# Uncovering Peculiar Double-Detonation Type Ia Supernovae

## The rare weirdos: SN 2020jgb & SN 2022joj

Liu et al., 2023a, ApJ, 946, 83
Liu et al., 2023b, ApJ, 958, 178

**Chang Liu,** Adam Miller

**2024.2**


## Type Ia Supernovae (SNe Ia)

- **Rare:** extragalactic
- **Bright:** luminosity ~ the entire galaxy
- **Transient:** last for months

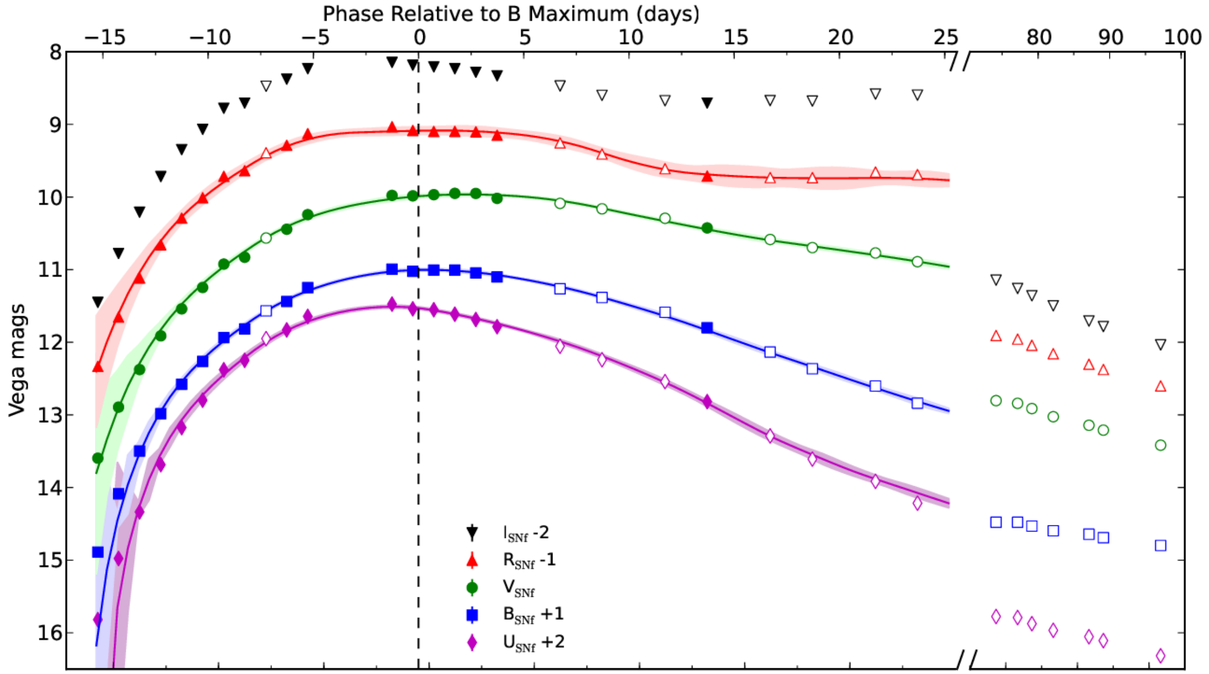

# Zwicky Transient Facility

- Wide field camera
- Repeatedly observe the Northern sky every ~2 nights
- Detected, classified, and monitored ~$10^4$ SNe Ia since 2018

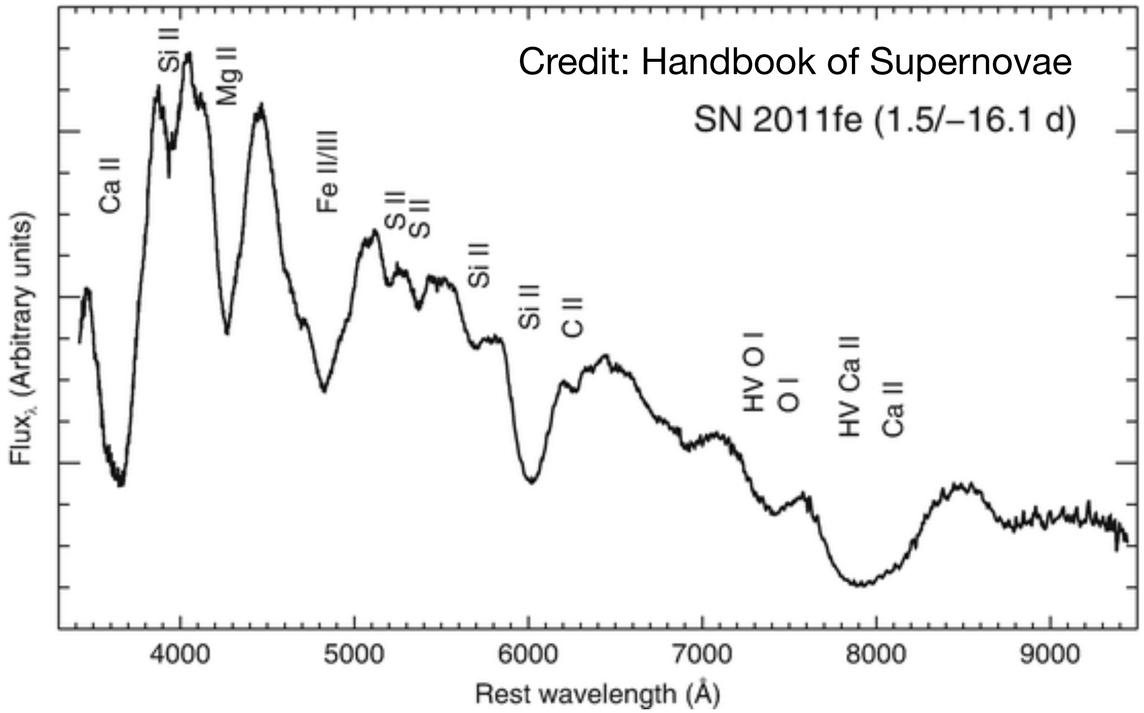
Image Credit: Palomar Observatory/Caltech

# Type Ia Supernovae

## Monitor cosmic explosions

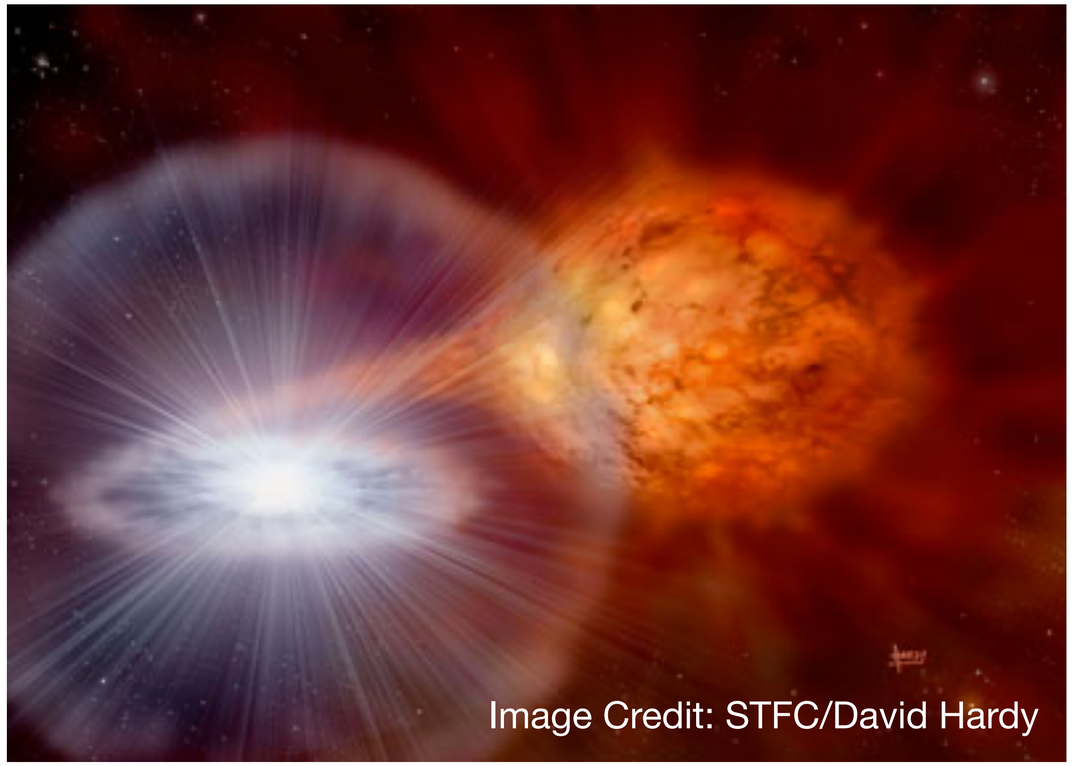



Credit: Nearby Supernova Factory



# An Unfinished Story…

## How to explode a C/O white dwarf (WD)?



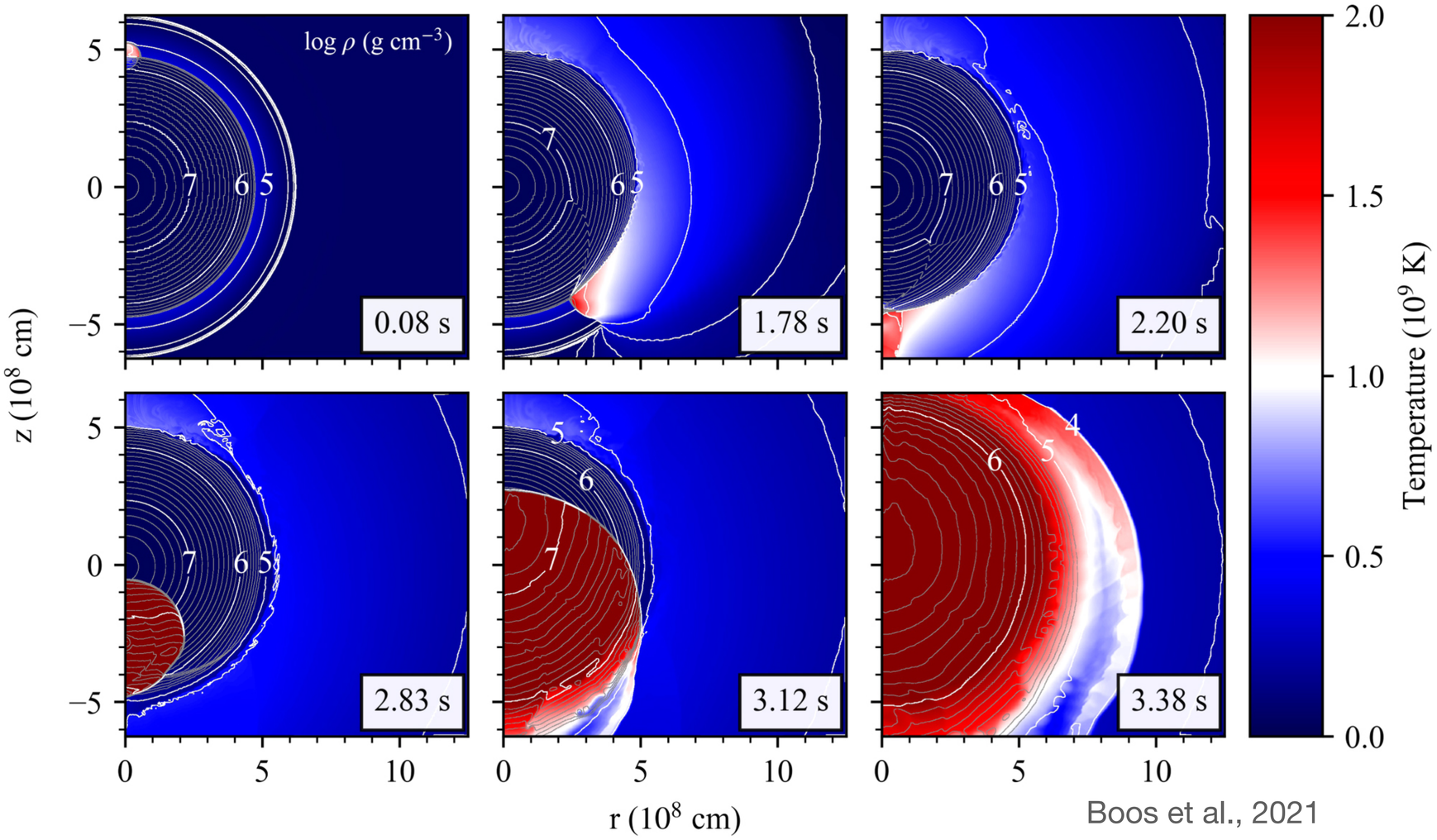

- Feeding the WD until it approaches **Chandrasekhar mass** ($M_{Ch}$ ~1.4 $M_{\odot}$)

  —> Properties around maximum light ✓
  —> Event rates ✗
  —> Diversity in the population ✗

- Dynamical ignition in a **sub-$M_{Ch}$** WD

# He-shell Double Detonation

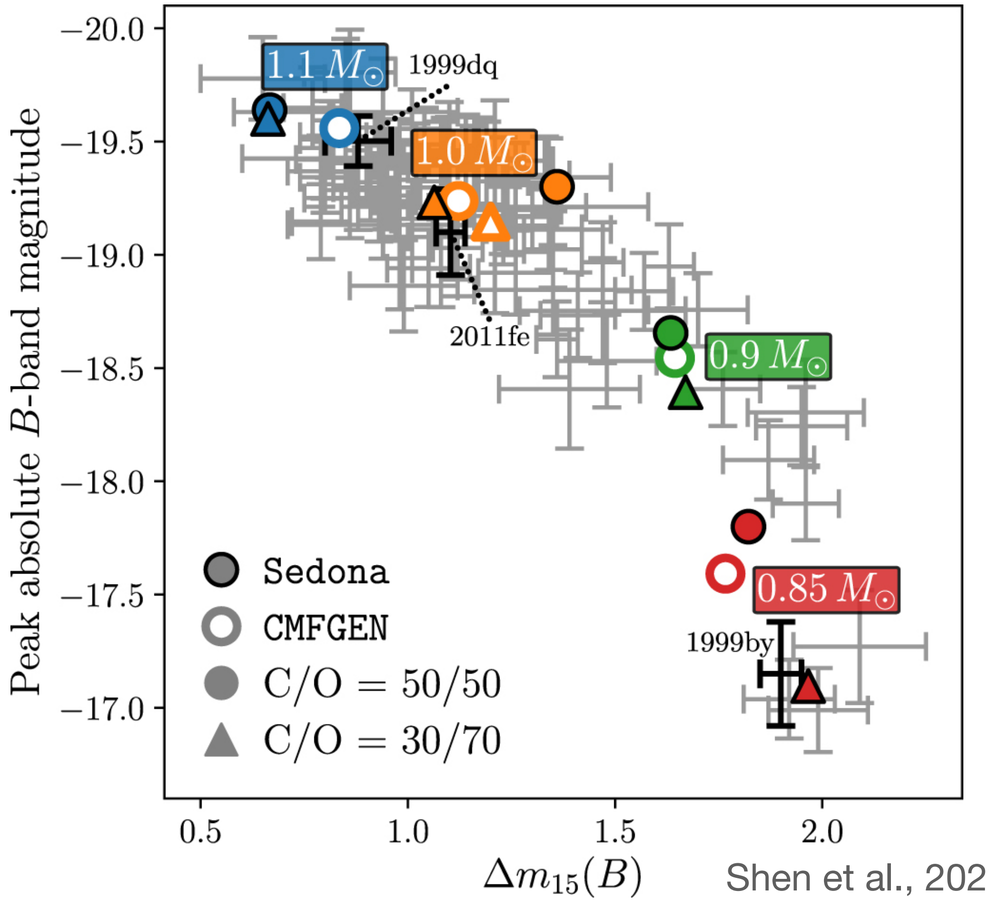
- **Detonation** of a helium shell triggers the **detonation** in the sub-$M_{Ch}$ C/O WD



# Thin He shell + sub-$M_{ch}$ C/O core

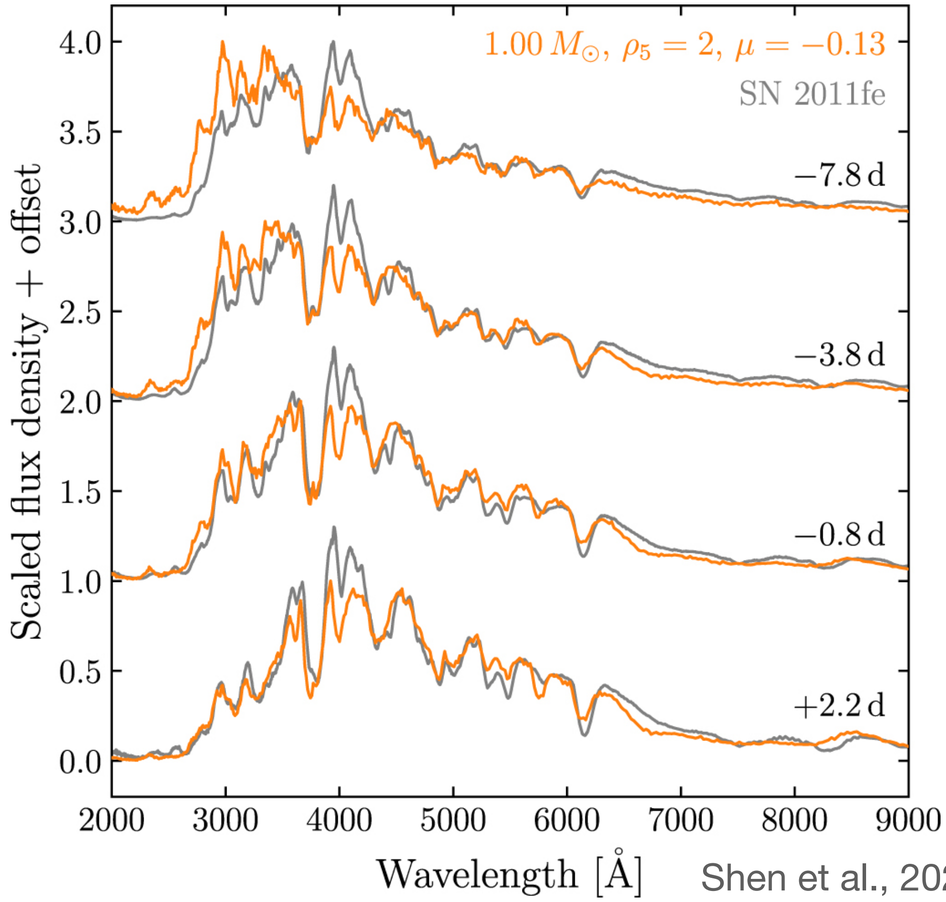
## Normal SNe Ia at peak? — under debate…

### Luminosity-width (Phillips) relation



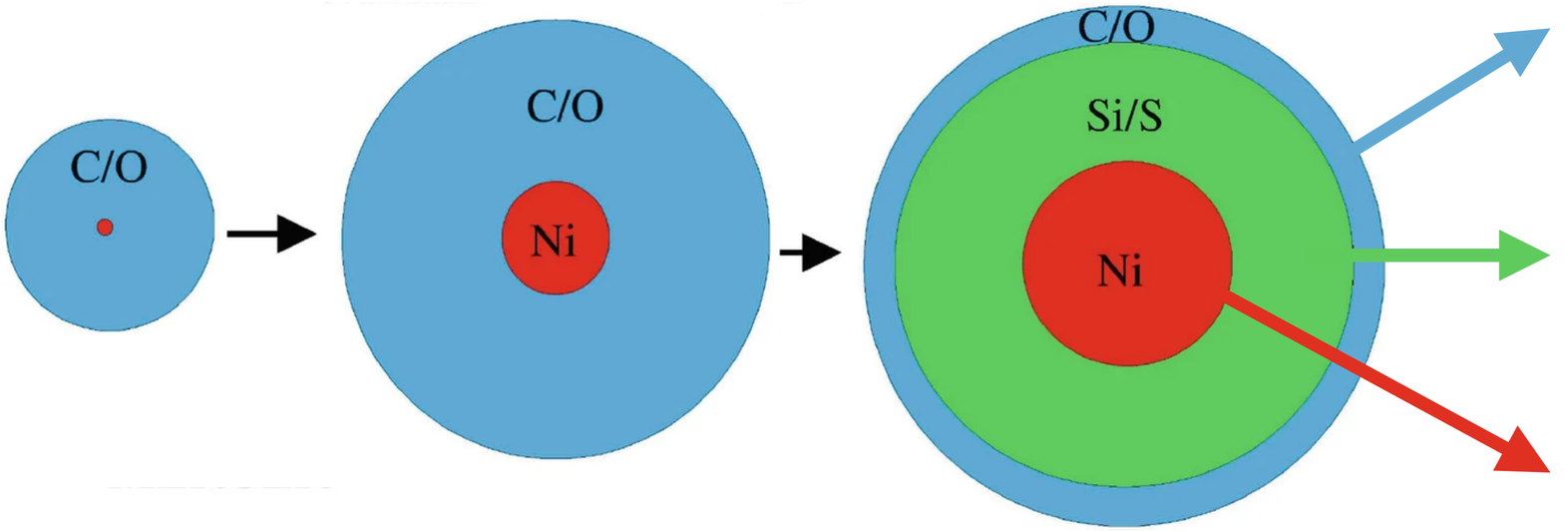

Shen et al., 2021a

### Spectroscopic features




Shen et al., 2021b

## Near-$M_{Ch}$ WD




**Early-time** (hours to days after the explosion)

Near **maximum** luminosity

**Late-time** (>200 days)

## Sub-$M_{Ch}$ WD in a double detonation

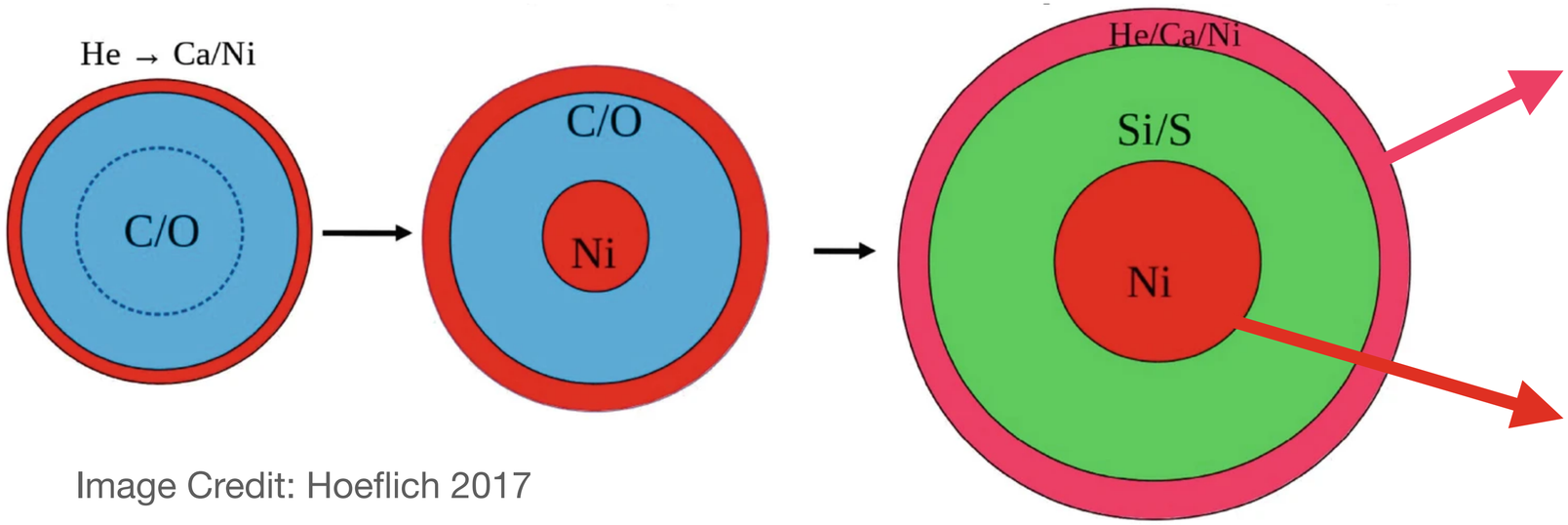



Image Credit: Hoeflich 2017

**Helium shell:** early times (depending on the shell mass)

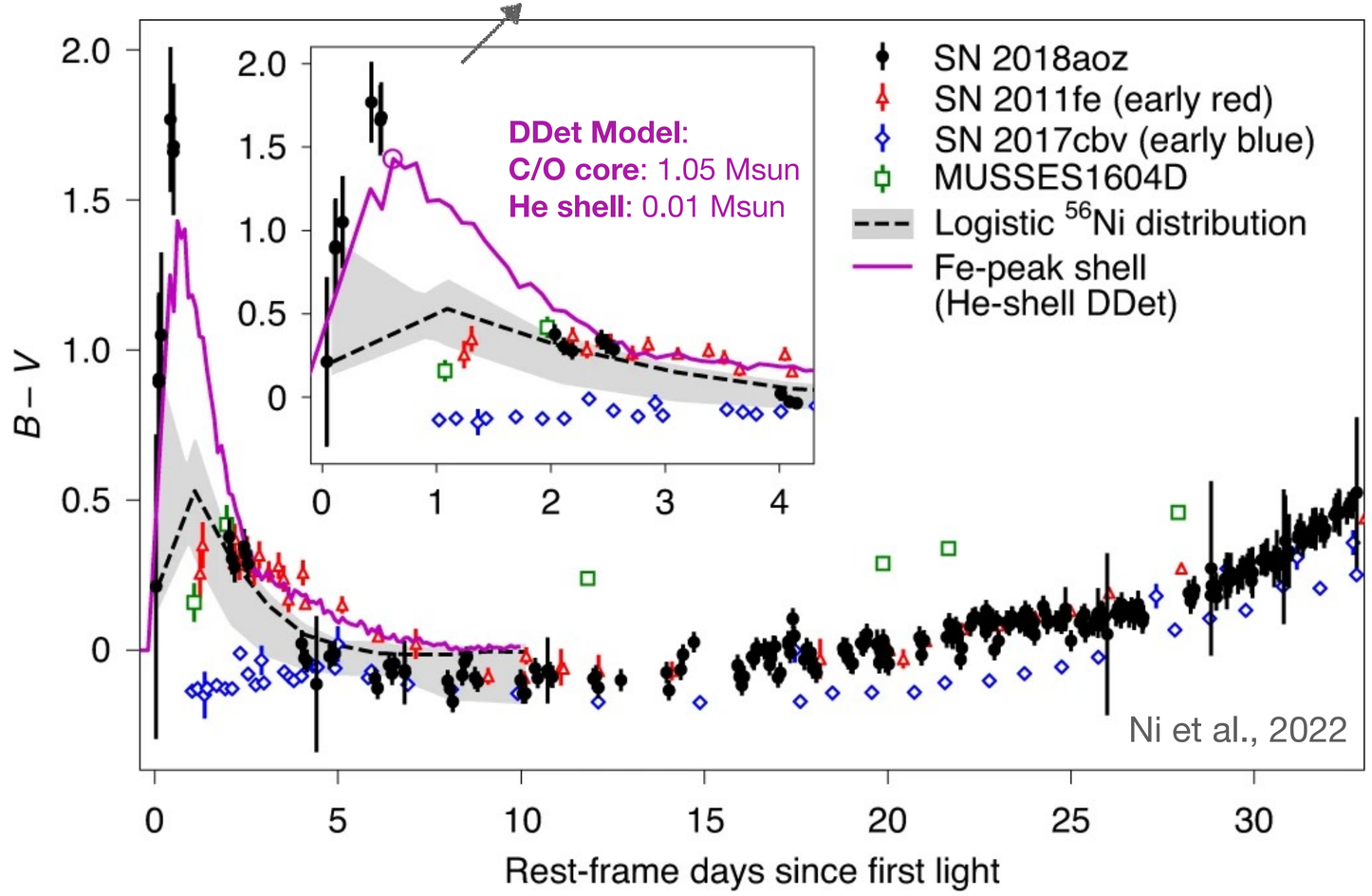
**Nucleosynthesis yields:** nebular phase

# Thin He shell + sub-$M_{ch}$ C/O core

## Exotic early colors?

**Fe-group** elements absorb UV photons

**SN 2018aoz**: Extremely red B-V color ~12 hr after the explosion

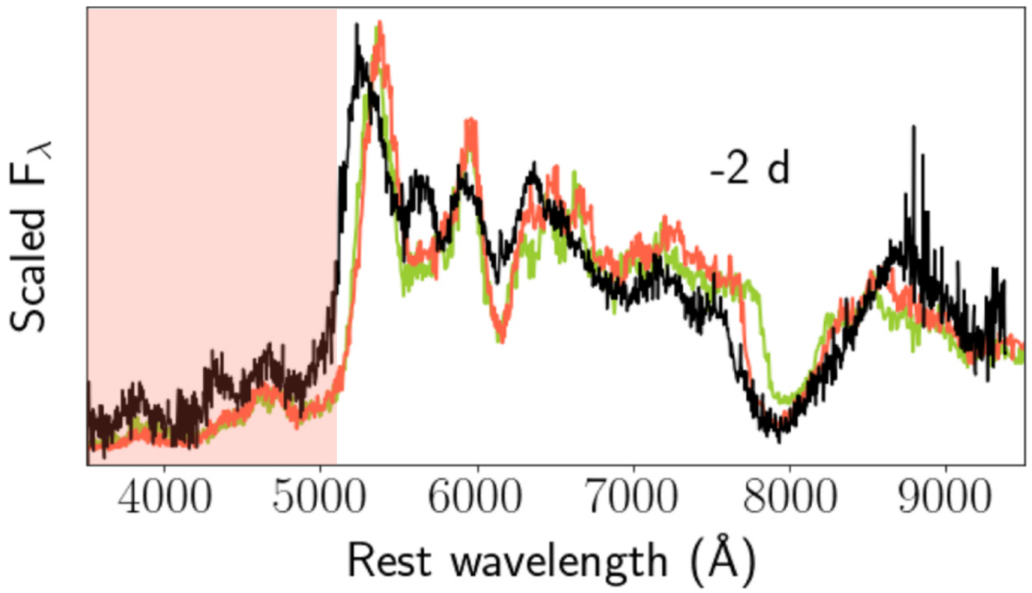


# Massive He shell + sub-$M_{ch}$ C/O core

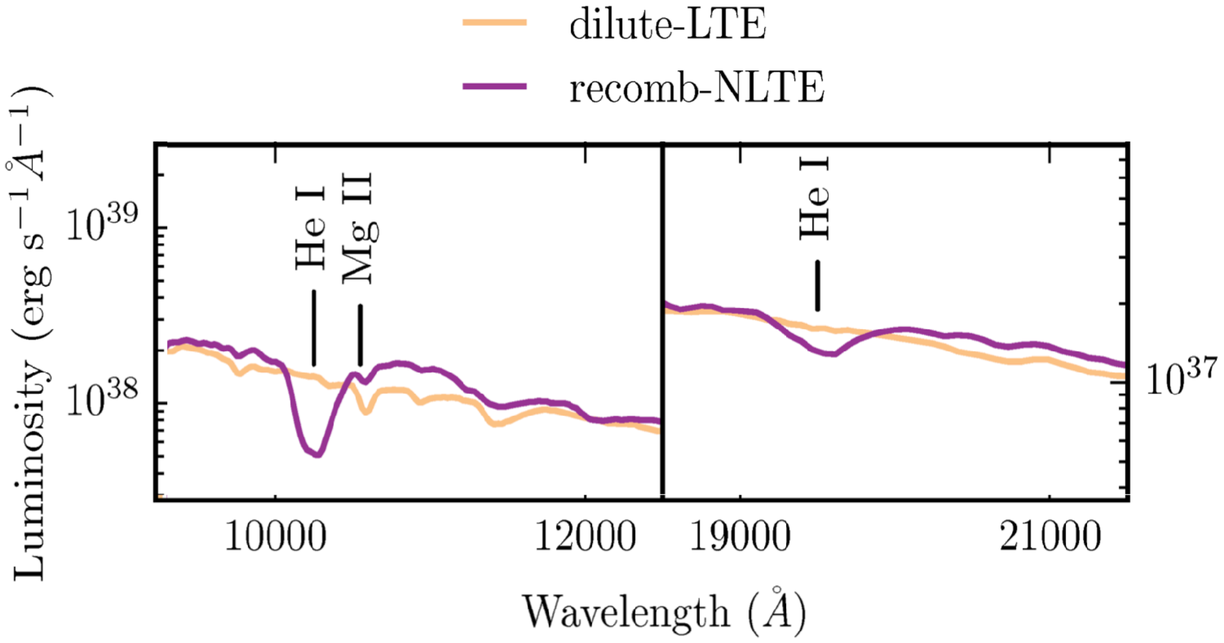
## Peculiarities to expect around maximum light

**Fe-group elements** ⟵ **He shell** ⟶ **Unburnt helium**

**SN 2018byg**: prototype




De et al., 2019



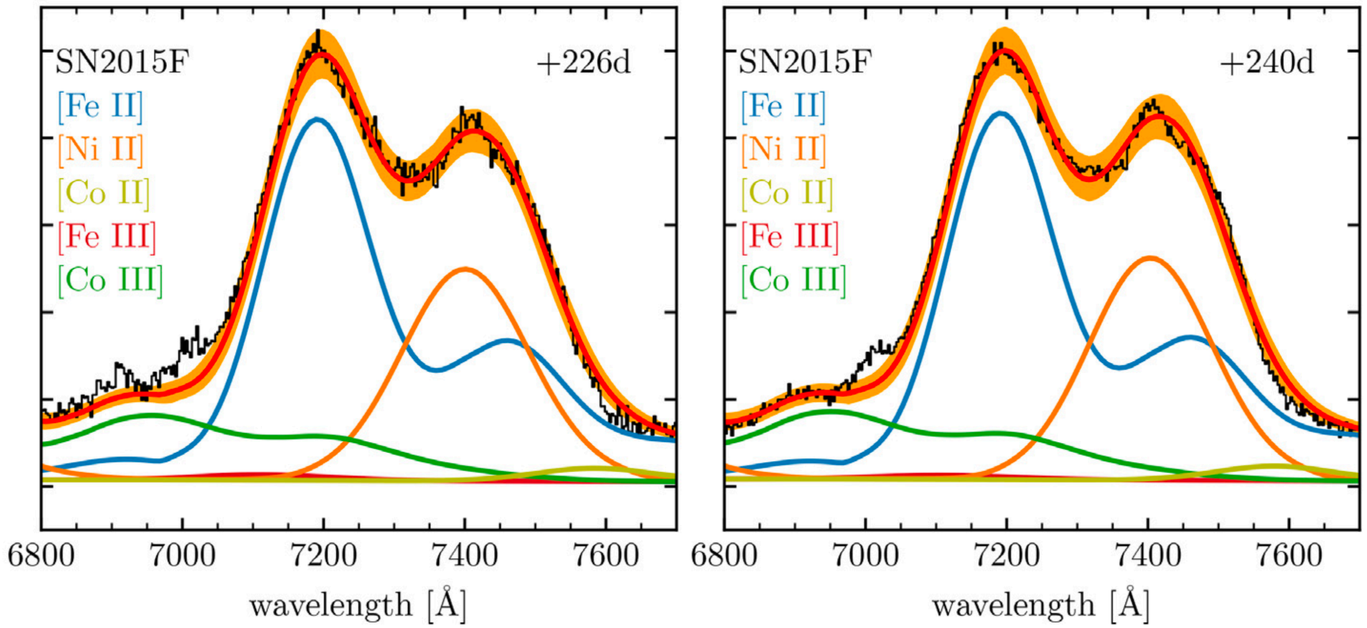

Boyle et al., 2017

# Massive He shell + sub-$M_{ch}$ C/O core

## Peculiarities to expect ~1 yr after explosion

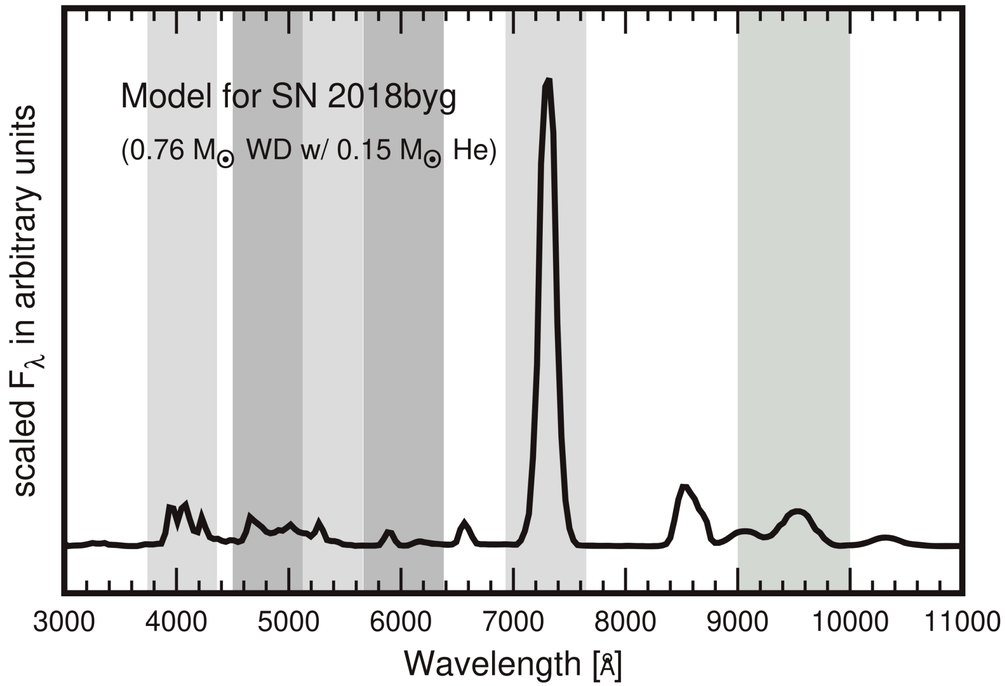
Ni-58/Ni-56

**Low Ni/Fe abundance**




Flörs et al., 2020

**Strong [Ca II] emission**




Polin et al., 2021

# Massive He shell + sub-$M_{ch}$ C/O core

## From the first to the last photon

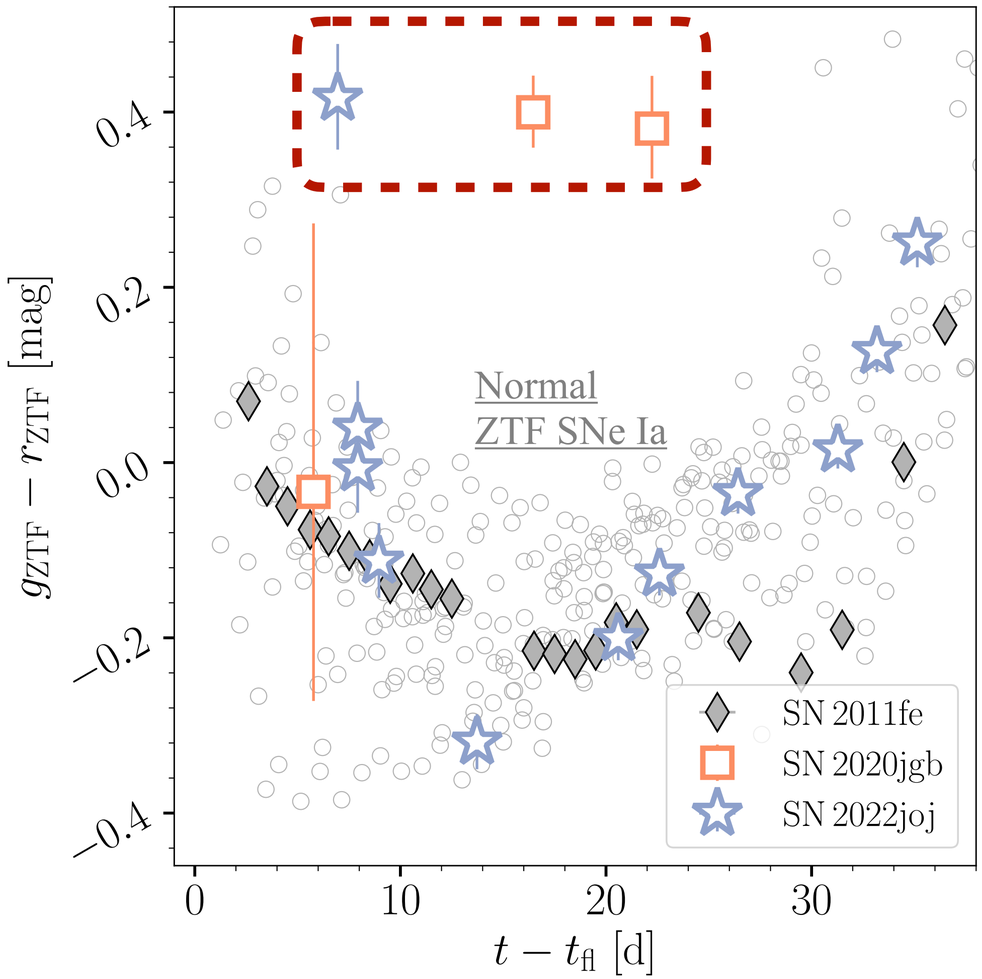
- **Days after explosion**
  - Flux excess — **early discovery & photometry**
- **Around maximum luminosity**
  - Dramatic color evolution — **multi-band photometry**
  - Line blanketing — **optical spectroscopy**
  - Unburnt helium — **NIR spectroscopy**
- **Late time**
  - [Ca II] emission, low Fe/Ni abundance ratio — **deep spectroscopy**

**SNe 2020jgb & 2022joj -** new members of this rare subclass discovered by ZTF!

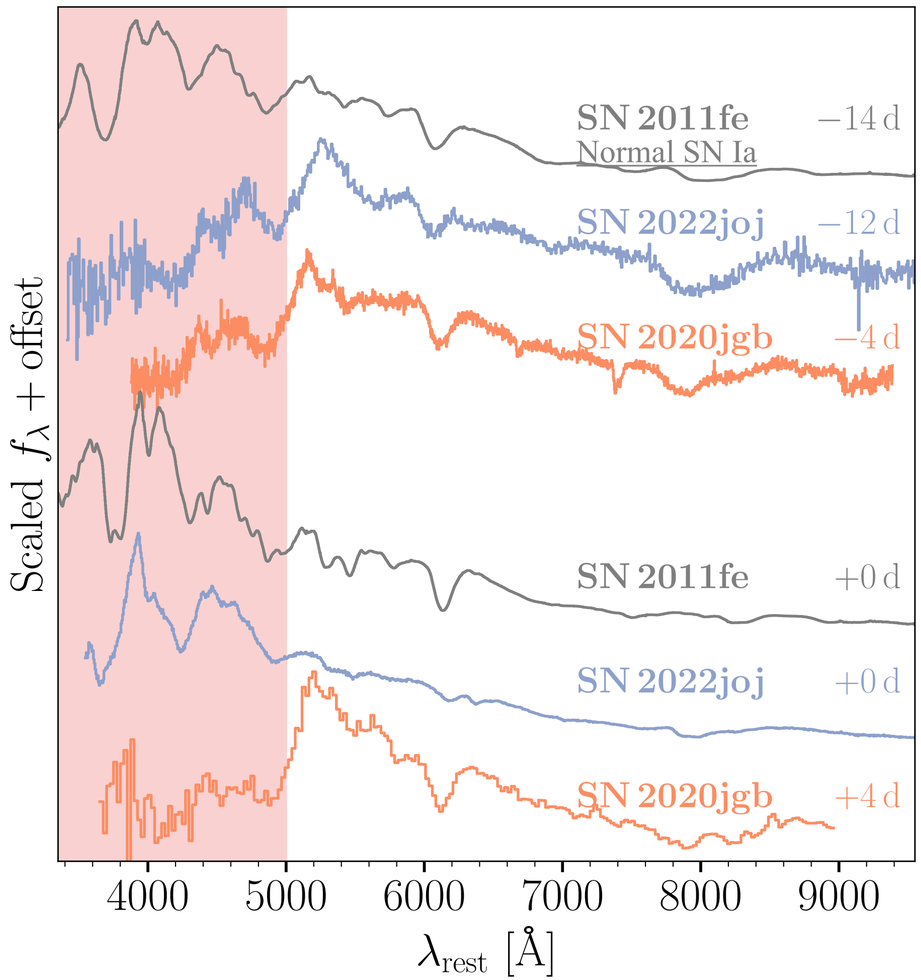
# Fe-group Elements in the Shell

## Line blanketing

Unusual **red** colors




Suppression of flux <5000 Å

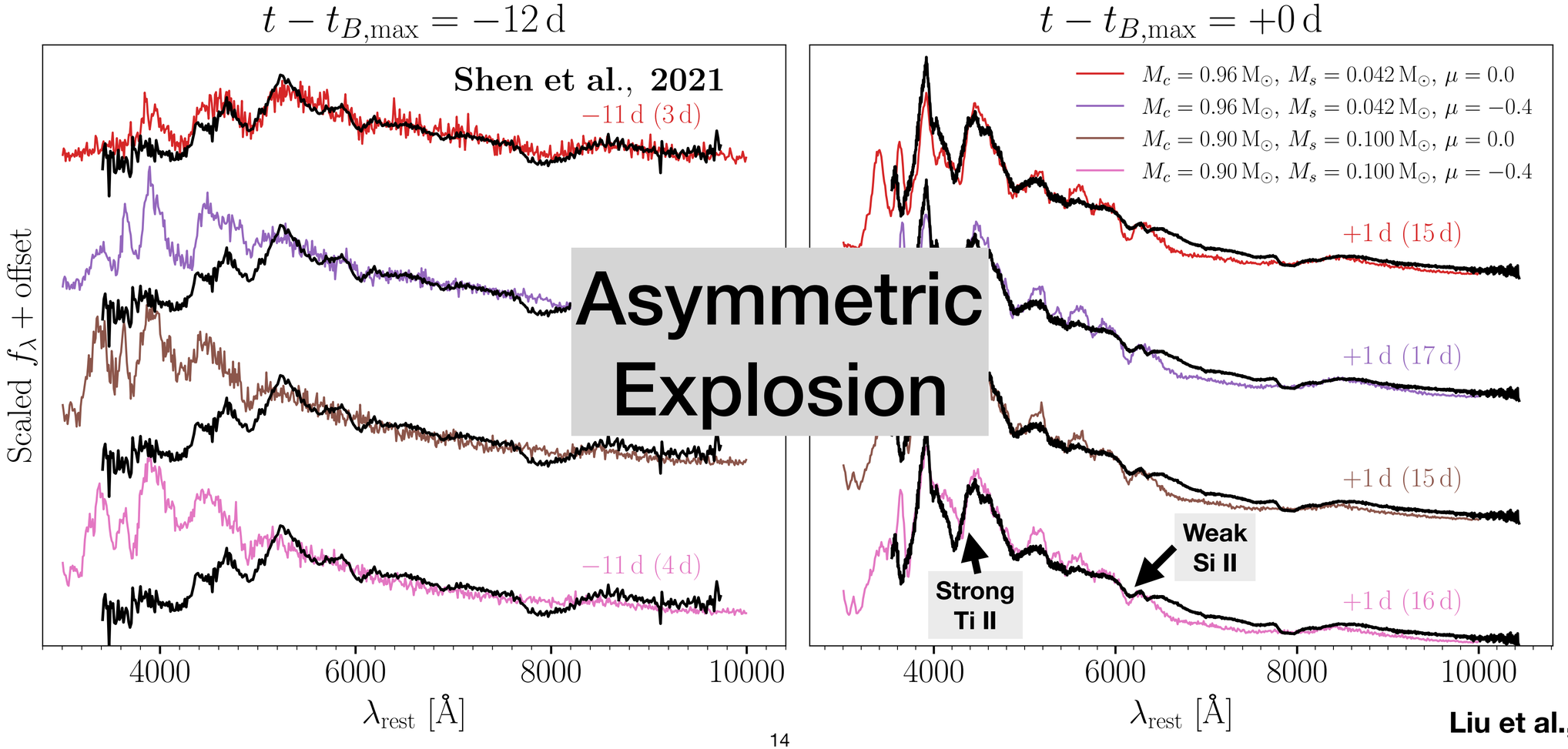


# 2D Simulations

## Spectral modeling

**SN 2022joj**

- ~0.96 $M_\odot$ (**core**) + ~0.04 $M_\odot$ (**shell**)
- Viewed from the **opposite** hemisphere of the shell detonation point



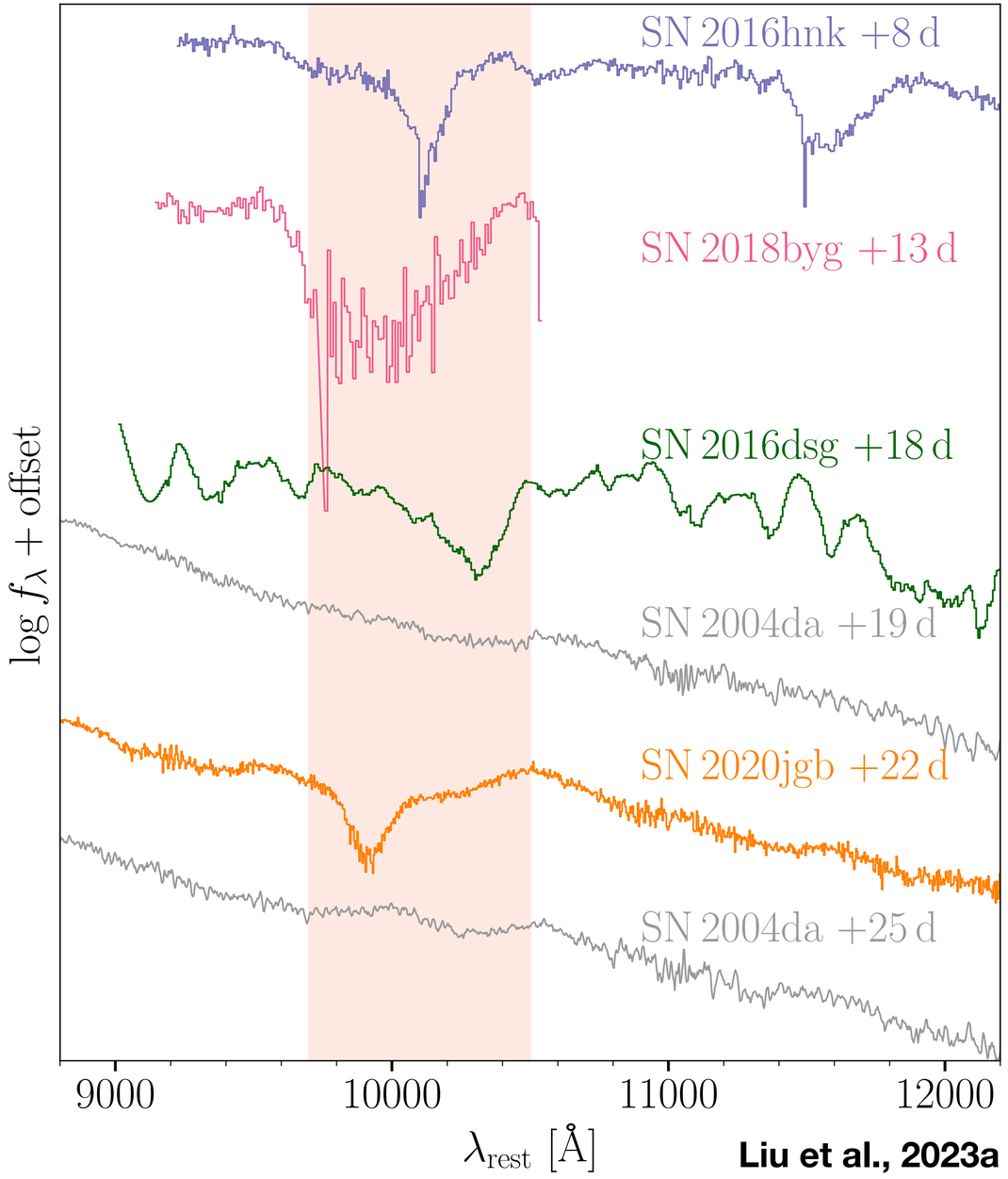

**Asymmetric Explosion**

Liu et al., 2023b

# Unburnt Helium

## He I λ10830

- Archival peculiar double detonation SNe: **<10**
- **Ubiquitous (?)** 1 micron features
  - **Helium** at a huge variety of **velocities**?
  - Viewing angle effects?

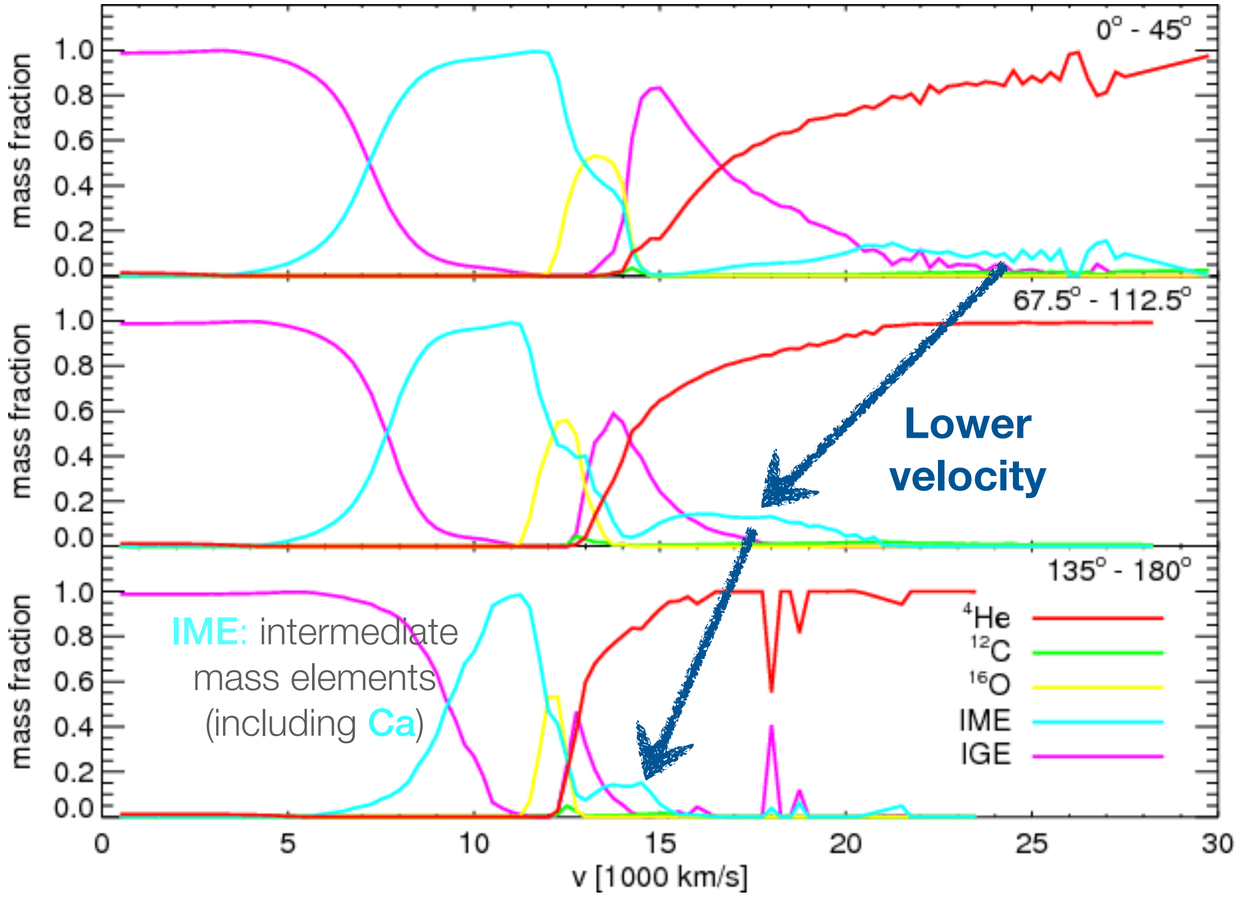


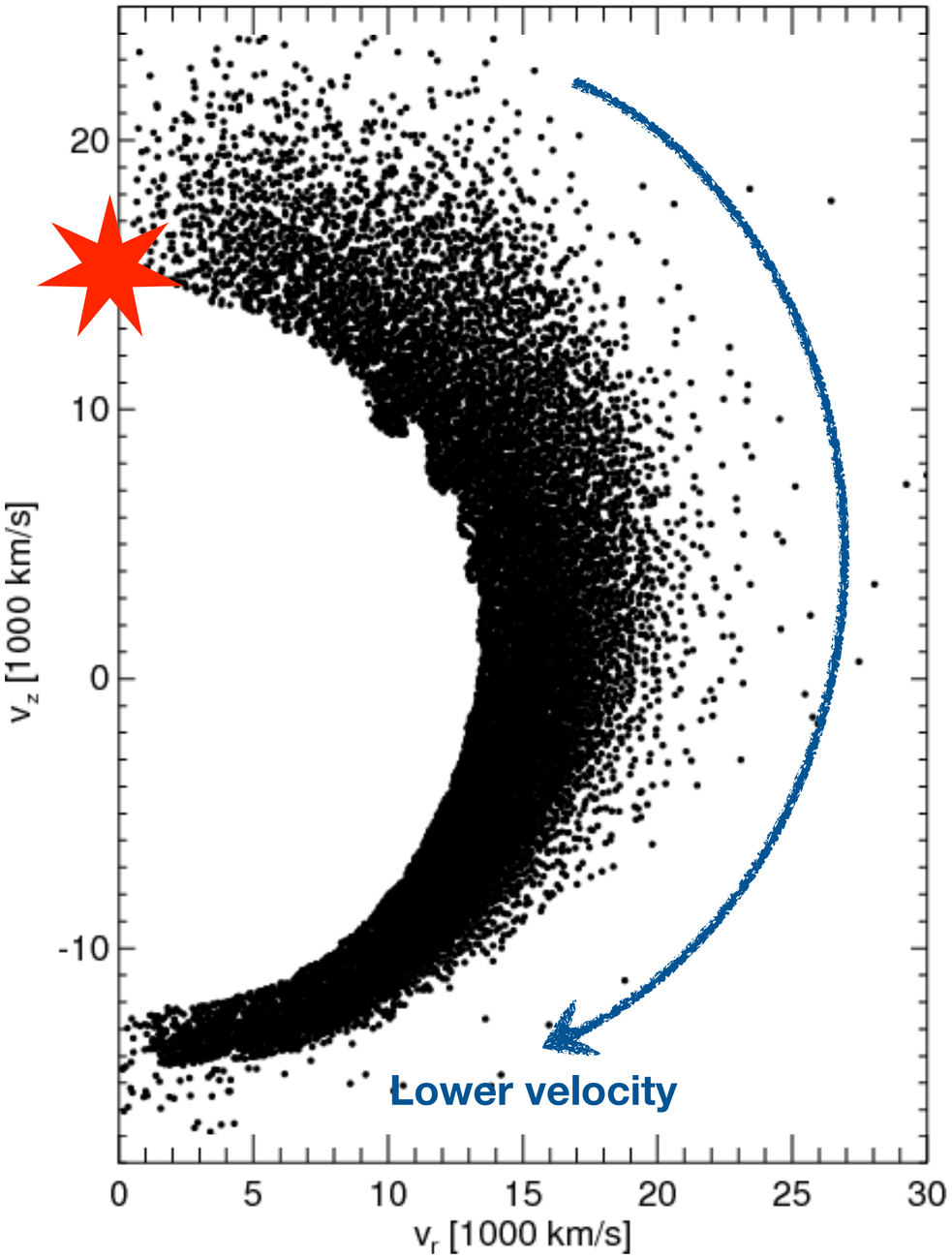

**Liu et al., 2023a**

# Unburnt helium

## Viewing angle effects

**2D Model** (Fink et al., 2010):
**C/O core**: 0.920 Msun
**He shell**: 0.084 Msun

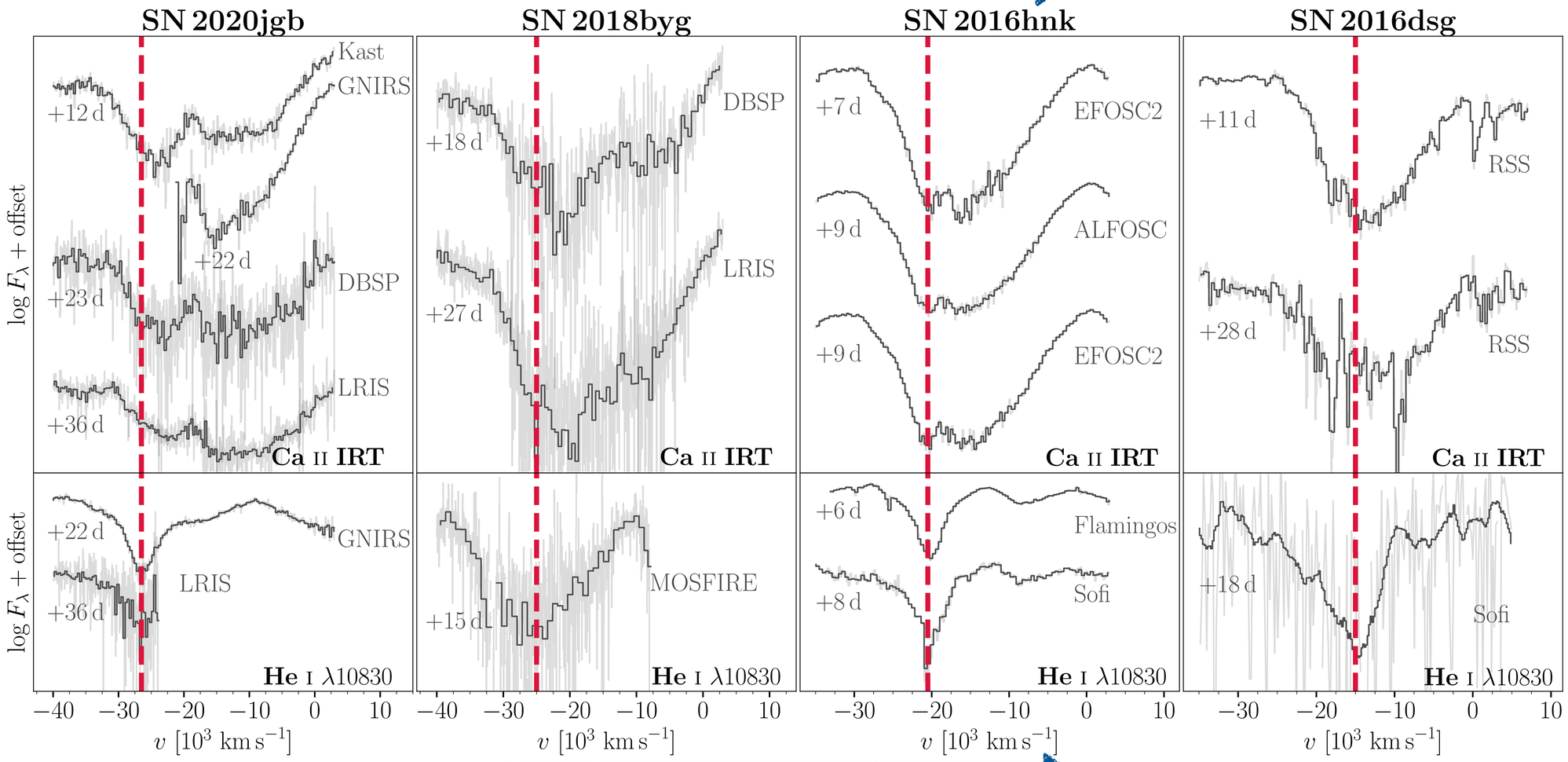


# Unburnt helium

## He I λ10830

**Less prominent** high-velocity features (HVFs) of Ca II IRT




**Lower** "He I" velocity

**Liu et al., 2023a**

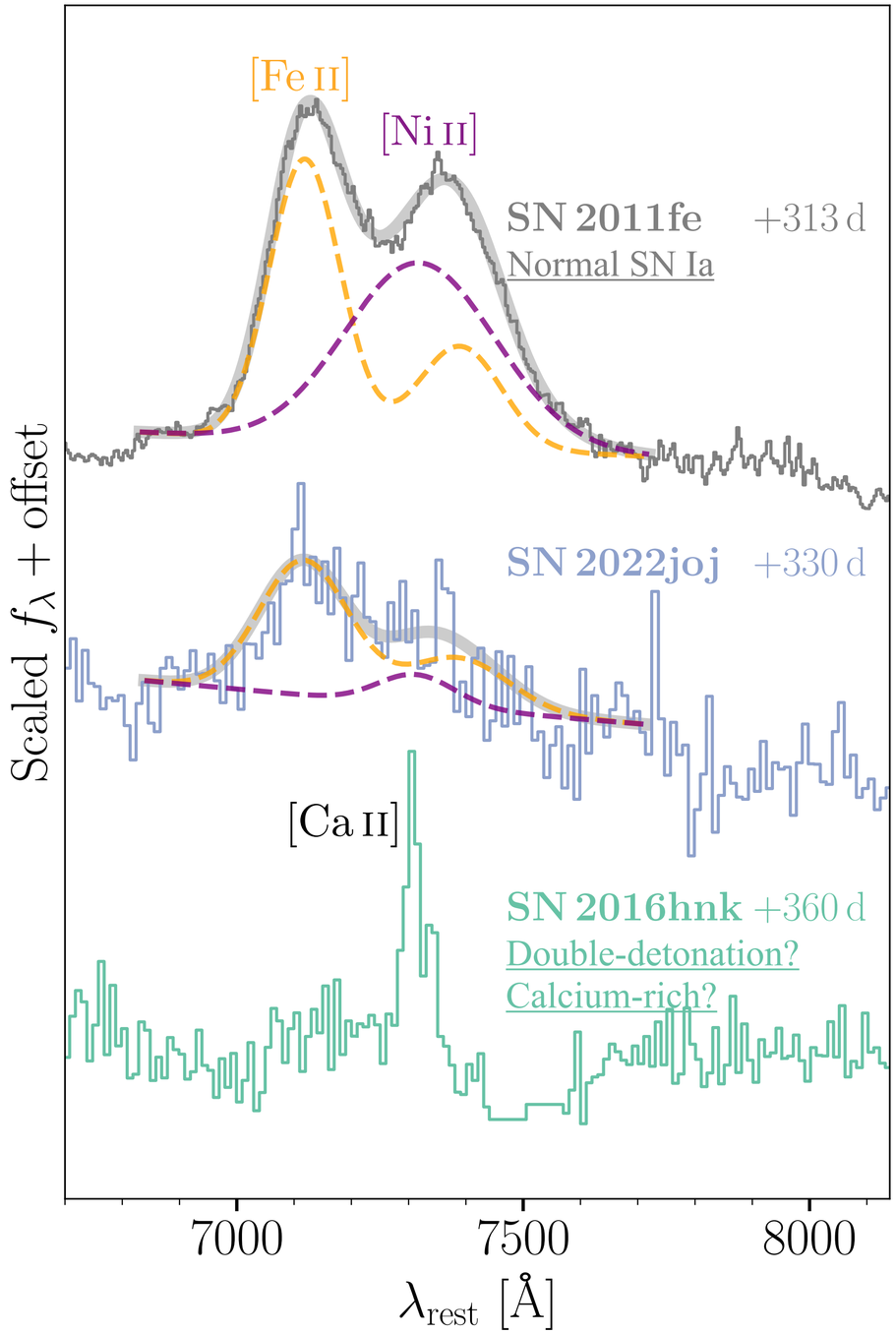
# Nebular-phase Spectra

**Ni/Fe Ratio**

- **SN 2022joj** shows **little [Ni II]**
- Ni/Fe ratio < 0.03 (3σ)
- **Low Ni abundance** is consistent with a **sub-$M_{Ch}$** progenitor

**Searching for [Ca II]**

- Not detected in either SN 2020jgb or SN 2022joj



# Uncovering Double Detonations

## From the first to the last photon

- **Days after explosion**
  - Flux excess — **early discovery & photometry**

La Silla Schmidt Southern Survey **(LS4)** is coming!

- **Around maximum luminosity**
  - Dramatic color evolution — **multi-band photometry**
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