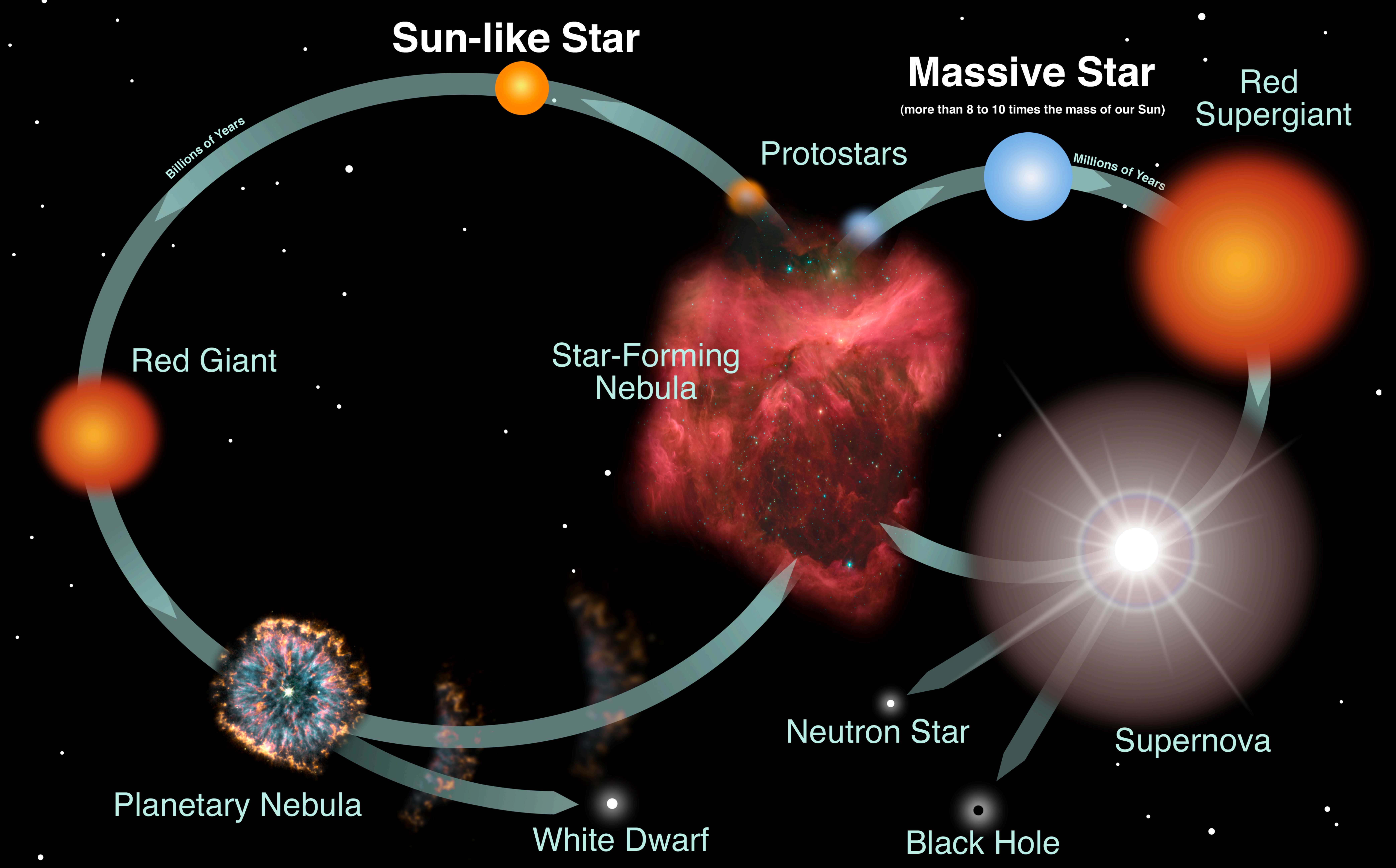
ERUPTIONS AND EXPLOSIONS OF MASSIVE STARS

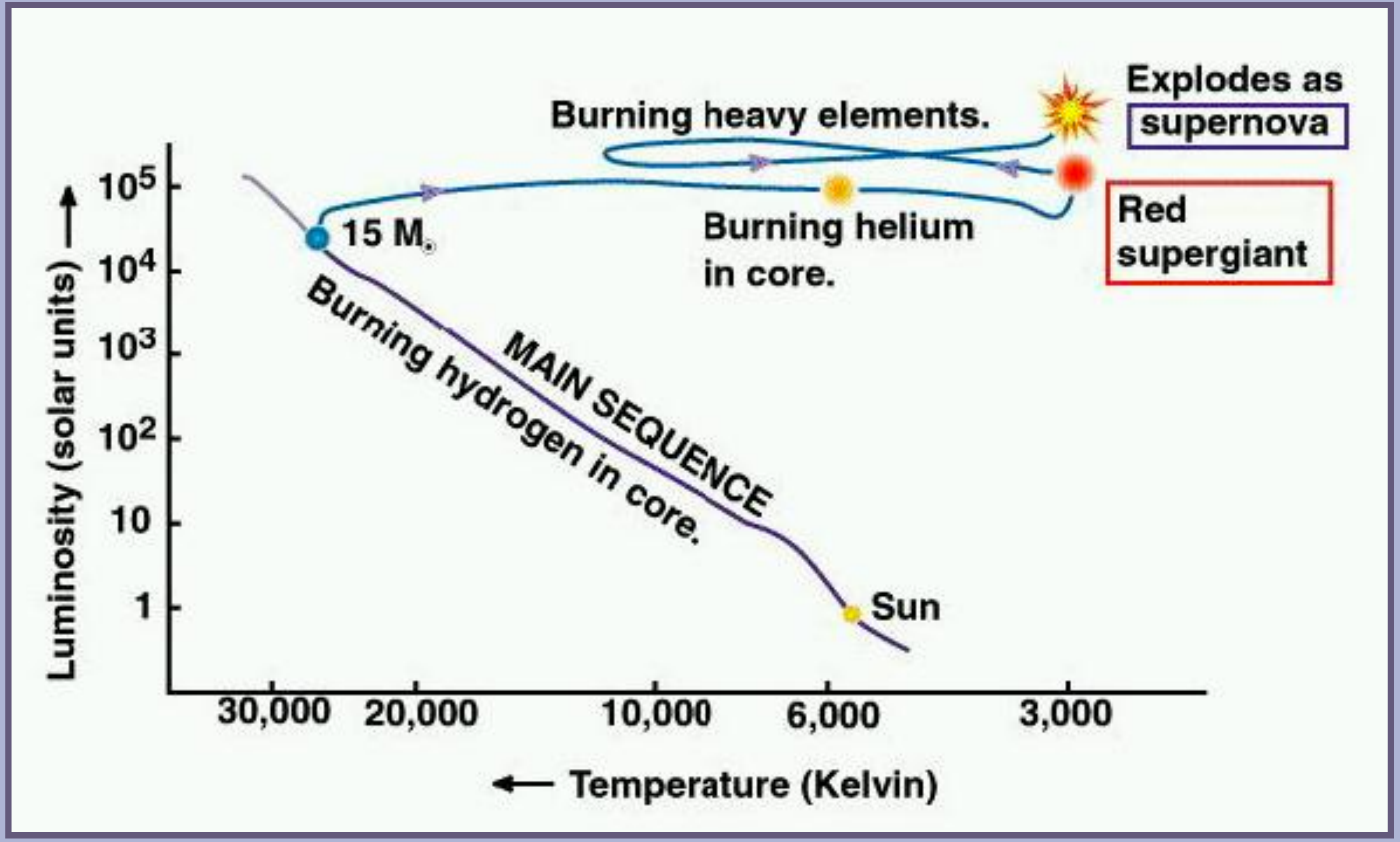
Jennifer Andrews
February 10, 2022

GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

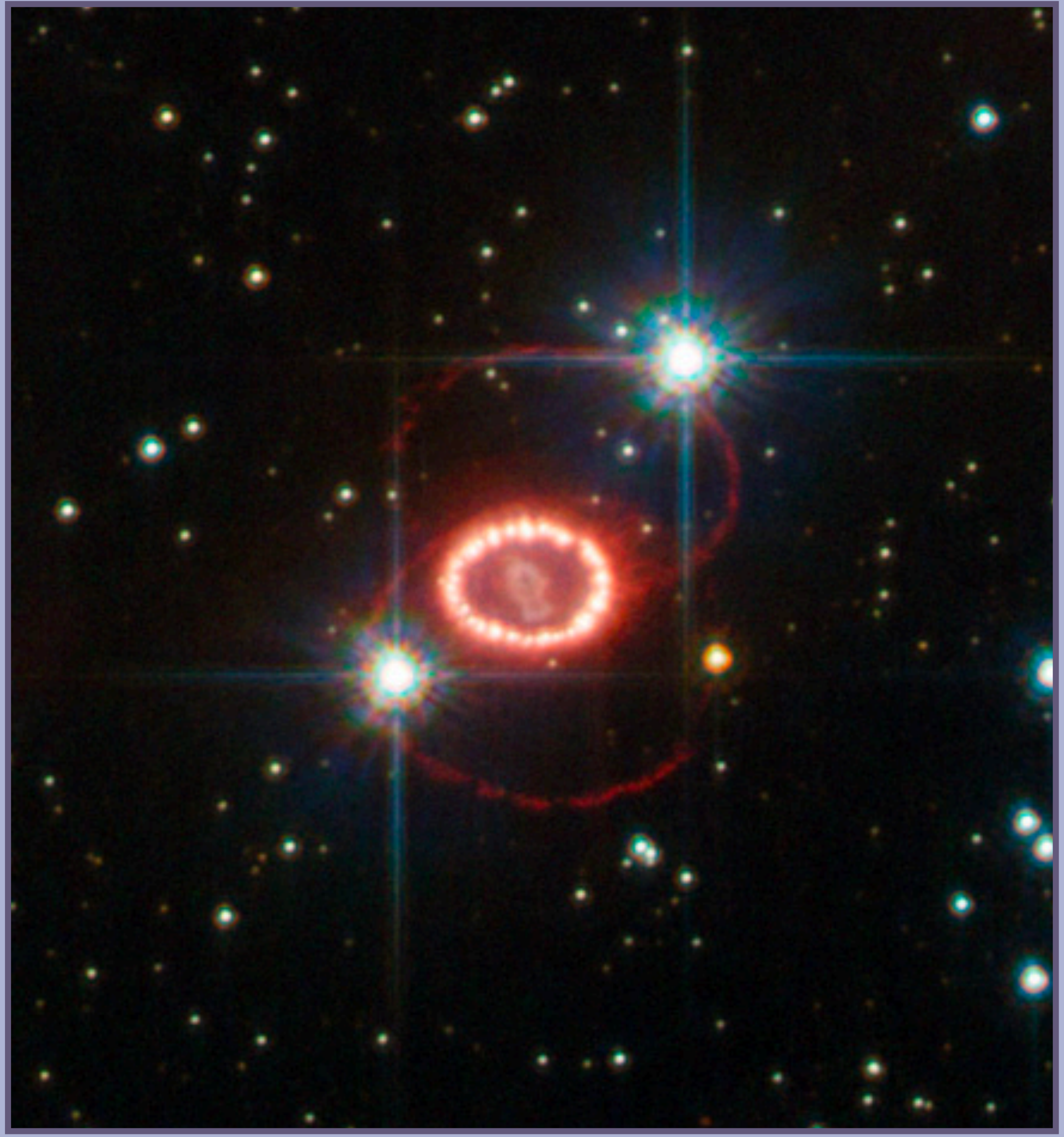

Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Billions of Years
Millions of Years
Red Giant
Star-Forming Nebula
Planetary Nebula
White Dwarf
Neutron Star
Black Hole
Supernova

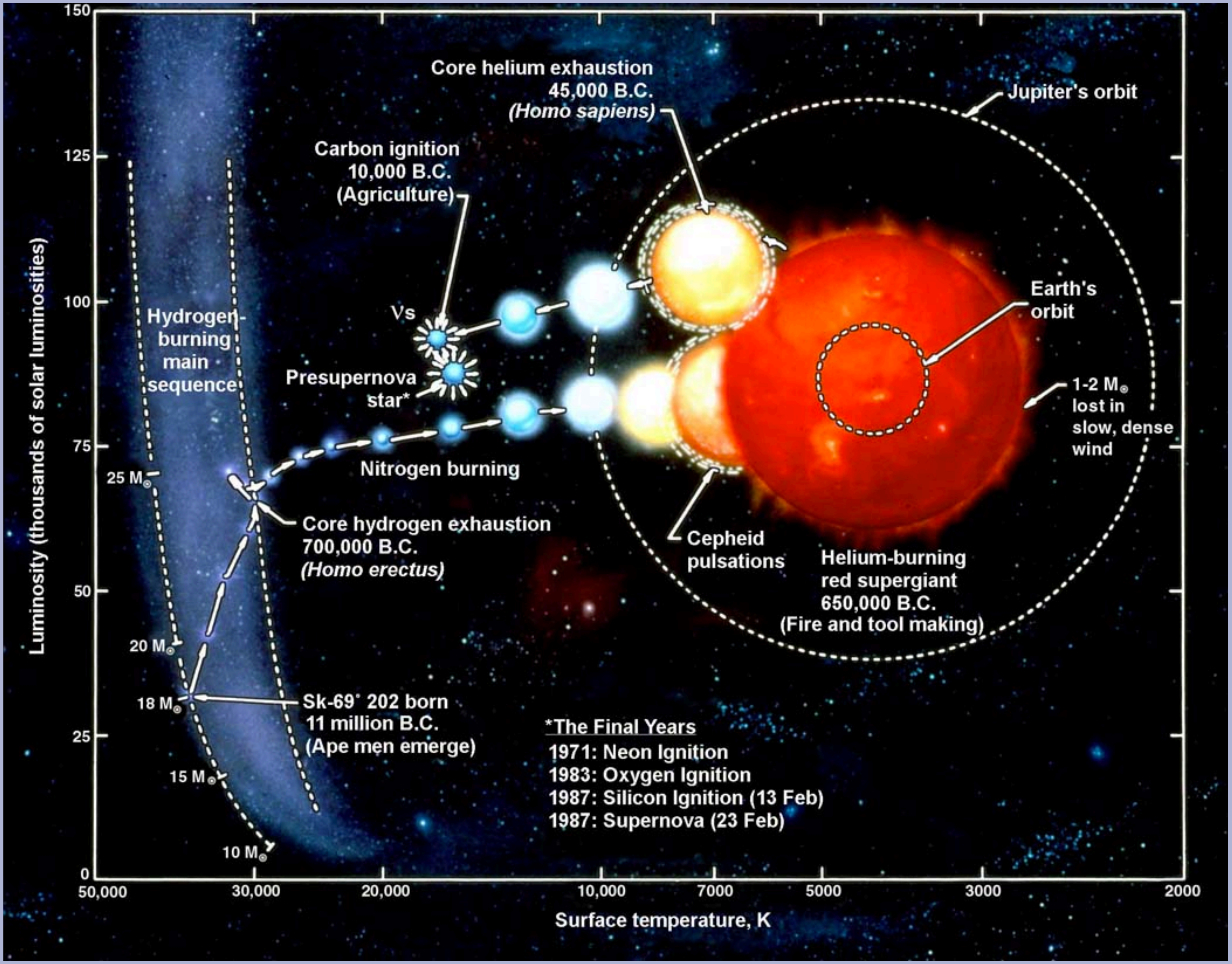
Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Millions of Years
Explodes as
supernova
Burning heavy elements.
Red
supergiant
Burning helium
in core.
15 M
Burning hydrogen in core.
MAIN SEQUENCE
Sun
Luminosity (solar units)
30,000
20,000
10,000
6,000
3,000
Temperature (Kelvin)
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole

SN 1987A



Explodes as
supernova
Burning heavy elements.
Red
supergiant
Burning helium
in core.
15 M☉
MAIN SEQUENCE
Burning hydrogen in core.
Sun
Luminosity (solar units)
10^5
10^4
10^3
10^2
10
1
30,000
20,000
10,000
6,000
3,000
← Temperature (Kelvin)

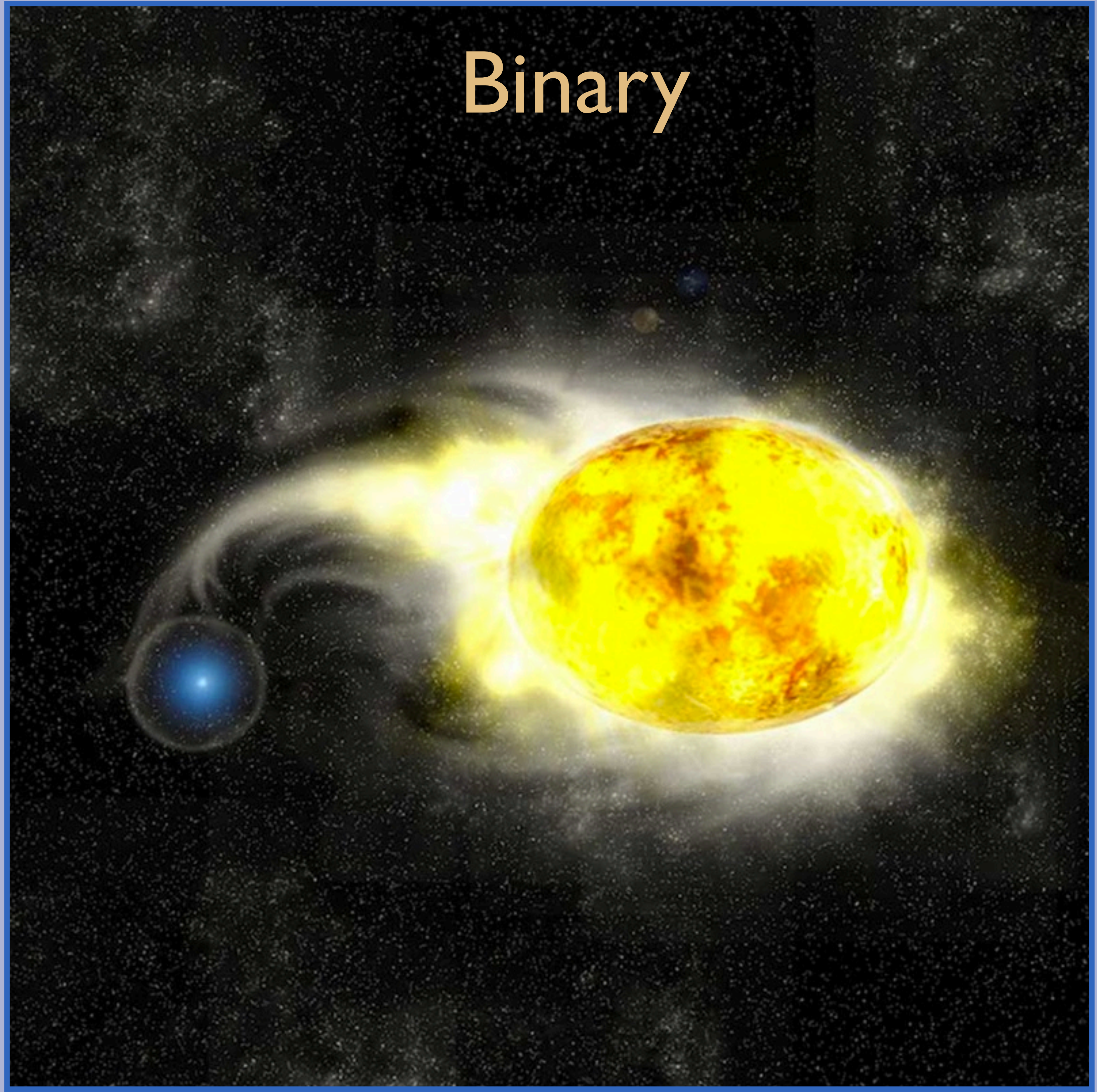




Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Earth's
orbit
Hydrogen-
burning
main
sequence
Vs
Presupernova
star*
1-2 M☉
lost in
slow, dense
wind
Nitrogen burning
25 M☉
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid
pulsations
Helium-burning
red supergiant
650,000 B.C.
(Fire and tool making)
20 M☉
18 M☉
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
15 M☉
10 M☉
Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Surface temperature, K

MASS LOSS IN MASSIVE STARS

- Unlike their less massive counterparts, massive star (20 $M_\odot$ and greater) evolution during and post main sequence is strongly influenced by mass loss.



- RLOF
- Mergers
- Common Envelope

- Stellar Winds
- Eruptions

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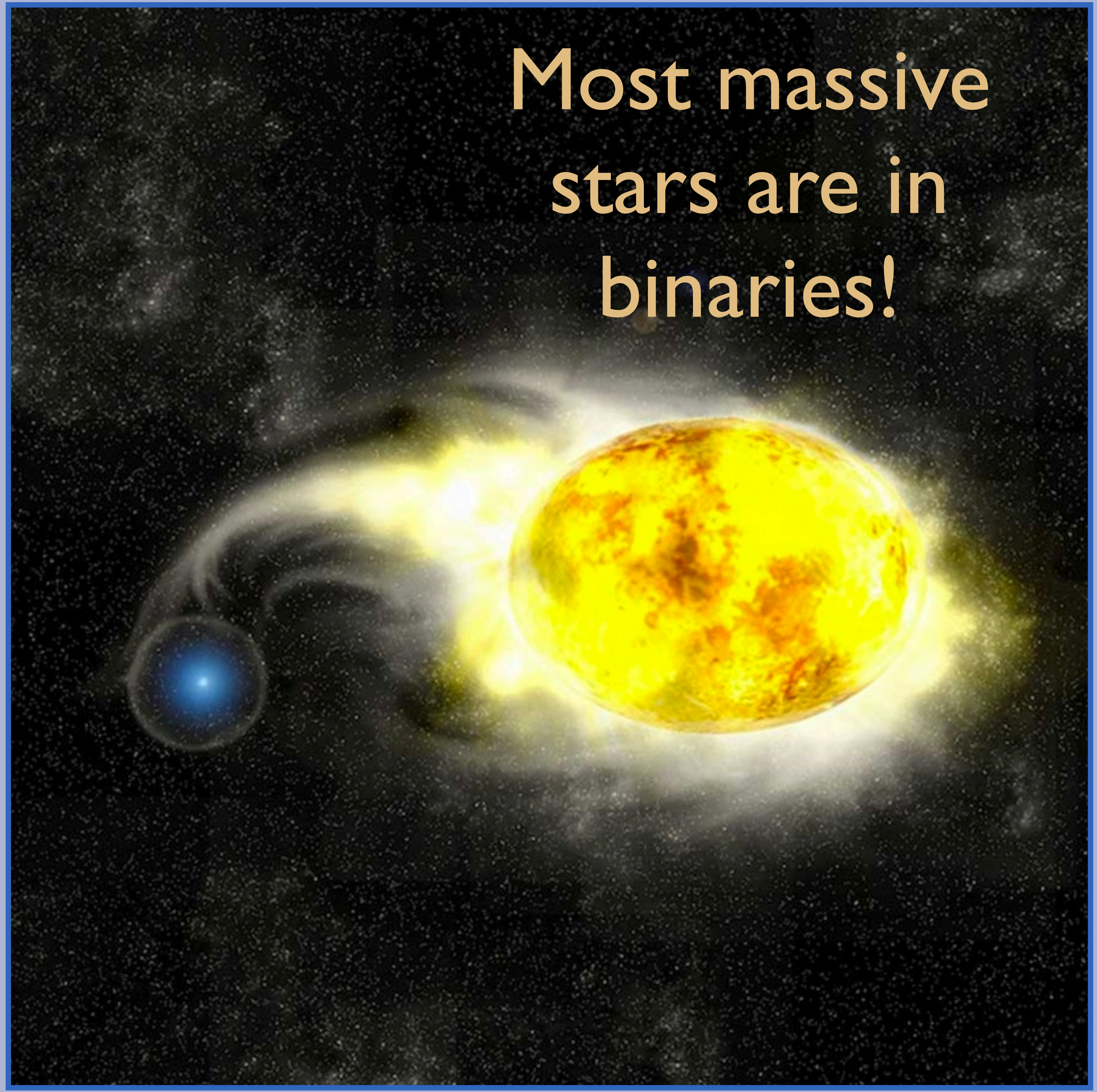


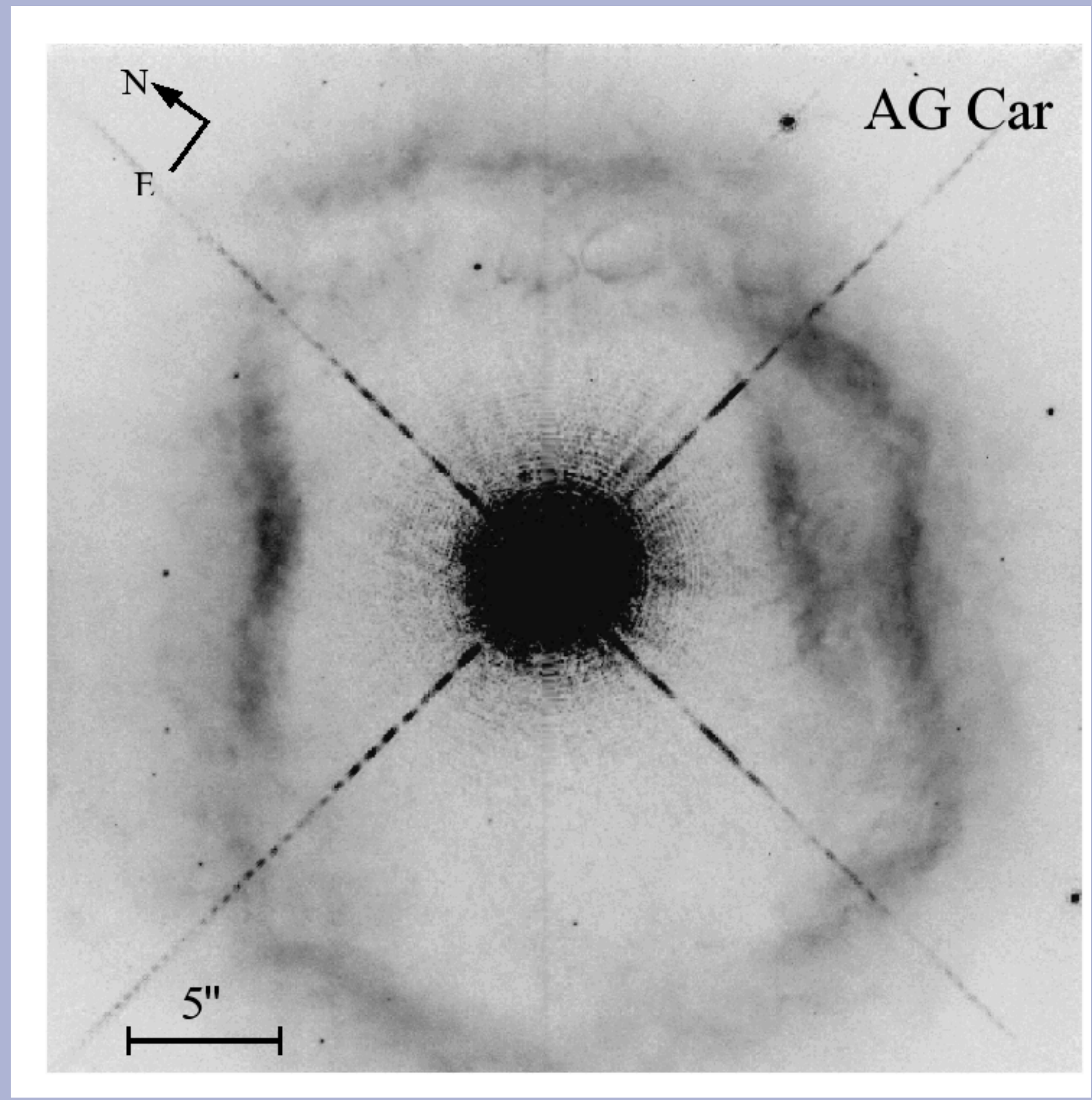
- RLOF
- Mergers
- Common Envelope

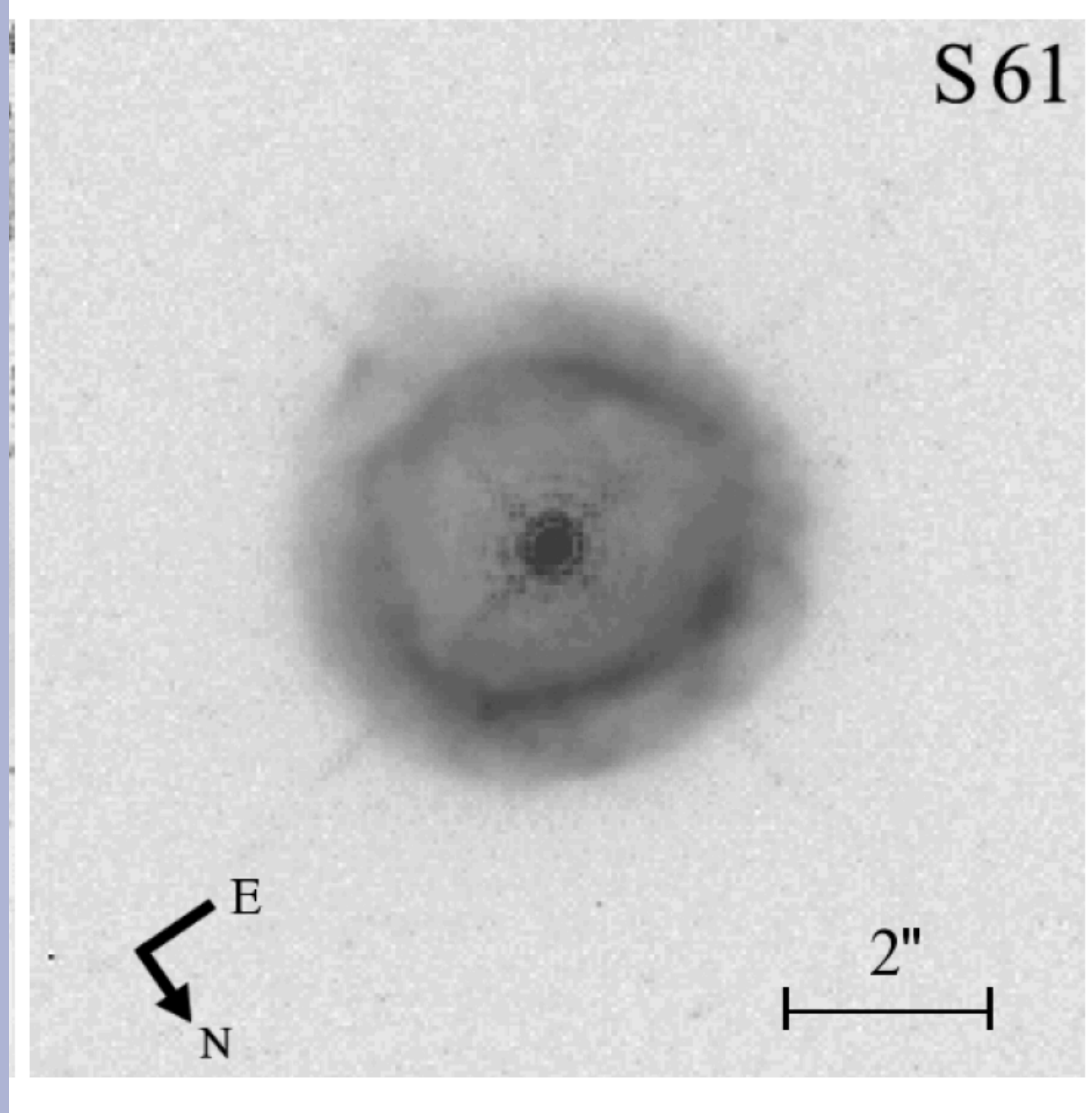
- Stellar Winds
- Eruptions

- Estimates are 25% of massive stars will merge and 33% will lose their H envelope (Sana et al. 2012)

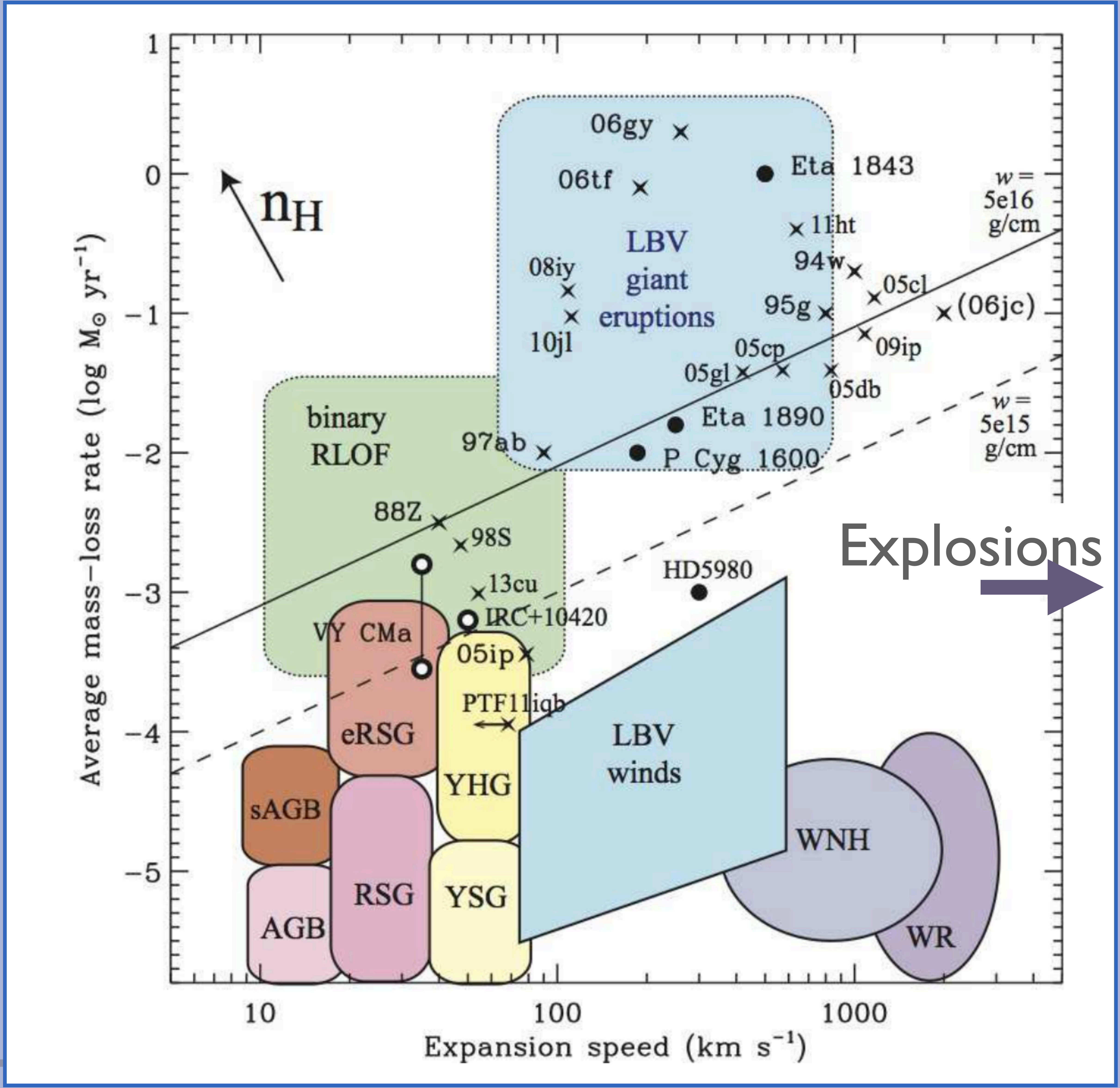
Eruptive variability or massive stellar mergers can form dense outflows of dust, obscuring the star in the optical

SINGLE STAR MASS LOSS

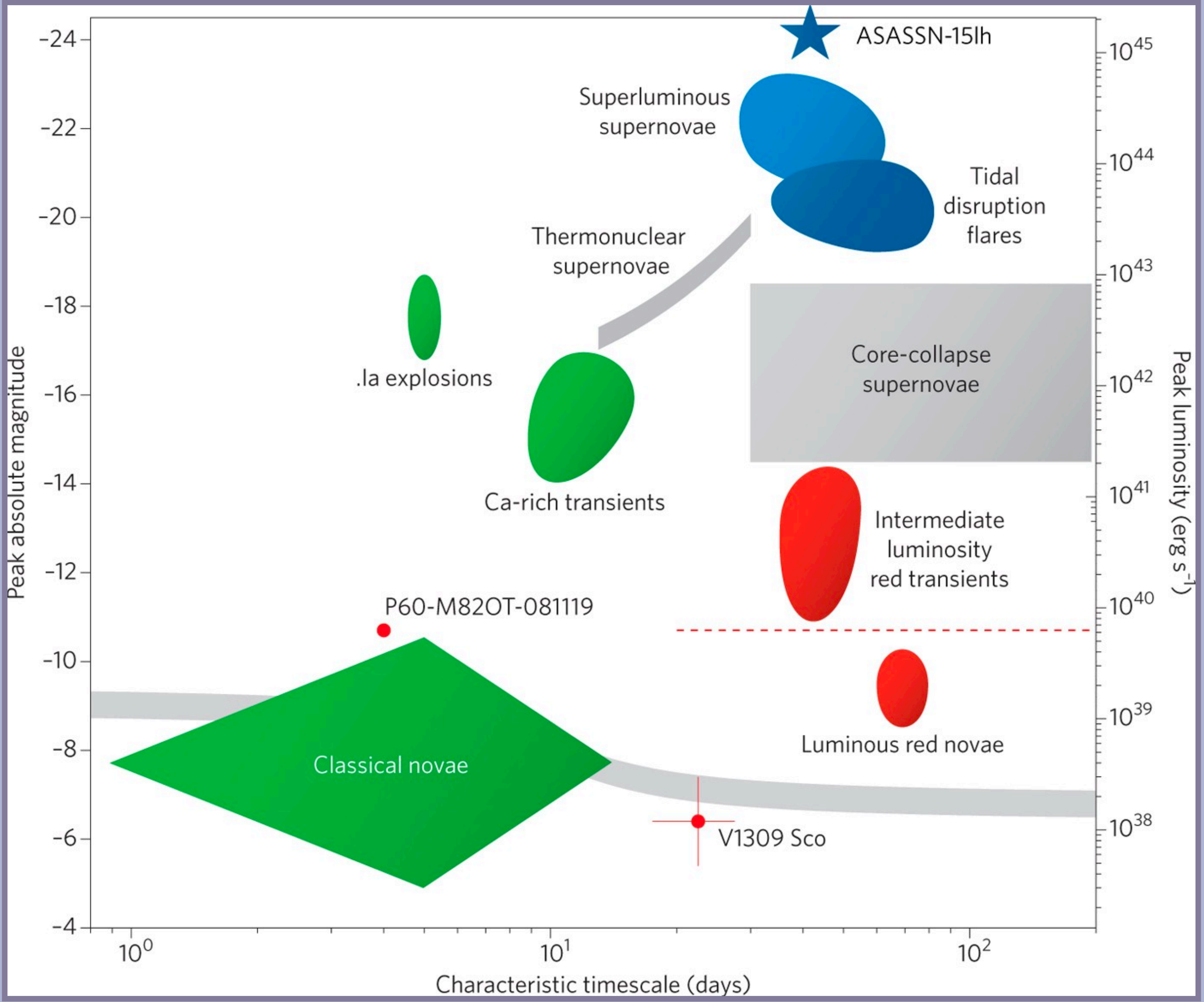




- Notice that LBVs have both a quiescent wind phase (low MLR) and giant eruptive phases (high MLR).



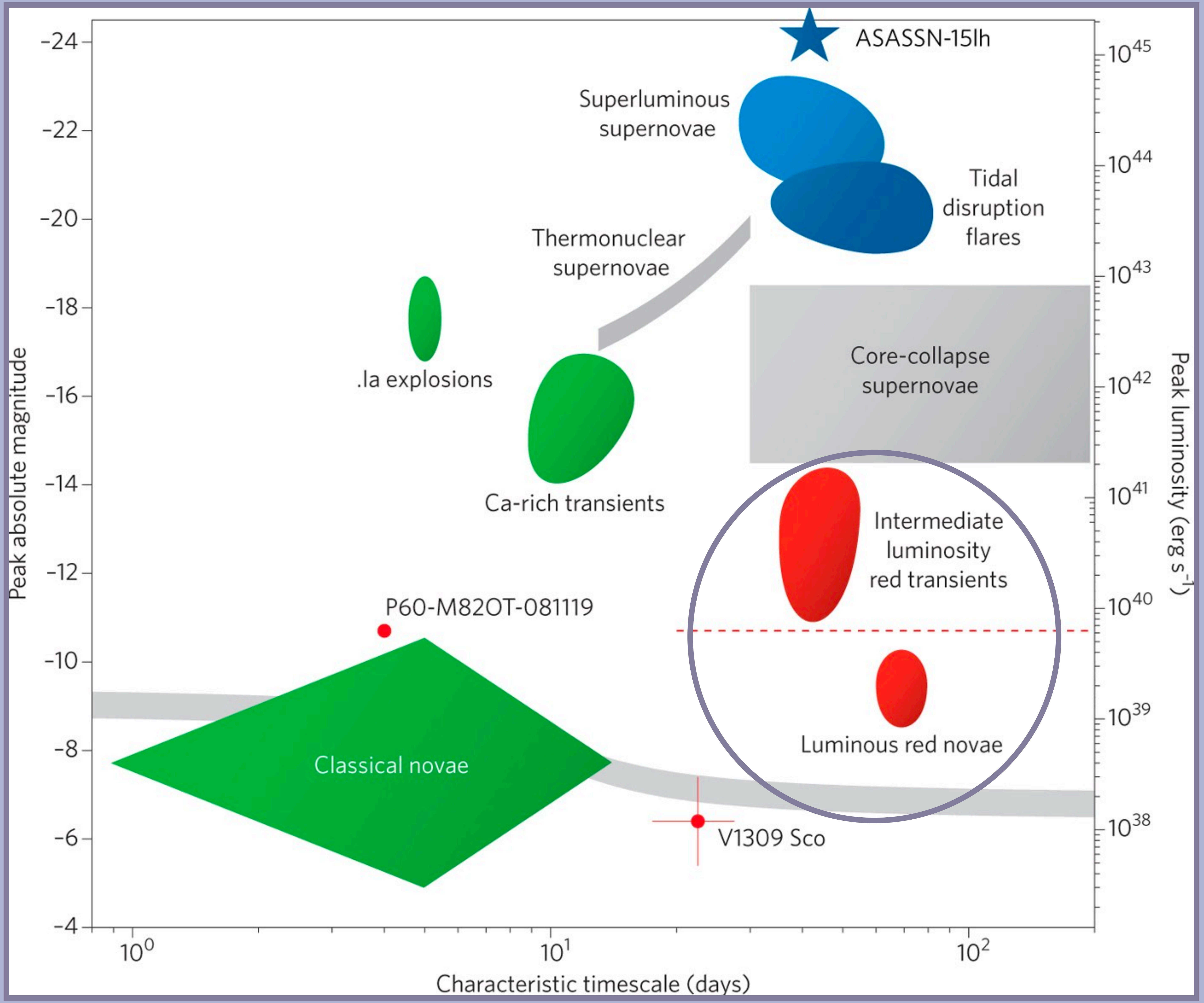
Explosions



Cenko 2017

GAP TRANSIENTS

- Dedicated transient searches have revealed a rich sample of objects less luminous than SNe, many associated with massive star evolution.



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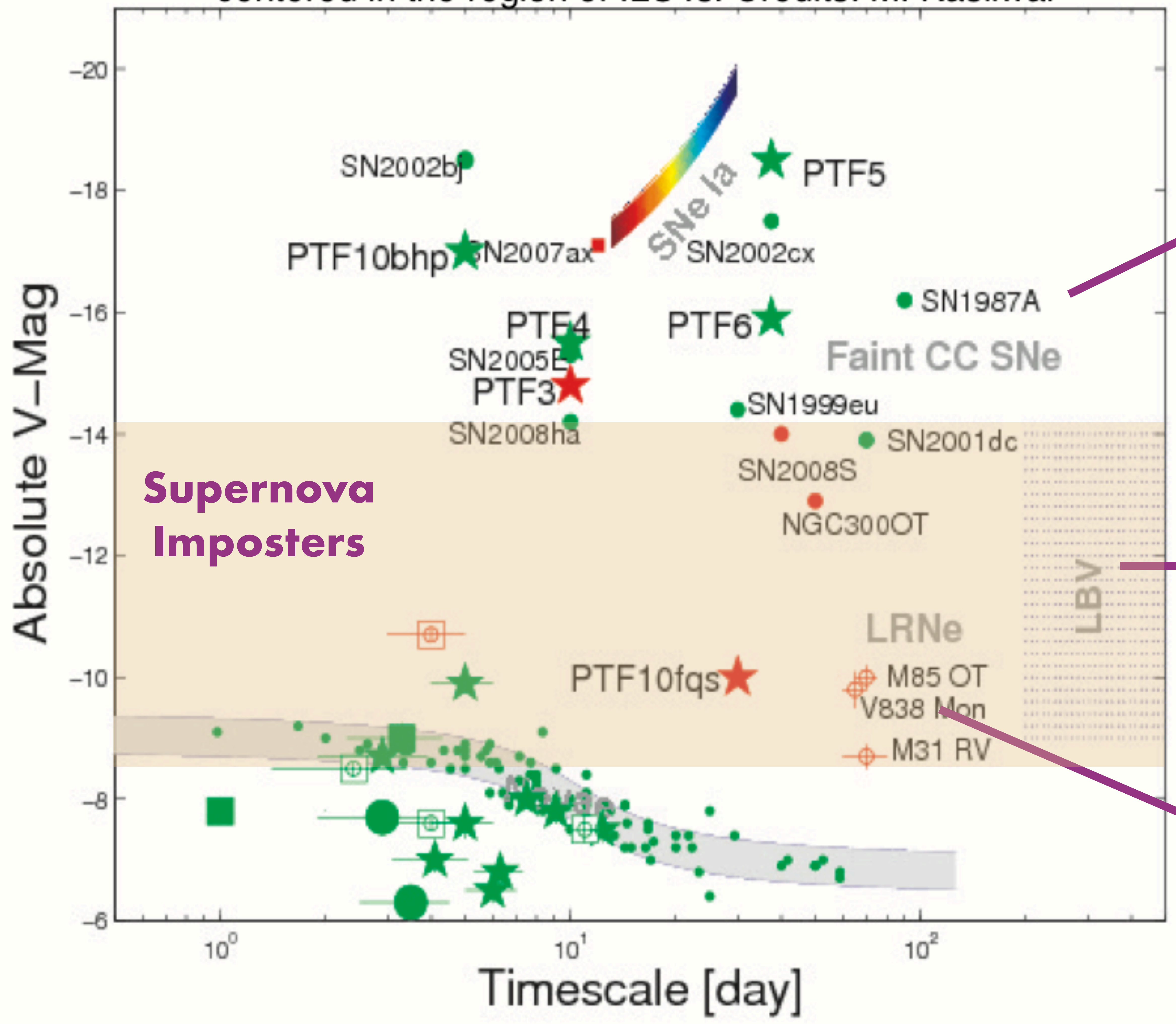
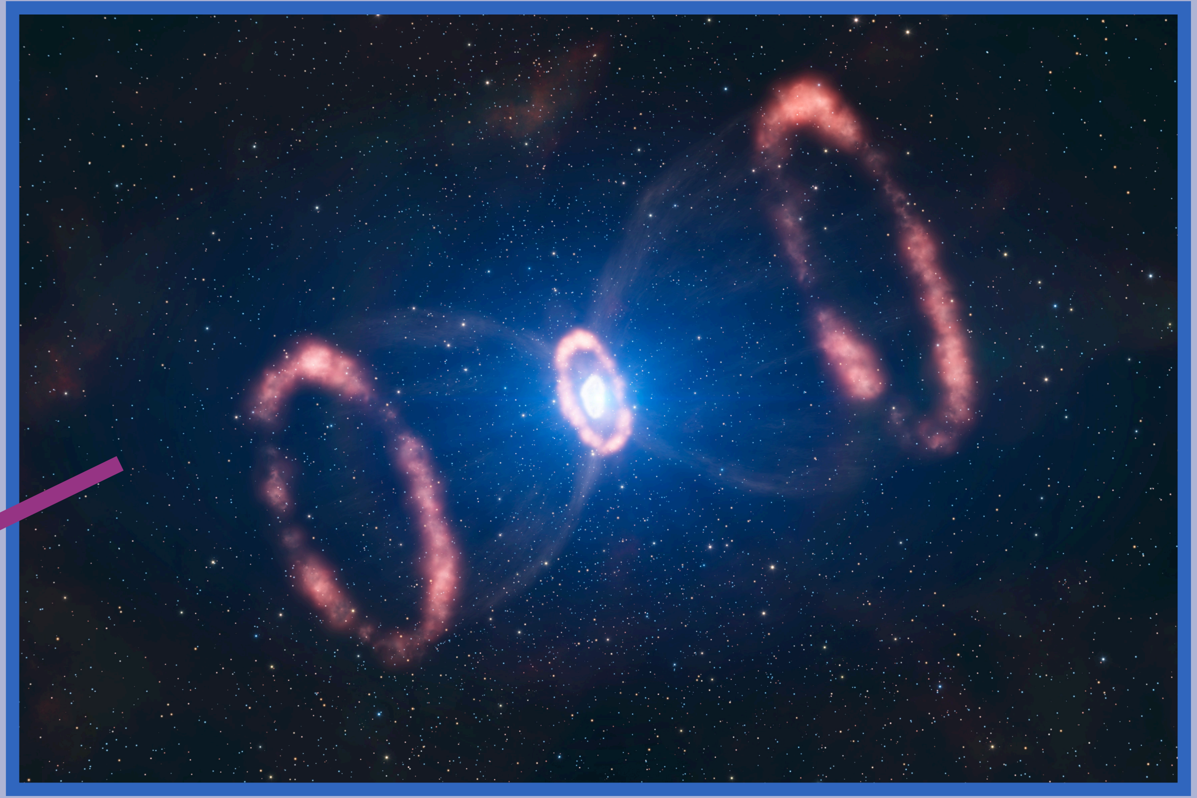
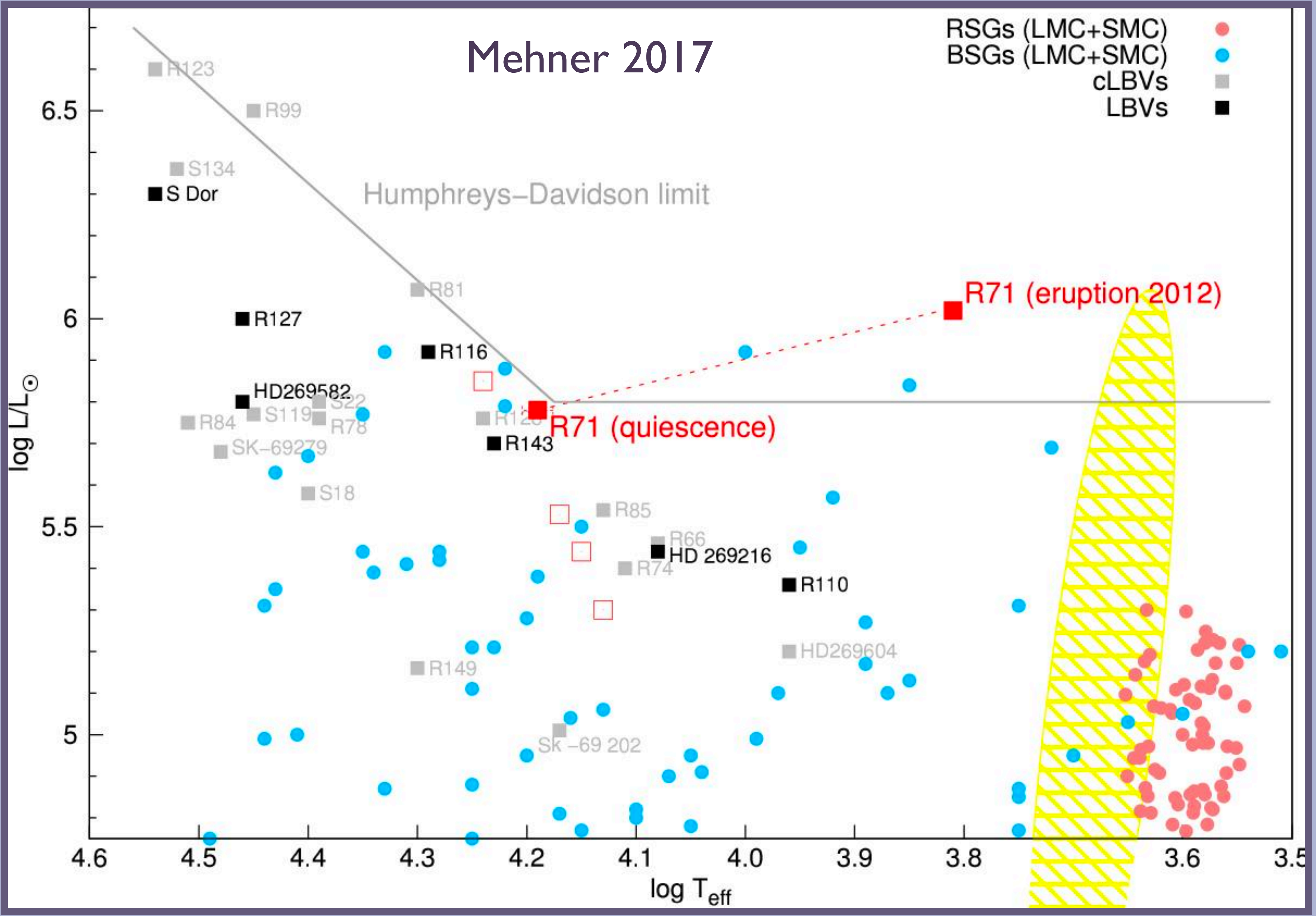
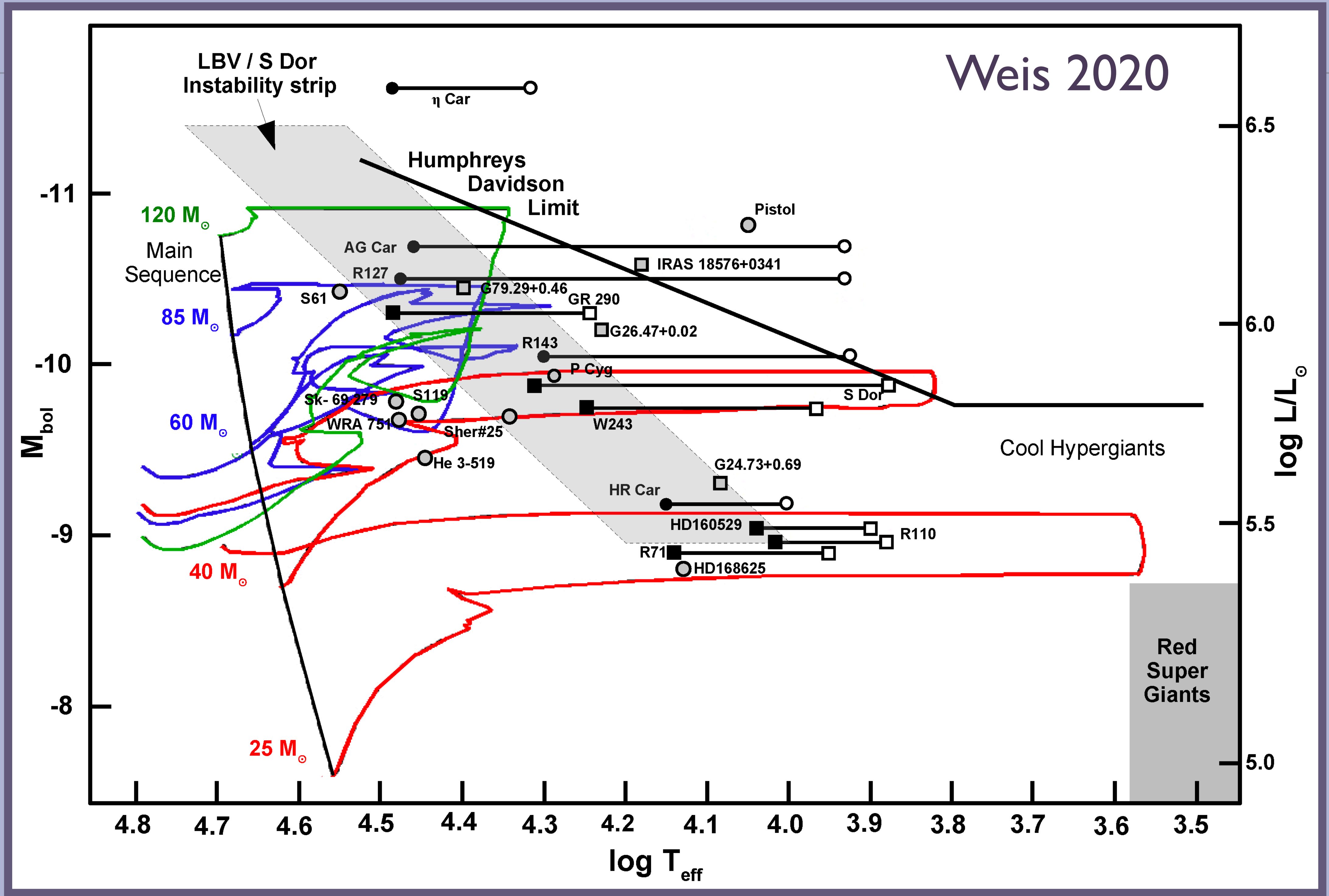
Luminosity decline time scale vs. absolute magnitude diagram, centered in the region of ILOTs. Credits: M. Kasliwal





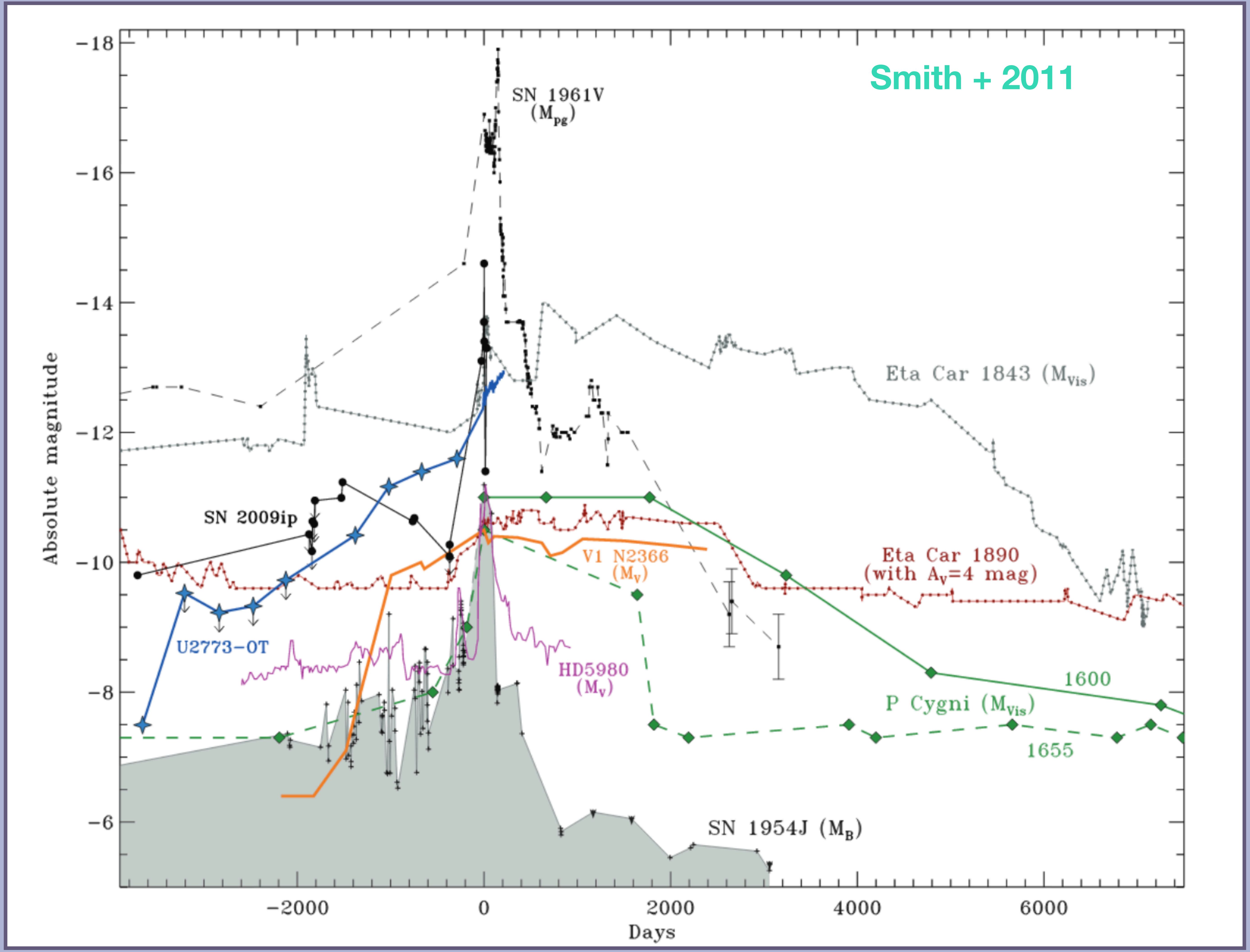
LUMINOUS BLUE VARIABLES





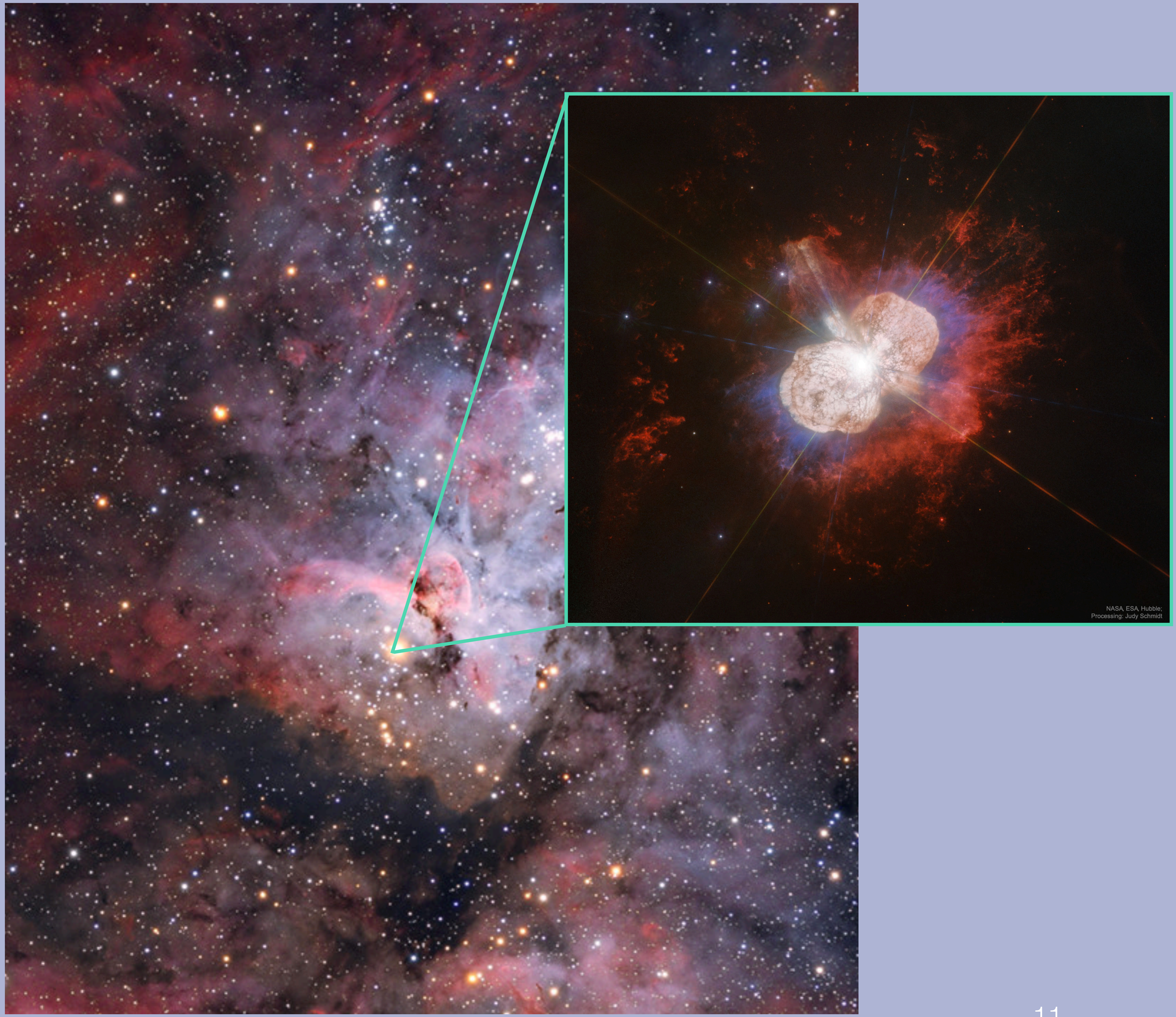
- Exact mechanism of instabilities are not yet fully known.
- Diverse class of objects with wide range of variabilities (both in time and magnitude).
- Extends to stars down to about 20 $M_\odot$.

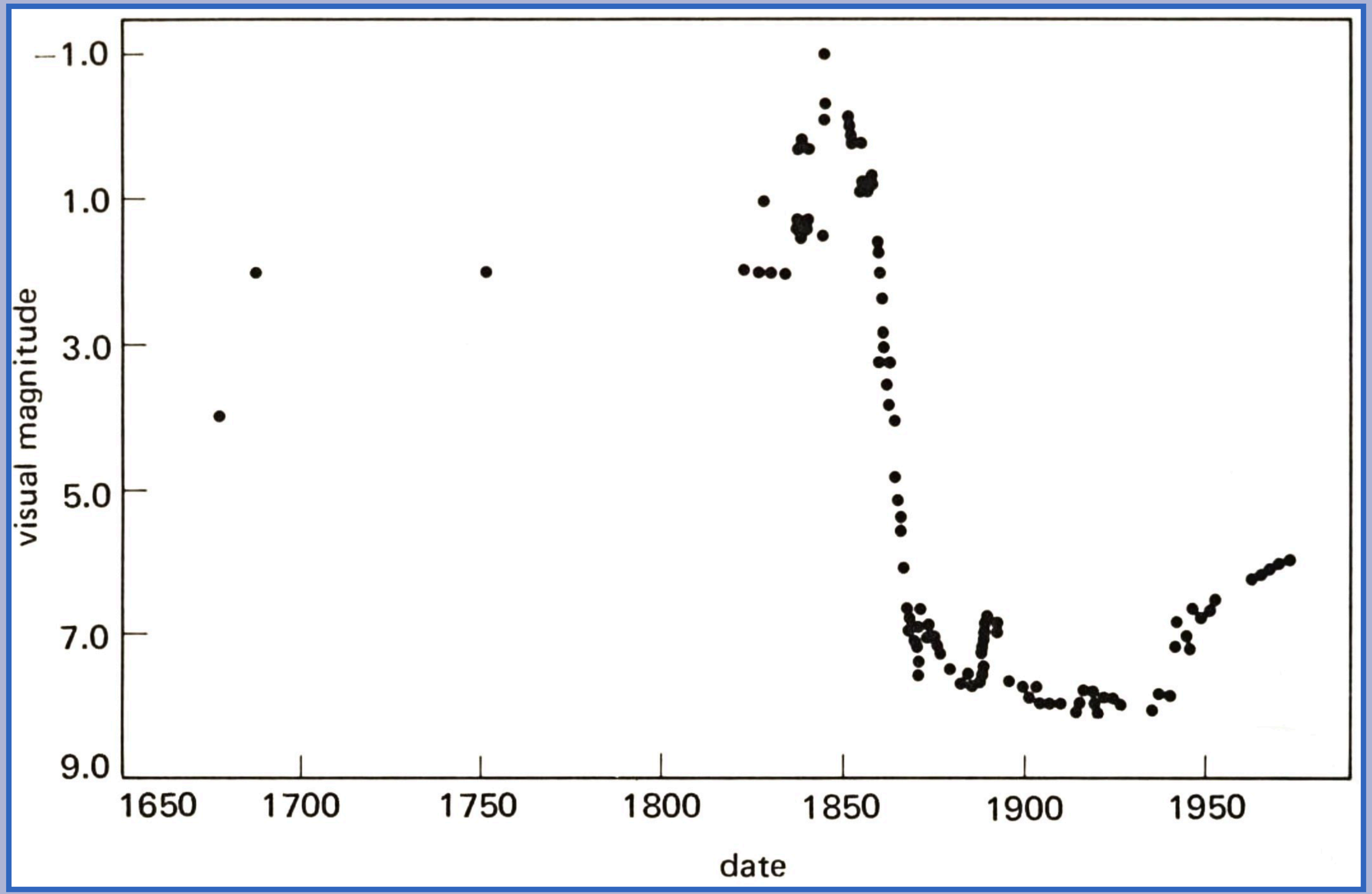
LBV GIANT ERUPTIONS



- Extreme mass loss and increase in bolometric luminosity.
- In extreme cases, more mass can be lost in a single major eruption than was lost on the whole MS
- Outburst can last years, but progenitor survives event.
- Many LBV candidates determined spectroscopically and with circumstellar shells, but need to observe an outburst for confirmation.

THE GREAT ERUPTION OF ETA CAR

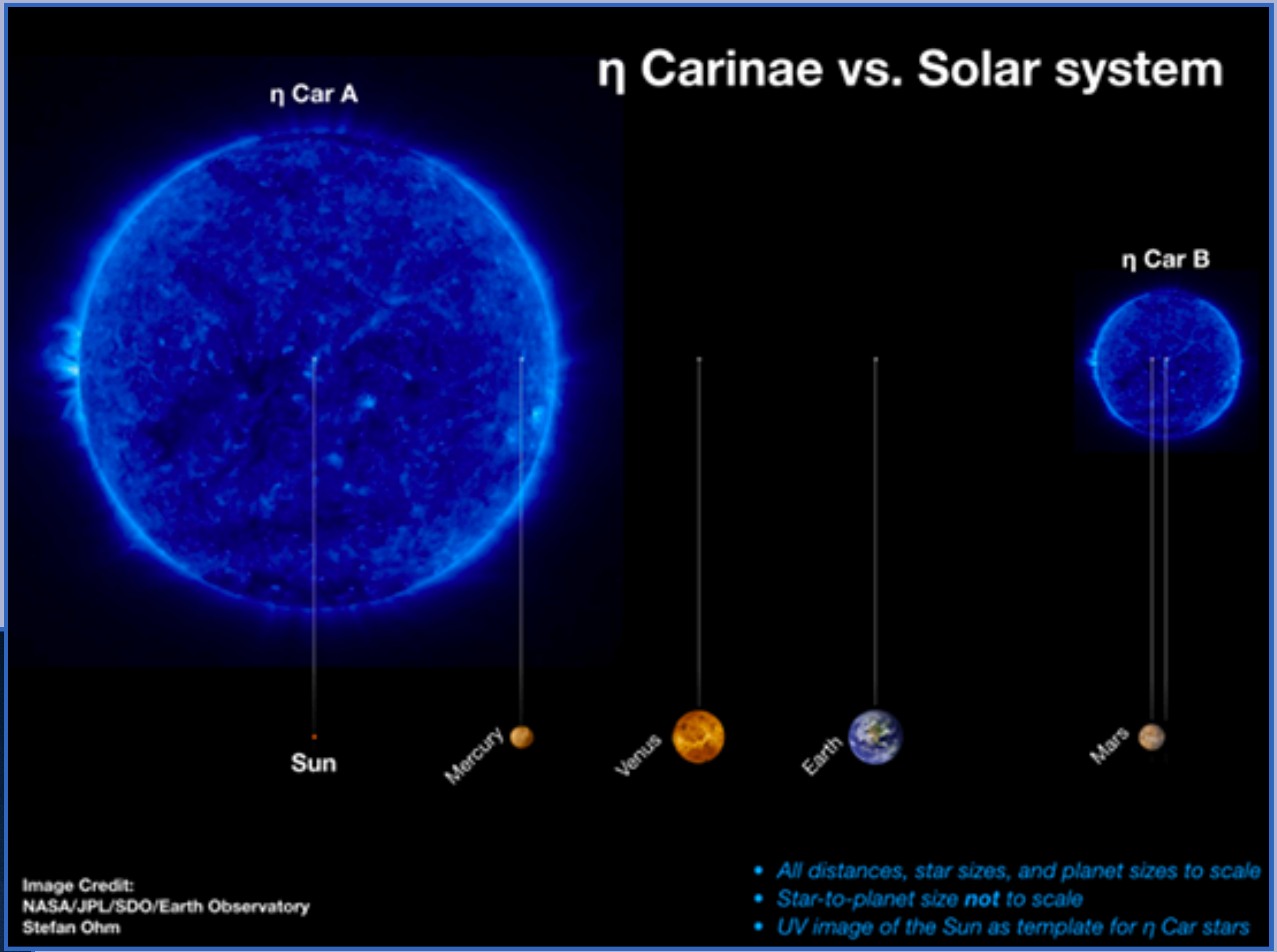


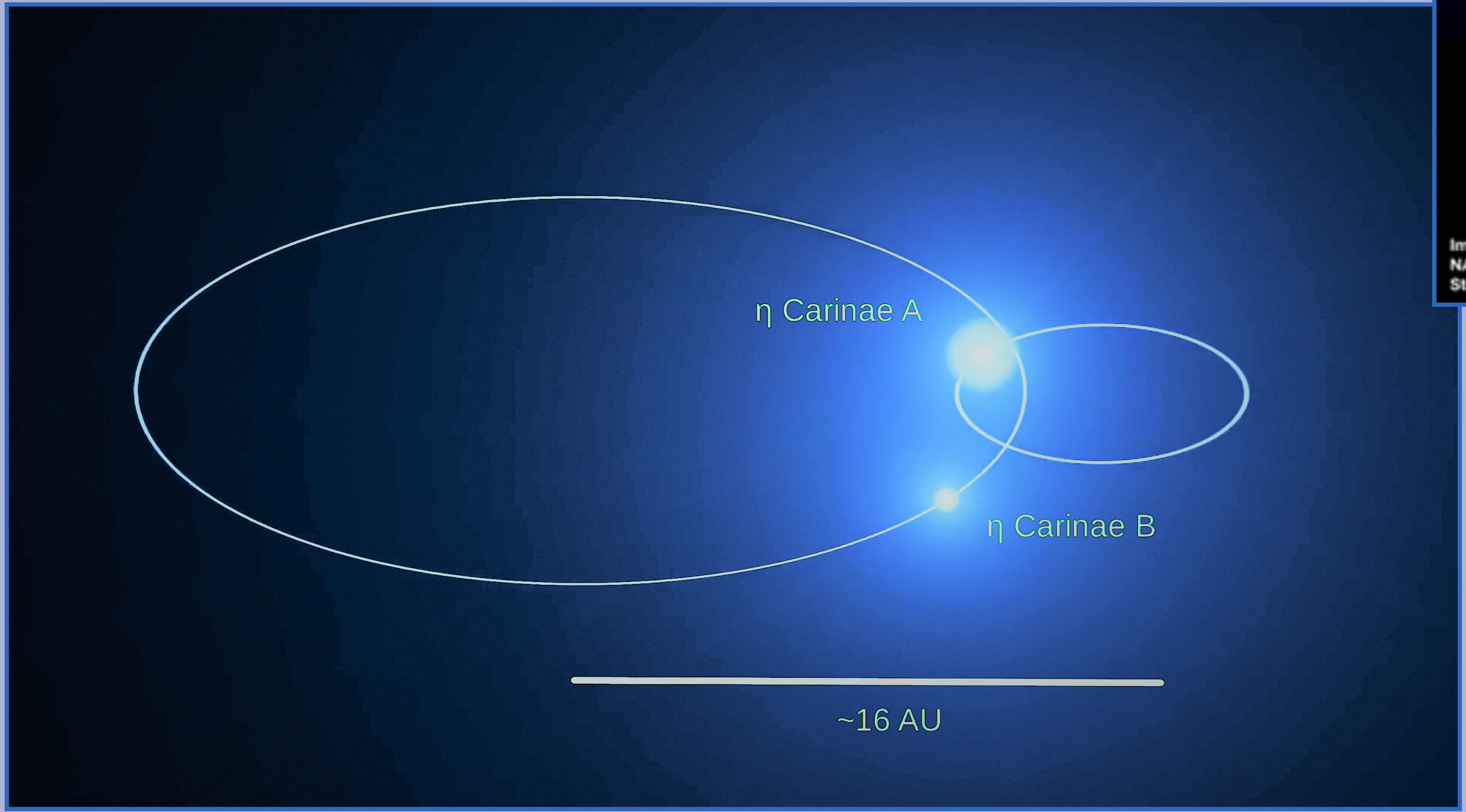


- 1838-1858
- 10 - 20 $M_\odot$ ejected
- Lesser eruption in 1890

ETA CAR

- 5.5 year orbit
- Colliding wind binary
- LBV + WR system

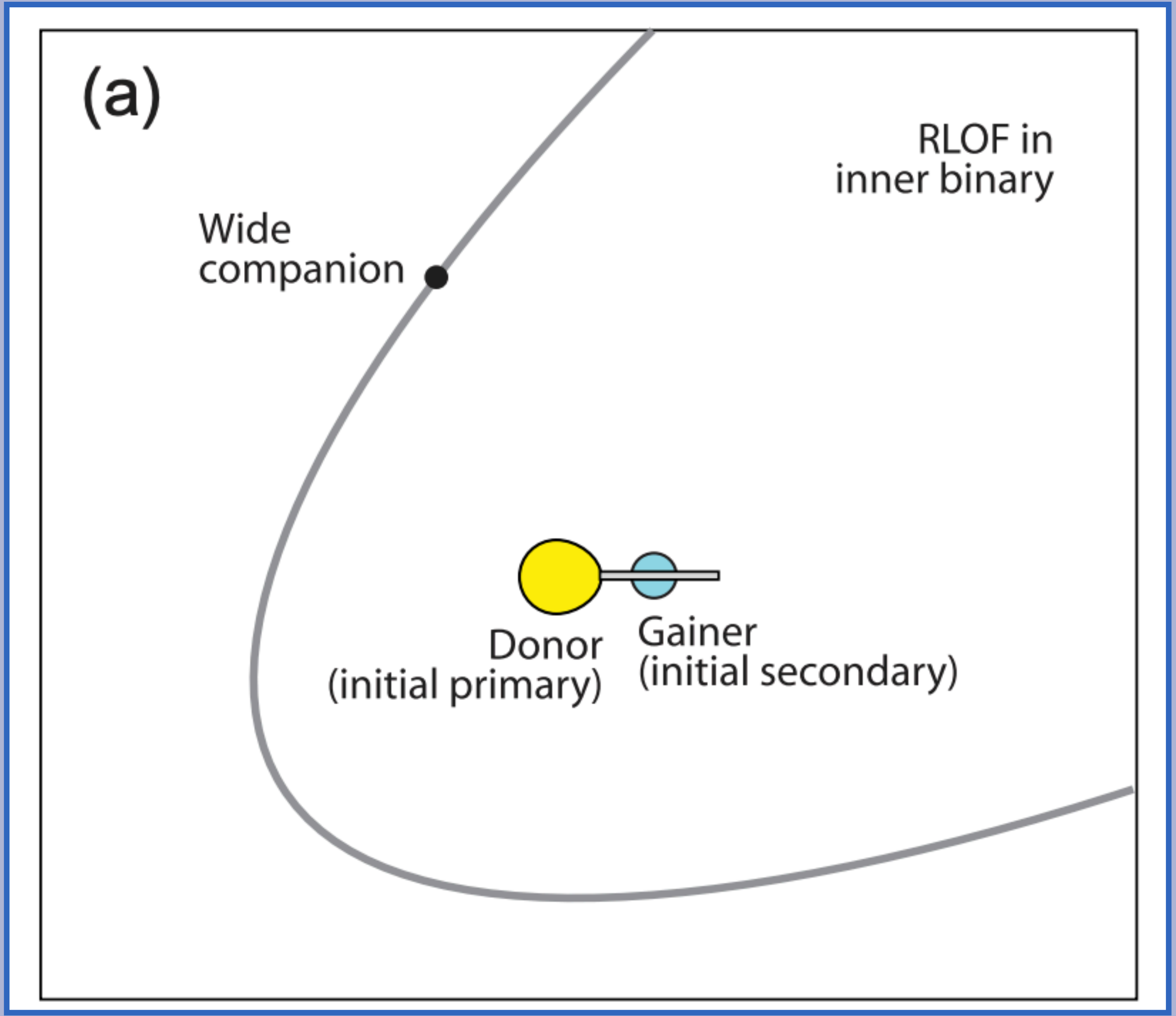




- $5 \times 10^6 L_\odot$ - most luminous in MW
- 120 $M_\odot$ total (90 + 30)

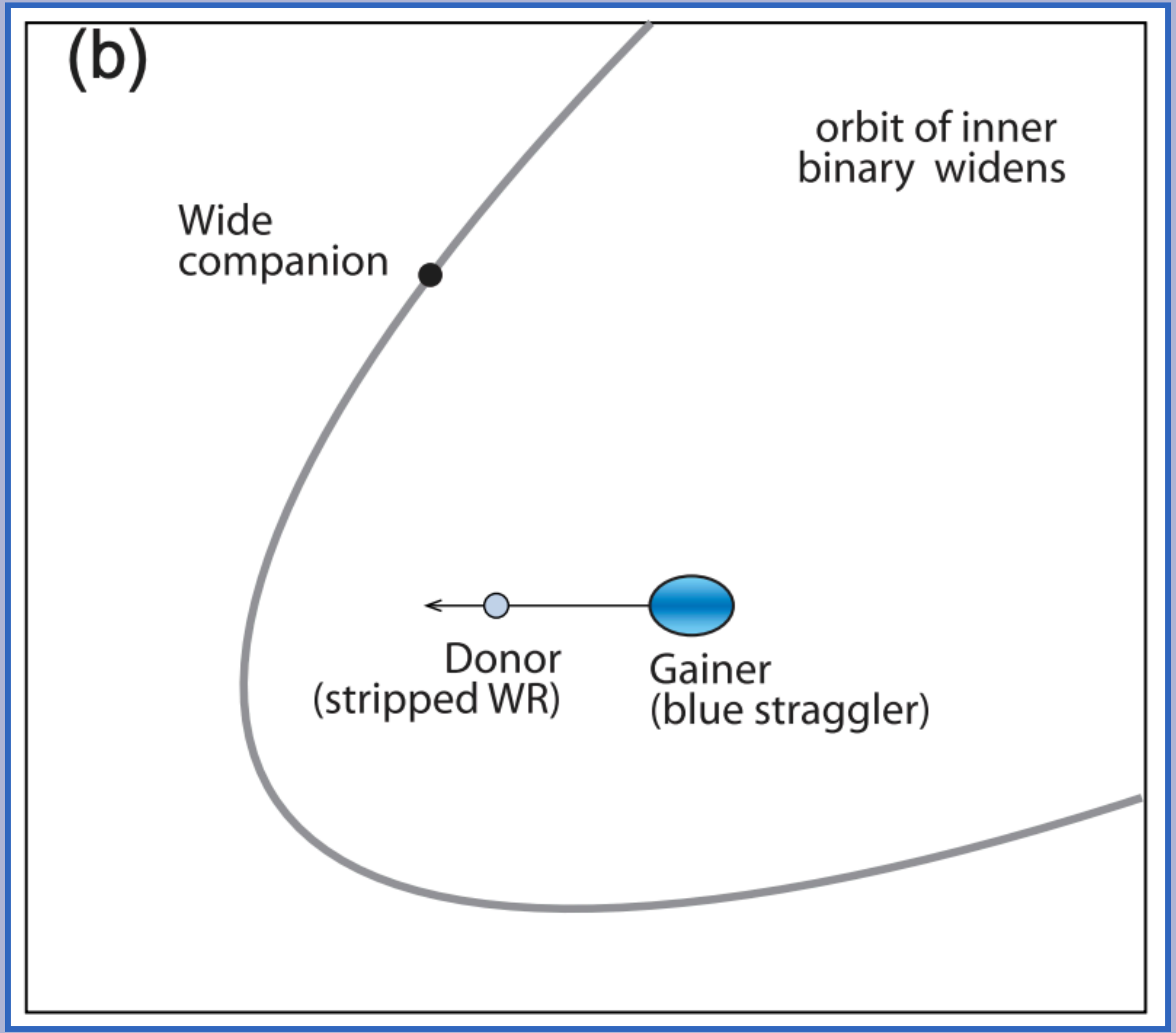
ETA CAR PRODUCT OF A MERGER?

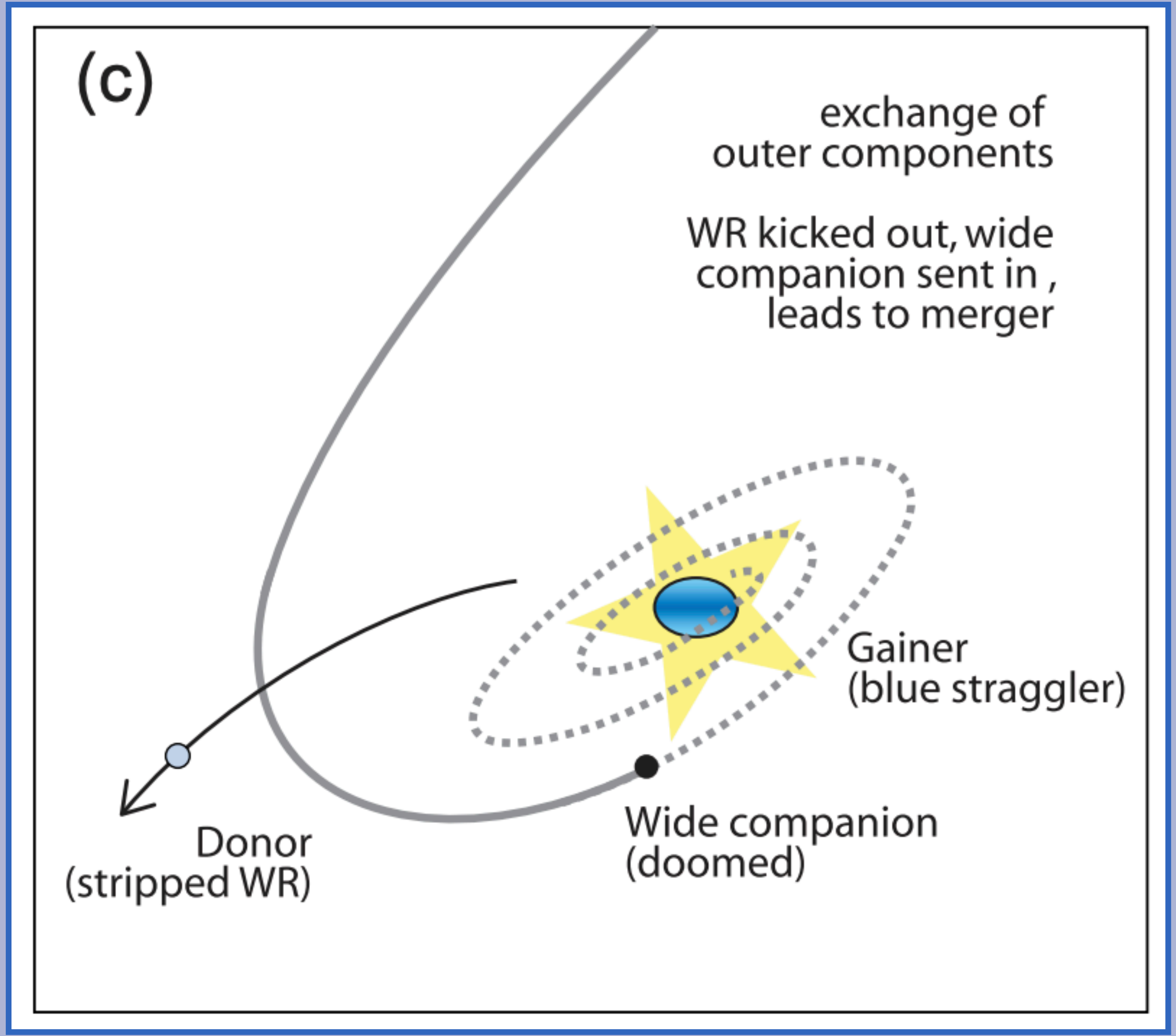
Smith, Andrews et al. 2018



Primary star begins to evolve off the MS and expands which initiates mass transfer

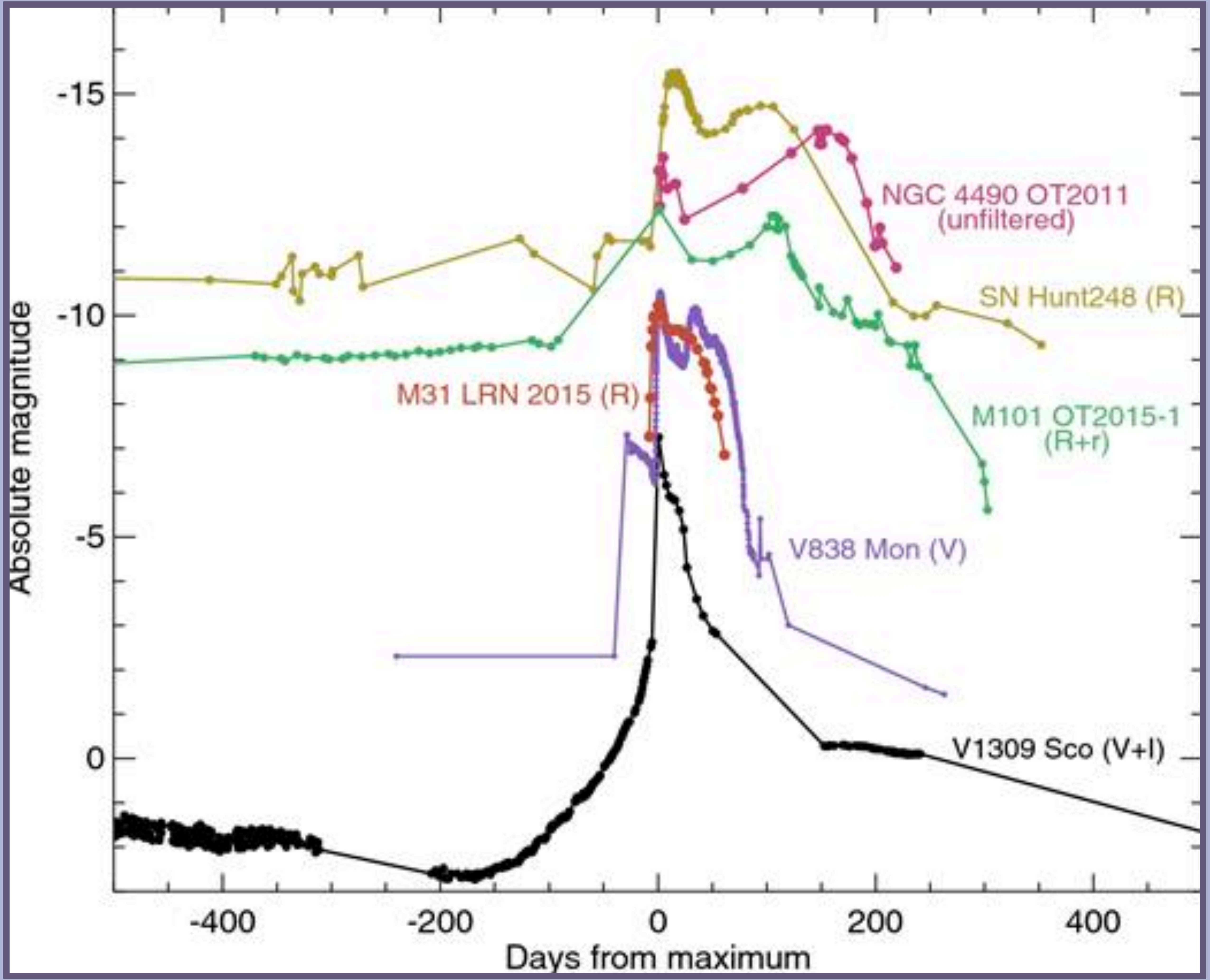
Primary now a WR star, gainer spun up and overluminous.

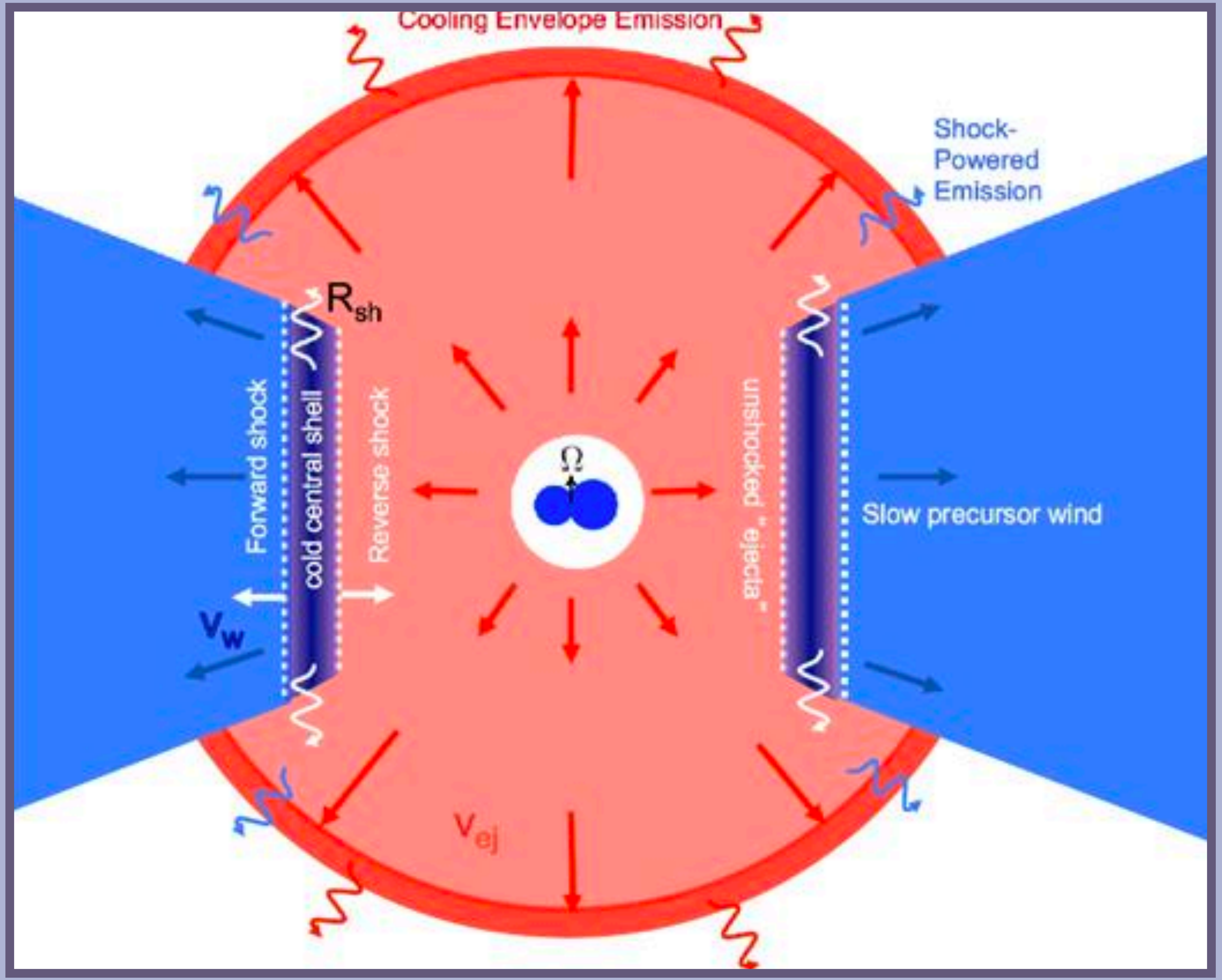




Orbit widens further due to mass loss, and the original primary switches places with tertiary

LUMINOUS RED NOVAE

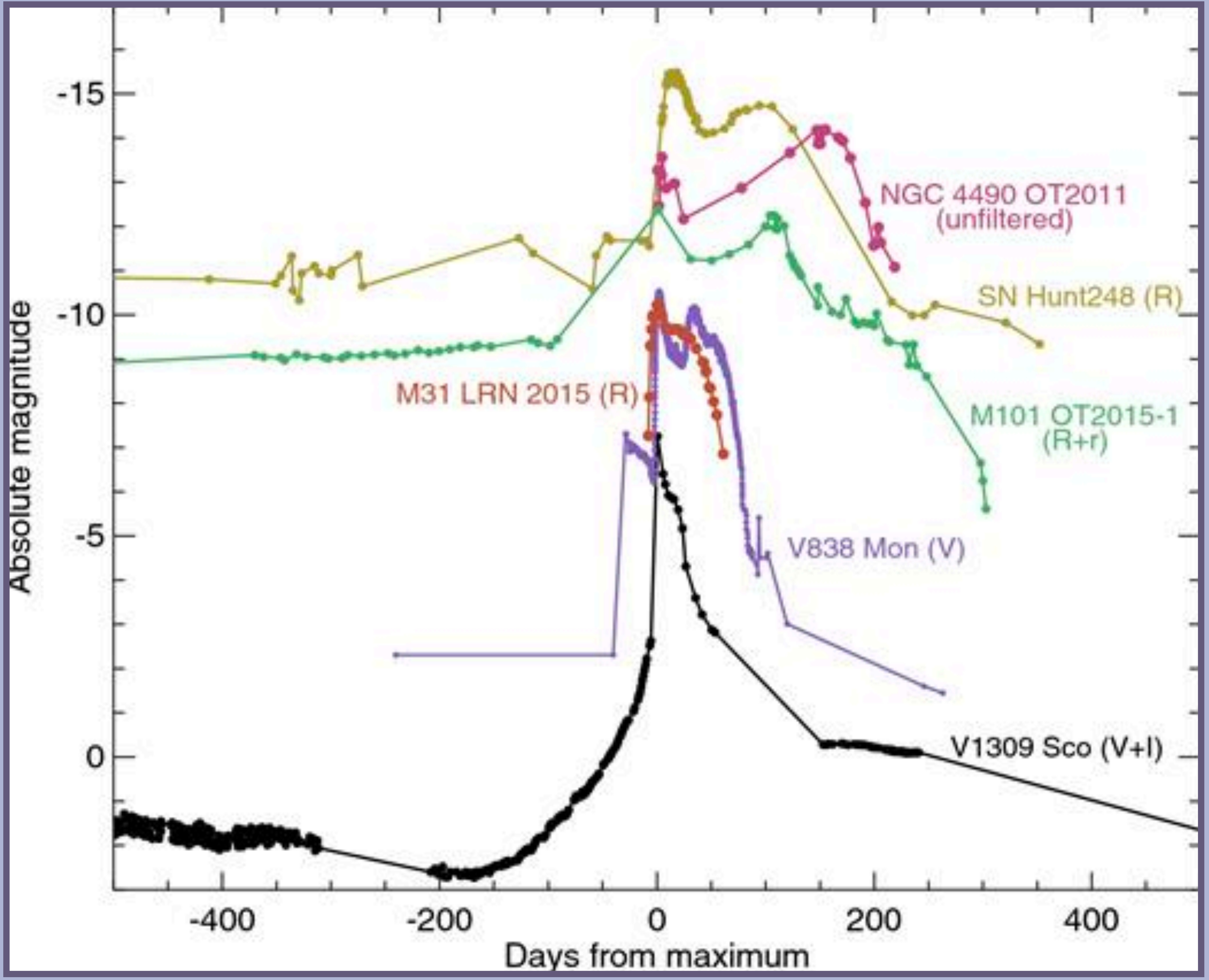


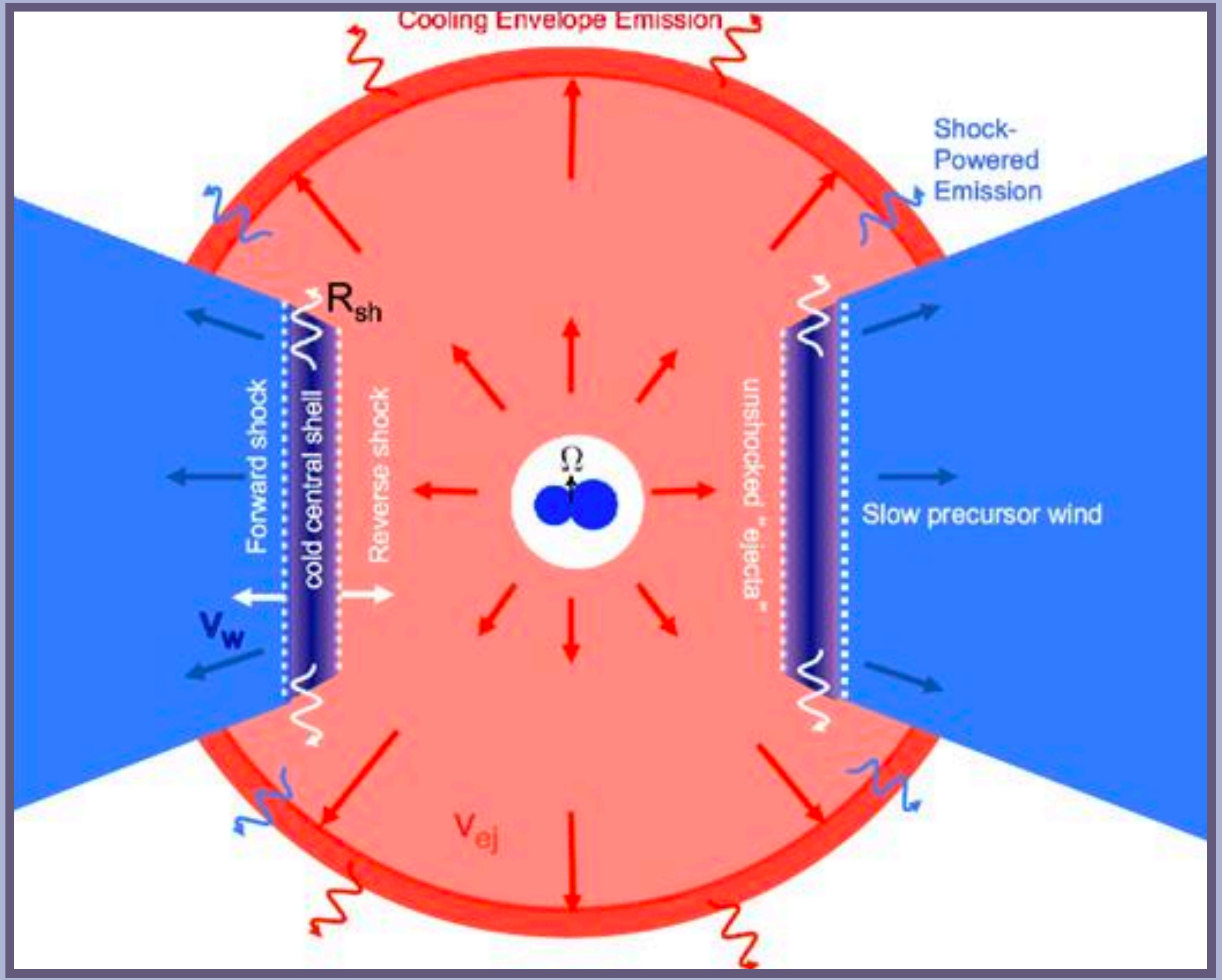


Metzger & Pejcha 2017

LUMINOUS RED NOVAE

- Mergers and/or CE ejection
- Low and high mass stars
- Light curve with multiple peaks





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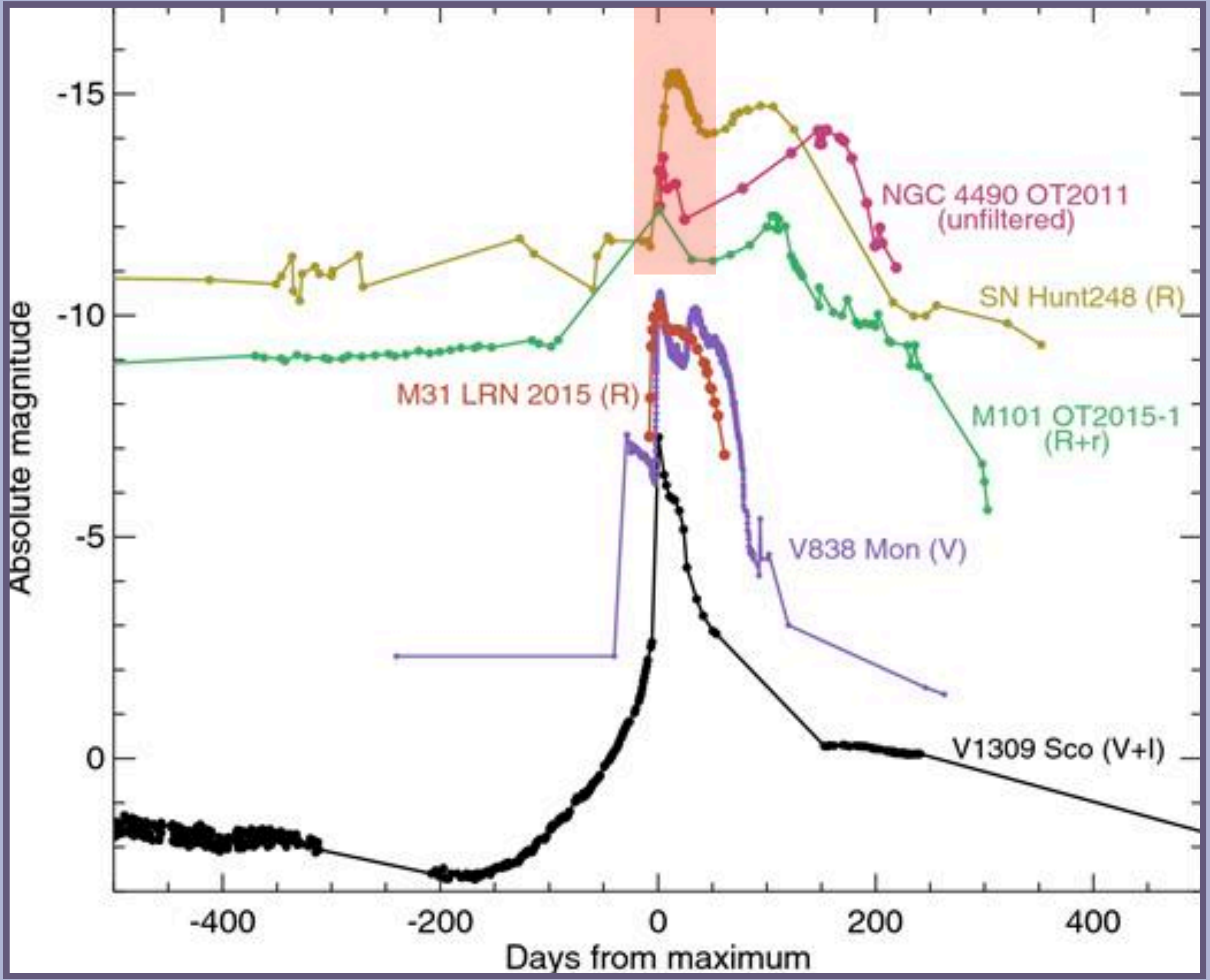

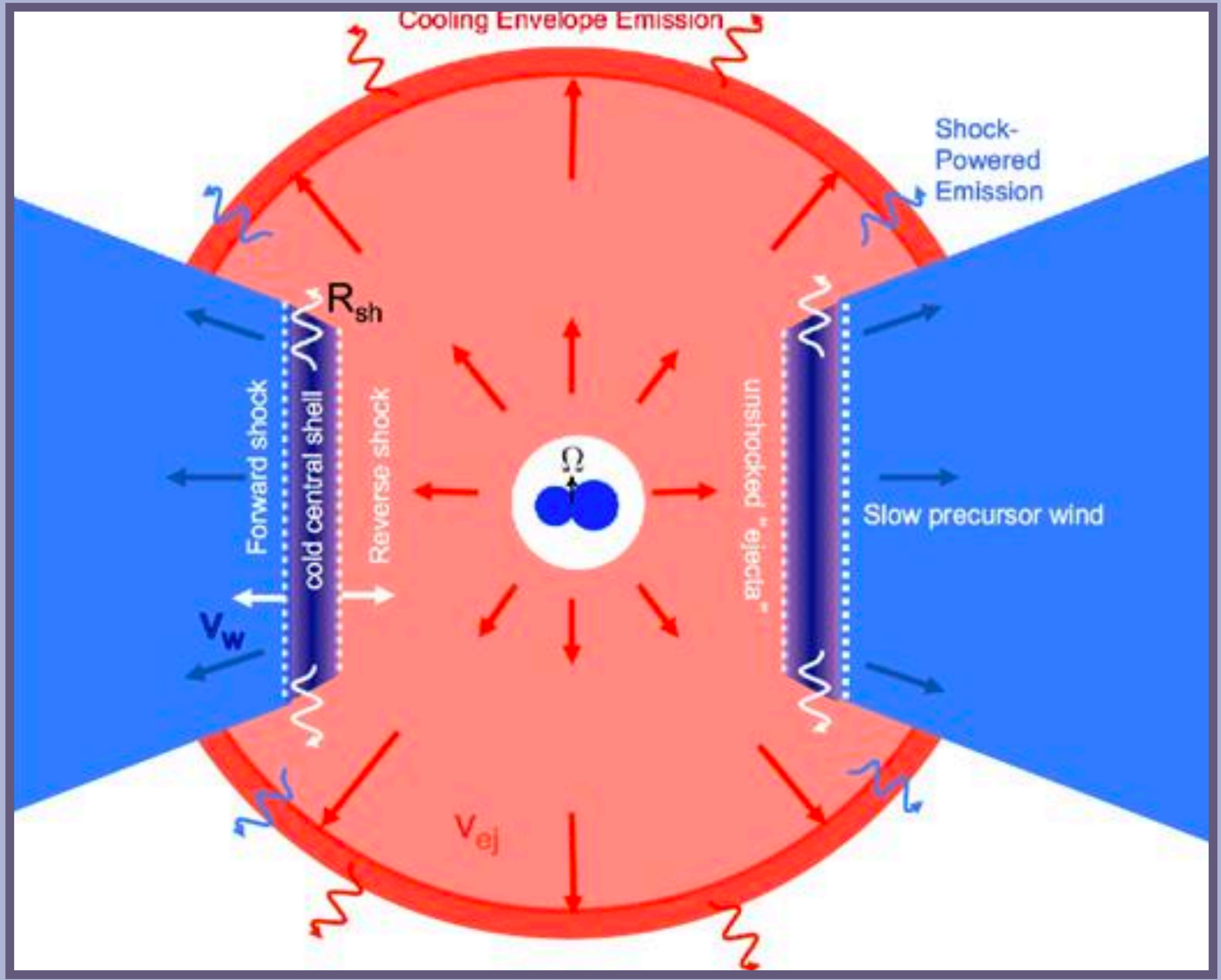

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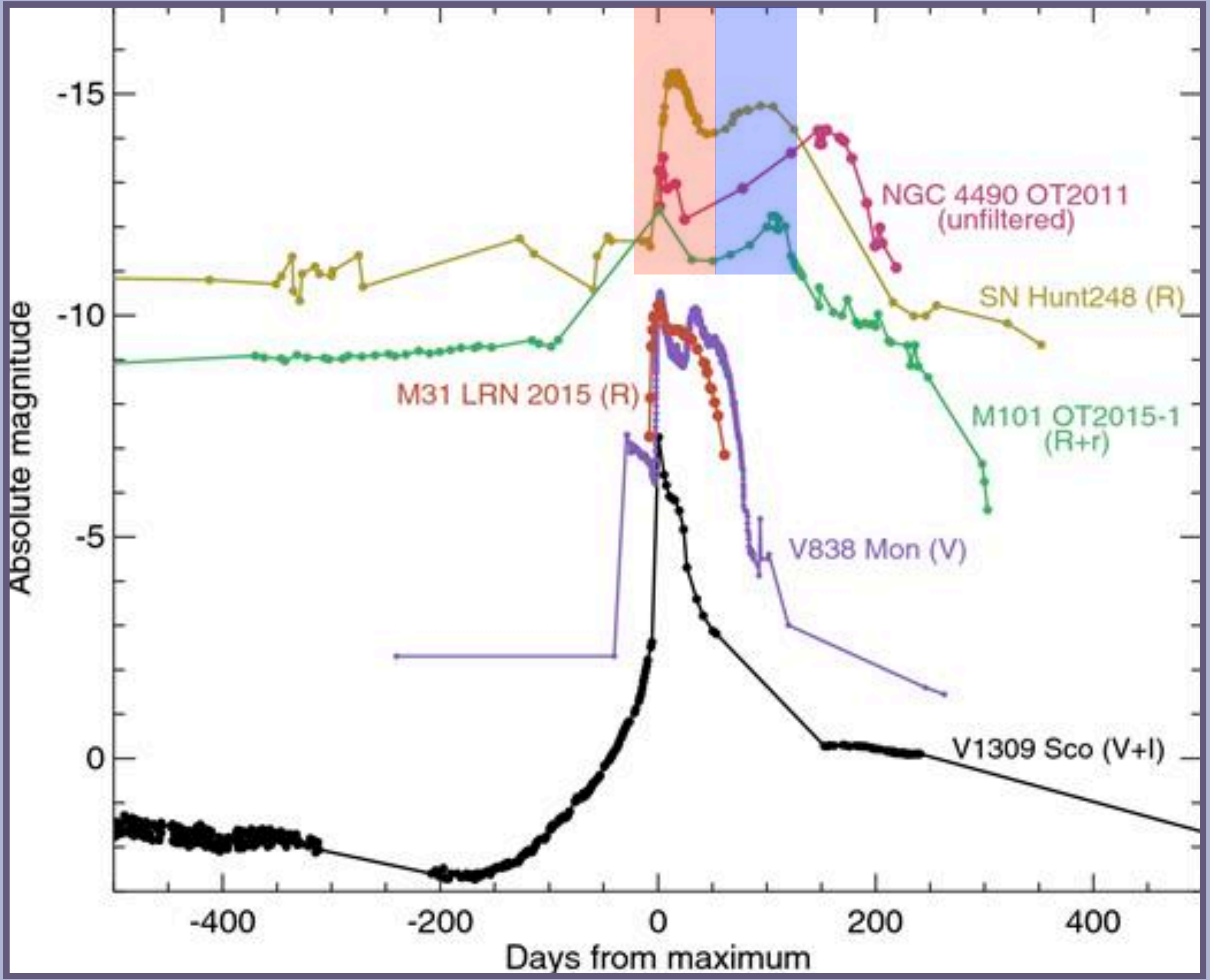

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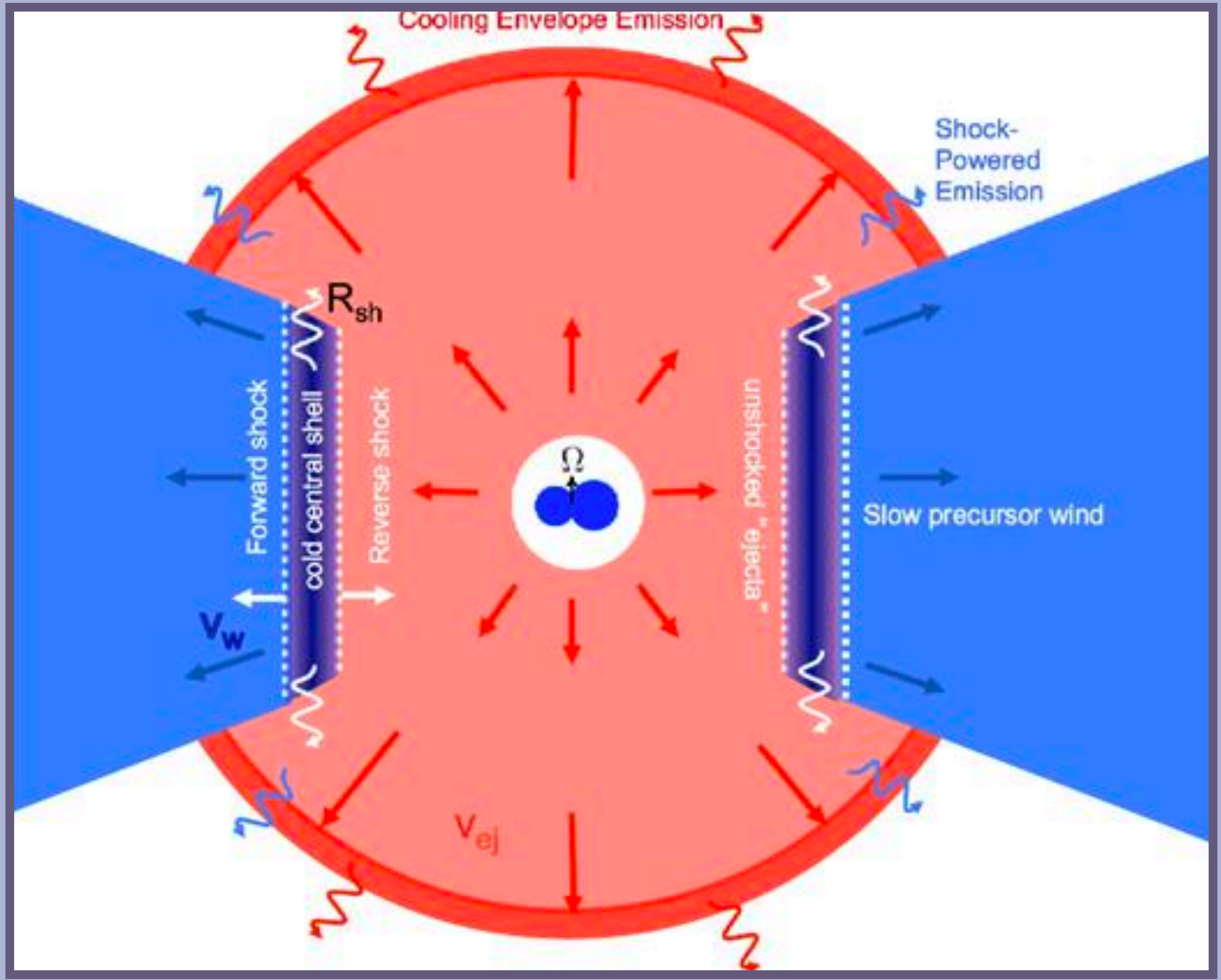
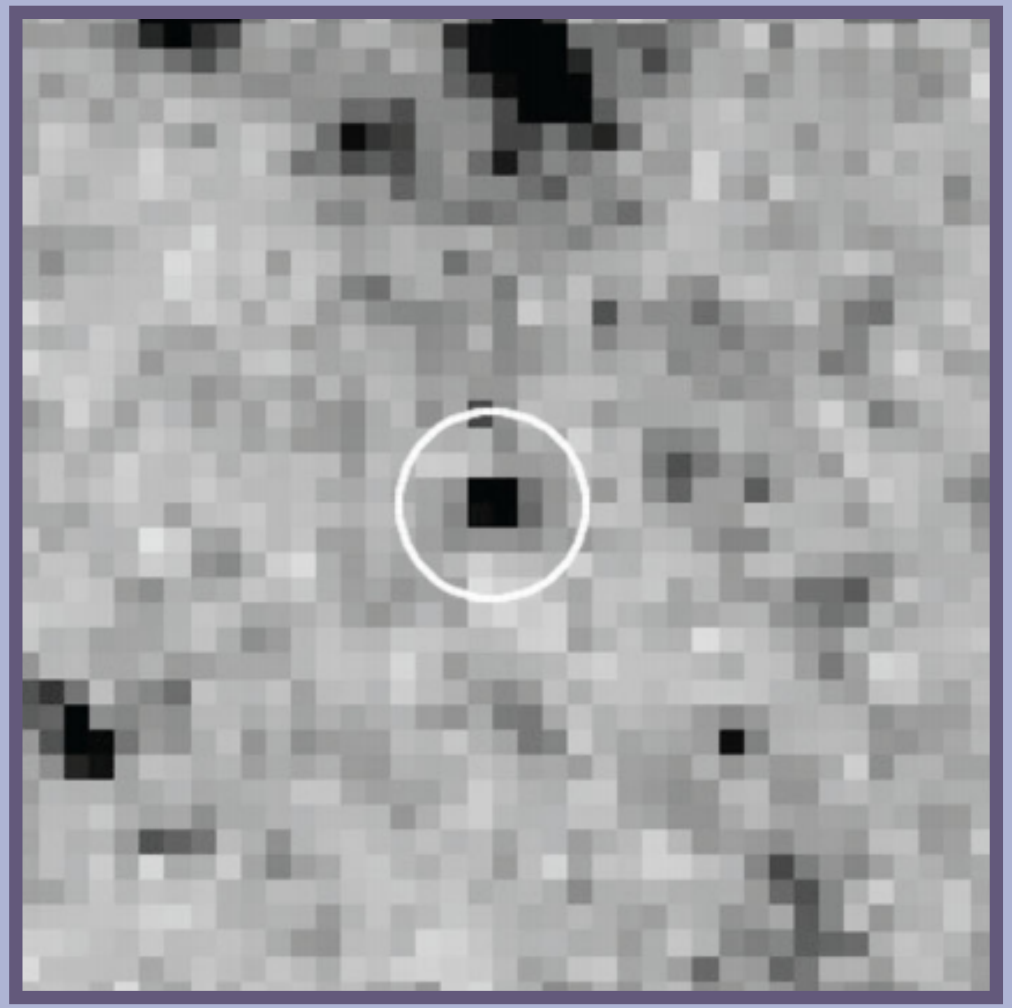


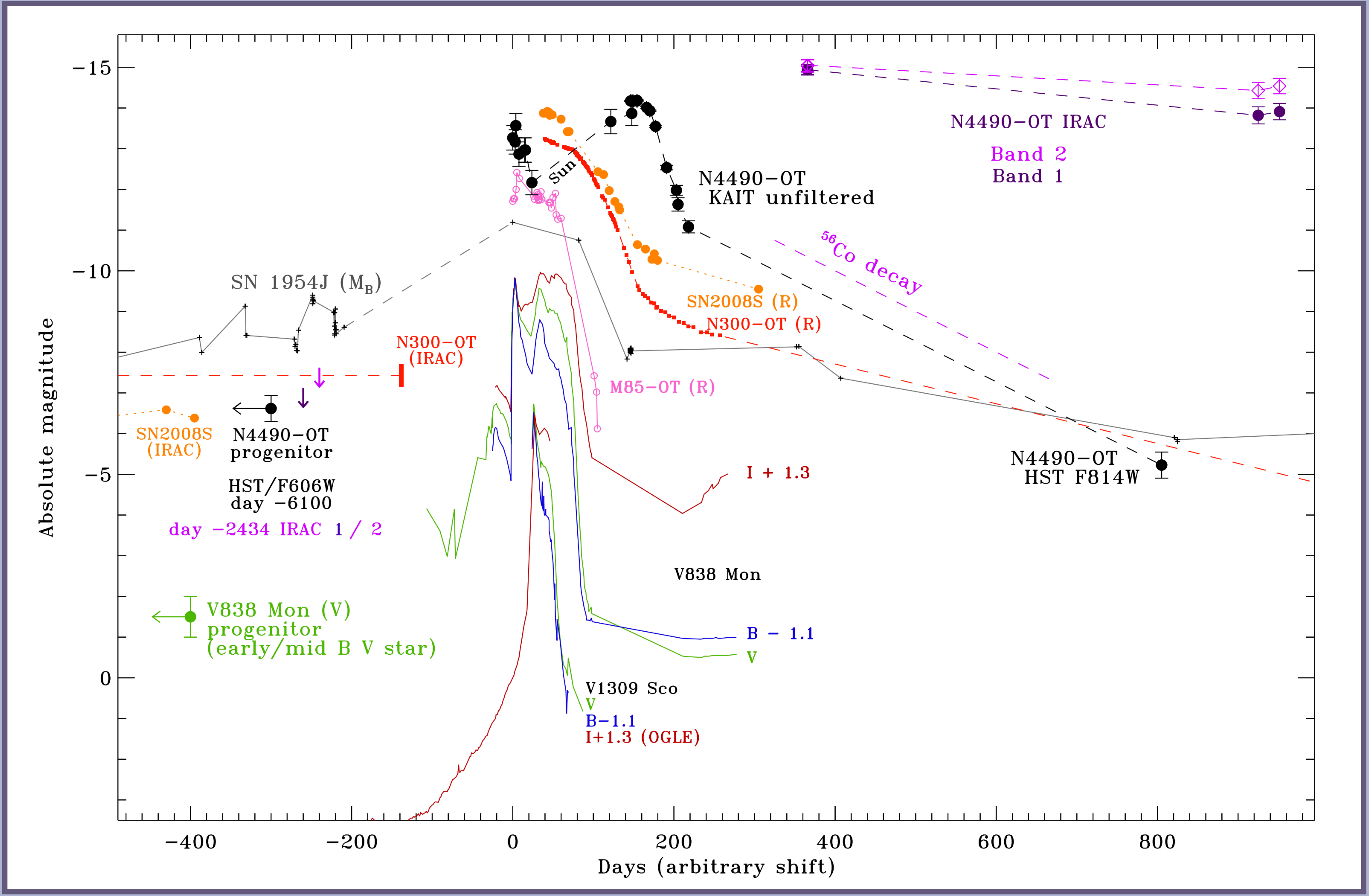
Metzger & Pejcha 2017

NGC4490-OT



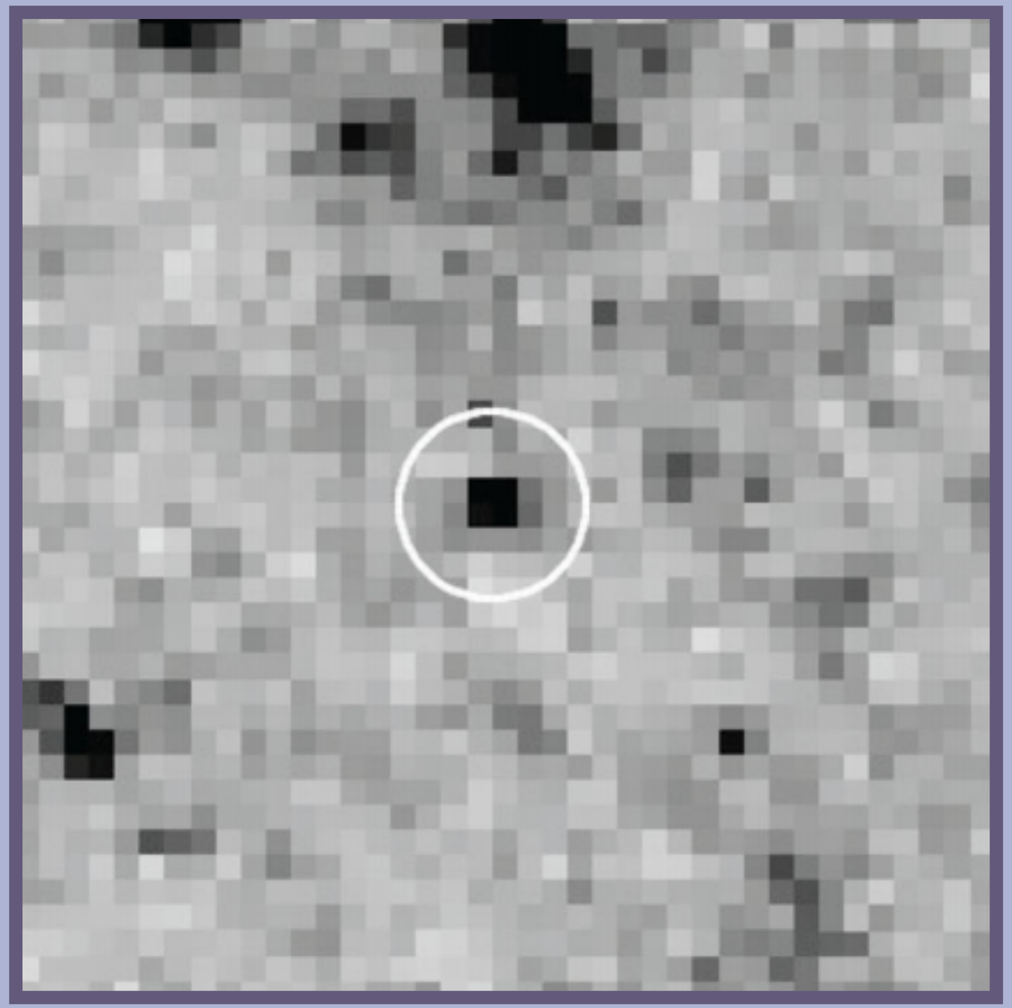
Progenitor was blue and luminous (only observed in one band).

Lightcurve was very similar to V1309 Sco and V838 Mon, but a longer time between peaks.



Smith, Andrews + 2016

NGC4490-OT



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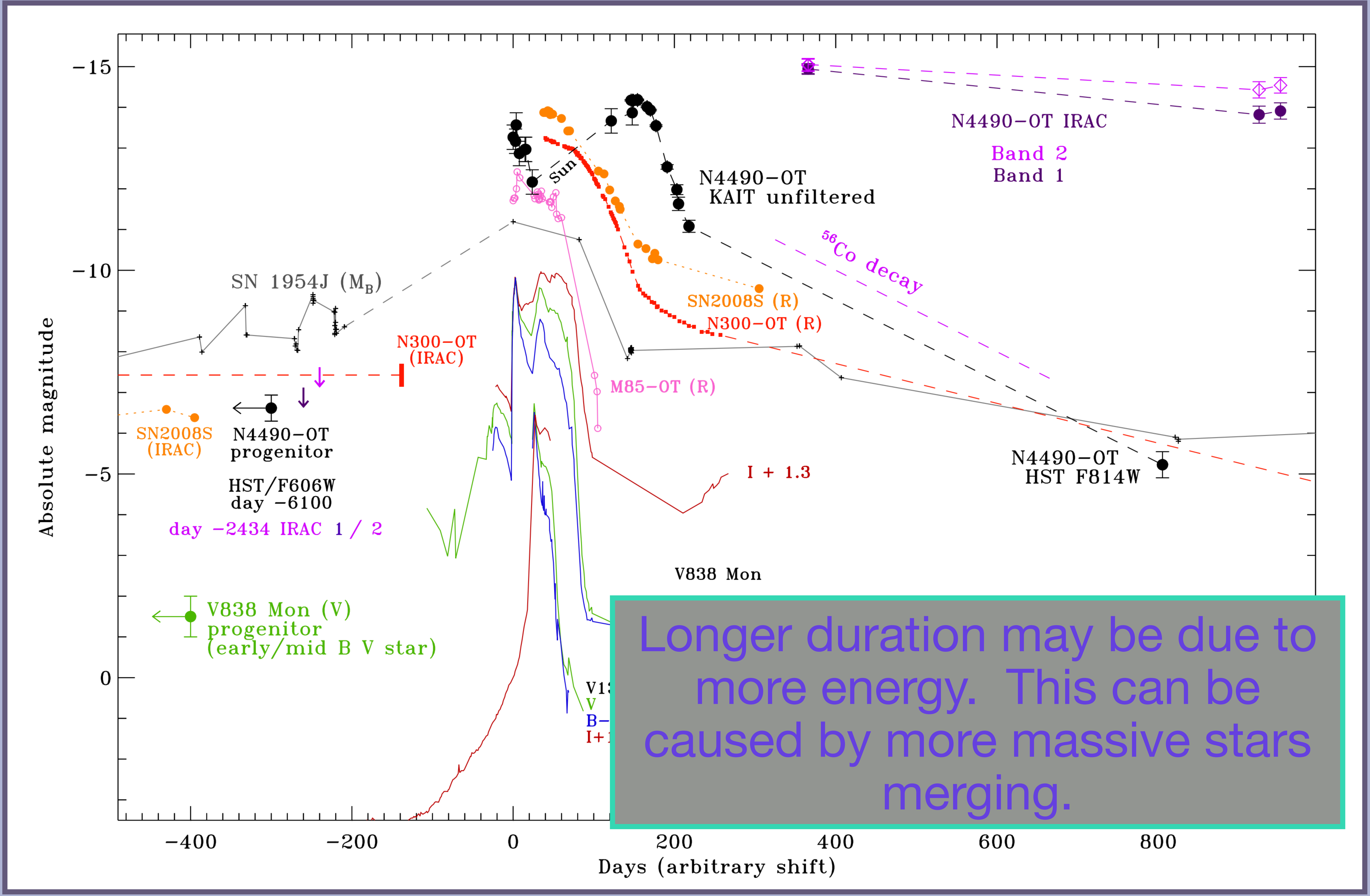
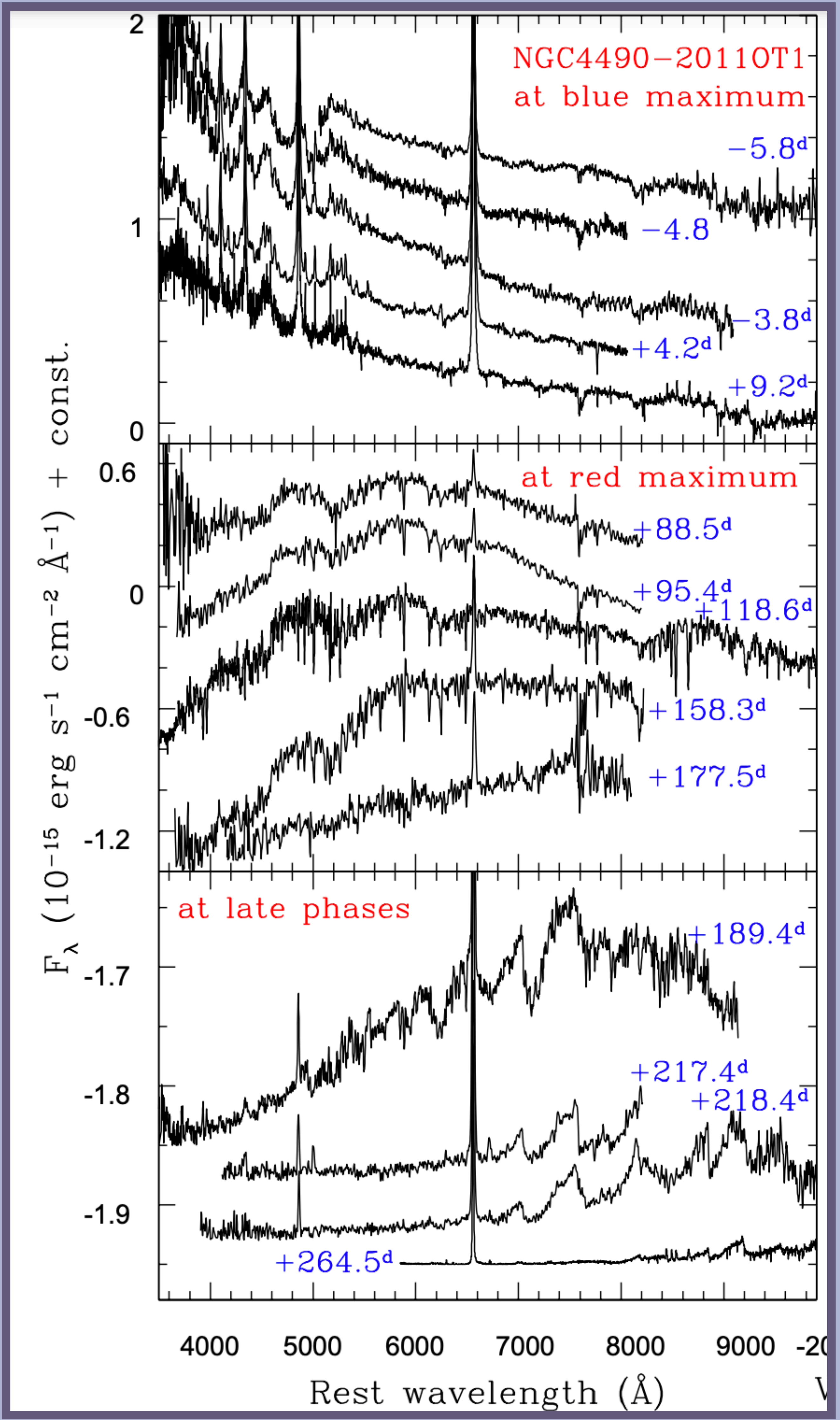


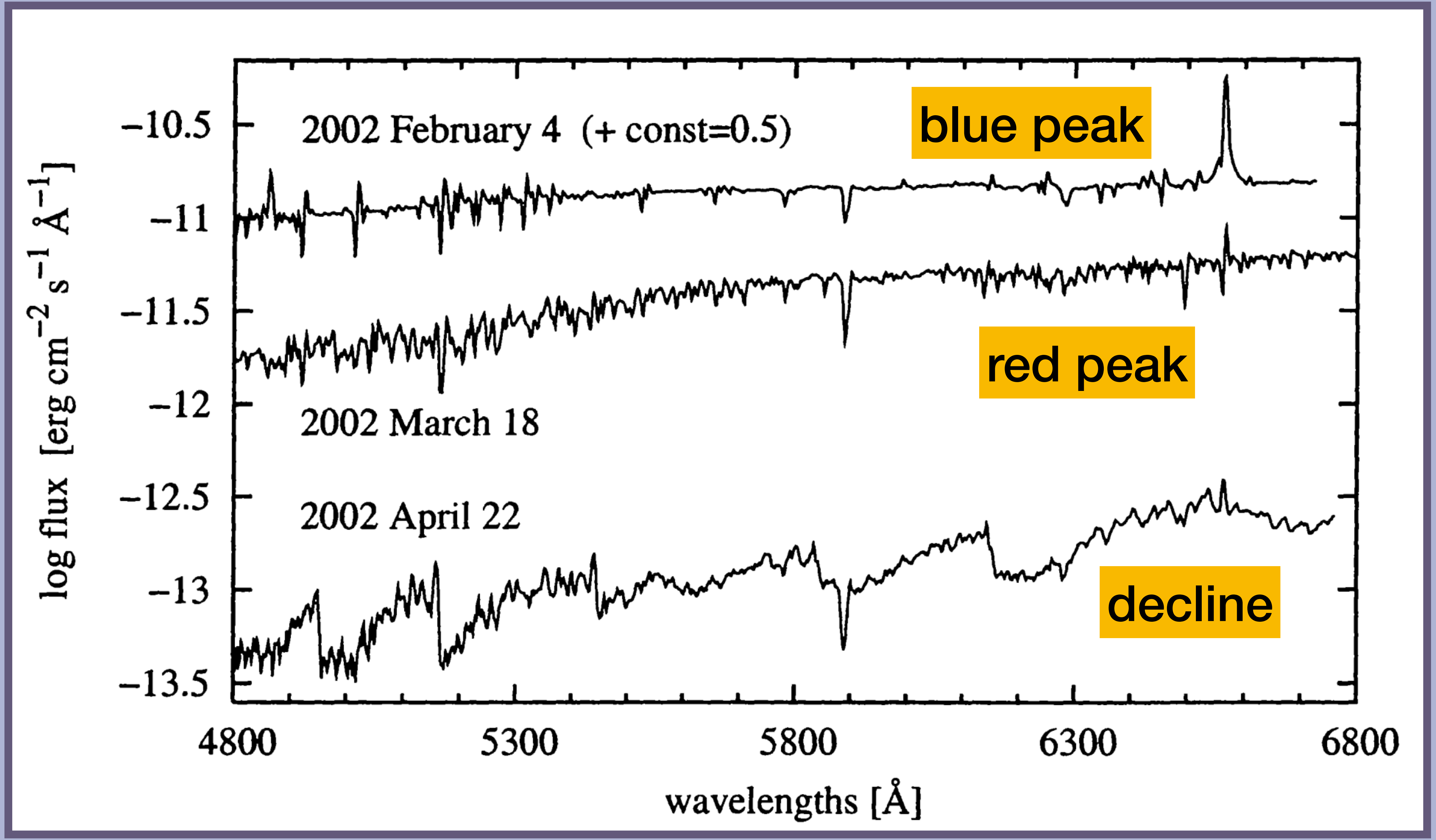
Longer duration may be due to more energy. This can be caused by more massive stars merging.

Smith, Andrews + 2016

LUMINOUS RED NOVAE



Pastorello et al. 2019



Osiwala et al. 2003

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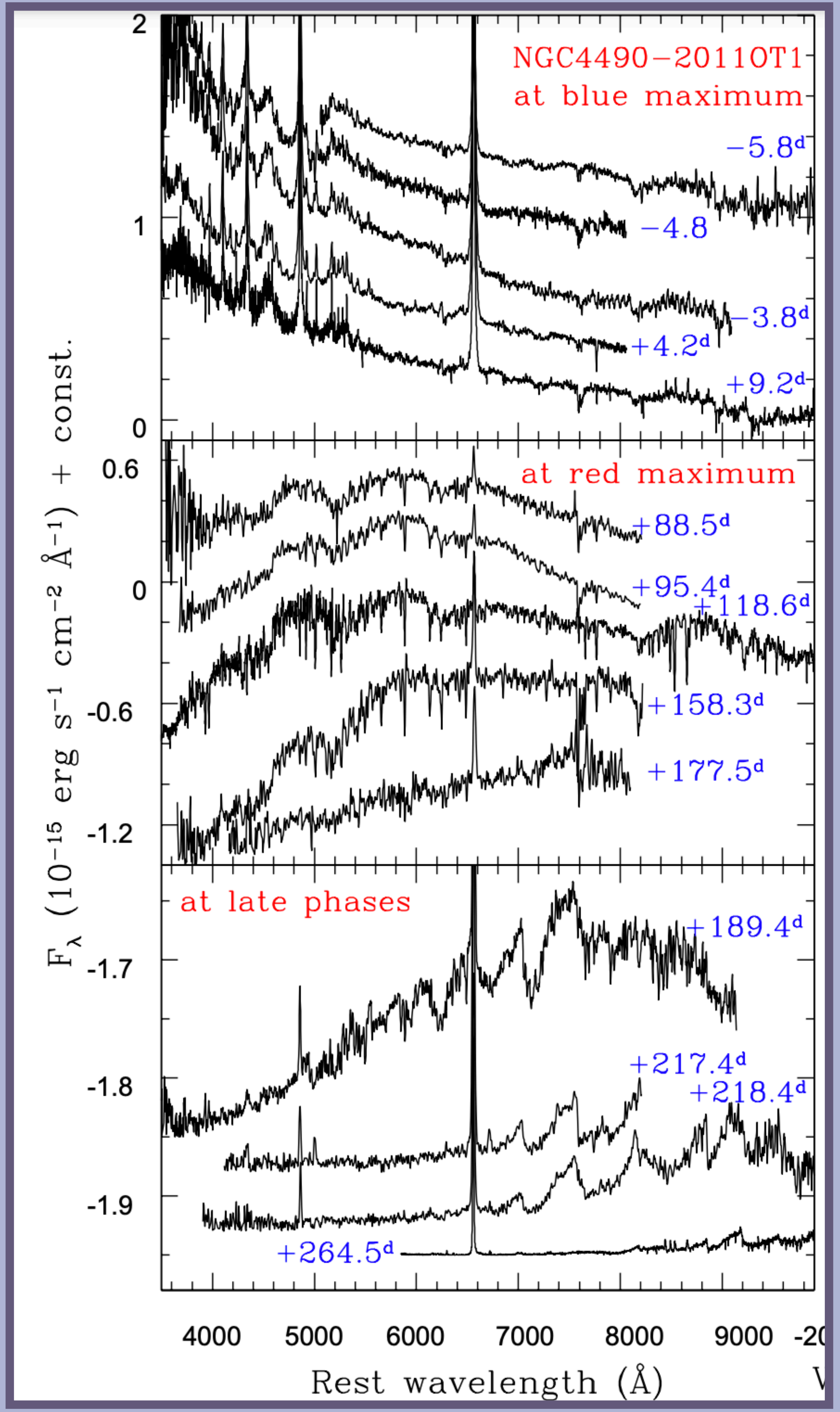
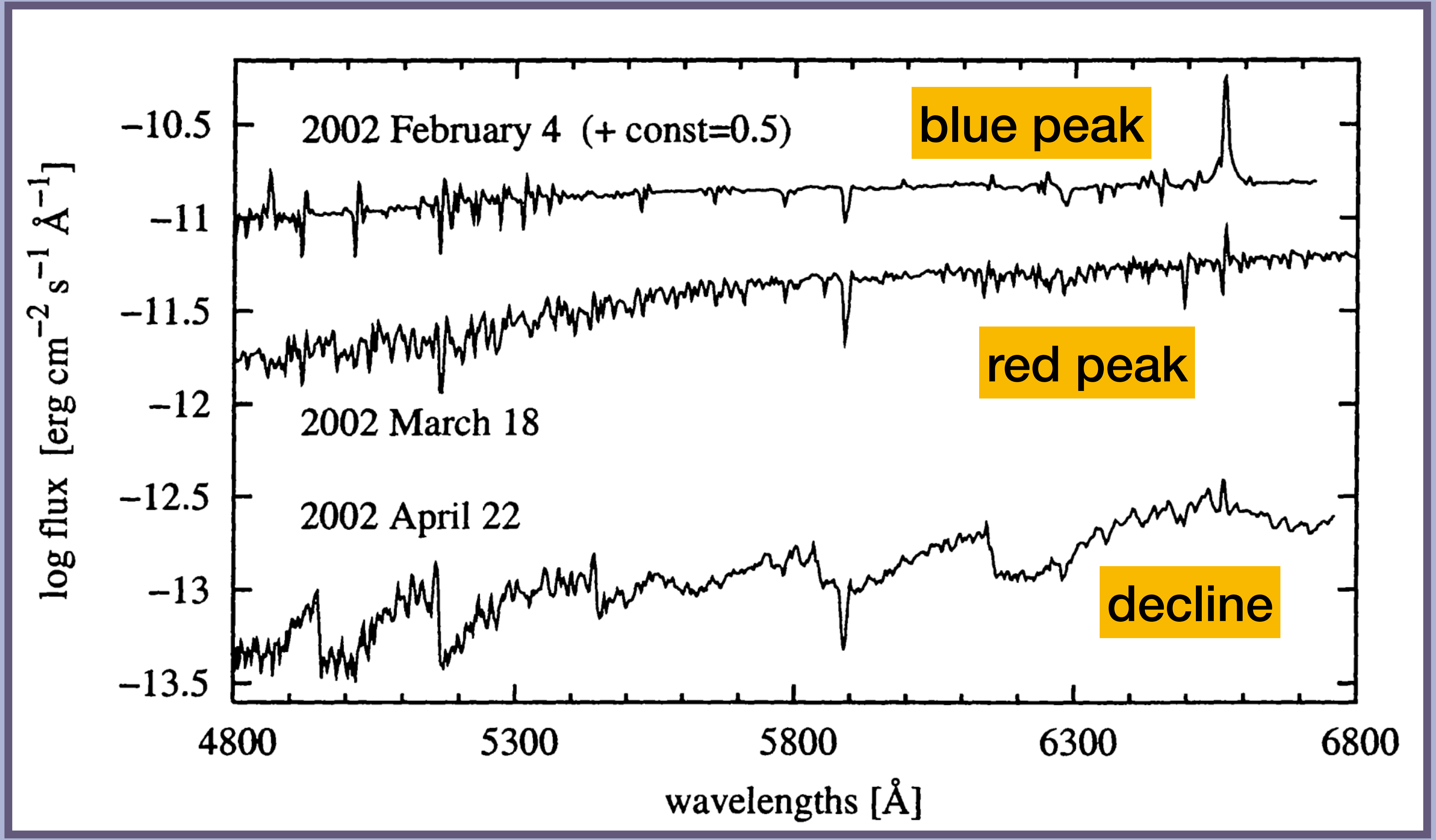


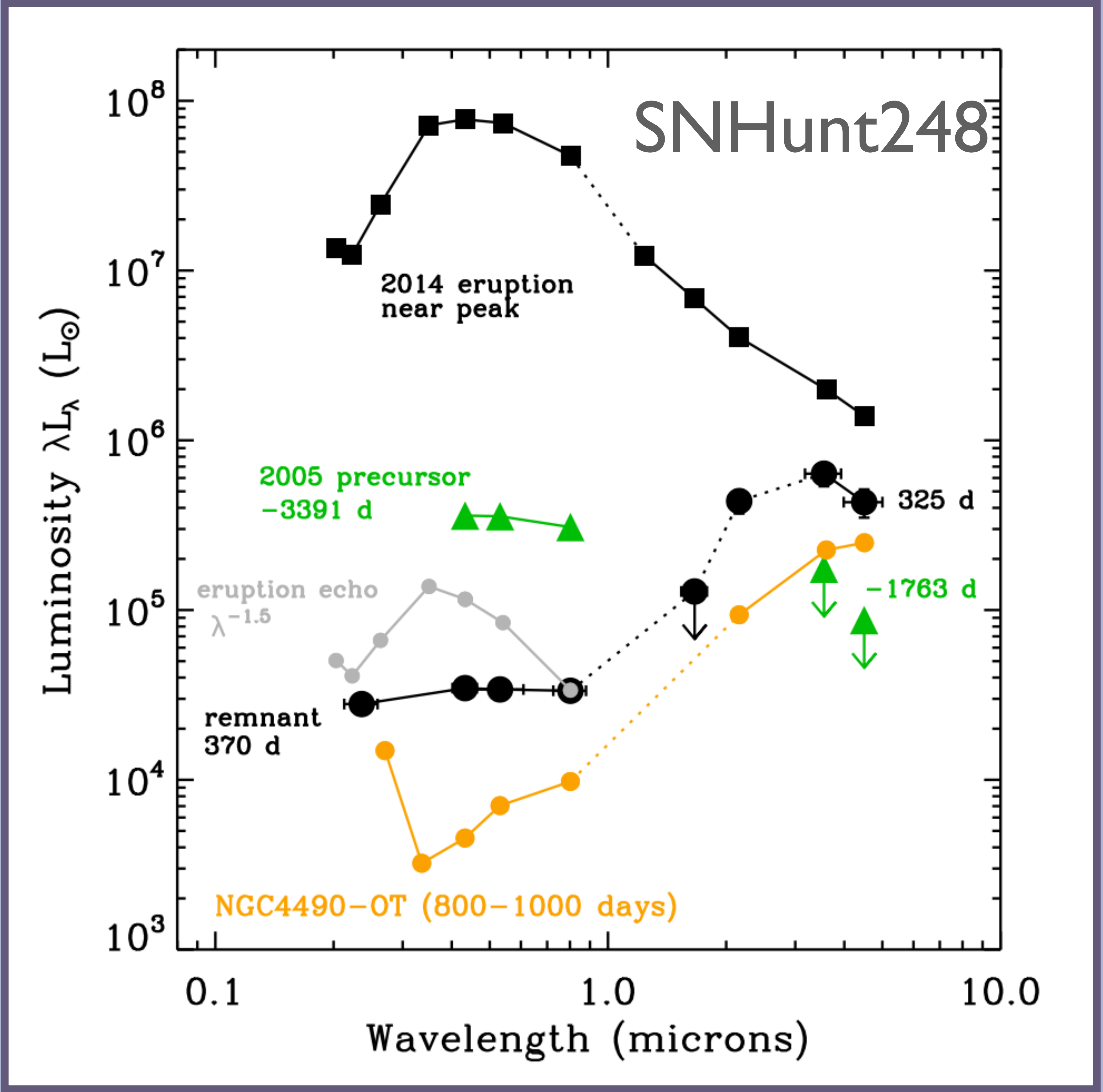
Pastorello et al. 2019

- First peak shows bluer colors and narrow emission lines.
- As you move to the second peak, spectra become much redder.
- At later times, molecules begin to form and dominate the spectra.

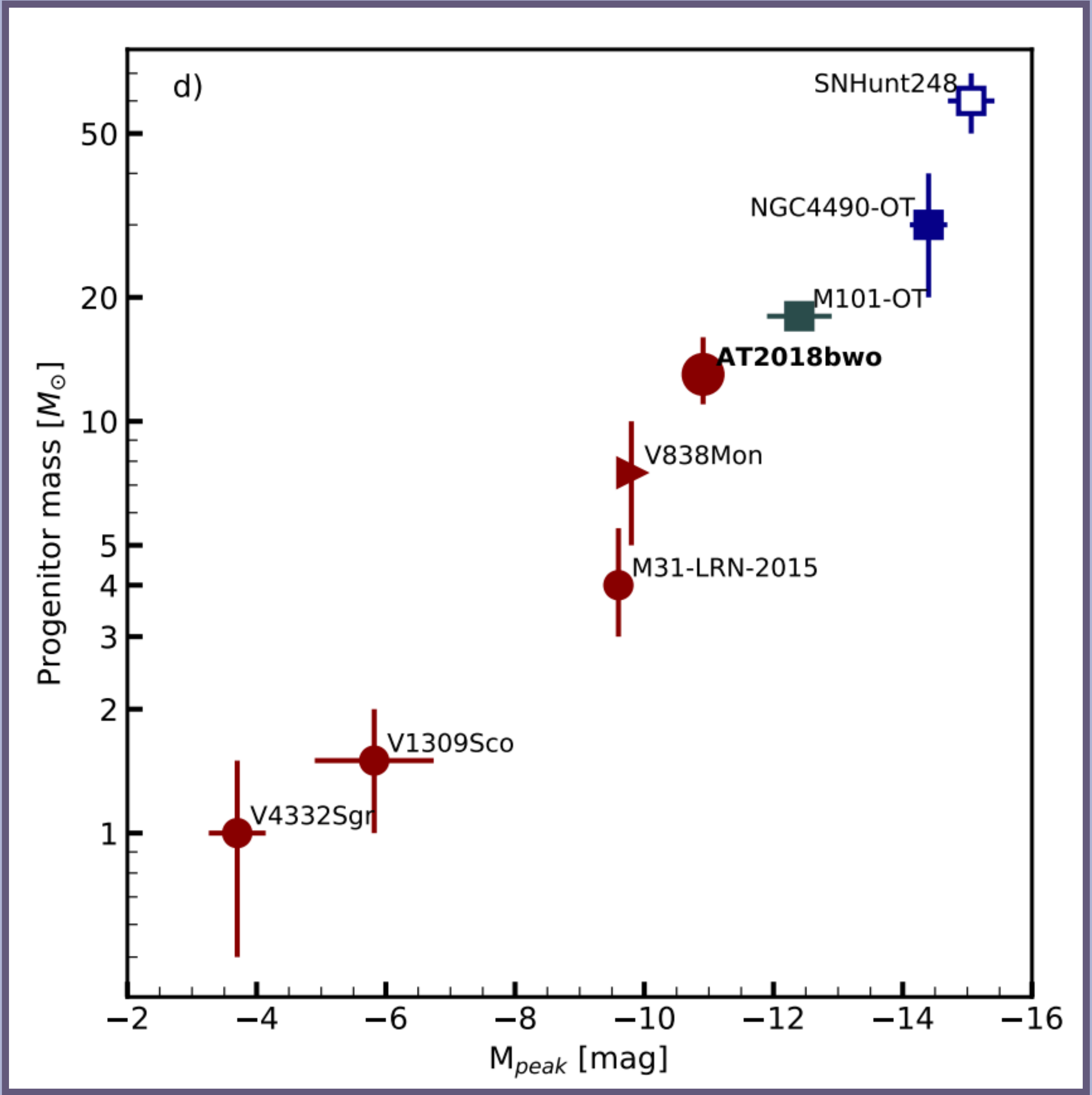


Osiwala et al. 2003

MERGERS

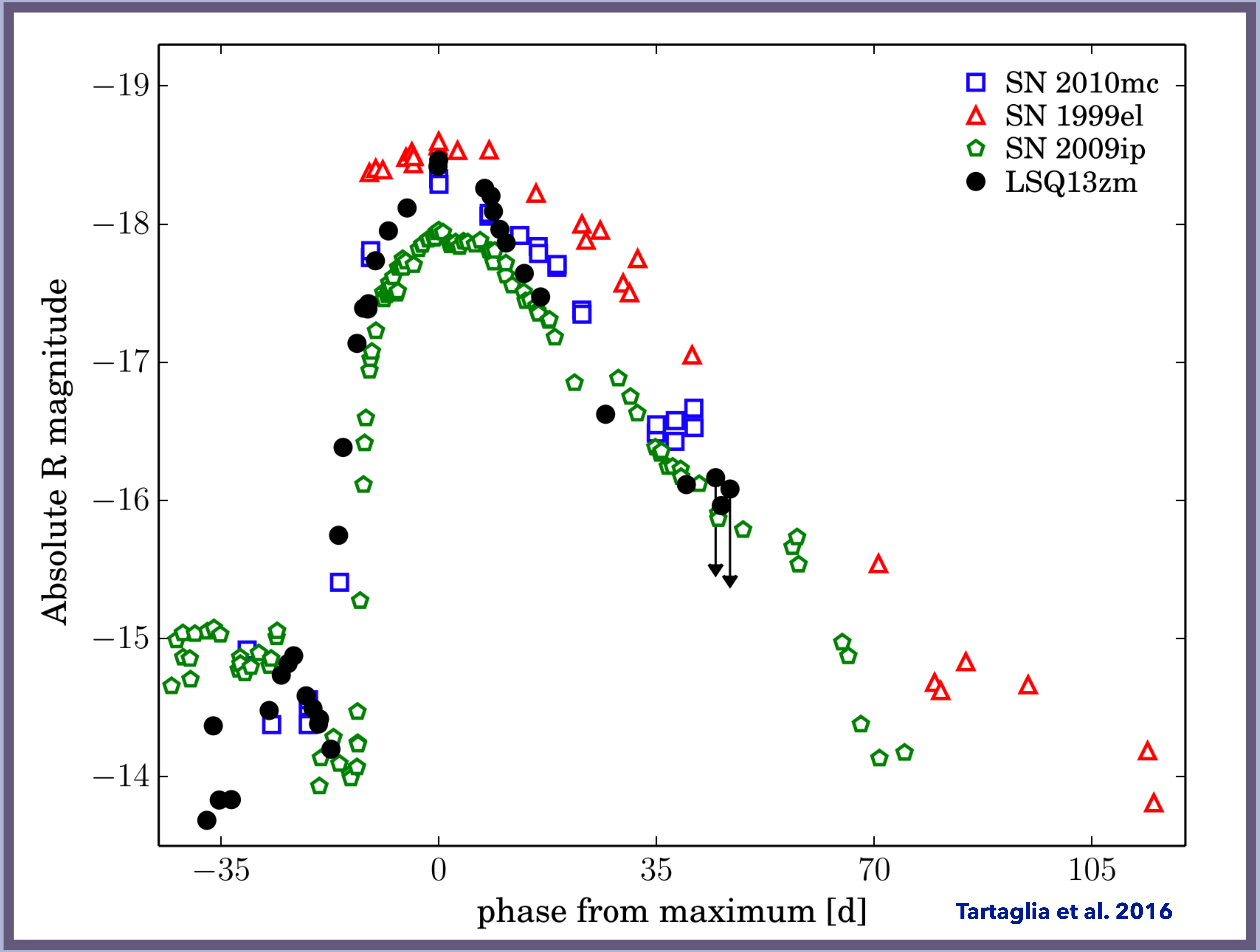


Mauerhan et al. 2018



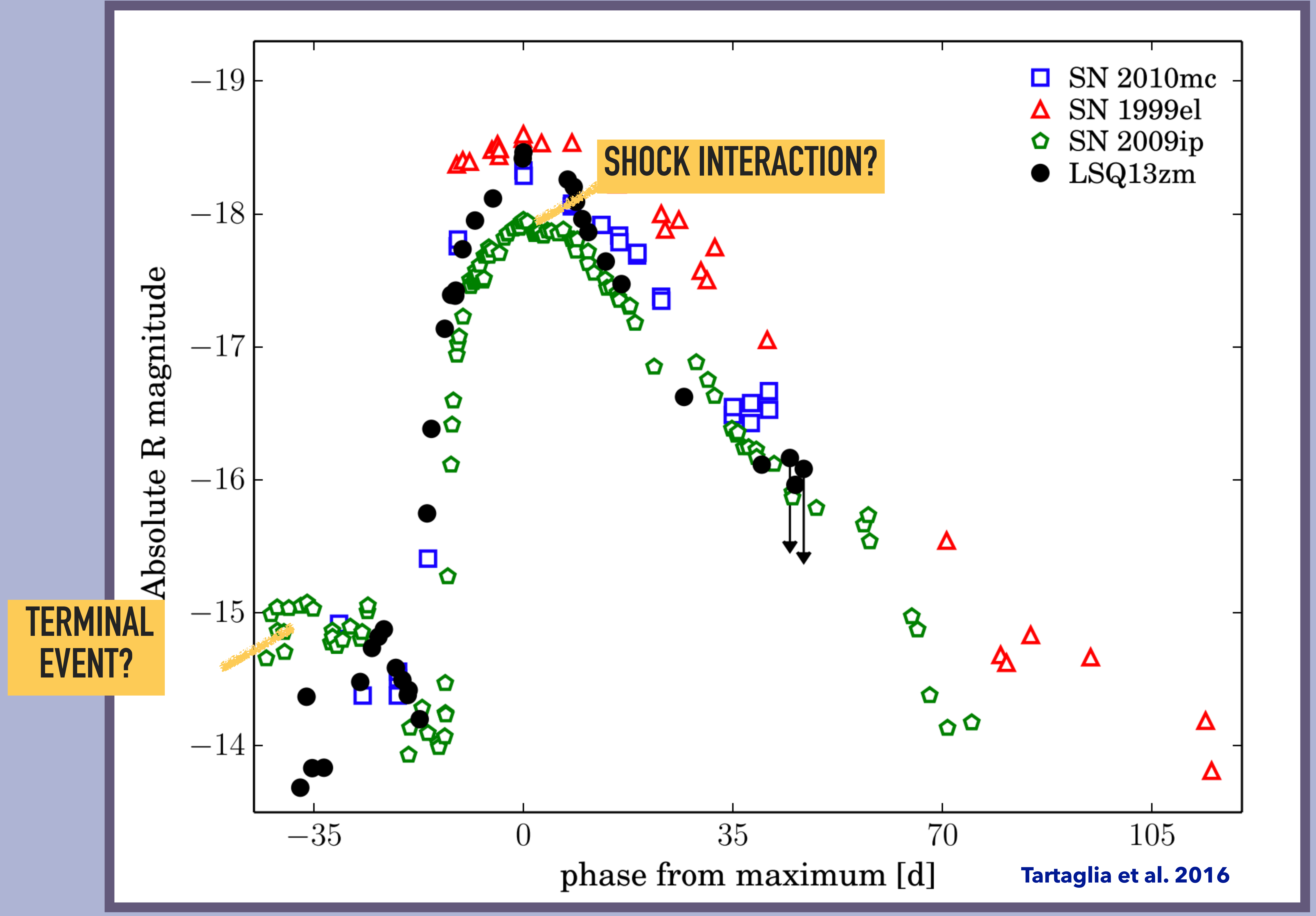
Blagorodnova et al. 2021

PRE-SUPERNOVA OUTBURSTS



More of these pre-supernova events will be discovered in the Rubin and Roman era.

PRE-SUPERNOVA OUTBURSTS



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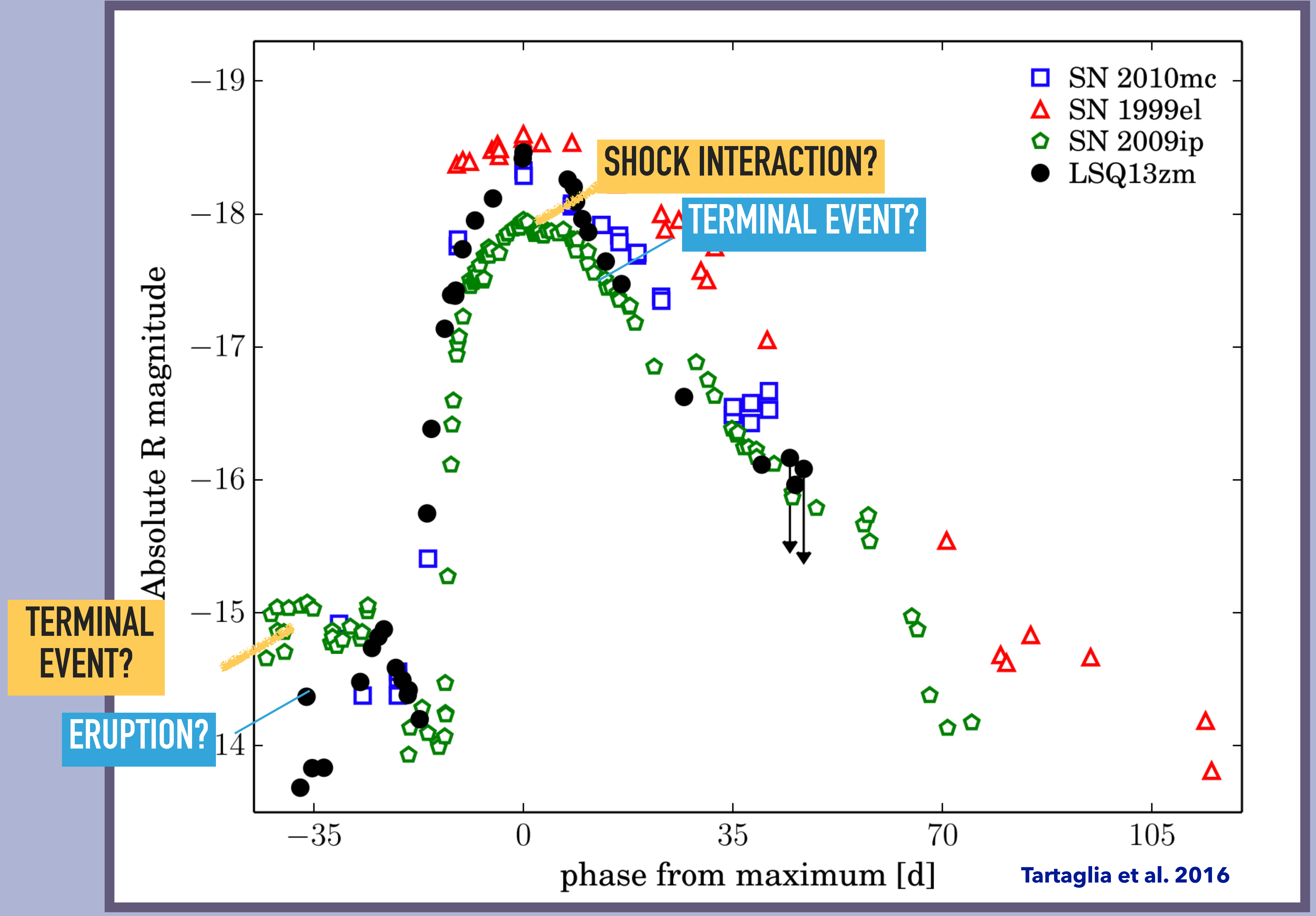
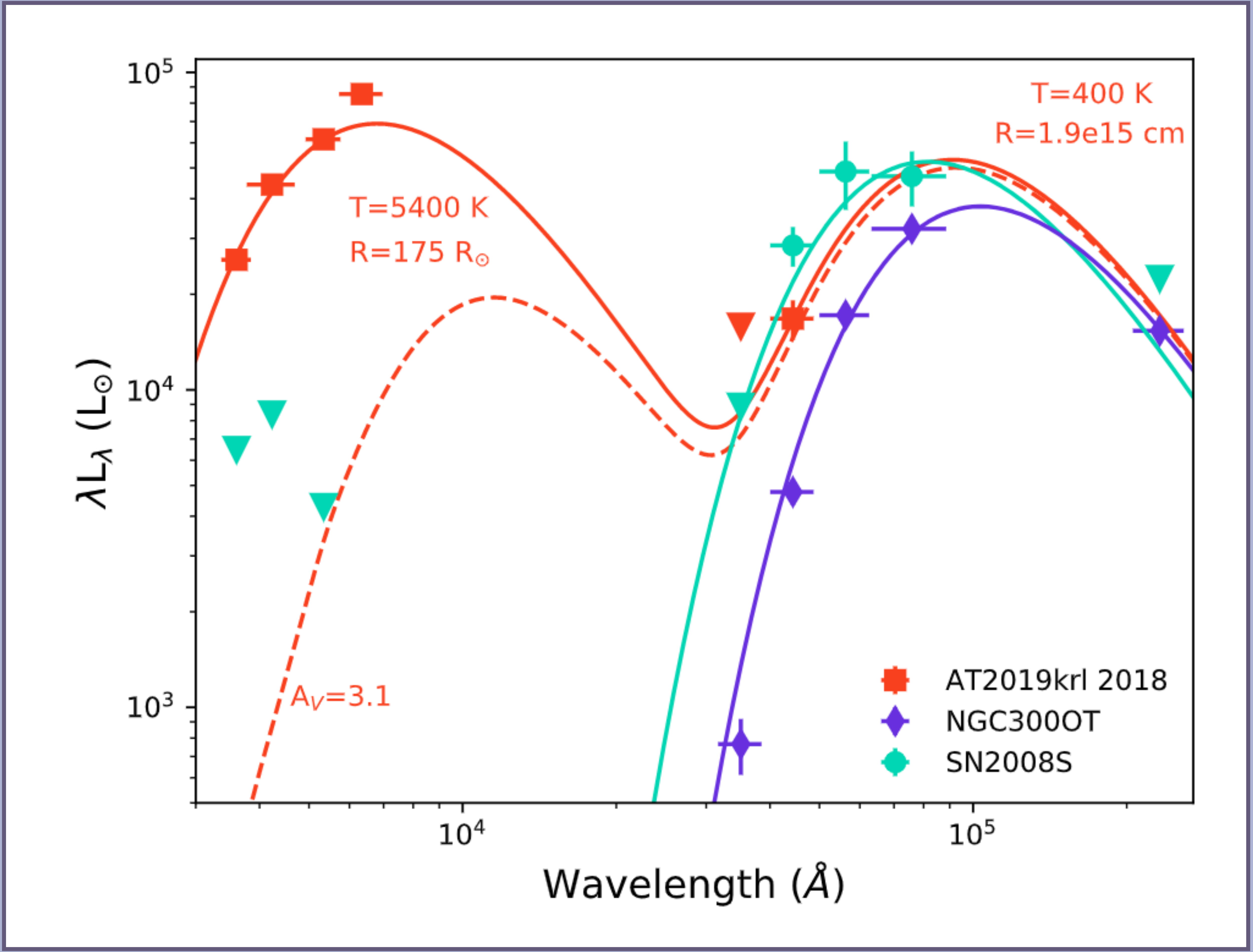


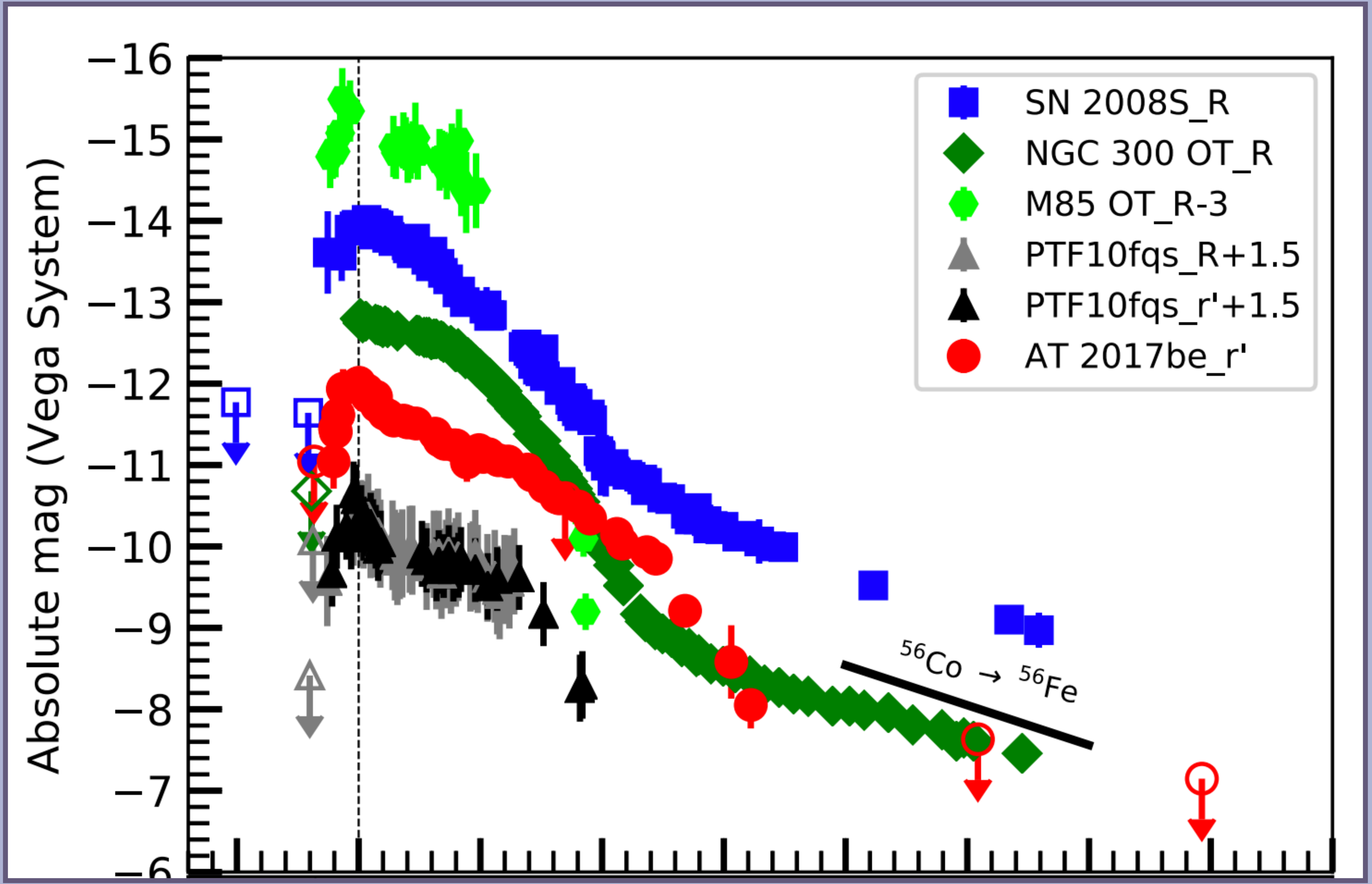
More of these pre-supernova events will be discovered in the Rubin and Roman era.

INTERMEDIATE LUMINOSITY TRANSIENTS

- Super AGB stars? (only 8-10 M☉)
- Terminal: Electron capture SN?
- Dust enshrouded progenitor; non-detection in optical

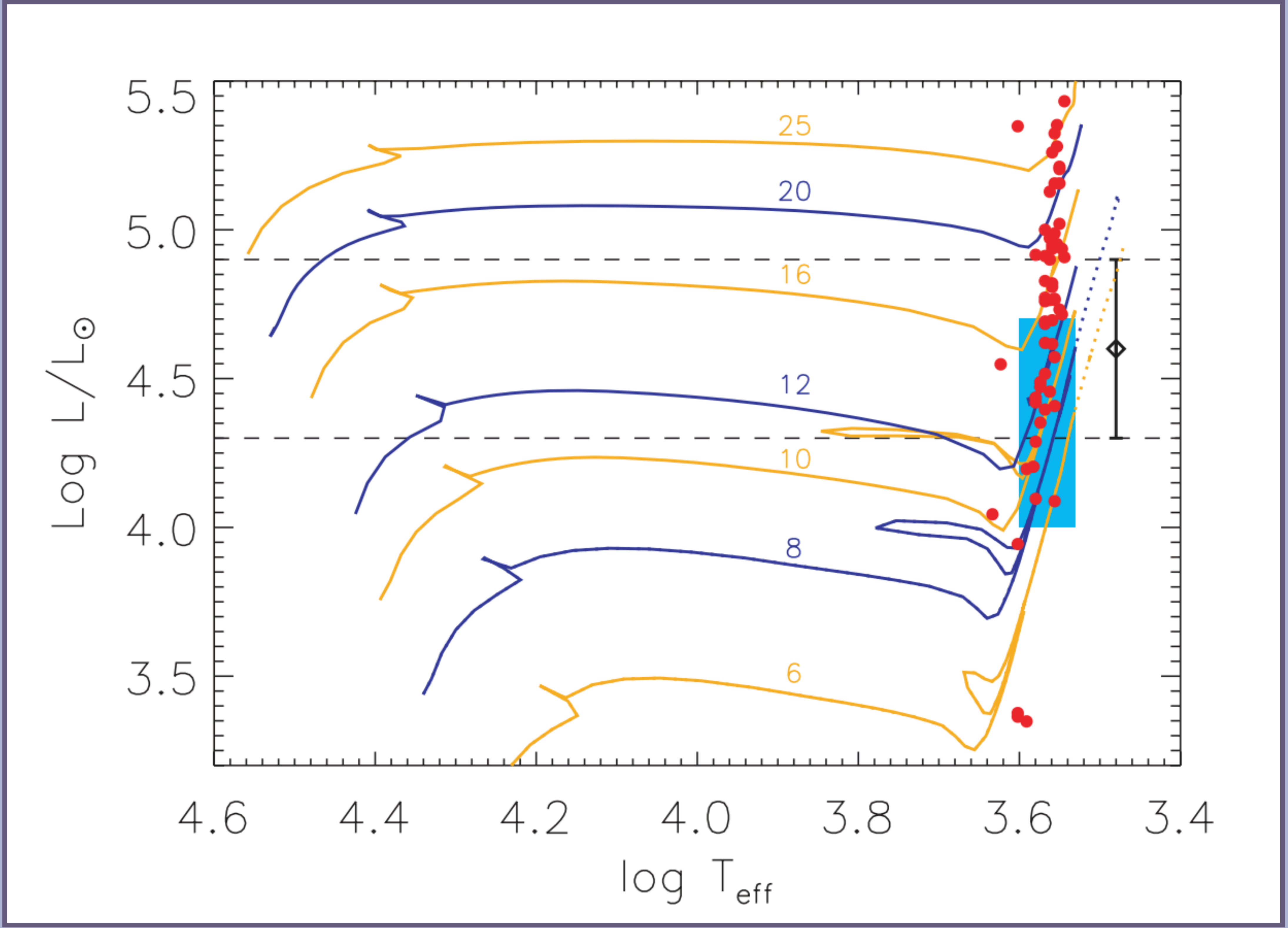


Andrews et al. 2021

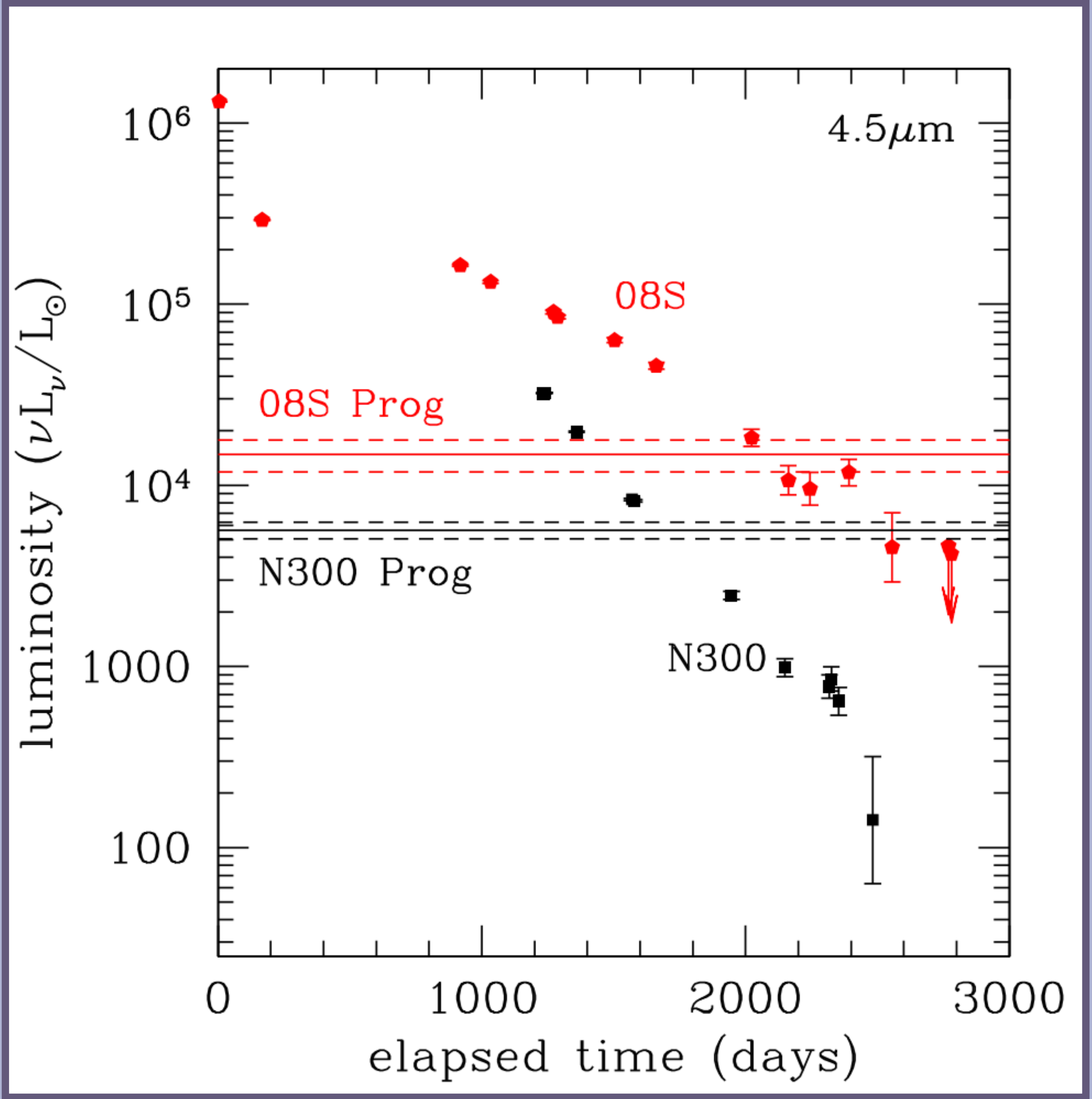


Cai et al. 2018

INTERMEDIATE LUMINOSITY TRANSIENTS



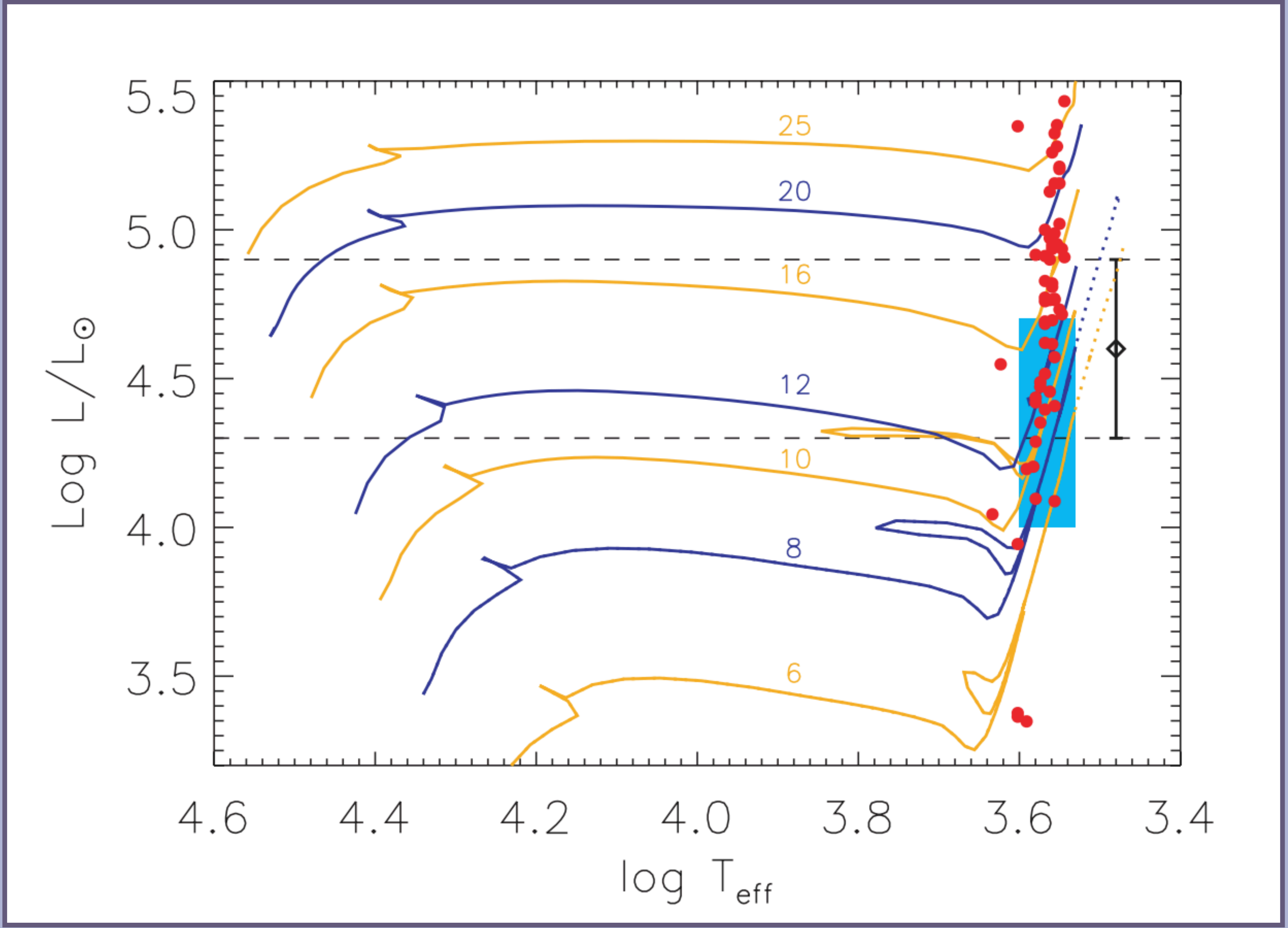
Botticella et al. 2009



Adams et al. 2016

INTERMEDIATE LUMINOSITY TRANSIENTS

- Continued observations are needed to determine if explosion was terminal (ECSNe) or dusty, massive star eruption.



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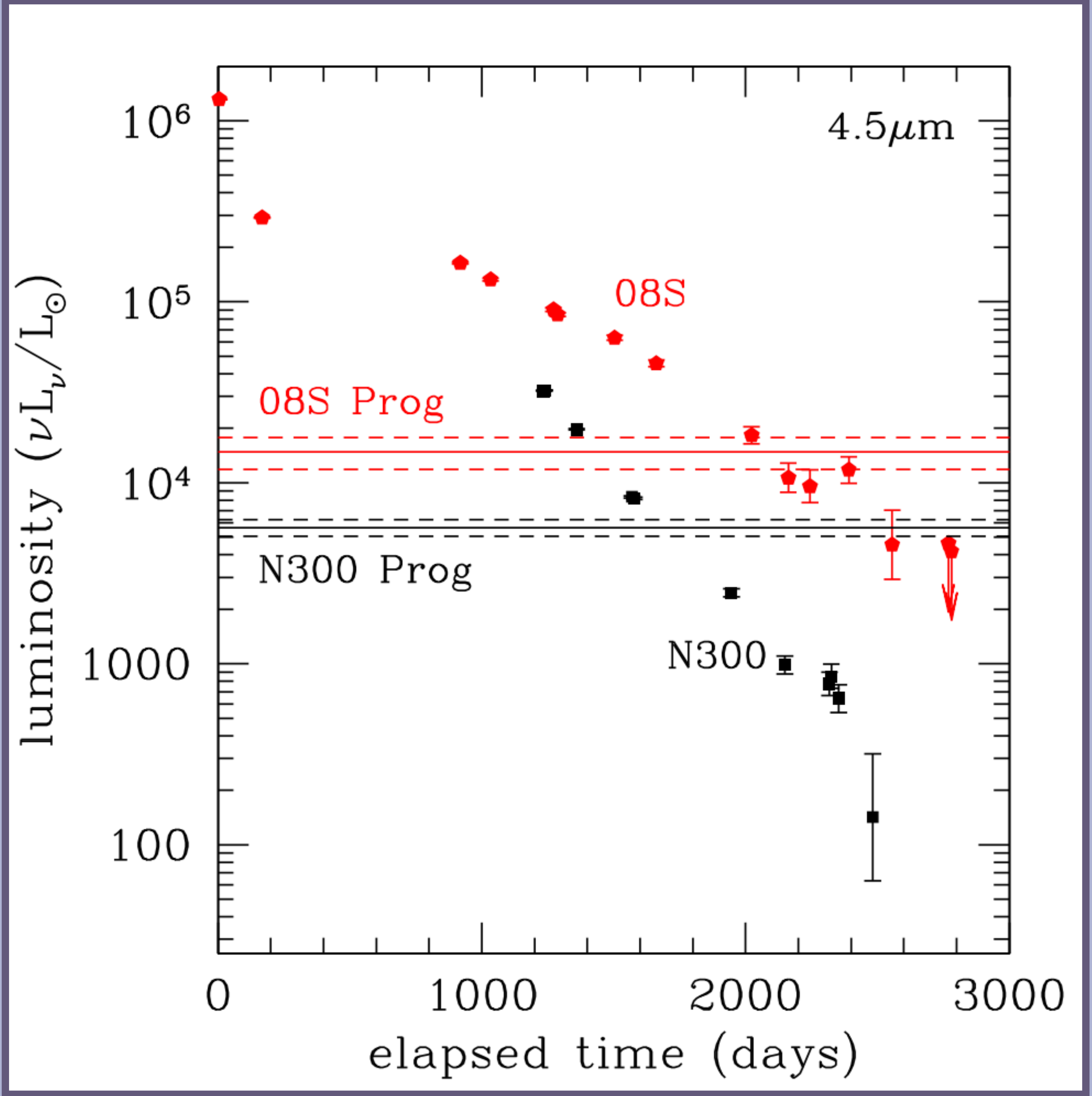

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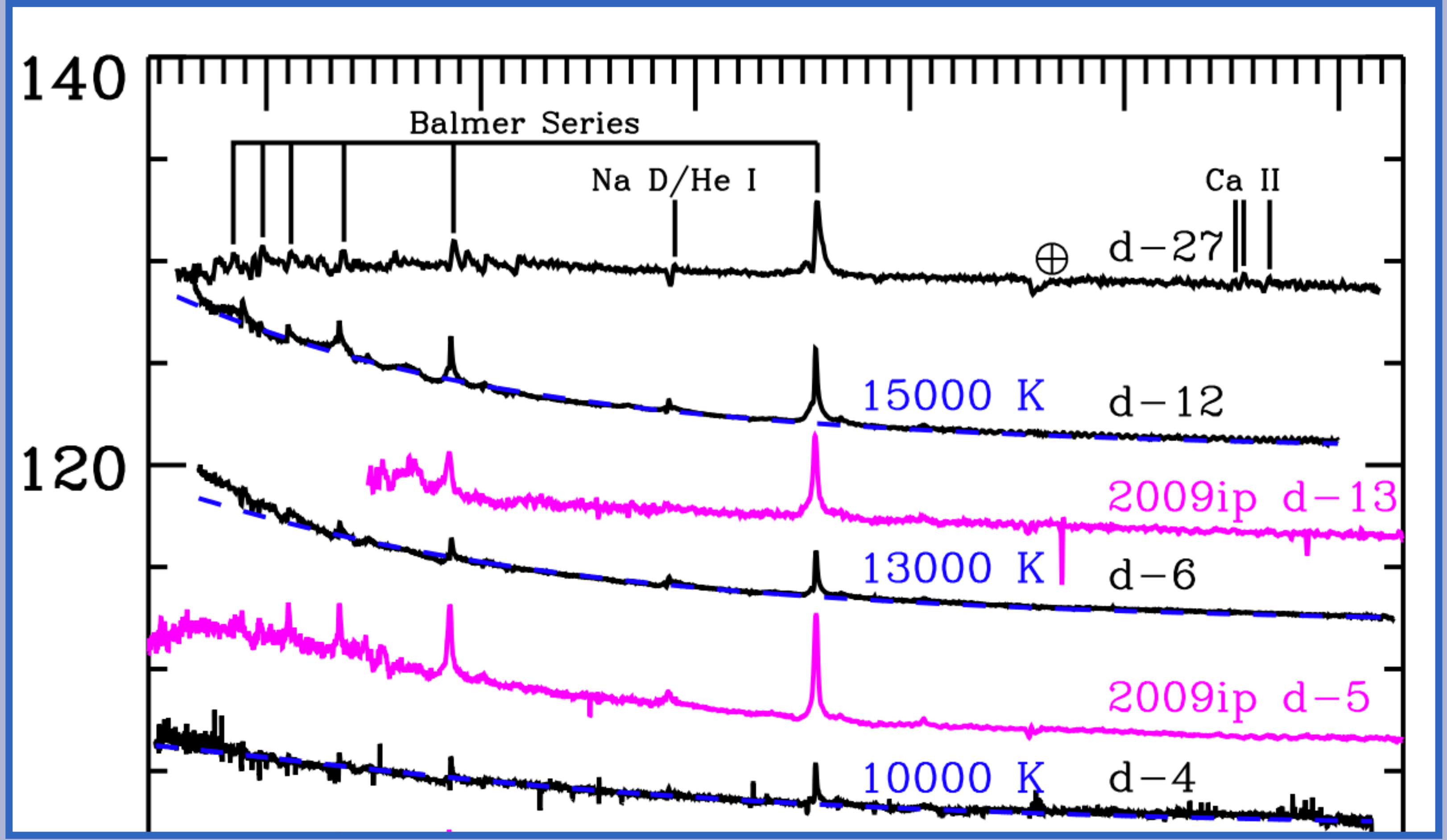
GAP TRANSIENTS - SIMPLE PICTURE

LBVs

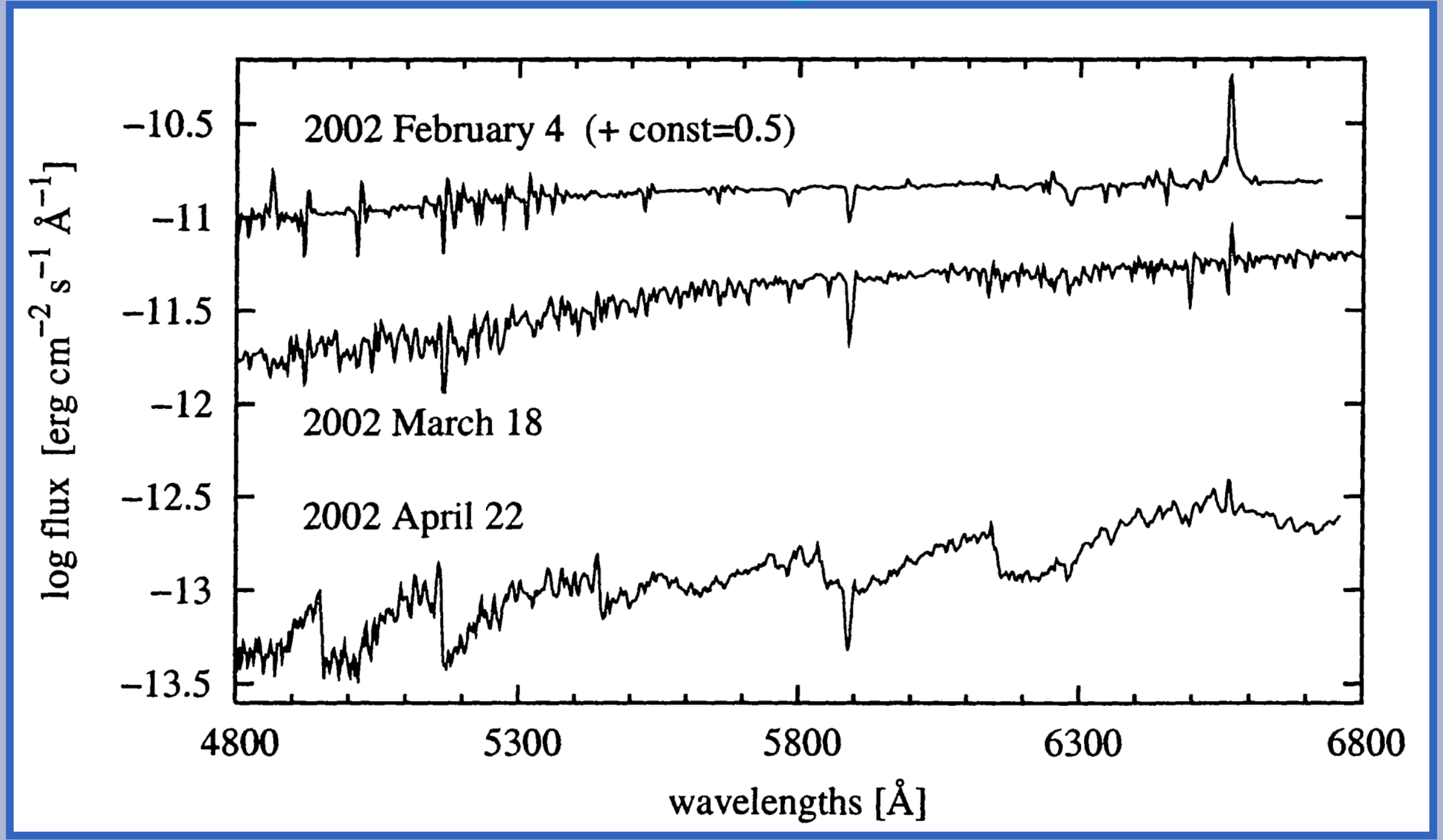
super-Eddington eruption in single massive star



Kilpatrick et al. 2018

LRNe/RNe

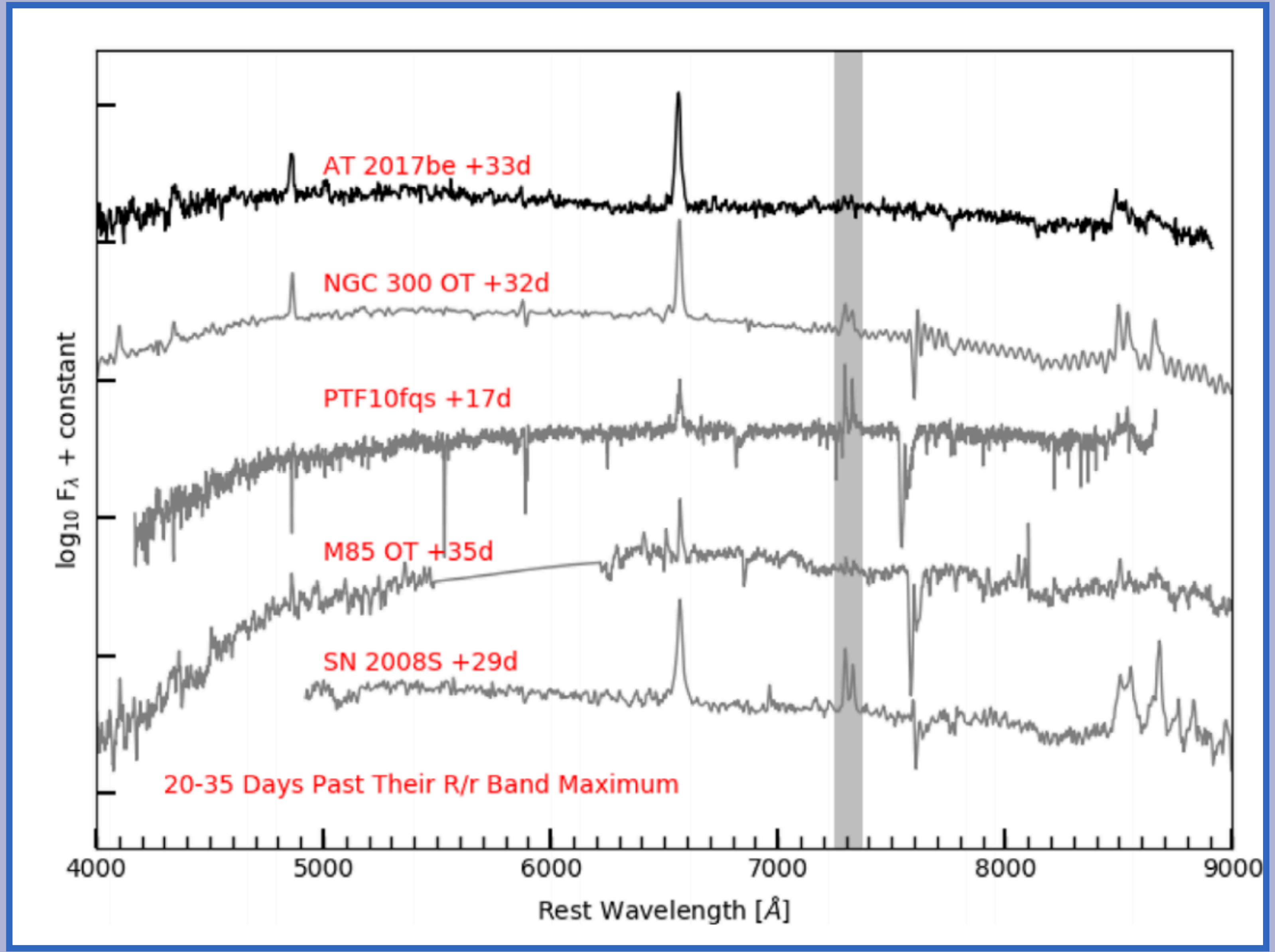
Mergers or CE Event of two stars, any mass



Osiwala et al. 2003

ILRT/ SN2008S-like

ECSNe of 8-10 $M_{\odot}$



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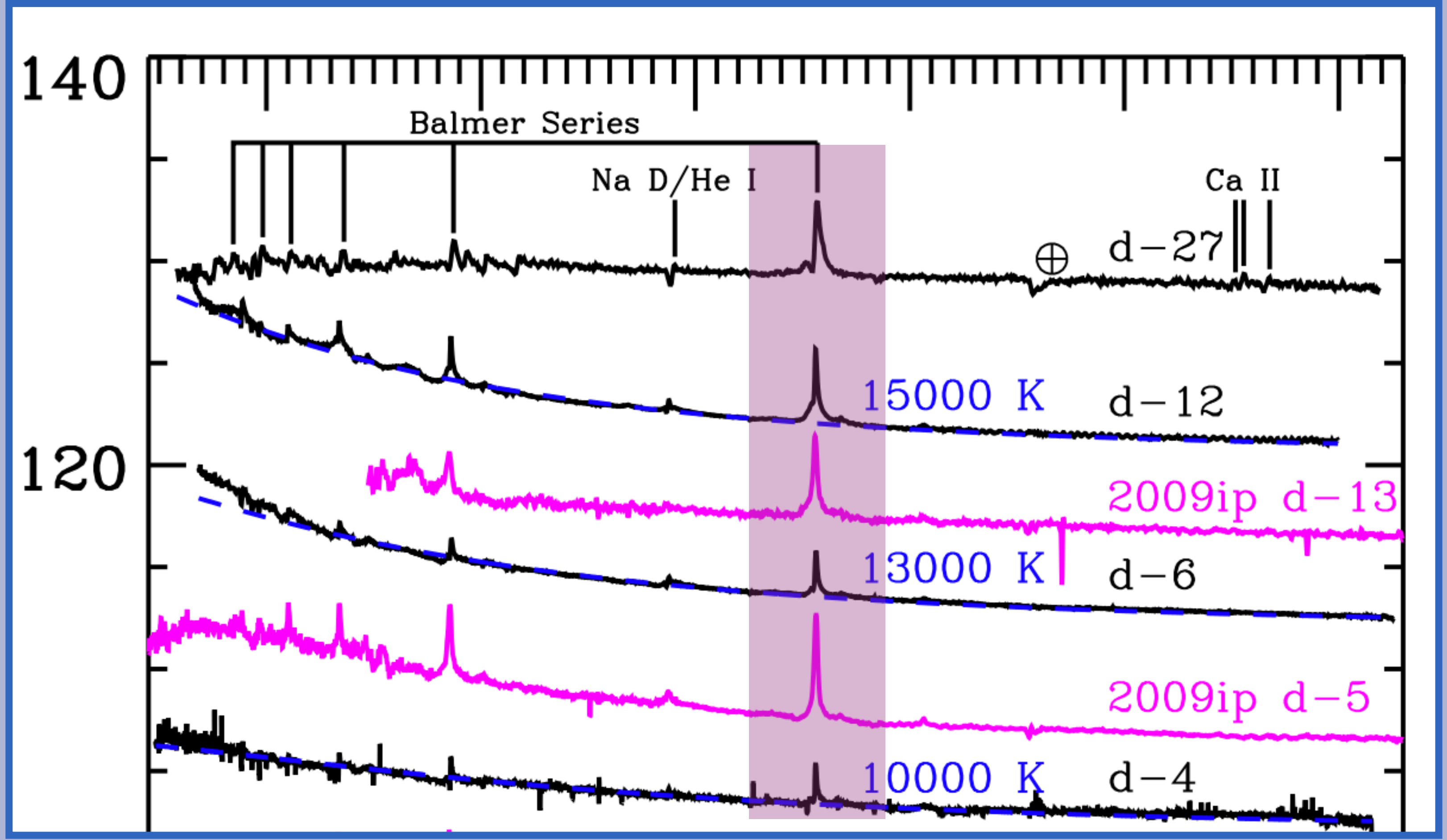

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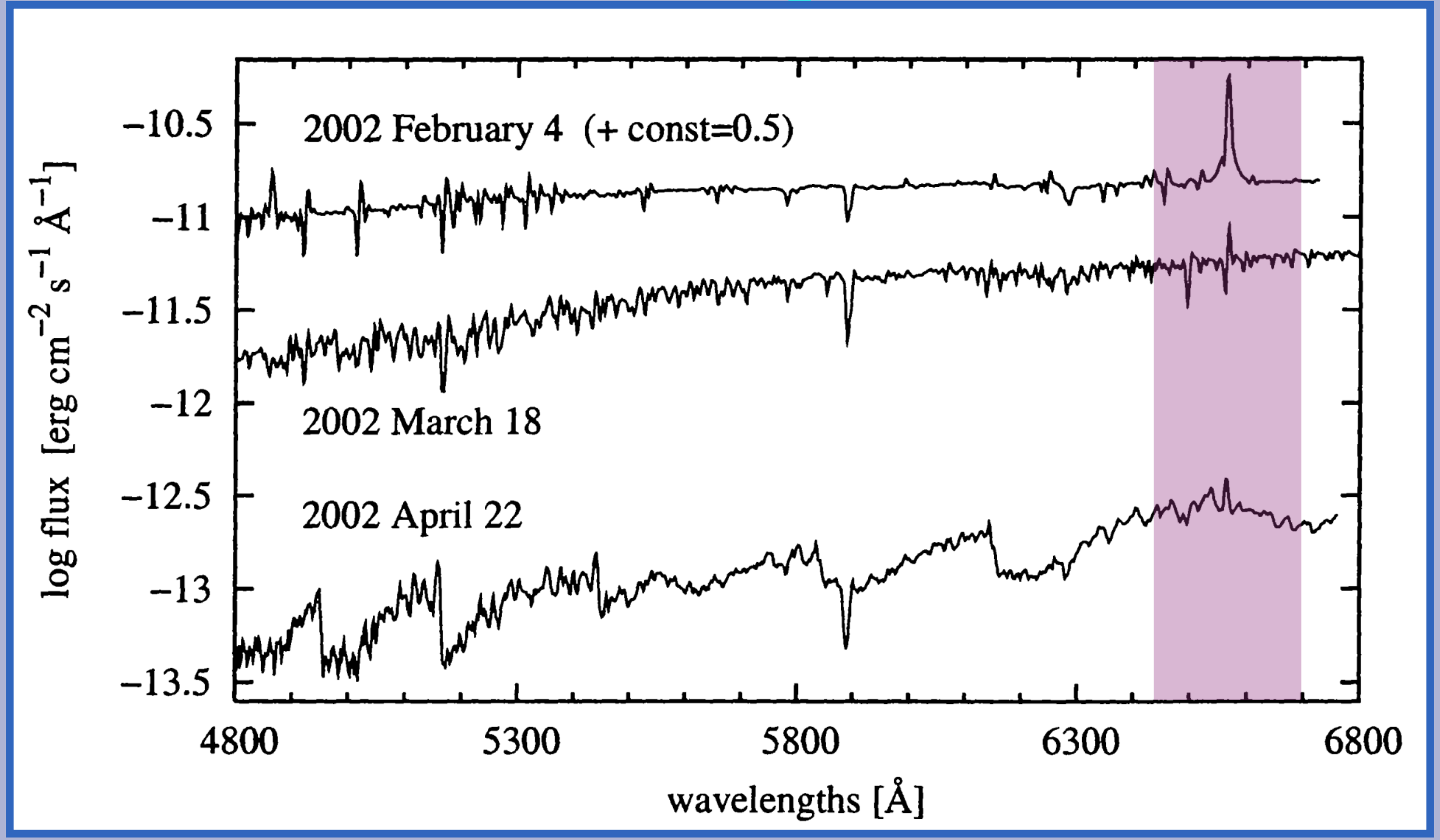

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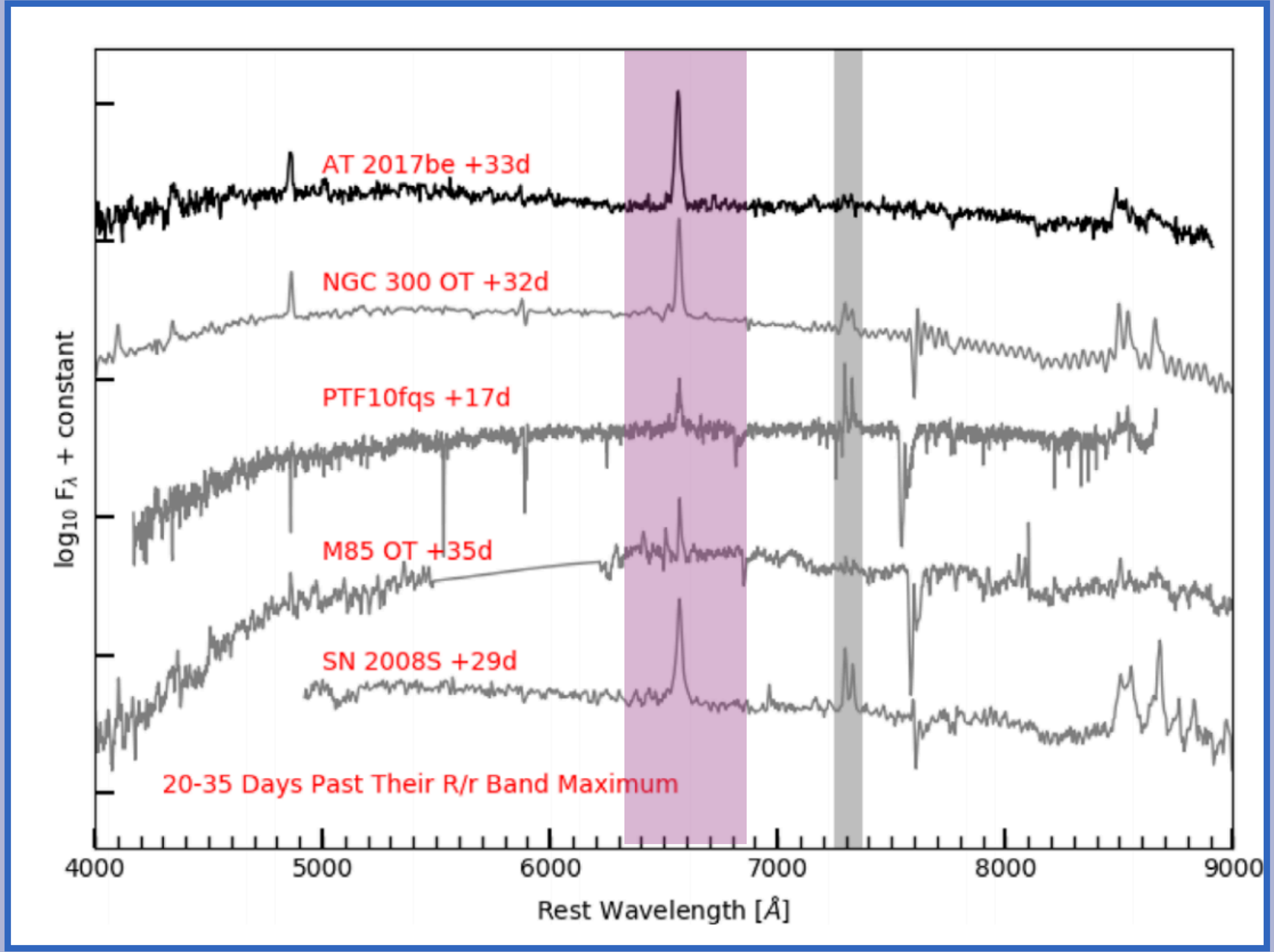

Cai et al. 2018

CONCLUSIONS

- Episodic and eruptive mass loss is a common occurrence for massive stars.
- Massive star eruptions are interesting in their own right, but also help frame our understanding of CCSNe with respect to mass-loss.
- Roman will be invaluable at probing dust enshrouded transients and will aid in differentiating terminal and non-terminal transients.
- Roman will provide us a rich database to search for pre-supernova outbursts.