Recent Advancements in Core-Collapse Supernova Observation Through the Global Supernova Project

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Kavli Institute for the Physics and Mathematics of the Universe

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Why Study Core-Collapse Supernovae?

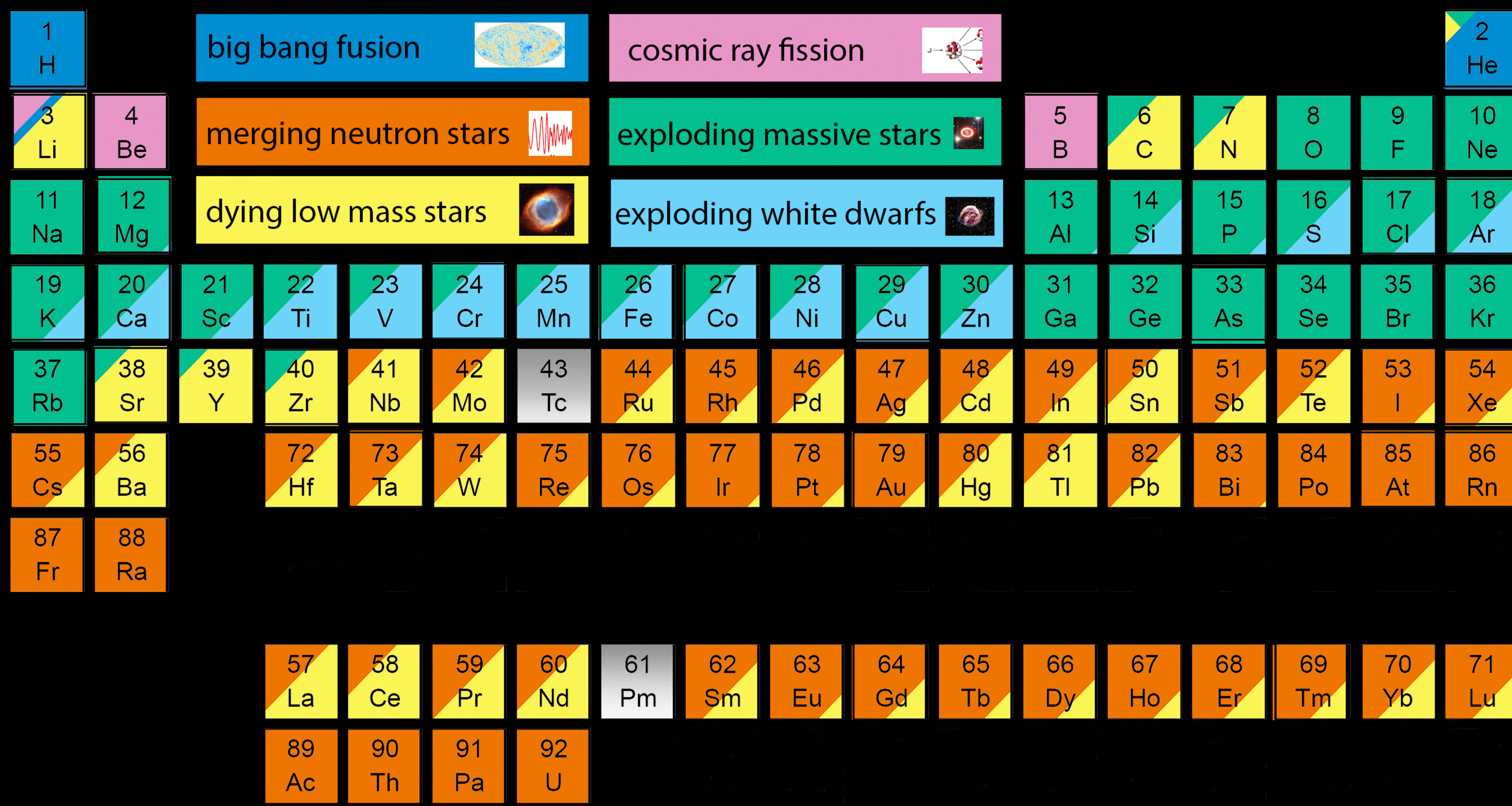
Supernovae (SNe) are among the most influential events in the Universe because SNe:

1. Synthesize heavy elements
2. Trigger starbursts
3. Drive galactic outflows
4. Form compact objects: neutron stars and black holes
5. Produce neutrinos and gravitational waves
6. and blah blah blah

Why Study Core-Collapse Supernovae?

Chemical Evolution

The Origin of the Solar System Elements

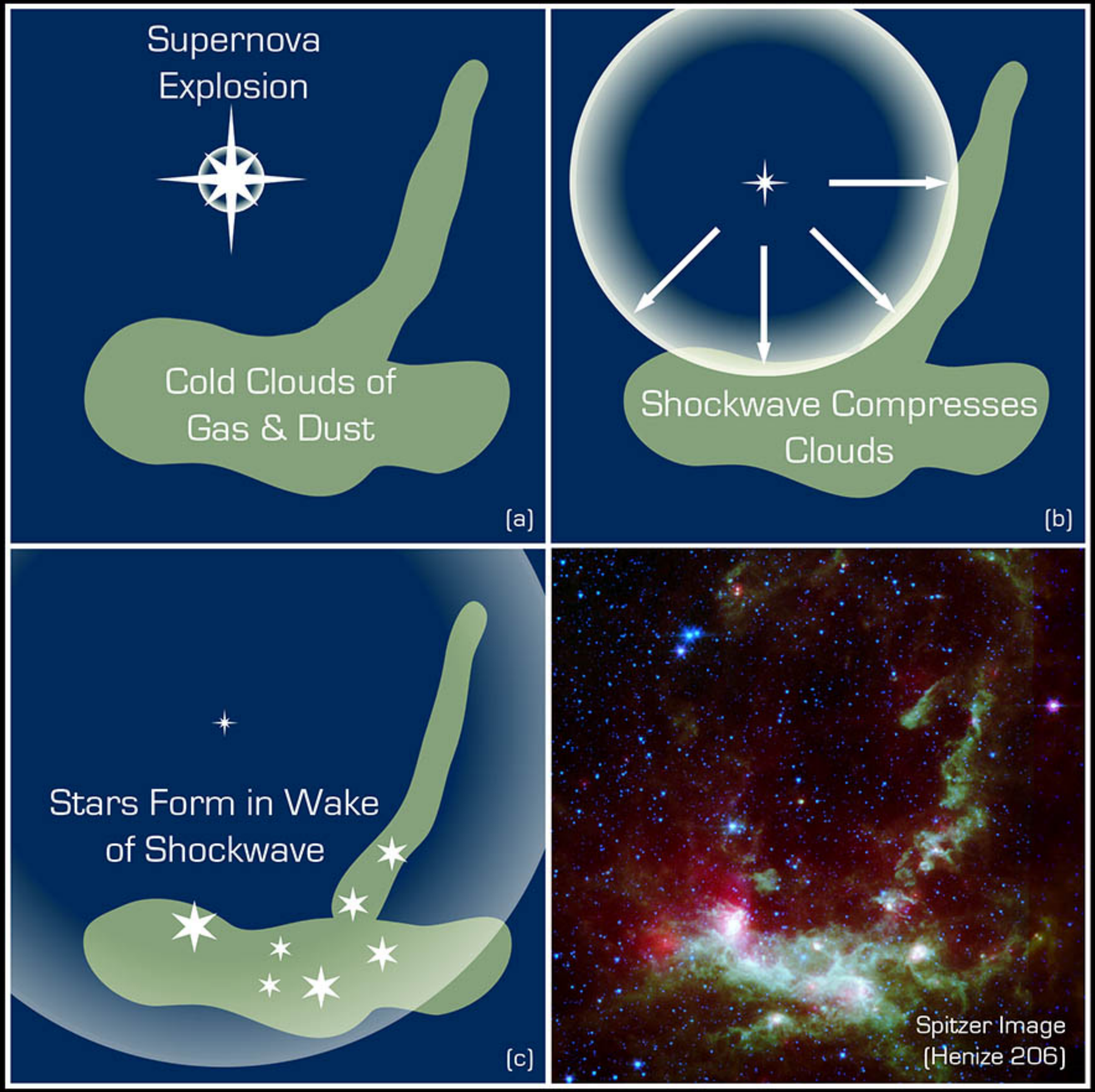


Astronomical Image Credits:
ESA/NASA/AASNova

Graphic created by Jennifer Johnson

Why Study Core-Collapse Supernovae?

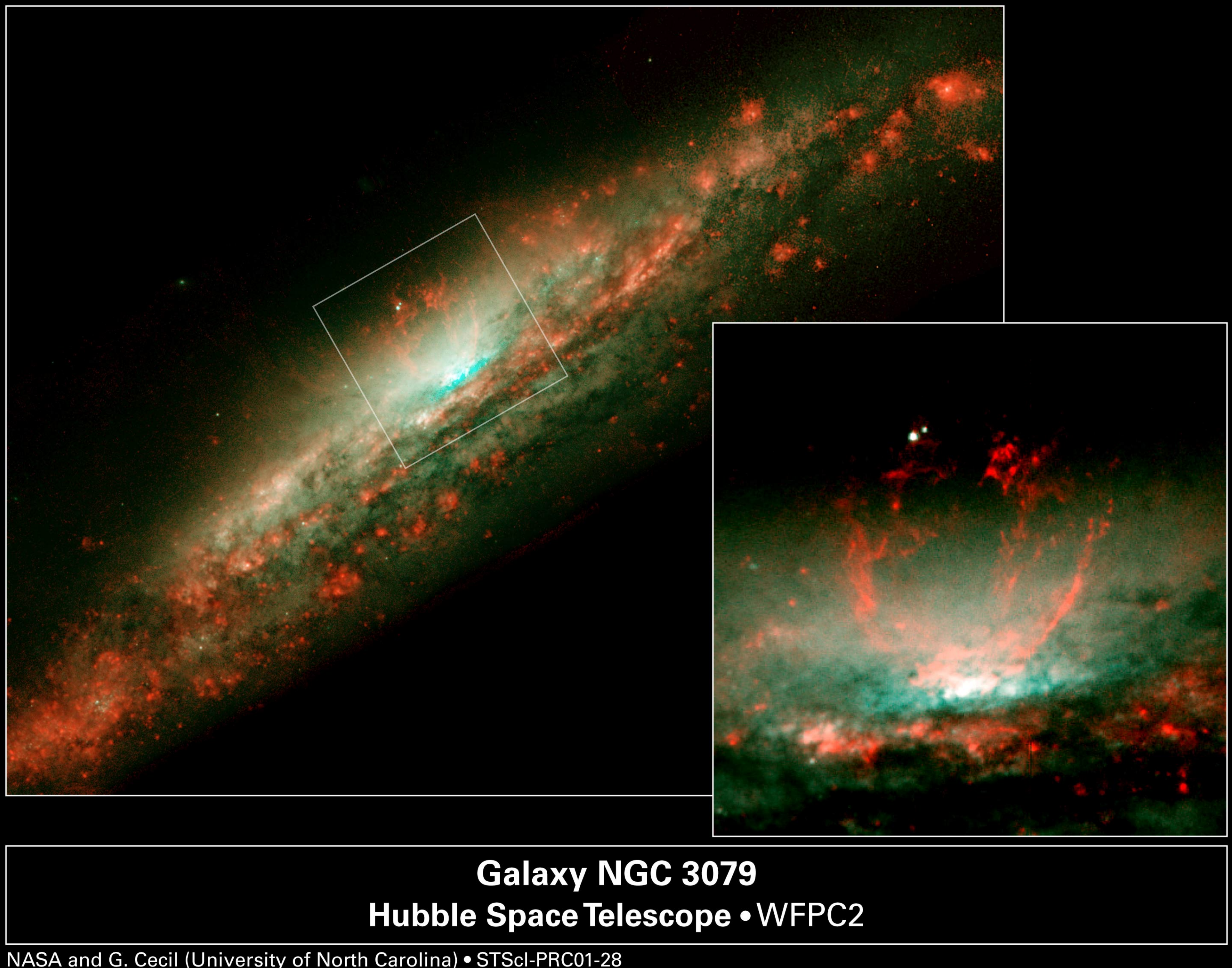
Star Formation



Spitzer Space Telescope • ssc2004-04b

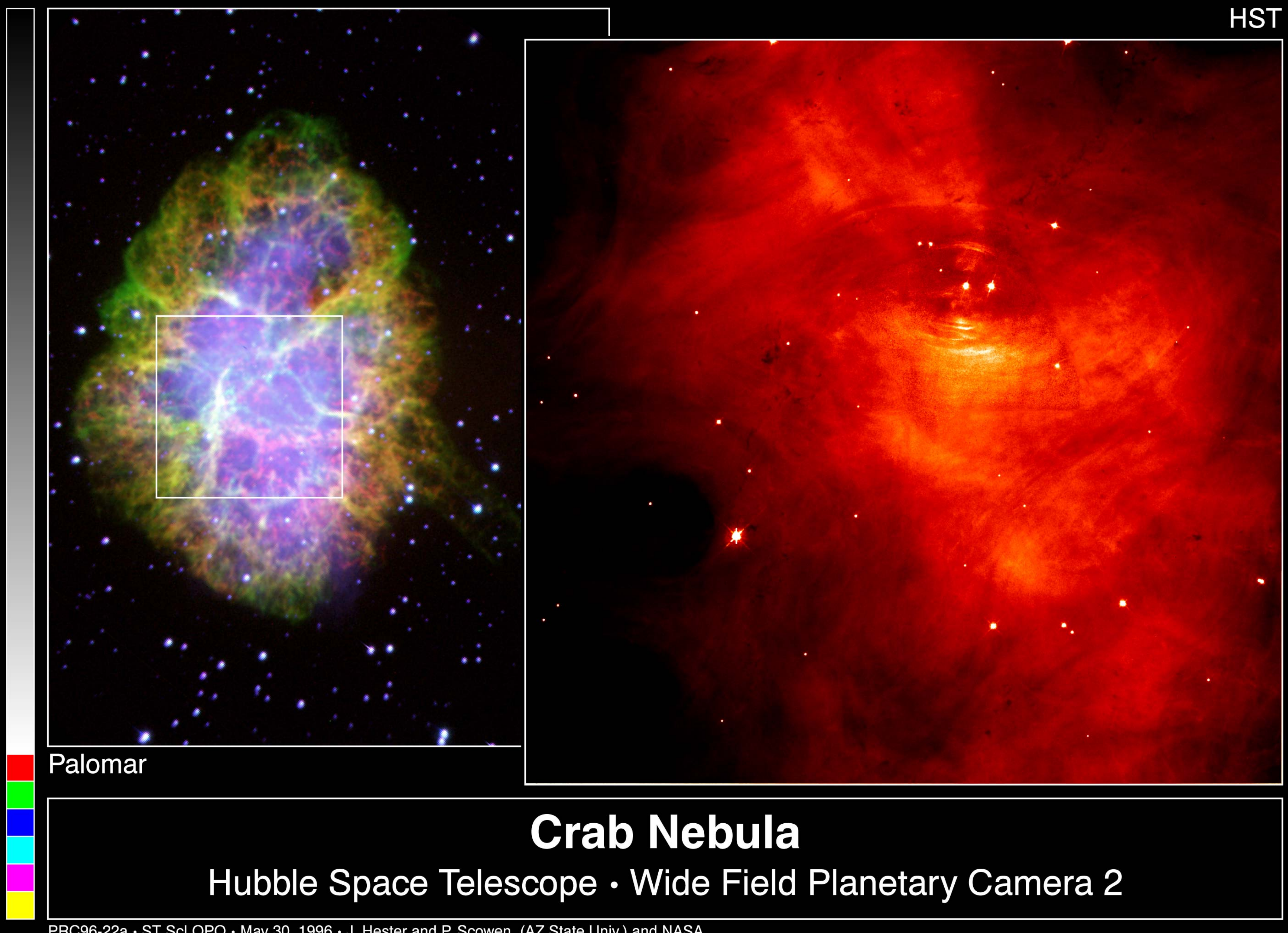
Why Study Core-Collapse Supernovae?

Galactic Evolution



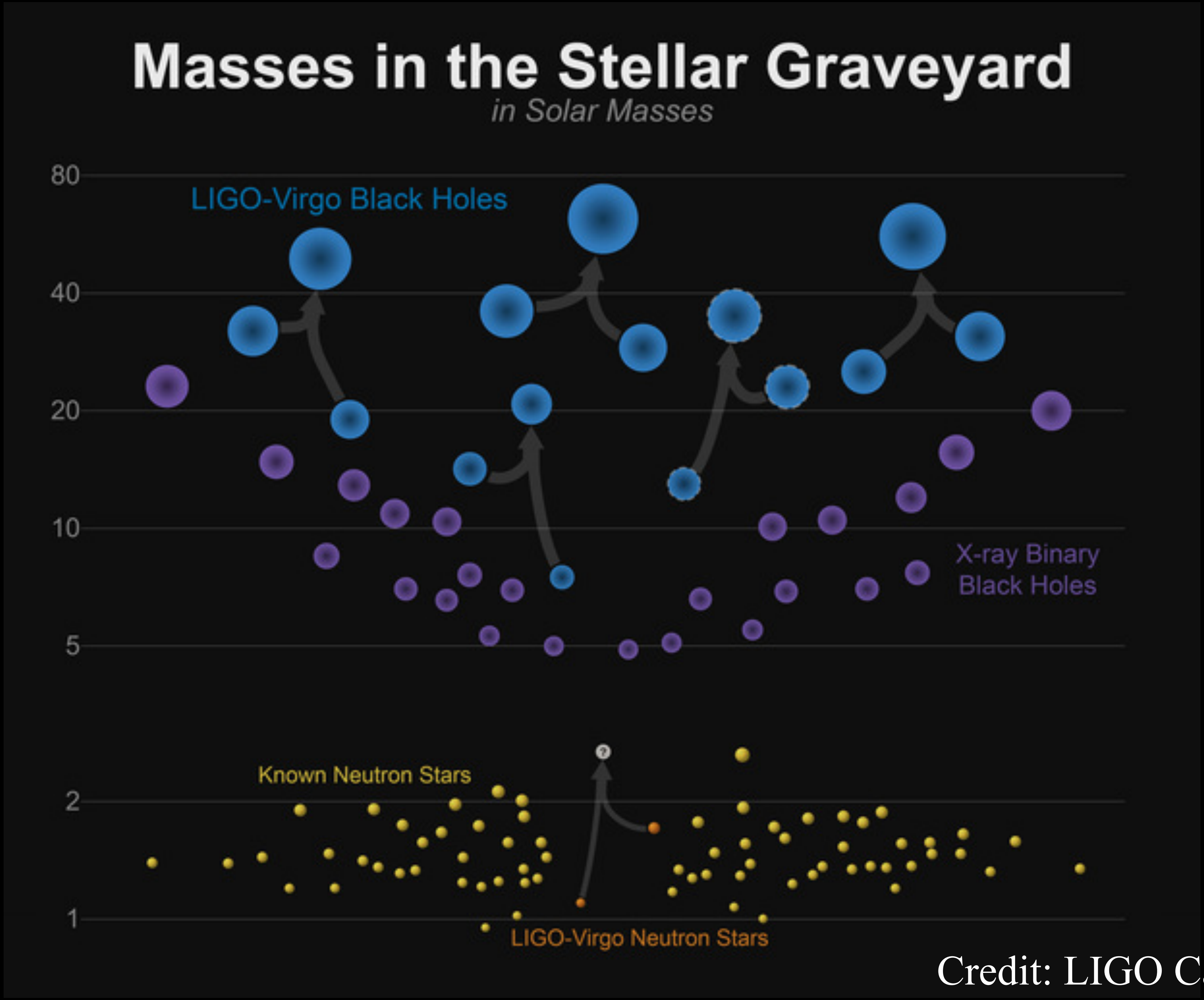
Why Study Core-Collapse Supernovae?

Neutron Stars



Why Study Core-Collapse Supernovae?

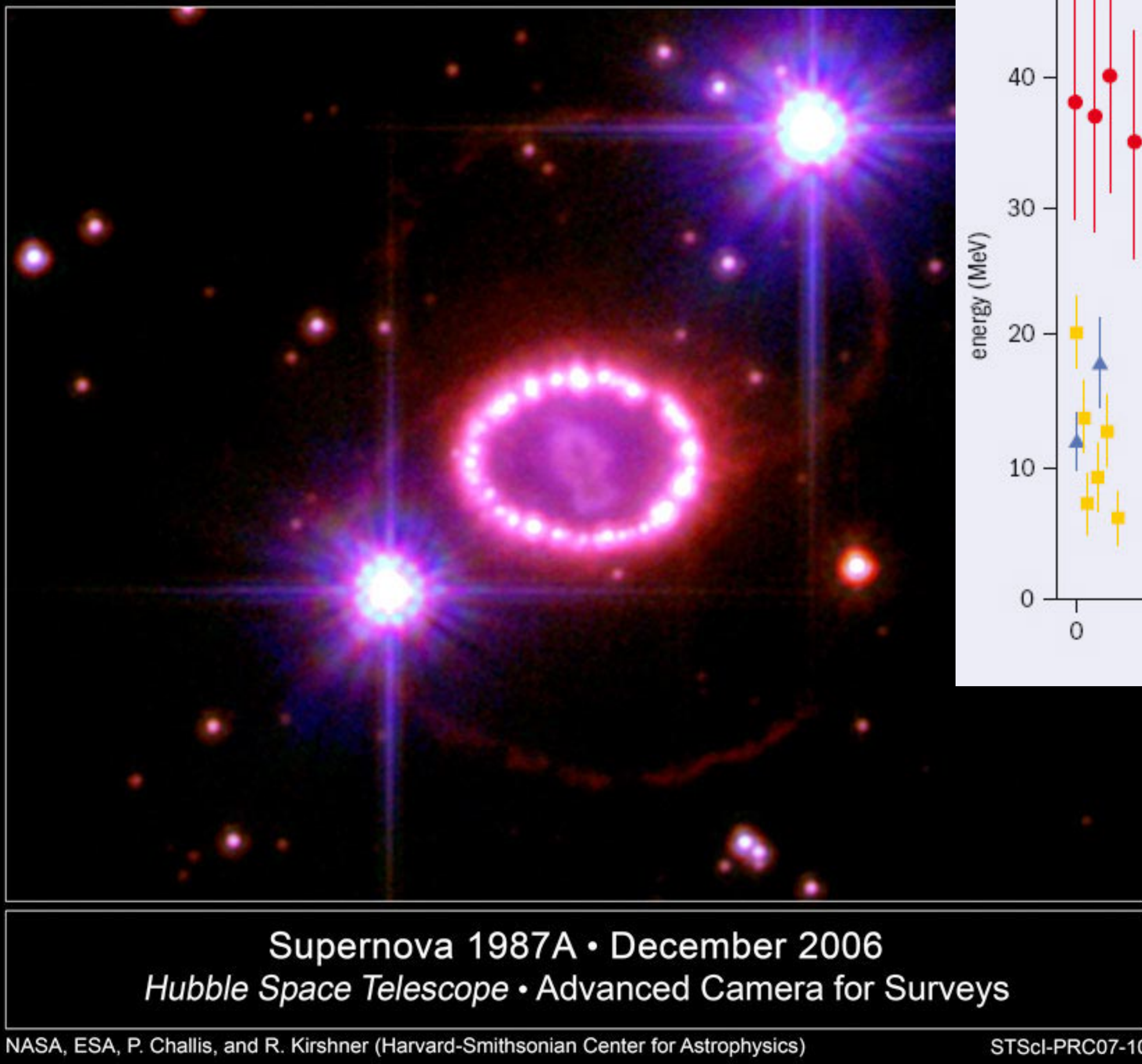
Neutron Stars and Black Holes

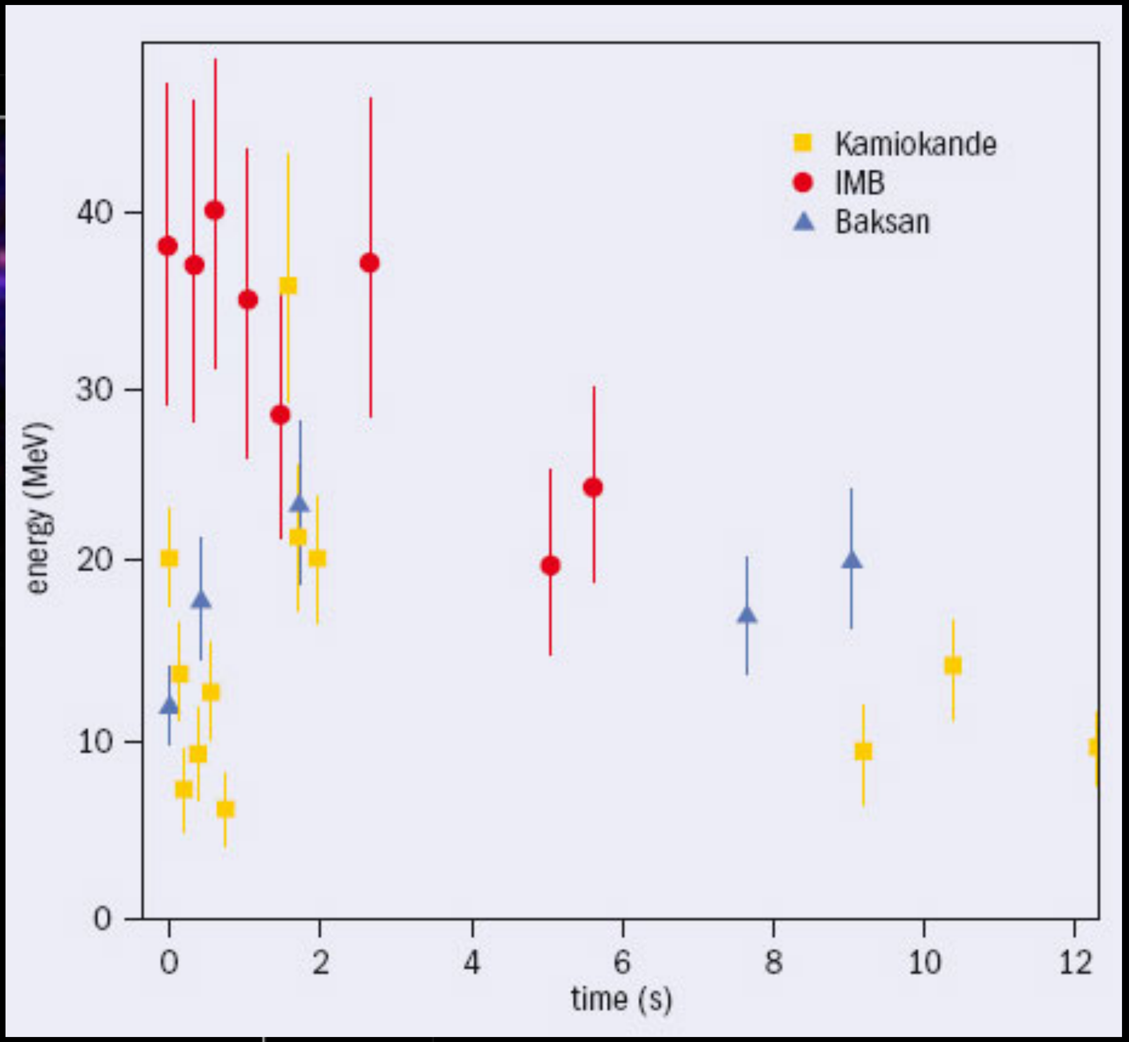


Credit: LIGO Caltech

Why Study Core-Collapse Supernovae?

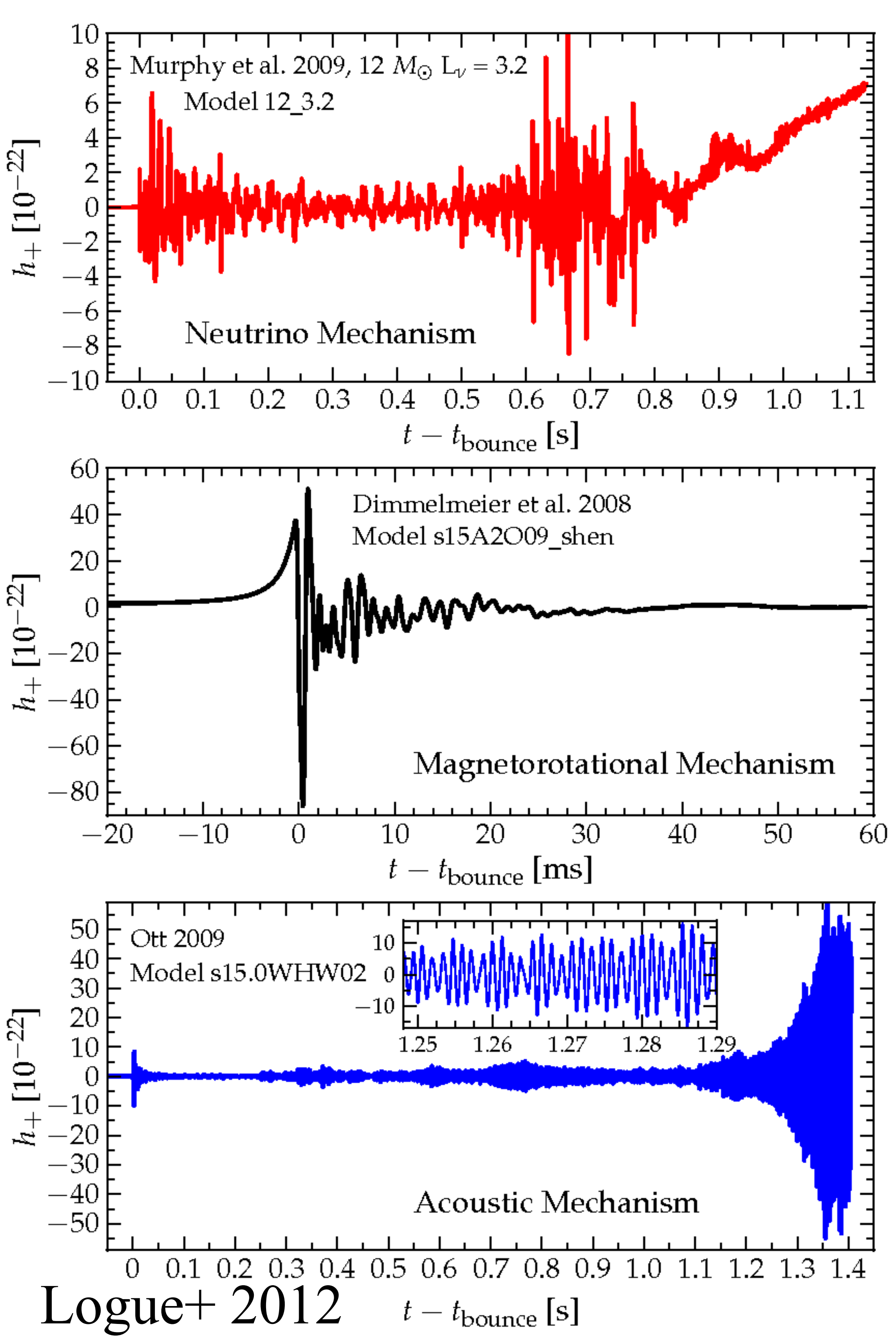
Neutrinos



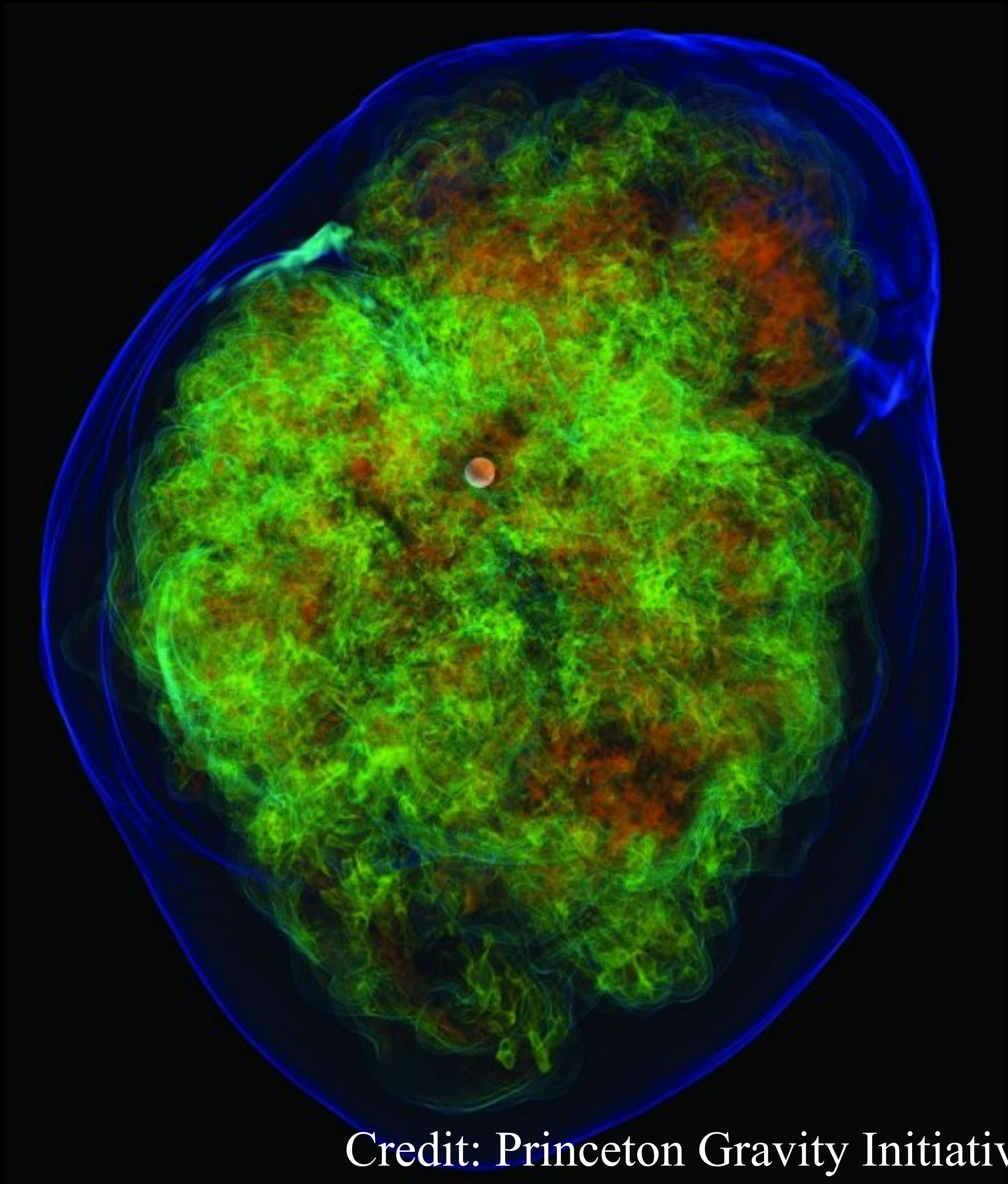


Why Study Core-Collapse Supernovae?

Gravitational Wave



Logue+ 2012



Credit: Princeton Gravity Initiative

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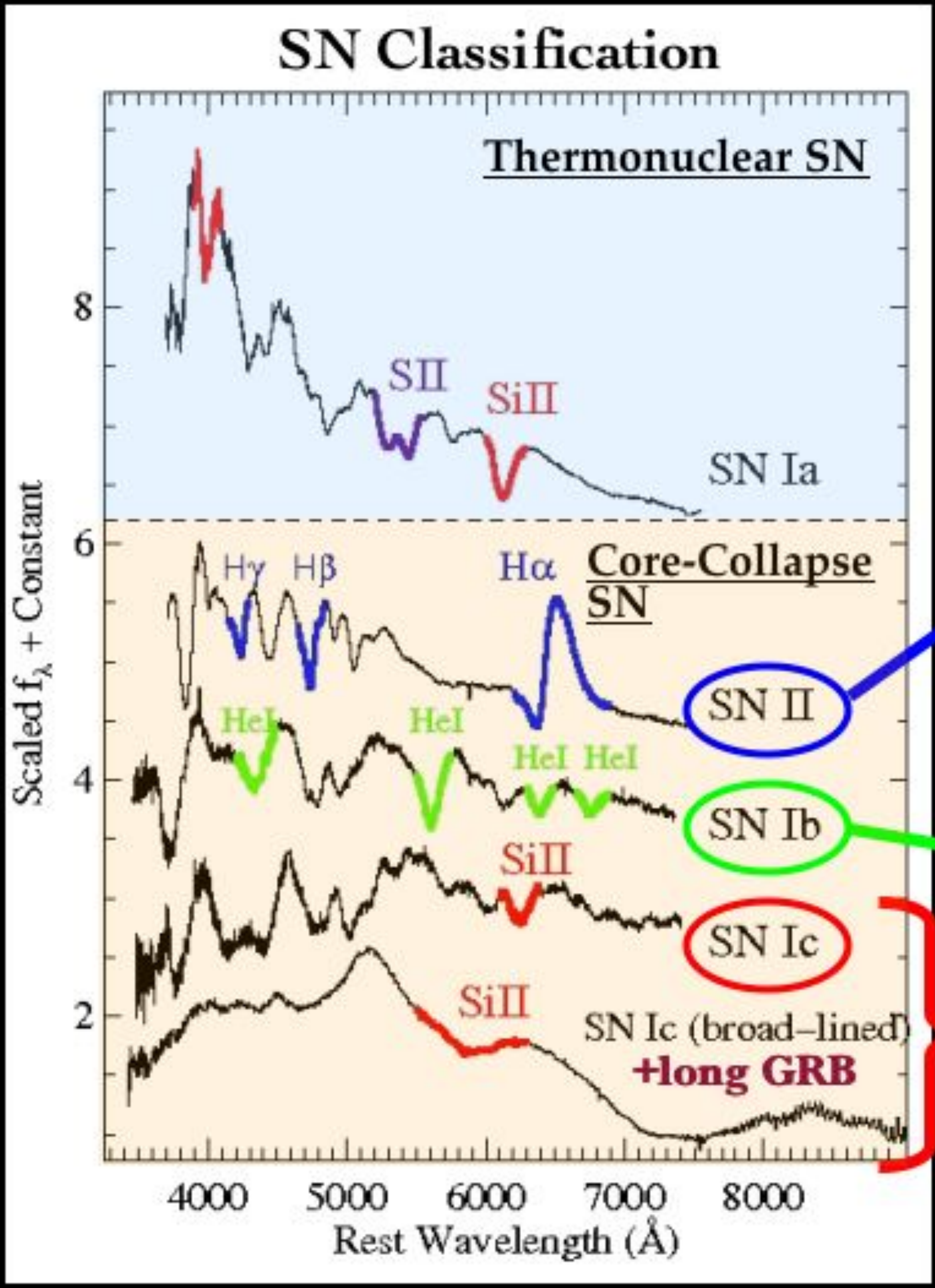
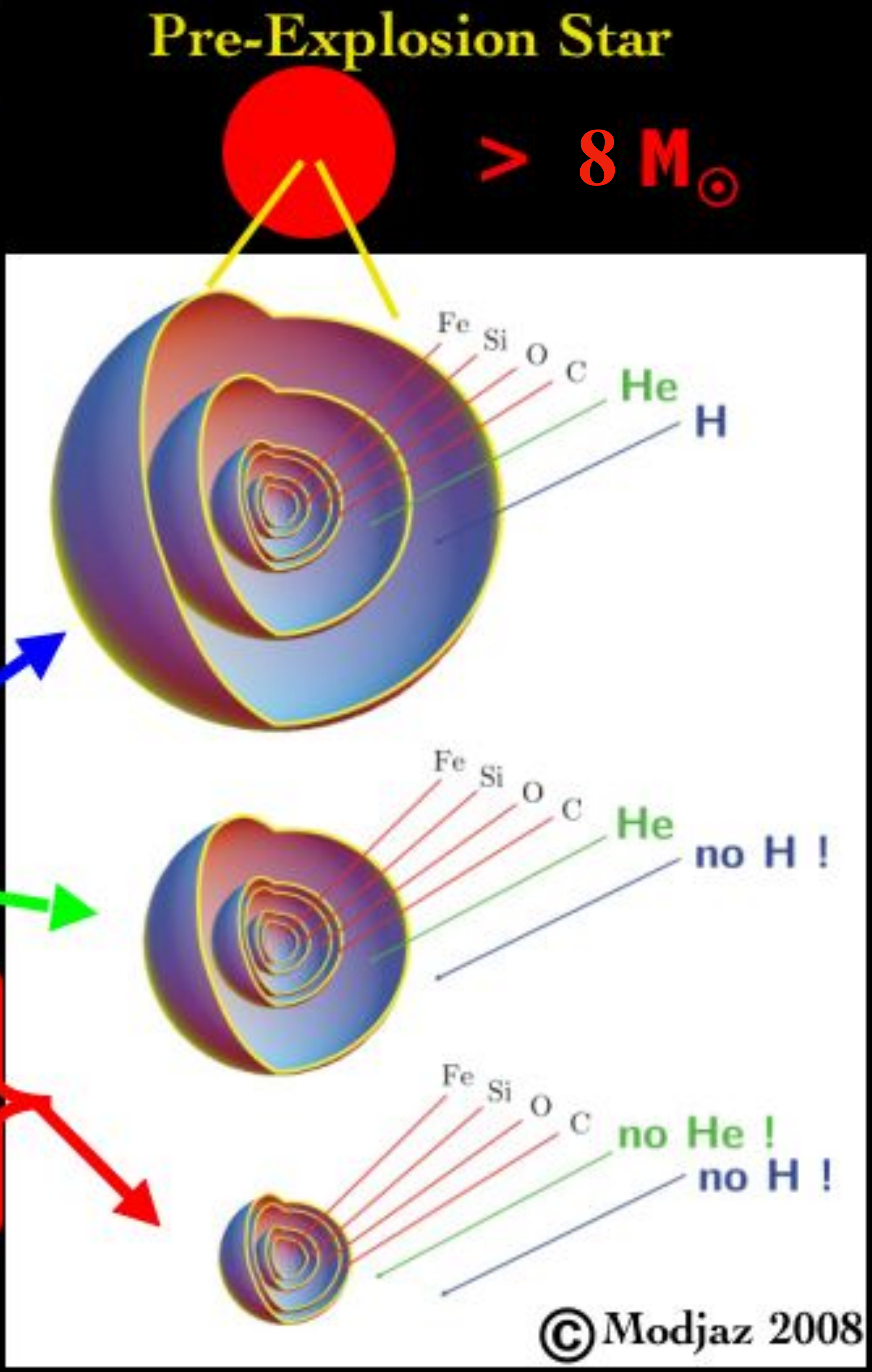
Core-Collapse Supernovae

Type I for Hydrogen-Poor and Type II for Hydrogen-Rich SNe



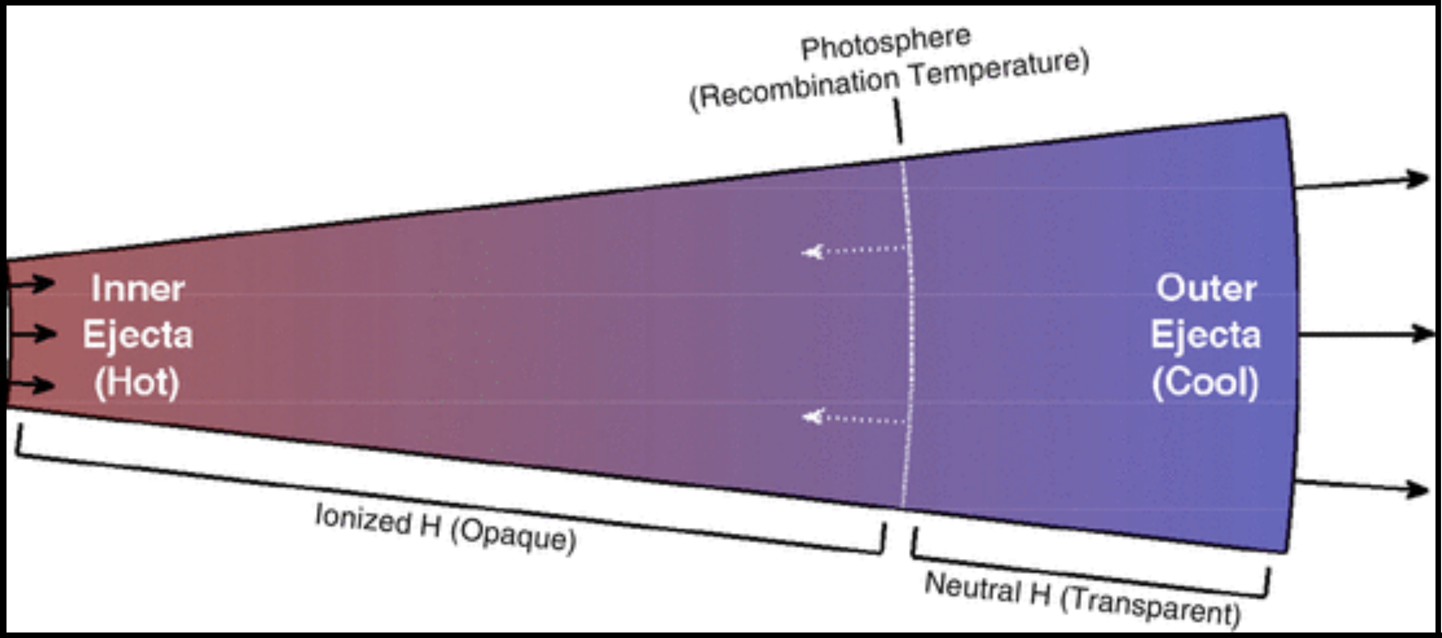


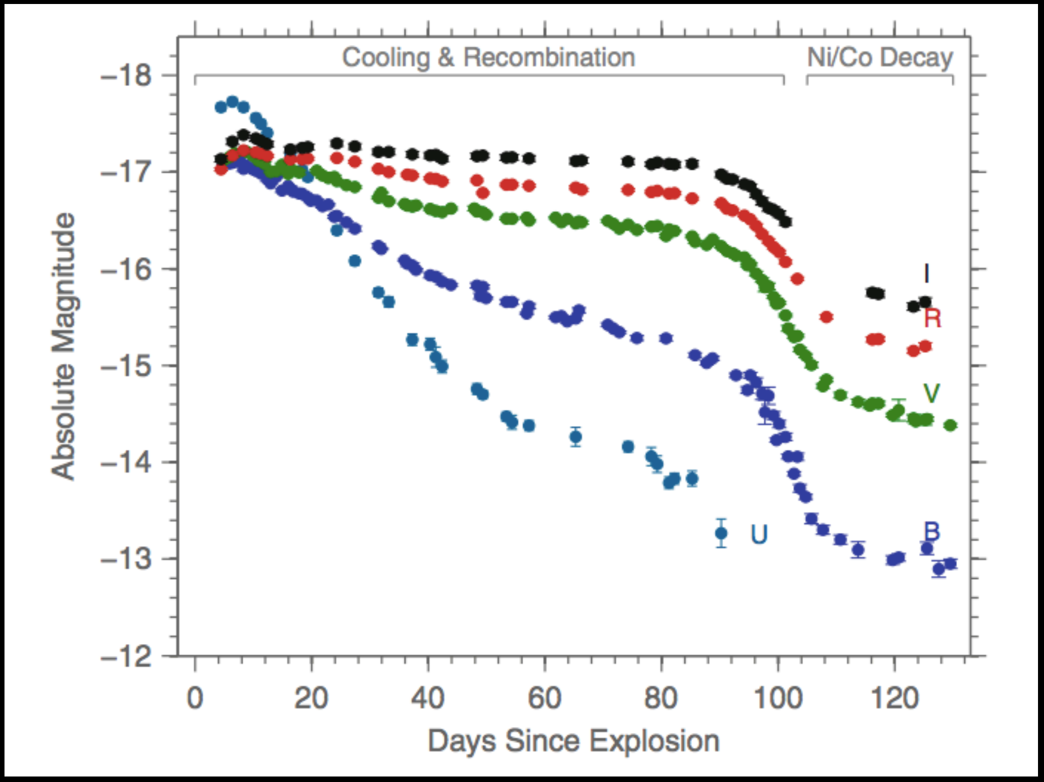
Core-Collapse Supernovae

Hydrogen-Rich Type II SNe

Subclass	Photometric properties	Spectroscopic properties	Prototypical example
IIP	Plateau in light curve		SN 1999em
IIL	Linear decline in light curve		SN 1979C?
IIn		Narrow hydrogen lines	
IIb		H-dominated then He-dominated	SN 1993J
87A-like	Long light curve rise		SN 1987A

Arcavi 2016





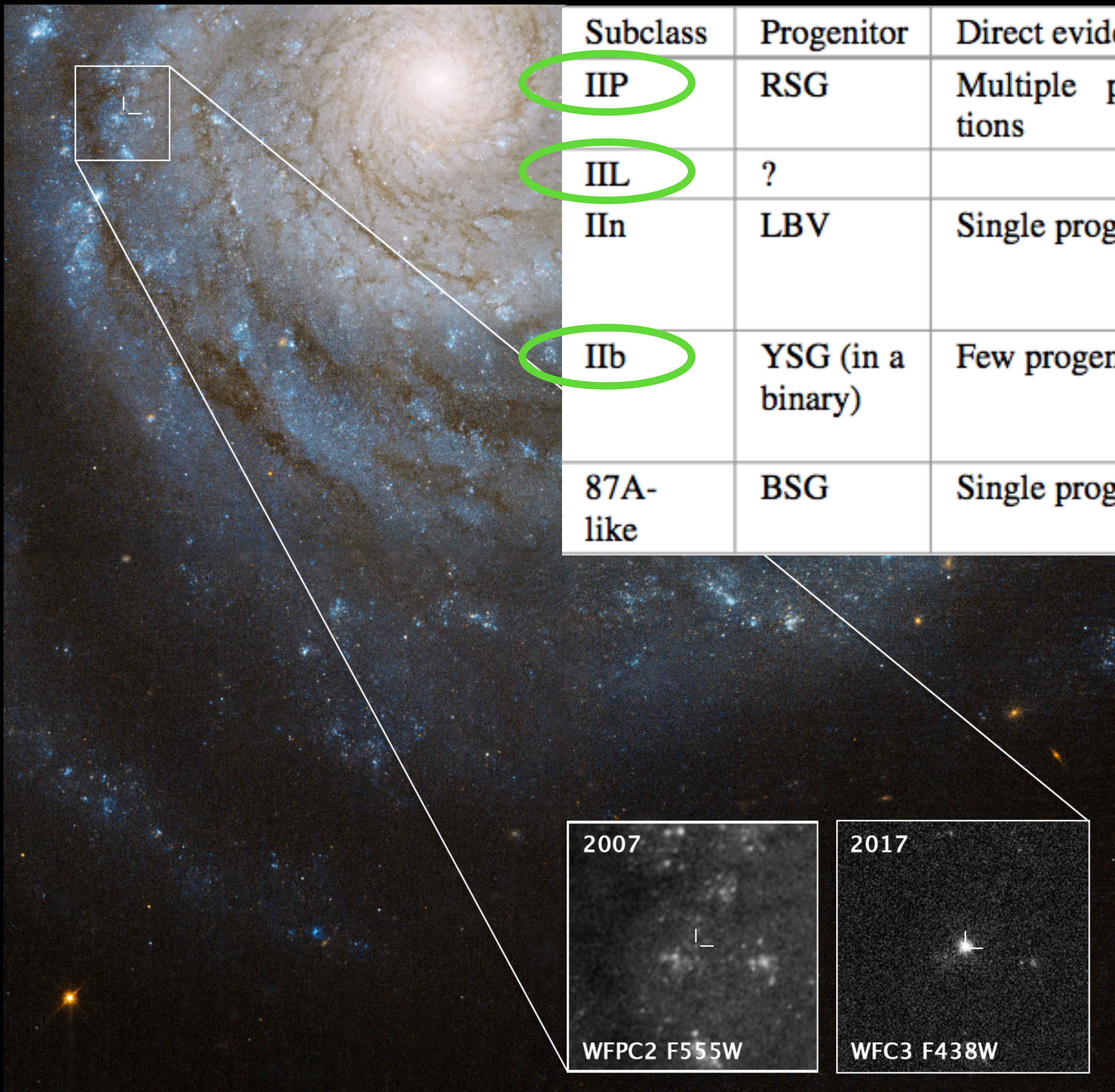
Core-Collapse Supernovae

Pre-explosion Direct Imaging

NASA/ESA, Van Dyk, & Li

Arcavi 2016

Subclass	Progenitor	Direct evidence	Indirect evidence
IIP	RSG	Multiple progenitor detections	Light curve plateau indicative of a thick H envelope
IIL	?		
IIn	LBV	Single progenitor detection[a]	Light curve and spectral features indicative of CSM interaction
IIb	YSG (in a binary)	Few progenitor detections	Light curve and spectral features indicative of a H-deficient envelope
87A-like	BSG	Single progenitor detection[b]	Light curve shape indicative of a compact progenitor



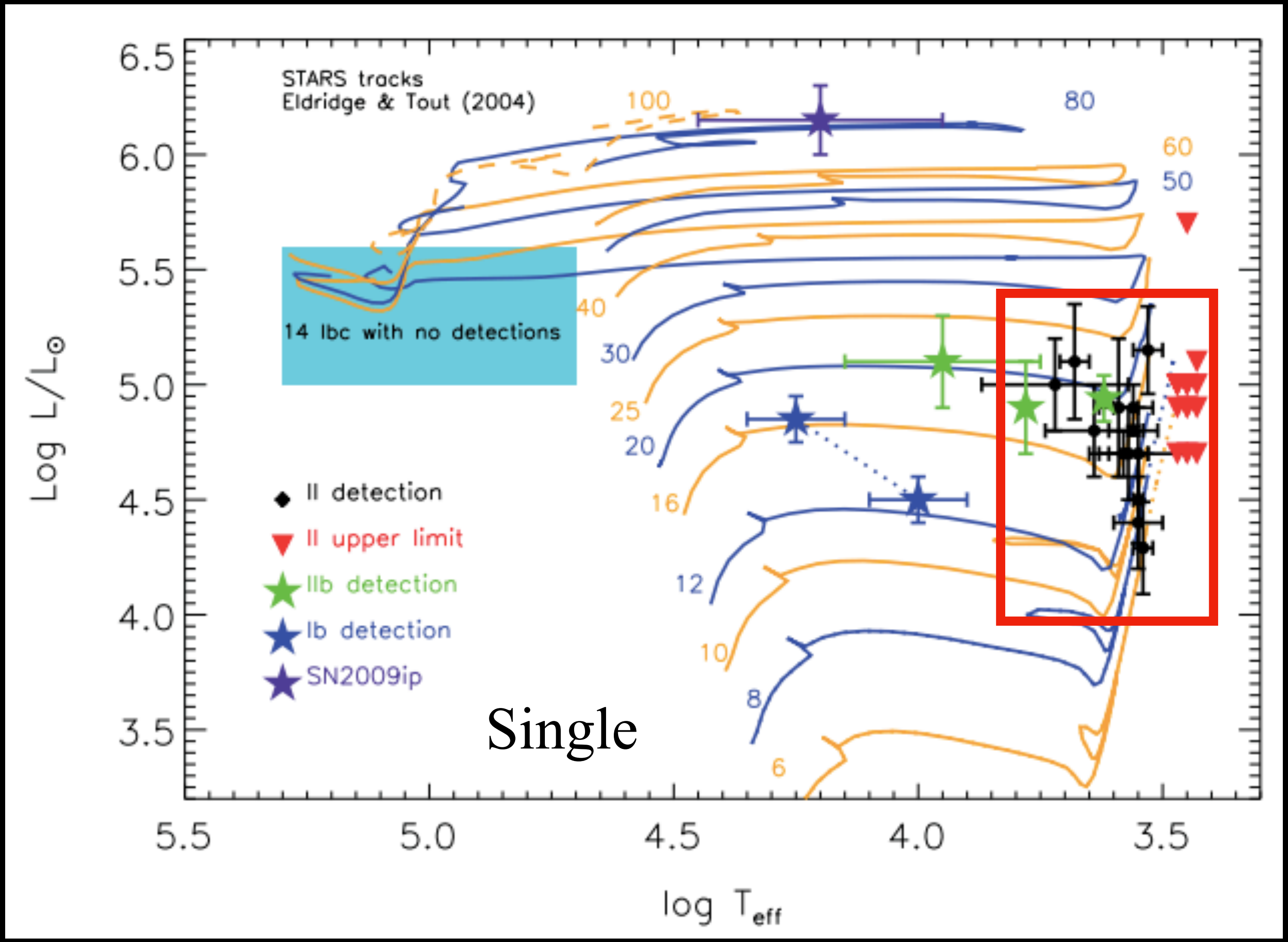
- ★ Need to be nearby (< *30 Mpc*) with pre-explosion high-resolution images.
- ★ Rely on theoretical stellar evolution tracks.

Core-Collapse Supernovae

Red Supergiant Problem

The observed RSG population lies in the mass range of *8-25 M*$_\odot$. However, the upper limit from a sample of 26 pre-explosion detections/limits of Type IIP/L SN progenitors is ~ *18 M*$_\odot$. Direct Collapse? Binary Evolution? Dust Extinction? Insufficient Statistics? ⇒ Need independent methods using SN observables.

Smartt 2015



Core-Collapse Supernovae

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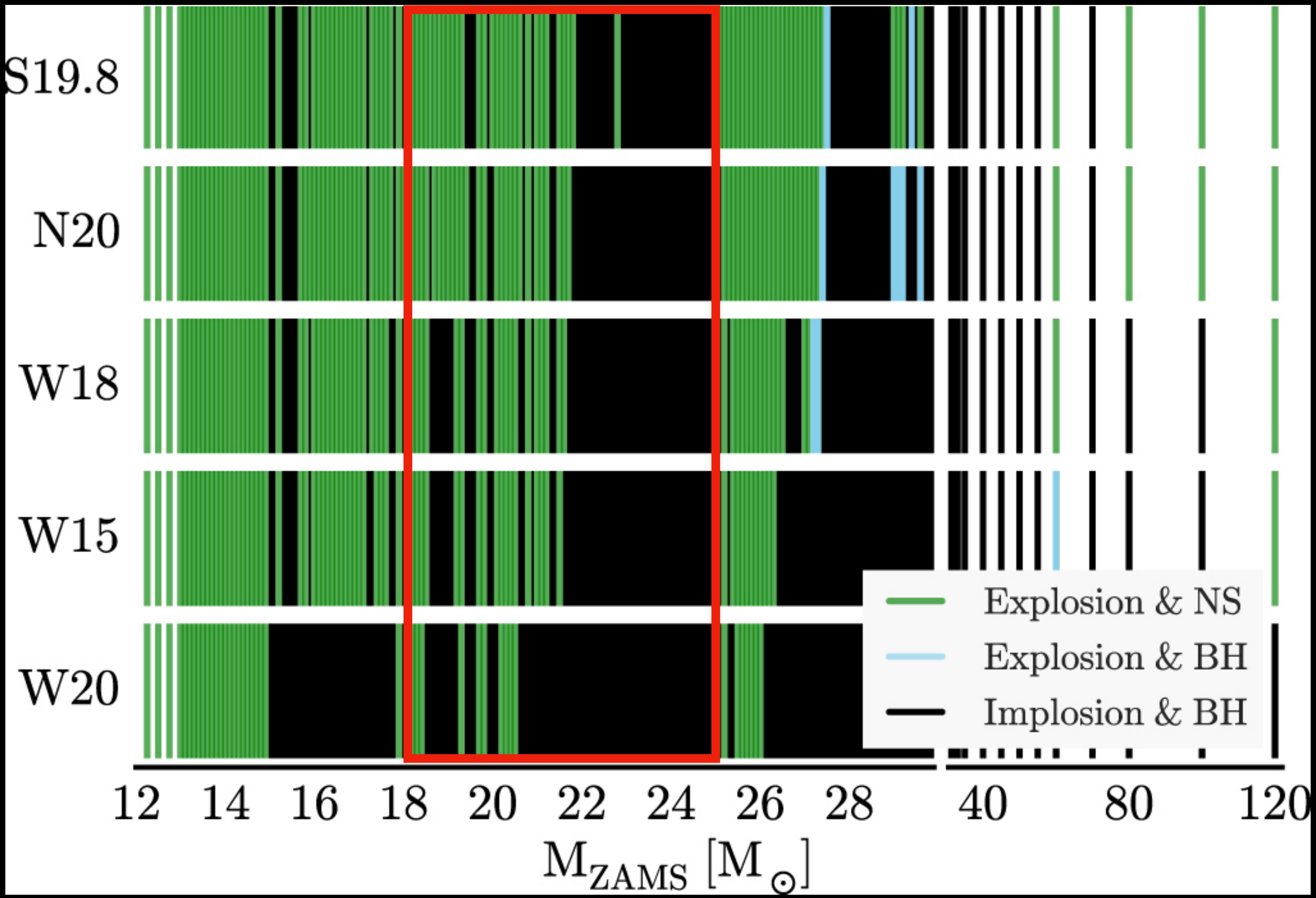
Direct Collapse (e.g. Sukhbold+ 2016)?



Core-Collapse Supernovae

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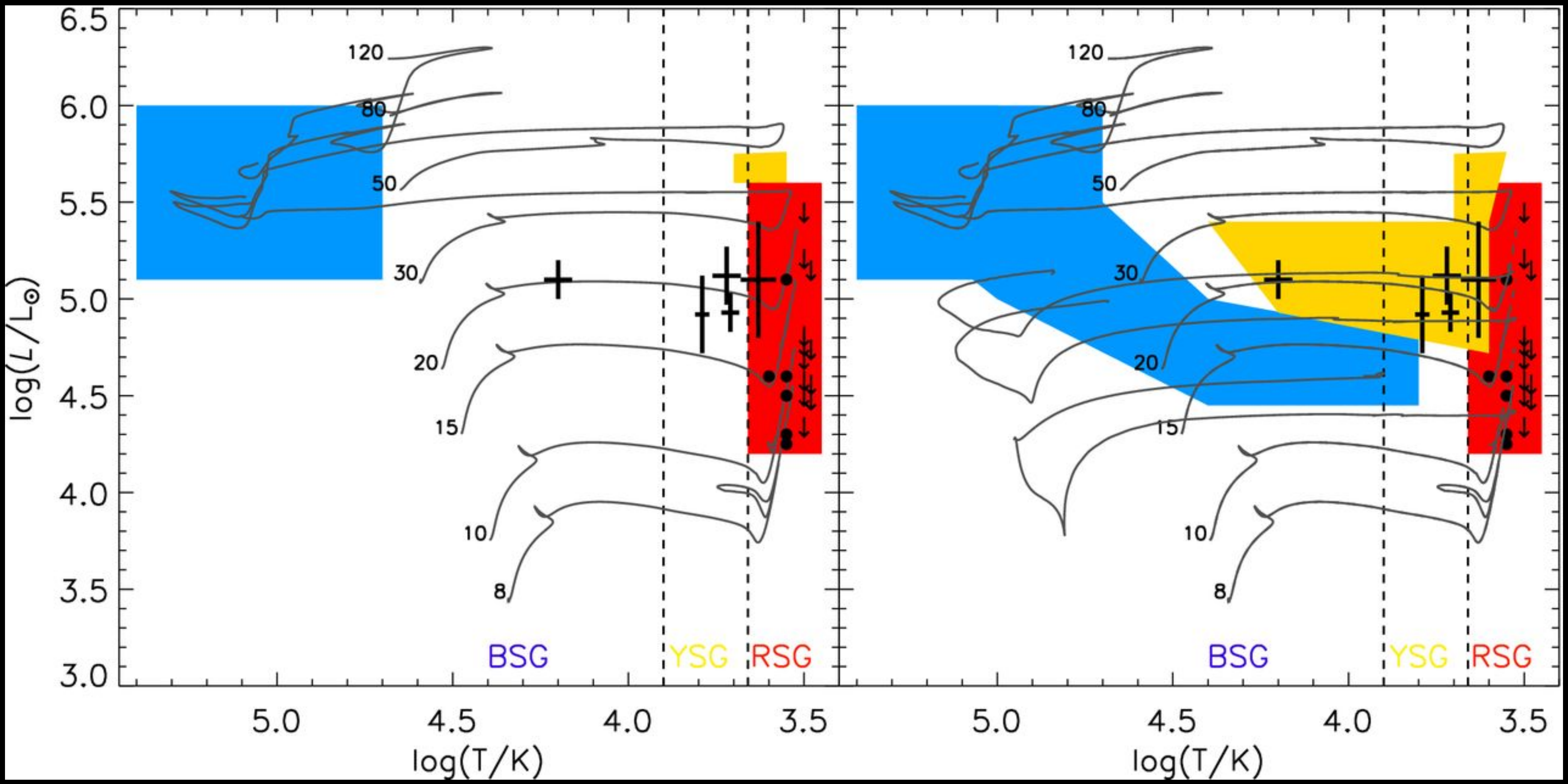
Single vs Binary (e.g. Eldridge+ 2013)?



Core-Collapse Supernovae

Red Supergiant Problem

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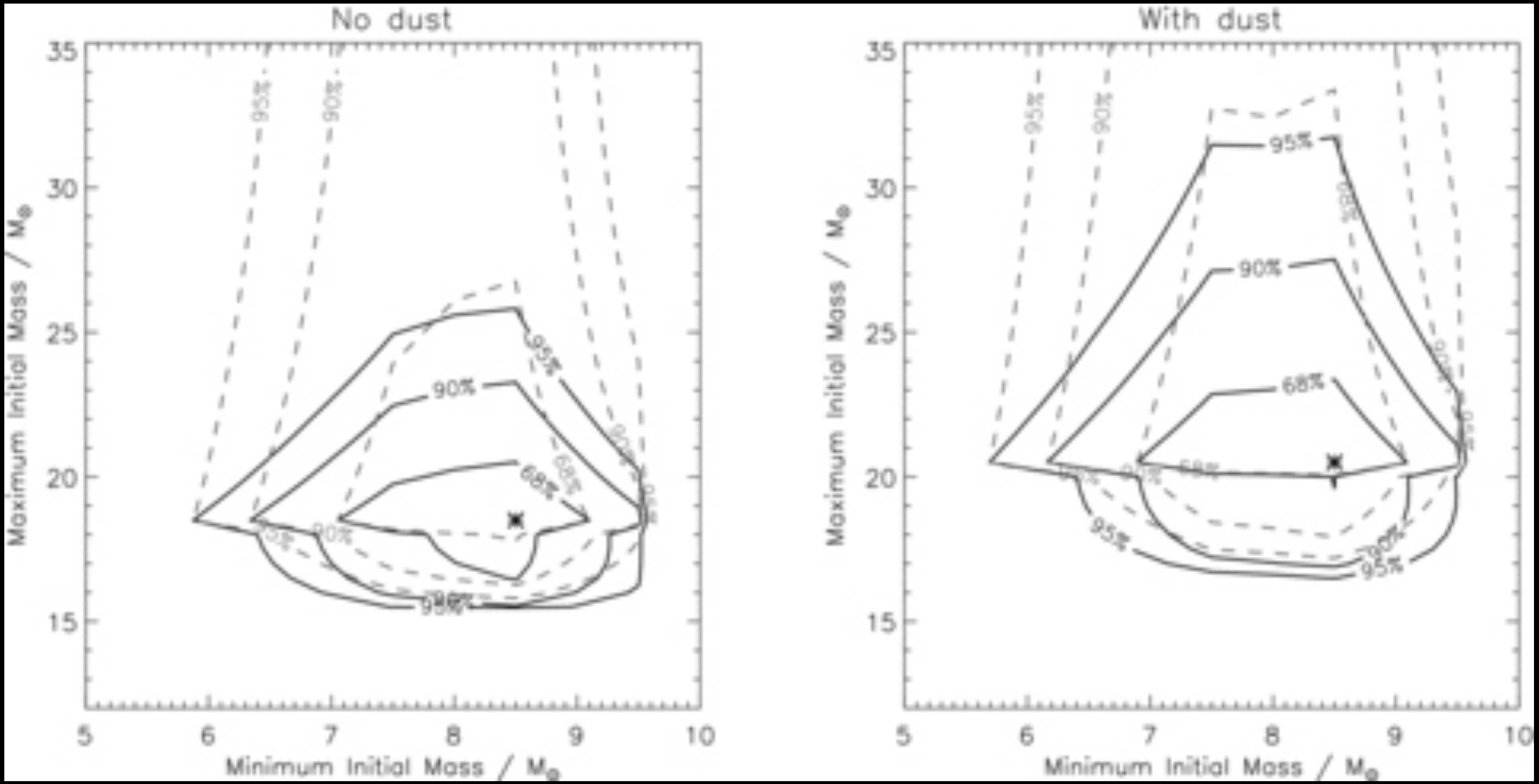
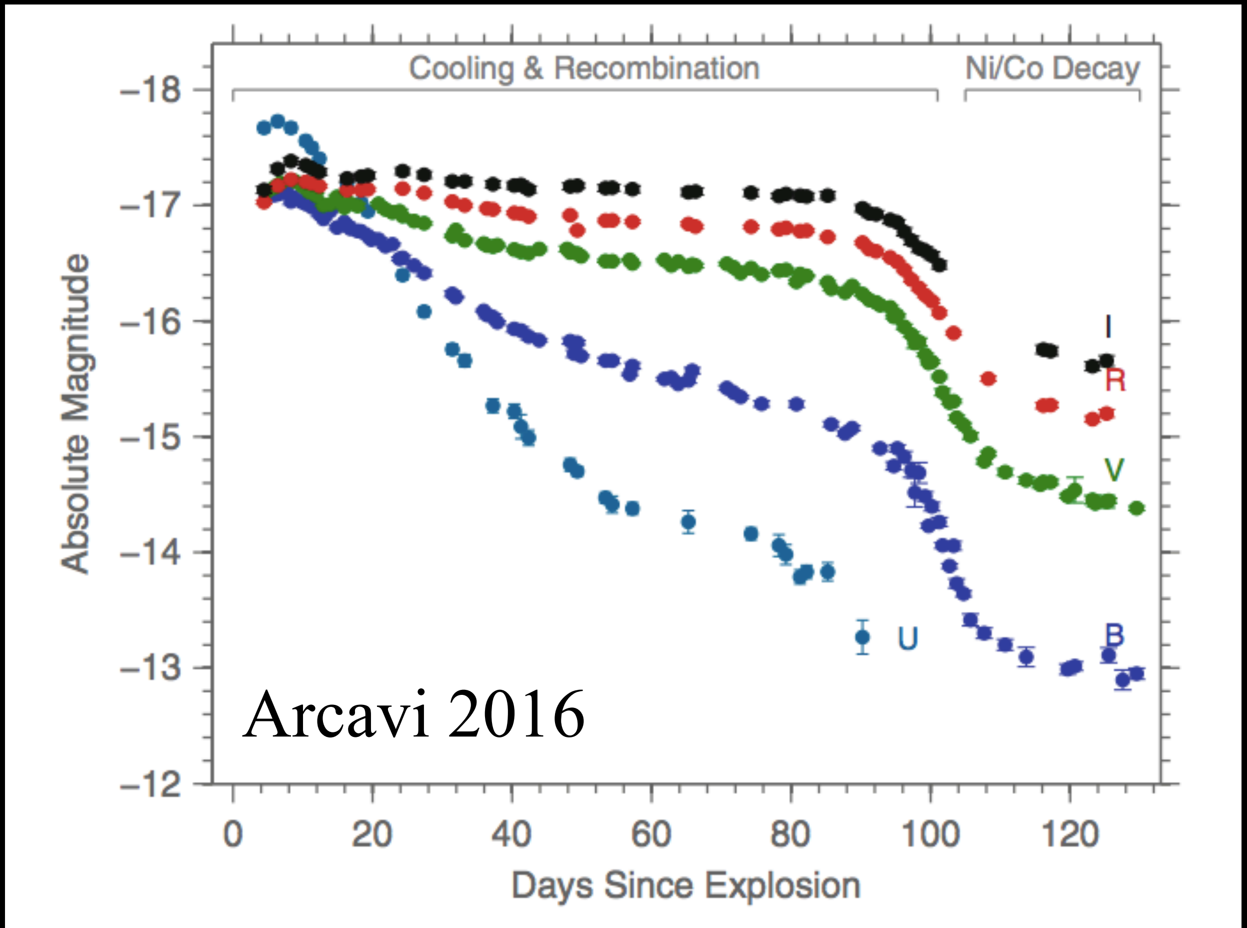
Dust (e.g. Walmswell & Eldridge 2012)?



Core-Collapse Supernovae

Type IIP Supernova Light Curve Scaling to Infer Explosion Properties

From Kasen & Woosley 2009 (see also Popov 1993, Sukhbold+ 2016, and Goldberg, Bildsten, & Paxton 2019),



$$L_{50} \propto E_{exp}^{5/6} M_{ej}^{-1/2} R_{pro}^{2/3} X_{He}^{1}$$

$$t_{p,0} \propto E_{exp}^{-1/4} M_{ej}^{1/2} R_{pro}^{1/6} X_{He}^{1/2}$$

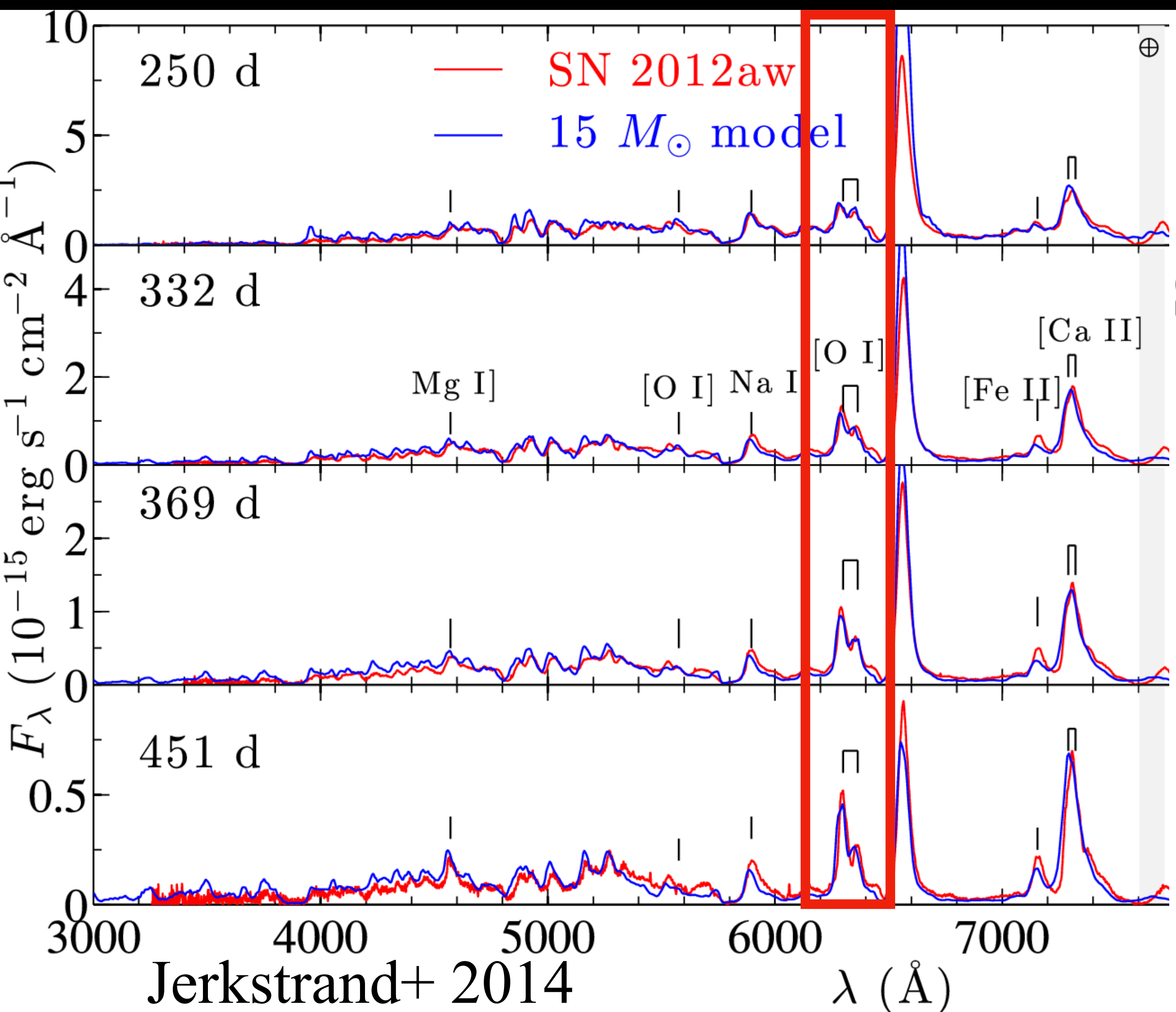
$$t_p = t_{p,0} \times (1 + C_f M_{Ni} E_{exp}^{-1/2} M_{ej}^{-1/2} R_{pro}^{-1})^{1/6}$$

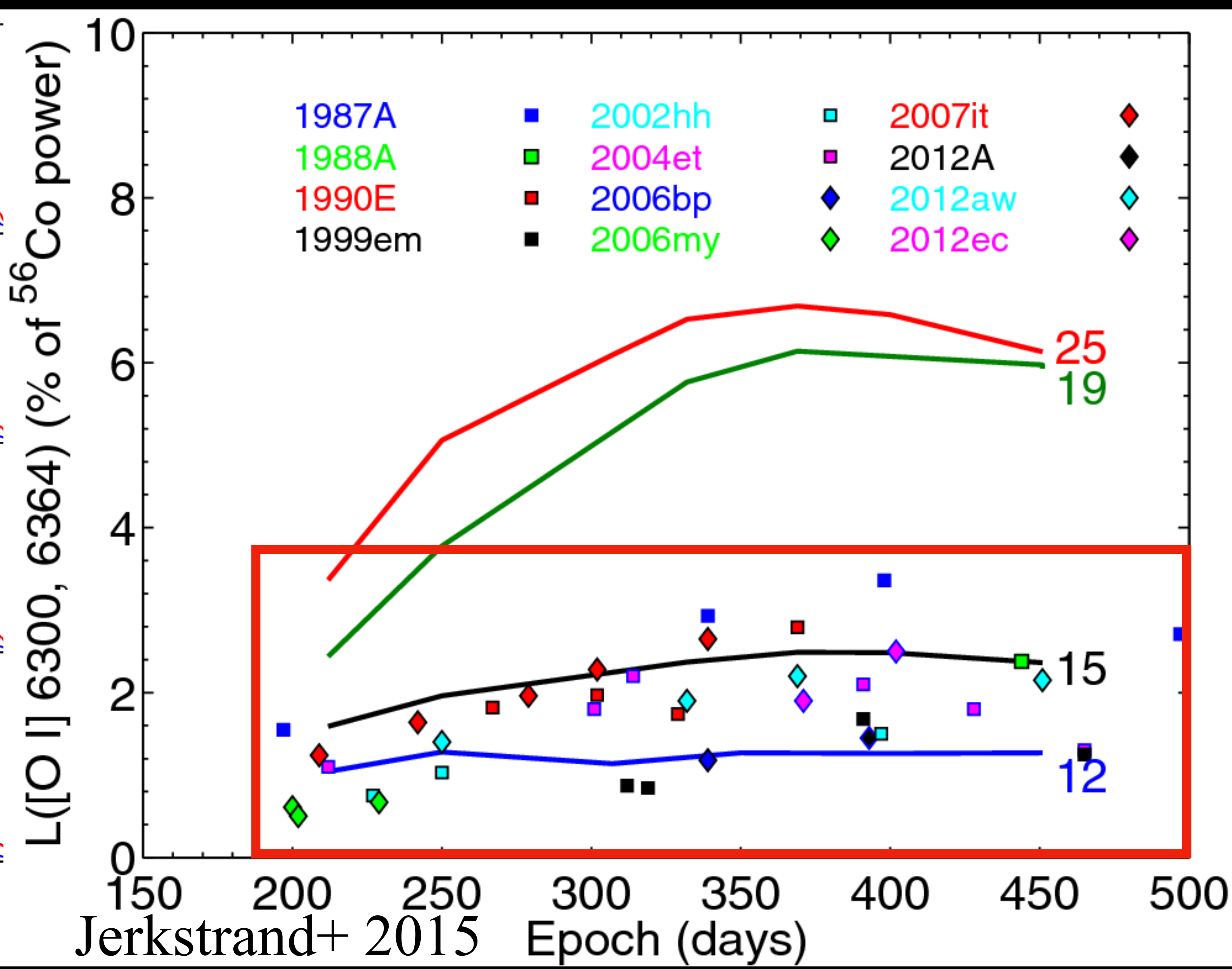
- ⋆ If Ni mass is high ($> 0.03\ M_\odot$), plateau duration is radius independent.
- ⋆ Three unknowns in two equations (assuming ~constant He fraction) => Degenerate solutions.

Core-Collapse Supernovae

Nebular Spectrum to Infer Progenitor Core Mass

The strength of [OI] emission lines scale monotonically with the core mass of a progenitor.

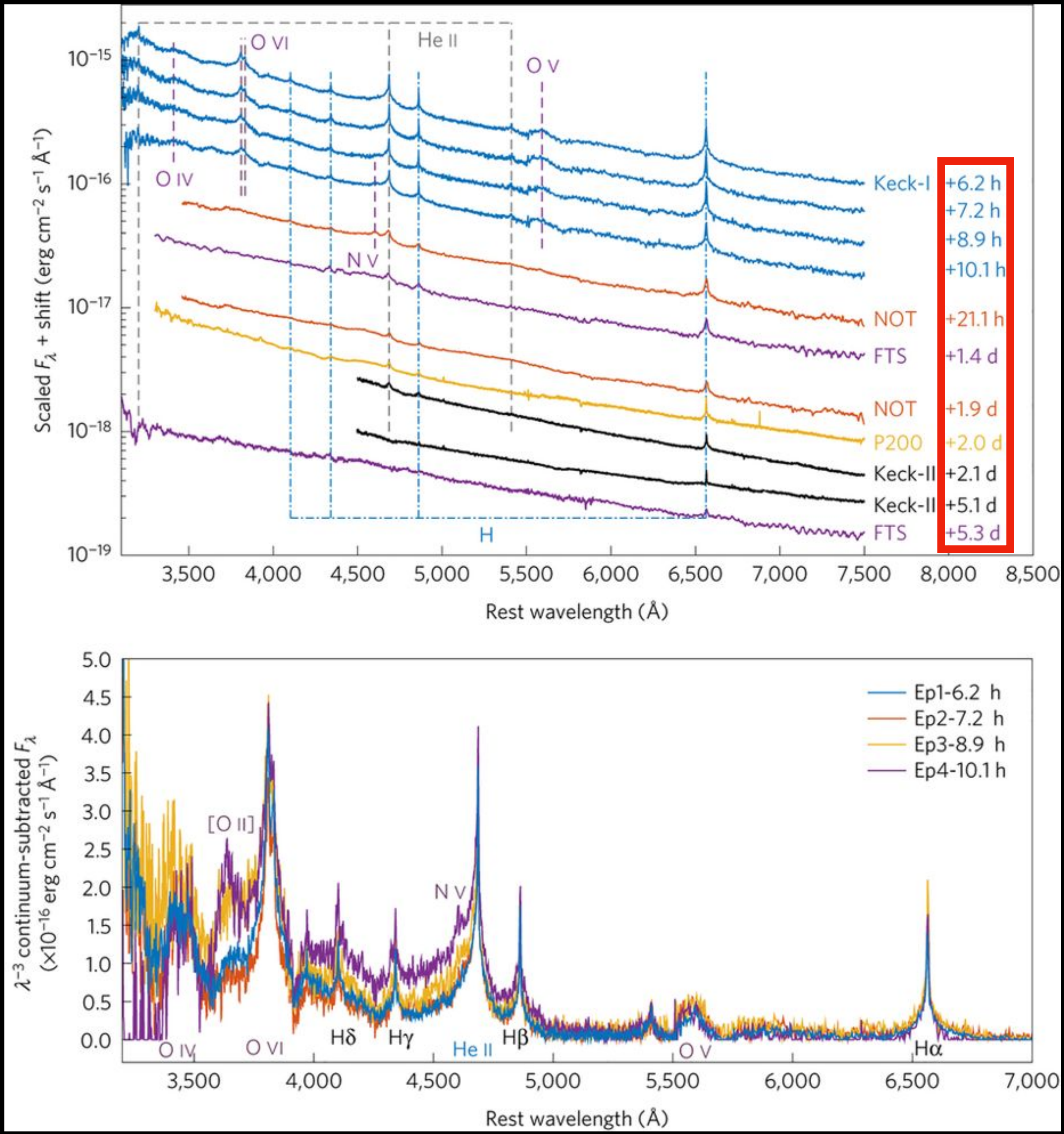


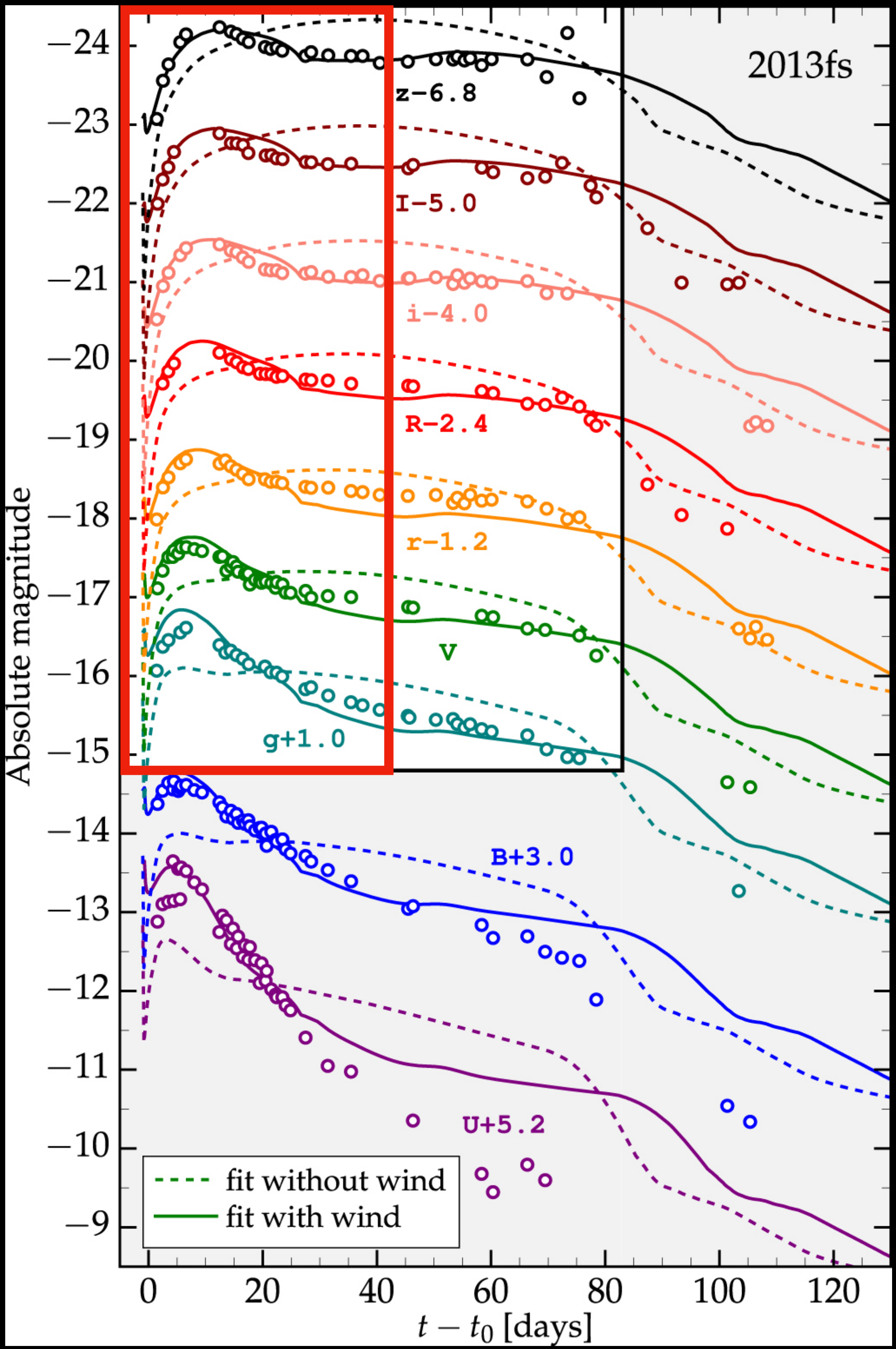


Core-Collapse Supernovae

Circumstellar Material (CSM) Interaction to Infer Pre-Explosion Mass Loss

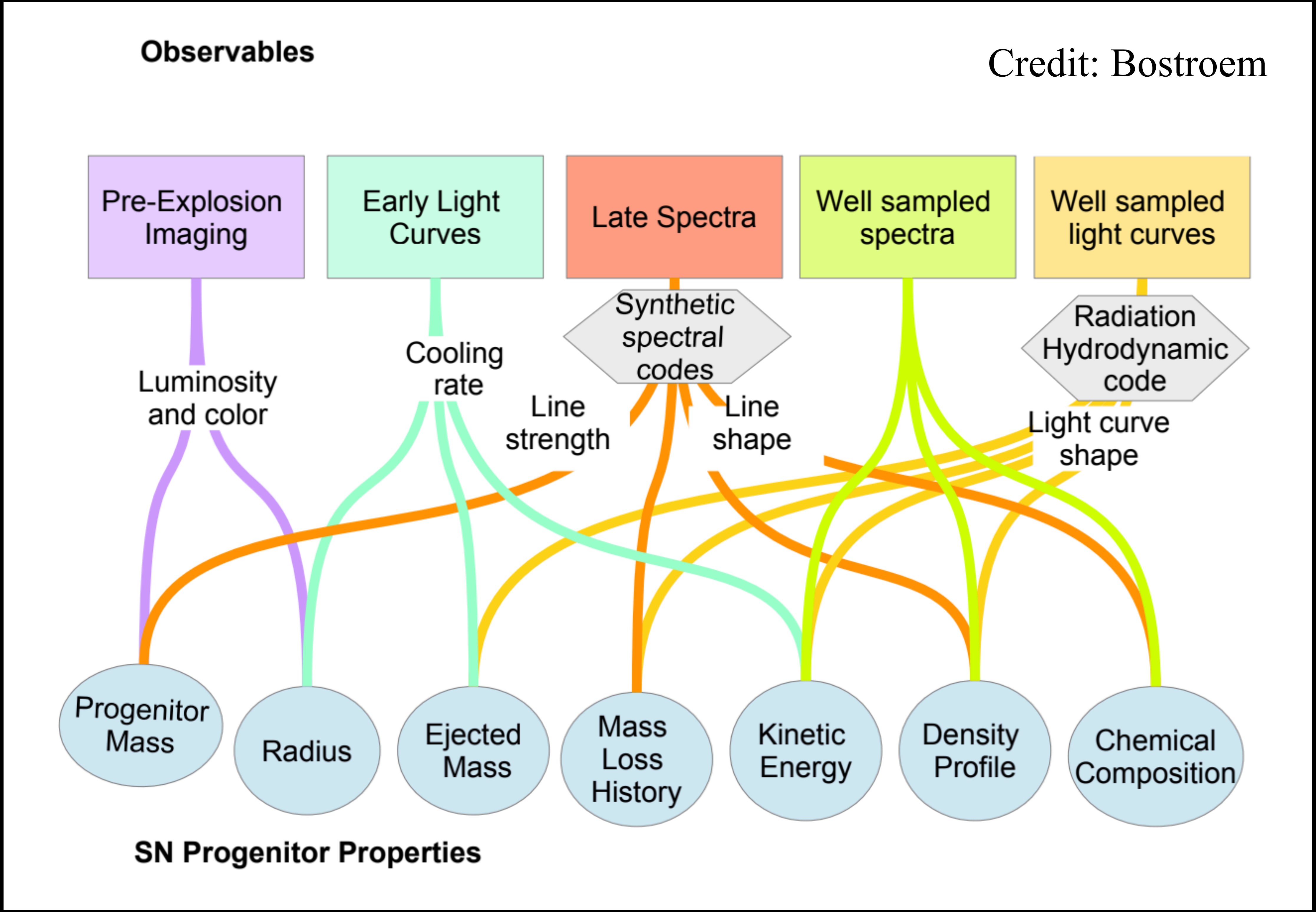
Flash Spectroscopy (e.g. Yaron+ 2017) & Early Light Curve (e.g Morozova, Piro, & Valenti 2017)





Core-Collapse Supernovae

In order to extract the progenitor and explosion properties from the supernova observables, early high-cadence and late continuous monitoring are required to capture the full evolution.



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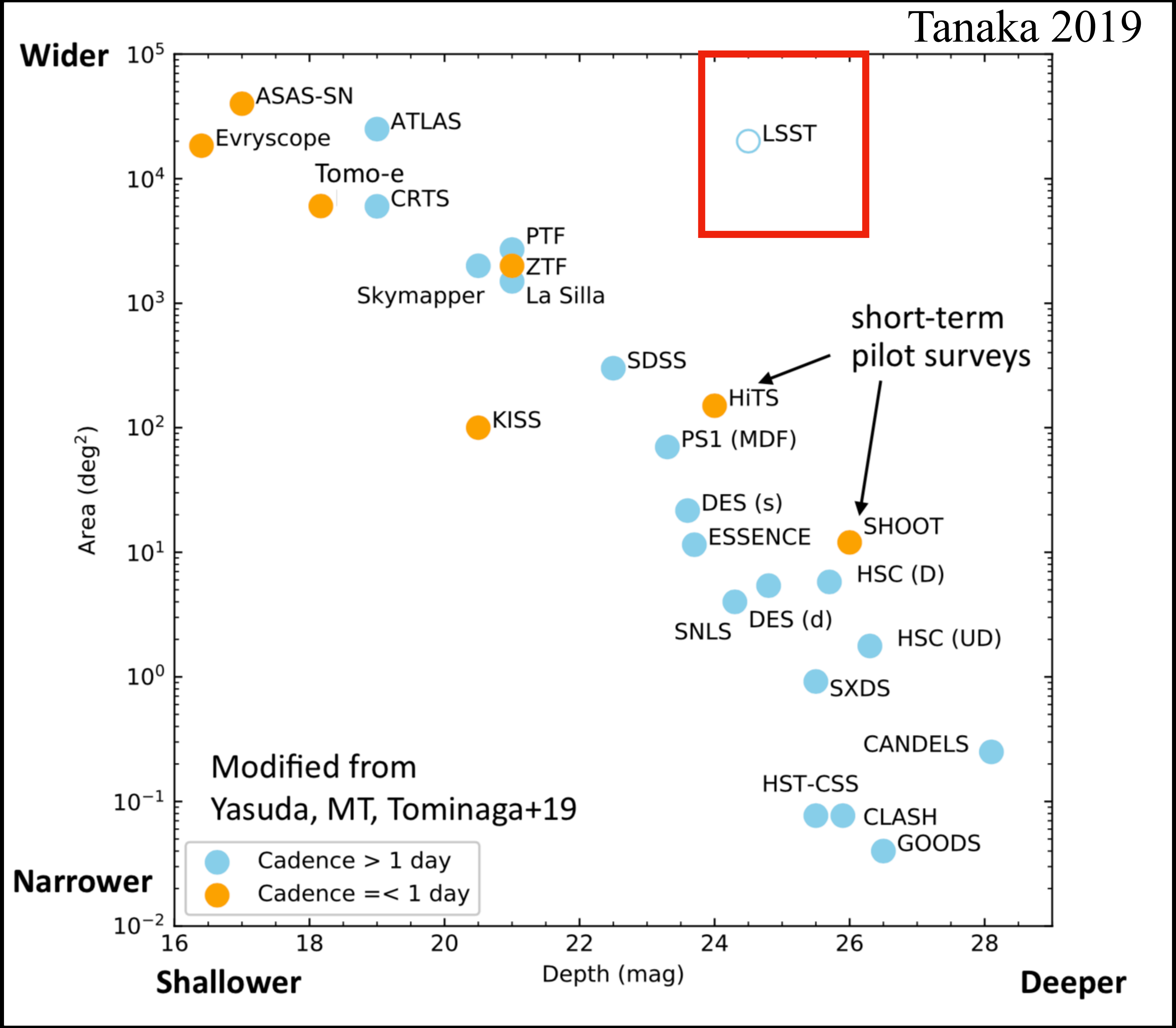
Transient Surveys

3D Problem: Wider, Deeper, and/or Faster

Current transient surveys: >100 supernovae/night. LSST (2023~): >1,000 supernovae/night.



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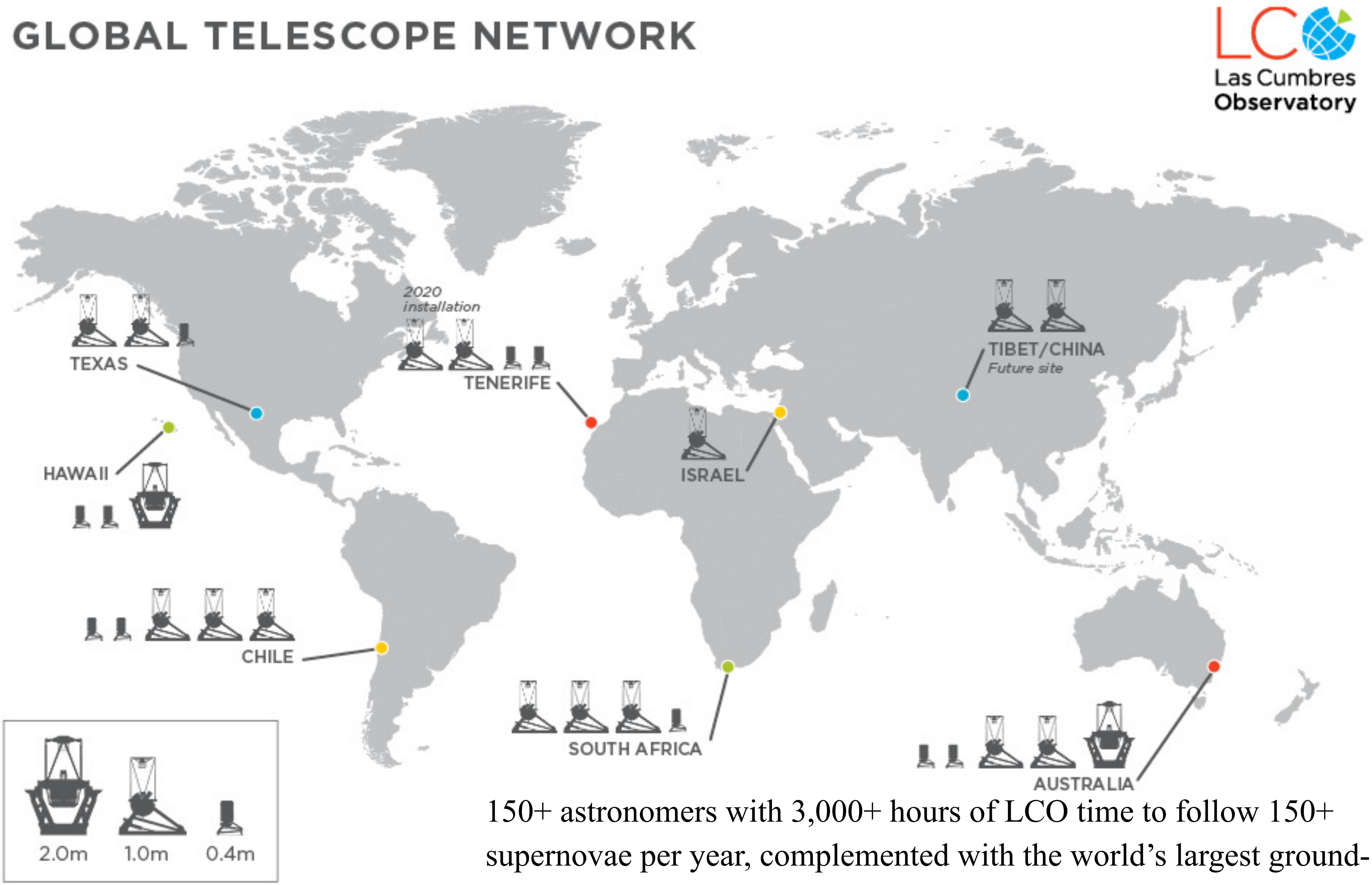
Las Cumbres Observatory and the Global Supernova Project



150+ astronomers with 3,000+ hours of LCO time to follow 150+ supernovae per year, complemented with the world's largest ground-based telescopes as well as space telescopes.

Las Cumbres Observatory and the Global Supernova Project

Daily Work:

- ⋆ Triggering: 100+ supernova discoveries every day by various surveys → Focus on nearby (< 100 Mpc) and young (< 5 days post explosion) transients.
- ⋆ Monitoring: 40+ supernovae followed at any time → Automate as many processes as possible to be managed by 5 members in the LCO supernova group.
- ⋆ Reducing: Dataflow from different telescopes, including non-LCO telescopes → Build and maintain customizable reduction pipelines.
- ⋆ SNEx

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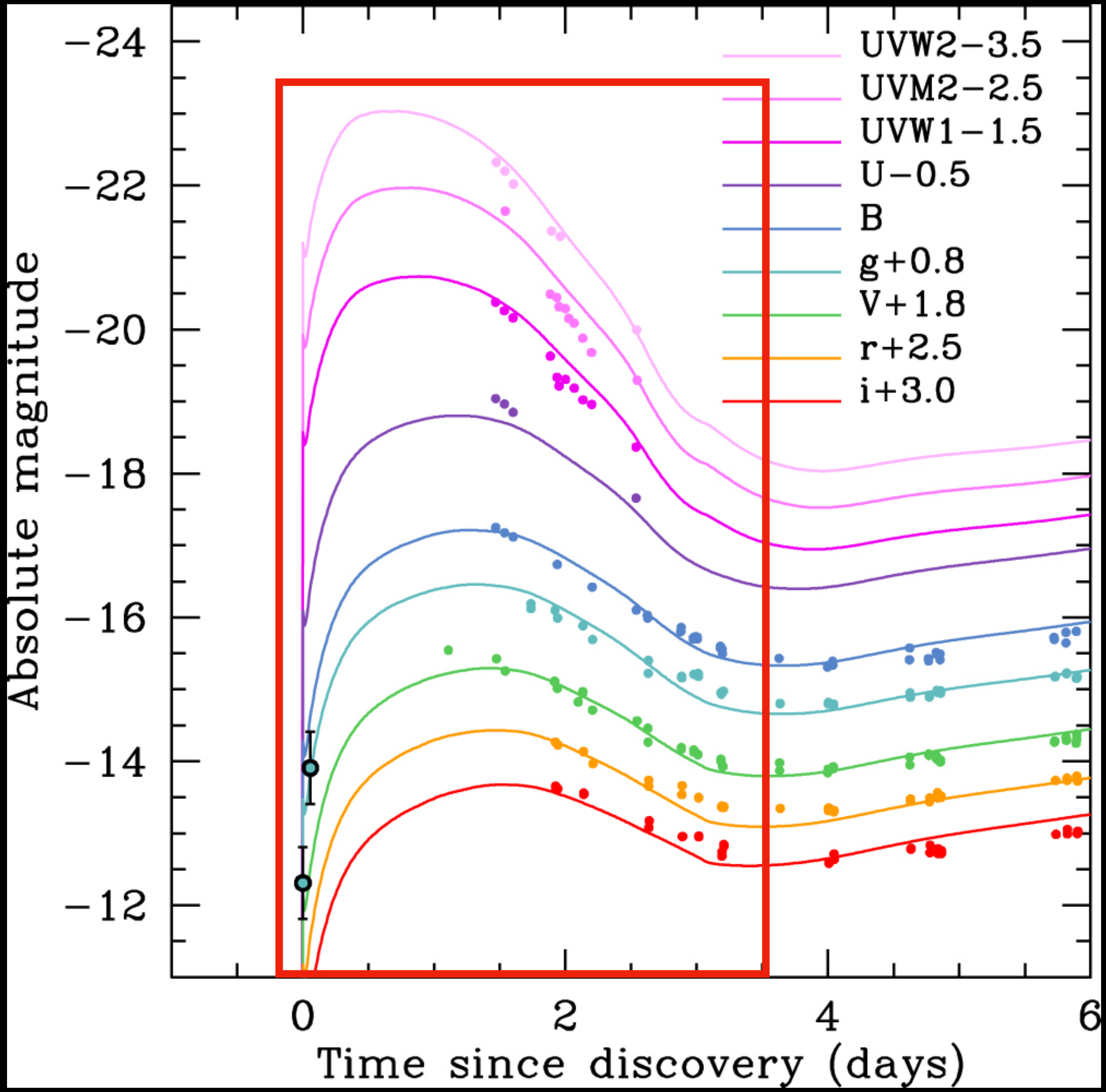
Numerical Shock-Cooling Light-Curve Modeling

SN 2016gkg: Double-Peak Type IIb ⇒ *0.02 $M_\odot$* of extended material at ≈*180−260 $R_\odot$*

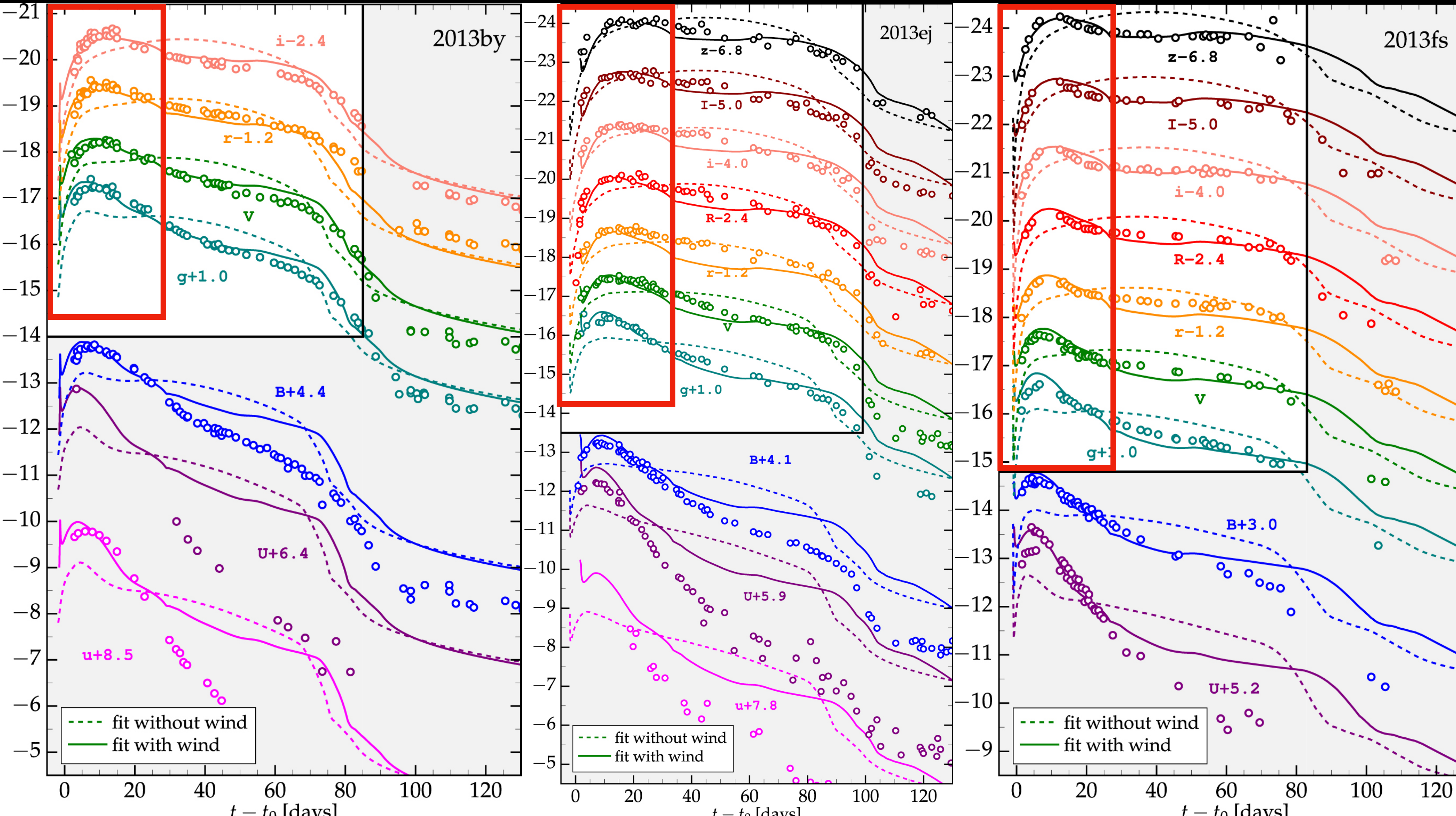
Arcavi+ 2017 & Piro+ 2017



Numerical CSM Light-Curve Modeling

CSM Light Curve Modeling: *~1e-1 M☉/yr* (>> standard stellar evolution) is required to capture the early peaks

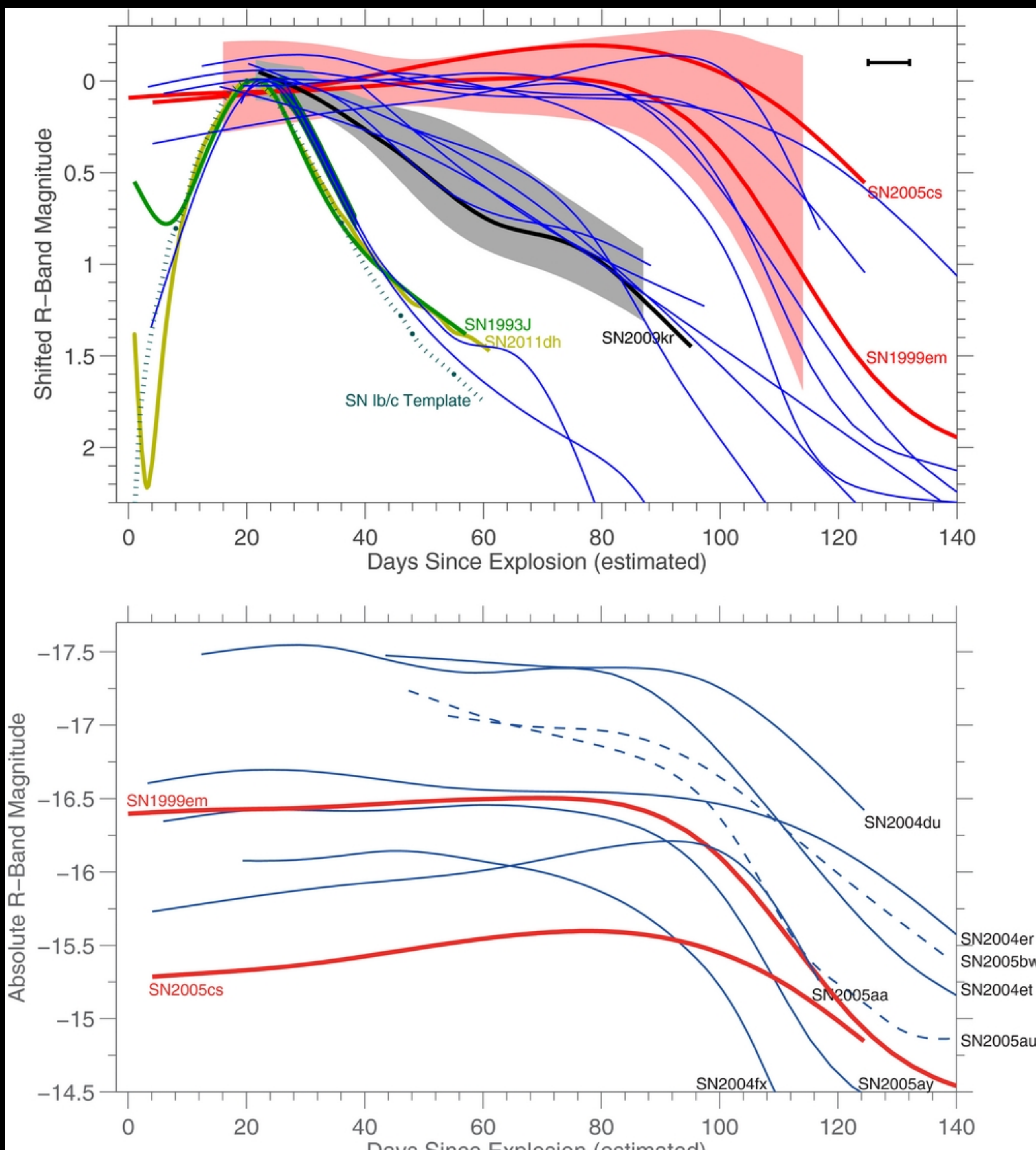
Morozova, Piro, & Valenti 2017 (see also Förster+ 2018 and Moriya+ 2018)



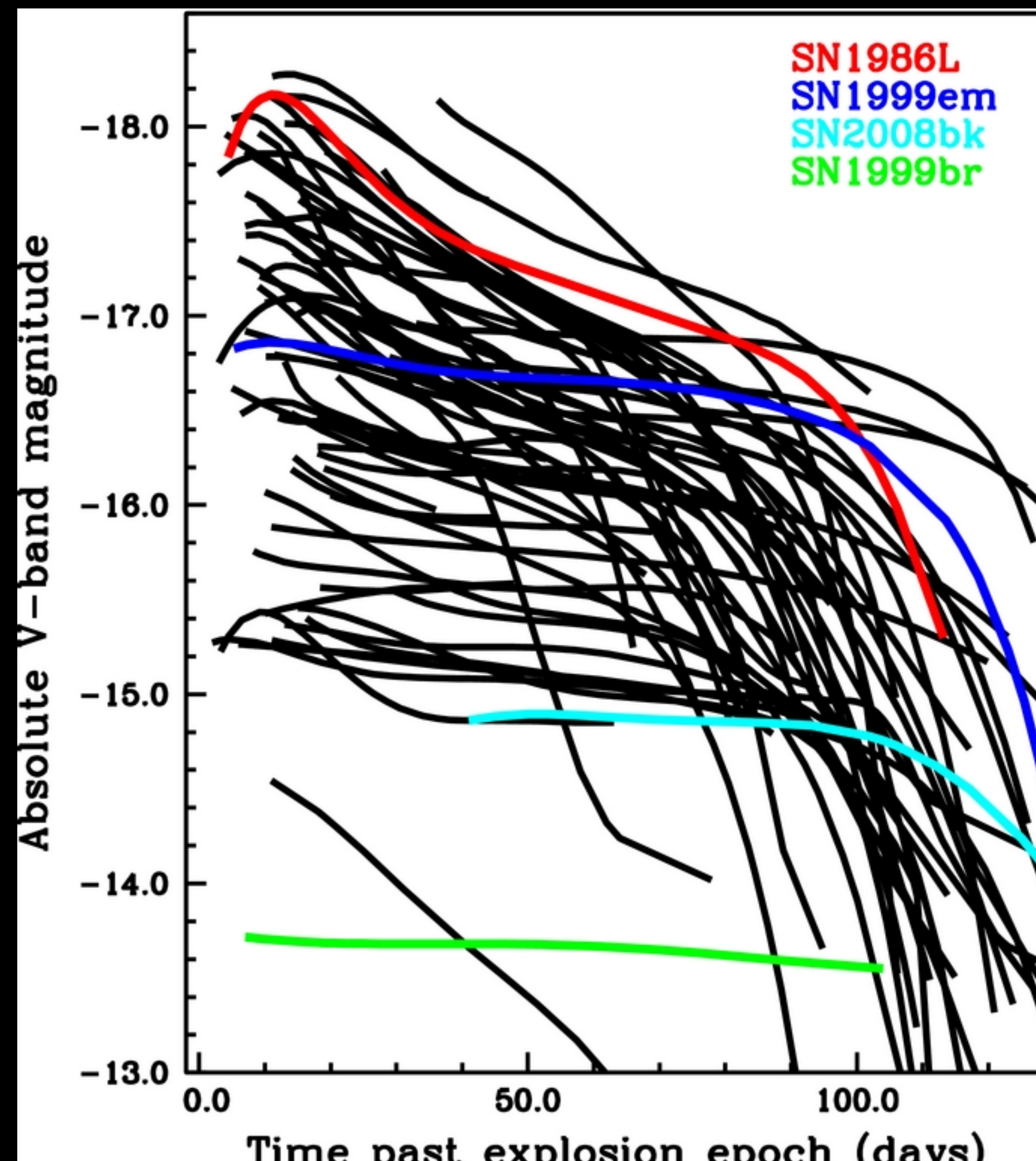
IIP vs IIL & Short-Plateau Supernovae

Type IIP/L SNe: Continuous Class or Distinct Classes? Why no short-plateau?

Arcavi+ 2012 (21 SNe with R band):
Distinct Classes?



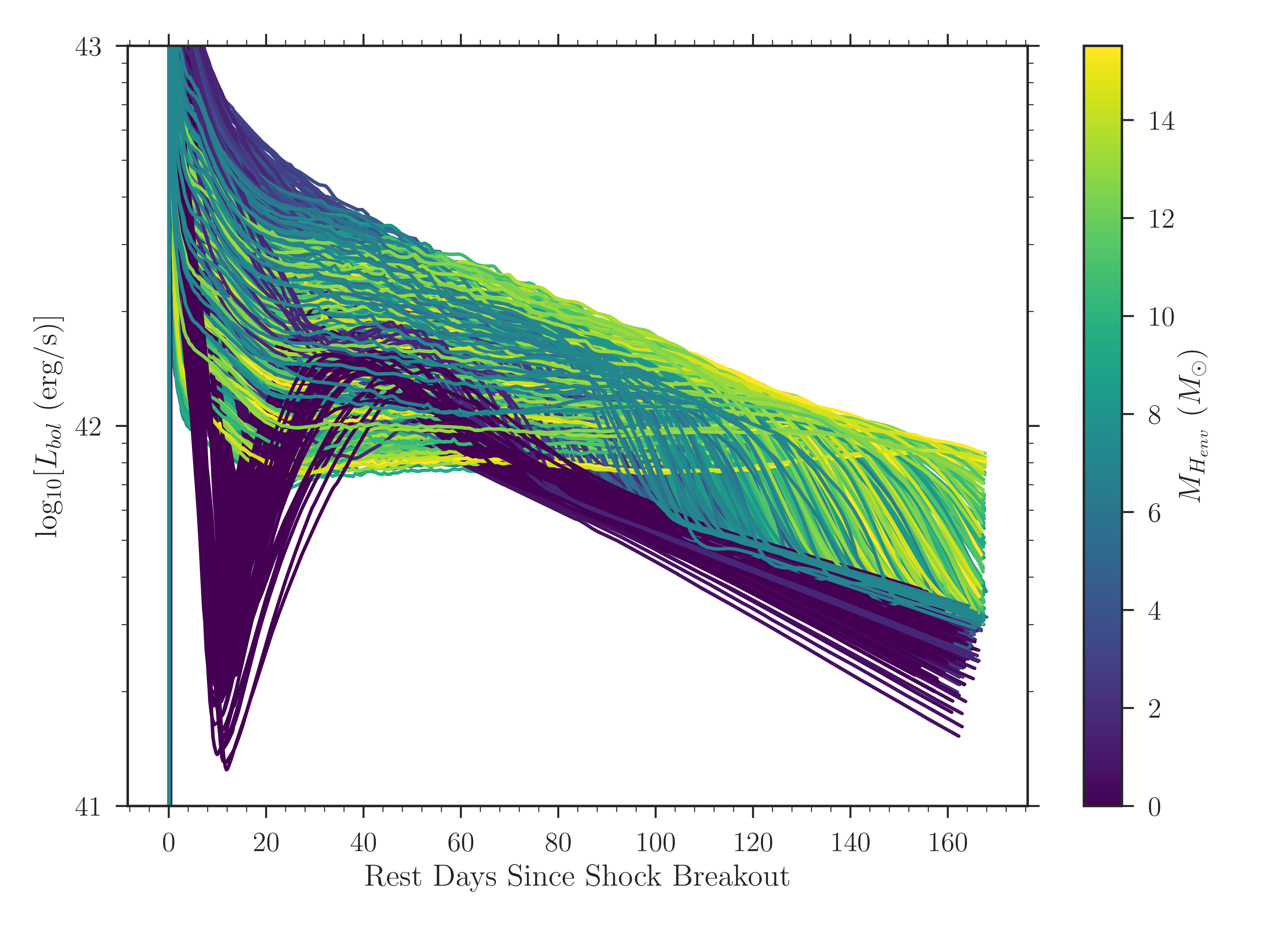
Anderson+ 2014 (116 SNe with V band):
Continuous Class?



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

Total of 1,267 MESA+STELLA models: IIP - IIL - Short Plateau - IIb in decreasing order of MHenv

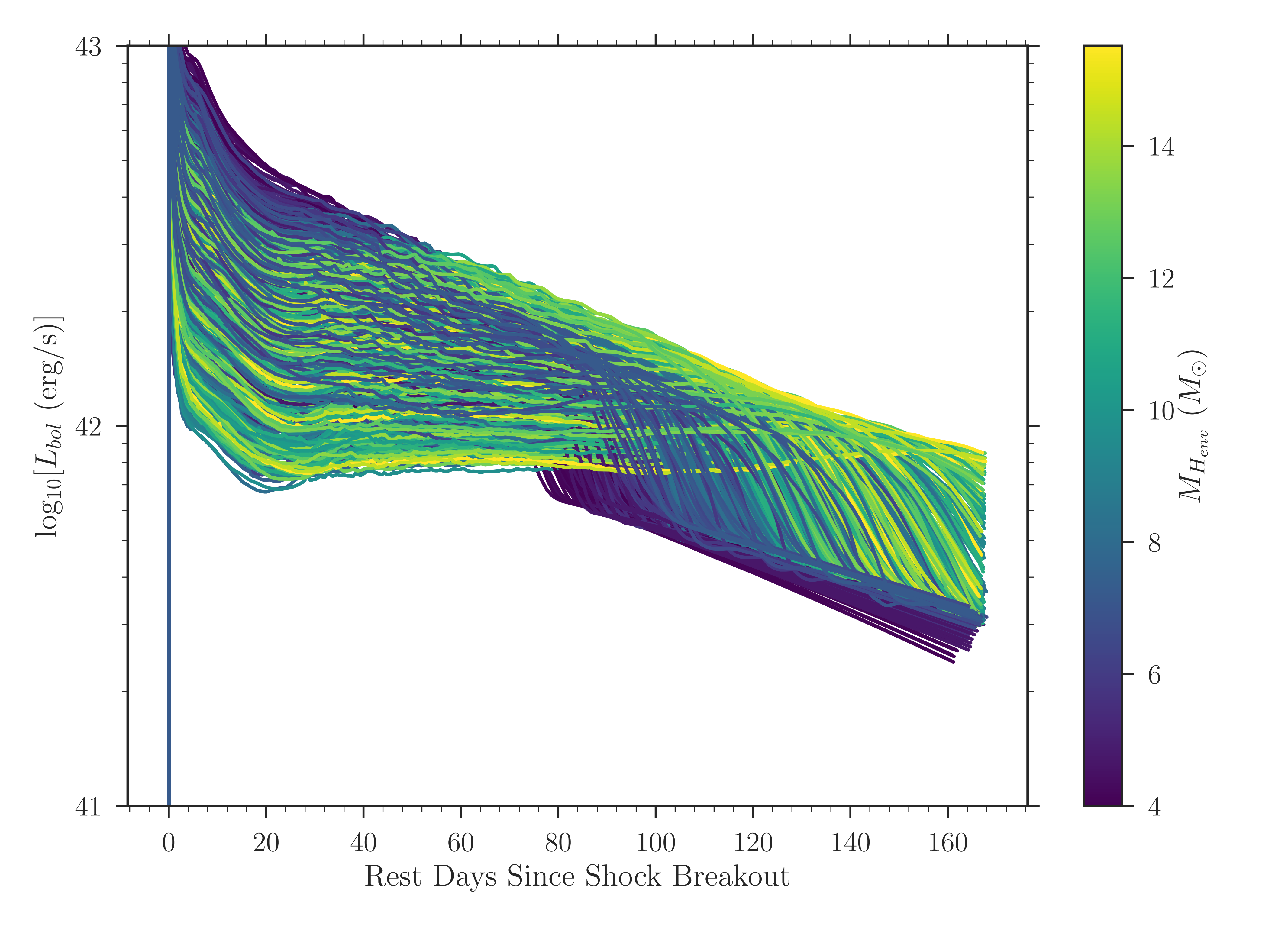
Hiramatsu+ in prep.



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

IIP [Shock cooling ⇒ Recombination (Rph const.) ⇒ Co tail]: MHenv > *4.00 M*$_\odot$

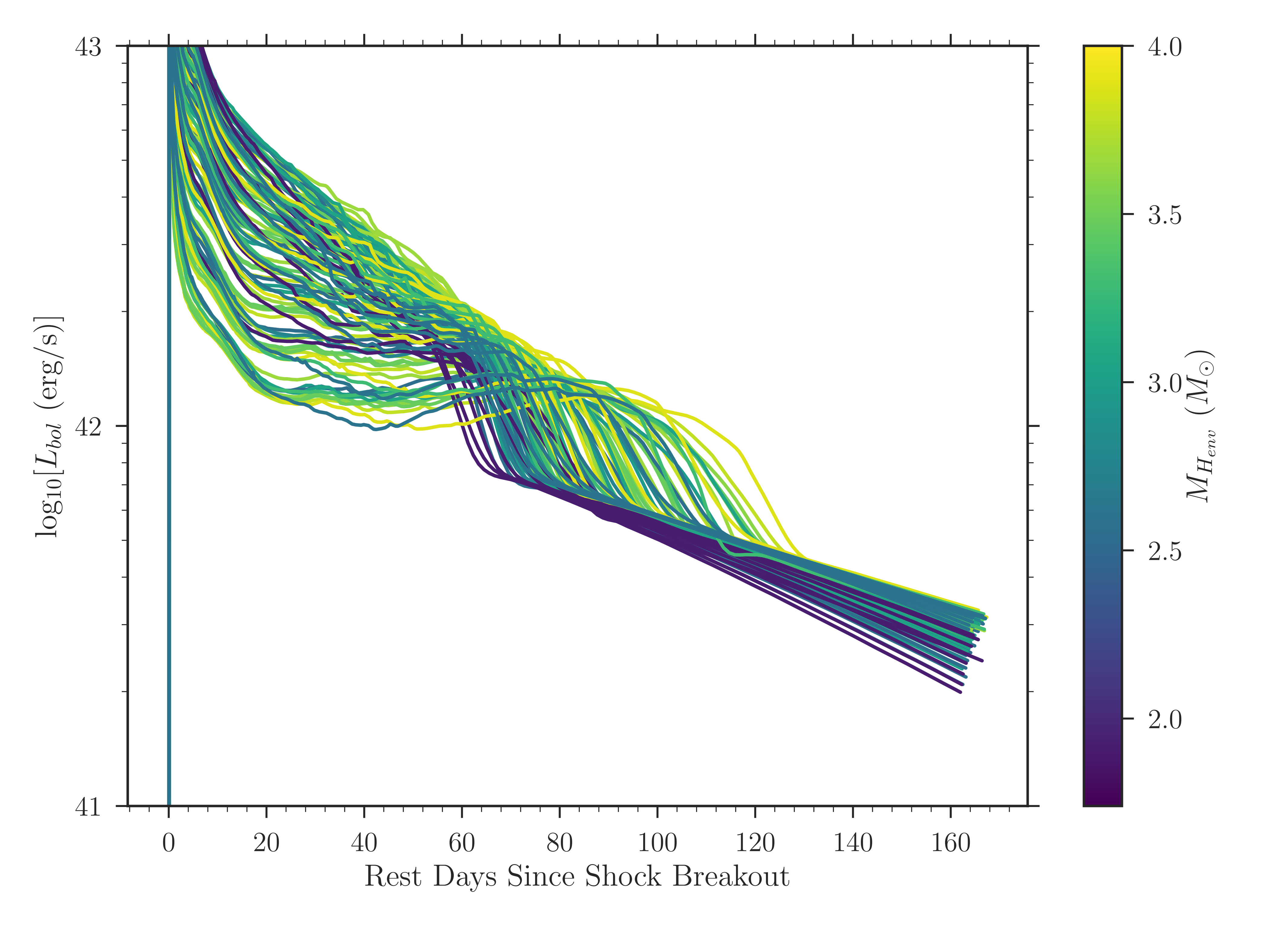
Hiramatsu+ in prep.



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

IIL [Shock cooling ⇒ Recombination (Rph ↓) ⇒ Co tail]: *1.74 $M_\odot$* < MHenv < *4.00 $M_\odot$*

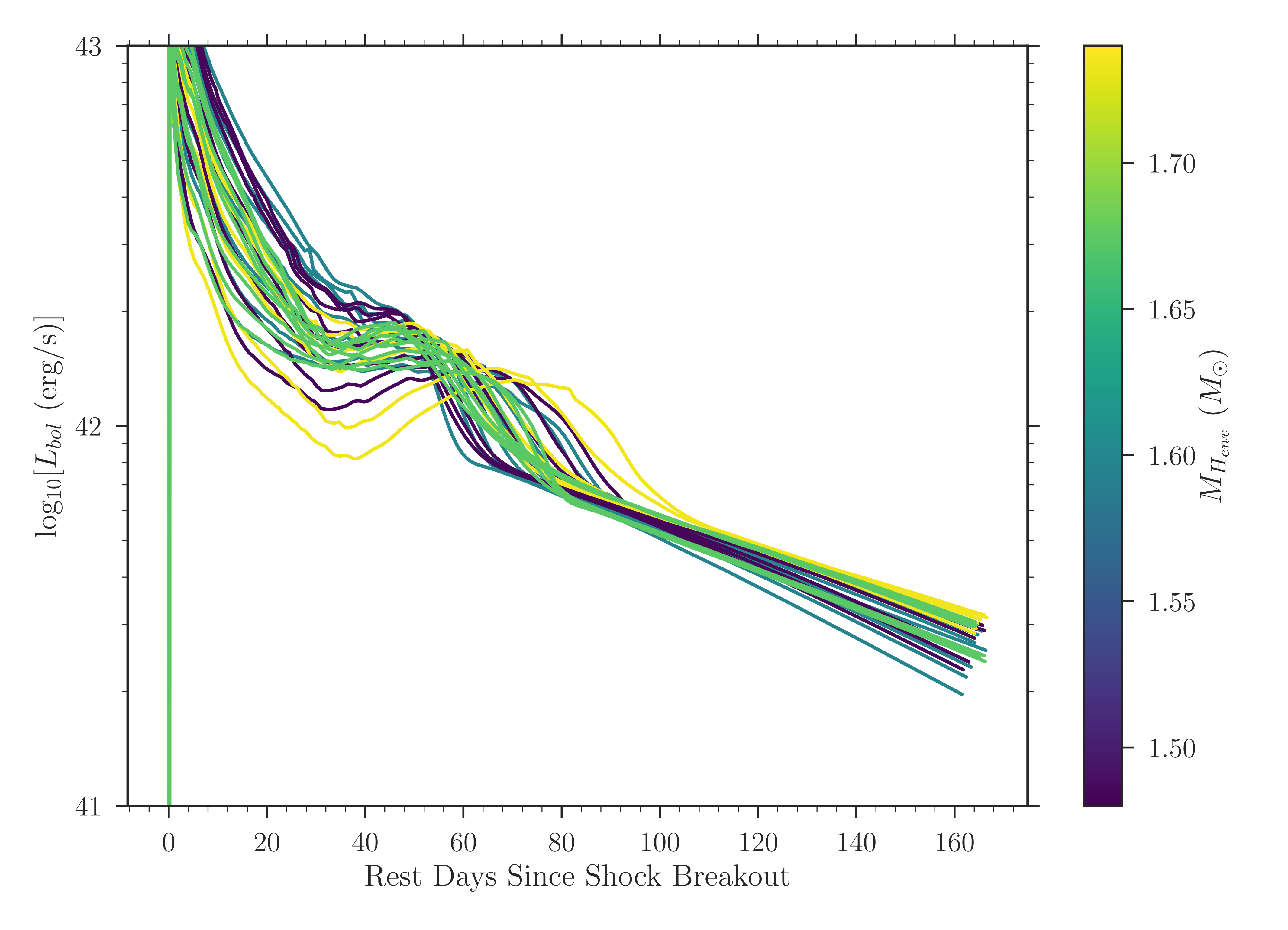
Hiramatsu+ in prep.



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

Short-plateau [Shock cooling ⇒ Recombination (Rph const.) ⇒ Co tail]: *1.48 $M_\odot$* < MHenv < *1.74 $M_\odot$*

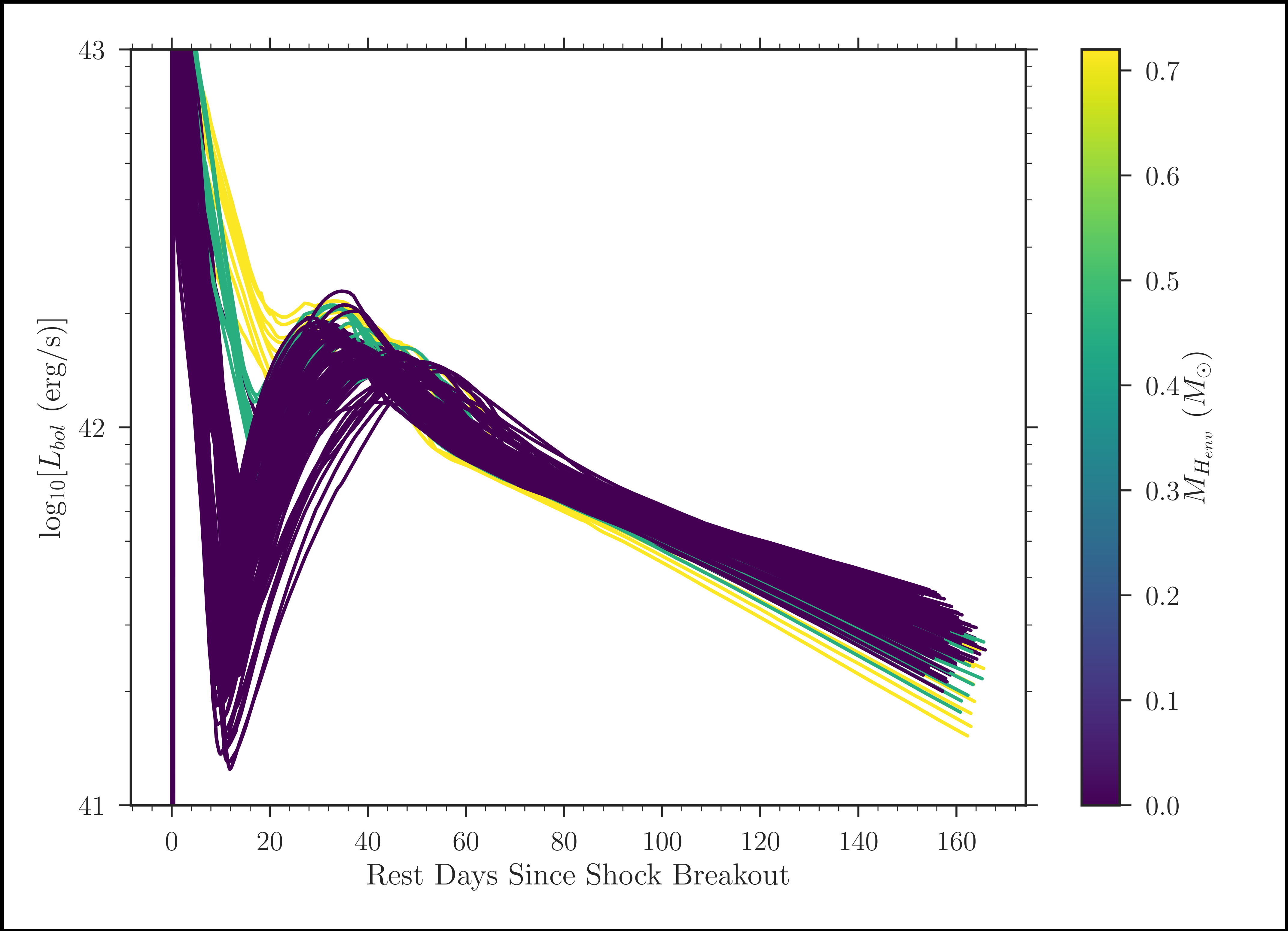
Hiramatsu+ in prep.



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

IIb [Shock cooling ⇒ Ni heating ⇒ Co tail]: MHenv < $0.72\ M_\odot$

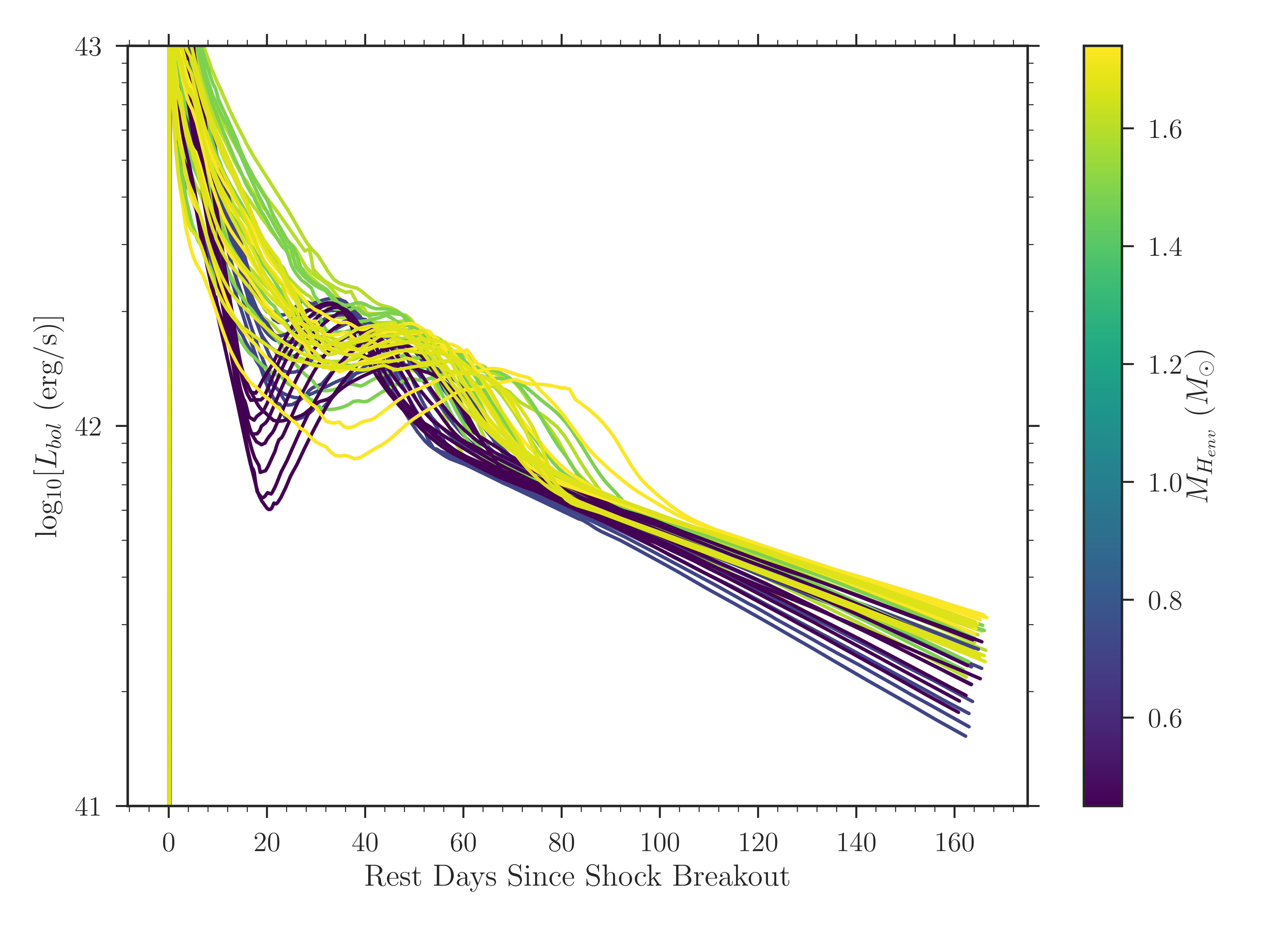
Hiramatsu+ in prep.



IIP vs IIL & Short-Plateau Supernovae: Numerical Light-Curve Modeling

IIL ⇒ Short-plateau ⇒ IIb in ~*1.3* $M_\odot$ difference in MHenv

Hiramatsu+ in prep.



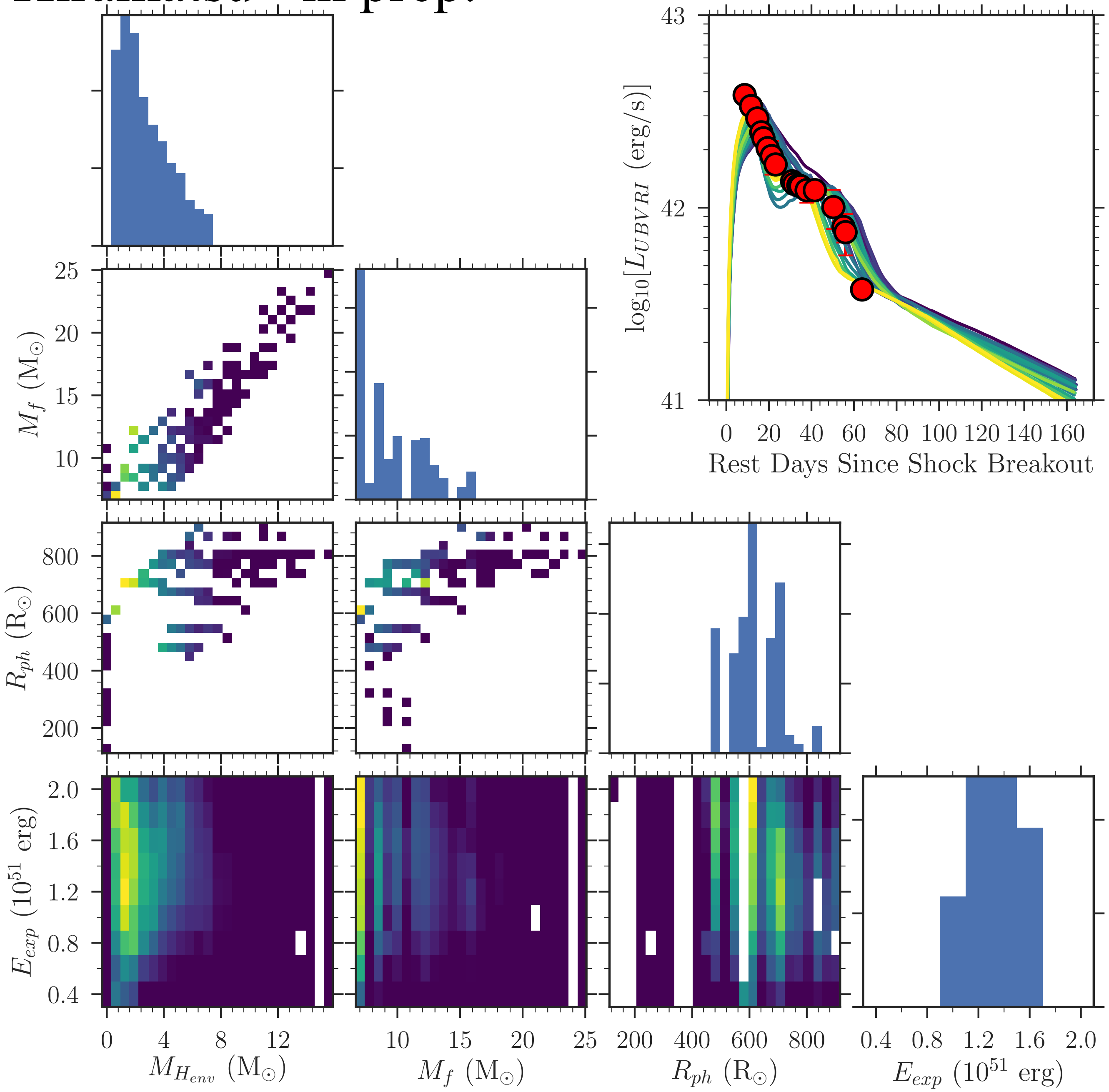
Short-Plateau Supernovae: Numerical Light-Curve Modeling

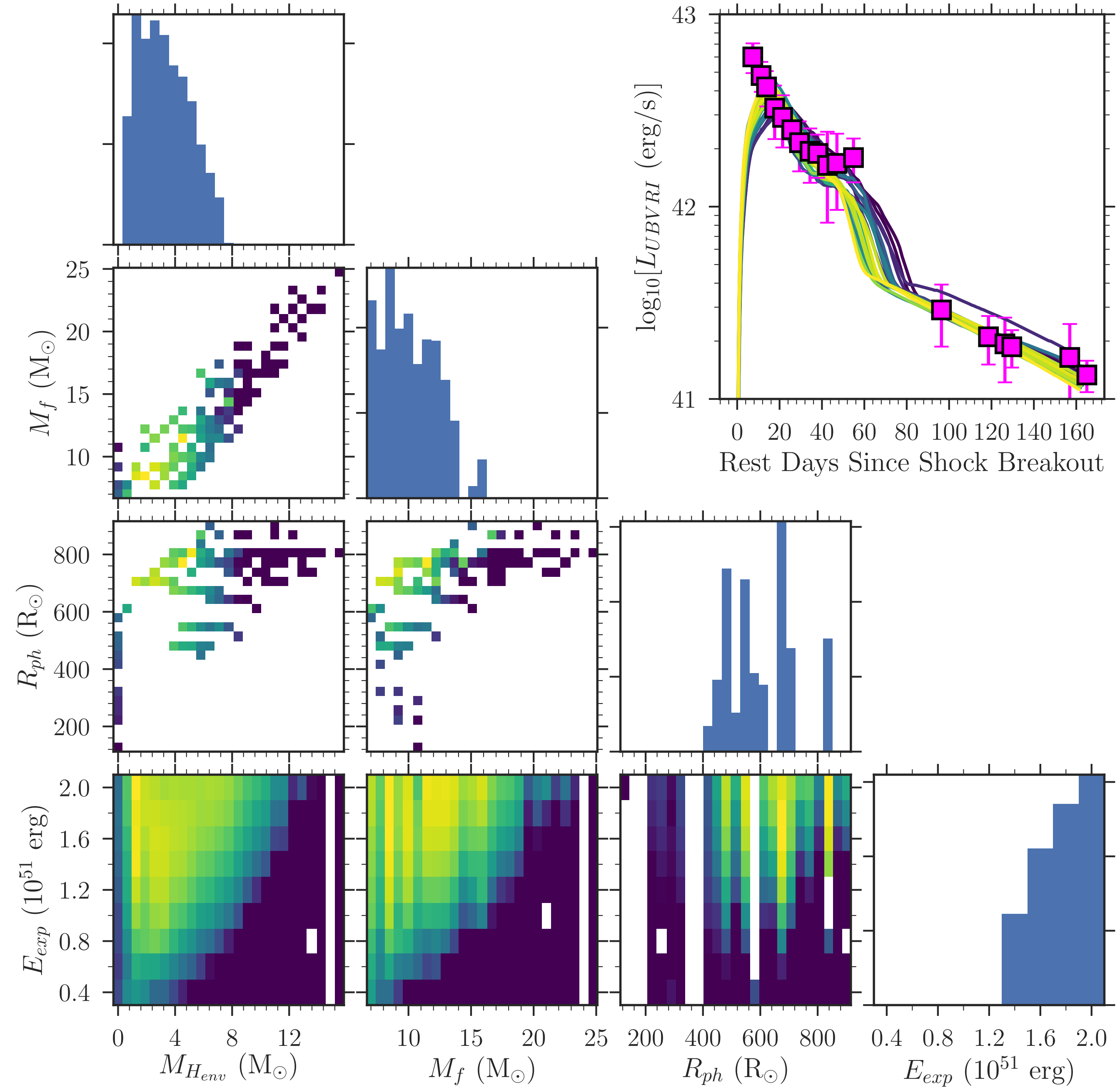
Short-Plateau supernovae from massive red supergiants: *17.5 - 22.5* $M_\odot$

SN 2006Y: He-core mass ~ *5.8* $M_\odot$

SN 2016egz: He-core mass ~ *7.2* $M_\odot$

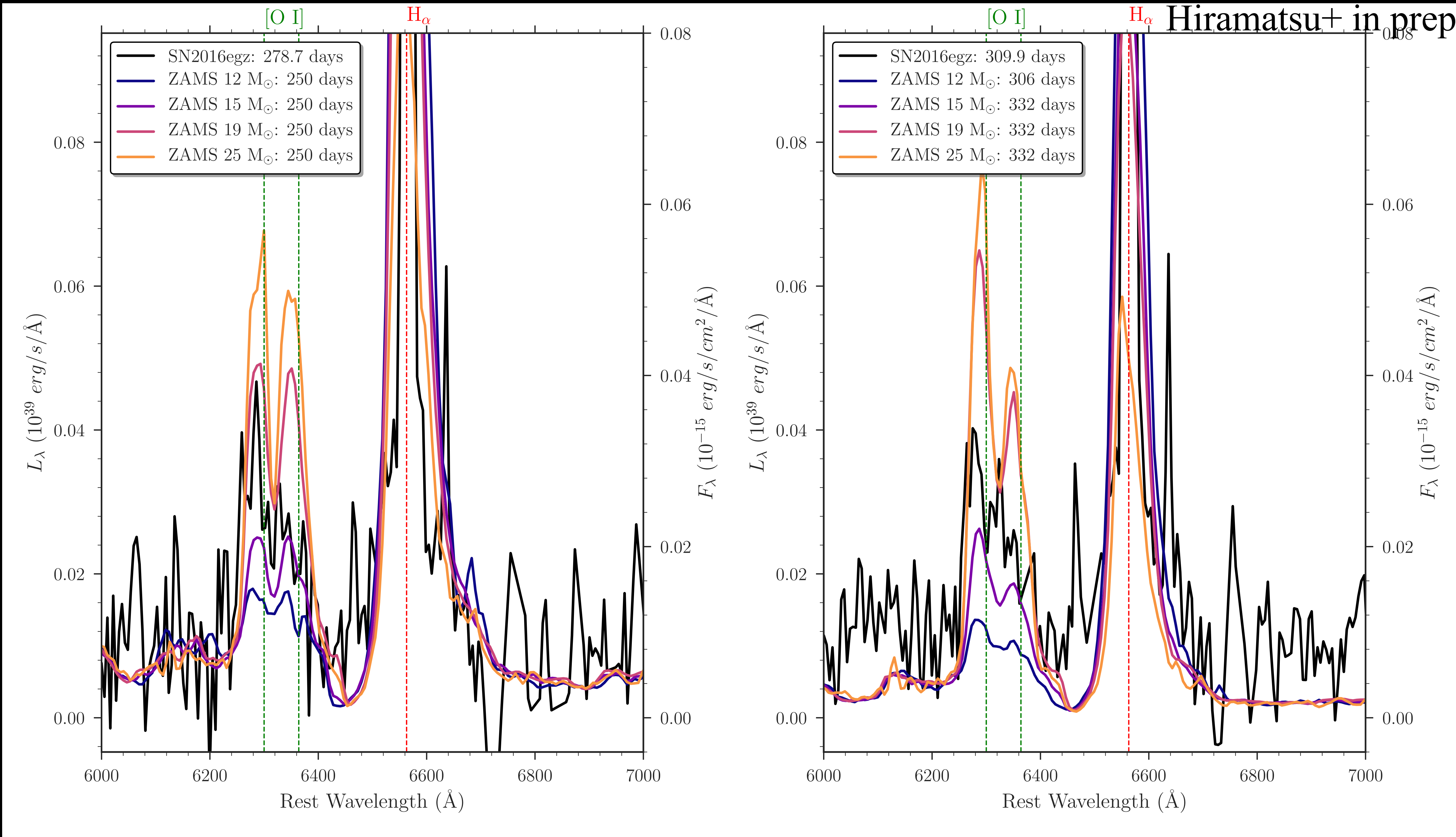
Hiramatsu+ in prep.





Short-Plateau Supernovae: Numerical Nebular Spectral Modeling

Short-Plateau supernovae from massive red supergiants: *15 - 25 M*$_\odot$

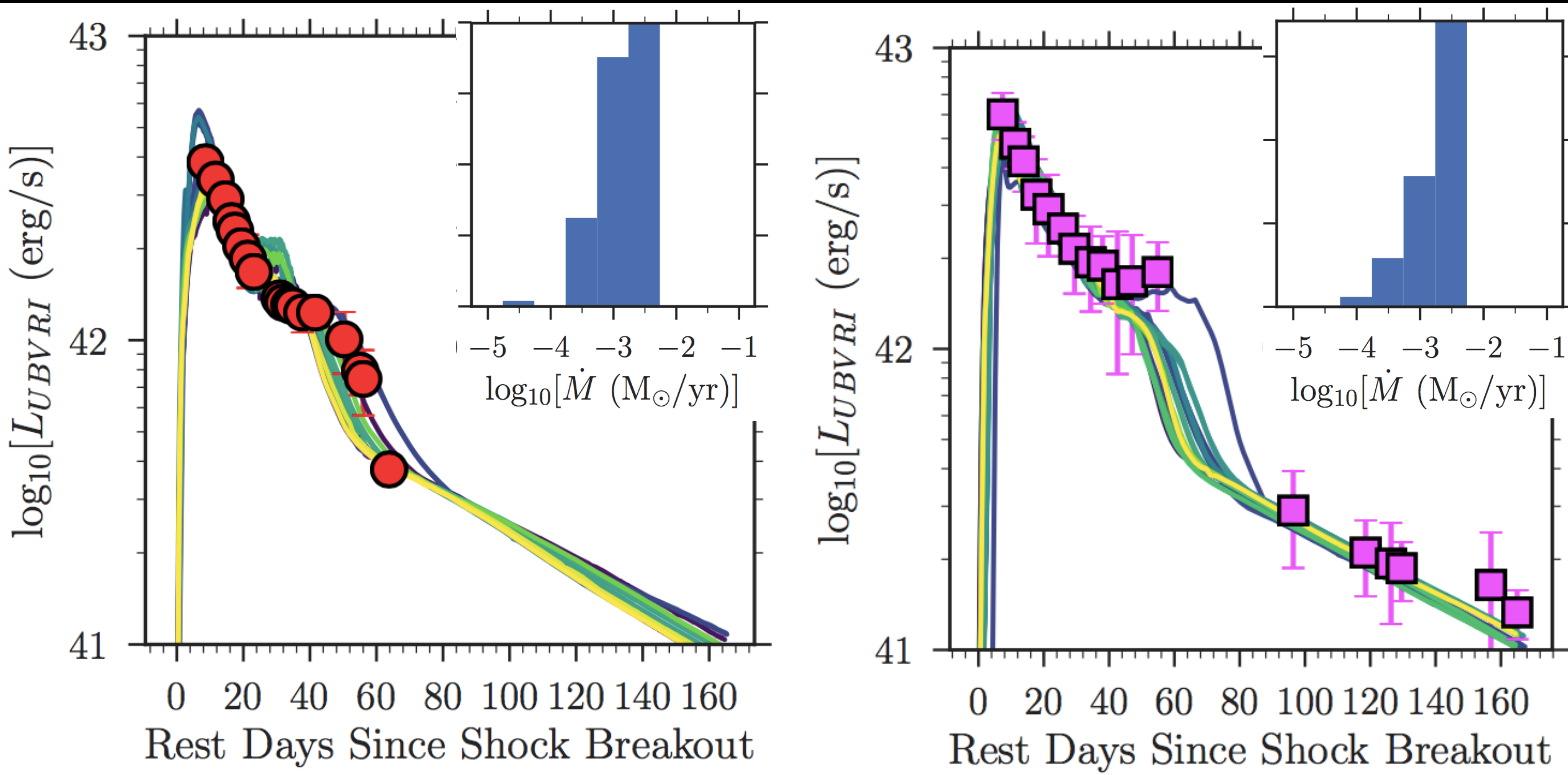


Short-Plateau Supernovae: Numerical CSM Light-Curve Modeling

Requires enhanced mass-loss, ~2 orders of magnitude greater than the standard stellar evolution

SN 2006Y: Mass-loss rate ~ *3e-3* $M_\odot$*/yr*　　SN 2016egz: Mass-loss rate ~ *3e-3* $M_\odot$*/yr*

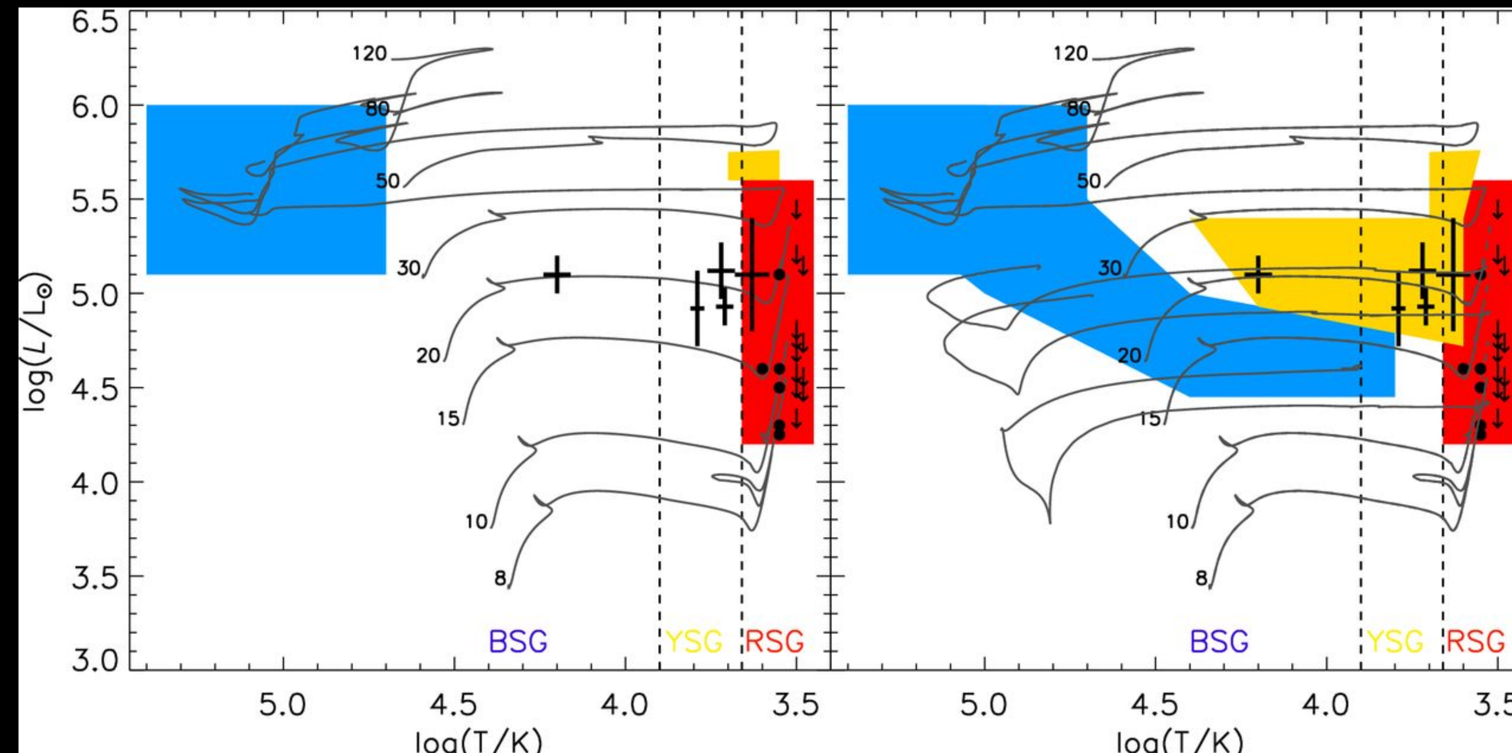
Hiramatsu+ in prep.



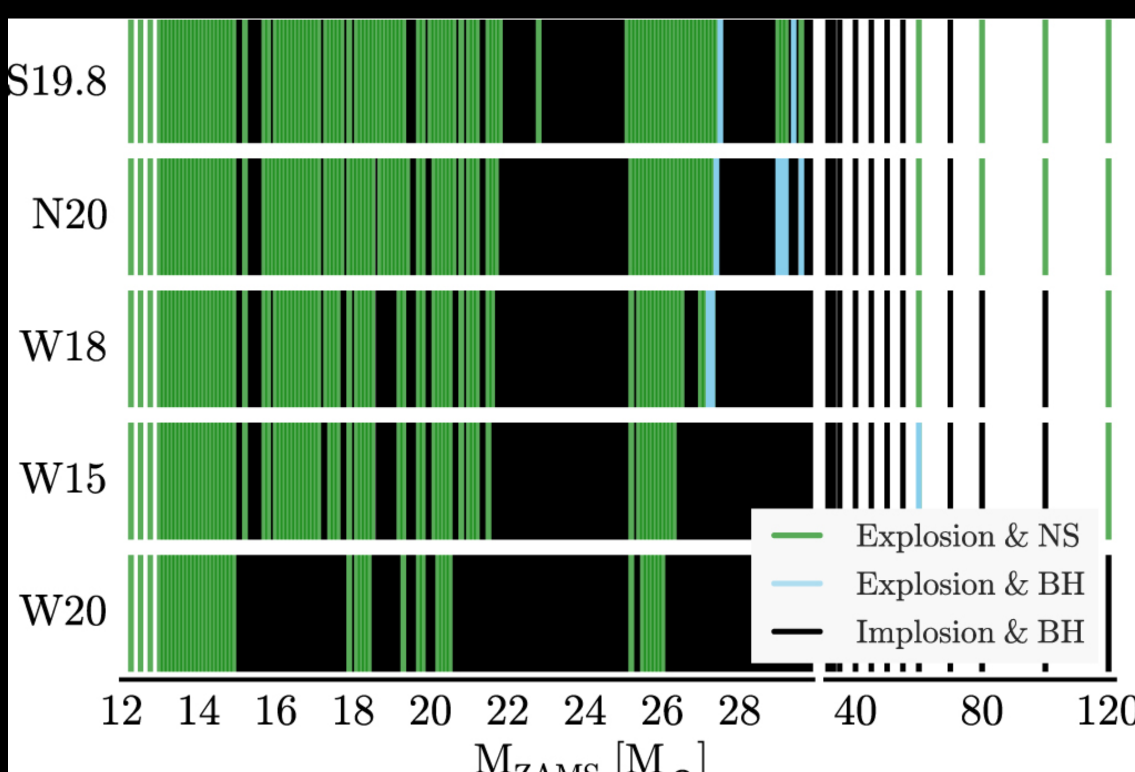
Short-Plateau Supernovae: Implication to the RSG problem

Based on the agreement of light-curve and nebular-spectrum modelings that short-plateau SN progenitors are massive RSG stars (ZAMS mass > *17.5* $M_\odot$) that experience significant pre-explosion mass-loss (high extinction), this rare class maybe a key to resolve the RSG problem.

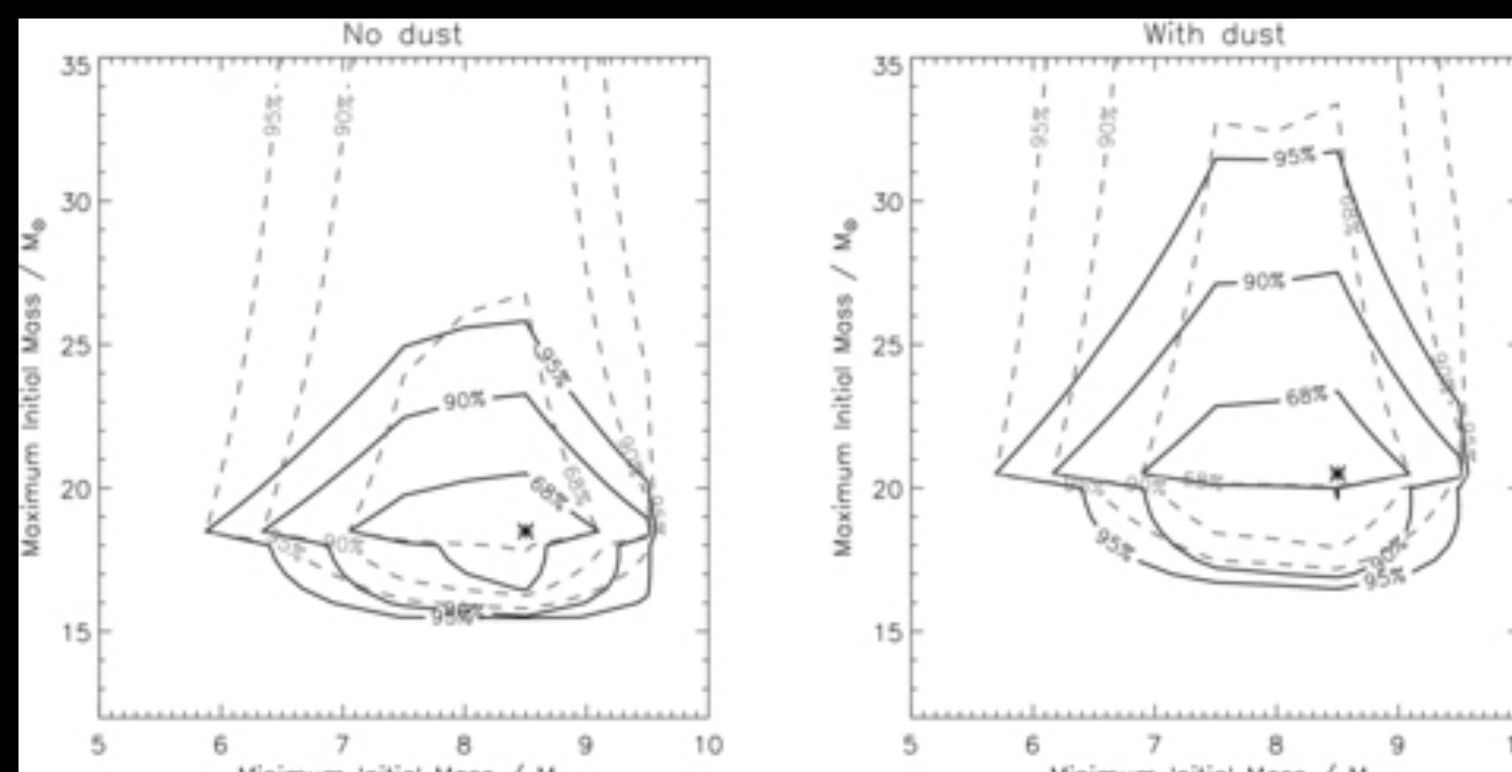
Single vs Binary (e.g. Eldridge+ 2013)?



Direct Collapse (e.g. Sukhbold+ 2016)?



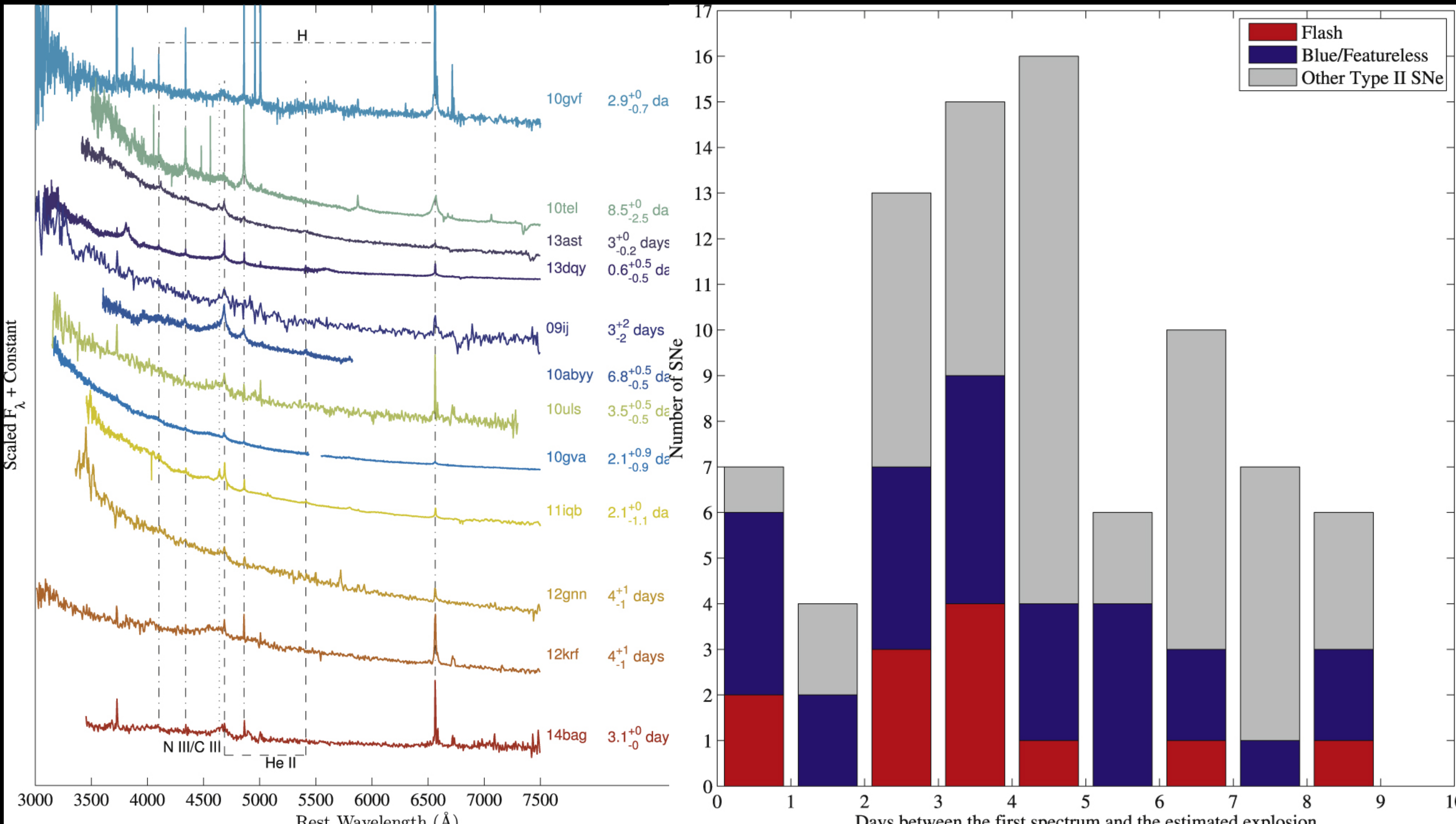
Dust (e.g. Walmswell & Eldridge 2012)?



Flash Spectroscopy Sample

Flash Spectroscopy: 18% of bright supernovae (<-17.6 mag) within 5 days of explosion ⇒ >*5e-4* $M_\odot$*/yr*

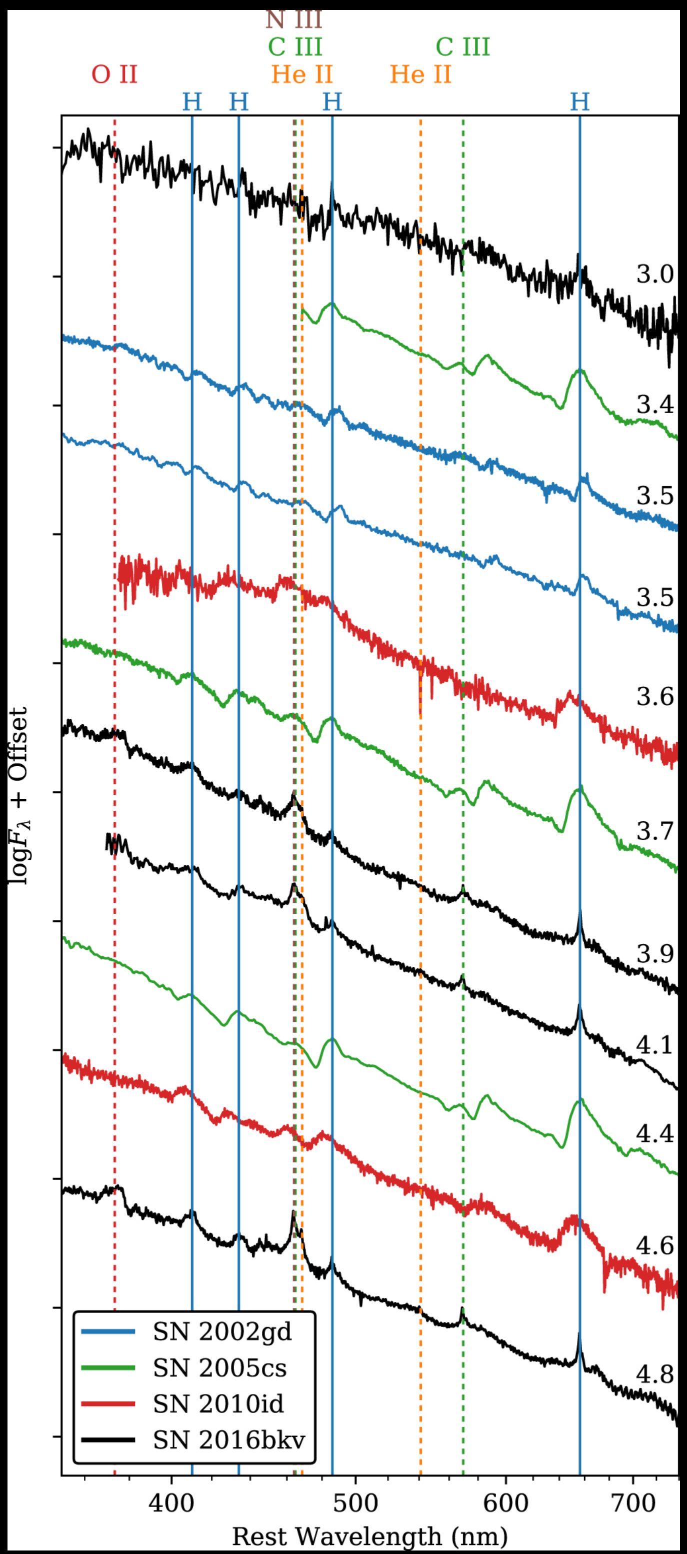
Khazov+ 2017, Boian & Groh 2018

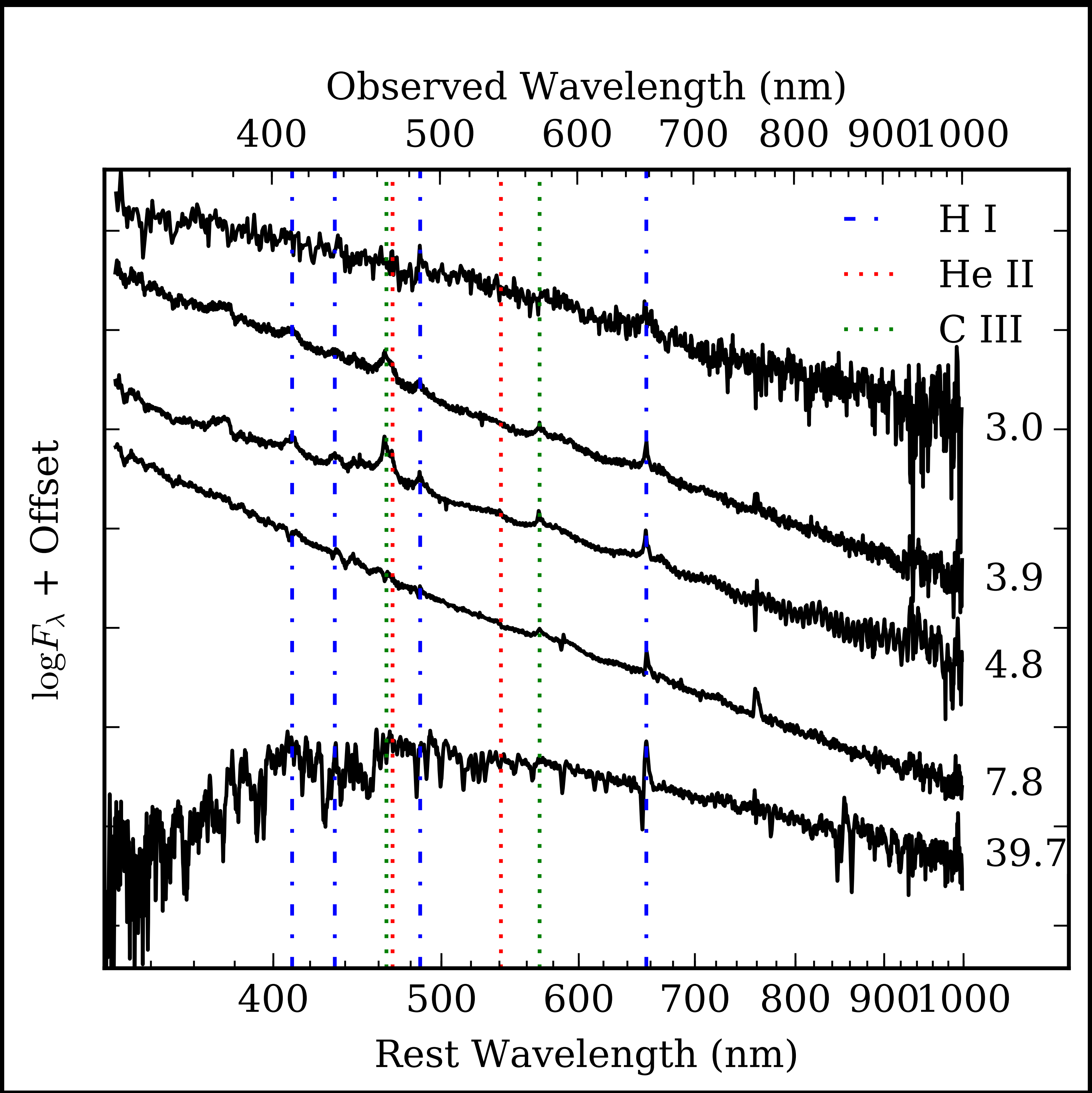


Flash Spectroscopy Sample

SN 2016bkv: First Faint (-16 mag) Type IIP with Flash Spectroscopy ⇒ ~*1e-3 $M_\odot$/yr* may be common

Hosseinzadeh+ 2018 (see also Nakaoka+ 2018)

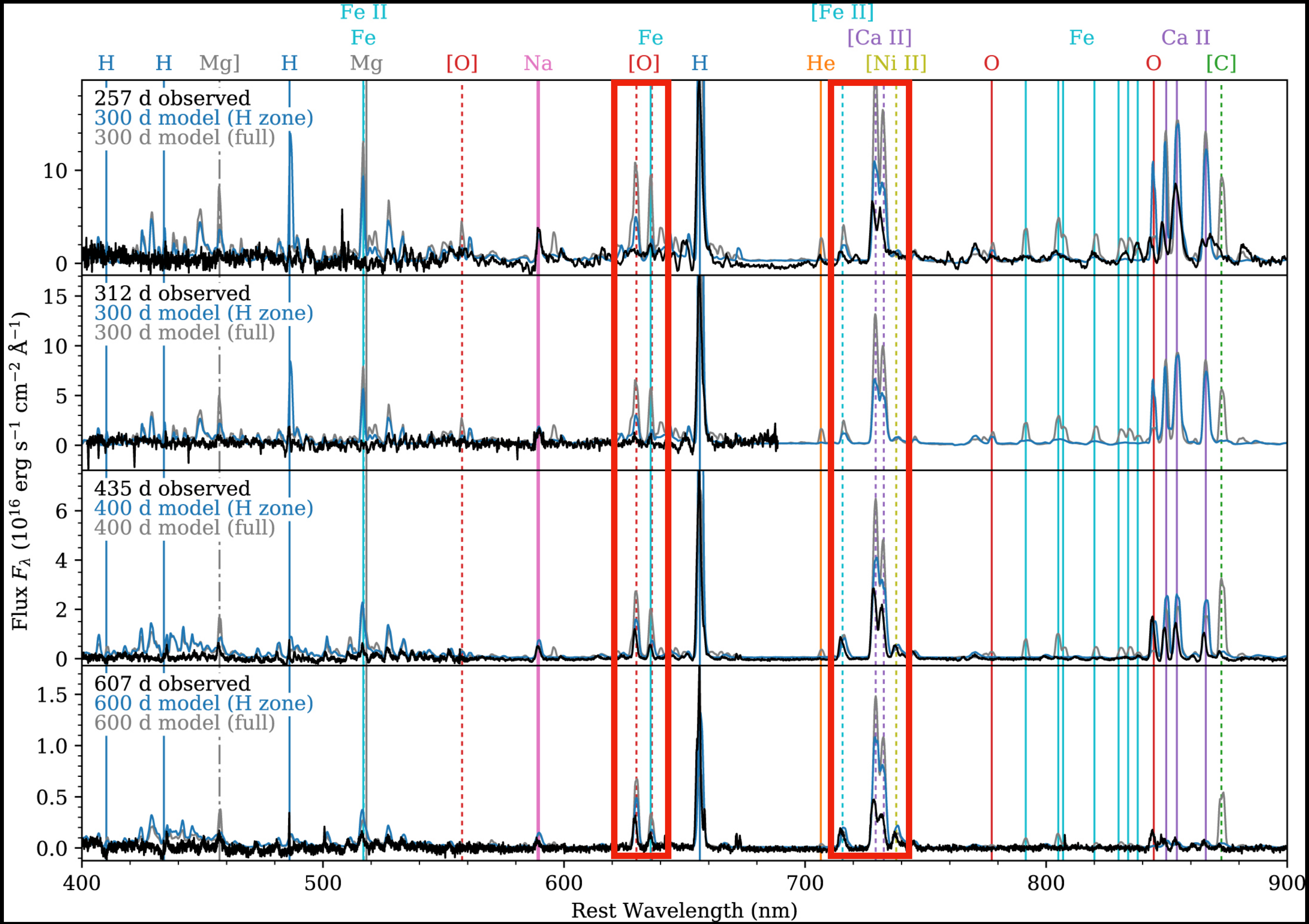




Nebular Spectroscopy

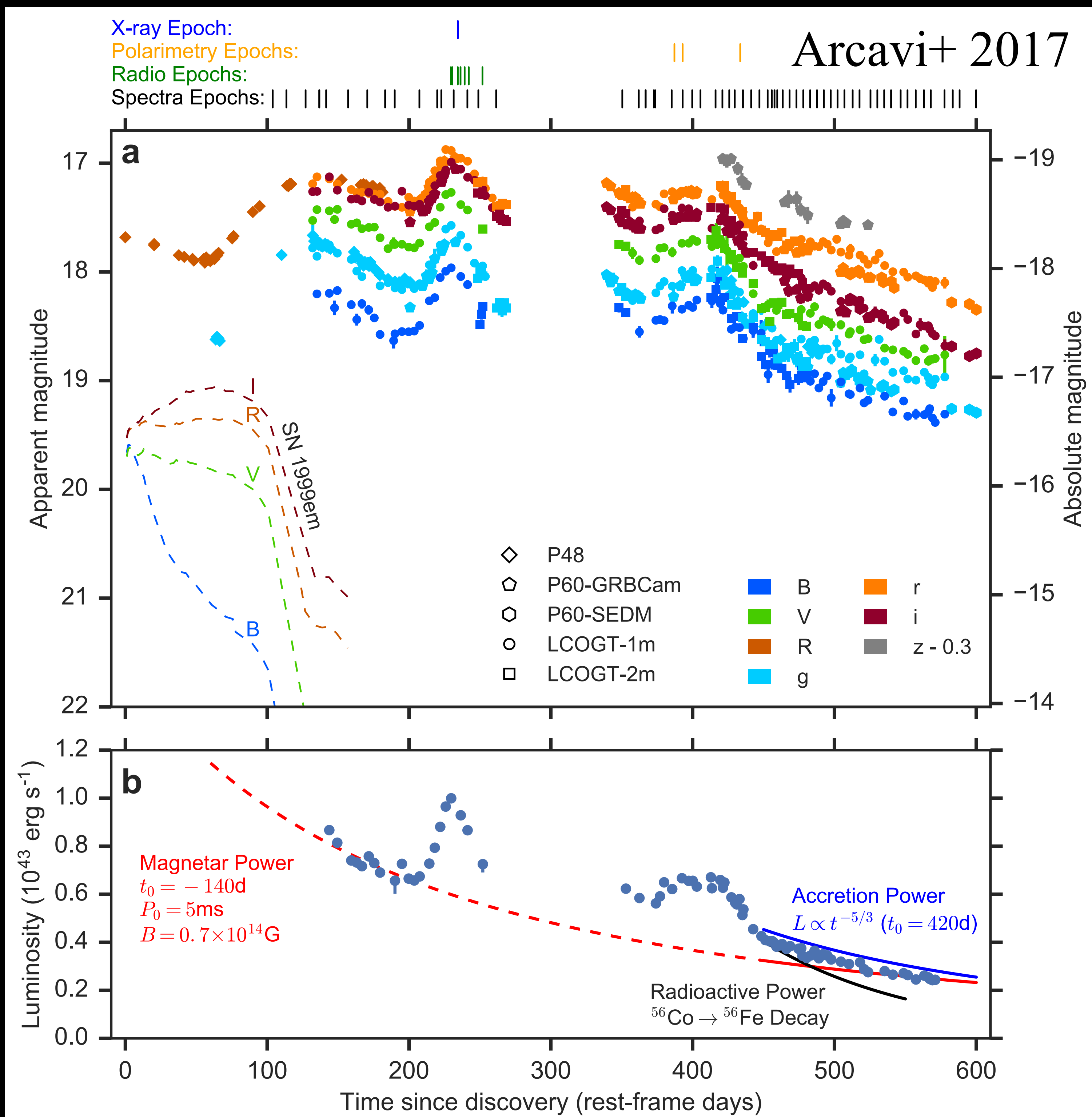
SN 2016bkv: Weak [O I] & [Fe II] lines ⇒ likely a low-mass progenitor (~9 $M_\odot$), possibly an electron-capture SN?

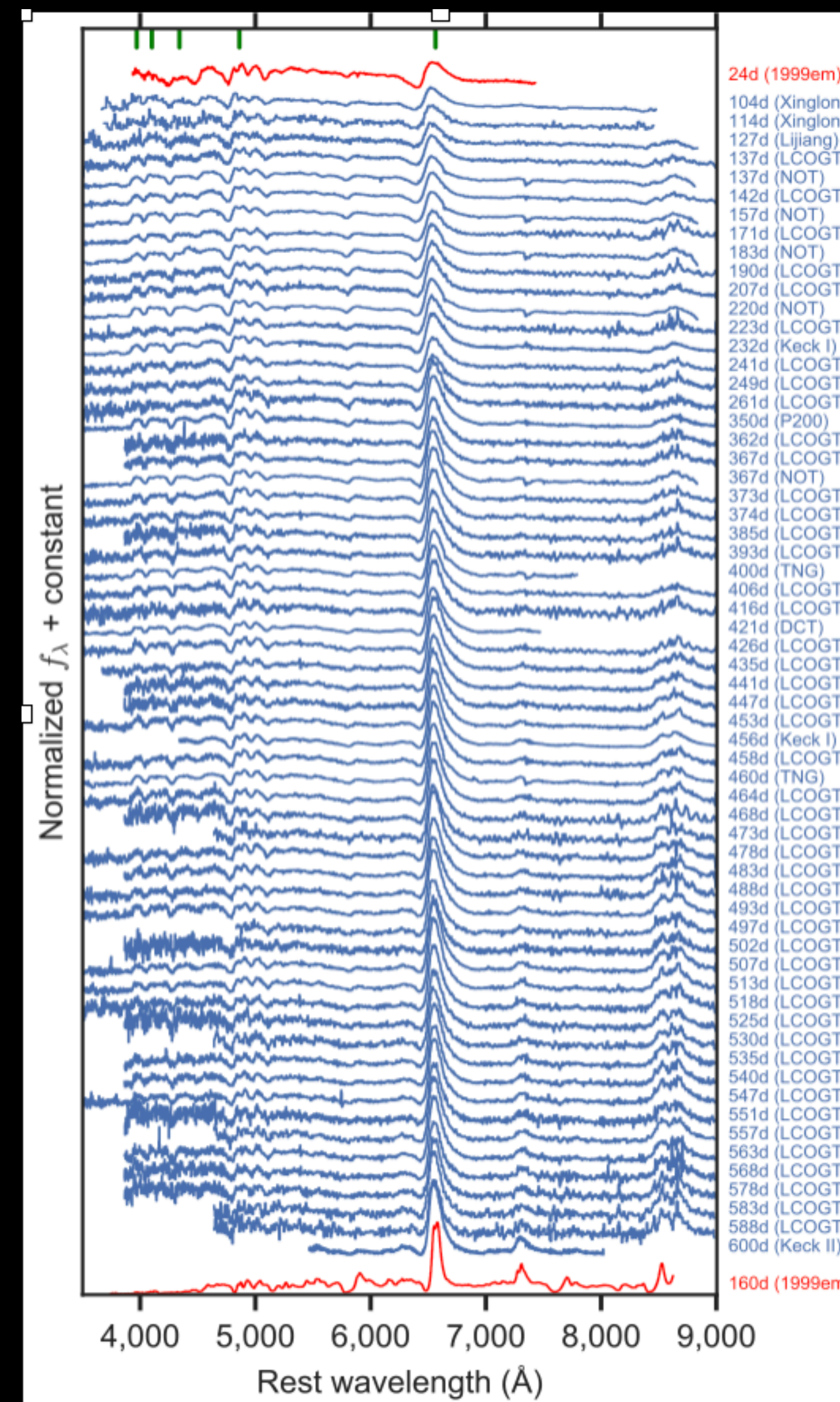
Hosseinzadeh+ 2018



#weird

iPTF14hls: Normal Type II spectra, but with the much slower evolution ⇒ a pulsation-pair instability supernova?





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Summary and Future Prospects:

- Supernovae are among the most influential events in the Universe.
- Type II supernovae are hydrogen-rich core-collapse of massive stars (>8 $M_\odot$).
- Current transient surveys discover >100 supernovae/night. LSST is expected to be online starting in 2023 and discover >1,000 supernovae/night.
- The Global Supernova Project is a world-wide collaboration of 150+ astronomers with 3,000+ hours of the Las Cumbres Observatory time to follow 150+ supernovae per year, complemented with the world's largest ground-based and space telescopes.
- Early high-cadence and late continuous follow-ups have revealed the progenitor structure and dense circumstellar material through shock-cooling and photospheric light curves and flash and nebular spectroscopy, as well as peculiar events, challenging our current understanding of massive star evolution and supernova explosion mechanism.
- The future is bright; we will have the big picture through large samples and self-consistent progenitor, light curve, and spectroscopy modeling.

Thank you! Please ask questions now and/or to dhiramatsu@lco.global