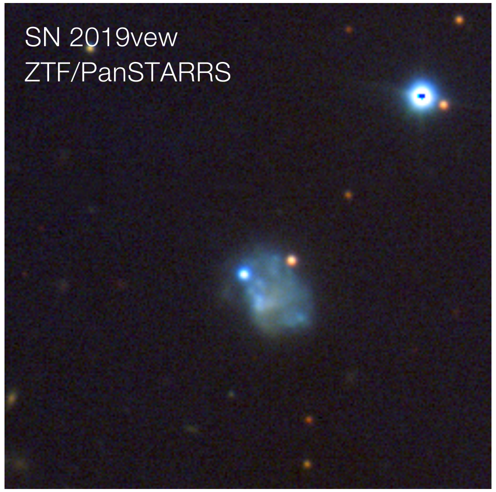
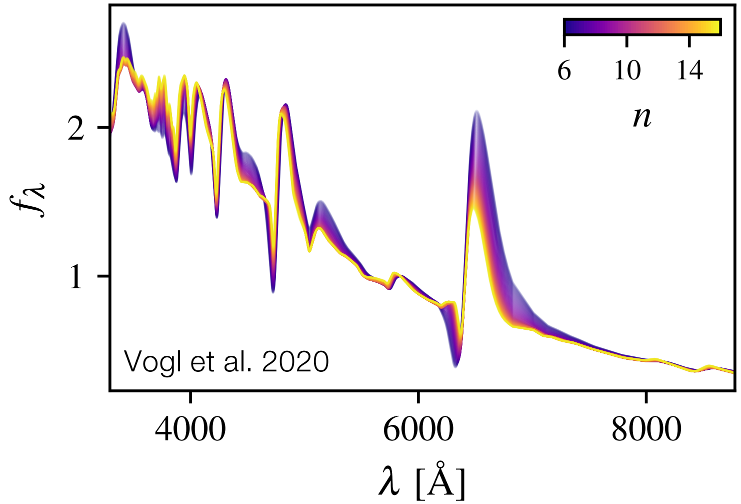
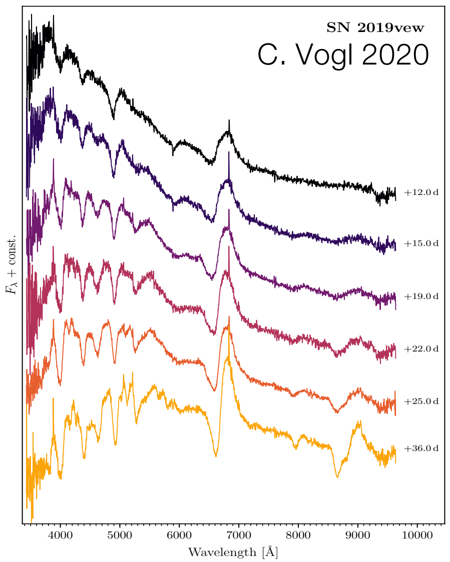
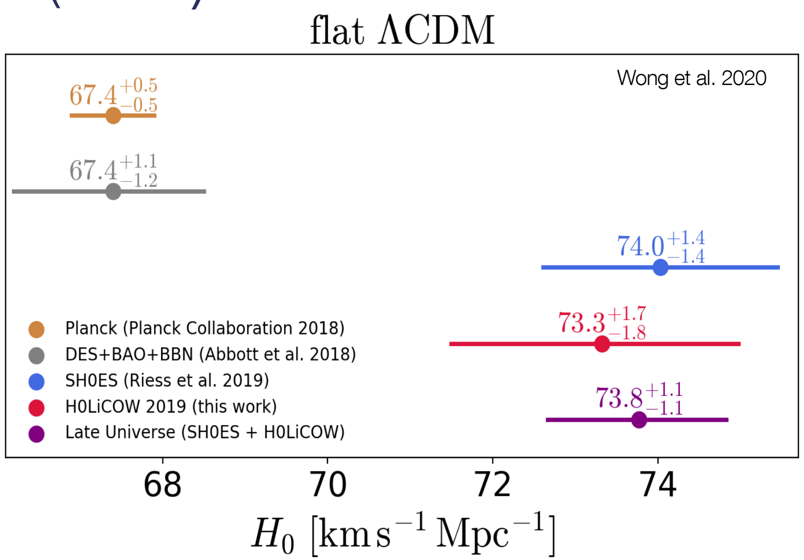




An independent way to measure extragalactic distances

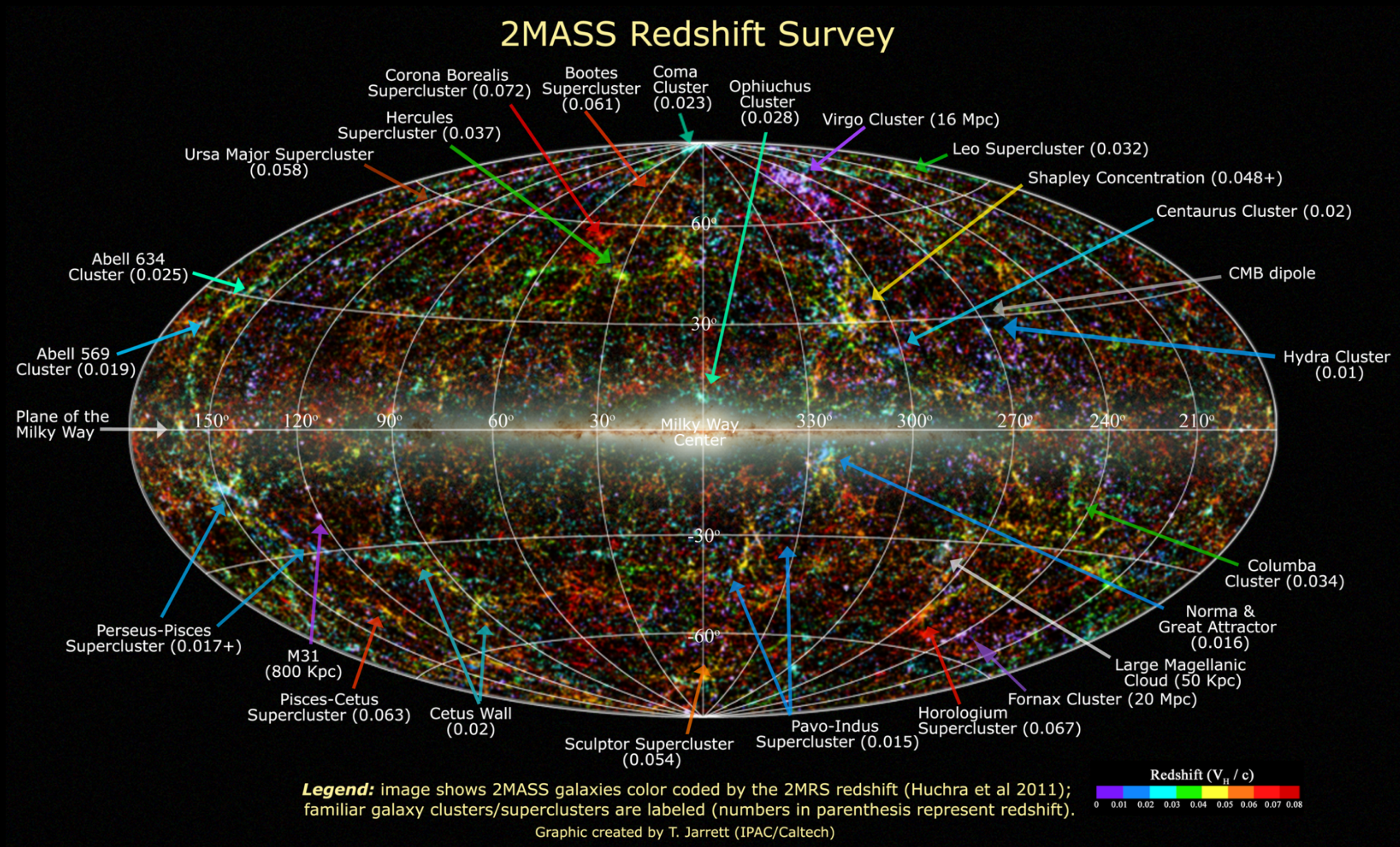
Bruno Leibundgut (ESO)





Extragalactic Distances

Required for a 3D picture of the (local)



Extragalactic Distances

- Difficulty to measure accurate distances
- Importance for local matter distributions
- Local expansion rate (Hubble constant)

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

Hubble-Lemaître Law — deceleration — jerk/equation of state

- Expansion history

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

Extragalactic Distances

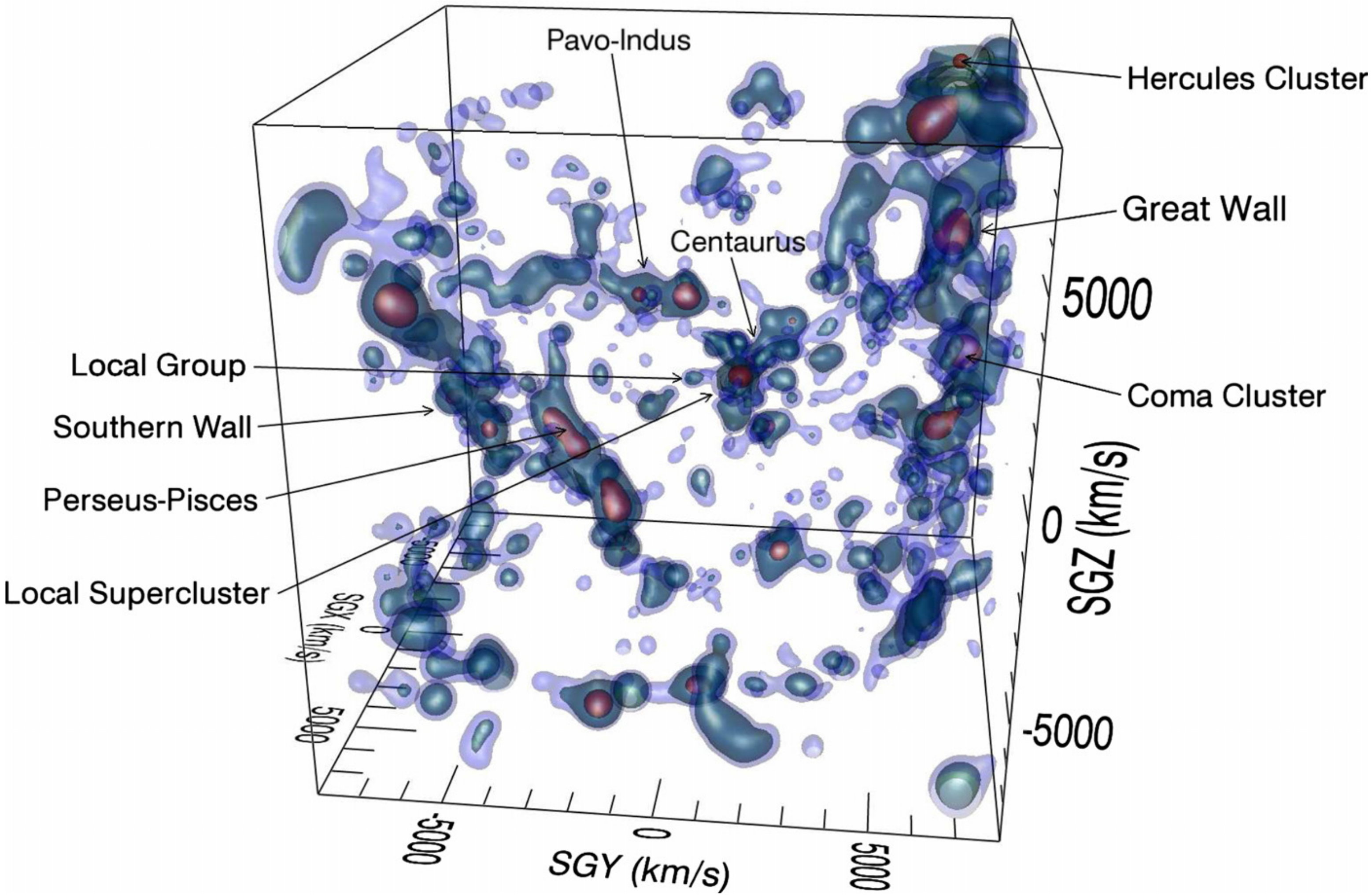
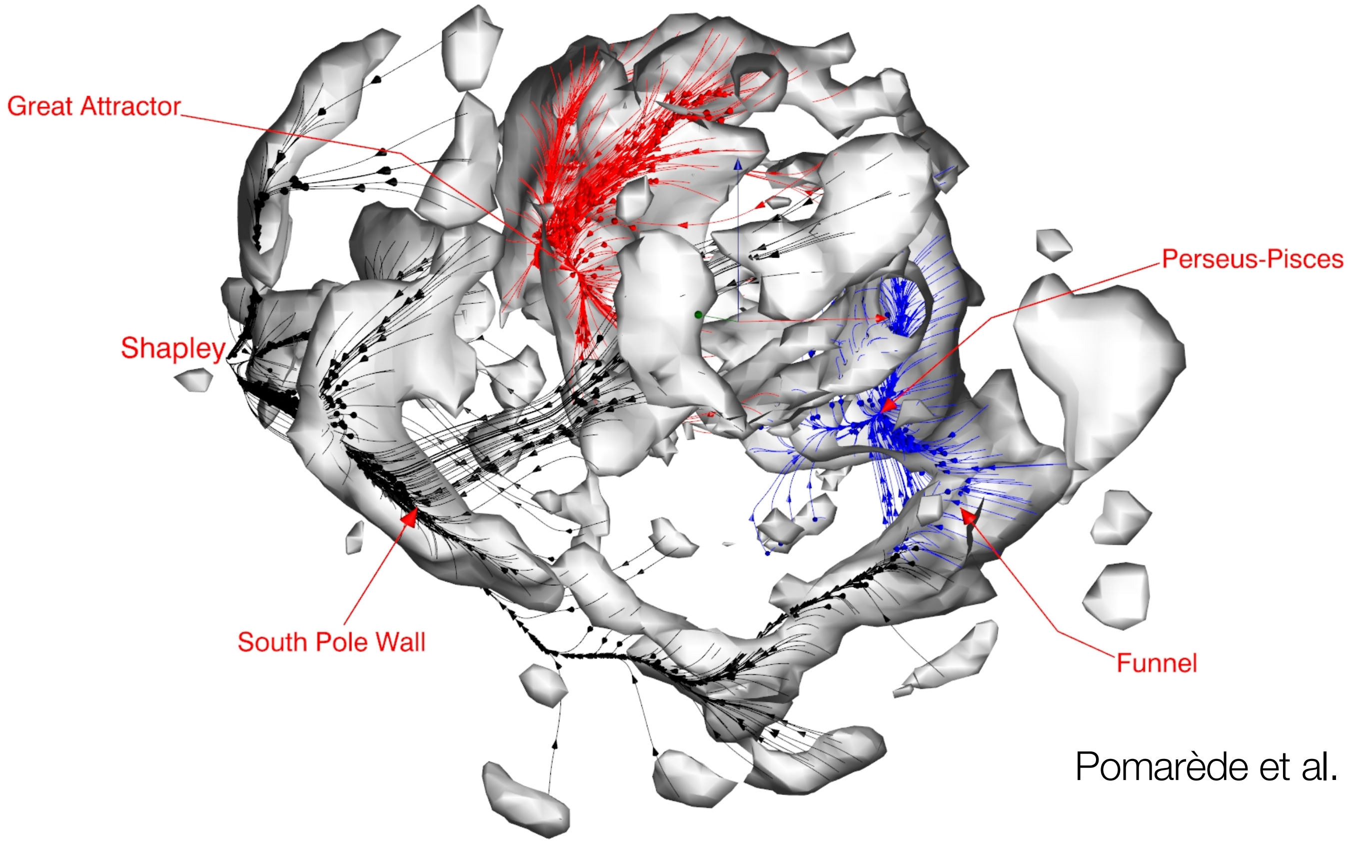


Figure 8. Perspective view of the V8k catalog after correction for incompleteness and represented by three layers of isodensity contours. The region in the vicinity of the Virgo Cluster now appears considerably diminished in importance. The dominant structures are the Great Wall and the Perseus–Pisces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

Local Flows

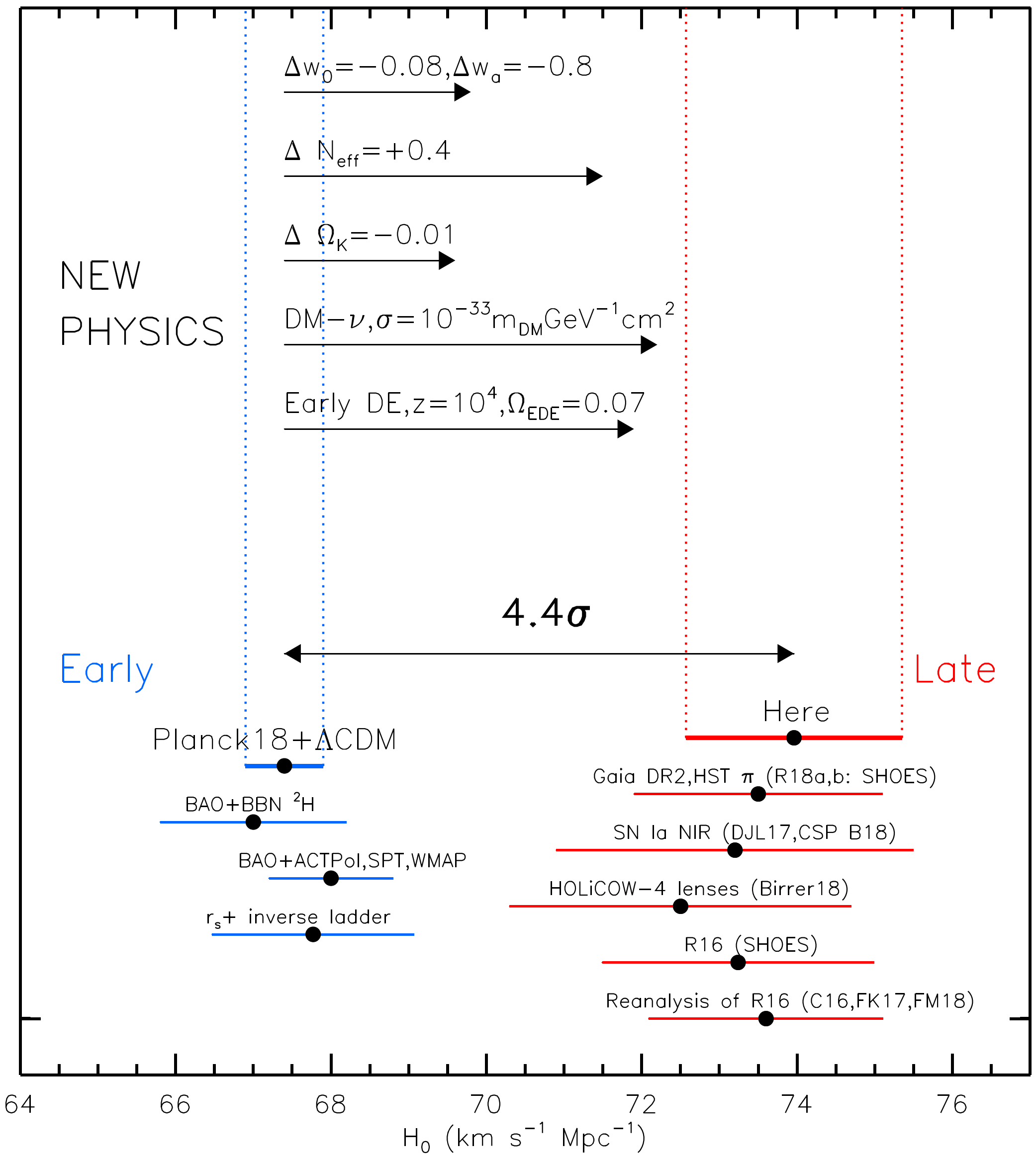
Inhomogeneous mass distribution in the local Universe



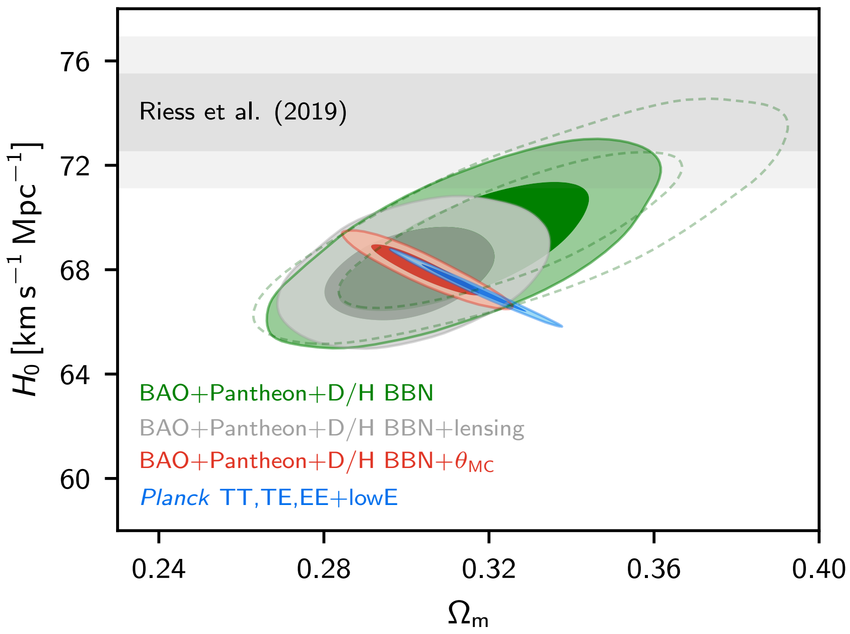
Pomarède et al. 2020

Hubble Constant(s)

Riess et al. 2019



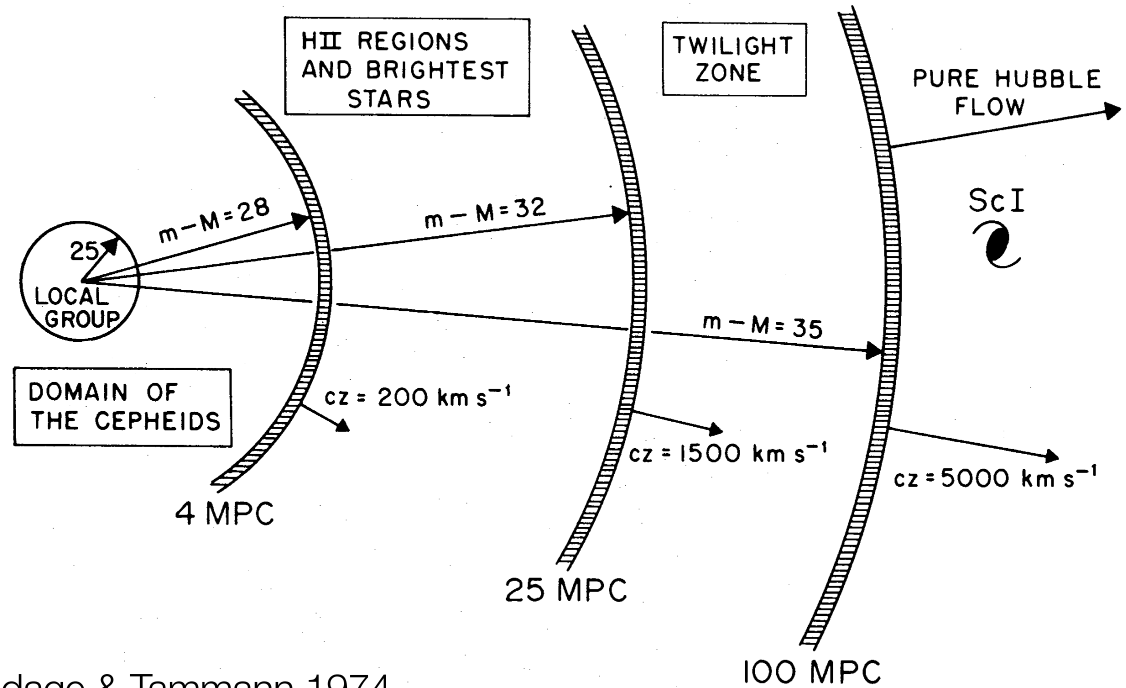
Planck 2018



Measuring H_0

Classical approach

→ distance ladder to reach (smooth) Hubble flow



Sandage & Tammann 1974

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

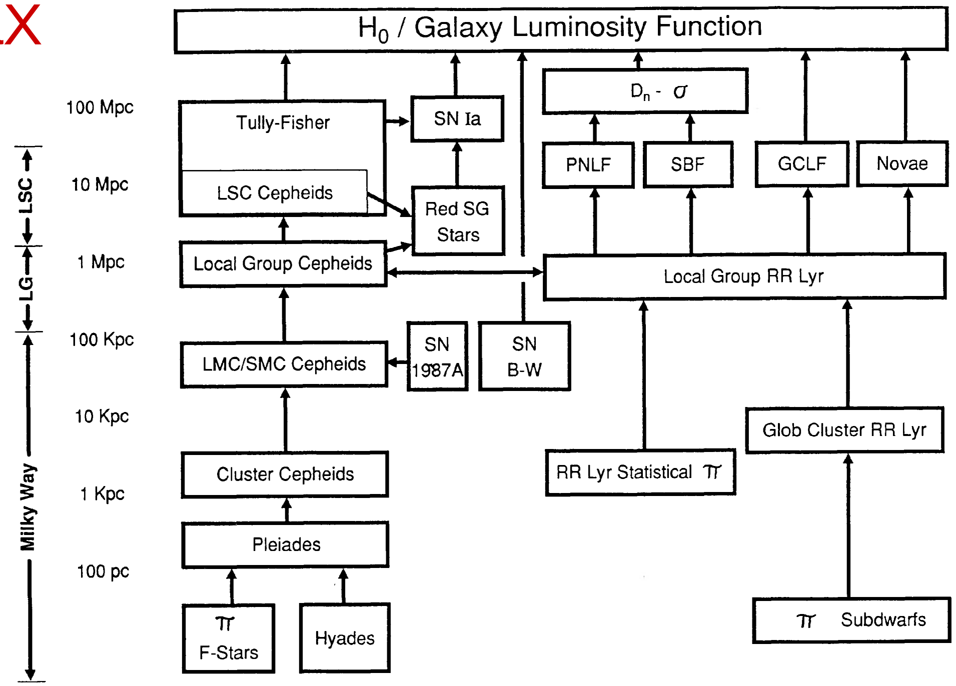
Three different methods

1. Distance ladder
   - Calibrate next distance indicator with the previous
2. Physical methods
   - Determine either luminosity or length through physical quantities
     - Lens delays
     - 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

Classic 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

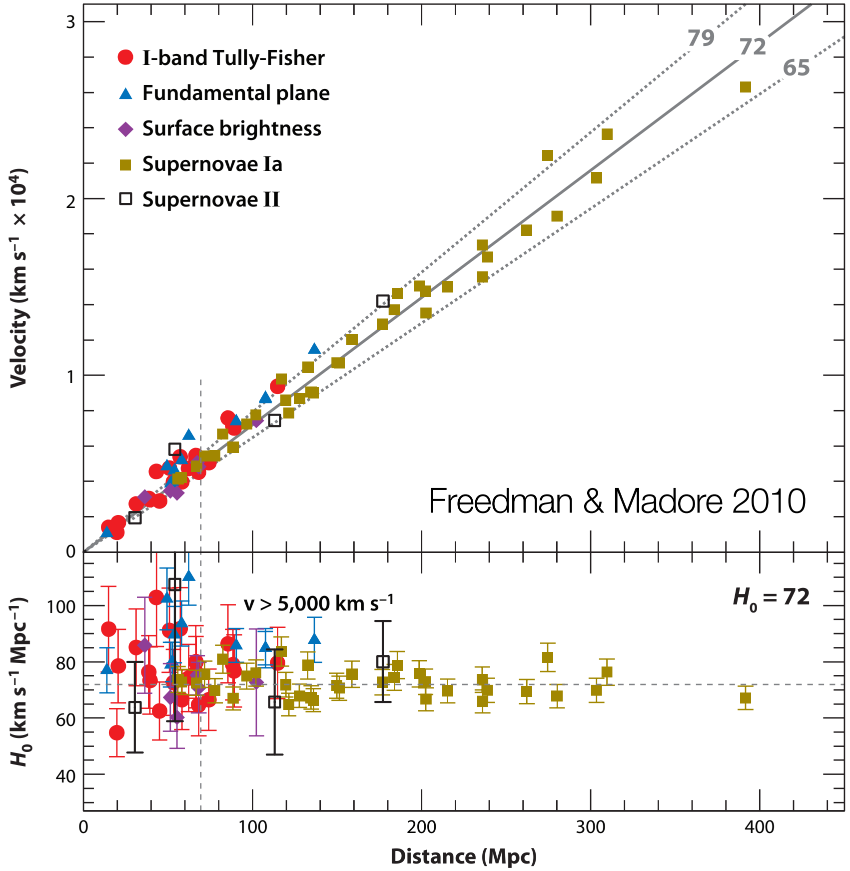
Jacoby et al. 1992

Classic 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

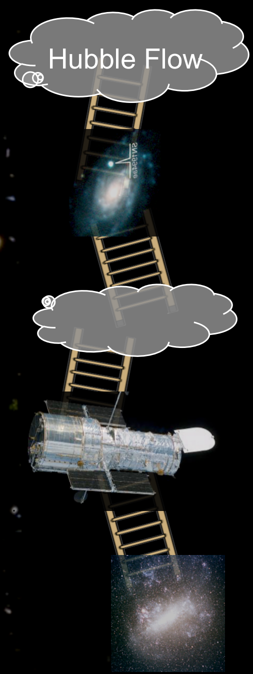


Hubble Constant

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

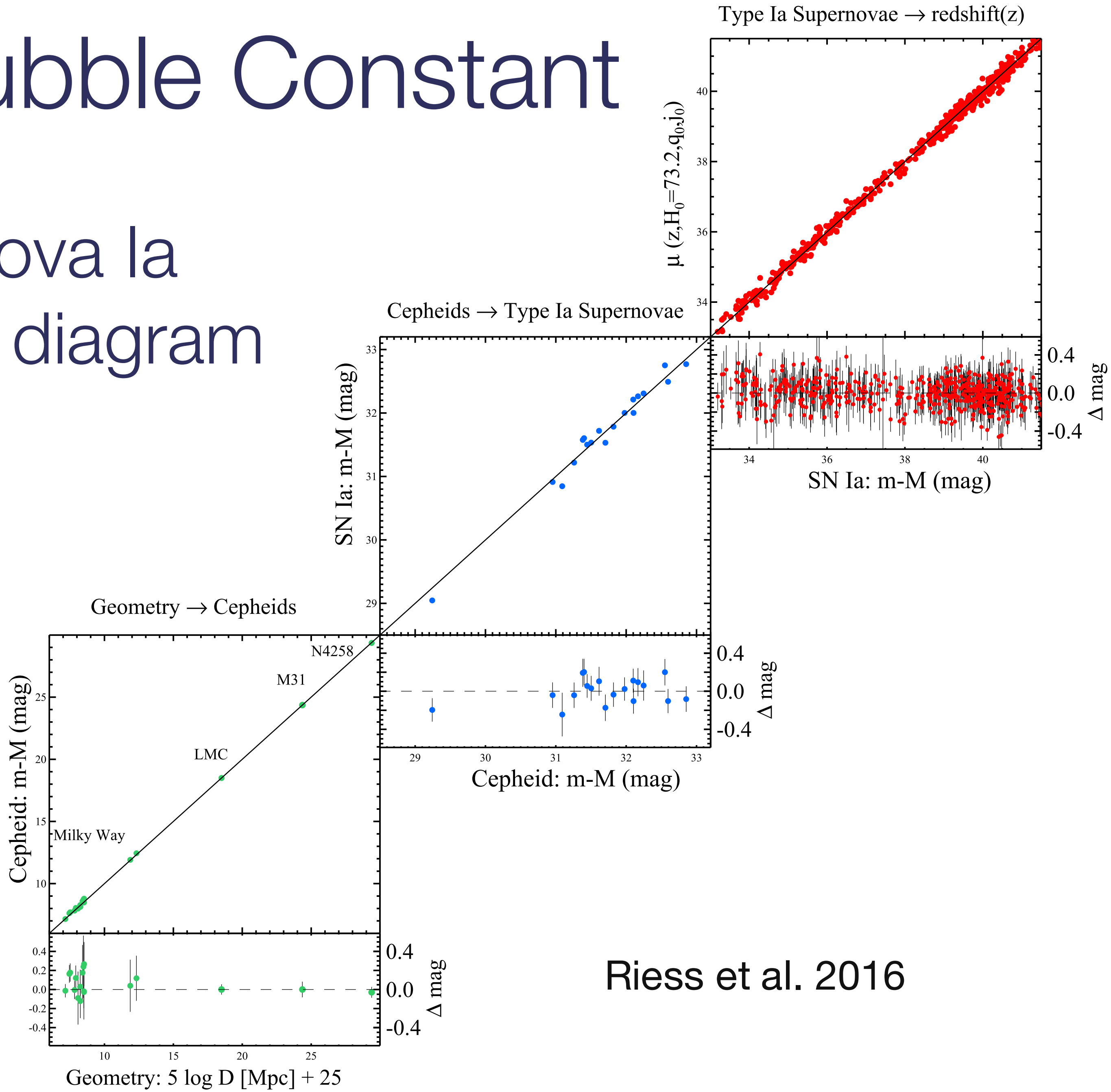
NA

3% Anchor: NGC4258

Adam Riess

Hubble Constant

Supernova Ia
Hubble diagram



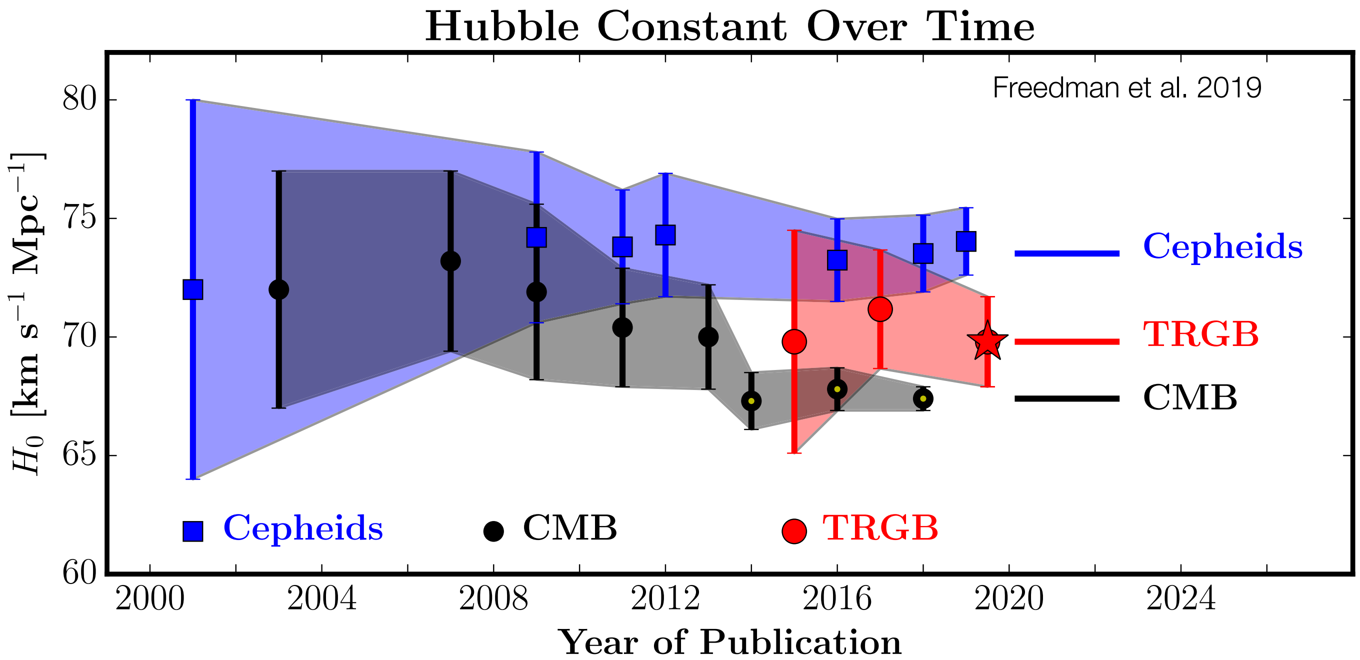
Riess et al. 2016

University of Chicago

Problem solved?

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

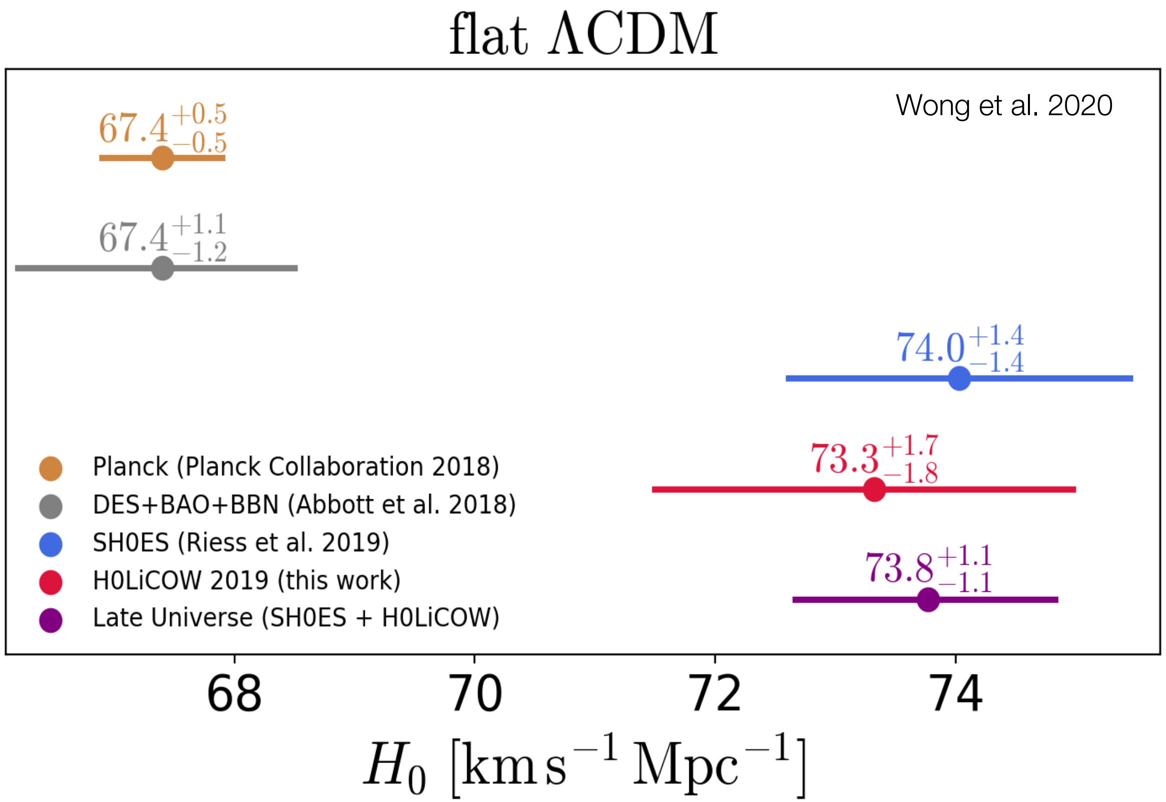
Indication of an incomplete model of cosmology?

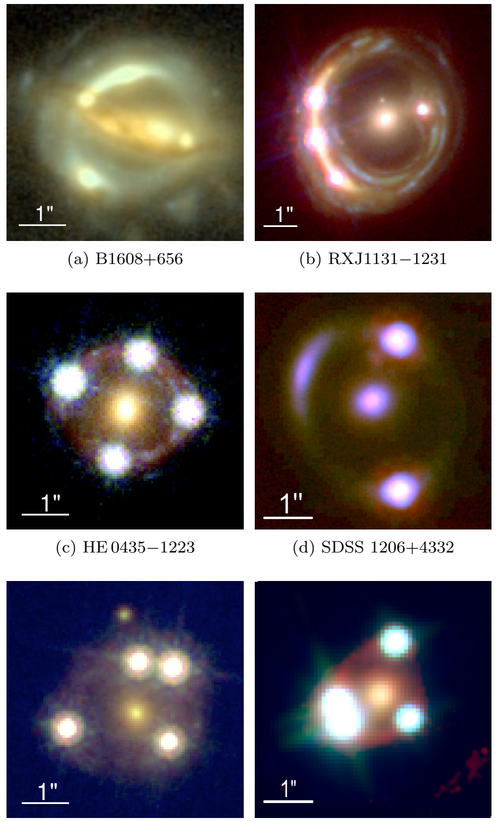


Gravitational Lenses

H0LICOW collaboration

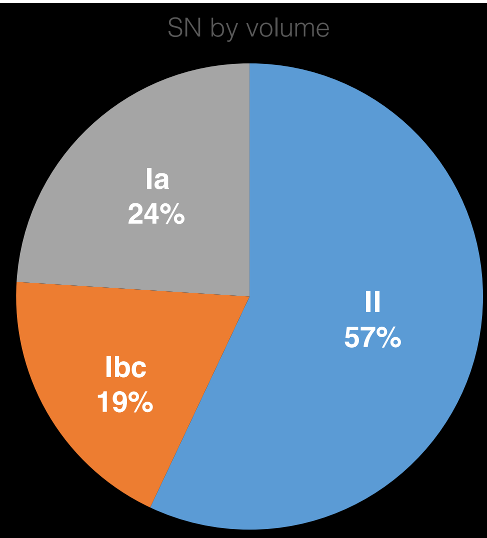
Sherry Suyu (J. Wiedersich / TUM)



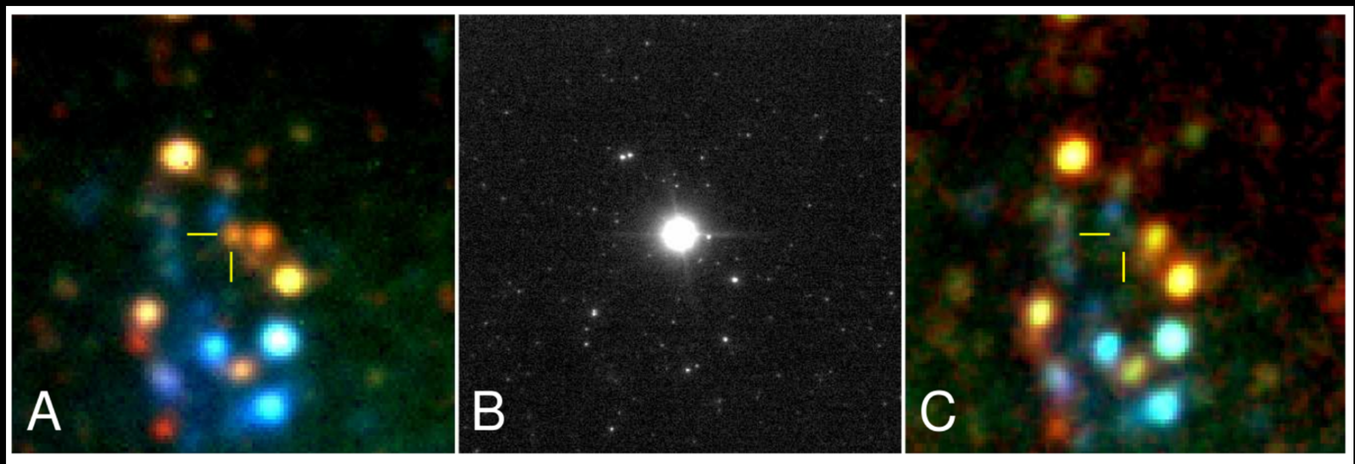


(a) B1608+656 (b) RXJ1131−1231 (c) HE 0435−1223 (d) SDSS 1206+4332 (e) WFI2033−4723 (f) PG 1115+080

Type II Supernovae



- Core-collapse explosions of massive, red-supergiant stars



Mattila et al. 2010

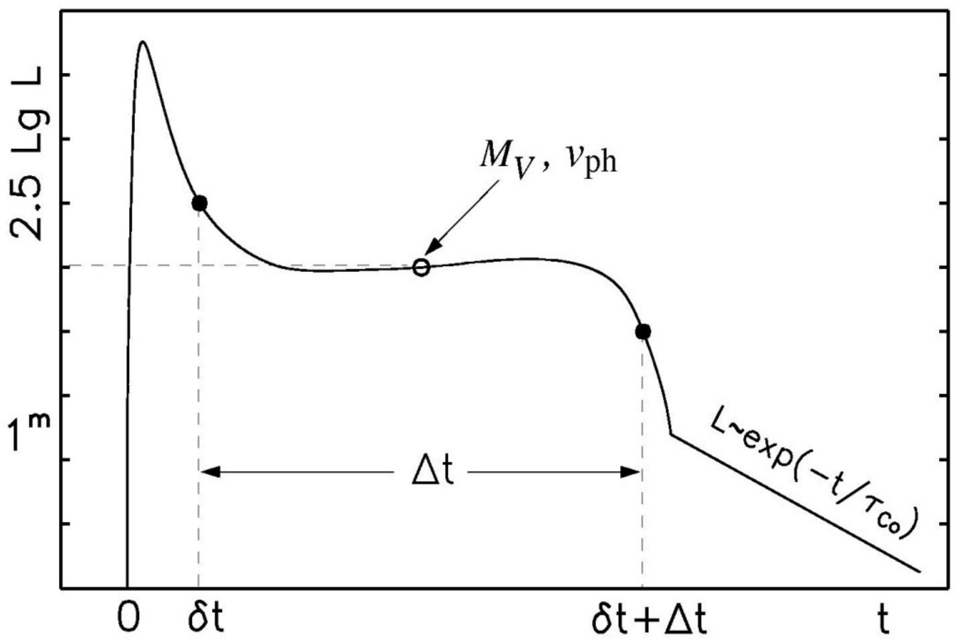
- Peak absolute mags between -16 and -18

  → observable up to $z \approx 0.4$

- Most common type of SN by volume

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



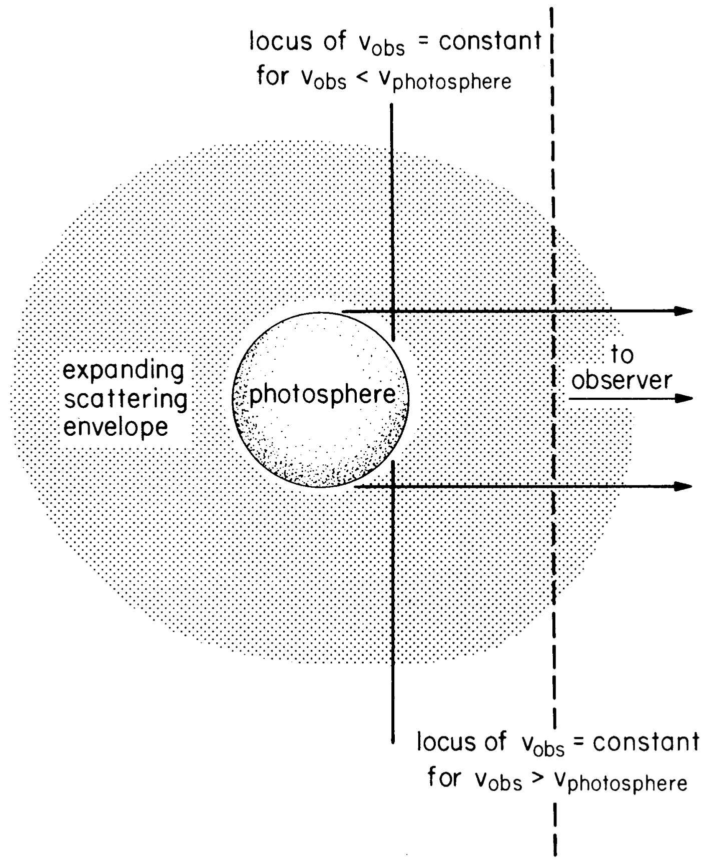
Observables (e.g. Popov 1993):

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

- $E \propto \Delta t^4 \cdot v_{ph}^5 \cdot L^{0.4}$
- $M \propto \Delta t^4 \cdot v_{ph}^3 \cdot L^{0.4}$
- $R \propto \Delta t^{-2} \cdot v_{ph}^{-4} \cdot L^{-0.8}$

Expanding Photosphere Method

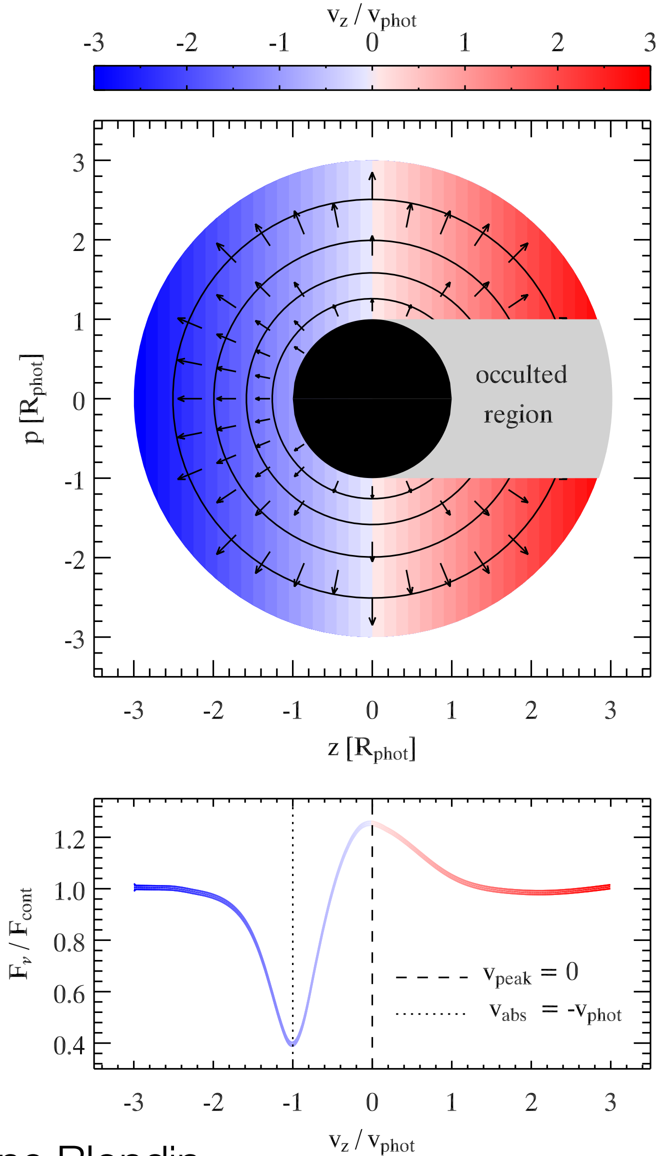
- Modification of Baade-Wesselink method for variable stars
- Assumes
  - Sharp photosphere
    → thermal equilibrium
  - Spherical symmetry
    → radial velocity
  - Free expansion



Kirshner & Kwan 1974

Expanding Photosphere Method

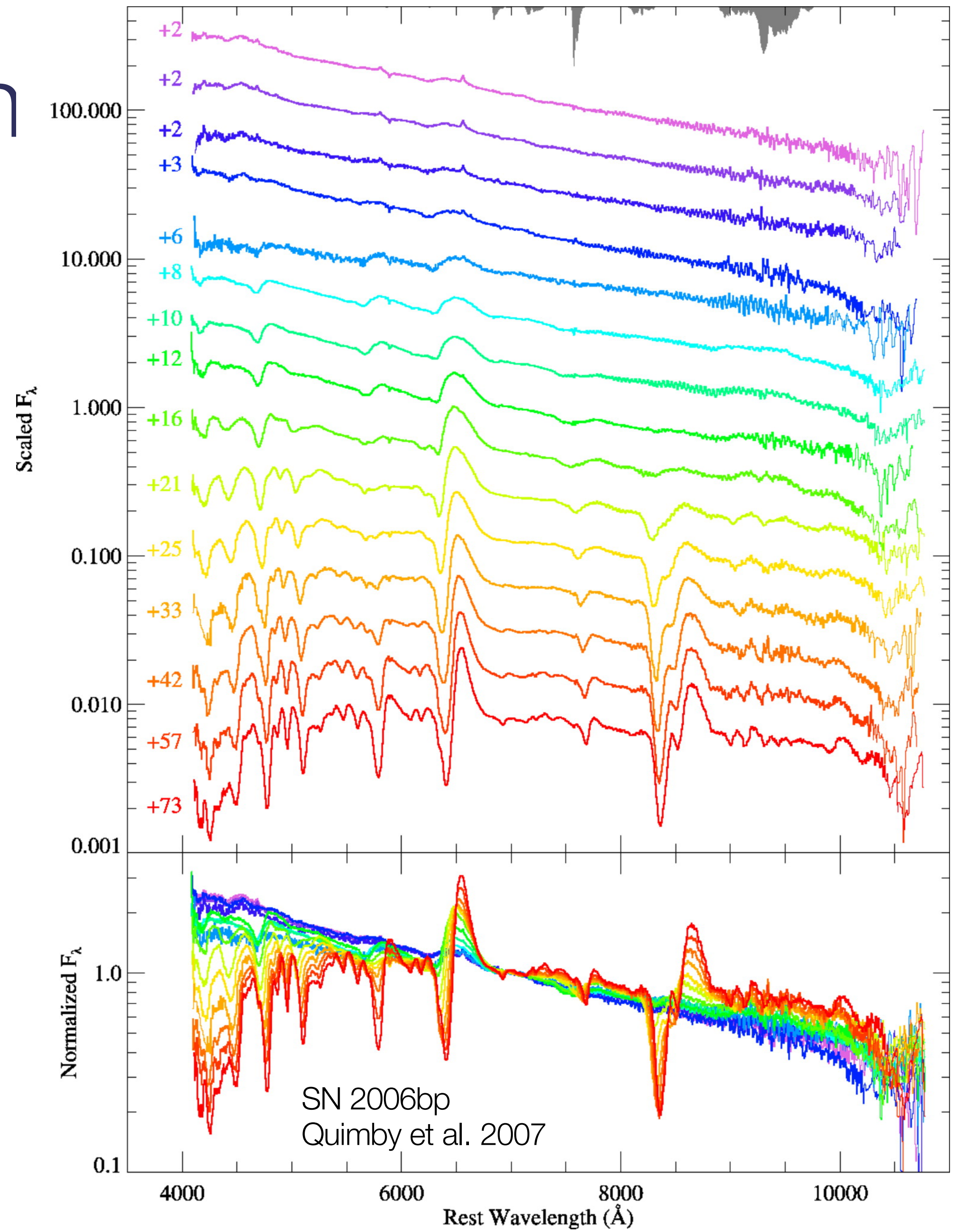
- Line formation in the expanding ejecta
- P Cygni line profile
  - absorption indicates photospheric position



Stéphane Blondin

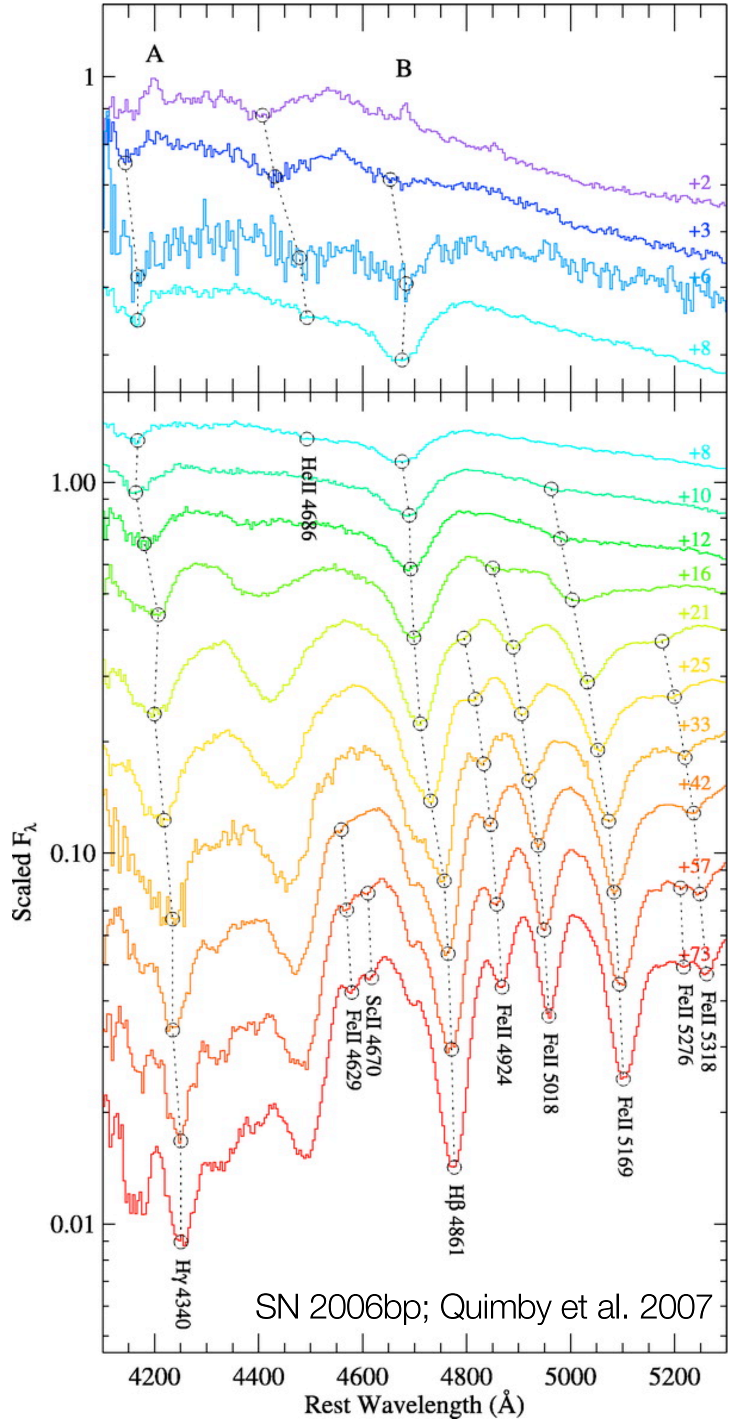
Spectral Evolution

Changing spectra with time as deeper and deeper layers of the supernova are exposed



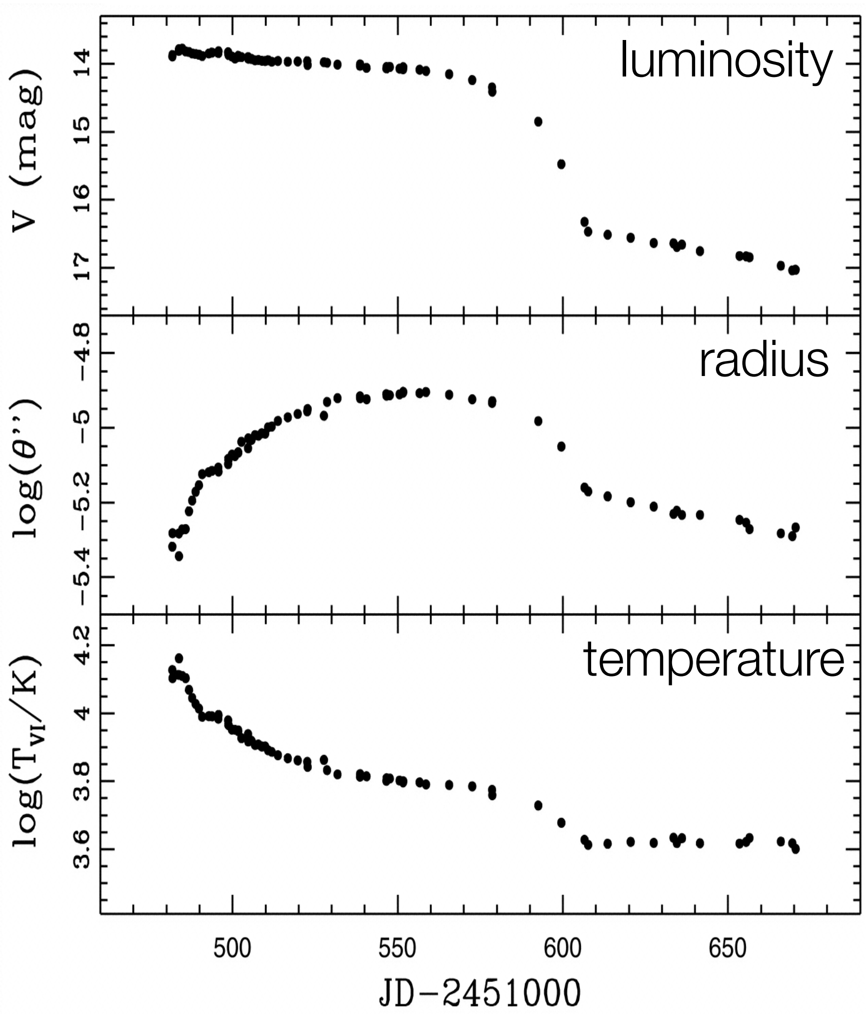
Photospheric Velocity

- Evolution from higher to lower expansion velocities
  - – deeper layers within a freely expanding envelope

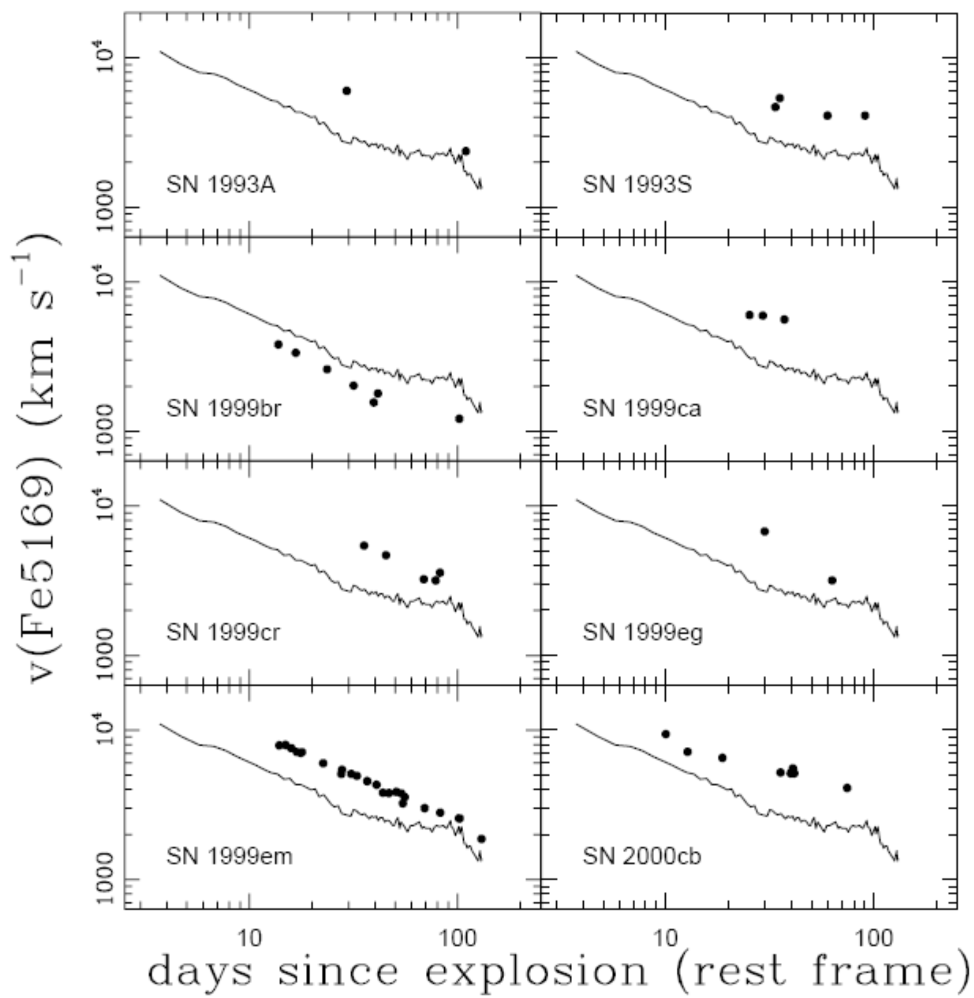


Photosphere Expansion

Hamuy et al. (2001)



Elmhamdi et al. (2003)



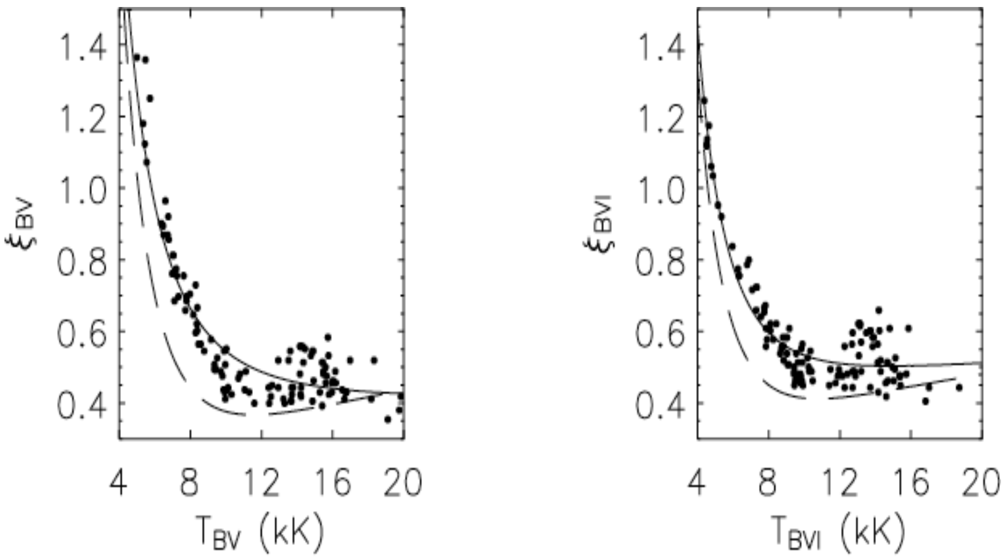
Expanding Photosphere Method

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

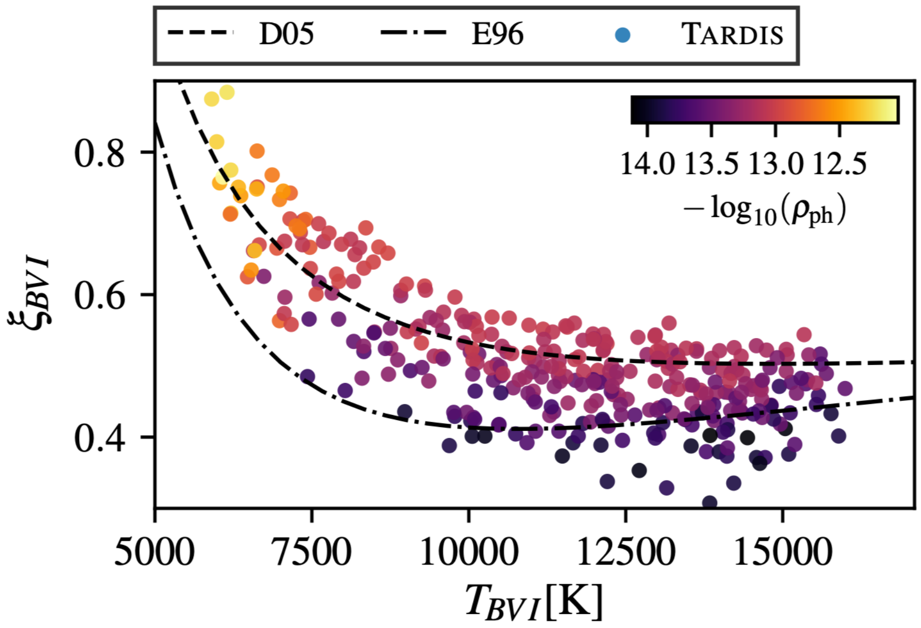
- R from radial velocity
  - Requires lines formed close to the photosphere
- θ from the surface brightness of the black body
  - Deviation from black body due to line opacities
  - Encompassed in the dilution factor ζ^2
- Dilution factor ζ^2 from models
  - Eastman et al. (1996), Dessart (2005)
  - applied to all SNe, significant differences

Dilution Factors

Depend on the models and filters

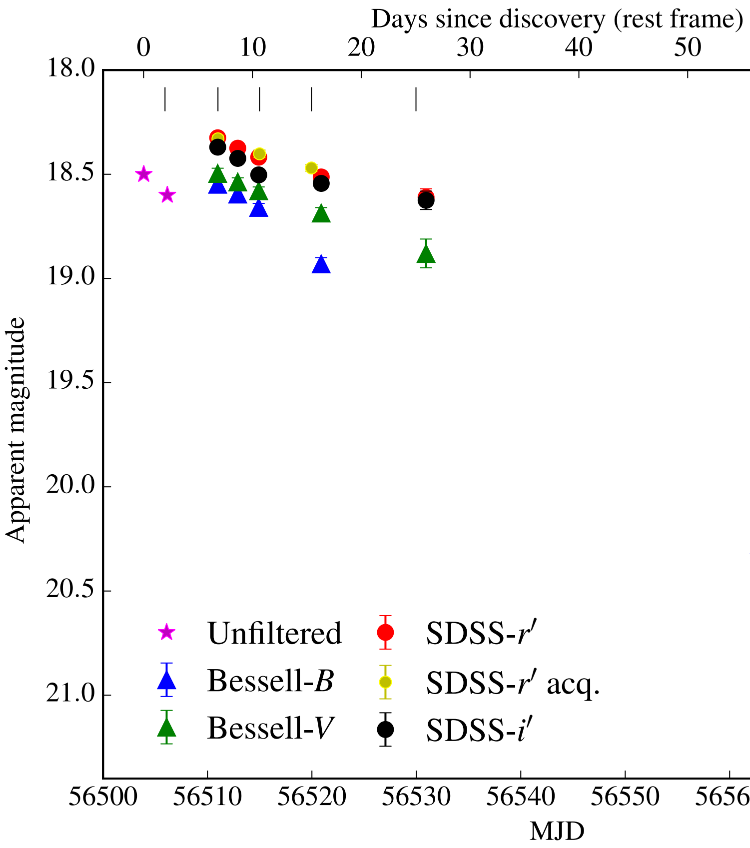


Dessart & Hillier 2005

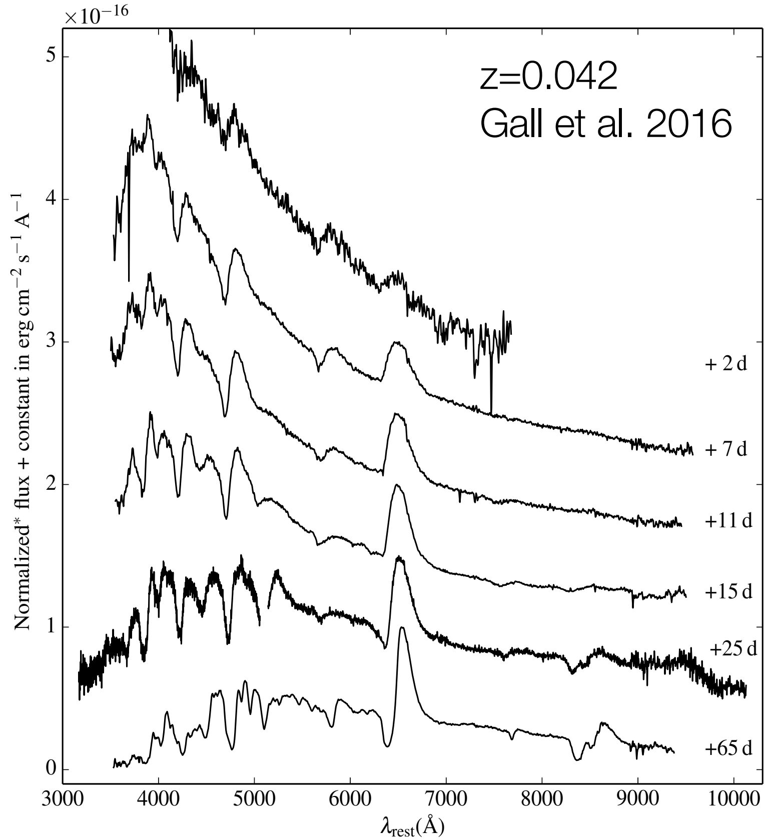


Vogl et al. 2019

SN 2013eq



Days since discovery (rest frame)
Apparent magnitude
MJD
Unfiltered
Bessell-B
Bessell-V
SDSS-r′
SDSS-r′ acq.
SDSS-i′

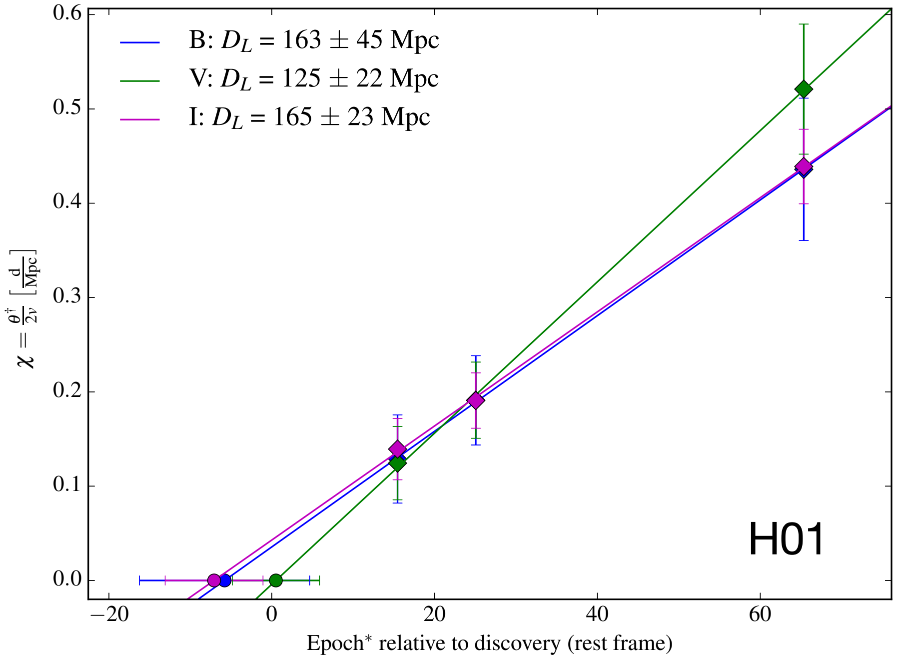


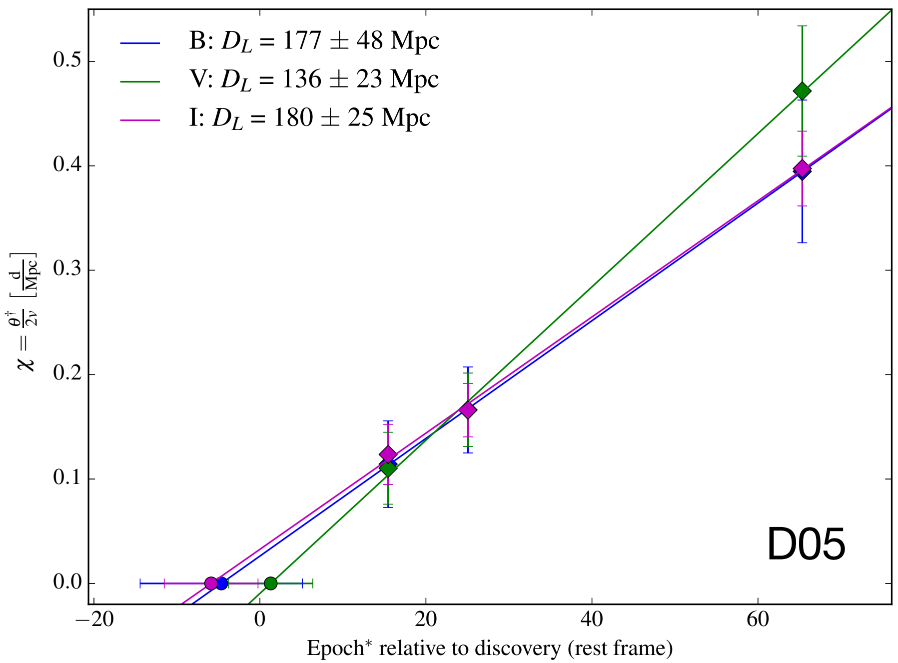
z=0.042
Gall et al. 2016
Normalized* flux + constant in erg cm^{-2} s^{-1} Å^{-1}
λ_{rest}(Å)
+ 2 d
+ 7 d
+11 d
+15 d
+25 d
+65 d

SN 2013eq

Two different dilution factors applied

- Hamuy et al. 2001 (H01)
- Dessart & Hillier 2005 (D05)
  - Both give a good distance to SN 1999em, e.g. Jones et al. (2009)



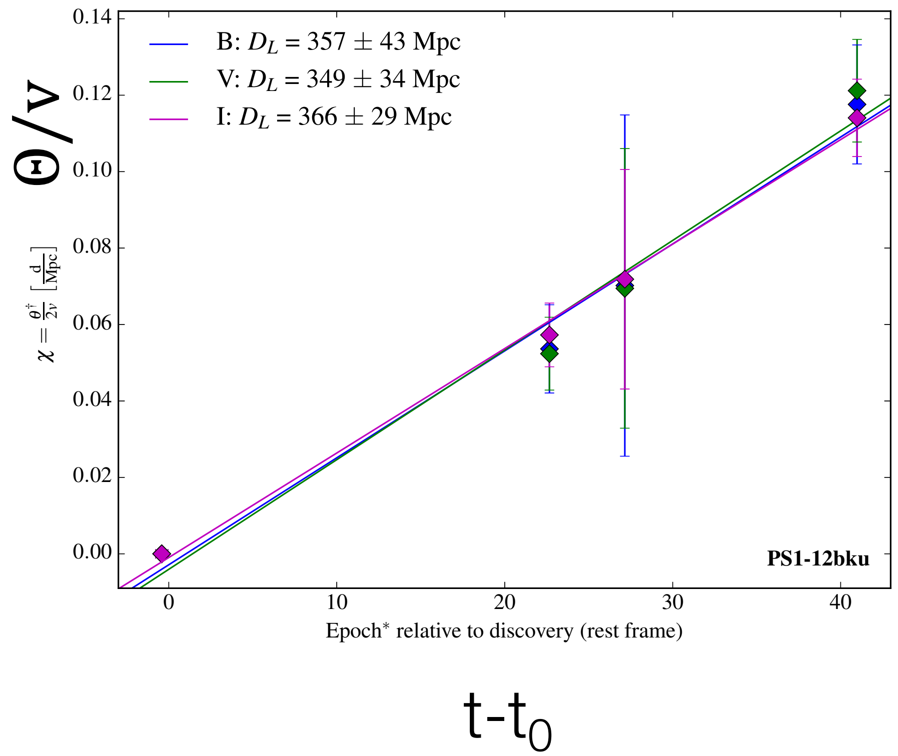


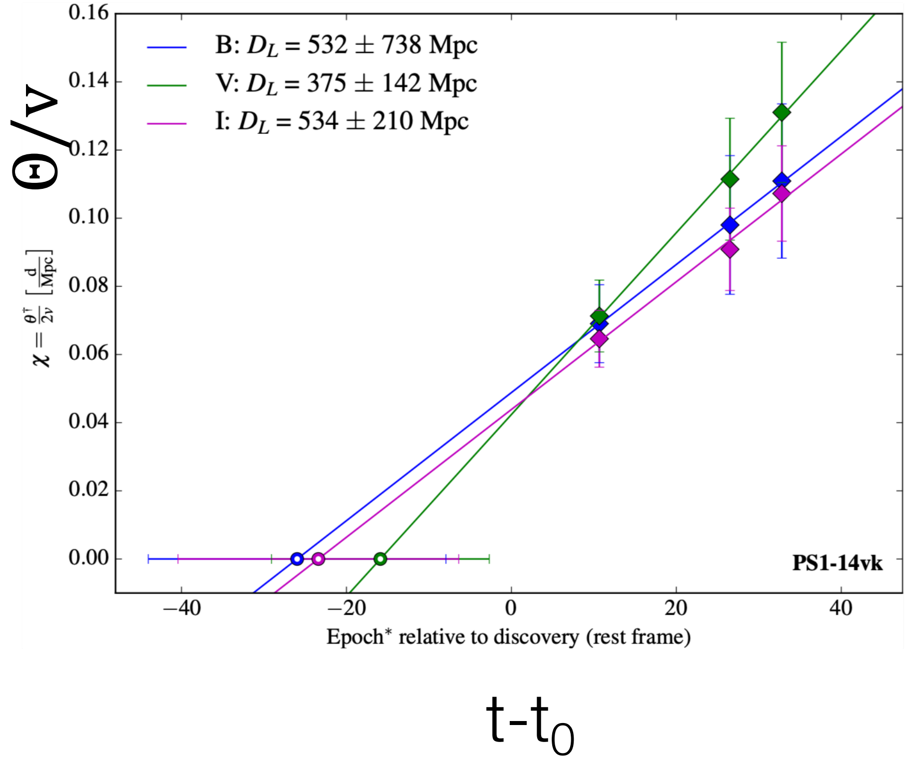
Expanding Photosphere Method

- It's all in the data...

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

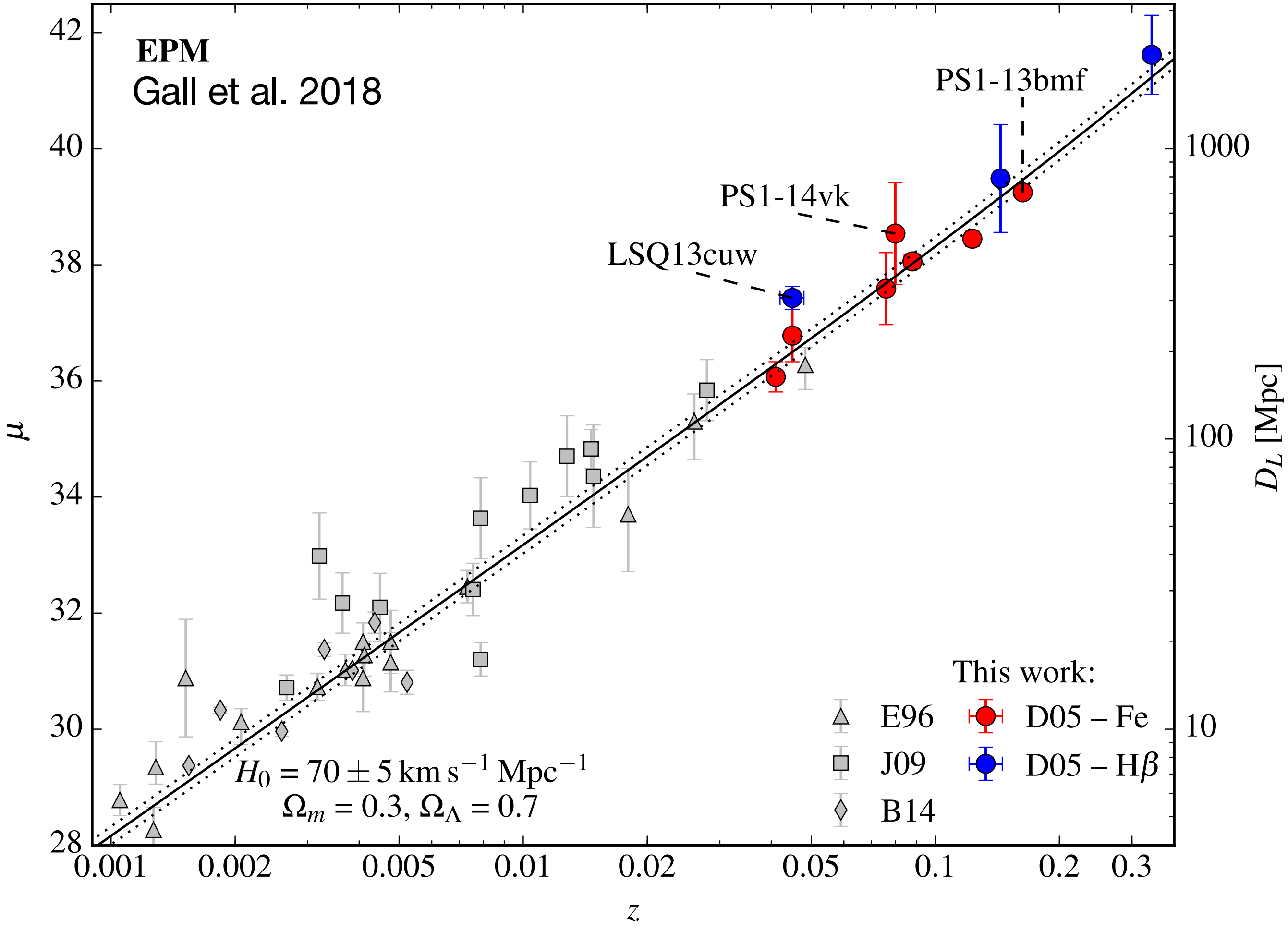
Gall et al. 2018





…not good enough

Data not constraining for accurate distances



Expanding Photosphere Method

- Main 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 absorption lines
  - Accurate photometry

Expanded Photosphere Method Reloaded

- Use individual atmospheric models for the spectral fits
  - use of the TARDIS radiation transport model

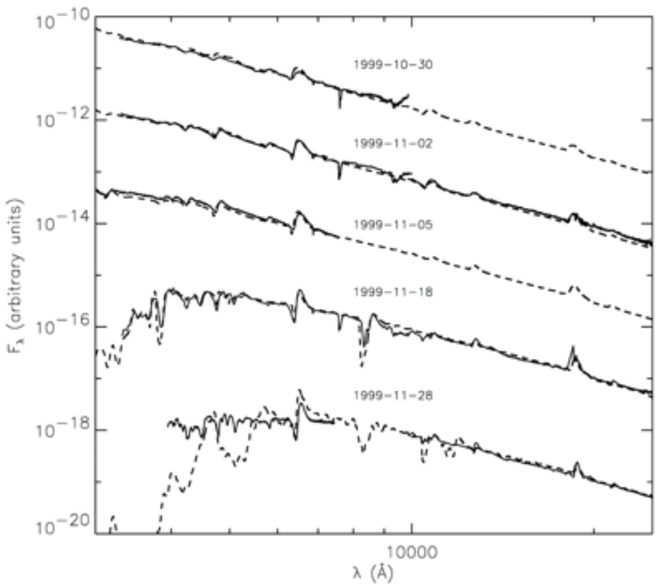
    → absolute flux emitted
- Accurate explosion date
  - accurate zero point
- At least 5 epochs per supernova

Distances from spectral fits

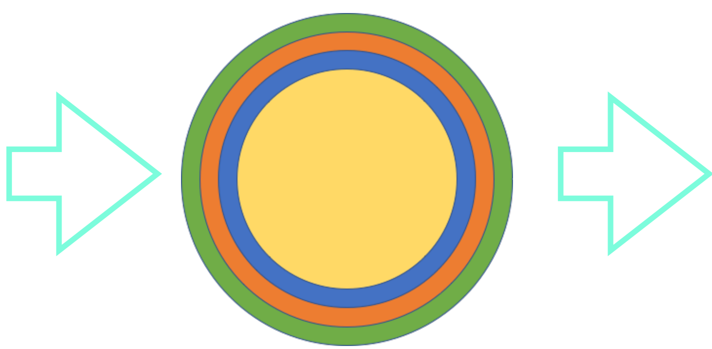
Spectral-fitting Expanding Atmosphere Method

  - Baron et al. (95, 96, 2004, 2007), Lentz et al. 2001, Mitchell et al. 2002

- Tailored Expanding Photosphere Method
  - Dessart et al. (2006, 2008)



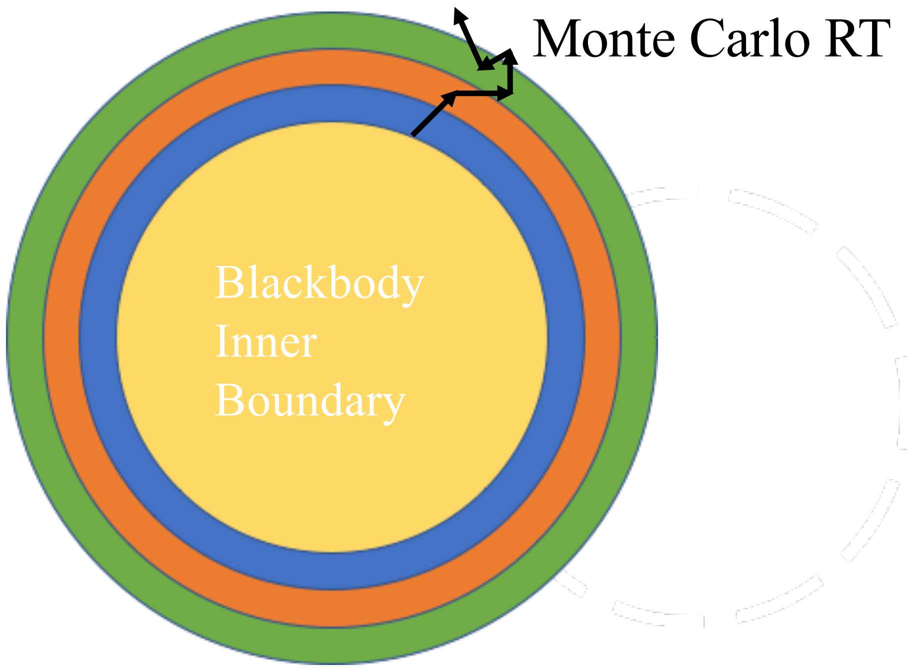
Baron et al. 2004



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

TARDIS

Kerzendorf & Sim 2014



But: Developed for Type Ia SNe not Type II

bound-free, free-free, collisional processes

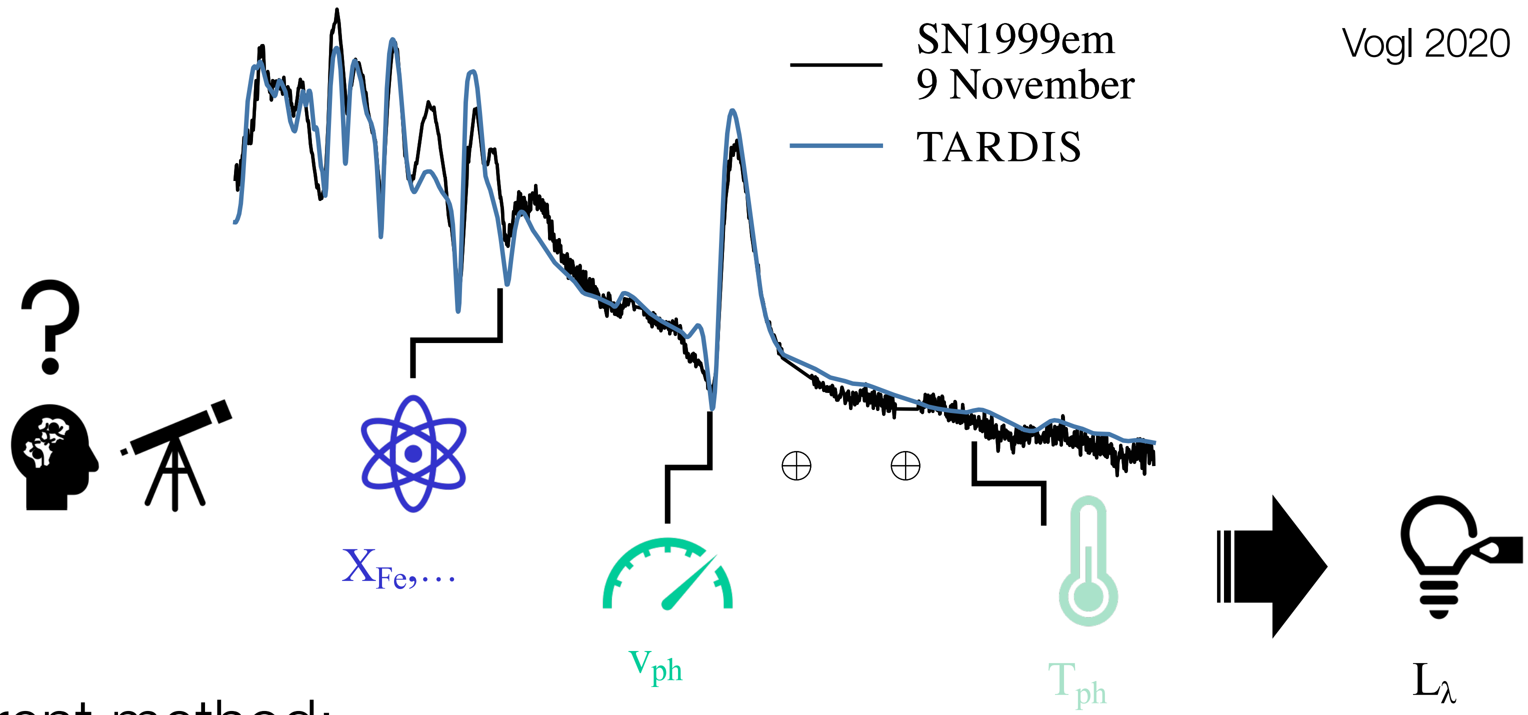
high optical depths (τ = 20-30)

NLTE and thermal structure

relativistic transport

Vogl et al. 2019

Parameter determination



Current method:

Optimization by hand and eye (e.g., Dessart & Hillier 2006, 2008)

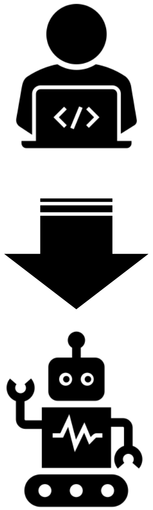
Advantages:

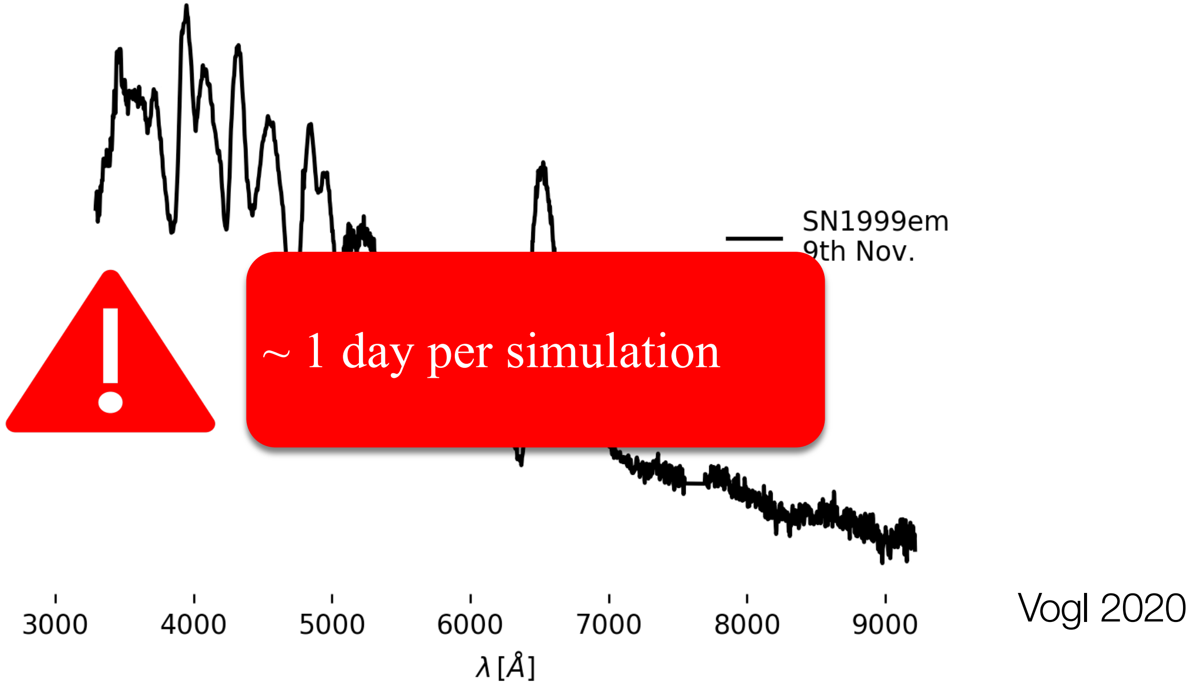
- efficiency
- uses spectroscopist's knowledge

Drawbacks:

- not reproducible
- no uncertainties
- infeasible for large datasets

Spectral emulation





Emulate instead of simulate

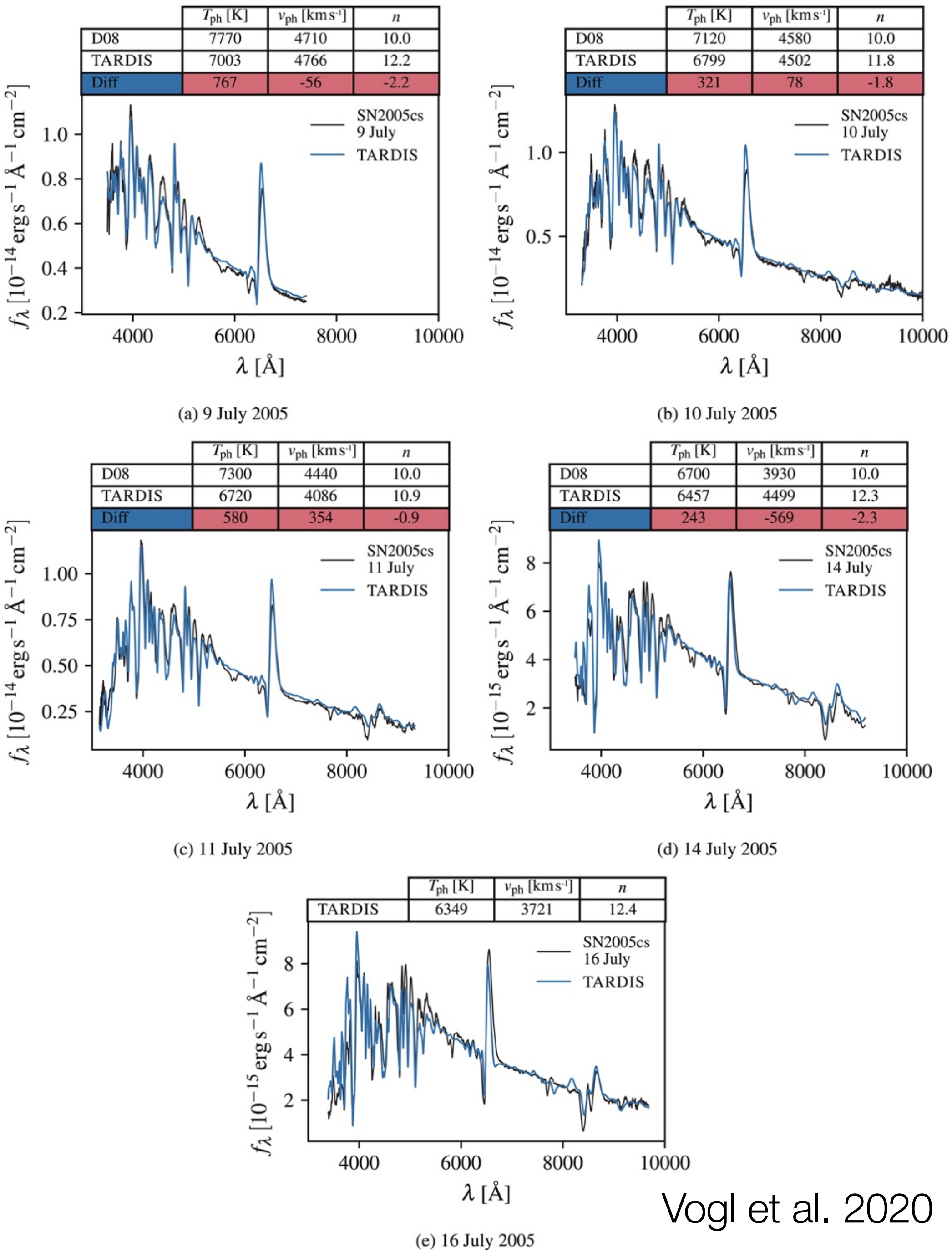
e.g. Heitmann et al. 2009, Czekala et al. 2015, Lietzau 2017

Reasoning:

- Spectra vary smoothly with the parameters $\theta = f(\mathrm{T_{ph}}, \mathrm{v_{ph}}, \ldots)$
- Interpolation uncertainties are likely subdominant

Atmosphere Models

TARDIS fits for different epochs

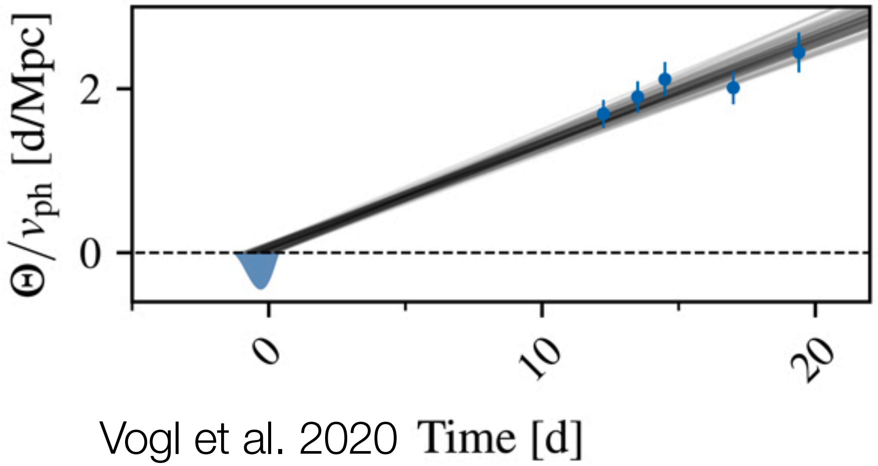


Vogl et al. 2020

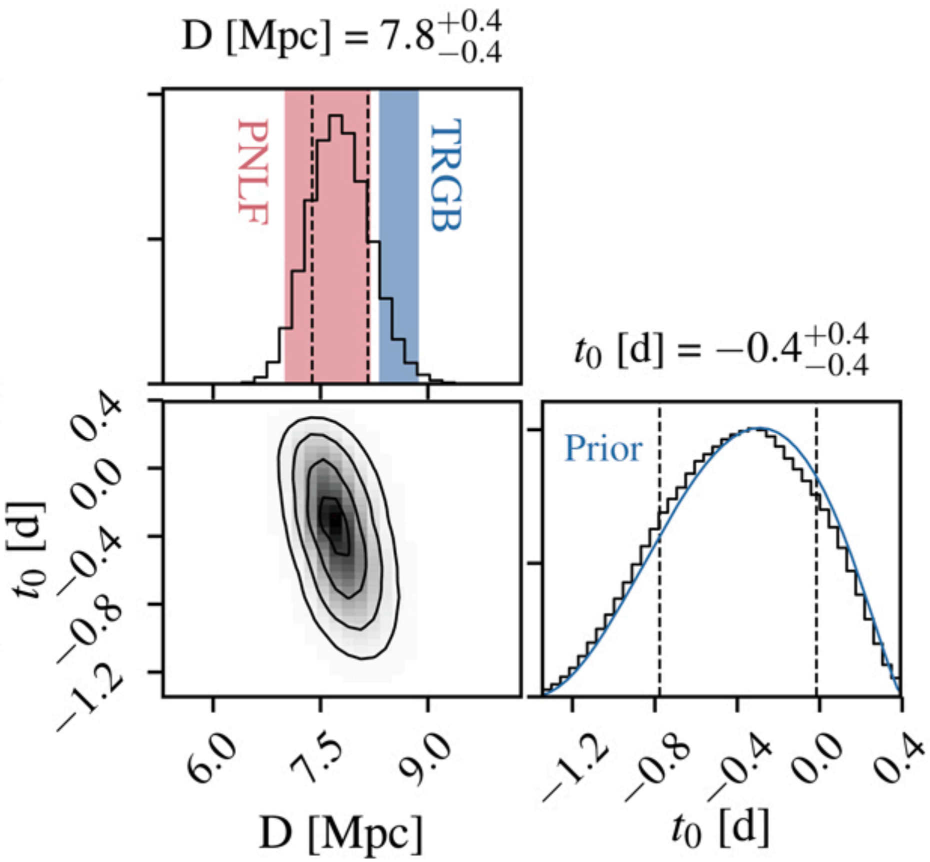
Distance Determination

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

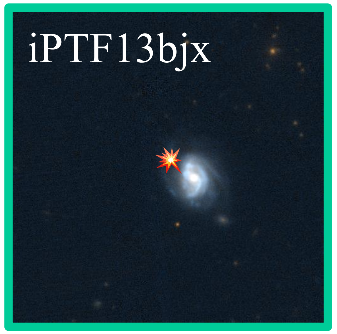
Date	Time [d]	Θ/v_{ph} [d/Mpc]
9 July 2005	12.25	1.69
10 July 2005	13.50	1.90
11 July 2005	14.50	2.12
14 July 2005	17.00	2.01
16 July 2005	19.40	2.44

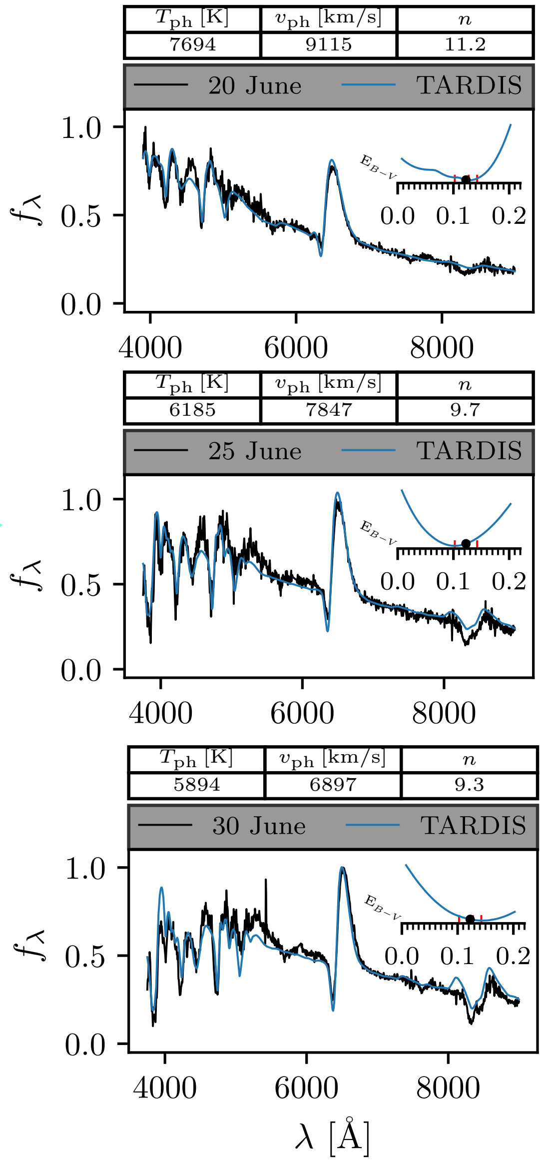


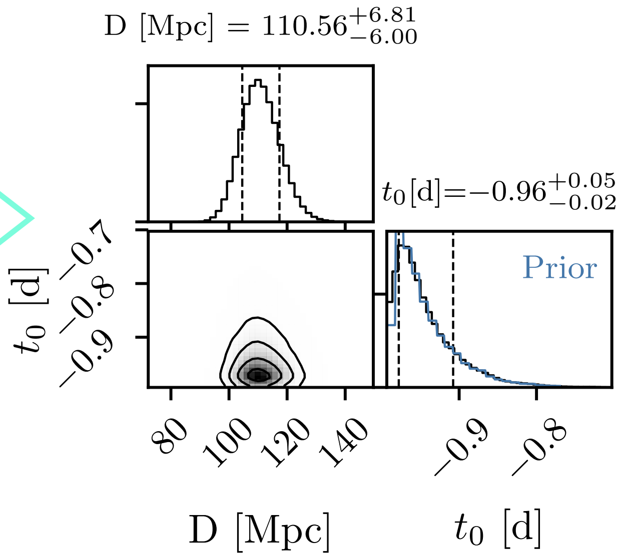
Vogl et al. 2020



Measuring distances







adH0cc

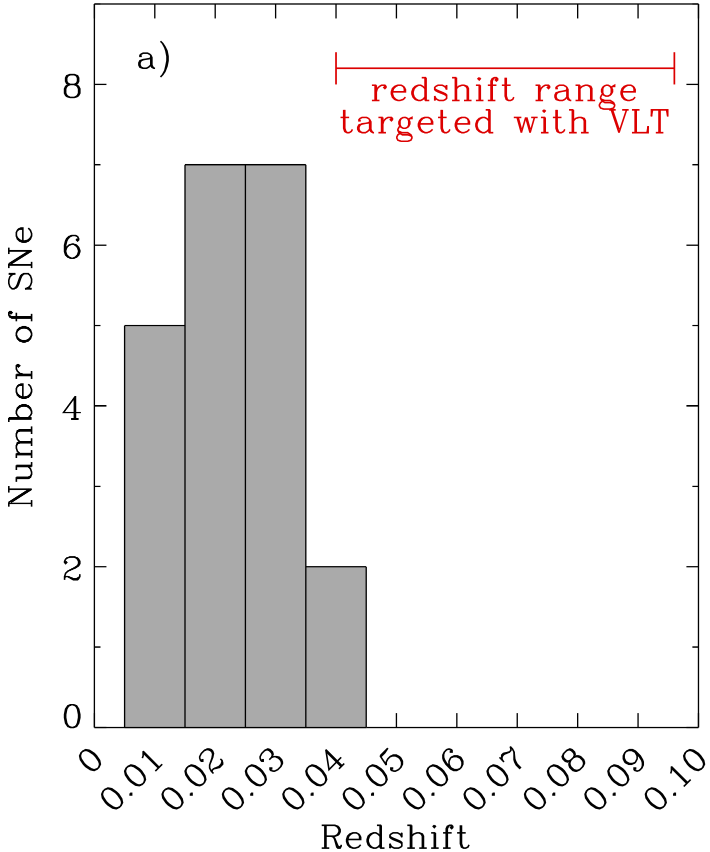
"*a*ccurate *d*etermination of *H0* with *c*ore-*c*ollapse supernovae"

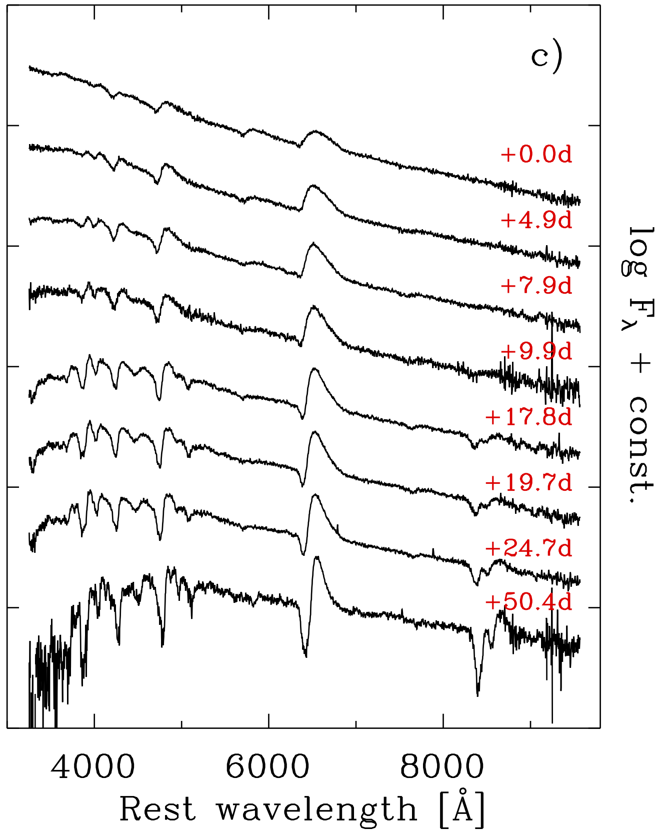
(Flörs, Hillebrandt, Kotak, Smartt, Spyromilio, Suyu, Taubenberger, Vogl)

- Use the Expanding Photosphere Method to ~30 Type II supernovae in the Hubble flow (0.03<z<0.1)
  - Goal: uncertainty on H_0 ~3%
- 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 20 SNe with $0.01 < z < 0.05$

adH0cc

Combination of existing data sample from the SN Factory

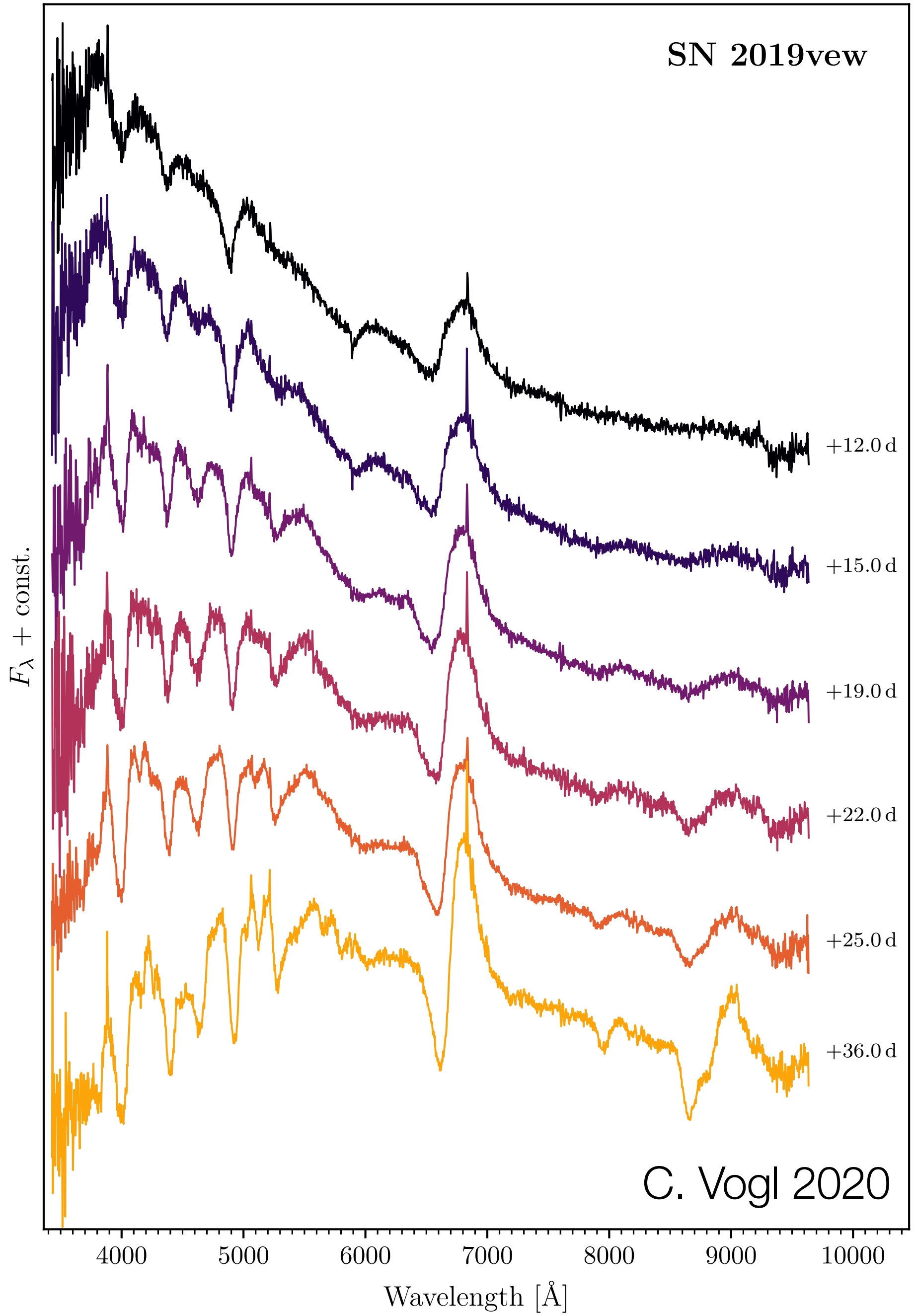




adH0cc

Critical observables

- time of explosion
- spectral coverage
  - before max until well into the plateau
- photometry
  - simultaneously with spectroscopy



Summary

- Significant progress in spectral fitting
  - Christian Vogl's PhD thesis
    - Vogl et al. 2019, 2020
- Importance of the data sampling
  - explosion dates!
  - sufficient coverage of the spectral evolution
- Redshift range
  - reach the Hubble flow ($z>0.03$)
- 1-stop method to measure H_0
  - independent of distance ladder
  - other cosmological parameters (densities)