Massive Stars explosions

Stefano Valenti

UCDAVIS
UNIVERSITY OF CALIFORNIA

credit: BJ Fulton

Core Collapse Supernovae

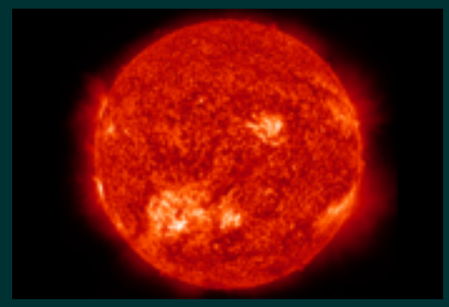
- SNe II
  - IIpec
  - IIP - IIL

- SNe Stripped Envelope
  - IIb - Ib - Ic - BLIc

- Interactive SNe
  - IIn

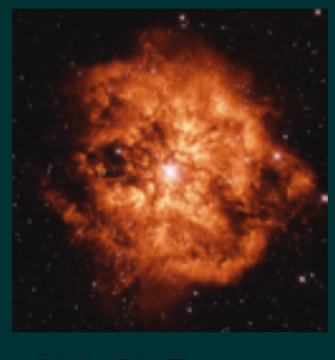
- Superluminous Supernovae
  - II - I

- New CC transients

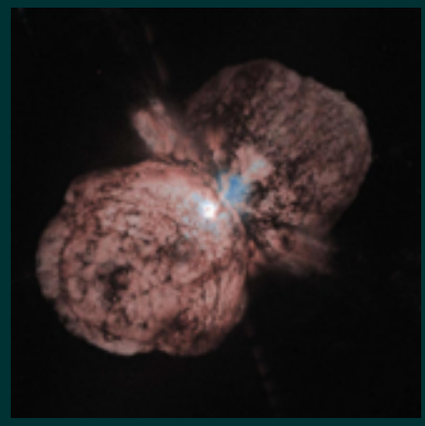


Red supergiant

Blue supergiant



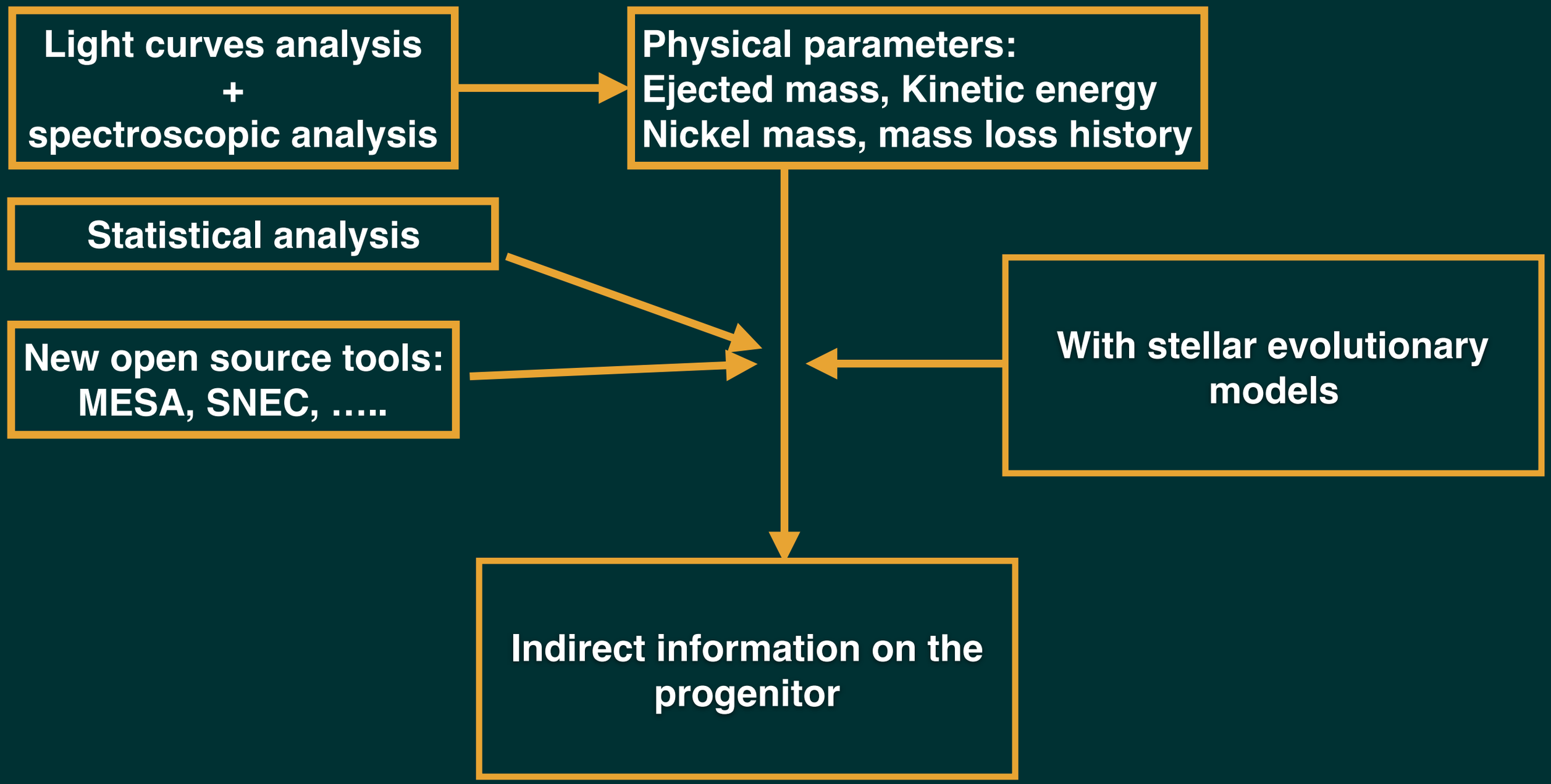
Wolf Rayet



Luminous Blue Variable

?

How we can get more information on the progenitor stars of Core Collapse SNe ?



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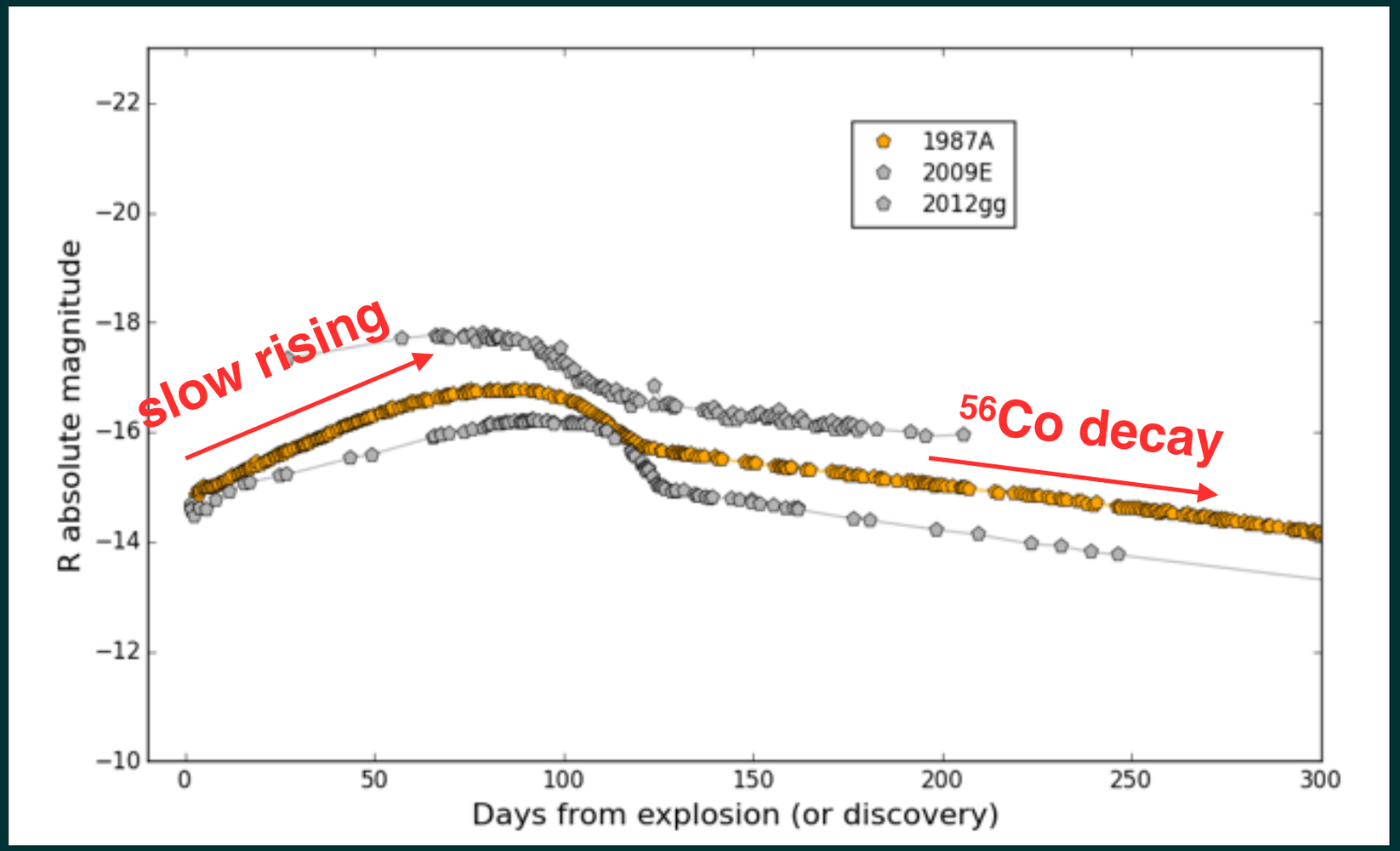
IIpec - 87A-like



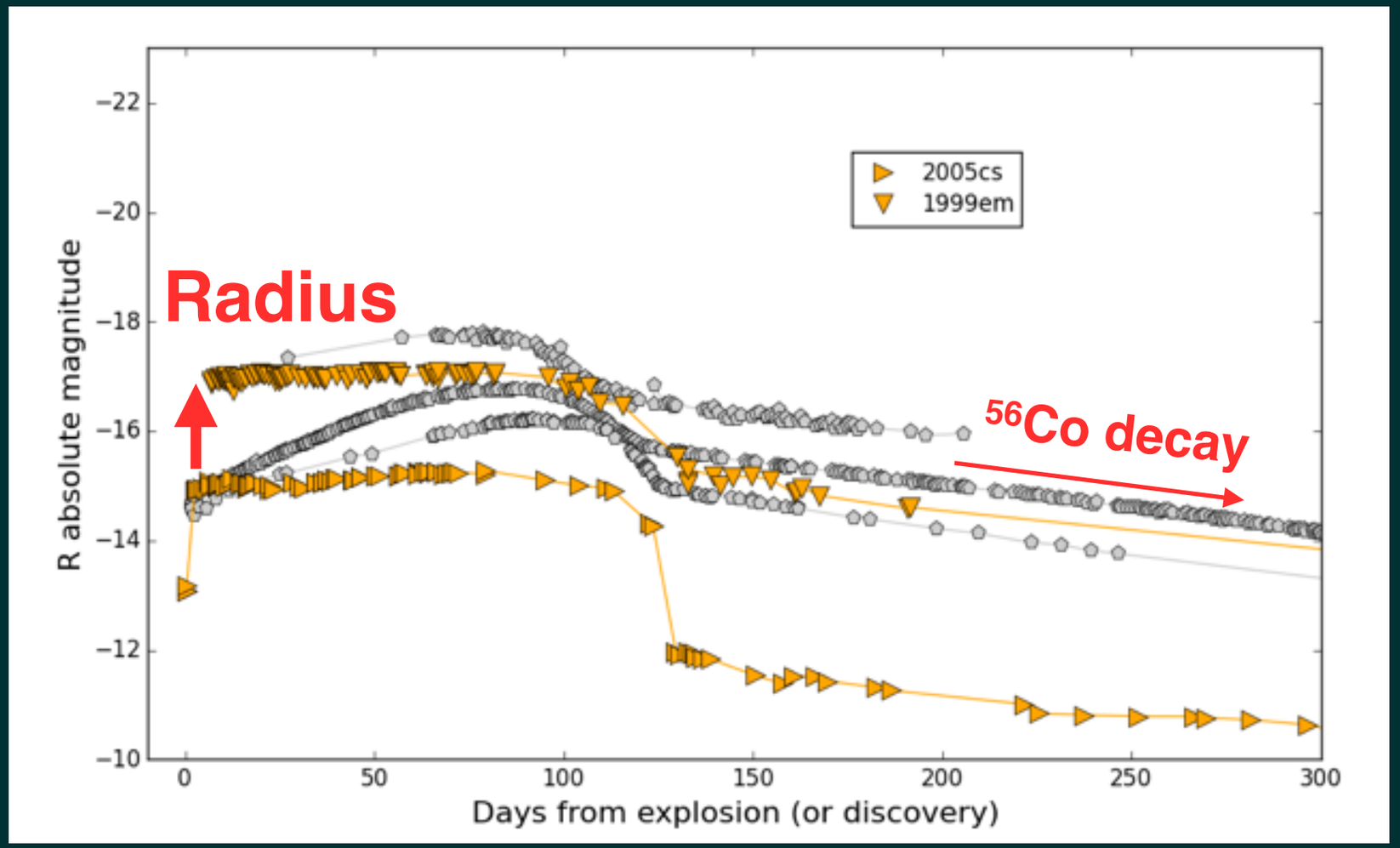
Blue supergiant

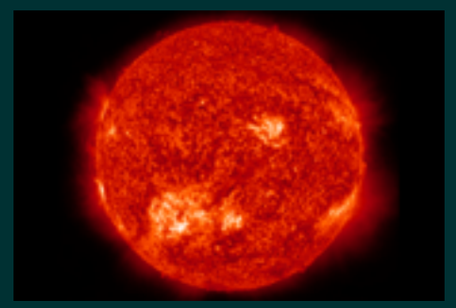
- 3% of all CC SNe
- Progenitors ~ 20 $M_\odot$
- Compact progenitors
- M_{Ni} ~0.04-0.23 $M_\odot$
- Sample ~ 10 objects
- Prefer low metallicity

1964 papers on SN1987A
Pastorello et al 2012, Taddia et al 2013,
Taddia et al 2016, Takats et al 2016

IIpec - 87A-like

SN II (IIP)





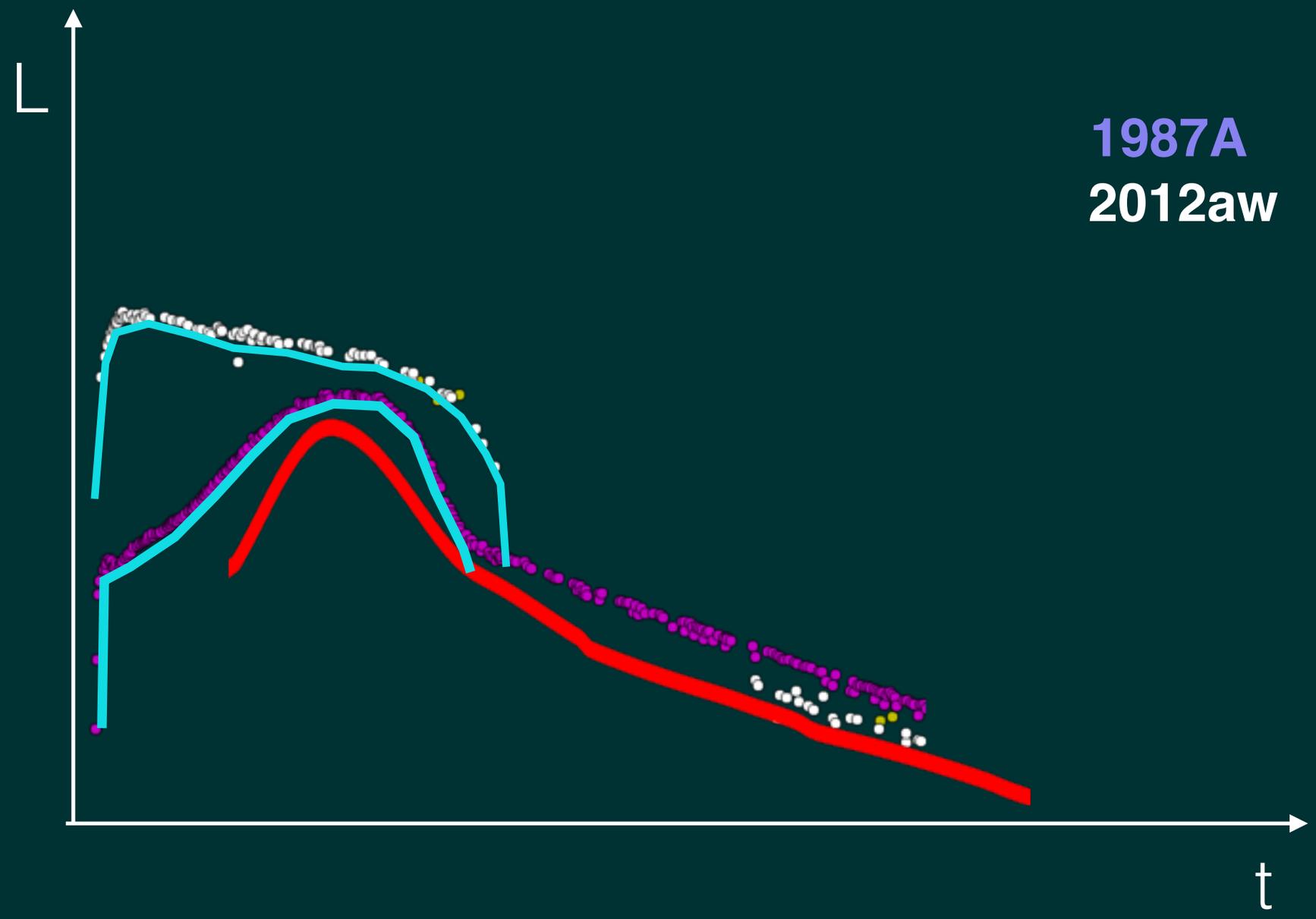
Red supergiant

- 62% of all CC SNe (IIP-IIL)
- Progenitors ~ 8 -16 $M_\odot$
- RSG (few 100 $R_\odot$)
- M_{Ni} ~0.002 - 0.2 $M_\odot$
- Sample ~ 100 -150 objects

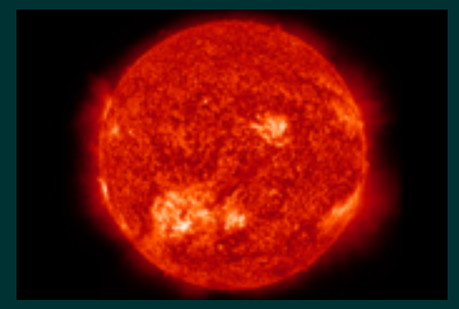
Smart et al 2009, Anderson et al 2014, Spiro et al 2014, Faran et al 2014a, Sanders et al 2015, Valenti et al 2016

Popov 1993 - Young 2004 - Utrobin 2007, Kasen & Woosley 2009
Bersten et al 2011

SN II (IIP)



Blue supergiant



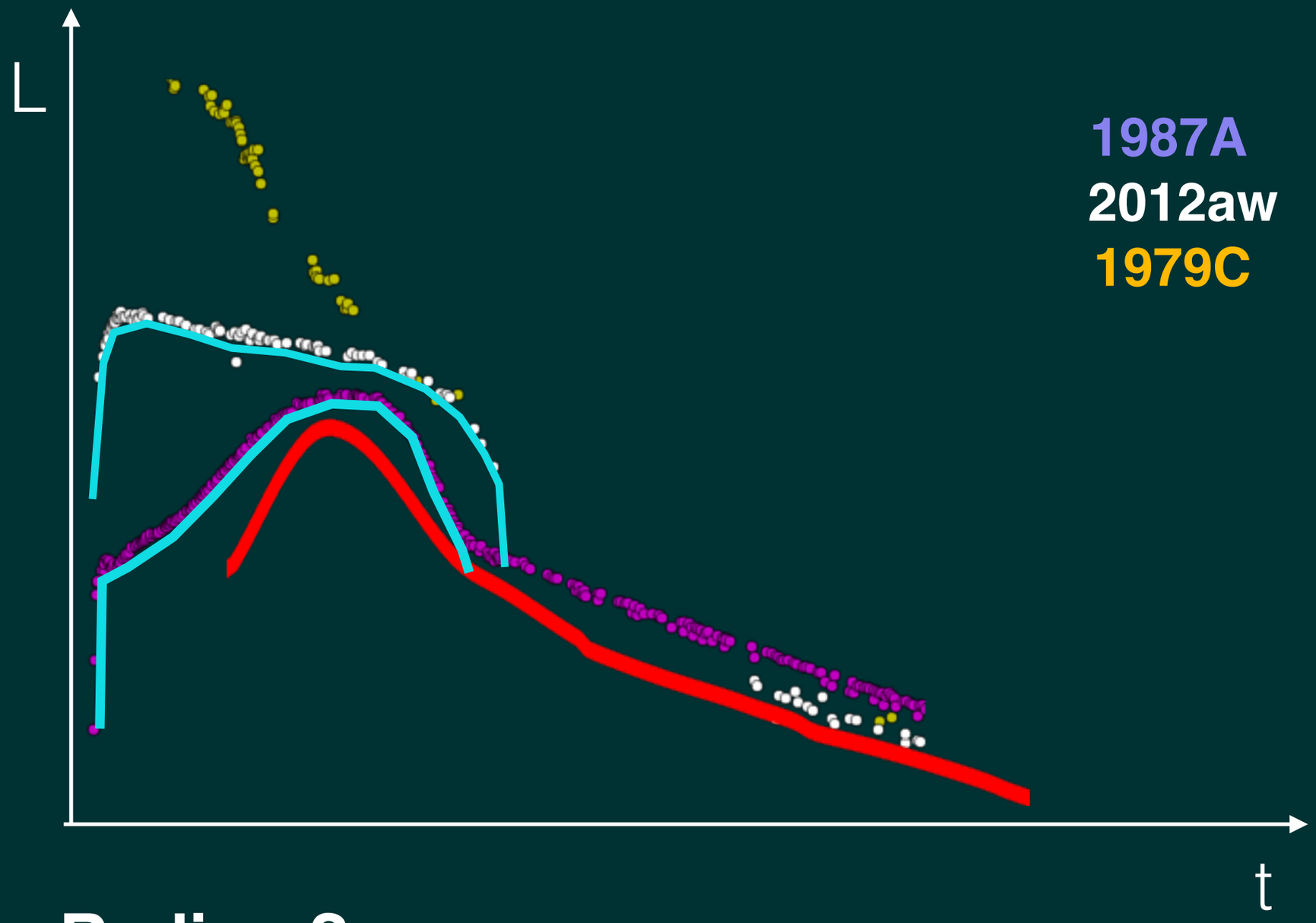
Red supergiant

1987A BSG
2012aw RSG

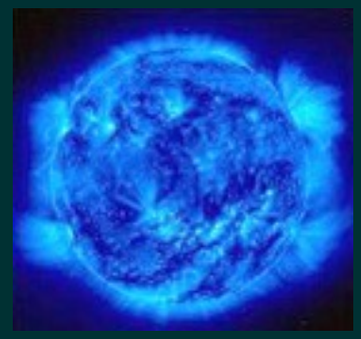
t ~ 122 (days) $E^{-1/4}$ $M^{1/2}$ $R^{1/6}$

Popov 1993 - Young 2004 - Utrobin 2007
Kasen & Woosley 2009 - Bersten et al 2011

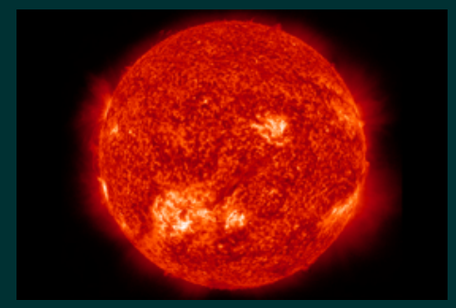
SN II (IIL)

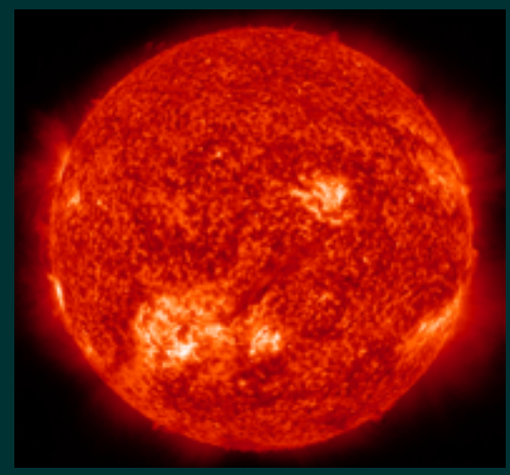


1987A	BSG
2012aw	RSG
1979C	?



Blue supergiant

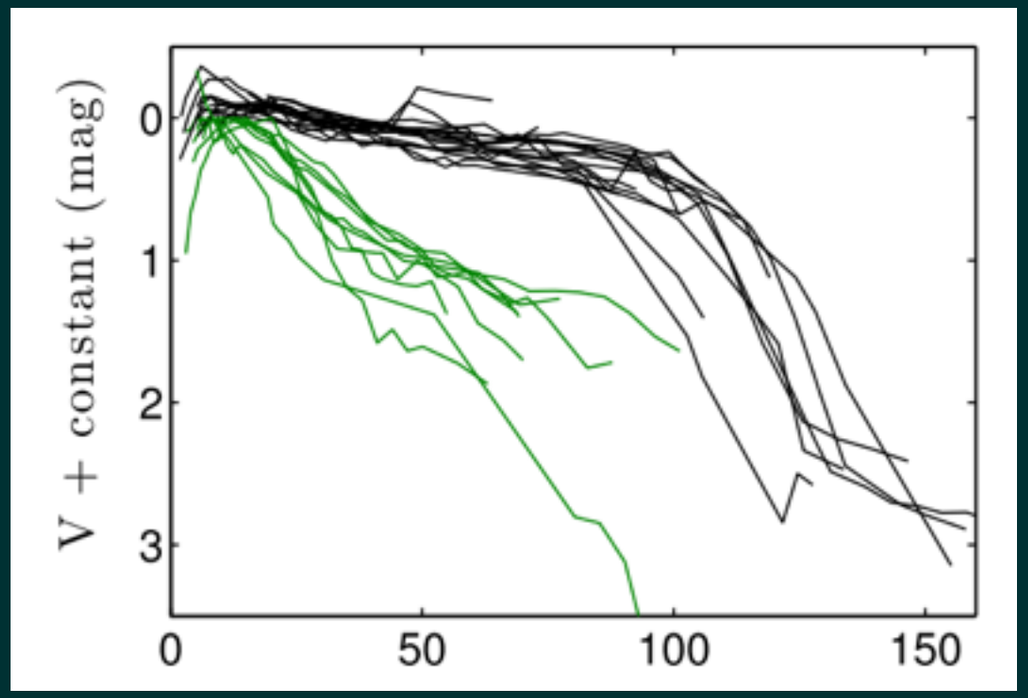




Radius ?
Interaction ?
smaller hydrogen mass ?

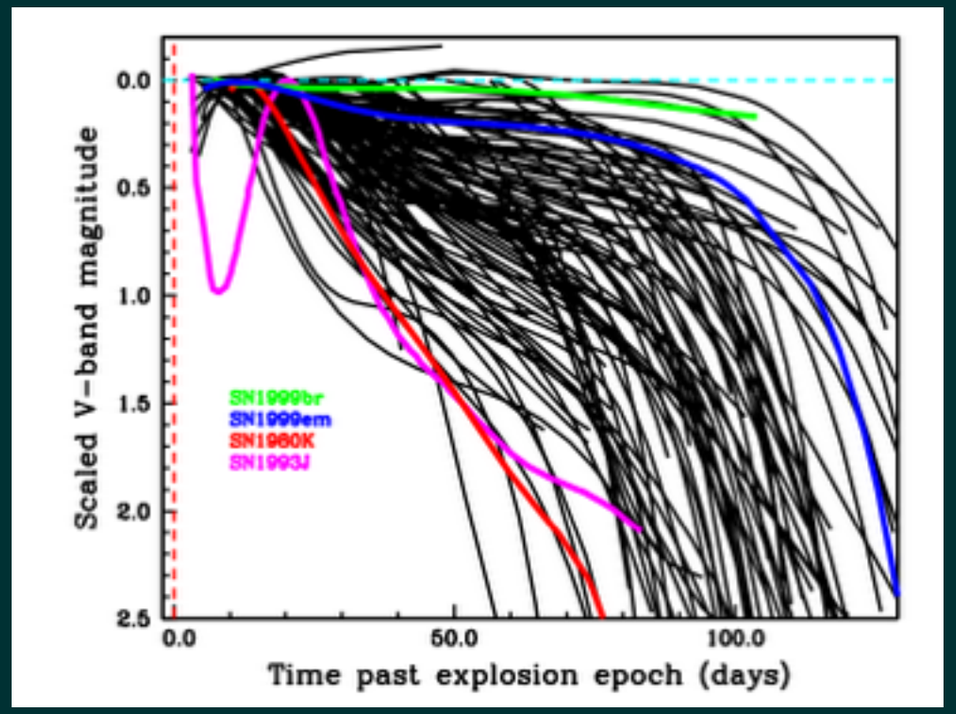
smaller H ejecta
radius ~ 6000 R⊙
(Blinnikov and Bartunov 1993)

SN II (IIP-IIL)



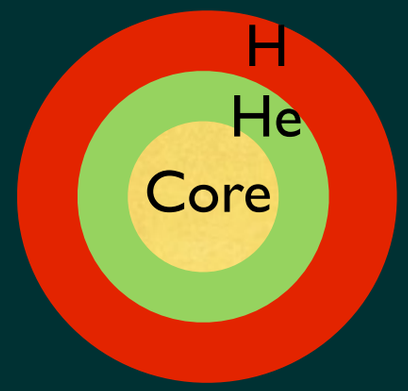
Arcavi et al 2012
Faran et al 2014a
Faran et al 2014b

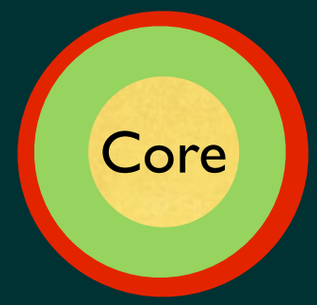
two distinct classes



Anderson et al 2014
Sanders et al 2015

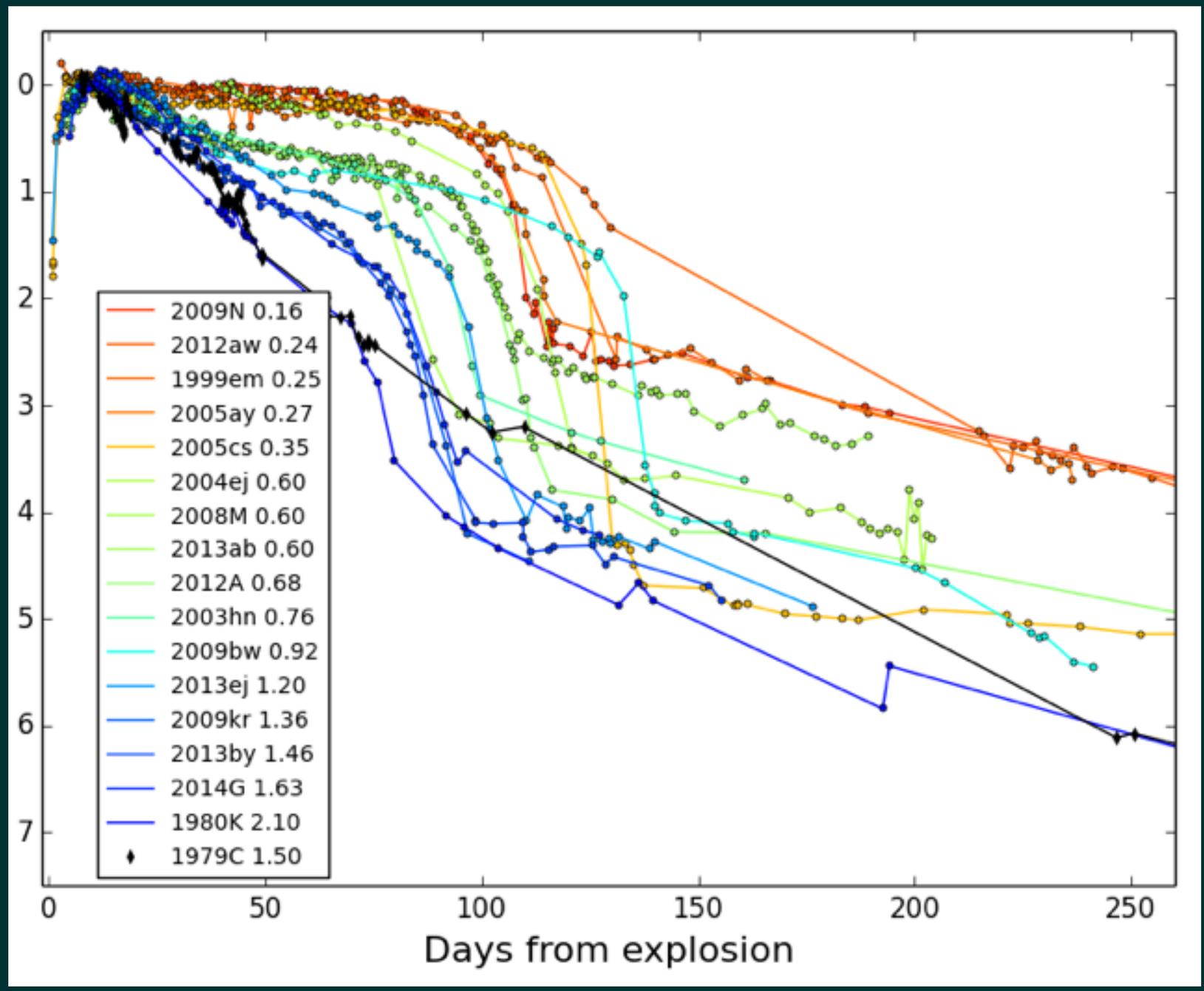
one class





SN II (IIP-IIL)

SNe IIL have a short plateau

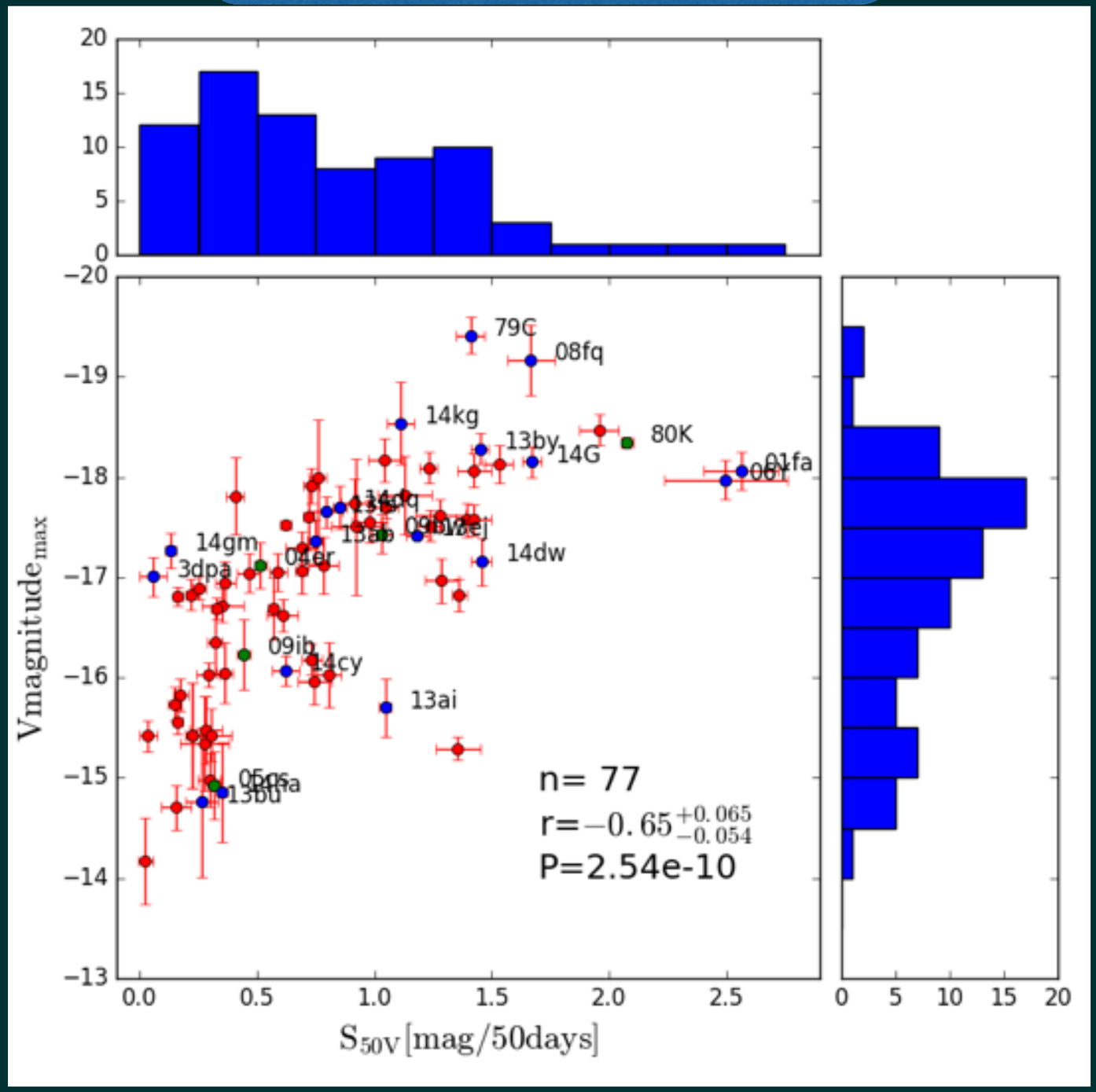


Anderson et al 2014
Faran et al 2014a
Faran et al 2014b

Sanders et al 2015
Valenti et al 2016

SN II (IIP-IIL)

SNe IIL are brighter

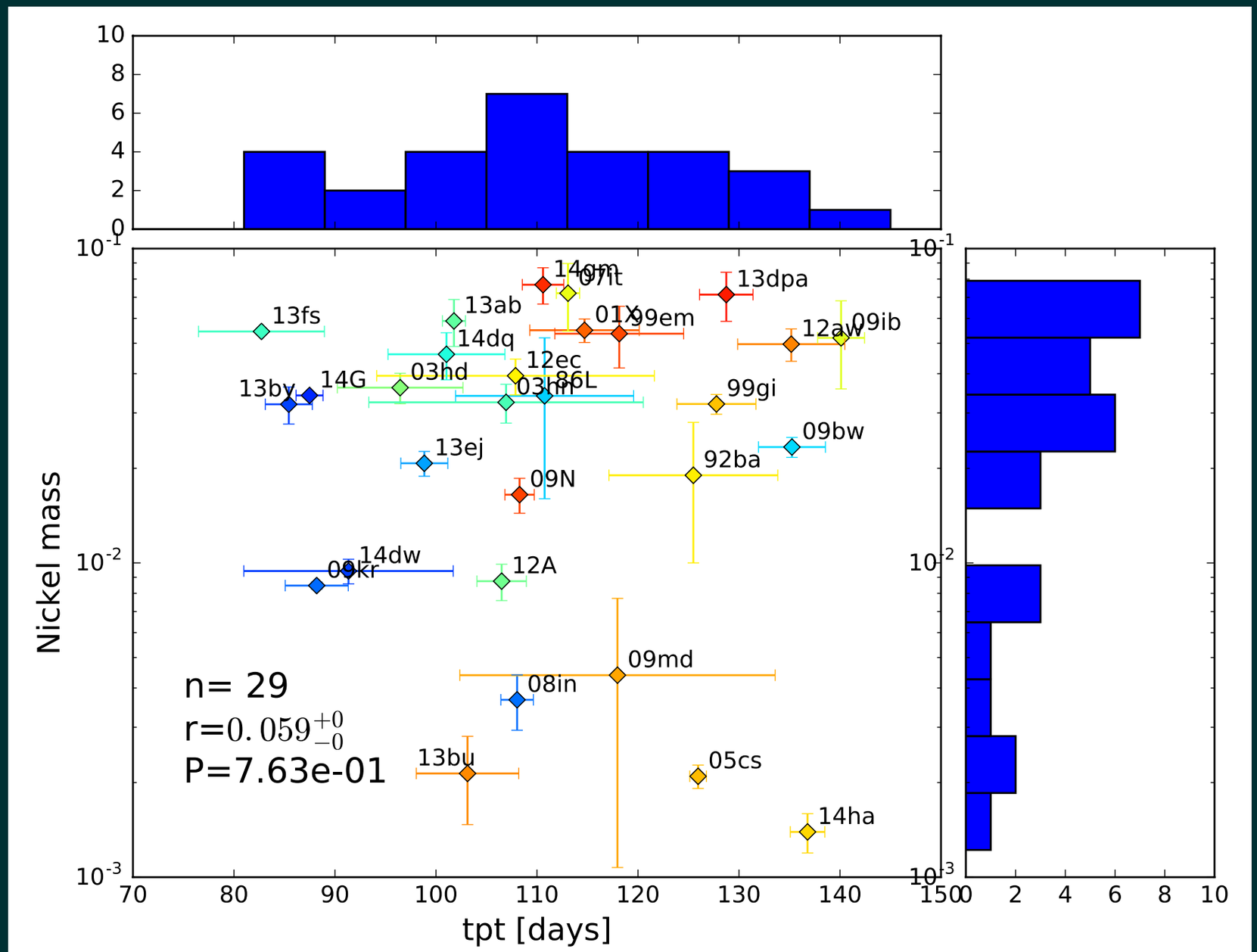


Anderson et al 2014
Faran et al 2014a
Faran et al 2014b

Sanders et al 2015
Valenti et al 2016

SN II (IIP-IIL)

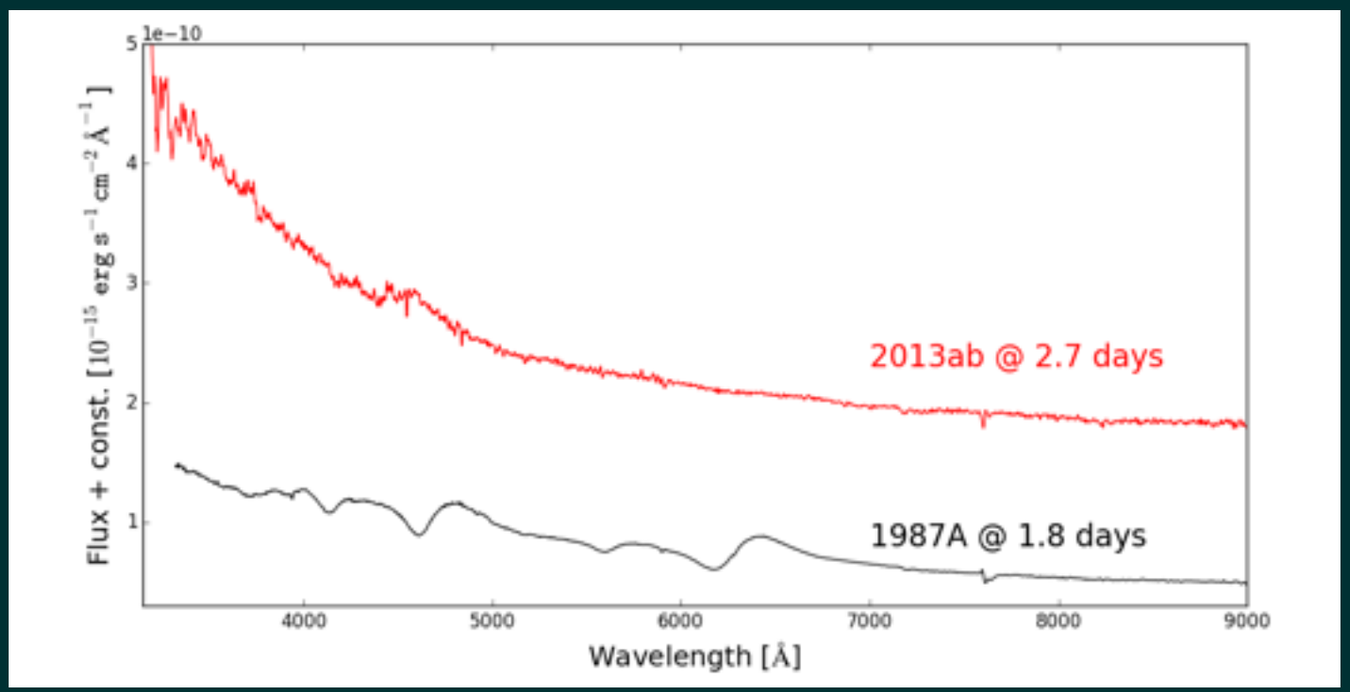
Similar Nickel



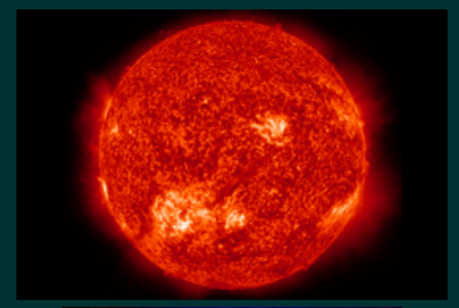
Anderson et al 2014
Faran et al 2014a
Faran et al 2014b

Sanders et al 2015
Valenti et al 2016

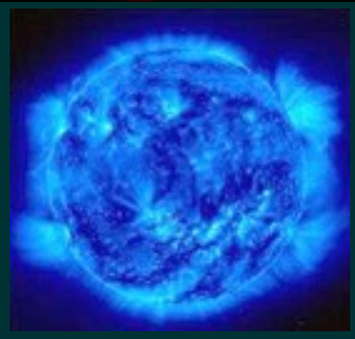
CC Compact Radius -> Cools faster

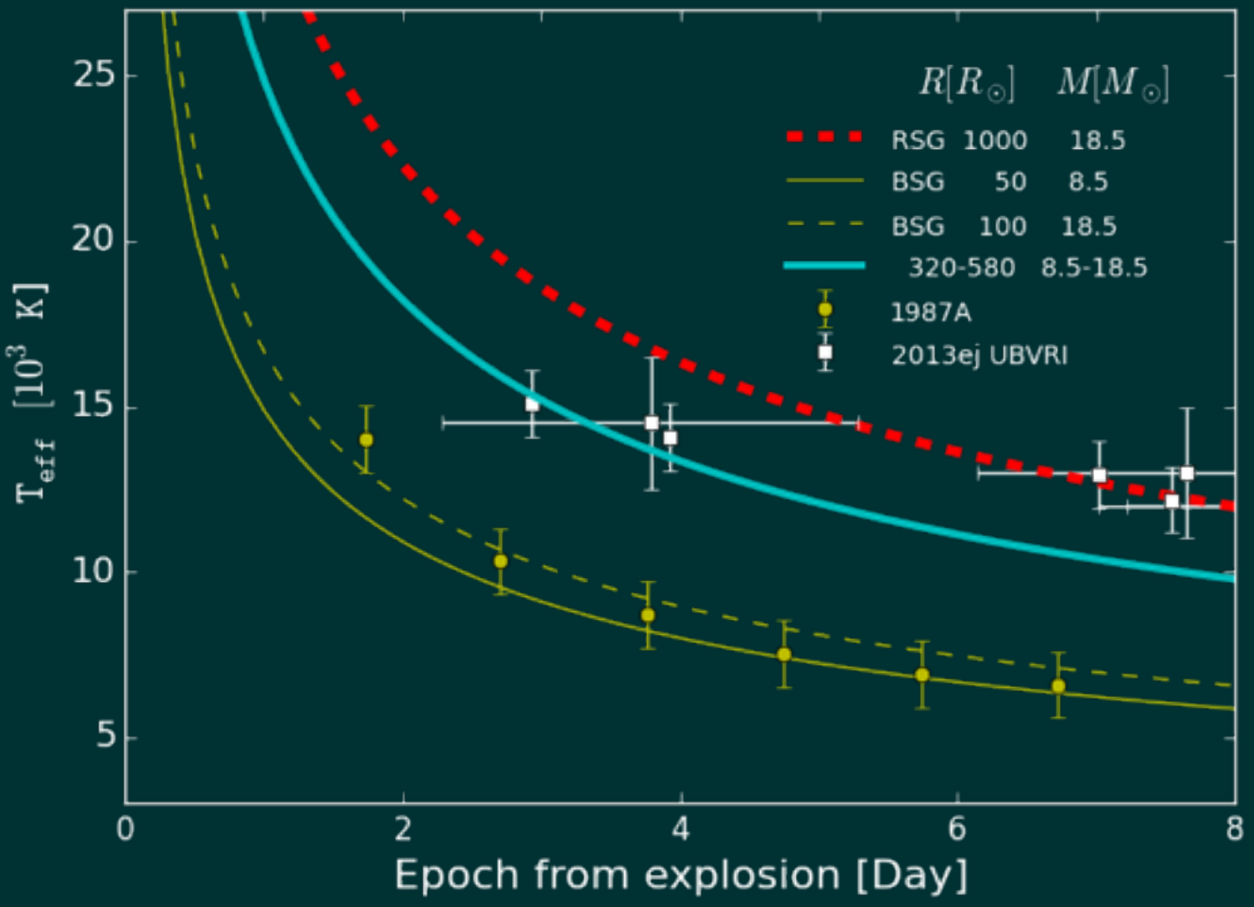


IIP-IIL



87A-like

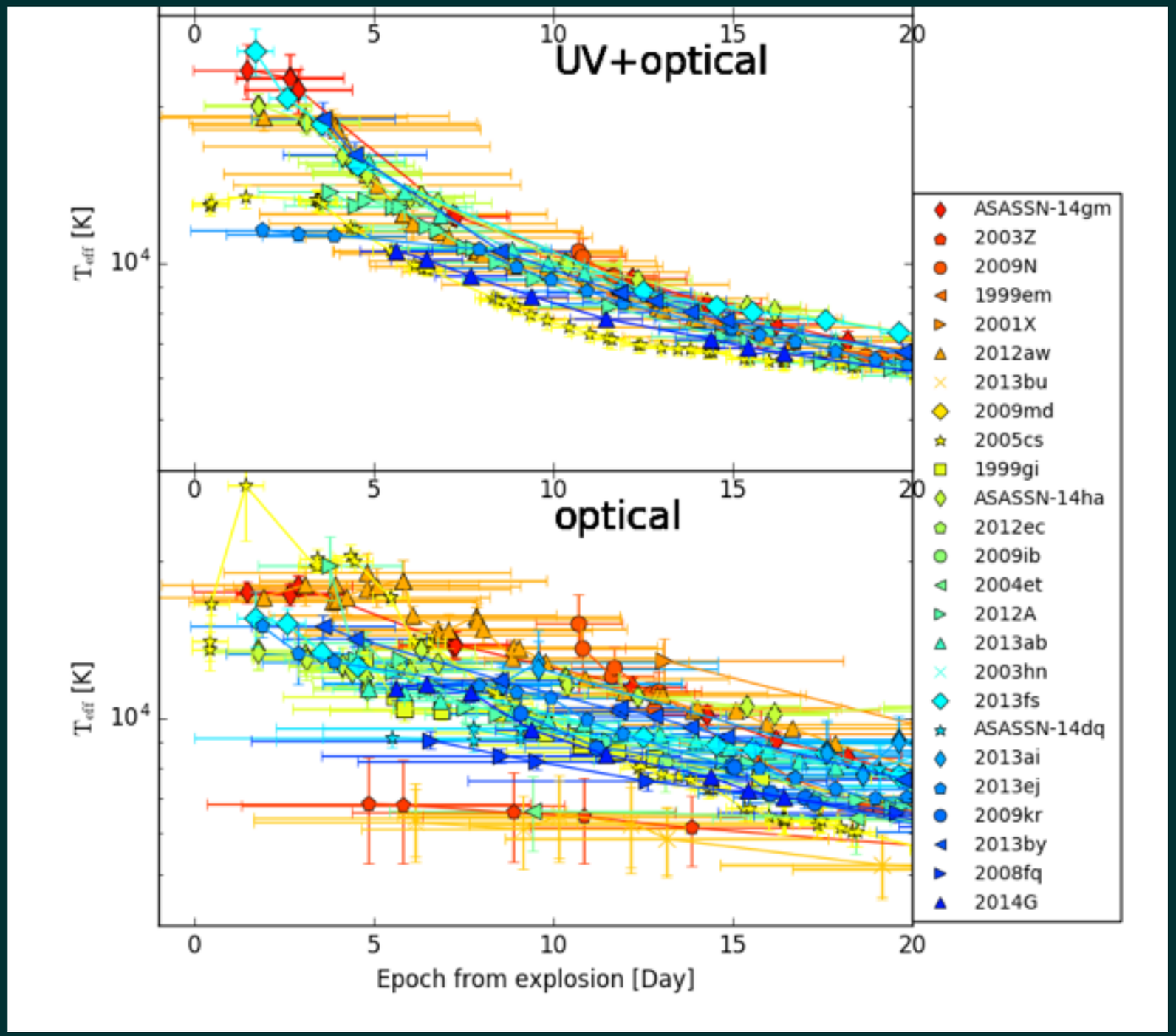


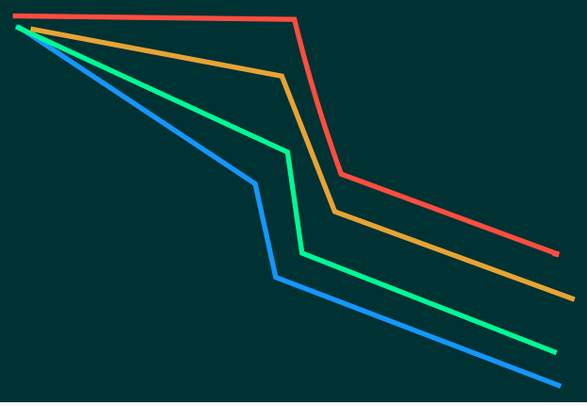


Compact Radius -> Cooling faster

Chevalier & Fransson (2008)
Rabinak & Waxman (2011)

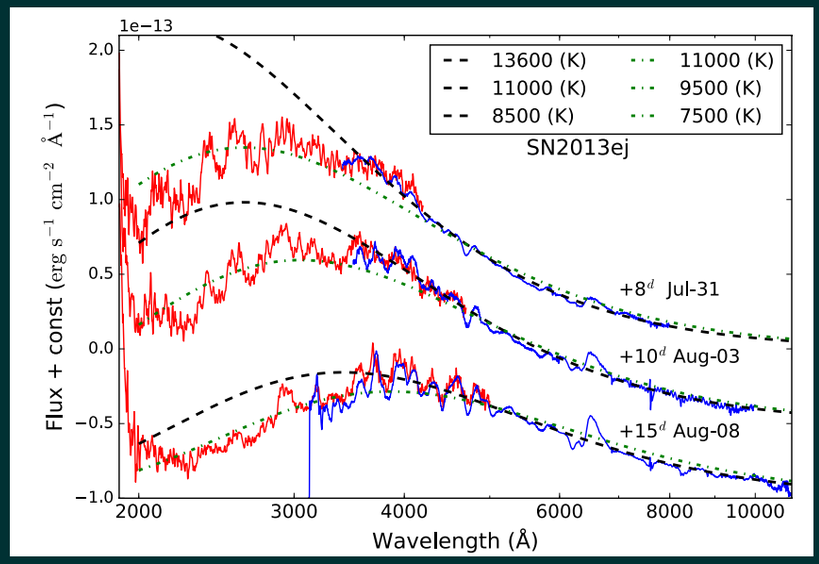
IIL - IIP radius





IIP-like are red

IIL-like are blue



Valenti et al 2016

Radius is not the key parameter to distinguish SNe IIP and IIL

Are IIL progenitors more massive than SNe IIP ?

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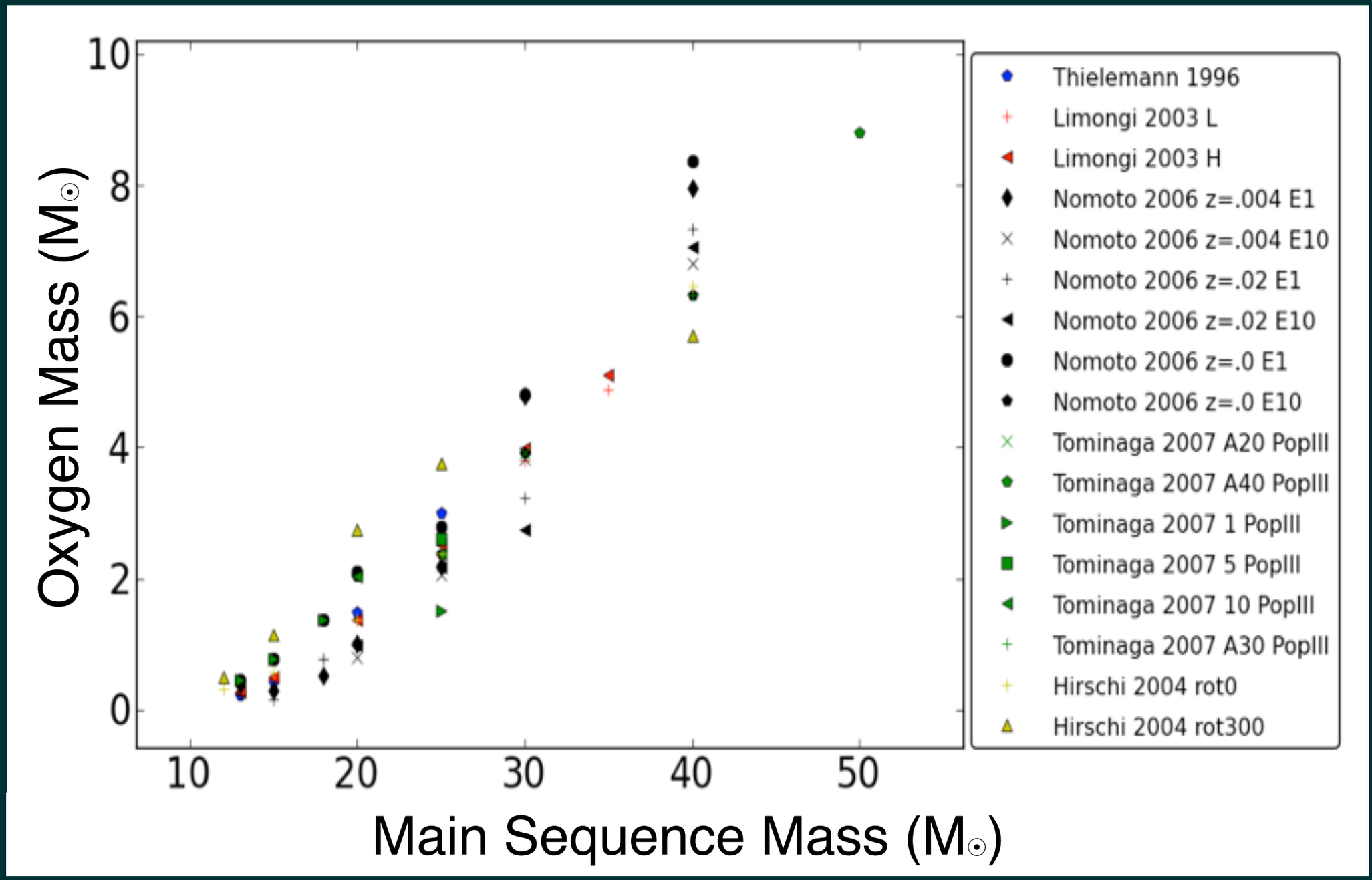
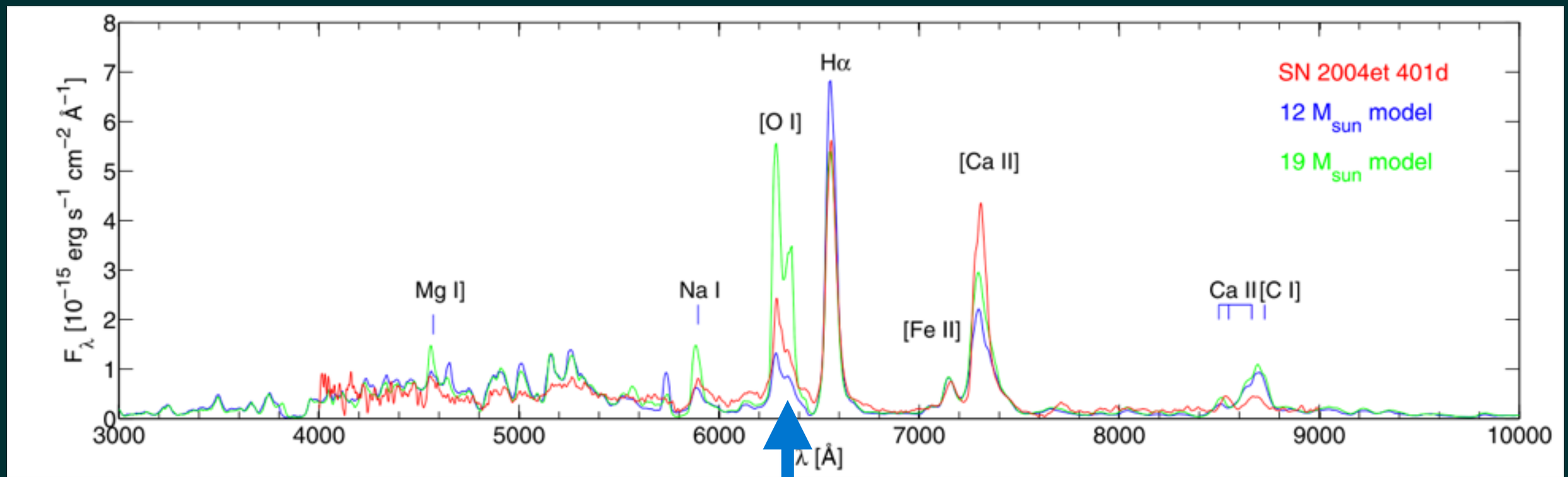


Oxygen is a good tracer for progenitor masses

Spectral Synthesis models

Evolve the stellar hydrodynamics code Kepler (Woosley & Heger 2007)

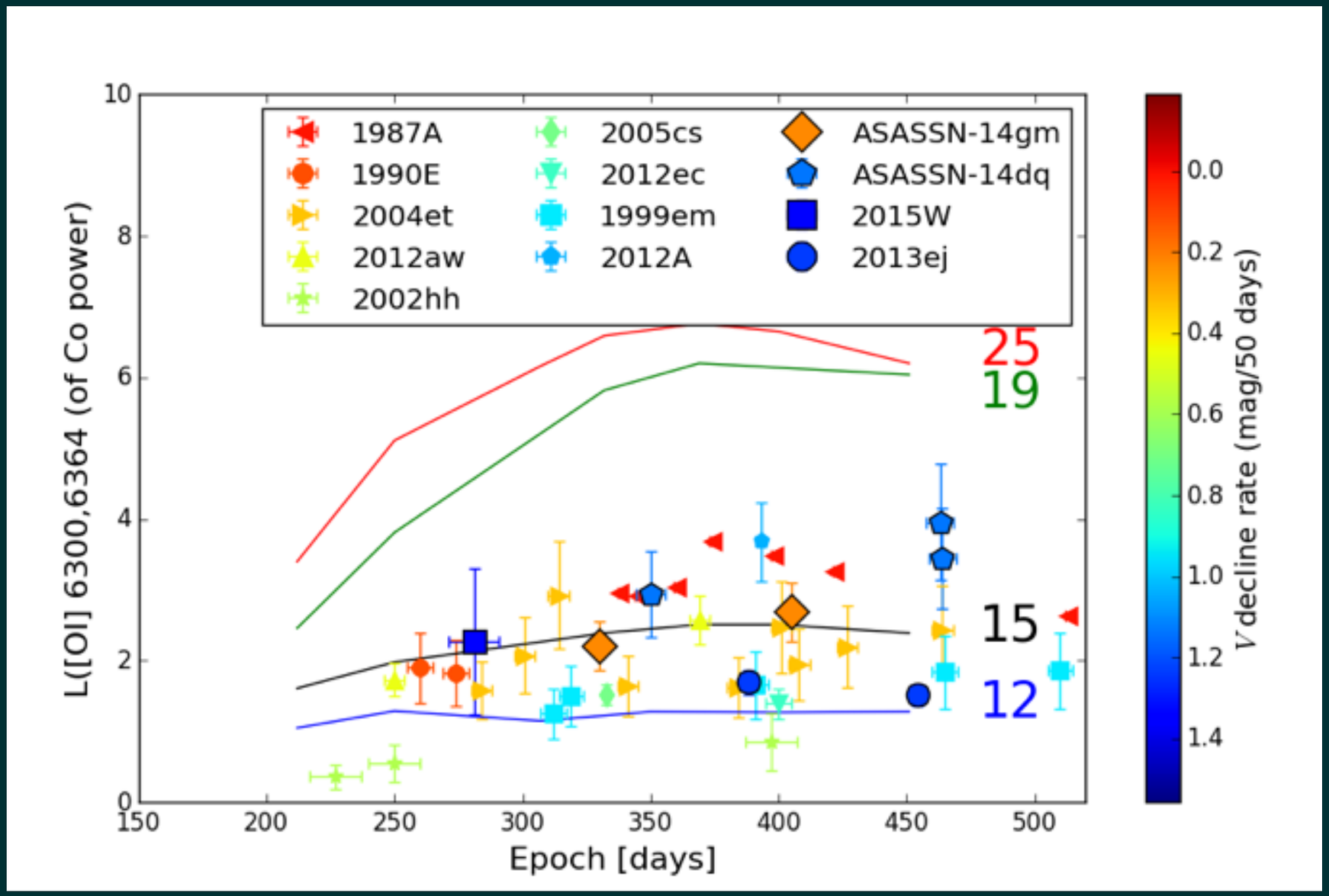
Follow the ɣ-Ray deposition (heating, ionizations and excitation)

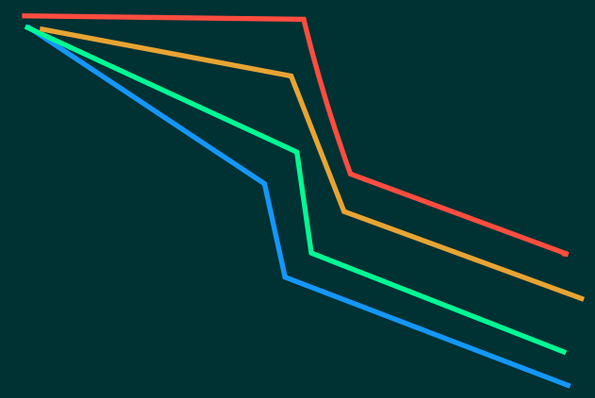


Jerkstrand et al 2011, 2012, 2014

(for nebular spectra see Fransson and Chevalier 1989)

SNe IIL come from progenitor 8-16 $M_\odot$





IIP-like are red

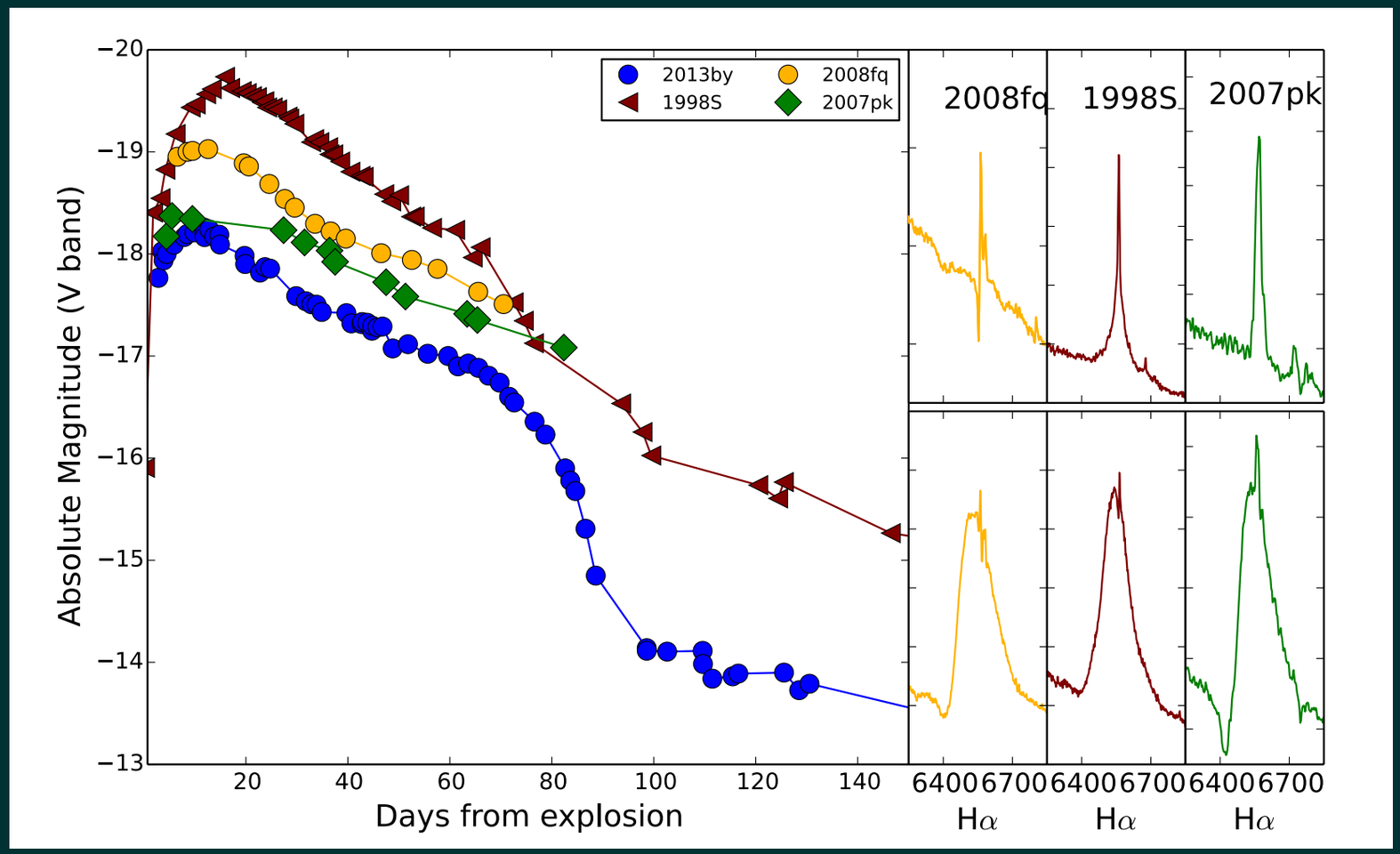
IIL-like are blue

Valenti et al 2016

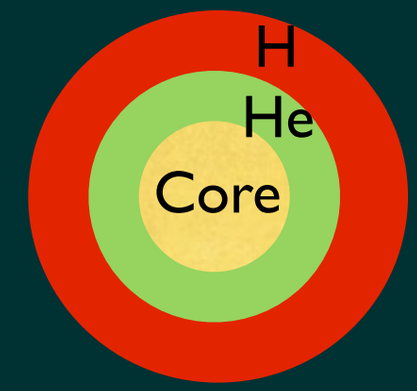
There is not a clear trend with SNe IIL being more massive than IIP

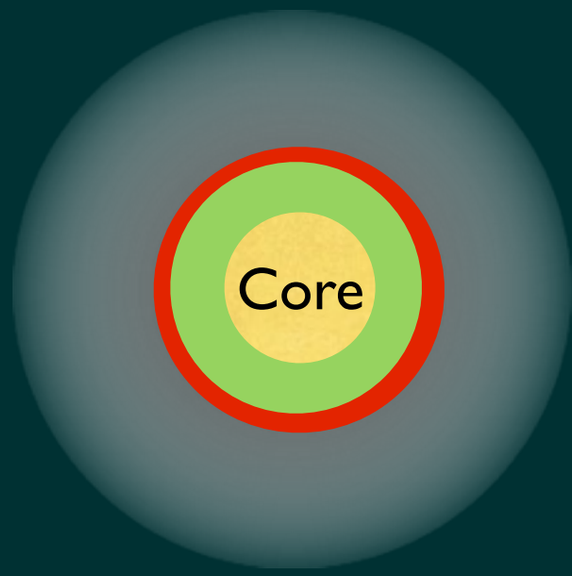
SNe IIL are brighter than SNe IIP

Are SNe IIL powered by extra energy source?
(CSM interaction)

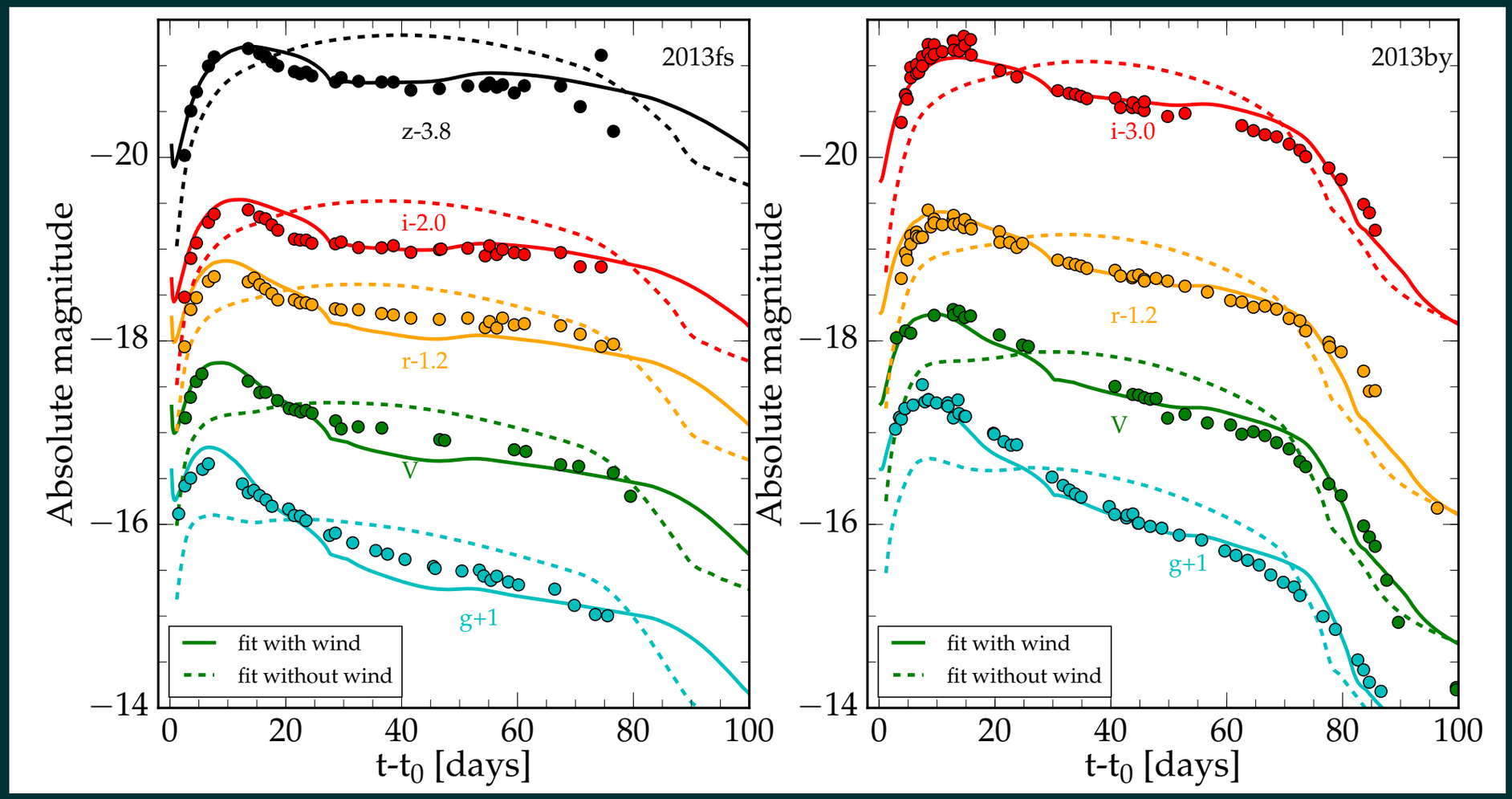


Valenti et al 2015a





Modeling CCSNe



KEPLER, MESA - SNEC

Dense CSM can be important for the majority of SNe II

Morozova et al (arXiv161008054M)

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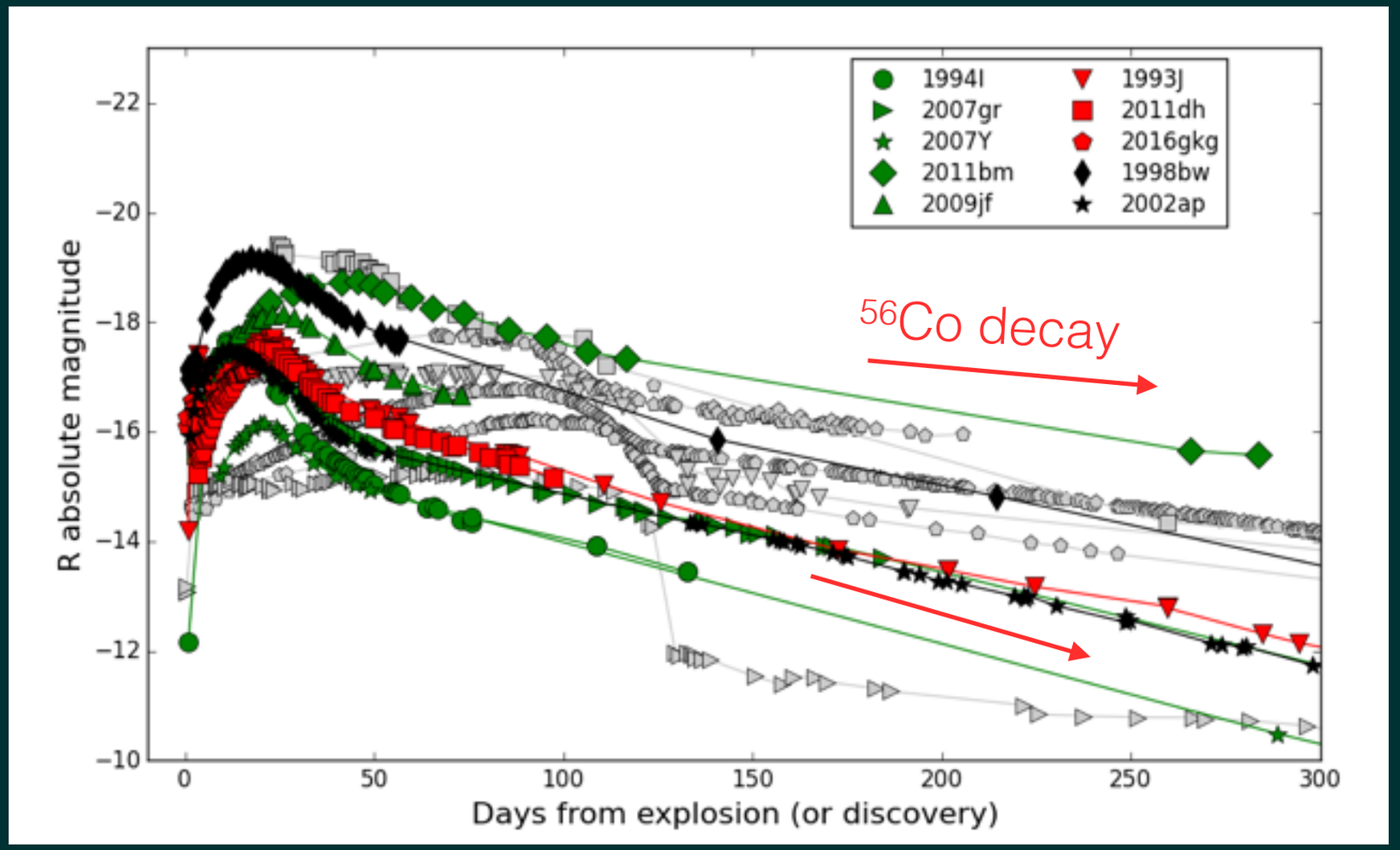
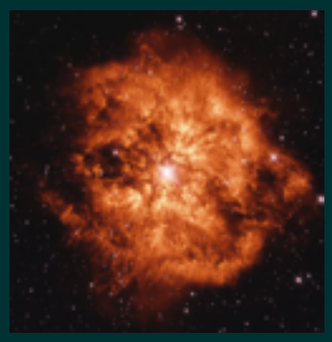
Stripped envelope SNe





Wolf Rayet

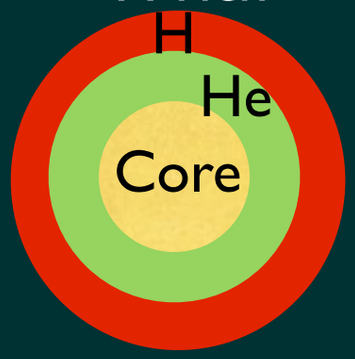
IIb/Ib/Ic/IcBL

- 30% of all CC SNe
- Progenitors ~ **> 20-25?** $M_\odot$
- No H, He (IIb little H)
- M_{Ni} .11 .14 .15 .34 $M_\odot$
- Sample ~ 50-100 objects

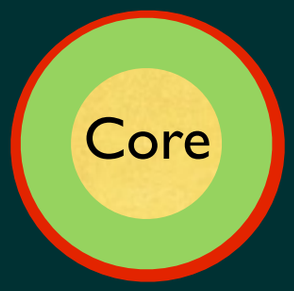
Modjaz et al. 2014, Bianco et al. 2014, Prentice et al 2016, Yu-Qian et al 2016, Lyman et al 2016

Stripped envelope SNe

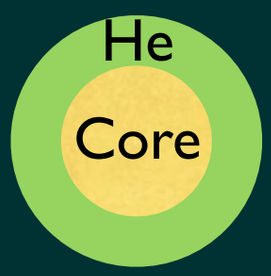
Type II
H rich



Type IIb

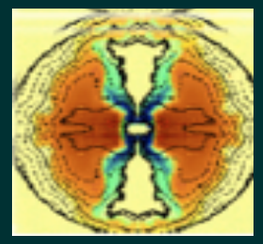


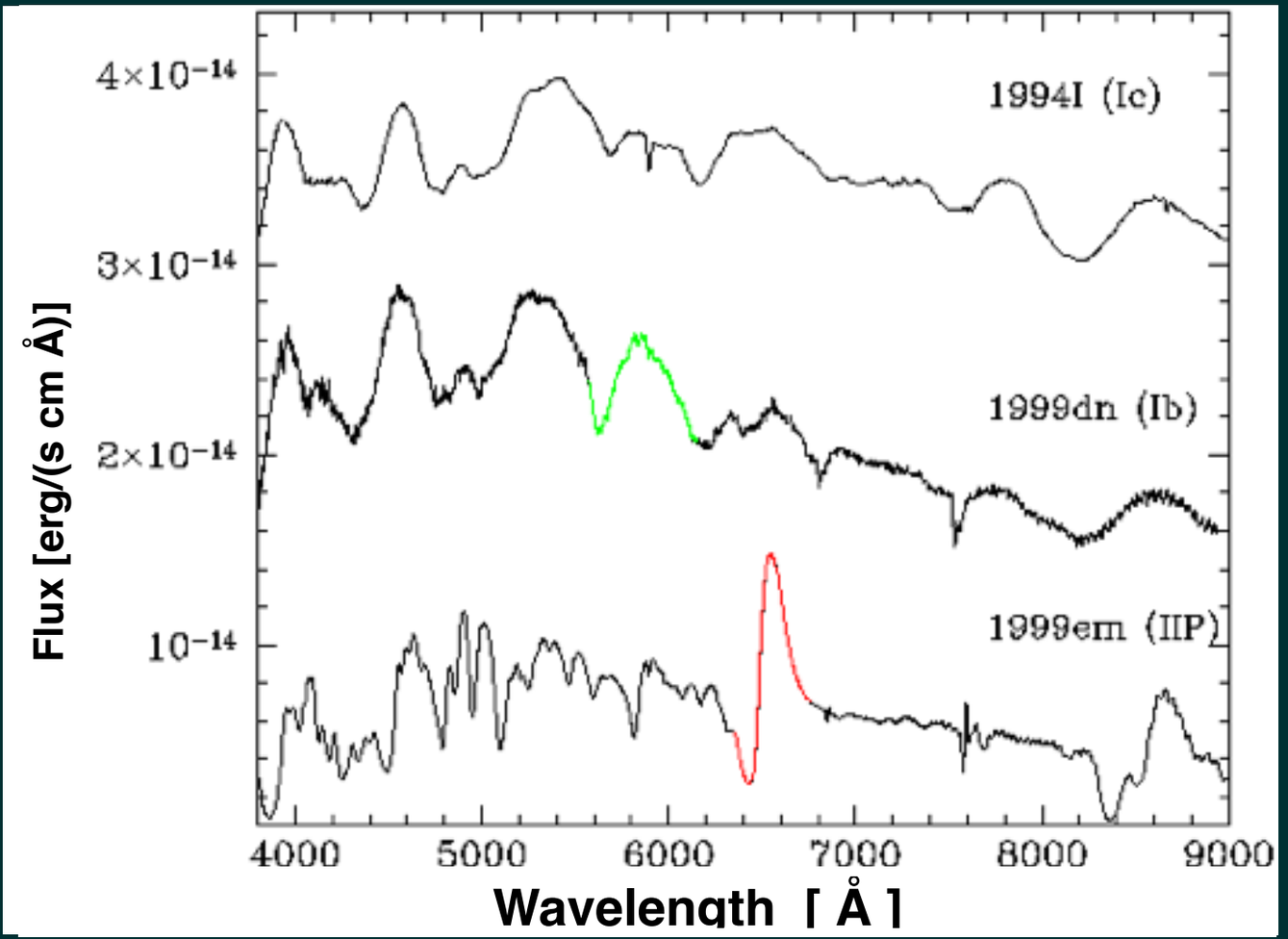
Type Ib
H poor, He rich

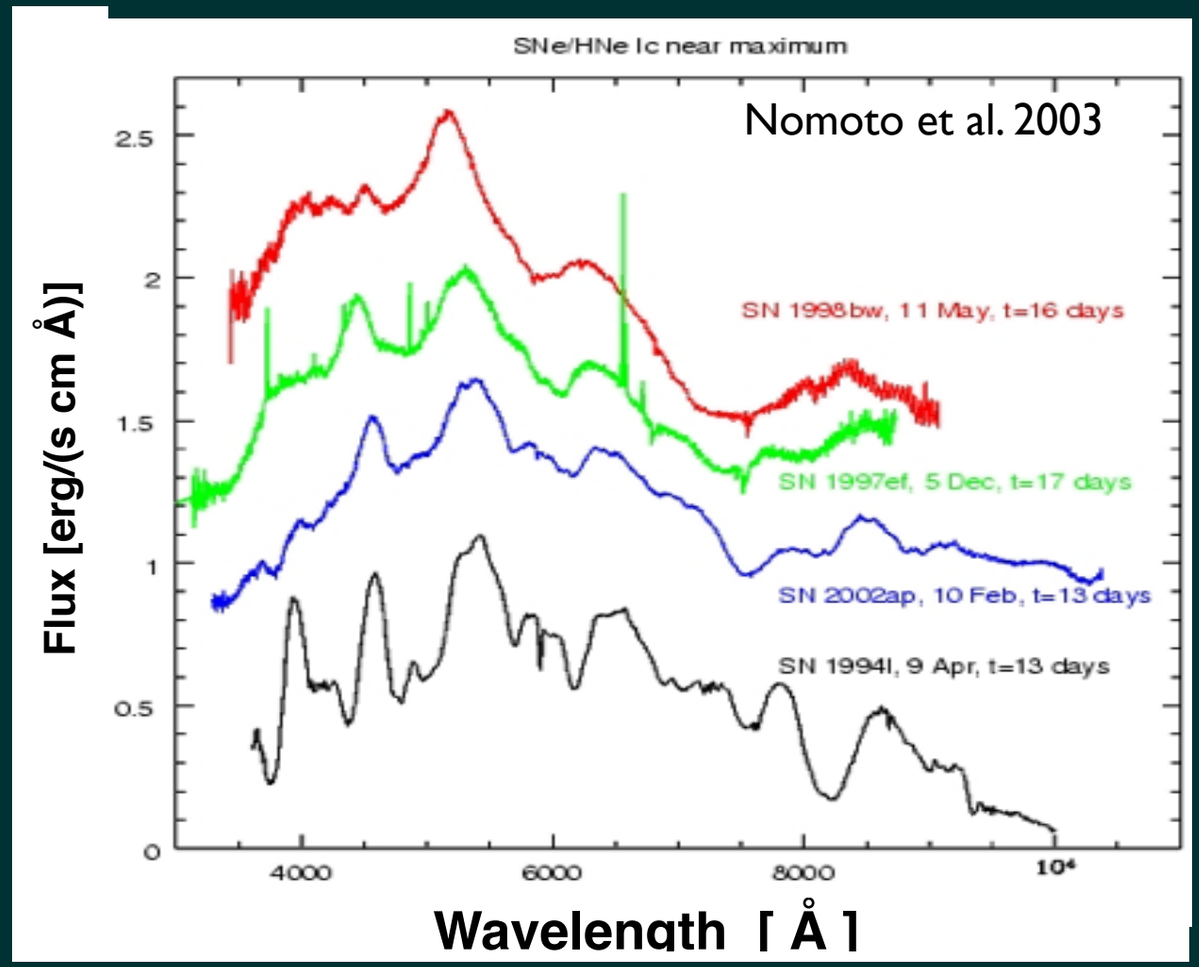


Type Ic
He poor

BroadLine-Ic Hypernovae

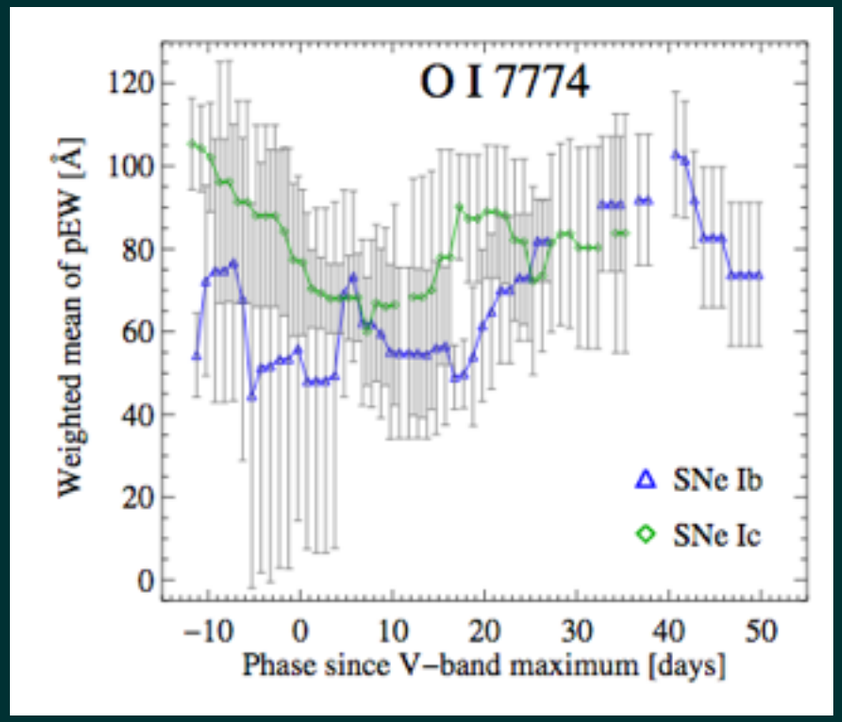


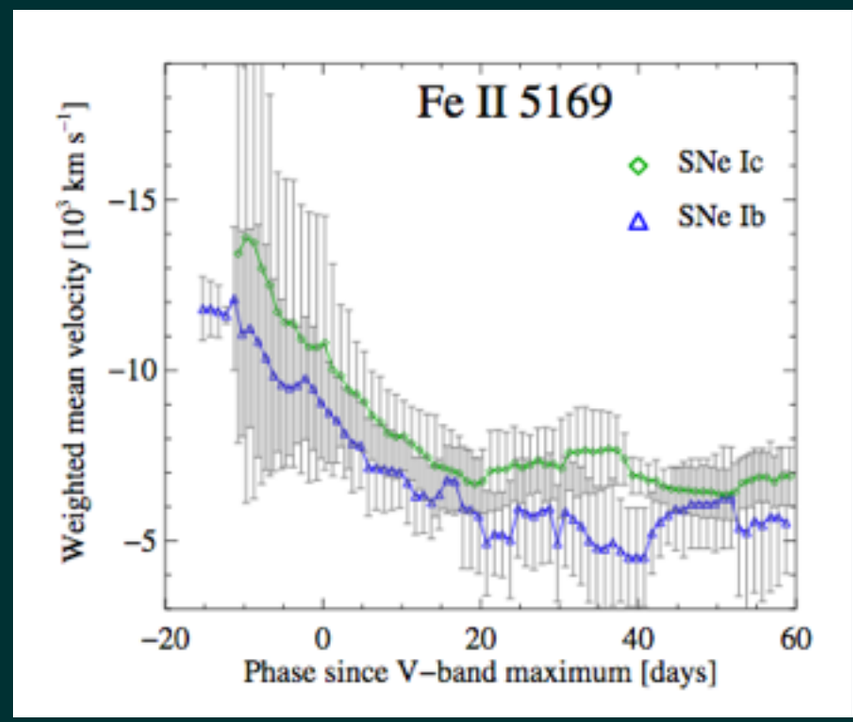


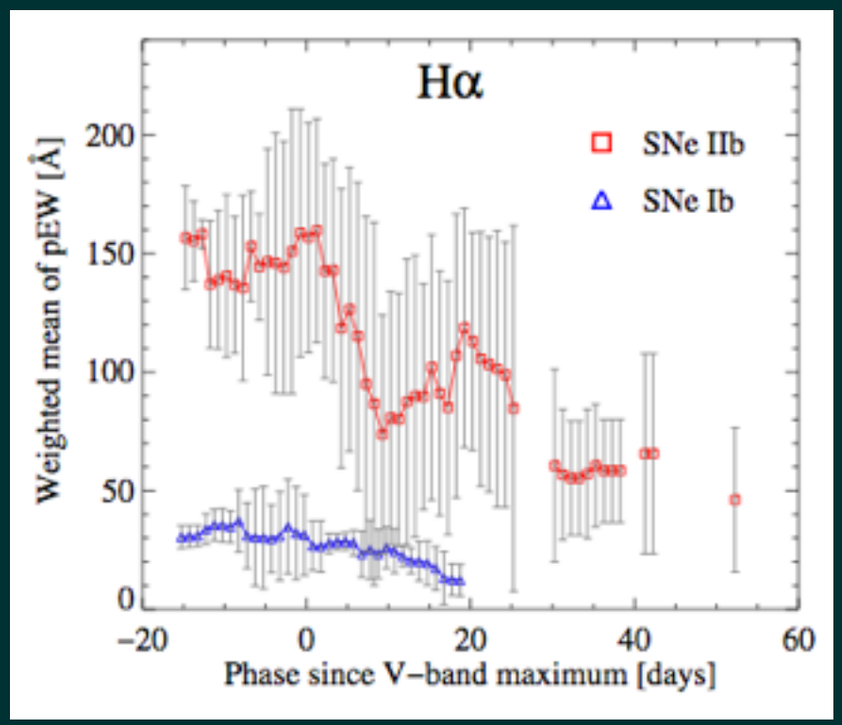


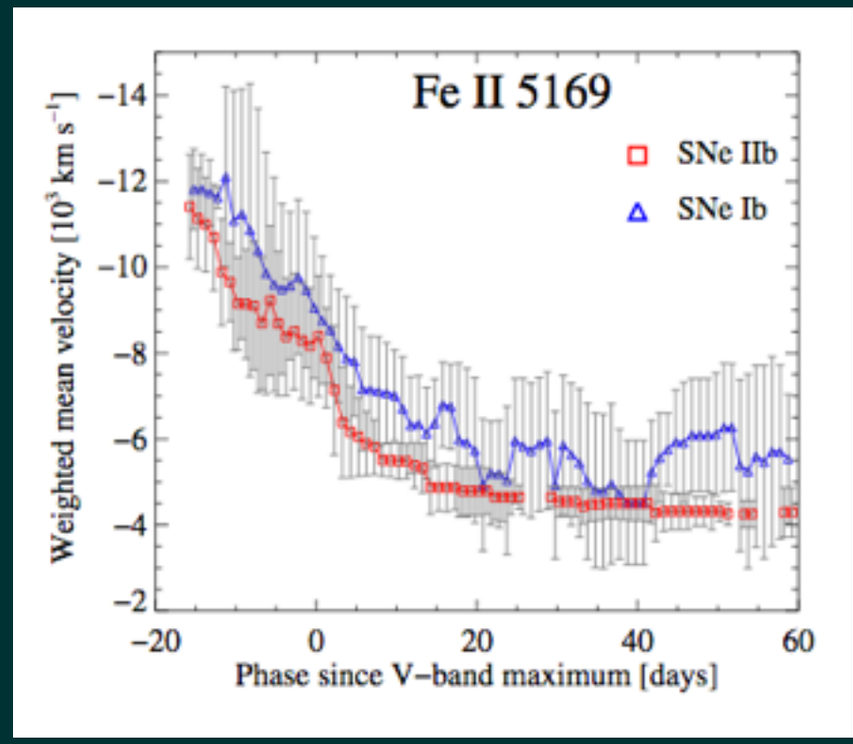
Stripped envelope SNe

II	H
IIb	H,He
Ib	He
Ic	~~H,He~~



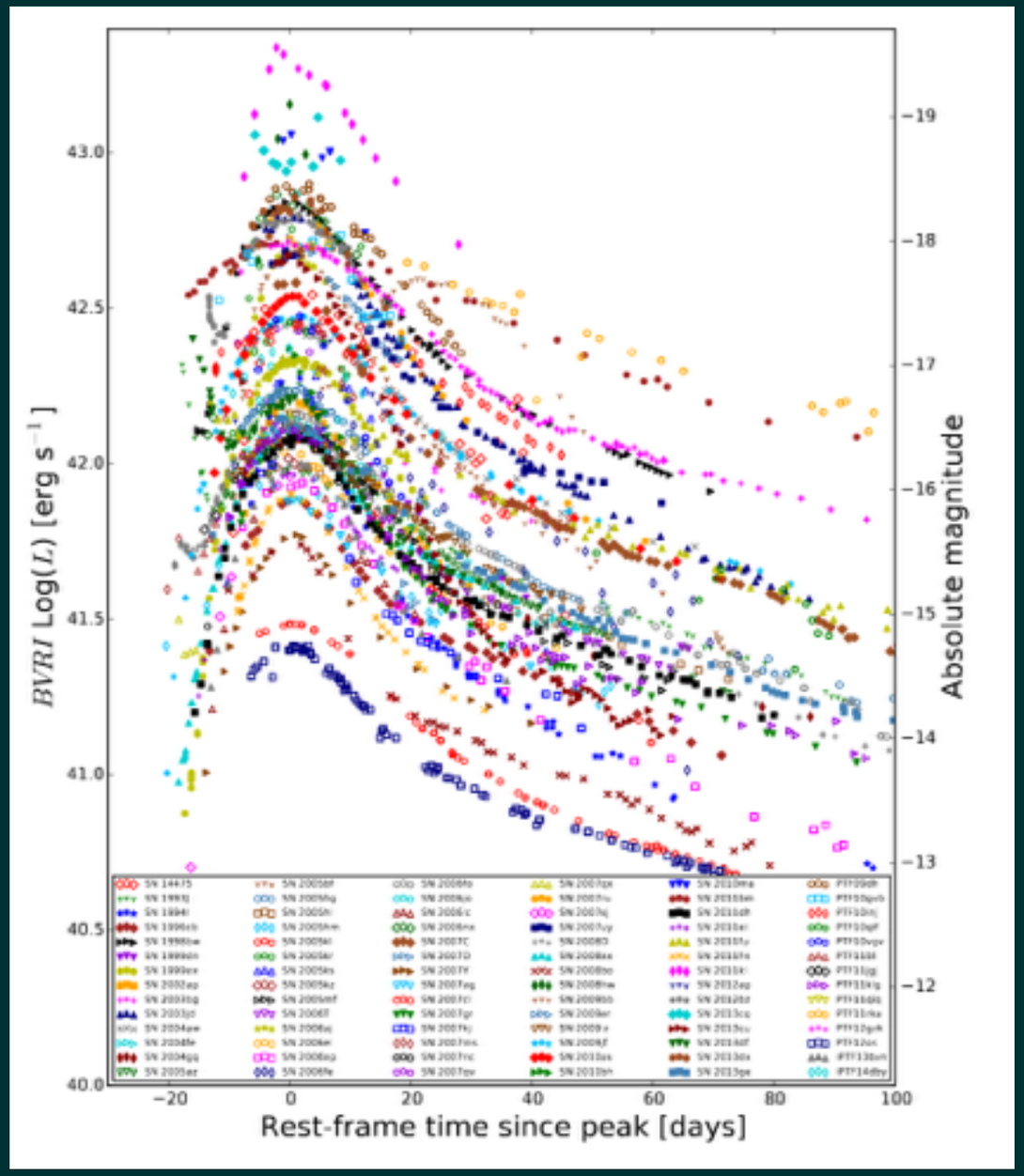




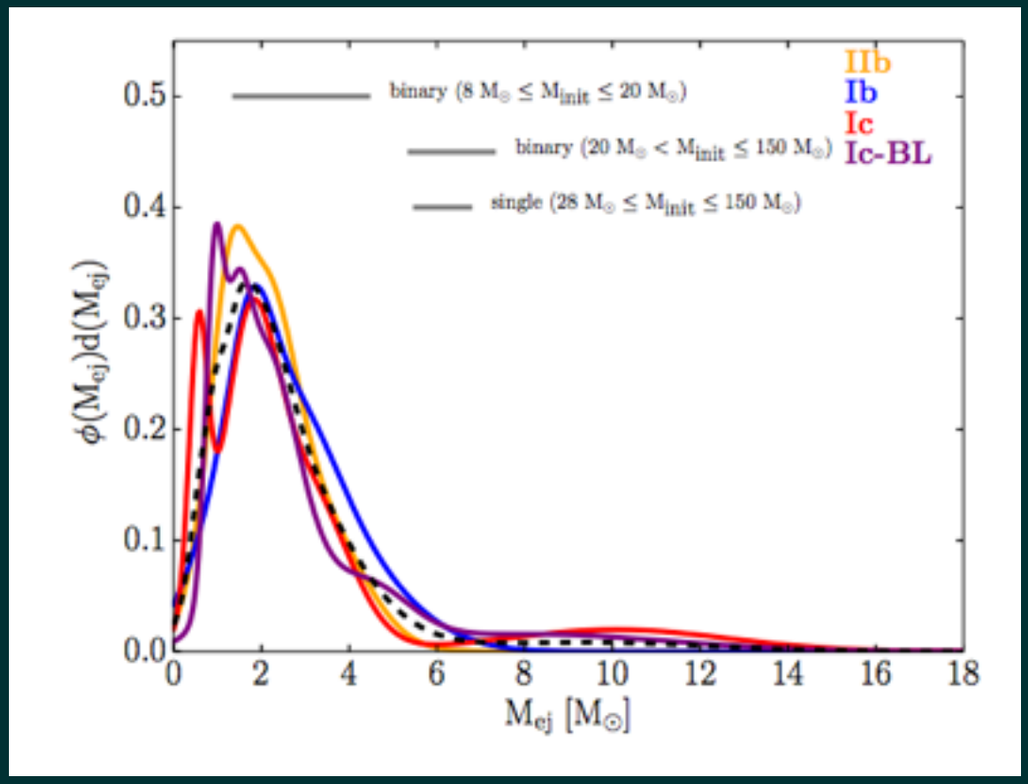


Modjaz et al 2014, Yu-Qian et al 2016, Modjaz et al 2016

Stripped envelope SNe



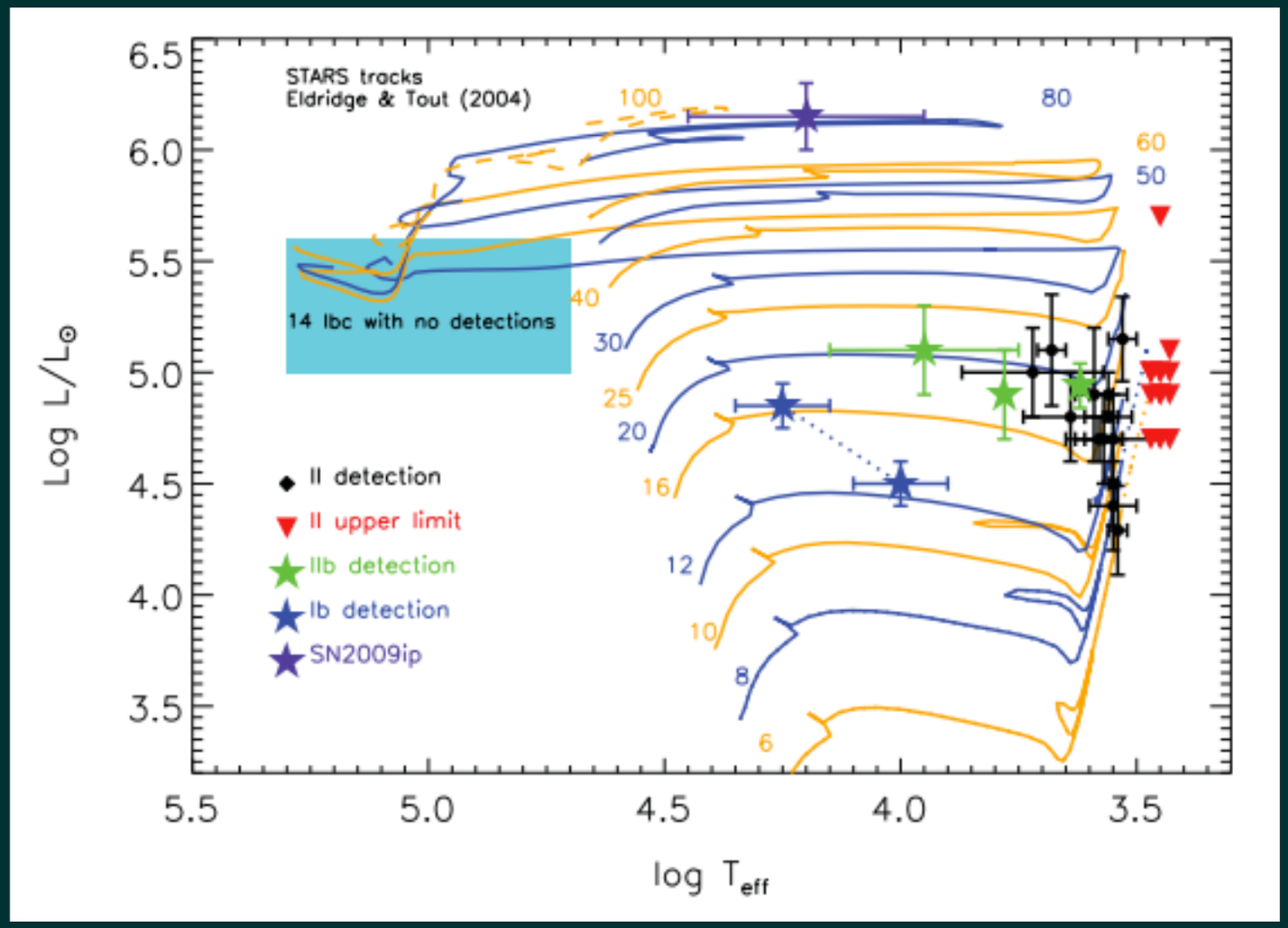
Bianco et al. 2014, Prentice et al 2016



Lyman et al 2016, Cano 2013

How 20-40 M$_\odot$ progenitors lose large amount of ejecta before explode ?

Stripped envelope SNe



Smartt et al 2015

Binary Systems

Germany et al 1980
Sana et al 2008, 2009, 2012

A fraction of SNe Ib/c are coming from stars > 8 $M_\odot$ in binary system

Podsiadlowski et al. 1993
Fryer et al 2007

Core Collapse Supernovae

- SNe II
    - IIpec
    - IIP - IIL

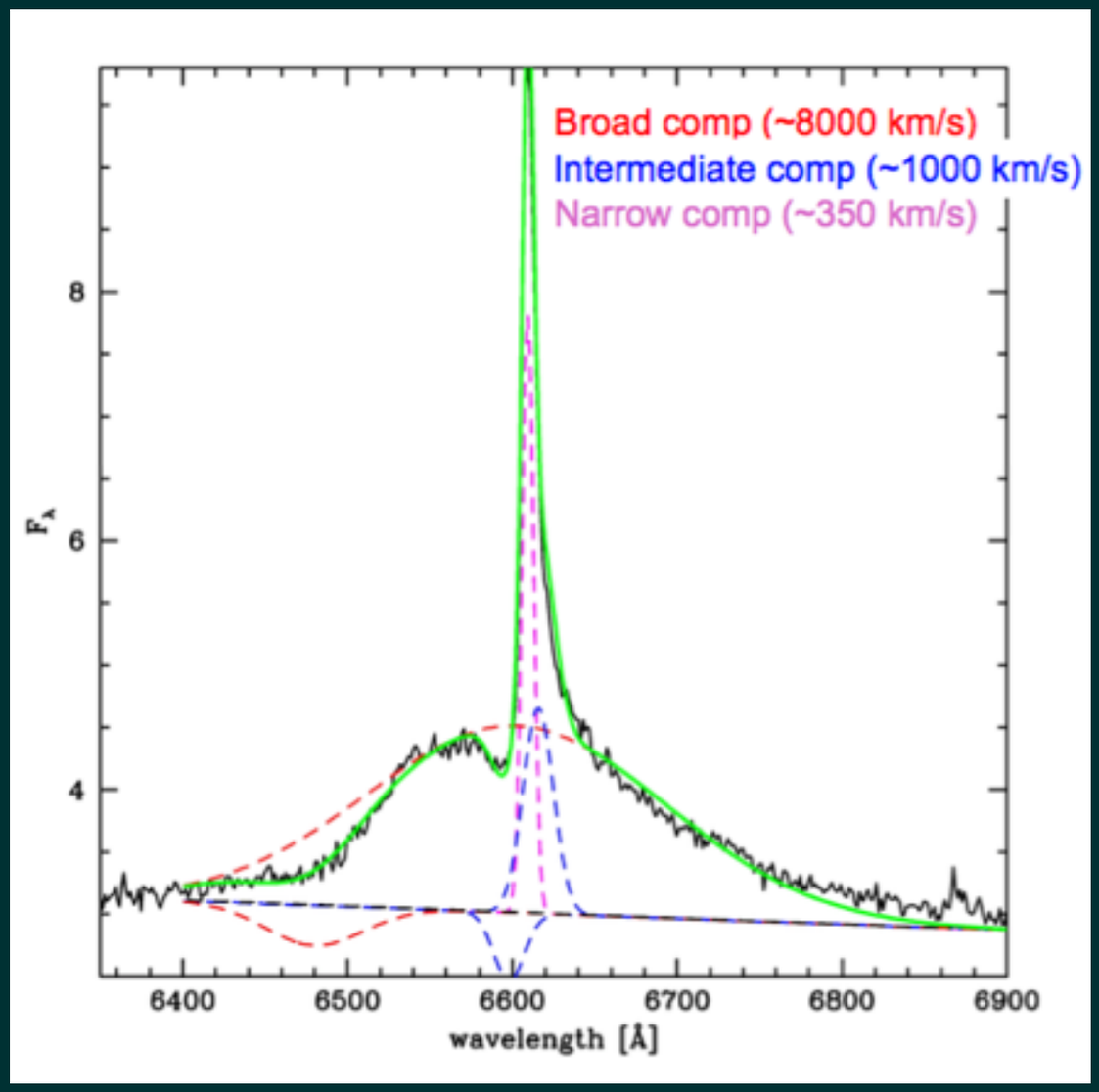
- SNe Stripped Envelope
    - IIb - Ib - Ic - BLIc

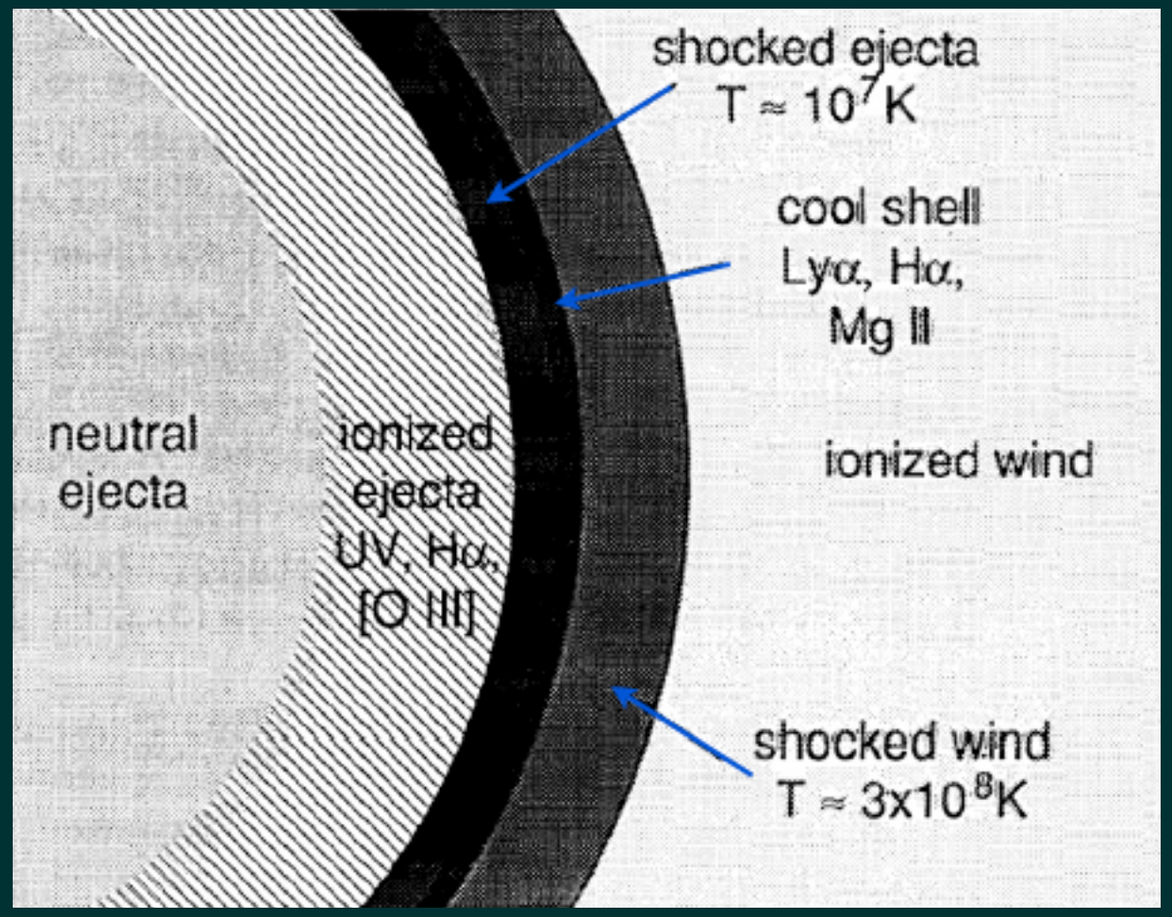
- **Interactive SNe**
    - **IIn**

- Superluminous Supernovae
    - II - I

- New CC transients

Interactive SNe IIn



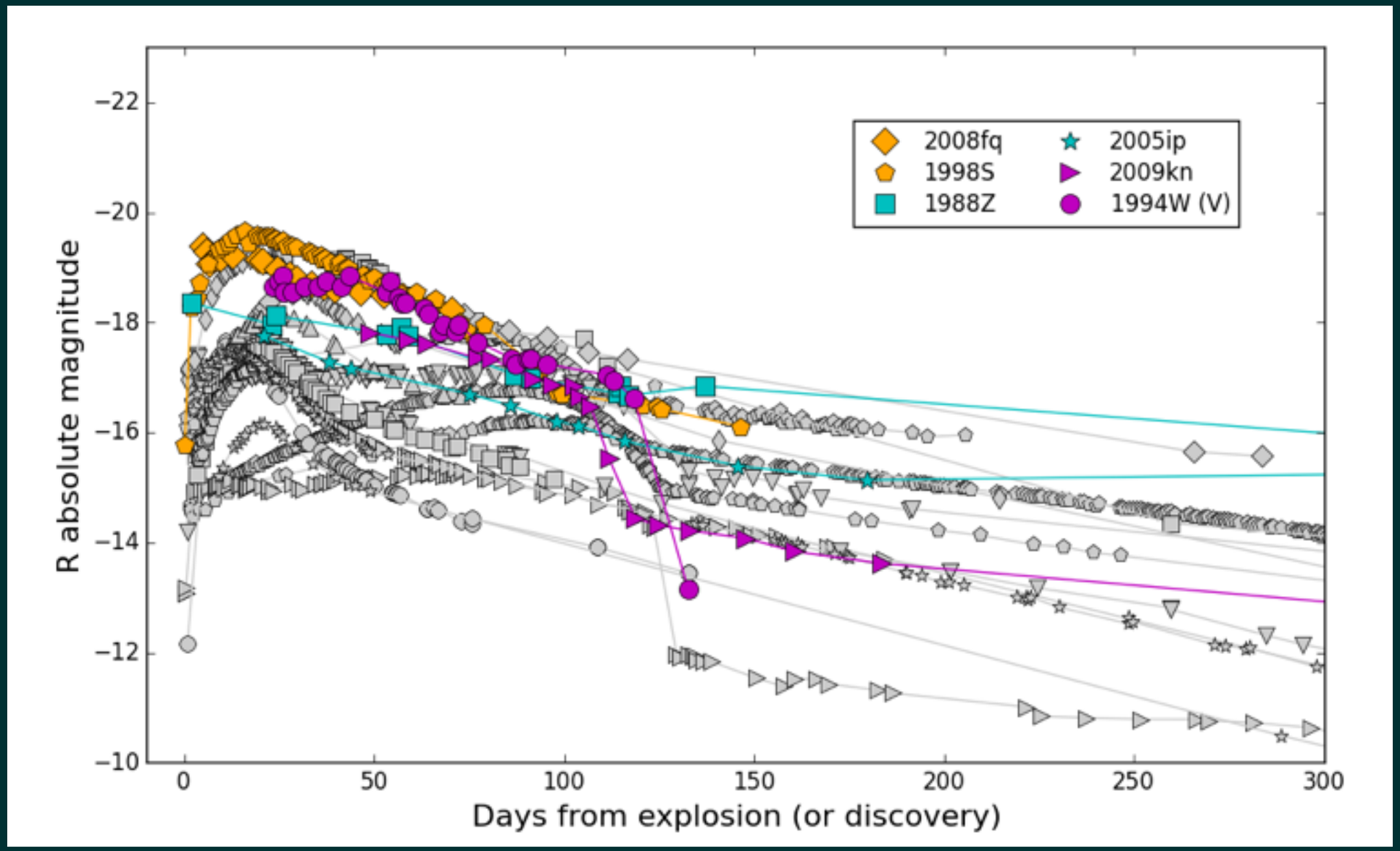


Chevalier & Fransson 1994

- 5% of all CC SNe
- Progenitors ~ LBV - RSG?
- Dense CSM
- Sample ~ 10 - 20 objects
- heterogeneous

Schlegel 1990, Chugai & Danziger 1994, Fransson et al. 2002, Gal-Yam et al 2006

Interactive SNe IIn



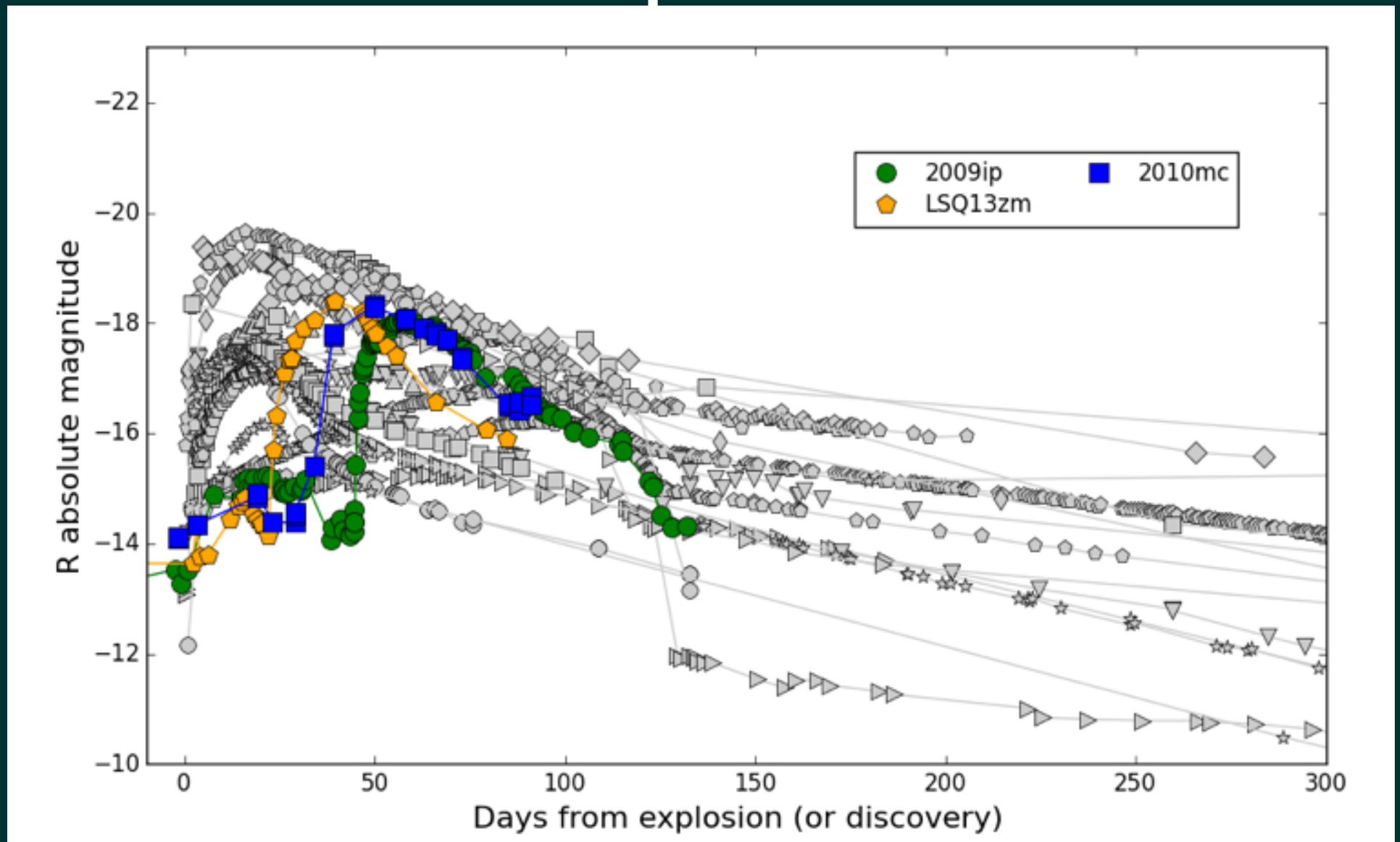
98S-like (IIn-L)

94W-like (IIn-P)

88Z-like (IIn)

Taddia et al 2013, Kankare et al 2013, Mauerhan et al. 2014

09ip-like



98S-like (IIn-L)

94W-like (IIn-P)

88Z-like (IIn)

09ip-like

Taddia et al 2013, Kankare et al 2013, Mauerhan et al. 2014,

Pastorello et al 2013 , Smith et al 2012, Fraser et al 2013, Foley et al 2011, Graham et al 2014, Mauerhan et al. 2013, Margutti et al 2014, Ofek et al 2013, Tartaglia et al 2016, Thöne et al 2016, ….

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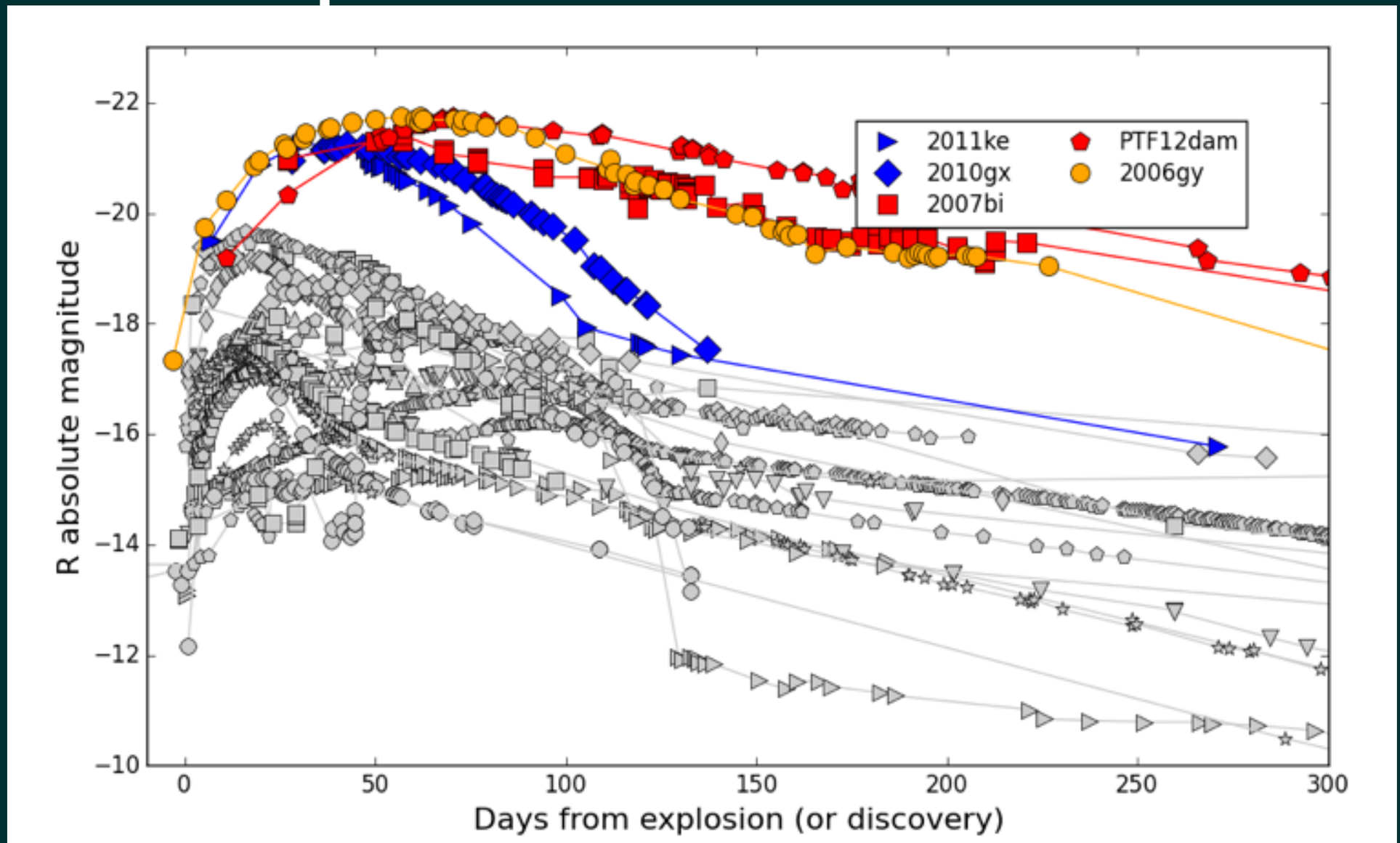
Super Luminous SNe



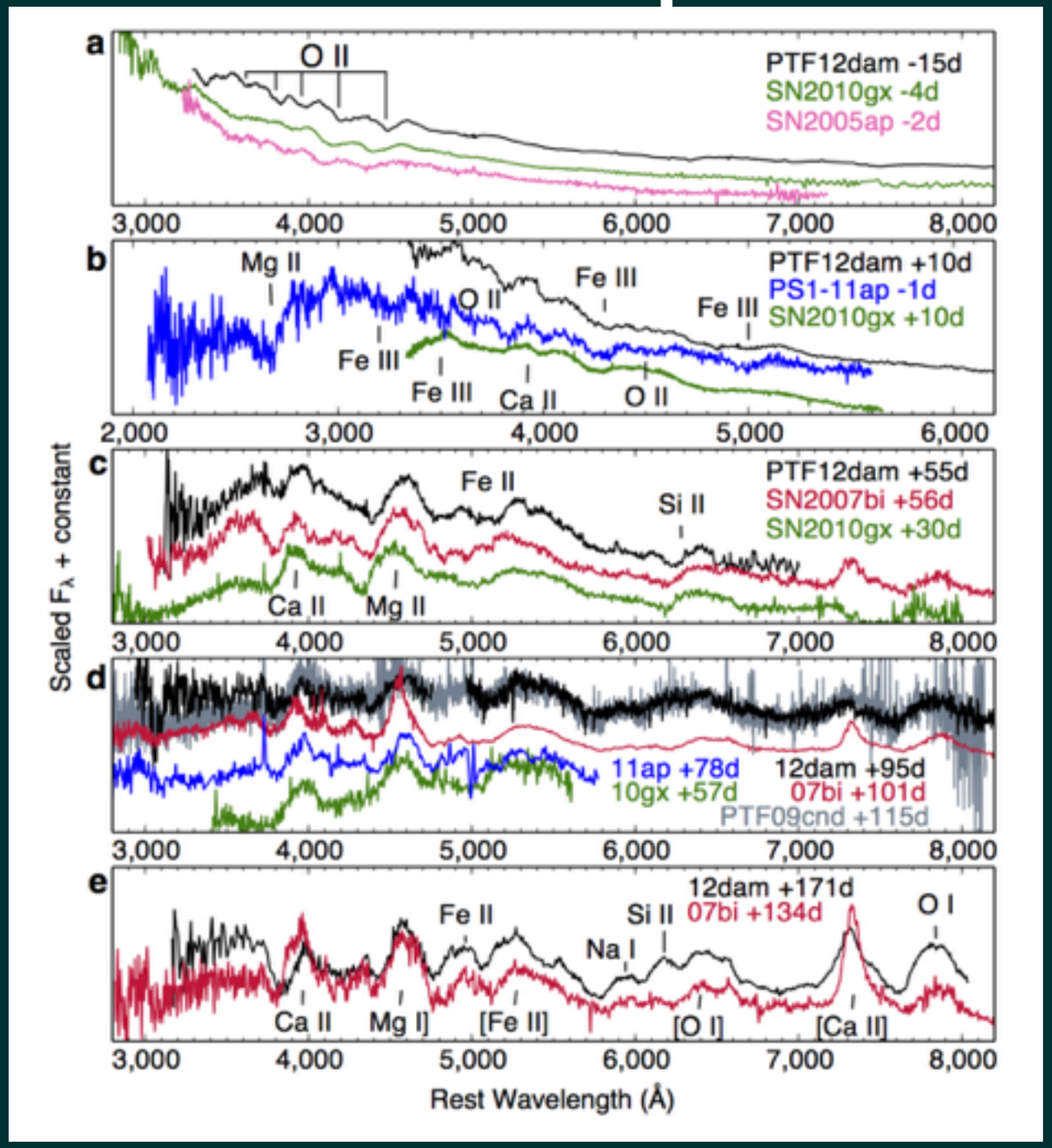
SLSN II

SLSN I

SLSN I-R

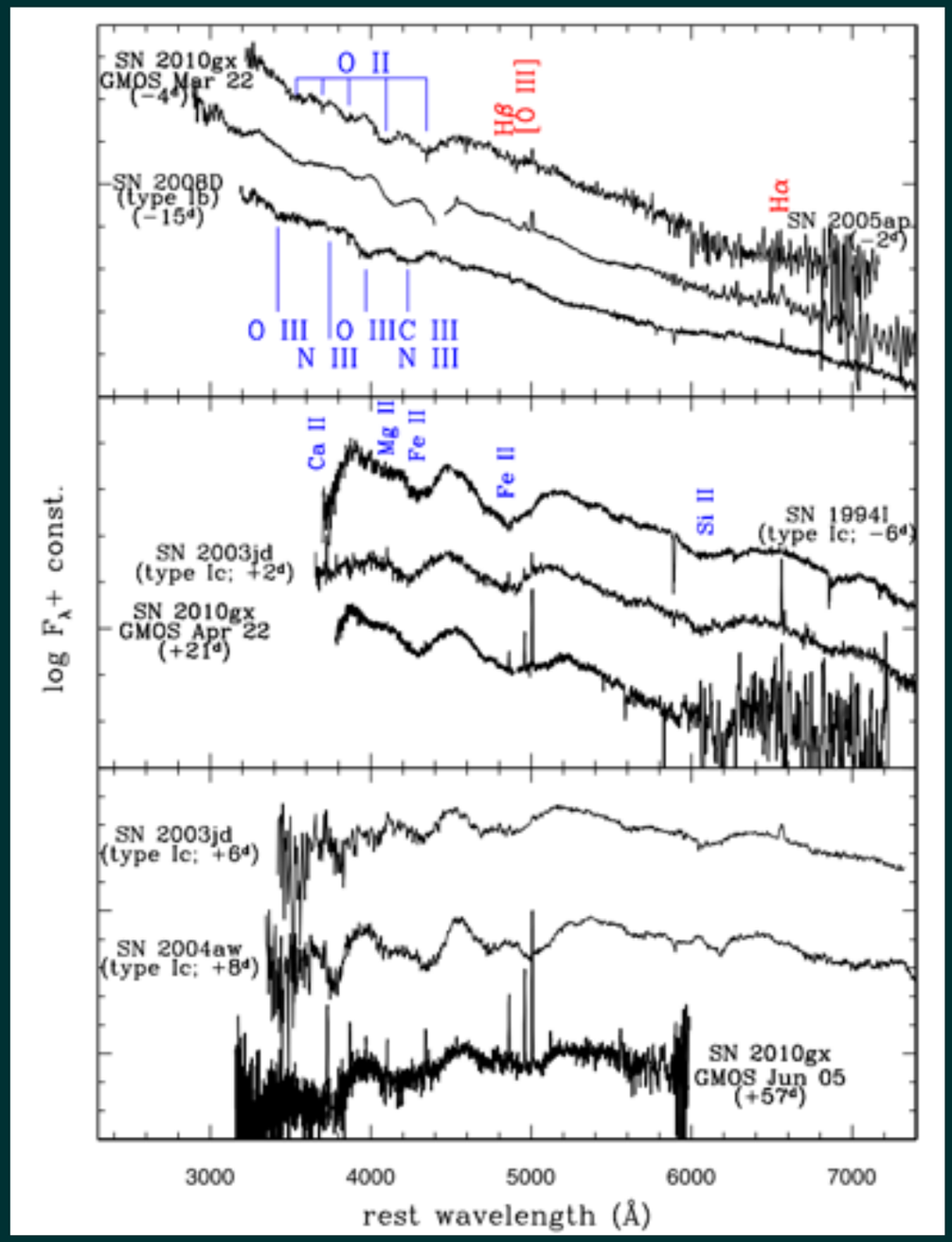
Smith et al 2007, Barbary et al 2008, Agnoletto et al 2009, Gal-Yam et al 2009, Young et al 2010, Pastorello et al 2010, Quimby et al 2011, Gal-Yam 2012, Benetti et al 2014, Inserra et al 2013,

Super Luminous SNe



SLSN II

Nicholl et al 2013



Pastorello et al 2010

SLSN I

SLSN I-R

→ **SLSN Ic**

Super Luminous SNe

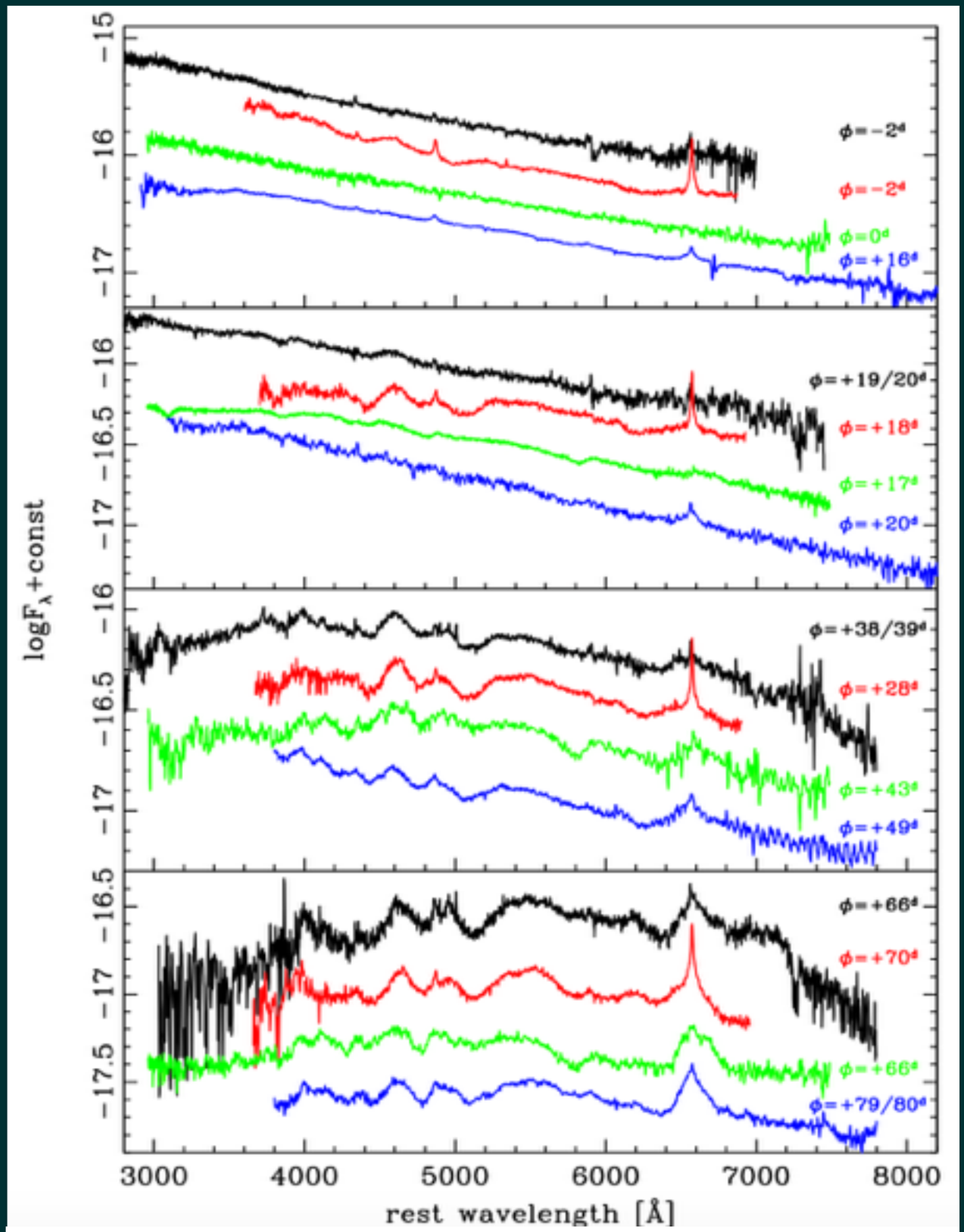
Smith et al 2007, Benetti et al 2014; Prieto et al. 2007; Aldering et al. 2006; Gezari et al. 2009; Miller et al. 2009, Agnoletto et al. 2010

- Blue spectra
- Ha visible
- Not strong sign of interaction
- If it is interaction, where are the intermediate cases

SLSN II

SLSN I

SLSN I-R → SLSN Ic



CSS151014 SN 2005gj

SN 2008es SN 2008fz

Super Luminous SNe

Magnetar model

Woosley 2010,
Kasen & Bildstein 2010,
Inserra et al. 2013,
Nicholl et al. 2013

SLSN II

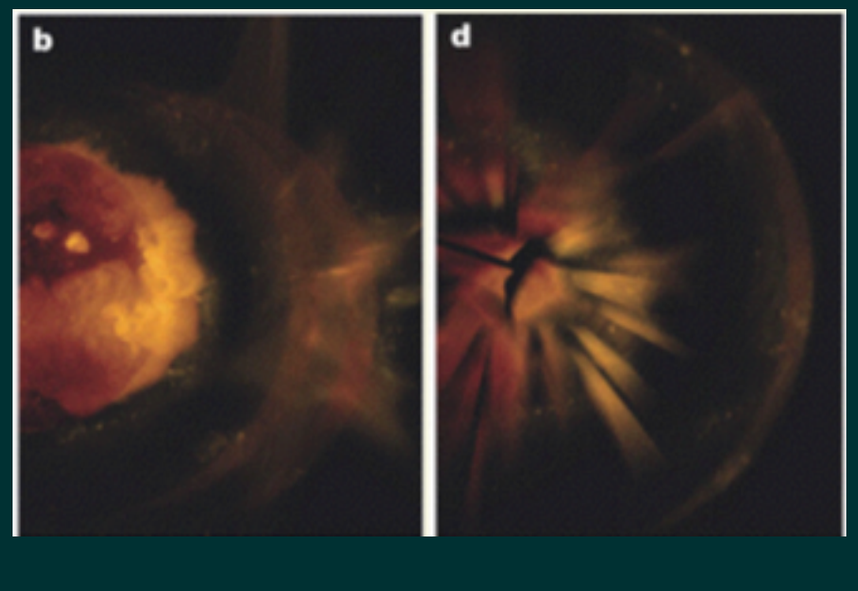
SLSN I

SLSN I-R

Pair Instability

Heger & Woosley 2002,
Gal-Yam et al. 2009

CSM-ej. interaction



Woosley 2007,
Chevalier & Irwin 2011,
Gizburg & Balberg 2012

SLSN Ic

Core Collapse Supernovae

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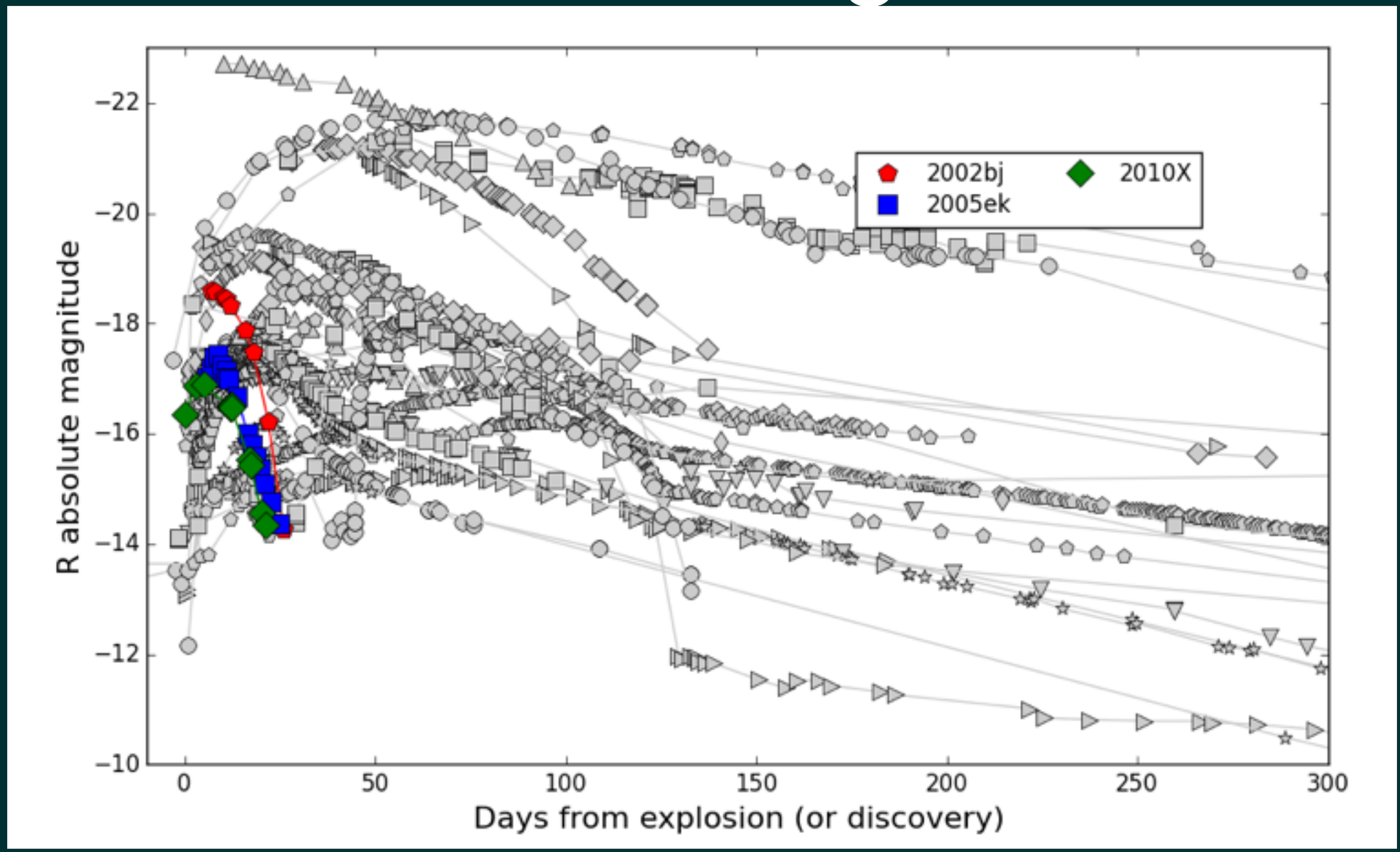
- **New CC transients**

Fast evolving SNe



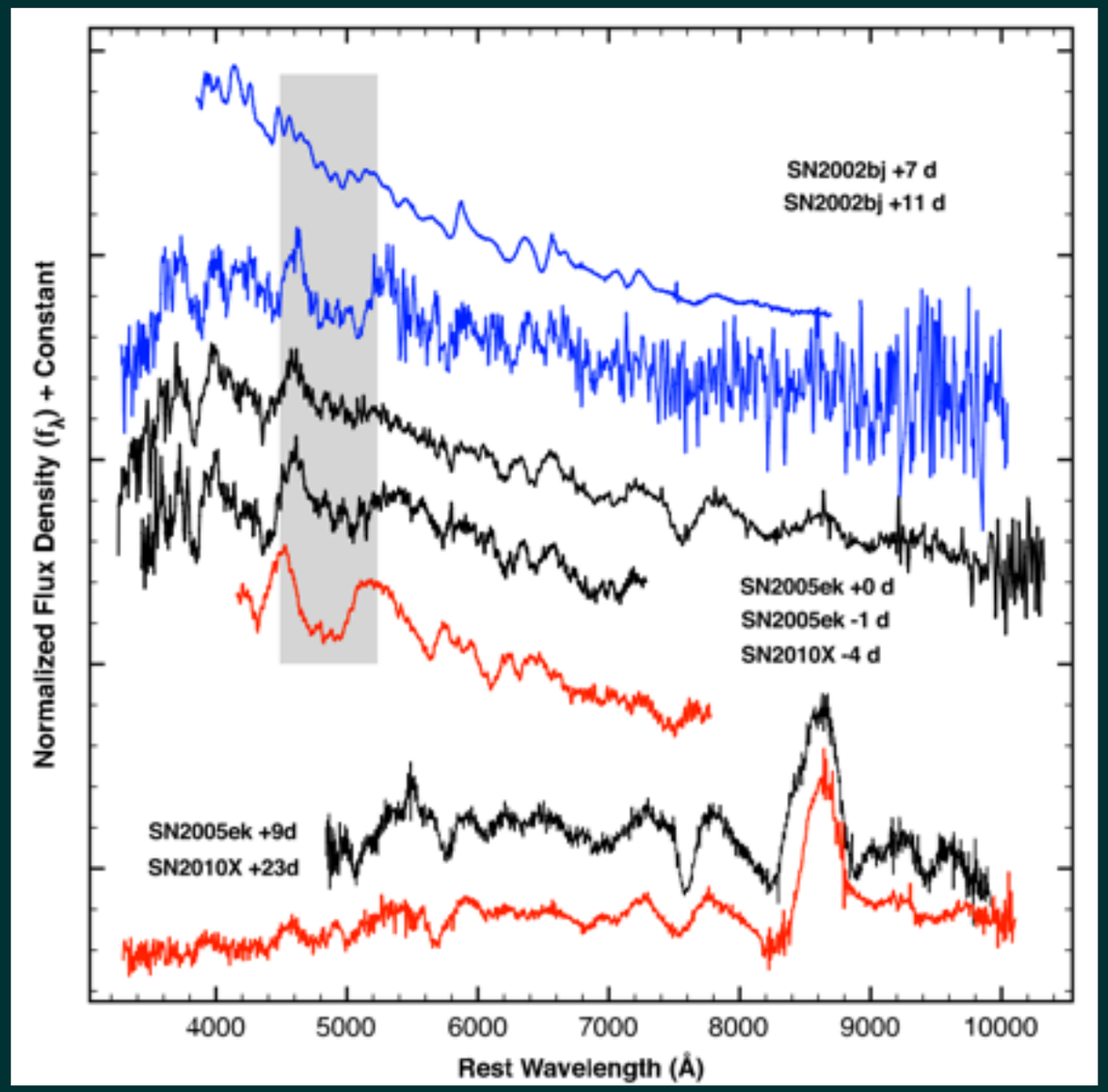
SN 2002bj Poznanski et al. 2010

SN 2010X Kasliwal et al 2010

SN 2005ek Drout et al 2013

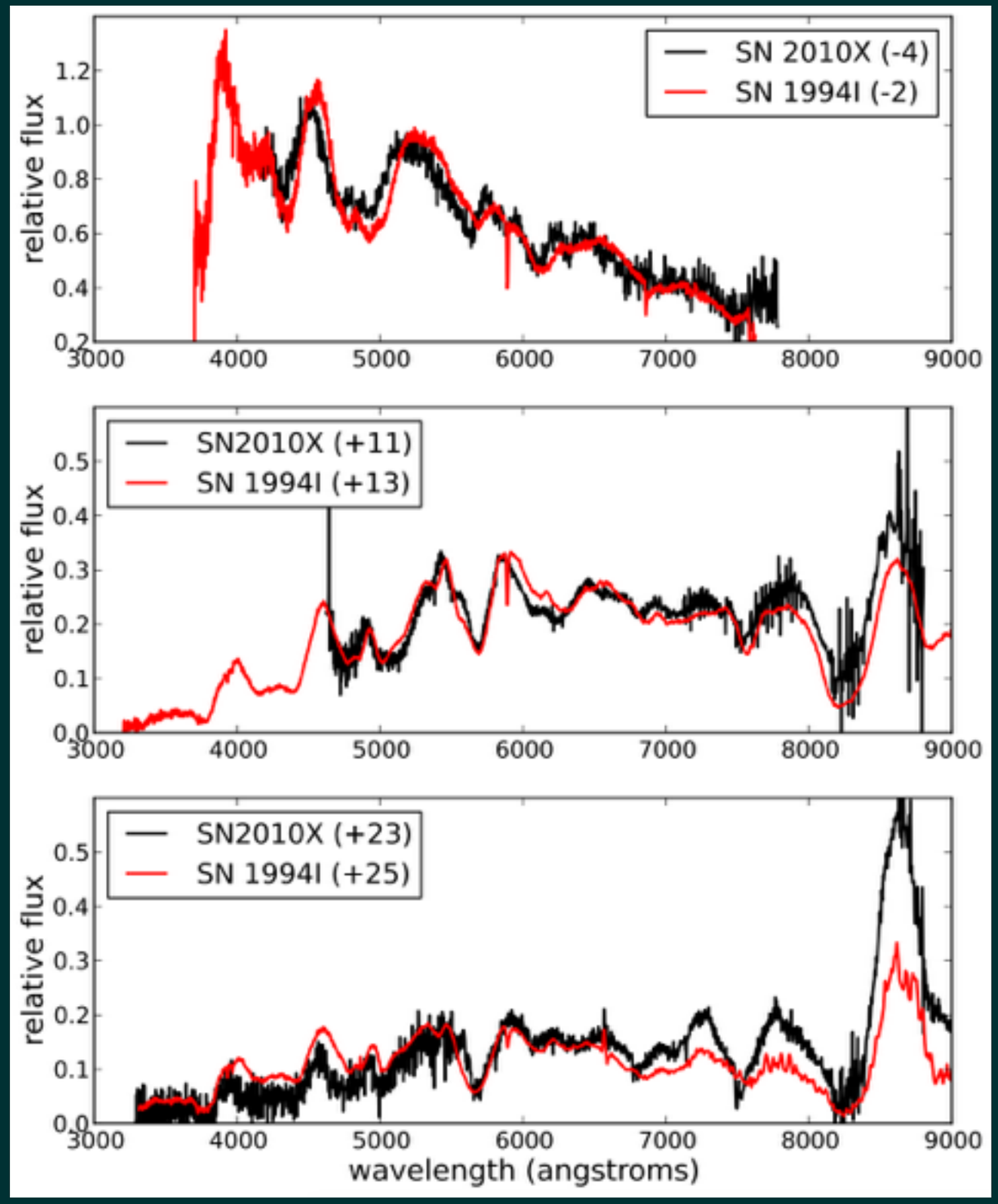
Exploded in late type galaxies

Fast evolving SNe



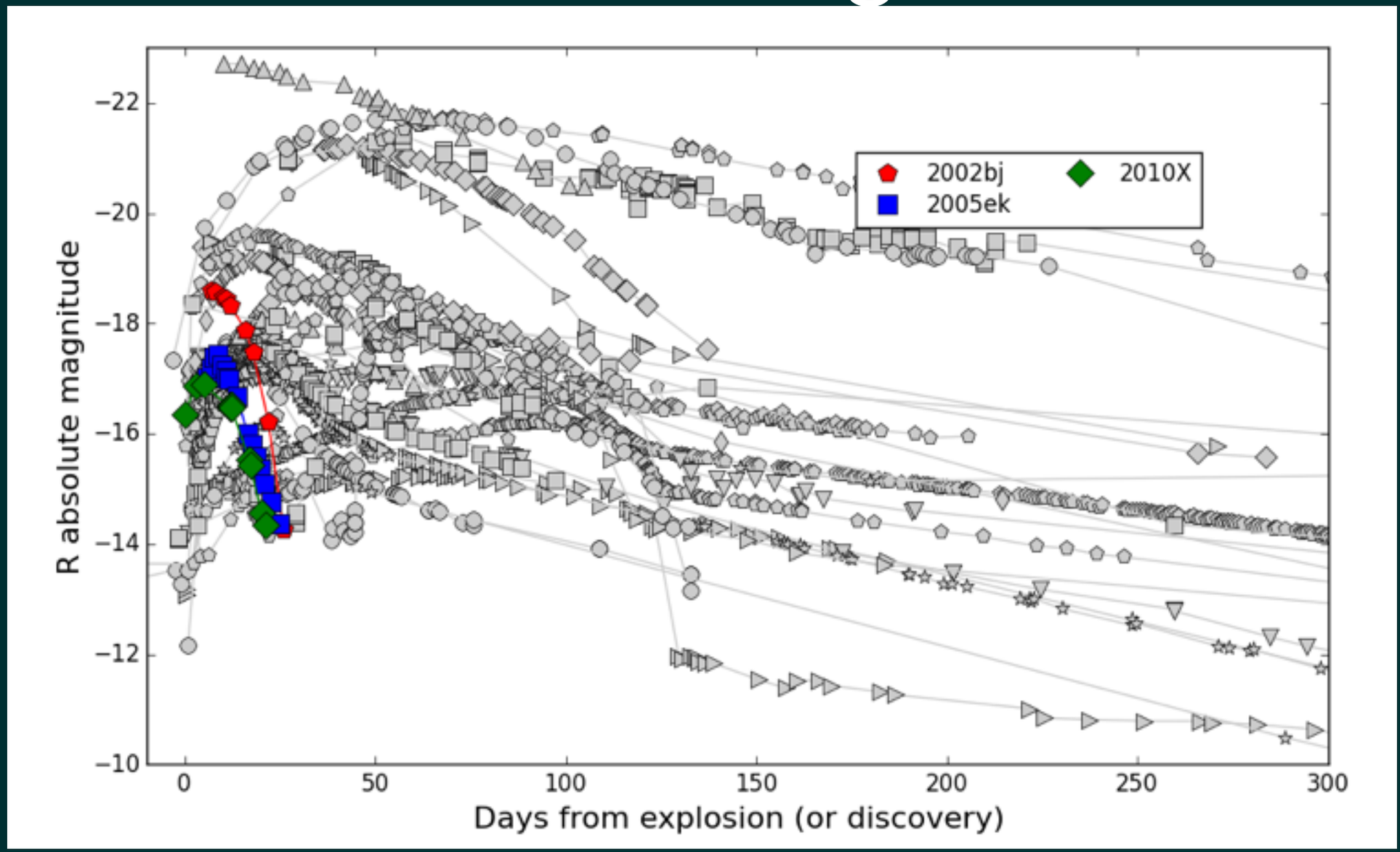
Drout et al 2013

2010X, 2005ek spectra similar to SNe Ic



Kleiser et al 2013

Fast evolving SNe

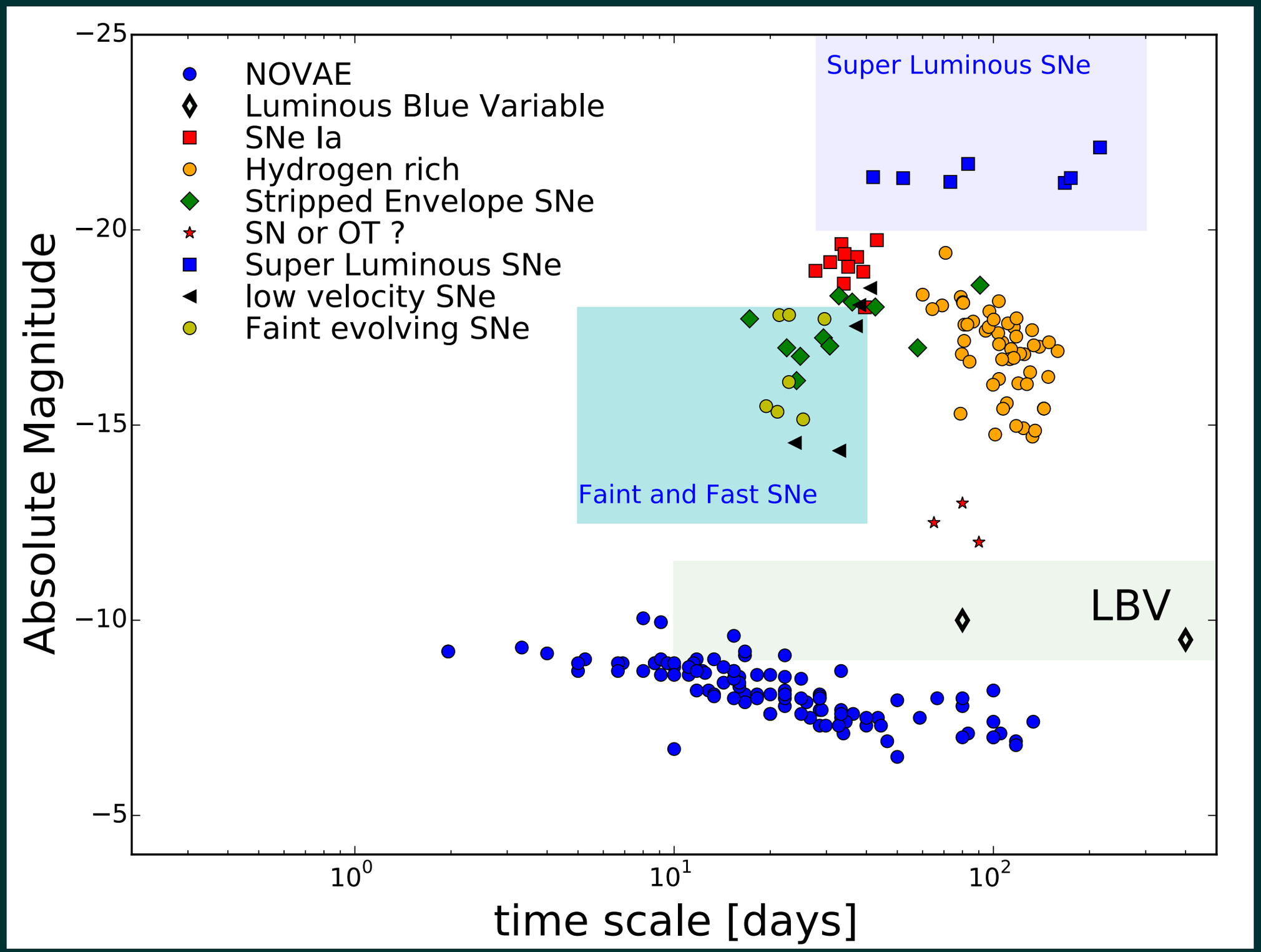


Massive stars low ejected mass 0.1-0.3 M_{ej} Drout et al 2013

Massive stars with no nickel ejected
LC powered by oxygen recombination (large radius)

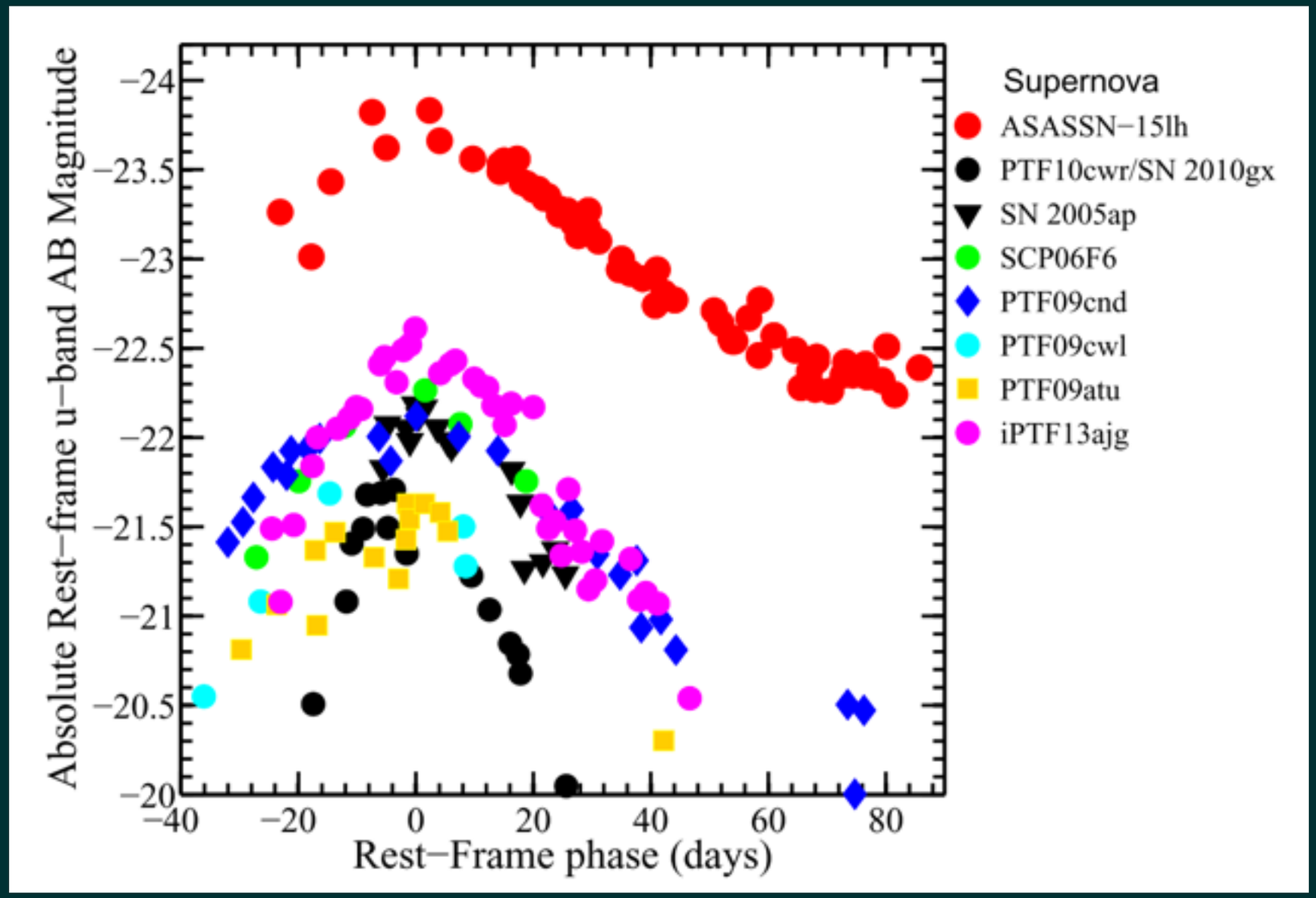
Kleiser et al 2013

Are there more ?



credits: Kulkarni

ASAS-SN15lh: SLSN or TDE?



A Highly Super-Luminous Supernova

Dong et al Science, 2015
Leloudas et Nature astronomy, 2016

Conclusions

- The sample of SNe Core Collapse with extended wavelength data is growing fast (**early phase, late phase, homogeneous set of data**)

- There is not a clear trend with SNe IIL being more massive than IIP

- Interaction seems to be important for a large fraction of SNe II

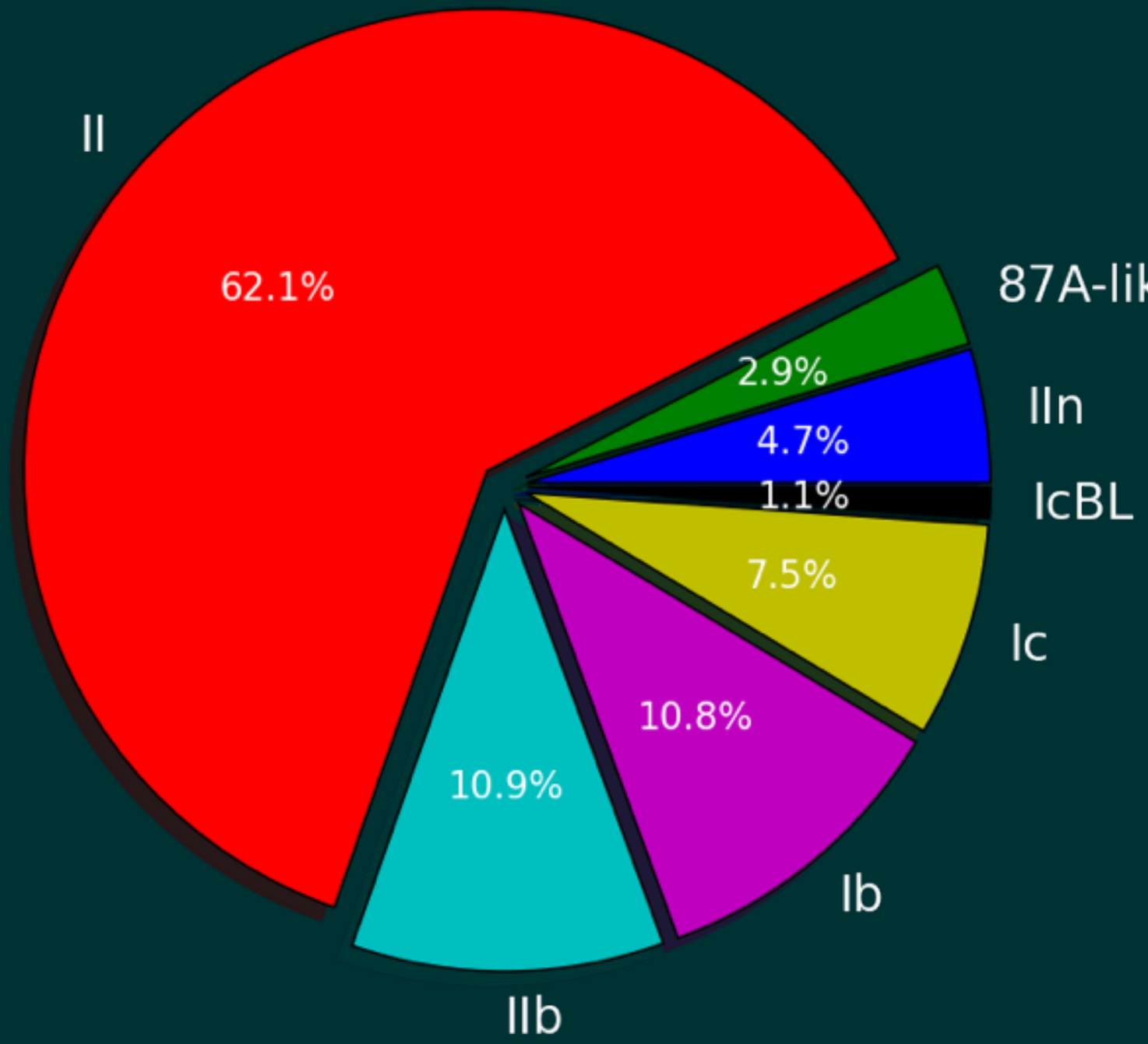
- A large fraction of SNe Ib/c are coming from stars > 8 $M_{\odot}$ in binary system

- The zoo of Core Collapse SNe is still not complete

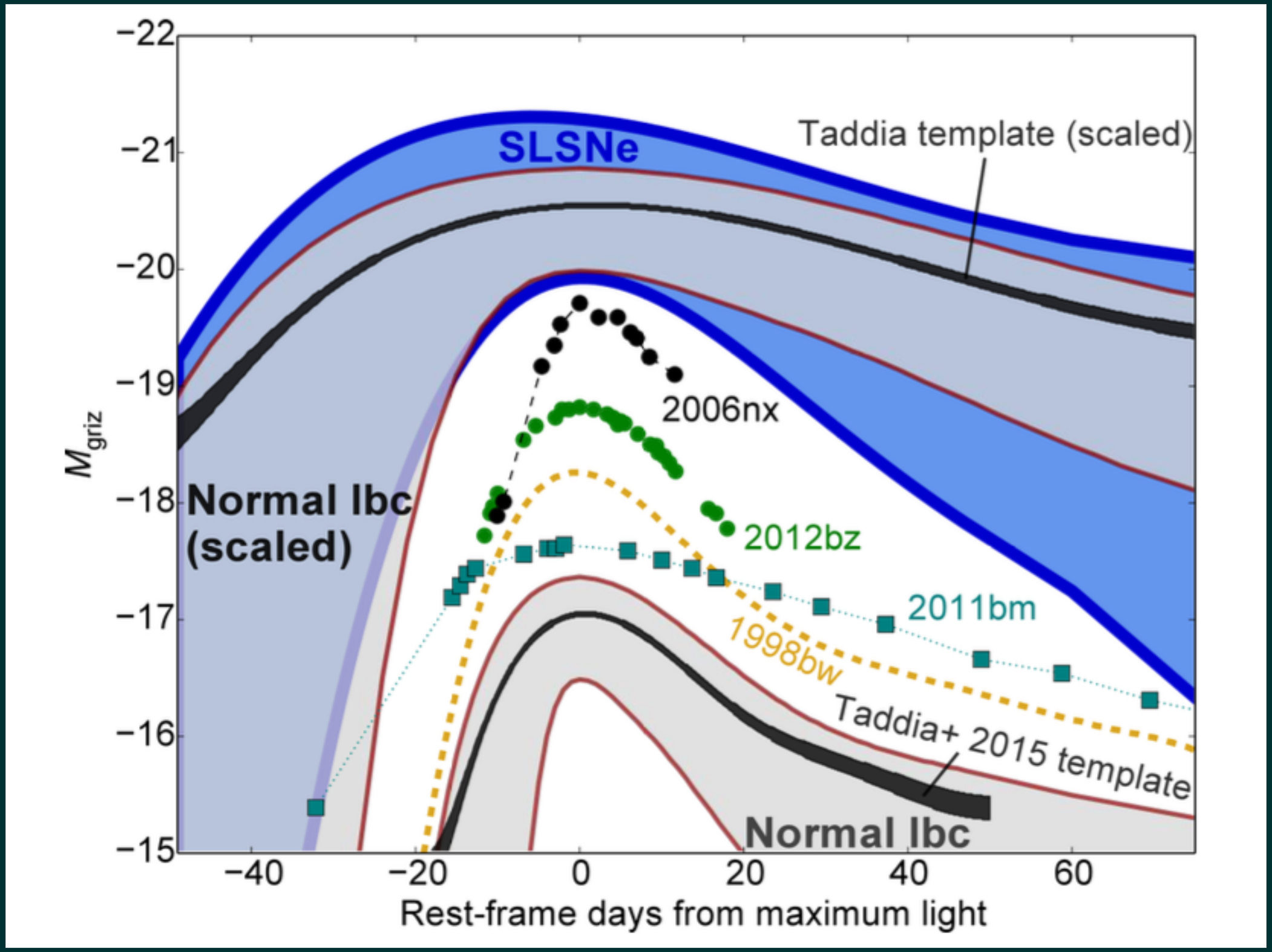
Thanks

extra slides

Core Collapse Supernovae



Shivvers et al 2016



Nicholl et al 2013

Geometry of the explosion