Recent Advances in our Understanding of Type Ia Supernovae

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Carnegie Observatories
Las Campanas Observatory

25 Years of the OGLE Project
July 2017

Photo: Yuri Beletsky

Ignacio Domeyko (1802-1889)

- Polish naturalist and mineralogist who carried out much of his work and research in Chile
- Participated in the unsuccessful Polish uprising against the Russian Empire in 1830, and was forced into exile in France
- Arrived in Chile in 1838 to teach chemistry and mineralogy in La Serena
- Carried out important scientific explorations in both the north and south of Chile, and served as President of the University of Chile from 1867-1883

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Wojtek Krzeminski

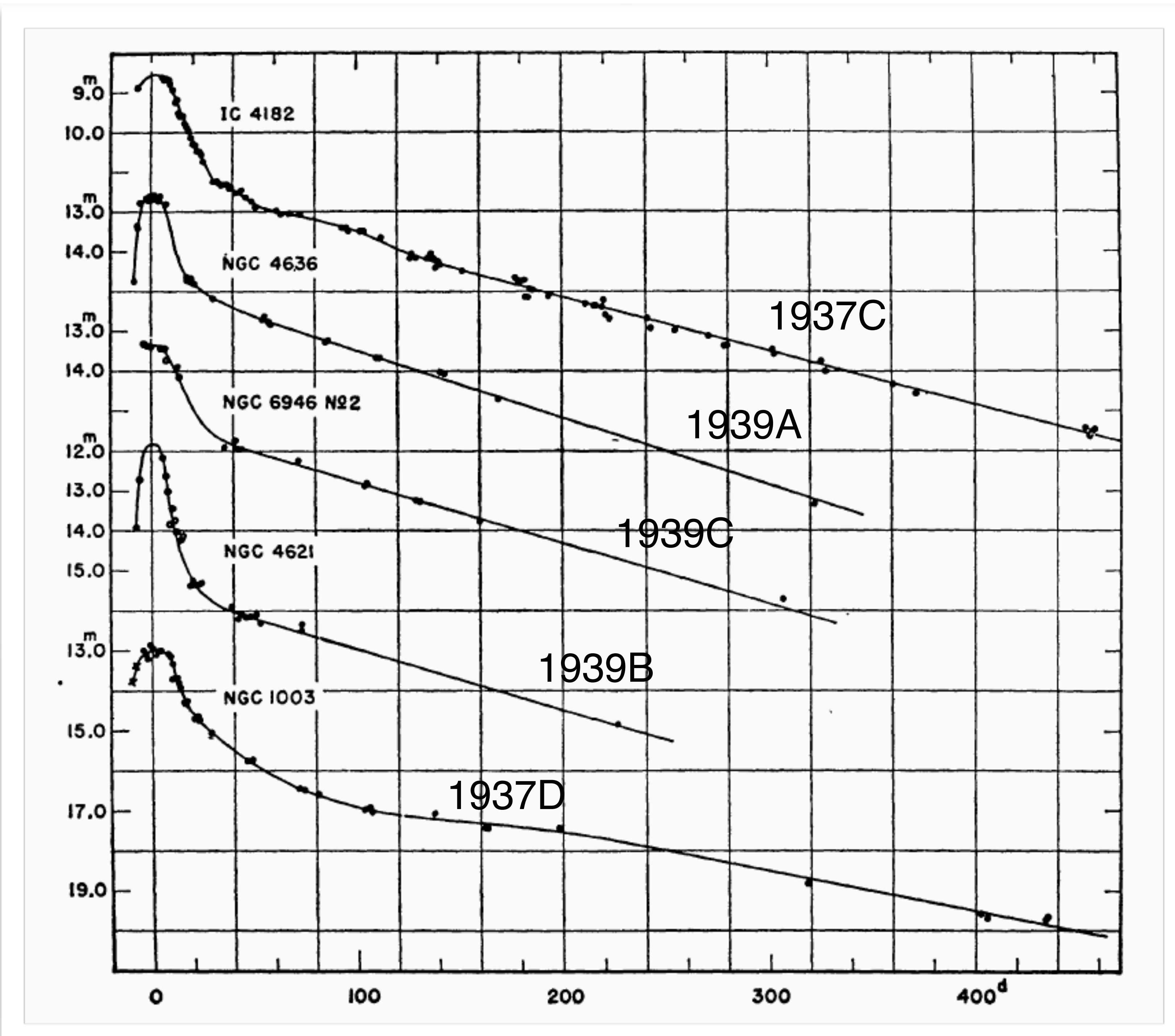
- Arrived at LCO in 1982
- Served initially as Resident Astronomer Administrator of LCO
- Well known for his work on CVs
- An early collaborator in the OGLE project
- Played a key role in establishing the Persson et al. (1998) NIR standards

- Observed > 500 nights on the LCO Swope 1 m telescope for the Carnegie Supernova Project (CSP) team

Outline

- Introduction to Type Ia Supernovae
- Progenitor Scenarios
- Host Dust Reddening

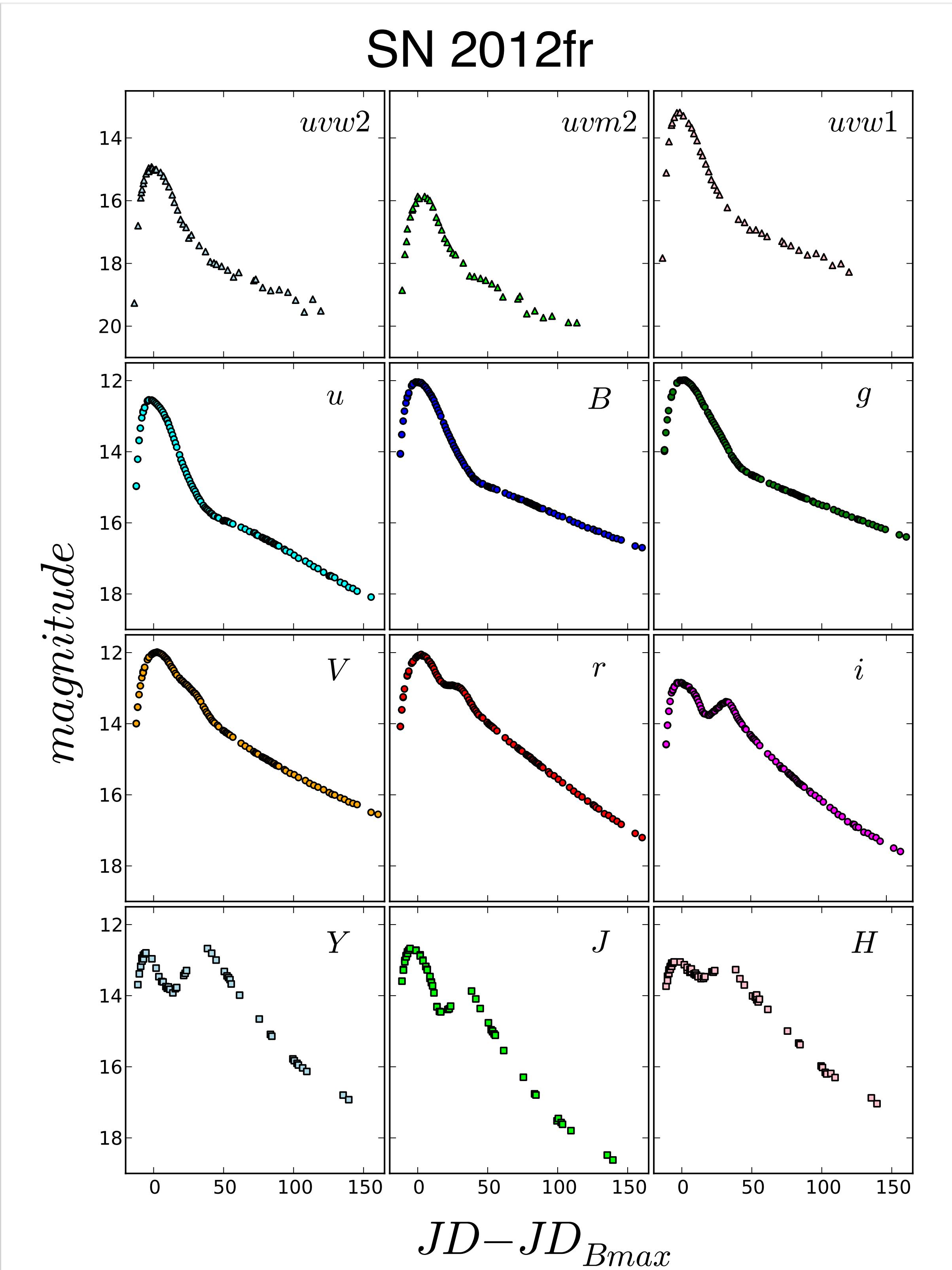
Part 1: Introduction to Type Ia Supernovae



Minkowski (1964)

- Since the pioneering work of Baade & Zwicky in the 1930s, the light curves of SN Ia have been known to be remarkably homogenous
- In 1938, Baade found that the absolute peak magnitudes of Type I SNe displayed a dispersion of ≤ 1 mag
- In 1960, Hoyle & Fowler concluded that SNe Ia were the observational signature of the thermonuclear disruption of a white dwarf in a binary system

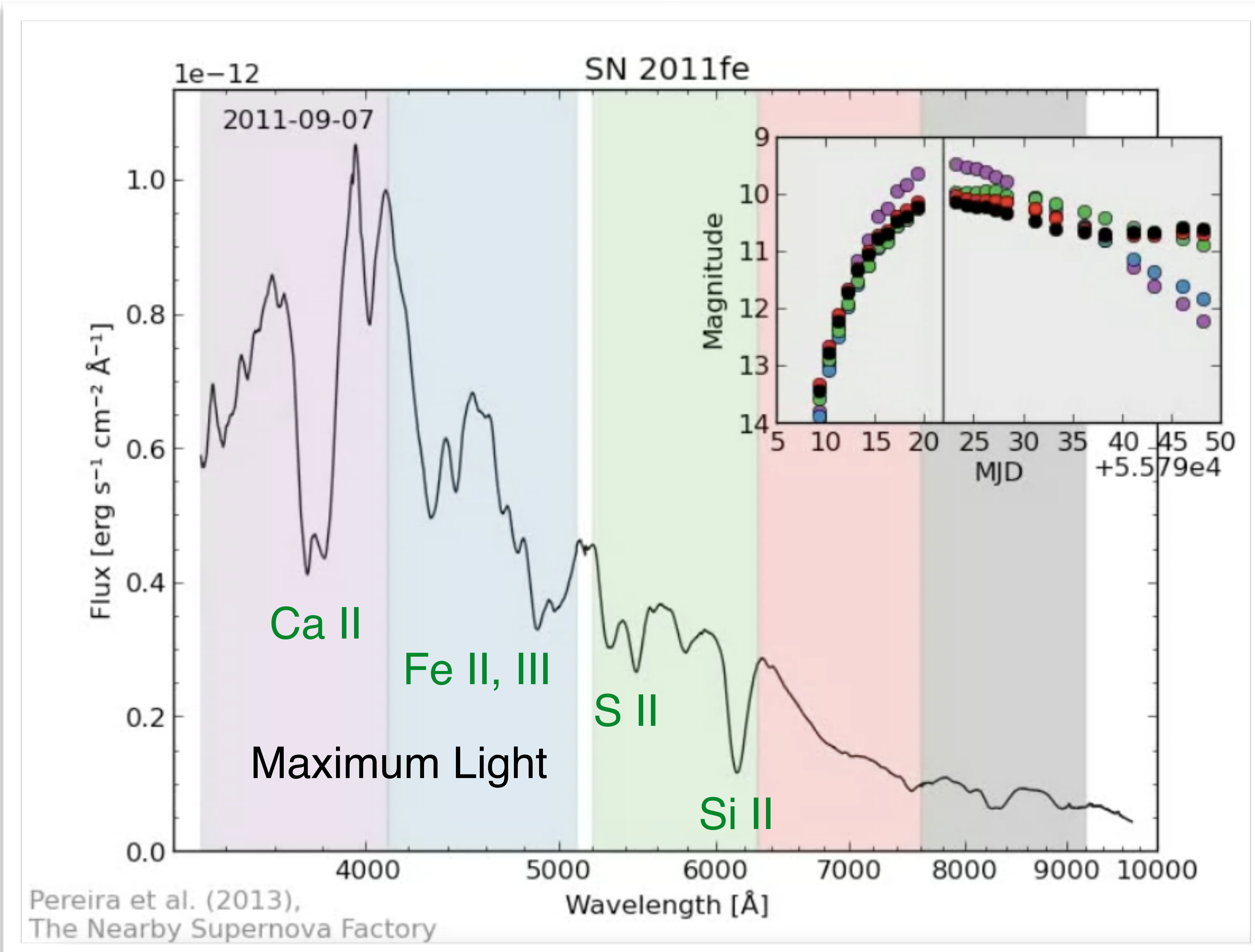
SN Ia UV/Optical/Near-IR Light Curves



- The luminosity of the SN is powered by the radioactive decay of ^{56}Ni produced in the explosion
- $^{56}\mathrm{Ni} \underset{6.1\ \mathrm{days}}{\Rightarrow} {}^{56}\mathrm{Co} \underset{77.2\ \mathrm{days}}{\Rightarrow} {}^{56}\mathrm{Fe}$
- The secondary maximum observed in the V to near-IR filters is related to the recombination of Fe III to Fe II in the inner ejecta

Contreras et al. (2017, in prep)

SN Ia Optical Spectral Evolution



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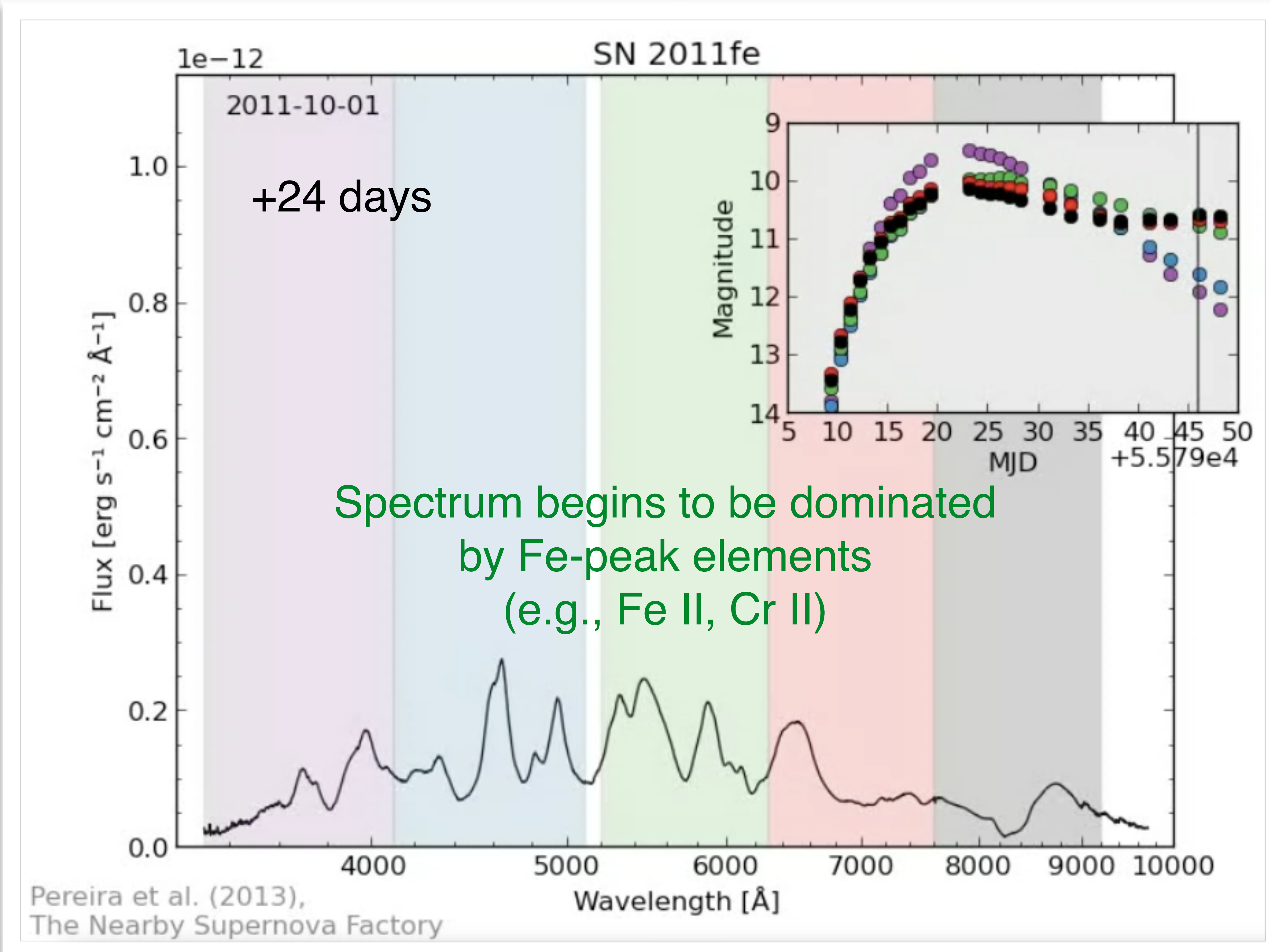
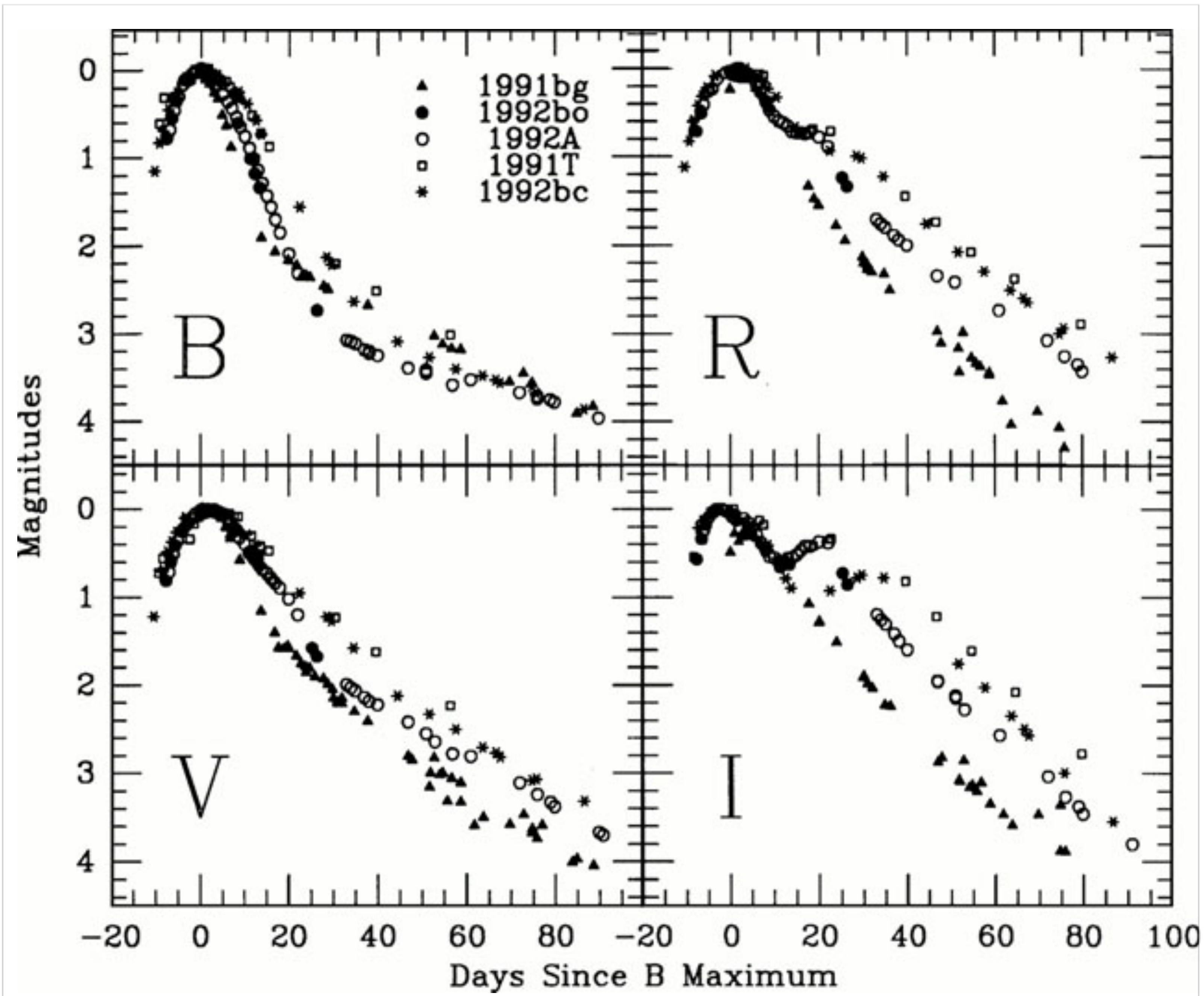


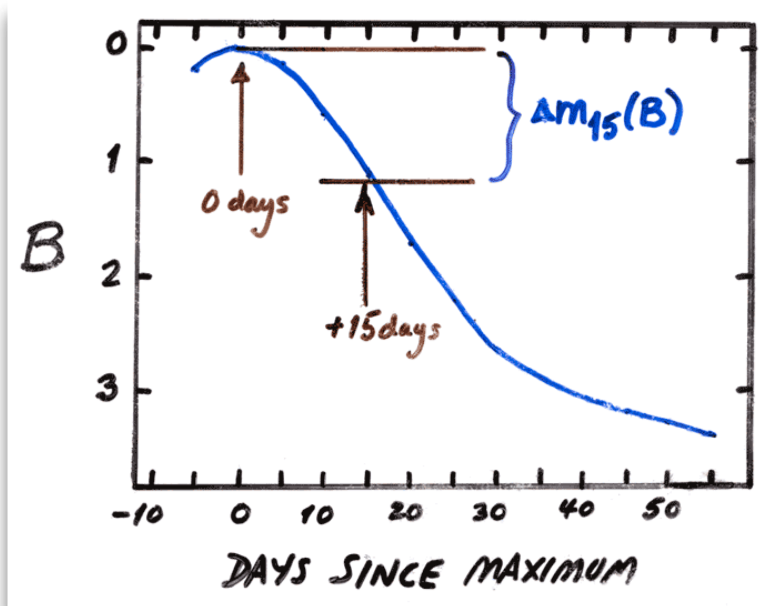
SN Ia Optical Light Curves: Early Indications of Inhomogeneity

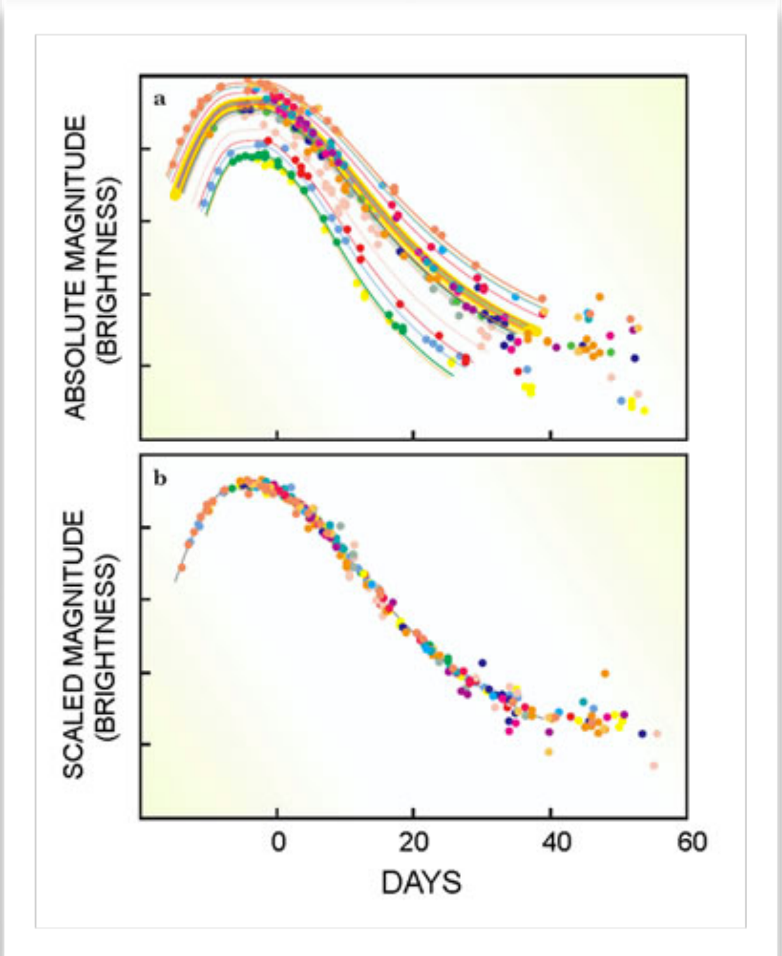


- CCD photometry in the late-1980's and early-1990's demonstrated that the *B* light curves of SNe Ia displayed a range of decline rates
- The timing and strength of the pronounced secondary maximum in the IYJHK bands was also correlated with the decline rate of the B light curve

Suntzeff (1996)

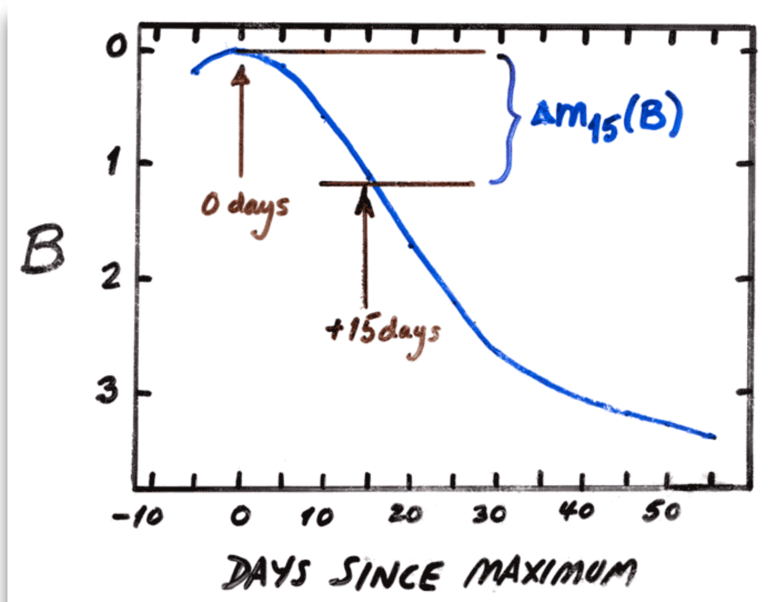
Measuring the Decline Rate

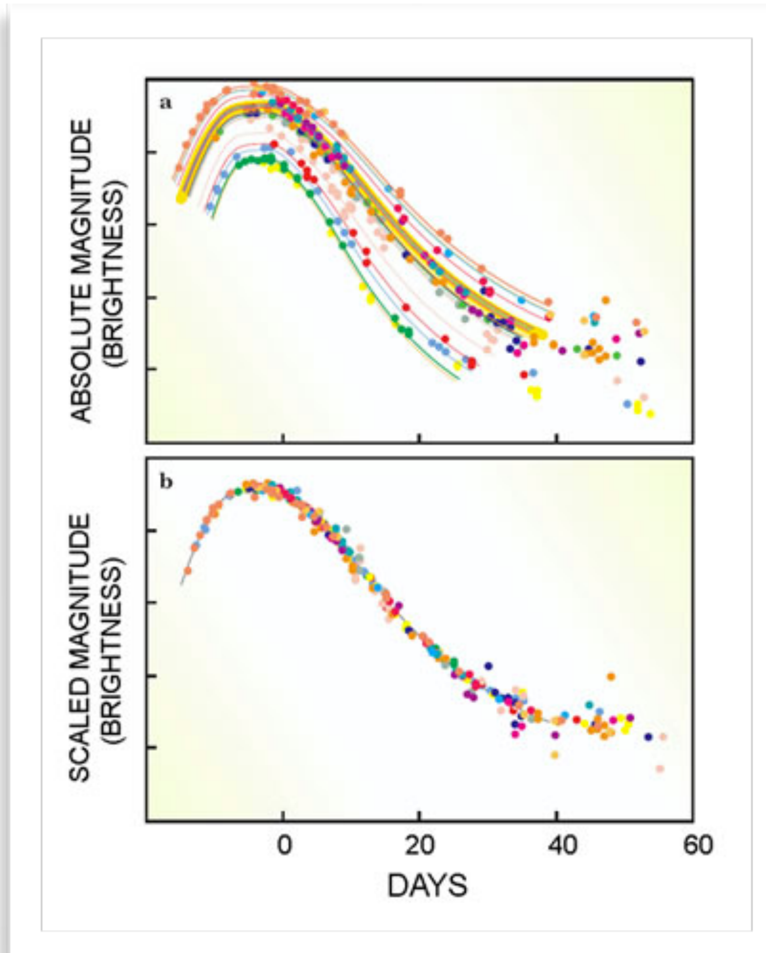


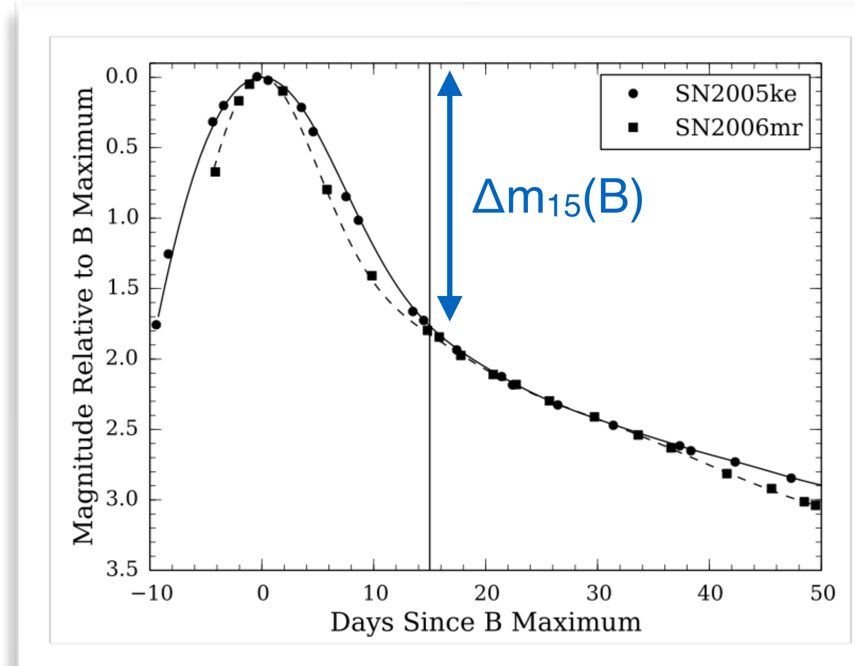


- Two of the most common methods for measuring decline rate are $\Delta m_{15}(B)$ and stretch (s)

Measuring the Decline Rate

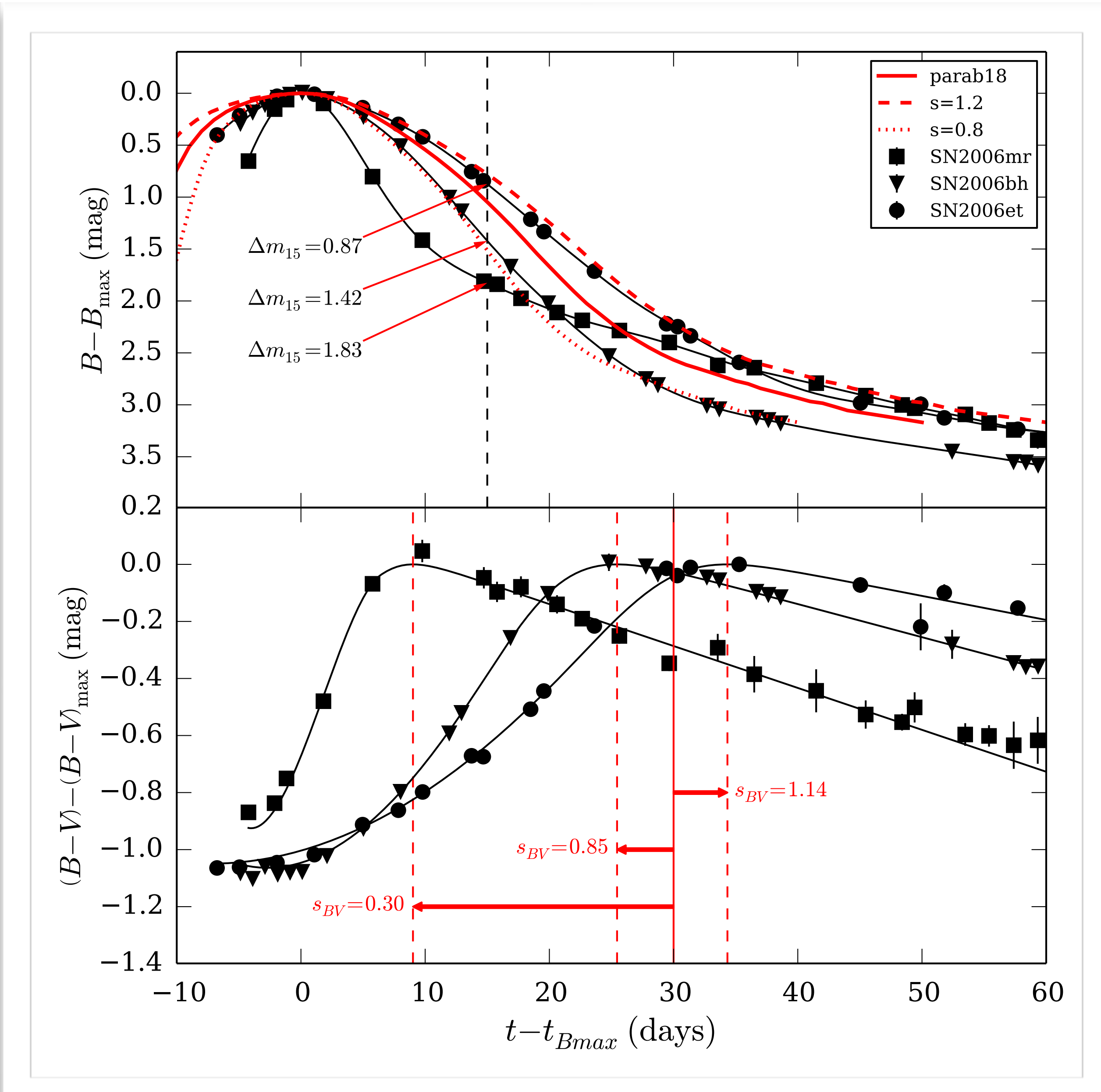


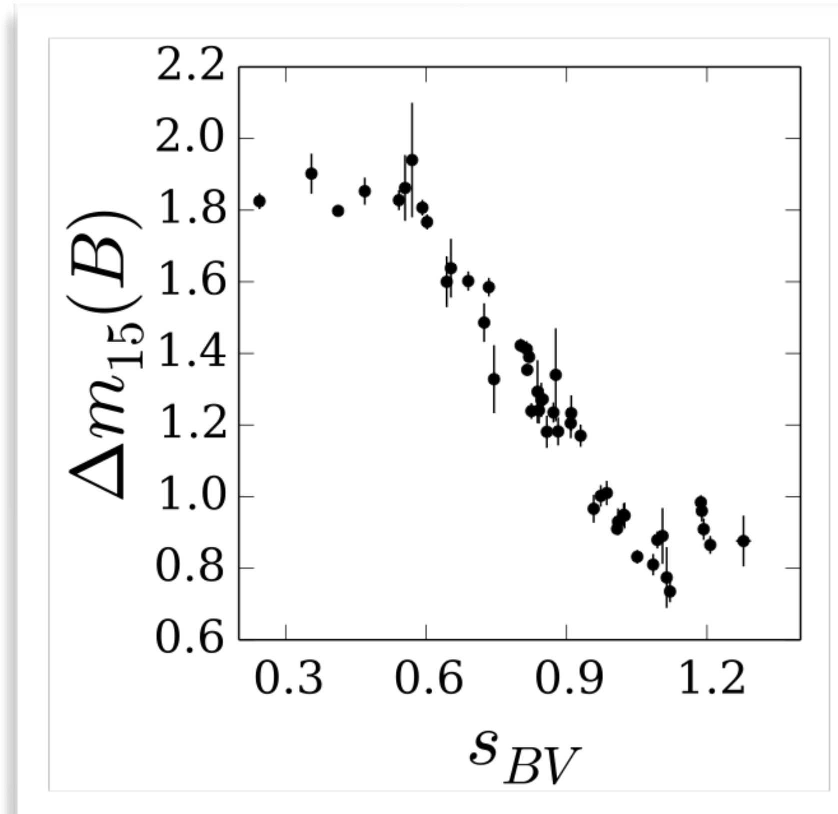




- Two of the most common methods for measuring decline rate are $\Delta m_{15}(B)$ and stretch (s)
- However, at the fastest decline rates, *both* methods break down as a measure of the light curve width

s_{BV}: A Better Way to Measure Light Decline Rate



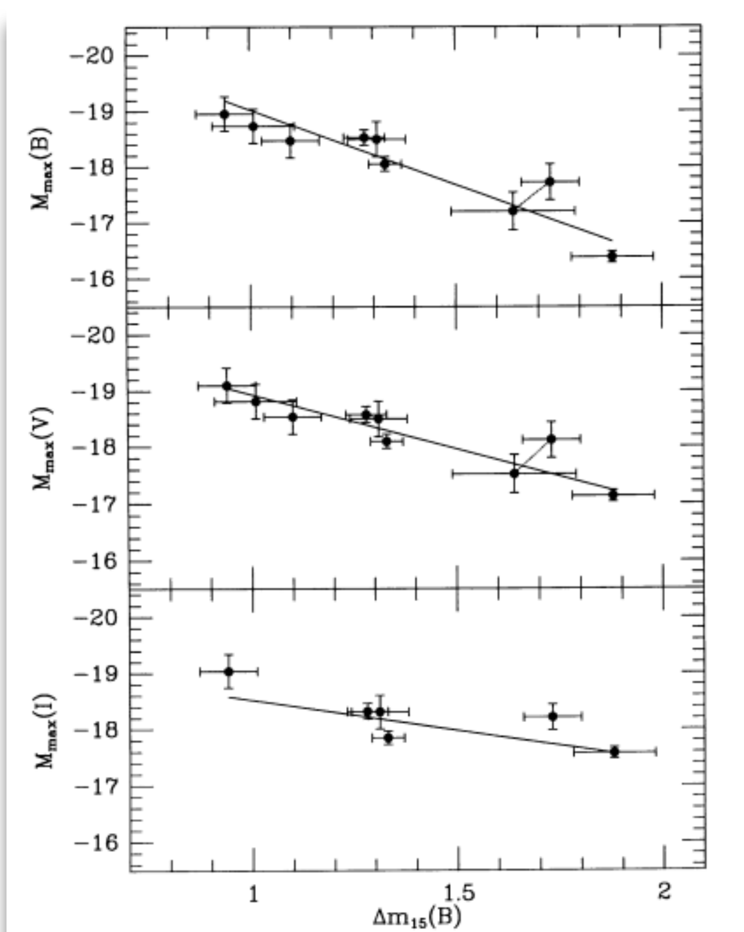


- At the fastest decline rates, *$\Delta m_{15}(B)$* breaks down as a measure of the light curve width

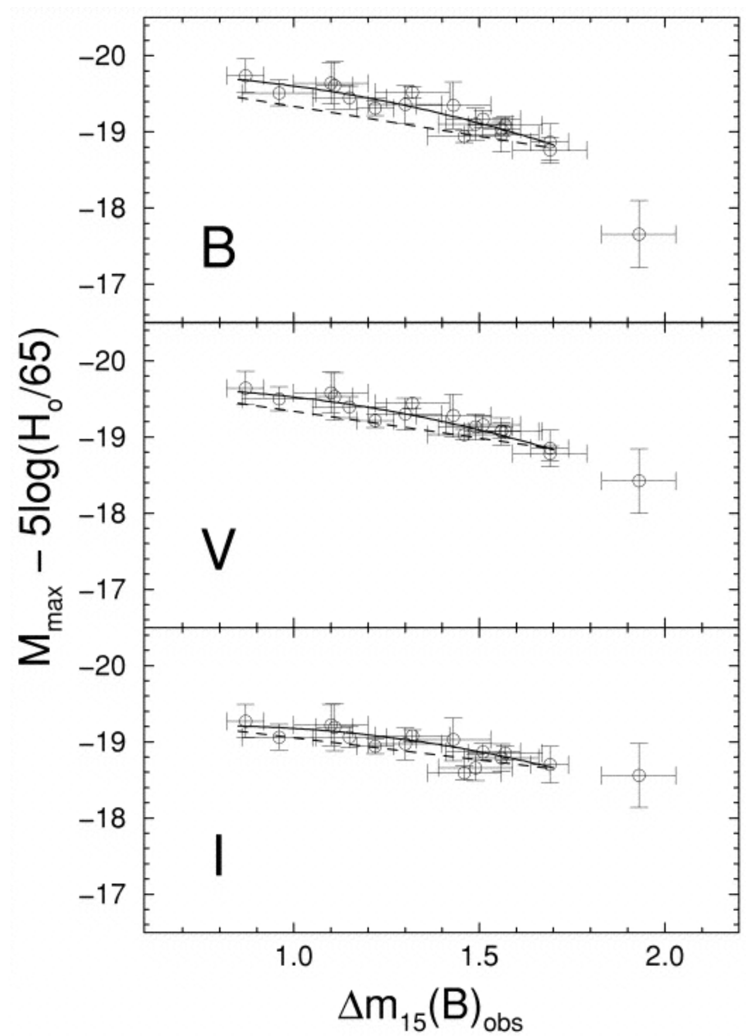
- Burns et al. (2014) defined a dimensionless stretch-like parameter *$s_{BV} = t(B-V)_{max} / 30days$*, which they called a “color-stretch” which is more effective at the fastest decline rates

The Luminosity-Decline Rate Relation

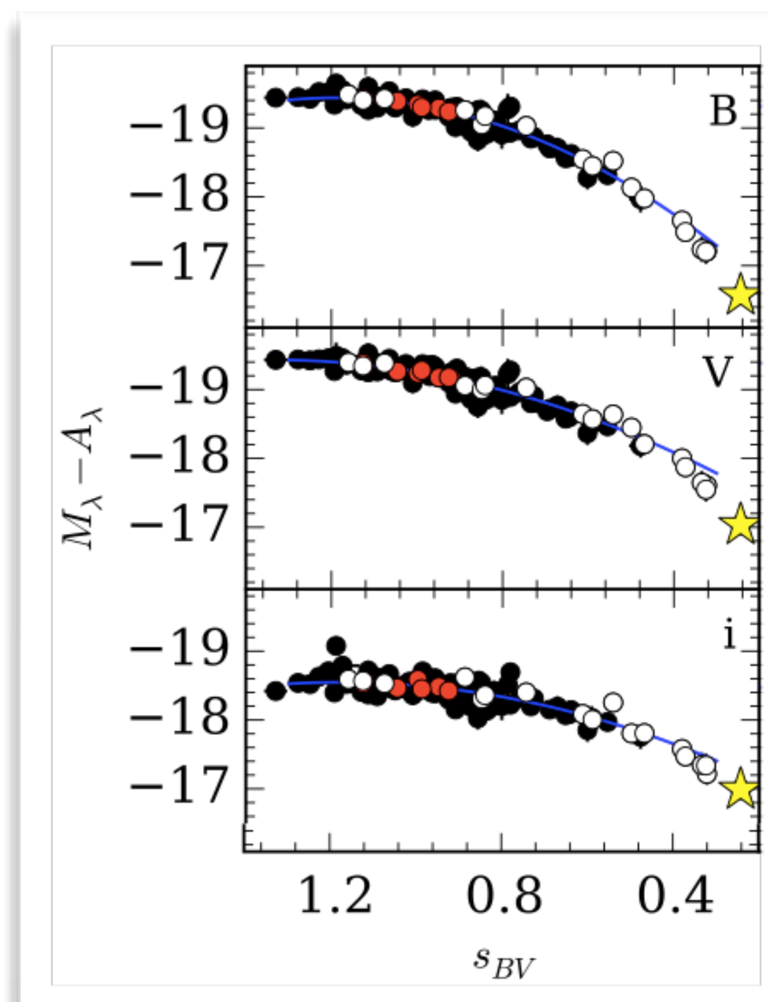
- In a series of papers, Pskovskii (1967, 1977, 1984) argued that SN Ia display a continuous range of decline rates which correlated with several different parameters, including absolute magnitude
- The luminosity-decline rate relation was confirmed in 1993, and is a fundamental characteristic of “normal” SNe Ia



Phillips (1993)



Phillips et al. (1999)



Burns et al. (2016, in prep)

A Selection of SNe Ia Hubble Diagrams Since 1968

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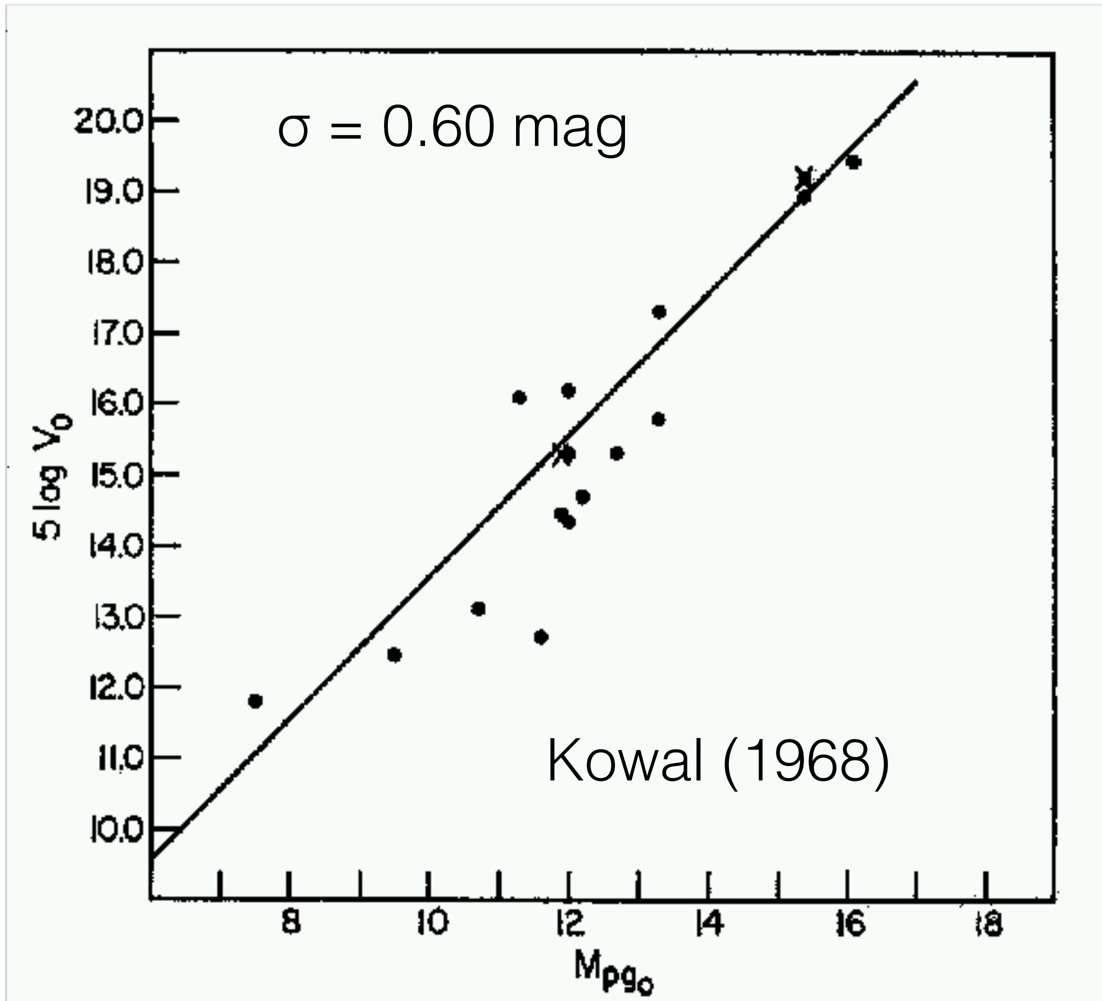

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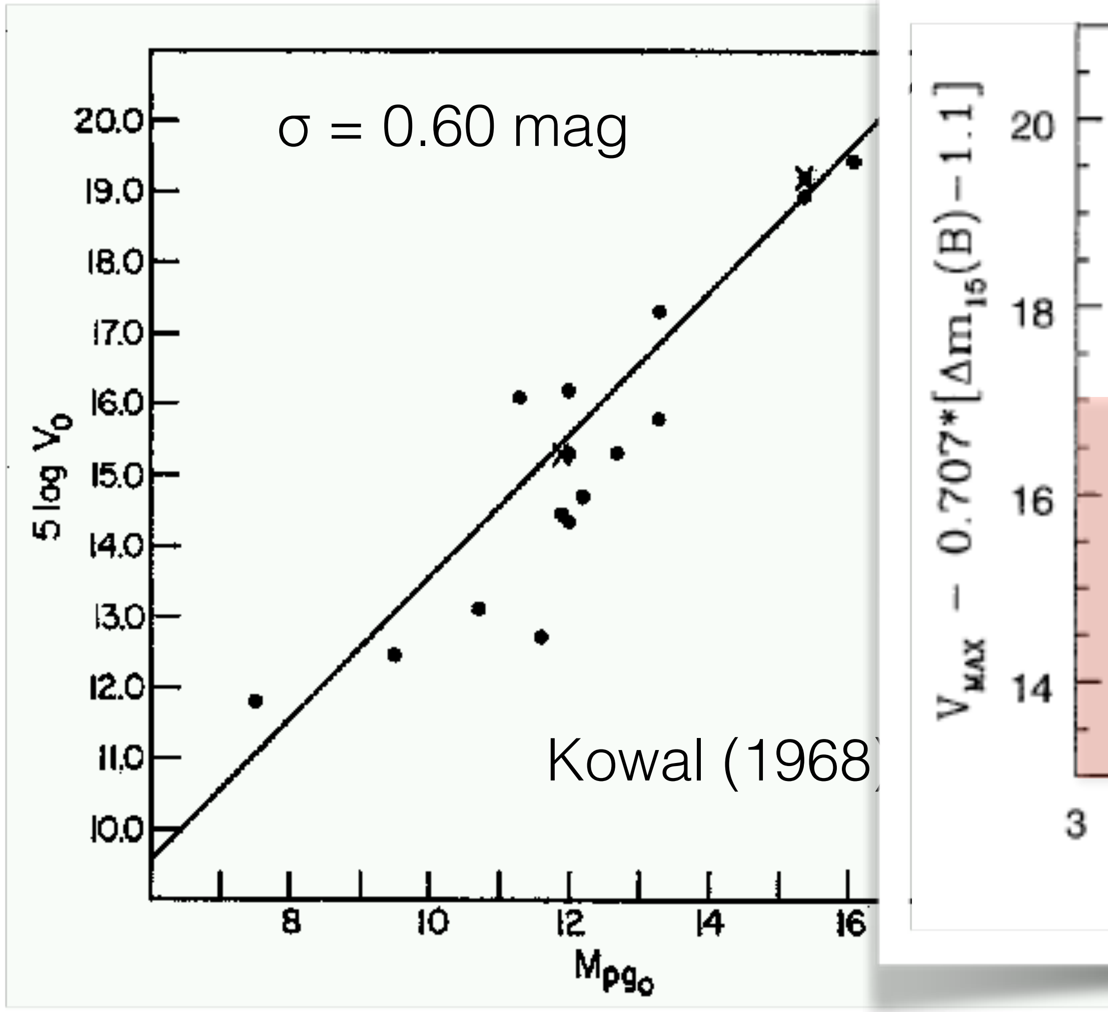

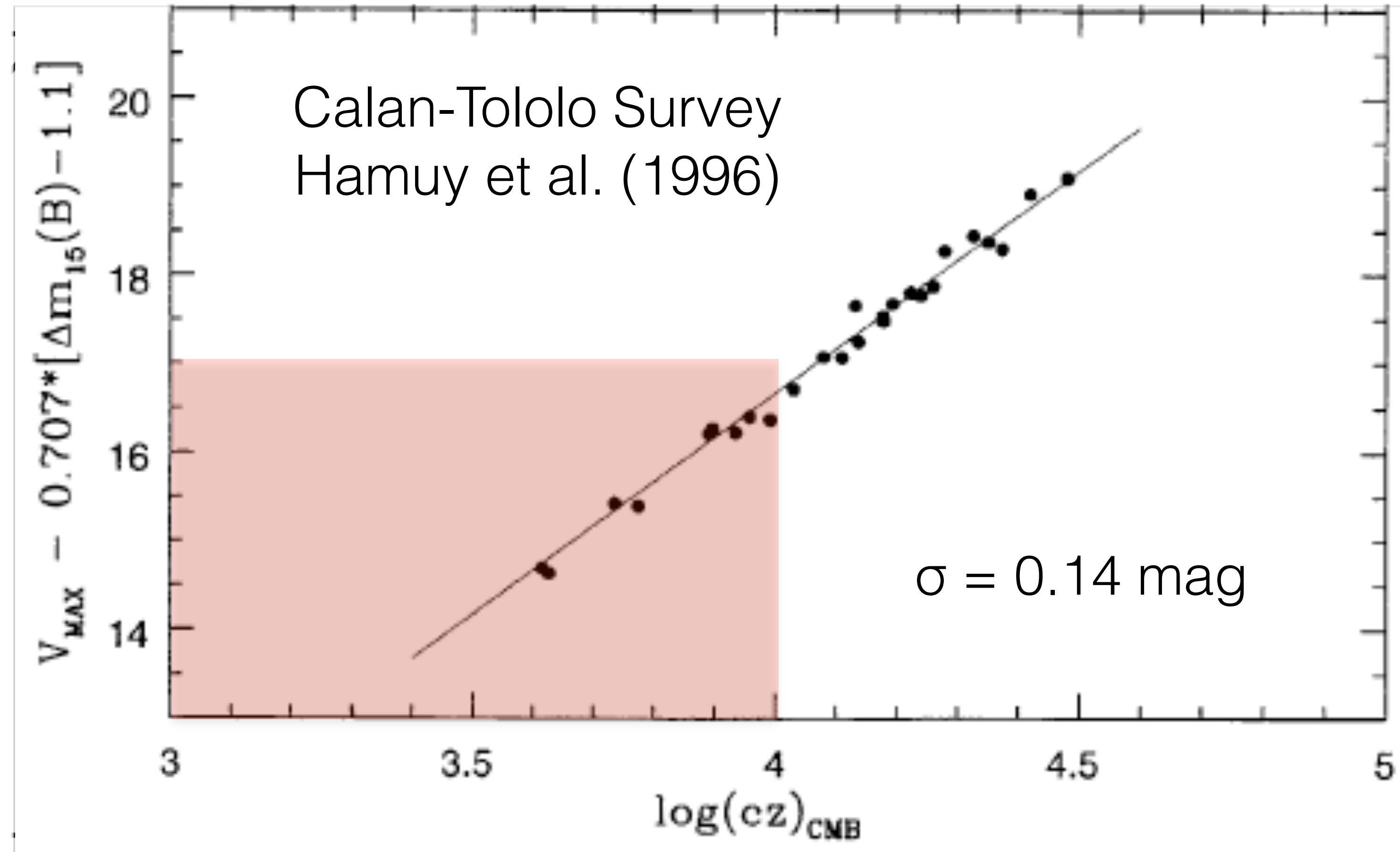

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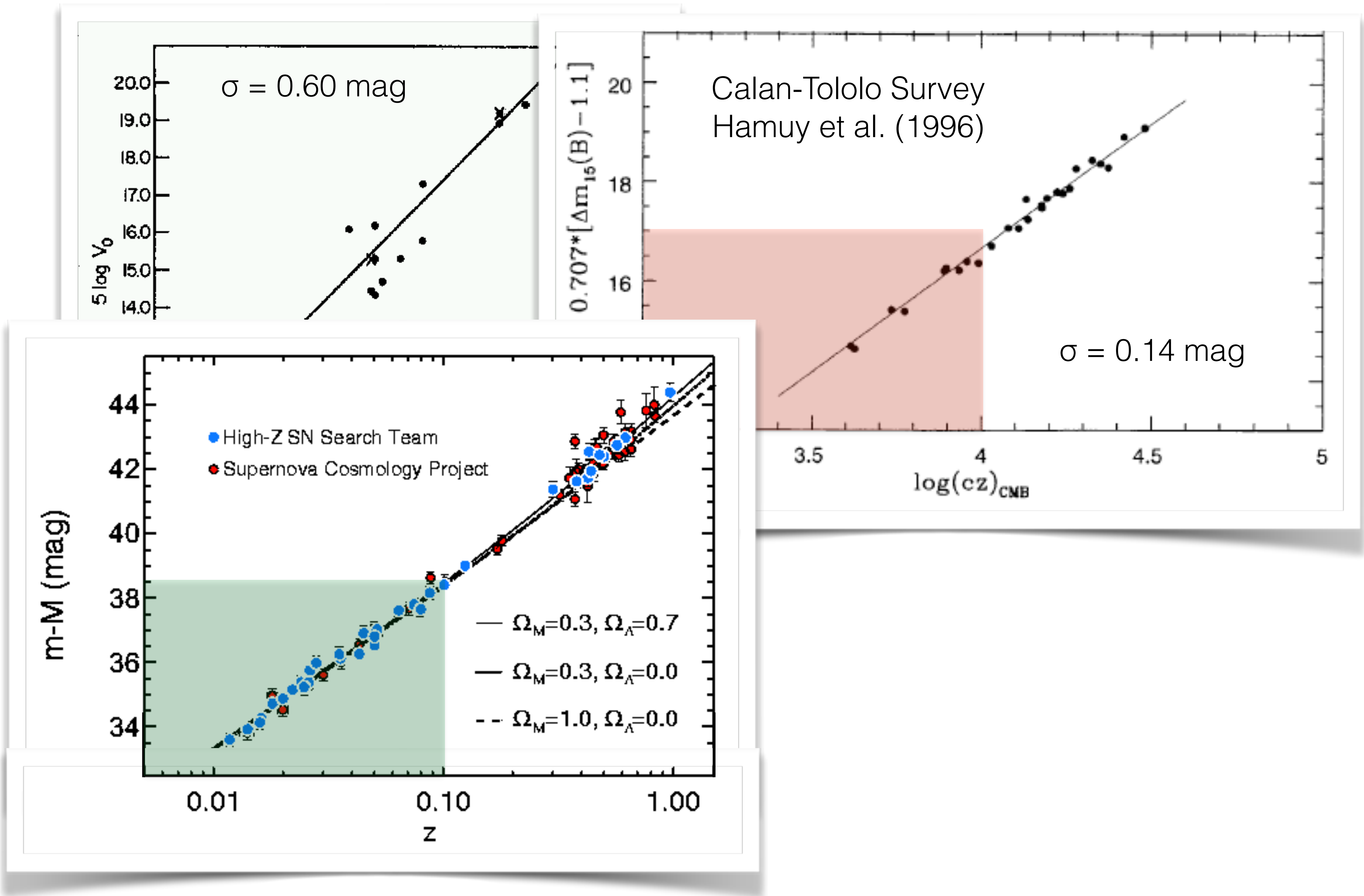

Riess et al. (1998); Perlmutter et al. (1999)

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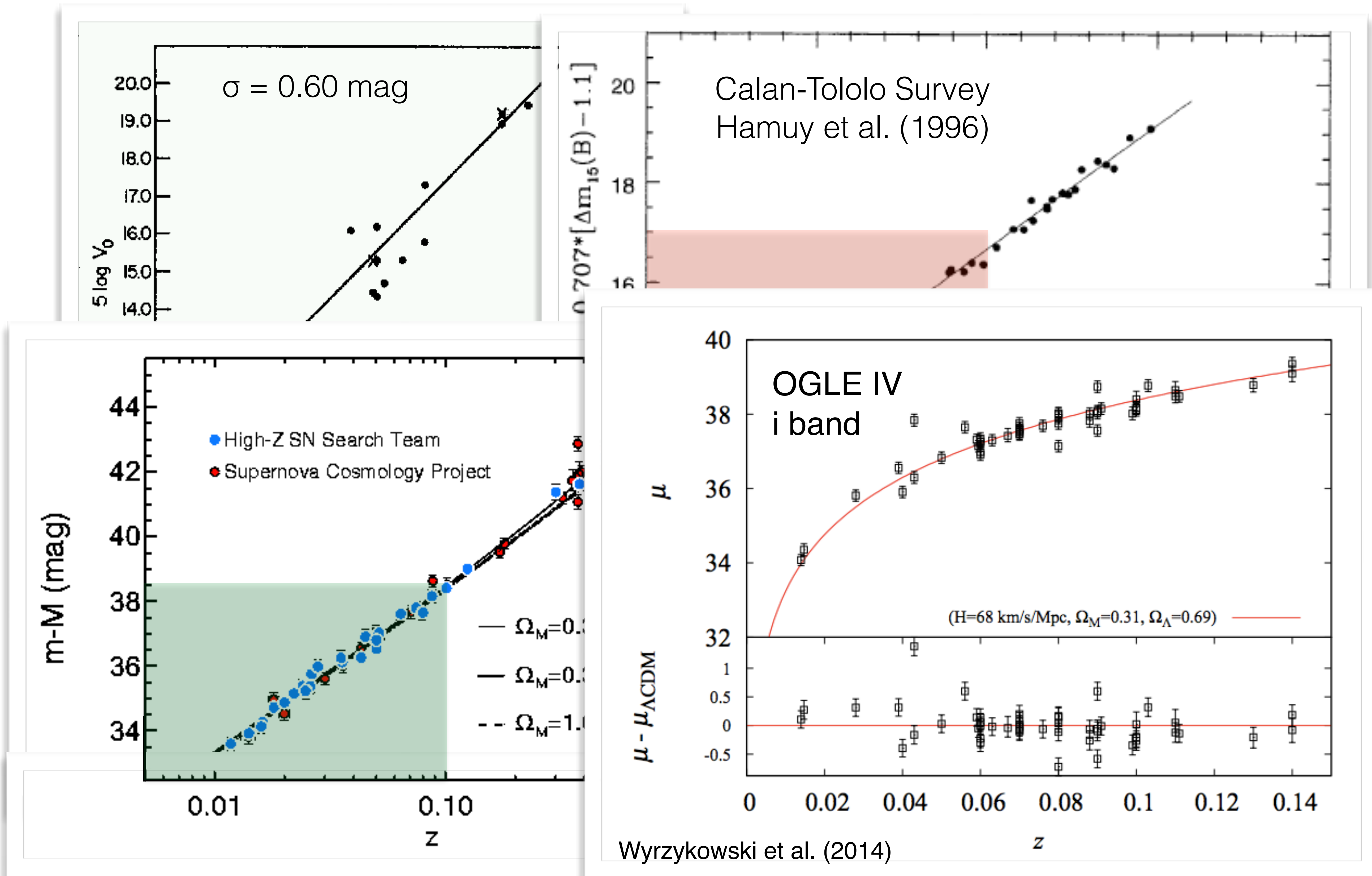

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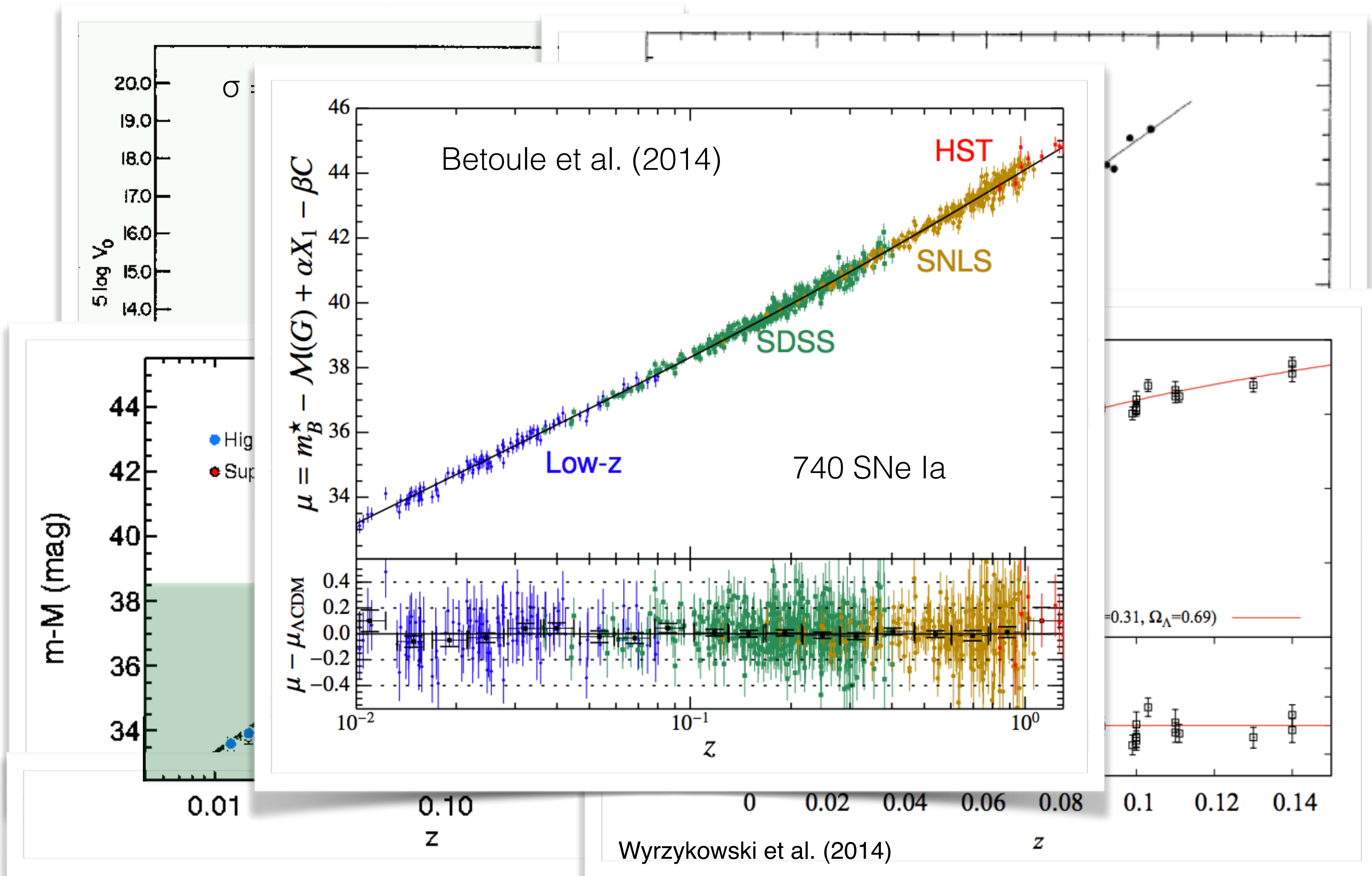

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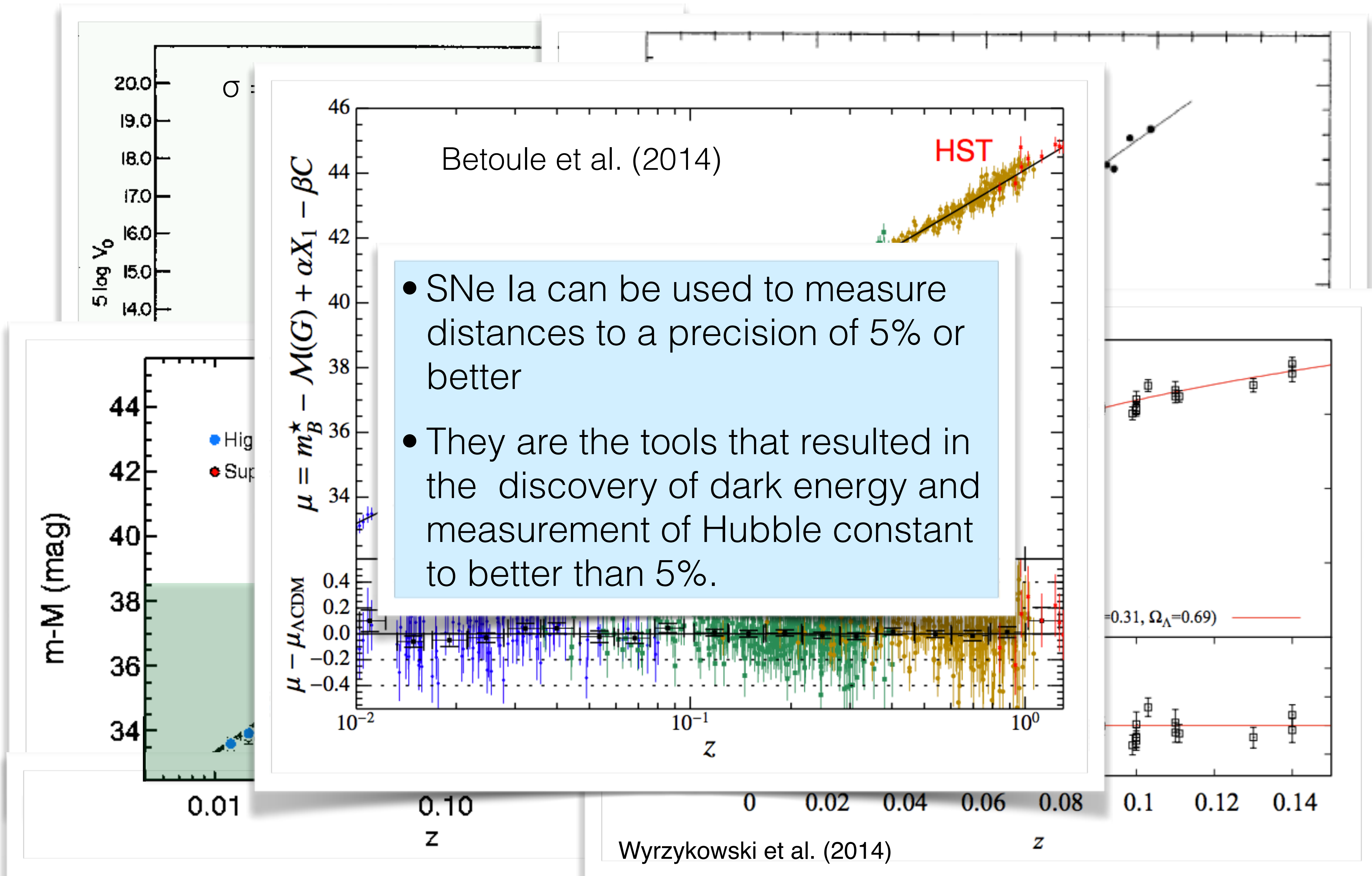
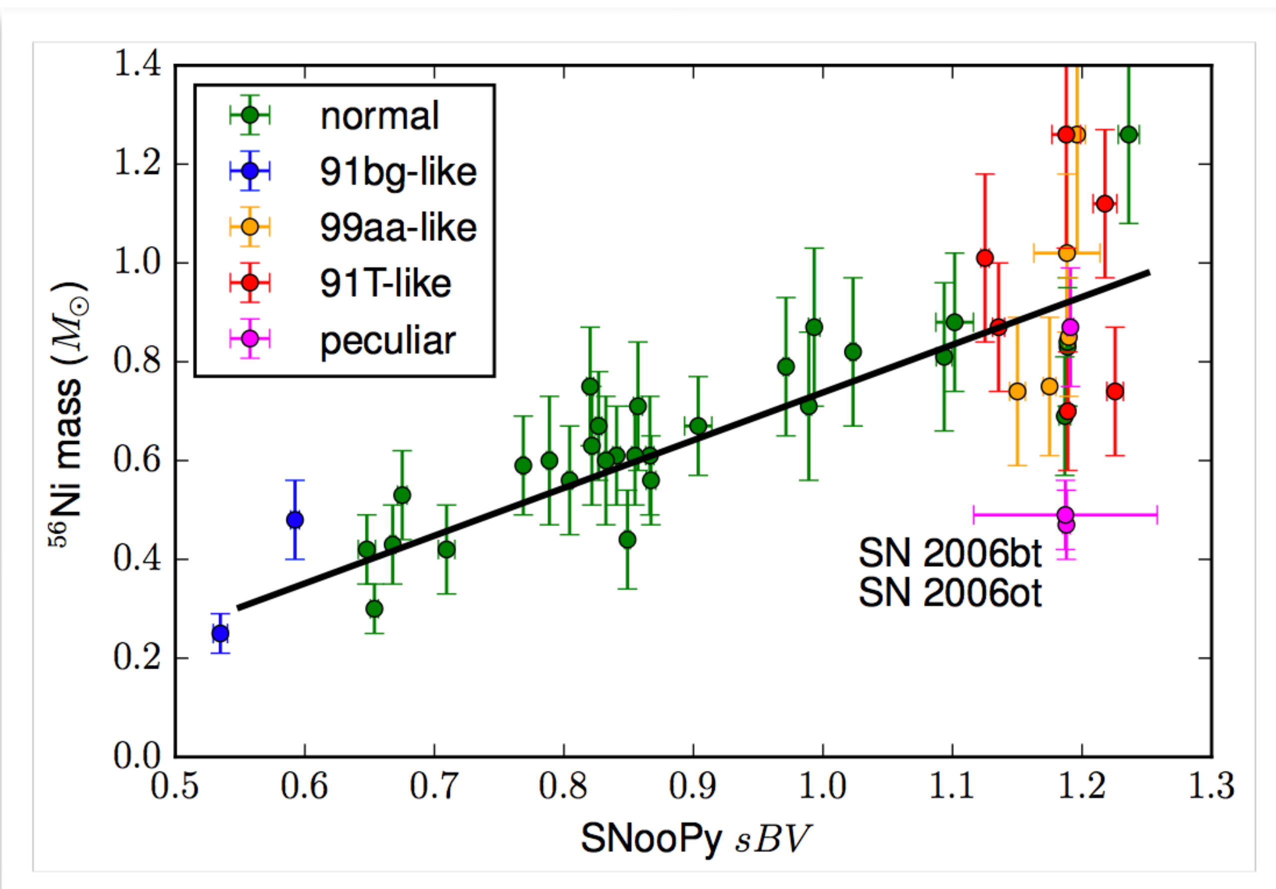


- SNe Ia can be used to measure distances to a precision of 5% or better
- They are the tools that resulted in the discovery of dark energy and measurement of Hubble constant to better than 5%.

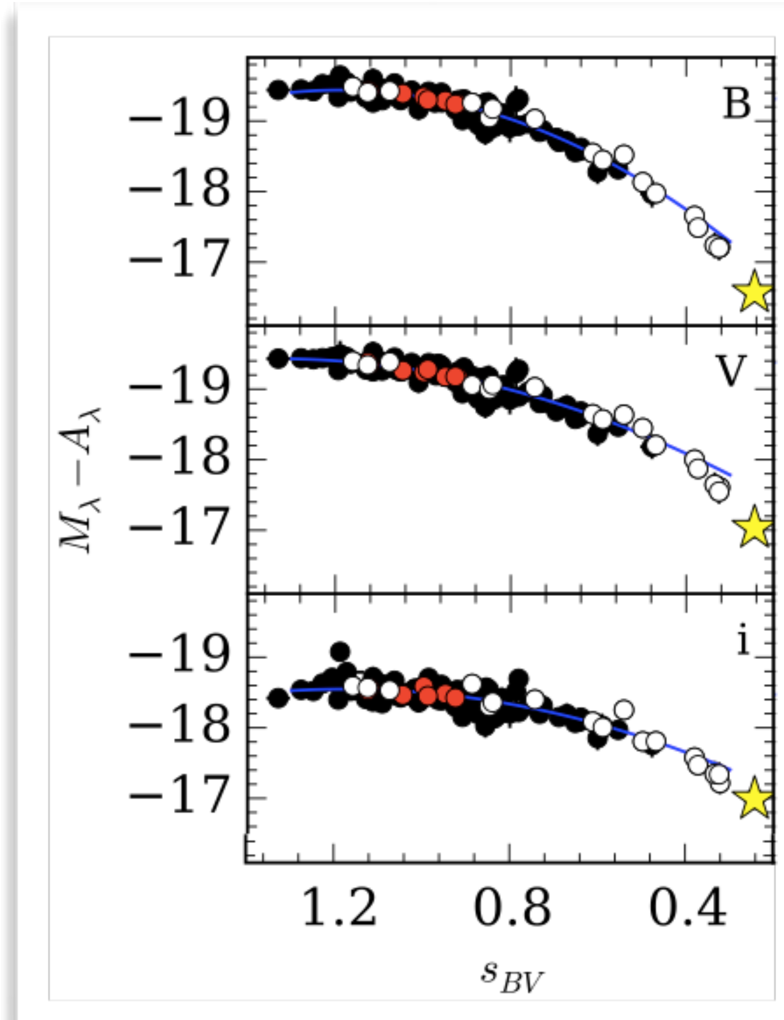
Riess et al. (1998); Perlmutter et al. (1999)

The Luminosity-Decline Rate Relation

- Spectroscopic and bolometric observations show that the observed luminosity range corresponds to a range of ^{56}Ni masses
- From theory, we know that many possible supernova models are *not* consistent with the peak luminosity–decline rate relation



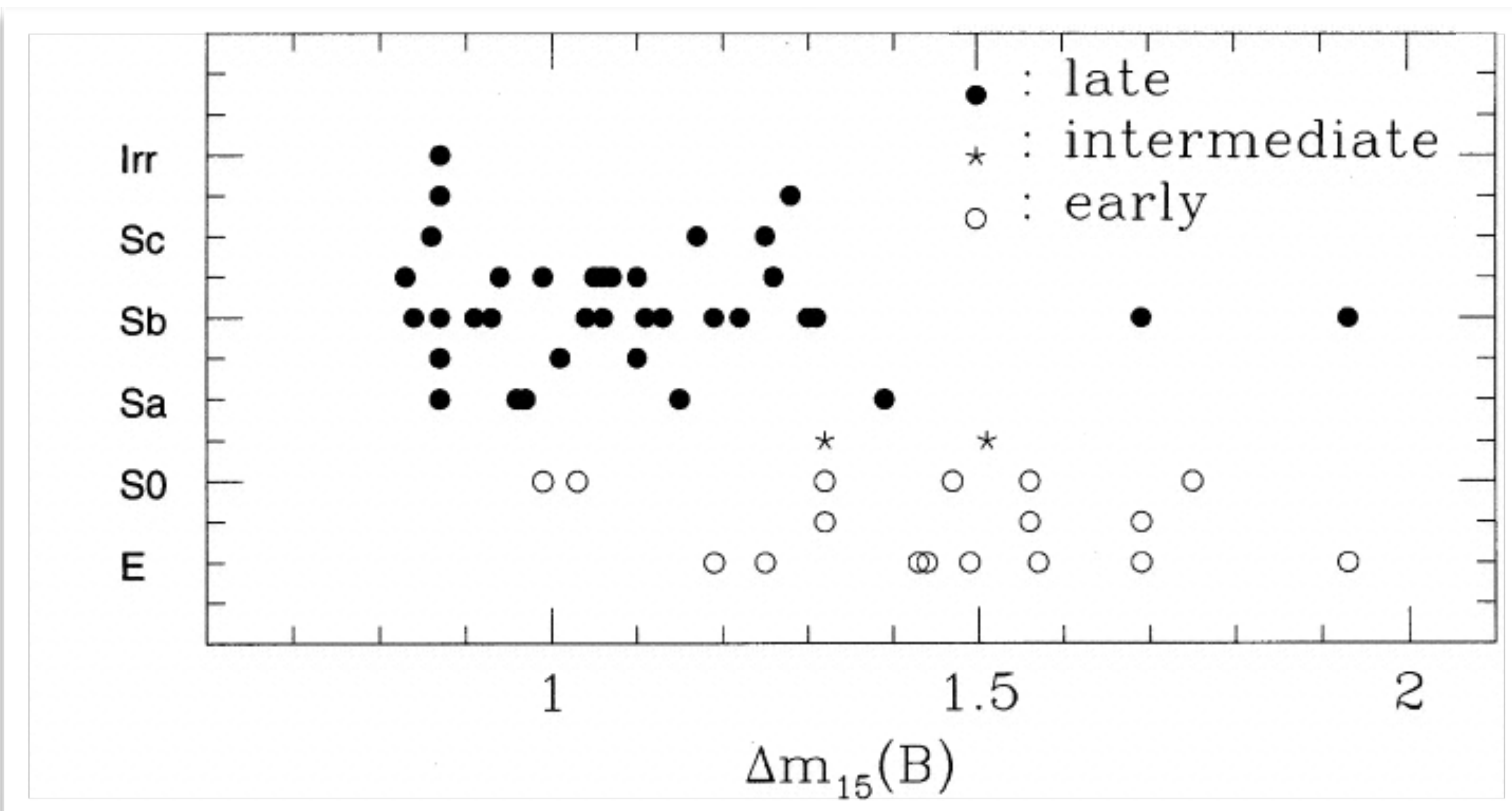
Scalzo et al., (2017, in prep)



- Thus, the existence of the luminosity-decline rate relation provides an important piece of evidence for deciphering the nature of the progenitors and explosion mechanism(s) of SNe Ia

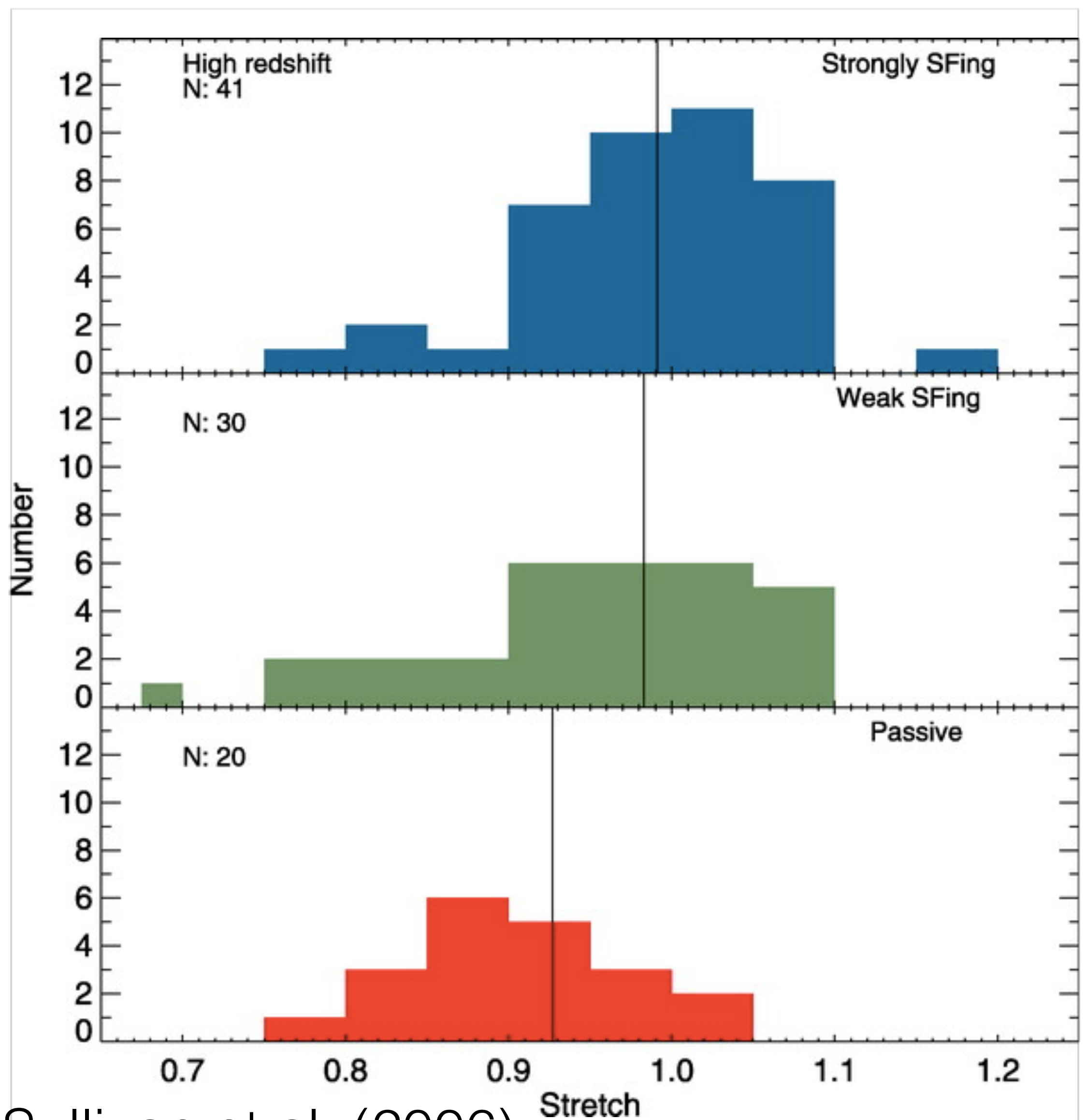
Correlation of Decline Rate with Host Galaxy Morphology

Fast-declining, less-luminous SNe Ia are found preferentially in early-type galaxies



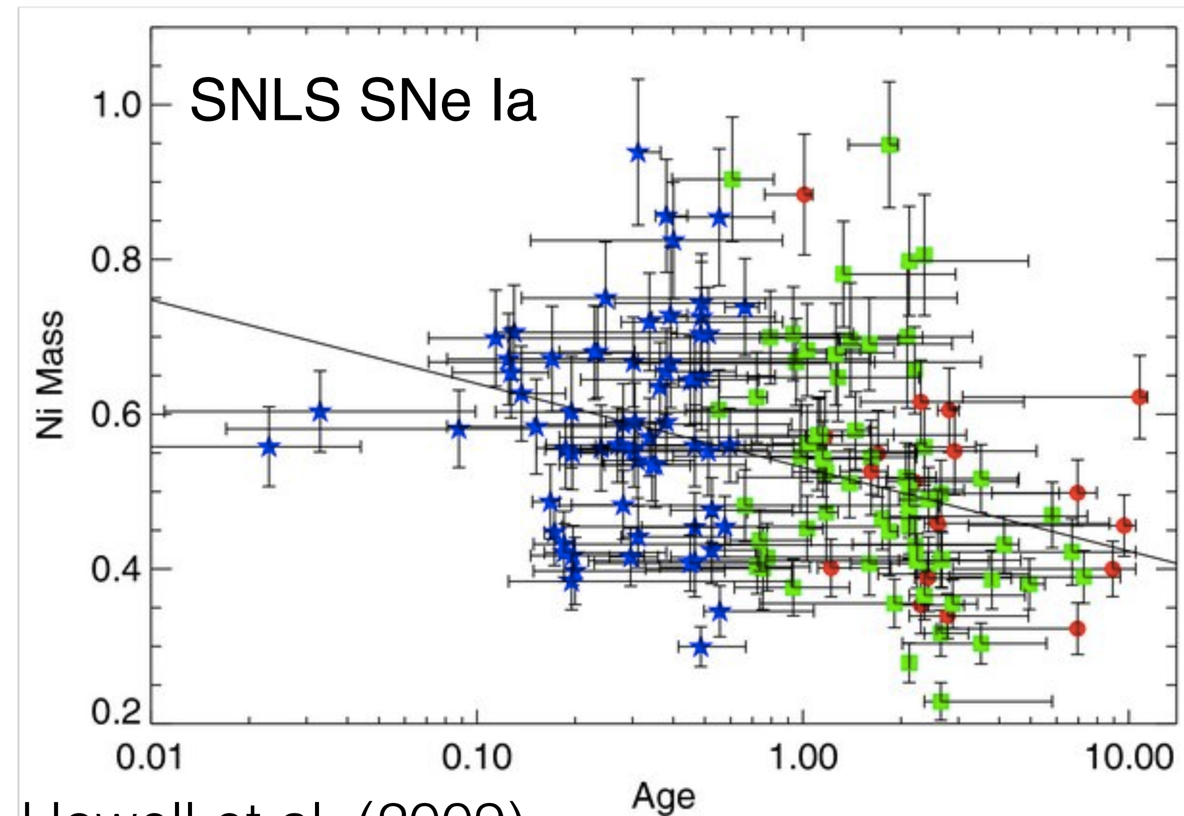
Hamuy et al. (2000)

Correlations with Star Formation Rate and Progenitor Age



Sullivan et al. (2006)

Similar correlations exist with star formation rate and luminosity-weighted age



Howell et al. (2009)

Suggests that the luminosity-decline rate relation is a sequence of progenitor age and/or metallicity

Part 2: SN Ia Progenitor Scenarios

Progenitor scenarios have traditionally focused on getting a C/O white dwarf (WD) to ignite by having it approach or exceed the Chandrasekhar mass of 1.44 $M_\odot$:

- **Single Degenerate (SD):** WD accretes matter from a non-degenerate companion causing it to explode near the Chandrasekhar limit
- **Double Degenerate (DD):** Two WDs in a close binary systems merge whose combined mass exceeds the Chandrasekhar limit

A typical galaxy hosts 10^7 SNe Ia over a Hubble time, so the progenitor systems should be observable!

Progenitor Candidates: SD Scenario

Recurrent Novae (e.g., RS Oph)

- WD accreting from non-degenerate companion
- WD mass is thought to be close to Chandrasekhar mass, but not clear if gaining or losing mass
- Not nearly enough systems in the Milky Way by an order of magnitude to explain the observed SN Ia rate

Progenitor Candidates: SD Scenario

Supersoft X-Ray Sources

- Hot WD in a close orbit with a non-degenerate companion with H burning stably to He on the WD surface
- Paucity of such sources in nearby galaxies and limits from the integrated X-ray emission of nearby ellipticals is inconsistent with expectations by an order of magnitude

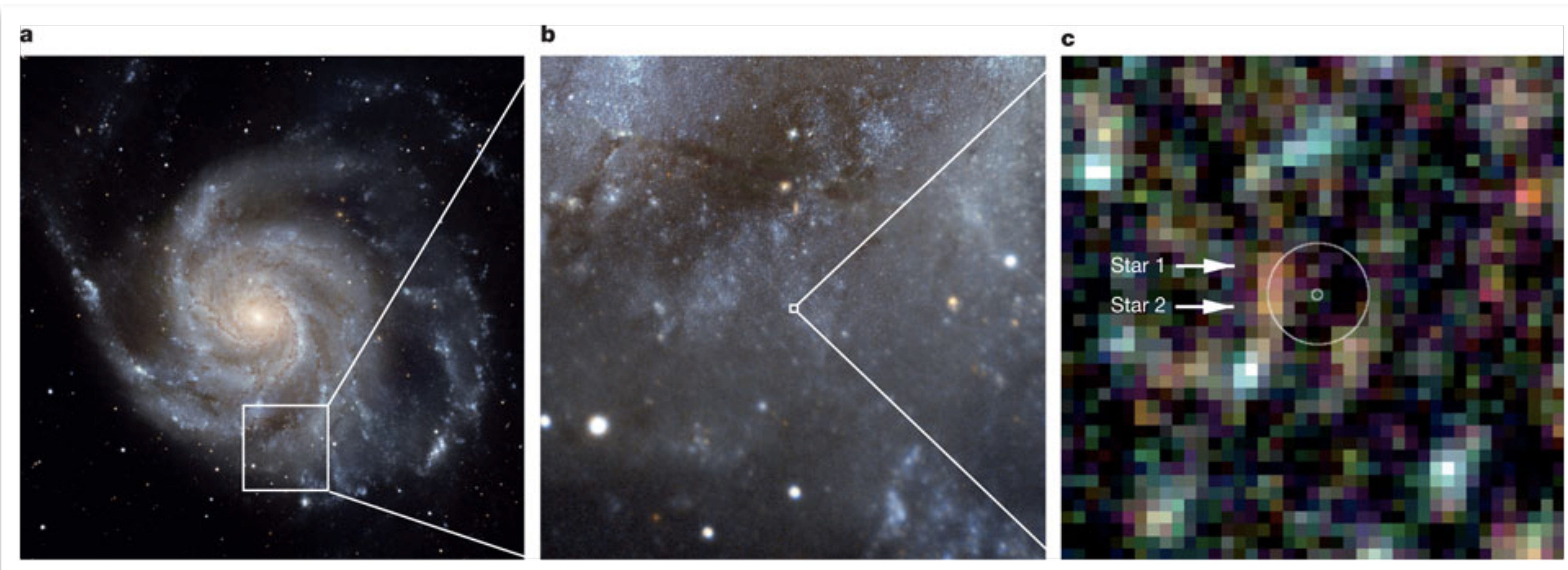
Progenitor Candidates: DD Scenario

Binary White Dwarfs

- A number of groups have searched for nearby short-period WD binaries whose orbits will gravitationally decay and merge within a Hubble time
- Badenes & Maoz (2012) have analyzed sub-exposures of spectra obtained of 4000 DA-type WDs in SDSS
- They conclude that there are not enough close binary white dwarf systems to reproduce the observed SN Ia rate in the “classic” double degenerate Chandrasekhar mass scenario
- However, if sub-Chandrasekhar mergers can lead to SNe Ia, they could make a major contribution to the overall SN Ia rate

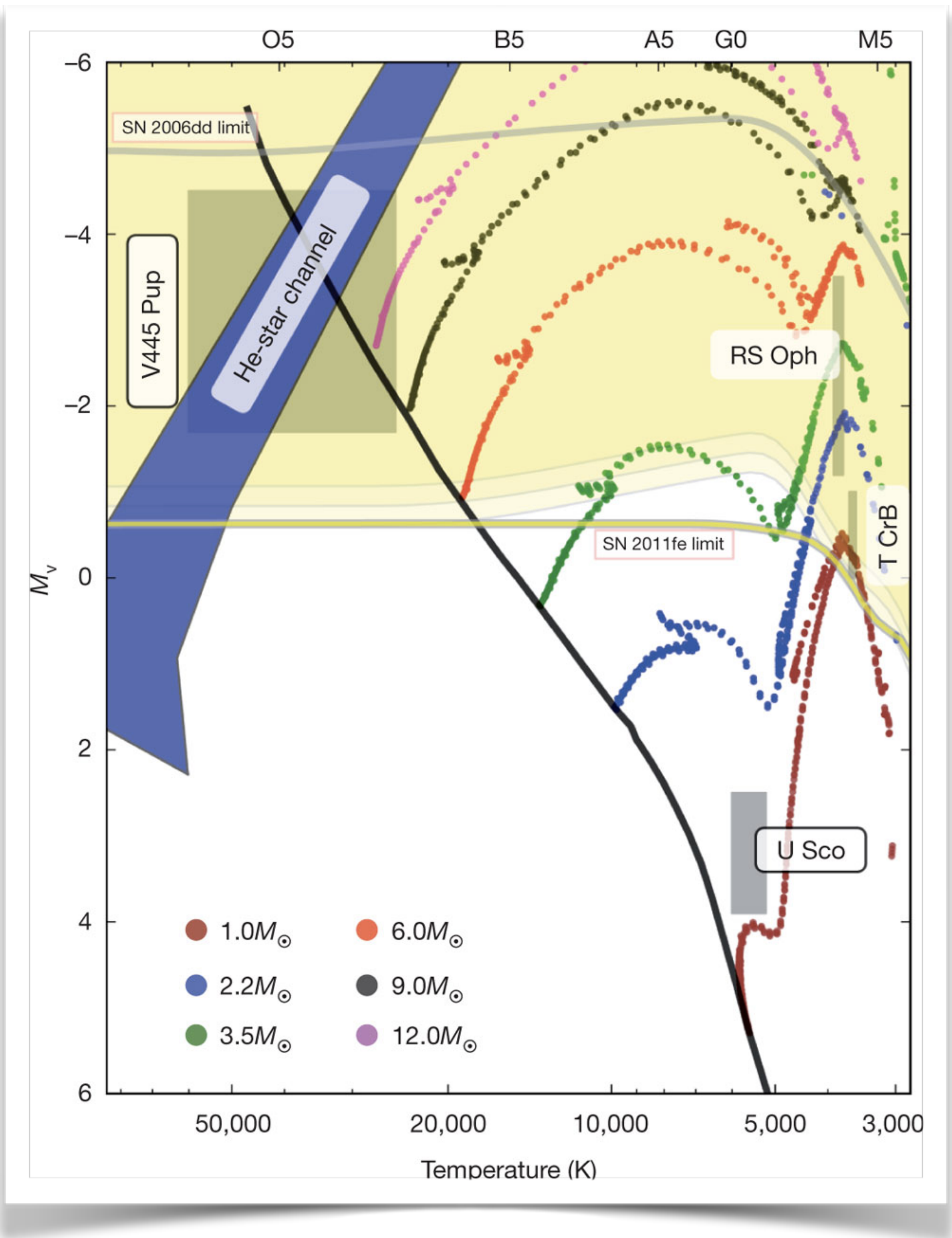
SN 2011fe in M101

SN 2011fe, the nearest SN Ia in the last 25 years, was about as typical as a SN Ia can be in all of its observed properties, making it extremely valuable for addressing the general question of the nature of the progenitors of SNe Ia



Li et al. (2011)

SN 2011fe in M101

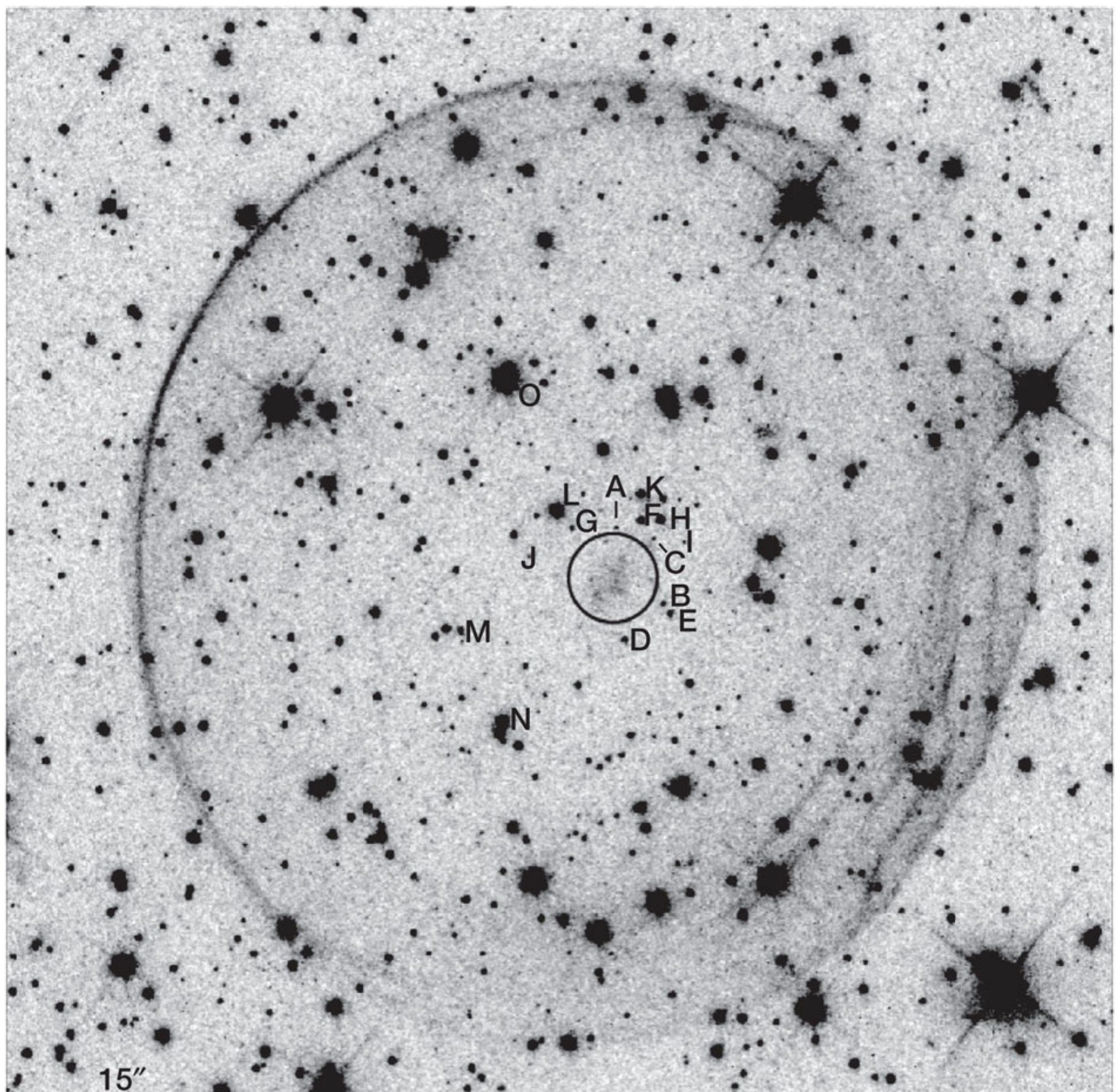


Li et al. (2011)

- Li et al. (2011) analyzed deep pre-explosion HST images of the site of the event
- No source was detected at the SN position
- These data strongly rule out the presence of a red giant
- Two Galactic recurrent novae (RS Oph & T CrB) would have been detected, as would the He nova V445 Pup in quiescence
- Main sequence and sub-giants with masses < 3.5 $M_\odot$ are allowed, as would be a recurrent nova like U Sco

SNR 0509–67.5 in the LMC

A light echo spectrum of SNR 0509-67.5 in the LMC obtained by Rest et al. (2008) showed it to have been a slow-declining SN Ia that exploded 400 ± 50 years ago

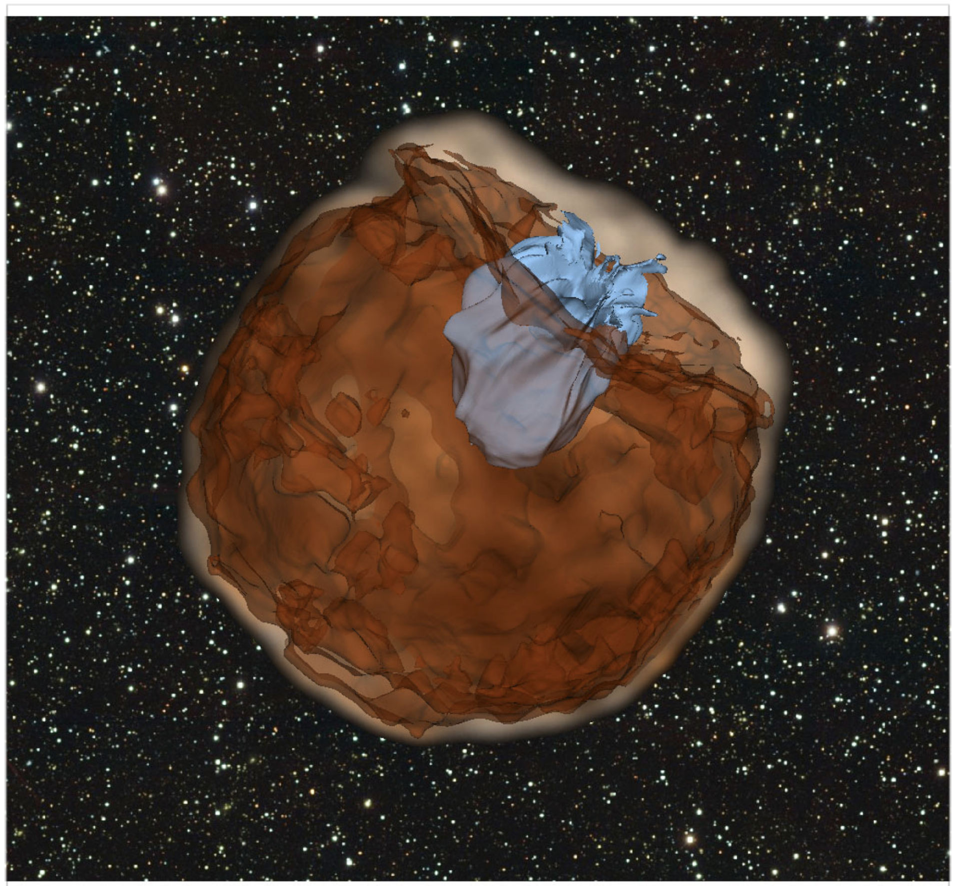


Schaefer & Pagnotta (2012)

- Schaefer & Pagnotta (2012) used HST images to show that there are no stars down to $L_V = 0.04\, L_{V\odot}$ in the area around the remnant's geometrical center that could be populated by a runaway donor star
- This luminosity corresponds to late-K-type main-sequence stars of mass ~0.5 $M_\odot$ and essentially rules out all traditional single-degenerate companions

Collision of the Supernova Ejecta with the Companion

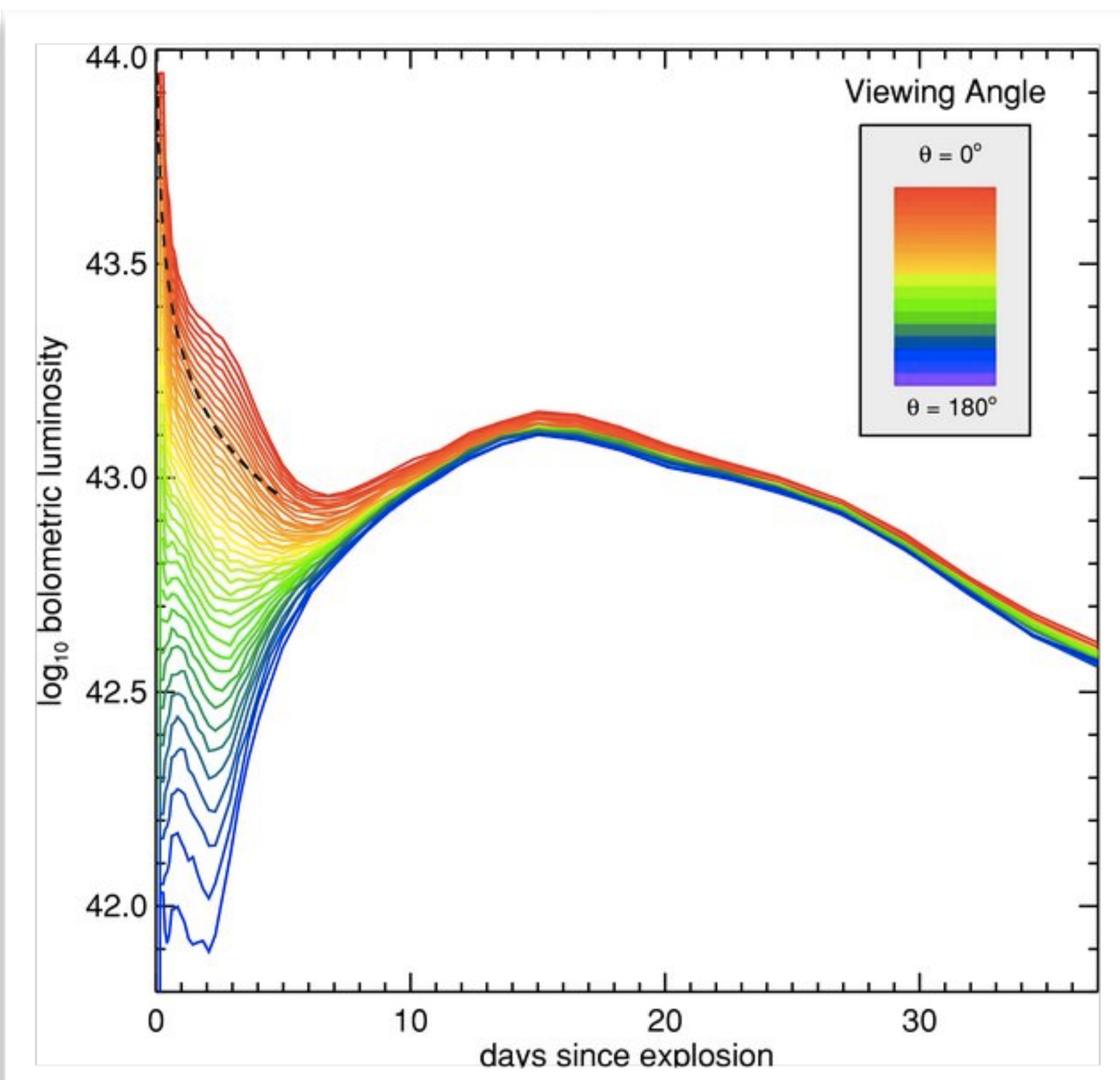
- Kasen (2010) showed that the collision of the supernova ejecta with its companion star should produce detectable emission in the hours and days following the explosion

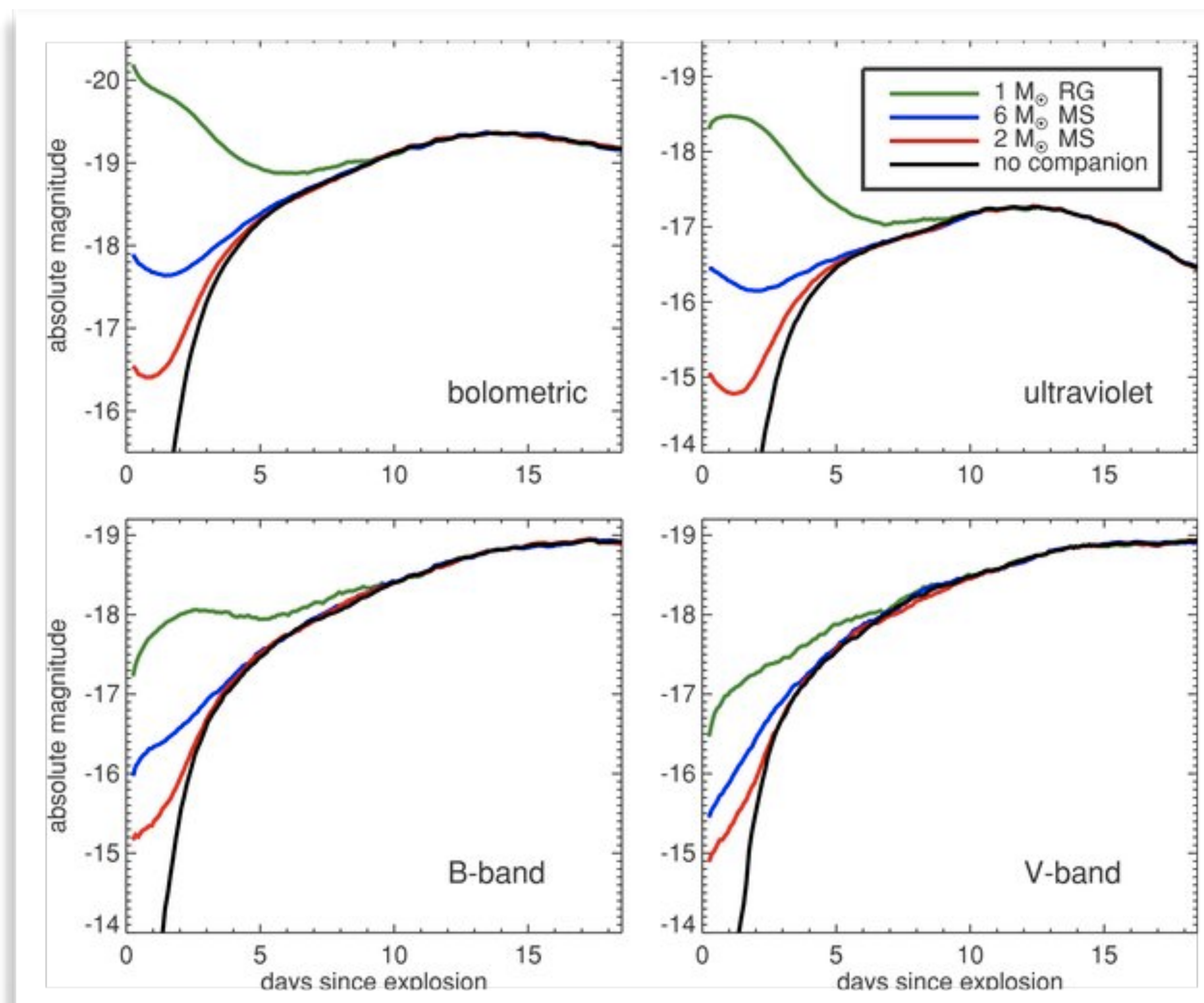


- Radiative diffusion from the shock-heated ejecta is predicted to produce optical/UV emission which exceeds the radioactively powered luminosity of the supernova for the first few days after the explosion
- This emission should be most prominent for viewing angles looking down upon the shocked region (or about 10% of the time)

Evidence for the Companion Star

The collision of the supernova ejecta with its companion star should produce detectable emission in the first days following the explosion, with the strength providing information on the radius of the companion



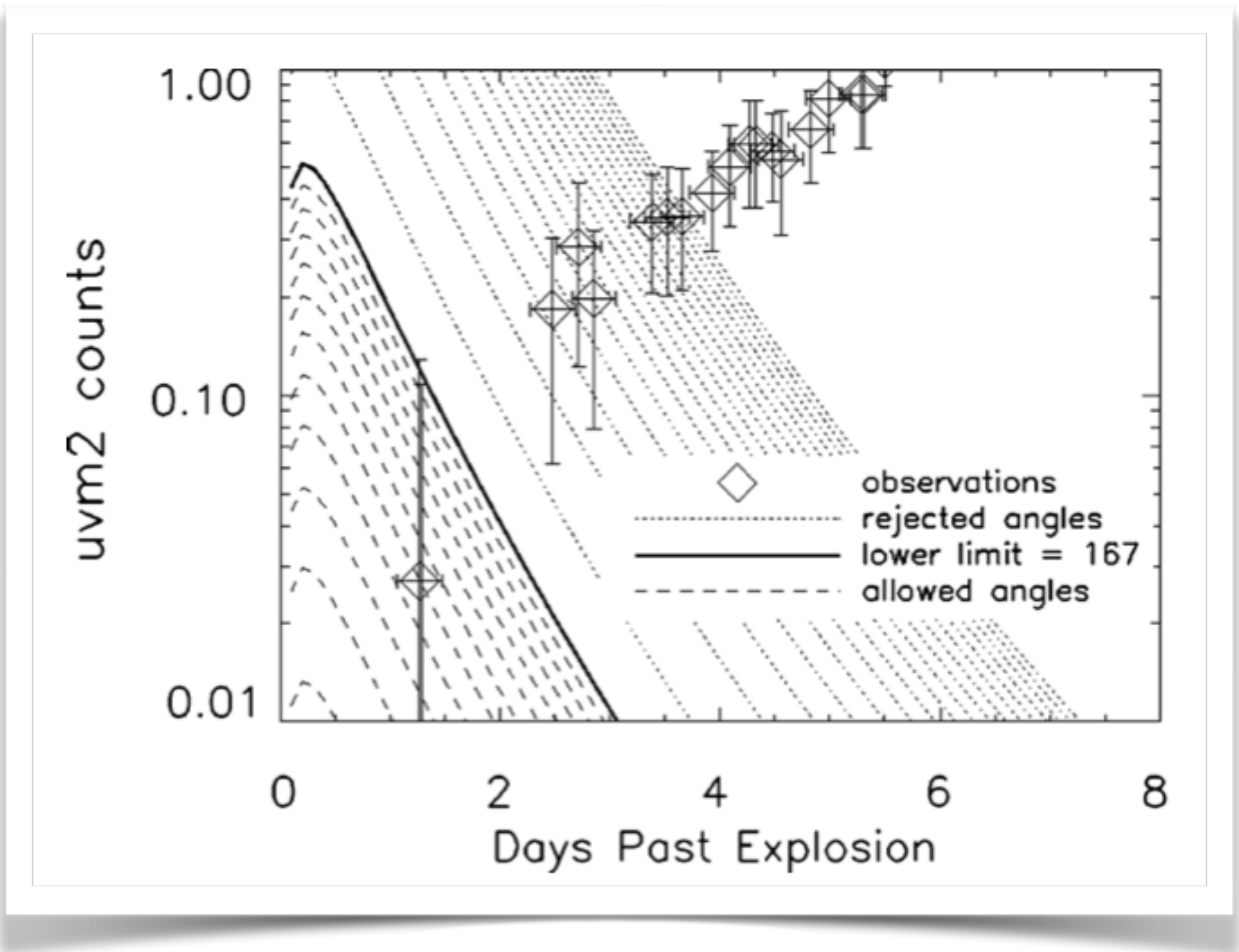


Kasen (2010)

SN 2011fe in M101

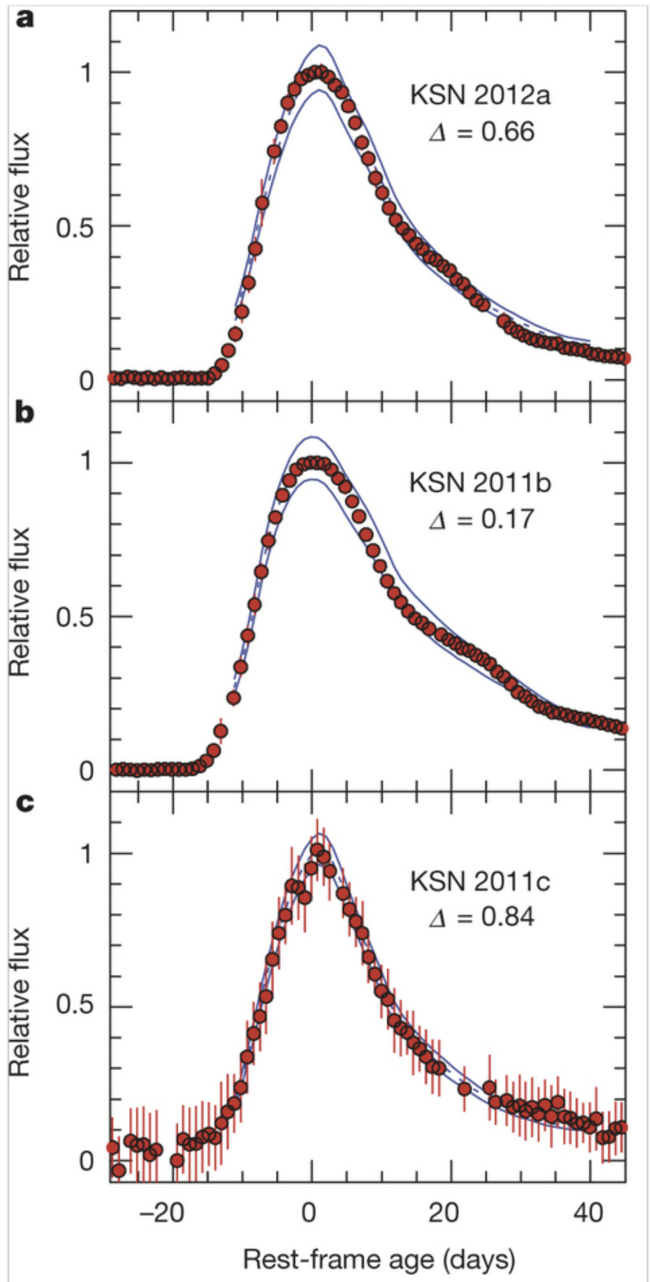
SN 2011fe was discovered within hours of explosion

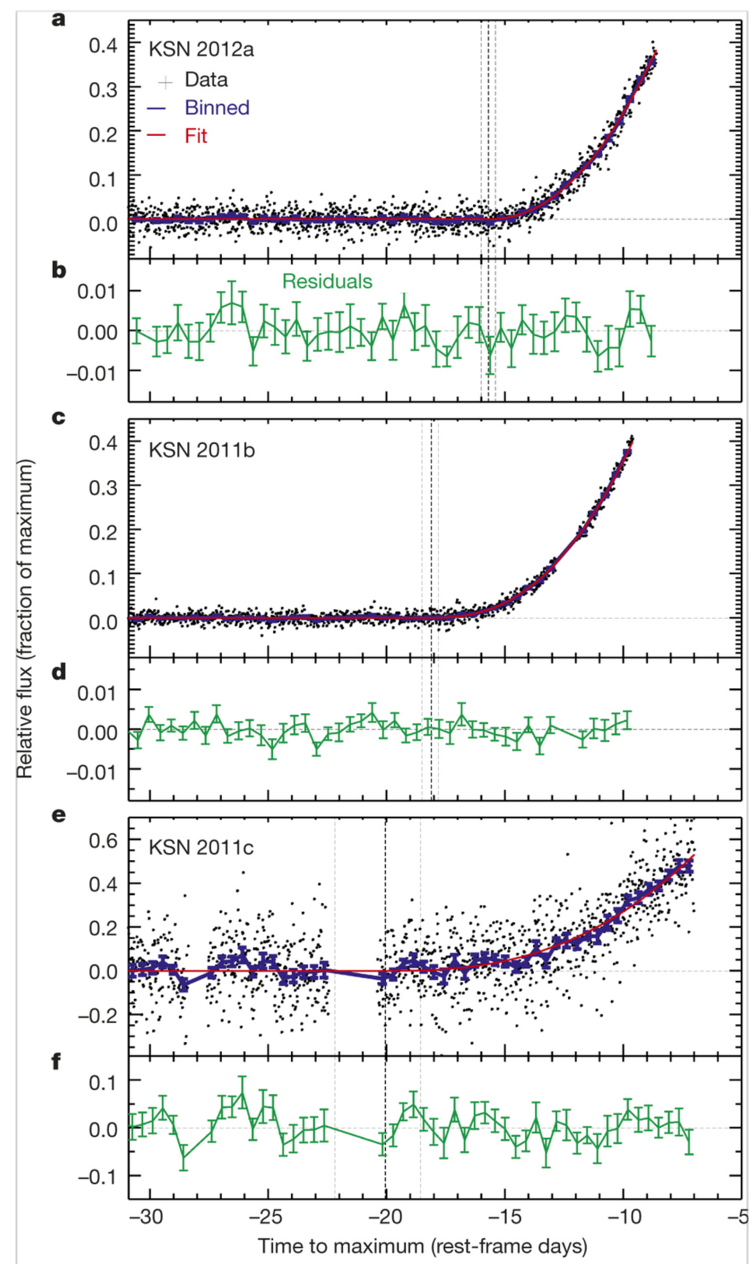
Early observations of the rising light curve of SN 2011fe in the optical and UV give an upper limit of $R_* < 1\ R_\odot$ for the size of the companion

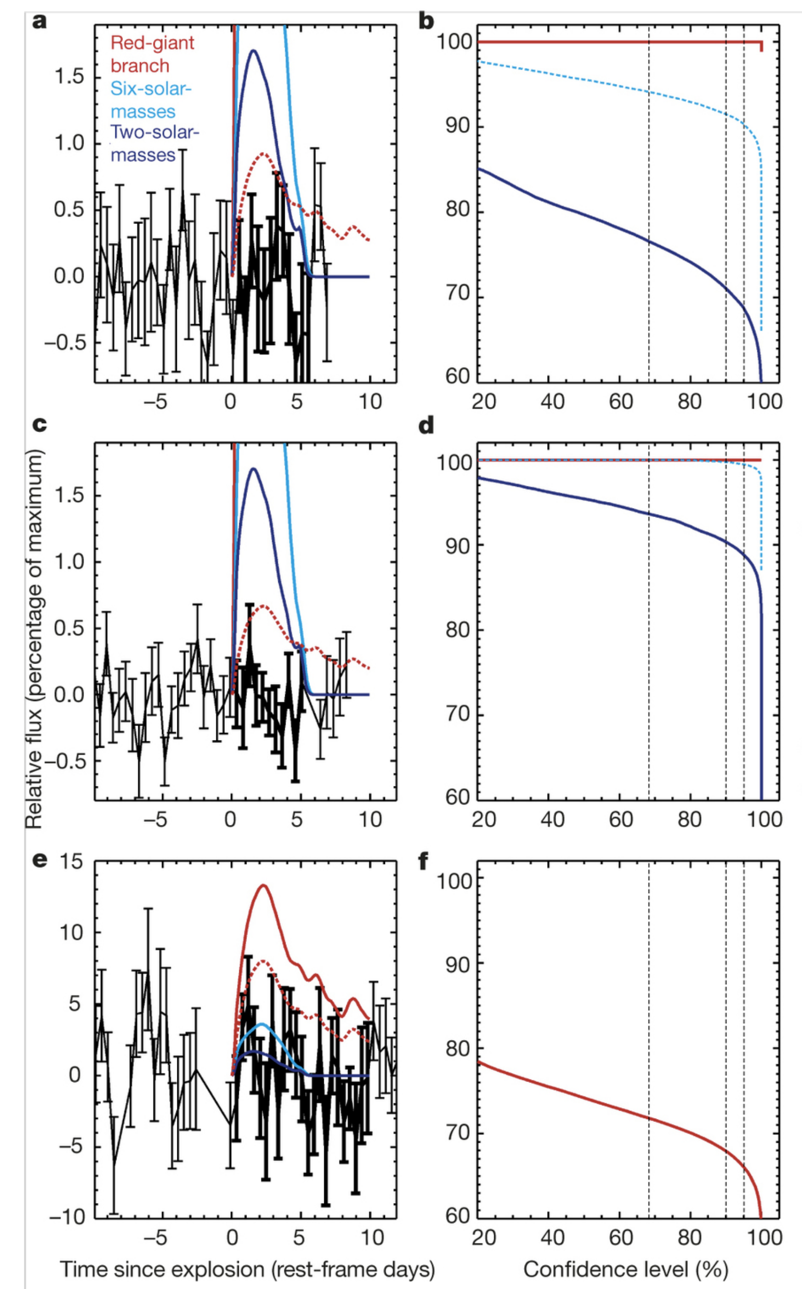


Brown et al. (2012)

Kepler Observations of 3 SNe Ia





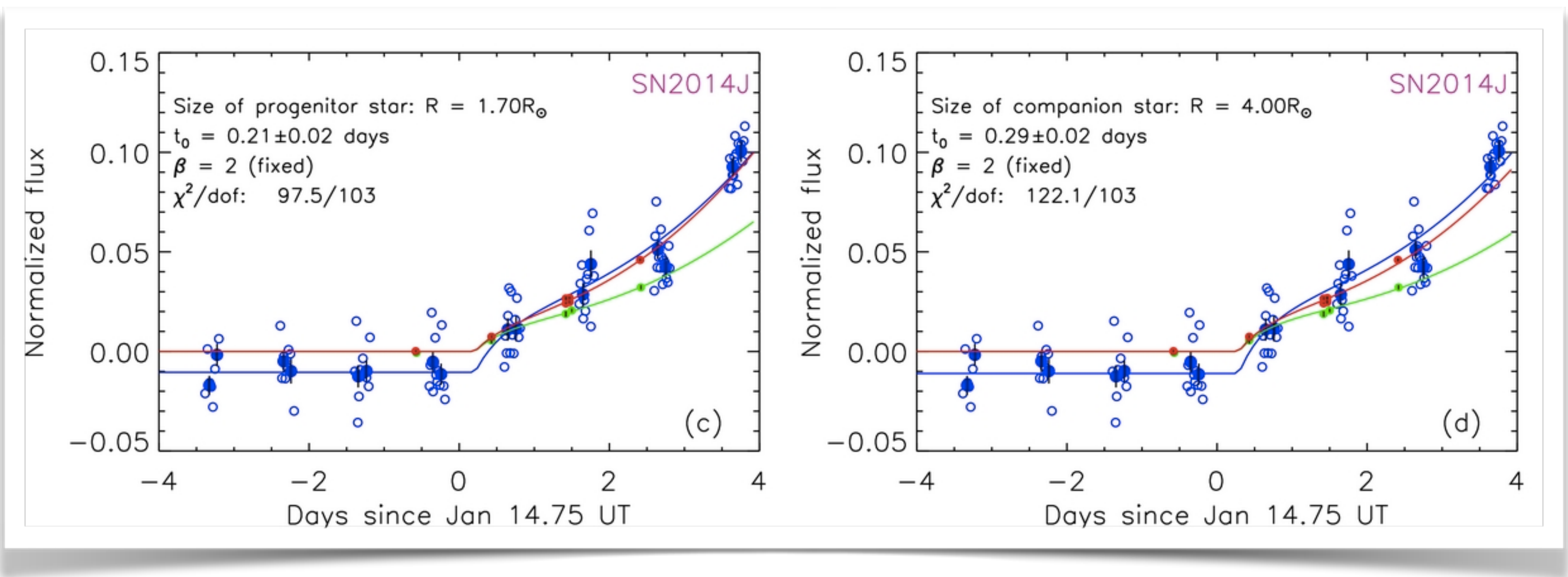


Power law fits to continuous coverage data obtained by Kepler of 3 SNe Ia reveal no signatures of companion impacts within the few days before first light

Olling et al. (2015)

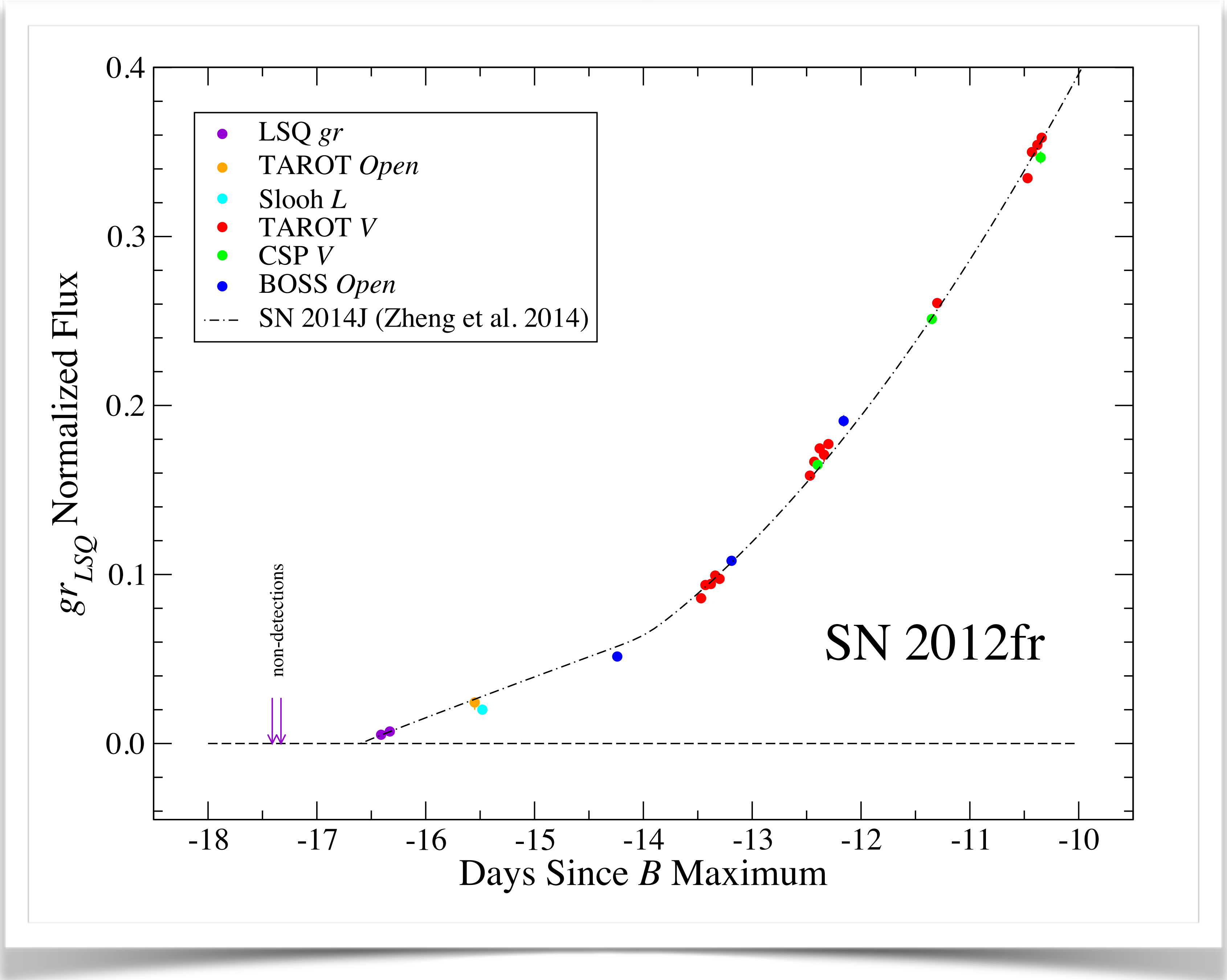
The Early Light Curve of SN 2014J

- An early-time light curve of SN 2014J using high-cadence broad-band imaging data obtained by the Kilodegree Extremely Little Telescope (KELT) shows an evolution consistent with the expected signal from the cooling of shock heated material with R >~ 1 $R_\odot$
- However, Zheng et al. (2014) found that a “broken power law” could be used to fit independent observations of SN 2014J



Goobar et al. (2015)

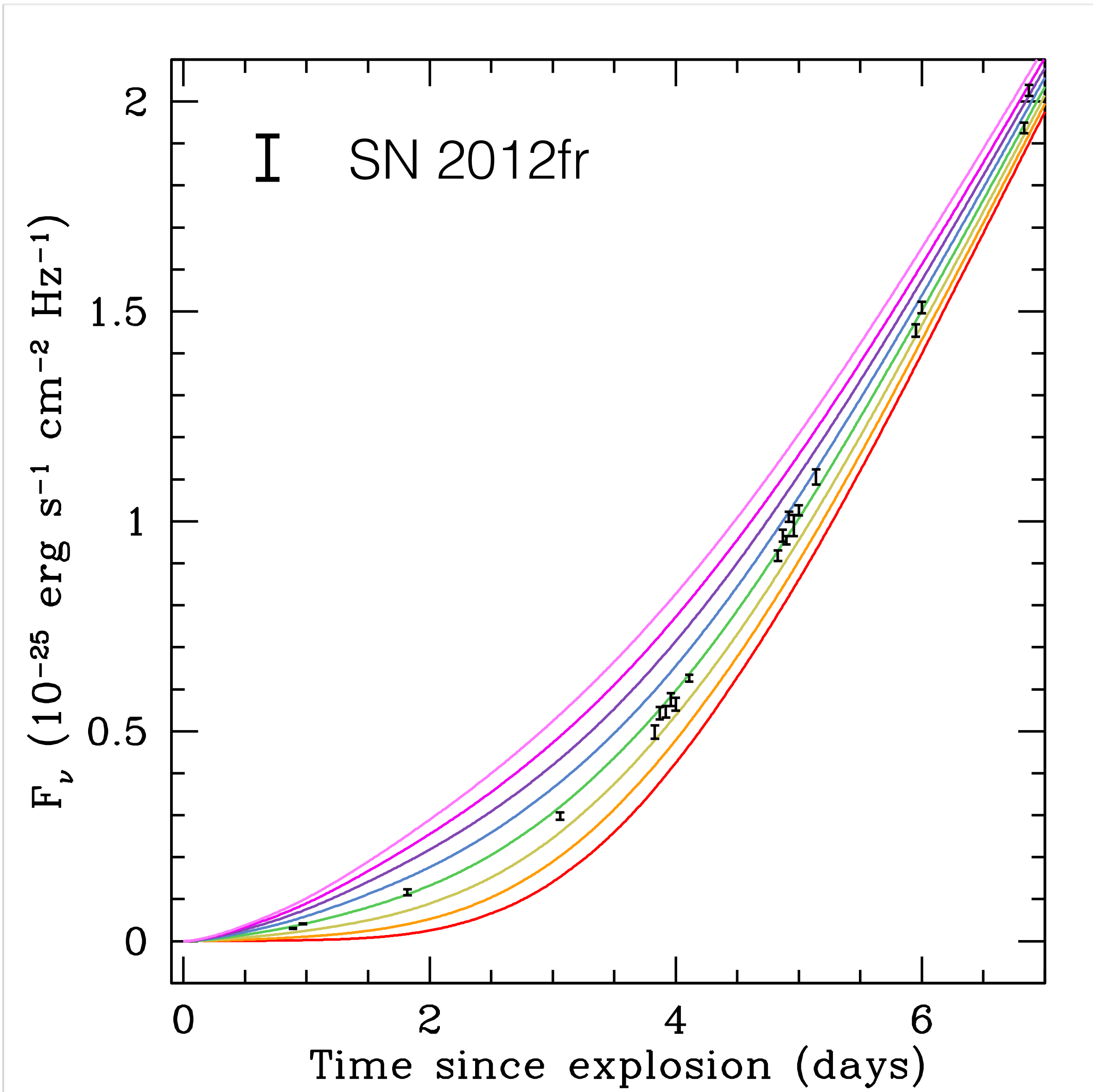
The Early Light Curve of SN 2012fr

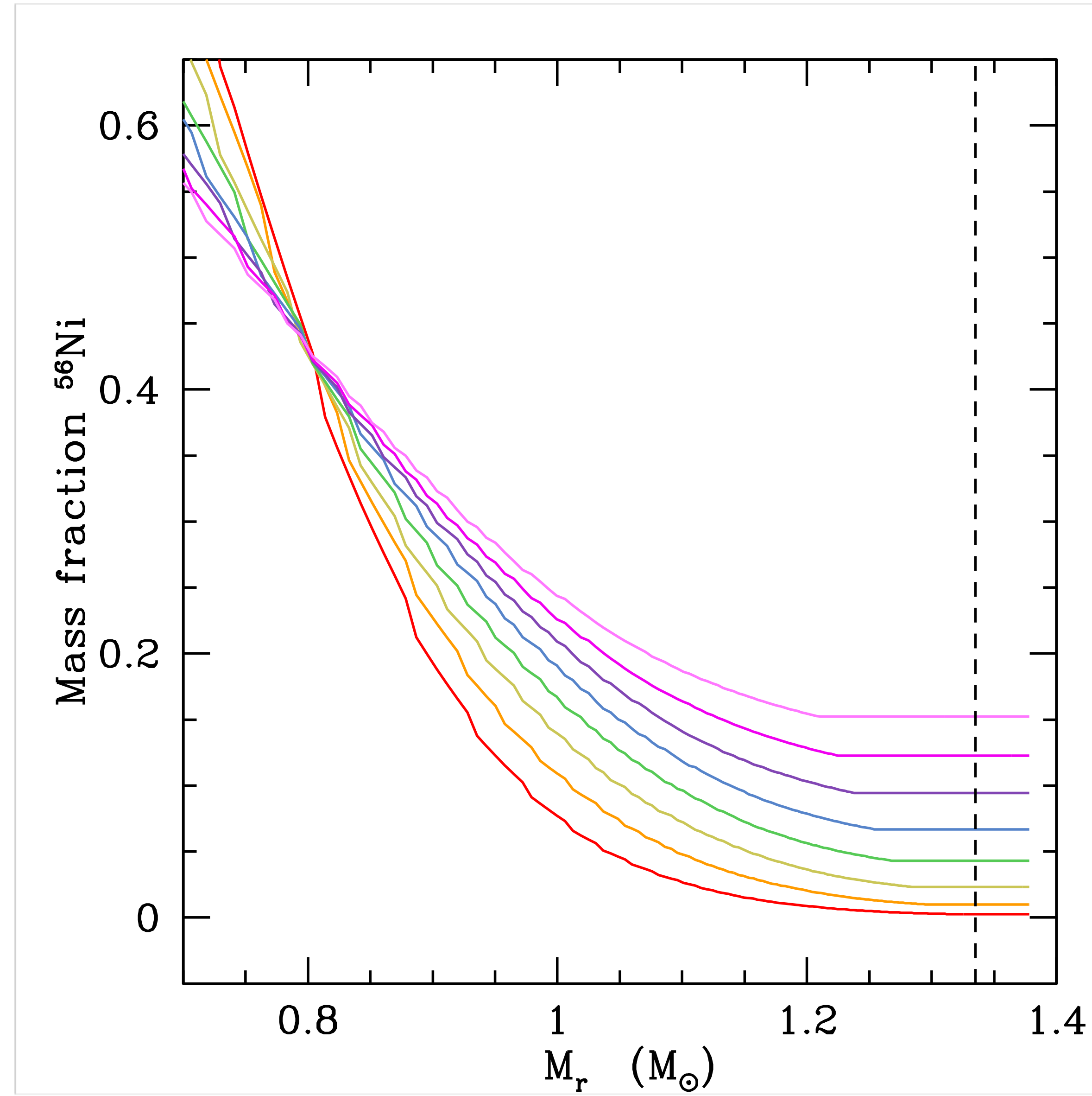


- The early light curve of SN 2012fr shows a slow initial rise after explosion
- This is reminiscent of the broken power-law fit of Zheng et al. for SN 2014J

Contreras et al. (2017, in prep)

The Effect of Different Mixings of ^{56}Ni

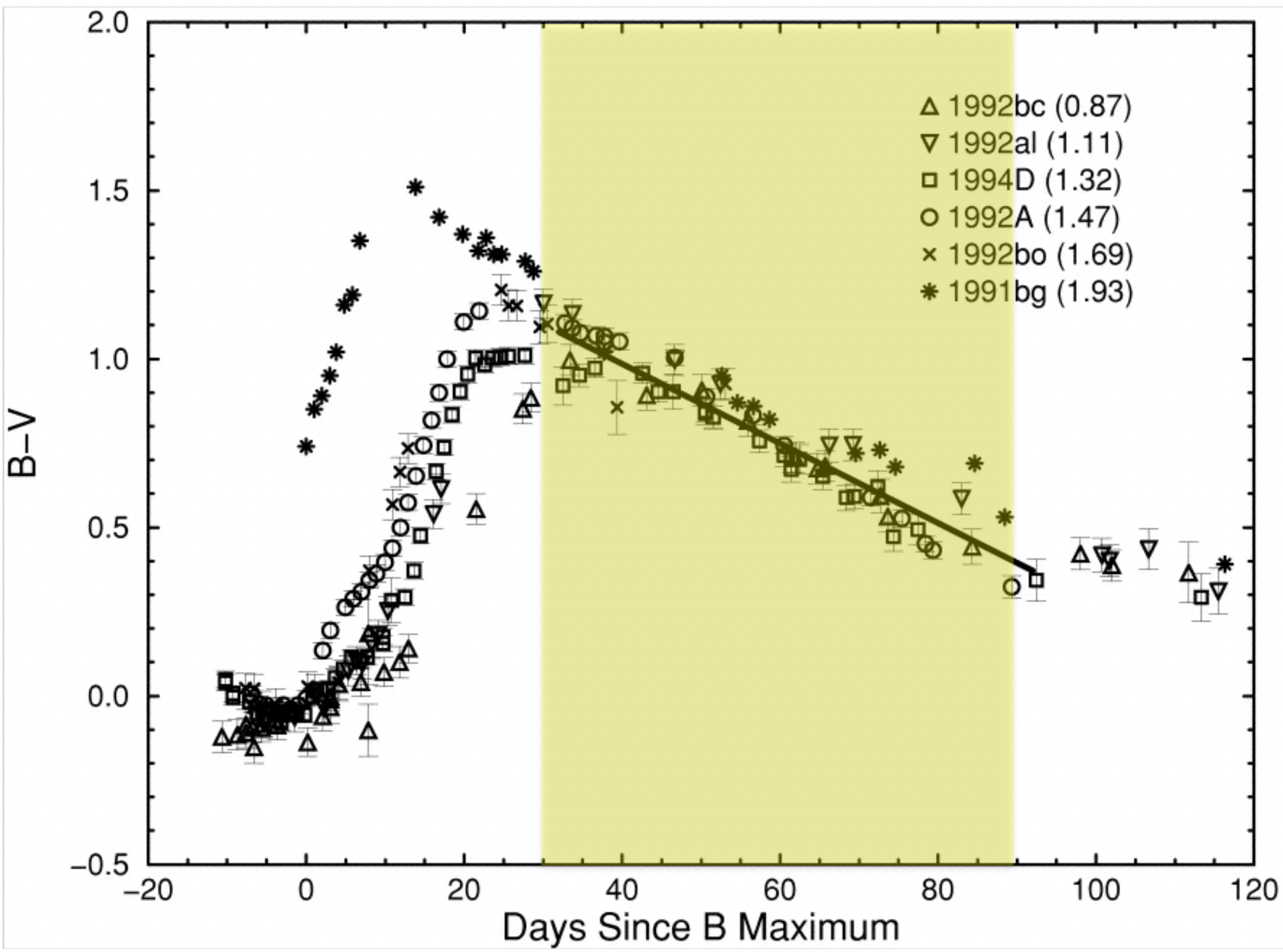




- Piro & Morozova (2016) have shown that the shape of the early rise of the light curves of SNe Ia is a function of the mixing of the ^{56}Ni in the ejecta
- The early light curves of SN 2012fr and SN 2014J are well fitted by an explosion model with moderate mixing

Contreras et al. (2017, in prep)

Part 3: Host Dust Reddening of SNe Ia



Phillips et al. (1999)

The Lira Relation

- The B-V color evolution of SNe Ia is remarkably similar between 30 and 90 days past B maximum
- This fact can be used to estimate the color excess

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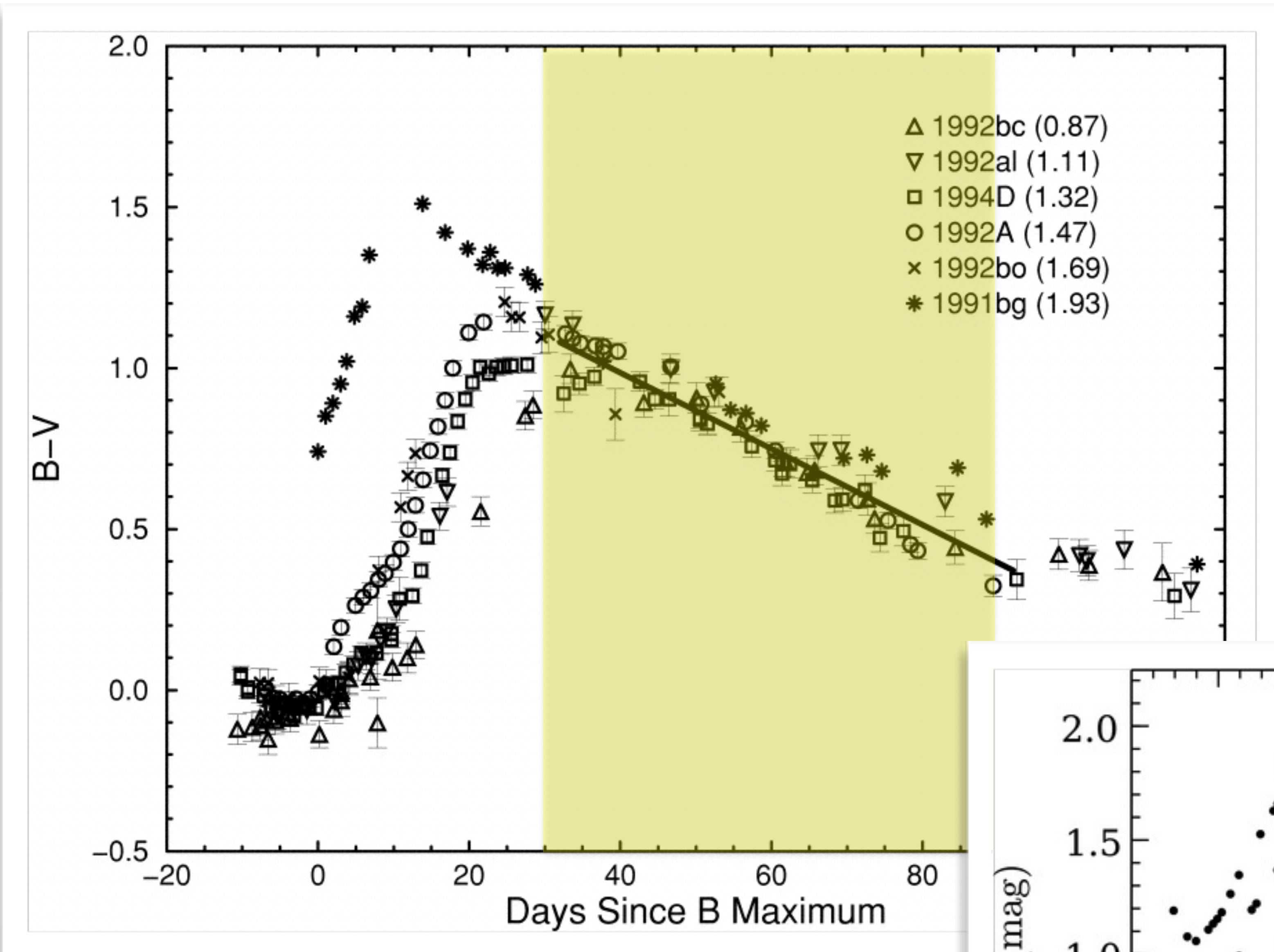

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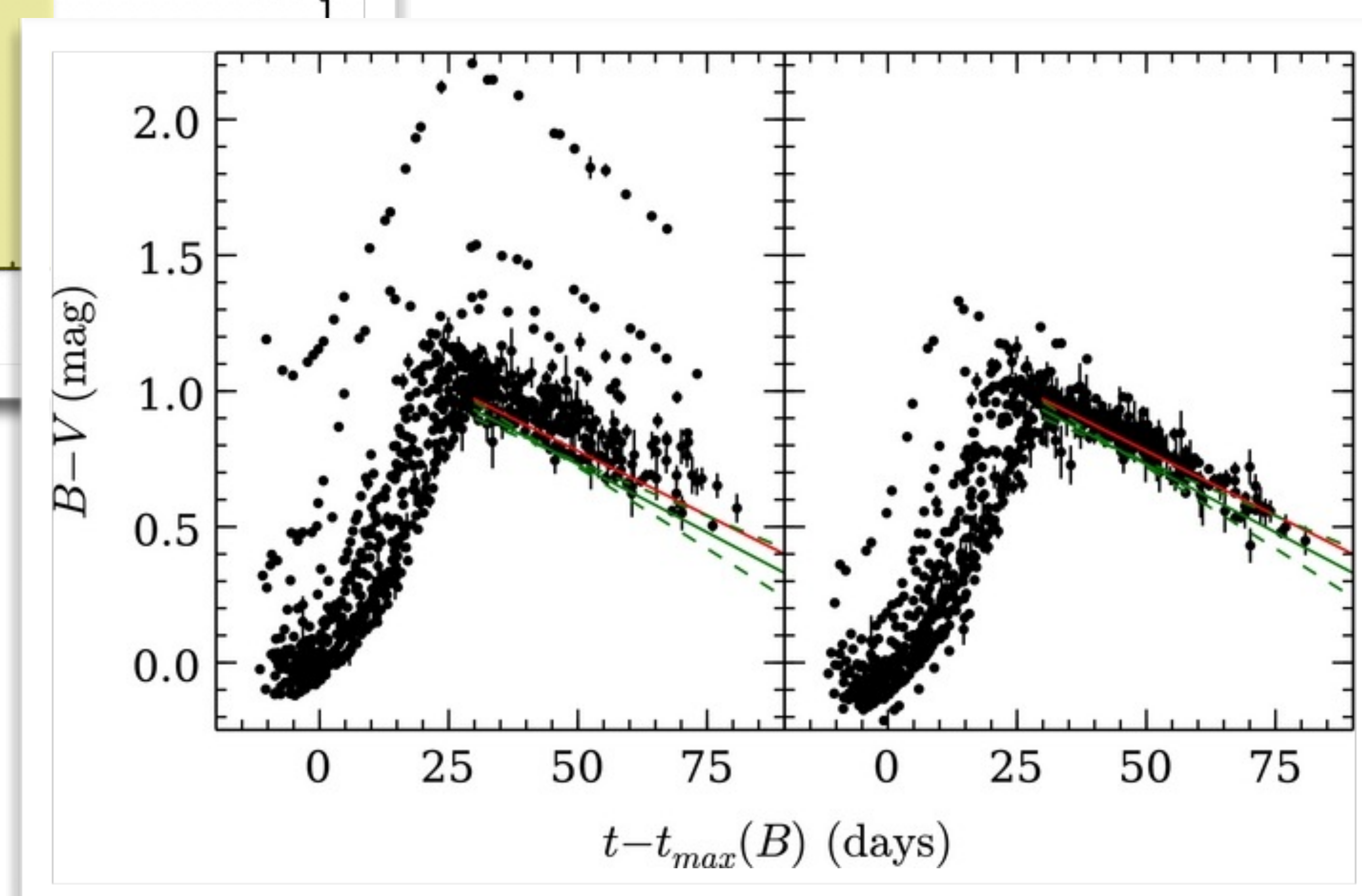
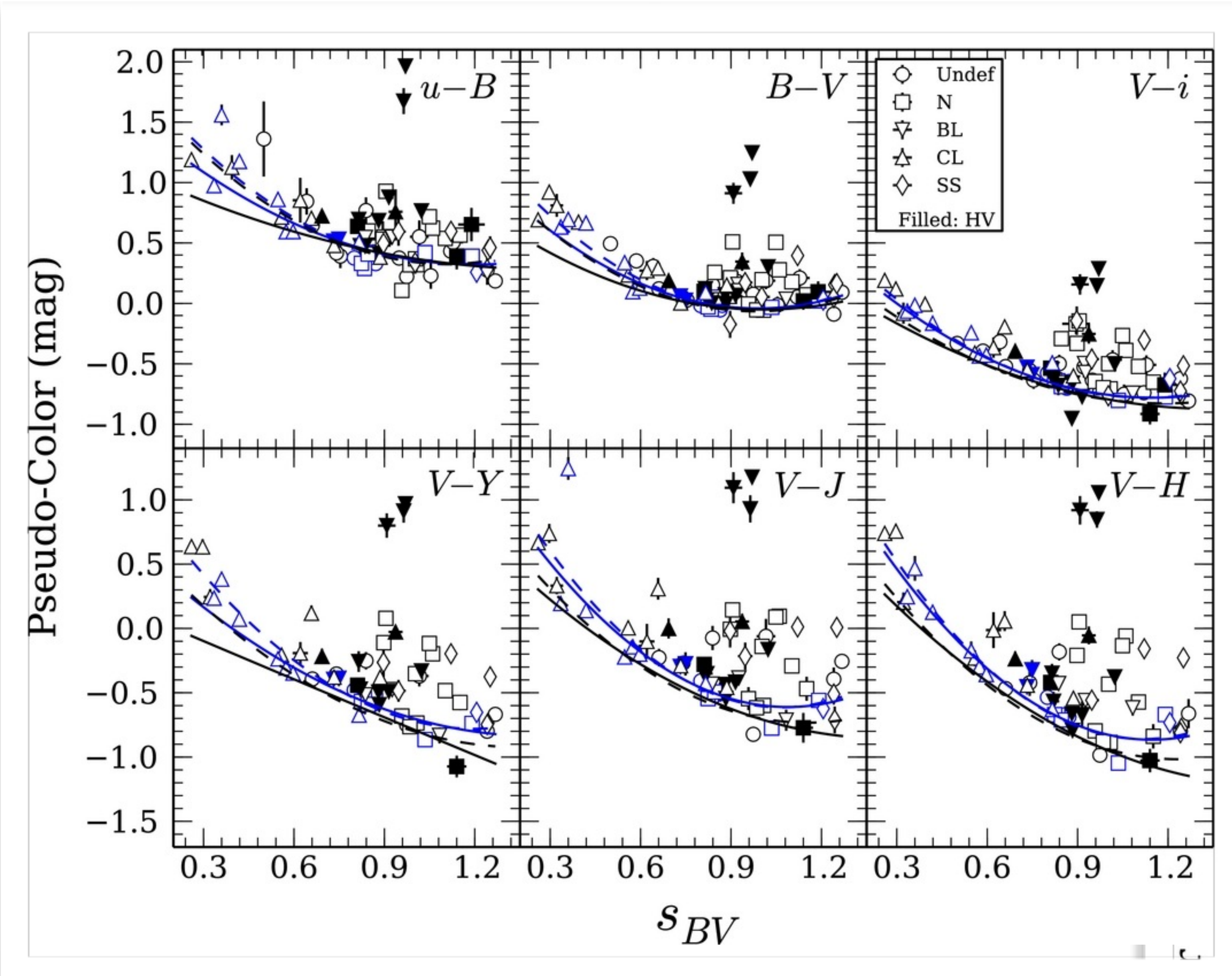


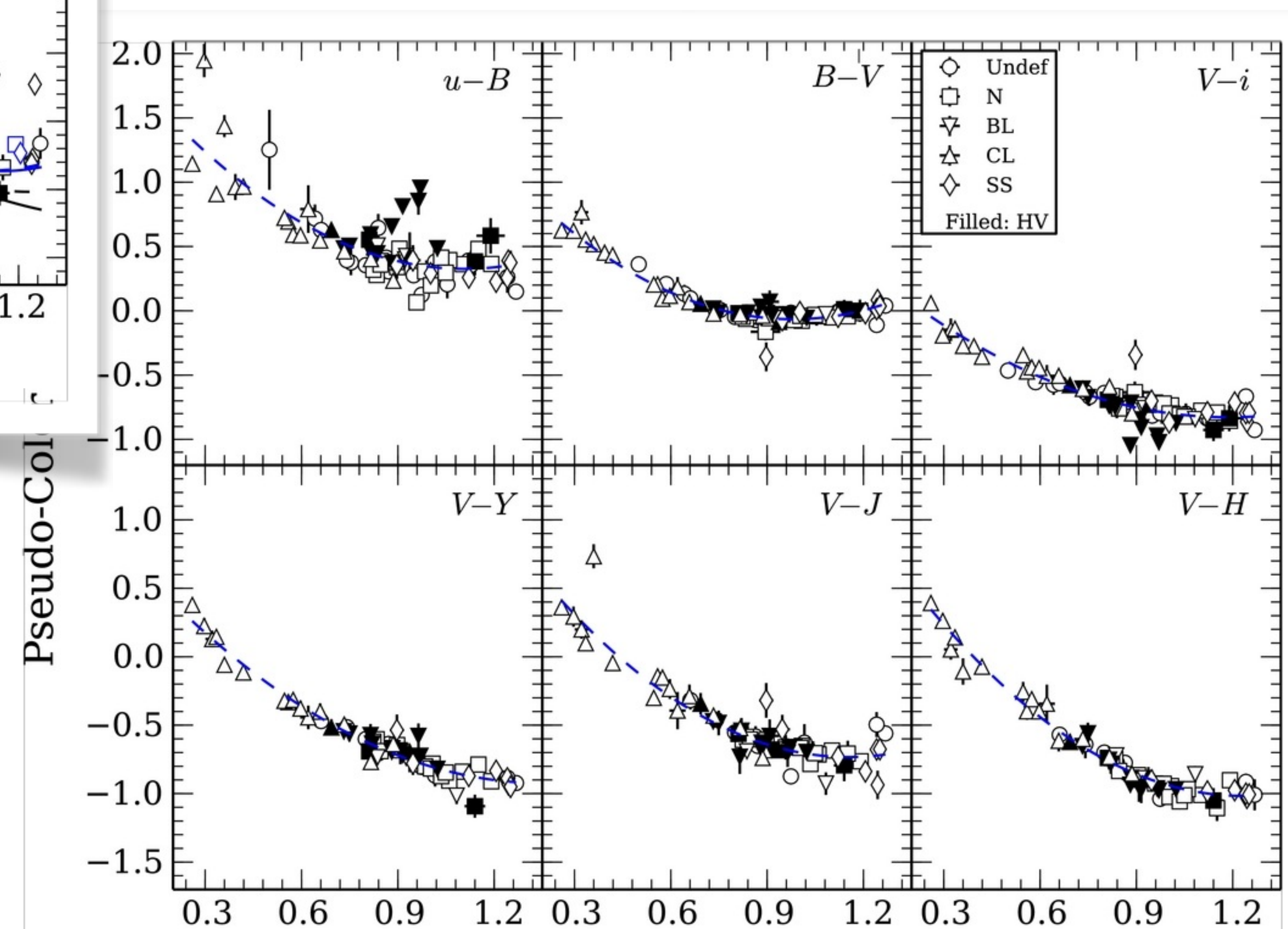
Burns et al. (2014)

Estimating SN Ia Color Excesses



Maximum Light Color vs. Decline Rate Relations

- The observed *(B-V)* colors of SNe Ia exhibit a “blue edge” when plotted vs. decline rate



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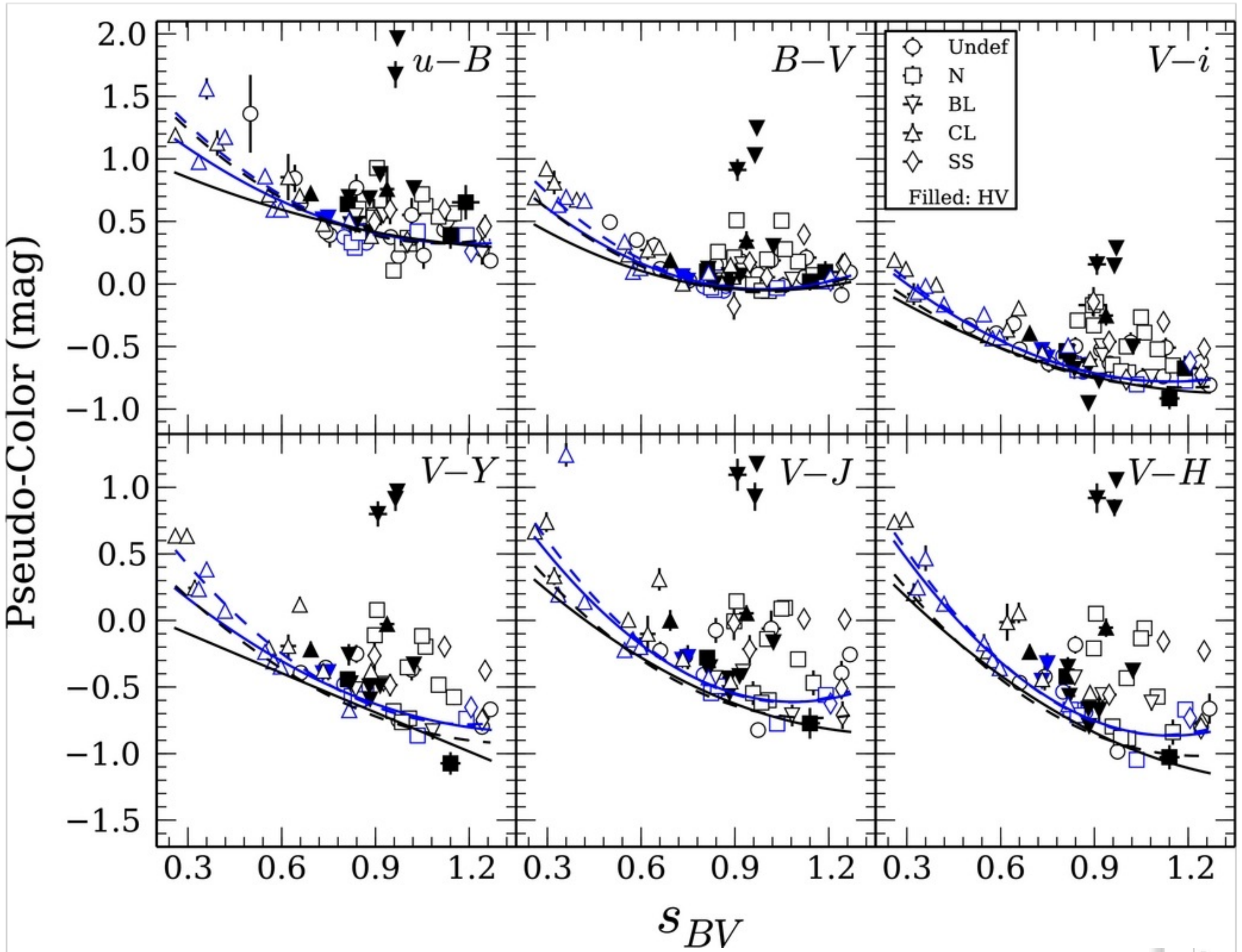
Estimating SN Ia Color Excesses



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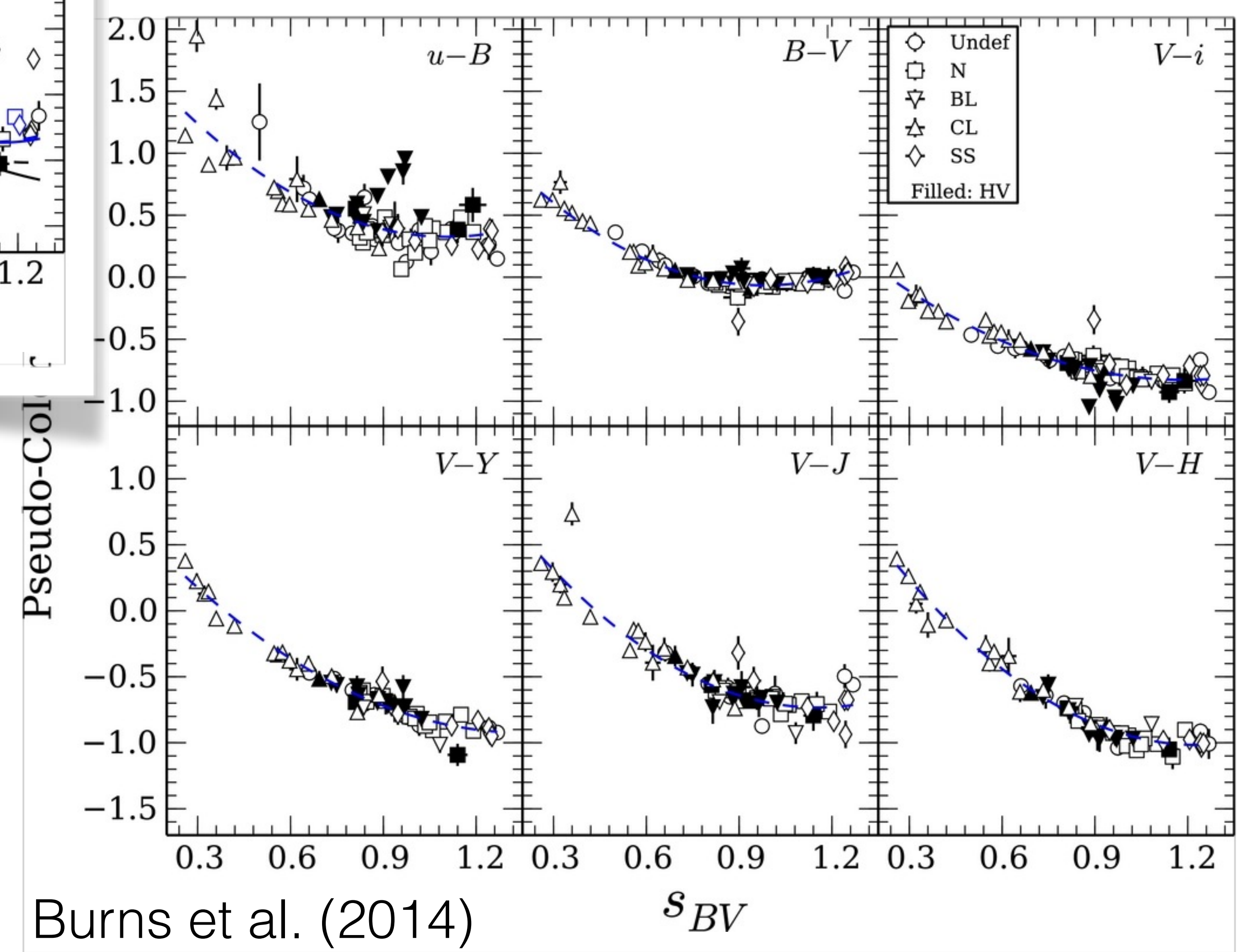
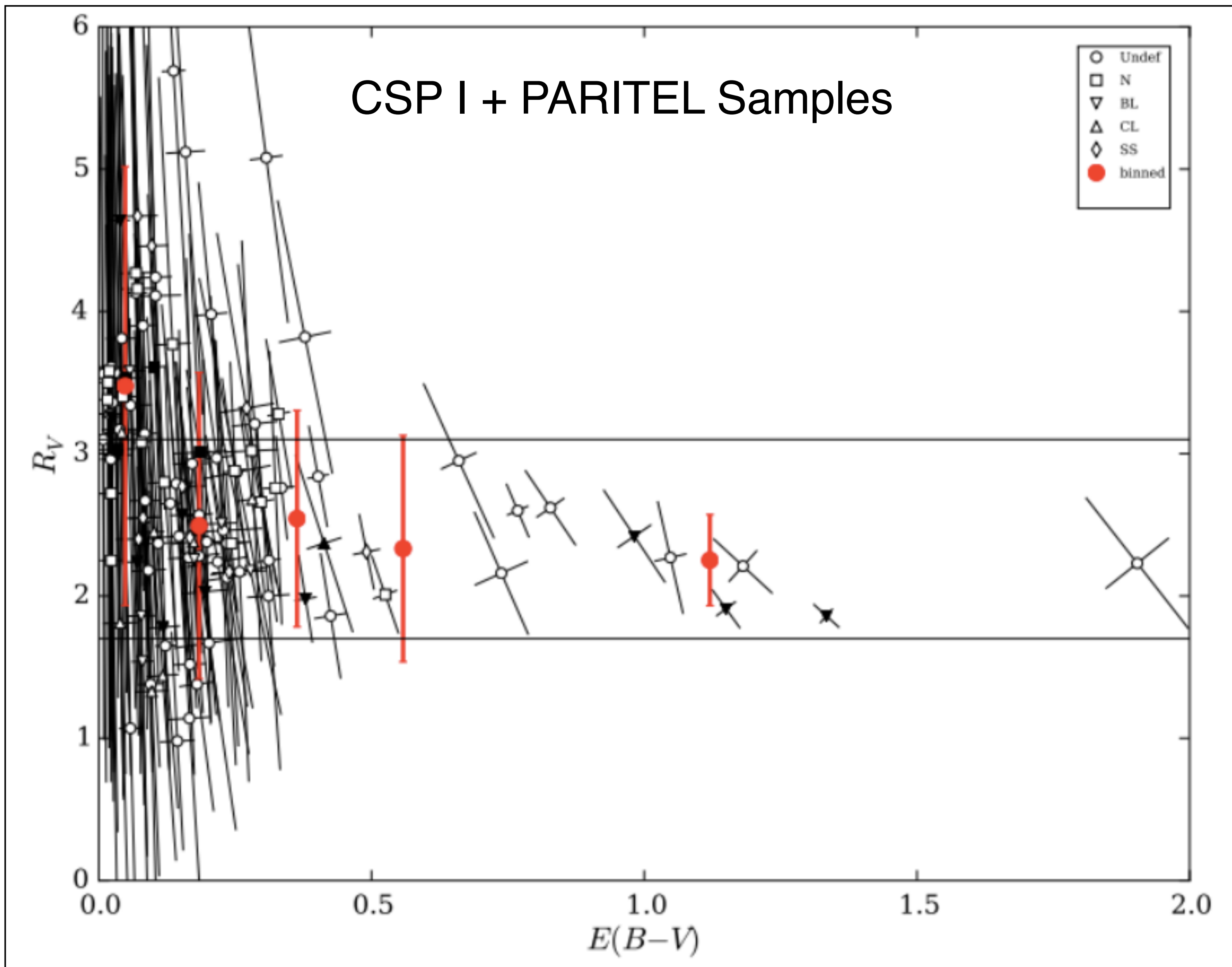


Burns et al. (2014)

- Color excesses can be measured with respect to these blue edges
- These, in turn, can be used to estimate A_V and R_V for an assumed reddening law
- Optical + Near-IR photometry critical

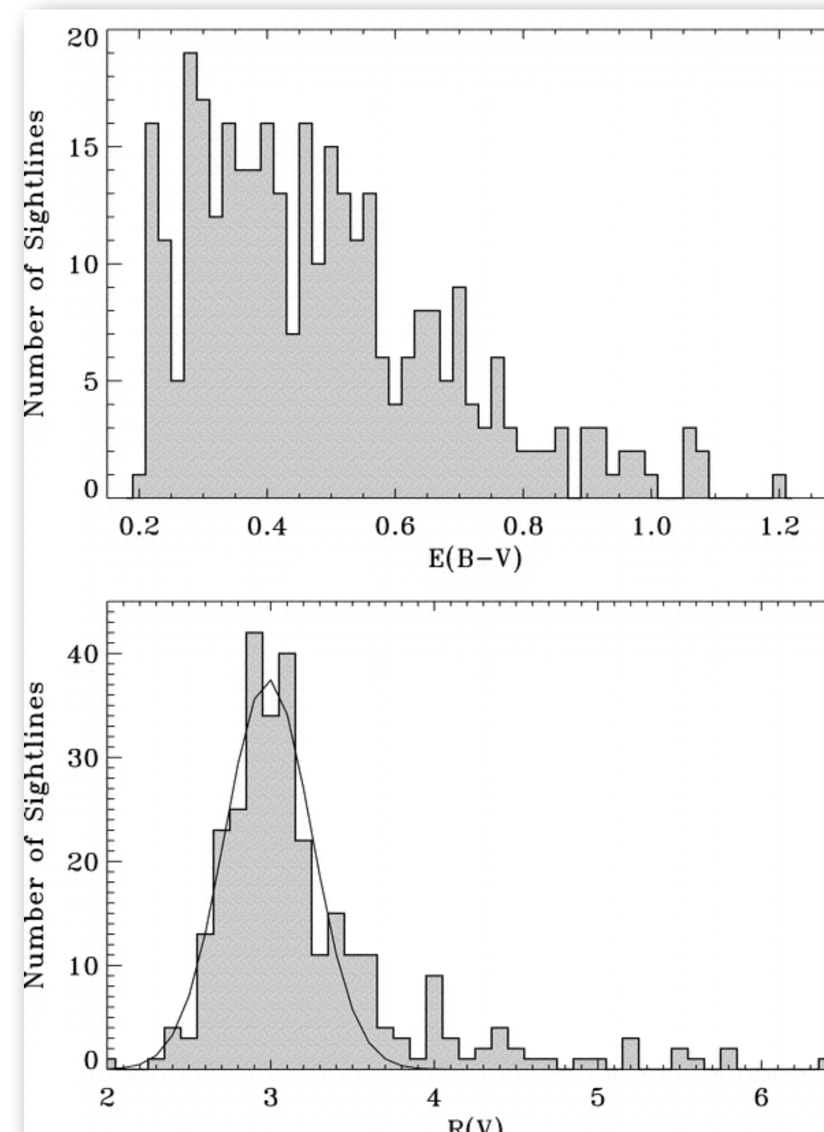
The Value of R_V is a Function of $E(B-V)$

- Low-extinction SNe Ia tend to have $R_V \sim 3$
- High-extinction SNe Ia tend to have $R_V \sim 2$; these SNe are also mostly HV events



Burns et al. (2017, in preparation; see also Chotard et al. 2011; Mandel et al. 2011)

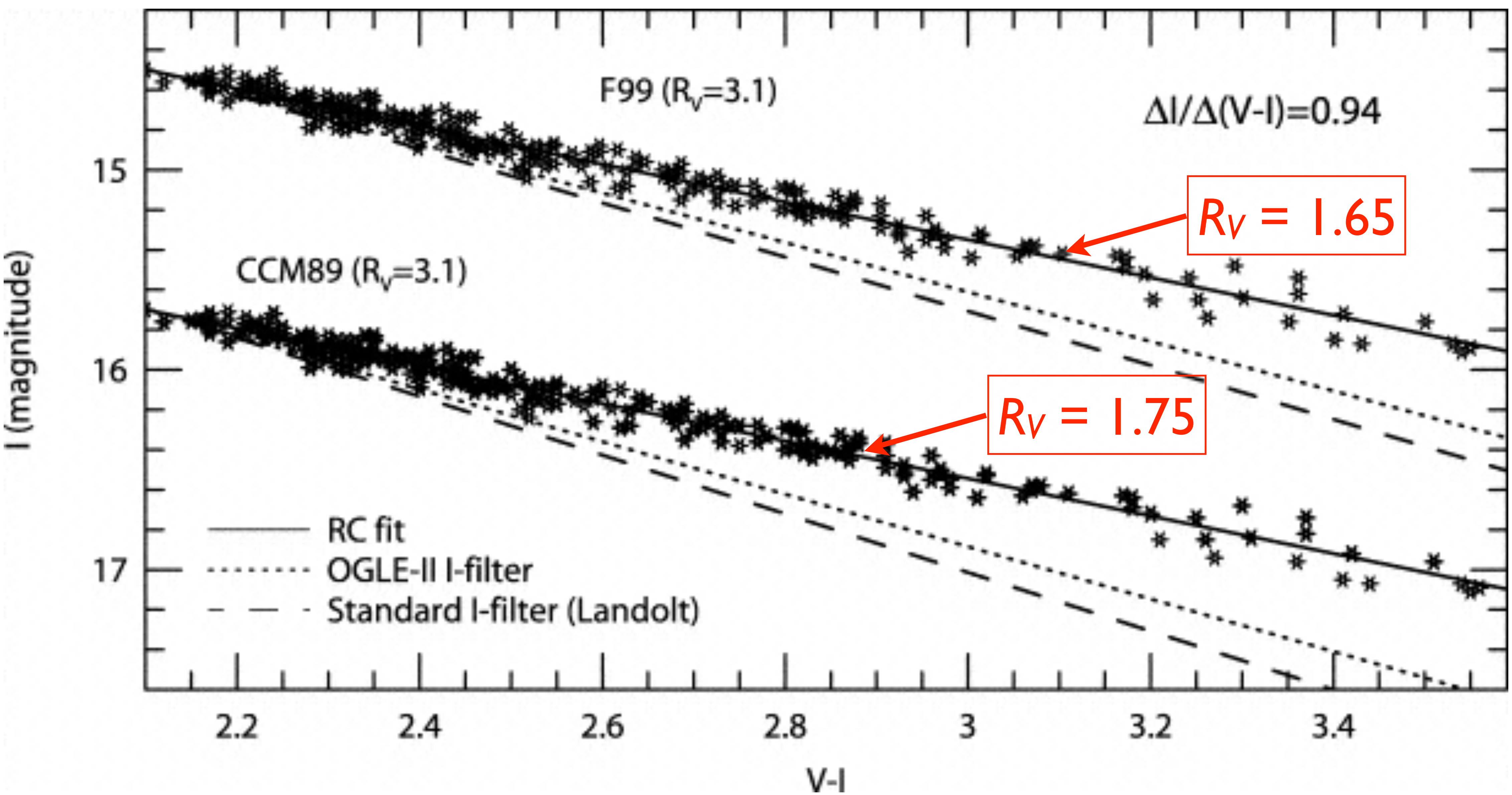
Fitzpatrick (1999) Reddening Law



Fitzpatrick & Massa 2015

Are Such Low Values of R_V Found in the Milky Way?

Unusually low values of R_V are observed toward the Galactic bulge (Udalski 2003; Nataf et al. 2013)



Udalski (2003)

Are Such Low Values of R_V Found in the Milky Way?

HD 210121: High-Galactic Latitude Molecular Cloud
Interstellar extinction curve fitting gives $R_V = 2.01 \pm 0.15$
(Fitzpatrick & Massa 2007)

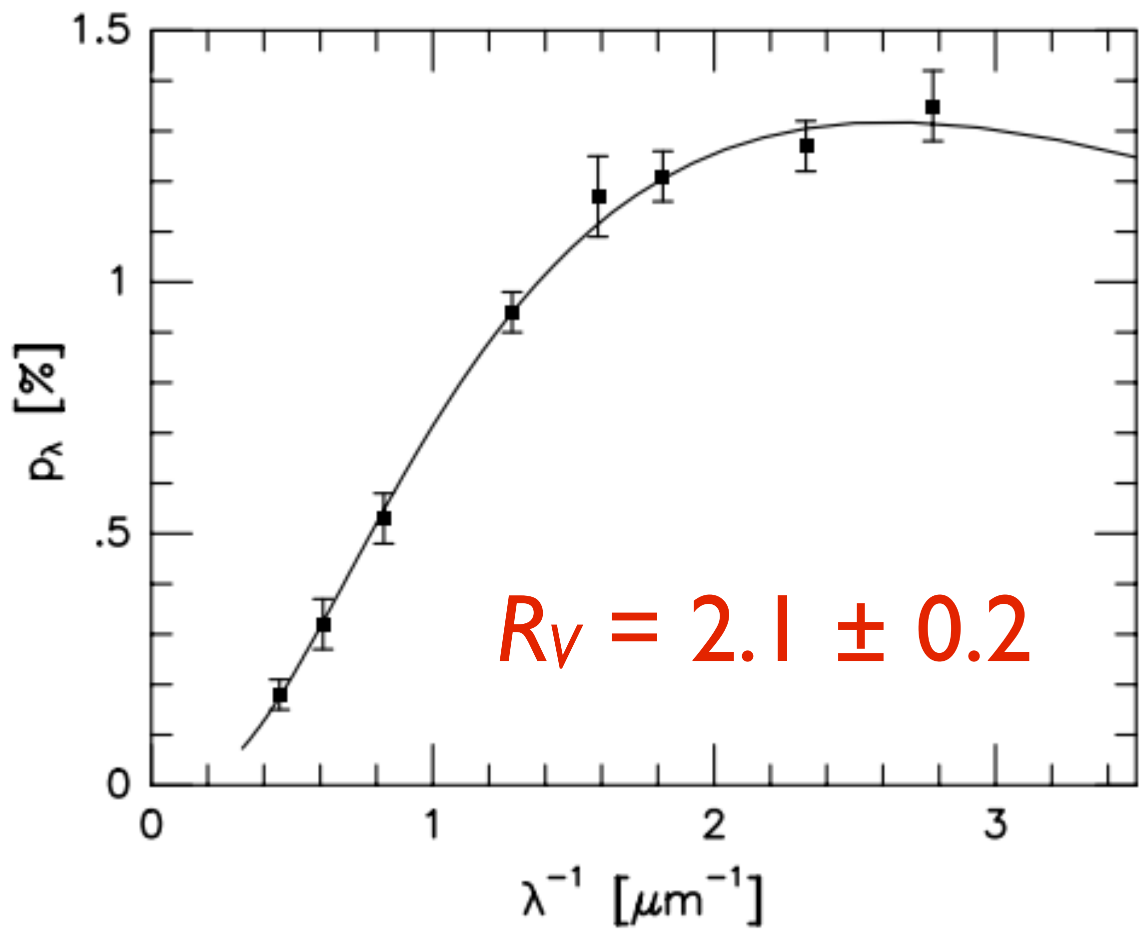
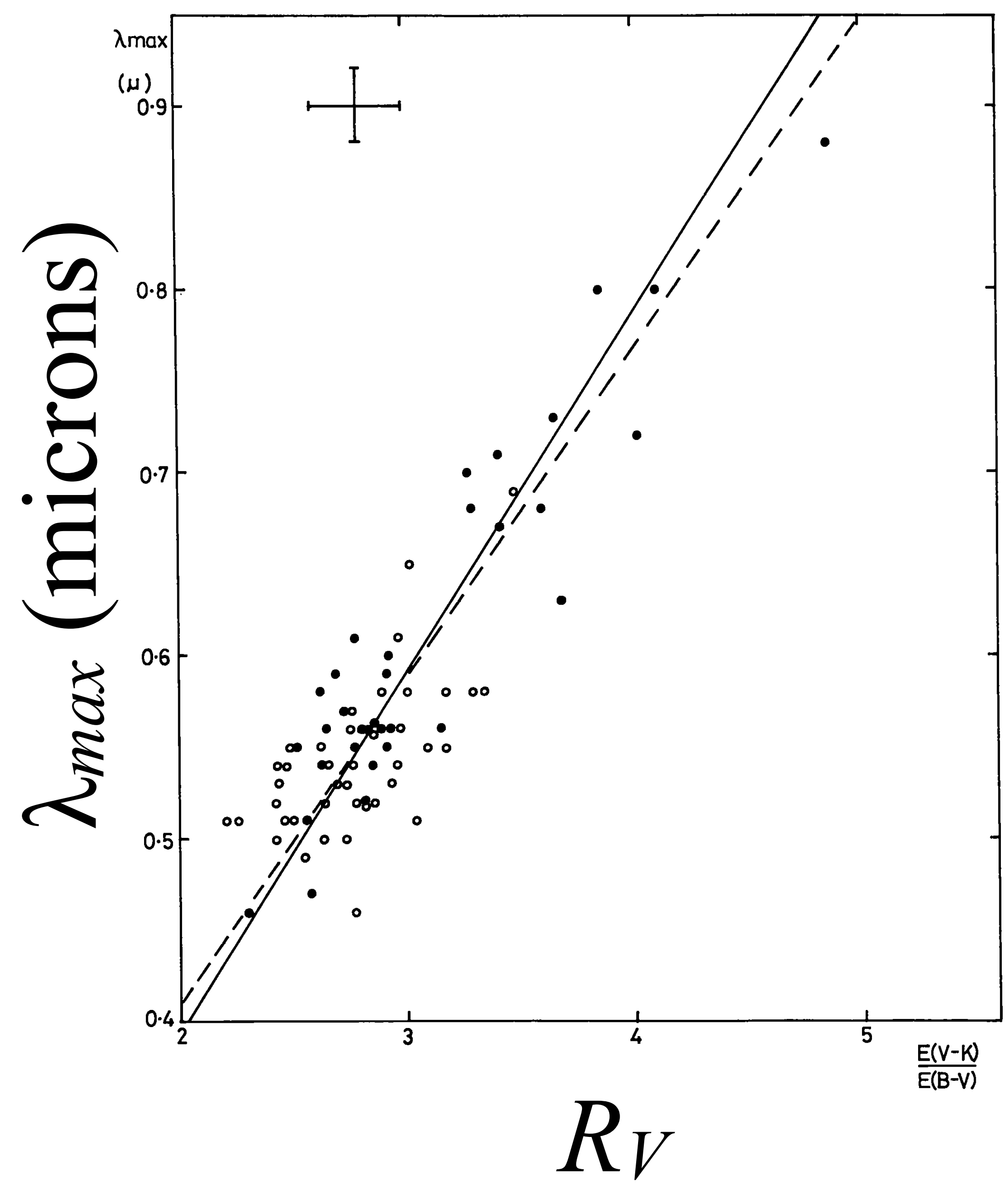


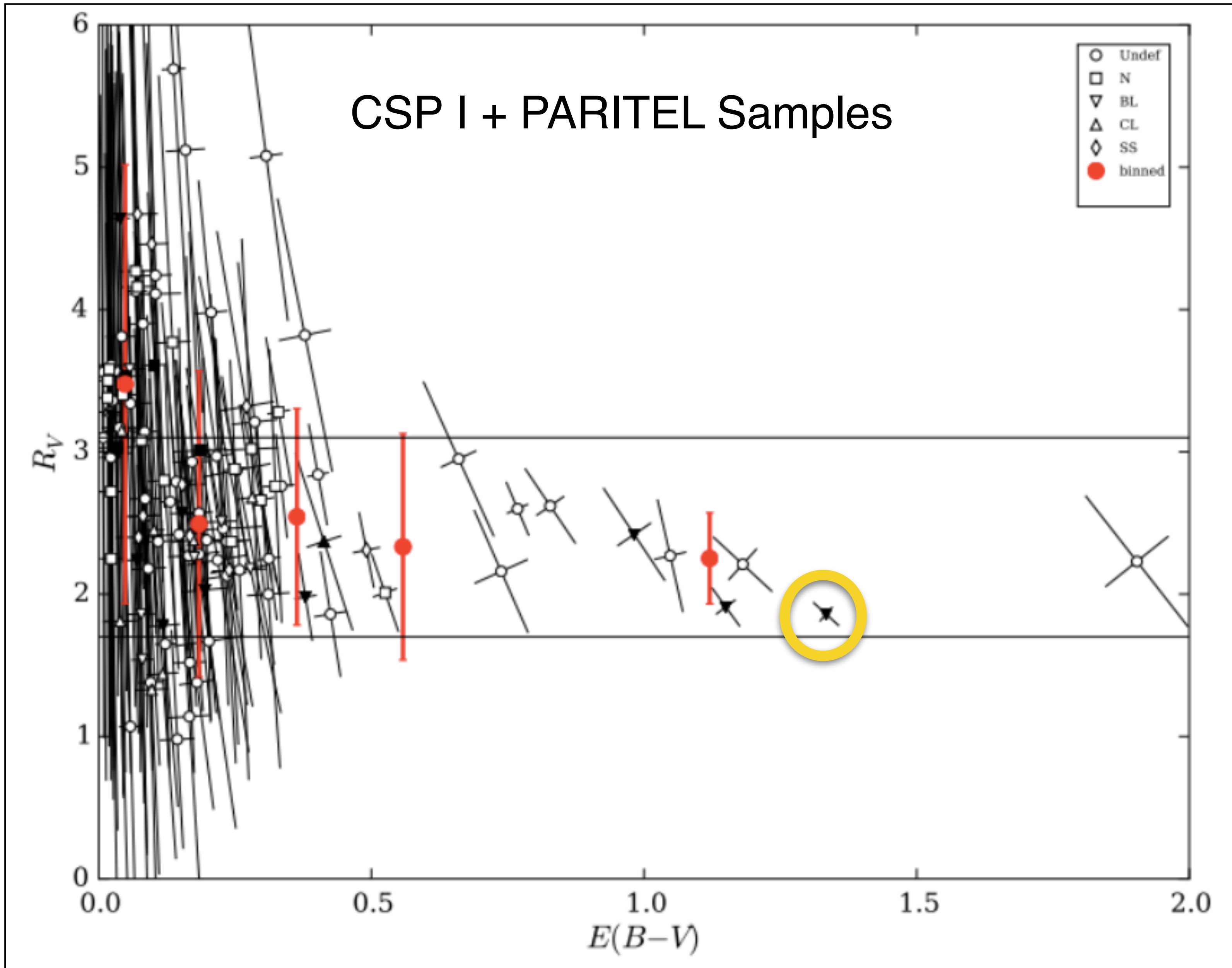
FIG. 2.—Interstellar polarization curve for HD 210121, based on data from Table 1 (*squares with error bars*). The curve is the best three-parameter fit obtained with the Serkowski formula ($p_{max} = 1.32 \pm 0.04\%$; $\lambda_{max} = 0.38 \pm 0.03$ μm ; $K = 0.66 \pm 0.09$).

Larson et al. (1996)

Whittet et al. 1978



SN 2006X in M100

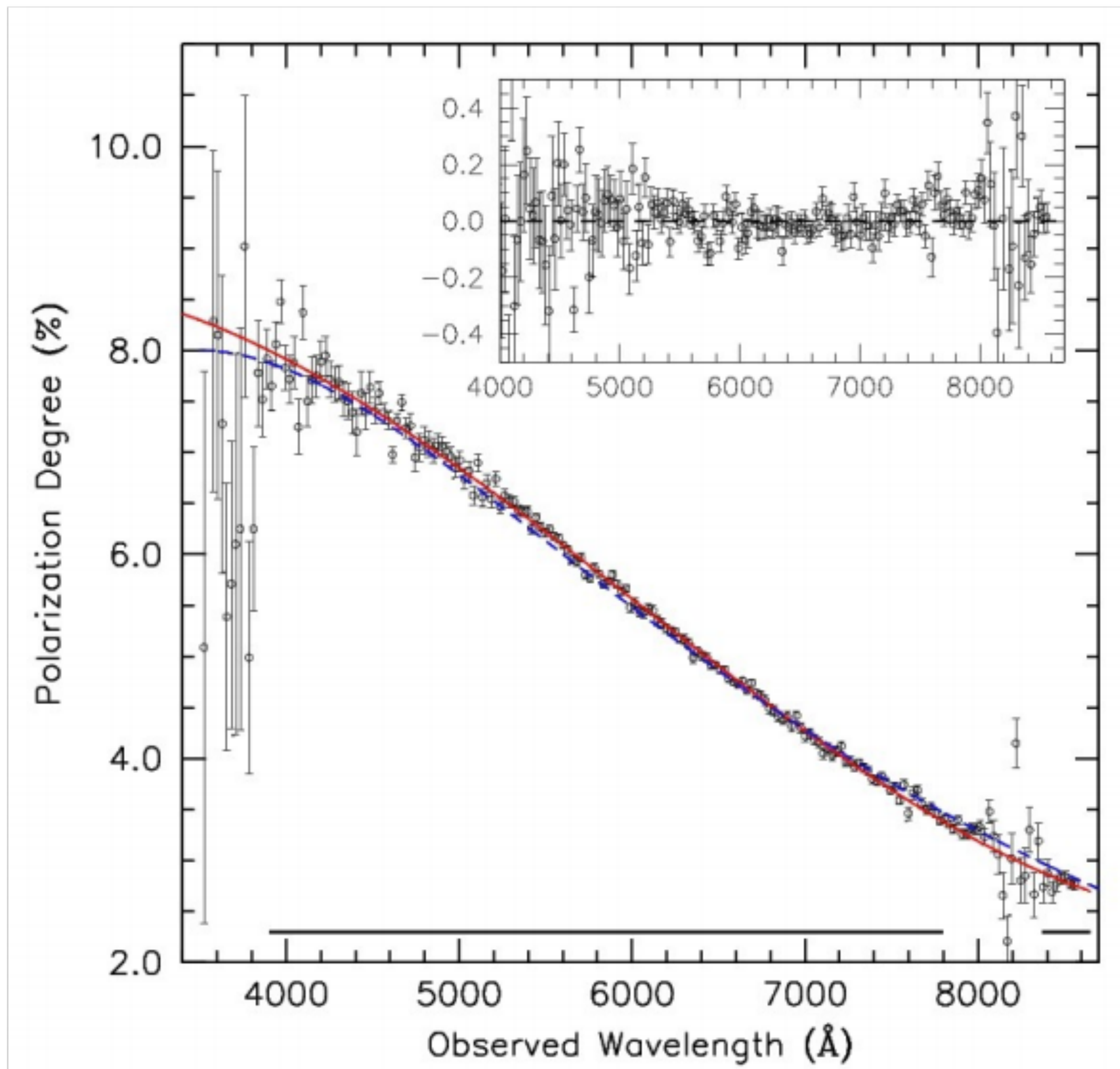


Burns et al. (2017)

- SN 2006X was a heavily reddened SN Ia that appeared in a spiral arm of M100
- Echelle spectra revealed strong interstellar lines typical of cold molecular clouds

Spectropolarimetry of SN 2006X

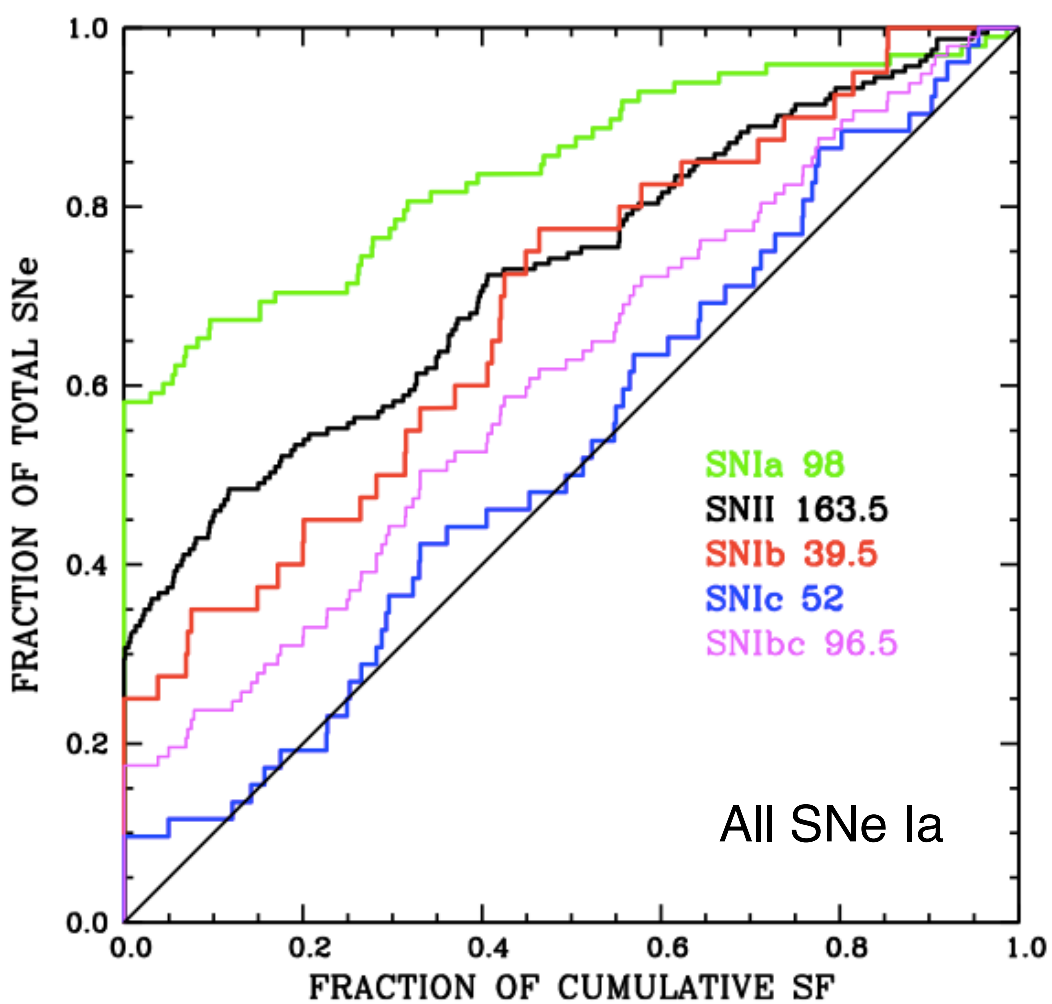
Measurements of the continuum polarization of SN 2006X peak at ≤ 3000 Å, implying $R_V < 2$ (cf. $R_V \sim 2$ from colors)

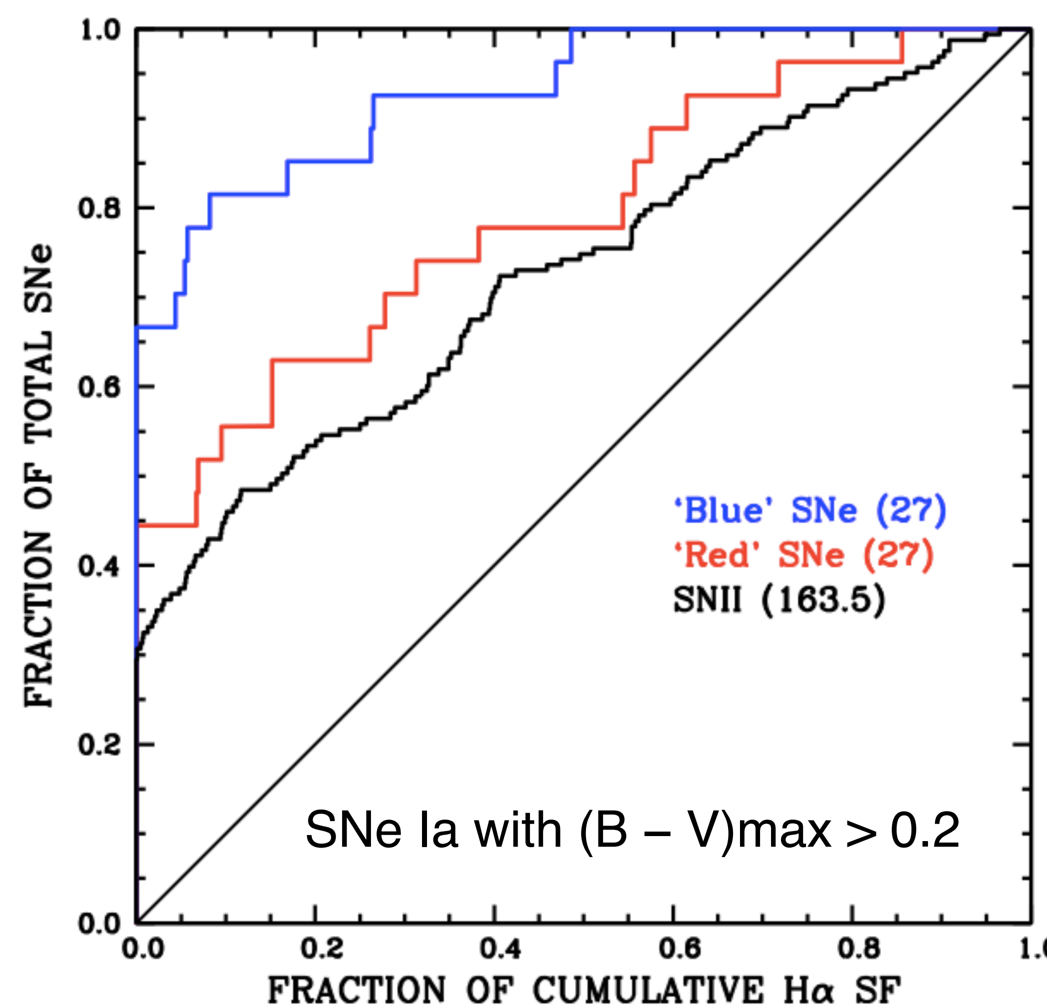


Patat et al. (2009)

SNe Ia in Star-Forming Galaxies

- SNe Ia show the lowest degree of association with Hα emission of all supernova (SN) types
- However, dividing SNe by their (B – V) colors at maximum light, ‘redder’ events show a higher degree of association with H II regions and are found more centrally within hosts

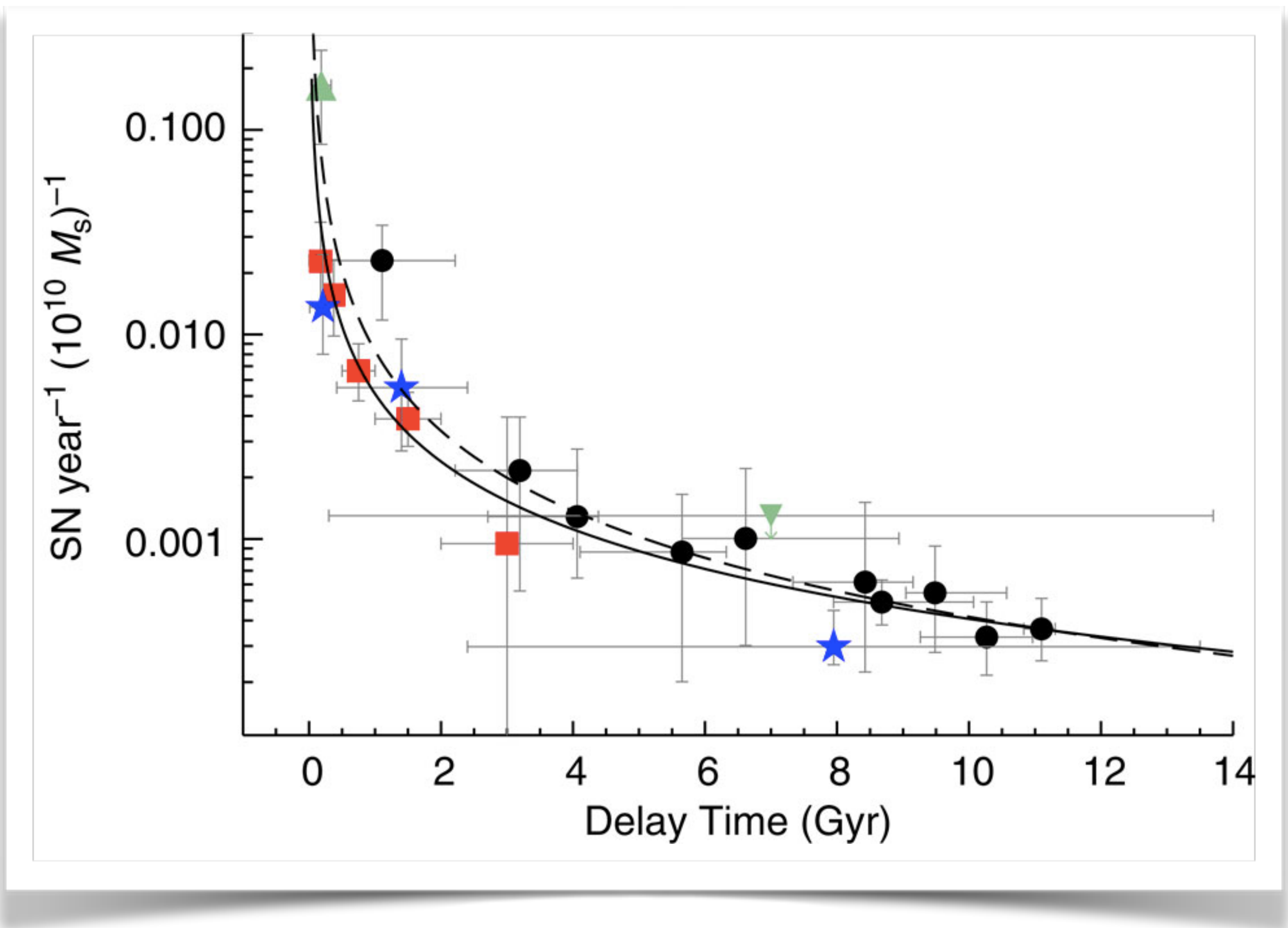




Anderson et al. (2015)

SNe Ia Rates

- The delay time between the birth of the progenitor system and the explosion as a SN Ia (the “delay time distribution”, or DTD) is proportional to t^{-1}
- The observed SN Ia rate decreases with increasing DTD



Howell (2011, adapted from Maoz et al. 2010)

SNe Ia Rates

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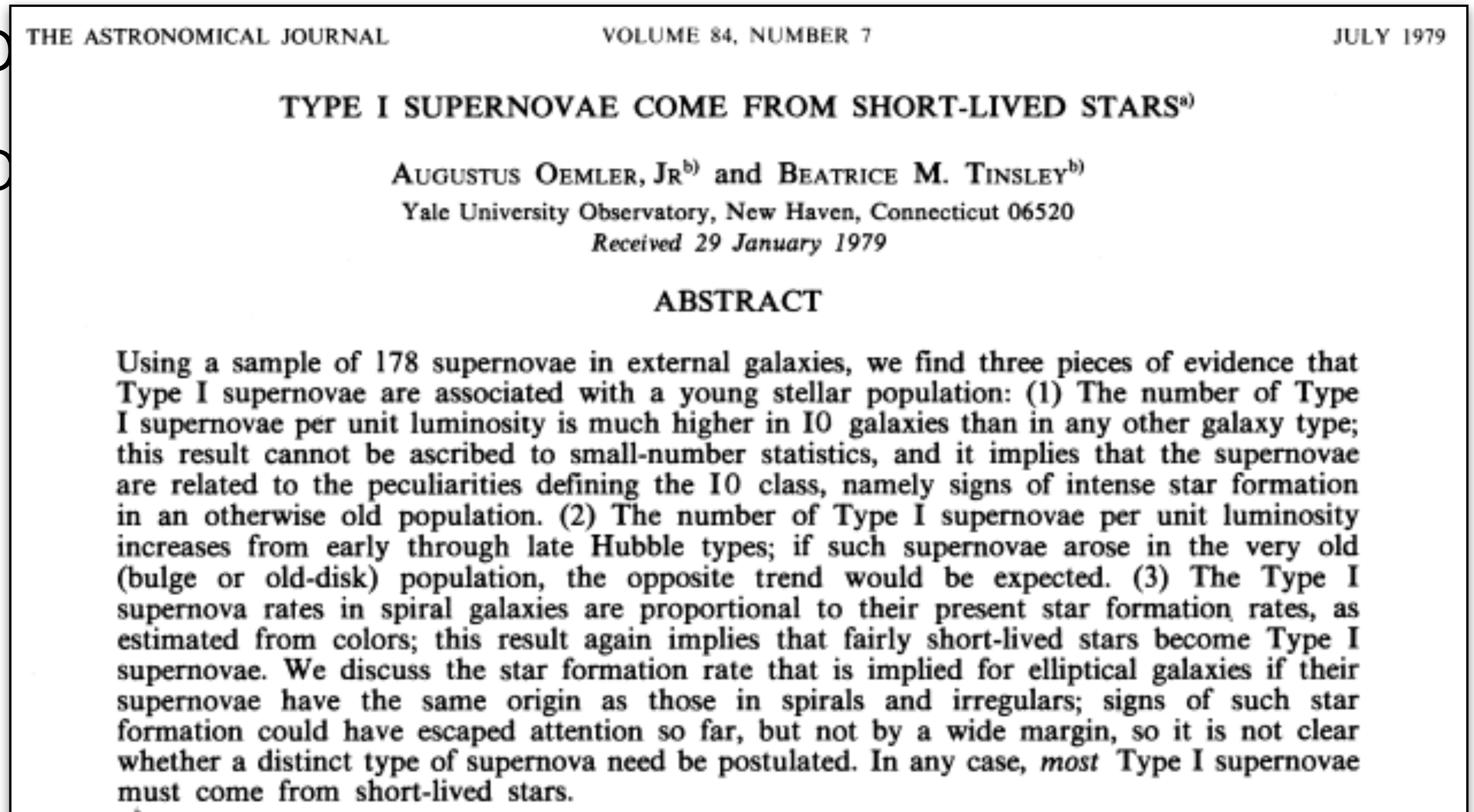

THE ASTRONOMICAL JOURNAL VOLUME 84, NUMBER 7 JULY 1979

TYPE I SUPERNOVAE COME FROM SHORT-LIVED STARS[a)]

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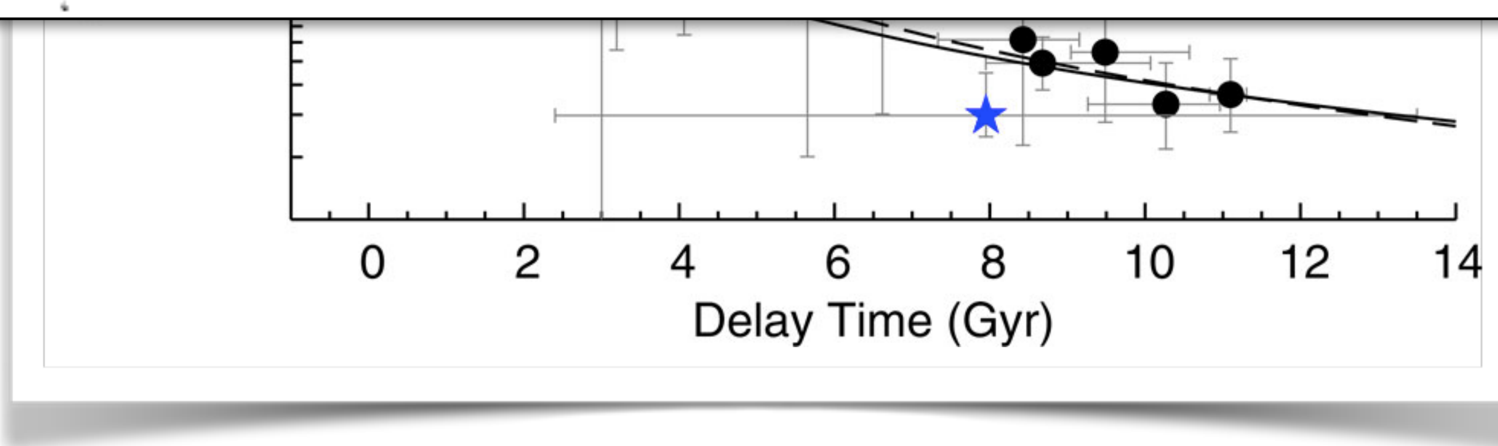
Received 29 January 1979

ABSTRACT

Using a sample of 178 supernovae in external galaxies, we find three pieces of evidence that Type I supernovae are associated with a young stellar population: (1) The number of Type I supernovae per unit luminosity is much higher in I0 galaxies than in any other galaxy type; this result cannot be ascribed to small-number statistics, and it implies that the supernovae are related to the peculiarities defining the I0 class, namely signs of intense star formation in an otherwise old population. (2) The number of Type I supernovae per unit luminosity increases from early through late Hubble types; if such supernovae arose in the very old (bulge or old-disk) population, the opposite trend would be expected. (3) The Type I supernova rates in spiral galaxies are proportional to their present star formation rates, as estimated from colors; this result again implies that fairly short-lived stars become Type I supernovae. We discuss the star formation rate that is implied for elliptical galaxies if their supernovae have the same origin as those in spirals and irregulars; signs of such star formation could have escaped attention so far, but not by a wide margin, so it is not clear whether a distinct type of supernova need be postulated. In any case, *most* Type I supernovae must come from short-lived stars.



Howell (2011, adapted from Maoz et al. 2010)

Conclusions

1. Whatever mechanism(s) can make SNe Ia, they must in combination reproduce the following properties:

- The observed smoothness of the luminosity-decline rate relation
- The range of ^{56}Ni masses underlying this sequence
- The dependence of explosion rates and light curve widths on galaxy mass and star formation rate
- The power law dependence of the delay time distribution

Conclusions (cont.)

2. In general, the unsuccessful search for evidence of the companions to normal SNe Ia would seem not to favor the single-degenerate model

- We need to obtain high s/n ratio imaging at UV and optical wavelengths of many more SNe Ia within hours of explosion to get a better idea of what is going on here
- This will require transient searches with cadences of hours, not days
- Such observations will also tell us more about the explosion physics (e.g., ^{56}Ni mixing)

Conclusions (cont.)

3. SN Ia colors at maximum can be used to determine host galaxy reddenings (A_V and R_V)

- The majority of SNe Ia are characterized by low-to-moderate dust extinction ($A_V < 1$ mag)
- The Value of R_V is a Function of *E(B-V),* with SNe with low reddenings consistent with $R_V \sim 3$, and SNe with high reddenings typically having $R_V \sim 2$
- Many highly reddened SNe Ia are associated with molecular clouds and regions of active star formation


Thank you!
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