Spectral modelling of kilonovae in 3D NLTE

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Co-supervisor: **Stephan Rosswog**

SirEN conference, 25. 06. 11.

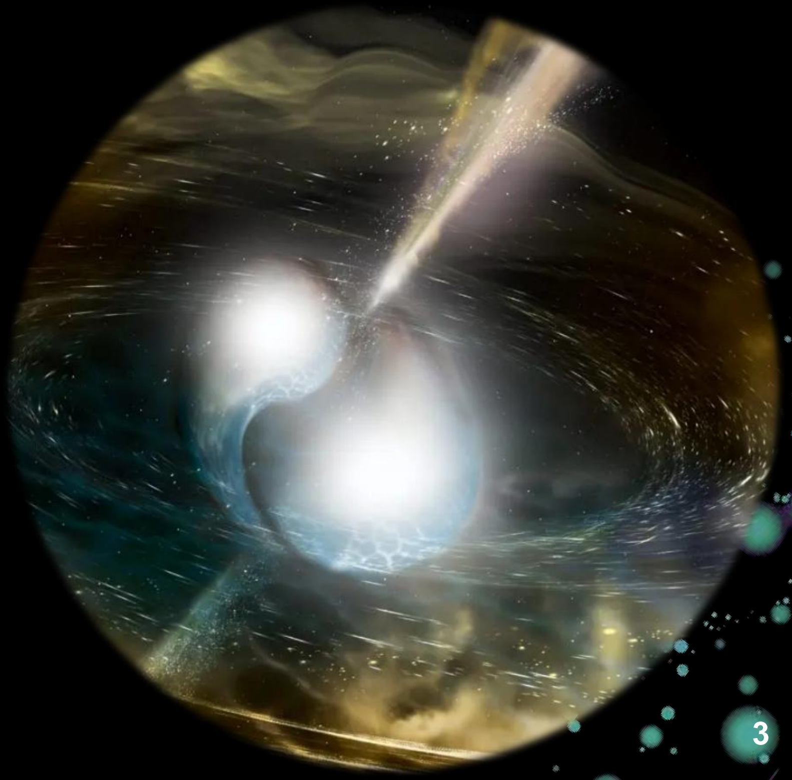
Stockholm University

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)

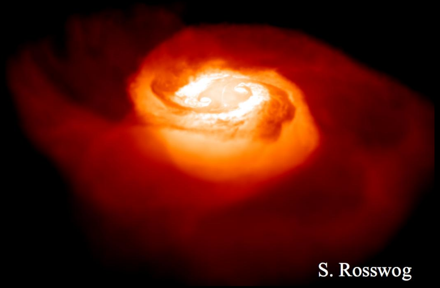


NLTE spectral modeling

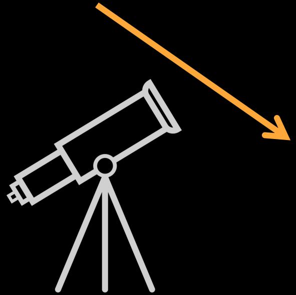
Spectral modelling

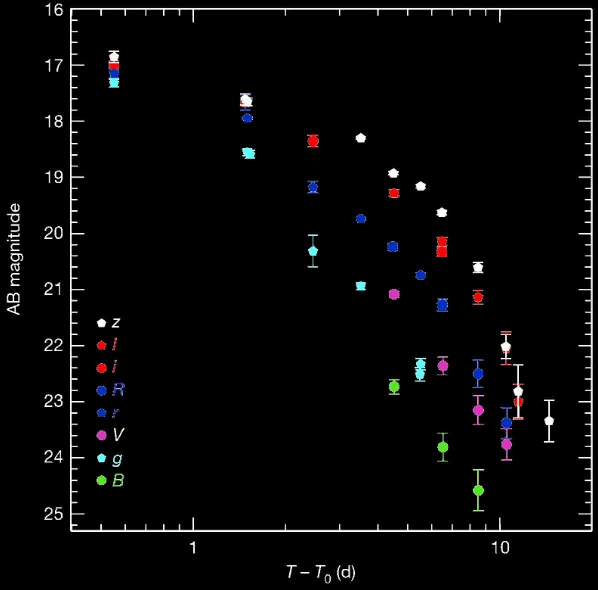
– Reproduce light curves, spectra

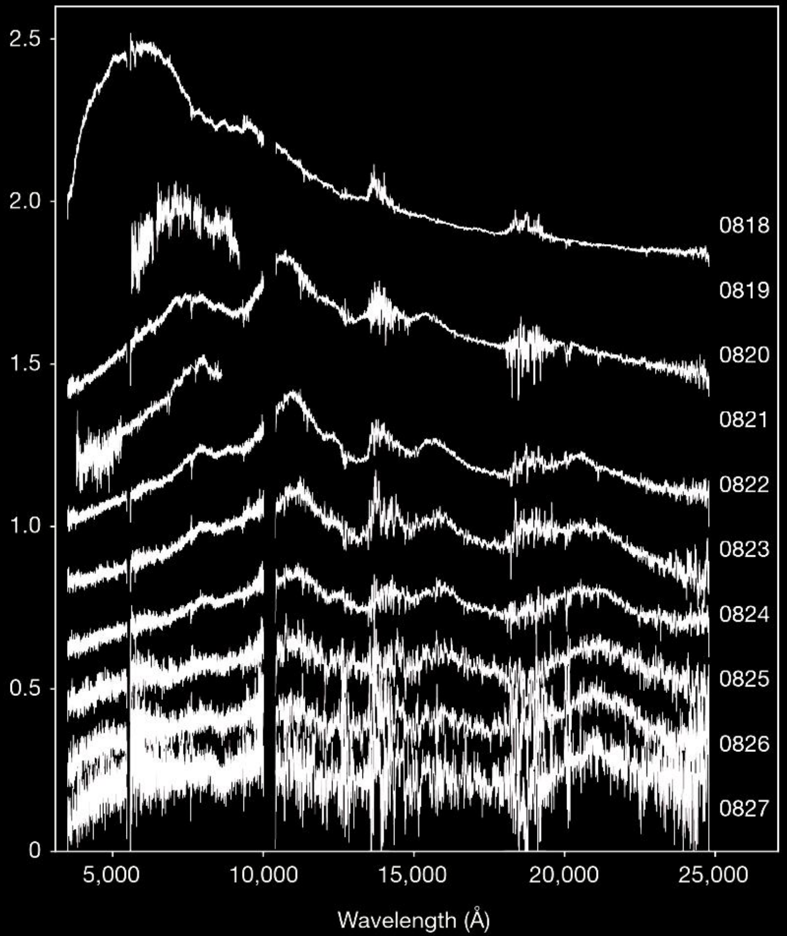
– Identify elements (+abundances)



S. Rosswog

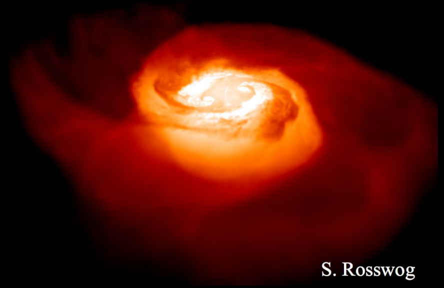






Pian+ 2017

Ingre-dients of spectral modeling

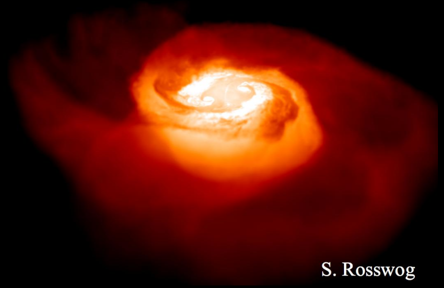


NSM model
(hydrodynamics - numerical relativity)

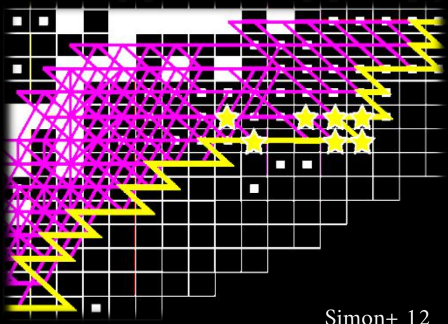
↓

Grid, ρ, v

Ingre-dients of spectral modeling



S. Rosswog



Simon+ 12

NSM model
(hydrodynamics - numerical relativity)

↓

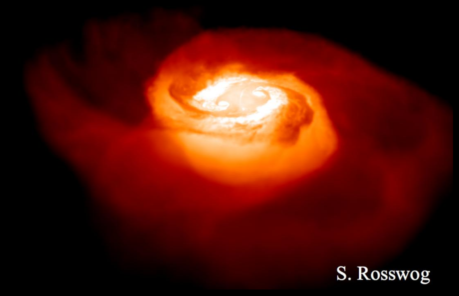
Grid, ρ, v

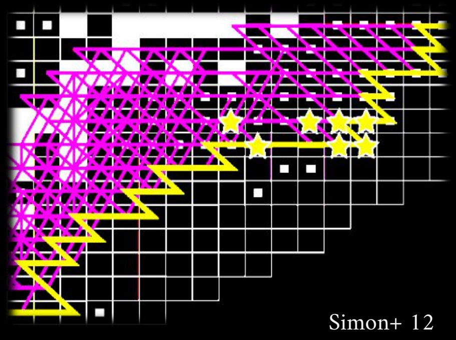
Nucl. reaction network

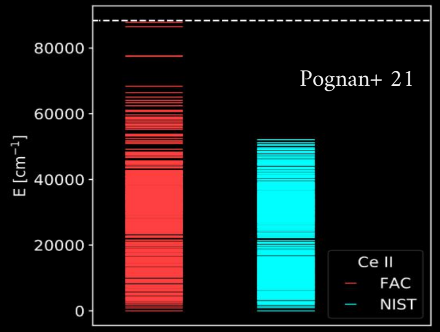
↓

Composition (Y_e)
Radioactive heat

Ingre-dients of spectral modeling





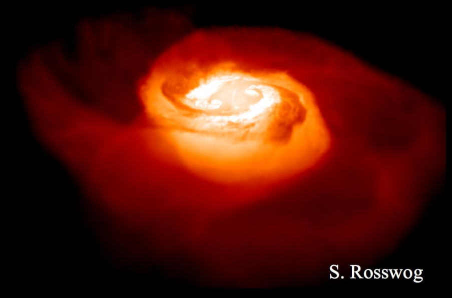


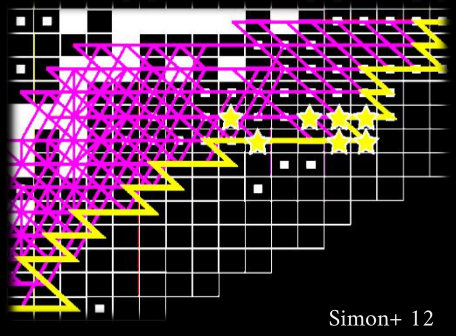
NSM model (hydrodynamics - numerical relativity)
→ Grid, ρ, v

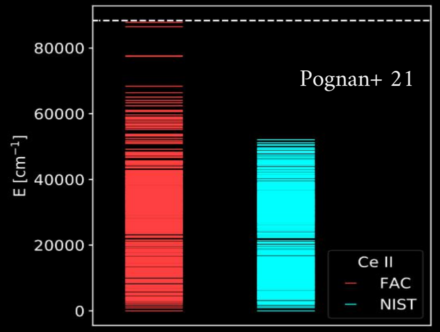
Nucl. reaction network
→ Composition (Y_e)
Radioactive heat

Atomic data
→ Lines, transitions

Ingre-dients of spectral modeling







NSM model
(hydrodynamics - numerical relativity)
↓
Grid, ρ, 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 ~ a week
- **NLTE** (non-local thermodynamic equilibrium)
  - Collisional excitations and de-excitations << radiative processes
  - Full rate equations

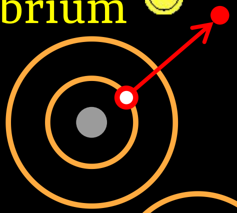
MATTER

Physical conditions:

- Temperature

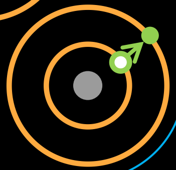
Thermal equilibrium

- Ionisation



Saha eq.

- Excitation



Boltzmann eq.

Emit

LTE

PHOTONS

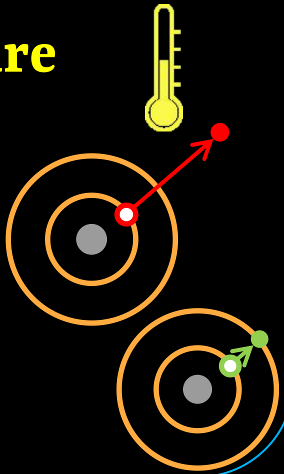
Radiation field

Density, spectrum

MATTER

Physical conditions:

- **Temperature**
- **Ionisation**
- **Excitation**



Emit

NLTE

PHOTONS

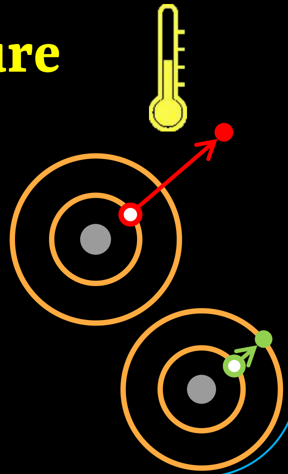
Radiation field

Density, spectrum

MATTER

Physical conditions:

- **Temperature**
- **Ionisation**
- **Excitation**



Emit

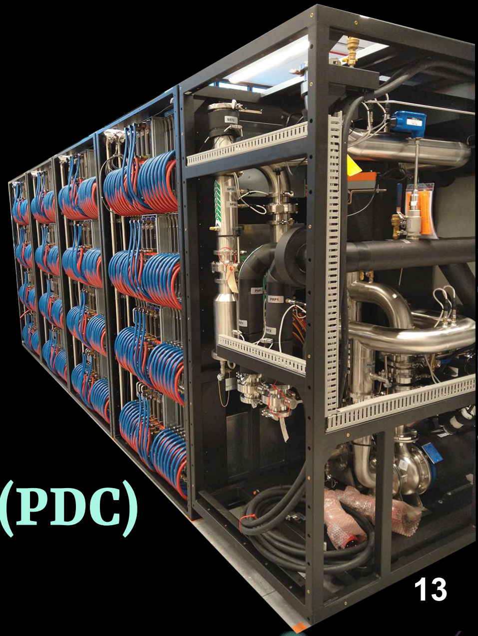
NLTE

Excite
(+ non-local)

PHOTONS

Radiation field

Density, spectrum



Dardel, KTH (PDC)

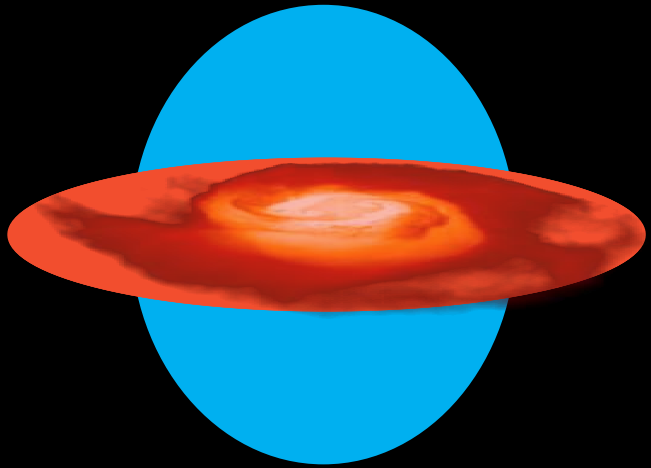
ExTraSS

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 **TRA**nsient **S**pectral **S**imulator) - *AJ, B. van Baal*
- My PhD: add KN physics to ExTraSS

	SUMO	**EXTRASS**
NLTE	✓	✓
3D	✗	✓
SNe	✓	✓
KNe	✓	...

Ejecta components



Disk wind / NS driven outflows (polar)

lighter r-nuclei, high Y_e

$v \sim 0.1\,c$

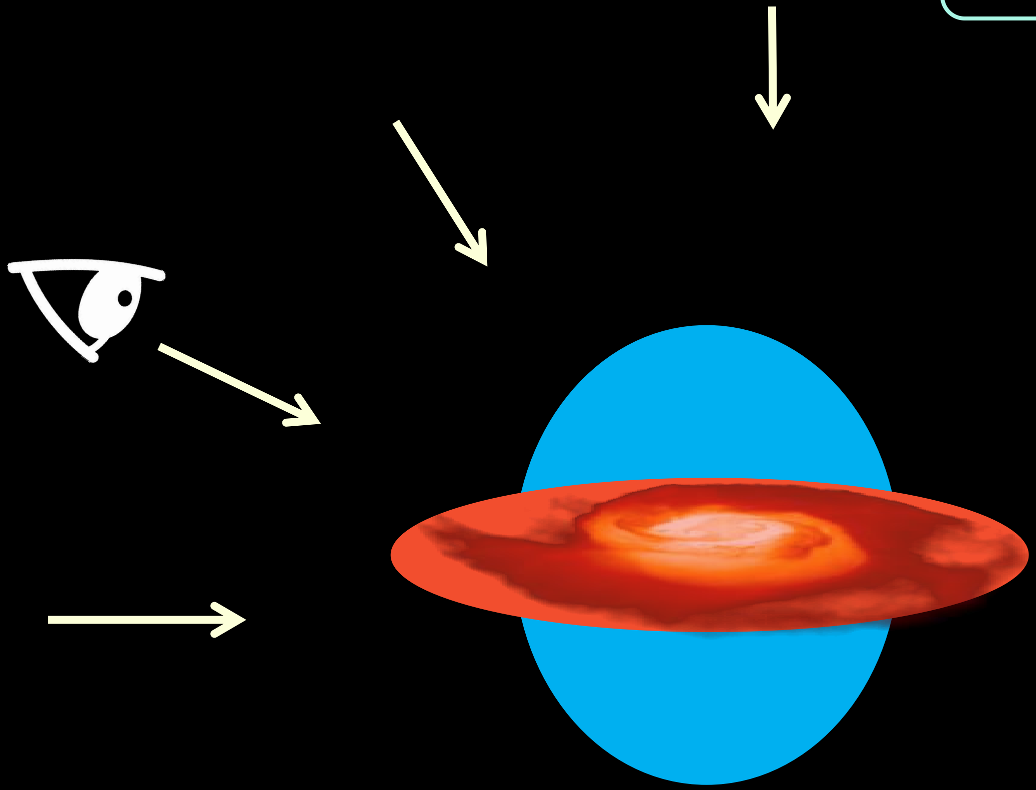
Dynamical ejecta (equatorial)

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

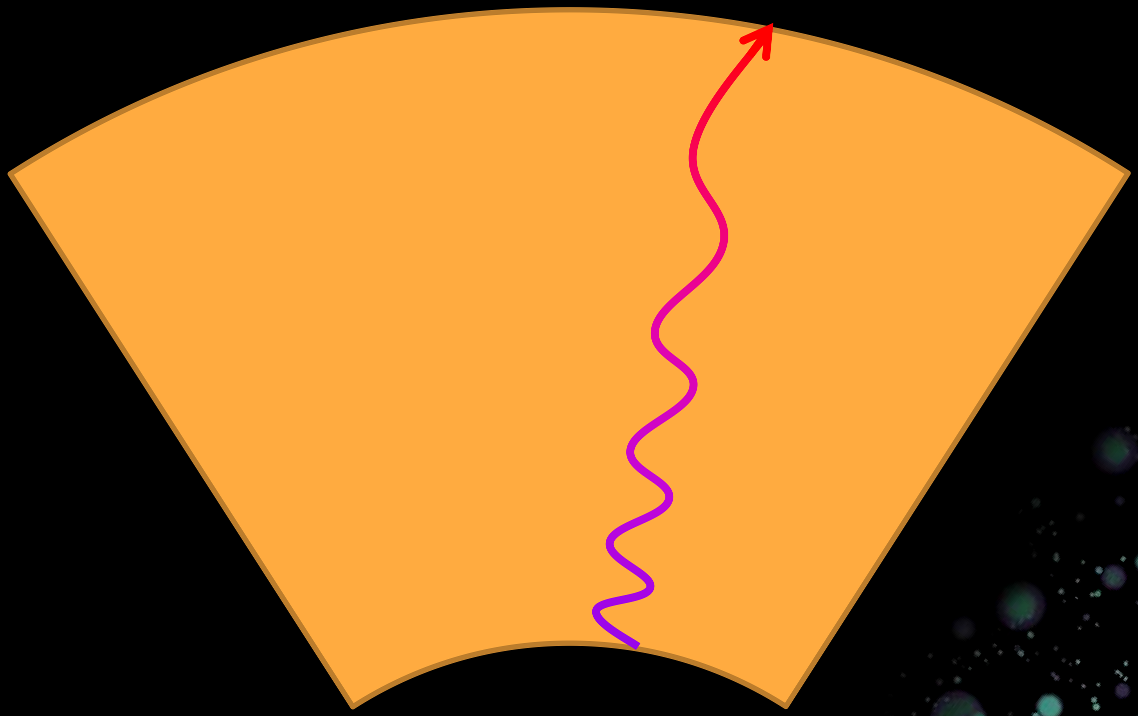
v ~ 0.1 c

Dynamical ejecta (equatorial)

heavy r-nuclei, low Y_e

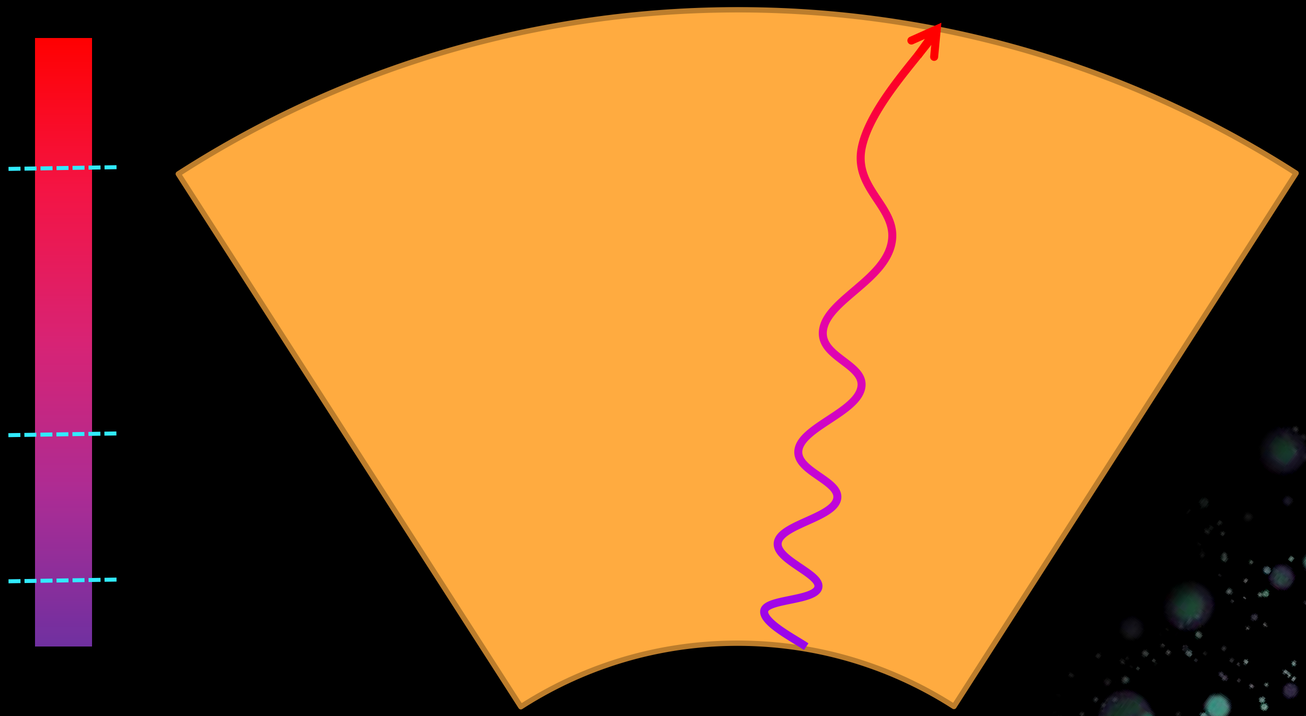
v ~ 0.3 c

Line-to-line photon transfer

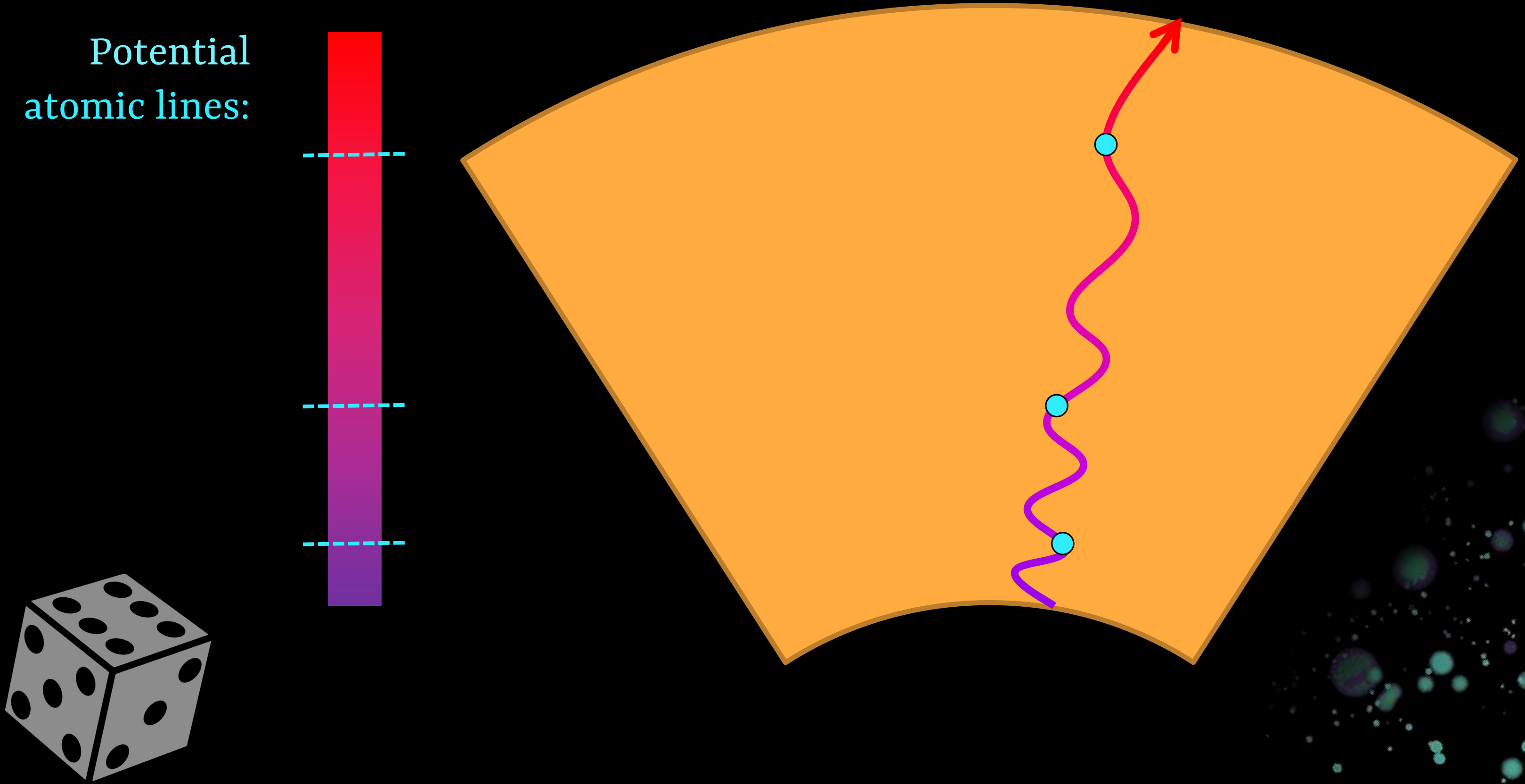


Line-to-line photon transfer

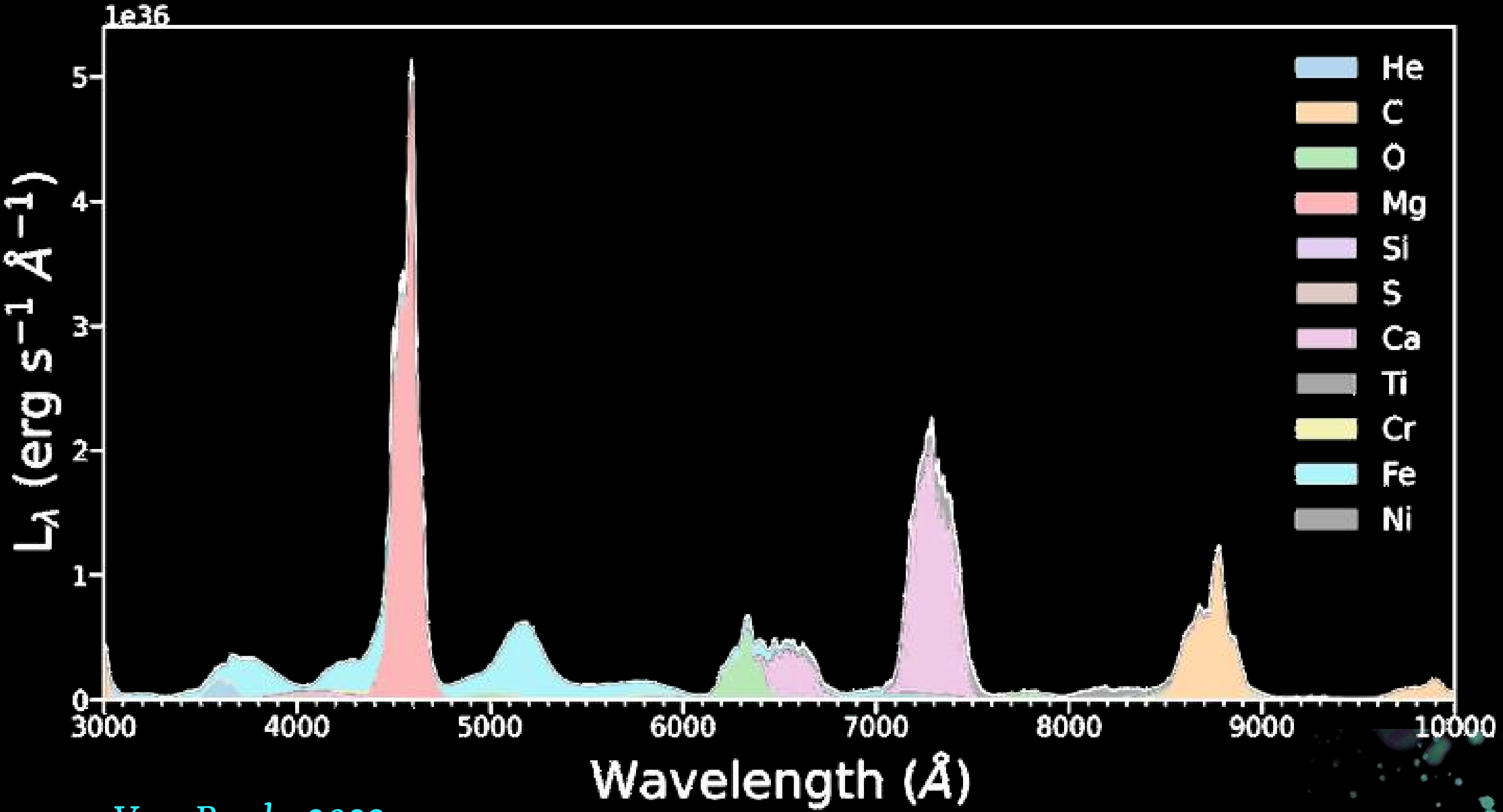
Potential
atomic lines:



Line-to-line photon transfer

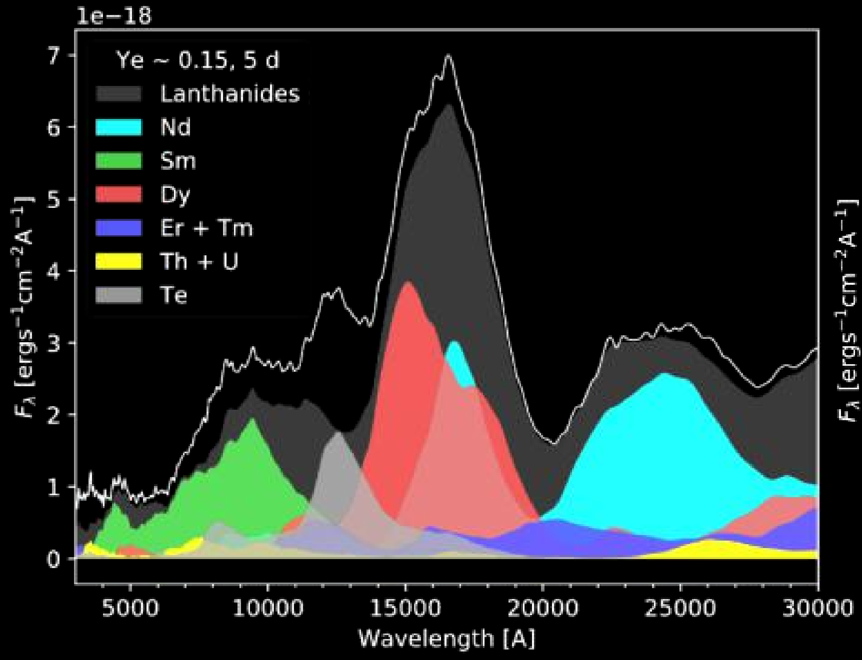


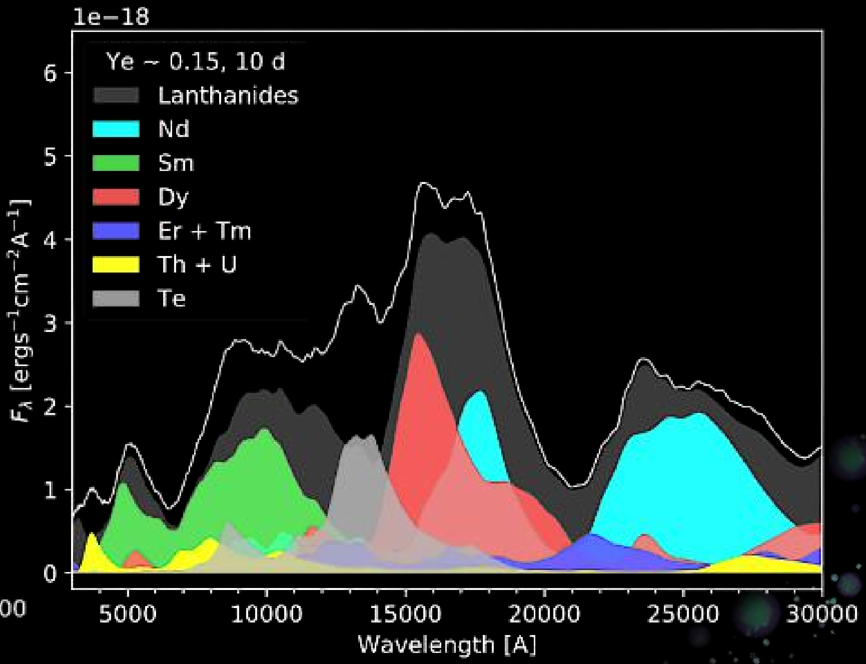
SN 3D spectrum (ExTraSS)



Van Baal+ 2023

KN 1D spectra (SUMO)





Pognan+ 2023

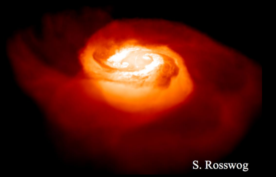
Towards KNe

What is different for KNe (vs SNe)?

- Higher velocity, lower ejecta mass
  - Very quickly diluted → NLTE effects
- Composition: heavy *r*-process elements
  - Radioactive heating: α + β + γ + fission (SNe: only γ-rays of Ni-56)
  - Atoms: many levels and line rich → heavier transfer
  - Lines blended, no distinct lines

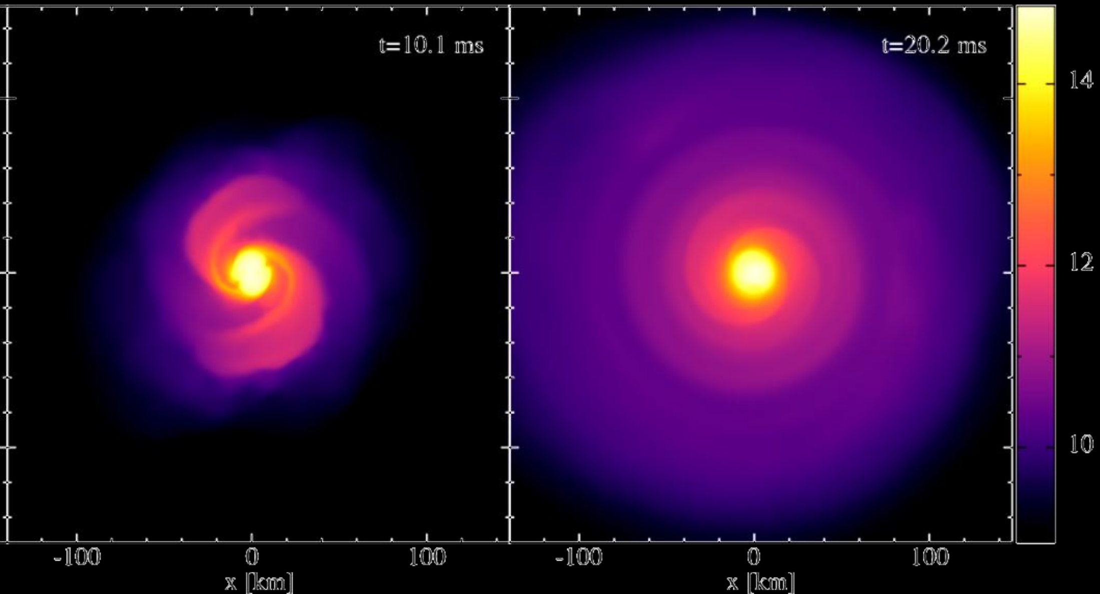
	SN	KN
M	$5\ M_\odot$	$0.05\ M_\odot$
V	0.01c	0.1c
t_{peak}	20d	2d
ρ_{peak}	10^{-11}	10^{-13}
$\frac{L(10t_{peak})}{L(t_{peak})}$	0.16	0.05
N_{lines}	$\sim 10^6$	$\sim 10^8$
% r.-a.	5%	100%

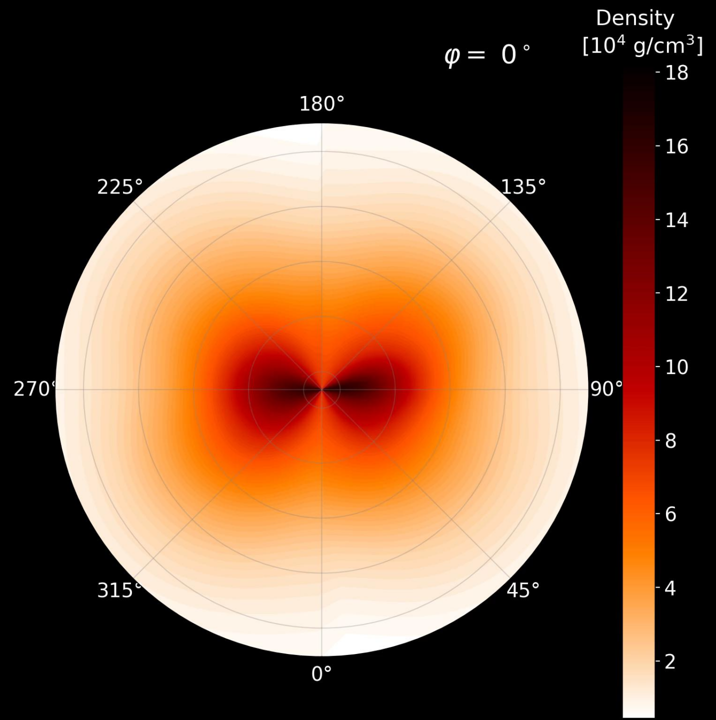
Input model



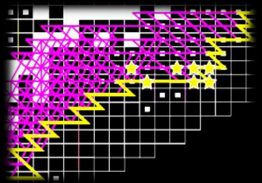
NSM model

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



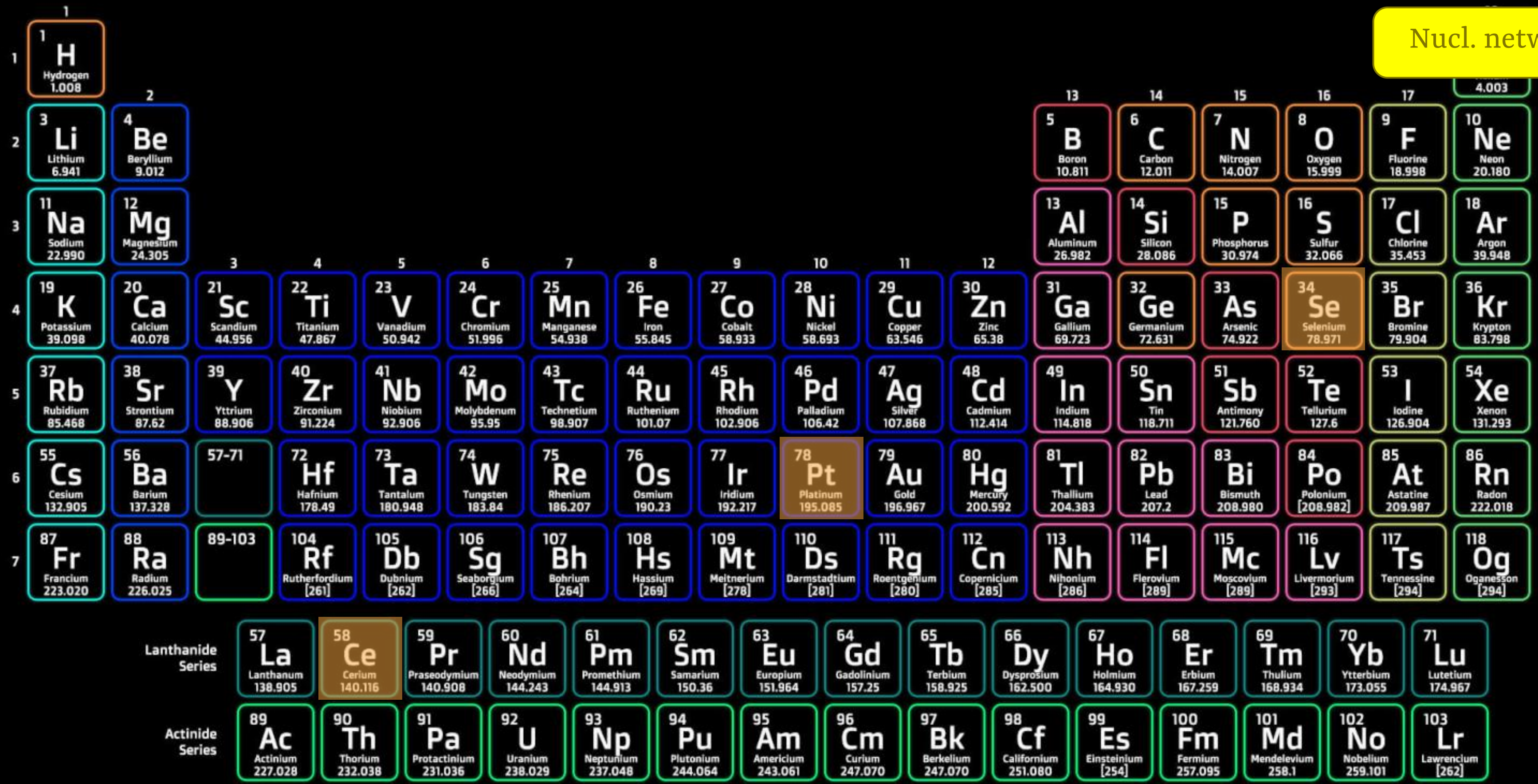


Input model – composition



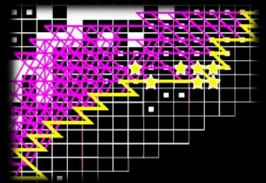
Simo n+ 12

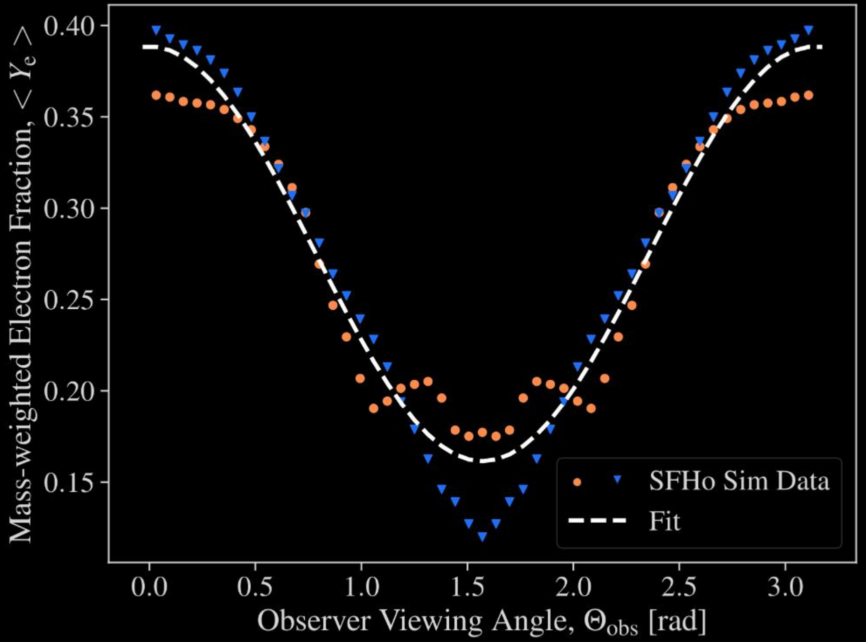
Nucl. network



Input model – composition

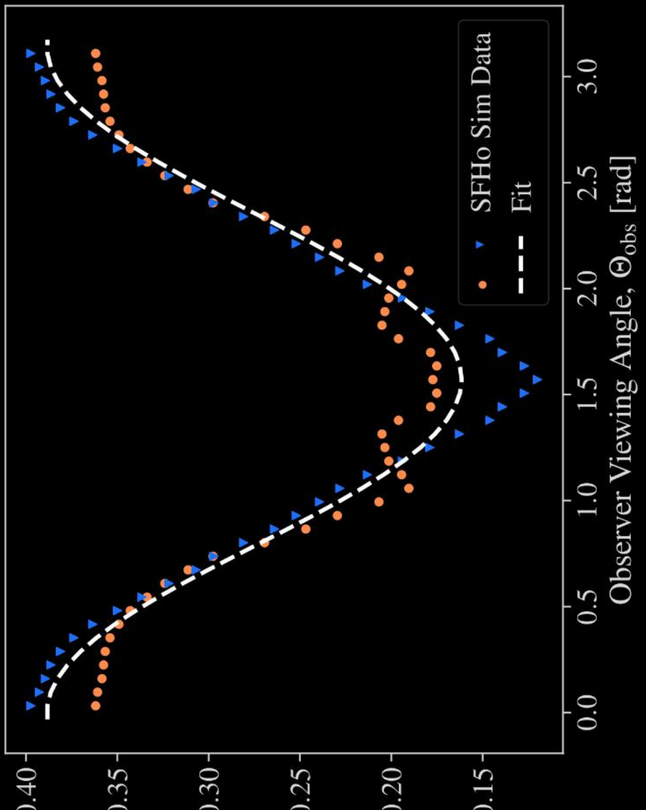
– Y_e distribution: *Setzer+ 2023*

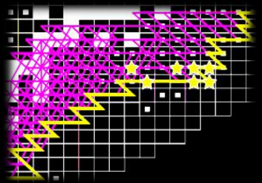




Input model – composition

– Y_e distribution: *Setzer+ 2023*



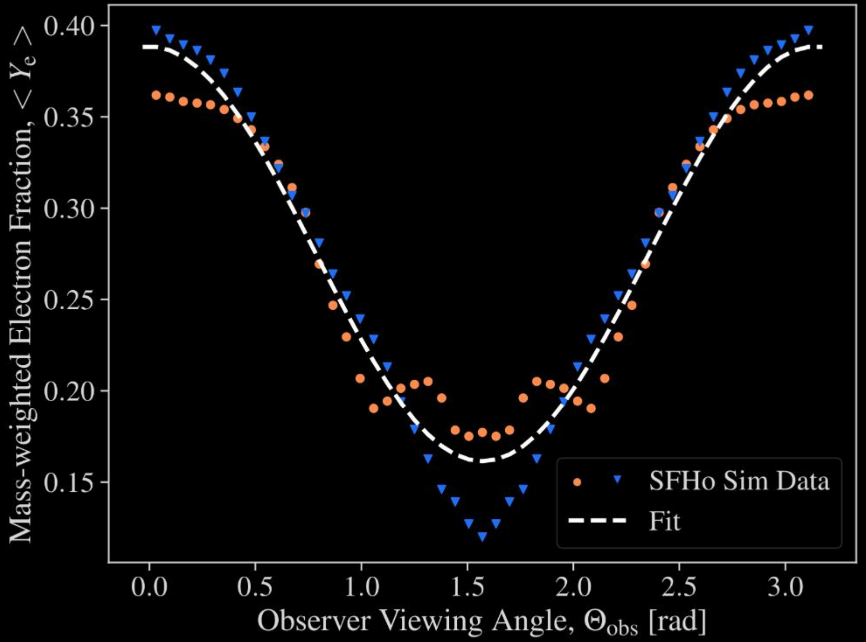


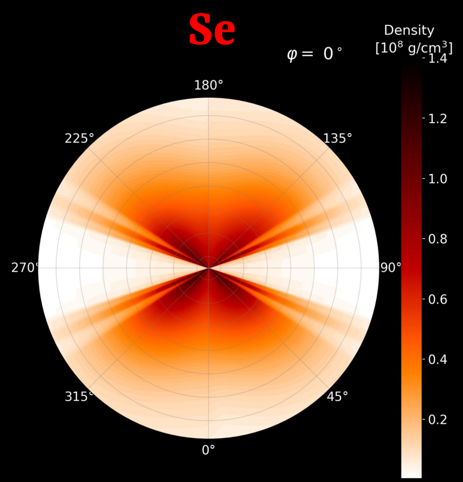
Simon+ 12

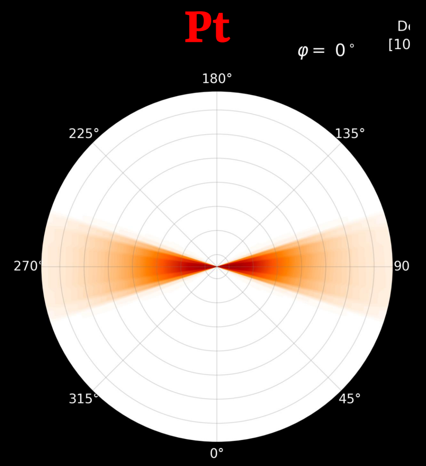
Nucl. network

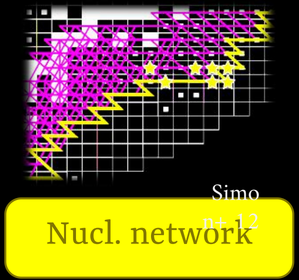
Input model – composition

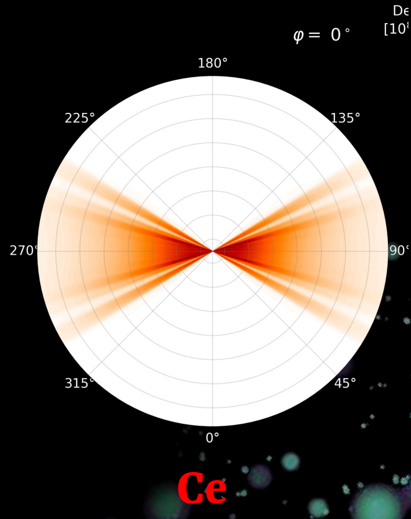
- Y_e distribution: *Setzer+ 2023*
- Y_e → composition, radioactive heating
  Wanajo+ 2018









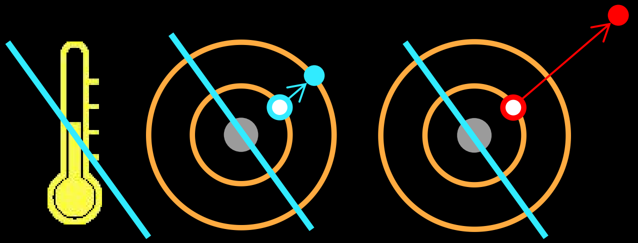


Preliminary spectra

Spectra so far

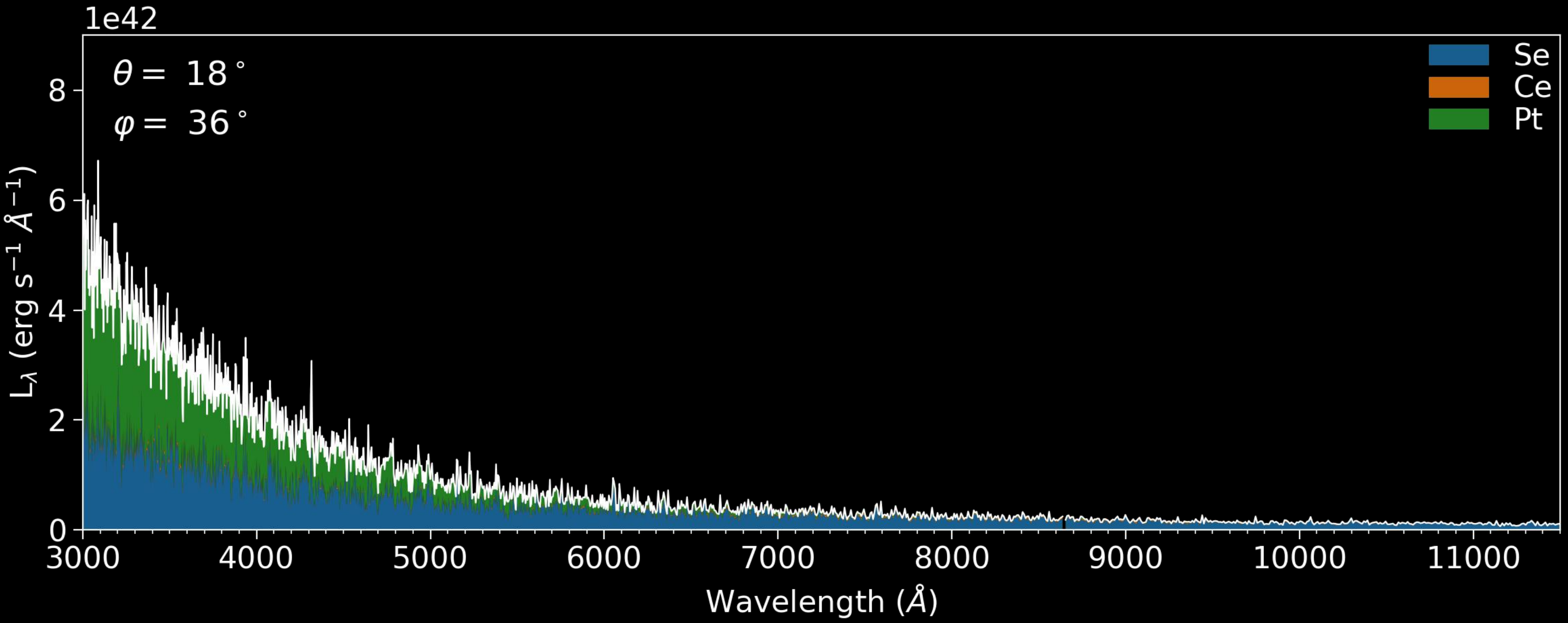
Spectral modelling of kilonovae in 3D ~~NLTE~~

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

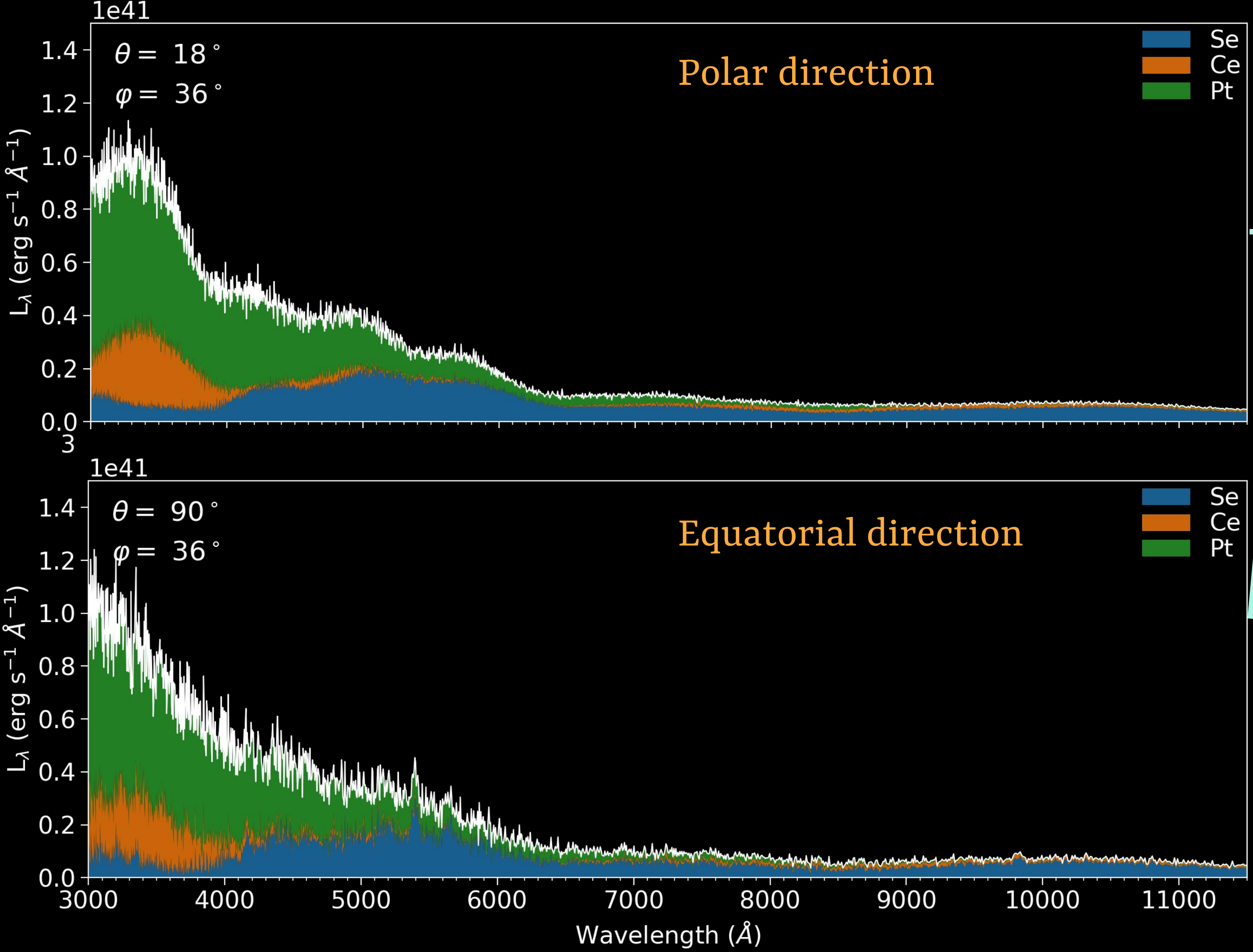


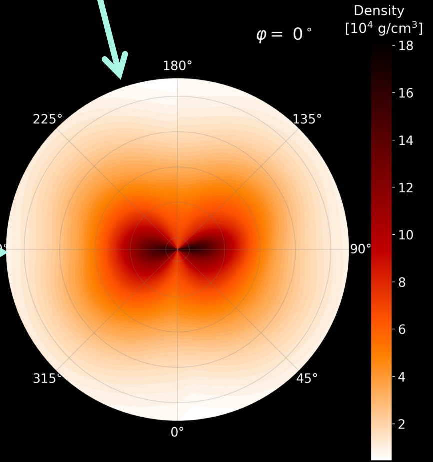
- What makes different spectra for diff. viewing angles?
  - Doppler factors
  - Composition

Original velocity



Velocity scaled down by 10



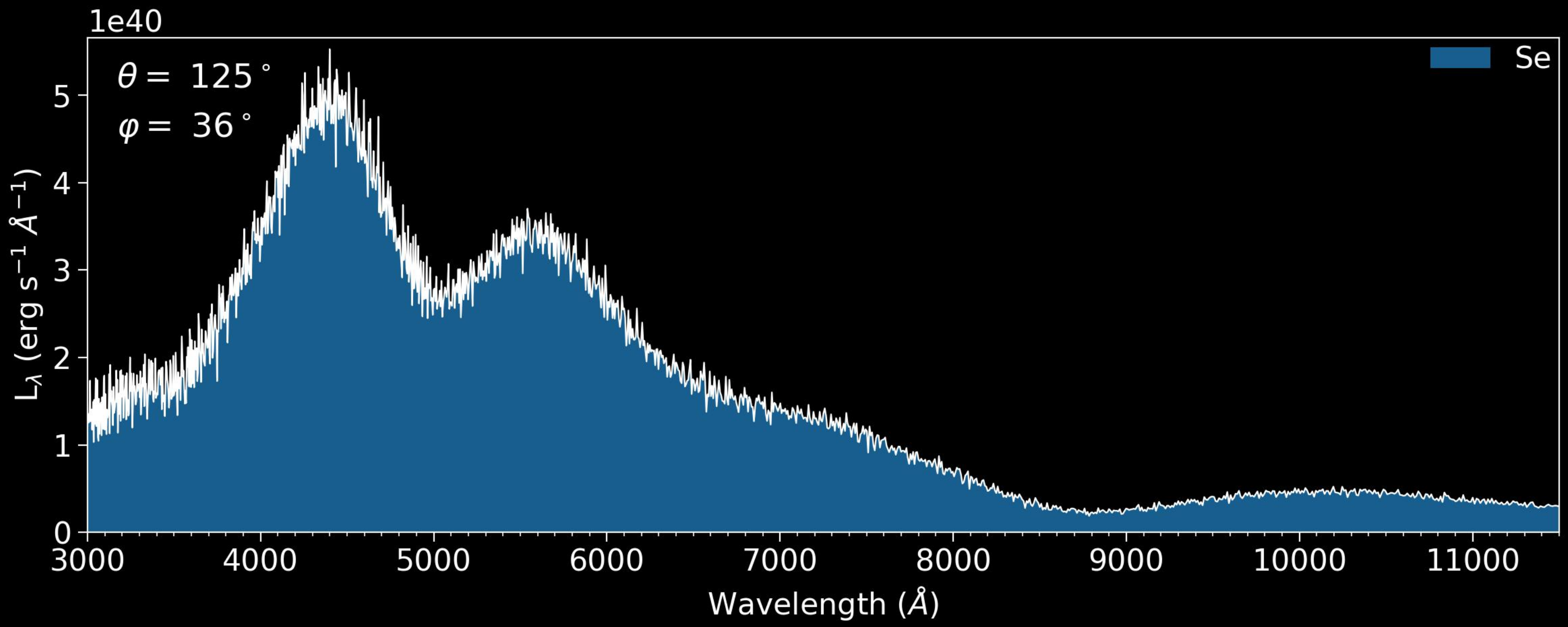


Future plans

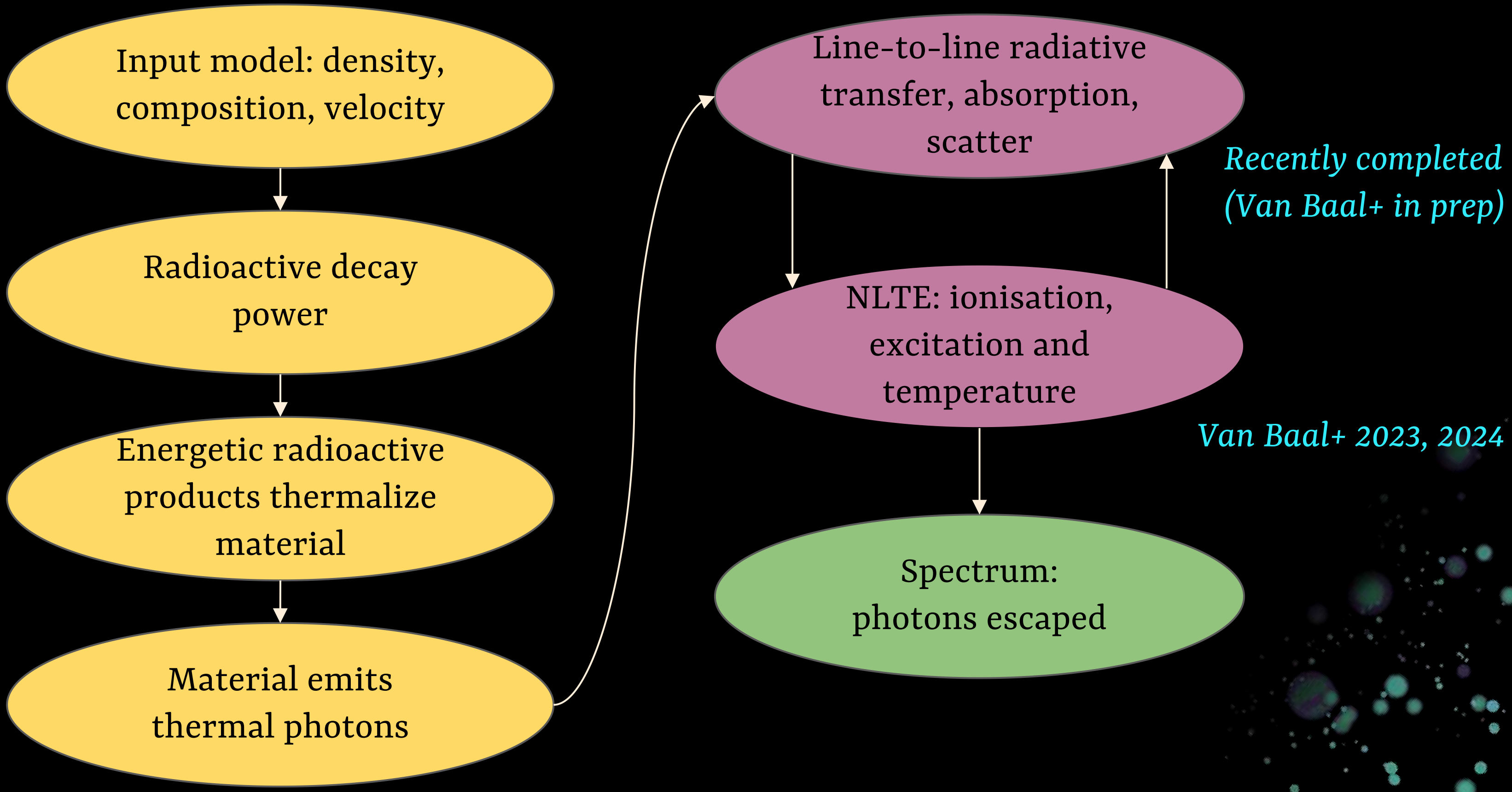
- **NLTE solver**
- Include multiple r-process elements
- Time dependence, light curves
- Different input models

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