Thorium in Kilonova Spectra: Exploring the Heaviest Detectable Element

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0. Summary

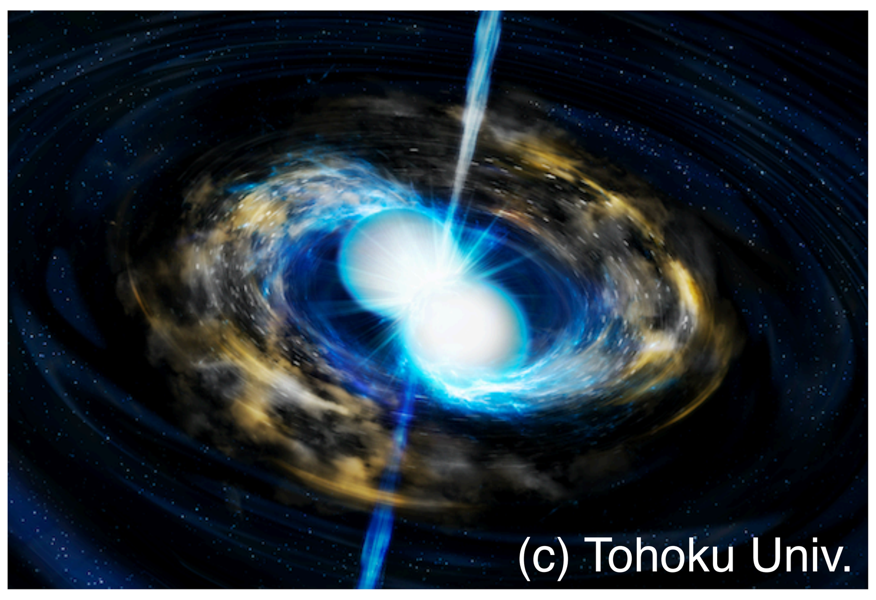
- Kilonvae: imprints of synthesized heavy elements in binary neutron star mergers
- Identification of elements in spectra is the direct way to study synthesized elements
- It has been found that elements on the left side of the periodic table (Ca, Sr, La, Ce) tend to produce prominent absorption features: a small number of valence electron -> higher transition probability (sum rule), higher level population in low-lying energy levels
- Are further heavier elements detectable? -> Th (Z=90) is the most promising element
- Th III absorption feature at ~ 18000 A can be found in the future event, but observations with no or little telluric absorption are needed

1. Neutron star mergers and Kilonovae

Origin of r-process elements

- Heavy elements are synthesized by r-process nucleosynthesis in neutron-rich ejected matter
- Thermal emission is powered by radioactivity ("kilonovae")

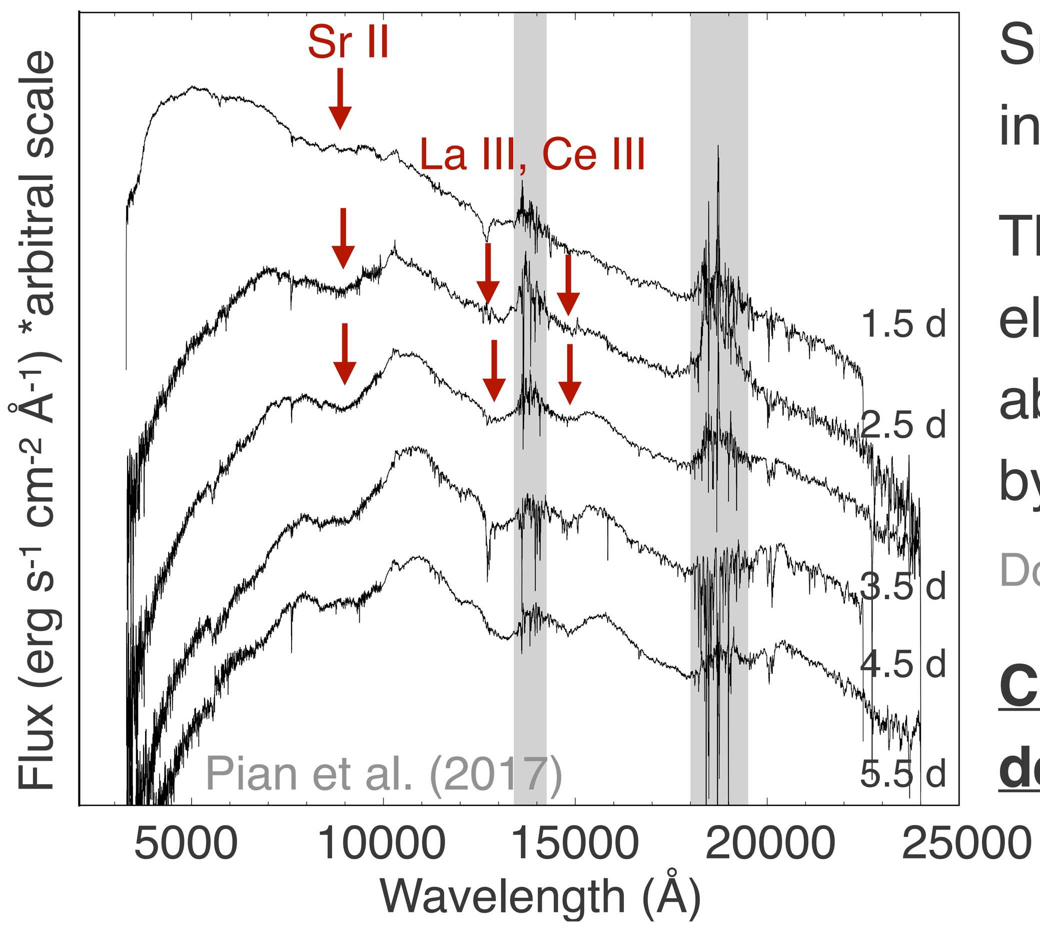
*One of the targets for multi-messenger astronomy (GW+EM)



—> The observational features of kilonovae are important to understand the production of heavy elements

2. Optical-infrared spectra of kilonovae

Spectral features = imprints of individual elements



Sr, La, and Ce were Identified in the observed spectra

The reason why these elements tend to produce absorption can be understood by atomic properties

Domoto et al. (2021, 2022)

Can heavier element be detected in spectra?

3. Methods & Results

Domoto et al. 2025, ApJ

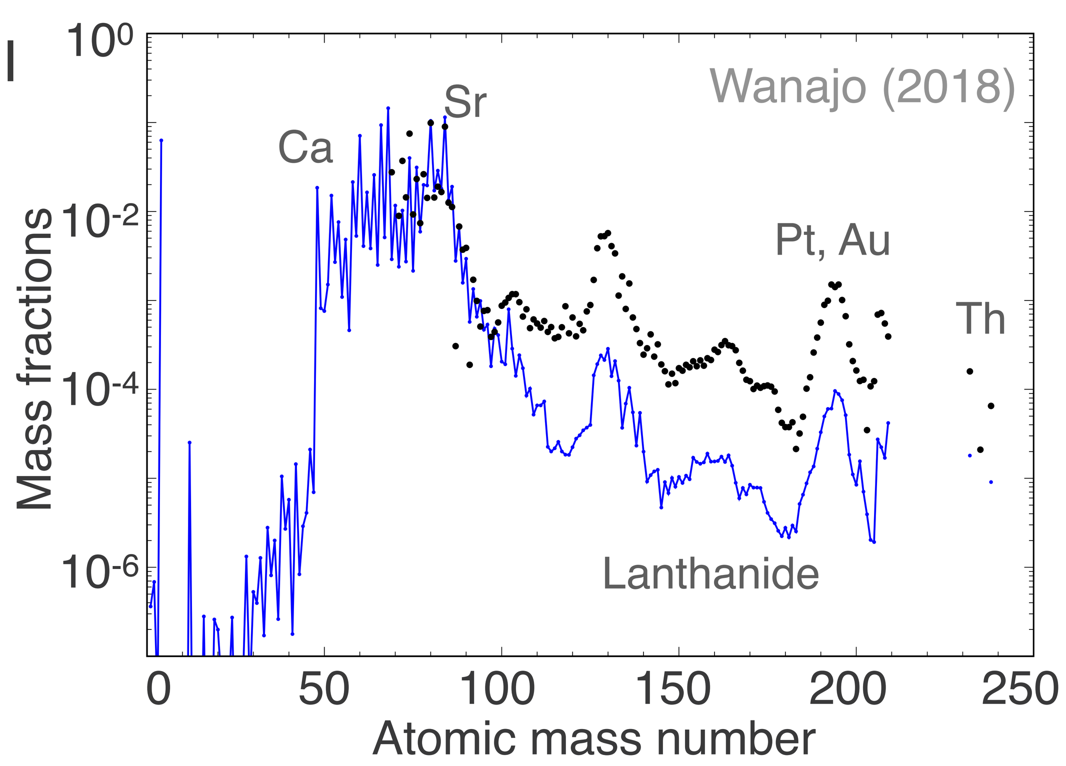
Atomic data NIST ASD

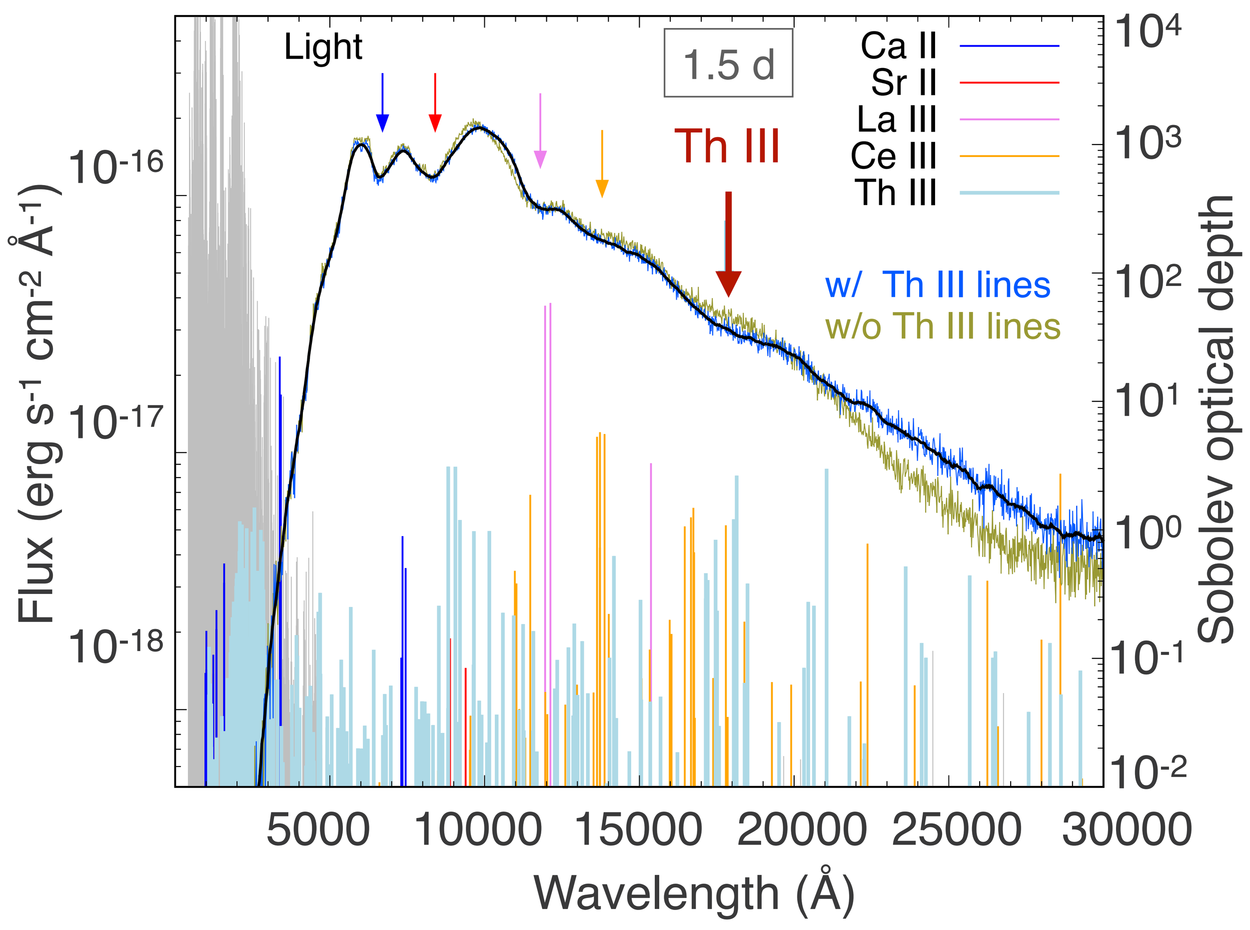
Adding experimental data of Ra II, Ac III, and Th III to the line list constructed in Domoto et al. (2022):
accurate for strong transitions, and
complete for weak transitions

Radiative transfer simulations

Tanaka & Hotokezaka (2013), Tanaka et al. (2014), etc.

- 1D power law density structure ($\rho \propto r^{-3}$)
- Homogeneous abundance distribution using solar-r-like pattern model
- Assuming LTE (ionization/excitation)





Exploration of effects by Ra II, Ac III, and Th III on spectra

Th III lines produce broad absorption features at ~18000 Å

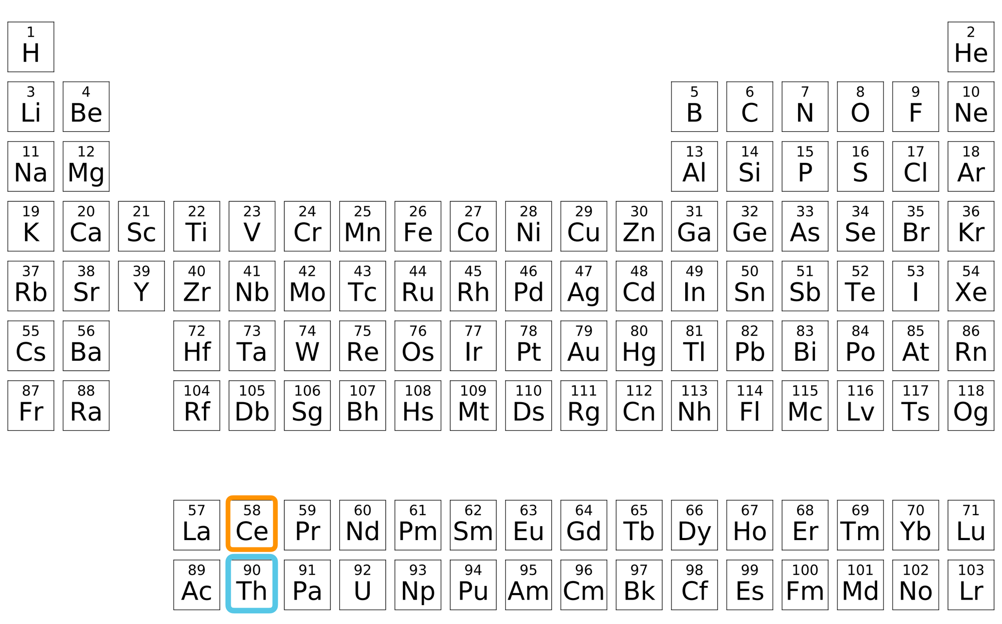
4. Discussions: Properties of Th / Conditions to find Th features

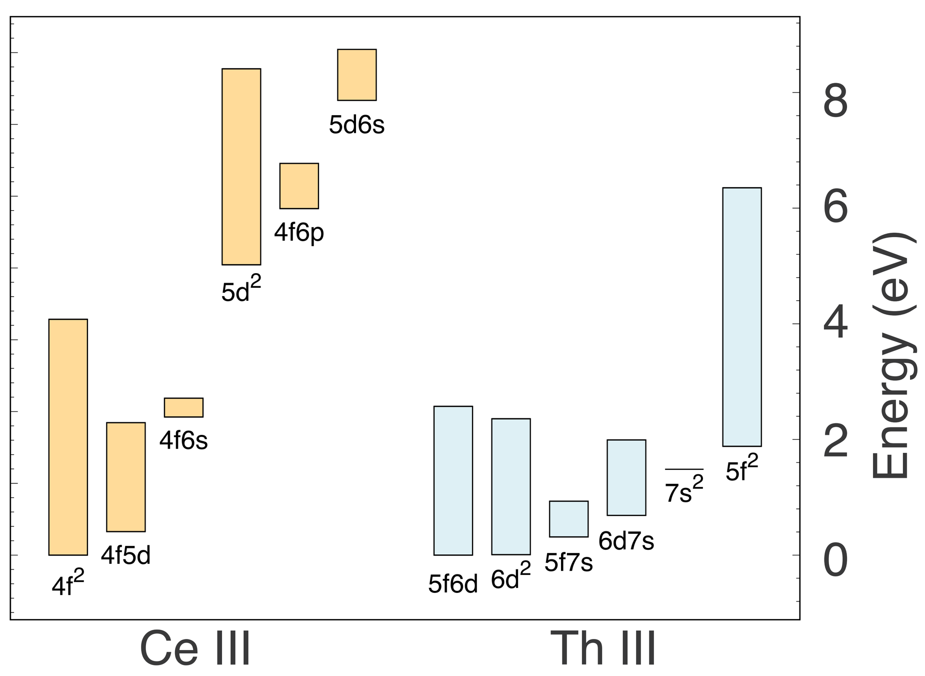
Th III has dense low-lying energy levels

-> higher level population tends to make Sobolev optical depth larger (comparable to, e.g., Ce III lines)

Th III is the most promising element to detect absorption features

Ra II and Ac III are found to be less promising, as they don't have lines involved in low-lying levels





Th III feature appear if X(lanthanide) <~ 6×10^{-4}

Too much heavy elements make photosphere outer where temperature is low and Th III is absent

Observations with no or little telluric absorption are needed to detect the Th features in the future events