28th February, 2020, The Evolution of Massive Stars
and Formation of Compact Stars@Waseda Univ.

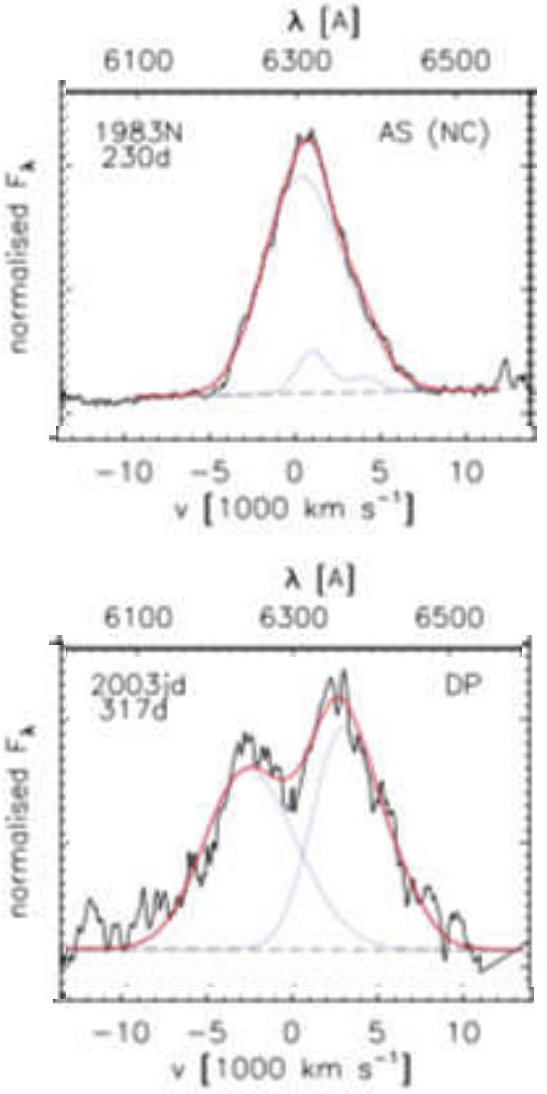
Shape of nebular emission line of core-collapse supernova exploded by neutrino heating mechanism

Yukari Ohtani (NAOJ), Ko Nakamura (Fukuoka Univ.),
Masaomi Tanaka (Tohoku Univ.) and Tomoya Takiwaki (NAOJ)

Emission line of the nebular phase

- >~ 200 days after explosion
- **directly related to the velocity of the ejecta** (along the line of sight)

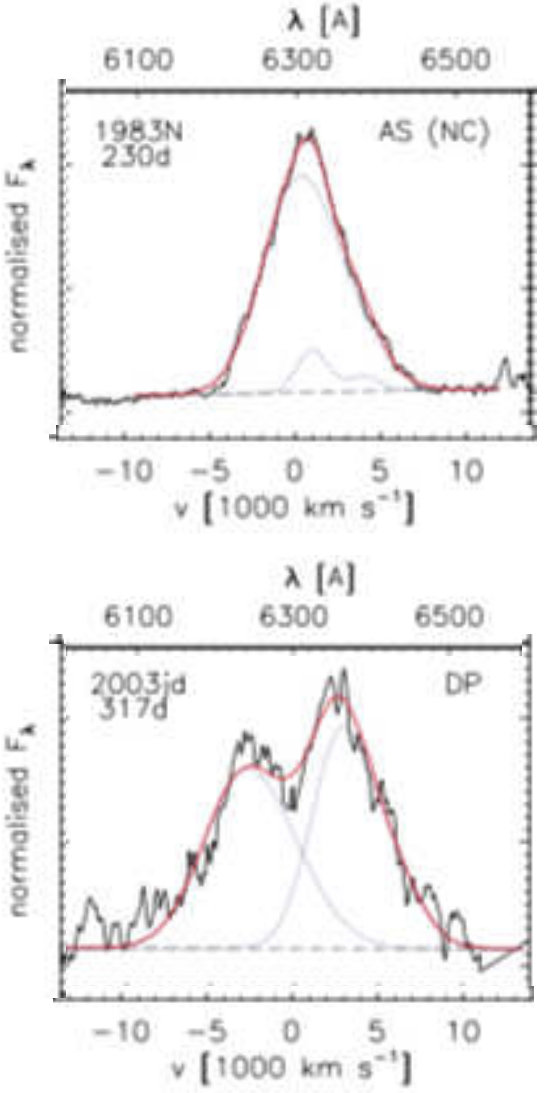
=> Information on the SN explosion mechanism



Examples of single-peaked and double-peaked O lines (Taubenberger+2009)

Observation of emission lines

- forbidden lines of e.g., O, Mg, Ca (Fe: blended)
- [OI]λλ6300 & 6364: blended
  - if τ<<1, the ratio of the emissivities is 3:1
- several types of profile
  - single-peak
  - double-peak
-

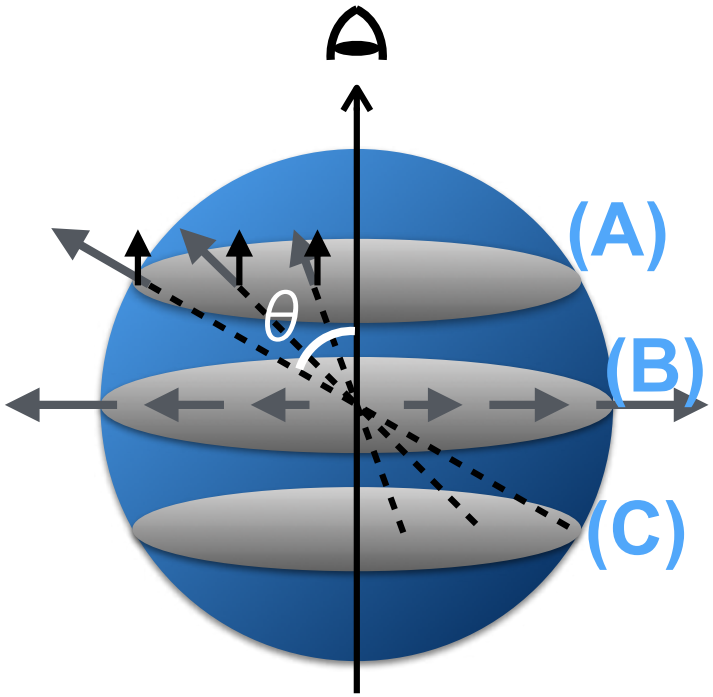


Examples of single-peaked and double-peaked O lines (Taubenberger+2009)

Relationship between 1D homologous expanding matter and line profile

If the expanding matter have

- uniform density
- **$V=V_r=r/t0$ (homologous)**

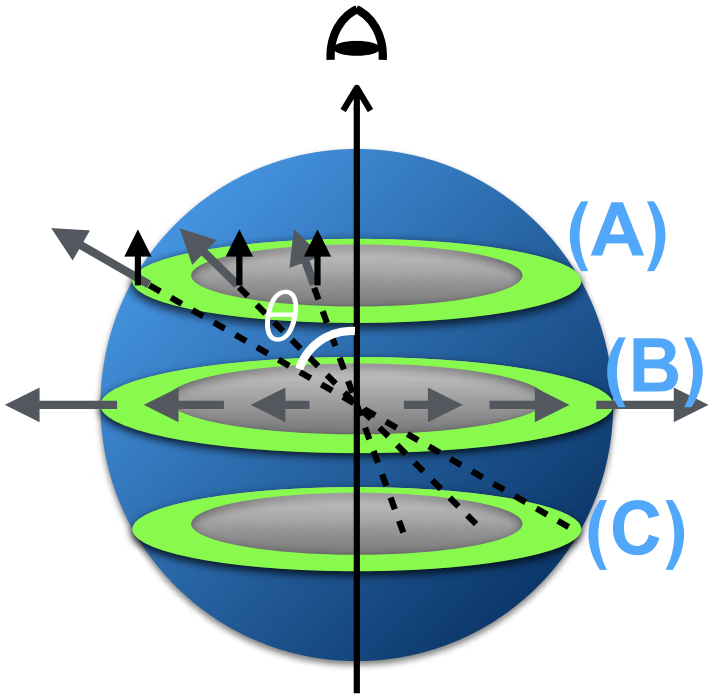


$V_{//}$ (= V cosθ) becomes the same at all points on a vertical plane

Relationship between 1D homologous expanding matter and line profile

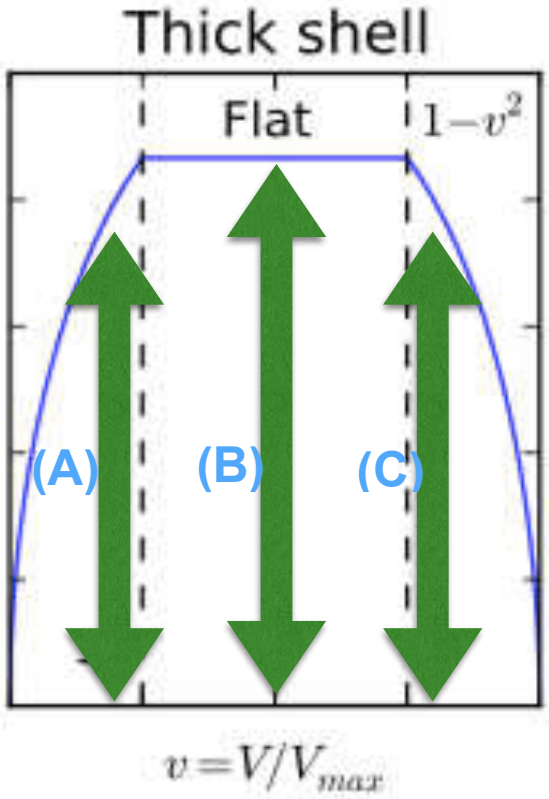
If the expanding matter have

- uniform density
- **$V=V_r=r/t0$ (homologous)**



$V_{//}$ (= V cosθ) becomes the same at all points on a vertical plane

- Even if a line has a single-peaked profile, multi-D hydrodynamic effect would be required. (e.g., Sollerman+2000)



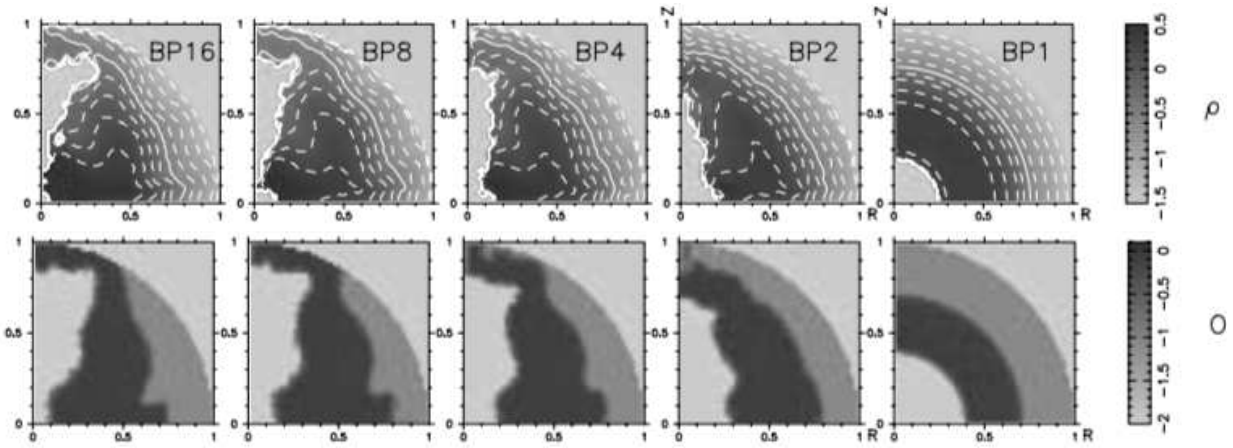
Jerkstrand (2017)

Previous studies

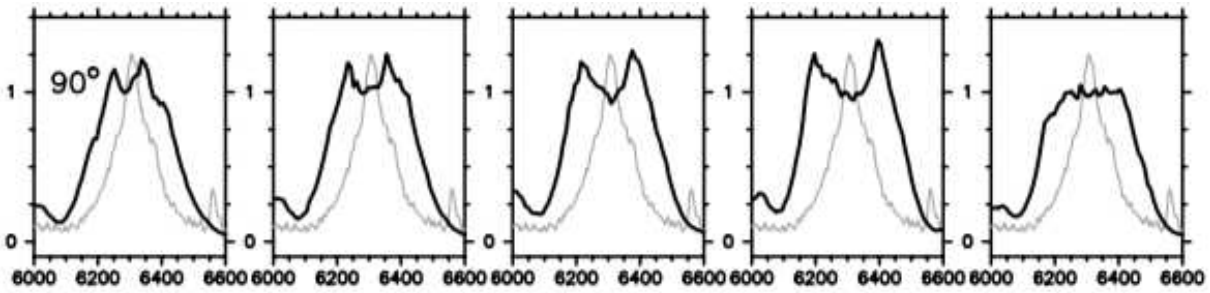
Previous studies

- Many radiative calculation using the results of hydro simulations or fixed mode
  (e.g., Maeda+2002, 2006 2008, Jerkstrand+2018, Tanaka+2009)

- Double-peaked O line = evidence of torus/disk?



Maeda et al. (2002)



Maeda et al. (2006)

This work

Investigate the relations between the geometry of ejecta and shapes of lines by using

- **a 2D hydrodynamic model (Nakamura et al. 2015) in which the neutrino-radiation hydrodynamics are solved self-consistently.**
-

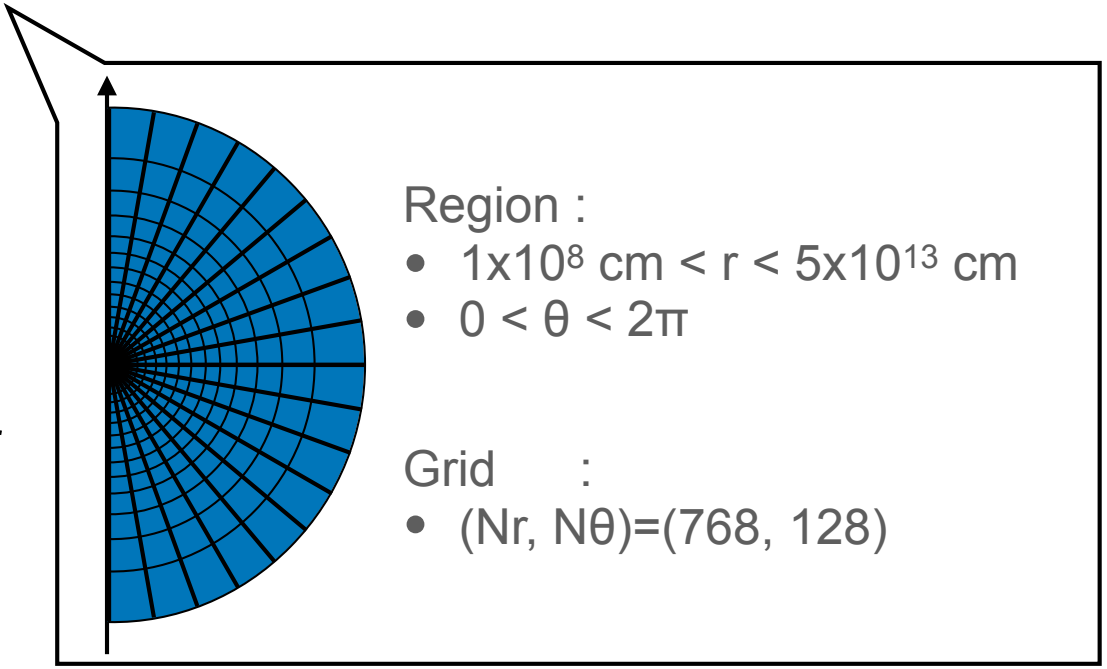
Settings for 2D hydrodynamic calculation

- **Initial condition:**
  - 2D models of **Nakamura+2015** (~7 sec after bounce)

Model	Eexp [erg]	M_{Ni} [Msun]	Unipolarity
s16.0_CO3.0	7.5×10^{50}	0.018	Strong
s17.0_CO3.4	1.5×10^{51}	0.031	Weak
s19.0_CO4.0	1.1×10^{51}	0.017	Strong
s20.0_CO4.5	1.1×10^{51}	0.019	Weak
s22.0_CO5.2	1.3×10^{51}	0.018	Weak

- **Code**: developed by Takiwaki et al.
  - Self-gravity & point-gravity (for 1.4 Msun)
  - Nucleosynthesis: switched off

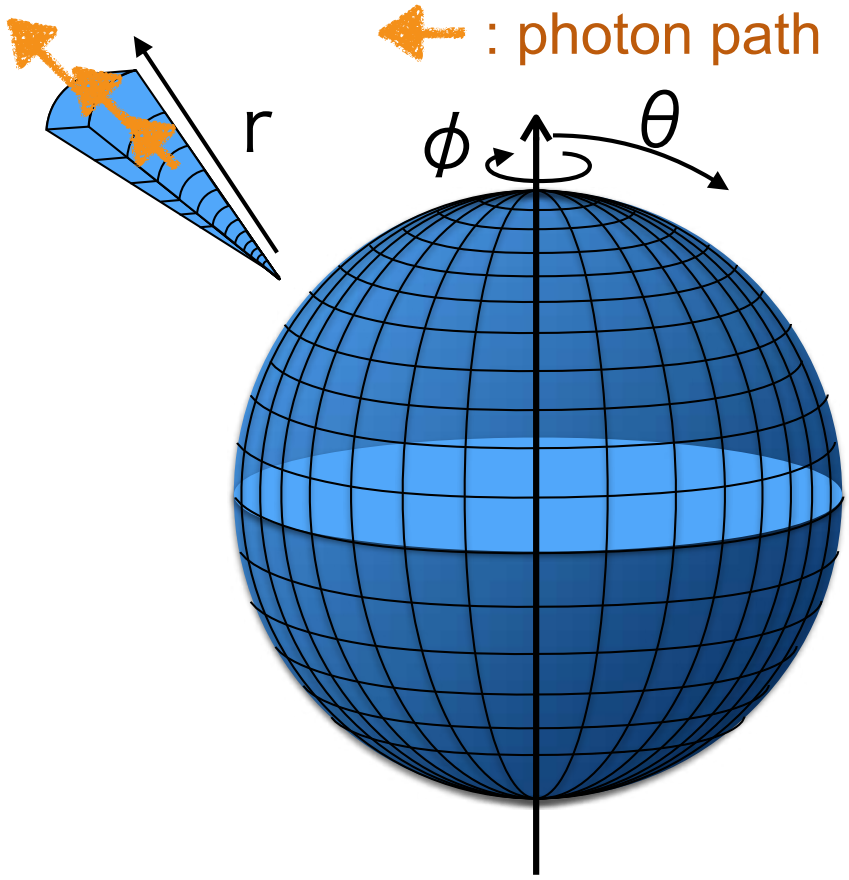
Stops at 1,000 s after the end of Nakamura-san's calculation.



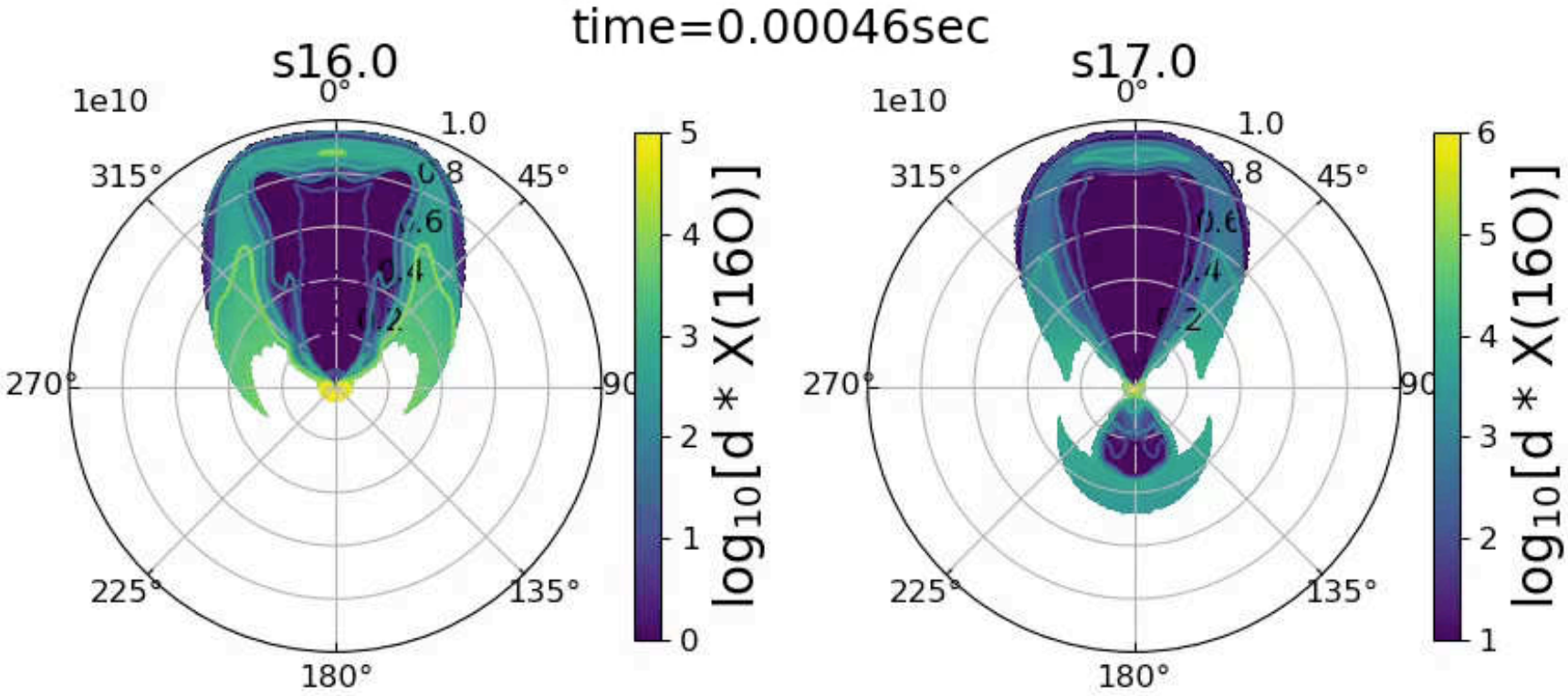
Settings for calculating spectrum

- Lines: [OI]λλ6300 & 6364, MgI]λλ4571, [Ca II]λλ7291, [Fe II]λλ5159

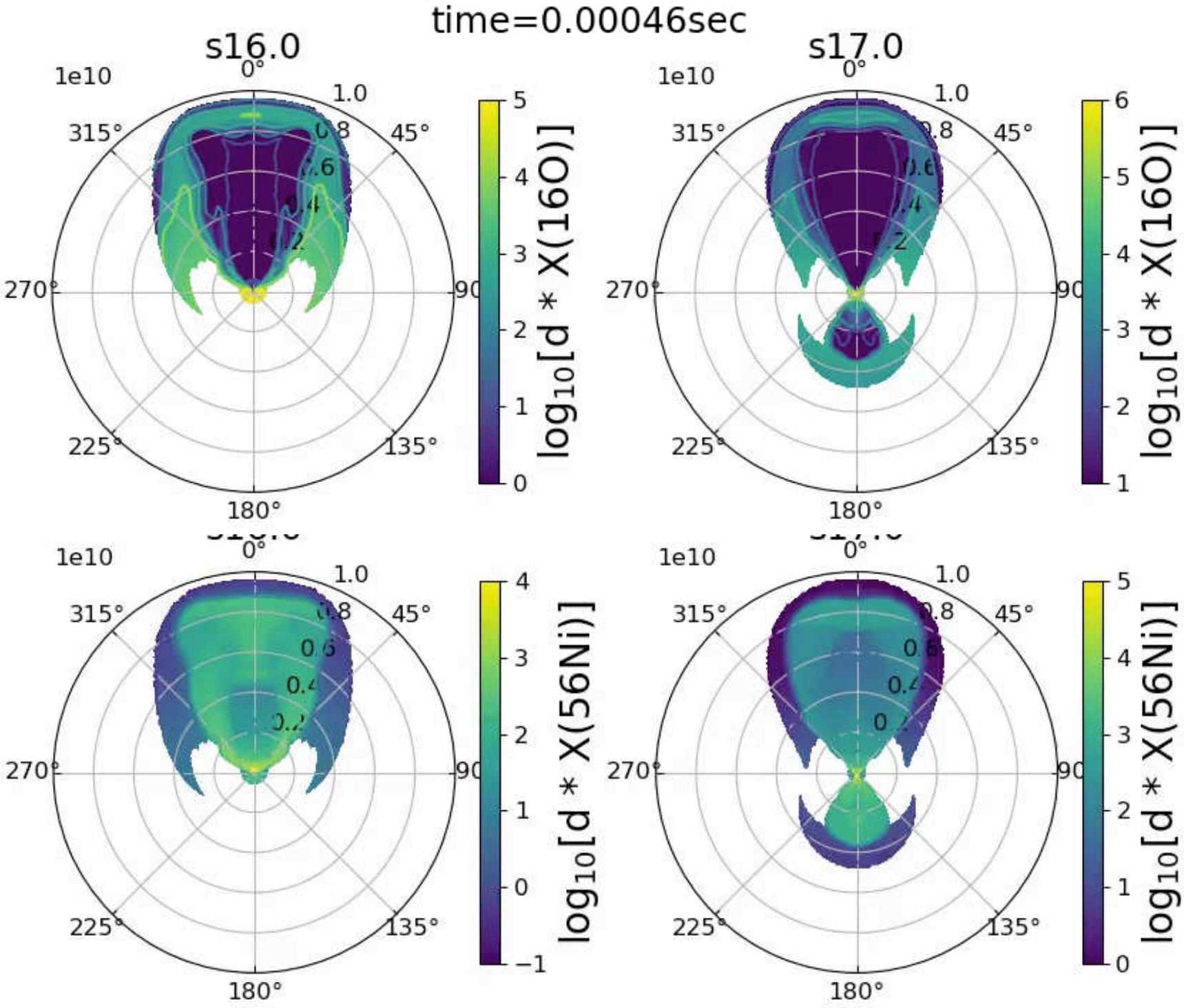
- Optically thin in the post-shock region
- Photons per mesh [a.u.]: ρX dV
  - where ρ is mass density, X mass fraction of each element, and dV volume
- Wavelength $\lambda = \lambda_0[1-V_{//}/c]$
  - $V_{//}$: velocity along the line of sight



Distribution of elements (mass density)

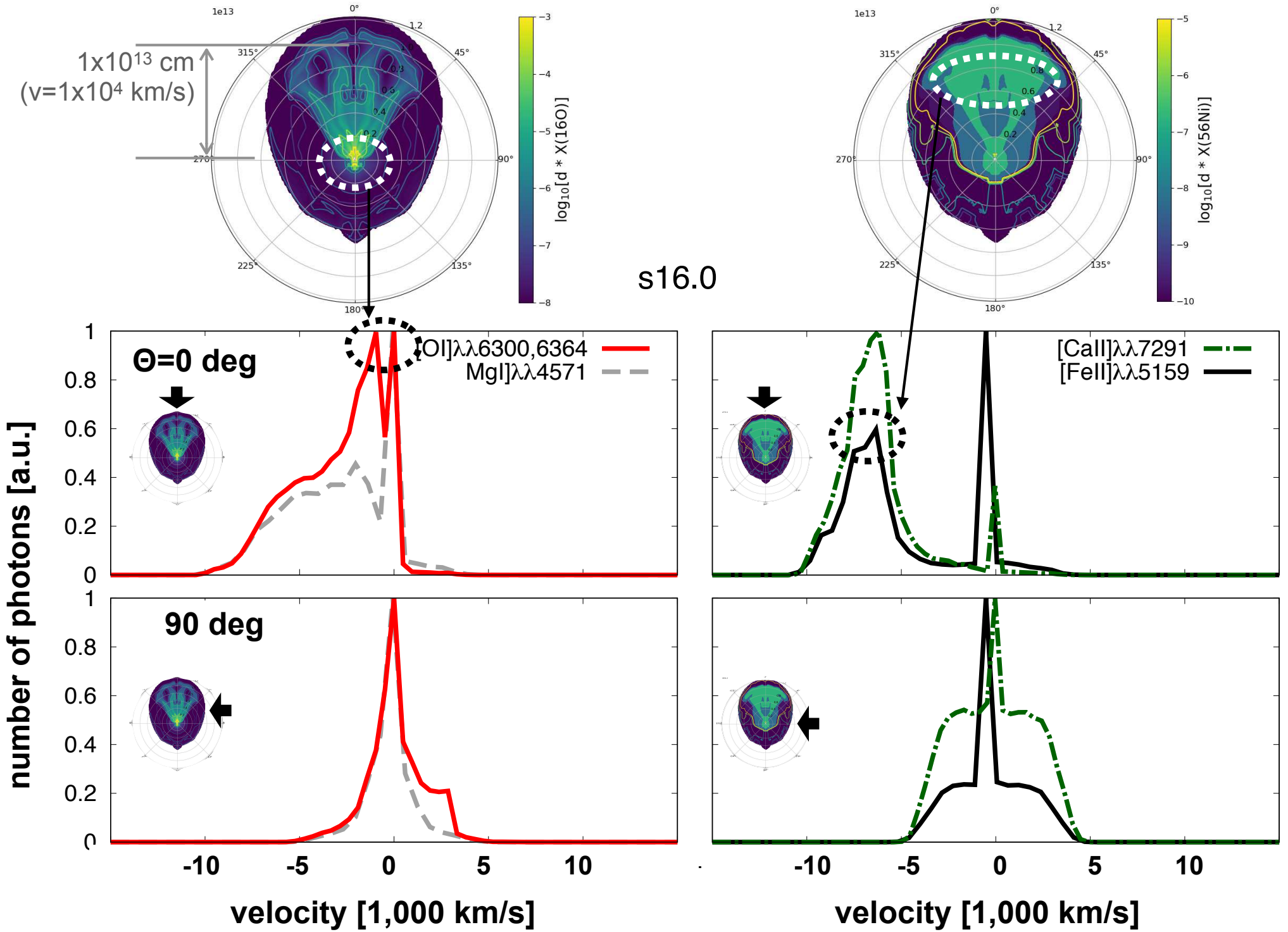


Distribution of elements (mass density)



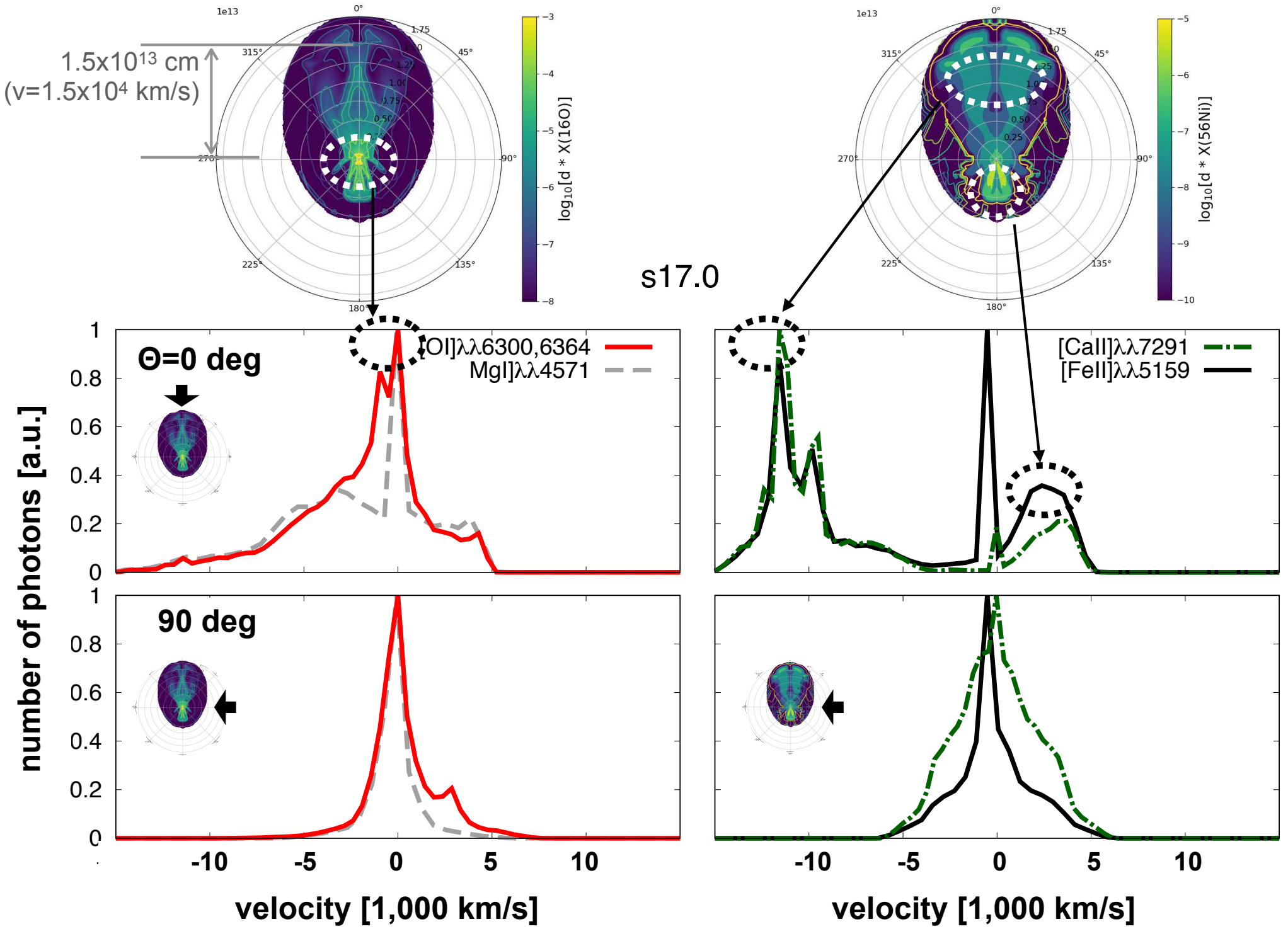
Spectrum (s16.0_CO3.0; Strongly unipolar)

v=0: rest-wavelength



Spectrum (s17.0_CO3.4; Weakly unipolar)

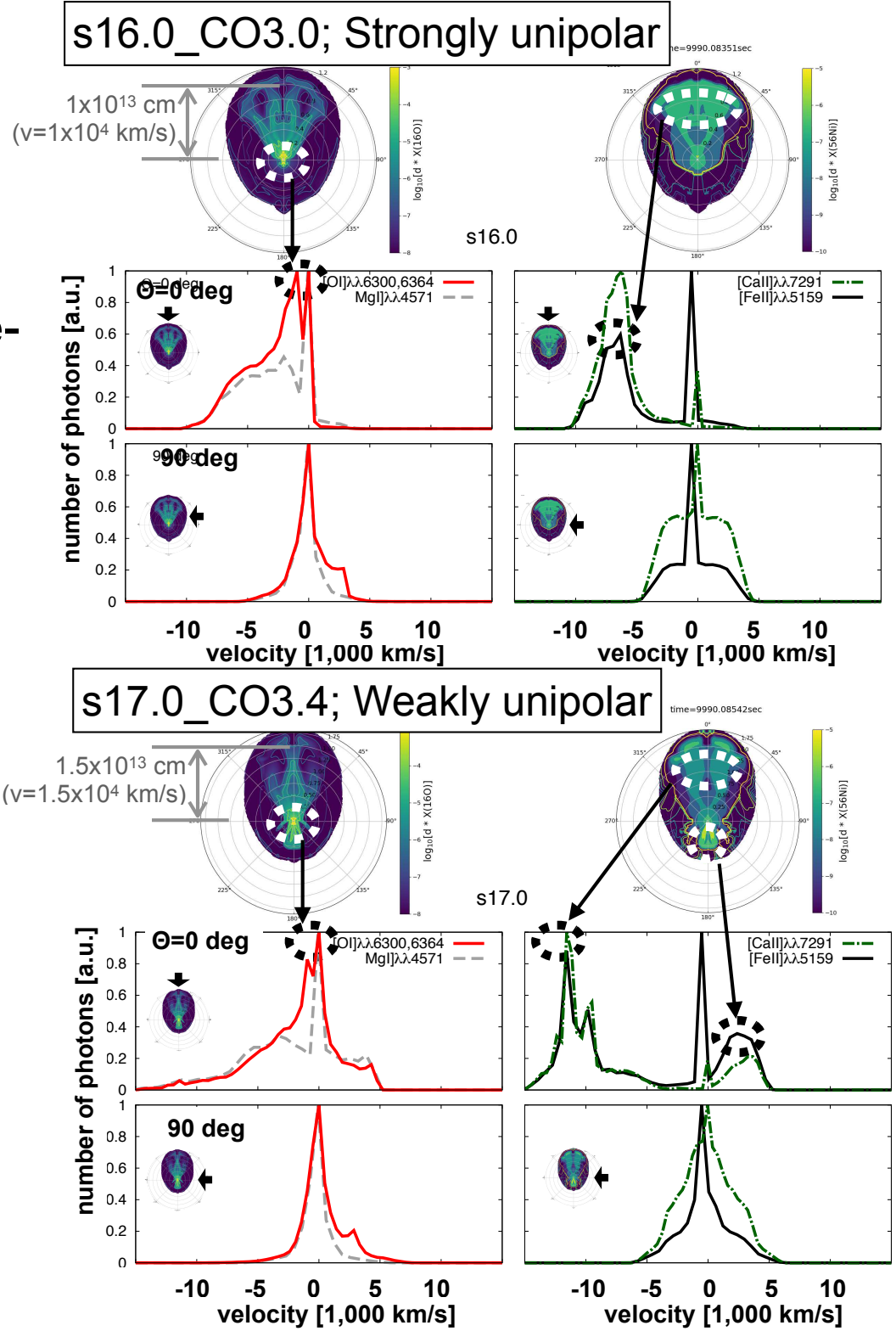
v=0: rest-wavelength



Summary for spectrum

- The profiles of almost all the calculated [OI] lines are single-peaked.
- In order to reproduce the observed double-peaked [OI] lines, a bipolar explosion would be needed.

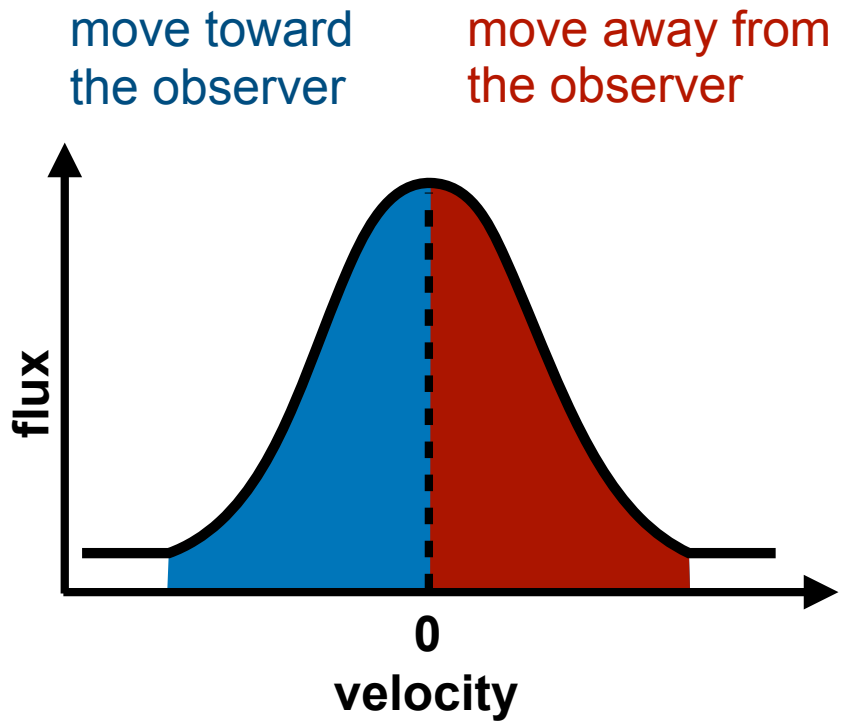
- The magnesium line and calcium line have similar tendencies with oxygen and iron, respectively.



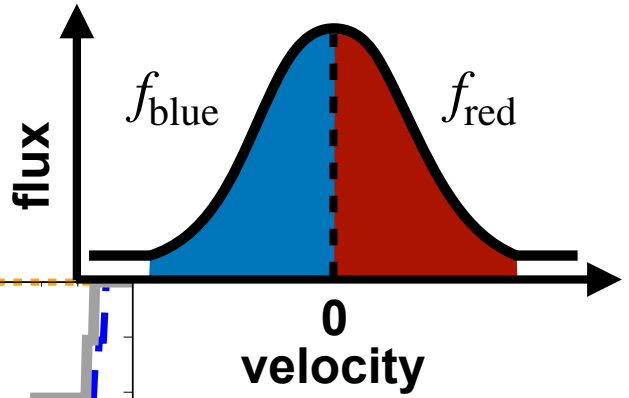
Asymmetry of emission lines

$$\text{area ratio} = \frac{\max(f_{\text{blue}}, f_{\text{red}})}{\min(f_{\text{blue}}, f_{\text{red}})}$$

- **f_blue**: integrated flux of the blue-shifted component
- **f_red** : integrated flux of the red-shifted component

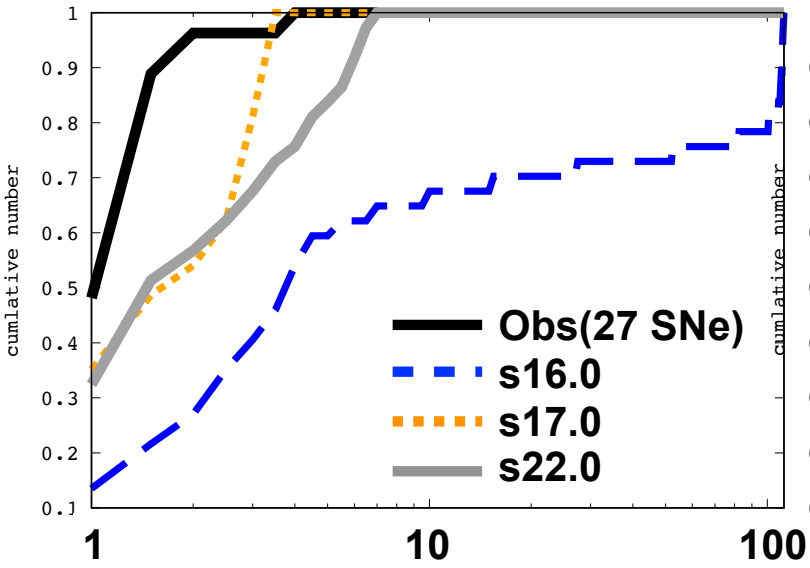


Asymmetry of emission lines

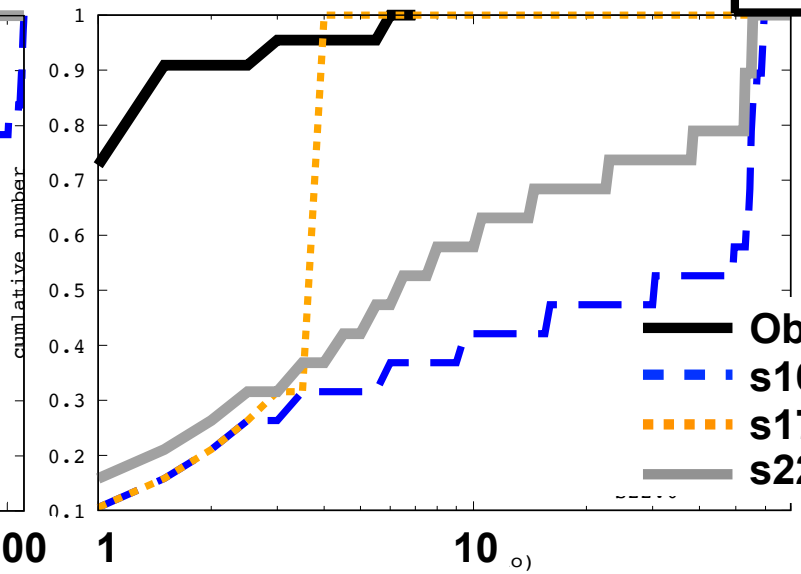


$$\text{area ratio} = \frac{\max(f_{\rm blue}, f_{\rm red})}{\min(f_{\rm blue}, f_{\rm red})}$$

[O I]λλ6300(1)+6364(0.3)

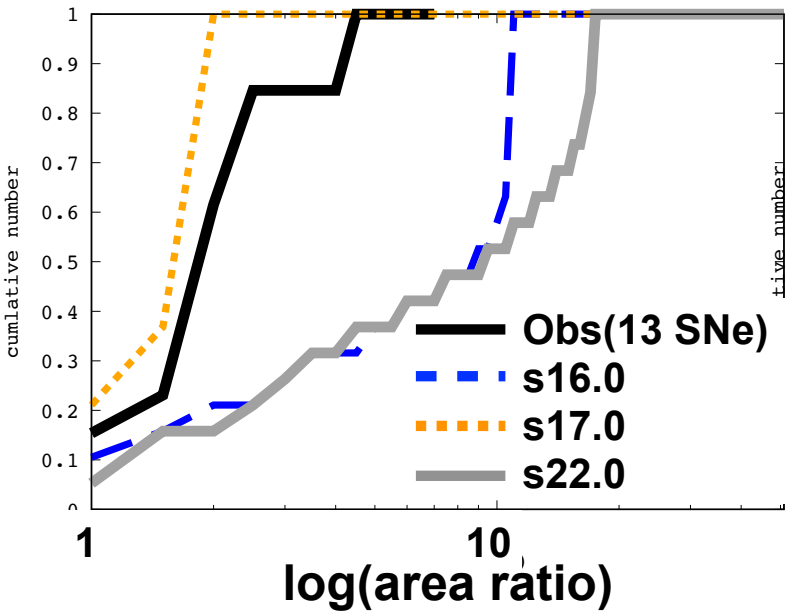


[Ca II]λλ7291

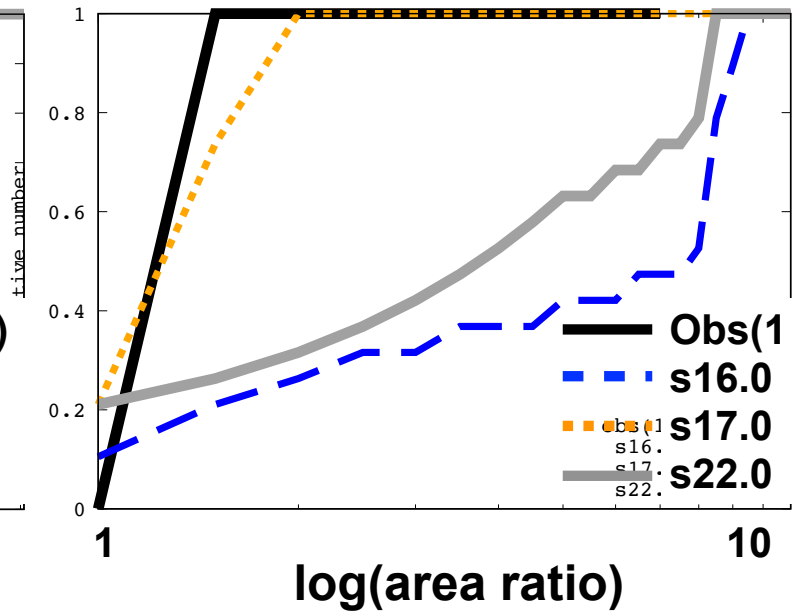


- model spectra:
  - for 19 different viewing angles

Mg I]λλ4571



[Fe II]λλ5159



Summary

- In the self-consistent calculation, the ejecta expansion is unipolar, and the resultant oxygen line has a single-peaked shape while in some observations oxygen lines have double-peaked shapes.

- **The asymmetries of the modeled emission lines are stronger than the observed lines.**

- **Emission lines using a 3D long-time calculation might be in better agreement with the observation.** (Note that if a 3D model also results in a unipolar explosion, the lines will have similar profile with those of the 2D model. Thus we can expect that such unipolar explosion is rare.)

- There might be a tendency that a SN with relatively high explosion energy has a weak unipolarity, while a SN with relatively low explosion energy has a strong unipolarity.