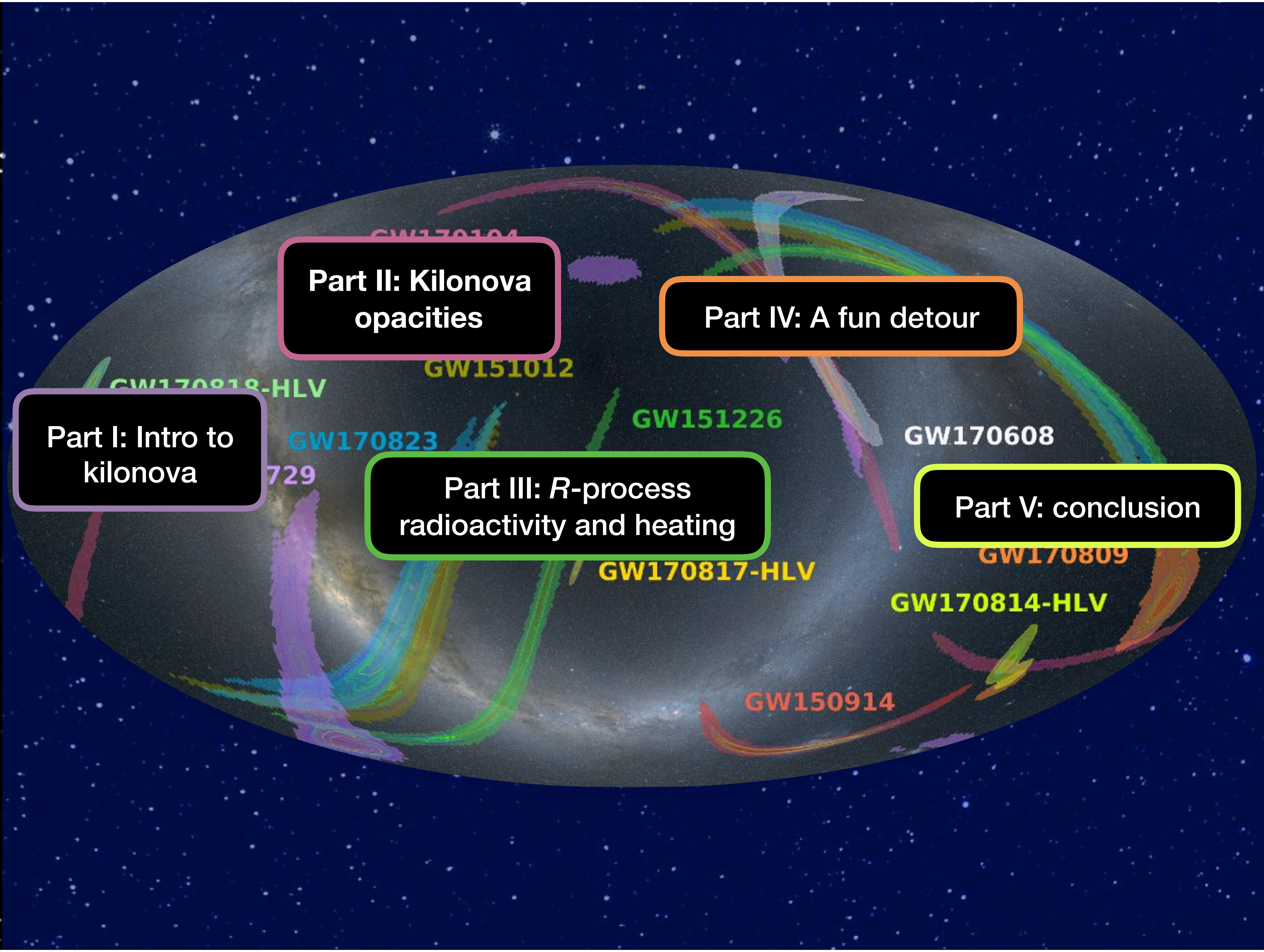
Electromagnetic emission from *r*-process-powered transients

MMGW19 @ YITP
Kyoto University
8 Oct 2019

Jennifer Barnes
NASA Einstein Fellow
Columbia University


Part I: Intro to kilonova
Part II: Kilonova opacities
Part III: *R*-process radioactivity and heating
Part IV: A fun detour
Part V: conclusion
GW151012
GW170823
GW151226
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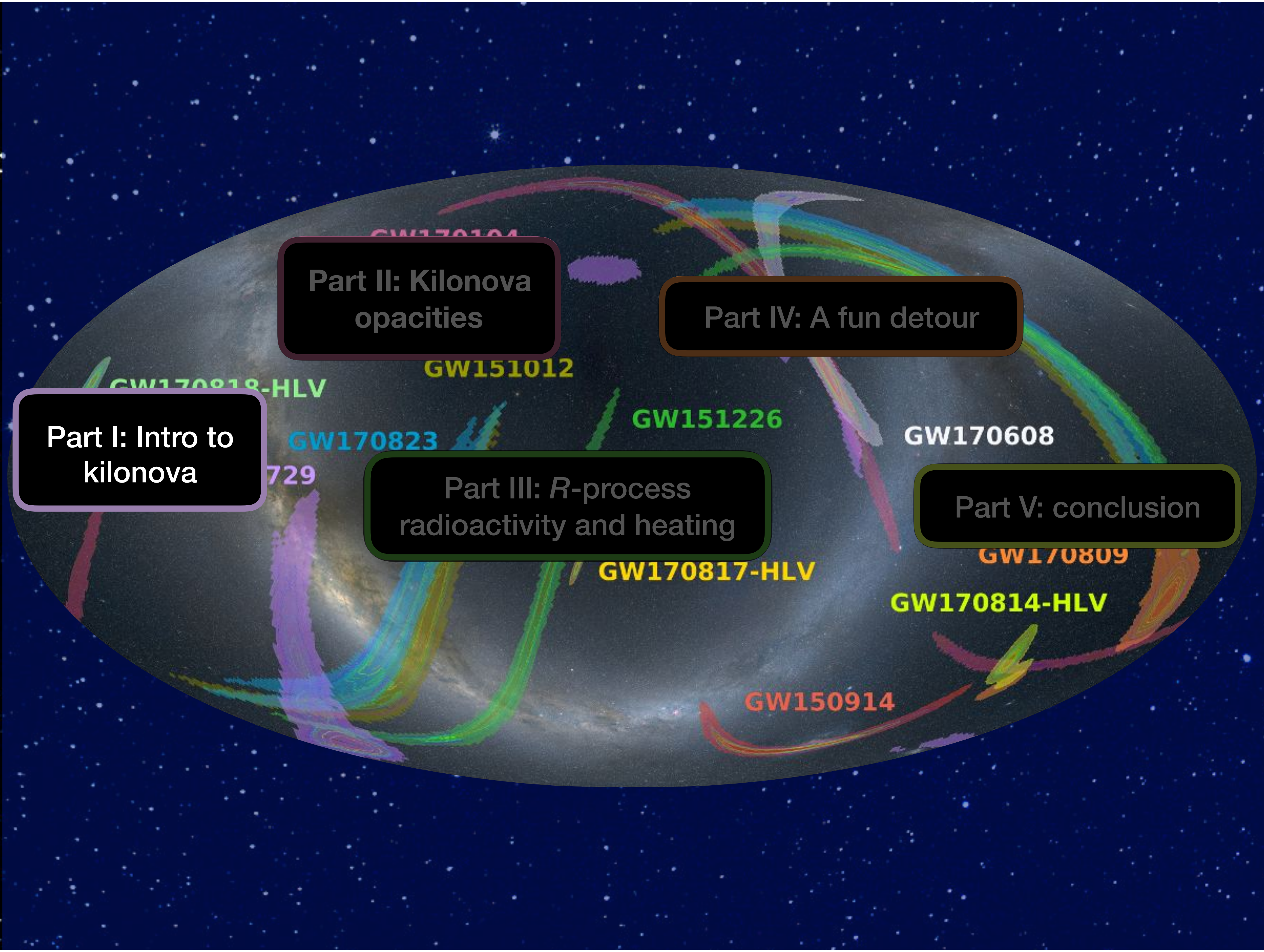
GW150914



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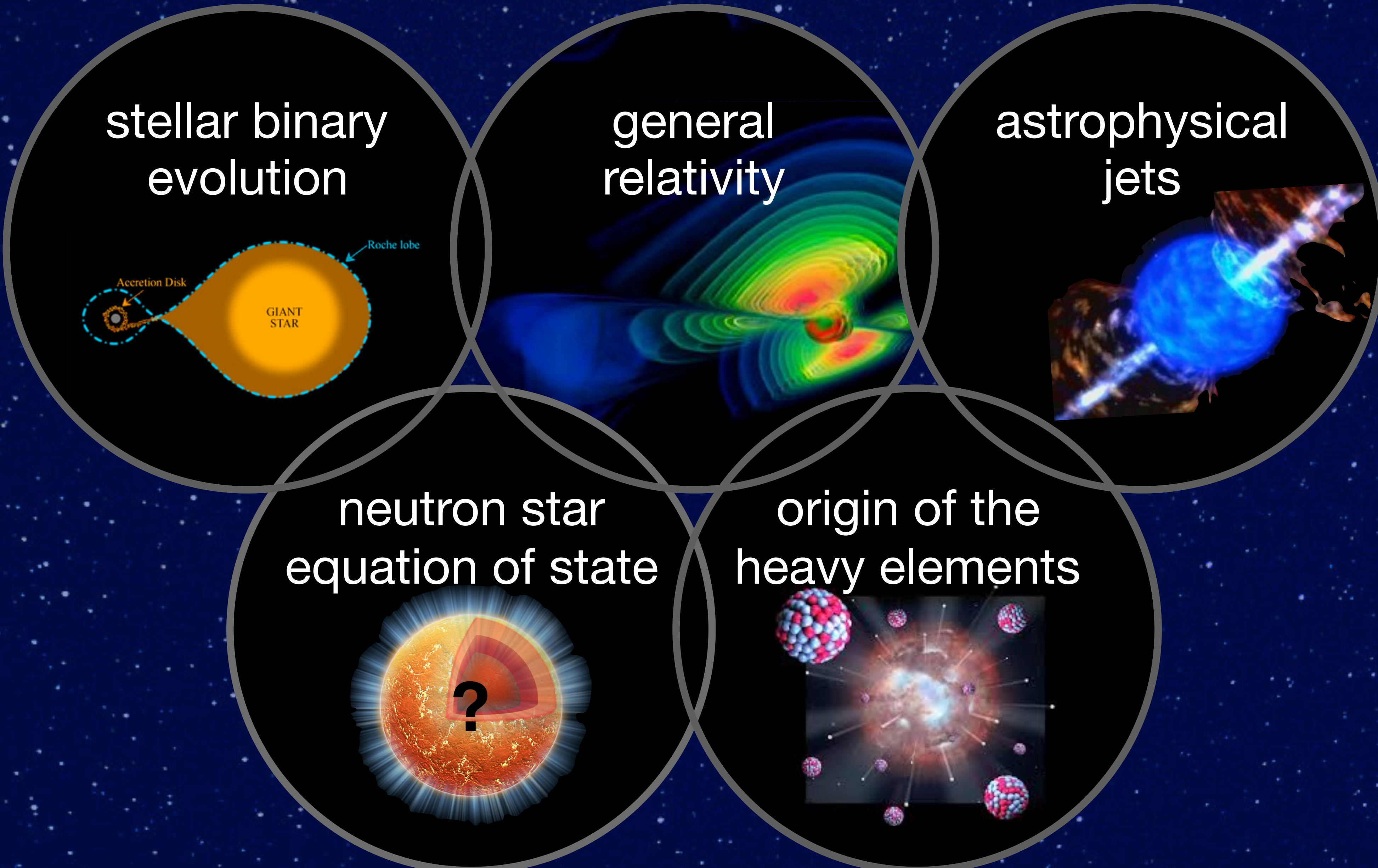
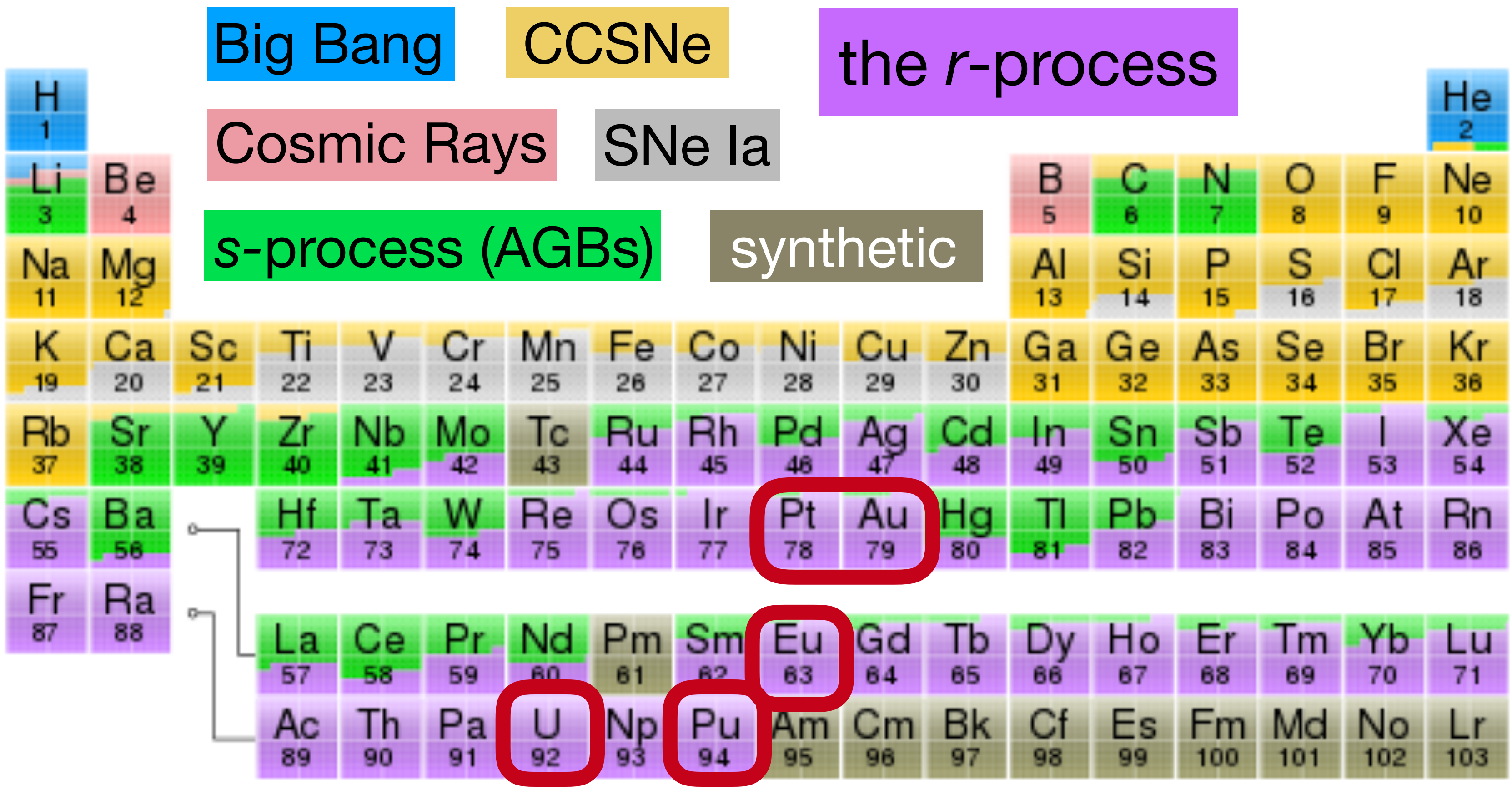
Open questions for the multi-messenger era



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



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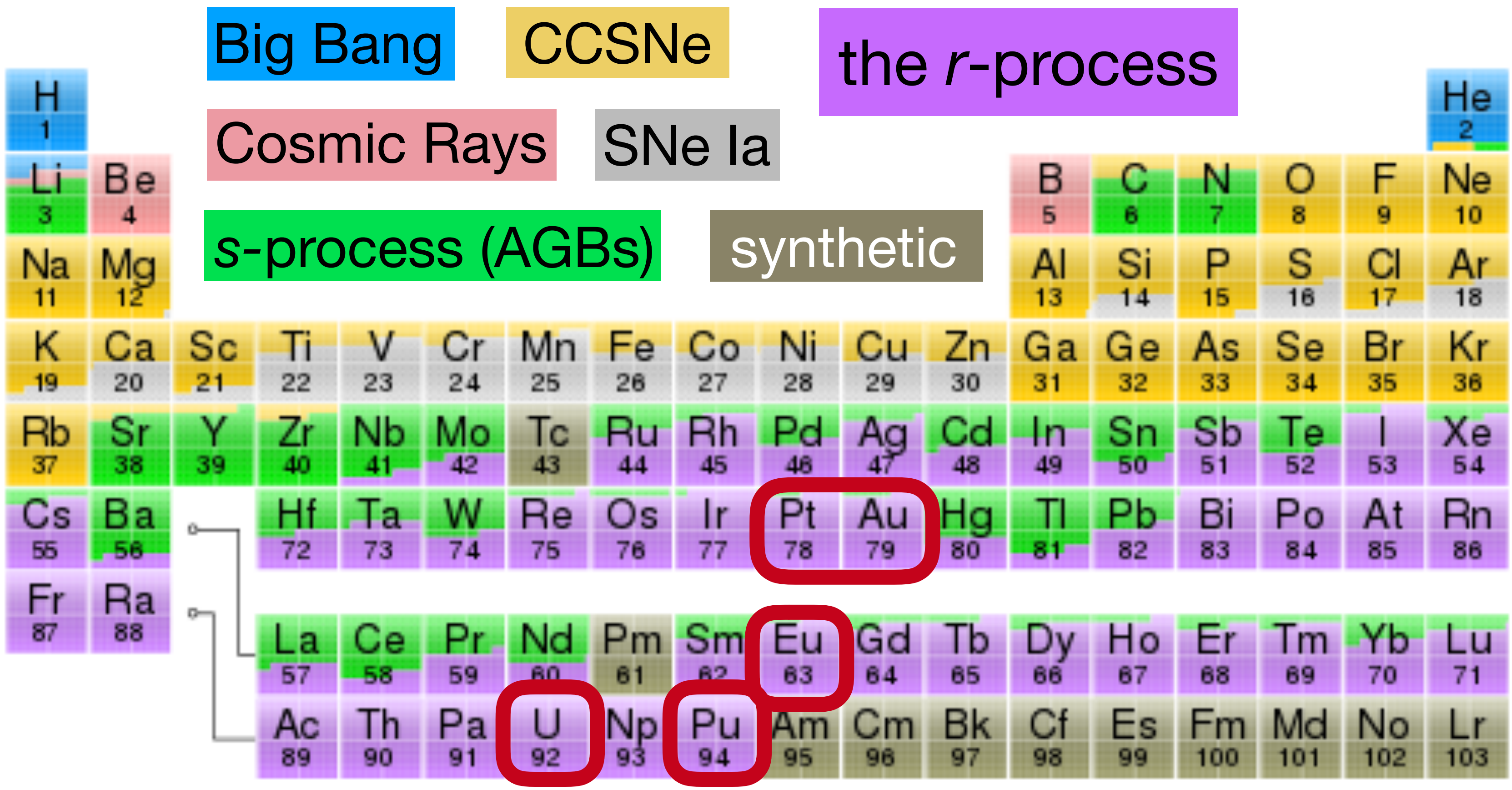
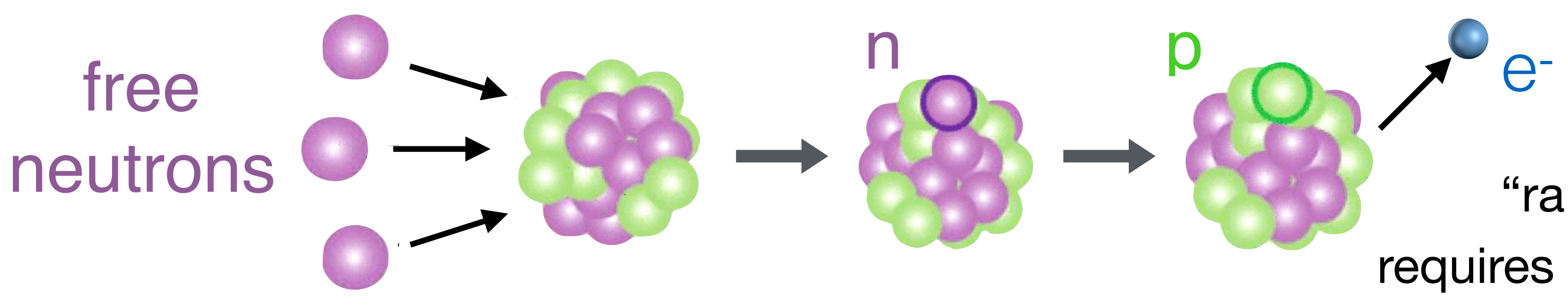
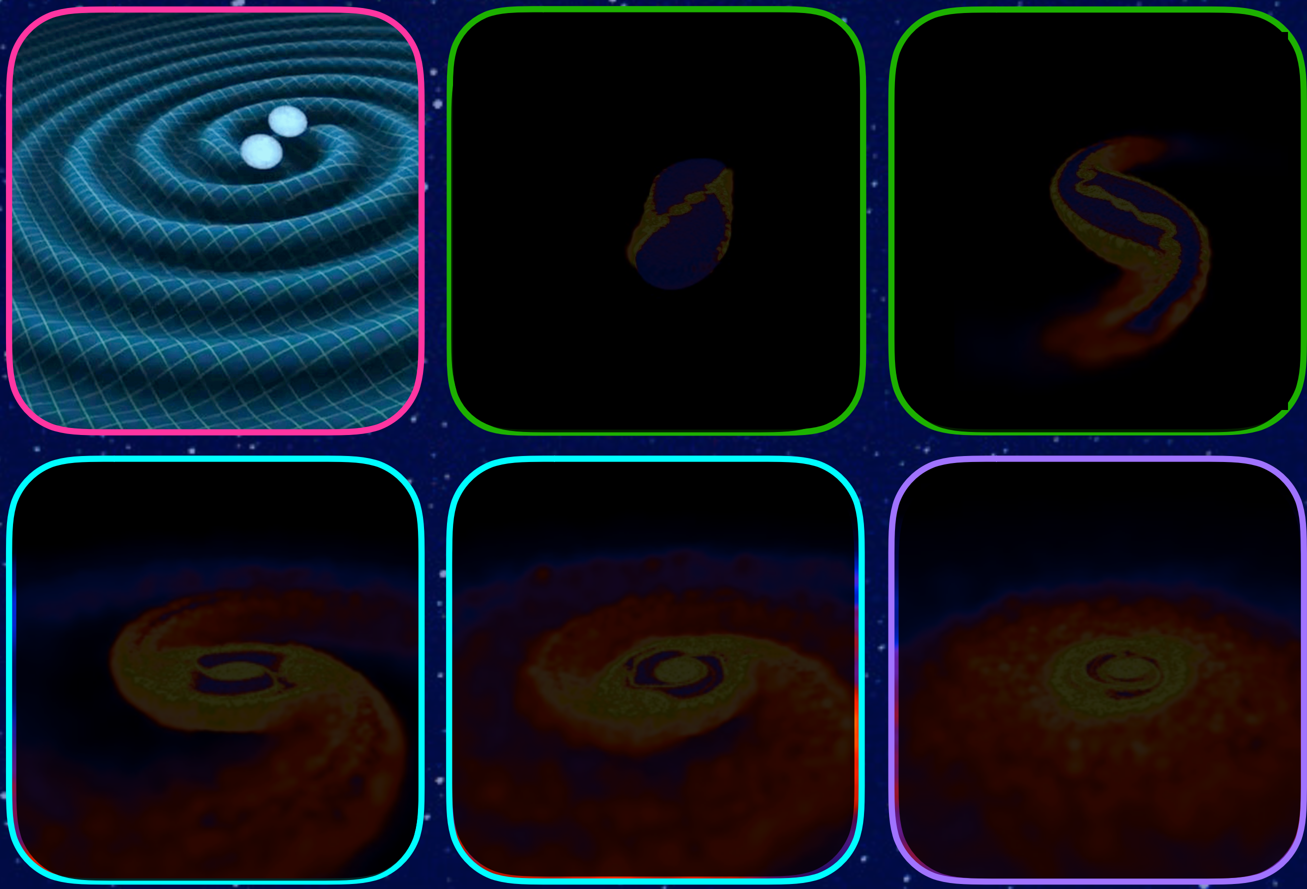




“rapid:”
requires $\tau_{\mathrm{n}} \ll \tau_{\beta^-}$

Mergers are natural sites of the *r*-process

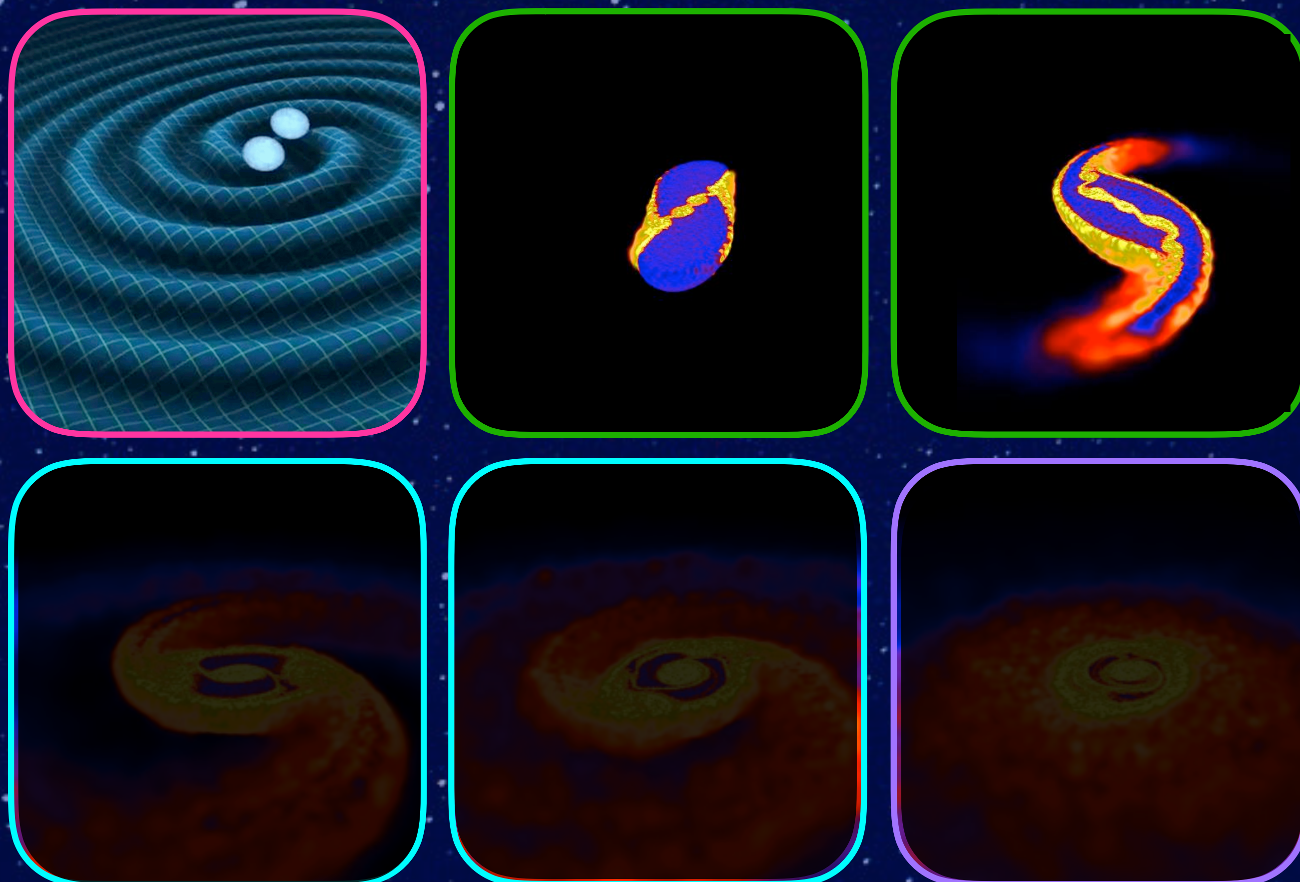
final orbits:
strong GW source



Mergers are natural sites of the *r*-process

merger: neutron star disrupts, central remnant forms

final orbits: strong GW source



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final orbits: strong GW source

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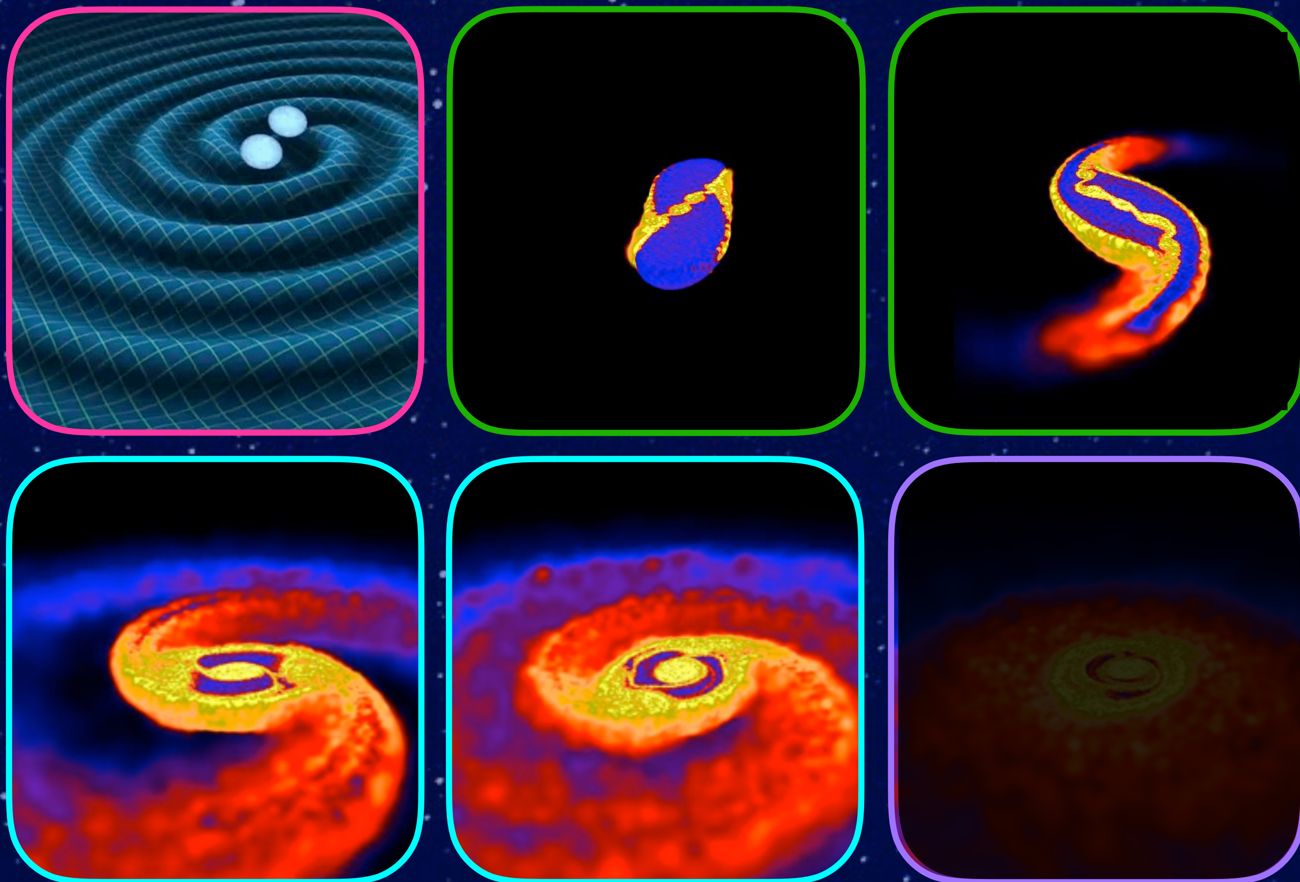
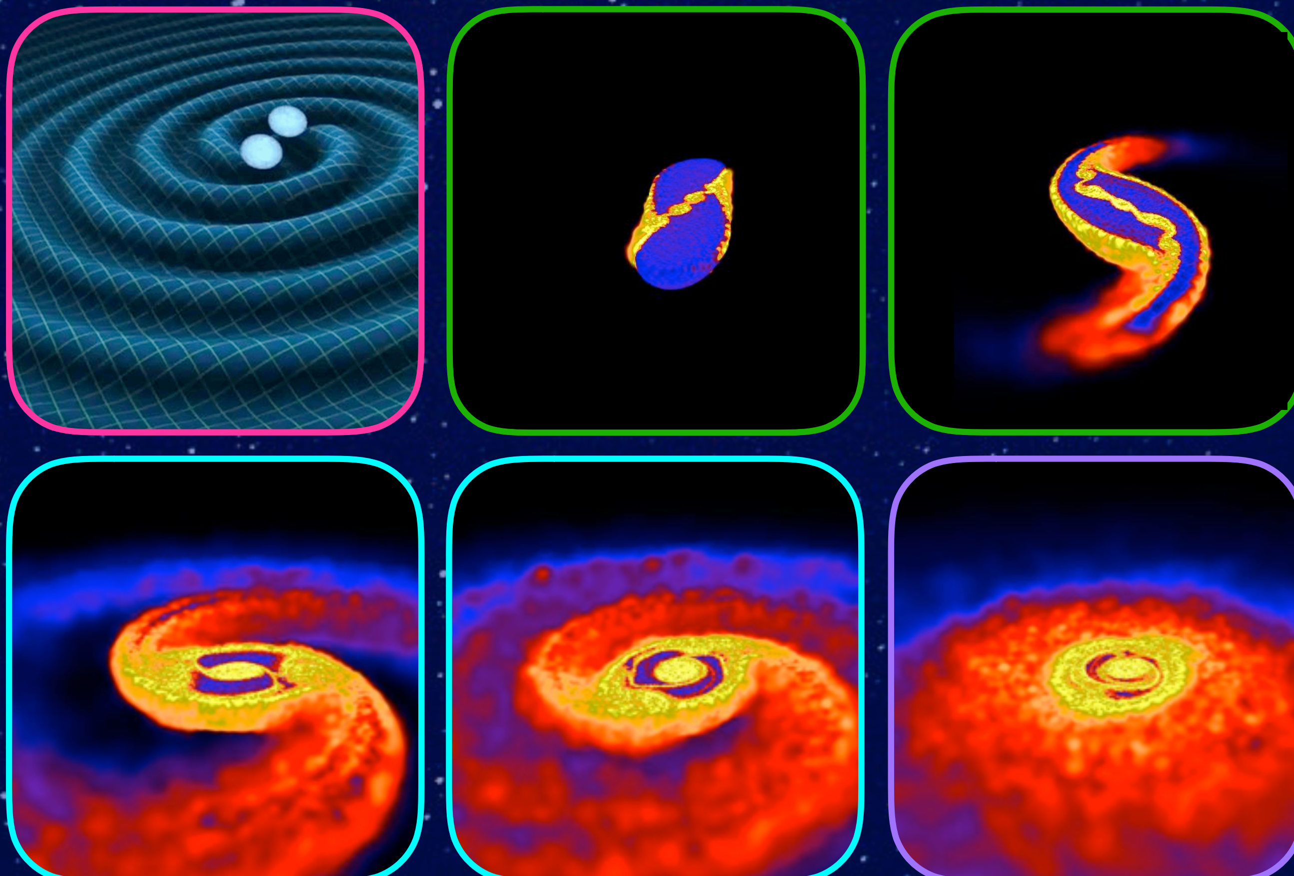


ejecta: some material escapes; some is bound

Mergers are natural sites of the *r*-process

merger: neutron star disrupts, central remnant forms

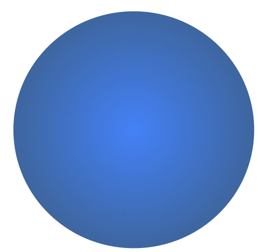
final orbits: strong GW source



ejecta: some material escapes; some is bound

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

The *r*-process assembles heavy nuclei in explosive environments

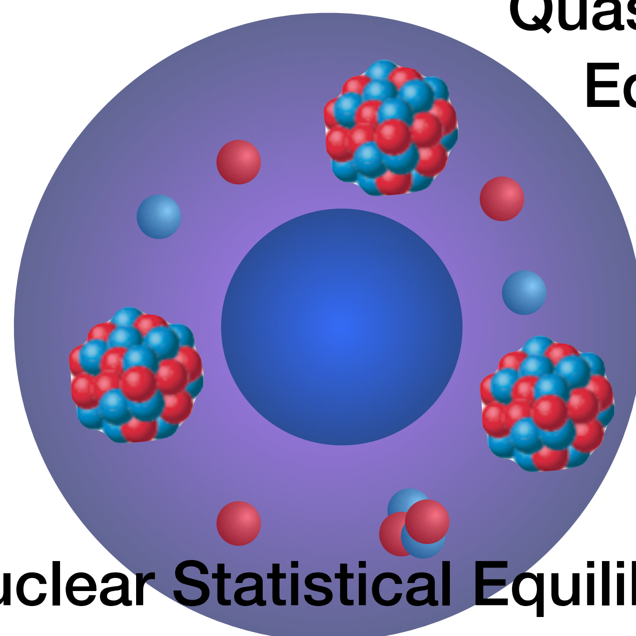


Nuclear Statistical Equilibrium

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

Composition depends on state variables, not on reaction rates

The *r*-process assembles heavy nuclei in explosive environments



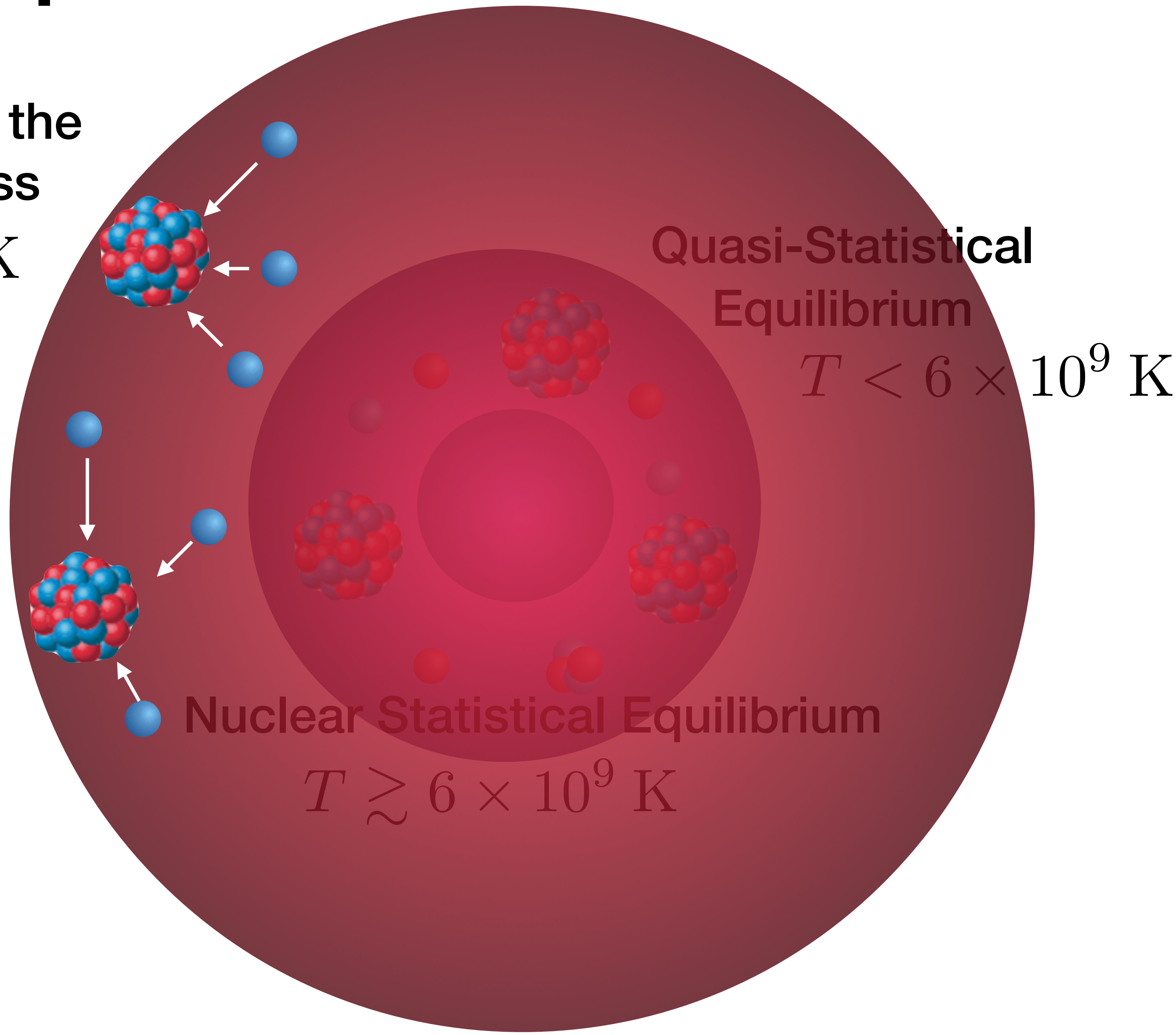
The *r*-process assembles heavy nuclei in explosive environments

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

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

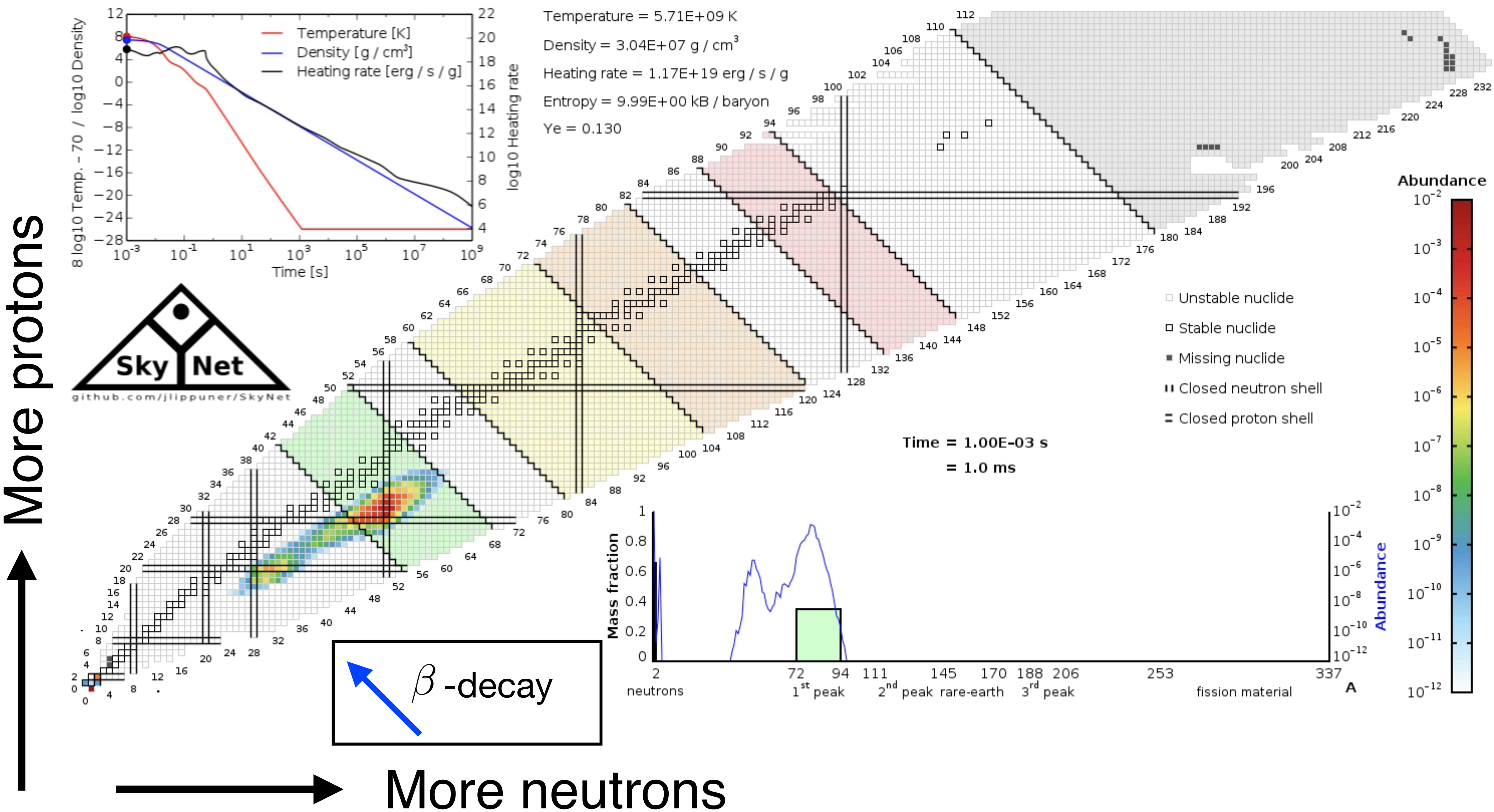
Changes to the composition are driven by n-capture

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



The *r*-process: a detailed look

courtesy J. Lippuner



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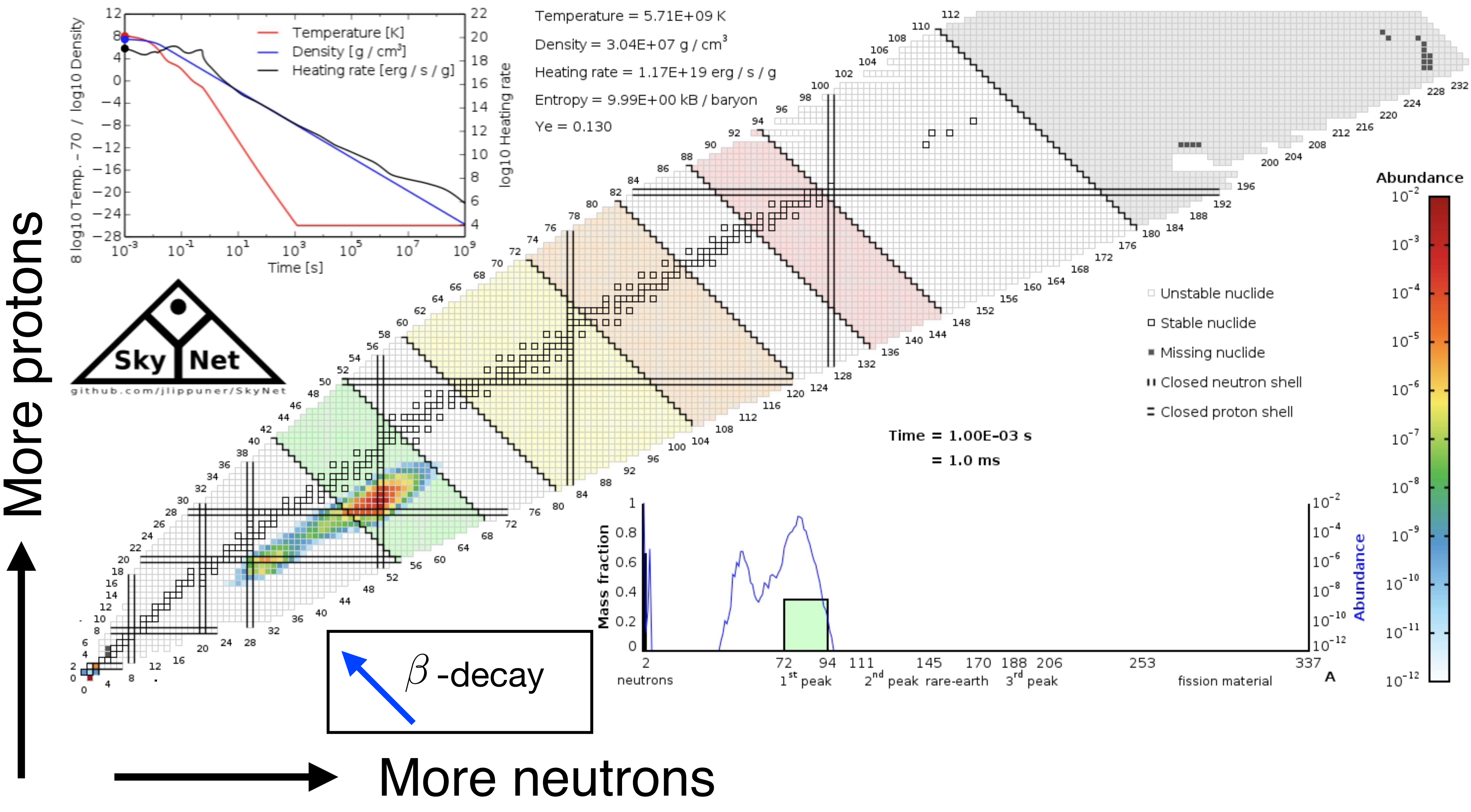


The decay of *r*-process elements powers a “kilonova”

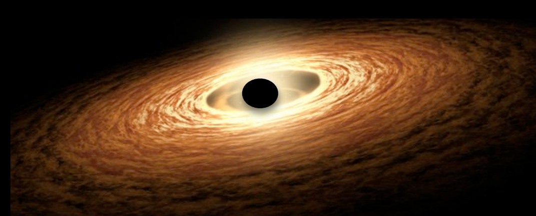
“kilonova”

- Mildly relativistic **neutron-rich** unbound material
- Synthesis of heavy elements

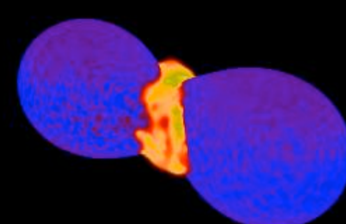
→ An expanding cloud heated by radioactive decays

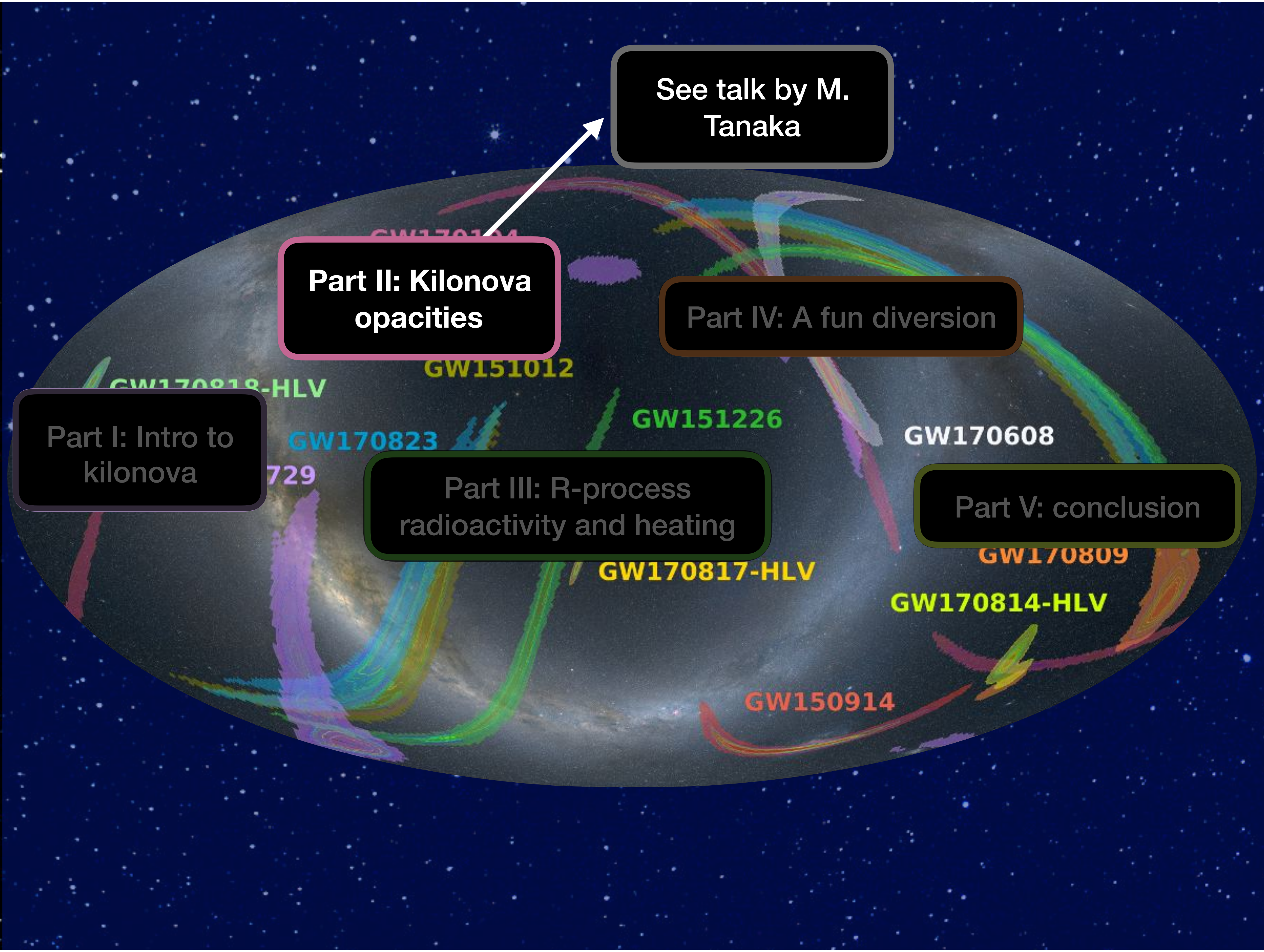
tidally stripped

disk outflows



dynamically squeezed




See talk by M. Tanaka
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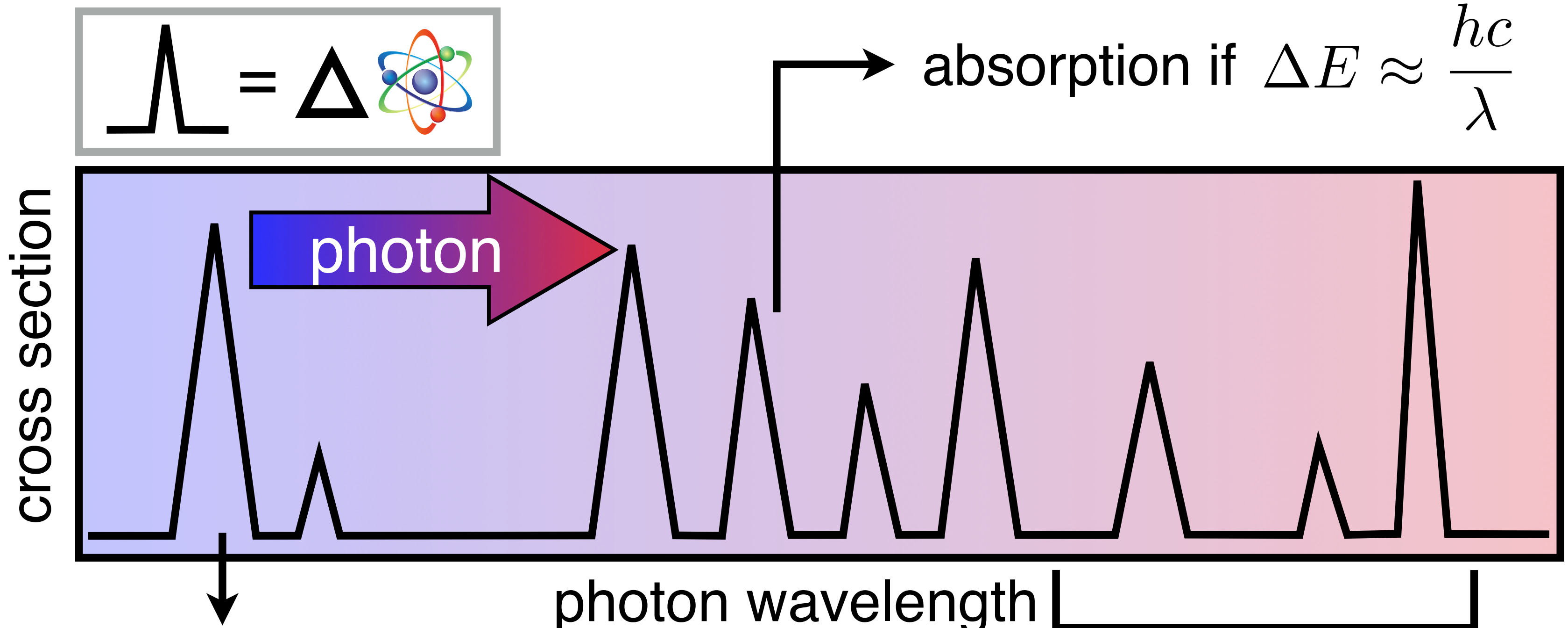
Kilonova composition and opacity

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



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

Sobolev optical depth sets interaction probability with a particular line

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

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

Understanding kilonova emission

Opacity and composition

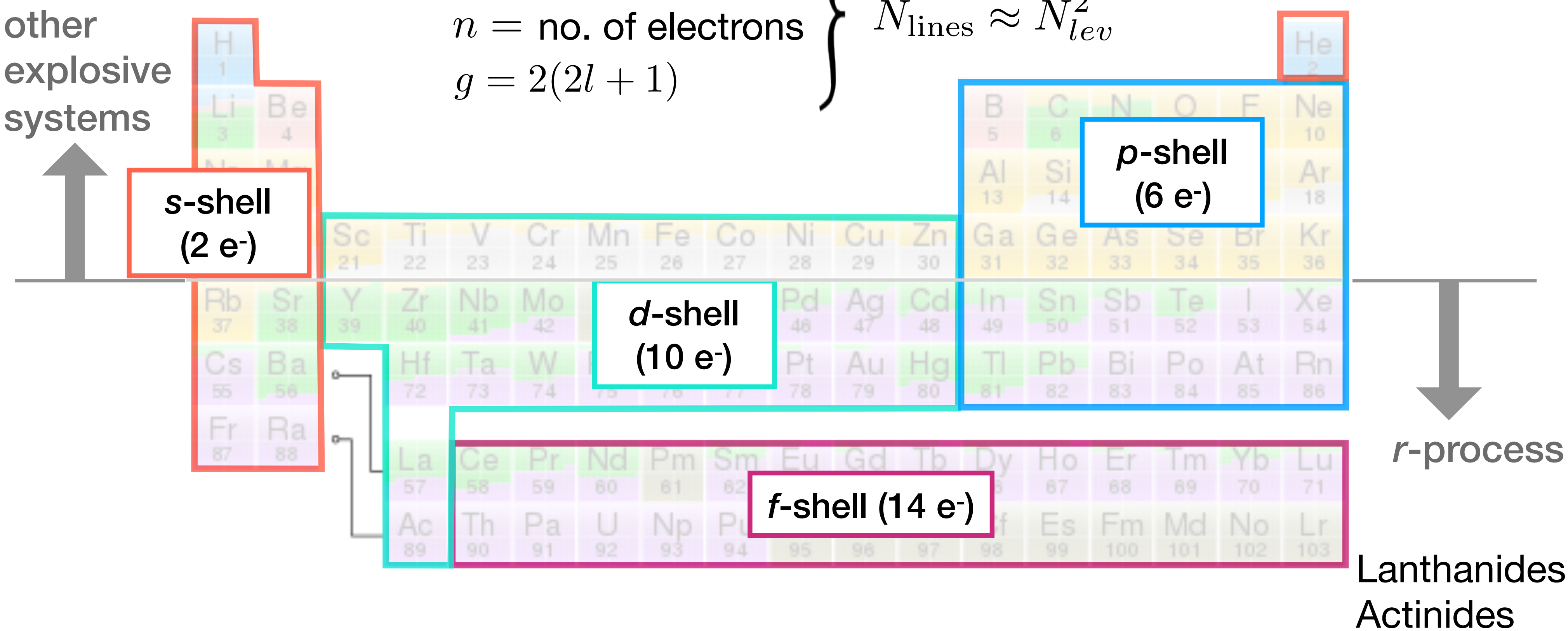
The *r*-process burns heavy elements with unique atomic structures and a **high density of strong lines**

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

$n =$ no. of electrons

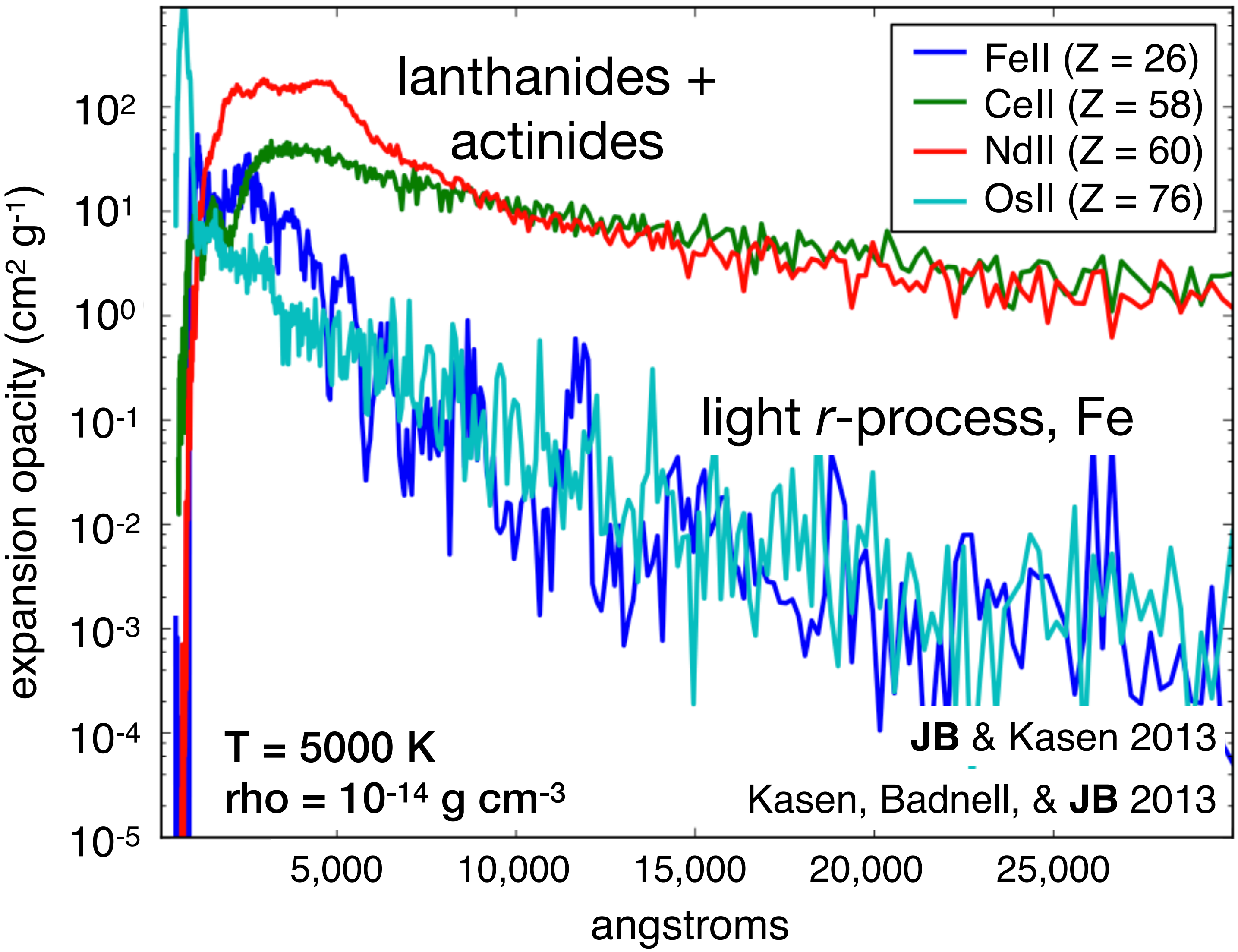
$g = 2(2l+1)$

$$N_{\text{lines}} \approx N_{lev}^2$$



Kilonova composition and opacity

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



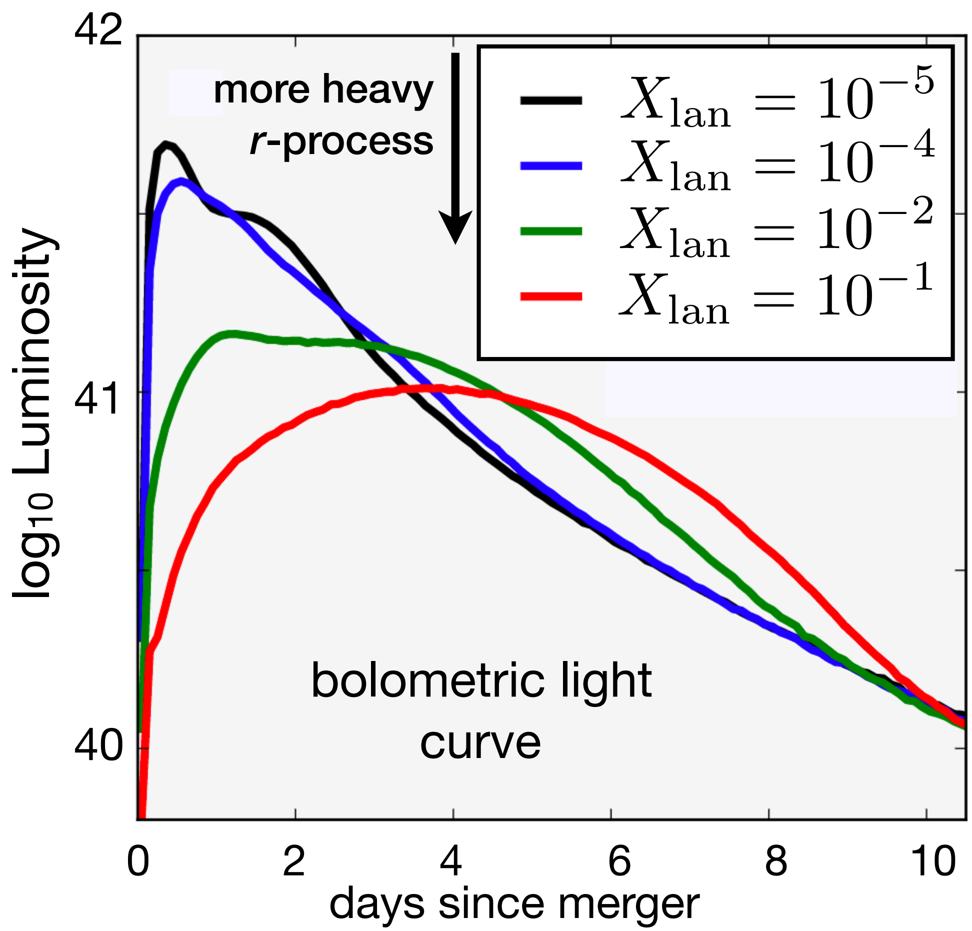
Kilonova composition and opacity

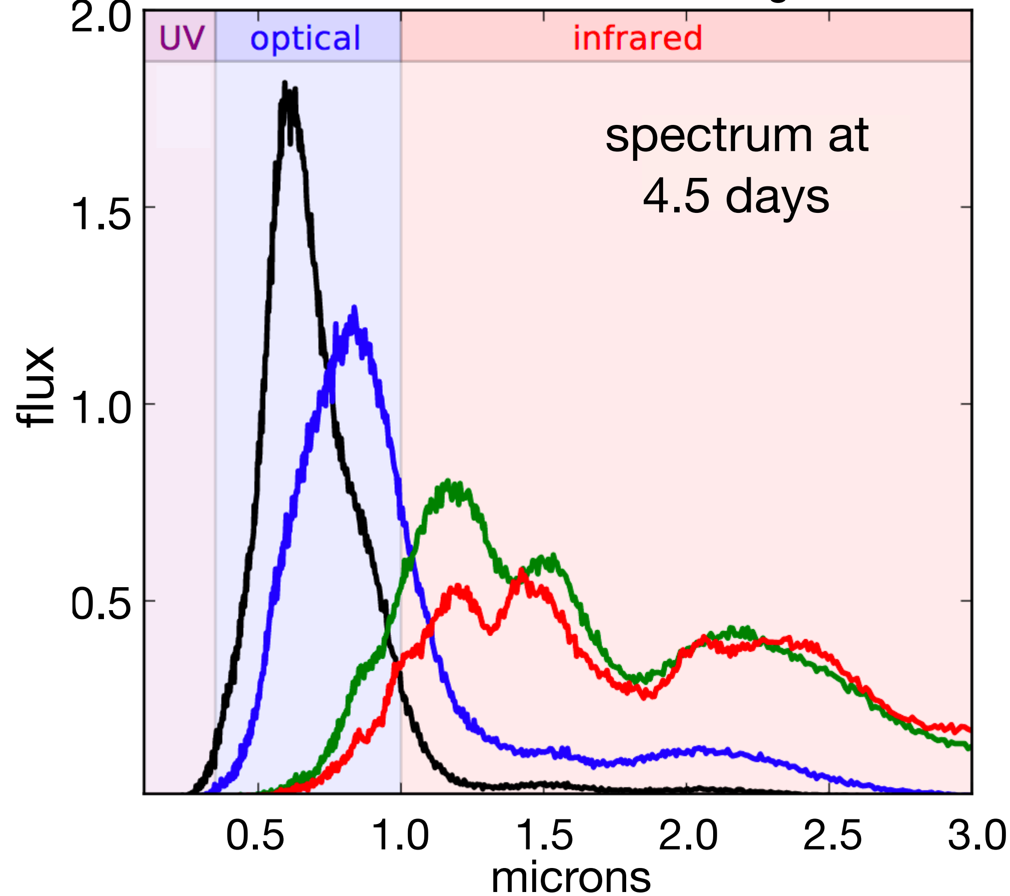
higher opacities ⟶ longer, dimmer, redder light curves

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

line blanketing at optical wavelengths

Kasen, Metzger, **JB**+17





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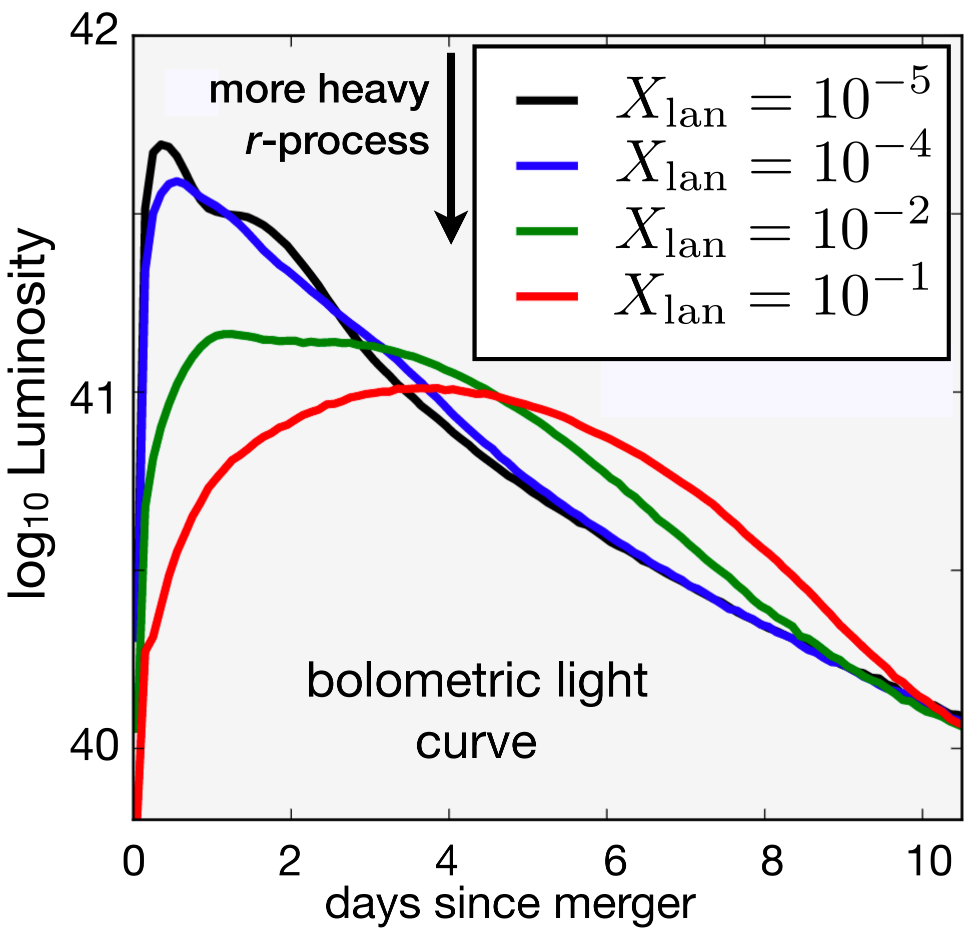
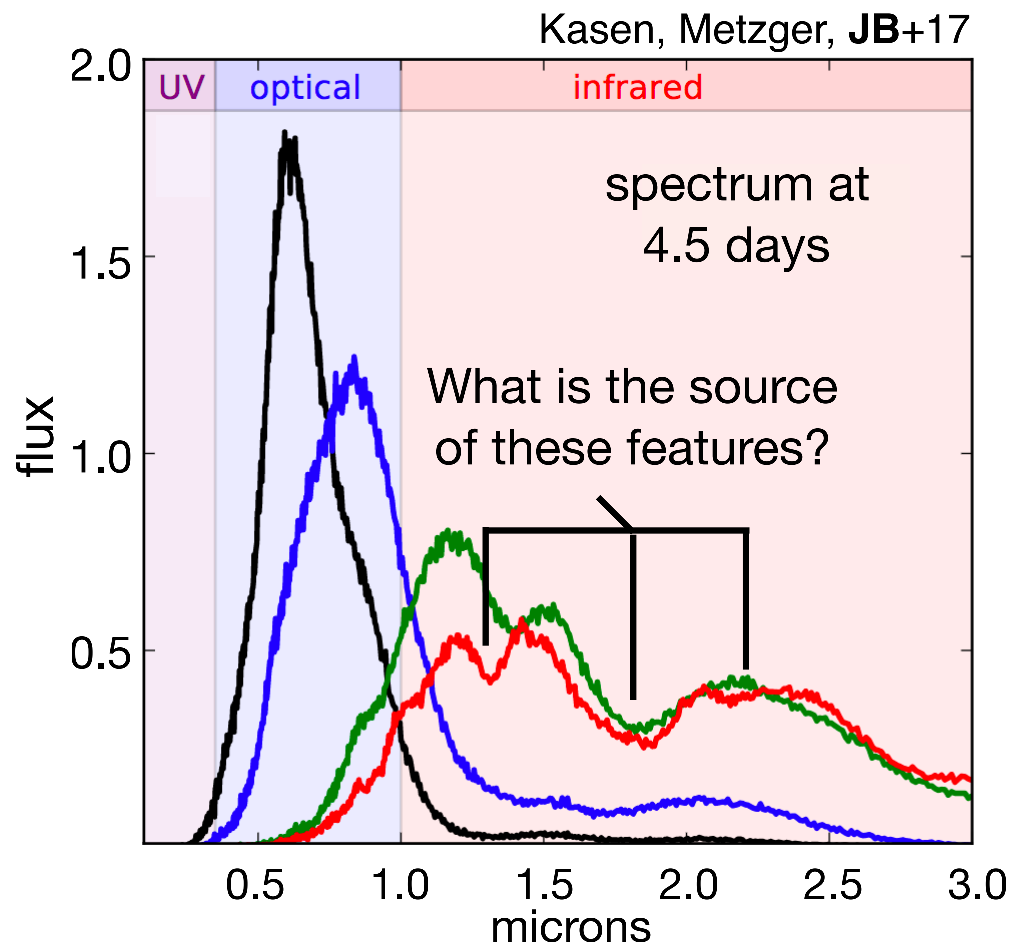
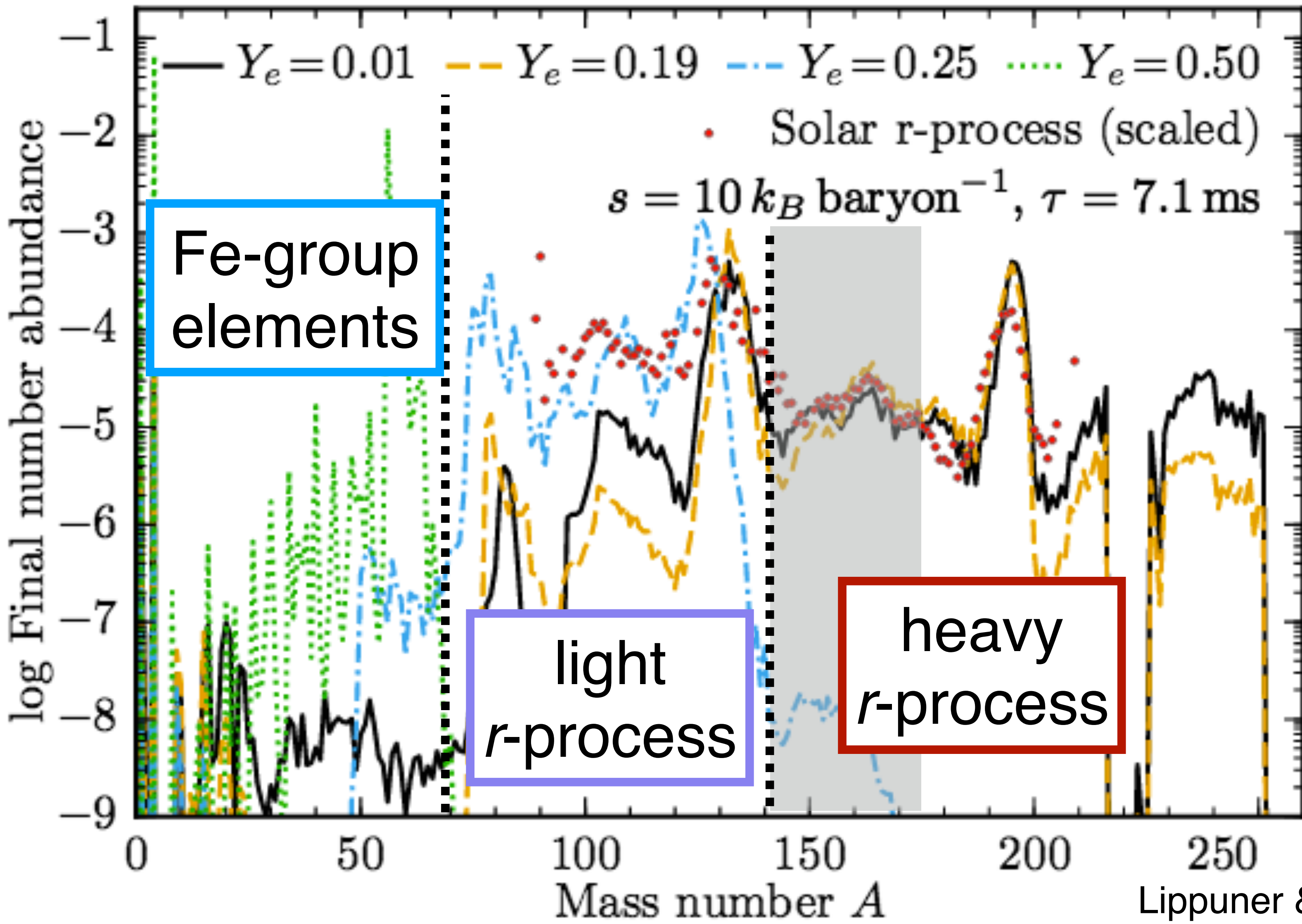




Kilonova composition and opacity

Outcomes of the *r*-process

fewer free n per seed ⟷ more free n per seed



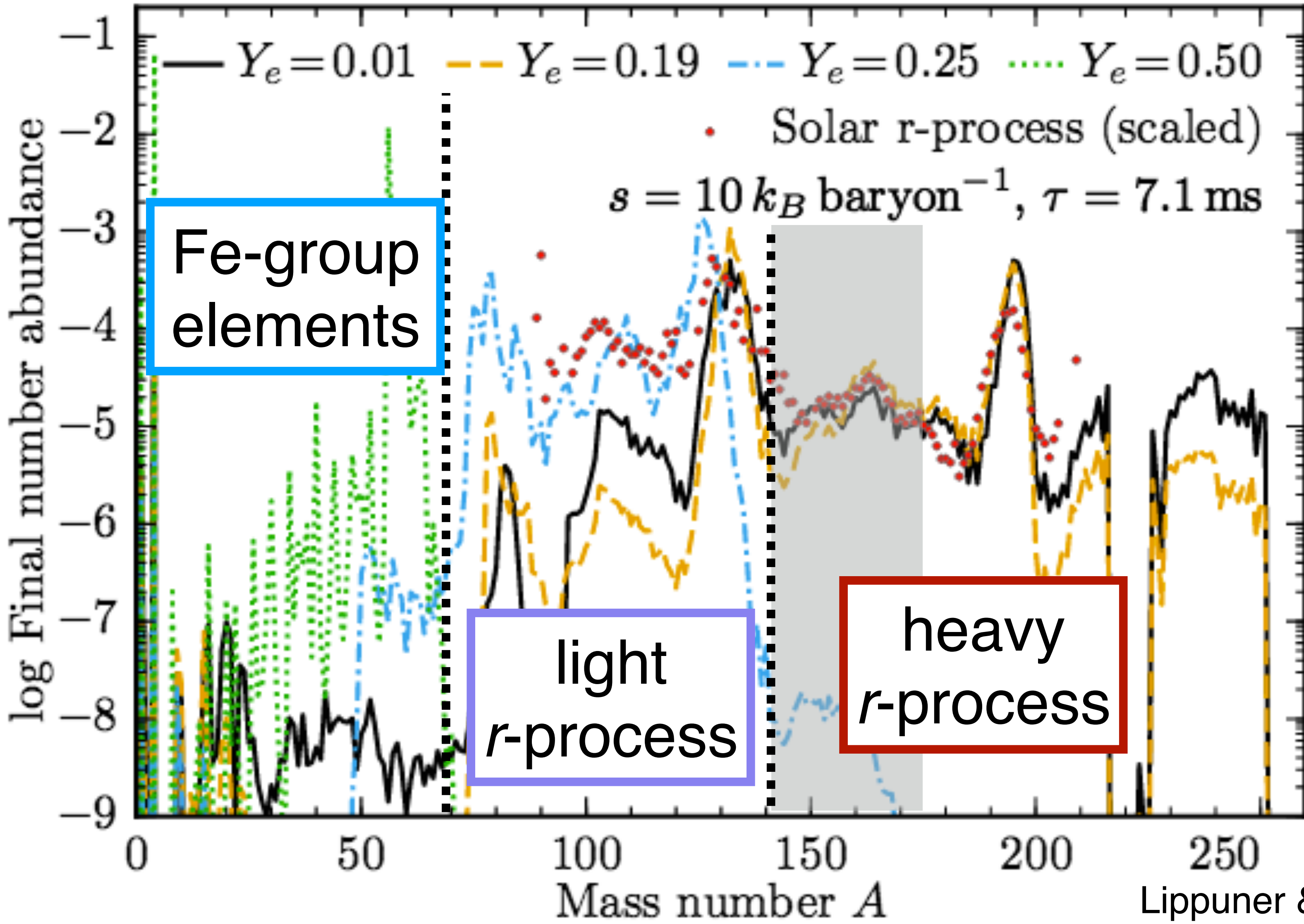
$$Y_\mathrm{e} = \frac{p}{p+n}$$

Lippuner & Roberts 2015

Kilonova composition and opacity

Outcomes of the *r*-process

fewer weak interactions ⟷ more weak interactions



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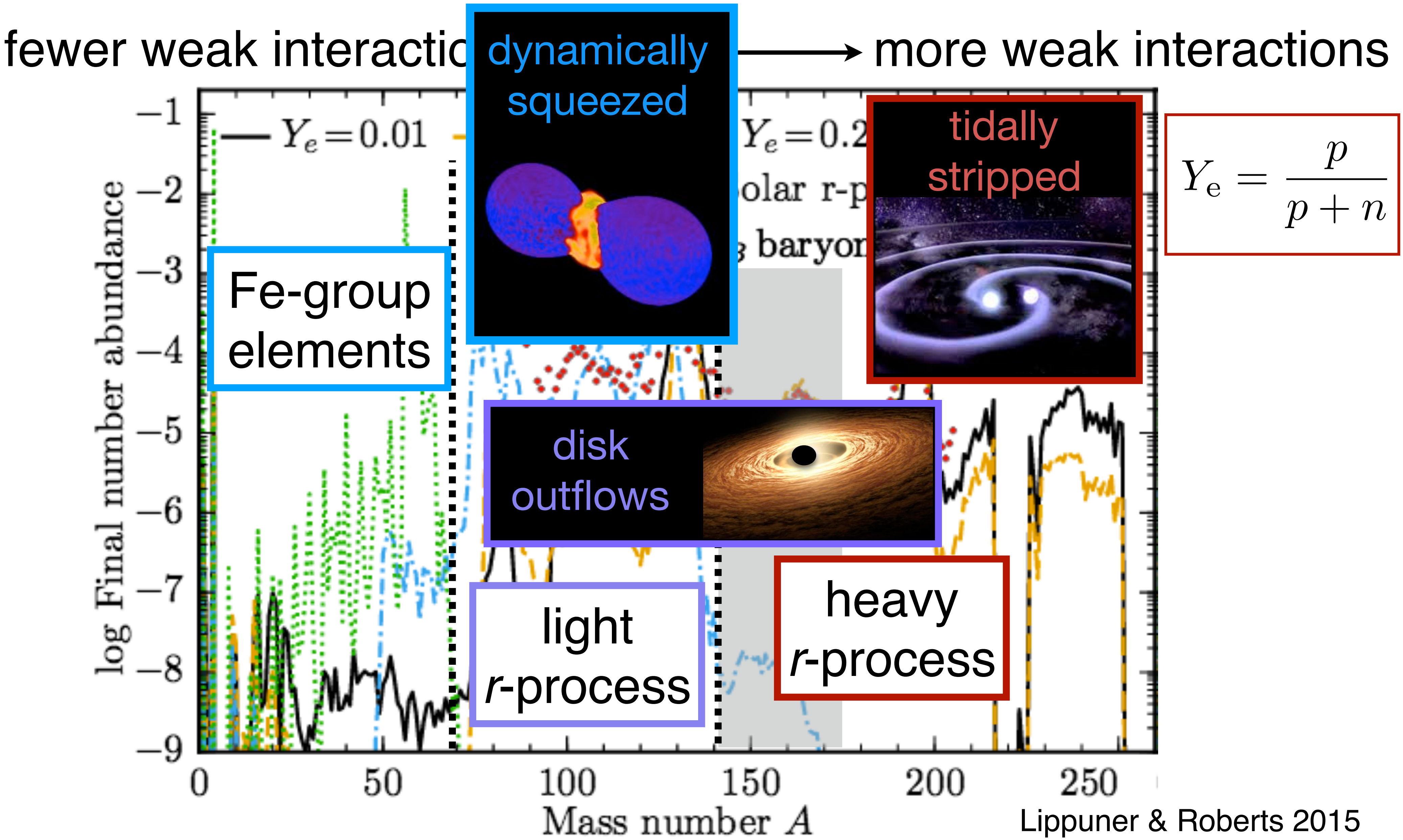
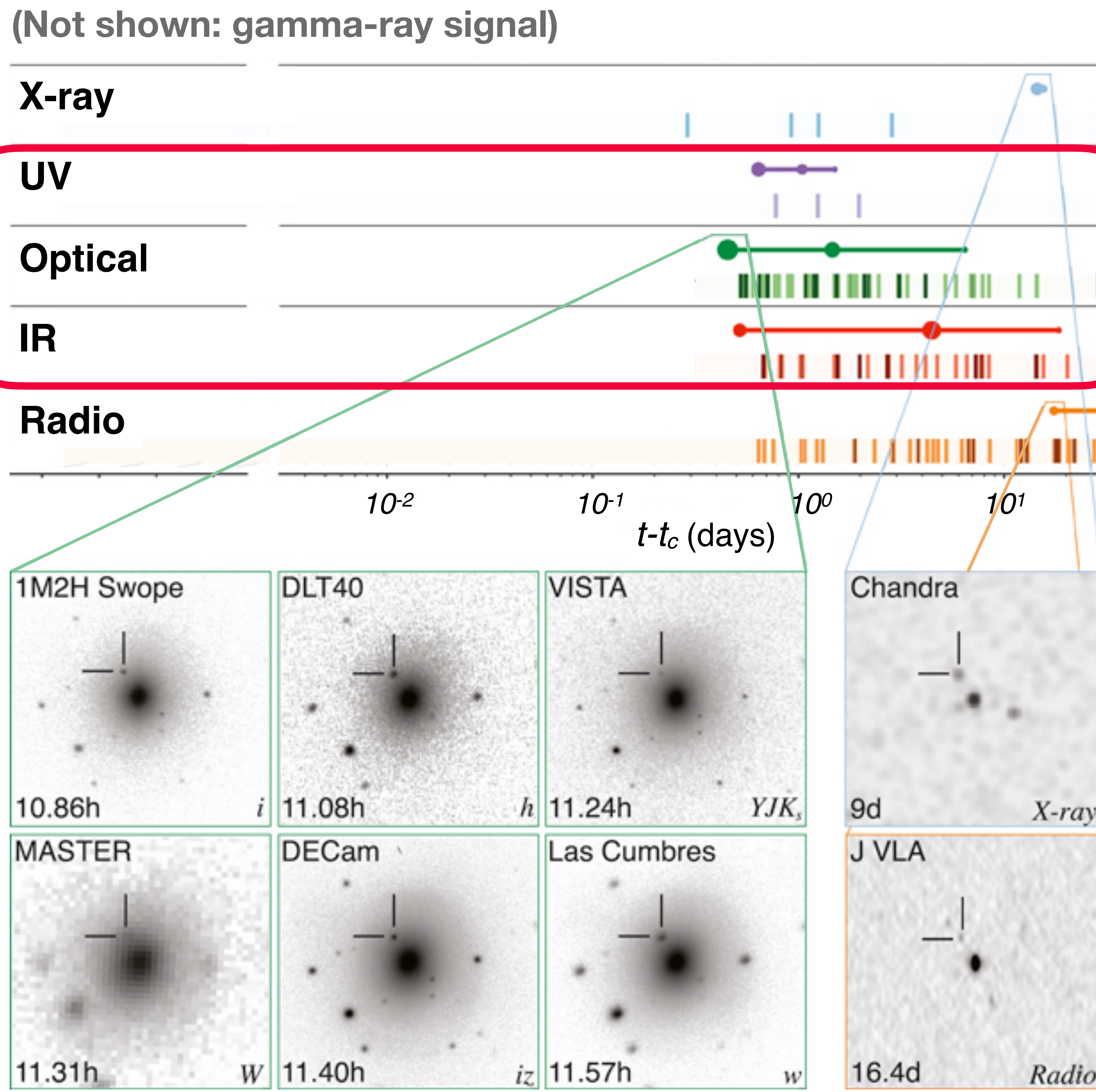
Outcomes of the *r*-process



Lippuner & Roberts 2015

Radioactive transient from dynamical ejecta and/or a disk wind.

transient source detected in galaxy NGC 4993



ad. from ALV + EM Partners 17

(Not shown: gamma-ray signal)

Radioactive
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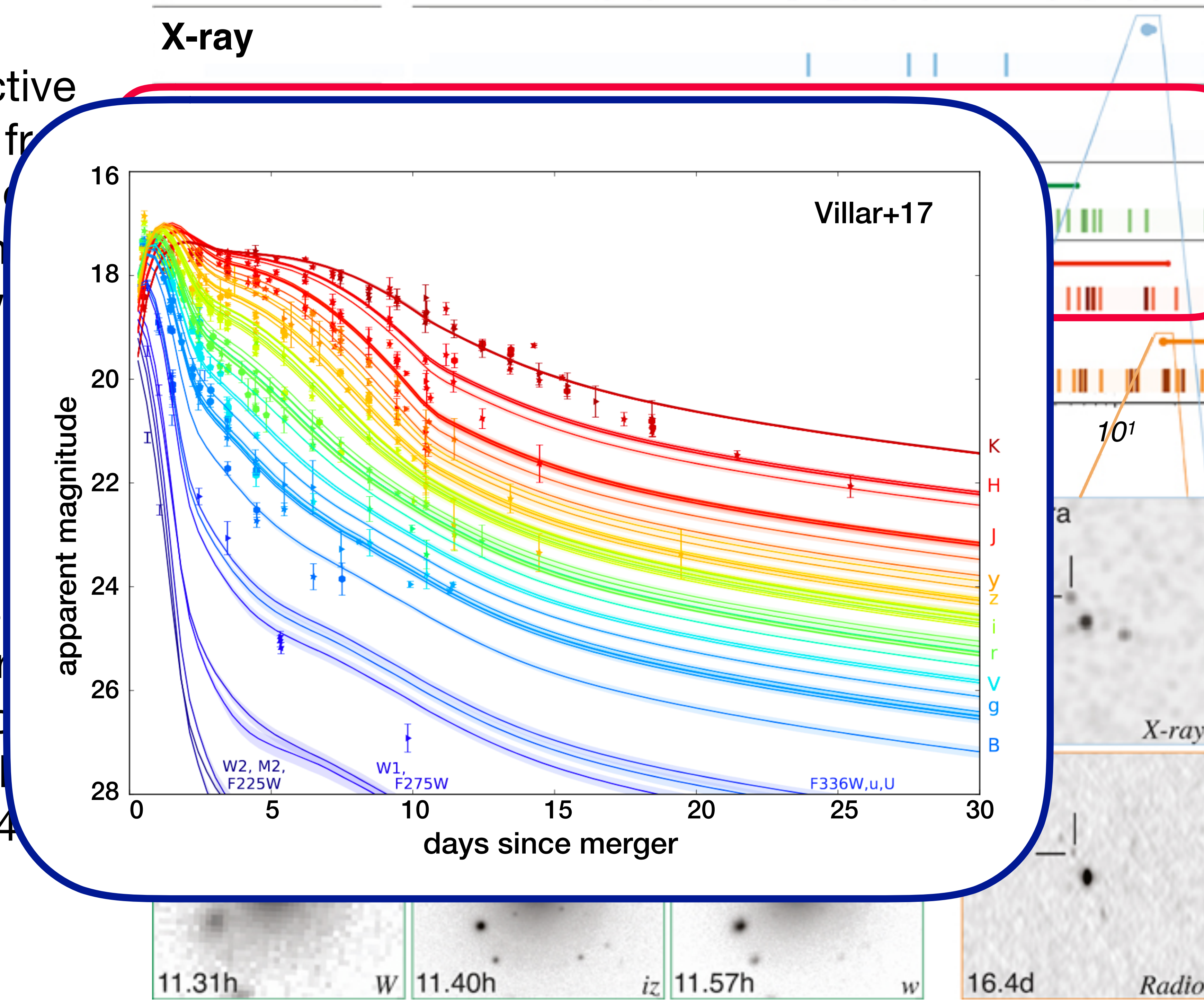


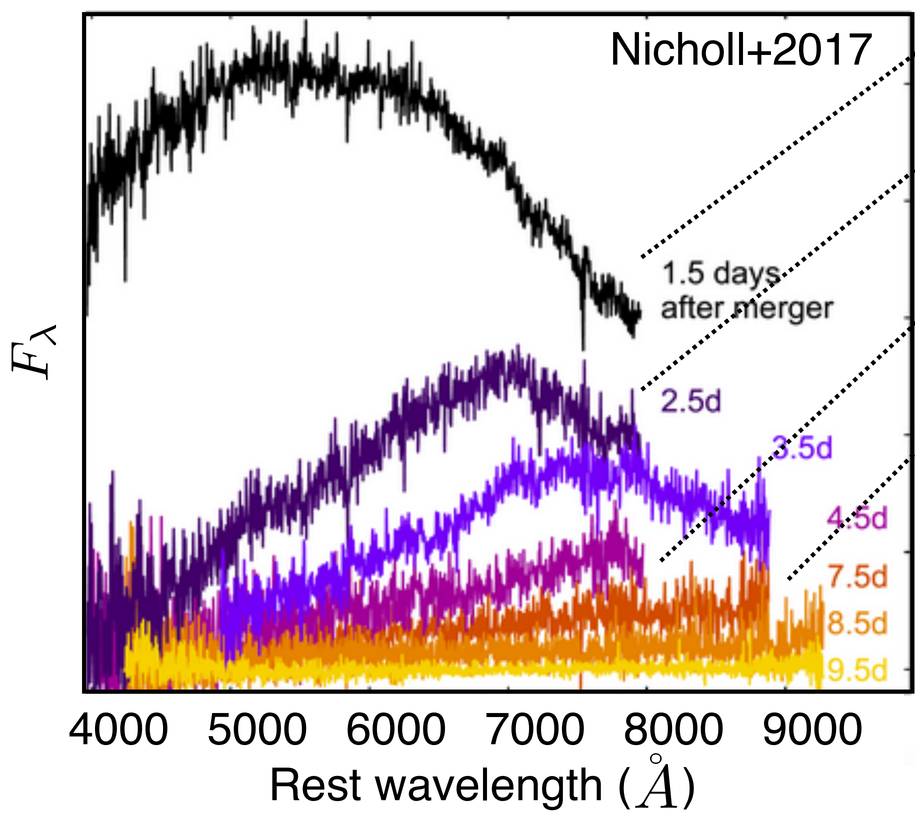
ad. from ALV + EM Partners 17

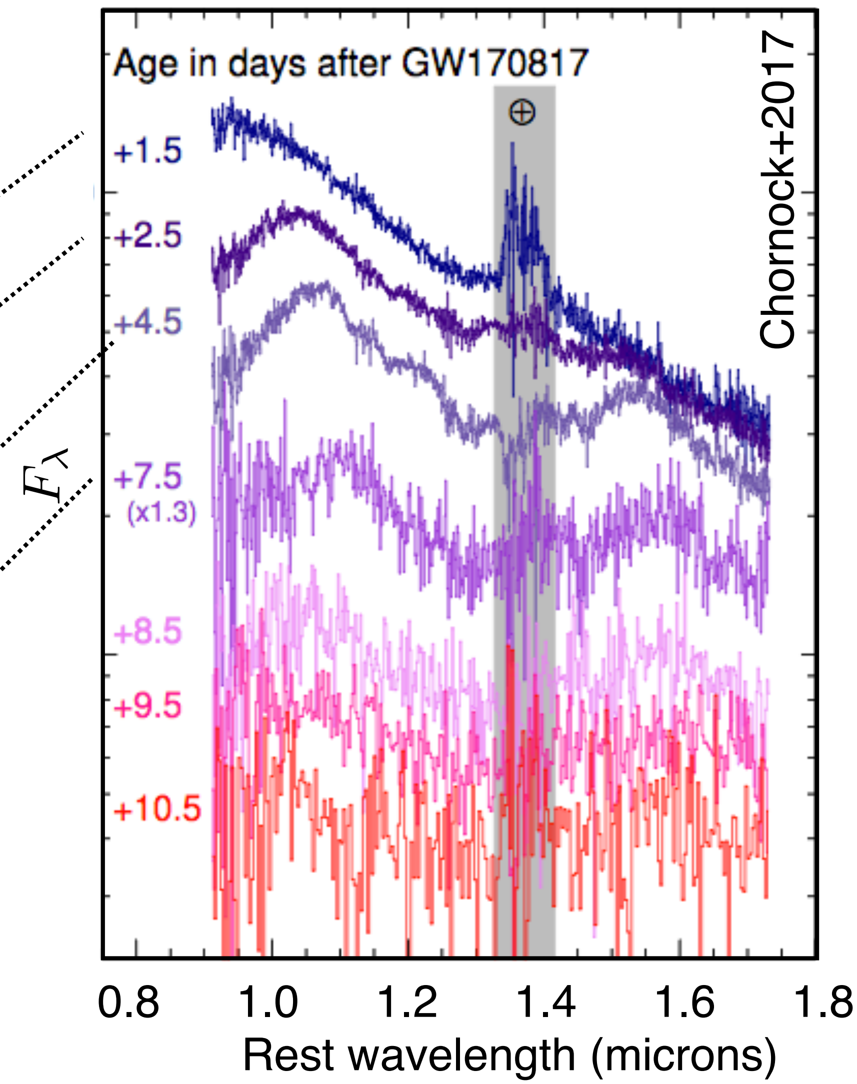
Interpreting the GW170817 kilonova

Spectra and ejecta structure

NIR: wide absorption features suggest slower velocities ~0.1 c

UV/optical: strong line-blending indicates high velocities ~0.3c





Interpreting the GW170817 kilonova

Spectra and ejecta structure

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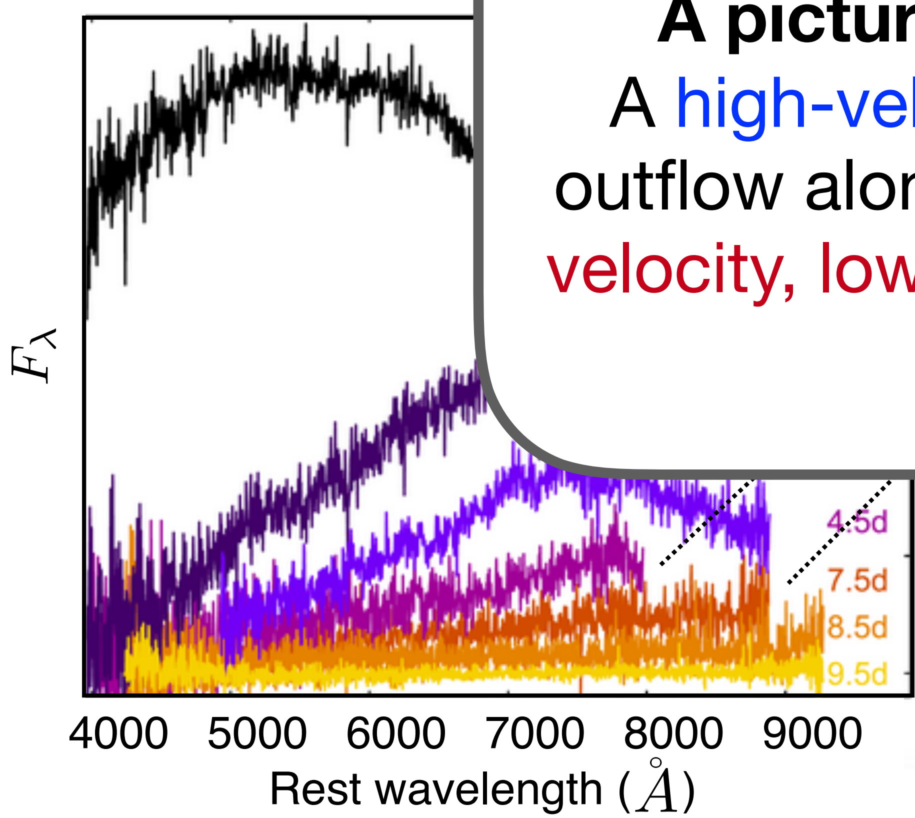
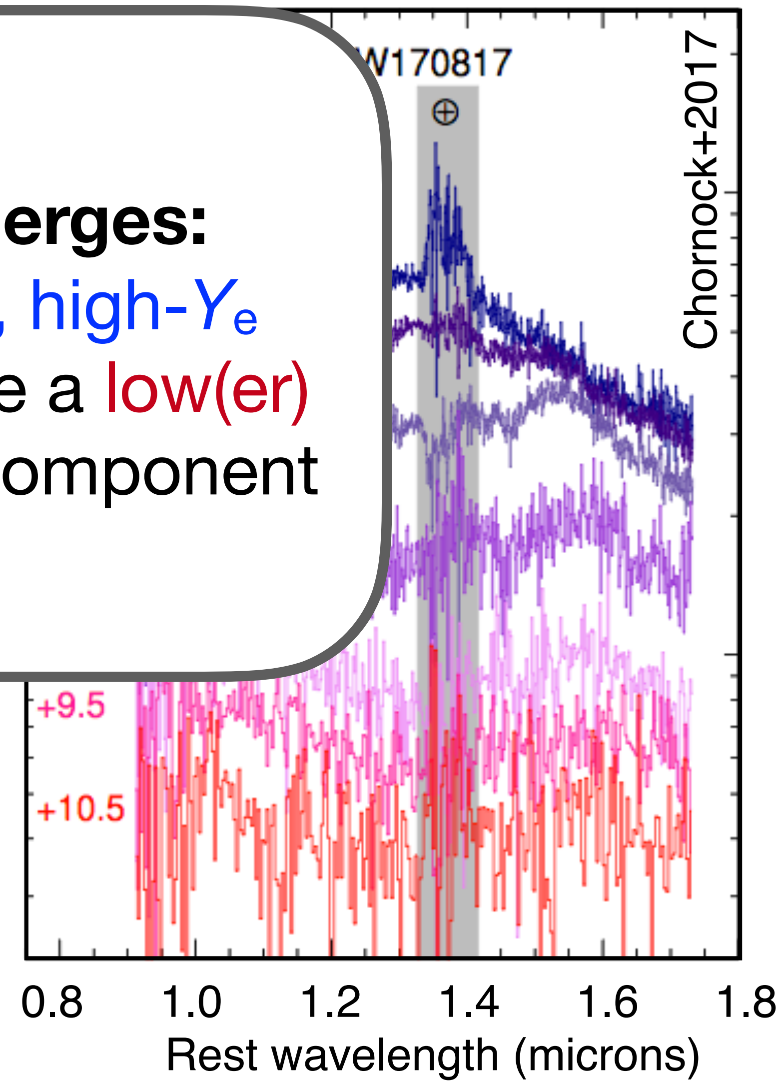
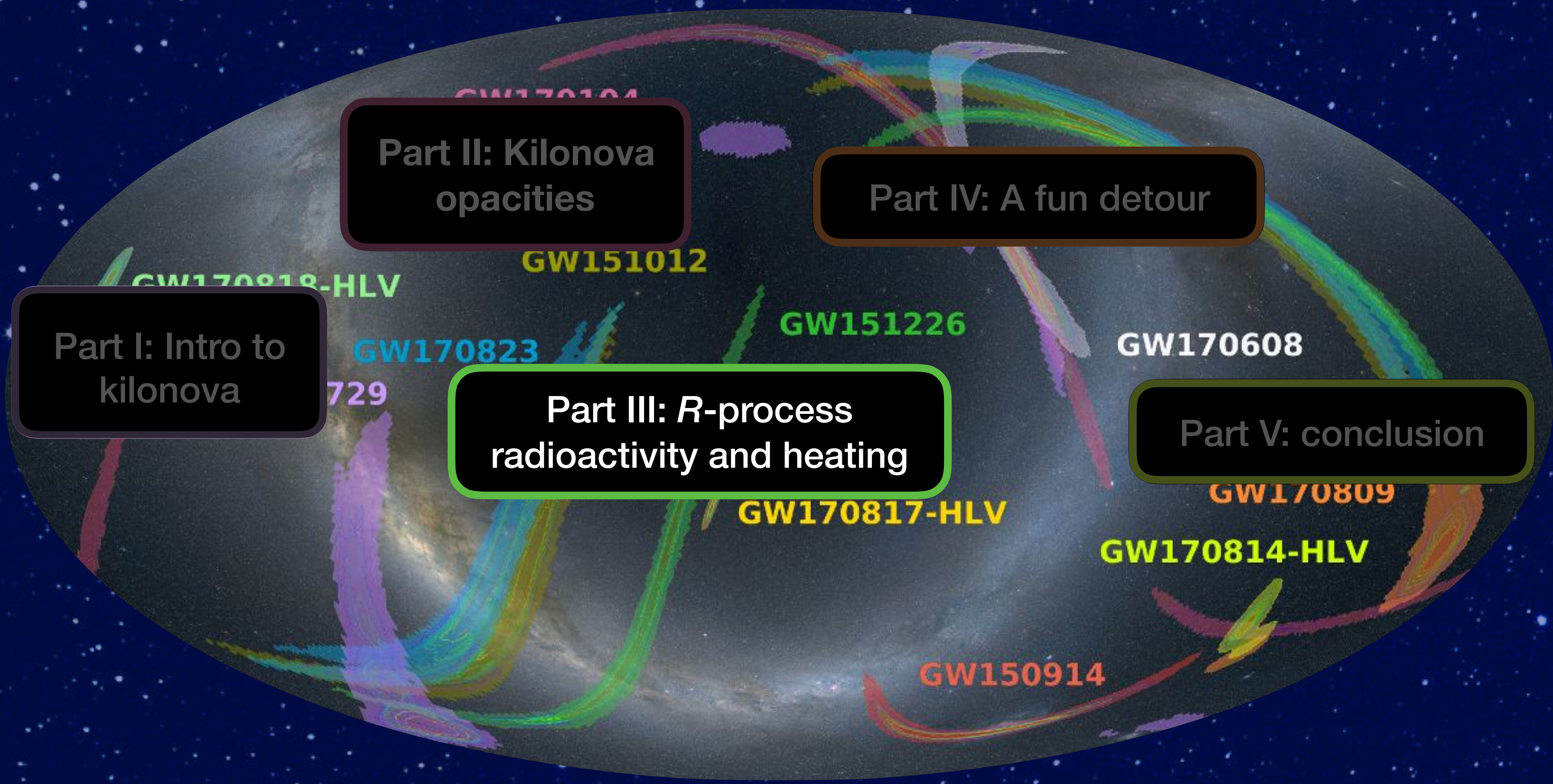
UV/optical: stron
indicates high v



A picture emerges:
A high-velocity, high-Y_e outflow alongside a low(er) velocity, low-Y_e component





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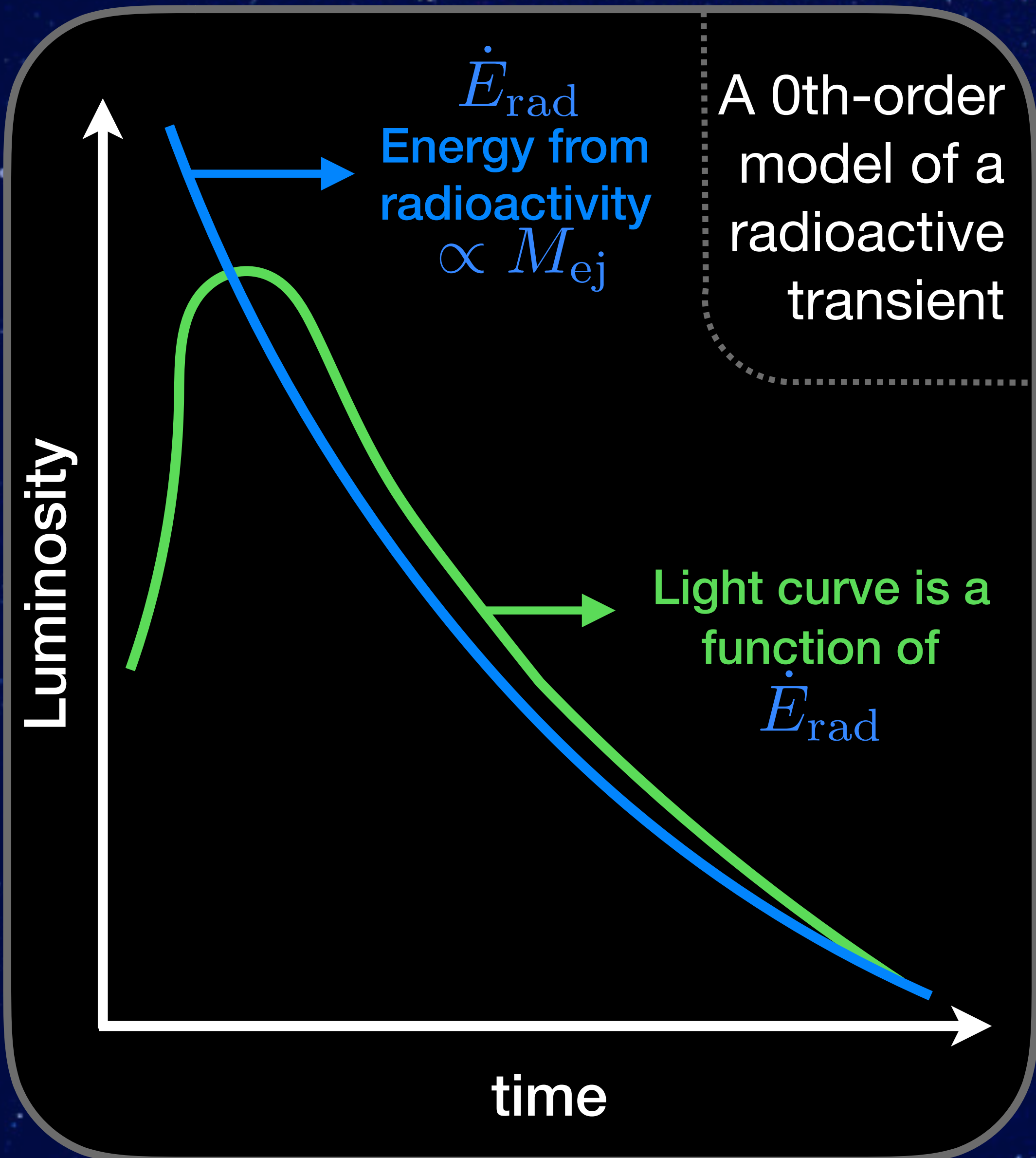
Kilonova heating and luminosity



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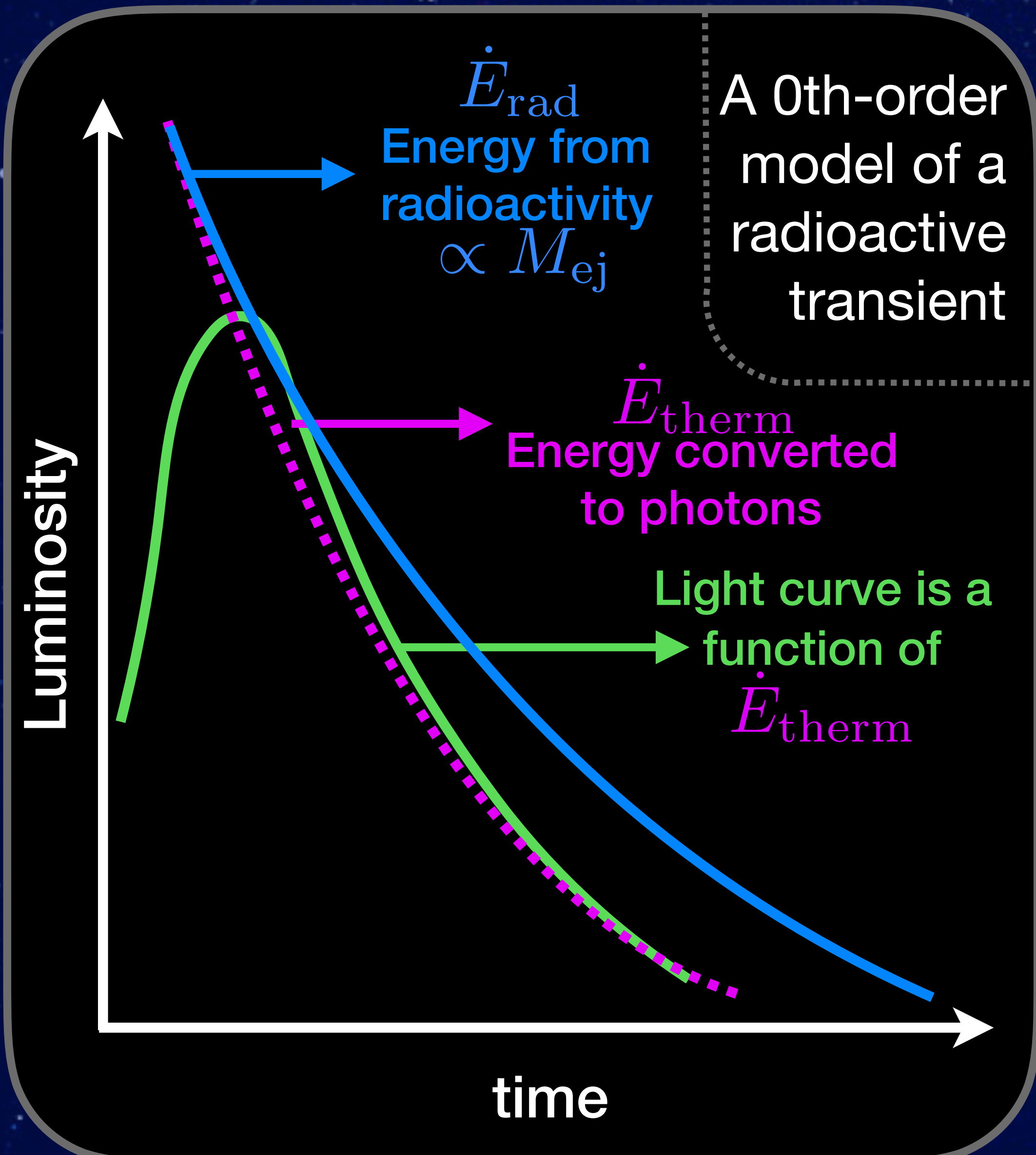

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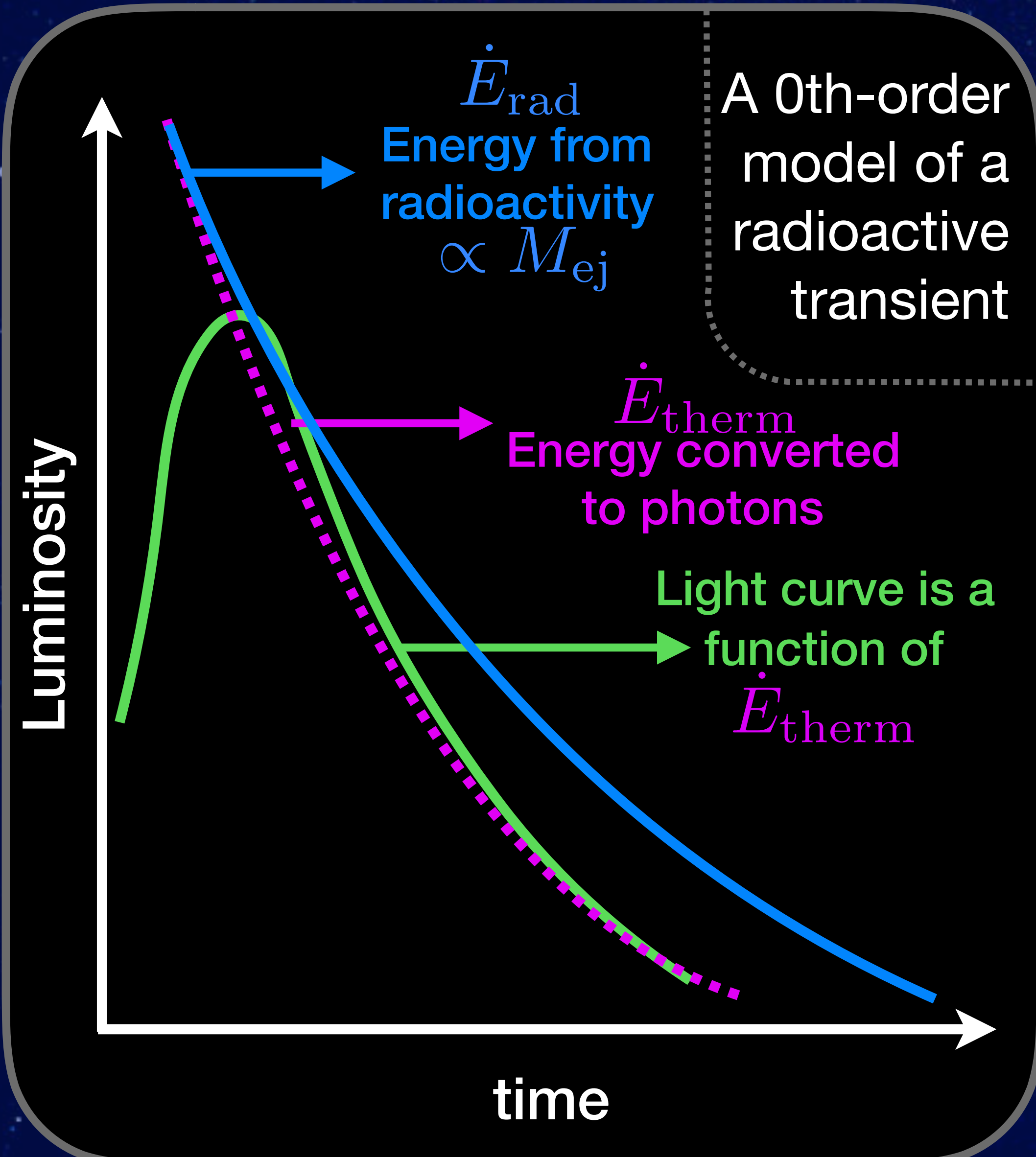
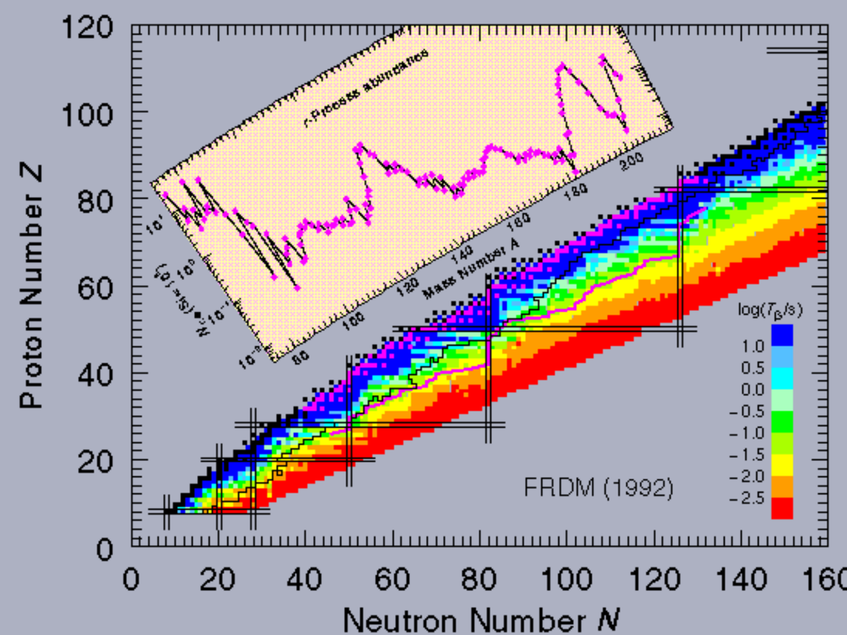




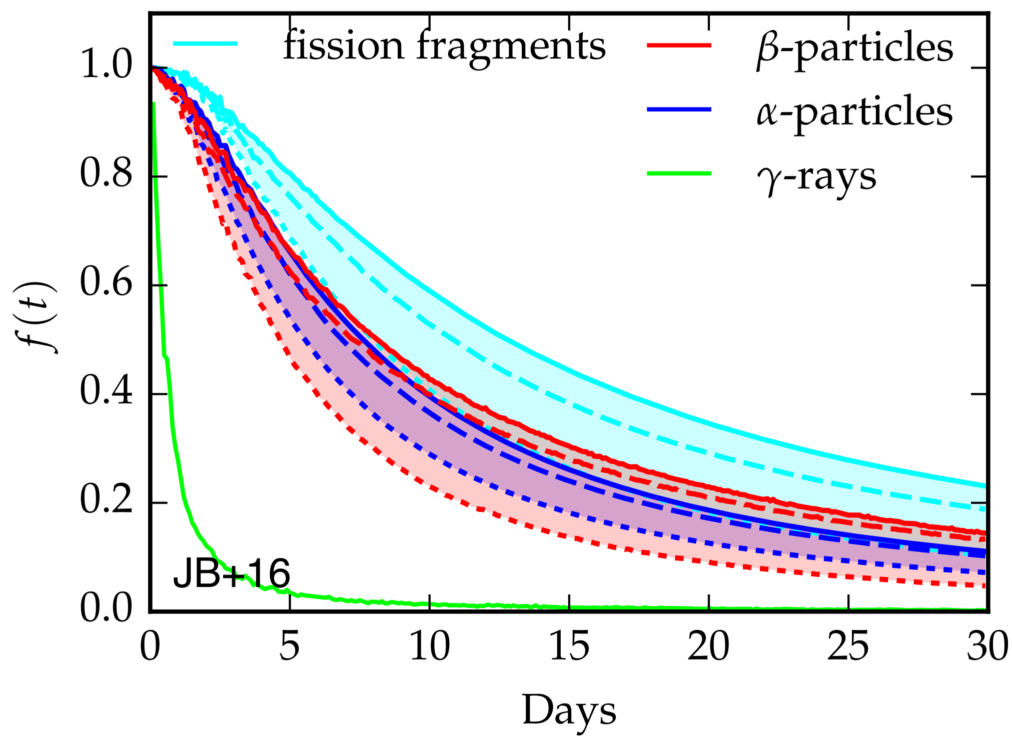
R-process radioactivity involves many decays with different time and energy scales

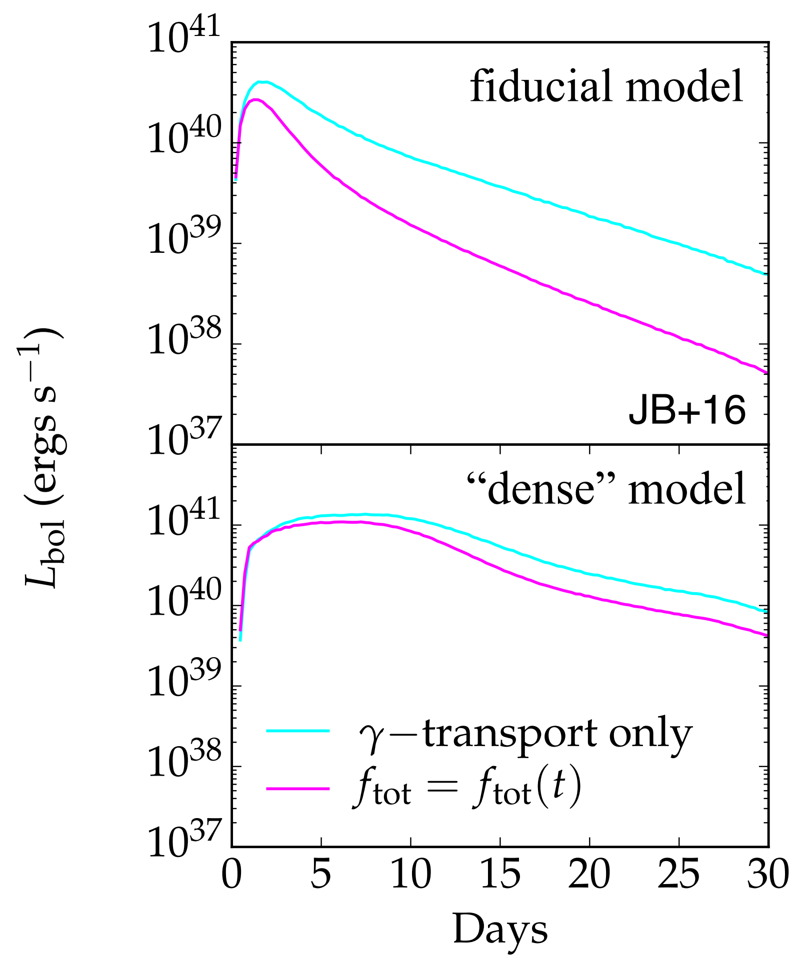
Kilonova heating and luminosity

The effect on light curves

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

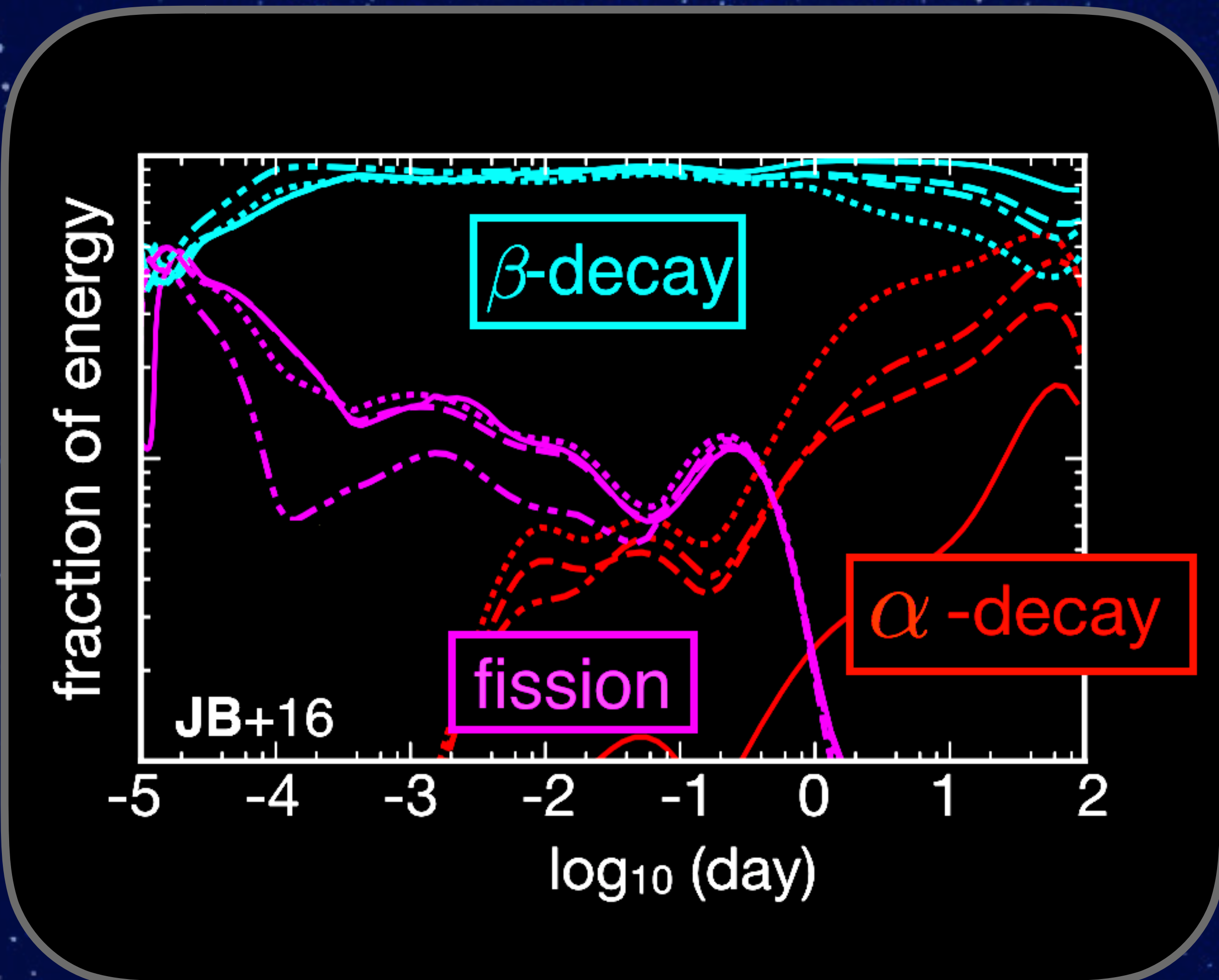
Thermalization efficiency for each decay product (fiducial model)





Kilonova heating and luminosity

The role of a given decay/channel is highly variable



R-process radioactivity depends on **initial conditions** and on **nuclear physics far from stability**

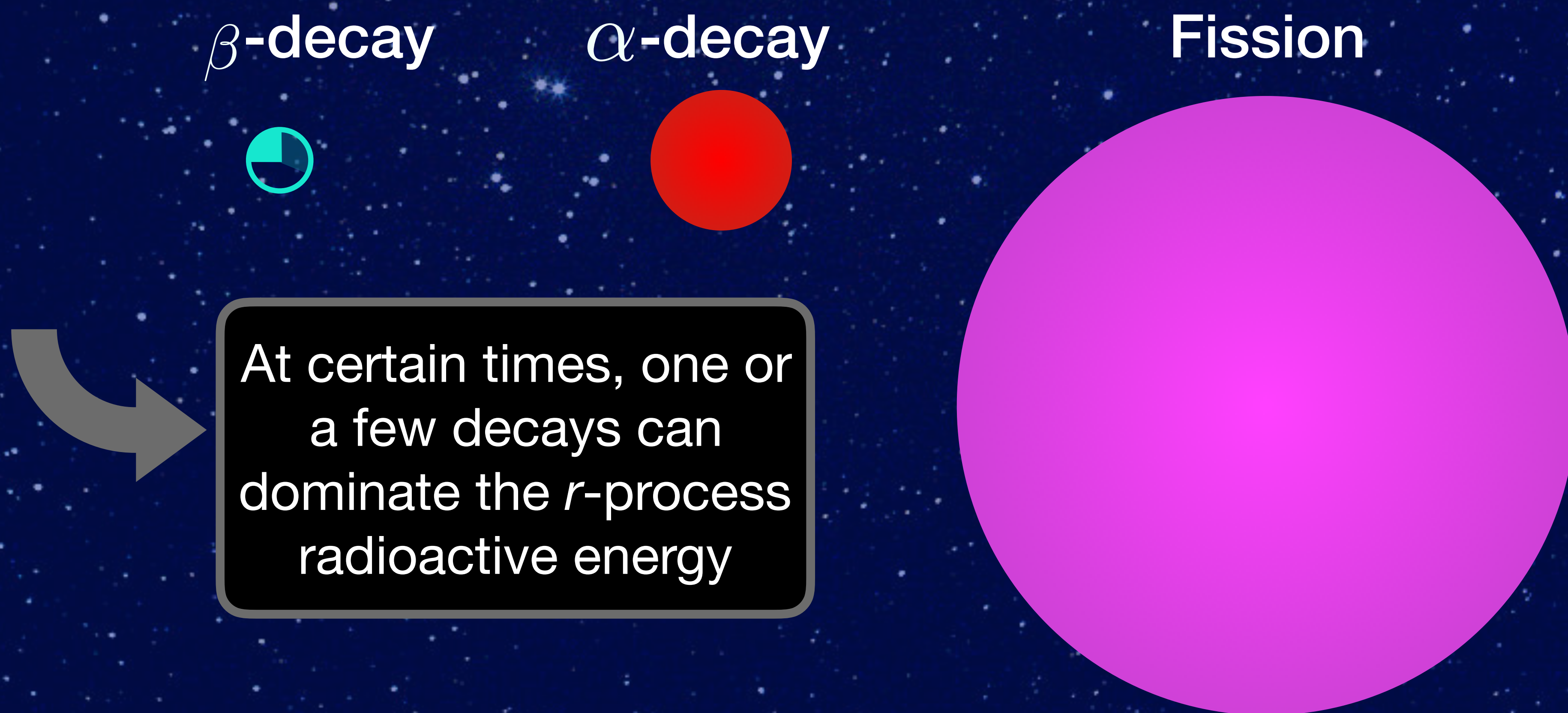
↓

Varying these will vary $L_{\rm bol}$

Kilonova heating and luminosity

Effect of decay channel

Decay channels with higher characteristic energies have higher cross-sections for energy loss



Kilonova heating and luminosity

The importance of individual nuclei

Ensemble *r*-process heating

$$\dot{n}(t) \propto t^{-1}$$

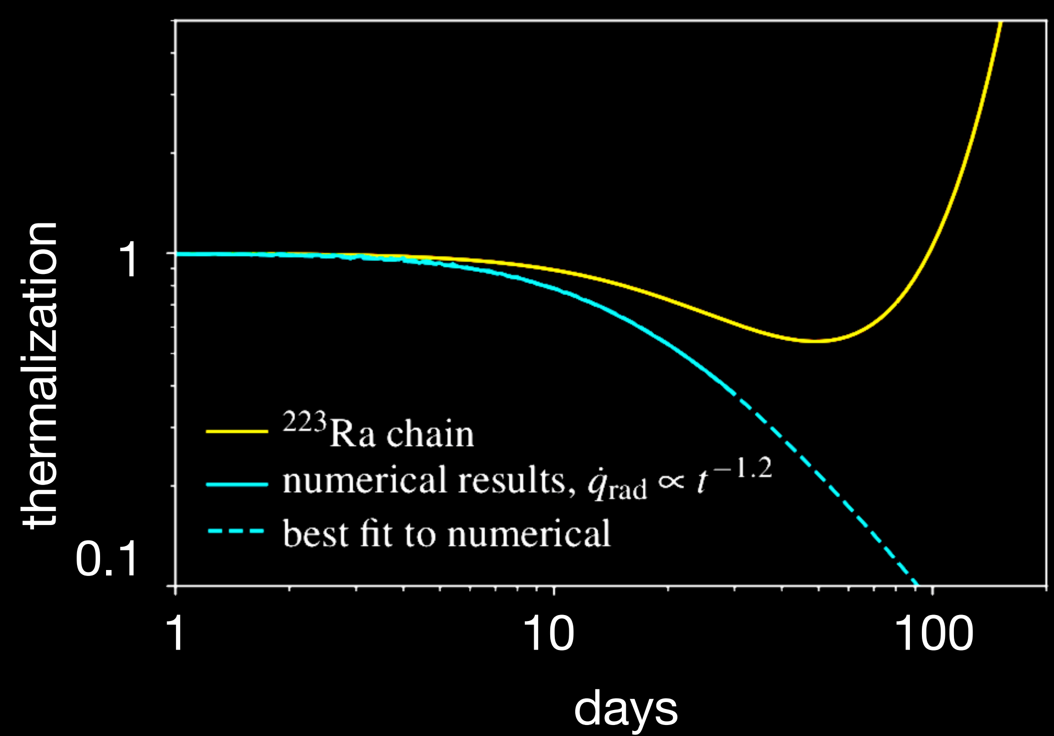
$$\epsilon_0(t) \propto t^{-1/3}$$

Single isotope heating

$$\dot{n}(t) \propto \exp[-t/\tau]$$

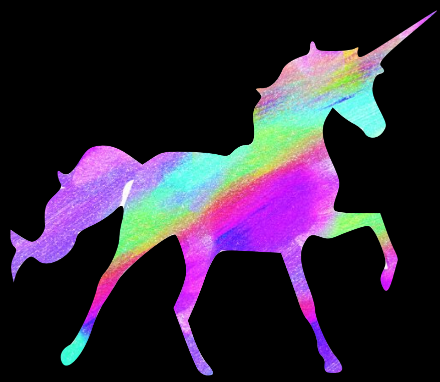
$$\epsilon_0 \neq \epsilon_0(\tau)$$

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}\tau} = -\frac{-2\epsilon}{\tau} - \frac{\epsilon^{-1/2}}{\tau^3}$$

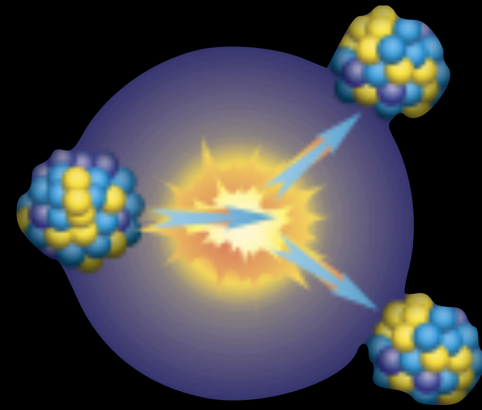


See Kasen & JB 19; Wu, JB+19

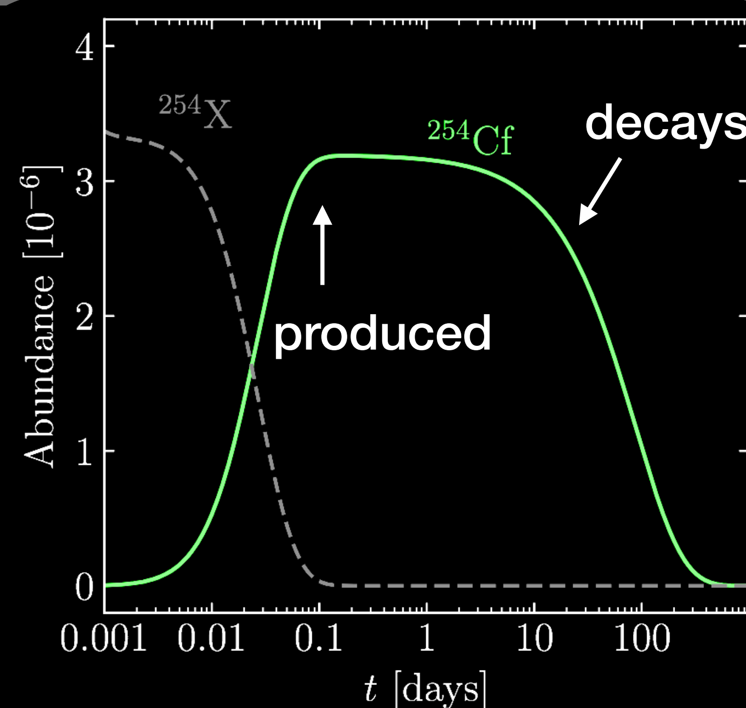
Case Study I: Californium Dreaming



Cf-254 fissions with a half-life τ~60.5 days, releasing a tremendous amount of energy



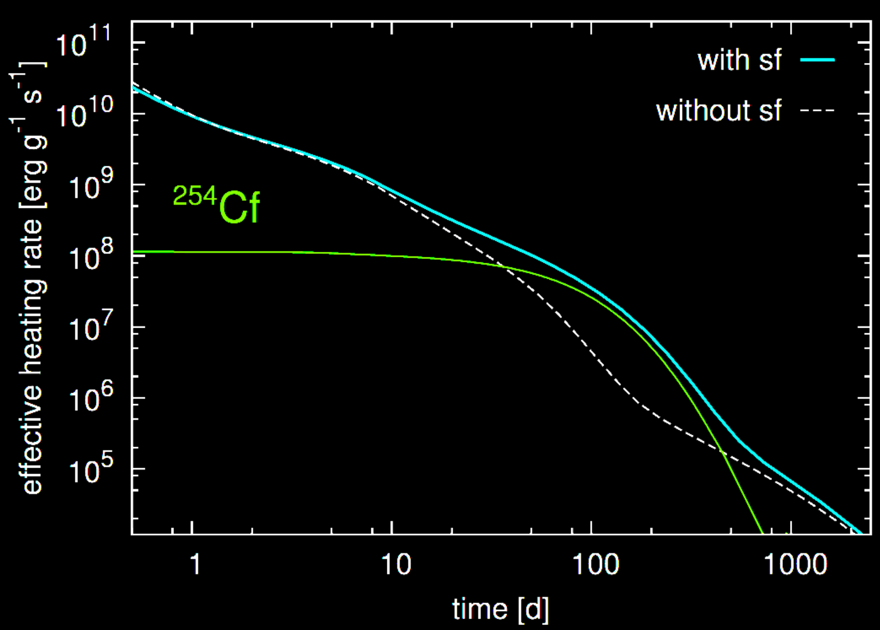
The role of fission in the *r*-process is highly uncertain, but Zhu+18 find Cf-254 is produced by β-feeders in the A=254 isobaric chain on timescales of ~0.1 days



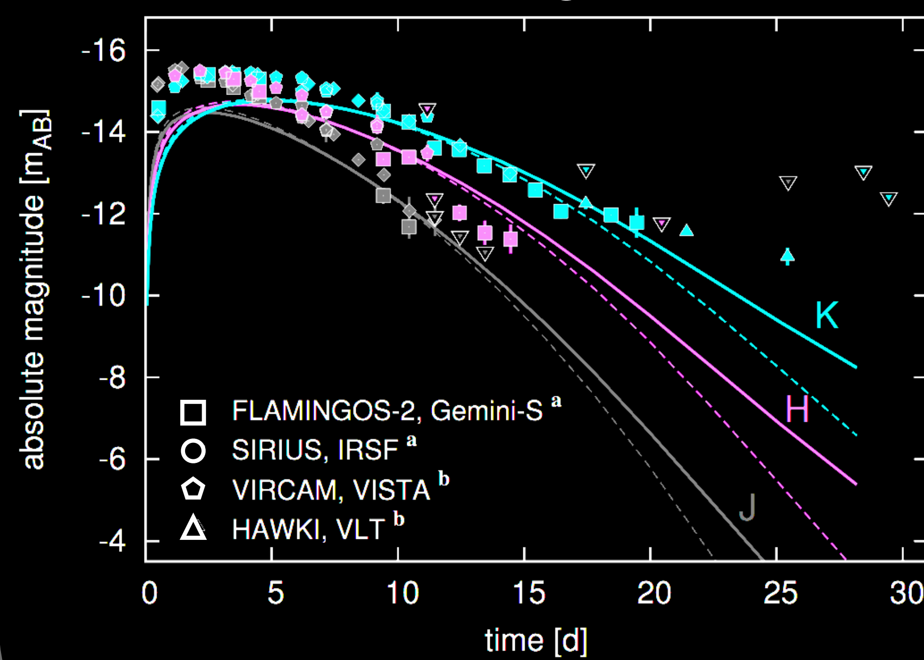
Case Study I: Californium Dreaming

Cf-254 can dominate heating and affect luminosity

Effective heating



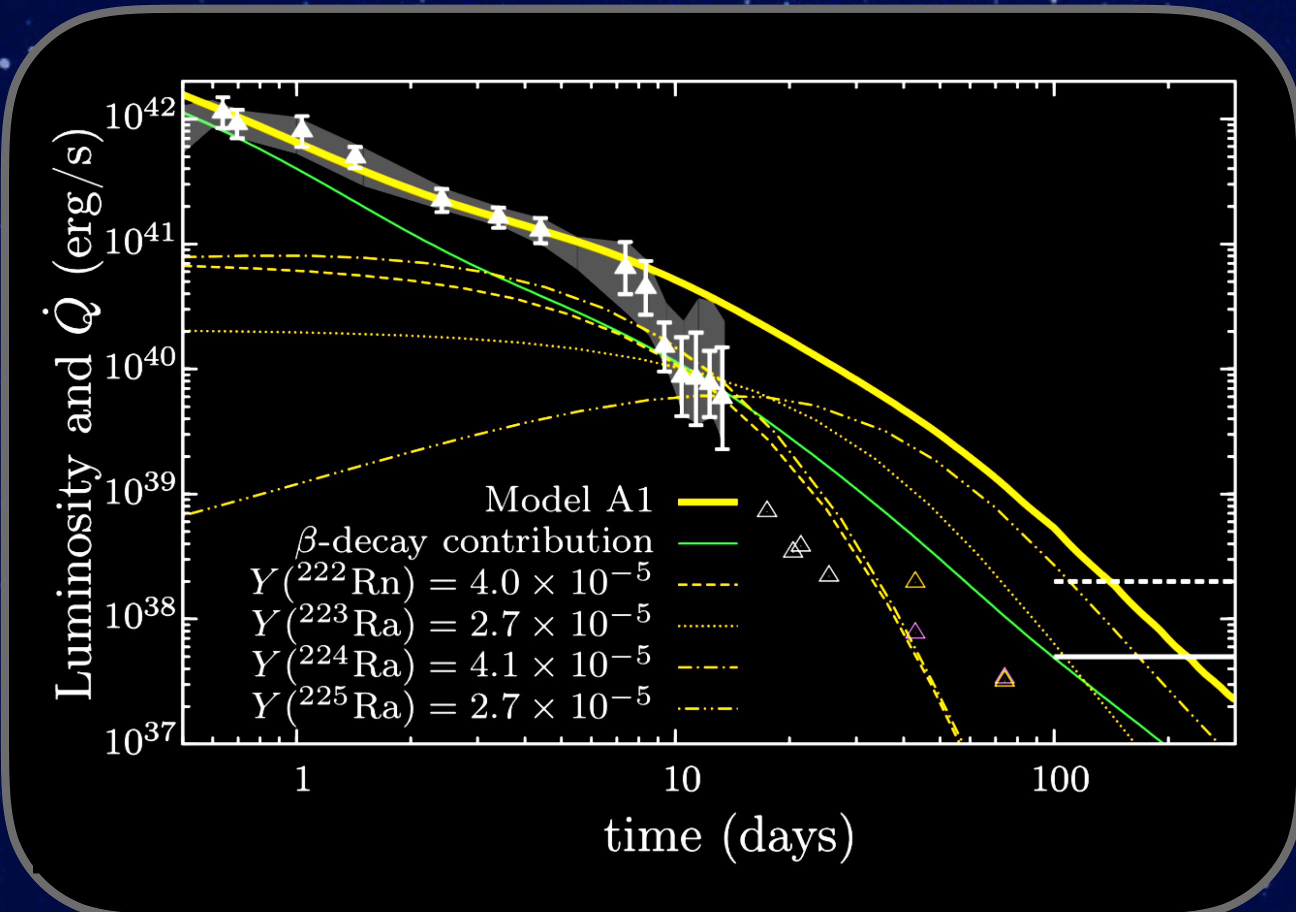
Broadband Light Curves



Zhu…JB+ 18

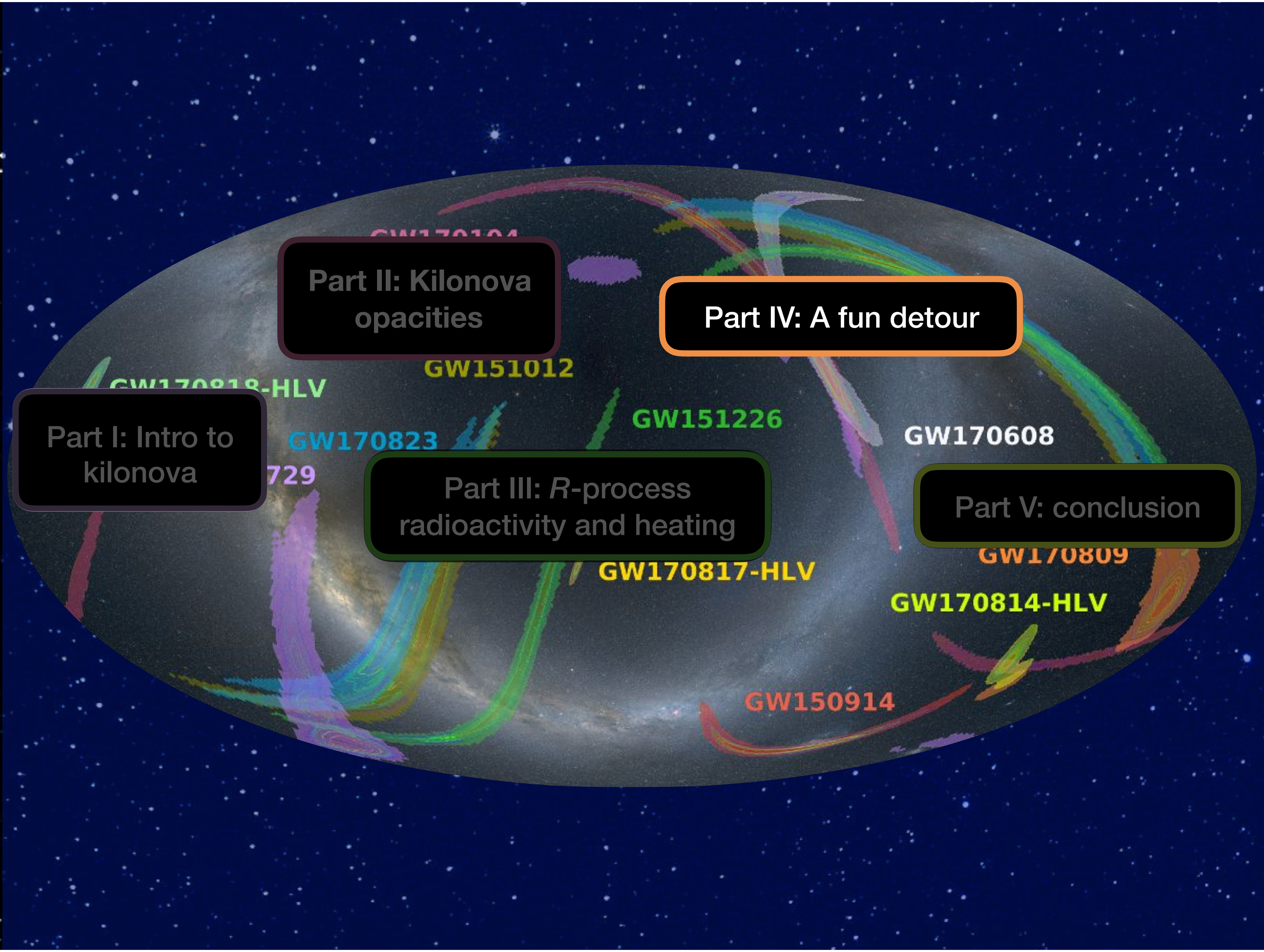
Case Study II: α-decaying actinides

Can long-lived actinides impact the bolometric luminosity?



- Find nuclear heating rates consistent with measured luminosity of AT1017gfo
- Resolve late-time alpha decays individually to predict late-time bolometric luminosity

Wu,JB+ 19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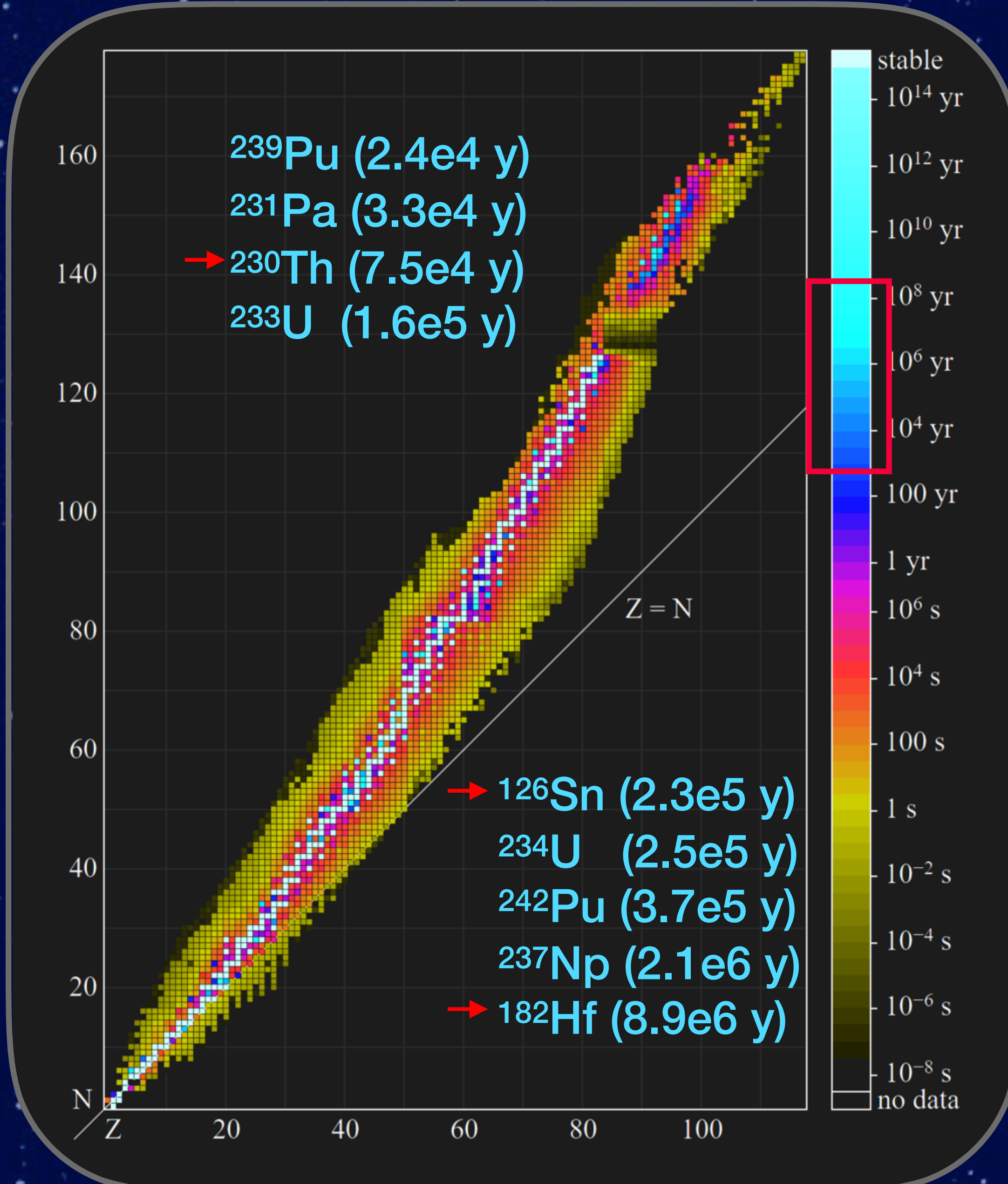
Can we find the last *galactic* NSM?

- Estimated present-day merger rate: 10 - 100 per Myr

→ The most recent mergers took place 10^4 - 10^5 year ago

- There are *r*-process nuclei with $\tau_{1/2} \approx$ the age of the last galactic NSM



Wu, Bannerjee…JB+19

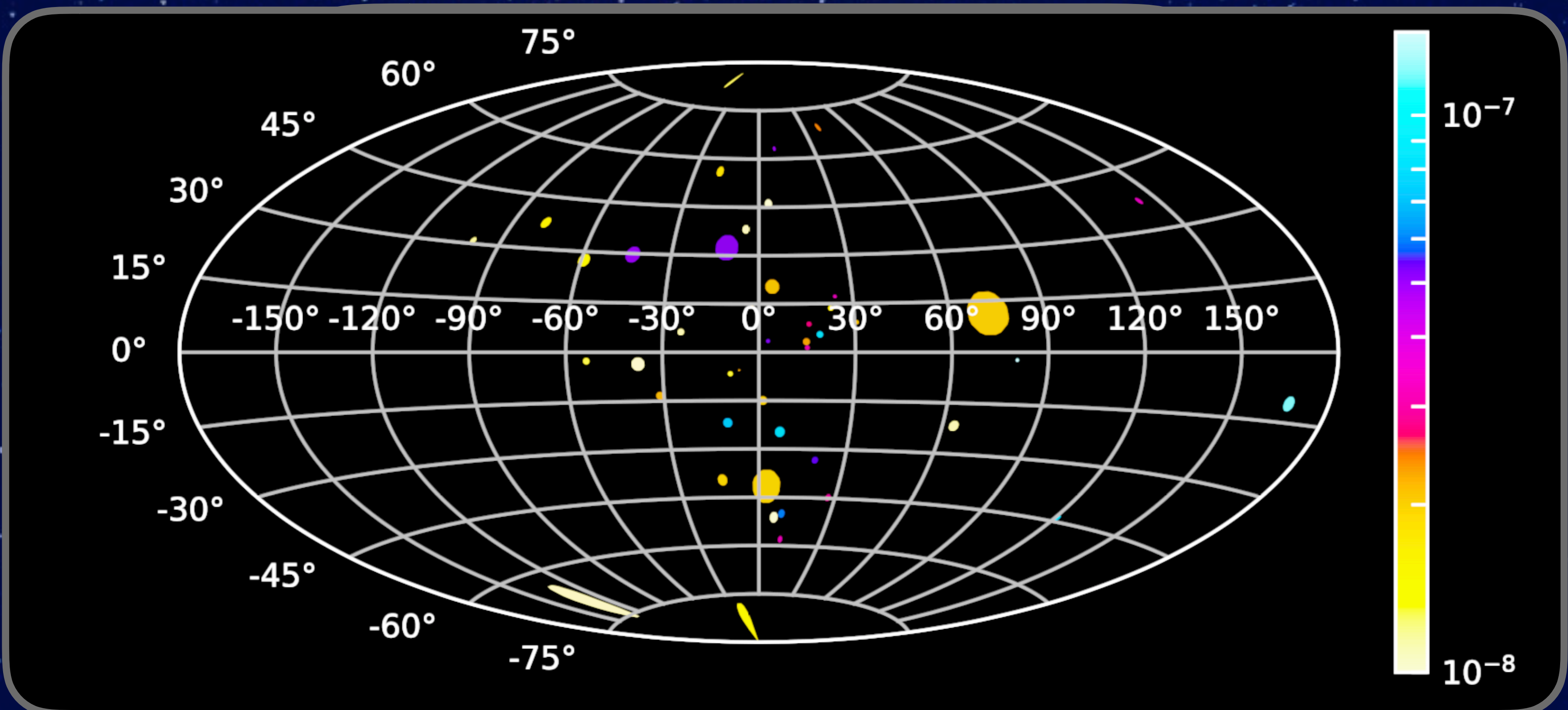
See also: Qian 98,99; Ripley+14

Can we find the last *galactic* NSM?

Assumptions of the model:

- Binary NS birth places trace stellar mass
- Binary NS systems acquire substantial kick velocities
- Rate: 10 Myr^{-1} or 100 Myr^{-1}

Individual sources



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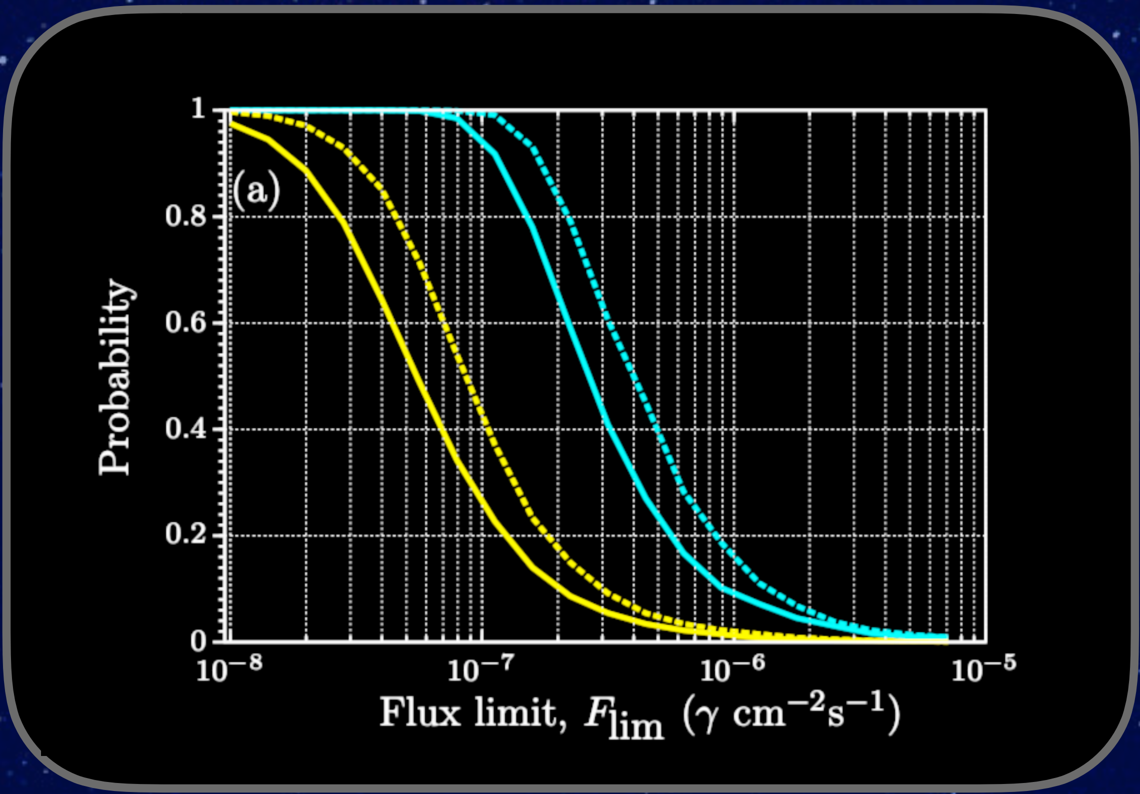
- Rate: 10 Myr^{-1} or 100 Myr^{-1}

Individual sources



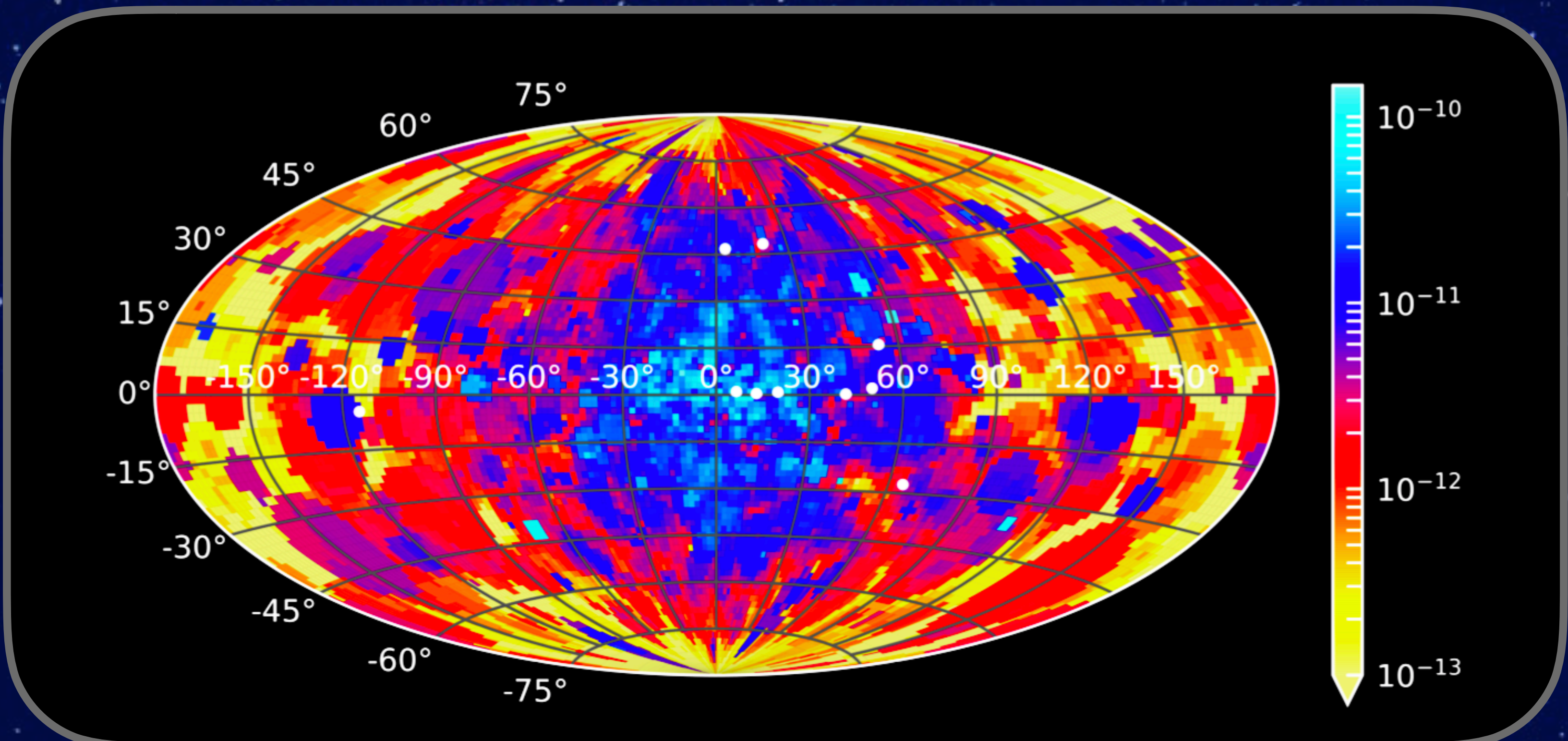
Wu, Bannerjee…JB+19

Can we find the last *galactic* NSM?

Assumptions of the model:

- Binary NS birth places trace stellar mass
- Binary NS systems acquire substantial kick velocities
- Rate: 10 Myr^{-1} or 100 Myr^{-1}

Diffuse sources (^{182}Hf)



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Summary & Conclusions

- Kilonova observations can help us understand merger-driven nucleosynthesis
  - This can reveal the mechanics of mass ejection and the fate of the central remnant
  - Can constrain sources of *r*-process material
- We need to develop more precise diagnostics of composition
  - Both spectra and light curves encode useful information
- We can look forward to the next nearby merger…but we can also look back to the last one.


Thank you!
Questions?