What in heaven's name are Type Ia supernovae?

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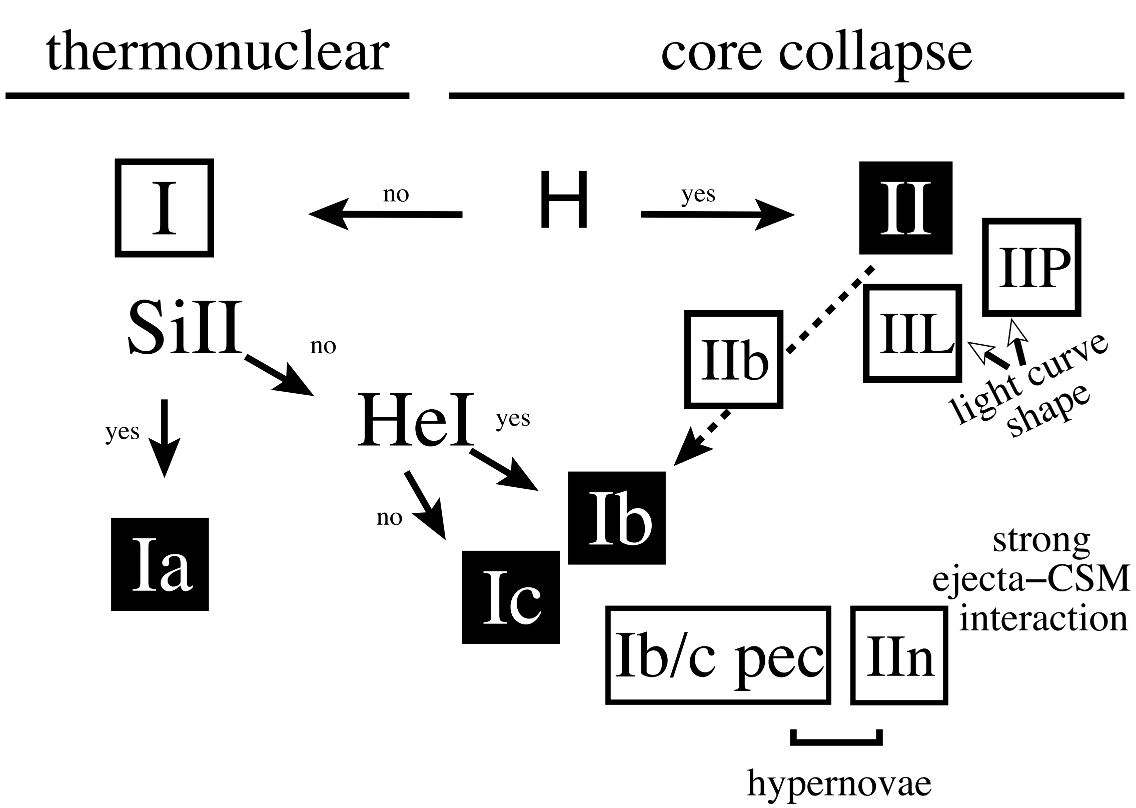
Outline of the talk

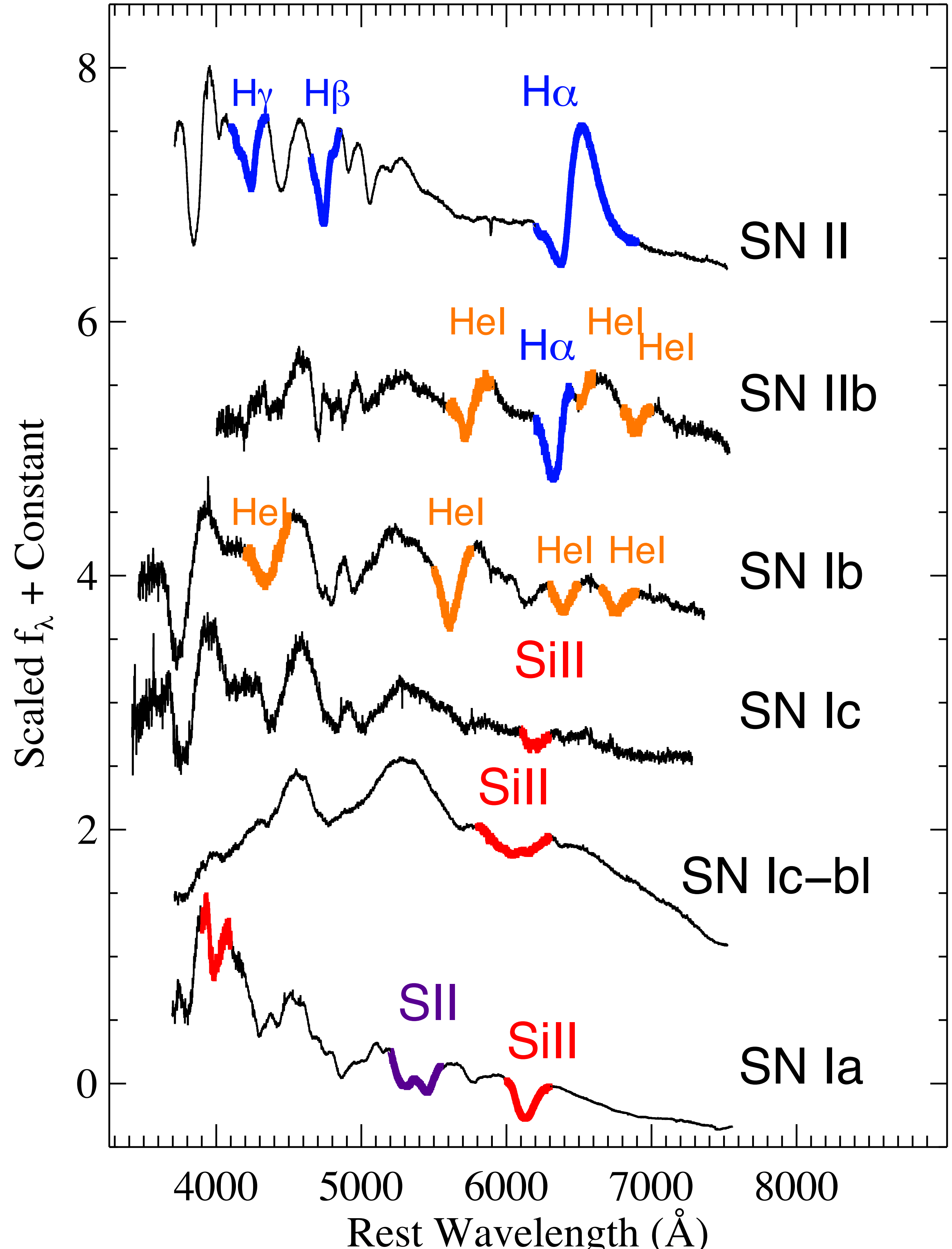
1. What we think Type Ia supernovae are today.
2. How do we learn more in the future.

Type Ia supernova

- Classification is based on spectrum near maximum.
- But how was Type Ia first identified?



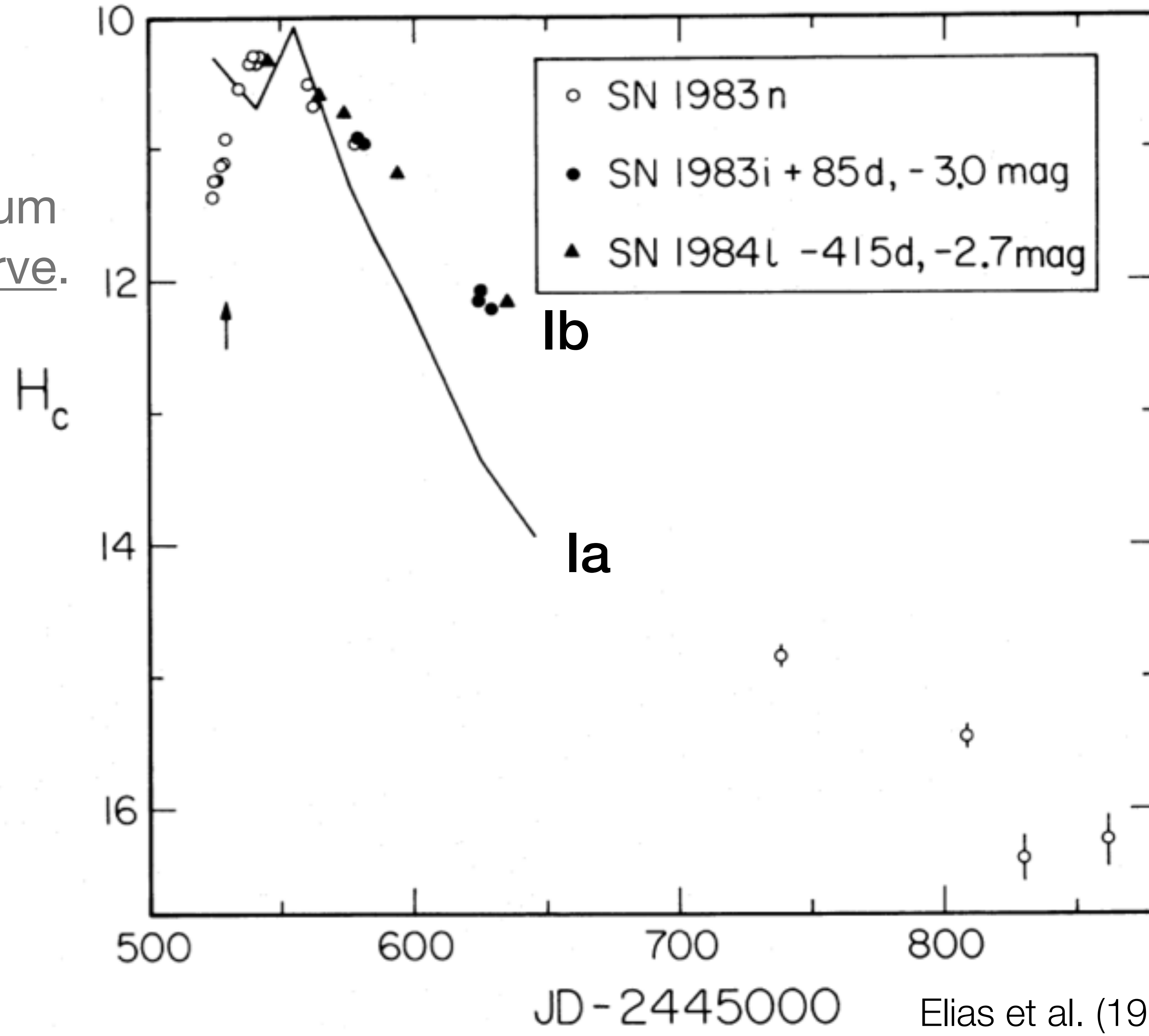
Turatto (2003)



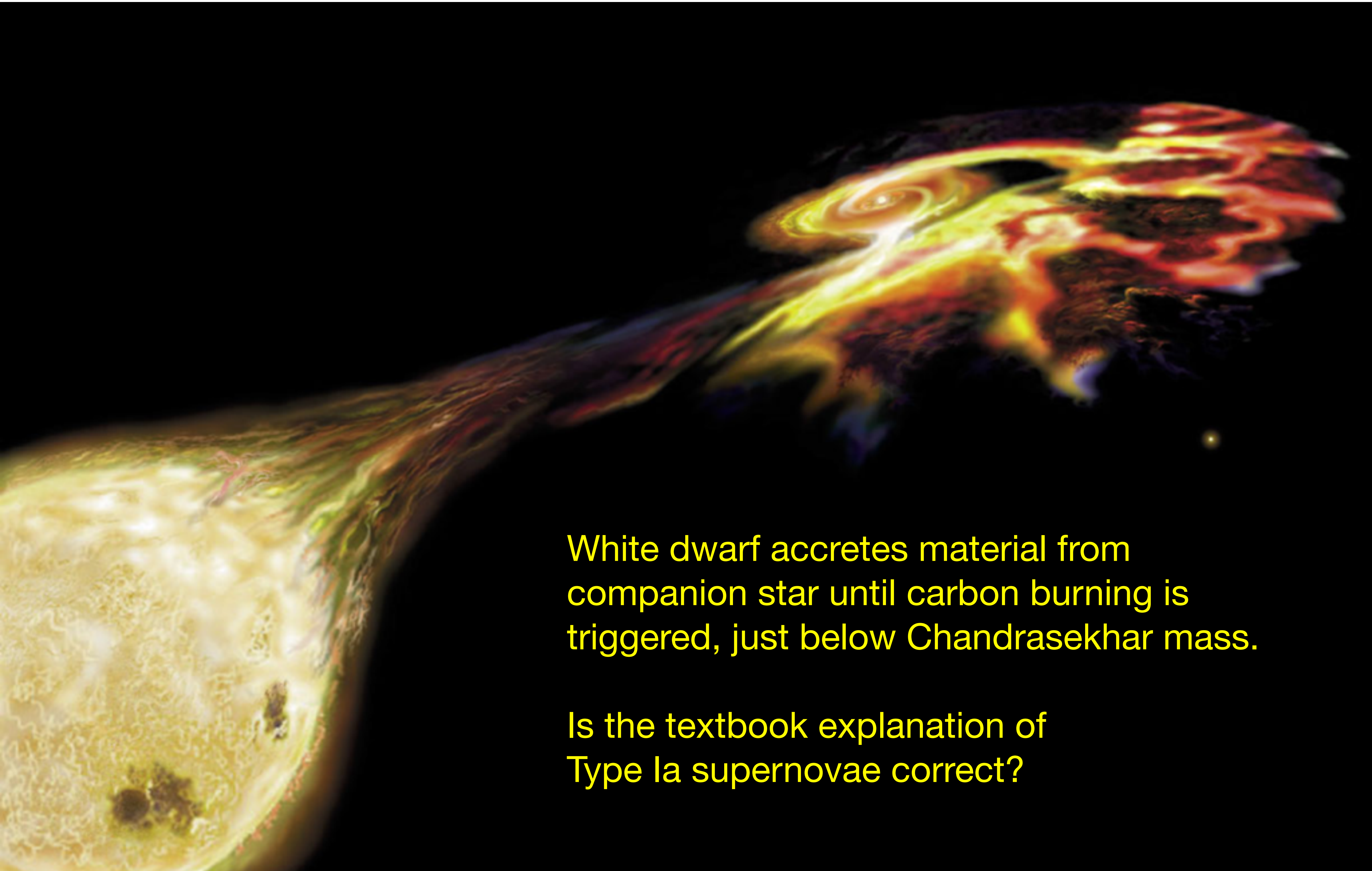
Modjaz et al. (2014)

Type Ia supernova

- “Type Ia” first identified by its secondary maximum in the NIR light curve.



Elias et al. (1985)

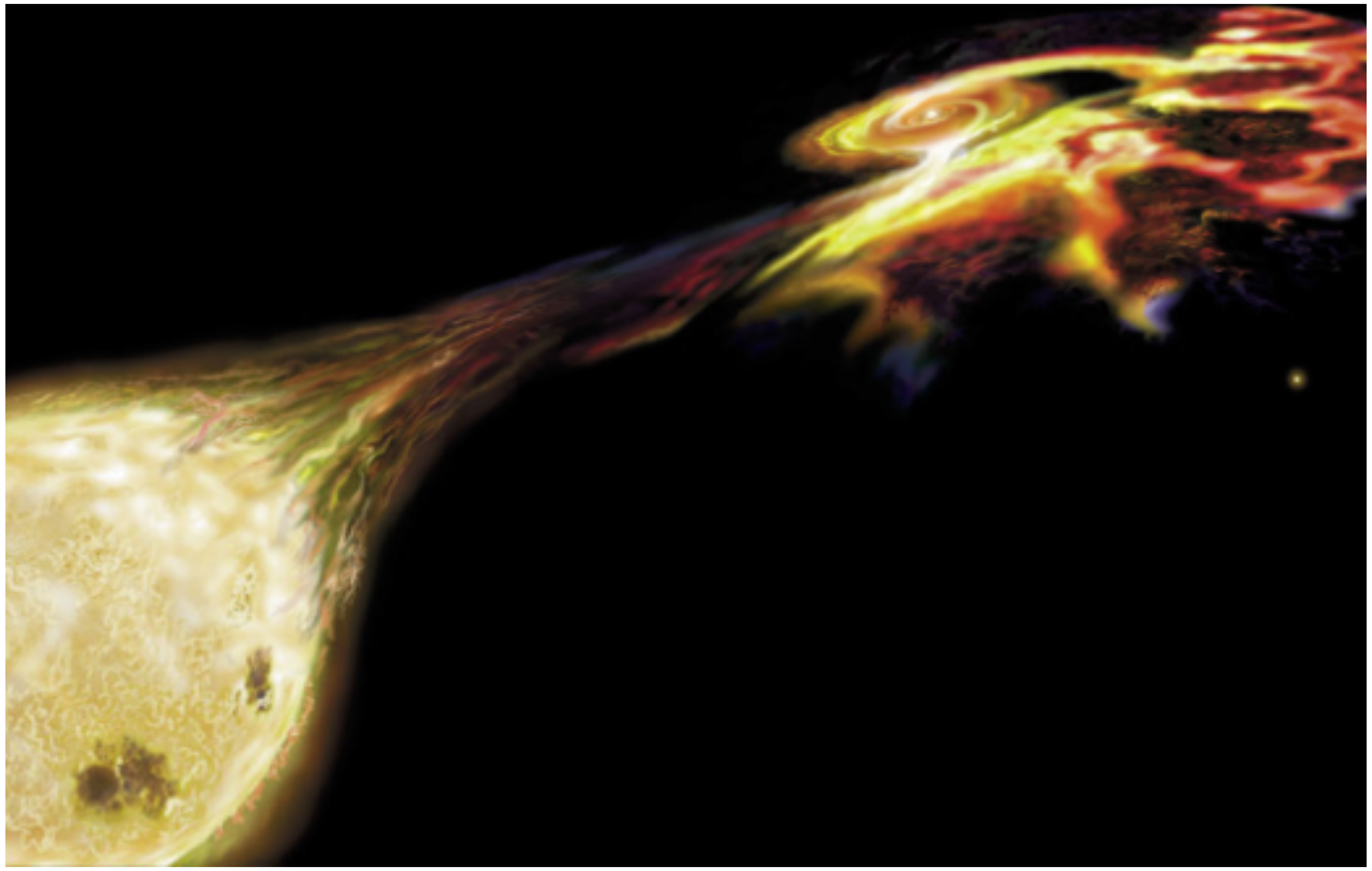


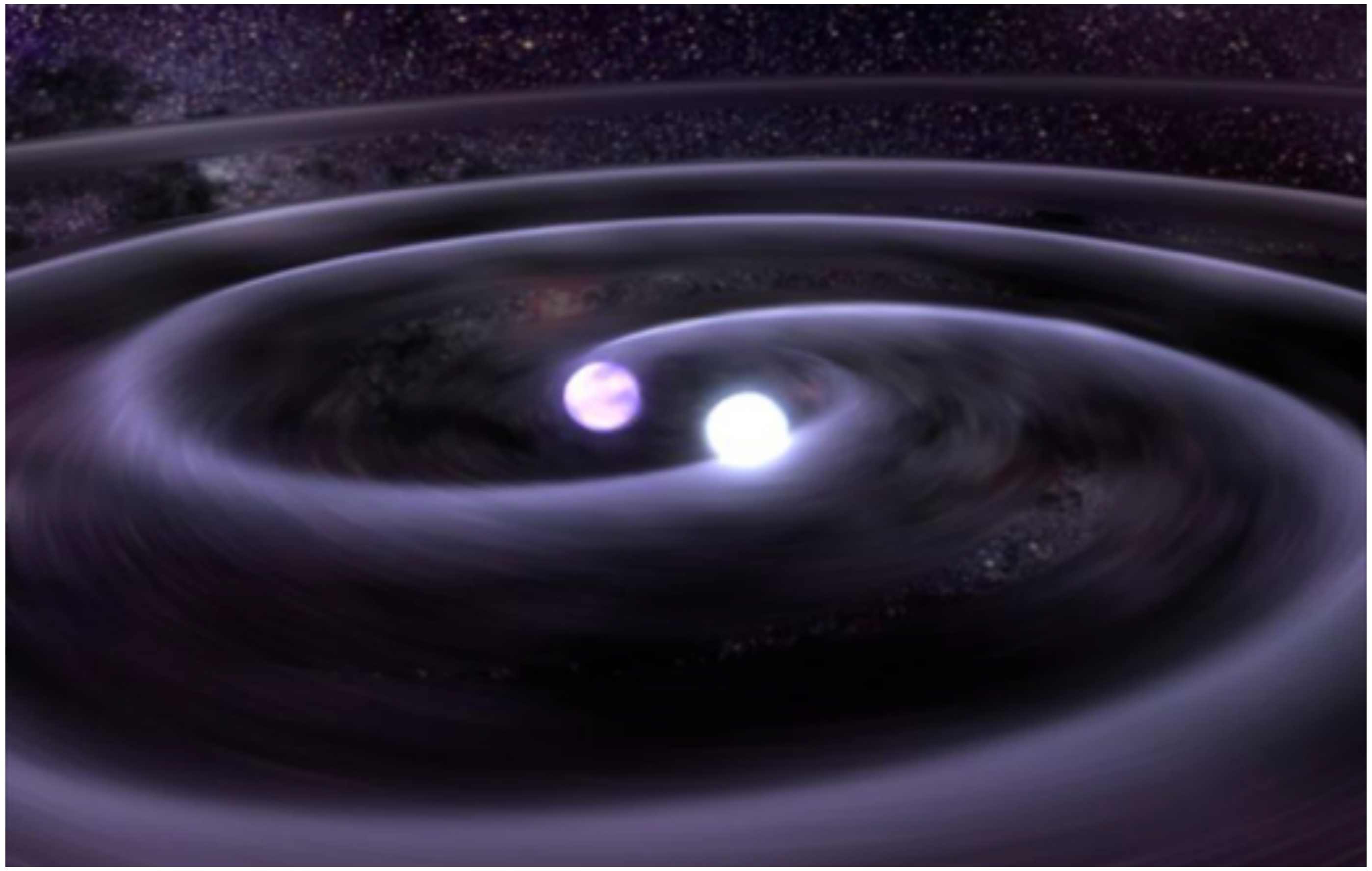
White dwarf accretes material from companion star until carbon burning is triggered, just below Chandrasekhar mass.

Is the textbook explanation of Type Ia supernovae correct?

Type Ia supernova

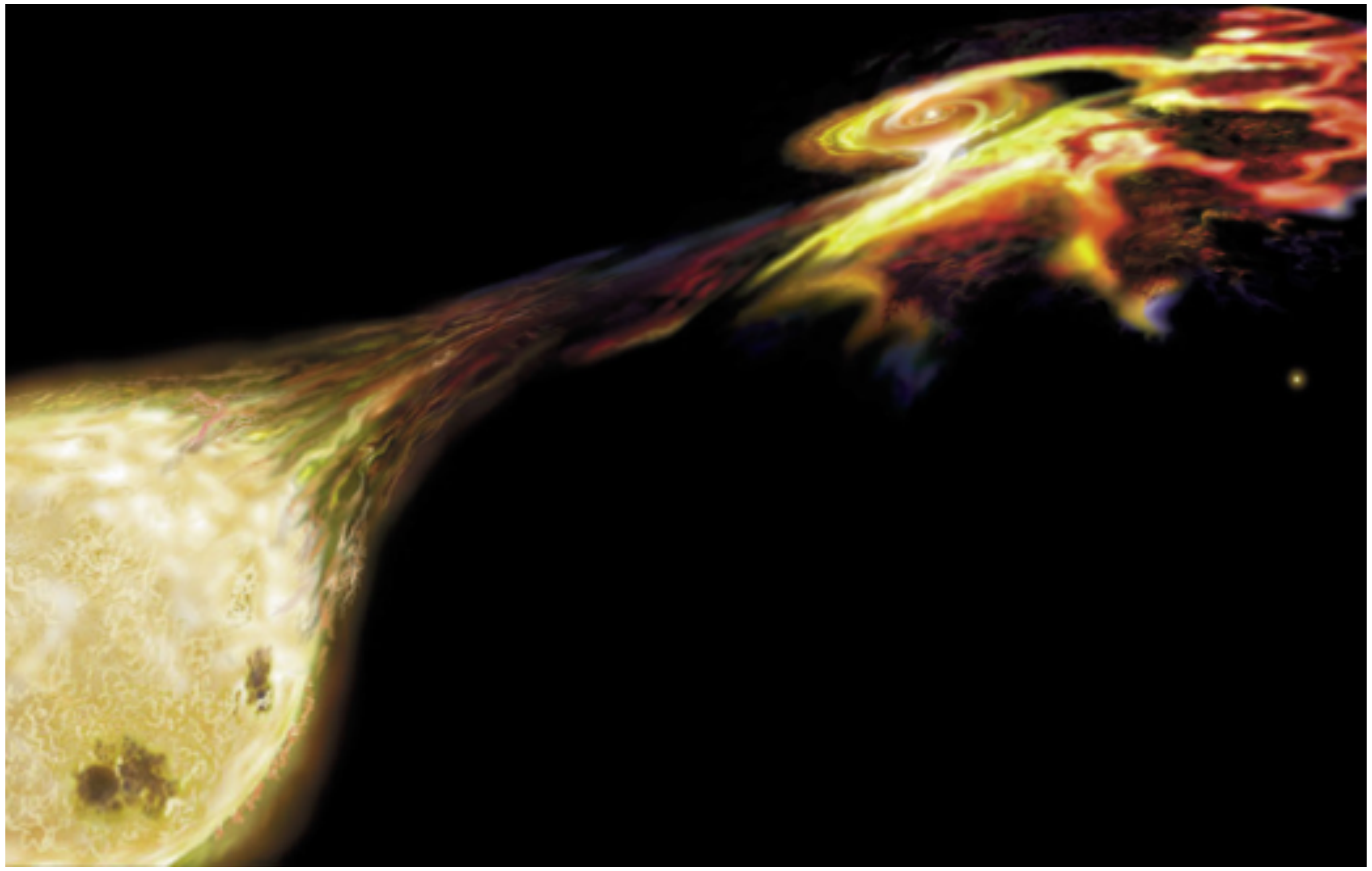
- Consensus explosion of a C/O WD undergoing thermonuclear runaway.
- Progenitor system
  single degenerate
  double degenerate
- Explosion mechanisms
  Chandrasekhar mass, **Mch**
  He detonation, **sub-Mch**
  dynamical mergers
  direct collision
  core degenerate

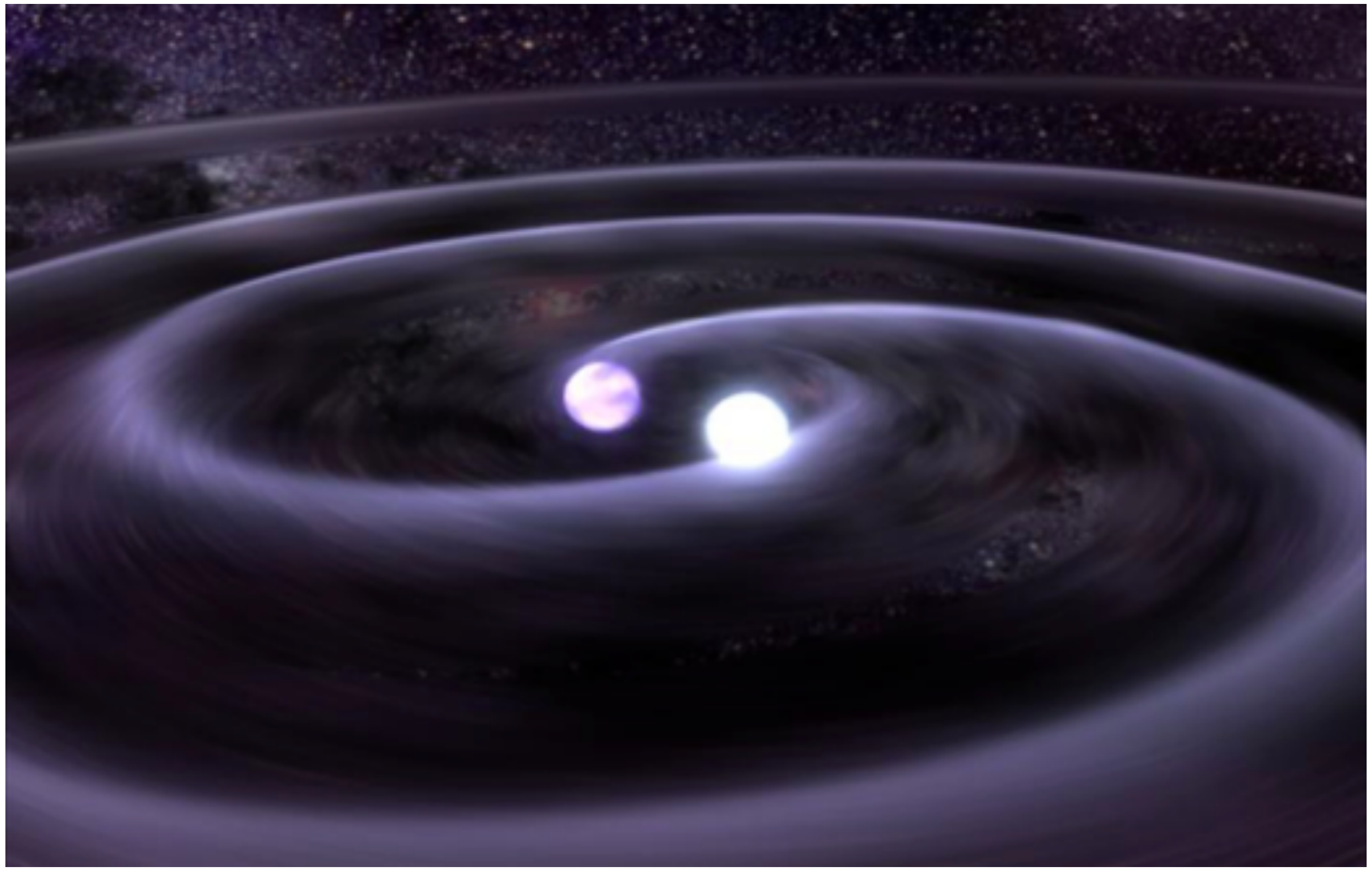




Type Ia supernova

- There is a tendency in the literature to mix and confuse progenitor system with explosion mechanism.
- Mch != single degenerate
  Mch != "dirty" surrounding
  e.g., Dragulin et al. (2016): wind from accretion disk carves out a low-density void several light years across.
- sub-Mch != double degenerate
  sub-Mch != "clean" surrounding
  e.g., Shen et al. (2013): H-rich material can be ejected prior to He WD and C/O WD merger.





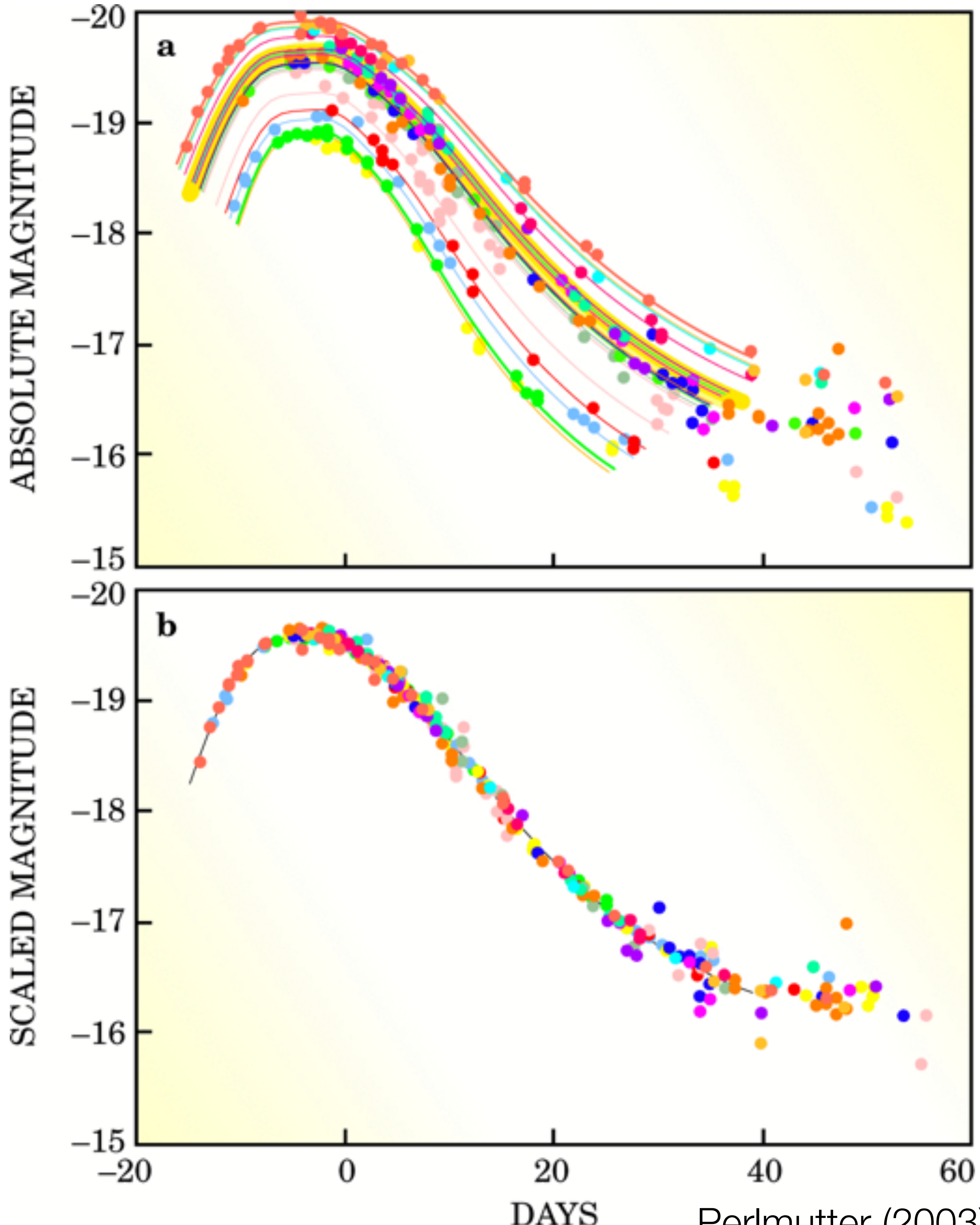
What is the companion star?

What is the explosion mechanism?

What is the origin of the observed homogeneity and diversity?

Diversity

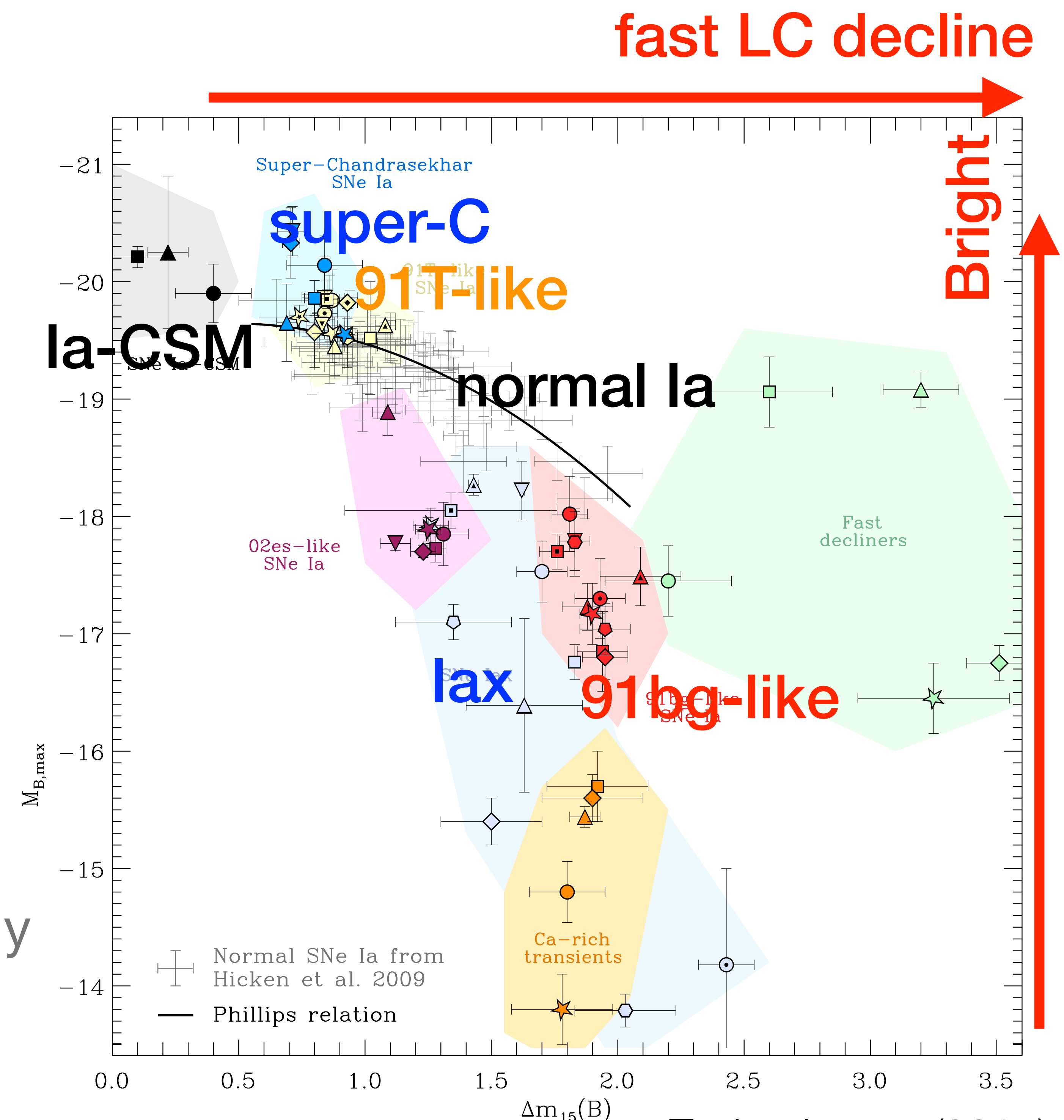
- Type Ia supernovae are not standard candles, but "standardizable candles."
- Width-luminosity relation (or Phillips relation) enables precision cosmology.
- Dimmer supernovae also decline faster.
- Vast majority of Ia follow this tight empirical relation.



Perlmutter (2003)

Diversity

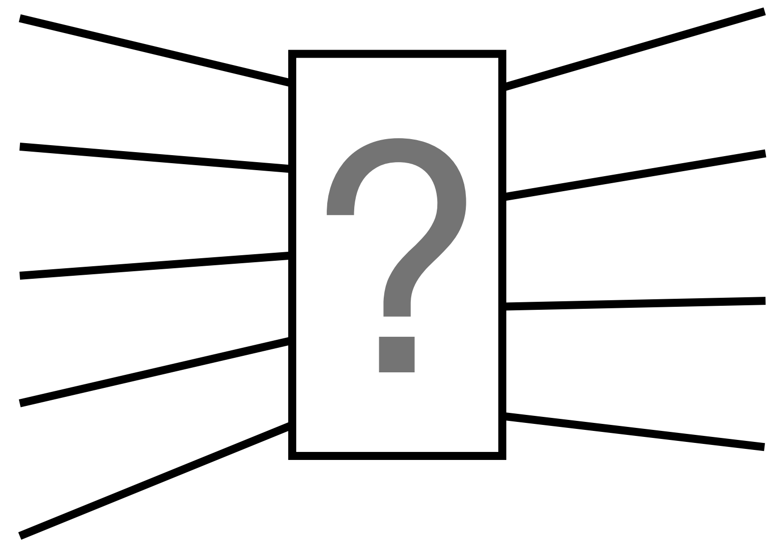
- But some Ia don't follow the rule.
- 91bg and 91T-like are spectroscopically distinct, and also sub- and over-luminous.
- Iax are low-velocity sub-luminous Ia with a wide range of peak mag.
- Super-C Ia are over-luminous, implying ejected mass significantly higher than Mch.



Taubenberger (2017)

Diversity

- Chandrasekhar mass (Mch)
- He detonation (sub-Mch)
- dynamical mergers
- direct collision
- core degenerate

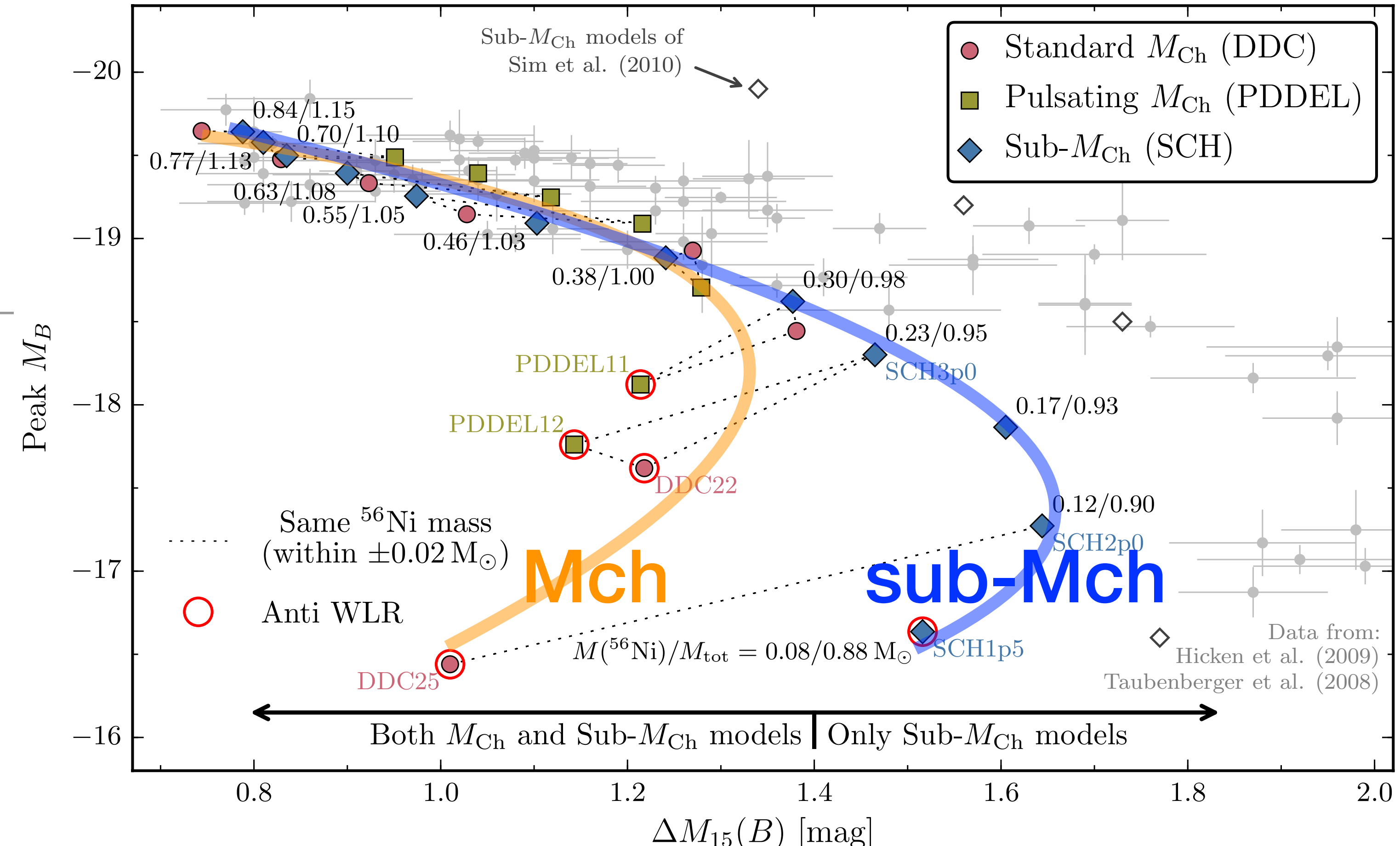


- Normal Ia
- super-Chandrasekhar
- Ia-CSM
- Iax

- It is easier (comparatively) to figure out the mechanisms of peculiar events with their extreme properties. In turn, this helps to determine possible mechanisms for the normal population.

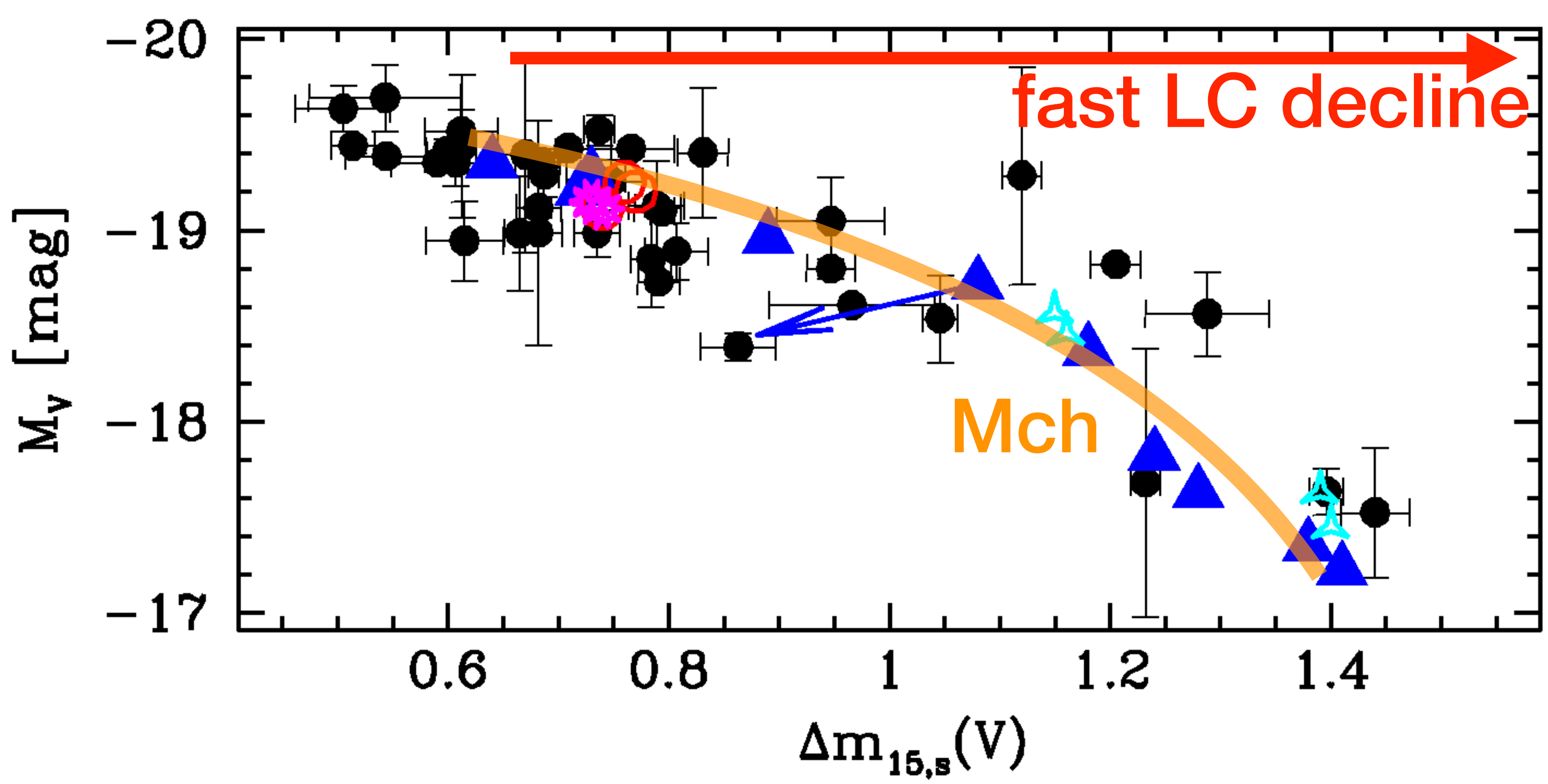
Photometric properties

- Dimmer Ia cannot come from Mch, but must come from sub-Mch channel exclusively.



Blondin et al. (2017)

- One mechanism, Mch, explains all normal Ia.



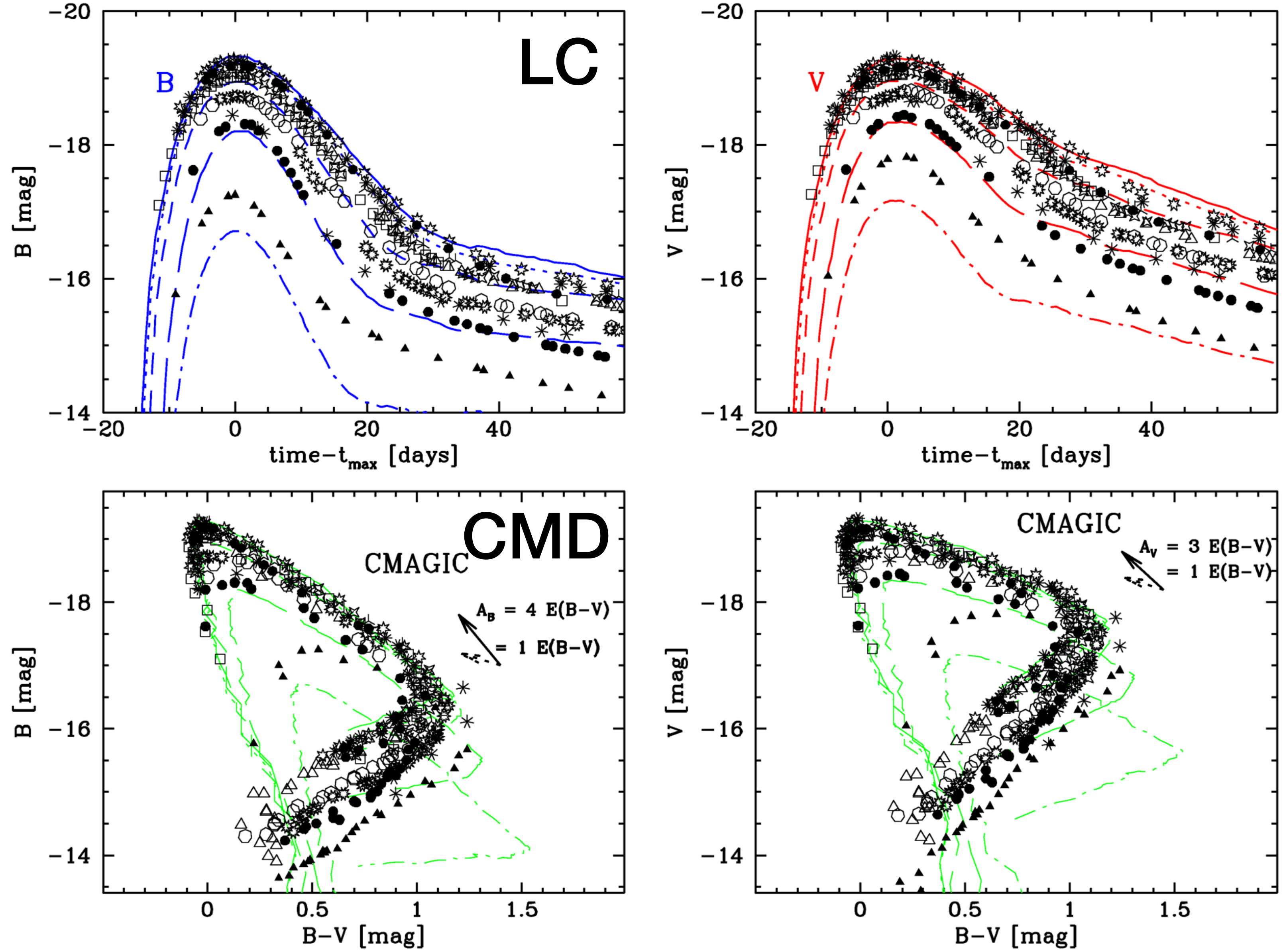
Hoeflich, Hsiao et al. (2017)

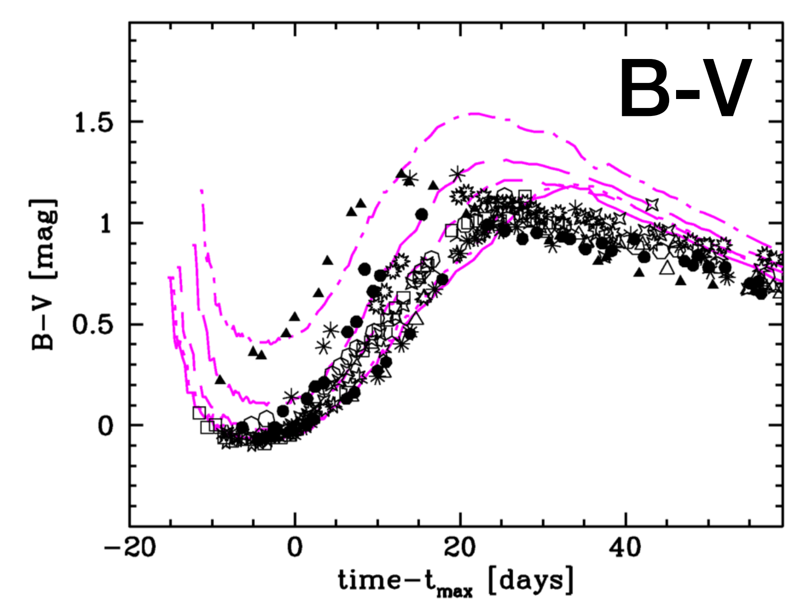
- Current interpretations of the Phillips relation yield conflicting results!

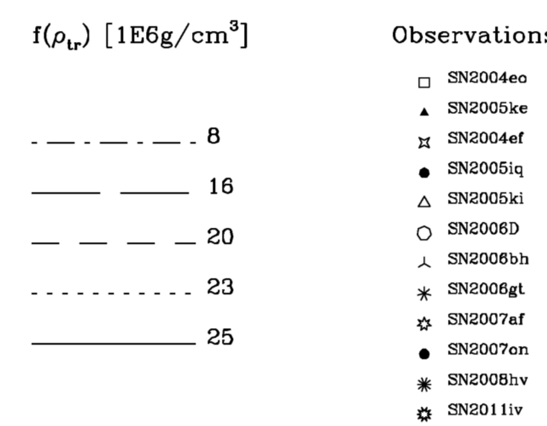
Photometric properties

- Mch models provide exceptional match to the observations, but only in 1D.
- Sub-Mch models do not.

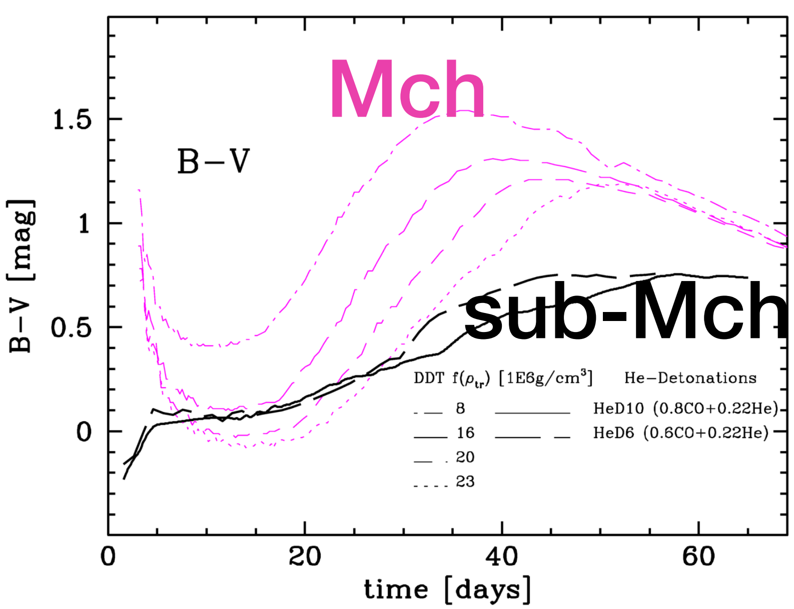
1D Mch models





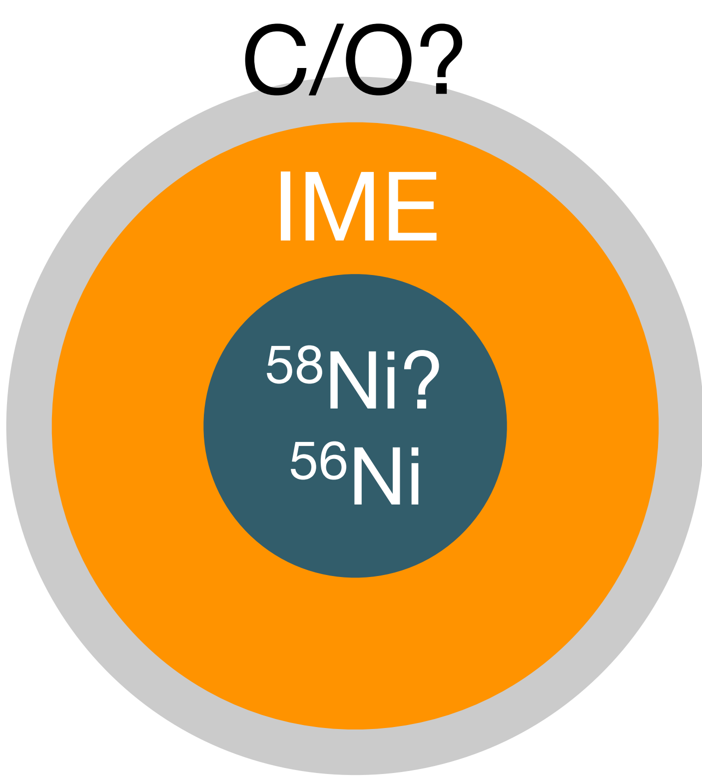


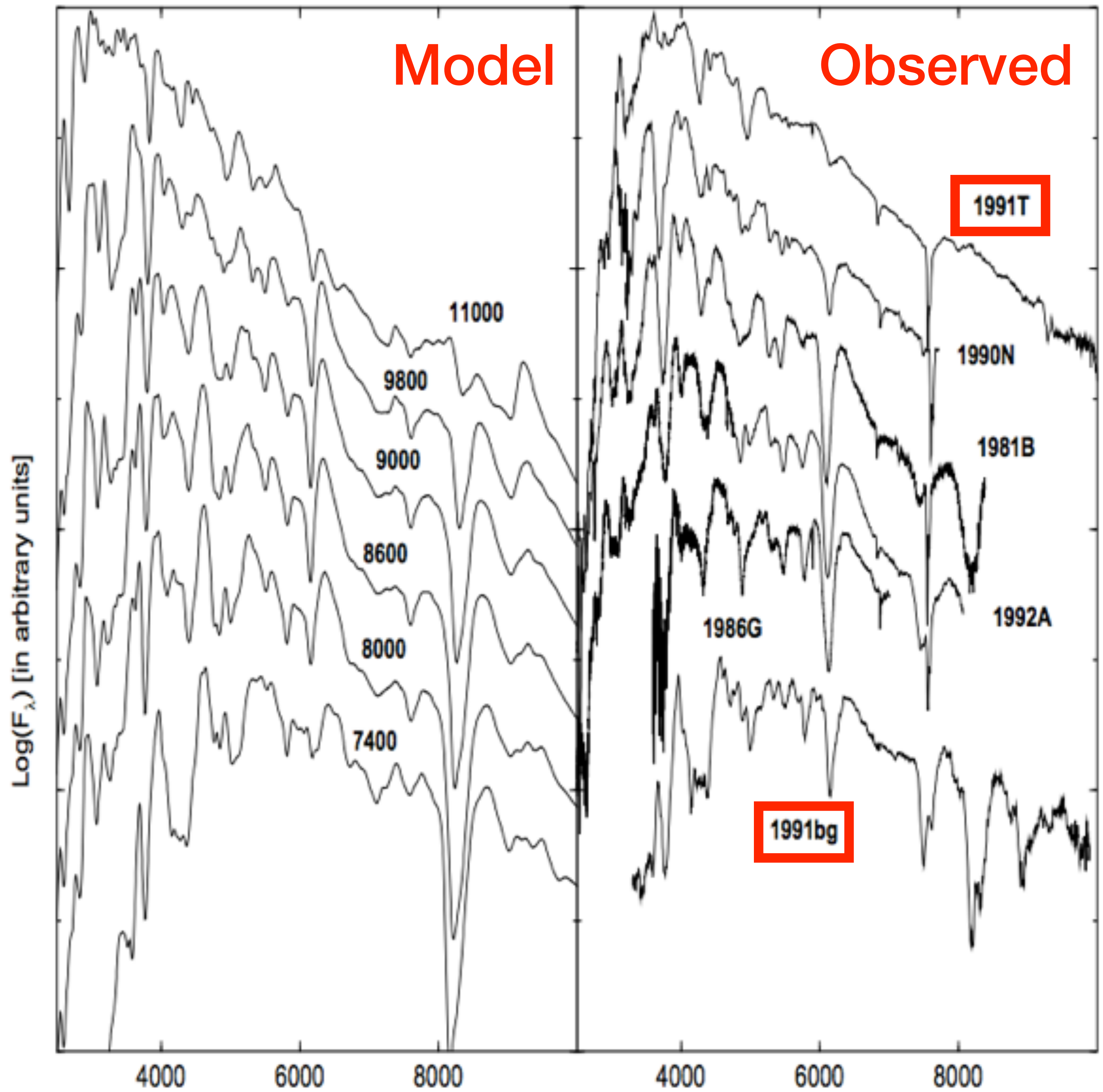
Hoeflich, Hsiao et al. (2017)



Spectroscopic properties

- Dialing the temperature of radiative transport appears to reproduce the observed spectroscopic diversity, including 91T, normal, 91bg.

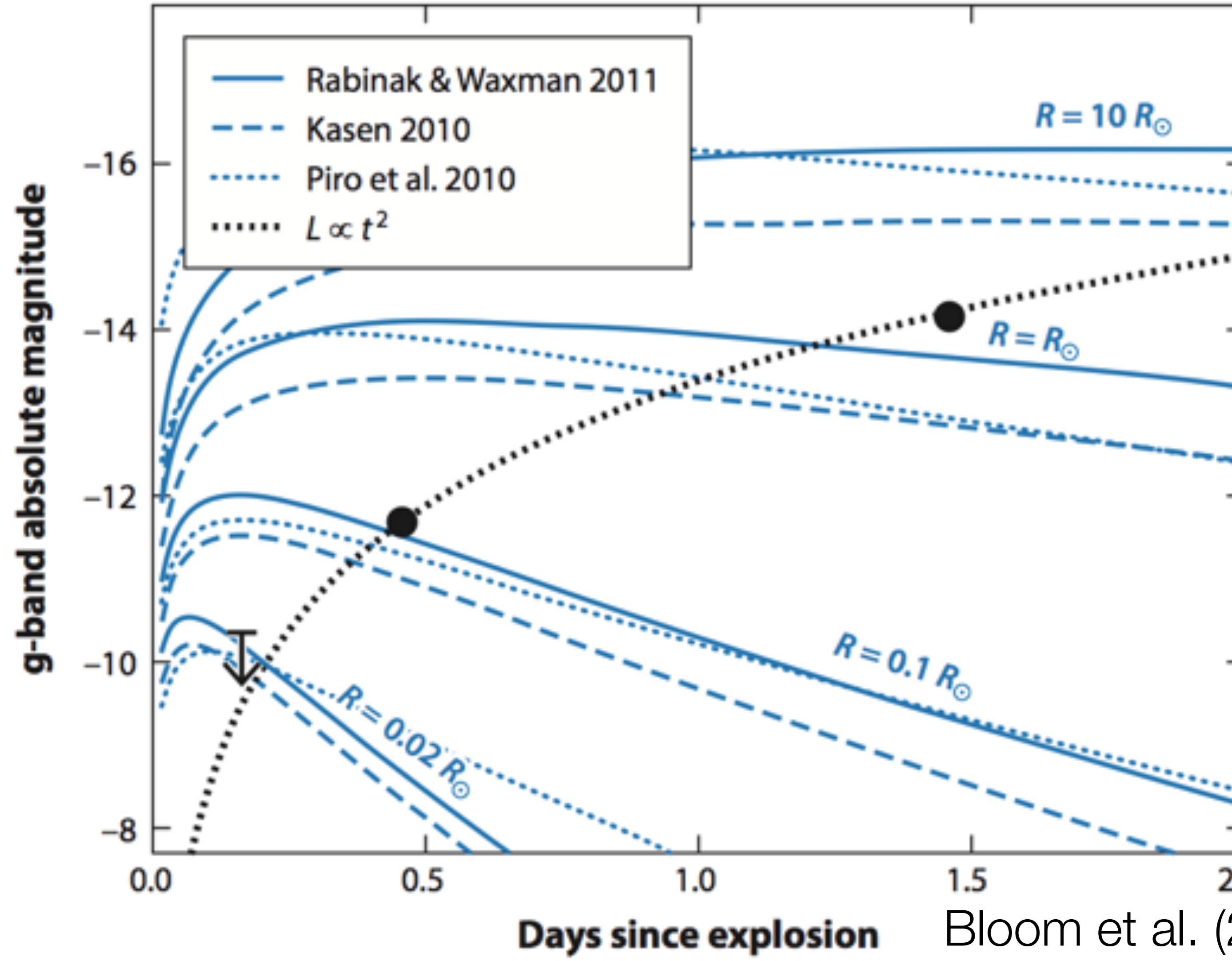




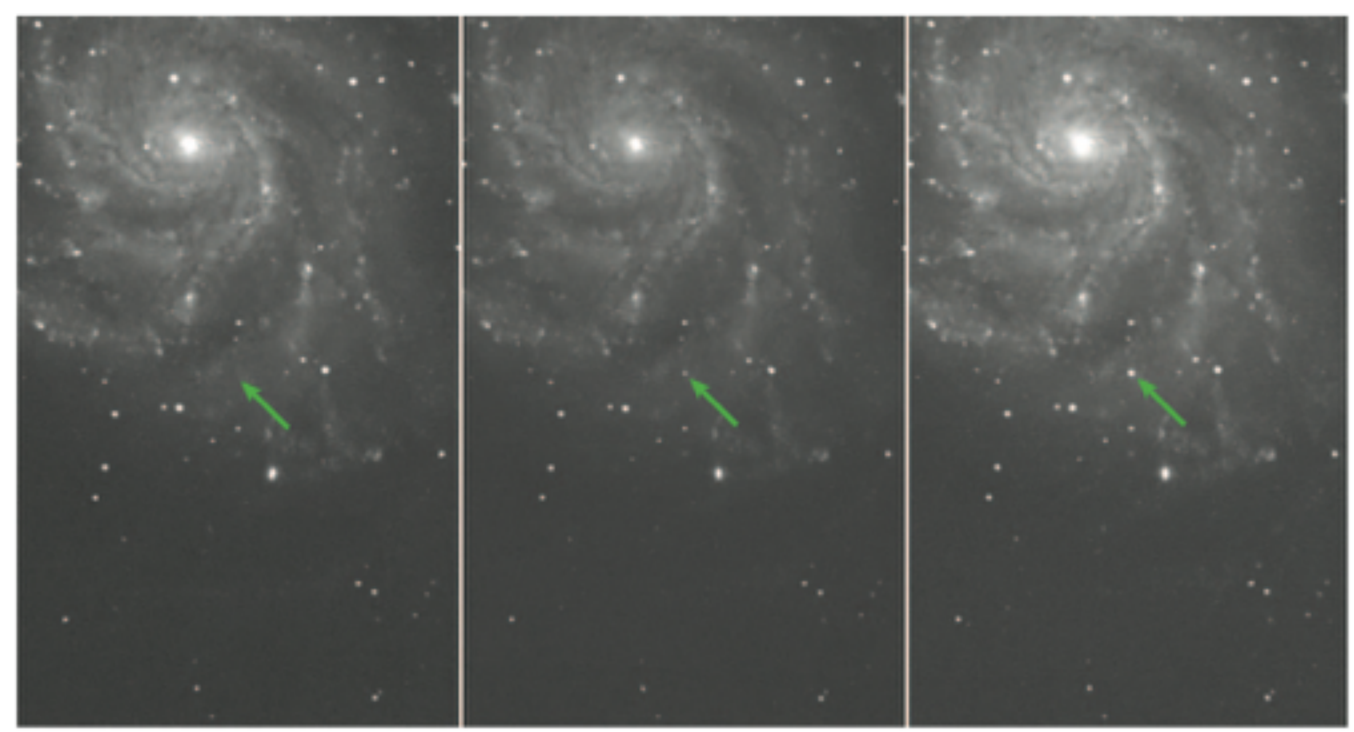
Nugent et al. (1995)

Primary star

- SN2011fe, a normal Ia, was discovered hours after its explosion in M101, 6.4 Mpc away.
- Cooling of shock-heated primary or companion depends on radius.
- R < 0.02 Rsun
  Only WD and NS are viable as primary star candidates.



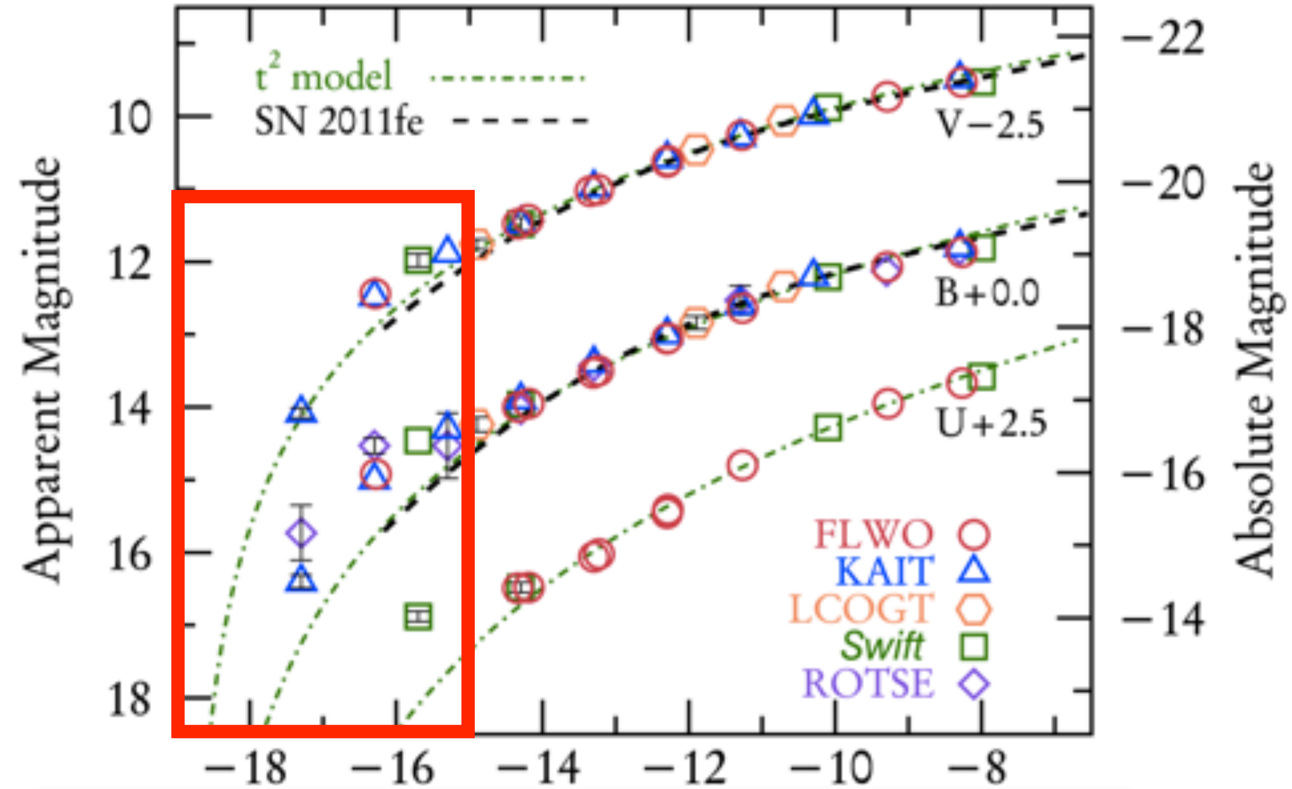
Bloom et al. (2012)

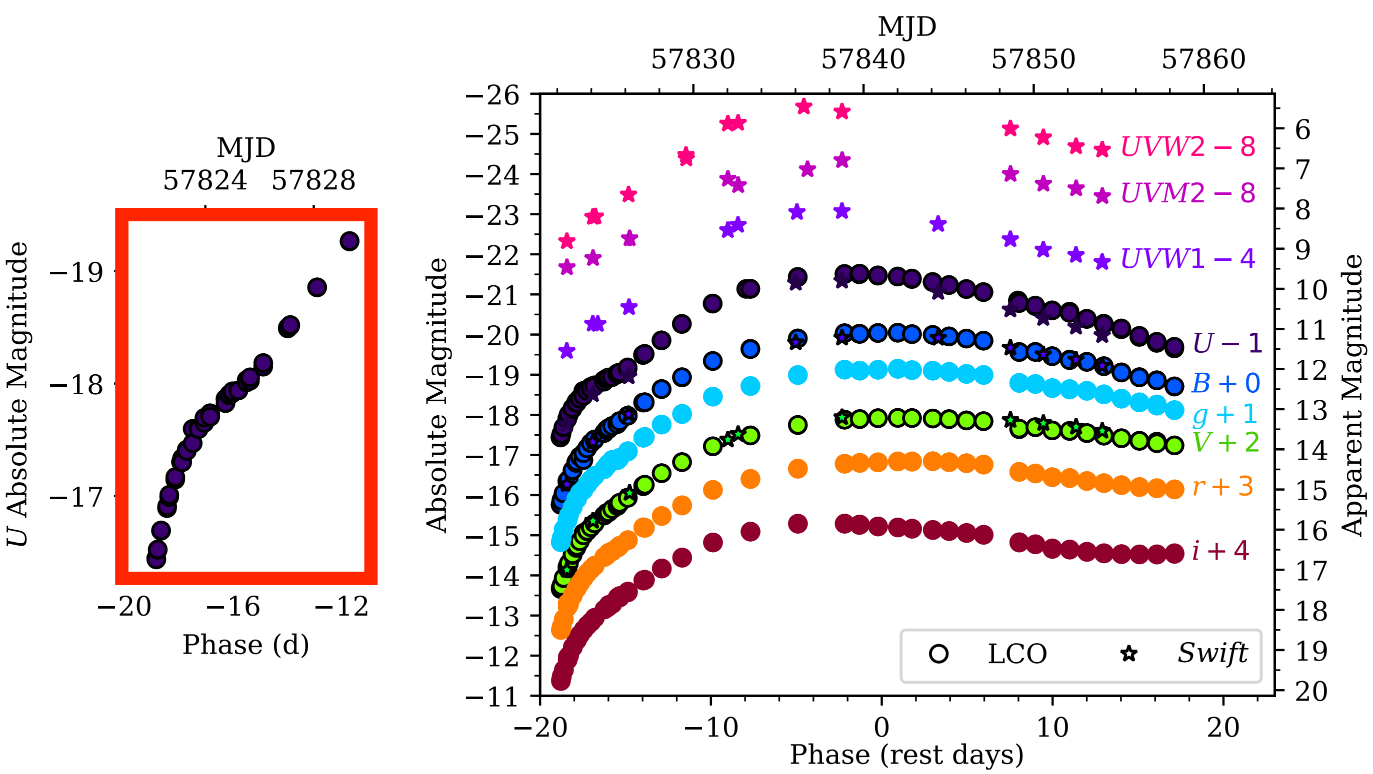


Nugent et al. (2011)

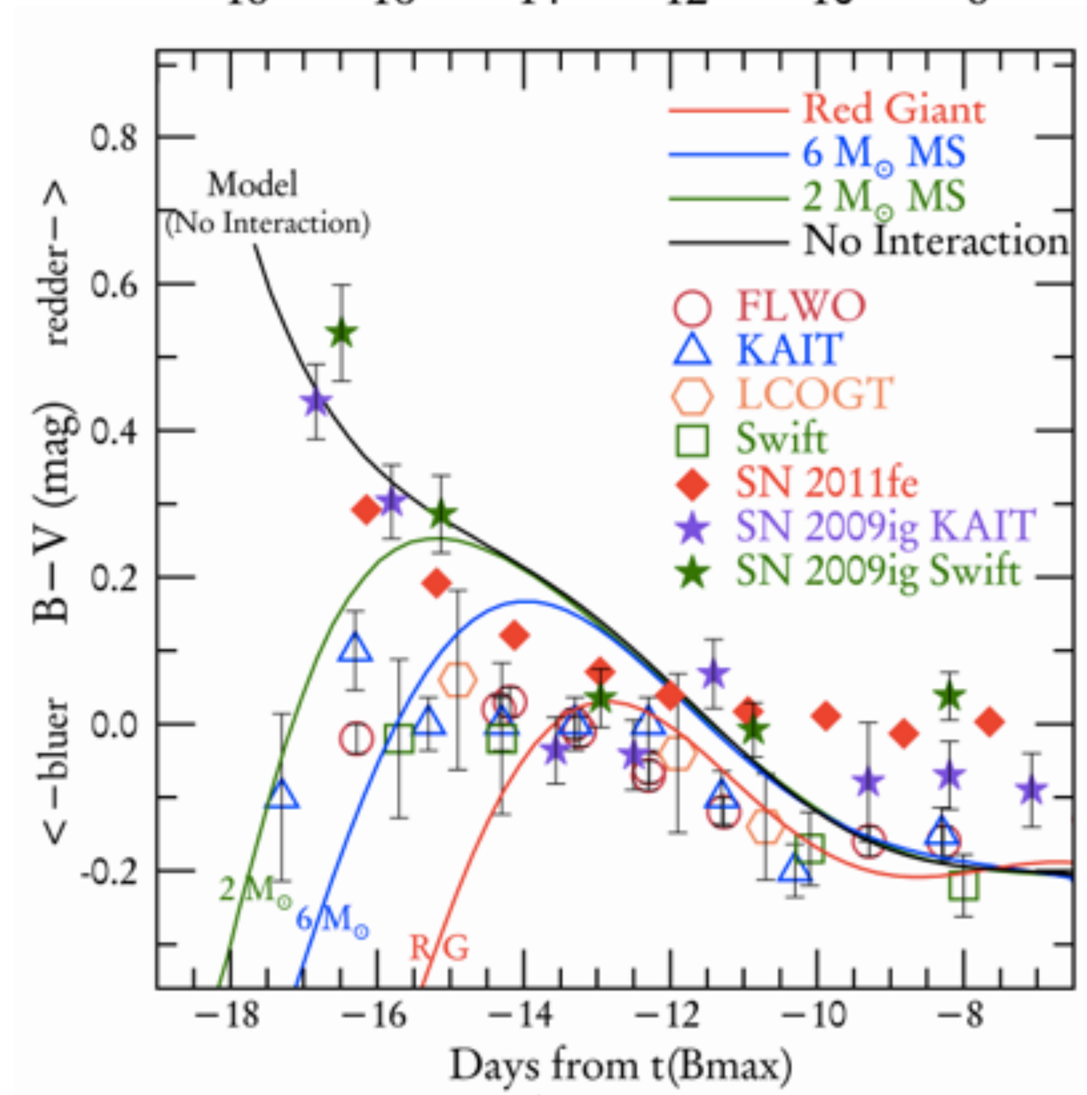
Companion star: shock heating

- There are now 2 examples of normal Ia showing "<u>bumps</u>" in their early light curves, interpreted as <u>shock heated companion</u>.





SN2017cbv; Hosseinzadeh et al. (2017)



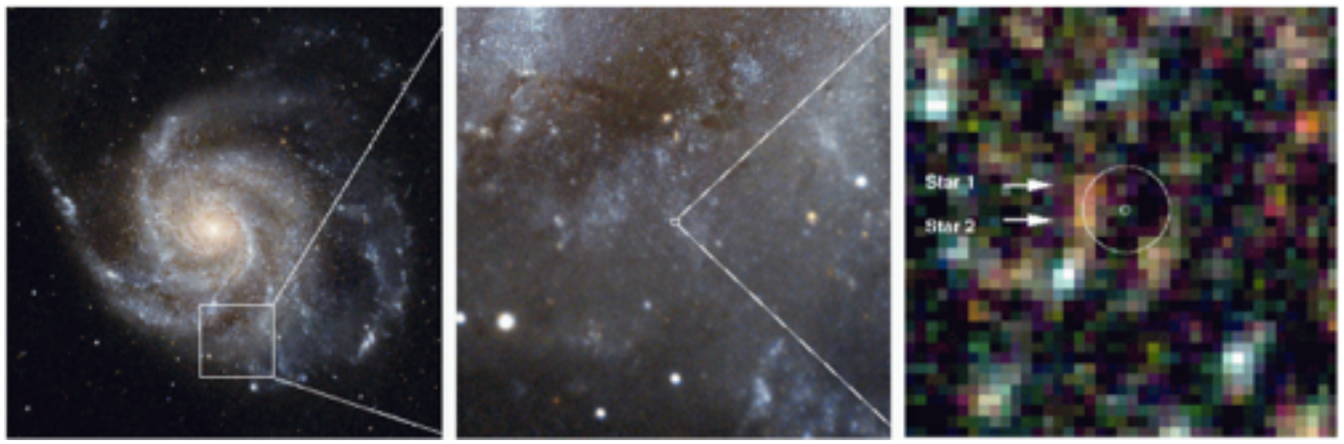
SN2012cg; Marion et al. (2015)

Companion star: shock heating

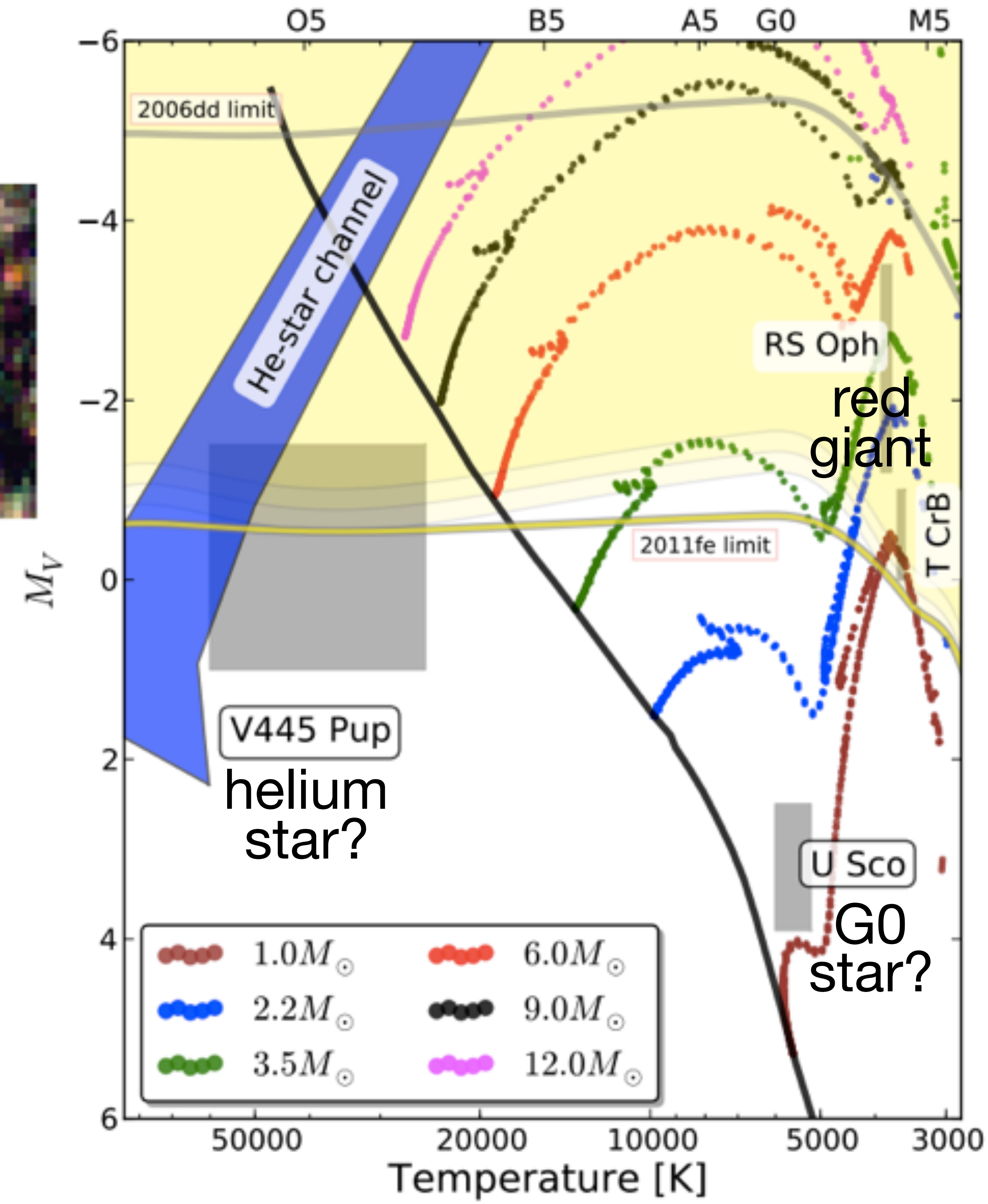
- These detections are rare.
  Most glaring, are all the non-detections from rolling searches.

Hayden et al. (2010)	SDSS-II	No detection
Bianco et al. (2011)	SNLS	No detection
Brown et al. (2012)	Swift nearby	No detection
Zheng et al. (2013)	SN2013dy	No detection
Yamanaka et al. (2014)	SN2012ht	No detection
Firth et al. (2015)	PTF/LSQ	No detection
Olling et al. (2015)	Kepler	No detection
Shappee et al. (2015)	ASASSN-14lp	No detection
Cao et al. (2015)	iPTF14atg	R ~ 20 Rsun
Marion et al. (2015)	SN2012cg	R ~ 10 Rsun
Hosseinzadeh et al. (2017)	SN2017cbv	R ~ 60 Rsun

Companion star: pre-explosion



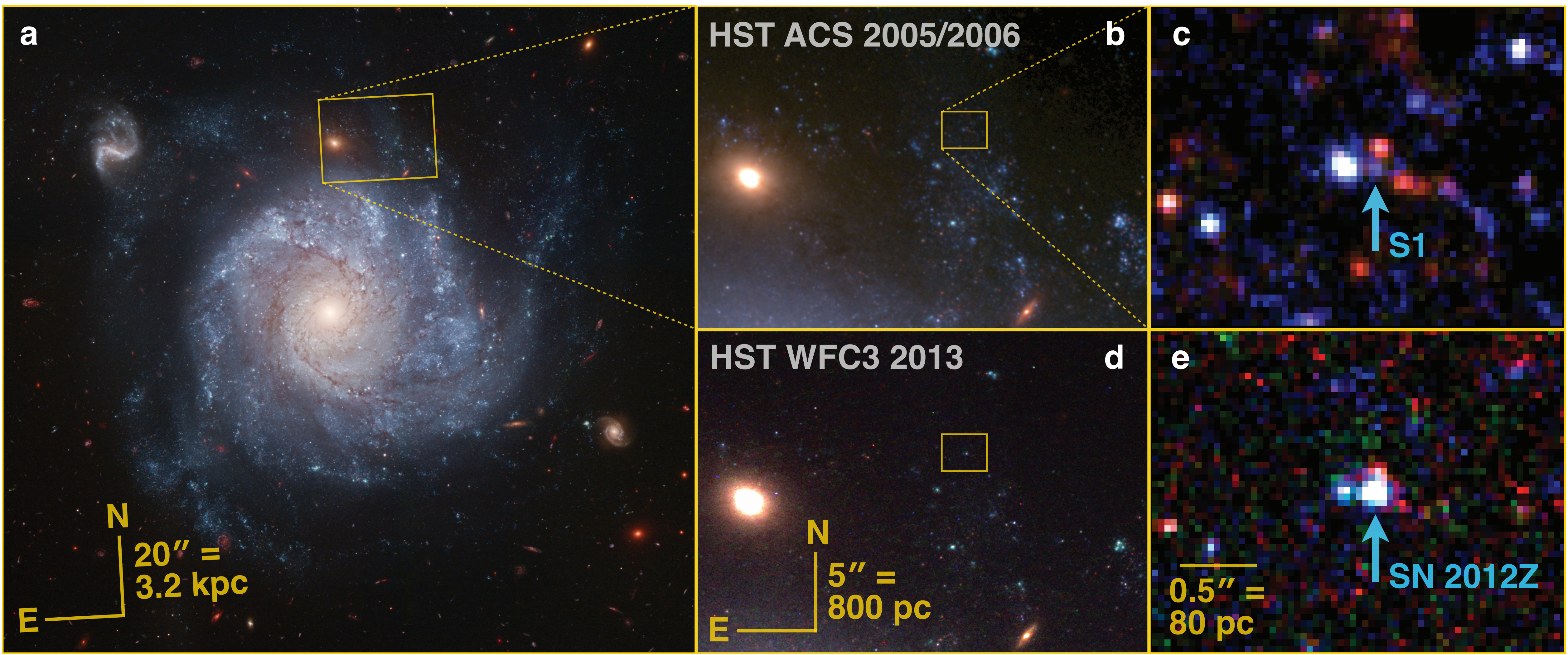
- Pre-explosion images rule out luminous RG and most He-star as companion for SN2011fe.



Li et al. (2011)

Companion star: pre-explosion

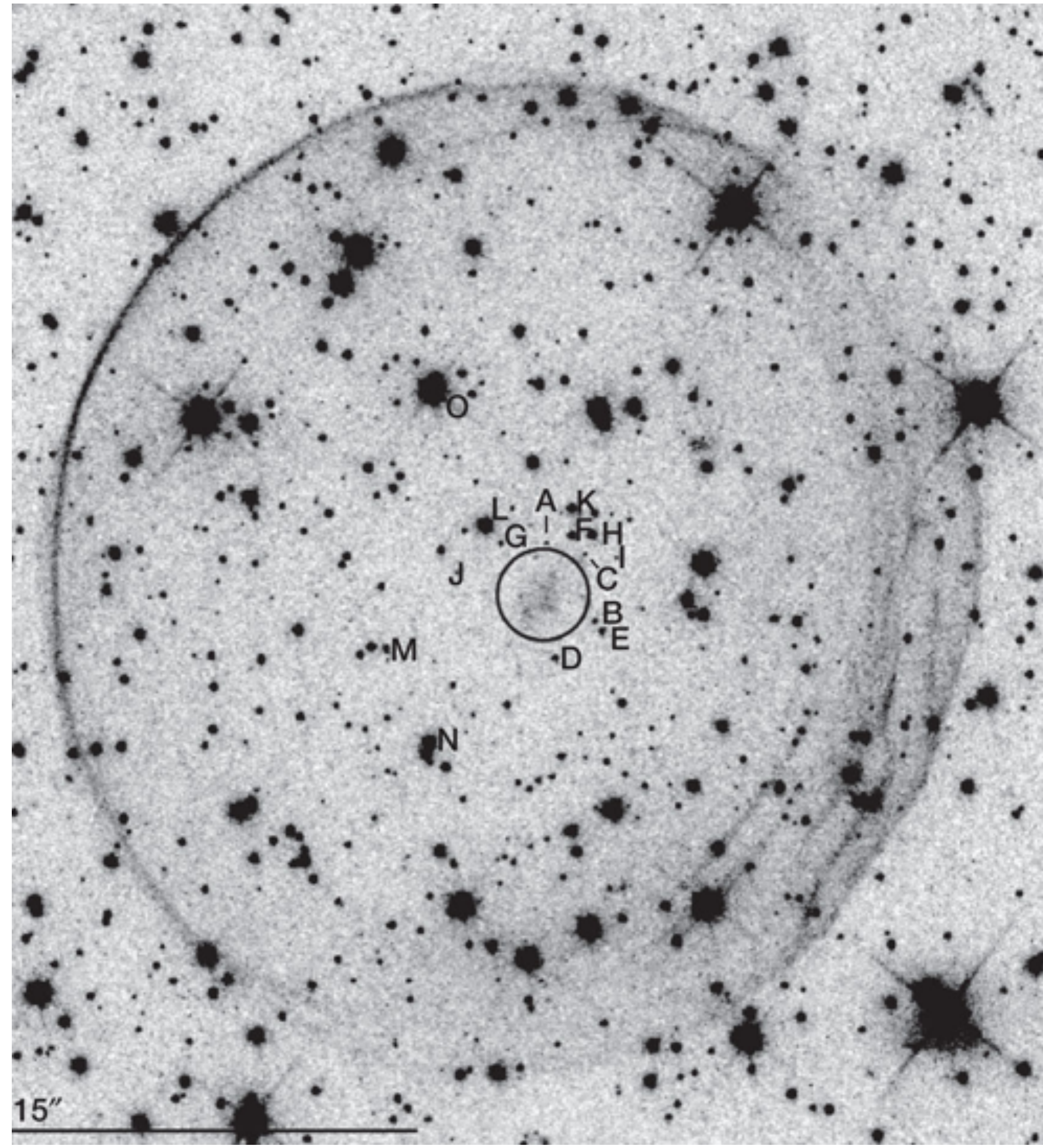
- Pre-explosion images of the site of Iax SN2012Z revealed a luminous blue star, believed to be a He star companion.
- No pre-explosion companion has ever been found for normal Ia.



McCully et al. (2014)

Companion star: post-explosion

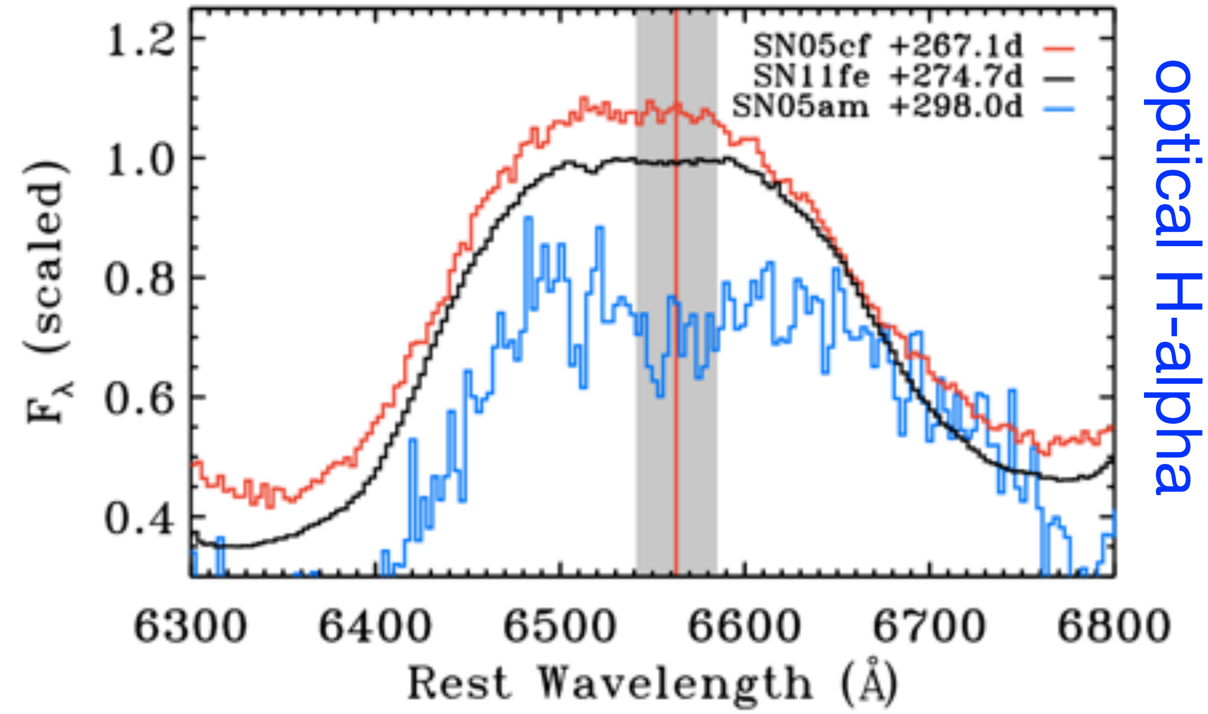
- The searches of companion star remnant in SNR have turned up none, but ever more stringent limit for the companion (Mv > 8 — 9 mag).



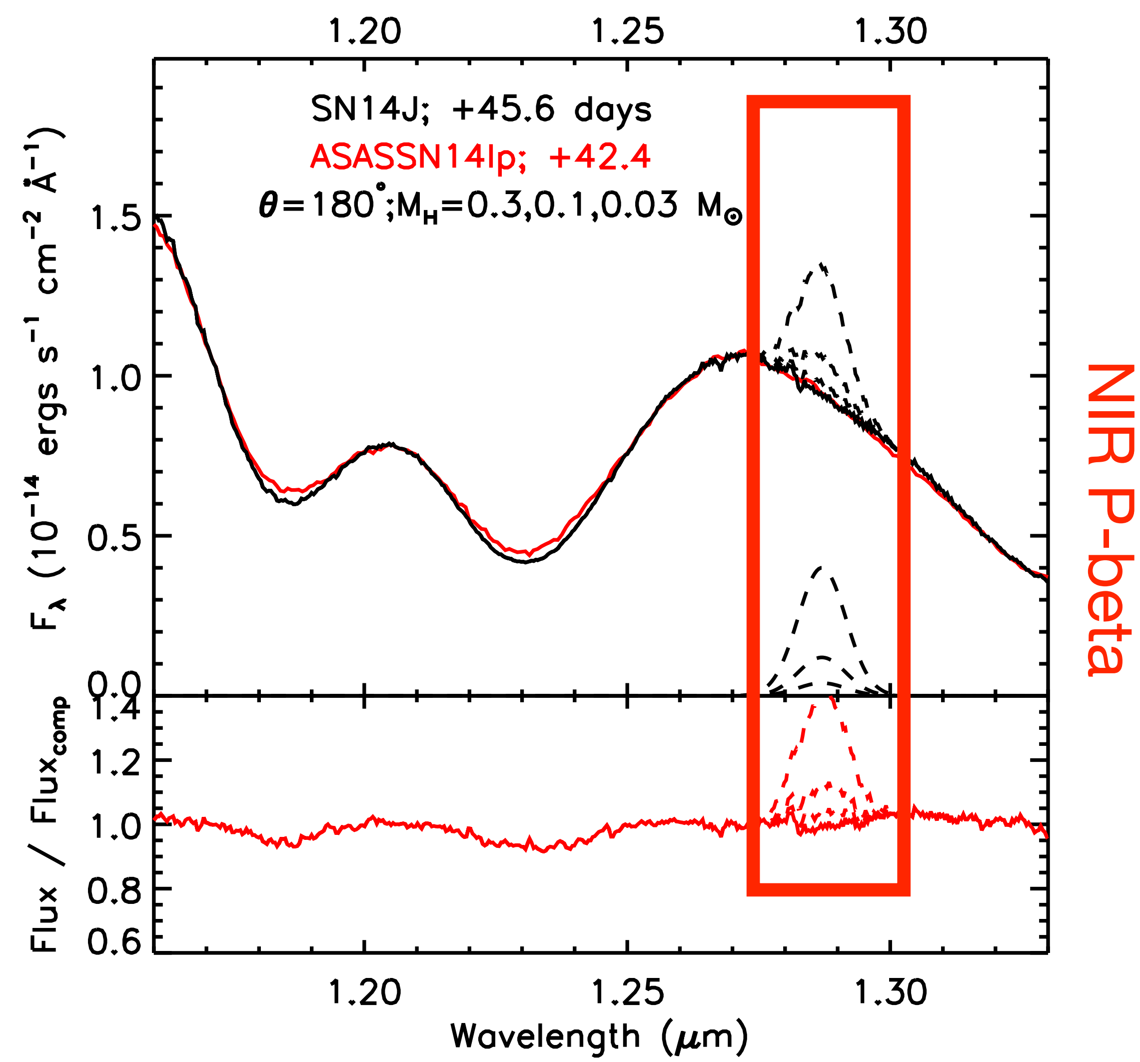
SNR 0509–67.5; Schaefer & Pagnotta (2012)

Companion star: stripped hydrogen

- Hydrogen stripped off non-degenerate companion should be embedded in SN ejecta at low velocity.
- High S/N late time spectra in both optical and NIR have turned up no stripped hydrogen so far.



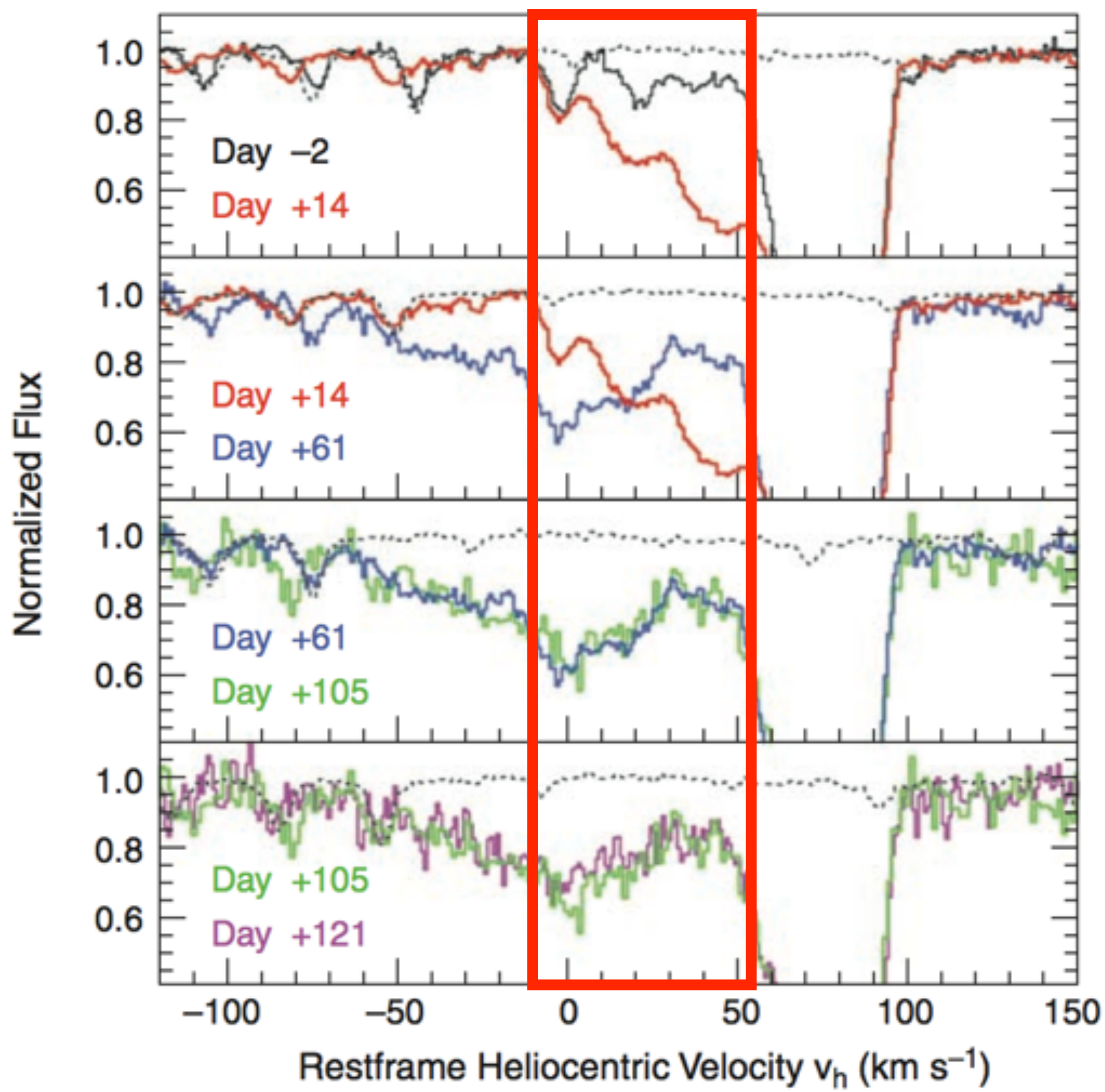
Shappee et al. (2013)



Sand, Hsiao et al. (2016)

Circumstellar material

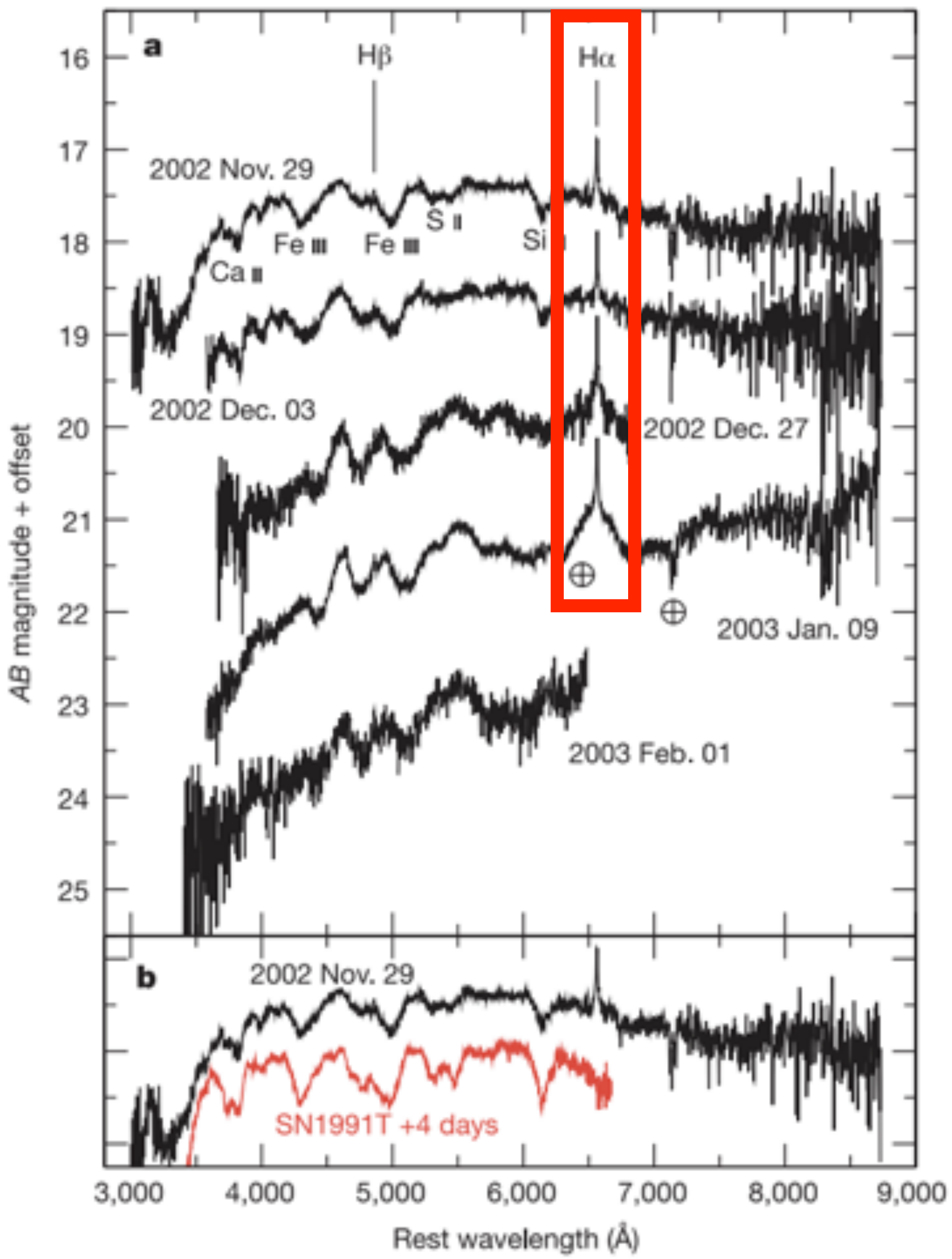
- CSM recombination after photoionization by explosion produces time-varying Na I D.
- There are rare, but definitive examples of time-varying Na I D.



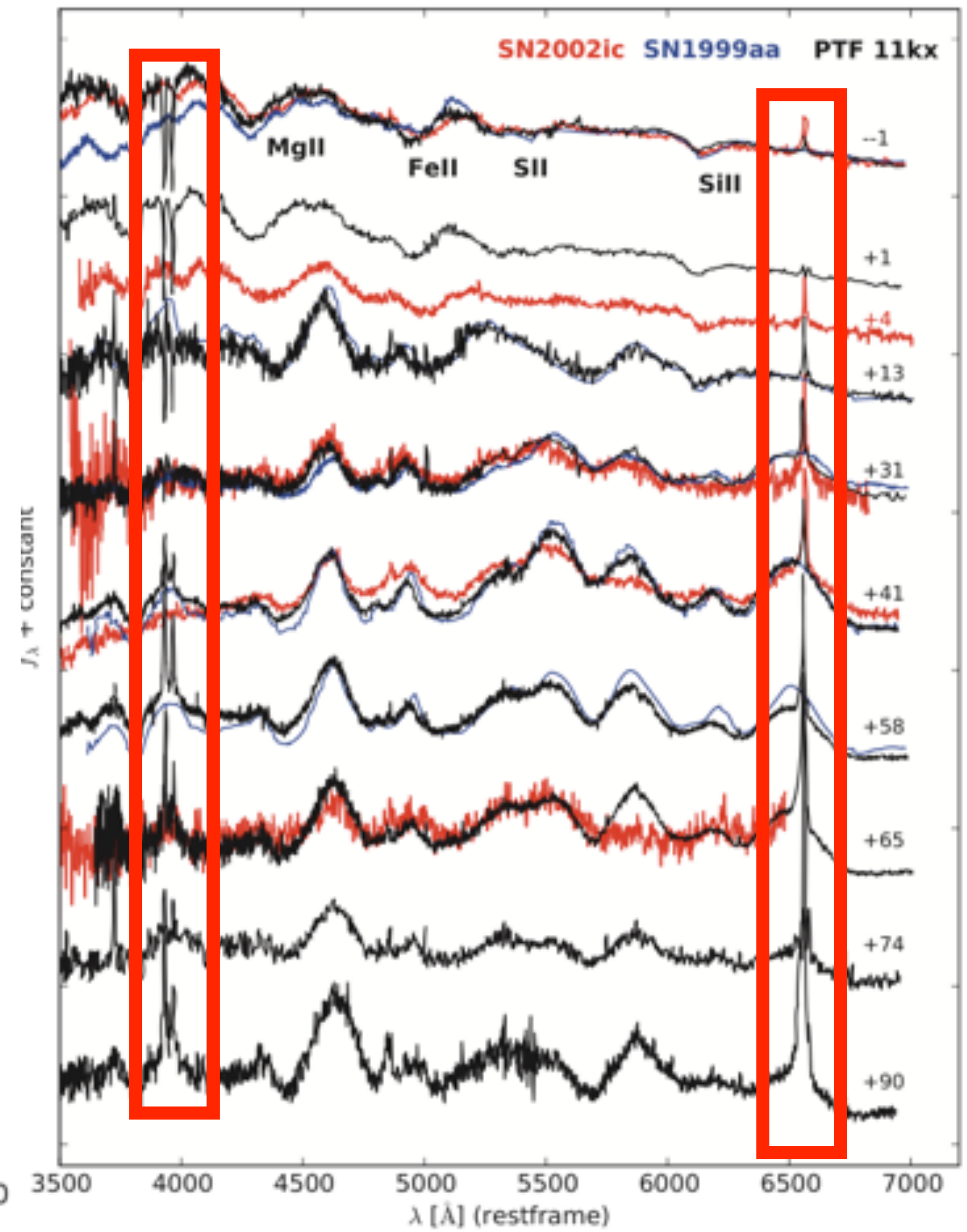
SN2006X; Patat et al. (2007)

Circumstellar material

- There are rare, but definitive examples of Ia-CSM interaction.



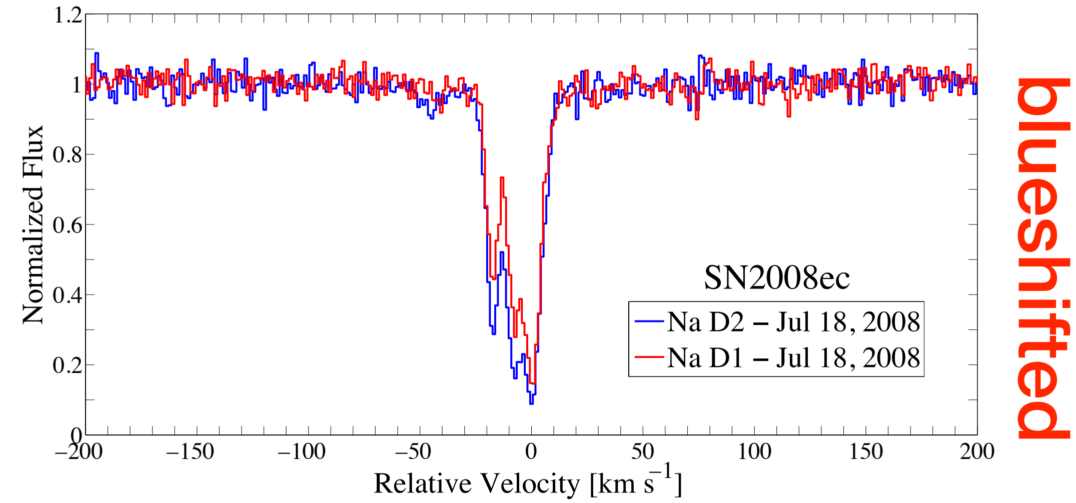
SN2002ic; Hamuy et al. (2003)

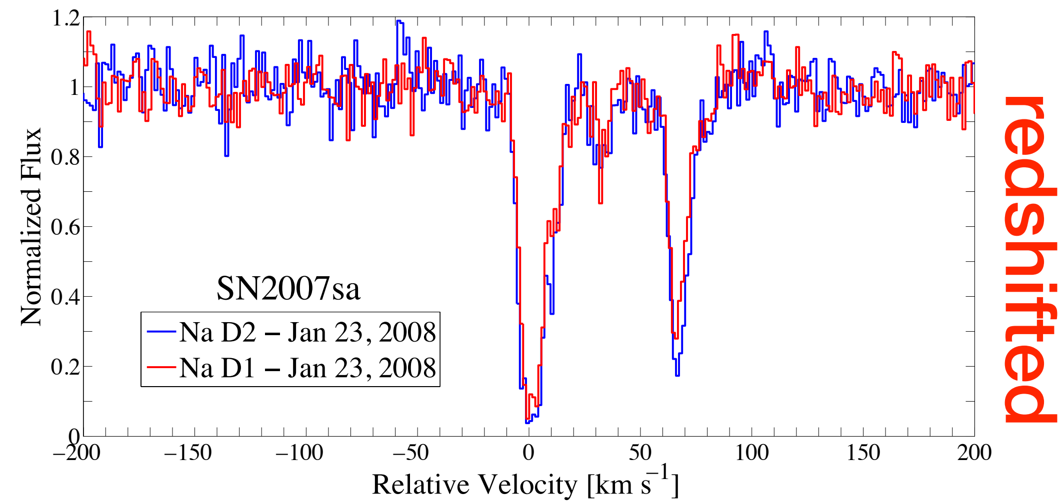


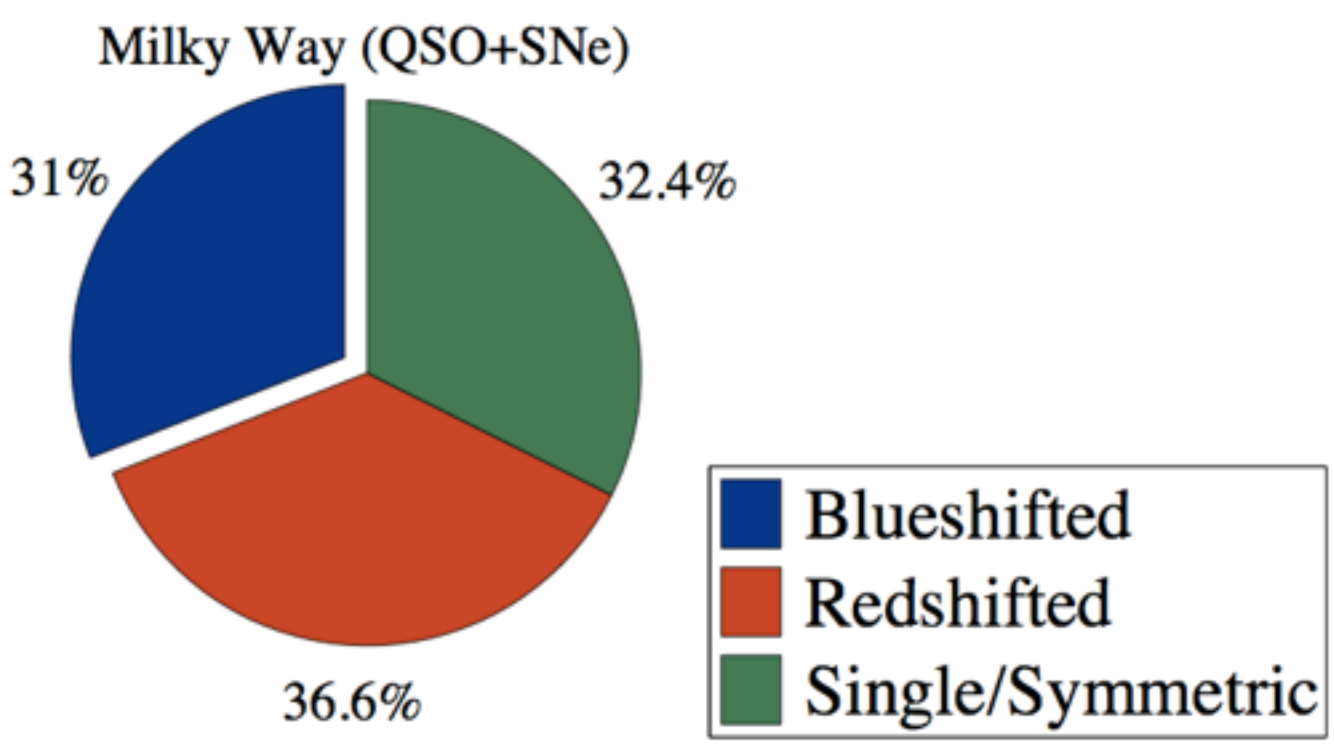
PTF11kx; Dilday et al. (2012)

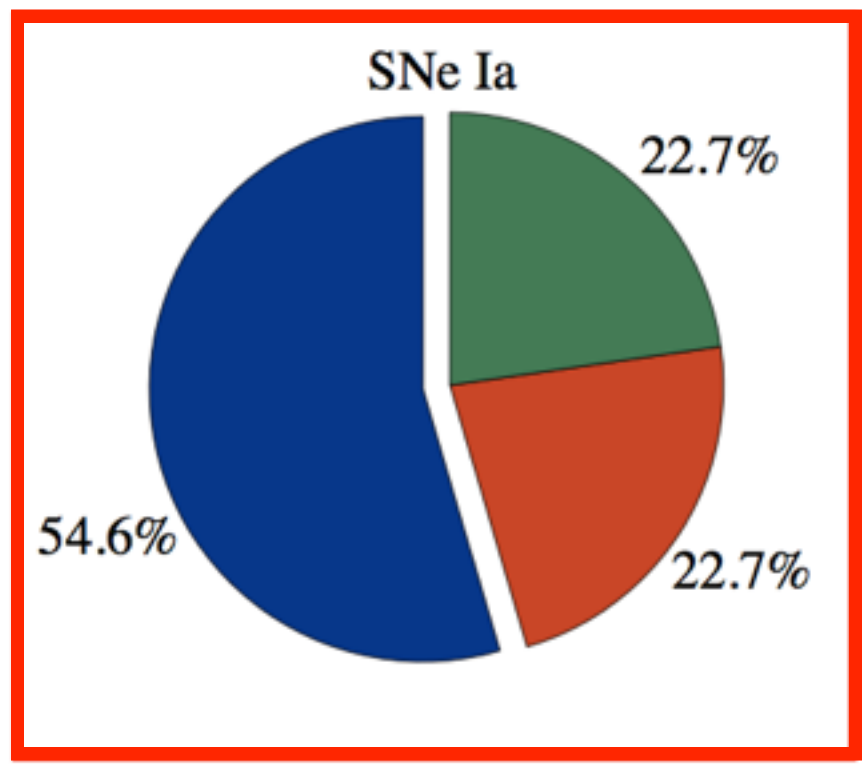
Circumstellar material

- Ia show strong preference for blueshifted Na I D structures, indicating gas outflows and CSM.





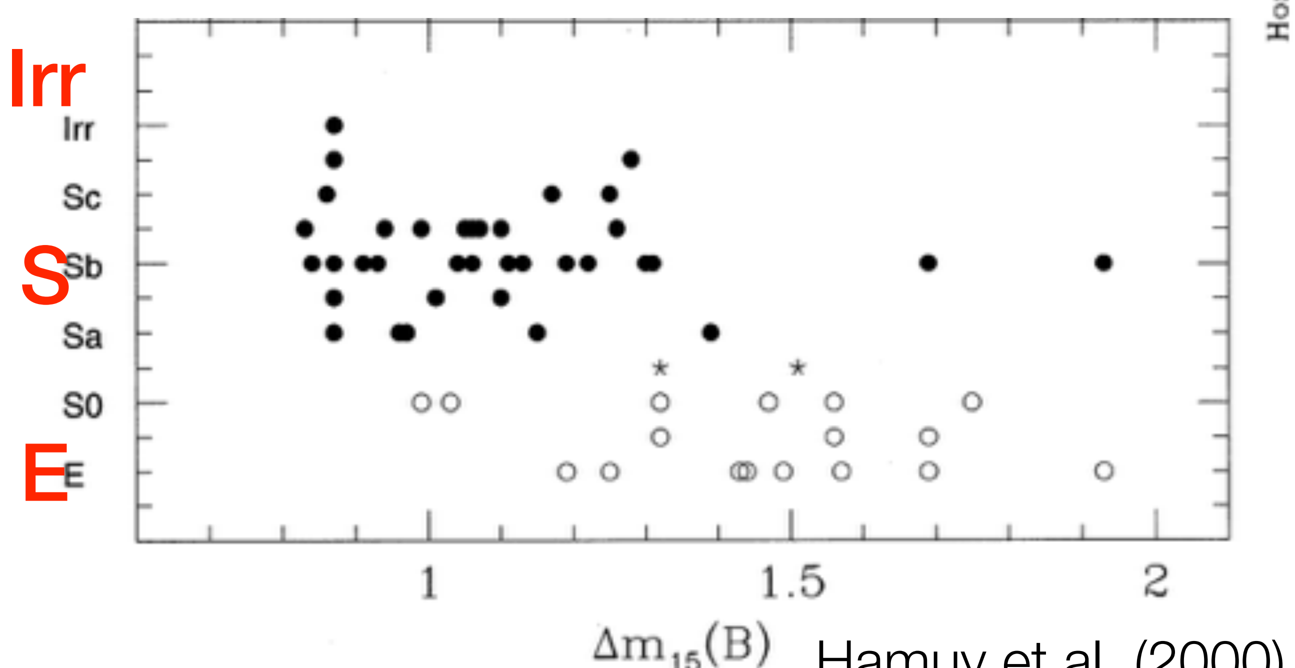




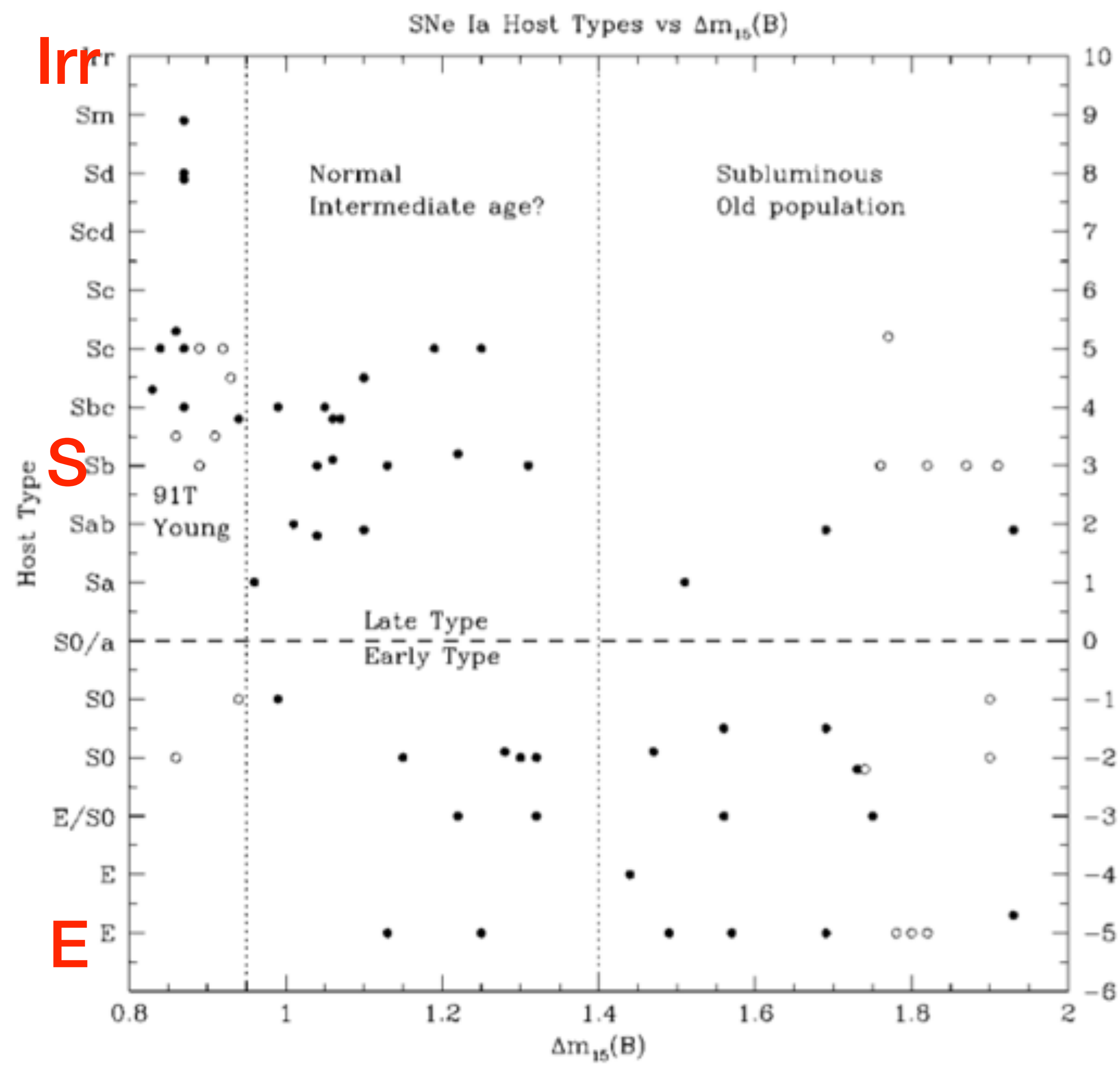
Sternberg et al. (2011)

Host environment

- SN Ia luminosity depends on host environment.
- Does not post a problem for cosmology if the width-luminosity relation does not evolve with redshift.



Hamuy et al. (2000)

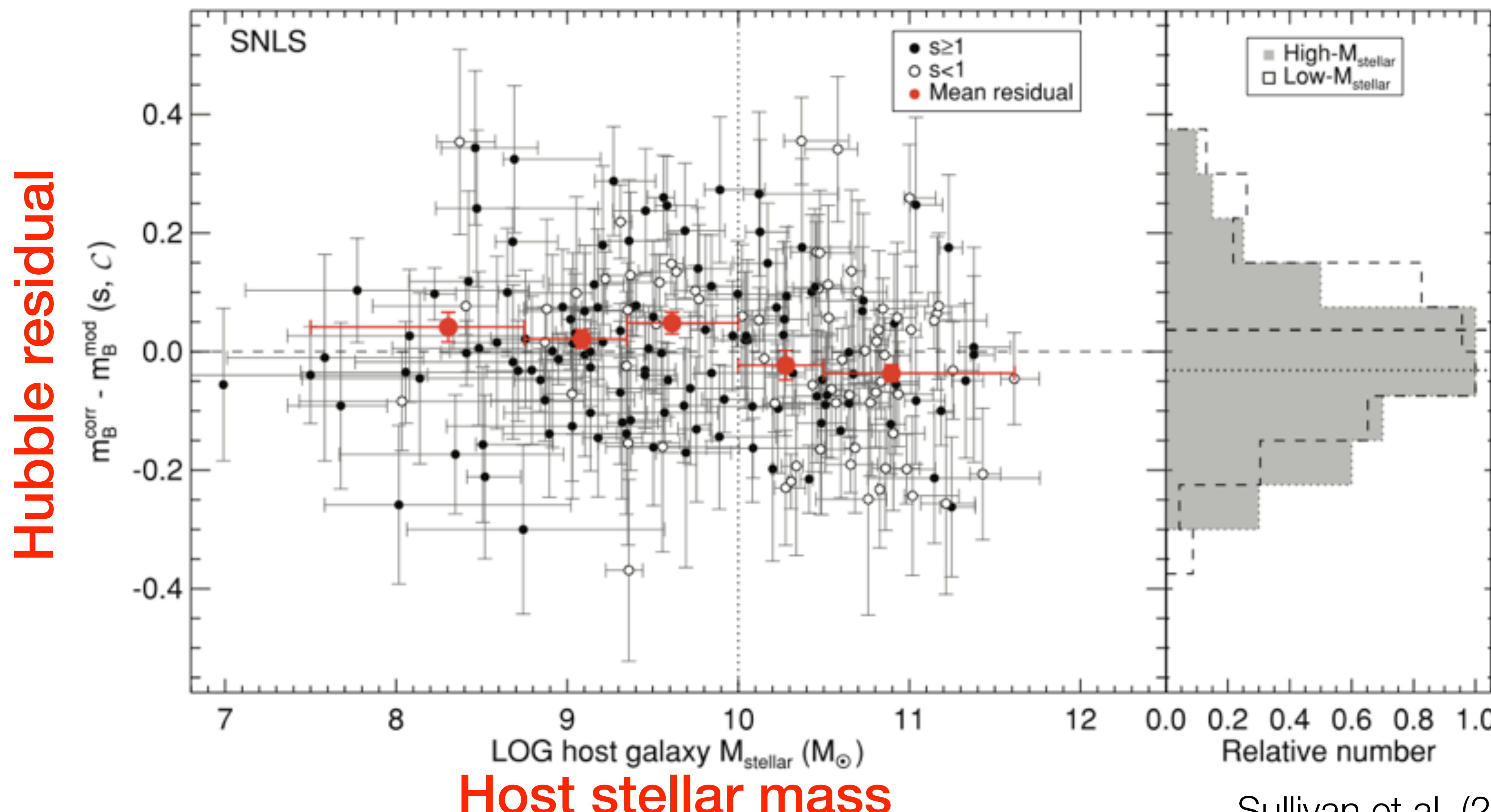


Howell et al. (2001)

fast LC decline

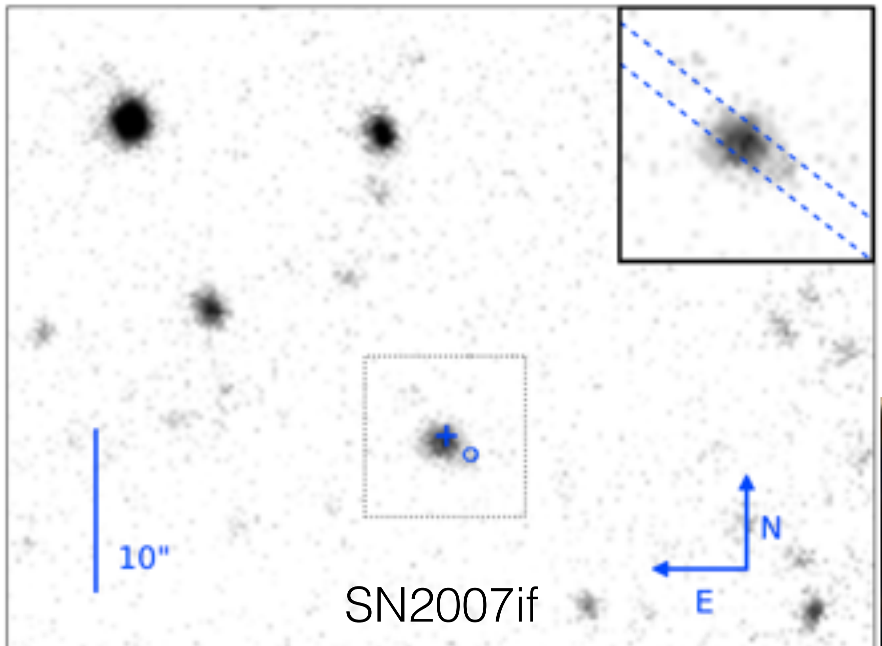
Host environment

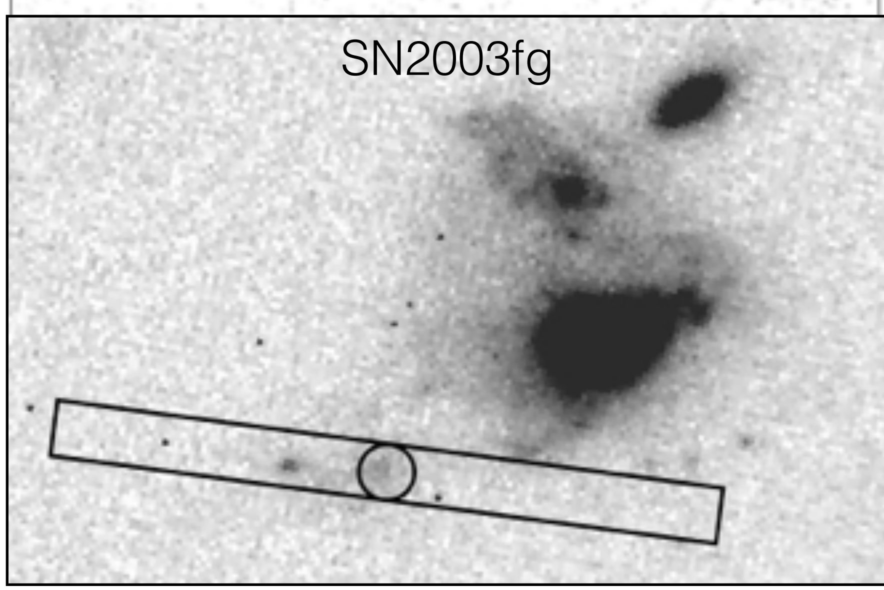
- Even after light-curve width and color corrections, normal Ia are 0.08 mag brighter in massive host galaxies.



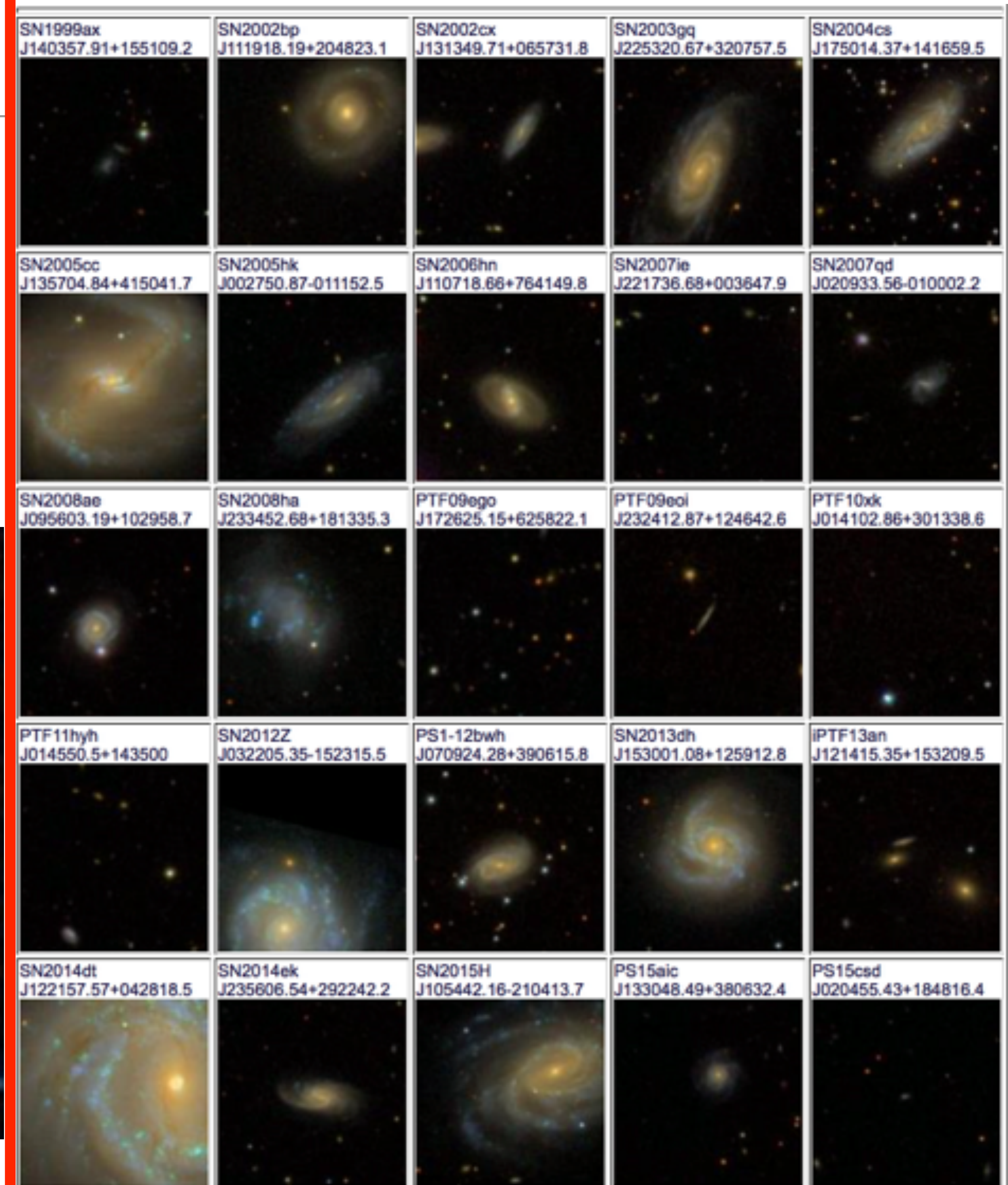
Sullivan et al. (2010)

Host environment





super-Chandrasekhar



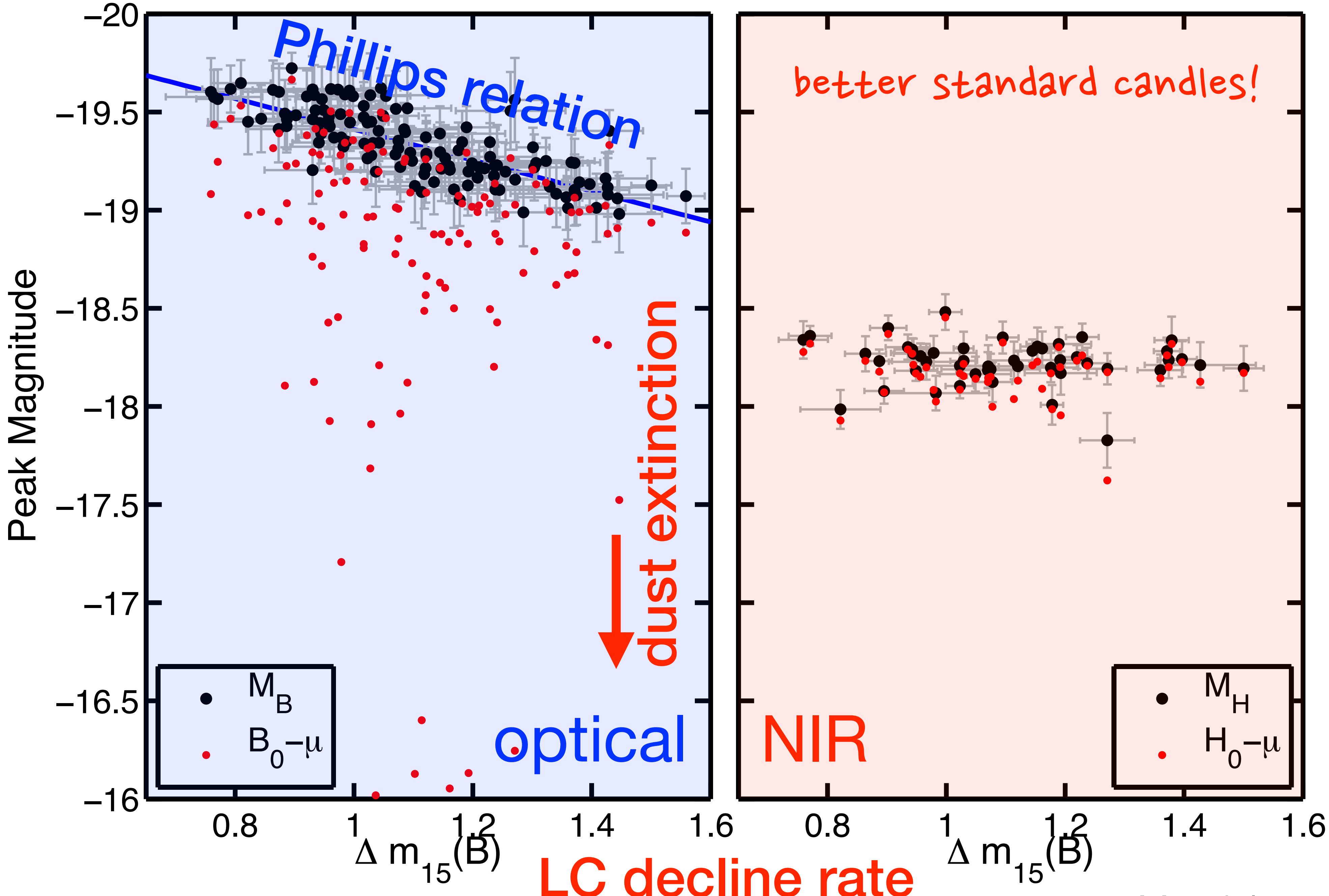
Jha (2017)

Iax

Where do we go from here?

- Despite major efforts in the optical, there has been few improvements Ia cosmology and understanding of their origins.
- Being limited by systematics, larger sample won’t help.
- There is one way forward… go to the NIR!

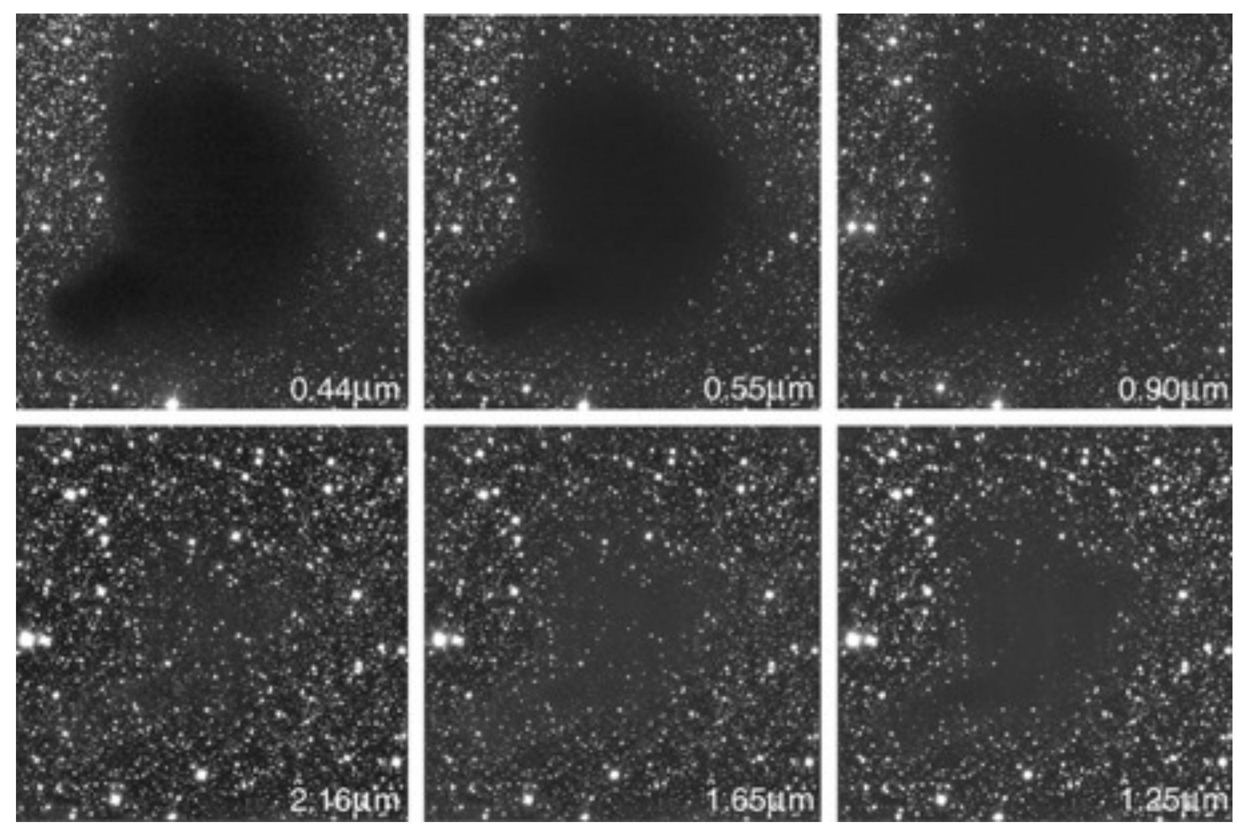
Why NIR?



Mandel et al. (2011)

Why NIR?

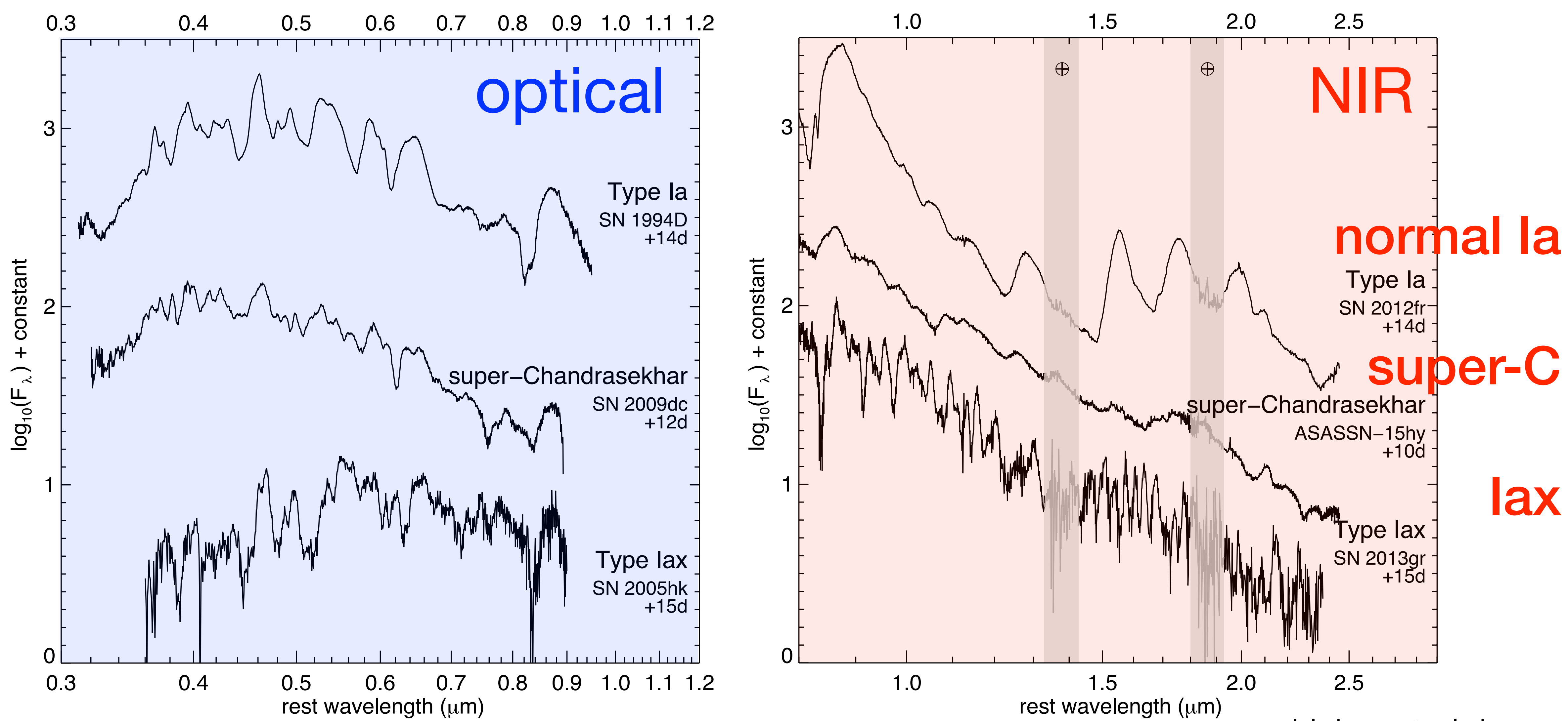
- Going to the NIR, we can achieve higher precision in cosmology through 2 routes
  1. By avoiding things we do not understand, like dust law and Phillips relation (shortcut).
  2. By opening a new window to understand the physics and origin(s) of Type Ia supernovae (more fun).



Credit: ESO

Why NIR?

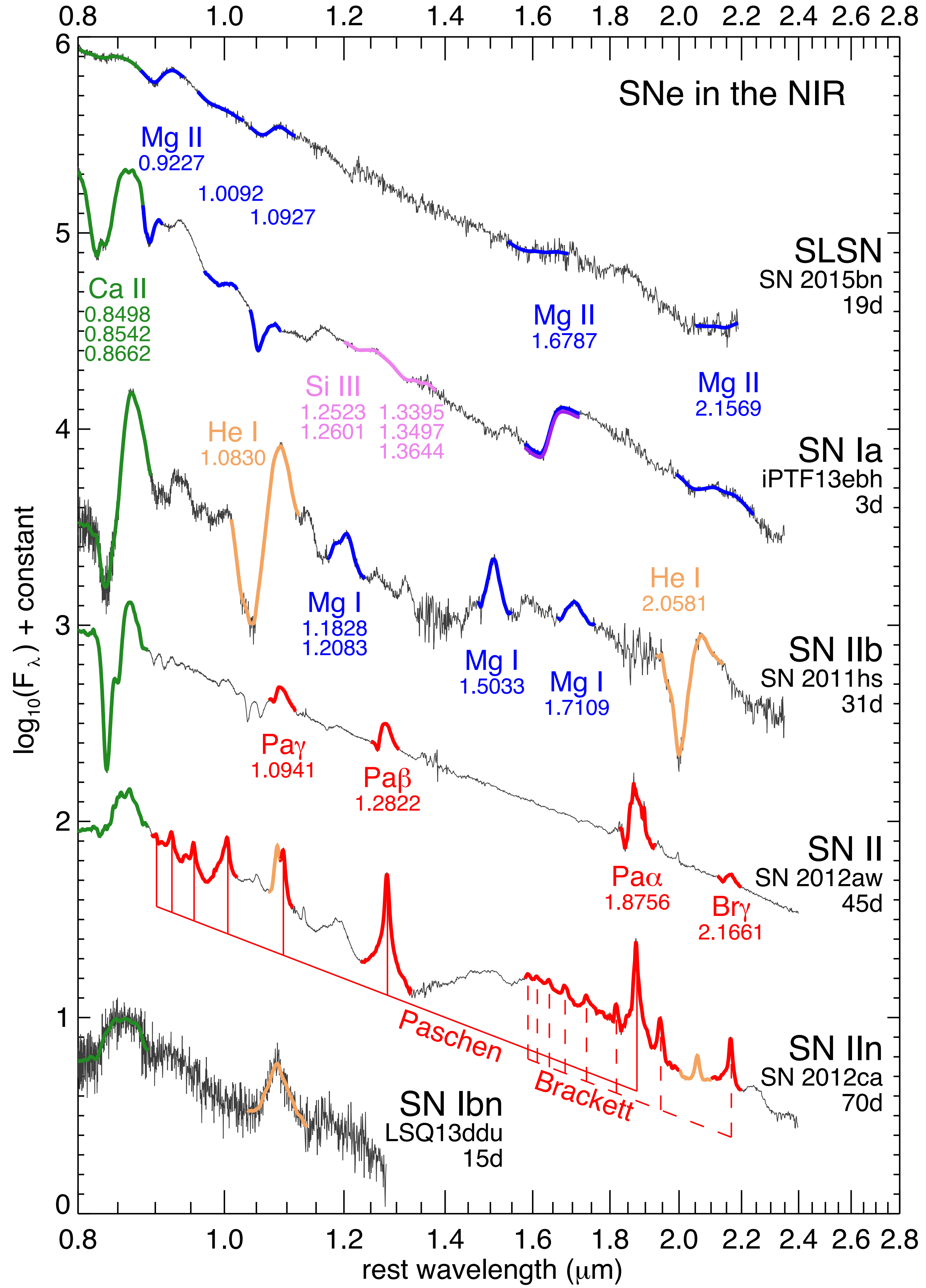
- Differences between normal and peculiar Ia's are subtle in the optical.
- NIR probes deeper in the ejecta and shows drastic differences.



Hsiao et al. in prep

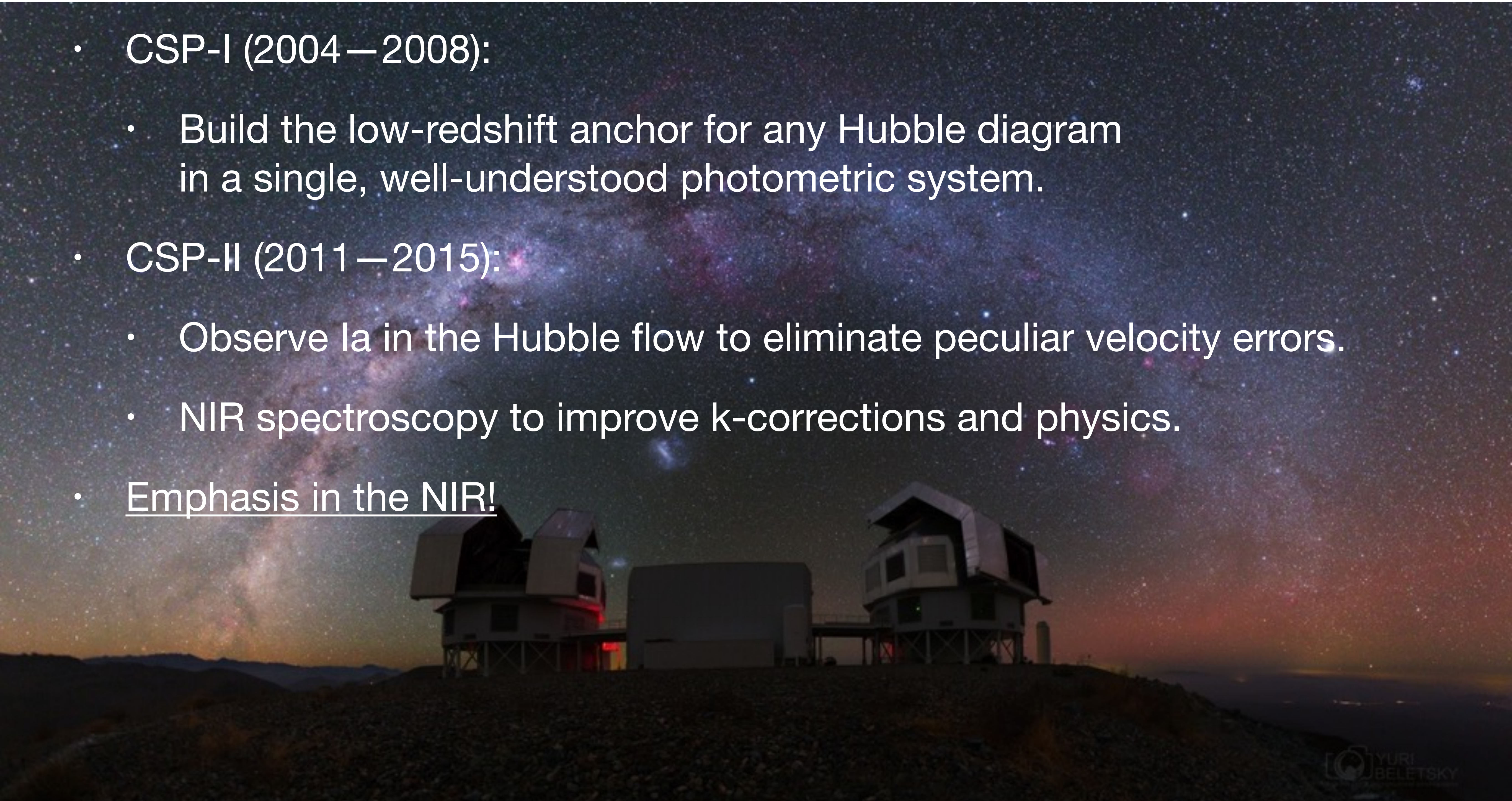
Why NIR?

- Stronger, more isolated lines in the NIR compared to optical.
- NIR probes different depths in the ejecta.
- Brackett, Paschen lines constrain level populations.
- 2 strong NIR He I lines.



Hsiao et al. in prep

Carnegie Supernova Project



- CSP-I (2004—2008):
  - Build the low-redshift anchor for any Hubble diagram in a single, well-understood photometric system.
- CSP-II (2011—2015):
  - Observe Ia in the Hubble flow to eliminate peculiar velocity errors.
  - NIR spectroscopy to improve k-corrections and physics.
- <u>Emphasis in the NIR!</u>

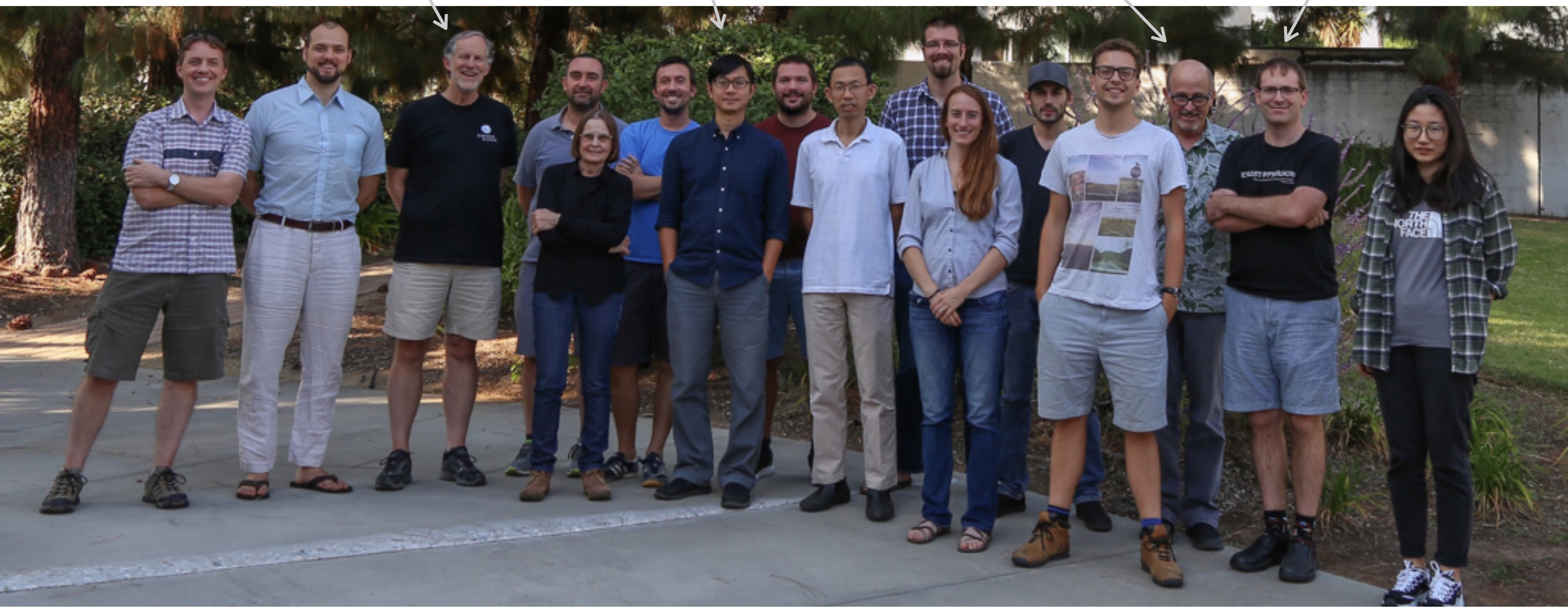
Carnegie Supernova Project

Mark Phillips
Carnegie PI

Eric Hsiao
FSU PI

Nick Suntzeff
Texas A&M PI

Max Stritzinger
Aarhus PI

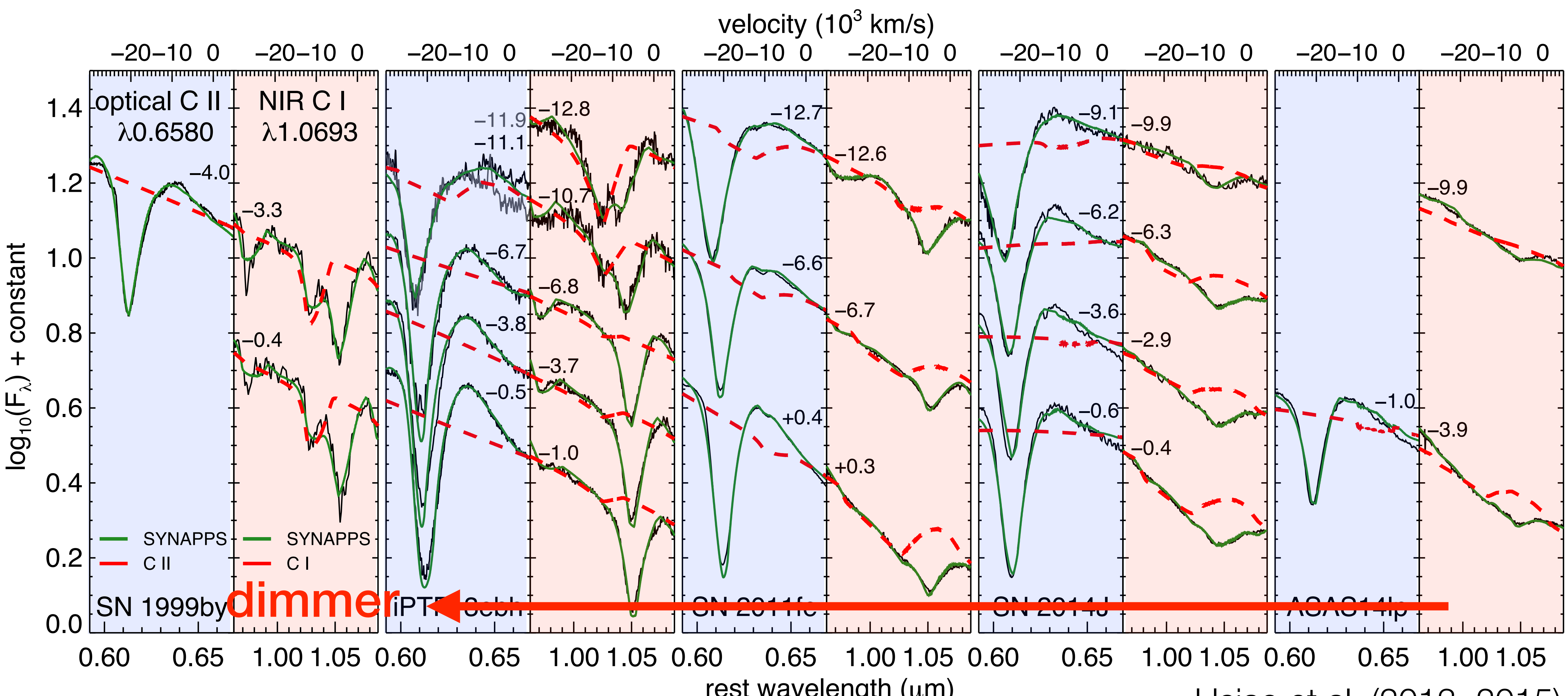


Probing Ia physics

- Unburned material
  Premax C I 1.069, He I 1.083
  Marion et al. (2006), Hsiao et al. (2013, 2015)
- Boundary between C/O burning
  Premax Mg II 1.093
  Wheeler et al. (1998), Hsiao et al. (2013)
- Radioactive nickel, ionization evolution
  Postmax H-band break
  Wheeler et al. (1998), Hoeflich et al. (2002), Hsiao et al. (2013)
- Stable nickel
  Transitional phase [Ni II] 1.939
  Friesen et al. (2014), Wilk et al. (2018)
- Companion signature
  Postmax P-beta 1.282
  Maeda et al. (2014), Sand et al. (2016), Botyanszki (2017)
- Central density and B-field
  Nebular phase [Fe II] 1.644
  Penney & Hoeflich (2014), Diamond et al. (2015), Diamond et al. (2018)

Unburned material

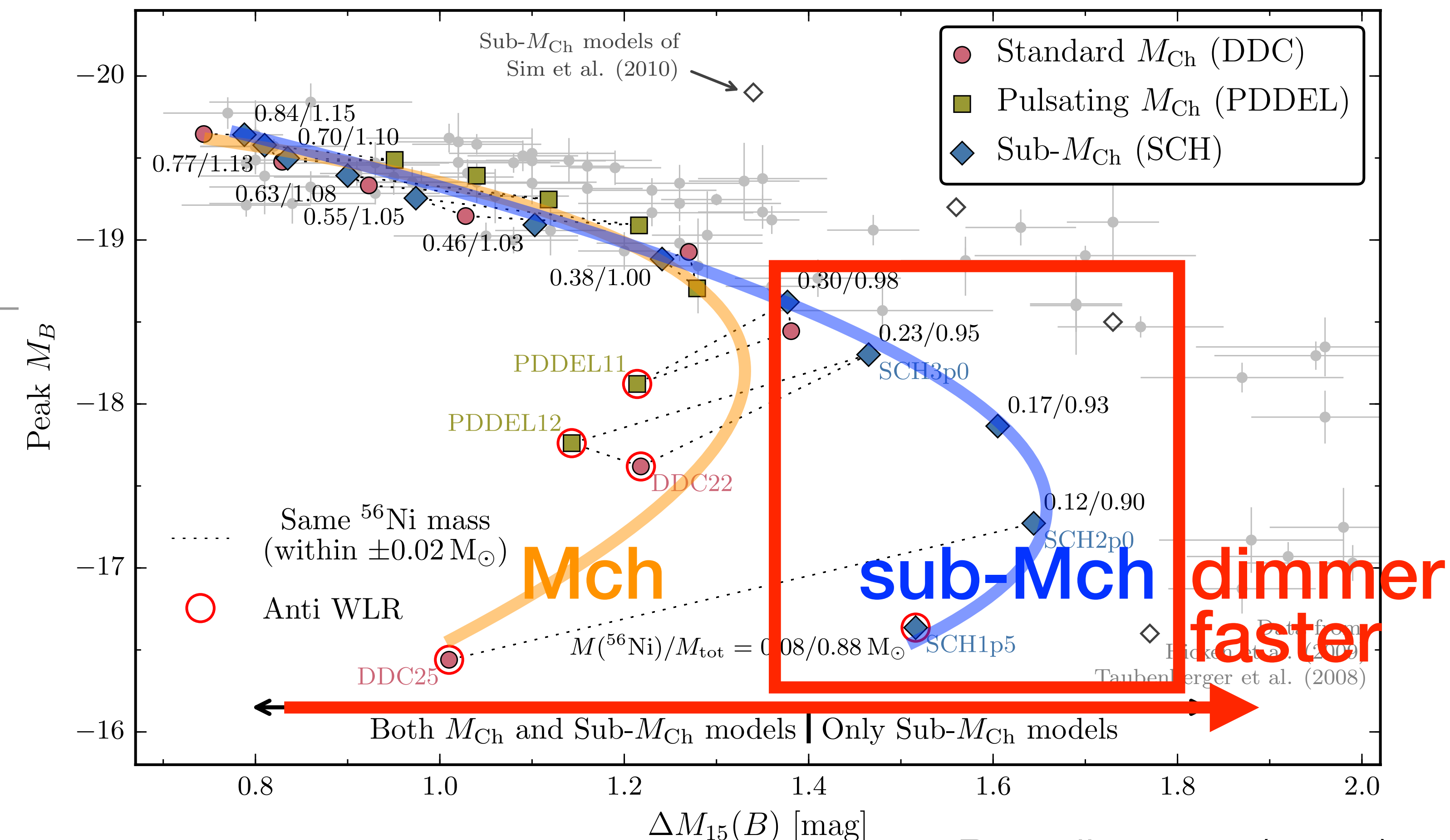
- Carbon detected in SN is pristine material from exploding white dwarf.
- In sub-Mch mechanism, carbon is not expected to survive due to the surface detonation.



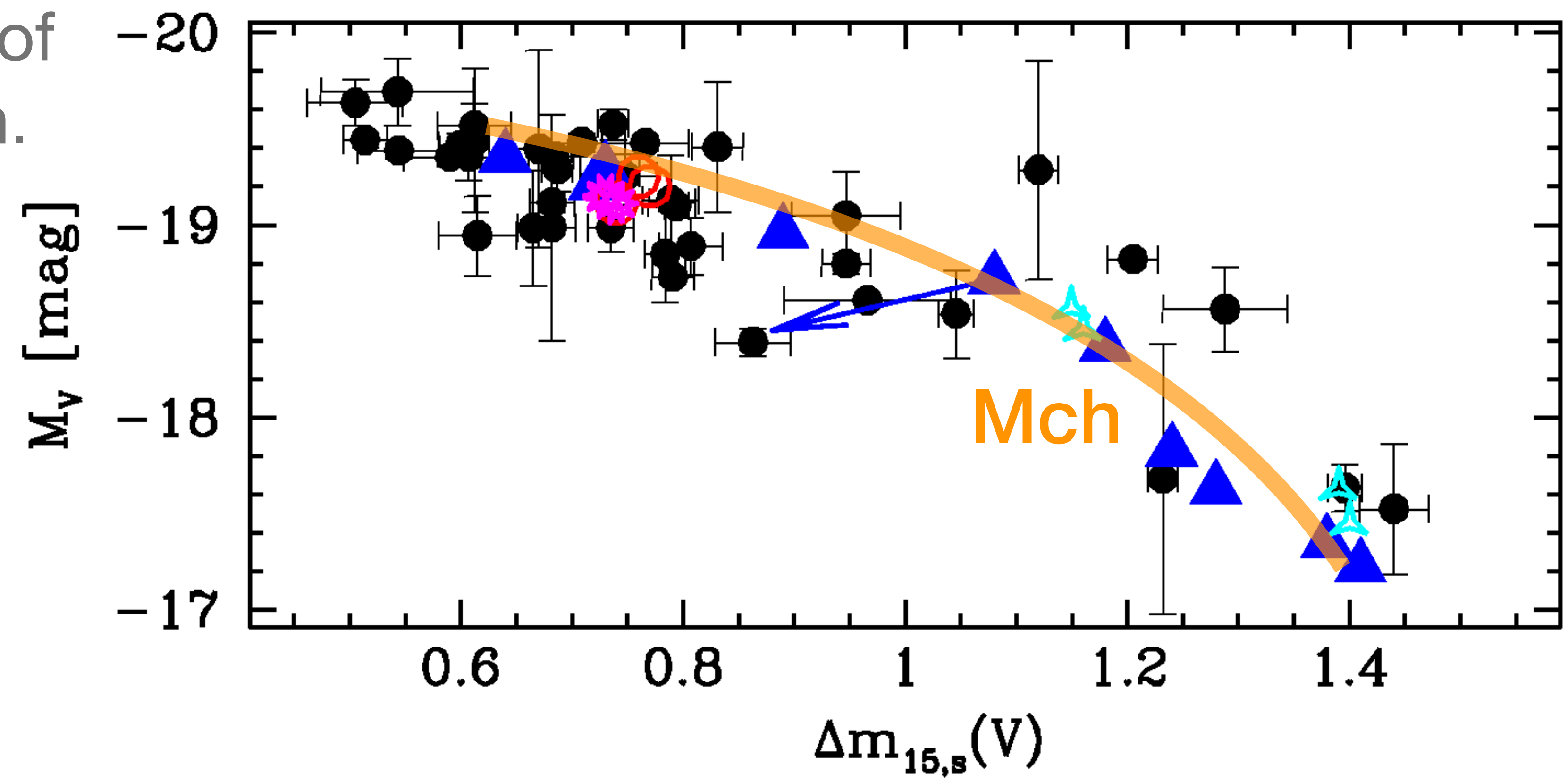
Hsiao et al. (2013, 2015)

Unburned material

- Recall the conflicting results interpreting the explosion mechanism(s) of normal Ia.
- Detection of strong carbon in dimmer Ia contradicts the claim of a sub-Mch population.



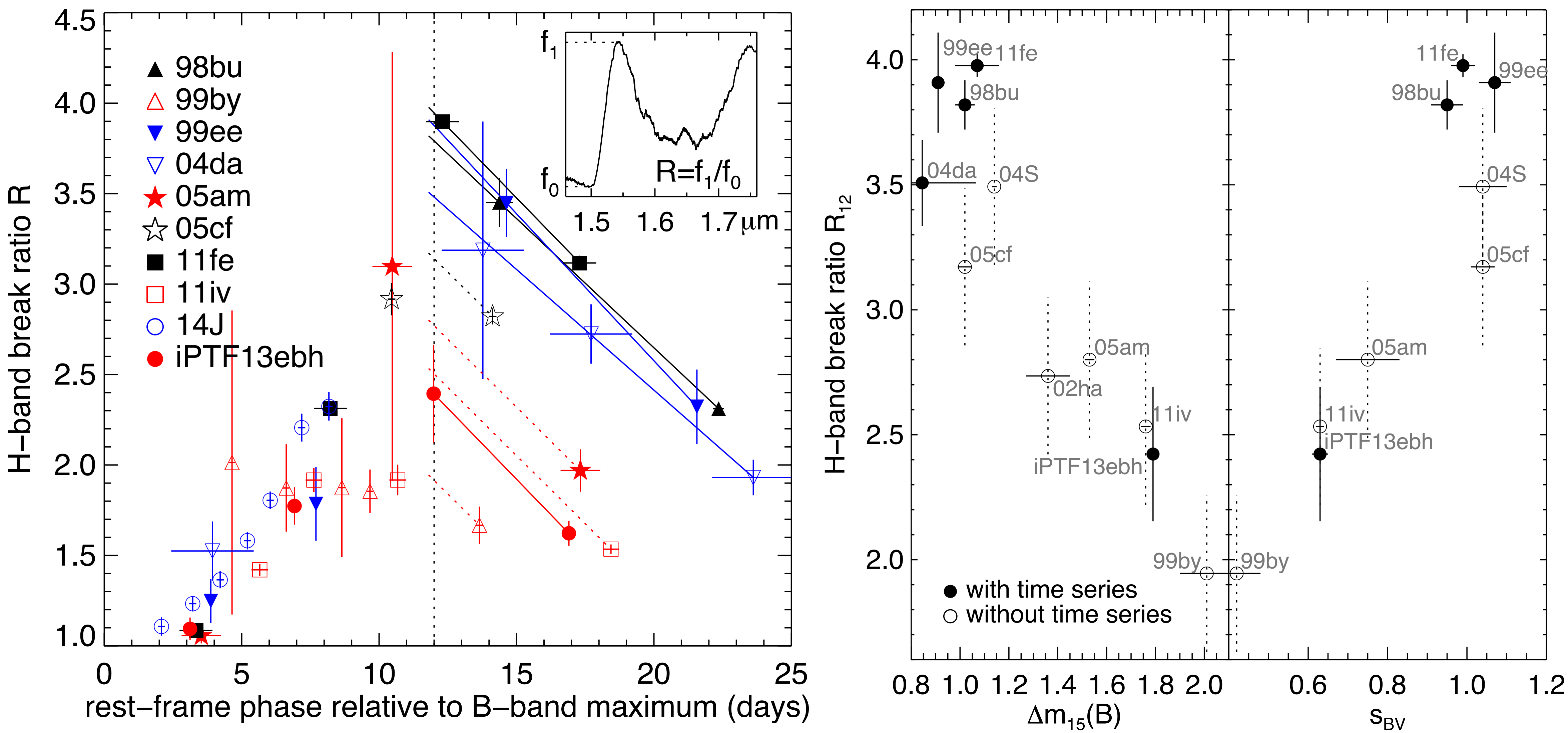
Blondin et al. (2017)



Hoeflich, Hsiao et al. (2017)

Radioactive nickel

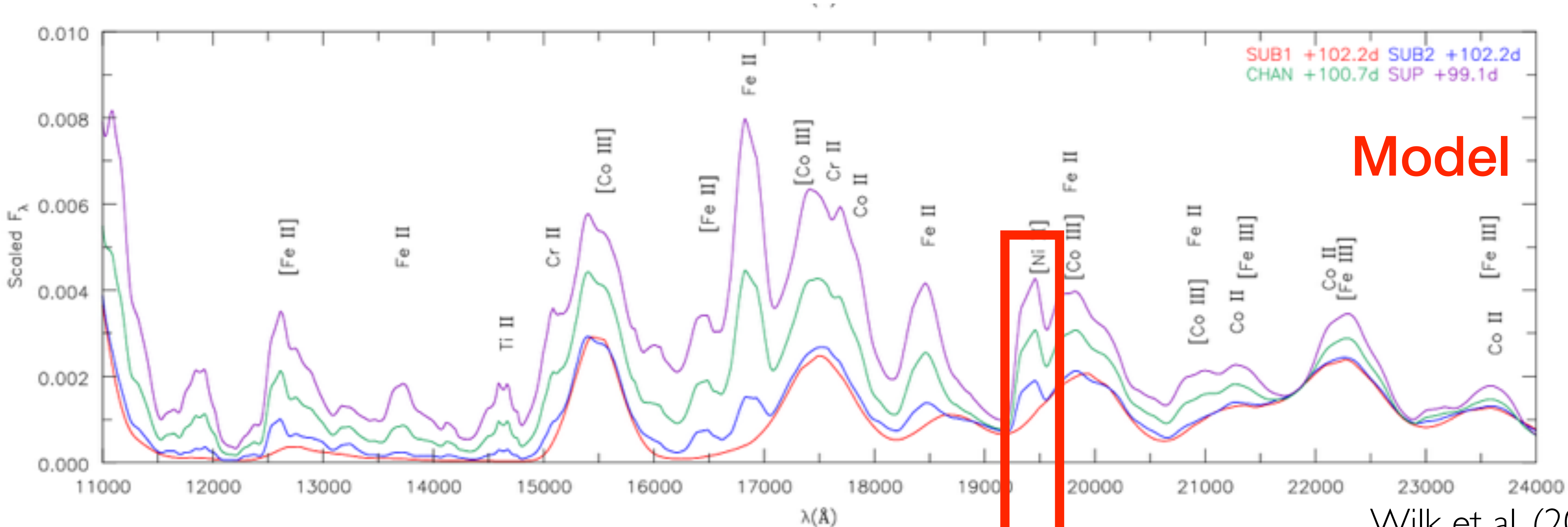
- Strength of the break depends on the 56Ni mass; rate at which it is exposed depends on the mass of “shielding” intermediate-mass elements.
- Potential to distinguish between explosion mechanisms.



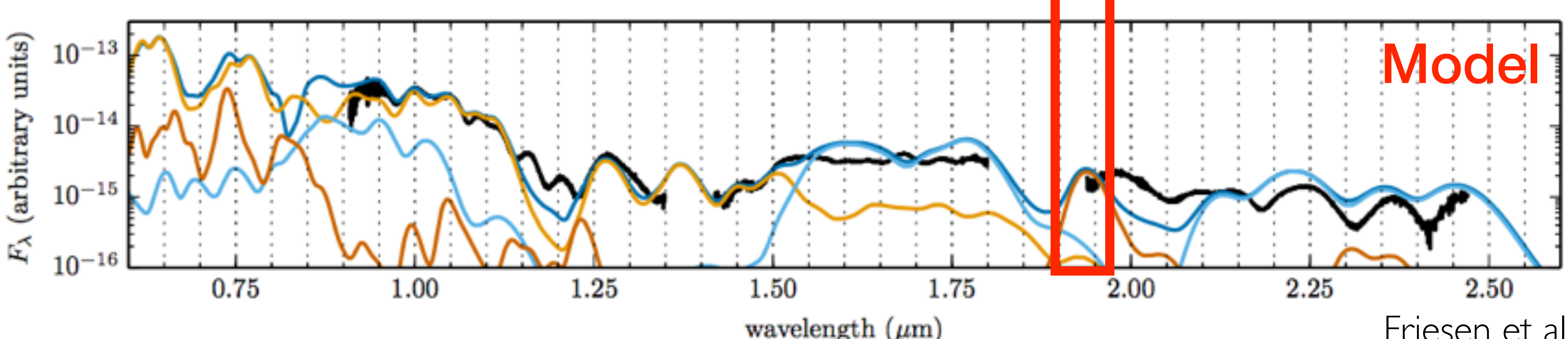
Hsiao et al. (2015)

Stable nickel

- Stable nickel can be produce only under high density condition, which in turn, is a strong indicator of a Mch explosion.



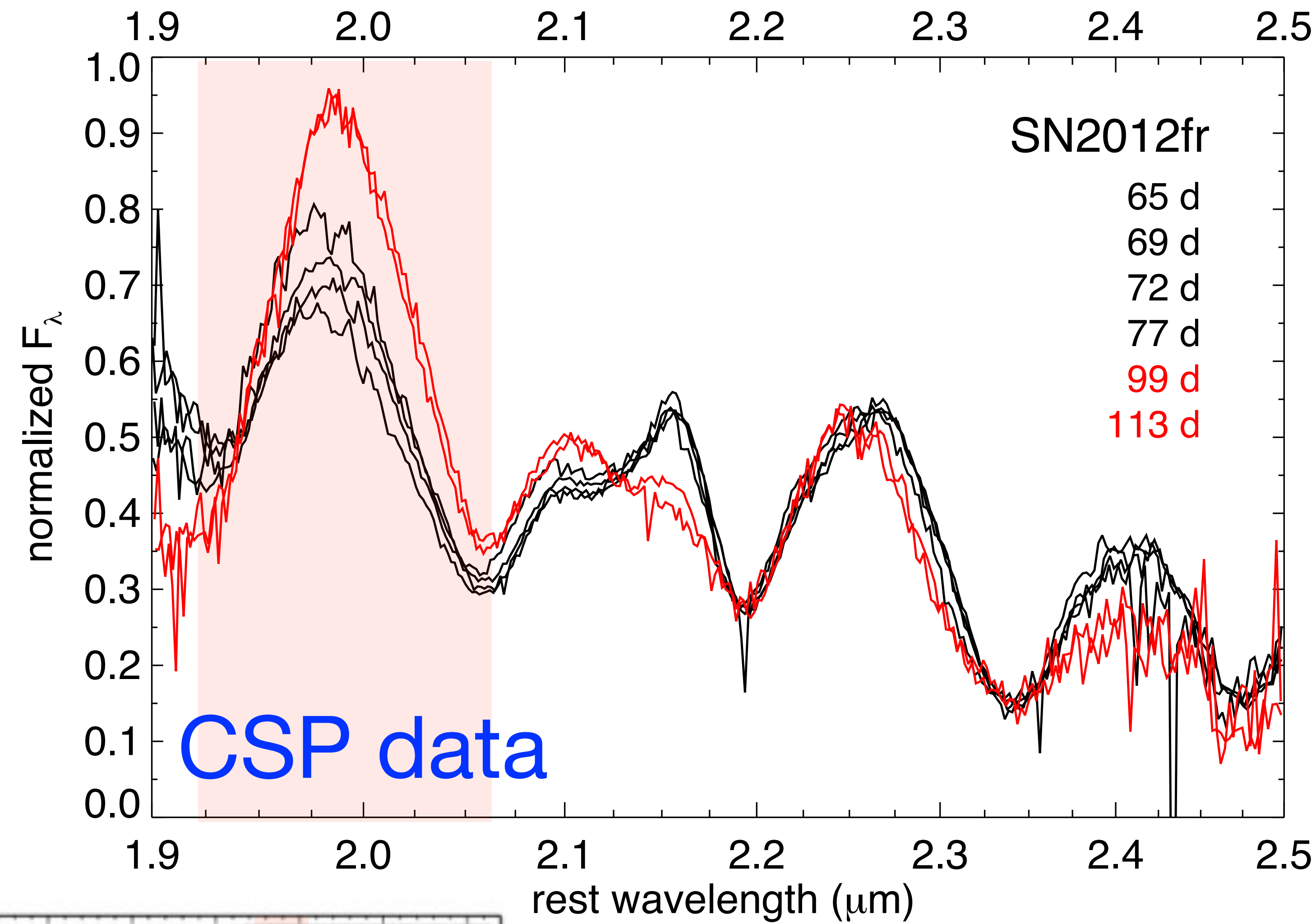
Wilk et al. (2018)



Friesen et al. (2014)

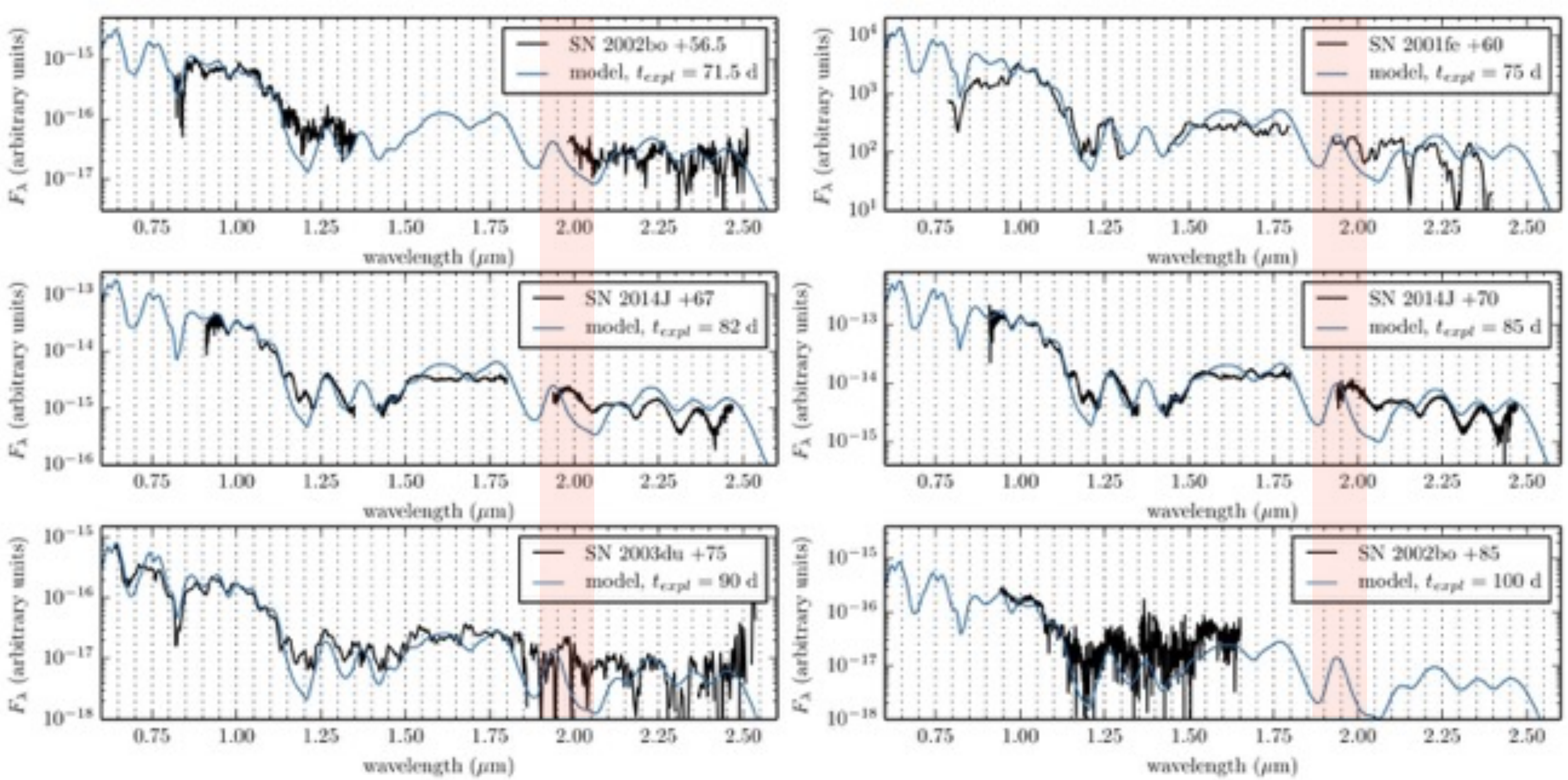
Stable nickel

- With improved NIR spectroscopy, we will have better constraint on this feature.



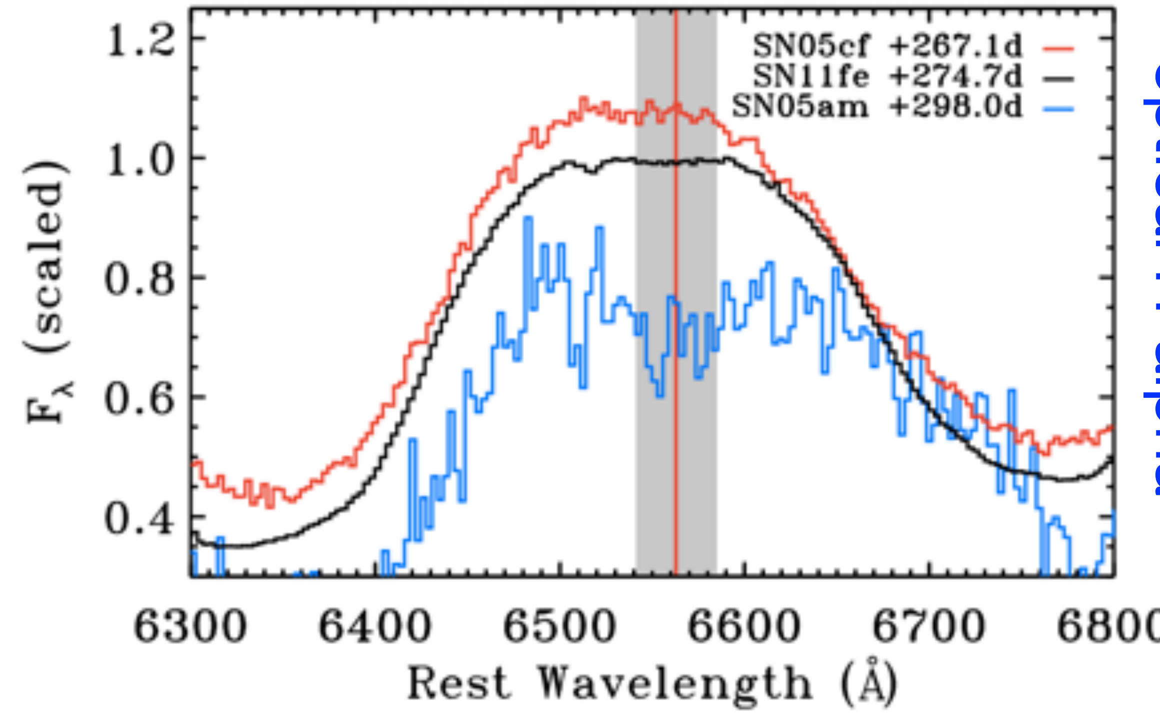
Kumar et al. in prep.

Archival data



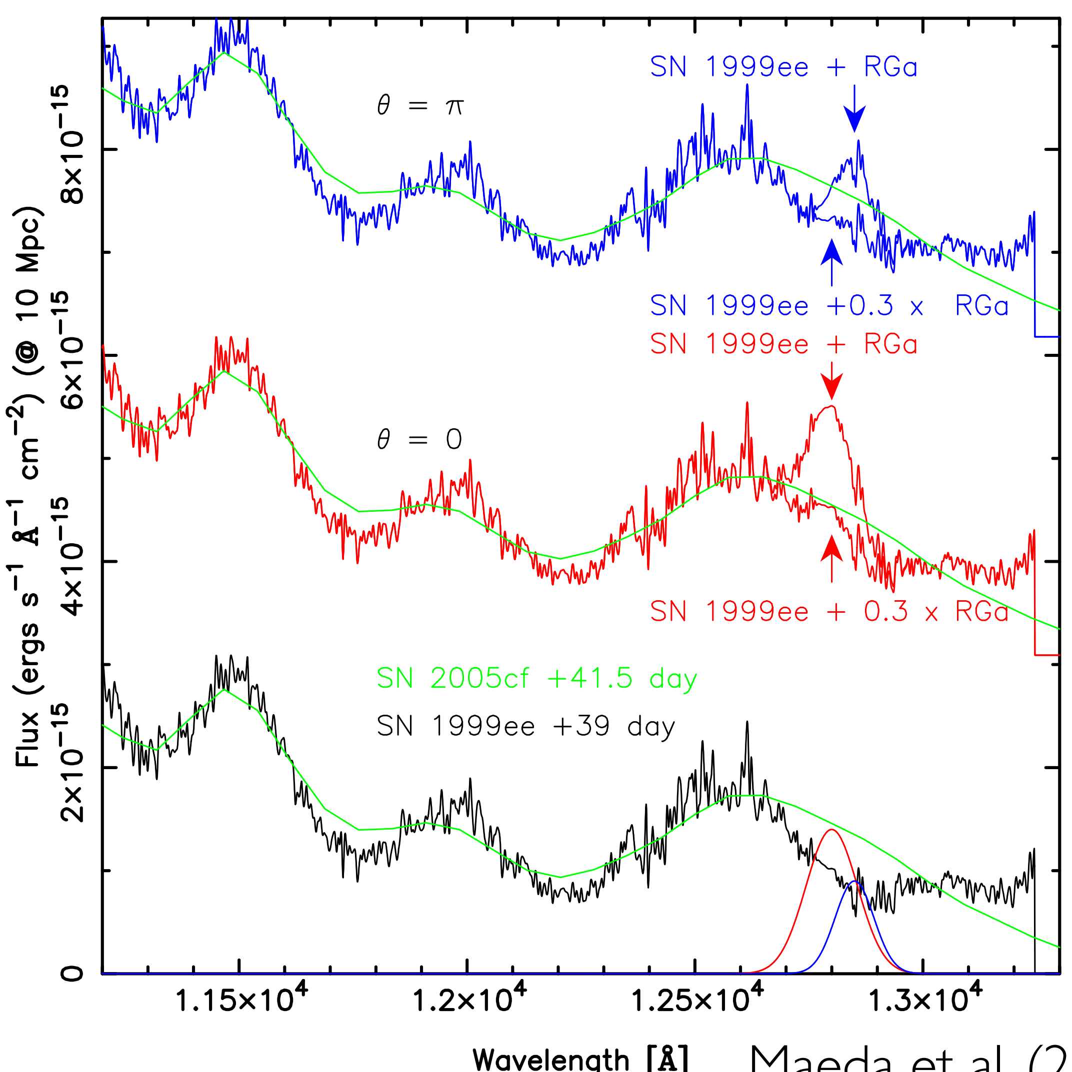
Companion signature

- NIR P-beta is a much more sensitive probe than optical H-alpha.

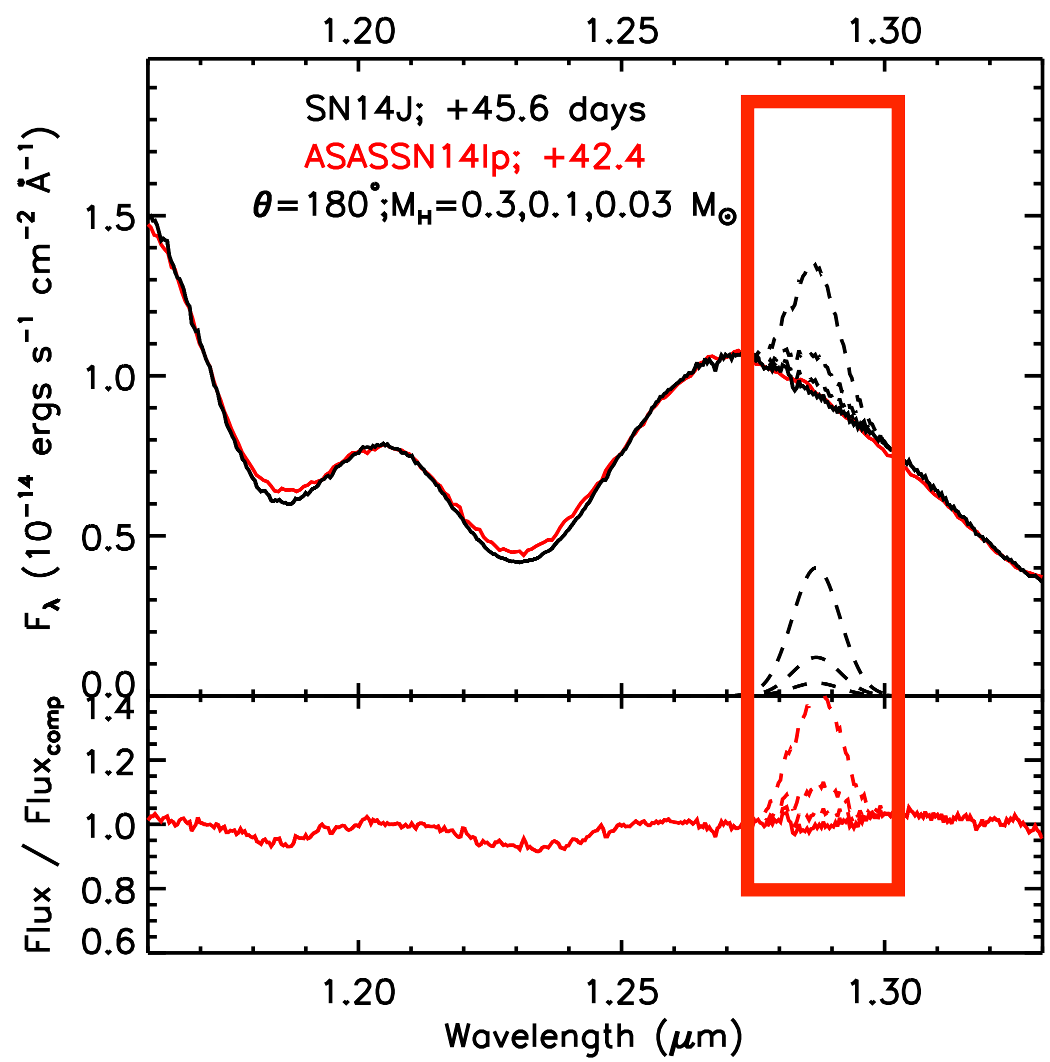


optical H-alpha

Shappee et al. (2013)



Maeda et al. (2014)

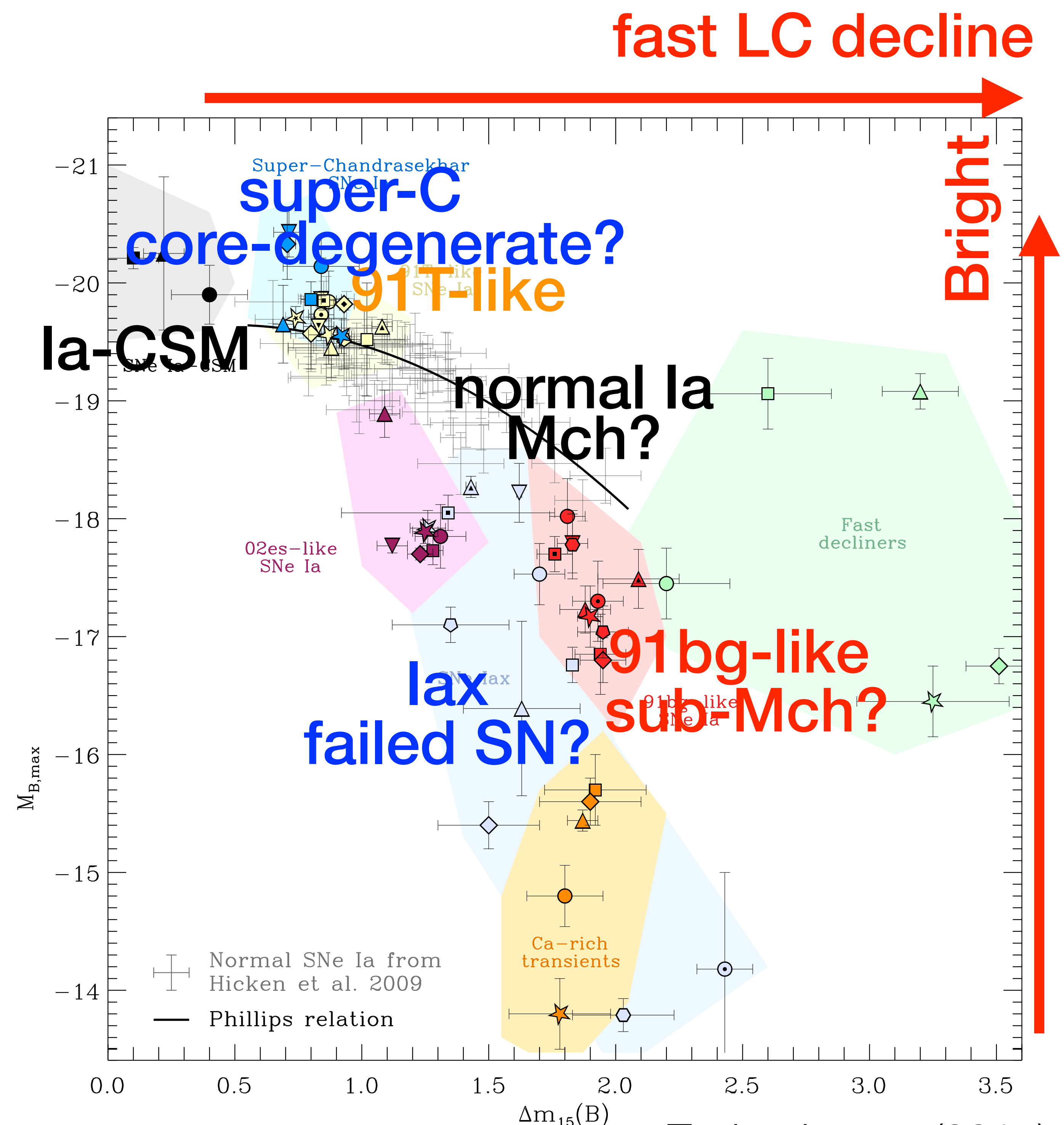


NIR P-beta

Sand, Hsiao et al. (2016)

Summary

- Primary star: The exploding star should be a white dwarf.
- Companion star: Except for rare cases, large companion stars are not favored.
- Explosion mechanism: It is unclear whether normal Ia's come from a single or multiple explosion mechanisms.
- NIR shows promise in providing substantial improvements in Ia cosmology and physics.



Taubenberger (2017)