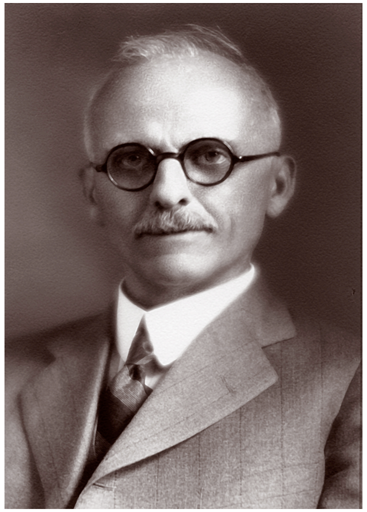
H_0 and the never-ending story of the expansion rate of the Universe

Bruno Leibundgut
ESO

Great Debate: What is the size of the Universe?

Presentations at the Annual Meeting of the National Academy of Sciences in Washington DC, 26. April 1920

Harlow Shapley vs. Heber Curtis



http://incubator.rockefeller.edu/geeks-of-the-week-harlow-shapley-heber-curtis/

Wikipedia

Models of the Milky Way

Jacobus Kapteyn (1922)

- based on stellar counts in selected areas
- Kapteyn contributed many stars in the southern hemisphere

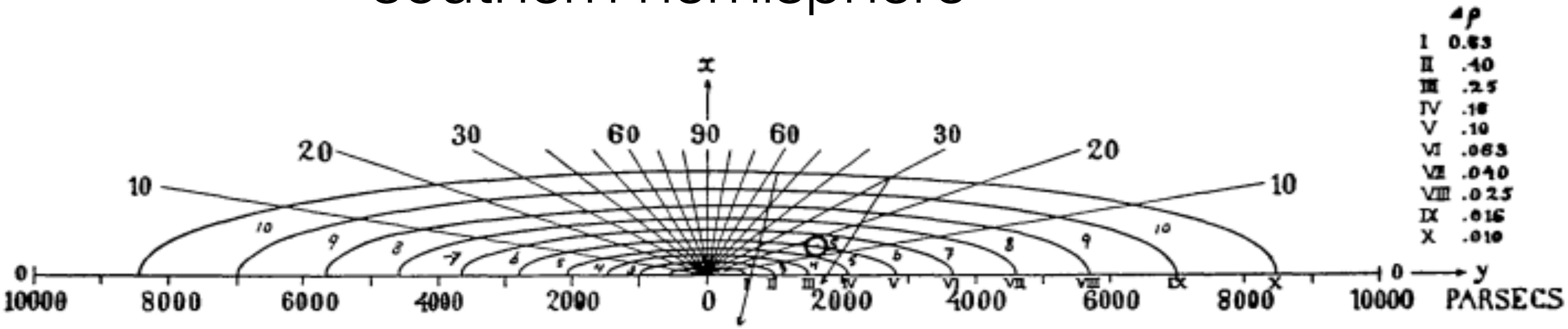


FIG. I

Background

Expanding universe

→ expansion rate critical for cosmic evolution

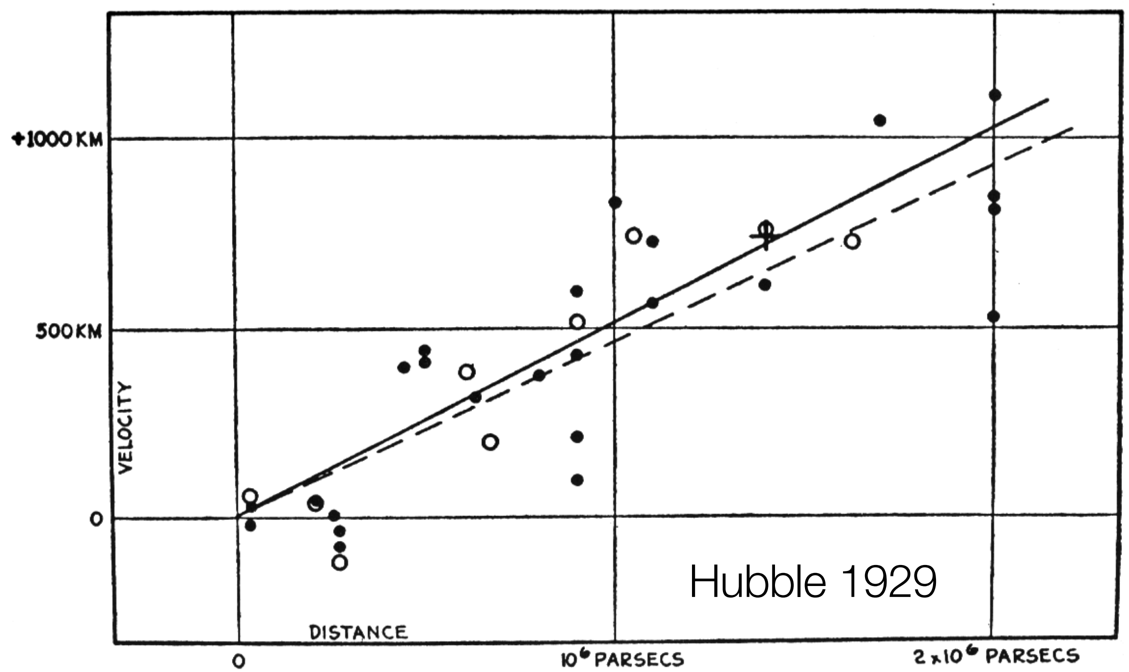
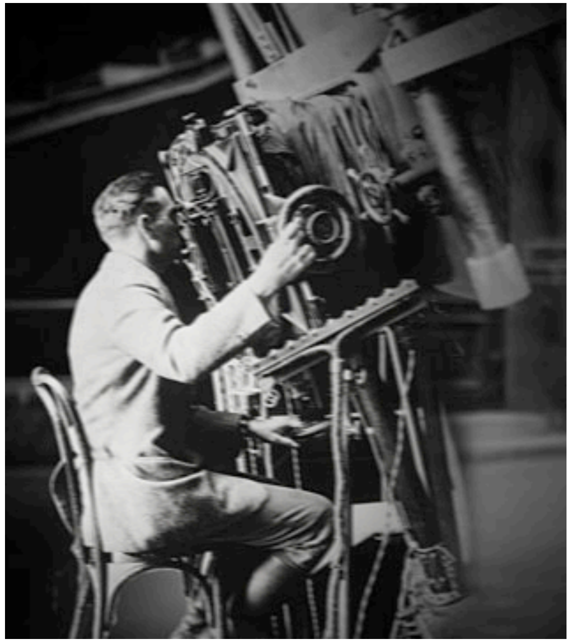


FIG. 9. *The Formulation of the Velocity-Distance Relation.*



STScI

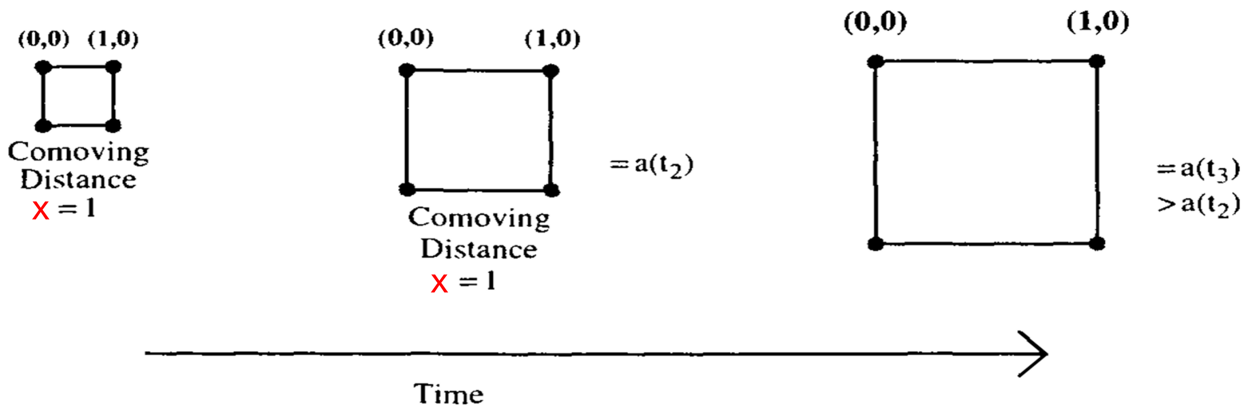
Leading Theory of the Universe

Dealing with an expanding Universe

Cosmic Distances

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

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



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 and a perfect fluid

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

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2 & 0 & 0 \\ 0 & 0 & a^2 & 0 \\ 0 & 0 & 0 & a^2 \end{pmatrix}$$

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

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

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

History of H_0

Expansion rate by G. Lemaître (1927)

de l'observateur. En effet, la période de la lumière émise dans des conditions physiques semblables doit être partout la même lorsqu'elle est exprimée en temps propre.

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \qquad (22)$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

Footnote!

(²) En ne donnant pas de poids aux observations, on trouverait 670 Km./sec à $1{,}16 \times 10^6$ parsecs, 575 Km./sec à 10^6 parsecs. Certains auteurs ont cherché à mettre en

Intermezzo
Age of the Universe

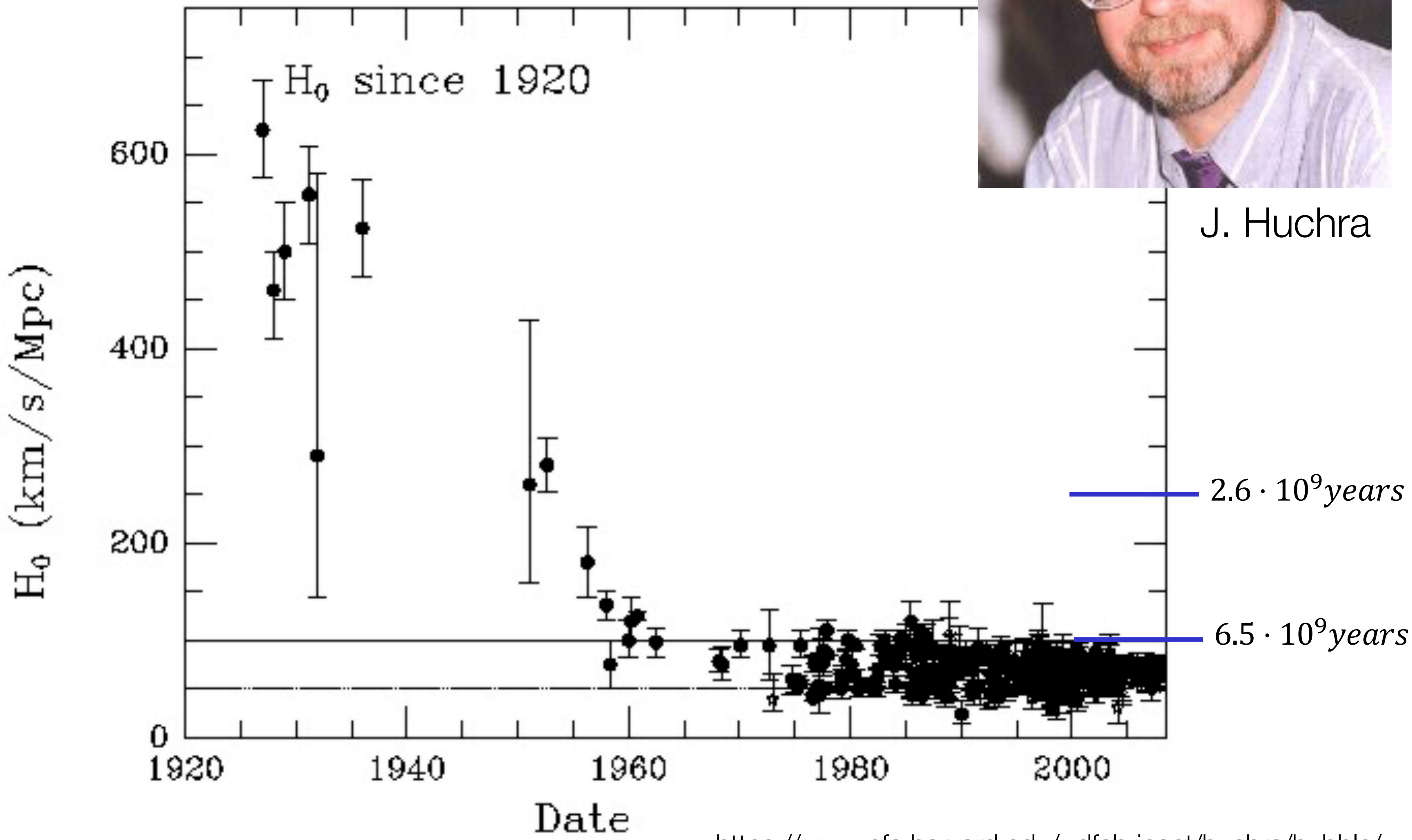
Matter-dominated universe has the following age

$$t_0 = \frac{2}{3H_0}$$

H_0 (km/s/Mpc)	t_0 (yr)
500	$1.30 \cdot 10^{9}$
250	$2.61 \cdot 10^{9}$
100	$6.52 \cdot 10^{9}$
80	$8.15 \cdot 10^{9}$
70	$9.32 \cdot 10^{9}$
60	$1.09 \cdot 10^{10}$
50	$1.30 \cdot 10^{10}$
30	$2.17 \cdot 10^{10}$

- age of the Earth: $4.5 \cdot 10^{9}$ years
- oldest stars: $\sim 1.2 \cdot 10^{10}$ years

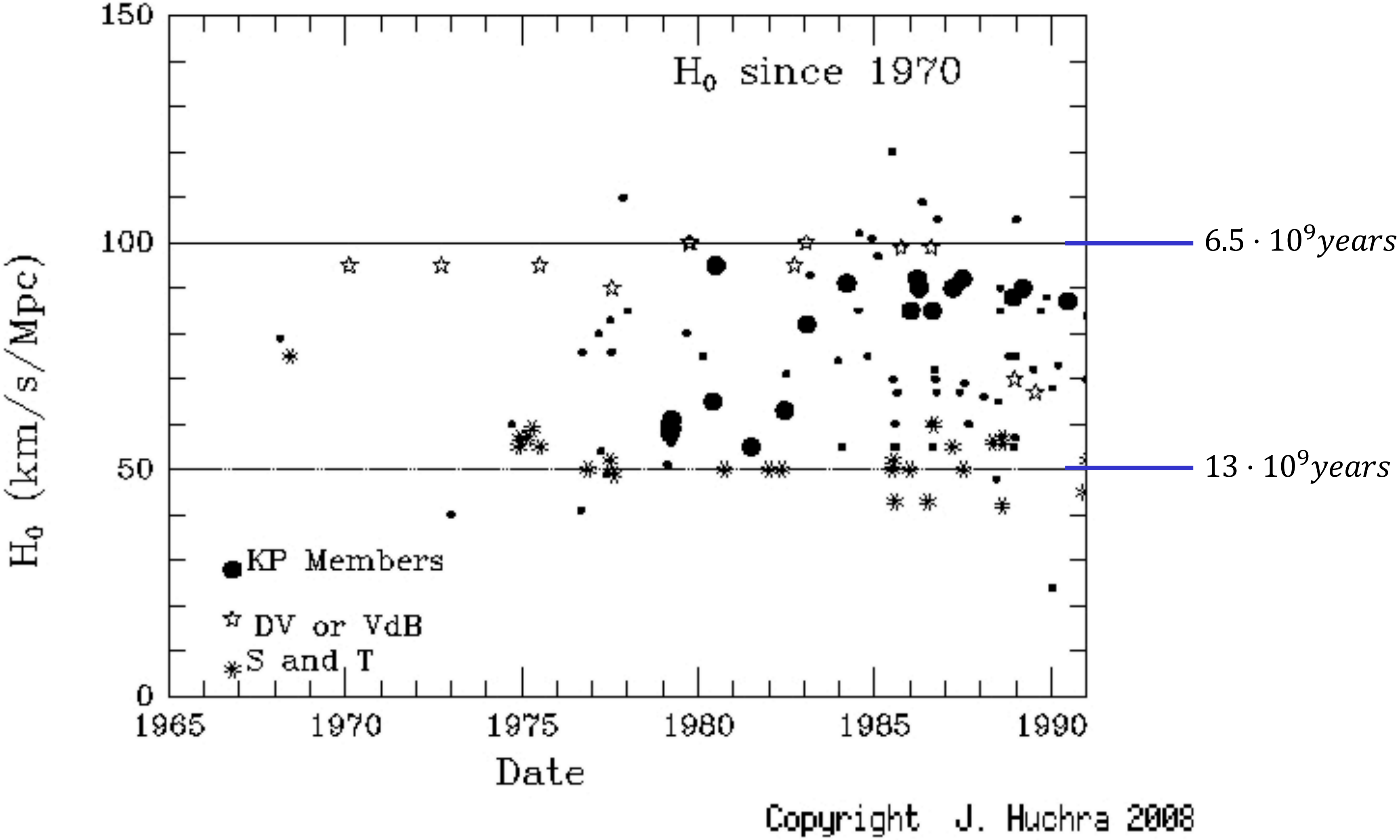
History of H_0



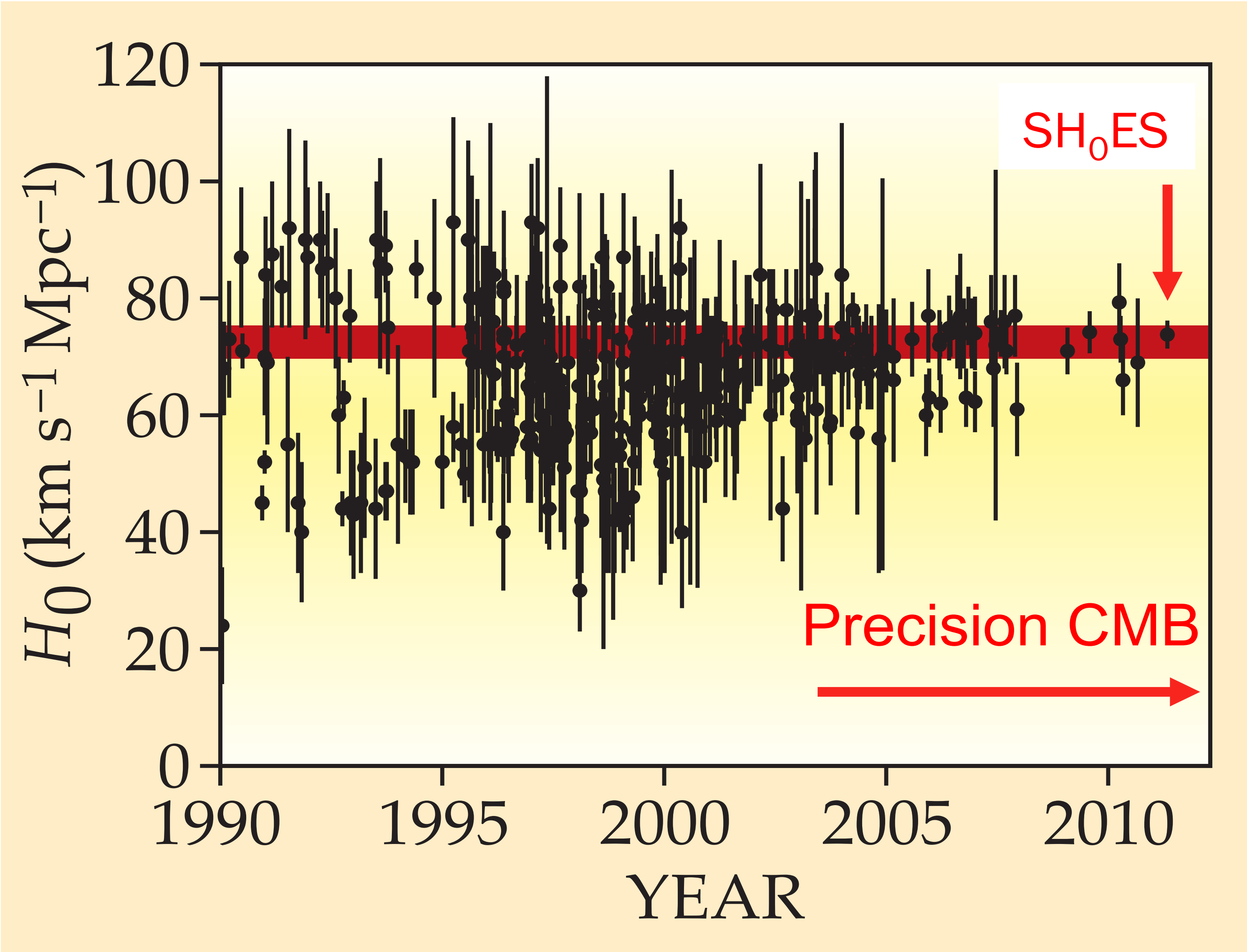
J. Huchra

https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

History of H_0



History of H_0



A. Riess

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-Lemaître Law | deceleration | jerk/equation of state

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

THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology

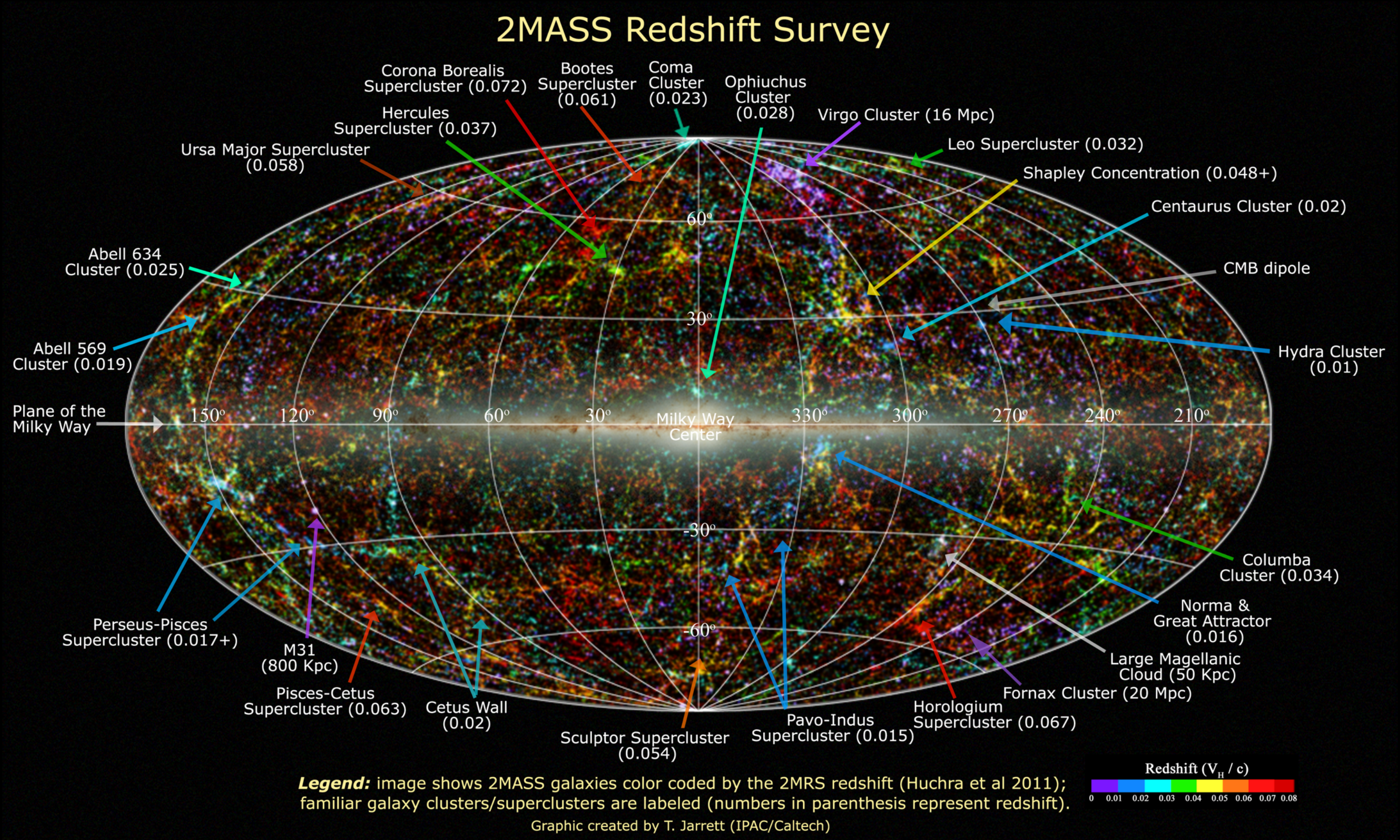
Received October 14, 1960; revised November 5, 1960

$$m_{bol} = 5 \log z + 1.086\,(1 - q_0)\,z + \ldots + \text{const.}\,, \qquad (15)$$

ApJ 1961

Extragalactic Distances

Required for a 3D picture of the (local) universe



Extragalactic Distances

THE ASTRONOMICAL JOURNAL, 146:69 (14pp), 2013 September
COURTOIS ET AL.

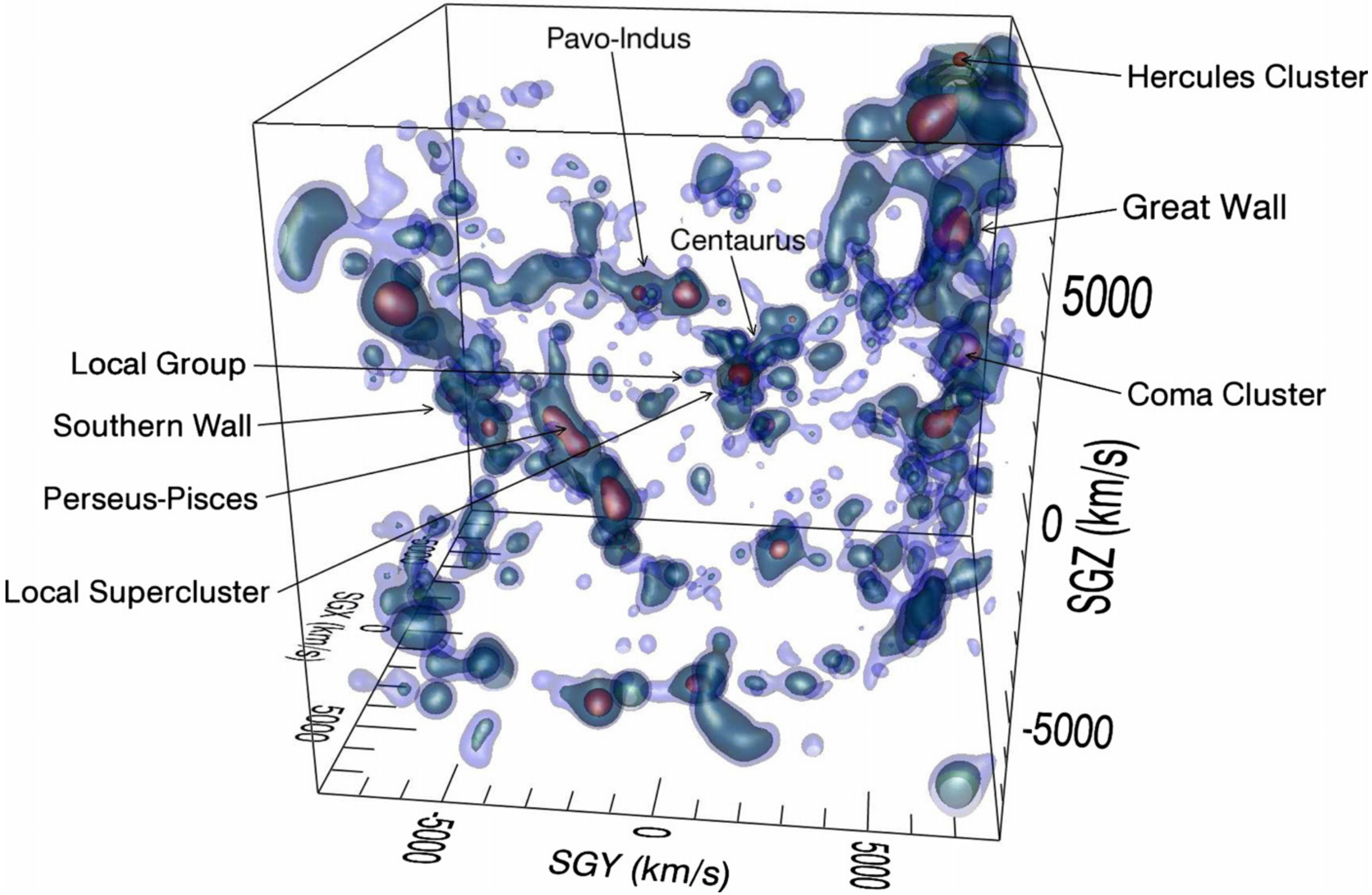
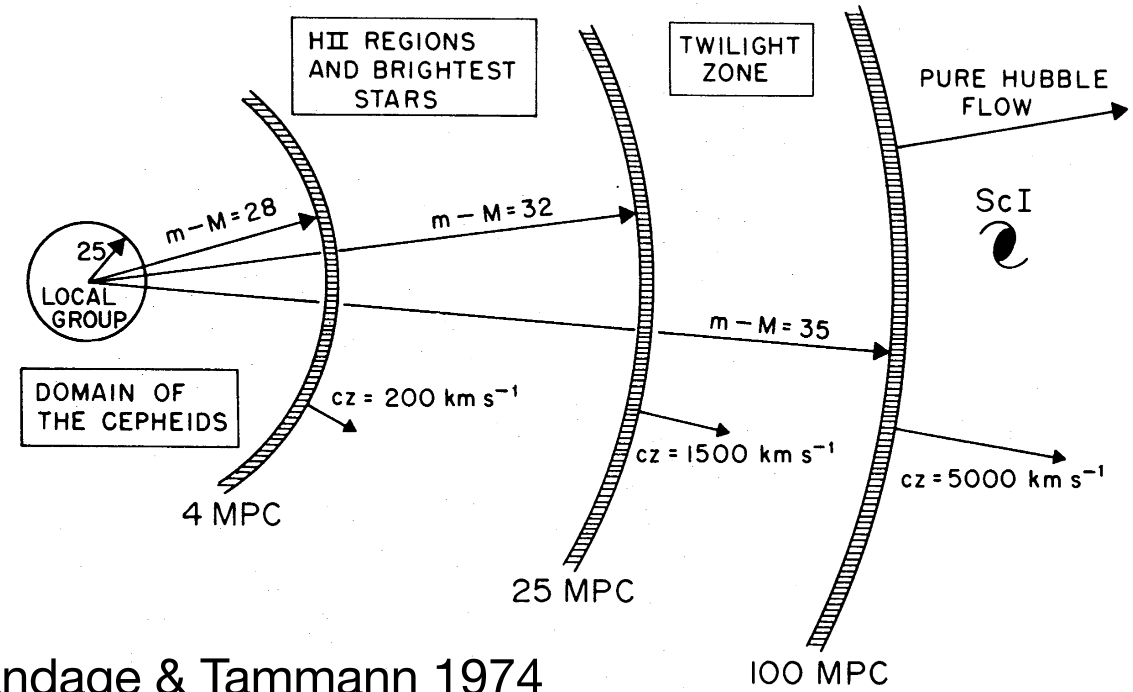


Figure 8. Perspective view of the V8k catalog after correction for incompleteness and represented by three layers of isodensity contours. The region in the vicinity of the Virgo Cluster now appears considerably diminished in importance. The dominant structures are the Great Wall and the Perseus–Pisces chain, with the Pavo–Indus feature of significance.

Measuring H_0

Classical approach

→ distance ladder to reach (smooth) Hubble flow



Sandage & Tammann 1974

Hubble Constant

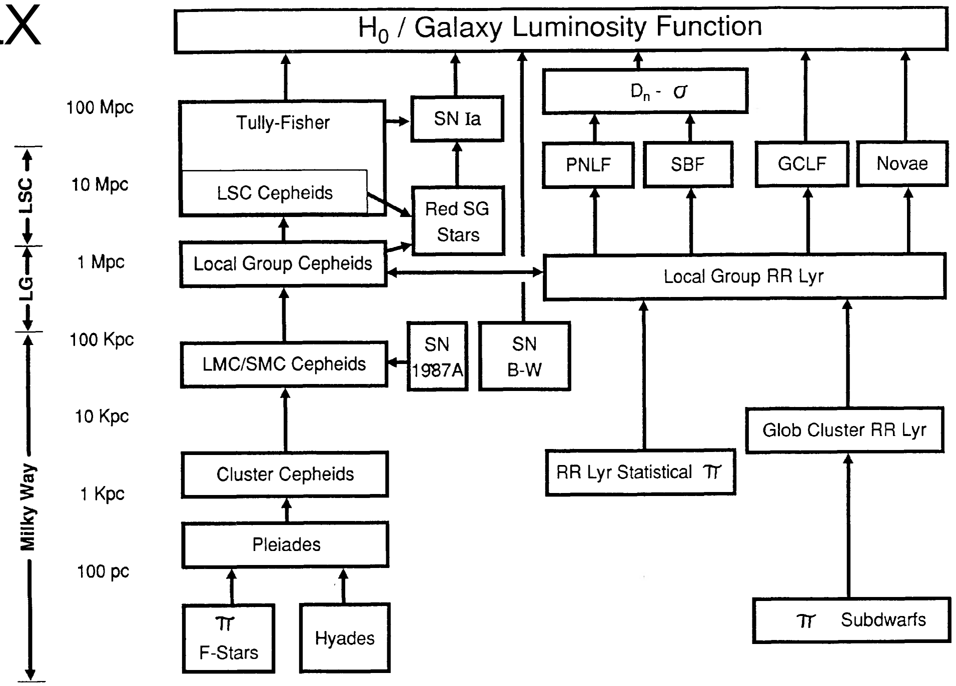
Three different methods

1. Distance ladder
   - Calibrate next distance indicator with the previous
2. Physical methods
   - Determine either luminosity or length through physical quantities
     - Sunyaev-Zeldovich effect (galaxy clusters)
     - Expanding photosphere method in supernovae
     - Physical calibration of thermonuclear supernovae
     - Geometric methods, e.g. masers
3. Global solutions
   - Use knowledge of all cosmological parameters
     - Cosmic Microwave Background

Classical Distance Ladder

Primary distance indicators (within the Milky Way)

- trigonometric parallax
- proper motion
- apparent luminosity
  - main sequence
  - red clump stars
  - RR Lyrae stars
  - eclipsing binaries
  - Cepheid stars



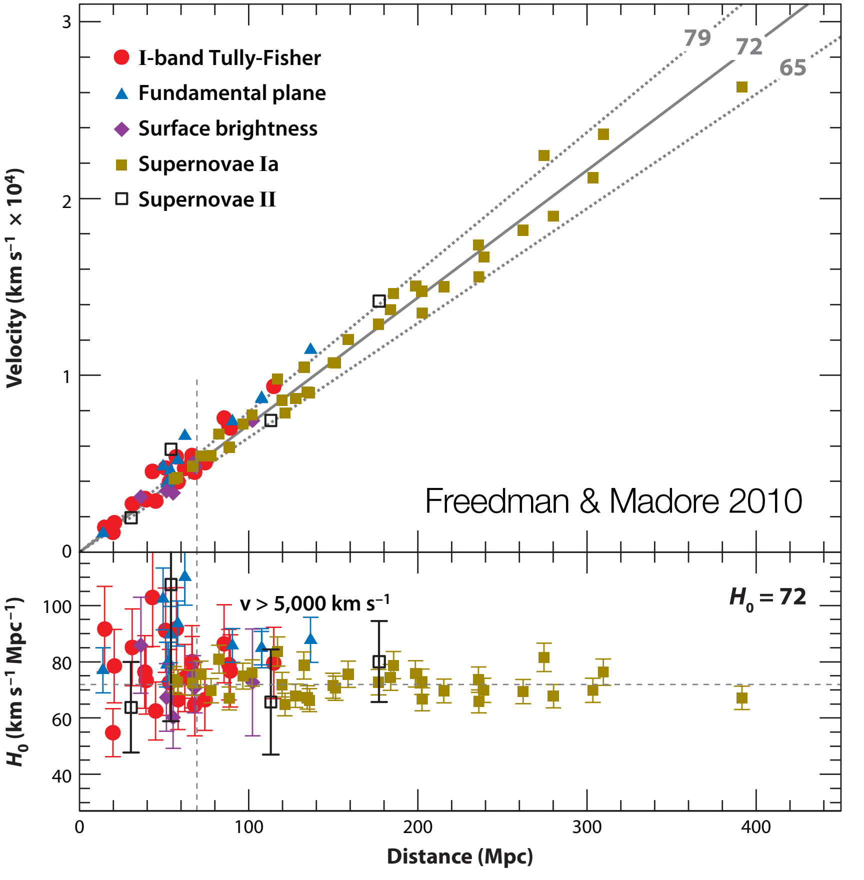
Pathways to Extragalactic Distances

Jacoby et al. 1992

Classical Distance Ladder

Gruber Cosmology Prize

- Secondary distance indicators (beyond the Local Group)
  - – Important check
    - Large Magellanic Cloud
  - – Tully-Fisher relation
  - – Fundamental Plane
  - – Supernovae (mostly SN Ia)
  - – Surface Brightness Fluctuations



Freedman & Madore 2010

Hubble Constant

Calibration of *M(SN Ia @ max)*

Distance ladder

PAST DISTANCE LADDER (100 Mpc)

11% error

1% # Modern, distant SNe Ia

3% # Modern, local hosts

3.5% SN Ia hosts, Metallicity change

4% long to short Period Cepheids

4.5% Ground to HST

5% Anchor: LMC

NEW LADDER (100 Mpc)

4 % error

1%

2%

Calibrator

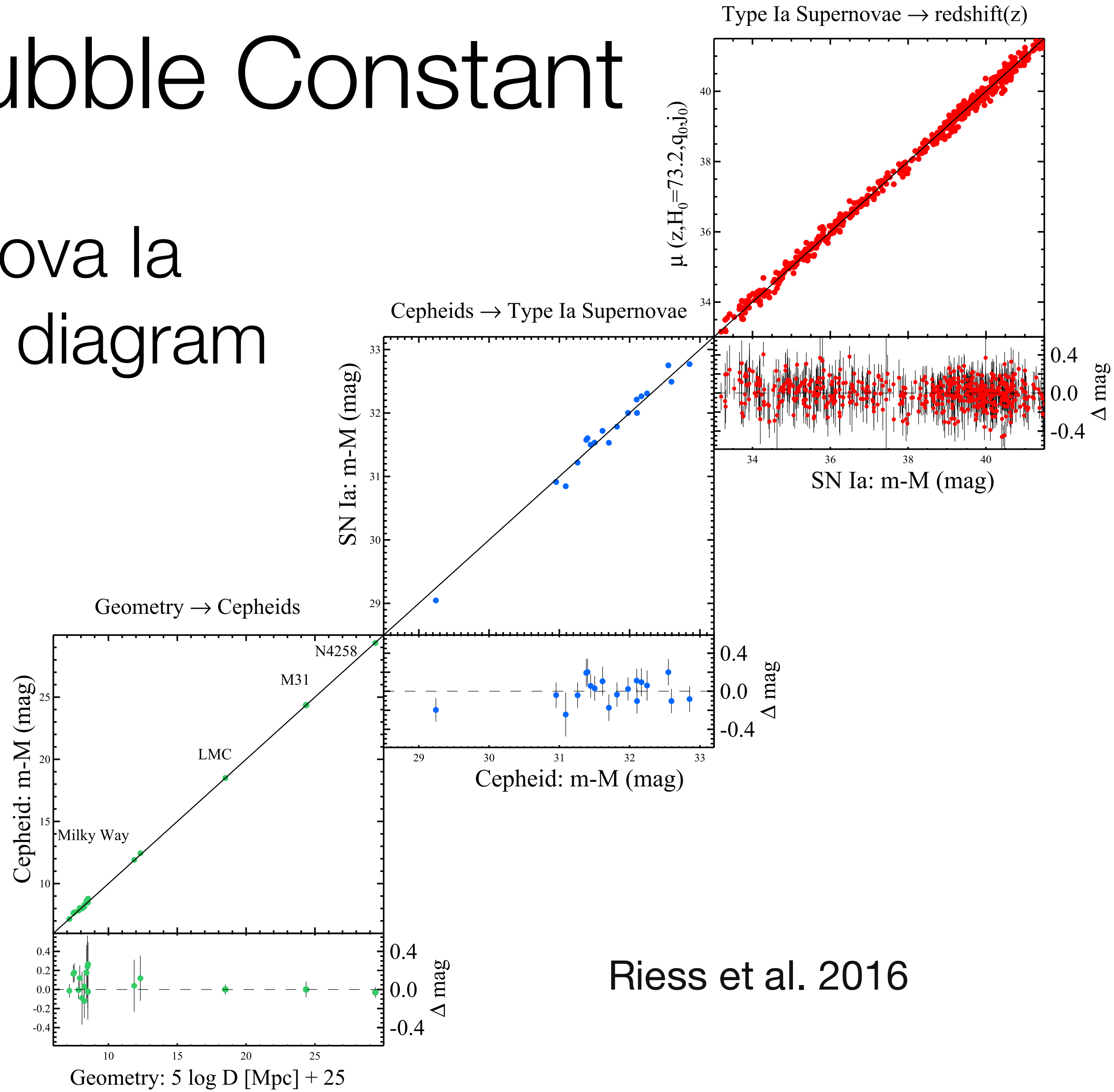
NA

3% Anchor: NGC4258

Adam Riess

Hubble Constant

Supernova Ia Hubble diagram



Riess et al. 2016

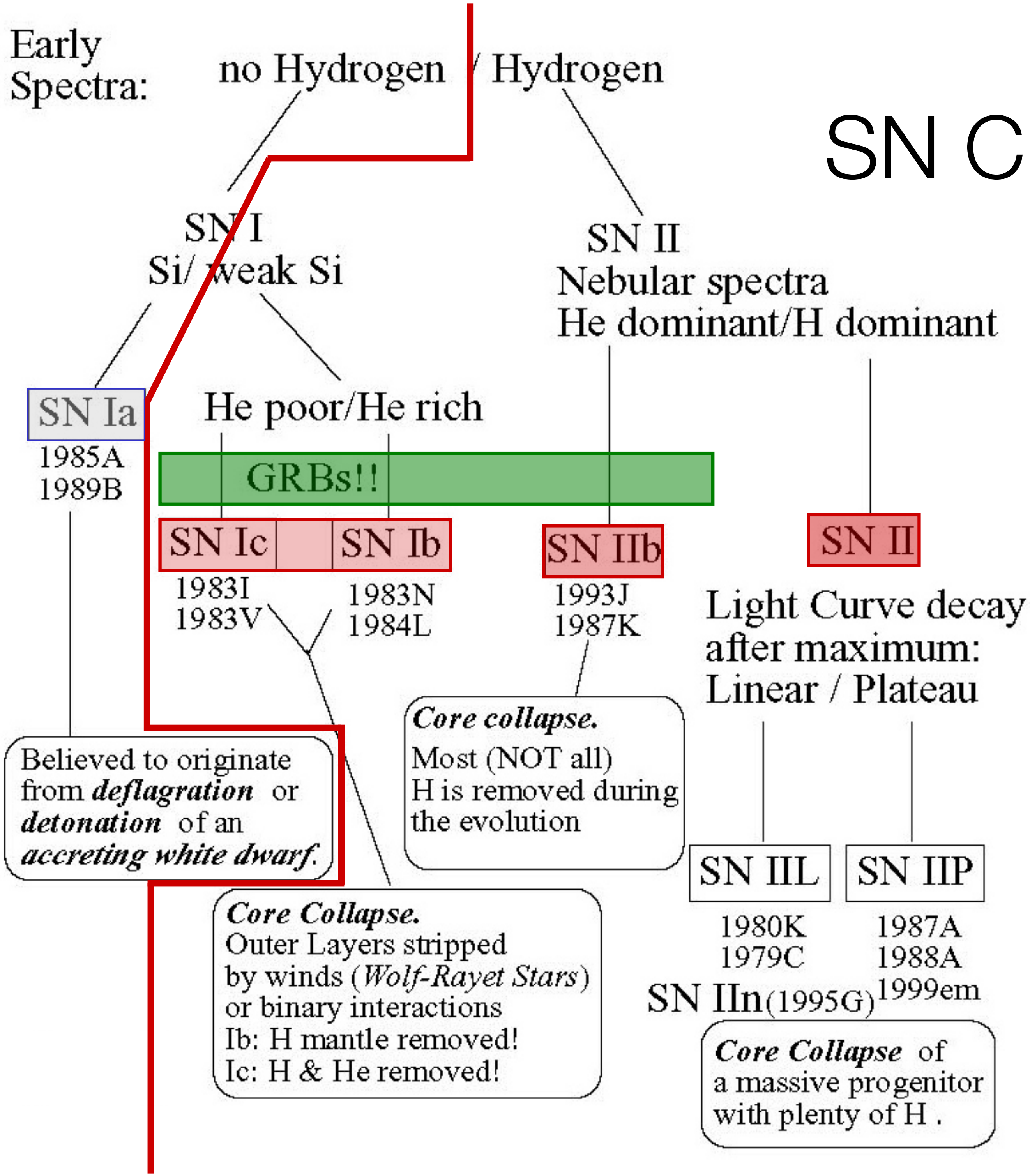
H_0 with Supernovae

- Local calibrators (calibrate the Cepheid L-P rel.)
  - Large Magellanic Cloud
    - 1% accuracy with eclipsing binaries (Pietrzyński et al. (2019)
  - Maser in NGC 4258
    - 3% accuracy (Humphreys et al. 2013)
  - geometric distances (parallaxes) to nearby Cepheids
- Extinction
  - absorption in the Milky Way and the host galaxy
  - corrections not always certain
- Peculiar velocities of galaxies
  - typically around 300 km/s

Gaia and H_0

- Calibrate Cepheid distances with parallaxes
  - long-period Cepheids so far not accessible
- Single step to the SNe Ia
  - reduced uncertainty on H_0
- Currently problems with systematic offsets between HST and Gaia (Riess et al. 2018)
  - Discrepancy of $(-46 \pm 13)\mu as$
- Goal: uncertainty less than 1%

SN Classification

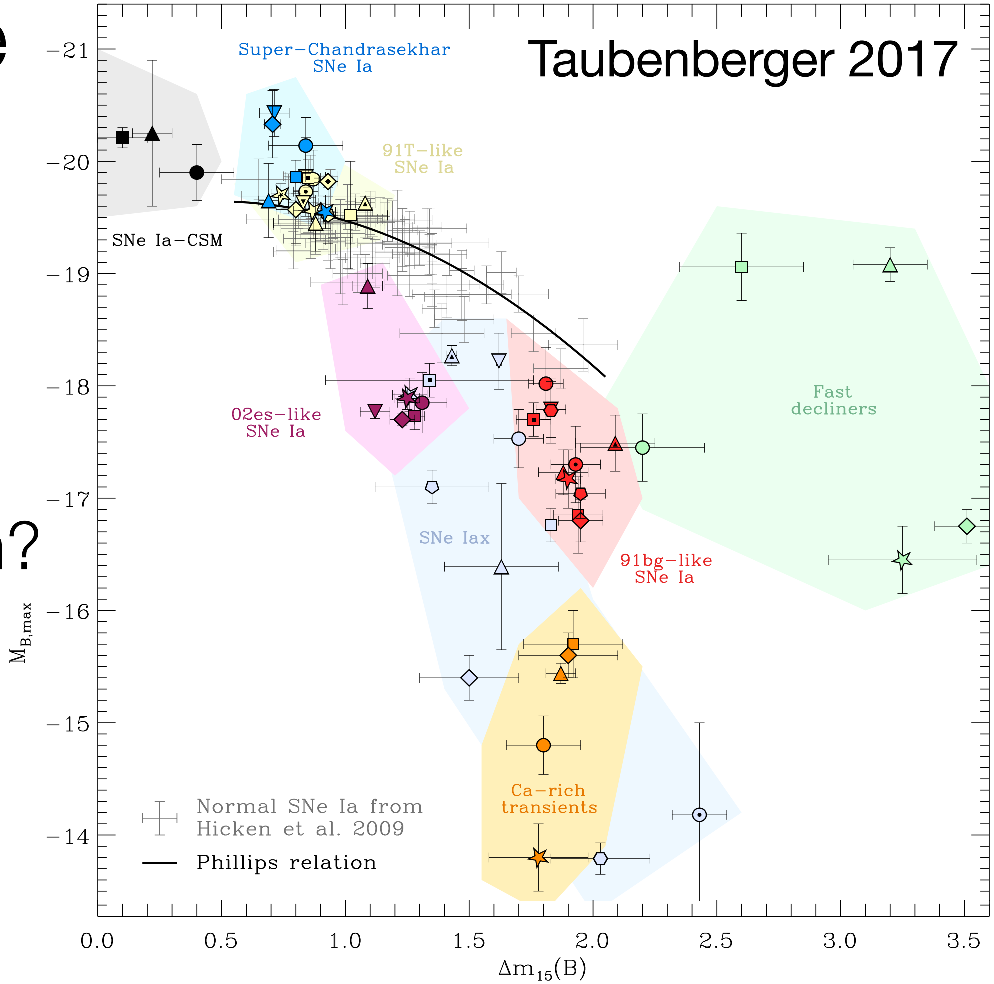


Bruno Leibundgut

Type Ia Supernovae

Variations on a theme

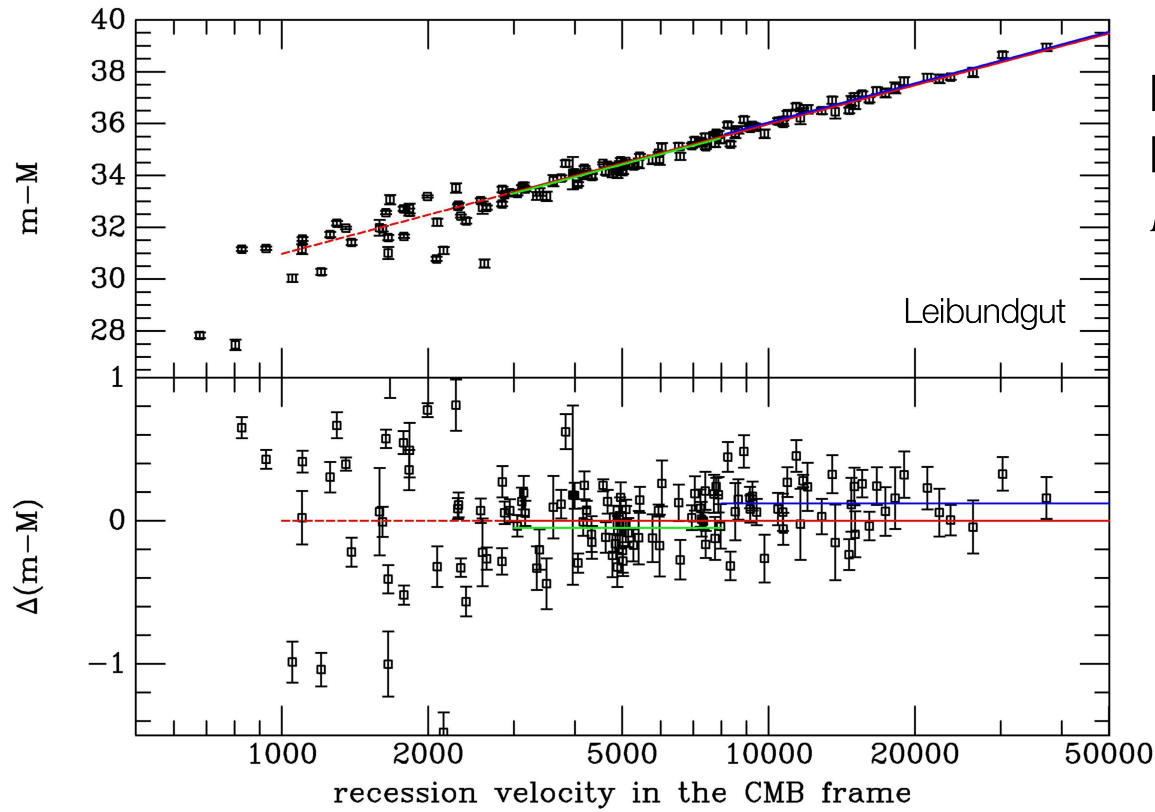
- critical parameters?
  - nickel mass
  - ejecta mass
  - explosion energy(?)
  - explosion mechanism?
  - progenitor evolution?



Hubble Constant

SN Hubble diagram

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

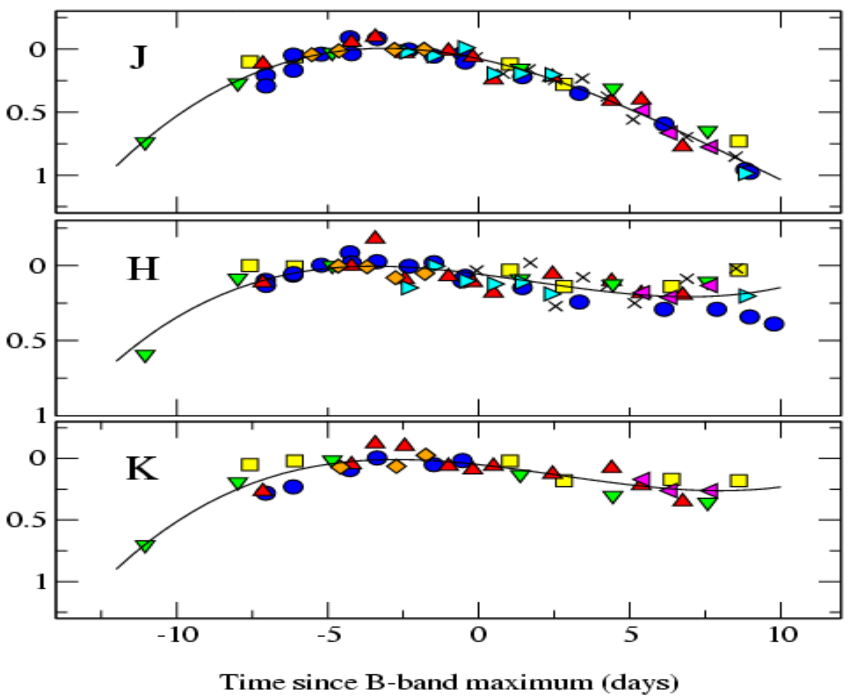


Proves M is constant

Direct connection of M and H_0

The Promise of the (Near-)Infrared

- Extinction is much reduced in the near-IR
  - $A_H/AV \cong \mathbf{0.19}$ (Cardelli et al. 1989)
- SNe Ia much better behaved

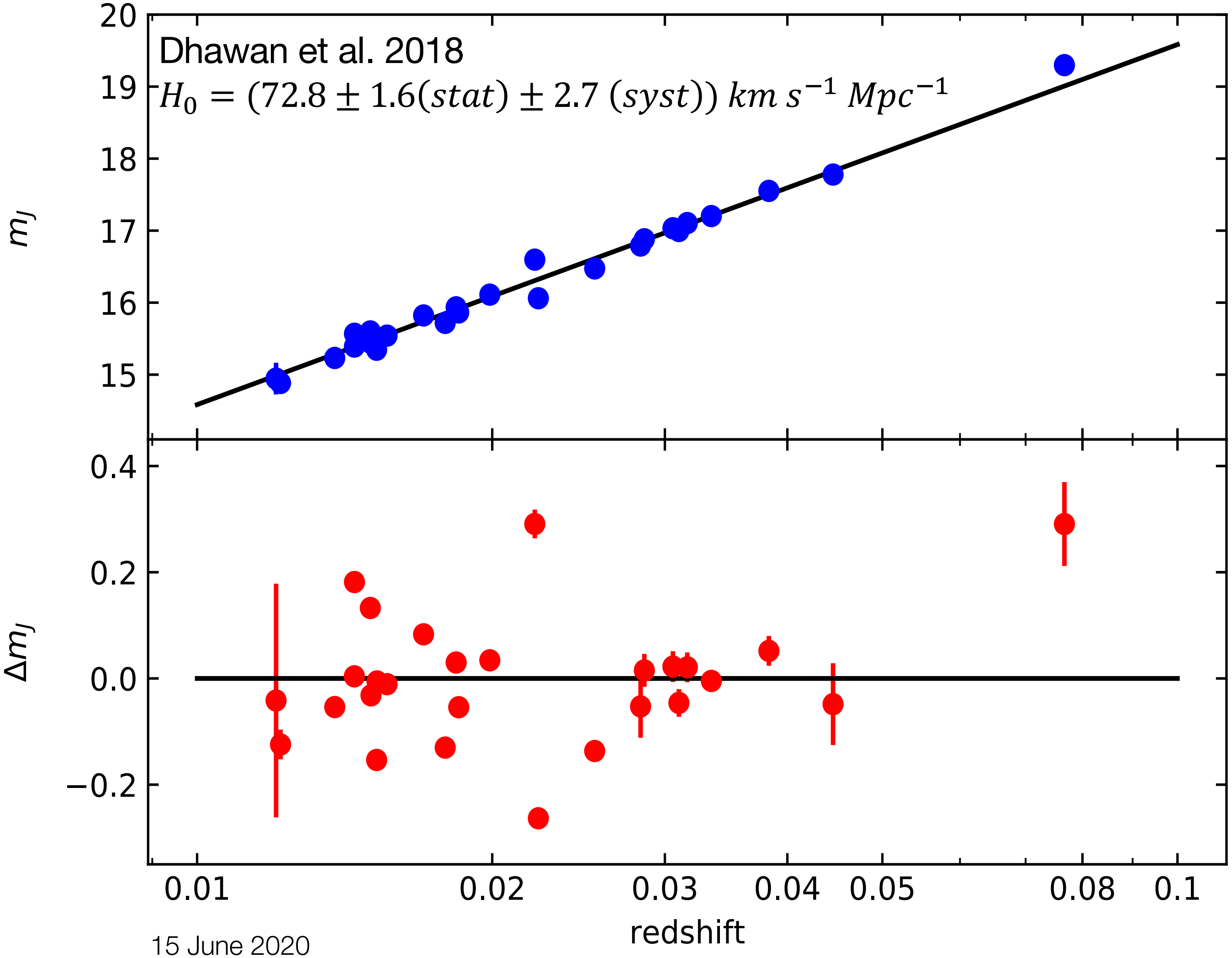


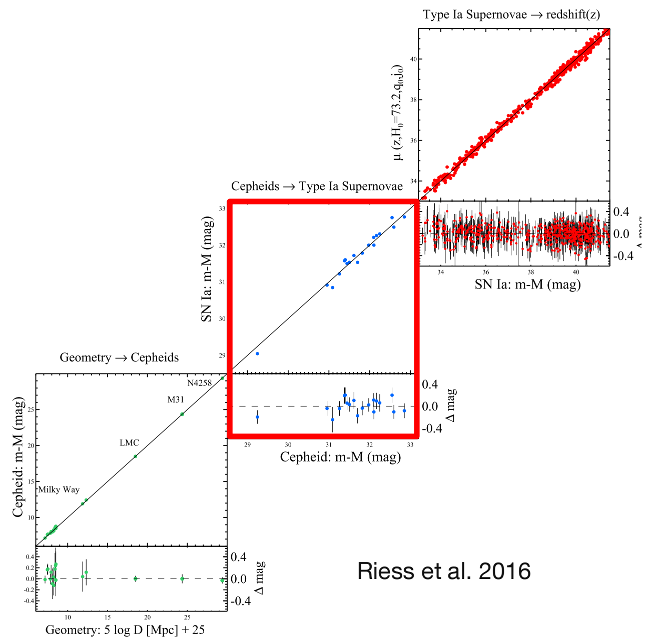
SN $\Delta m_{15}(B)$
= 1980N (1.29)
= 1986G (1.79)
= 1998bu (1.05)
= 1999aw (0.81)
= 1999ee (0.94)
= 2000ca (1.01)
= 2001el (1.15)

Krisciunas et al. (2004)
Mark Phillips

Current Status (NIR)

9 calibrators + 27 Hubble flow SNe

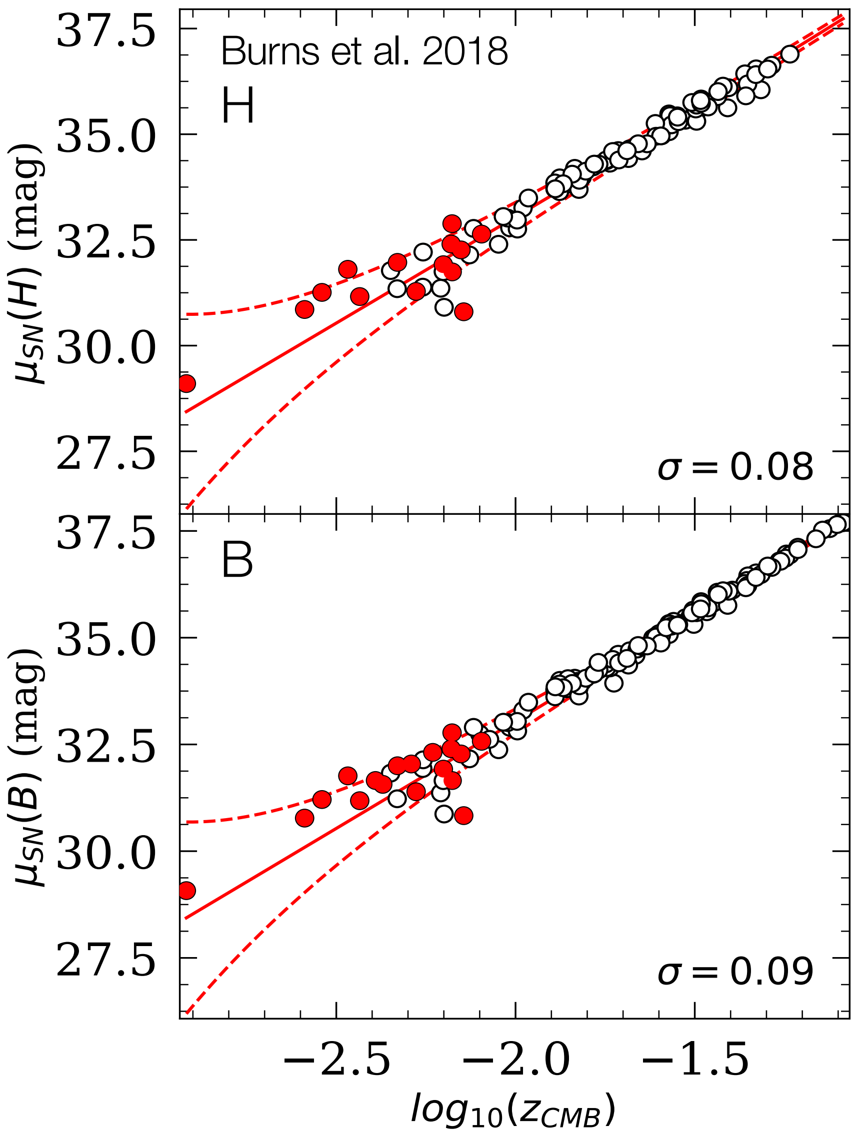




Riess et al. 2016

Infrared SN Hubble Diagrams

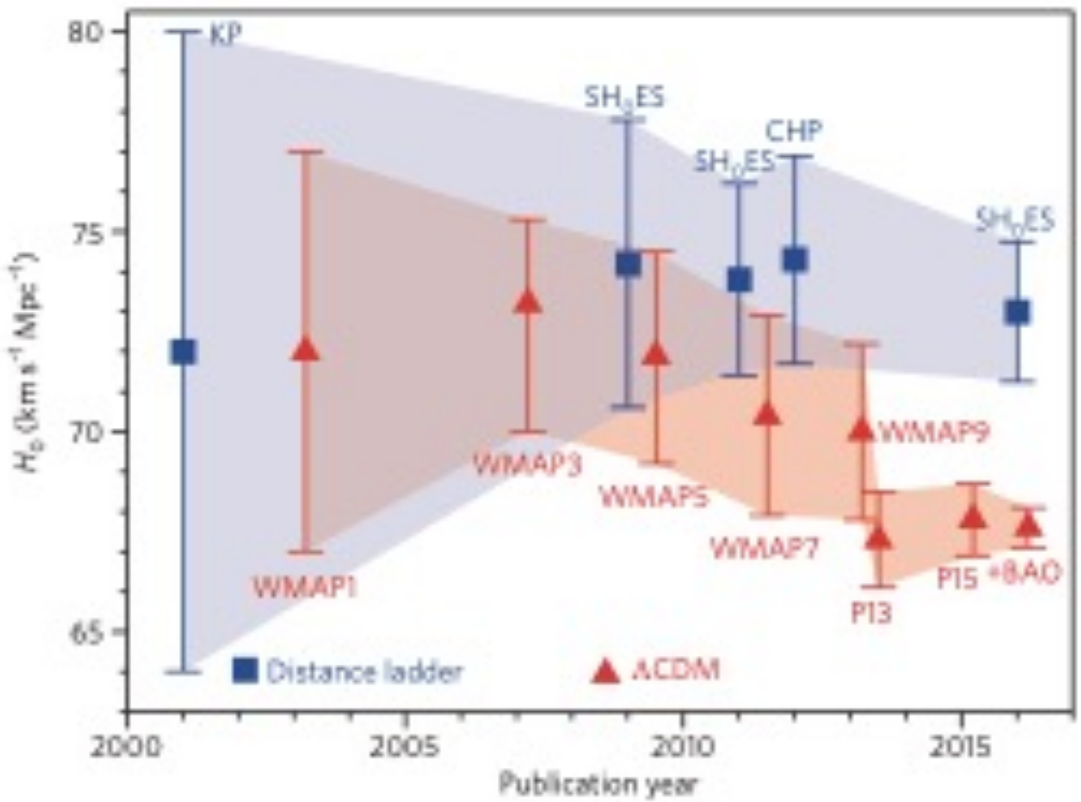
NIR Hubble diagram becoming competitive



Problem solved?

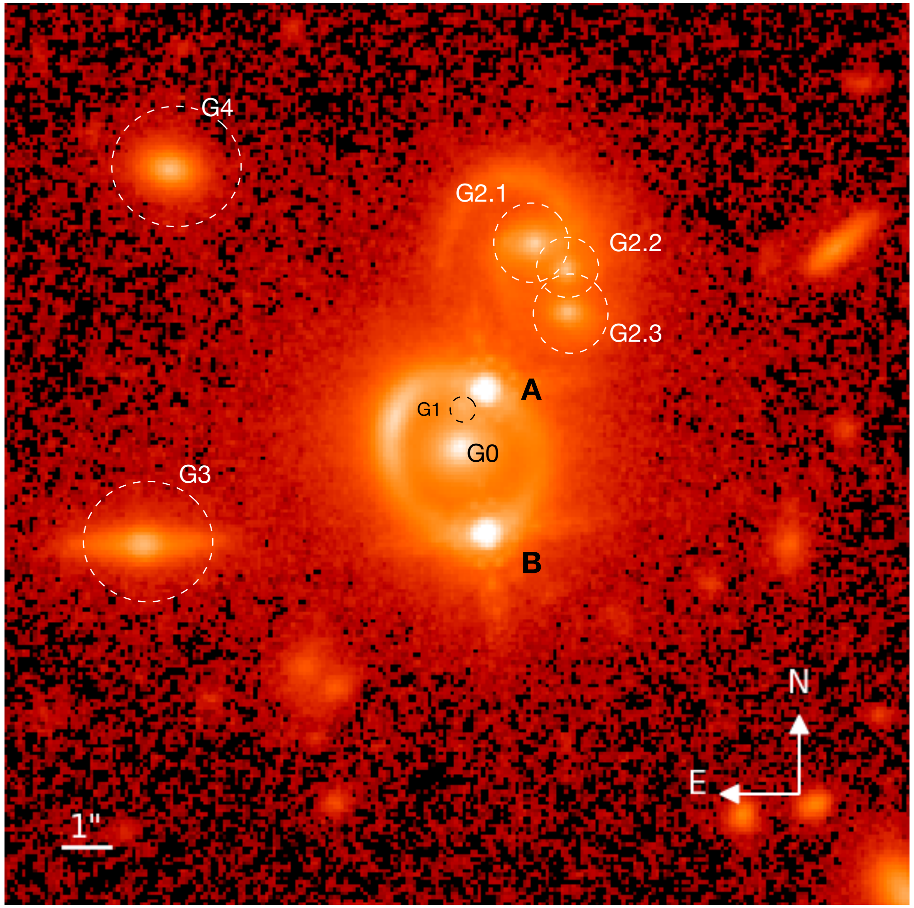
New discrepancy between the measurements of the local H_0 (distance ladder) and early universe (CMB)

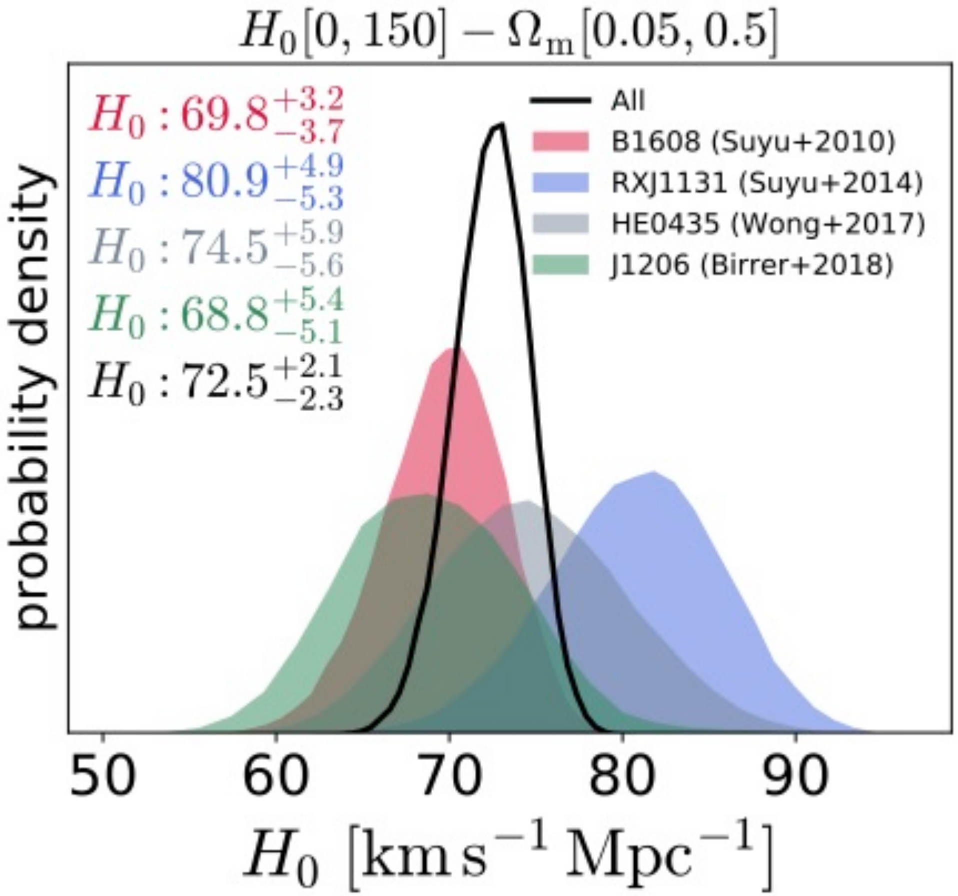
Indication of an incomplete model of cosmology?



Promising Results from strong lensing

Time delays in lensed quasars



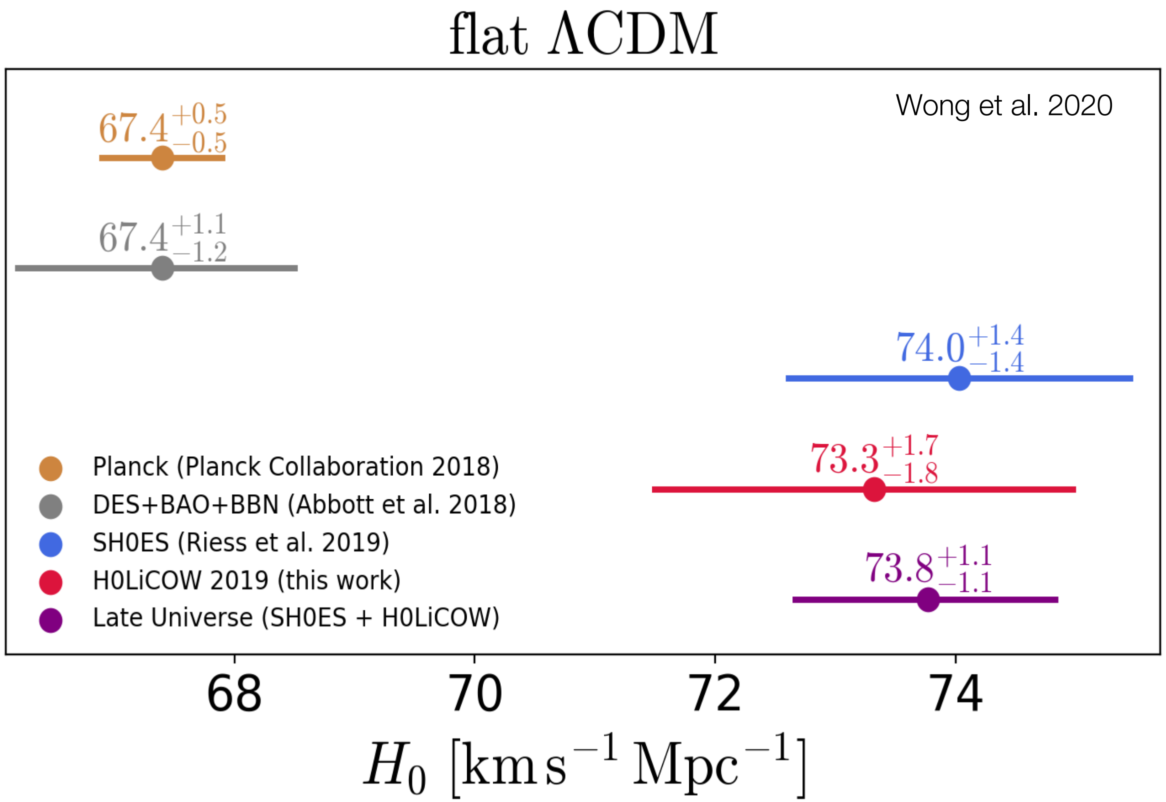


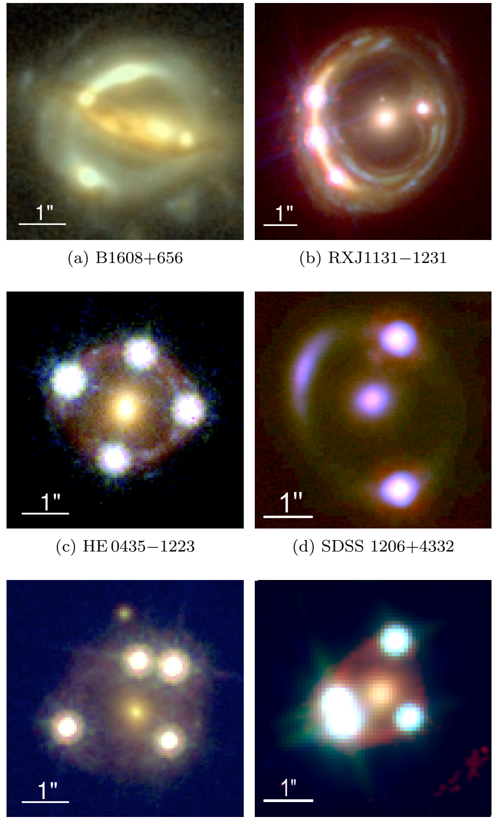
Birrer et al. 2018

Sherry Suyu (J. Wiedersich / TUM)

Gravitationslinsen

H0LICOW collaboration





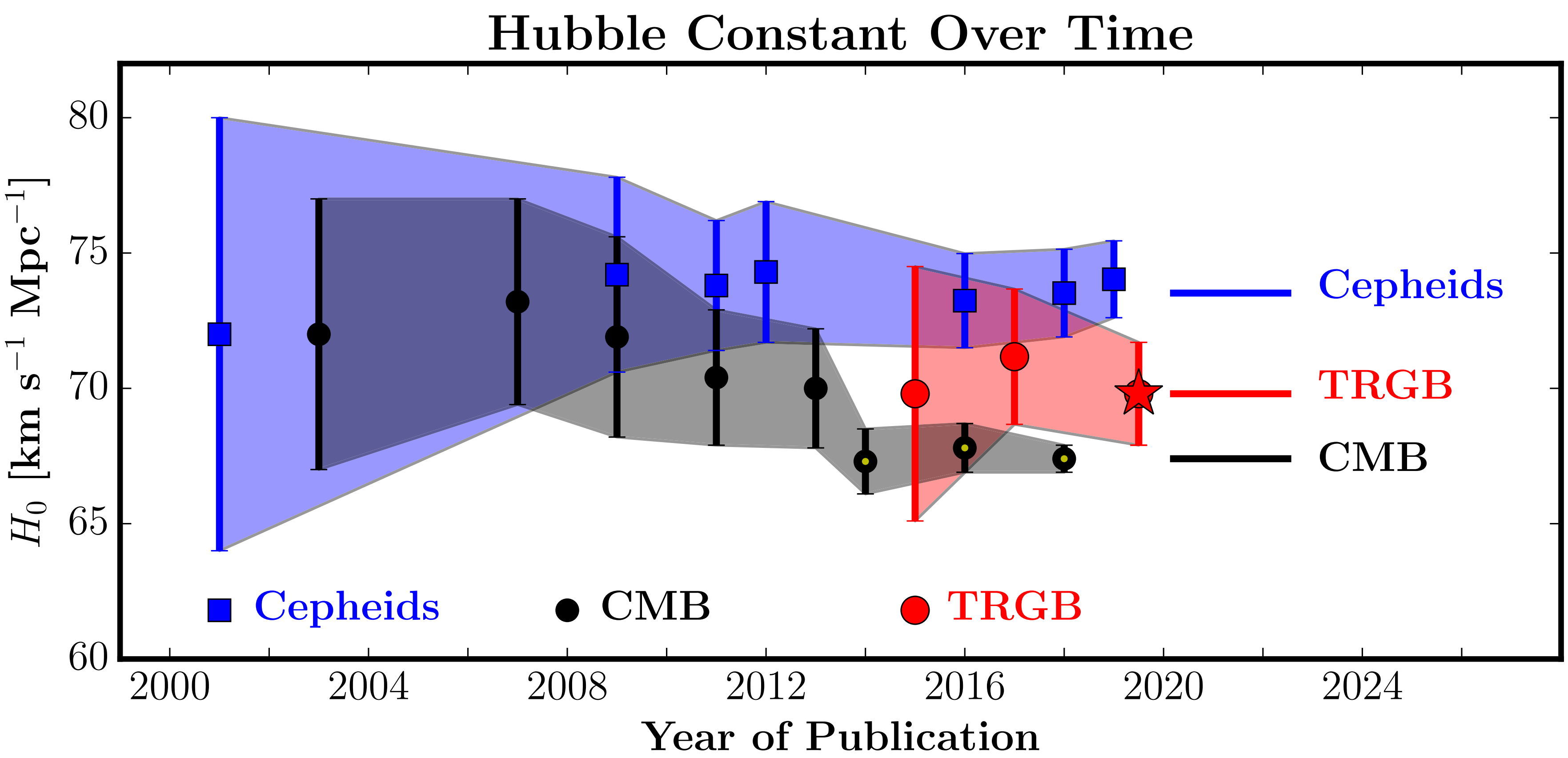
(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

…and another attempt

Tip of the Red Giant Branch



Hubble Constant(s)

Planck satellite (CMB; 2018)

measurement at $z \approx 1000$

$$H_0 = (67.4 \pm 0.5)\ km\ s^{-1} Mpc^{-1}$$

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)

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

Riess et al. (local; 2019)

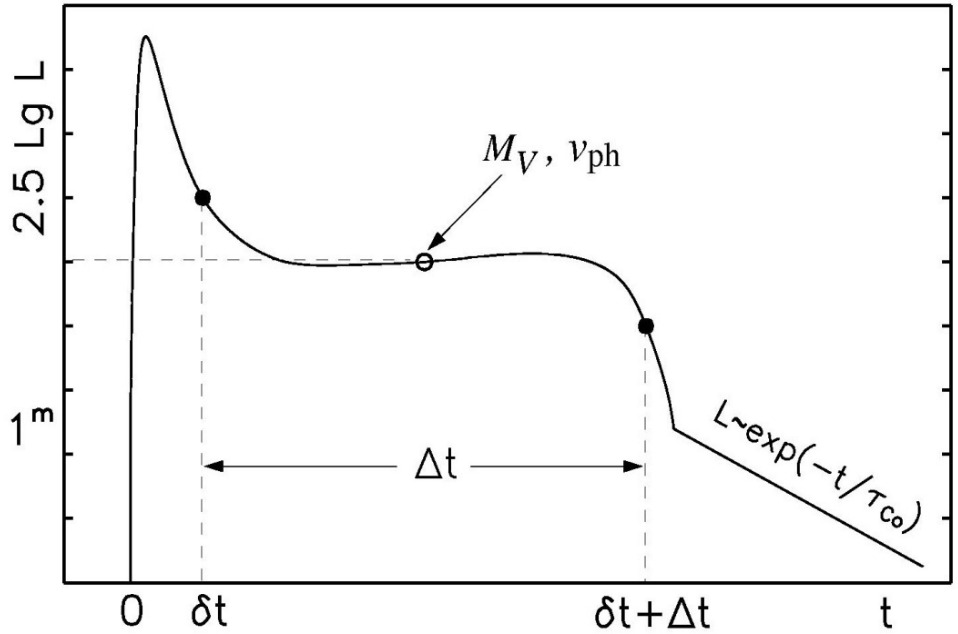
$$H_0 = (74.22 \pm 1.82)\ km\ s^{-1}\ Mpc^{-1}$$

Freedman et al. (local, TRGB; 2019)

$$H_0 = (69.8 \pm 0.8 \pm 1.7) km\ s^{-1}\ Mpc^{-1}$$

Physical parameters of core collapse SNe

Light curve shape and the velocity evolution can give an indication of the total explosion energy, the mass and the initial radius of the explosion



Observables:

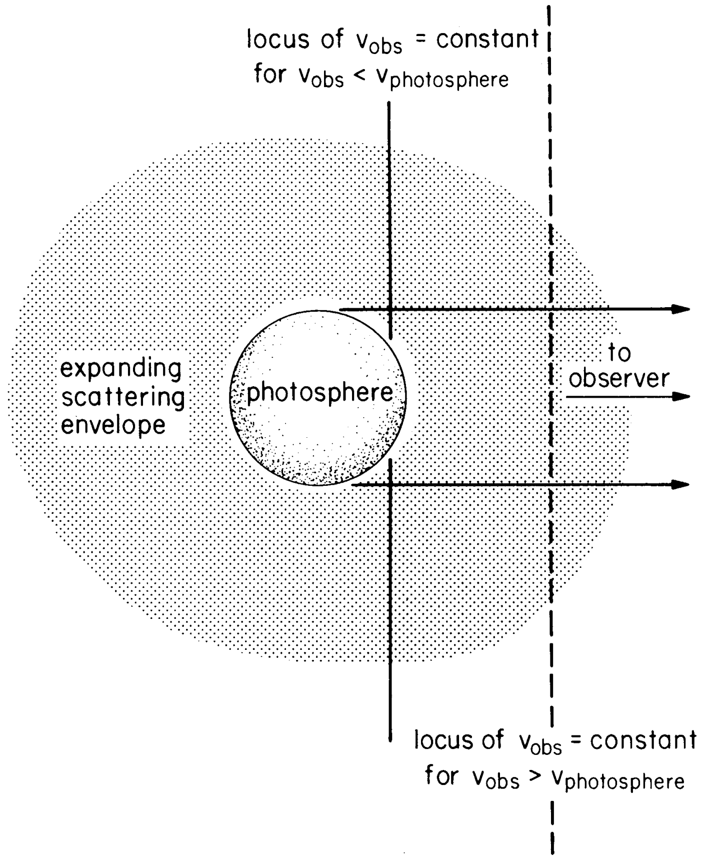
- length of plateau phase Δt
- luminosity of the plateau L_V
- velocity of the ejecta v_{ph}

- $E \propto \Delta t^4 \cdot v_{ph}^5 \cdot L^{-1}$
- $M \propto \Delta t^4 \cdot v_{ph}^3 \cdot L^{-1}$
- $R \propto \Delta t^{-2} \cdot v_{ph}^{-4} \cdot L^2$

Expanding Photosphere Method

Modification of Baade-Wesselink method for variable stars

- Assumes
  - Sharp photosphere
    → thermal equilibrium
  - Spherical symmetry
    → radial velocity
  - Free expansion



Kirshner & Kwan 1974

Expanding Photosphere Method

$$\theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\Lambda(T)}};\ R = v(t - t_0) + R_0;\ D_A = \frac{v}{\theta}(t - t_0)$$

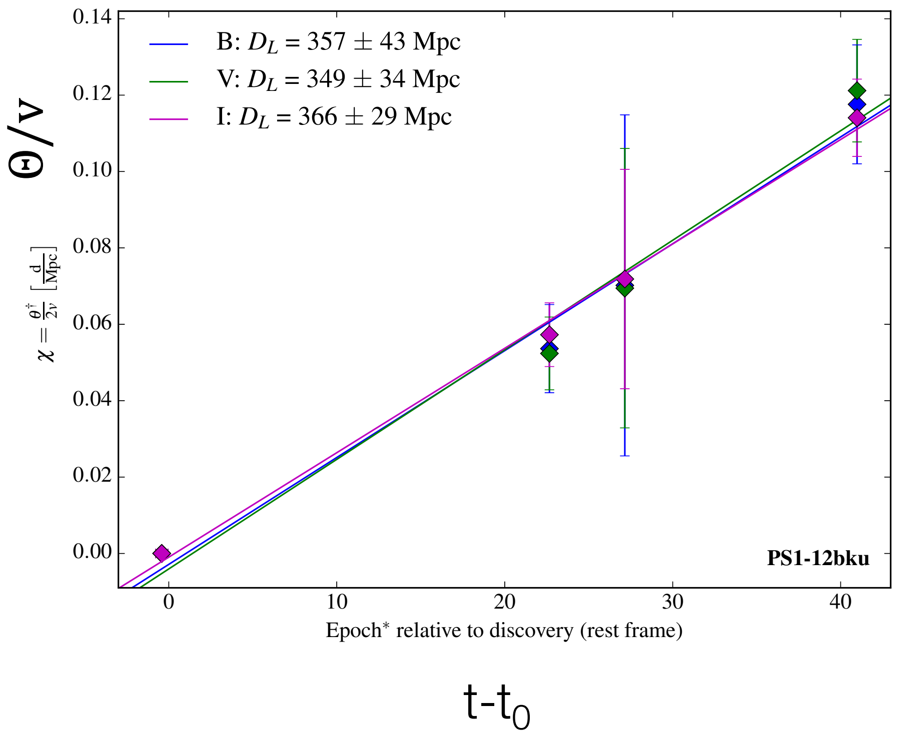
- *R* from radial velocity
  - Requires lines formed close to the photosphere
- *D* from the surface brightness of the black body
  - Deviation from black body due to line opacities
  - Encompassed in the dilution factor ζ^2

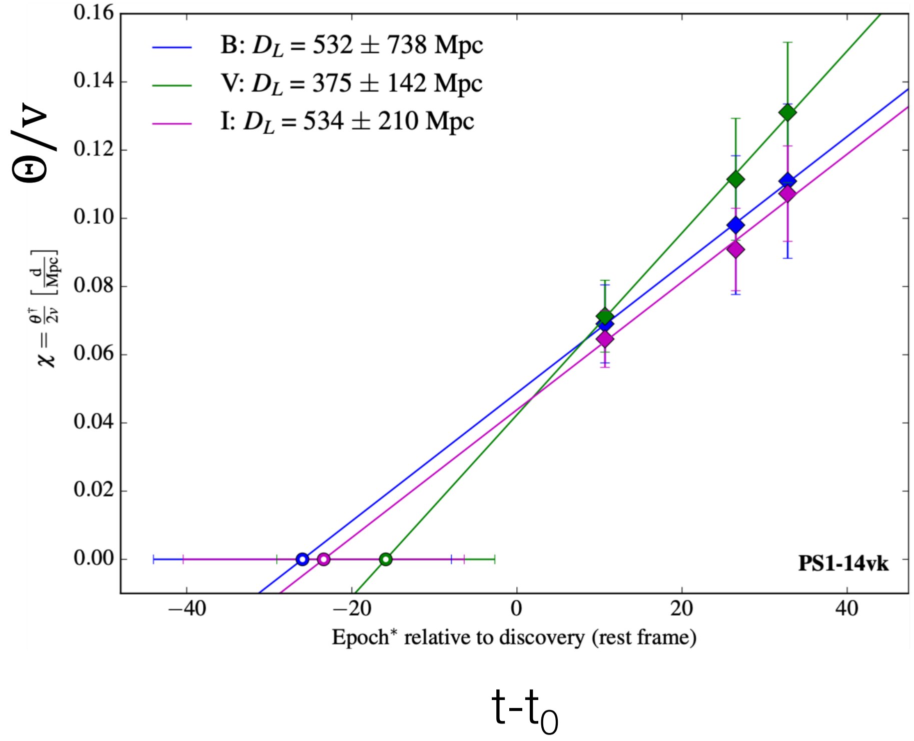
Expanding Photosphere Method

- It's all in the data...

$$\frac{\Theta}{v} = \frac{1}{D_A}(t - t_0)$$

Gall et al. 2018



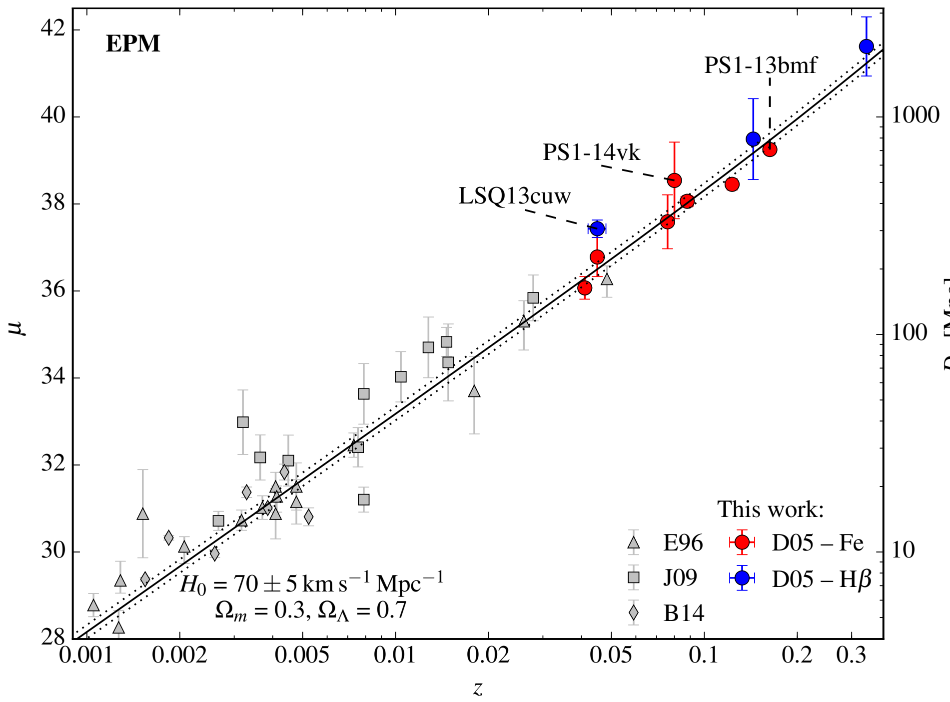


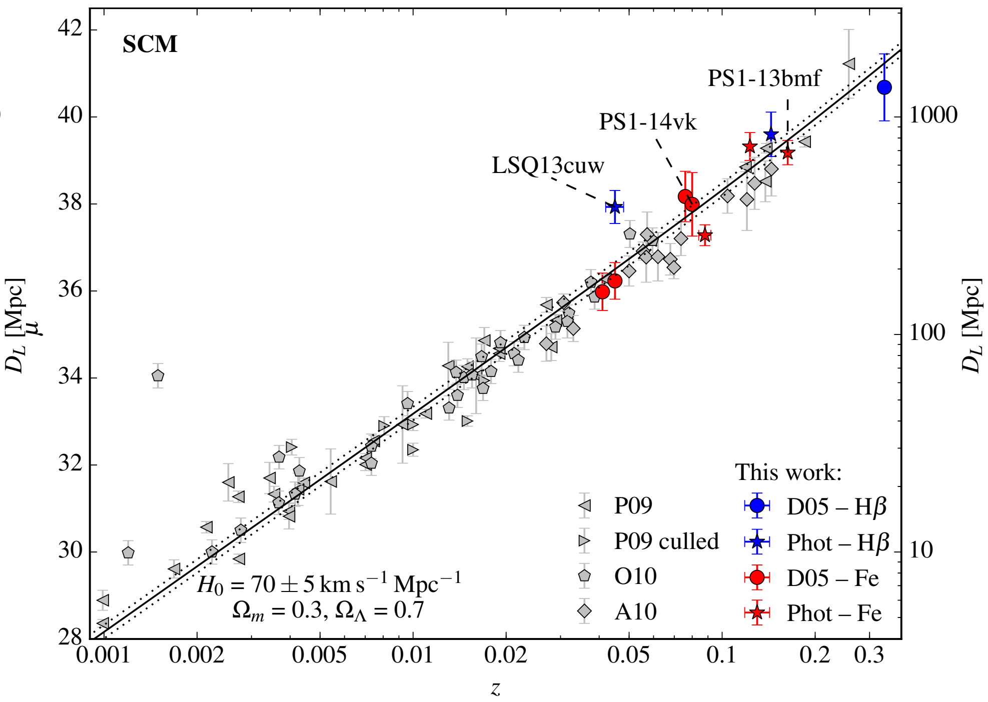
Preliminary Results

Consistent results

– not independent as local calibration required

Gall et al. 2018



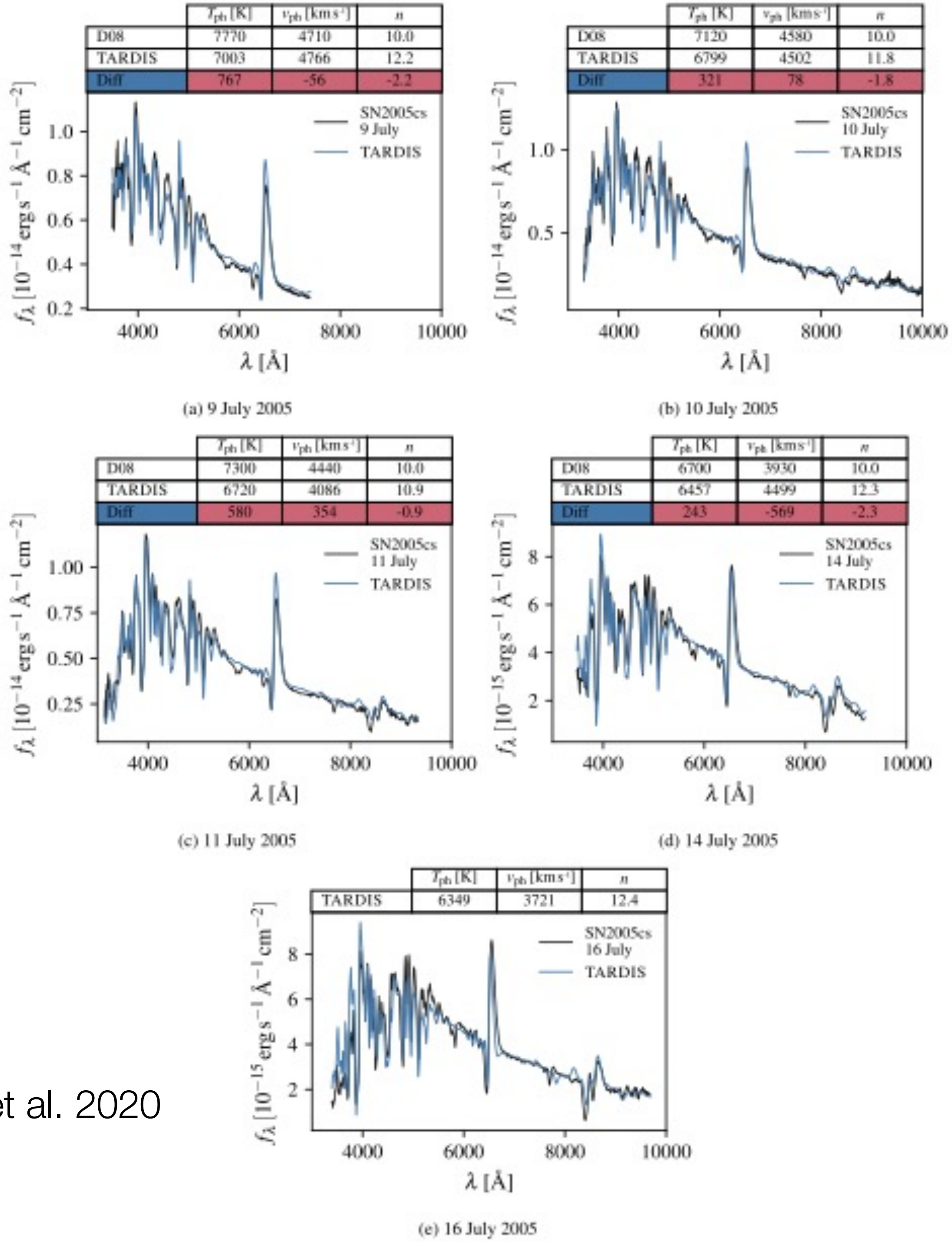


Expanded Photosphere Method Reloaded

- Use individual atmospheric models for the spectral fits
  – use of the TARDIS radiation transport model
  – absolute flux emitted
- Accurate explosion date
  – accurate zero point
- At least 5 epochs per supernova

Atmosphere Models

TARDIS fits for different epochs



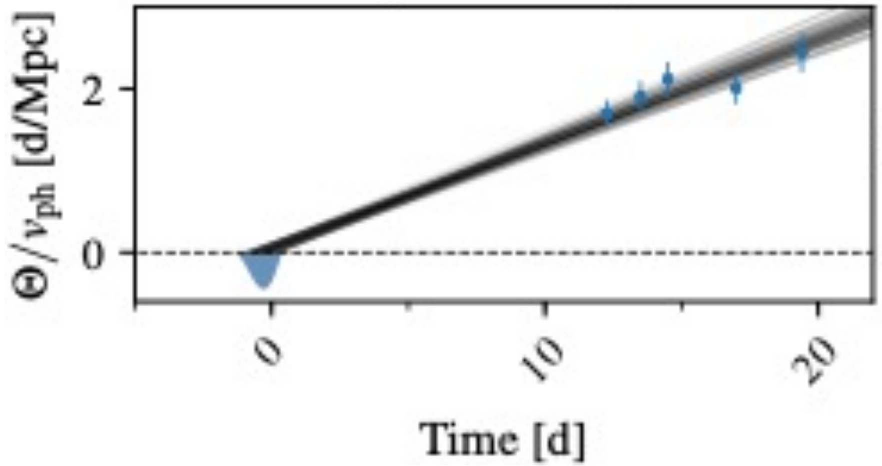
Vogl et al. 2020

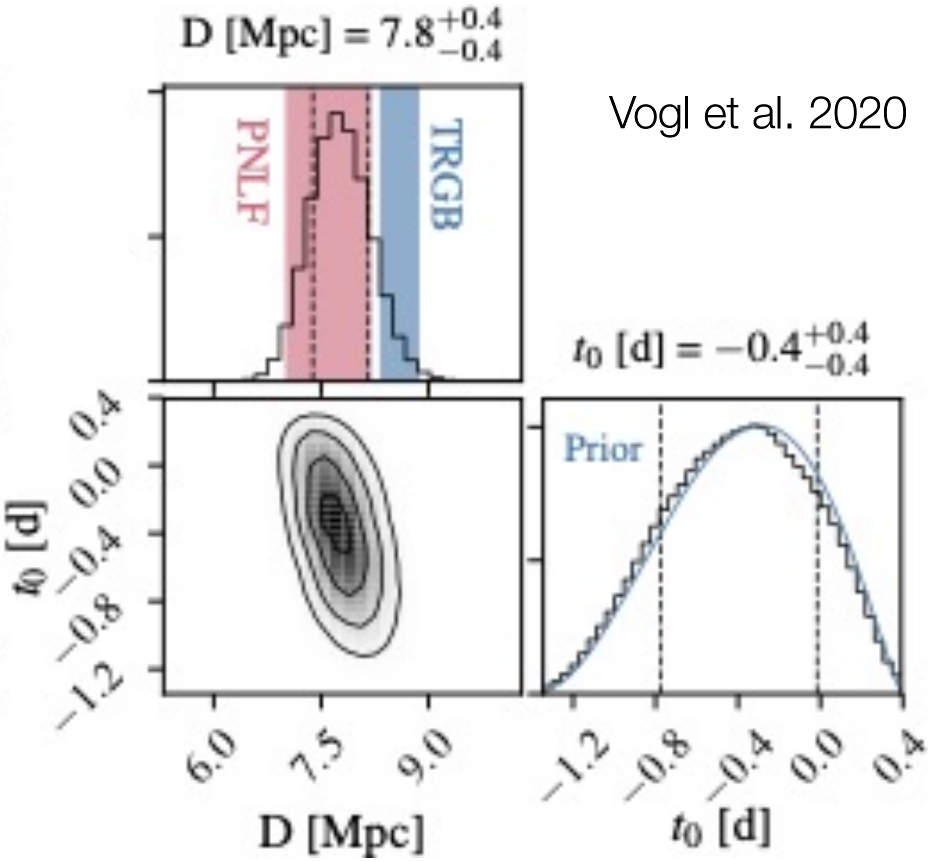
Distance Determination

Slope is inverse distance: $\frac{\Theta}{v} = \frac{1}{D_A}(t - t_0)$

Vogl et al. 2020

Date	Time [d]	Θ/v_{ph} [d/Mpc]
9 July 2005	12.25	1.69
10 July 2005	13.50	1.90
11 July 2005	14.50	2.12
14 July 2005	17.00	2.01
16 July 2005	19.40	2.44





adH0cc

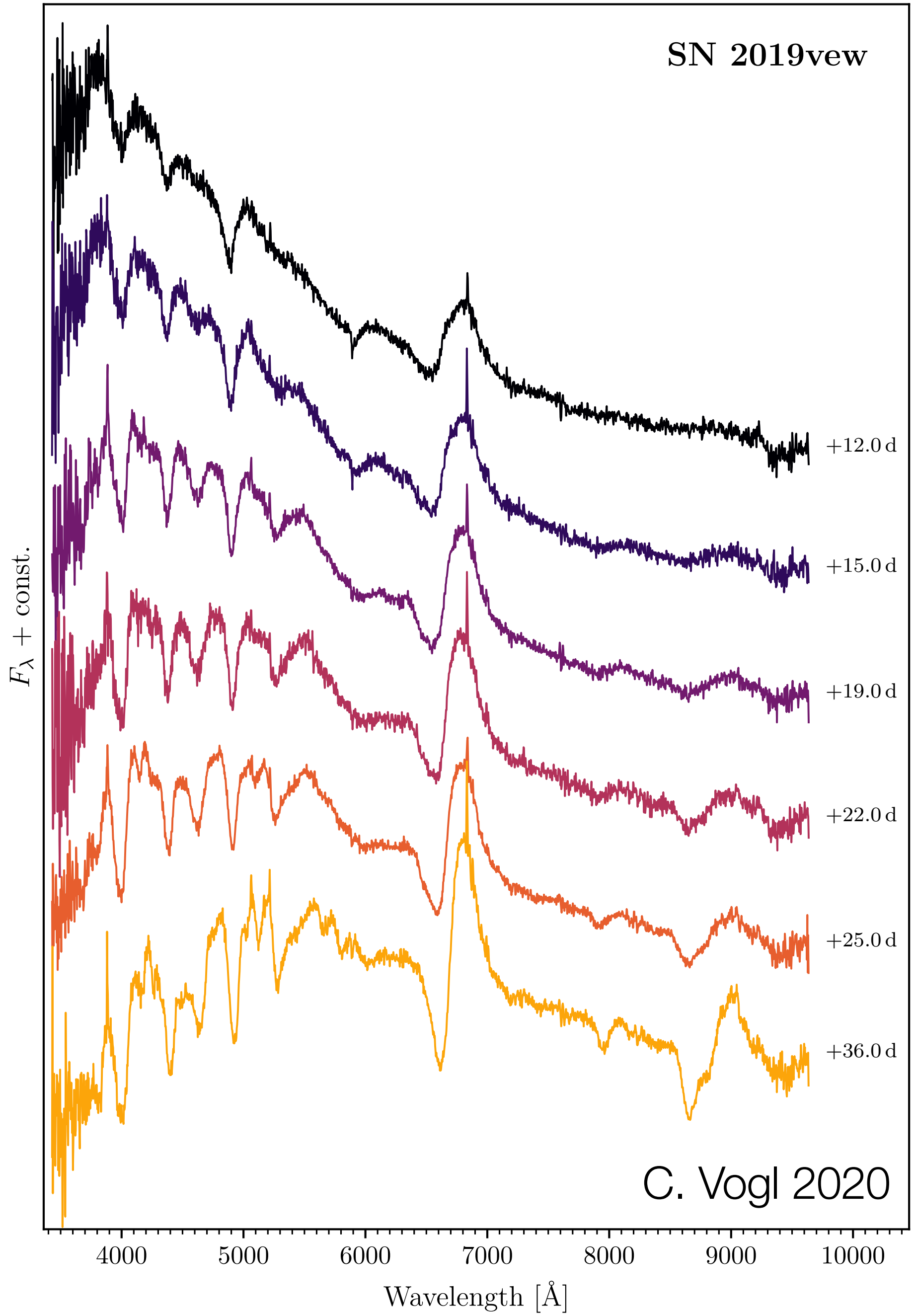
“*a*ccurate *d*etermination of *H0* with *c*ore-*c*ollapse supernovae”

- Use the Expanding Photosphere Method to ~30 Type II supernovae in the Hubble flow ($0.03<z<0.1$)
- Independent of distance ladder
  - no parallaxes, no Cepheids, no Type Ia supernovae
- FORS2 Large Programme over 3 semesters
  - 6 epochs spectroscopy and photometry per supernova
  - 8 SNe followed in first semester (P104)
  - currently on hold
- SNFactory data
  - about 15 SNe with $0.01<z<0.05$

adH0cc

Critical observables

- time of explosion
- spectral coverage
  - before max until well into the plateau
- photometry
  - simulatenously to spectroscopy



Conclusions

Hubble constant sets absolute scale (and age) of the universe

– Past conflicts resolved

- Age of Universe is bigger than age of the Earth
  – recognition of different stellar populations
- Age of Universe bigger than oldest stars
  – cosmological constant

Conclusions

Current discrepancy of $\sim 4.4\sigma$ between

- H_0 measured locally (distance ladder) and
- H_0 measured at z=1100 (CMB)

Significance?

- systematics based on Cepheid calibration

Extreme accuracy required

- e.g. Cepheid parallax zeropoint

Independent measurement needed

- Expanding Photosphere Method