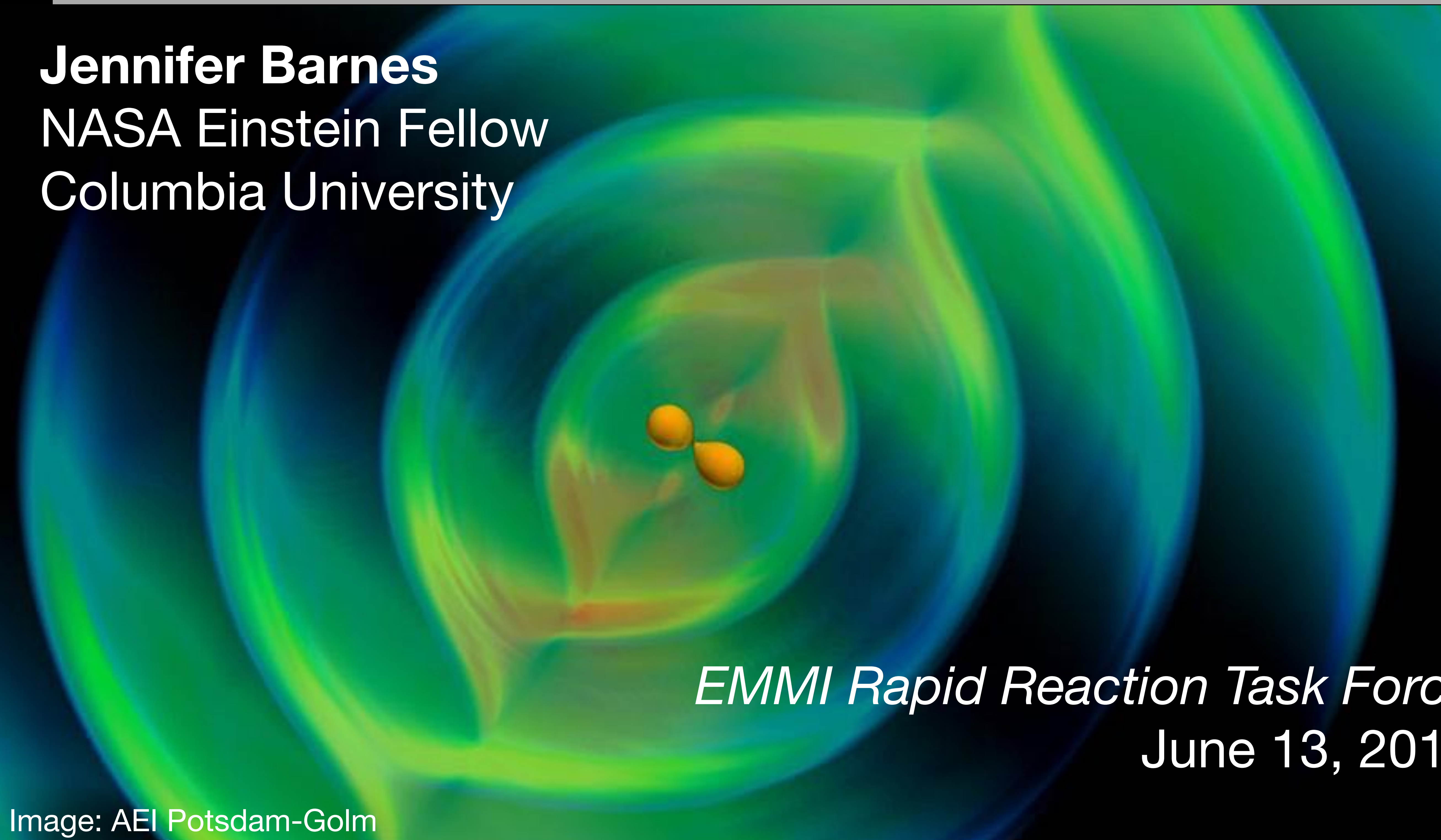
Kilonovae, Nuclear Physics, and Observations



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Columbia University

EMMI Rapid Reaction Task Force
June 13, 2018

Image: AEI Potsdam-Golm

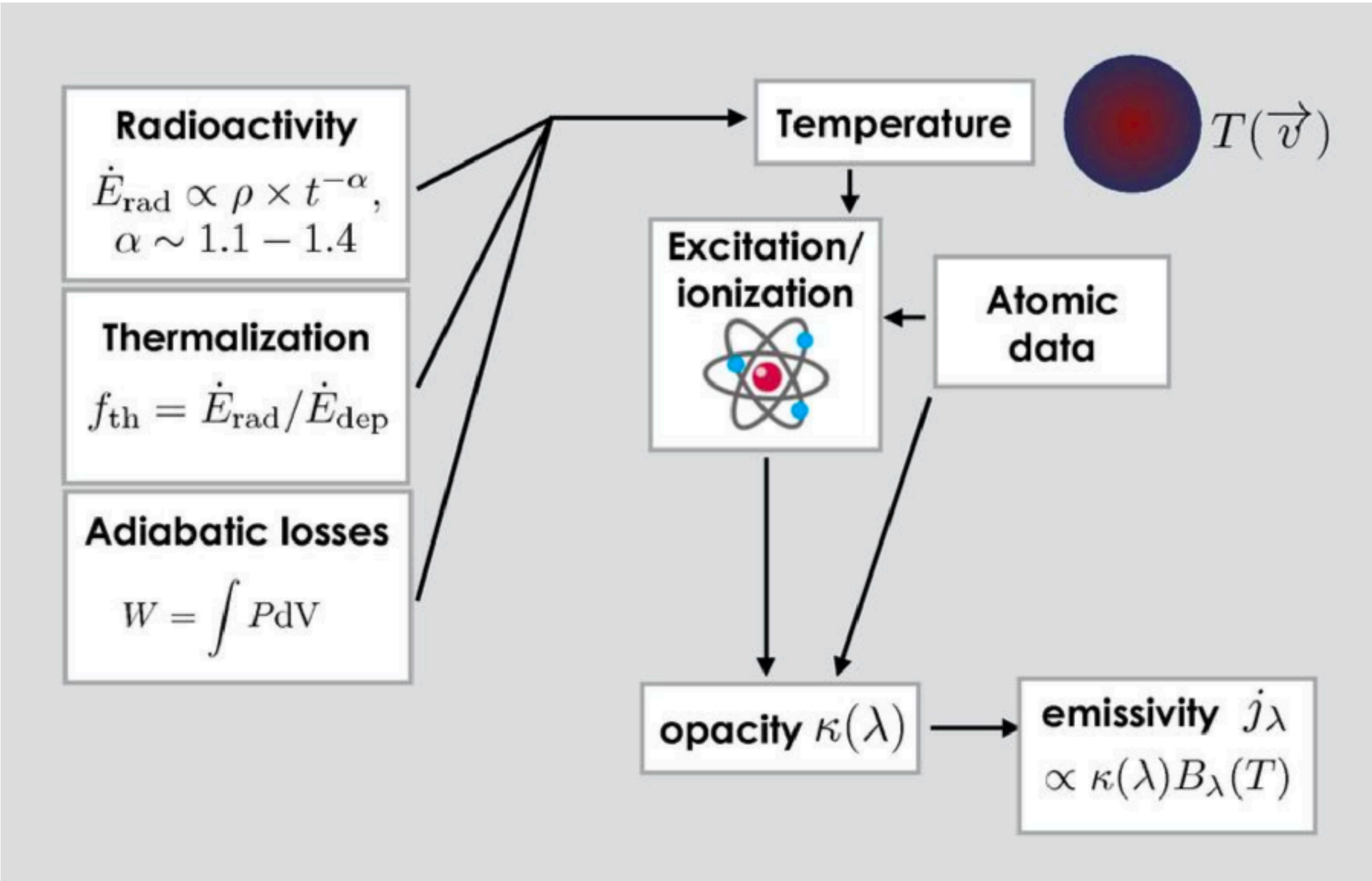
The kilonova-nuclear physics connection(s)

Nuclear physics questions:

- How is mass ejection affected by NS EOS?
- How is nucleosynthesis impacted by NS EOS/the central remnant
  - Weak interactions
- How is energy injected by radioactivity and how might this vary?
  - Power P(t)
  - Decay modes and spectra?

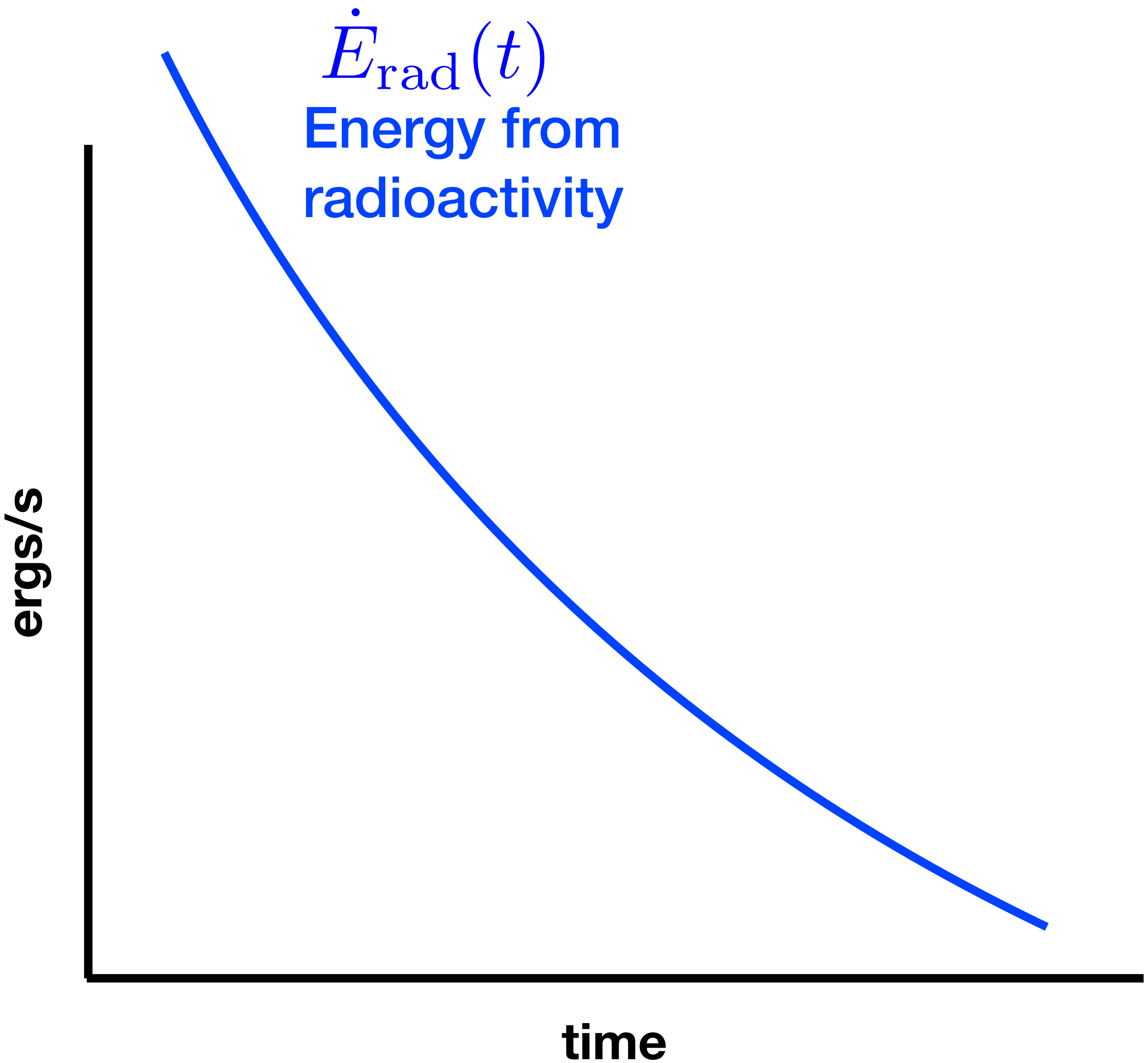
→ **Goal**: understand how all of this variation will affect the light curves/spectra of radioactive transients

tool of the trade: radiation transport



basics of radiation transport

(bolometric) light curves



colors & spectra

- Quasi-blackbody with temperature set by the net effect of radioactivity, thermalization, photon absorption/ emission, and cooling
- Line-blanketing can affect the spectrum
- Individual features correspond to particular atoms or ions

basics of radiation transport

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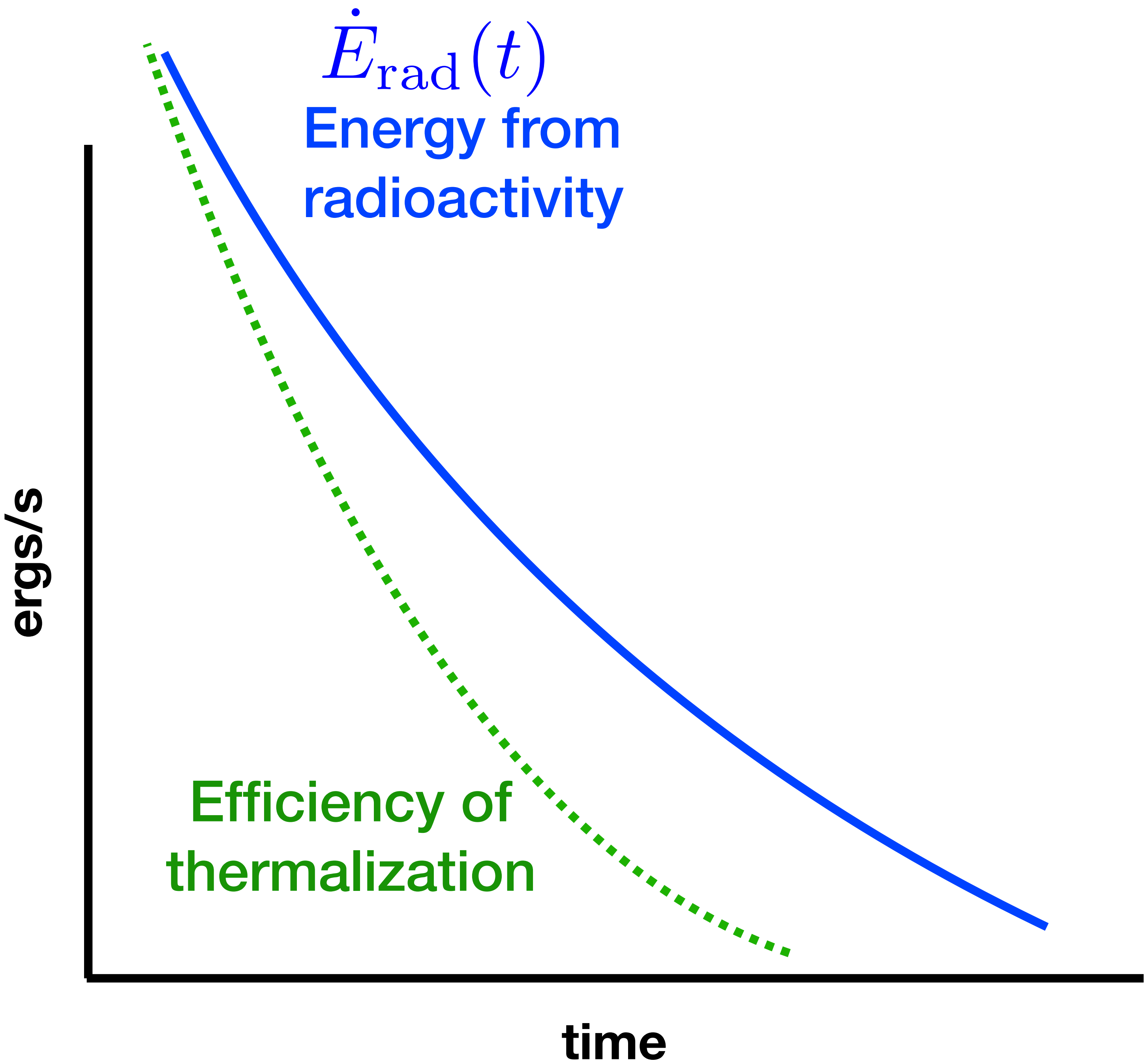

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basics of radiation transport

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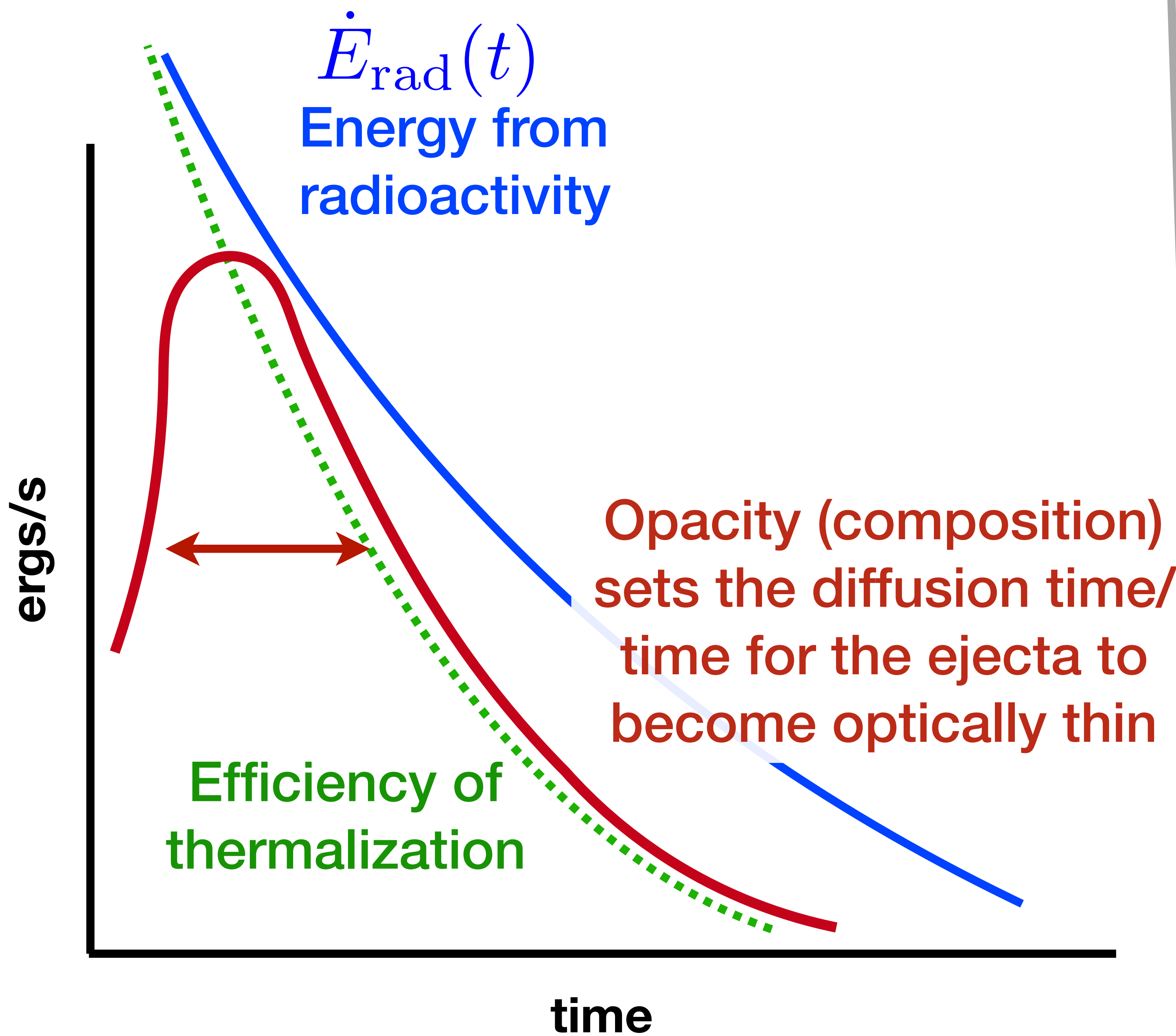

colors & spectra

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determining the power input $\dot{E}_{\rm rad}(t)$

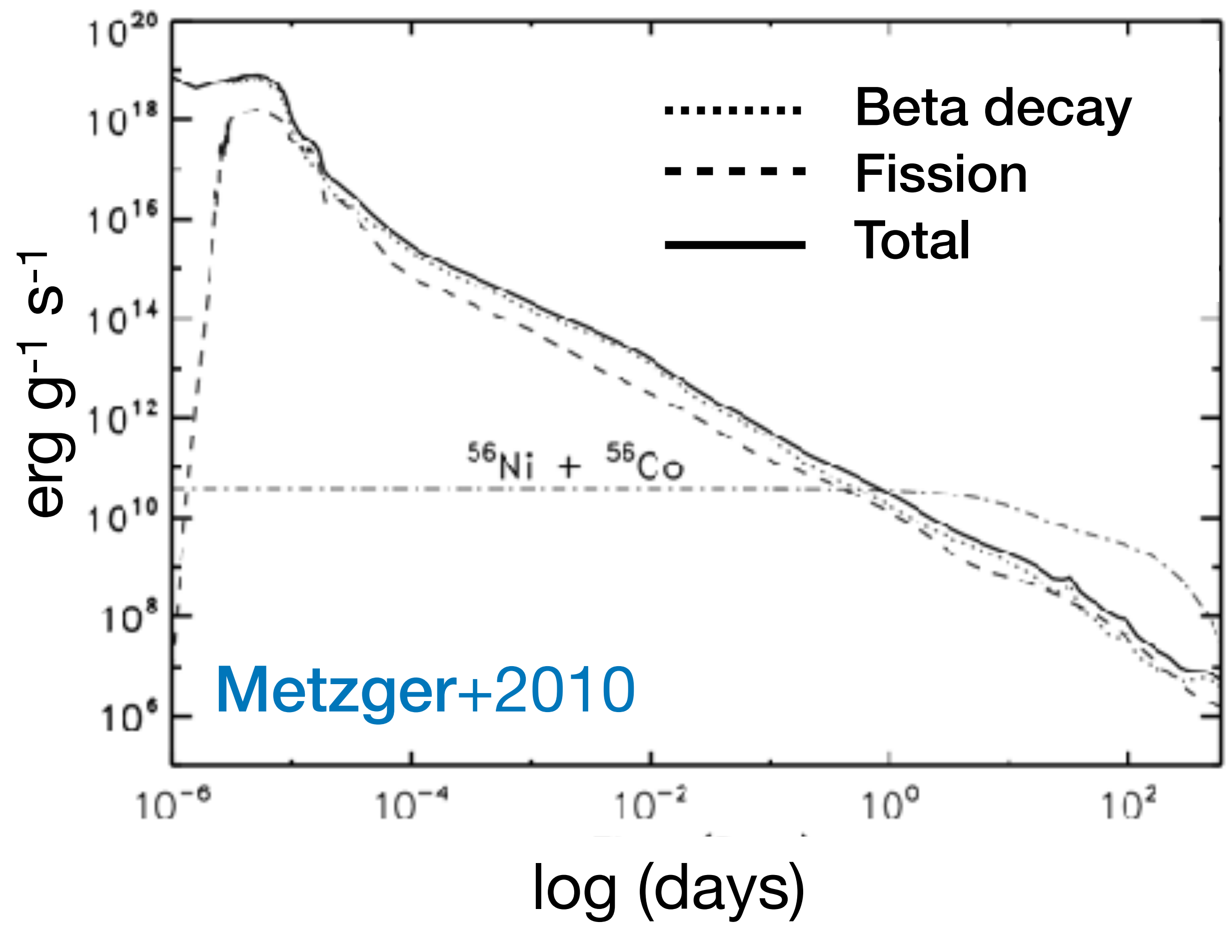
Analytic estimates are possible. Li & Paczyński (1998):

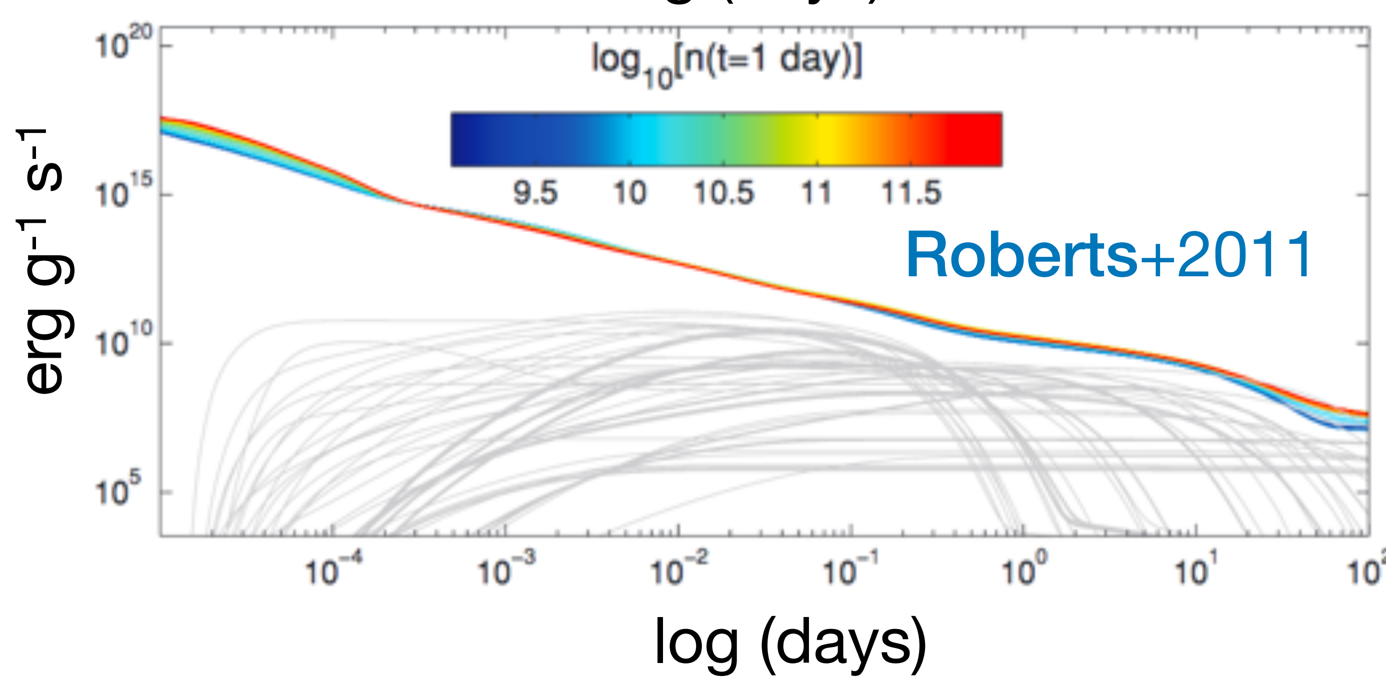
$$\dot{E}_{\rm rad}(t) = \frac{fc^2}{t}$$

(see also Hotokezaka+17)

Nuclear network calculations can determine the *total power* and the importance of *different decay modes and isotopes*.

- requires measured or calculated half-lives and decay energies

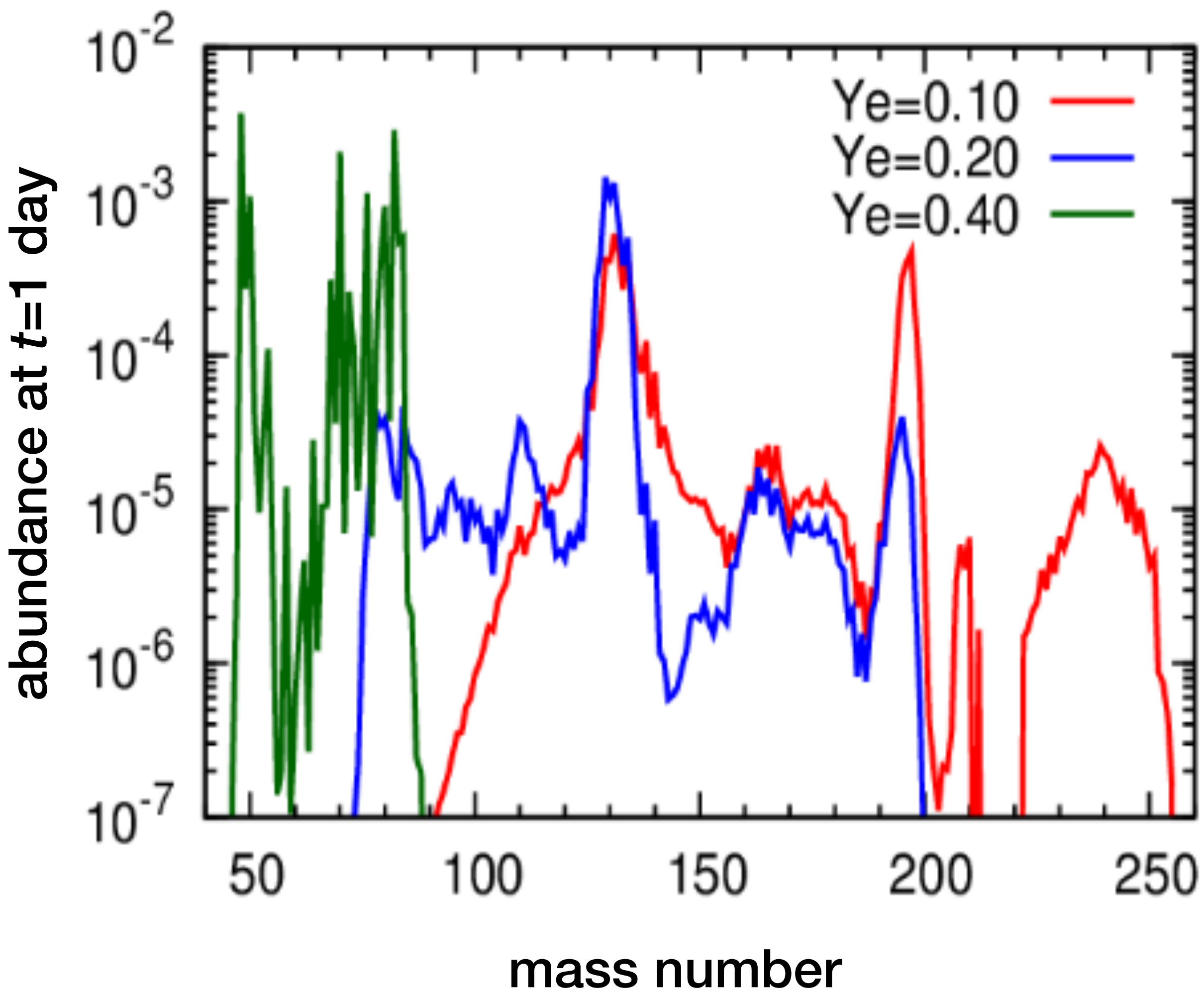


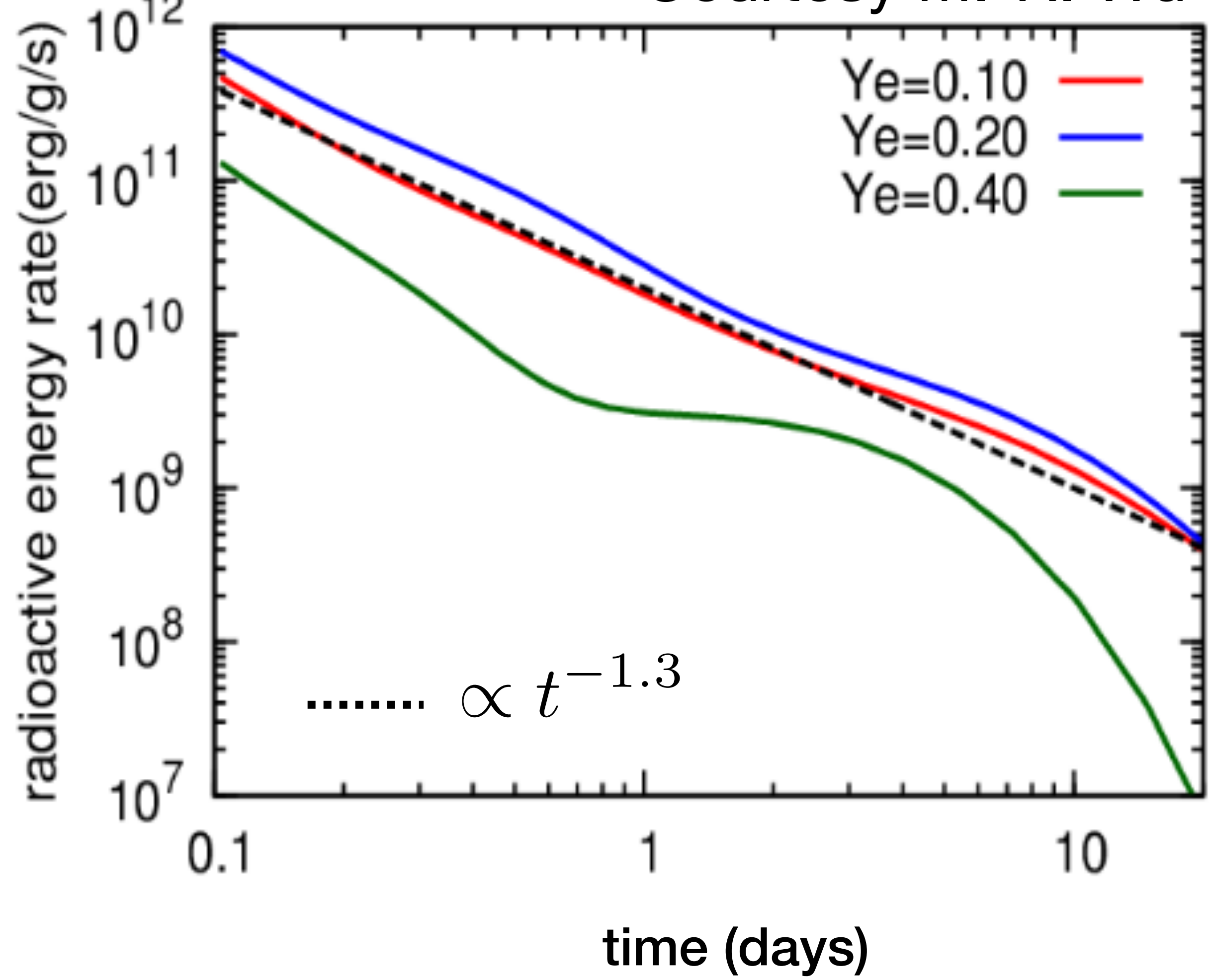


$\dot{E}_{\rm rad}(t)$ depends on, e.g., Y_e and mass model

- total heating rate (see below)
- division of heating into different decay channels

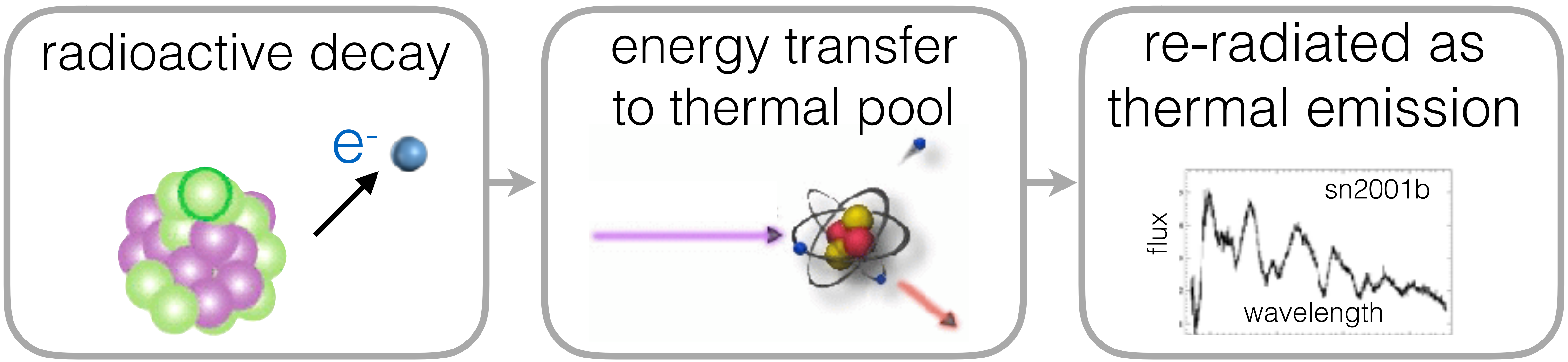
Courtesy M.-R. Wu





the *r*-process and kilonova thermalization

Thermal emission is **reprocessed kinetic energy**;
thermalization efficiency sets the luminosity budget



thermalization efficiency depends on

- ejecta: mass, velocity, composition, magnetic fields
- decay products:
  - decay channel, decay timescales, emission spectrum

a rigorous calculation of thermalization

$\boxed{\text{nuclear reaction networks to determine } r\text{-process yields}}$

a rigorous calculation of thermalization

nuclear reaction networks to determine *r*-process yields

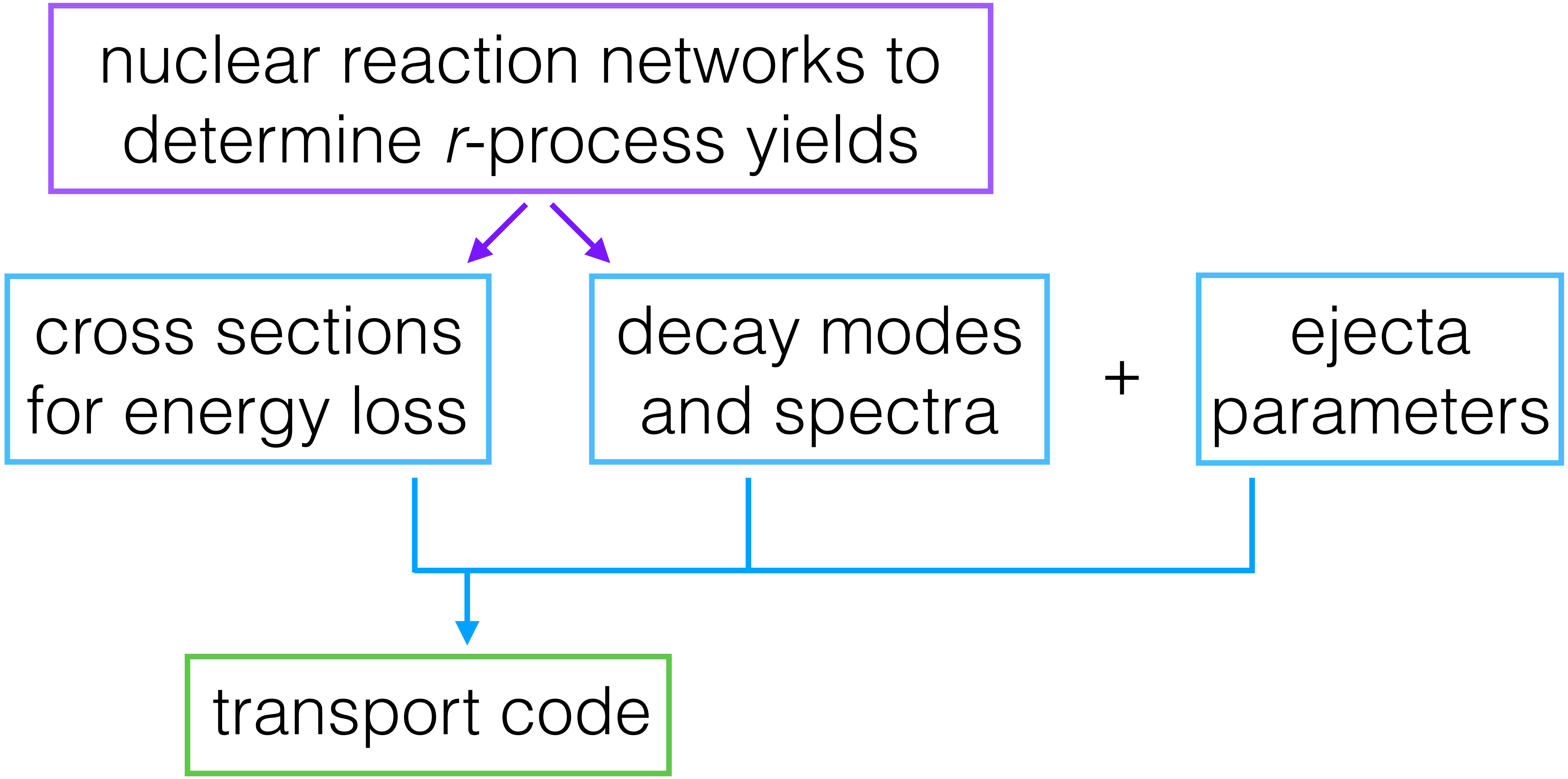
cross sections for energy loss

decay modes and spectra

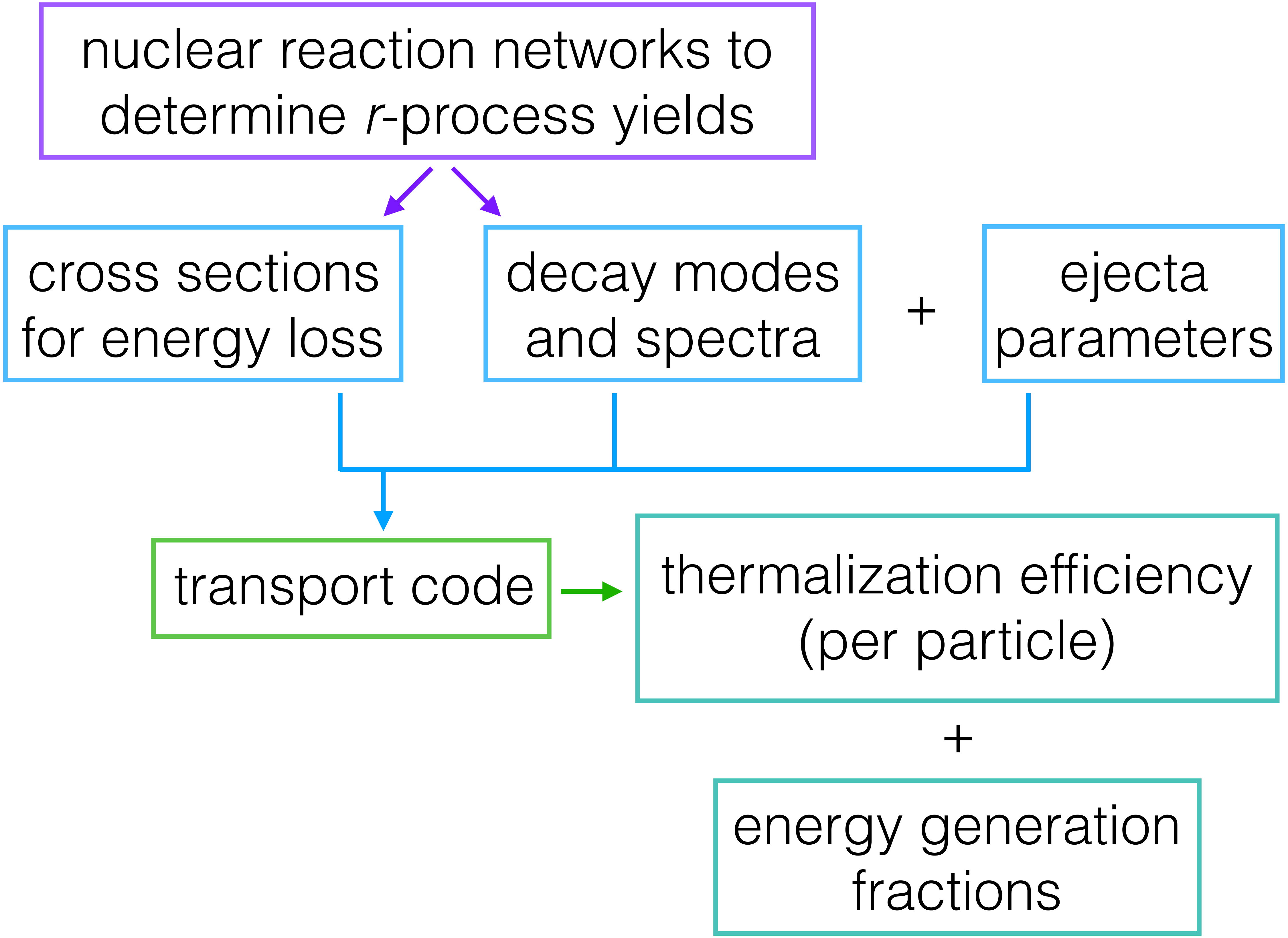
+

ejecta parameters

a rigorous calculation of thermalization



a rigorous calculation of thermalization



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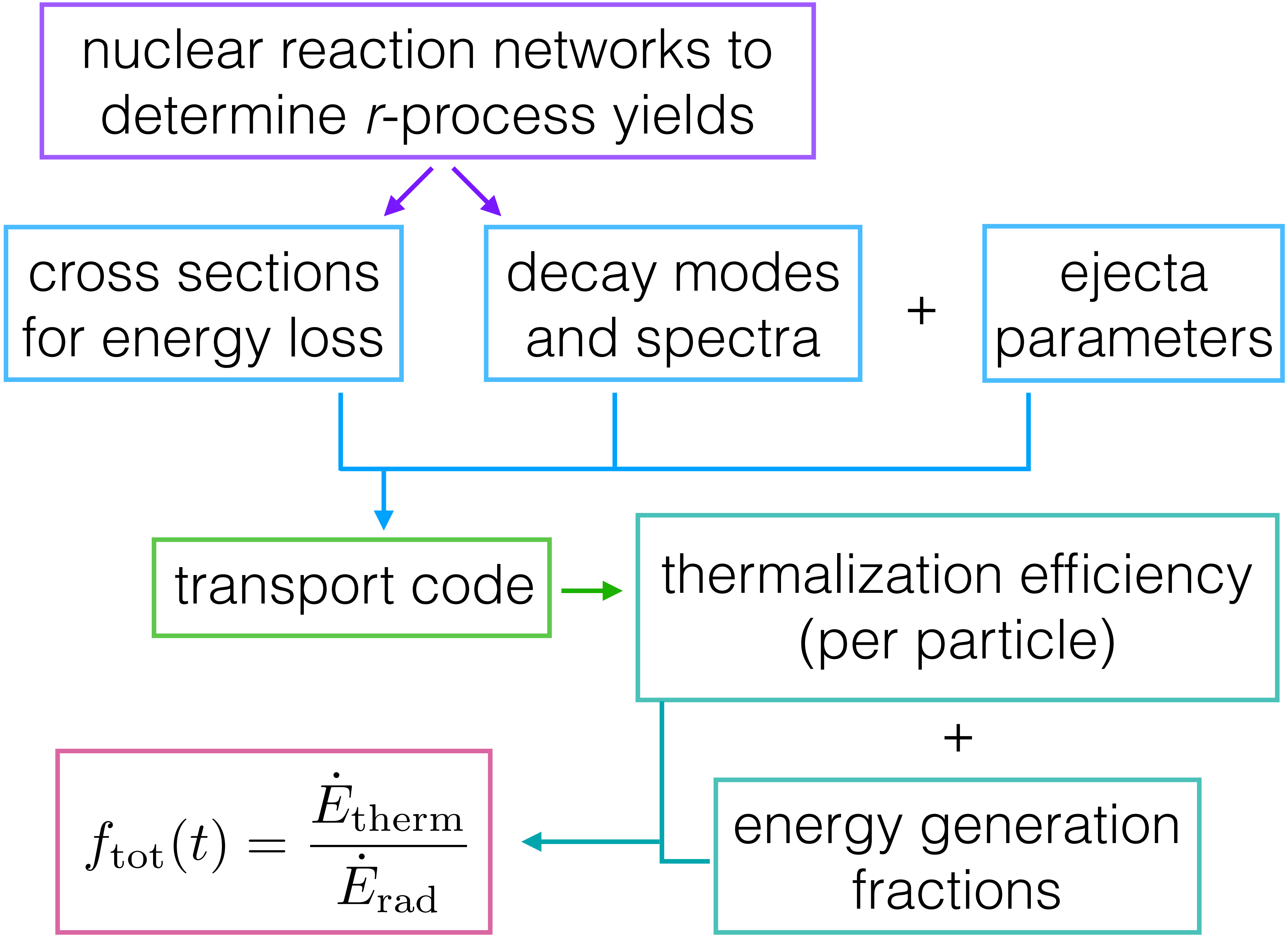
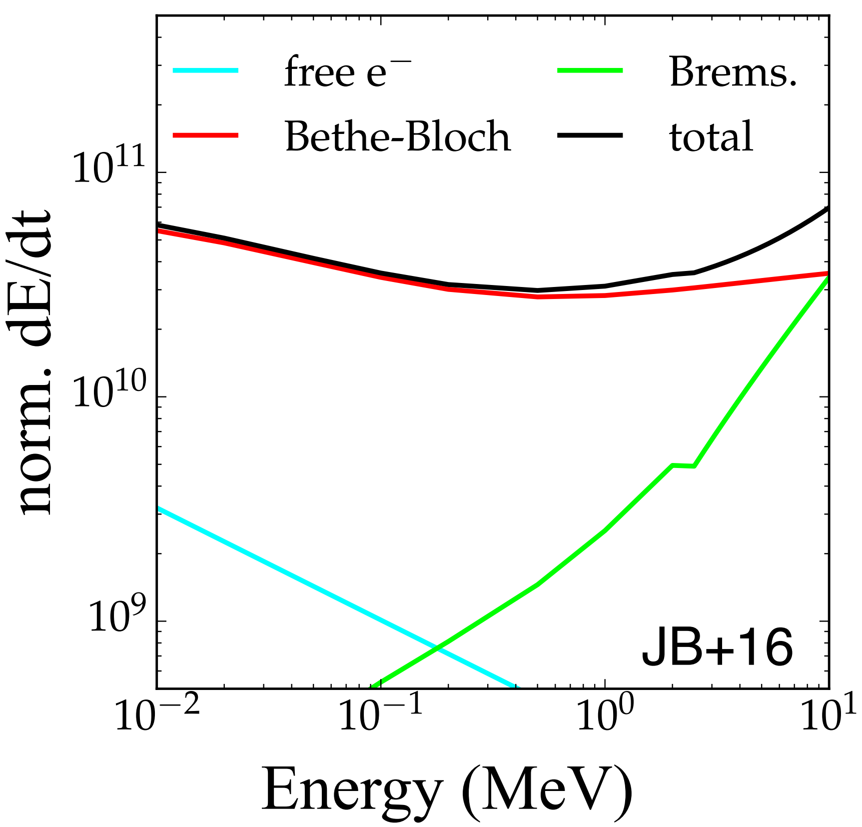
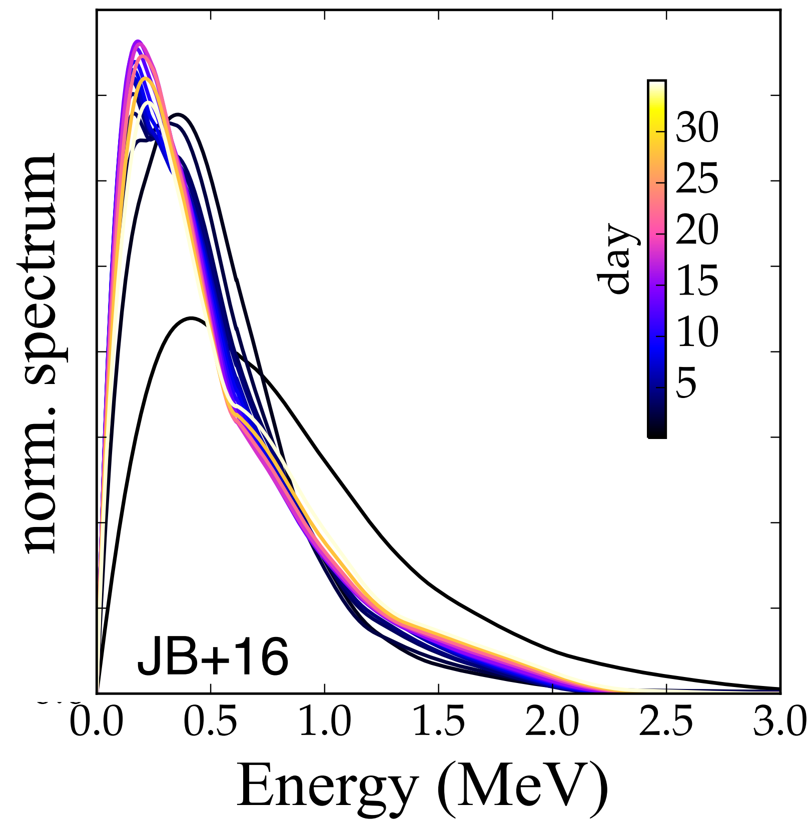


a case study: β-particles

Energy-loss channels:

- Bethe-Bloch
- Plasma losses
- Bremsstrahlung



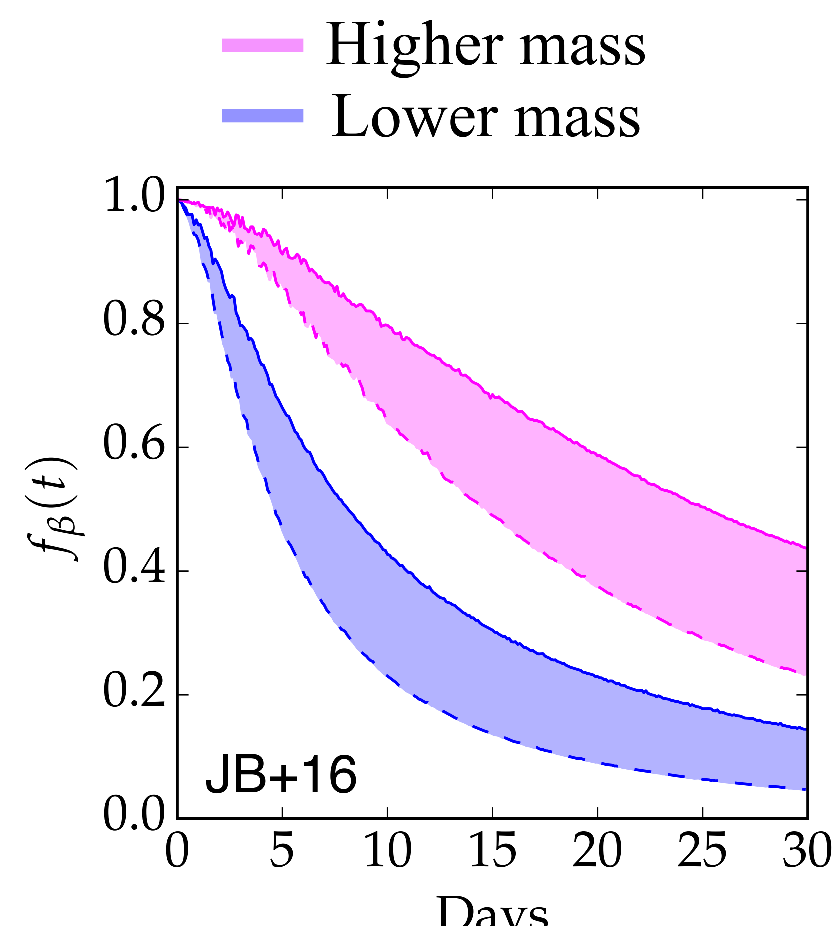


Time-dependent spectra

- from *r*-process yields and nuclear data

Time-dependent $f_\beta(t)$

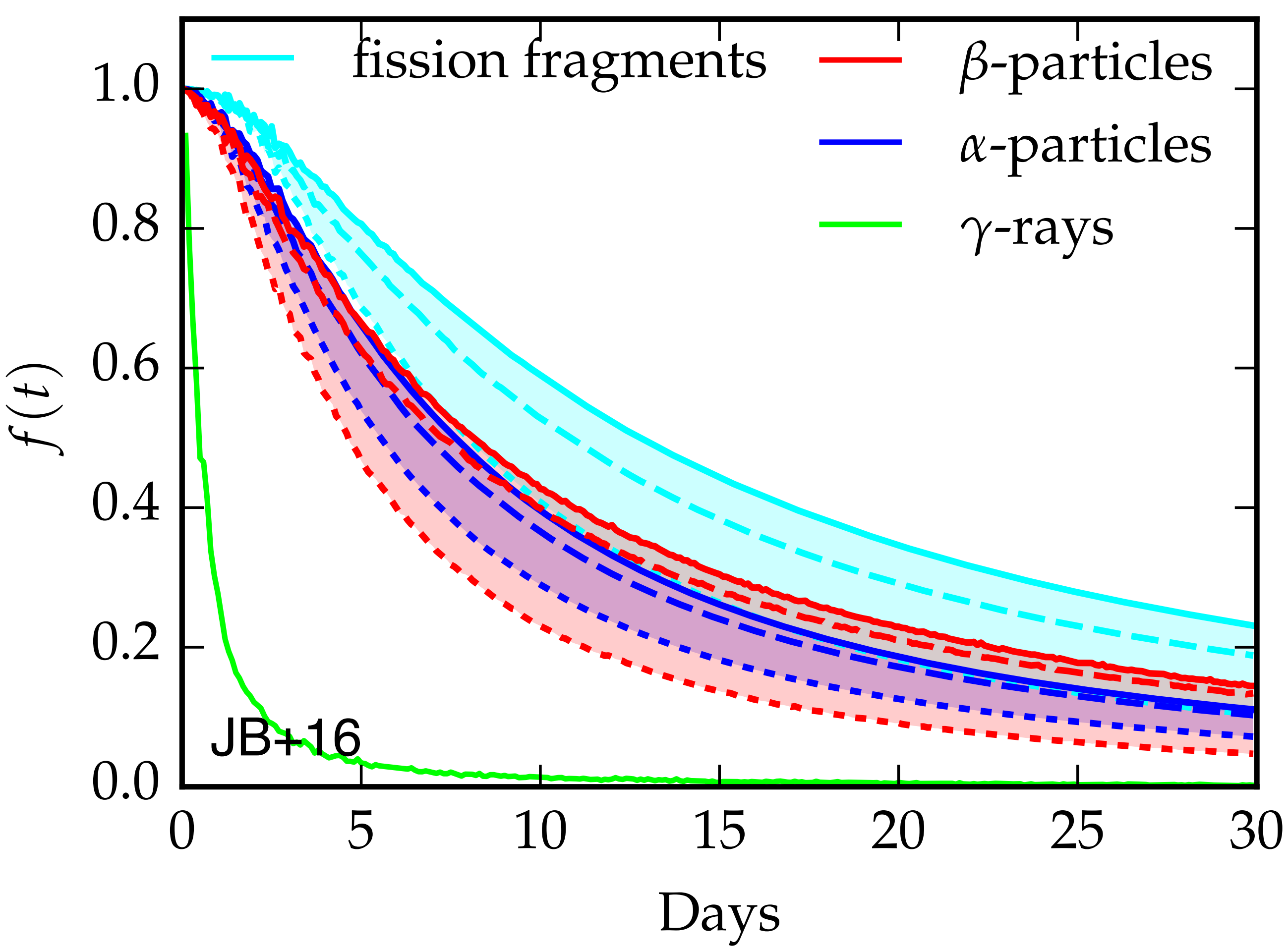
- for a range of ejecta properties

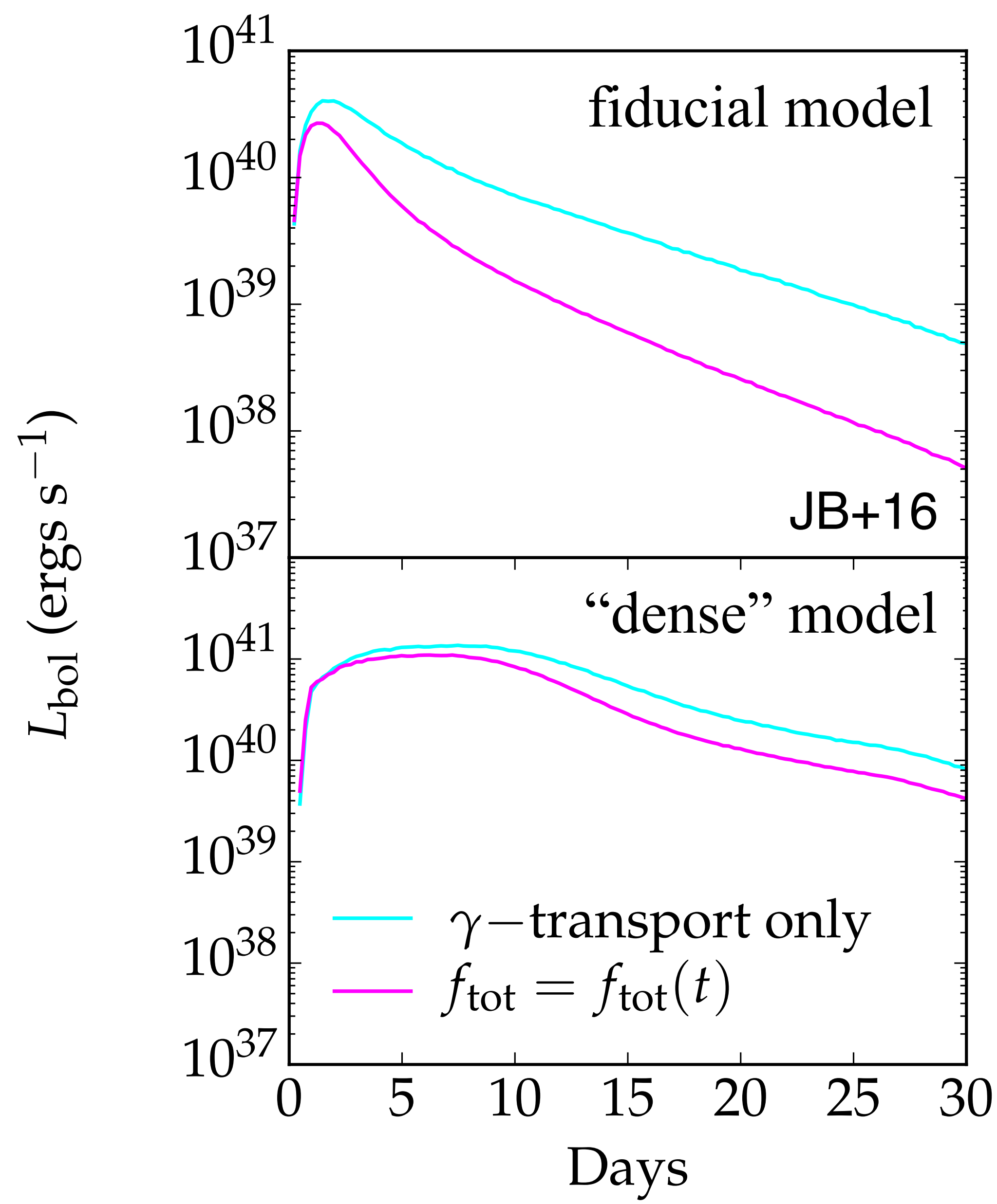


thermalization: effect on light curves

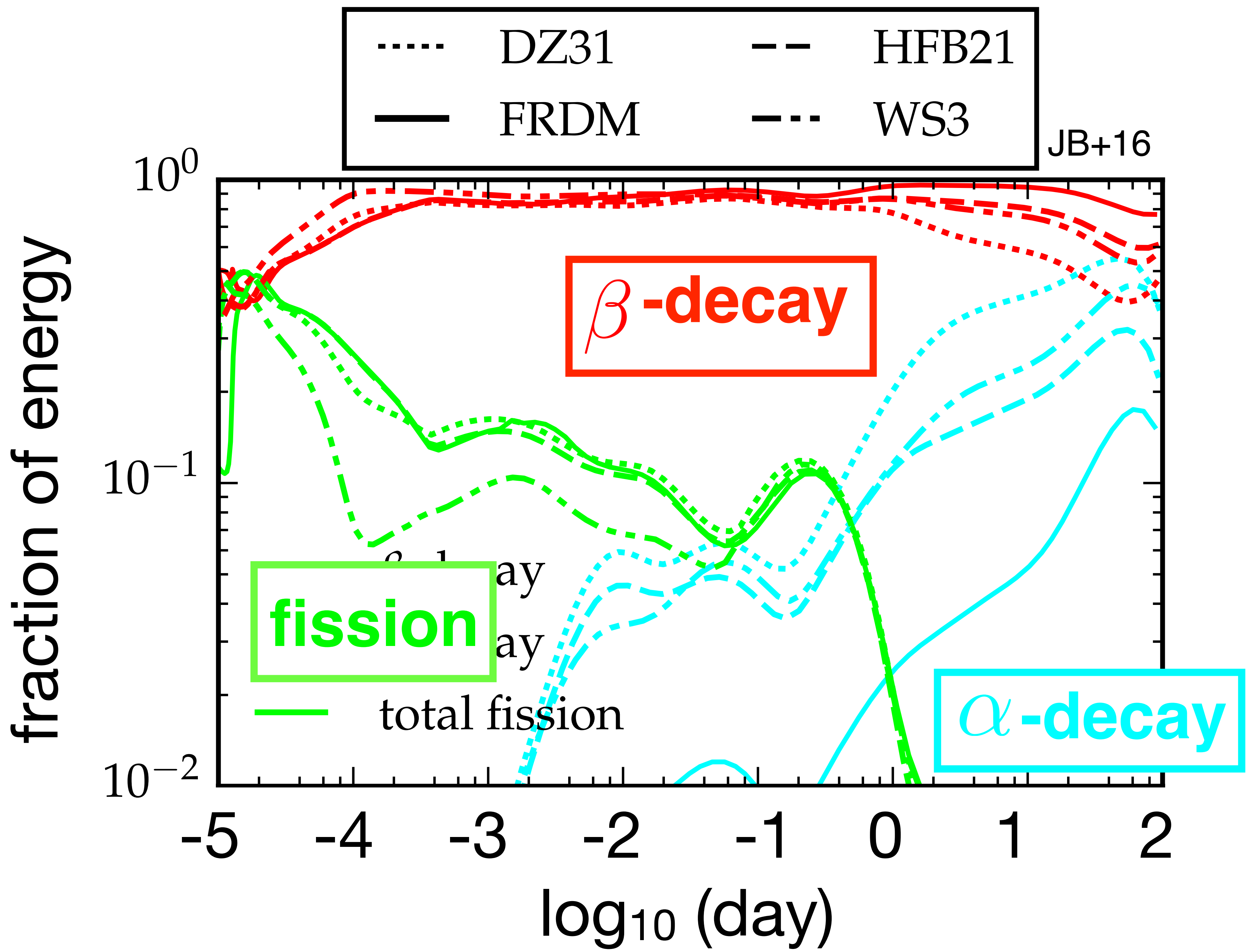
- lower luminosity (especially for less massive ejecta)
- allows more better estimate of mass from observations

Thermalization efficiency for each decay product (fiducial model)





the prominence of different decay modes is mass-model dependent



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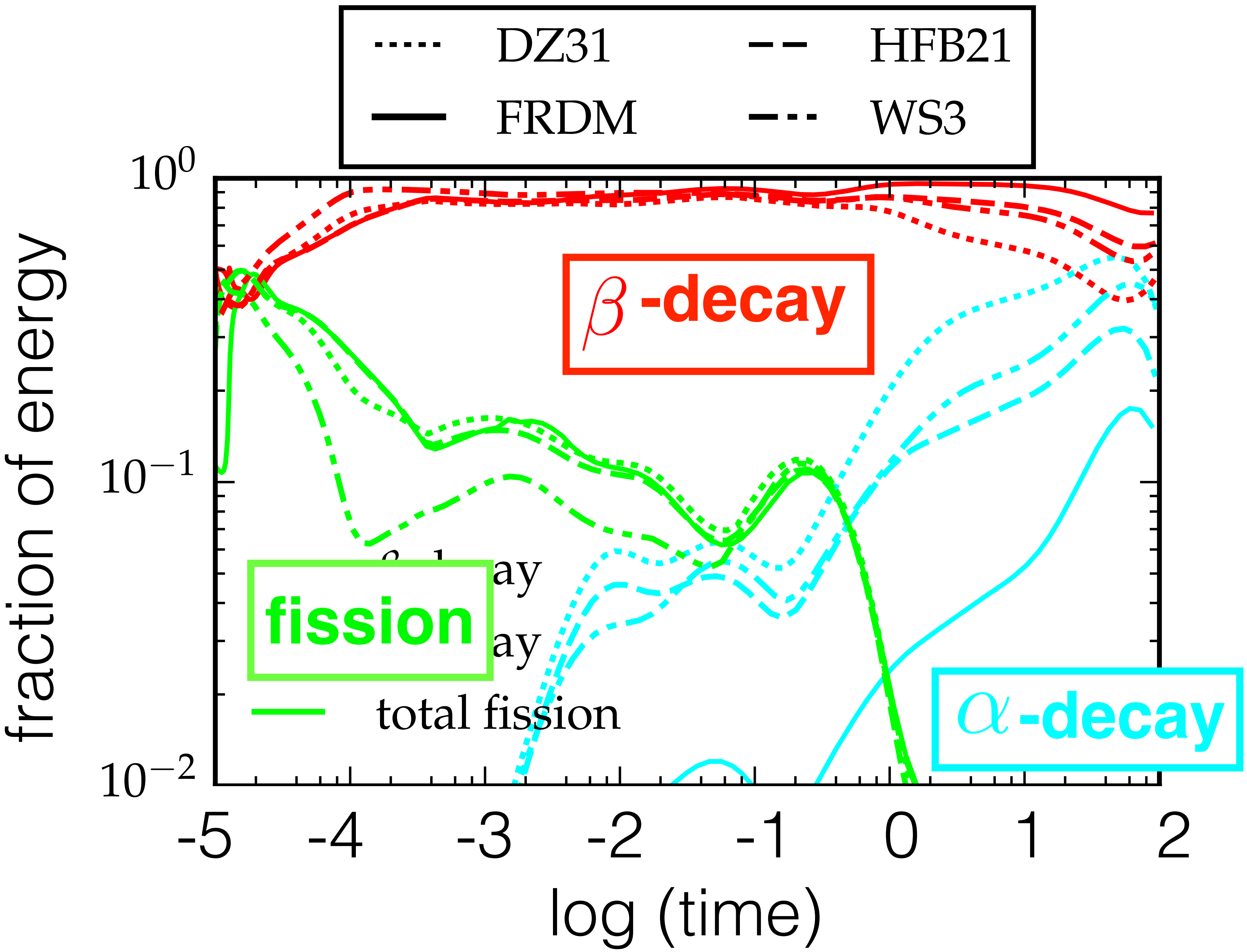

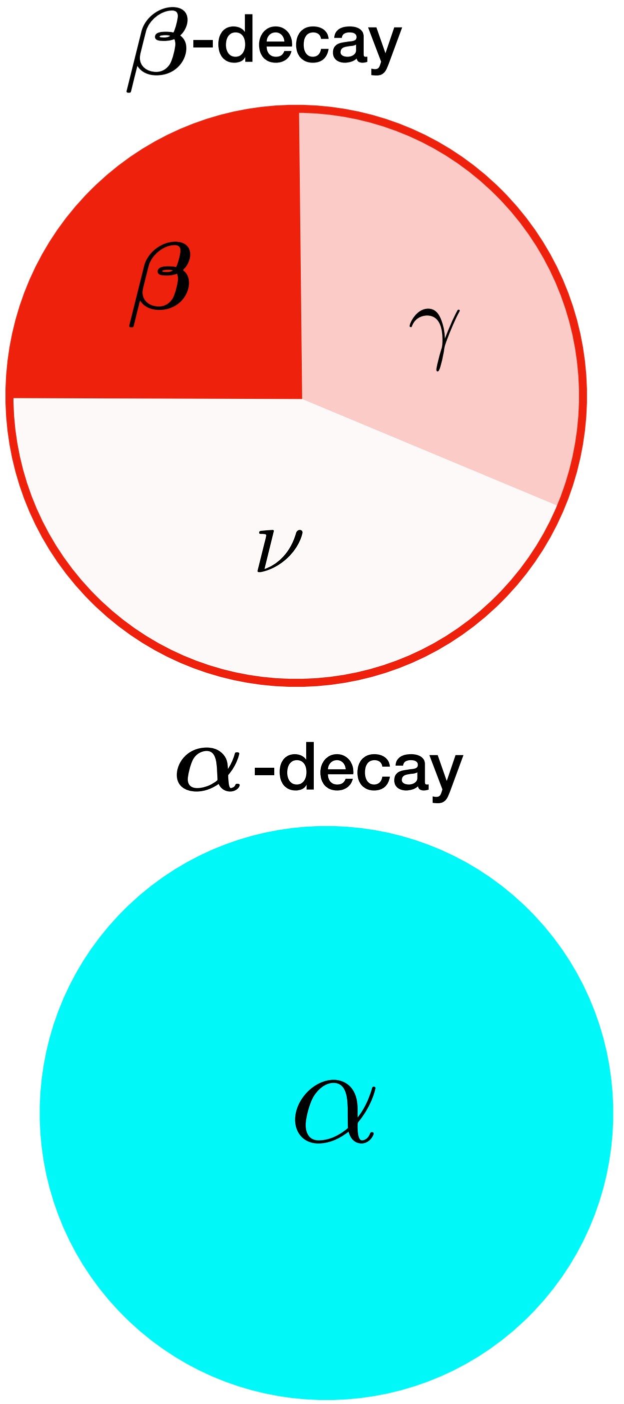

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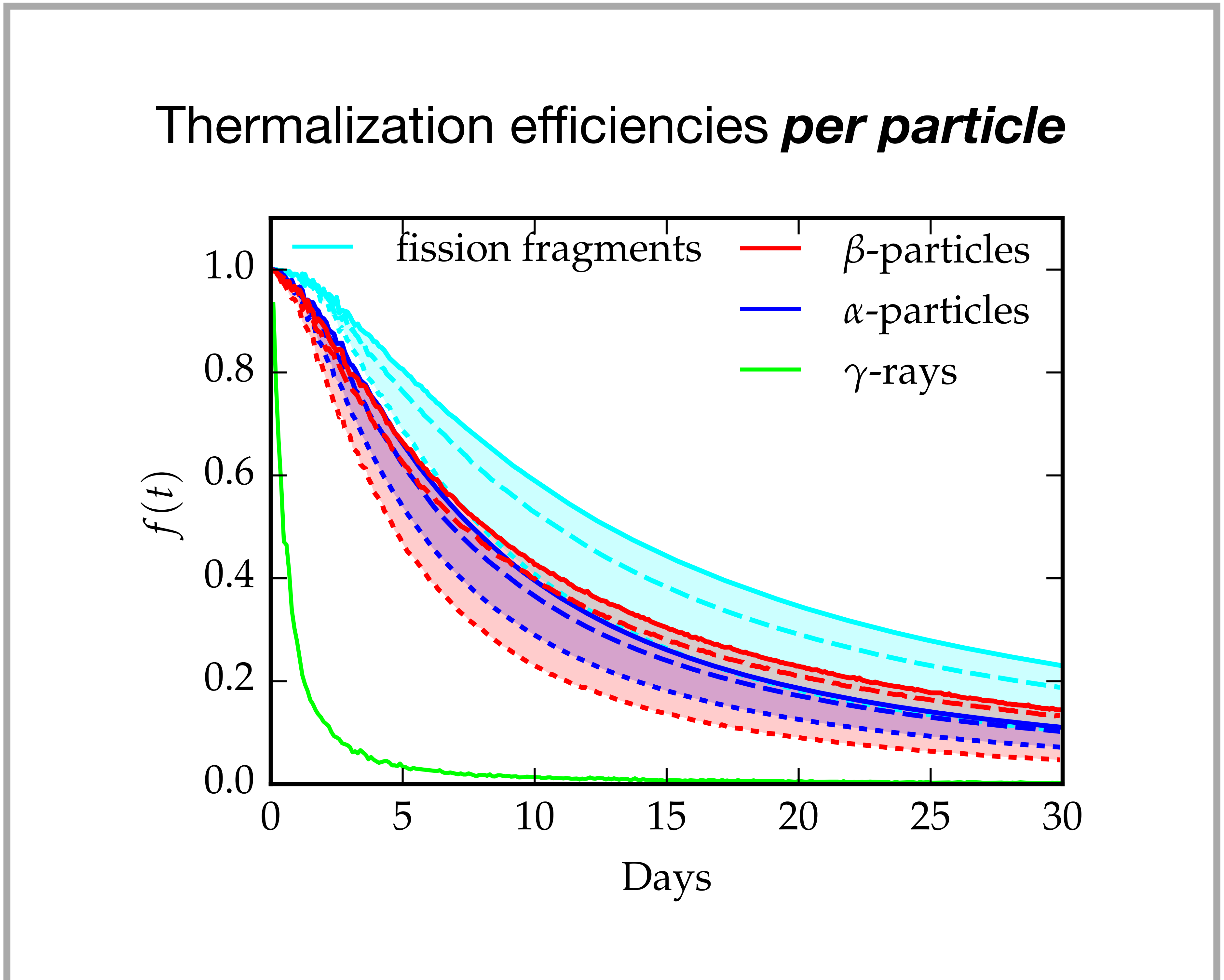

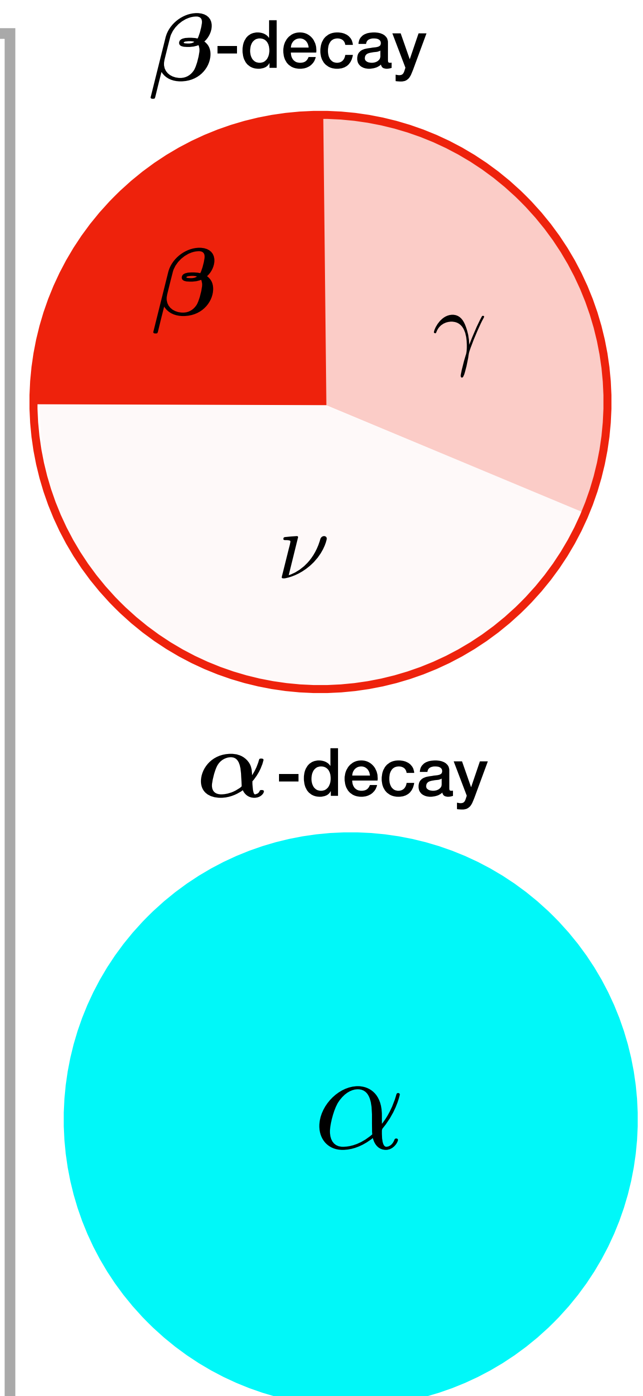

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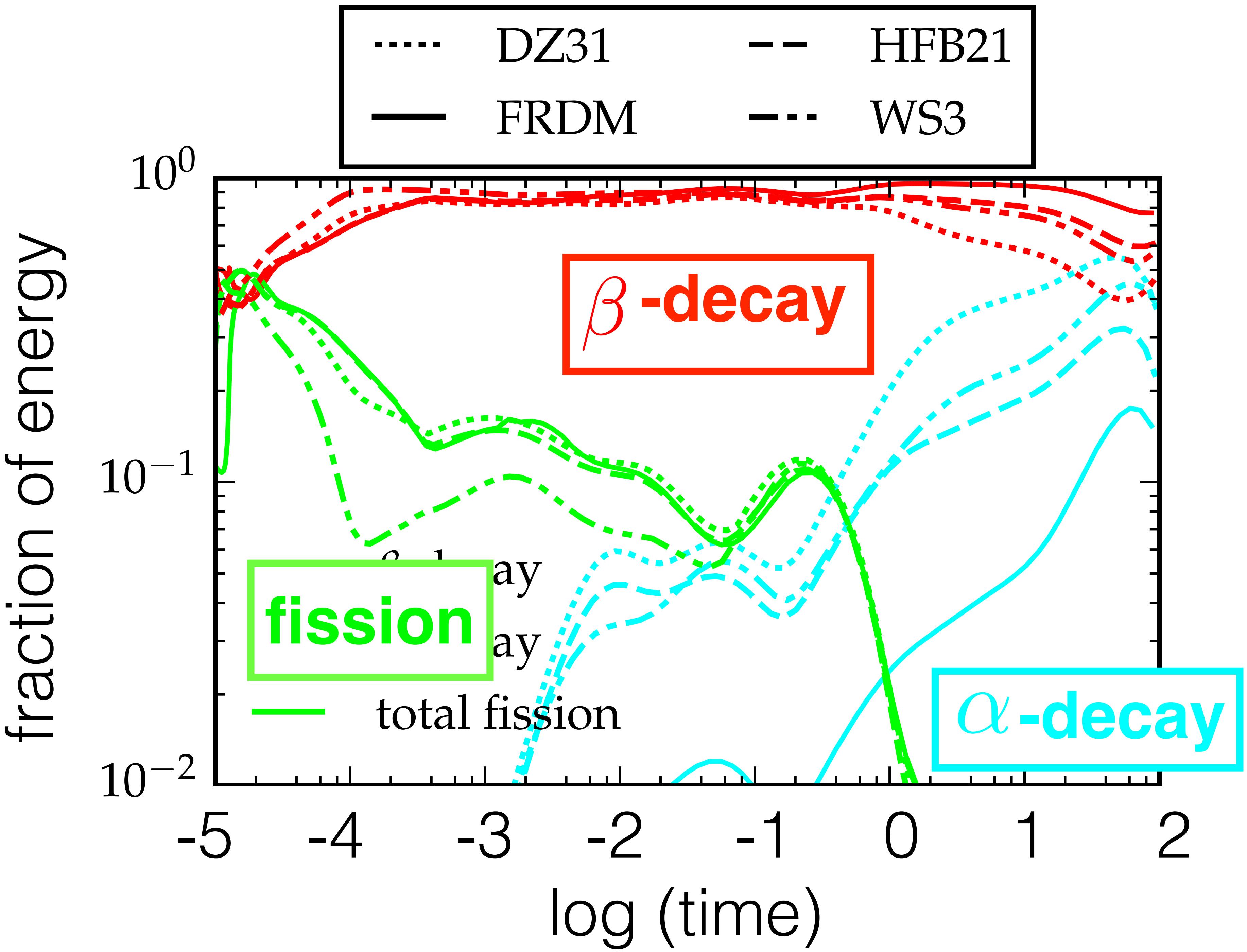
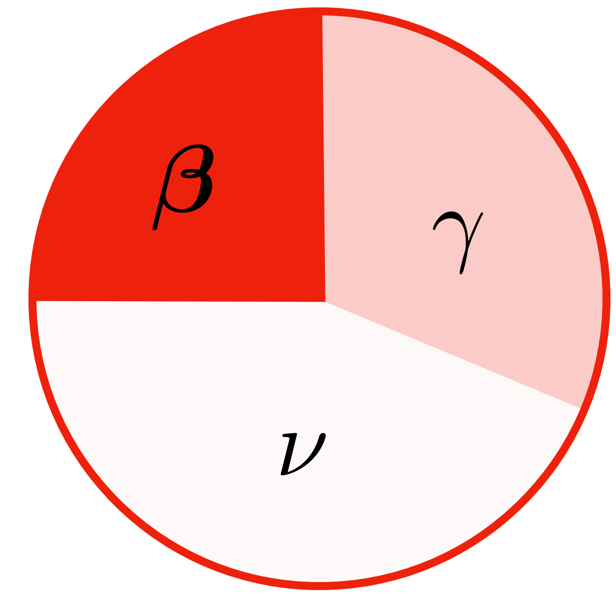
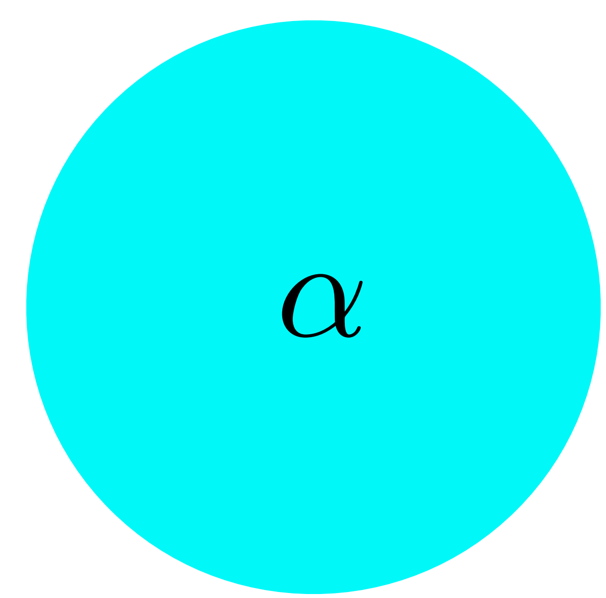


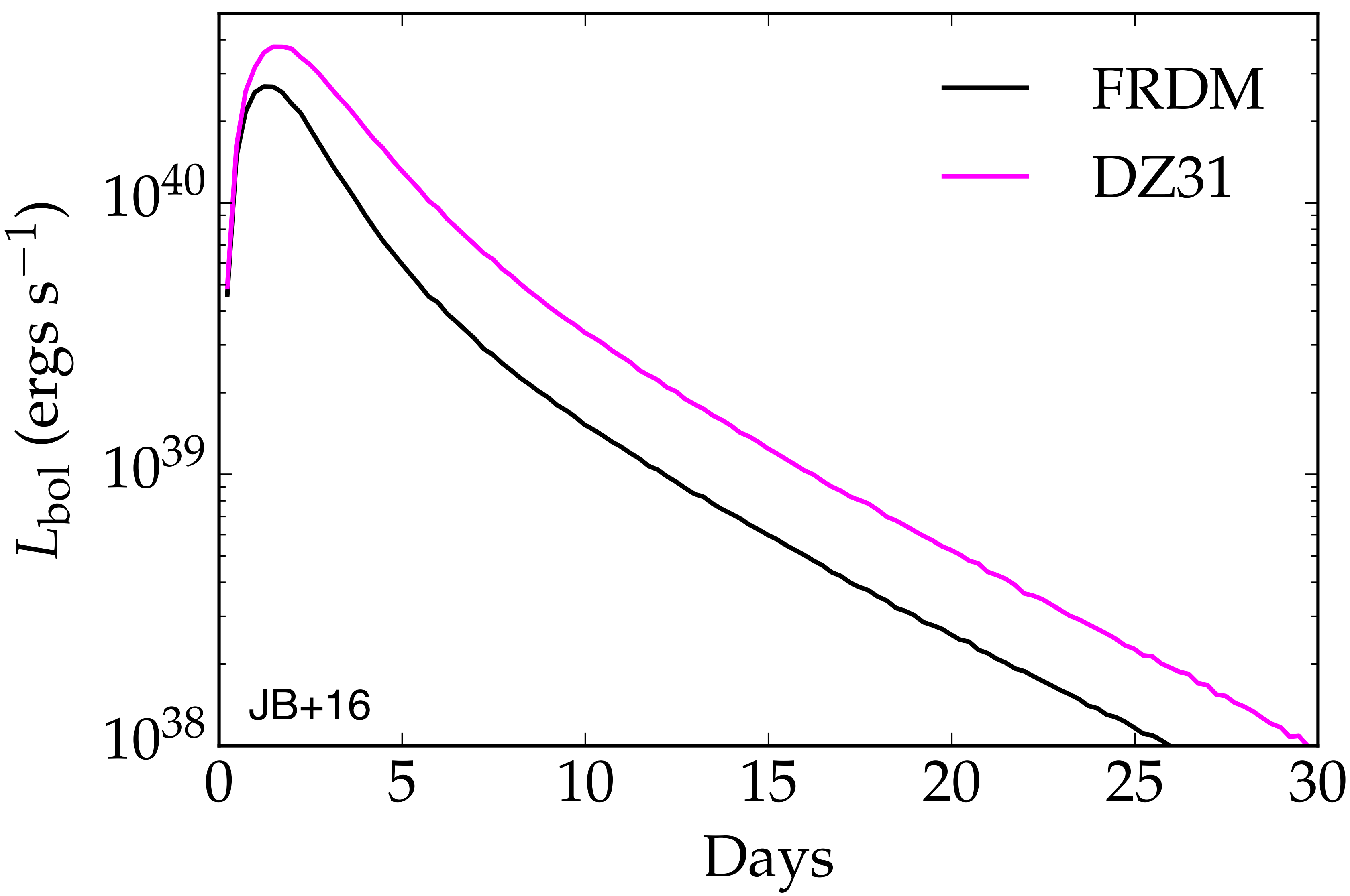
$\boldsymbol{\beta}$-decay



$\boldsymbol{\alpha}$ -decay



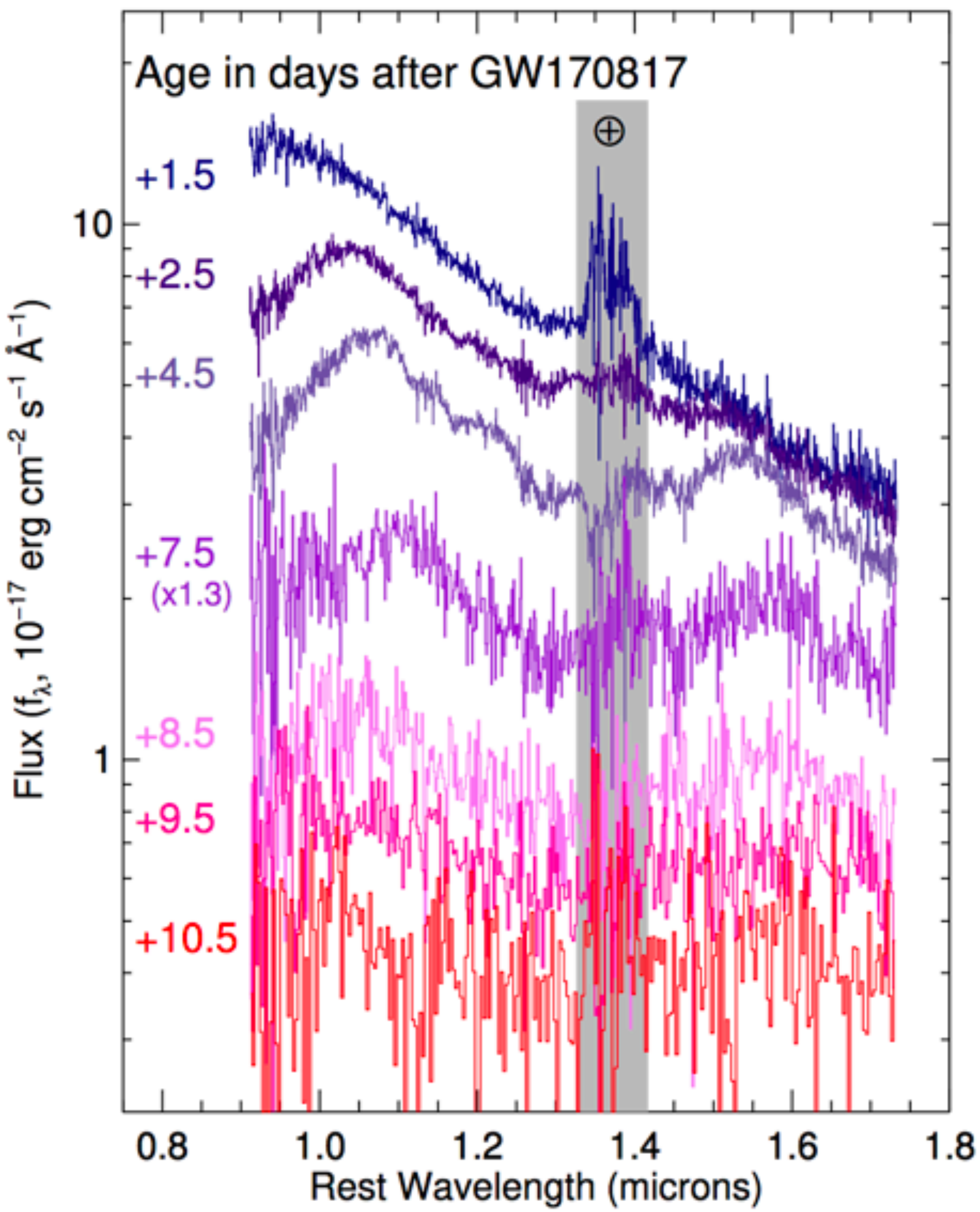
The role of α-decay



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

understanding opacities allows us to move beyond L_{bol}

Chornock+17

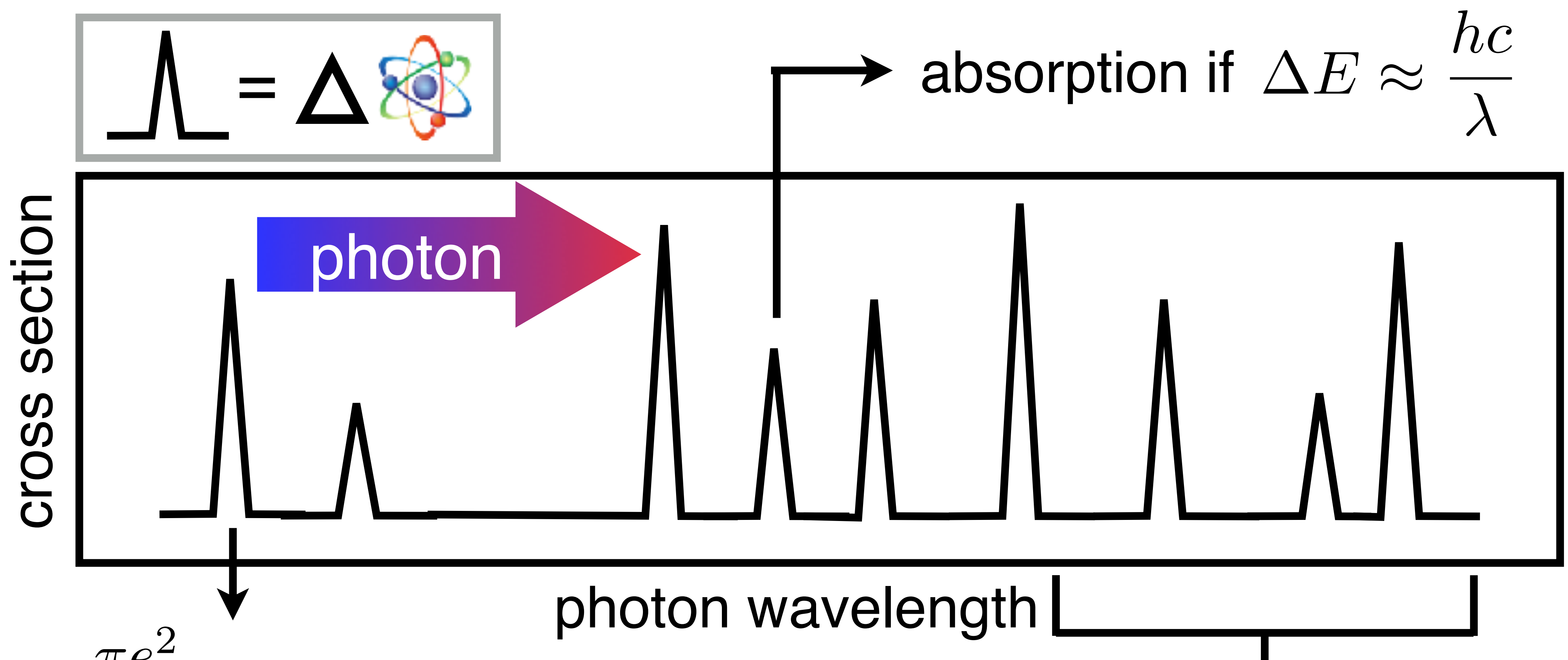


We learn a lot from spectra and colors

- Line widths ⟶ energy (velocity) of the ejecta
- Temperature evolution
- Absorption features ⟶ presence of particular elements or ions?

opacity is composition-dependent (part 1)

- **Bound-bound** opacity ($cm^2\ g^{-1}$) sets the photon mean free path.



$$\tau = \frac{\pi e^2}{m_\mathrm{e} c} f_\mathrm{osc} n_1 t_\mathrm{exp} \lambda_0$$

$$\kappa_\mathrm{exp}(\lambda_\mathrm{c}) = \frac{1}{\rho c t_\mathrm{exp}} \sum_i \frac{\lambda_i}{\Delta\lambda_\mathrm{c}} \left(1 - e^{-\tau_i}\right)$$

Sobolev optical depth sets interaction probability with a particular line

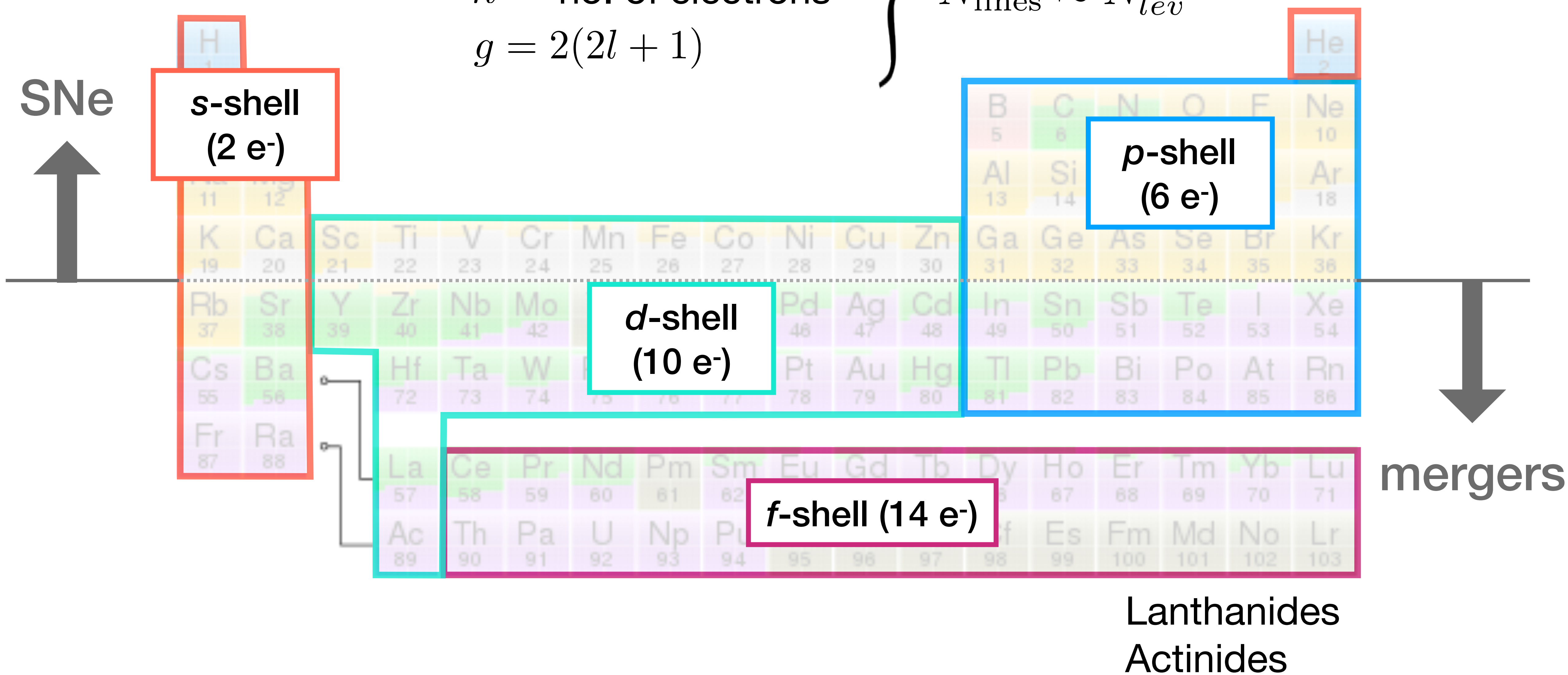
The **expansion opacity** determines the effective continuum opacity

opacity is composition-dependent

The *r*-process produces elements with atomic structures that are unique among explosively-synthesized compositions.

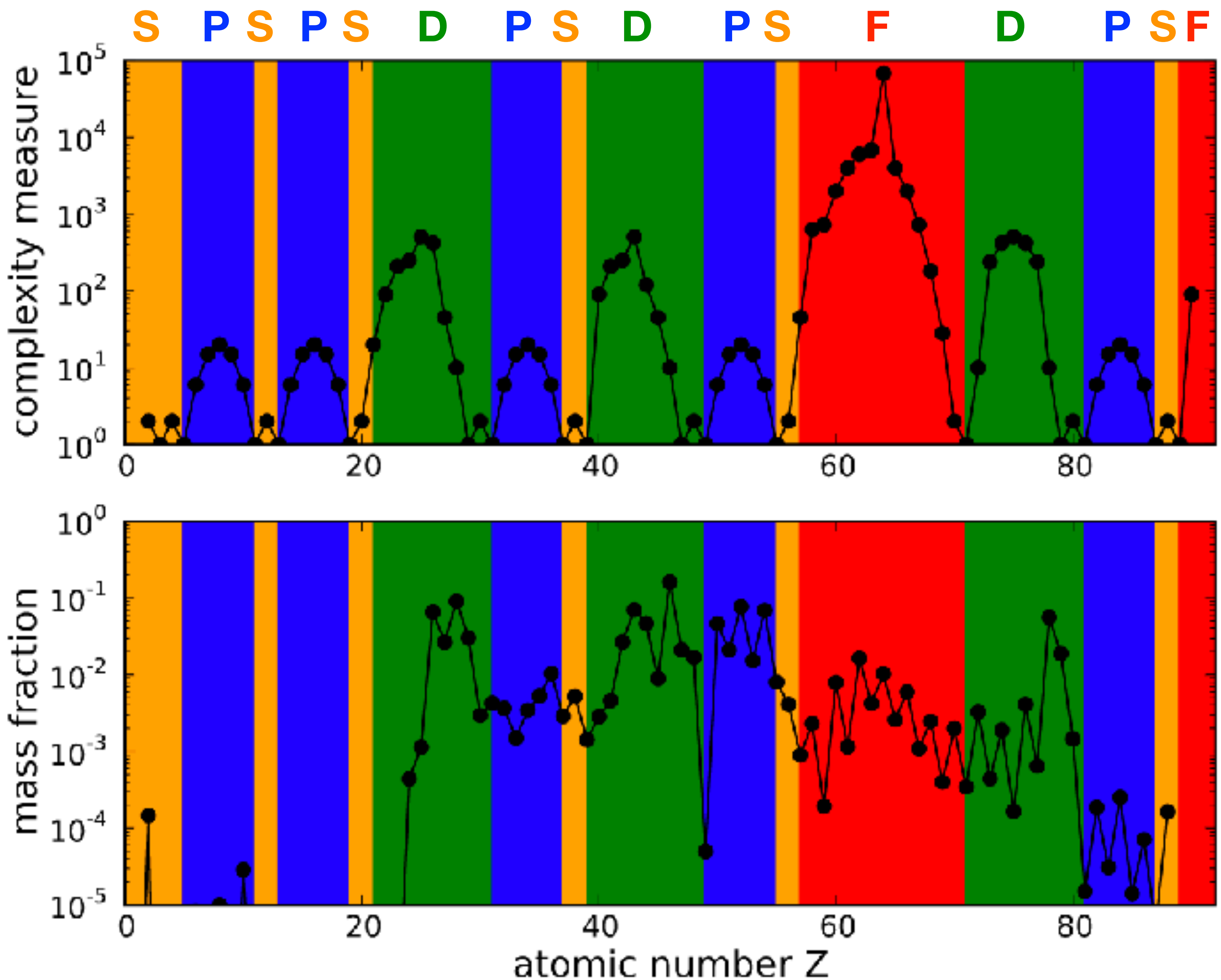
Simple analytic estimates:

$$\left.\begin{aligned} N_{\rm lev} &\approx \frac{g!}{n!(g-n)!} \\ n &= \text{no. of electrons} \\ g &= 2(2l+1) \end{aligned}\right\} \quad N_{\rm lines} \approx N_{lev}^2$$



opacity is composition-dependent

An open *f*-shell results in high atomic complexity



Kasen, Badnell, JB+17

opacity is composition-dependent

- Atomic structure modeling compensates for missing data
- Lanthanides/actinides increase the opacity

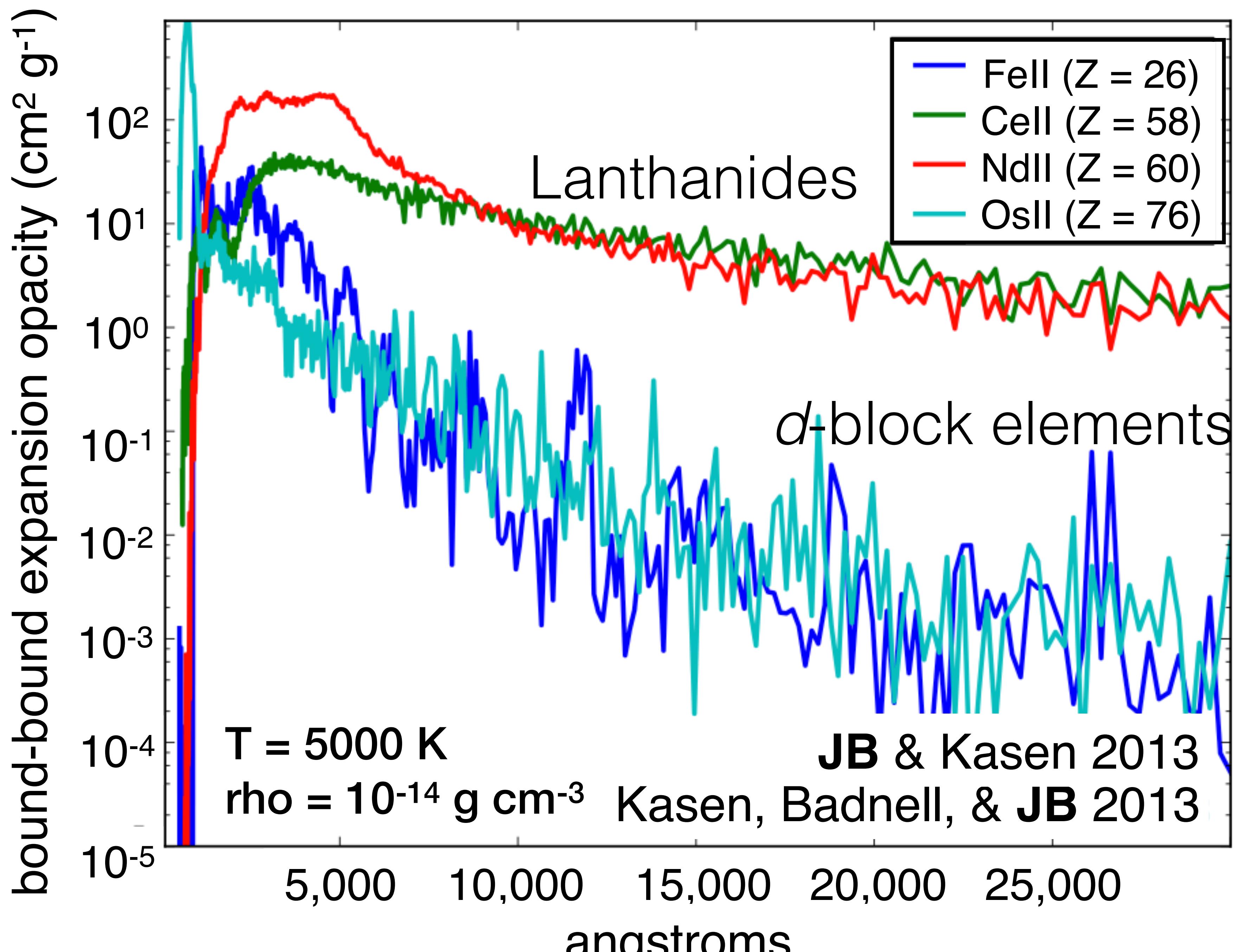
many-body Quantum Mechanical system

↓

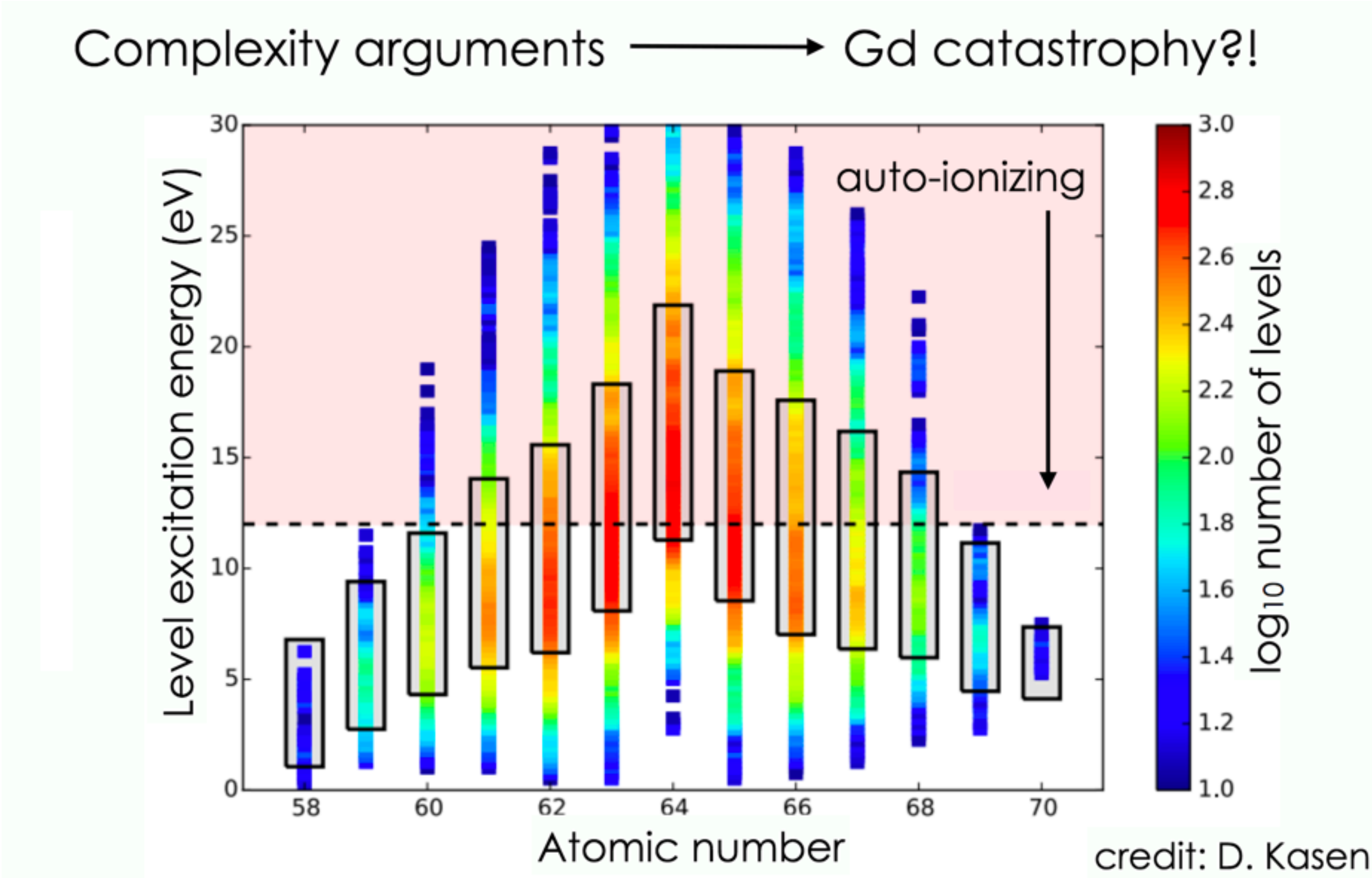
lines, levels, oscillator strengths

↓

synthetic opacities



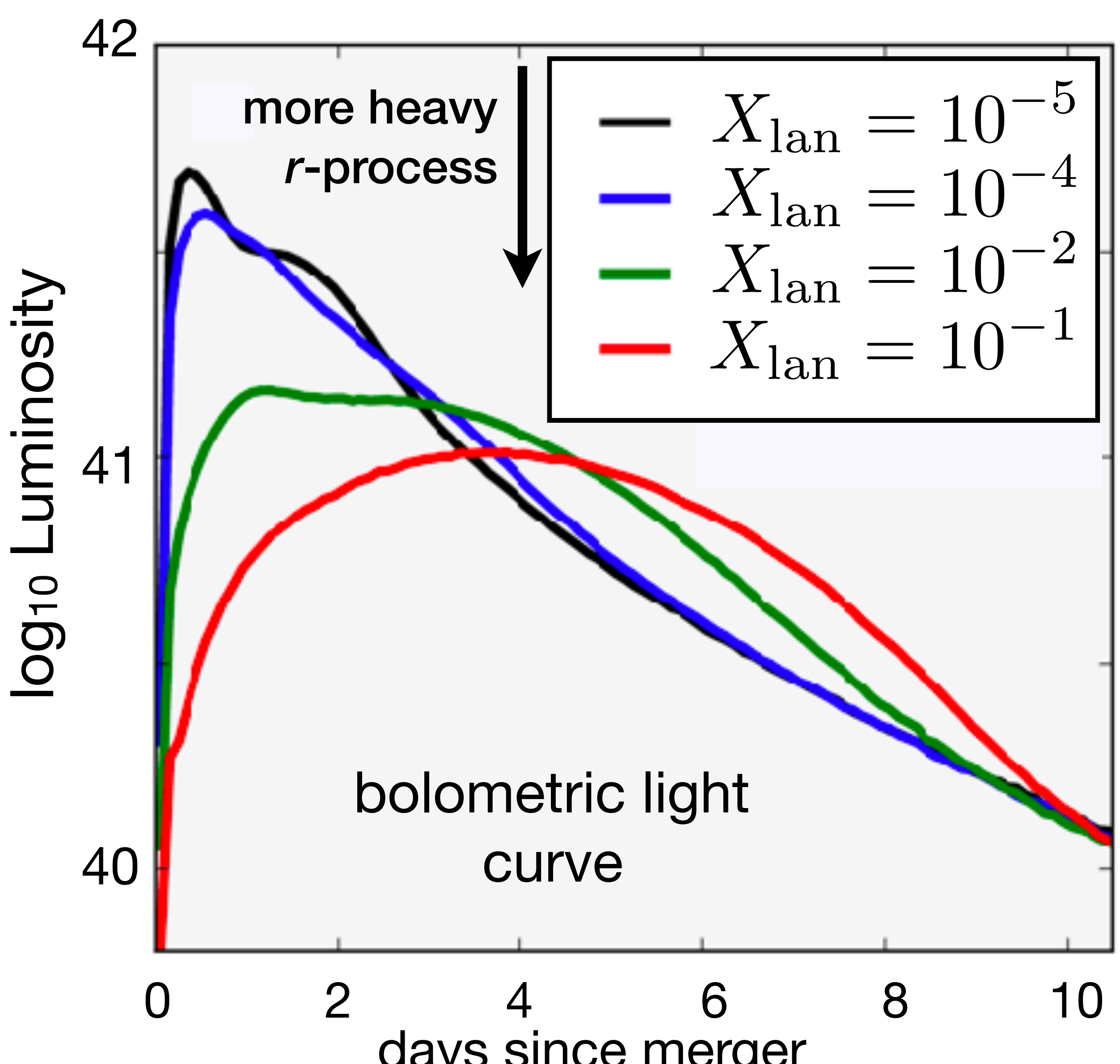
toward a full set of lanthanide opacities

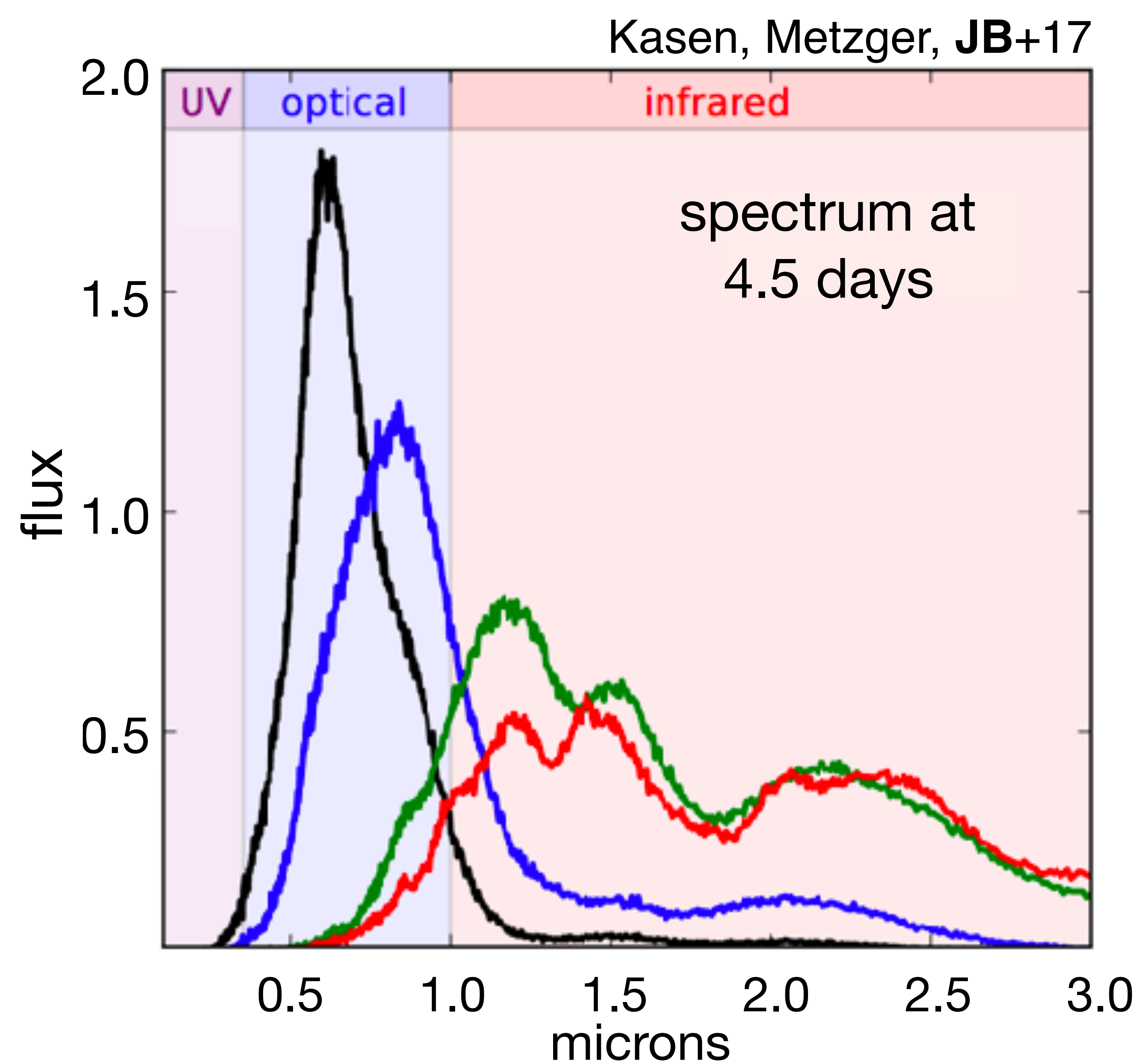


higher opacities lead to longer, dimmer, redder light curves

diffusion time: $t_{\mathrm{diff}} \approx \left(\frac{M\kappa}{vc}\right)^{1/2}$ **adiabatic losses:** $E_{\mathrm{phot}} \sim t^{-1}$

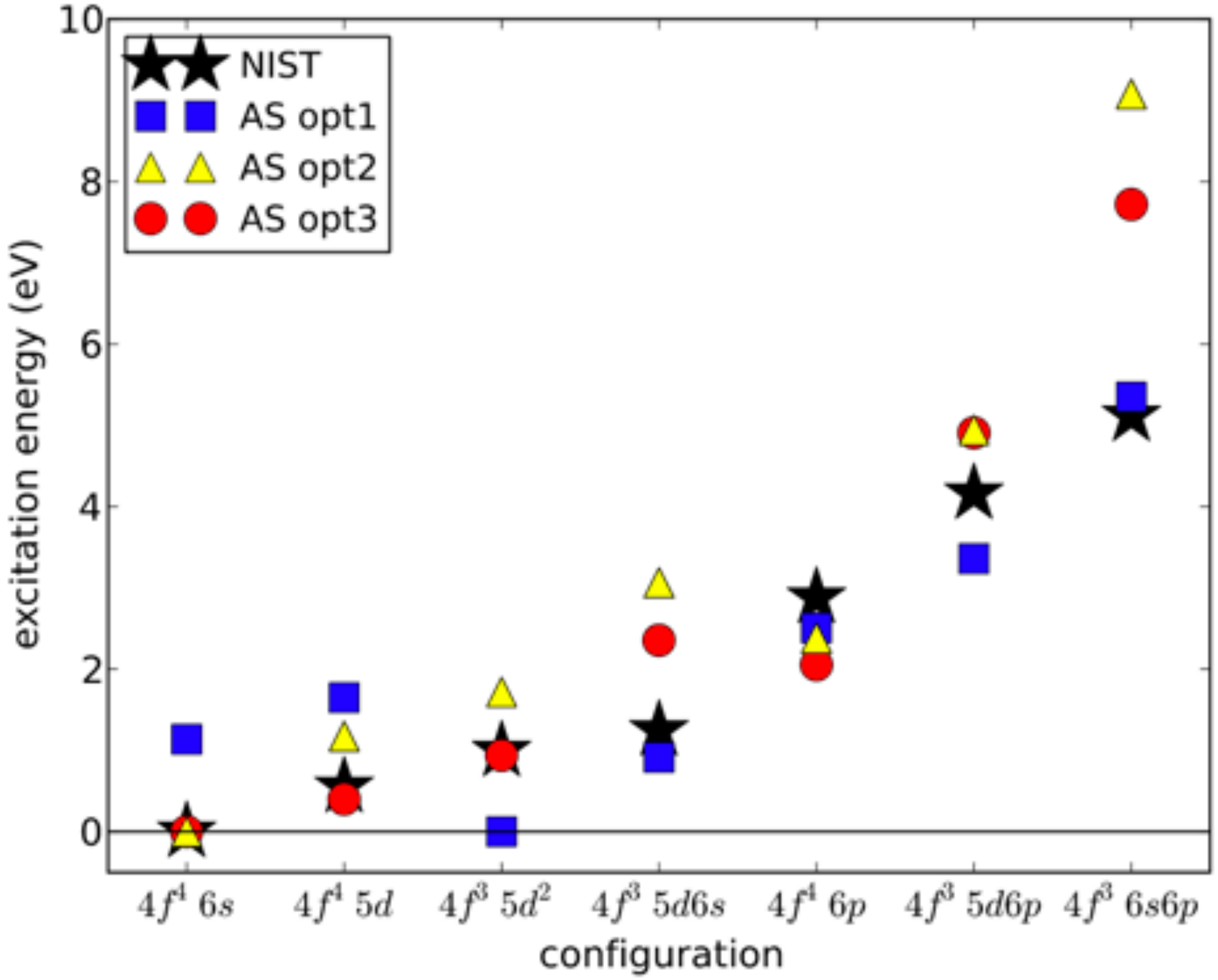
line blanketing at optical wavelengths



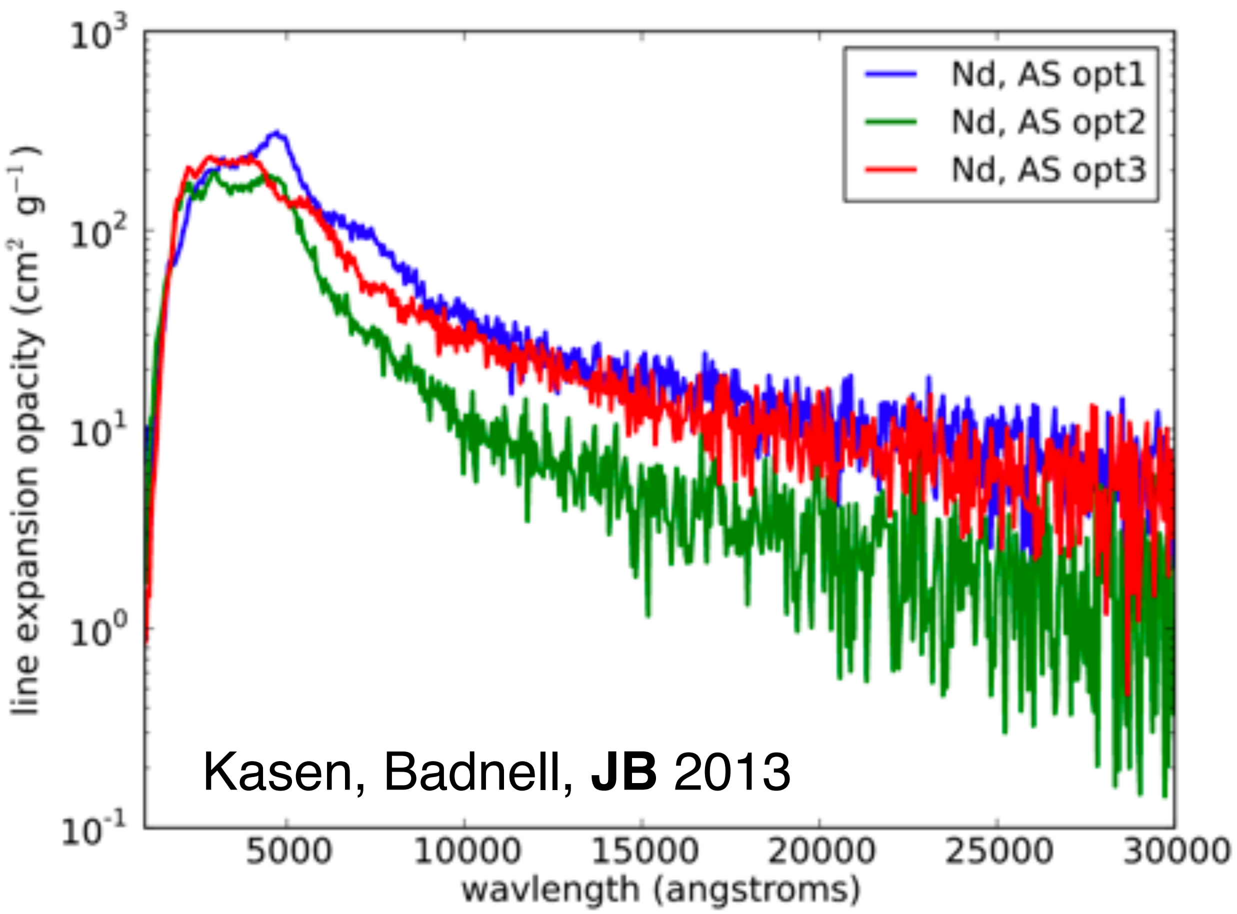


Uncertainties in synthetic atomic data

Energy levels

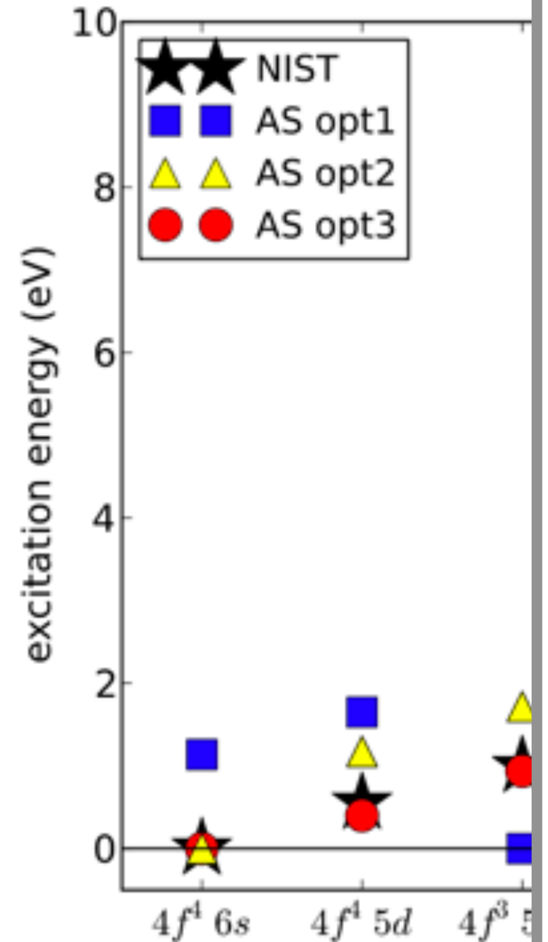


Expansion opacities

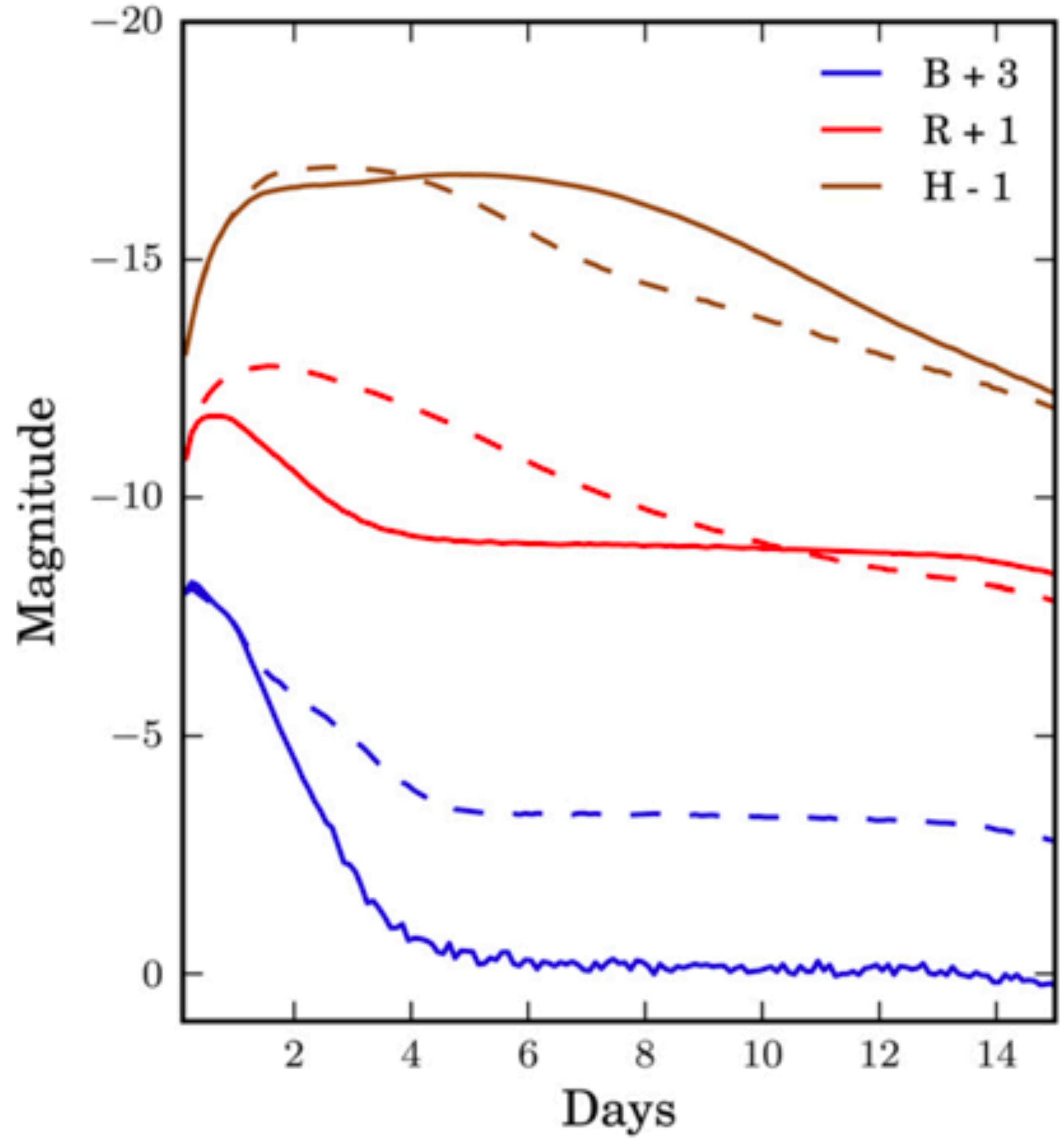


Uncertainties in synthetic atomic data

E

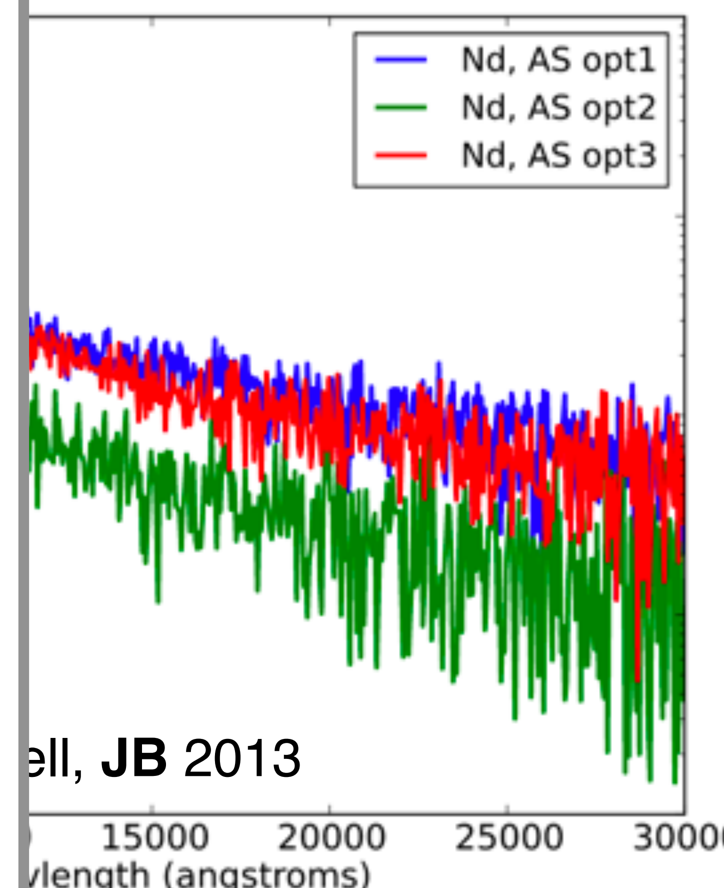


Light Curves & Spectra



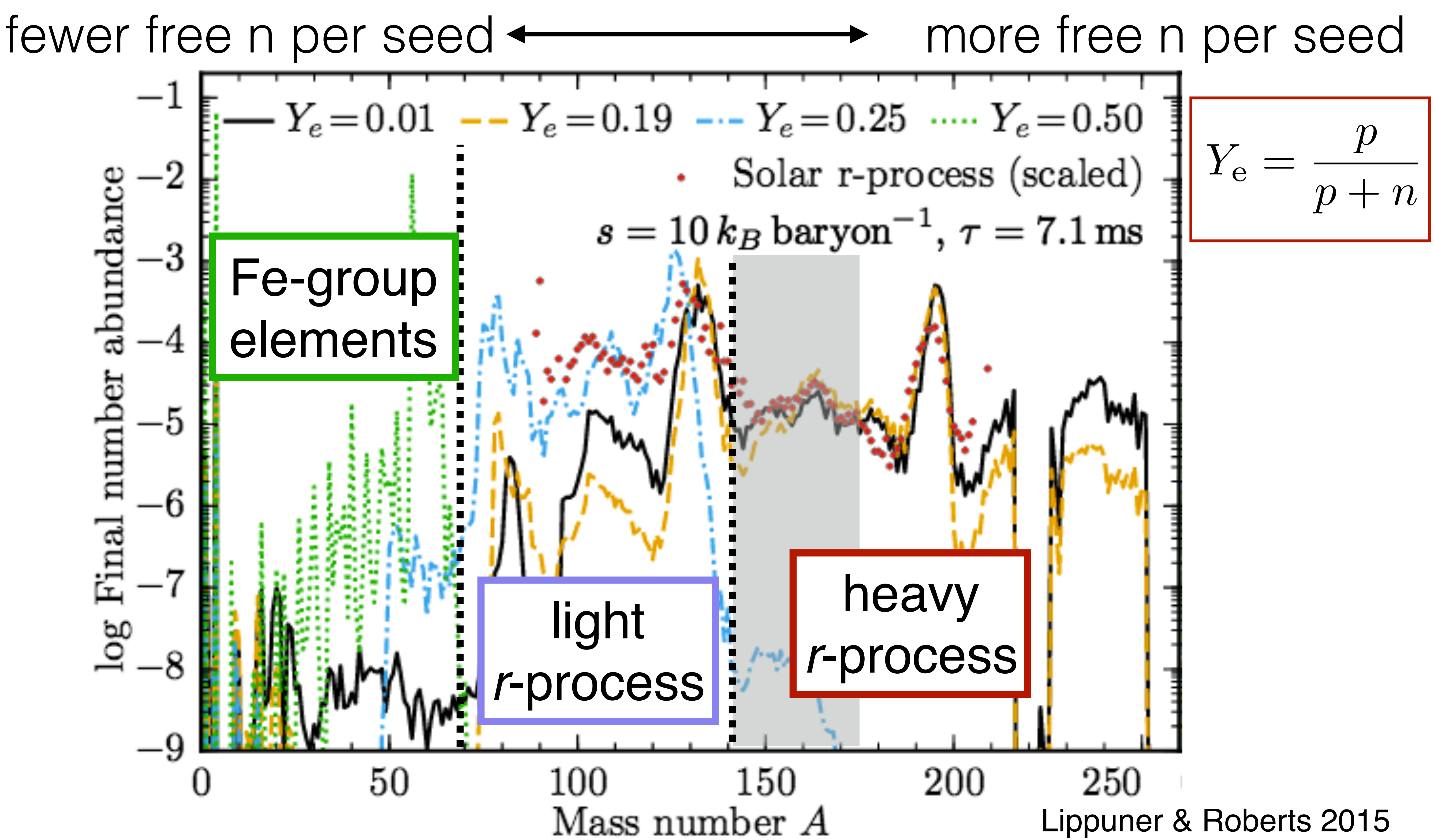
JB & Kasen 2013

nsion opacities



ell, **JB** 2013

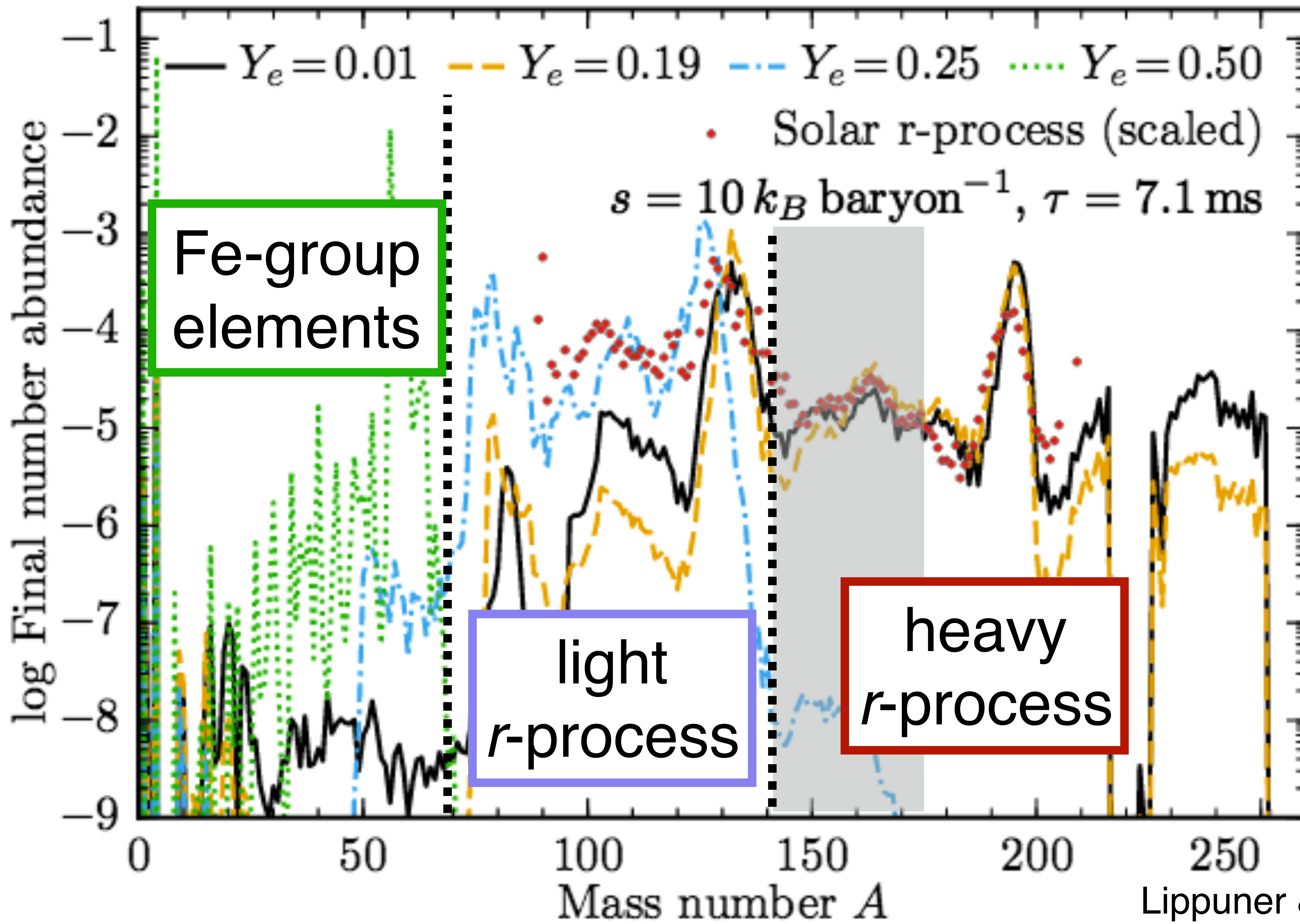
kilonova emission is tied to the strength of the *r*-process!



Lippuner & Roberts 2015

kilonova emission is tied to the strength of the *r*-process!

more weak interactions ⟶ fewer weak interactions



$$Y_\mathrm{e} = \frac{p}{p+n}$$

Lippuner & Roberts 2015

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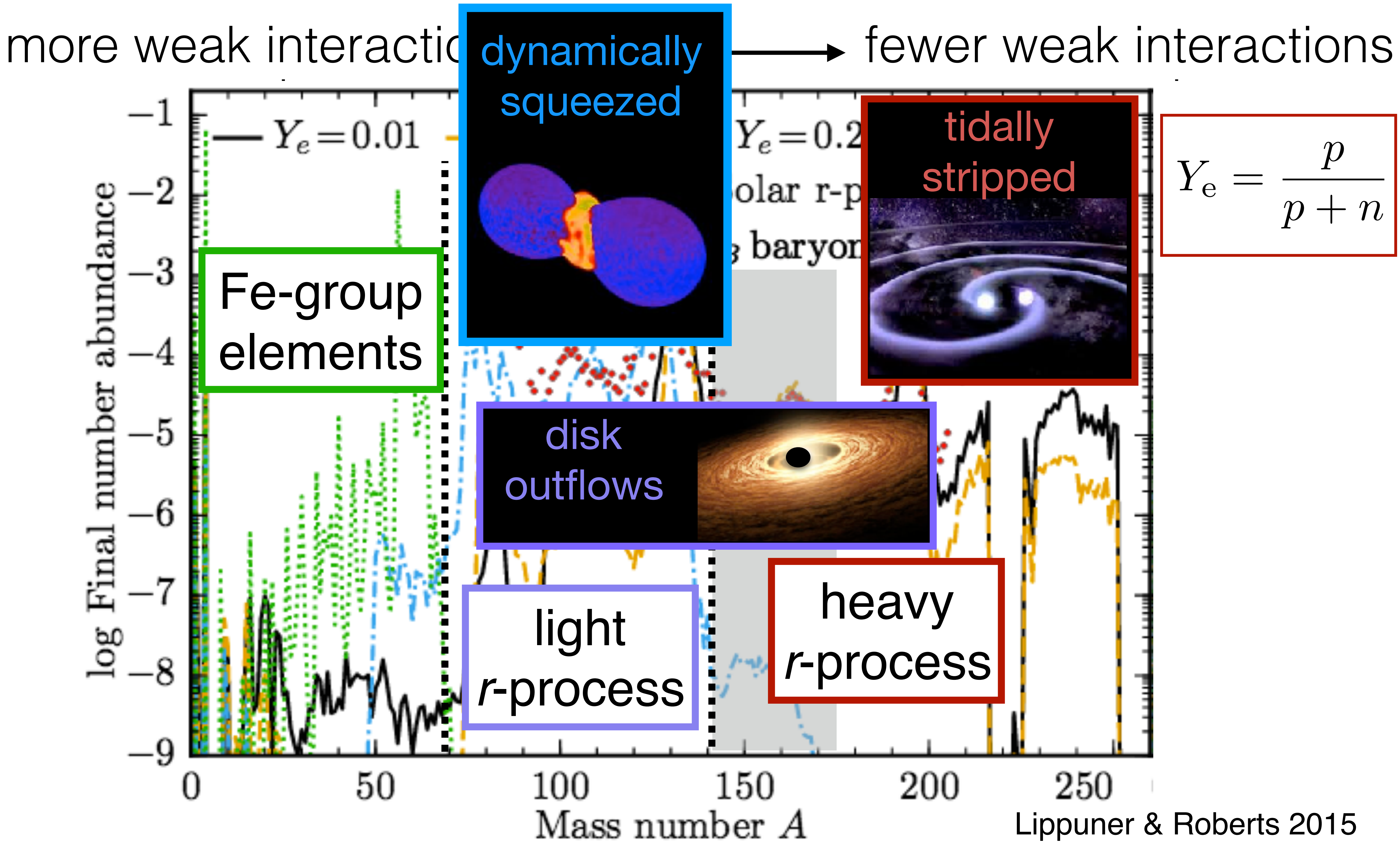
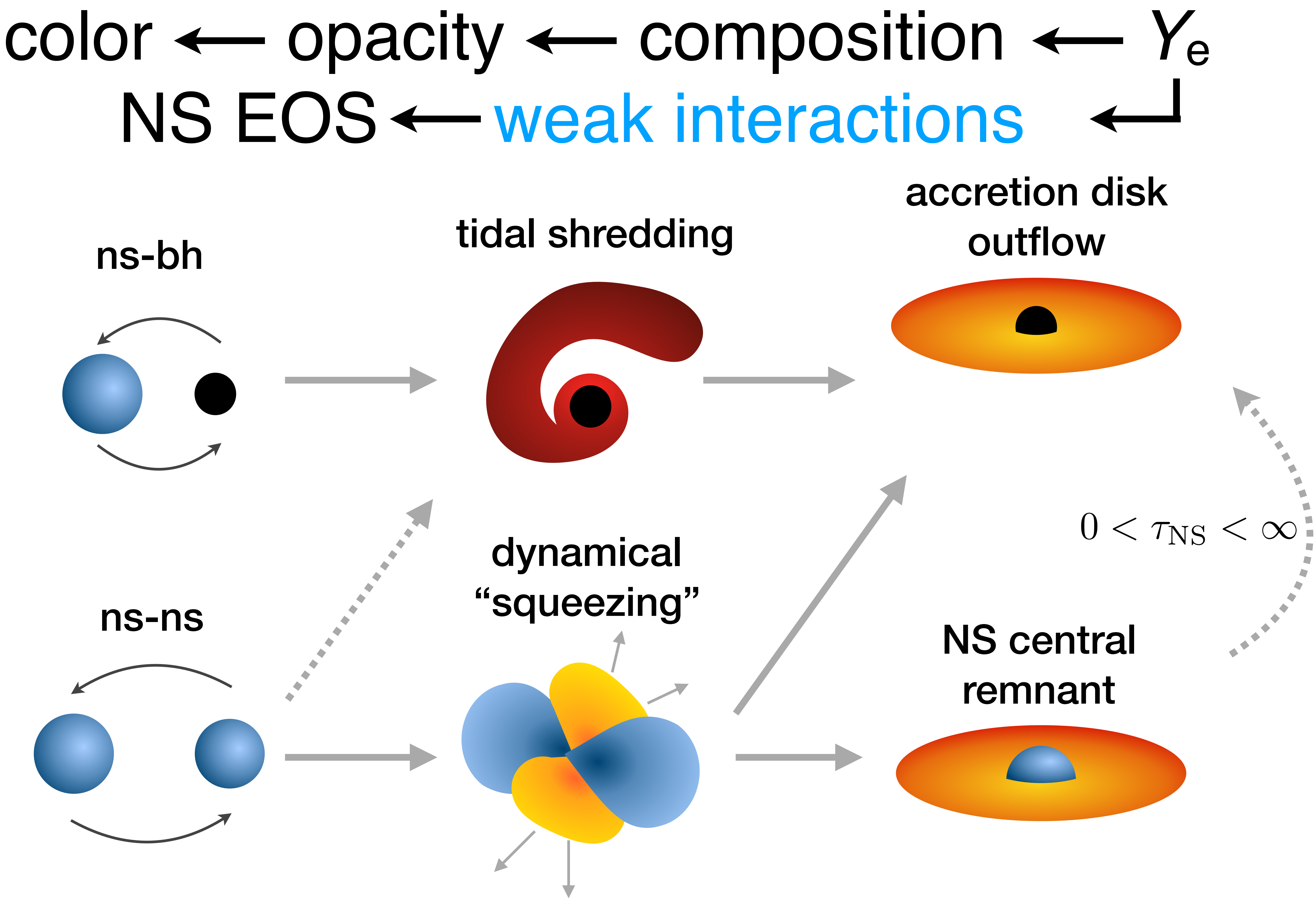
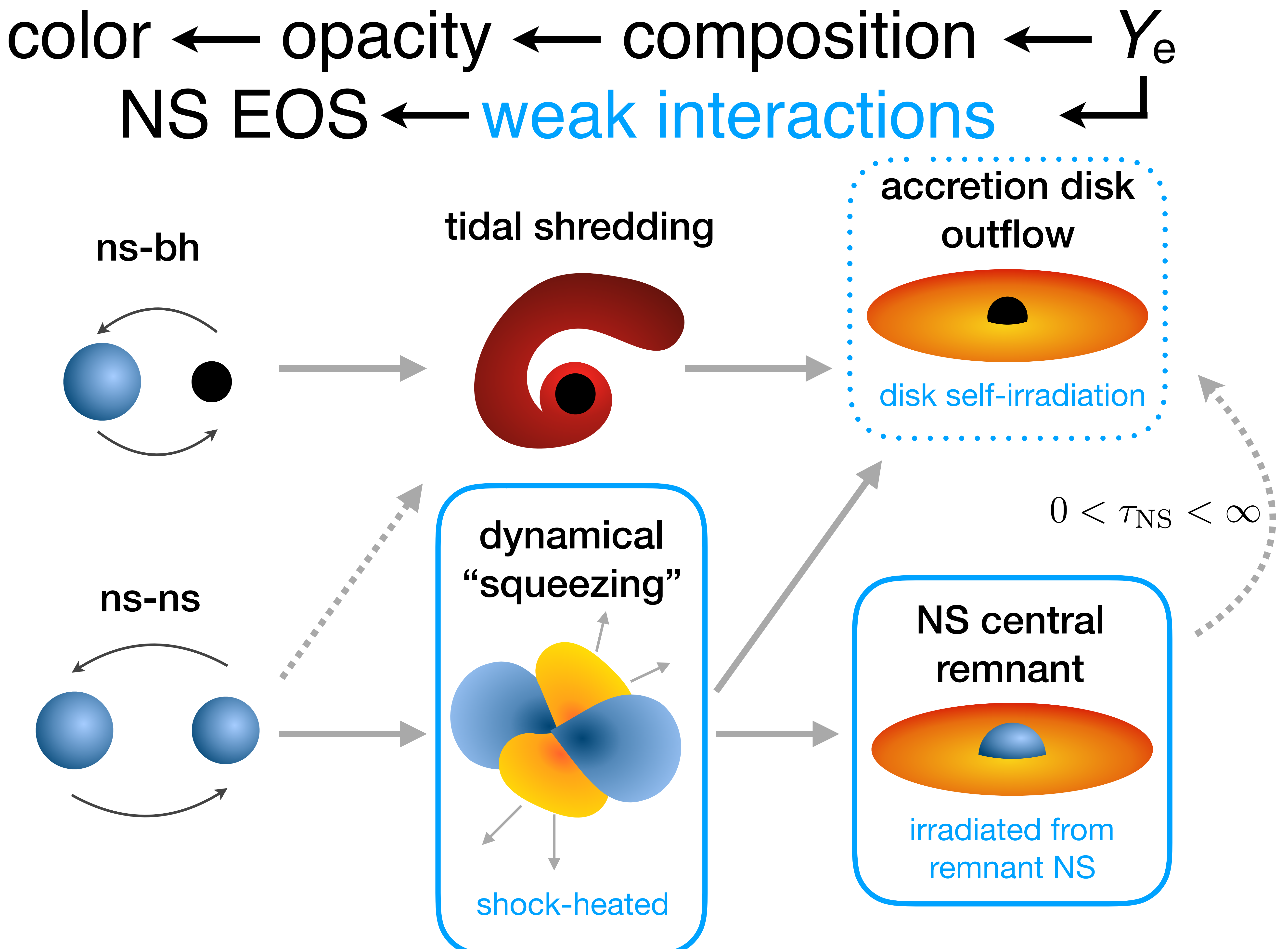
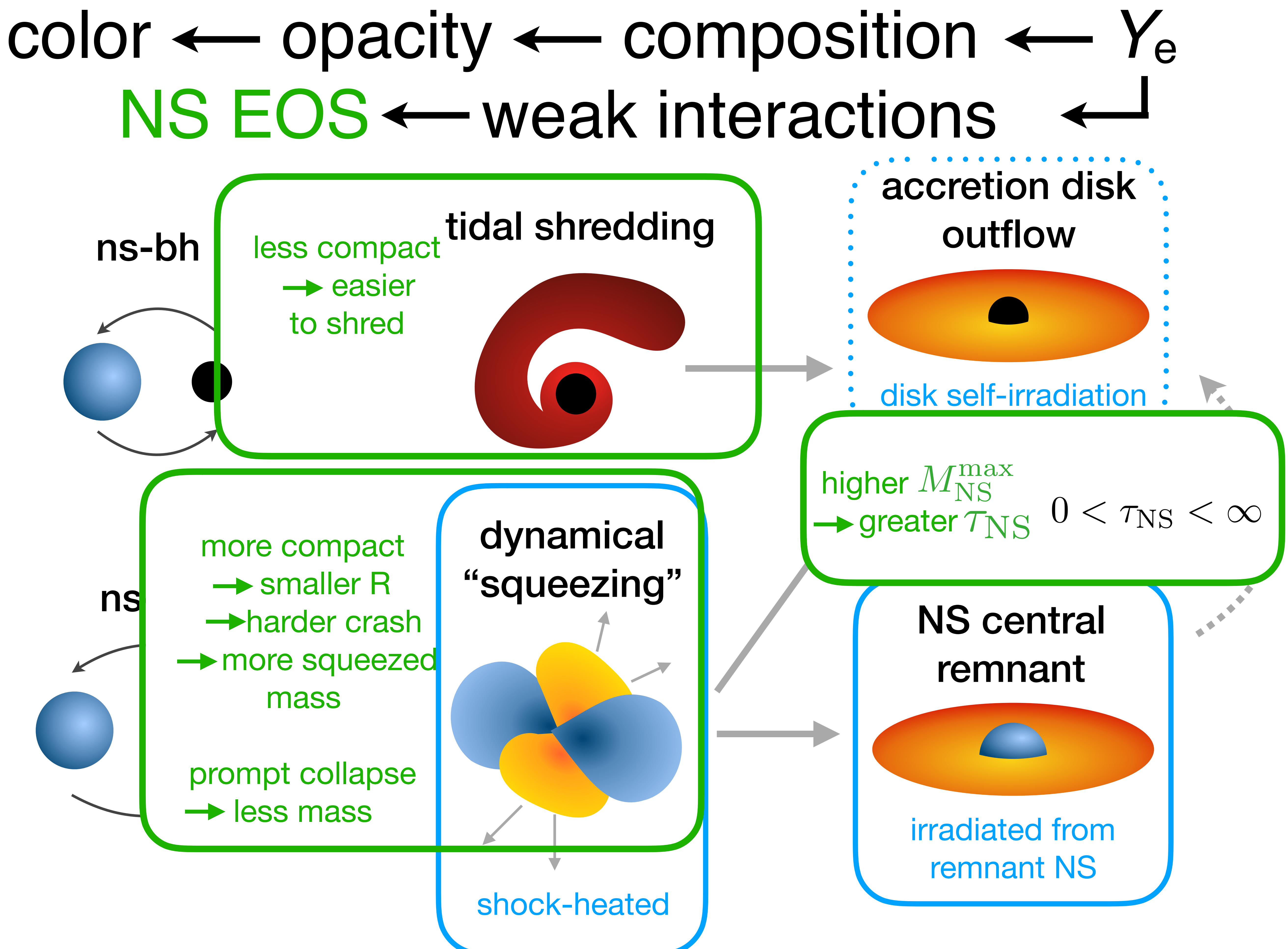


Lippuner & Roberts 2015


color ← opacity ← composition ← Y_e
NS EOS ← weak interactions
ns-bh
tidal shredding
accretion disk outflow
$0 < \tau_{NS} < \infty$
ns-ns
dynamical "squeezing"
NS central remnant


color ← opacity ← composition ← Y_e
NS EOS ← weak interactions
ns-bh
tidal shredding
accretion disk outflow
disk self-irradiation
$0 < \tau_{\rm NS} < \infty$
ns-ns
dynamical "squeezing"
shock-heated
NS central remnant
irradiated from remnant NS



color ⟵ opacity ⟵ composition ⟵ Y_e
NS EOS ⟵ weak interactions
ns-bh
tidal shredding
less compact
→ easier
to shred
accretion disk
outflow
disk self-irradiation
higher $M_{\rm NS}^{\rm max}$
→ greater $\tau_{\rm NS}$
$0 < \tau_{\rm NS} < \infty$
ns
more compact
→ smaller R
→ harder crash
→ more squeezed
mass
prompt collapse
→ less mass
dynamical
“squeezing”
shock-heated
NS central
remnant
irradiated from
remnant NS

spectral identification: the next frontier!