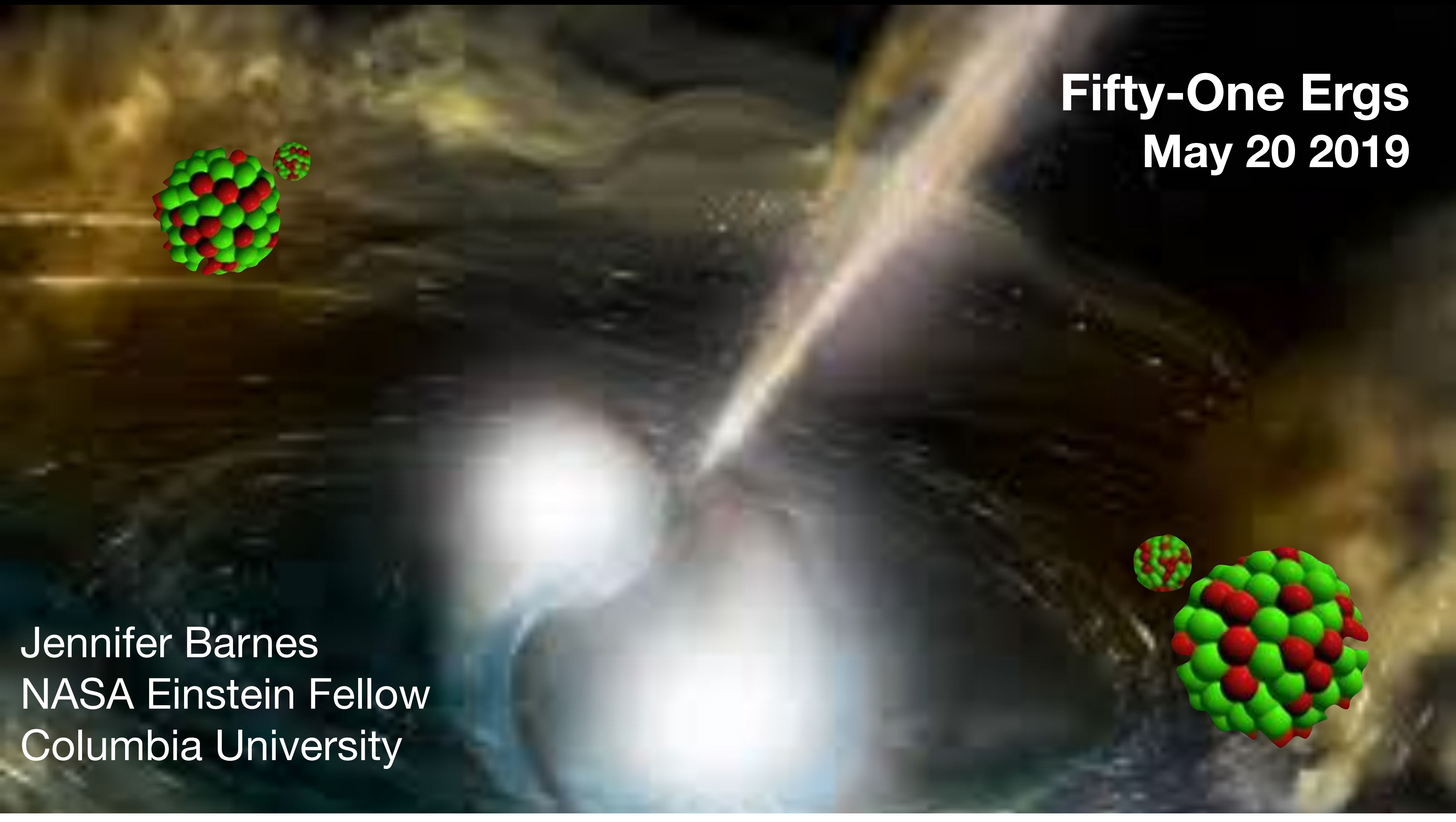
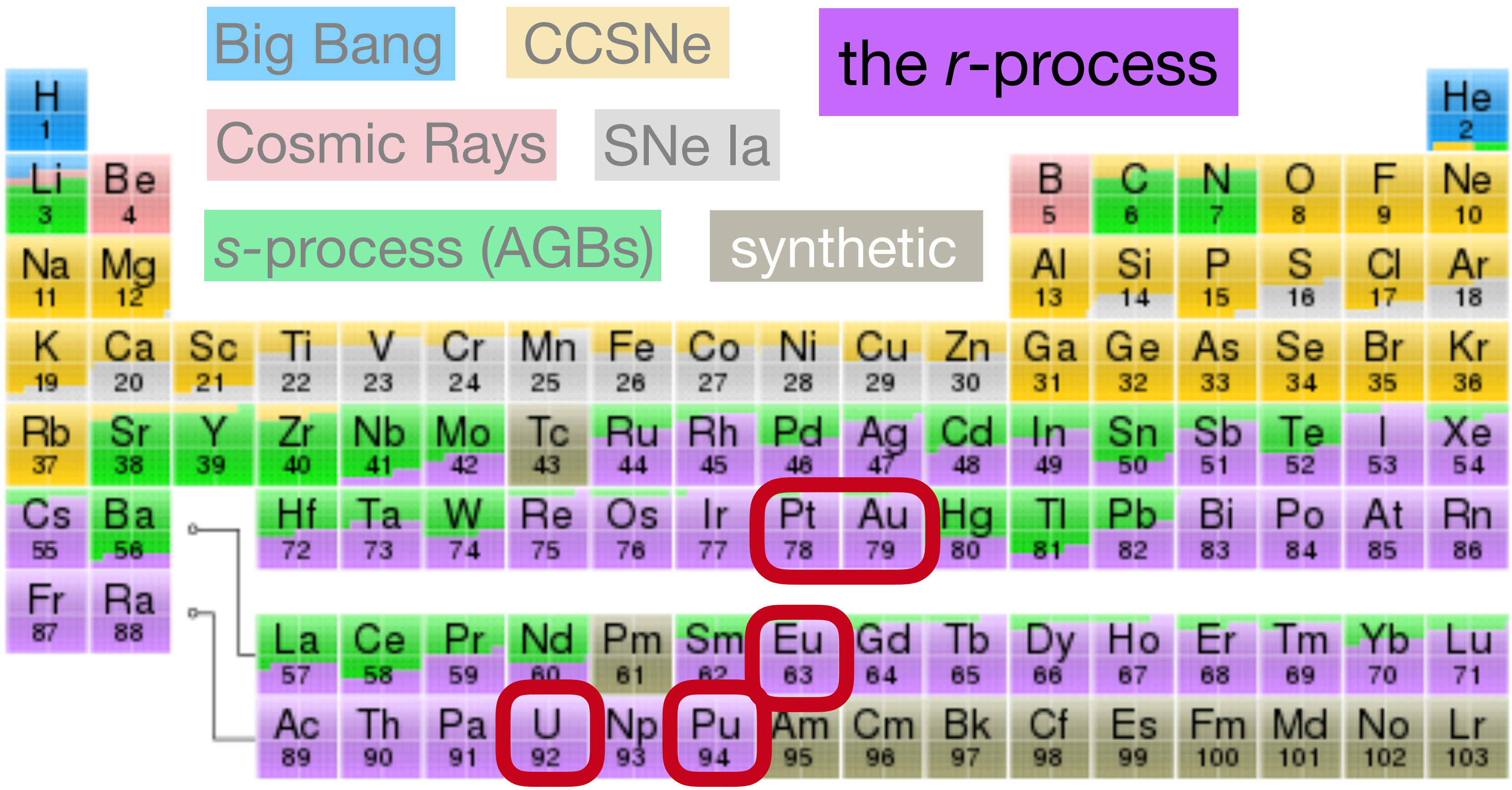
The *r*-process from neutron star mergers



Fifty-One Ergs
May 20 2019

Jennifer Barnes
NASA Einstein Fellow
Columbia University

The *r*-process produces ~half of elements heavier than Fe



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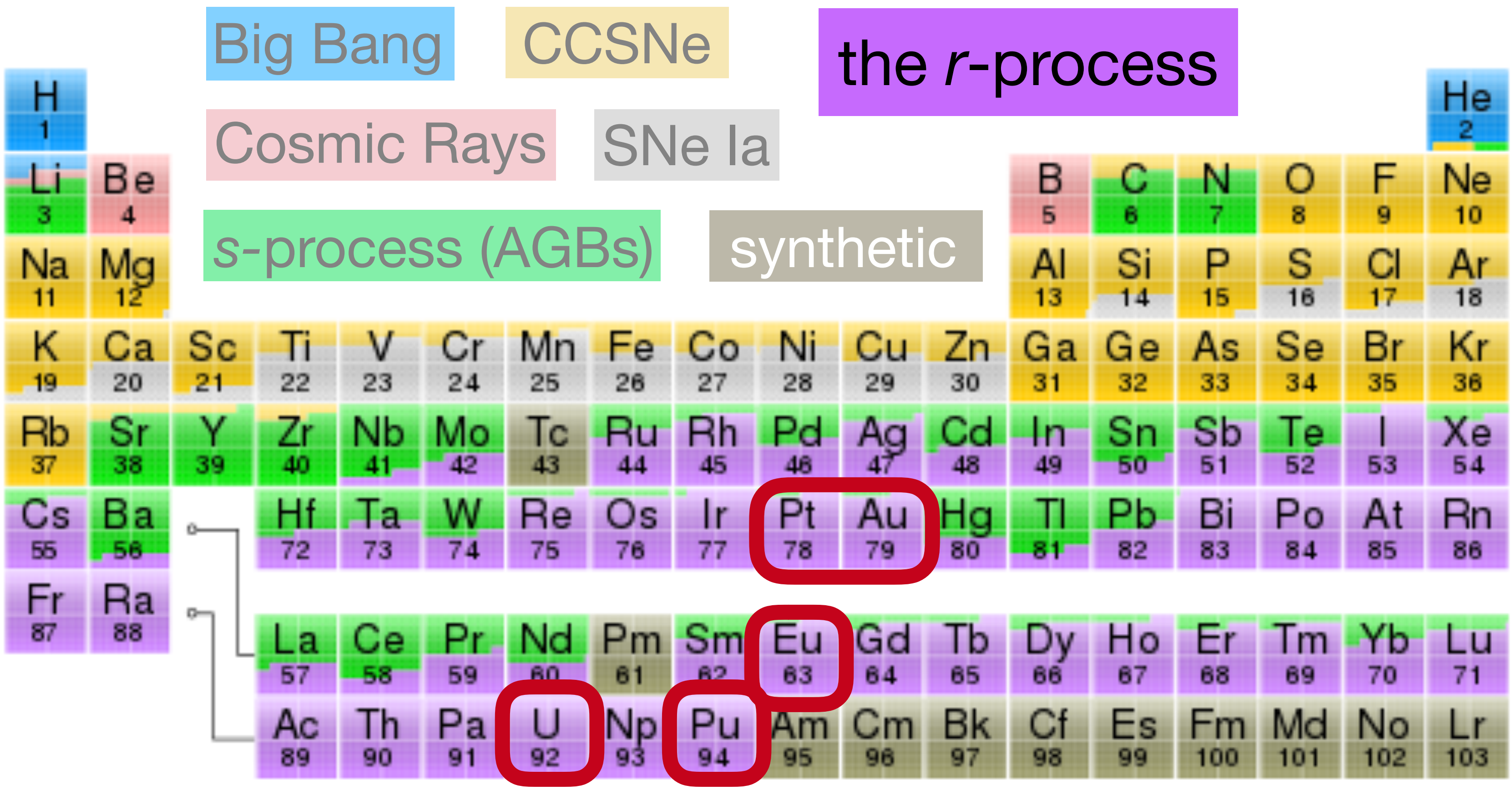

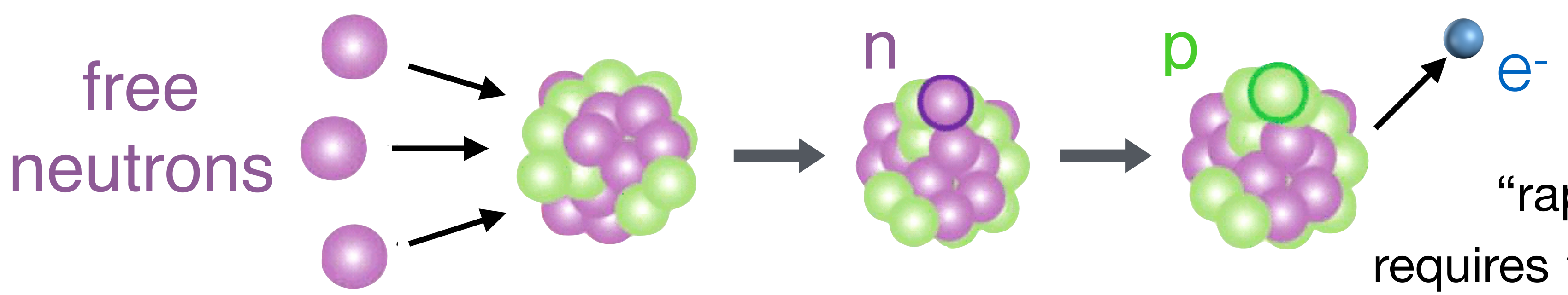

“rapid:”
requires $\tau_{\rm n} \ll \tau_{\beta^-}$

Neutron star merger outflows can support an *r*-process

final few orbits:
strong GW source

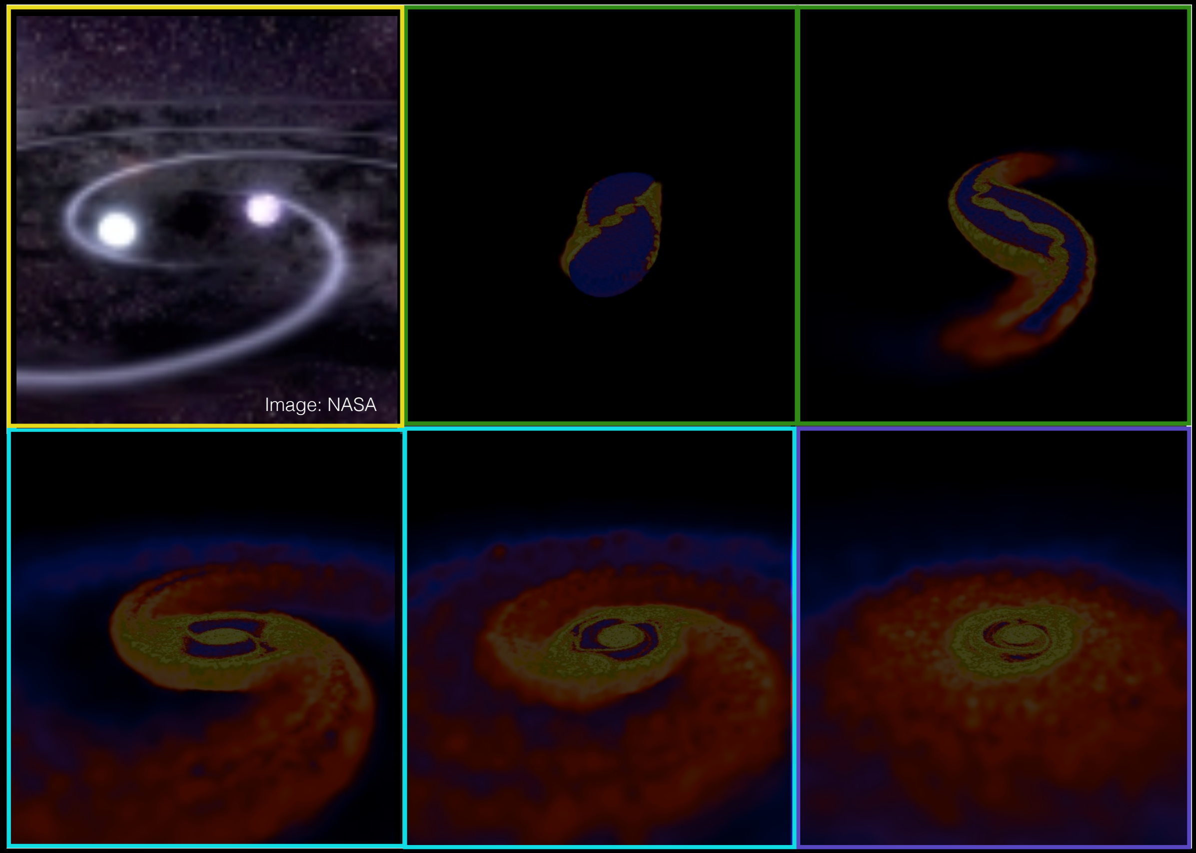

Image credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

Neutron star merger outflows can support an *r*-process

final few orbits: strong GW source

merger: neutron star is partially disrupted, central remnant forms

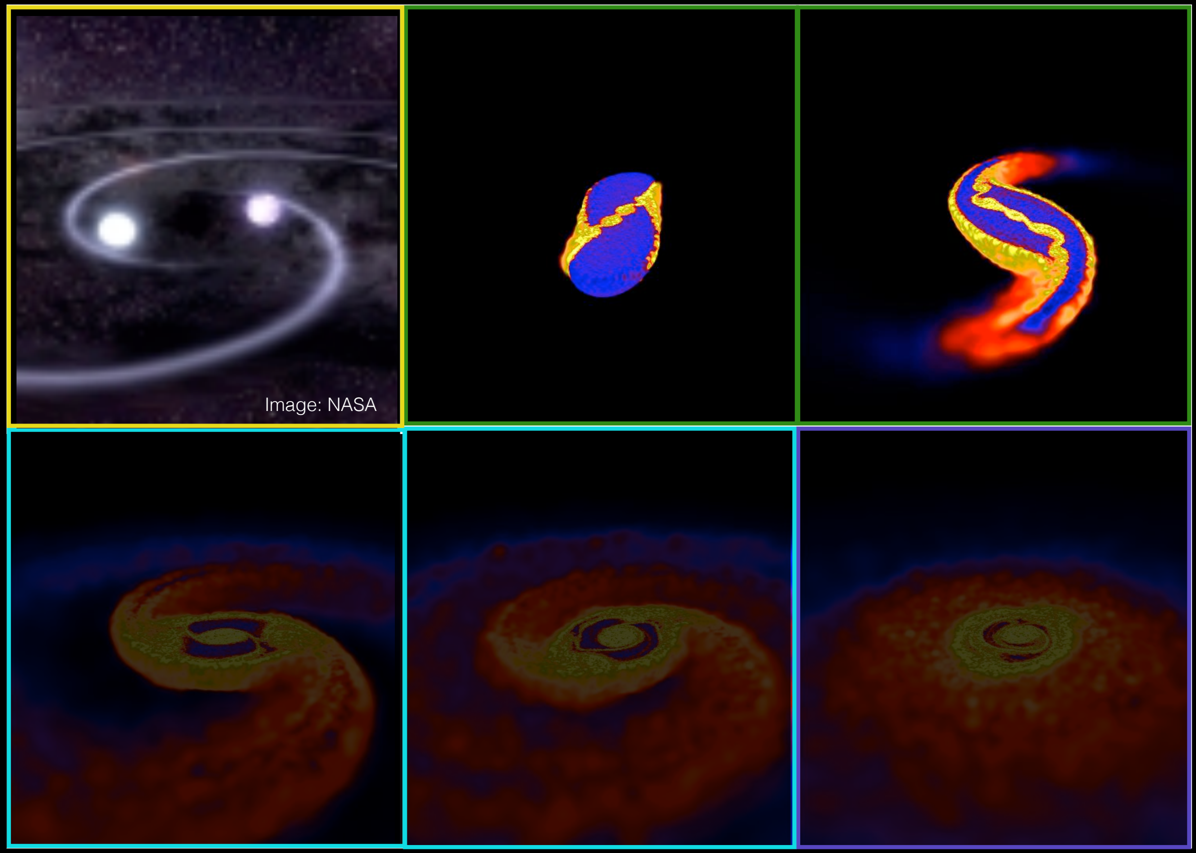

Image credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

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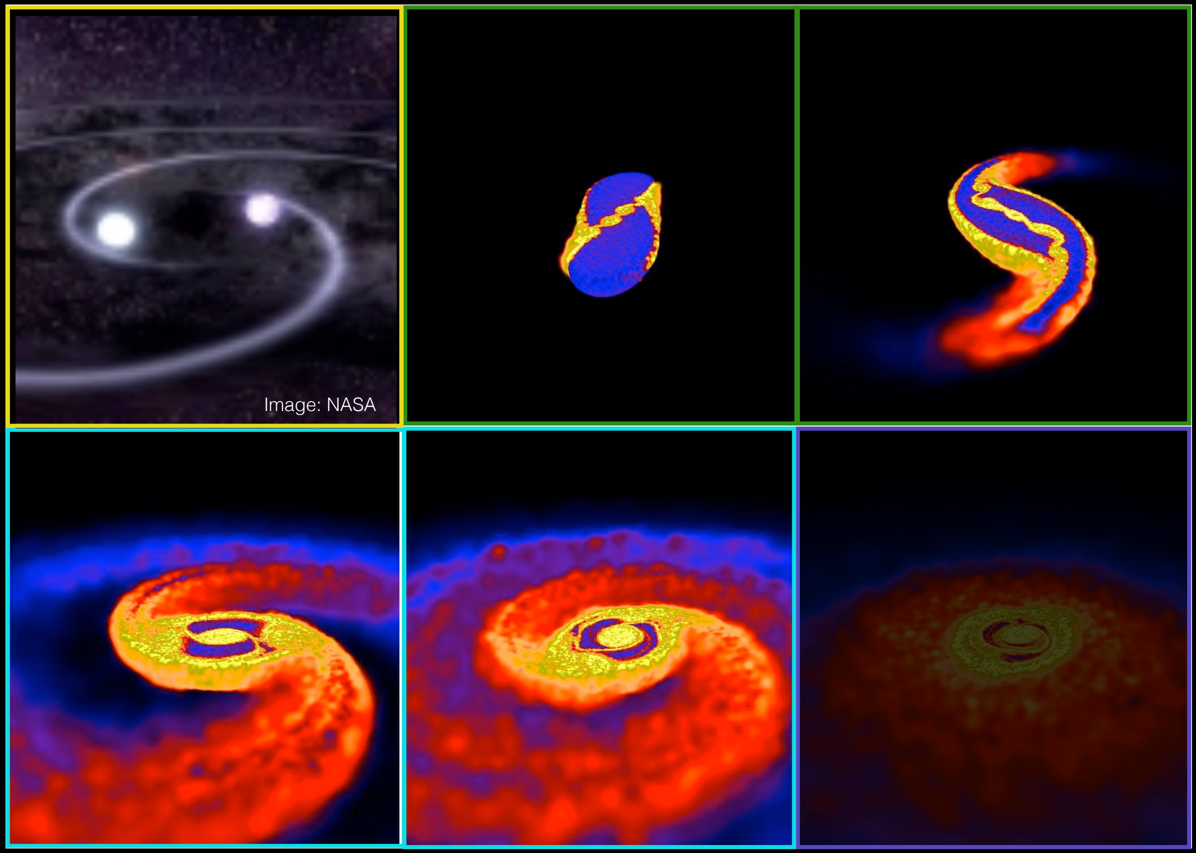

ejecta: some material escapes; some is bound

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

Neutron star merger outflows can support an *r*-process

final few orbits: strong GW source

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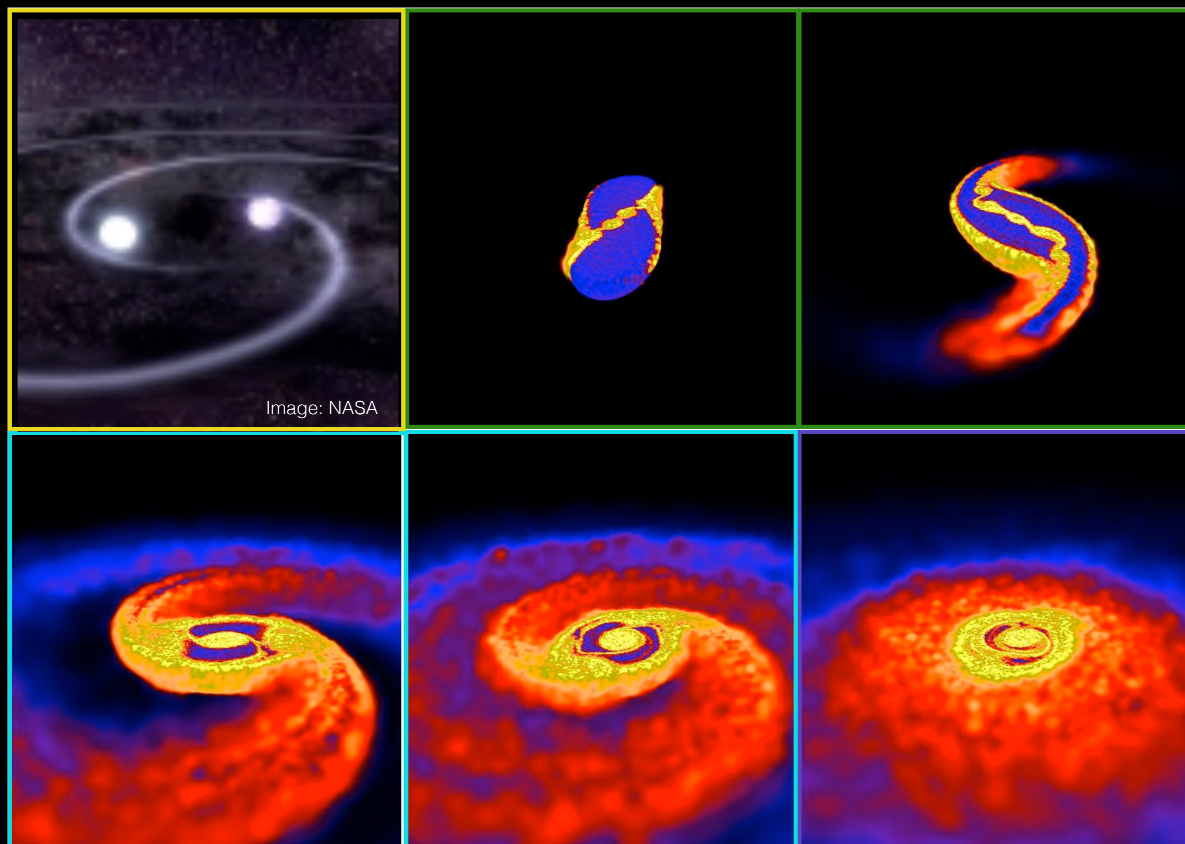
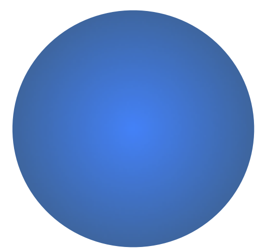


ejecta: some material escapes; some is bound

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

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

The explosive *r*-process: a summary



Nuclear Statistical Equilibrium

$$T \gtrsim 6 \times 10^9 \text{ K}$$

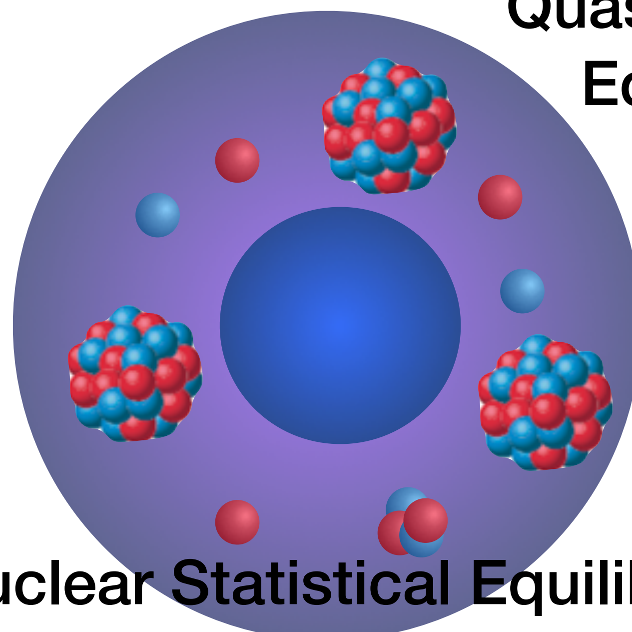
Composition depends on state variables, not on reaction rates

The explosive *r*-process: a summary

Quasi-Statistical Equilibrium

$T < 6 \times 10^9$ K

Start to build up heavier nuclei: ^{12}C and beyond



Nuclear Statistical Equilibrium

$T \gtrsim 6 \times 10^9$ K

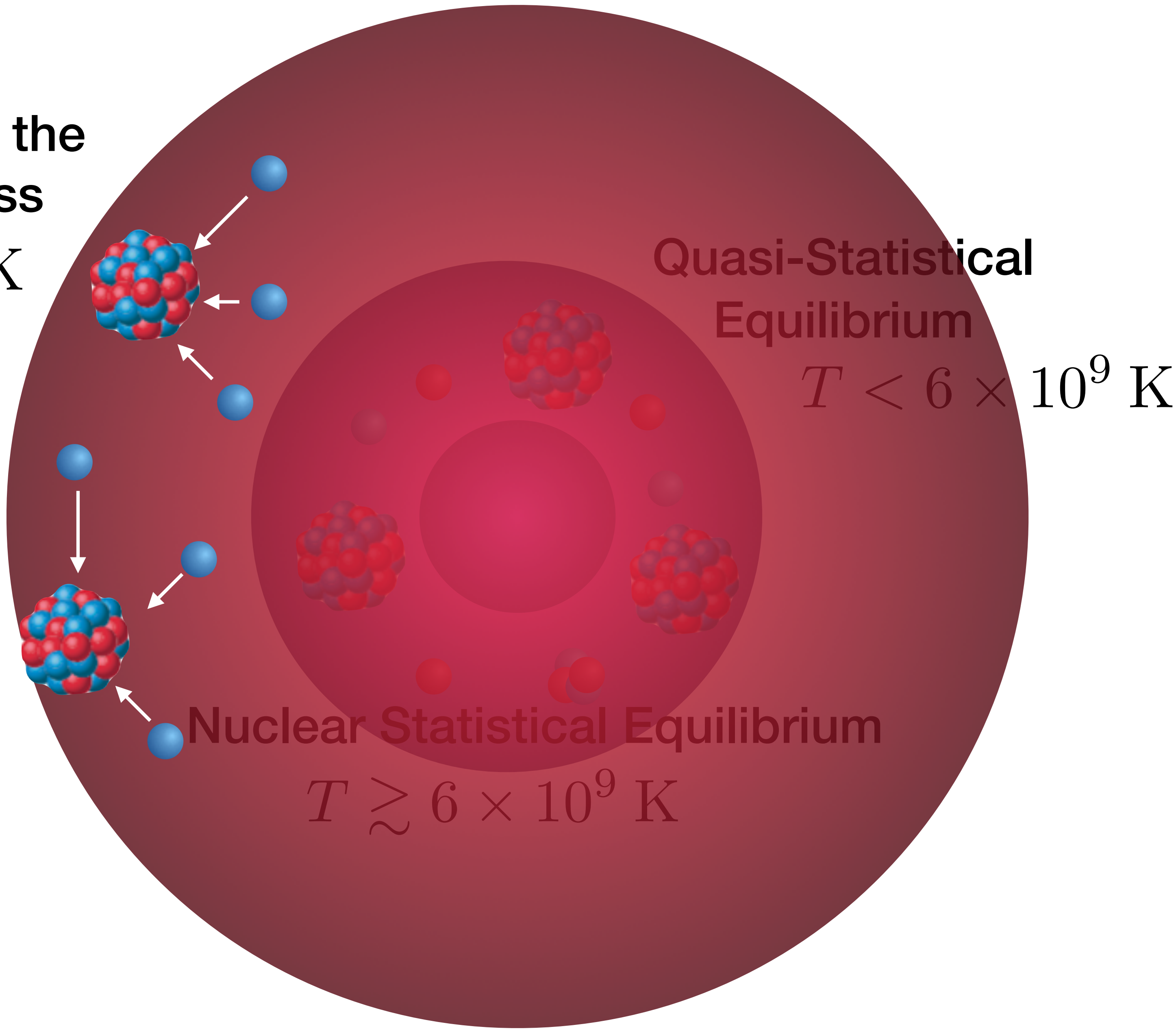
The explosive *r*-process: a summary

QSE Freeze-out and the start of an *r*-process

$$T \approx 2 - 4 \times 10^9 \text{ K}$$

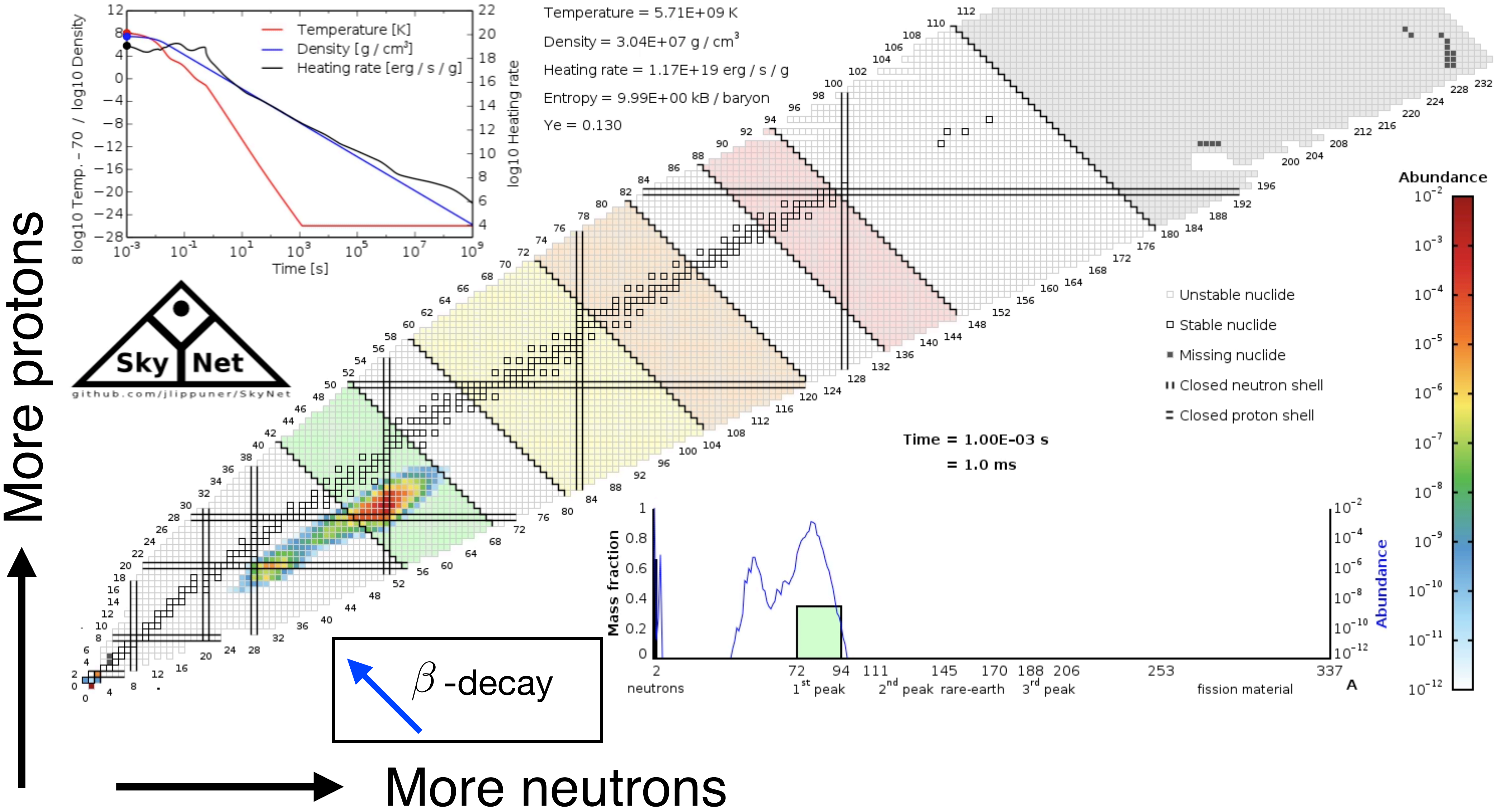
Changes to the composition are driven by n-capture

Final composition set by <A>, $R_{n/s}$



The explosive *r*-process: a movie

courtesy J. Lippuner



The explosive *r*-process: a movie

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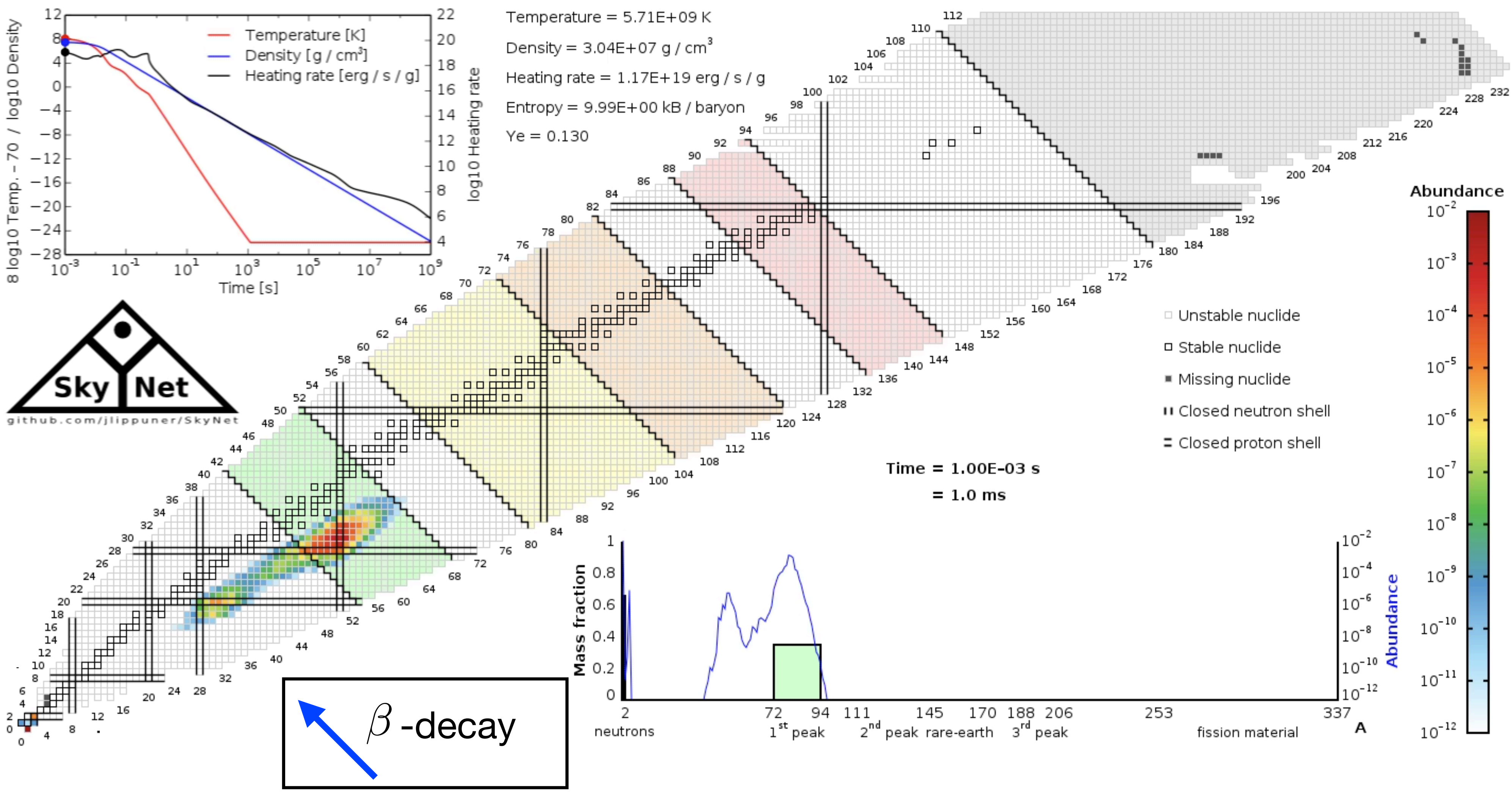


More protons

More neutrons

Kilonovae are radioactive transients powered by the *r*-process decay

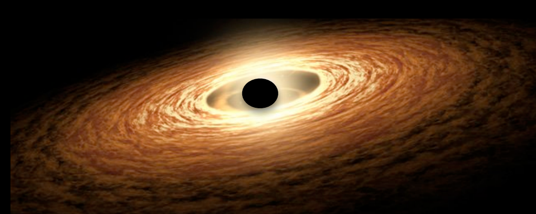
"kilonova"

- Mildly relativistic unbound material
- Synthesis of heavy elements

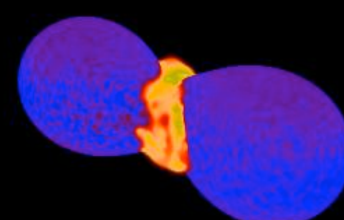
→ An expanding cloud heated by radioactive decays

tidally stripped

disk outflows



dynamically squeezed



Kilonovae are radioactive transients powered decay

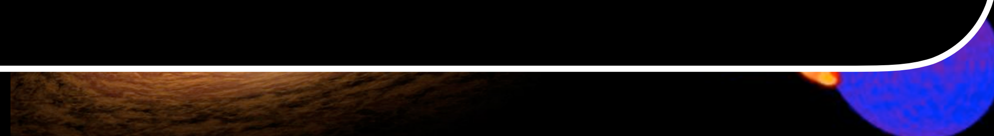
“kilonova”

bound

elements

cloud heated decays

tidally stripped



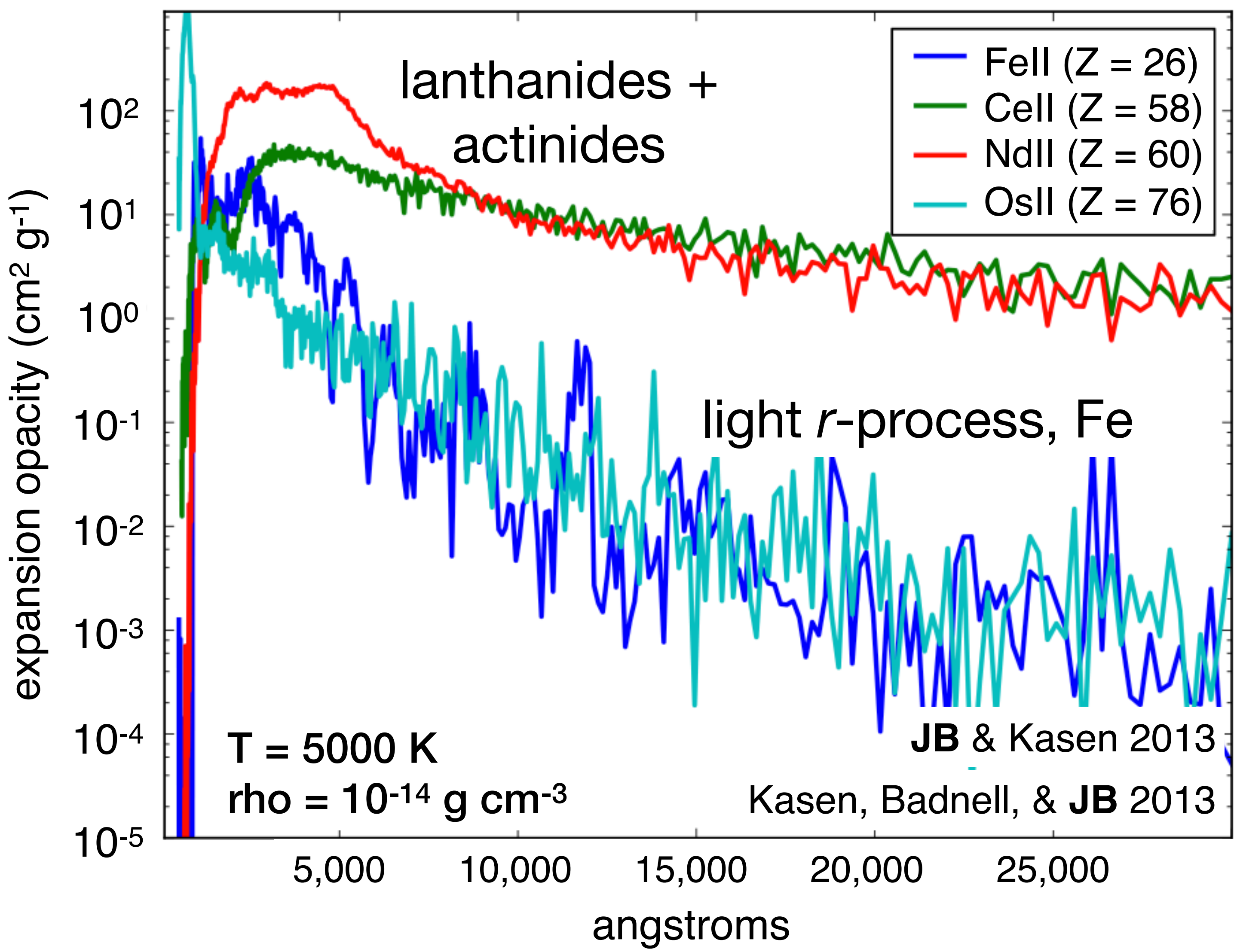
Goals:

- Determine in detail the enrichment of the Universe by neutron star mergers
  - Do mergers produce *r*-process elements?
  - Are mergers *unique* in this regard?

Nucleosynthesis + Opacity

Composition, opacity, and color I

The opacity of certain *r*-process elements (**lanthanides** and **actinides**) is very high

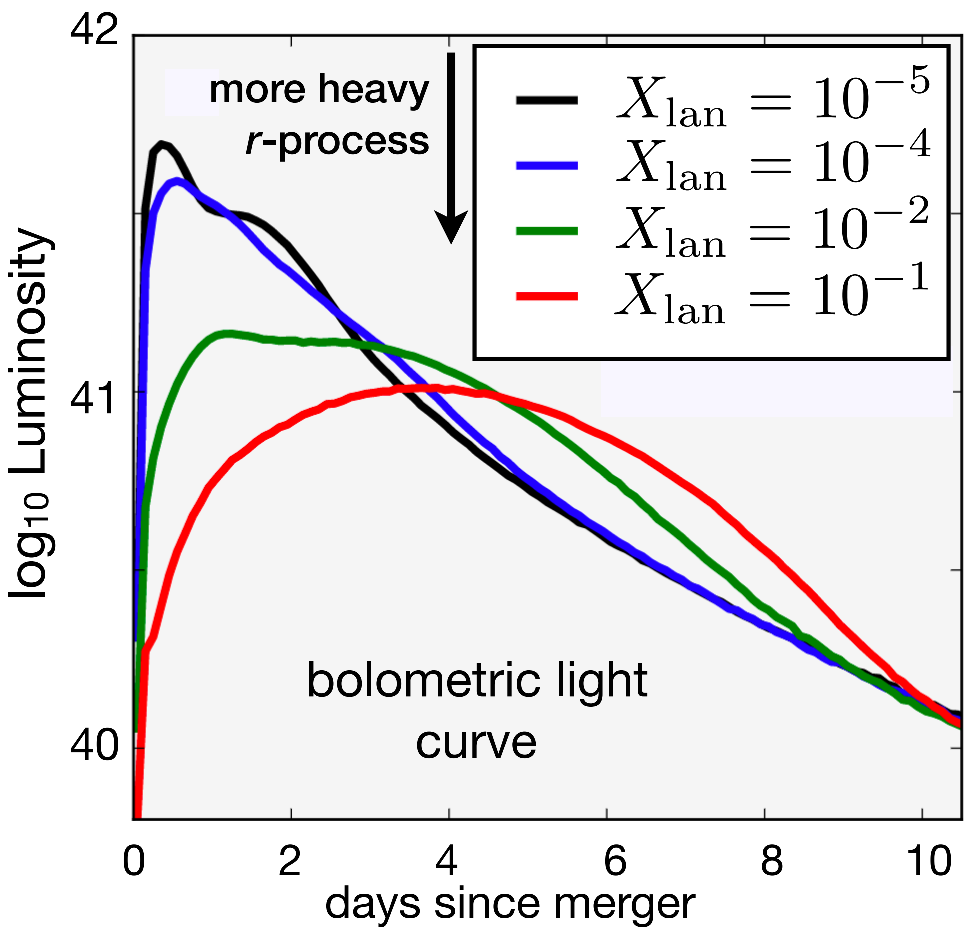


Composition, opacity, and color II

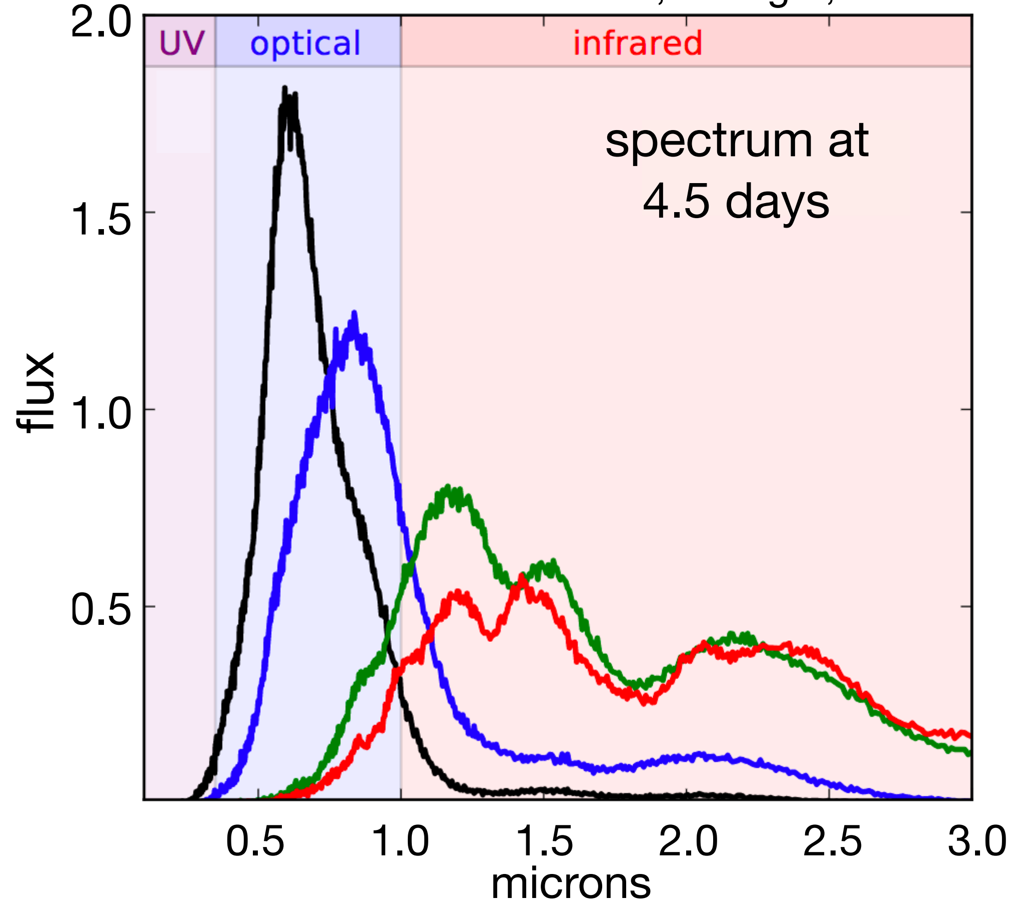
higher opacities ⟶ longer, dimmer, redder light curves

diffusion time: $t_{\rm diff} \sim \kappa^{1/2}$ **adiabatic losses:** $E_{\rm phot} \sim t^{-1}$

line blanketing at optical wavelengths



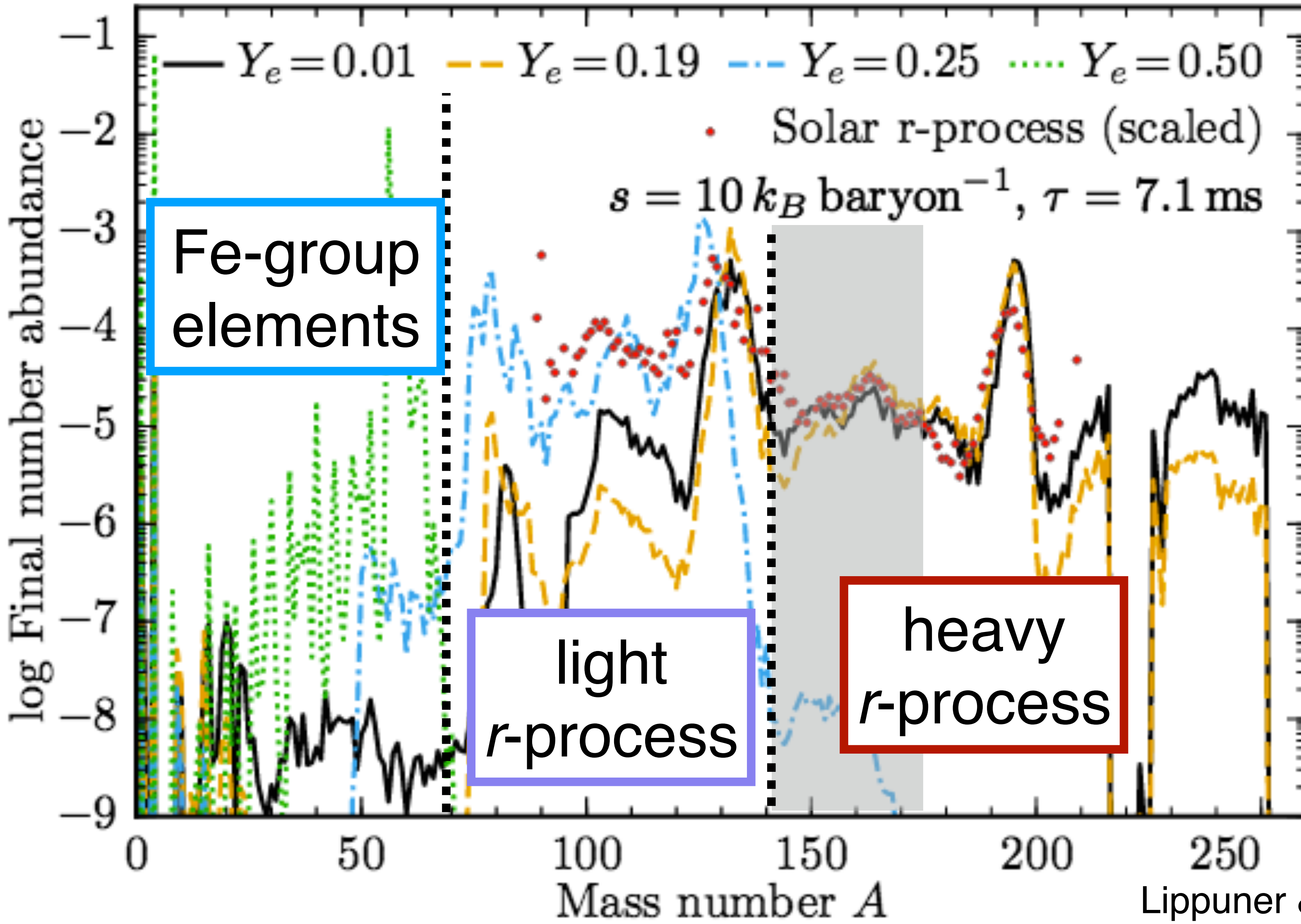
Kasen, Metzger, **JB**+17



Composition, opacity, and color III

Outcomes of the *r*-process

fewer free n per seed ⟵⟶ more free n per seed



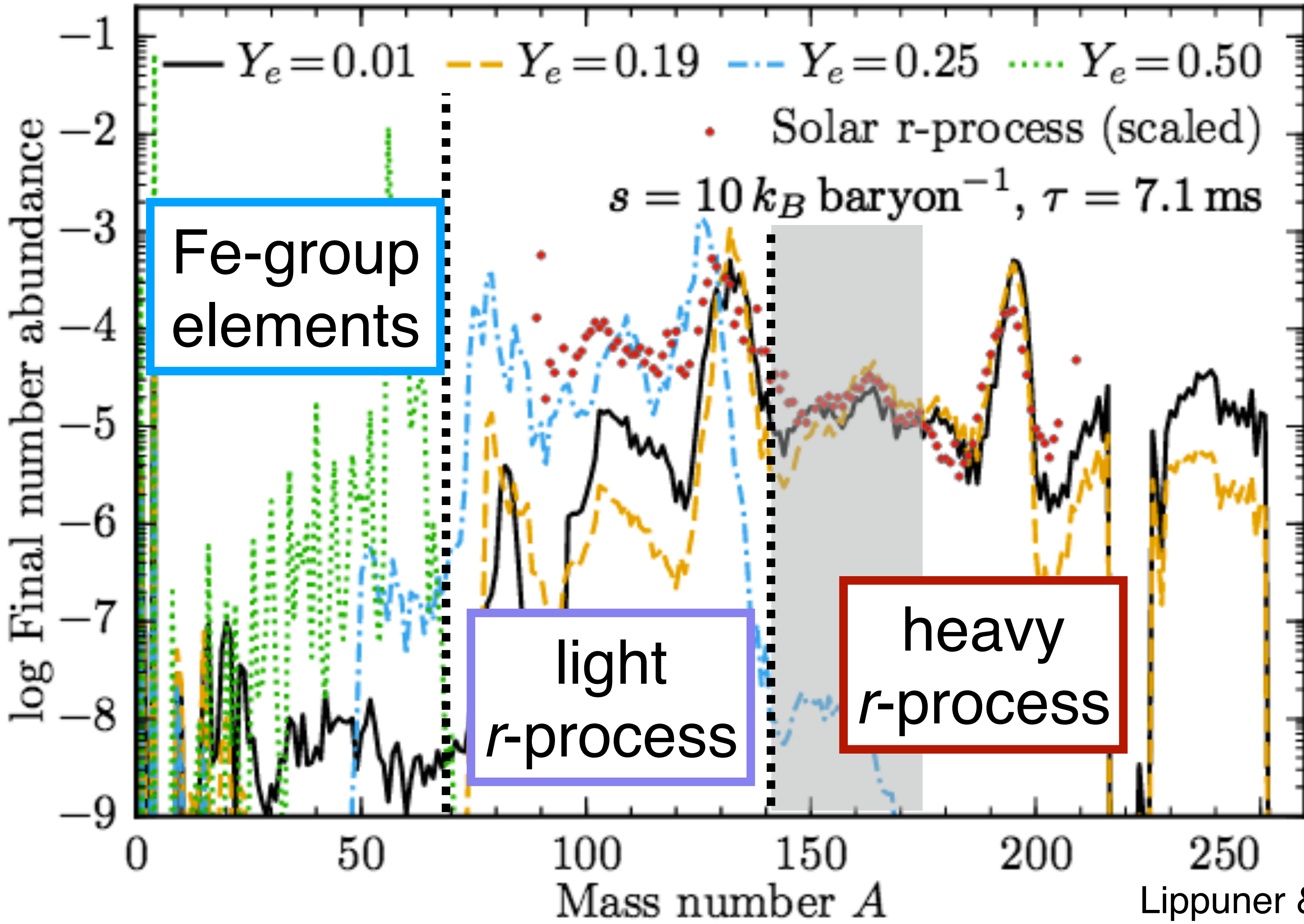
$$Y_\mathrm{e} = \frac{p}{p+n}$$

Lippuner & Roberts 2015

Composition, opacity, and color III

Outcomes of the *r*-process

fewer weak interactions ⟷ more weak interactions

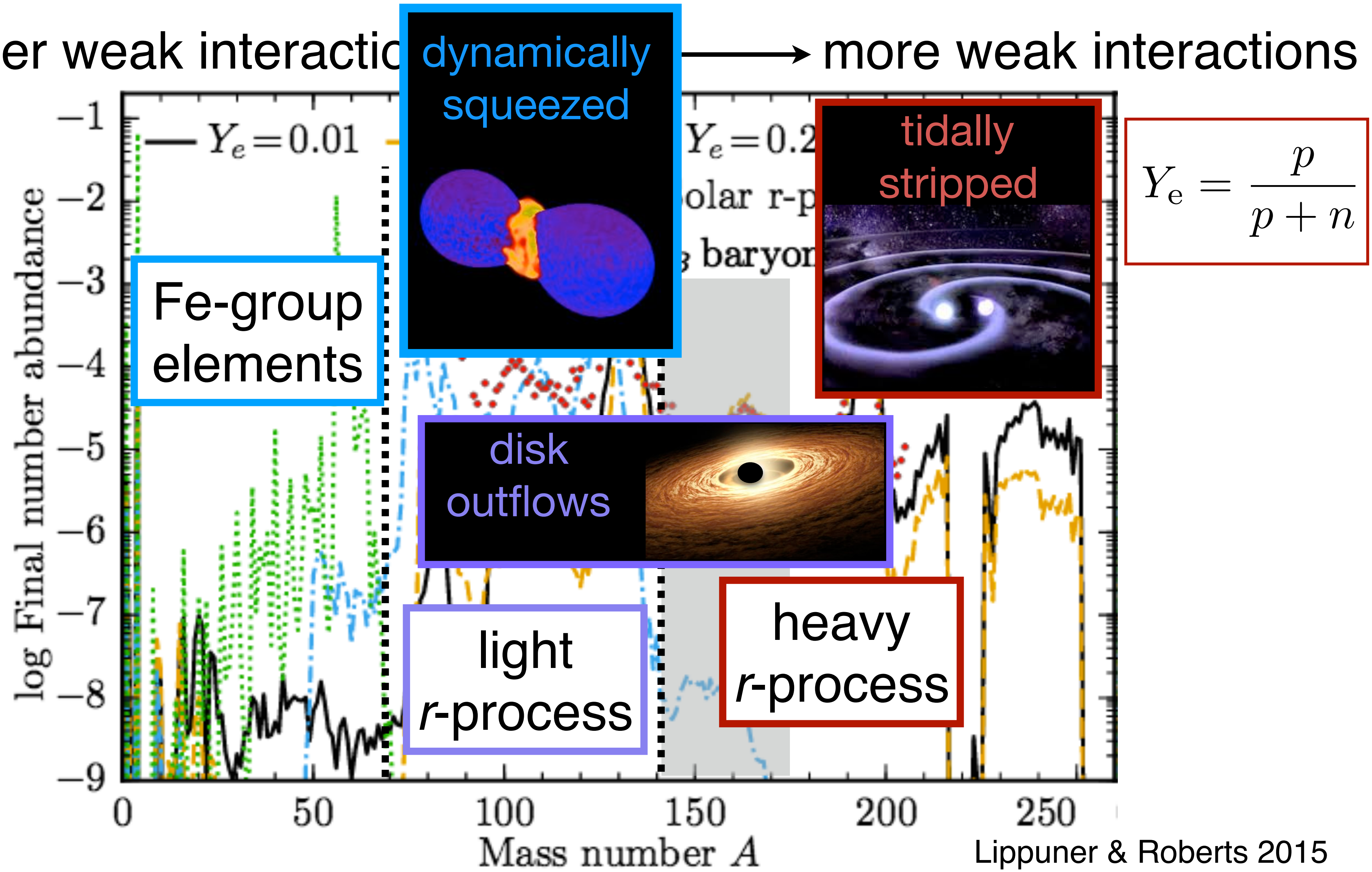


$$Y_\text{e} = \frac{p}{p+n}$$

Lippuner & Roberts 2015

Composition, opacity, and color III

Outcomes of the *r*-process



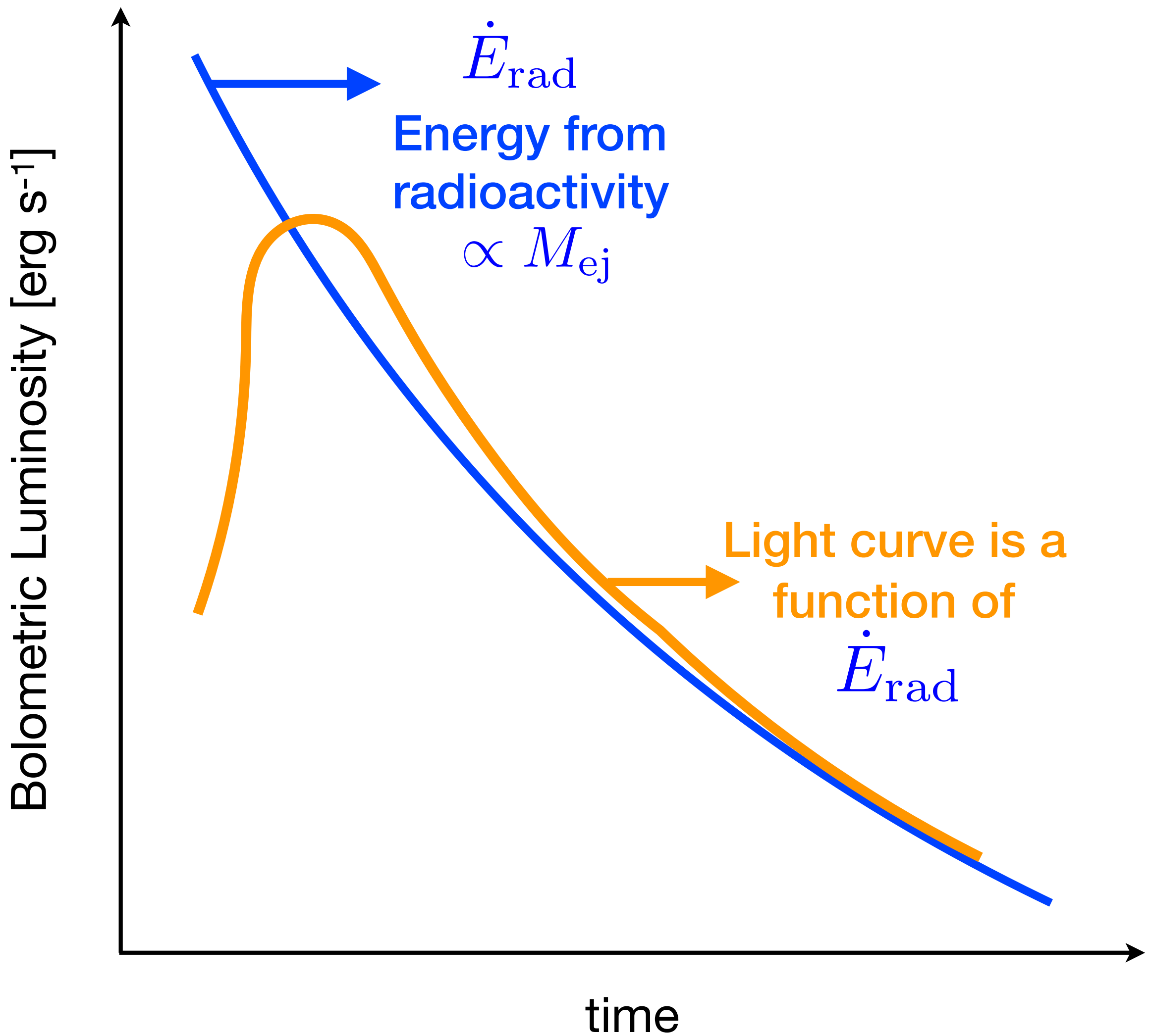
Lippuner & Roberts 2015

Radioactivity + Luminosity

Luminosity and thermalization I

R-process-powered transients

Generic radioactive transient



Luminosity and thermalization I

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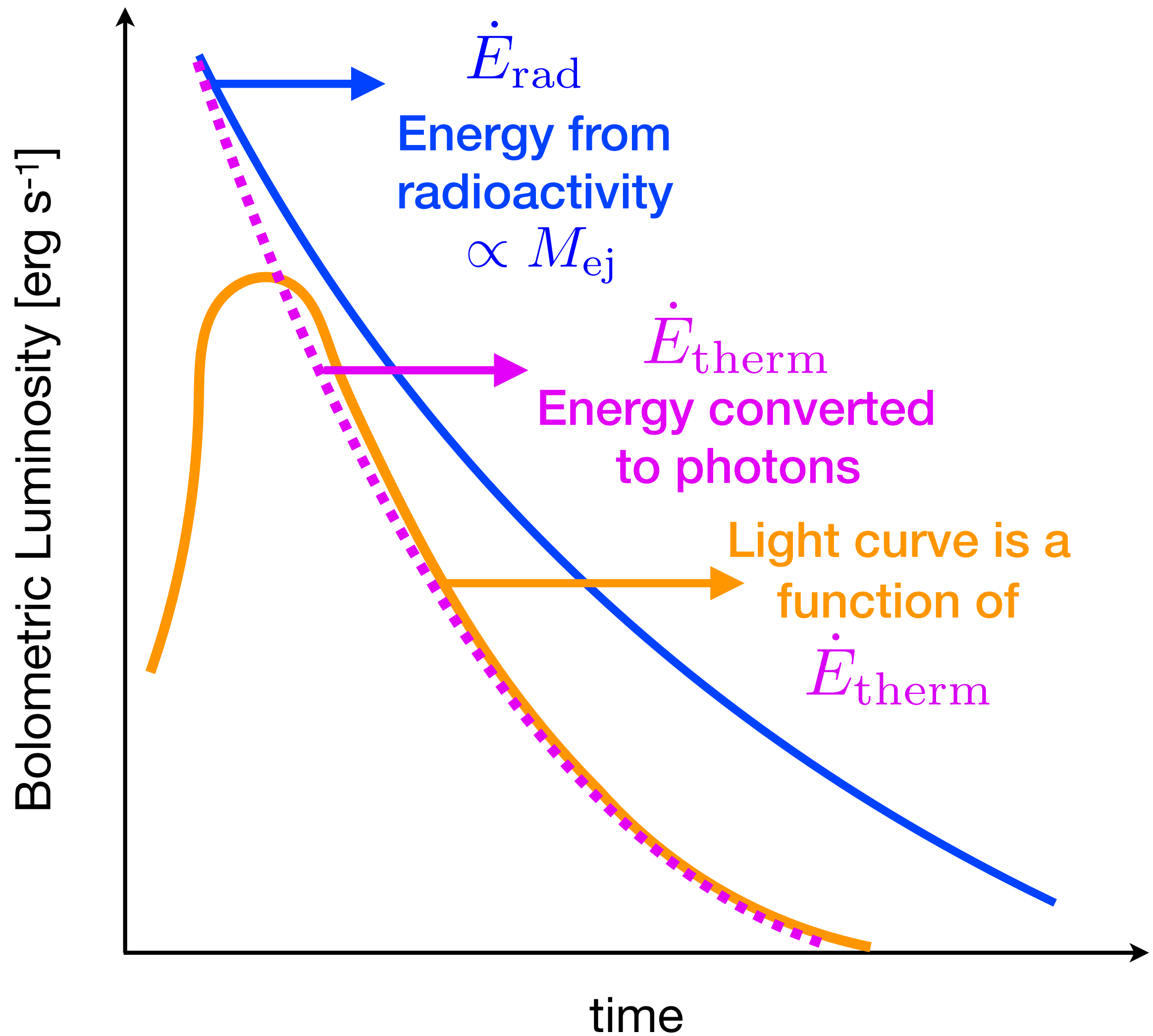
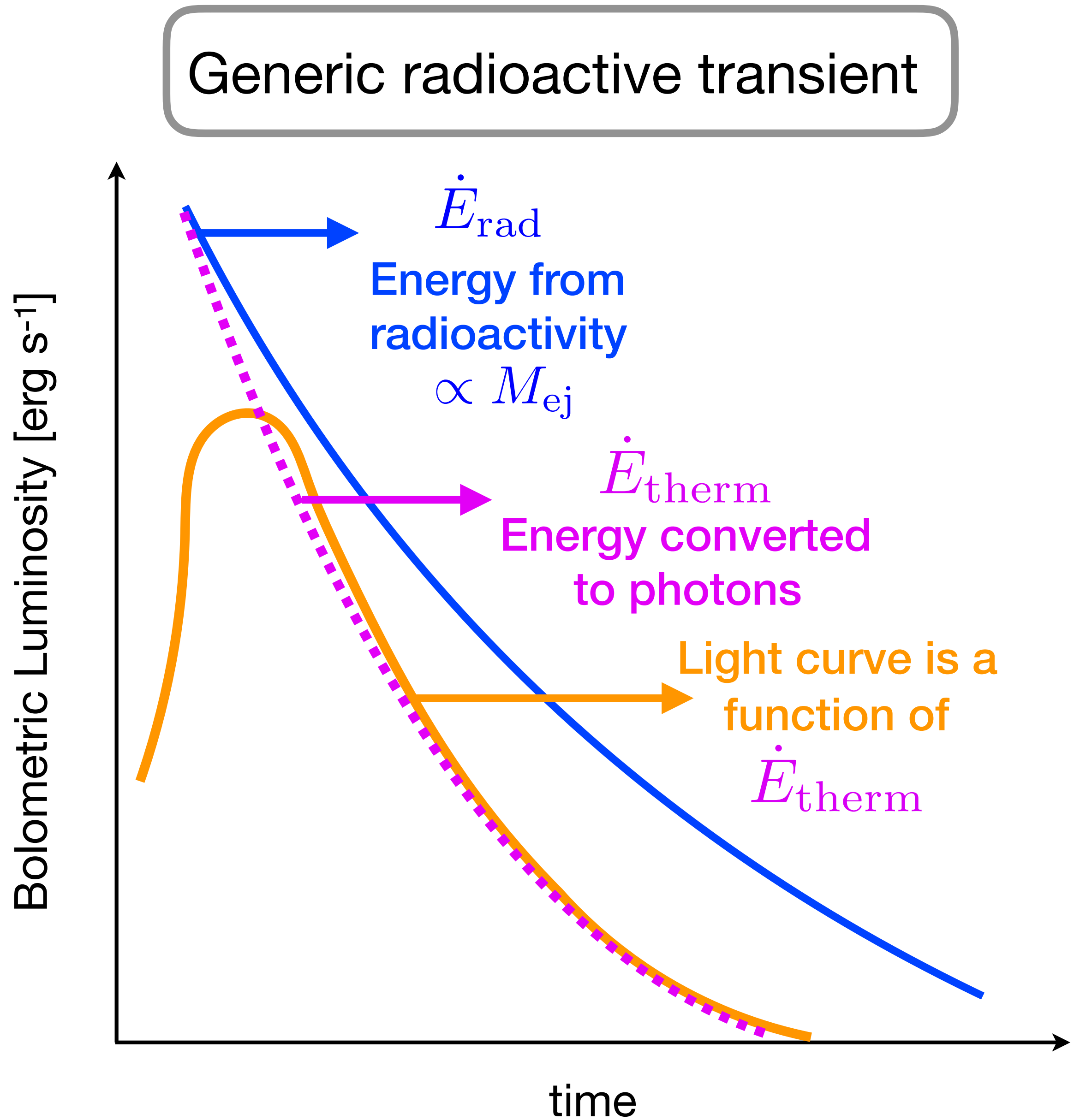


Luminosity and thermalization I

R-process-powered transients



Luminosity and thermalization I

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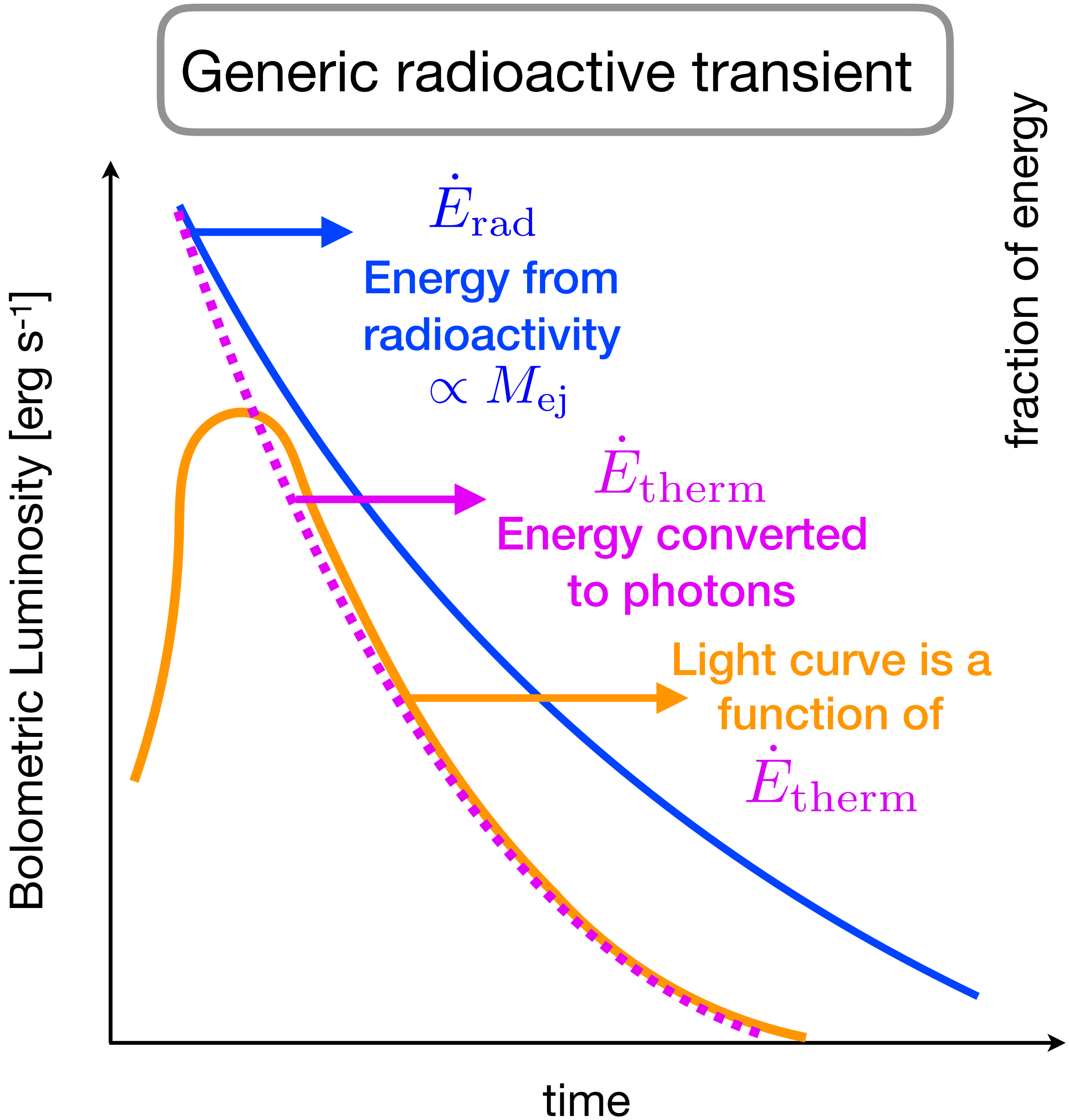
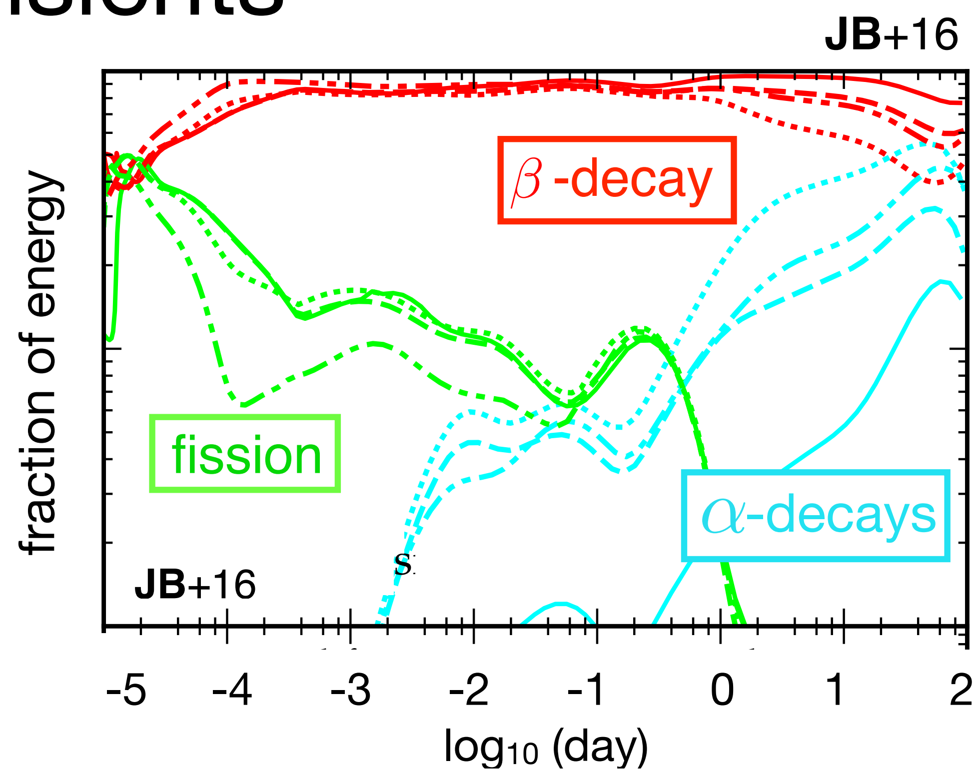
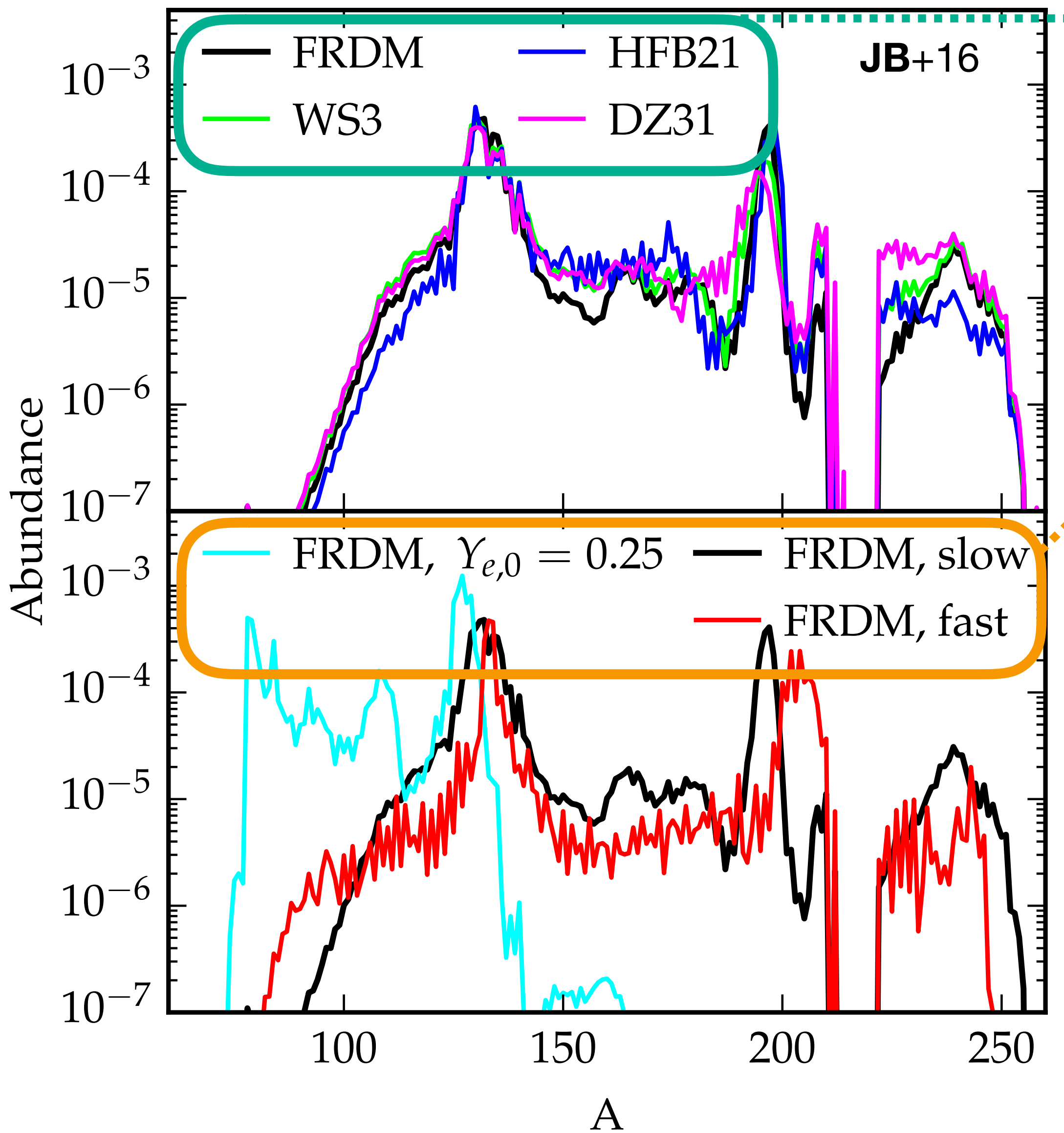




R-process radioactivity includes β-decays, α-decays, and fission, each of which has its own thermalization profile

Thermalization and luminosity II

R-process heating is variable

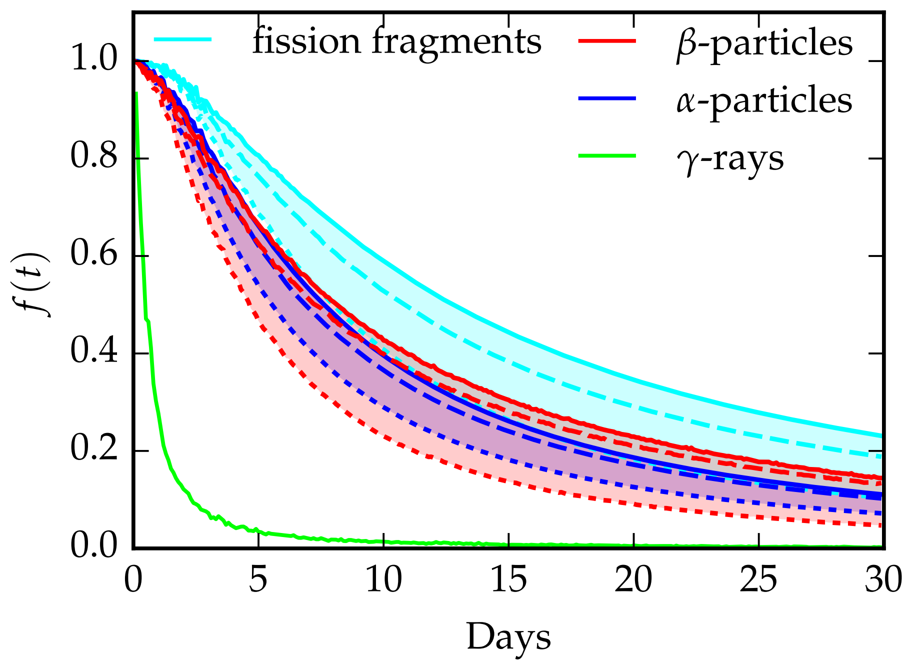


Both $\dot{E}_{\rm rad}$ and $\dot{E}_{\rm therm}$ depend on outcome of the *r*-process, which varies with both astrophysical conditions ($Y_{\rm e}$, $\tau_{\rm exp}$, $s_{\rm bar}$) and theoretical inputs (nuclear masses, β-decay rates, *n*-capture cross sections

Thermalization and luminosity II

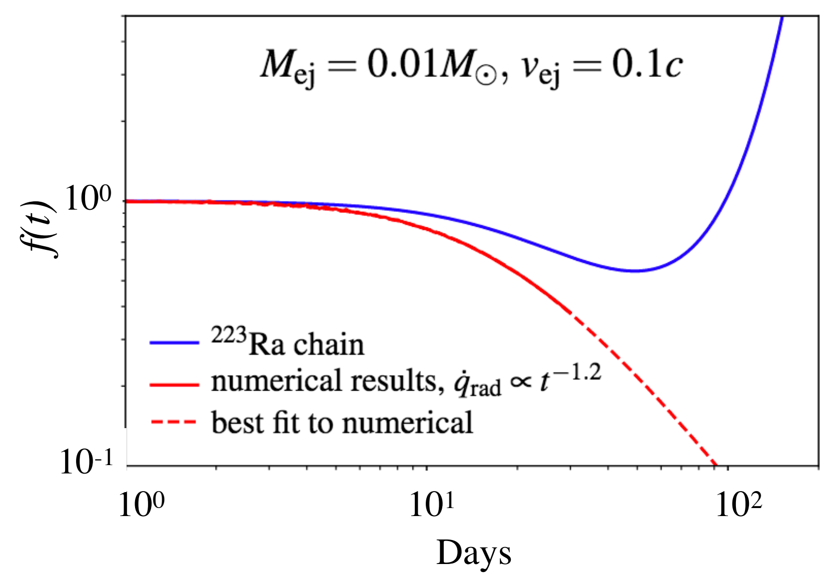
Luminosity ⟵ thermalization ⟵ radioactivity

Alpha-decays heat more effectively than ***beta-decays***



JB+16

Single-isotope radioactivity heats more effectively than a ***statistical ensemble*** of decays

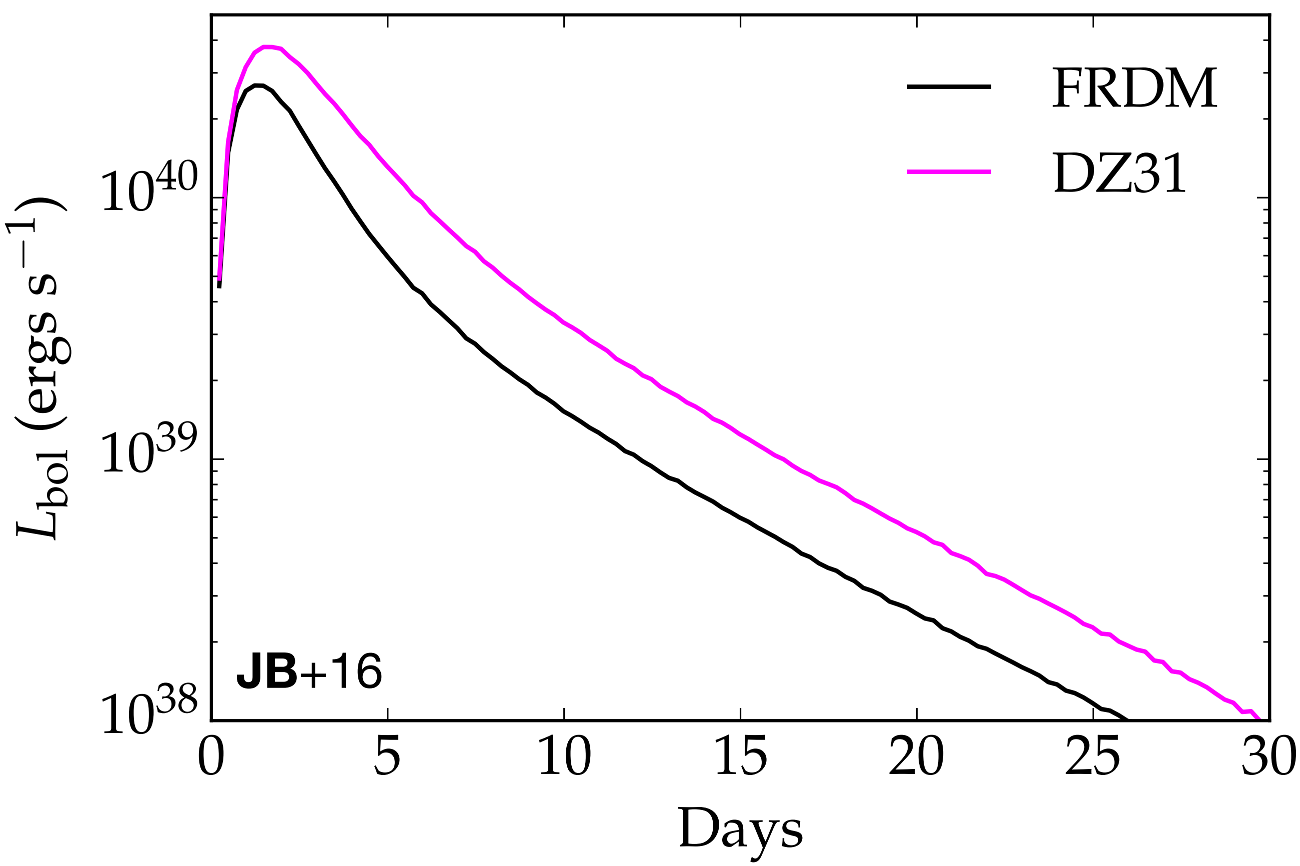


Wu, JB+19; see also Kasen & JB+19

Thermalization and luminosity III

Constraints from bolometric luminosity

I. The more we know about the nuclear physics underlying *r*-process, the more accurately we can measure $M_{\rm ej}$

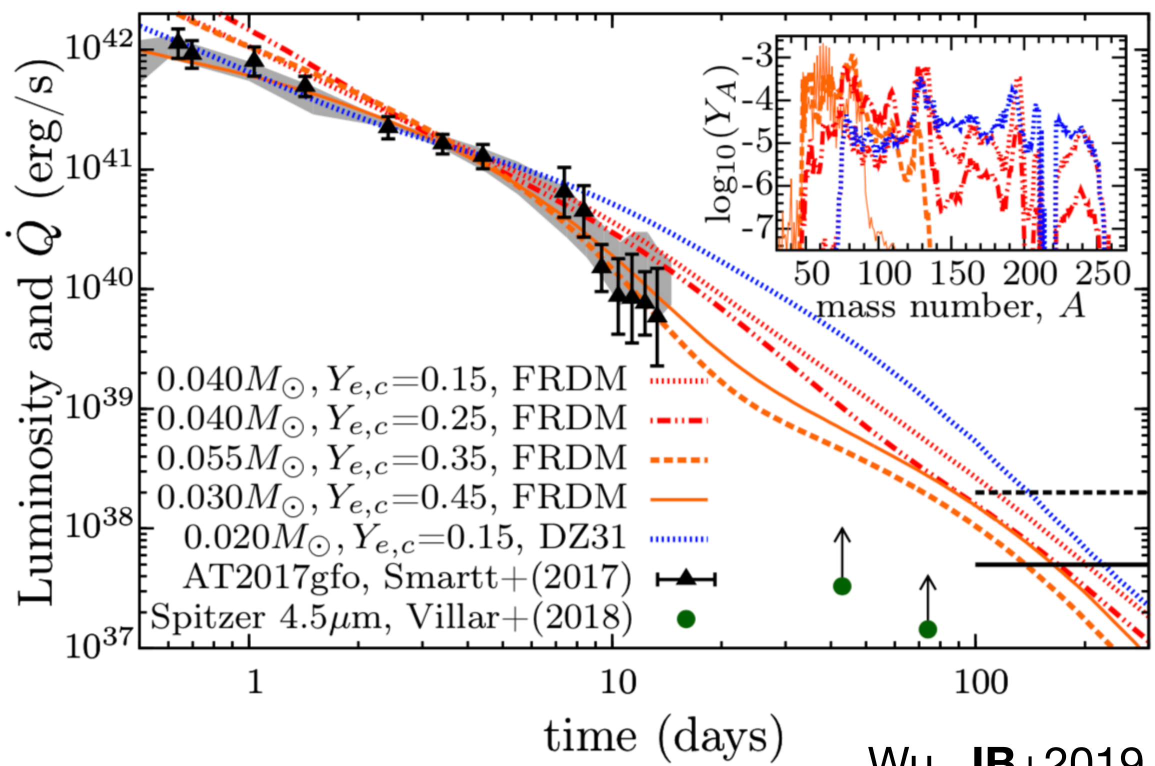


Thermalization and luminosity III

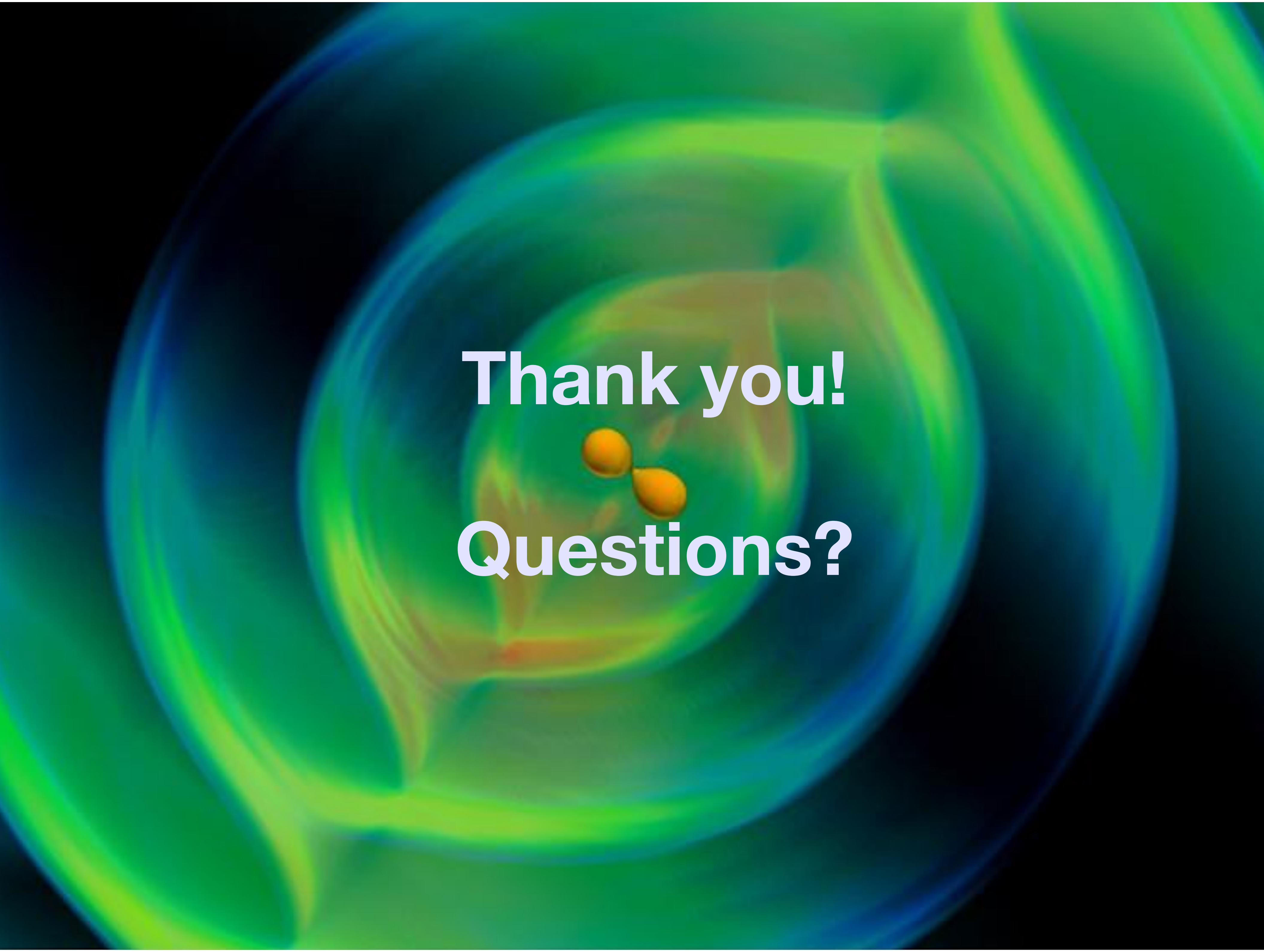
Constraints from bolometric luminosity

I. The more we know about the nuclear physics underlying *r*-process, the more accurately we can measure $M_{\rm ej}$

II. What we *already* know about heating and thermalization may allow us to detect the signatures of particular isotopes in kilonova emission



Wu, **JB**+2019 (PRL)


Thank you!
Questions?