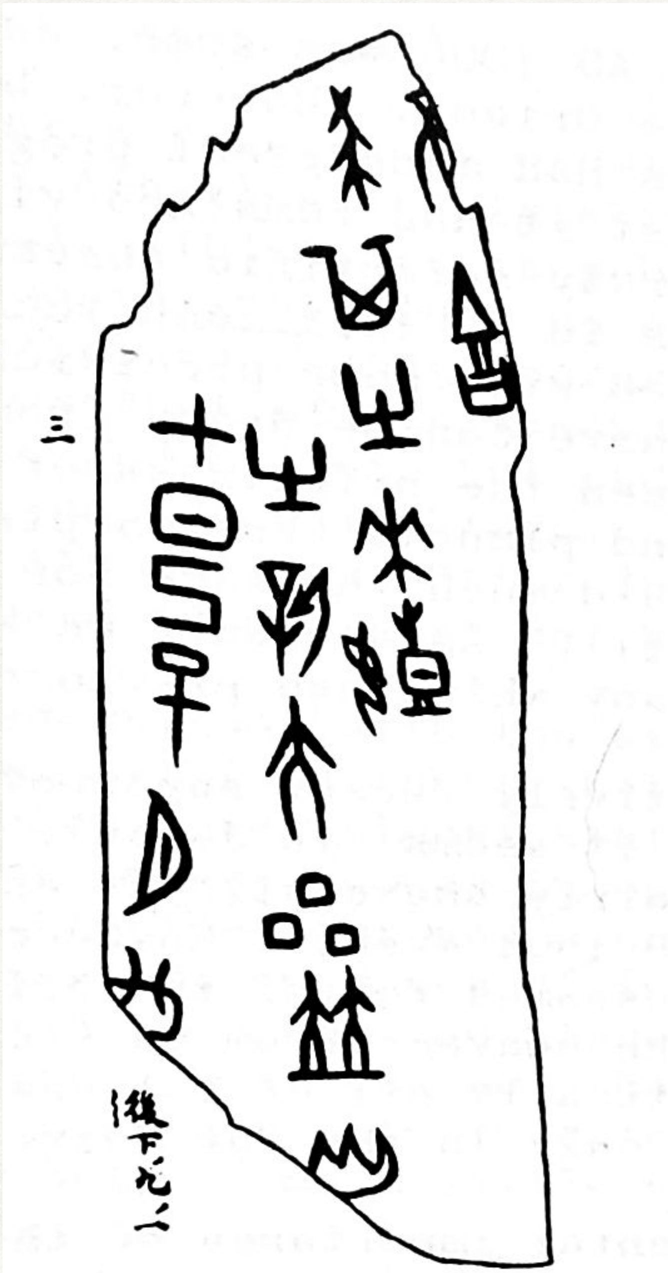
ПРОБЛЕМЫ ИССЛЕДОВАНИЯ СВЕРХНОВЫХ ЗВЁЗД

М. В. Пружинская

PLAN

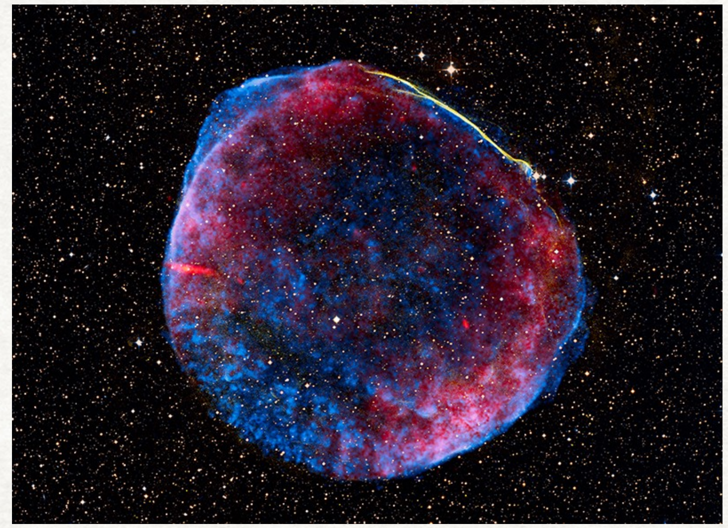
- Historical aspect
- Classification problem
- Statistics
- Core-collapse supernovae
    - SN IIP vs. SN IIL
    - Progenitors
    - Stripped-envelope supernovae
    - SNe and GRBs
- Thermonuclear supernovae or Type Ia Supernovae
    - Progenitor problem
    - Cosmology
        - Standardization problem
        - Modern cosmological analyses
        - H0 tension
- Super-luminous supernovae (homework)

HISTORICAL SUPERNOVAE



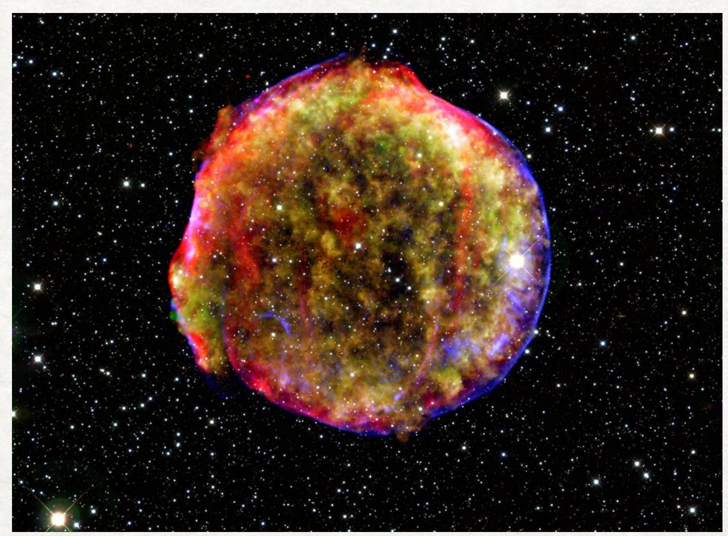
«On the 7th day of the month, a chi-szū day, a great new star appeared in company with Antares», 1500 BC, China

SN 1006

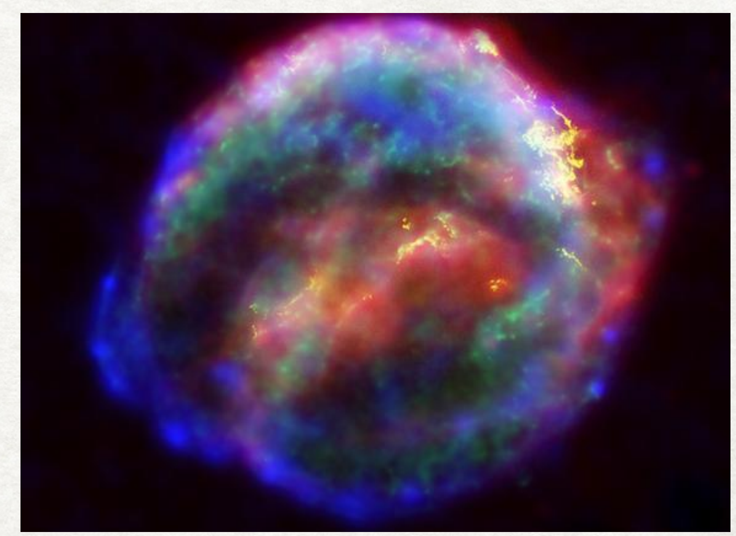


SN 1054 (Crab Nebula)

SN 1572 (Tycho Brahe)



SN 1604 (Johannes Kepler)

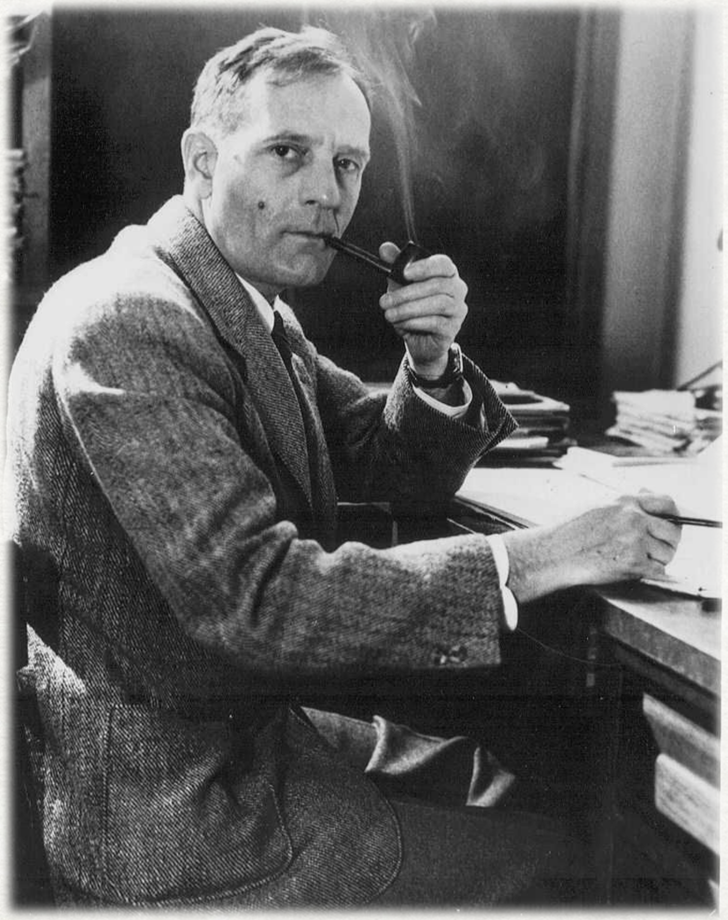


GREAT DEBATE, 1920

«ISLAND UNIVERSES»

Harlow Shapley

Heber D. Curtis



Edwin Hubble

CONSEQUENCES

THERE ARE TWO CLASSES OF OBJECTS

$$F = \frac{L}{4\pi d_L^2}$$

The luminosity of Novae in «Nebulae» is

$$> 10^{44}\ \mathrm{erg\ s^{-1}}\ (10^{11} L_{\odot})$$

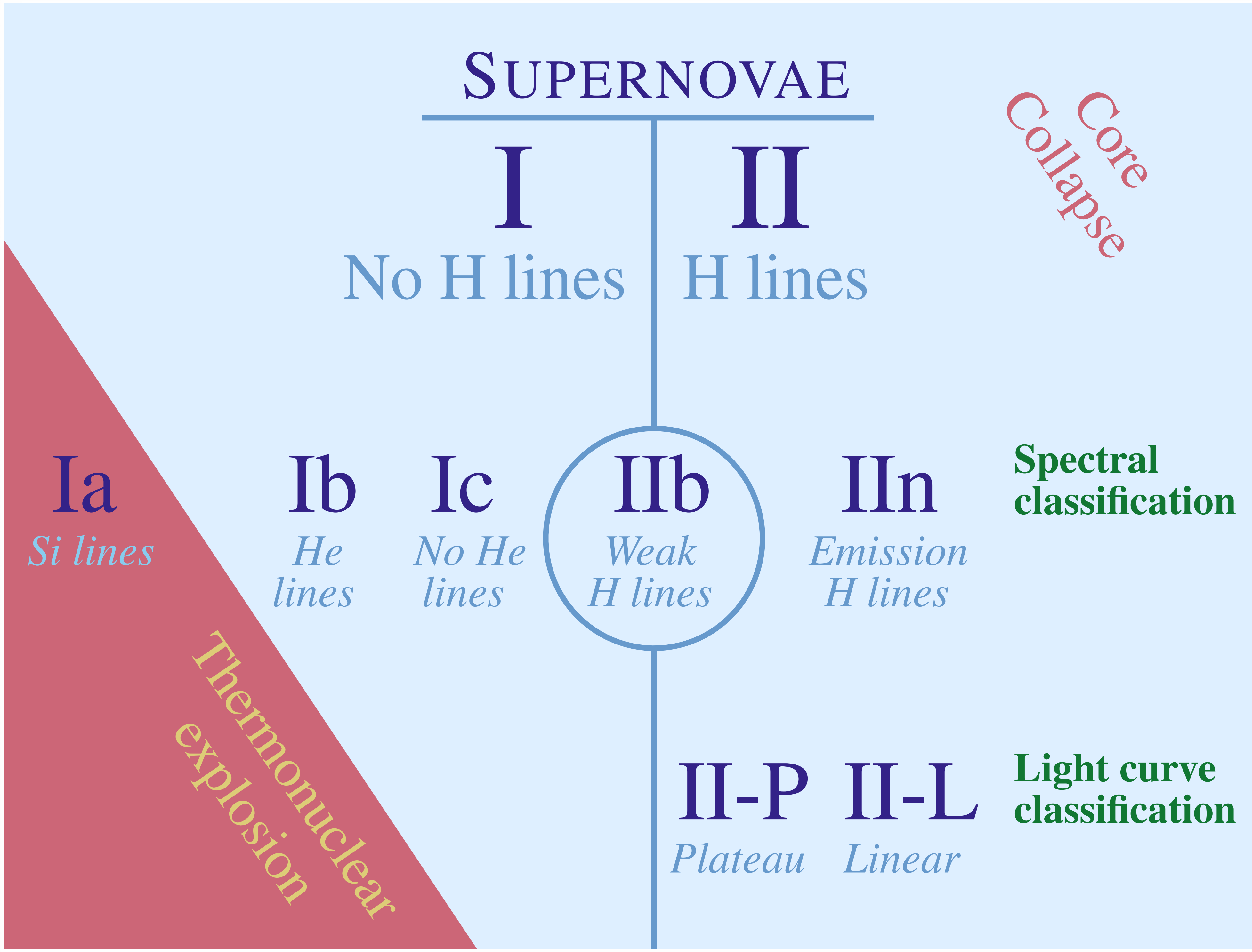
«ON SUPER-NOVAE»

- 1934 – term «super-nova»
- 1936 – first supernova survey at the Palomar observatory (US)
- 1938 – SNe are more uniform than novae, that makes them suitable as extragalactic distance indicators

Walter Baade

Fritz Zwicky

CLASSIFICATION PROBLEM



- Ia: 91T-like, 91bg-like, super-Chandra events, 2002cx-like (Iax), Ia-CSM
- Ib/Ic: Ibn, double-peaked Ib, Ca-rich Ib, long rising events, rapid decliners
- II: slowly-rising, IIb, IIn, low-luminosity IIP

CLASSIFICATION PROBLEM

Avishay Gal-Yam «Observational and Physical Classification of Supernovae», 2017

Main idea: class names clearly separate assumptions about the physical origin of events and observational properties

SNAAX.Y iX.Y mX.Y vX.Y rX.Y dX.Y

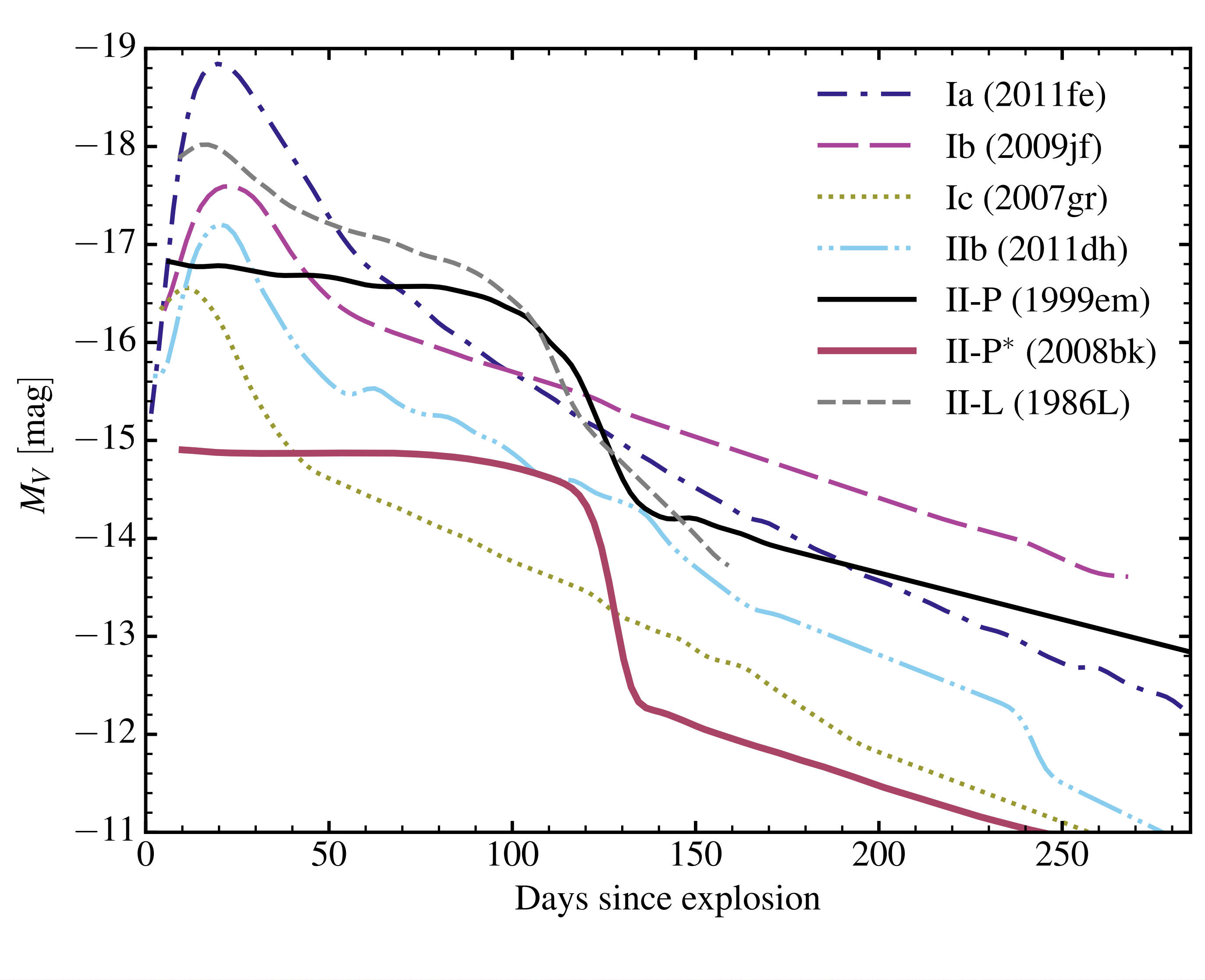
AA = «Ia» or «CC»

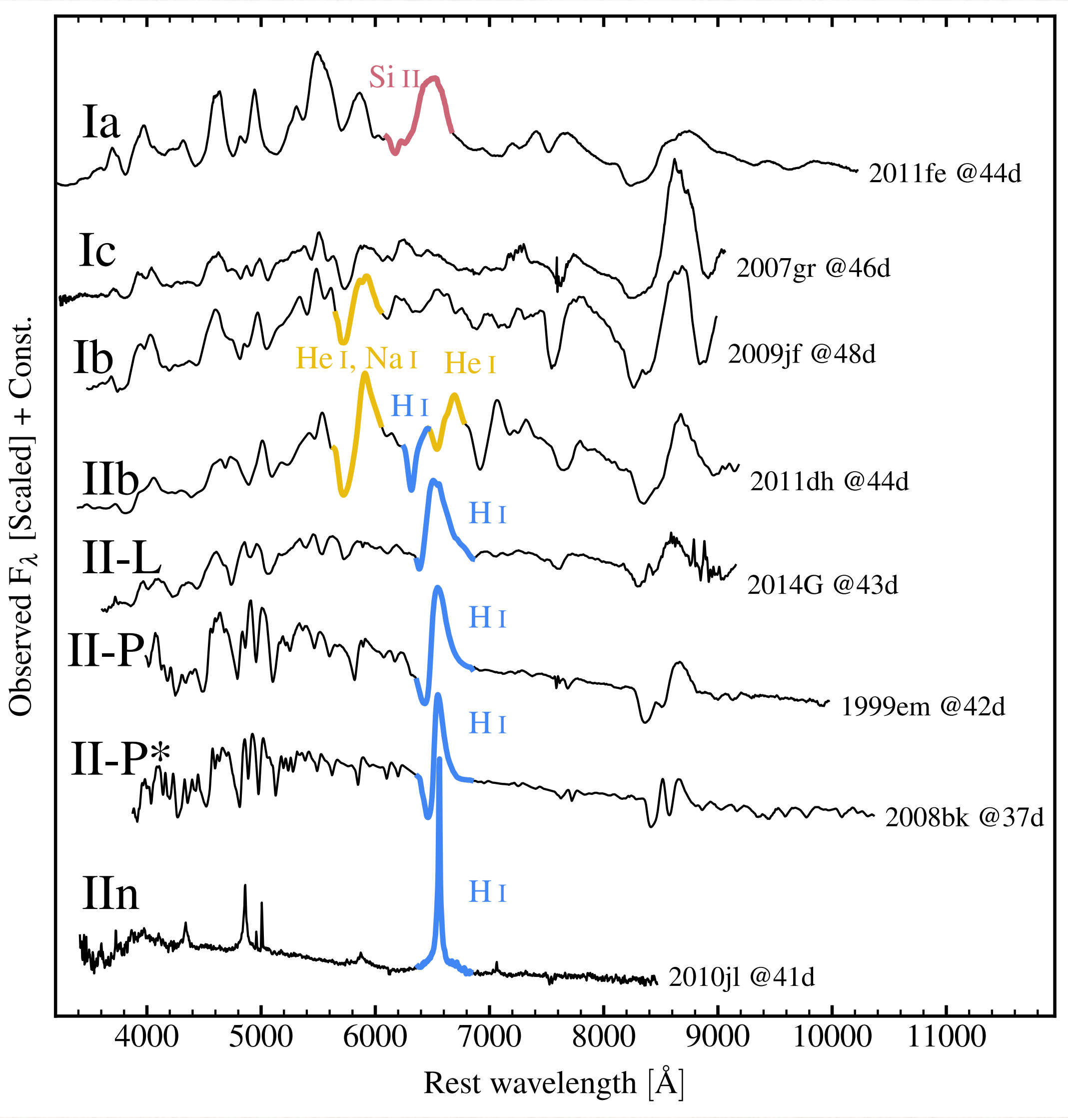
«0» – H, «1» – no H but He, «2» – neither H, no He

optional tags: «i» – interaction; «m» – magnitude offset; «v» – shift in velocity; «r» – rise time to peak, «d» – decline rate

- See also Prentice & Mazzali for «physically motivated classification of stripped-envelope supernovae», 2017.

LIGHT CURVES AND SPECTRA

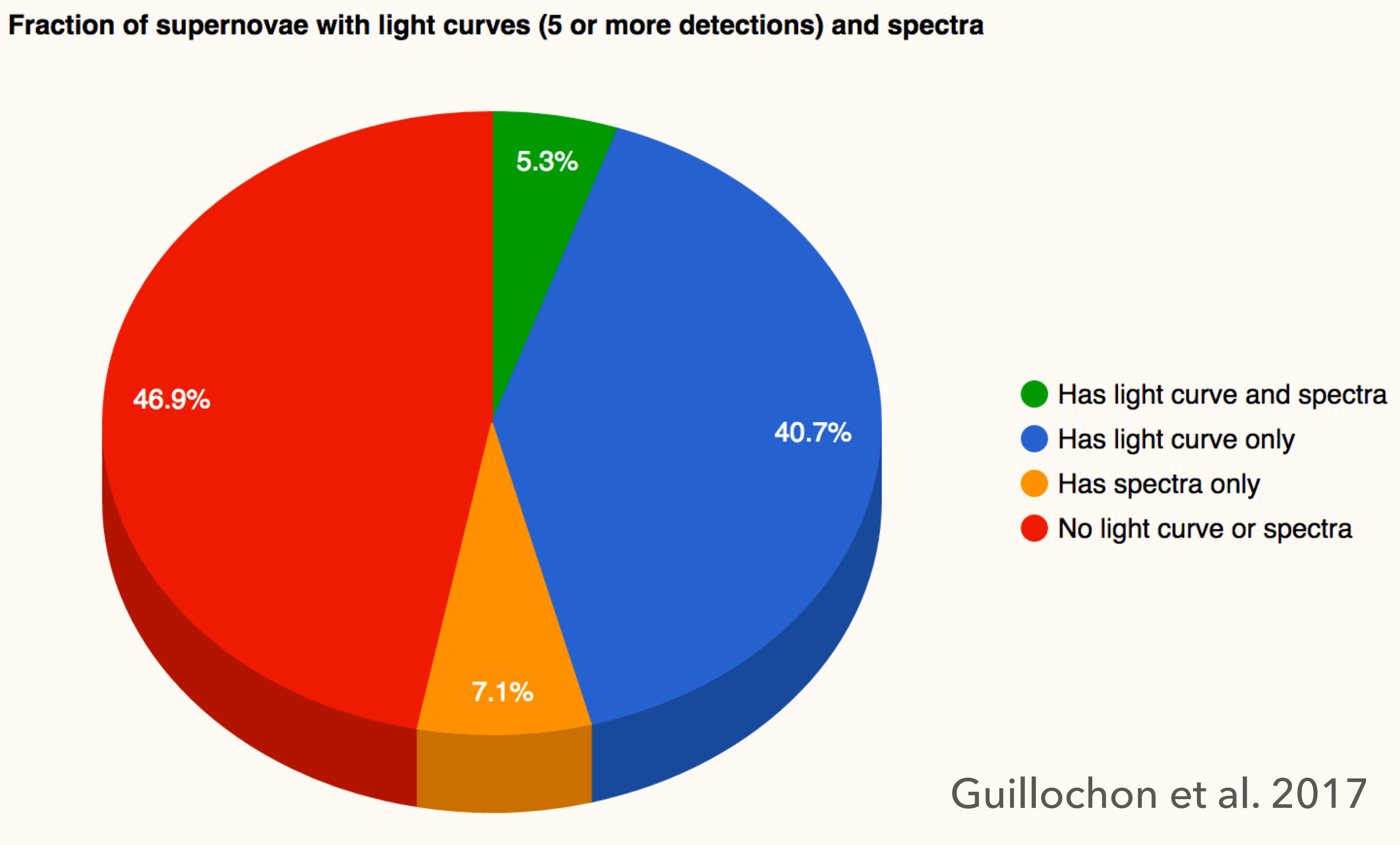




S. Lisakov, PhD 2018

STATISTICS

The Open Supernova Catalog includes metadata for 59,603 supernovae



Guillochon et al. 2017

The spectroscopic support is needed

CORE-COLLAPSE SUPERNOVAE

CORE-COLLAPSE SUPENOVAE

BASIC PROPERTIES

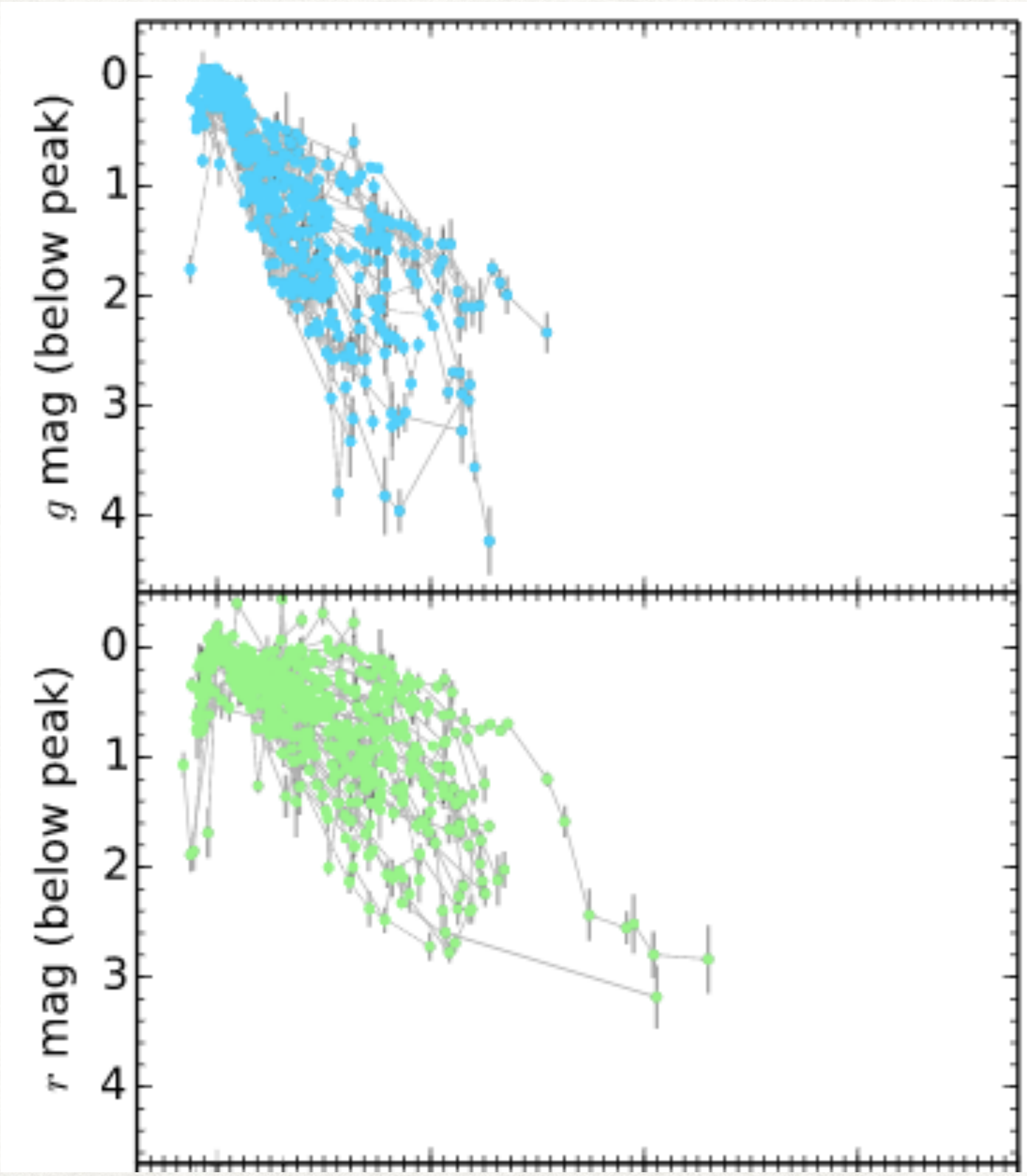
- Explosion of massive stars ($> 8 - 10\ M_{\odot}$)
- SNe II: red supergiant progenitor (pre-explosion images)
- Formation of compact object (i.e., NS/BH)
- SNe II: strong hydrogen lines in peak light and late time spectra
- In star forming regions of spiral galaxies (not found in elliptical)
- Core-collapse SNe in the Milky Way: SN 1054 (Crab Nebula)
- Cosmology with SN IIP (the Expanding Photosphere Method; see Kirshner & Kwan 1974; Nugent & Hamuy, 2017):

  +: direct, no cepheid calibration

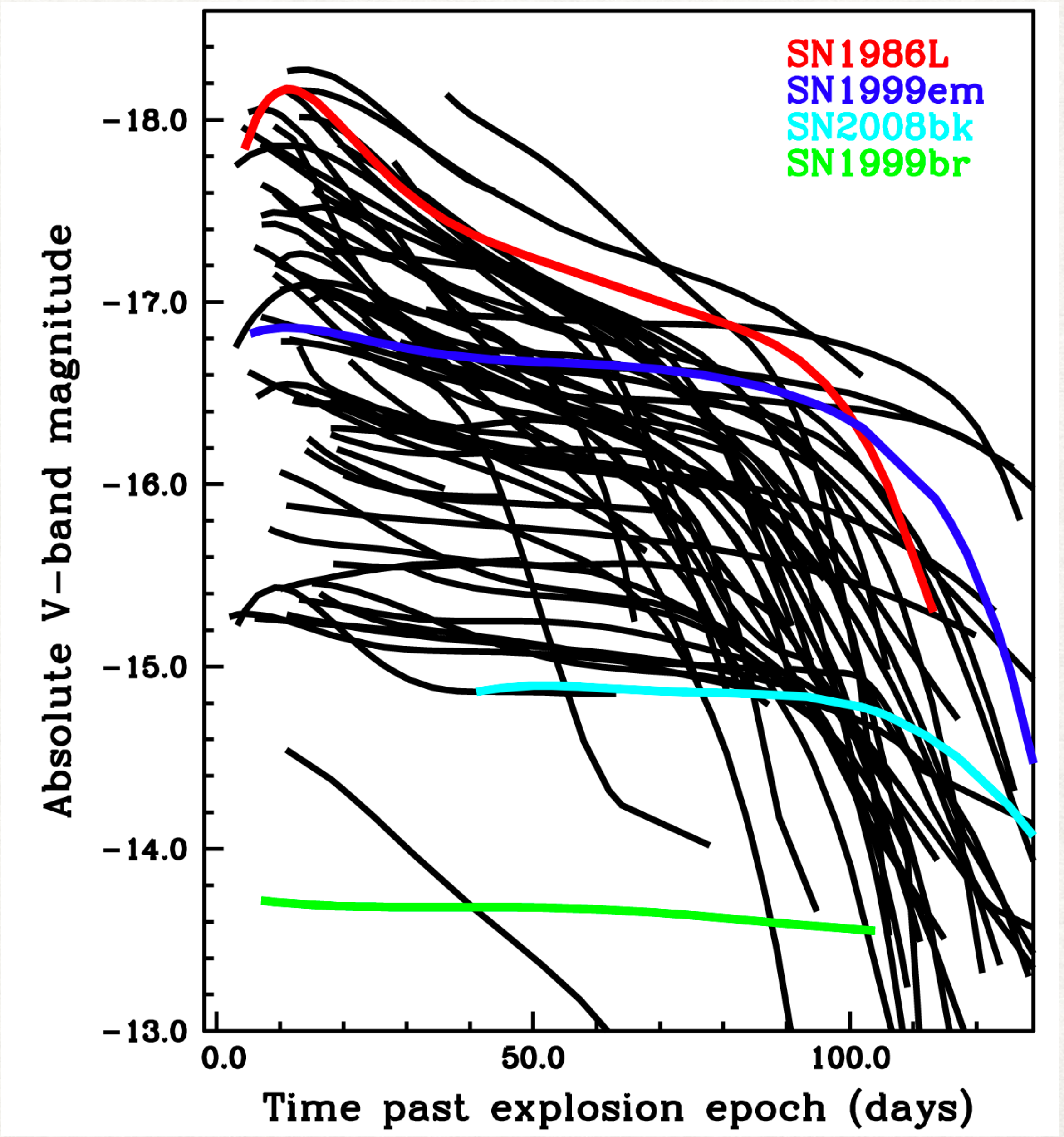
  –: SNe IIP are not luminous

SN IIP VS. SN IIL

Barbon et al. 1979: P – «Plateau»; L – «Linear»



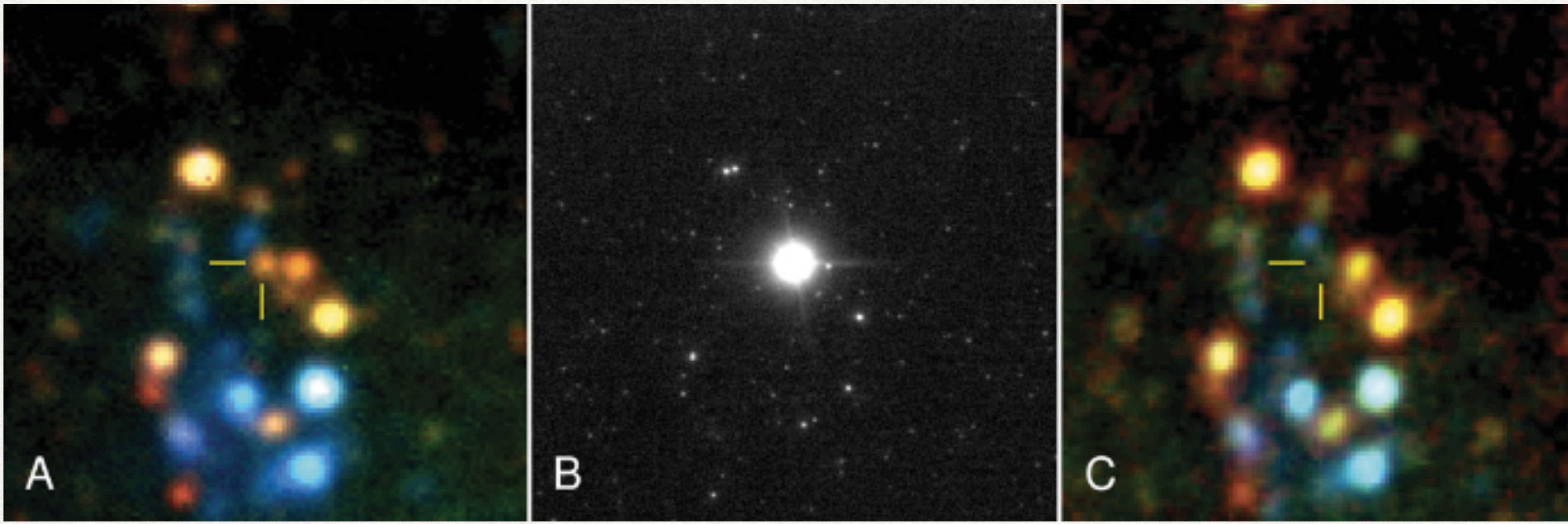
Sanders et al. 2015



Anderson et al., 2014

PROGENITORS

Red Supergiant Progenitor of Supernova 2008bk

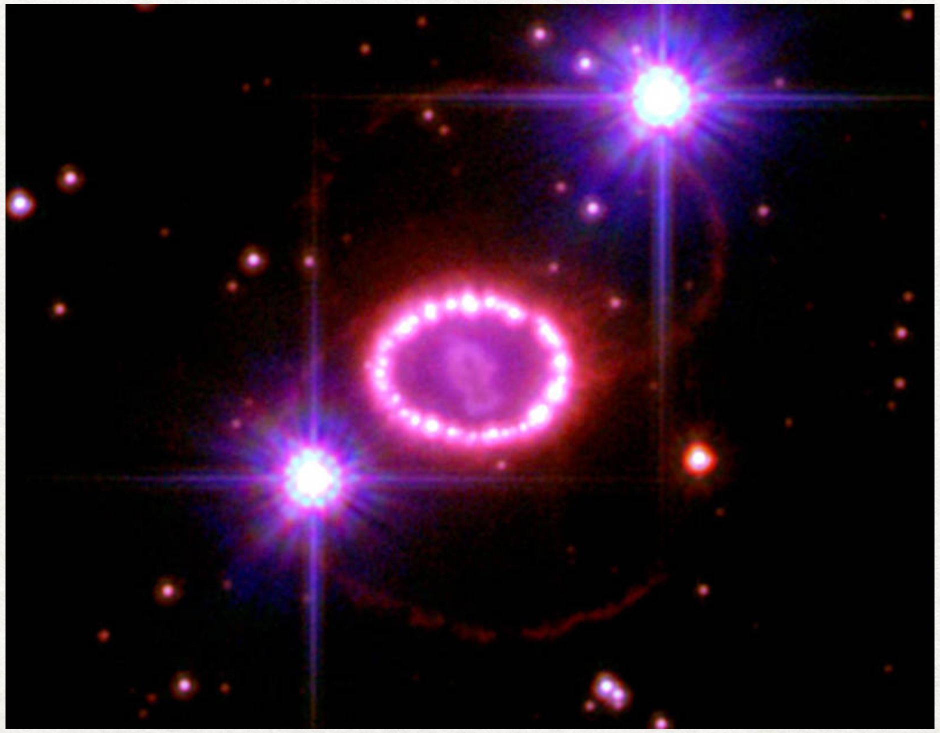


Mattila et al. (2010)

PROGENITORS

SN 1987A

- 23 Feb 1987 in LMC
- Brightest SN since 1604
- First SN detected in neutrinos.
- Visible (reached 3 mag) by naked eye
- Progenitor: ~20 $M_{\odot}$ blue supergiant (e.g., Woosley, Pinto & Ensman 1988; Podsiadlowski, 2017; Fröhlich et al., 2019)
- 3-ring structure (pre-SN wind)



NASA, ESA, R. Kirshner, P. Challis

STRIPPED-ENVELOPE SUPERNOVAE

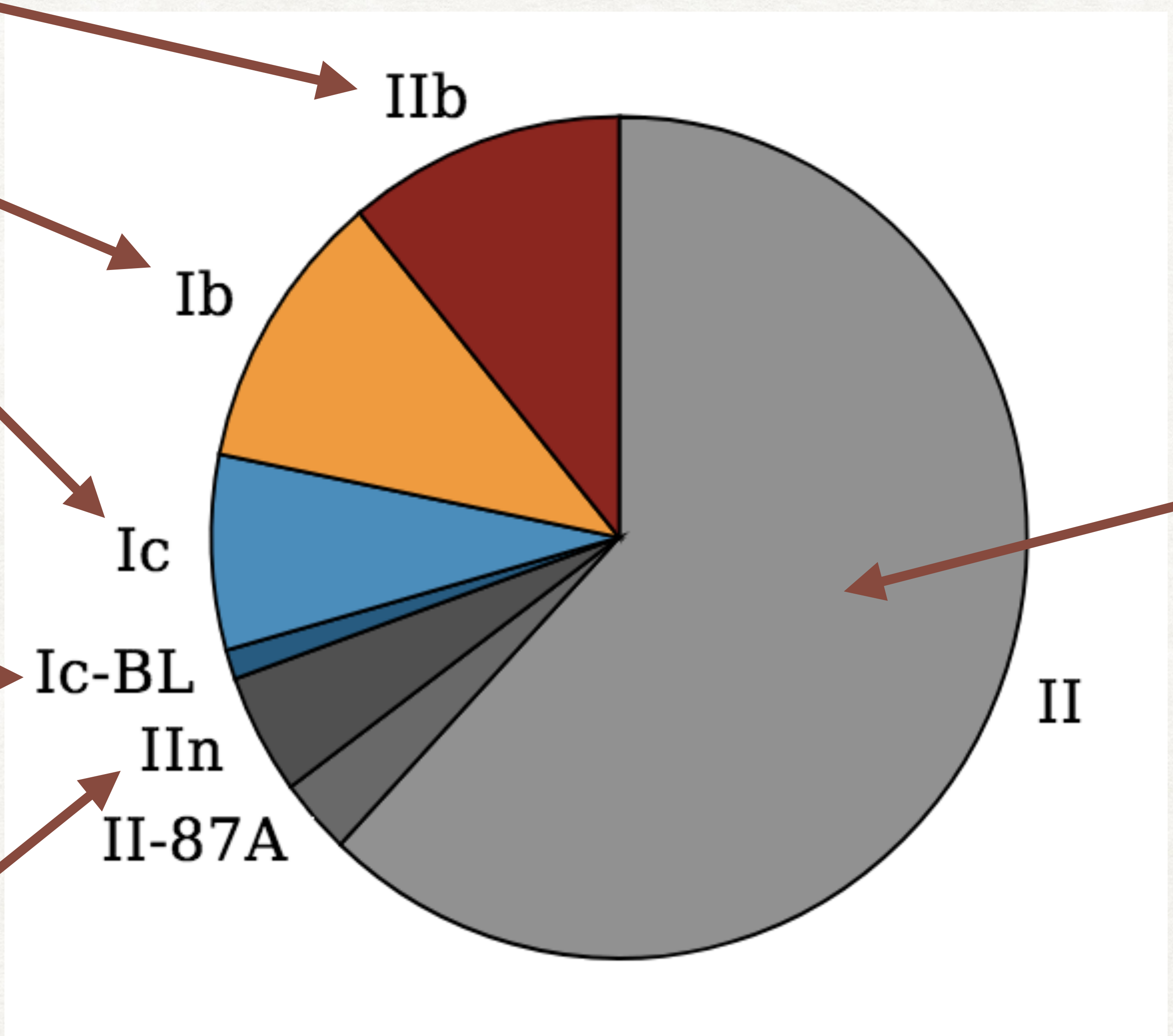
WR progenitors?

Probably stripped via binary interactions

can be associated with long GRBs

Interaction with circumstellar matter

RSG



Shivvers et al. 2017

CORE-COLLAPSE SUPERNOVAE AND GAMMA-RAY BURSTS

- Up to now: ~20 spectroscopically confirmed GRB-SNe
- ~30 photometrical detections of GRB-SNe
- For a review see Z. Cano 2017

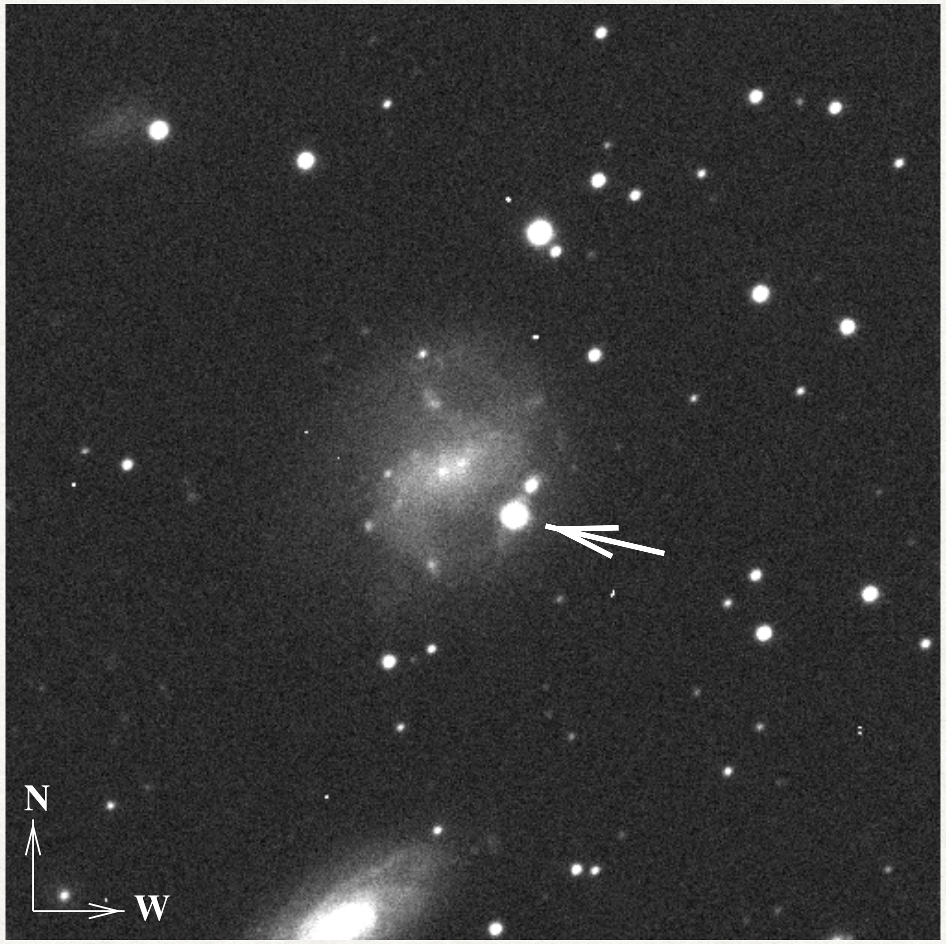
Observational problems:

not all GRBs are accompanied with SNe

never with Ib only Ic-BL

there are Ic-BL without GRB (e.g. Japelj et al., 2018)

GRB 980425 / SN 1998bw
First optical counterpart



Galama et al. 1998

$z = 0.0085, \sim 40 \text{ Mpc}$

$M_R = -19.36^m \pm 0.05^m$

TYPE IA SUPERNOVAE

TYPE IA SUPENOVAE

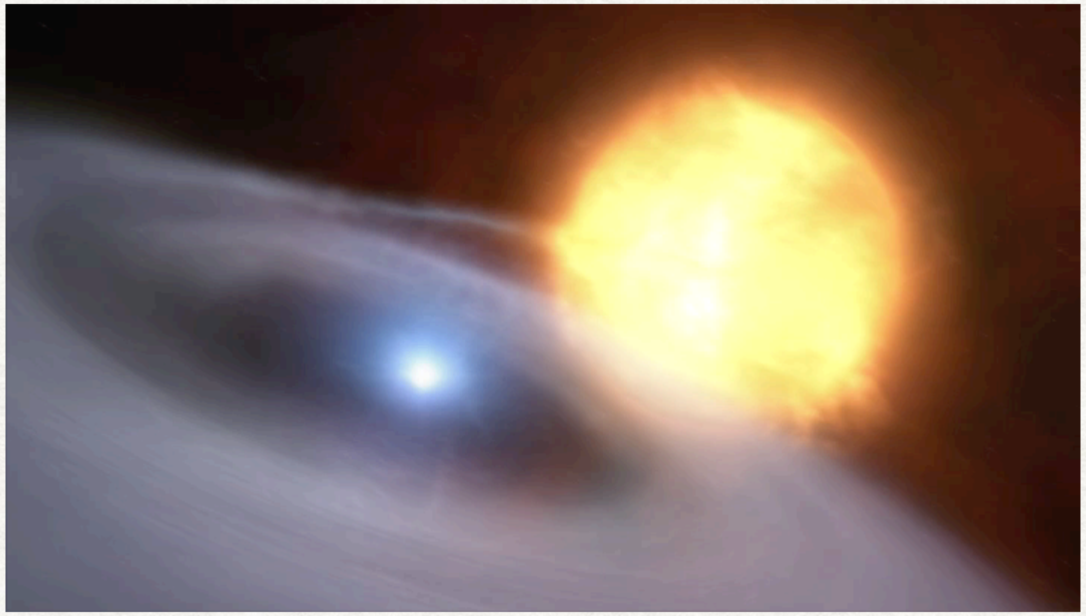
BASIC PROPERTIES

- Thermonuclear explosion of Chandrasekhar mass (~1.4 $M_\odot$) CO white dwarf
- Matter accretion onto a white dwarf in a binary system
- No compact remnant
- The burning produces ~0.6 $M_\odot$ of ^{56}Ni, the decay of which powers the light curve ($^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$)
- In all types of galaxies
- Possible Type Ia in the Milky Way: Tycho, Kepler SNe

SN IA PROGENITOR PROBLEM

Single degenerate scenario (SD)

Whelan and Iben 1973



ESO/M. Kornmesser

No confident detection the hydrogen from the non-degenerate companion

Double degenerate scenario (DD)

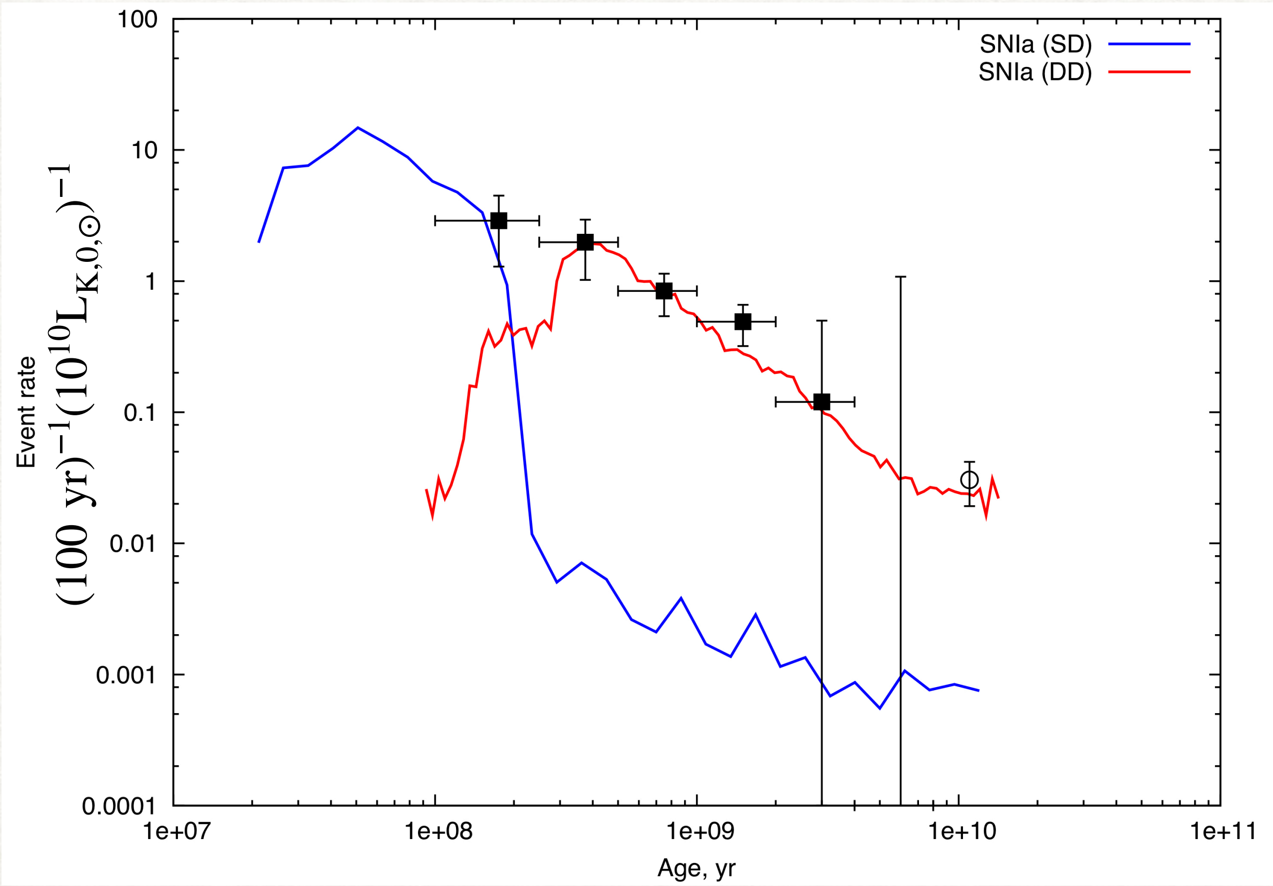
Iben and Tutukov 1984; Webbink 1984

ESO/L. Calçada

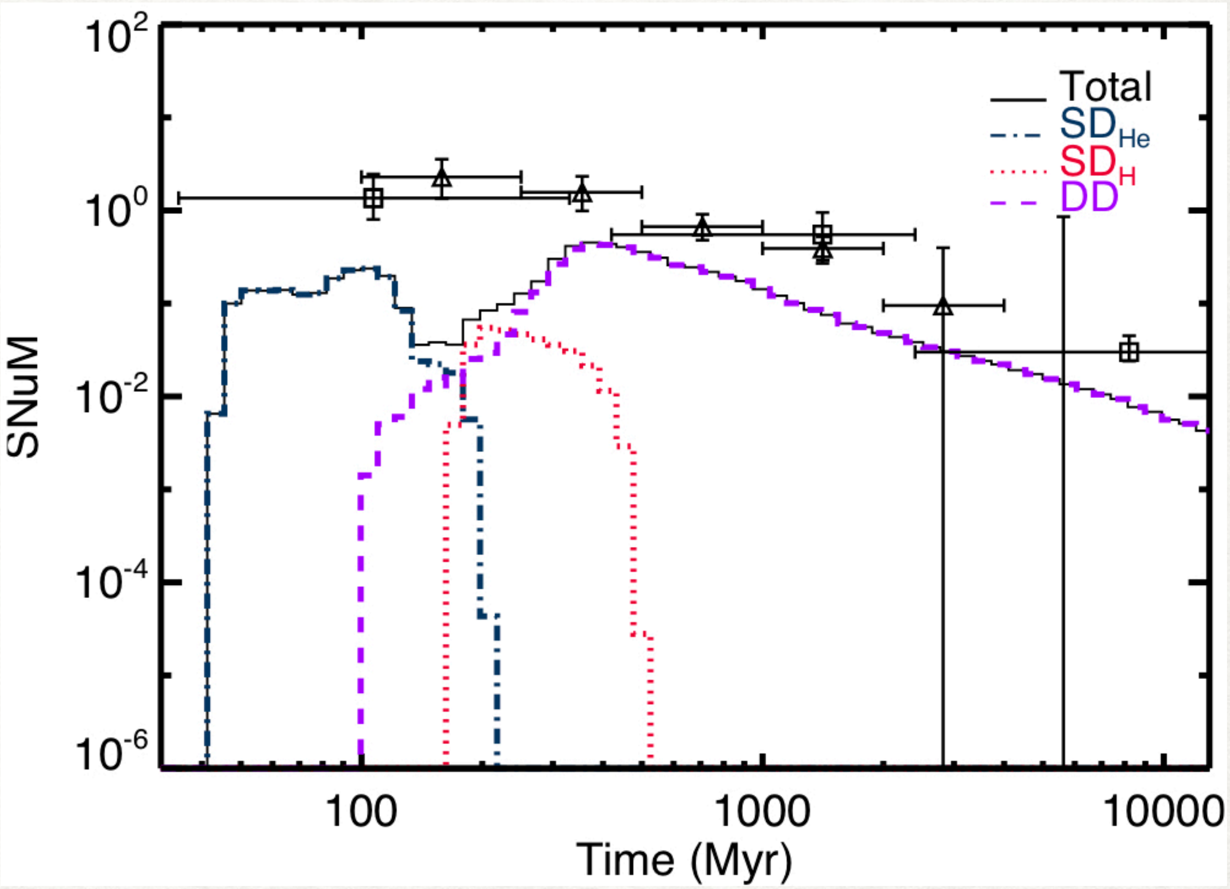
The collapse is expected rather than the explosion (e.g., Nomoto & Kondo, 1991; Pakmor et al., 2010)

SN IA PROGENITOR PROBLEM

DELAY TIME DISTRIBUTIONS



Lipunov et al., 2011



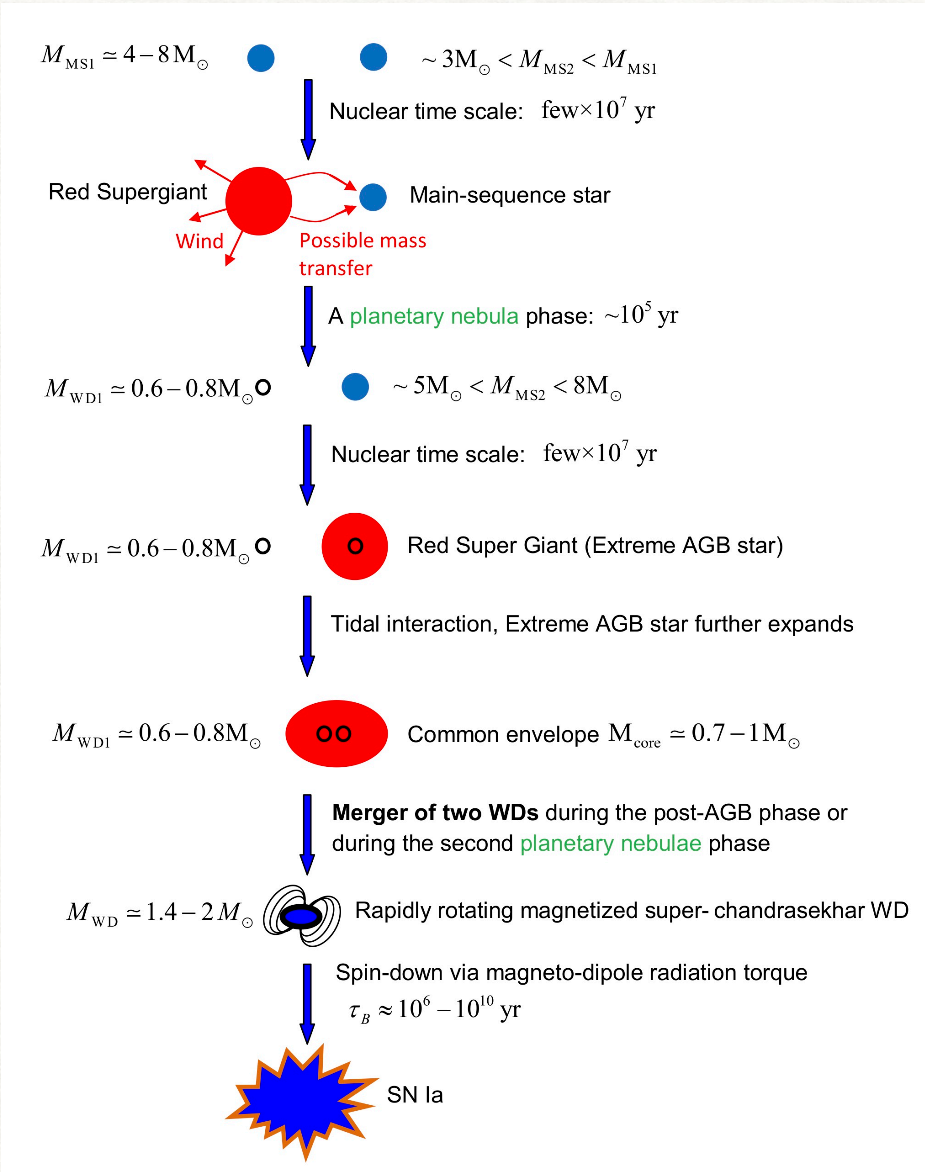
Claeys et al., 2014

- Polarization observations (Wang & Wheeler, 2008)
- Measurement of unburnt fuel (e.g., Livio 2000; Parrent et al., 2011, Taubenberger et al., 2011)

To correctly compare the observations with theory the full-scale 3D simulations are needed.

SN IA PROGENITOR PROBLEM

Core degenerate scenario (CD)



Soker 2011; Wang et al., 2016

Non-Chandrasekhar-mass Explosions

Sub-Chandrasekhar
e.g. Polin et al., 2019

Super-Chandrasekhar
e.g. Fink et al., 2018

to account for all sub-classes and peculiar events

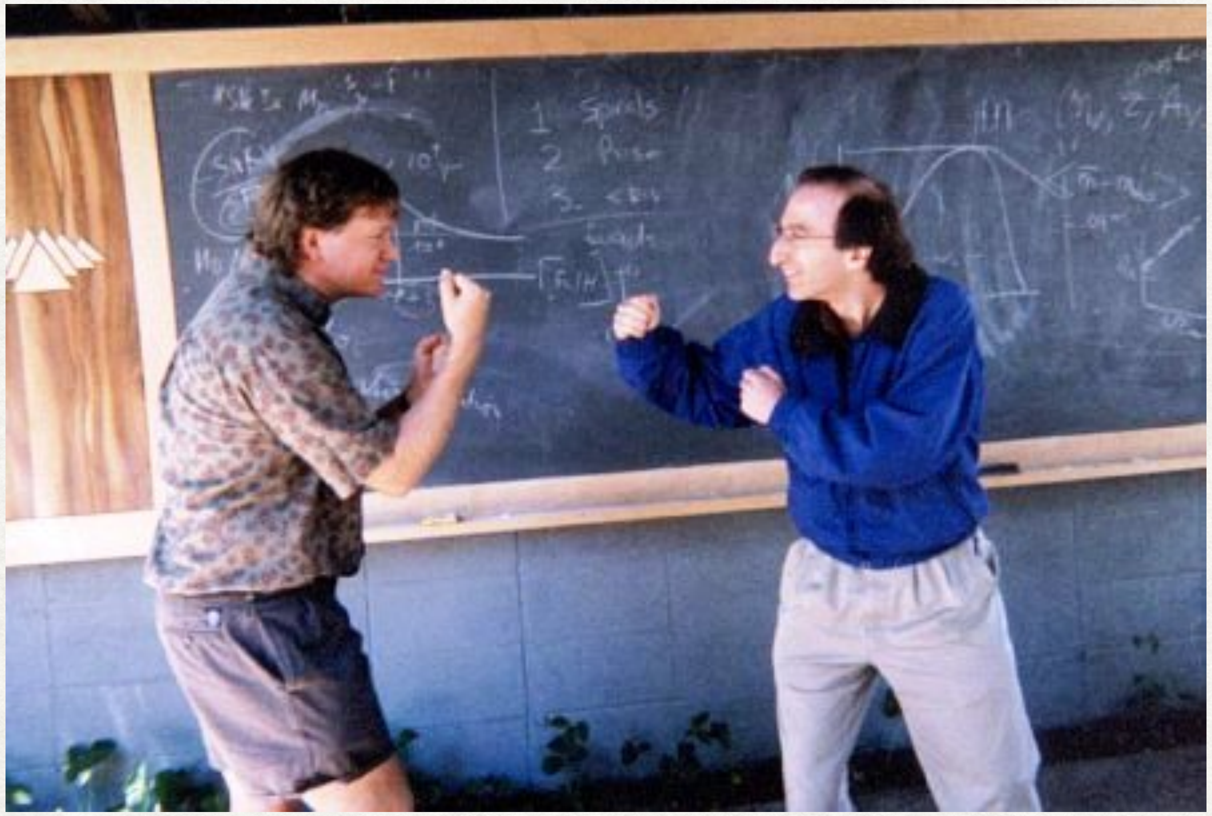
«The fact that we are still uncertain about the nature of the progenitor systems of Type Ia supernovae – some of the most powerful explosions in the universe – has become a major embarrassment for modern astrophysics».

– M. Livio

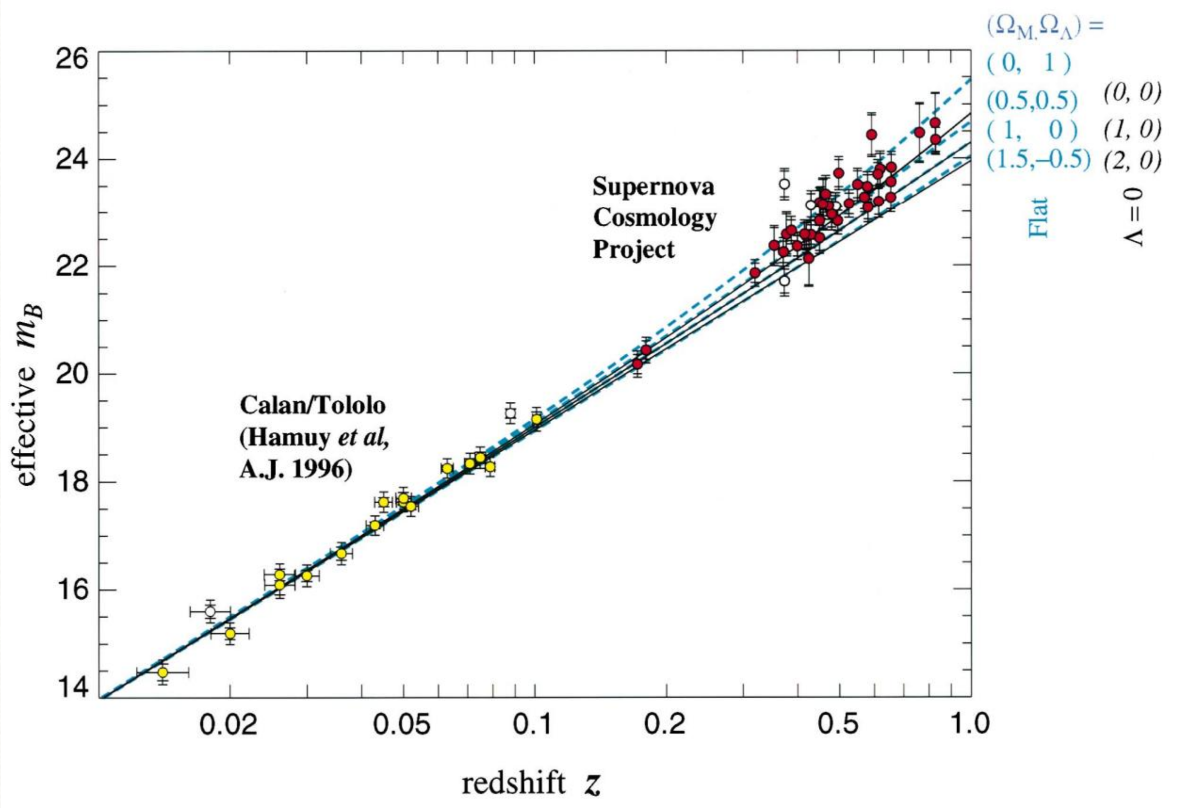
WHY SN IA FOR COSMOLOGY?

- ☑ Very luminous ($L \sim 10^{43}$ erg s^{-1}, $M_B^{max} \sim -19.5^m$)
- ☑ Uniform light curves

B. Schmidt & A. Riess (High-z SN Search);
S. Perlmutter (Supernova Cosmology Project)



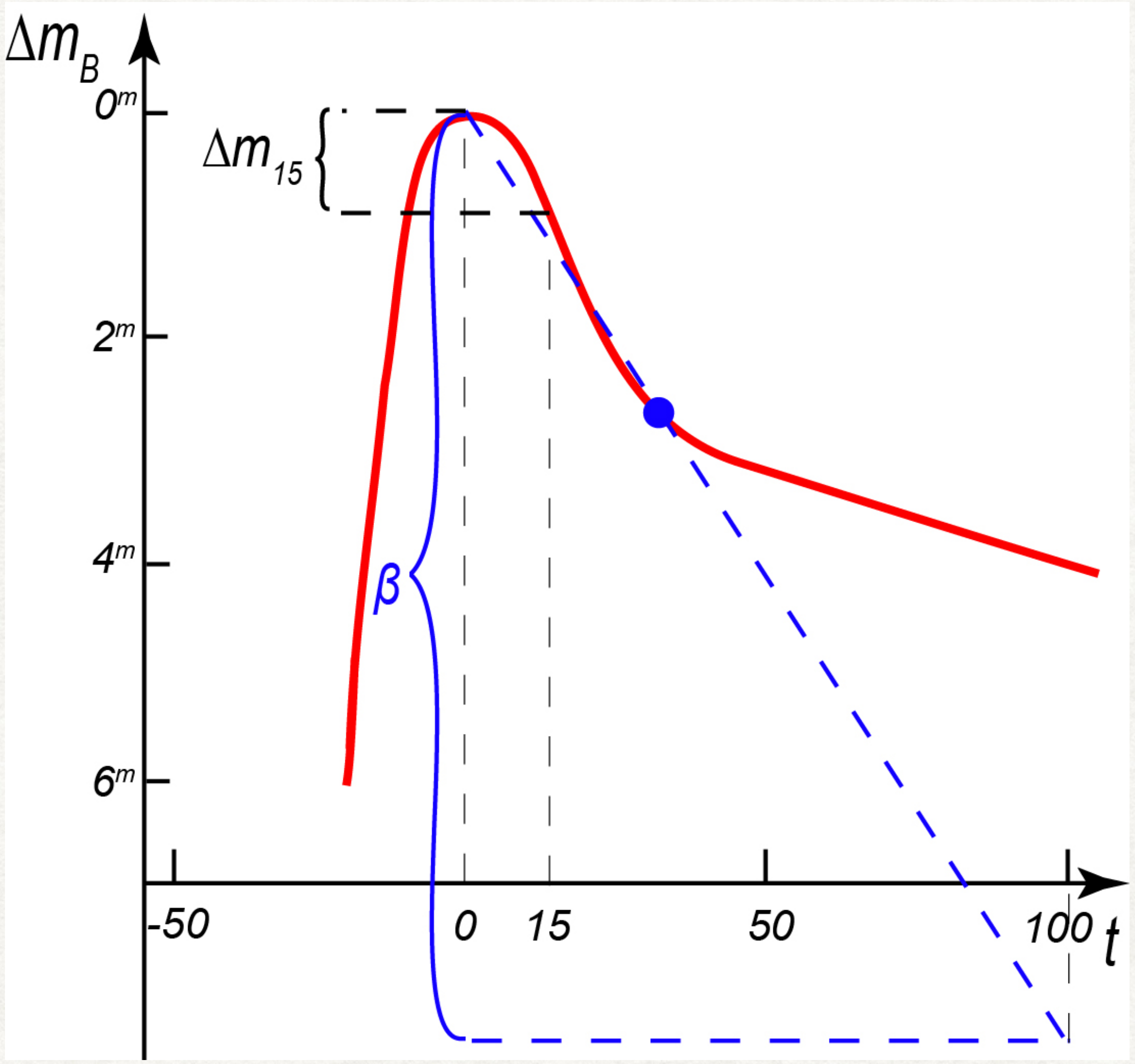
B. Schmidt vs. S. Perlmutter
(Noble Prize 2011)



70% Dark Energy
25% Dark Matter
5% Ordinary Matter

STANDARDIZATION PROCEDURE

RUST-PSKOVSKII RELATION



- Yu. P. Pskovskii, Soviet Astronomy 21, 675-682, 1977

$$-21.3 + 0.11\beta = M_{pg} \pm 0.5$$

- B. W. Rust, BAAS 7, 236, 1975 (PhD thesis 1974)

$$M_0 = (-18.55 \pm 0.68) - (0.0512 \pm 0.0359)\Delta t_c$$

- M. M. Phillips, Astrophysical Journal Letters, 413, 105–108, 1993

$$M_B^{max} = (-21.726 \pm 0.498) + (2.698 \pm 0.359)\Delta m_{15}(B)$$

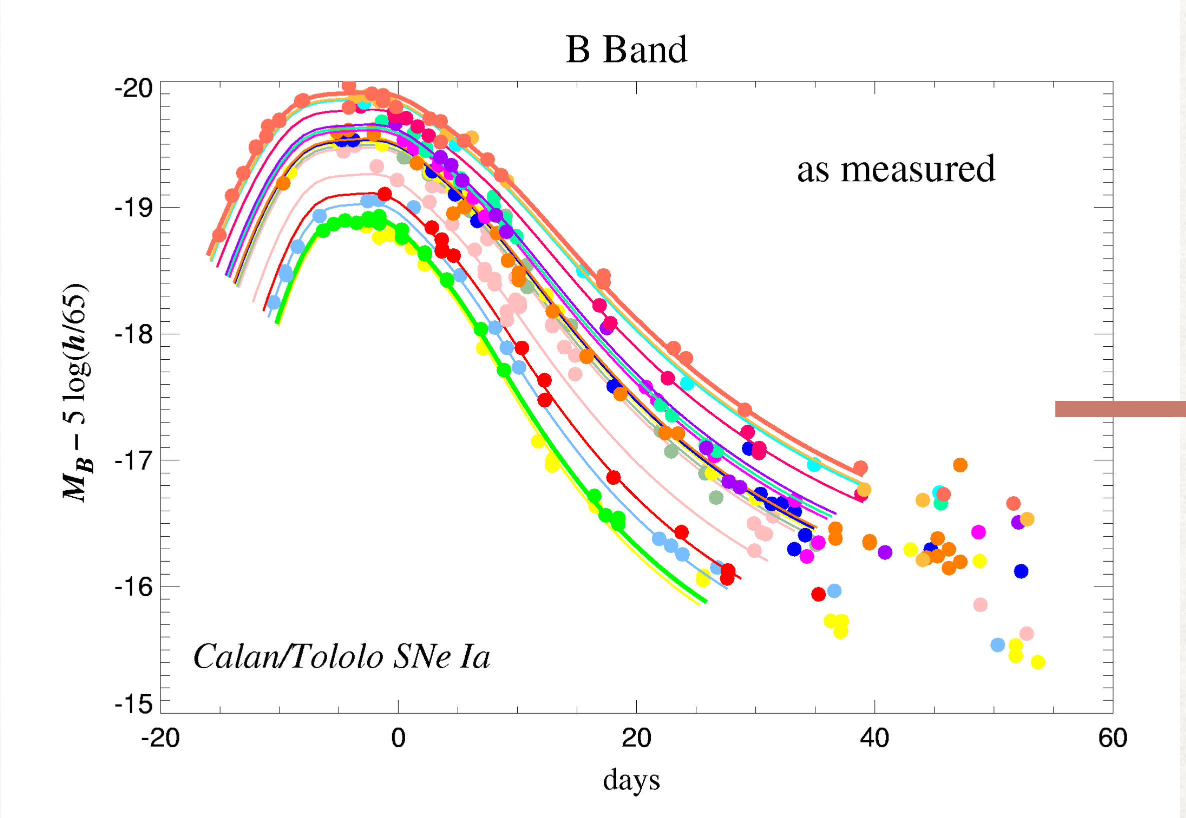
STANDARDIZATION PROCEDURE

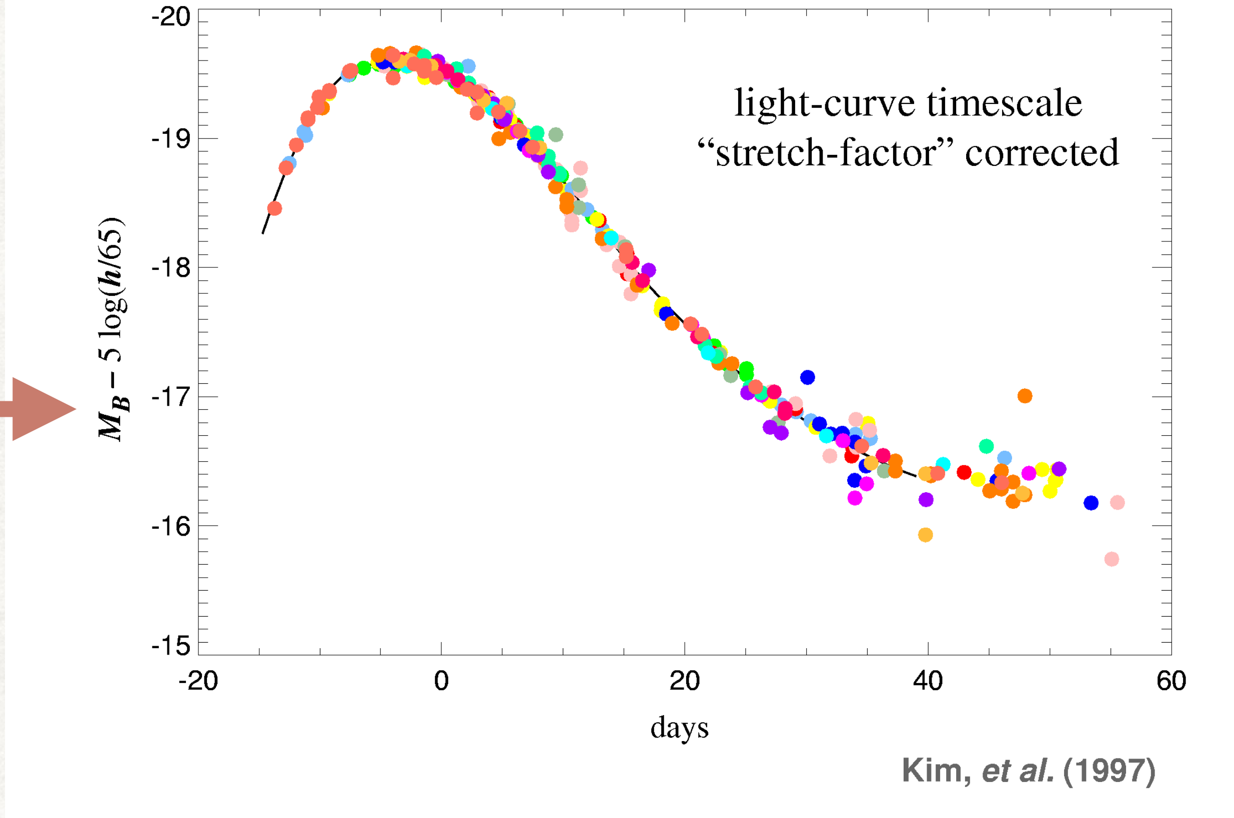
CURRENT STATE

- ✦ SALT2 (Guy et al., 2007) ✦ SUGAR (Léget et al., 2020)

$$\mu = m_B - (M_B - \alpha x_1 + \beta c)$$

x_1 – stretch factor, c – colour correction





Intrinsic luminosity dispersion in JLA ~0.11 mag

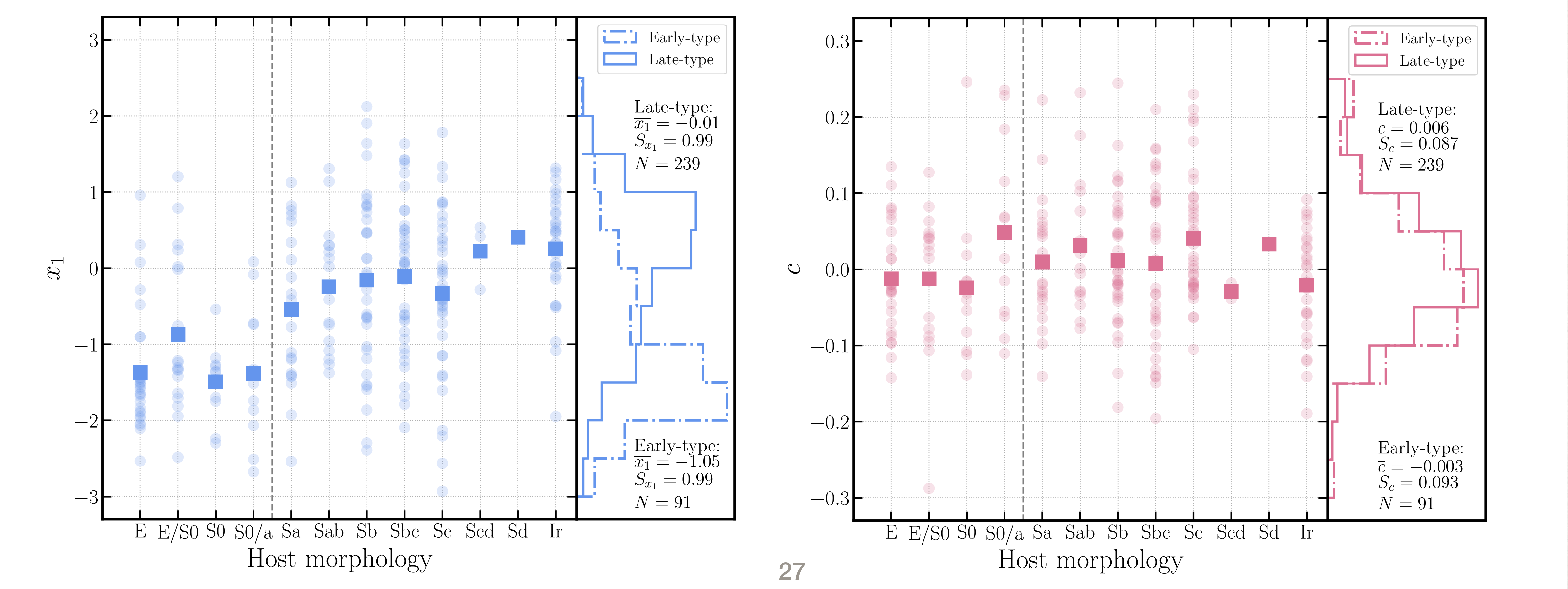
SNe Ia are neither standard candles, nor standardizable!

SN IA — STANDARD CANDLES?

- Absorption in the Galaxy, in host galaxies (e.g. Goobar, 2008; Brout & Scolnic, 2020)
- Chemical composition of progenitor systems
- Different scenarios of Type Ia SNe explosions (SD, DD)
- Evolution of the mass of white dwarfs with Hubble time (e.g. Bogomazov & Tutukov, 2011)
- Observational selection effects (e.g. Malmquist bias)

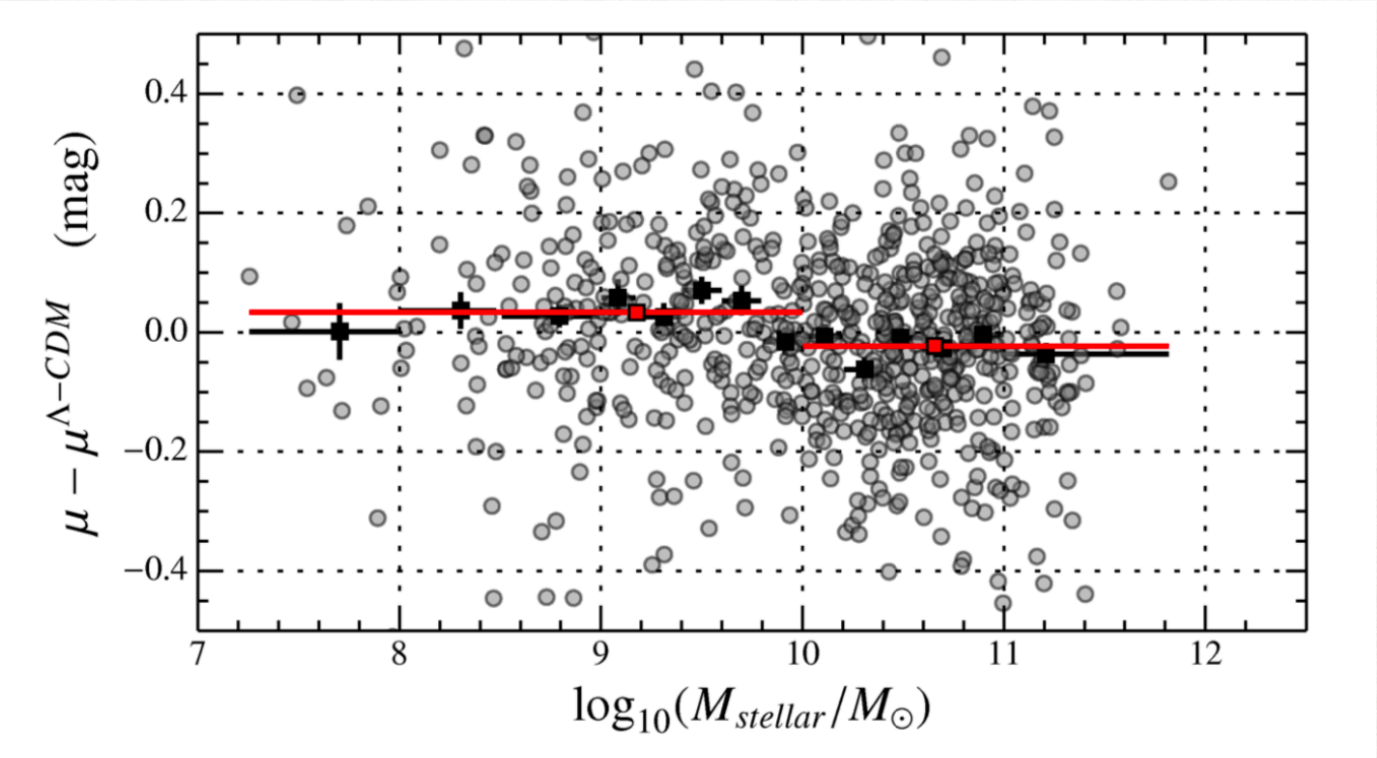
ENVIRONMENTAL DEPENDENCIES

- host galaxy morphology and stellar population age (Hamuy et al., 1995,1996,2000; Riess et al., 1999; Sullivan, 2003; Hicken et al., 2009; Pruzhinskaya et al., 2011; Hill et al., 2016; Henne et al., 2017)
- galocentric distance (Sullivan et al., 2003; Hill et al., 2016)
- SFR (Sullivan et al., 2006; Neill et al., 2009; Lampeitl et al., 2010; Sullivan et al., 2010; Smith et al., 2012; Johansson, 2013)
- local SFR and local colour (1-3 kpc; Rigault et al., 2013; Roman et al., 2018)
- stellar mass of host galaxy (Kelly et al., 2010; Sullivan et al., 2010; Johansson 2013; Kim et al., 2019)
- host metallicity (Gallagher et al., 2005,2008; Howell et al., 2009)



Pruzhinskaya & Novinskaya, 2020

ENVIRONMENTAL DEPENDENCIES



Betoule et al., 2014

The environmental correction
is not implemented to the SN Ia standardization equation

MODERN COSMOLOGICAL ANALYSES

LUMINOSITY DISTANCE-REDSHIFT RELATION

$$\mu = m_B - (M_B - \alpha x_1 + \beta c)$$

$$\mu^{th} = 5\lg d_L - 5$$

$$d_L(z) = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_k(1+z')^2 + \Omega_{DE}(1+z')^{3(1+w)}}}$$

- Flat ΛCDM model ($w = -1$, $\Omega_k = 0$)
- Non-flat oCDM model ($w = -1$, Ω_k varies)
- Flat wCDM model (w_0 varies, $w_a = 0$, $\Omega_k = 0$)
- Flat $w_0 w_a$CDM model (w_0 and w_a both vary, $\Omega_k = 0$)

$$p = w\rho$$

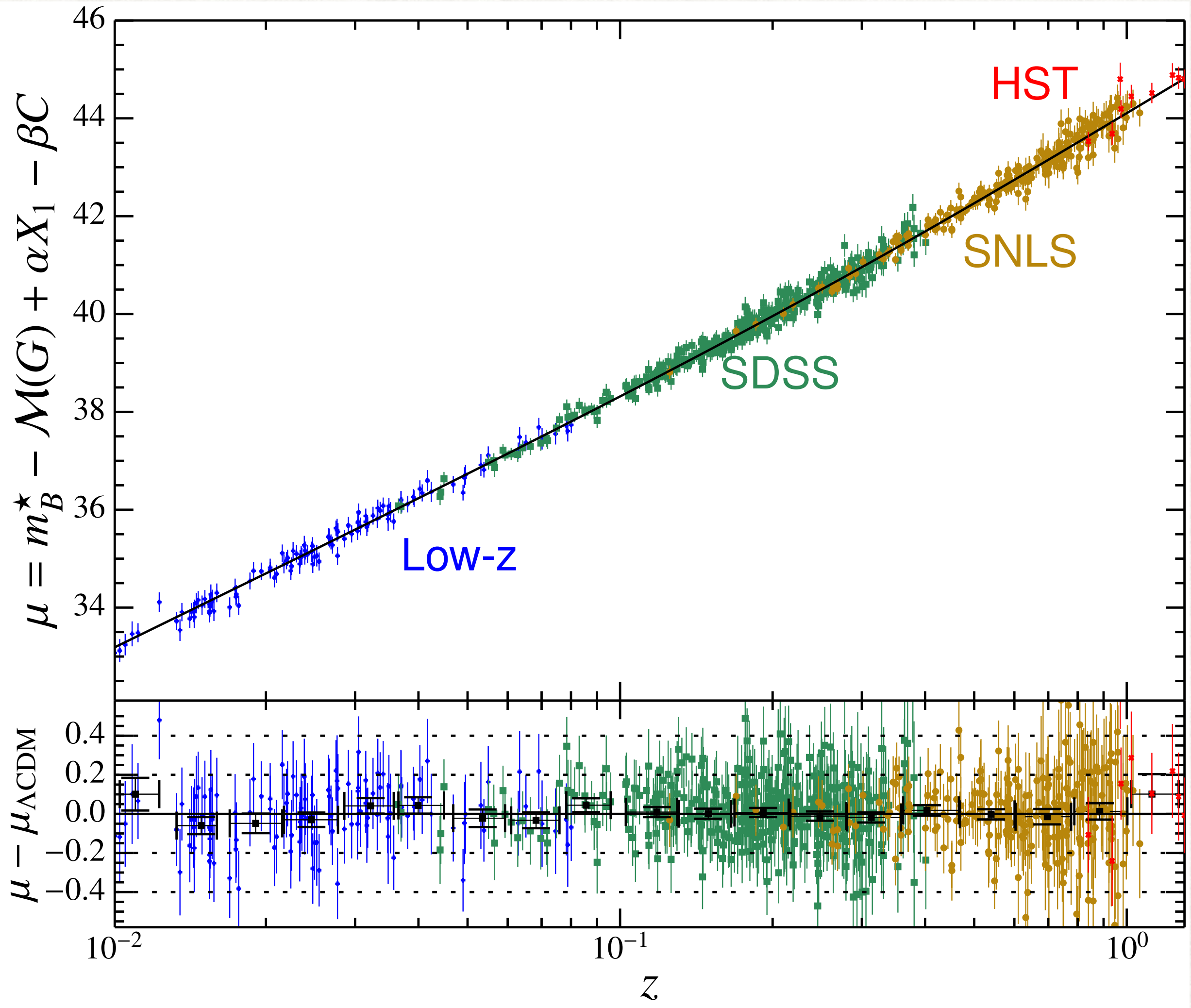
$$w(a) = w_0 + w_a(1-a),$$
$$a = 1/(1+z)$$

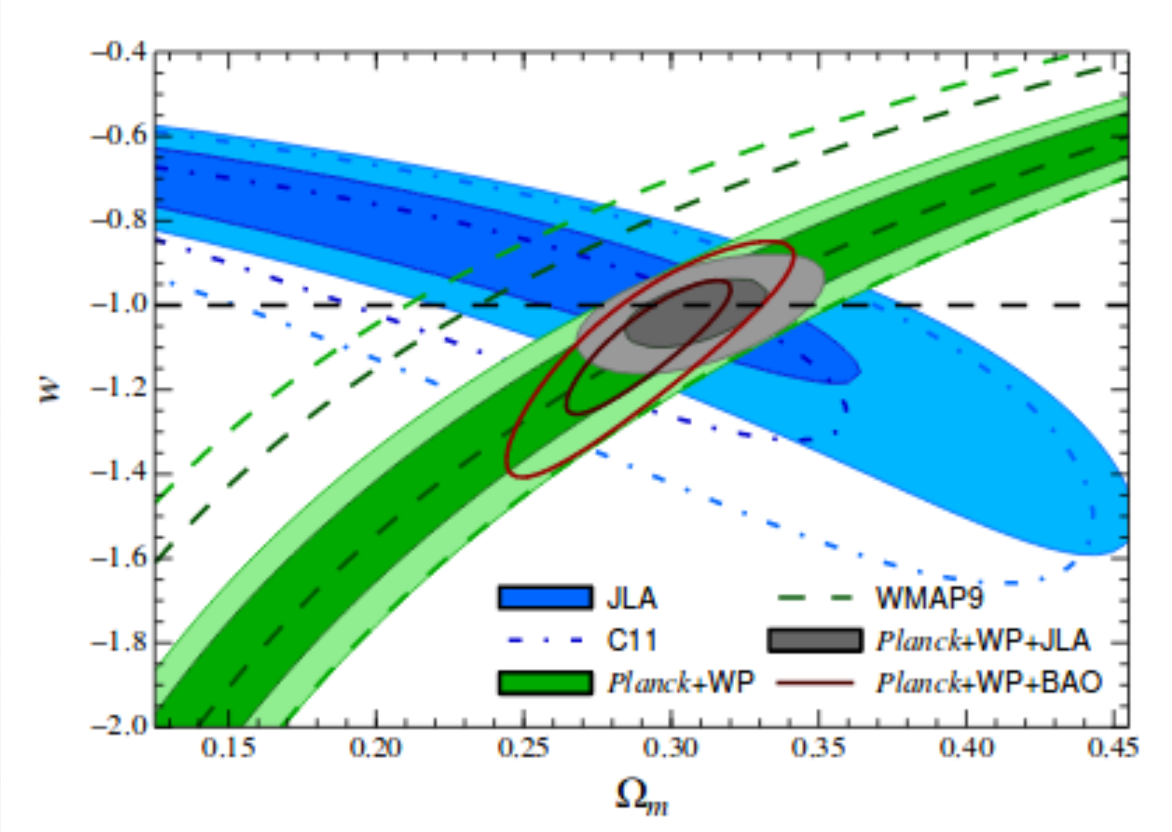
MODERN COSMOLOGICAL ANALYSES

Joint Light Curve Analysis (JLA, Betoule et al., 2014)

740 spectroscopically confirmed SNe Ia:

- Low-z ($z < 0.1$)
- SDSS ($0.05 < z < 0.4$)
- SNLS ($0.2 < z < 1$)
- HST ($0.7 < z < 1.4$)





For the flat ΛCDM cosmology

$\Omega_\Lambda = 0.705 \pm 0.034$

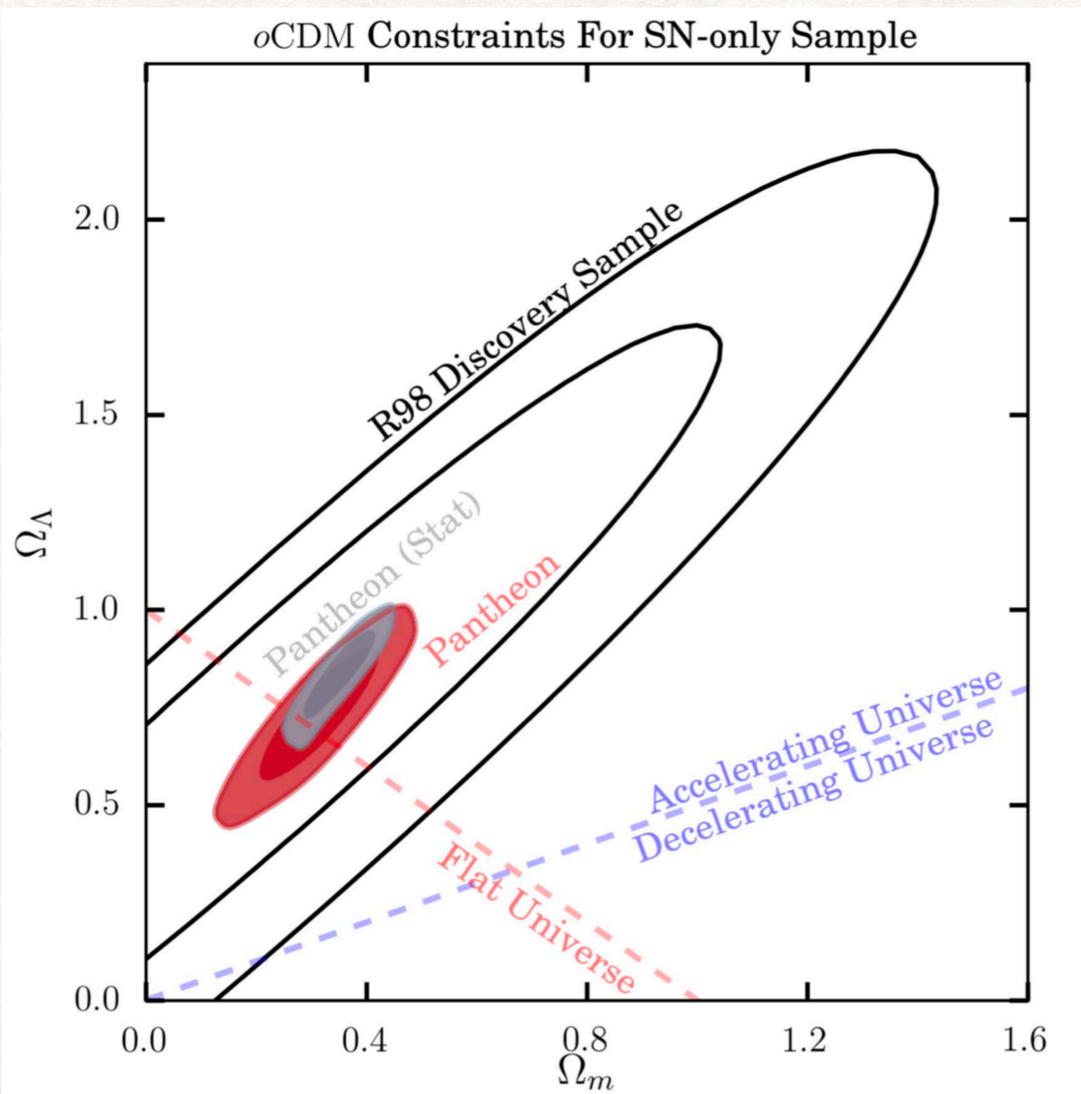
(Betoule et al., 2014)

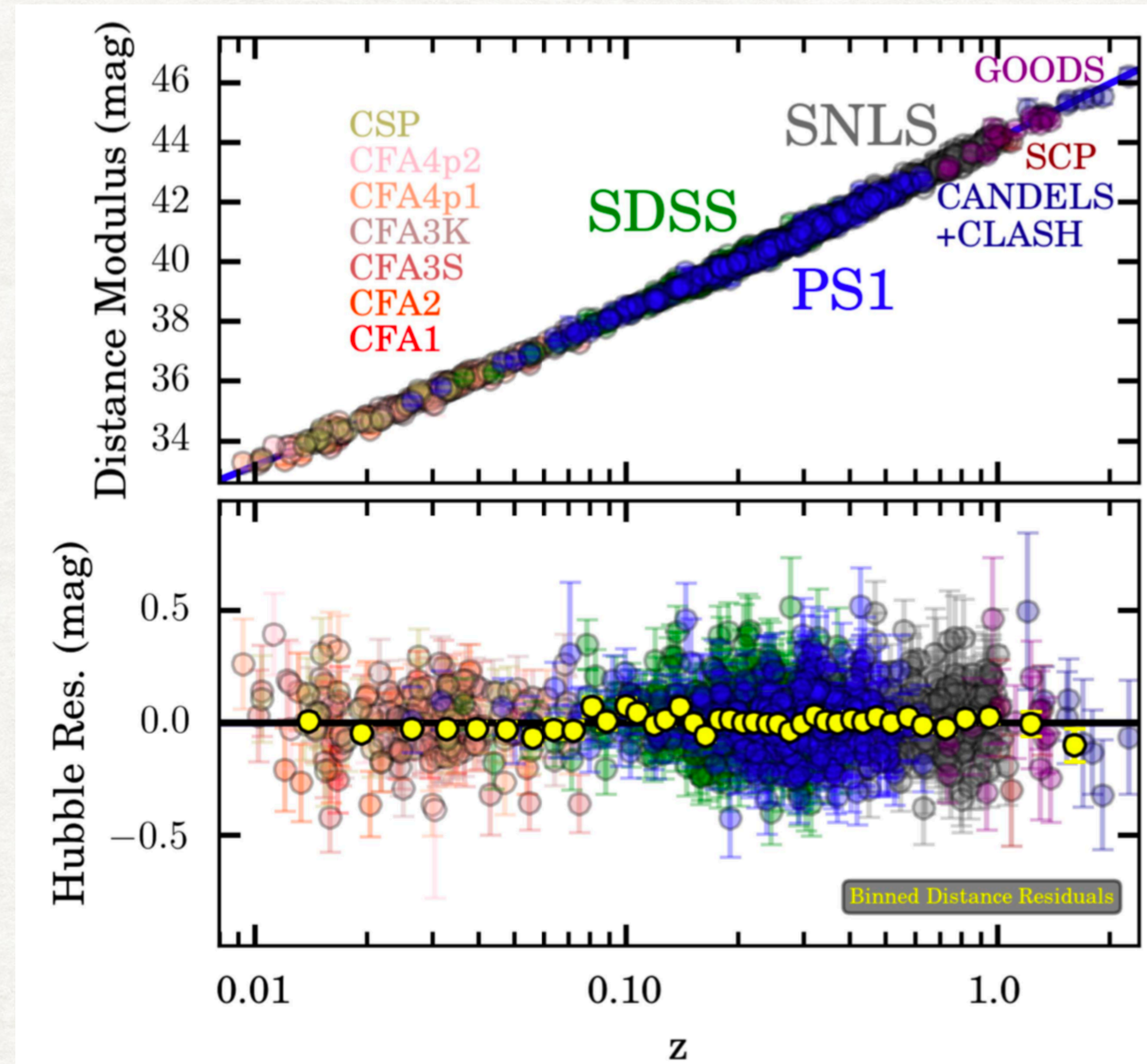
MODERN COSMOLOGICAL ANALYSES

Pantheon sample (Scolnic et al., 2018)

1048 spectroscopically confirmed SNe Ia:

- Low-z, SDSS, SNLS, HST
- +279 Pan-STARRS1 ($0.03 < z < 0.68$)





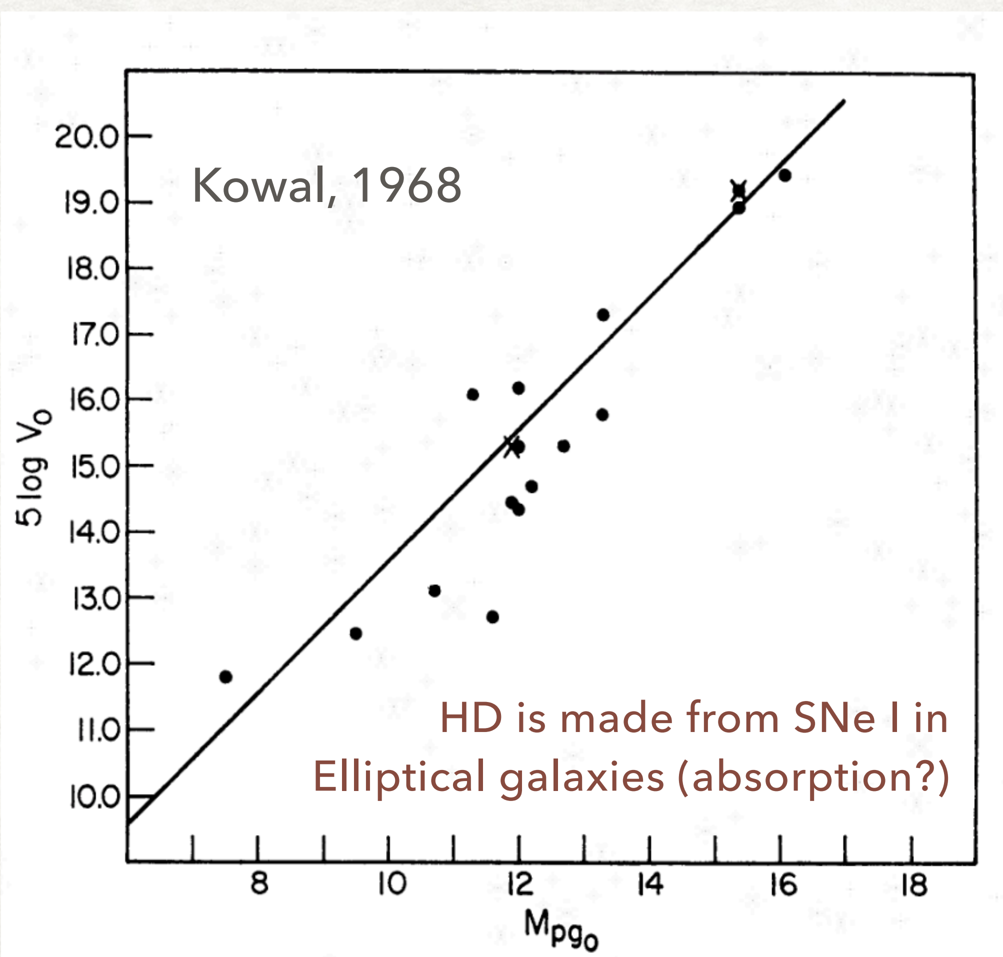
For the flat ΛCDM cosmology
$\Omega_\Lambda = 0.702 \pm 0.022$
(Scolnic et al., 2018)

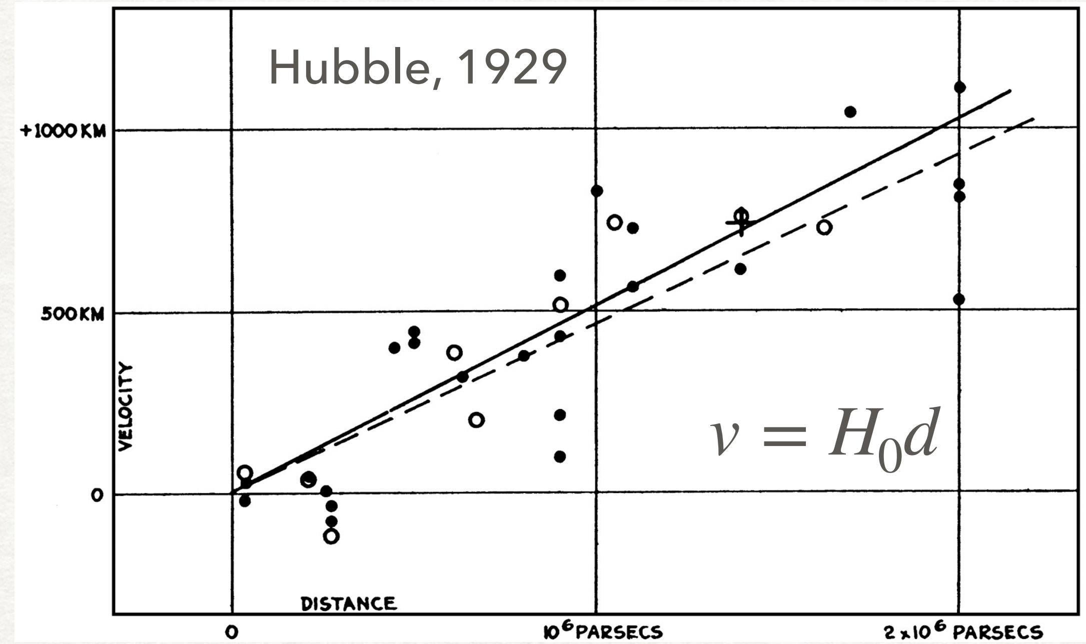
H0 TENSION

- **H0 = 627 km s^{-1} Mpc^{-1}** (Lemaître, 1927; 1931)
- **H0 = 461 km s^{-1} Mpc^{-1}** (Robertson, 1928)
- **H0 = 500 km s^{-1} Mpc^{-1}** (Hubble, 1929)

«If true, – will enable us to establish a relative, as well as absolute, cosmic distance scale which is more reliable than any of the scales currently in use»

– Zwicky 1961





Before 1992 *(see Branch & Tammann, 1992)*

Table 5. Summary of SN Ia absolute magnitude calibrations

Method	M_B^{oo}	Weight
Historical Galactic supernovae	-19.7 ± 0.6	1
SNe Ia in nearby galaxies	-19.8 ± 0.3	1
SNe Ia in the Virgo Cluster	-19.6 ± 0.4	2
Thermal emission	-20.1 ± 0.7	0
Nickel–Cobalt Radioactivity	-19.4 ± 0.4	2
Adopted:	-19.6 ± 0.2	

After 1992

– Cepheids based calibration (P–L relation)

The method became available with commissioning of the HST

H0 TENSION

SH0ES: SNe, H0, for the Equation of State of dark energy

Riess et al., 2005:

$$H0 = 73 \pm 6.4 \frac{\mathrm{km/s}}{\mathrm{Mpc}} (8\%)$$

Riess et al., 2009:

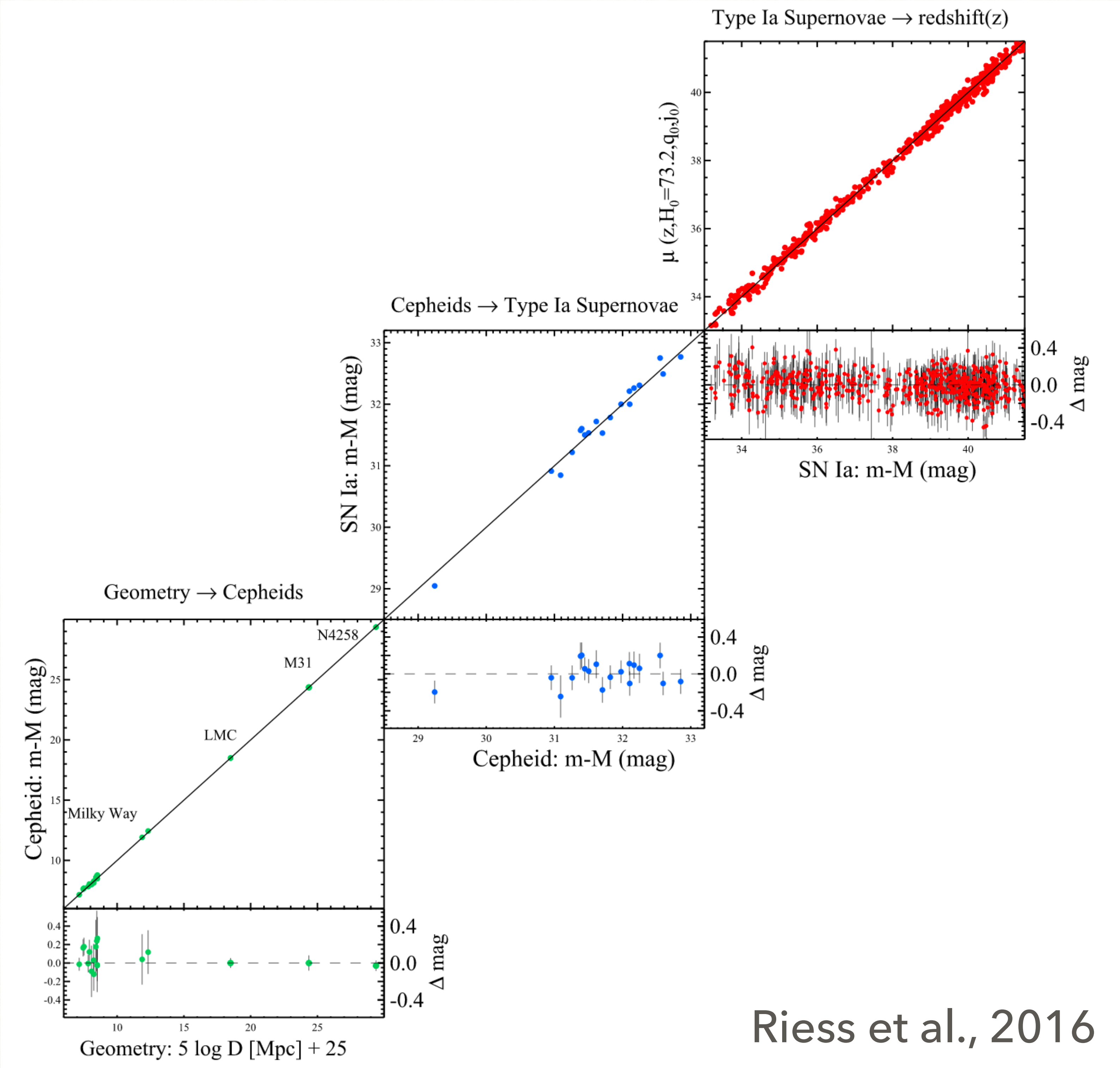
$$H0 = 74.2 \pm 3.6 \frac{\mathrm{km/s}}{\mathrm{Mpc}} (4.8\%)$$

Riess et al., 2011:

$$H0 = 73.8 \pm 2.4 \frac{\mathrm{km/s}}{\mathrm{Mpc}} (3.3\%)$$

Riess et al., 2016:

$$H0 = 73.24 \pm 1.74 \frac{\mathrm{km/s}}{\mathrm{Mpc}} (2.4\%)$$



Riess et al., 2016

H0 TENSION

Riess et al., 2019:

- ☑ HST 70 new cepheids in LMC
- ☑ new 1.2% geometric distance to the LMC measured by Pietrzynski et al., 2019
- ☑ **H0 = 74.03 ± 1.42 km s^{-1} Mpc^{-1}** (1.9%)

It is $6.6\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ larger and 4.4σ discrepant with the value of

H0 = 67.4 ± 0.5 km s^{-1} Mpc^{-1}

(Planck Collaboration et al., 2018)

It represents a 10% difference between the two distance scales

- ☐ SN systematics: for their presence in nearby ($z \leq 0.01$), late-type, globally star forming, non-edge on hosts which would thus be expected to yield a good sample of Cepheids
- ☐ 50% of HD SN sample from star-forming environment
- ☐ Environmental parameter that appears to correlate with SN distance residuals → no influence (?) → use same environment

Correcting for this bias **Rigault et al., 2015 (SNfactory)** found

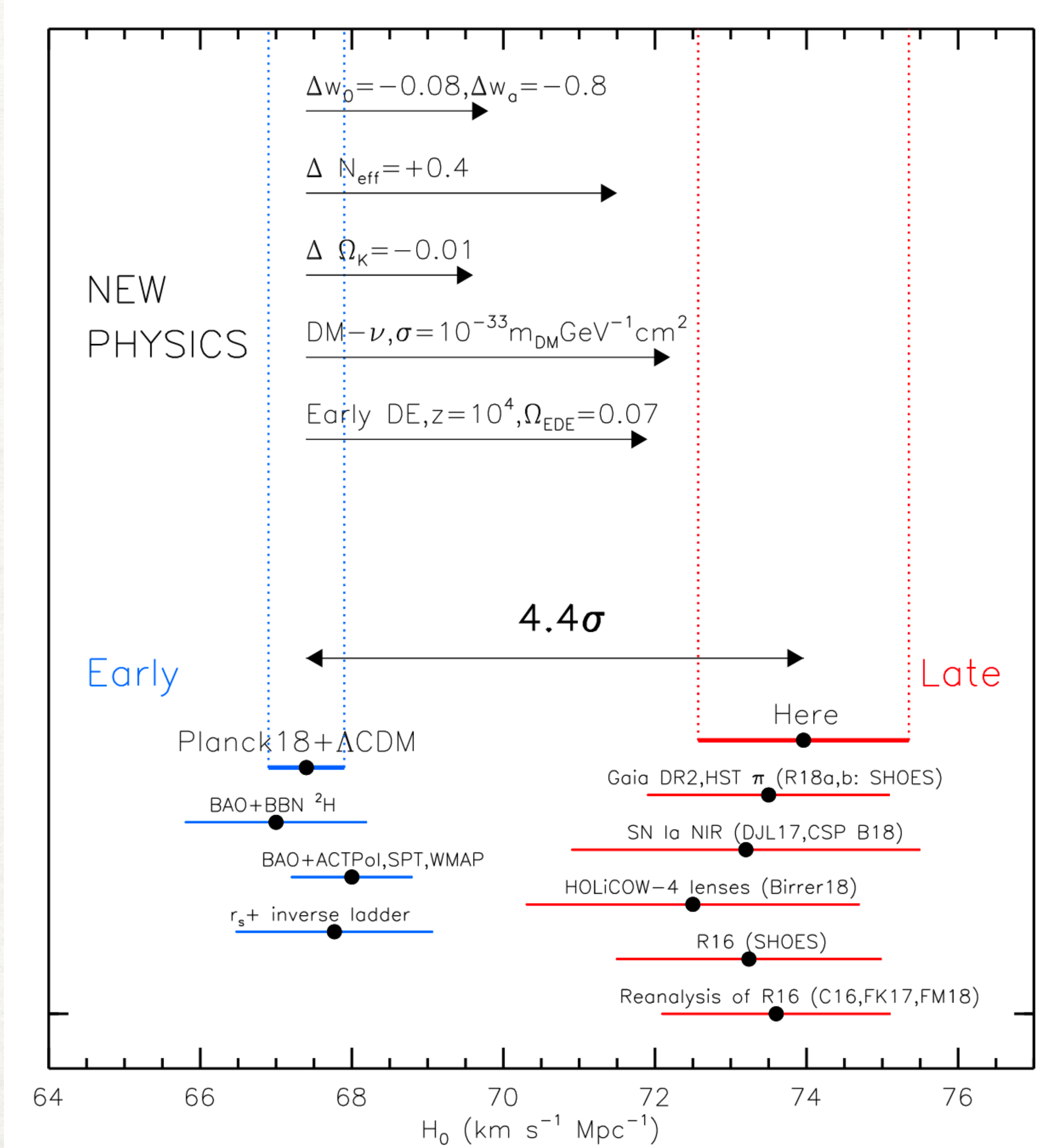
H0 = 70.6±2.6 km s^{-1} Mpc^{-1} when using the LMC distance, Milky Way parallaxes and the NGC 4258 megamaser as the Cepheid zeropoint,

H0 = 68.8±3.3 km s^{-1} Mpc^{-1} when only using NGC 4258. This correction brings the direct measurement of H0 within $\sim 1\sigma$ of measurements based on the CMB power spectrum.

H0 TENSION

Riess et al., 2019:

- ✦ **New physics** – as Riess suggested; could include evolution of the dark energy equation of state, or an increase in the energy density of radiation in the early universe.
- ✦ **Local bubble** – an effect of this kind is too small to explain the magnitude of observed tension (Wu & Huterer, 2017; Lombriser 2020)
- ✦ Effect of **weak lensing** on the SNe Ia measurements (increases with redshift)



H0 TENSION

Freedman et al., 2019:

- Use calibration of the Tip of the Red Giant Branch
- Cepheid independent
- HD 100 well-observed SNe Ia (Carnegie Supernova Project)
- **H0 = 69.8 ± 0.8 (stat) ± 1.7 (sys) km s⁻¹ Mpc⁻¹**

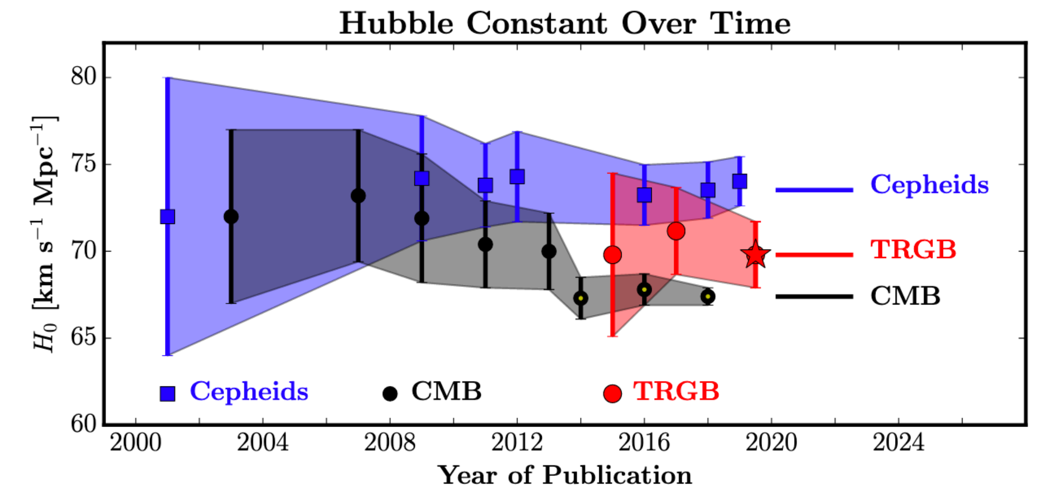
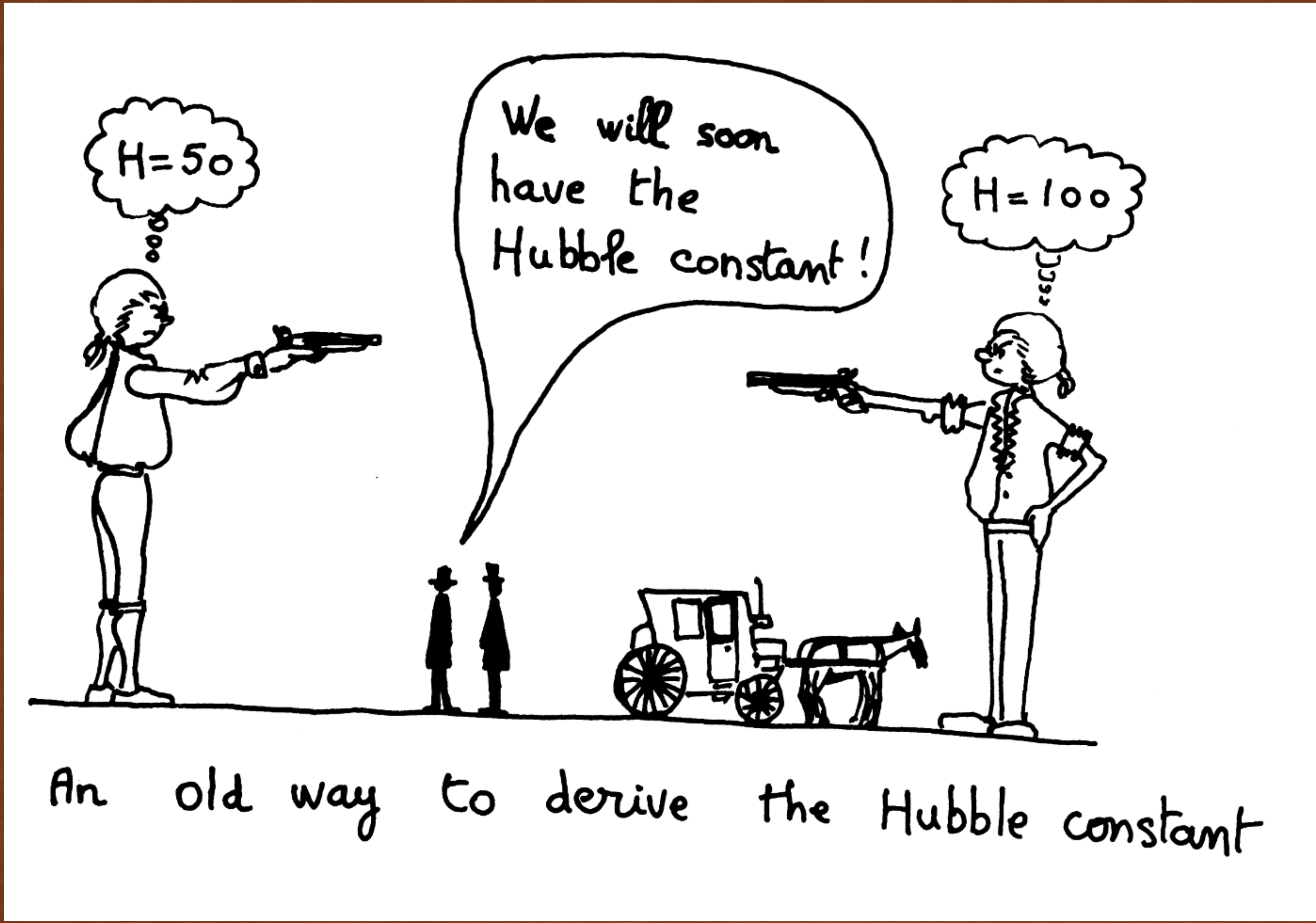


Figure 17. A plot of H_0 values as a function of time. The points and shaded region in black are those determined from measurements of the CMB; those in blue are Cepheid calibrations of the local value of H_0; and the red points are TRGB calibrations. The red star is the best-fit value obtained in this paper. Error bars are 1σ.

It agrees at the 1.2σ level with that of the Planck Collaboration et al. (2018) estimate, and at the 1.7σ level with the HST SH0ES measurement of H0 based on the Cepheid distance scale

«Recent measurements of the local expansion rate have been made based on a number of alternative methods including strong gravitational lensing (Suyu et al., 2017; Birrer et al., 2018), the Tully-Fisher relation using the TRGB (Mould & Sakai, 2008) or Cepheids (Sorce et al., 2013), the optical counterpart to GW170817 (Abbott et al., 2017), in addition to the Cepheid calibration of SNe Ia (Riess et al., 2011; Freedman et al., 2012; Riess et al., 2016; Burns et al., 2018). All of these studies find H0 values in the range of 70–74 km s^{-1} Mpc^{-1}, with individual uncertainties quoted in the 3–10% (2–7 km s^{-1} Mpc^{-1}) range. **None of them meaningfully overlap the Planck result**, **none of them fall on the low side of the Planck result**, as would be expected if they were randomly sampled measurements and the Planck H0 value were the 'true' H0 value» – Freedman et al., 2019.

G. Paturel in **1983:**

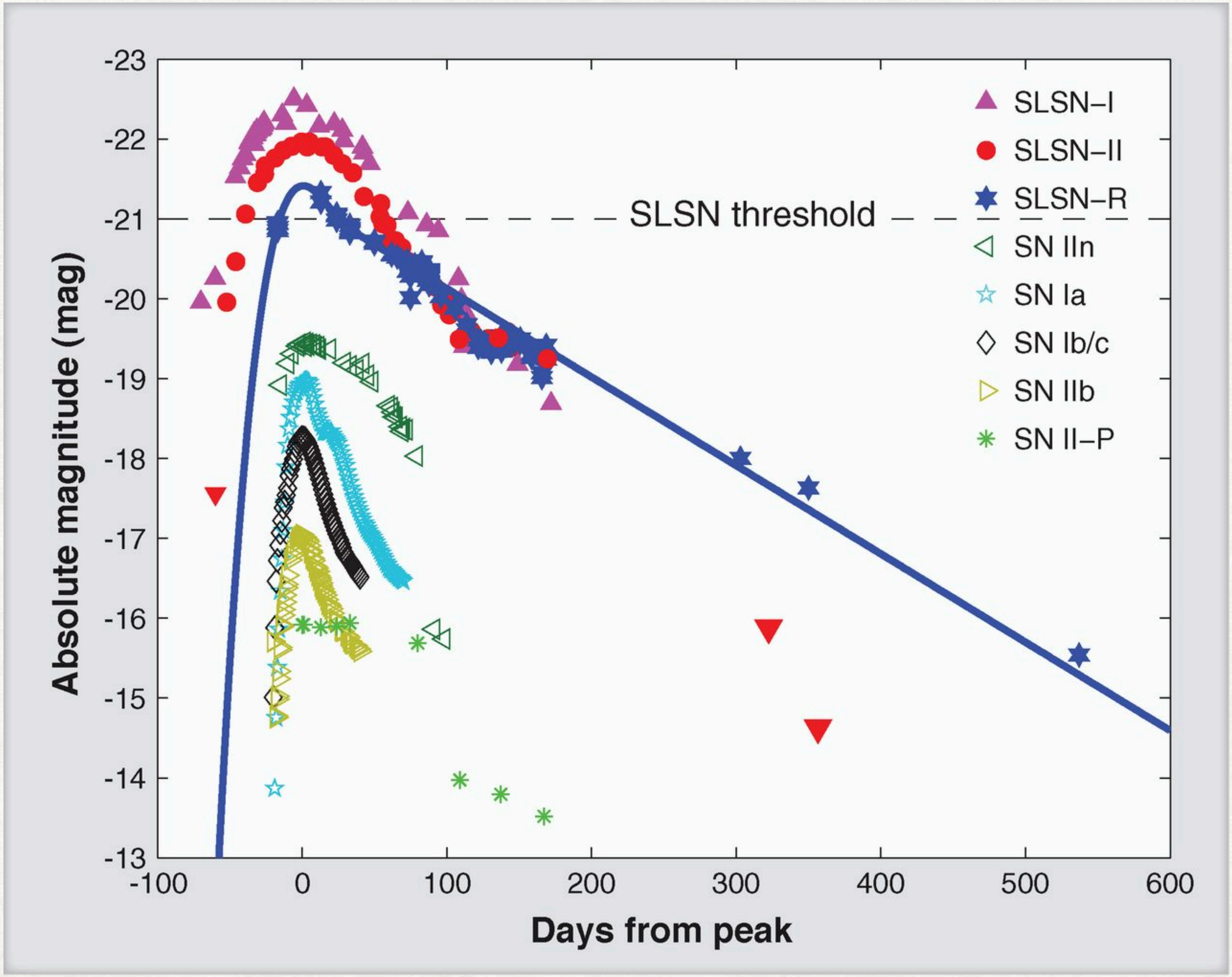


A. Sandage in **1993:**
Fig.8.2. A not really so old way to H, devised by Paturel (1983).

We in **2020:**
Really, not …

SUPER-LUMINOUS SUPERNOVAE

SUPER-LUMINOUS SUPERNOVAE



Gal-Yam 2012

SUPER-LUMINOUS SUPERNOVAE

- SLSN I

  hydrogen-poor, fast-evolving light curves

- SLSN II

  hydrogen-rich, signs of interaction with CSM

- SLSN R

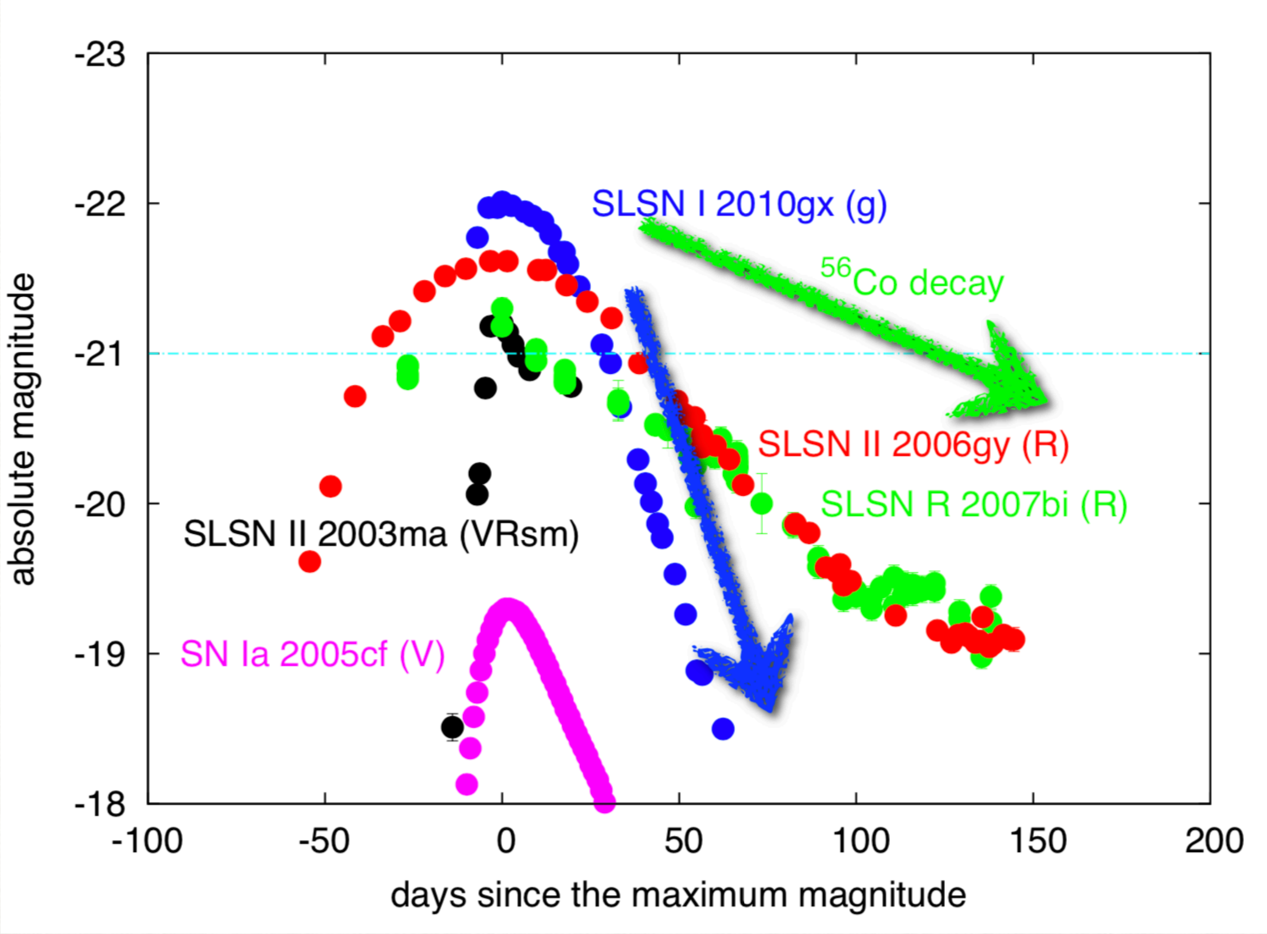
  hydrogen-poor events with slowly-evolving light curves, powered by the radioactive decay of ^{56}Ni

For review see Moriya et al., 2018

SLSN I

- Extreme peak luminosities (brighter than −22 mag absolute)
- Very blue spectra with significant ultra-violet flux persisting for many weeks
- The host galaxies of these events are typically dwarf galaxies
- LC rise times below 50 days and post-peak slopes that decline substantially faster than radioactive cobalt decay rates

Magnetars?



Moriya et al., 2014

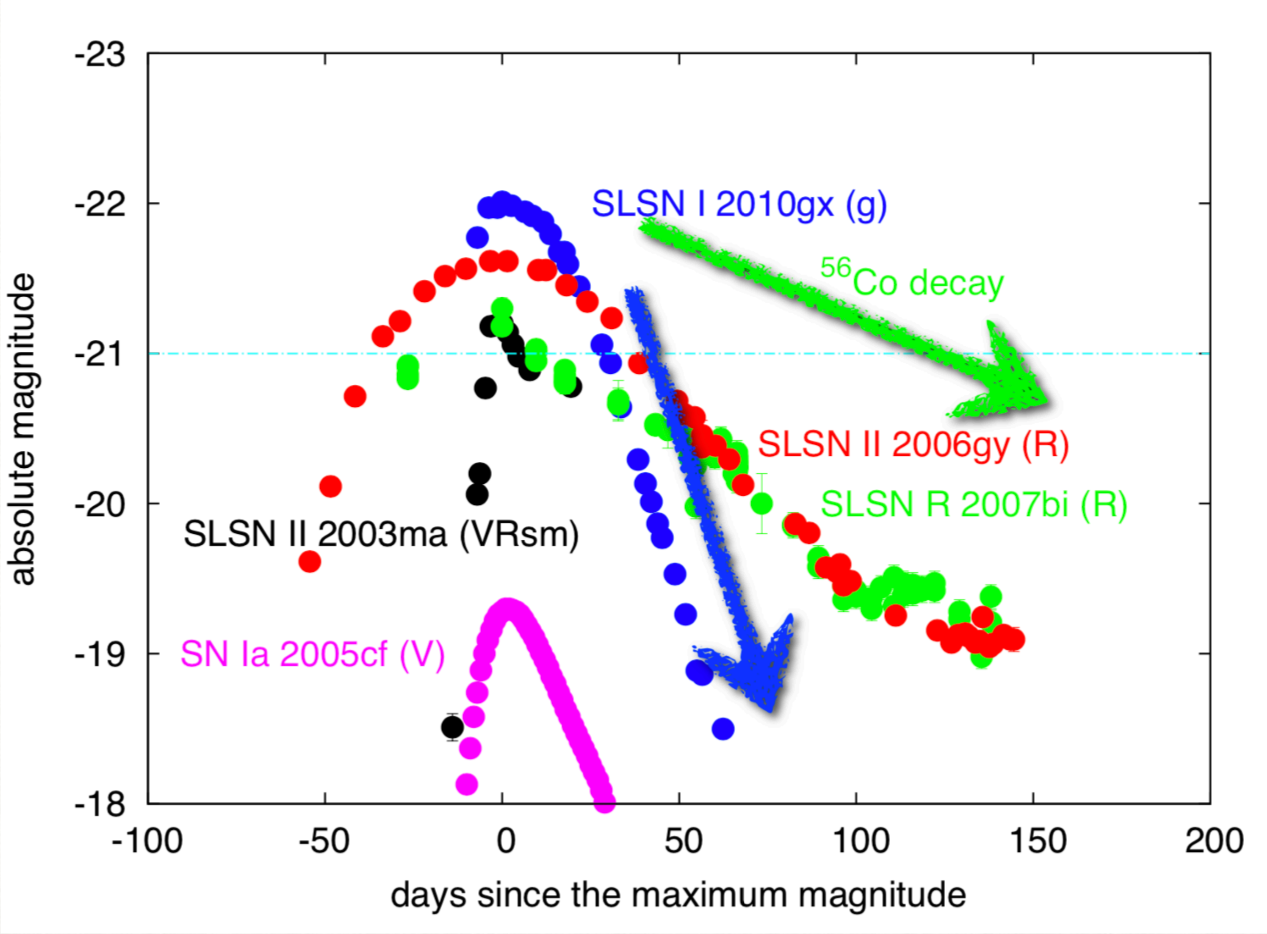
SLSN R

- Objects of this sub-class are exceedingly rare
- Powered by large amounts (~5 M⊙, SN Ia: ~0.6 M⊙) of radioactive ^{56}Ni (suffix «R»), produced during the explosion of a very massive star

Pair-instability SN?

Energetic core-collapse SN?

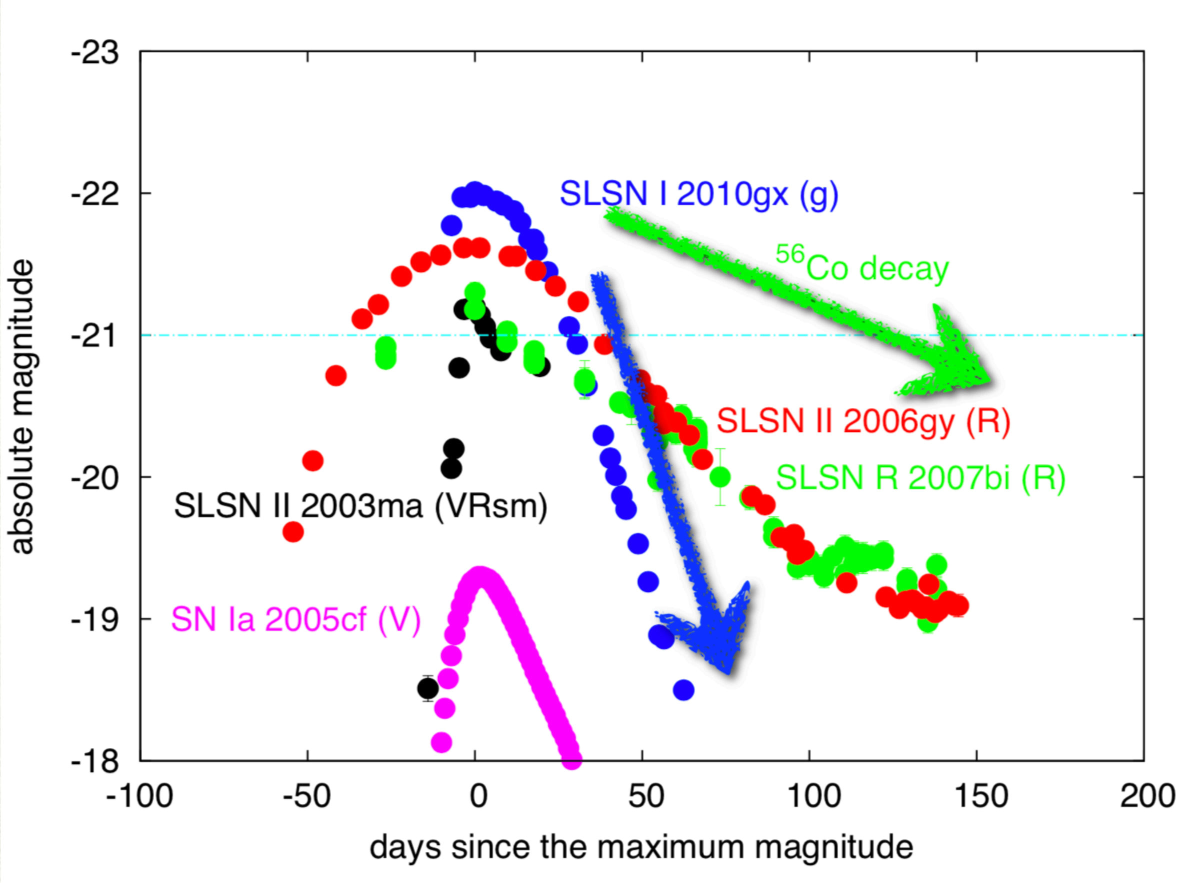
Moriya et al., 2014



SLSN II

- The most commonly observed class of SLSN
- Interaction between SN Ejecta and Dense CSM

LBVs as SN progenitors?



Moriya et al., 2014

A LOT OF PROGRESS IS ACHIEVED IN SUPERNOVA STUDIES BUT THERE IS ALWAYS ROOM FOR IMPROVEMENT