Nebular Nitrogen as a Diagnostic for Supernova Progenitor Mass

MODELLING SUPERNOVA SPECTRA

STAN BARMENTLOO

Stockholm University

Oskar Klein centre

Based on the results from arXiv:2403.0891 by
S. Barmentloo, A.Jerkstrand, K. Iwamoto, I. Hachisu,
K. Nomoto, J. Sollerman, S. Woosley

Image credit:
Hunter Wilson

[N II] feature in nebular spectra

- Feature centred on 6550 Å present in multiple Type IIb spectra starting at ~200 days
- Varying strengths per SN
- Found to be caused by [N II] doublet at 6548, 6583 Å

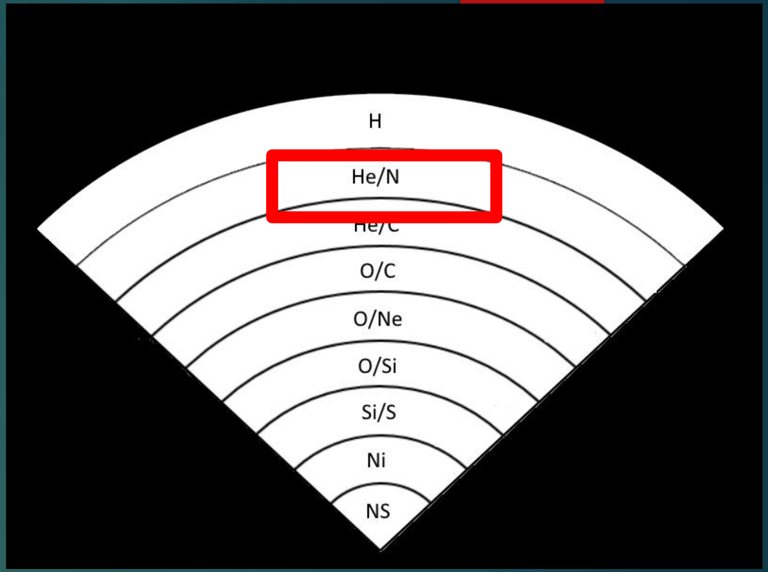
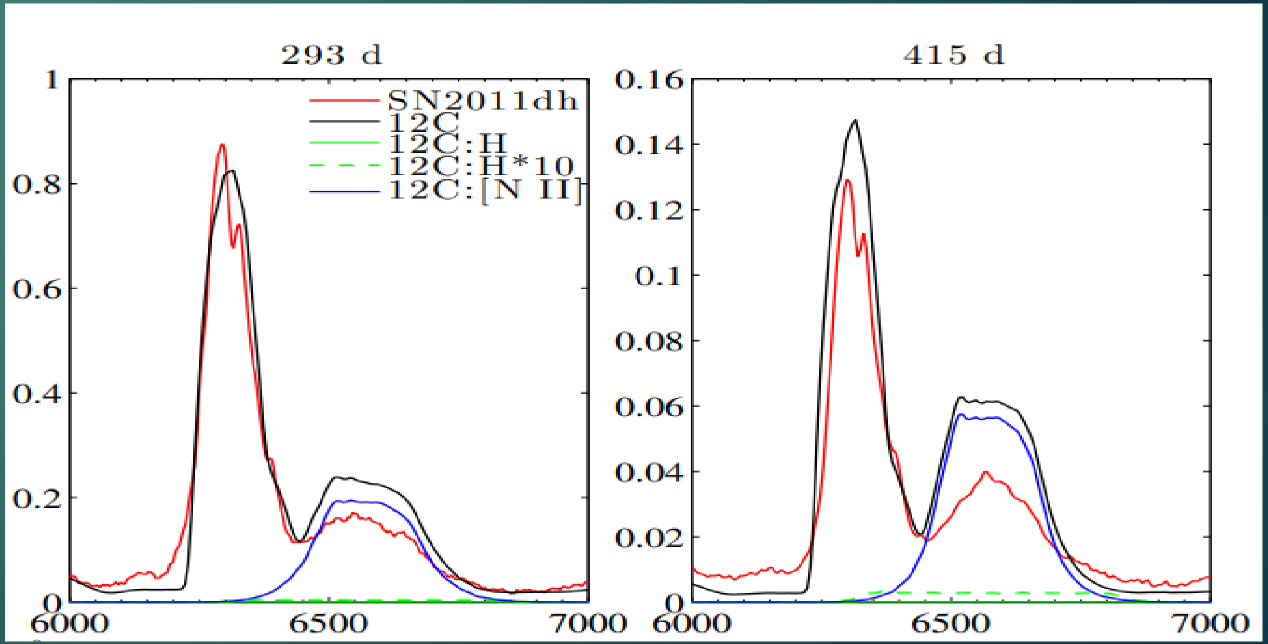
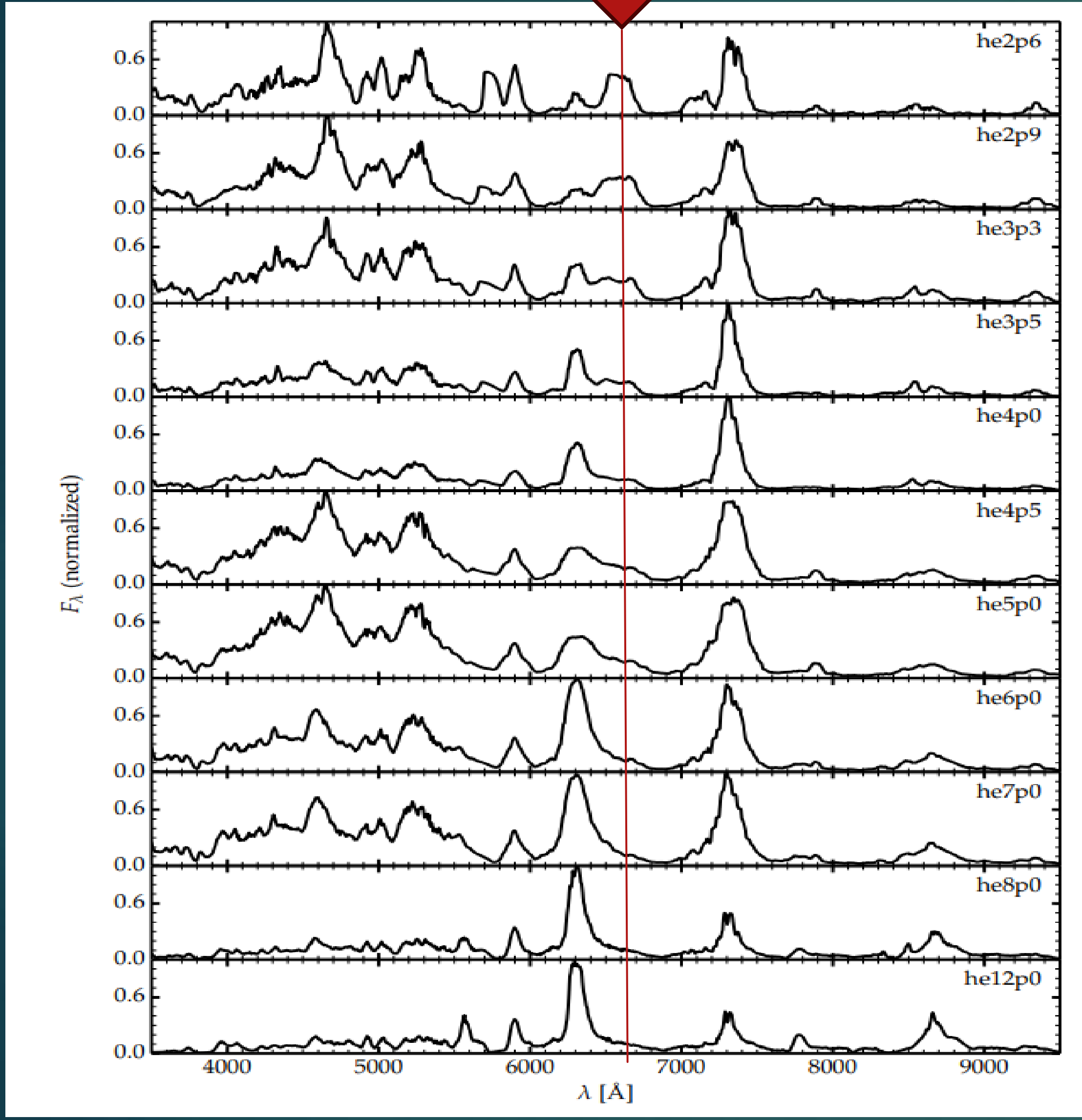


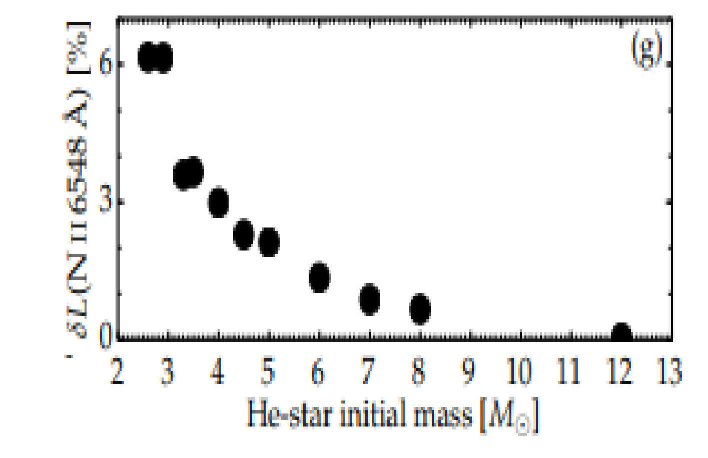
Image credit: Schofield+2022



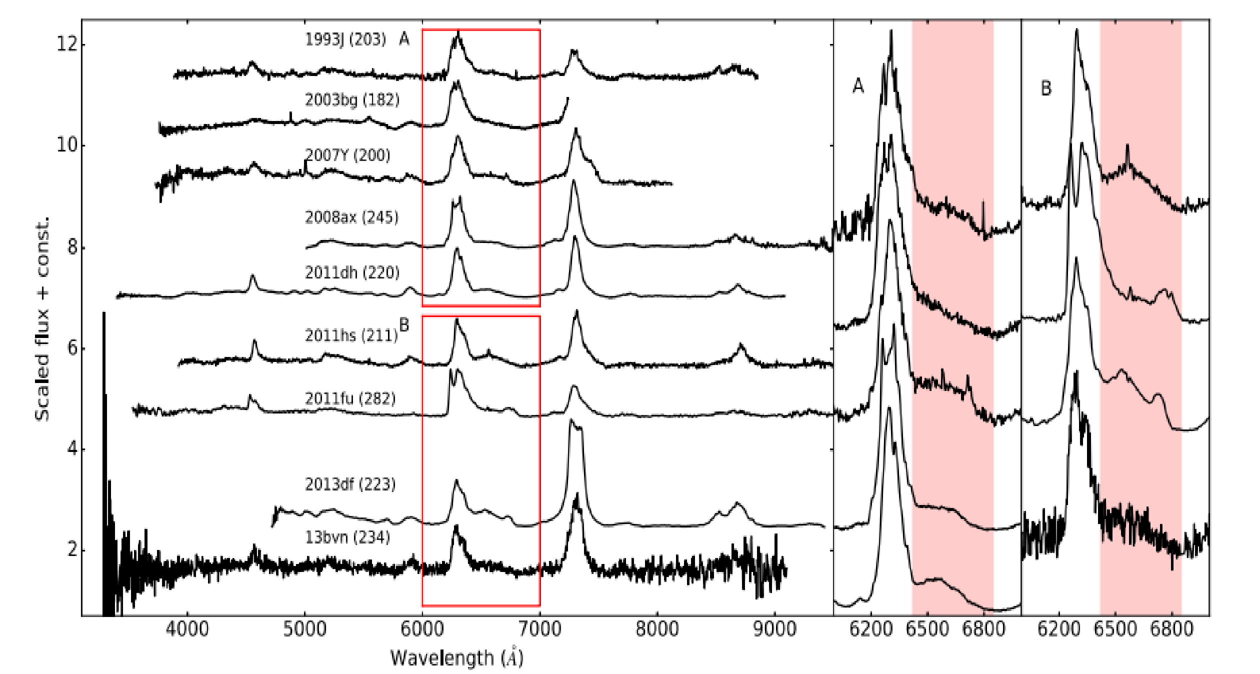
Jerkstrand +2015

Usecase: Potential As a Mass diagnostic





Dessart+2021

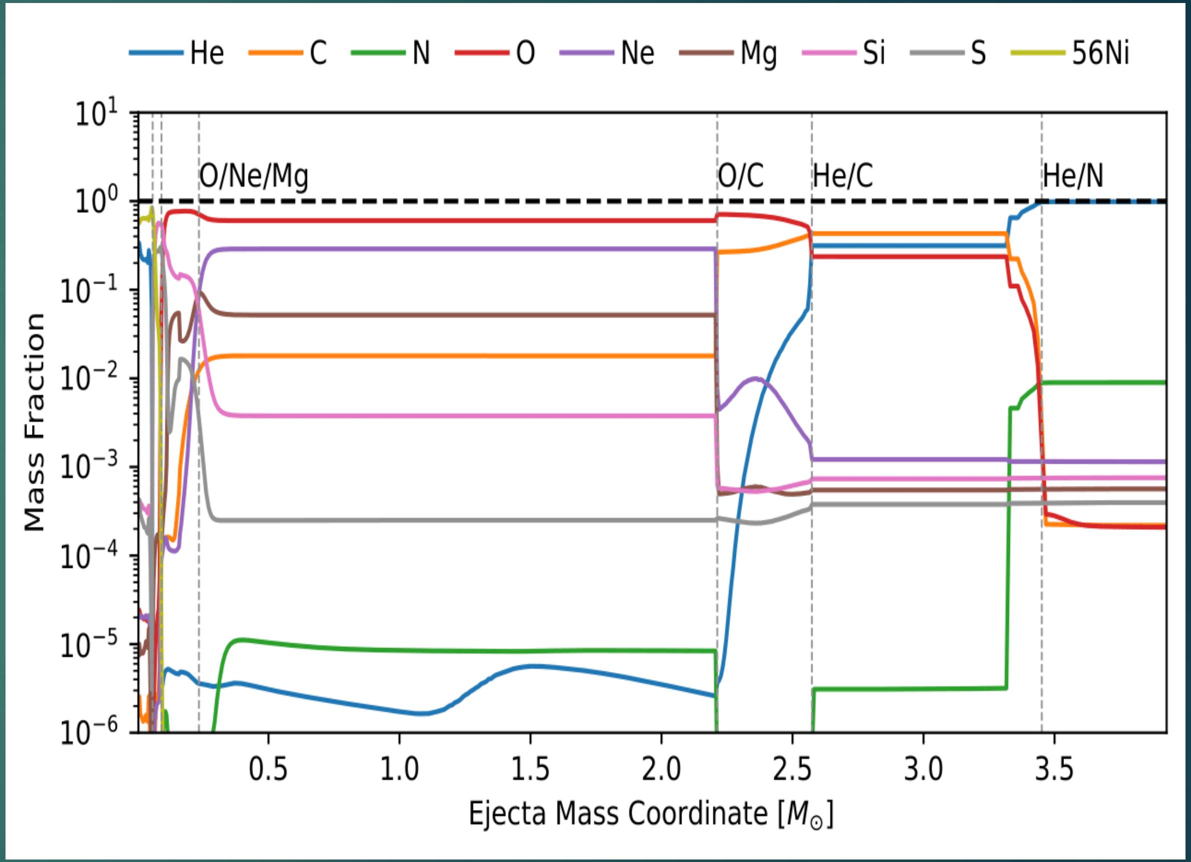


Dessart+2021

Fang & Maeda, 2018

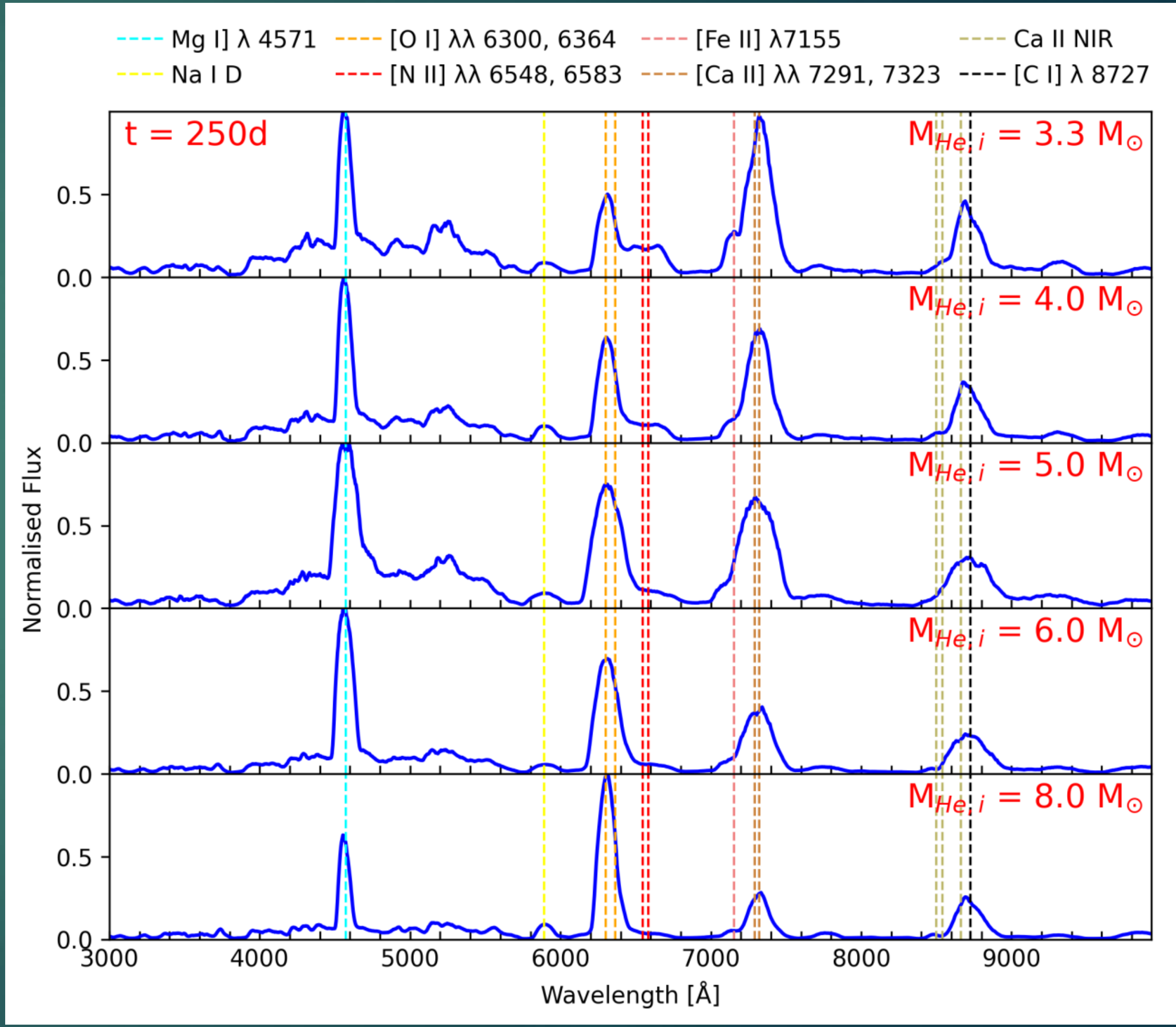
Usecase: Tracer of He/N zone

- In the current paradigm, Type Ib and Ic differ due to presence of a He-zone
- However, there has been debate on if He could be 'hidden' in spectra (He-lines hard to excite)
- The nitrogen emission directly traces the He/N zone, allowing us to further test this question



Project: Model the [N II] Emission

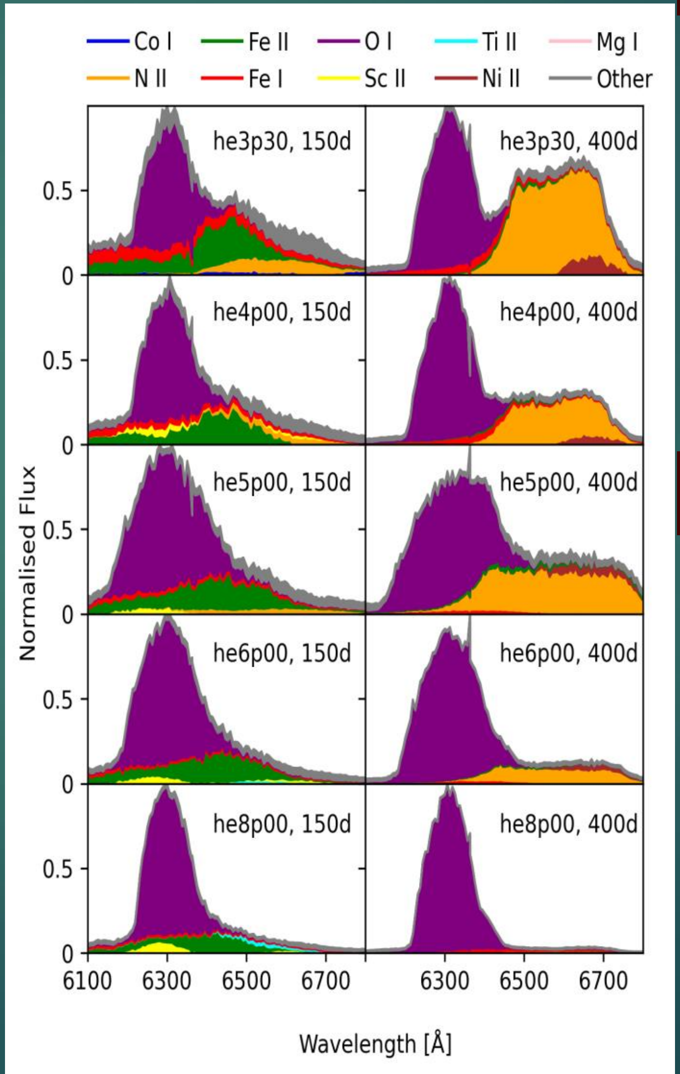
- Use as input model 5 different Helium core pregintors from Woosley+2019 and Ertl+2020 ($M_{He,i}$ Masses 3.3, 4.0, 5.0, 6.0 and 8.0 $M_\odot$)
- Evolve their spectra using SUMO NLTE code (Jerkstrand+2011)
- Track [N II] evolution through time (150-400 days)
- Compare the results to observed SNe spectra



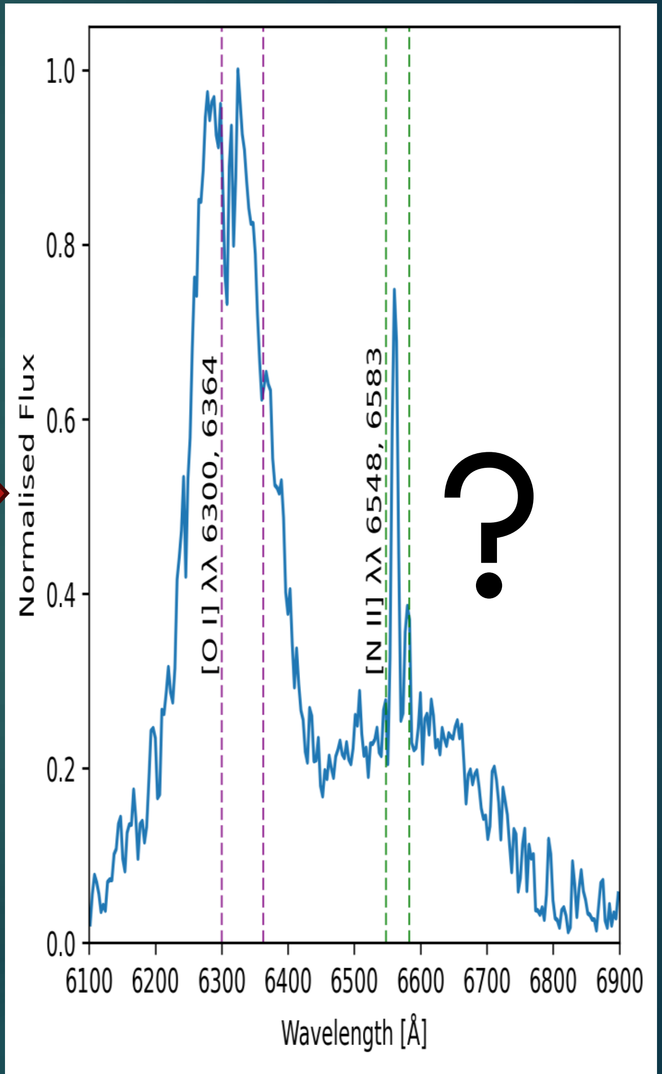
Methodology: Fitting [N II] Contribution

- [N II] is not isolated, so need to estimate its contribution
- Fit with a two-component profile, with a <u>time-consistent linewidth</u>
- Define a diagnostic, f_{NII}, as the fit [N II] contribution over total optical luminosity

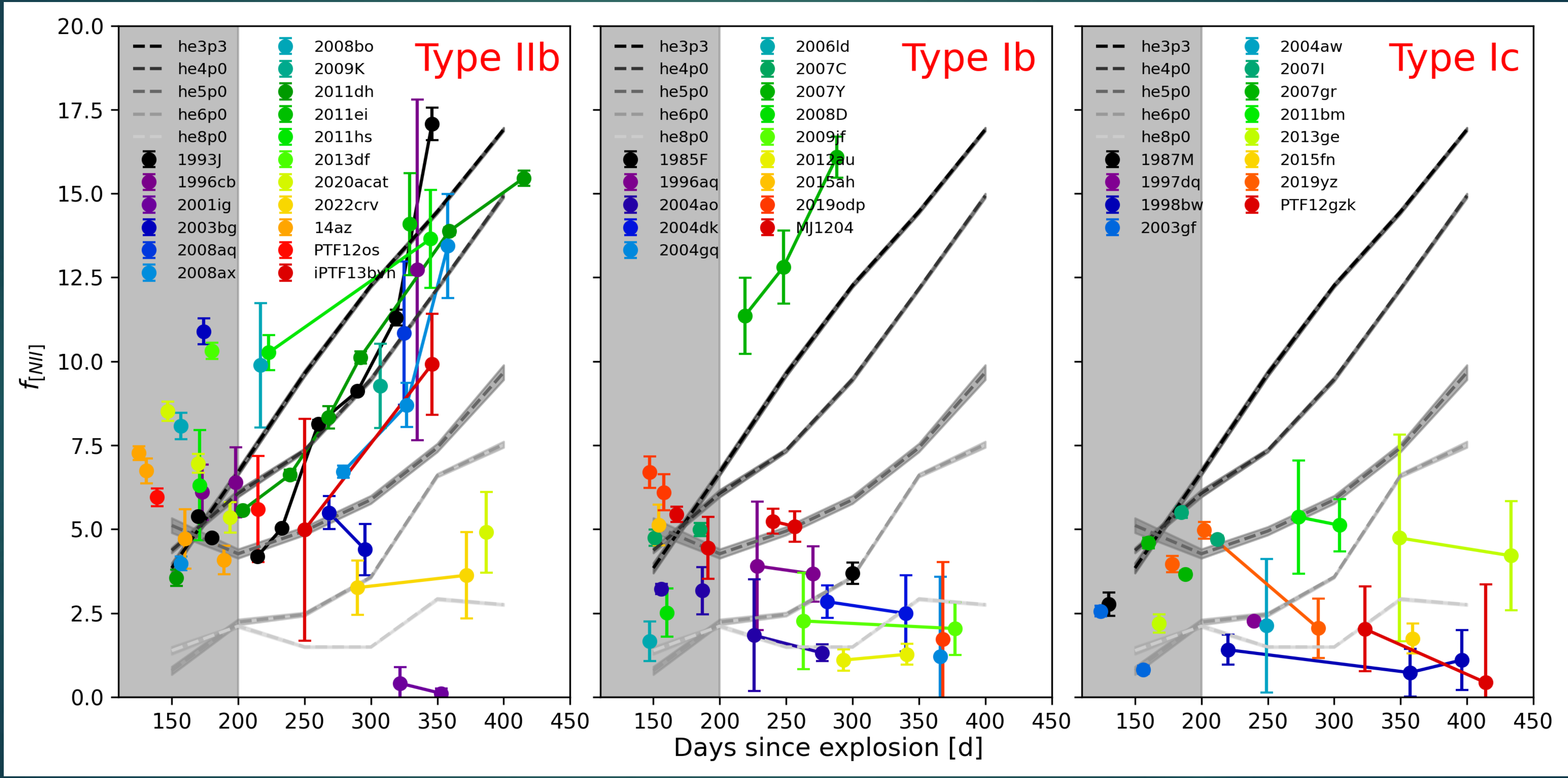
Models



Observations



Results: Models and Observations



Caveats: Mass Loss and Stellar Evolution

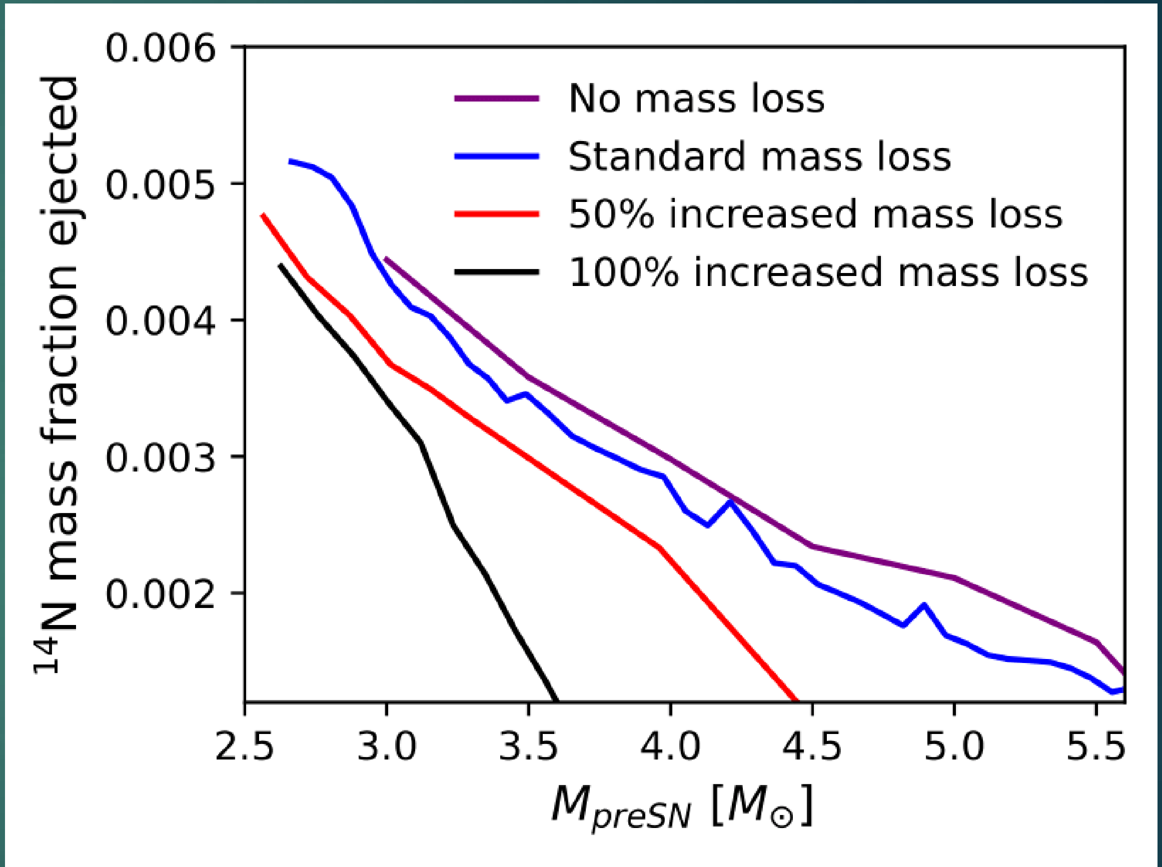
Main source of uncertainty:

- Timing and rate of mass loss is uncertain, so mapping to M_preSN is non-trivial

Also presents opportunities: constraining mass loss

Minor sources:

- Stellar Evolution
- Transition rates



Discussion: Mass and Radius

- In Type IIb, find both weak and strong [N II] emission
- For those with radii predictions, find tentative trend
- Yoon+2017 find larger radius for larger separation. However, not clear why separation would correlate to core mass

Name	Radius (Rsun)	Most Similar Model (Msun)	Radius Reference
2011hs	500	3.3	Bufano+2014
2013df	500	3.3	Van Dyk+2014
1993J	500	4.0	Maund+2004
2011dh	200	3.3-4.0	Bersten+2012
2008ax	50	4.0-5.0	Folatelli+2015
iPTF13bvn	10	4.0-5.0	Fremling+2016
2003bg	~1	6.0	Söderberg+2006
2001ig	~1	8.0	Ryder+2004
2022crv	~1	8.0	Gangopadhyay+2023

Summary

1. The strength of the nebular [N II] emission feature is anti correlated with progenitor mass
2. Using [N II] as a diagnostic, find that low-mass progenitors are overwhelmingly Type IIb, and almost no low-mass progenitors are Type Ib or Type Ic SNe
3. Find no clear proof of existence of a He/N layer in Type Ic SNe, but also can not rule out its existence
4. Find good agreement between [N II] mass estimates and literature estimates, making it a valuable new tool for SN progenitor research

Thank you for your attention!

stan.barmentloo@astro.su.se

Paper:

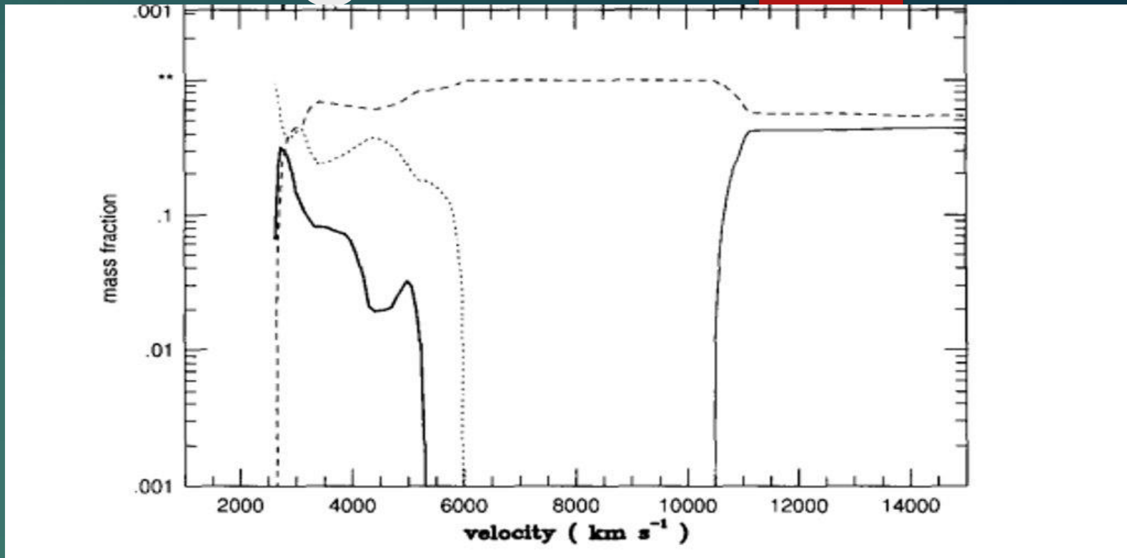
Stockholm University

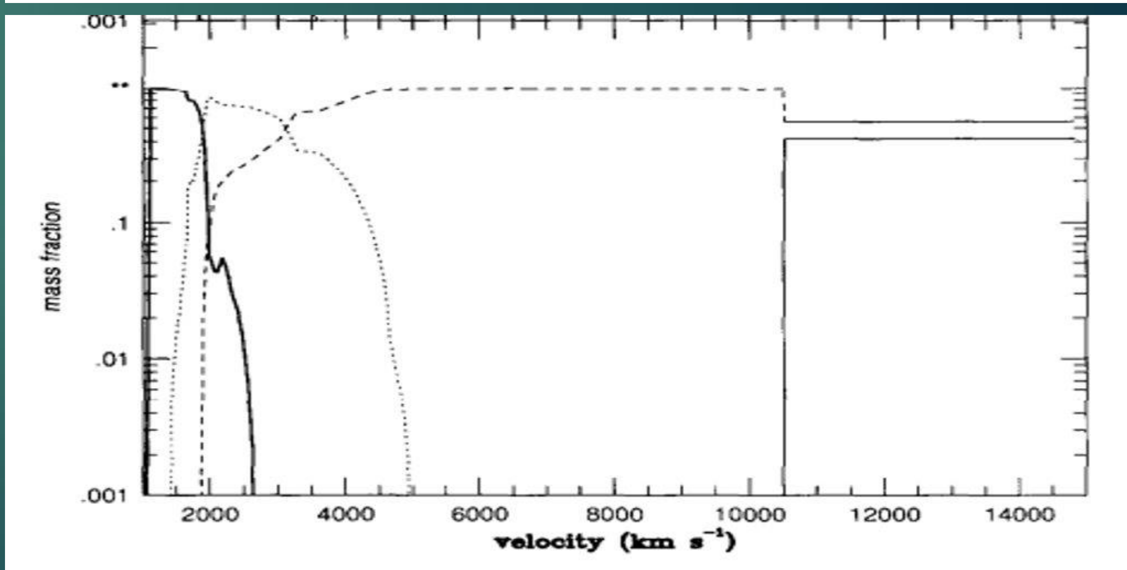
Oskar Klein centre

Image credit: Donald P. Waid

Modelling: The Effect of Mixing

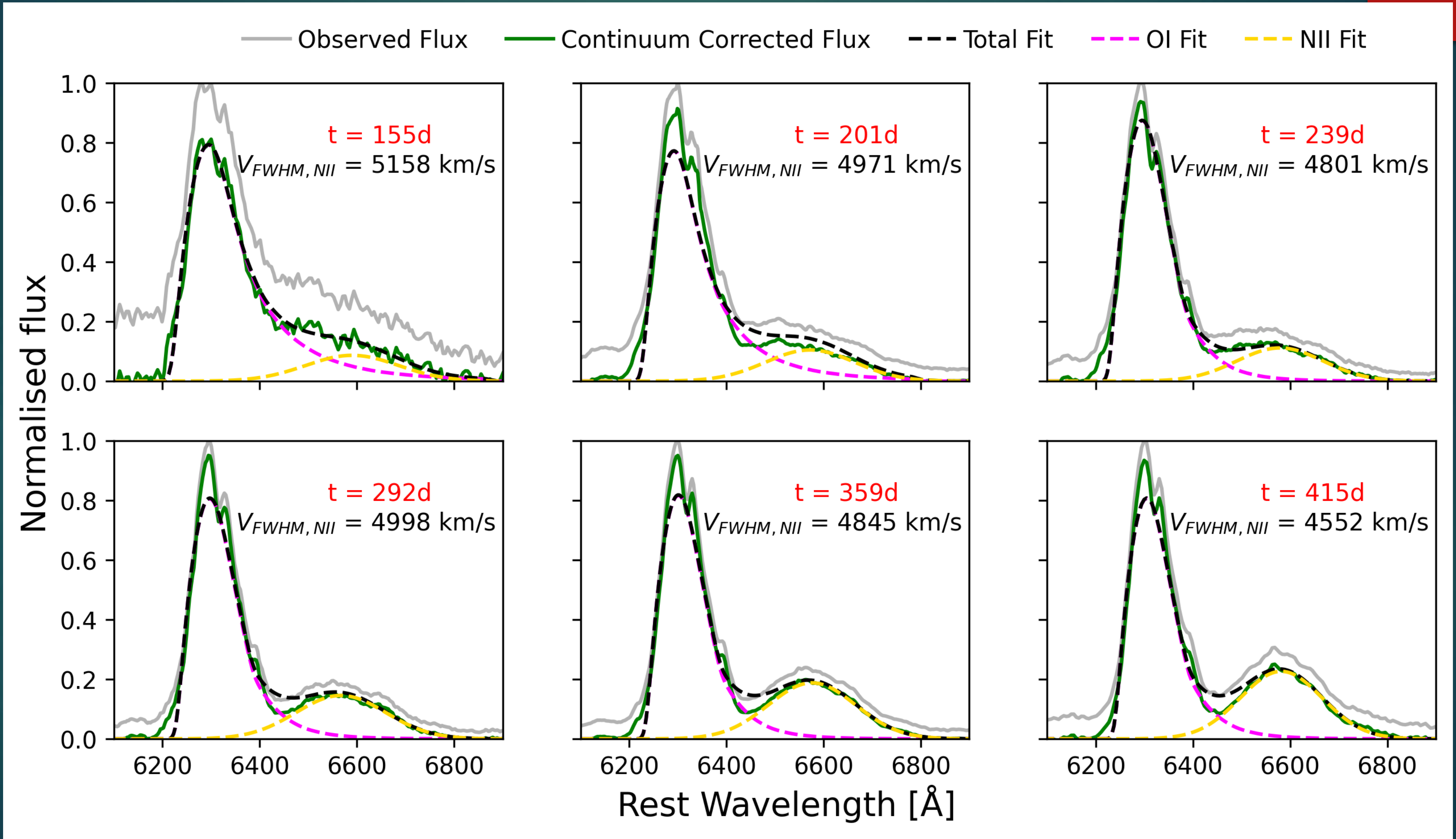
- During explosion, SN ejecta get mixed to varying degrees
- Multiple sets of 2D-simulations show that lower mass means more mixing
- More mixing leads to more Ni^{56} close to outer layer material --> stronger N II emission
- Use new modelling results (Iwamoto+2024, in prep) to determine amount of mixing per mass



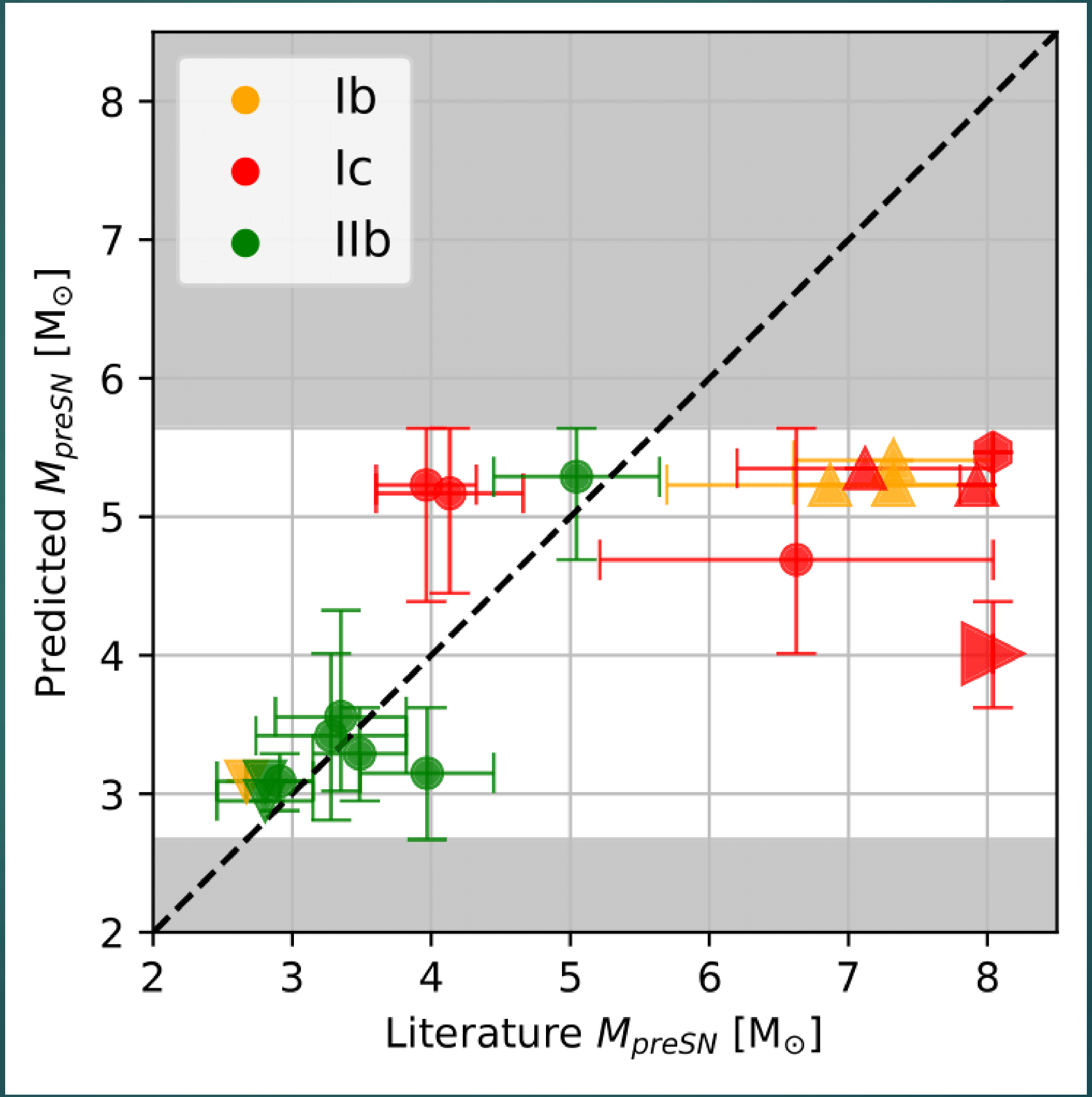


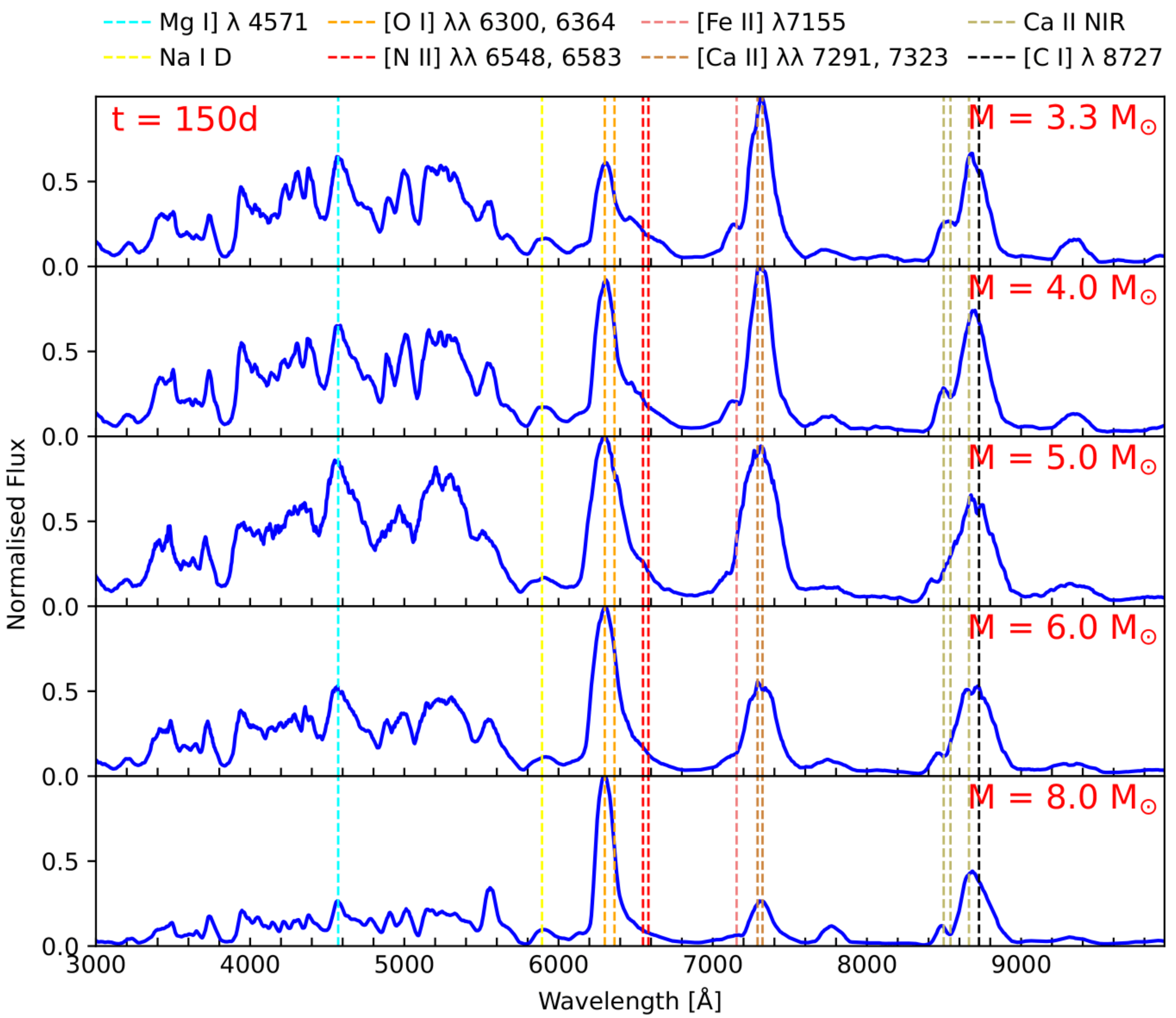
Nomoto et al., 1995

An example: 2011dh

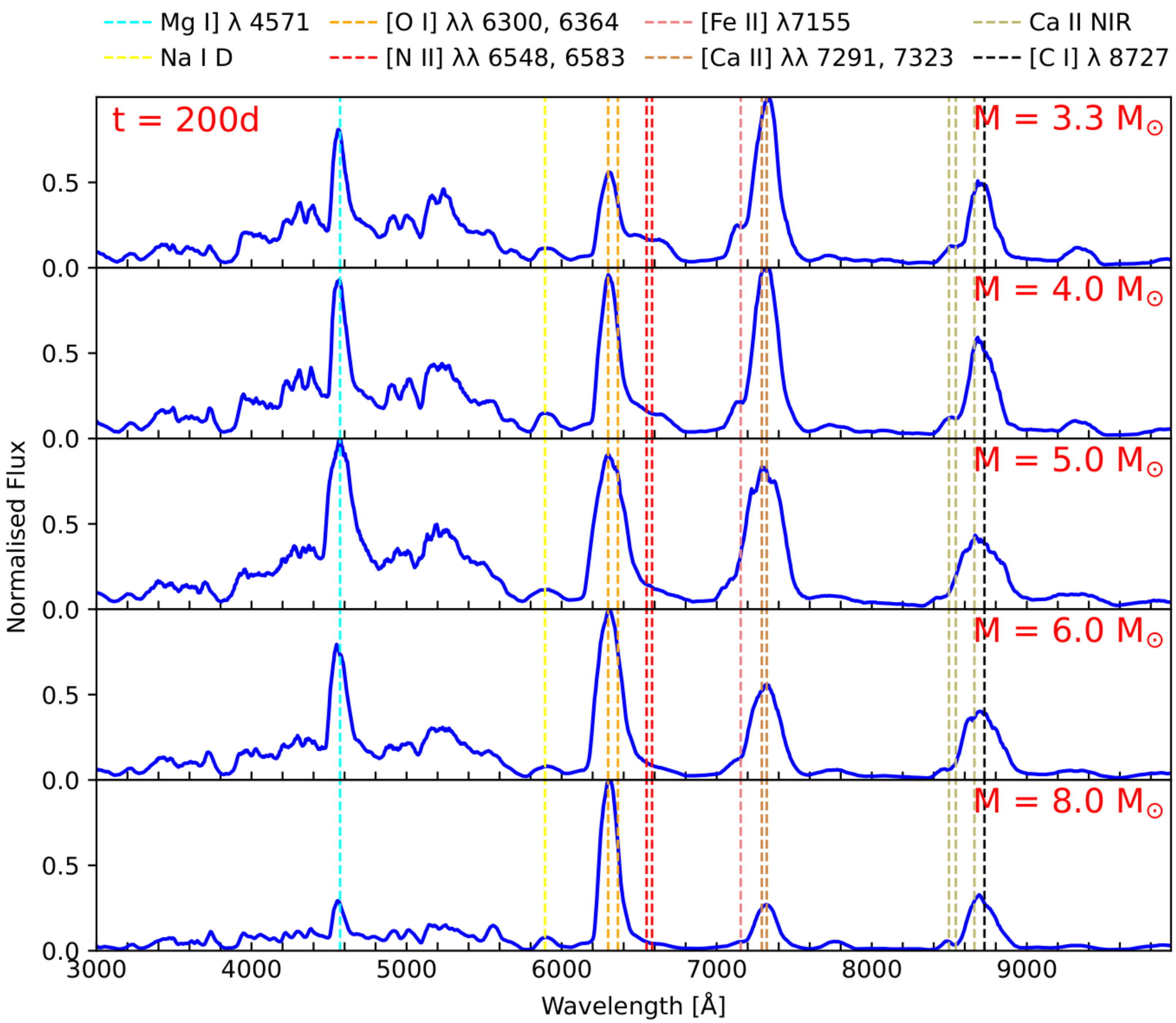


Results: Mass estimates for progenitors

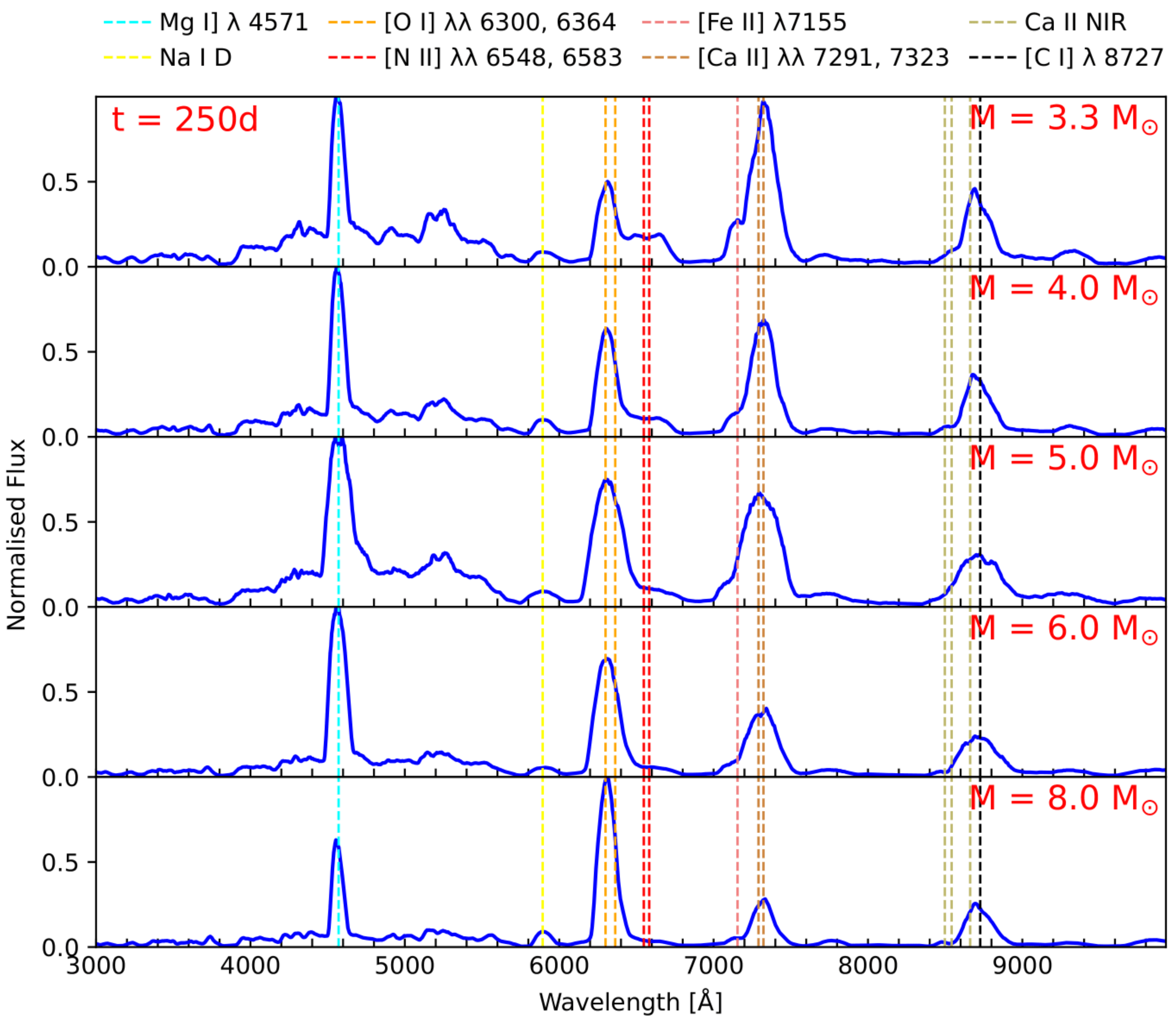




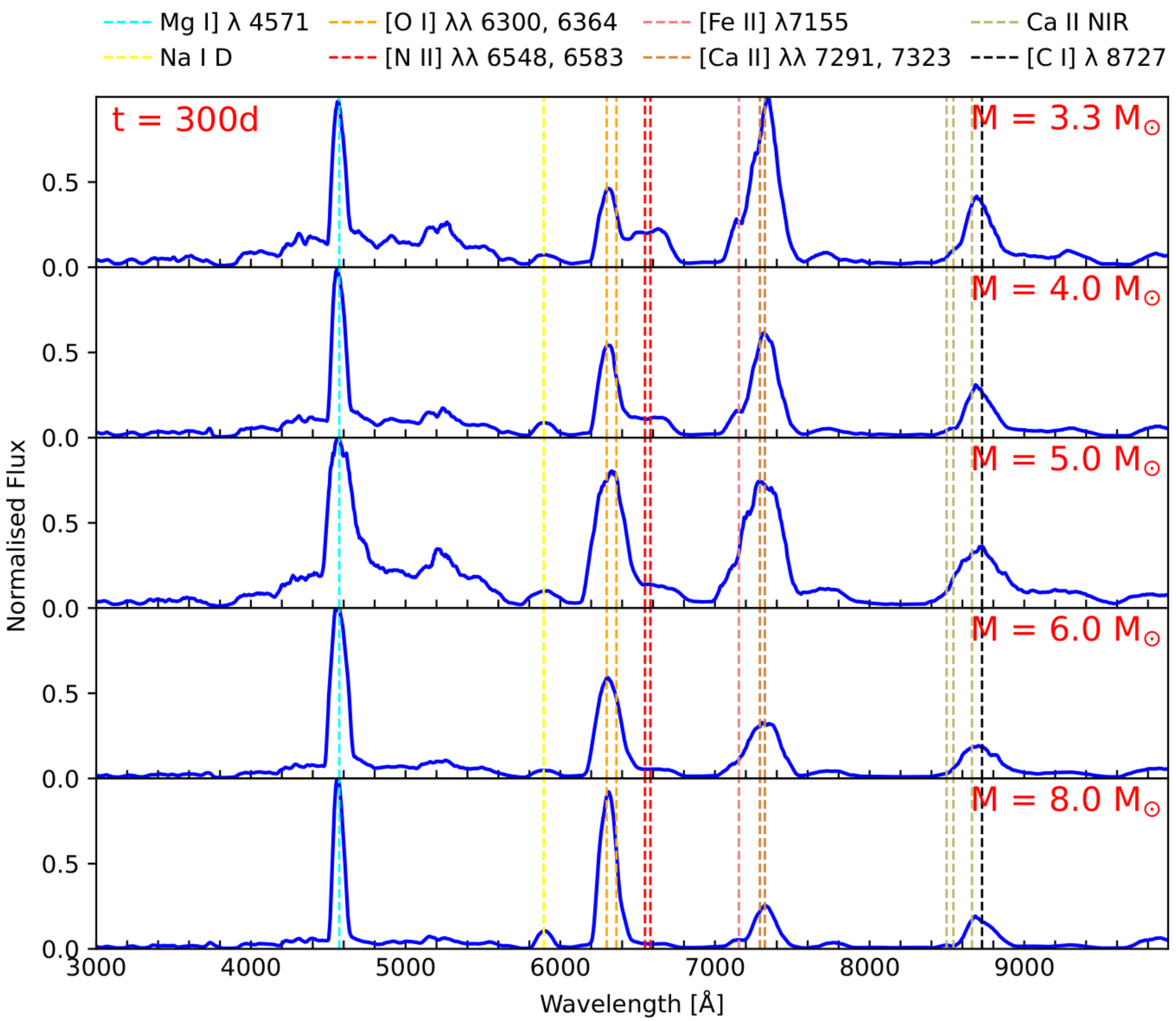
Mg I] λ 4571
[O I] λλ 6300, 6364
[Fe II] λ7155
Ca II NIR
Na I D
[N II] λλ 6548, 6583
[Ca II] λλ 7291, 7323
[C I] λ 8727
t = 150d
M = 3.3 M$_\odot$
M = 4.0 M$_\odot$
M = 5.0 M$_\odot$
M = 6.0 M$_\odot$
M = 8.0 M$_\odot$
Normalised Flux
0.0
0.5
3000
4000
5000
6000
7000
8000
9000
Wavelength [Å]

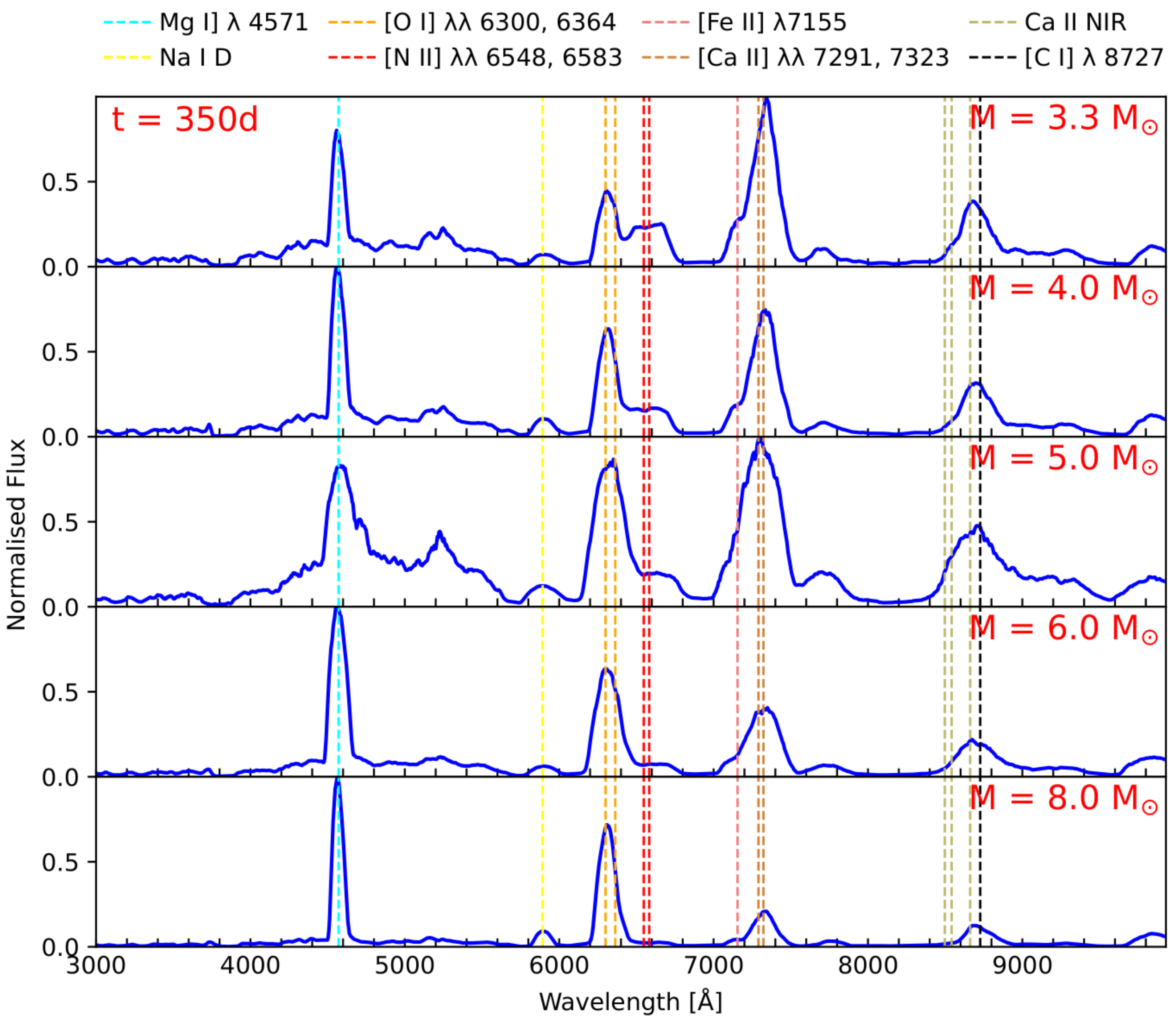


Mg I] λ 4571
Na I D
[O I] λλ 6300, 6364
[N II] λλ 6548, 6583
[Fe II] λ7155
[Ca II] λλ 7291, 7323
Ca II NIR
[C I] λ 8727
t = 200d
M = 3.3 M⊙
M = 4.0 M⊙
M = 5.0 M⊙
M = 6.0 M⊙
M = 8.0 M⊙
Normalised Flux
Wavelength [Å]

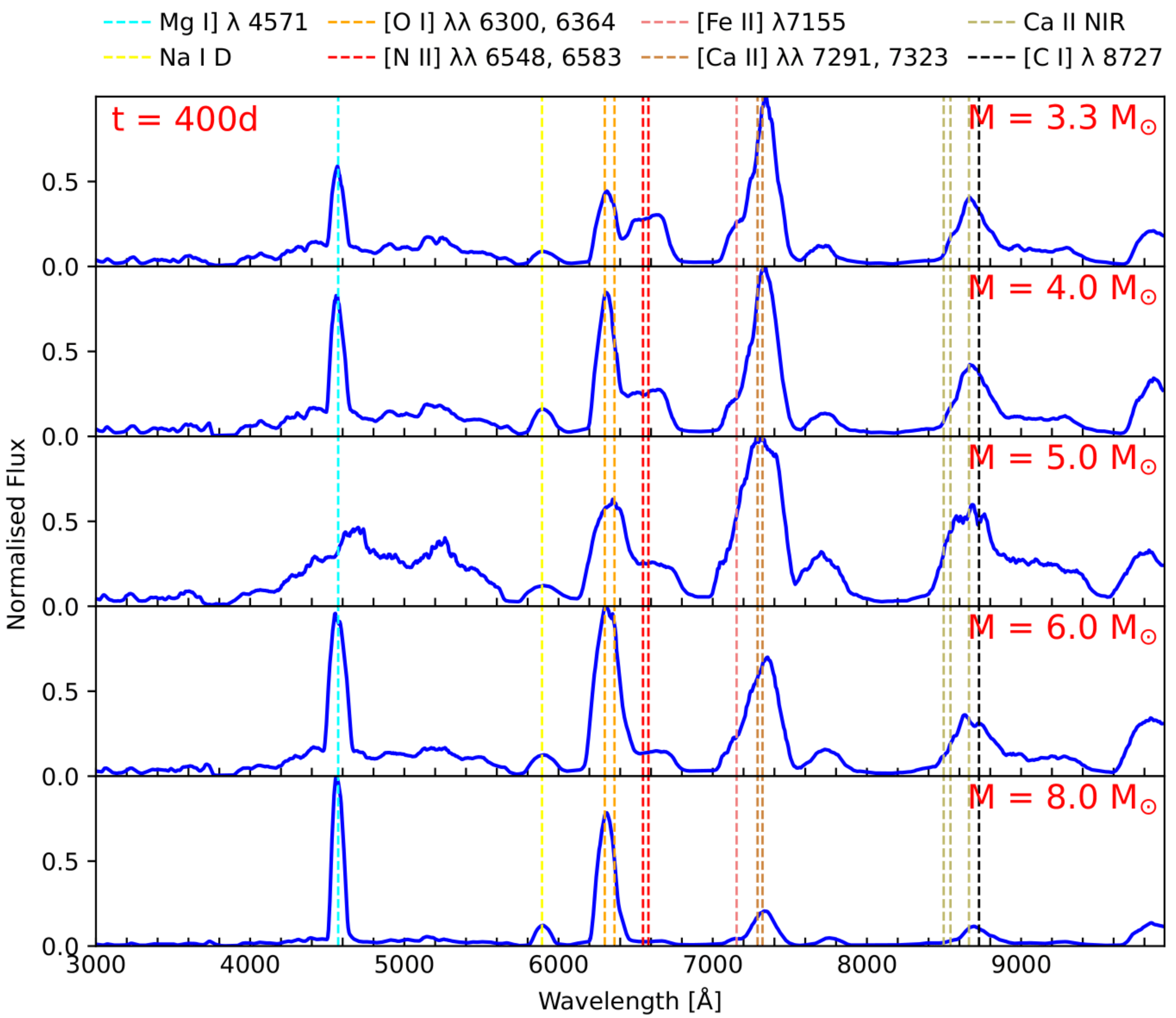


Mg I] λ 4571
Na I D
[O I] λλ 6300, 6364
[N II] λλ 6548, 6583
[Fe II] λ7155
[Ca II] λλ 7291, 7323
Ca II NIR
[C I] λ 8727
t = 250d
M = 3.3 M⊙
M = 4.0 M⊙
M = 5.0 M⊙
M = 6.0 M⊙
M = 8.0 M⊙
Normalised Flux
Wavelength [Å]


Mg I] λ 4571
Na I D
[O I] λλ 6300, 6364
[N II] λλ 6548, 6583
[Fe II] λ7155
[Ca II] λλ 7291, 7323
Ca II NIR
[C I] λ 8727
t = 300d
M = 3.3 M$_\odot$
M = 4.0 M$_\odot$
M = 5.0 M$_\odot$
M = 6.0 M$_\odot$
M = 8.0 M$_\odot$
Normalised Flux
Wavelength [Å]
0.0
0.5
3000
4000
5000
6000
7000
8000
9000



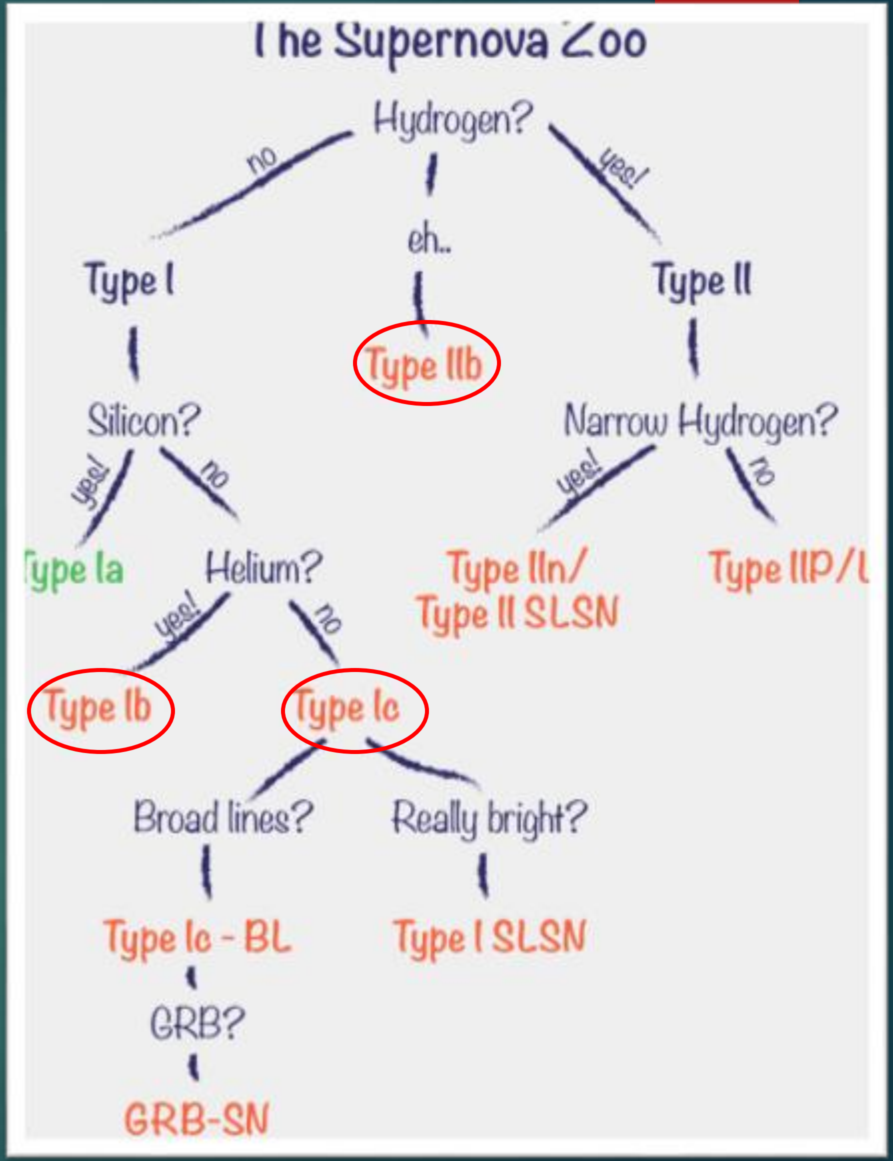
Mg I] λ 4571
Na I D
[O I] λλ 6300, 6364
[N II] λλ 6548, 6583
[Fe II] λ7155
[Ca II] λλ 7291, 7323
Ca II NIR
[C I] λ 8727
t = 350d
M = 3.3 M⊙
M = 4.0 M⊙
M = 5.0 M⊙
M = 6.0 M⊙
M = 8.0 M⊙
Normalised Flux
Wavelength [Å]
0.0
0.5
3000
4000
5000
6000
7000
8000
9000



Mg I] λ 4571
Na I D
[O I] λλ 6300, 6364
[N II] λλ 6548, 6583
[Fe II] λ7155
[Ca II] λλ 7291, 7323
Ca II NIR
[C I] λ 8727
t = 400d
M = 3.3 M⊙
M = 4.0 M⊙
M = 5.0 M⊙
M = 6.0 M⊙
M = 8.0 M⊙
Normalised Flux
Wavelength [Å]

Stripped Envelope Supernovae

- Caused by massive (8 – 11 $M_{\odot}$) stars which used up all fusion fuel, leading to core collapse
- Many combinations of lightcurve + spectral evolution, giving rise to many different types
- Most of the time no image of progenitor
- Determining Ejecta mass from Lightcurve modelling is degenerate with explosion energy and opacity



- Why is it not Halpha? 1 Not the same profile if CSM 2 Fine tuning of obs reproducing models via other channel 3 If not CSM simply too little emission (J15)
- Why do we need another diagnostic than O I? --> 1 can combine with O I for less errors 2 May be useful tool for constraining mass loss, as it comes from outer He/N zone, e.g. measure O I mass and N II mass, if it differs mass loss. 3 Molecules in O/C create uncertainty. 4 O I is absolute, this is a ratio,avoids extinction etc.