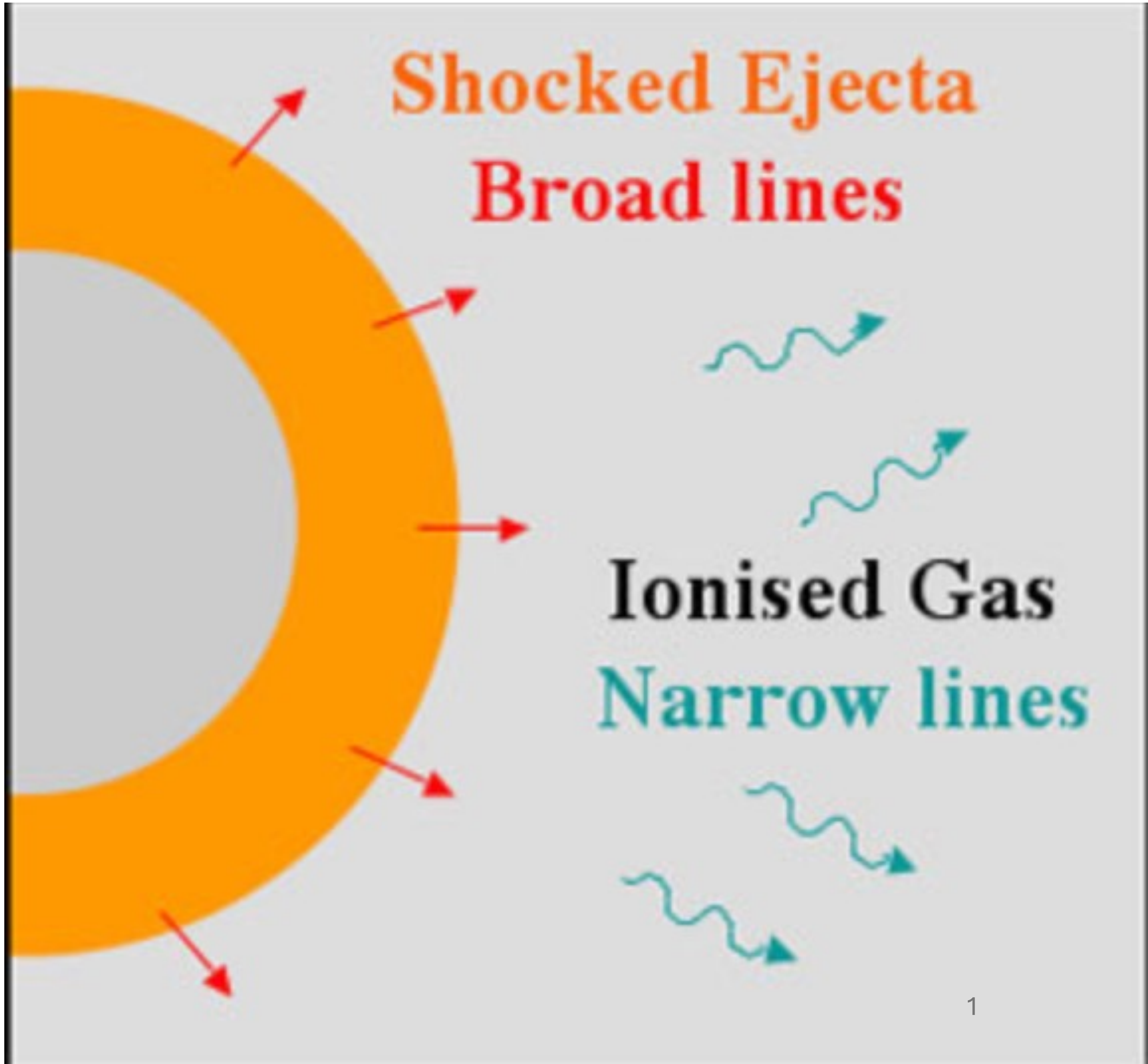
Line profiles in supernovae

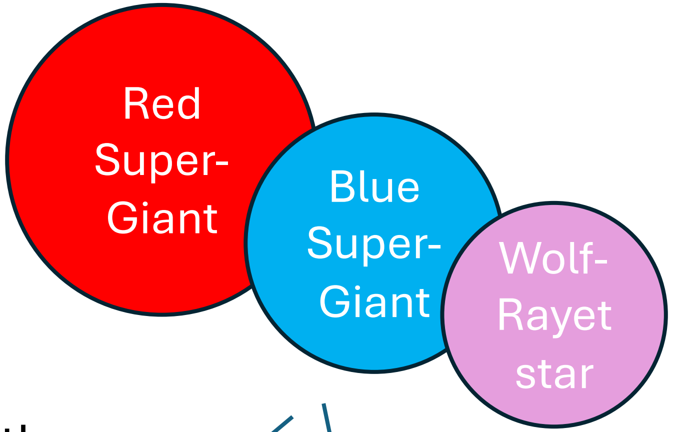
Anders Jerkstrand
Department of Astronomy,
Stockholm University



Supernovae

1) Massive star

Core collapses
→ explosion



Little mass loss

Type IIP
P for plateau

Type II-peculiar

Type IIL
L for linear

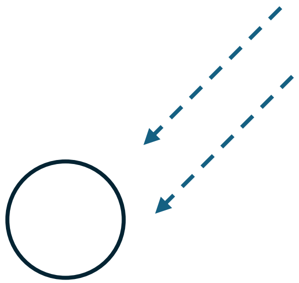
Strong mass loss

Type IIb
Some H

Type Ib
No H

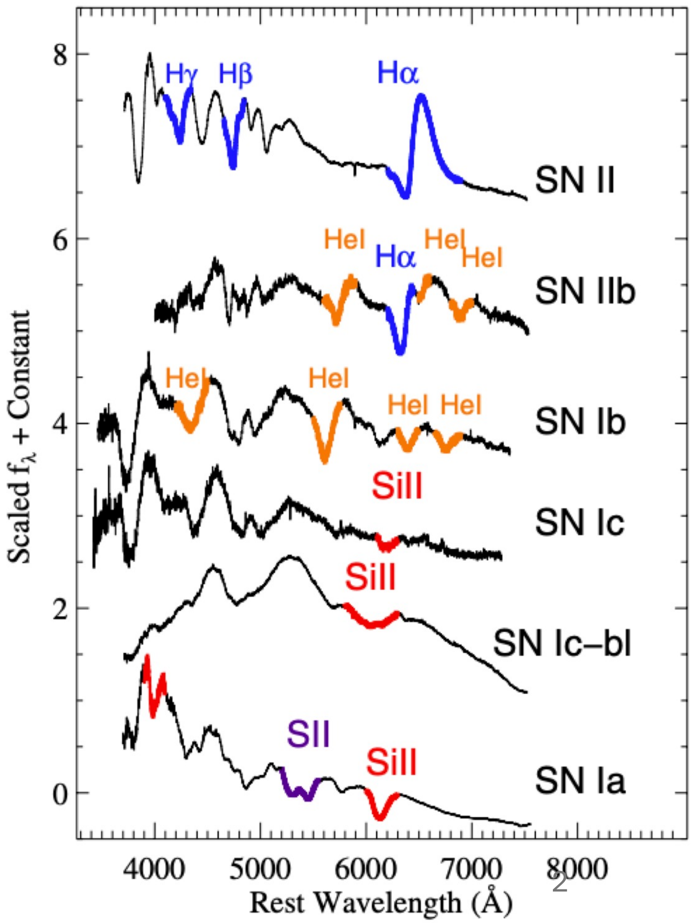
Type Ic & Ic-bl
No H or He

2) White dwarf



Mass accretion heating
→ degenerate C ignition

Type Ia



Line transfer in differentially moving media

Homologous expansion : $\mathbf{r = v_r * t}$

Velocity gradient **dv/ds** $\mathbf{= dv_r /dr =}$ **<u>1/t</u>**
From each point, expansion looks isotropic, "Hubble Flow"

Resonance layer width Δs = $\mathbf{c/\nu_0}$ * $\mathbf{\Delta\nu}$ **(line width)* t**
$\mathbf{= c * (v_{th} / c) * t = v_{th} * t}$

→ **Δs / R (size of nebula)** $\mathbf{= v_{th} / v_{exp}}$

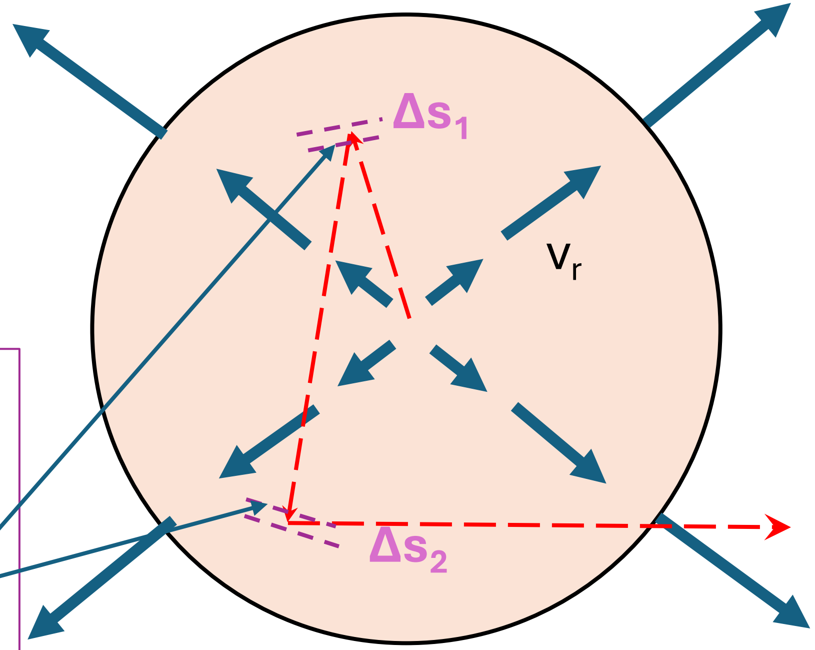
$\mathbf{v_{th} \sim \sqrt{(k\,T/ m)} \sim 1}$ **km/s**

$\mathbf{v_{exp} \sim 10^4}$ **km/s**

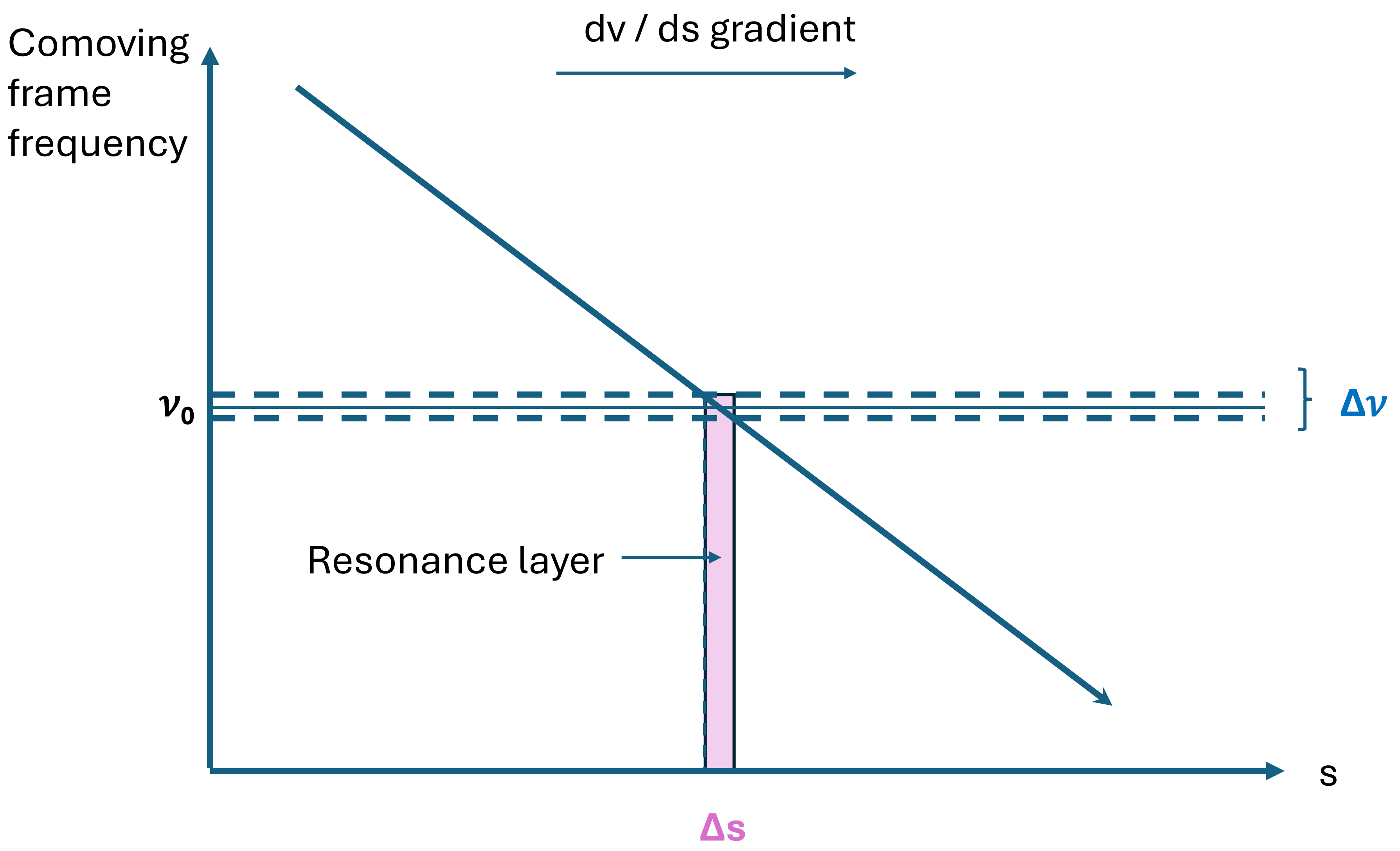
→ **Δs / R << 1**

→ <u>Line interaction occurs over a very small part of the nebula – '**resonance points**'.</u>

$v = v_{exp}$
at outer
radius R



Line transfer in differentially moving media



Line transfer in differentially moving media

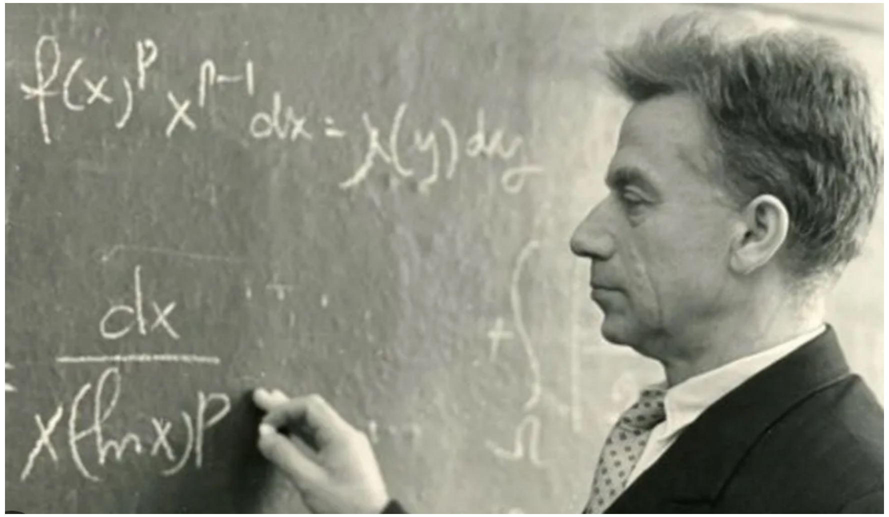
$$\tau_{Sobolev} = \frac{1}{8\pi}\frac{g_u}{g_l}A\lambda^3 * n_l * t$$

(ignoring stimulated emission correction)

Line atomic data constants

Number density of lower state (at resonance point)

Inverse of velocity gradient ($\Delta s \propto t$)



Very differently to static media, here τ

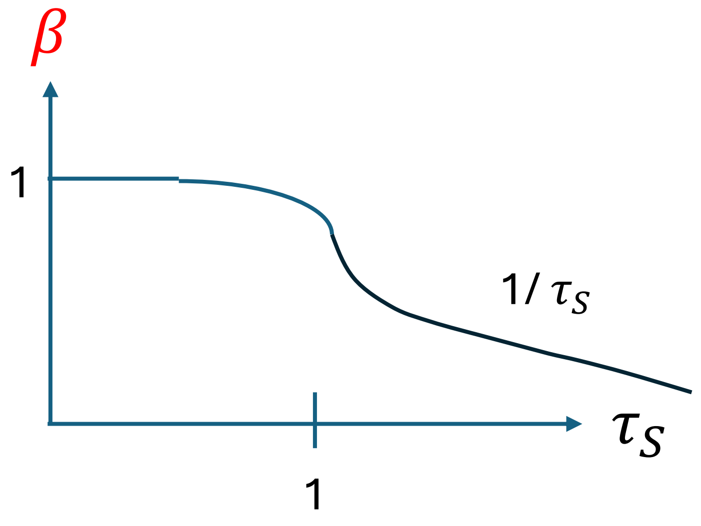
1) Is a **line-integrated** quantity.

2) Depends on the **number density** n_l **(at the resonance point),** rather than the integrated column density (N_l).

Line transfer in differentially moving media

The **Sobolev escape probability** β (homologous case):

$$\beta = \frac{1 - e^{-\tau_S}}{\tau_S}$$



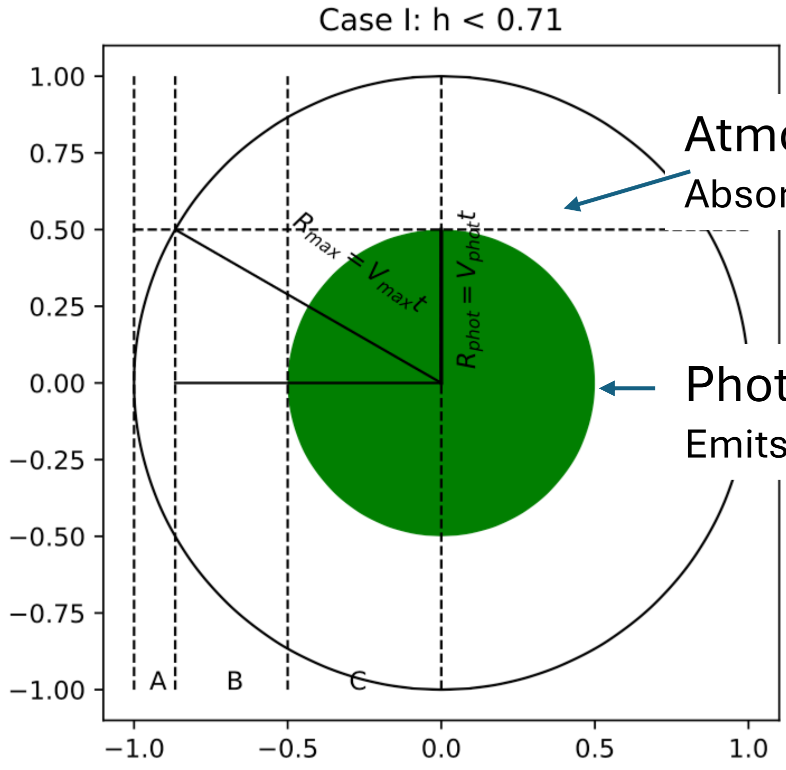
Can be used in the **statistical equilibrium equations** to simplify

$$n_u A - n_l B_{lu} \bar{J} \left(1 - \frac{n_u g_l}{n_l g_u}\right) \rightarrow n_u A \beta - n_l B_{lu} \beta J_{ext} \left(1 - \frac{n_u g_l}{n_l g_u}\right)$$

Don't need to solve for radiation field in the line ($\bar{J}$).

Derived with Complete Redistribution assumption but accurate (few %) also with Partial Redistribution (Chugai 1980, Hummer+1992)

The P-Cygni line profile

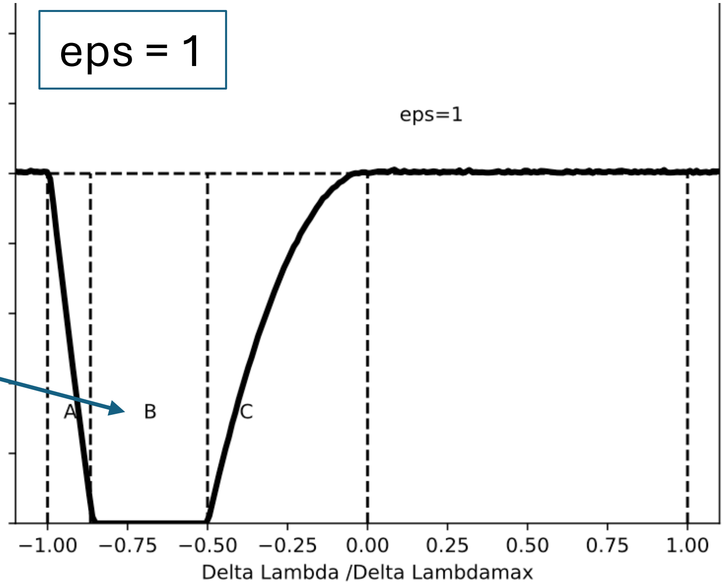


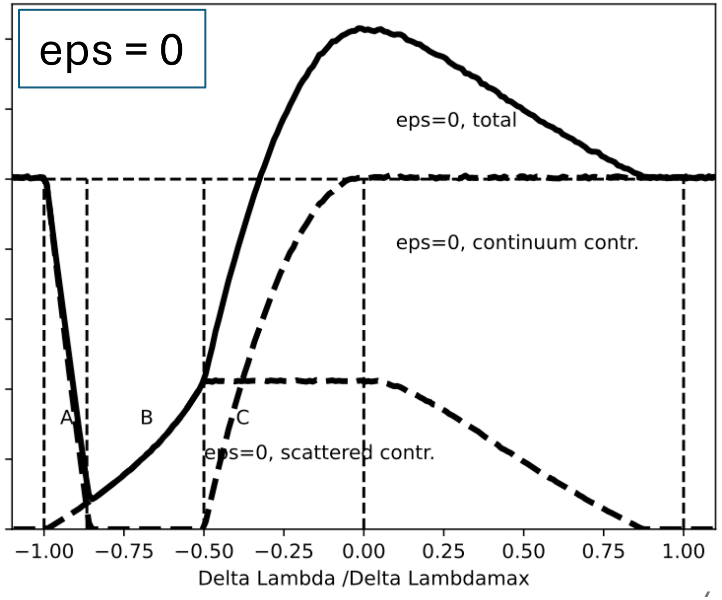
Atmosphere
Absorbs and scatters the continuum

Photosphere
Emits continuum radiation

Height of peak:
→ infer ε (= thermalization probability)

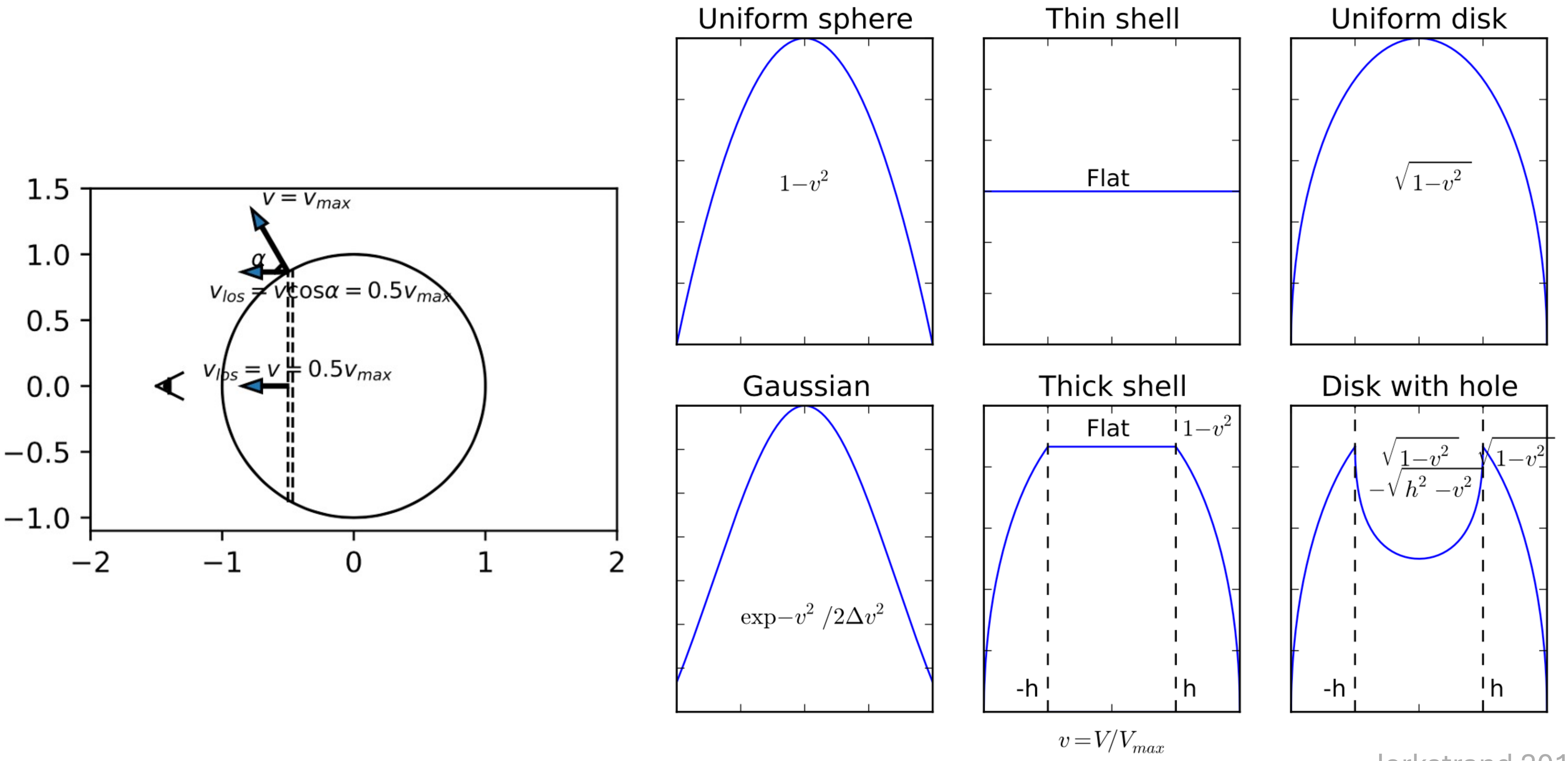
Peak occurs at λ_0
→ identify the line





Absorption part:
→ infer geometry

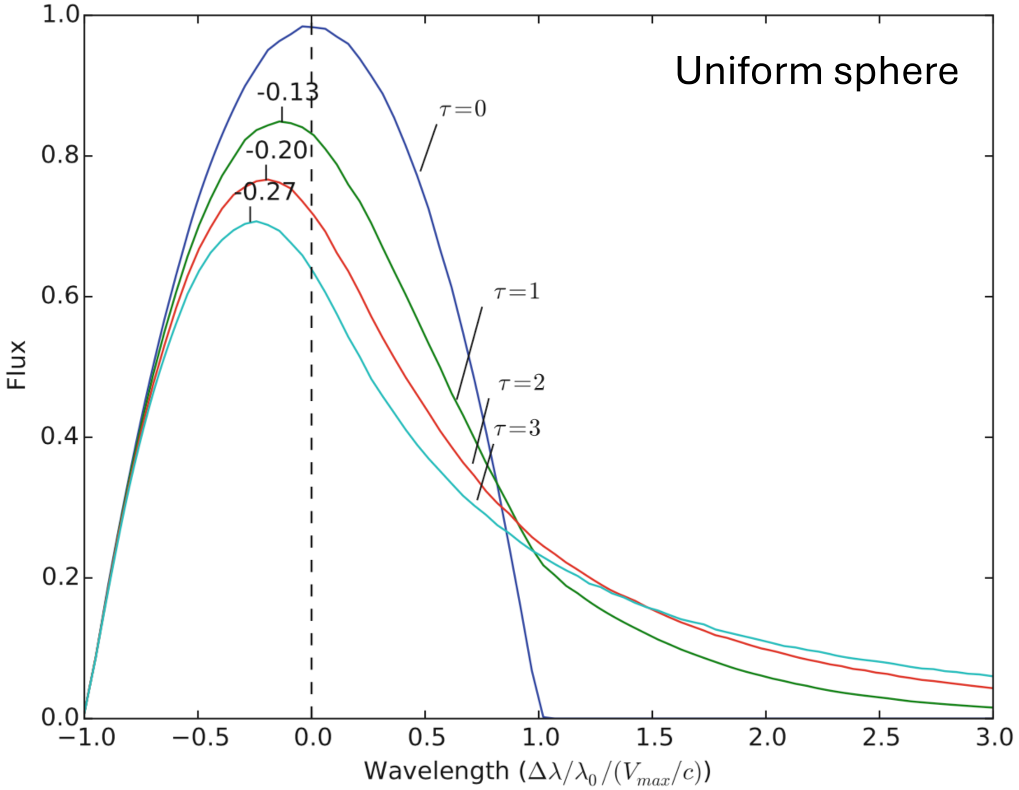
Emission line profiles



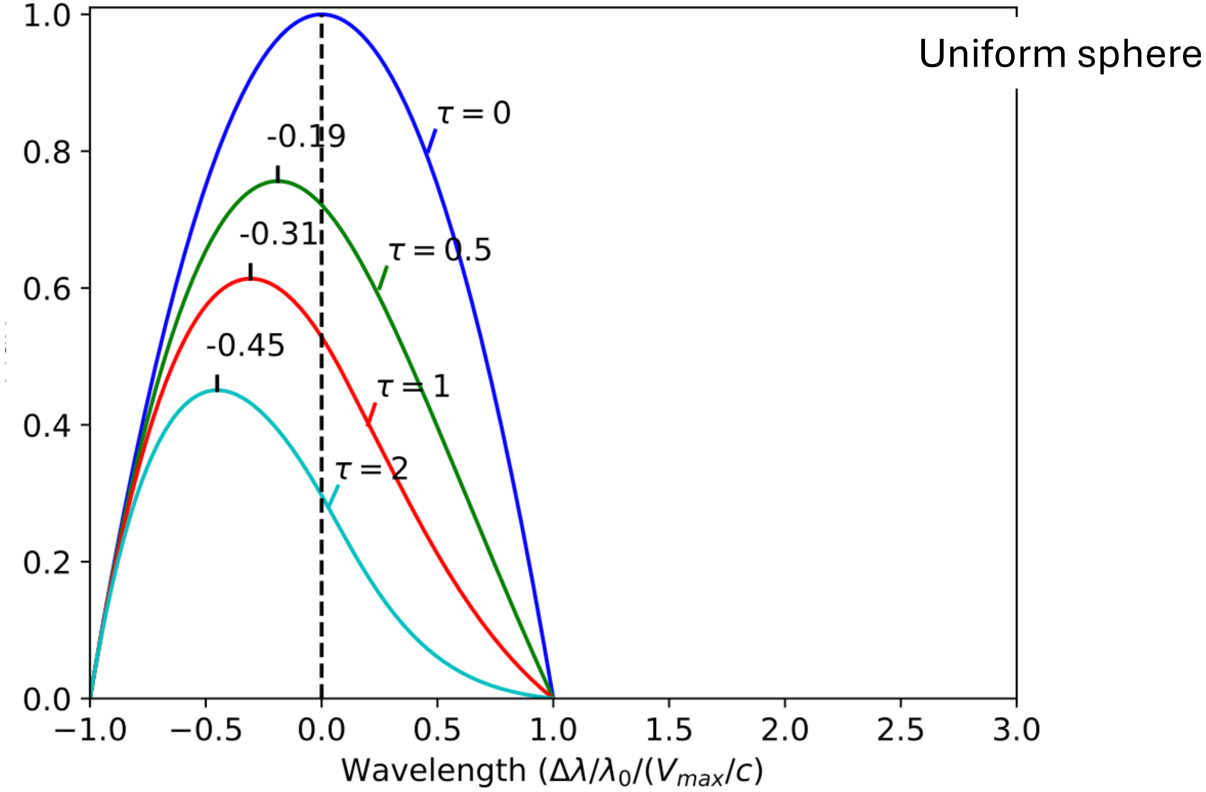
Jerkstrand 2017, Handbook of SNe

Emission line profiles : radiative transfer effects

Scattering (e.g. by free electrons):



Absorption (e.g. by dust):



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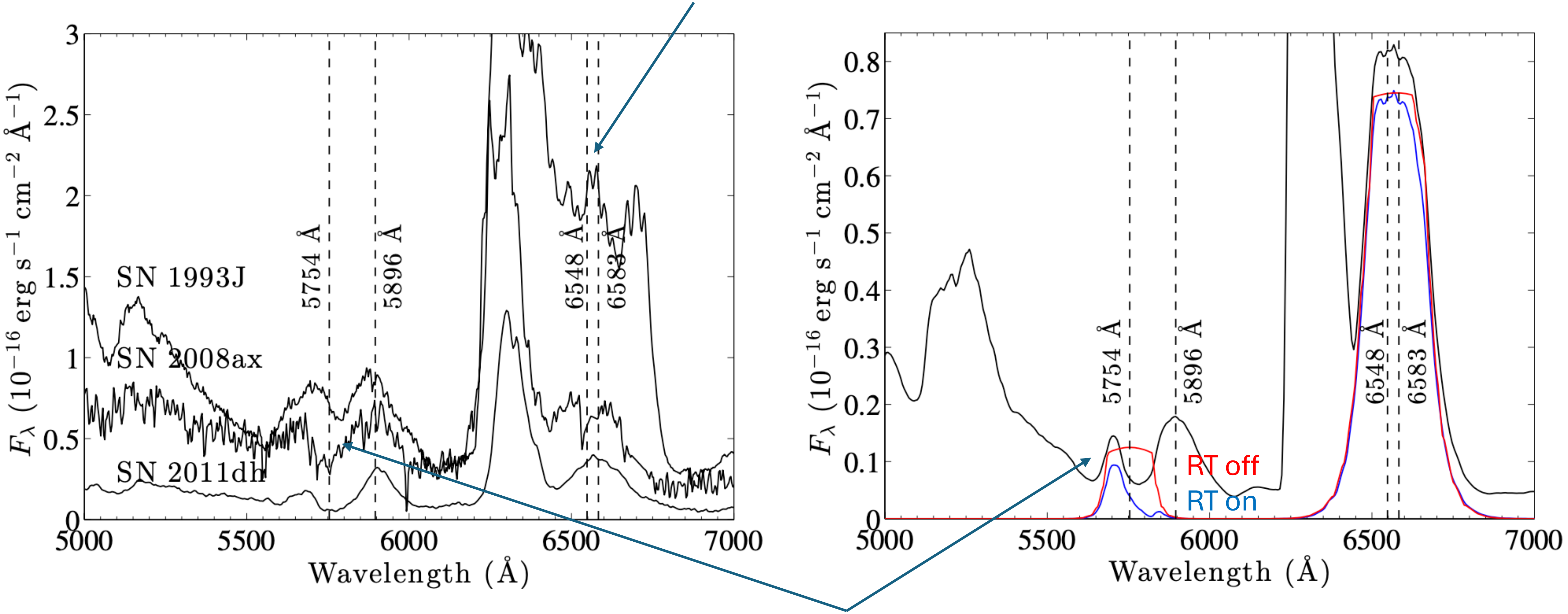
Example of radiative transfer effects

Strong emission at ~6560 Å : Hα or [N II] 6548, 6583?



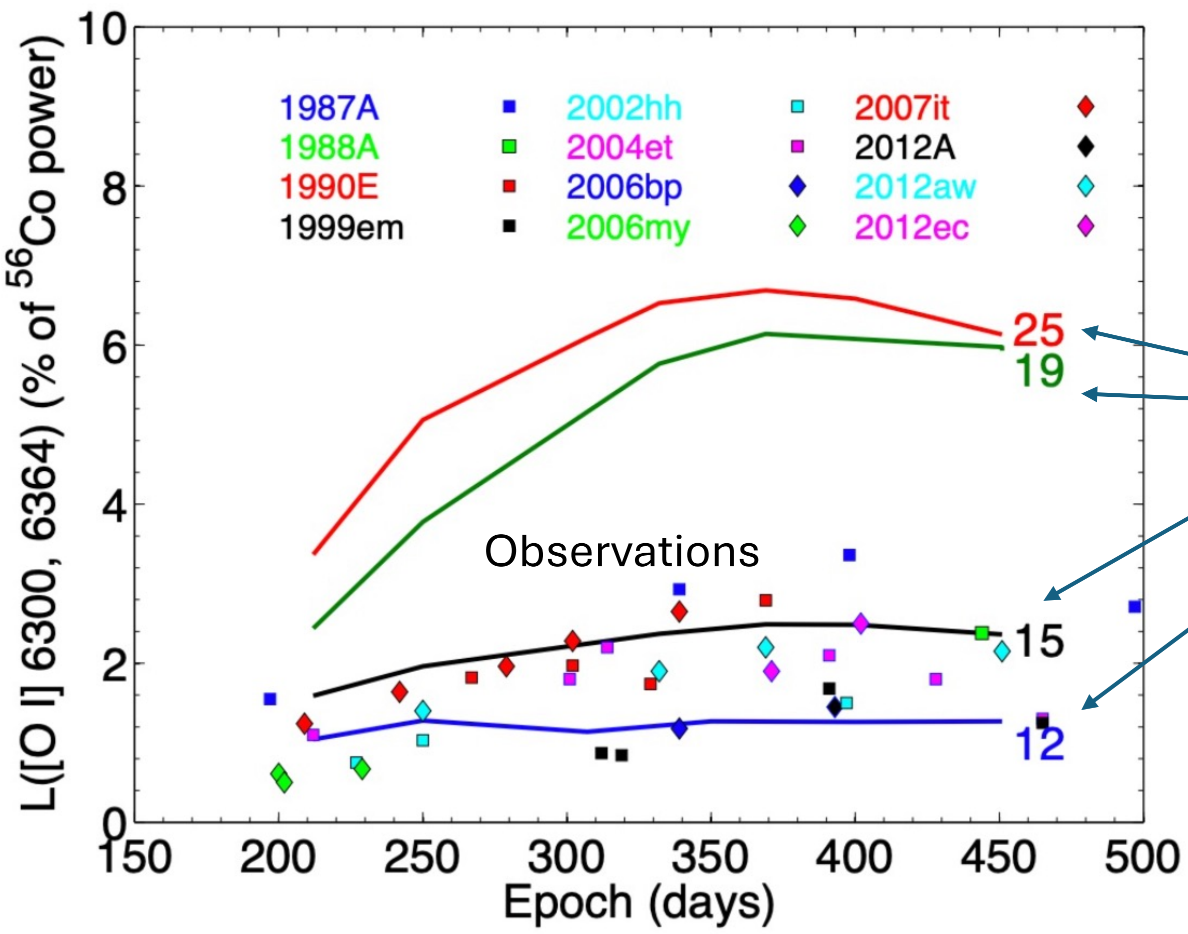
Identify [N II] 5754 by understanding the radiative transfer

→ Confirm it's [N II]

Jerkstrand+2015 (MNRAS)

Auroral oxygen lines in supernovae

[O I] 5577
[O I] 6300, 6364



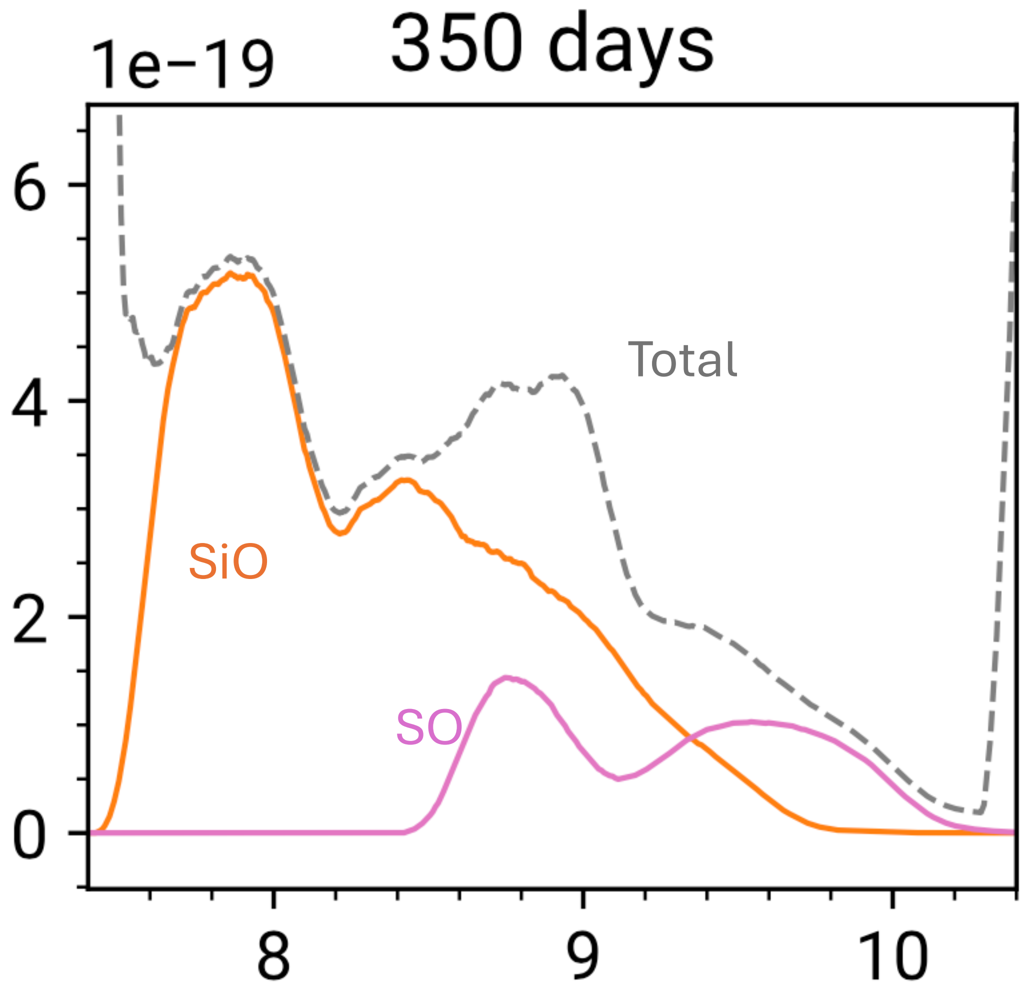
Full NLTE radiative model predictions (SUMO code) for different stellar masses.

Jerkstrand+2014

Important new microphysics: Molecules (Liljegren,AJ+2020,2023) , charge transfer (Reja, Barklem,AJ+2025), dust.

Recent addition to SUMO: Molecules

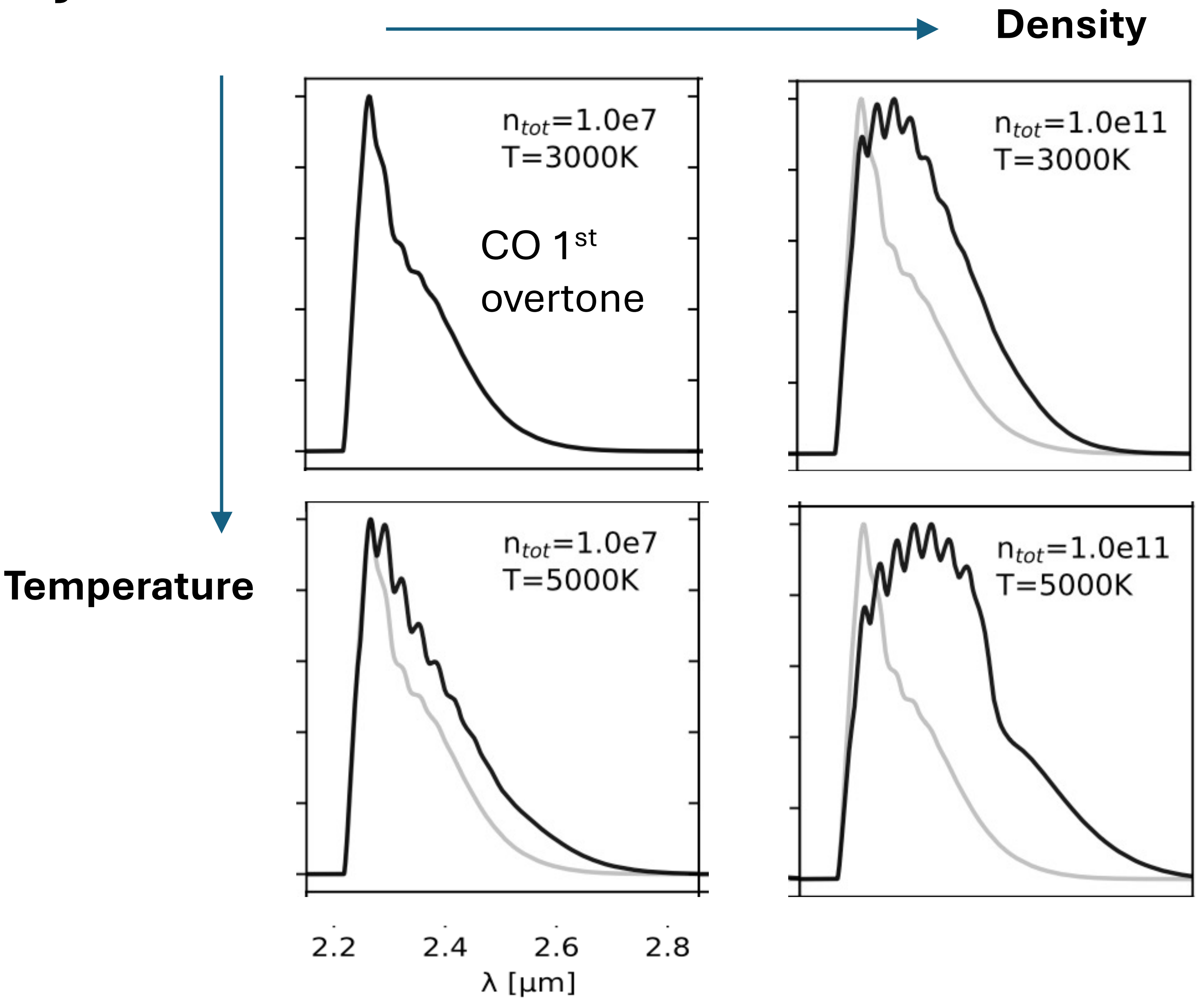
Liljegren+2023



Chemical network with 22 molecules, 4 in full NLTE.

Full chemical modelling needed to understand blended line profiles,

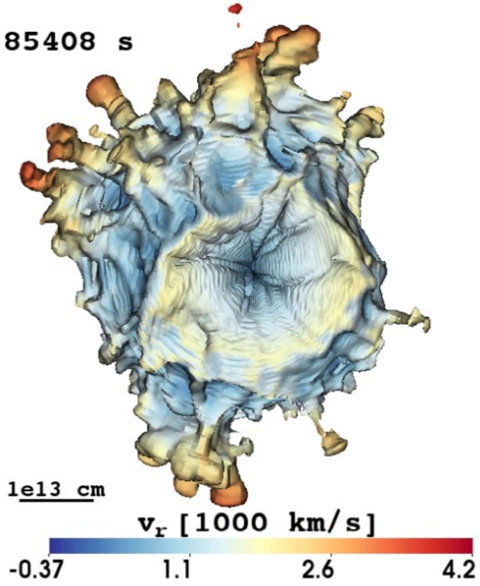
In contrast to atomic lines: molecular features probe also local physical conditions



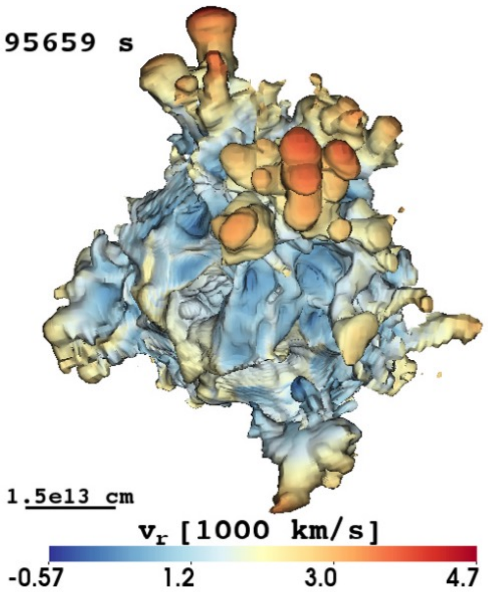
Liljegren, AJ+2023

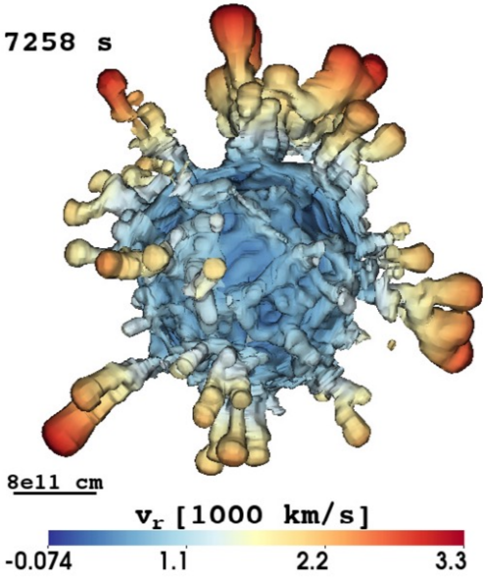
3D modelling

3D modelling

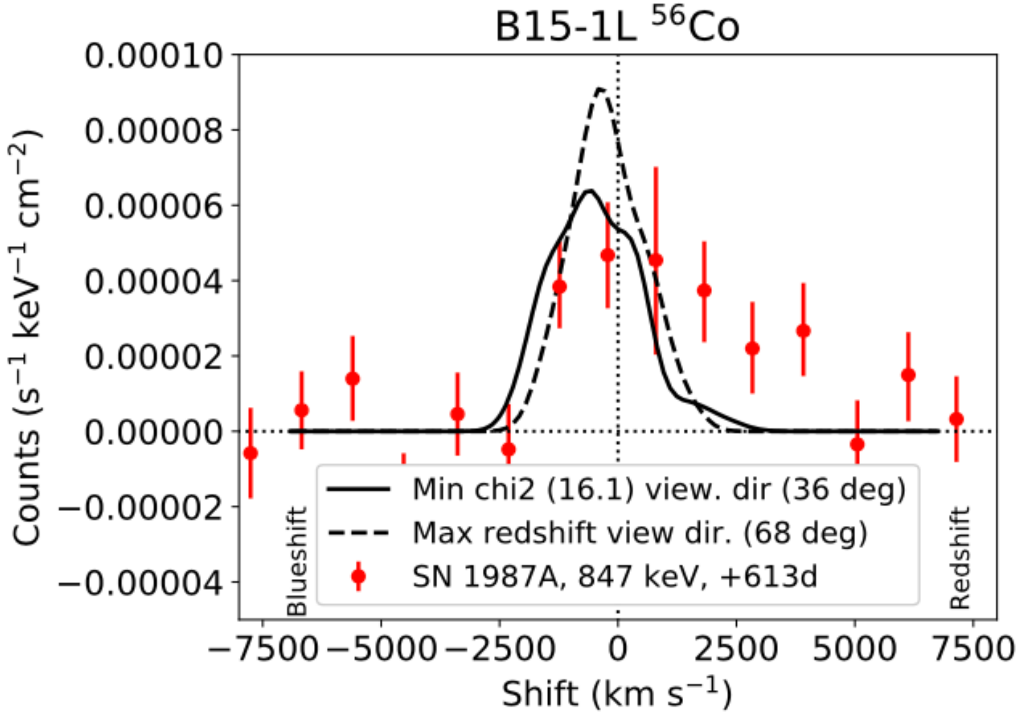


Long-term 3D simulations from MPA Garching group





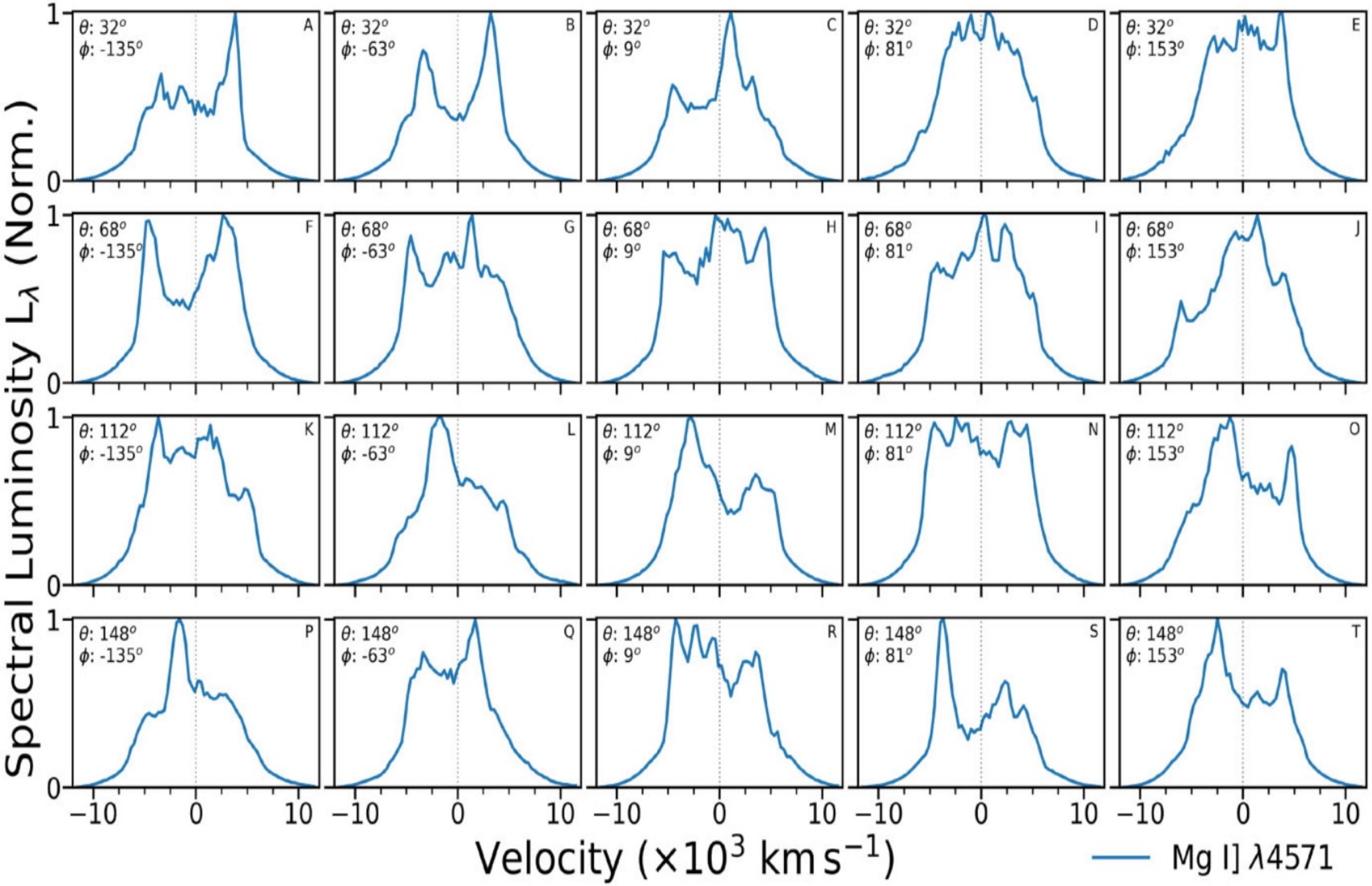
3D radiative transfer



AJ+2020, MNRAS

3D modelling, optical lines

Van Baal+2023



Can get complex shapes with severe viewing angle variations

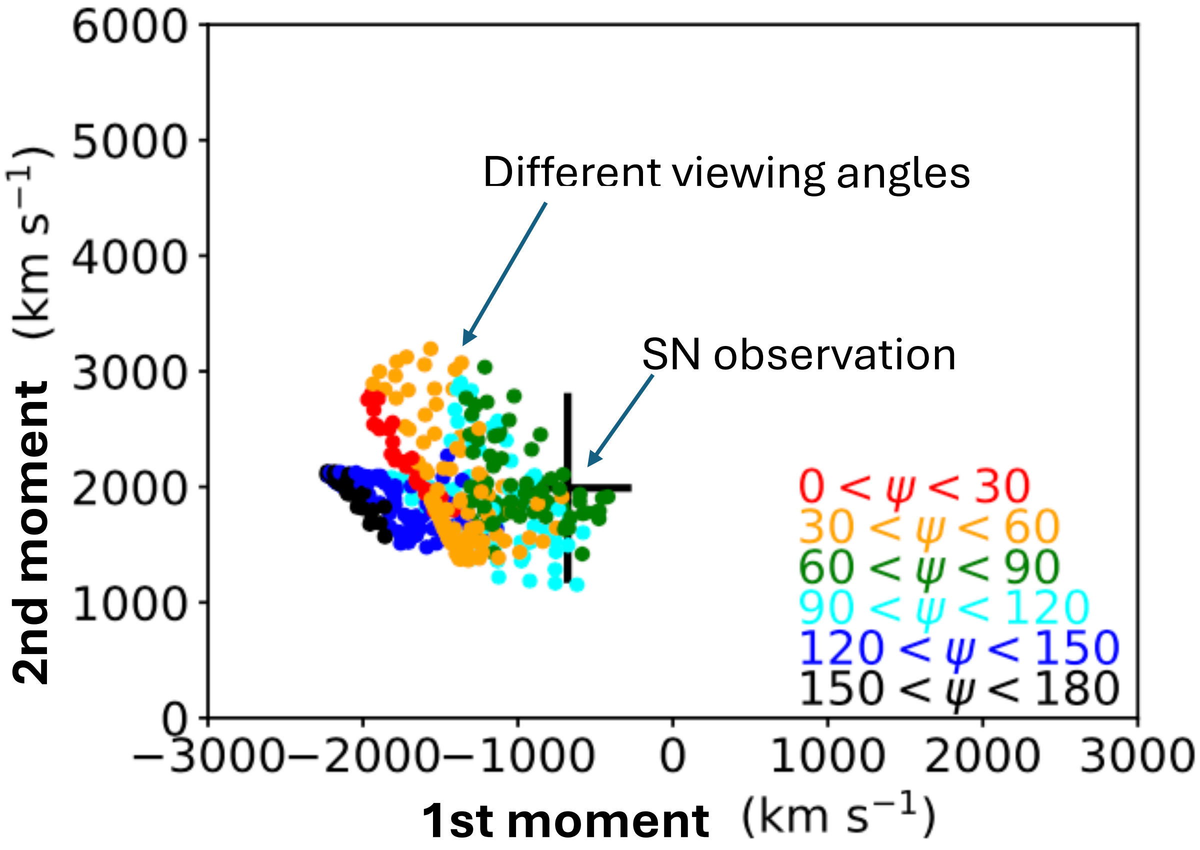
Characterizing line profiles by **1st, 2nd, 3d moments**:

AJ+2020, van Baal, AJ+2023

$$v_{\rm shift} = \frac{\int_{-v_{max}}^{v_{max}} L_\lambda v(\lambda) d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda},$$

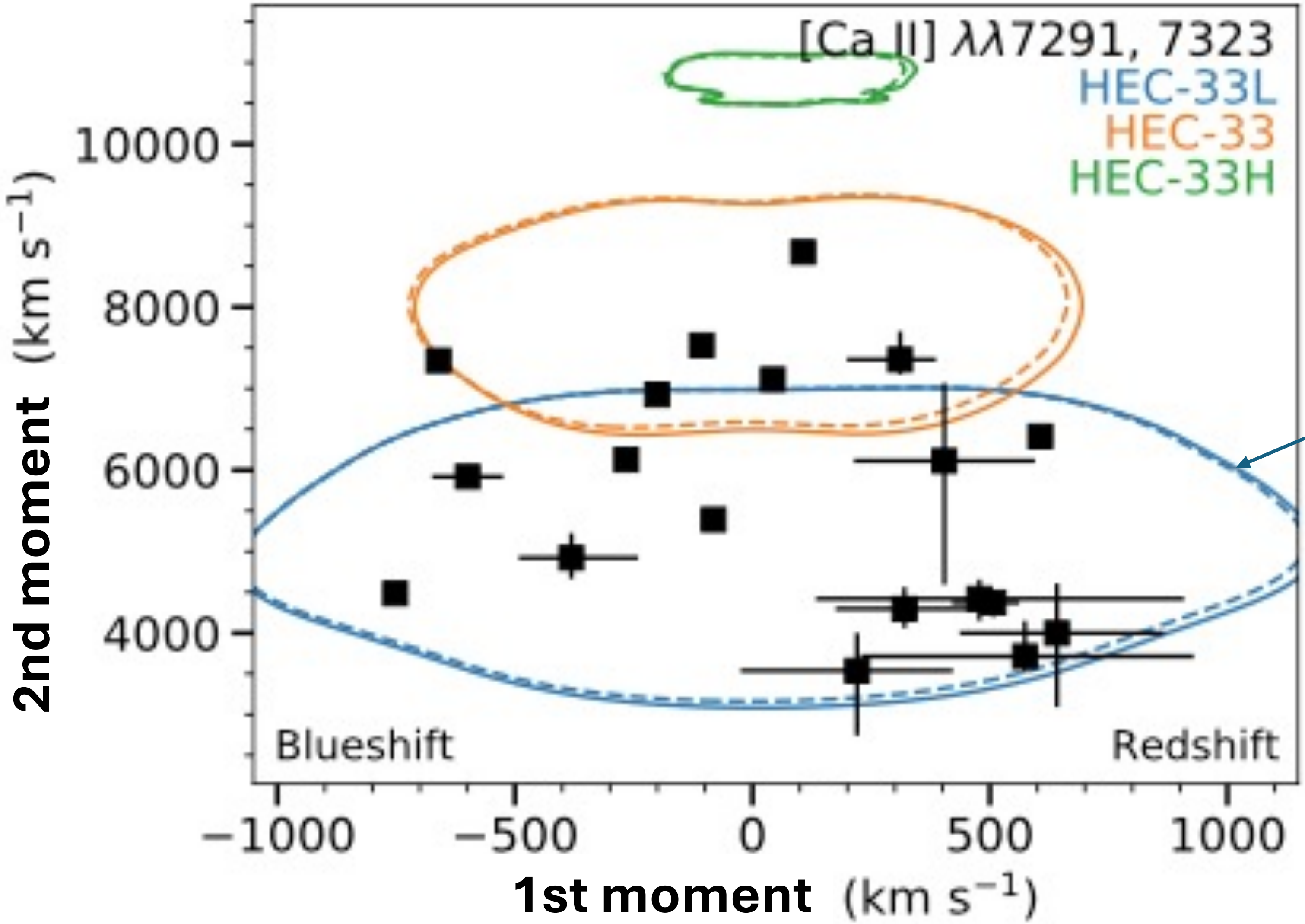
$$v_{\rm width} = 2.35 \times \left(\frac{\int_{-v_{max}}^{v_{max}} [v(\lambda) - v_{\rm shift}]^2 L_\lambda d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda} \right)^{1/2},$$

$$v_{\rm skew} = \left(\frac{\int_{-v_{max}}^{v_{max}} [v(\lambda) - v_{\rm shift}]^3 L_\lambda d\lambda}{\int_{-v_{max}}^{v_{max}} L_\lambda d\lambda} \right)^{1/3}.$$



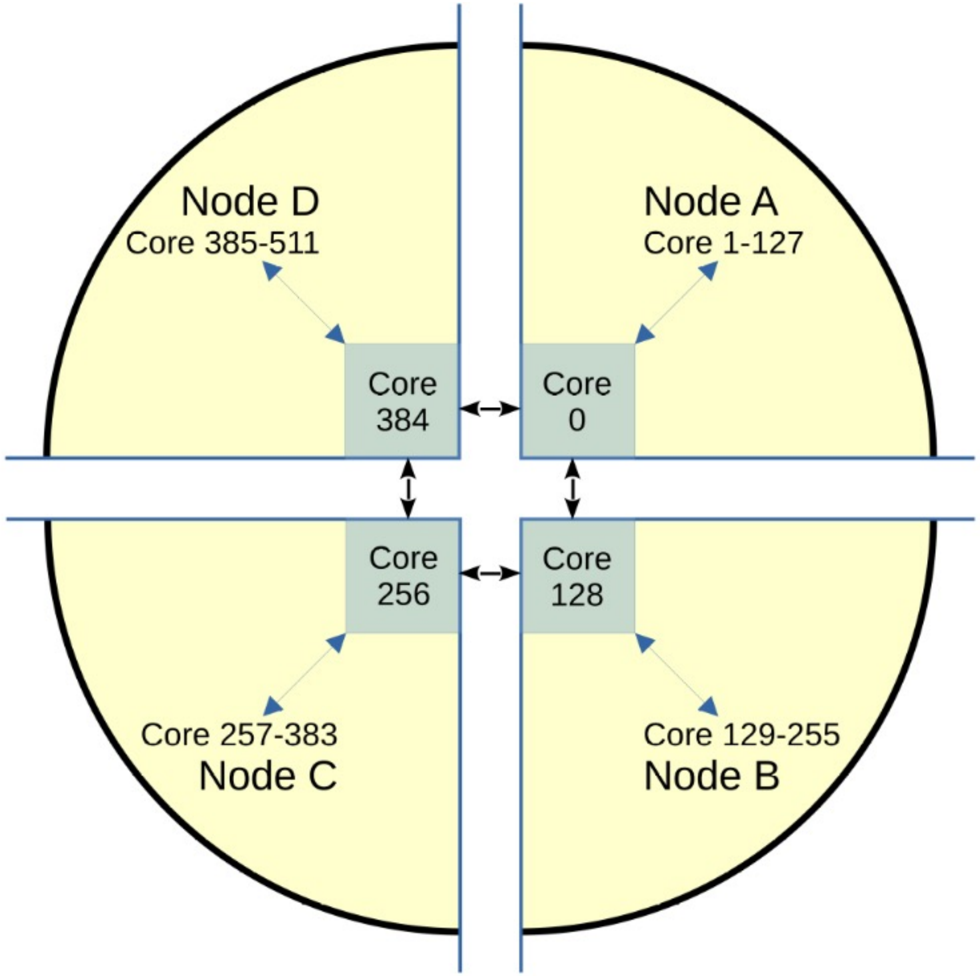
Optical lines, sample analysis

van Baal, AJ+2023, 2024



Domain covered
by all viewing angles

Computational aspects



- 3D NLTE needs to compute and store many photoexcitation rates.

E.g., 30^3 cells, 30 elements, 4 ion stages, 100 levels each → 3E10 rates.

Full star-in-node treatment becomes limiting.

- Solution (ERC project SUPERSPEC) : Domain Decomposition (van Baal & AJ 2026).

Summary

- Line profiles in supernovae probe the kinematic structure of the expanding nebula.
  * Early phases: P-Cygni lines probe outer layers.
  * Late phases: Emission lines probe inner layers. Sometimes with radiative transfer modulations.

- High velocities → localized transfer. Can use escape probabilities in transfer and rate equations.

- Joint modelling of luminosities and profiles needed to determine abundances. Auroral [O I] lines give O nucleosynthesis. Also [N II] 6548, 6583, [Ca ıı], Mg I] 4571, [Fe II] 7155.

- 3D modelling begun in 2020 : Extensive work on Type Ib SNe so far.

- Outlook: Kilonovae (neutron star merger ejecta), Tidal Disruption Events, Active Galactic Nuclei, ..

Thank you for listening!