

# Spectral modelling of kilonovae in 3D NLTE

**Blanka Világos**

Supervisor: **Anders Jerkstrand**

Co-supervisor: **Stephan Rosswog**

SirEN conference, 25. 06. 11.



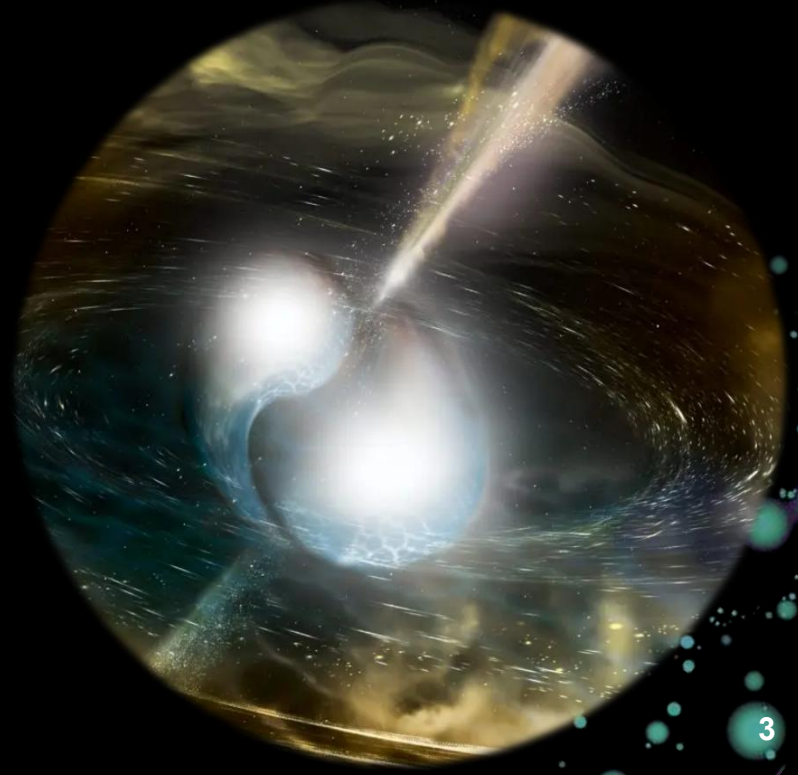
*Knut and Alice  
Wallenberg  
Foundation*

# Spectral modelling of kilonovae in 3D NLTE



# Kilonovae (KN)

- Transients powered by the radioactive r-process elements
- Compact object mergers (NS-NS, NS-BH)

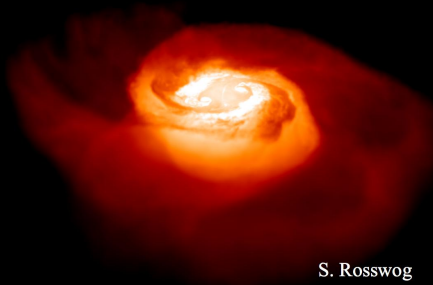


# NLTE spectral modeling

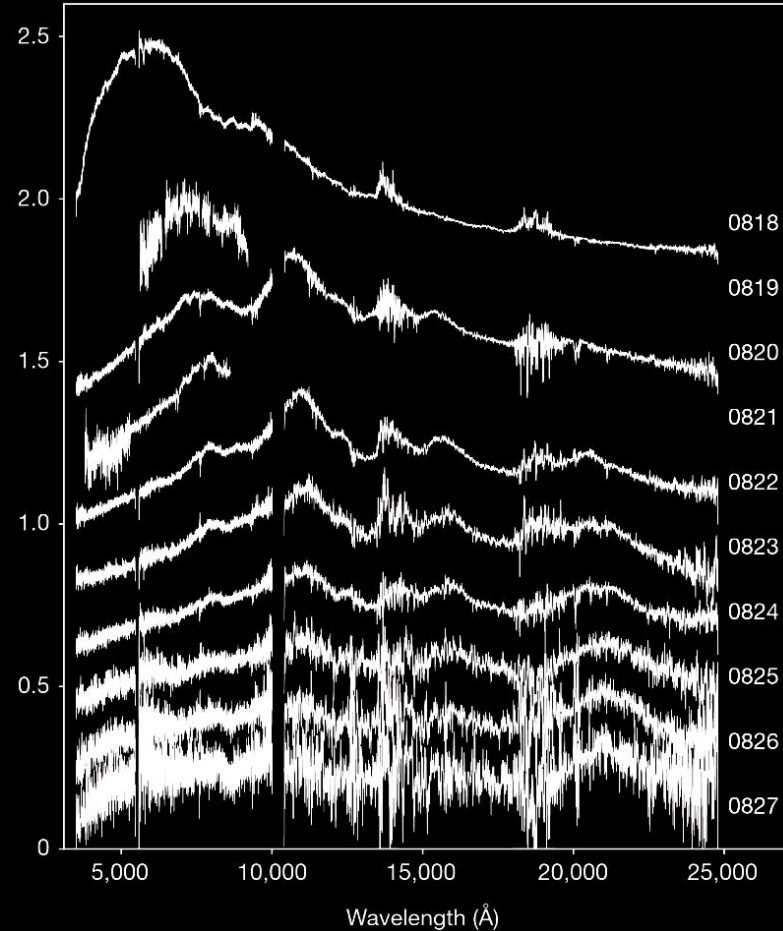
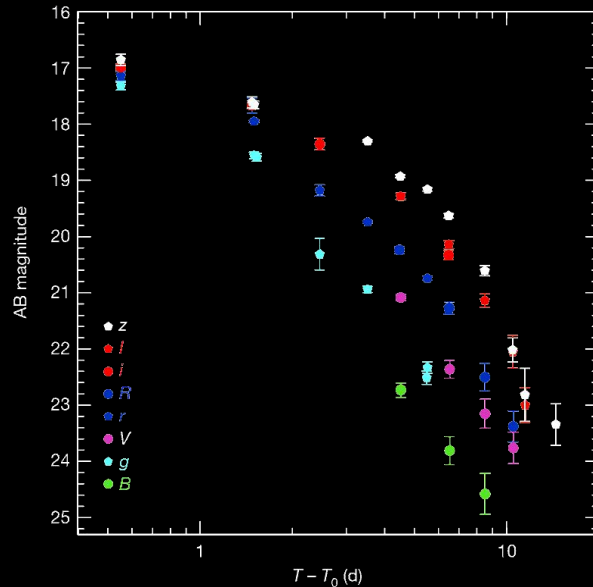
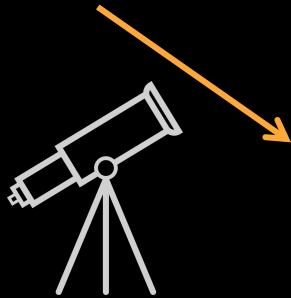


# Spectral modelling

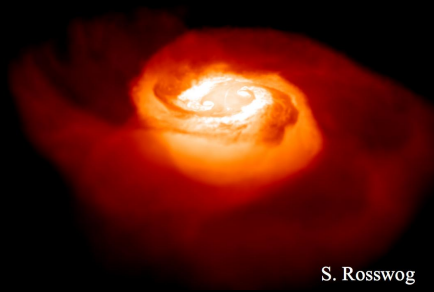
- Reproduce light curves, spectra
- Identify elements (+abundances)



S. Rosswog



# Ingredients of spectral modeling

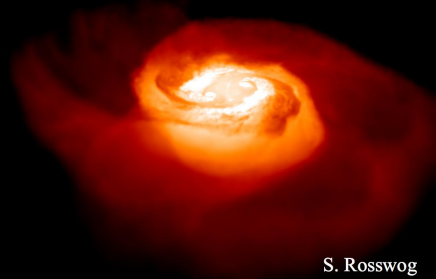


NSM model  
(hydrodynamics -  
numerical relativity)



Grid,  $\rho$ ,  $v$

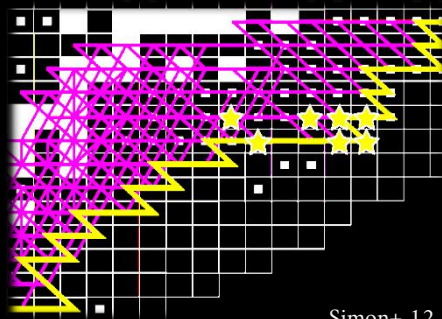
# Ingredients of spectral modeling



NSM model  
(hydrodynamics -  
numerical relativity)



Grid,  $\rho$ ,  $v$

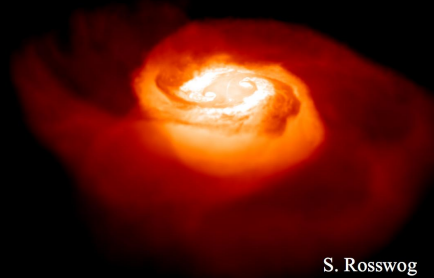


Nucl. reaction  
network



Composition ( $Y_e$ )  
Radioactive heat

# Ingredients of spectral modeling

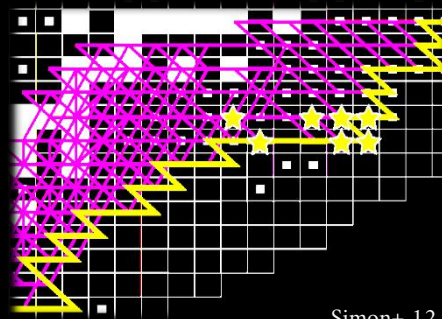


S. Rosswog

NSM model  
(hydrodynamics -  
numerical relativity)



Grid,  $\rho$ ,  $v$

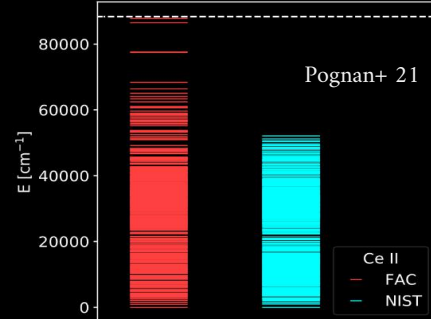


Simon+ 12

Nucl. reaction  
network



Composition ( $Y_e$ )  
Radioactive heat



Pognan+ 21

Atomic  
data



Lines, transitions

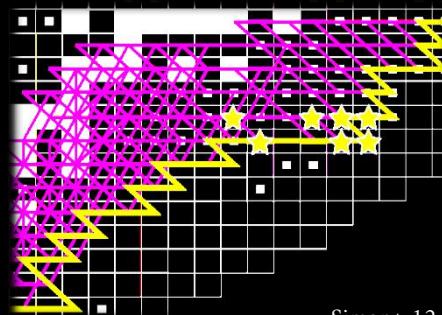
# Ingredients of spectral modeling



NSM model  
(hydrodynamics -  
numerical relativity)



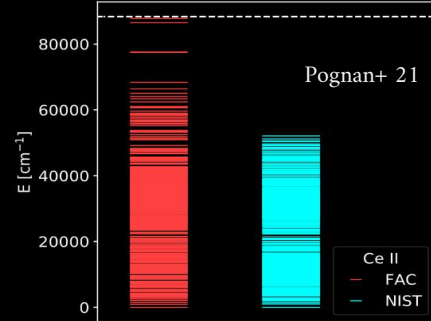
Grid,  $\rho$ ,  $v$



Nucl. reaction  
network



Composition ( $Y_e$ )  
Radioactive heat



Atomic  
data



Lines, transitions

Spectral model

# Nebular phase

- **Nebular phase** = low density, emission lines
- Important for...
  - Nucleosynthesis (bulk of material, emission lines)
  - Physical conditions (e.g. morphology, velocity)
  - For KNe, after  $\sim$  a week
- **NLTE** (non-local thermodynamic equilibrium)
  - Collisional excitations and de-excitations  $\ll$  radiative processes
  - Full rate equations

# MATTER

Physical conditions:

- **Temperature**

Thermal equilibrium

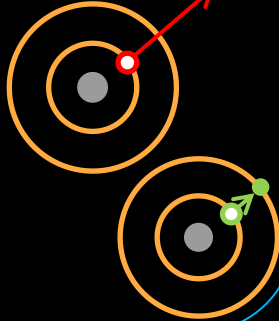


- **Ionisation**

Saha eq.

- **Excitation**

Boltzmann eq.



Emit

LTE

# PHOTONS

Radiation field

Density, spectrum

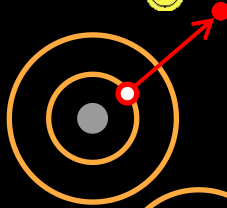
# MATTER

Physical conditions:

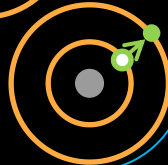
- **Temperature**



- **Ionisation**



- **Excitation**



Emit

**NLTE**

# PHOTONS

**Radiation field**

Density, spectrum

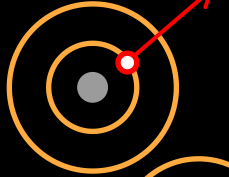
# MATTER

Physical conditions:

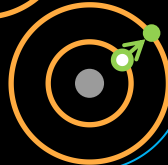
- **Temperature**



- **Ionisation**



- **Excitation**



Emit

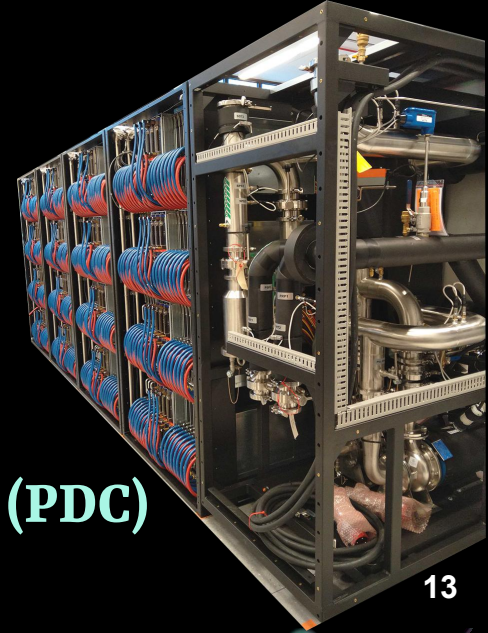
**NLTE**

Excite  
(+ non-local)

# PHOTONS

**Radiation field**

Density, spectrum



**Dardel, KTH (PDC)**

**ExTraSS**

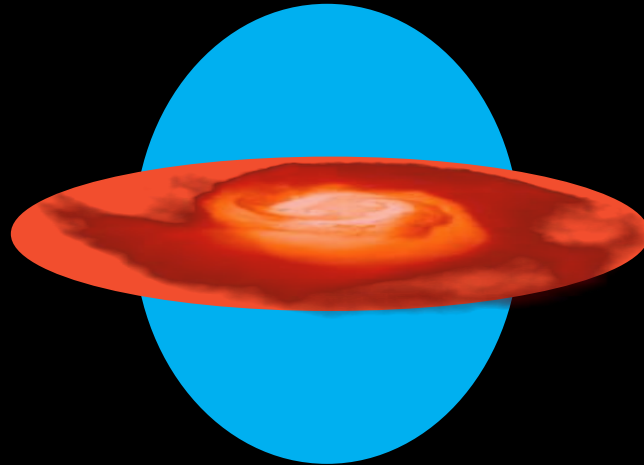


# Stockholm codes for spectral modeling

- NLTE spectral codes for transients
- 1D: **SUMO** (**SU**pernova **MO**nte carlo code) - [A. Jerkstrand, Q. Pognan](#)  
3D: **ExTraSS** (**EX**plosive **TR**Ansient **S**pectral **S**imulator) - [AJ, B. van Baal](#)
- My PhD: add KN physics to ExTraSS

|      | <b>SUMO</b> | <b>EXTRASS</b> |
|------|-------------|----------------|
| NLTE | ✓           | ✓              |
| 3D   | ✗           | ✓              |
| SNe  | ✓           | ✓              |
| KNe  | ✓           | ...            |

# Ejecta components



Disk wind / NS driven  
outflows (polar)

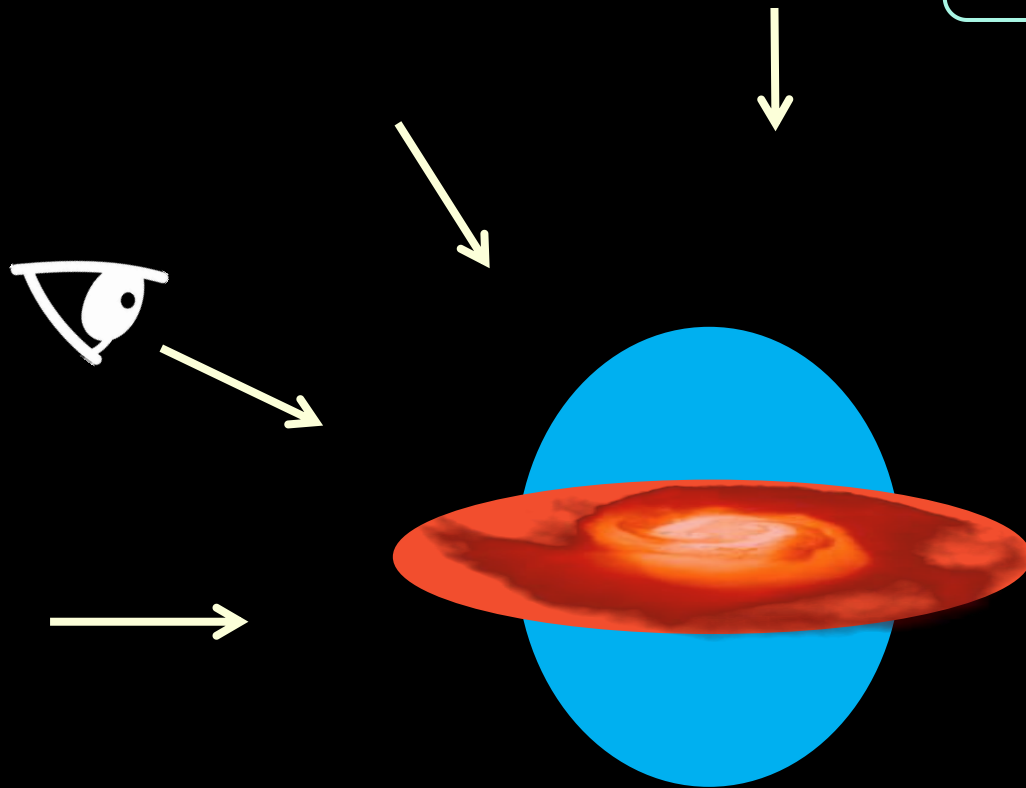
lighter r-nuclei, high  $Y_e$   
 $v \sim 0.1 c$

Dynamical  
ejecta (equatorial)

heavy r-nuclei, low  $Y_e$   
 $v \sim 0.3 c$

# Ejecta components

3D needed!!



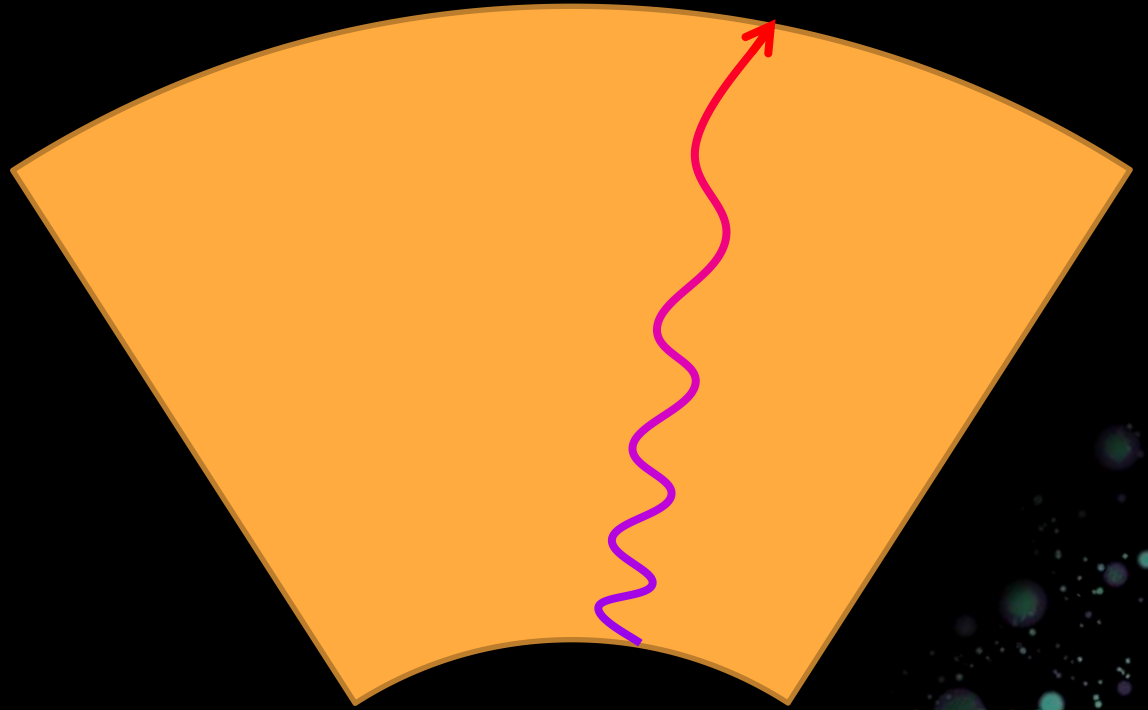
Disk wind / NS driven  
outflows (polar)

lighter r-nuclei, high  $Y_e$   
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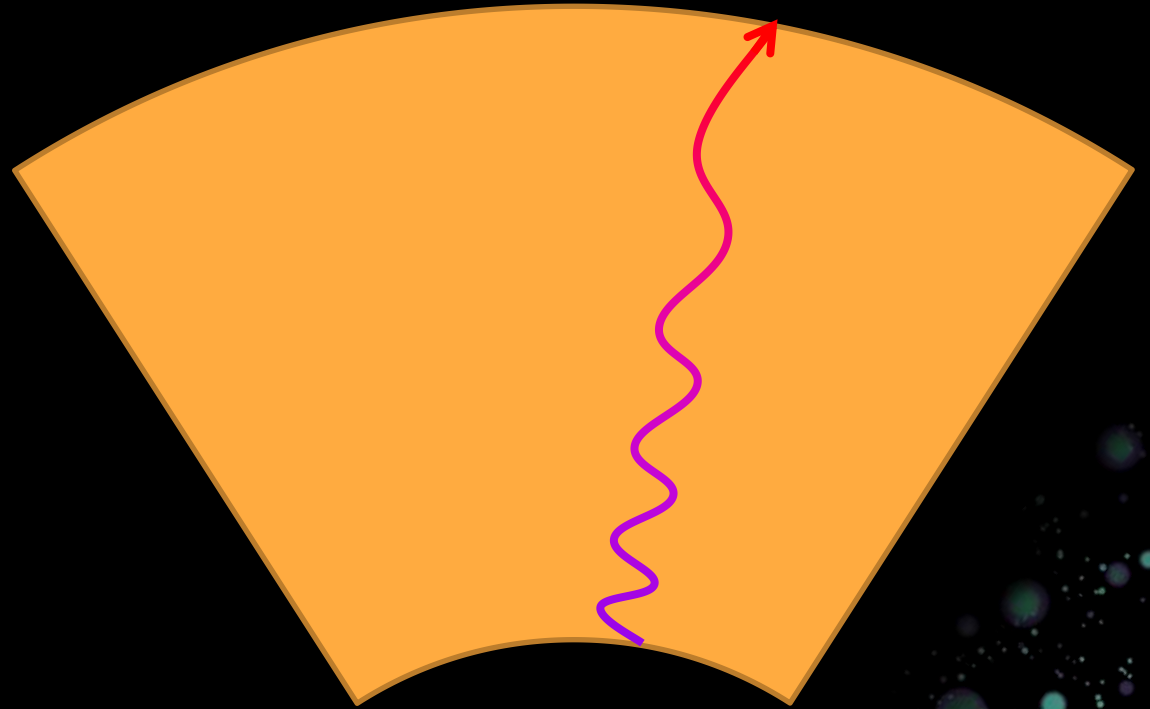
heavy r-nuclei, low  $Y_e$   
 $v \sim 0.3 c$

# Line-to-line photon transfer



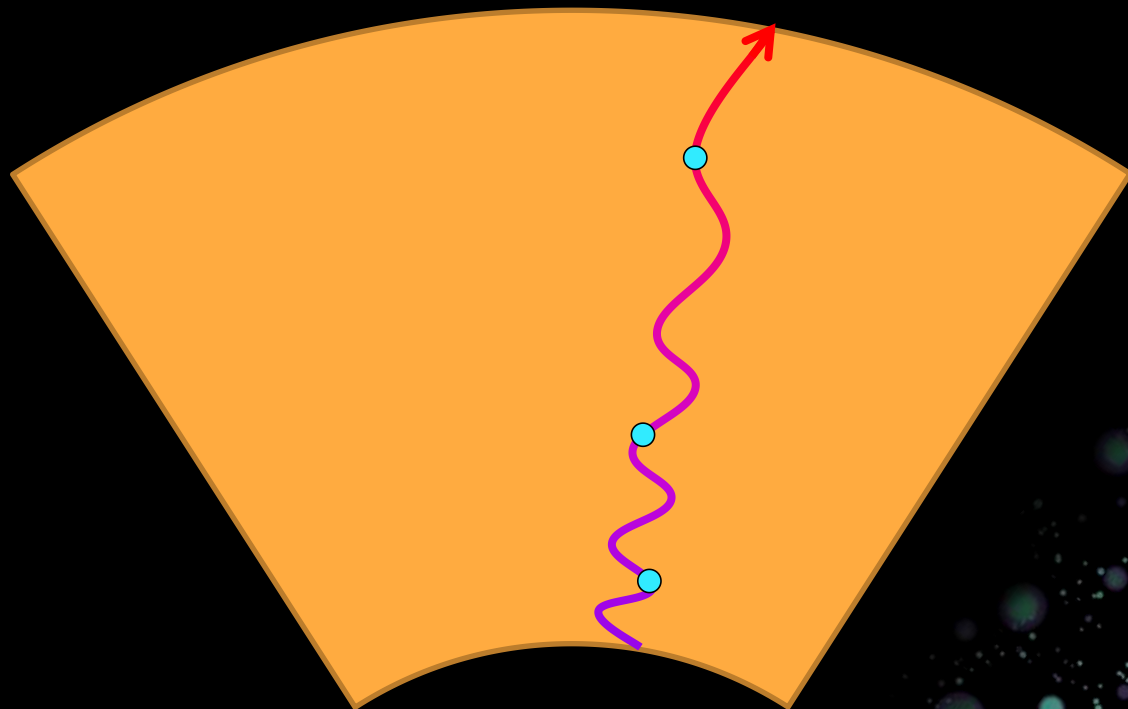
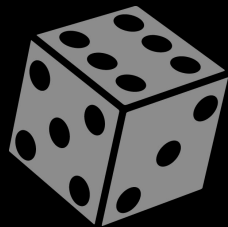
# Line-to-line photon transfer

Potential  
atomic lines:

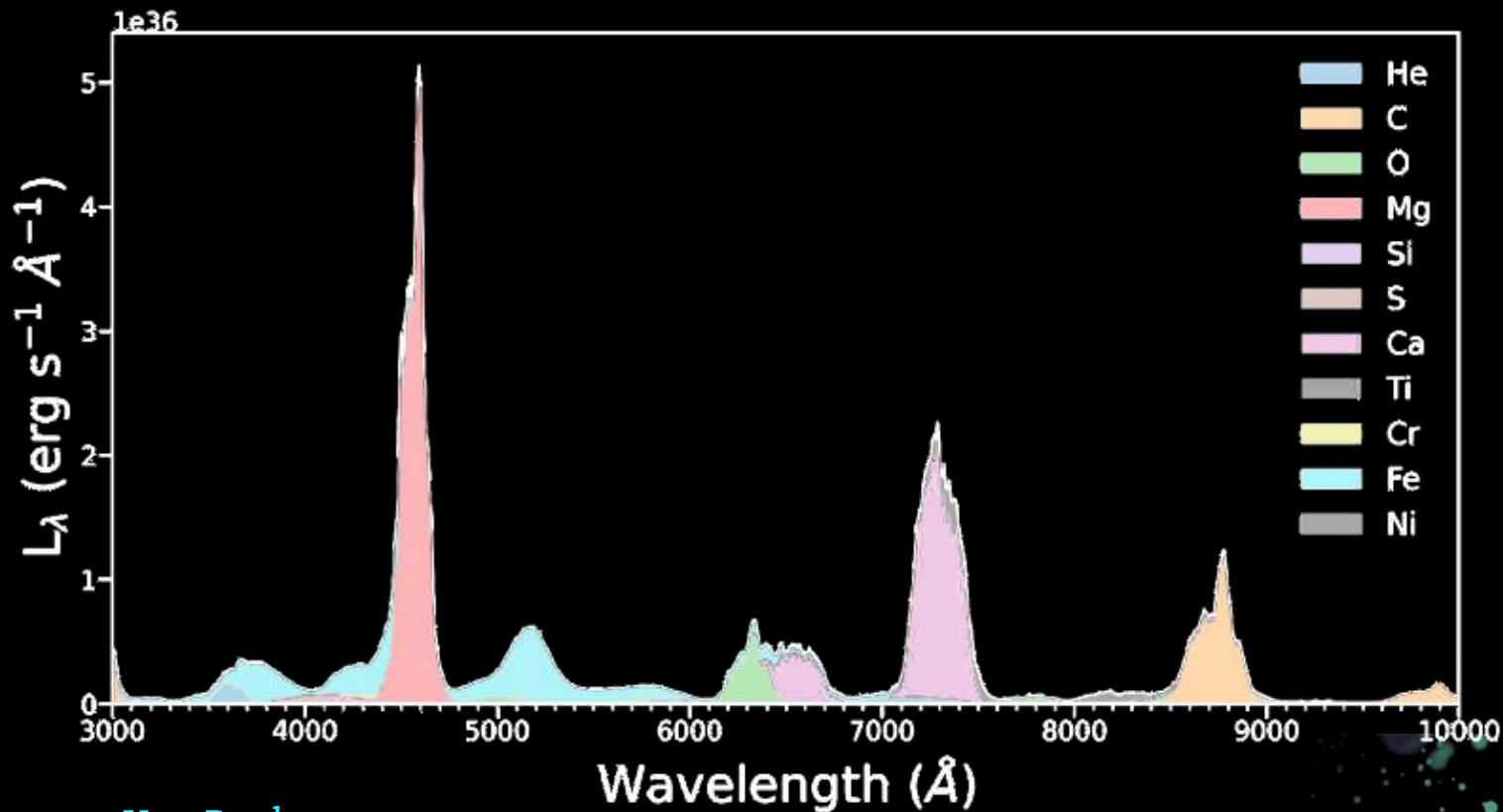


# Line-to-line photon transfer

Potential  
atomic lines:

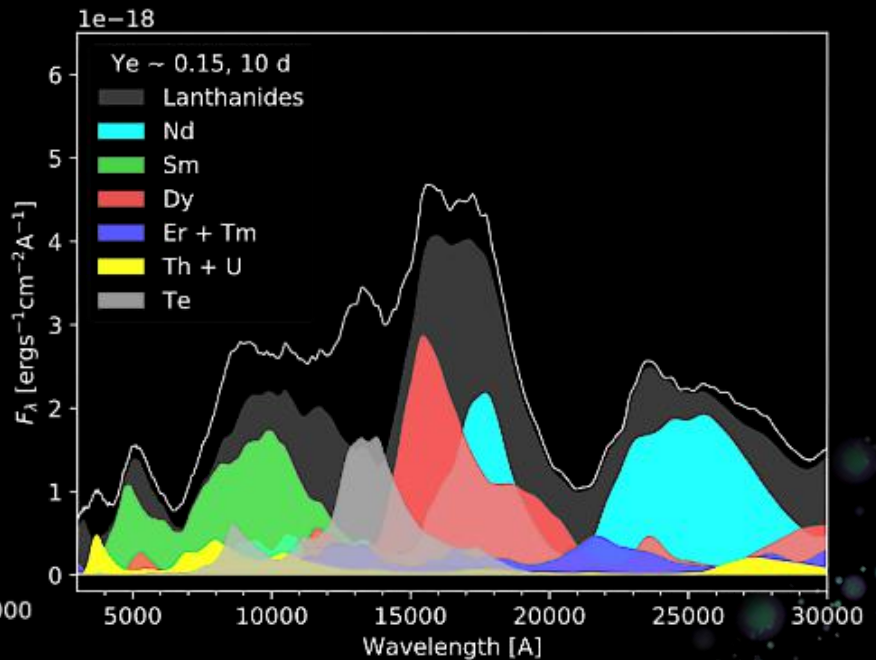
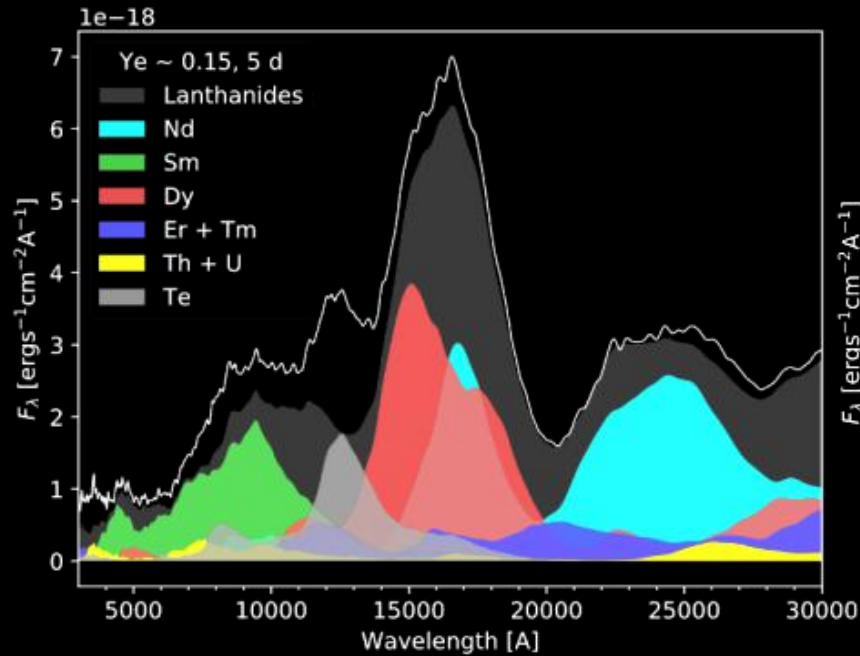


# SN 3D spectrum (ExTraSS)



Van Baal+ 2023

# KN 1D spectra (SUMO)



Pognan+ 2023

**Towards KNe**



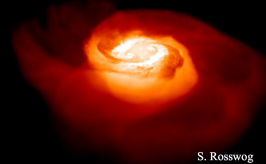
# What is different for KNe (vs SNe)?

- Higher velocity, lower ejecta mass
  - Very quickly diluted  $\rightarrow$  NLTE effects
- Composition: heavy  $r$ -process elements
  - Radioactive heating:  $\alpha + \beta + \gamma +$  fission  
(SNe: only  $\gamma$ -rays of Ni-56)
  - Atoms: many levels and line rich  
 $\rightarrow$  heavier transfer
  - Lines blended, no distinct lines

|                                     | SN            | KN               |
|-------------------------------------|---------------|------------------|
| $M$                                 | $5 M_{\odot}$ | $0.05 M_{\odot}$ |
| $V$                                 | $0.01c$       | $0.1c$           |
| $t_{peak}$                          | 20d           | 2d               |
| $\rho_{peak}$                       | $10^{-11}$    | $10^{-13}$       |
| $\frac{L(10t_{peak})}{L(t_{peak})}$ | 0.16          | 0.05             |
| $N_{lines}$                         | $\sim 10^6$   | $\sim 10^8$      |
| % r.-a.                             | 5%            | 100%             |

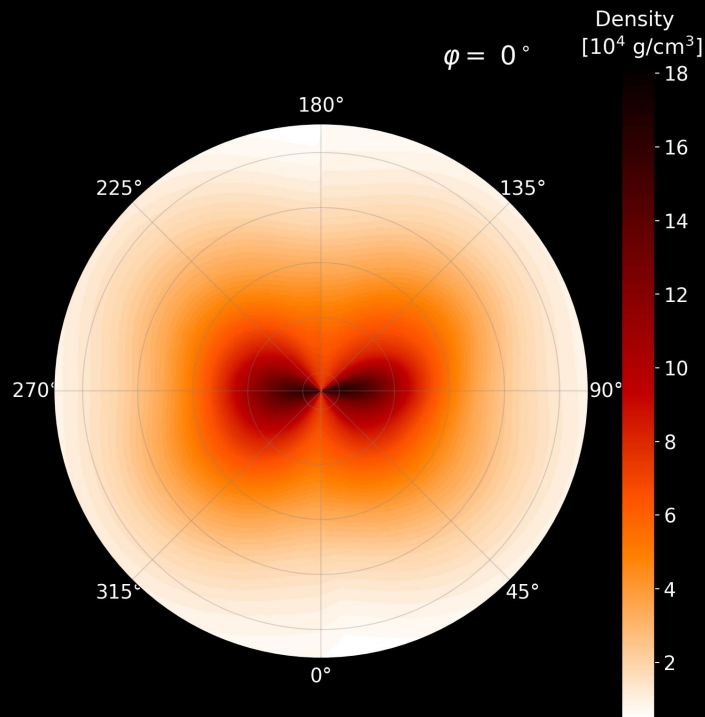
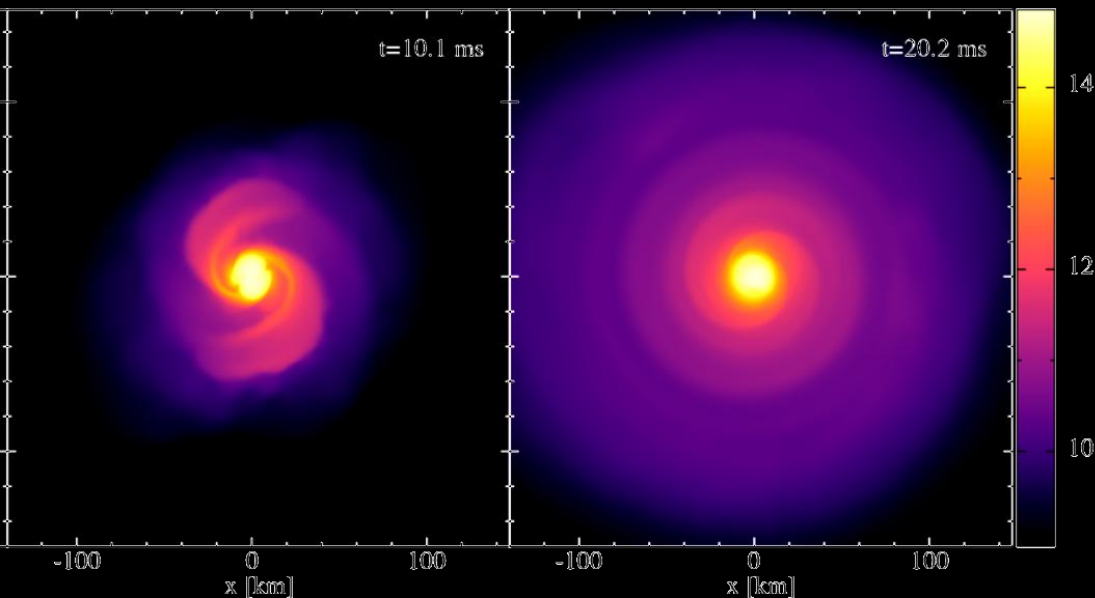
# Input model

- SPHINCS\_BSSN Lagrangian Numerical Relativity model  
(only dynamical ejecta) *Rosswog+ 2025*
- $1.3 + 1.3 M_{\odot}$  NS;  $M_{\text{ej}} 7 \cdot 10^{-4} M_{\odot}$

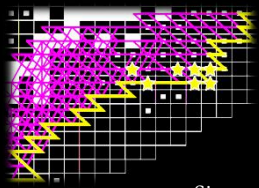


S. Rosswog

NSM model



# Input model – composition



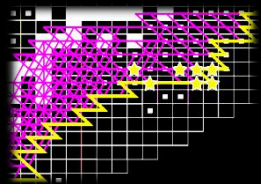
Simo

Nucl. network

|                                 |                                 |                               |                                     |                                 |                                     |                                  |                                   |                                  |                                    |                                   |                                   |                                    |                                  |                                 |                                   |                                  |                                  |                                |                               |                               |                             |                               |                            |
|---------------------------------|---------------------------------|-------------------------------|-------------------------------------|---------------------------------|-------------------------------------|----------------------------------|-----------------------------------|----------------------------------|------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|----------------------------------|---------------------------------|-----------------------------------|----------------------------------|----------------------------------|--------------------------------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|----------------------------|
| Nucl. netw                      |                                 |                               |                                     |                                 |                                     |                                  |                                   |                                  |                                    |                                   |                                   |                                    |                                  |                                 |                                   |                                  |                                  |                                |                               |                               |                             |                               |                            |
| 1<br>H<br>Hydrogen<br>1.008     |                                 |                               |                                     |                                 |                                     |                                  |                                   |                                  |                                    |                                   |                                   |                                    |                                  |                                 |                                   |                                  |                                  | 13<br>B<br>Boron<br>10.811     | 14<br>C<br>Carbon<br>12.011   | 15<br>N<br>Nitrogen<br>14.007 | 16<br>O<br>Oxygen<br>15.999 | 17<br>F<br>Fluorine<br>18.998 | 18<br>Ne<br>Neon<br>20.180 |
| 2<br>Li<br>Lithium<br>6.941     | 4<br>Be<br>Beryllium<br>9.012   |                               |                                     |                                 |                                     |                                  |                                   |                                  |                                    |                                   |                                   |                                    |                                  | 13<br>Al<br>Aluminum<br>26.982  | 14<br>Si<br>Silicon<br>28.086     | 15<br>P<br>Phosphorus<br>30.974  | 16<br>S<br>Sulfur<br>32.066      | 17<br>Cl<br>Chlorine<br>35.453 | 18<br>Ar<br>Argon<br>39.948   |                               |                             |                               |                            |
| 3<br>Na<br>Sodium<br>22.990     | 12<br>Mg<br>Magnesium<br>24.305 | 3<br>K<br>Potassium<br>39.098 | 20<br>Ca<br>Calcium<br>40.078       | 21<br>Sc<br>Scandium<br>44.956  | 22<br>Ti<br>Titanium<br>47.867      | 23<br>V<br>Vanadium<br>50.942    | 24<br>Cr<br>Chromium<br>51.996    | 25<br>Mn<br>Manganese<br>54.938  | 26<br>Fe<br>Iron<br>55.845         | 27<br>Co<br>Cobalt<br>58.933      | 28<br>Ni<br>Nickel<br>58.693      | 29<br>Cu<br>Copper<br>63.546       | 30<br>Zn<br>Zinc<br>65.38        | 31<br>Ga<br>Gallium<br>69.723   | 32<br>Ge<br>Germanium<br>72.631   | 33<br>As<br>Arsenic<br>74.922    | 34<br>Se<br>Selenium<br>78.971   | 35<br>Br<br>Bromine<br>79.904  | 36<br>Kr<br>Krypton<br>83.798 |                               |                             |                               |                            |
| 37<br>Rb<br>Rubidium<br>85.468  | 38<br>Sr<br>Strontium<br>87.62  | 39<br>Y<br>Yttrium<br>88.906  | 40<br>Zr<br>Zirconium<br>91.224     | 41<br>Nb<br>Niobium<br>92.906   | 42<br>Mo<br>Molybdenum<br>95.95     | 43<br>Tc<br>Technetium<br>98.907 | 44<br>Ru<br>Ruthenium<br>101.07   | 45<br>Rh<br>Rhodium<br>102.906   | 46<br>Pd<br>Palladium<br>106.42    | 47<br>Ag<br>Silver<br>107.868     | 48<br>Cd<br>Cadmium<br>112.414    | 49<br>In<br>Indium<br>114.818      | 50<br>Sn<br>Tin<br>118.711       | 51<br>Sb<br>Antimony<br>121.760 | 52<br>Te<br>Tellurium<br>127.6    | 53<br>I<br>Iodine<br>126.904     | 54<br>Xe<br>Xenon<br>131.293     |                                |                               |                               |                             |                               |                            |
| 55<br>Cs<br>Cesium<br>132.905   | 56<br>Ba<br>Barium<br>137.328   | 57-71                         | 72<br>Hf<br>Hafnium<br>178.49       | 73<br>Ta<br>Tantalum<br>180.948 | 74<br>W<br>Tungsten<br>183.84       | 75<br>Re<br>Rhenium<br>186.207   | 76<br>Os<br>Osmium<br>190.23      | 77<br>Ir<br>Iridium<br>192.217   | 78<br>Pt<br>Platinum<br>195.085    | 79<br>Au<br>Gold<br>196.967       | 80<br>Hg<br>Mercury<br>200.592    | 81<br>Tl<br>Thallium<br>204.383    | 82<br>Pb<br>Lead<br>207.2        | 83<br>Bi<br>Bismuth<br>208.980  | 84<br>Po<br>Polonium<br>[208.982] | 85<br>At<br>Astatine<br>209.987  | 86<br>Rn<br>Radon<br>222.018     |                                |                               |                               |                             |                               |                            |
| 87<br>Fr<br>Francium<br>223.020 | 88<br>Ra<br>Radium<br>226.025   | 89-103                        | 104<br>Rf<br>Rutherfordium<br>[261] | 105<br>Db<br>Dubnium<br>[262]   | 106<br>Sg<br>Seaborgium<br>[266]    | 107<br>Bh<br>Bohrium<br>[264]    | 108<br>Hs<br>Hassium<br>[269]     | 109<br>Mt<br>Meitnerium<br>[278] | 110<br>Ds<br>Darmstadtium<br>[281] | 111<br>Rg<br>Roentgenium<br>[280] | 112<br>Cn<br>Copernicium<br>[285] | 113<br>Nh<br>Nihonium<br>[286]     | 114<br>Fl<br>Flerovium<br>[289]  | 115<br>Mc<br>Moscovium<br>[289] | 116<br>Lv<br>Livermorium<br>[293] | 117<br>Ts<br>Tennessine<br>[294] | 118<br>Og<br>Oganesson<br>[294]  |                                |                               |                               |                             |                               |                            |
| Lanthanide Series               |                                 |                               | 57<br>La<br>Lanthanum<br>138.905    | 58<br>Ce<br>Cerium<br>140.116   | 59<br>Pr<br>Praseodymium<br>140.908 | 60<br>Nd<br>Neodymium<br>144.243 | 61<br>Pm<br>Promethium<br>144.913 | 62<br>Sm<br>Samarium<br>150.36   | 63<br>Eu<br>Europium<br>151.964    | 64<br>Gd<br>Gadolinium<br>157.25  | 65<br>Tb<br>Terbium<br>158.925    | 66<br>Dy<br>Dysprosium<br>162.500  | 67<br>Ho<br>Holmium<br>164.930   | 68<br>Er<br>Erbium<br>167.259   | 69<br>Tm<br>Thulium<br>168.934    | 70<br>Yb<br>Ytterbium<br>173.055 | 71<br>Lu<br>Lutetium<br>174.967  |                                |                               |                               |                             |                               |                            |
| Actinide Series                 |                                 |                               | 89<br>Ac<br>Actinium<br>227.028     | 90<br>Th<br>Thorium<br>232.038  | 91<br>Pa<br>Protactinium<br>231.036 | 92<br>U<br>Uranium<br>238.029    | 93<br>Np<br>Neptunium<br>237.048  | 94<br>Pu<br>Plutonium<br>244.064 | 95<br>Am<br>Americium<br>243.061   | 96<br>Cm<br>Curium<br>247.070     | 97<br>Bk<br>Berkelium<br>247.070  | 98<br>Cf<br>Californium<br>251.080 | 99<br>Es<br>Einsteinium<br>[254] | 100<br>Fm<br>Fermium<br>257.095 | 101<br>Md<br>Mendelevium<br>258.1 | 102<br>No<br>Nobelium<br>259.101 | 103<br>Lr<br>Lawrencium<br>[262] |                                |                               |                               |                             |                               |                            |

# Input model – composition

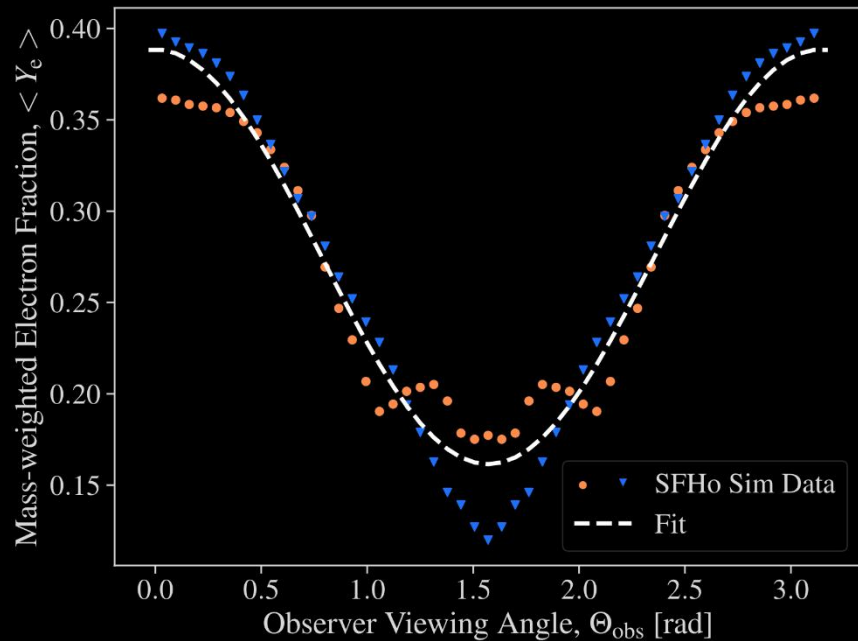
- $Y_e$  distribution: *Setzer+ 2023*



Simo

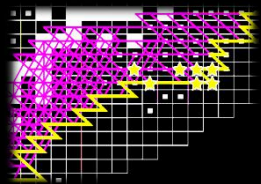
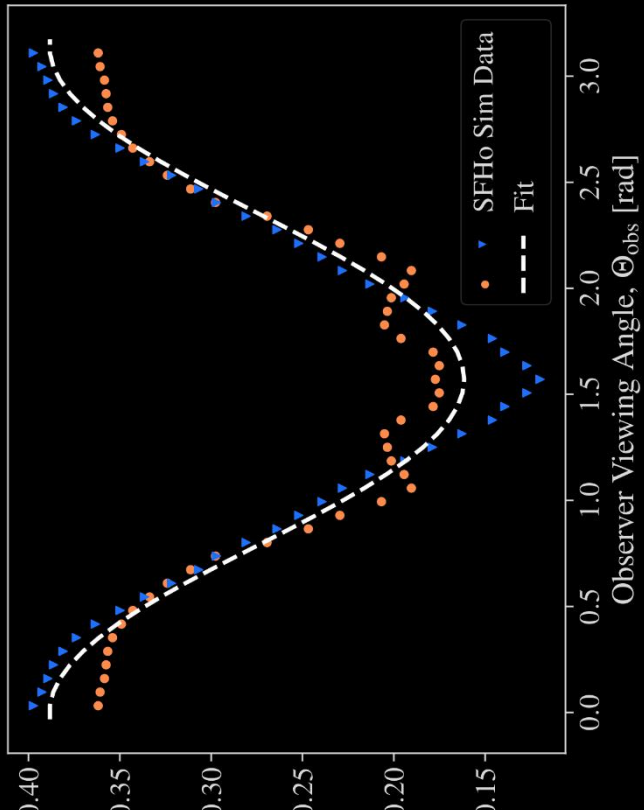
ns 12

Nucl. network



# Input model – composition

- $Y_e$  distribution: *Setzer+ 2023*



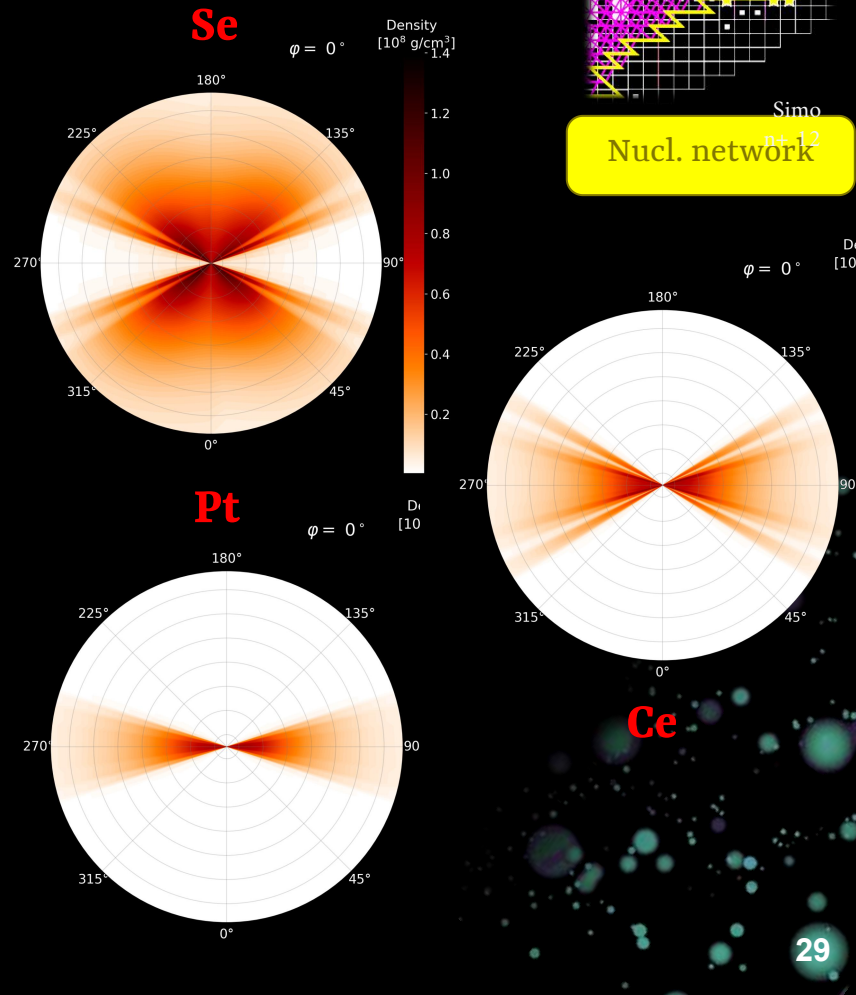
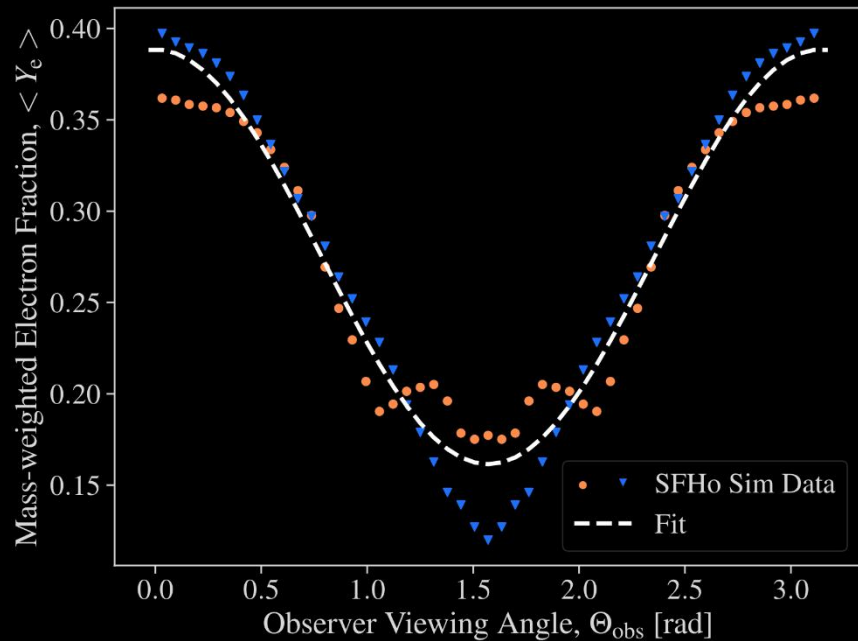
Simo

ns 12

Nucl. network

# Input model – composition

- $Y_e$  distribution: *Setzer+ 2023*
- $Y_e \rightarrow$  composition, radioactive heating  
*Wanajo+ 2018*





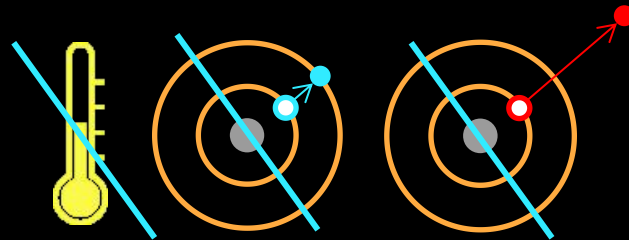
*Preliminary spectra*

# Spectra so far

## Spectral modelling of kilonovae in 3D NLTE

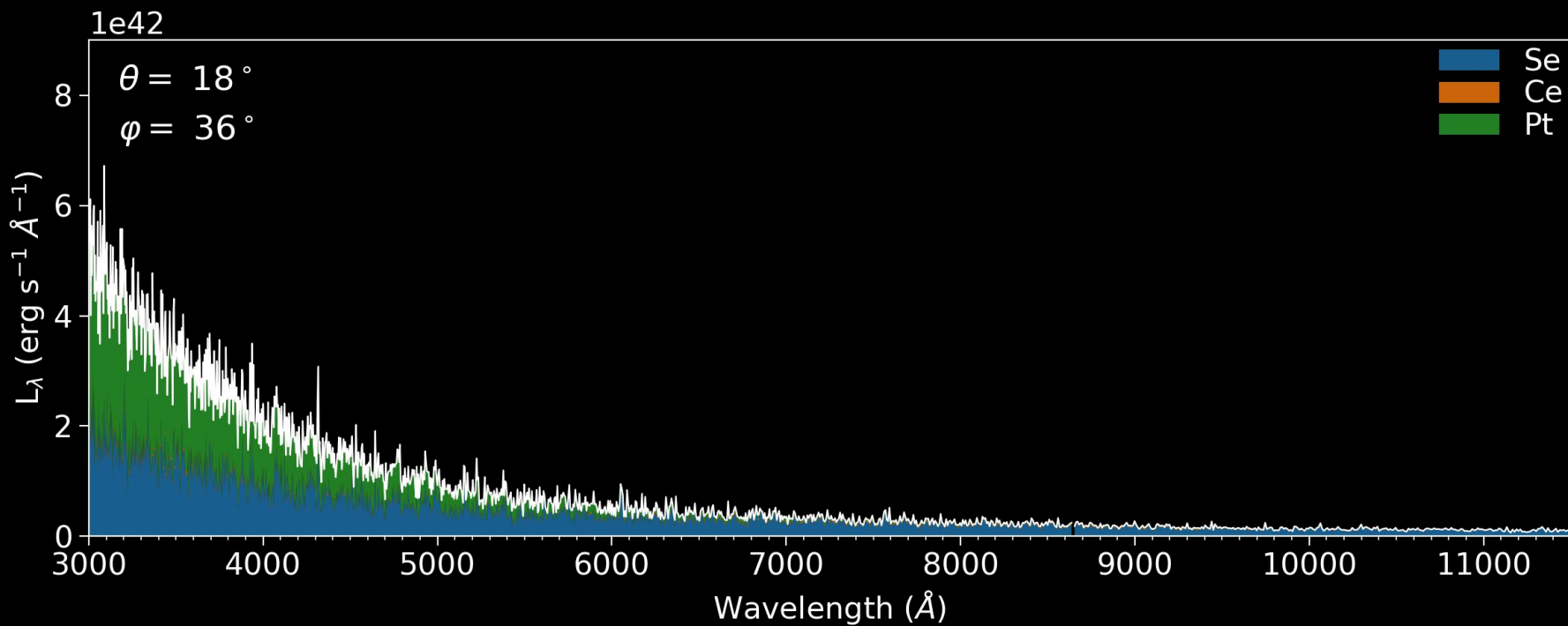
- Locked physical conditions:

- T fixed (5000 K)
- Excitation: LTE (Boltzmann)
- Ionisation: fixed

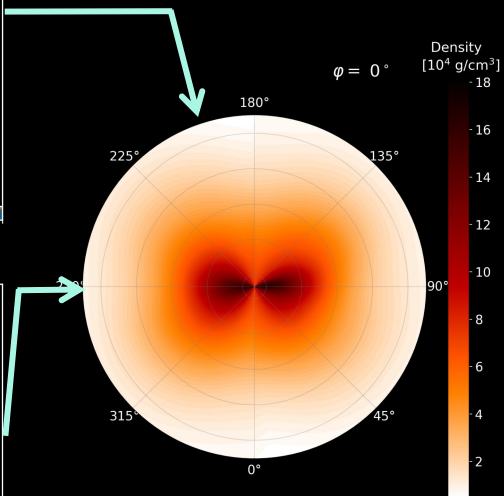
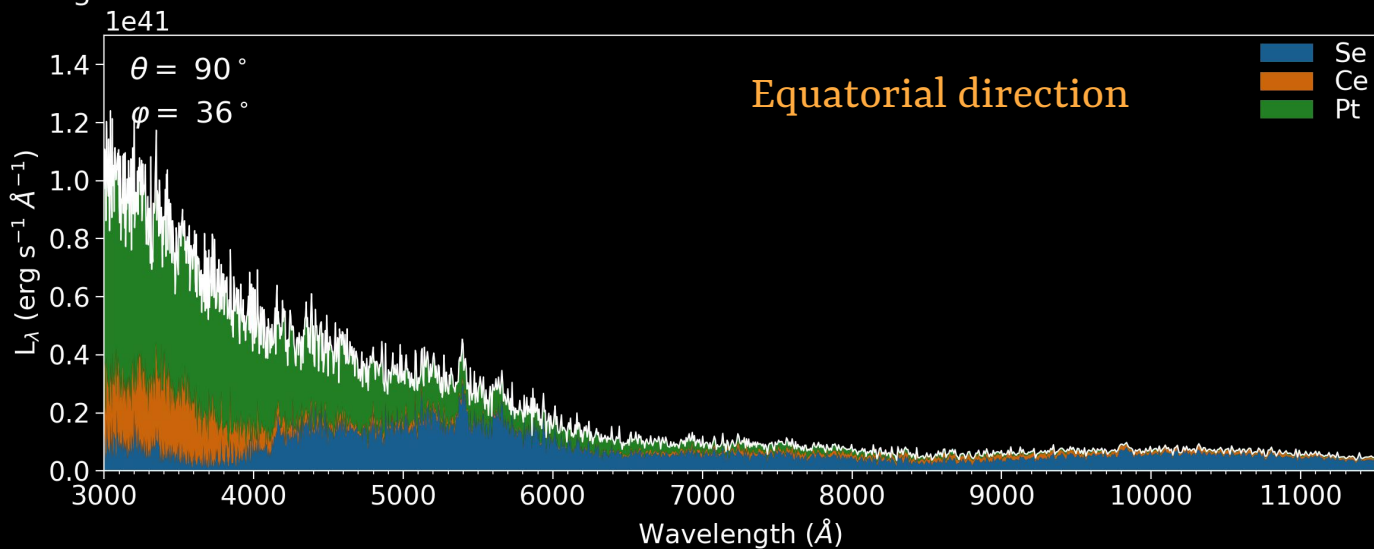
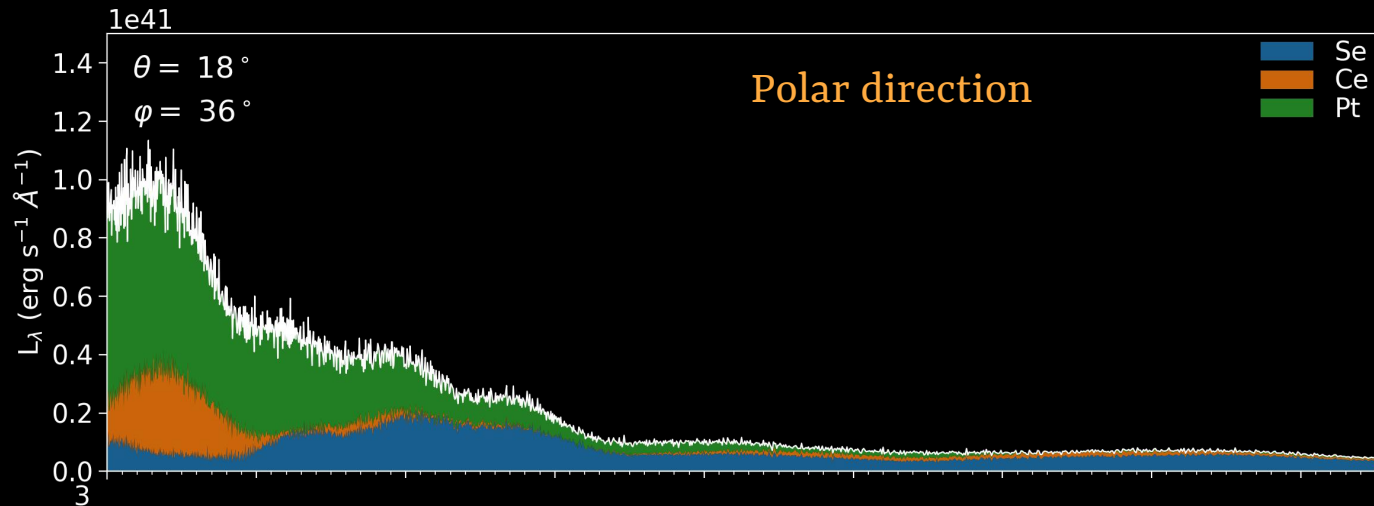


- What makes different spectra for diff. viewing angles?

- Doppler factors
- Composition



Velocity scaled  
down by 10



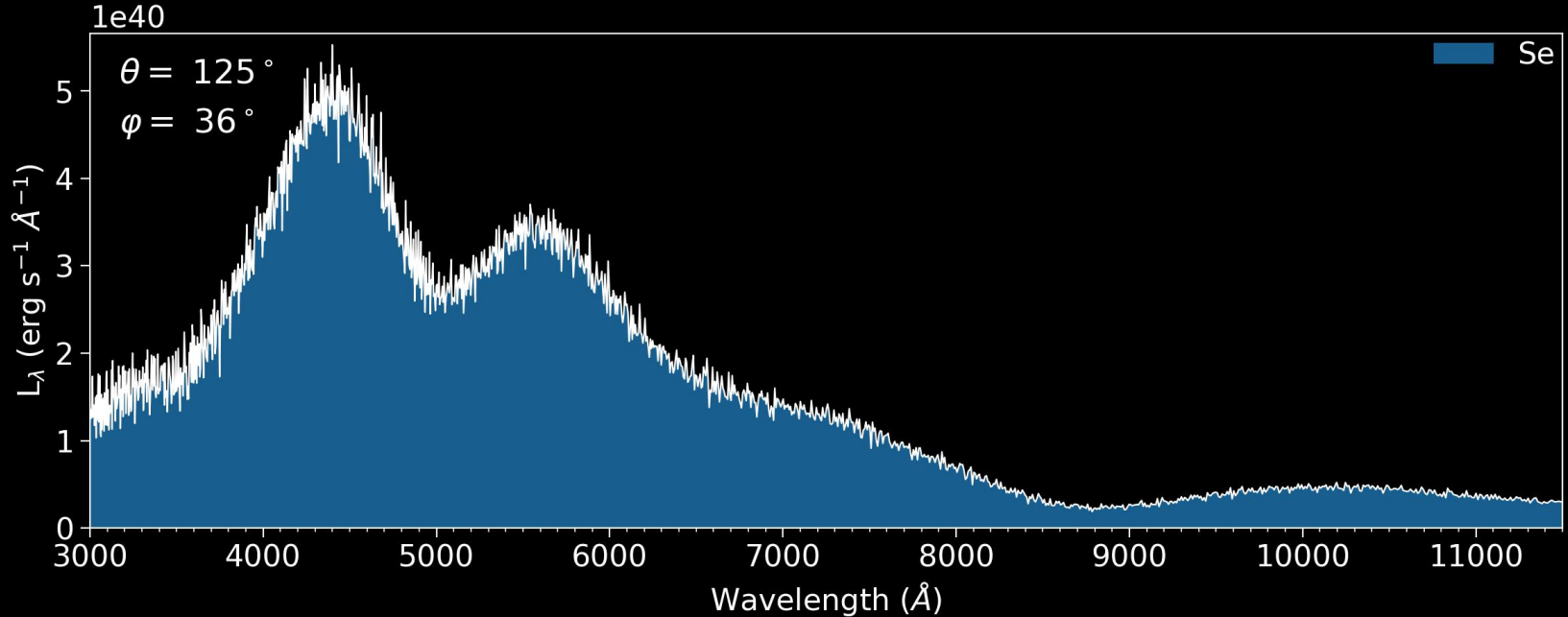
# Future plans

- **NLTE solver**
- Include multiple r-process elements
- Time dependence, light curves
- Different input models

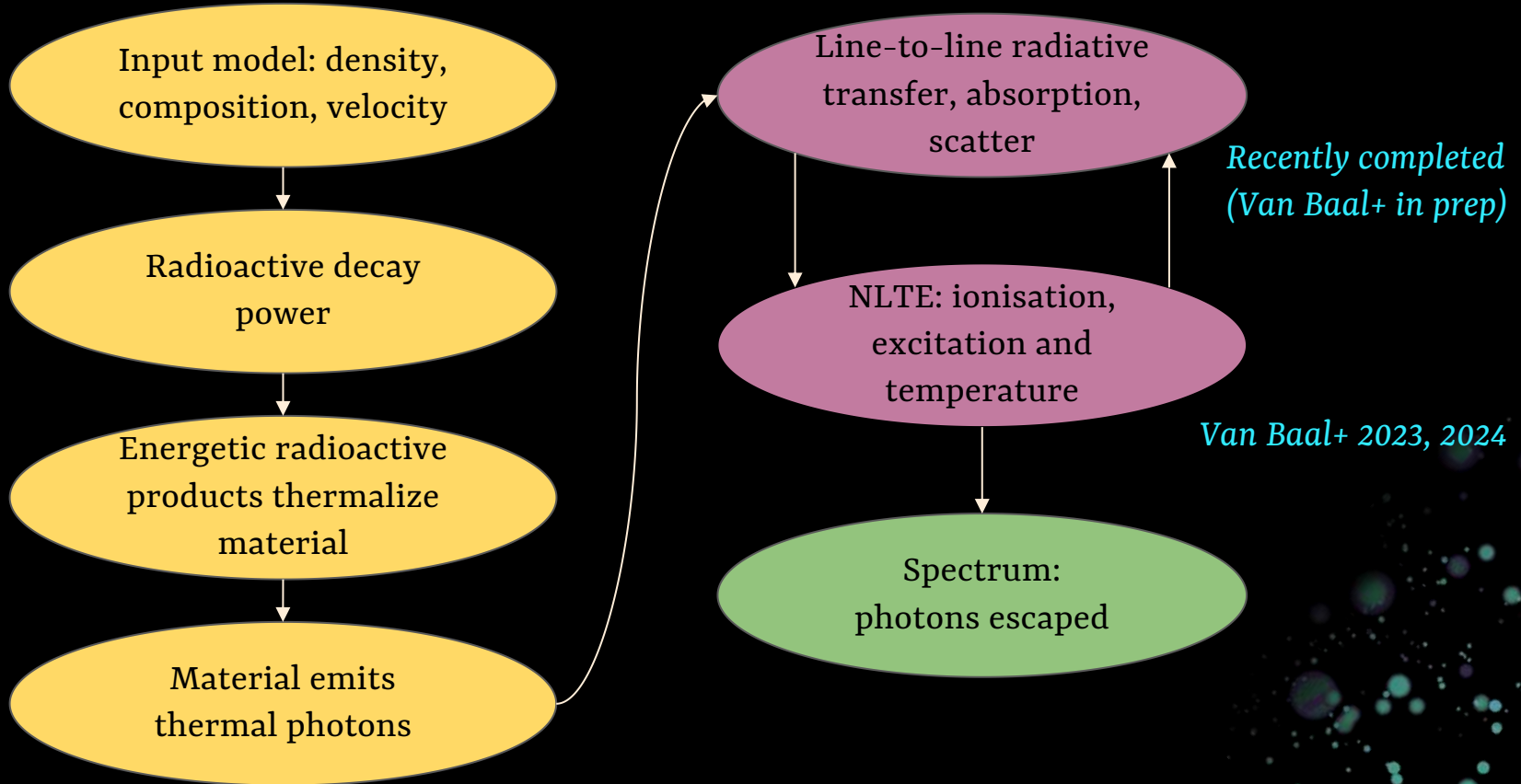


# Toy model

- Homogenous sphere (1D),  $0.1 M_{\odot}$ ,  $v = 0.1 c$ ,  $t = 2d$
- Pure Se



# Structure of the code



# Stockholm codes for spectral modeling

- Photons **Doppler shifted** in expanding material (comoving frame treatment)
- Photon transfer by **Monte Carlo** random sampling
- **Line-to-line radiative transfer**
  - No assumptions of optical thinness or opacity