THE PROGENITOR ENVIRONMENTS OF CALCIUM-RICH TRANSIENTS

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WHAT IS THE PHASE SPACE OF CALCIUM-RICH TRANSIENTS?

WHAT CAN IT TELL US ABOUT THEIR PROGENITORS?

Credit: NOIRLab

Credit: Aaron M. Geller, Northwestern University IT

LIGHT CURVE EVOLUTION

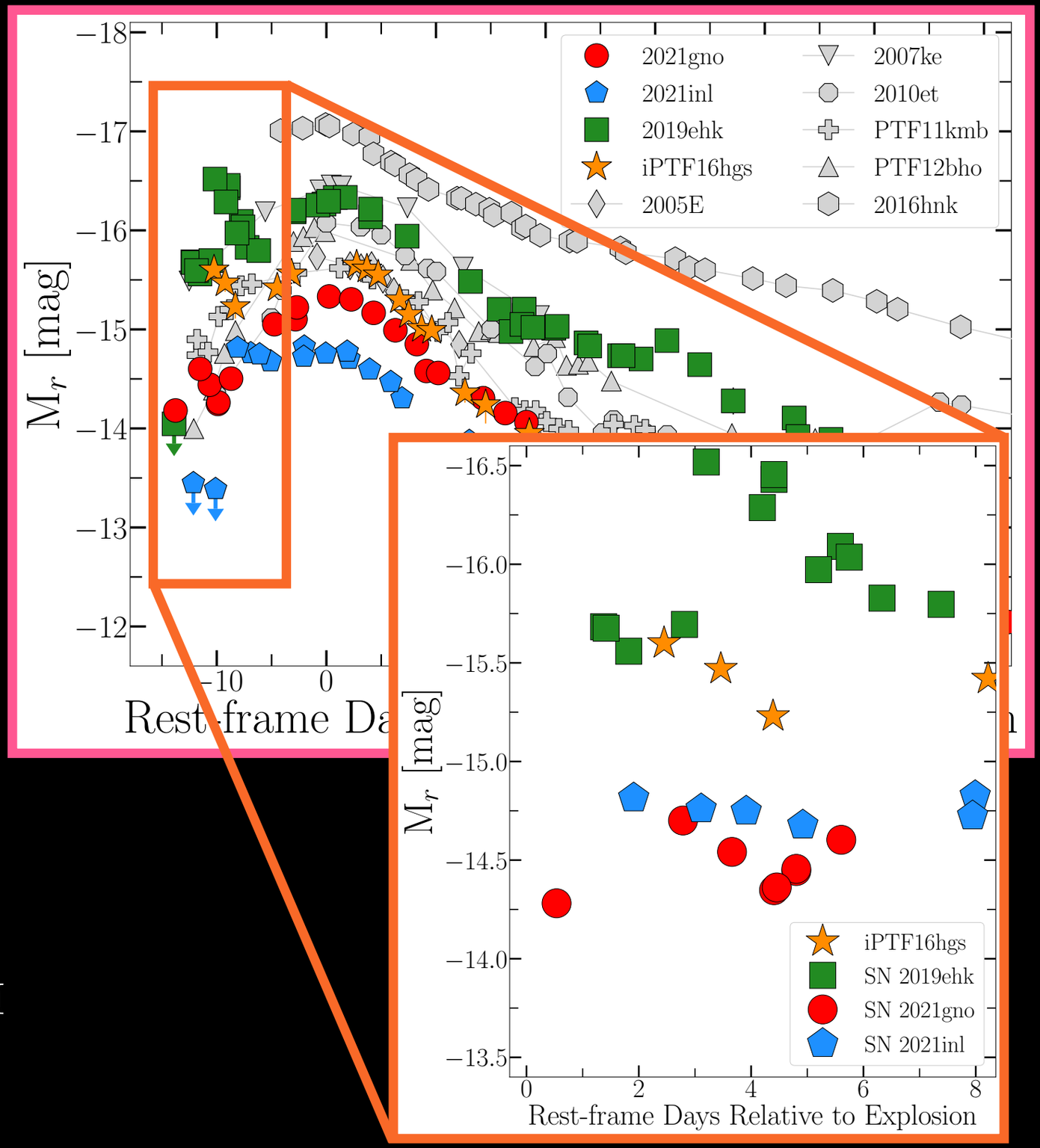
Characteristics:

- ★ M_{peak} : -15.5 to -16.5mag
- ★ $t_r \leq 15$ days
- ★ Fast decline after peak ($\Delta m_{15} = 1.8 - 2.0$ mag)

Double-peaked Events:

- ★ 2021gno, 2021inl, 2019ehk, iPTF16hgs, 2018lqo
- ★ Rise in ~1 day, declines in ~6 days
- ★ Emission from shock cooling or CSM interaction

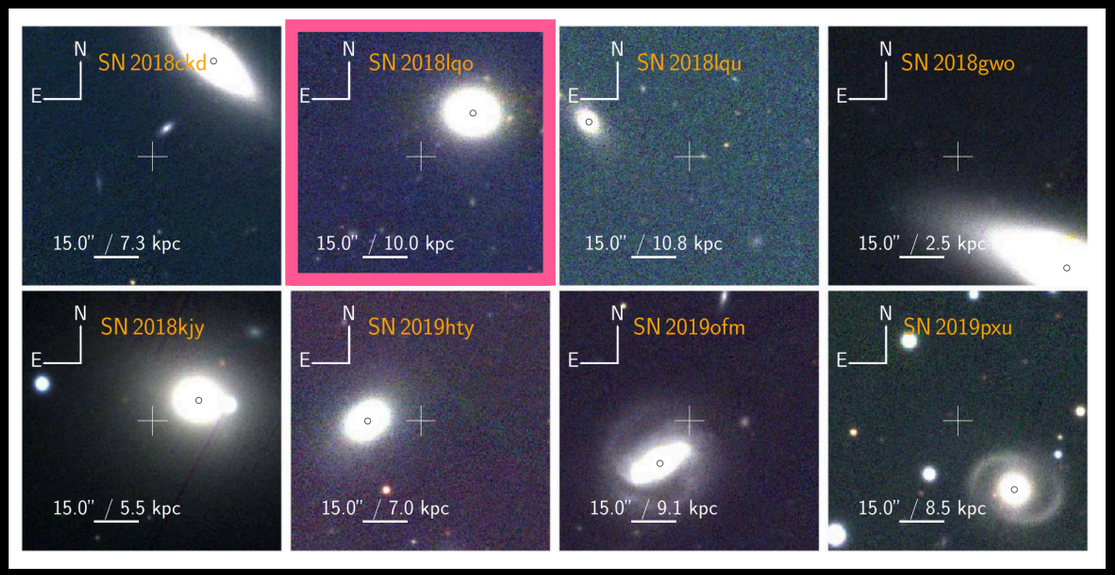
(Jacobson-Galán+ 2020a,b, 2021a, 2022b)



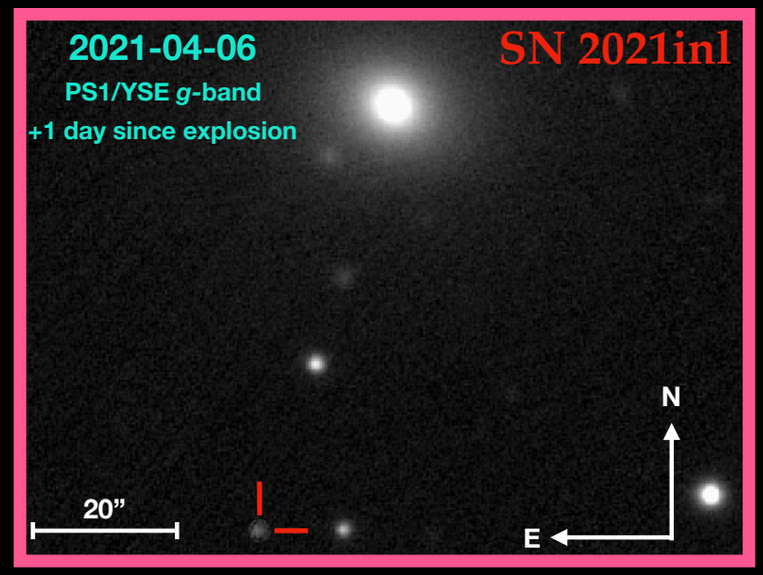
HOST ENVIRONMENTS

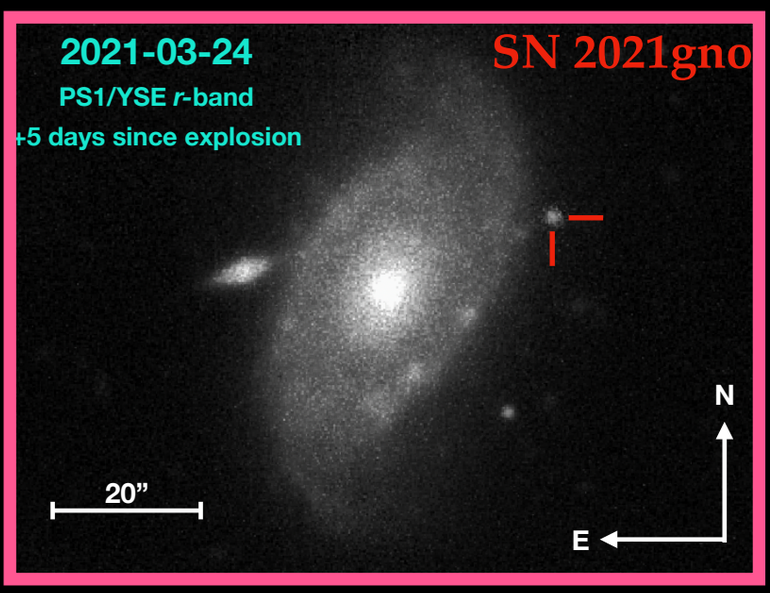
Characteristics:

- ★ Variety of host morphology and offsets
- ★ Preference to locations of low star formation
- ★ Pre-explosion imaging of SN 2019ehk only allows for WD systems and $M_\star < 10\ M_\odot$ (unlikely)

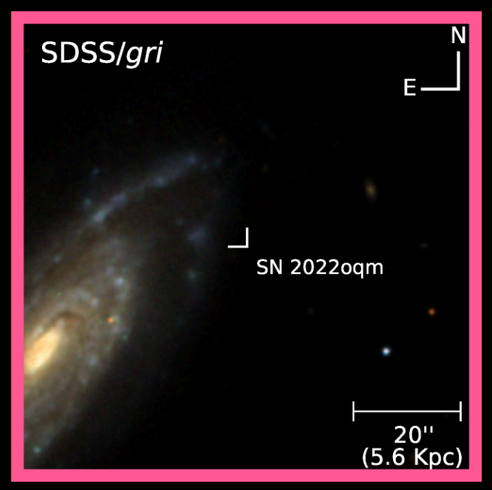


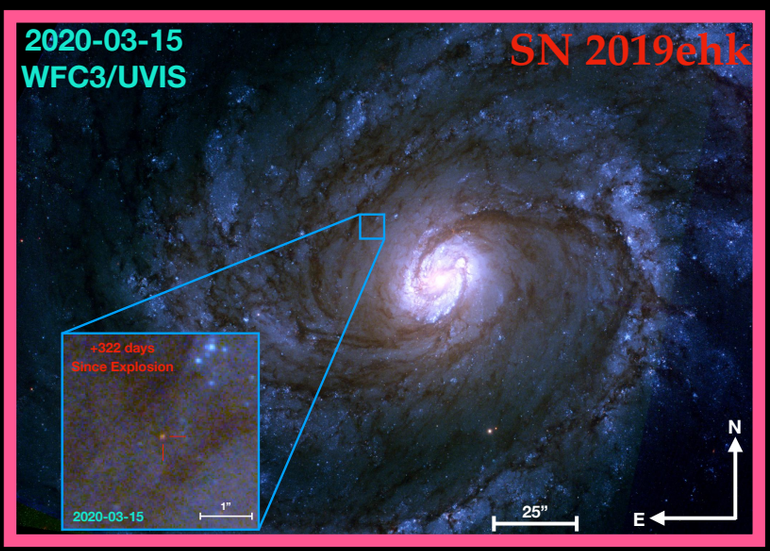
(De+ 2020)



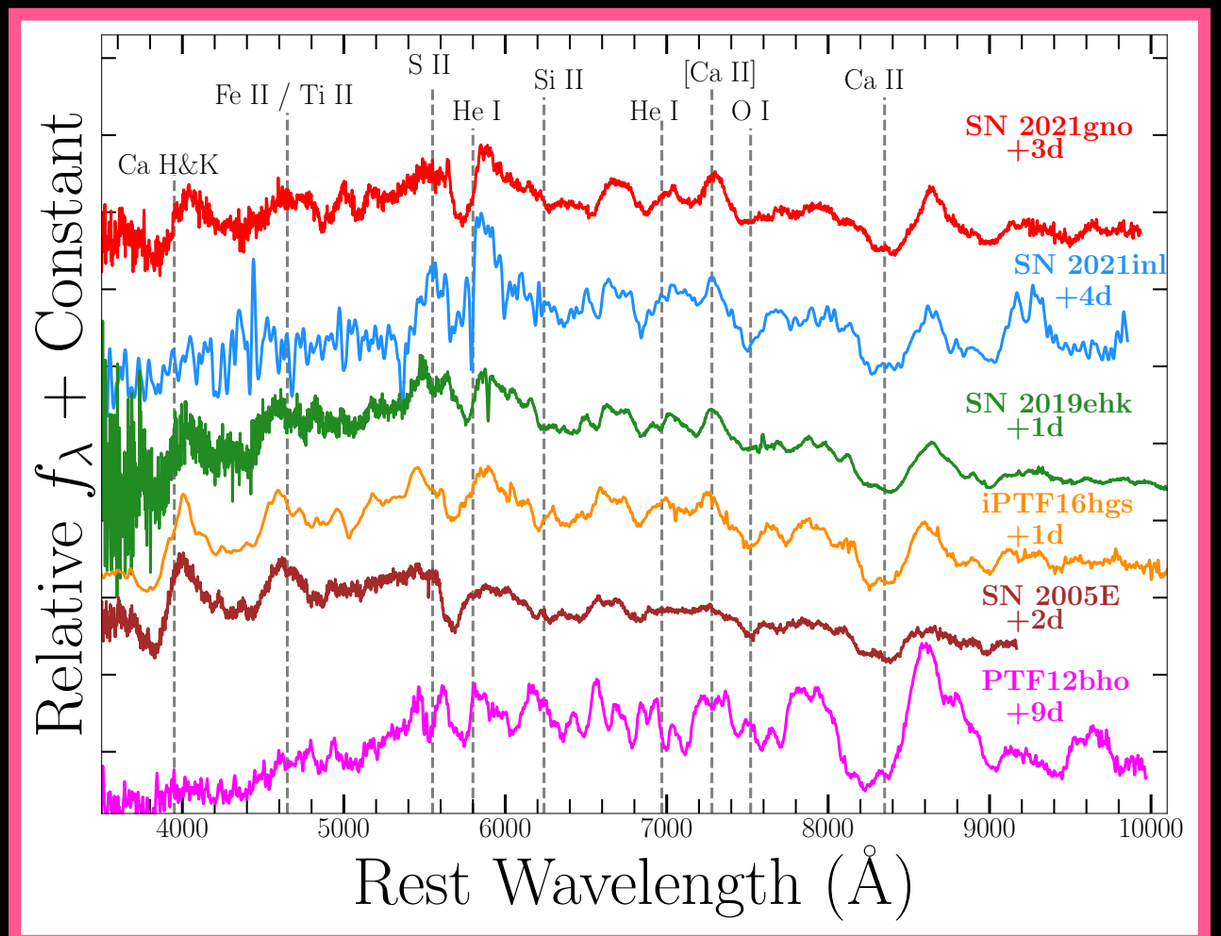


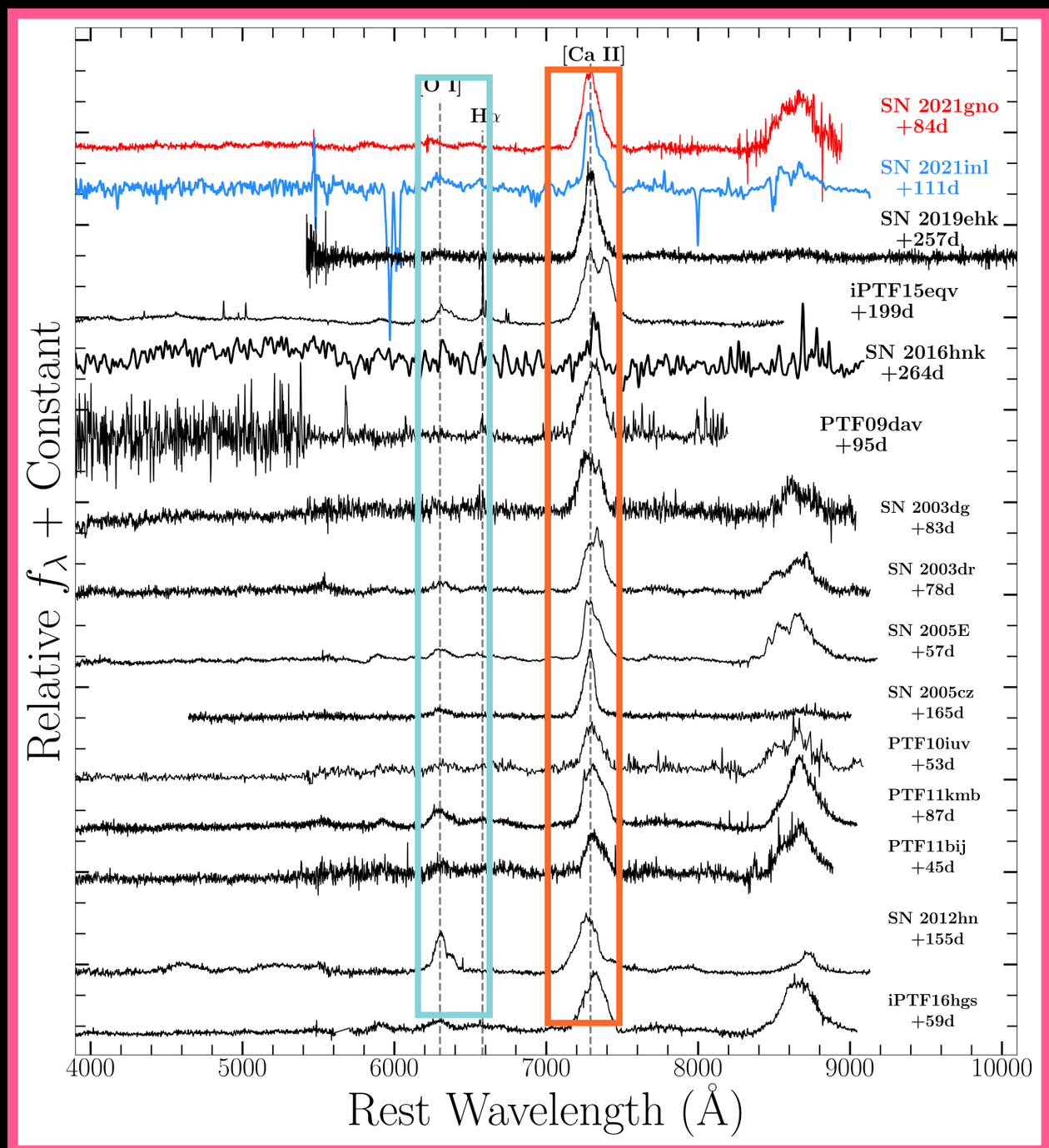
(Irani+ 2022)





SPECTROSCOPIC EVOLUTION





Characteristics:

- ★ Type I spectra + Helium (sometimes)
- ★ Velocities: 6000 - 11,000 km/s
- ★ Strong Calcium features

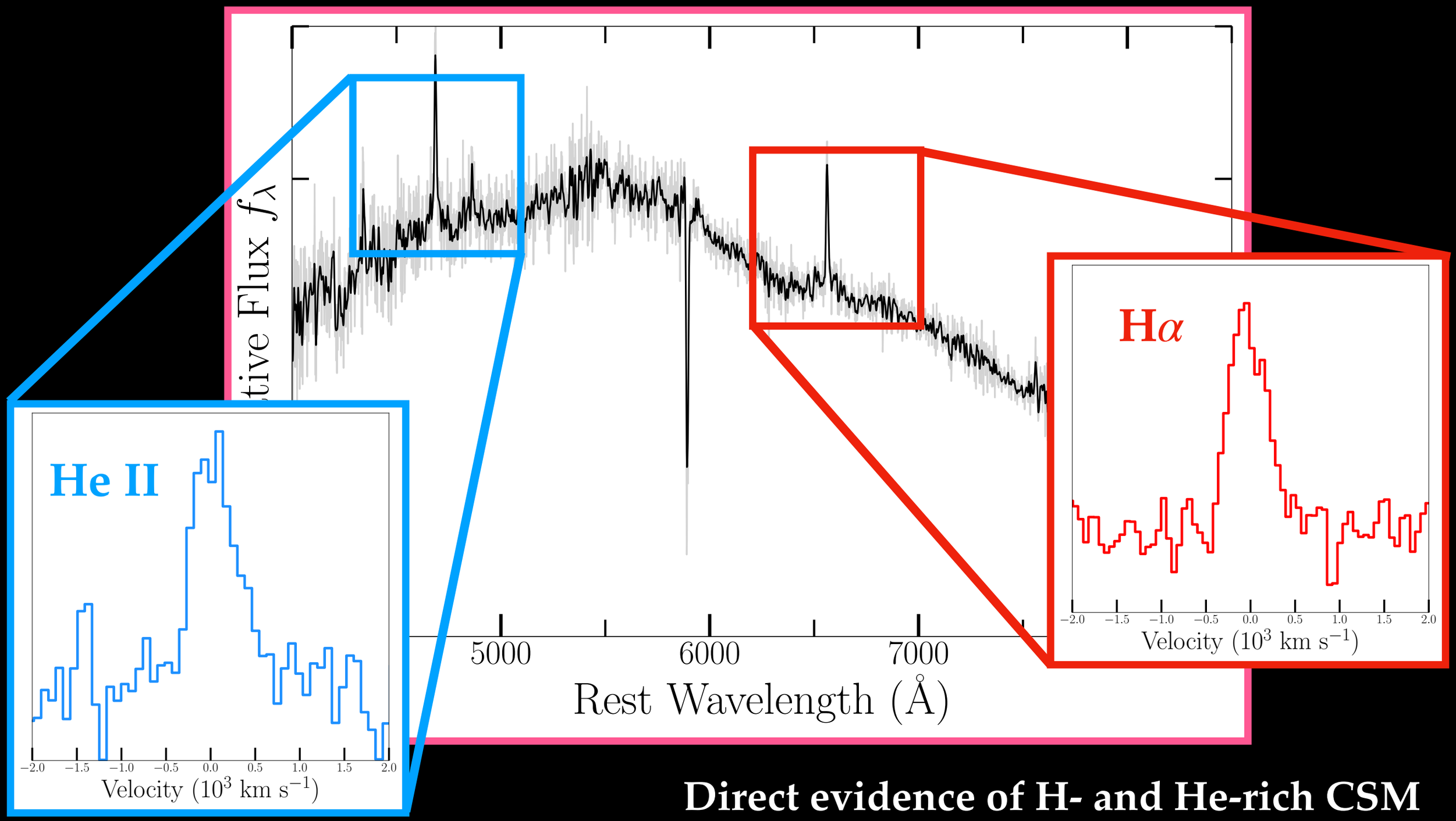
[Ca II] / [O I] > 2

"Calcium-rich" –> "Calcium-strong"

Shen+ 2019

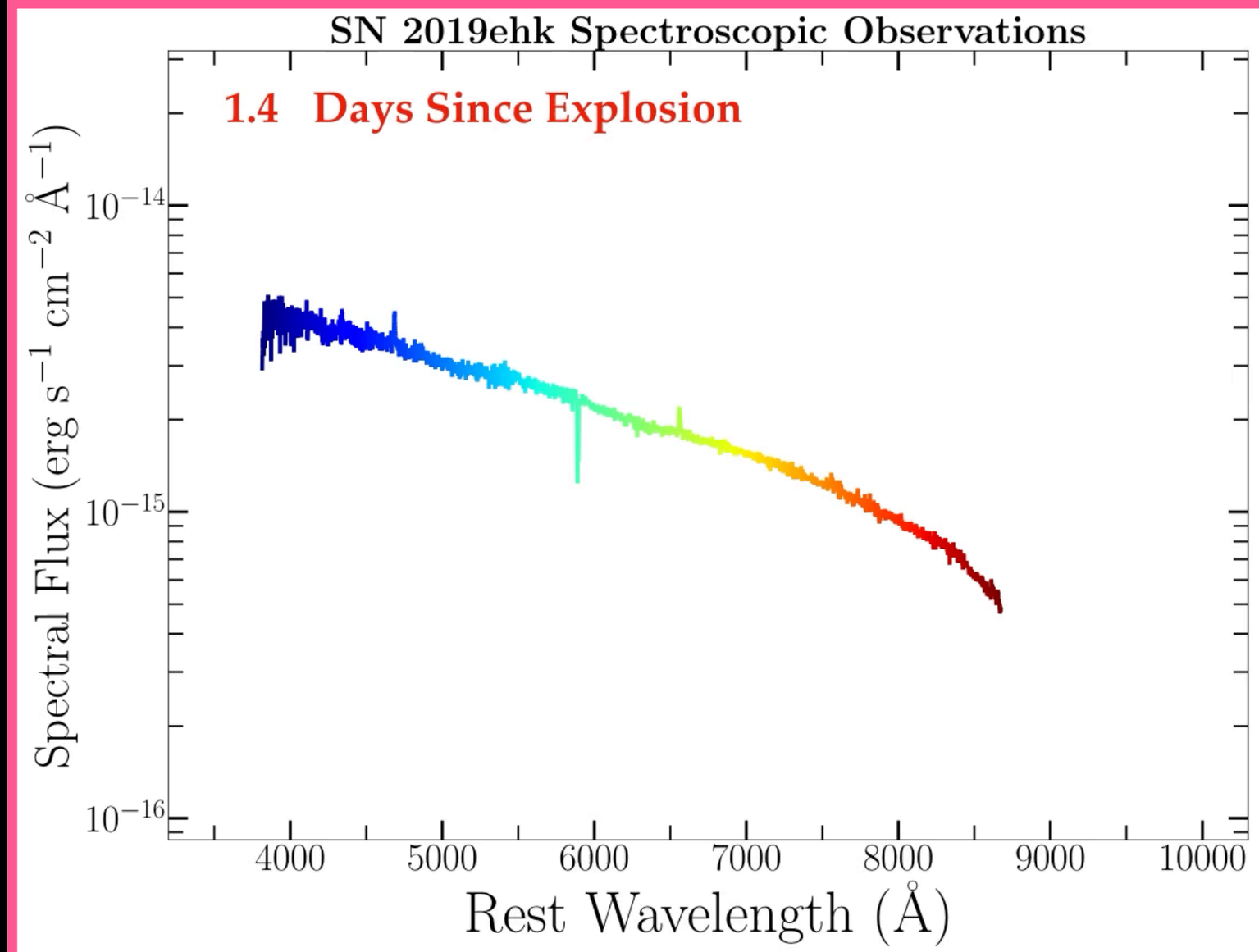
"FLASH" SPECTROSCOPY

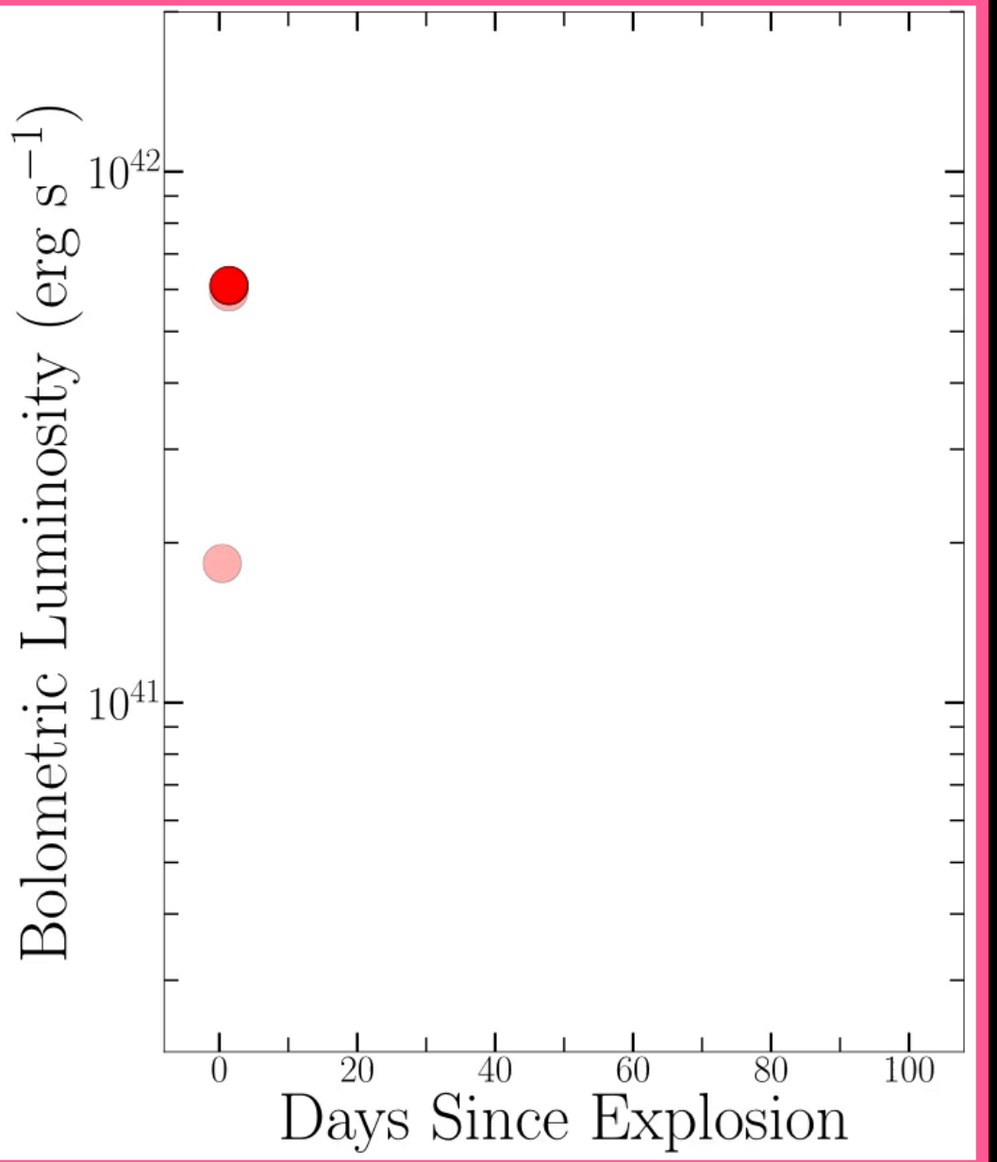
SN 2019ehk at 1.5 days post-explosion



Direct evidence of H- and He-rich CSM surrounding progenitor of a Ca-rich SN

OPTICAL+UV+IR EVOLUTION



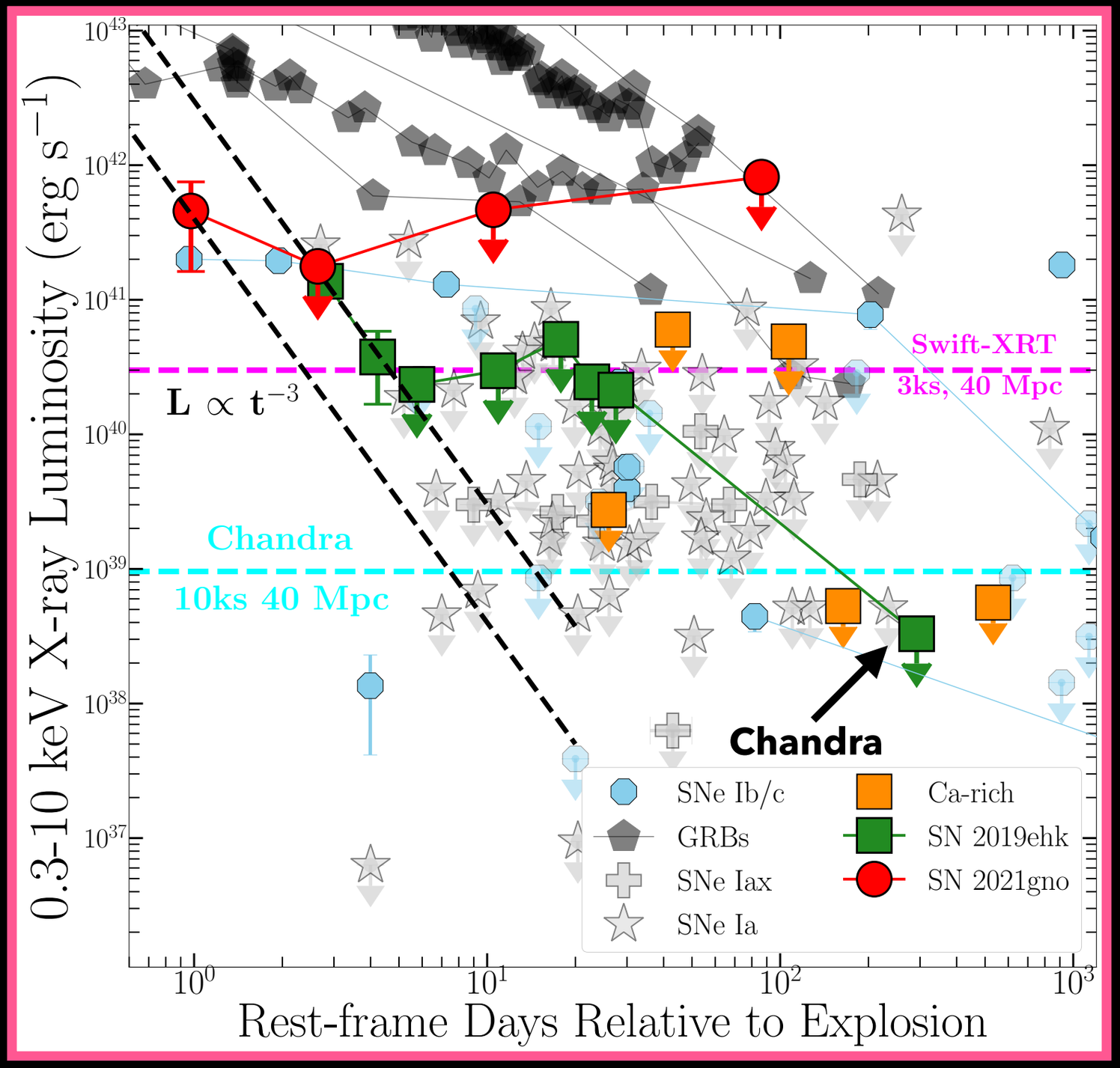


Proposed Progenitor Channels:

- ★ Stripped-envelope massive stars
- ★ WD disruption by NS or BH
- ★ Low mass WD merger
- ★ WD He-shell detonation

CALCIUM-RICH X-RAY PHASE SPACE

- ★ No observations at $t < 20$ days
- ★ SNe 2019ehk & 2021gno are the only Ca-rich transients with X-ray detections
- ★ Luminous, fast-fading X-rays detected by *Swift*-XRT
- ★ *Chandra* provided deepest X-ray observation of Ca-rich SN
- ★ Indicates shock interaction with confined CSM



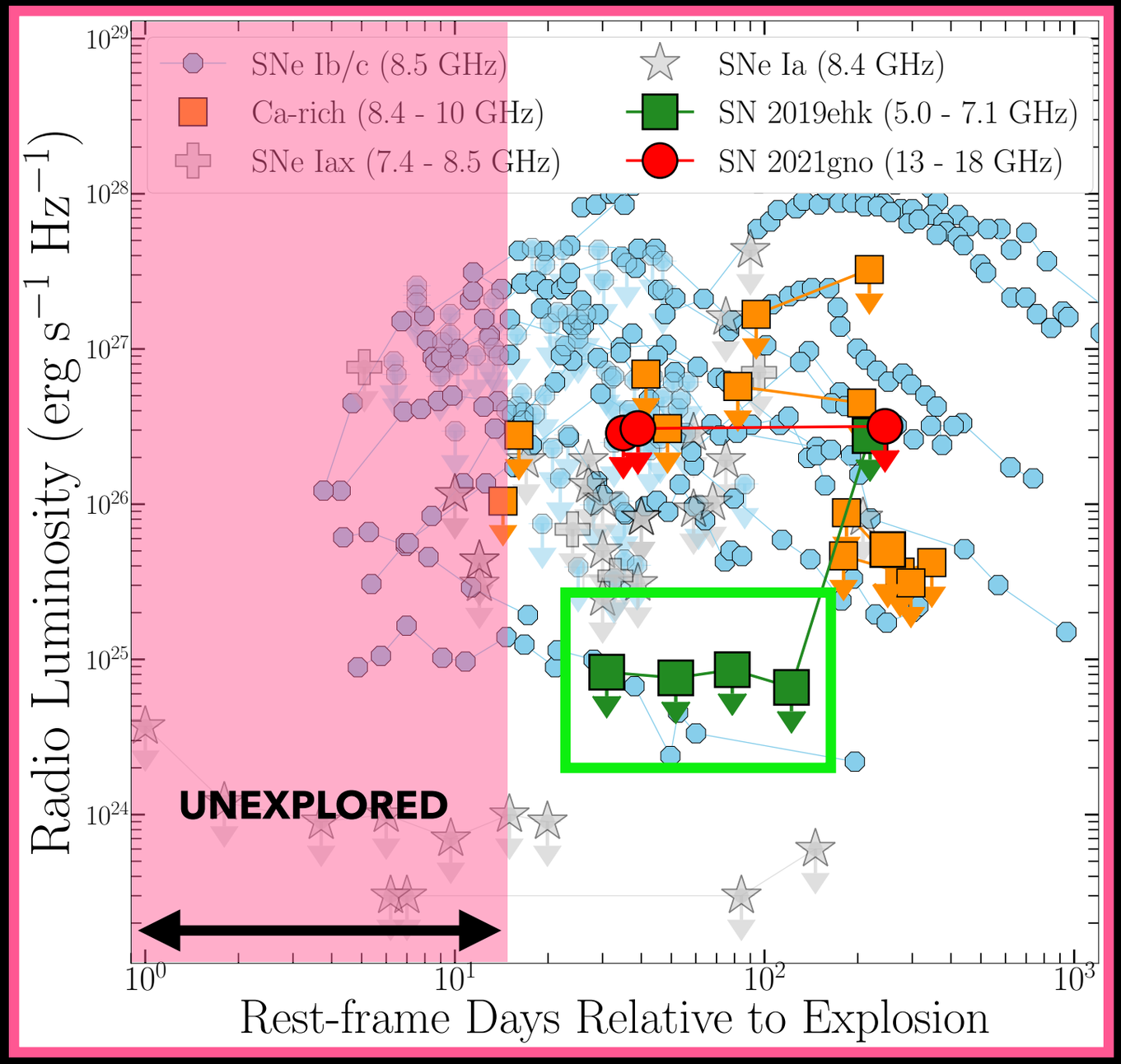
CALCIUM-RICH RADIO PHASE SPACE

★ $t < 20$ days is unconstrained

★ Deep upper limits in SNe 2019ehk & 2021gno

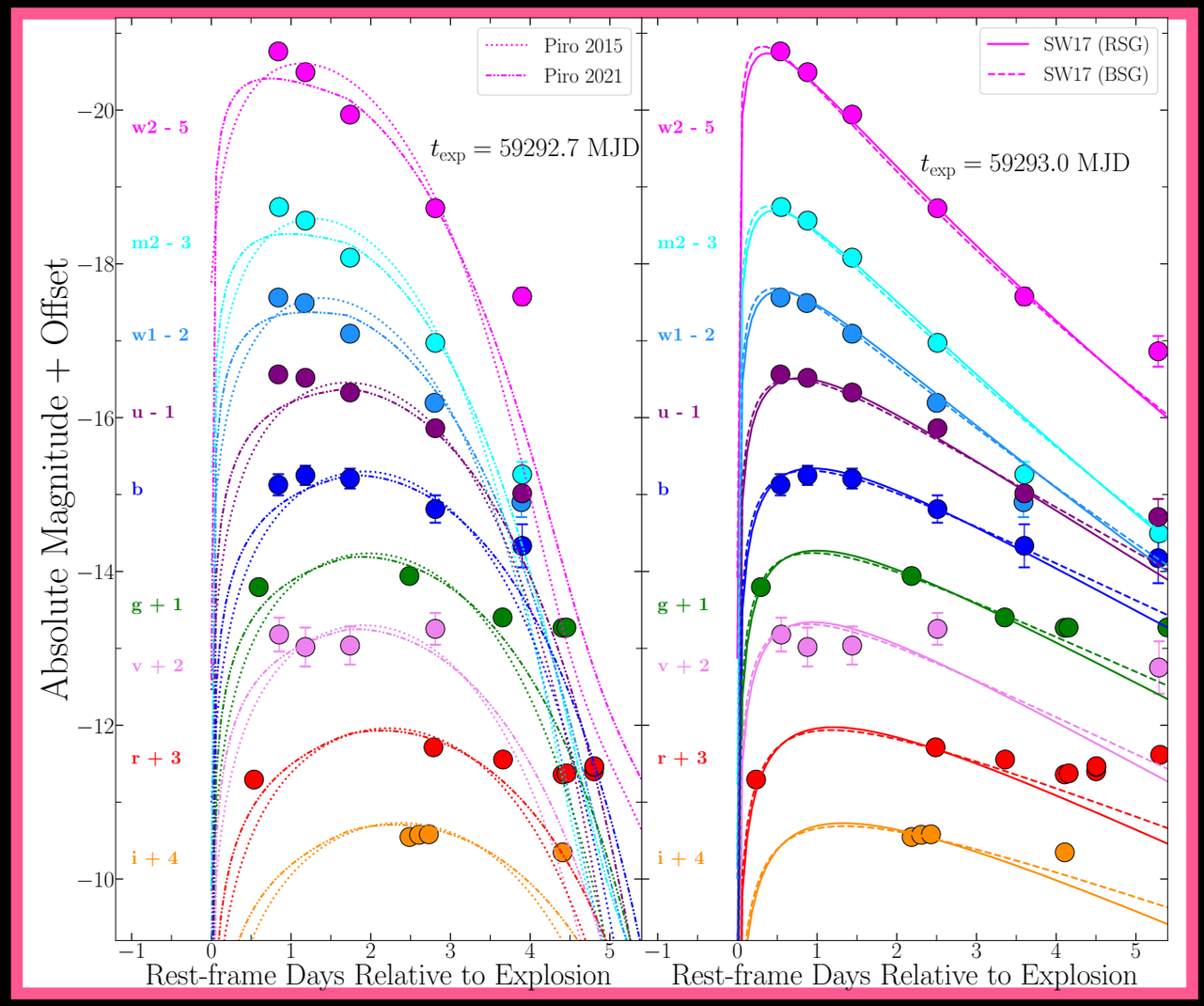
★ Low density medium at $\geq 10^{16}$cm

★ Mass-loss model: $\dot{M} < 10^{-5}\ M_{\odot}\mathrm{yr}^{-1}\ (\Gamma\beta \approx 0.1c)$

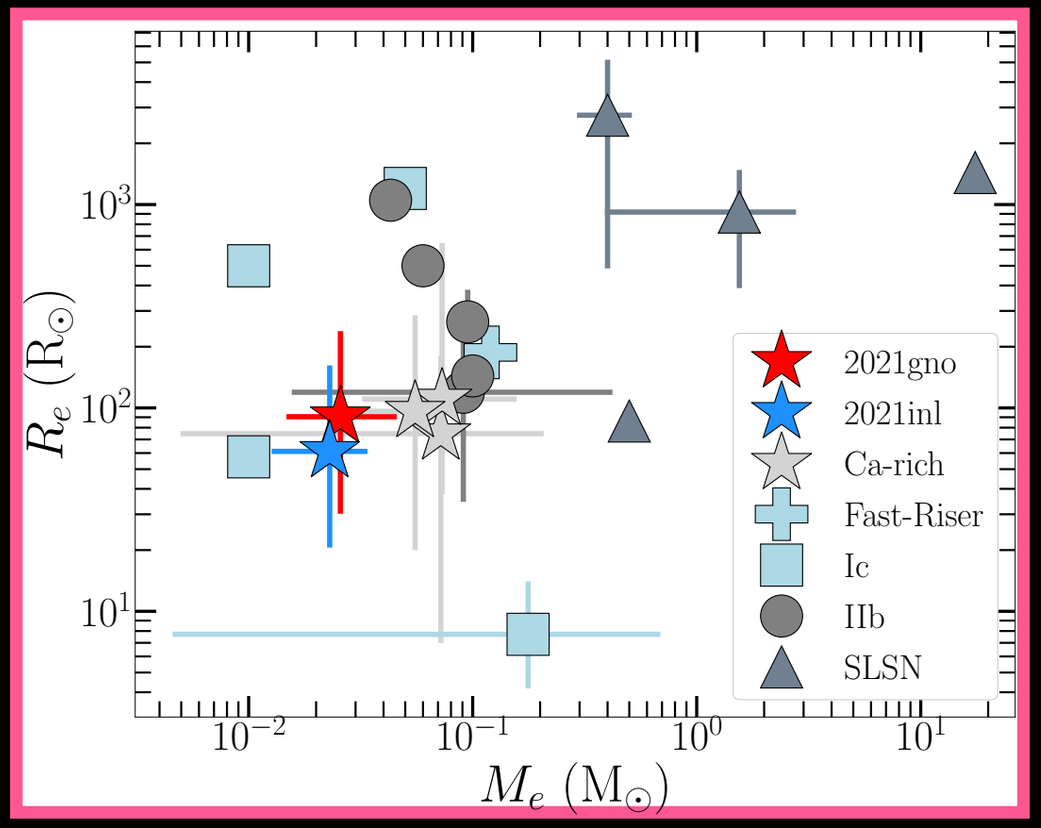


SHOCK COOLING EMISSION

- ★ Shock breakout into extended material with radius and mass
- ★ Material expands and cools down, emitting photons
- ★ Model emission in double-peaked events



(WJG, **Venkatraman**+ 2022b)



(**Venkatraman**+ 2022, in prep)

https://github.com/padma18-vb/shock-cooling-curve

PRE-EXPLOSION ENVIRONMENT

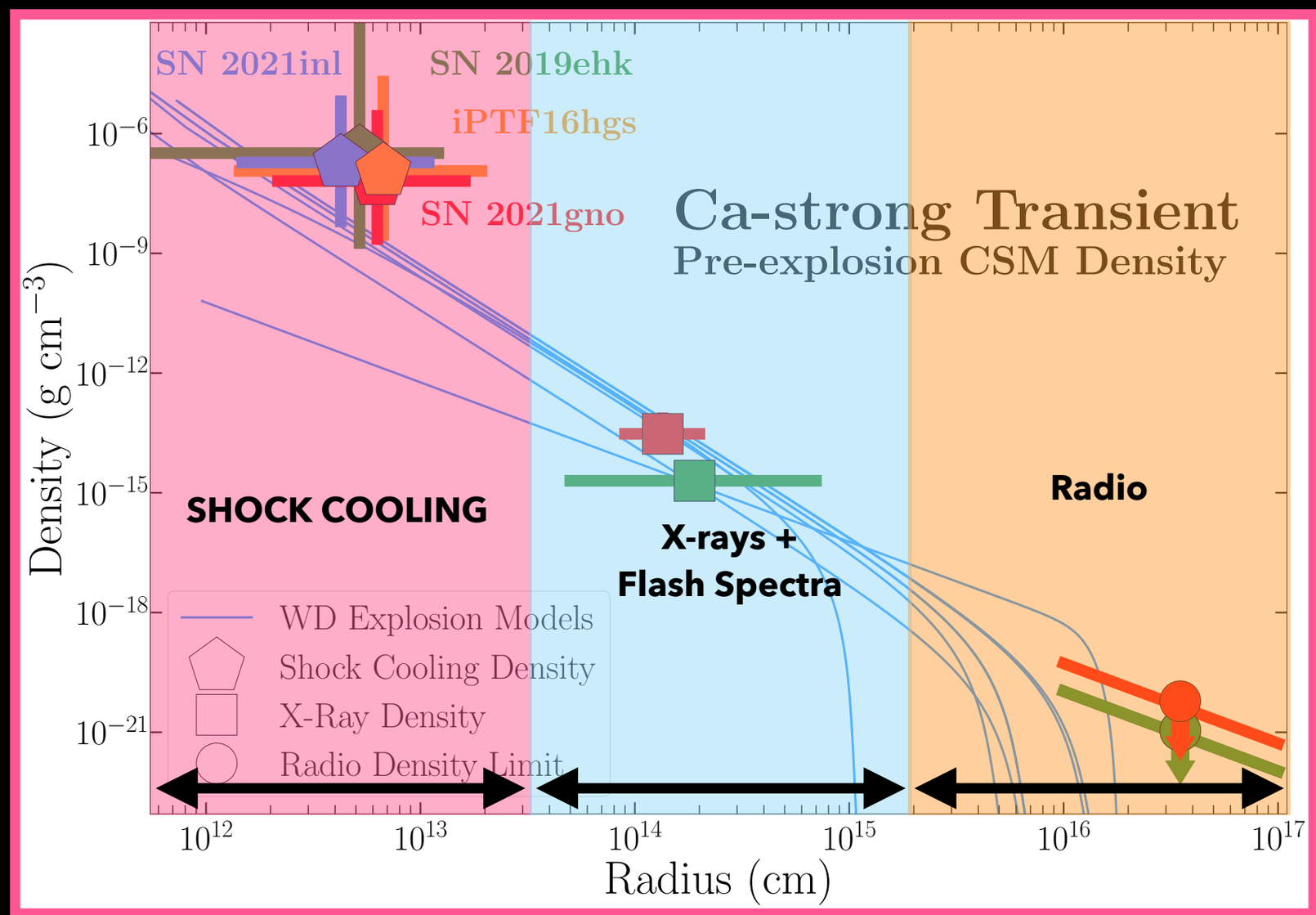
★Direct probe of circumstellar environment in the last ~days before explosion

★Constrains progenitor composition & mass-loss

CSM in SN 2019ehk:

- **Composition: H- + He-rich**
- **Velocities: ~500 km/s**
- **Mass:** $\sim 7 \times 10^{-3}\ M_\odot$
- **Radius:** $\lesssim 10^{15}$cm

SCE + X-rays + Flash Spectroscopy + Radio:



WHAT HAVE WE LEARNED?

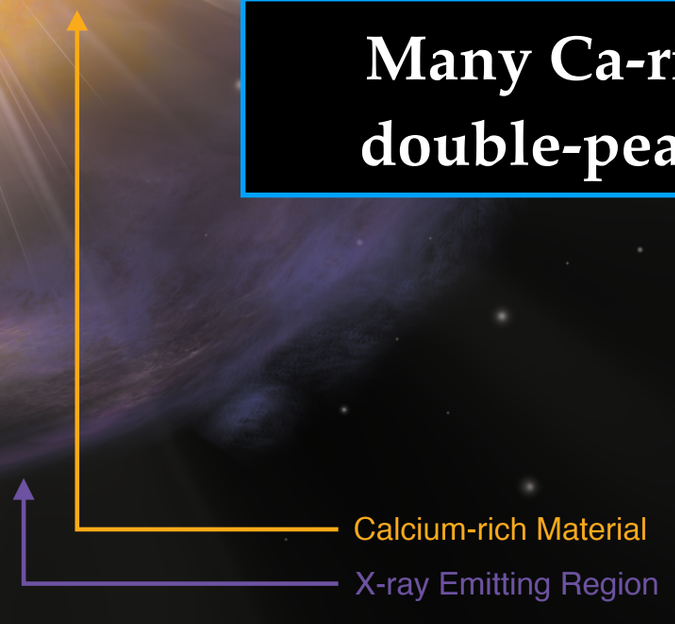
X-rays + radio + flash spectra are direct probes of mass-loss

Ca-rich SNe can emit X-rays

WHERE DO WHITE DWARFS FIT IN?

Ca-rich SNe progenitors lose mass in their final months

Many Ca-rich SNe are double-peaked -> SCE



Credit: Aaron M. Geller, Northwestern University IT

QUESTIONS?

Referenced Papers:

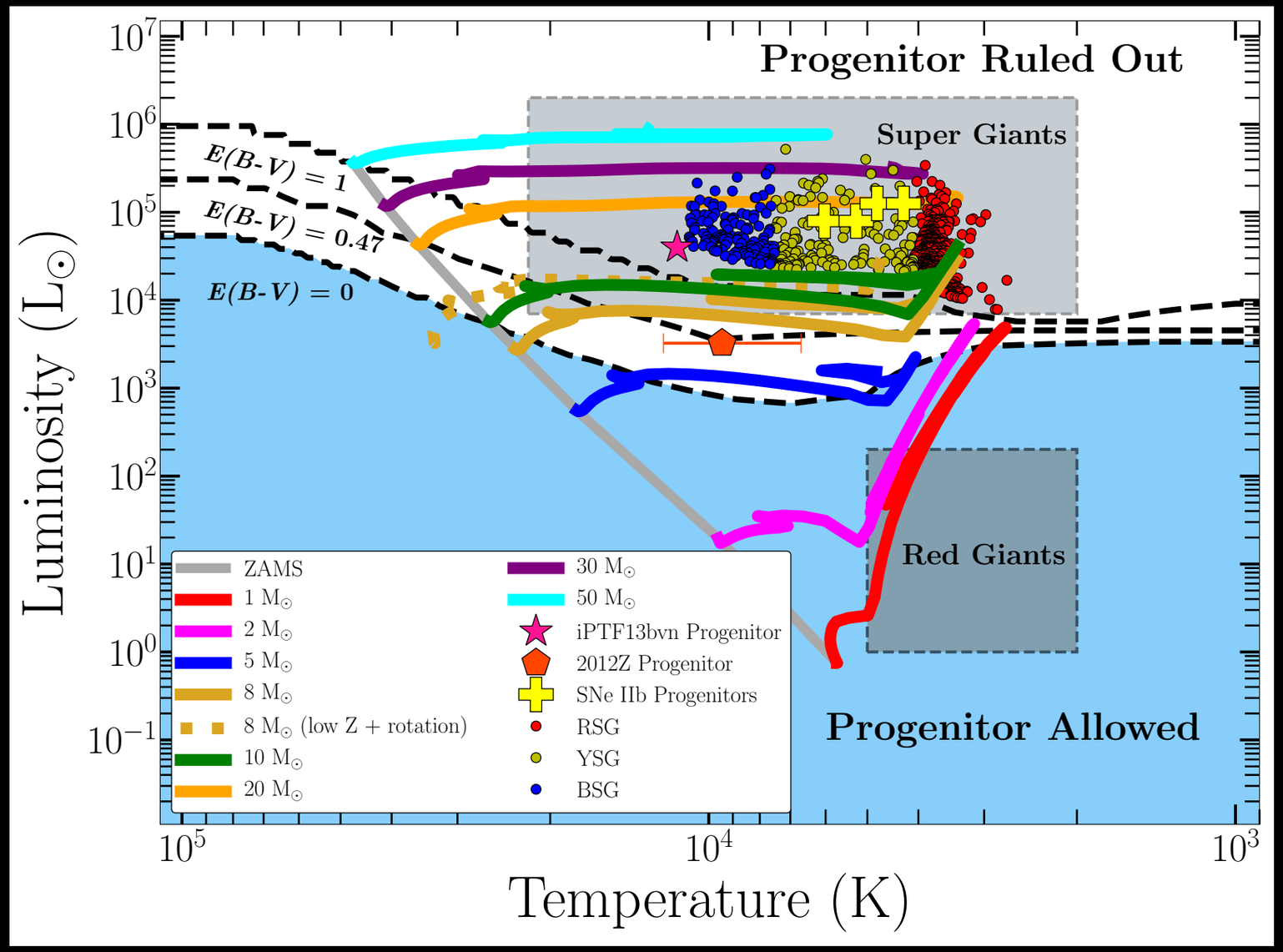
1) SNe 2021gno & 2021inl: arXiv 2203.03785

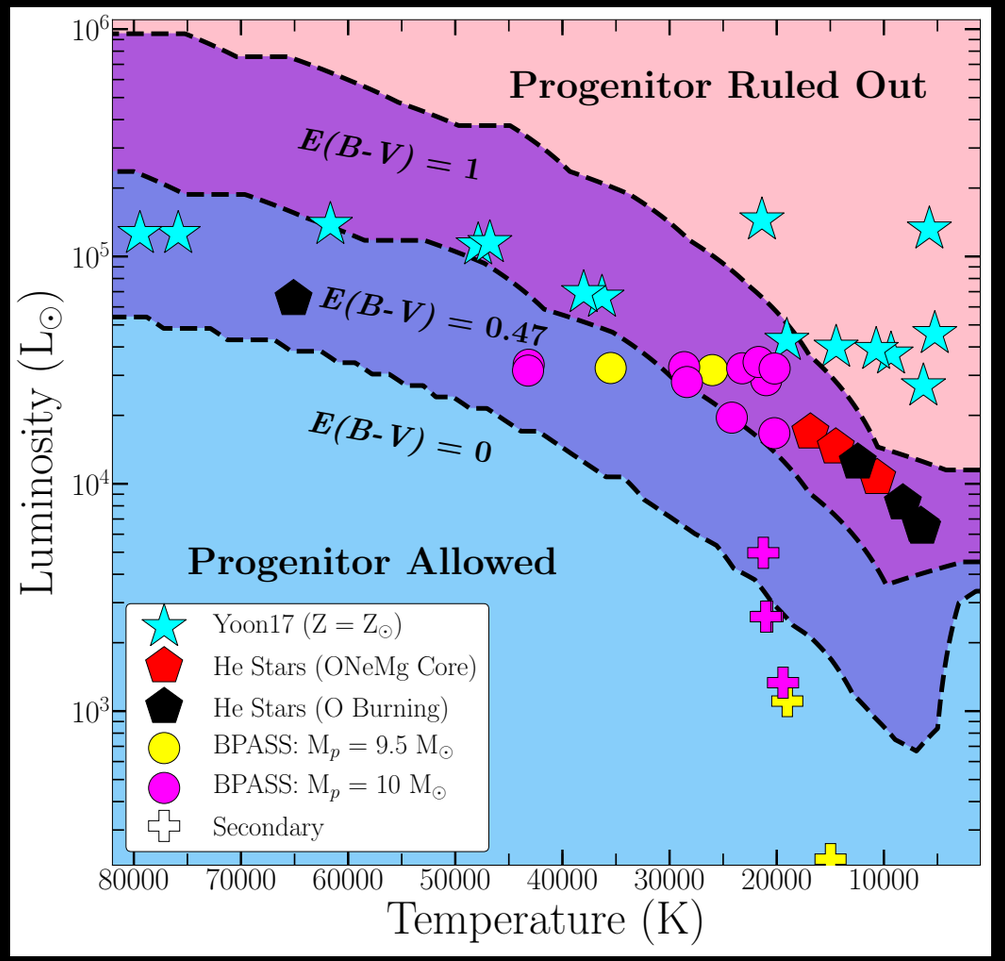
2) SN 2019ehk main paper: arXiv 2005.01782

3) Late-time Ca-rich evolution: arXiv 2010.15863

4) Ca-rich SNe from He-shell detonations: arXiv 1910.05436

EXTRA SLIDES





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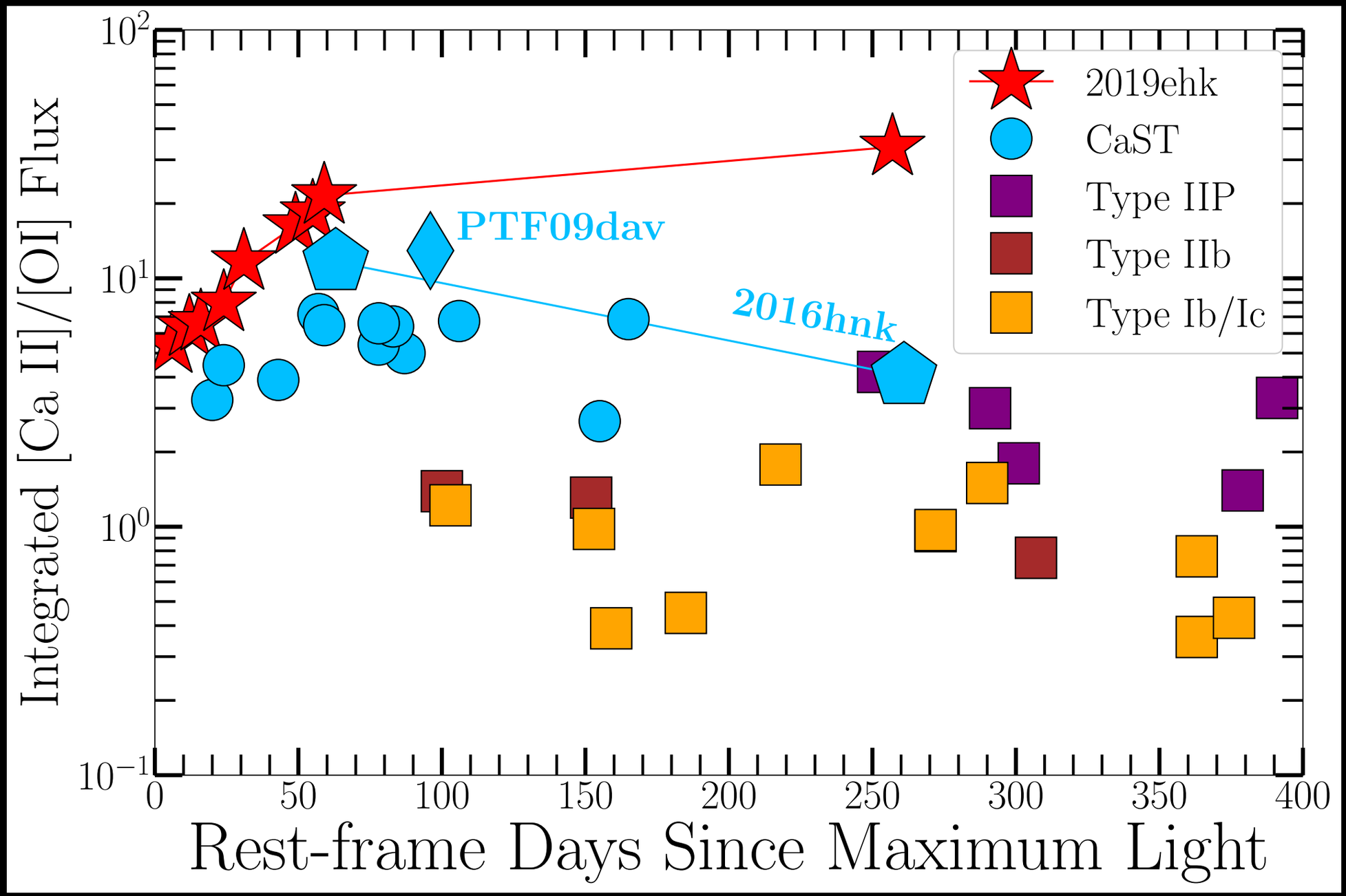

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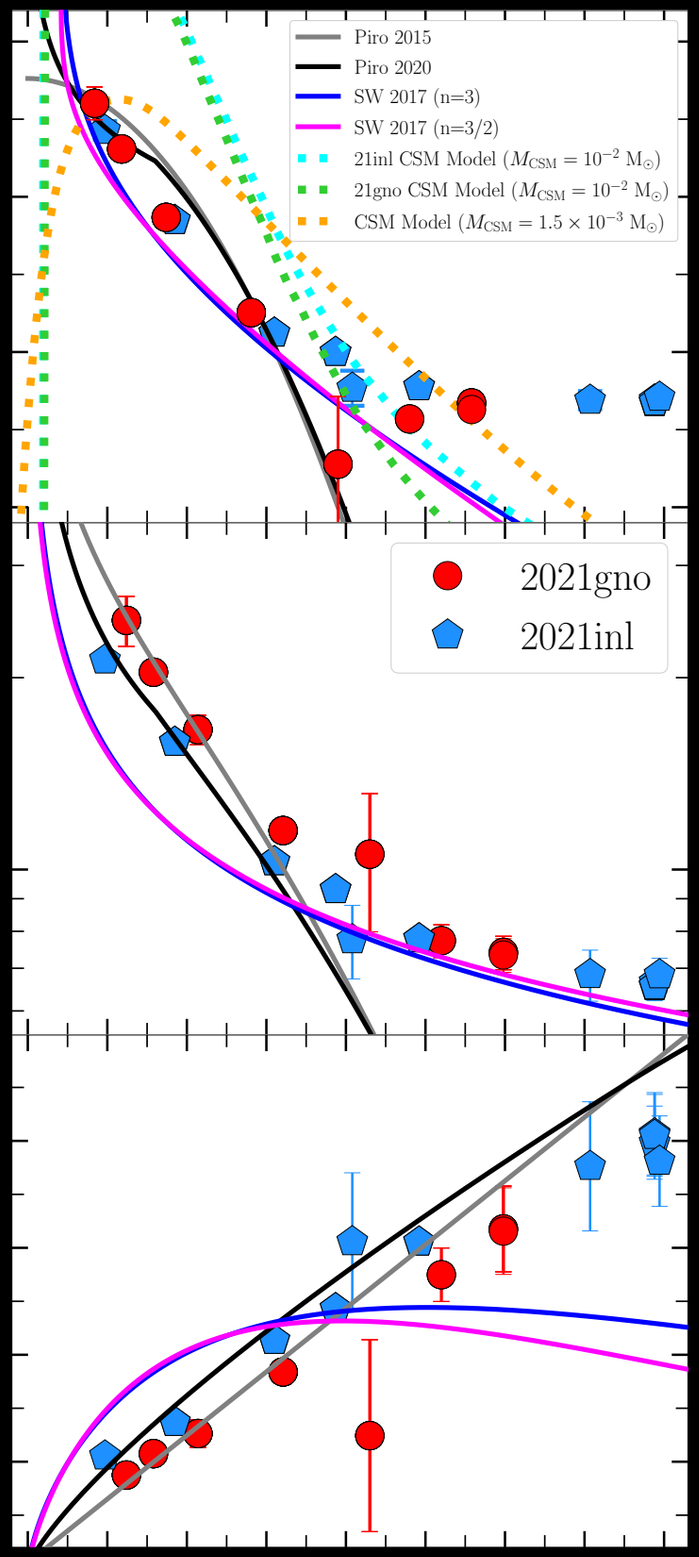
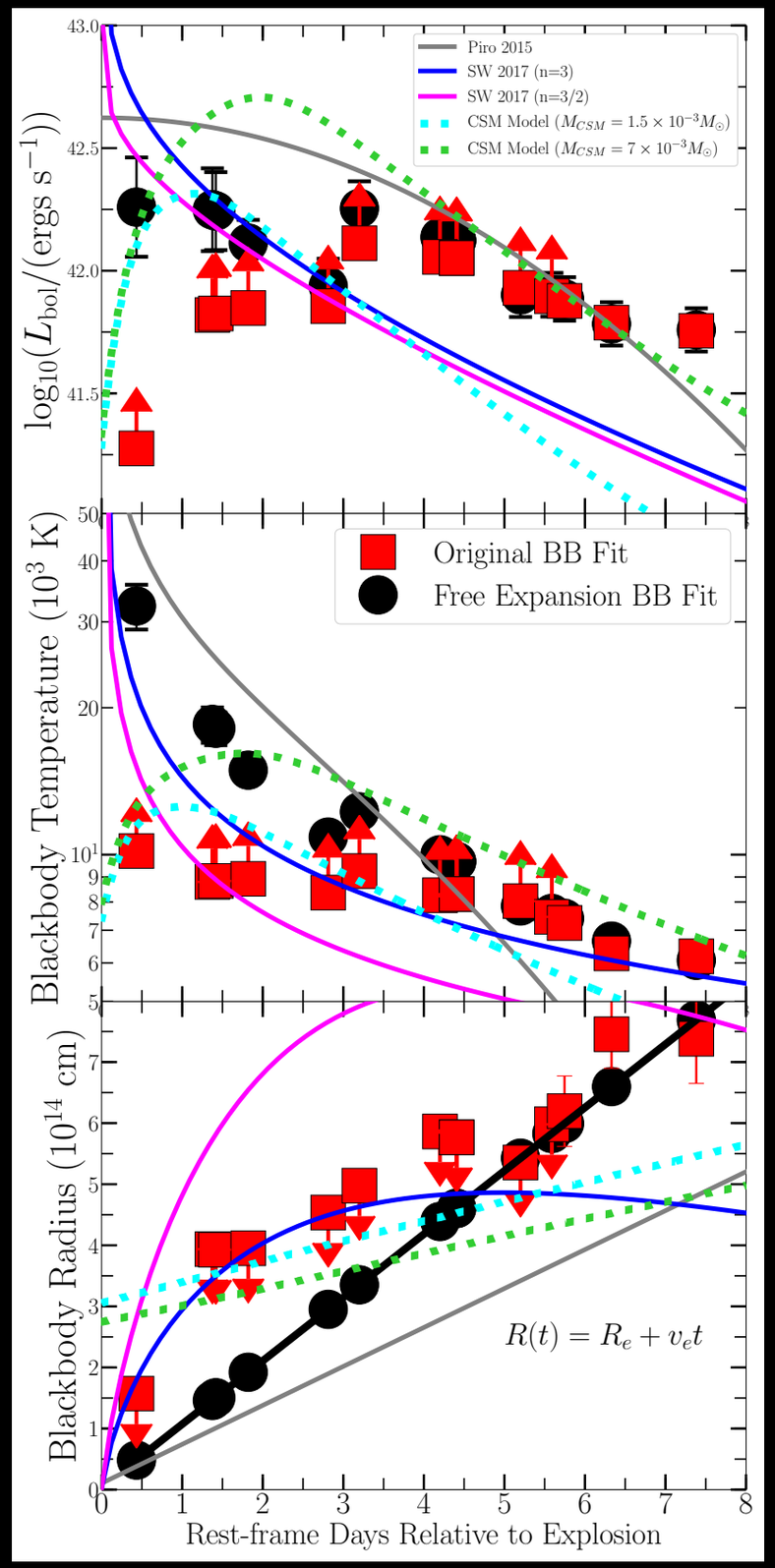
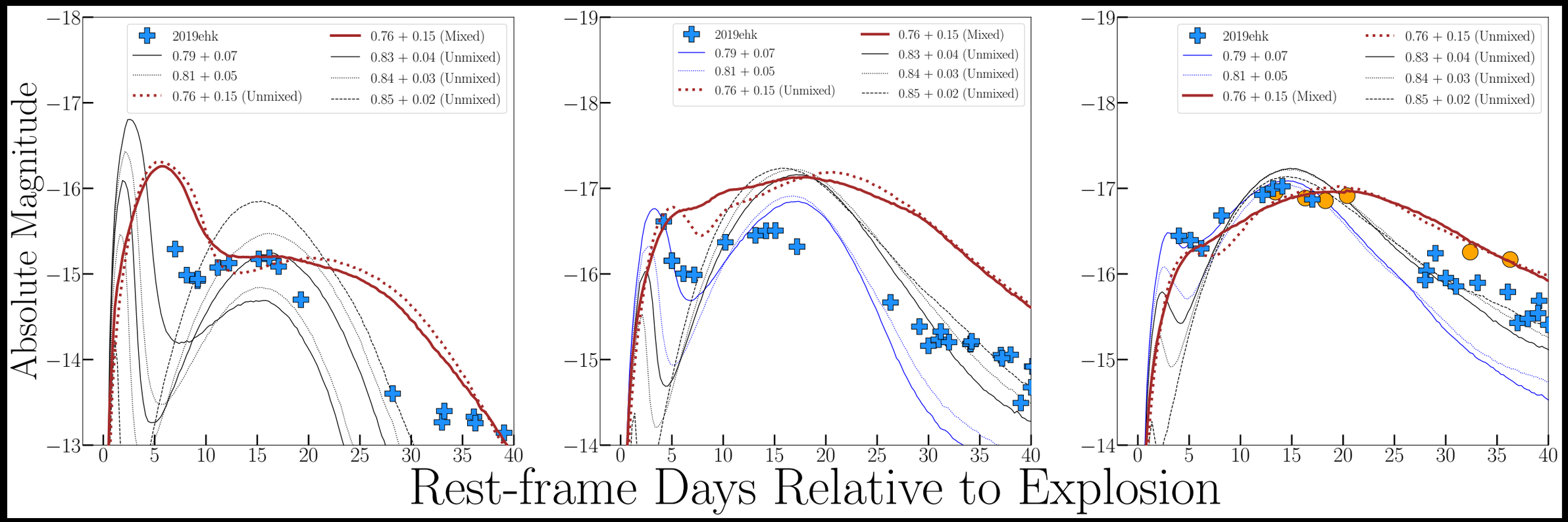




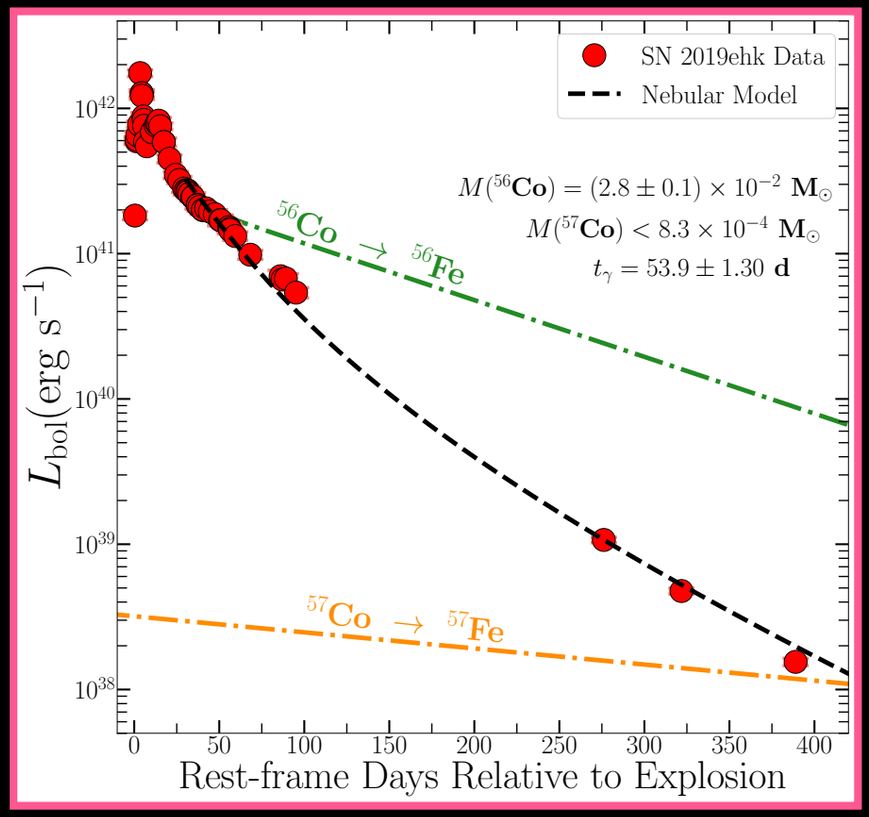
EXTRA SLIDES

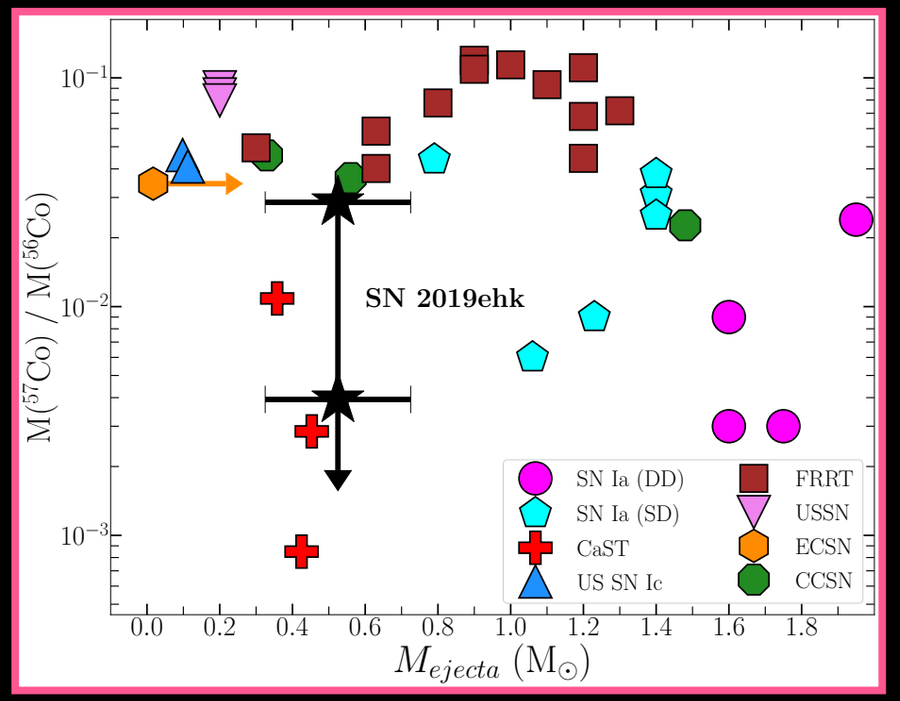


LIGHT CURVE EVOLUTION

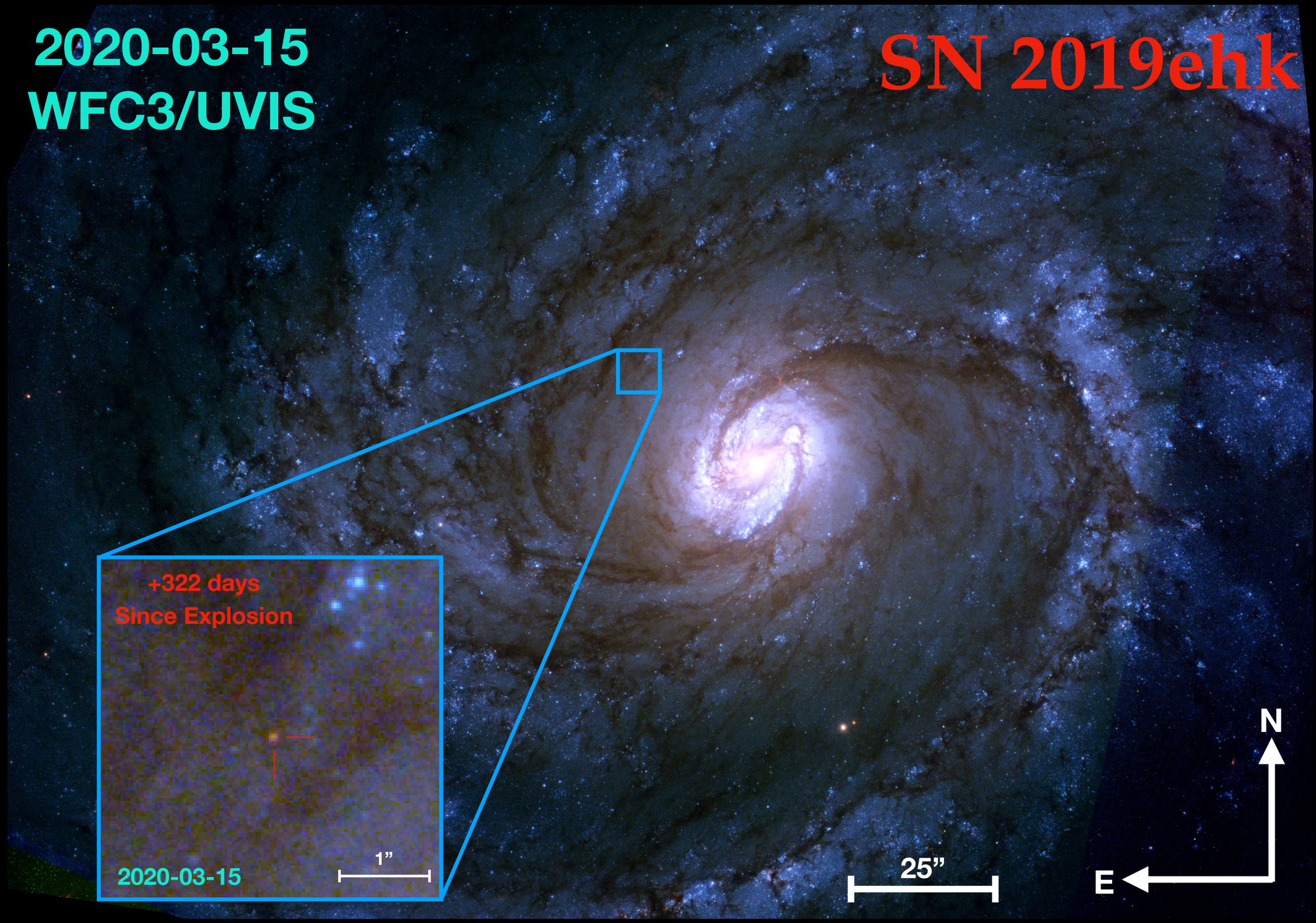
Extremely late-time follow-up:

- ★ Very few Ca-rich imaged at >250 days
- ★ 2019ehk has first multi-color late-time light curve
- ★ Constrains:
  1. explosion properties
  2. power source
  3. progenitor system





SN 2019ehk consistent with WD progenitor



(Jacobson-Galán et al. 2020c)

t_0

$v_{He} \approx 500$ km s^{-1}

Extended Envelope

Compact Progenitor

$R_{\rm env} \lesssim 200\ R_\odot$

$M_{\rm env} \approx 10^{-2}\ M_\odot$

$v_H \approx 400$ km s^{-1}

CSM

$R_{CSM} \lesssim 10^{15}$ cm

$M_{CSM} \approx 7 \times 10^{-3}\ M_\odot$

*BINARY COMPANION NOT INCLUDED

t_1

Optical 1

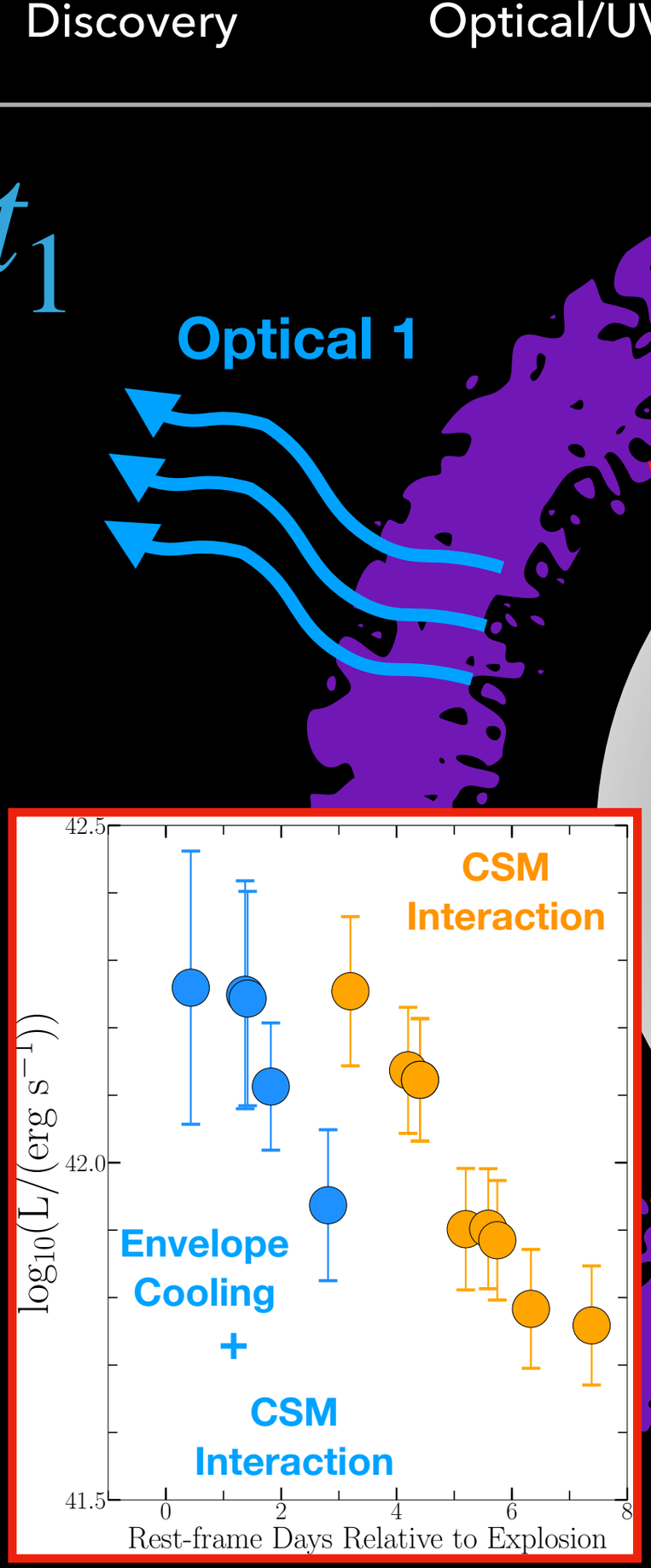
X-ray

Optical 2

$v_{\rm shock}$

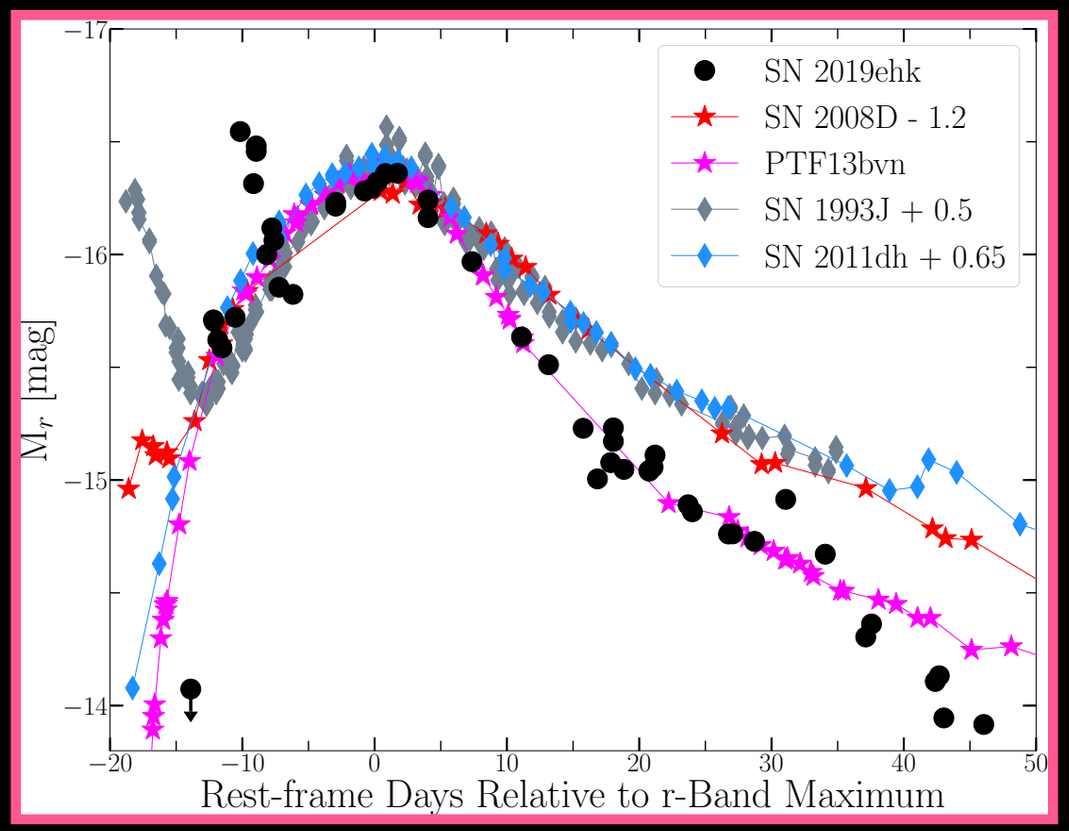
$v_{\rm shock}$

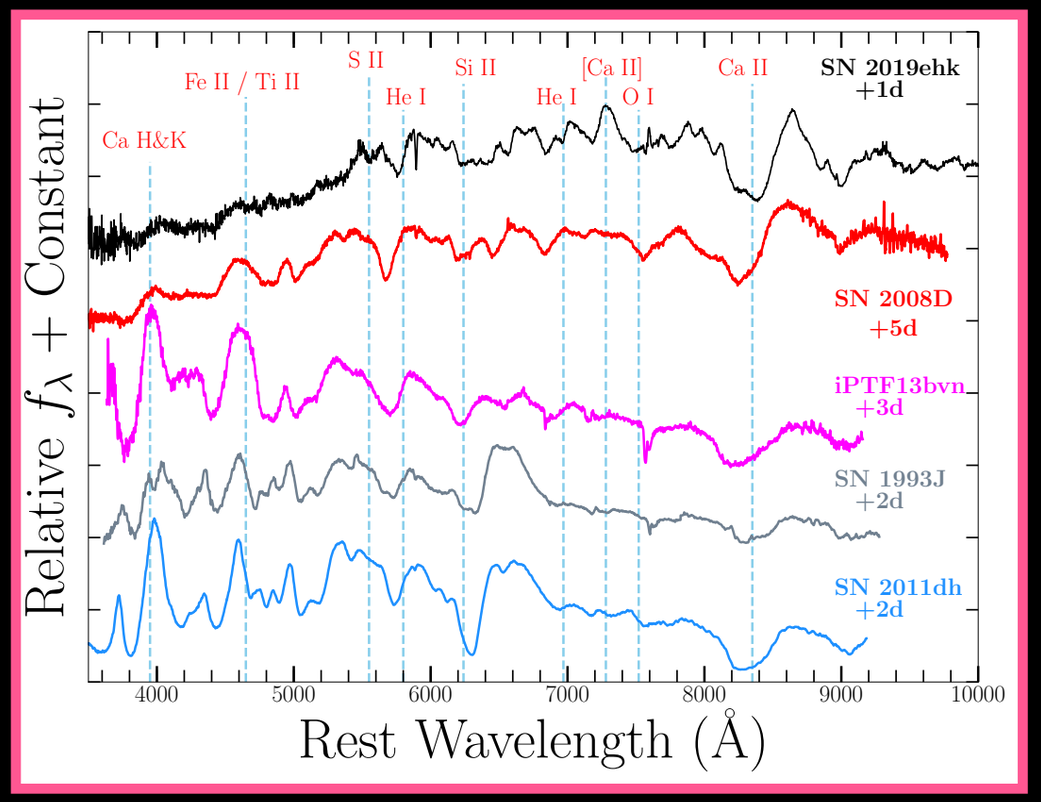
Optical 1

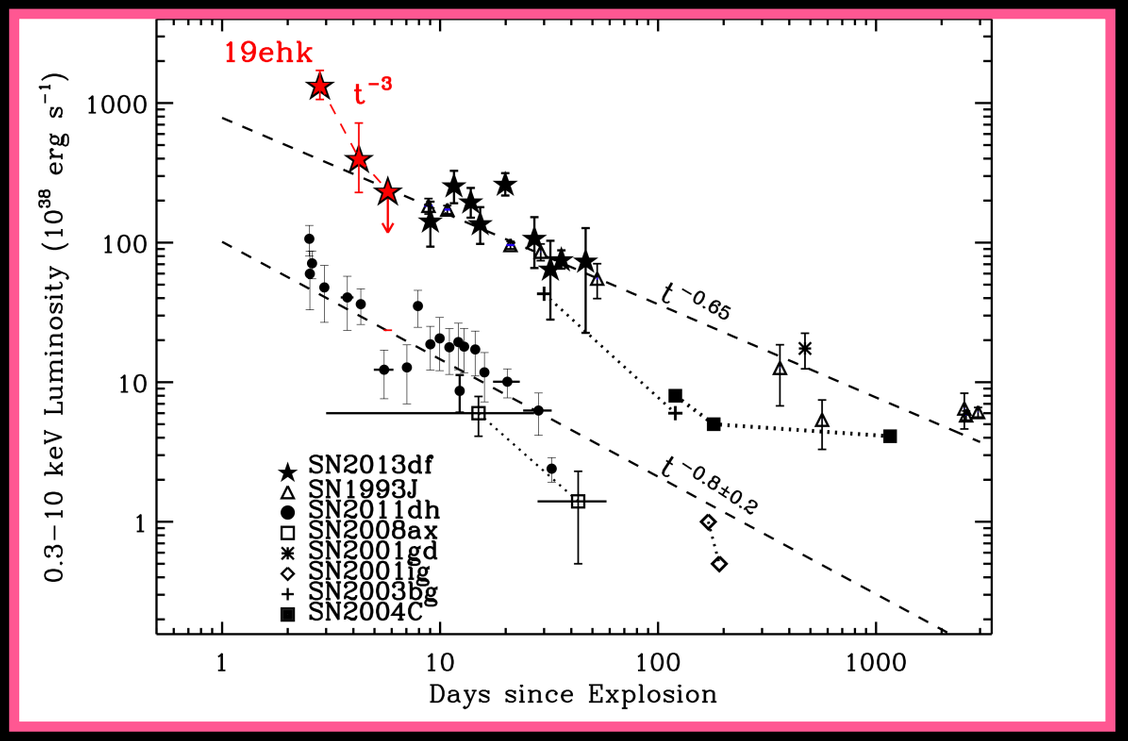


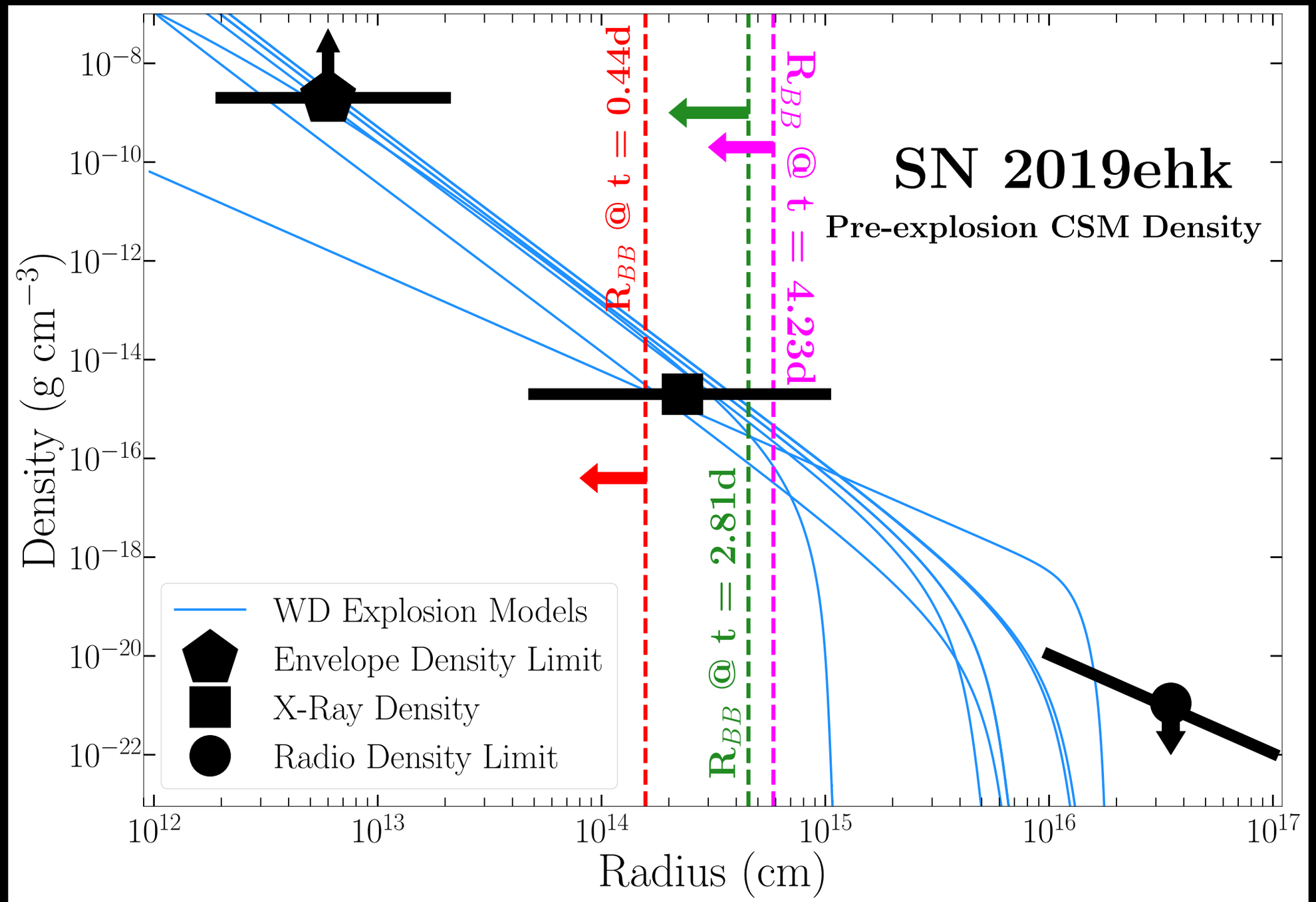
COMPARISONS

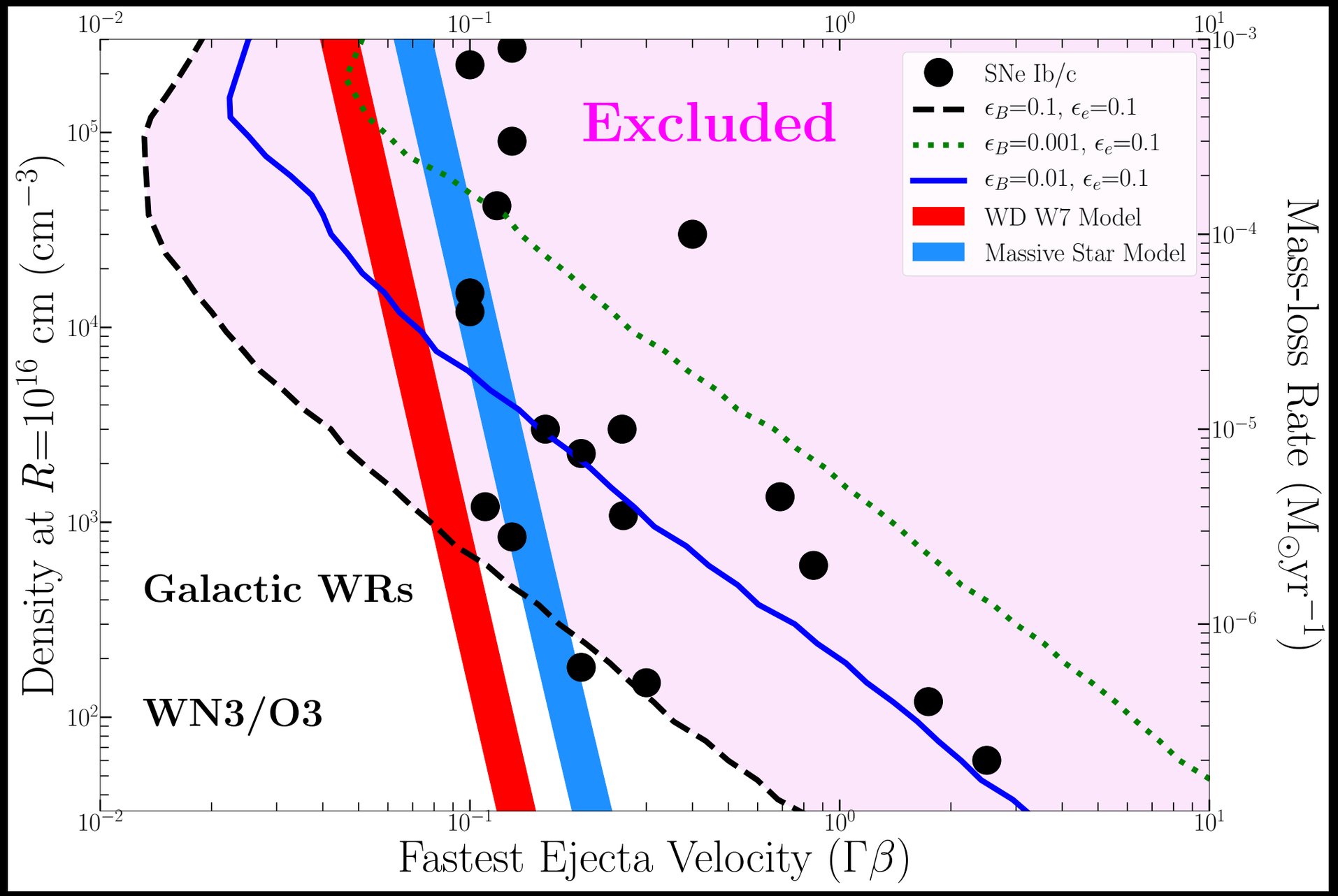
Type IIb SN Comparison








SN 2019ehk
Pre-explosion CSM Density
R_{BB} @ t = 0.44d
R_{BB} @ t = 4.23d
R_{BB} @ t = 2.81d
WD Explosion Models
Envelope Density Limit
X-Ray Density
Radio Density Limit
Density (g cm^{-3})
Radius (cm)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}


Excluded
SNe Ib/c
ϵ_B=0.1, ϵ_e=0.1
ϵ_B=0.001, ϵ_e=0.1
ϵ_B=0.01, ϵ_e=0.1
WD W7 Model
Massive Star Model
Galactic WRs
WN3/O3
Density at R=10^{16} cm (cm^{-3})
Mass-loss Rate ($M_\odot$yr^{-1})
Fastest Ejecta Velocity ($\Gamma\beta$)