Impact of internal-conversion X-rays and nuclear isomers on X-ray and gamma-ray emission from neutron-rich ejecta in a binary compact-star merger

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Summary

Present work

We have examined the impact of internal-conversion X-rays and nuclear isomers on X- and gamma-ray emission from neutron-rich ejecta in a binary compact-star merger on the epoch within approximately one month after the merger.

We have calculated the time evolution of line fluxes of nuclear gamma-ray and internal-conversion X-ray, whose detection is a "smoking gun" of the production of r-process nuclei and which are originating from the decay of neutron-rich nuclei synthesized via the r-process in gas ejected during compact star mergers.

Our key findings

1. The flux enhancement below approximately 100 keV due to internal-conversion X-rays, by order-of-magnitudes, particularly below 60–70 keV ranges.
2. Plenty of internal-conversion X-ray lines via the decay of heavy nuclei (A>190) are emitted with high fluxes from the ejecta with high neutron excess Ye <= 0.2
3. Each peaks in the spectrum originating from a few nuclei, which emits at the fixed line-energies with fixed flux ratios with the synchronously decreasing fluxes on timescale of the half-life.

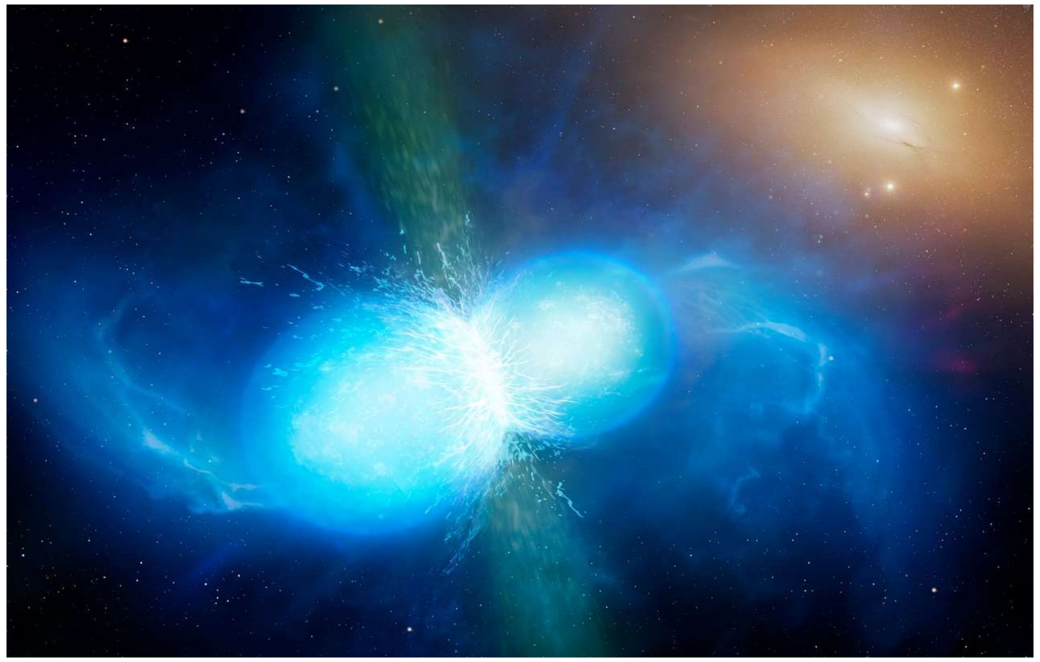
Future works

1. Self-absorption of X-ray and gamma-ray in the ejecta
2. Discussion on the detectability with current and future detectors

Introduction: Binary compact-star merger and Kilonovae

Binary compact-star merger

- The merger of binary of black hole (BH) or neutron star (NS) (BH-BH/BH-NS/NS-NS)
- Gravitational wave source
- Heavy element production via R-process nucleosynthesis in the ejecta from
  - NS-NS binary merger
  - BH-NS binary merger



Credit: University of Warwick/Mark Garlick:
Taken from https://www.eso.org/public/images/eso1733s/

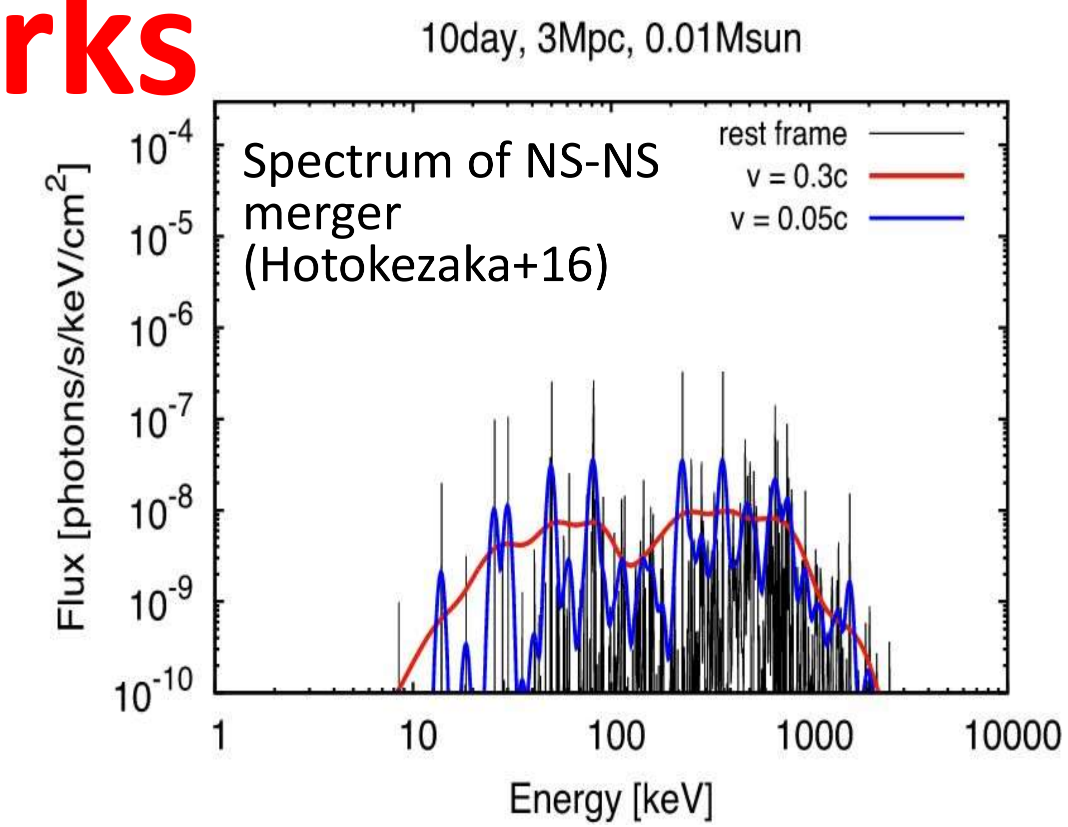
Kilonovae

- Powered by the radioactive-decay heat of neutron-rich nuclei synthesized via R-process
- Detected in visible and infrared bands in the gravitational wave event GW170817
- Detection of Sr and Te (Z=38 and 52) was observationally suggested by identifying infrared spectral lines
- The optical and infrared light curves and spectral evolution strongly suggest the synthesis of lanthanides (Z = 57–71).
- The observational confirmation of third-peak nuclei (Z ～ 80) remains elusive.

Introduction: Previous works

Hotokezaka et al. 2016

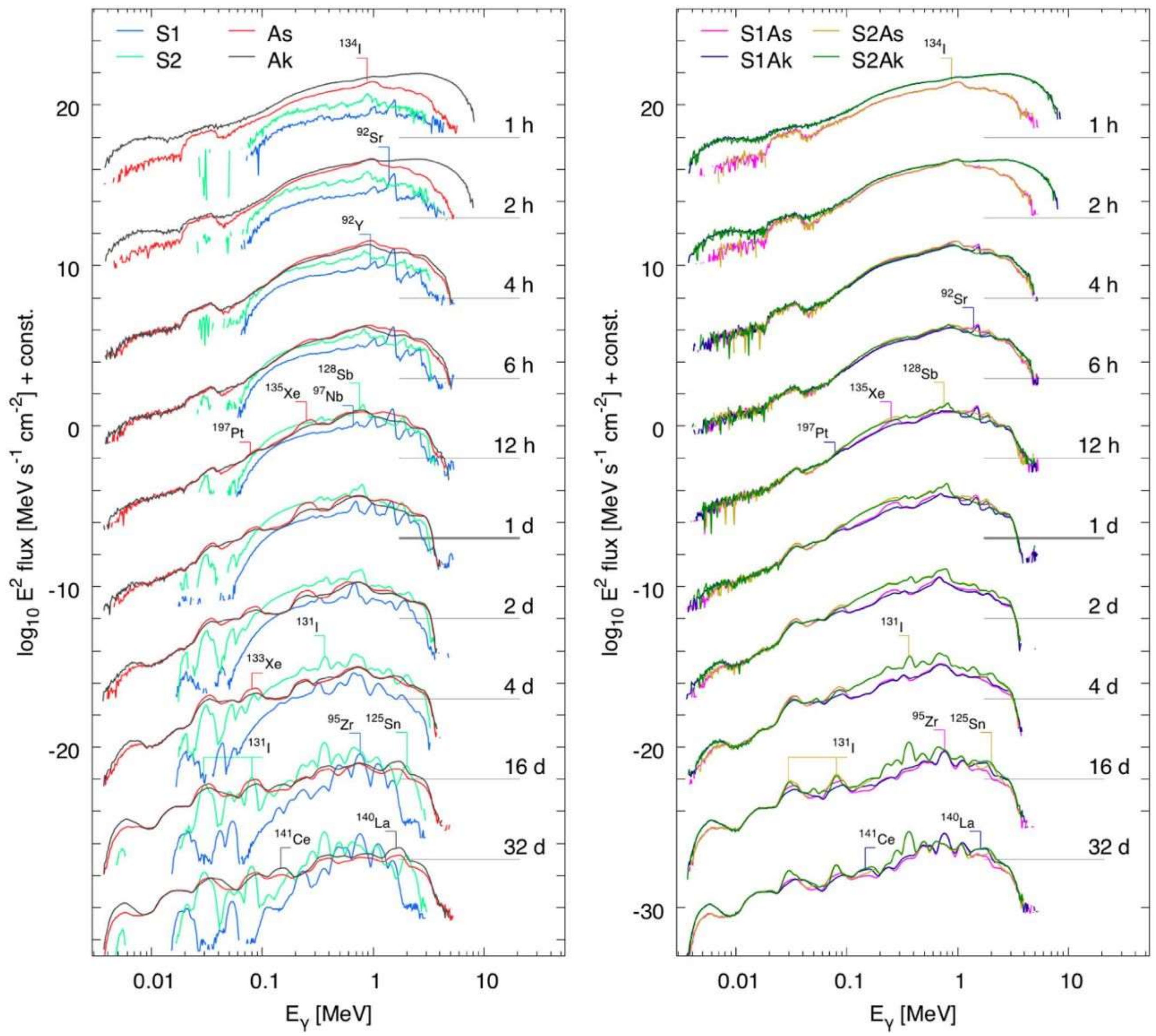
- Flux evolution of X-ray and gamma-ray from NS-NS merger
- Nuclear gamma-ray accompanied with nuclear decays
- Doppler-broadening and self absorption



Korobkin et al. 2020

- Simplified radiation transport but with the Fe opacity, largely underestimated below 100keV
- Identifying prominent nuclear lines

Spectra of compact star mergers (Korobkin+20)



Terada et al. 2022

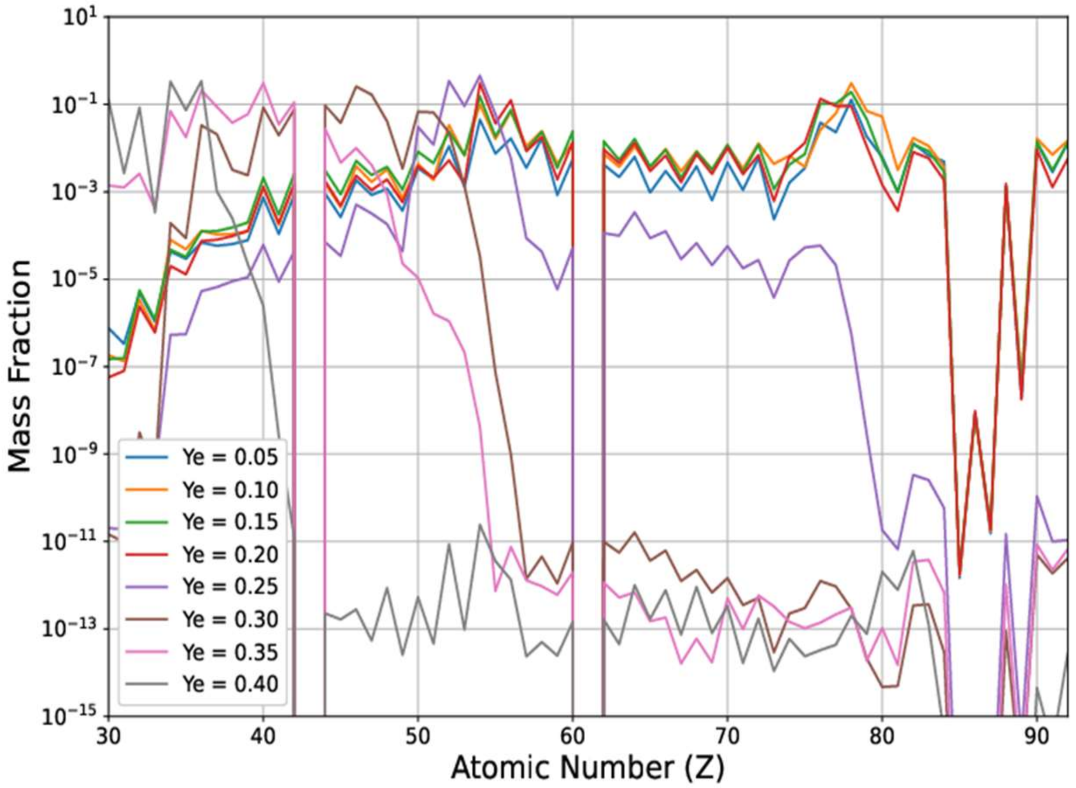
- focusing on the late phase(>3 yrs after the merger)
- including nuclear isomers

Purpose and formalism of our work

Purpose

- Impact on the X- and gamma-ray emission from binary NS-NS/BH-NS merger
  - Internal-conversion X-rays
  - Nuclear isomers
- within a few month after the merger

Mass fraction VS Atomic number (Z) (after decays): Ye = 0.05 - 0.4



Formalism (as in Terada+22)

- Spherical symmetric, constant-velocity (Vej) expansion model for the ejecta from NS-NS/BH-NS merger
- Large nuclear reaction network and decay network including isomers

Time evolution

Temperature, density, abundances, and X- and Gamma-ray flux in the ejecta

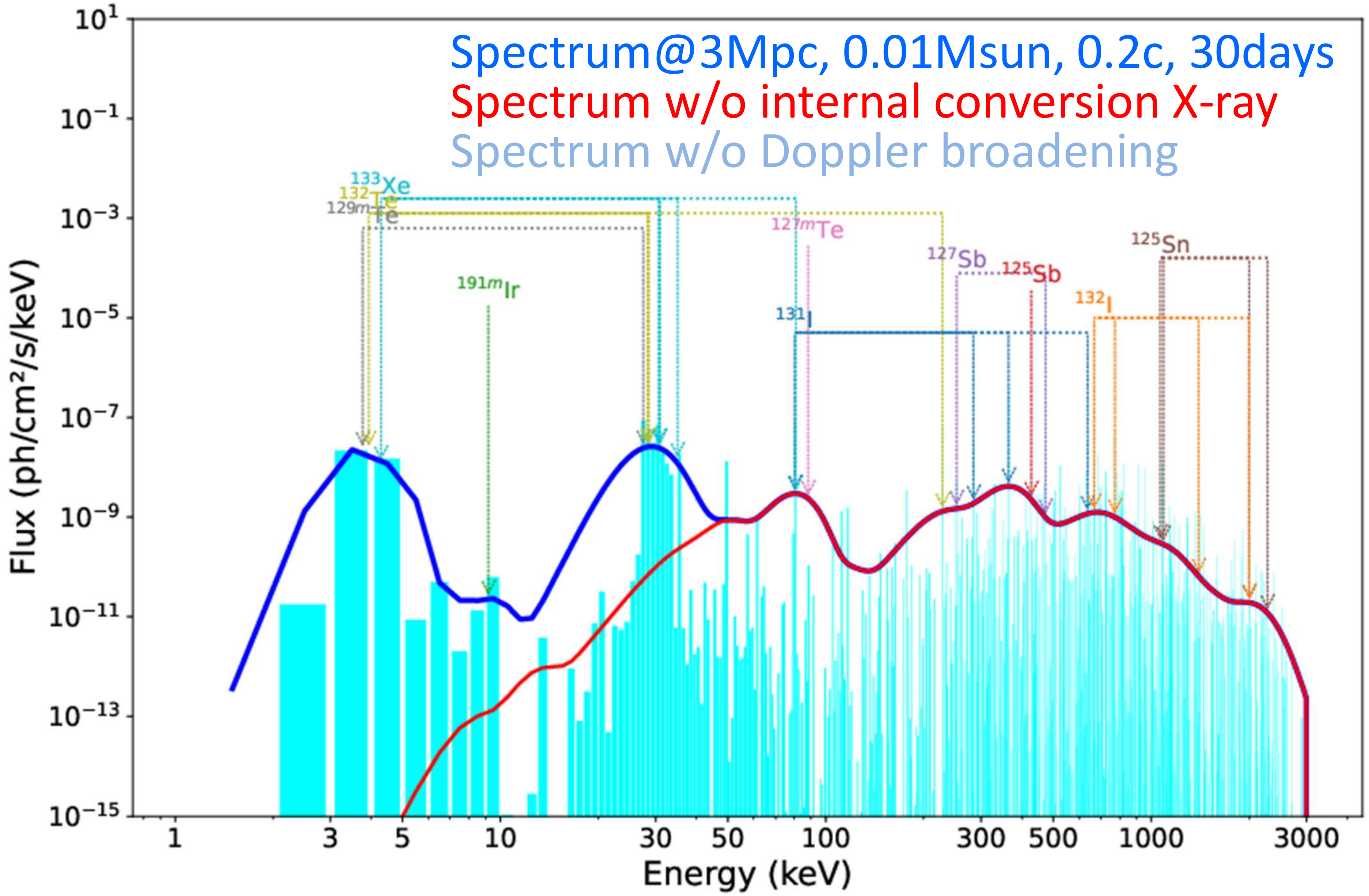
Parameters of our model

Vej = 0.2c (expansion velocity), Mej = 0.1Msun
Ye = 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4 (electron fraction)

Abundances

Ye = 0.05-0.2: similar and abundant nuclei of Z = 40 - 92
Ye = 0.25: intermediate
Ye = 0.3, 0.35: abundant nuclei of Z < 50
Ye = 0.4: abundant nuclei of Z < 40

X- and γ-ray spectrum: Ye = 0.25



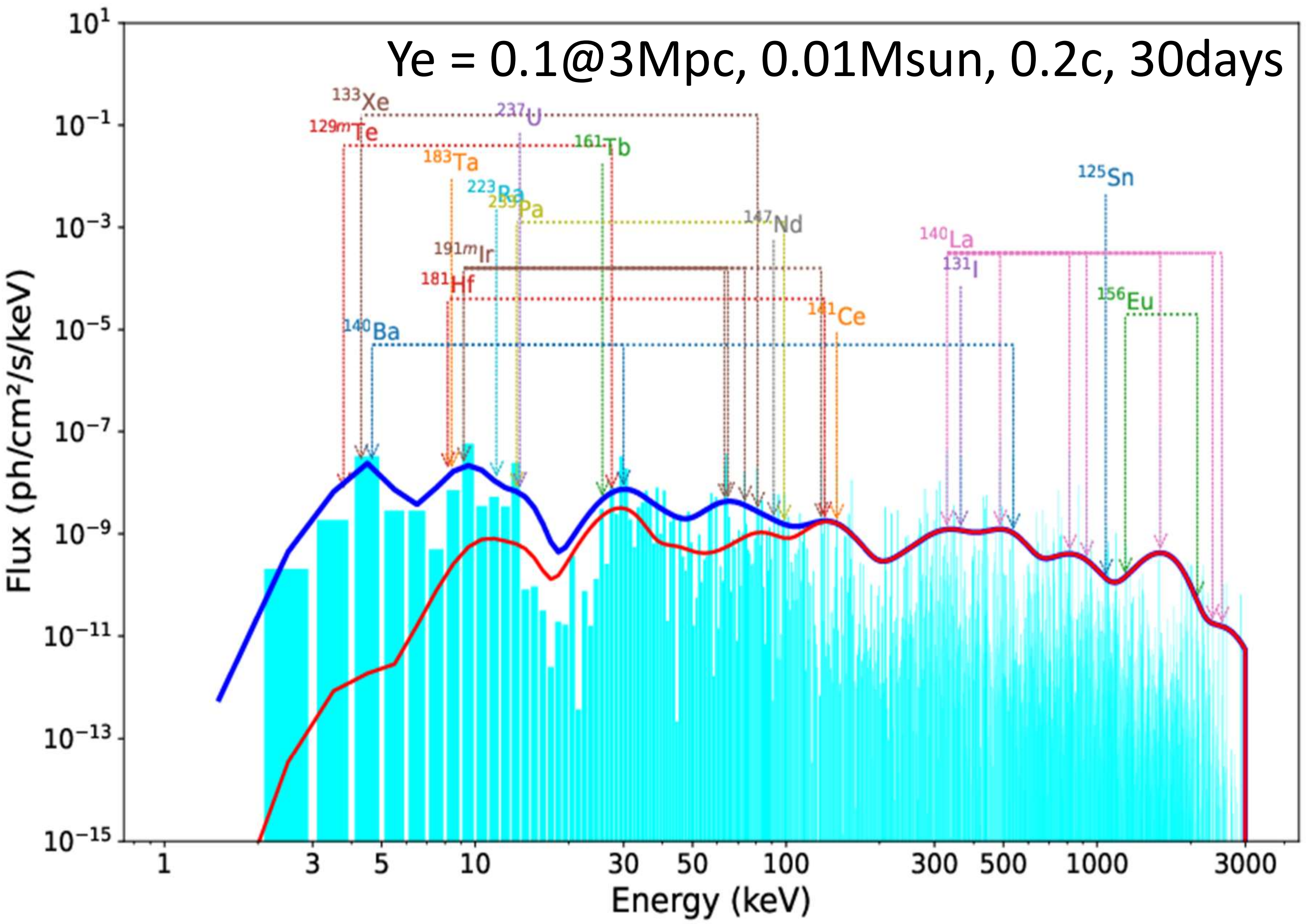
Flux@3Mpc, 30days:
in units of photons/cm^2/s/keV
without the self-absorption
Energy bin:
E<100keV: 1keV
E>100keV: 1.1 +0.5*(E/MeV) -0.017*(E/MeV)^2
(Eres of INTEGRAL SPI)

Ex.) 133Xe decays with a half life of 5.2days and emits lines at 4.29keV (6.1%), 30.6keV (14.1%), 31.0keV (26.1%), 35.0KeV (9.5%), and 81.0keV (38.0%) per decay

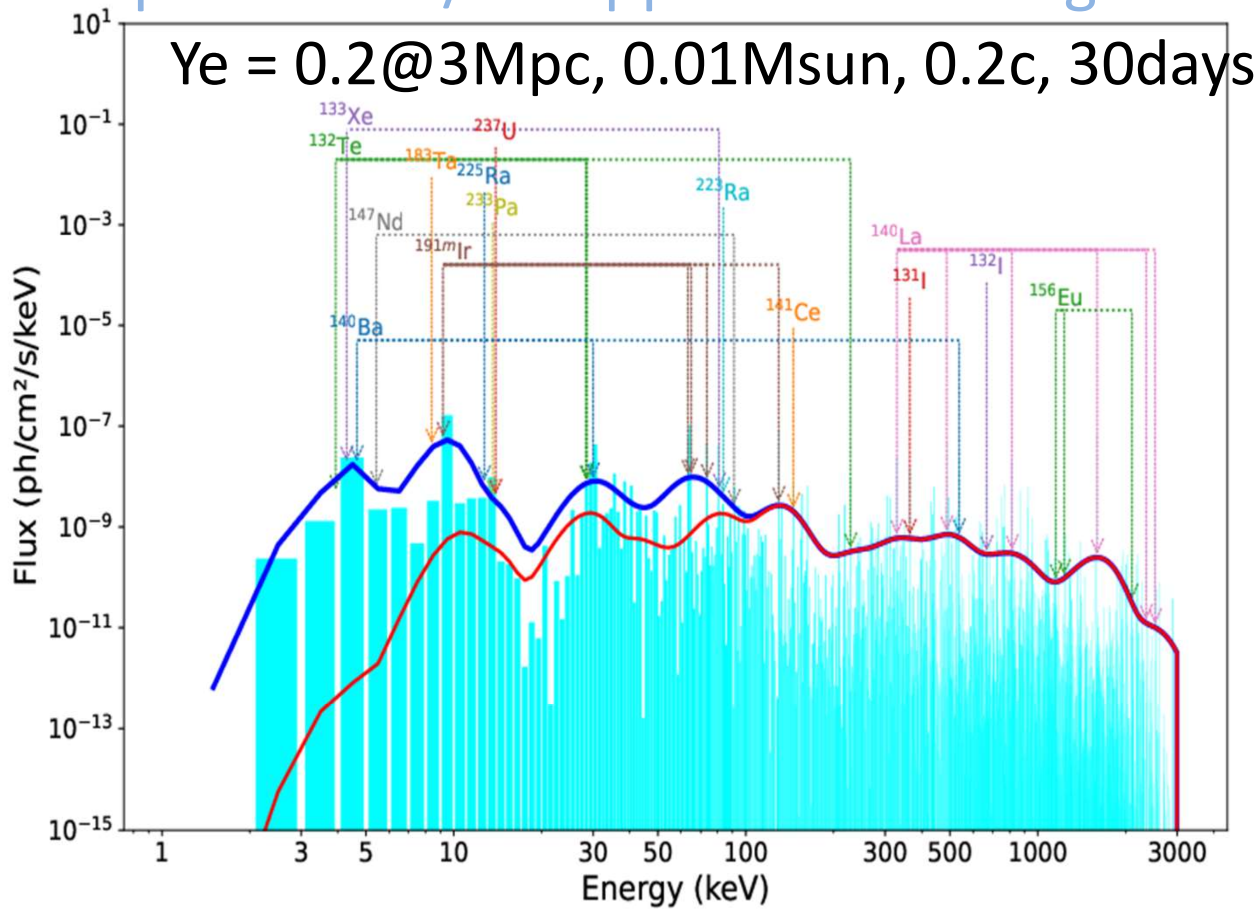
Ex.) the peak around 30keV originating from 129mTe, 132Te, and 133Xe

1. Internal conversion X-ray dominant@<50keV
2. dominant nuclei of A=120-135 for each energy ranges
3. prominent isomers of 127Te, 129Te, and 191I
4. Each nuclei emits at the fixed line-energies with fixed flux ratio and the line fluxes synchronously decrease with the half-life
5. Each peaks in the spectrum originating from a few nuclei
6. Future observation of the decrease of the peaks could lead to the identification of neutron-rich nuclei

X- and γ -ray spectra: Ye=0.1, 0.2



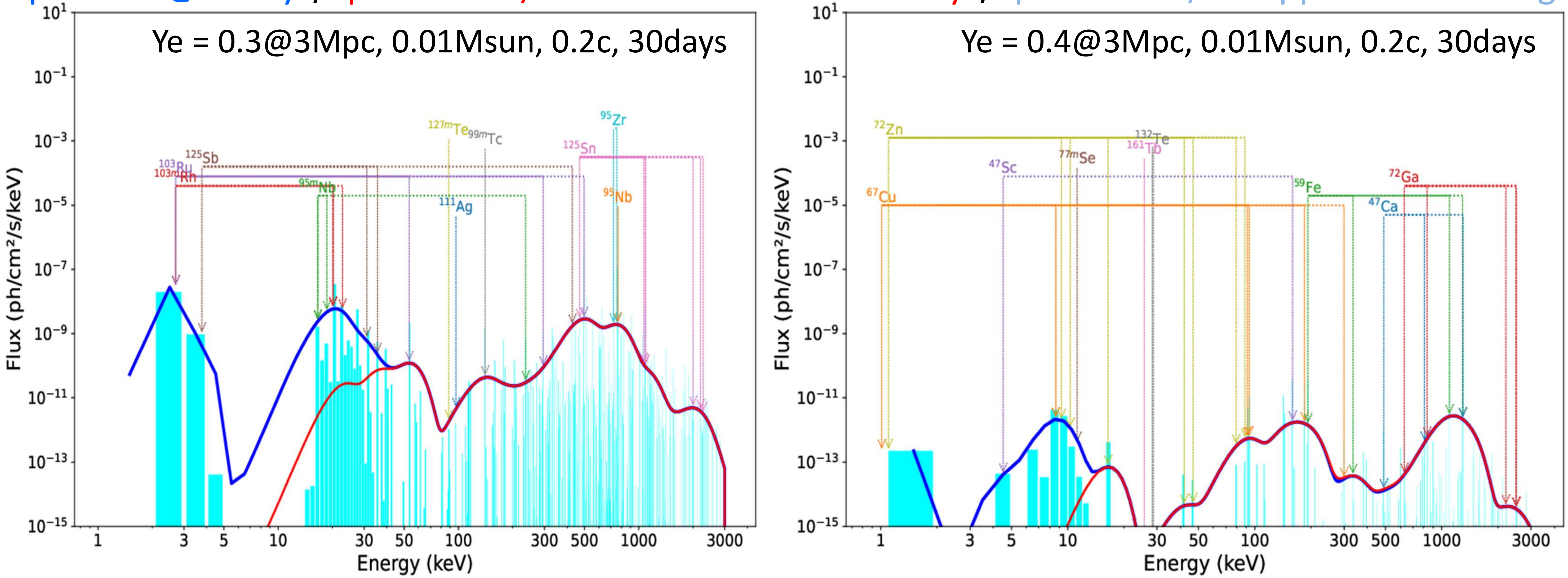
Spectrum@3Mpc,30days
Spectrum w/o internal conversion X-rays
Spectrum w/o Doppler broadening



1. Internal conversion X-ray dominant@<100keV
2. dominant nuclei of A=120-260 for each energy ranges
3. prominent isomer of 191I
4. bump around 10-20keV from 223Ra, 233Pa, and 237U
5. very similar spectra for cases of Ye = 0.1 and 0.2 (also 0.05 and 0.15) because of the similar abundances
6. Each peaks in the spectrum originating from a few nuclei, as in Ye = 0.25

X- and γ -ray spectra: Ye=0.3, 0.4

Spectrum@30days/Spectrum w/o internal conversion X-rays/Spectrum w/o Doppler broadening



1. Internal conversion X-ray dominant@<40keV (Ye=0.3) / < 15keV (Ye=0.4)
2. dominant nuclei of A=100-130 (Ye=0.3)/ A<80 (Ye=0.4) for each energy ranges
3. dimmer than the cases of Ye <= 0.25