r-process nucleosynthesis and kilonovae from compact binary mergers

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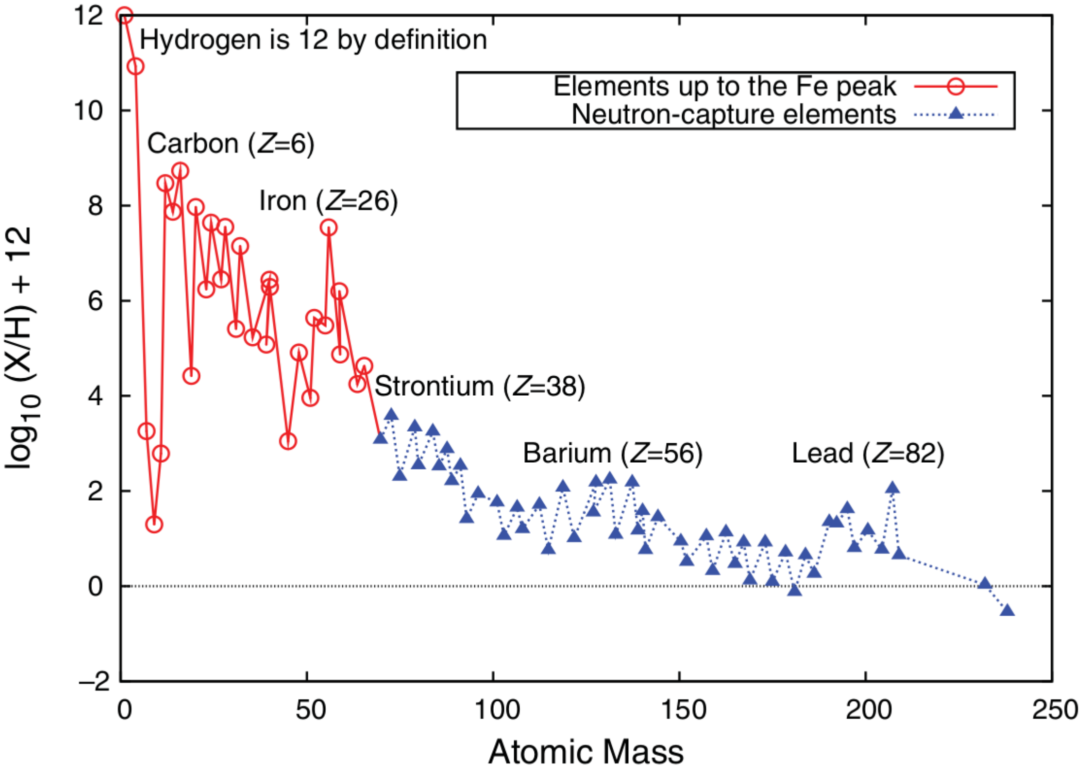
Plasmas for
Astrophysics
Nuclear
Decay
Observation and
Radiation for
Archaeometry

2nd PANDORA Progress Meeting
INFN-LNS Catania - Italy, 16-17 December 2021

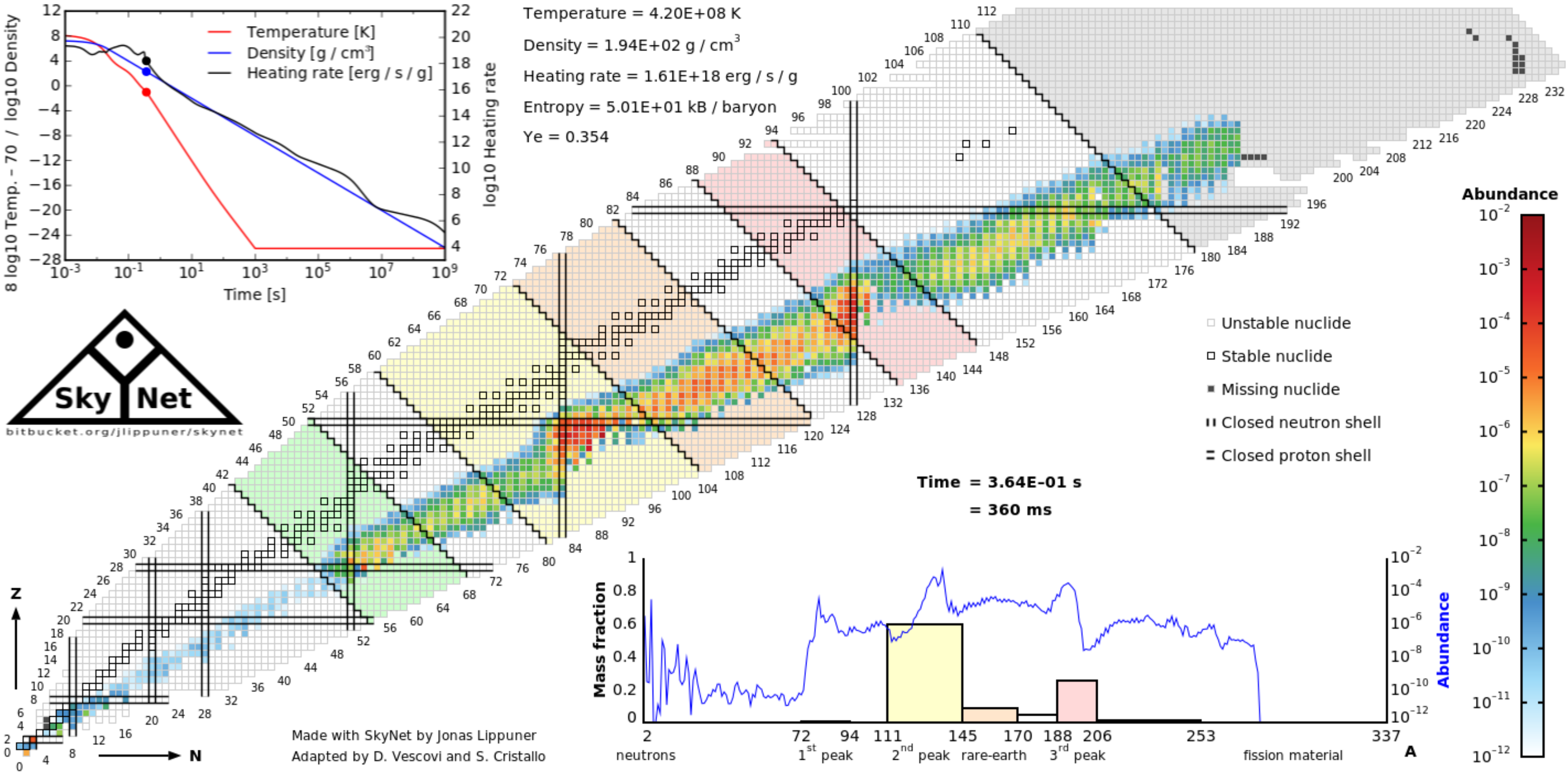
The origin of heavy elements in the Solar System

- Fusion reactions between charged particles
- Neutron capture processes :
  - **r(apid)-process**
  - **s(low)-process**



r-process: basic ideas

- key reactions: $(A, Z) + n \leftrightarrow (A + 1, Z) + \gamma$
- *r*-process requires initial high n_n and T
  - → high n_n : $\tau_{(n,\gamma)} << \tau_{\beta\text{-decay}}$
- equilibrium freeze-out: n_n drops and β-decays take over



Made with SkyNet by Jonas Lippuner
Adapted by D. Vescovi and S. Cristallo

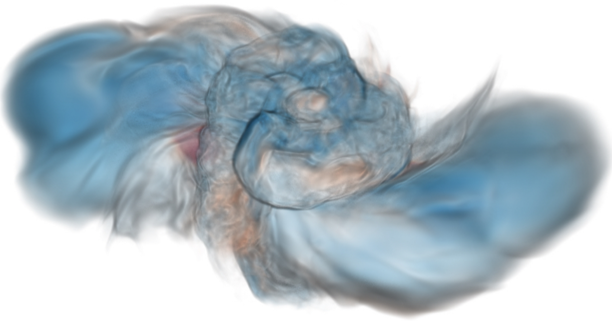
Where can the *r*-process occur?

1) Neutrino-driven winds from core-collapse supernovae (CCSN)

2) Neutron-rich polar jets of magneto-rotational supernovae (MHD-SNe) or accretion disk outflows of collapsars

3) Ejecta from binary neutron star mergers (BNS) or neutron star-black hole (NS-BH) systems

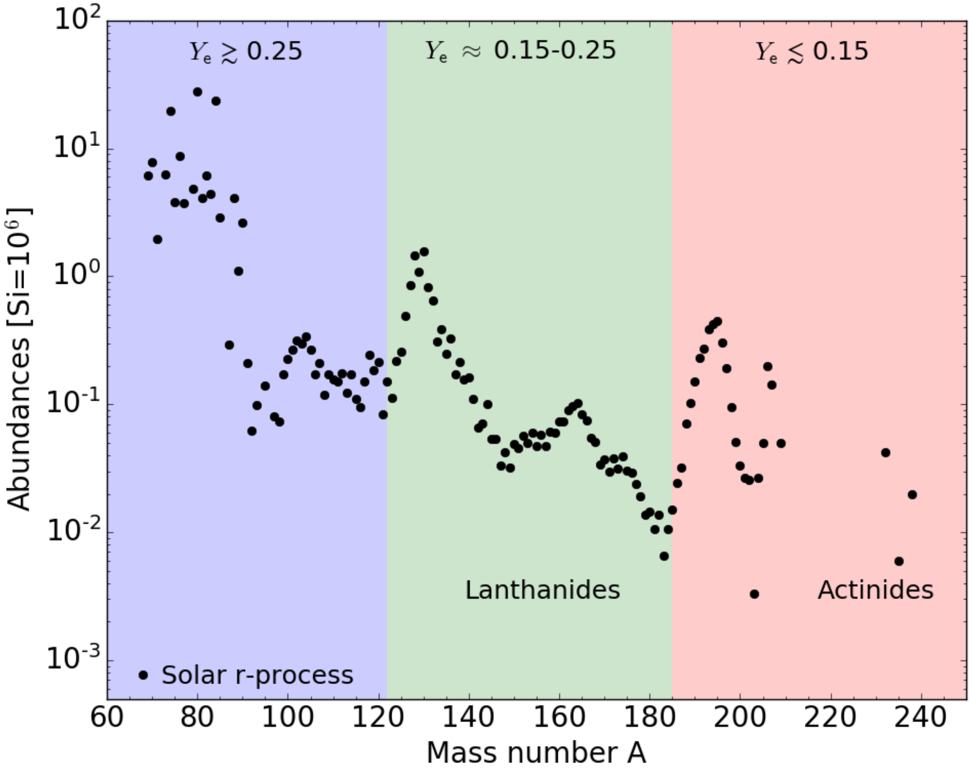
First evidence of *r*-process nucleosynthesis in kilonova from GW170817



r-process nucleosynthesis in BNS mergers

- Electron fraction $Y_e \sim n_p/(n_n+n_p)$ → **dominant parameter**

→ Threshold value $\boldsymbol{Y_{e,crit}} \approx$ **0.25**



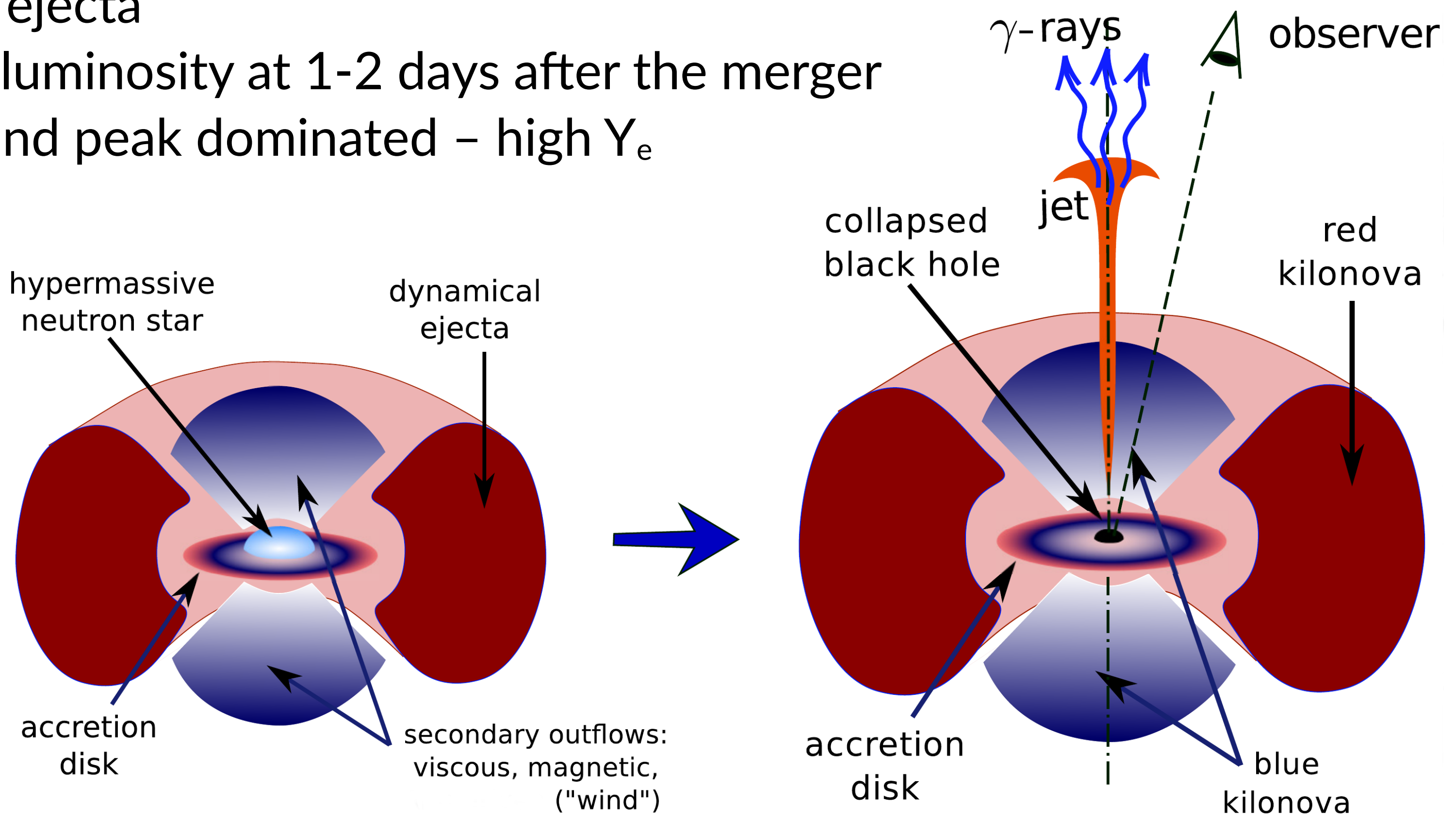
Production of lanthanides dramatically changes photon opacity κ_γ

- no lanthanides:
  low opacity ($\kappa_\gamma \lesssim 1$ cm²/g)
- presence of lanthanides:
  increased opacity ($\kappa_\gamma \gtrsim 10$ cm²/g)

BNS merger + kilonova

- Red emission:
  - Tidal ejecta
  - Peak luminosity at days - 1 week after the merger
  - Lanthanide dominated – low Y_e

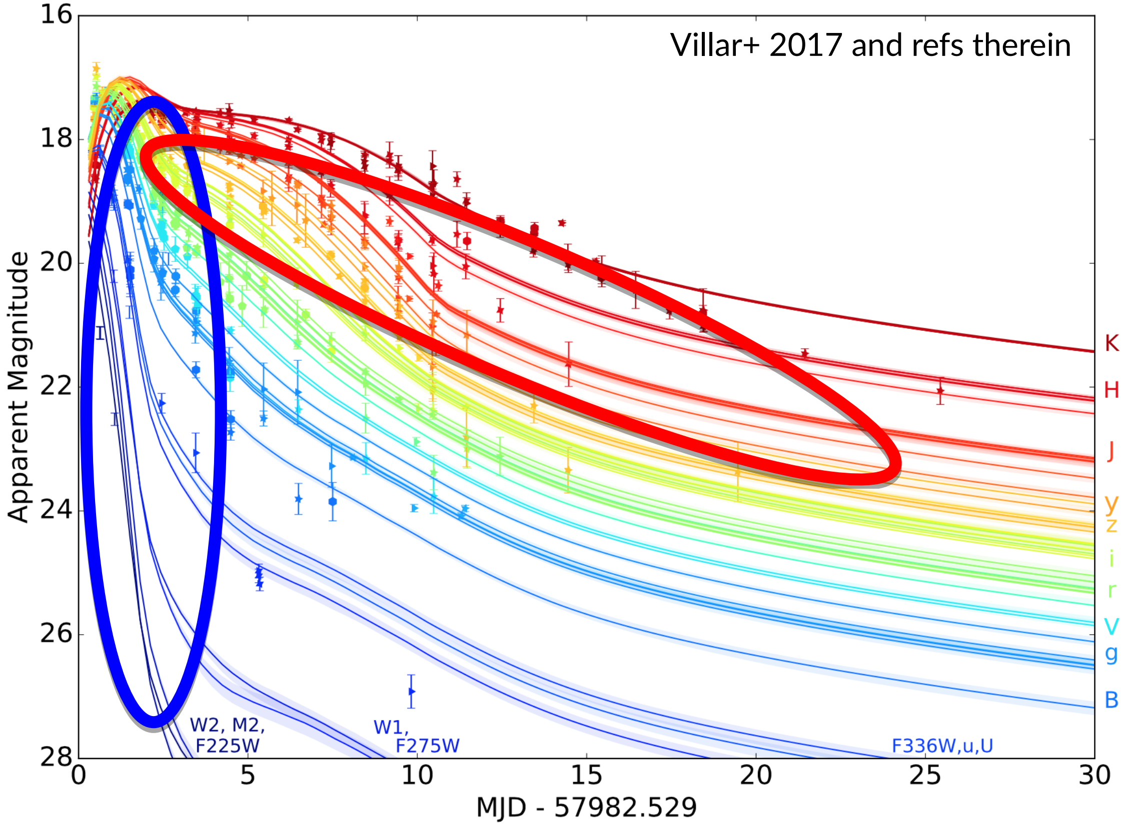
- Blue emission:
  - Polar ejecta
  - Peak luminosity at 1-2 days after the merger
  - 1st/2nd peak dominated – high Y_e



Courtesy of O. Korobkin

Properties of GW170817/AT2017gfo

- 17/08/17, GW+EM detection of an event compatible with BNS merger (LVC PRL 2017)
- Blue component
- Red component
- Thermal emission by radioactive decay of heavy elements synthesized in multi-component (2-3) ejecta



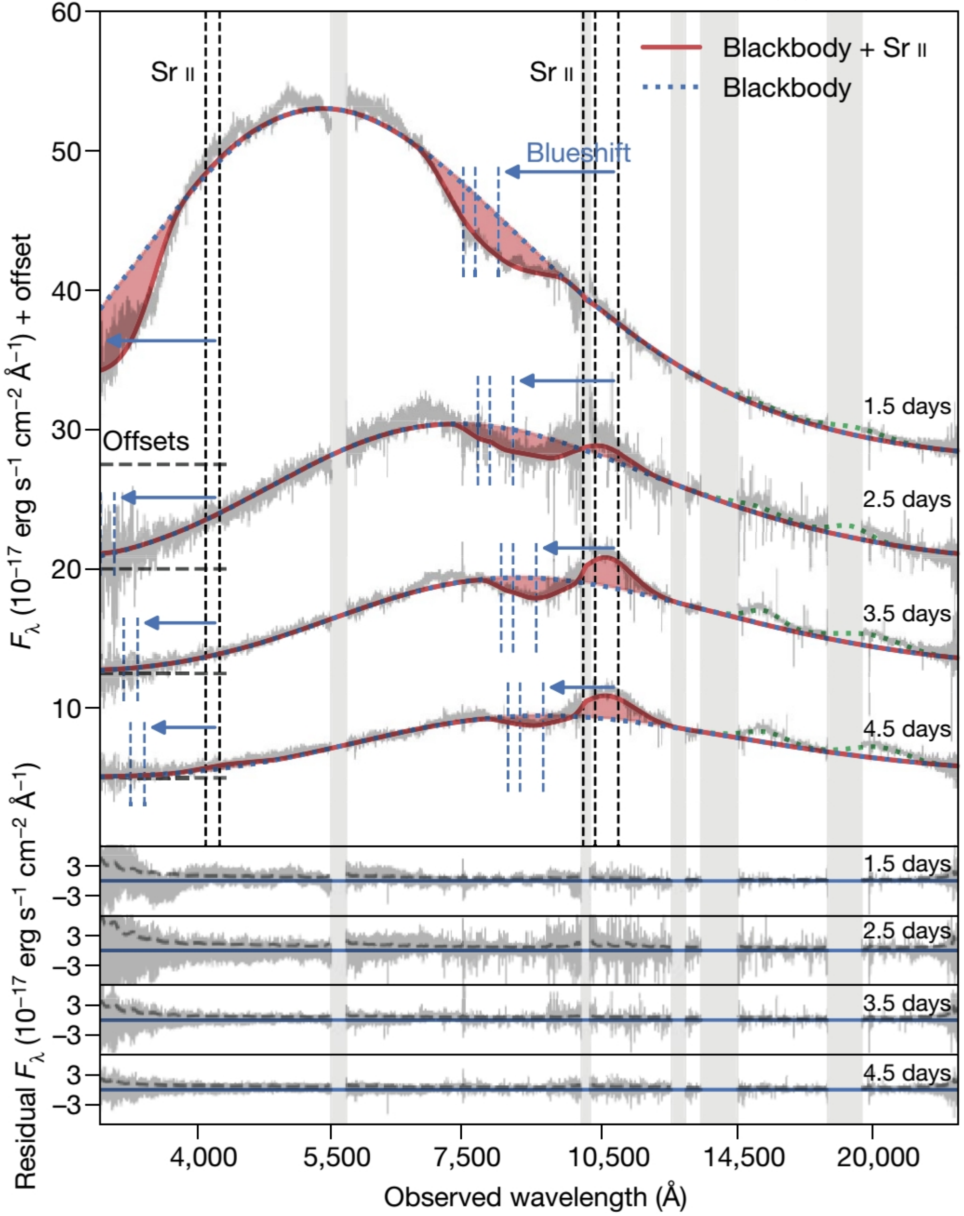
Properties of GW170817/AT2017gfo

Spectral analysis hampered due to:

- Heavy elements have **forest of lines** hence strong blending
- **Relativistic velocity** makes for extremely broad lines (multi-components and different velocities)
- Atomic data are incomplete and uncertain

→ The analysis of the spectrum at 1.5 days suggested the presence of **strontium** (Watson +19)

Watson+ 19



Composition effects on kilonova spectra and lightcurves

- Light curve profile depends on the properties of the ejecta (e.g., mass, velocity, composition → opacity)

→ $$t_{\rm peak} \equiv \left(\frac{3M\kappa}{4\pi\beta v c}\right)^{1/2} \approx 1.6\,{\rm d}\,\left(\frac{M}{10^{-2}\,M_\odot}\right)^{1/2}\left(\frac{v}{0.1\,{\rm c}}\right)^{-1/2}\left(\frac{\kappa}{1\,{\rm cm}^2\,{\rm g}^{-1}}\right)^{1/2}$$

→ $$L_{\rm peak} \approx M\dot{e}_r(t_{\rm peak}) \approx 10^{41}{\rm erg\,s}^{-1}\left(\frac{\epsilon_{th,v}}{0.5}\right)\left(\frac{M}{10^{-2}\,M_\odot}\right)^{0.35}\left(\frac{v}{0.1\,{\rm c}}\right)^{0.65}\left(\frac{\kappa}{1\,{\rm cm}^2\,{\rm g}^{-1}}\right)^{-0.65}$$

- The kilonova emission is reprocessed by atomic opacities (mainly bound-bound transitons) to optical and infrared wavelengths

→ $T_{\rm peak}$ ~ 5000 - 10000 K

→ The emission in these wavelengths can **probe the composition of the ejecta**

Opacities for kilonova lightcurve calculations

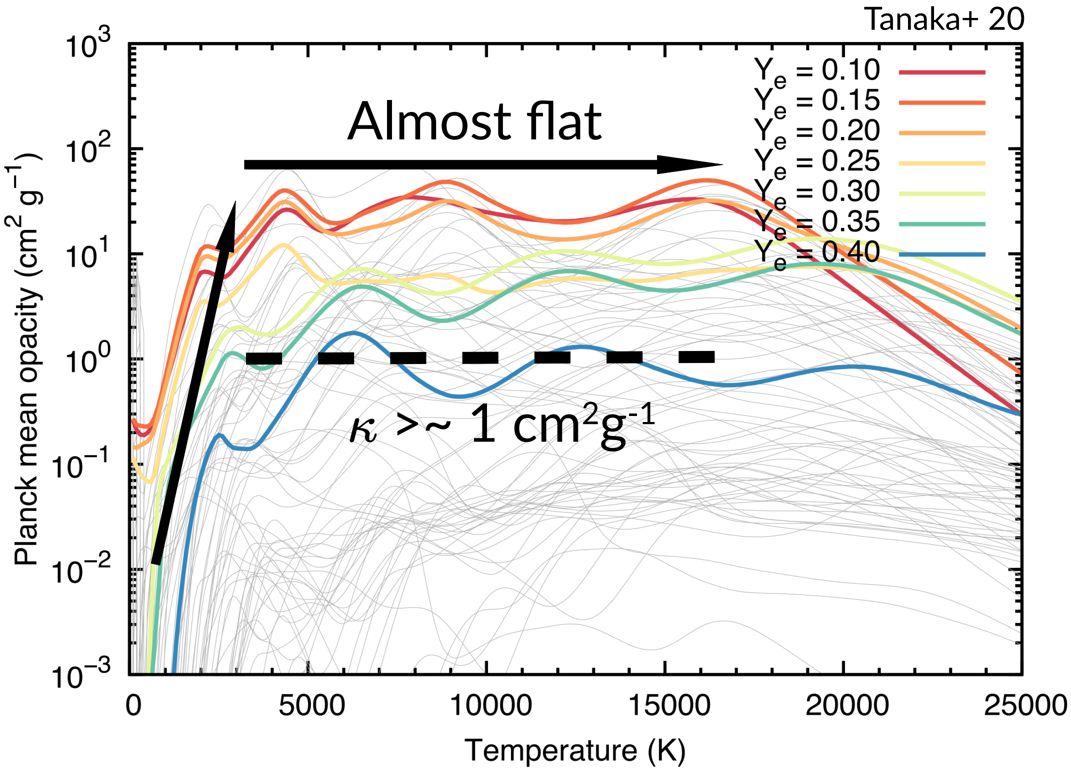
- Usually, <u>constant 'grey' opacities</u> are assumed (e.g. Perego+ 17; Villar+ 17)

➔ Need to consider **detailed atomic opacities of r-process elements**

- <u>Systematic opacity calculations</u> covering all relevant r-process elements are now available (e.g., Fontes+ 20, Tanaka+ 20)

➔ Understand general features

... but not accurate in transition wavelengths → not suitable for **element identification**



Tanaka+ 20

Almost flat

κ >~ 1 cm^{2}g^{-1}

Elements’ signatures in kilonova spectra I

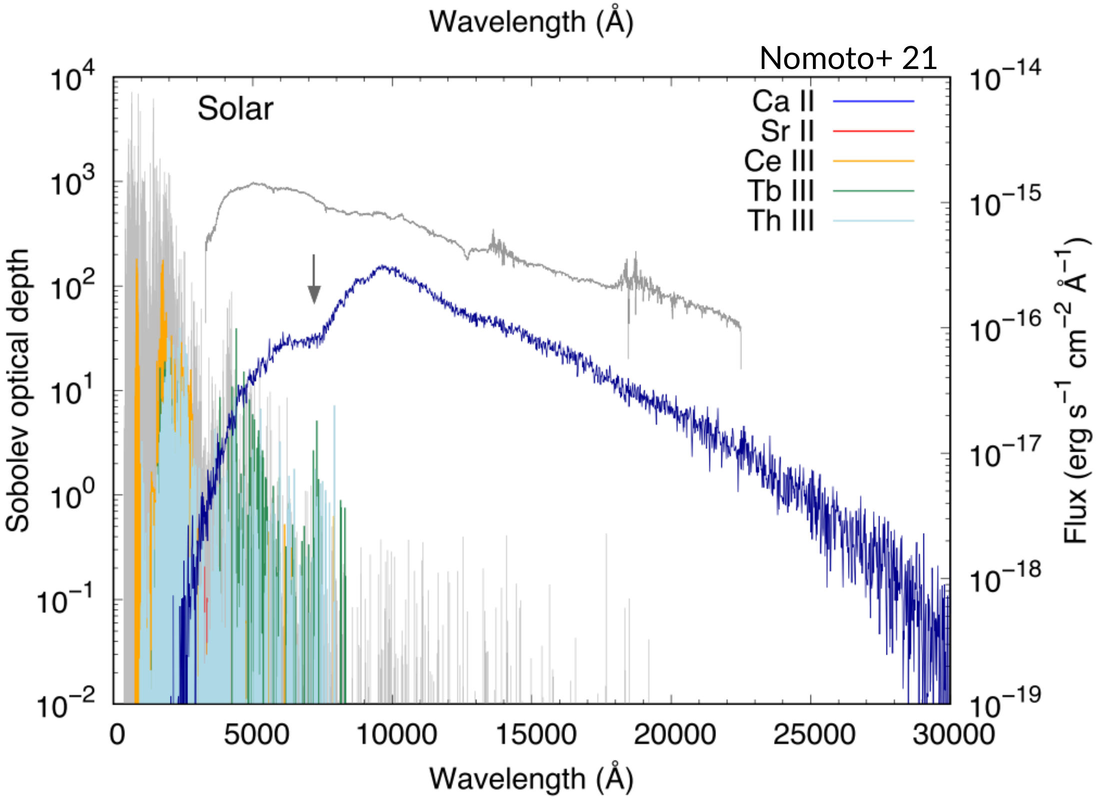
- To identify particular spectral features, we need accurate transiton data (e.g., VALD database)

- Not complete in the NIR region

- Synthetic spectra at 1.5 days from parameterized outflows (Nomoto+ 21)

→ For a lanthanide-rich model, features of doubly ionized heavier elements, such as **Ce**, **Tb**, and **Th**.

→ Possibility to detect them in future NS merger events



Elements' signatures in kilonova spectra II

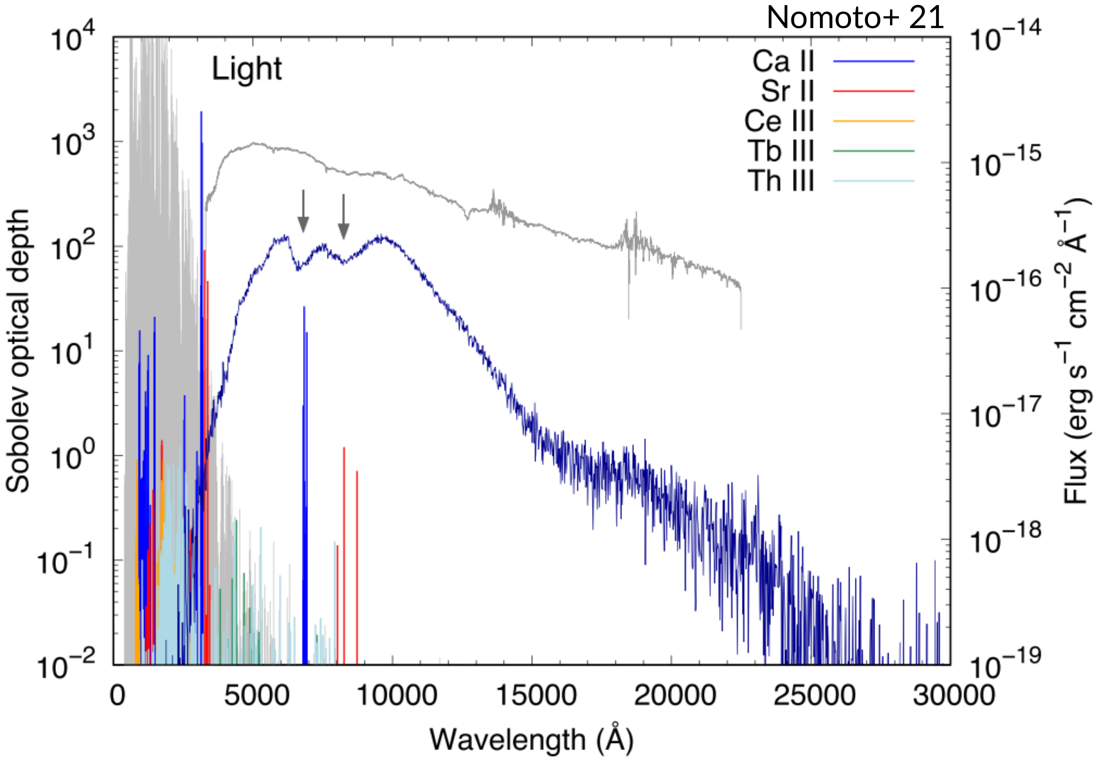
- Presence of Sr confirmed in lanthanide-poor ejecta

➔ **Ca absorption feature** is also identified → <u>tracer of high-Y_e ejecta</u> (>~ 0.40)

- AT2017gfo spectra do not exhibit such features

  ➔ Ca abundance too low

- Systematic calculations and radiative transfer simulations including the NIR lines are **inconclusive**



Elements' signatures in kilonova spectra III

- **H and He are abundant**

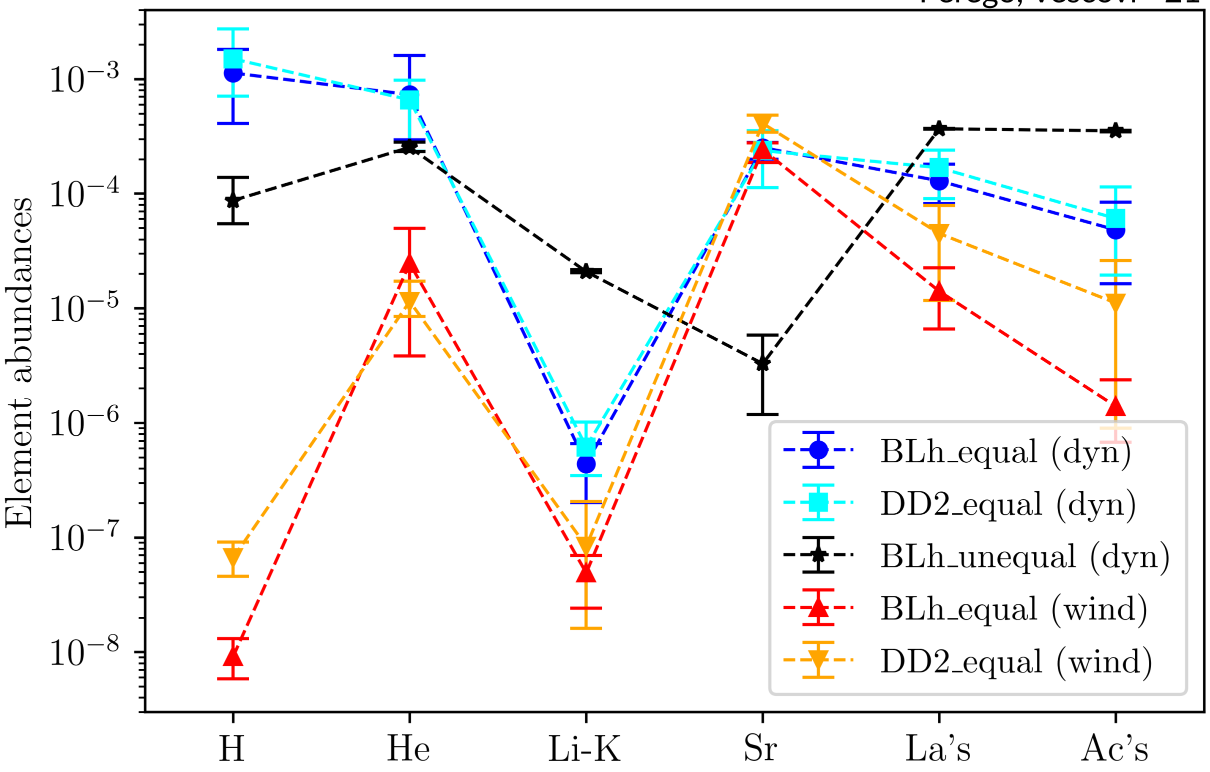
- The amount of Sr predicted by ab-initio BNS models is **consistent** with the one required by the analysis reported in Watson+ 19

- However, they probably **never contribute** to the kilonova spectrum

- Presence of H/He lines

  → Supernovae

Perego, Vescovi+ 21



Summary

- BNS mergers are major production sites of *r*-process elements

- Thermal emission from radioactively-heated multi-component ejecta from BNS mergers accounts for the kilonova AT2017gfo

- No clear chemical signatures for heavy r-process elements

- Evidence for light r-process elements → Sr

- Future element detection?
  - ➔ **Yes**: Ca, Sr, Ce, Tb, Th (+ Nd and U, see Even+ 20)
  - ➔ **No**: H, He

- Atomic data in the NIR wavelengths are **crucial** to fully decode kilonova spectra