Estimates for the nebular emission from r-process elements

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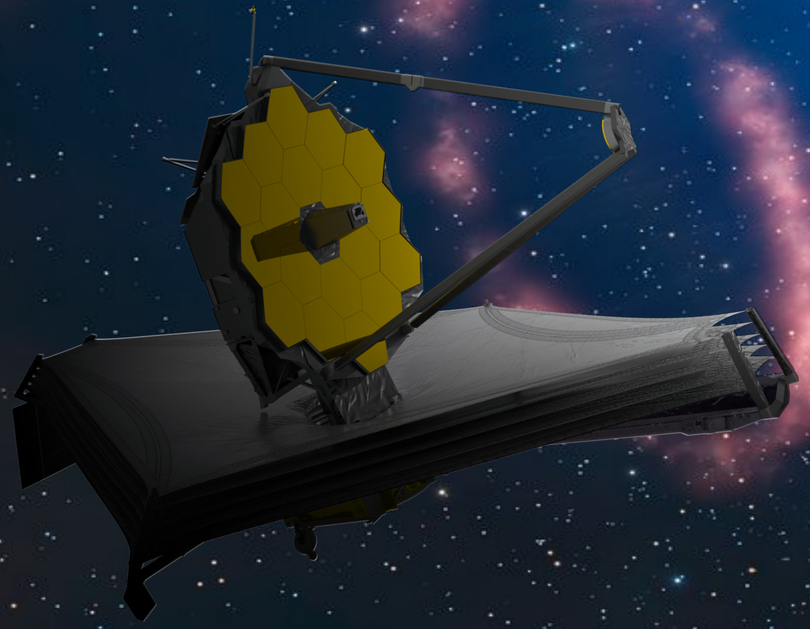
Collaborators:
Kenta Hotokezaka
Almudena Arcones

sirEN Conference

10/06/2025 - Giulianova

TECHNISCHE
UNIVERSITÄT
DARMSTADT



Searching for r-process in GRB Supernovae

Ricigliano, Hotokezaka & Arcones

2025, submitted to MNRAS

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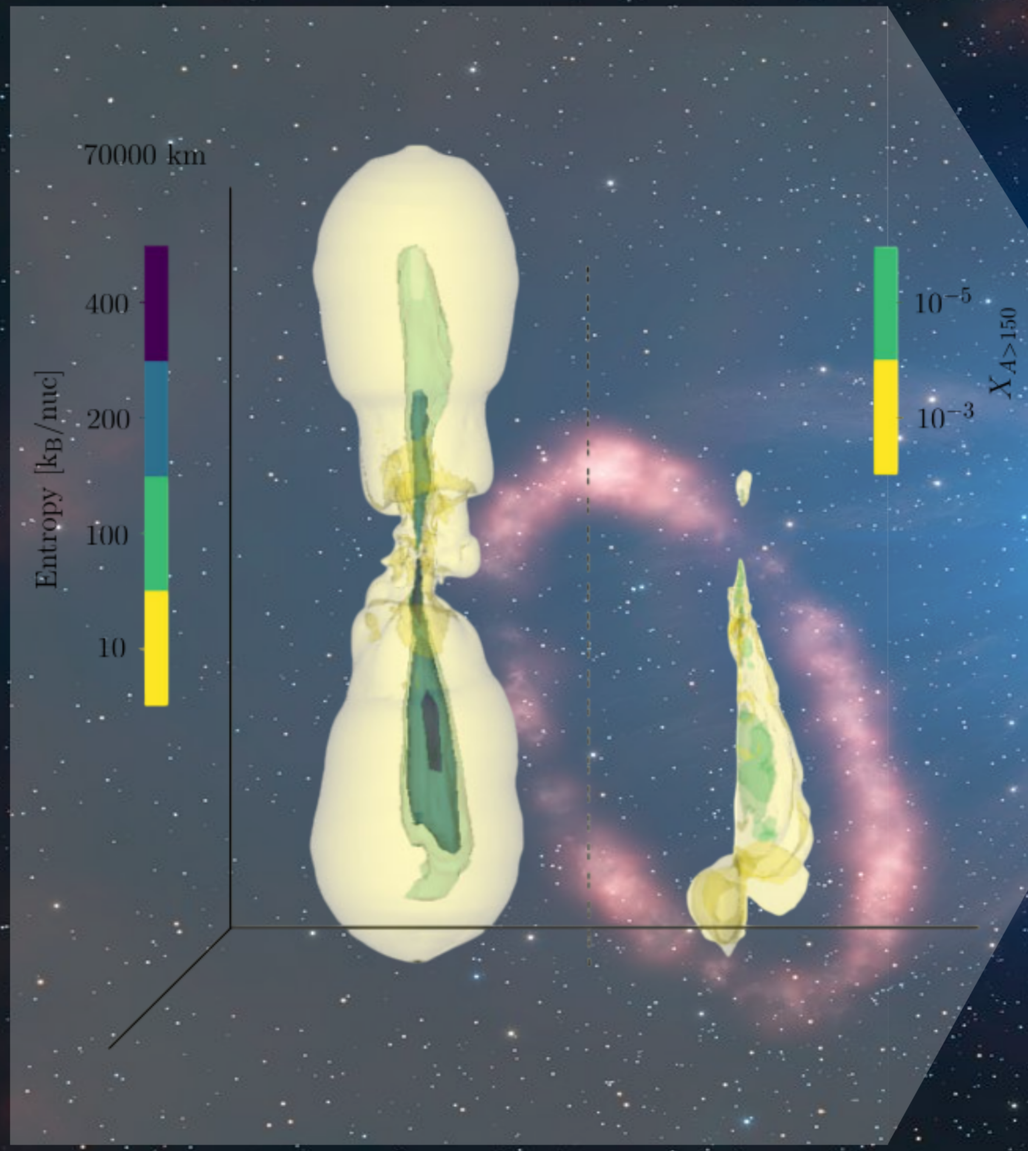
Magnetorotational SN



See, e.g.:
Mösta et al. 2018
Siegel et al. 2019
Reichert et al. 2023
But see also:
Just et al. 2022
Fujibayashi et al. 2023
Dean et al. 2024

Reichert et al. 2023, MNRAS 518

Art Credit: ESO/L. Calçada

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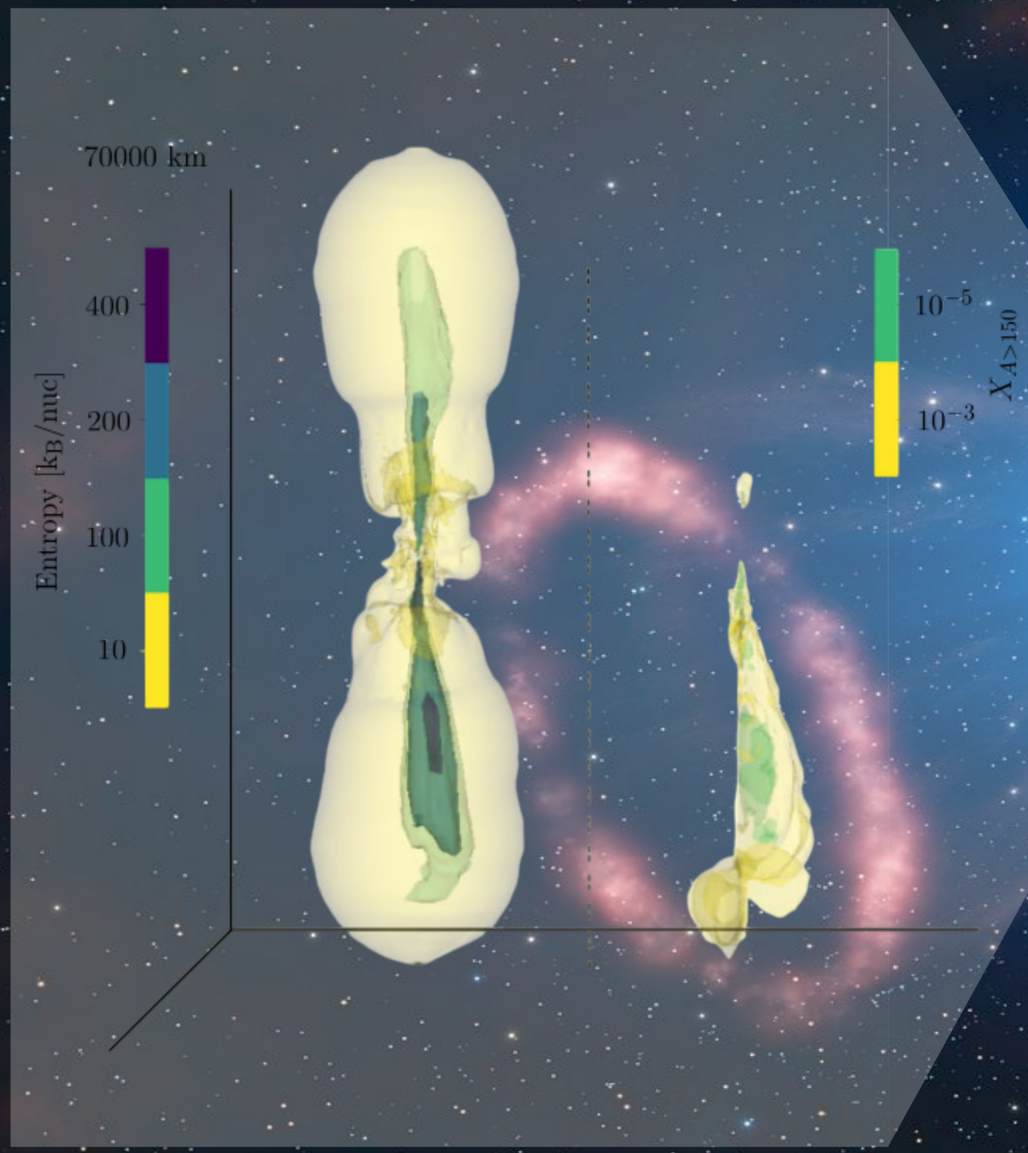
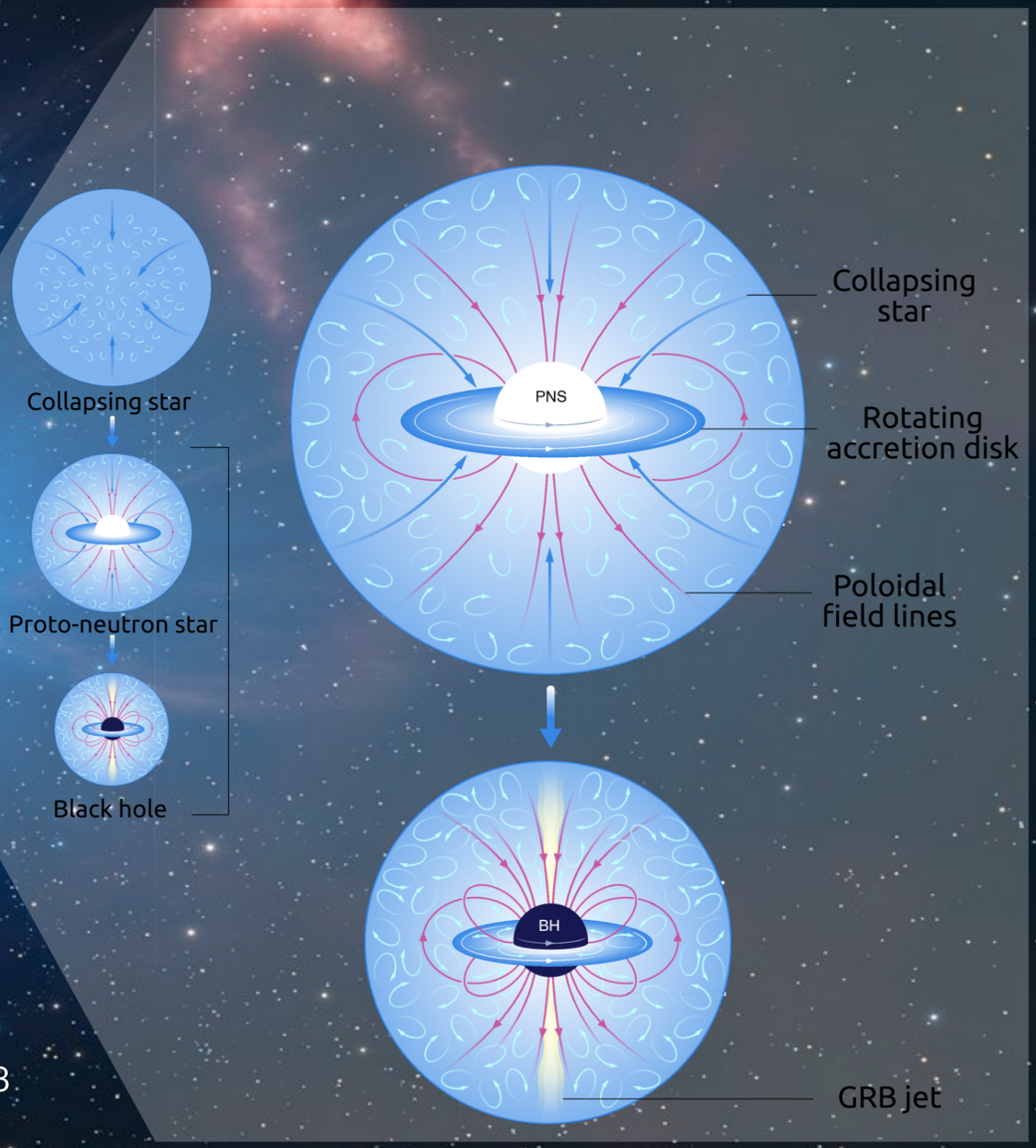


Collapsar



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Art Credit: ESO/L. Calçada

Gottlieb et al. 2024, ApJL 976

Modeling the nebular emission

Ejecta in **Non-Local Thermodynamic Equilibrium**

Modeling the nebular emission

Ejecta in **Non-Local Thermodynamic Equilibrium**

Assumptions

- Steady-state regime
- Optically thin material

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Ingredients

- Energy levels
- Radiative transition rates
- Collisional strengths
- Recombination rates
- Photoionization cross-sections

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No important absorptions

Available data is sparse but growing

See, e.g.:
Banerjee et al. 2025, ApJ
Ferreira da Silva et al. 2025, Phys Rev A
Mulholland et al. 2024, MNRAS 532/534

Modeling the nebular emission

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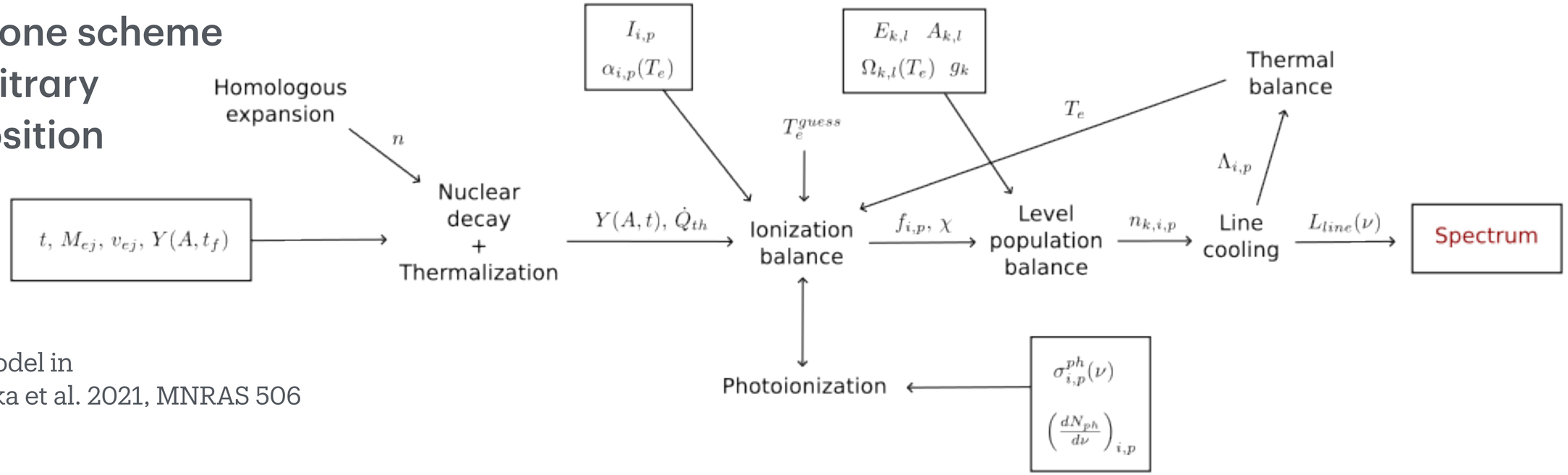
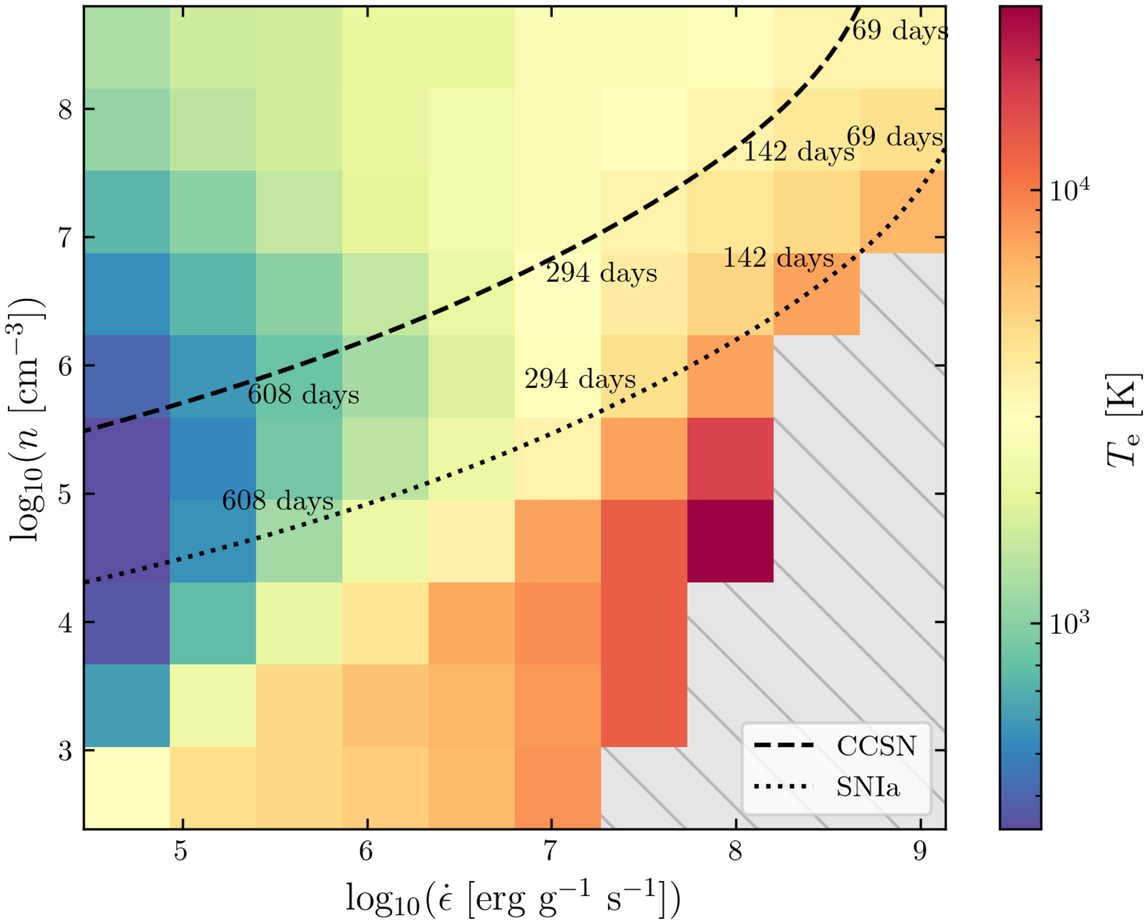
Multi-zone scheme for arbitrary composition



Similar model in
Hotokezaka et al. 2021, MNRAS 506

Modeling the nebular emission

The parameter space



Modeling the nebular emission

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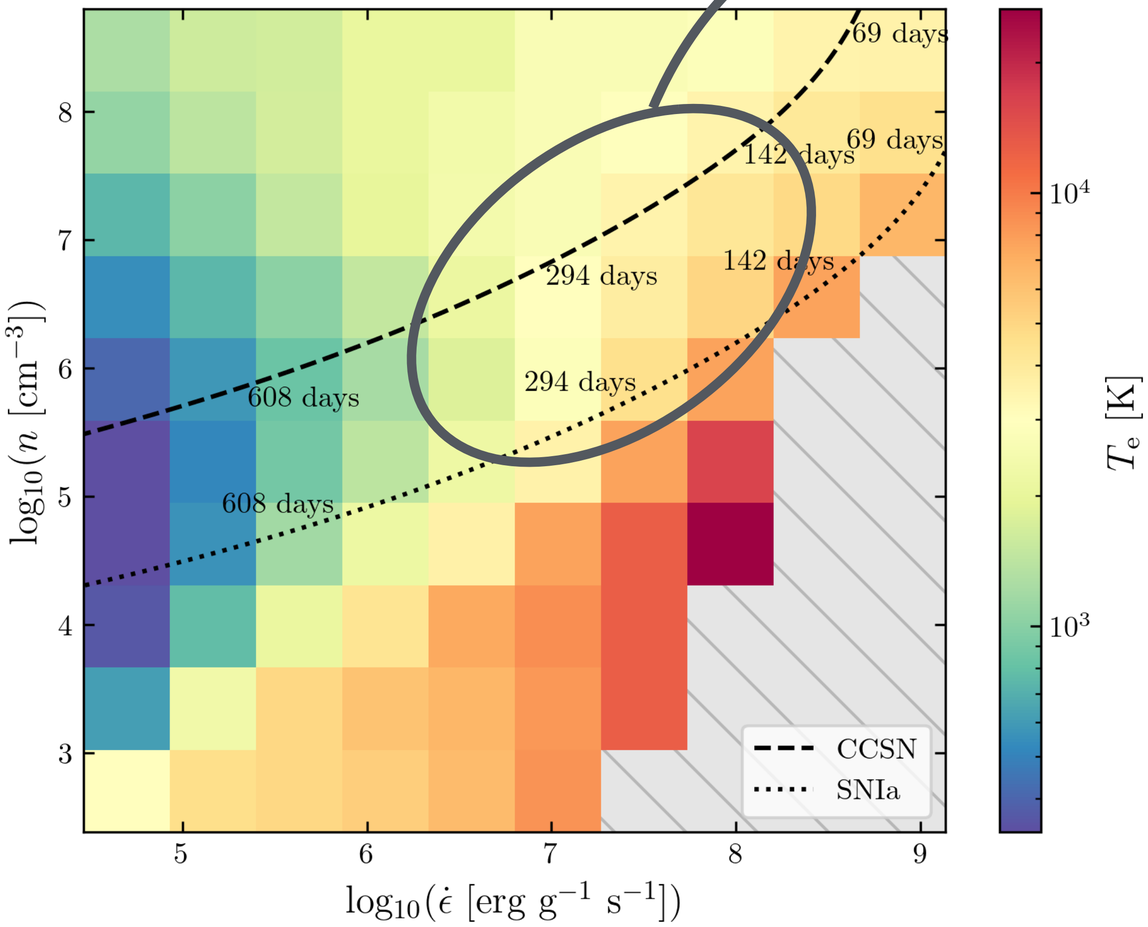
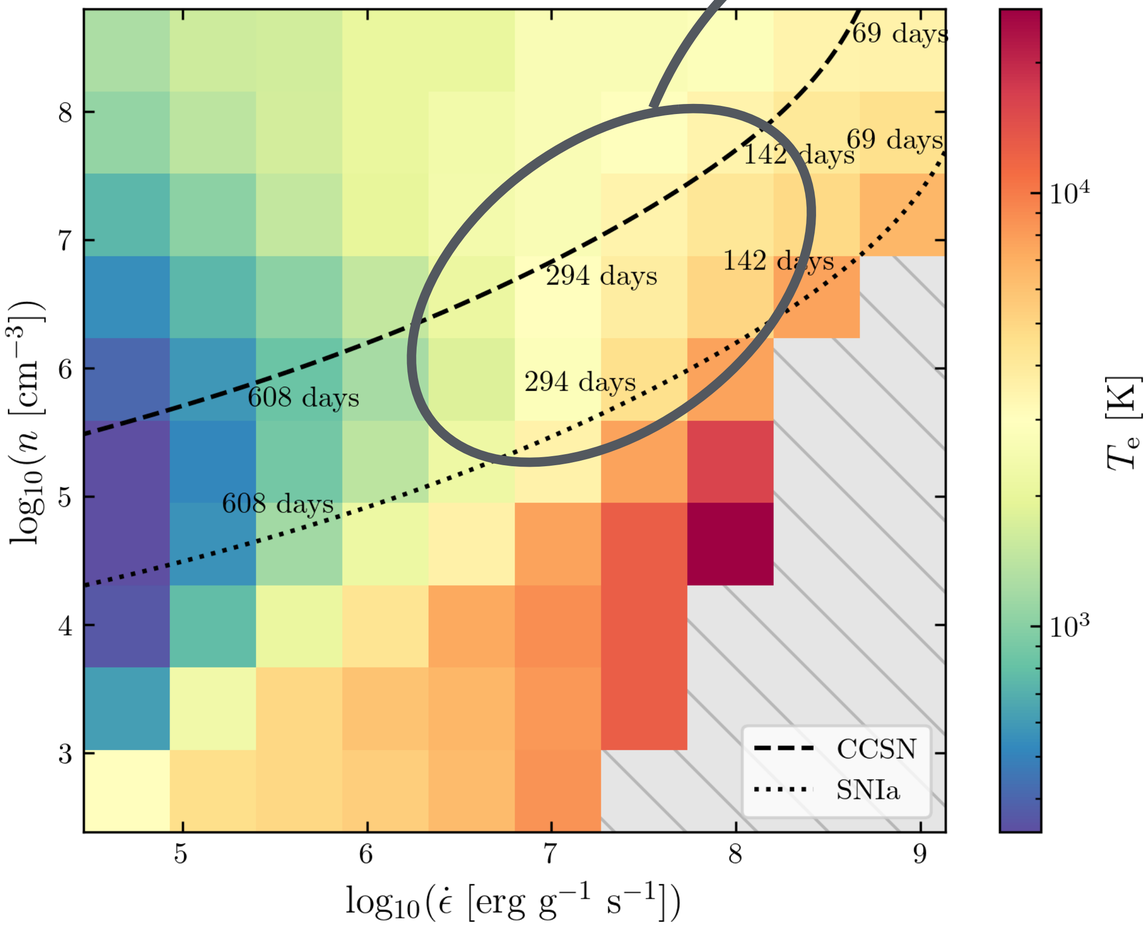


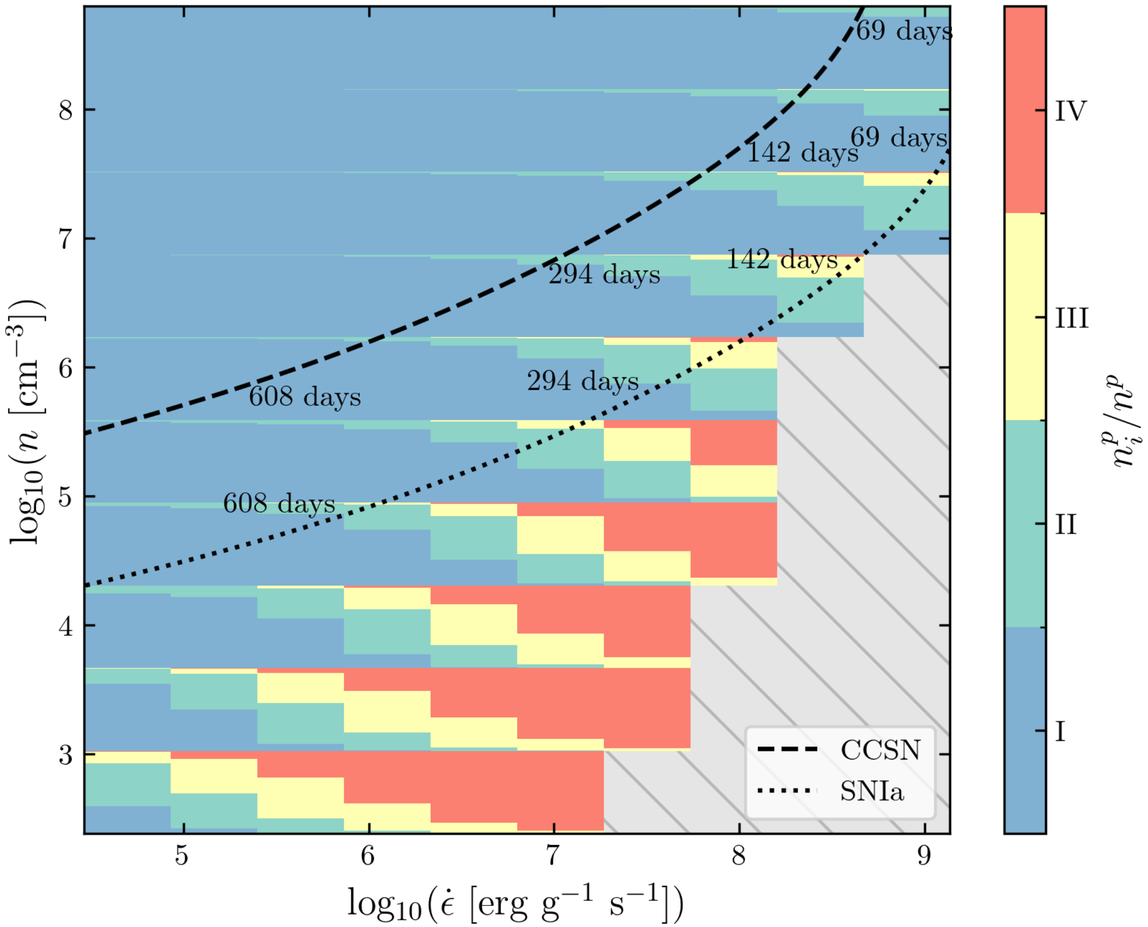
Sweet spot for model at few thousands K

Modeling the nebular emission

The parameter space

Sweet spot for model at few thousands K





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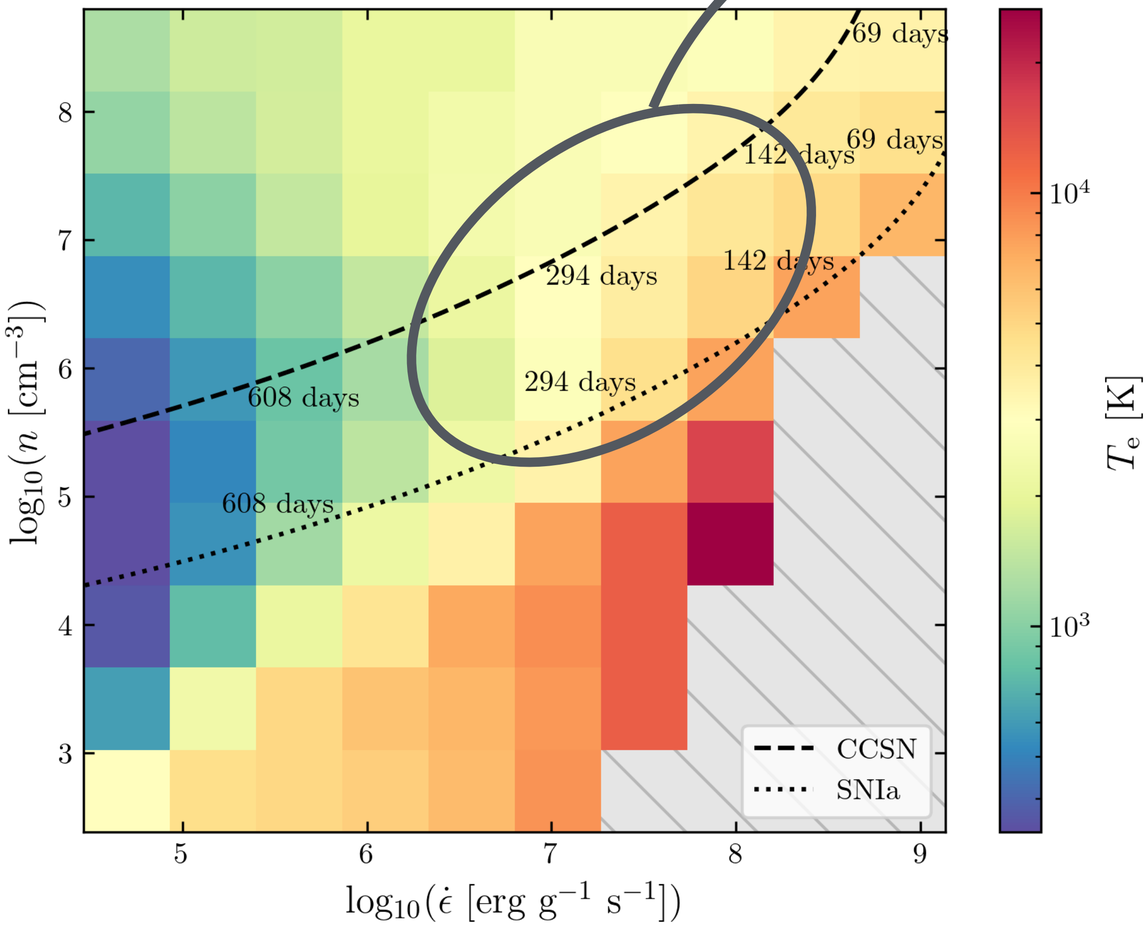
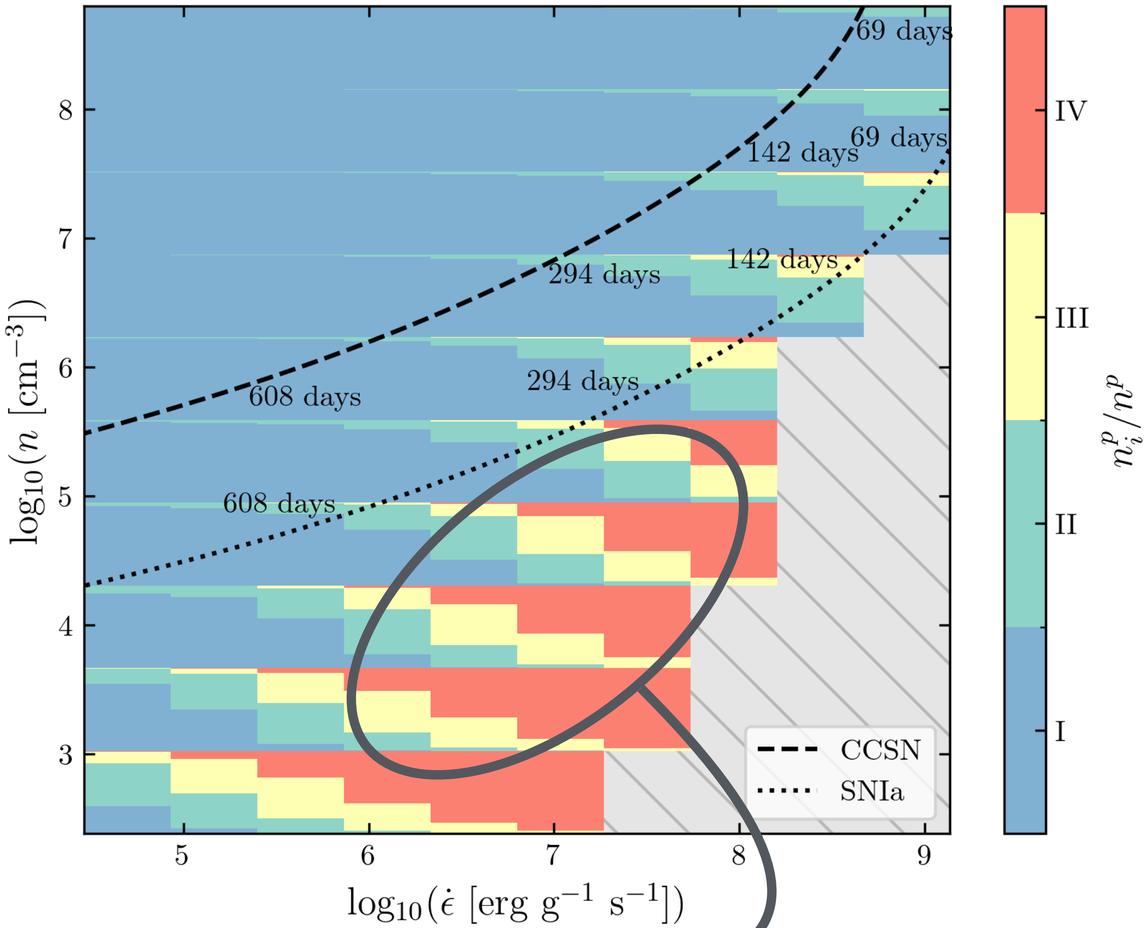
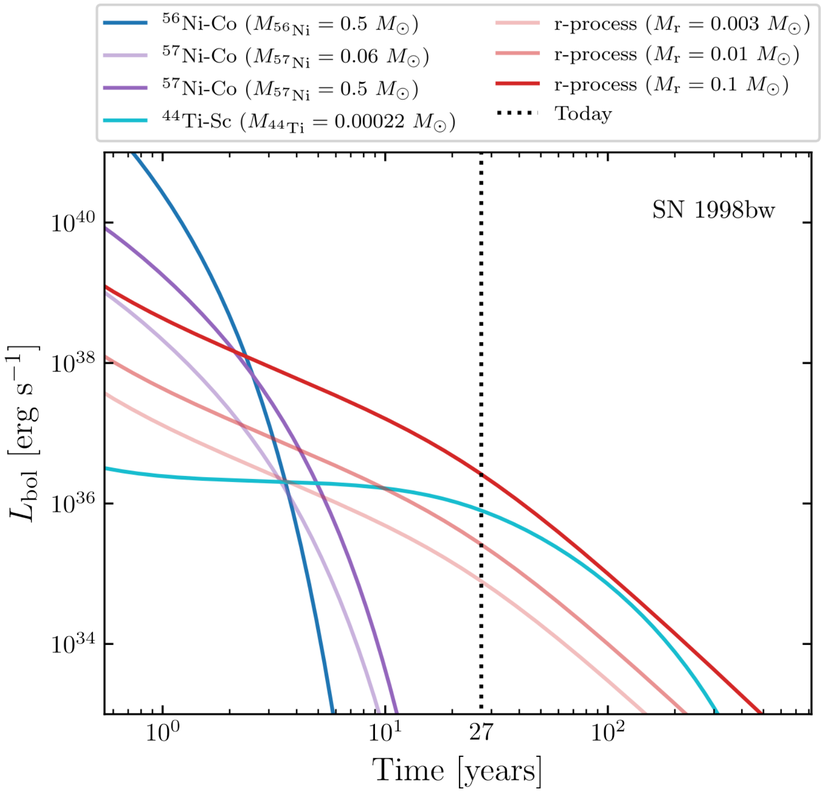




Relevant contribution from recombination photons to ionization of stages I-II

The role of heavy elements...

...in heating the ejecta



- **~0.1%** of ejecta mass as r-process would be visible at **~10 years**...
- ...but slope can be polluted by other sources

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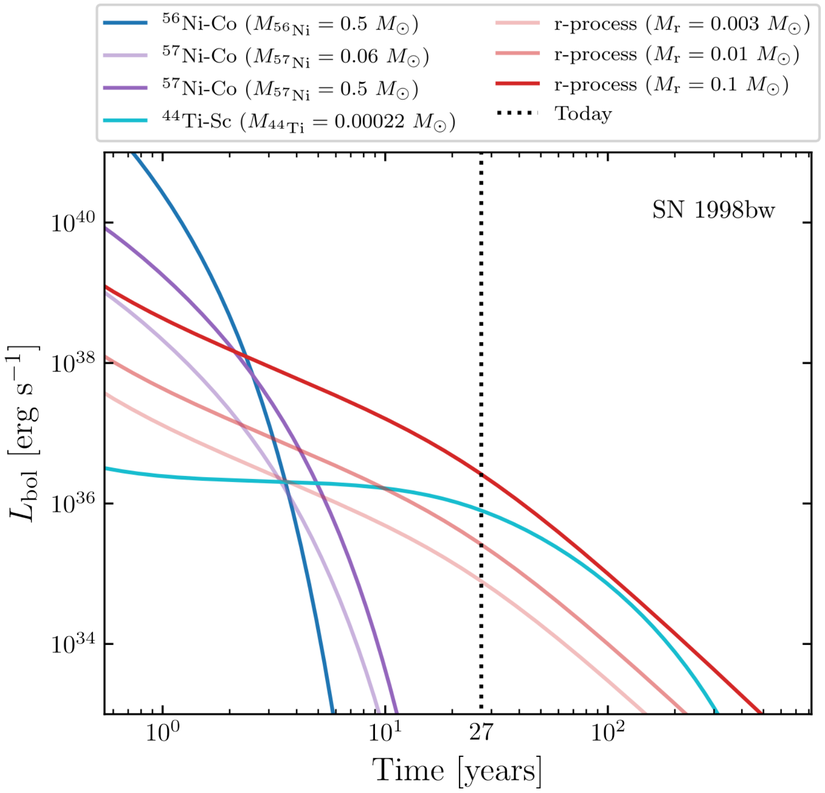
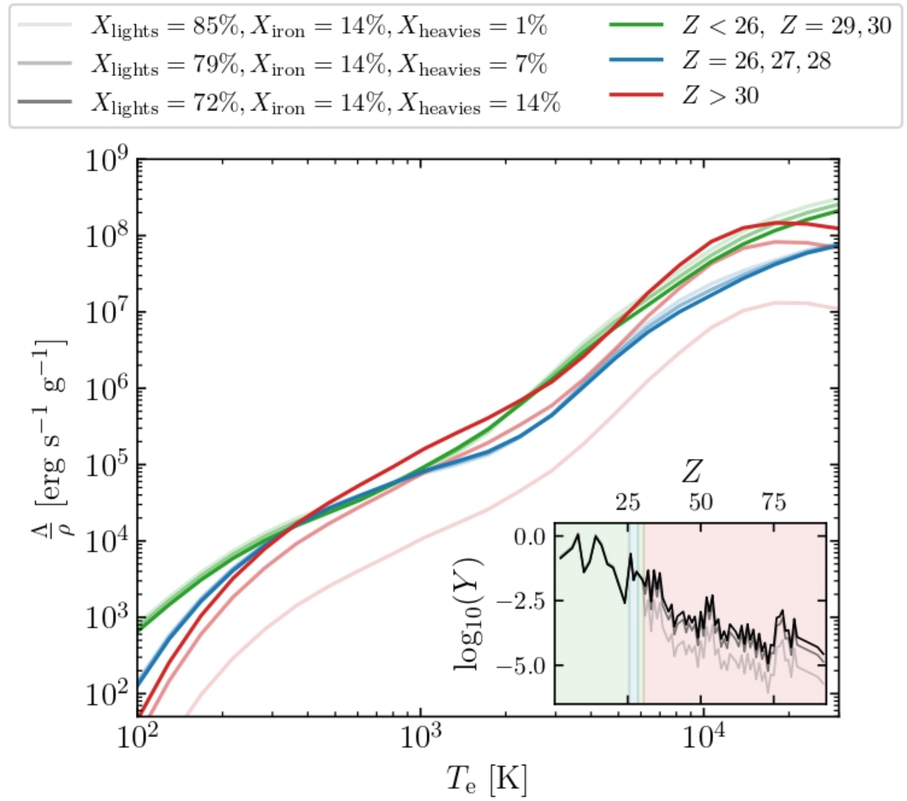


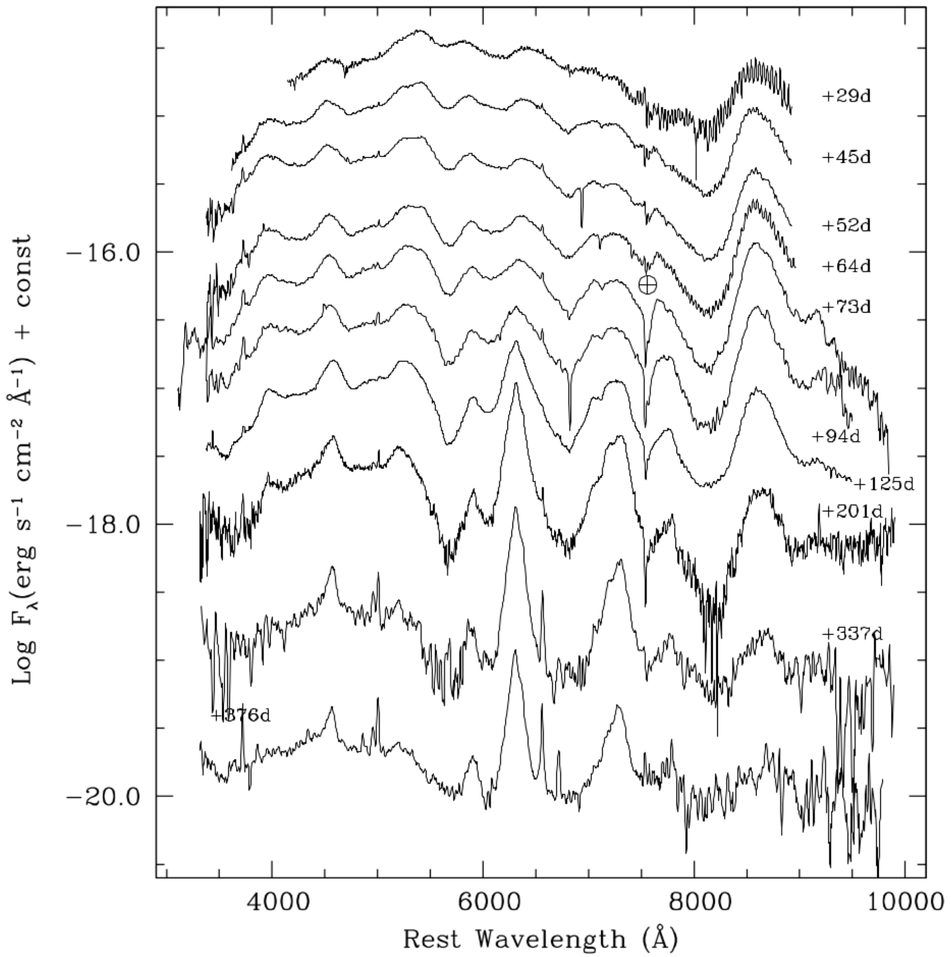
- **~0.1%** of ejecta mass as r-process would be visible at **~10 years**...
- ...but slope can be polluted by other sources
- At least **~10%** of total mass in r-process needed to dominate over lighter species!

...in cooling the ejecta



A case of study: GRB SN Ic bl 1998bw

Late evolution



Short rise time,
narrow light peak,
huge luminosity,
broad spectral lines

Decrease of
continuum

Still high luminosity,
narrow spectral lines,
low ionization

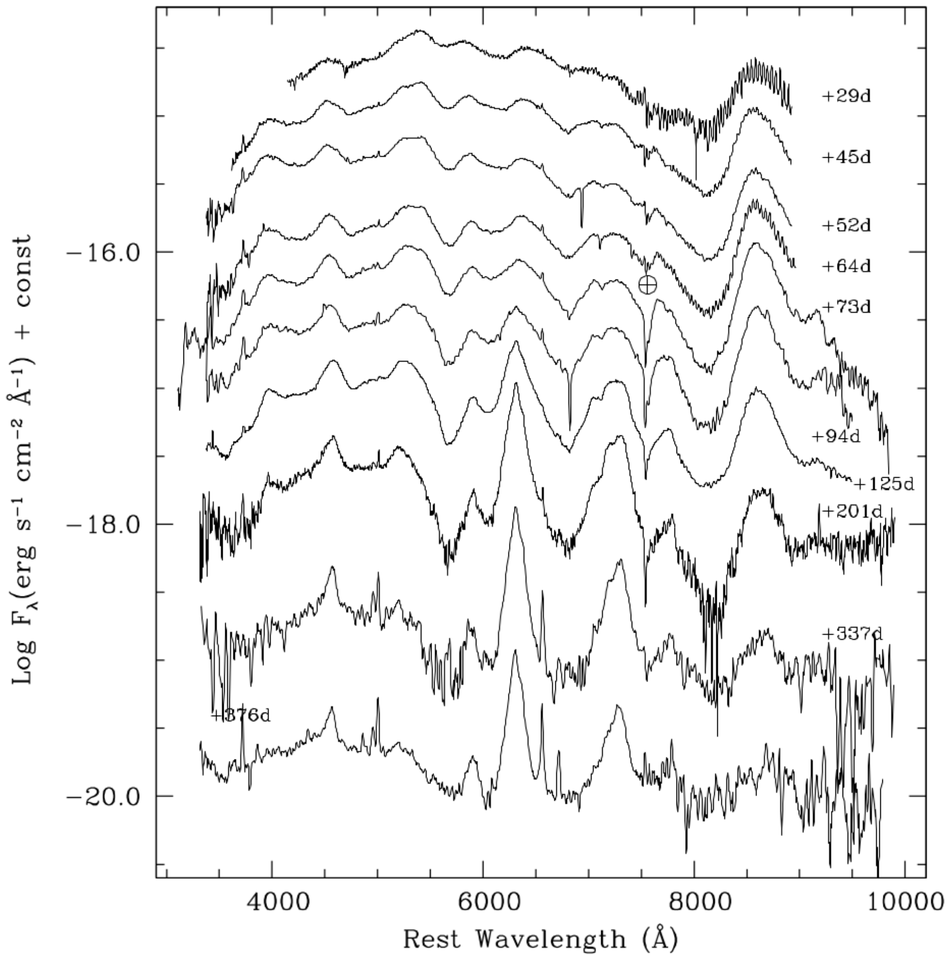
Collapsar scenario

- Association to GRB 980425
- High energetics $\sim 10^{52}$ erg and velocities up to $\sim 0.1c$
- Possibly aspherical explosion

Patat et al. 2001, ApJ 555

A case of study: GRB SN Ic bl 1998bw

Late evolution

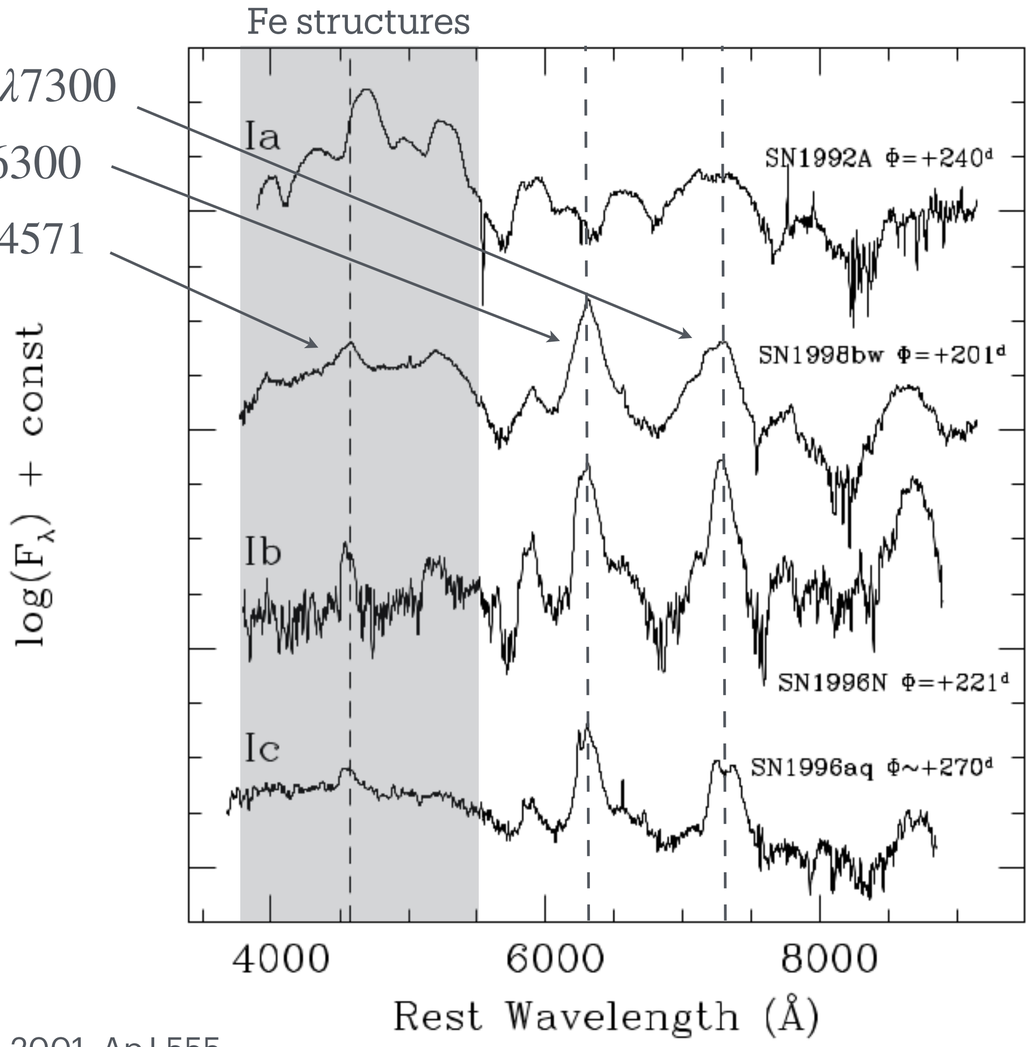


Comparison with similar events

[Ca II] λ7300

[O I] λ6300

Mg I] λ4571



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Benchmark for nebular phase

WR star models with different rotation rates, metallicities and explosion energies (Dessart et al. 2017, A&A 603)

- Stellar evolution with MESA (Paxton et al. 2015)
- Explosion with V1D (Livne 1993, Dessart et al. 2010)

Model	M_r $[M_\odot]$	M_e $[M_\odot]$	E_{kin} $[10^{51}$ erg]	$\langle V_m \rangle$ [km s^{-1}]	He $[M_\odot]$	C $[M_\odot]$	O $[M_\odot]$	Si $[M_\odot]$	Ca $[M_\odot]$	^{56}Ni $[M_\odot]$
r0e2	1.71	9.69	4.12	6530	0.181	1.326	5.471	0.112	0.0061	0.122
r0e4	1.54	9.86	12.31	11210	0.205	1.298	5.590	0.181	0.0098	0.172
r4e4	1.88	8.12	13.44	12900	0.286	1.302	3.852	0.458	0.0410	0.583
r6e4	1.62	4.97	12.41	15840	0.324	1.051	2.072	0.315	0.022	0.300
r6ze4	1.99	7.70	13.70	13370	1.453	0.822	3.017	0.429	0.0386	0.696
r6e4BH	4.04	2.55	11.63	21420	0.456	0.910	0.515	0.051	0.0036	0.435

See also Jerkstrand et al. 2017, Mazzali et al. 2001 for similar SN Ic nebula models

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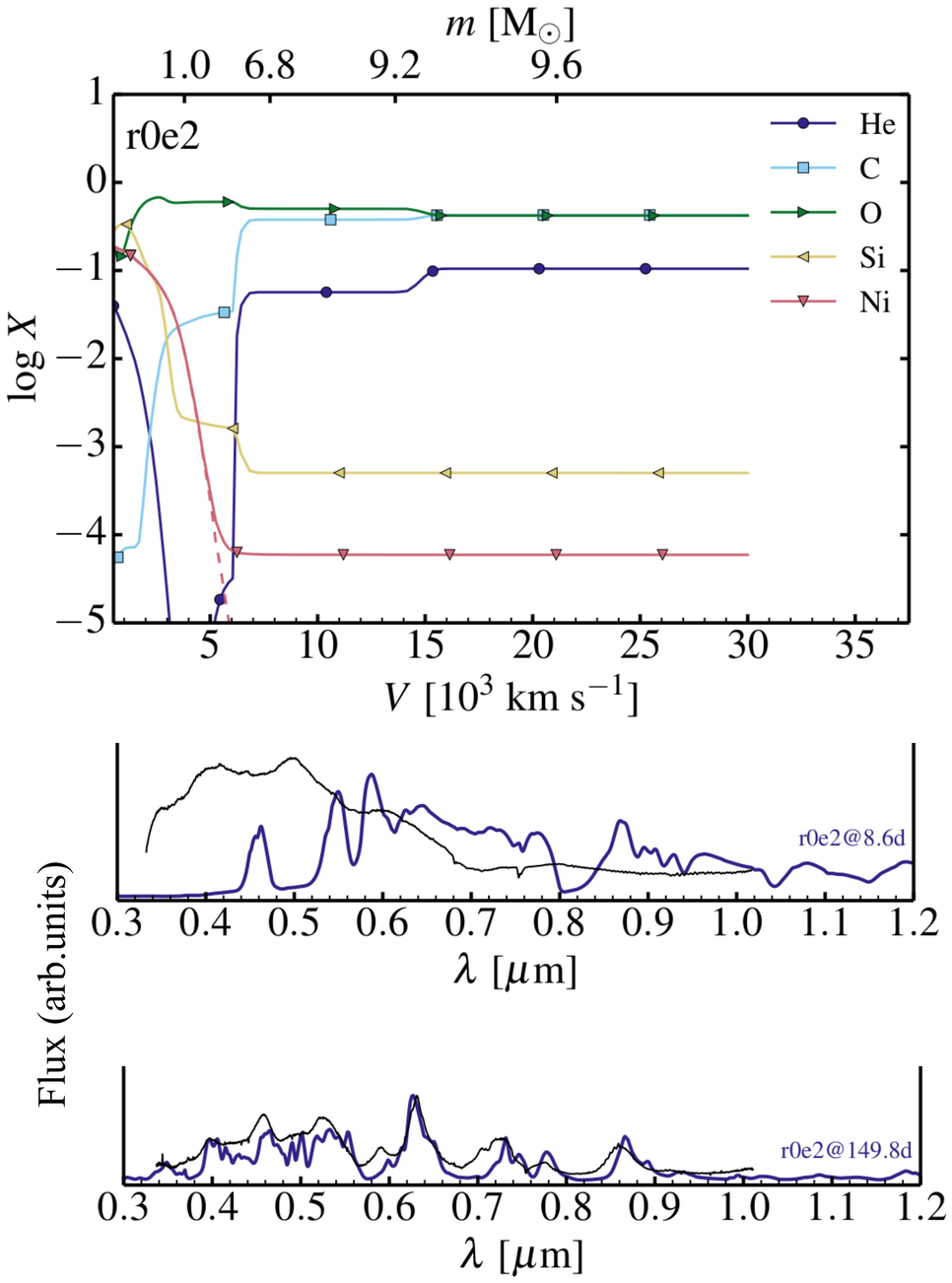

Dessart et al. 2017, A&A 603

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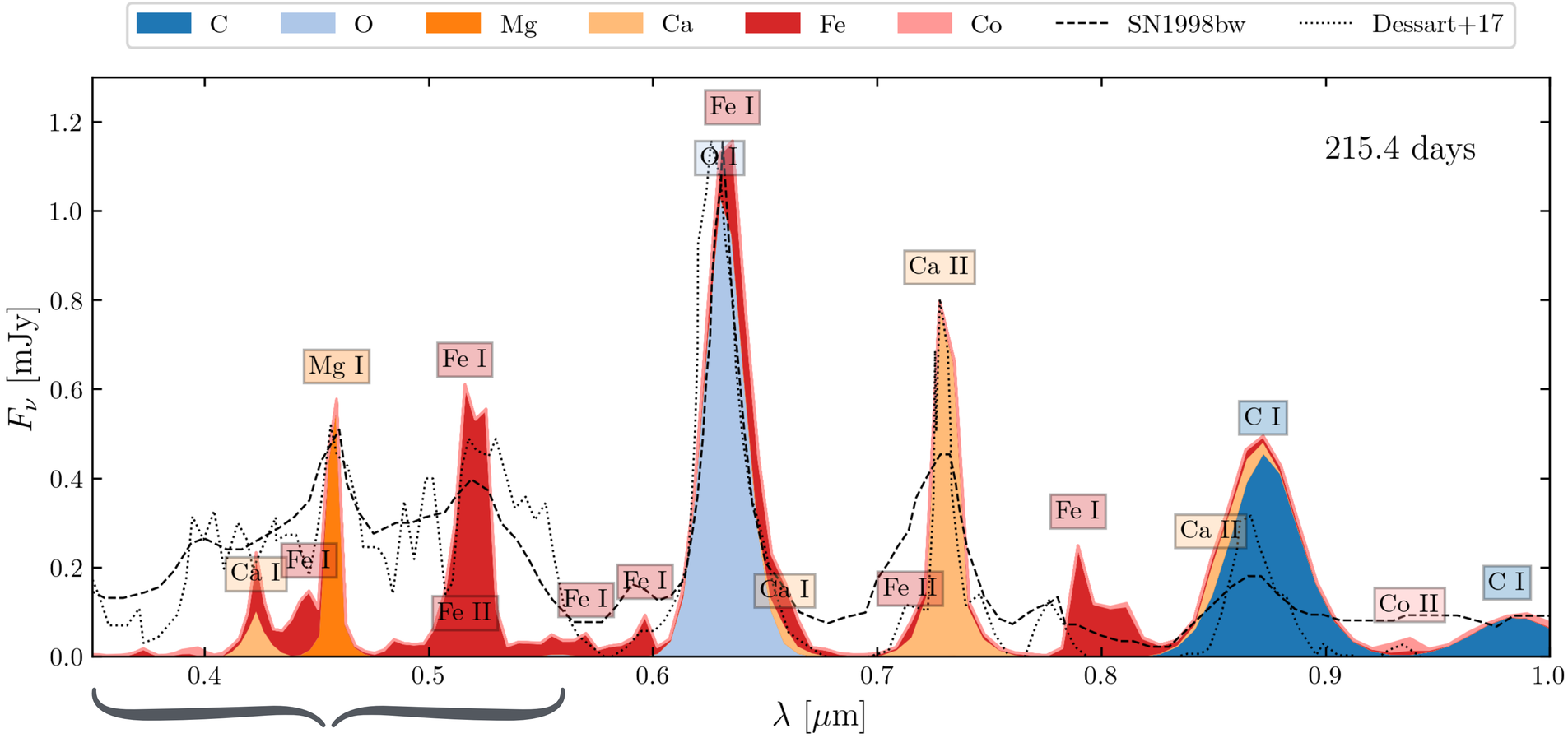
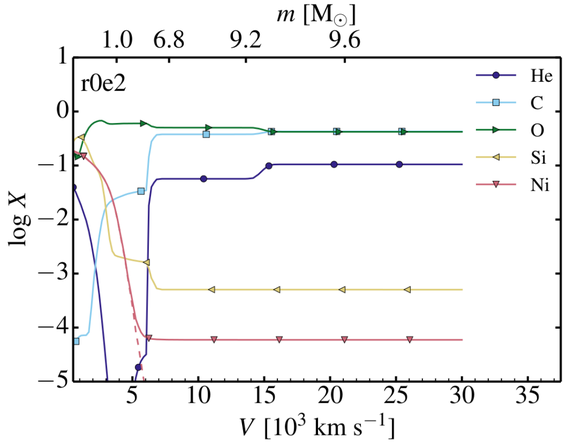




Dessart et al. 2017, A&A 603

Main features roughly reproduced

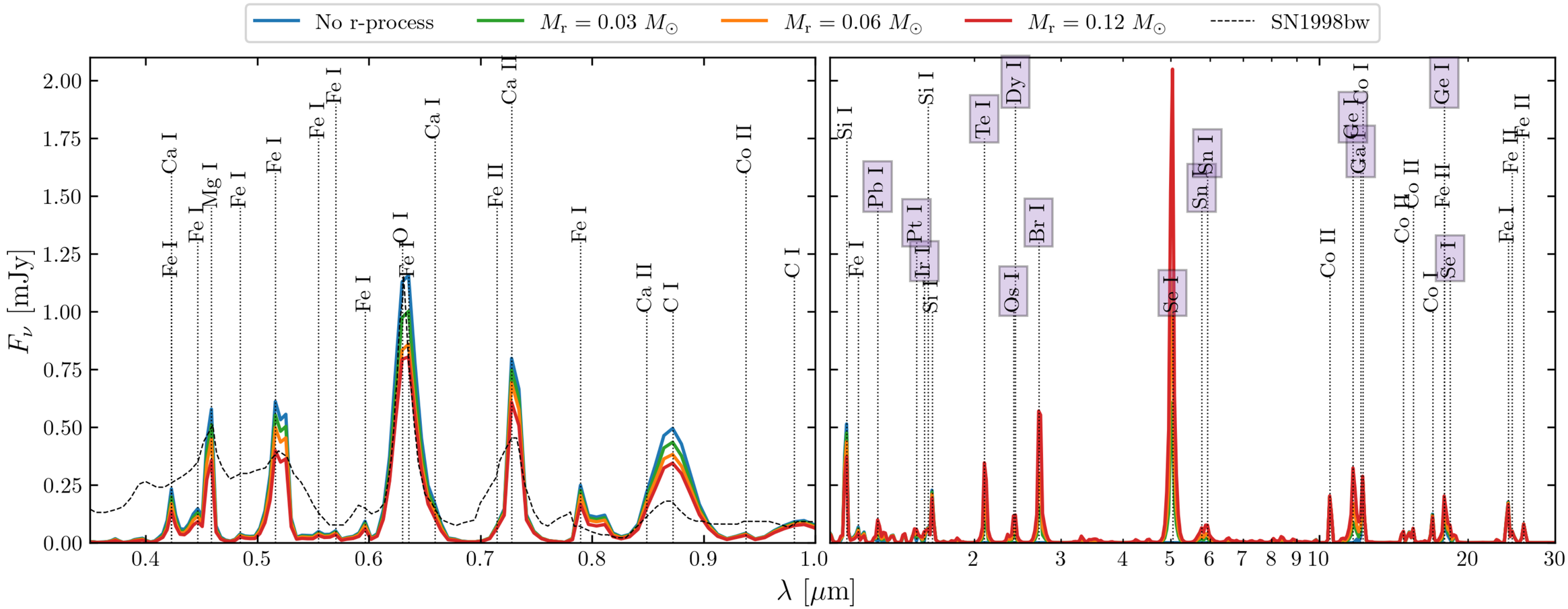
Expected flux levels

Residual continuum, Fe blanketing...

Heavy elements in the spectrum

Injection of solar r-process material

- IR flux excess $\dfrac{F_{>1\mu\mathrm{m}}}{F_{\leq 1\mu\mathrm{m}}} \gtrsim 0.1$



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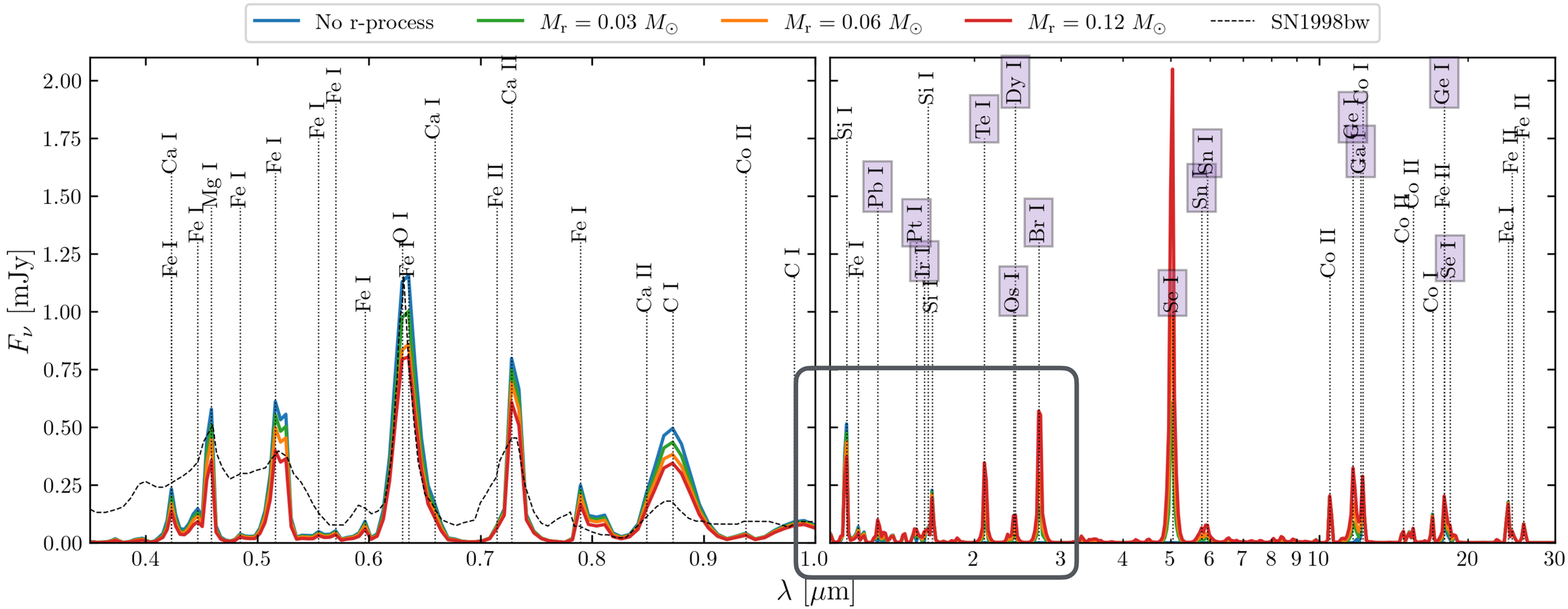

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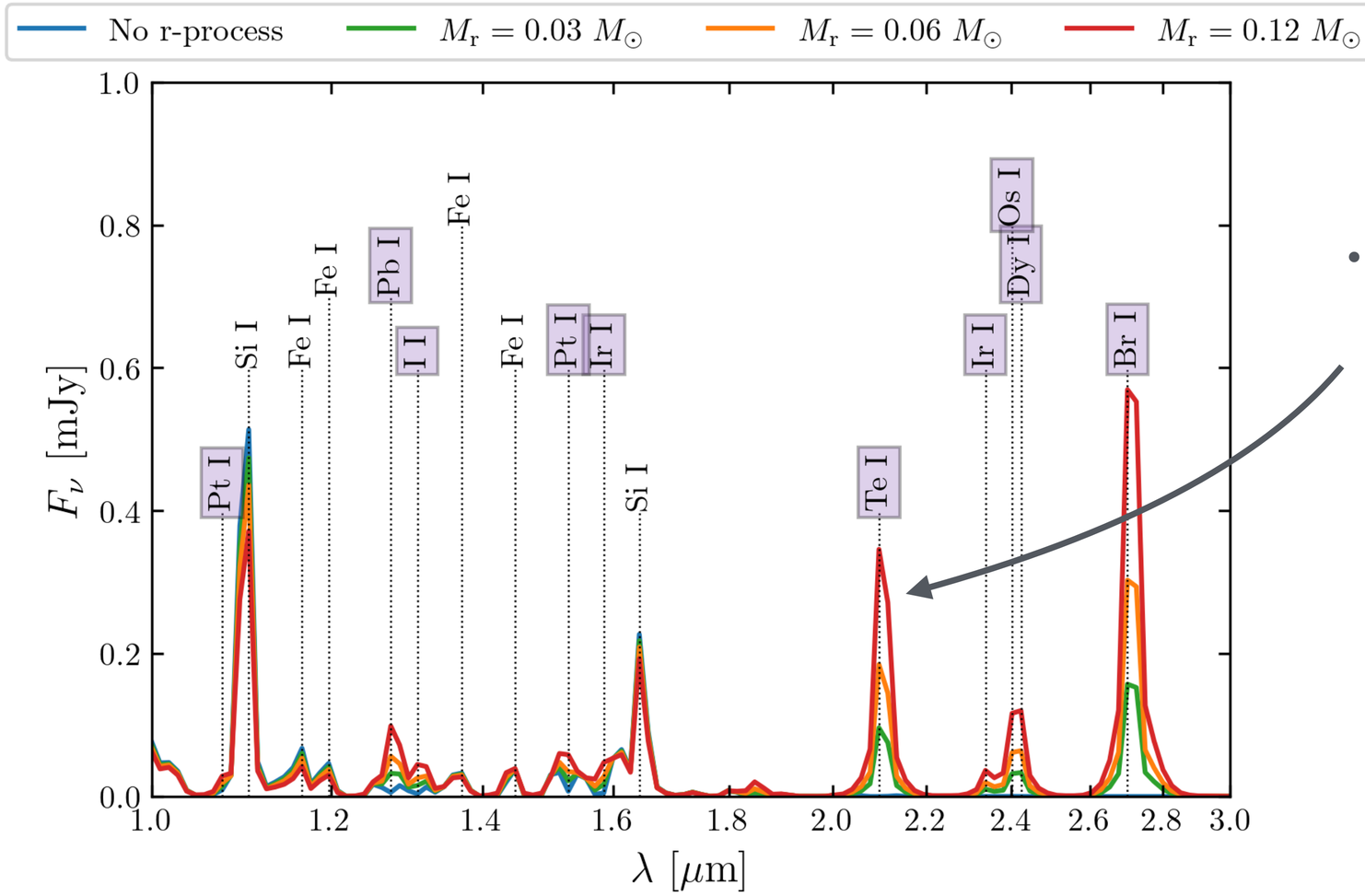


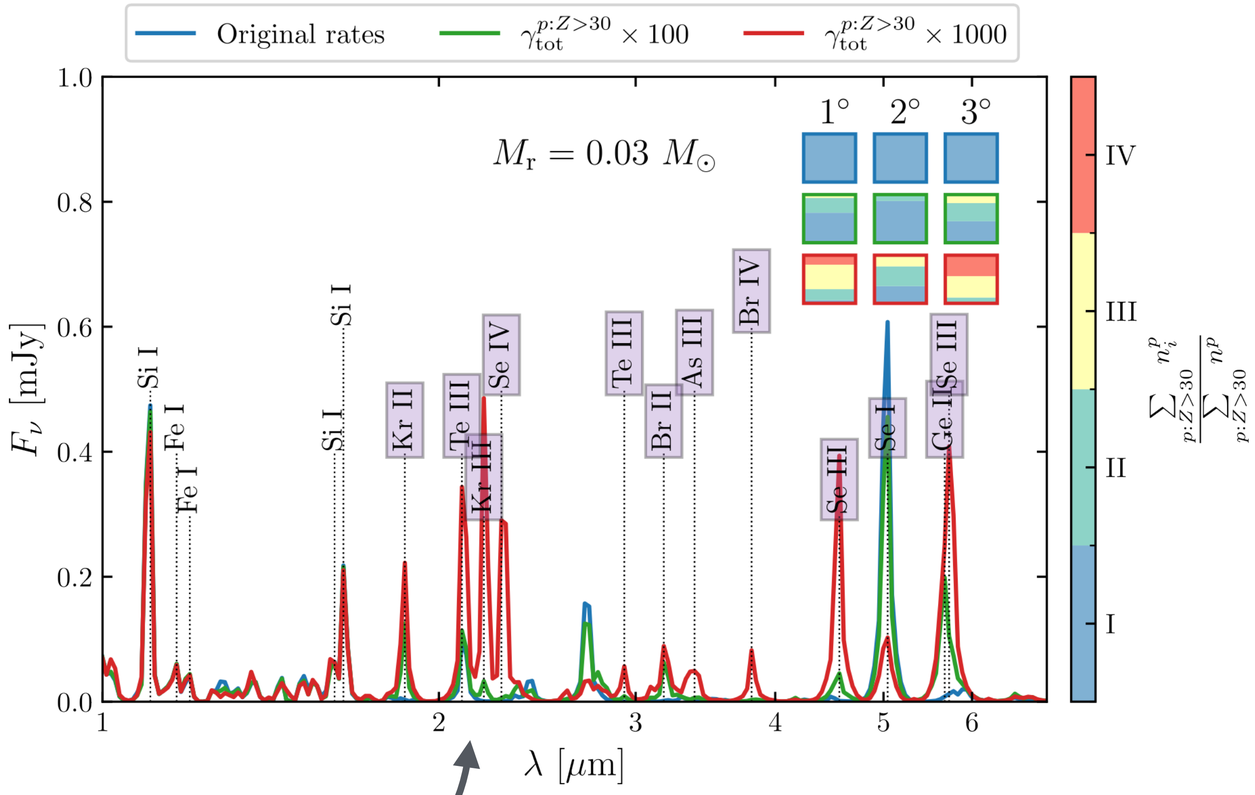
- IR flux excess $\dfrac{F_{>1\mu\mathrm{m}}}{F_{\leq 1\mu\mathrm{m}}} \gtrsim 0.1$

- **Te I** at $2.10\ \mu$m ($5p^4 3P_1 - 5p^4 3P_2$) comparable to Si I features

Presence (absence) easily verifiable with **JWST** due to extremely **good sensitivity** $\sim \mu Jy$

Evidence robustness

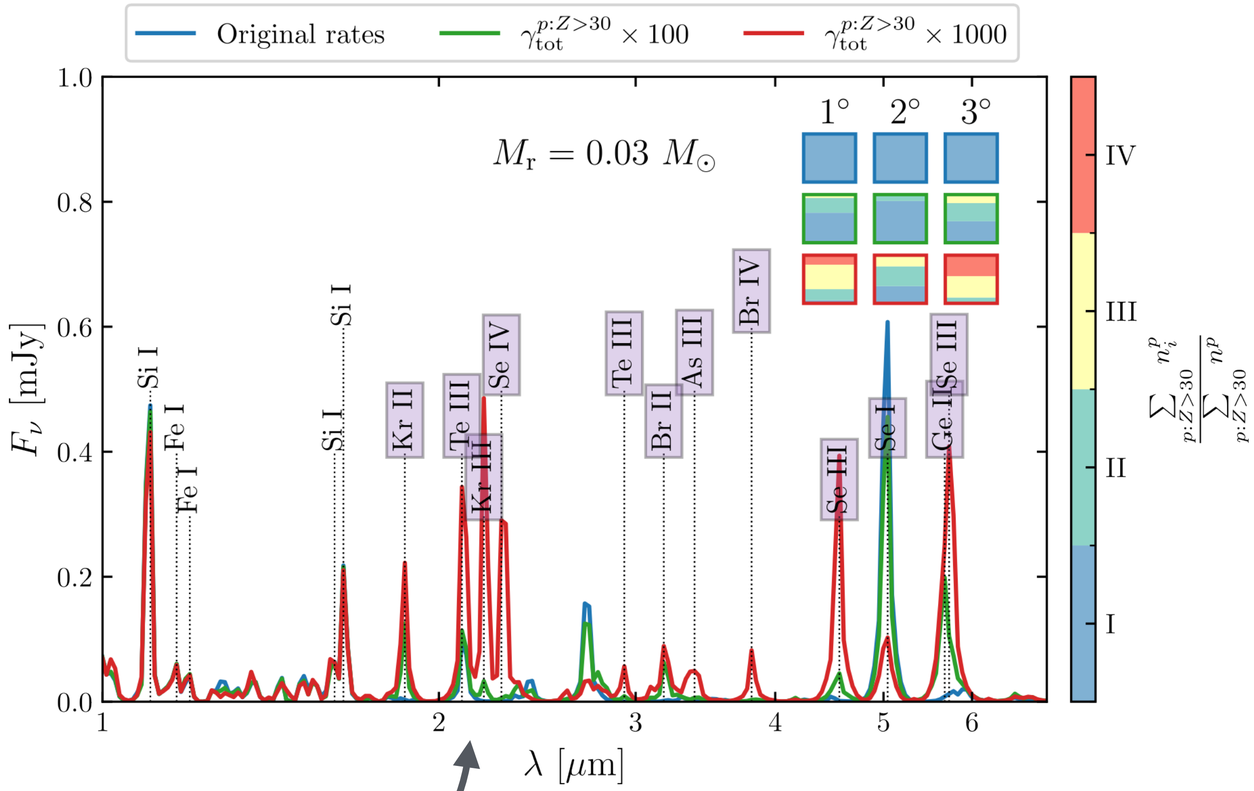
Effect of ionization level



Different lines,
same purpose

Evidence robustness

Effect of ionization level



Different lines,
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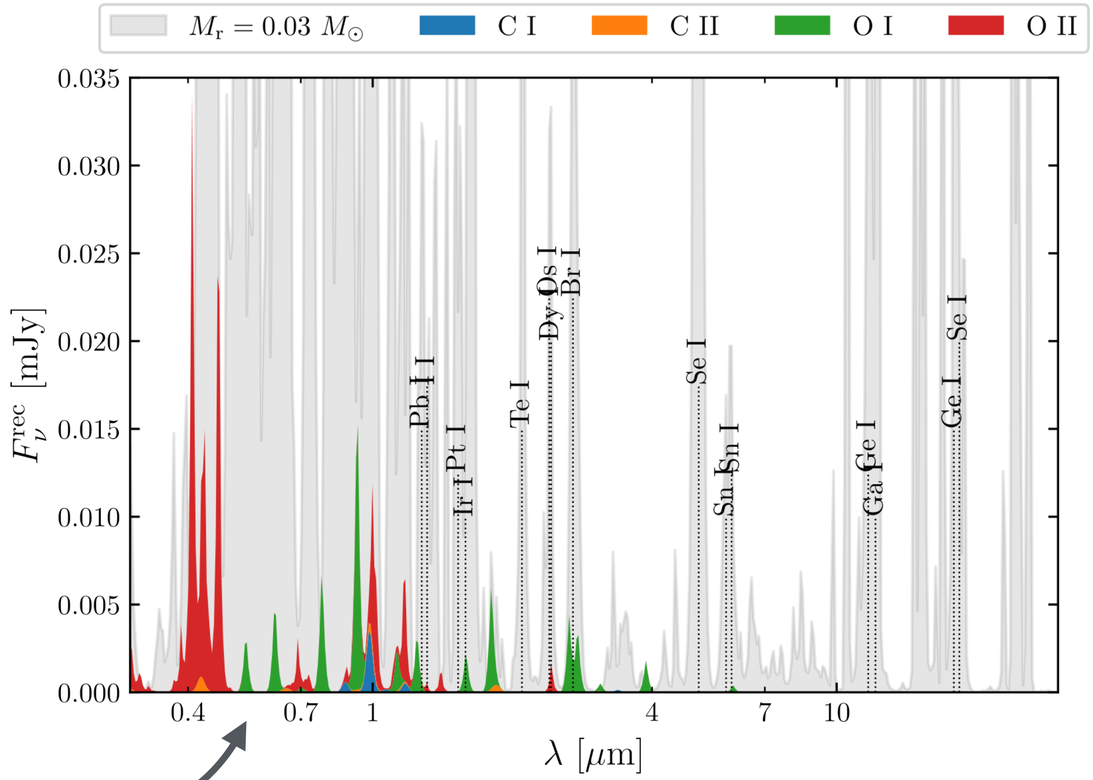
Recombination spectrum



Recombination lines **weaker**
than collisionally excited lines

Evidence robustness

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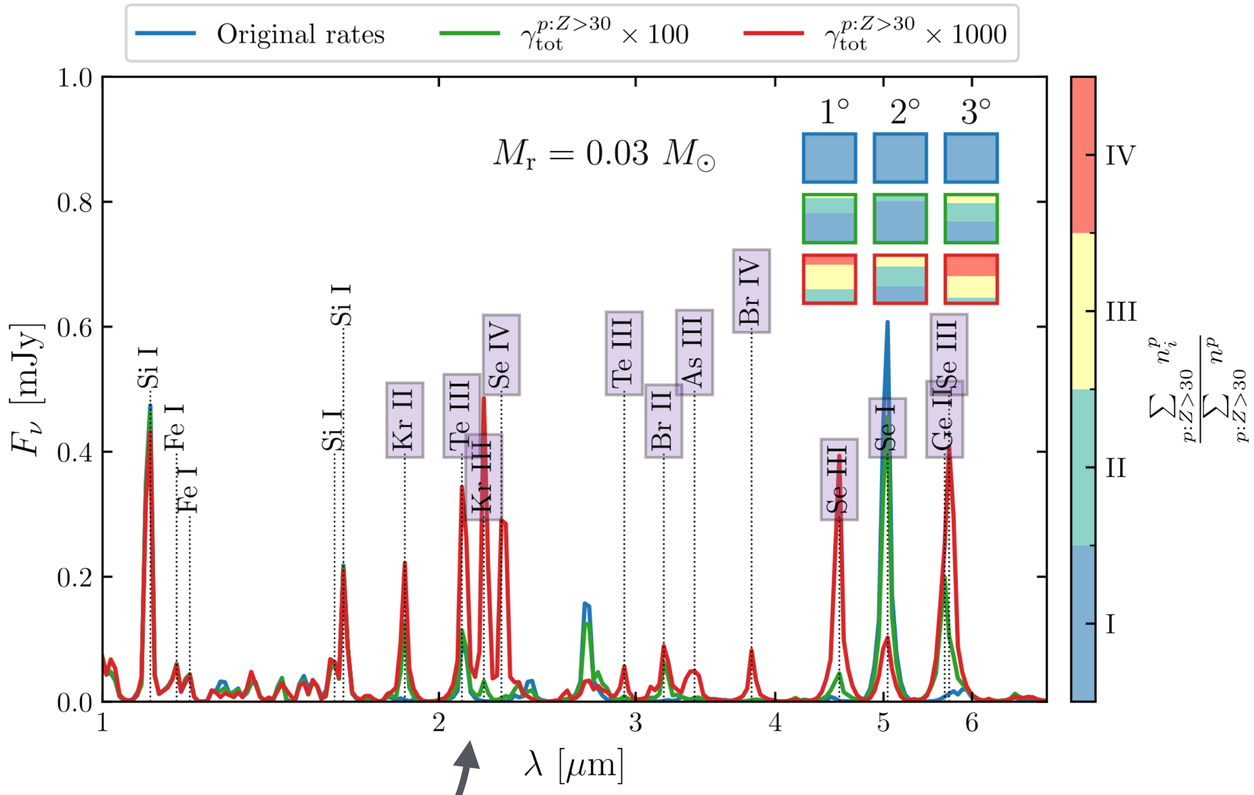
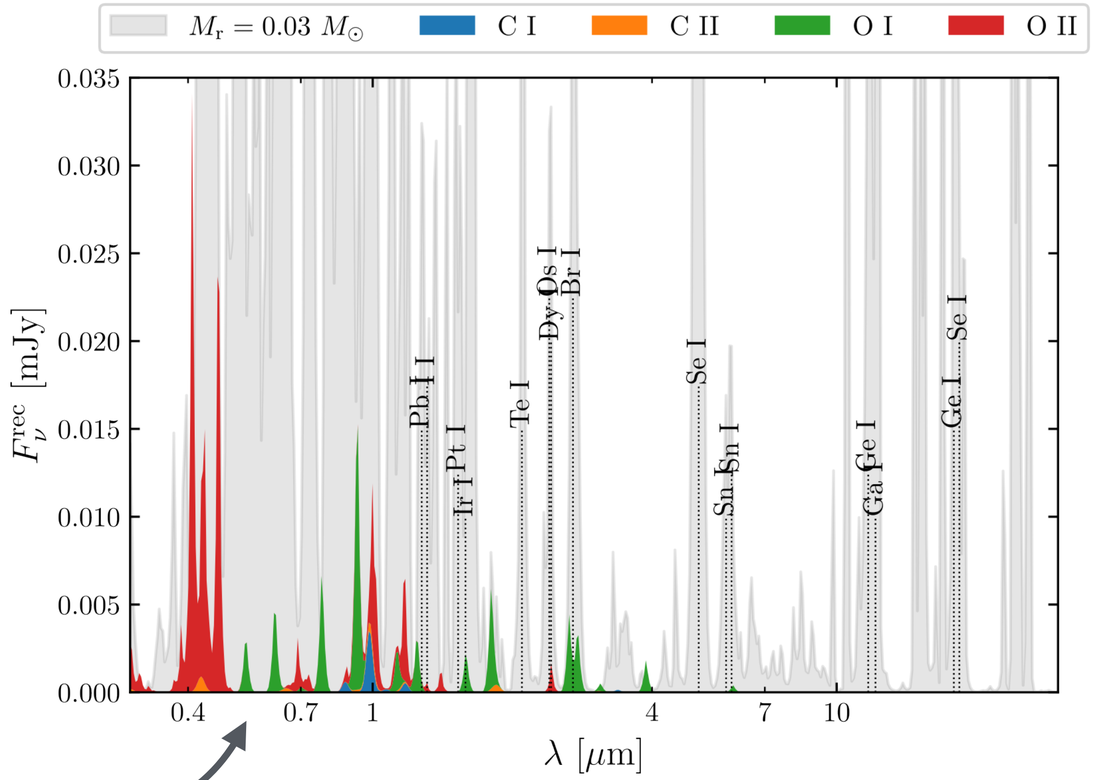


Different lines, same purpose

Features from heavy elements **appear regardless** of conditions/uncertainties

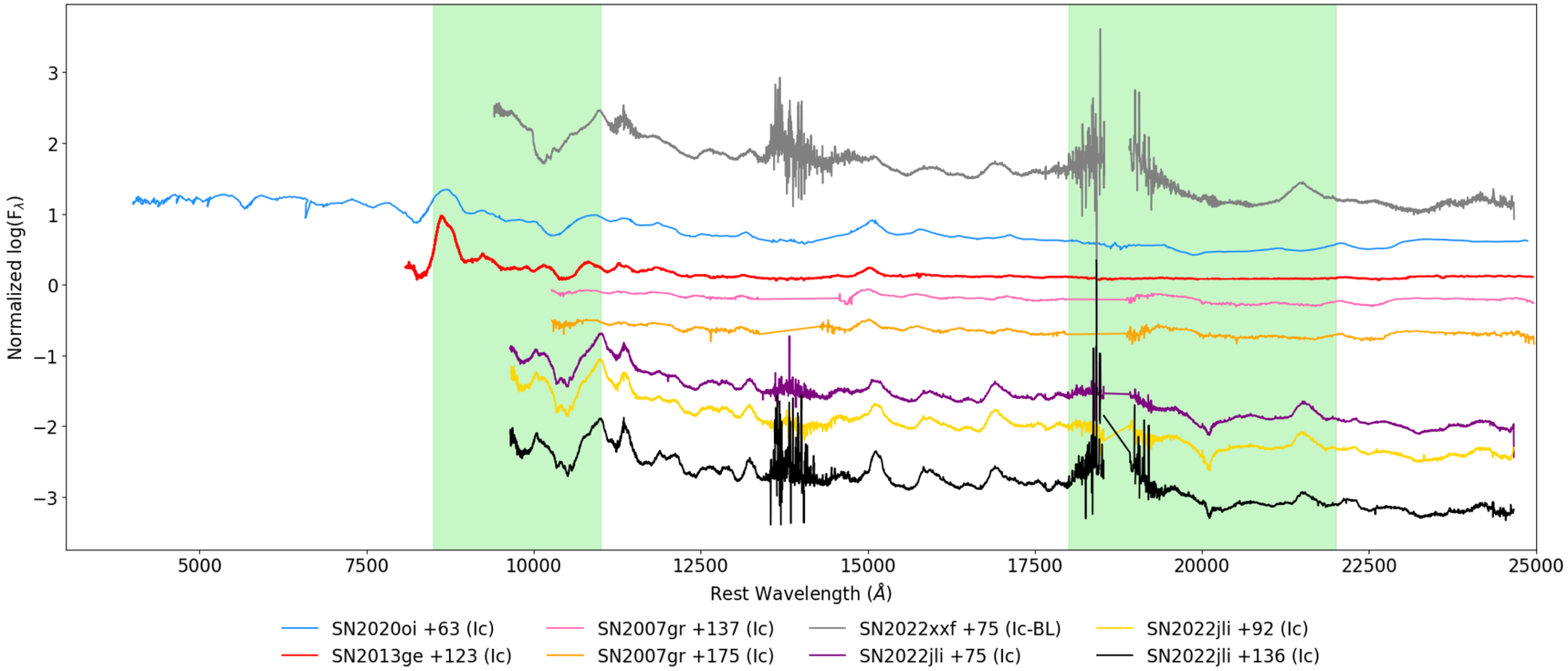
Recombination spectrum



Recombination lines **weaker** than collisionally excited lines

Comparison with normal SN Ic events

Margutti 2025B U242

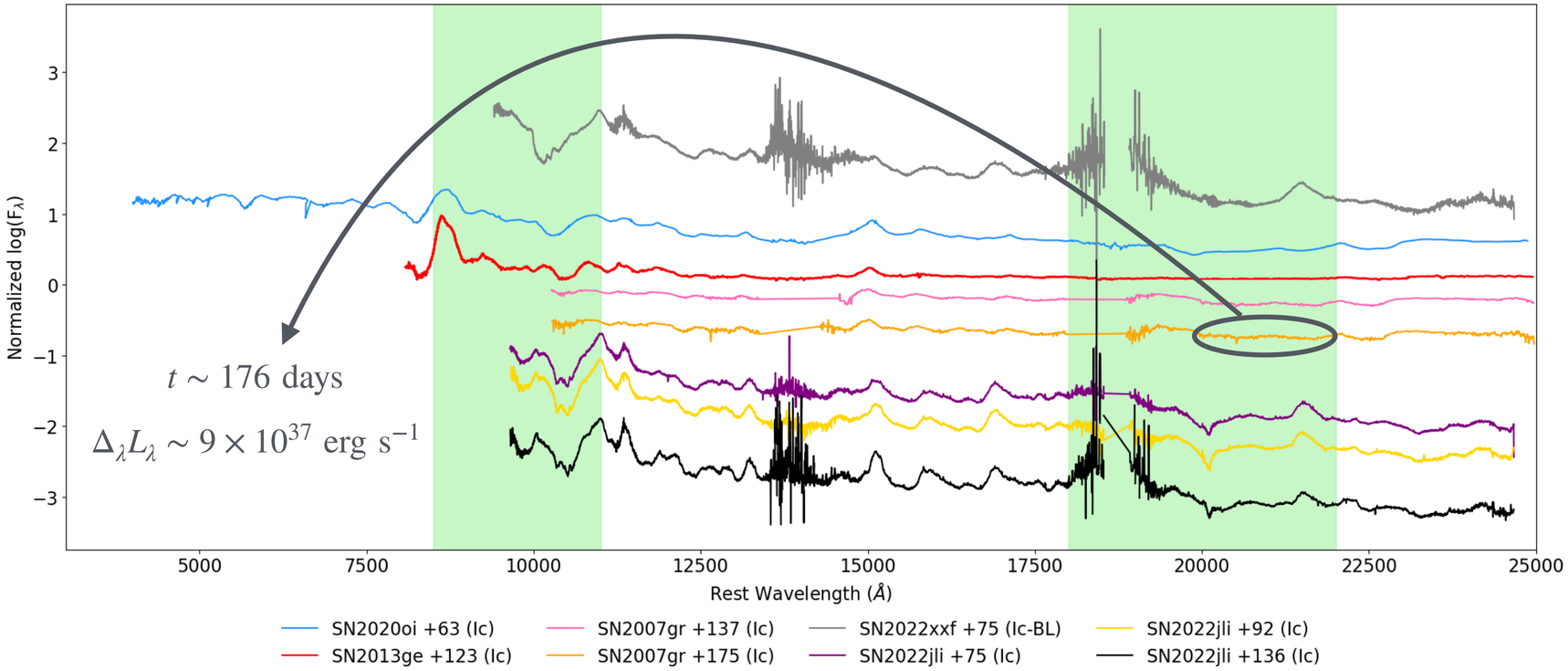


Comparison with normal SN Ic events

Example: SN Ic 2007gr

Margutti 2025B U242

Searching for Te line...



Comparison with normal SN Ic events

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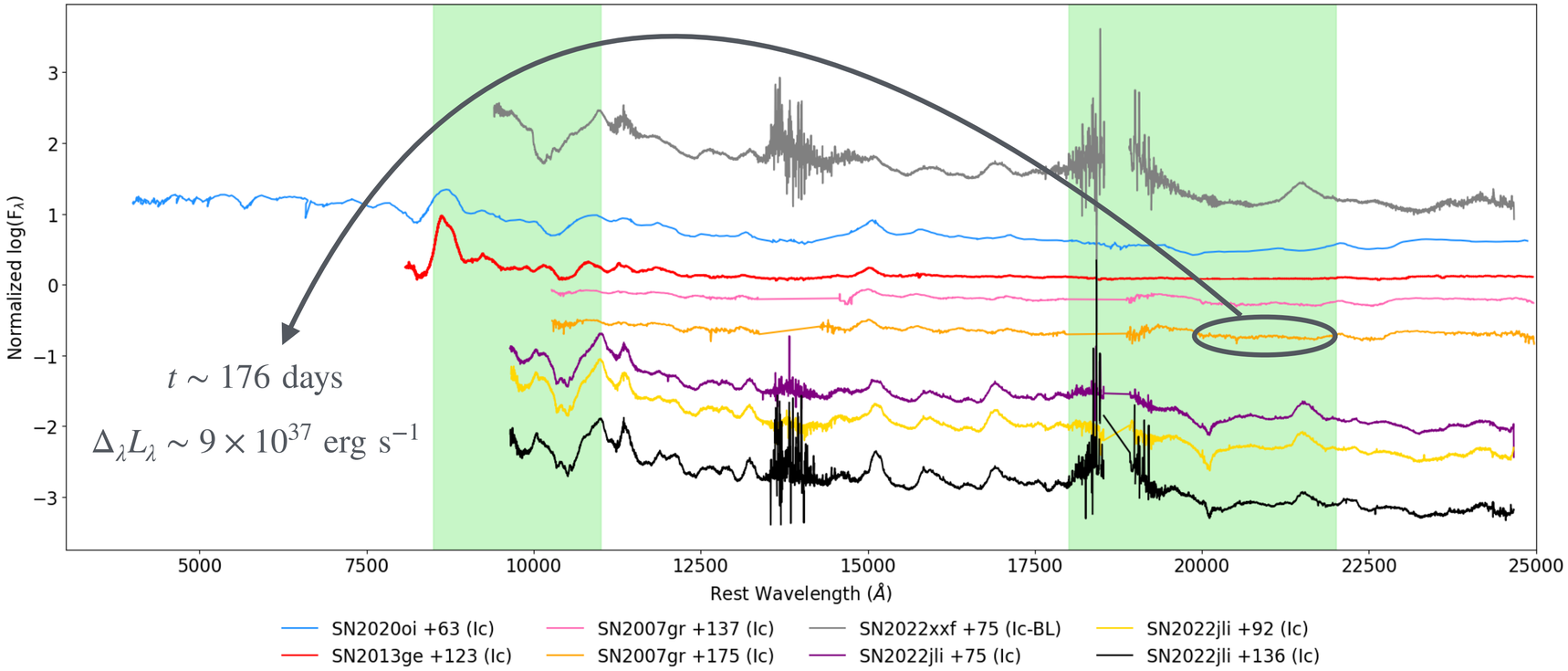
Searching for Te line...

$T_e \sim 4000$ K $n_e \sim 10^7$ cm^{-3}

Line dominated by radiative de-excitation:

$$\Delta_\lambda L_\lambda = N_{\mathrm{Te}} E_\lambda n_e k_\lambda$$



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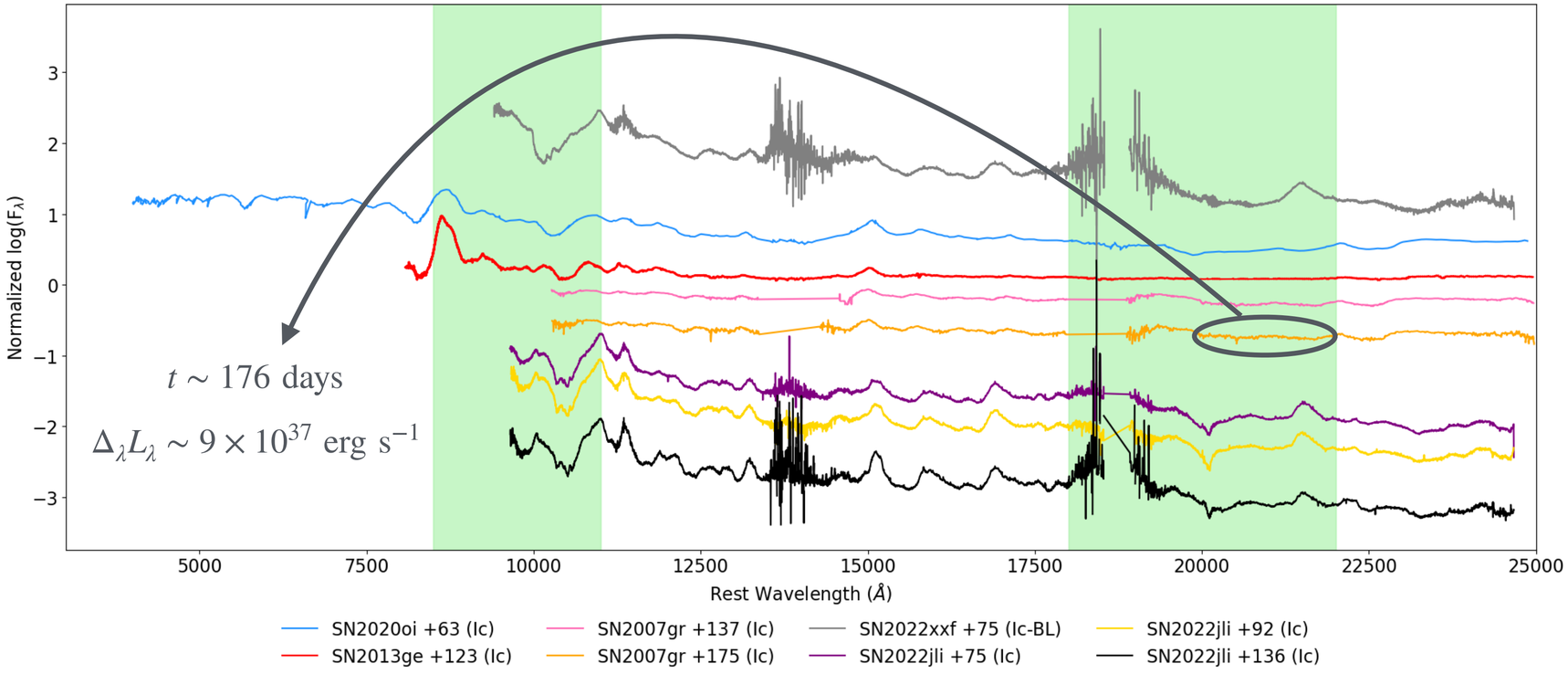

$$M_{\rm r} \lesssim \left(\frac{\Delta_\lambda L_\lambda}{5\times10^{41}\ {\rm erg\ s^{-1}}}\right)\left(\frac{X_{\rm r,Te}}{0.03}\right)^{-1}\left(\frac{n_e \Omega_\lambda}{10^7\ {\rm cm^{-3}}}\right)^{-1} M_\odot$$

Limit to r-process mass:

$$M_{\rm r} \lesssim 2\times10^{-4}\ M_\odot$$

Outlook

Art Credit: NASA

Searching in special SNe…

- r-process material could be seen in **light curve** at **tens of years** only with good sampling
- Difficult for heavy elements to dominate **cooling** of ejecta (**lot of mass needed**)

- Presence of heavy elements expected to be **detectable** in **broad-line Ic nebulae** with **JWST**, in range $\sim 1 - 10\ \mu\mathrm{m}$, due to otherwise relatively flat spectrum
- For example, **Te** at $2.10\ \mu\mathrm{m}$ as possible **fingerprint**