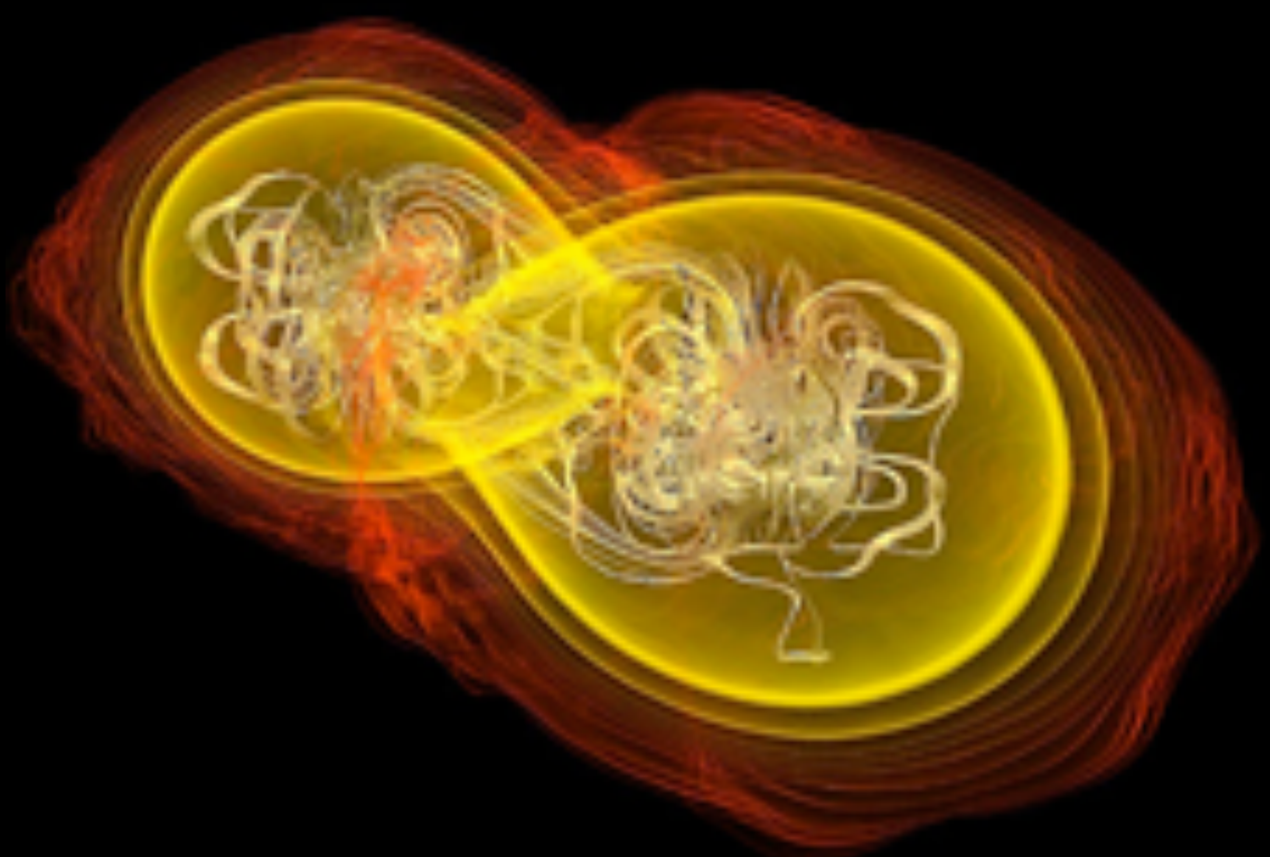
The *r*-process and kilonova observables

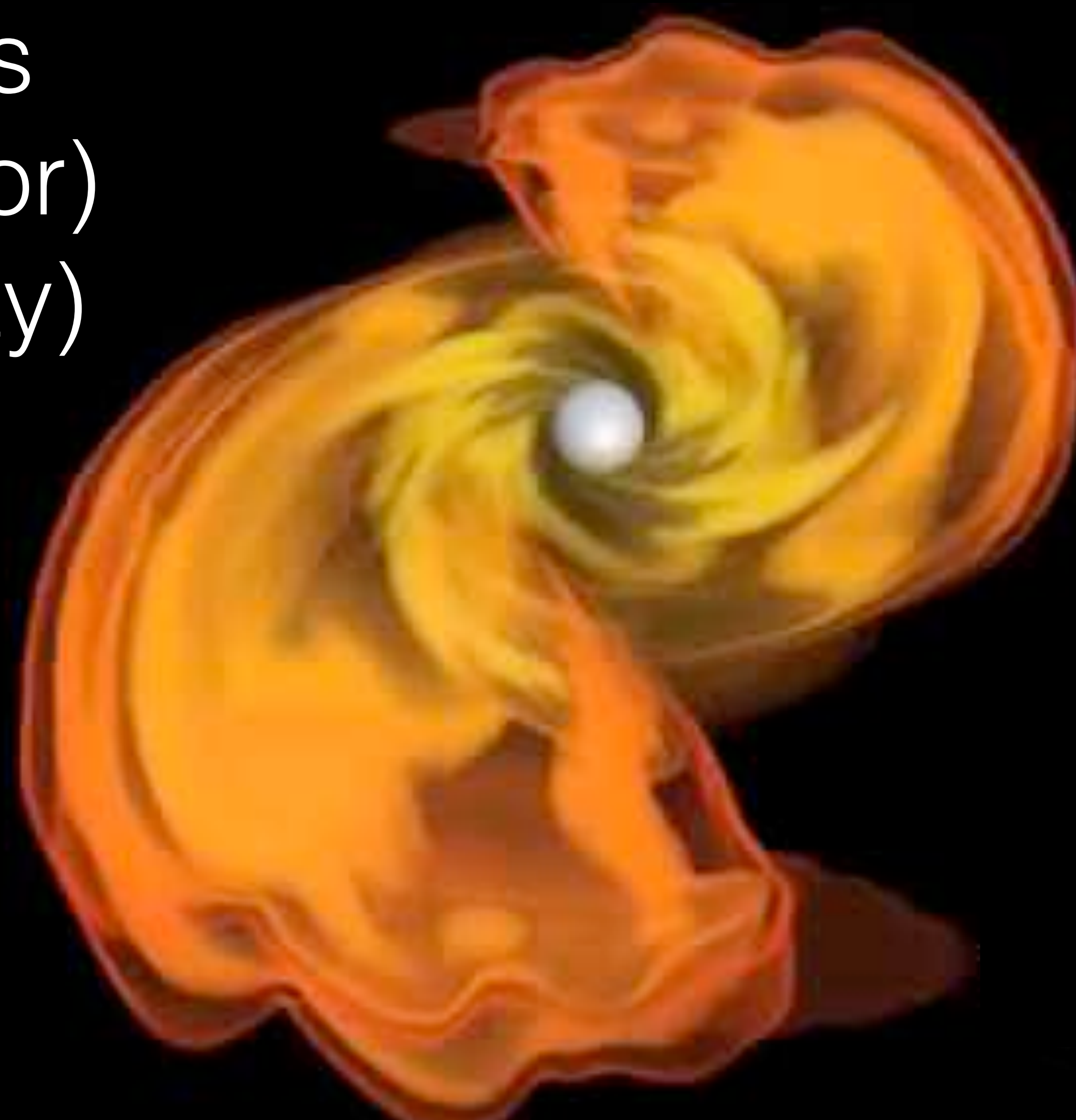
Jennifer Barnes
Hirschegg Workshop
January 18, 2017



Credit: Koppitz & Rezzolla

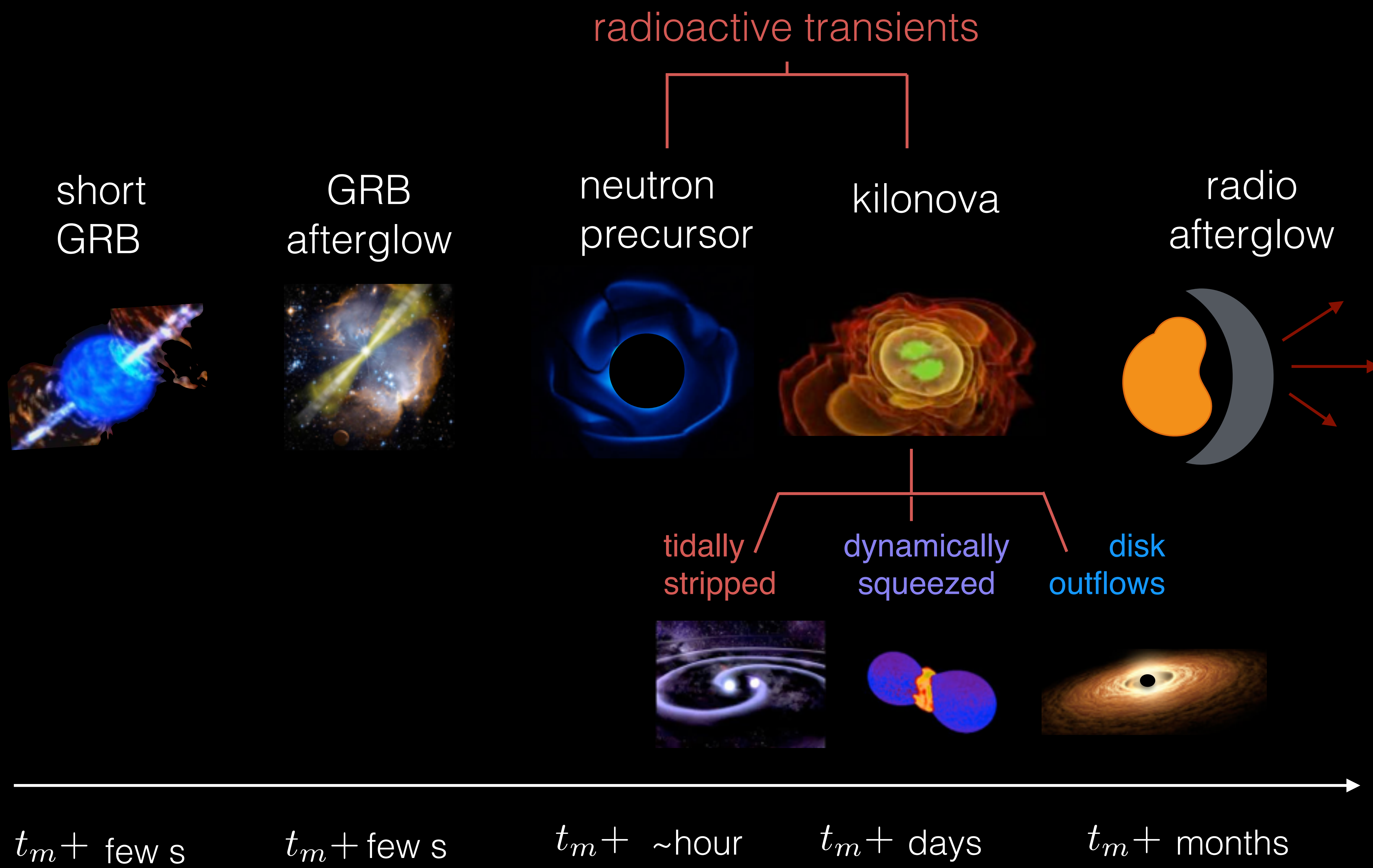
Roadmap

- Kilonova 101
  - background
  - early models
- Progress and uncertainties
  - *r*-process opacities (color)
  - thermalization (luminosity)



Credit: Baiotti, Giacamazzo & Rezzolla

EM Counterparts



EM counterparts: kilonovae

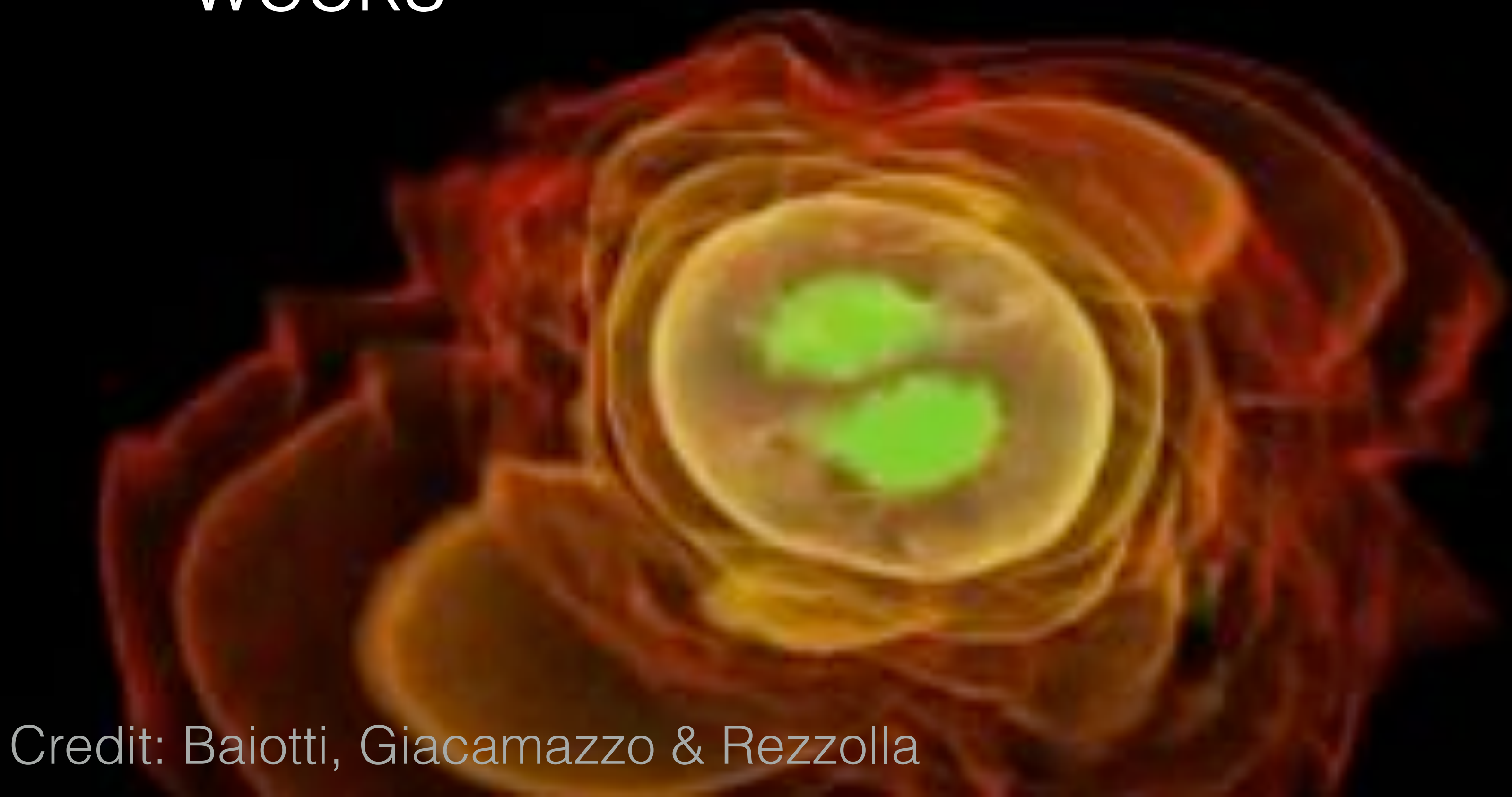
mini-supernova powered by radioactive decay in the dynamical ejecta and disk winds

- isotropic
- timescales of days to weeks

kilonovae offer us a window into heavy element production via the *r*-process

↓

origin of the heavy elements



EM counterparts: kilonovae

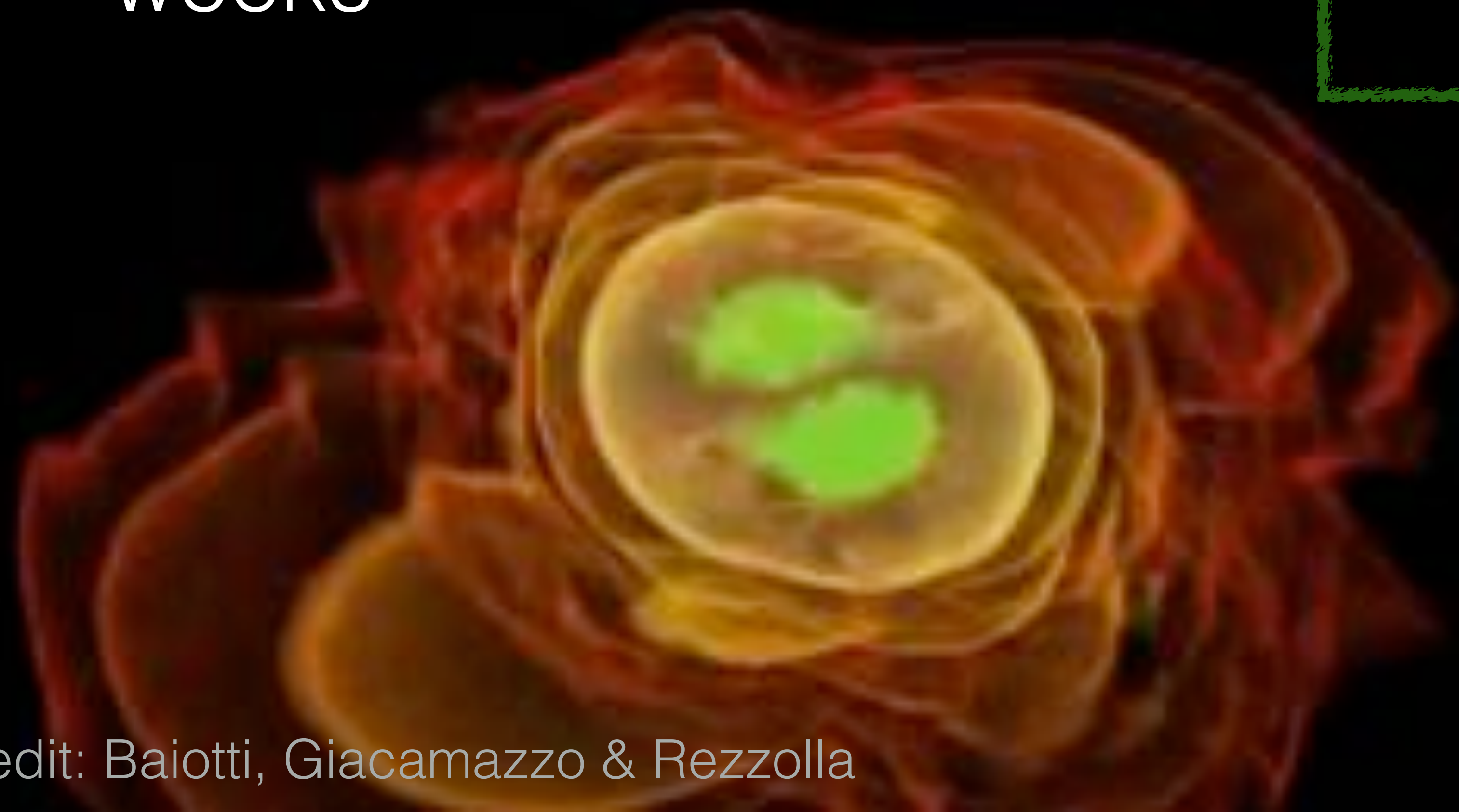
mini-supernova powered by radioactive decay in the dynamical ejecta and disk winds

- isotropic
- timescales of days to weeks

kilonovae offer us a window into heavy element production via the *r*-process

↓

origin of the heavy elements

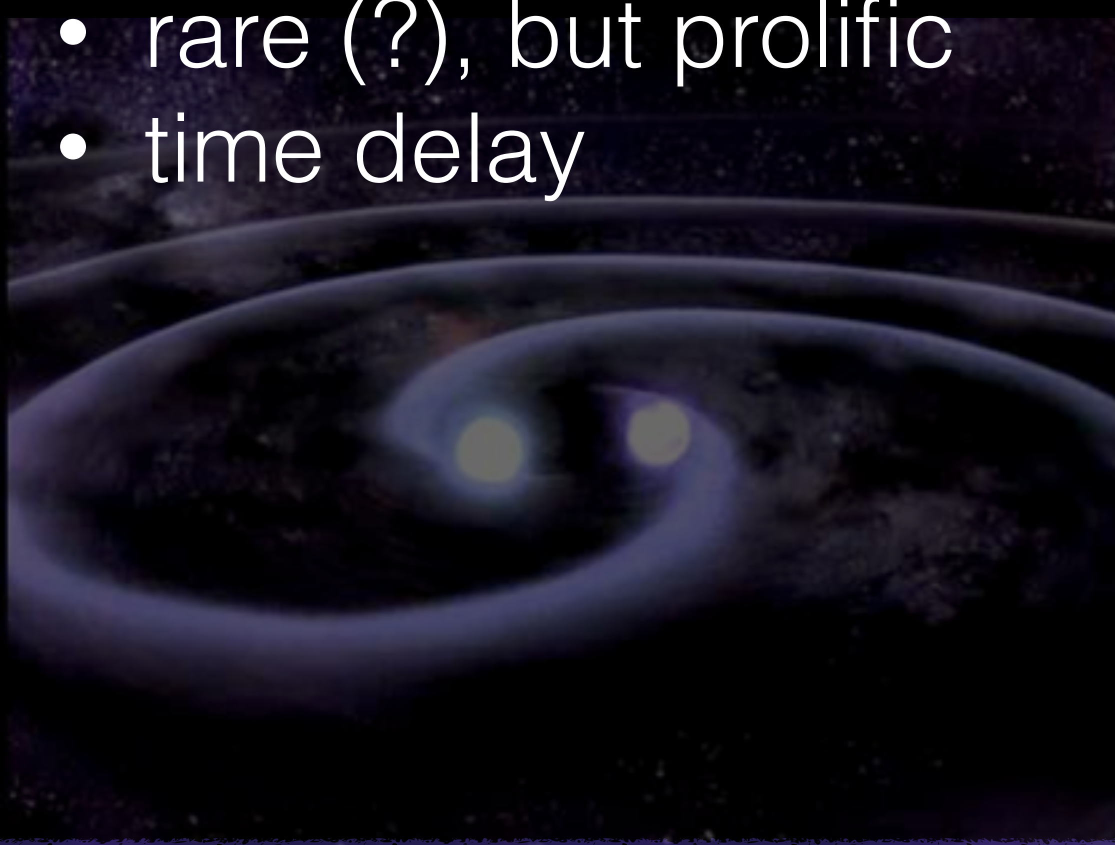


Credit: Baiotti, Giacamazzo & Rezzolla

r-process origins

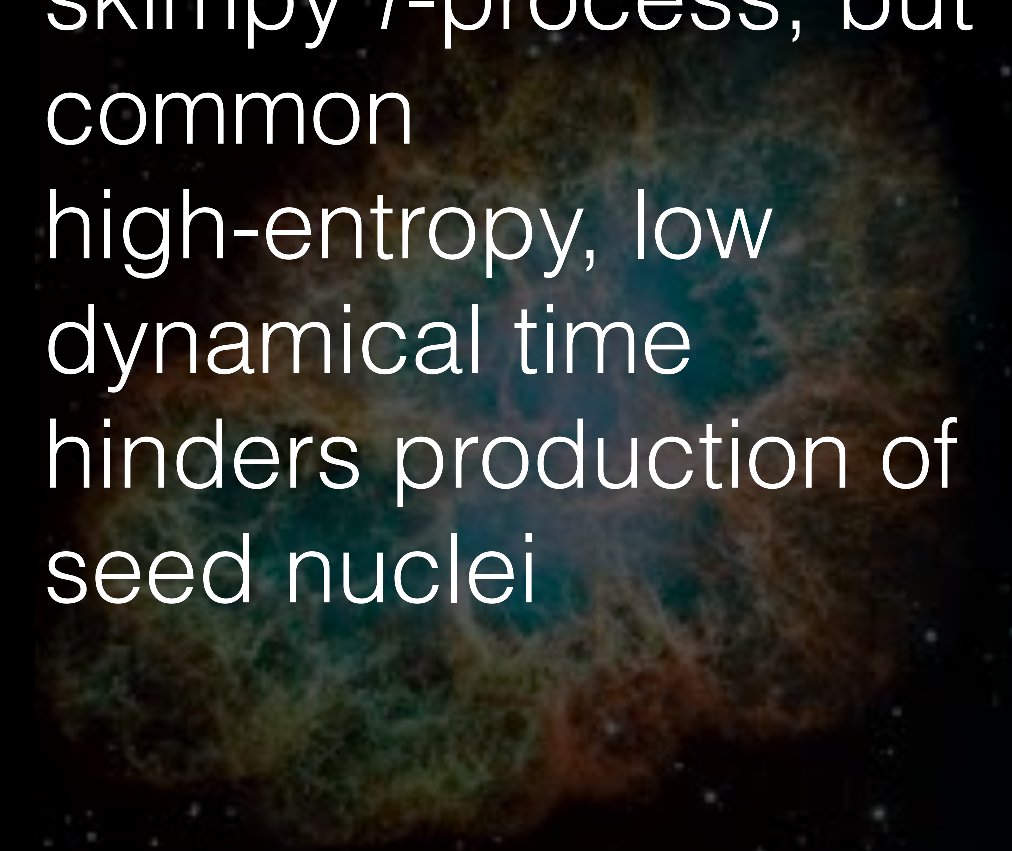
Compact Object Mergers

- naturally produce low-entropy, neutron rich conditions
- rare (?), but prolific
- time delay



Core Collapse SNe
(ν-driven winds)

- *r*-process abundance in old stars
- skimpy *r*-process, but common
- high-entropy, low dynamical time hinders production of seed nuclei

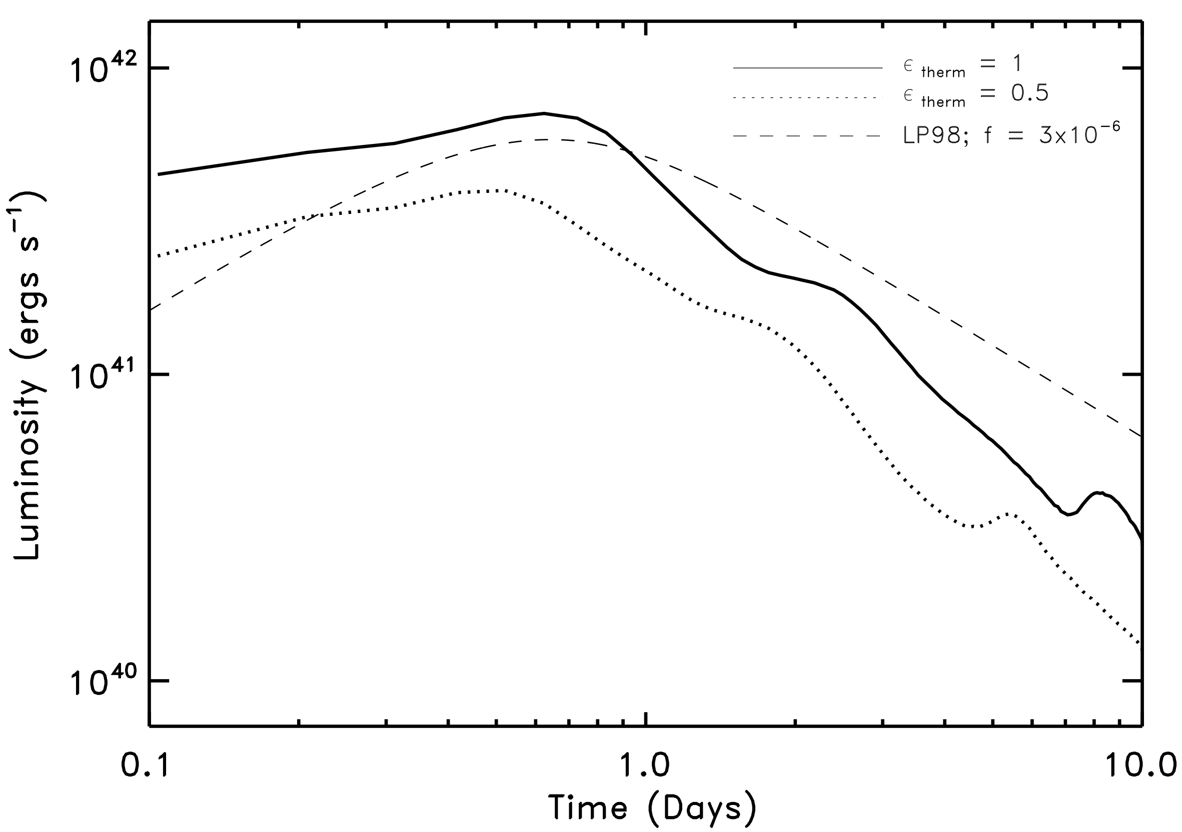


Kilonovae: early models

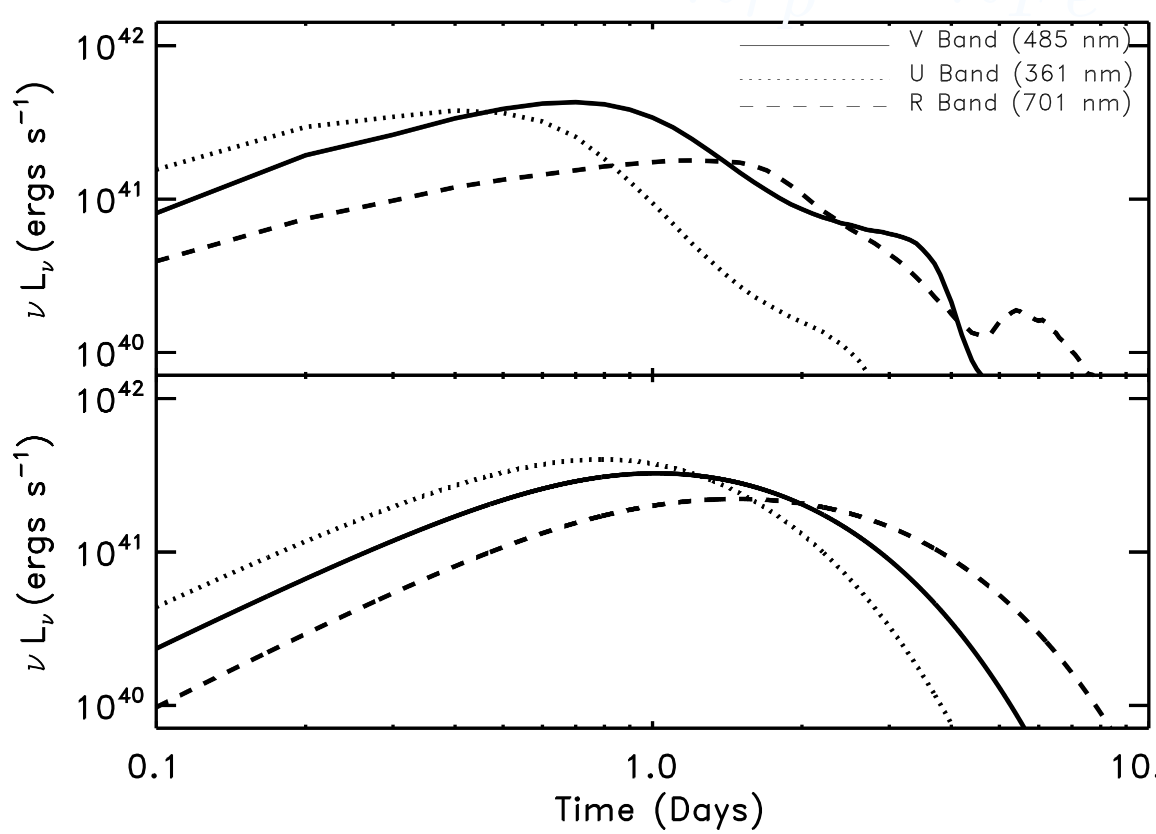
Lattimer and Schramm 1974, 1976
Li & Paczynski 1998, Kulkarni 2005
Metzger et al. 2010, Roberts et al. 2011

$$t_p \simeq 1 \text{ day}$$

$$L_{bol,p} \lesssim 5 \times 10^{41} \text{ergs s}^{-1}$$



Emission peaks in V-band



Metzger et al. 2010

The *r*-process: challenges

Endgame: determine ejected mass, composition from data

Obstacles: unusual nucleosynthesis with limited experimental measurements

optical properties of the *r*-process-rich ejecta → color and luminosity

r-process energy generation and thermalization efficiency → luminosity, light curve shape

The *r*-process: challenges

Endgame: determine ejected mass, composition from data

Obstacles: unusual nucleosynthesis with limited experimental measurements

optical properties of the *r*-process-rich ejecta → color and luminosity

r-process energy generation and thermalization efficiency → luminosity, light curve shape

Expansion opacity

Sobolev optical depth:

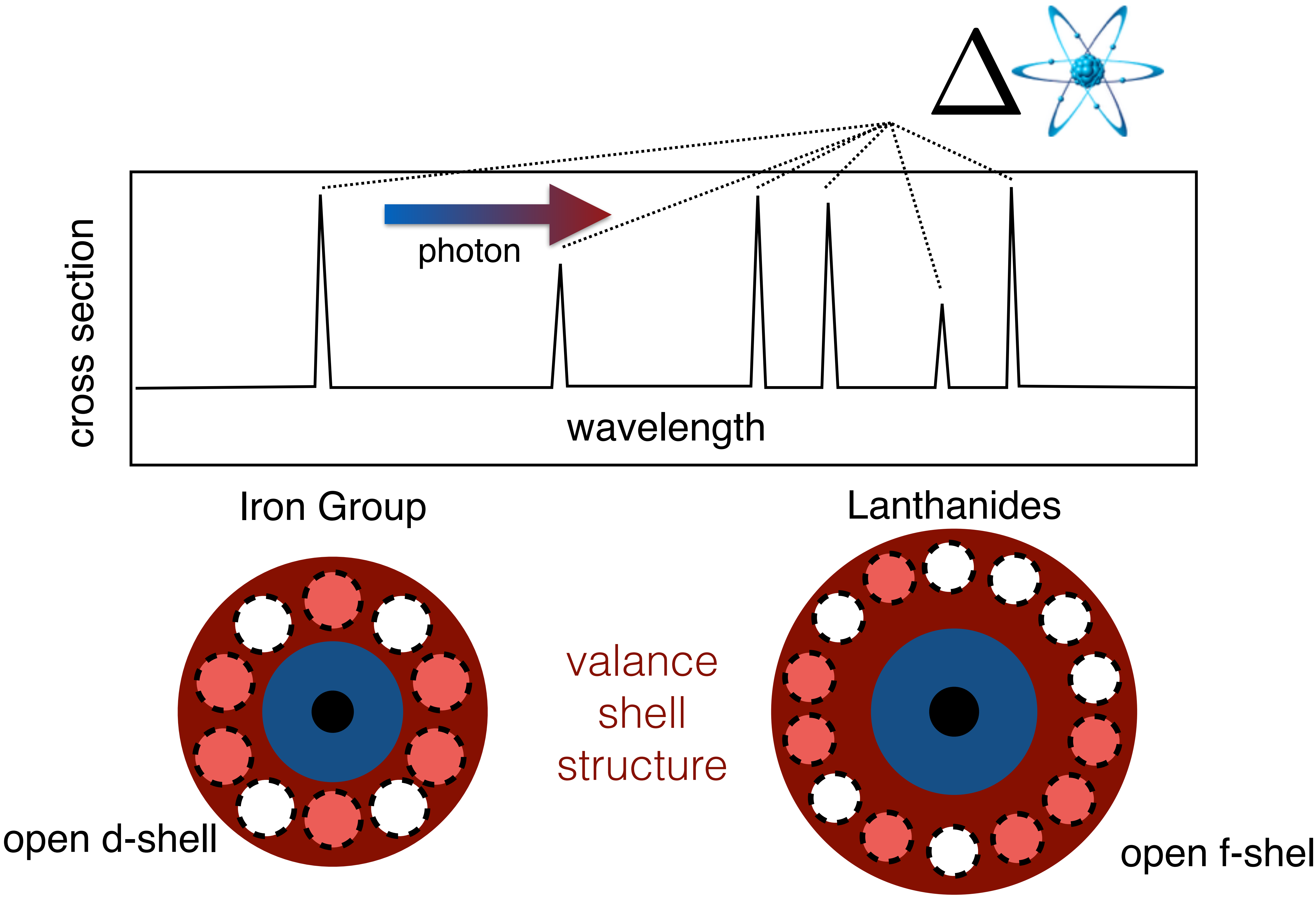
$$\tau_{\rm i} = \frac{\pi e^2}{m_{\rm e} c} f N_{\rm l} \frac{\lambda_0^2}{c} \left(1 - \frac{N_{\rm u} g_{\rm l}}{N_{\rm l} g_{\rm u}}\right) \times c \frac{t_{\rm exp}}{\lambda_0}$$

Expansion opacity (e.g Karp 1977, Eastman & Pinto 1993)

$$\kappa_{\rm exp} = \frac{1}{\rho c t_{\rm exp}} \sum_{\rm i} \frac{\lambda_{\rm i}}{\Delta \lambda_{\rm c}} \left(1 - e^{-\tau_{\rm i}}\right)$$

Assumes line profiles widths are small and that strong lines do not overlap in wavelength space

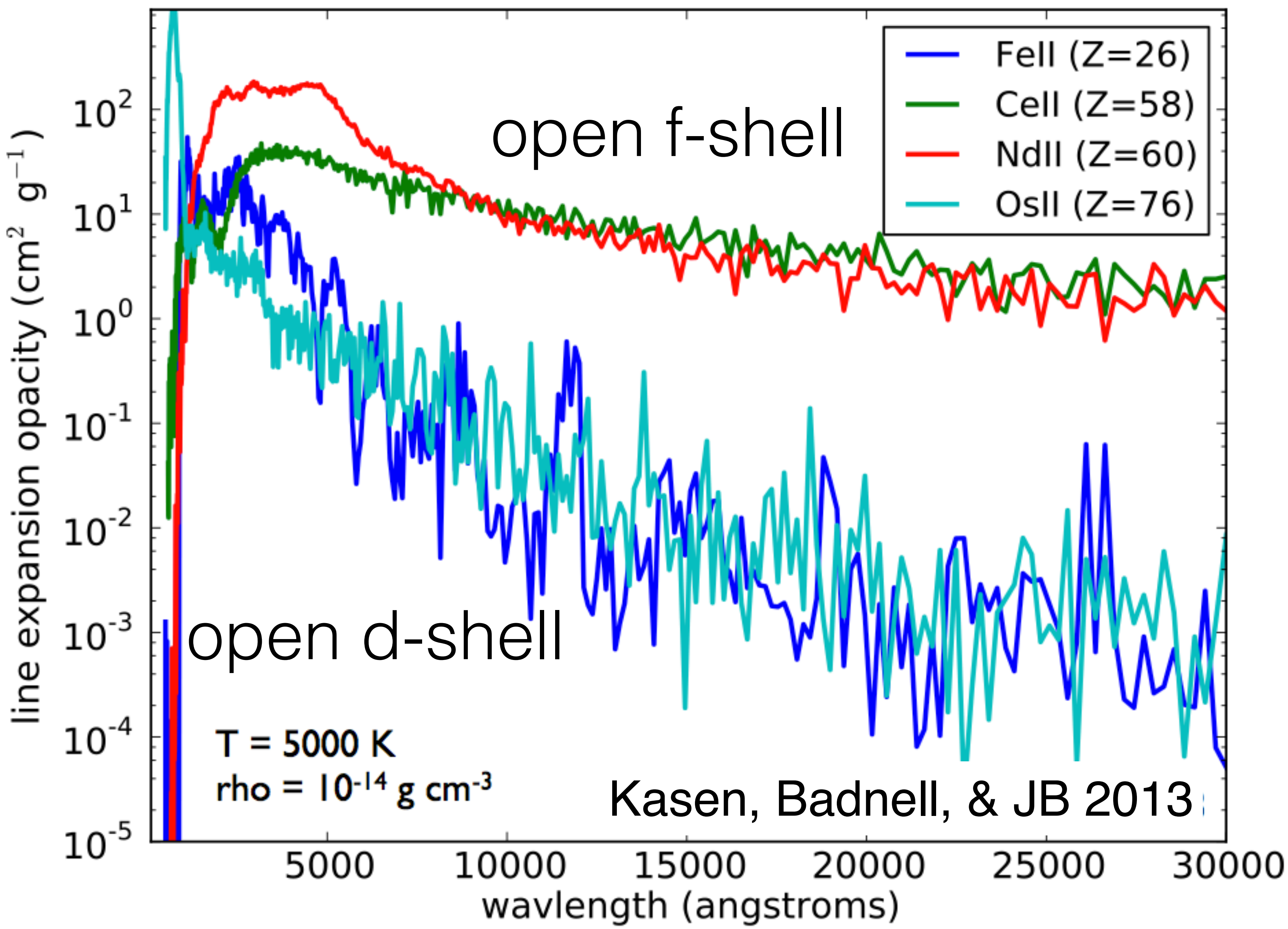
Kilonovae: opacity



Kilonovae: opacity

bound-bound opacity (lines) is a function of atomic structure:

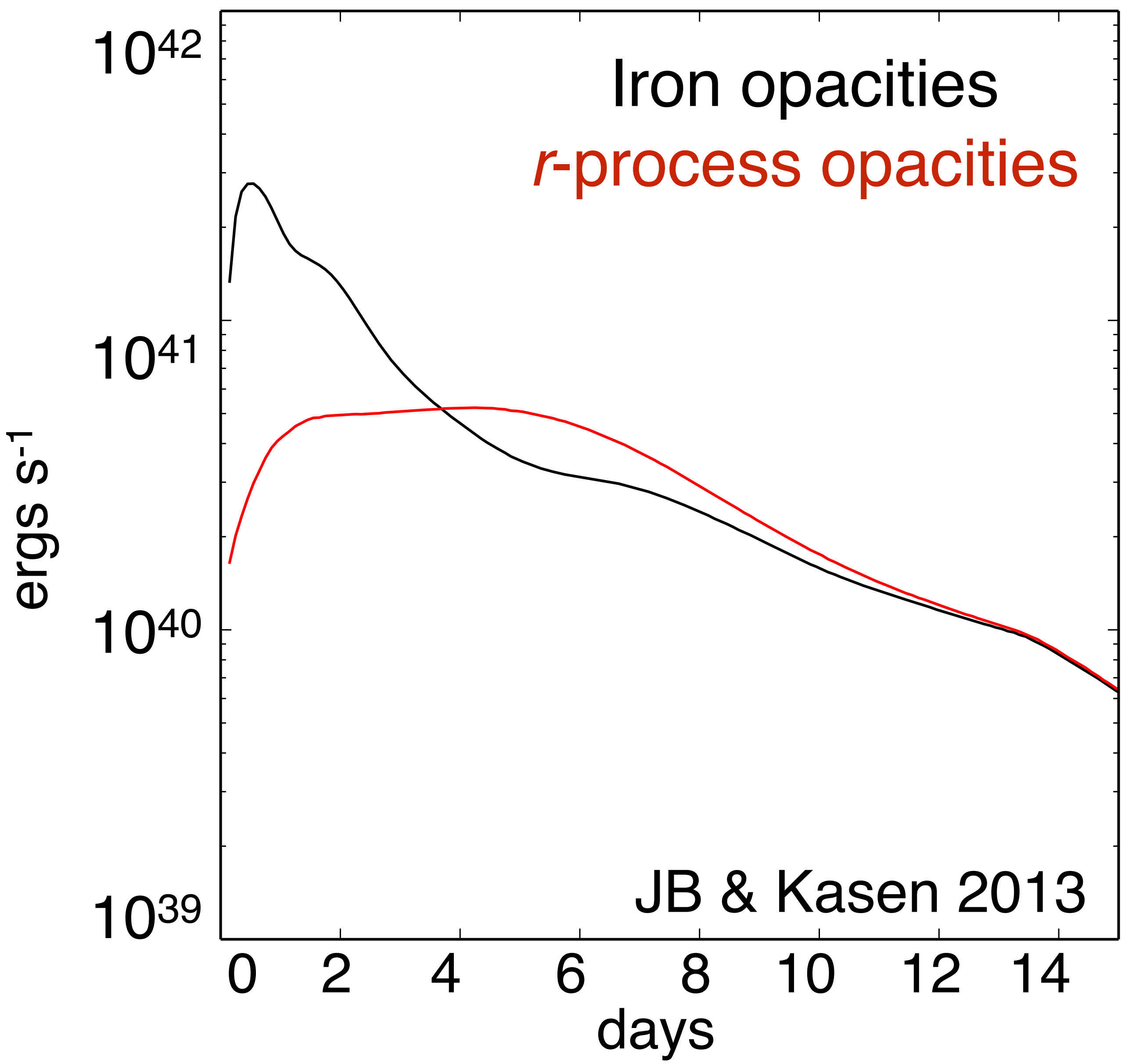
more valence e^- $\longrightarrow$ more lines $\longrightarrow$ higher κ



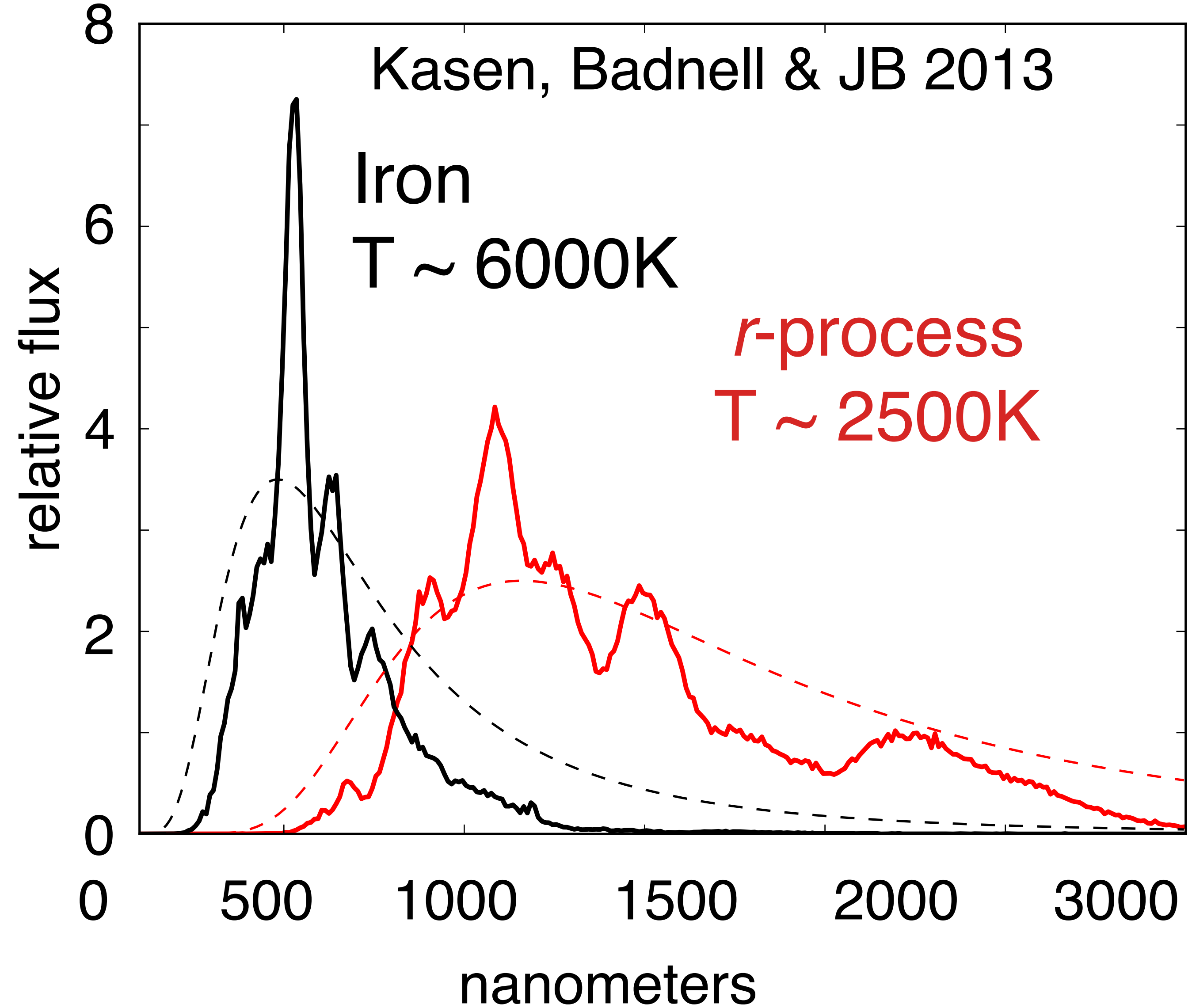
opacity → observables

composition → **shine blue** or **glow red**?

Bolometric Luminosity



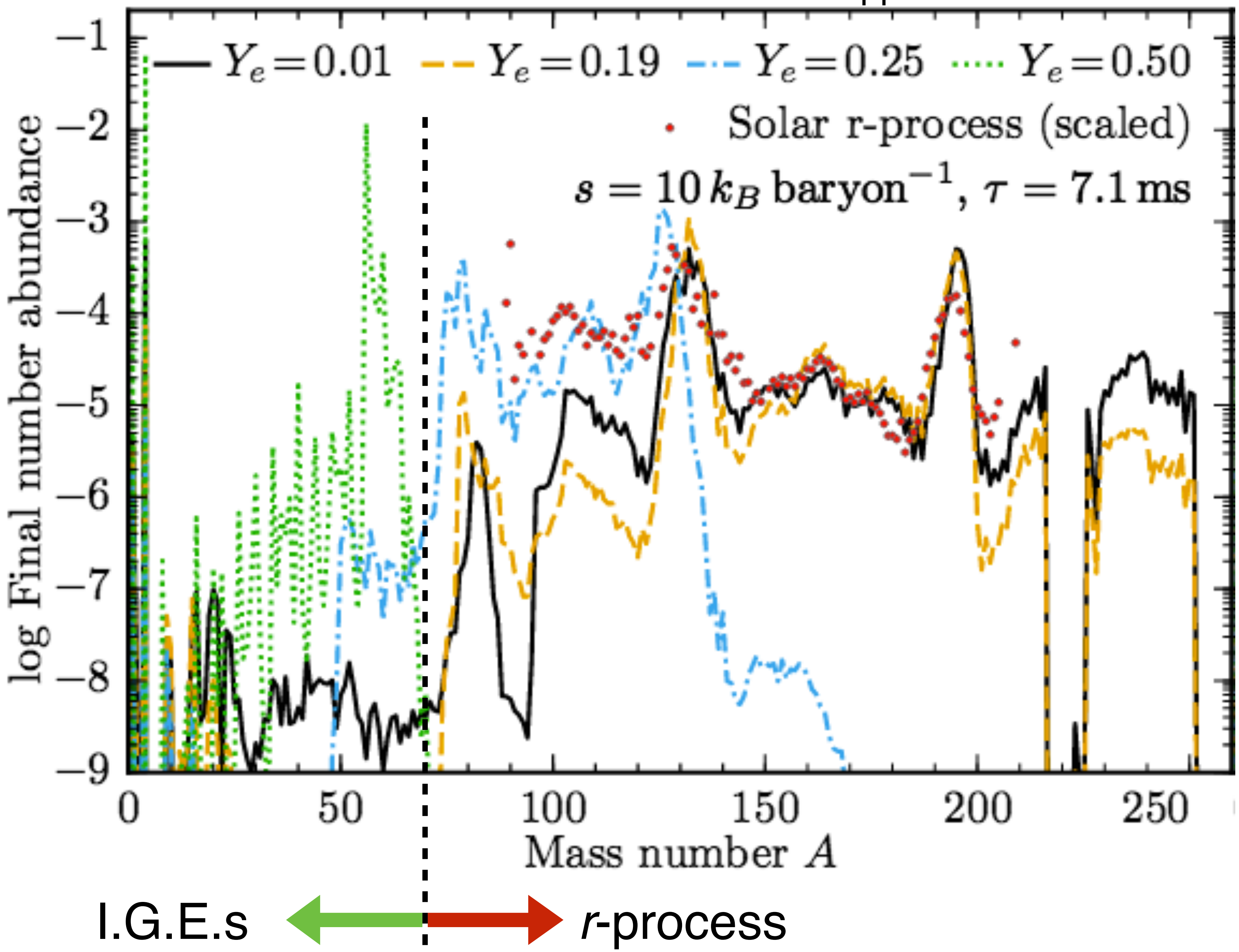
Spectra



opacity: multi-component light curves

r-process yields are not guaranteed!

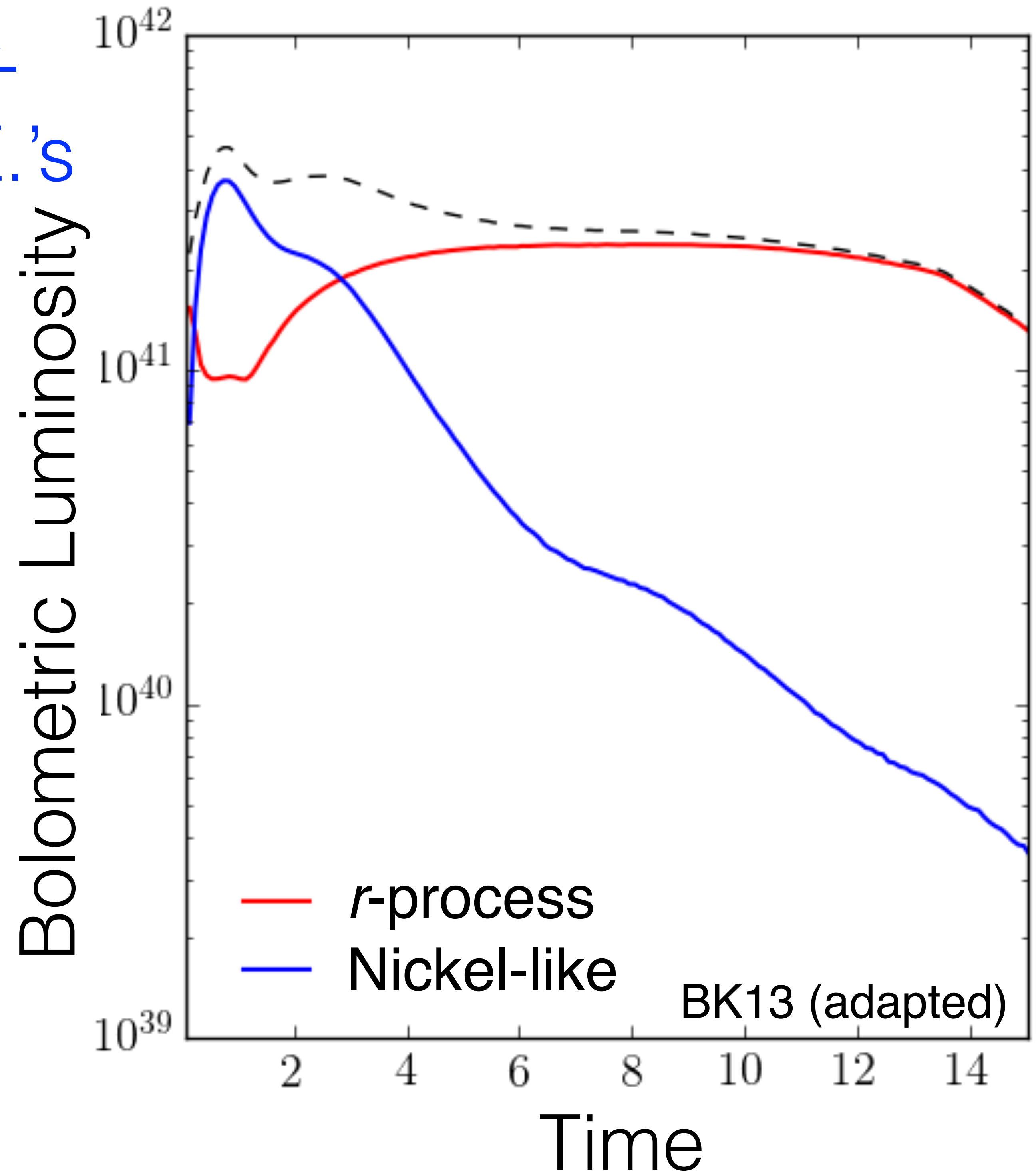
Lippuner & Roberts 2015



opacity: multi-component light curves

different ejection mechanisms + ν-interactions

ν-irradiated disk wind (light *r*-process/I.G.E.'s



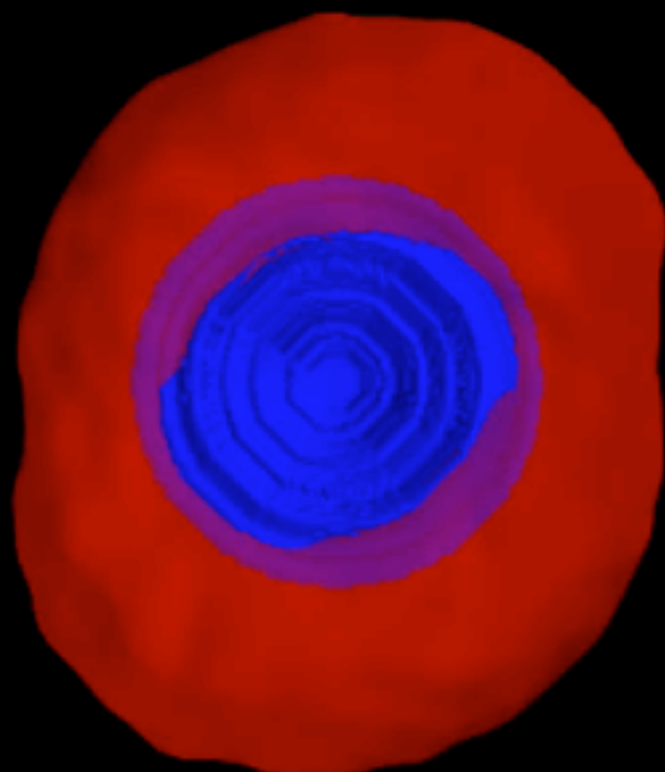
neutron-rich dynamical ejecta (heavy *r*-process)

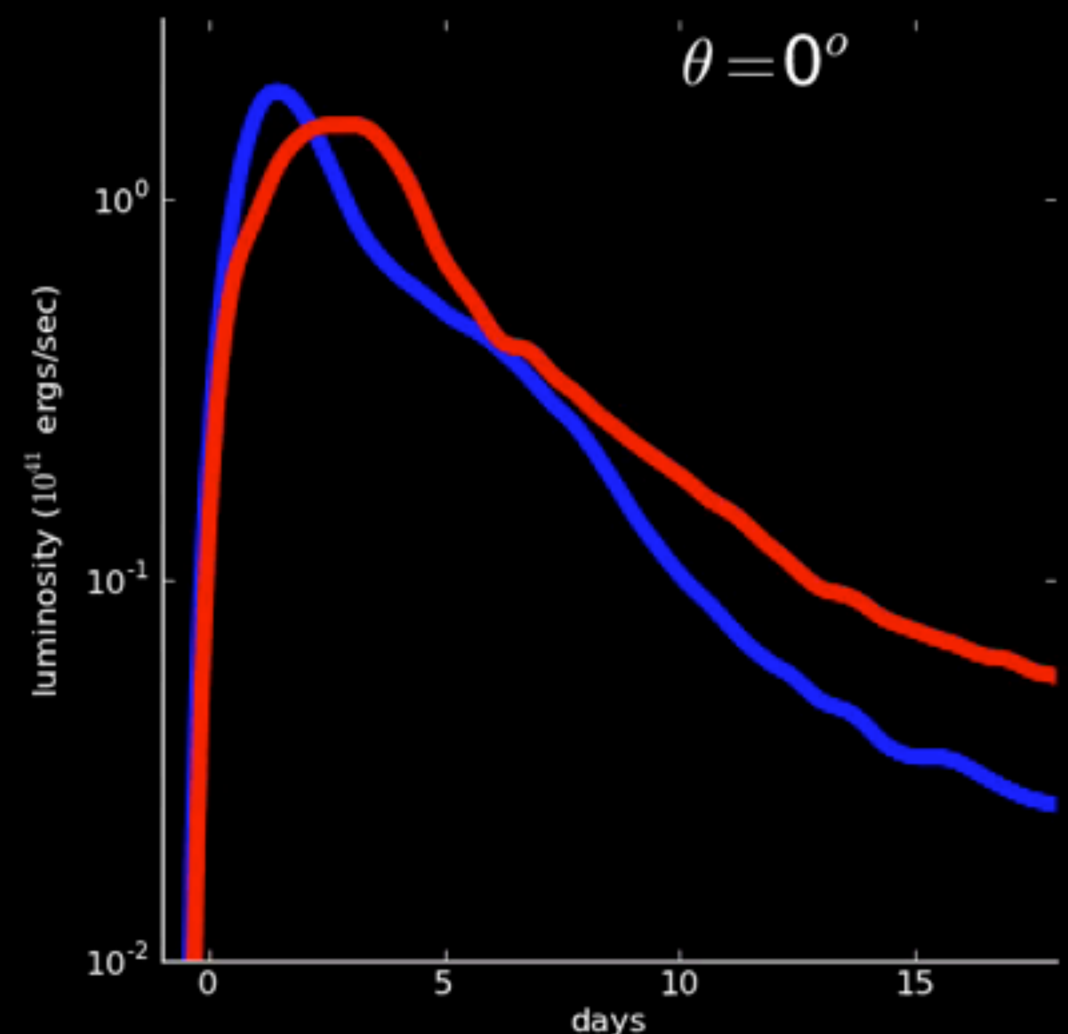
Kilonovae: interactions

wind + dynamical ejecta

Kilonovae: interactions

wind + dynamical ejecta





The *r*-process: challenges

Endgame: determine ejected mass, composition from data

Obstacles: unusual nucleosynthesis with limited experimental measurements

optical properties of the *r*-process-rich ejecta → color and luminosity

r-process energy generation and thermalization efficiency → luminosity, light curve shape

The *r*-process: challenges

Endgame: determine ejected mass, composition from data

Obstacles: unusual nucleosynthesis with limited experimental measurements

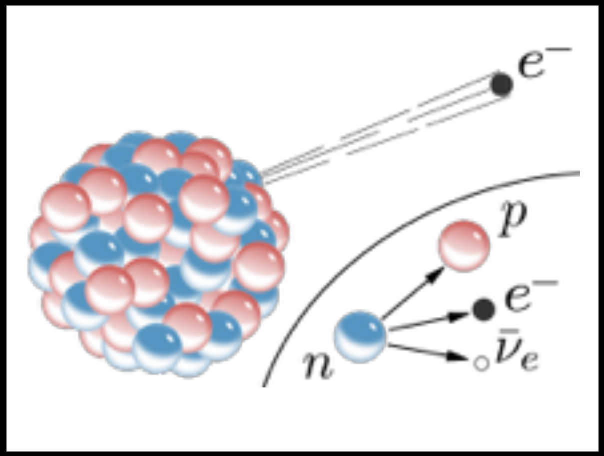
optical properties of the *r*-process-rich ejecta → color and luminosity

r-process energy
efficiency

with Meng-Ru Wu, Gabriel Martinez-Pinedo

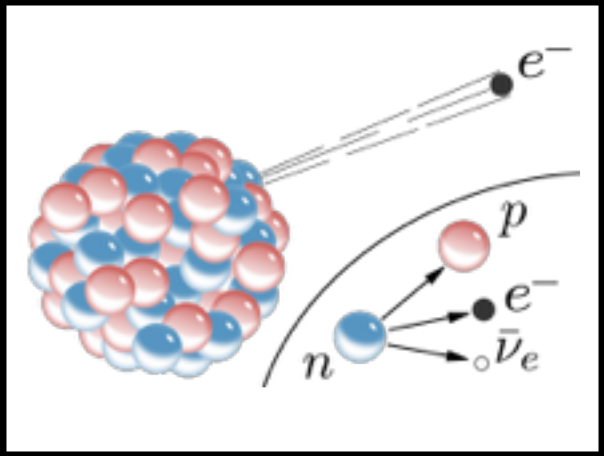
Thermalization in kilonova

radioactive decay

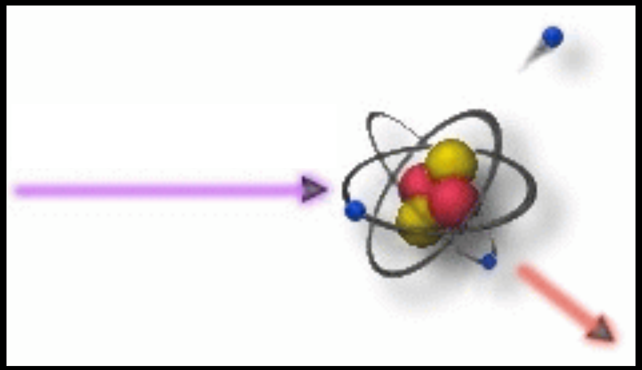


Thermalization in kilonova

radioactive decay

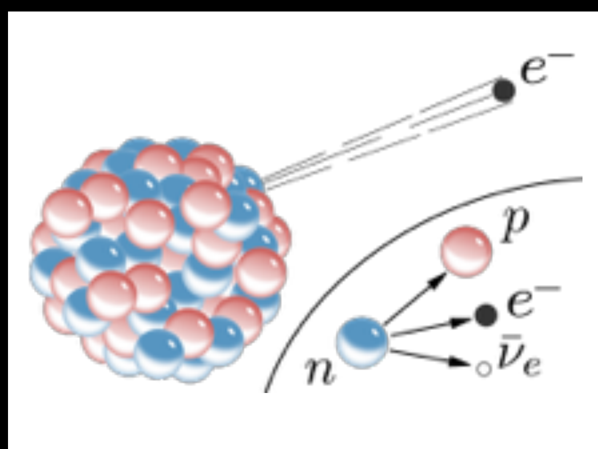


transfer to the thermal pool

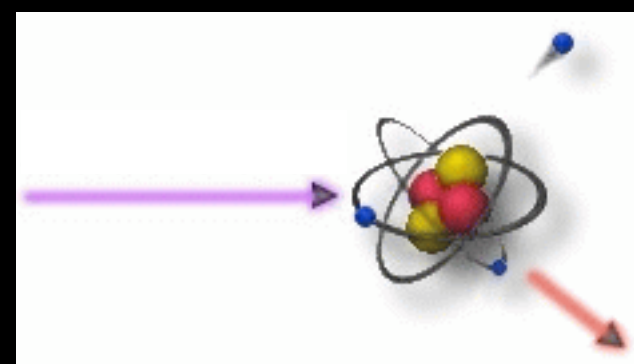


Thermalization in kilonova

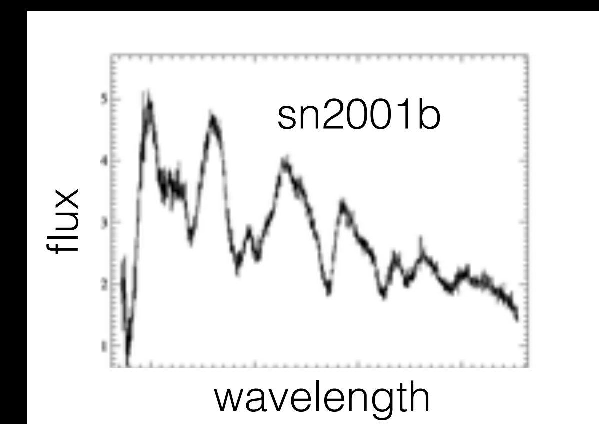
radioactive decay



transfer to the thermal pool

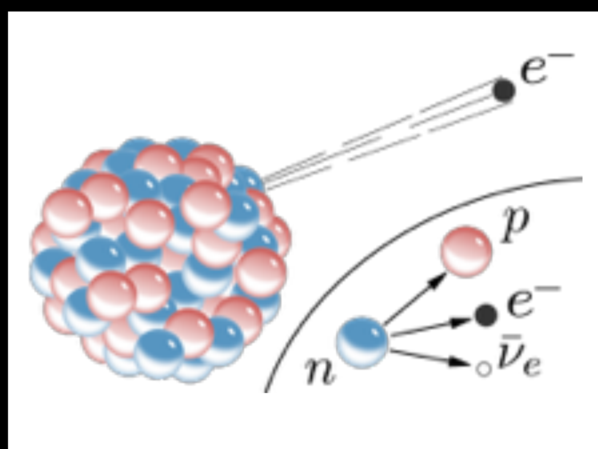


re-radiated as thermal emission

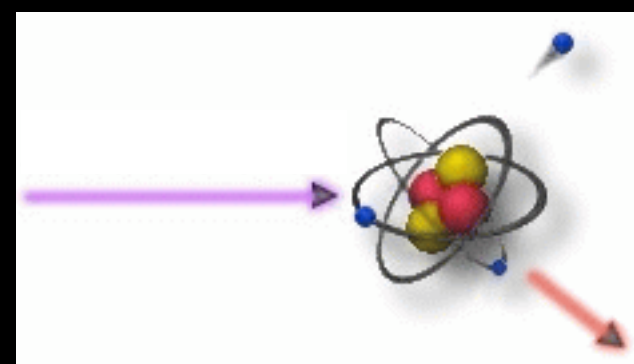


Thermalization in kilonova

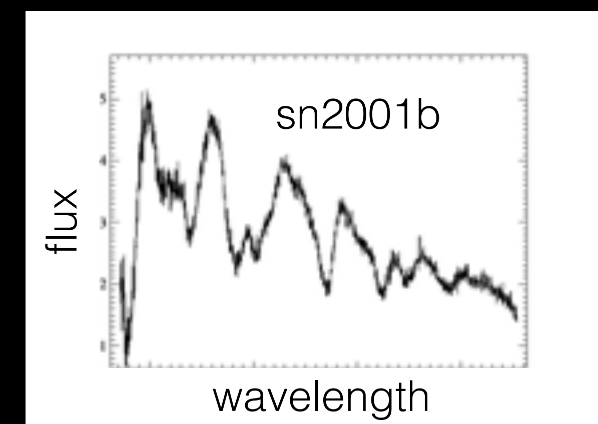
radioactive decay



transfer to the thermal pool



re-radiated as thermal emission



Challenges:

1. Exotic composition with unknown cross-sections
2. Multiple decay chains generating β, α, γ- and x-rays, and fission fragments, each at distinct, often unknown, rates and energies
3. Uncertainties in ejecta parameters

Thermalization: methods

nuclear reaction networks to determine *r*-process yields

Thermalization: methods

nuclear reaction networks to determine *r*-process yields

cross sections for energy loss

decay modes and spectra

+

ejecta parameters

Thermalization: methods

nuclear reaction networks to determine *r*-process yields

cross sections for energy loss

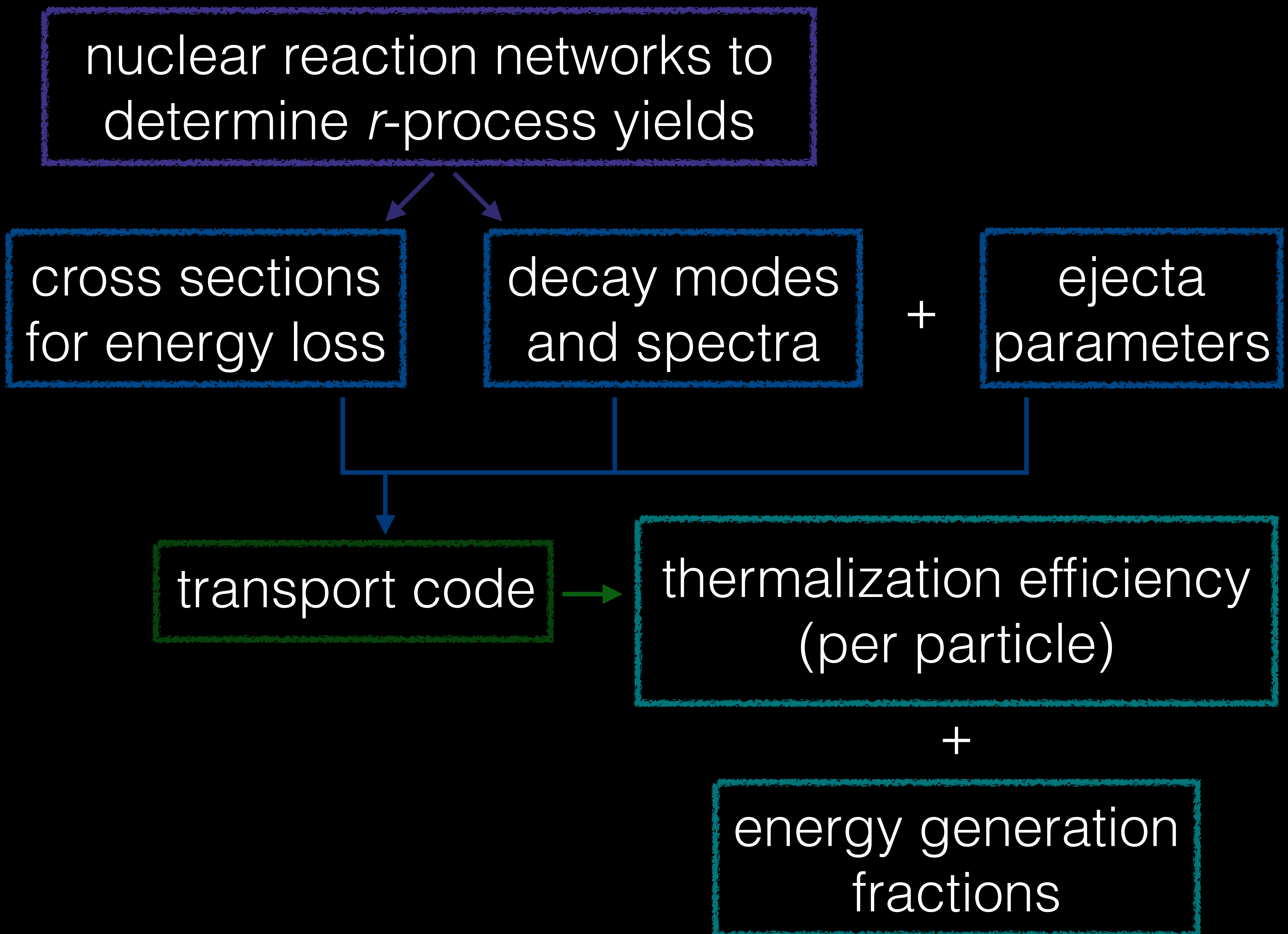
decay modes and spectra

+

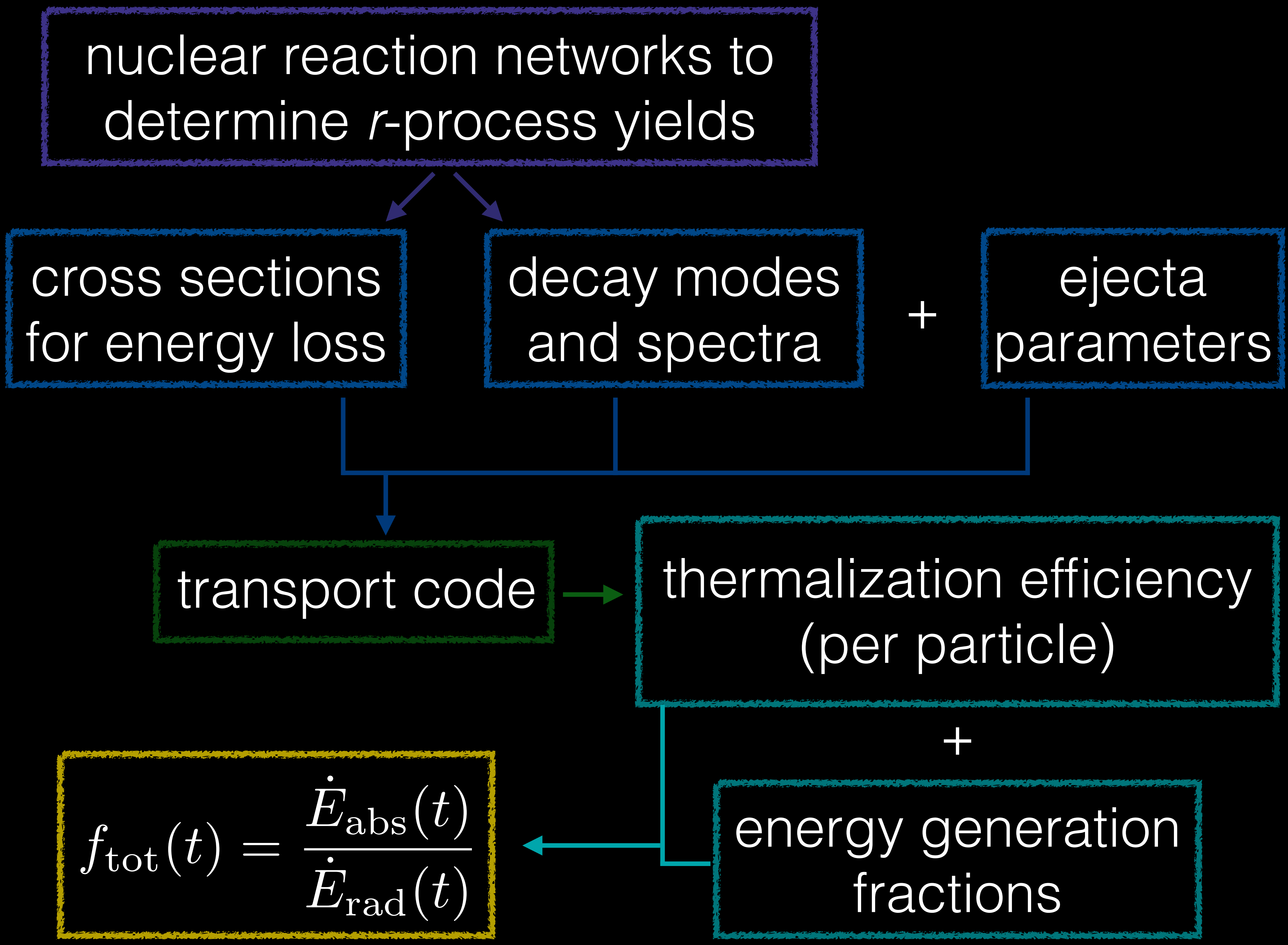
ejecta parameters

transport code

Thermalization: methods



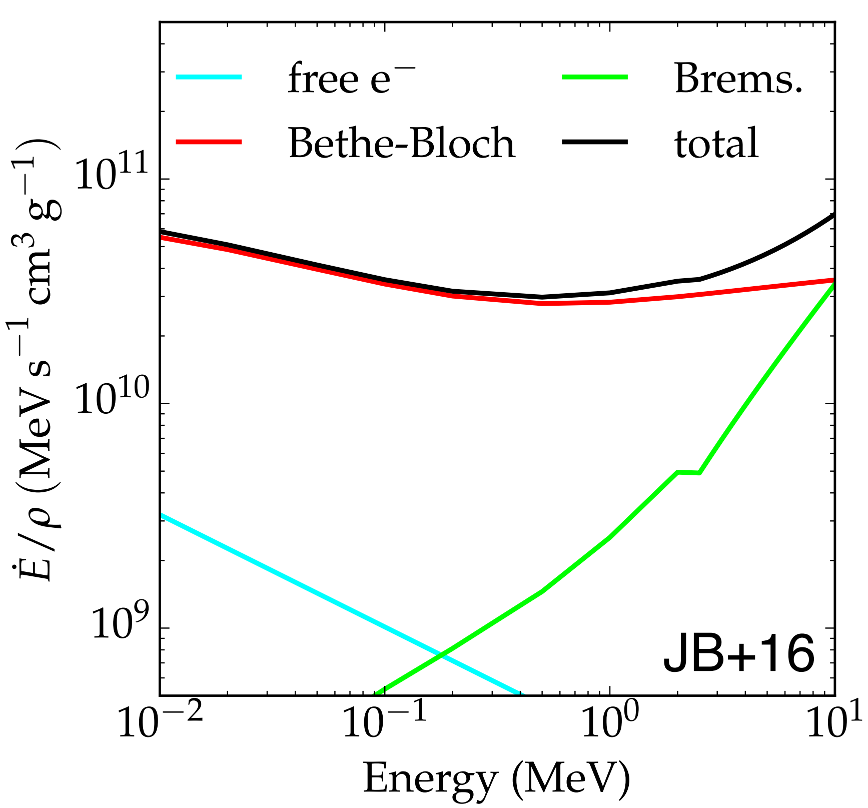
Thermalization: methods

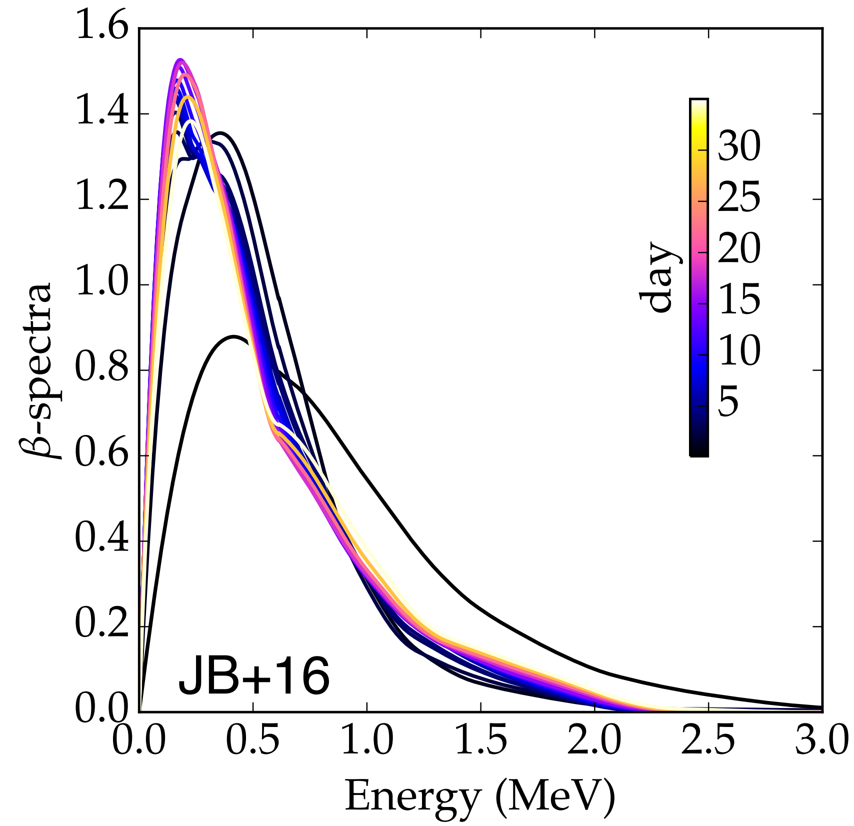


Case study: β-particles

Energy-loss channels:

- Bethe-Bloch
- Plasma losses
- Bremsstrahlung



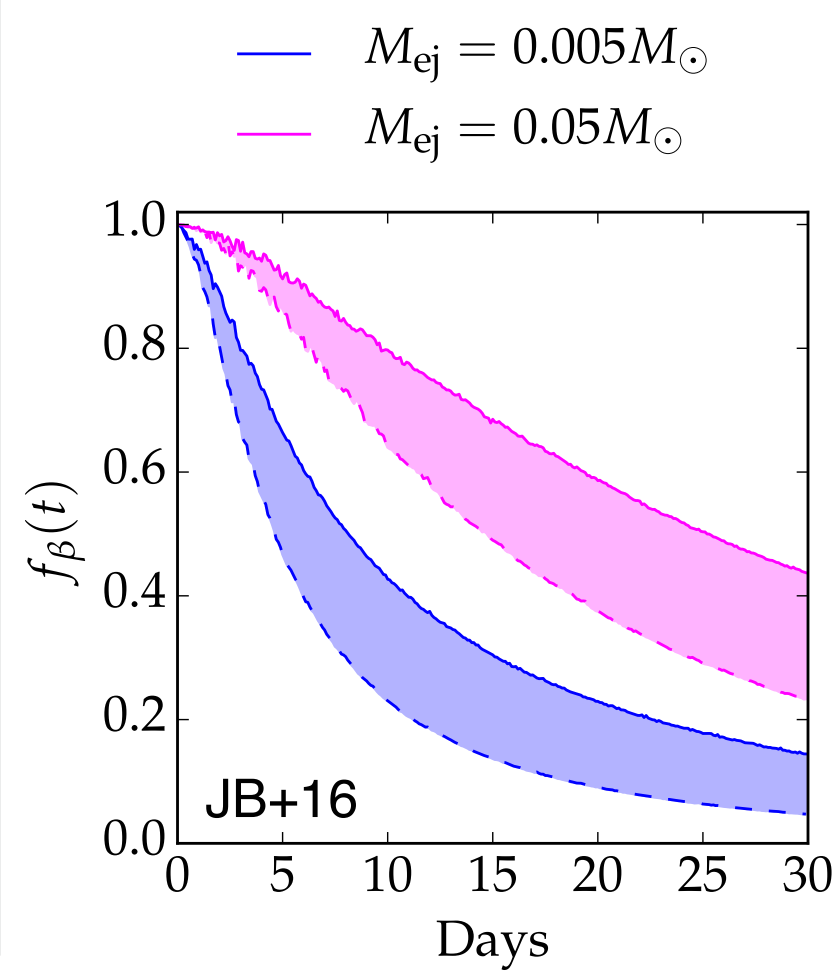


Time-dependent spectra

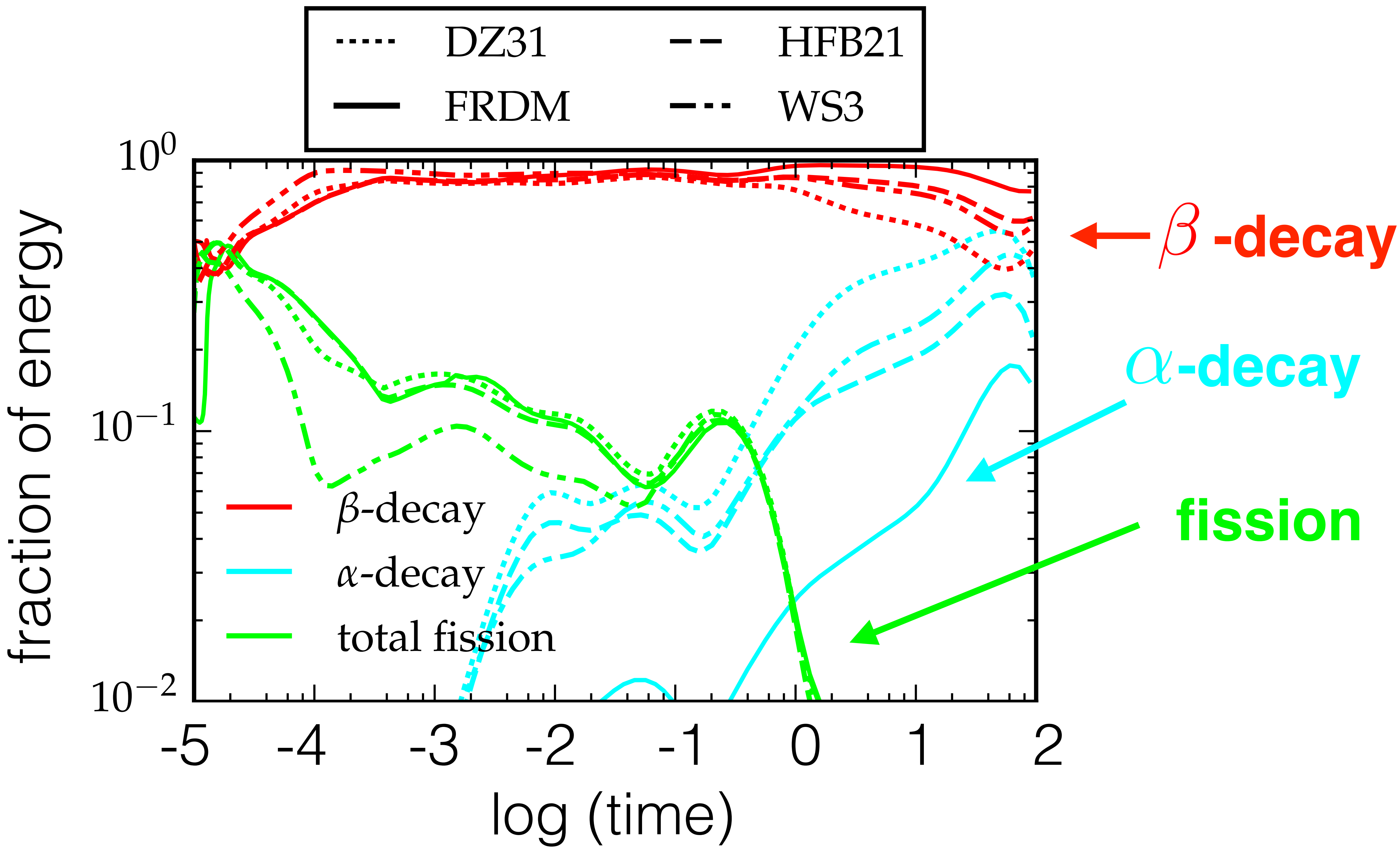
- from *r*-process yields and nuclear data

Time-dependent $f_\beta(t)$

- for a range of ejecta parameters

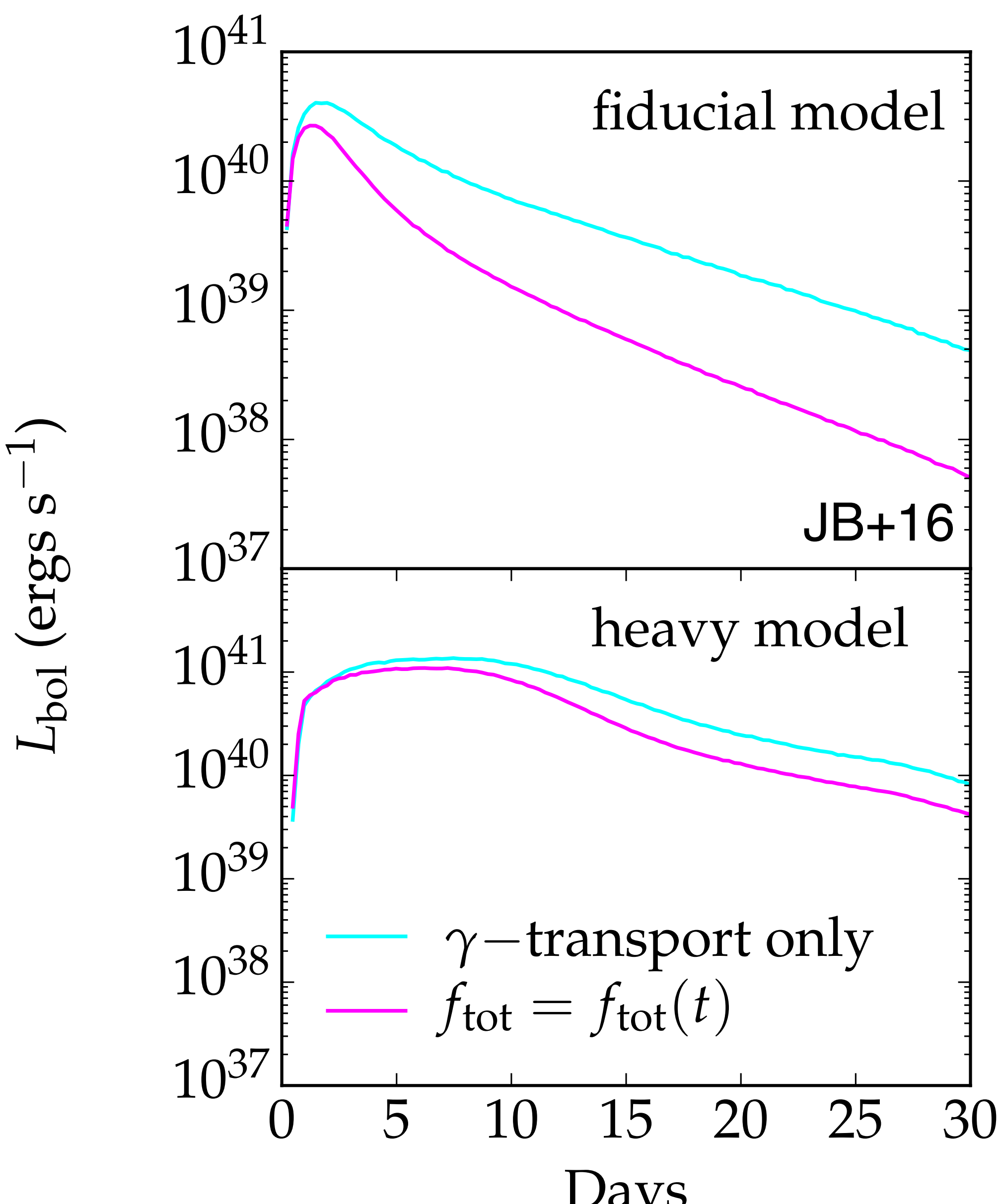


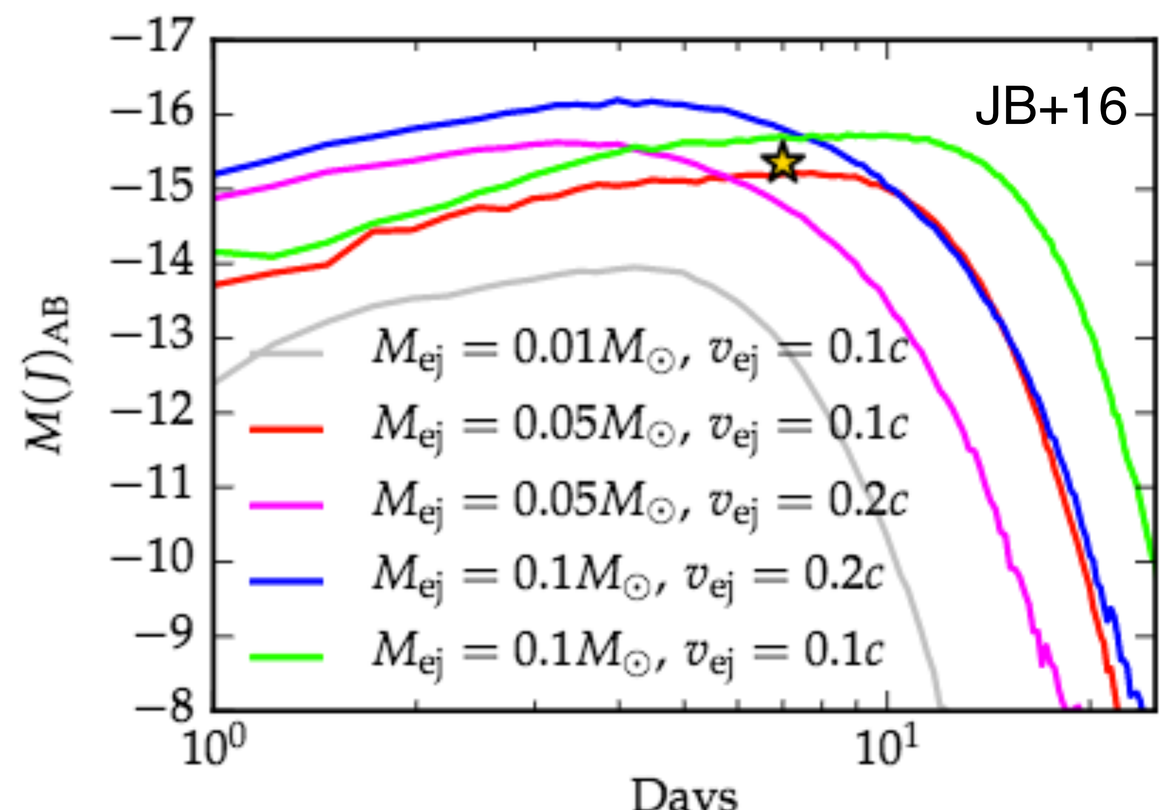
Energy-generation rates



Thermalization: effect on light curves

- lower luminosity (especially for less massive ejecta)
- allows more better estimate of mass from observations

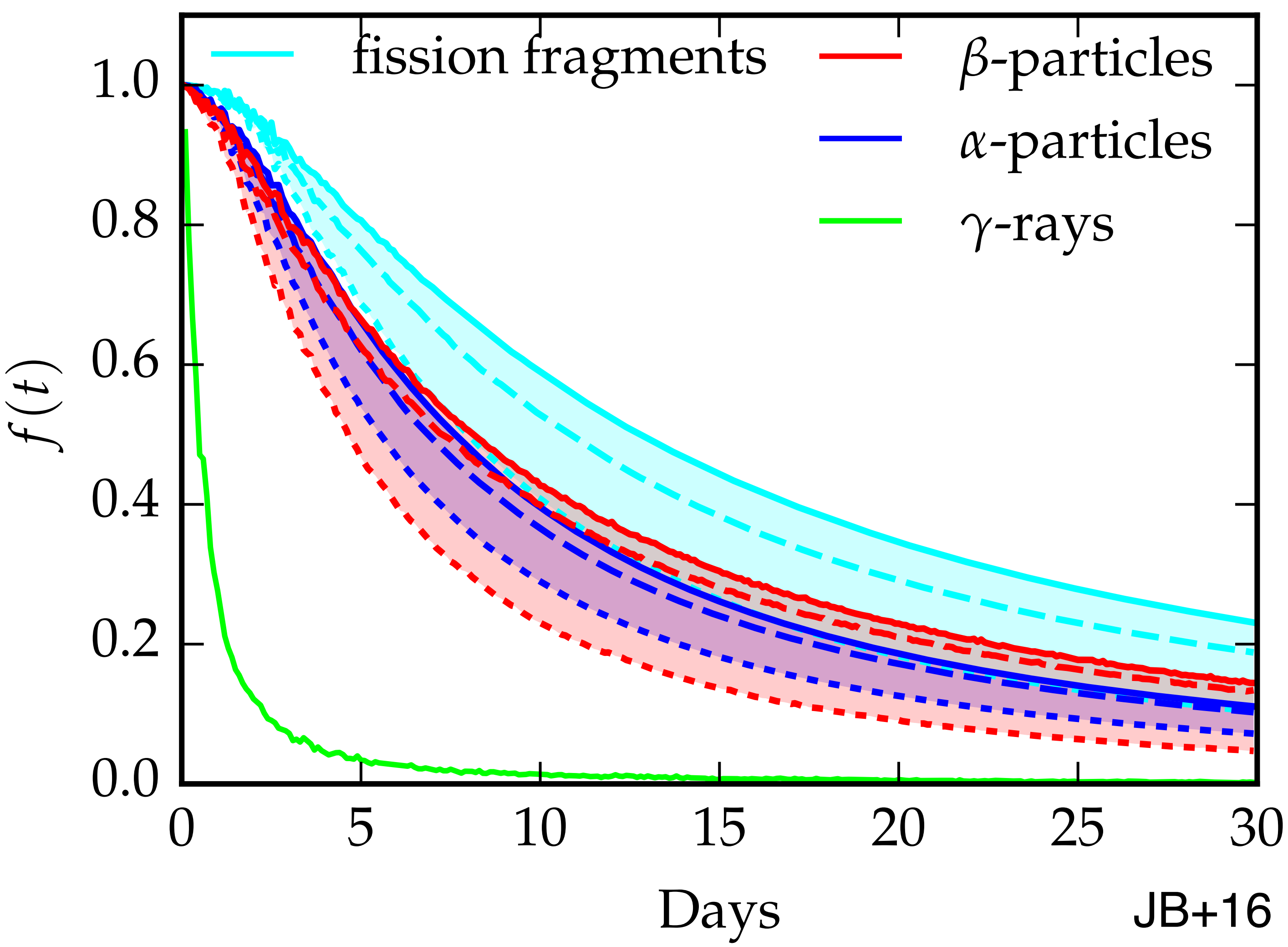


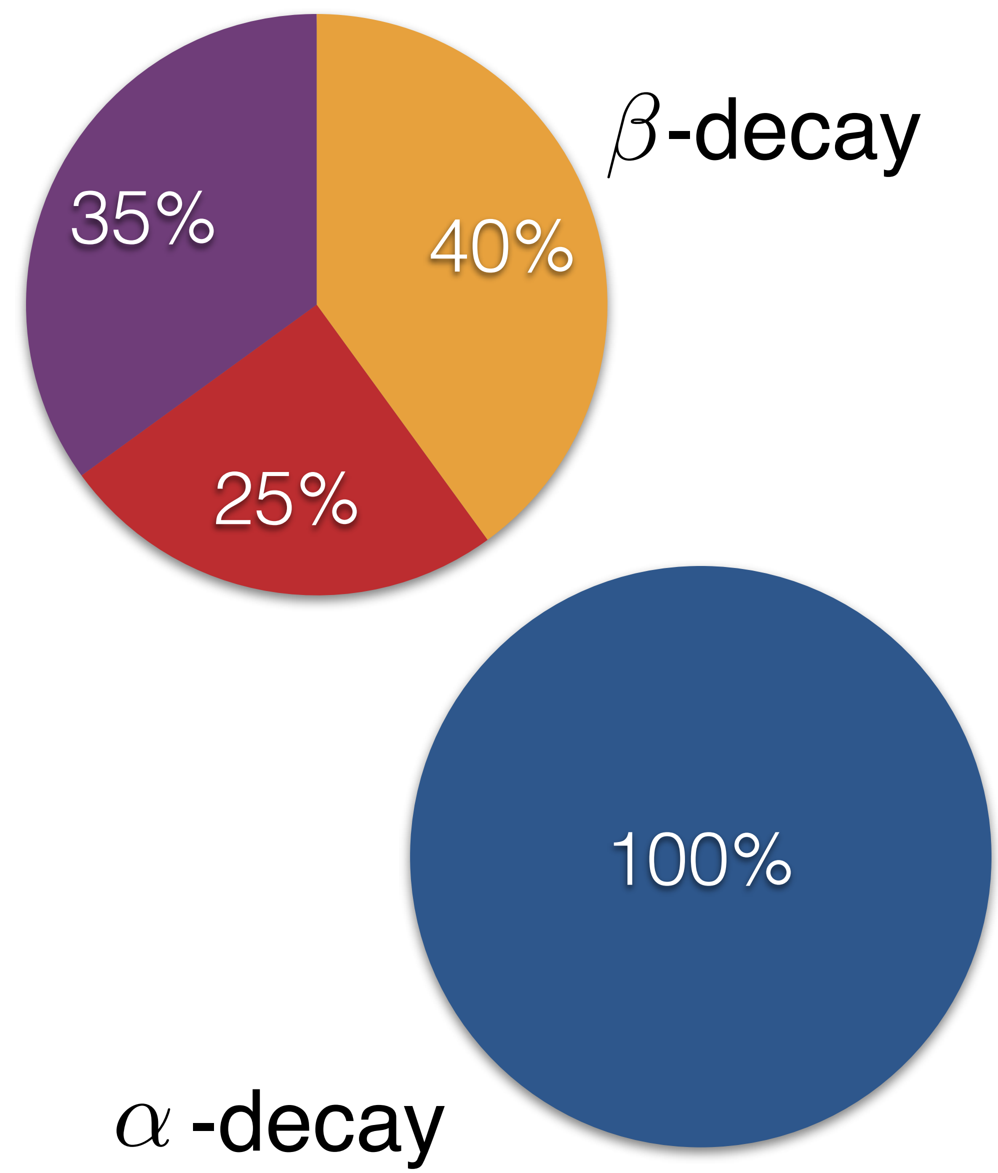


application to kn (?) associated with 130603B (Berger+ 13, Tanvir+ 13)

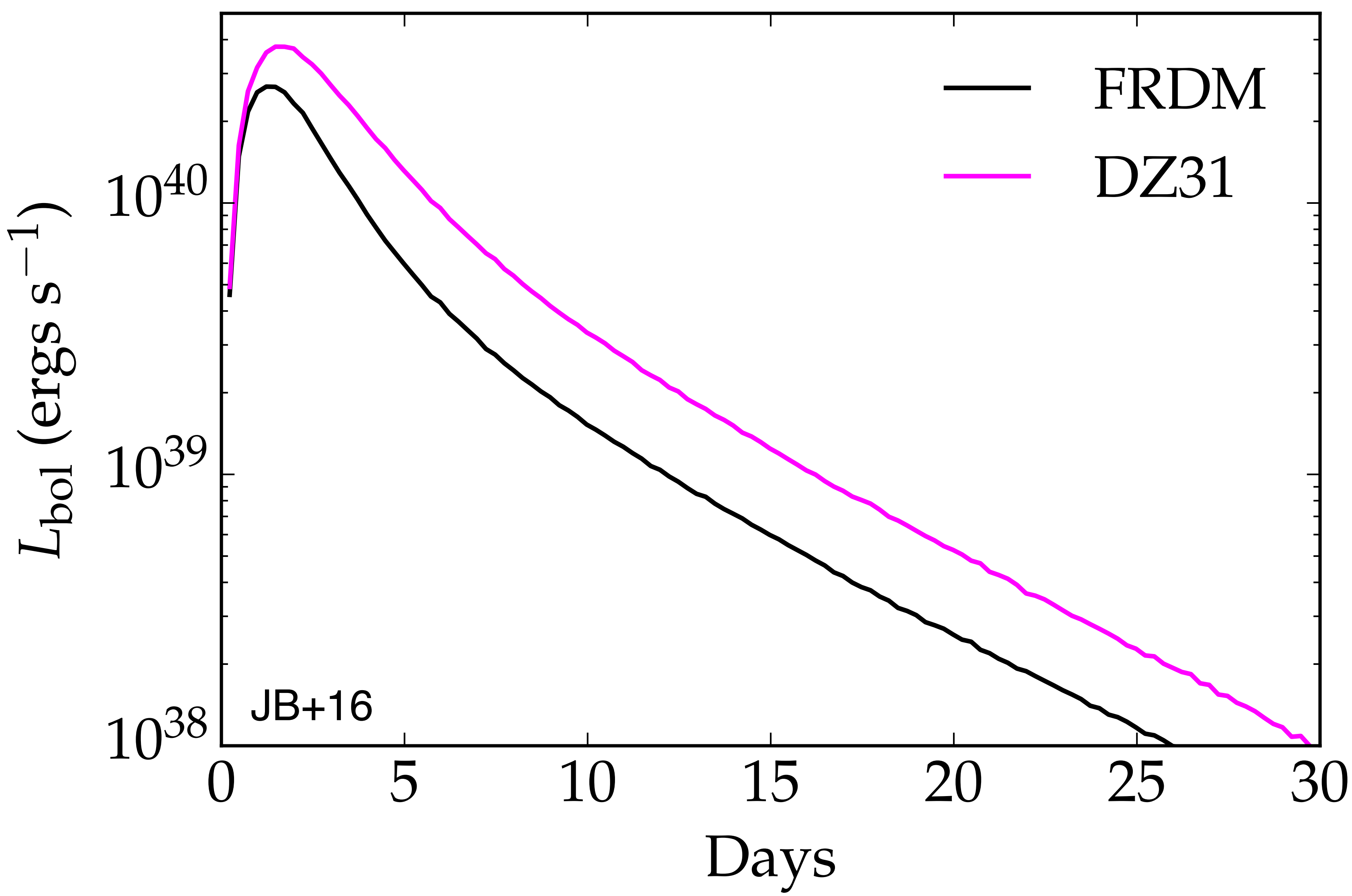
Footnote: the role of α-decay

Not all decay modes thermalize equally: thermalization is more efficient for compositions where α-decay and fission are important





Footnote: the role of α-decay



Luminosity (especially at late times) could indicate the importance of α-decay (or of fission!)