Kilonova signatures and the *r*-process

FRIB and the GW170817 kilonova

Jennifer Barnes
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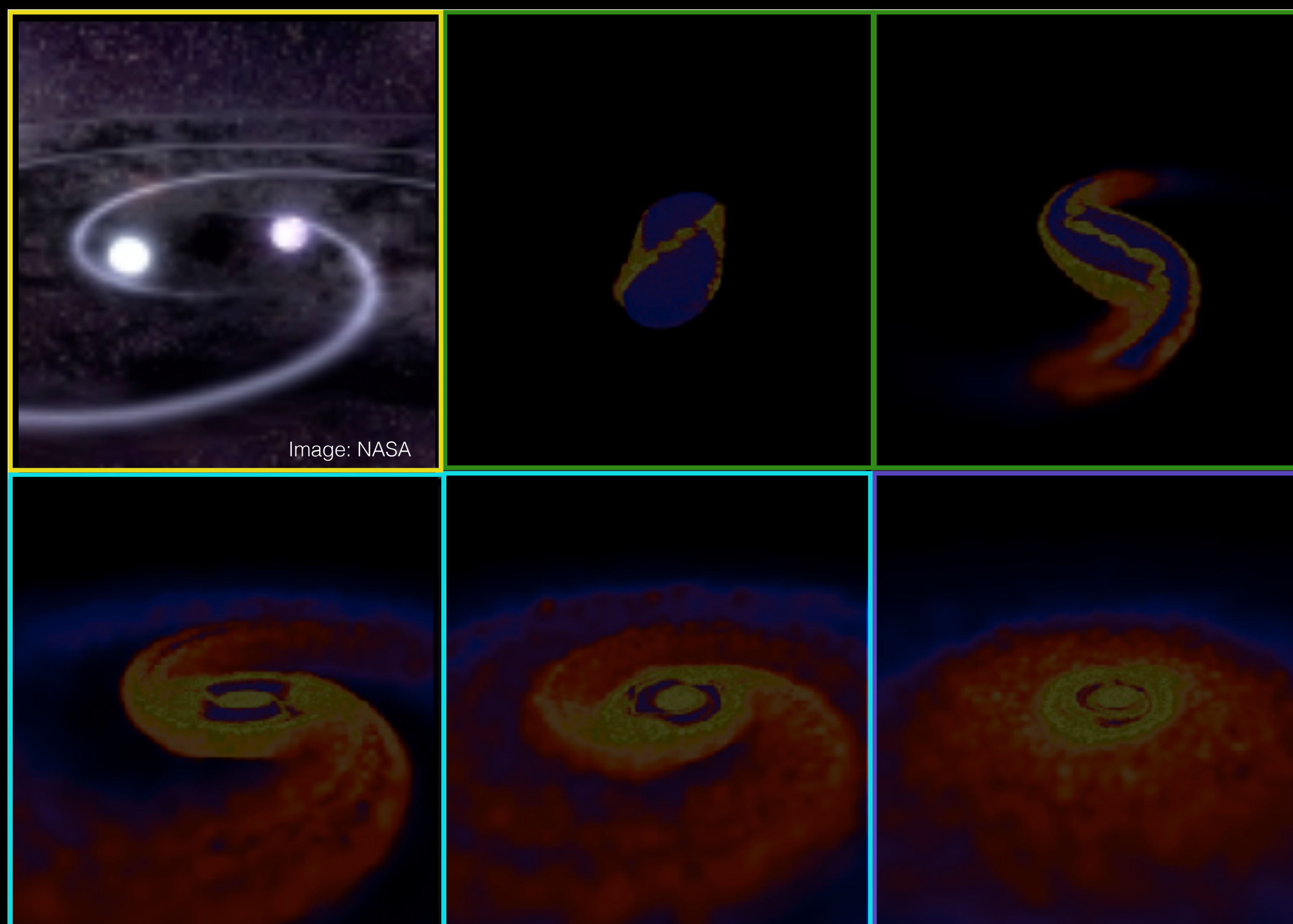
Columbia University

mergers: a stellar danse macabre

final few orbits:
strong GW source



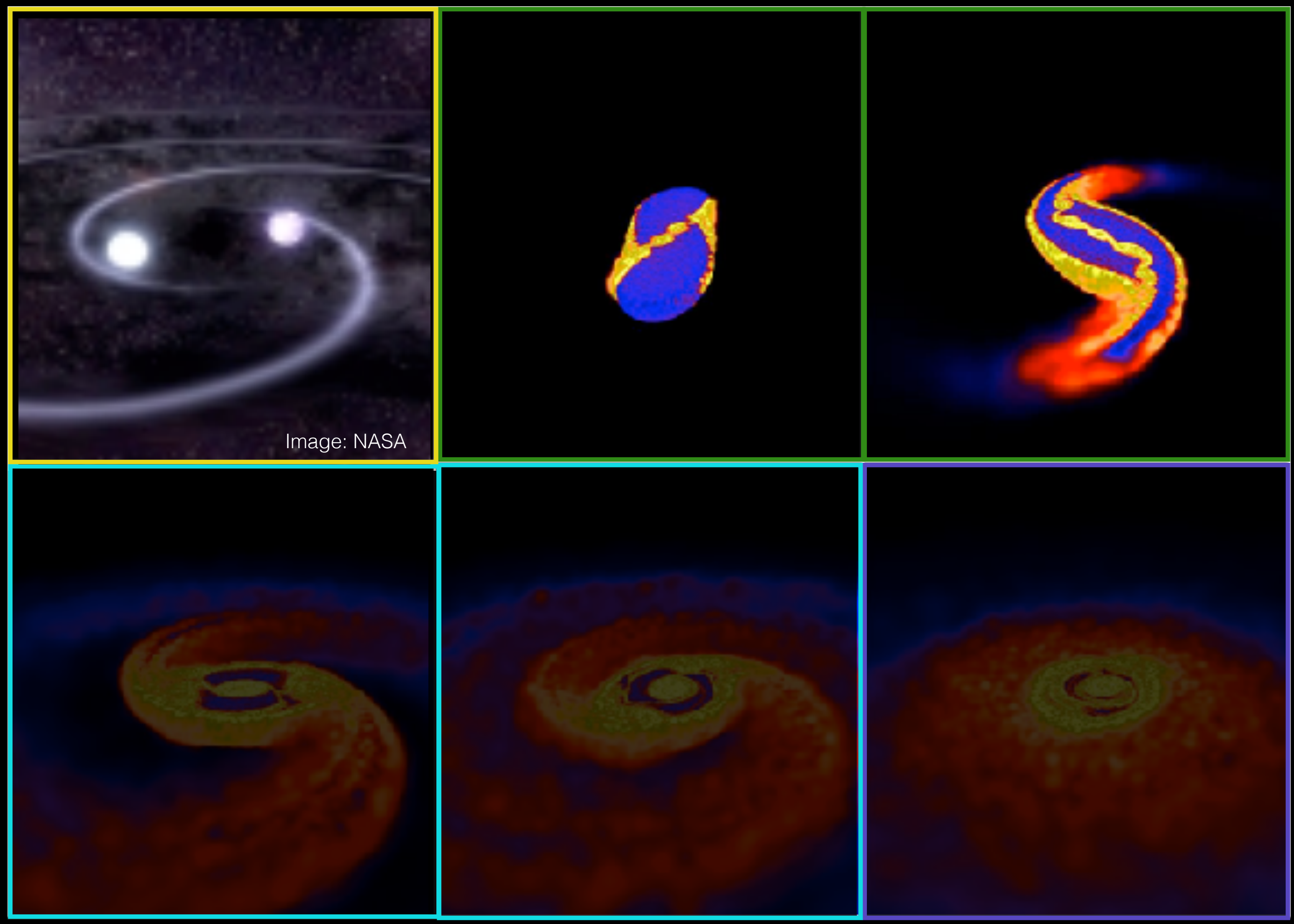
e.g. Lattimer & Schramm 1974, 1976
Li & Paczynski 1998

Image credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

mergers: a stellar danse macabre

final few orbits: strong GW source

merger: neutron star is partially disrupted, central remnant forms



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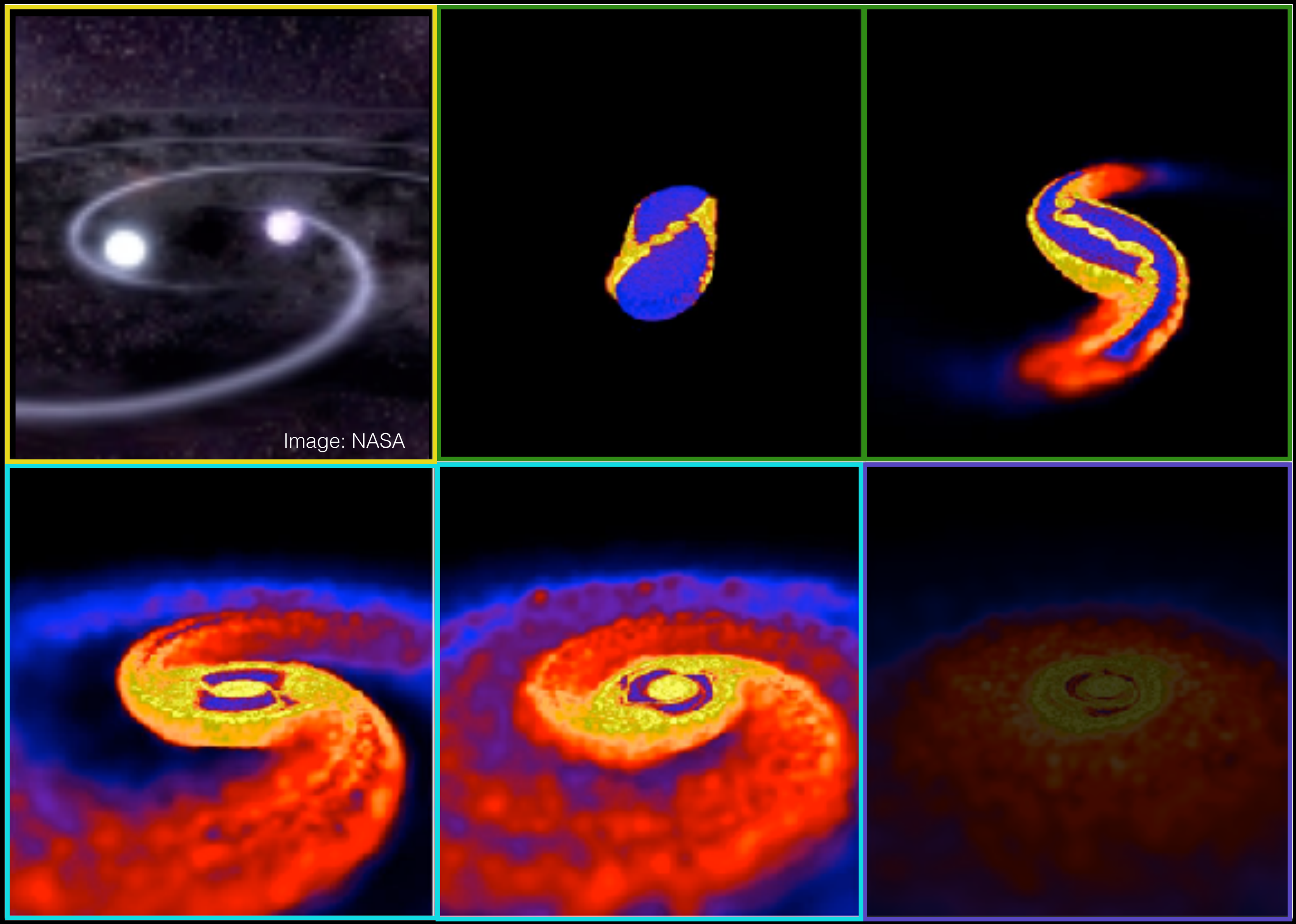

ejecta: some material is escapes; some is bound

e.g. Lattimer & Schramm 1974, 1976
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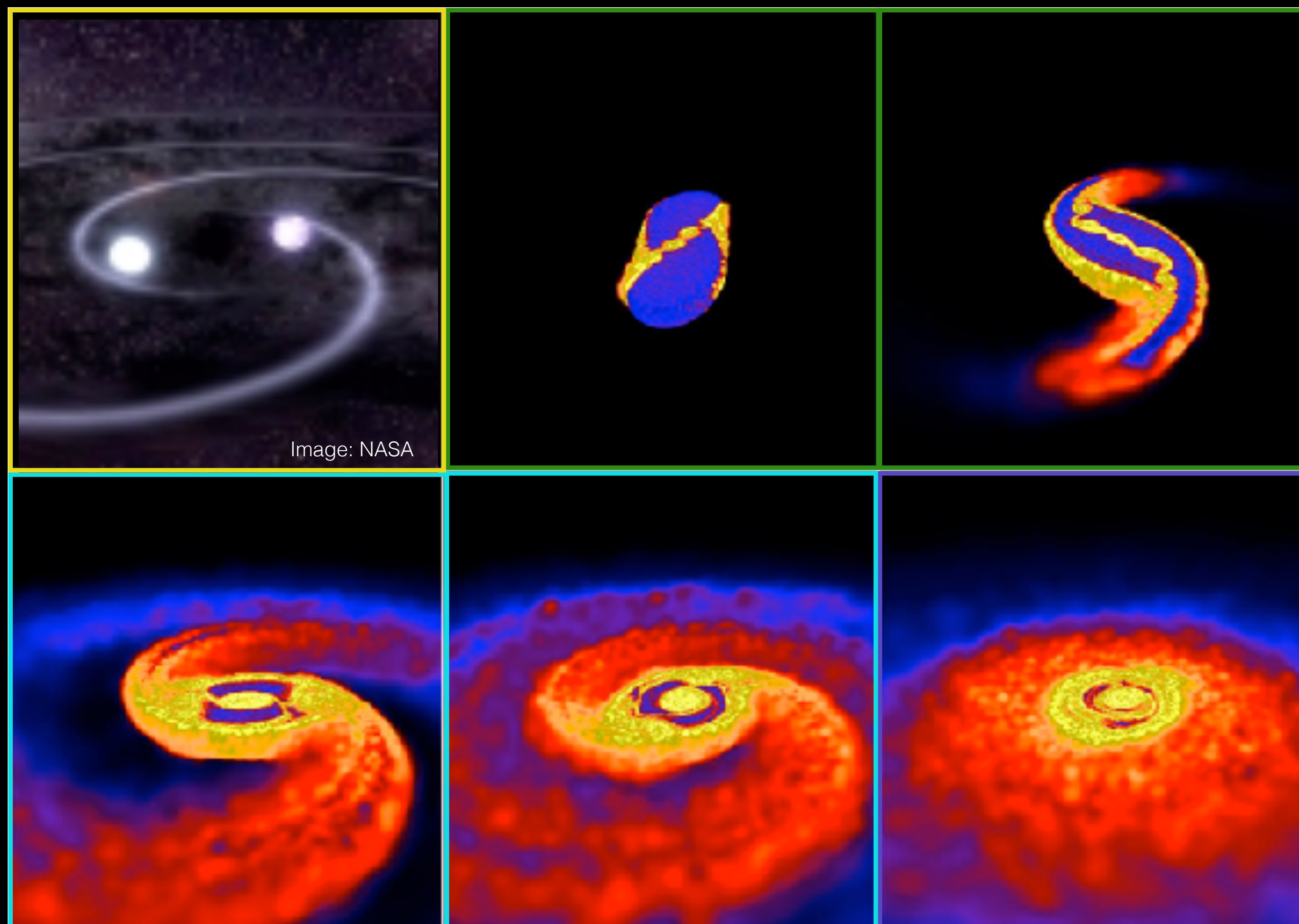

ejecta: some material is escapes; some is bound

final: a central NS or BH, an accretion disk, unbound ejecta

e.g. Lattimer & Schramm 1974, 1976
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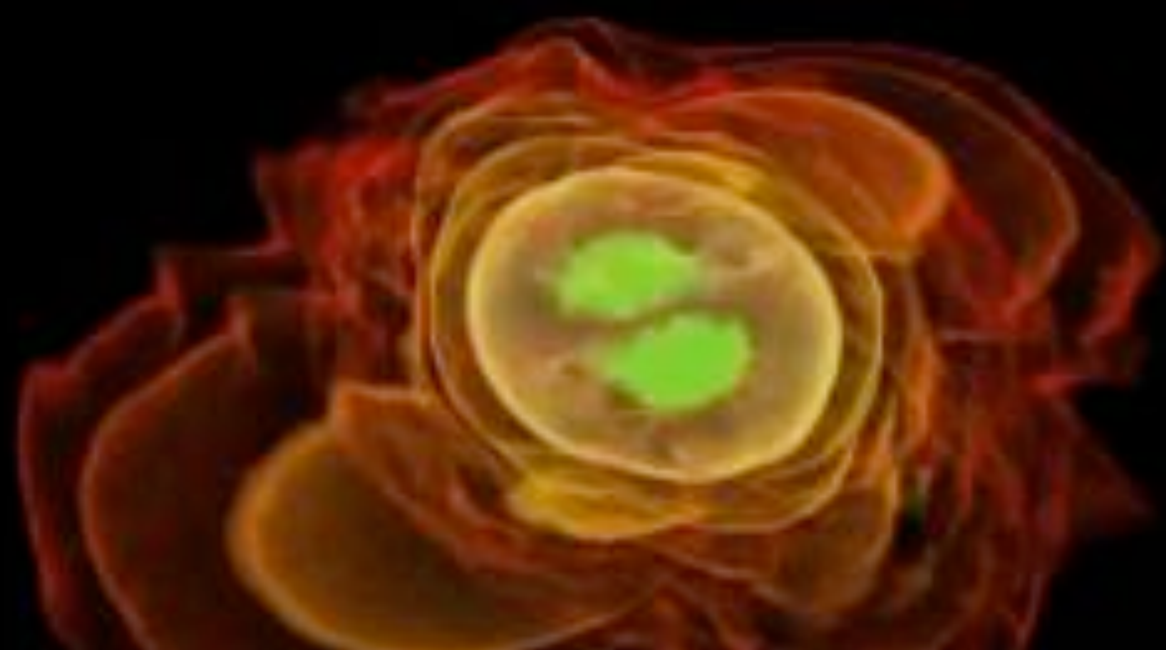
Image credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

radioactive transients are probes of the *r*-process

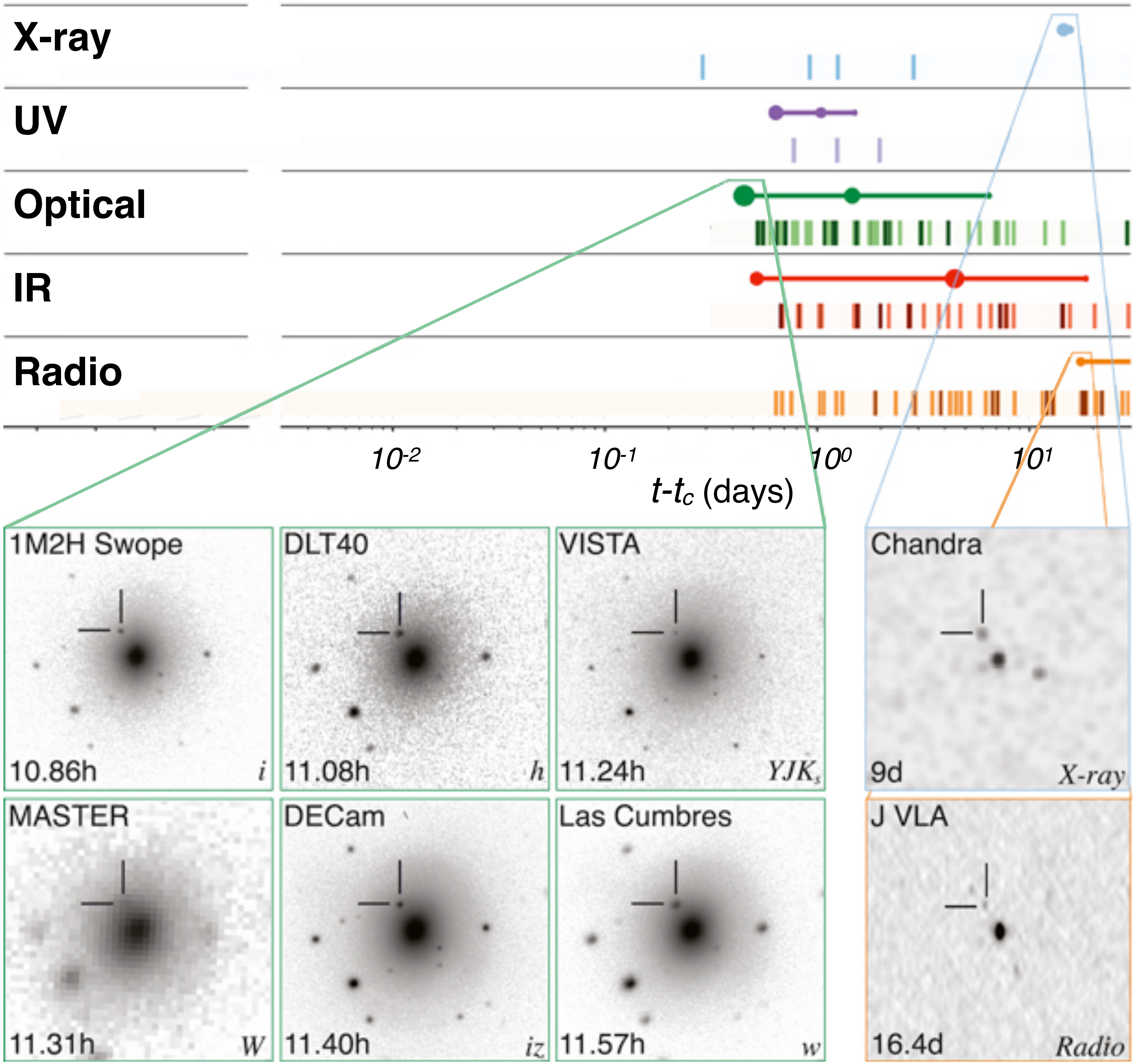
"kilonova"



- Mildly relativistic unbound material
- Heavy elements are synthesized

⟶ An expanding cloud heated by radioactive decays

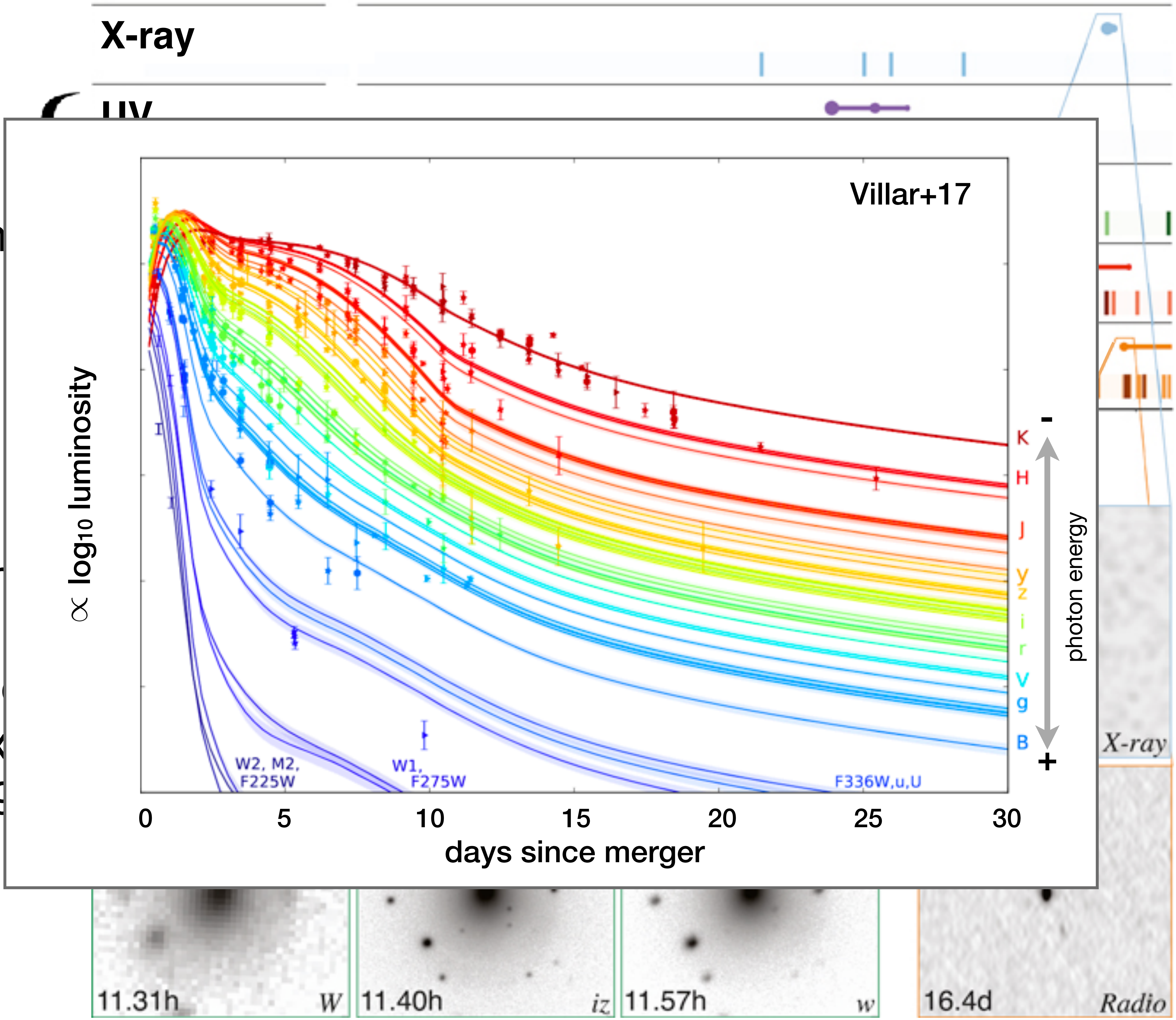
Let’s zoom in



transient source detected in galaxy NGC 4993

ad. from ALV + EM Partners 17

Let’s
zoom in

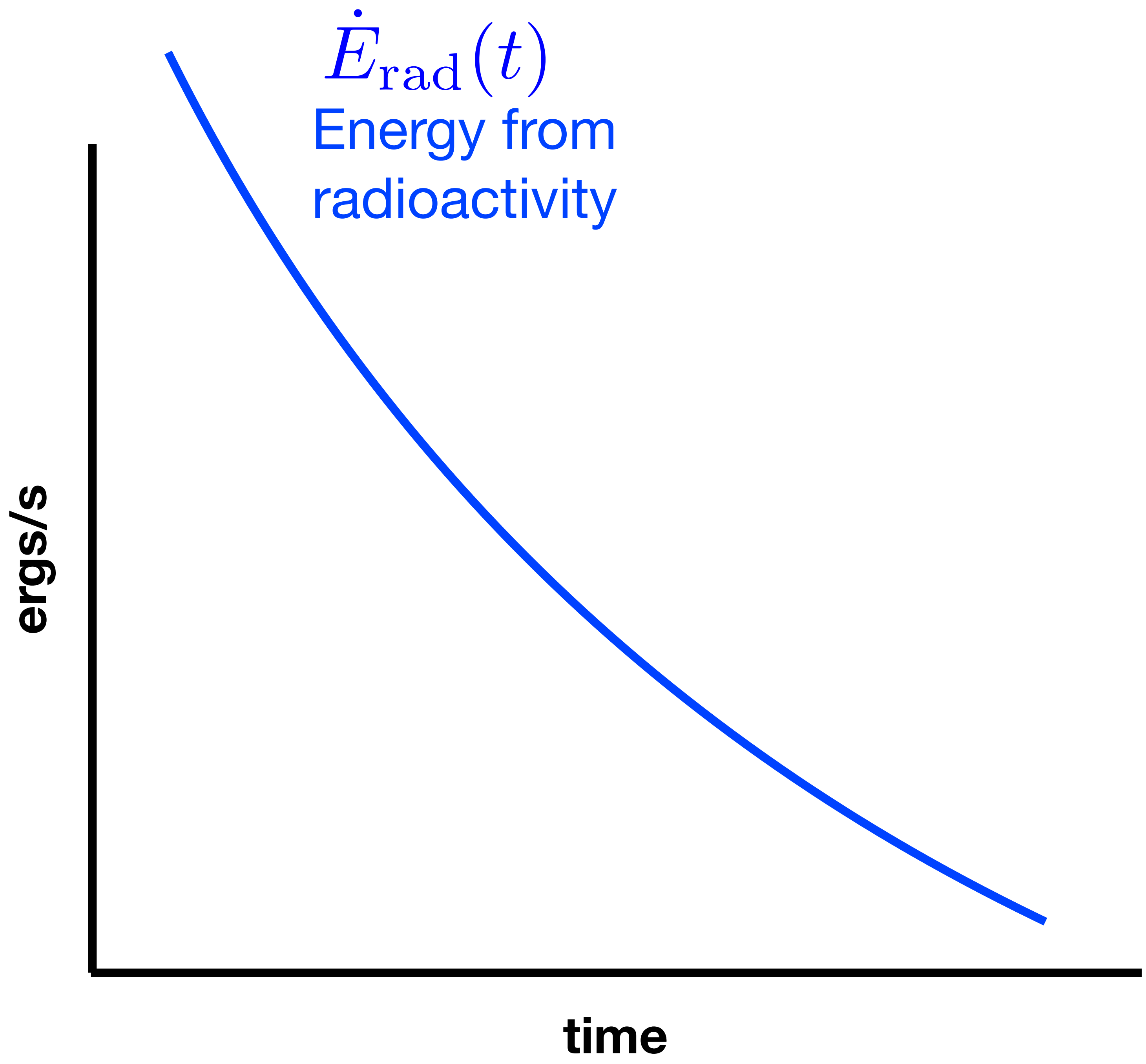


transien
source
detecte
in galax
NGC 49

ad. from ALV + EM Partners 17

ingredients for a kilonova model

(bolometric) light curves



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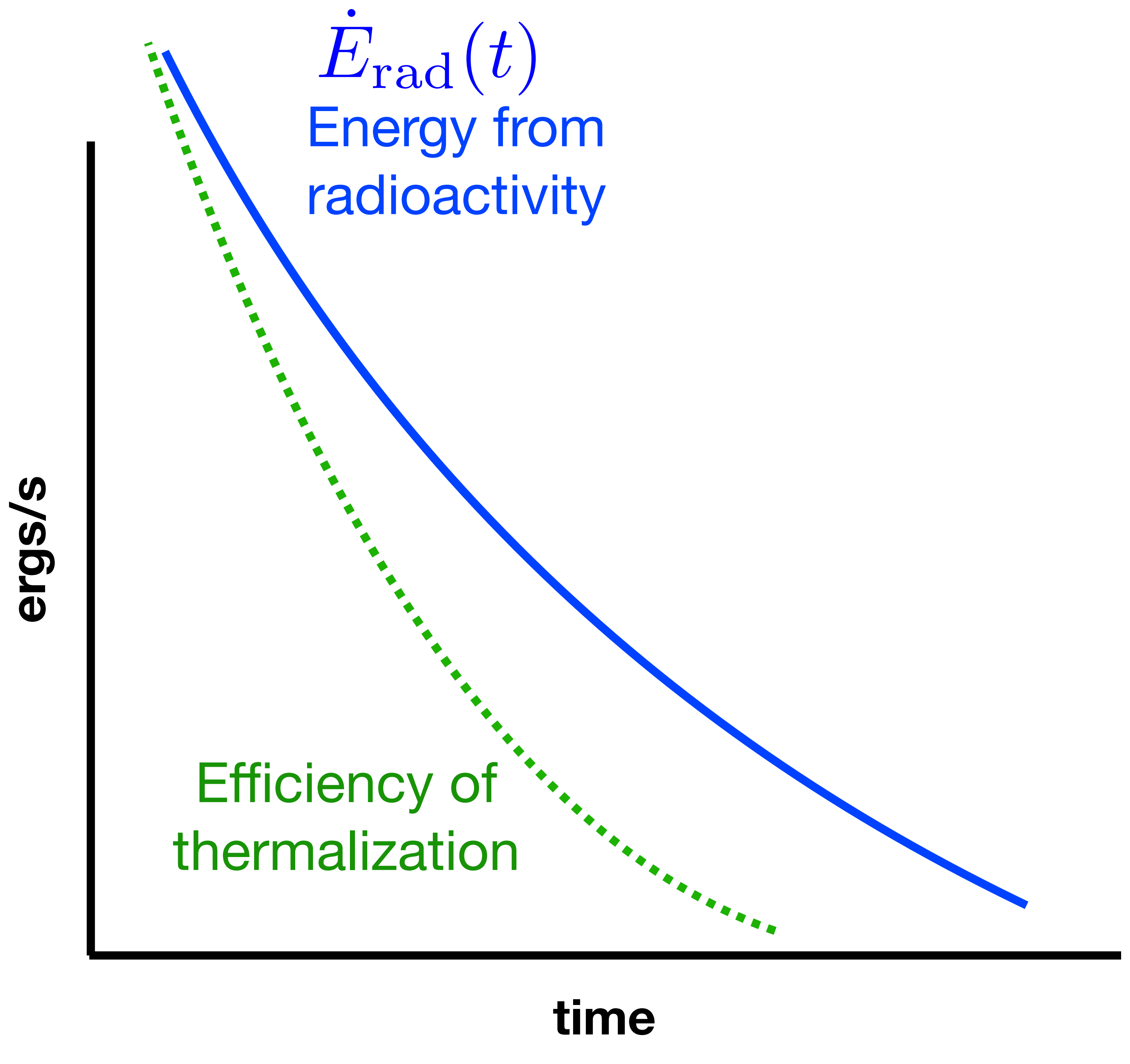

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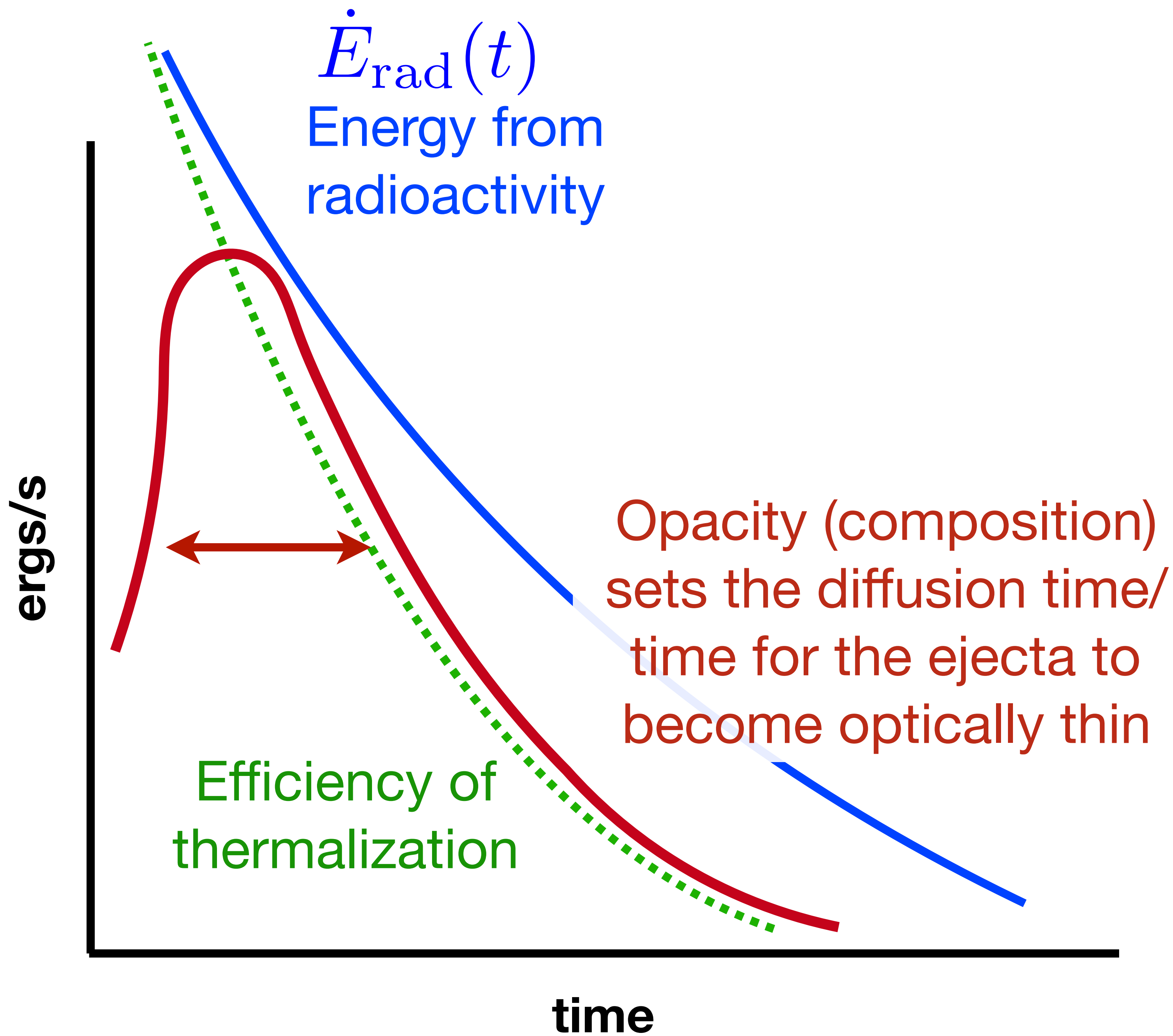

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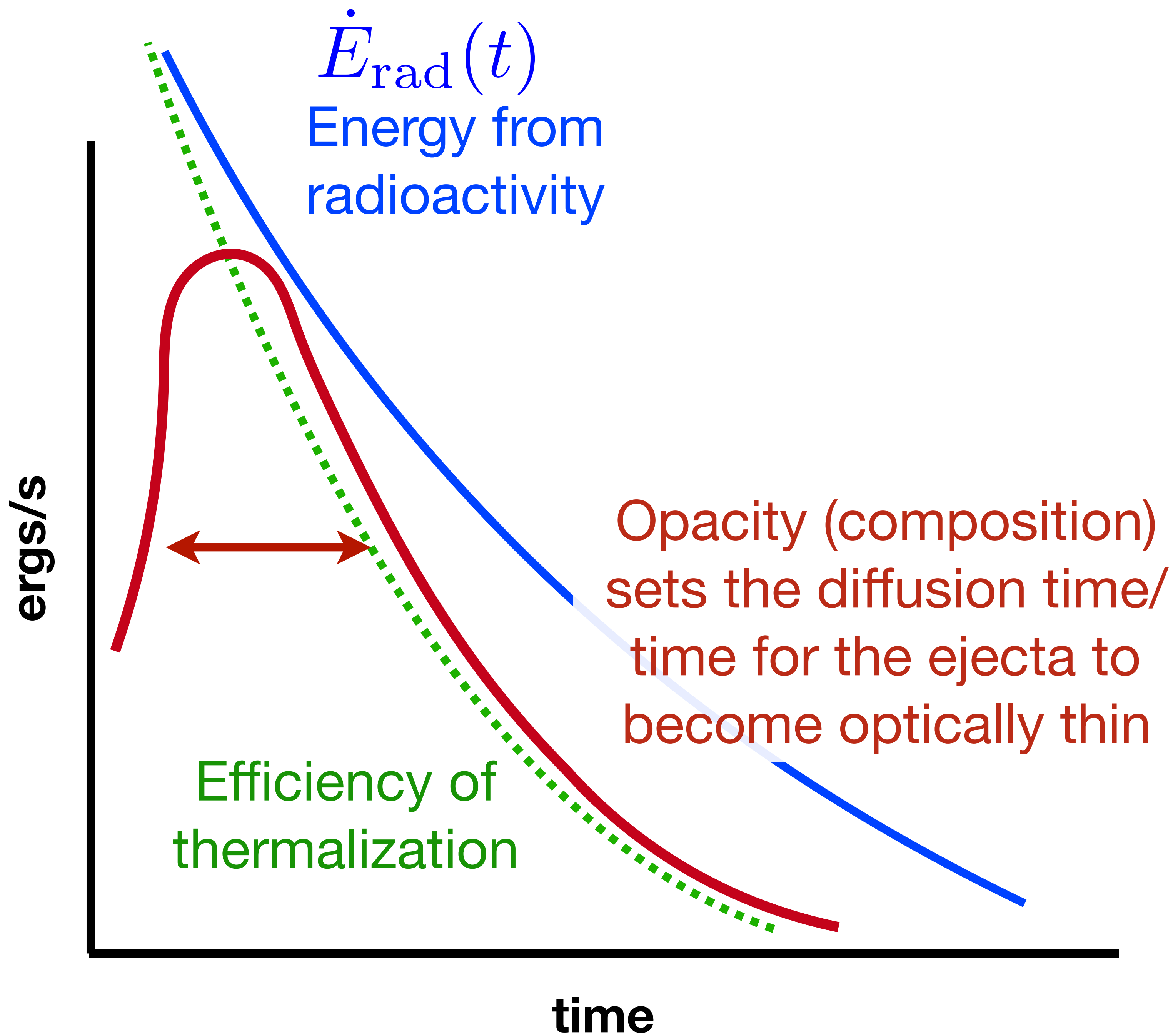


colors & spectra

- 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

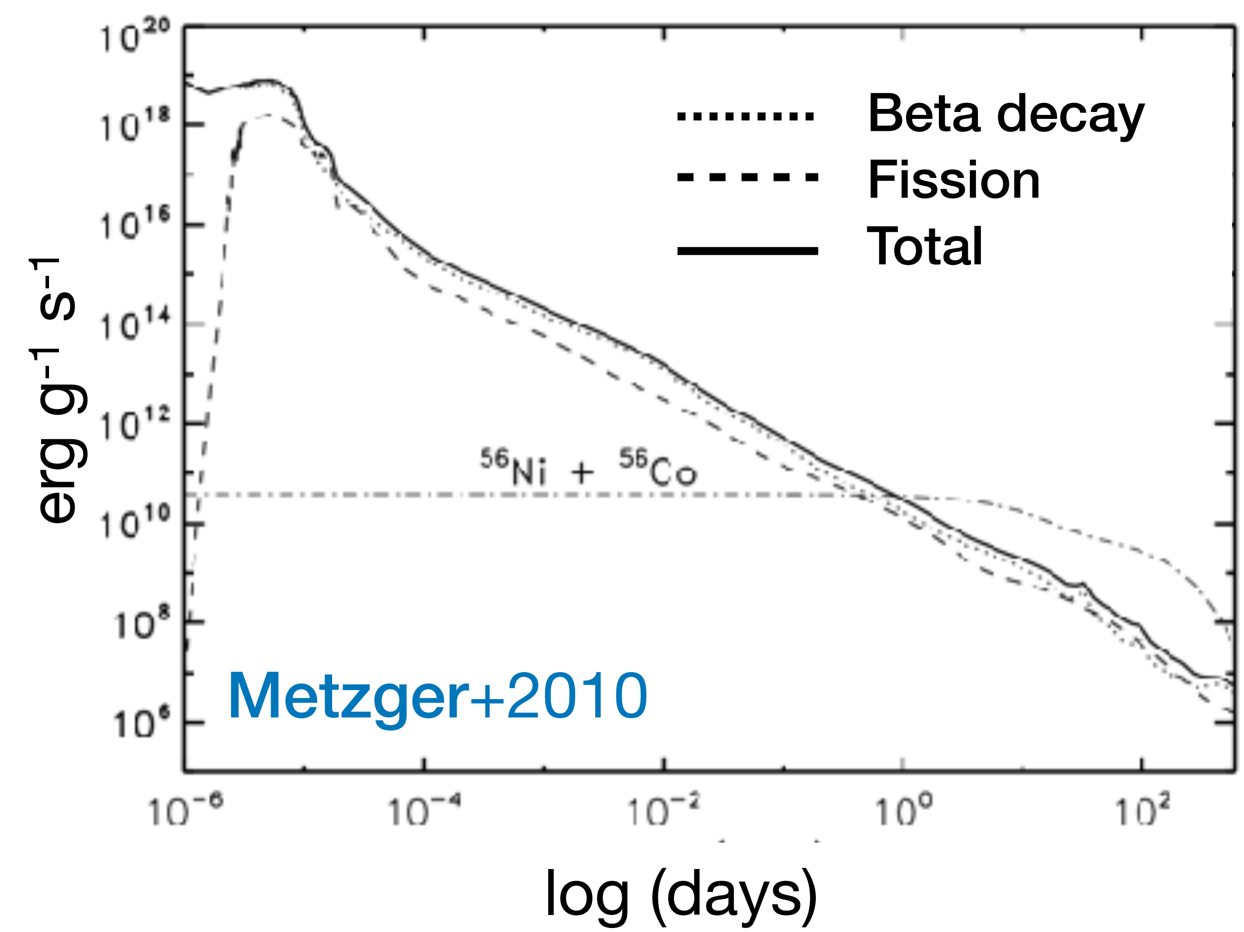
Because there are many contributing decays, $\dot{E}_{\rm rad}(t)$ follows a ~power law

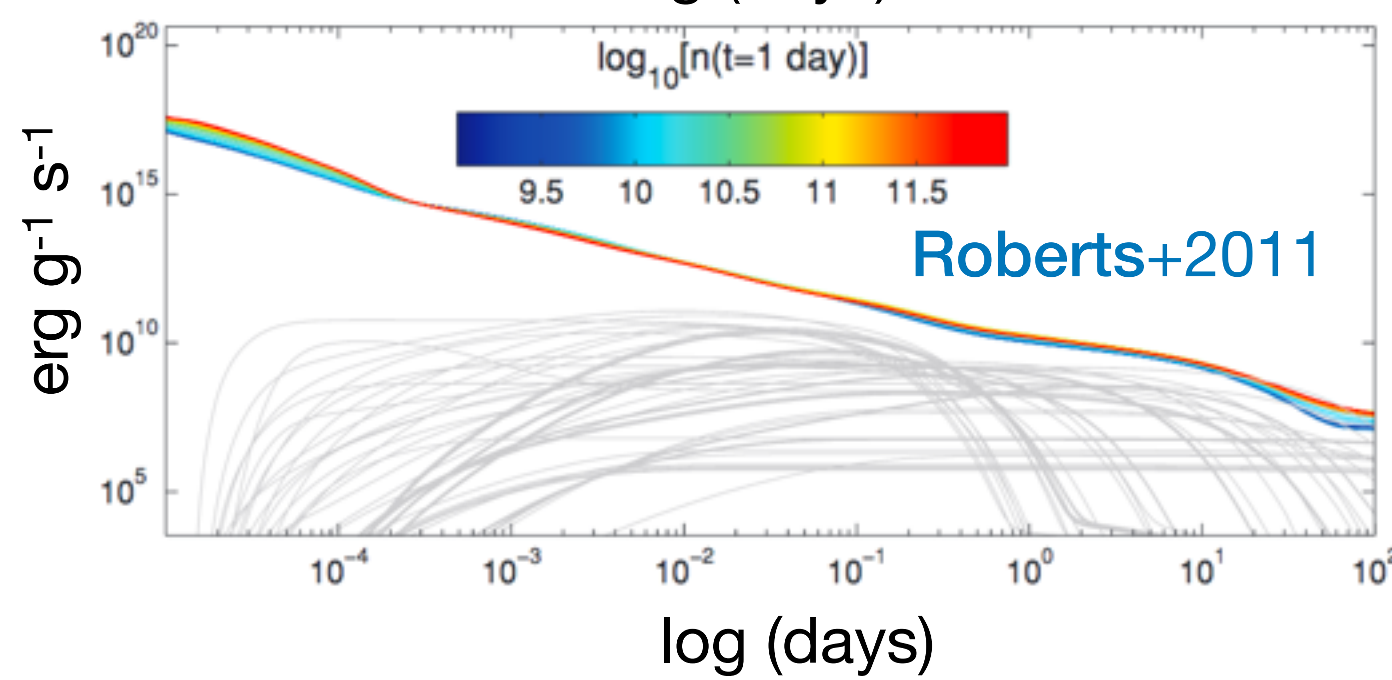
The expression $\dot{E}_{\rm rad}(t) = \frac{fc^2}{t}$

was first derived **analytically** (Li & Paczyński 1998; see also Hotokezaka+17)

The basic behavior has since been borne out by **nuclear network calculations**

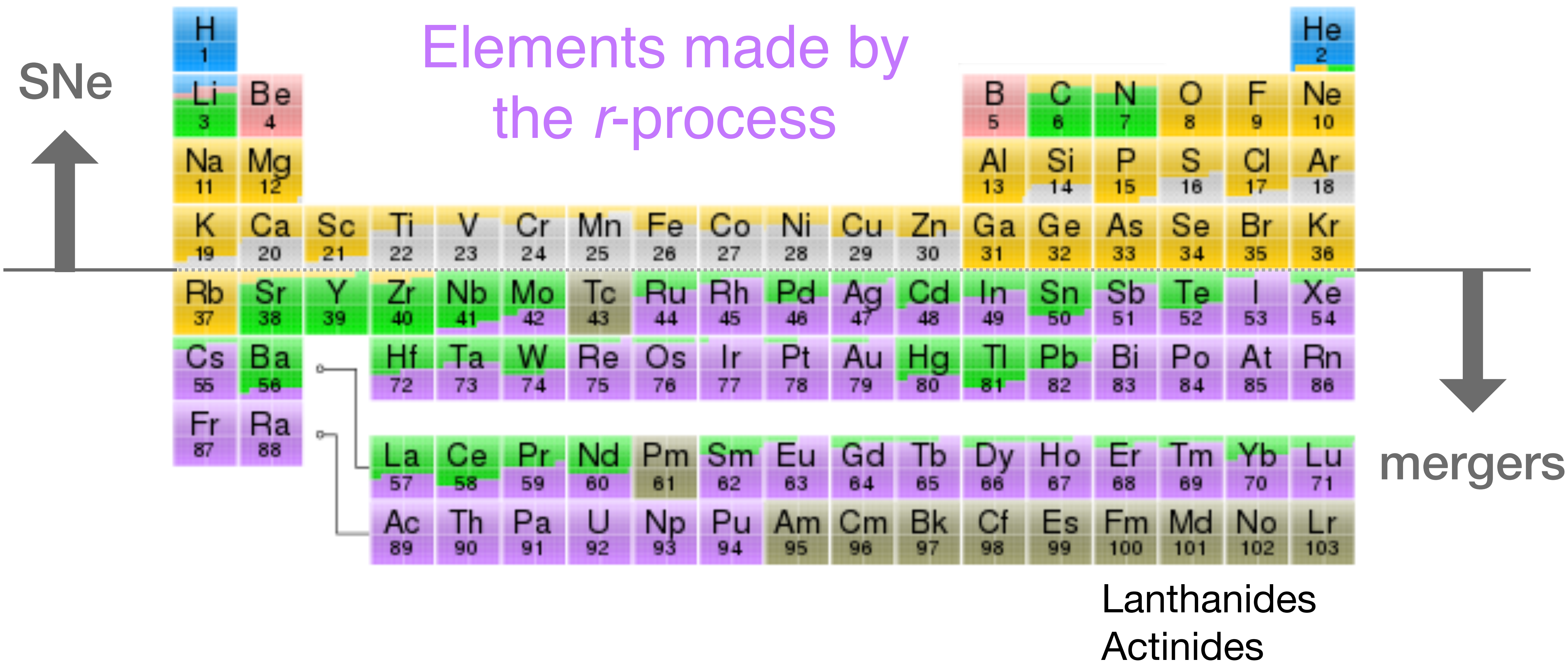
- however, the power-law behavior may break down at late times.





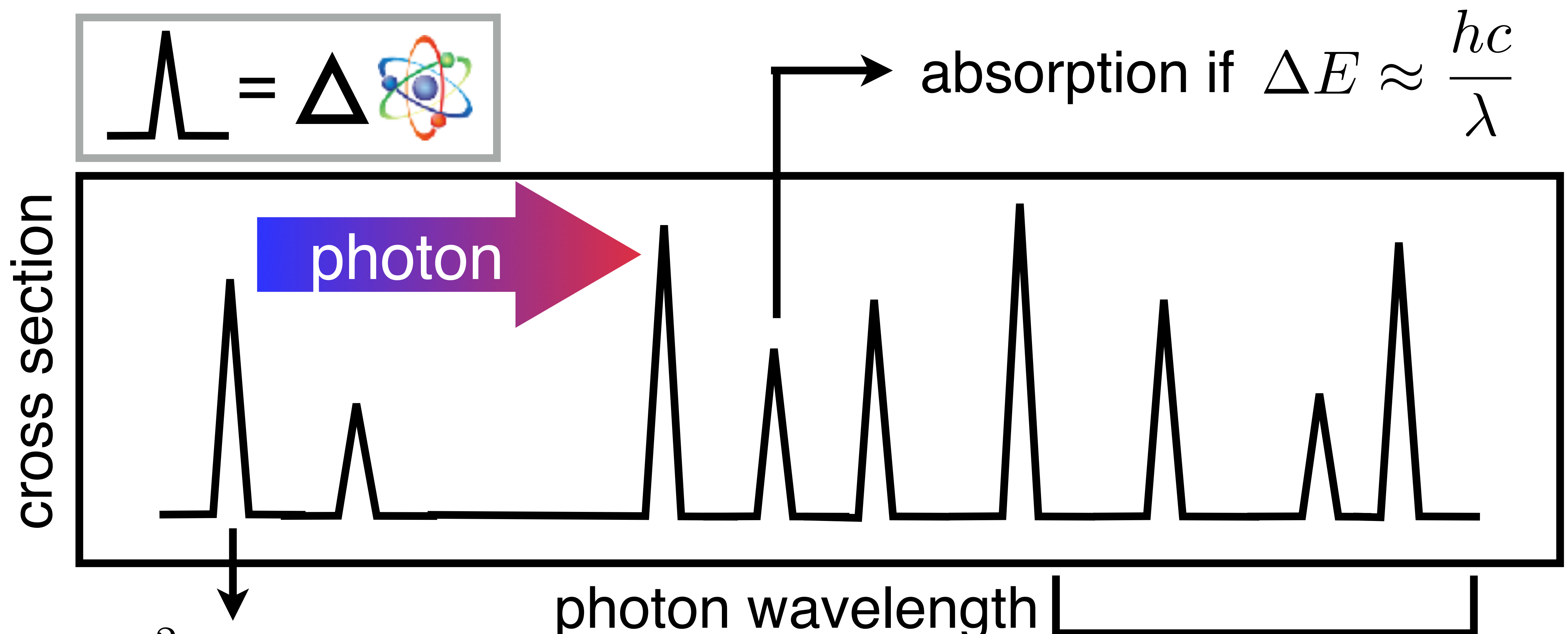
opacity is composition-dependent

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



opacity is composition-dependent

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



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

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

Sobolev optical depth sets interaction probability with a particular line

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

opacity is composition-dependent

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

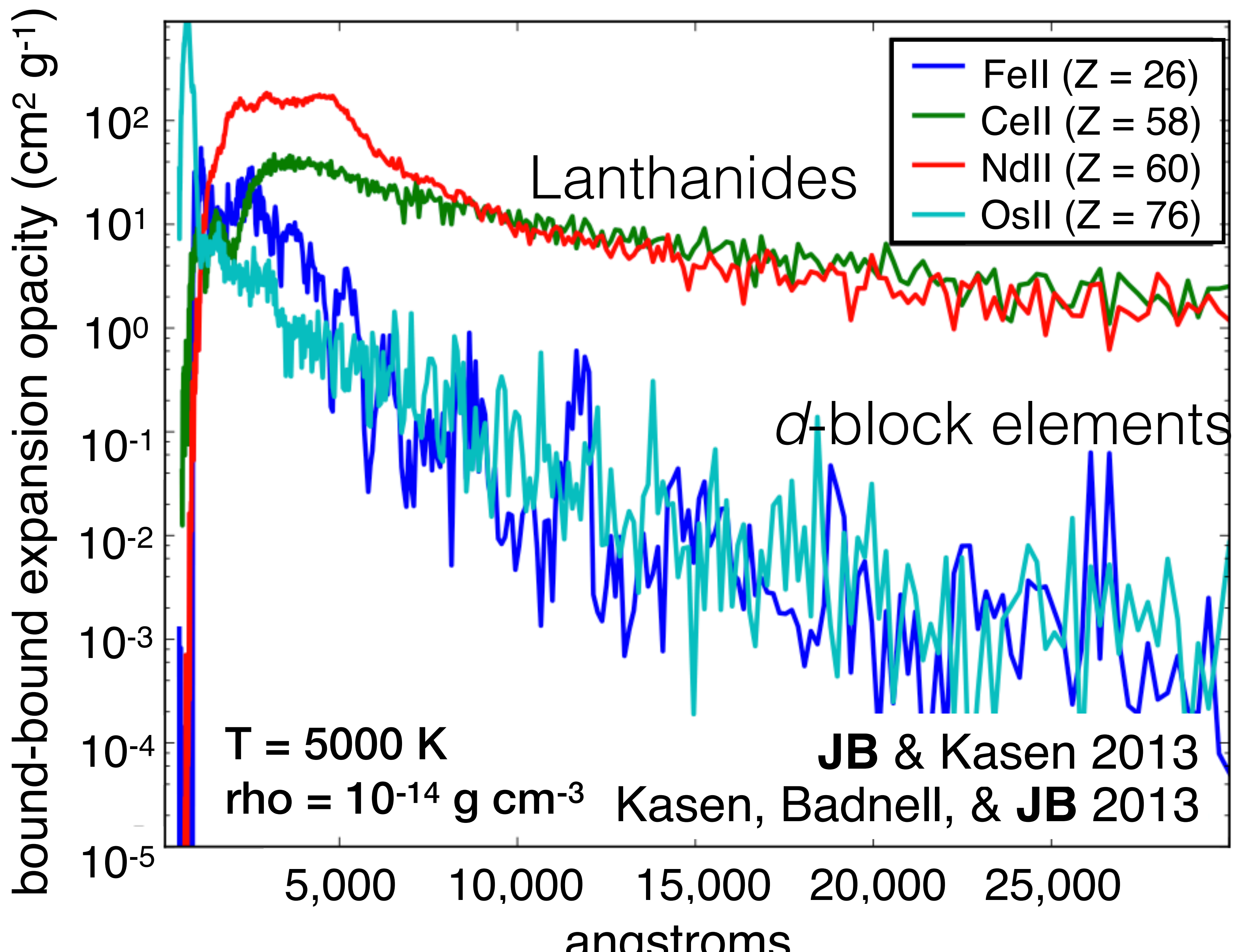
many-body Quantum Mechanical system

↓

lines, levels, oscillator strengths

↓

synthetic opacities



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

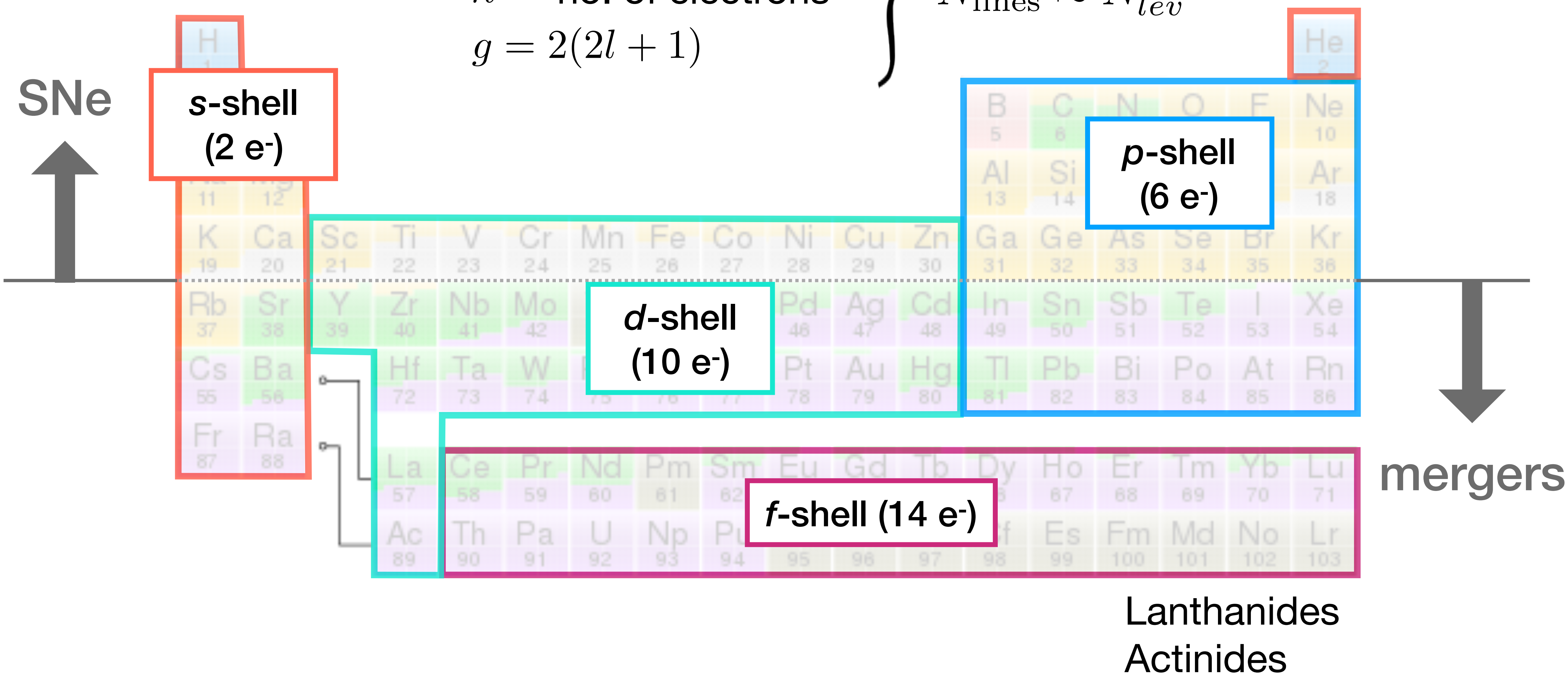
Simple analytic estimates:

$$N_{\rm lev} \approx \frac{g!}{n!(g-n)!}$$

$$n = \text{no. of electrons}$$

$$g = 2(2l+1)$$

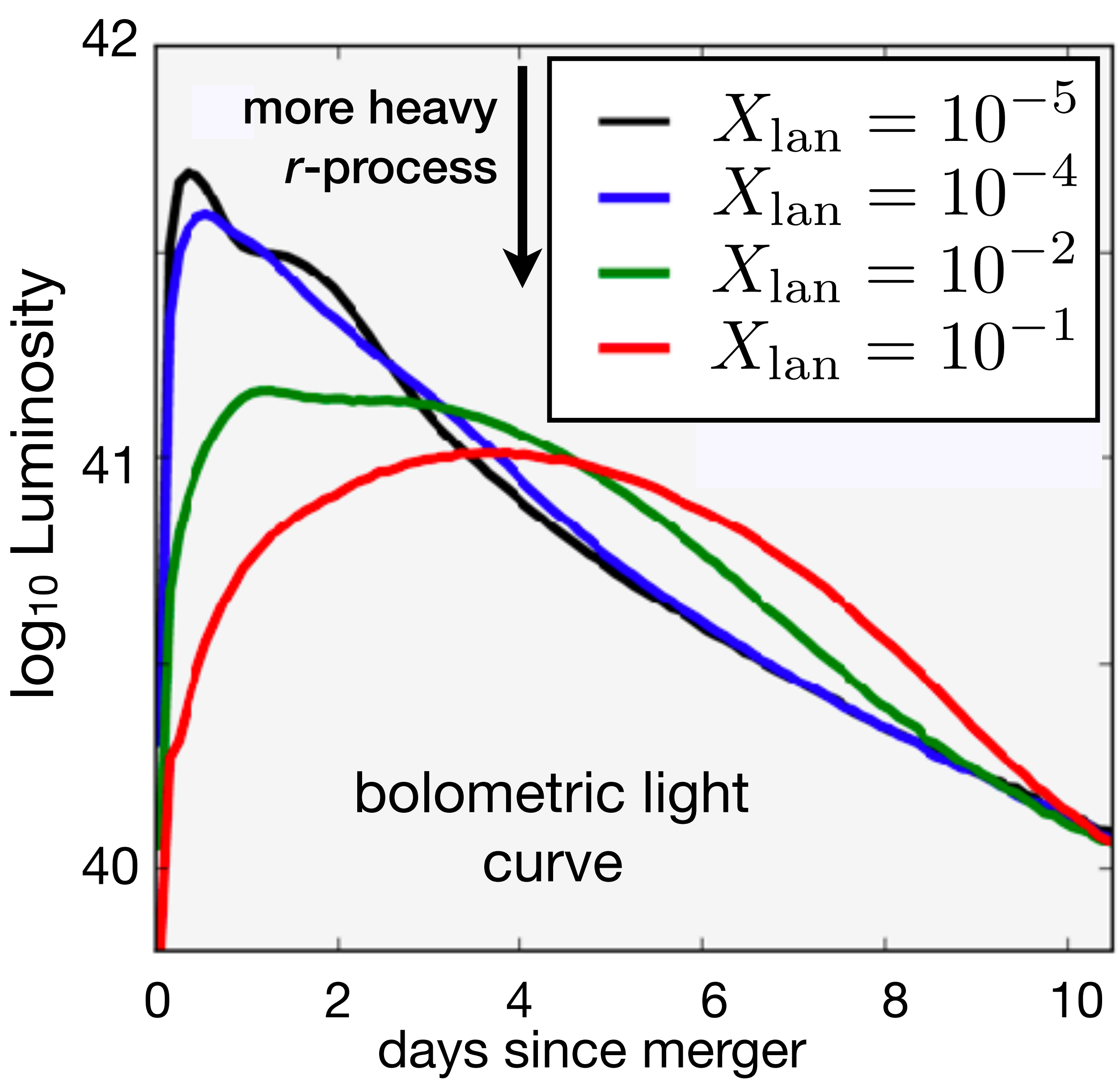
$$\left.\right\} \quad N_{\rm lines} \approx N_{lev}^2$$



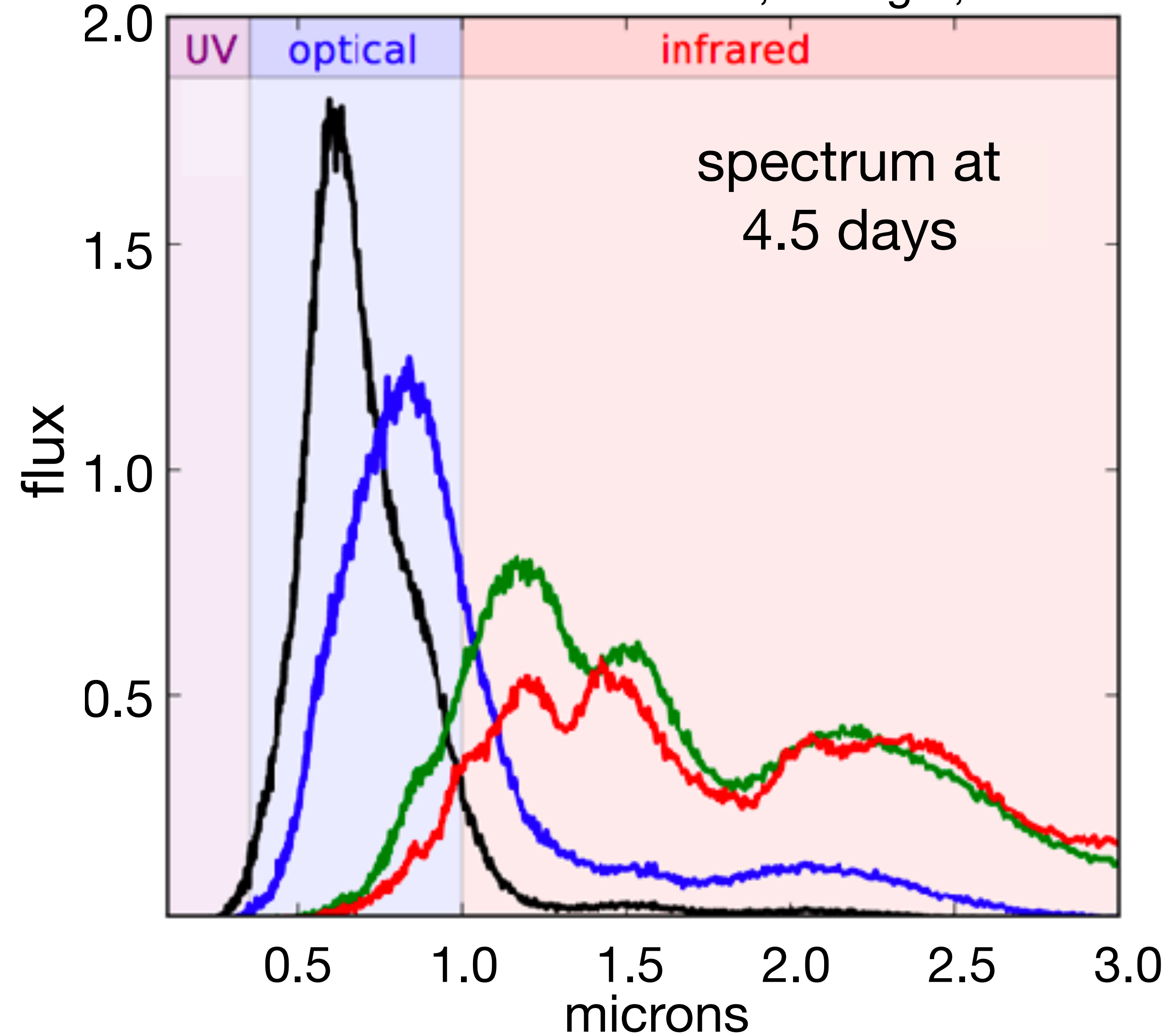
higher opacities lead to longer, dimmer, redder light curves

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

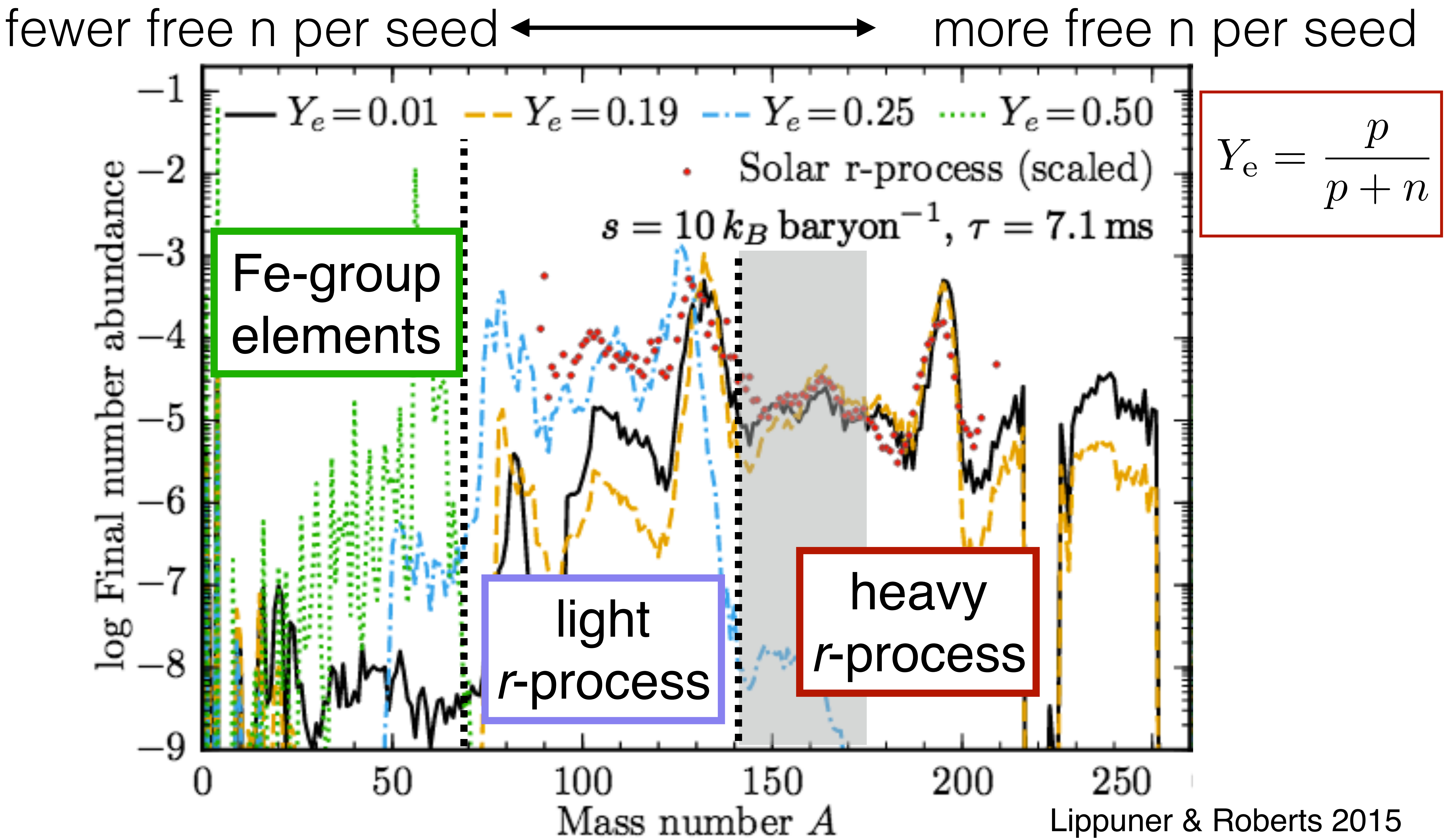
line blanketing at optical wavelengths



Kasen, Metzger, **JB**+17

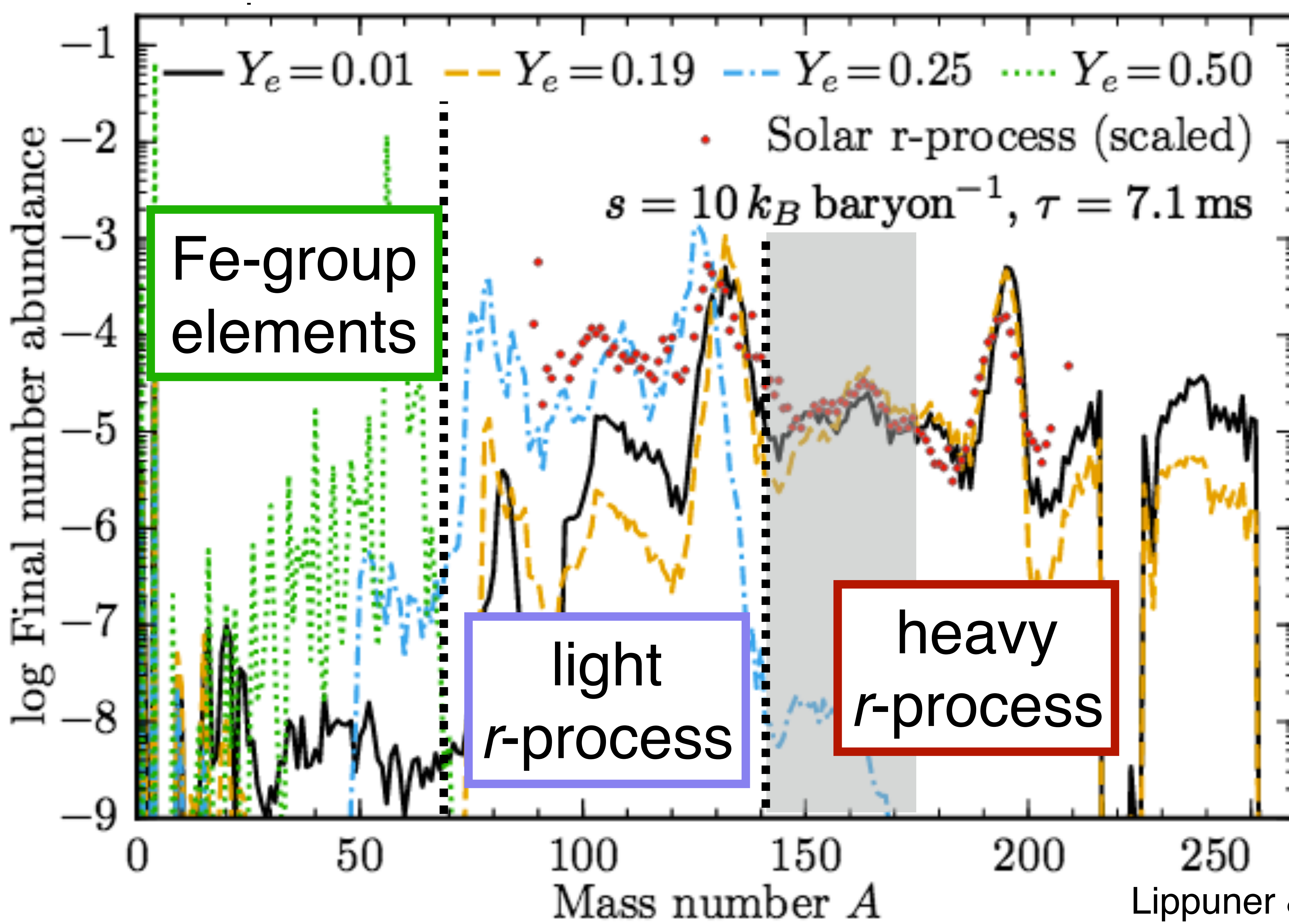


kilonova emission is tied to the strength of the *r*-process!



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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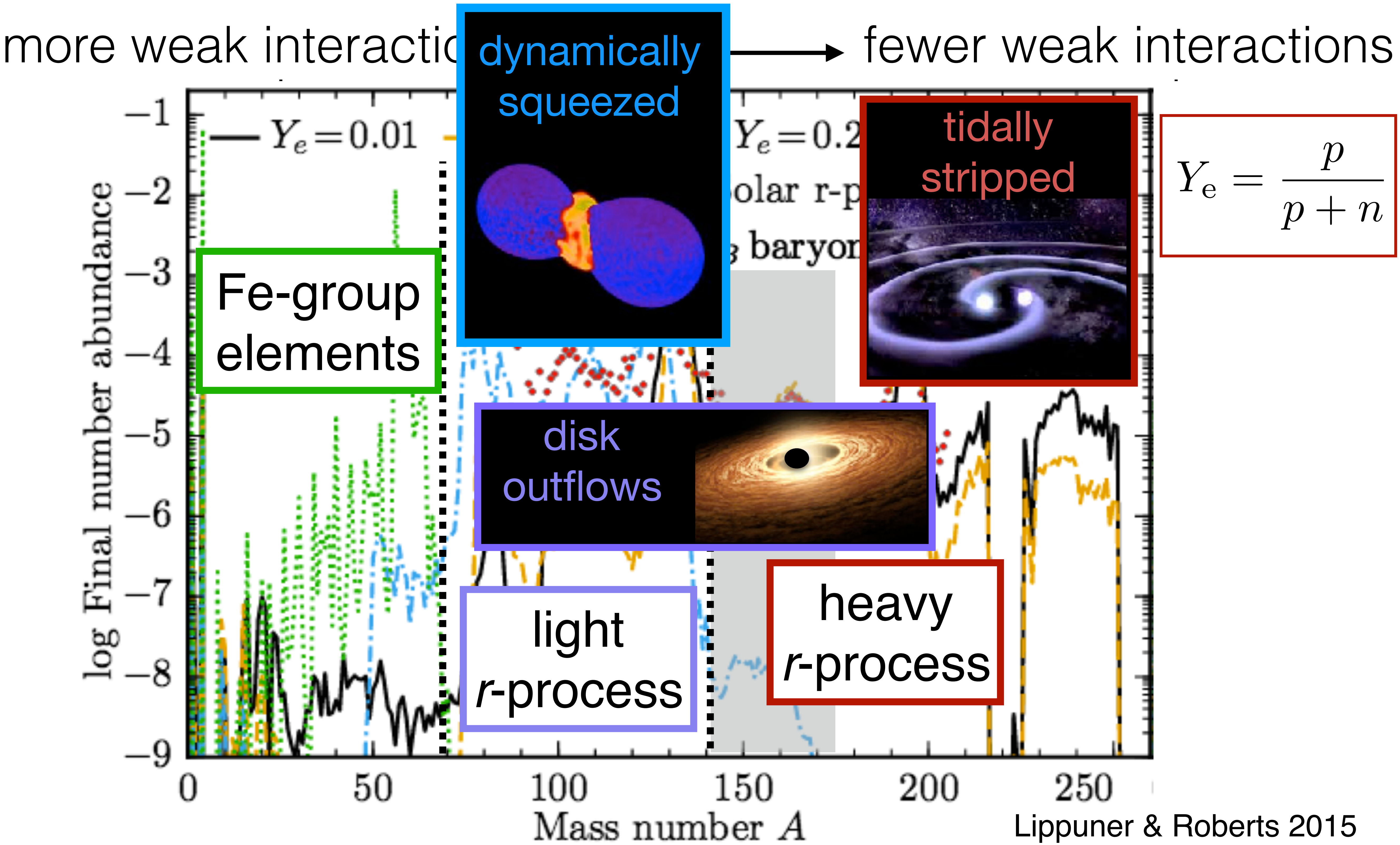
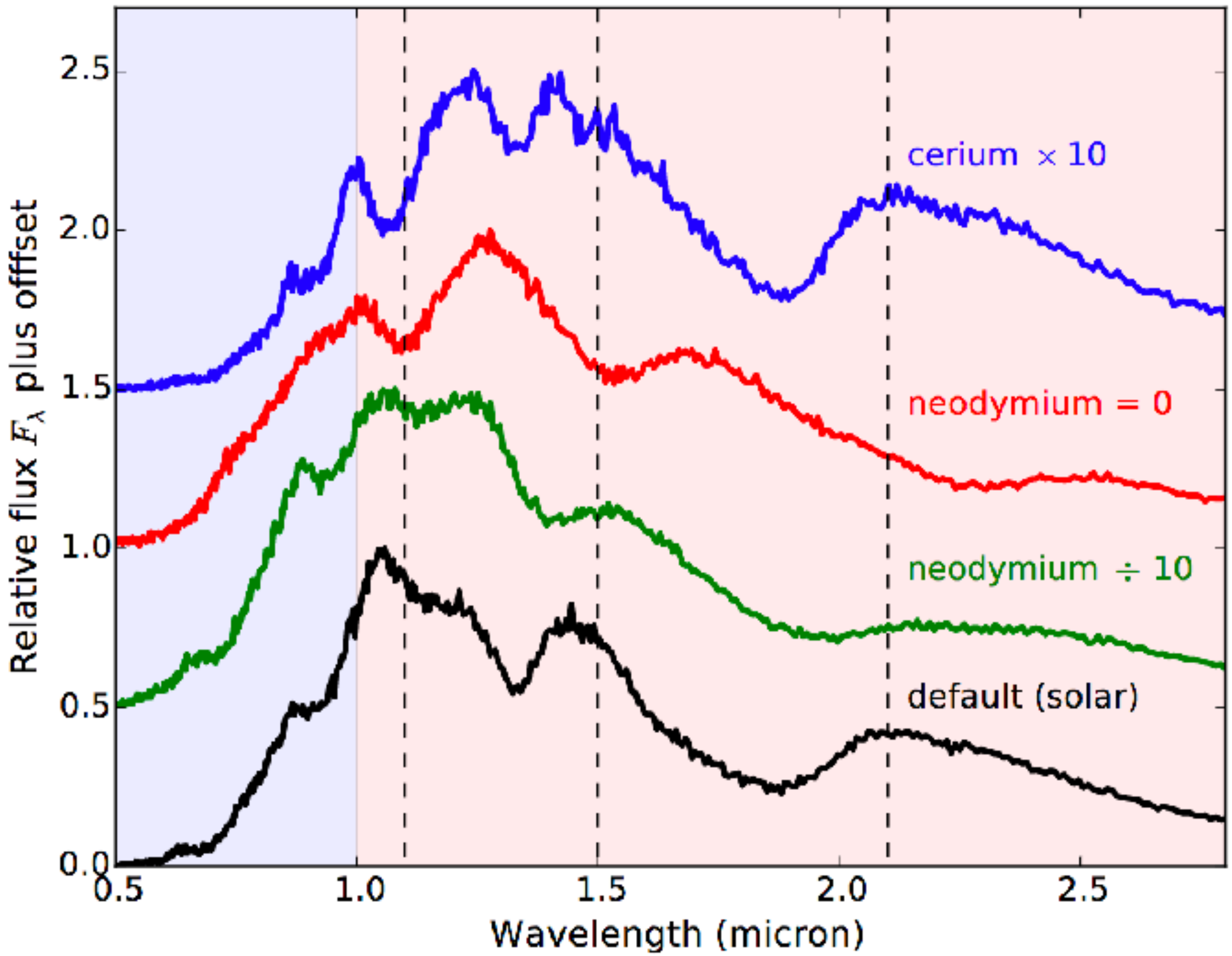
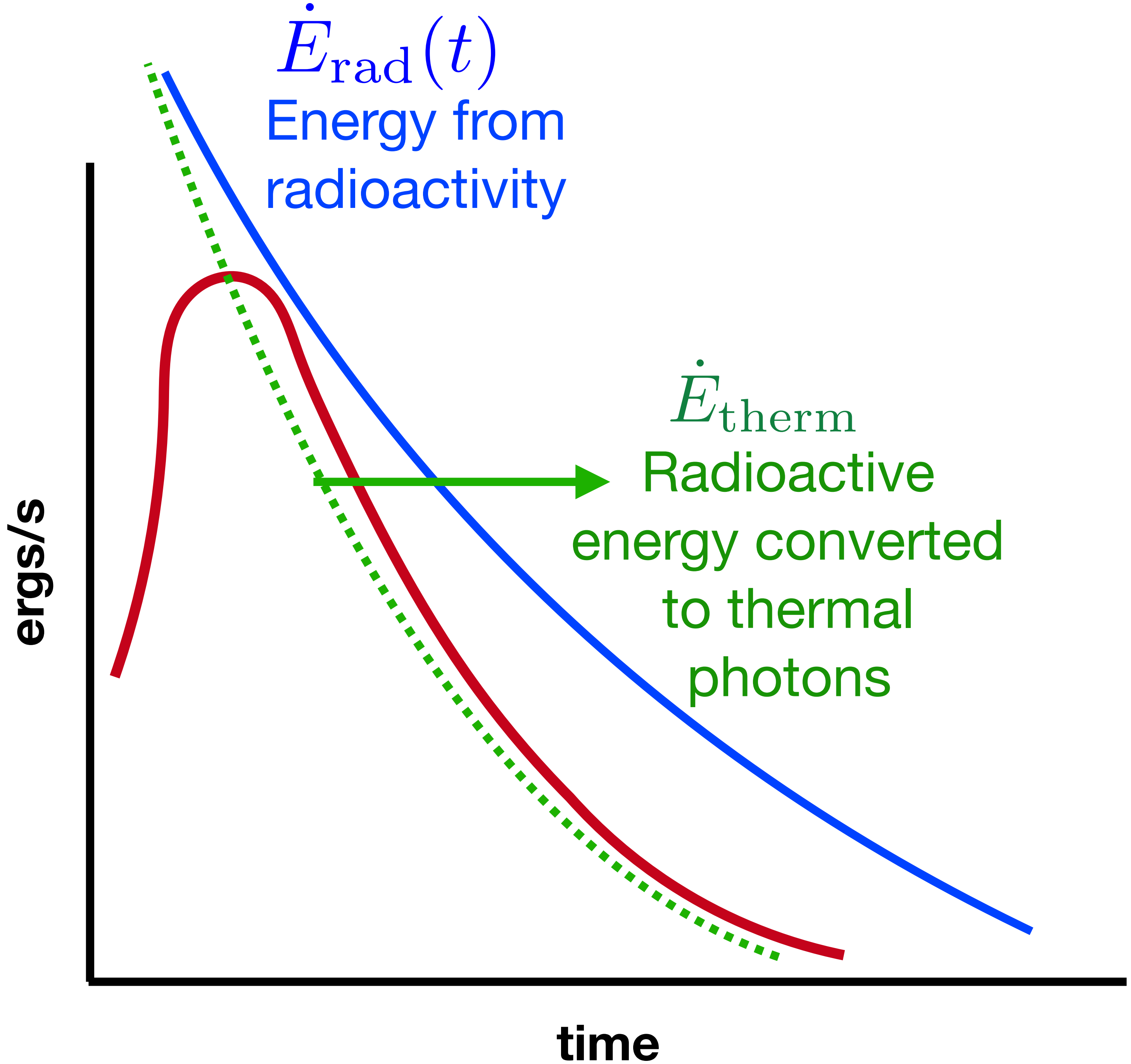


spectral identification: the next frontier!



the *r*-process and kilonova thermalization

(bolometric) light curves



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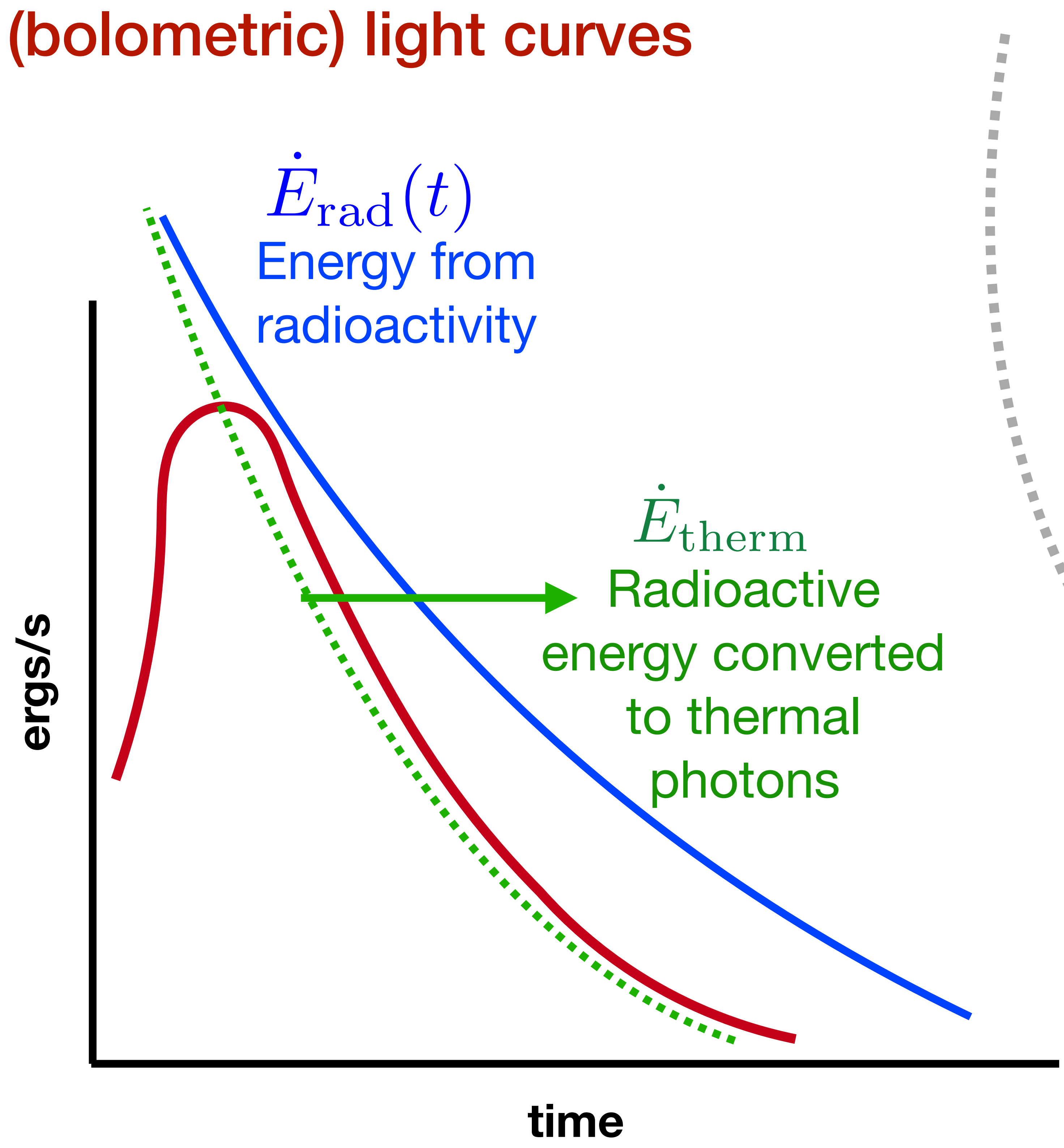
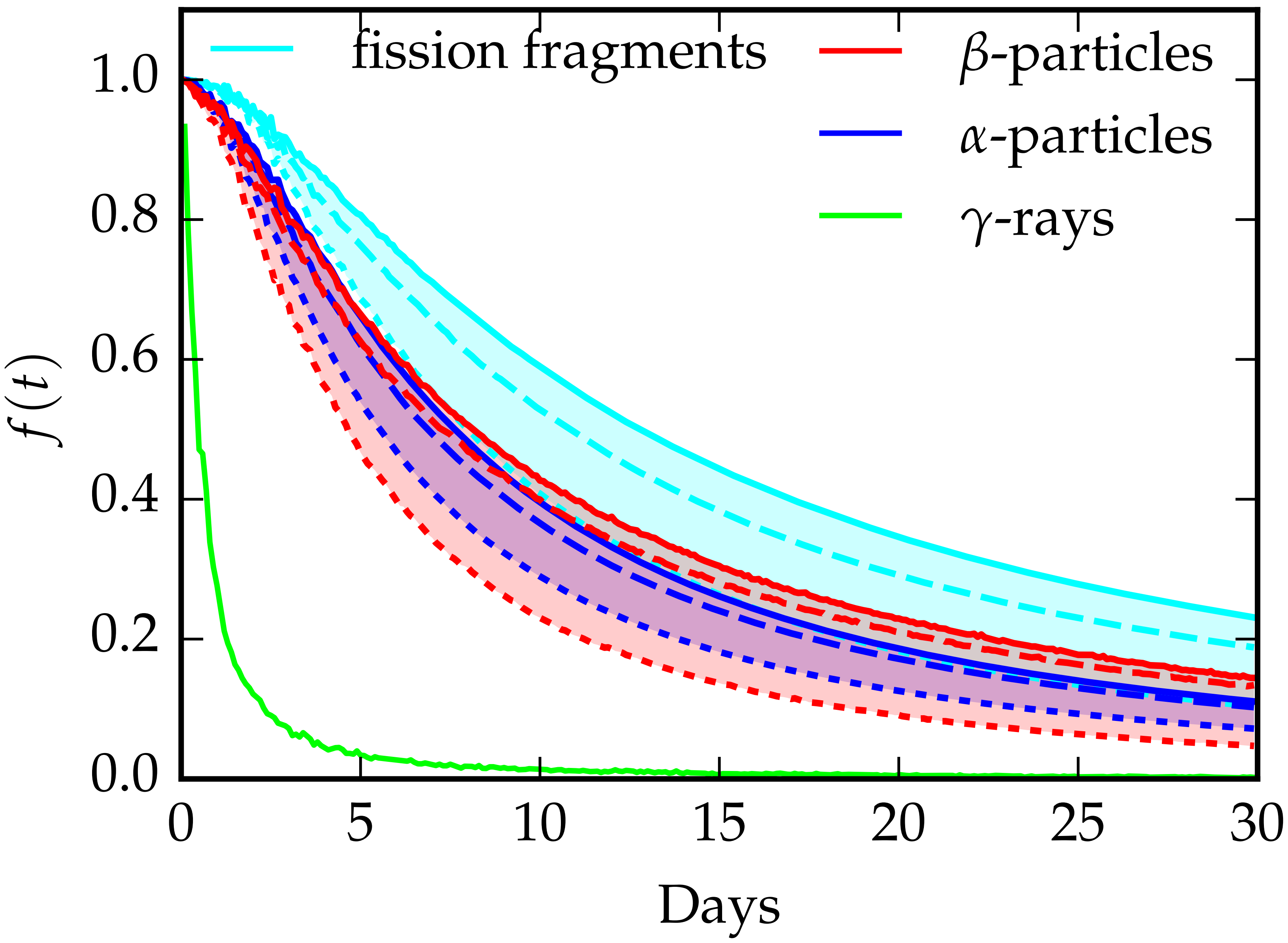


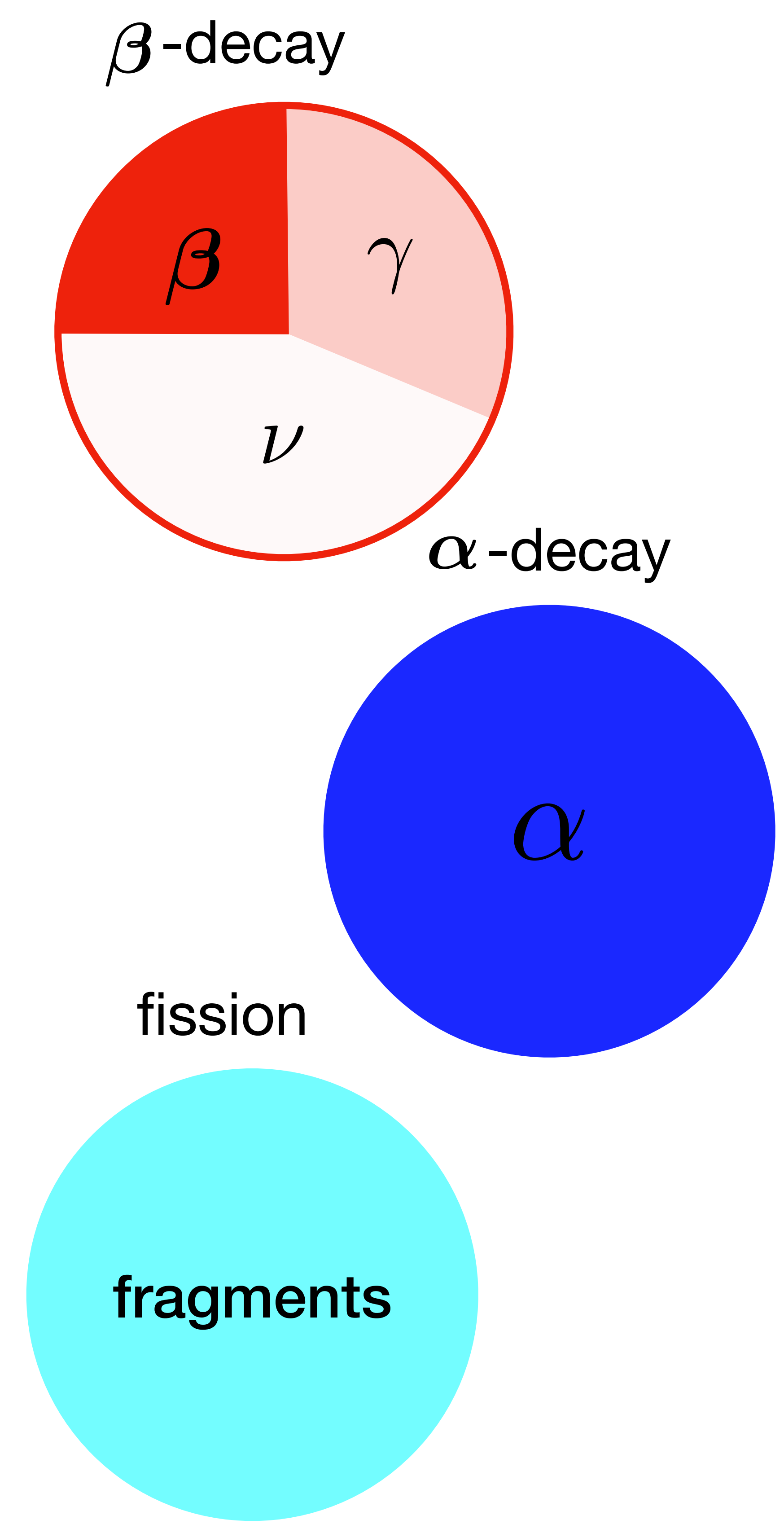
thermalization efficiency depends on:

- decay mode
- decay spectra
- composition (cross-sections)
- ejecta mass, velocity

thermalization depends on decay mode

Thermalization efficiencies ***per particle***





At late times, a few decays may dominate the heating

Fissioning or α-decaying nuclei with $\tau \sim$ weeks or months could substantially affect the luminosity

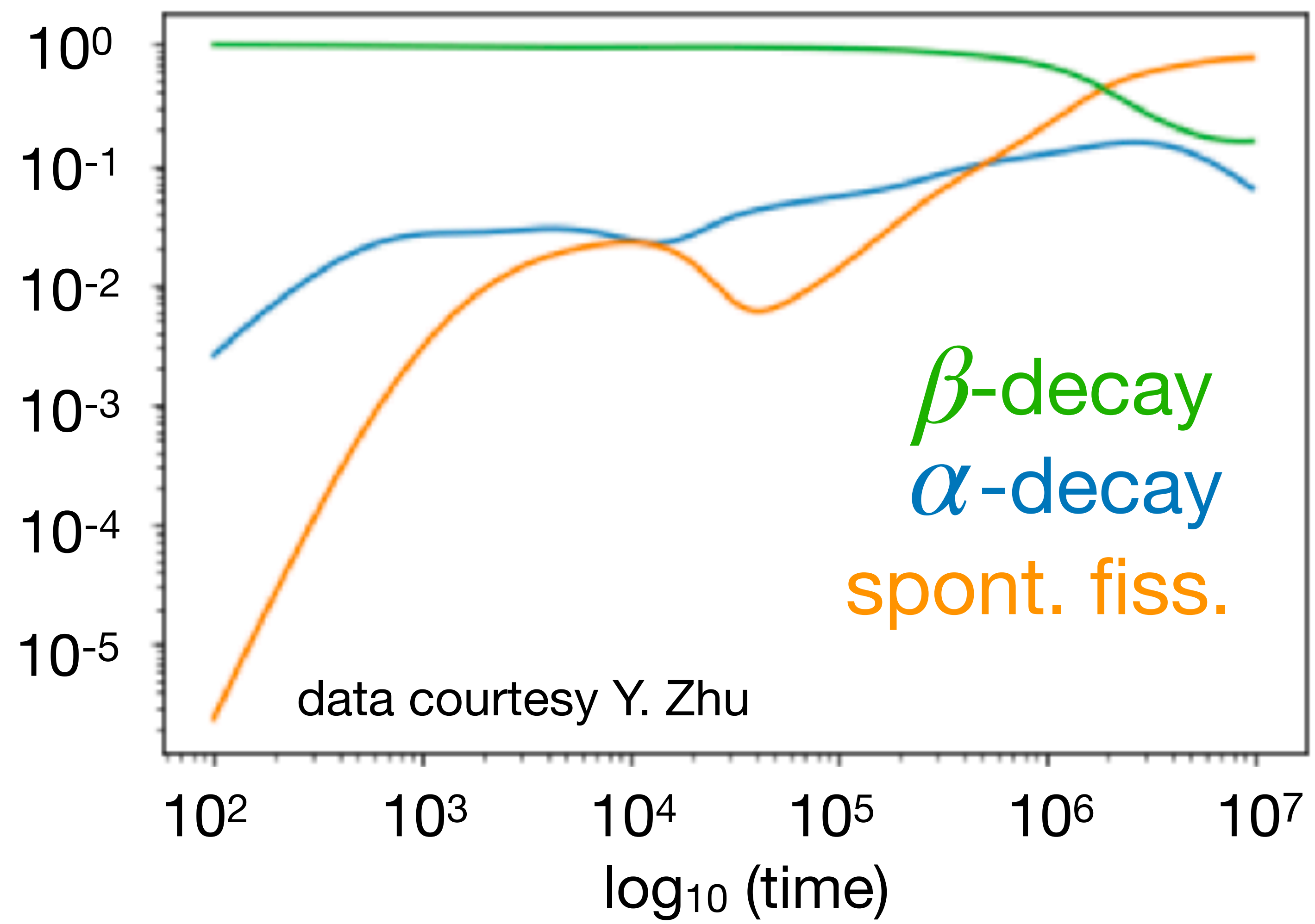
- High Q-values (compared to β-decay)
- Efficient thermalization

Californium-254

$Q_{\rm SF} \approx 200$ days

$\tau_{1/2} = 60.5$ MeV

Fraction of energy in each channel



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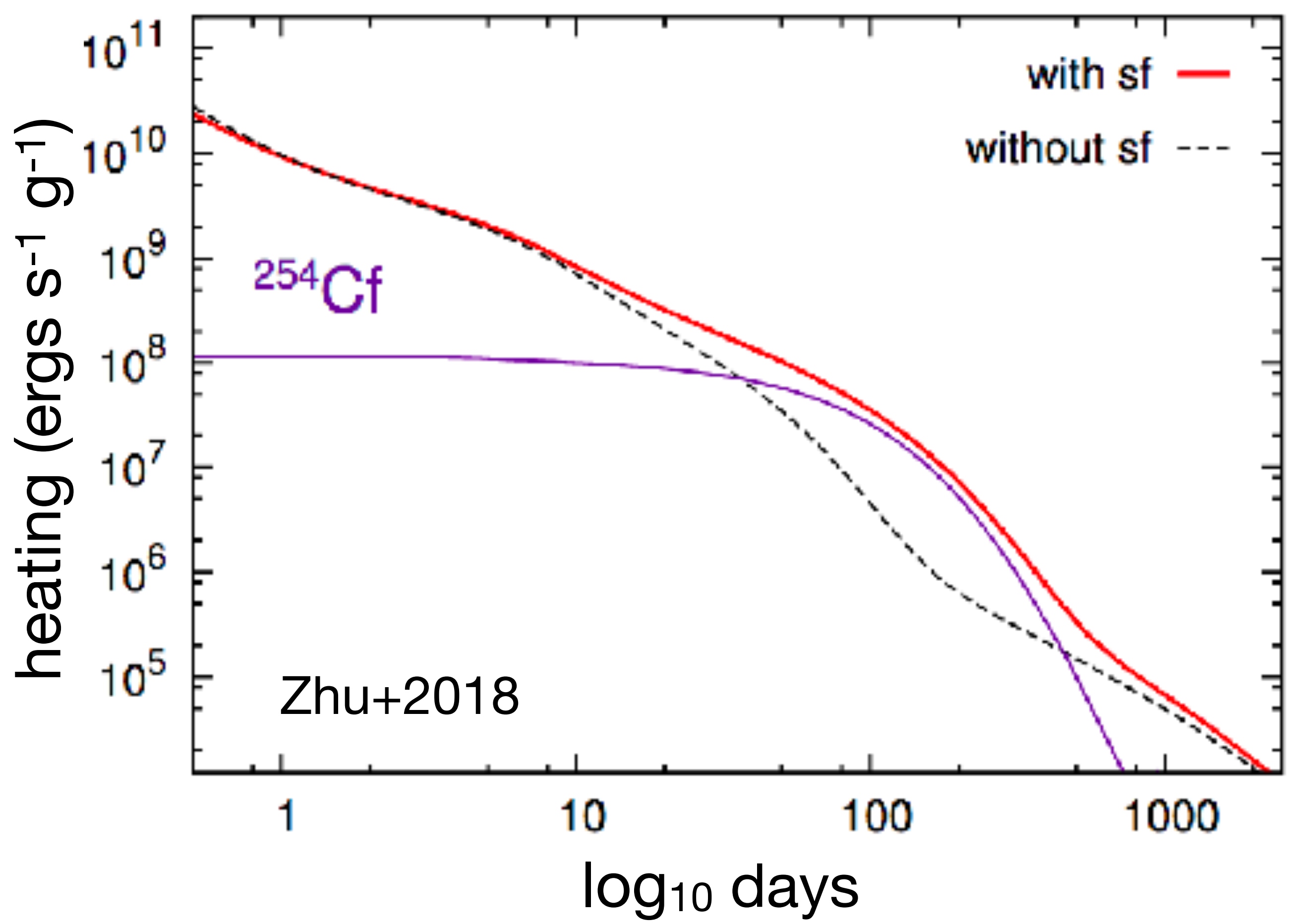
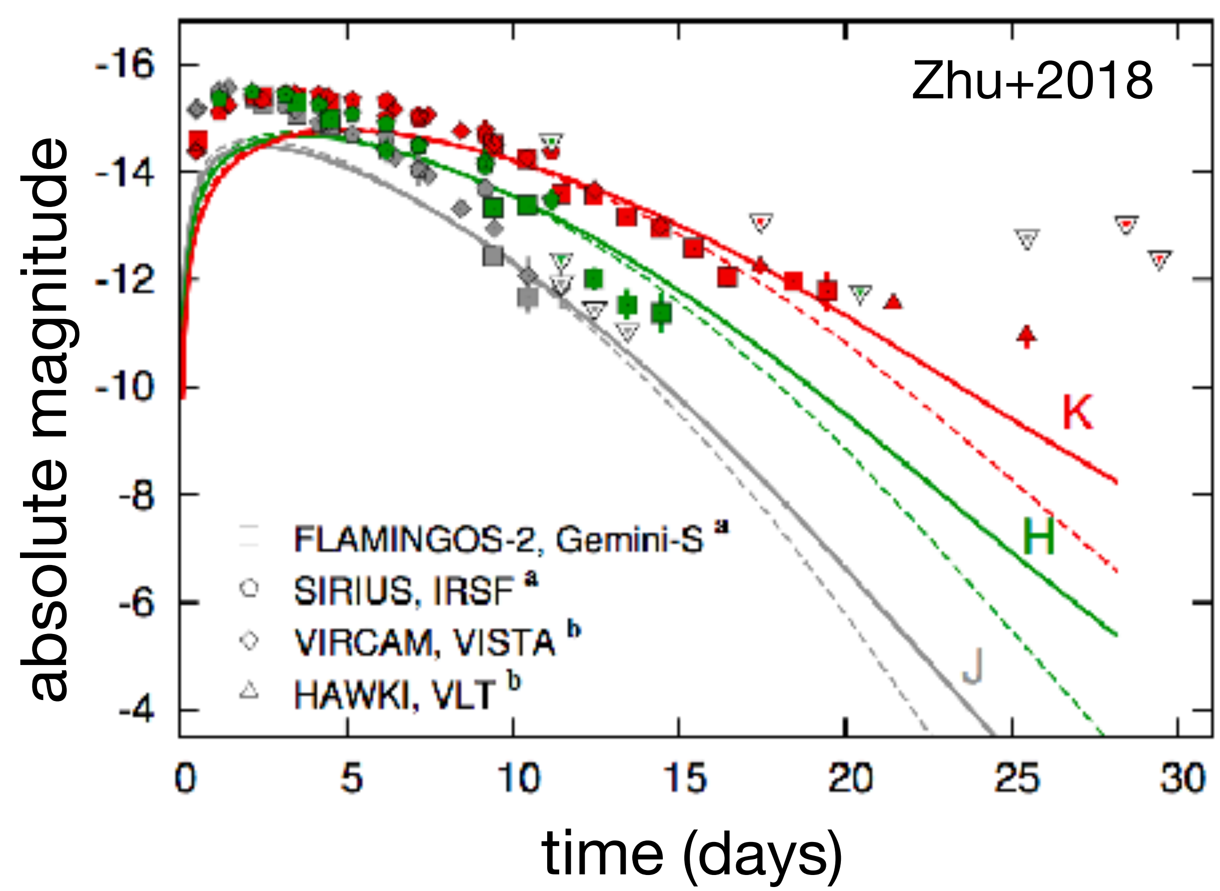
Heating from spontaneous fission of Cf-254 impacts kilonova light curves

Energy Released



Light Curves Observed



Late-time light curves can probe the production of the heaviest nuclei and give more detailed information about the composition