Recent Advances in our Understanding of Type Ia Supernovae

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CARNEGIE INSTITUTION FOR SCIENCE

National Science Foundation
WHERE DISCOVERIES BEGIN

OCIW, July 2015

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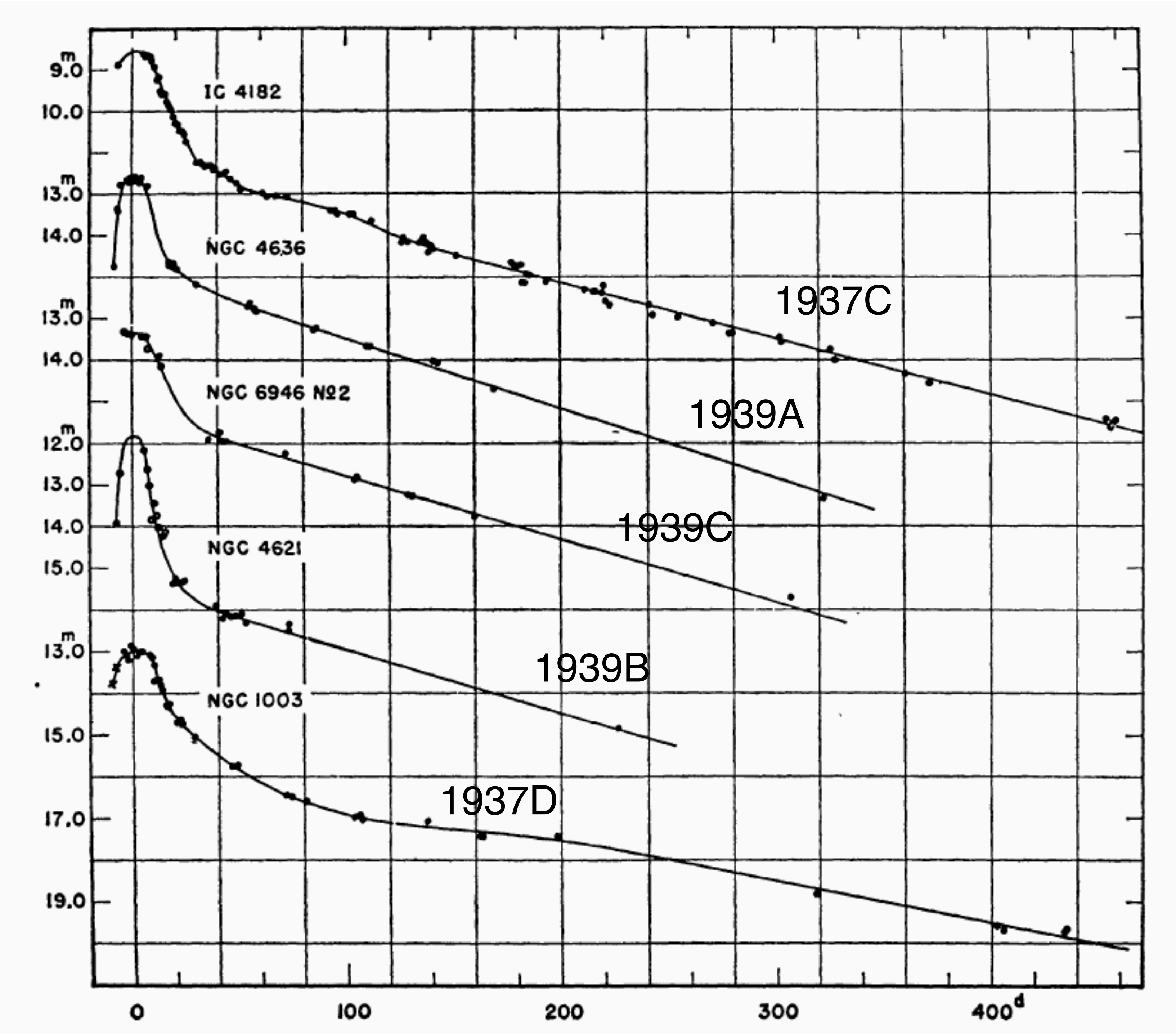
Outline

1. Basic overview
   a. Observational properties of SNe Ia
   b. Progenitor models
2. Recent observational advances
3. Conclusions

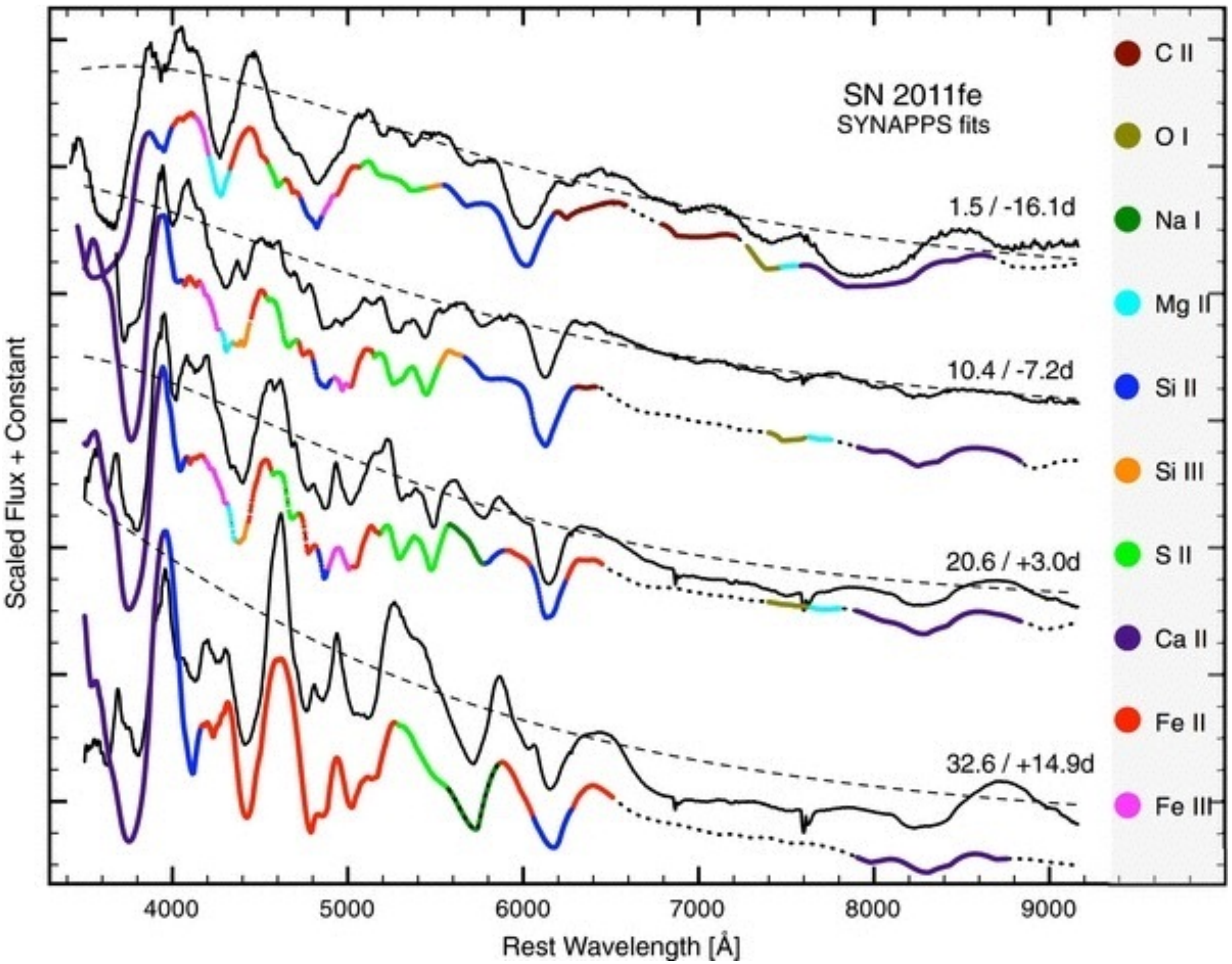
Type Ia Supernovae (SNe Ia): Observations



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 proposed using them as cosmological standard candles, and until 1986, most researchers assumed SNe Ia were identical

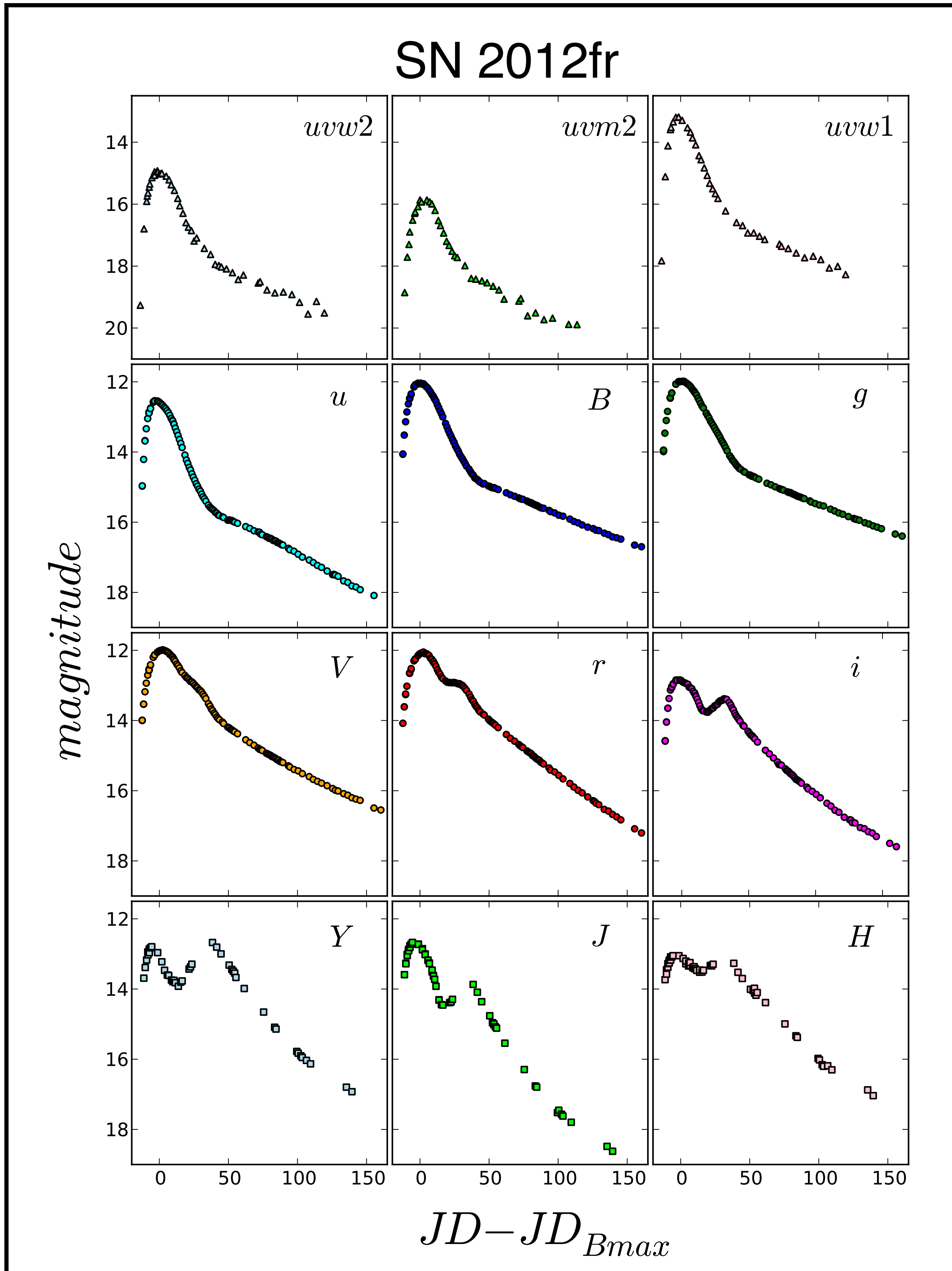
SN Ia Optical Spectral Evolution



Parrent et al. 2012

- At early phases, the spectra of SNe Ia are dominated by features due to intermediate mass elements (Ca, Si, S, Mg)
- Within a few weeks after maximum light, the spectra show mostly features due to Fe-peak elements
- At all phases, no evidence for H is observed

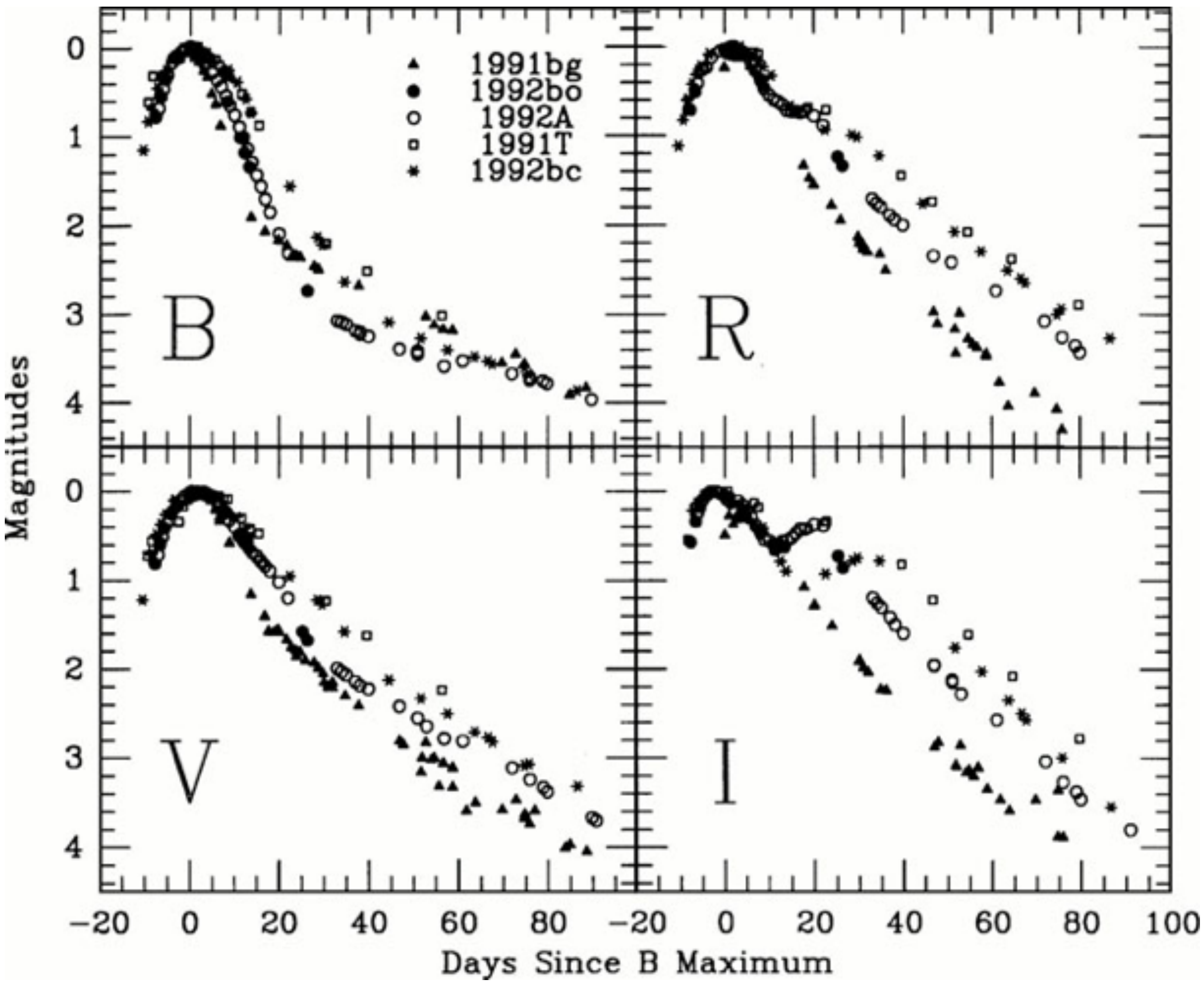
SN Ia UV/Optical/Near-IR Light Curves



- The luminosity of the SN is powered by the radioactive decay of ^{56}Ni produced in the explosion
- $^{56}Ni \Rightarrow ^{56}Co \Rightarrow ^{56}Fe$
  6.1 days 77.2 days
- 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. 2015

SN Ia Optical Light Curves: Early Indications of Inhomogeneity

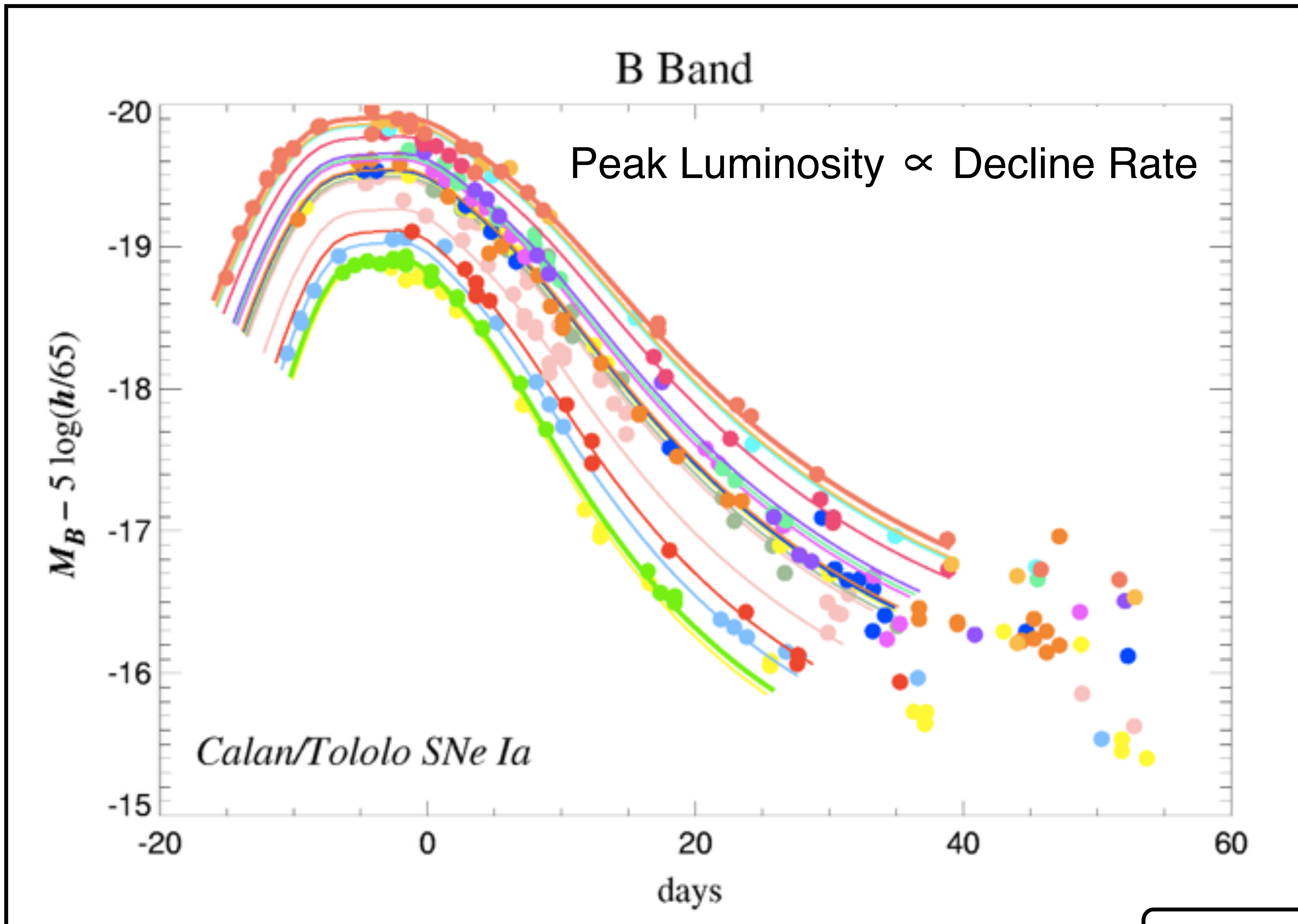


Suntzeff 1996

- CCD photometry in the late-1980's and early-1990's demonstrated that the light curves of SNe Ia displayed a range of decline rates
- The light-curve morphology in the NIR is markedly different from that in the optical with a pronounced secondary maximum in IY JHK

The Luminosity-Decline Rate Relation

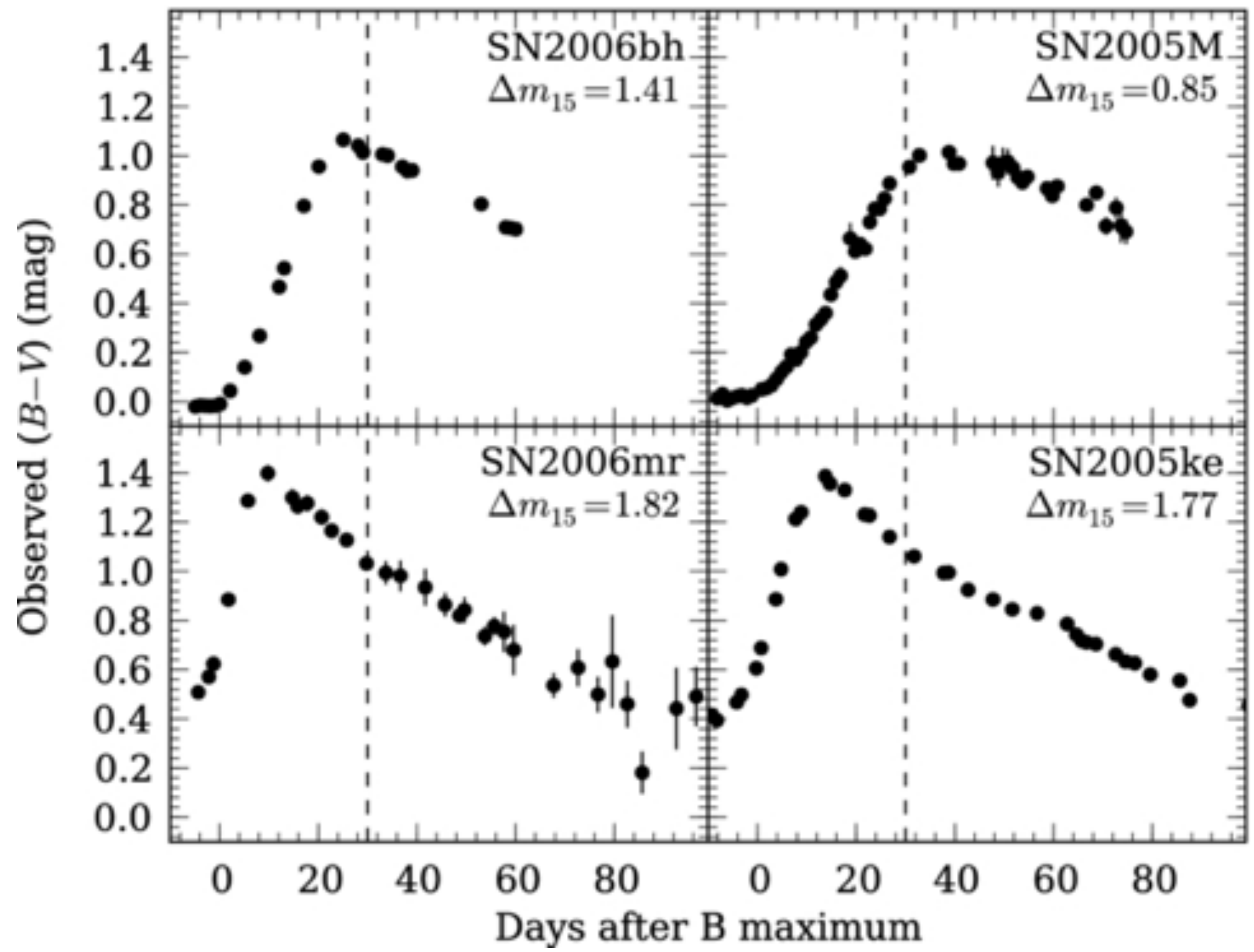
The luminosity-decline rate relation is a fundamental characteristic of "normal" SNe Ia



Perlmutter 2003

The Origin of the Luminosity-Decline Rate Relation

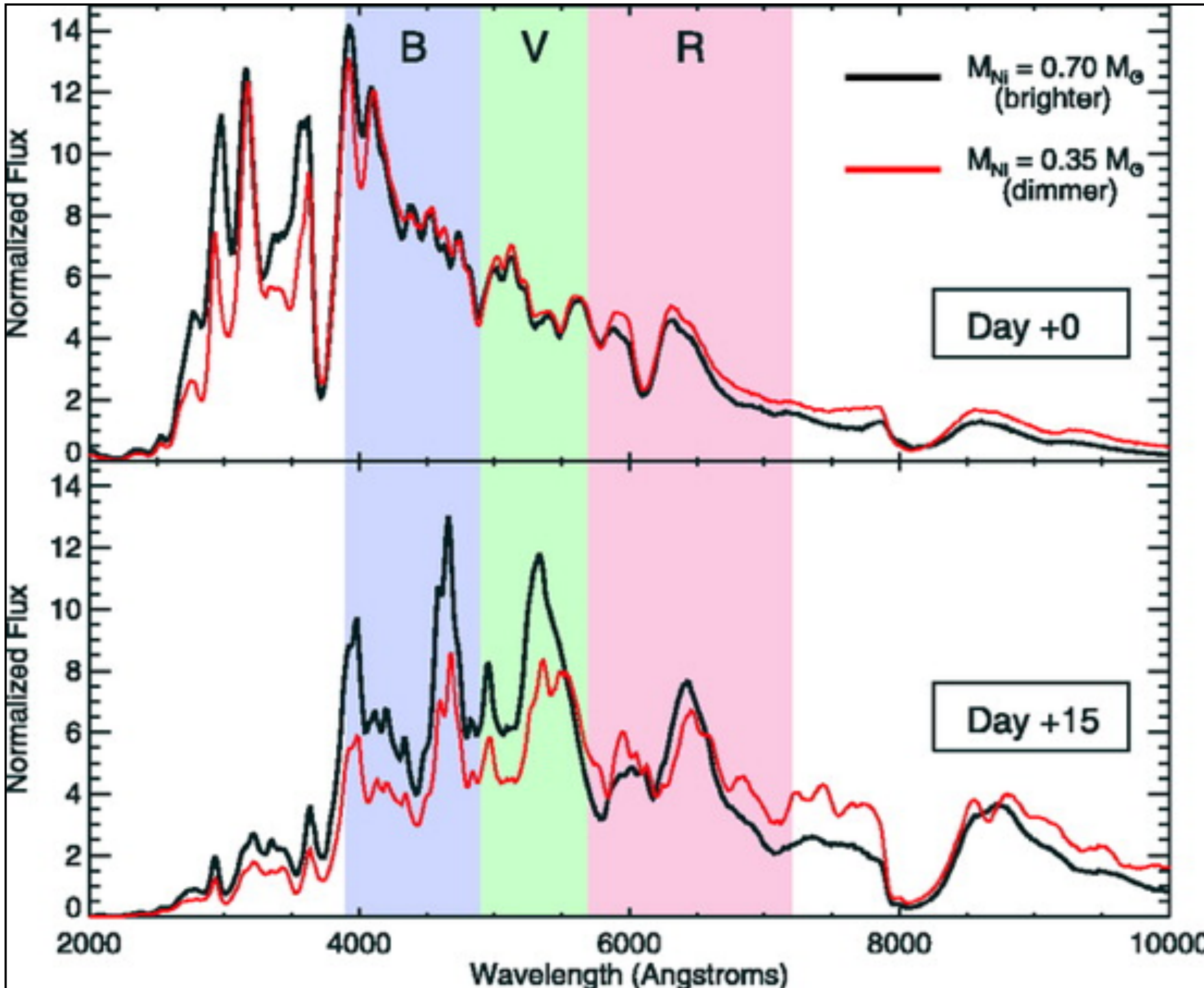
Following maximum light, the SN colors are increasingly governed by the blanketing of numerous Fe II and Co II lines that particularly affect the B band



Burns et al. 2014

Because dimmer SNe Ia are cooler, they experience an earlier onset of Fe III to Fe II recombination, resulting in more rapid evolution of the SN colors to the red

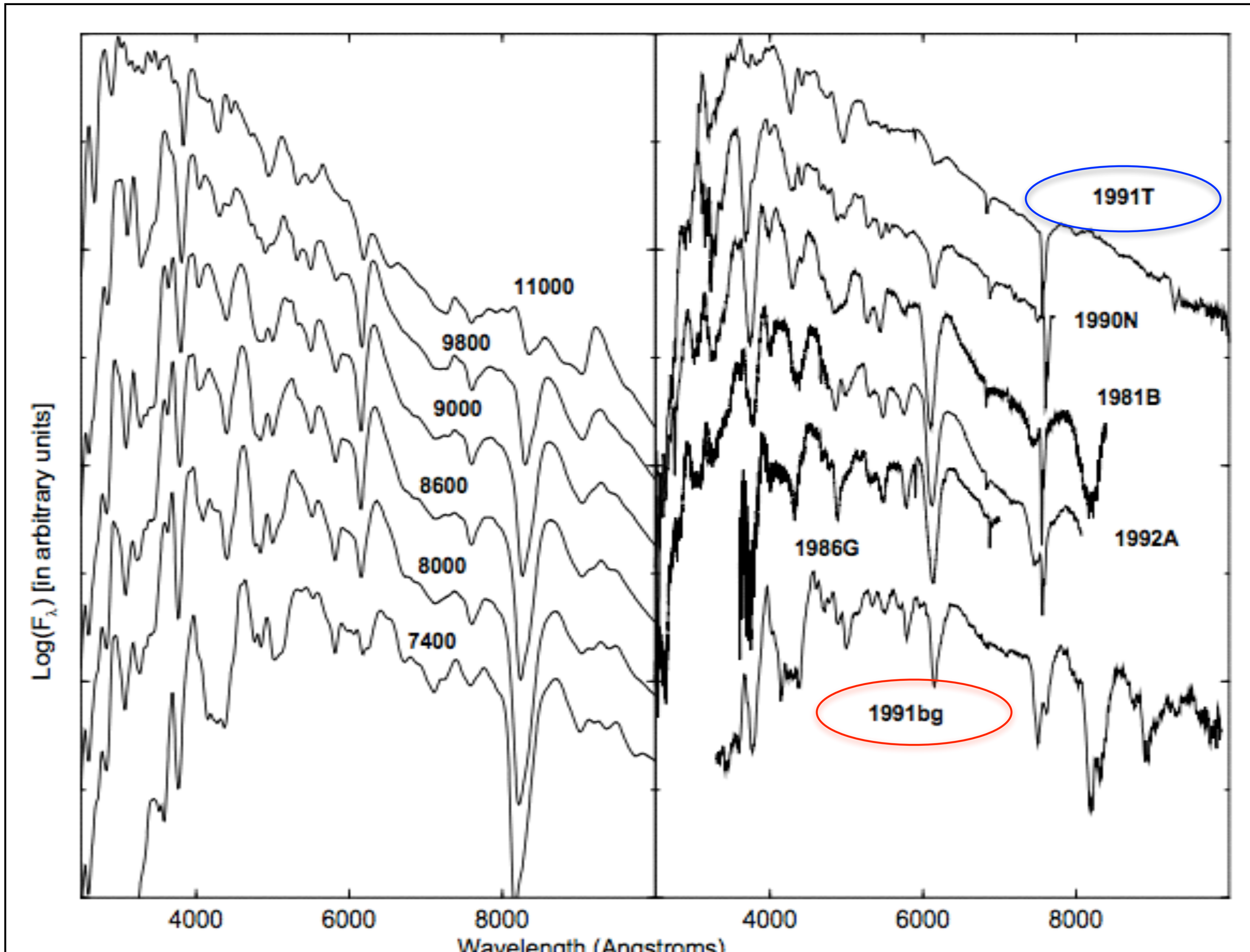
The Origin of the Luminosity-Decline Rate Relation



Kasen & Woosley 2007

The faster *B*-band decline rate of dimmer SNe Ia thus reflects their faster ionization evolution

Correlation of Decline Rate with ^{56}Ni Mass



$\Delta m_{15}(B)$

0.9

1.1

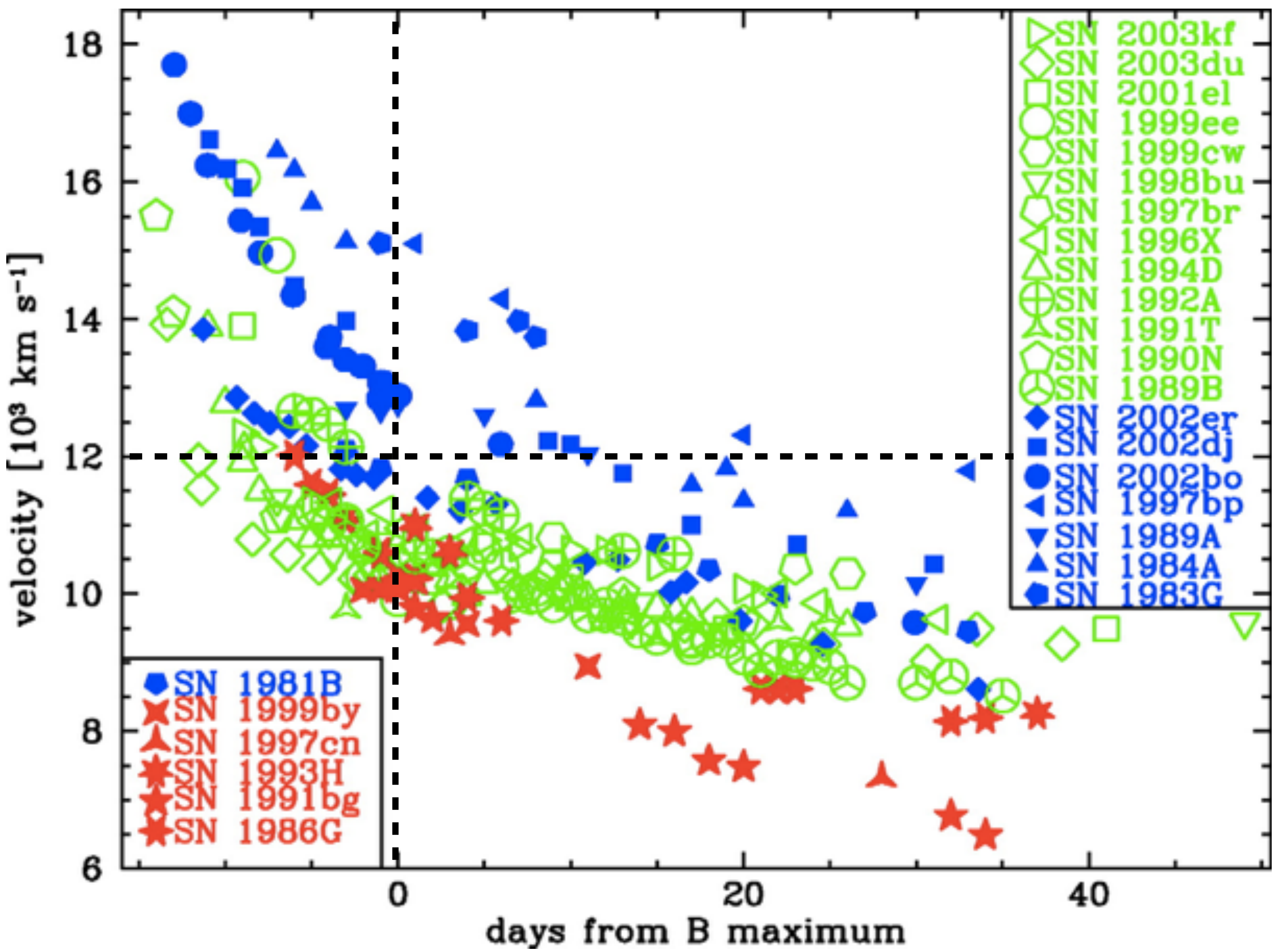
1.5

1.9

Nugent et al. 1995

A temperature sequence is observed as a function of decline rate, corresponding to the amount of ^{56}Ni produced in the explosion (typically 0.4-0.9 solar masses)

Evidence for Diversity from Si II λ6355 Expansion Velocities



Benetti et al. 2005

Benetti et al. (2005):

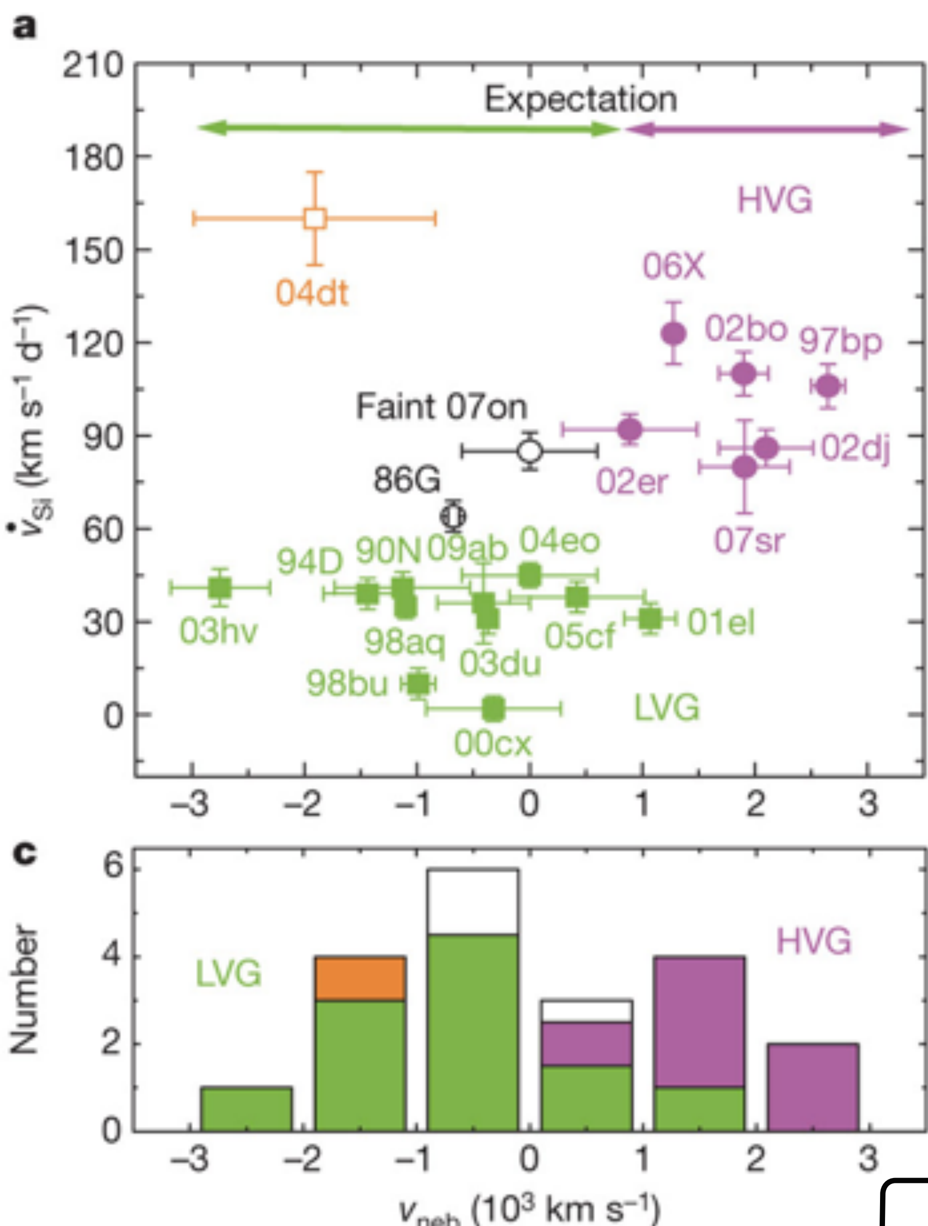
- "Low-velocity gradient" (LVG)
- "High-velocity gradient" (HVG)
- "FAINT"

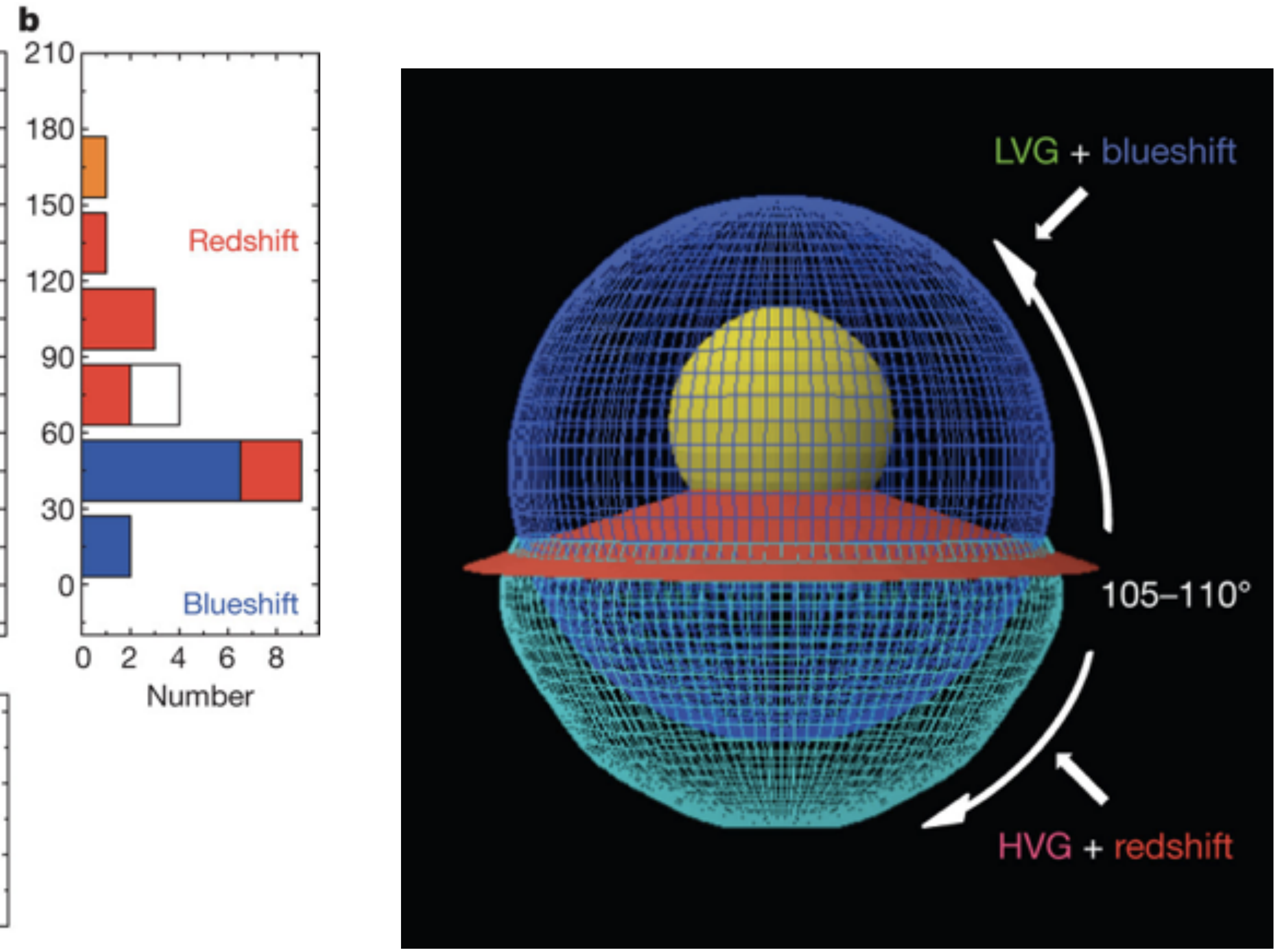
Wang et al. (2013):

- "Normal"
- "High-velocity" (HV)

Evidence for Asymmetrical Explosions

- Late phase nebular spectra of SNe Ia reveal large velocity shifts in the [Fe II] λ7155 and [Ni II] λ7388 emission lines
- The shifts are correlated with the velocity gradient of the Si II λ6355 absorption at early phases

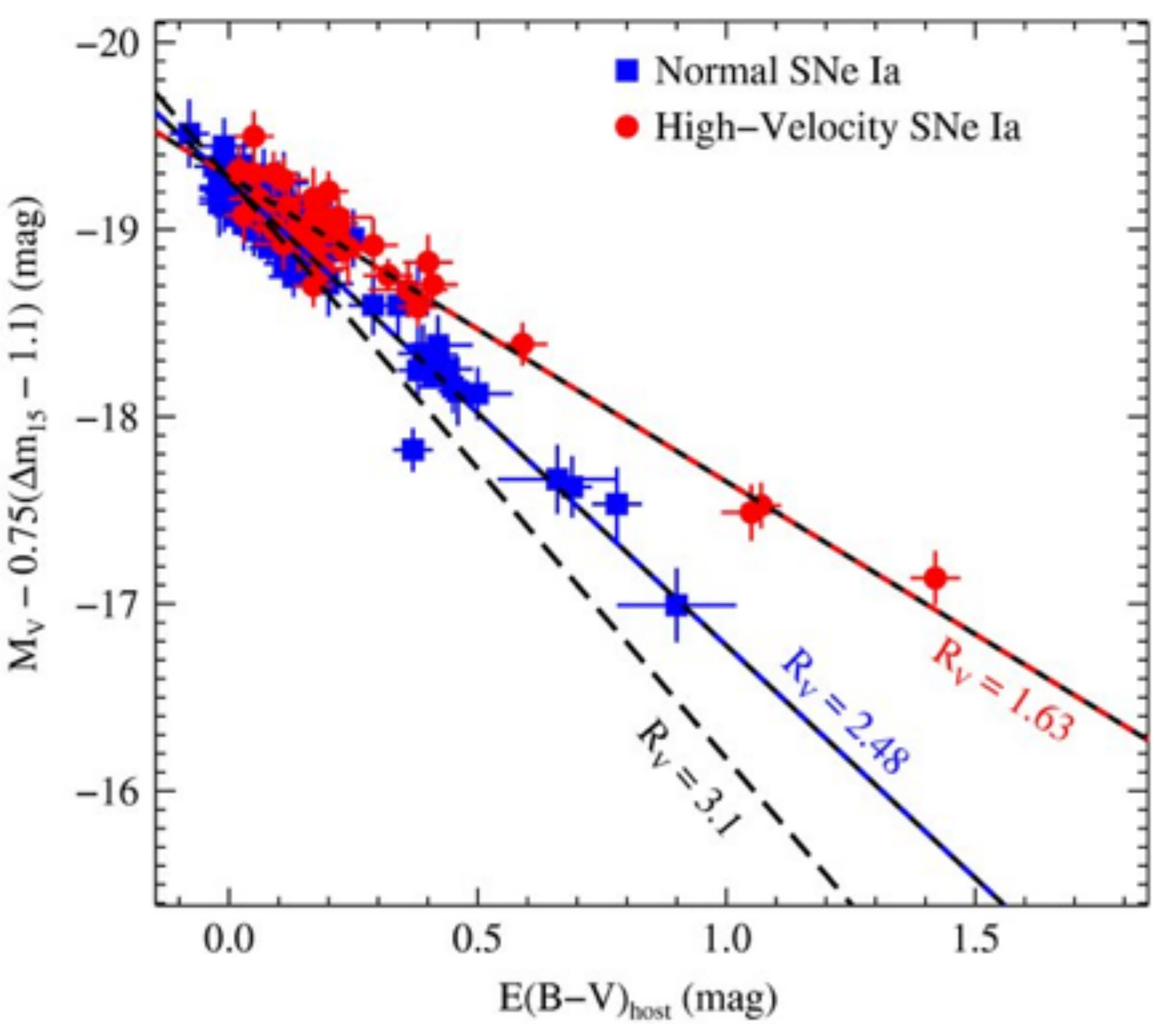




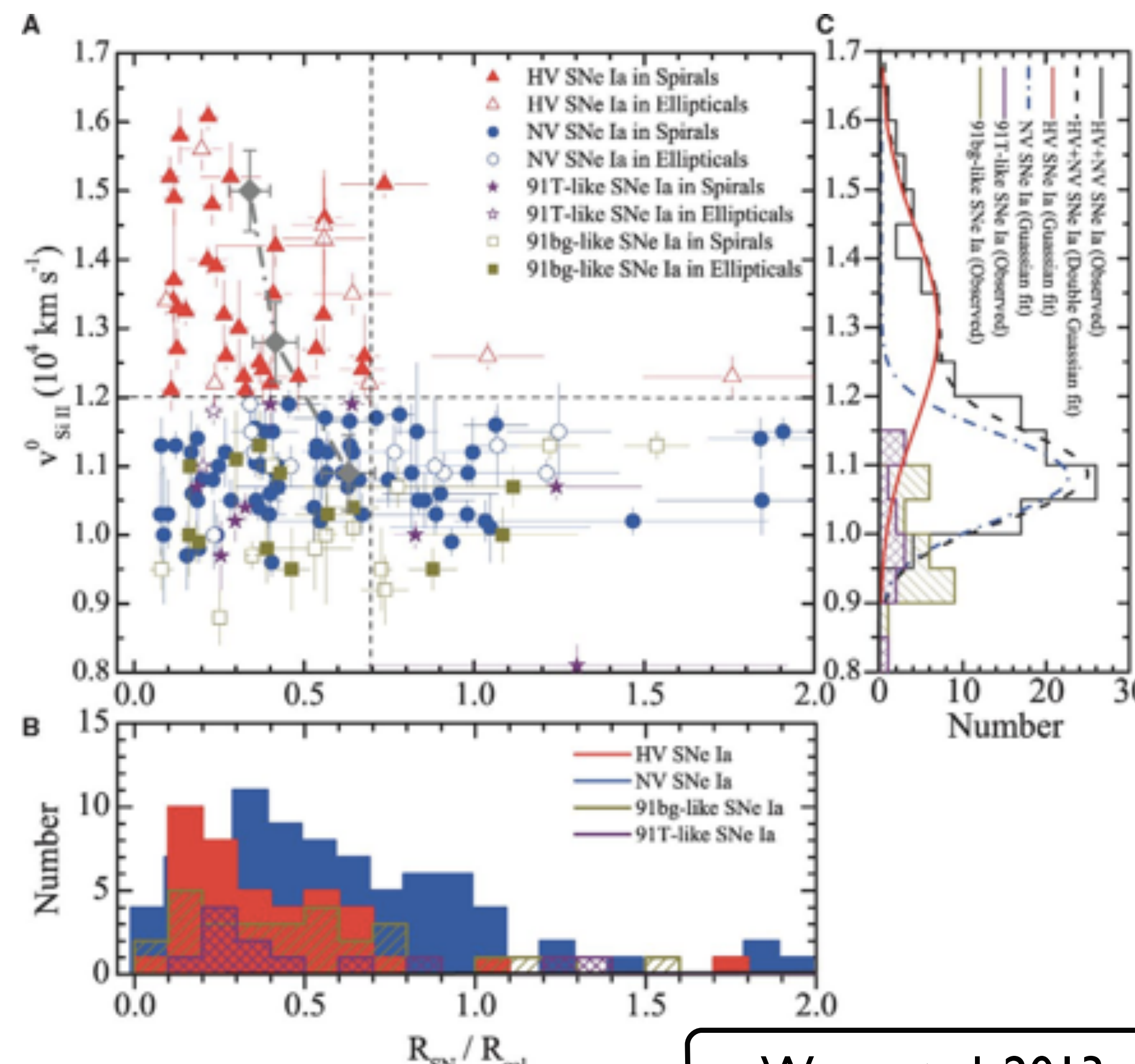
Maeda et al. 2010

High-Velocity SNe Ia: A Distinct Population?

- The reddening law for HV SNe Ia appears to be different than that for LV SNe
- HV SNe Ia are more concentrated in the inner and brighter regions of their host galaxies than are normal-velocity SNe Ia.

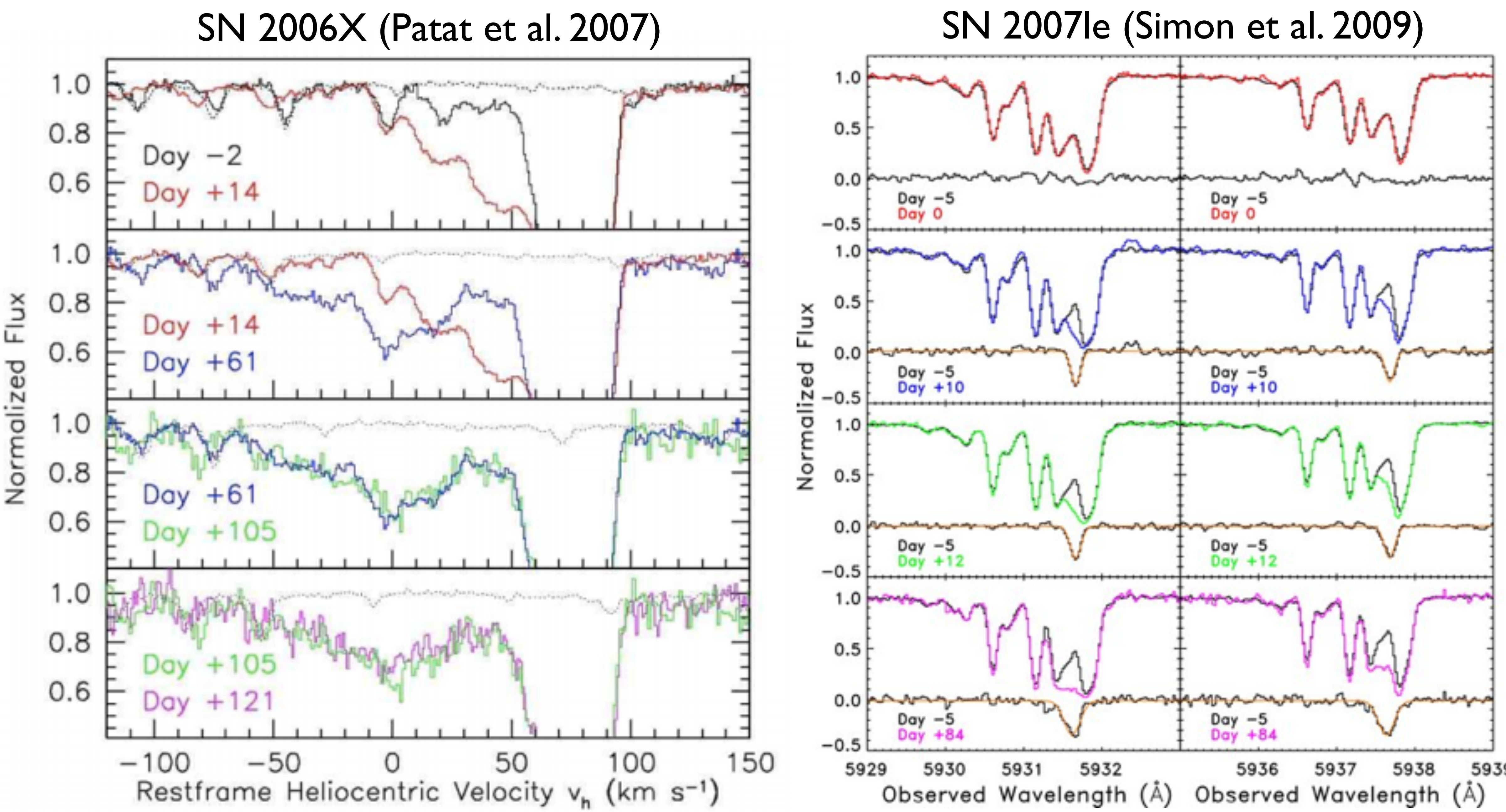


Wang et al. 2009



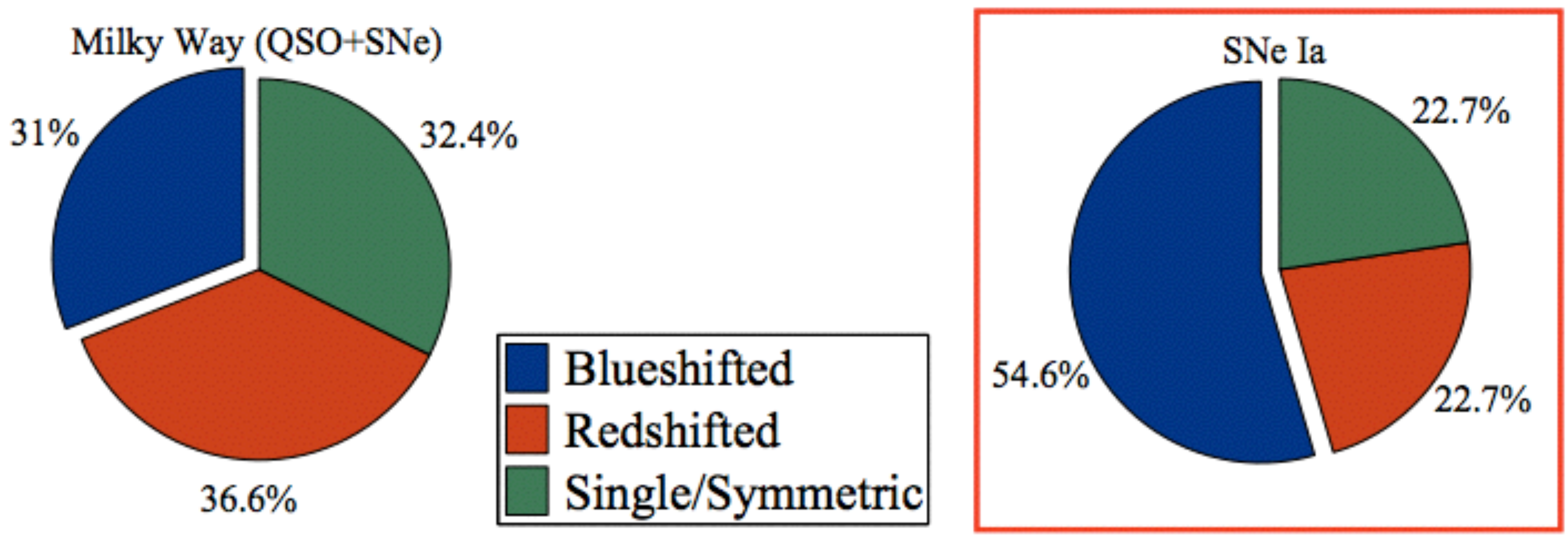
Wang et al. 2013

Evidence for Circumstellar Material (CSM): Variable Na I D Absorption



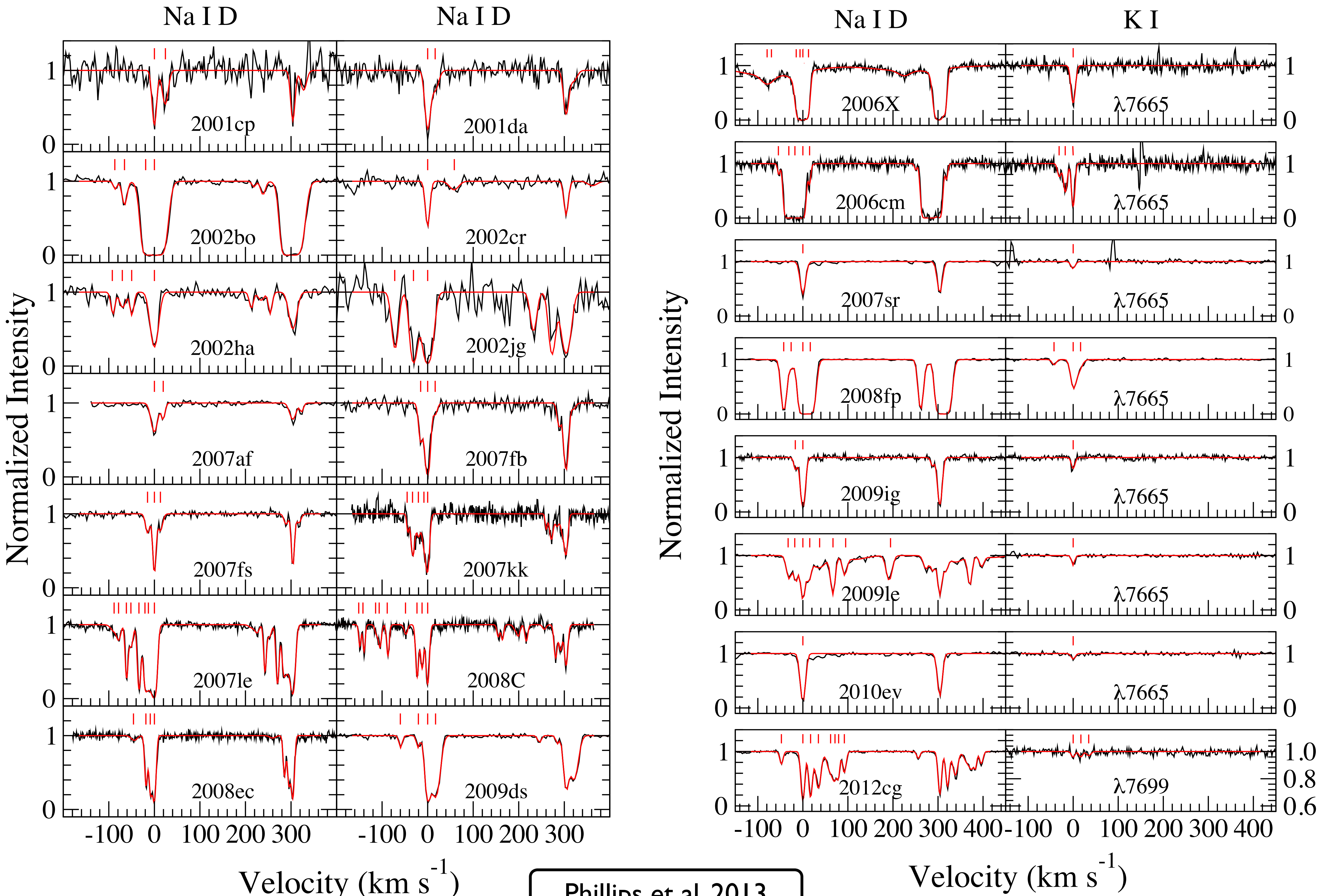
The host Na I D profiles of a handful of reddened HV SNe Ia have been seen to vary, presumably due to recombination of a pre-existing CSM after photoionization by UV photons from the SN explosion

Evidence for CSM: Sternberg et al. (2011)



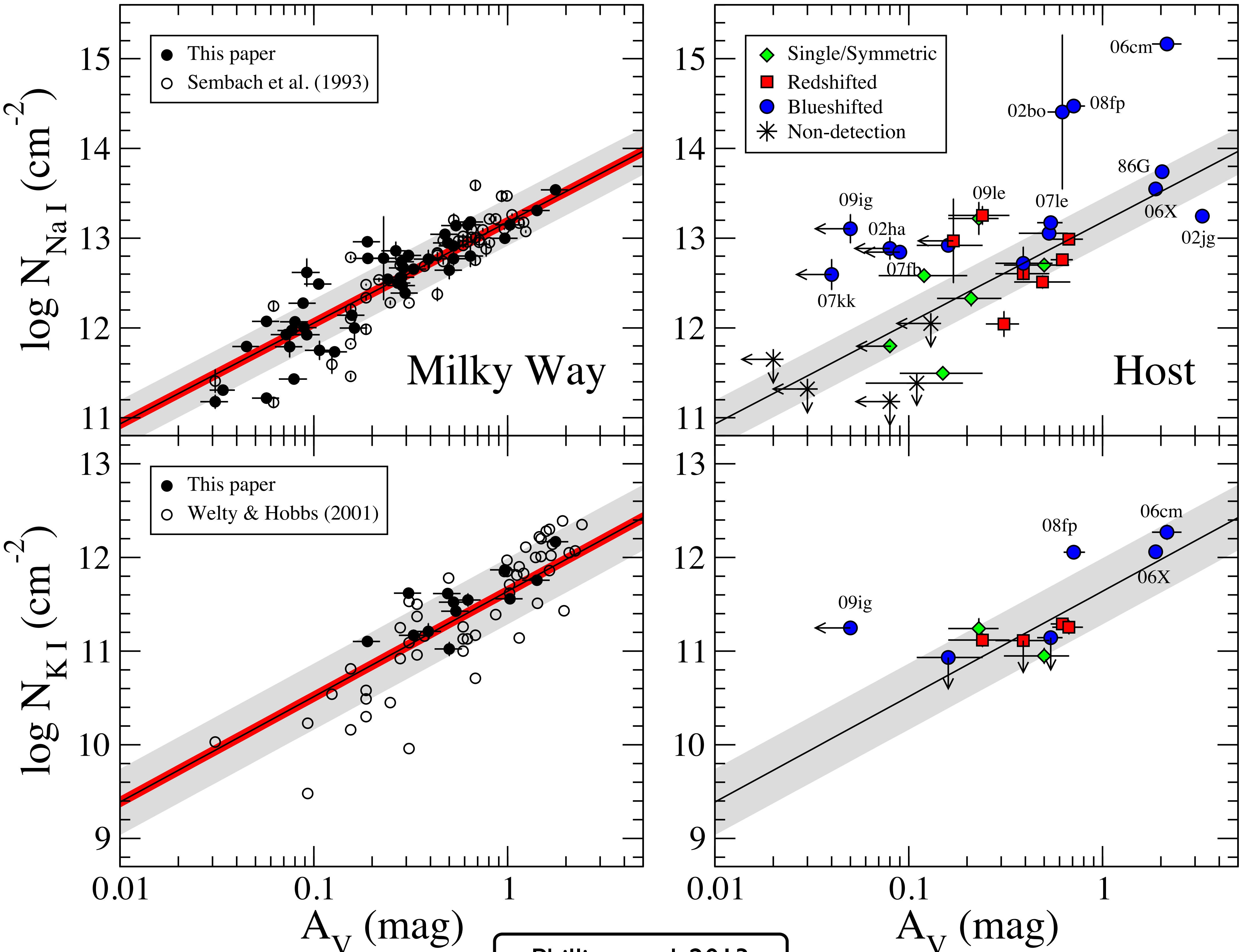
- The SN Ia sample displays a strong preference for blueshifted structures (confirmed by Maguire et al. 2013 using different definition of zero velocity)
- The Milky Way sample shows no significant preference, nor do SNe II
- Blueshifted structures were interpreted as signatures of gas outflows from the supernova progenitor systems

Na I and K I Absorption in SNe Ia



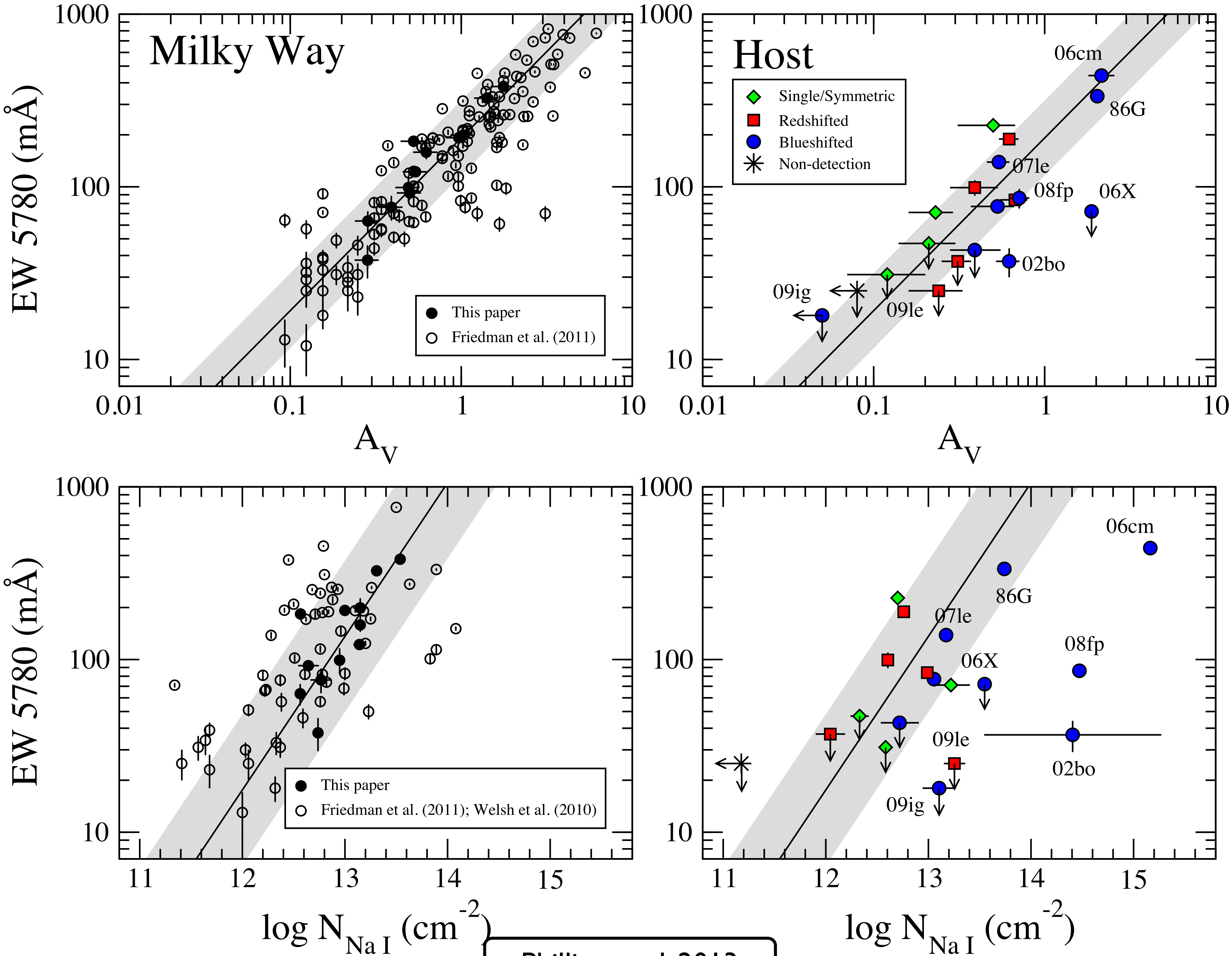
Phillips et al. 2013

Results for the Na I and K I lines



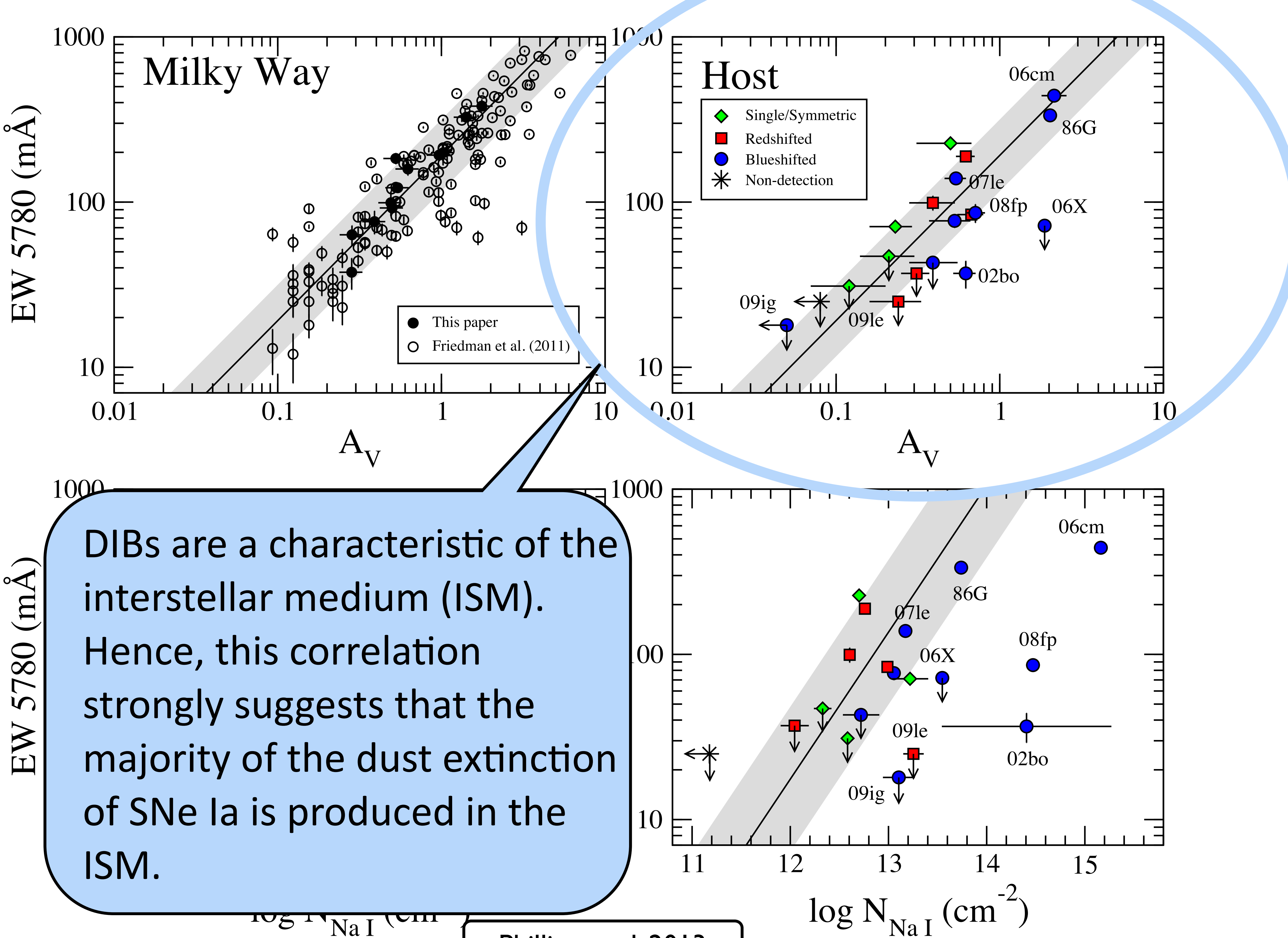
Phillips et al. 2013

5780 Å DIB Absorption in SNe Ia



Phillips et al. 2013

Results for the 5780 Å DIB

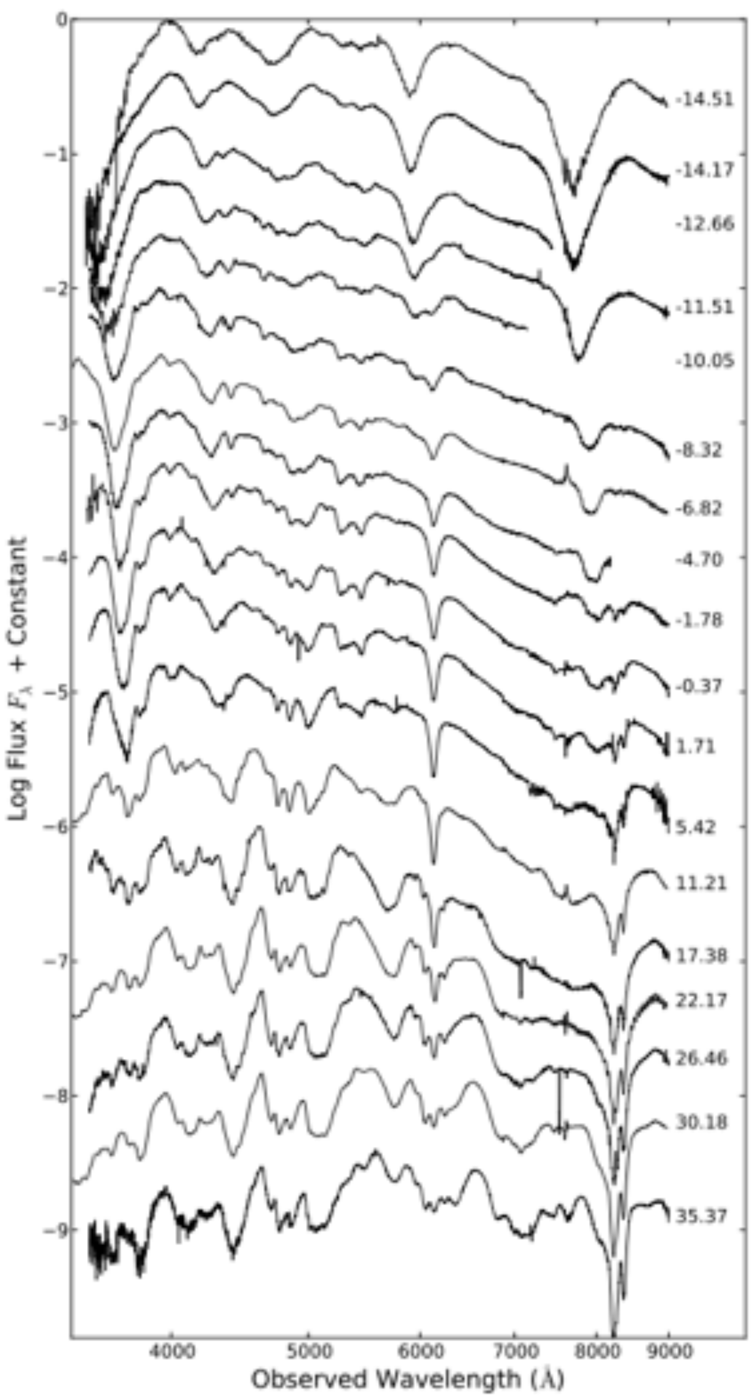


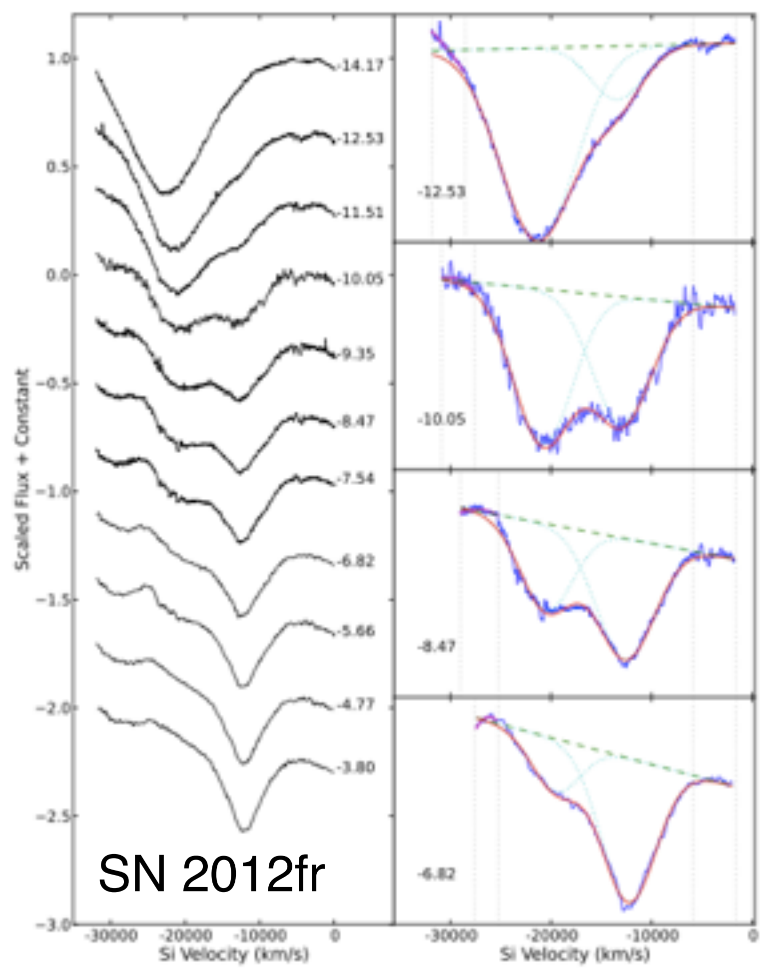
DIBs are a characteristic of the interstellar medium (ISM). Hence, this correlation strongly suggests that the majority of the dust extinction of SNe Ia is produced in the ISM.

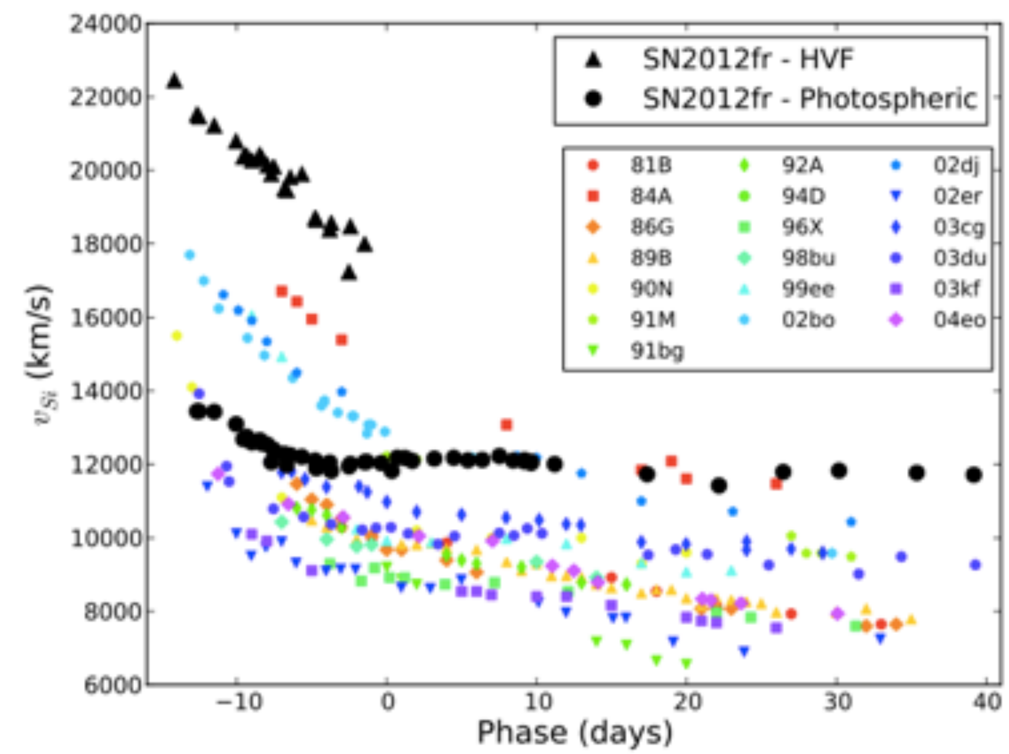
Phillips et al. 2013

High-Velocity Features of Ca and Si

- High velocity absorption due to Ca II and Si II are commonly observed in the early-time spectra of SNe Ia
- Their origin remains a mystery

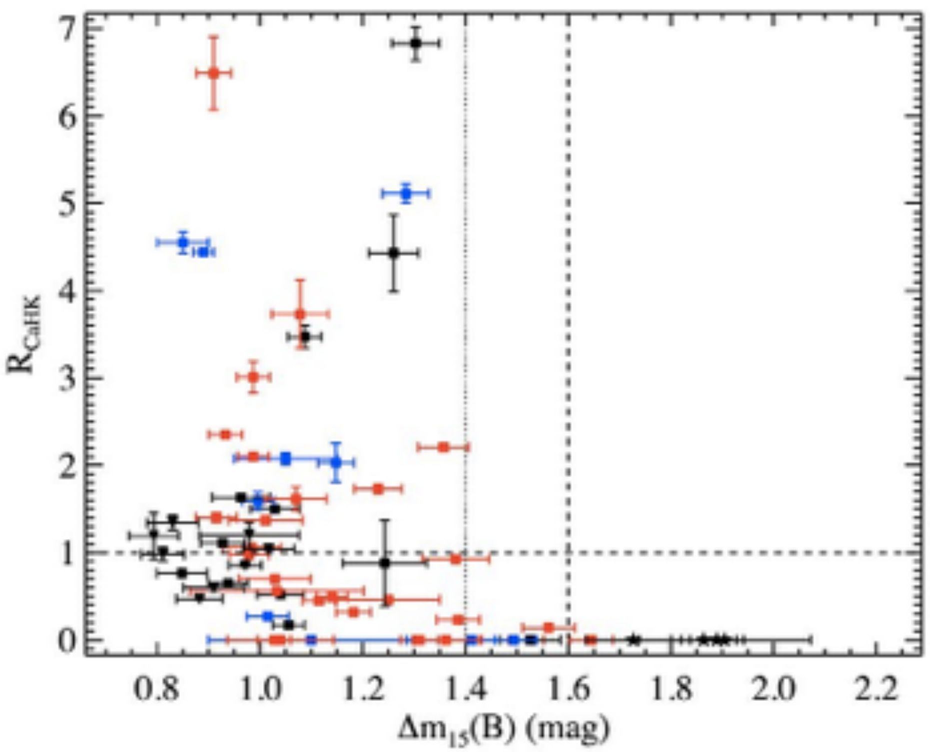


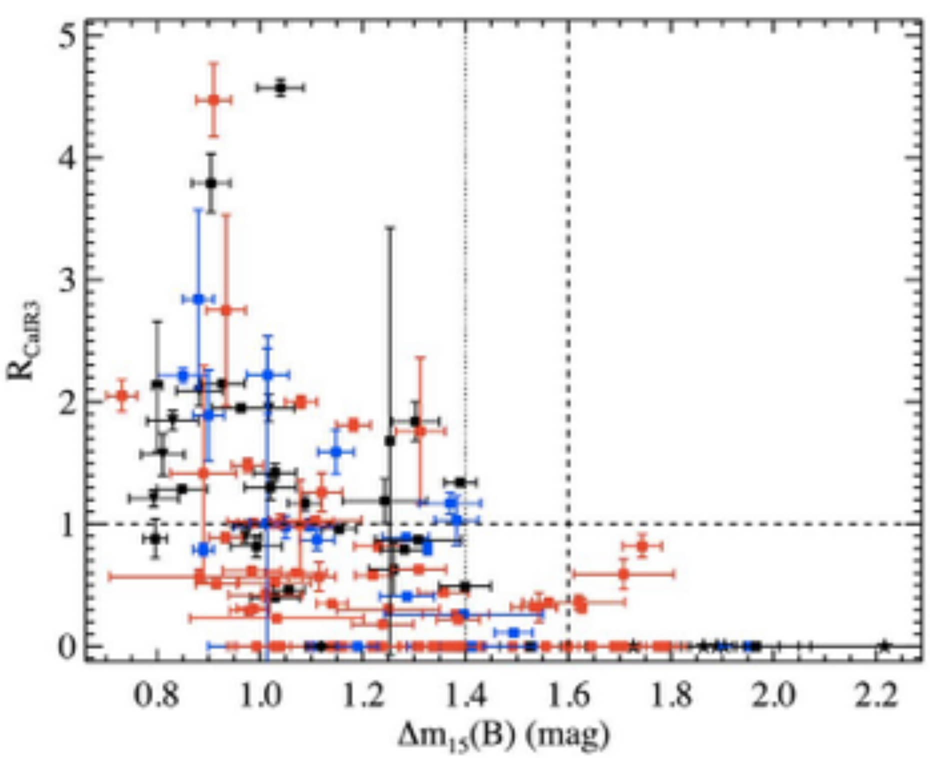




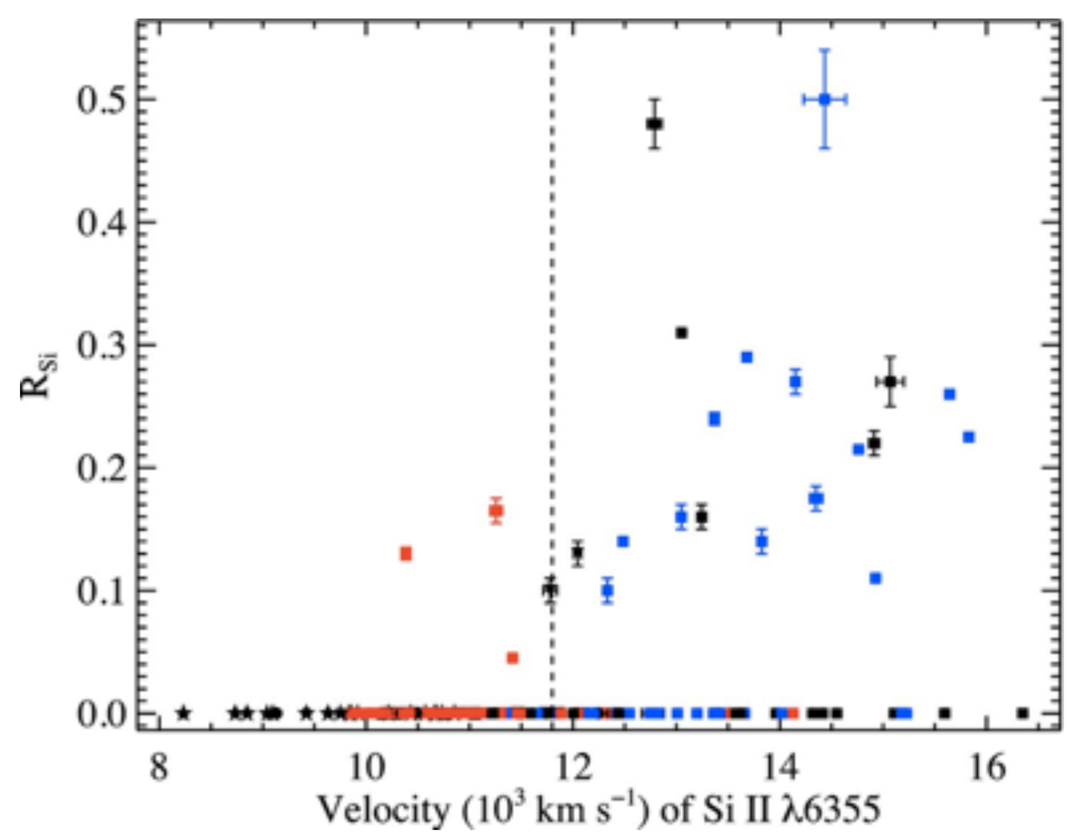
Childress et al. 2013

High-Velocity Features of Ca and Si





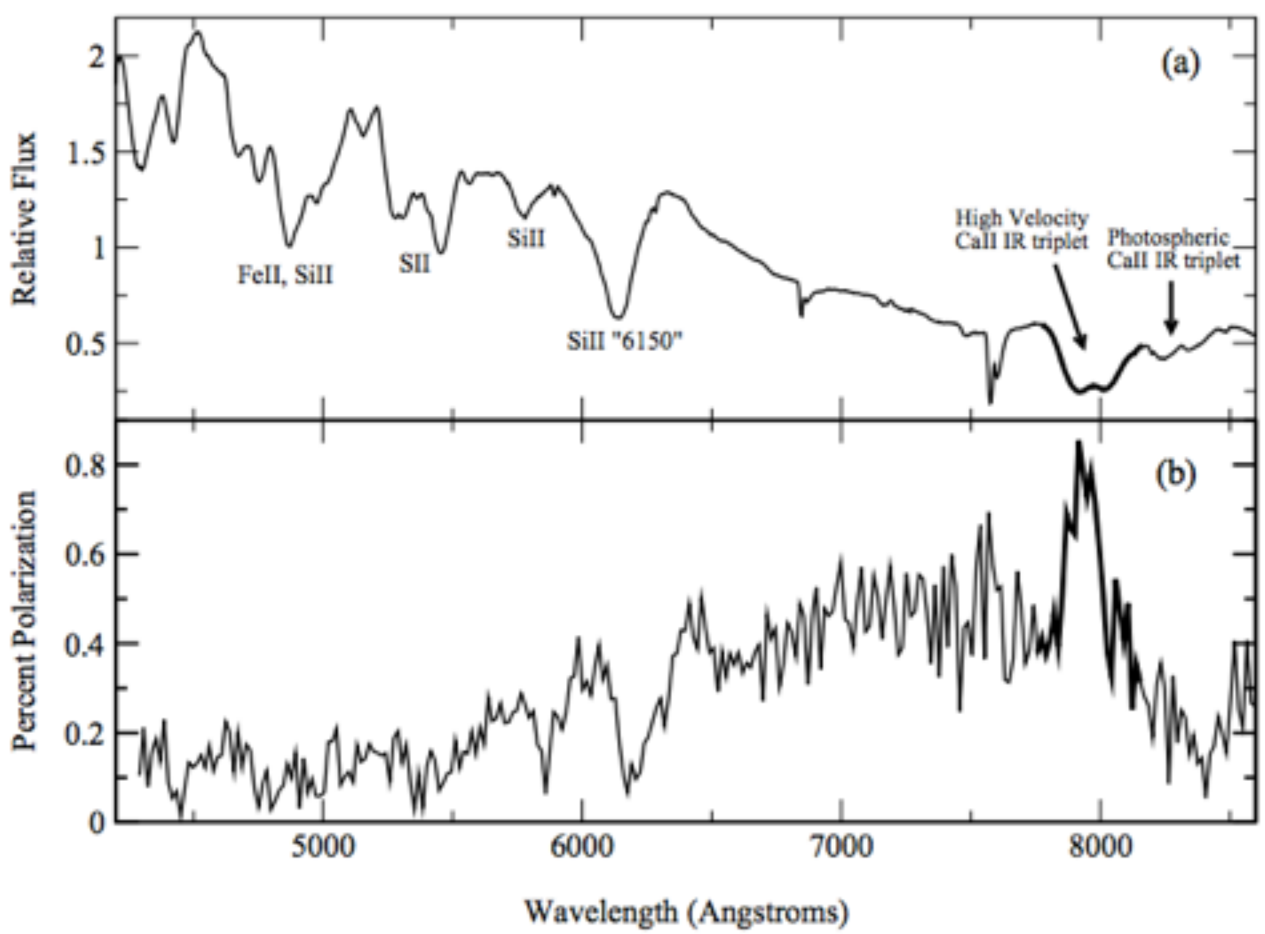
- High velocity features (HVFs) are essentially never found in fast-declining SNe Ia
- HVFs of Ca II are regularly observed
- HVFs of Si II λ6355 are significantly rarer, and tend to be observed only at the earliest epochs and mostly in HV SNe Ia



Silverman et al. 2015

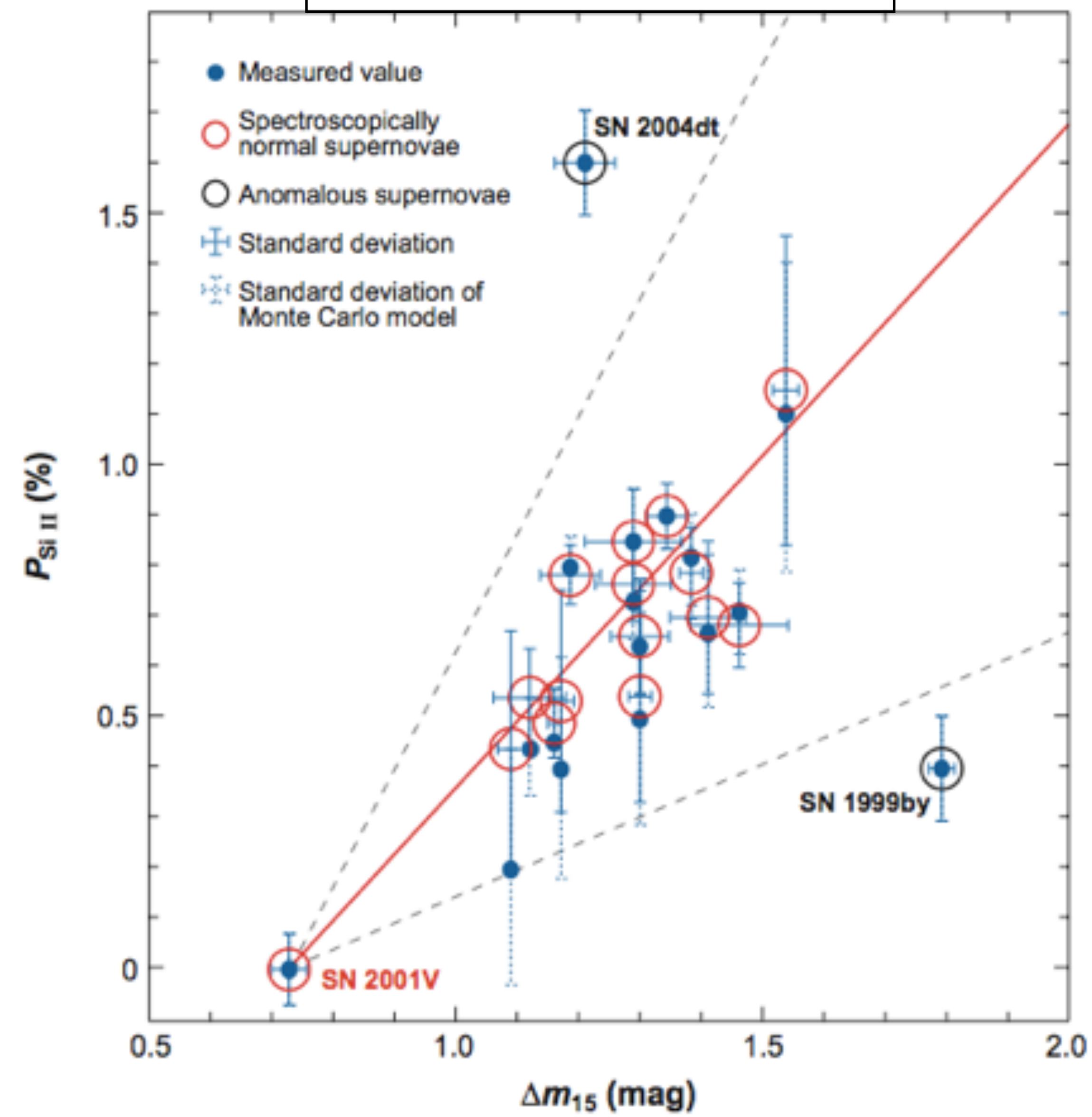
Polarization of SNe Ia

- Type Ia supernovae are more polarized in the outer layers than in the inner layers
- The continuum polarization is low, showing that the explosion is nearly spherical, but the line polarization can be very strong
- SNe with a faster light-curve decline rate tend to be more highly polarized



Kasen et al. 2003

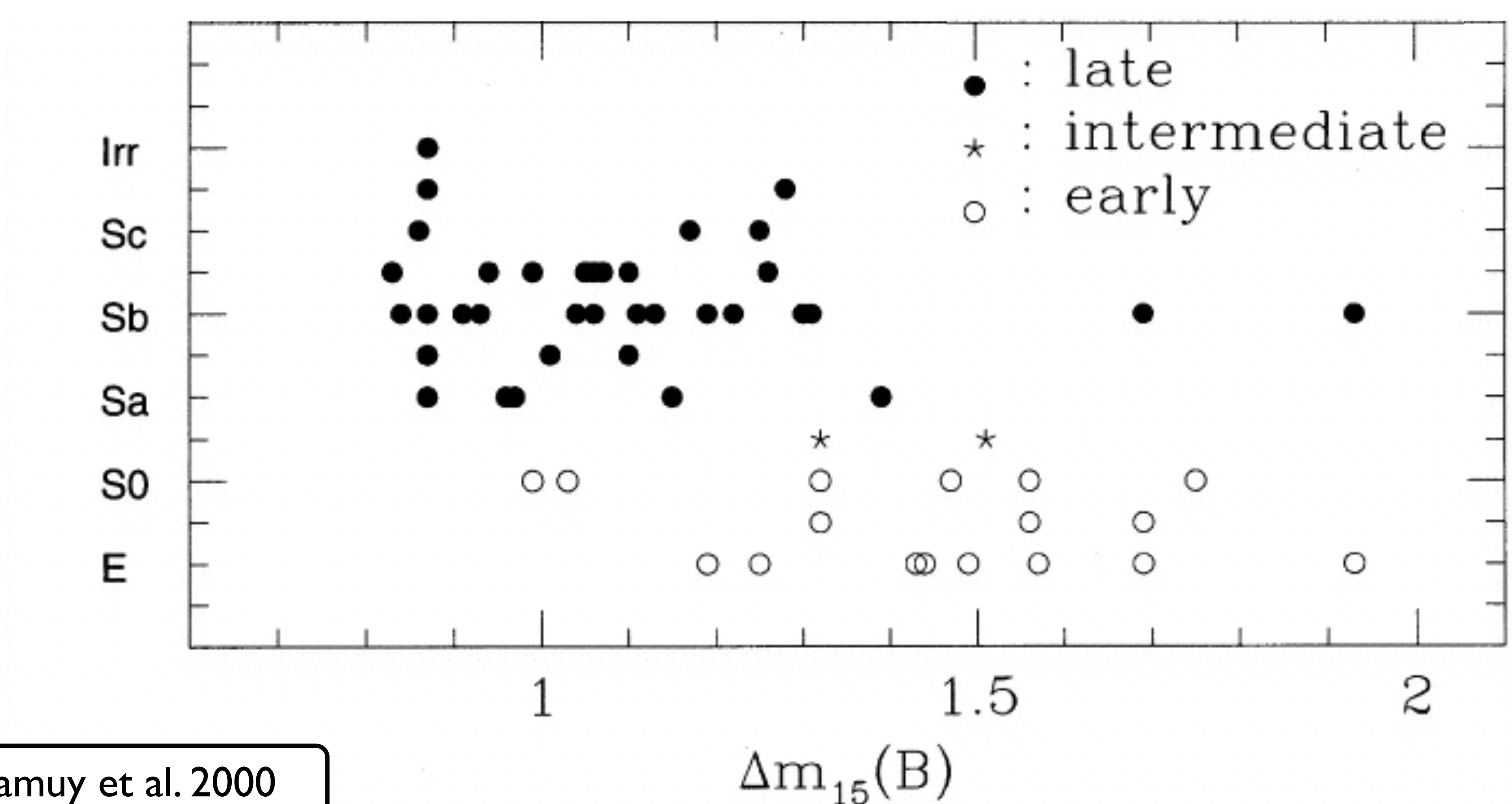
Polarization Across Si II 6355



Wang et al. 2007

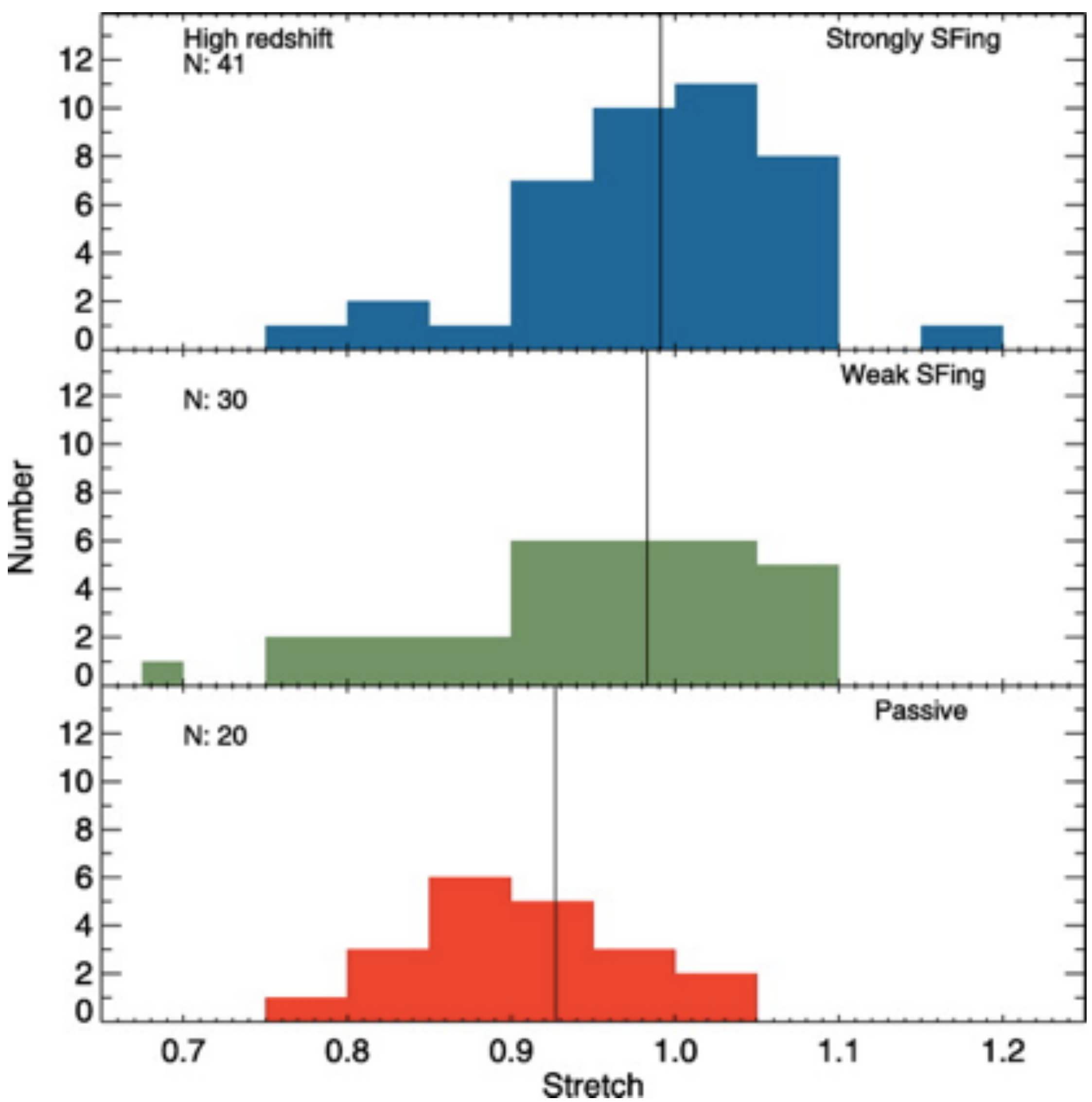
Correlation with Host Galaxy Morphology

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



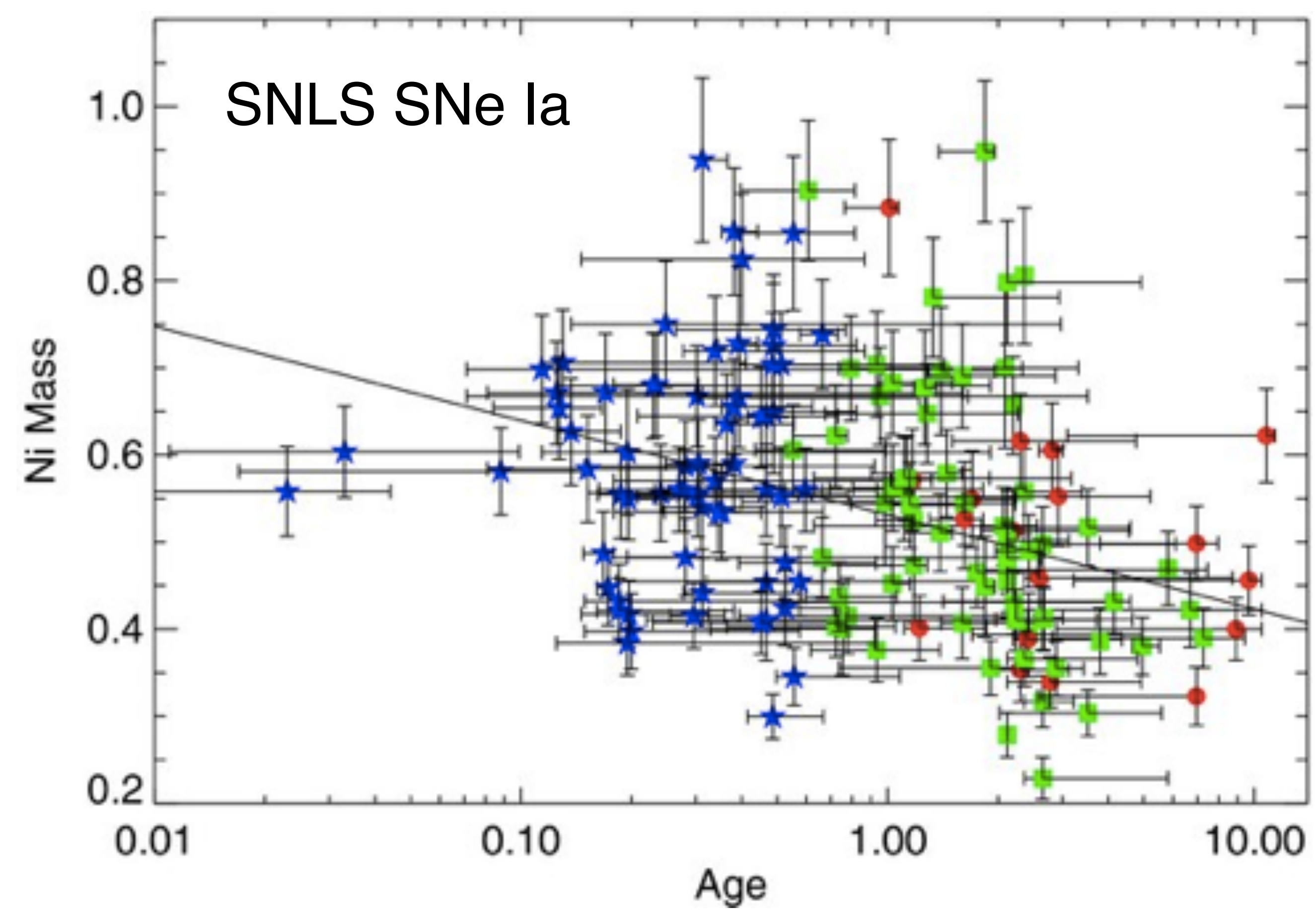
Hamuy et al. 2000

Correlations with Star Formation Rate and Progenitor Age



Sullivan et al. 2006

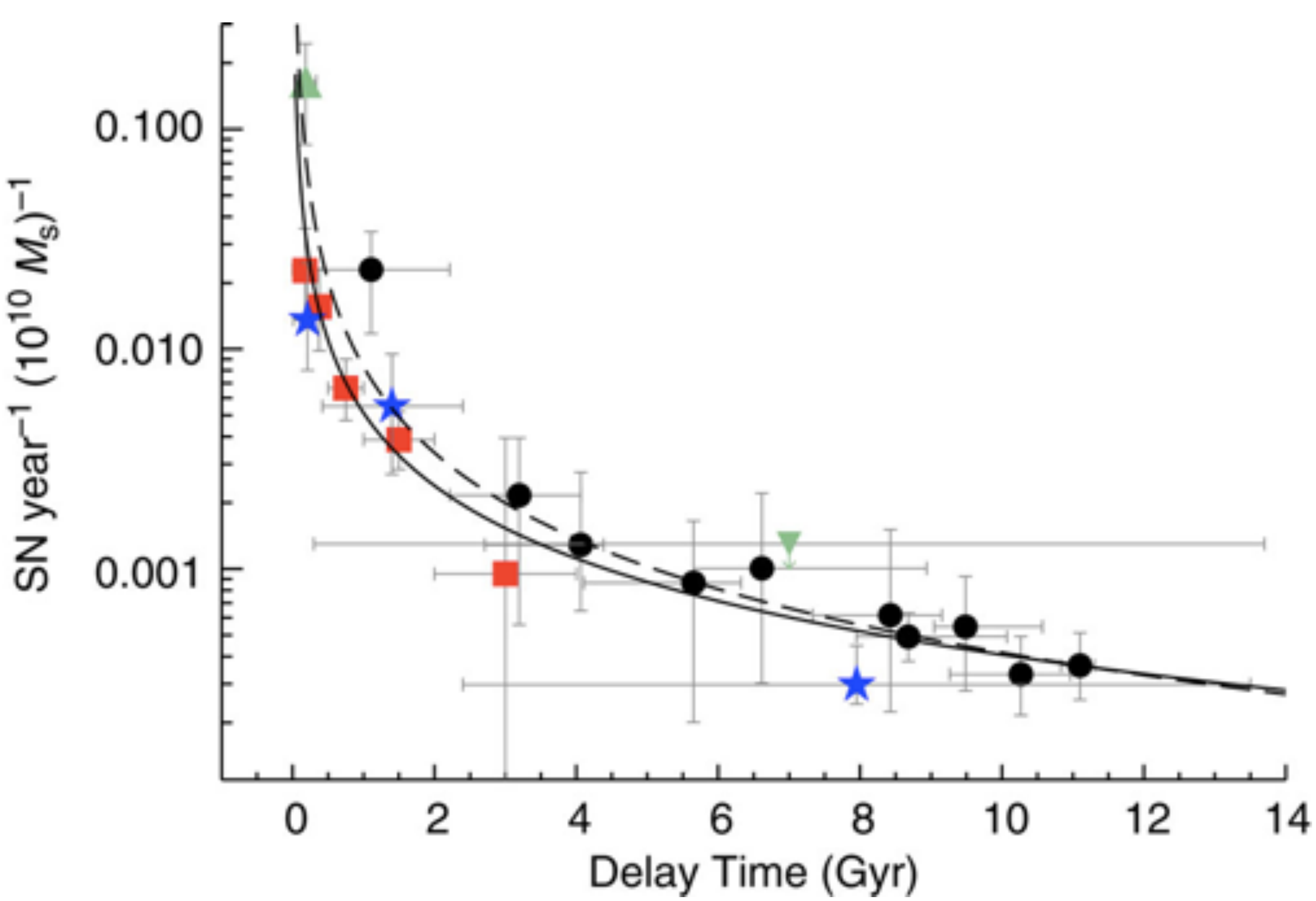
Similar correlations exist with star formation rate and luminosity-weighted age



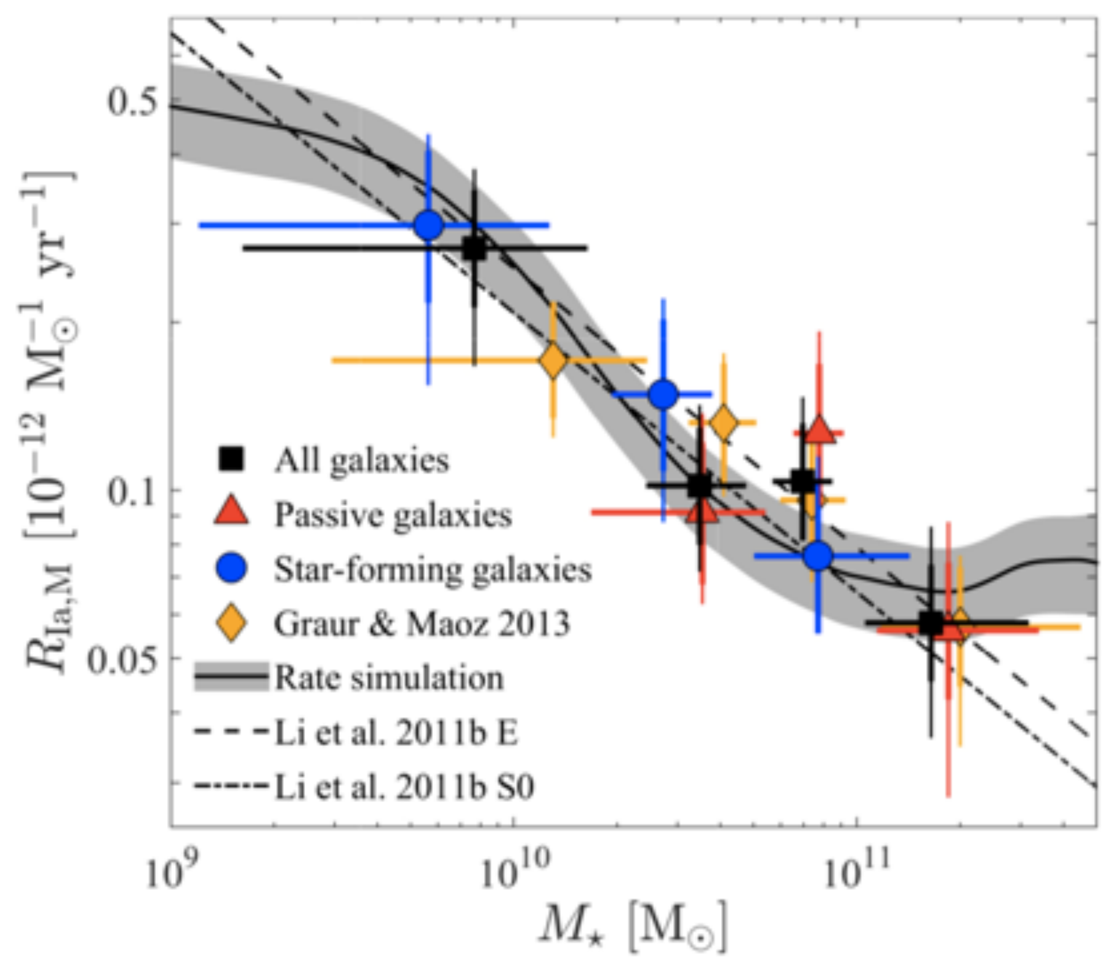
Howell et al. 2009

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 galaxy mass



Howell 2011 (Adapted from Maoz et al. 2010)



Graur et al. 2015

SNe Ia Rates

- The … tem and the ex… r DTD) is pro…
- The … xy mass

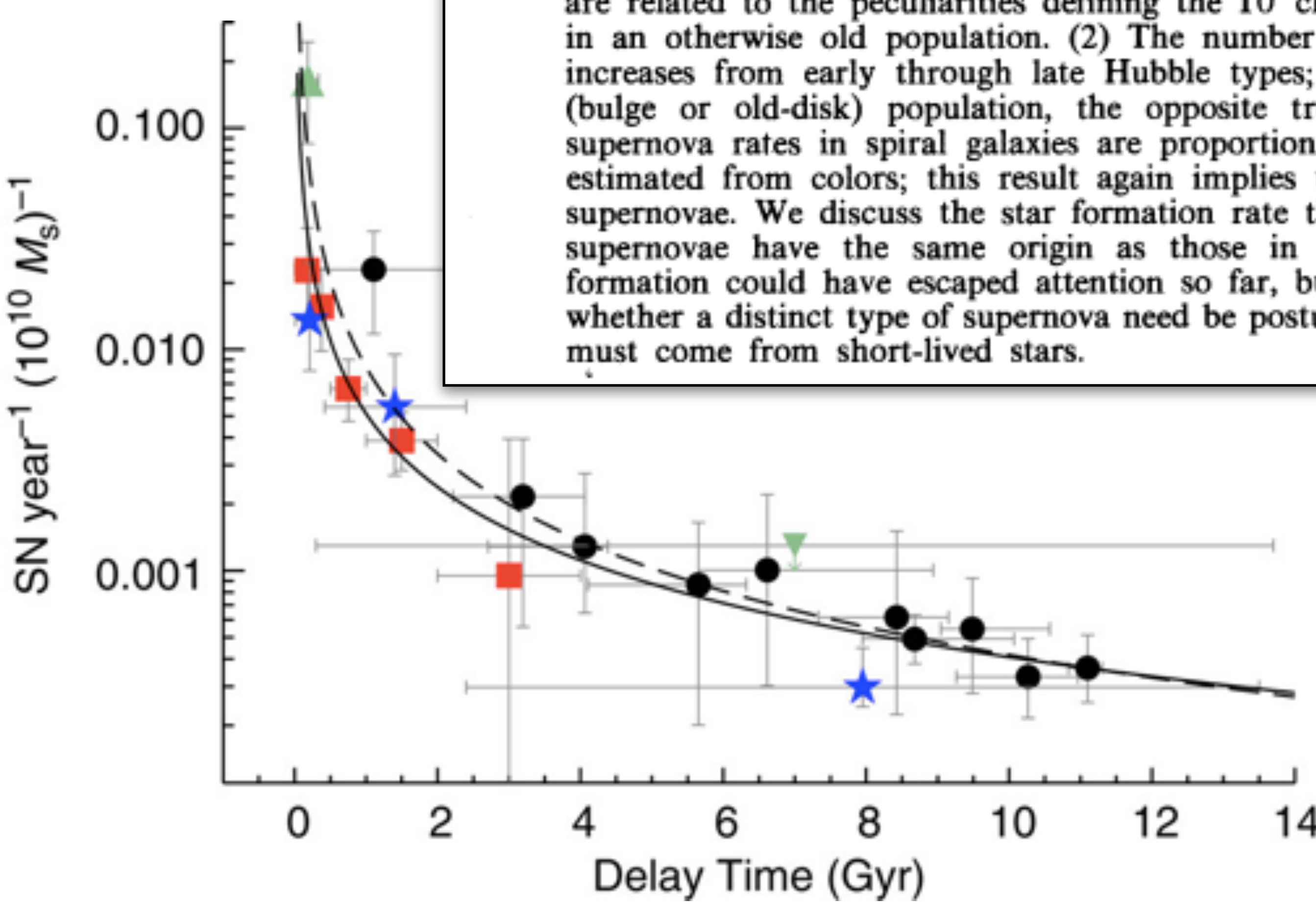
THE ASTRONOMICAL JOURNAL VOLUME 84, NUMBER 7 JULY 1979

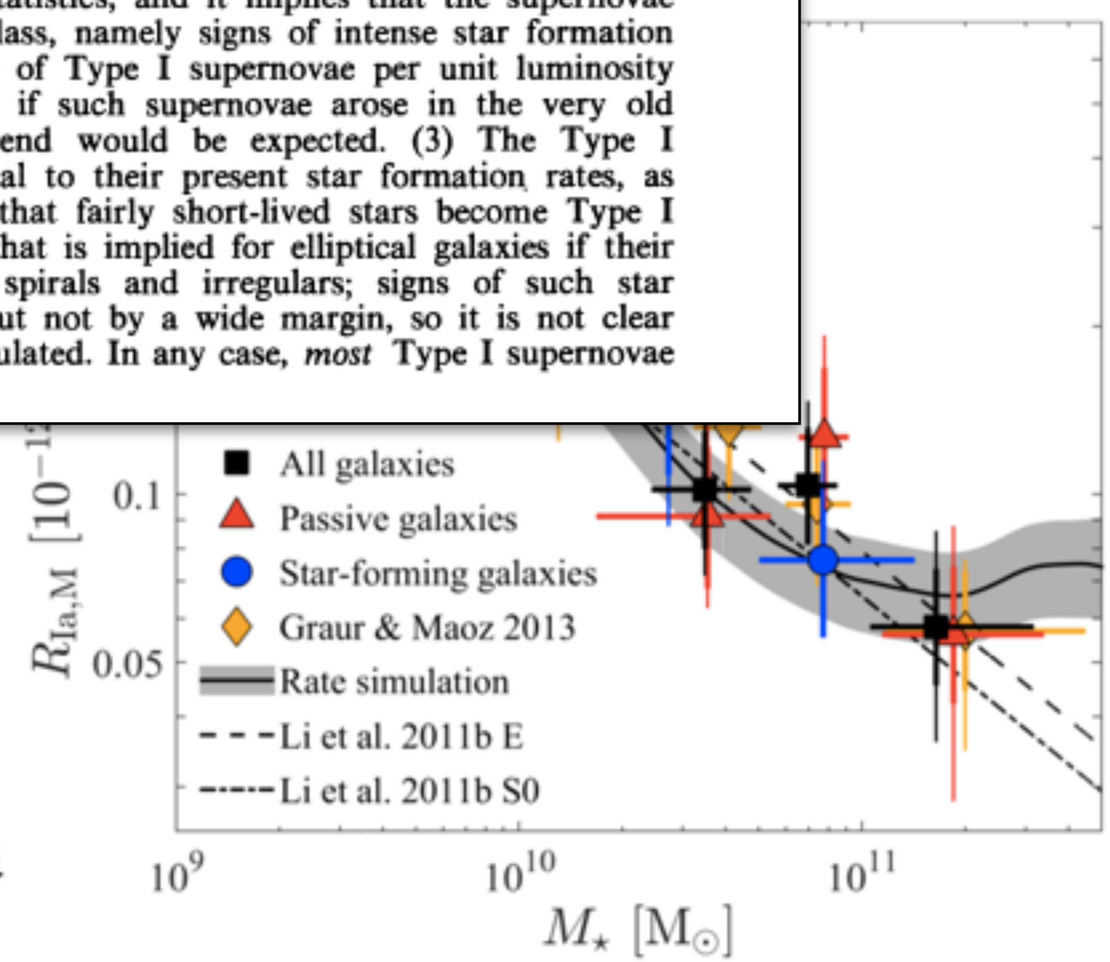
TYPE I SUPERNOVAE COME FROM SHORT-LIVED STARS[a)]

Augustus Oemler, Jr[b)] and Beatrice M. Tinsley[b)]
Yale University Observatory, New Haven, Connecticut 06520
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.



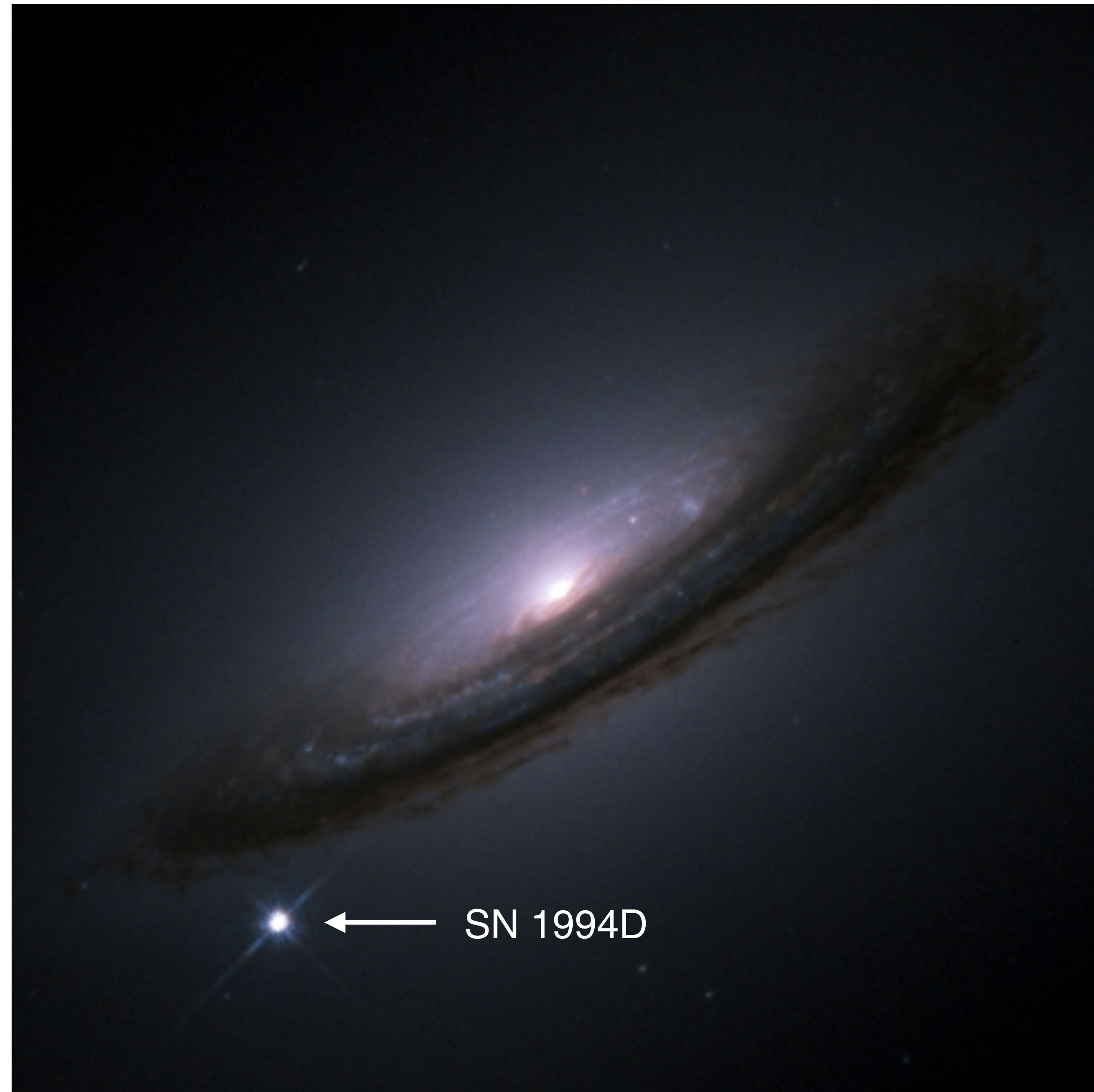


Howell 2011 (Adapted from Maoz et al. 2010)

Graur et al. 2015

SNe Ia: Progenitor Models

- In order to explain the fact that some SNe Ia occur in old stellar populations and lack hydrogen, Hoyle & Fowler (1960) first proposed that they were the observational signature of the thermonuclear disruption of a degenerate star, presumably in a binary system
- However, many uncertainties still exist regarding the nature of the progenitors and the explosion mechanism



Chandrasekhar Mass Models

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: WD accretes matter from a non-degenerate companion causing it to explode near the Chandrasekhar limit (Whelan & Iben 1973)
- Double Degenerate: Two WDs in a close binary systems merge whose combined mass exceeds the Chandrasekhar limit (Webbink 1984; Iben & Tutukov 1984)

Delayed Detonation Mechanism

- A problem common to Chandrasekhar mass models is that the energetics and spectra do not match the observations unless as an initial subsonic deflagration allows the WD to expand and, at the right time, spontaneously to evolve into a supersonic detonation (Khokhlov 1991)
- Pure deflagrations would produce a subclass of sub-luminous SNe Ia — perhaps corresponding to the 2002cx-like events (a.k.a. "Type Iax")
- Pure detonations of would burn the C+O mixture to Fe–peak elements entirely, in conflict with observations that show intermediate–mass elements at maximum light

Violent Mergers and Collisions of C/O White Dwarfs

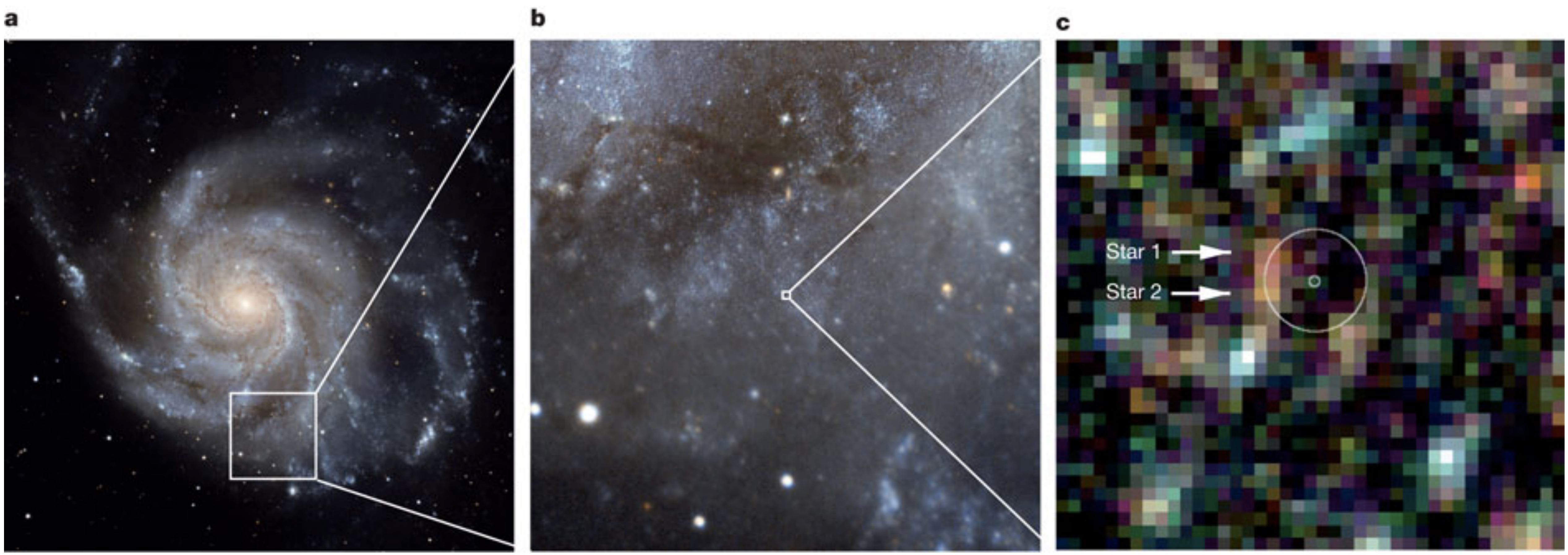
- Recent 3D hydrodynamical modeling suggests that the merger of two C/O WDs may actually occur explosively (Pakmor et al. 2013)
- As the material of the disrupted secondary WD is accreted violently onto the primary, it is compressed and heats up the surface
- If the temperature is high enough, a C detonation wave can propagate into the central region of the WD, with the amount of ^{56}Ni produced being proportional to the mass of the primary WD
- Direct collisions of a WD-WD pair in a triple system could lead to the same scenario (Katz & Dong 2012)

Double Detonation Model

- Accretion from a non-degenerate helium star or a helium WD can accumulate a He layer that is sufficiently massive and degenerate that ignition becomes explosive (Taam 1980)
- The detonation drives a shock wave into the core of the WD that ignites the C at or near the center
- The He layer must be sufficiently small so as not to produce early-time spectra rich in ^{56}Ni
- Requires WD mass to be in range 0.8-1.1 $M_{\odot}$
- Because the sub-Chandrasekhar WD has a lower density throughout, the detonation does not burn the entire star to iron-peak elements

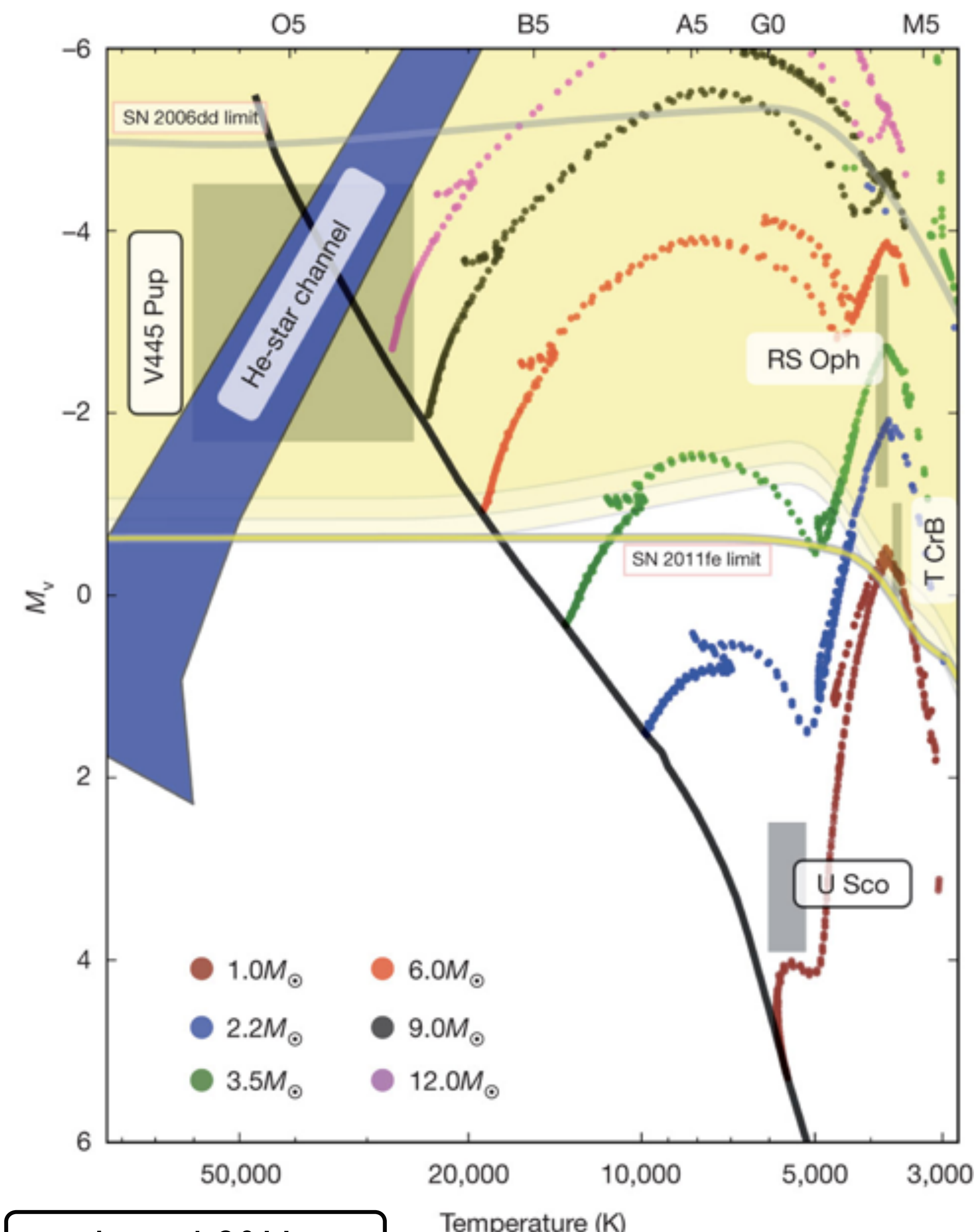
Recent Observational Advances: SN 2011fe in M101

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

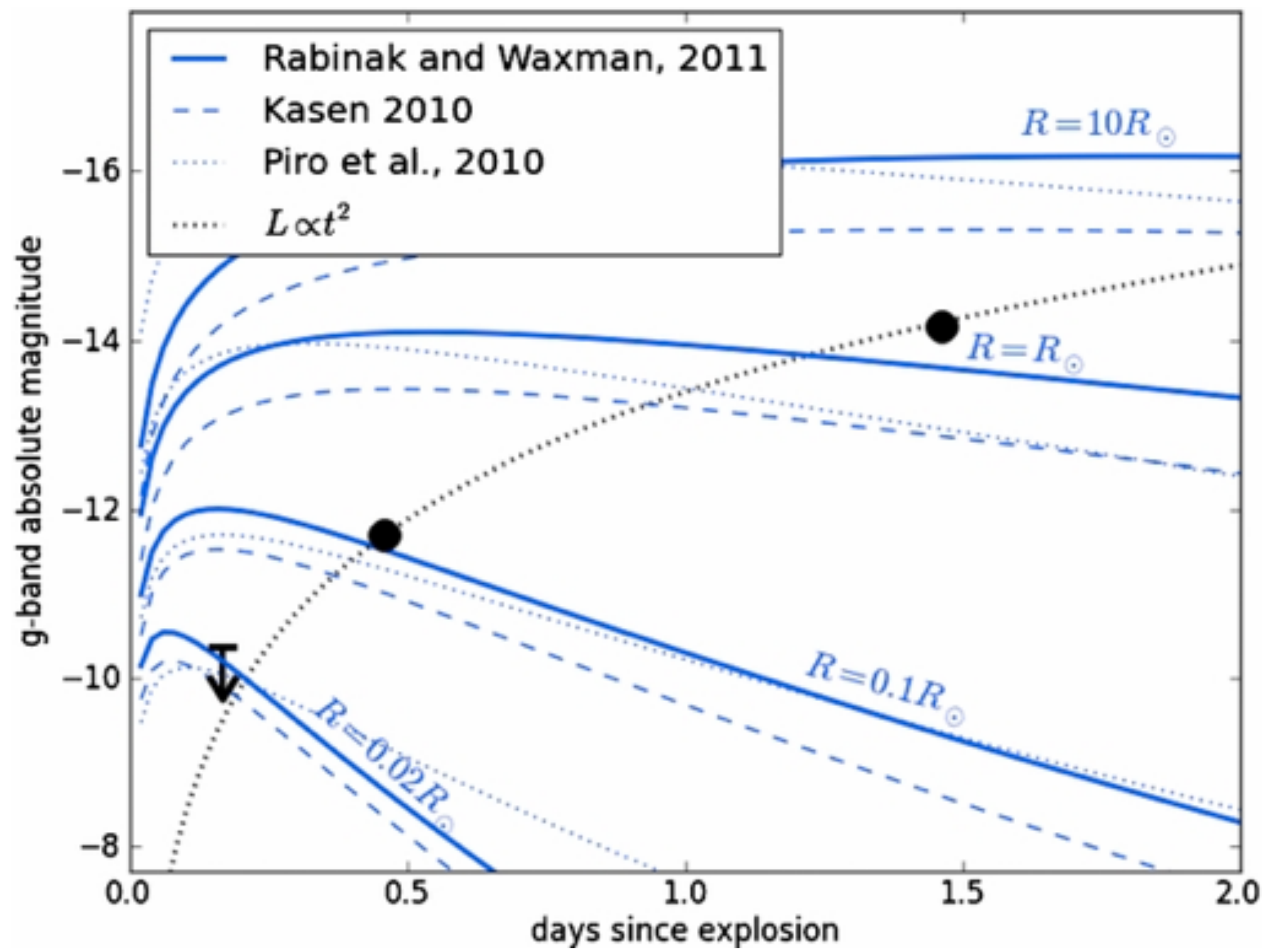


Li et al. 2011

- 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

SN 2011fe in M101

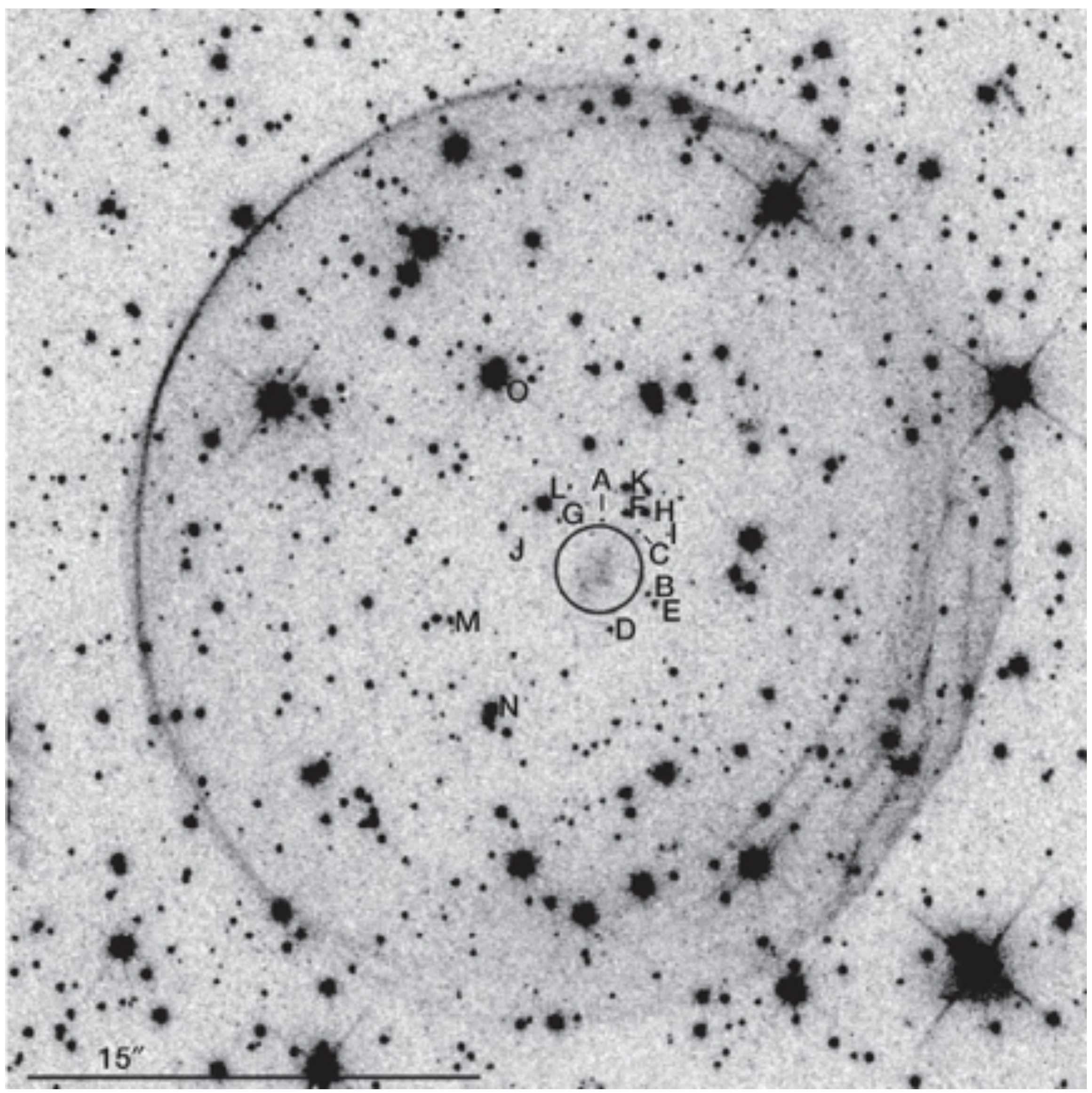
- SN 2011fe was discovered within hours of "first light"
- Bloom et al. (2012) used a non-detection obtained 8 hours before discovery to place a limit on the initial stellar radius of $R_* < 0.02\ R_\odot$ from shock outbreak models
- However, Piro & Nakar (2013) argued that the explosion time was not known to better than ±0.5 days, which weakens the Bloom et al. upper limit to $R_* < 0.1\ R_\odot$



Bloom et al. 2012

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

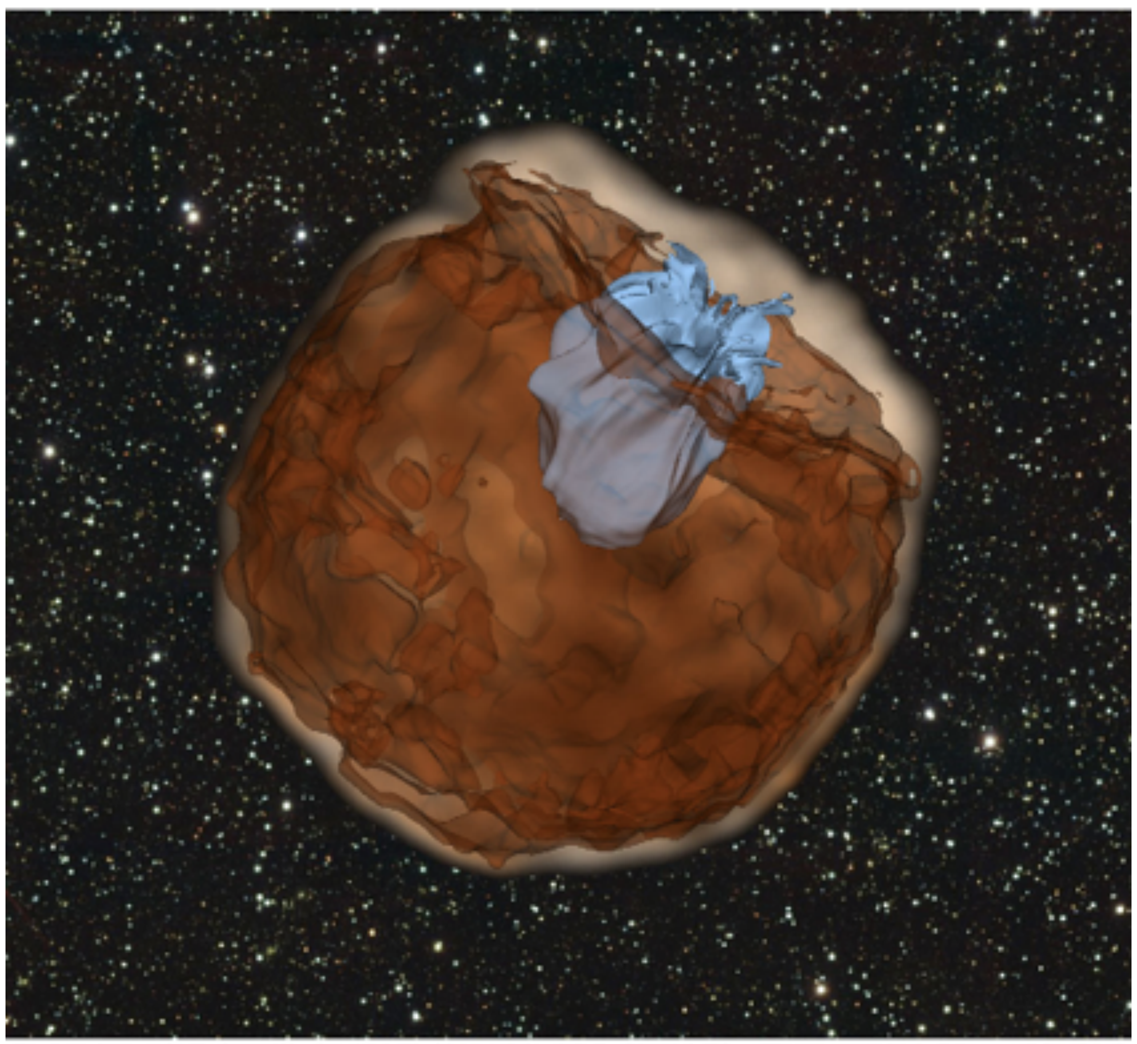


Schaefer & Pagnotta 2012

- 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 $\sim$0.5 $M_\odot$ and essentially rules out all traditional single-degenerate companions

Collision of the Supernova Ejecta with the Companion

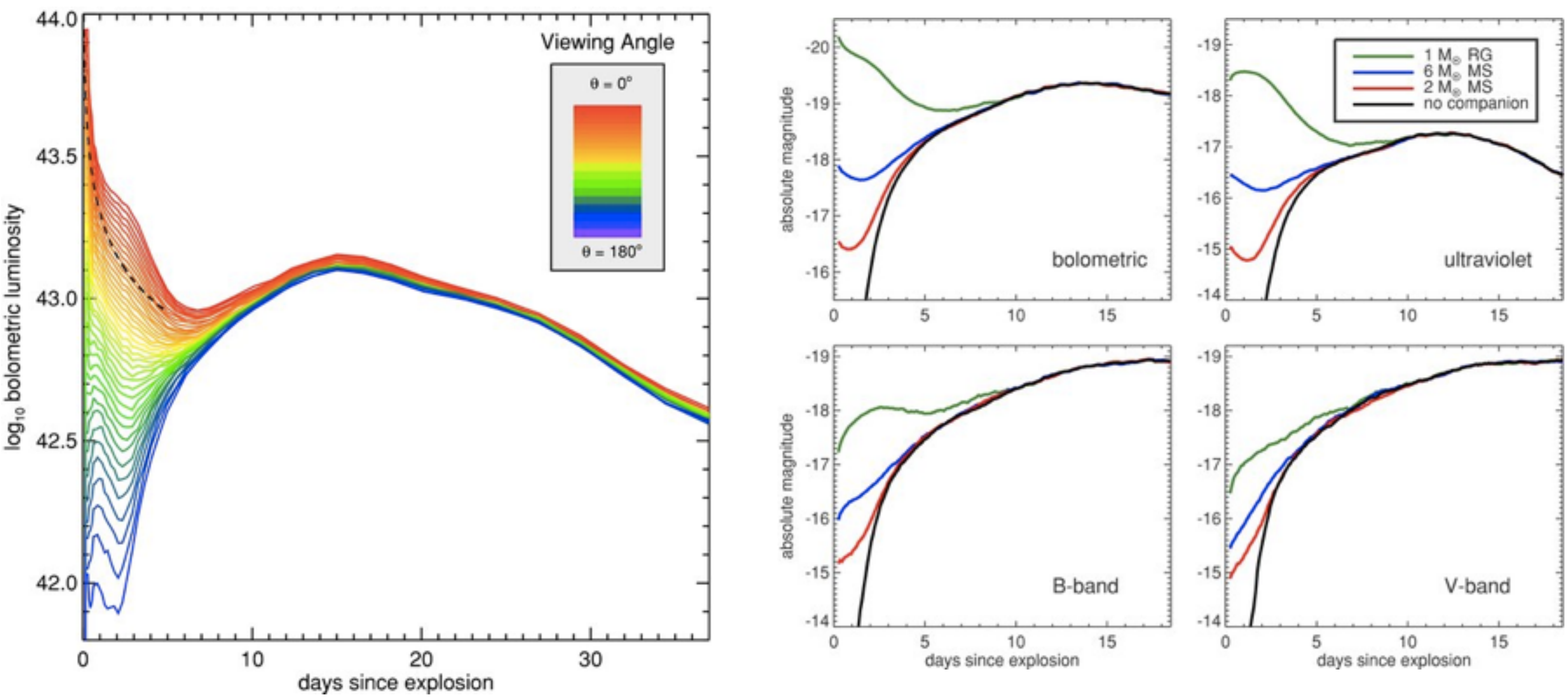
- Kasen (2010) showed that the collision of the supernova ejecta with its companion star should produce detectable emission in the hours and days following the explosion



- 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)

Collision of the Supernova Ejecta with the Companion

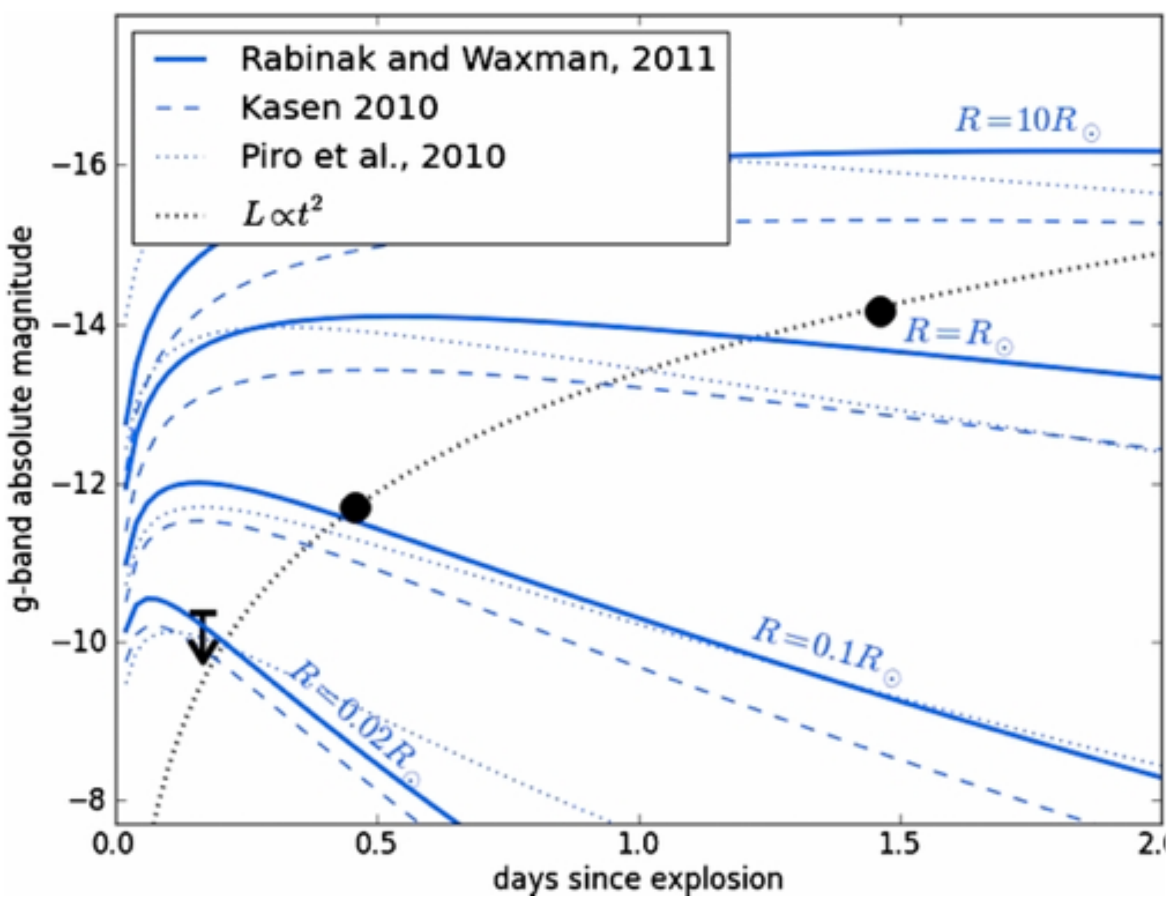
- The strength of the emission provides information on the radius of the companion
- It is strongest in the ultraviolet, but weaker at optical bandpasses



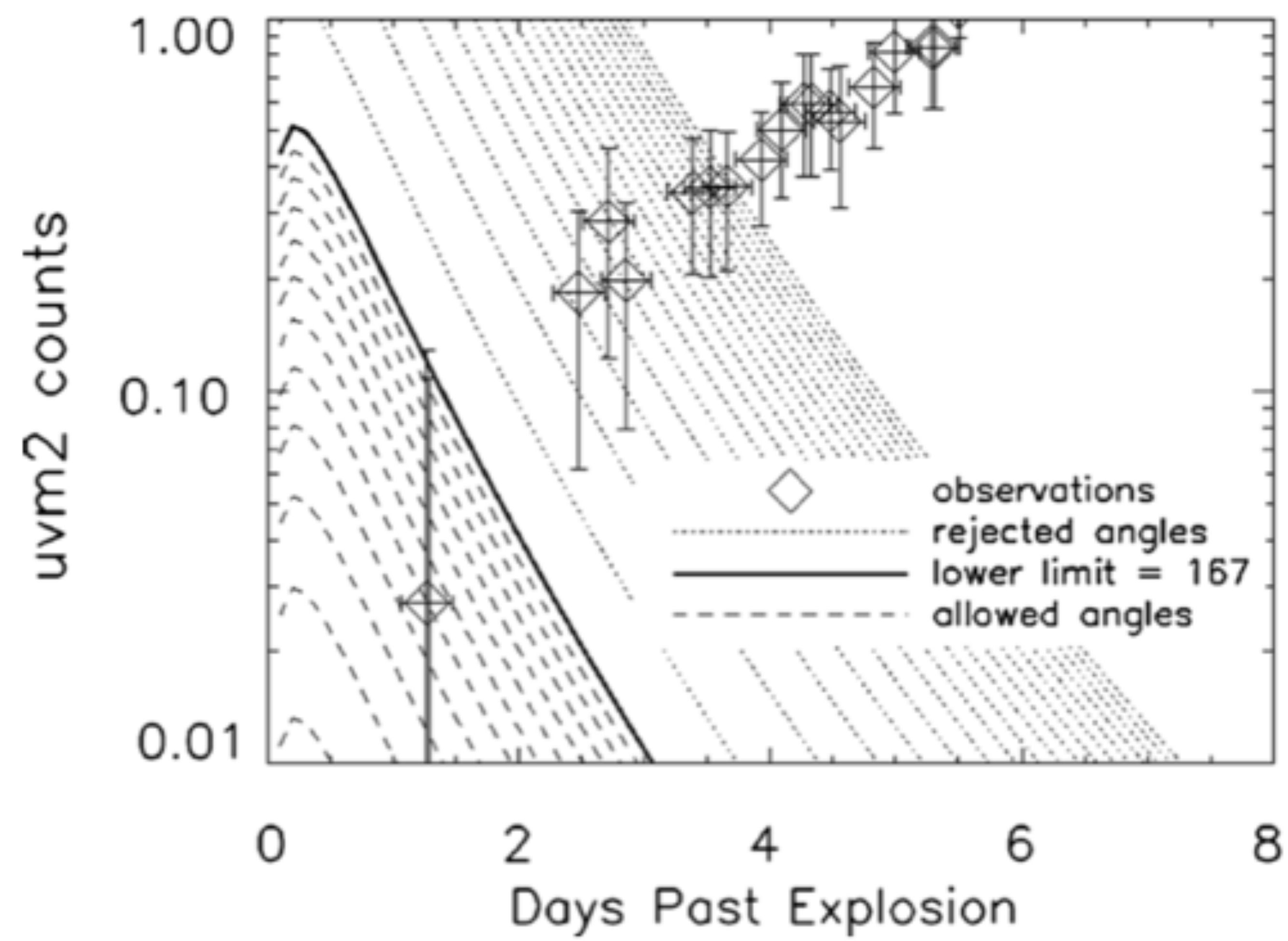
Kasen 2010

SN 2011fe in M101

- 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

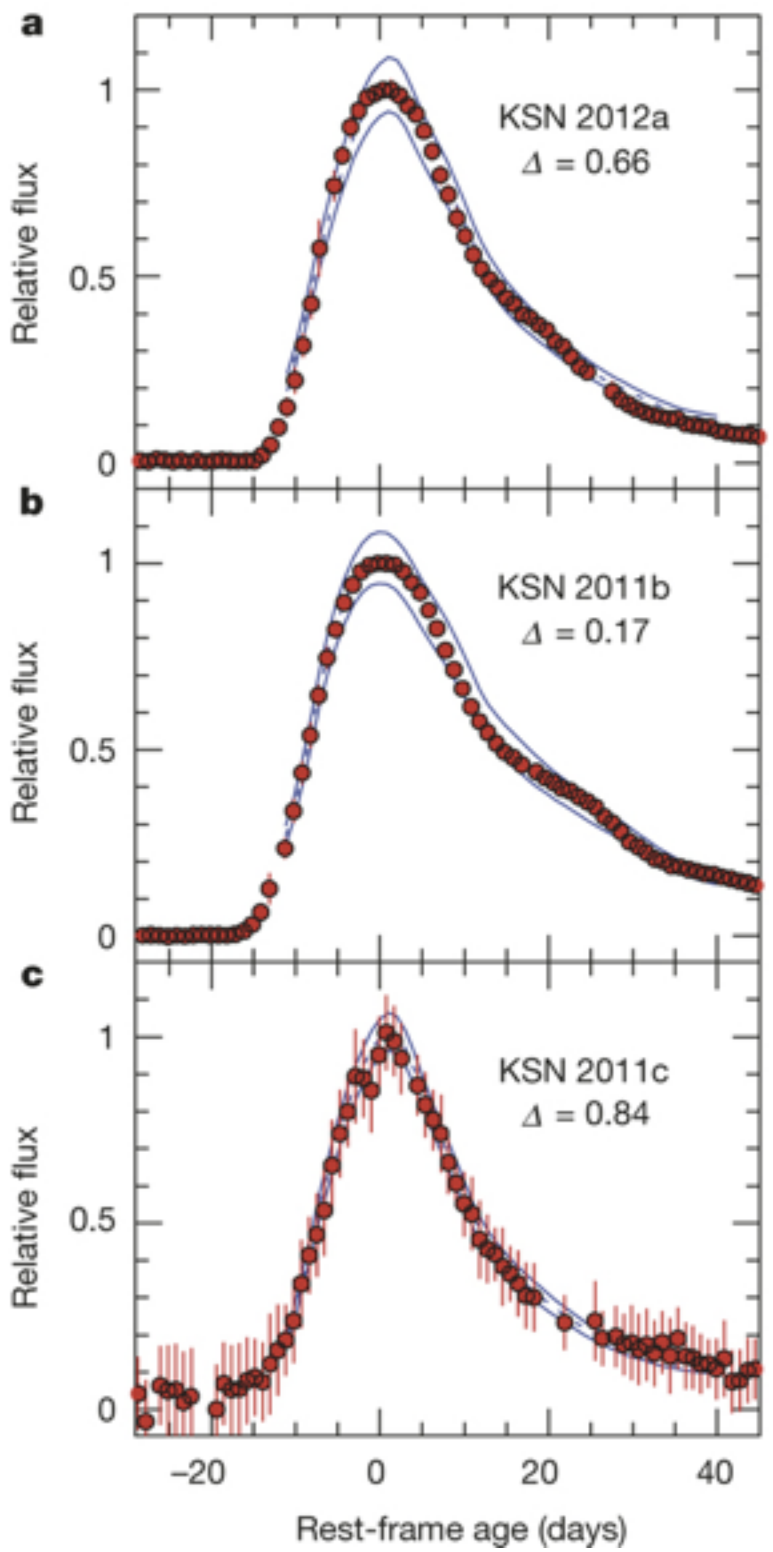


Bloom et al. 2012



Brown et al. 2012

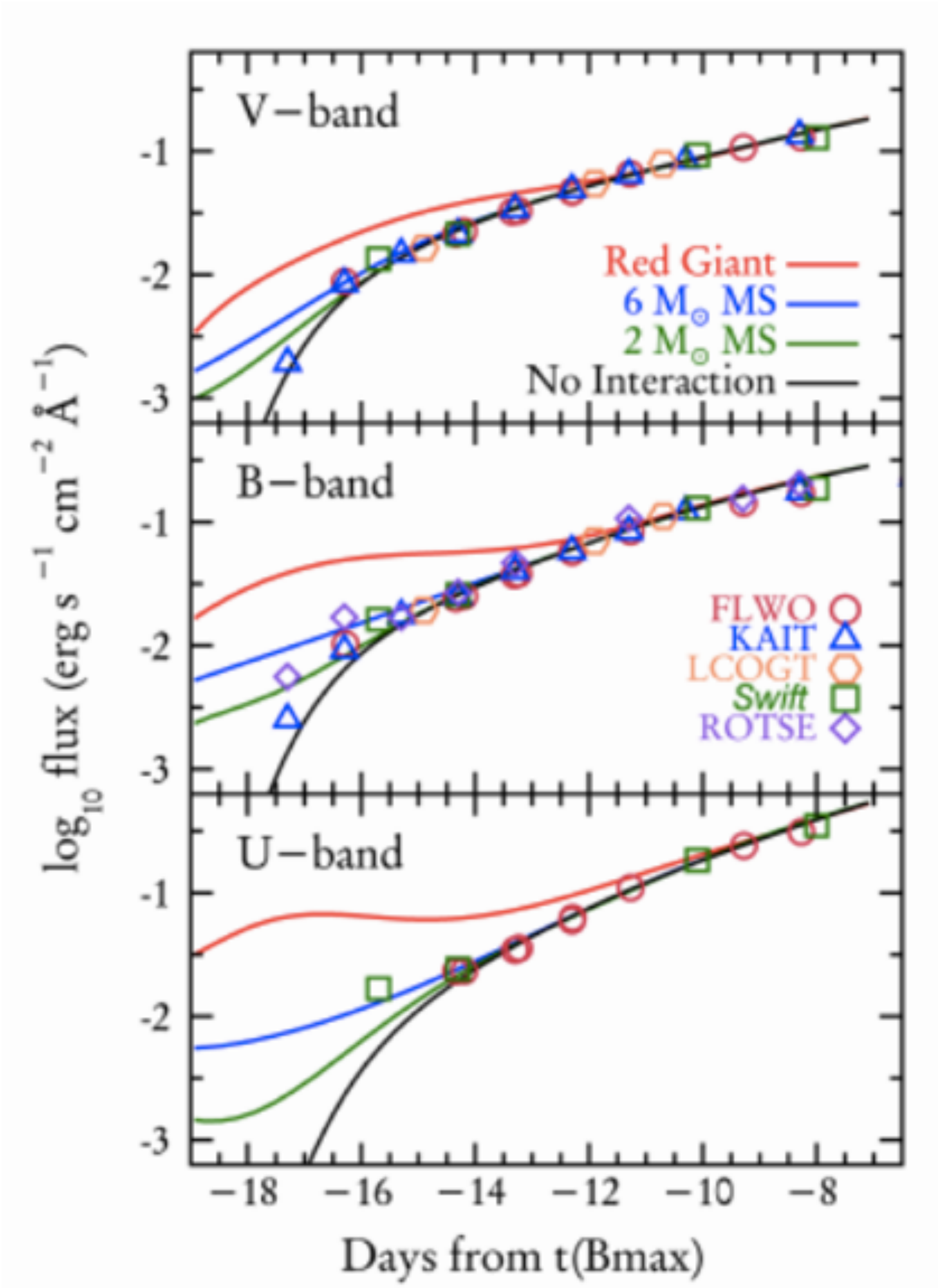
Kepler Observations of 3 SNe Ia



- Kepler monitored 400 galaxies for two to three years, discovering five supernovae near explosion
- Three events observed in 2011 and 2012 are likely SNe Ia, with two clearly showing the presence of a secondary 'bump' in the post-maximum light curve
- The continuous coverage reveals no signatures of companion impacts within the few days before first light, when the actual explosion must have occurred

Olling et al. 2015

The Early Light Curve of SN 2012cg

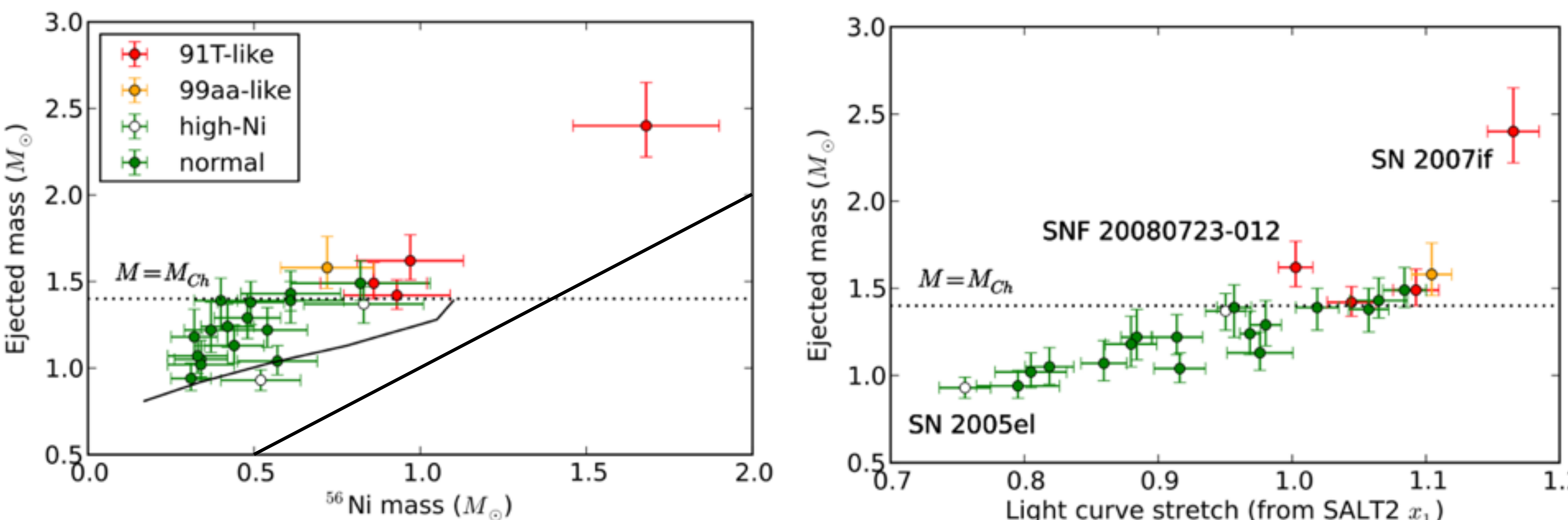


Marion et al. 2015

- Marion et al. (2015) report evidence for excess blue light from the Type Ia supernova SN 2012cg at 15 and 16 days before B maximum
- The emission is consistent with predictions for the impact of the SN on a non-degenerate binary companion — the data suggest that a main sequence companion of about 6 $M_\odot$ is the smallest allowed companion

^{56}Ni and Ejecta Masses

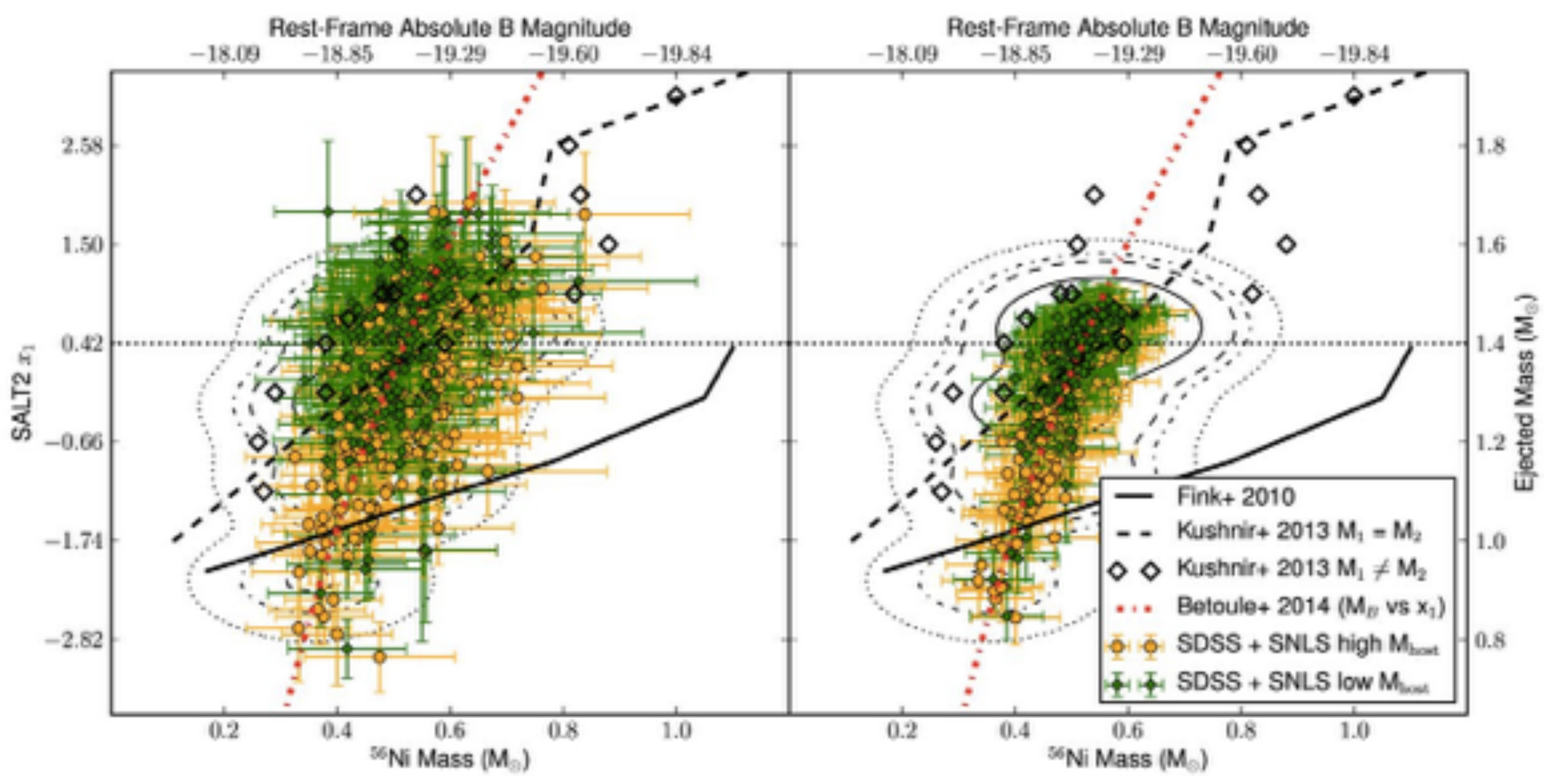
- Stritzinger et al. (2006) and Scalzo et al. (2014) have reconstructed the ejecta masses of SNF SNe Ia using the semi-analytic formalism of Arnett (1982) and Jeffries (1999)
- Scalzo et al. found that ejected mass was found to correlate strongly with light curve decline rate
- Fast-declining SNe Ia (Δm15(B) > 1.6) appear to have sub-Chandrasekhar ejecta masses



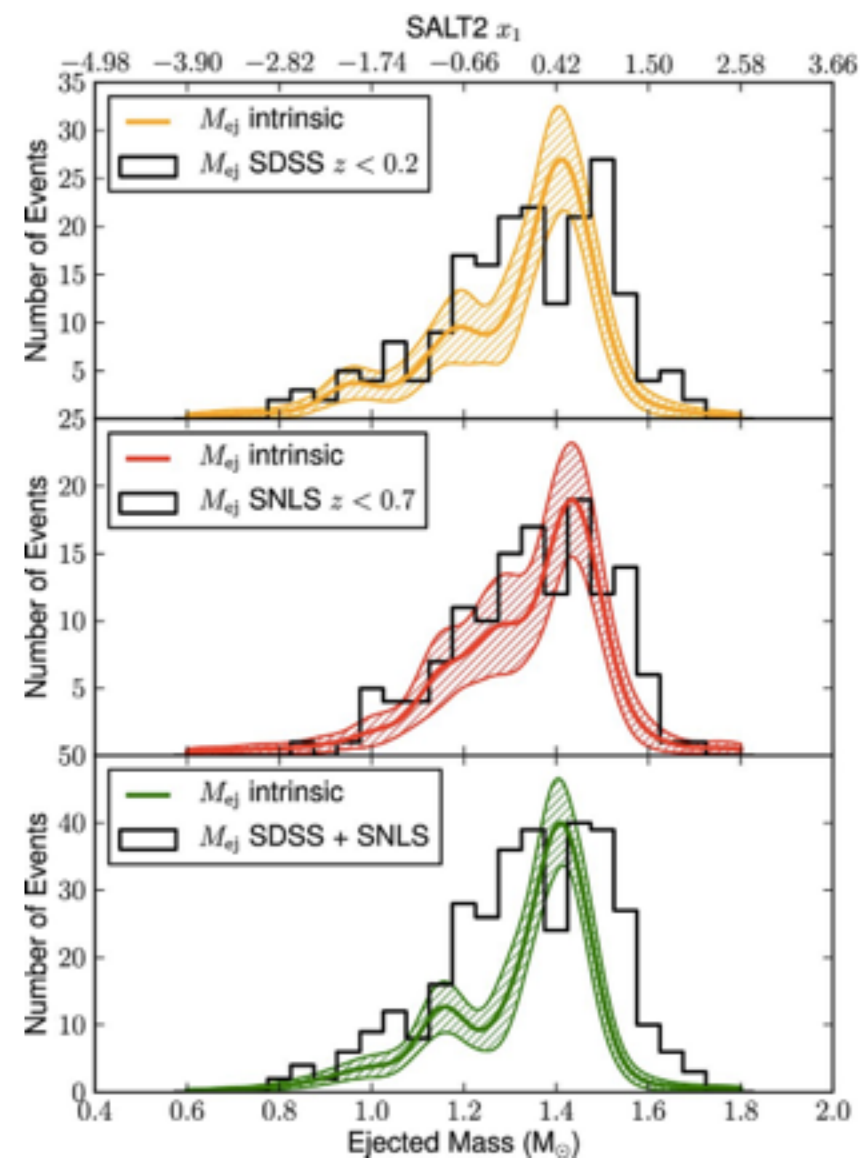
Scalzo et al. 2014

^{56}Ni and Ejecta Masses

- Scalzo, Ruiter, & Sim (2014) used the relation between the ejected mass and decline rate from Scalzo et al. (2014) to derive ejected masses ejecta and ^{56}Ni masses for a sample of 337 SNe Ia with redshifts $z < 0.7$
- 25–50% of normal SNe Ia appear to be inconsistent with Chandrasekhar-mass explosions



Caution: These results rely on the accuracy of the Scalzo et al. (2014) SNF results, and on assumptions of spherically symmetric ejecta, with a stratified composition and a universal functional form for the radial density profile



Scalzo, Ruiter, & Sim 2014

Conclusions

- Whatever mechanism(s) can make SNe Ia, they must in combination reproduce the following properties:
  - The observed smoothness of the luminosity-decline relation
  - The range of ^{56}Ni masses underlying this sequence
  - The lack of evidence for large asphericities in the ejecta
  - 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

- In general, the unsuccessful search for evidence of the companions to normal SNe Ia would seem not to favor the single-degenerate model, but at least one events (2012cg) seems likely to have had a non-degenerate companion (or circumstellar material) — we need to obtain both imaging and spectroscopy of many more SNe Ia within hours of outburst to get a better idea of what is going on here
- The power law dependence of the delay-time distribution is difficult to explain in the single-degenerate model, but arises fairly naturally in double-degenerate scenarios and for double detonations of a CO-He WD pair
- The evidence for circumstellar material in SN Ia progenitor systems is mixed — many seem to explode in a relatively clean environment

Conclusions

- It is easy to believe that SNe Ia are produced through more than one mechanism
- My favorite candidates for subgroups are:
  - The fast decliners (Δm15(B) $\gtrsim$ 1.6)
  - High-velocity SNe Ia

Conclusions

- It is easy to believe that SNe Ia are produced through more than one mechanism
- My favorite candidates for subgroups are:
  - The fast decliners ($\Delta m15(B) \gtrsim 1.6$)
  - High-velocity SNe Ia
- Some unanswered questions:
  - Can the Maeda et al. (2010) viewing angle hypothesis explain the diversity of normal SNe Ia?
  - Why do some SNe Ia appear to be associated with regions of star formation with unusual dust properties?
  - Why do SNe Ia with "blueshifted" Na I D profiles show anomalously high Na I column densities?
  - What are the High Velocity Features telling us?


Thank you!