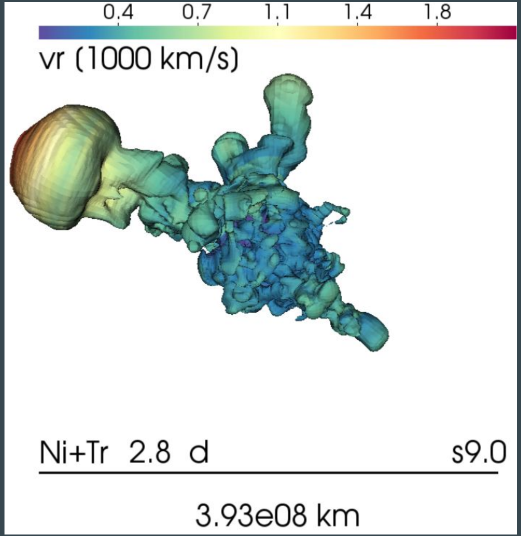
3D NLTE Spectral Modelling of Low-Luminosity Type IIP SNe in the Nebular Phase

Bart van Baal

Collaborators

Anders Jerkstrand   Daniel Kresse
Thomas Janka   Annop Wongwathanarat



Credit: Stockinger+2020

02/04 - An Extraordinary Journey into the Transient Sky

What are LLIIP SNe

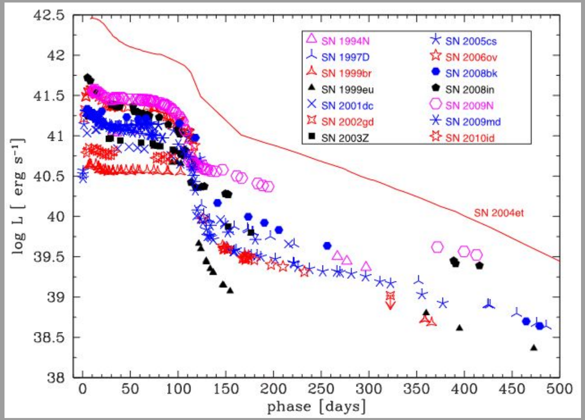
SN 1997D (Turatto++1998)
prototypical first SN

Type IIP SNe with low peak luminosity

$M_{r,peak} \geqslant -16$ (Das++2025)

Short plateau phase ~100 days

(Spiro+2014)

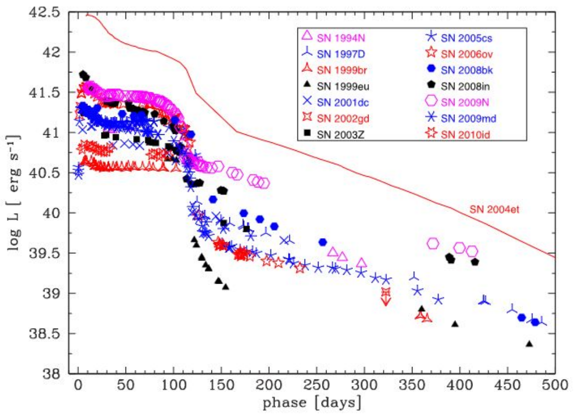


What are LLIIP SNe

SN 1997D (Turatto++1998)
prototypical first SN

Type IIP SNe with low peak luminosity

(Spiro+2014)



$M_{r,peak} \geqslant -16$ (Das++2025)

Short plateau phase ~100 days

Low estimates for ^{56}Ni masses

Roughly $0.005\ M_\odot \leqslant M_{Ni} \leqslant 0.01\ M_\odot$; typical IIP SNe ~ $0.1\ M_\odot$

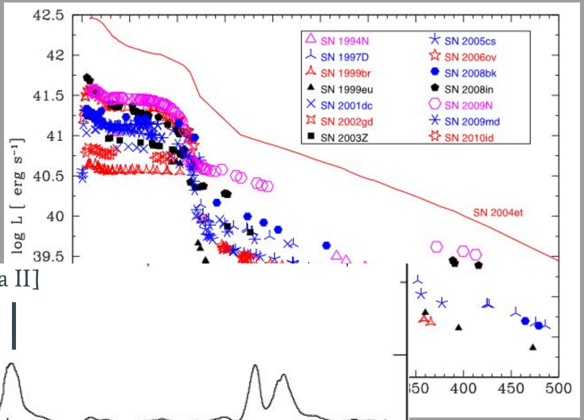
What are LLIIP SNe

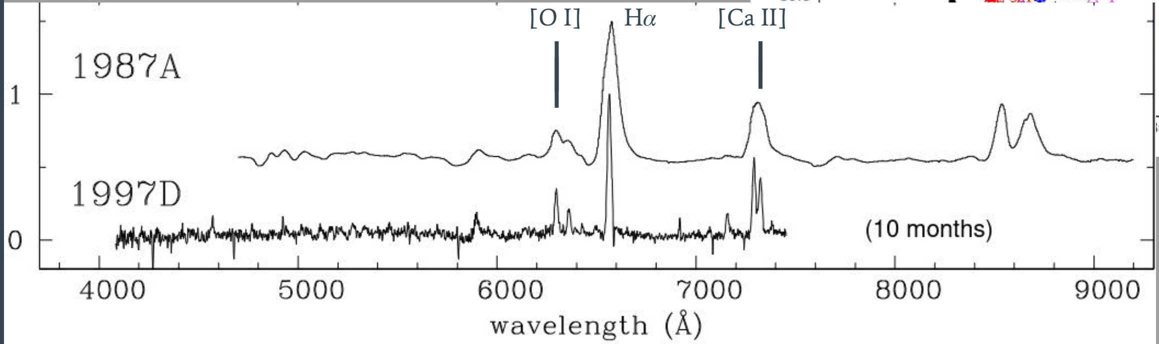
Type IIP SNe with low peak luminosity

(Spiro+2014)

$M_{r,peak} \geqslant -16$ (Das++2025)

Short plateau phase ~100 days





$0.1\ M_\odot$

SN 1997D (Turatto++1998)
prototypical first SN

Low explosion energies and expansion velocities
Rare class containing ~few dozen objects

Origin of LLIIP SNe

Progenitor Mass

Origin of these SNe debated from day 1

Initial confusion about progenitor mass for SN 1997D
either low mass progenitors (e.g. Chugai&Utrobin 2000; 8-12 M_{ZAMS})
or massive ones with fallback (e.g. Zampieri++2003; 25-30 M_{ZAMS})

Origin of LLIIP SNe

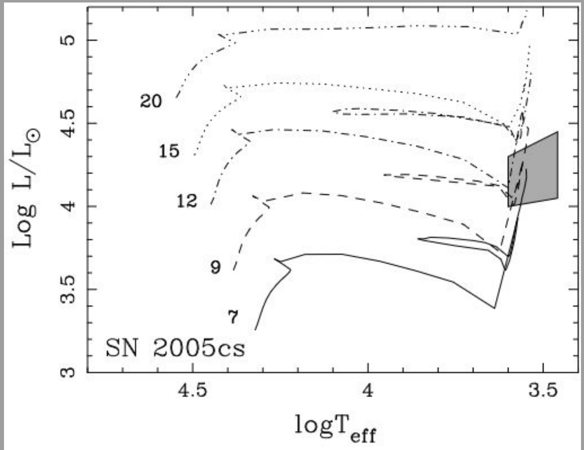
Progenitor Mass

Origin of these SNe debated from day 1

Initial confusion about progenitor mass for SN 1997D
either low mass progenitors (e.g. Chugai&Utrobin 2000; 8-12 M_{ZAMS})
or massive ones with fallback (e.g. Zampieri++2003; 25-30 M_{ZAMS})

Progenitor images for later LLIIP SNe settled the debate

SN 2005cs (Maund++2005)
$7\,M_\odot \leqslant M_{ZAMS} \leqslant 12\,M_\odot$



Origin of LLIIP SNe

Progenitor Mass

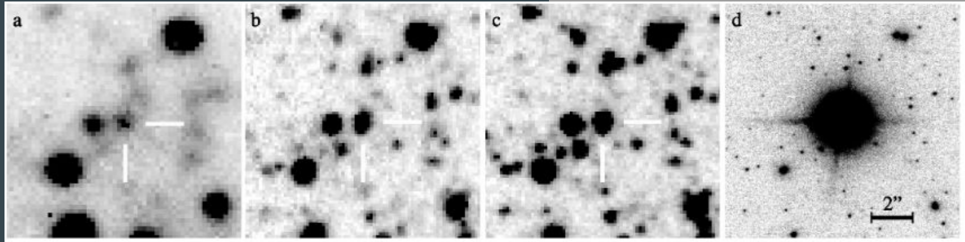
Origin of these SNe debated from day 1

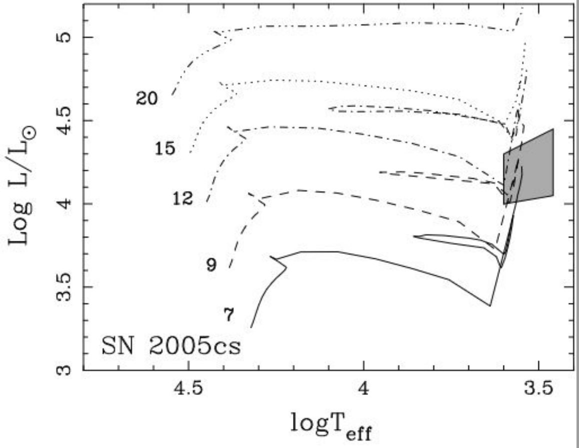
Initial confusion about progenitor mass for SN 1997D
either low mass progenitors (e.g. Chugai&Utrobin 2000; 8-12 M_{ZAMS})
or massive ones with fallback (e.g. Zampieri++2003; 25-30 M_{ZAMS})

Progenitor images for later LLIIP SNe settled the debate

SN 2005cs (Maund++2005)
$7\,M_\odot \leqslant M_{ZAMS} \leqslant 12\,M_\odot$

SN 2008bk (Mattila++2008)
$M_{ZAMS} = 8.5 \pm 1\,M_\odot$





Origin of LLIIP SNe

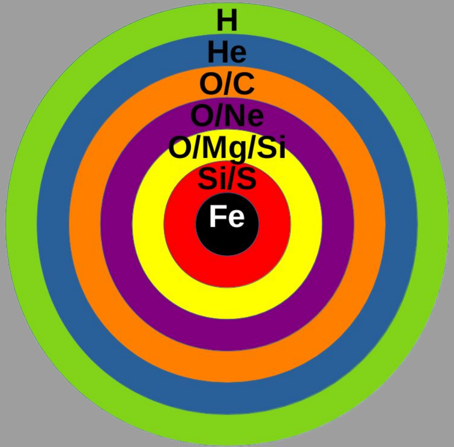
Explosion Mechanism

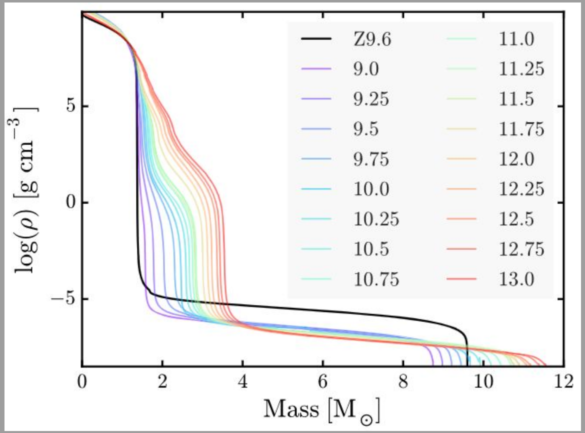
Fe-core or ONeMg-core

How do these 8 – 12 M_{ZAMS} stars explode?

Fe-core collapse?

Peculiar density structure makes these stars ‘simple’ to explode (even in 1D!)





(Sukhbold+2016)

Origin of LLIIP SNe

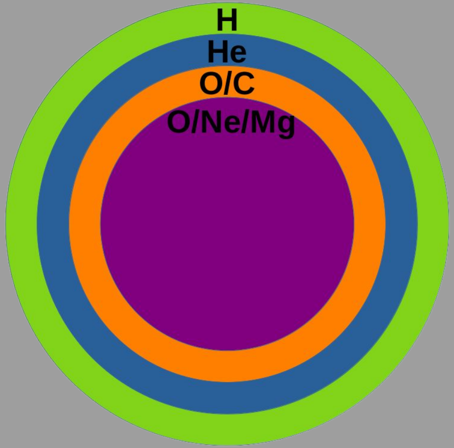
Explosion Mechanism

Fe-core or ONeMg-core

How do these 8 – 12 M_{ZAMS} stars explode?

~~Fe-core collapse~~?

Upon finishing C-burning, electron captures eat away at pressure support for the core

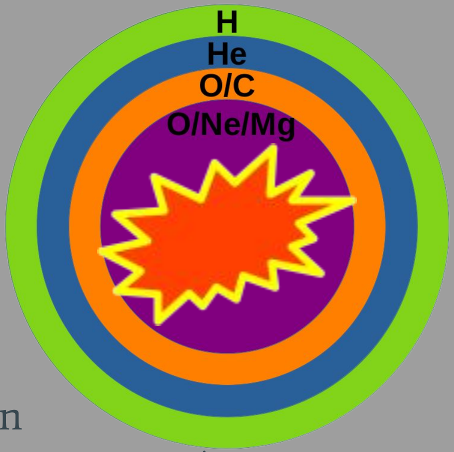


Origin of LLIIP SNe

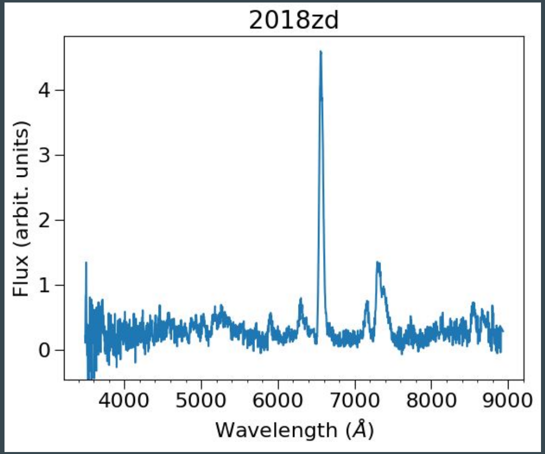
How do these 8 – 12 M_{ZAMS} stars explode?

~~Fe-core collapse~~?

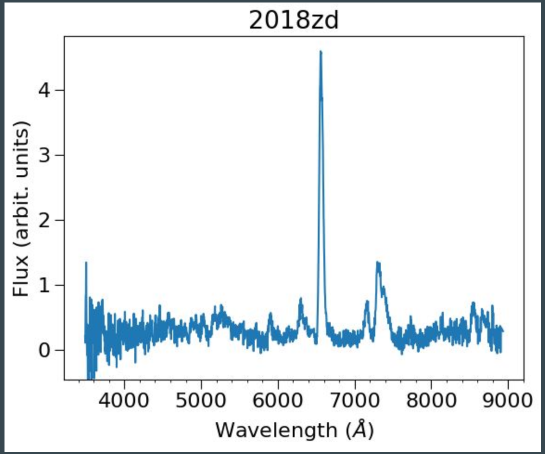
Upon finishing C-burning, electron captures eat away at pressure support for the core



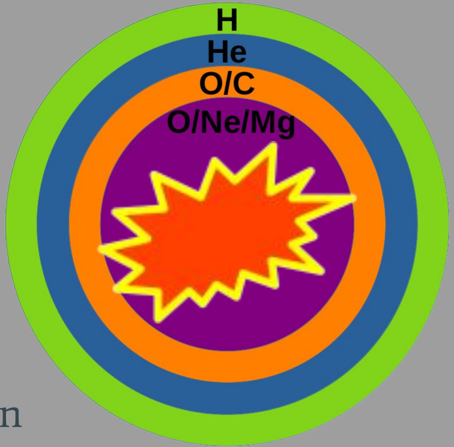
'Electron Capture' SN
No true unambiguous detection
SN 2018zd best candidate (Hiramatsu++21)



Origin of LLIIP SNe



How do these 8 – 12 M_{ZAMS} stars explode?



~~Fe-core collapse~~?

Upon finishing C-burning, electron captures eat away at pressure support for the core

'Electron Capture' SN
No true unambiguous detection
SN 2018zd best candidate (Hiramatsu++21)

ECSNe have unique nucleosynthesis yields

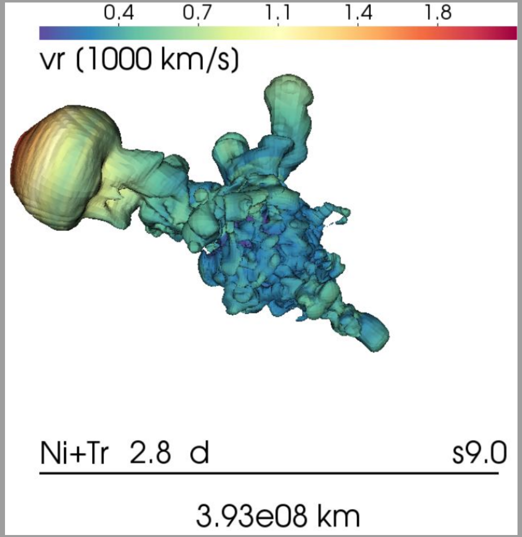
Lack of lines in nebular spectra; Fe/S/Si/Mg weak or absent

LLIIP in 3D

Fe-CCSN model

Cannot test mixing or asymmetries in 1D models

S9.0 model: a 9.0 $M_\odot$ progenitor, evolved for ~20 days post-explosion



Exploded in Prometheus-VERTEX (Melson++2020)

Long-time simulation in P-HotB (Stockinger++2020)

LLIIP in 3D

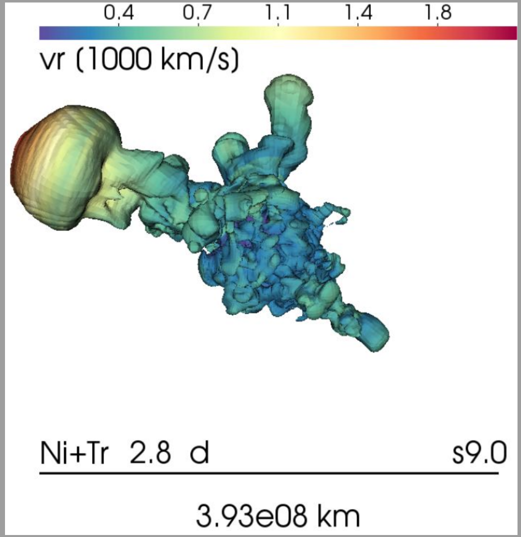
ExTraSS

Fe-CCSN model

Forward to nebular phase

Cannot test mixing or asymmetries in 1D models

S9.0 model: a 9.0 $M_\odot$ progenitor, evolved for ~20 days post-explosion



Exploded in Prometheus-VERTEX (Melson++2020)

Long-time simulation in P-HotB (Stockinger++2020)

Forward it to 400 days by homologeous expansion (v=r/t) with ExTraSS

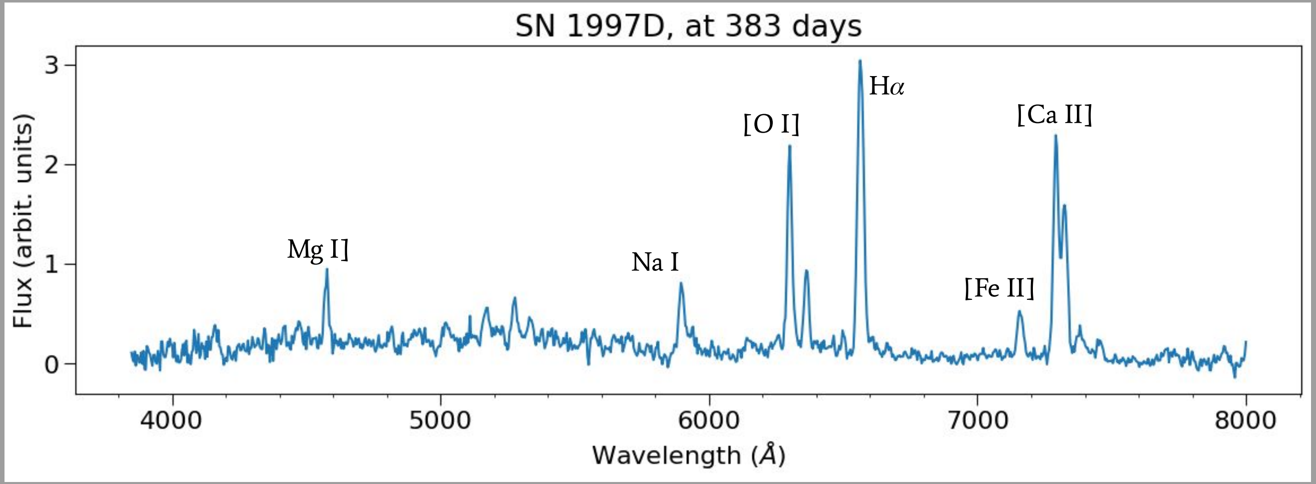
EXplosive TRAnsient Spectral Simulator (Van Baal++2023,2024)

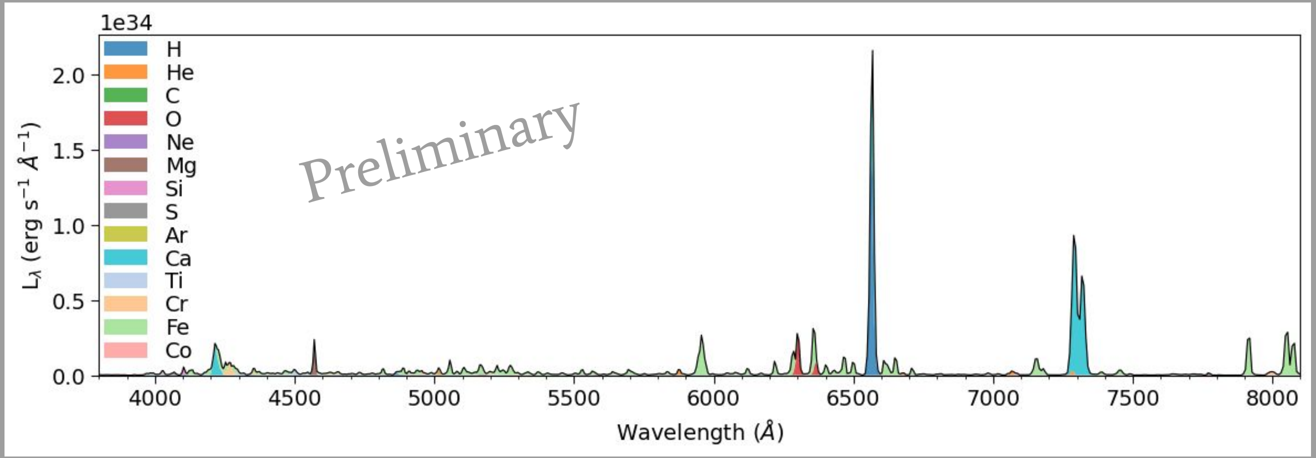
3D NLTE Radiative Transfer code

Preliminary Results

ExTraSS

3D NLTE
Radiative Transfer

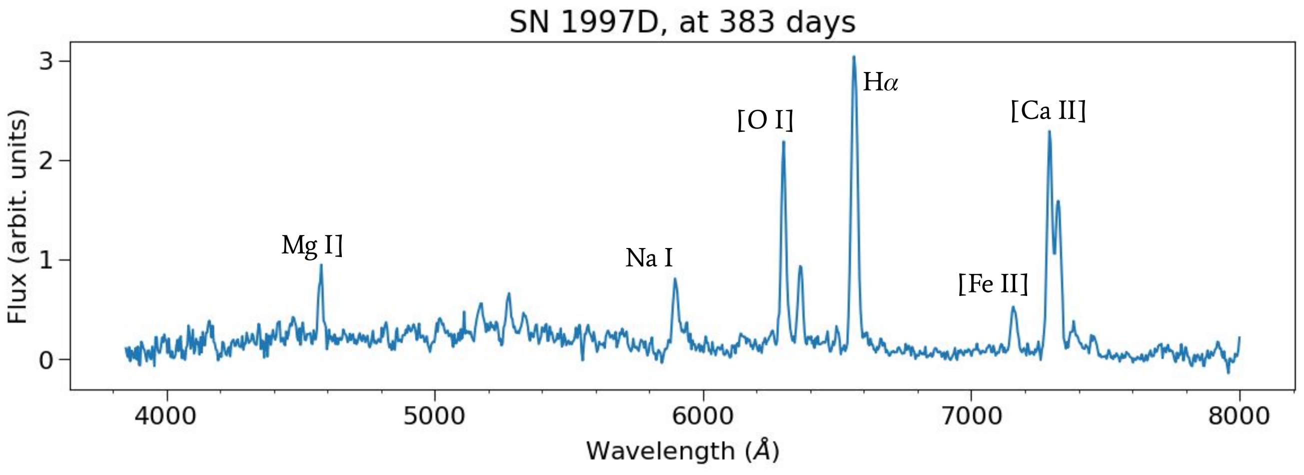


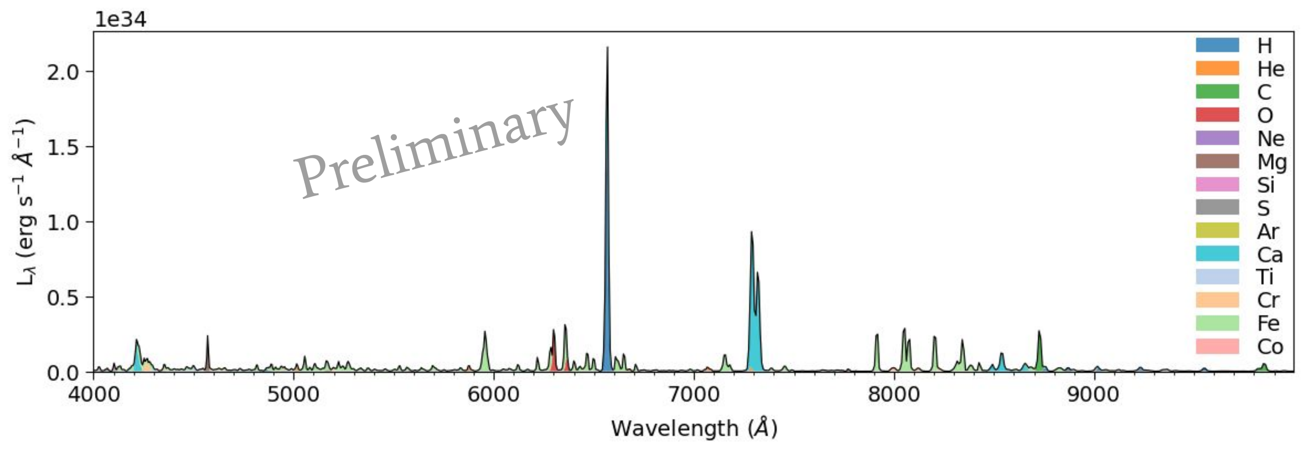


Preliminary Results

ExTraSS

3D NLTE
Radiative Transfer



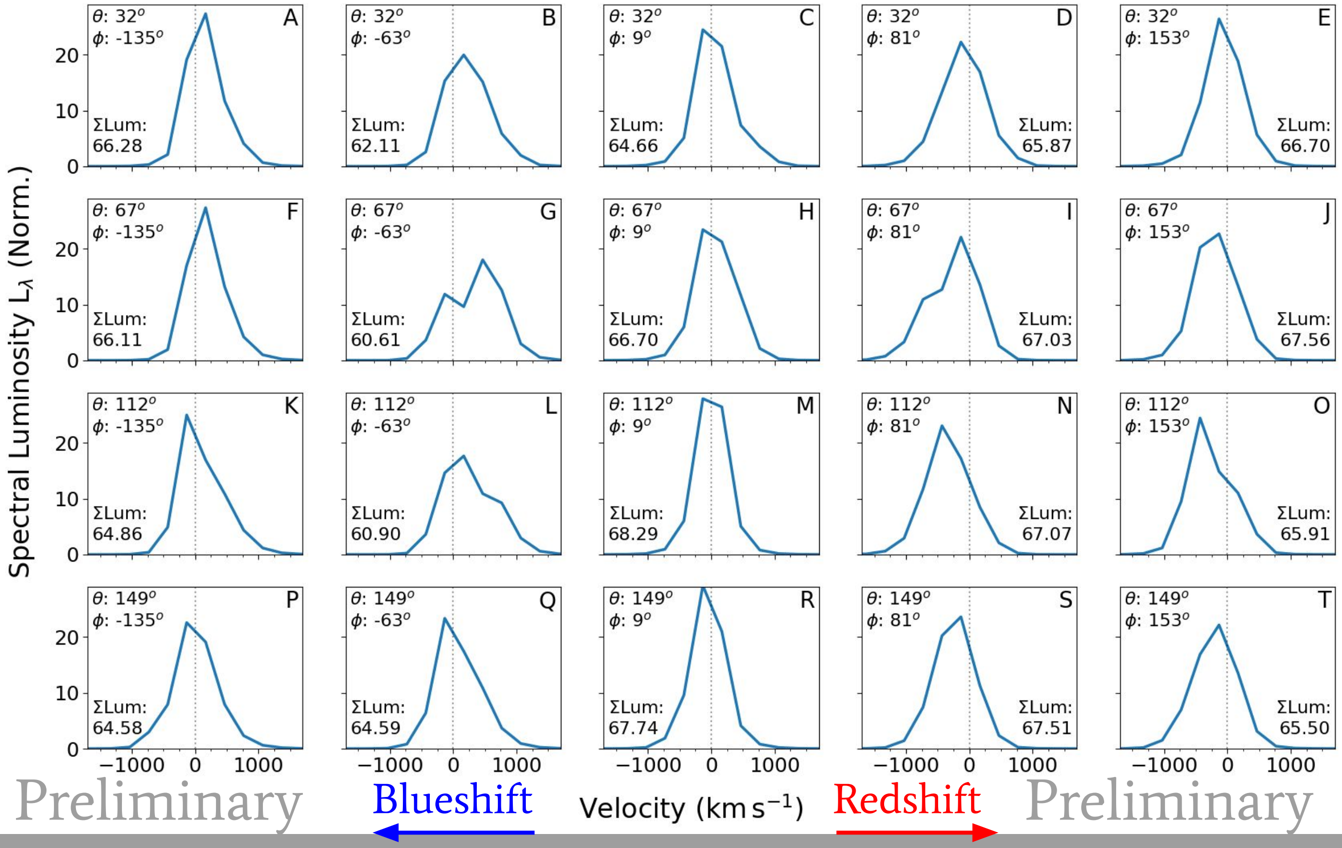


Preliminary Results

ExTraSS

3D NLTE Radiative Transfer

Hα viewing angle impacts



Summary & Outlook

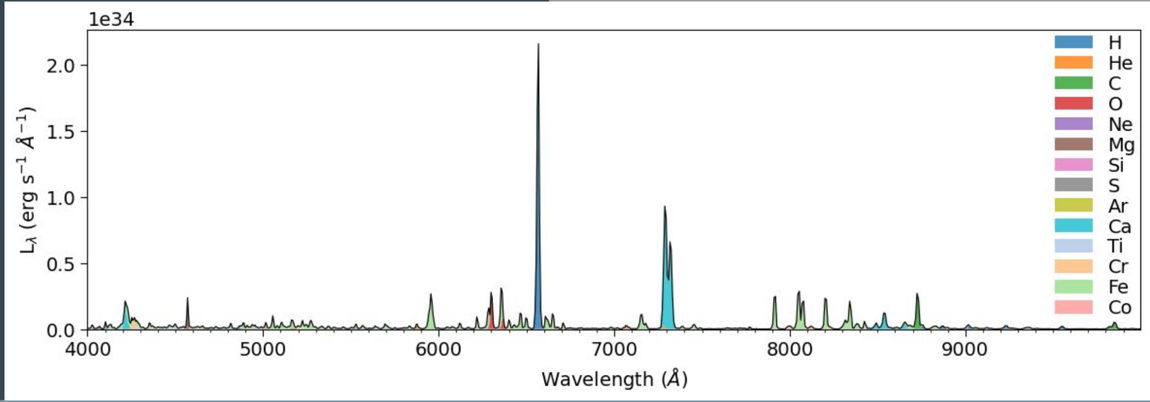
Created 3D NLTE Radiative Transfer code (ExTraSS)

Applied to 9.0 $M_{\odot}$ progenitor, Fe-CCSN at 400 days

Preliminary spectral investigation & viewing angle effects

Identify differences to 1D and particular spectral signatures to differentiate between ECSNe and CCSNe

Future plans include:



More models

More detailed physics

Different Transients

(kilonovae, in progress)