

# Probing heavy element nucleosynthesis through electromagnetic observations

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TECHNISCHE  
UNIVERSITÄT  
DARMSTADT



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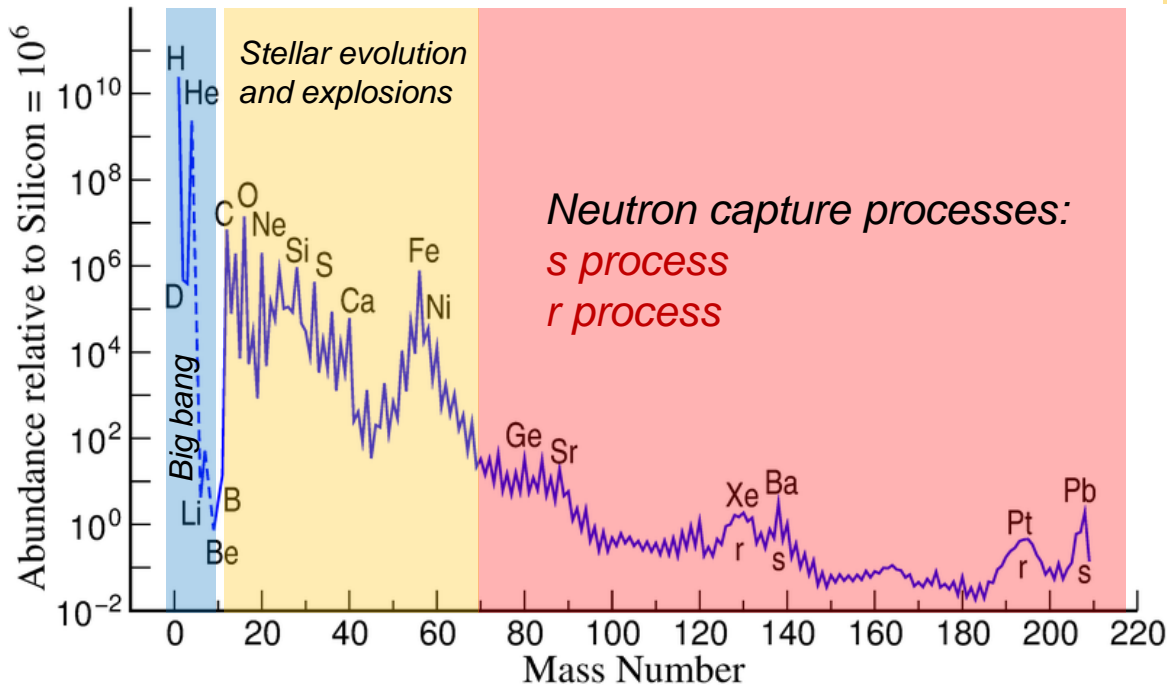


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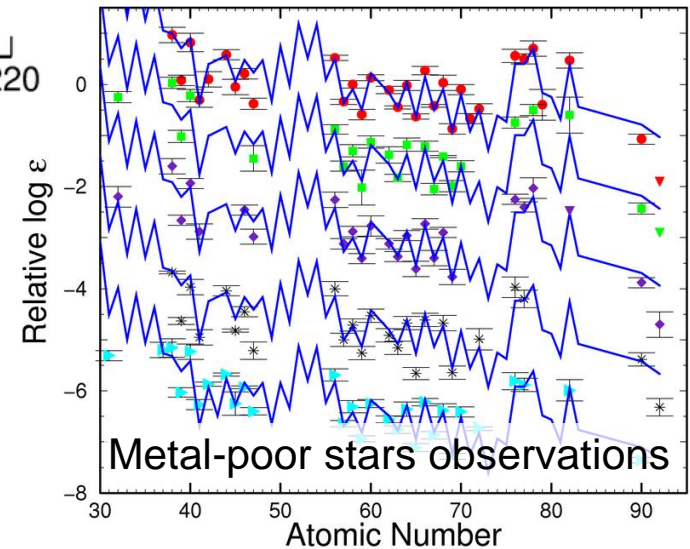
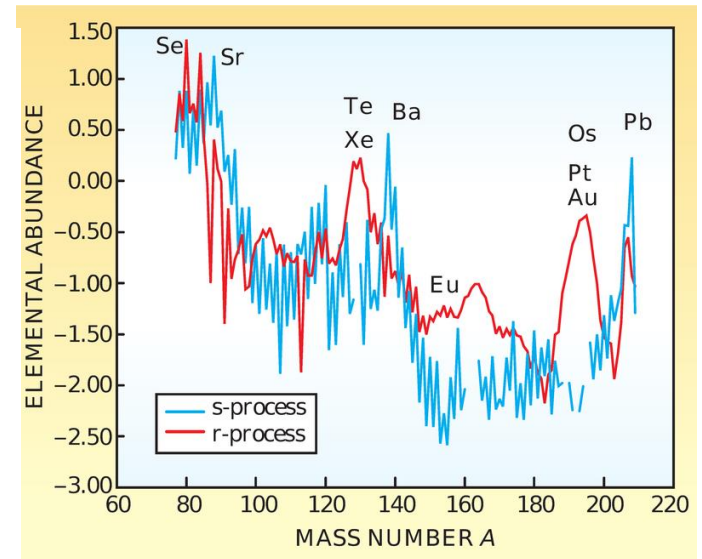
ERC AdG KILONOVA



# Signatures of nucleosynthesis



- Heavy elements produced in neutron capture processes
- Observations indicate that *r* process operates from early Galactic history in rare (high yield) events

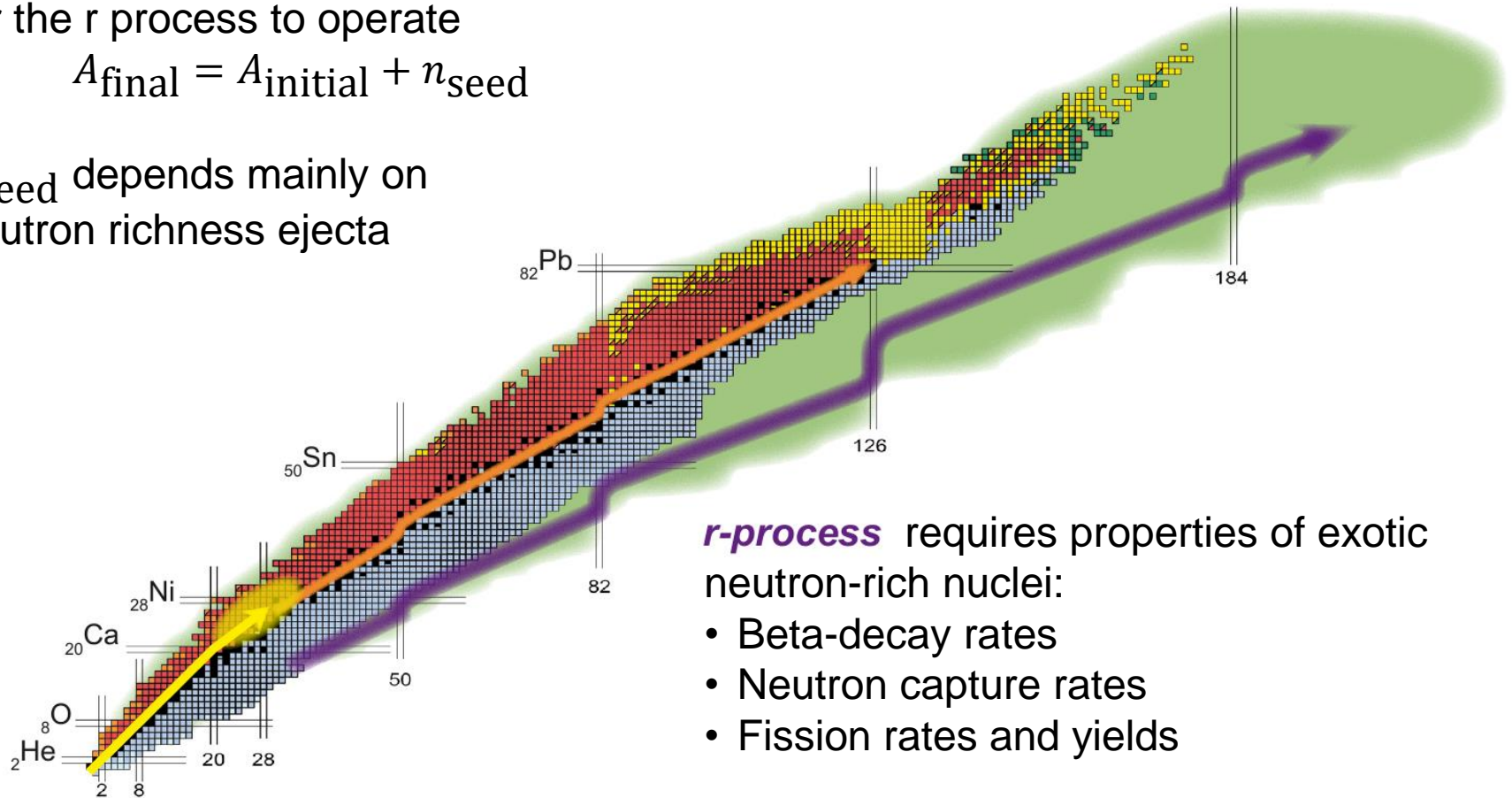


# R process needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

$n_{\text{seed}}$  depends mainly on neutron richness ejecta



**r-process** requires properties of exotic neutron-rich nuclei:

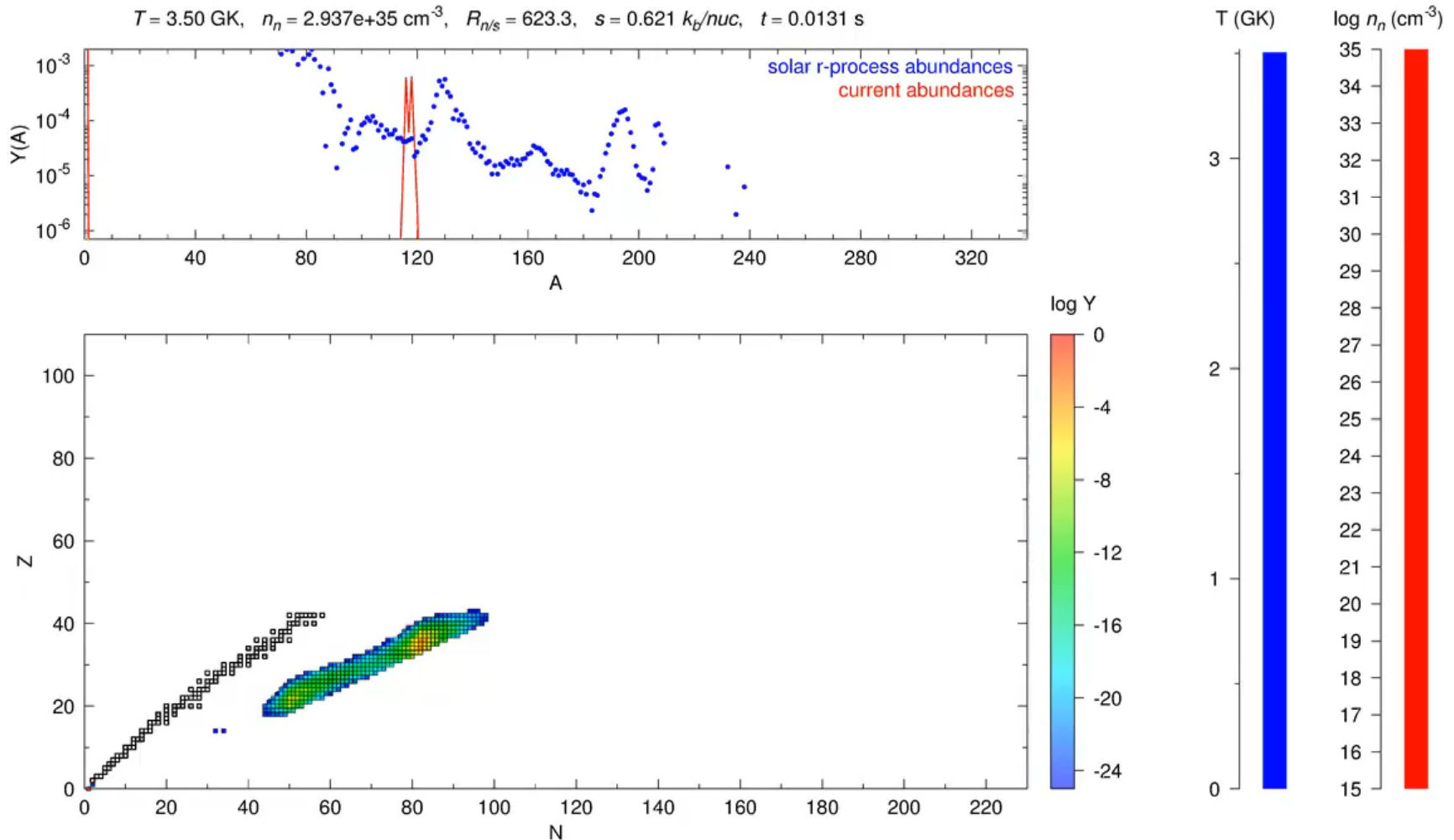
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

Benchmark against observations:

- Indirect: Solar and stellar abundances (contribution many events, chemical evol.)
- Direct: Kilonova electromagnetic emission (single event, sensitive Atomic and Nuclear Physics)

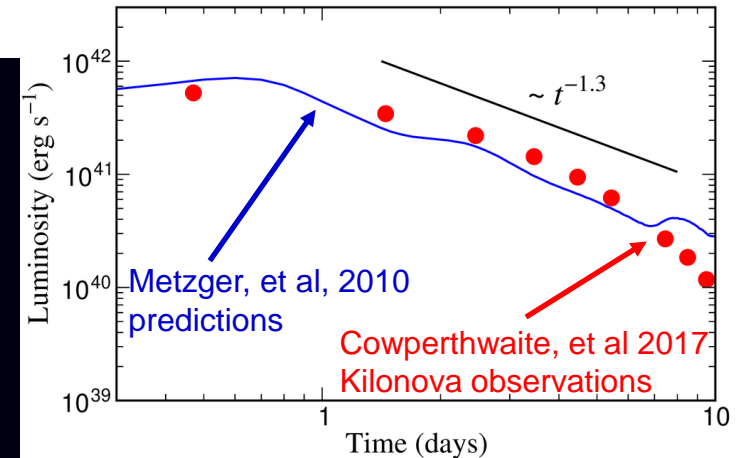
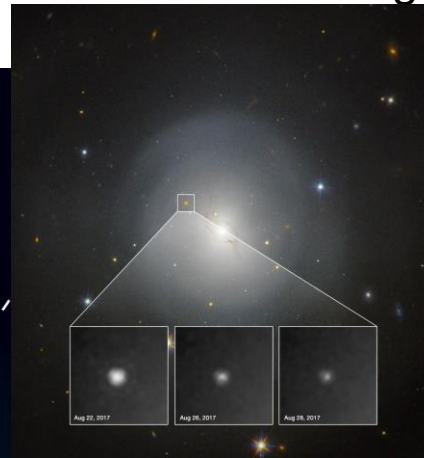
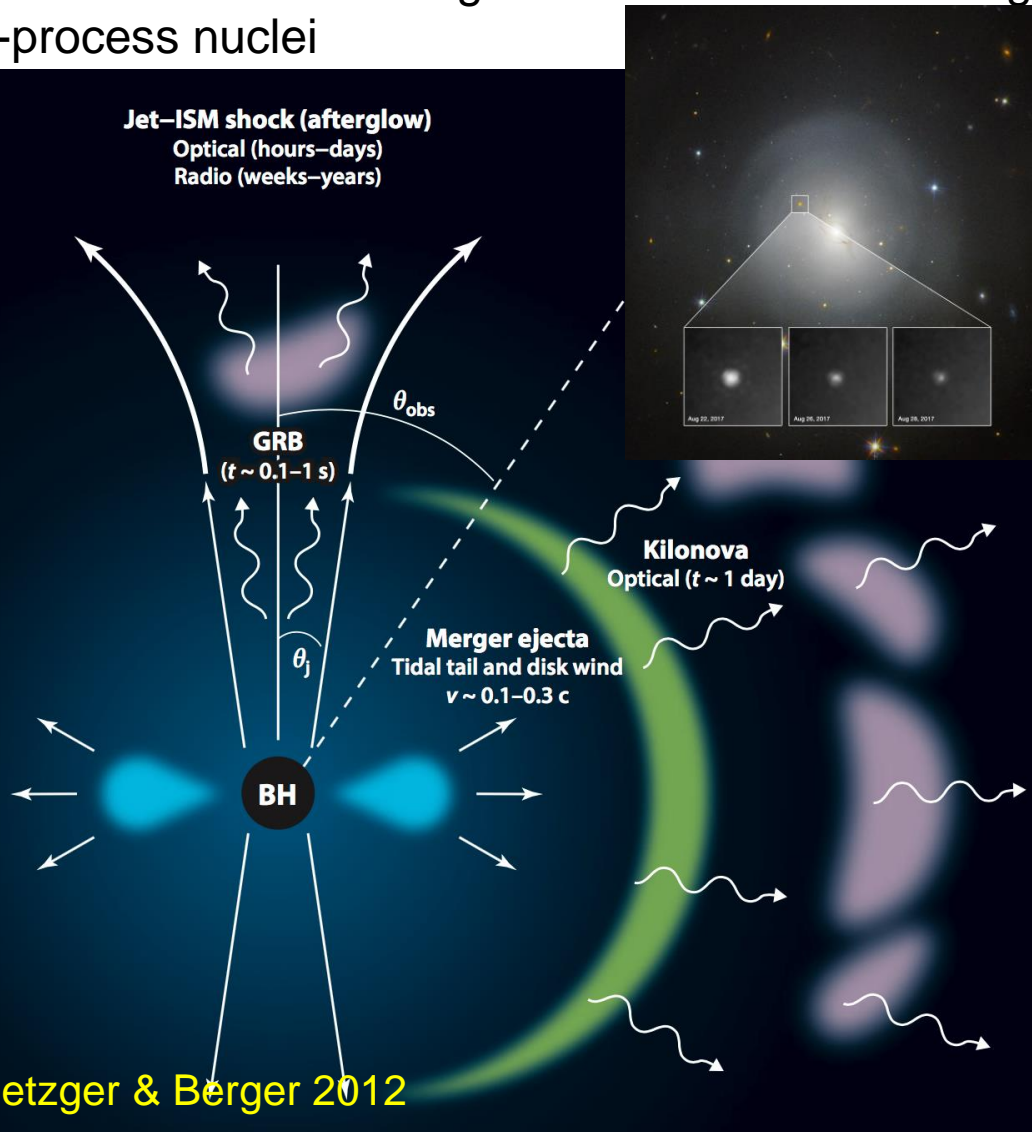
# R-process operation

Heavy elements produced by the r-process. Radioactive decay liberates energy



# Kilonova: signature of the r-process

Kilonova: An electromagnetic transient due to long term radioactive decay of r-process nuclei

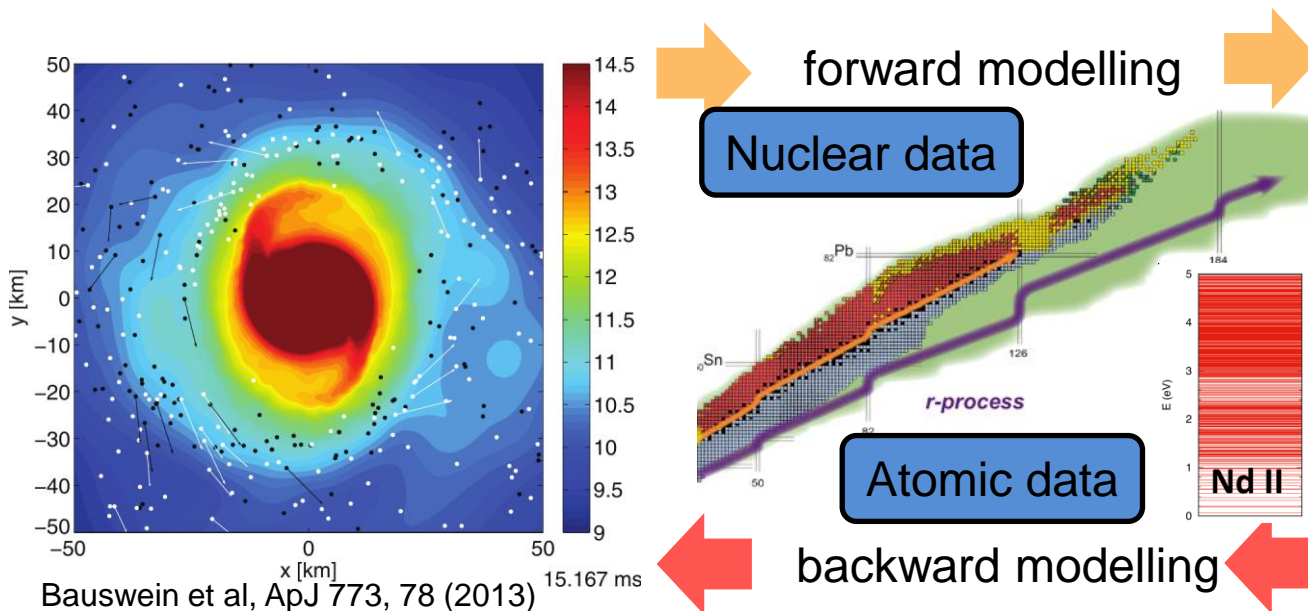


- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei
- Information elements produced single event

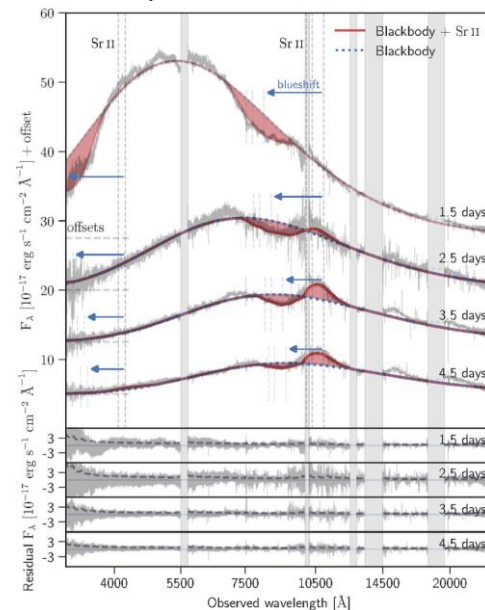
# Pipeline for r-process in mergers

- Properties ejecta: proton-to-nucleon ratio ( $Y_e$ )
- Role of equation of state
- Role of neutrinos
- Physics of neutron-rich and heavy nuclei
- Atomic data

- Radioactive transfer modelling
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)



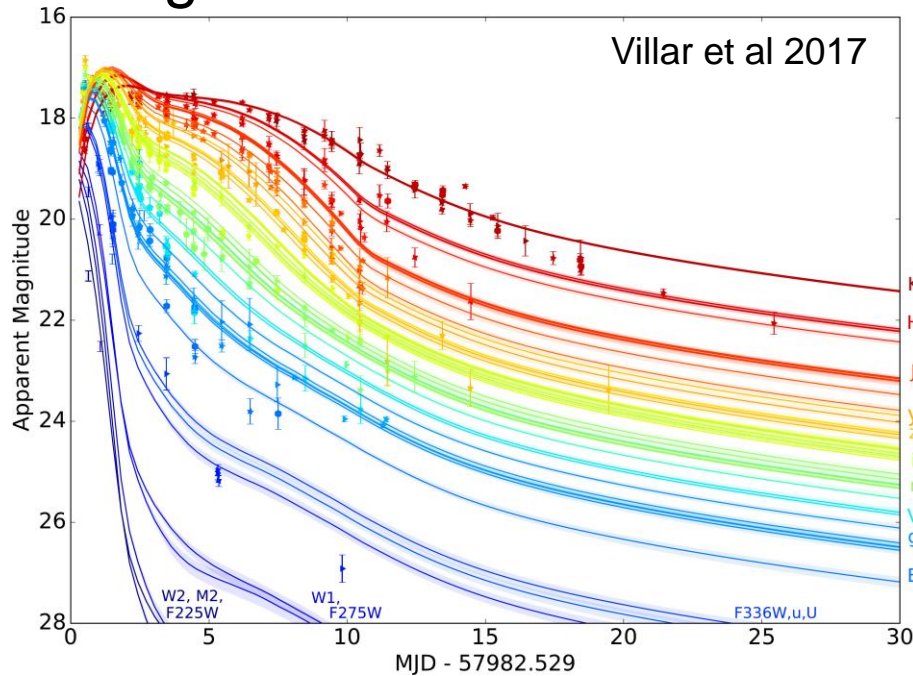
Infer components ejecta ( $Y_e$ )



Watson et al, Nature **574**, 497 (2019)

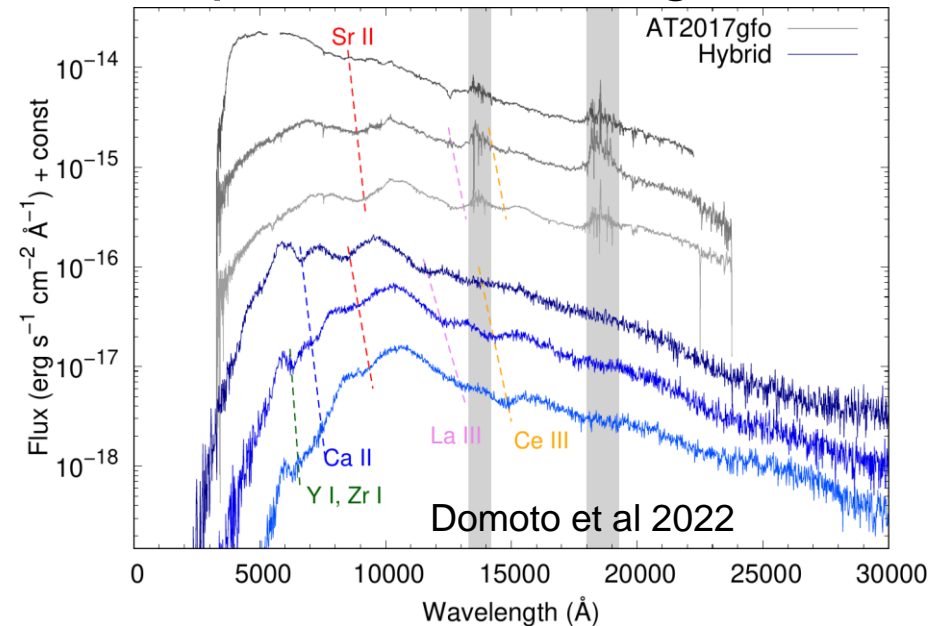
- Which r-process elements are produced in mergers?
- Are mergers the (main) r-process site?

## Light curve



- Energy deposition and thermalization
- **Complete** transition data: total opacity
- Color evolution: High vs Low opacity material
- Presence of Lanthanides/Actinides (high opacity)

## Spectral modelling



- Accurate data
  - LTE: line list bound-bound transitions
  - NLTE: + electron ion and photoionization cross sections, recombination coefficients
- Several elements observed Sr (Watson+22), Y, Zr, La, Ce (Domoto+22, Gillanders+23, Sneppen+23)

# Available experimental data

1 IA																	18 VIIIA						
1 H Hydrogen 1.008																	2 He Helium 4.002602						
3 Li Lithium 6.94	4 Be Beryllium 9.0121831																	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 Al Aluminium 26.9815386	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948						
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798						
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.90625	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.363	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.603	53 I Iodine 126.90545	54 Xe Xenon 131.29						
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)						
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)						

- All relevant levels & transitions known
- Some levels & transitions known
- Very incomplete levels & transitions data

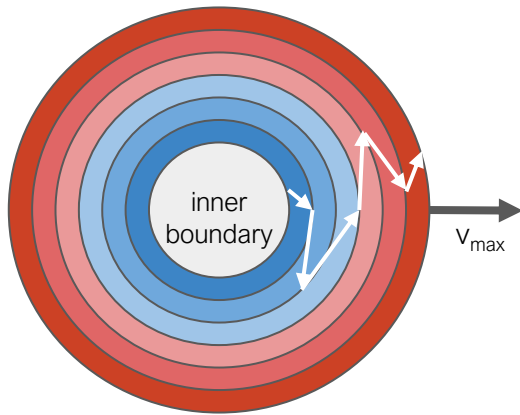
57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)

- Energies and transition probabilities between many levels required
- Systematic improvement of atomic data possible with the use of experimental data or *ab initio* calculations for few low lying levels



# Atomic Opacities (LTE)

- Sobolev optical depth (for a line  $l$ )



$$\tau_l = \frac{\pi e^2}{m_e c} t f_l n_l \lambda_l$$

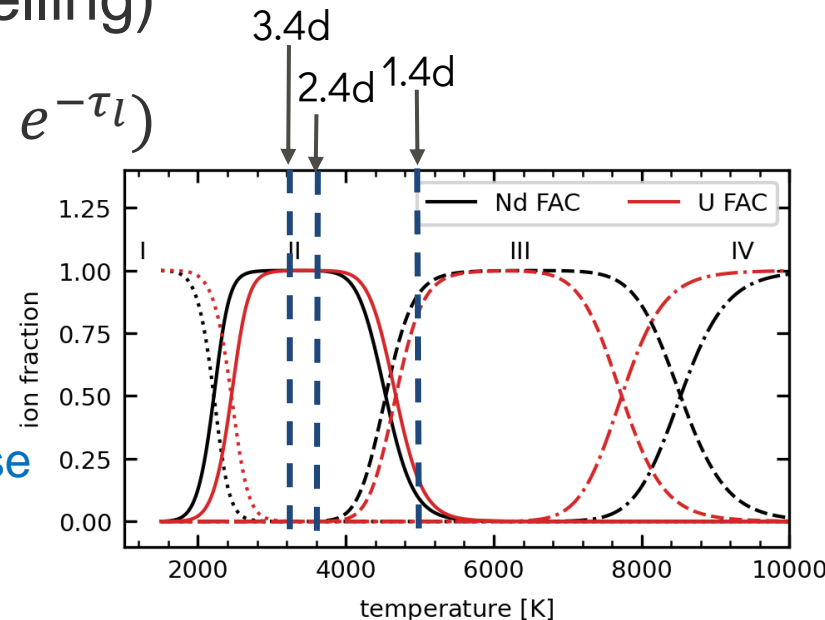
Transition wavelength

Oscillator strength

Population lower level (Saha eq. and partition functions)

- Expansion opacity (homologous expanding material, not used in the radiation transport modelling)

$$\kappa_{\text{exp}}^{\text{bb}} = \frac{1}{\rho c t} \sum_l \frac{\lambda_l}{\Delta \lambda_{\text{bin}}} (1 - e^{-\tau_l})$$



A. Flörs

G. Leck

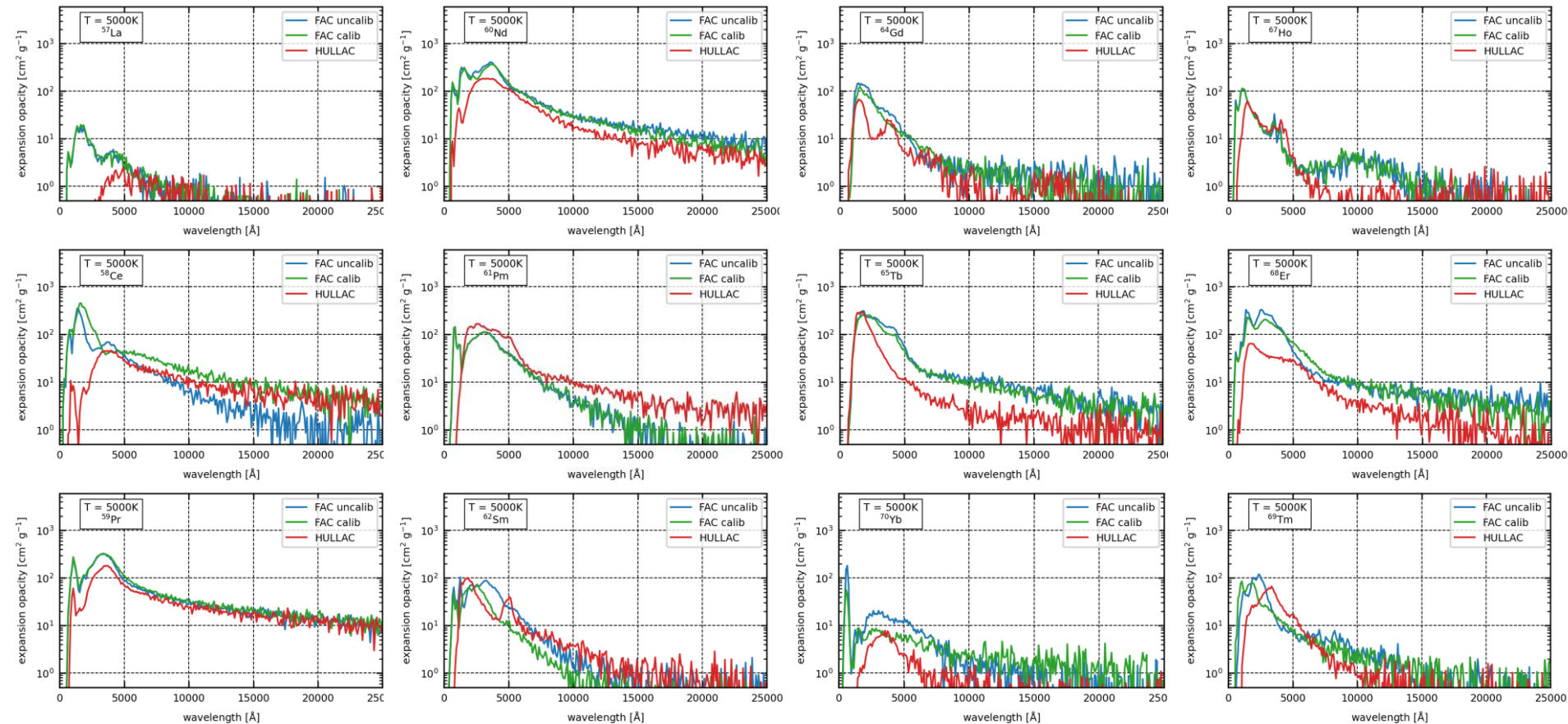
R. Silva



Goal: Develop database well calibrated atomic opacities

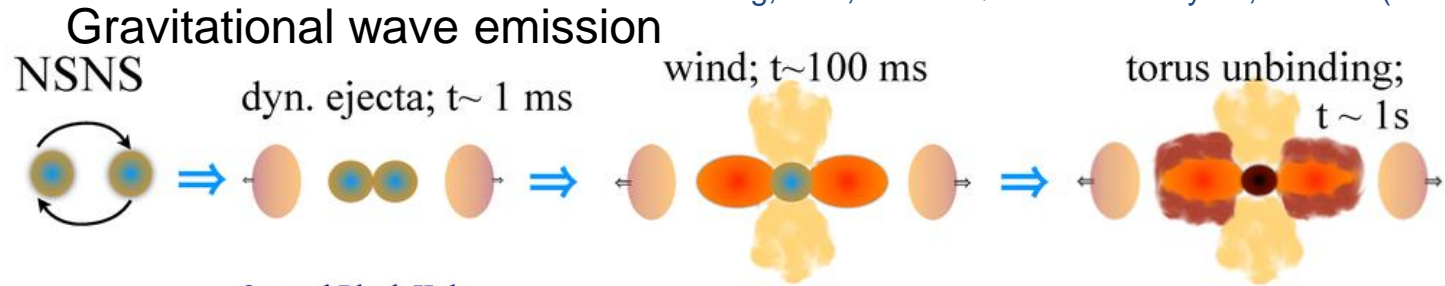
# Lanthanide Opacities

■ FAC uncalib    ■ FAC calib    ■ HULLAC



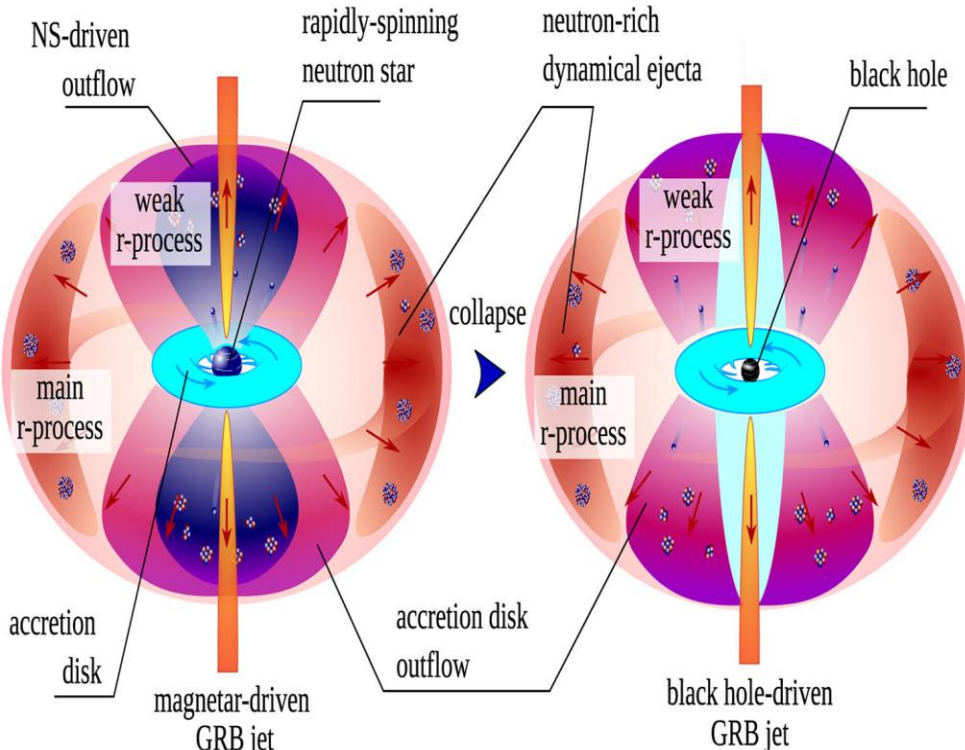
# Neutron star mergers: Different ejection mechanisms

S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

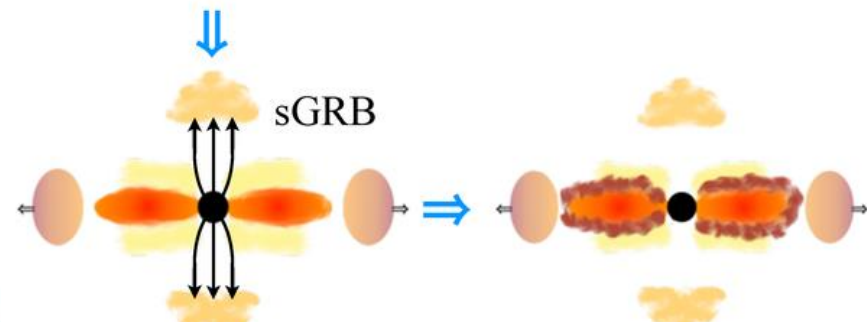


Central Neutron Star

Central Black Hole



BH formation



Two sources of ejecta:

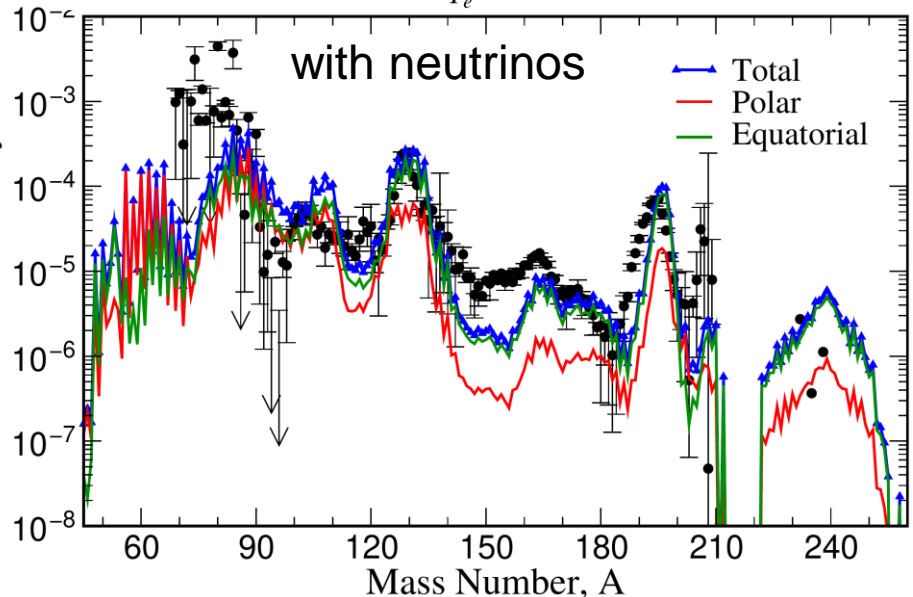
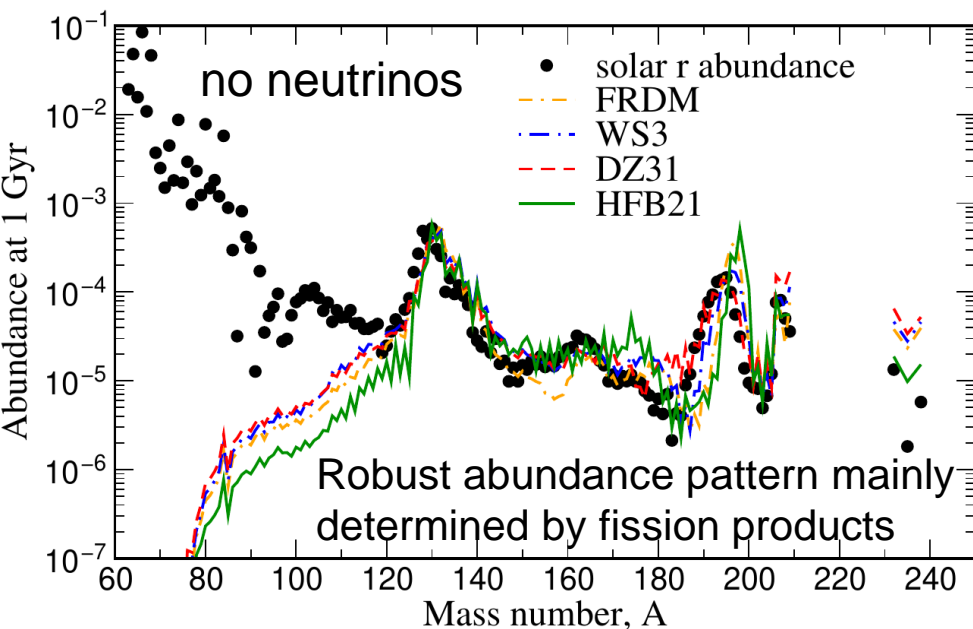
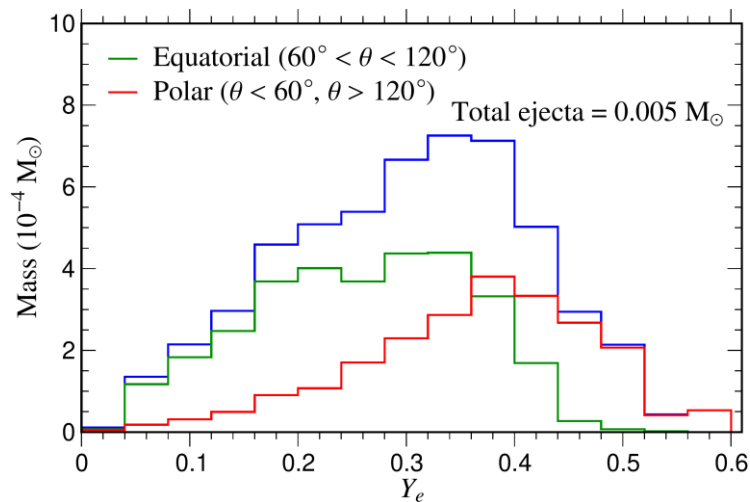
- Dynamical during the early phases of the merger ( $M \lesssim 0.01 M_{\odot}$ )
- Accretion disc on longer timescales ( $M \lesssim 0.05 M_{\odot}$ )
- Lifetime neutron-star determines impact neutrinos

S. Rosswog and O. Korobkin, Annalen Der Physik **2022**, 2200306 (2022).

# Dynamical ejecta (simulations)

SPH Simulation **Vimal Vijayan**  
 Neutrino transport: ILEAS  
 1.35 – 1.35  $M_{\odot}$ , SFHo EoS

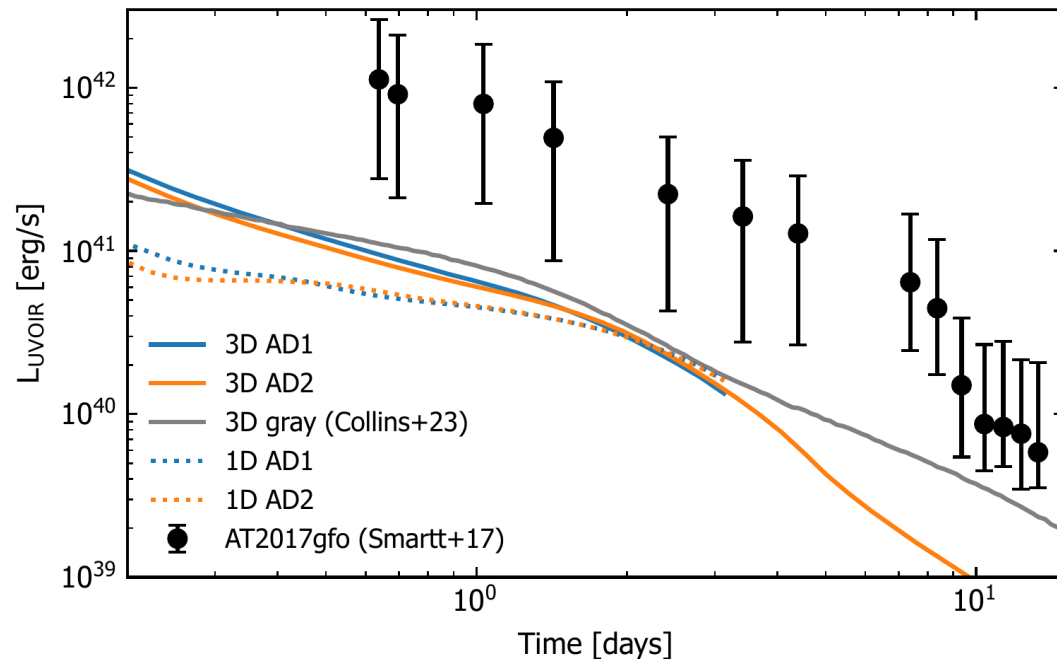
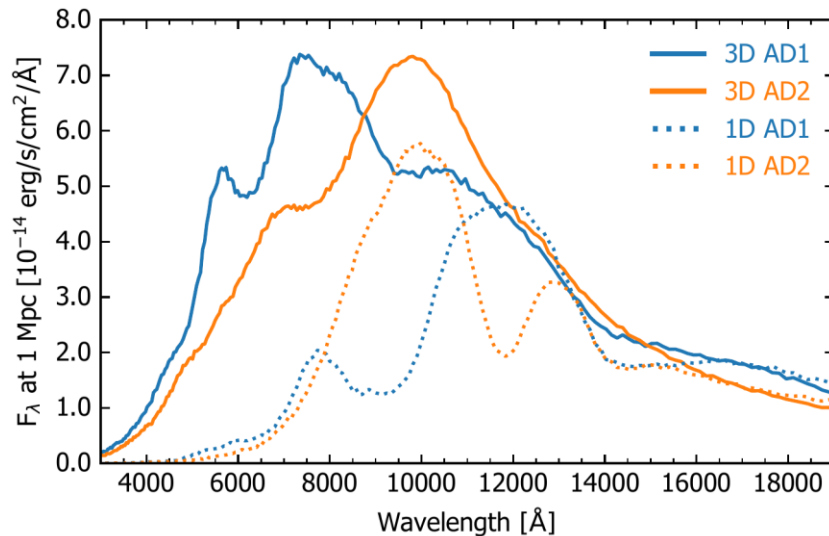
- Initially dynamical ejecta was assumed to be very neutron rich ( $Y_e \lesssim 0.1$ ).
- Starting with the work of Wanajo et al 2014, several studies have shown that weak processes modify the neutron-to-proton ratio
- Largest impact in the polar regions



Mendoza-Temis, et al, PRC 92, 055805 (2015)

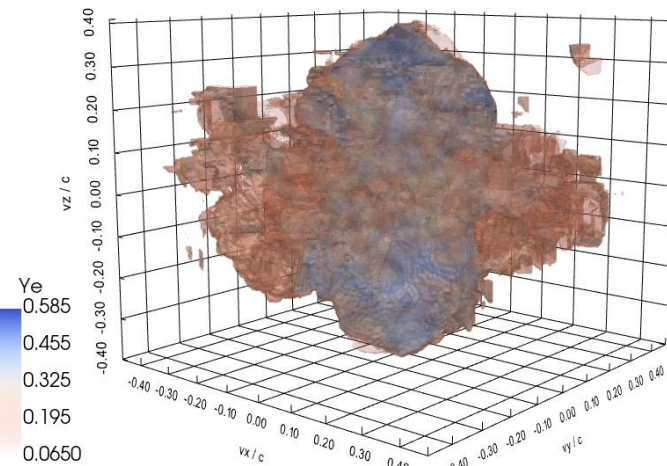
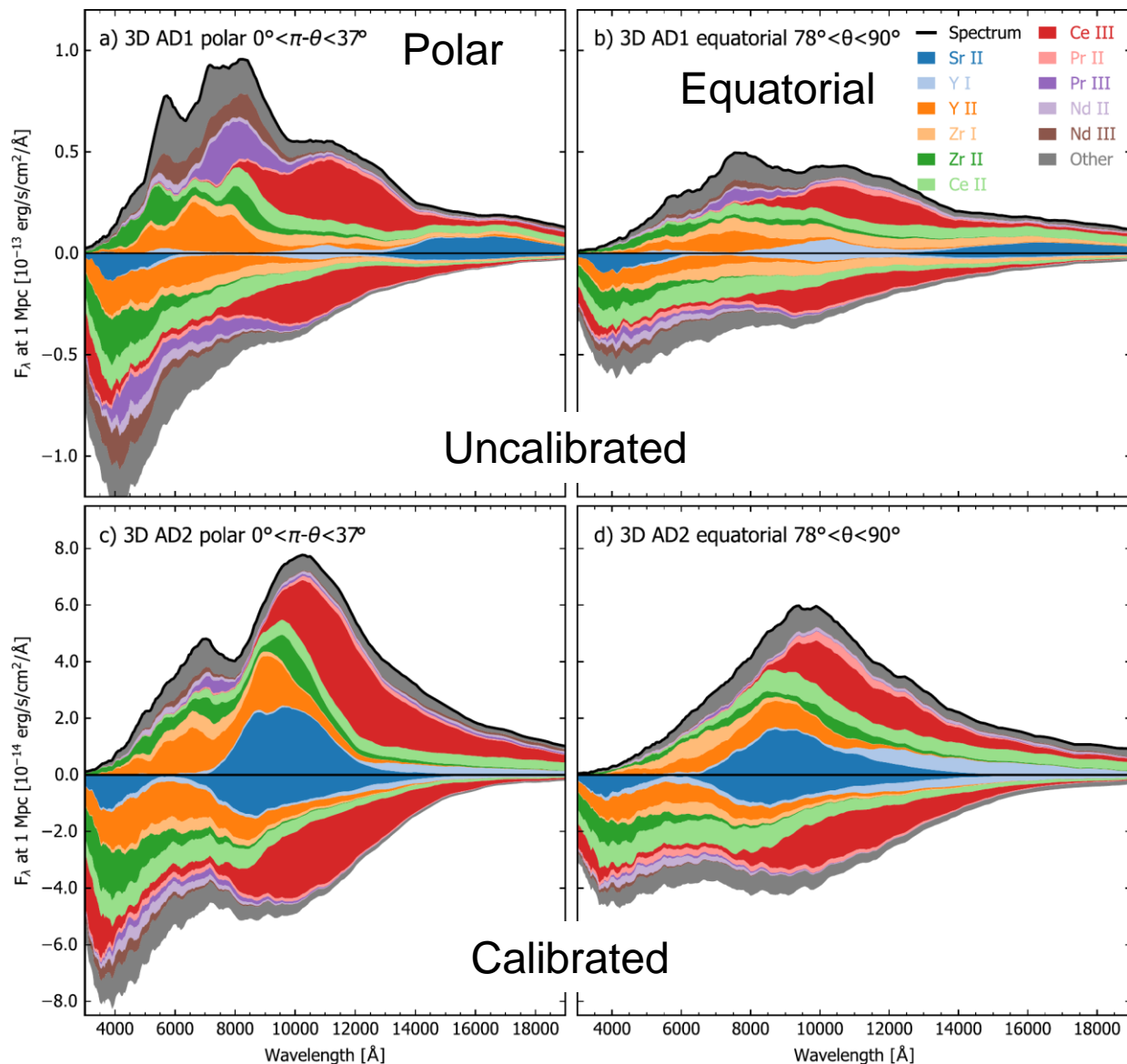


- Monte Carlo 3D radiative transfer using the ARTIS code.  
<https://github.com/artis-mcrt/artis>
- Matter distribution based on SPH Dynamical ejecta ( $0.005 M_{\odot}$ )
- LTE simulation: follows 2591 nuclei (283 ions with gamma-ray transport and electron thermalization, 44 millions atomic transitions lines  
AD1: Japan-Lithuania database Z=28-88, Tanaka+ 2020  
AD2: AD1 + calibrated lines for Sr, Y, and Zr, Kurucz 2018



Shingles et al, ApJ **954**, L41 (2023)

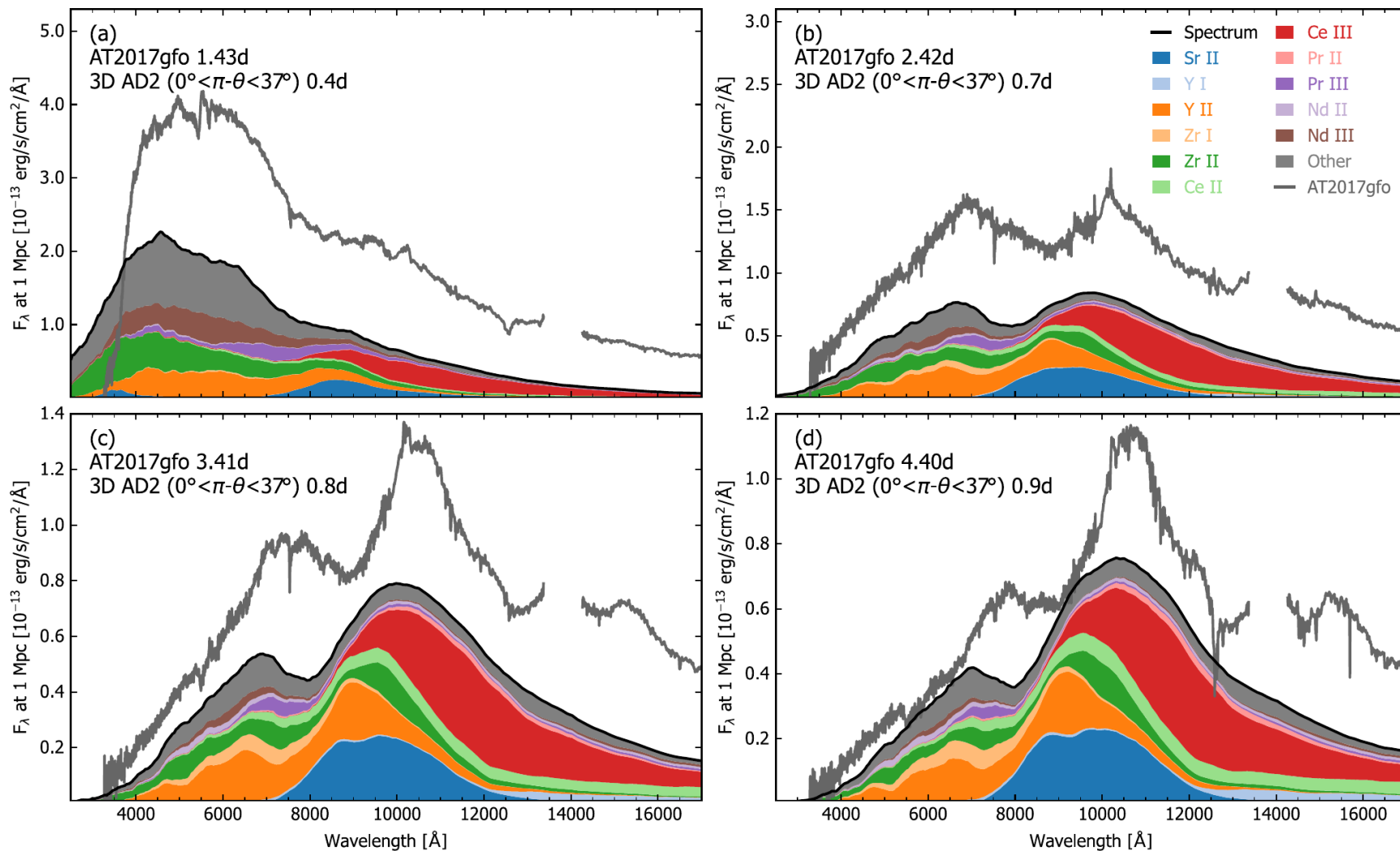
# Angular dependence spectra



Differences reflect directional dependence of nucleosynthesis yields

Shingles et al, ApJ 954, L41 (2023)

# Comparison AT2017gfo

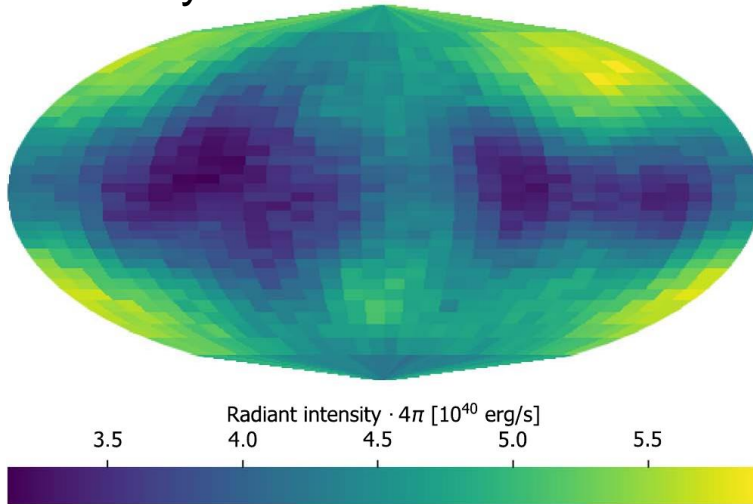


Similar spectral evolution that AT2017gfo once differences in brightness are accounted

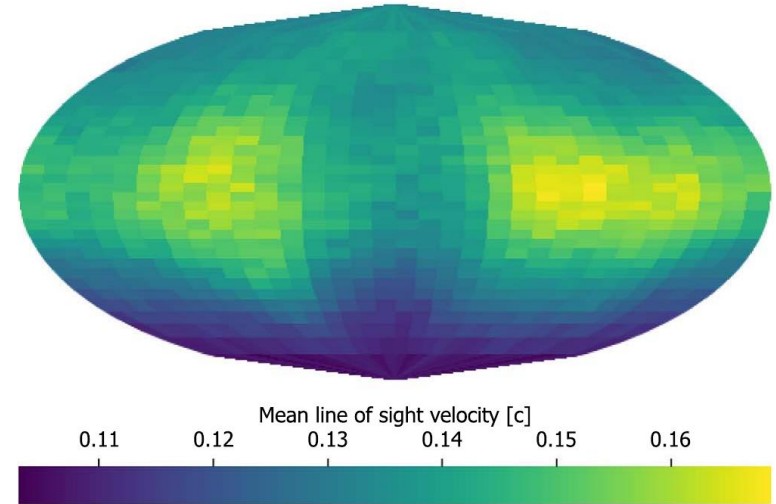
Shingles et al, ApJ 954, L41 (2023)

# Asymmetry observables

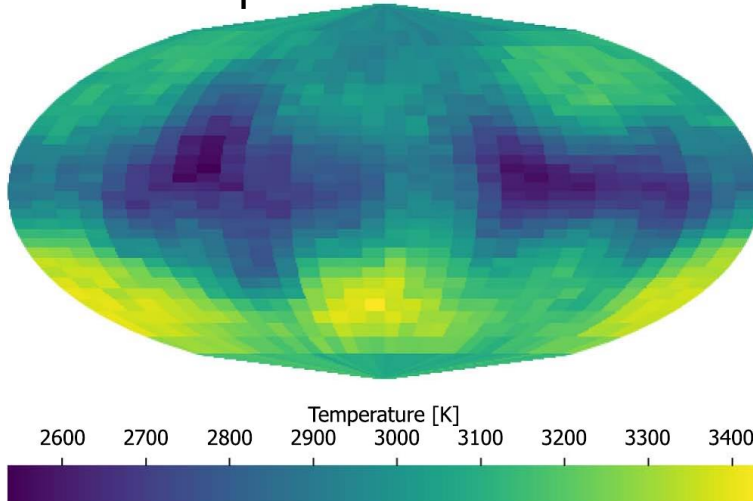
Intensity



Line-of-sight velocity



Mean temperature



- Strong asymmetry observables
- Need of further observations

Shingles et al, ApJ 954, L41 (2023)

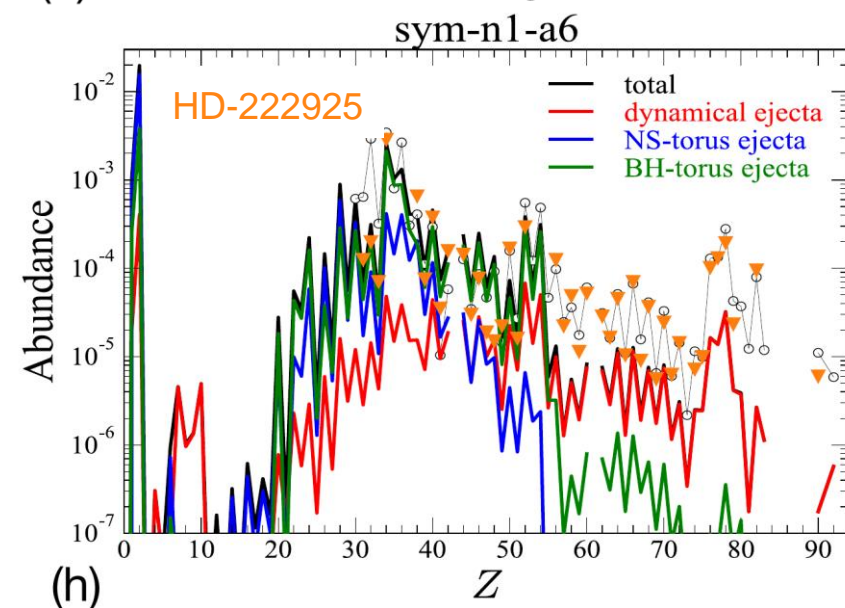
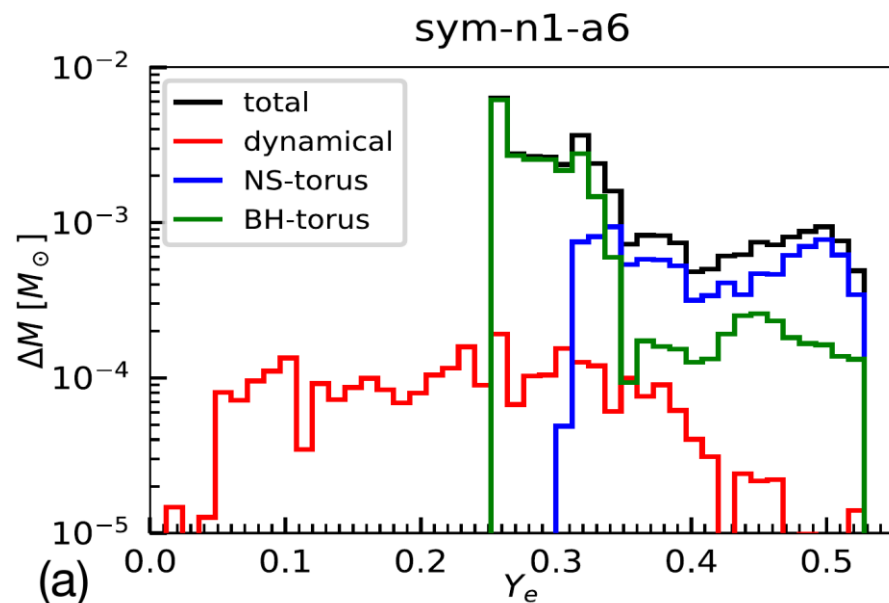
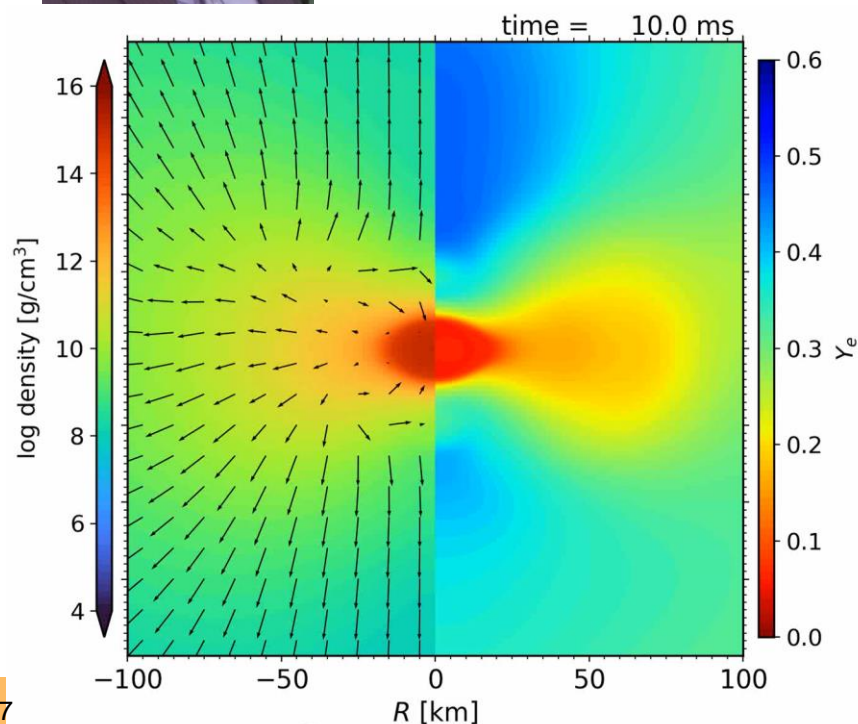


# Long term merger simulations

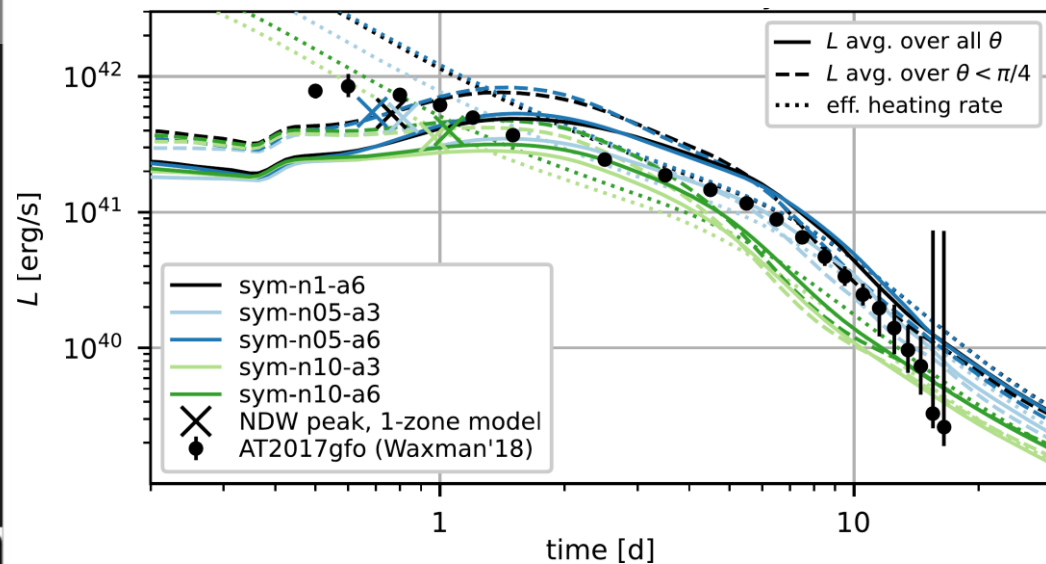
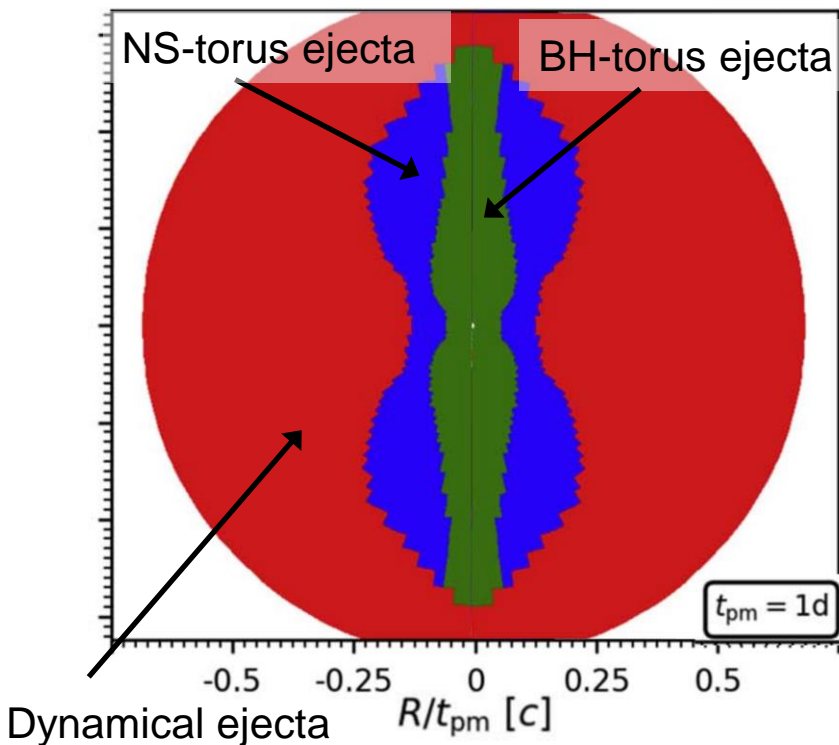
Long-term simulations with neutron star lifetimes 0.1-1 s and describe all components of the ejecta: dynamical, NS-torus ejecta, and final viscous ejecta from BH torus.



Just et al, ApJL, L12 (2023)

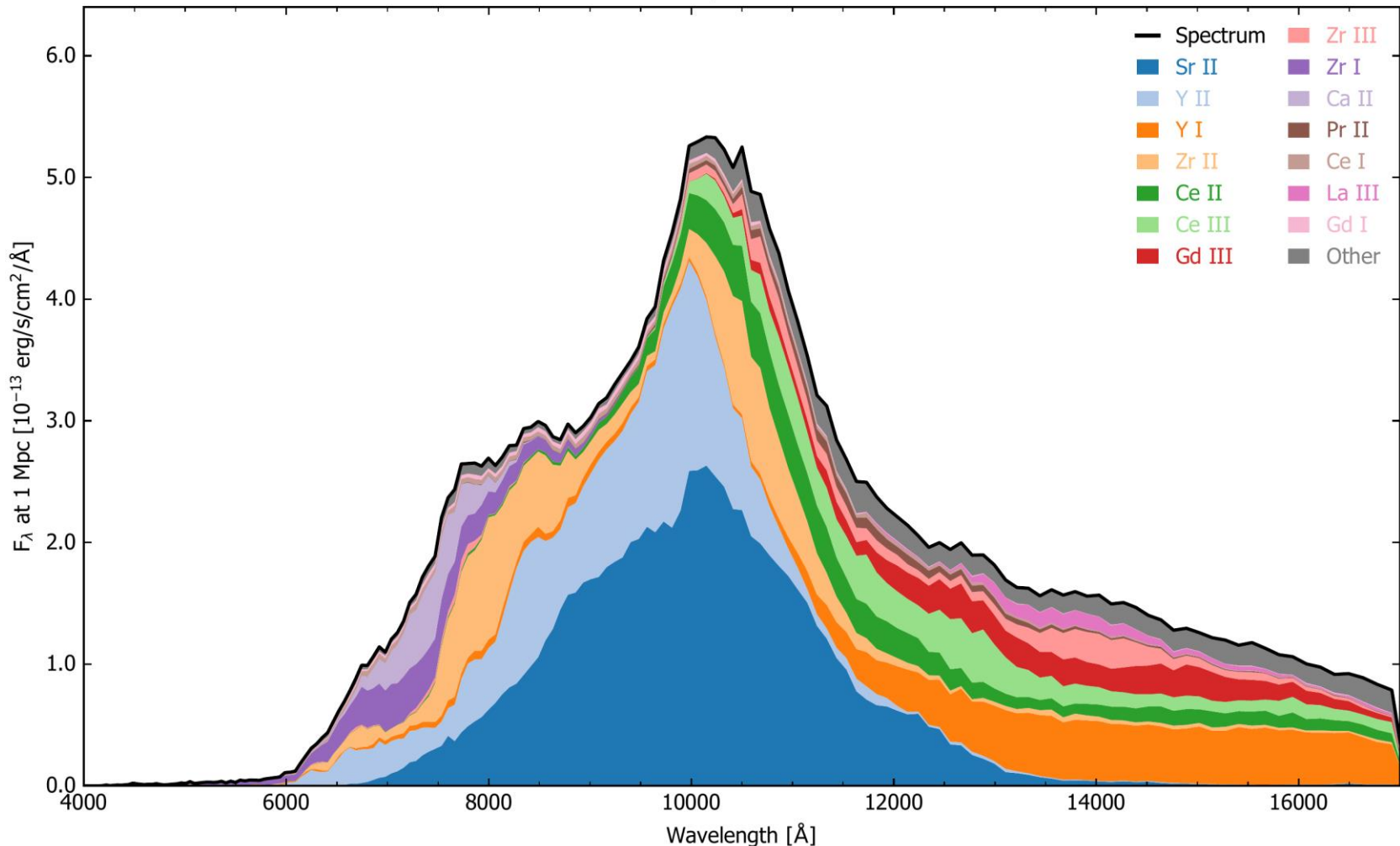


- Based on grey opacities using approximate radiative transfer model (generalization ALCAR neutrino module)
- Agreement with AT2017gfo after times of several days
- Accounting for all ejecta components fundamental to reproduce light curve



Just et al, ApJL, L12 (2023)

2D AD3 just138n1a6  
3.14d to 3.87d,  $-1.0 \leq \cos \theta < -0.8$



- Different spectral features than model considering dynamical ejecta
- Possible dependence on dimensionality simulation (here 2D)

Shingles et al, in preparation

# Can we find a signature of actinides?

## Relevant $\alpha$ -decays

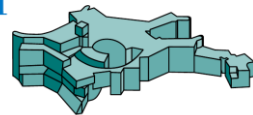
Wu, Barnes, GMP, Metzger, PRL 122, 062701 (2019)



- If actinides are present alpha-decay chains may dominate the energy generation on days.
- Fission plays a secondary role except perhaps the presence of  $^{254}\text{Cf}$

- Multi-messenger observations (Gravitational and Electromagnetic waves) from binary neutron star mergers provide unique opportunities to study the production of heavy elements:
  - Neutron star mergers identified as one astrophysical site where the r-process operates
  - Kilonova observations provide direct evidence of the “in situ operation of the r-process”
  - 3D radiative transfer allows to benchmark models with observations.
- Challenges:
  - Impact of weak processes and EoS in the ejecta properties
  - Improved nuclear and atomic input
  - Kilonova spectral modelling

# Collaborators



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