Cosmology with Supernovae

Lecture 1

Bruno Leibundgut

Programme

Lecture 1

- Hubble Constant H_0
  - Importance of H_0
  - Measurements of H_0
    - local → distance ladder
    - global → gravitational lensing, cosmic microwave background
  - H_0 today and tomorrow

Programme

Lecture 2

- Tests for General Relativity
  - Expansion
    - time dilation
  - Distance duality
    - relation between luminosity distance and angular size distance
- Cosmological parameters
  - Evidence for acceleration
- Future of SN cosmology

Forces in the Universe

- Gravity is the dominant force
- Nuclear forces only short range
  - only importance in the very early universe
- Electromagnetic force is based on charges
  - in a neutral universe not important
  - magnetic fields!
- Need a theory for gravity → relativity

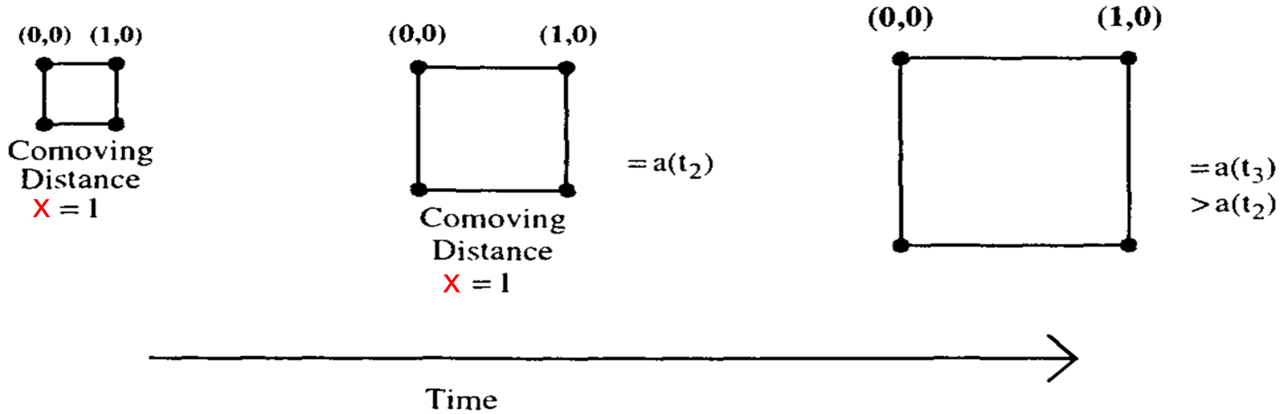
Metric

- Why do we have to bother with the metric?
  - Euclidian (flat space) is not good enough
- Reason: expansion of the universe
- Due to the expansion the coordinates are moving
  - need a translation from the coordinates to the physical distances

Distances

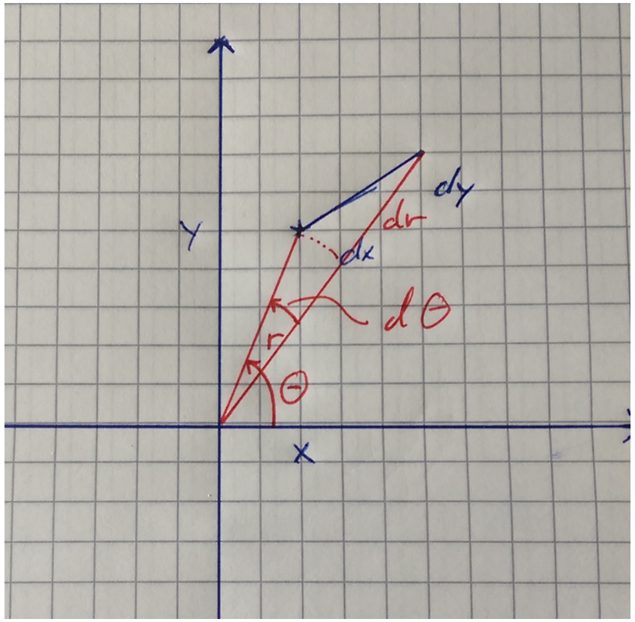
We separate the observed distances *r(t)* into the expansion factor *a(t)* and the fixed part *x* (called *comoving* distance)

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



Calculating Distances

- Simple example of distances in flat space:
- Coordinates x and y
- Distance: $dl^2 = dx^2 + dy^2$ *(Euclid)*
- Coordinates r and Θ
- Distance: $dl^2 = dr^2 + r^2\, d\Theta^2$
- (think of crane) or Earth and Sky
- In general:
  $(dl)^2 = \Sigma_{i,j=1,2}\, g_{ij} dx^i\, dx^j$



Calculating Distances

In 4 dimensions

- time as the 0th coordinate) this becomes

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

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

or explicitly:

– Minkowski (flat) space

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

Calculating Distances

Expanding universe with scale parameter a(t)

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

➔ 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


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

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* $R_{00} - \frac{1}{2} g_{00} R = \frac{3}{c^2}\left(\frac{\dot{a}}{a}\right)^2$

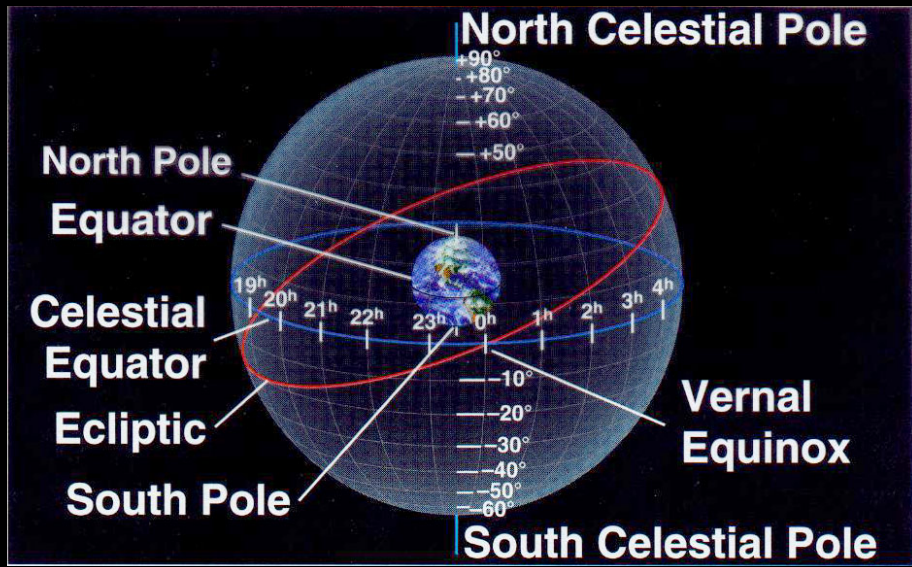
Recap Einstein Equations

- 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

Robertson Walker Metric

As an observer at the origin of the coordinate system it is best to use polar coordinates

- think of 'celestial sphere'
- reason for right ascension and declination as coordinates on the sky
- also longitude and latitude on Earth



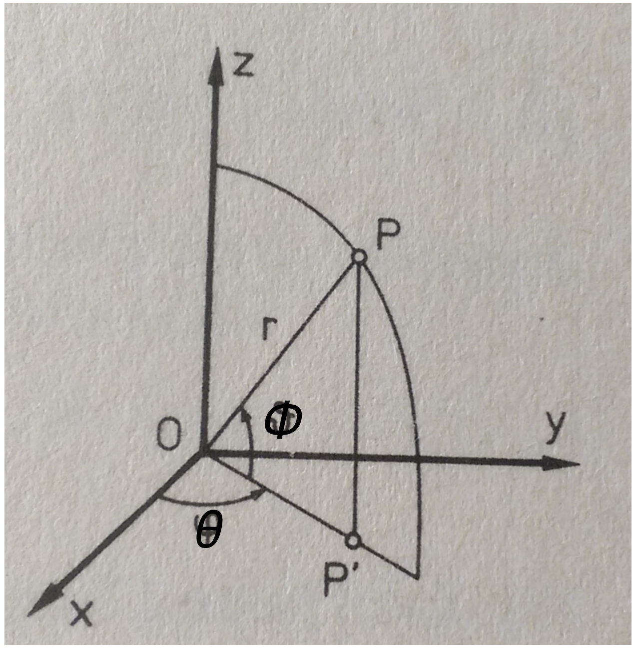
Robertson Walker Metric

Line element has angular and radial components

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

$$g_{00} = -1; g_{xx} = \frac{a^2(t)}{1-kx^2};$$

$$g_{\theta\theta} = a^2(t)x^2; \mathrm{g}_{\phi\phi} = a^2(t)x^2\sin^2\theta$$



The Energy-Momentum Tensor

Use the form for the 'perfect fluid'

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

The energy conservation requires that the covariant derivative

$$0 = T^{\mu\nu}_{;\mu} = \frac{\partial T^{0\mu}}{\partial x^{\mu}} + \Gamma^{0}_{\mu\nu} T^{\nu\mu} + \Gamma^{\mu}_{\mu\nu} T^{0\nu} = \frac{\partial T^{00}}{\partial t} + \Gamma^{0}_{ij} + \Gamma^{i}_{i0} T^{00} = \frac{c^2 d\rho}{dt} + 3\frac{\dot{a}}{a}(p + \rho c^2)$$

$$c^2 \dot{\rho} + 3\frac{\dot{a}}{a}(p + \rho c^2) = 0$$

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
  - expanding forever
- k=-1
  - open universe
  - expands forever

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

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

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

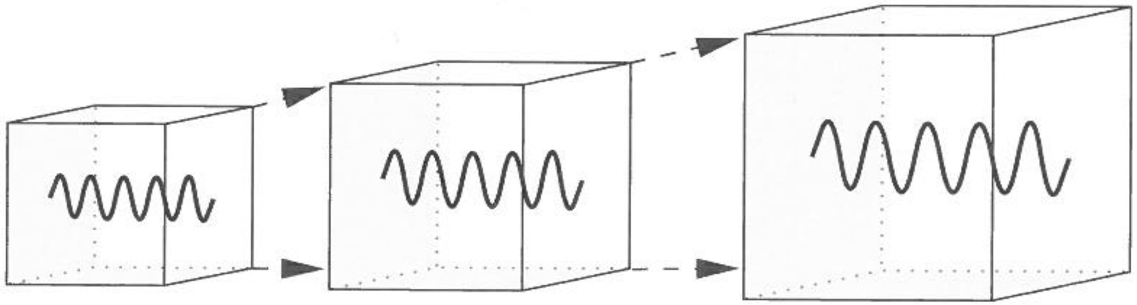
- If the time intervals *dt* are interpreted as oscillation periods, e.g. of a photon, then

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

- with z as the redshift between the two times

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

Distances

Different methods to measure distances

– Luminosity distance

$$l = \frac{L}{4\pi D^2}; l\ observed\ brightness; L\ emitted\ luminosity; D\ distance$$

– The distance is the comoving distance x_1 times the scale factor at the time of observation (for us 'today') $a(t_0)$

$$D = x_1 a(t_0)$$

Luminosity Distances

- The rate of the photons 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*ν) 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 $l = \frac{L}{4\pi D_L^2}$

Expansion and Contents

2nd derivative of the scale factor gives the dynamics of the expansion, i.e. differentiation of the Friedmann equation

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

– expect only deceleration ($\ddot{a}<0$), since density (ρ) and pressure (p) are positive

– acceleration requires (ρc^2+3p)<0 or ϖ=-1/3

Friedmann Equation

Put the various densities into the Friedmann equation

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

Define the critical density for a flat universe (k=0) $\rho_{crit} = \frac{3H^2}{4\pi G}$ we can define the ratio to the critical density $\Omega = \frac{\rho}{\rho_{crit}}$

Most compact form of Friedmann equation

$$1 = \Omega_{matter} + \Omega_{rad} + \Omega_{vac} + \Omega_k \text{ with } \Omega_k = -\frac{k}{a^2 H^2}$$

Dependence on Scale Parameter

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

$$\rho_{matter} \propto a^{-3} \qquad \rho_{rad} \propto a^{-4} \qquad \rho_{\Lambda} = const.$$

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

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

and the Friedmann equation

$$H^2 = H_0^2\left[\Omega_{matter}(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_{\Lambda} + \Omega_k(1+z)^2\right]$$

Expansion of the Universe

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

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

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<<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 10pc

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

The original Hubble Diagram

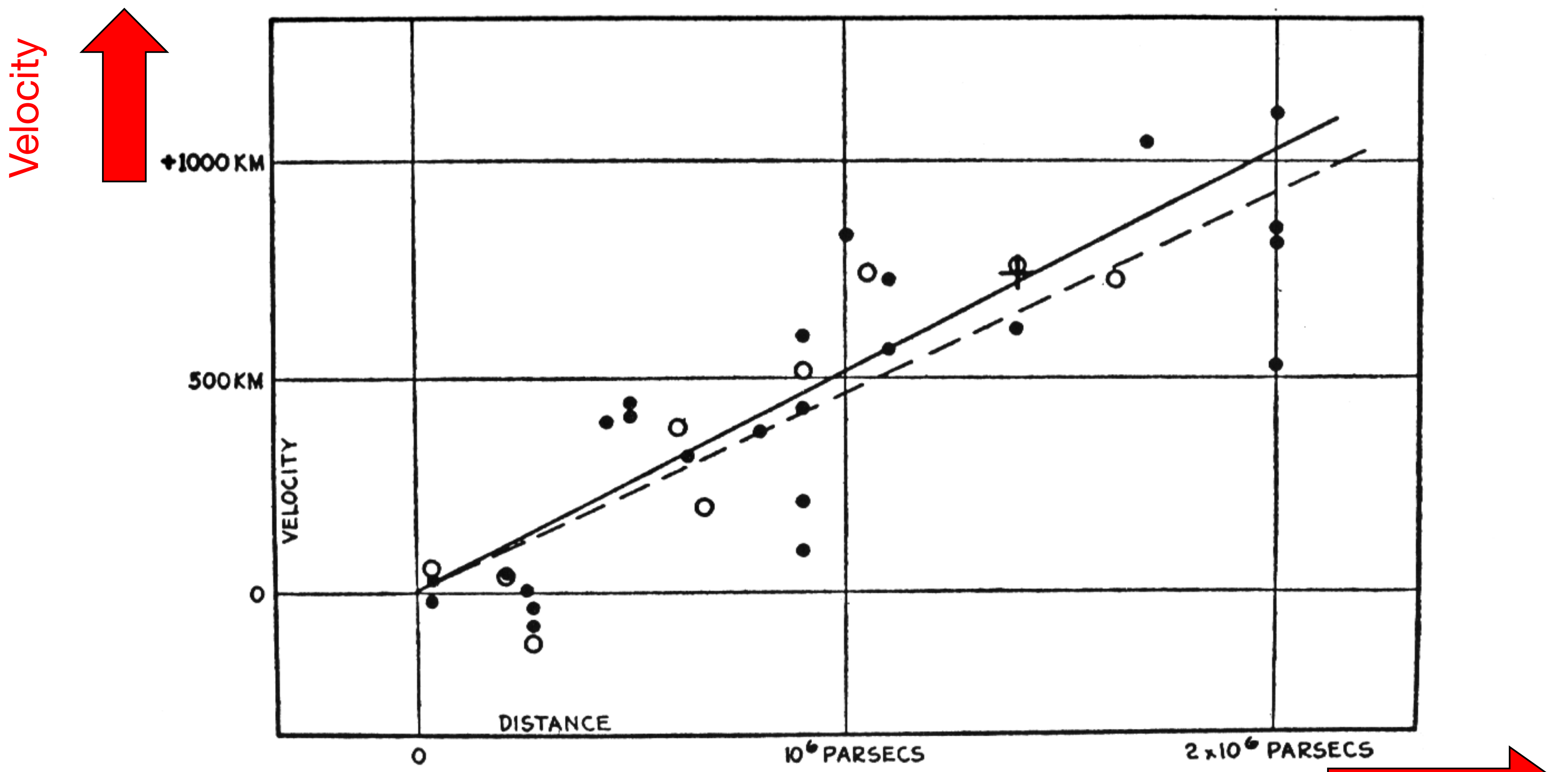
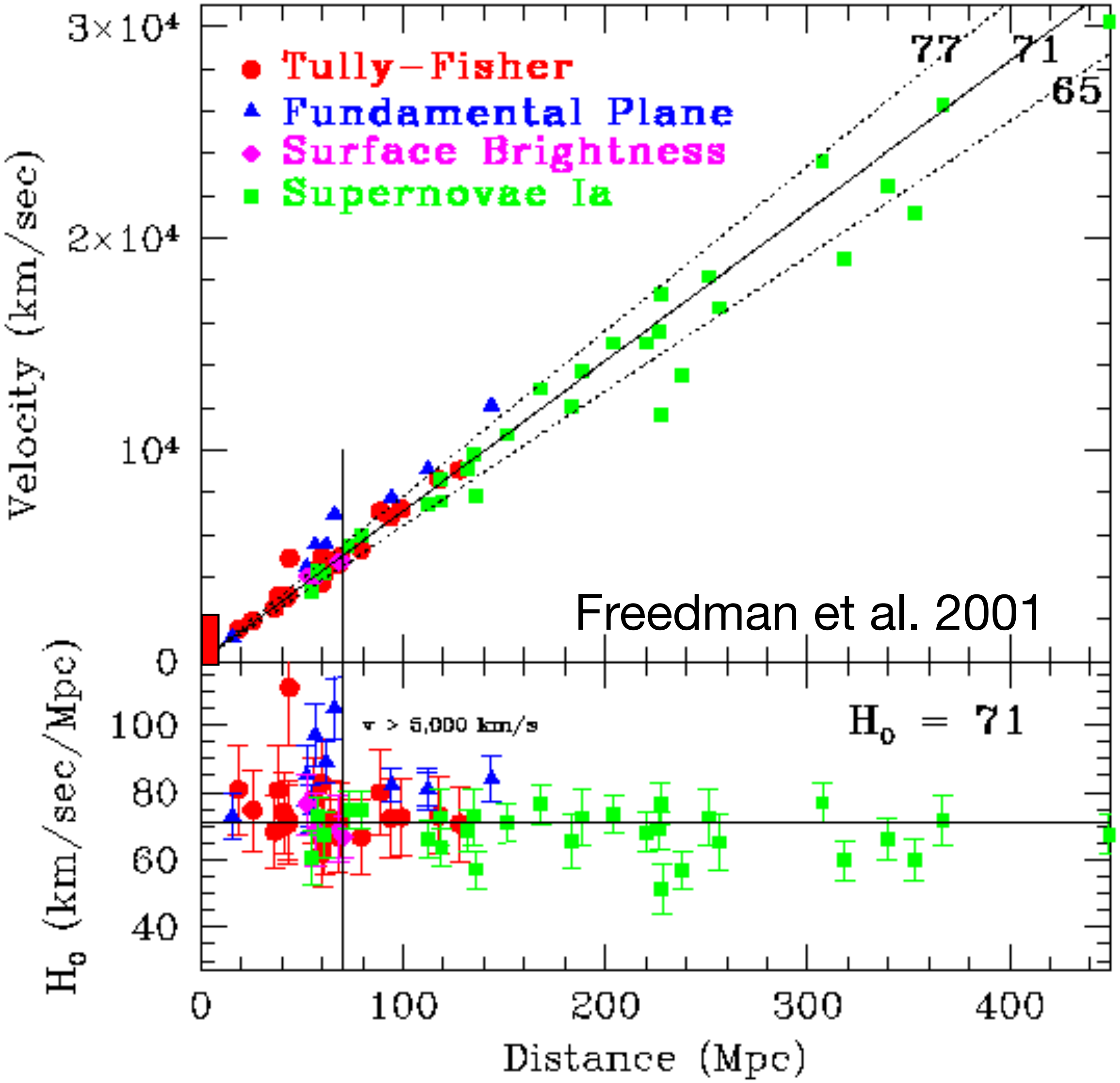


Fig. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble Diagram



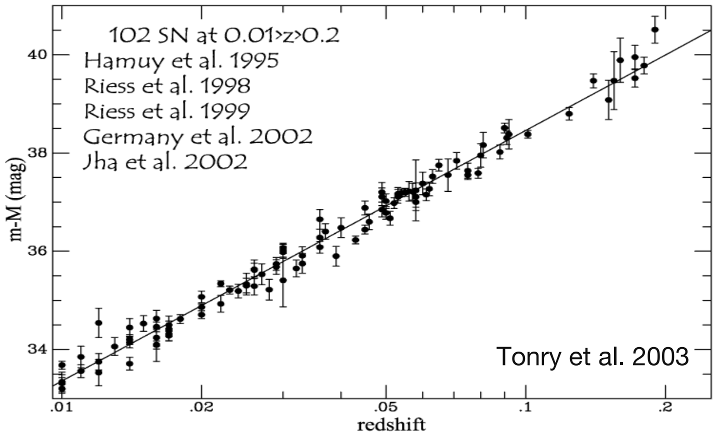
Hubble Diagram

Distance modulus vs. redshift

$$m - M = 5\log\left(\frac{cz}{H_0}\right) + 25$$

$$m - M = 5\log(z) + 5\log(c) - 5\log(H_0) + 25$$

$$H_0 = cz \cdot 10^{-0.2(m-M)+5}$$



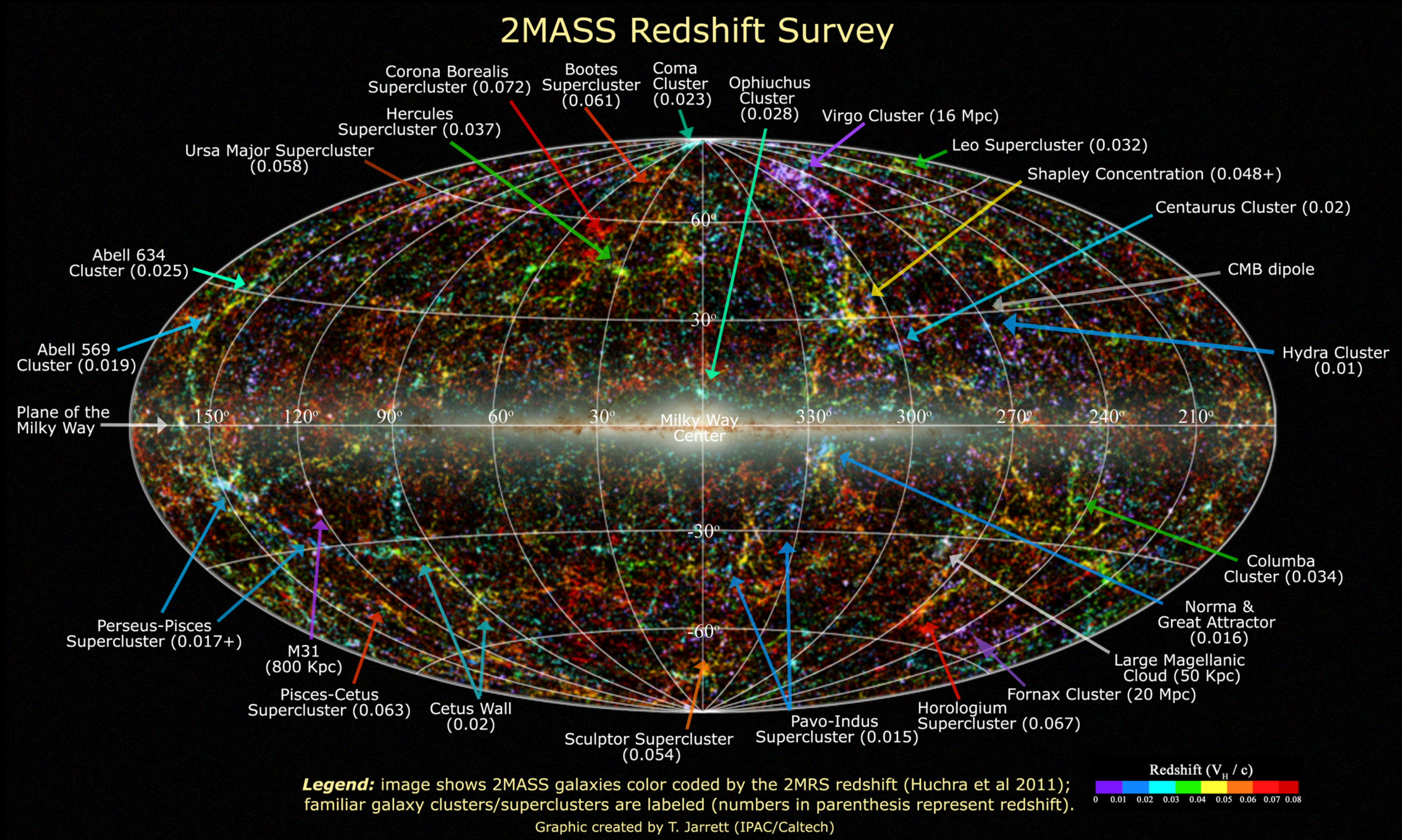
Absolute Calibration

Need to calibrate the absolute luminosity of the objects in the Hubble flow

- distance ladder
  - calibrate distance indicator from known distances
  - parallaxes (geometric) → main sequence fitting (photometric) → Cepheid stars → SNe Ia
- alternative
  - calibrate luminosity on physical grounds
    - expanding photosphere method (EMP)

Extragalactic Distances

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



Extragalactic Distances

The Astronomical Journal, 146:69 (14pp), 2013 September Courtois et al.

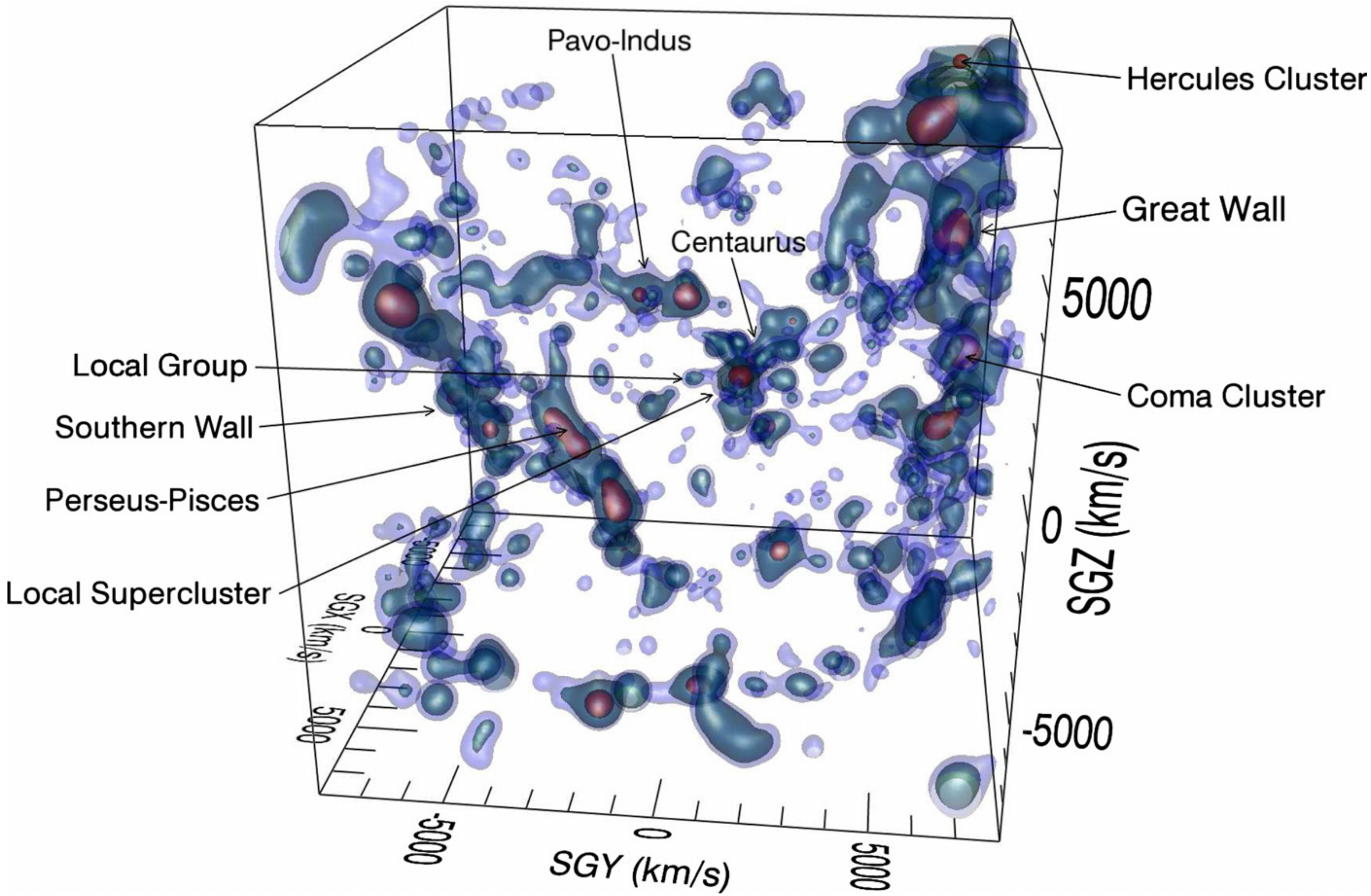


Figure 8. Perspective view of the V8k catalog after correction for incompleteness and represented by three layers of isodensity contours. The region in the vicinity of the Virgo Cluster now appears considerably diminished in importance. The dominant structures are the Great Wall and the Perseus–Pisces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

Extragalactic Distances

Many different methods

- Galaxies
  - Mostly statistical
  - Secular evolution, e.g. mergers
  - Baryonic acoustic oscillations
- Supernovae
  - Excellent (individual) distance indicators
  - Three main methods
    - (Standard) luminosity, aka ’standard candle’
    - Expanding photosphere method
    - Angular size of a known feature

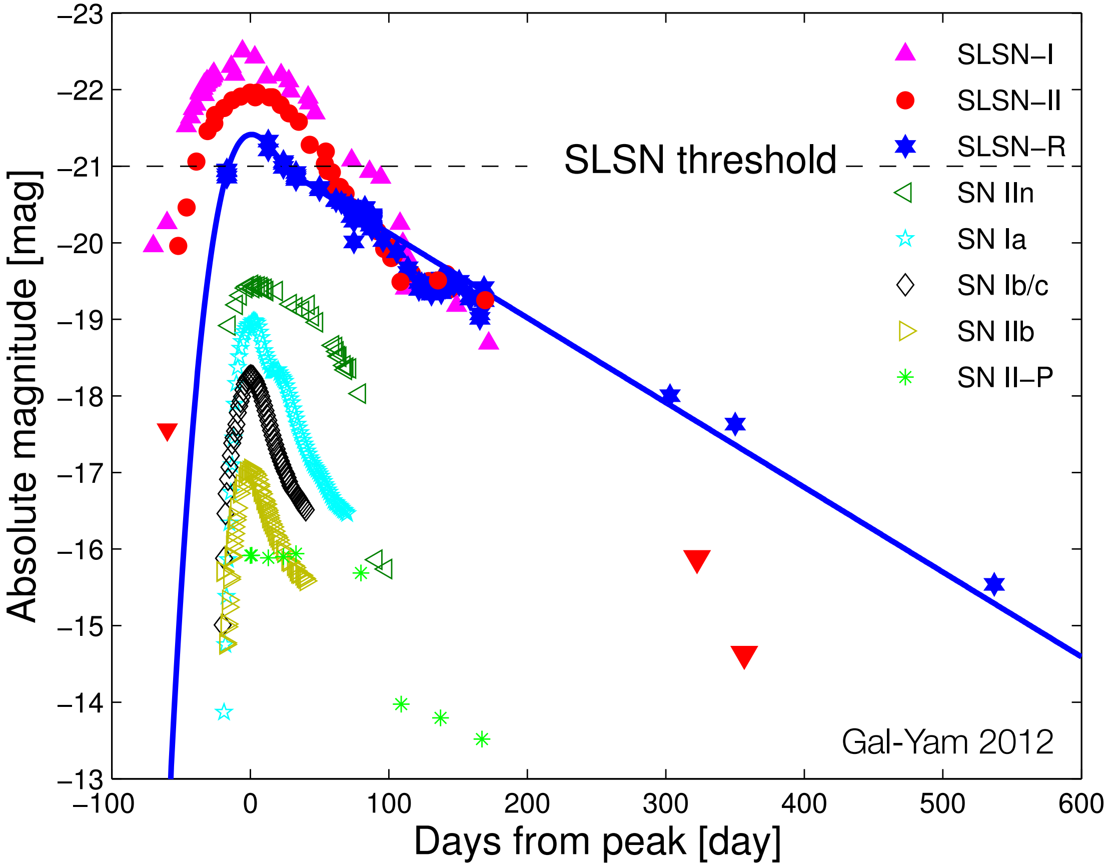
Hubble Constant

- 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

Hubble Constant

Stellar objects

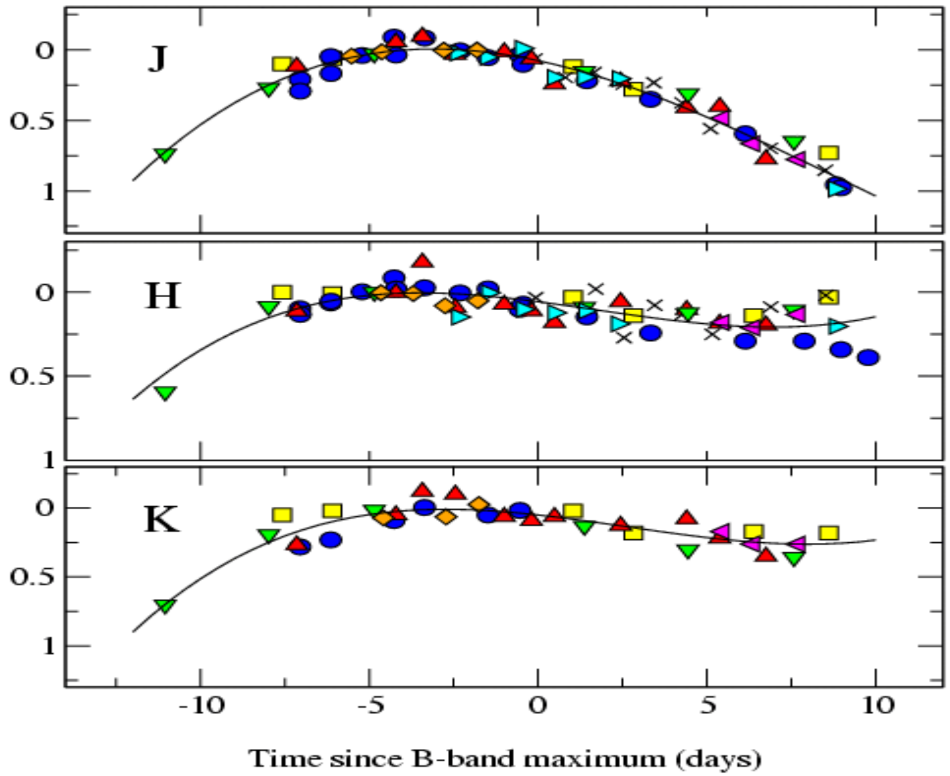
- Supernovae



Hubble Constant

- Problem
  - calibration of *M* for supernovae
    - transient objects!
    - explosions!
- Solution
  - Type Ia supernovae at maximum

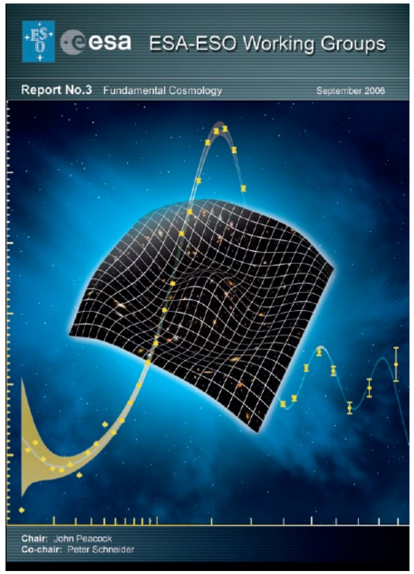
Krisciunas et al. 2004



Supernova Systematics

- Contamination
- Photometry
- K-corrections
- Malmquist bias
- Normalisation
- Evolution
- Absorption
- Local expansion field

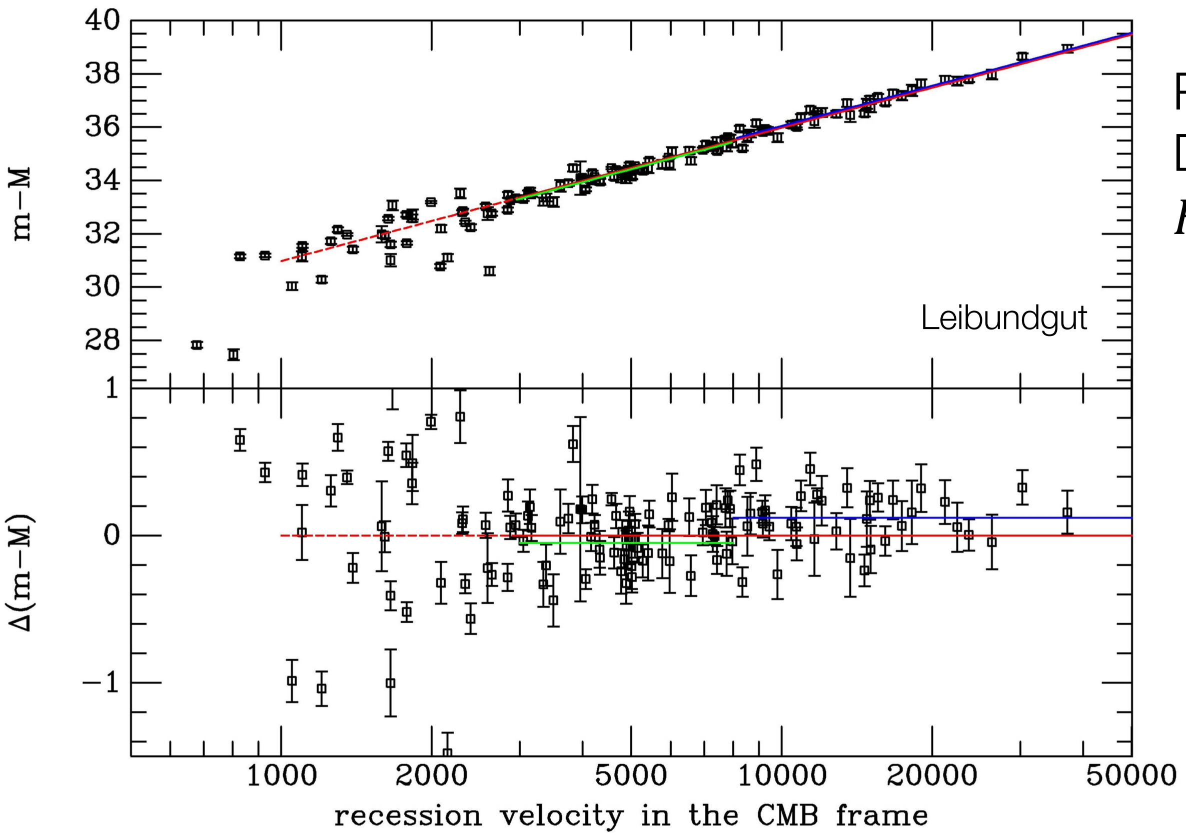
“[T]he length of the list indicates the maturity of the field, and is the result of more than a decade of careful study.”



Hubble Constant

- SN Hubble diagram

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

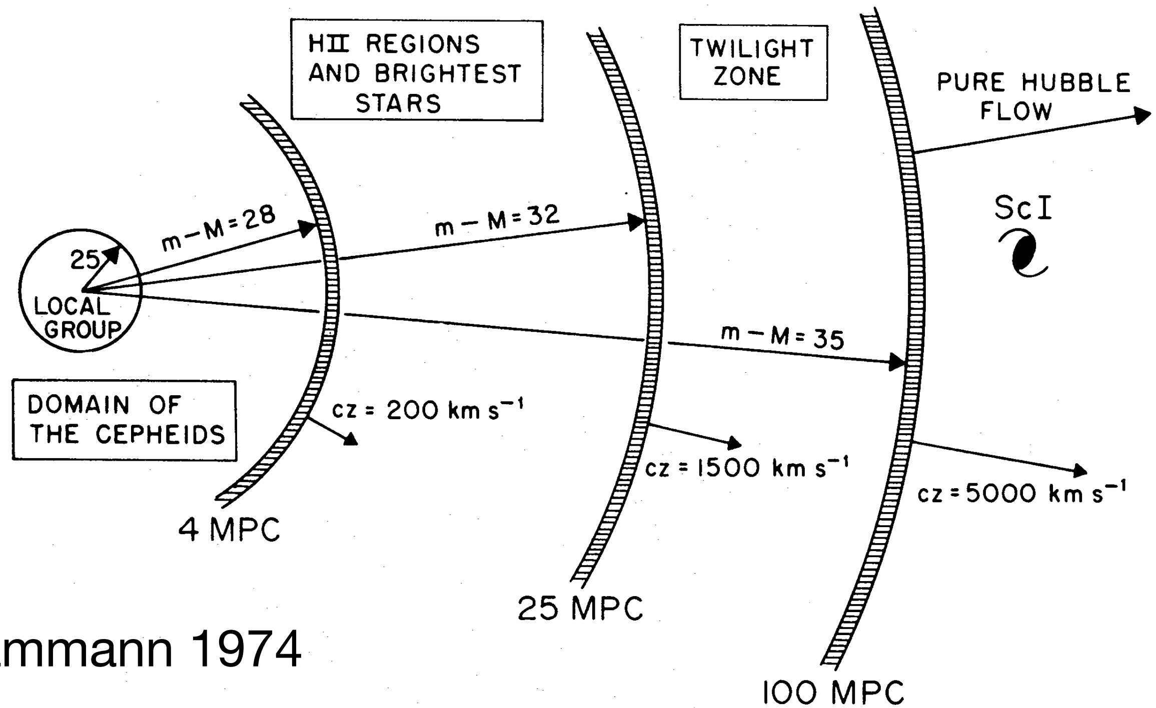


Proves *M* is constant
Direct connection of *M* and H_0

Hubble Constant

In the local universe ($z<<1$) the linear expansion law applies

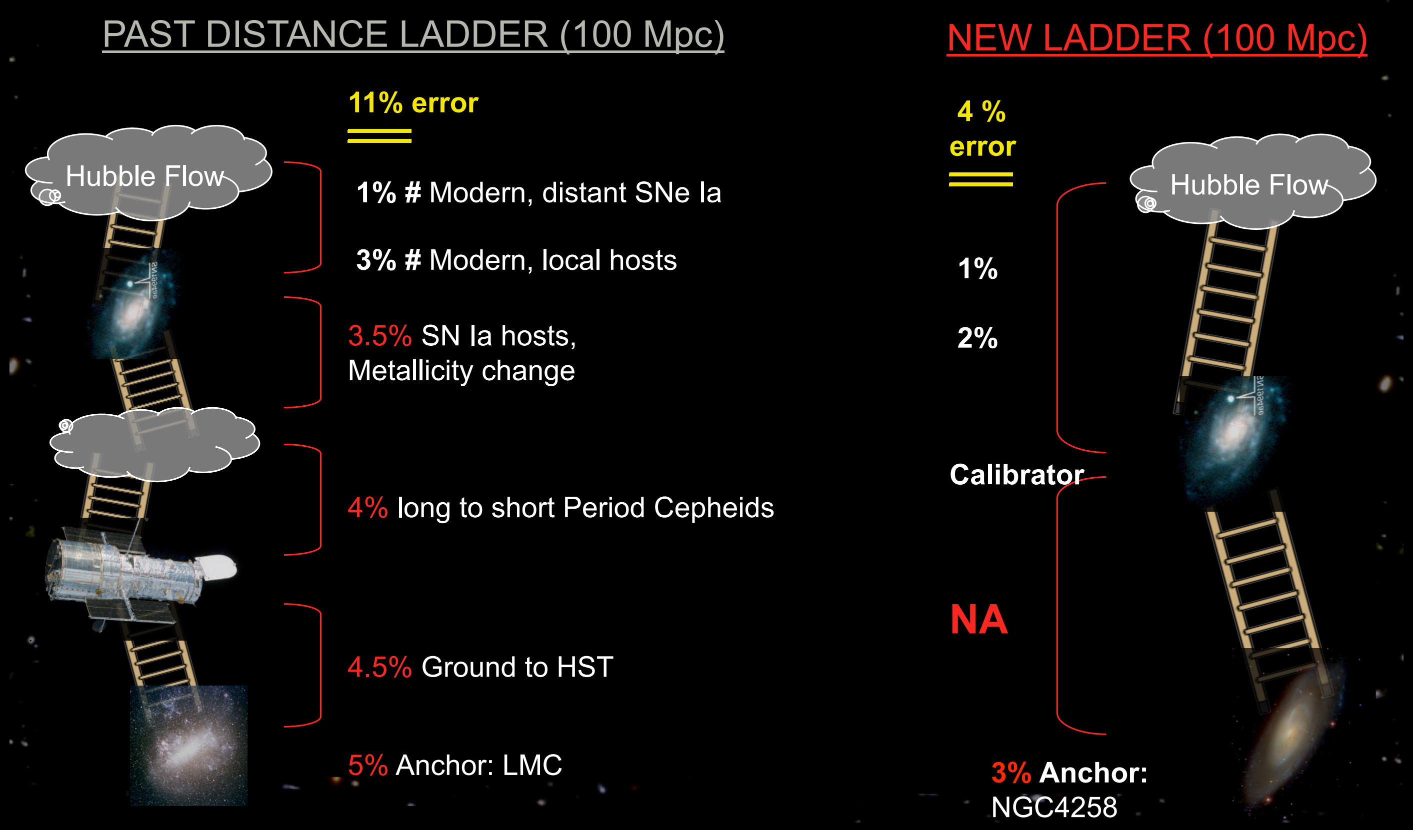
$$D_L = D_A = \frac{zc}{H_0} = \frac{v}{H_0}$$



Sandage & Tammann 1974

Hubble Constant

- Calibration of *M(SN Ia @ max)*
- Distance ladder



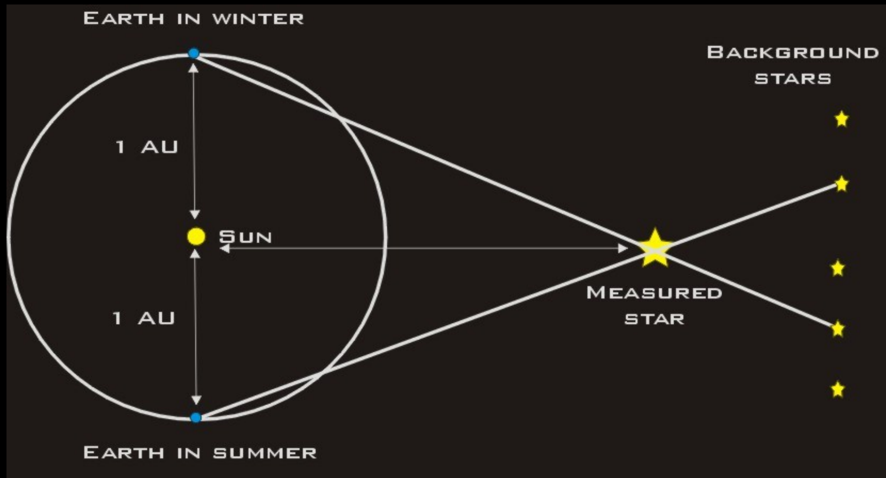
Adam Riess

Primary and Secondary Distance Calibrators

- Primaries are used to calibrate the secondary distance indicators to step out into the Hubble flow
- LMC as the anchor for most methods
- Use galaxies or similarly bright objects to measure the Hubble flow

Cosmic Distances

Trigonometric parallax: geometric projection of the Earth's orbit around the Sun on the sky.



1 parsec (pc) equals the distance of an angle of 1 arcsecond

$$1pc = \frac{\text{Sun-Earth distance}}{1\text{ arcsecond}} = \frac{1AU}{1''} = 149.6 \cdot 10^6\, km \,/\, \frac{\pi}{180 \cdot 3600} = 3.086 \cdot 10^{13}\, km$$
$$= 3.26 \text{ light years}$$

Cepheid Stars

Henrietta Swan Leavitt (1912)

– Cepheid stars in the Small Magellanic Cloud show a regular period luminosity relation

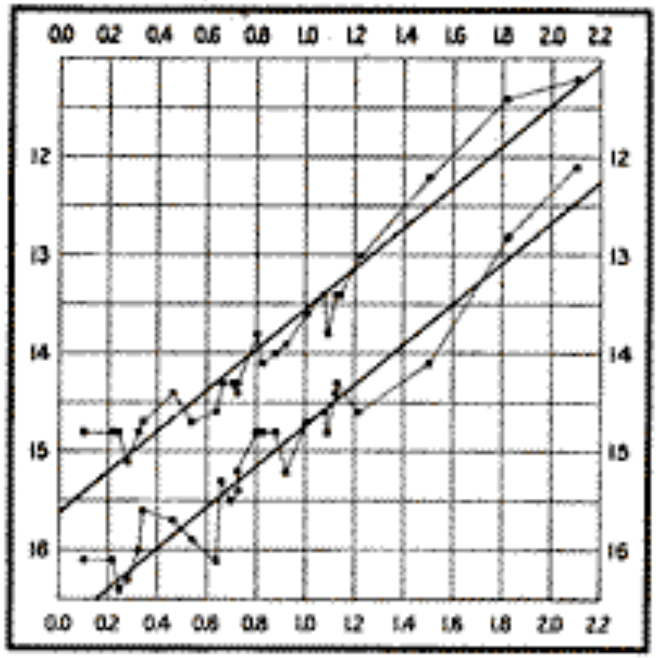
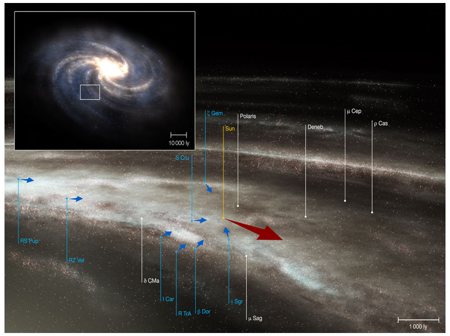
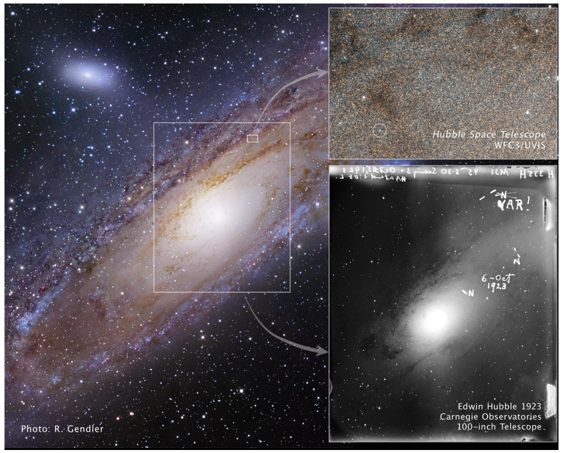


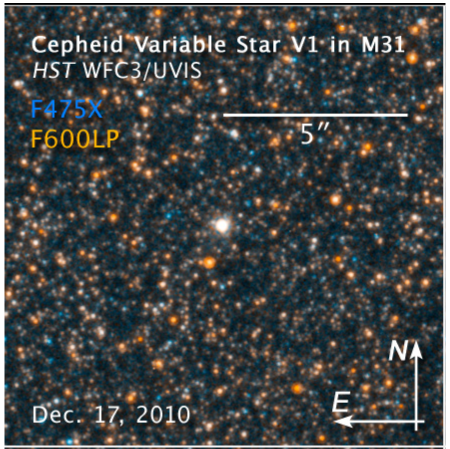
FIG. 2.

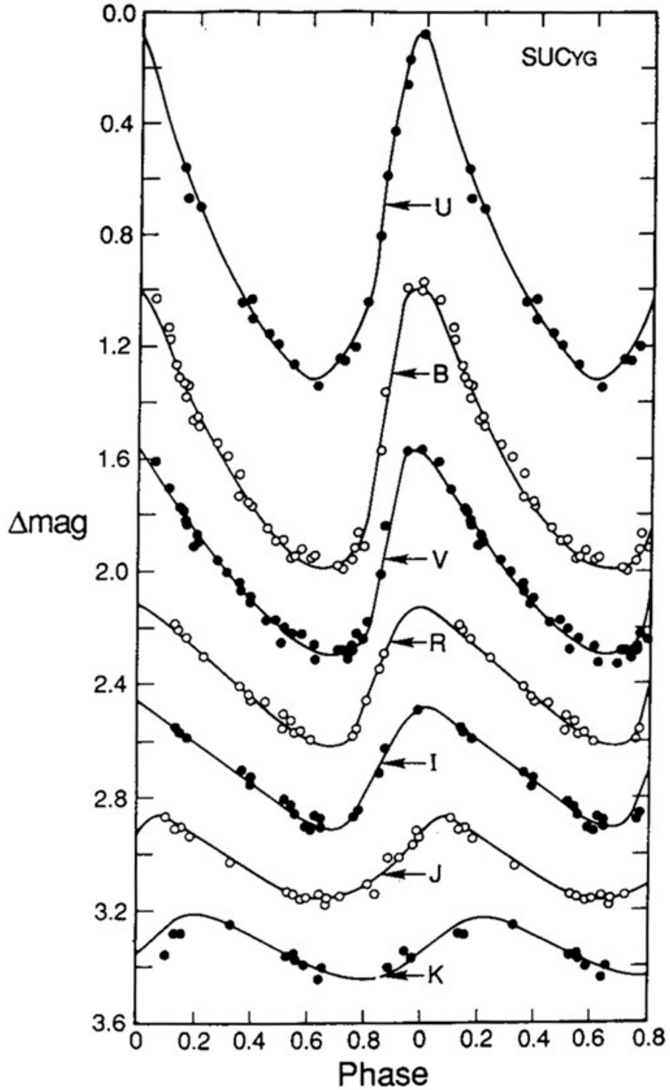
Cepheid Stars

- Pulsationally variable stars
- Are observed in the solar neighbourhood and in distant galaxies





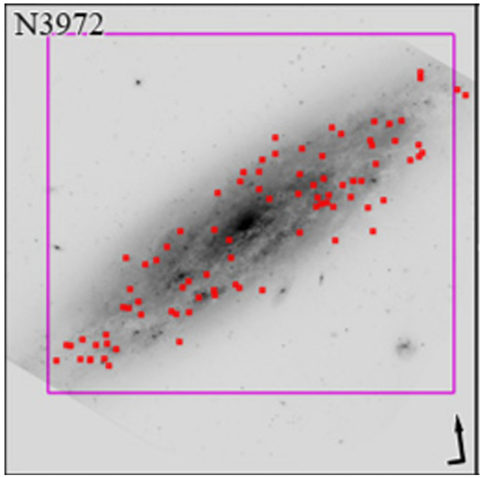


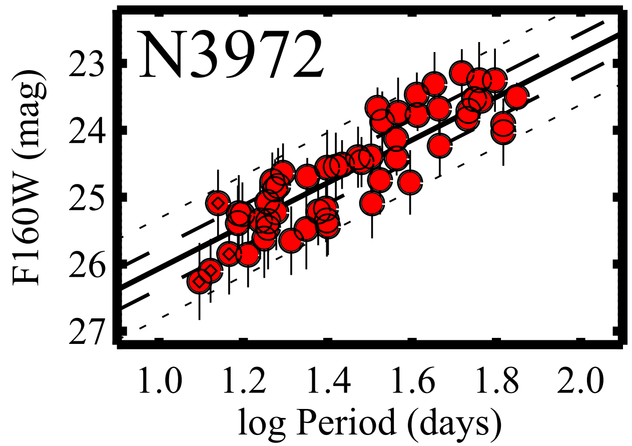


Madore & Freedman (1991)

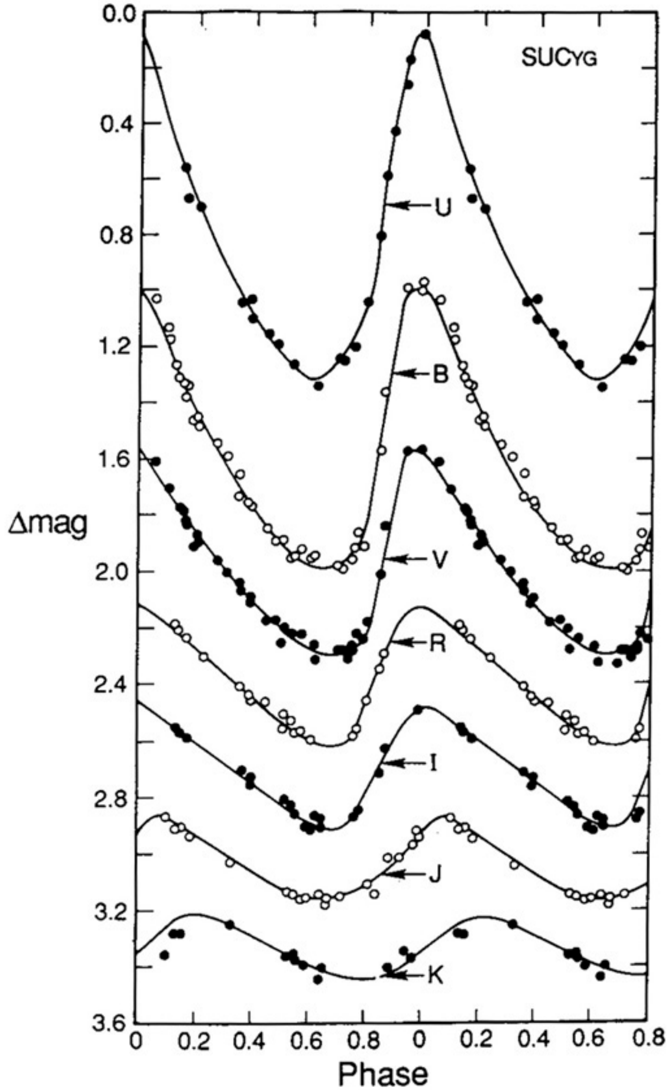
Hubble Constant

- Calibration
  - Cepheid distances to galaxies with well-observed SNe Ia





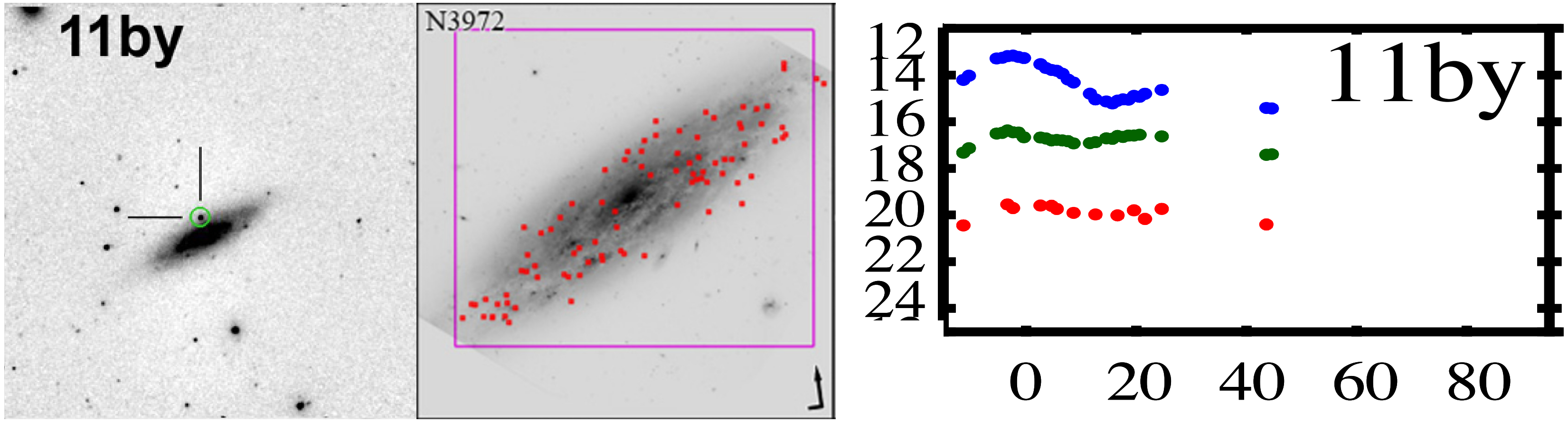
Riess et al. 2016



Madore & Freedman (1991)

Hubble Constant

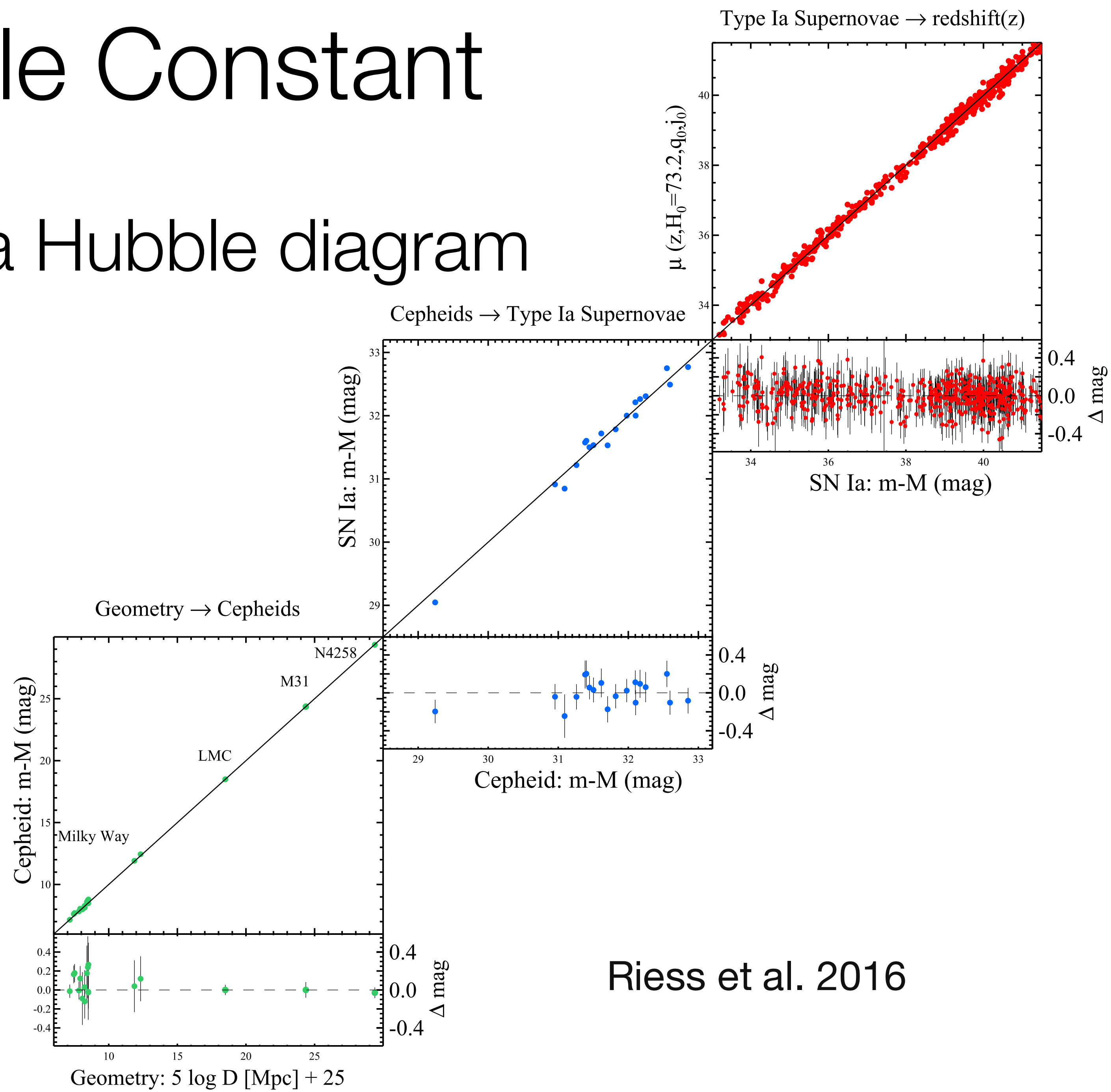
- An example: SN 2011by



Friedman et al. 2014

Hubble Constant

Latest SN Ia Hubble diagram



Riess et al. 2016

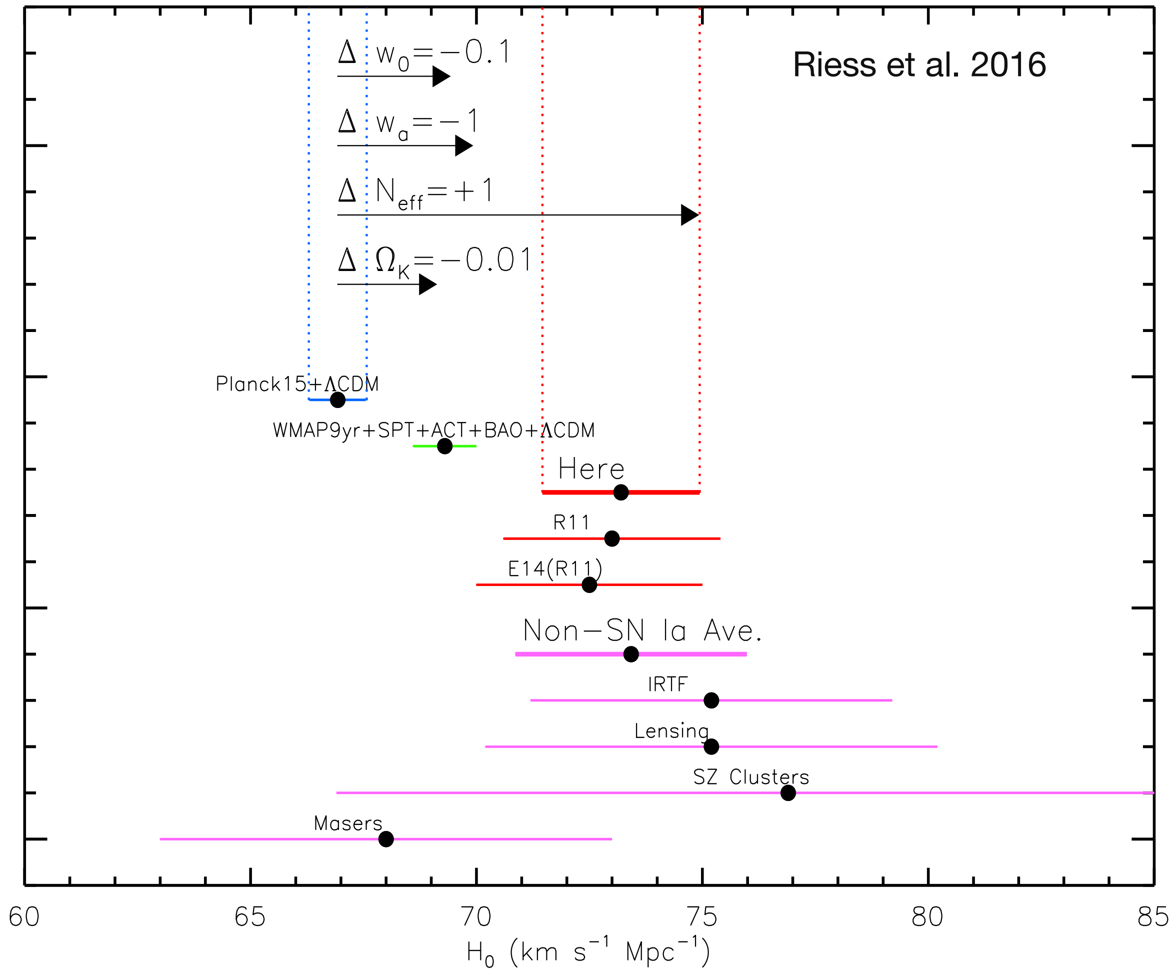
Hubble Constant

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

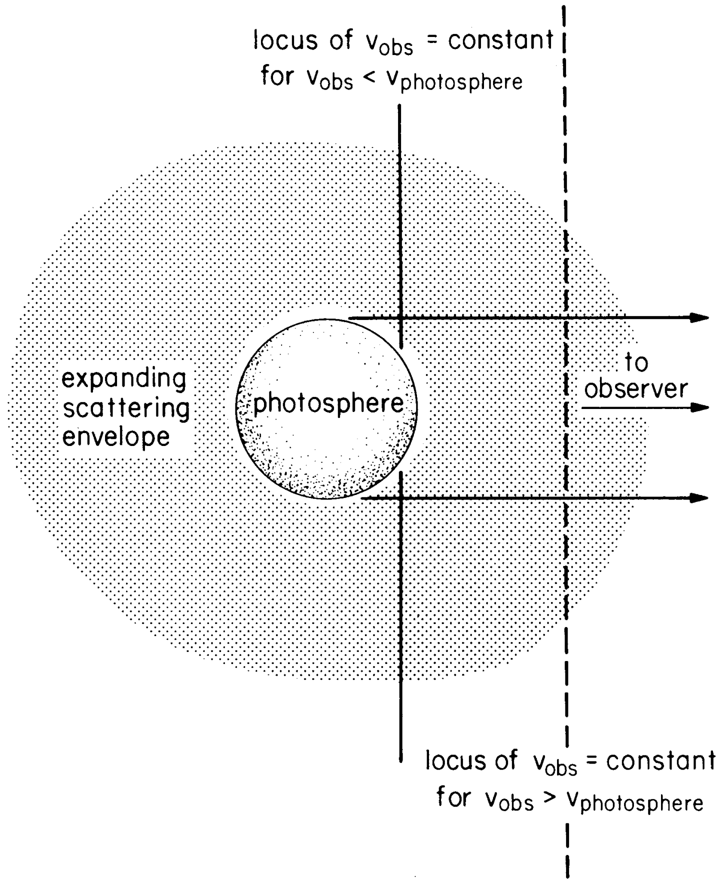
Hubble Constant

Latest values



Expanding Photosphere Method

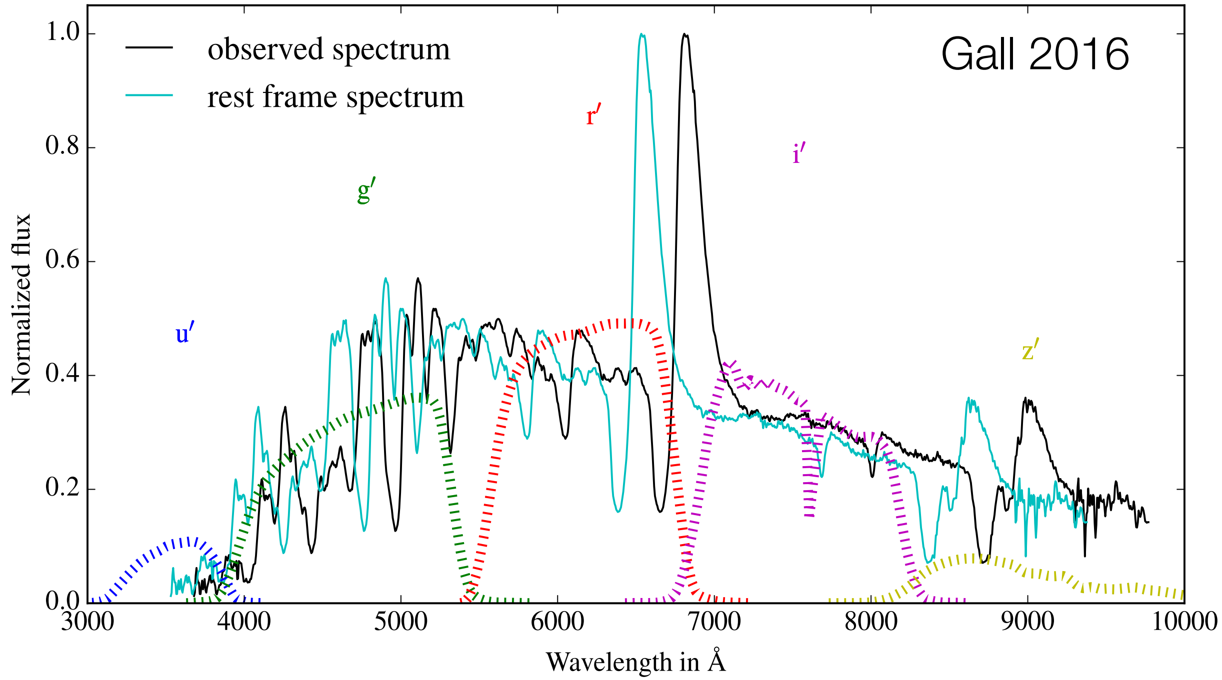
- Modification of Baade-Wesselink method for variable stars
- Assumes
  - Sharp photosphere
    → thermal equilibrium
  - Spherical symmetry
    → radial velocity
  - Free expansion



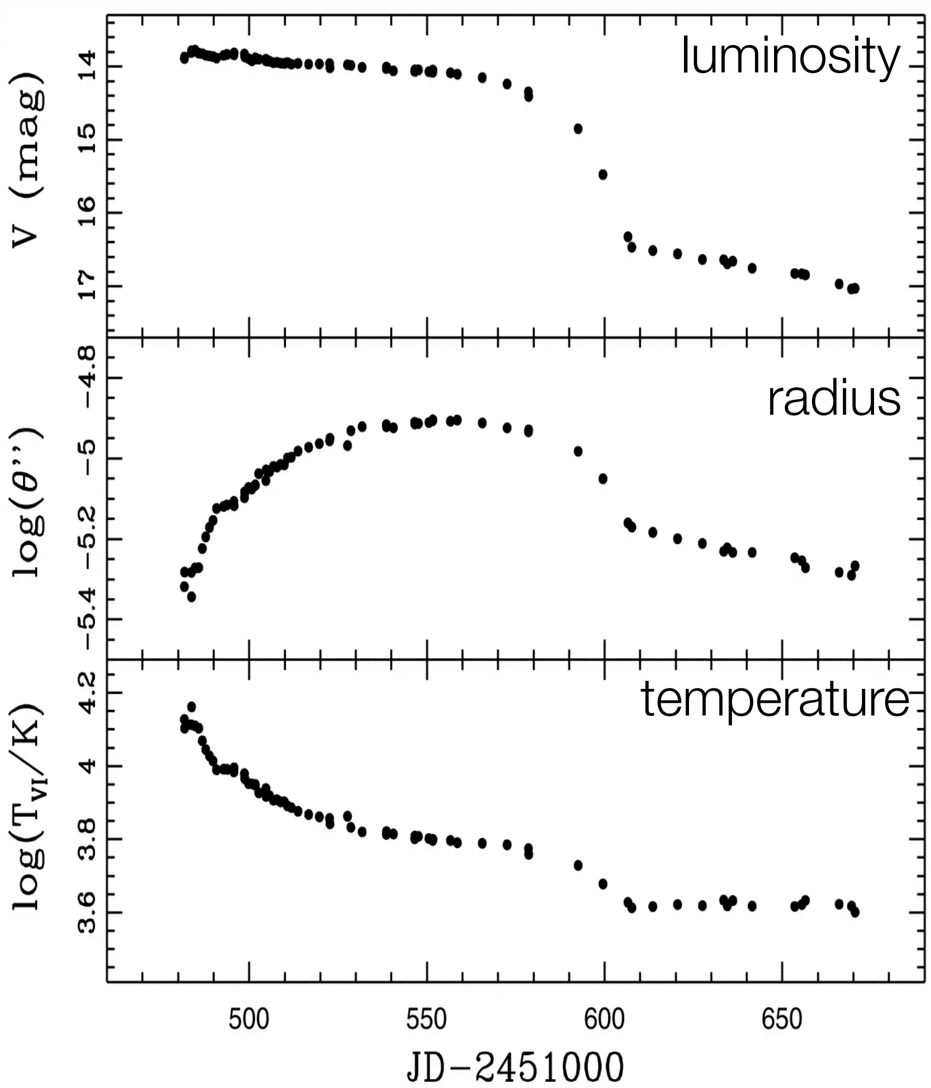
Kirshner & Kwan 1974

Photosphere Expansion

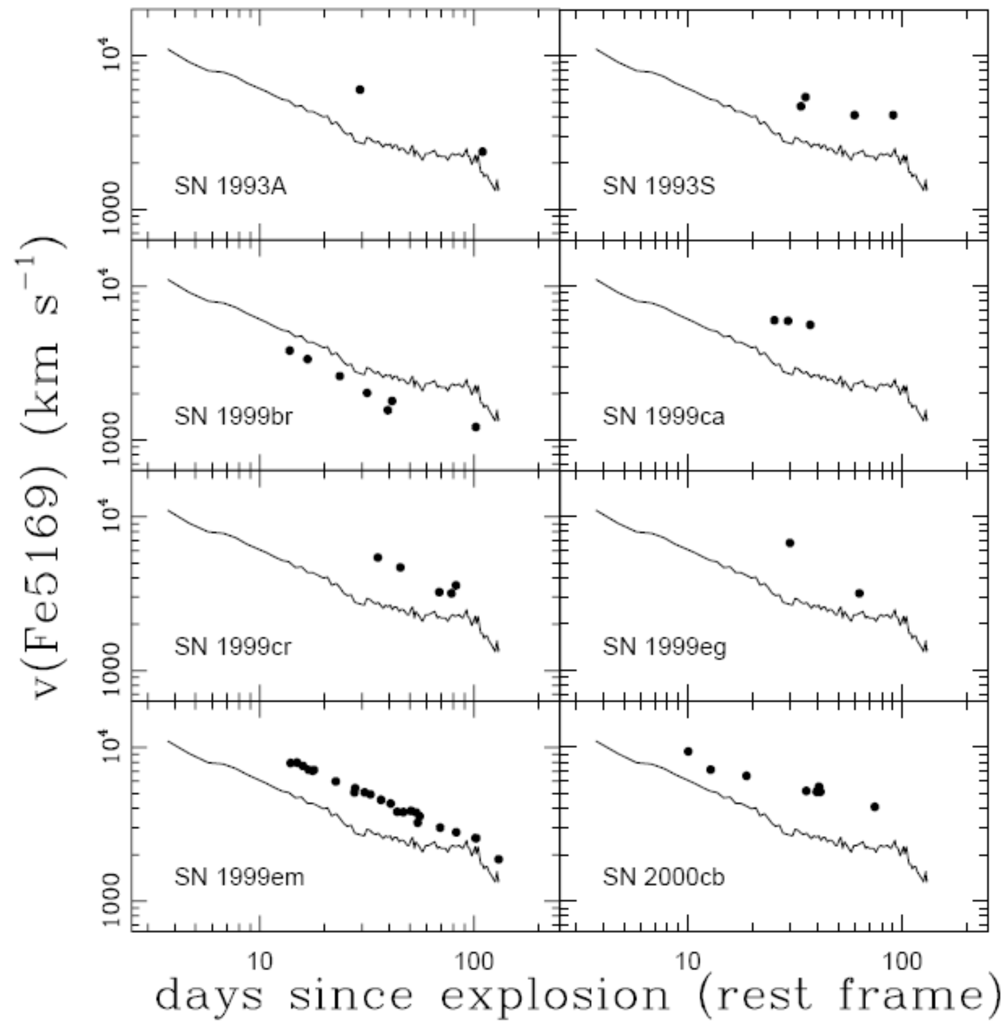
- Measured from absorption lines
  - formed close to the photosphere
    - not hydrogen lines → Fe II
  - remove redshift (from galaxy spectrum)
- Colour
  - K-corrections (redshift)



Photosphere Expansion



Hamuy et al. (2001)



Elmhamdi et al. (2003)

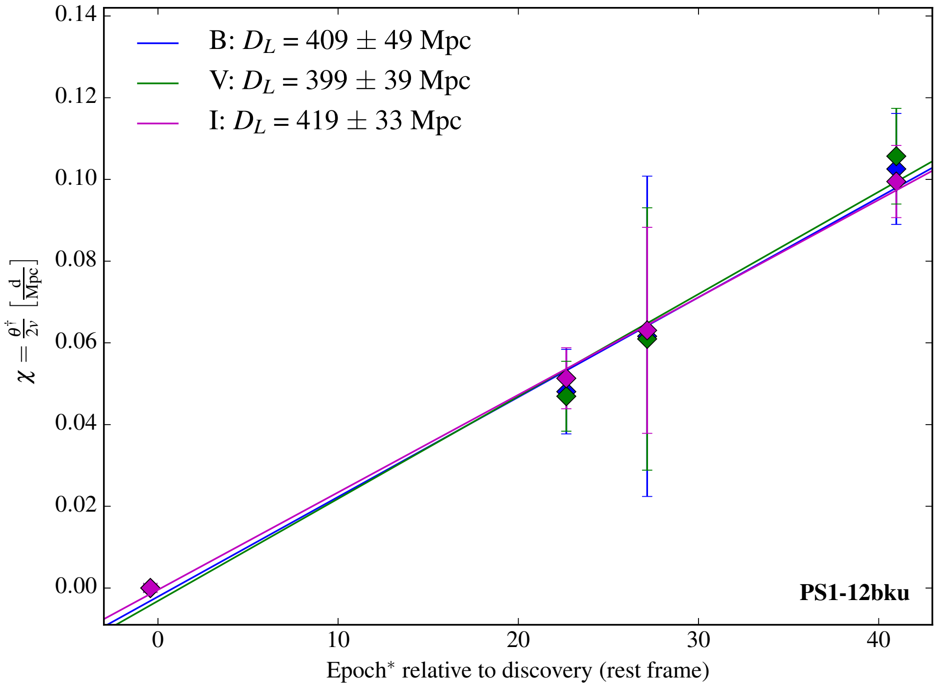
Expanding Photosphere Method

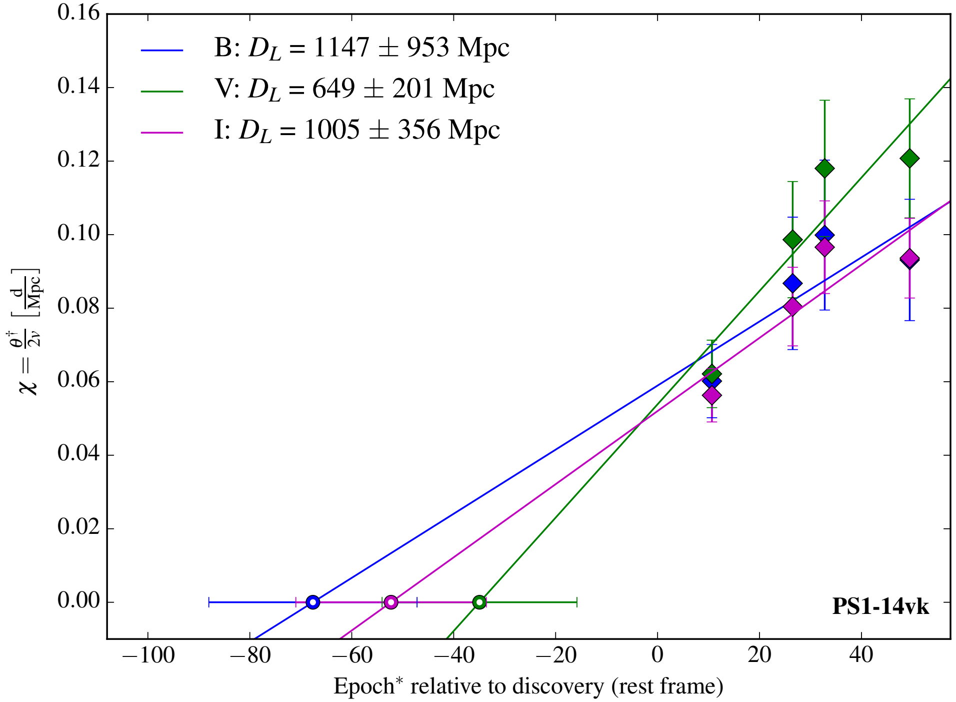
$$\theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\Lambda(T)}};\ R = v(t - t_0) + R_0;\ D_A = \frac{v}{\theta}(t - t_0)$$

- *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

- Multiple filters
- Influence of known date of explosion





Gall et al., in prep.

Expanding Photosphere Method

- Principle difficulties
  - Explosion geometry/spherical symmetry
  - Uniform dilution factors?
    - Develop tailored spectra for each supernova → Spectral-fitting Expanding Atmosphere Method (SEAM)
  - Absorption
- Observational difficulties
  - Needs multiple epochs
  - Spectroscopy to detect faint lines
  - Accurate photometry

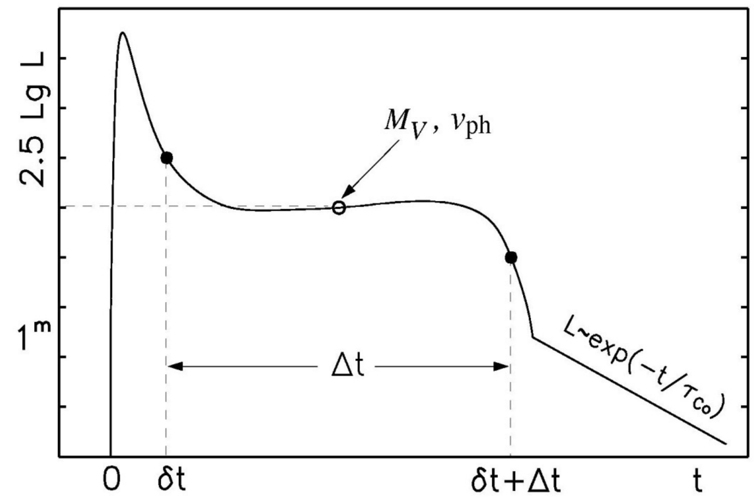
Standardizable Candle Method

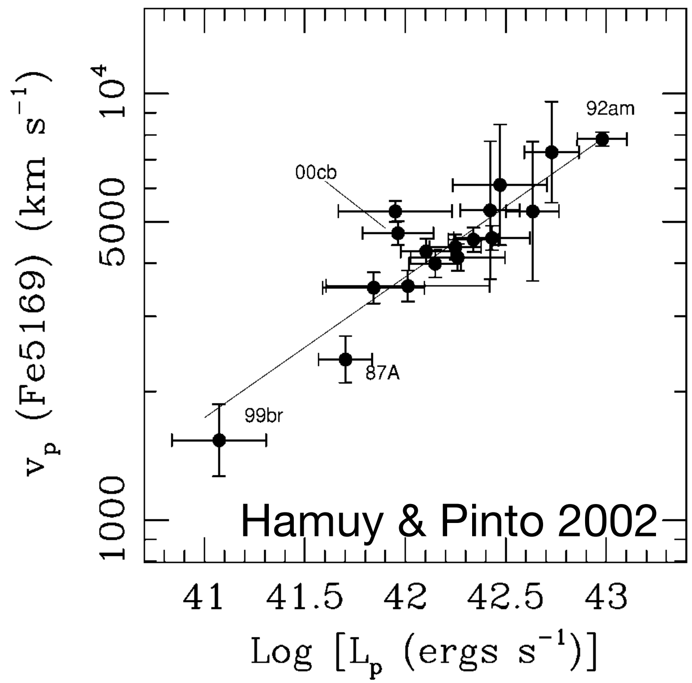
Introduced by Hamuy & Pinto (2002)

- Normalised luminosity during the plateau phase of SNe IIP
- Normally at 50 days after explosion

Used widely for SNe IIP

- Nugent et al. 2006
- Poznanski et al. 2009
- Olivares et al. 2010
- Maguire et al. 2010
- Polshaw et al. 2015



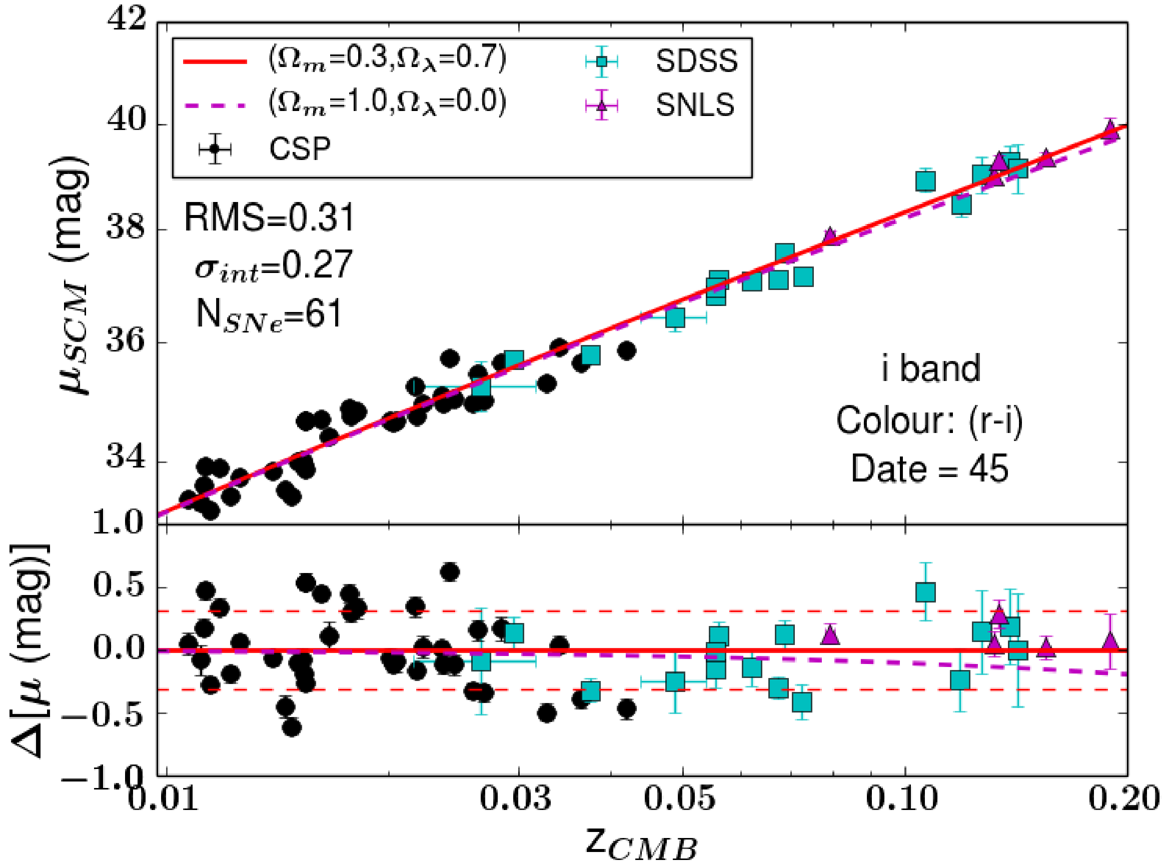


Standardizable Candle Method

- Straightforward simple method
  - Only few observations required
- Issues
  - Need to know explosion time
    - Often not too obvious from observational data
  - Measurement during a ’faint’ epoch
    - Plateau and not maximum
  - Spectroscopy often difficult
    - Faint phase and faint lines
    - Attempts to use prominent hydrogen lines

Standard Candle Method

- Applied to significant samples now



de Jaeger et al. 2017

Summary

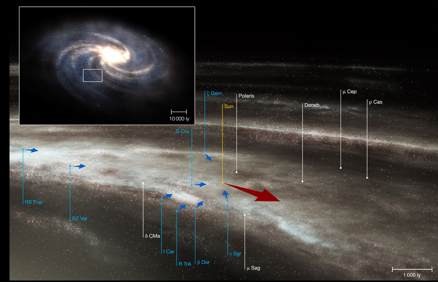
Hubble constant

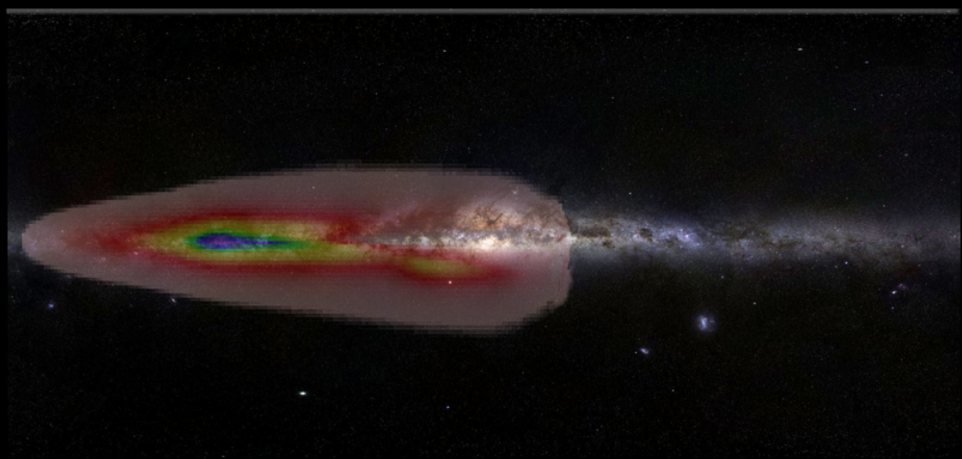
- local value through distance ladder
  - parallax → Cepheids → SNe Ia
  - EPM
  - yield values around 70 km s^{-1} Mpc^{-1}
- consistent with values derived from cosmic microwave background (Planck, WMAP)
  - requires full cosmological model

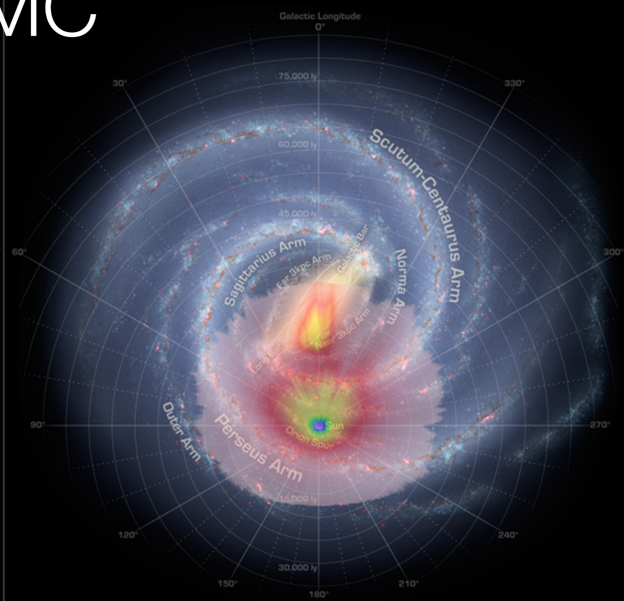
Reach of Gaia

Parallaxes to a fair fraction of the Milky Way

- galaxy structure
  - spiral arms, disk, bulge, halo
- galaxy dynamics
- average distance to the LMC







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%

Literature

- Scott Dodelson, Modern Cosmology, Boston, Academic Press 2013 ISBN: 0122191412
- Steven Weinberg, Gravitation and cosmology : principles and applications of the general theory of relativity, New York, Wiley 1972 ISBN: 0471925675
- John Peacock, Cosmological physics , Cambridge University Press, 1999 ISBN: 0521422701
- Jim Peebles, Principles of physical cosmology, Princeton University Press, 1993, ISBN: 0691074283 (hc); 0691019339 (pb)
- Steven Weinberg, Cosmology, Oxford University Press, 2008, ISBN 9780198526827
- Lars Bergström and Ariel Goobar, Cosmology and Particle Physics, Springer Verlag, 2004, ISBN 3-540-43128-4

Literature

- Steven Weinberg, Gravitation and cosmology : principles and applications of the general theory of relativity, New York, Wiley 1972 ISBN: 0471925675
- Wendy Freedman and Barry Madore, The Hubble Constant, Annual Reviews of Astronomy and Astrophysics 48, 673 (2010); http://www.annualreviews.org/doi/full/10.1146/annurev-astro-082708-101829
- Michael Rowan-Robinson, The Cosmological Distance Ladder, New York, W.H. Freeman and Company, 1985, ISBN o-7167-1586-4
- Stephen Webb, Measuring the Universe – The Cosmological Distance Ladder, Springer Verlag, 1999, ISBN 1852331062
- Edwin Hubble, The Law of Red-Shifts, 1953, Monthly Notices Royal Astronomical Society 113, 658
- Alan Sandage, The Ability of the 200-inch Telescope to Discriminate between Selected World Models, 1961, Astrophys. J. 133, 355
- Alan Sandage and Gustav Tamman, Series of papers “Steps towards the Hubble Constant” between 1974 and 1995 in the Astrophysical Journal
- Michael Perryman, The Making of History’s Greatest Star Map, Heidelberg, Springer Verlag, 2009, ISBN 978-3-642-11601-8, e-ISBN 978-3-642-11602-5
- An Atlas of the Universe, http://www.atlasoftheuniverse.com/index.html
- Talks at the Munich Institute for Astro- and Particle Physics (MIAPP) conference “The Extragalactic Distance Scale”, June 2014 (http://www.munich-iapp.de/scientific-programme/programmes-2014/extragalactic/)