Frontiers in Nuclear Astrophysics summer school 2025

Supernova spectroscopy

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What is a supernova?

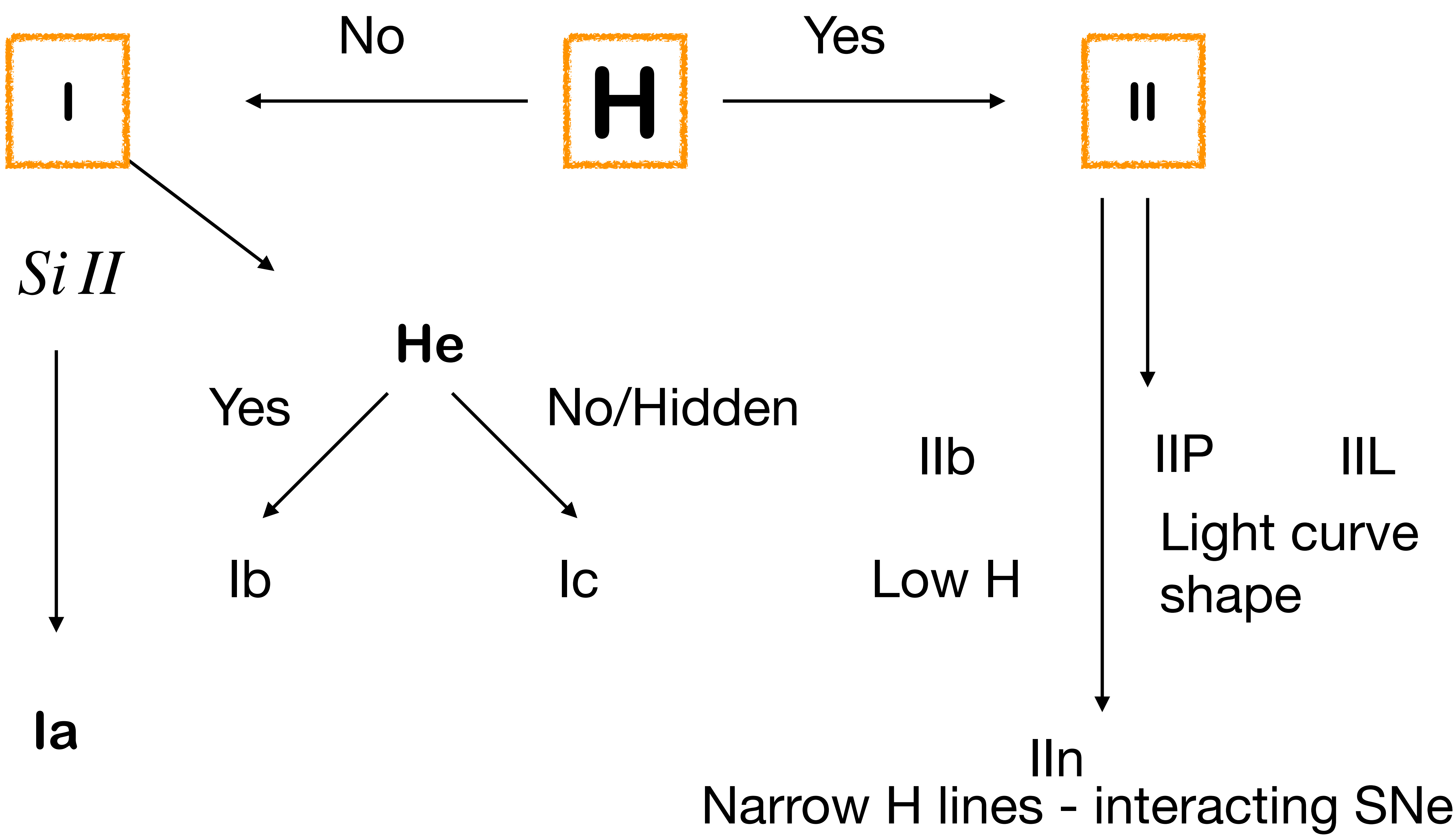
'Novae' - new stars, super - luminous than novae

Supernovae are stellar explosions.

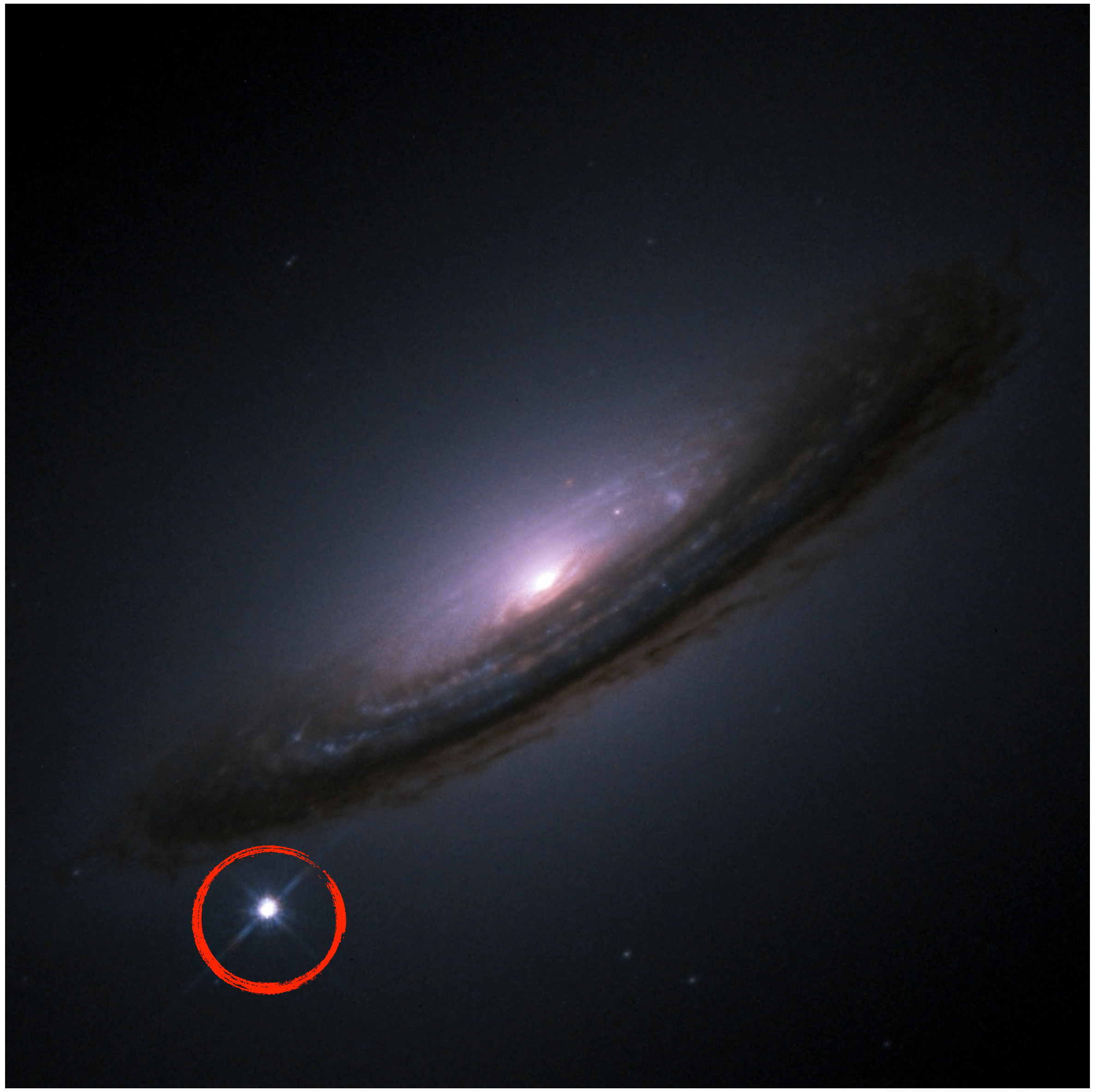
10^{51} ergs (foe) of kinetic energy is released in the explosion.

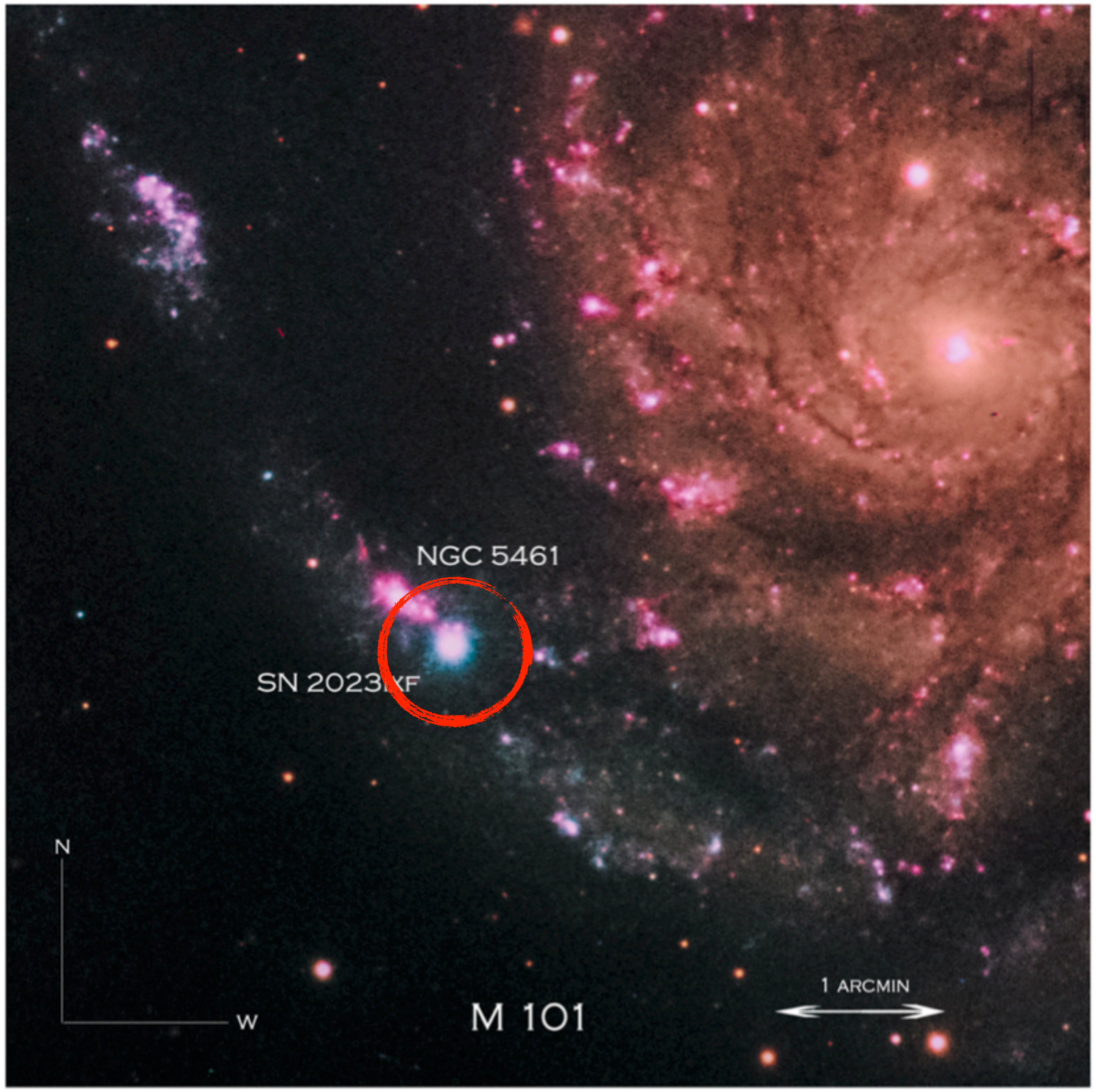
The bolometric luminosity of the sun ~ 3.8 X 10^{33} erg/s. In a year the sun releases ~1.2 X 10^{41} ergs. So the sun if it releases same amount of energy would roughly take 8.3 B years to emit this much energy

The observed supernova zoo



The zoo tells us that the stars are not exploding in the same way.





Color Composite image of SN 1994D in NGC 4526.

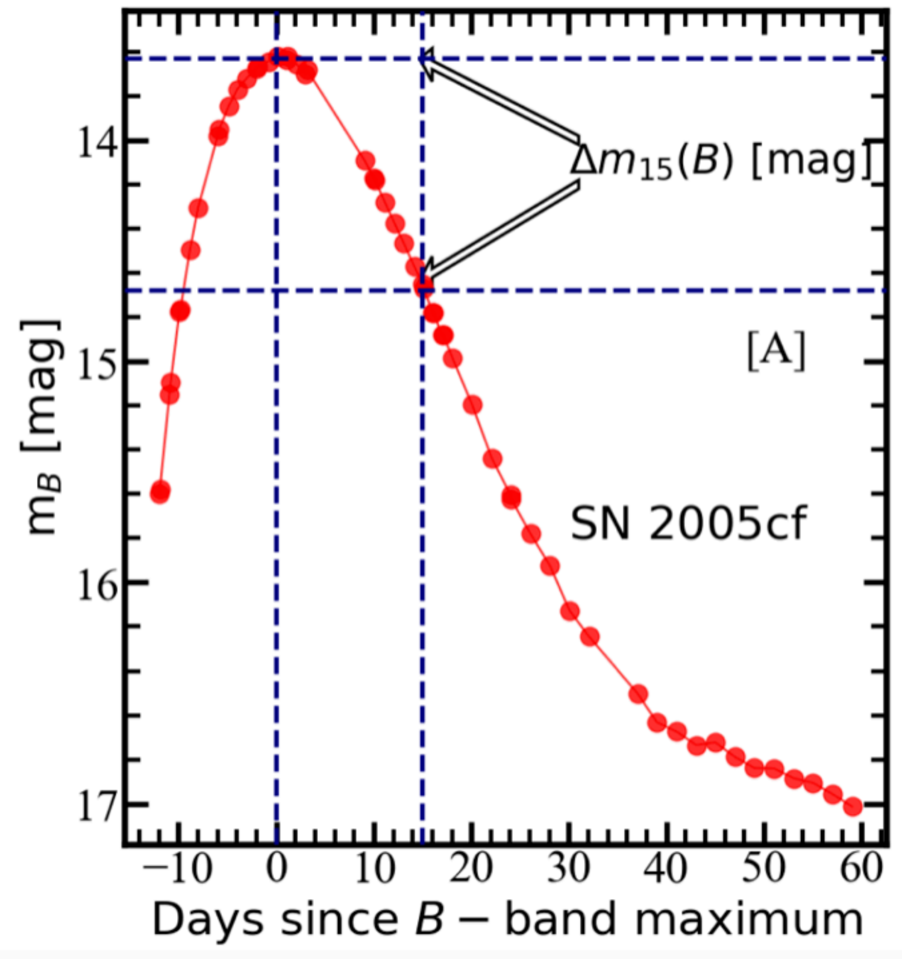
Credits: HST/NASA

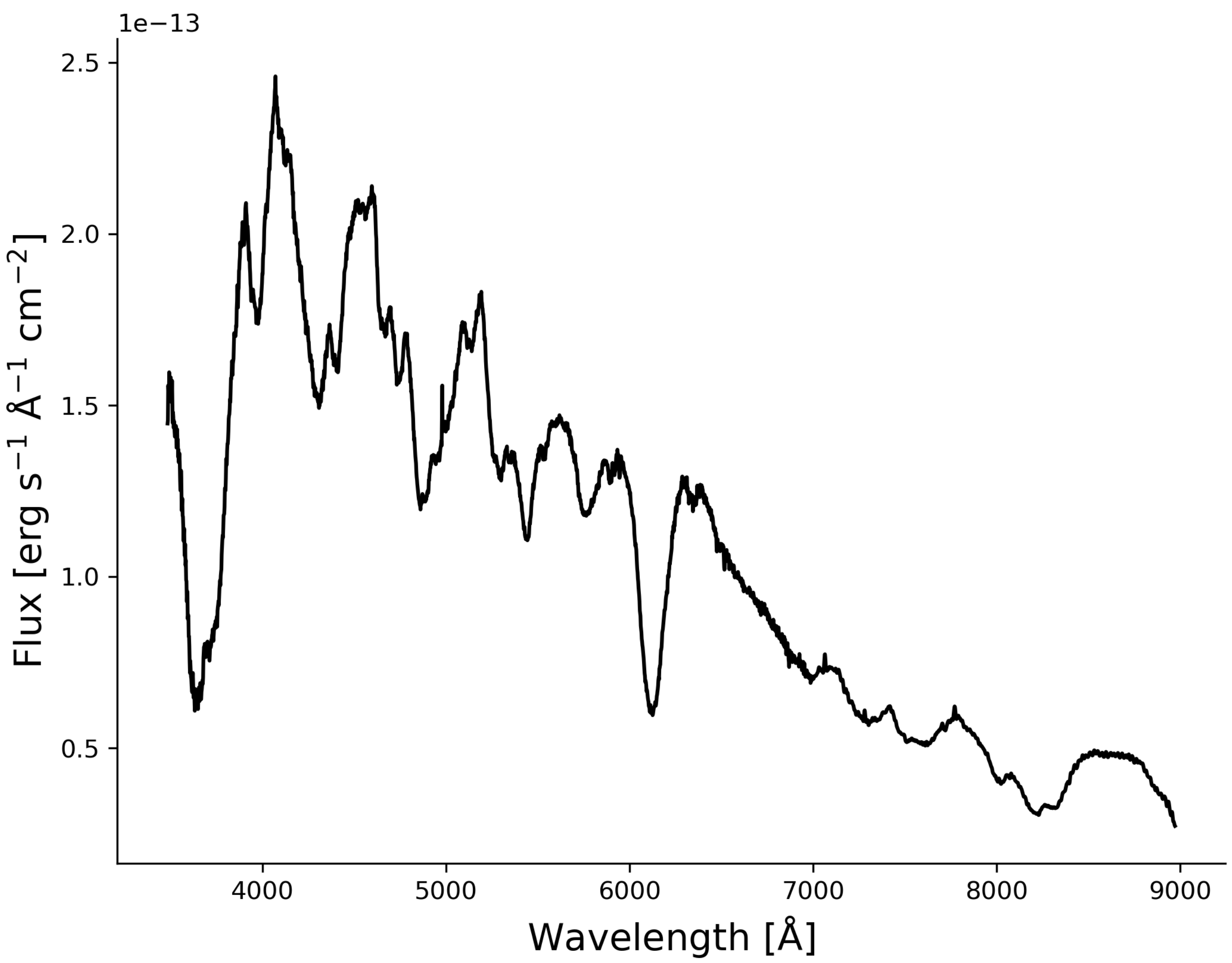
rgb image of SN 2023ixf in M101

Credits: Avinash Singh

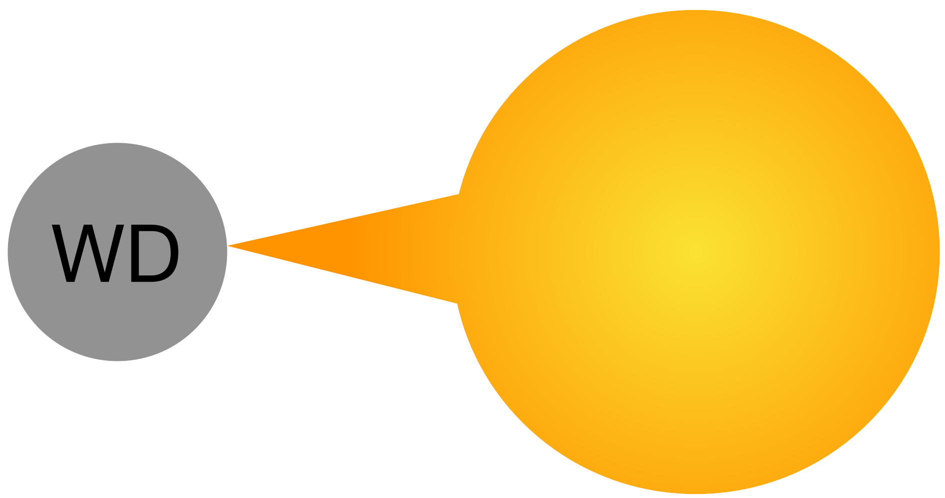
What can we learn from observations?

Observations - Light curves, spectra, polarization, pre/post-explosion imaging.





Thermonuclear Explosions



Accretion scenario

The fundamental question is how can a WD explode.

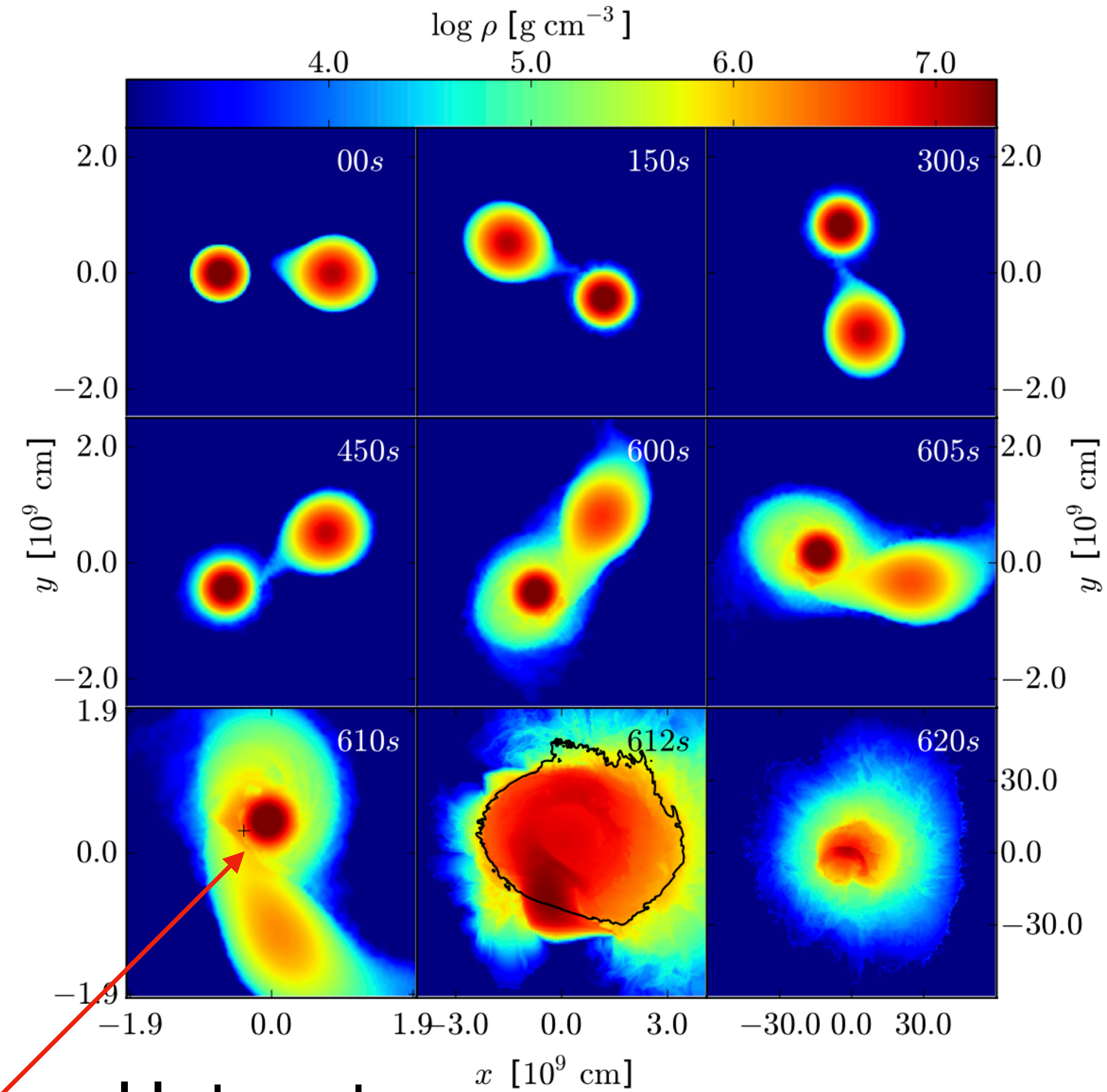
An isolated WD is stable and inert.

A WD in a binary system can increase its mass by accretion.

As the material is compressed the temperature increases - initiating thermonuclear reactions.

The ignition can be located at the centre, off-centre or in the outer layers.

Thermonuclear Explosions



Hotspot

Merger scenario

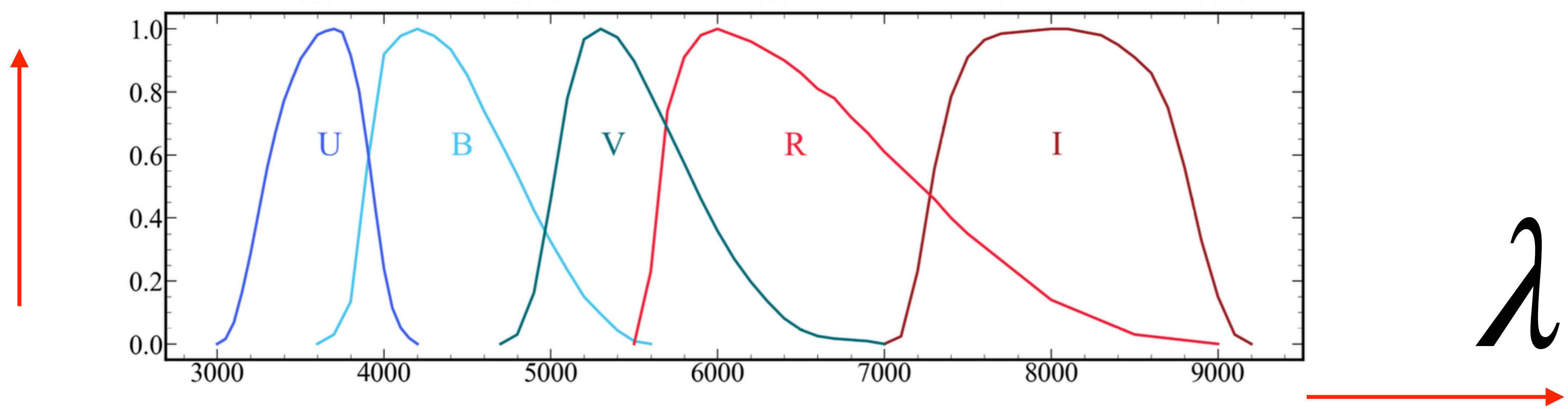
Pakmor+ 2012

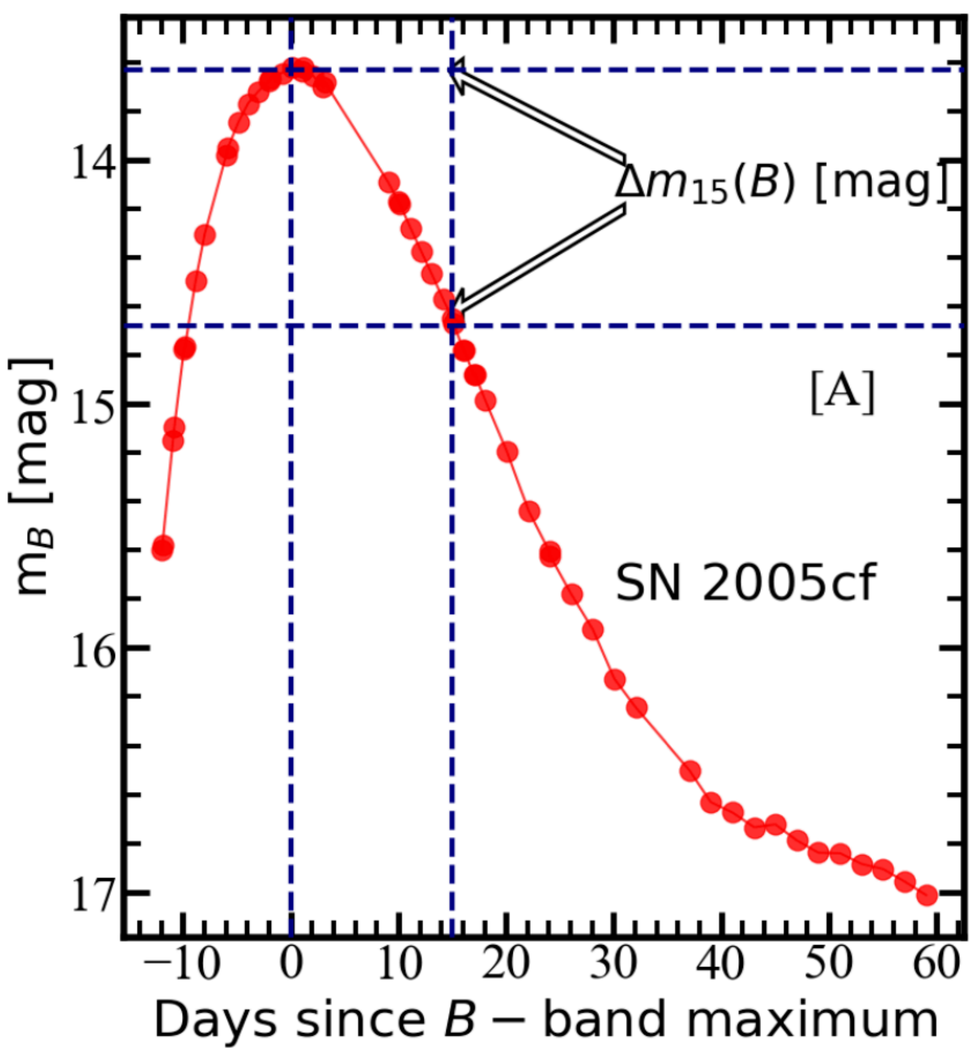
Merger of two WD of masses 1.1 and 0.9 $M_{\odot}$

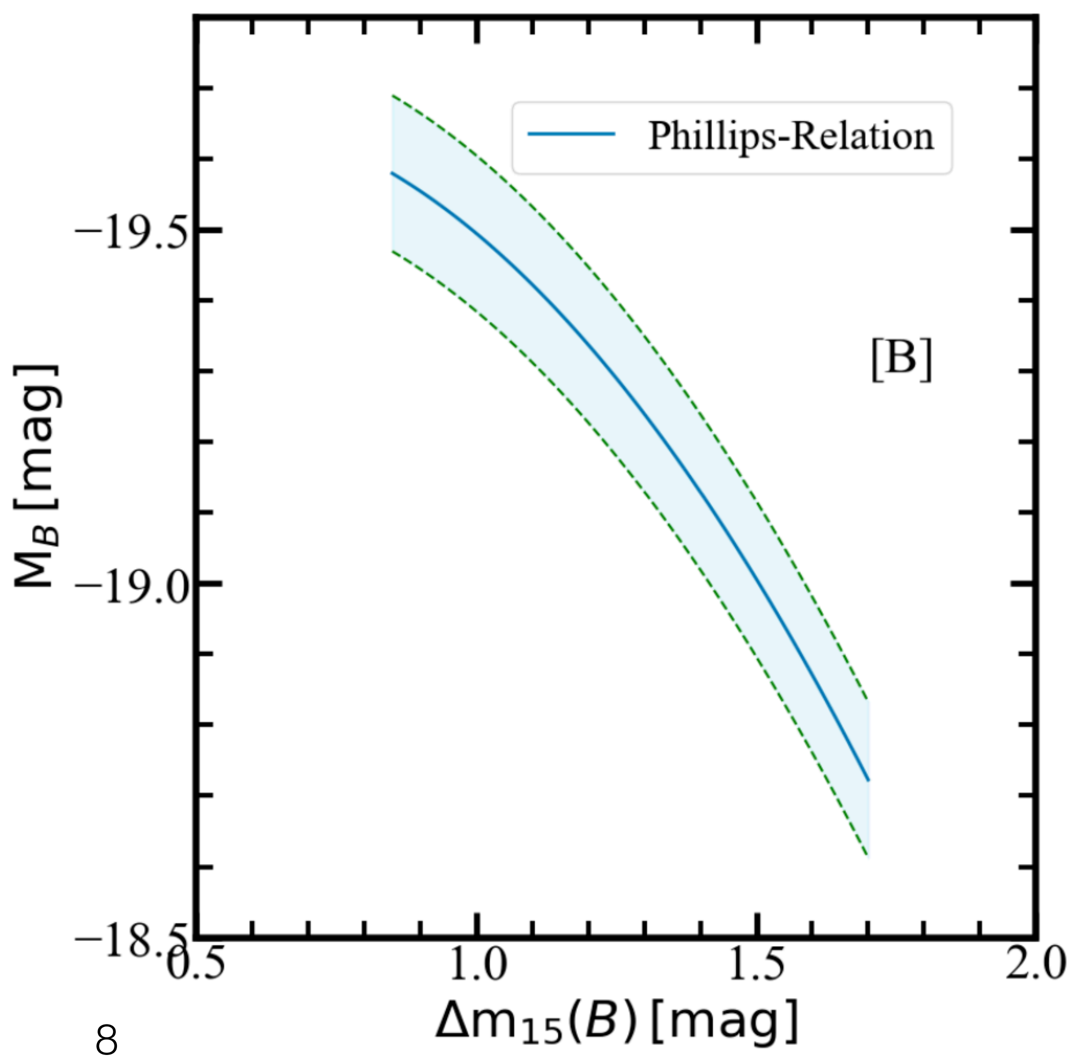
After about 600 s the secondary WD becomes dynamically unstable and and is accreted violently on the primary.

The material is compressed and the temperature is increased.

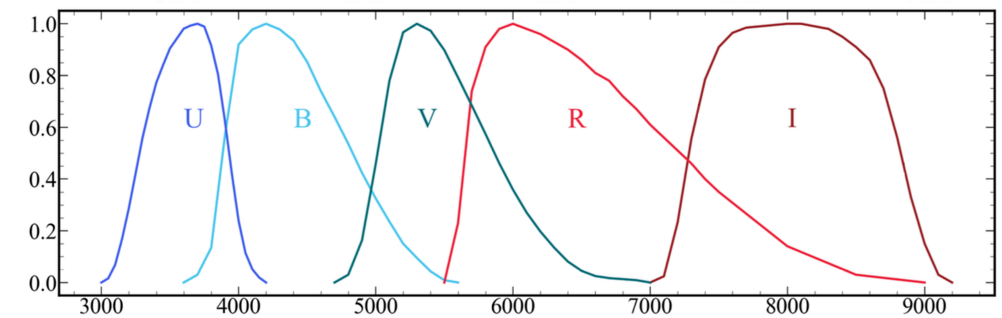
The peak luminosity - decline rate relation

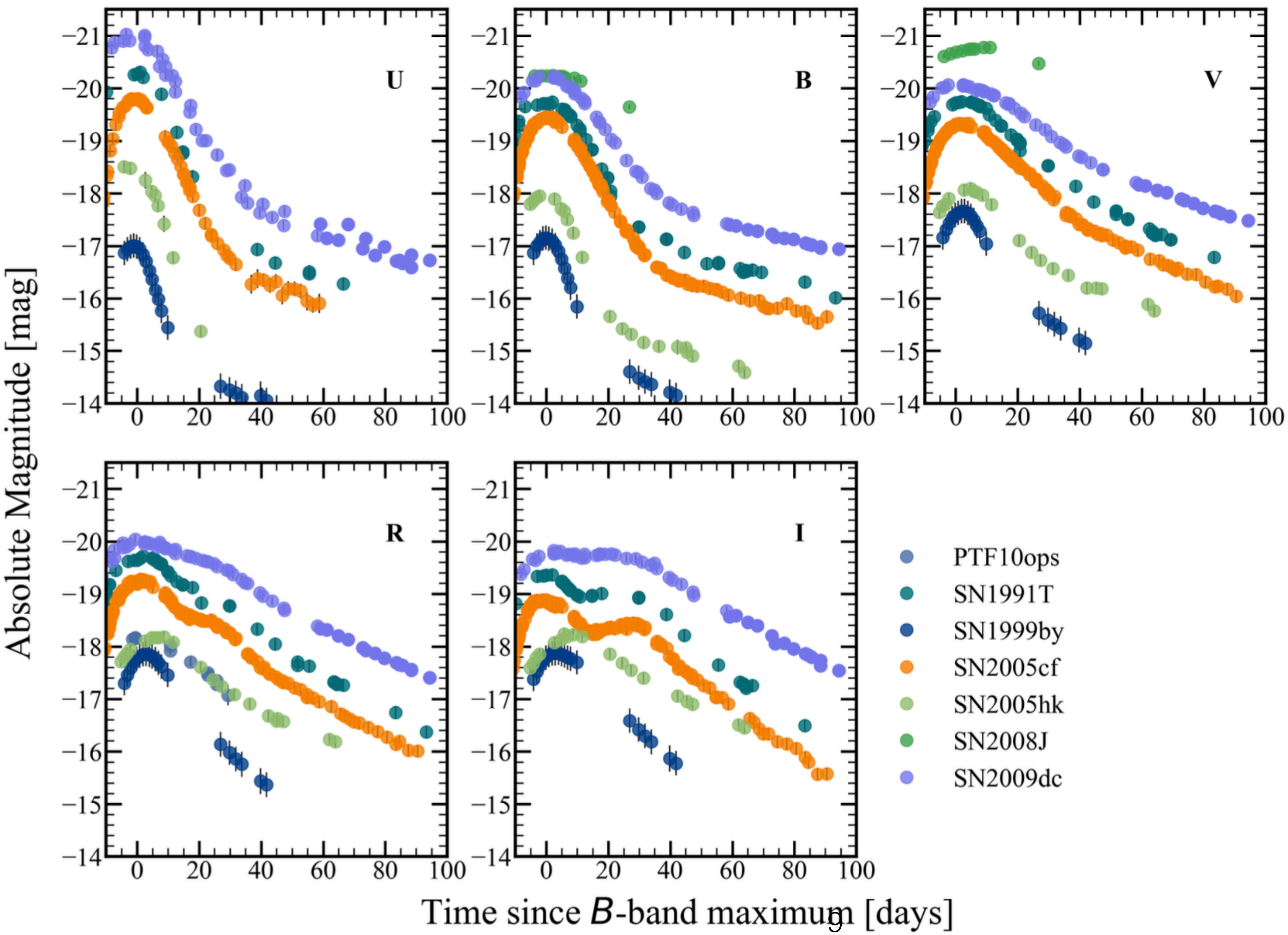






Light curves of thermonuclear explosion



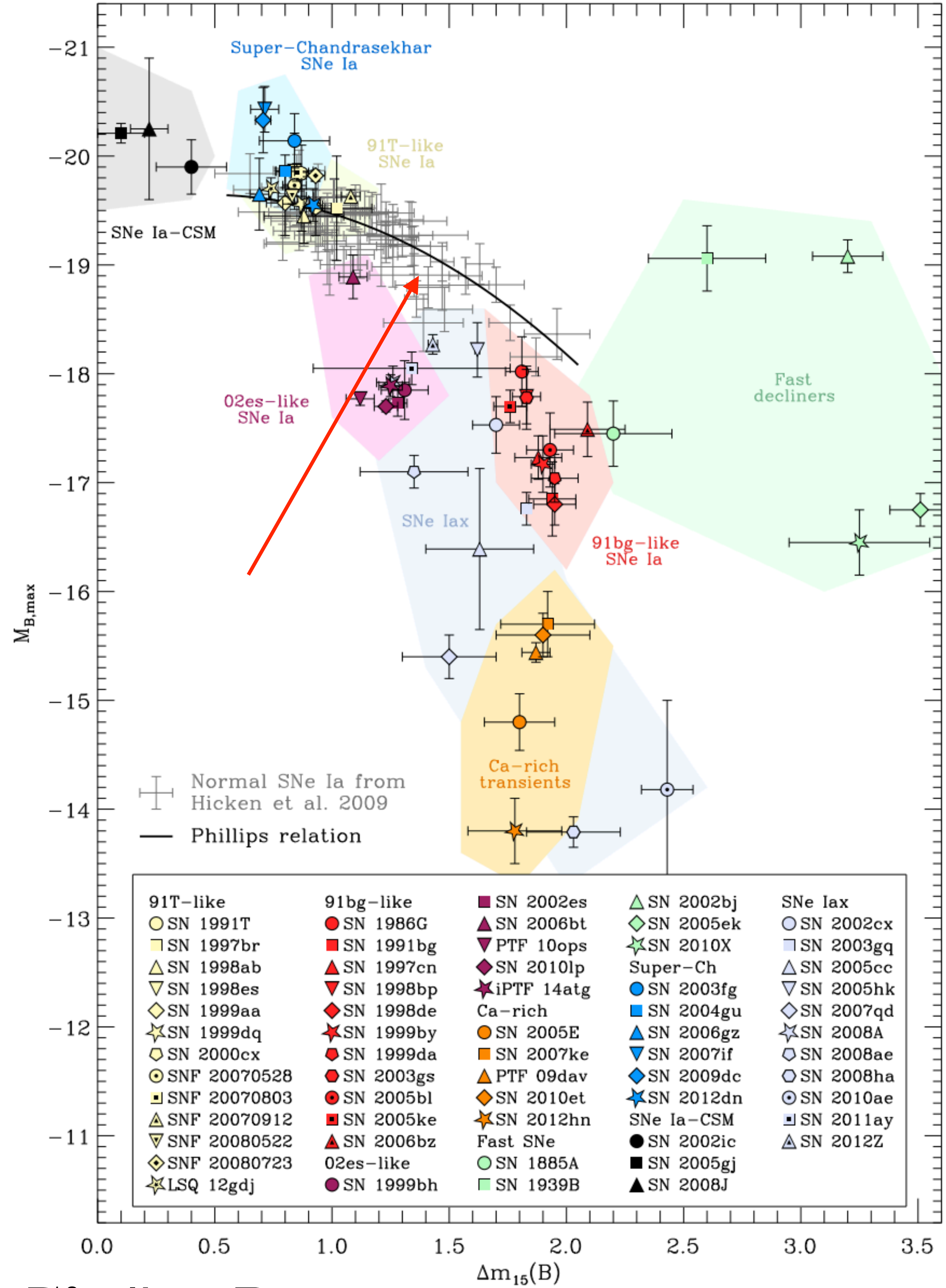


The Thermonuclear Supernova Zoo

Diversity in light curve

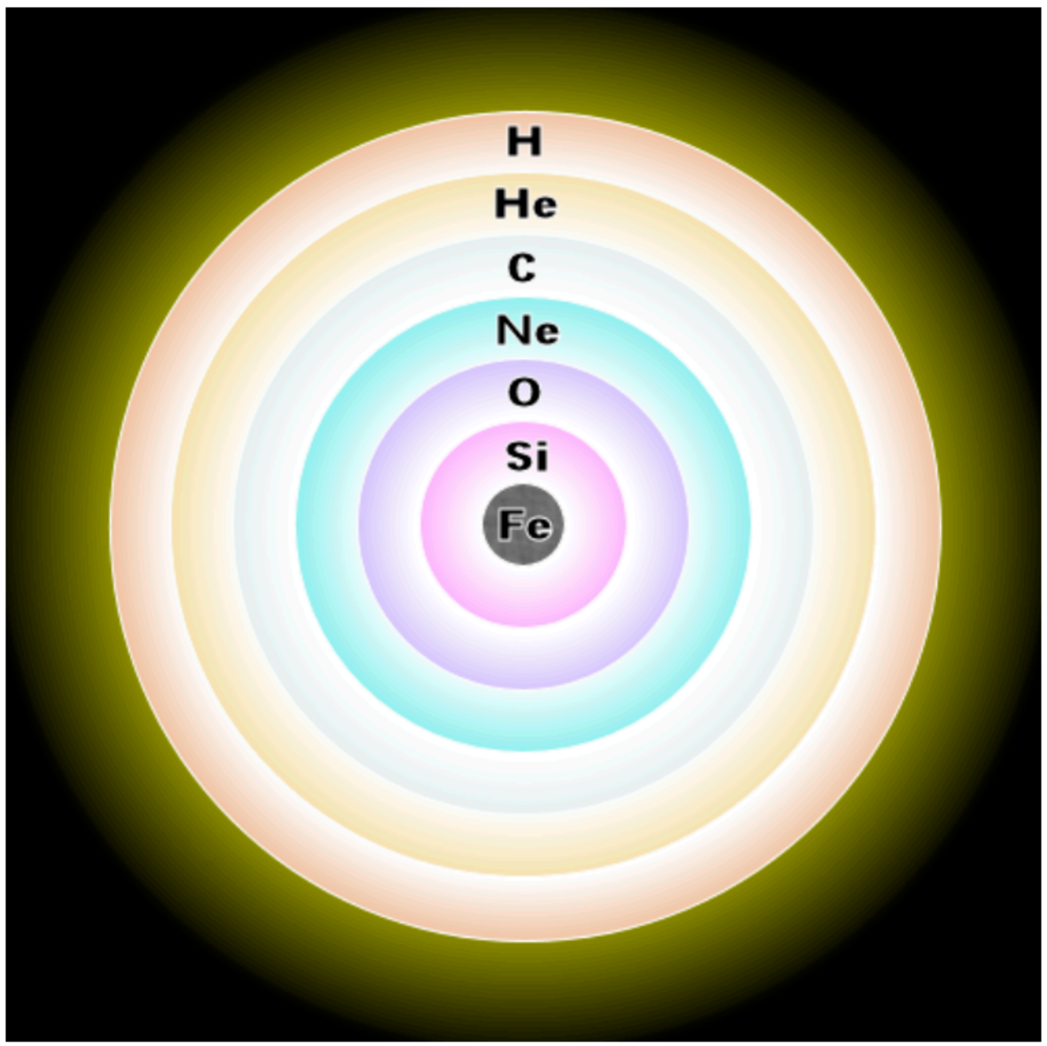
Diversity in spectral evolution.

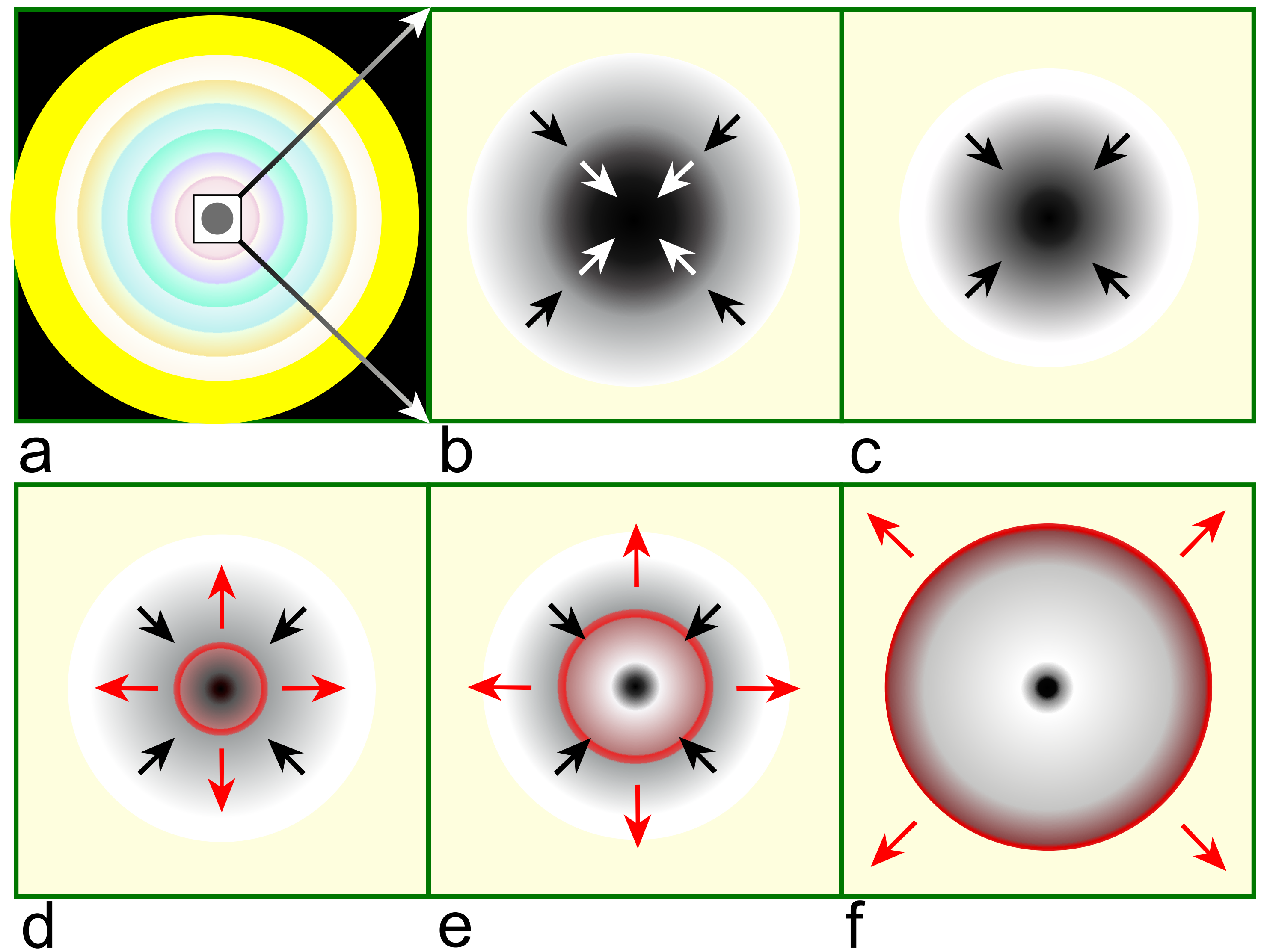
Absolute magnitude



Decline Rate

Core-collapse Explosion





Wiki article

Understanding a supernova spectrum

Elementary supernova model

Used in codes like synow

Useful for identifying lines, velocities

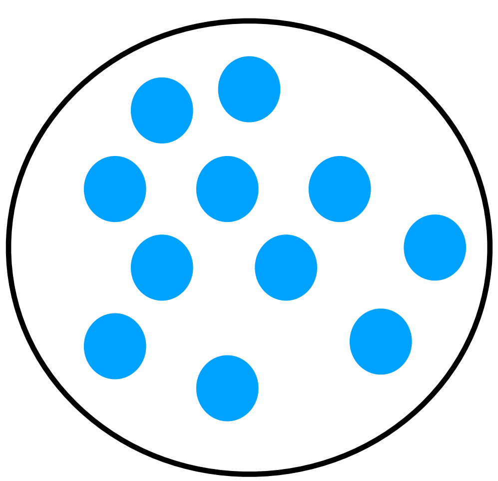
Today I will talk about the photospheric phase.

What is optical depth?

Optical depth is a measure of howmuch of a star's intensity is attenuated after travelling a distance L.

$$\tau = \int_0^L \alpha dz' \qquad I = I_0 e^{-\tau}$$

Attenuation coefficient



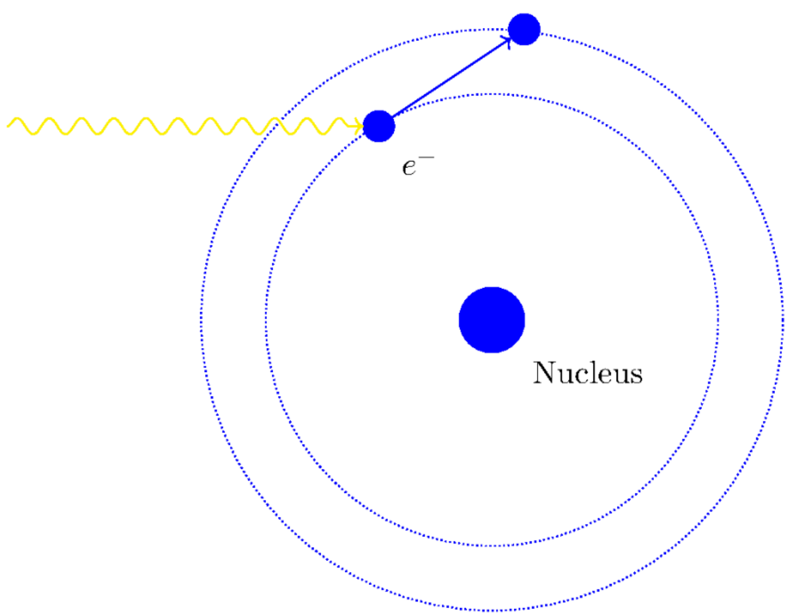
$$< \tau > = \int_0^\infty \tau e^{-\tau} d\tau = 1$$

$\tau = 1$ means that the intensity falls of as 1/e of its initial value.

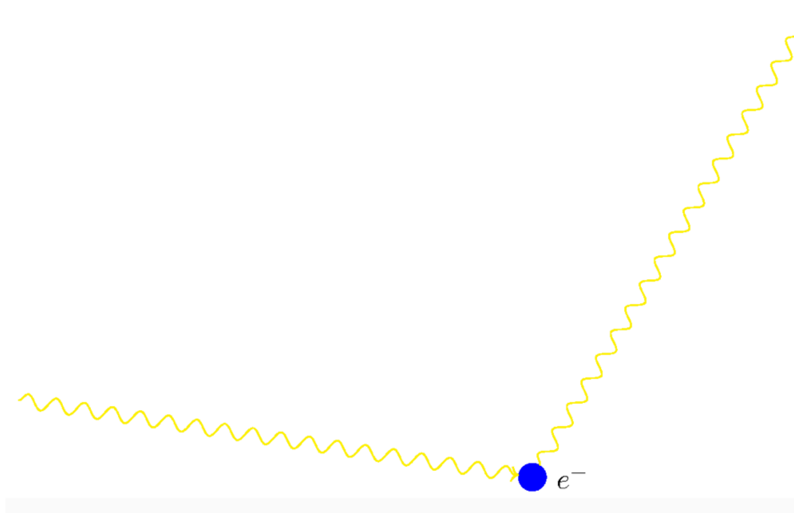
τ depends on the number density, and the cross-section of the intervening particles.

Opacity

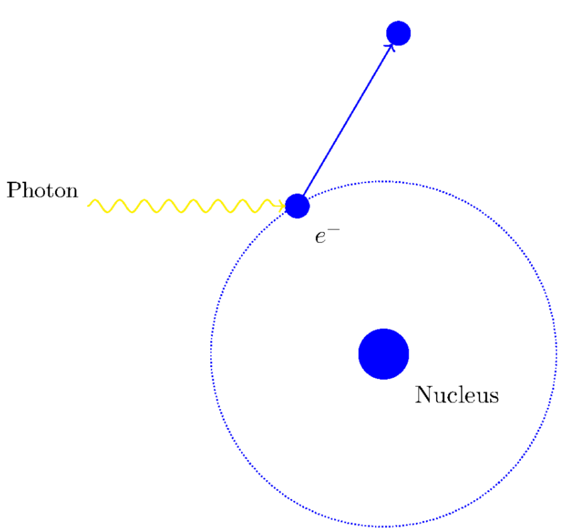
Bound-bound



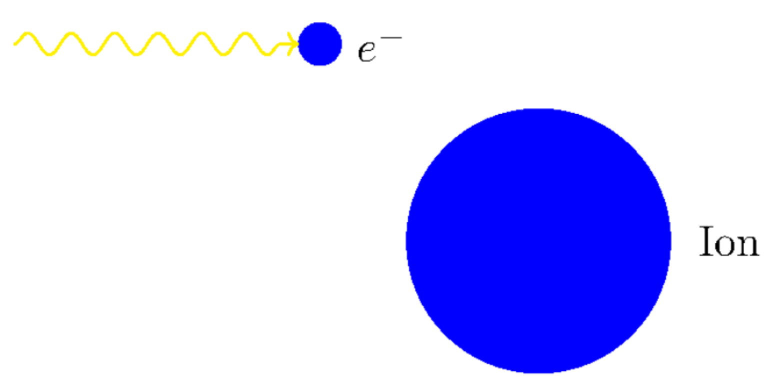
Electron scattering



Bound-free

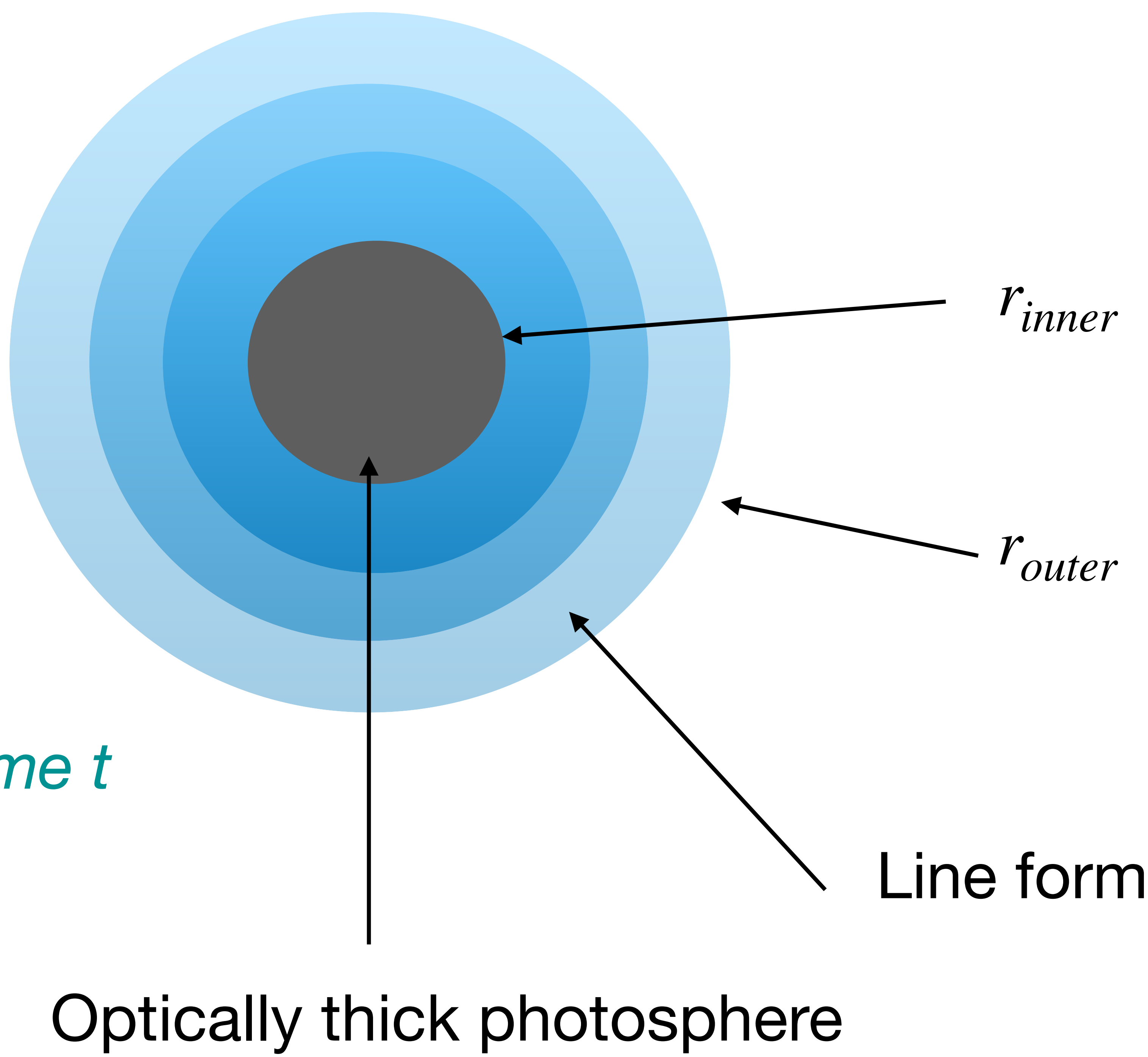


Free-Free



Supernova ejecta model

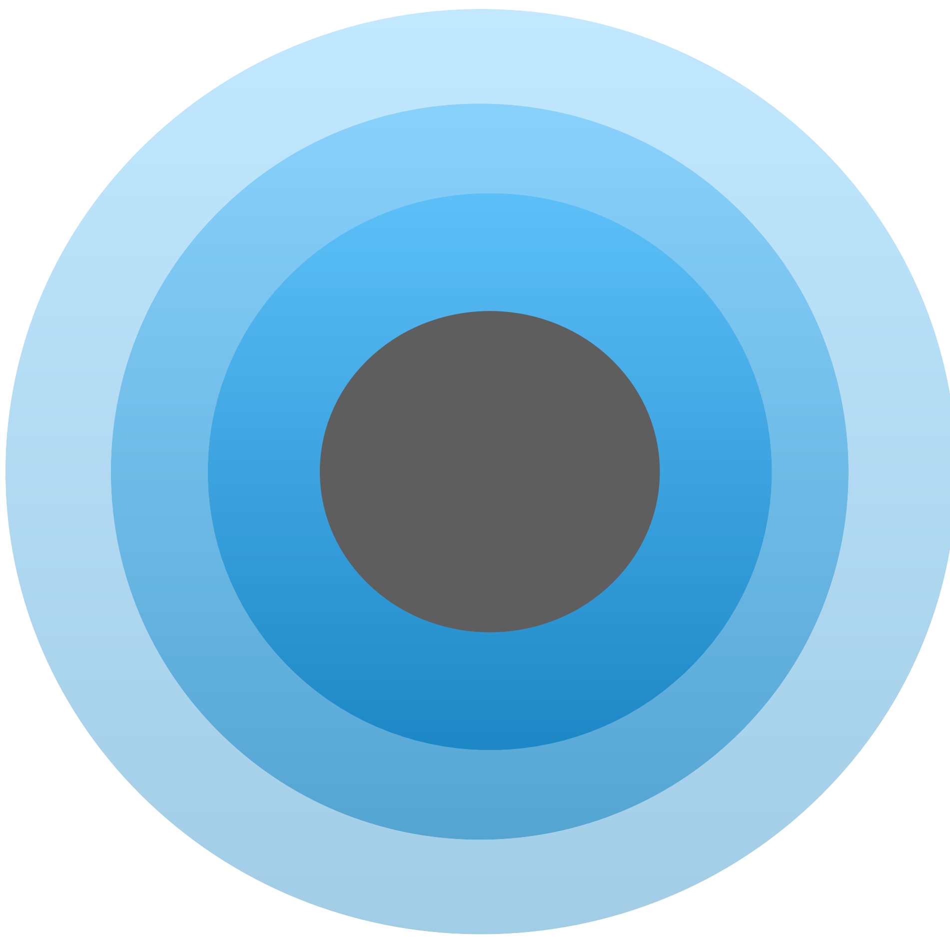
Spherically symmetric ejecta.



At a specific time t

Supernova ejecta model

The photosphere radiates as a blackbody



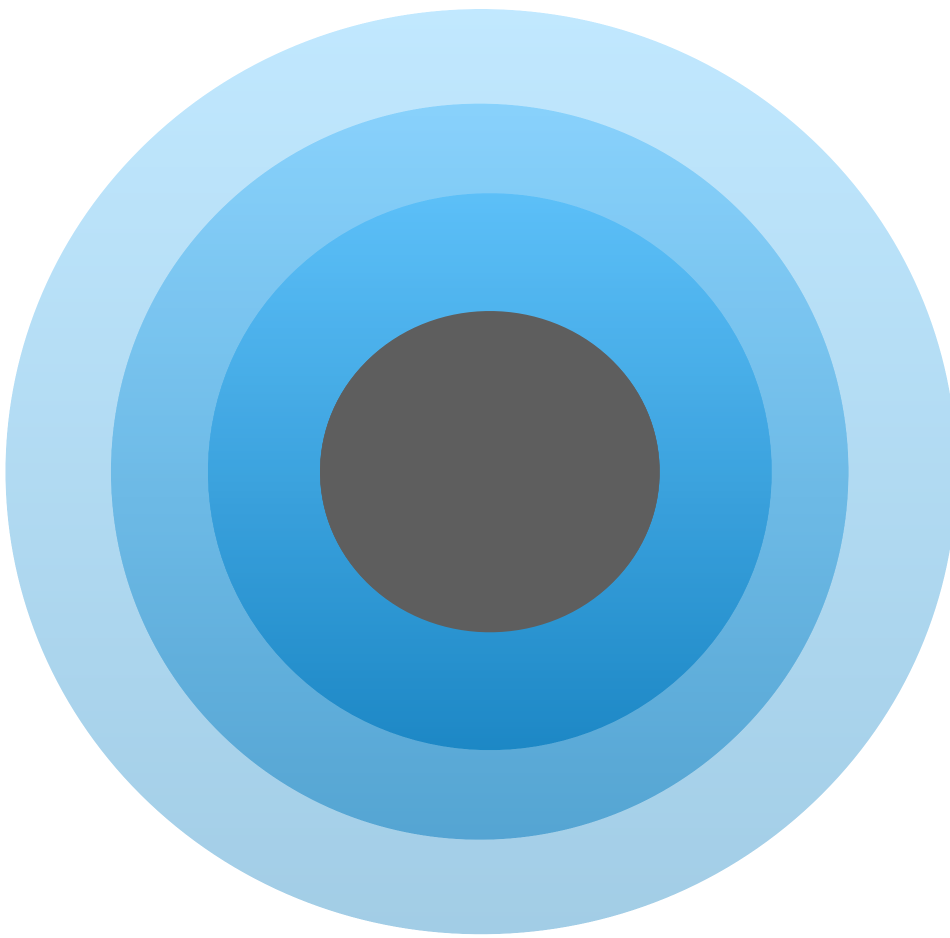
The photosphere (lets say $\tau = 1$) emits with a constant intensity in all directions.

$$I_{ph} = B_\lambda(T_{ph})$$

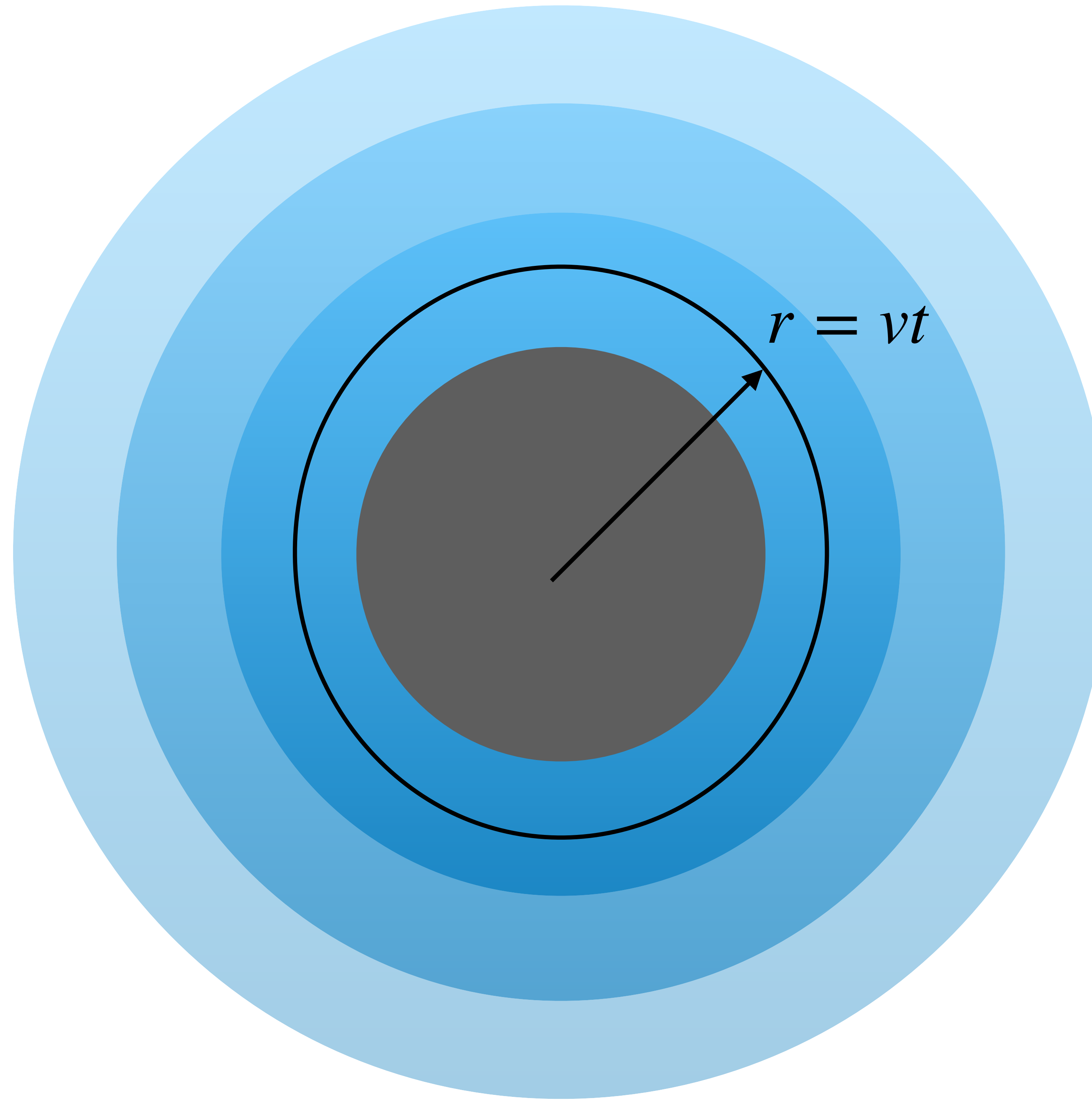
$$B_\lambda(T_{ph}) = \frac{2hc^2}{\lambda^5}\frac{1}{exp(\frac{hc}{\lambda kT}) - 1}$$

At a specific time t

Homologous expansion of the ejecta



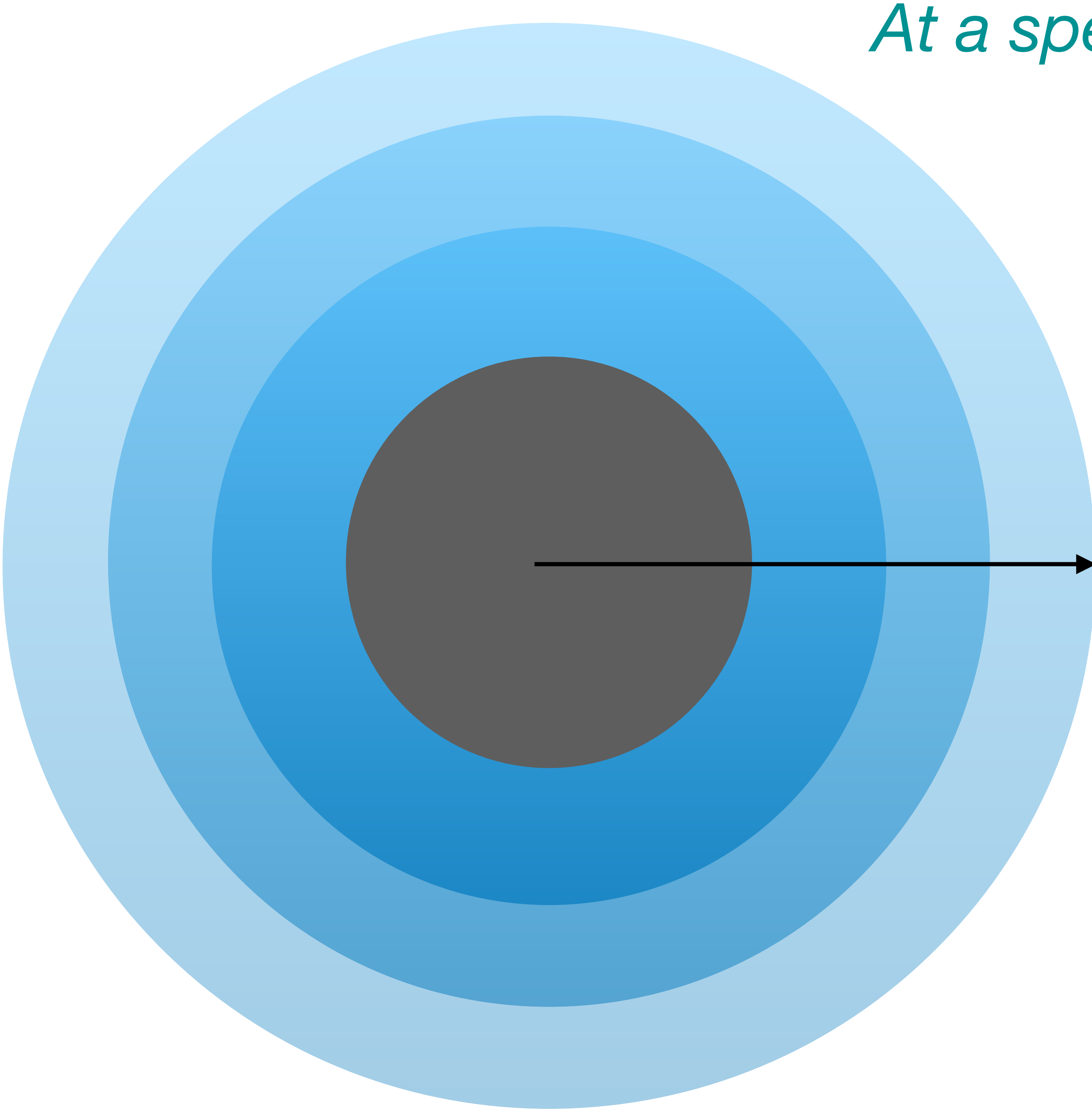
At a specific time t



At a specific time t' > t

Homologous expansion of the ejecta

At a specific time t



$$v(r) = r/t$$

$$v_{outer} = r_{max}/t$$

$$t_{lc} = \frac{r_{max}}{c} = \frac{v_{outer}t}{c}$$

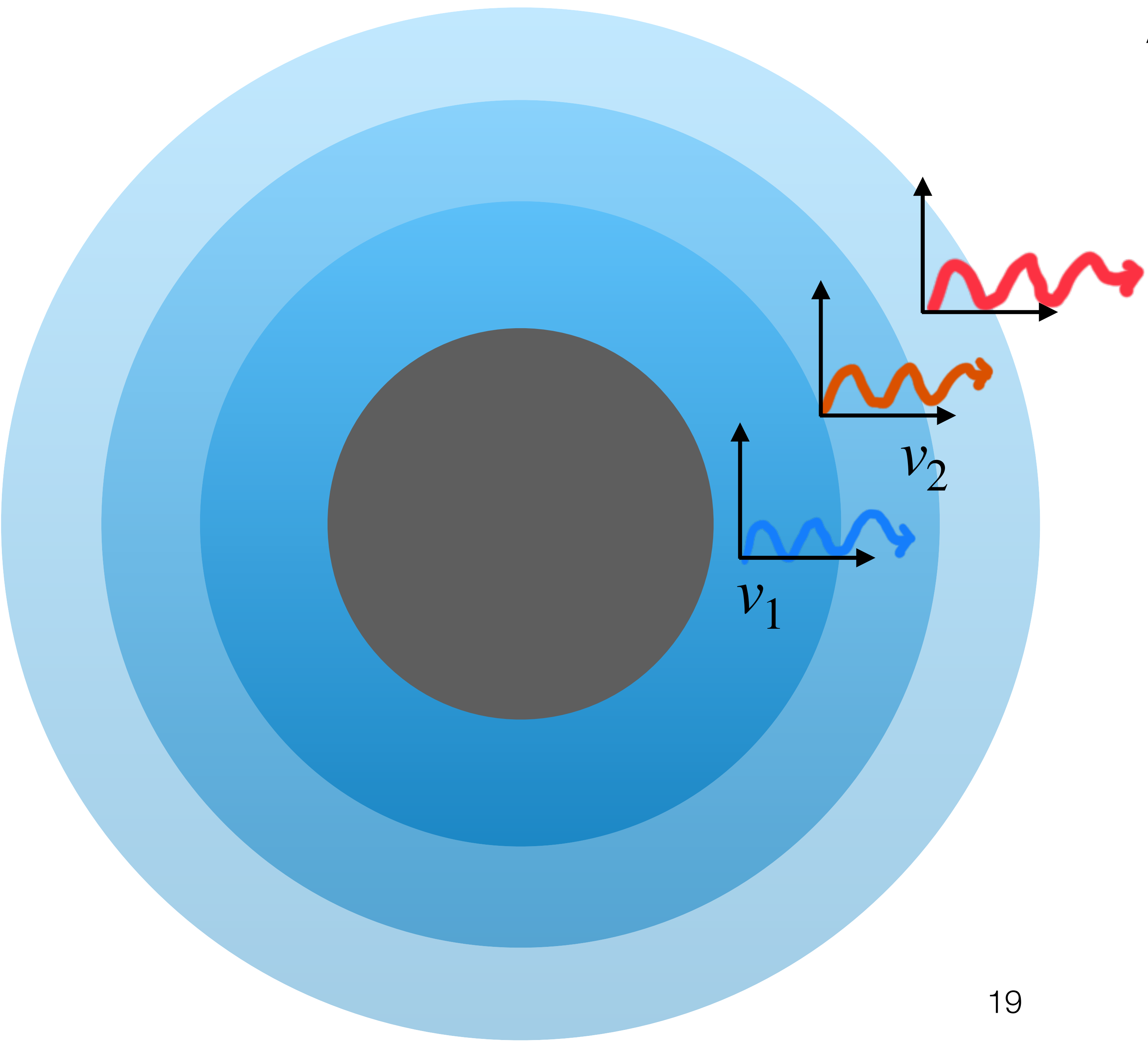
$$\frac{t_{lc}}{t} = \frac{v_{outer}}{c} << 1$$

We assume, the ejecta is stationary, since the time scale of interest is much smaller than the time in which the ejecta changes appreciably.

The ejecta is *moving but stationary in time* is one of the assumptions

Spectral studies consider the “snapshot technique”.

The moving ejecta is important for how the lines are formed.



A photon (λ_{cmf}) as it propagates continously redshifts.

$$\lambda'_{cmf} = \lambda_{cmf}(1 + \frac{v_2 - v_1}{c})$$

$$\Delta\lambda = \lambda_{cmf}\frac{\Delta v}{c}$$

Some recap of atomic physics

Boltzmann equation

$$\frac{P_b}{P_a} = \frac{g_b}{g_a} e^{-\frac{E_b - E_a}{kT}}$$

g_b and g_a are the degeneracy of state b and a with energy E_b and E_a.

Atomic orbital (n, l, m_l, m_s) of higher energy are less likely to be occupied by electrons at a particular T.

Saha Equation

We also need to consider the relative number of atoms in the different ionization states.

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\frac{\chi_i}{kT}}$$

$$Z_i = \sum_{j=1}^{\infty} g_j e^{-(E_j - E_i)/kT}$$

χ_i is the ionization potential of the ith ion.

Some recap of atomic physics

Finally, we get the number density of the element z, in an ionization state i and and excited state n

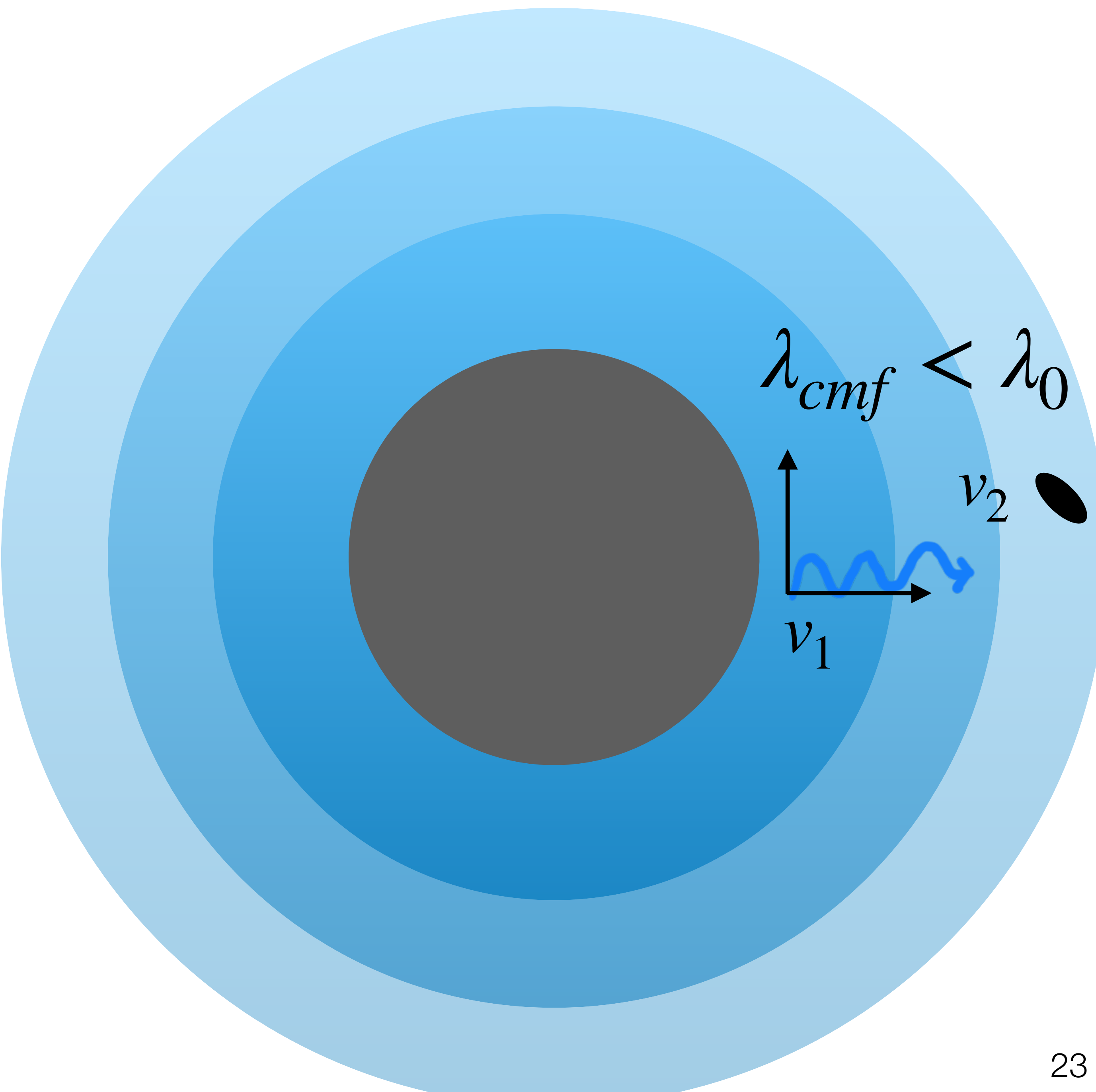
$$N_{z,i,n} = \frac{\rho X_z}{m_z} N_{z,i} \left(\frac{g_n e^{-\frac{E_n}{kT}}}{\sum_j g_j e^{-(E_j - E_i)/kT}} \right)$$

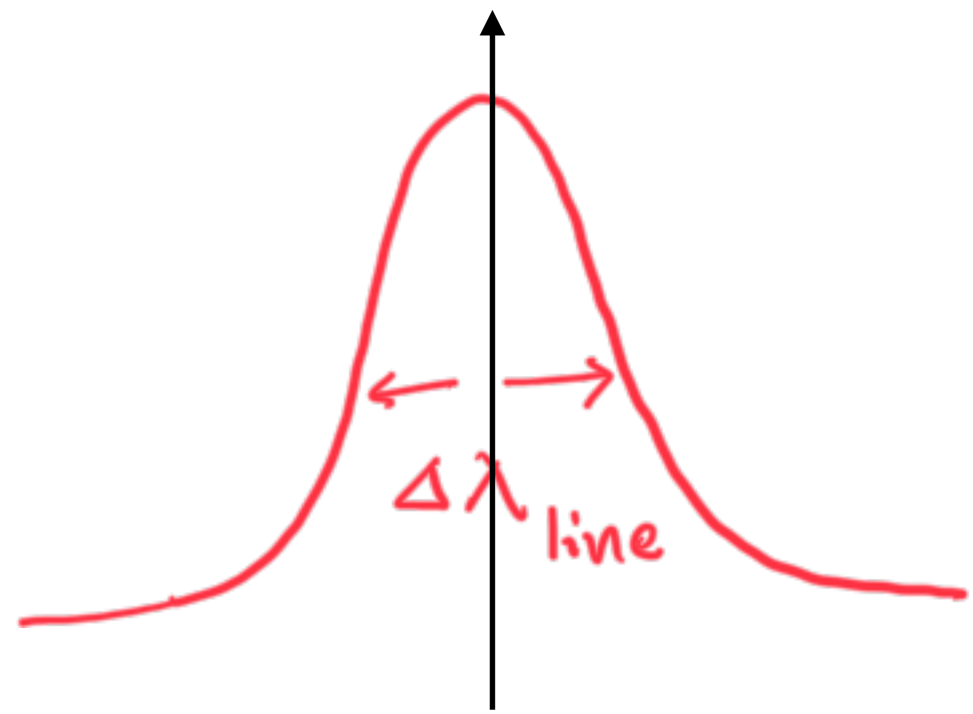
We use a density profile, mass fractions, temperature from an explosion model and atomic data to calculate the various level number densities.

Line transition is dominant and very complex in a SN ejecta.

Sobolev approximation

The properties of the ejecta are constant over a resonance region.





λ_0 MB - distribution

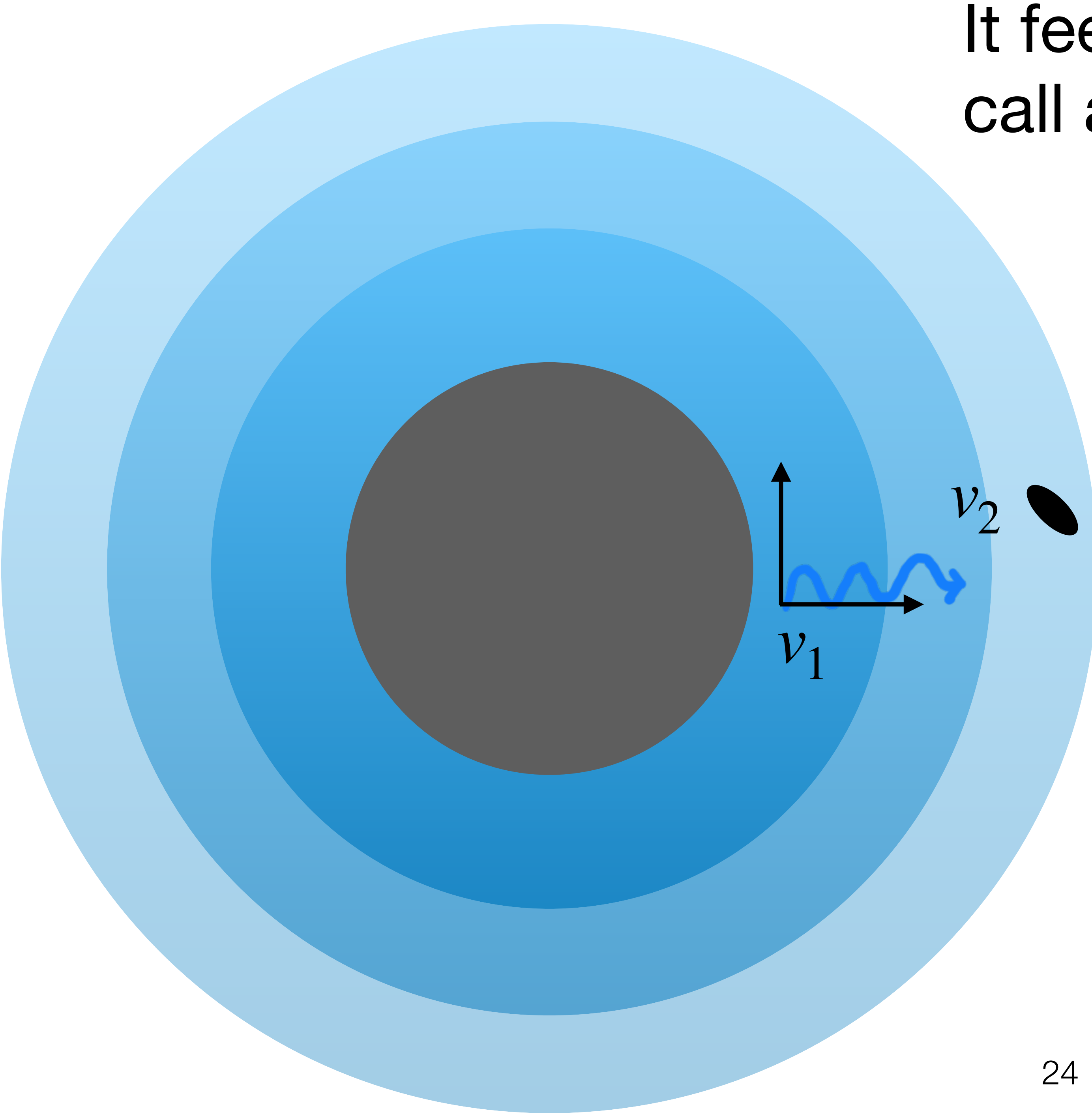
$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

$$v_T << v_{ejecta}$$

$$\lambda'_{cmf} \sim \lambda_0$$

Sobolev approximation

Consider a photon passing into resonance with a line

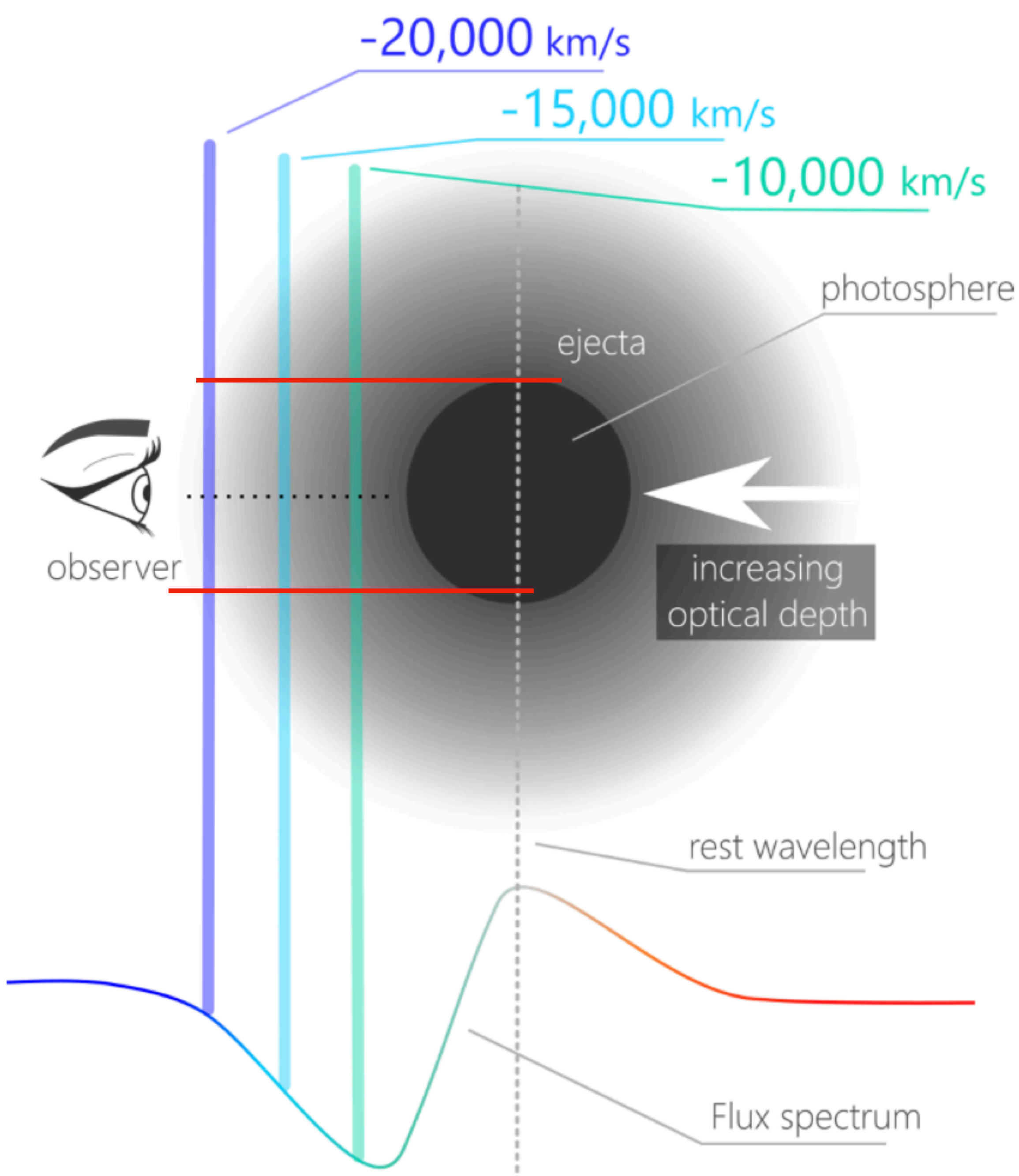


It feels the optical depth which we call as Sobolev optical depth.

$$\tau_{sob} \propto N g_n f_{osc} \lambda_0 e^{-\frac{\Delta E_n}{kT}}$$

From the optical depth you can calculate the opacity.

Line profile

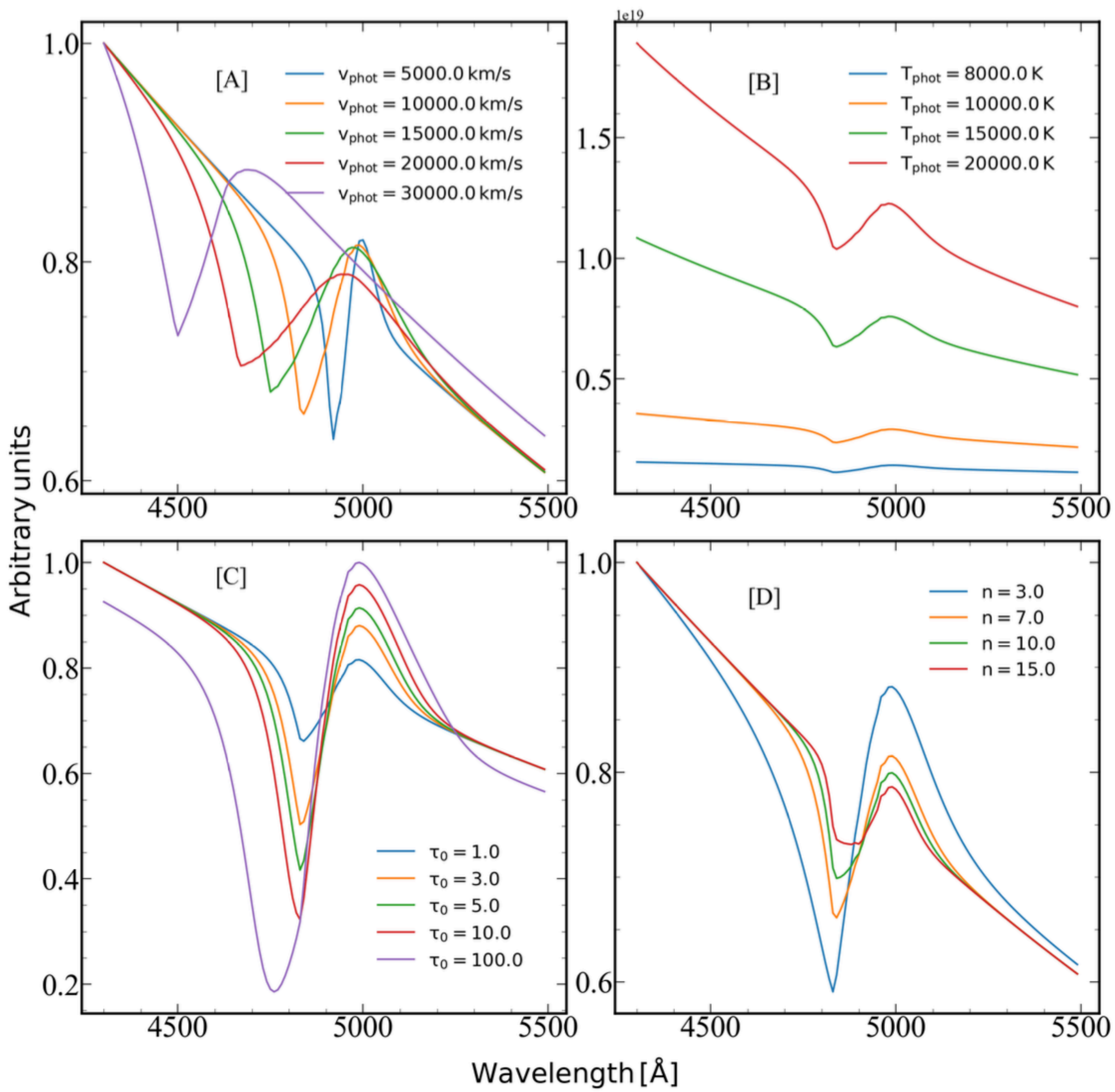


Stevance 2019

As the ejecta is moving towards the observer there is a blue-shifted absorption component.

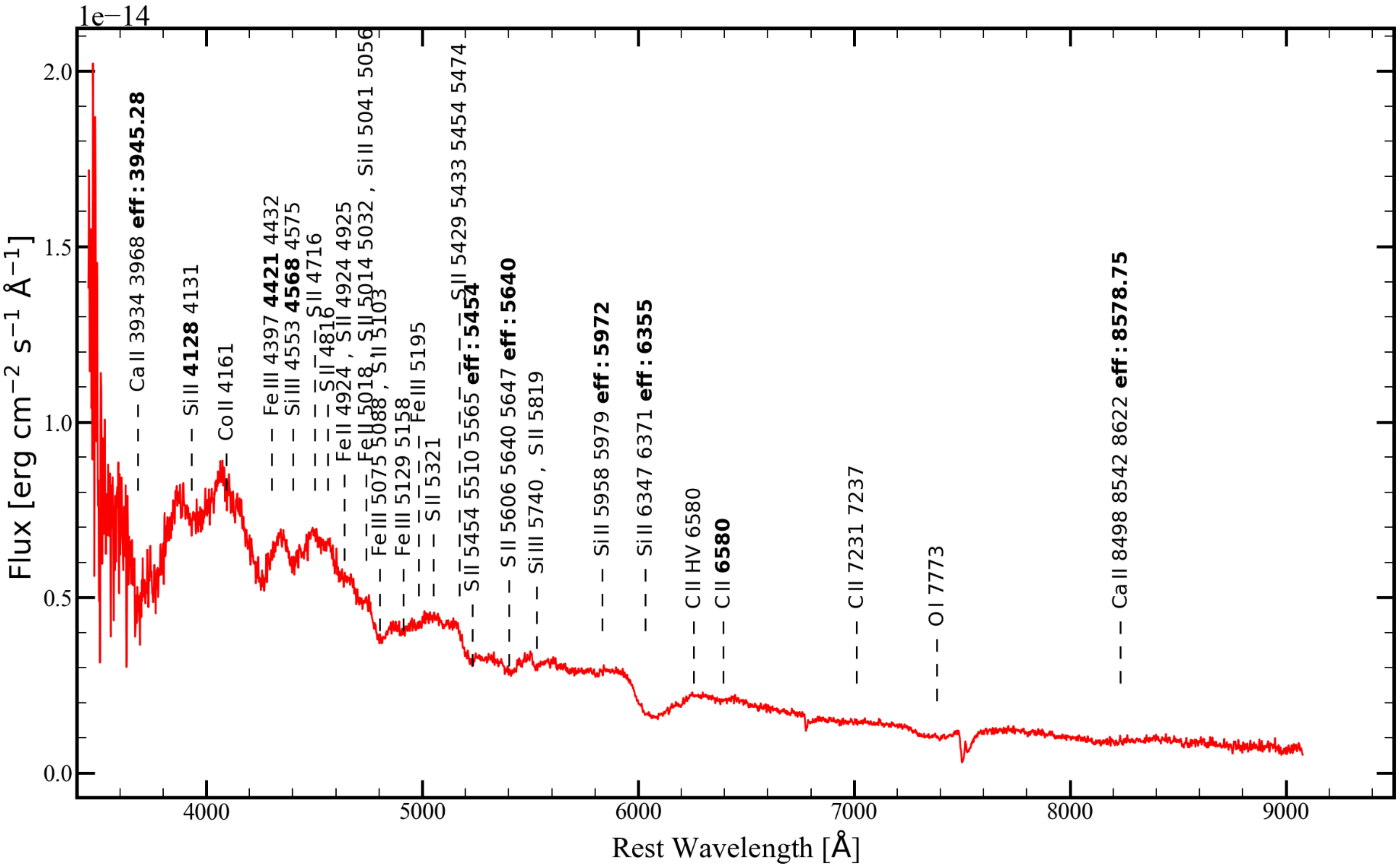
All the other regions which are not directly in the line-of-sight of the observer have a net emission with a peak at the rest wavelength.

In the notebook we will build our own P-Cygni profile and then see the effect of various parameters on line formation.

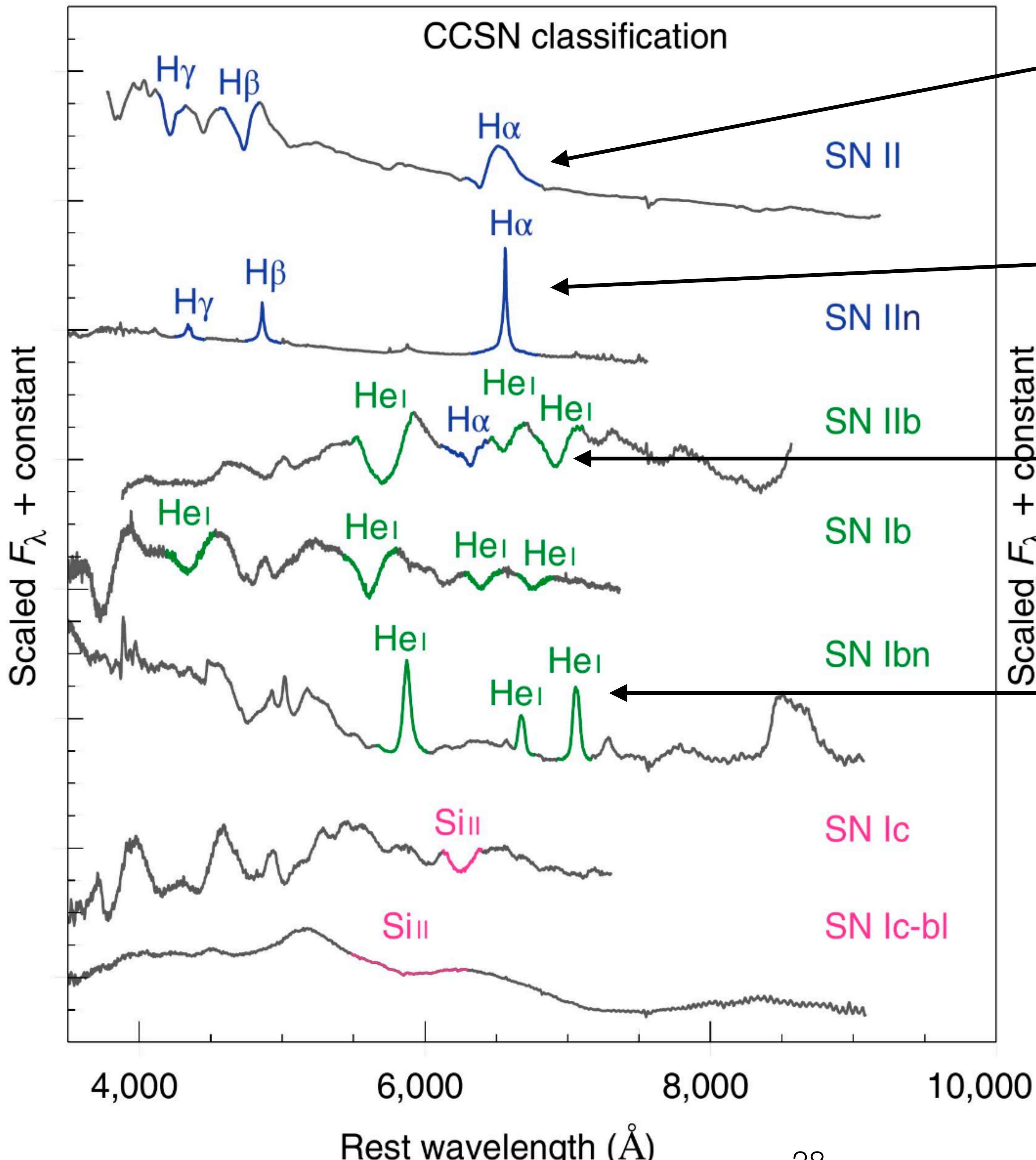


The effect of changing the inner velocity, temperature, the optical depth of the line, and the index of a density profile.

A SN Ia spectrum at maximum



Spectra of core-collapse explosions



H - lines

Narrow emission lines

Strong He features

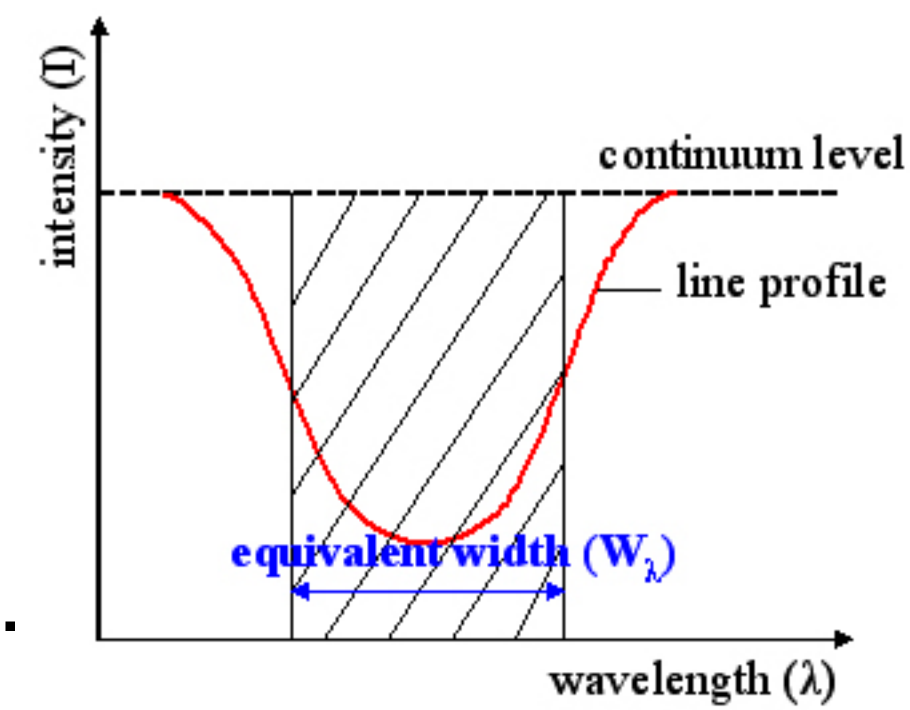
Interacting He features

Modjaz+ 2019

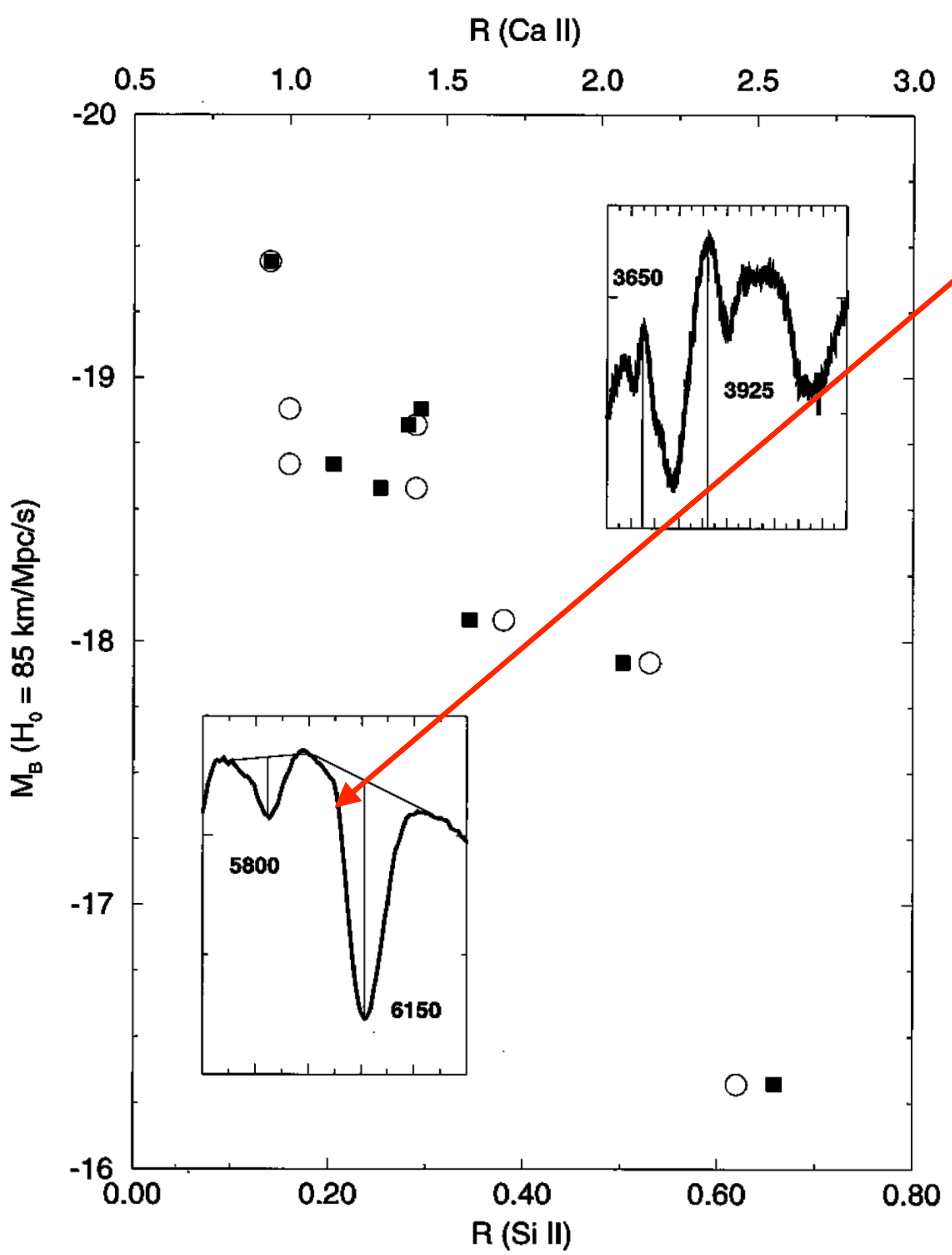
Equivalent widths

The width of a rectangle with the same area as the area under the line profile.

Useful for measuring line strengths.



Line ratios as diagnostics for the luminosity



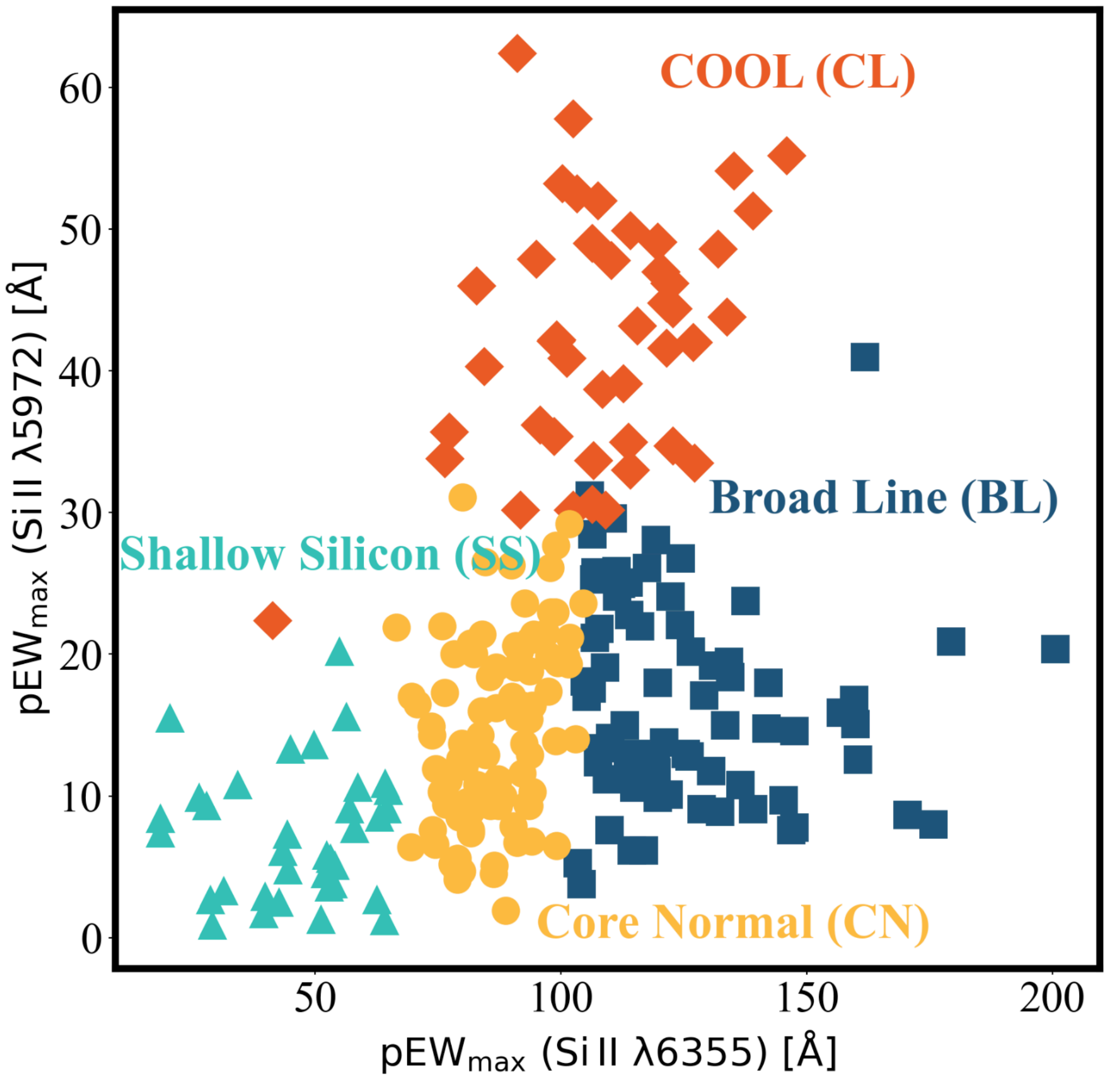
Nugent+ 1995

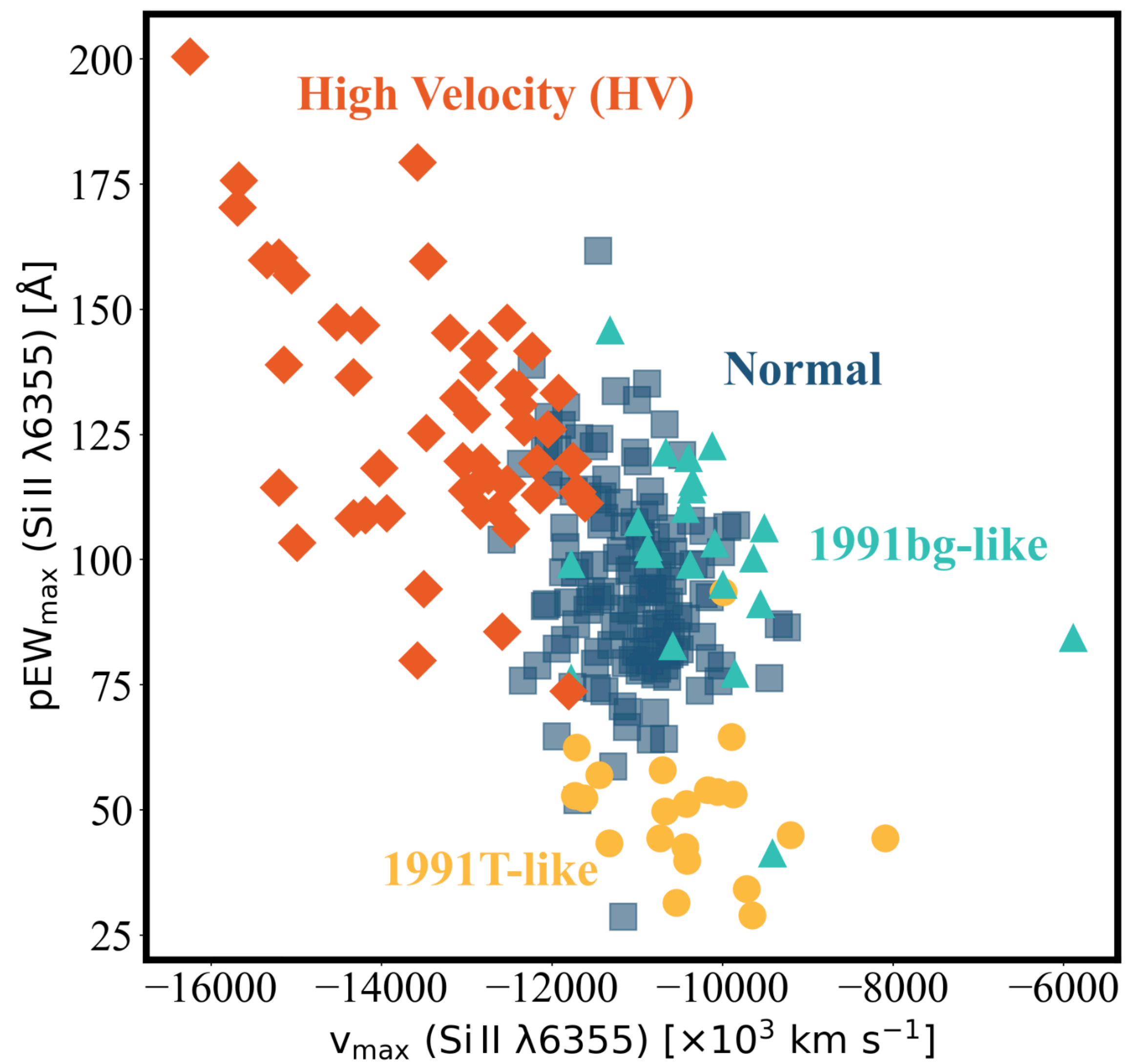
Measurement of the ratio of Si II at two different wavelengths provide a relationship absolute magnitude.

As the temperature increases the line strength of Si II line around 5800 decreases.

Complex interplay of line blanketing but it proposed a sequence to measure luminosity independent of distance.

The thermonuclear supernova zoo and the spectroscopic classifications





Based on the measurement of two lines of Si II.

pEW of Si II with velocity

These are ways of classifying supernova spectra based on observed properties.

TARDIS

Kerzendorf and Sim 2014

A radiative transfer code to model spectra of SNe at different epochs.

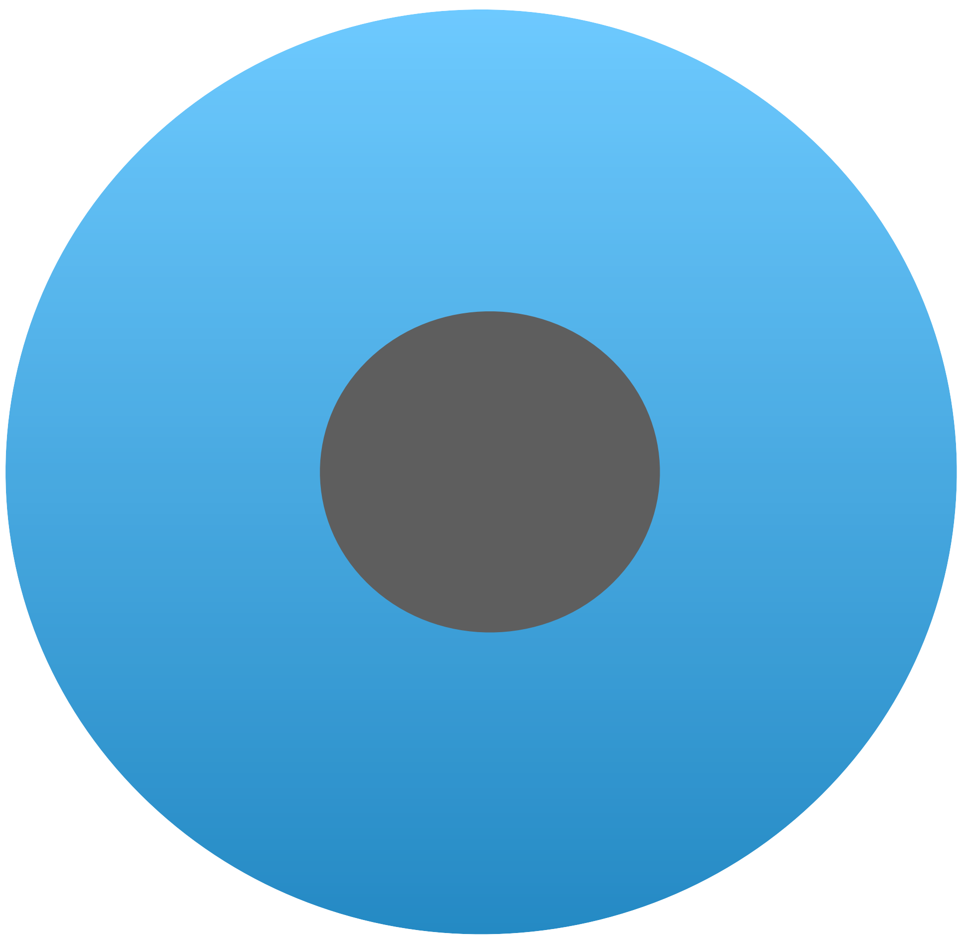
This includes two different kinds of radiation matter interaction-bound-bound, Thomson scattering.

Time-independent modelling of supernova spectra

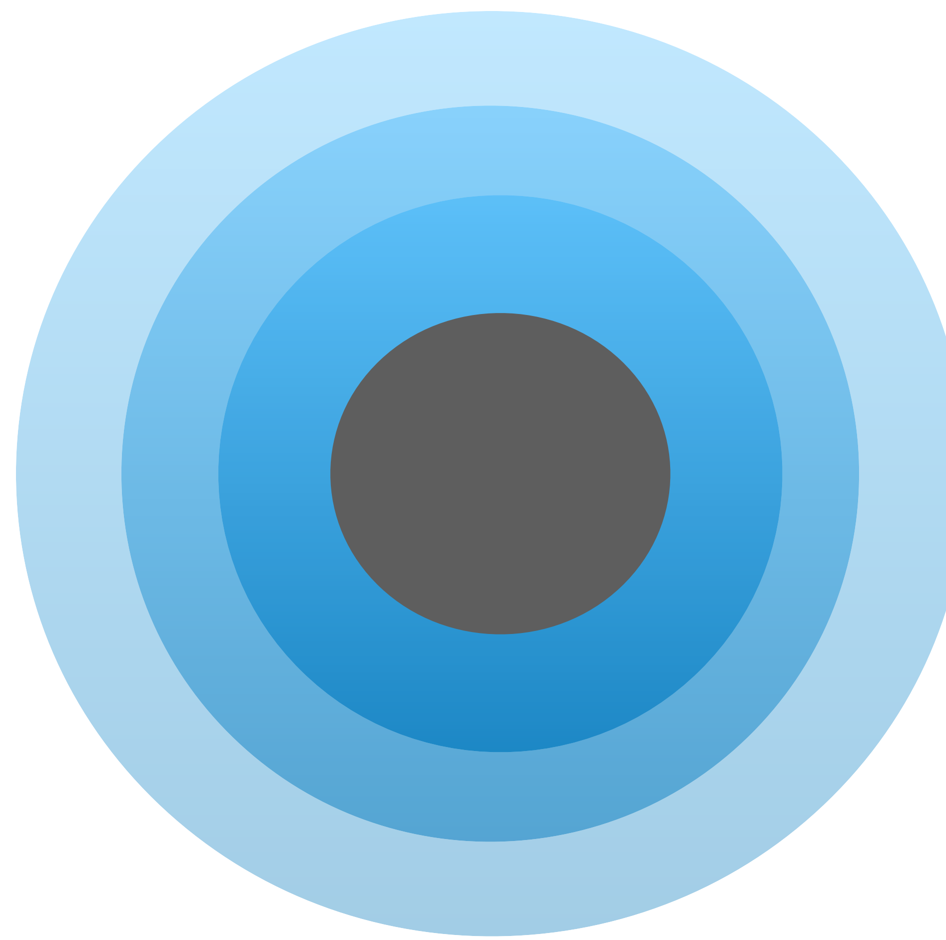
Time dependence added recently in Dutta+ 2025

TARDIS modelling of supernova spectra

We need a density profile and mass fractions of different elements. Mostly these come from hydrodynamic models.

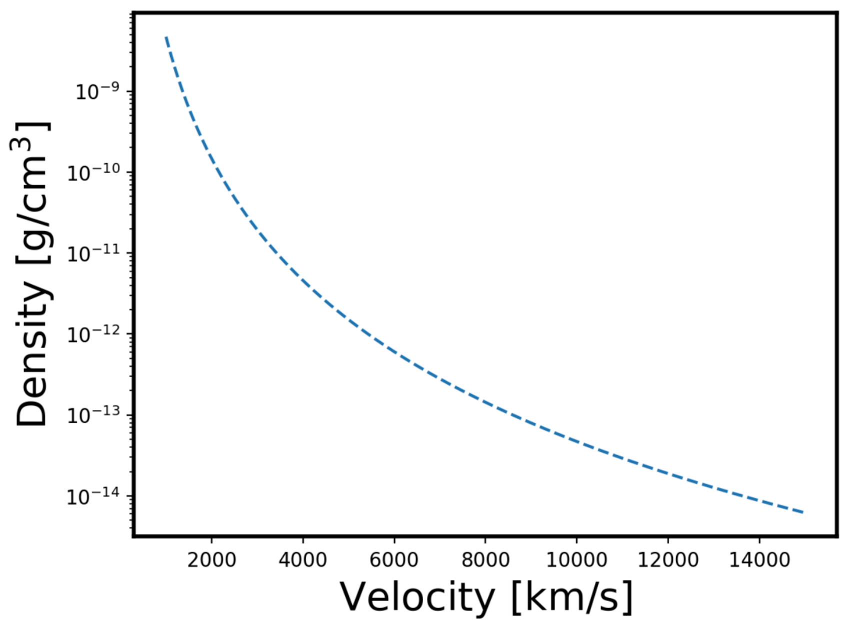


Uniform ejecta

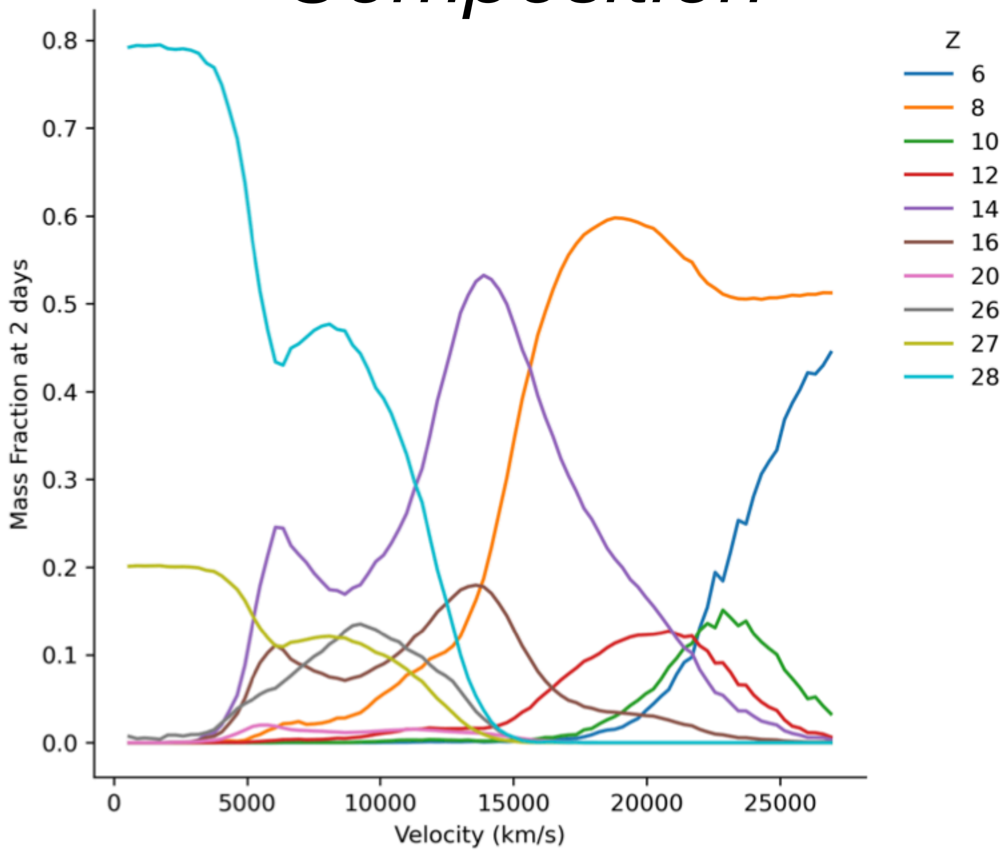


Stratified ejecta

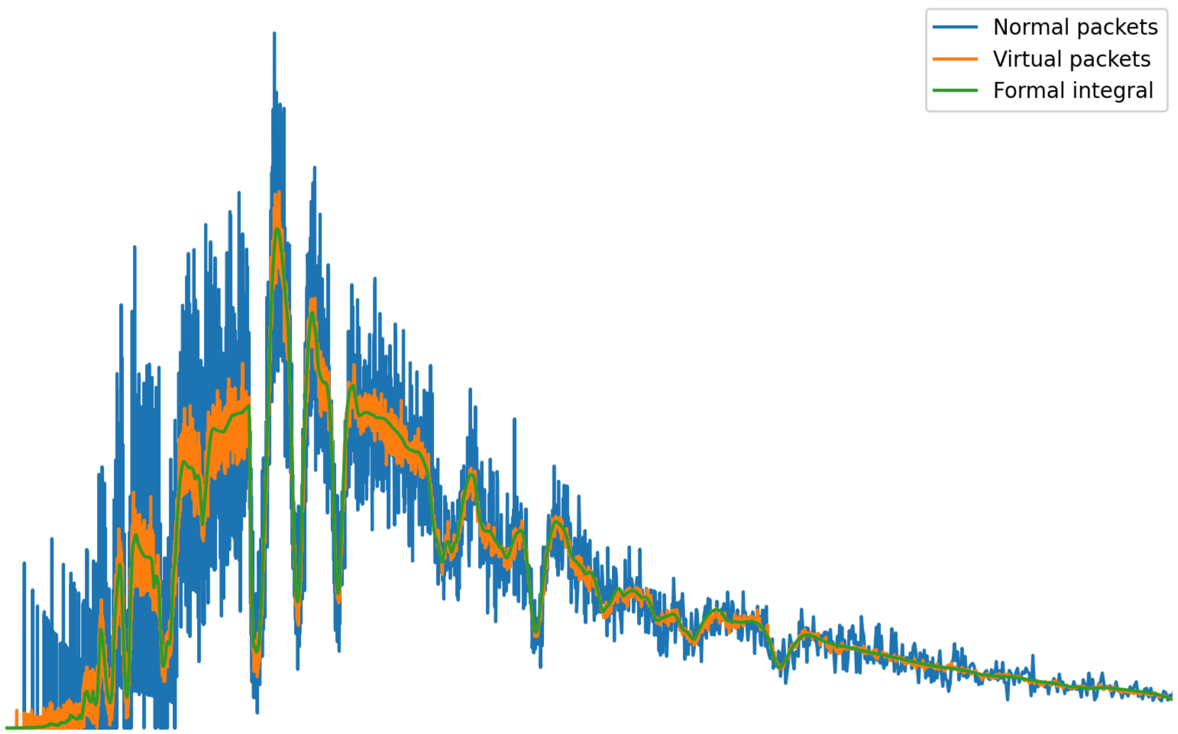
Density



Composition

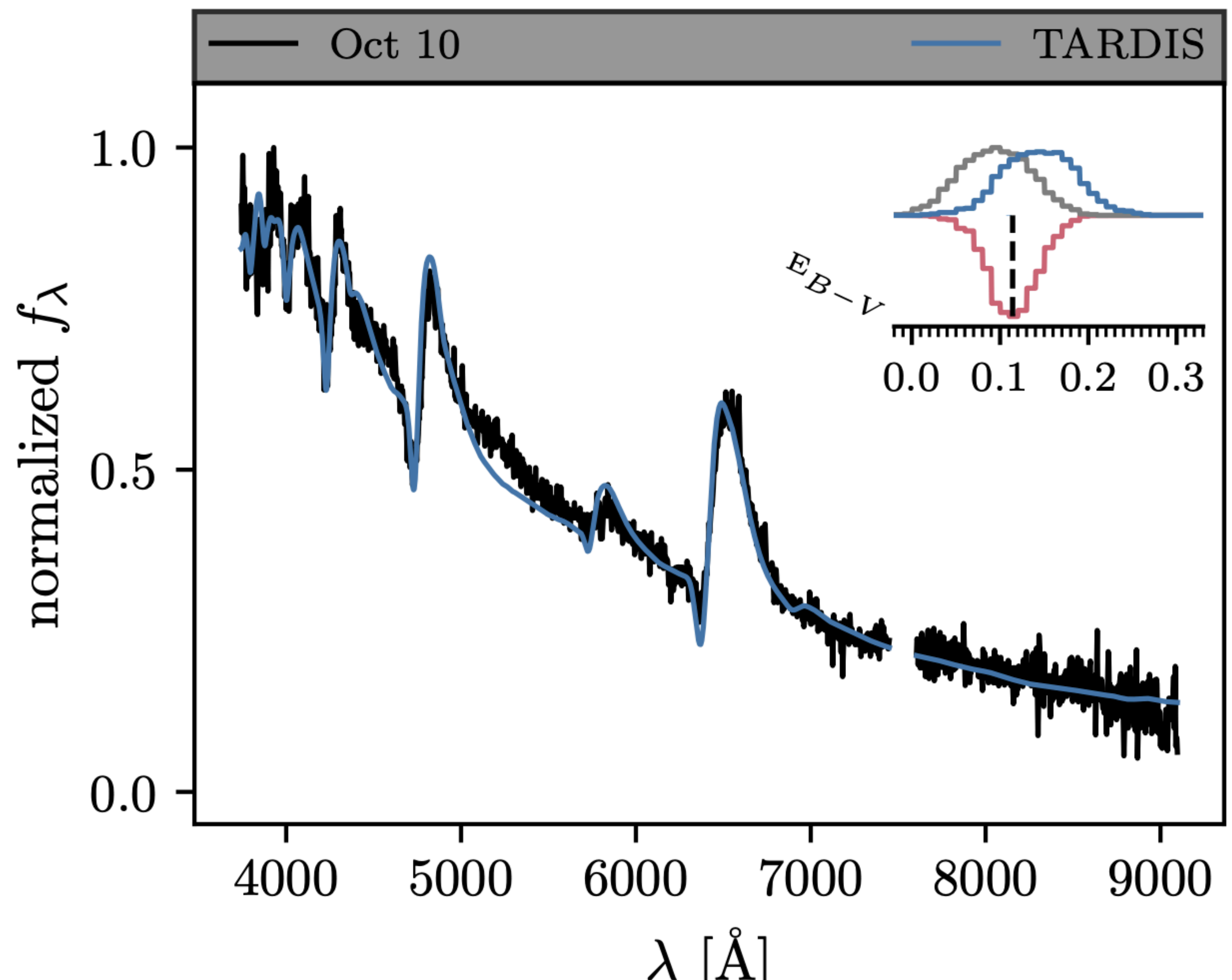


Luminosity, time since explosion, inner velocity



Type II supernovae as distance indicators

T_{ph} [K]	v_{ph} [km/s]	n
9446	8043	10.9

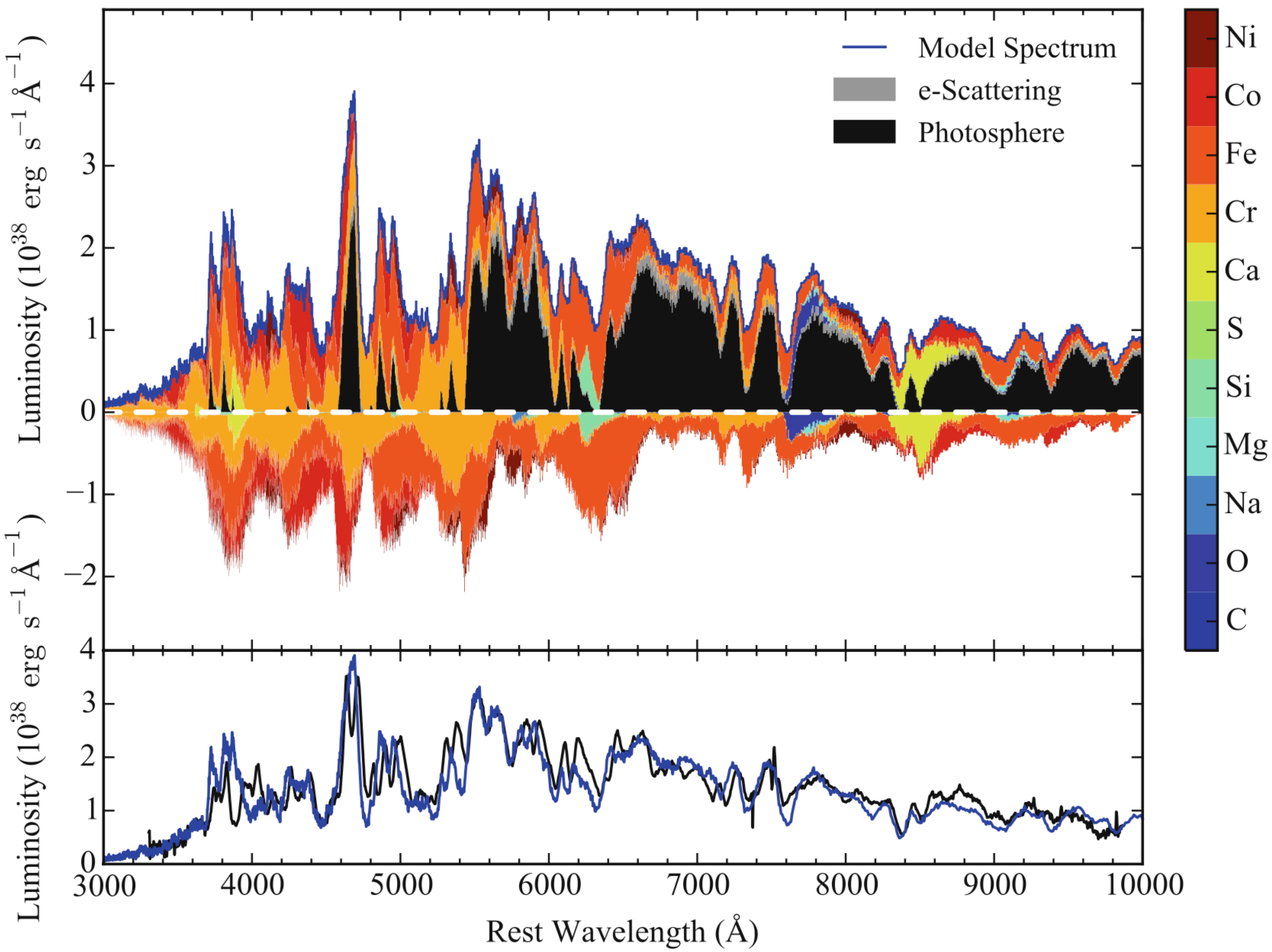


Modelling of Type II supernova spectra with TARDIS to measure value of H_0

In this pilot study they used SNe II between z = 0.01 and 0.04

Vogl+ 2024

Realistic line identification in a supernova

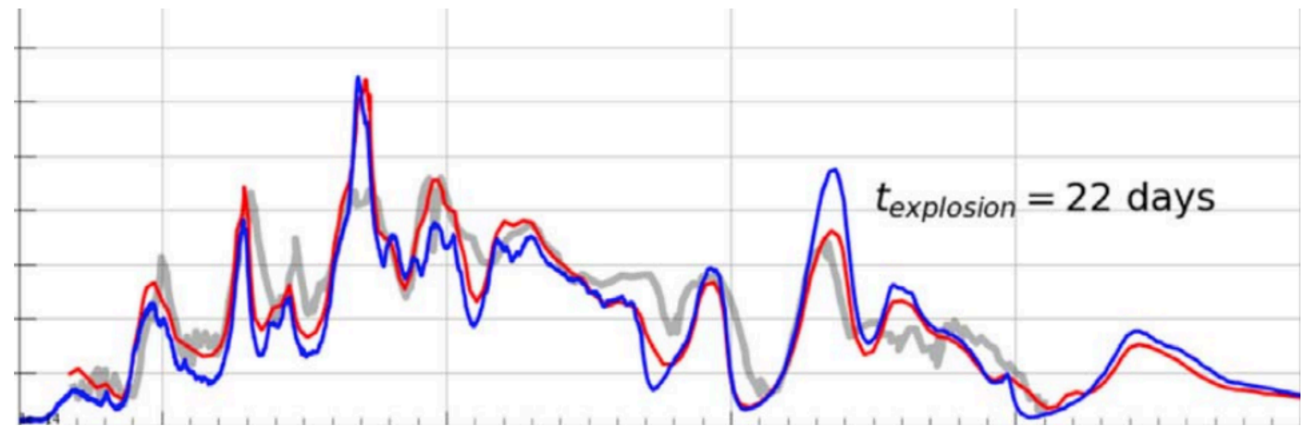


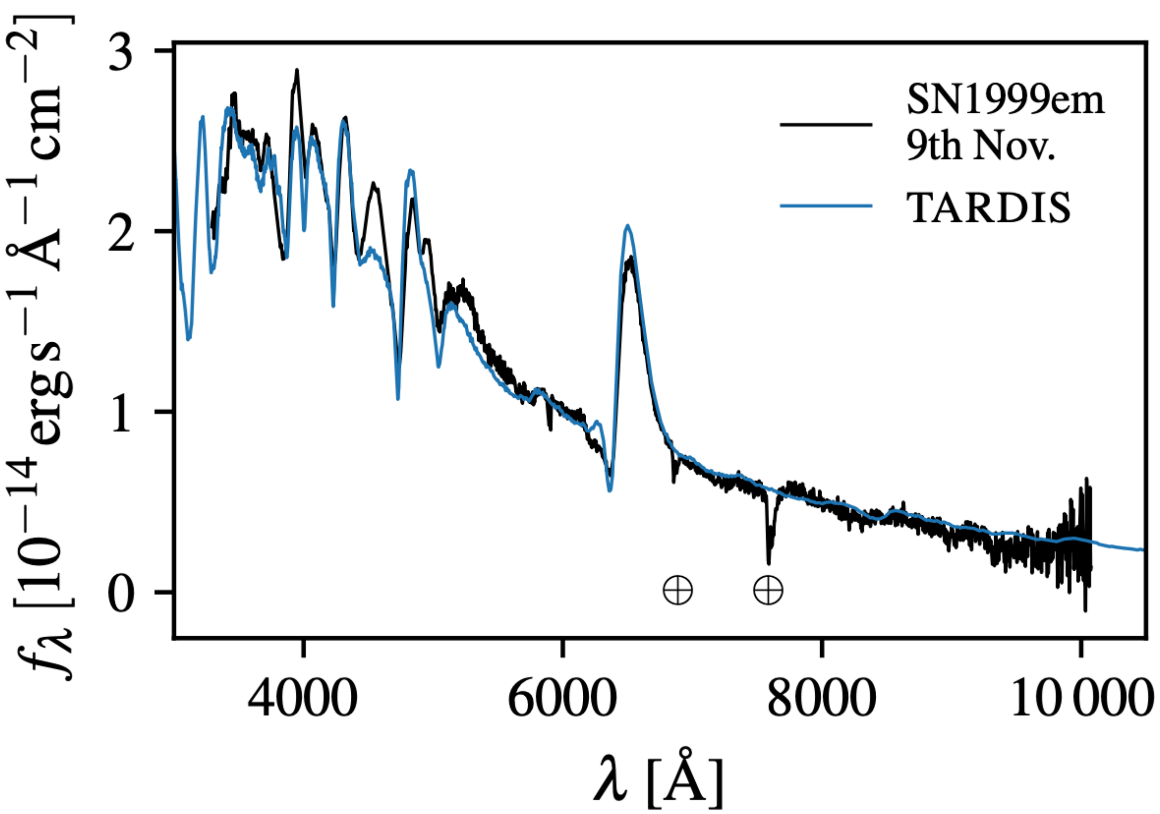
A spectrum of SN 2015H showing the contributions from different elements at different wavelengths.

Magee+ 2017

TARDIS have been used to model different types of supernovae

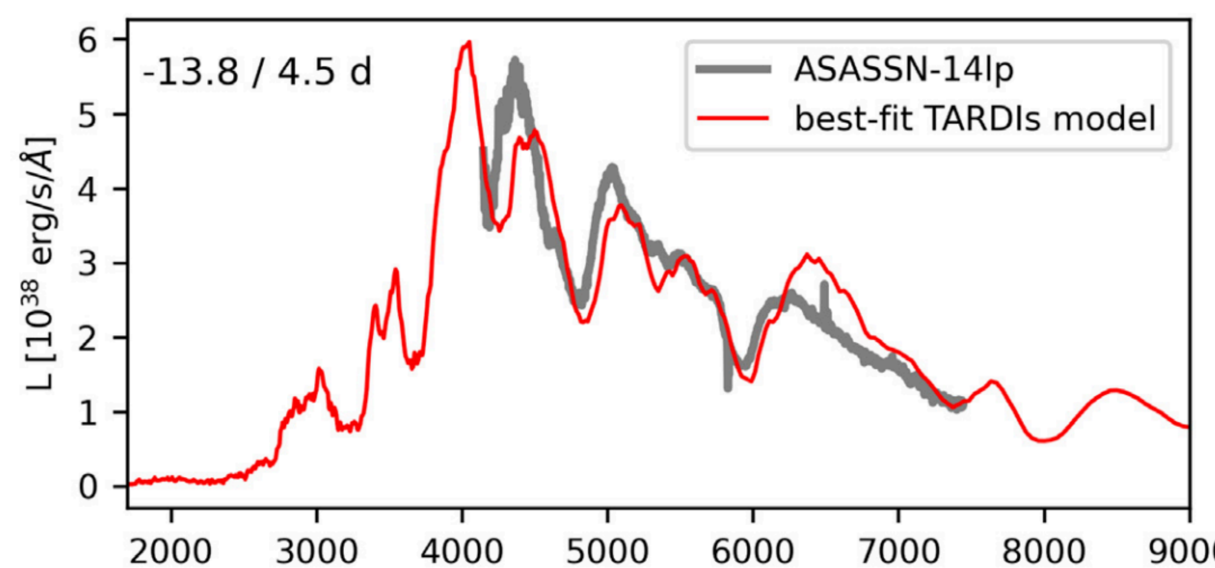
Type Ic SN 1994I





Type II SN 1999em

Type Ia ASASSN-14lp



Conclusions

Spectra in the γ-ray, UV, NIR, MIR offers further stringent constraint on the explosion mechainsm and progenitors.

The spectra at later phases when the ejecta density decreases and the SN is essentially a nebula offers direct probe of the inner regions of the explosion.

JWST spectra in the nebular phase is now confirming predictions from various models.

A quickstart to TARDIS

Installation instructions for tardis

wget -q https://raw.githubusercontent.com/tardis-sn/tardis/master/conda-{platform}-64.lock

Here {platform} can be osx / linux

Download the lock file

conda create --name tardis --file conda-{platform}-64.lock conda activate tardis

git clone git@github.com:username/tardis.git

cd tardis

pip install -e .

See more here https://tardis-sn.github.io/tardis/installation.html

If you do not have conda installed, then please try to install miniforge from here https://github.com/conda-forge/miniforge

then run the above commands with conda with mamba

The documentation for TARDIS can be found at -

https://tardis-sn.github.io/tardis/