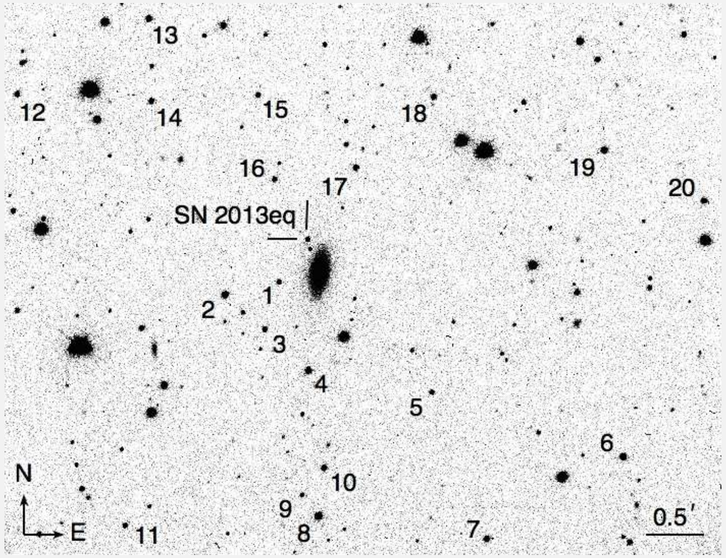
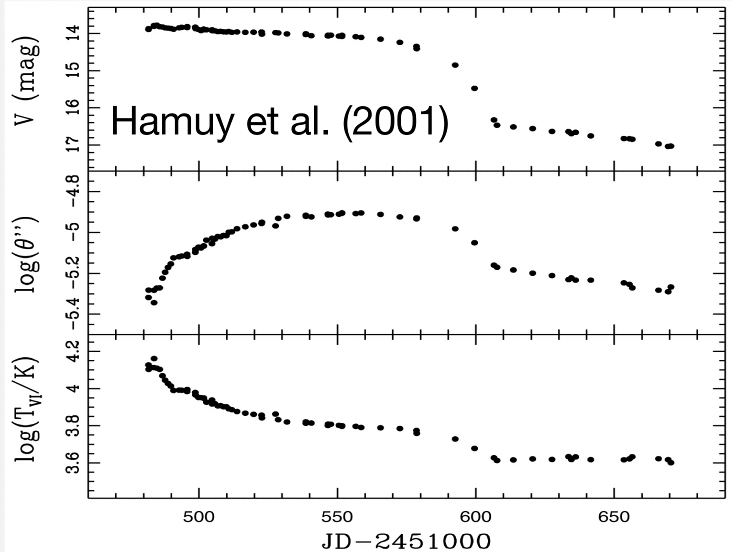



# Distances to core-collapse supernovae

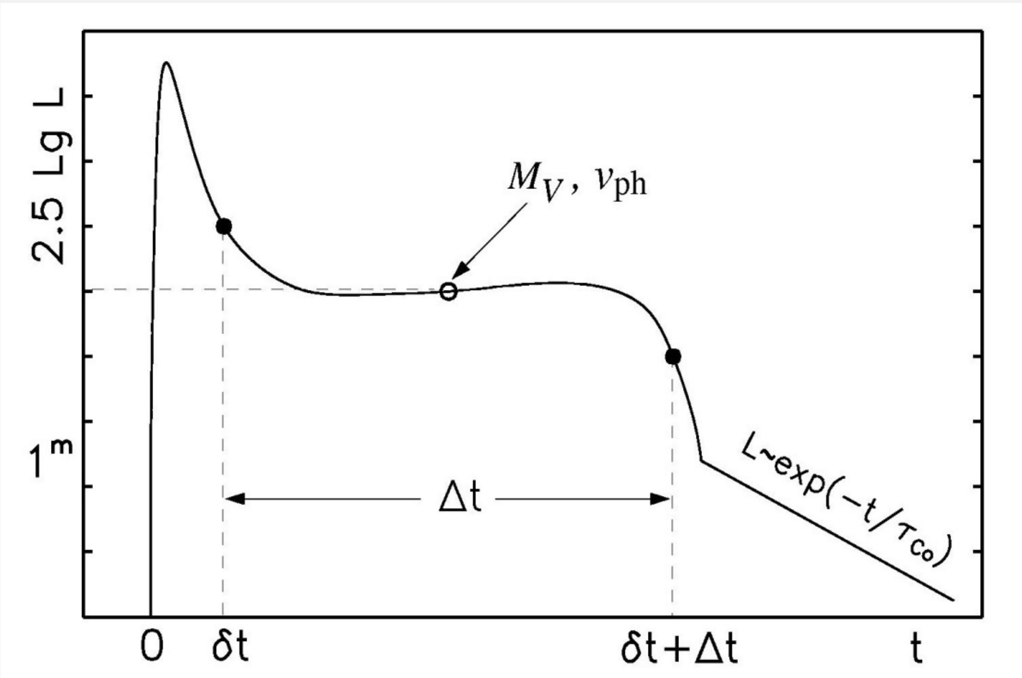
Elisabeth Gall (QUB/MPA), Rubina Kotak (QUB),
Bruno Leibundgut (ESO),
Stefan Taubenberger (ESO/MPA),
Wolfgang Hillebrandt (MPA),
Markus Kromer (Stockholm)

# 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

# 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



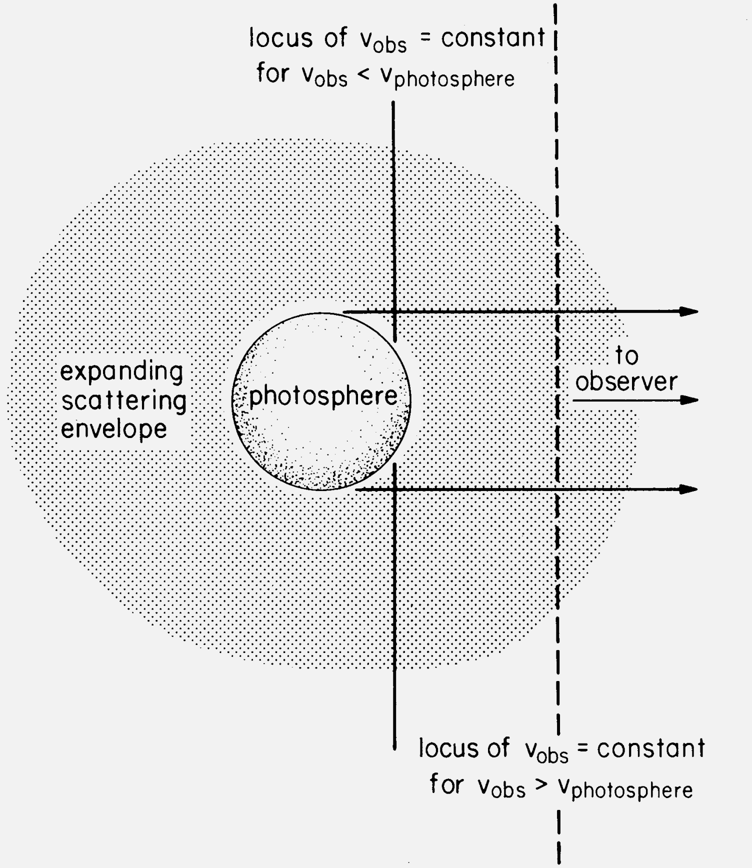

Observables:

- 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

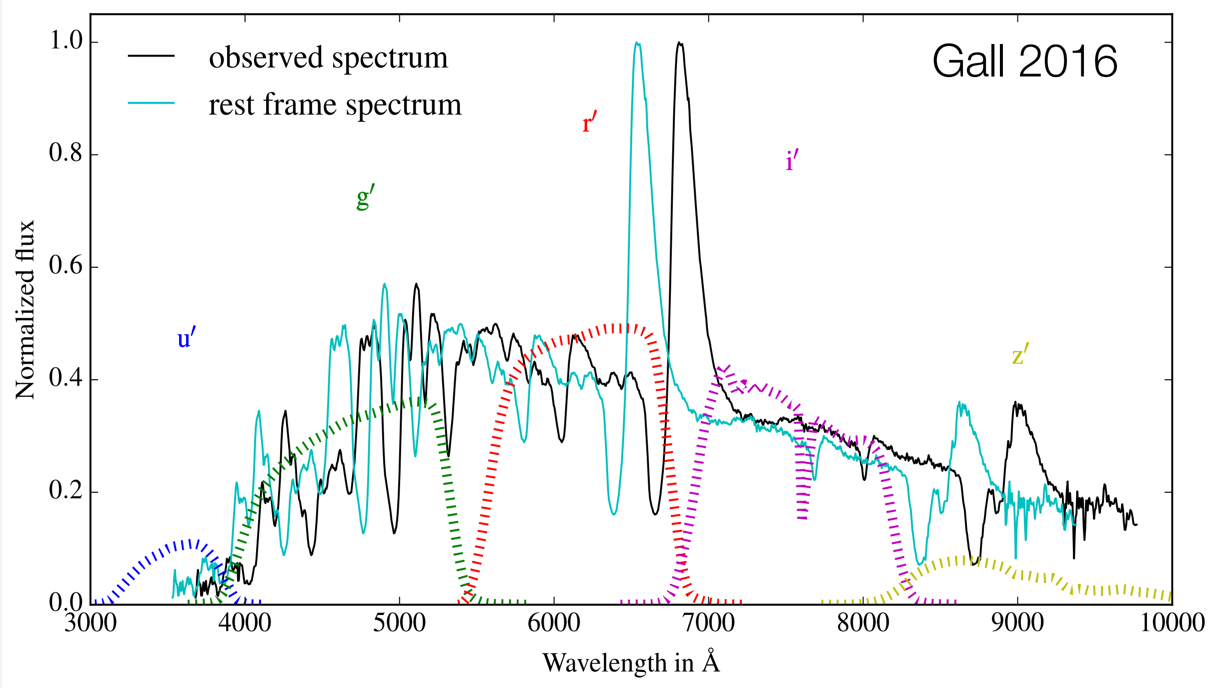
- Modification of Baade-Wesselink method for variable stars
- Assumes
  - Sharp photosphere
    → thermal equilibrium
  - Spherical symmetry
    → radial velocity
  - Free expansion



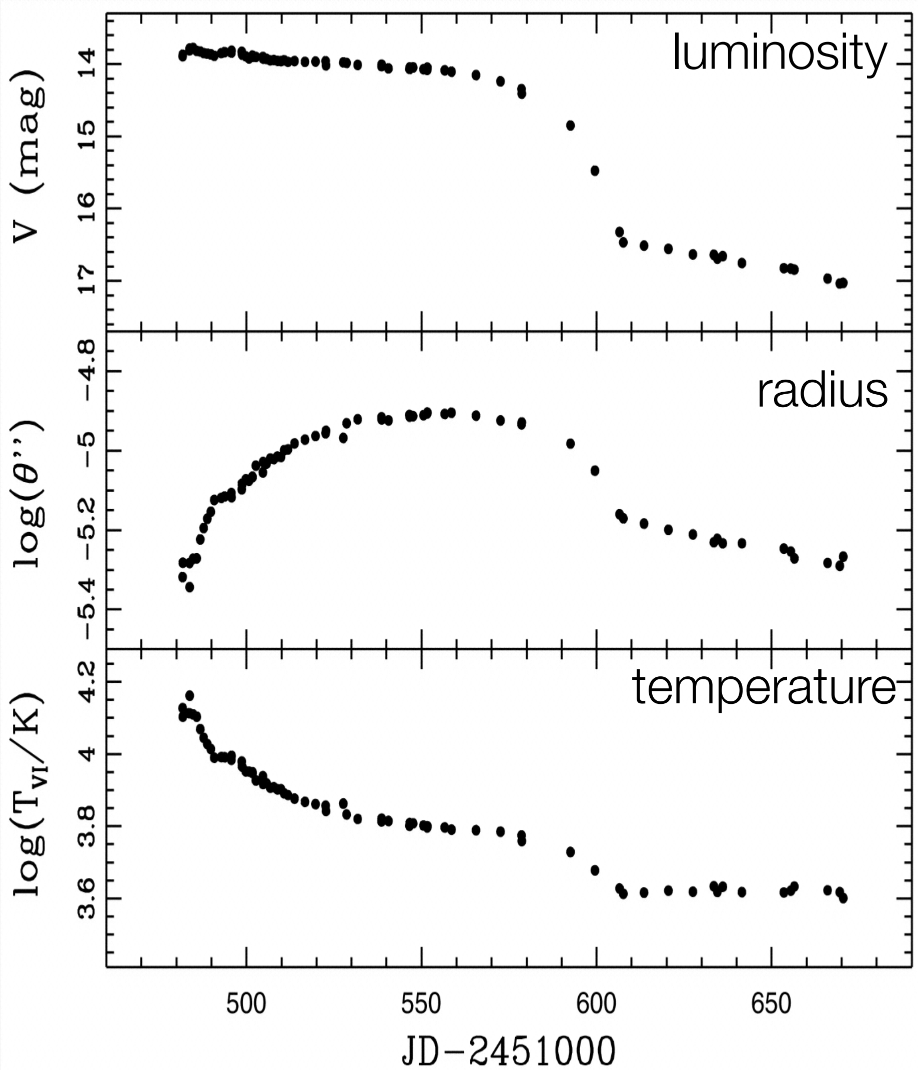

Kirshner & Kwan 1974

# Photosphere Expansion

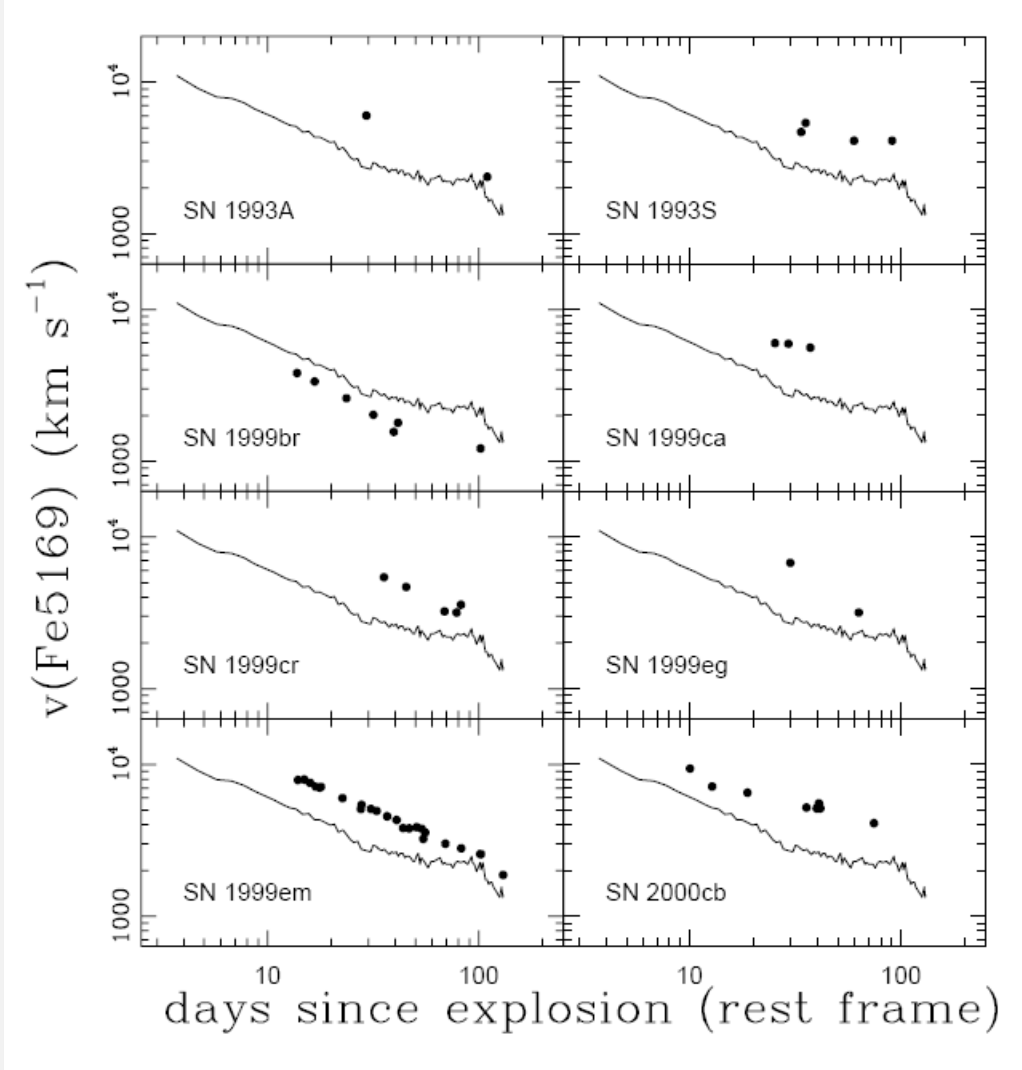
- Measured from absorption lines
  – formed close to the photosphere
    - not hydrogen lines → Fe II
  – remove redshift (from galaxy spectrum)
- Colour
  – K-corrections (redshift)



# Photosphere Expansion




Hamuy et al. (2001)




Elmhamdi et al. (2003)

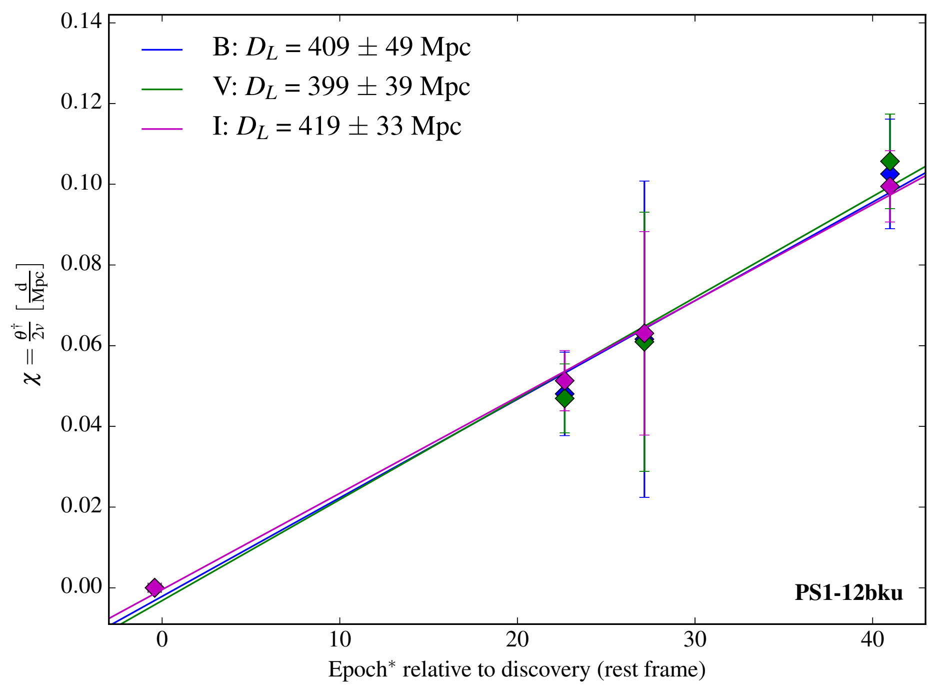
# Expanding Photosphere Method

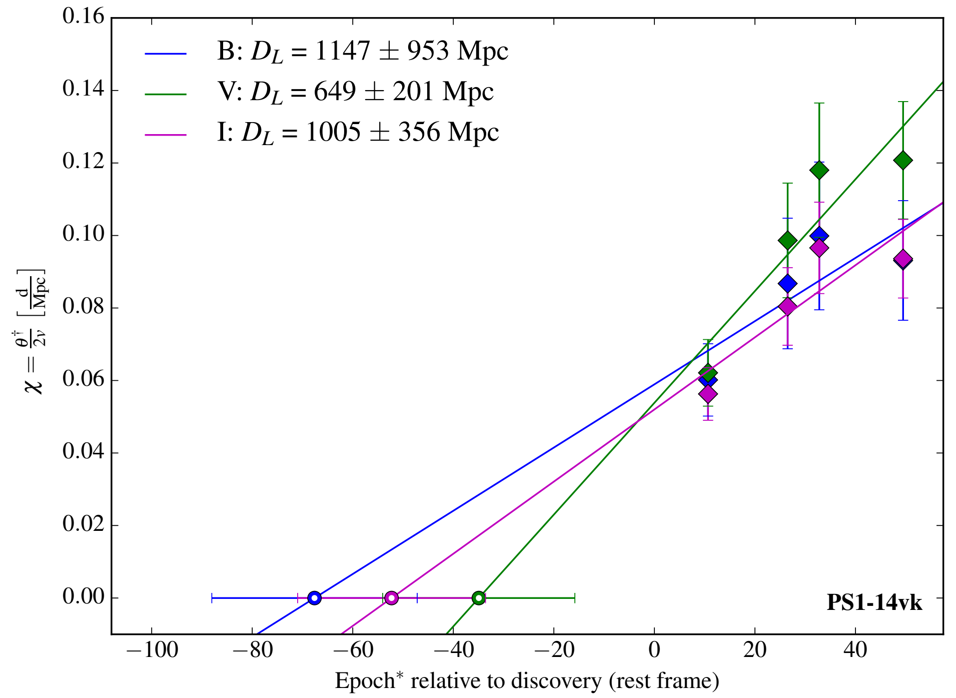
$$\theta = \frac{R}{D} = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\Lambda(T)}}; \; R = v(t - t_0) + R_0; \; D_A = \frac{v}{\theta}(t - t_0)$$

- *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 $\zeta^2$

# Expanding Photosphere Method

- Multiple filters
- Influence of known date of explosion




Gall et al., in prep.

# Expanding Photosphere Method

- Measures an angular size distance
  - Not important in the local universe
  - Interesting for cosmological applications
  - Mostly for $H_0$
- Cosmology
  - Include time dilation
  - Metric theories of gravity imply

$$D_L = (1+z)^2 D_A$$

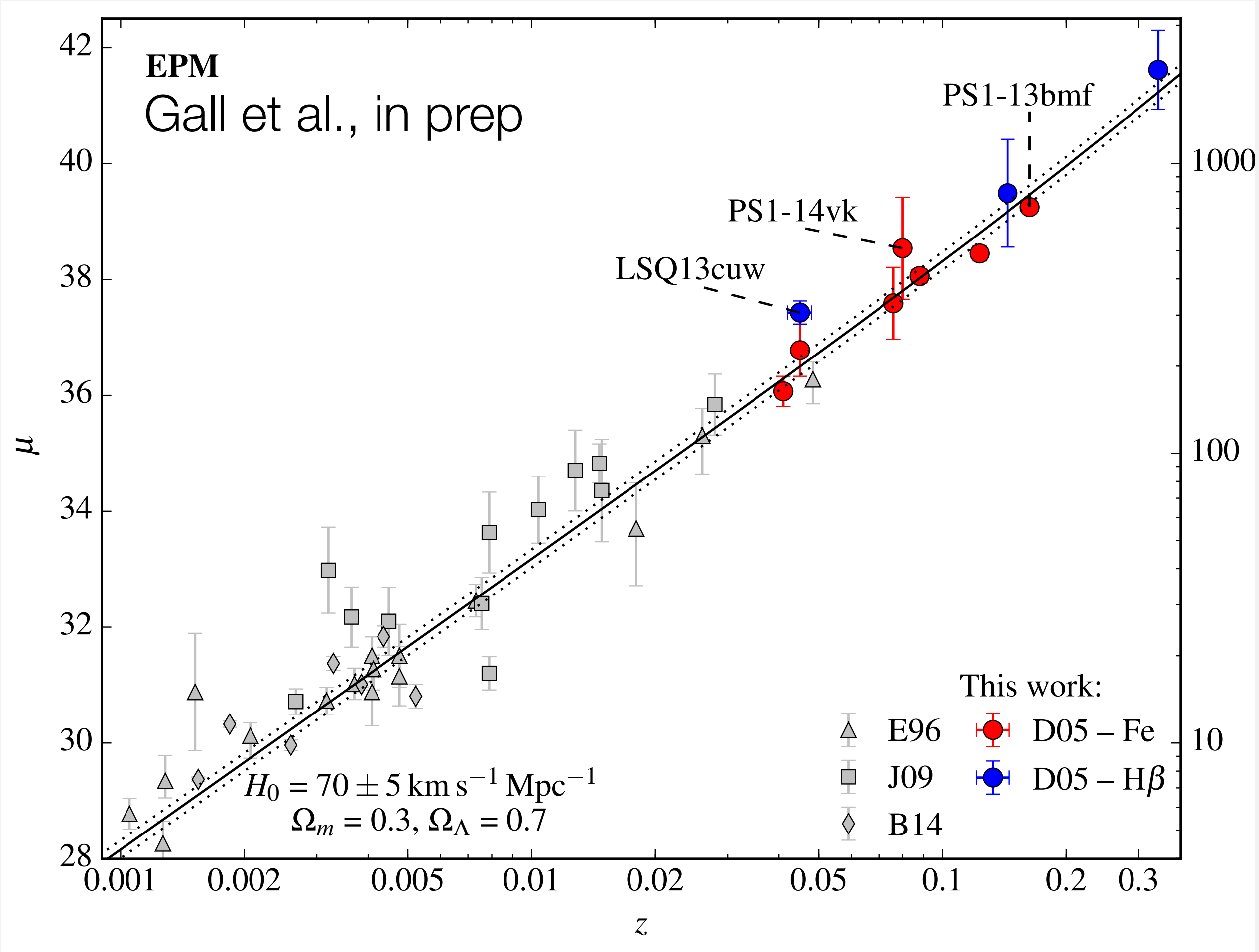
| $z$ | $\frac{D_L}{D_A}$ |
|---|---|
| 0.1 | 1.21 |
| 0.15 | 1.32 |
| 0.2 | 1.44 |
| 0.25 | 1.56 |
| 0.3 | 1.69 |
| 0.35 | 1.82 |

# 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

# Hubble Diagram

- Independent of distance ladder



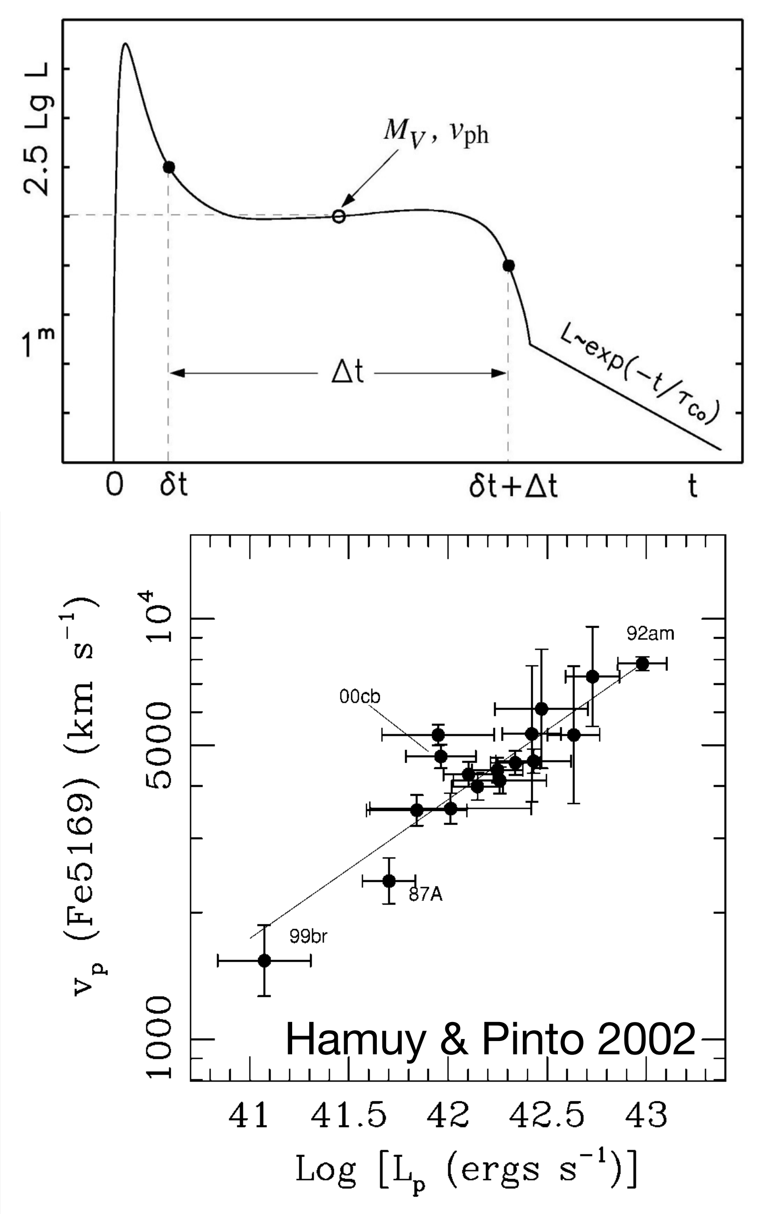
# Standardizable Candle Method

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

# Distance to SN 2013eq

(z=0.041)

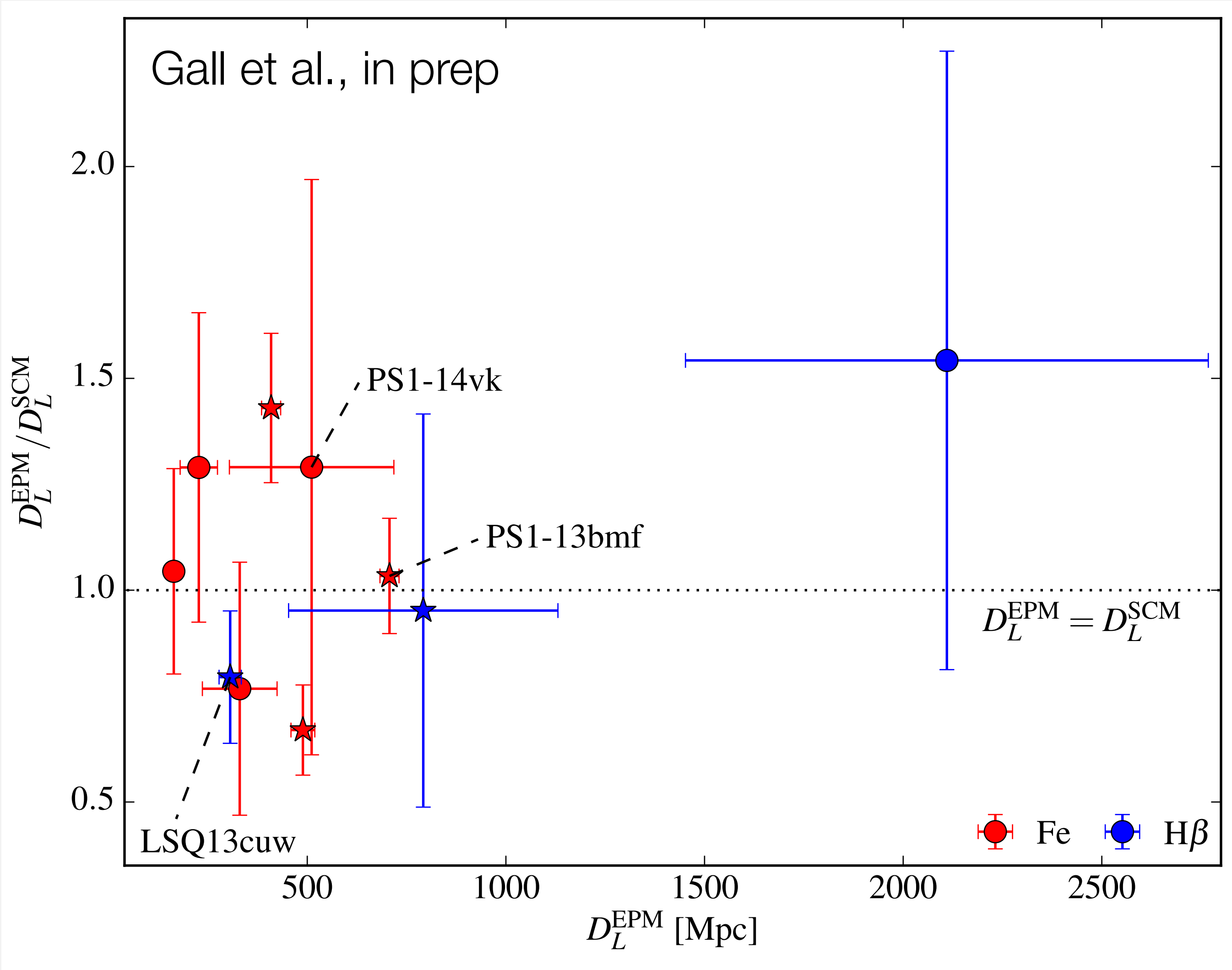
- Use EPM and CSM to measure distance to same supernova
- EPM provides explosion date to be used by CSM

Gall et al. 2016

| Dilution factor | Filter | $D_L$ Mpc | Averaged $D_L$ Mpc | $t_0^{\star}$ days* | Average $t_0^{\star}$ days* | $t_0^{\diamond}$ MJD |
|---|---|---|---|---|---|---|
| H01 | *B* | 163 ± 45 | 151 ± 18 | 5.8 ± 10.5 | 4.1 ± 4.4 | 56 499.6 ± 4.6 |
| | *V* | 125 ± 22 | | −0.5 ± 5.4 | | |
| | *I* | 165 ± 23 | | 7.1 ± 6.0 | | |
| D05 | *B* | 177 ± 48 | 164 ± 20 | 4.7 ± 9.8 | 3.1 ± 4.1 | 56 500.7 ± 4.3 |
| | *V* | 136 ± 23 | | −1.3 ± 5.1 | | |
| | *I* | 180 ± 25 | | 5.9 ± 5.6 | | |

| Estimate of $t_0$ via | $t_0^{\diamond}$ MJD | $V_{50}^{*}$ mag | $I_{50}^{*}$ mag | $v_{50}$ km s$^{-1}$ | $\mu$ mag | $D_L$ Mpc |
|---|---|---|---|---|---|---|
| EPM – H01 | 56 499.6 ± 4.6 | 19.05 ± 0.09 | 18.39 ± 0.04 | 4880 ± 760 | 36.03 ± 0.43 | 160 ± 32 |
| EPM – D05 | 56 500.7 ± 4.3 | 19.06 ± 0.09 | 18.39 ± 0.04 | 4774 ± 741 | 35.98 ± 0.42 | 157 ± 31 |
| Rise time – G15 | 56 496.6 ± 0.3 | 19.03 ± 0.05 | 18.39 ± 0.04 | 5150 ± 353 | 36.13 ± 0.20 | 168 ± 16 |

# Testing GR



Gall et al., in prep
PS1-14vk
PS1-13bmf
LSQ13cuw
$D_L^{EPM} = D_L^{SCM}$
Fe
Hβ
2.0
1.5
1.0
0.5
500
1000
1500
2000
2500
$D_L^{EPM}$ [Mpc]
$D_L^{EPM} / D_L^{SCM}$