WG5: Thermonuclear supernovae

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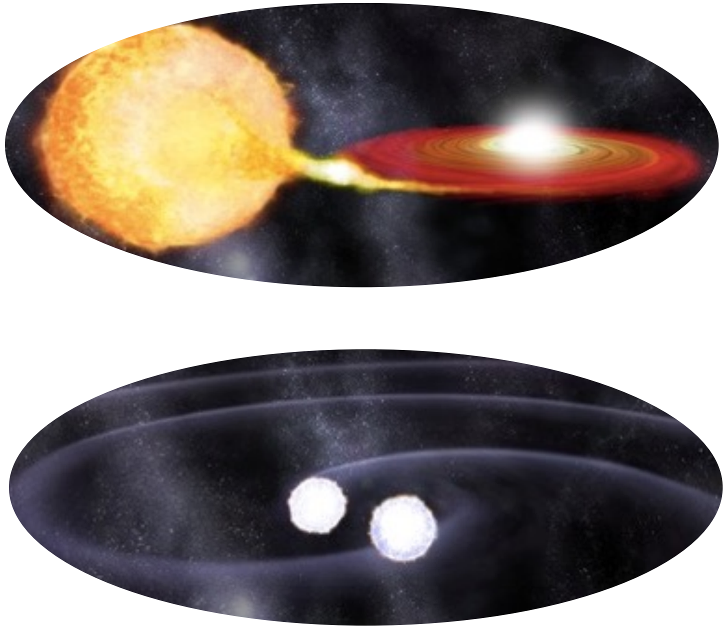
Overview

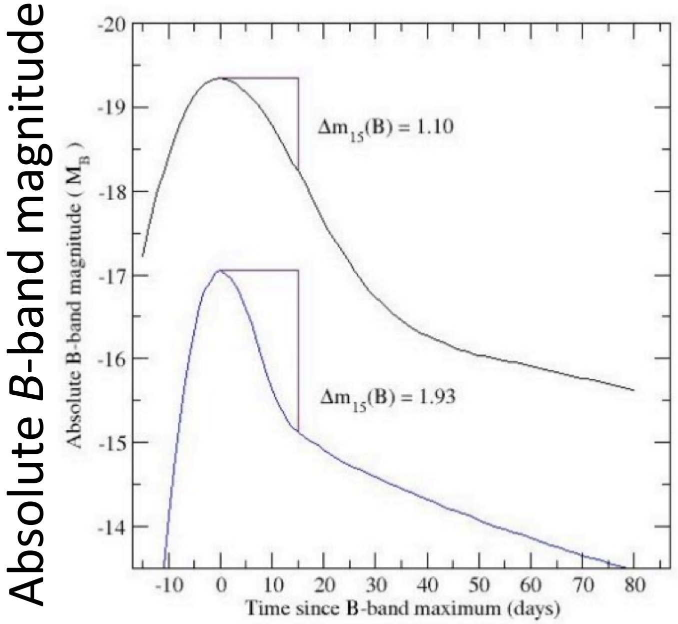
- Type Ia supernovae in a nutshell
- GTO targets
- Diversity among the SNe Ia population
- Science Traceability Matrix
- Infant SN Ia observations
- Additional work packages in brief
- SOXS as a spectroscopic workhorse facility and scope of WG5 followup
- Summary

Type Ia supernovae

Progenitor systems



Standardizable Candles (WLR)

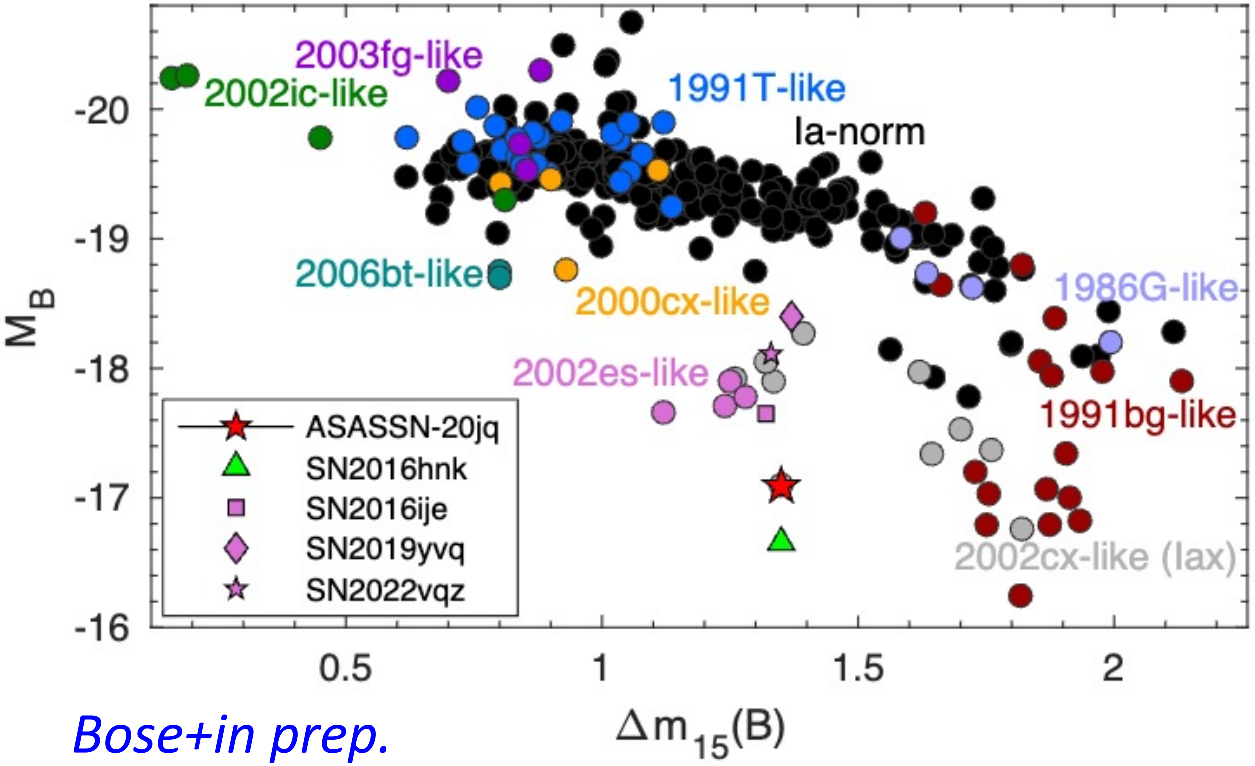


Time since *B*-band maximum

H_0 & SNe Ia cosmology

Despite years of detailed studies, the origins of thermonuclear supernovae and how they explode remains rather elusive...

Luminosity-width relation reveals significant diversity



Bose+in prep.

- 1991T-like overluminous
- Normal to transitional
- 1991bg-like sub-luminous

Rare peculiar types (*bright-to-faint*)

- 2002ic-like: Circum-stellar Interaction (CSI)
- 2003fg-like: Over-luminous, UV blue
- 2002cx-like: Low-velocity, range of peak M_B
- 2002es-like + zoo: Under-luminous peak M_B, range of velocities, w/ & w/o early bumps

Implies a range of progenitor scenarios and/or explosion physics

GTO work packages

- Galactic SN Ia
- < 20 Mpc SNe Ia *"…provide the opportunity to do the BIG science"*, M. Turatto
- Highly-reddened SNe Ia and/or those exhibiting CSM interaction
  → re-calibration of NaID vs. SNe Ia E(B-V) relations of a ZTF sample 50 2x25H
- Objects in the outer-banks of their hosts, and/or "hostless"
- Multi-epoch spectrocopy of calibator SNe Ia extending from early-to-late phase
- **Peculiar SNe Ia discovered *just* after first light*** *(requires an aggressive classification strategy)*

* Early observations do not suffer from stellar amnesia (see slide 8).

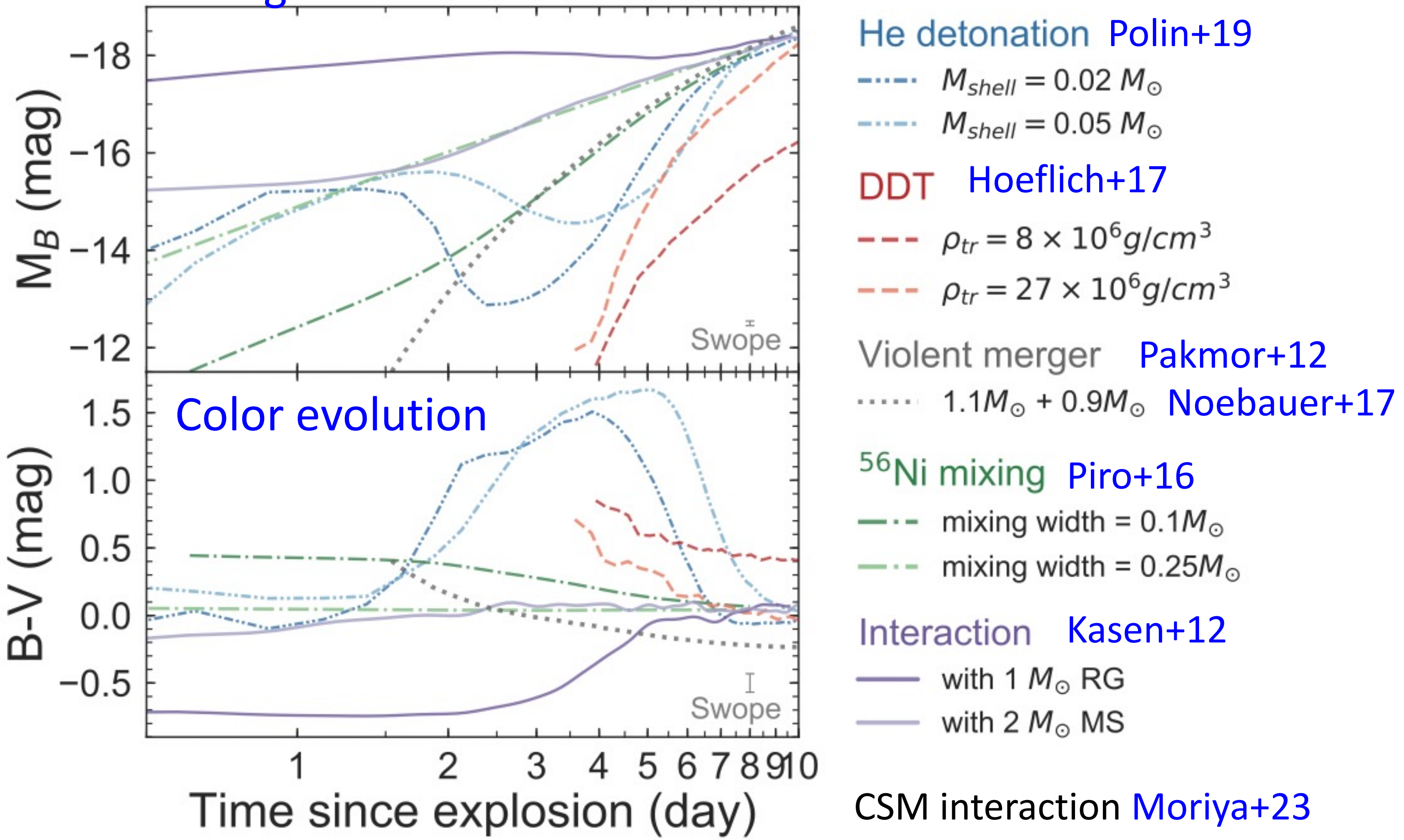
Infant SNe Ia Science Traceability Matrix

Key Questions	Science Objectives	Physical Parameters	Observables		
			Optical spectroscopy	NIR spectroscopy	Photometry
What are the progenitor systems?	What is the companion star?	Progenitor or companion star type, mass and radius	Nebular phase: embedded H, [OI], [FeII], [CaII]	H-band break Embedded H and He [FeII] line profiles	Early light and color curves within a few days of explosion
	What are the properties of CSM or wind?	Mass-loss rate and composition	Narrow H & He emissions lines	Narrow H and He emissions	
What are the explosion mechanisms?	What are the surface conditions?	Outermost burning products	Ti, Cr, and Ni within hours of explosion High-velocity extent of Si II	High-velocity extent of Mg CI & HI lines	
		Strength, velocity and ionization of unburned material	C II within a few days of explosion	C I and He I within a few days of explosion	Speed of color evolution

Infant SNe Ia observations

Brightness evolution

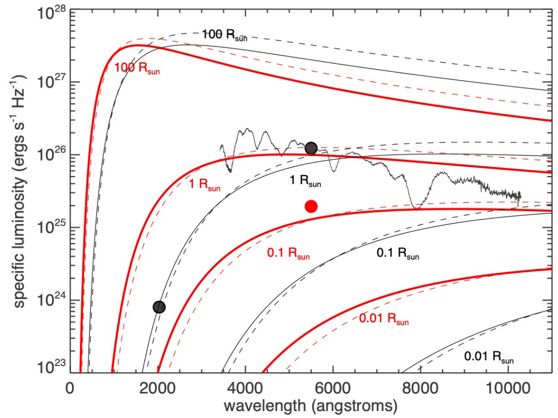
Color evolution



CSM interaction Moriya+23

- Direct constraint on the size of the WD progenitor: SN 2011fe i.e., r< 0.1R⦿

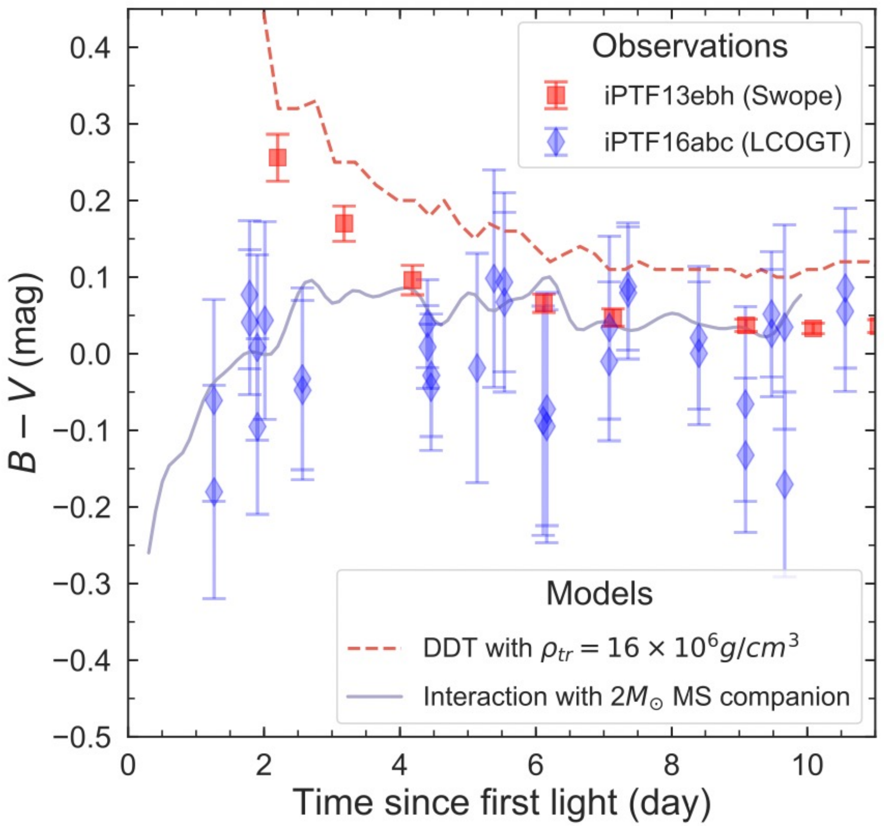
Nugent+11, Bloom+12



- The conditions of the outermost layers are key

→break the degeneracy between leading scenarios caused by stellar amnesia (see left > +5 days)

Early colors of Red & Blue SN Ia vs. model predictions



POISE collaboration

- Red object is consistent with the evolution of DDT model
- Blue object consistent with similar model + interaction with companion

- Are short-lived radioactive species produced in the outer layers driving blue colors and particular ions?

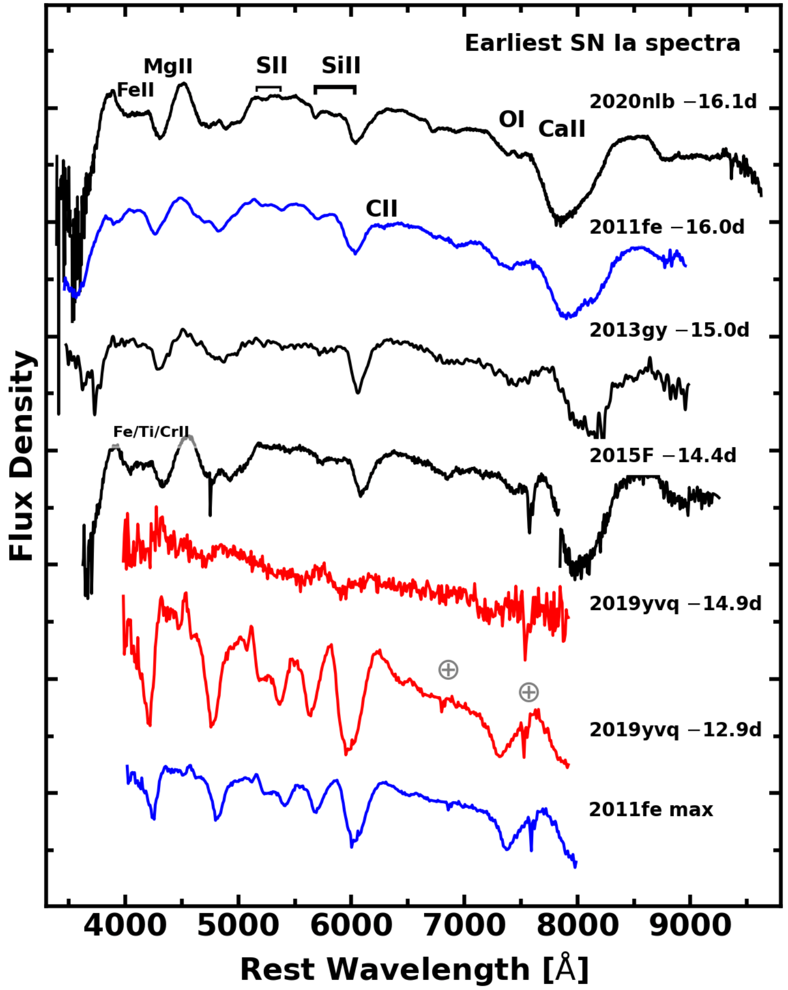
- Interaction with CSM?

- Mixing of ^{56}Ni ?

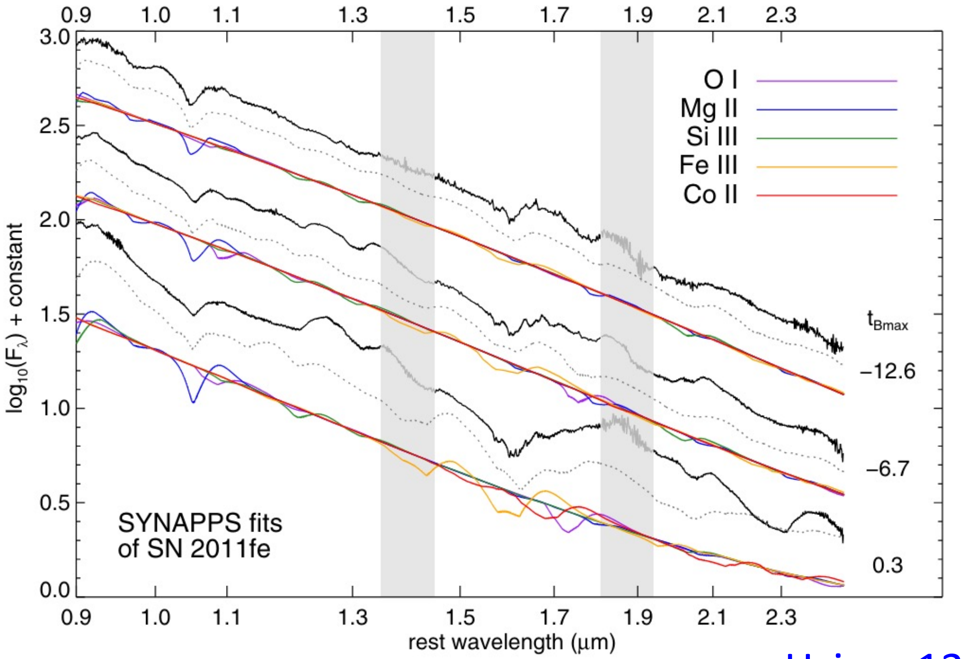
- Interaction with companion star?

Requires *early* observations and spectra!

Earliest SNe Ia spectra in the literature



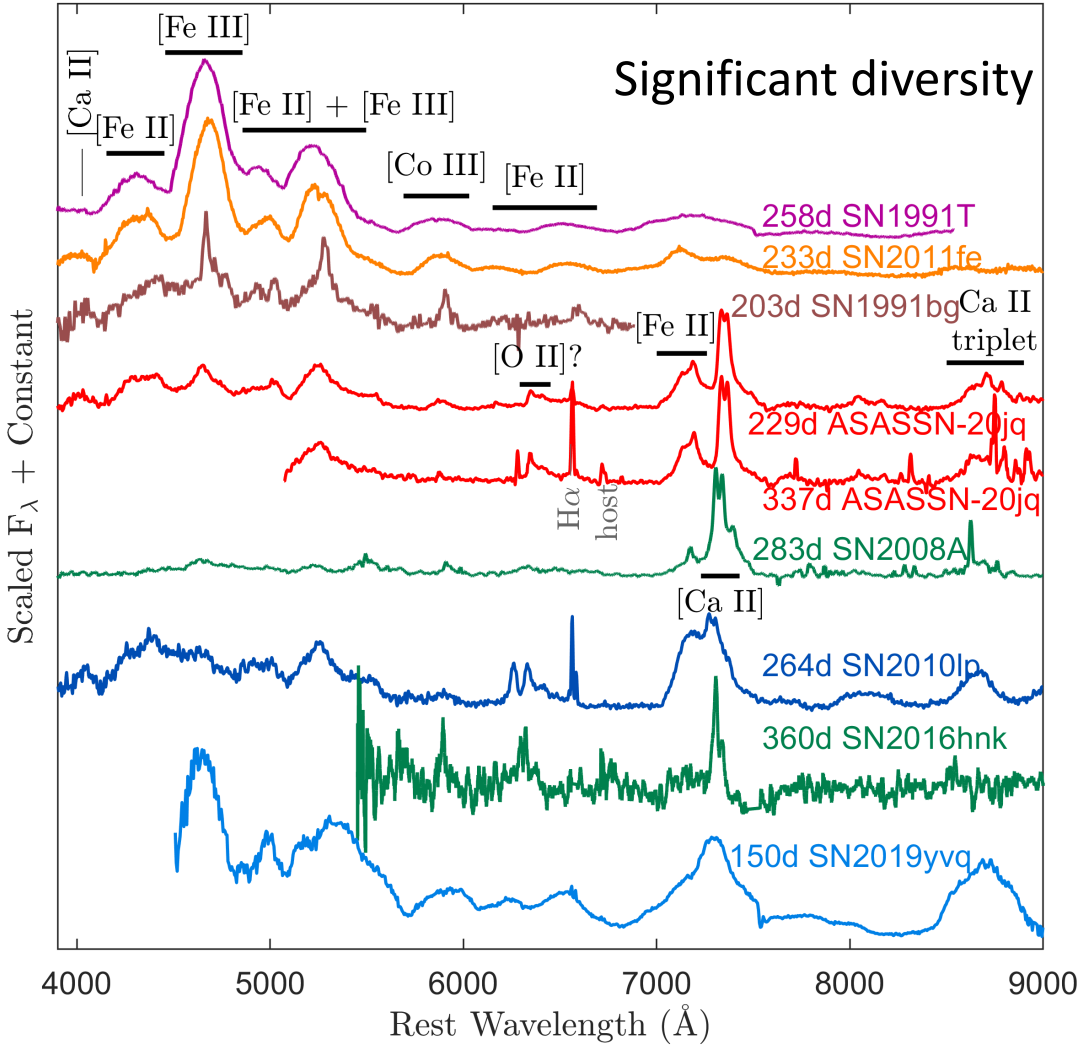
- Presence and/absence of ions →model constraints
- Optical: CII, Fe/Ti/CrII, Si II
- Near-IR: CI, MgII
- Post-maximum *H*-band break (mass constraints)
- Maximum light spectral diagnostics



Hsiao+13

- Dearth of early spectra
- Diversity among the current sample

SOXS will deliver quality nebular phase spectra



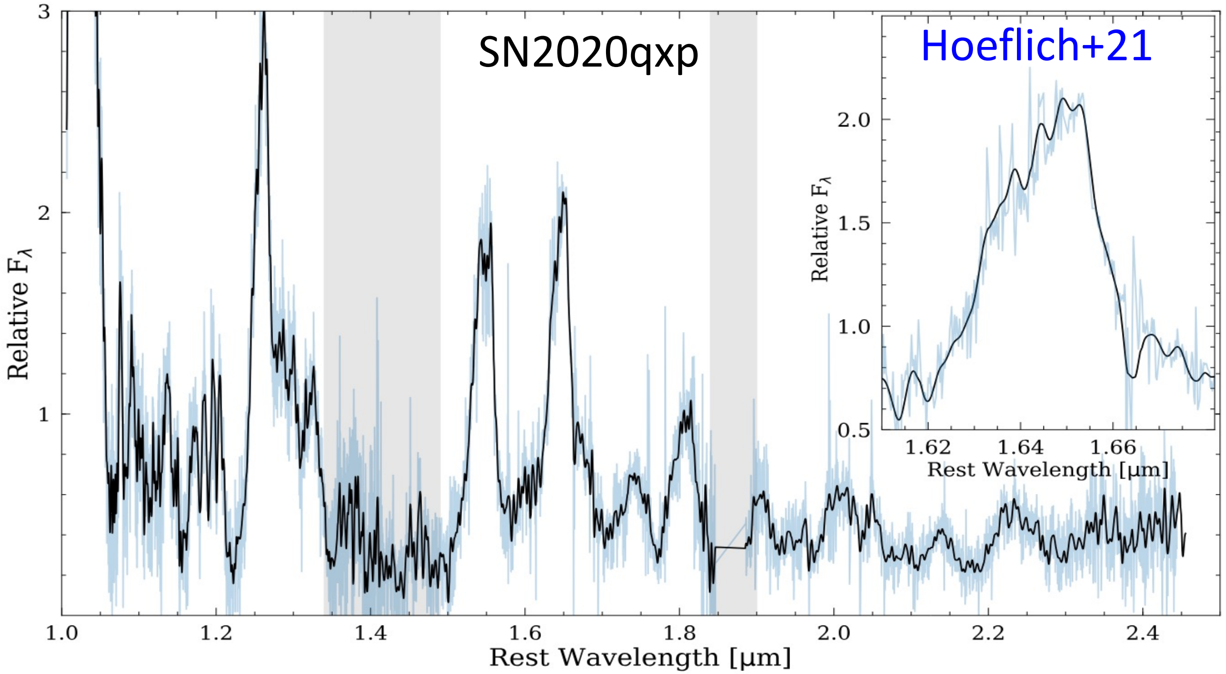
Bose+in prep

Presence/absent of ions provide constraints:

- Progenitors: H, [OI], [CaII]?, [NiII], [FeII] profile, ratios

Explosion physics:

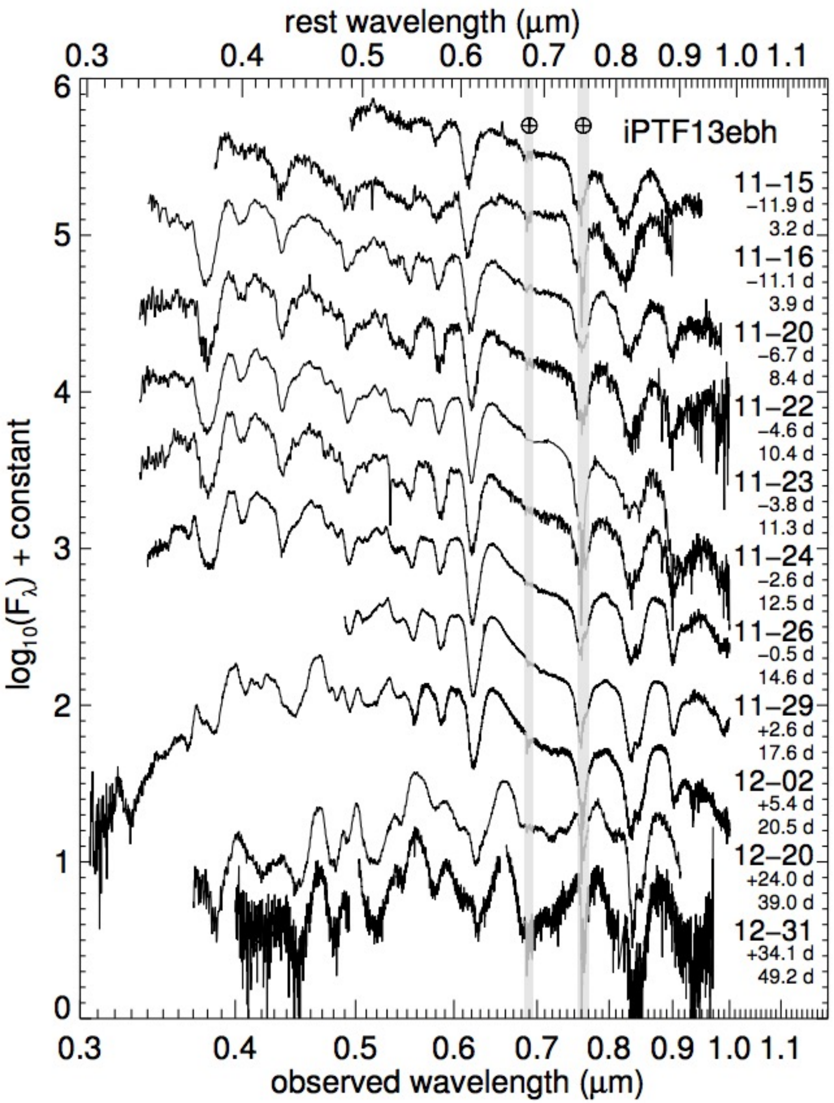
- [FeII] profile, shifts & asymmetries
- *B*-field strength

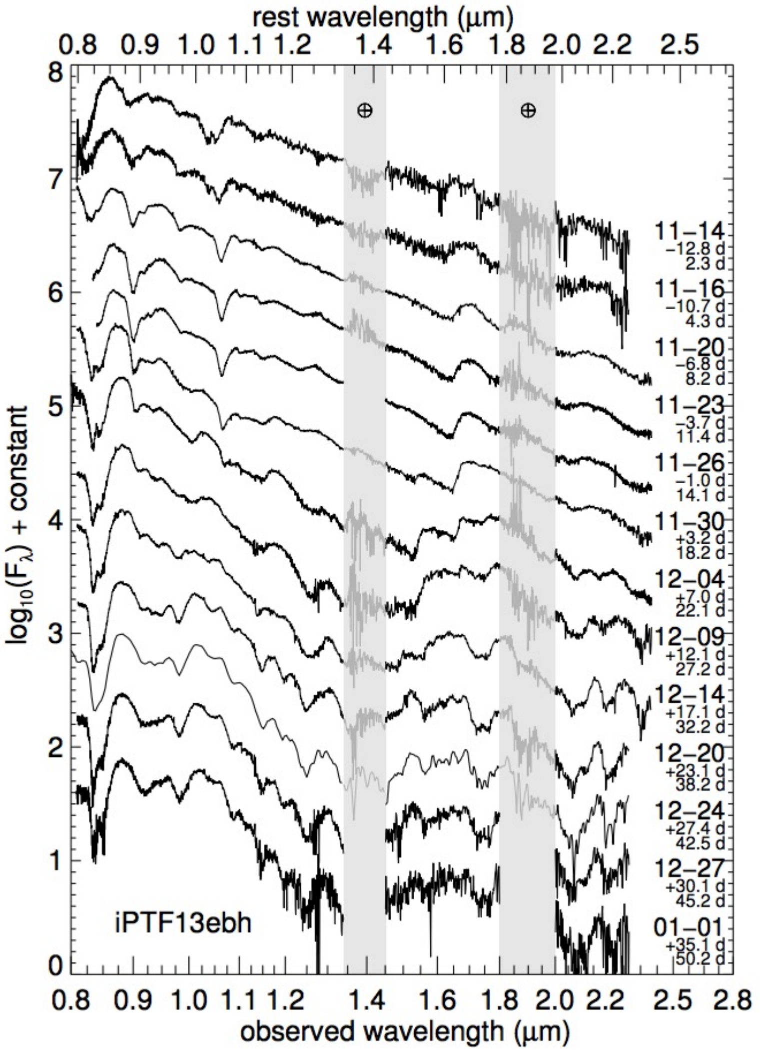


Hoeflich+21

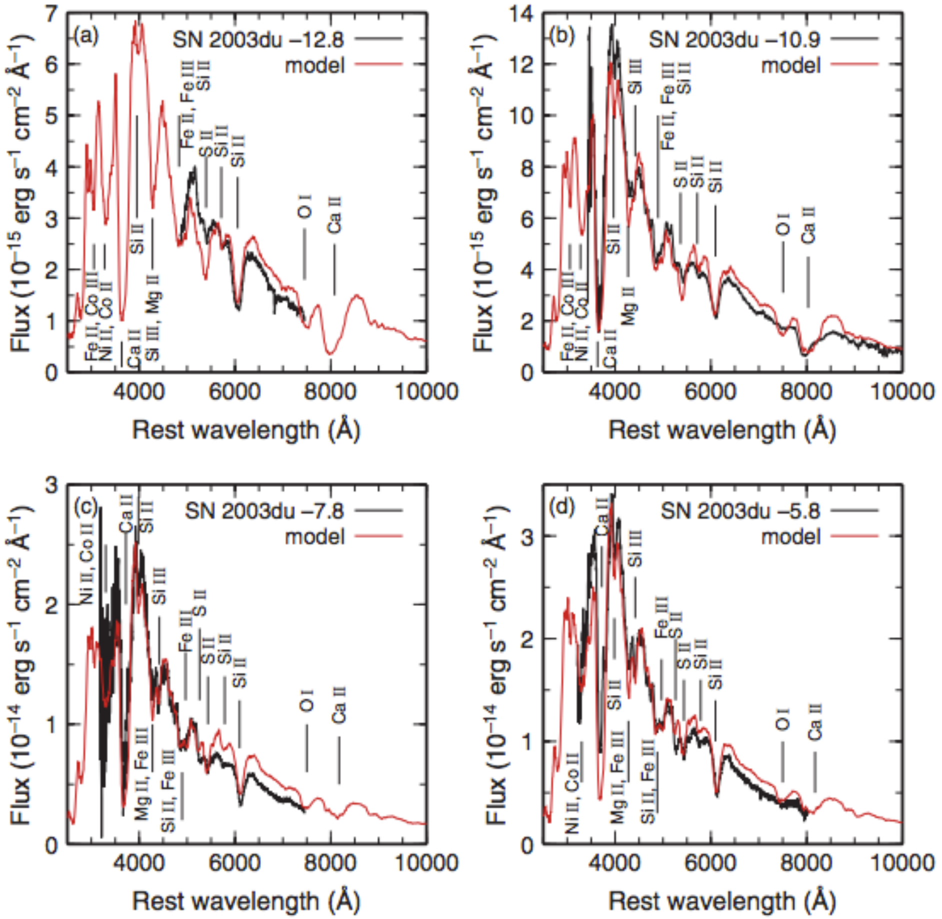
Time-series→ Abundance Tomography I

Hsiao+15



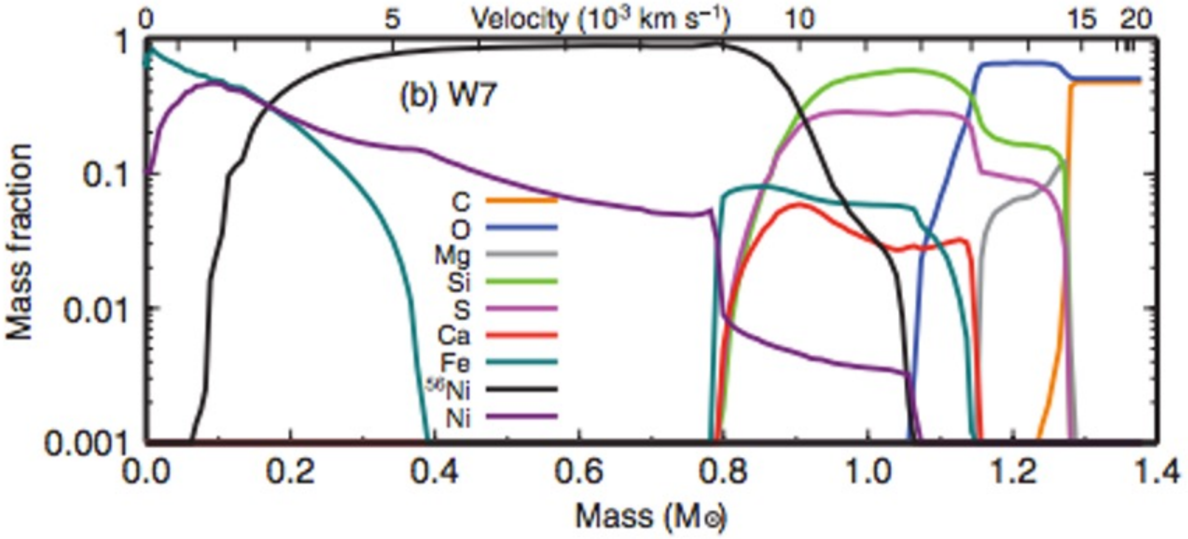


Abundance Tomography II



e.g., Stehle+05, Tanaka+11, etc…

Layered structure



- ^{56}Ni mass is most abundant isoptope
- Estimated ^{56}Ni mass is consistent Arnett's Rule
- Provides clear indication of *radially stratified ejecta*

→ points towards detonation burning phase in normal SNe Ia, while SNe IaX stratification remains debated

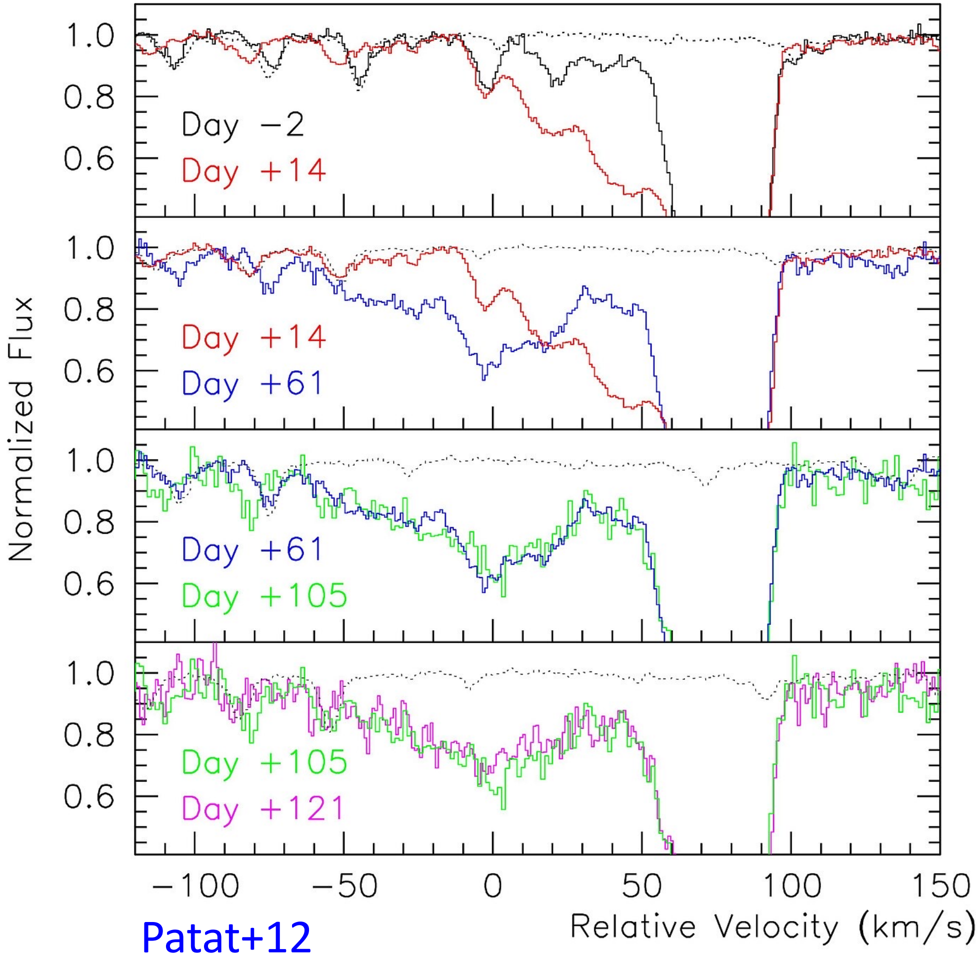
Highly-reddened and 2002ic-like SNe

NaID, KI, CaII, DIBs, He, He, wind velocity

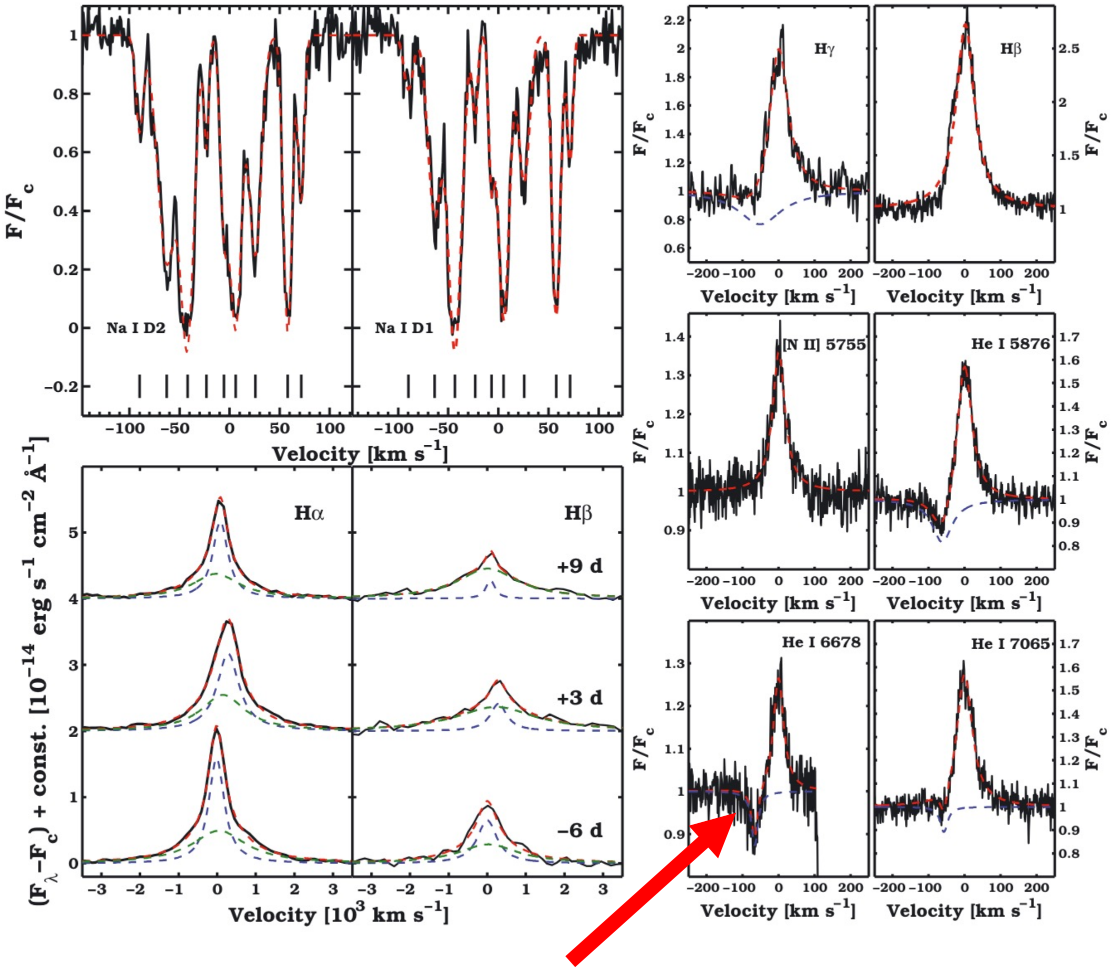
CSI 2002ic-like SN 2008J

- AGB companion? Hamuy+03
- He-star donor?
- Nova shell, e.g., Dilday+12
- SOXS near-IR and resolution!!

Highly-reddened SN 2006X & CS dust



Patat+12



CSM wind velocity

Taddia+12

SOXS: constructing a golden SNe Ia sample

Some guesstimates:

- 1 object < 20 Mpc ($z=0.005$) per year observable < +30 degrees
- 4 Infant SNe Ia around per year
- 4-5 peculiar objects –02es, 02cx, 03fg, CSM+Ia– per year

→ WG5 google page estimation of 10 hours of SOXS time per object

- Weizmann group: 2x25H maximum light spectra of ZTF sub-sample to test the Na ID vs. E(B-V) relations

Summary

- Challenging to obtain infant SNe Ia spectra
  →success can be achieved by implementing an aggressive classification protocol

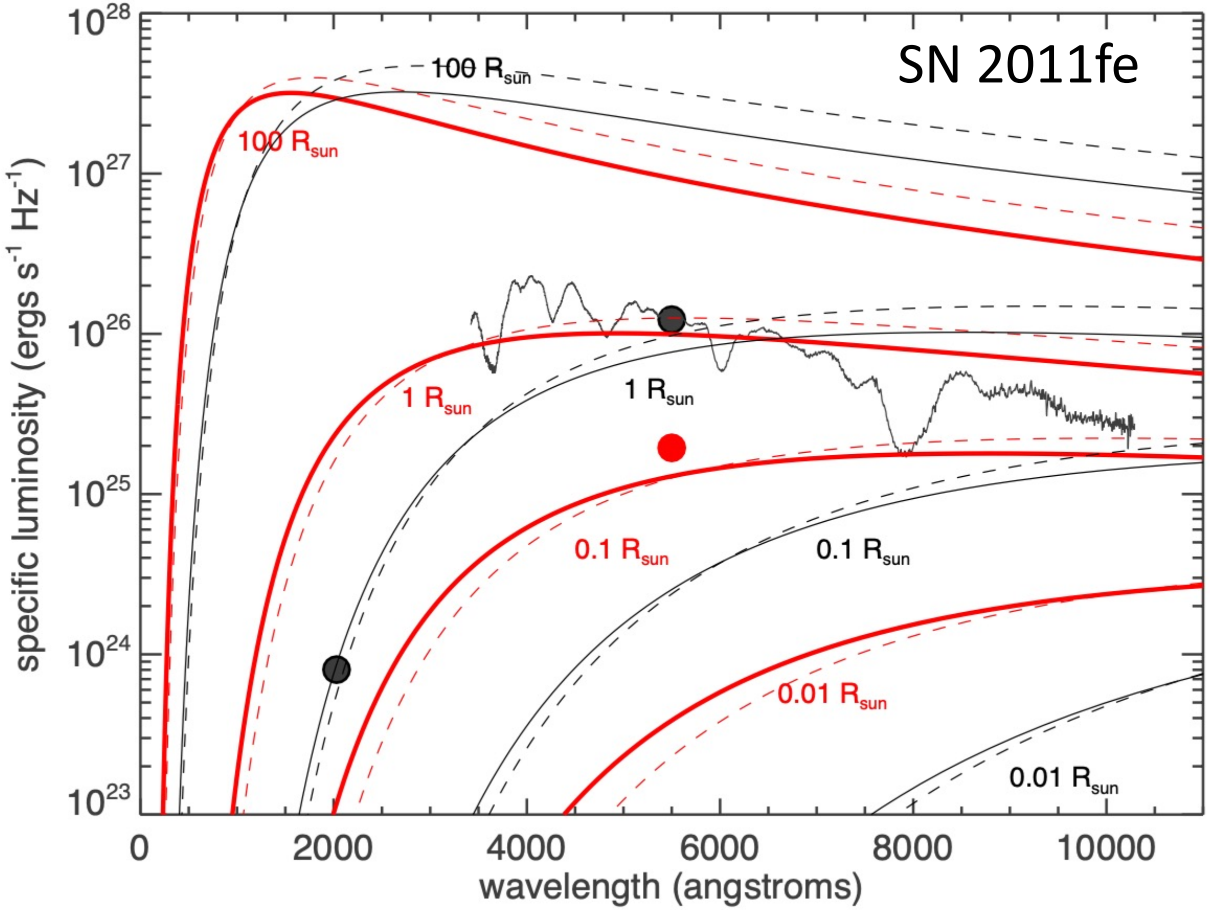
- Infant observations provide a means to test leading progenitor and explosion models

- SOXS sensitivity and rapid access will facilitate the studies of infant/peculiar SNe Ia

- Late-phase SOXS observations are also essential: SOXS + VLT

- SOXS resolution will open the studies of CS environment without the need for large glass

Radius of SN Ia Progenitor from infant observations



- SN 2011fe: normal type Ia, among the closests SN Ia discovered in 25 years found soon after explosion

- Red dot is luminosity at ~0.5 days past explosion
- Spectrum is obtained soon after red dot

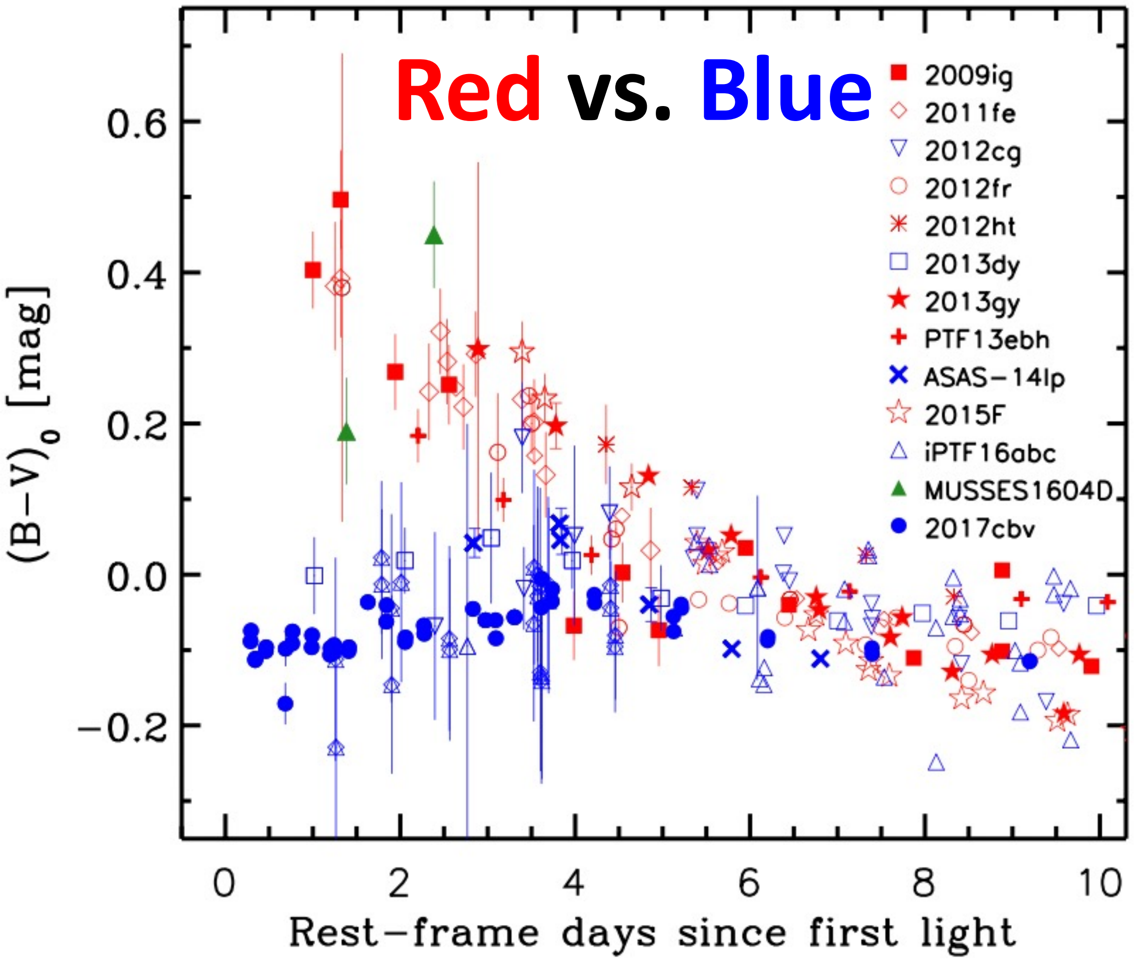
- Red lines are best-fit black-body functions for different stellar radii
- Black points and lines are model predictions of brightness for various size progenitor models at 1.5 days for different radii

→ The red point indicates progenitor R = 0.1 $R_{\odot}$!

Nugent et al. (2011)

What about early B-V color evolution?

Color traces temperature of underlying emission



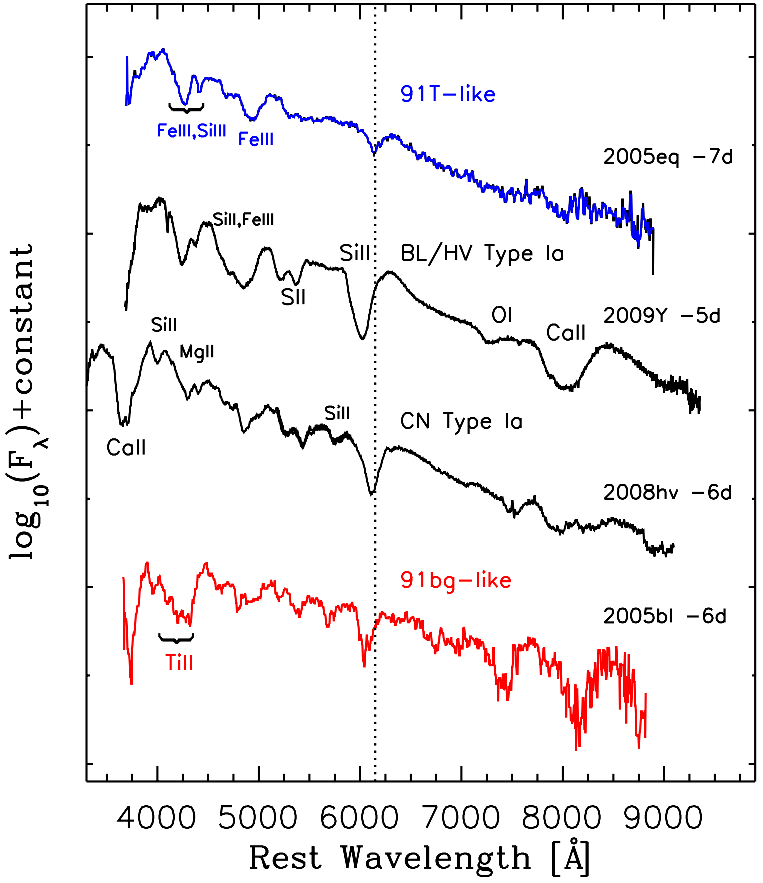
Stritzinger et al. (2018)

- All SNe Ia discovered within 3 days of ”time of first light”
- Blue objects, slowly evolve and are brighter at peak, 1991T-like
- Red objects, rapidly evolve and are fainter at peak, normal SN Ia
- 50% difference in flux
- Multiple populations, red, blue & green?

Optical Spectroscopy

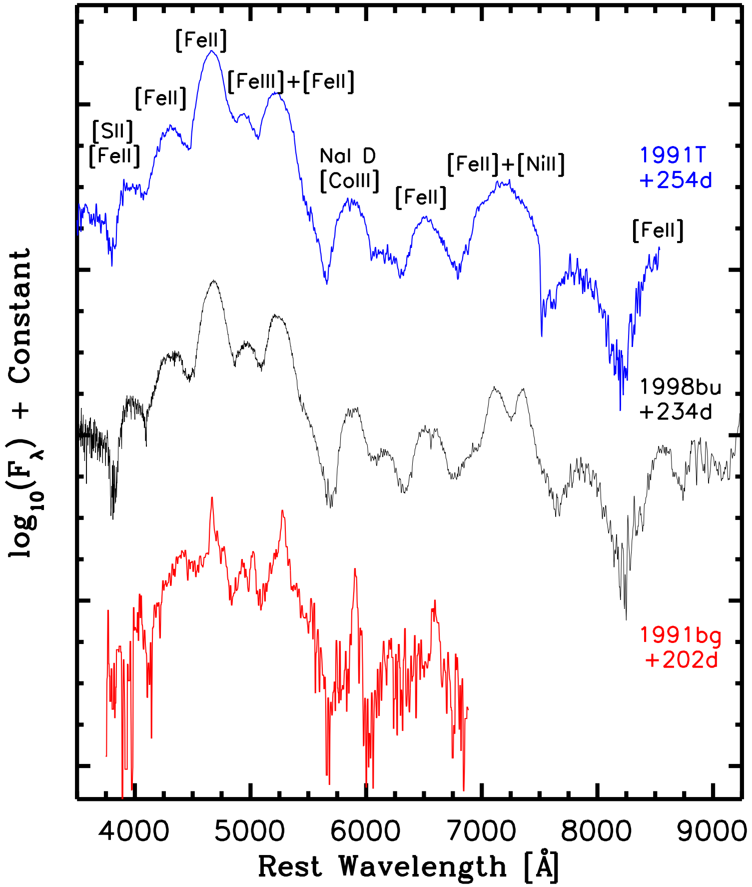
Pre-max spectroscopy

- Prevalent IME features, e.g., Si, **S**, Mg, Ca, Fe, no **H**
- 1991T-like hot spectra; 1991bg-like cool spectra
- Diversity is largely driven by temperature



Nebular spectroscopy

Peering into the heart of the explosion

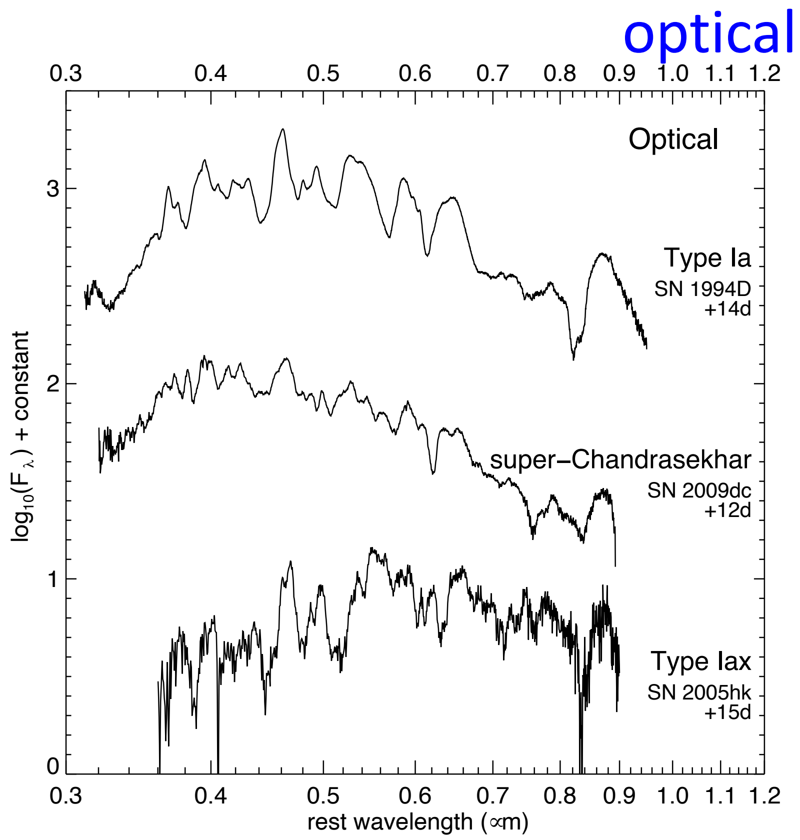


- Broad features of mostly [FeII],[FeIII]

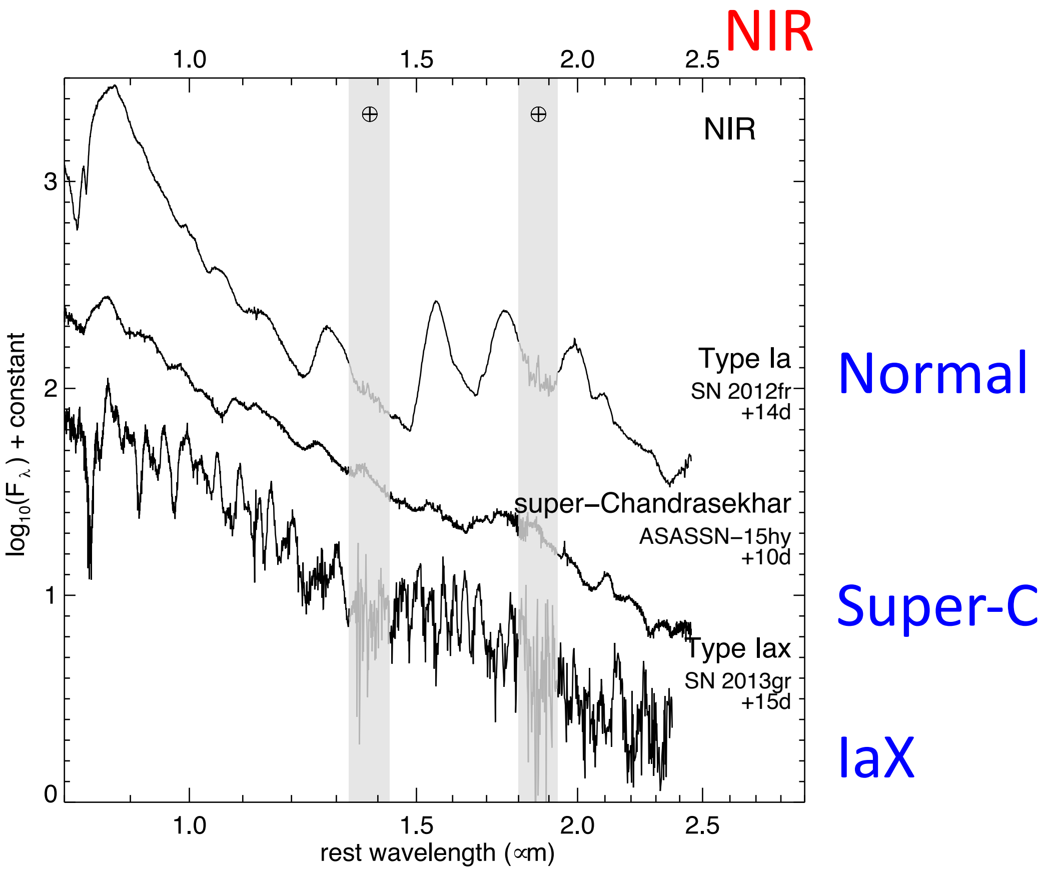
NIR spectroscopy

Hsiao+2019

- The difference between normal and peculiar SNe Ia can be subtle in the optical
- At NIR wavelengths the spectra are *significantly different for Type Ia sub-types*



Rest Wavelength (microns)



Rest Wavelength (microns)

SNe Ia spectroscopic sub-typing

(Diversity is driven by temperature)

- Core Normal (CN)

→ 'Normal' in v_{SiI} criteria of Wang+06
→ Low Velocity Gradient (LVG; Benetti+05)

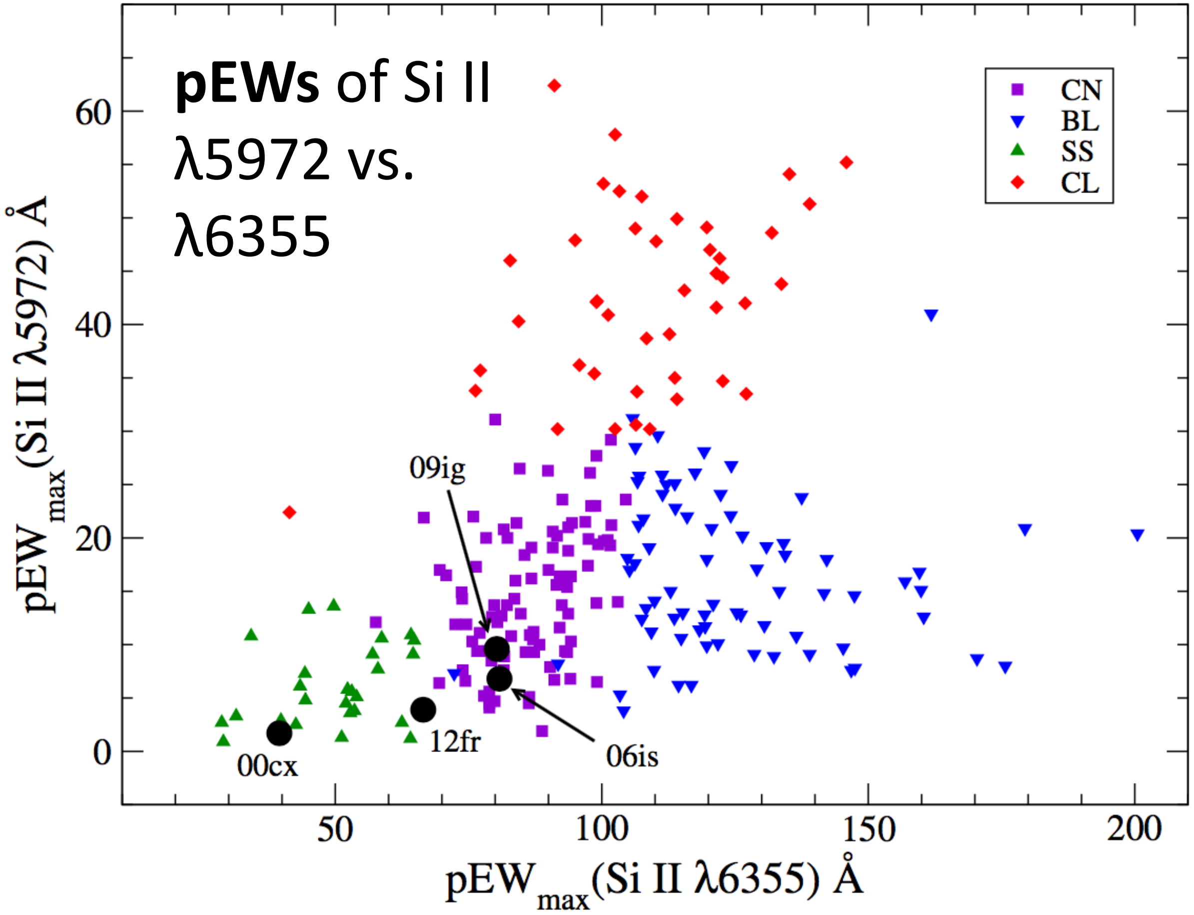
- Broad Lined (BL)

i. BL objects are High-Velocity (HV; v_{SiII}>11,800 km/s) objects in Wang+06
ii. ≈85% of HV are HVG objects (Foley+11, Silverman+12)

- Shallow Silicon (SS): 1991T-like

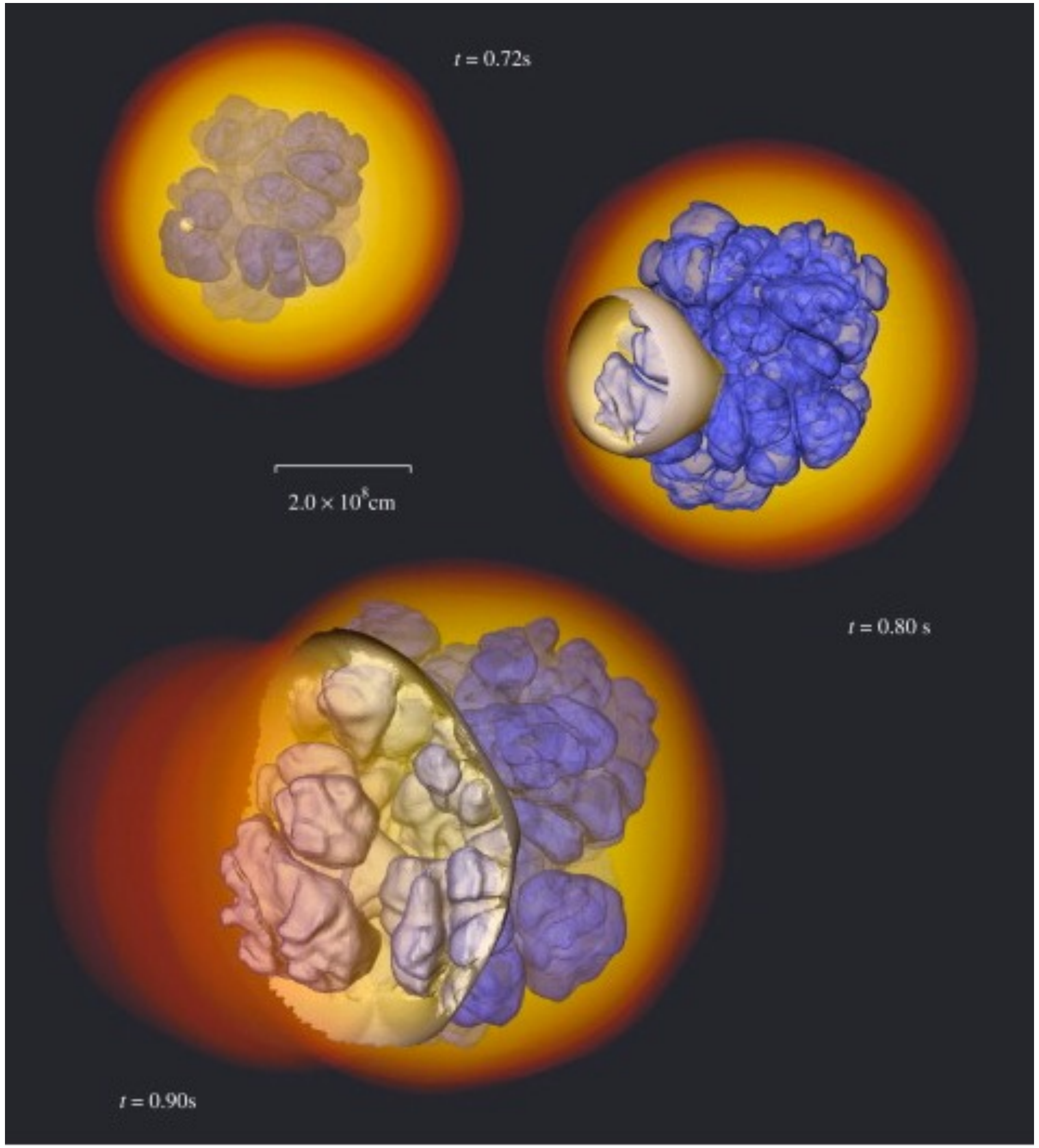
- CooL (CL): 1991bg-like

Branch Diagram



Contreras+*18, data from* Blondin+12

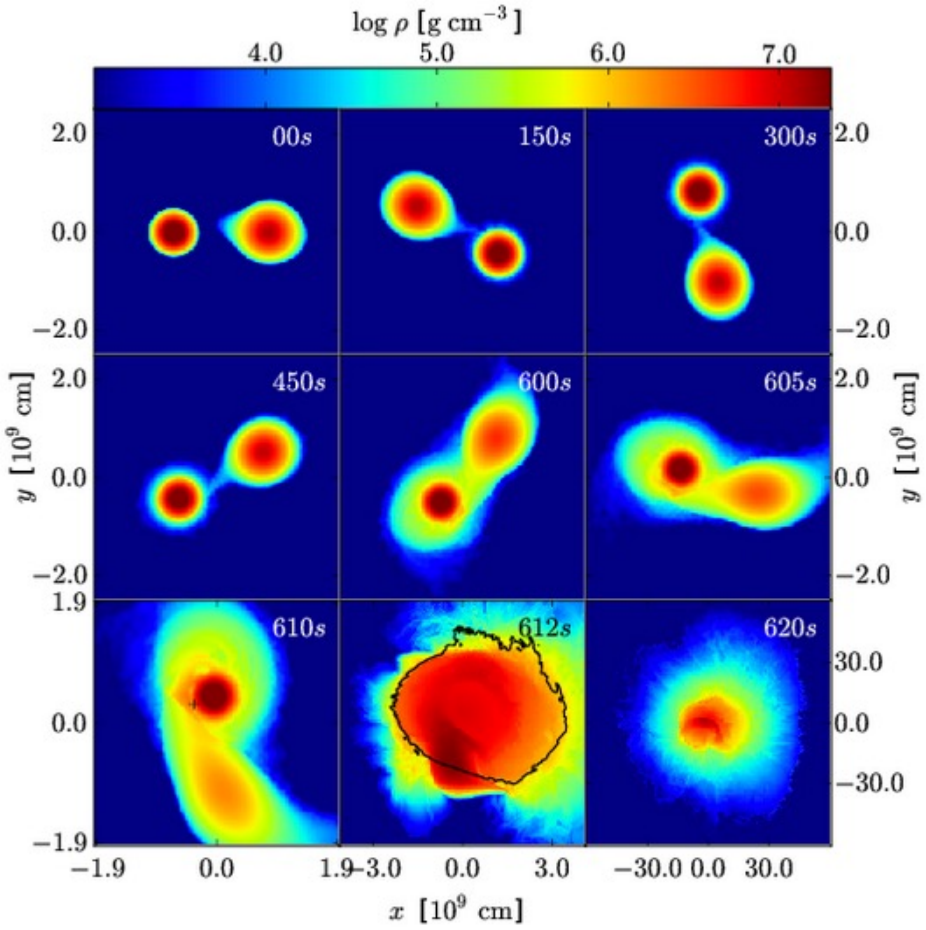
Delayed Detonation Transition (DDT)



M_{CH} C-O WD with core ignition of a deflagration flame, followed by a transition to a detonation having a **supersonic** flame front → Delayed Detonation Transition (DDT)

Fritz Röpke and MPA group

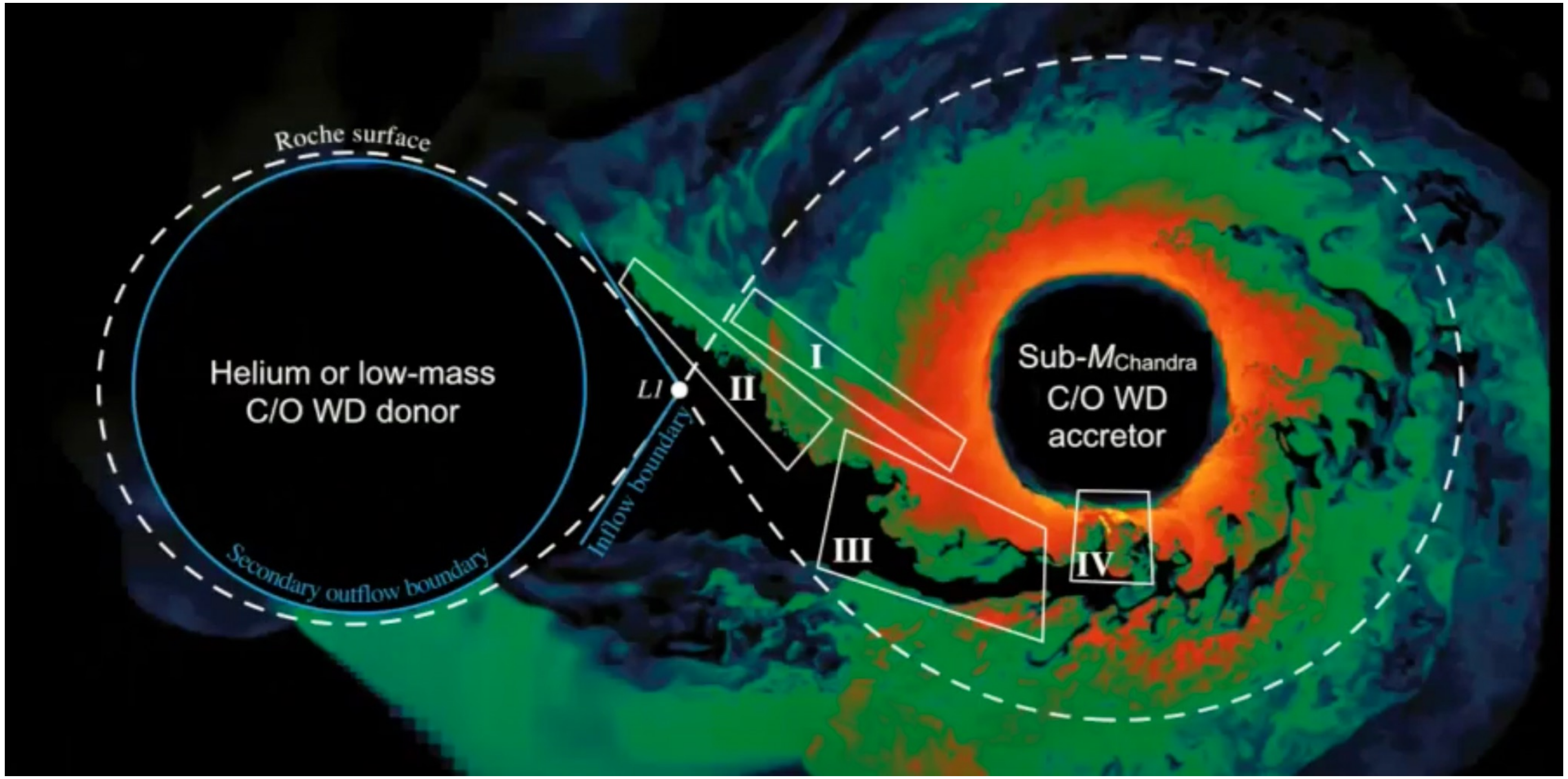
Double Degenerate Merger



- 1.1 & 0.9 $M_\odot$ WDs, P= 35 seconds
- After several orbits secondary is tidally disrupted and collides with primary
- 610 s detonation ignites
- 612 s detonation nearly complete

Pakmor et al. 2012, MPA

Dynamically Driven Double Degenerate (He-shell) Double Detonation: "D^6 model"



Guillochon, Shen, Polin, and collaborators (circa 2020s)

- sub-M_{CH} C-O WD with He-shell
- Shell ignites as detontation
- → rapidly consumes He and compression wave detonates the core

- Produces a range of ^{56}Ni
- Stratified ejecta

BUT

- *Lacks signatures of M_{ch} WD progenitor*
  → no stable ^{58}Ni and other electron capture elements
- *No helium lines!*

Degeneracy between today's data set and predictions of DDT and D^6 models