# Nebular emission modeling for collapsar

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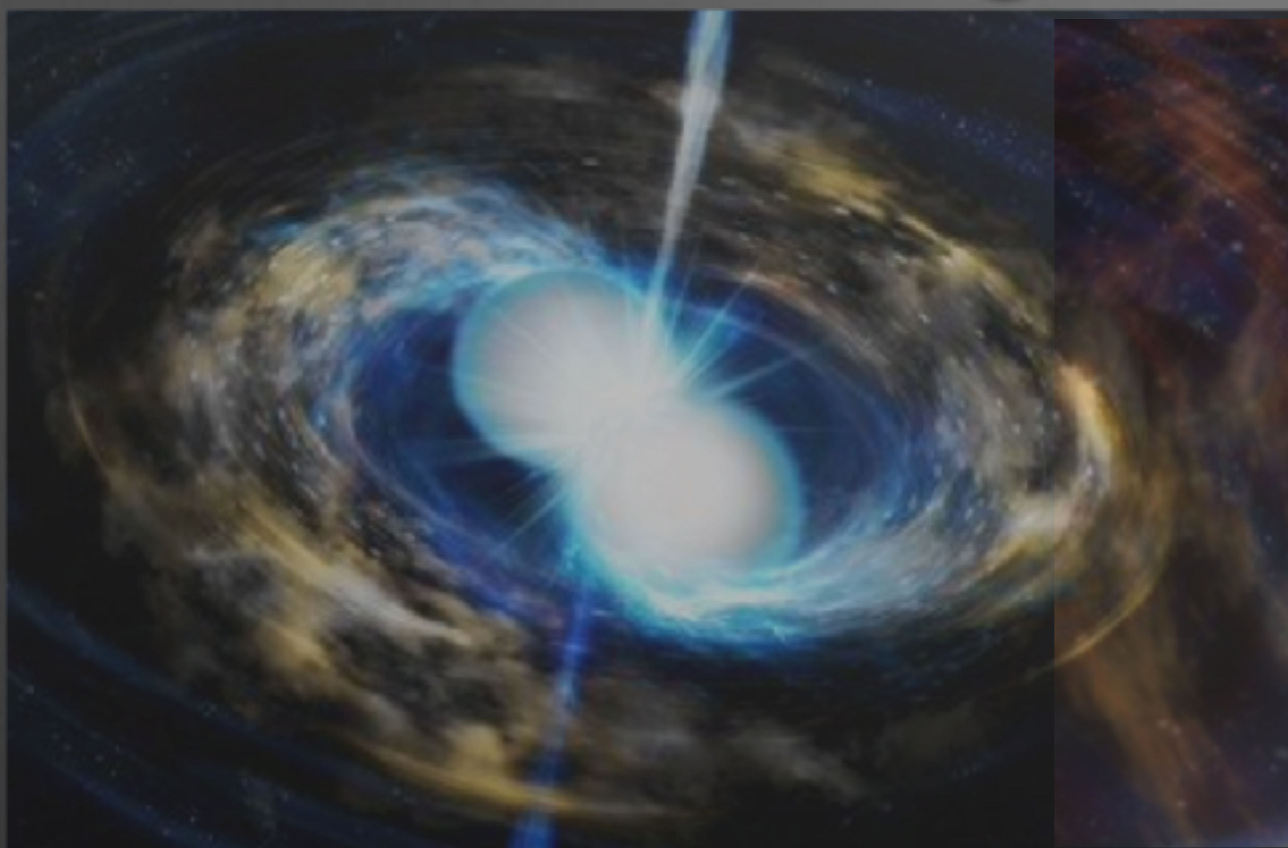
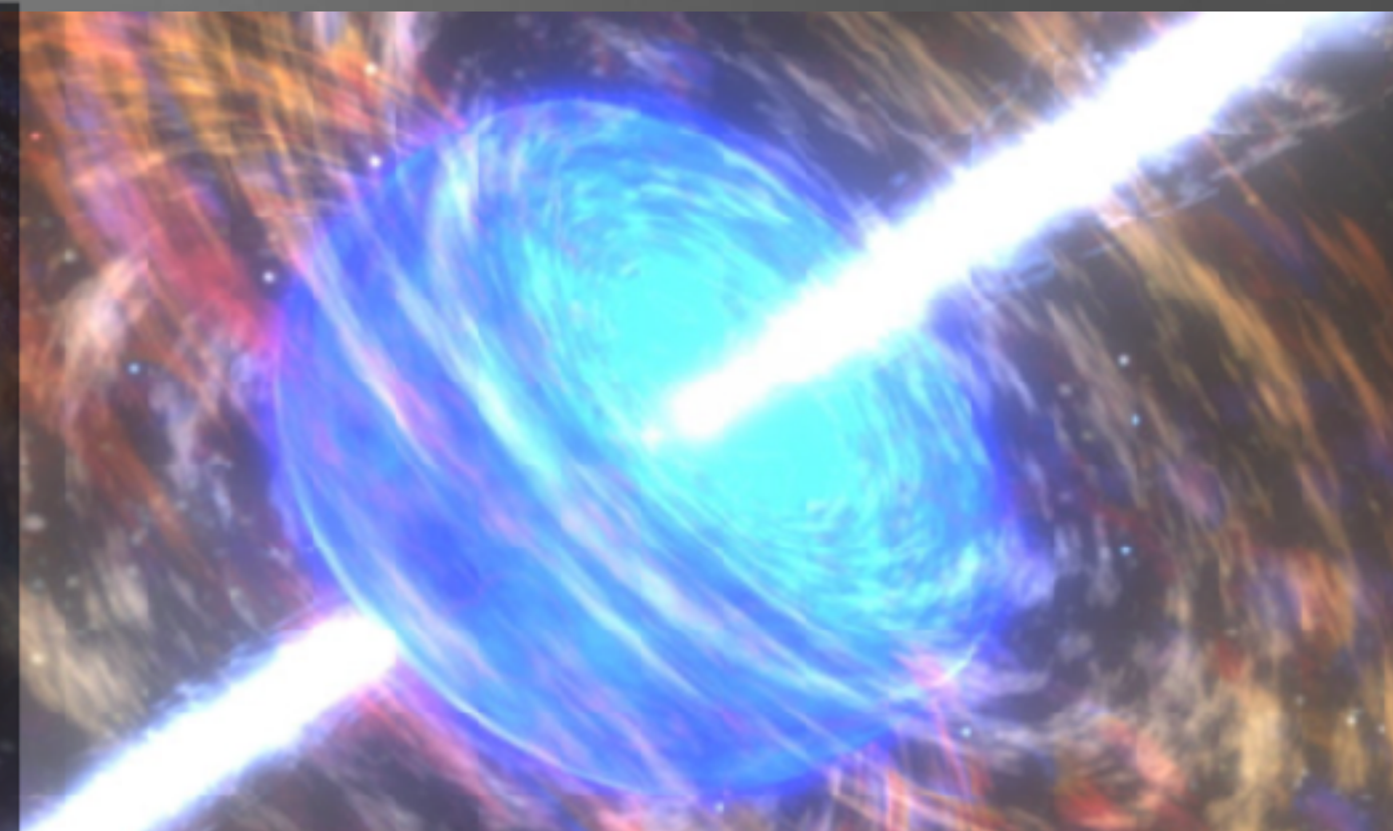
collaboration with Giacomo Ricigliano (Darmstadt), Masaomi Tanaka (Tohoku), Ehud Nakar (Tel Aviv)

# The r-process origin

Neutron star merger?



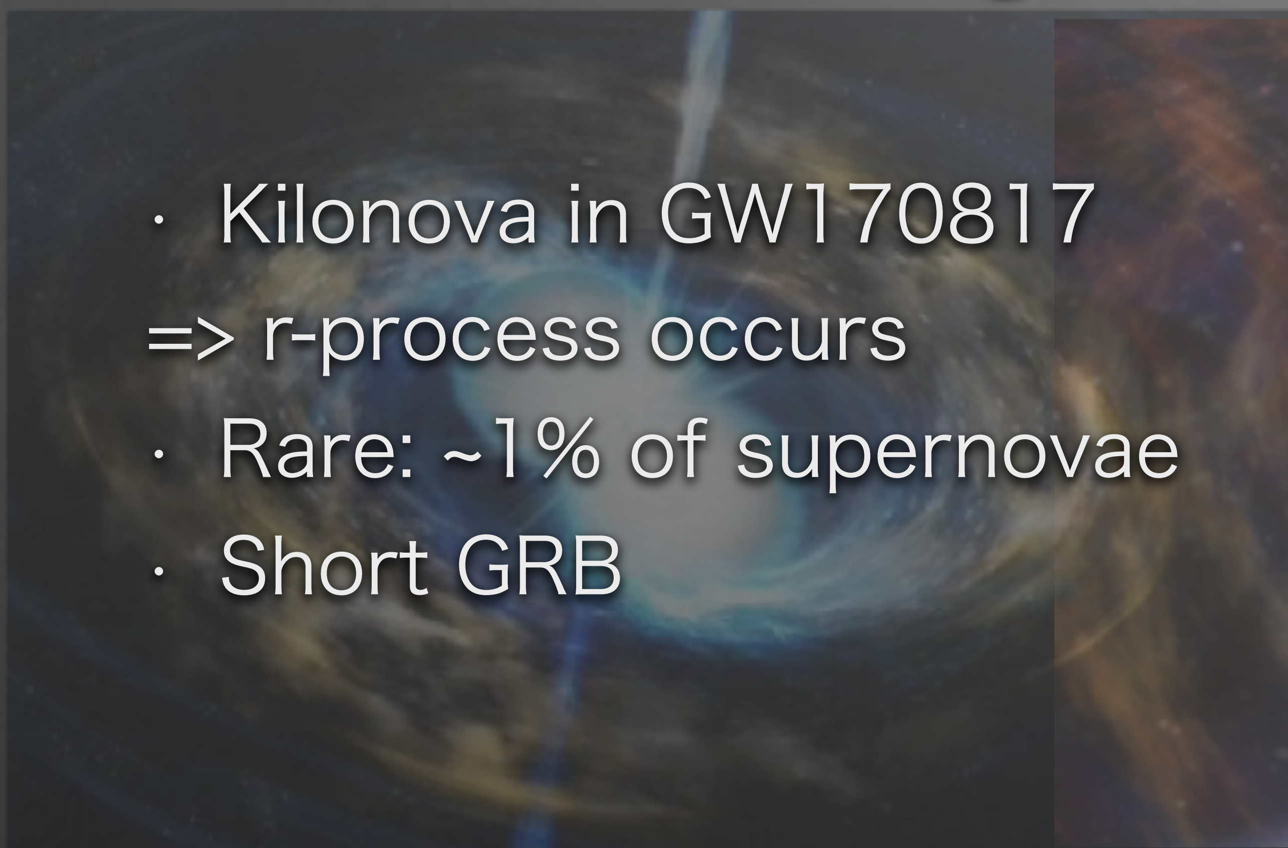
Collapsar?



Something else?

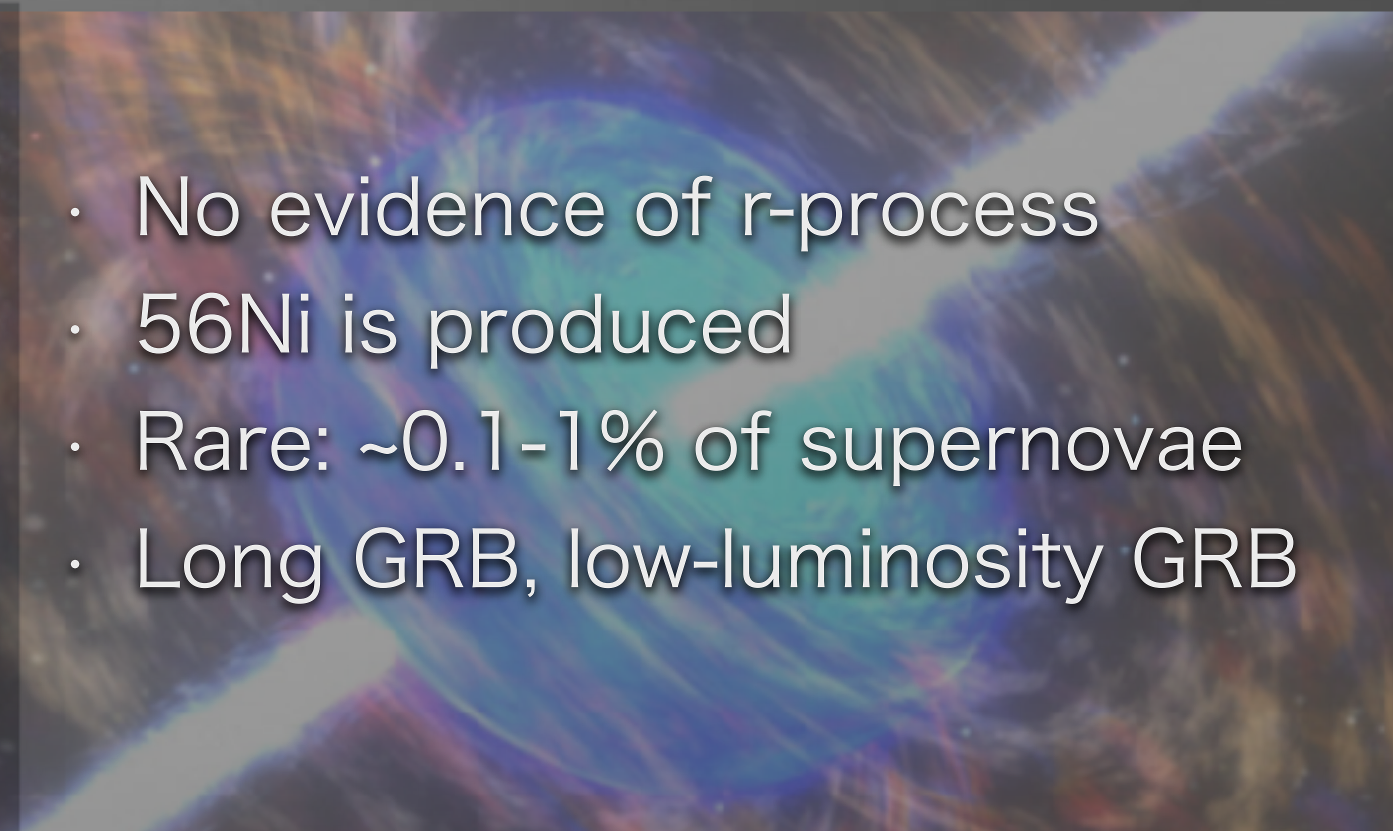
# The r-process origin

## Neutron star merger?



- Kilonova in GW170817
=> r-process occurs
- Rare: ~1% of supernovae
- Short GRB

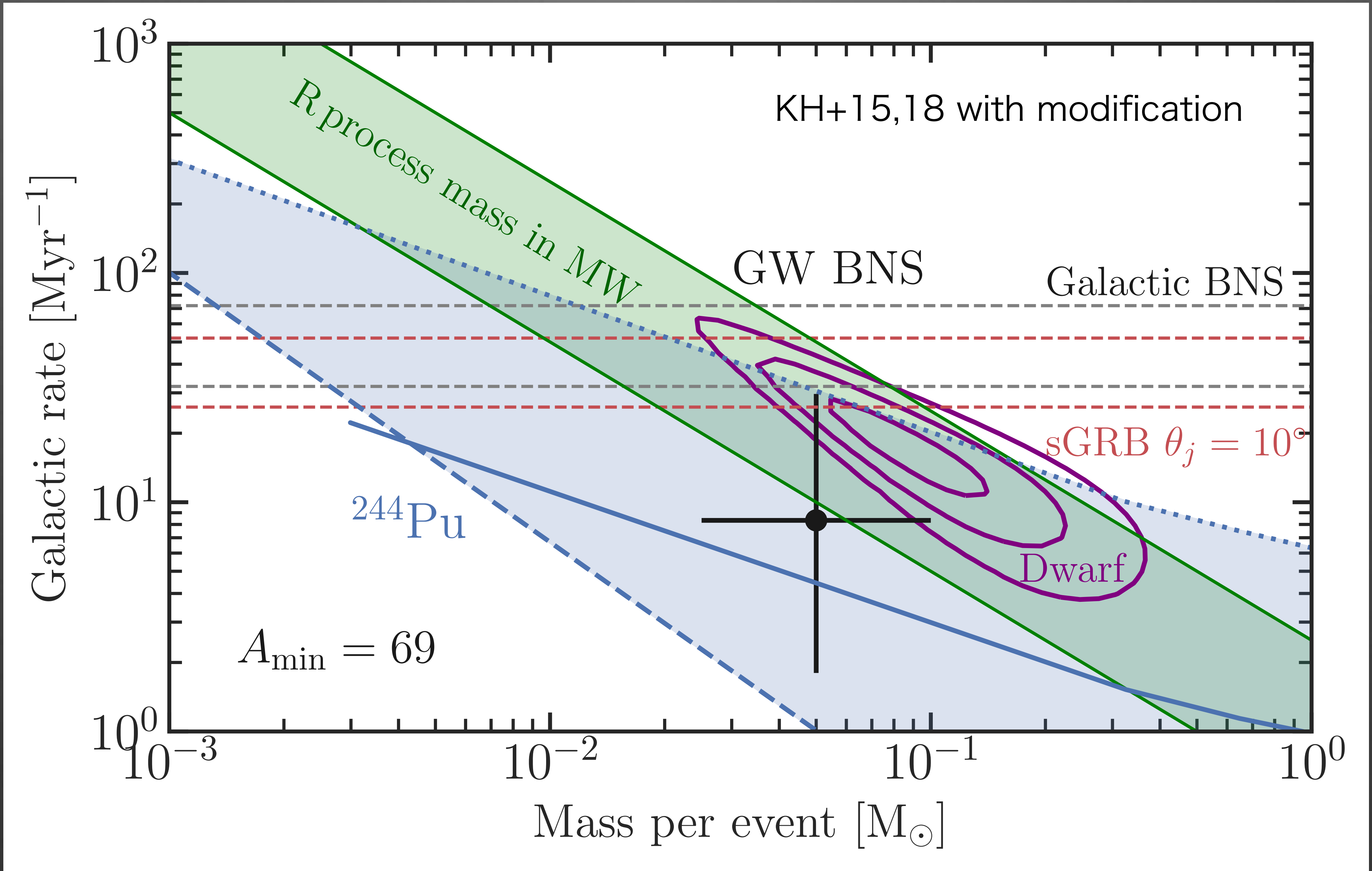
## Collapsar?



- No evidence of r-process
- 56Ni is produced
- Rare: ~0.1-1% of supernovae
- Long GRB, low-luminosity GRB

Shibata-san, Sekiguchi-san, Fujibayashi-san: numerical simulation
Tanaka-san, Hamid-san, Domoto-san, Rahmouni-san, Chibata-san, :
Modeling and Observation

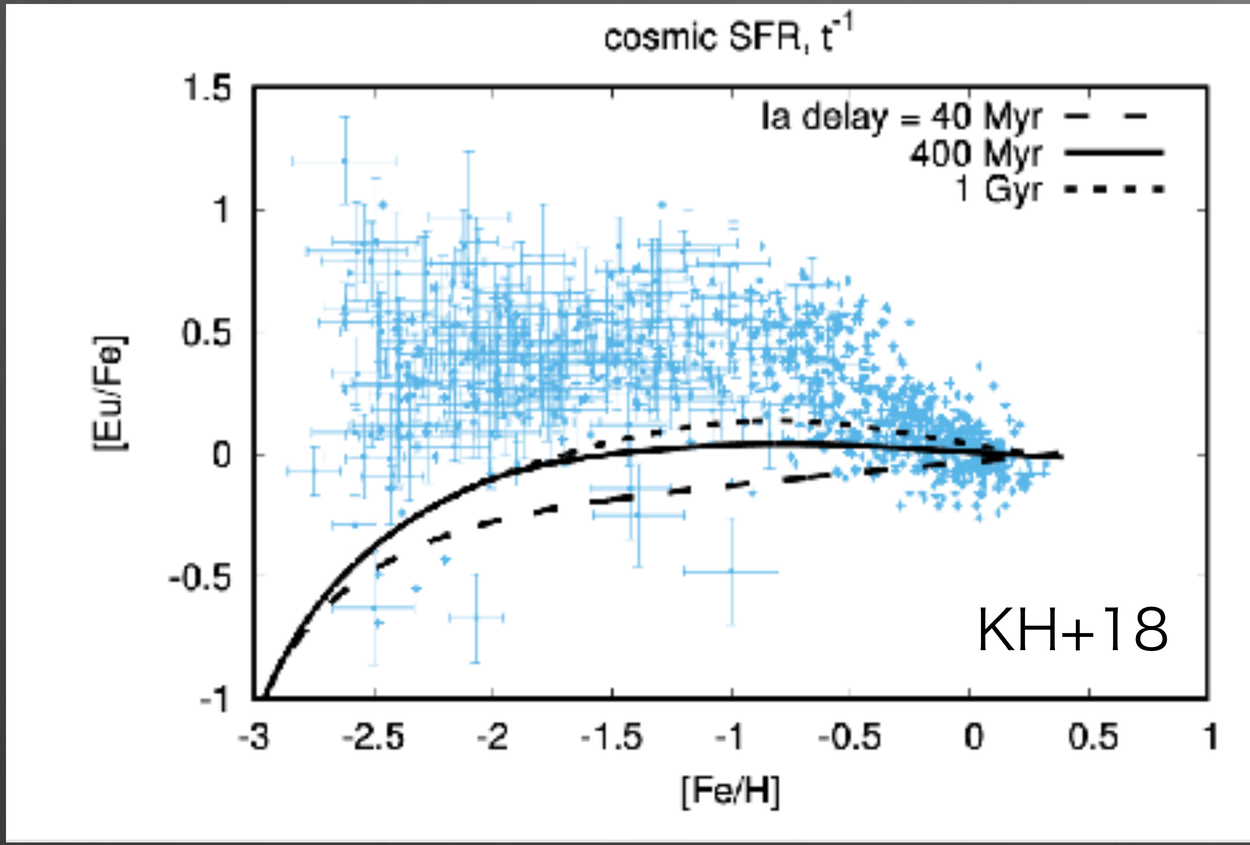
# R-process: Rate and Mass



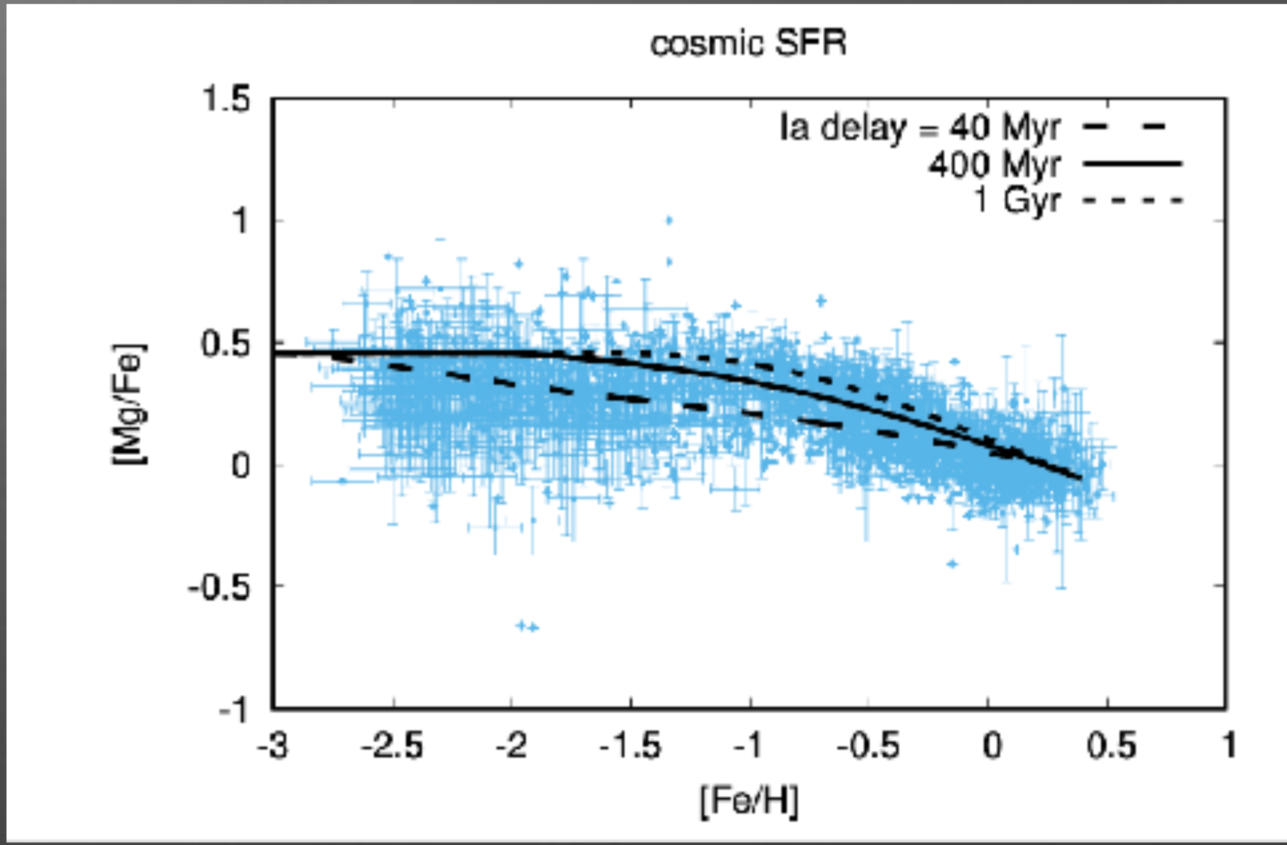

In principle, neutron star mergers can provide all the r-process elements.

# Delay problem of NS mergers

Neutron star mergers (delay)

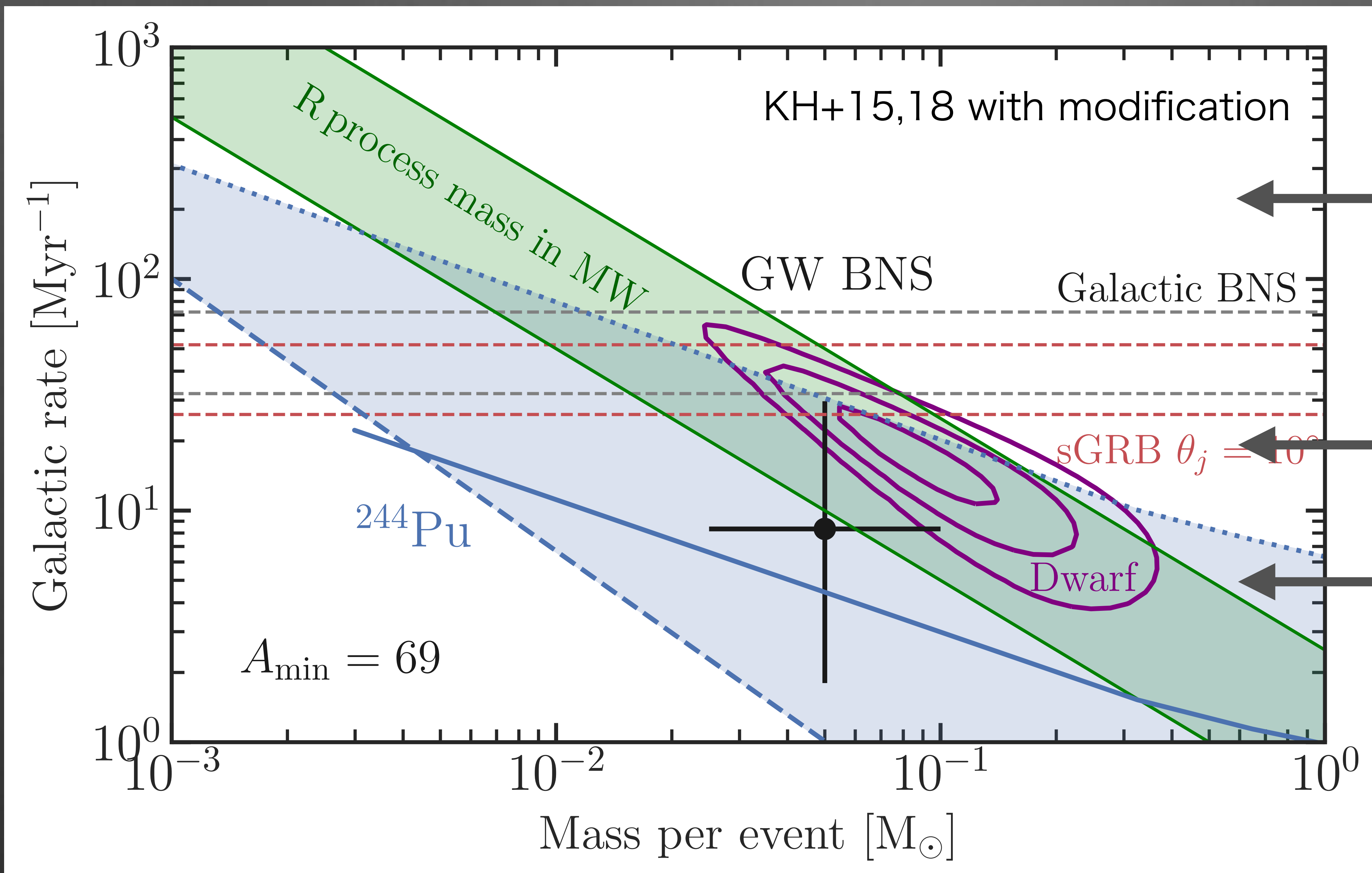



Core collapse (no delay)




- **R-process production** rate follows the star formation **without delay** at least in our Galaxy.
- This fact challenges neutron star mergers as the dominant production site, c.f., 1-10 Gyr delay for GW170817.

# R-process: Rate and Mass




normal SNe II

Broad-line SNe Ic

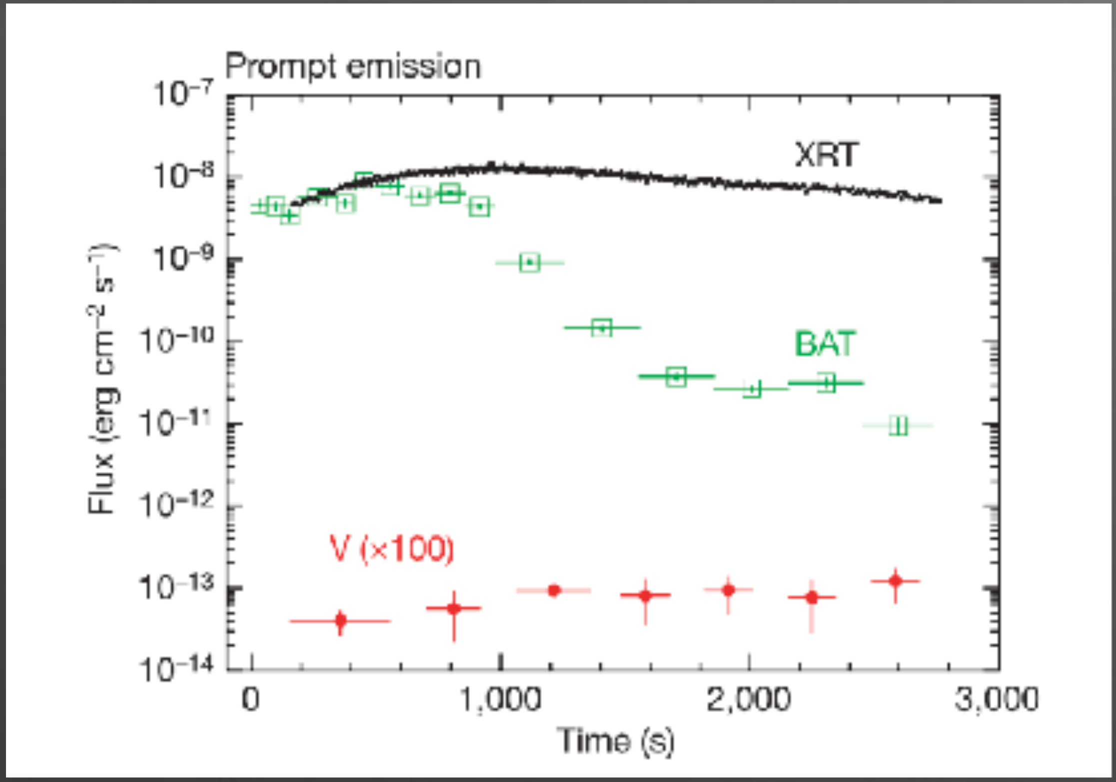
Low-luminosity GRBs

Long GRBs

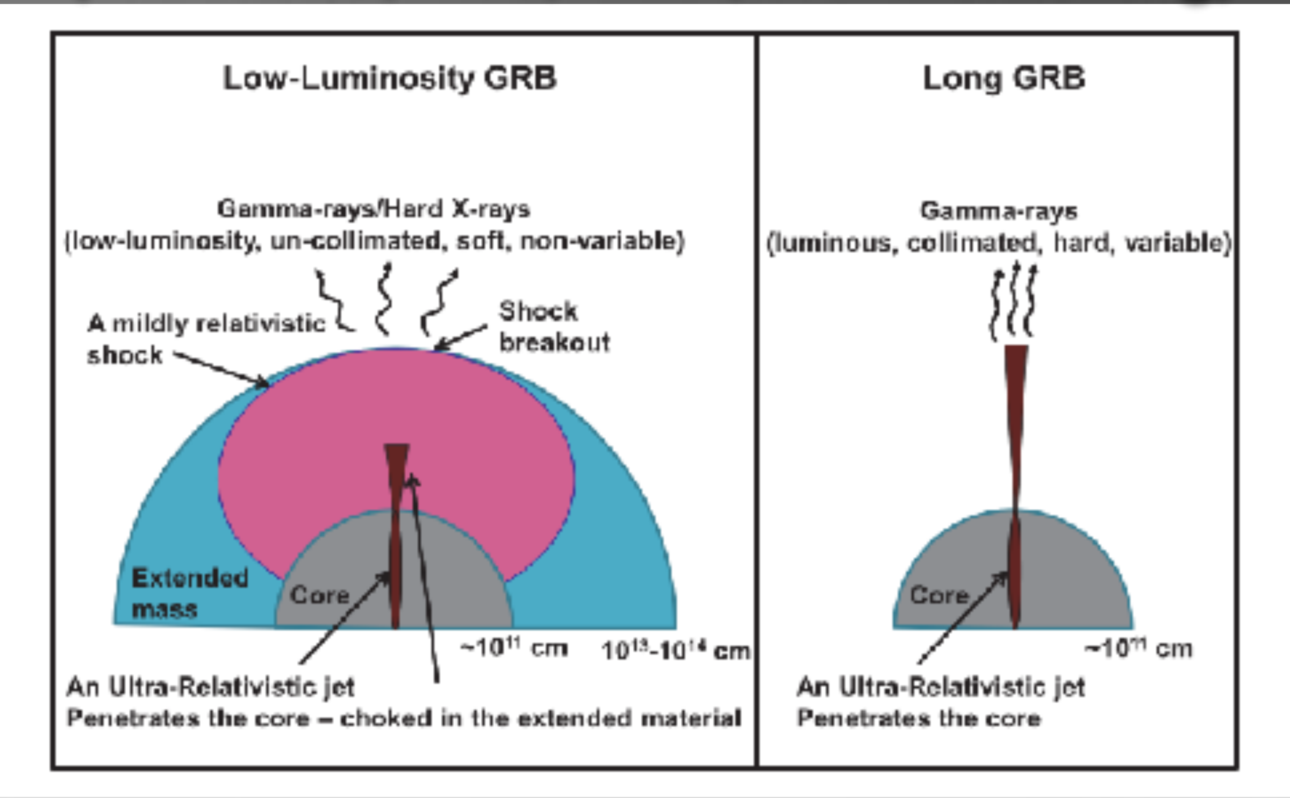
The rates of mergers, llGRBs, long GRBs correspond to **0.01 - 0.1Msun**.
We'd like to test whether these events produce r-process elements or not.

# Low-luminosity GRBs

GRB 060218 (Campana+06)




Unified scenario
(Nakar 15, also, Irwin, KH submitting)

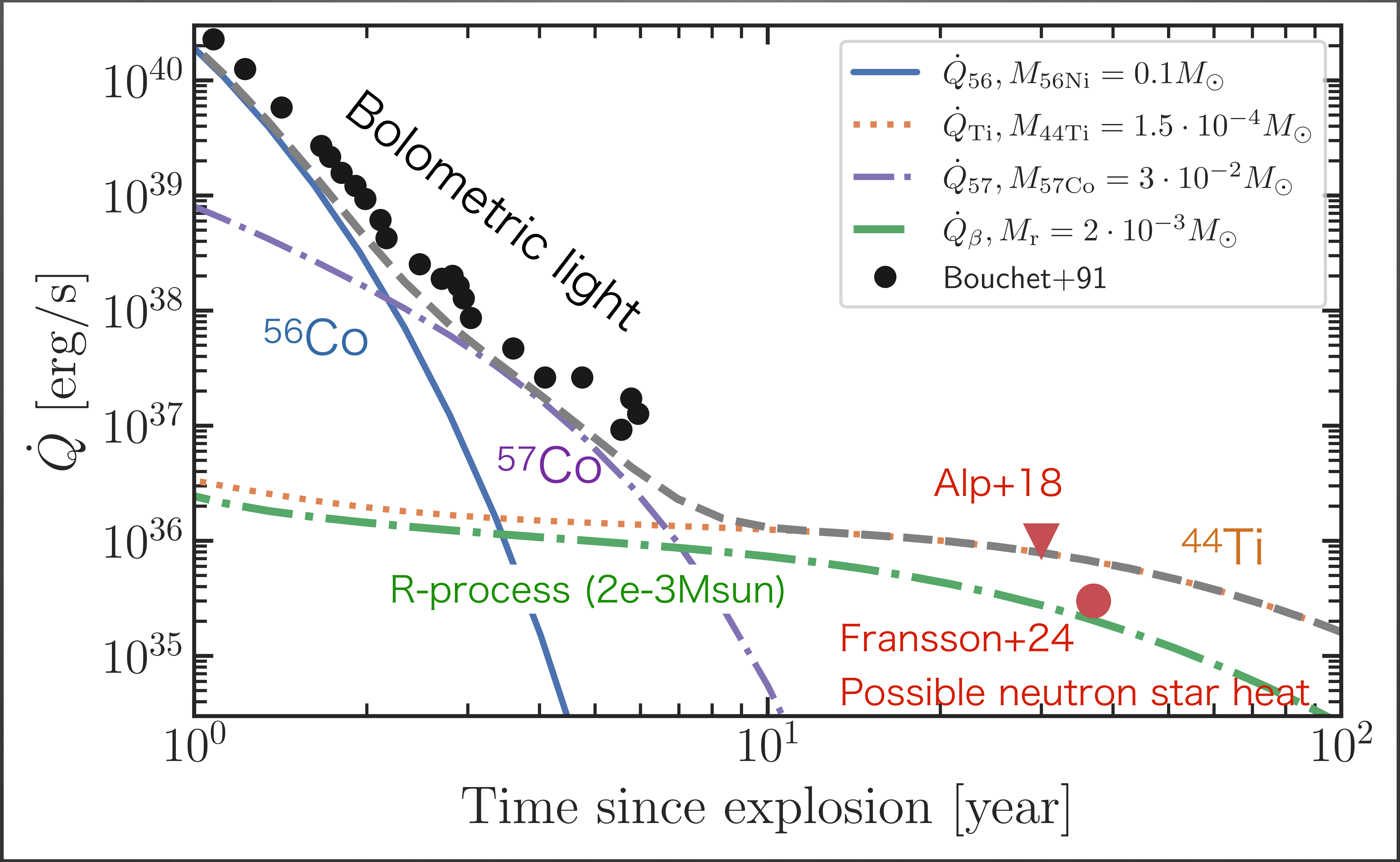



- GRB 060218-like llGRBs: faint, soft, and smooth emission.
- Bright supernova without H and He.
- Einstein Probe and HiZ-GUNDAM will find many (EP 240414a, Sun+24).
- Closer distance and fainter afterglow compared to long GRBs => Excellent targets for r-process search.

# Outline

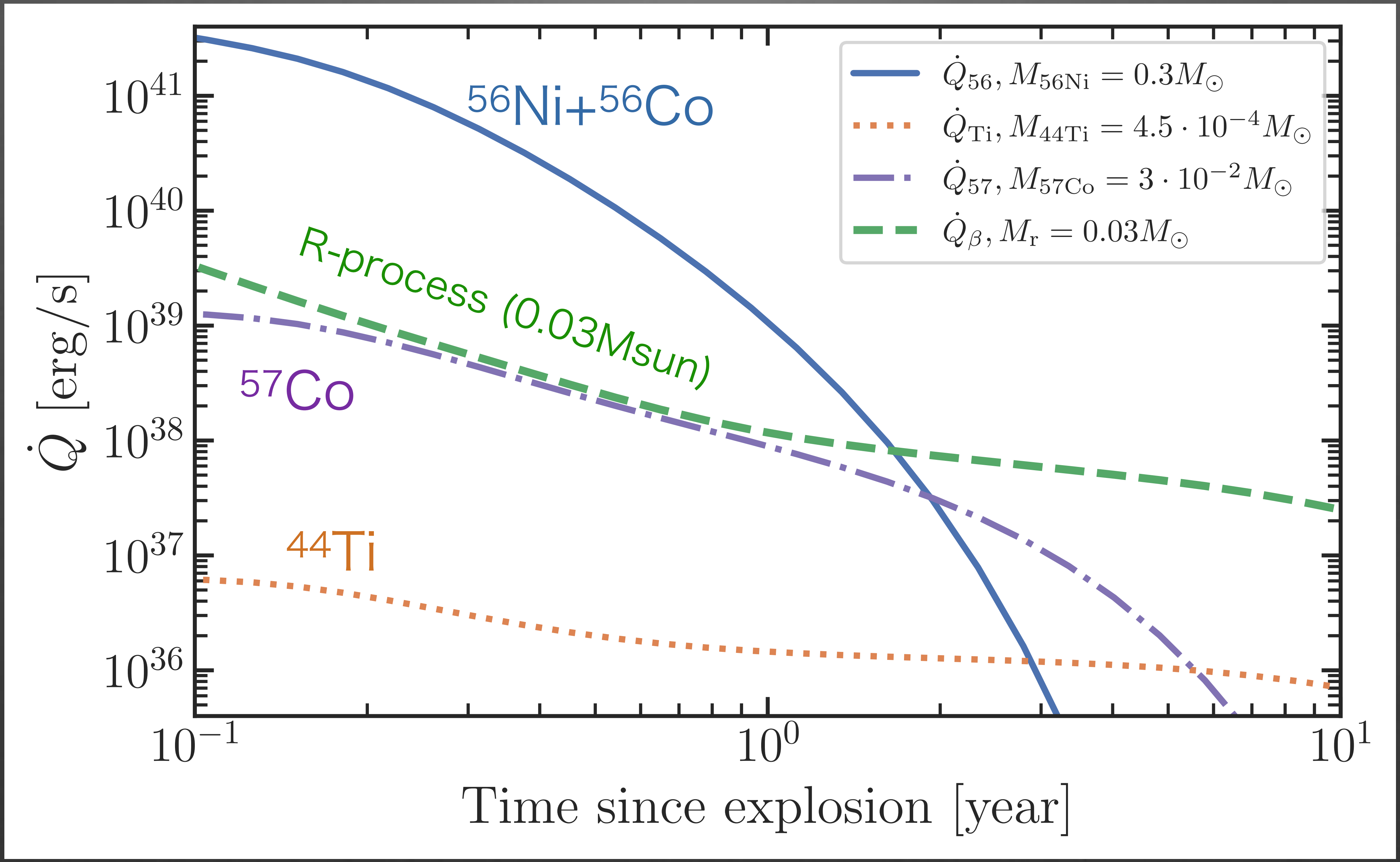
- Energy budget constraints
- Nebular lines of r-process elements
- Summary

# Energy budget in SN 1987A




- We can rule out the production of r-process >5e-3Msun from the energy budget.
- But, normal core-collapse SNe should not produce >1.0e-3Msun from the rate.

# Energy budget in broad-lined SN Ic including GRB/SNe



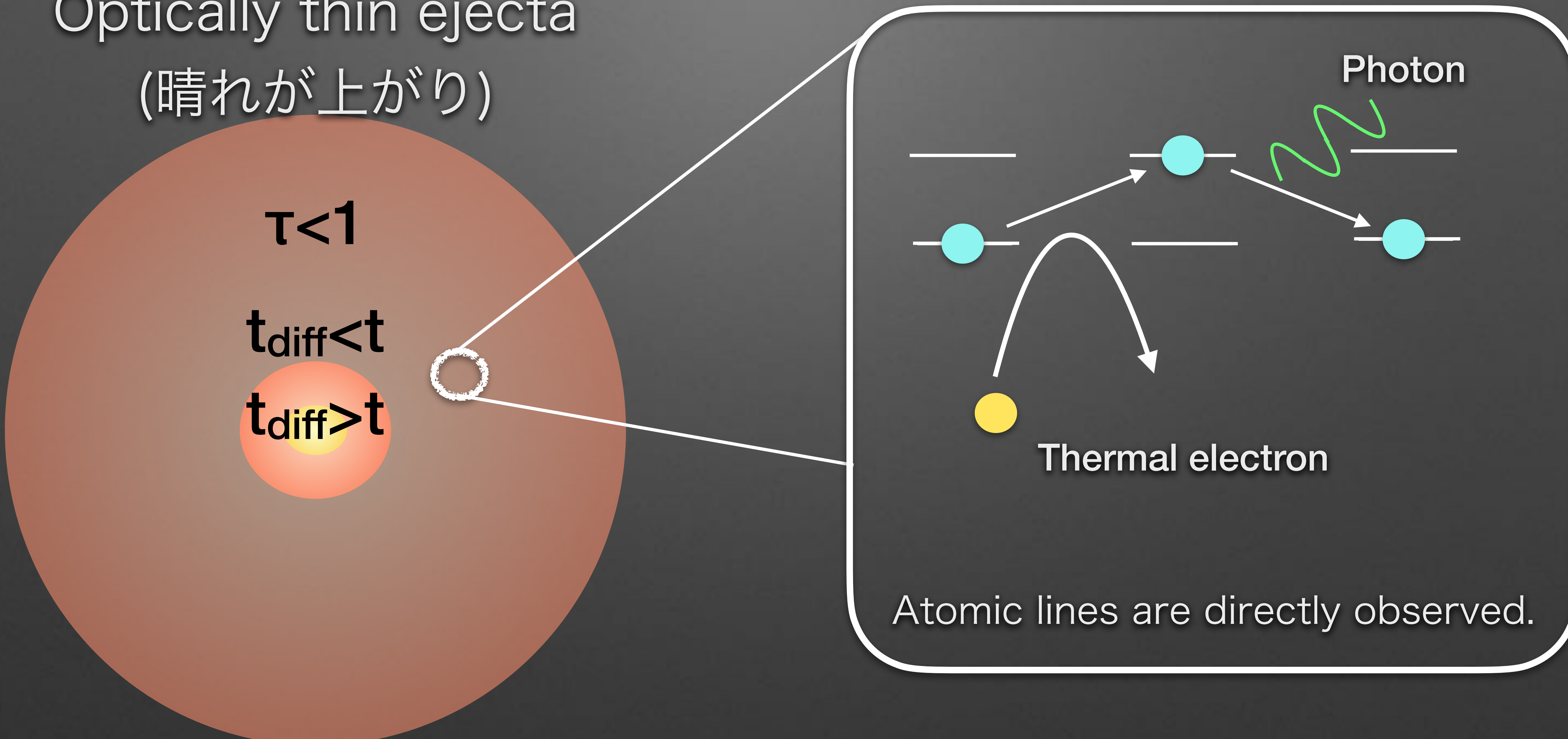

R-process of 0.03Msun can dominate the heating t>2yr.

However, it is likely difficult to distinguish from overproduction of $^{44}$Ti.

# Nebular emission lines

Optically thin ejecta

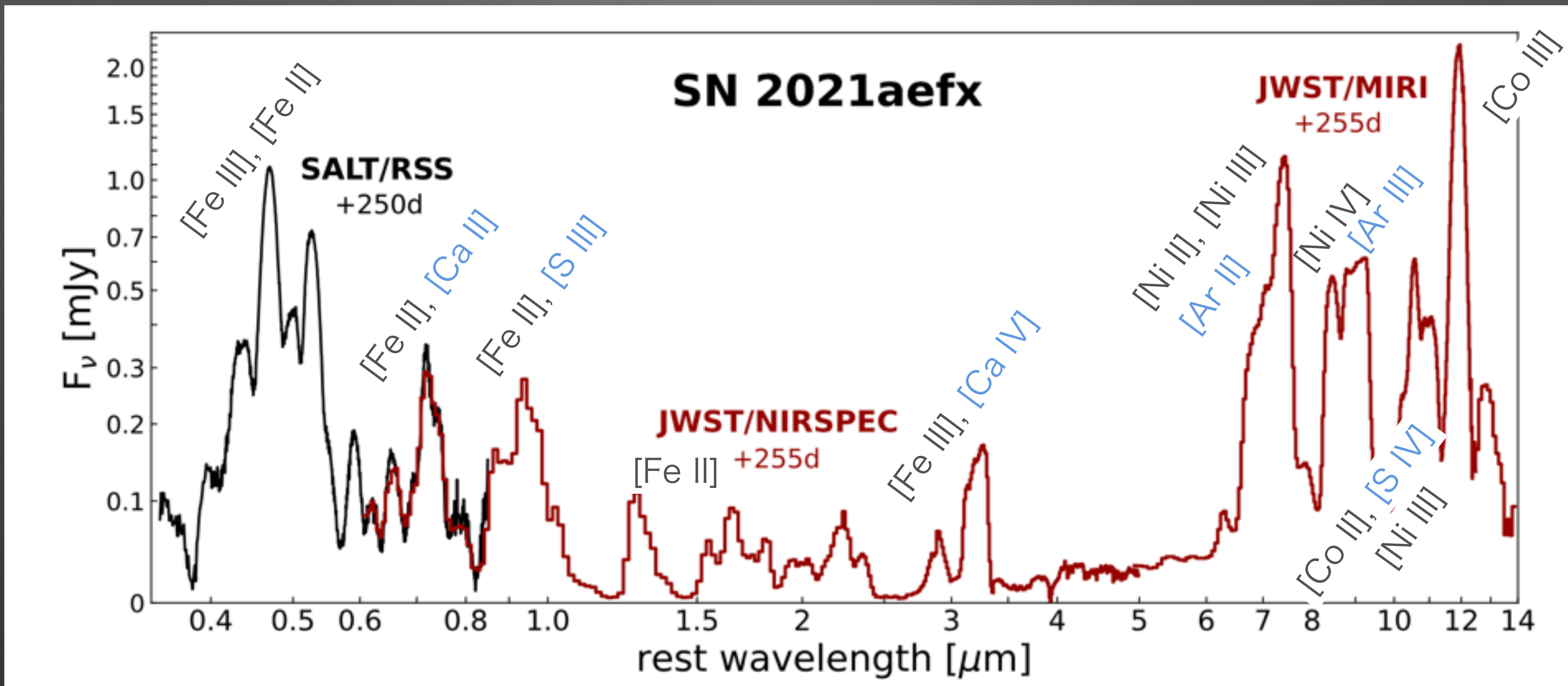
(晴れが上がり)




The line intensity is roughly proportional to the mass of an emitting ion.

# SN Ia Nebula seen by JWST

Kwok+23




- IR lines are particularly useful because their strengths usually do not depend excitation cross sections and depend weakly on the temperature and density.
- The $^{56}$Ni mass estimated only from IR lines is ~ 0.5 Msun, which agrees with the light curve modeling.

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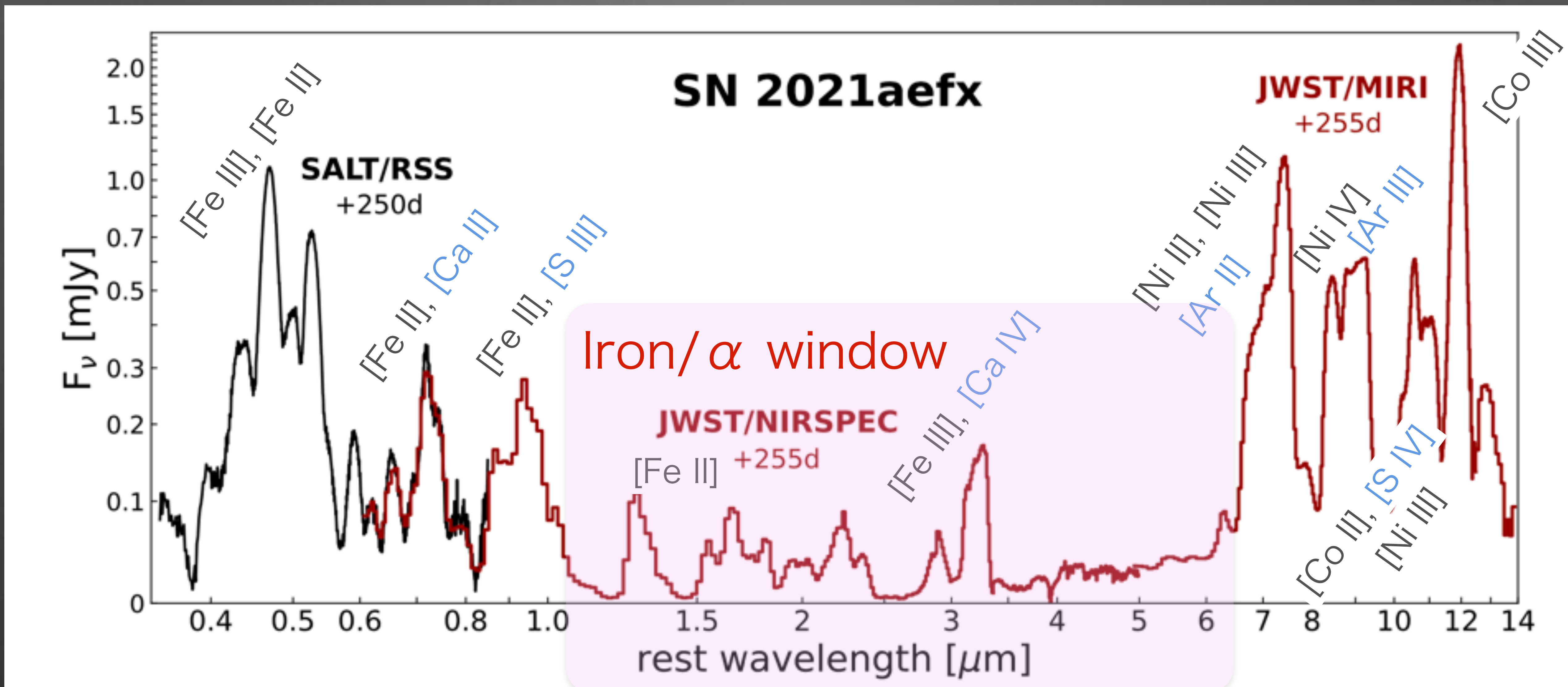


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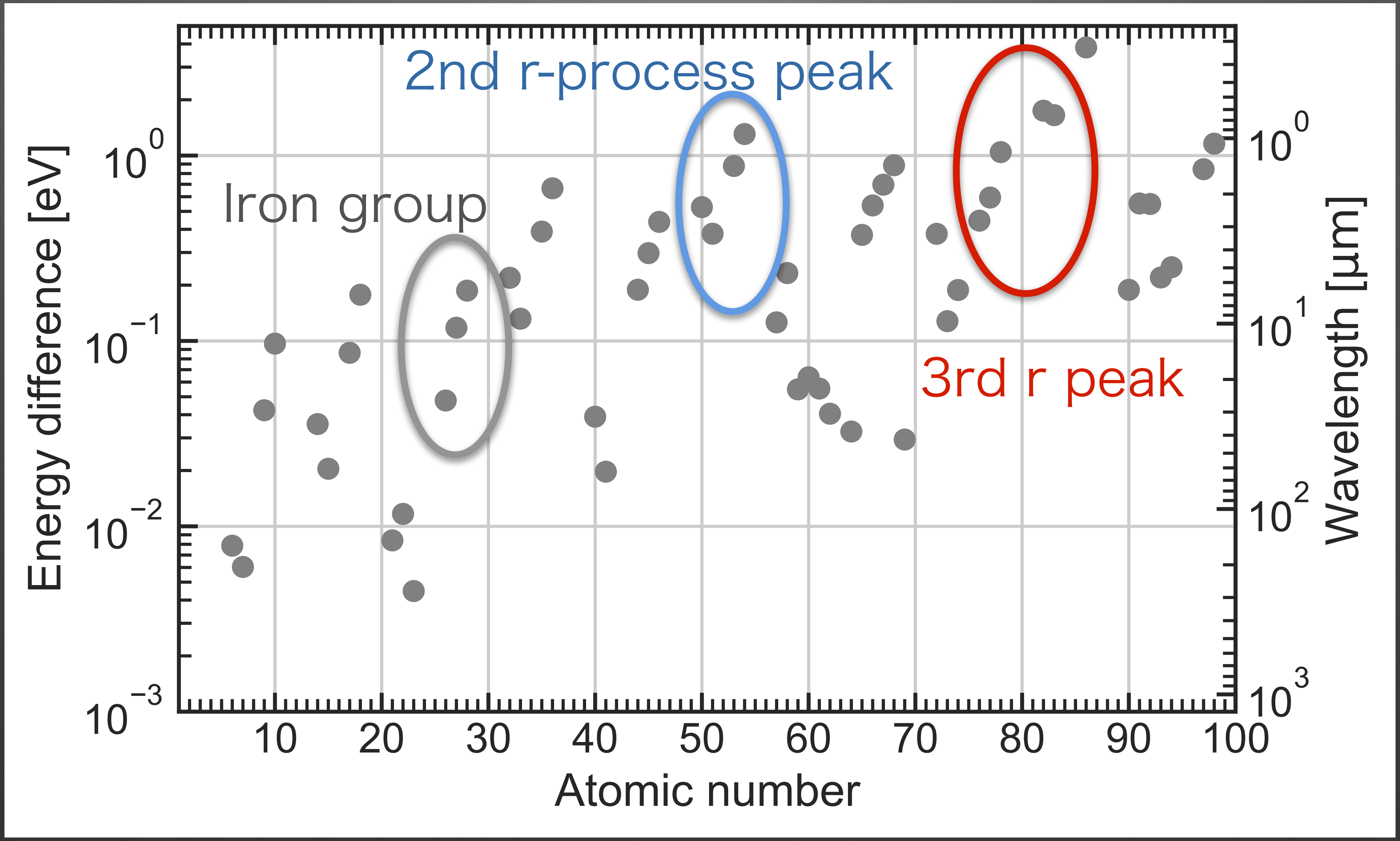
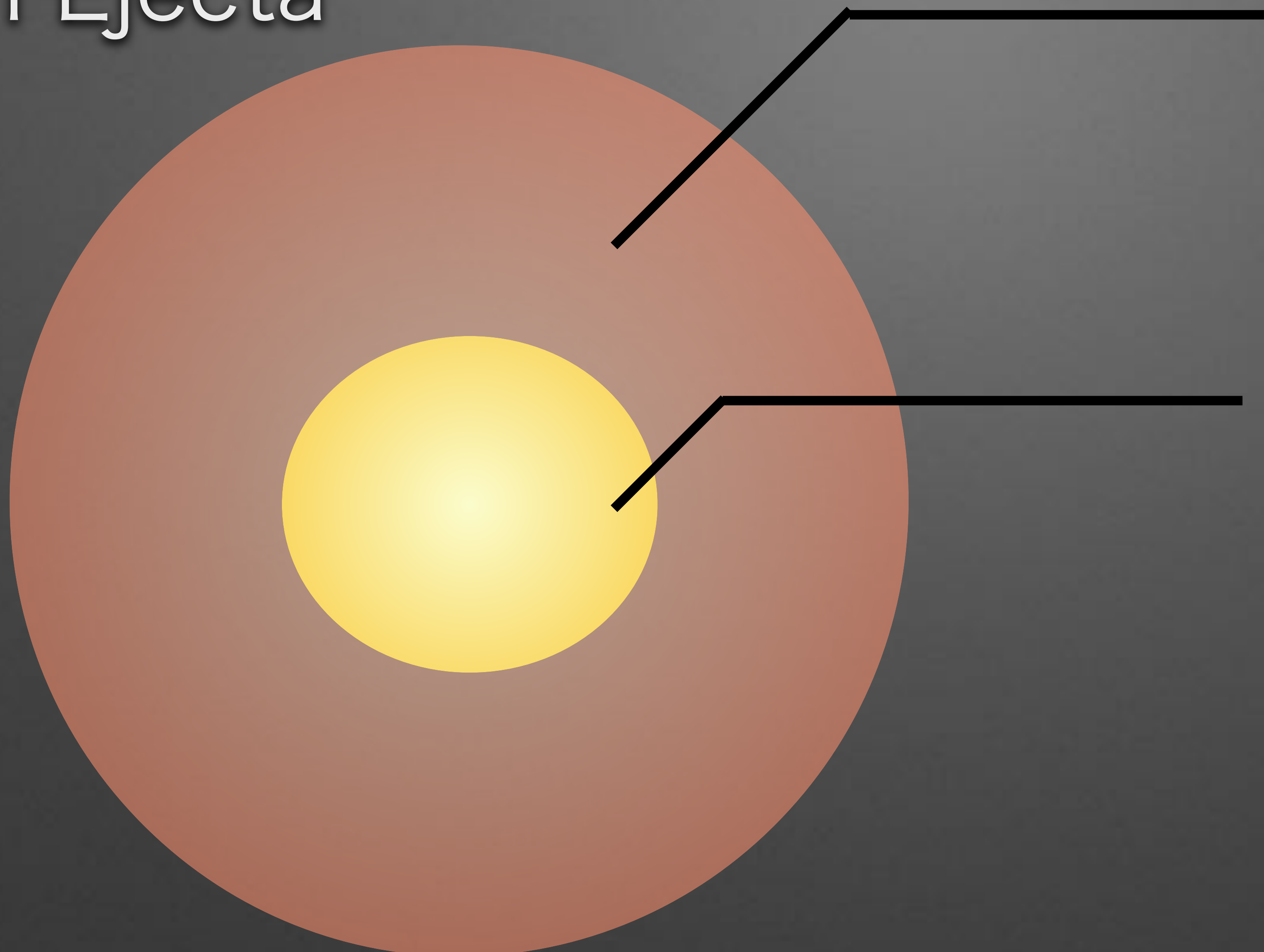
# Energy scales of atomic emission lines




- R-process elements have strong emission lines in the iron-$\alpha$ window.

# Set up

Thin Ejecta



Envelope

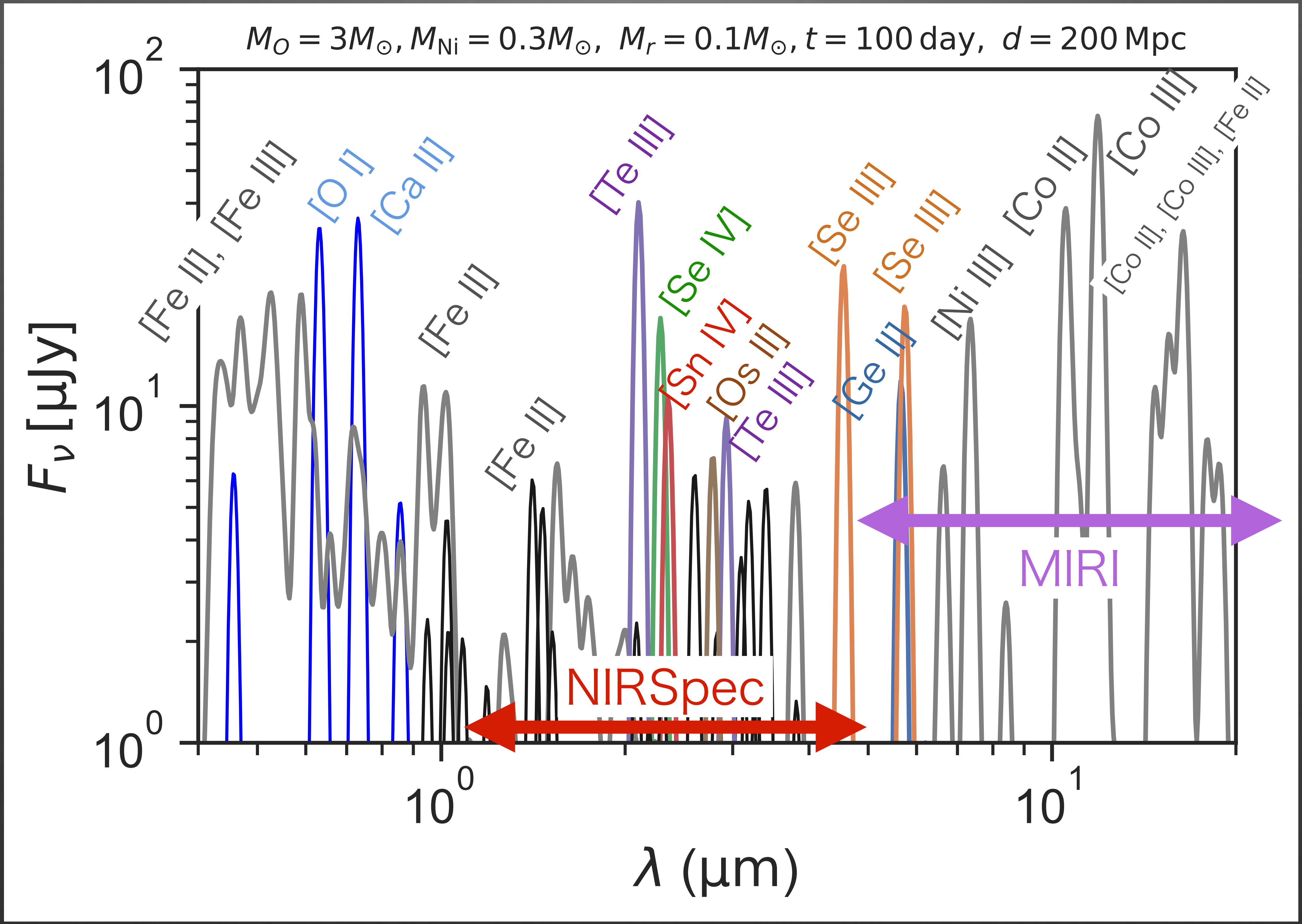
- $\alpha$-elements
- no radioactivity
- no emission

Radioactive Core

- $\alpha$-elements (~3Msun)
- Iron group (0.3Msun)
- R-process (0.1Msun)
- $v_{exp}$ ~ 7000km/s
- Solar r-process abundance
- No molecules

- Collision excitation/deexcitation, radiative decay, escape probability are included. For r-process, only M1 lines are included.
- Temperature is set such that the optical spectrum agrees with SN 1998bw (see, Patat+01, Mazzalli + 01, Maeda+06).

# Synthetic Nebular Spectrum




Caveat: our model doesn't include optical lines of r-process elements.

# Summary

- The production of r-process elements in supernovae is an open question.
- Rare core collapse events can be the main r-process sources.
- Bolometric light curves at late times may hint the r-process production but $^{44}$Ti can mimic r-process heating.
- Nebular spectrum has an iron-$\alpha$ window at 1 - 5 $\mu$m. Importantly, r-process elements have strong lines in the window. (CO vibration modes might pollute the window)
- JWST follow-up of llGRBs can tell us (1) the amount of $^{56}$Ni and ionization stage (promising), (2) r-process production if $M_r > 0.03$Msun.

# Nebular phase of GRB-SN 1998bw