

# Kilonova as a probe of r-process nucleosynthesis

Gabriel Martínez-Pinedo

“The r-process and the nuclear EOS after LIGO-Virgo's  
third observing run”

INT Workshop, May 23-27, Seattle, USA



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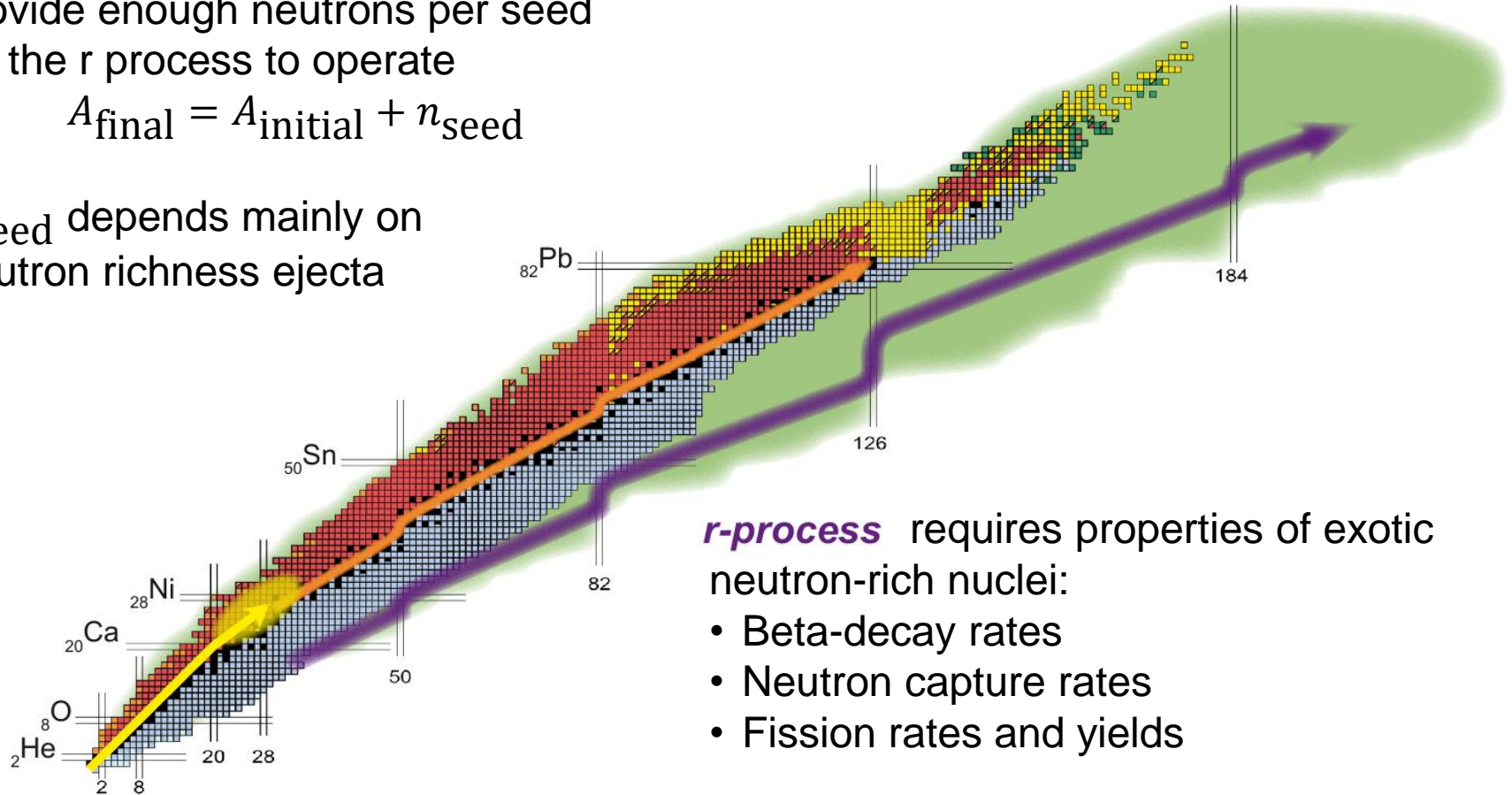
C. Robin

S. Giuliani, L. Robledo

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:

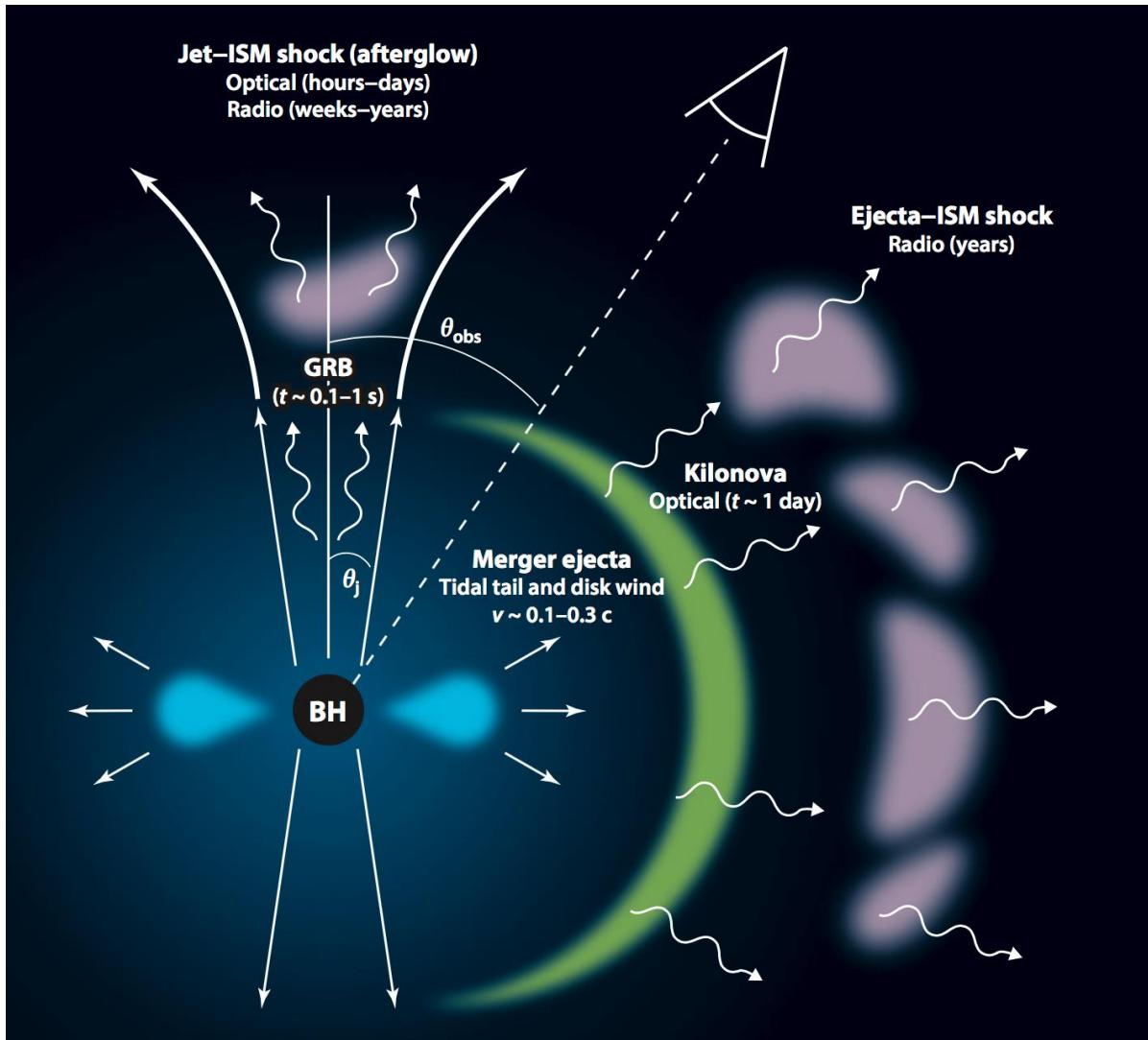
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

Benchmark against observations:

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

# Kilonova: signature of the r-process

Line of view GW170817



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

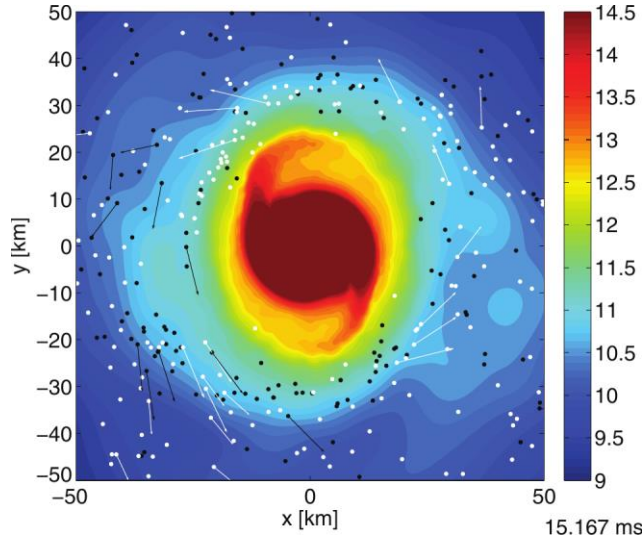
- Direct probe of the formation r-process nuclei
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger

Metzger & Berger 2012

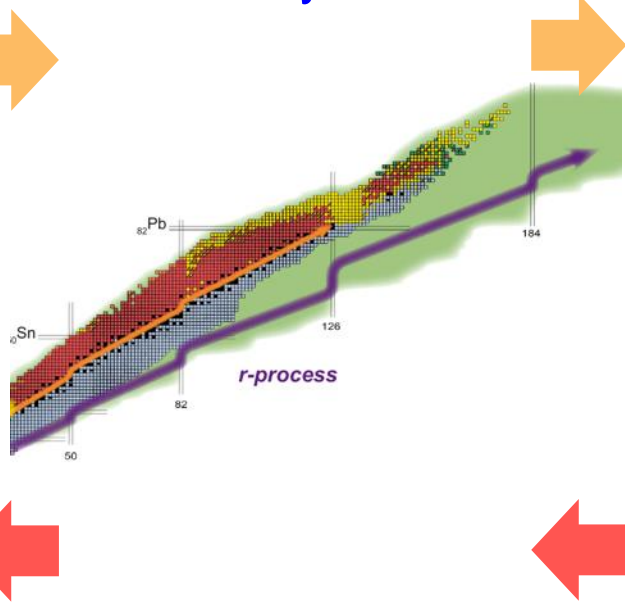
# R-process in mergers

## Simulations

Bauswein et al, ApJ 773, 78 (2013)

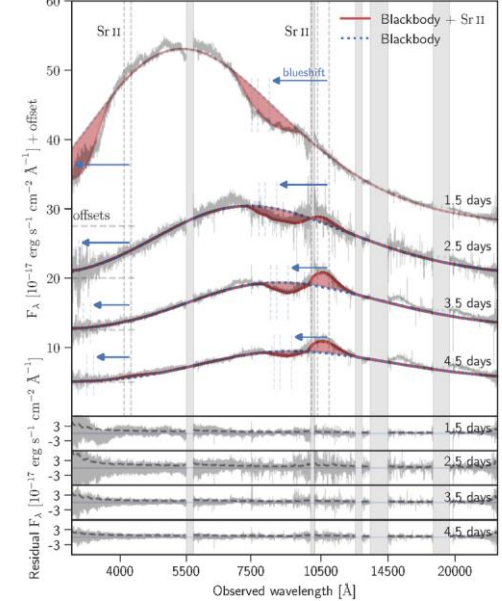


## Nucleosynthesis



## Light curve and spectra modelling

Watson et al, Nature 574, 497 (2019)

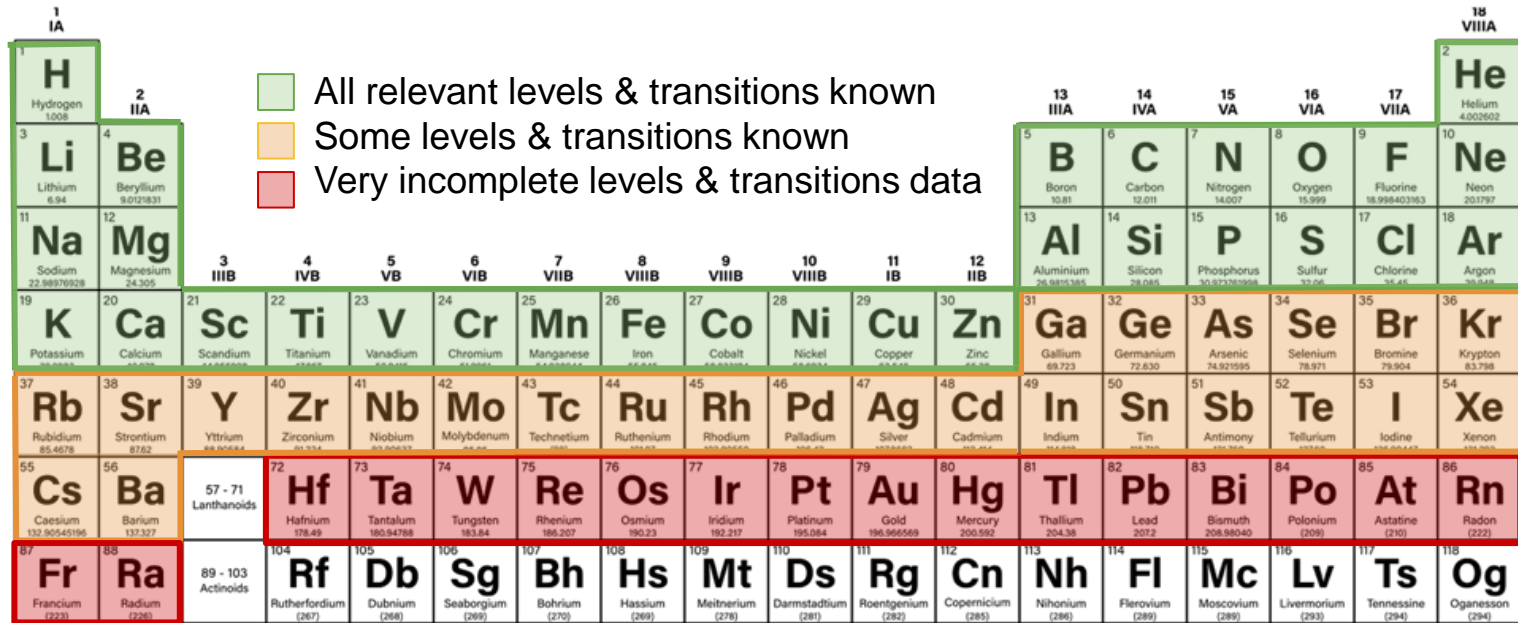


- Different sources of ejecta with different properties ( $Y_e$ )
- Role of equation of state
- Role of neutrinos

- Physics of neutron-rich and heavy nuclei

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

# Energy levels - Opacity



Legend:

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

1 1A H Hydrogen 1.008																	18 VIIIA He Helium 4.002602
3 IIA Li Lithium 6.94	4 Be Beryllium 9.0121831											5 IIIA B Boron 10.81	6 IVA C Carbon 12.011	7 VA N Nitrogen 14.007	8 VIA O Oxygen 15.999	9 VIIA F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305	3 IIIB Sc Scandium 44.955912	4 IVB Ti Titanium 47.88	5 VB V Vanadium 50.9415	6 VIB Cr Chromium 51.9961	7 VIIB Mn Manganese 54.938044	8 VIIIB Fe Iron 55.845	9 VIIIB Co Cobalt 58.933195	10 VIIIB Ni Nickel 58.6934	11 IB Cu Copper 63.546	12 IIB Zn Zinc 65.38	13 Al Aluminium 26.9815385	14 Si Silicon 28.0855	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 106.36	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 126.90447	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)

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 174.9668
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)

- Early evolution ( $t \lesssim 1$  week, local thermodynamic equilibrium)
  - Bound-bound opacities
  - Not enough data: levels and transitions (theory: Gaigalas+ 2019, Tanaka+ 2020, Fontes+ 2020)
- Nebular evolution ( $t \gtrsim 1$  week, non LTE)
  - Electron-ion cross sections, photoionization cross sections, recombination coefficients (Hotokezaka+ 2021, Pognan+ 2022)

# Atomic opacities and spectral modelling

- Systematic opacity calculations
  - All elements between Iron and Actinides computed using Flexible Atomic Code [Gu CJP 86, 675 (2008), <https://github.com/flexible-atomic-code/fac>], U Lisbon same set of configurations than Tanaka et al 2020.
  - Extended set of configurations to ensure convergence low lying states and density of levels
  - Benchmark against data or calculations with alternative codes (HFR, U Mons)



G. Leck



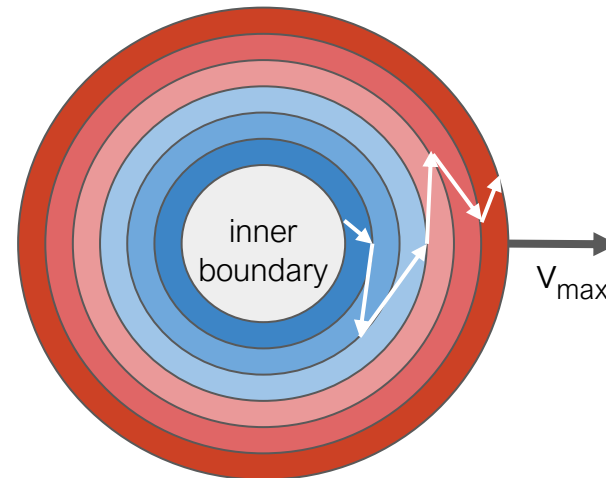
A. Flörs



L. Shingles

-  **TARDIS!**  
Kerzendorf & Sim, MNRAS 440, 387 (2014)  
<https://tardis-sn.github.io/>

- 1D Monte Carlo Spectral Synthesis Code
- Inner boundary: only early spectra possible



- ARTIS** Kromer & Sim, MNRAS 398, 1809 (2009)  
<https://github.com/artis-mcrt/artis>

- 3D Monte Carlo Radiative Transfer
- Consistent description of energy deposition, transport and spectral formation
- 3D geometry ejecta
- Both photospheric and nebular epochs.



L. Shingles

- 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

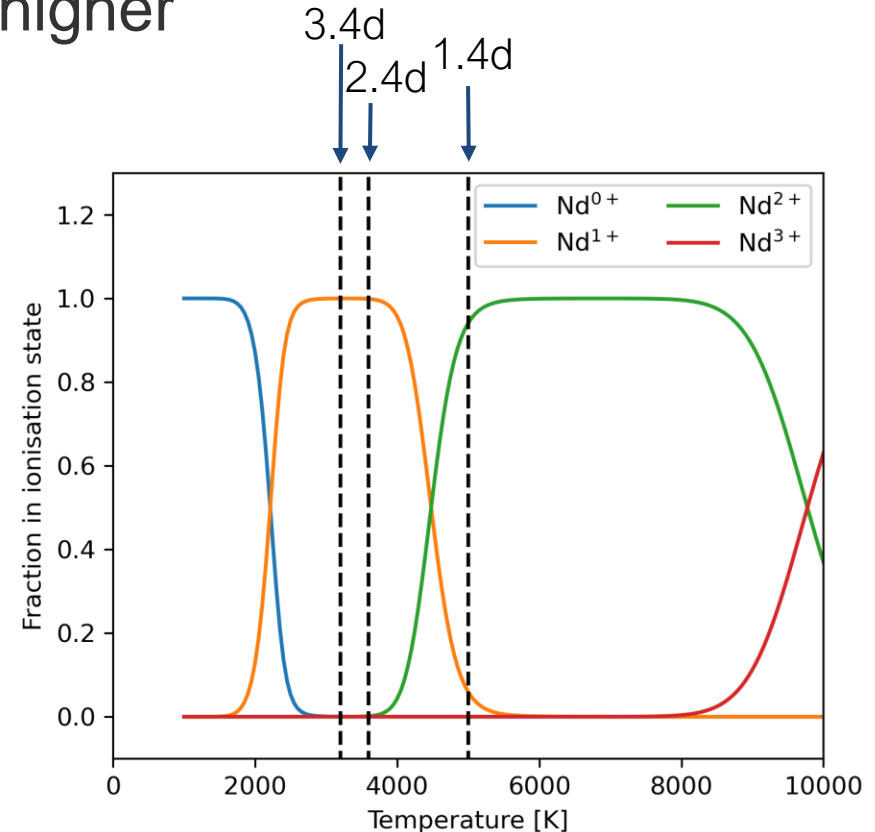
Population lower level (Saha eq. and partition functions)

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

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

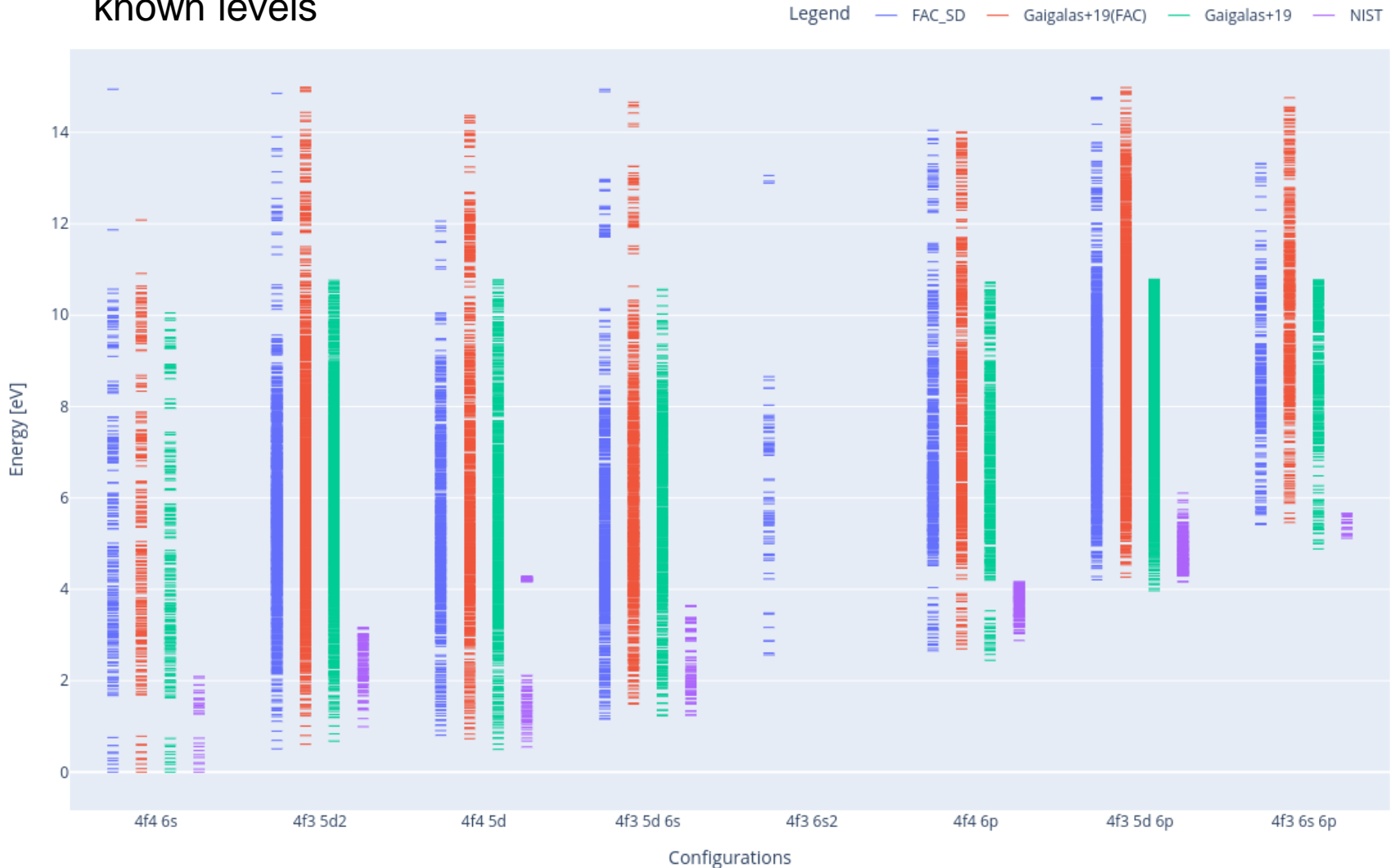


- Lanthanides and Actinides: large contribution to opacity, more highly ionized than iron-group
  - Early phases: double ionized
  - After ~ 2 days: single ionized
- Single ionized material has higher bound-bound opacity than double ionized
- Ionization transition can potentially be observed in the spectrum

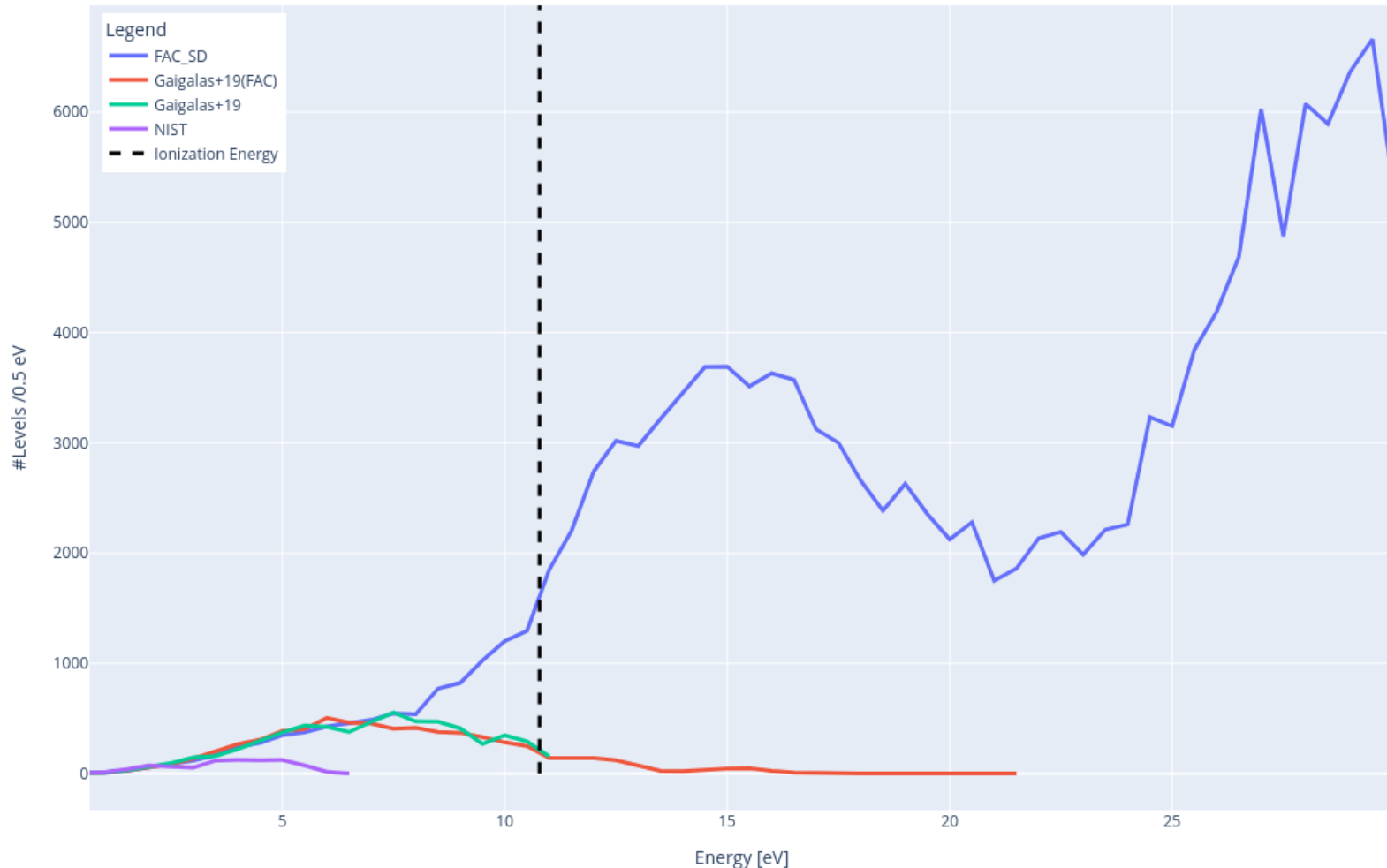


# Level energies: Nd II

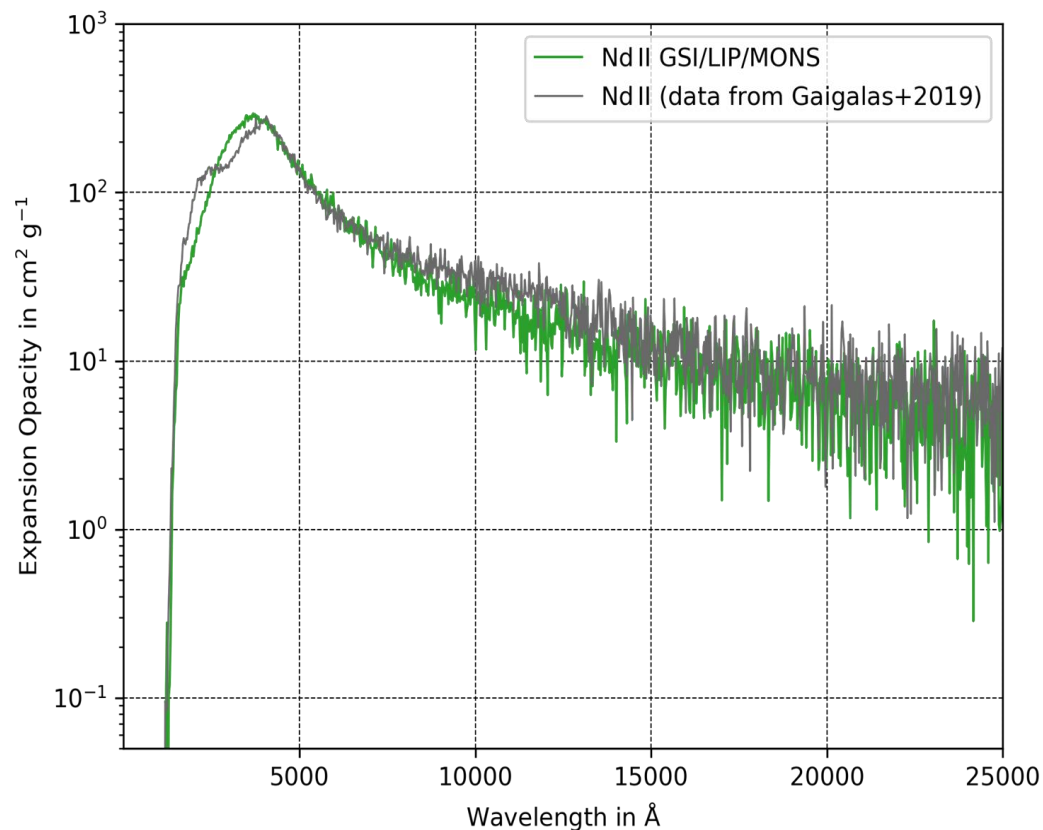
- Consider enough configurations to achieve convergence low lying states and level densities.
- Opacities after energy matching to known levels



- Large number configurations required to reproduce level density up to ionization energy

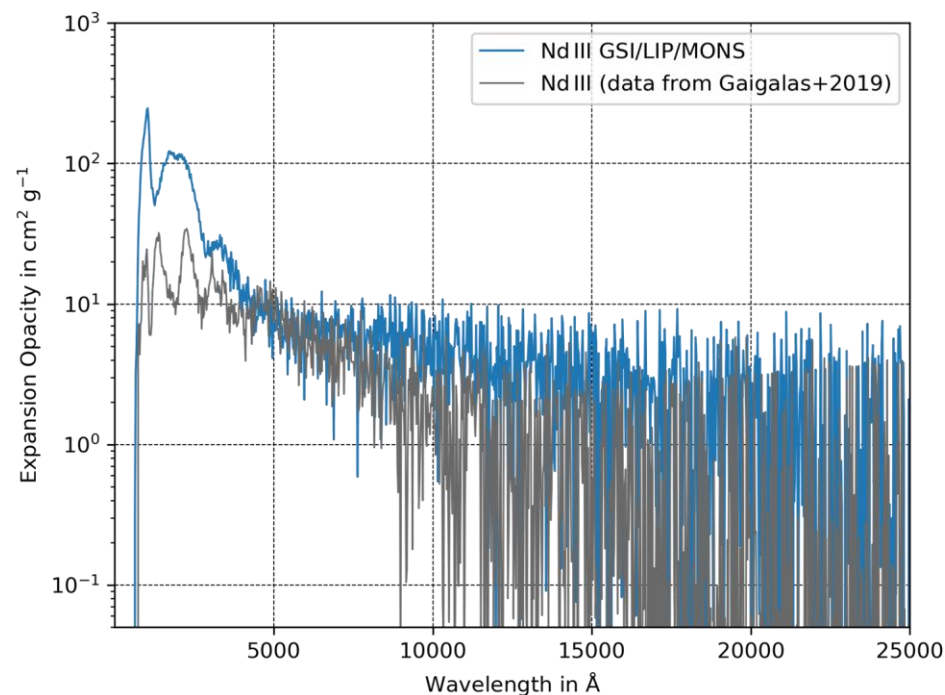


- Good agreement with published results [Gaigalas et al, ApJS **240**, 29 (2019)]
- Small differences due to different atomic codes



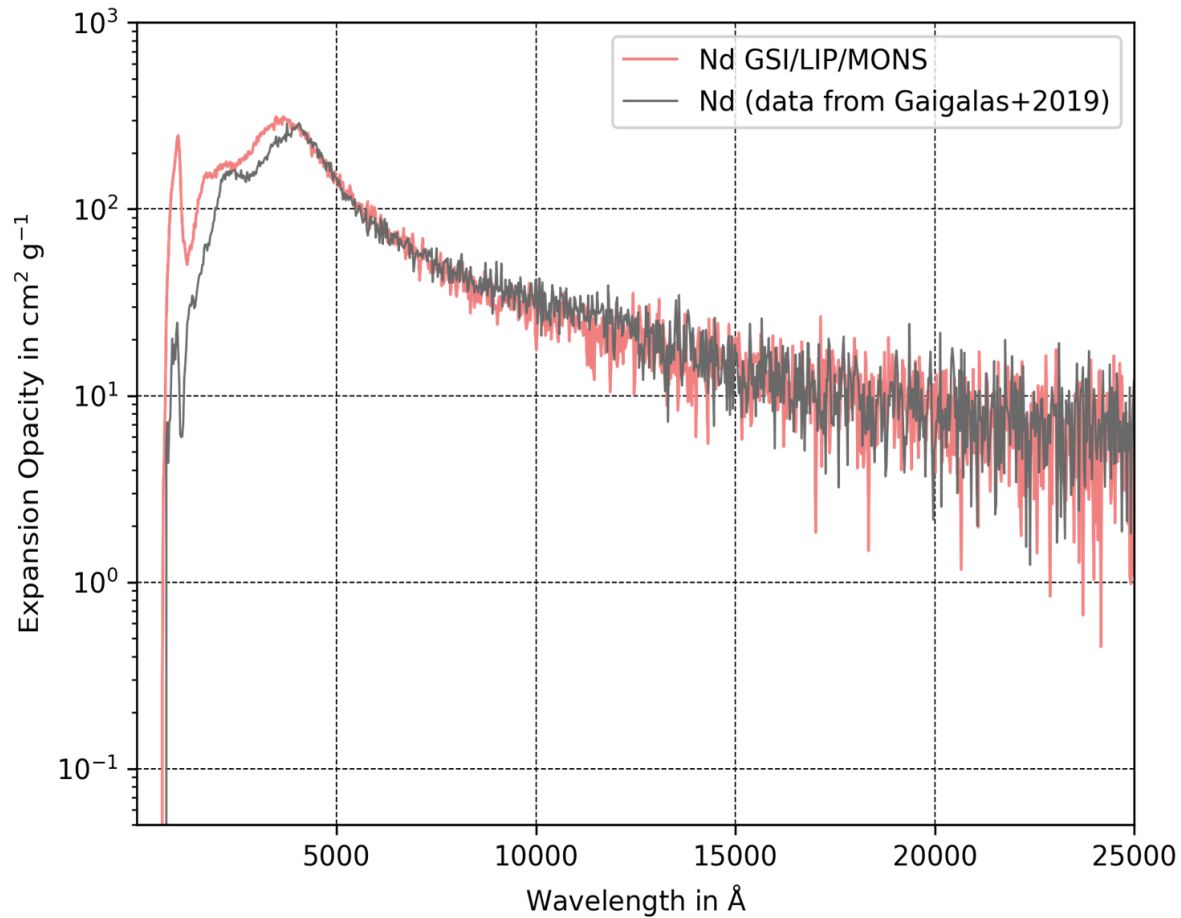
$$\rho = 10^{-13} \text{ g cm}^{-3} \quad T = 5000 \text{ K}$$

- Differences below 2000 Å
- Very limited measured data available
- Calibration to levels difficult



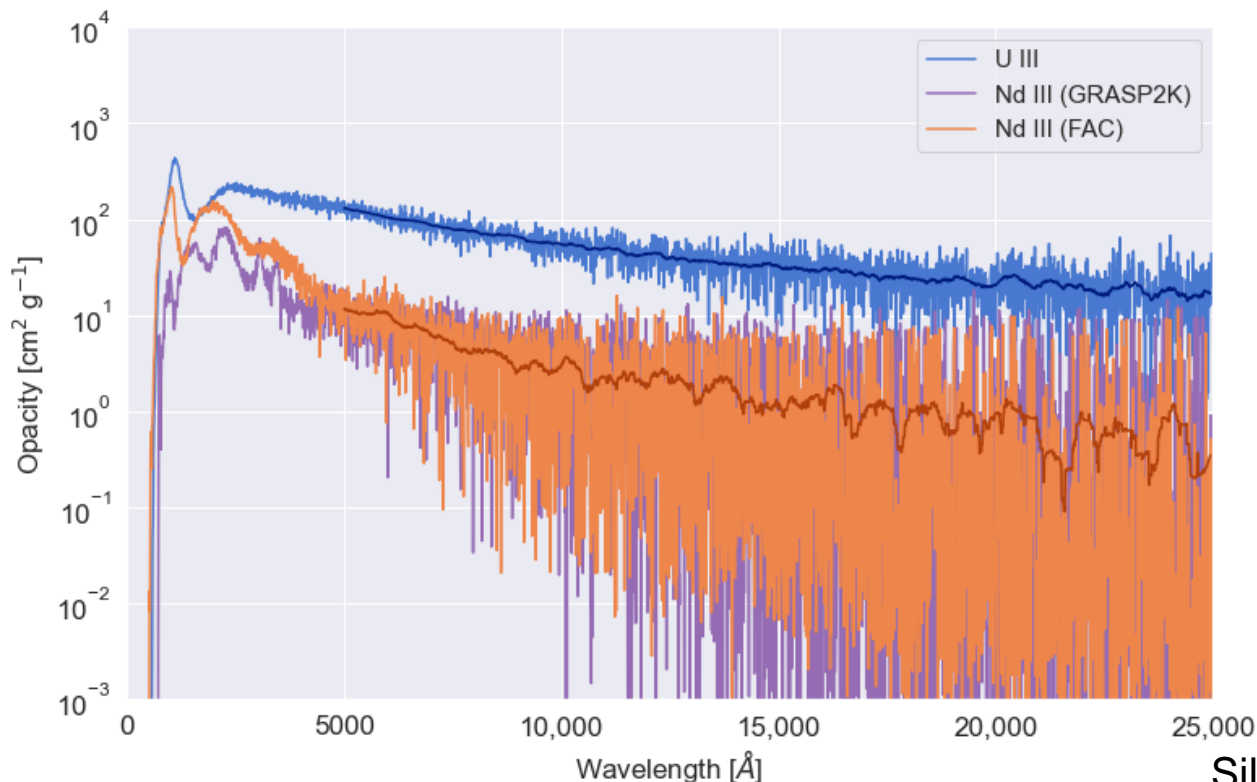
$$\rho = 10^{-13} \text{g cm}^{-3} \quad T = 5000 \text{ K}$$

Good agreement with Gaigalas+ 2019 for  $T \lesssim 5000$  K



$$\rho = 10^{-13} \text{g cm}^{-3} \quad T = 5000 \text{ K}$$

- How do the Actinides opacities compare to Lanthanides?
- Important to identify Actinides to determine what are the heavier elements produced.
- Actinides may be an important source of heating at late times (Zhu+ 2018, Wu+ 2019)



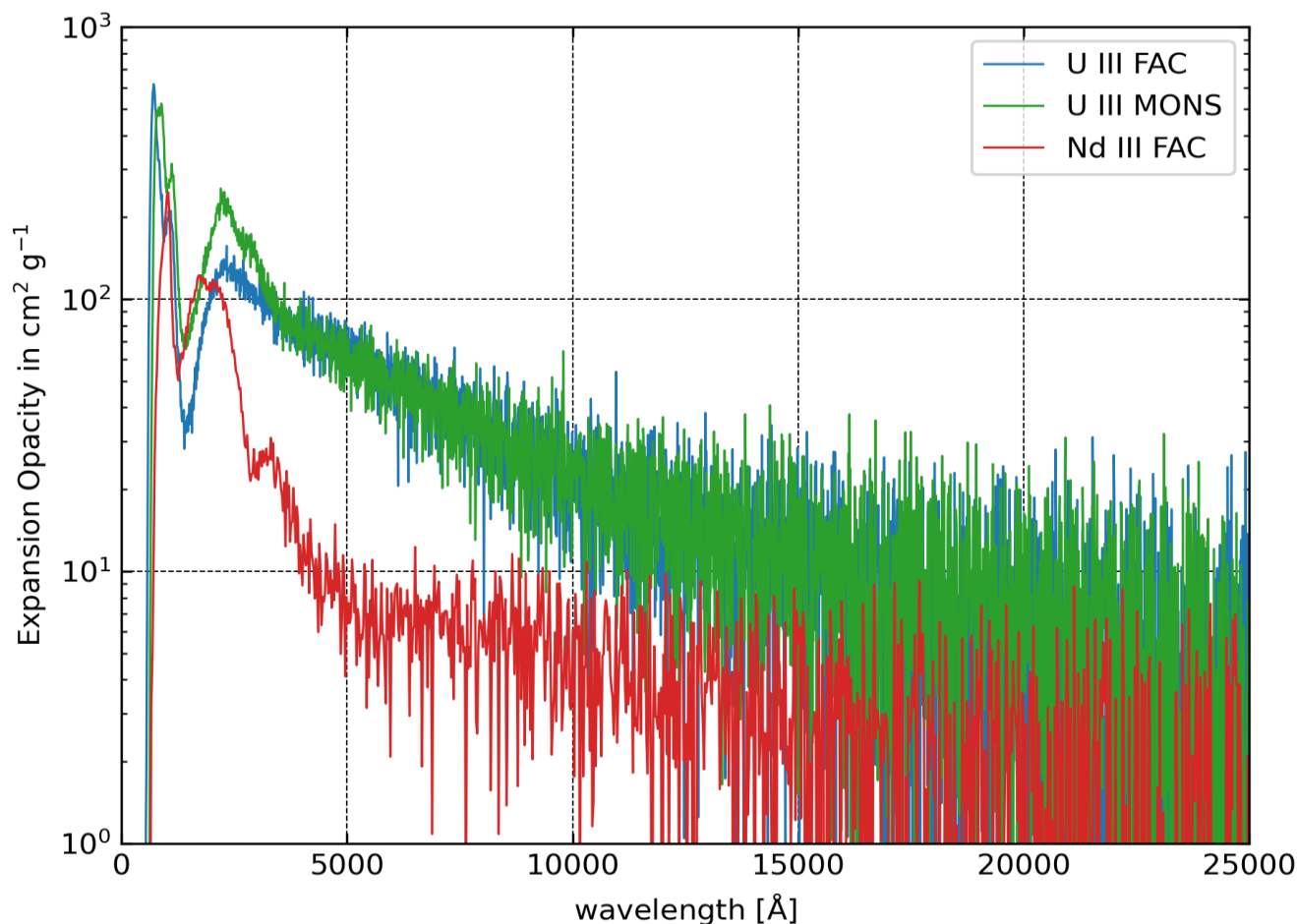
Larger opacities for U III than Nd III

No data available

Opens possibility of identifying features of actinides

Silva et al, Atoms 10, 18 (2022)

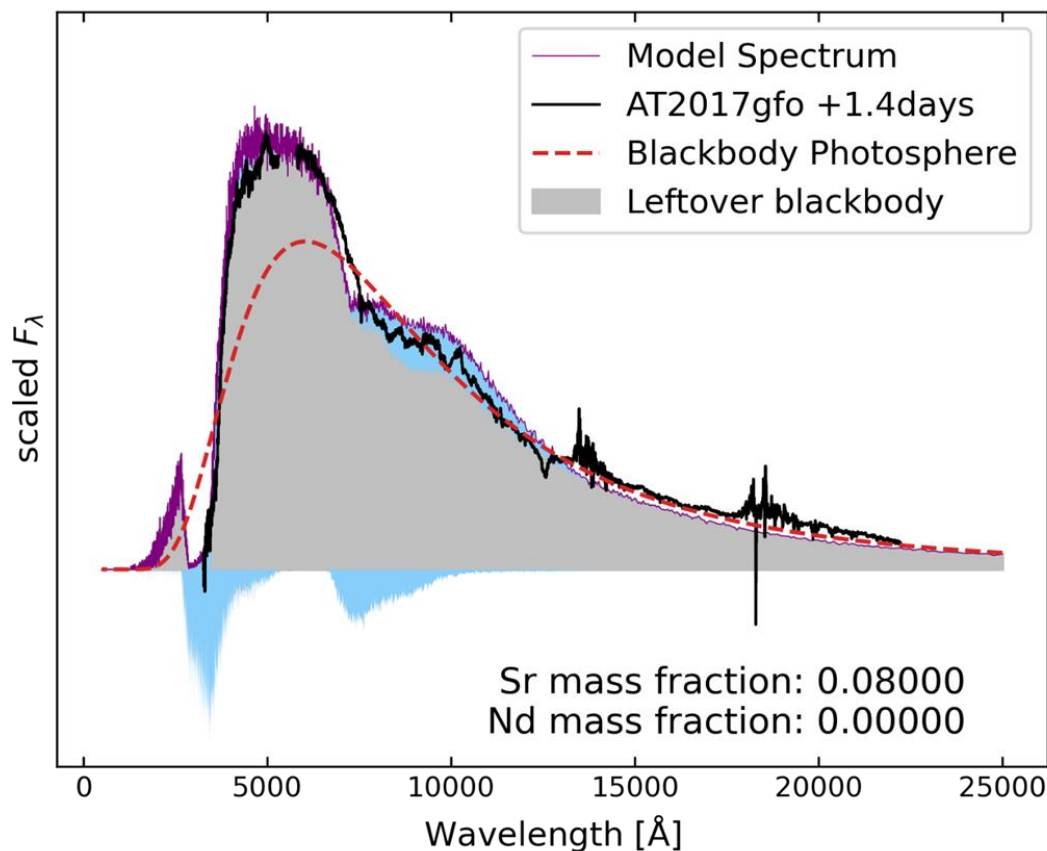
- Benchmark against calculations using HFR code (U Mons). Confirms larger opacity of U III vs Nd III



Extension to U II in progress



# Modelling a Nd kilonova



Exponential density profile

$$\rho(v, t_{\text{exp}}) = \rho_0 \left( \frac{t_0}{t_{\text{exp}}} \right)^3 \left( \frac{v}{v_0} \right)^{-\Gamma}$$

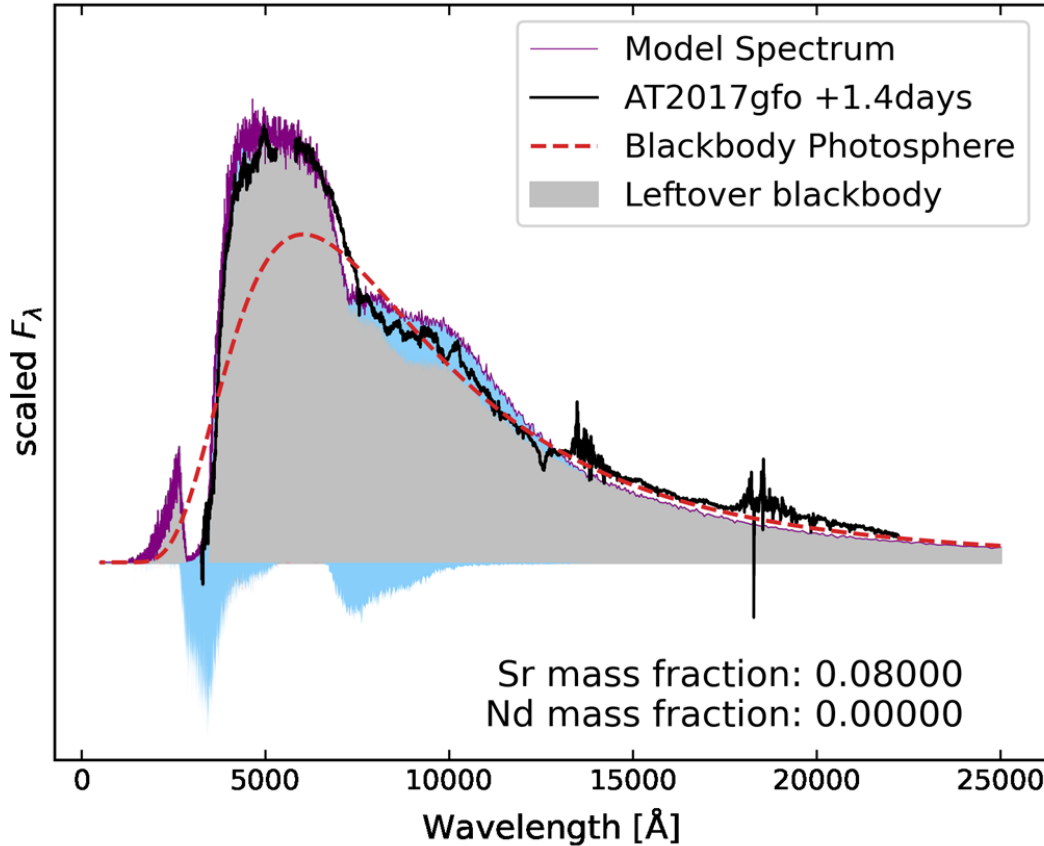
with power-law index  $\Gamma = 3$

Nd III  
 Nd II  
 Increase the Nd mass fraction from  $10^{-5}$  to  $10^{-1}$

Sr II  
 Low abundance: only line blanketing

High abundance: line blanketing in addition to spectral features in the NIR

# Modelling a Nd kilonova



Exponential density profile

$$\rho(v, t_{\text{exp}}) = \rho_0 \left( \frac{t_0}{t_{\text{exp}}} \right)^3 \left( \frac{v}{v_0} \right)^{-\Gamma}$$

with power-law index  $\Gamma = 3$

Nd II Increase the Nd mass fraction from  $10^{-5}$  to  $10^{-1}$

Sr II Low abundance: only line blanketing

High abundance: line blanketing in addition to spectral features in the NIR

- Non-thermal particle deposition (Shingles+ 2020 and 2022, SN Ia):
  - continuous input of high-energy decay particles that do not thermalize efficiently, their energy distribution stays non-Maxwellian
  - non-thermal electron distribution by numerically solving the Spencer & Fano (1954) equation using the method of Kozma & Fransson (1992)
  - integrating over the energy distribution, we obtain rates for non-thermal ionization, excitation, and heating
- ARTIS developments for Kilonova
  - Kilonova: non-thermal effects expected as early as 3 days (Pognan+ 2022)
  - Non-thermal solver: non-LTE level populations, binned radiation field and detailed photoionisation rate estimators (Shingles+ 2020)
  - Decays included in a more generalize way
    - 2502 nuclides with alpha and beta-minus decay data from ENDF/B-VII.1 (Chadwick+ 2011 via Hotokezaka's data file)
    - Abundance calculation from Bateman equation describing decays (no capture reactions, no fission)
    - Gamma-ray decay spectra from NNDC and full transport
    - Particle emission using average kinetic energy per decay local but non-instantaneous deposition (assumed to be fully trapped)

L. Shingles



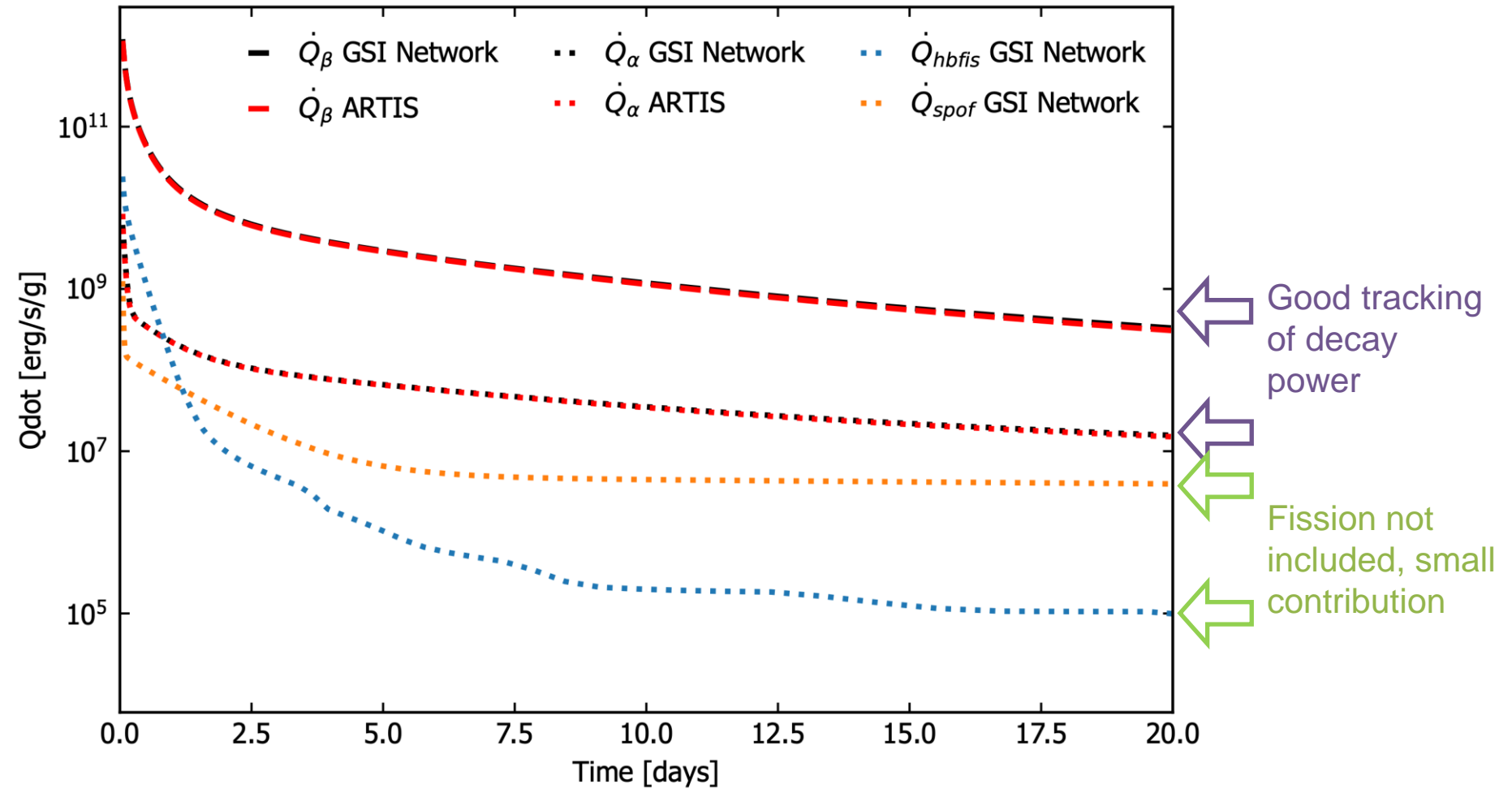
# Light curve and spectra from mergers

- Dynamical ejecta from SPH simulations including neutrinos (ILEAS): simulation by V. Vijayan ( $1.35-1.35 M_{\odot}$ , SFHo EoS,  $0.004 M_{\odot}$  ejecta)
- Abundances determined from detailed network calculations
- 1D average (extension to 3D planned)
- ARTIS follows density (homologous) and abundance evolution (decays) while calculating radiative transfer
- Grey opacities based on Tanaka+ 2020 with  $Y_e$  dependence. Future: line-by-line Sobolev treatment with detailed composition and NLTE level populations

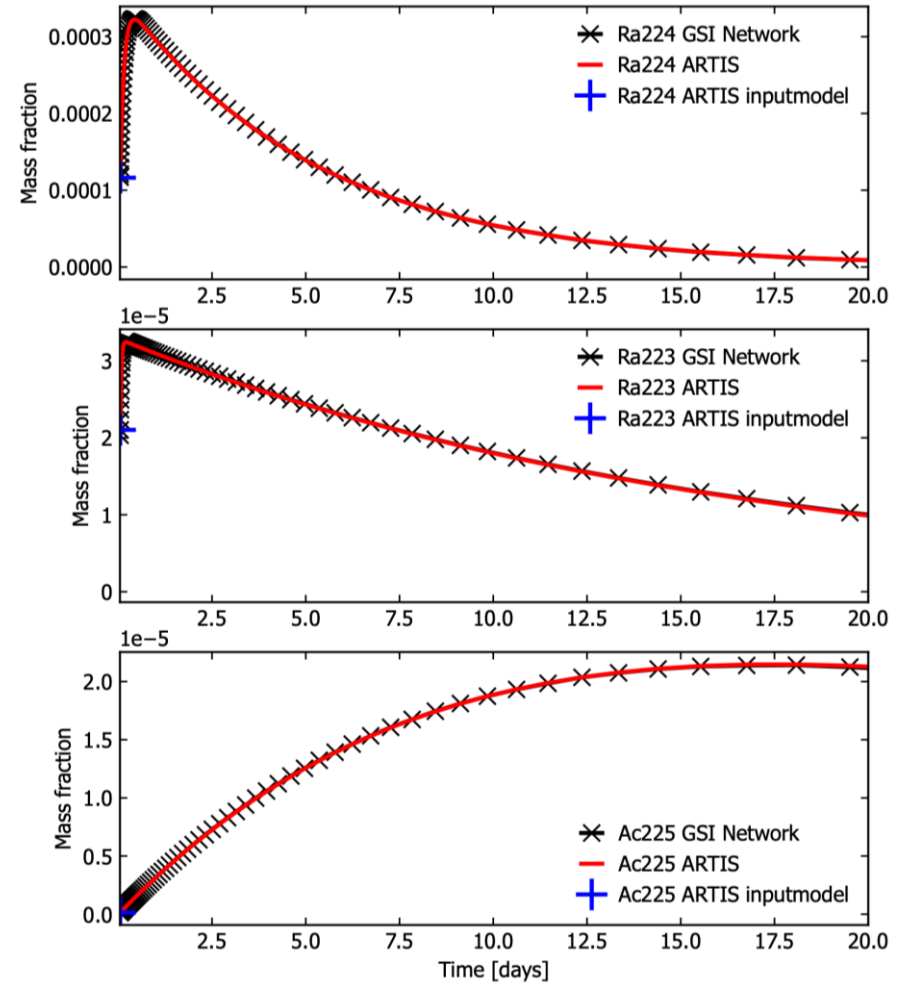
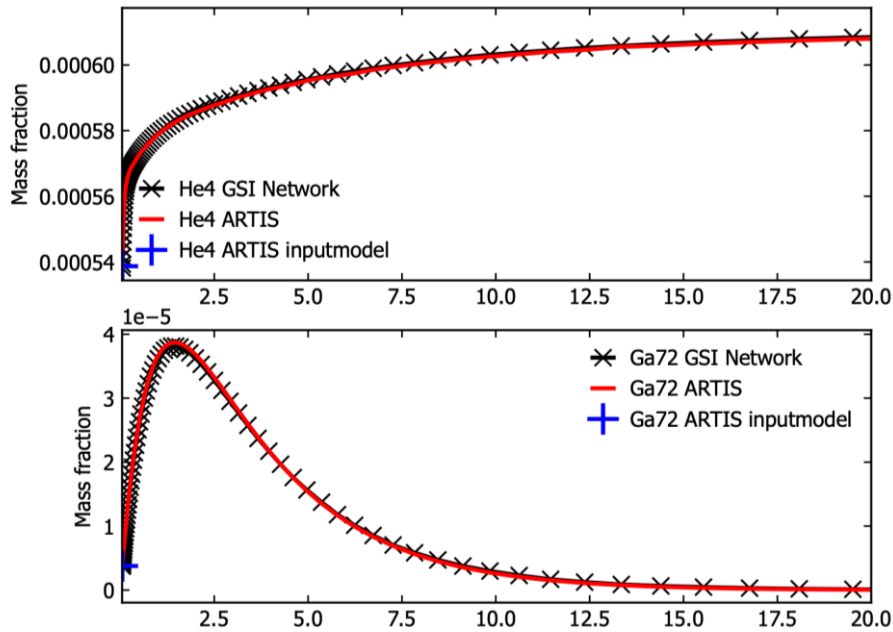
L. Shingles



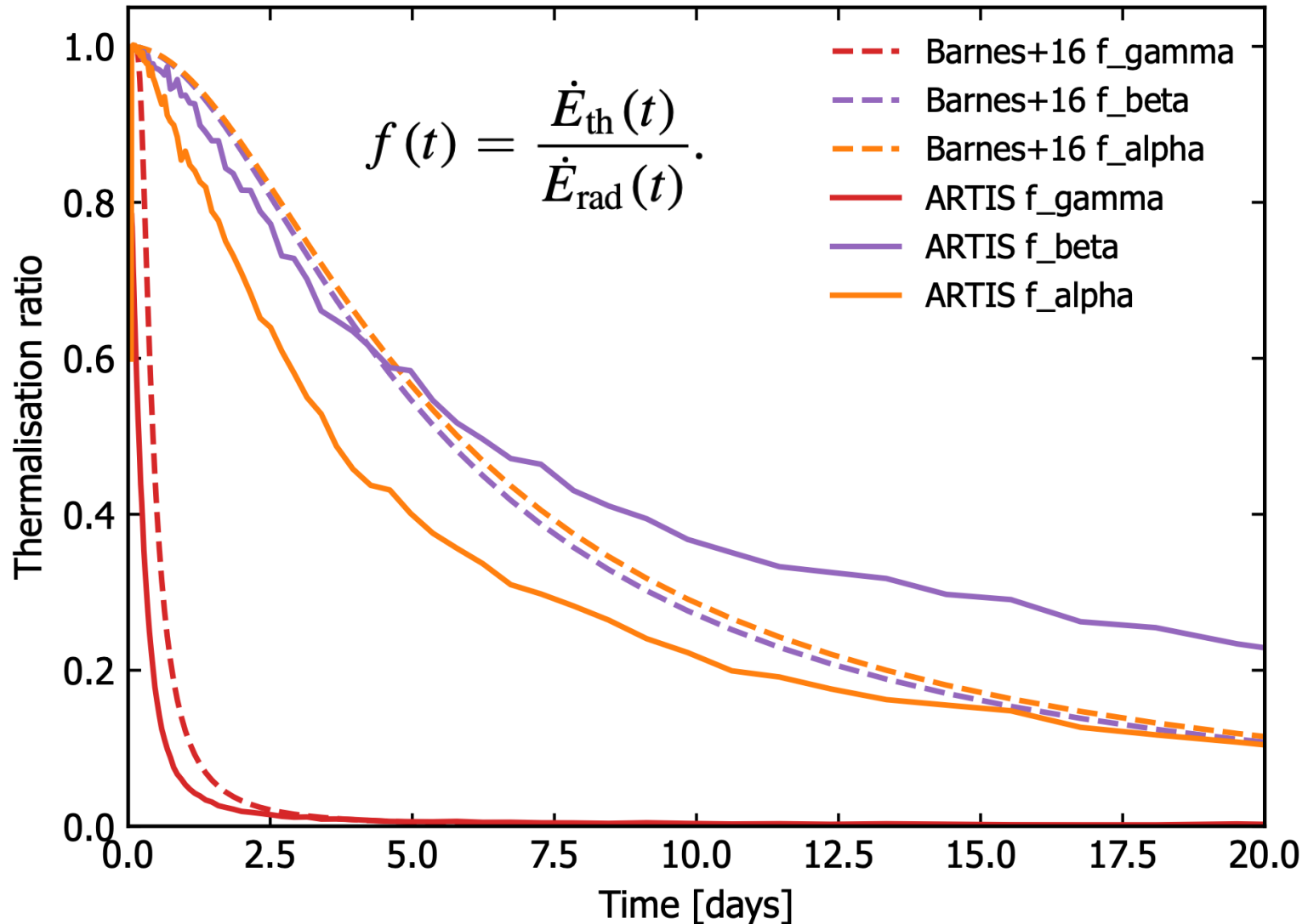
# Radioactive heating: ARTIS vs network



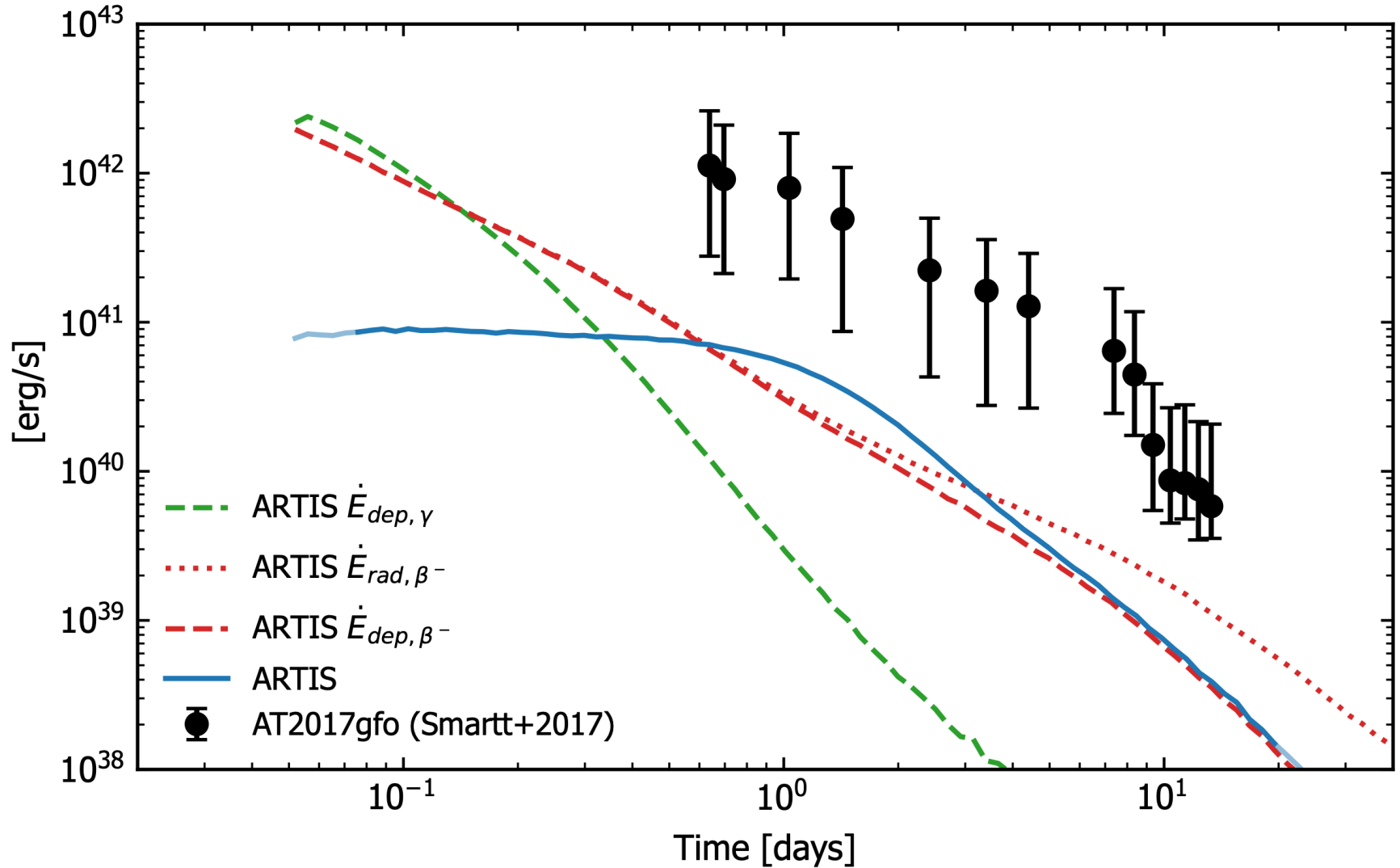
# Abundance evolution vs network



Comparison with Barnes+ 2016 approximation

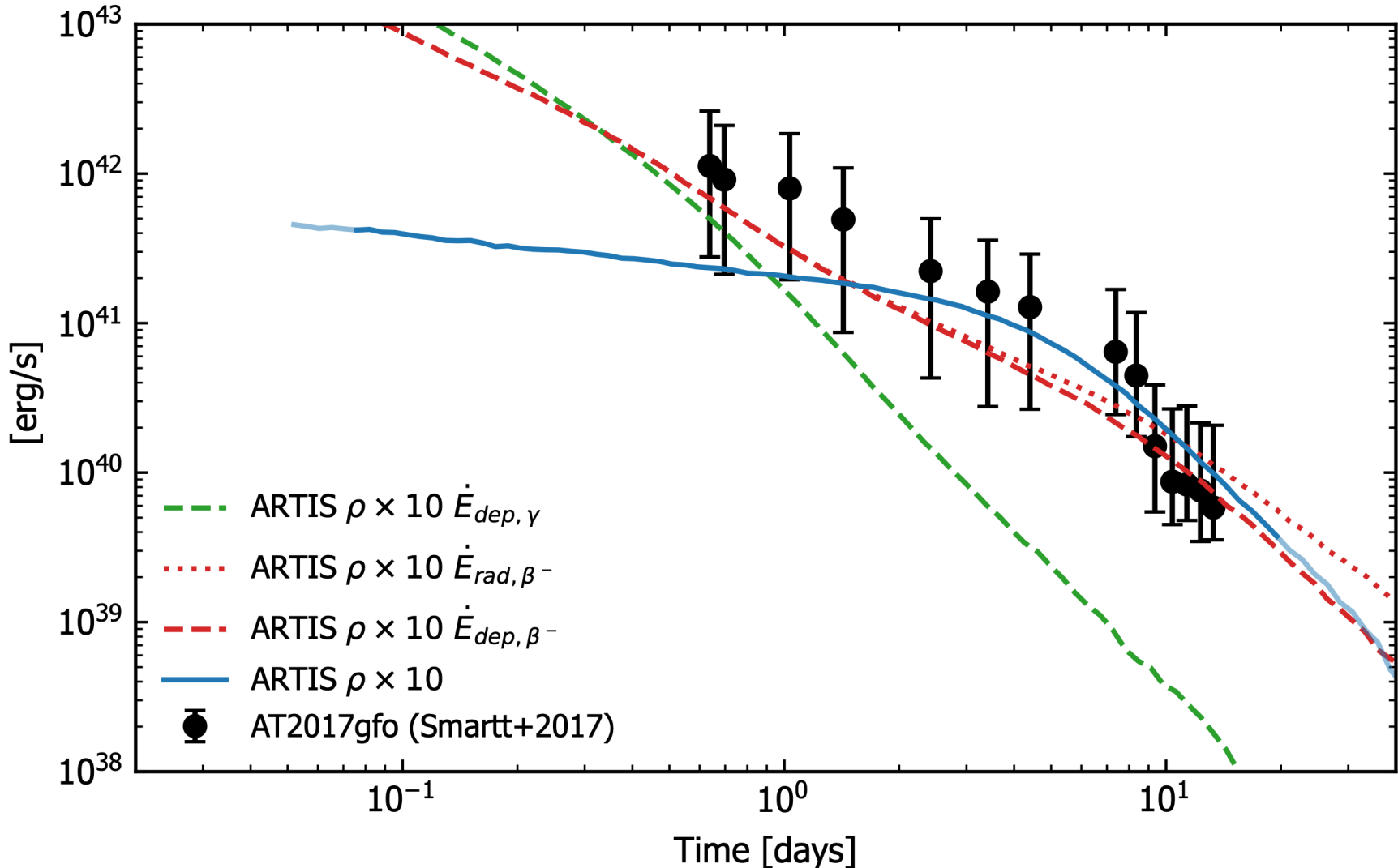


Ejected mass  $0.004 M_{\odot}$  is too low to explain AT2017gfo observations





Ejected mass increased by a factor 10 to  $0.04 M_{\odot}$



Late time break related to ejecta becoming transparent, nebular phase:  
 Hotokezaka & Nakar, ApJ **891**, 152 (2020)

- Systematic calculations of bound-bound opacities in progress
  - Calibrated to data when available
  - Benchmarks of different atomic structure codes
- Implementation in radiative transfer codes TARDIS and ARTIS in progress
- Future: extension to Non-LTE (Nebular) phases.