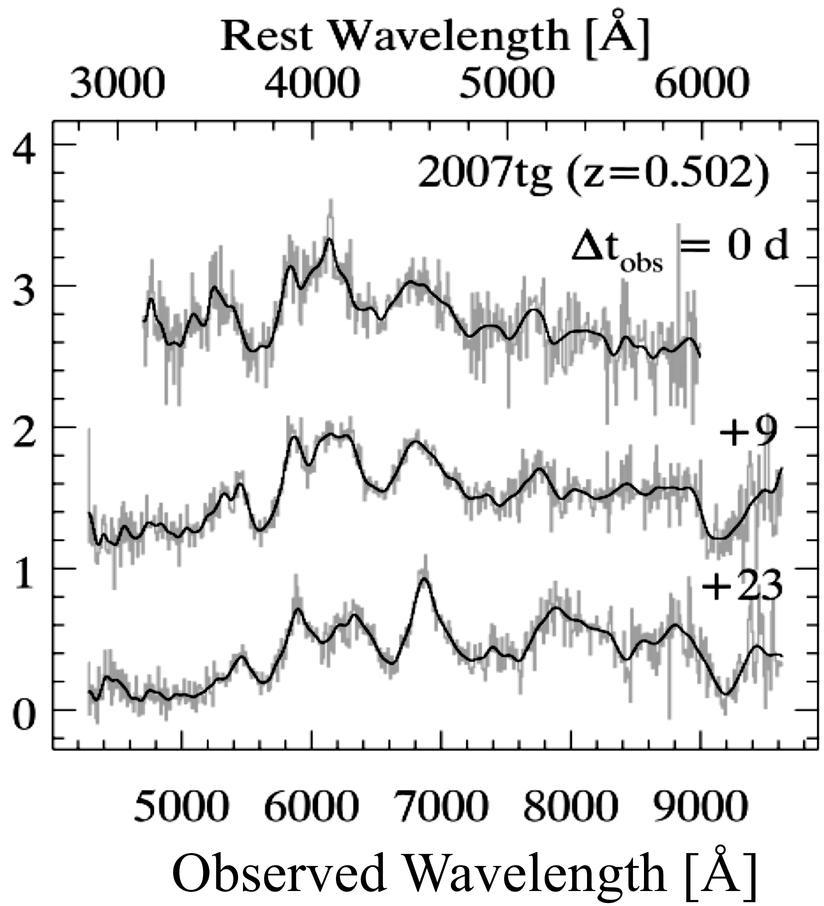
Leibundgut et al. 1996



Time dilation

Spectroscopic clock in the distant universe

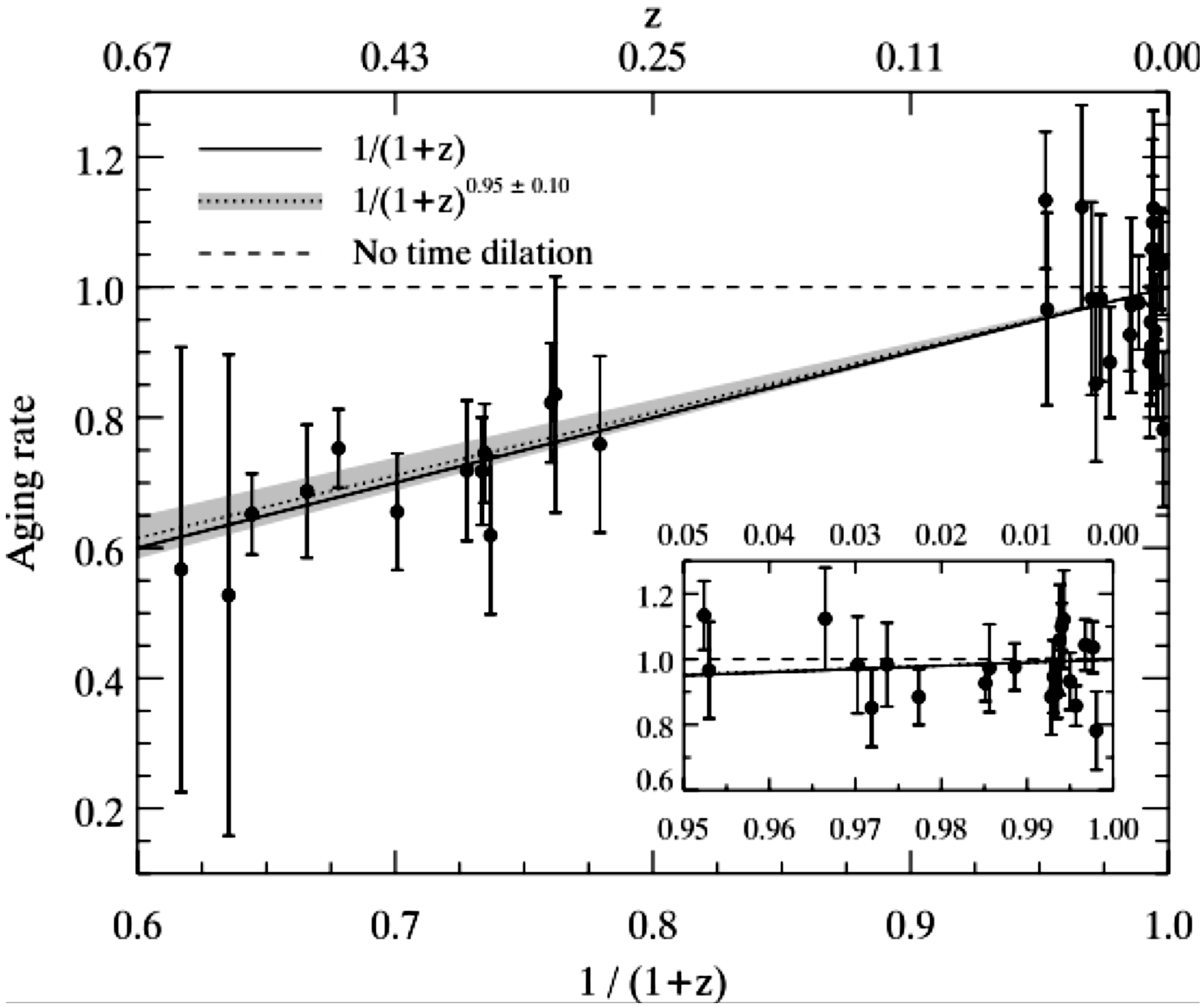




Blondin et al. (2008)

Time Dilation

'Tired Light' can be excluded beyond doubt ($\Delta\chi^2 = 120$)

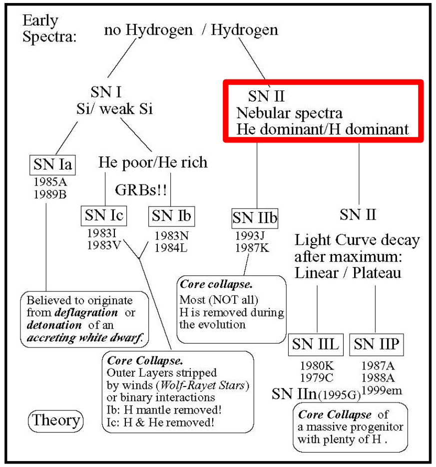


Blondin et al. (2008)

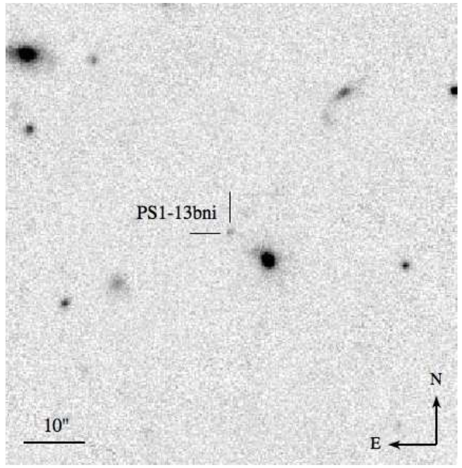
Distance to SN PS1-13bni

$(z = 0.335)$

Use EPM and CSM to measure distance to same supernova



SN	Dilution factor	Filter	D_L Mpc	Averaged D_L Mpc	$t_0^\star$ days*	Averaged $t_0^\star$ days*	$t_0^\diamond$ MJD	Estimate of t_0 via
PS1-13bni	H01 – Hβ	B	1699 ± 451	1772 ± 538	7.3 ± 12.4	8.1 ± 5.9	56 401.3 ± 7.9	EPM
		V	1538 ± 1109		5.4 ± 8.3			
		I	2078 ± 1082		11.7 ± 9.7			
	D05 – Hβ	B	2019 ± 542	2110 ± 658	8.6 ± 13.6	9.5 ± 6.4	56 400.0 ± 8.6	
		V	1823 ± 1349		6.6 ± 8.8			
		I	2488 ± 1336		13.4 ± 10.5			

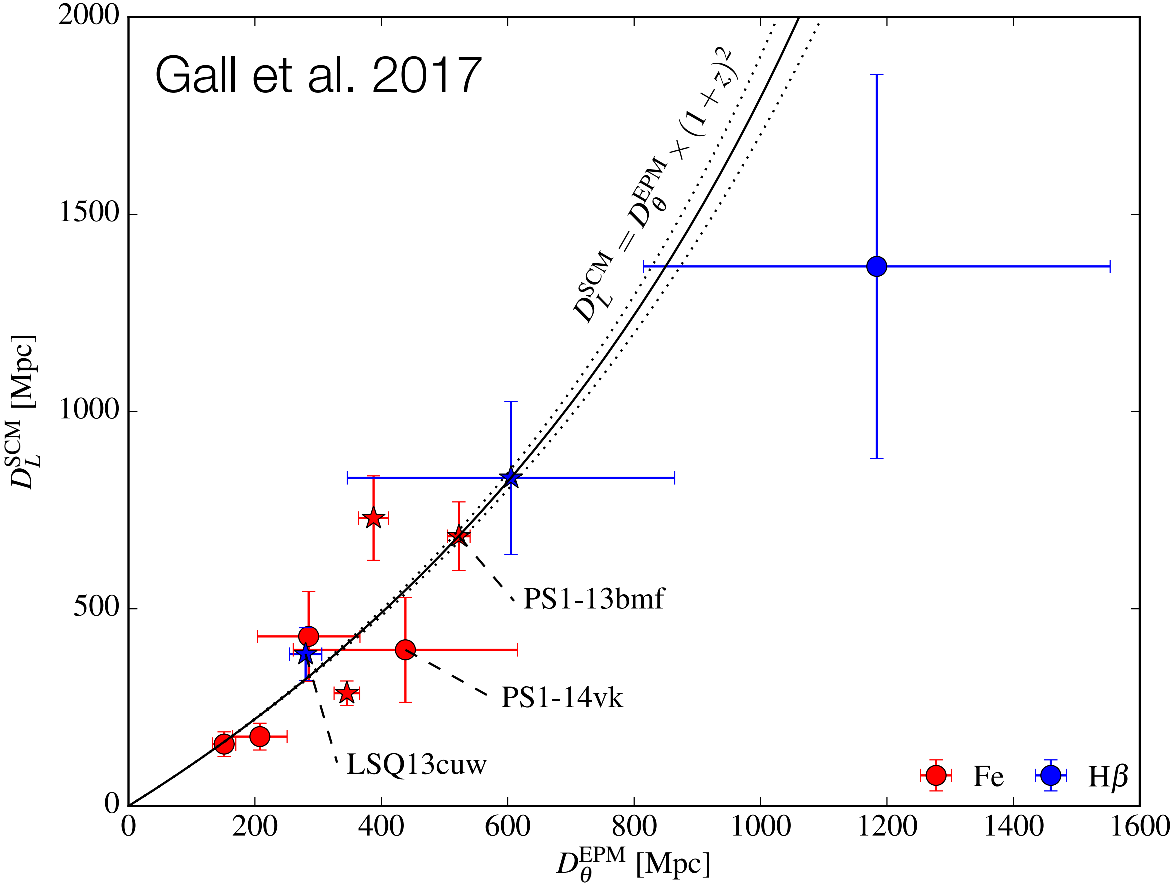


Gall et al. 2018

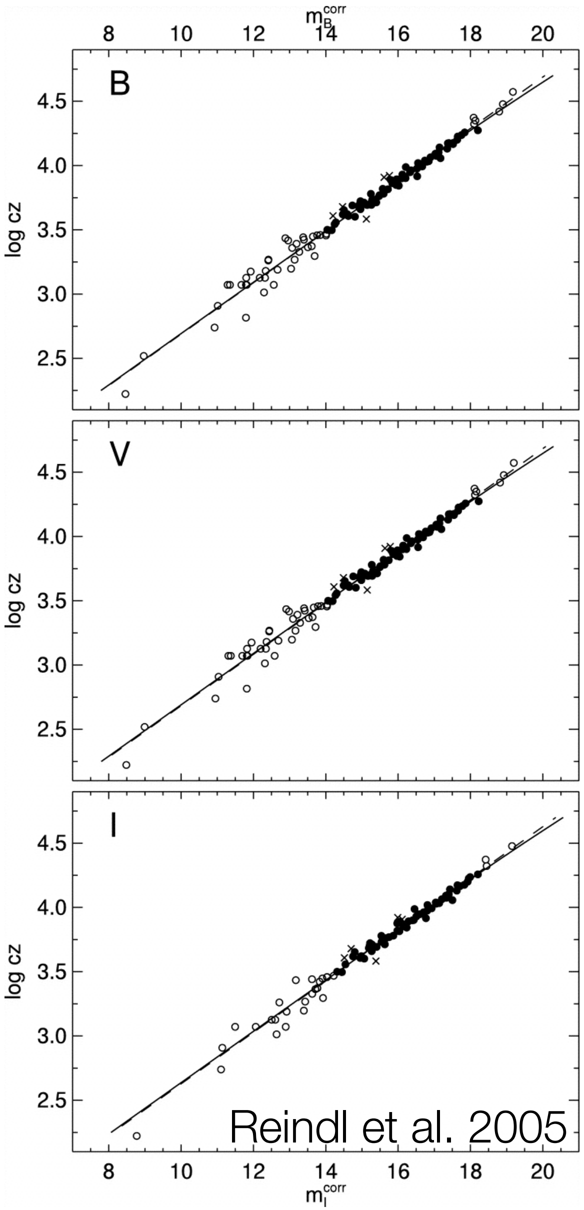
SN	Estimate of t_0 via	$t_0^\diamond$ mjd	V_{50}^* mag	I_{50}^* mag	v_{50} km s^{-1}	Estimate of velocity via	μ mag	D_L Mpc
PS1-13bni	EPM – H01	56 401.3 ± 7.9	23.39 ± 0.26	23.18 ± 0.20	5814 ± 1175	Hβ	40.65 ± 0.76	1348 ± 470
	EPM – D05	56 400.0 ± 8.6	23.39 ± 0.26	23.19 ± 0.20	5913 ± 1237		40.68 ± 0.77	1368 ± 487

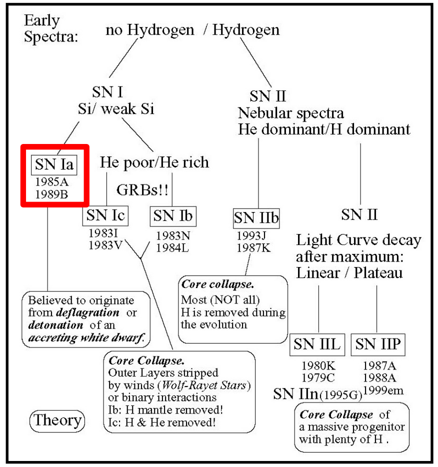
Distance Duality

First attempts inconclusive



SN Ia Hubble diagram



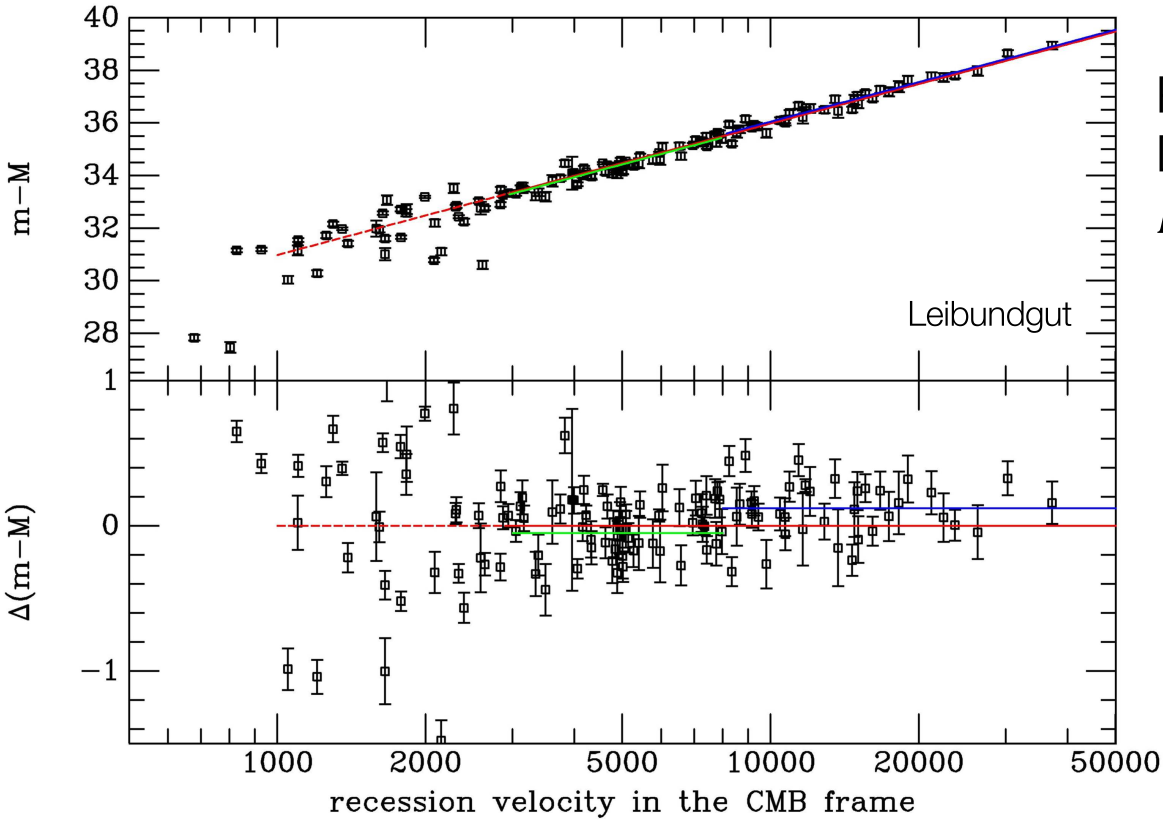


- Excellent distance indicators
- Experimentally verified
- Work of several decades
- Best determination of the Hubble constant

Hubble Constant

- SN Hubble diagram

$$m - M = 5\log v + 25 - 5\log H_0$$

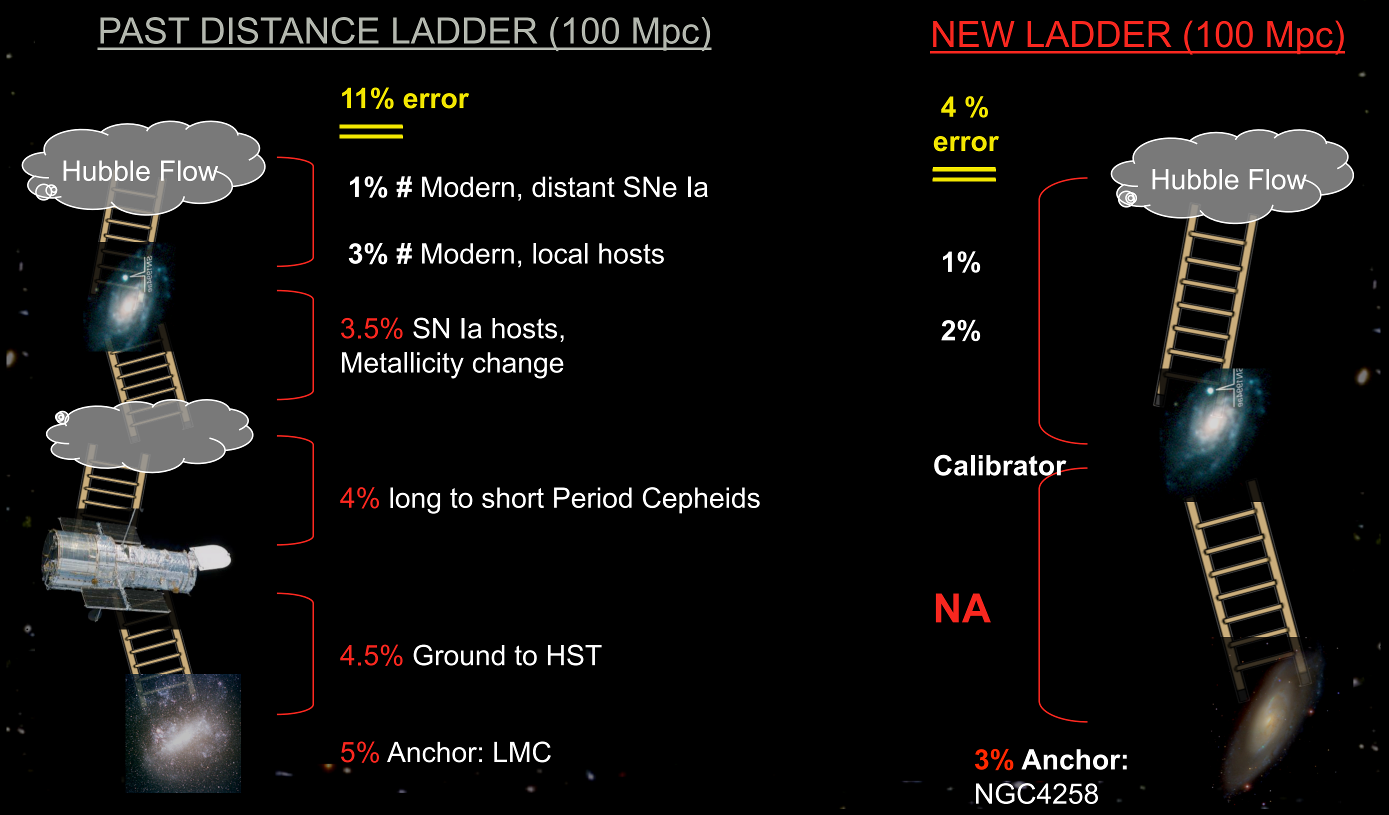


Proves M is constant
Direct connection of M and H_0

Hubble Constant

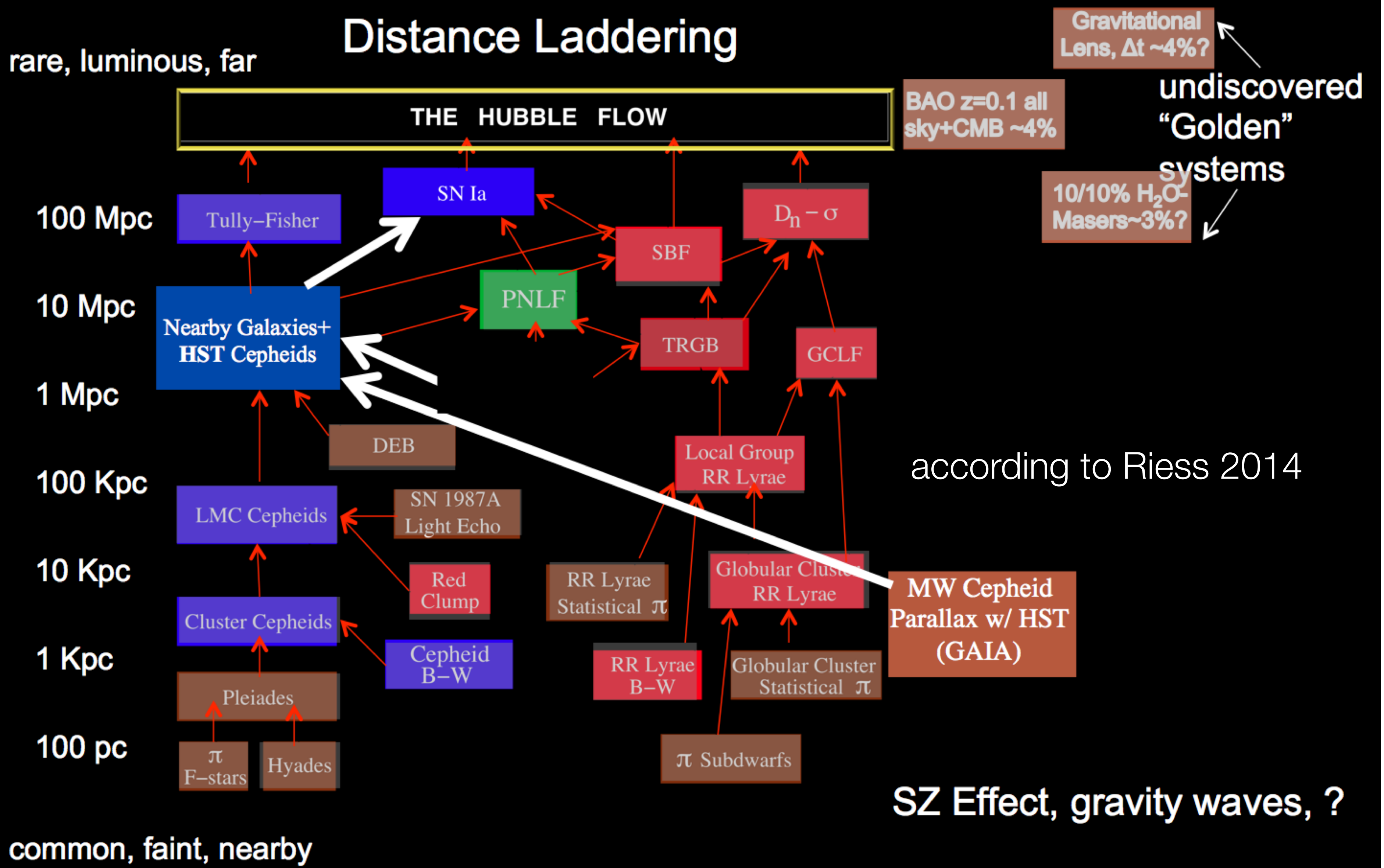
Calibration of *M(SN Ia @ max)*

- Distance ladder



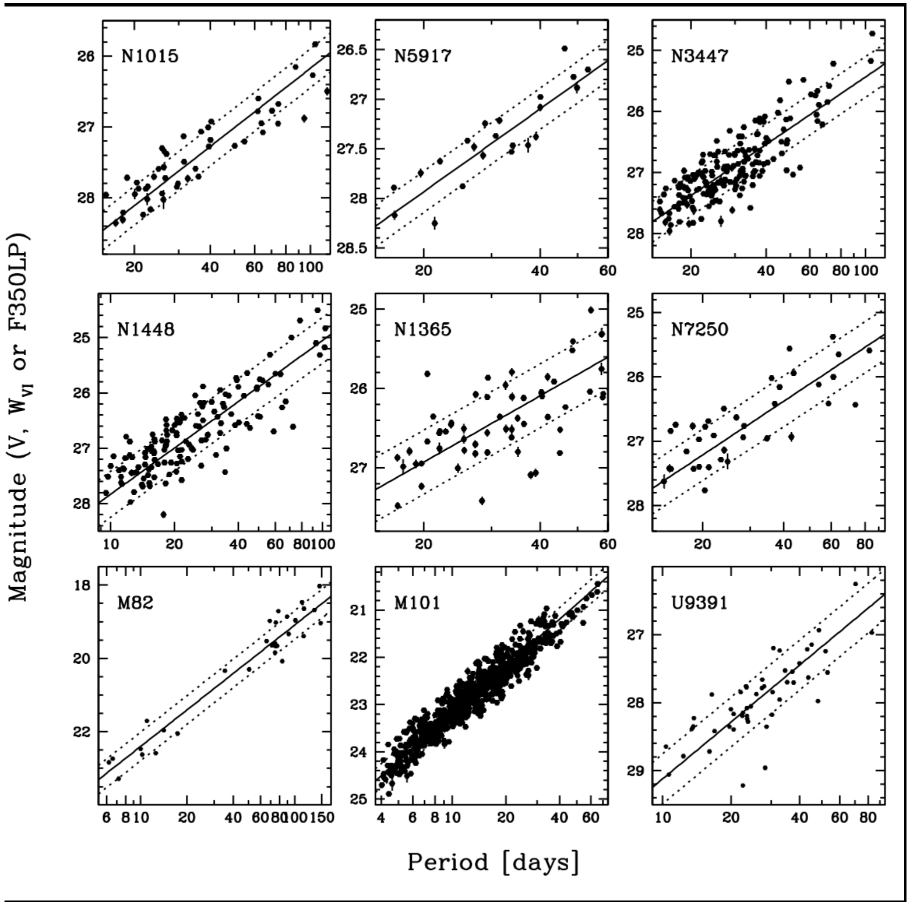
Adam Riess

Distance ladder

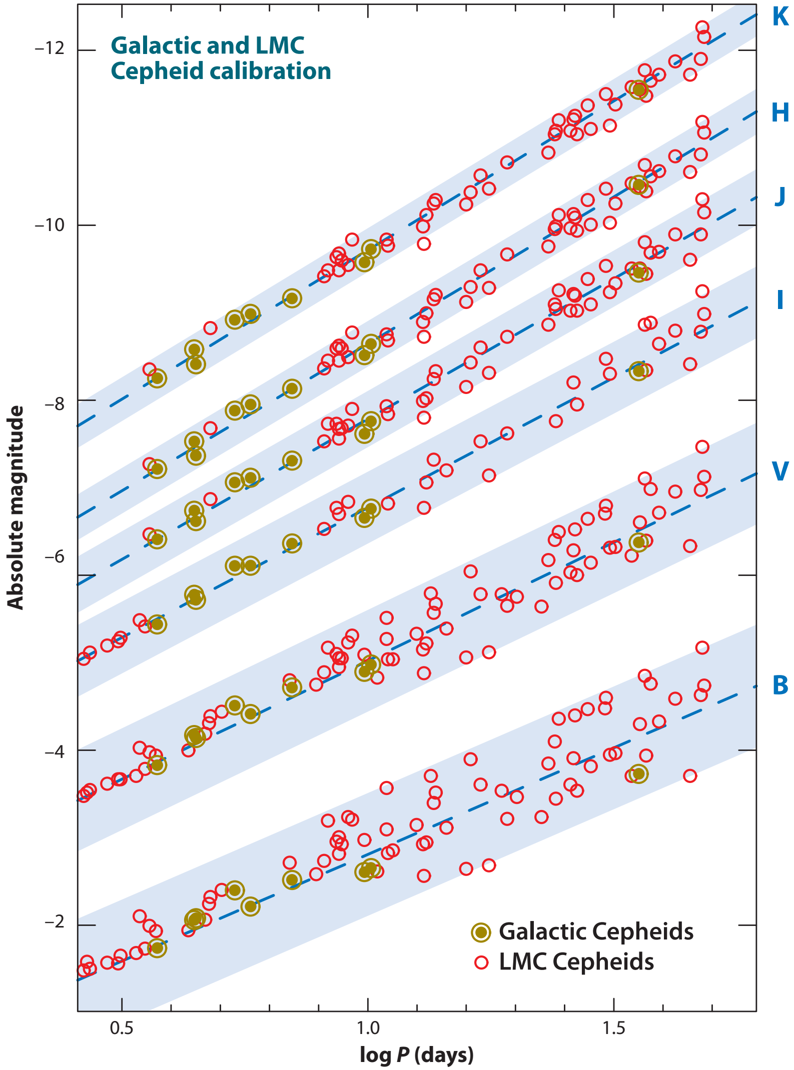


Cepheid Stars

Period-luminosity relation



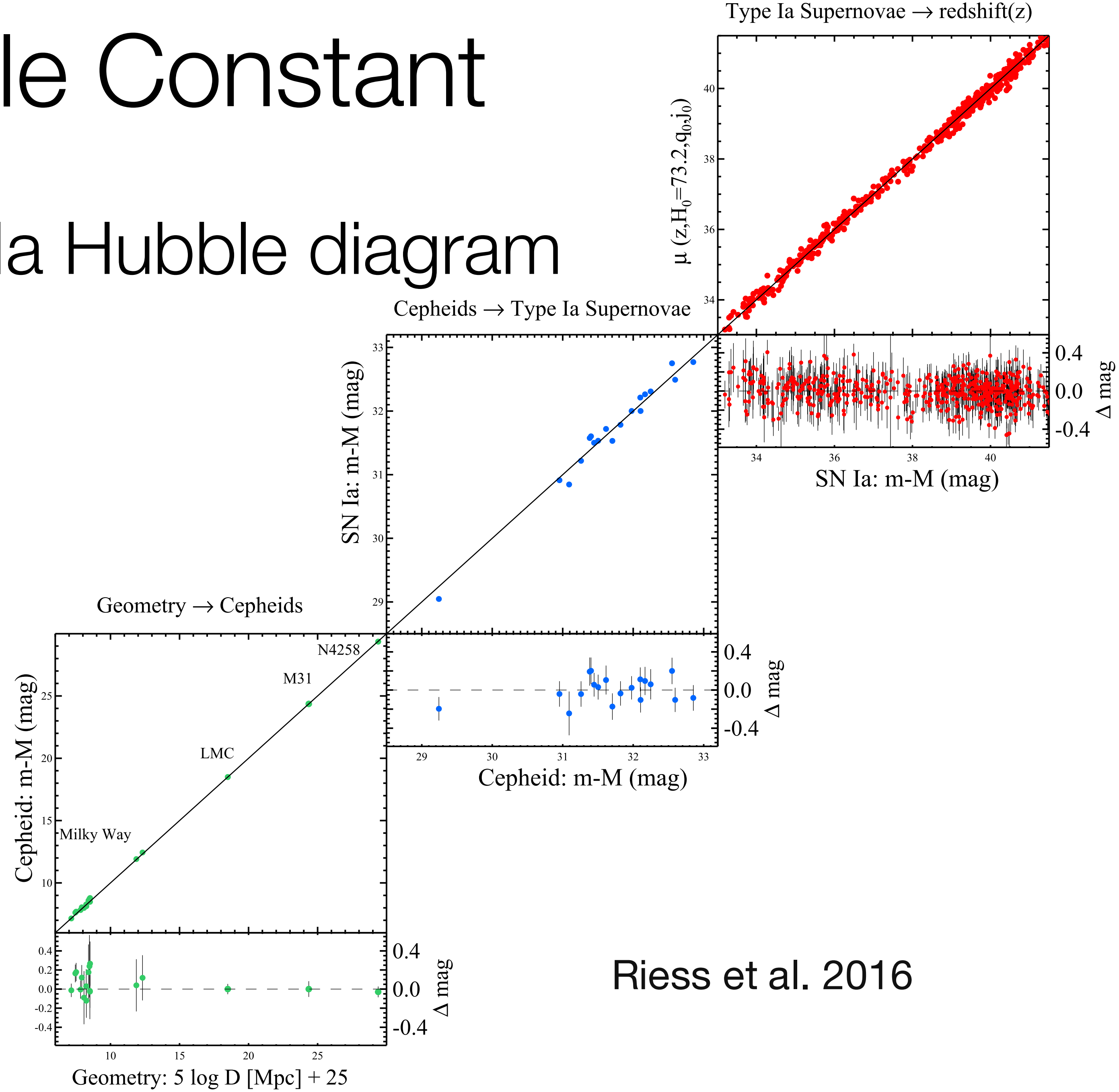
Riess et al. 2011



Freedman & Madore 2010

Hubble Constant

Supernova Ia Hubble diagram



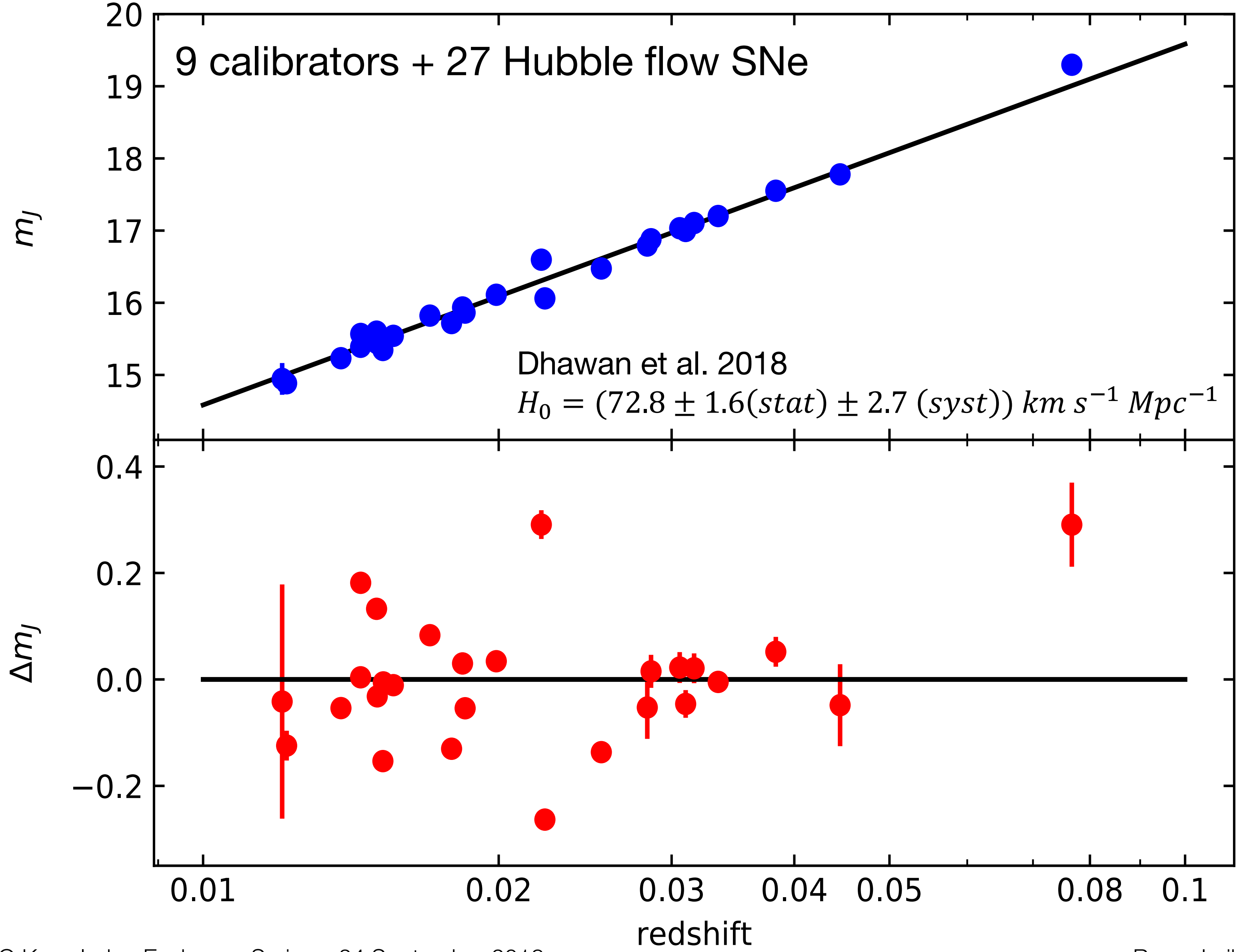
Riess et al. 2016

Hubble Constant

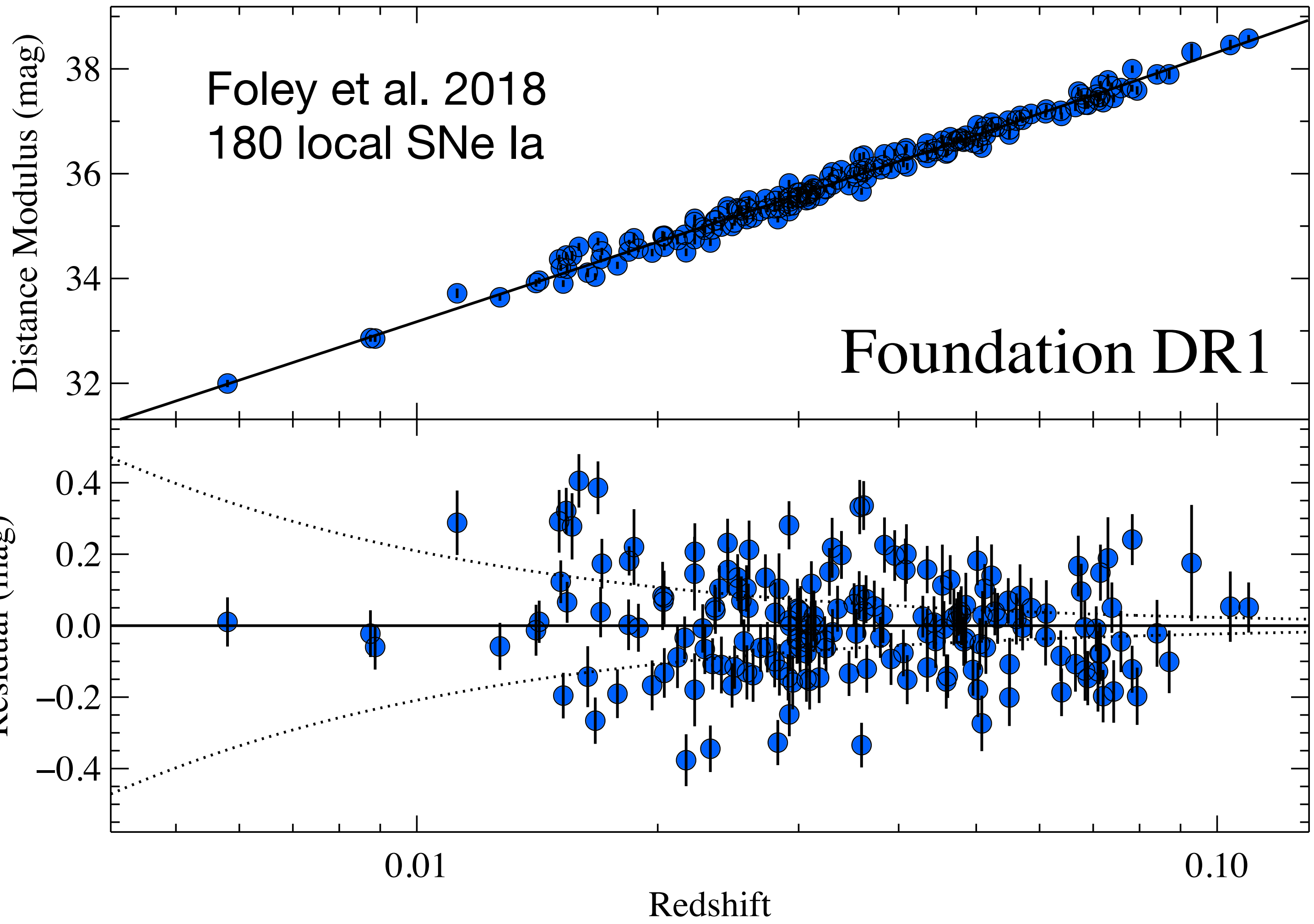
Caveats

- local calibrators still uncertain
  - Large Magellanic Cloud
  - Maser in NGC 4258
  - in the future geometric distances (parallaxes) to nearby Cepheids
- extinction
  - absorption of light by dust in the Milky Way and in the host galaxy
  - corrections not always certain
- peculiar velocities of galaxies
  - typically around 300 km/s

Current Status (NIR)



Foundation Survey



Hubble Constant(s)

Planck satellite (CMB; 2016)

measurement at $z \approx 1000$

$$H_0 = (67.8 \pm 0.9)\ km\ s^{-1} Mpc^{-1}$$

Riess et al. (local; 2016)

$$H_0 = (73.24 \pm 1.74)\ km\ s^{-1}\ Mpc^{-1}$$

Dhawan et al. (local; NIR; 2018)

same zero-point as Riess et al. (2016)

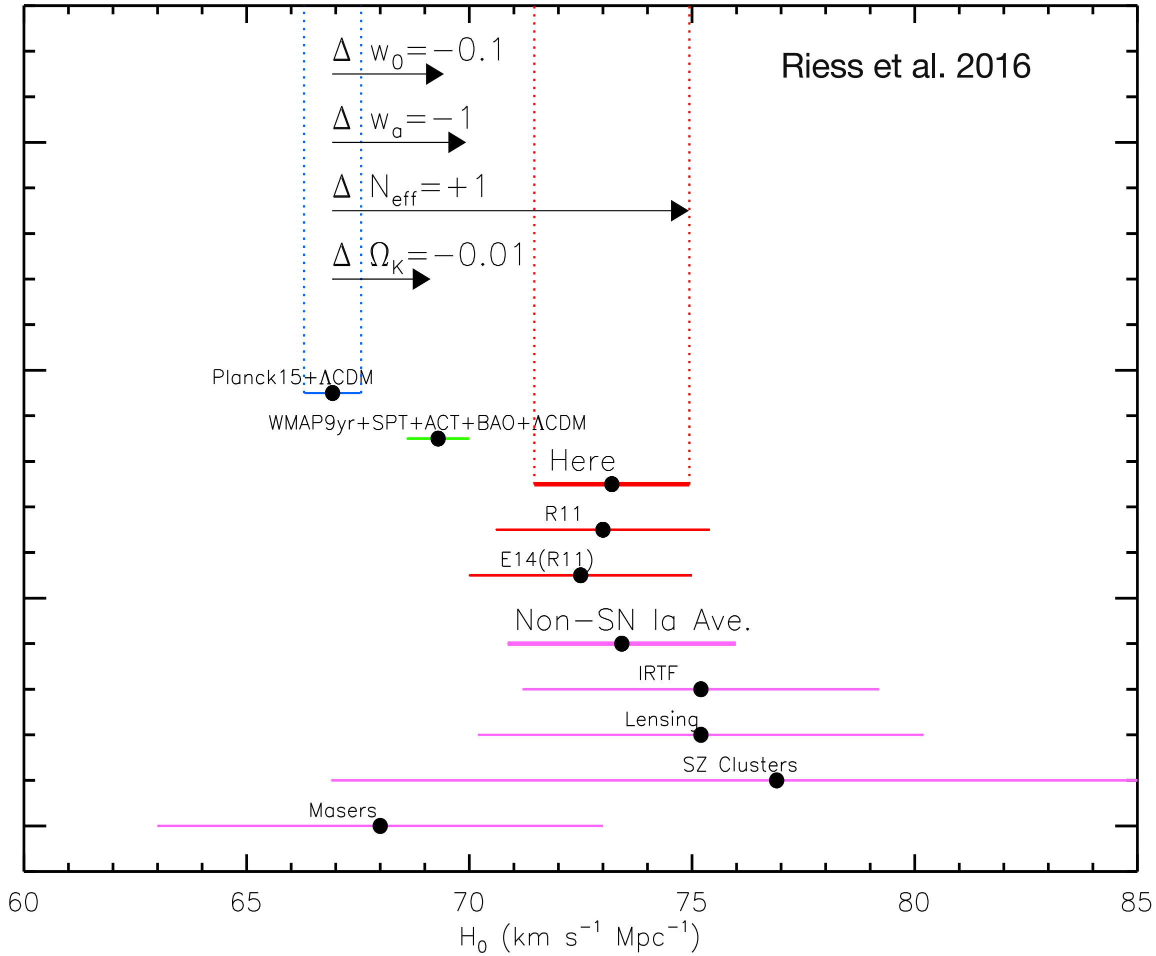
$$H_0 = (72.8 \pm 1.6(stat) \pm 2.7\ (syst))\ km\ s^{-1}\ Mpc^{-1}$$

Riess et al. (local; 2018)

$$H_0 = (73.53 \pm 1.62)\ km\ s^{-1}\ Mpc^{-1}$$

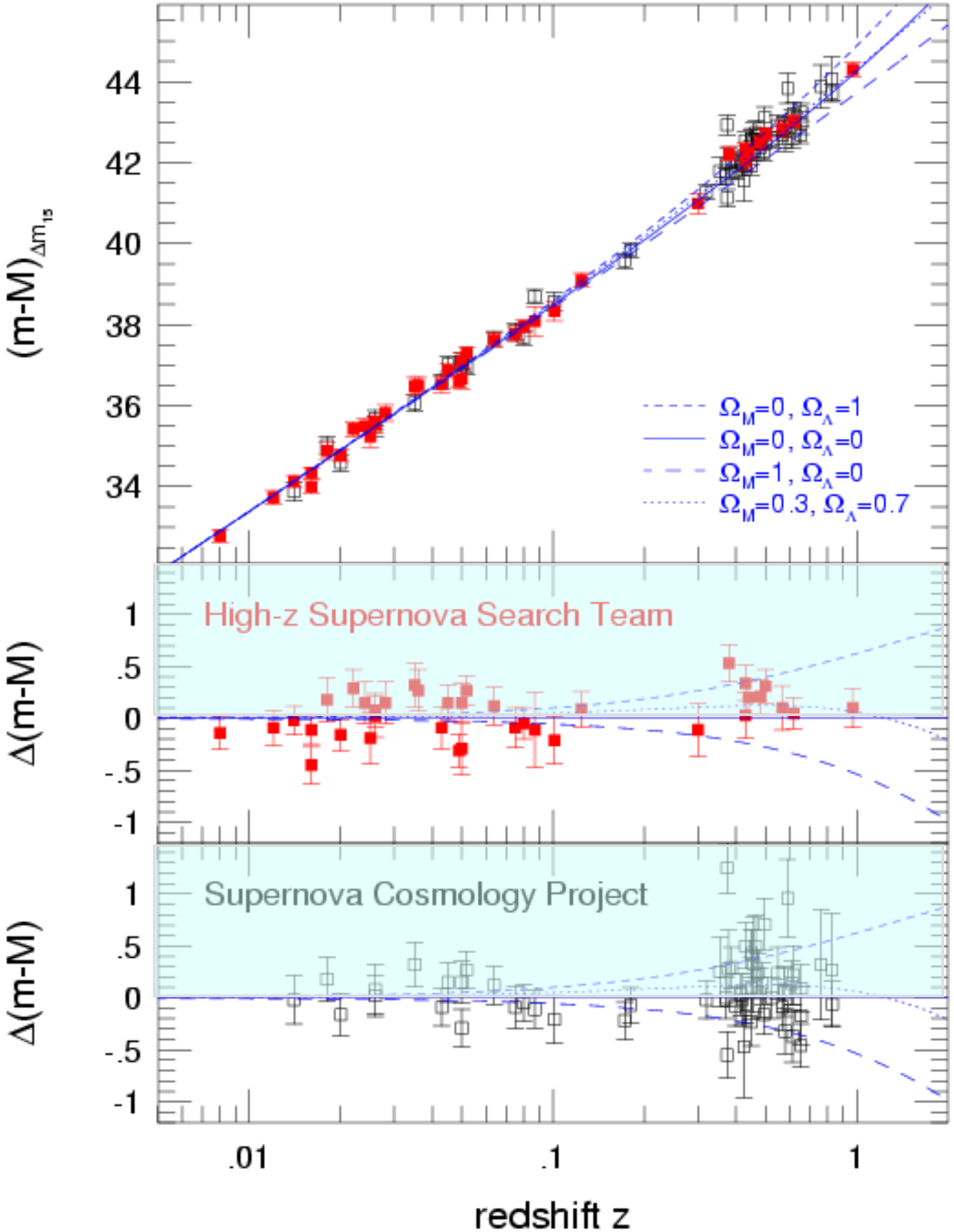
Hubble Constant

Latest values



Gaia and H_0

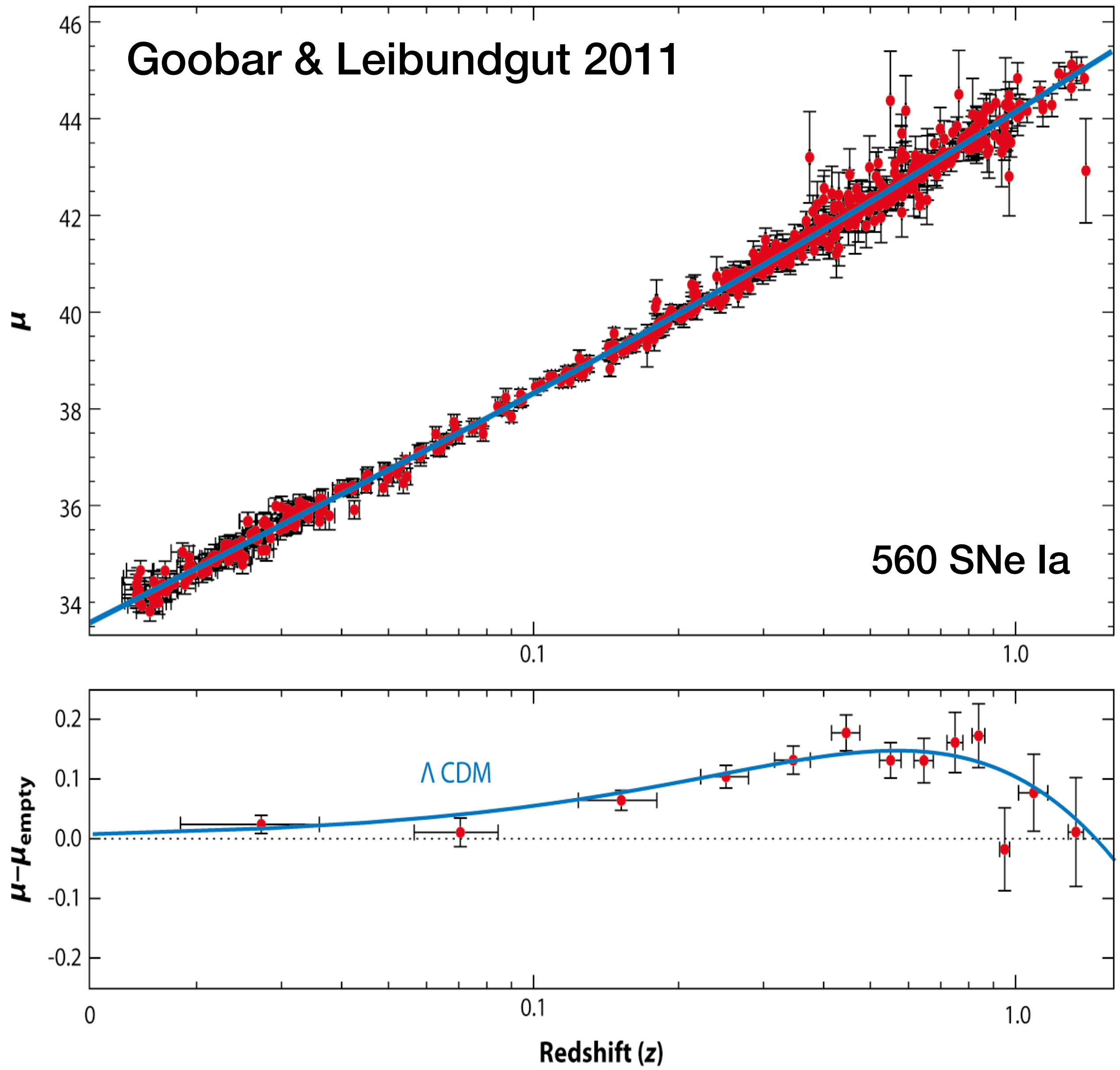
- Calibrate Cepheid distances with parallaxes
  - long-period Cepheids so far not accessible
- Single step to the SNe Ia
- Helps to bypass intermediate steps and calibrators
  - reduced uncertainty on H_0
- Goal: uncertainty less than 1%



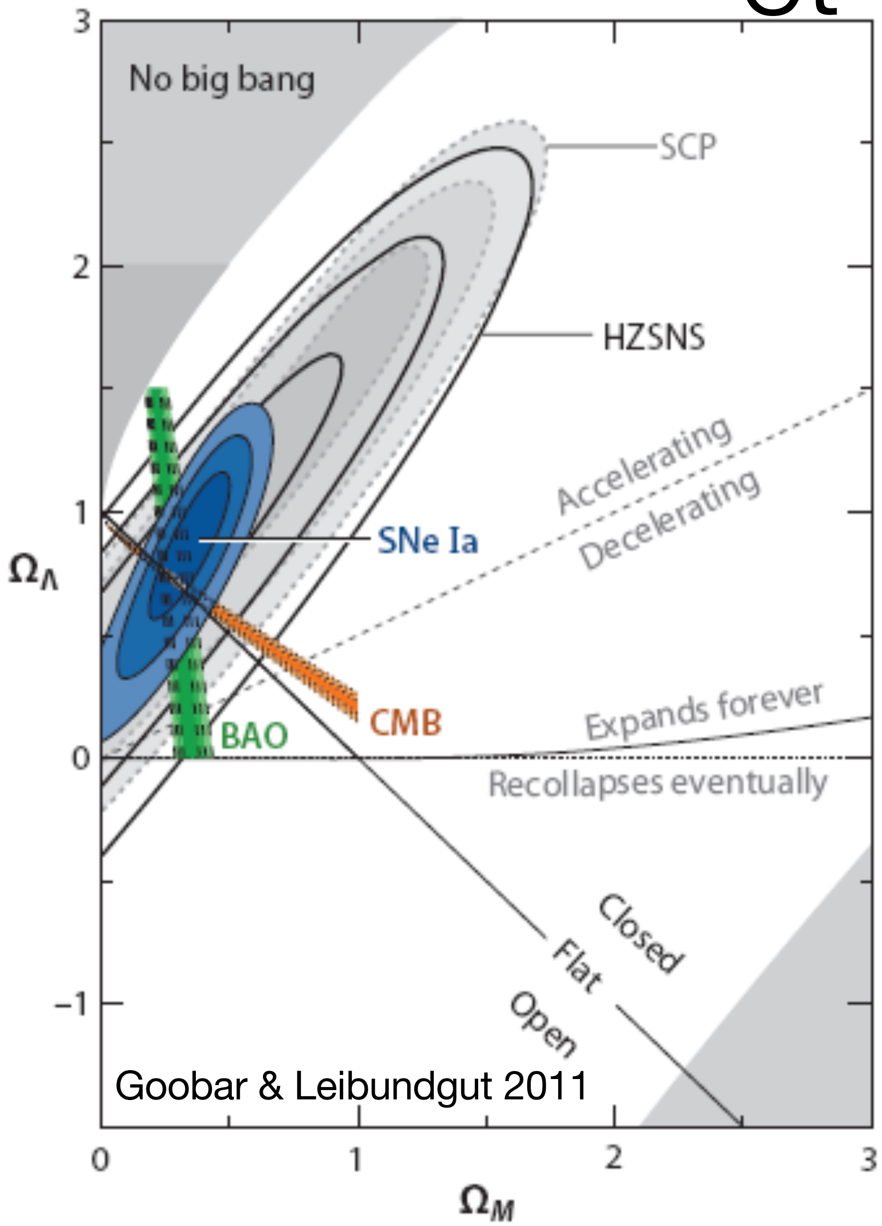
The SN Hubble Diagram

Bruno Leibundgut

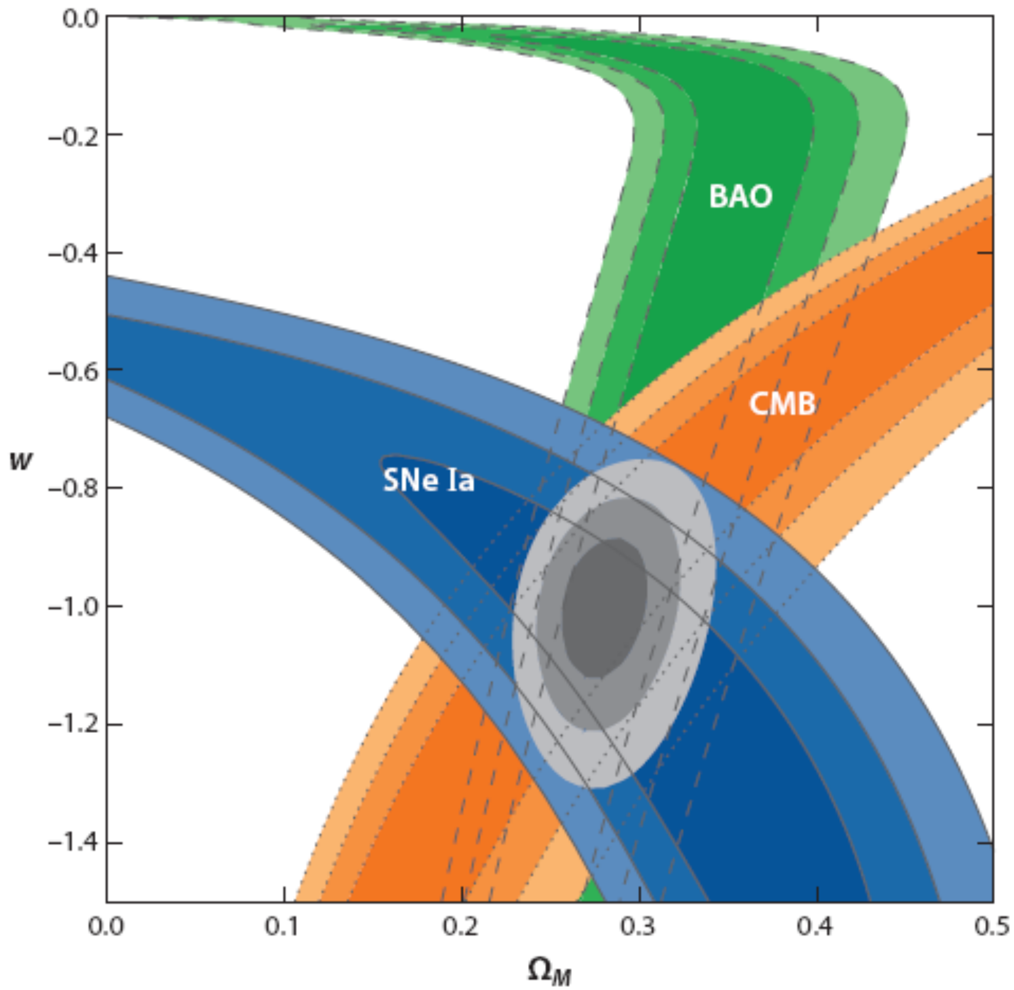
Supernova Cosmology



et voilà ...



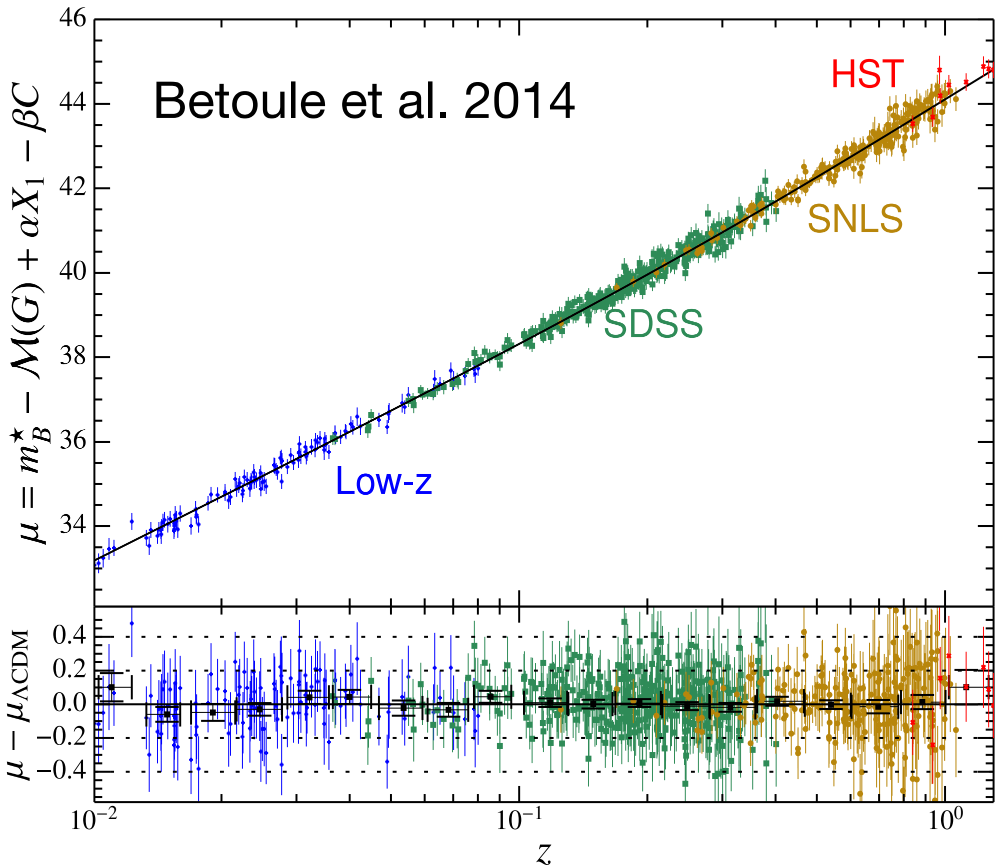
10 years of progress



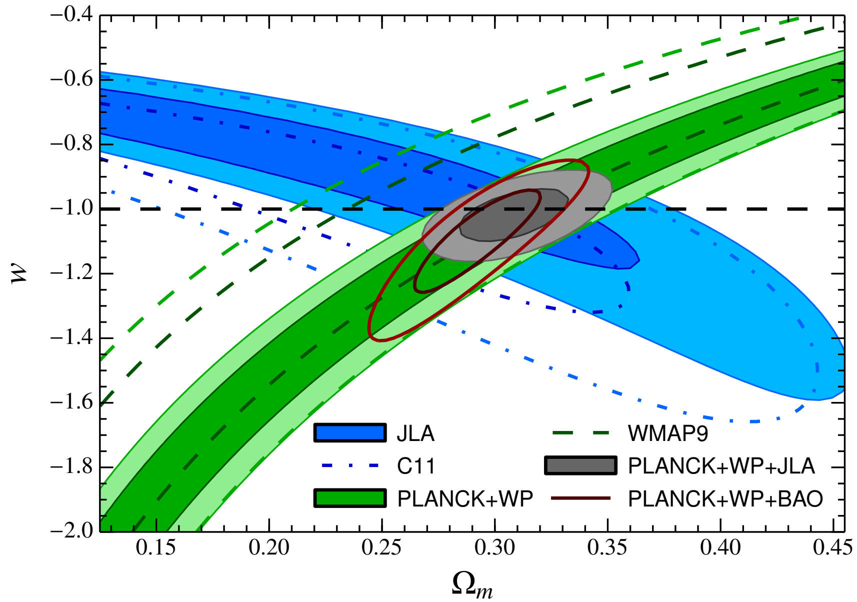
Constant ω firmly established

N_{SN}	Ω_M(flat)	*w* (constant, flat)	Light curve fitter	Reference
115	$0.263^{+0.042}_{-0.042}{}^{+0.032}_{-0.032}$	$-1.023^{+0.090}_{-0.090}{}^{+0.054}_{-0.054}$	SALT	Astier et al. 2006
162	$0.267^{+0.028}_{-0.018}$	$-1.069^{+0.091}_{-0.083}{}^{+0.13}_{-0.13}$	MLCS2k2	Wood-Vasey et al. 2007
178	$0.288^{+0.029}_{-0.019}$	$-0.958^{+0.088}_{-0.090}{}^{+0.13}_{-0.13}$	SALT2	
288	$0.307^{+0.019}_{-0.019}{}^{+0.023}_{-0.023}$	$-0.76^{+0.07}_{-0.07}{}^{+0.11}_{-0.11}$	MLCS2k2	Kessler et al. 2009
288	$0.265^{+0.016}_{-0.016}{}^{+0.025}_{-0.025}$	$-0.96^{+0.06}_{-0.06}{}^{+0.13}_{-0.13}$	SALT2	
557	$0.279^{+0.017}_{-0.016}$	$-0.997^{+0.050}_{-0.054}{}^{+0.077}_{-0.082}$	SALT2	Amanullah et al. 2010
472		$-0.91^{+016}_{-0.20}{}^{\pm0.07}_{-0.14}$	SiFTO/SALT2	Conley et al. 2011
472	0.269 ± 0.015	$-1.061^{+0.069}_{-0.068}$	SALT2	Sullivan et al. 2011
580	0.271 ± 0.014	$-1.013^{+0.077}_{-0.073}$	SALT2	Suzuki et al. 2011
740	0.295 ± 0.034	-1.018 ± 0.057 CMB	SALT2	Betoule et al. 2014
		-1.027 ± 0.055 CMB+BAO		
313	$0.277^{+0.010}_{-0.012}$	$-1.186^{+0.076}_{-0.065}$	SALT2	Rest et al. 2014
1049	0.306 ± 0.012	-1.031 ± 0.040	SALT2	Scolnic et al. 2018
1369	0.324 ± 0.042	-0.986 ± 0.058	SALT2	Jones et al. 2018

Status 2014

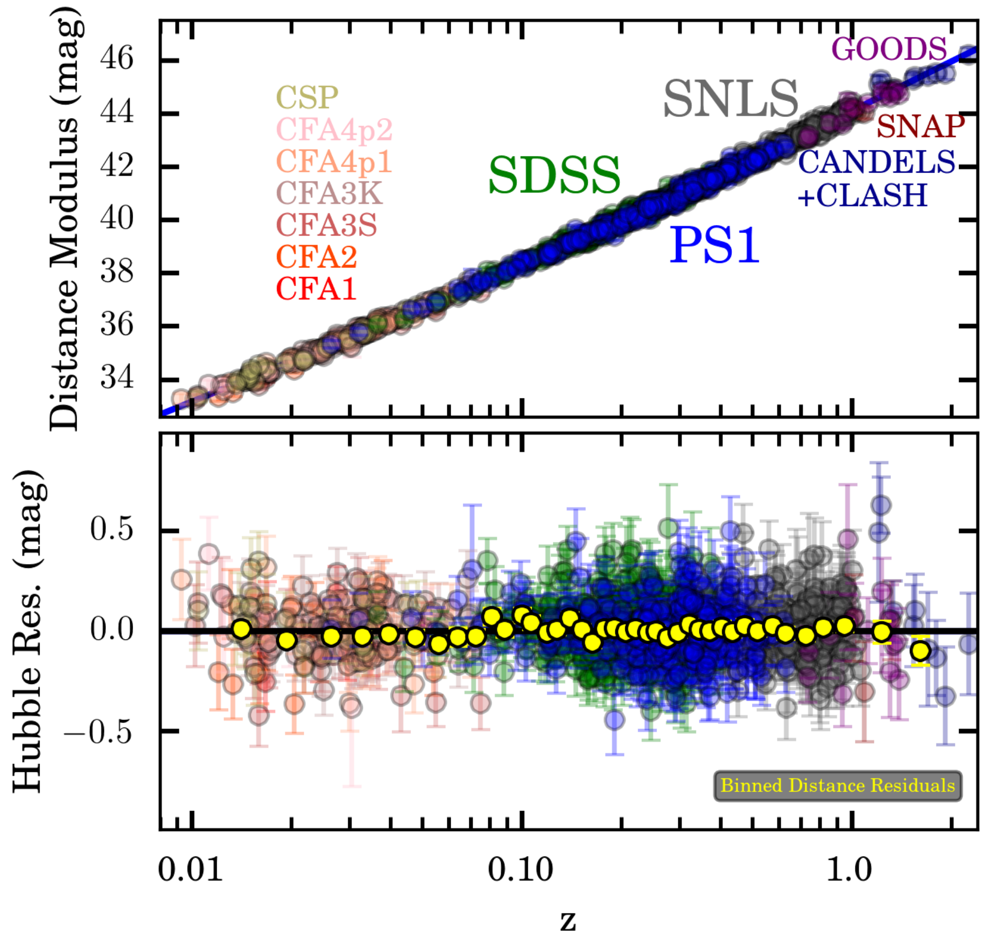


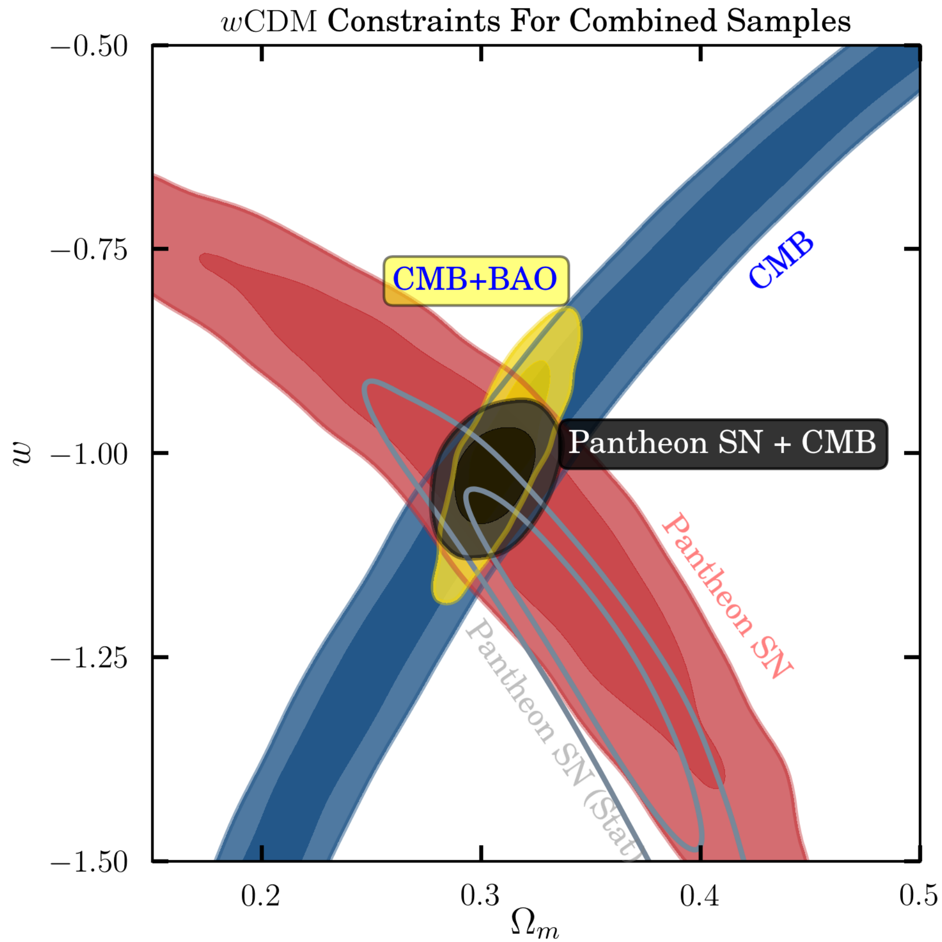
Betoule et al. 2014
HST
SNLS
SDSS
Low-z
$\mu = m_B^\star - \mathcal{M}(G) + \alpha X_1 - \beta C$
$\mu - \mu_{\Lambda CDM}$
46
44
42
40
38
36
34
0.4
0.2
0.0
−0.2
−0.4
10^{-2}
10^{-1}
10^{0}
z



−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
w
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Ω_m
JLA
C11
PLANCK+WP
WMAP9
PLANCK+WP+JLA
PLANCK+WP+BAO

Status 2018





Scolnic et al. 2018

What next?

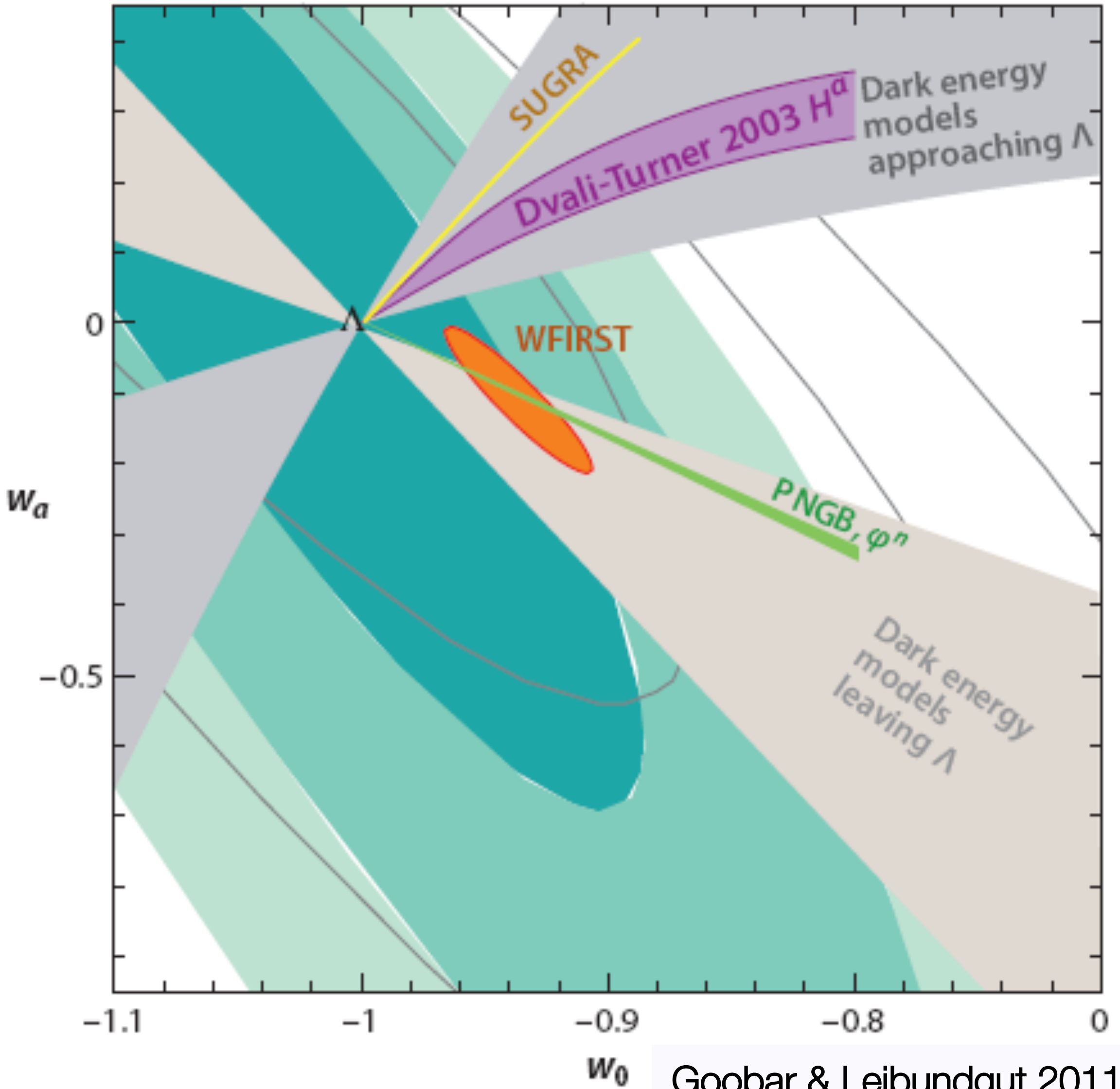
Already in hand

- >1000 SNe Ia for cosmology
- constant ω determined to 5%
- accuracy dominated by systematic effects

Missing

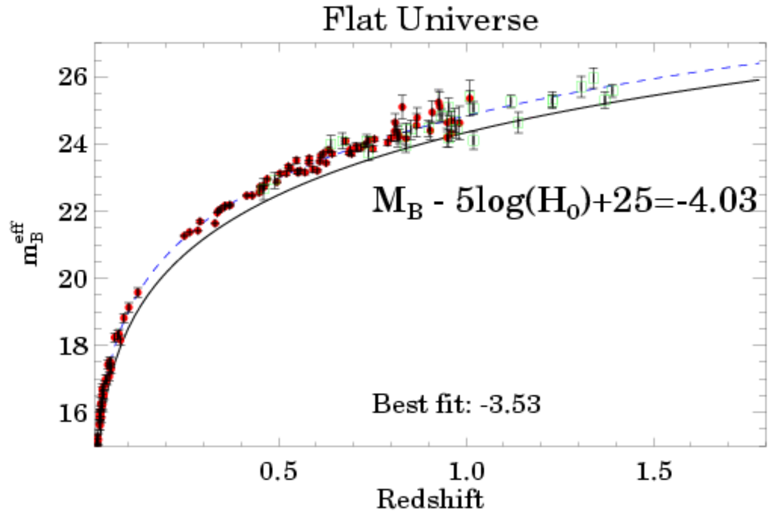
- good data at z>1
  - light curves and spectra
- good infrared data at z>0.5
  - cover the restframe B and V filters
  - move towards longer wavelengths to reduce absorption effects

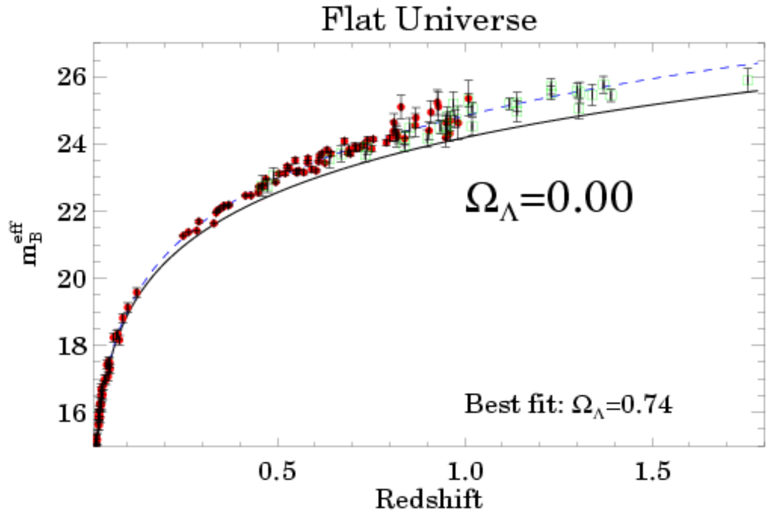
Cosmology – more?

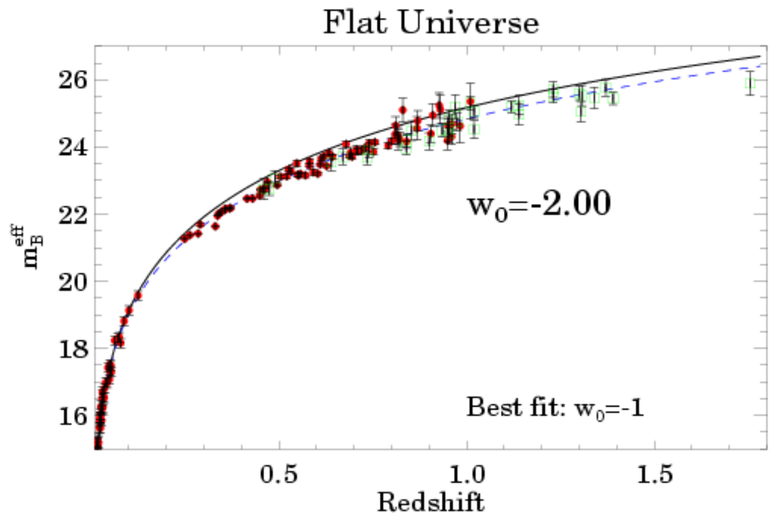


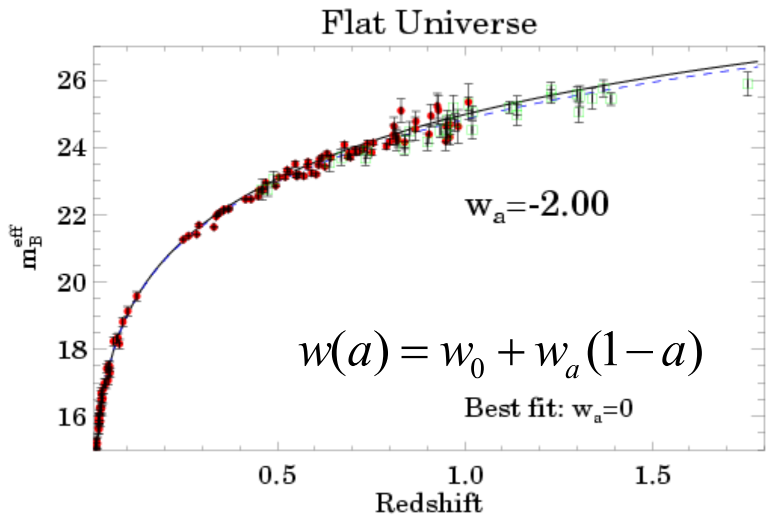
Goobar & Leibundgut 2011
(courtesy E. Linder and J. Johansson)

Multi-parameter problem









Ariel Goobar
Bruno Leibundgut

Speculations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein's cosmologal constant

- No explanation in particle physics theories

Quintessence

- Quantum mechanical particle field releasing energy into the universe

Signatures of high dimensions

- Gravity is best described in theories with more than four dimensions

Phantom Energy

- Dark Energy dominates and eventually the universe end in a (Big Rip)