Astrophysics of gravitational wave sources

Lecture 3: Electromagnetic and multi-messenger signatures of the merger

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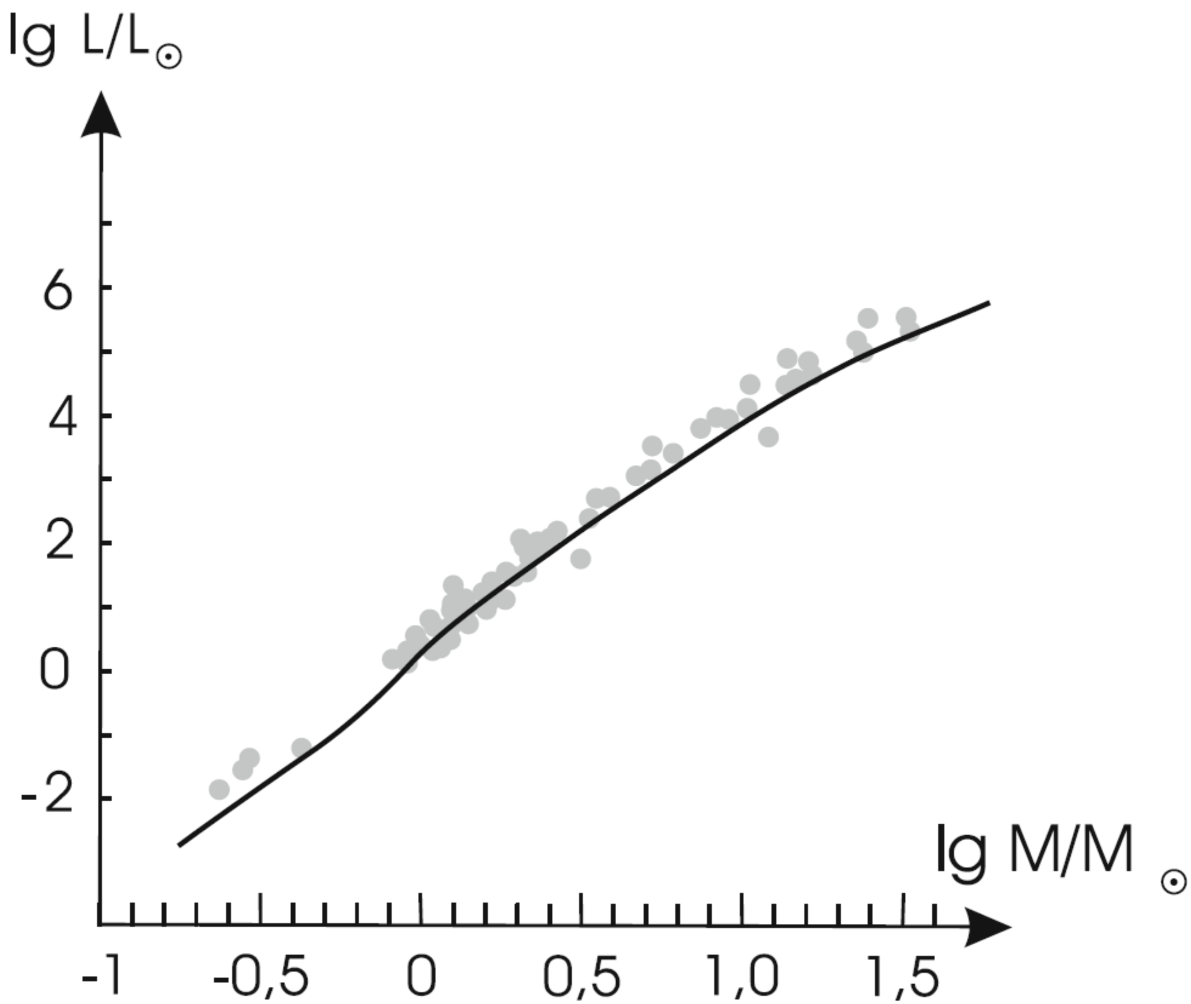


Kippenhahn & Weigert

Homology relations

Review of basic physics of transients

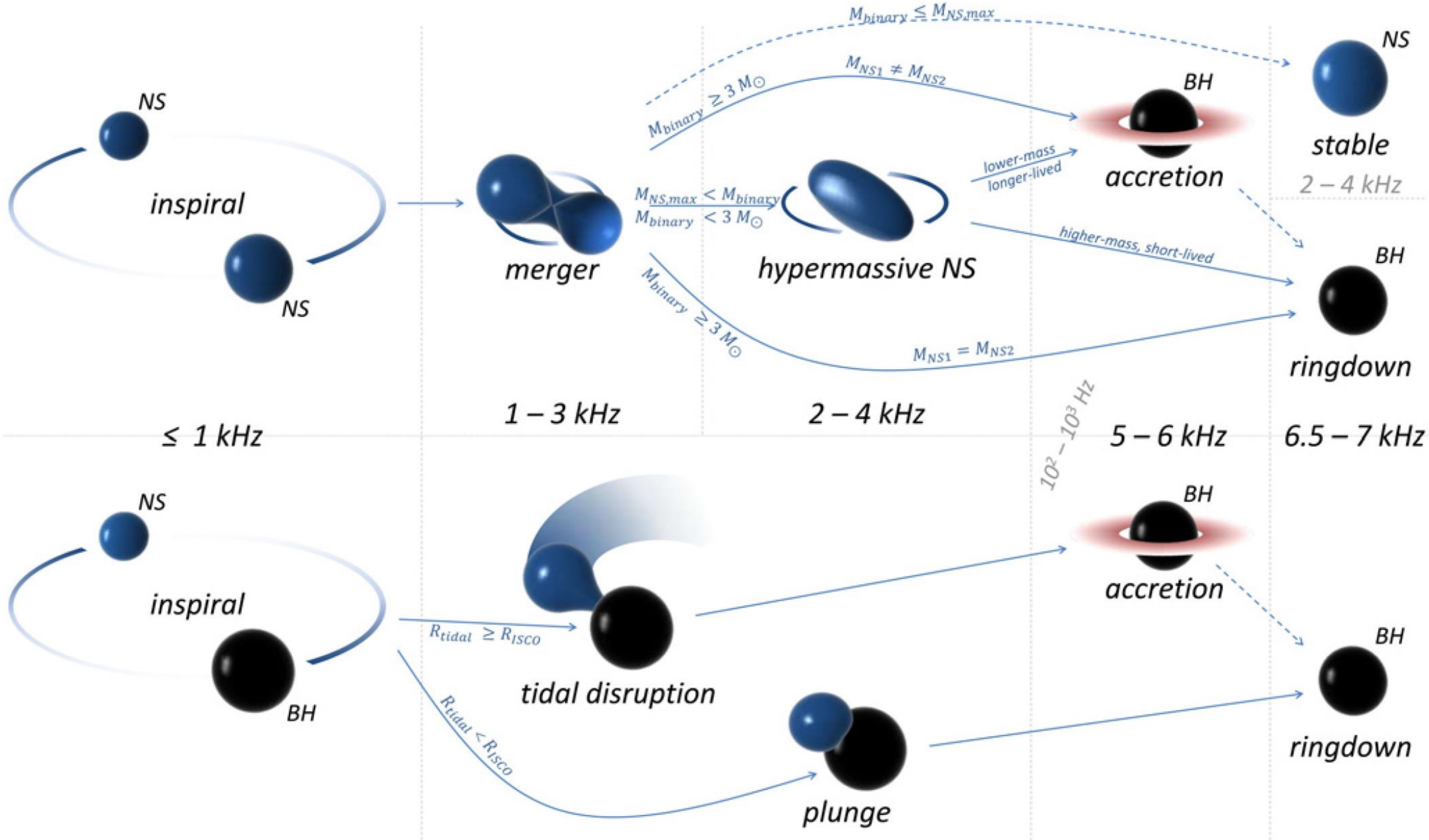
Gravitational wave merger time

$$\tau_{merge}(a_o, e_o) \simeq \frac{768}{425}\tau_{circ}(a_o)(1 - e_o^2)^{7/2}$$

$$\tau_{circ}(a_o) = \frac{a_o^4}{4\beta}$$

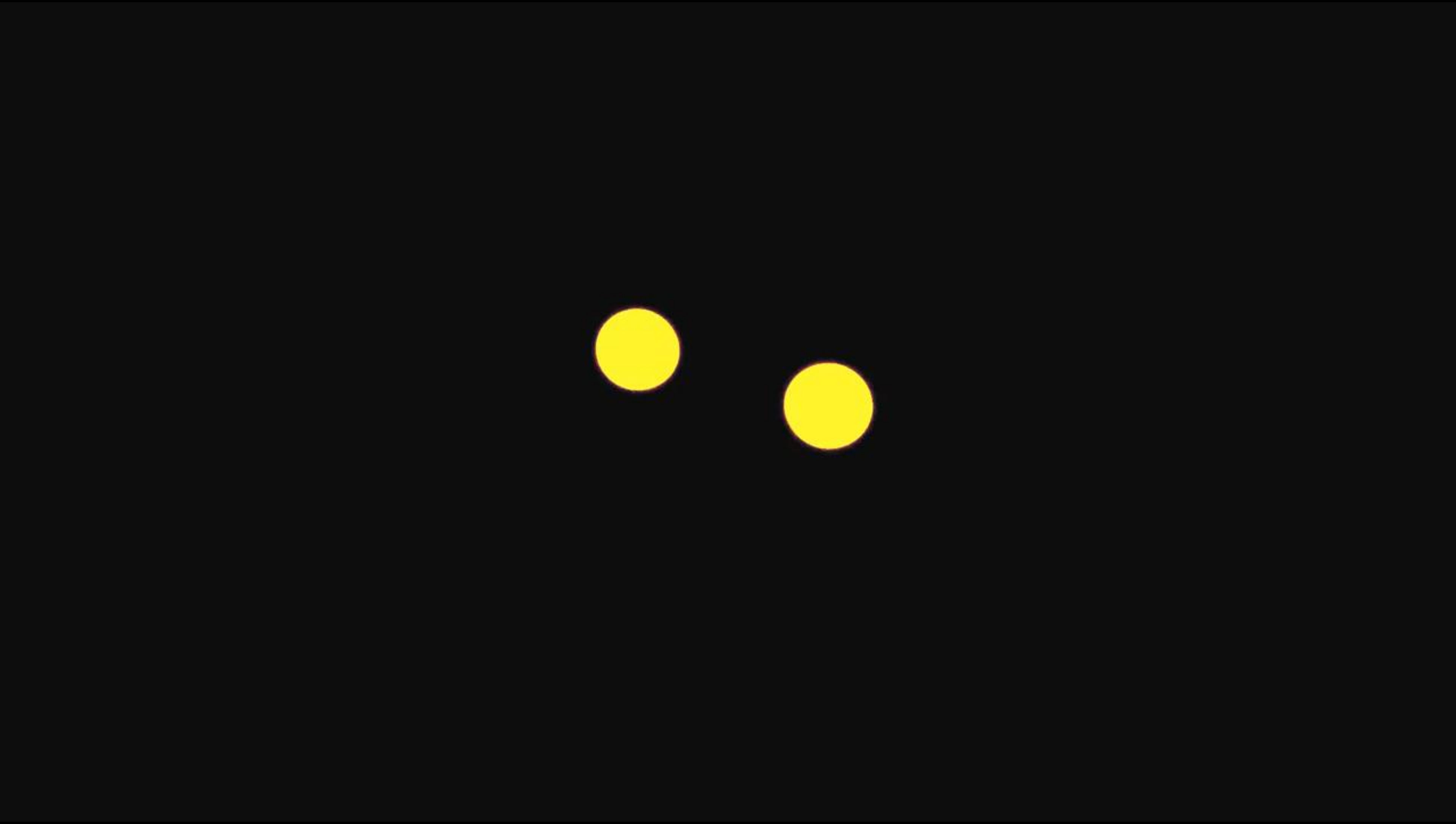
$$\beta = \frac{64}{5}\frac{G^3}{c^5}m_1 m_2(m_1 + m_2)$$

Peters (1964)

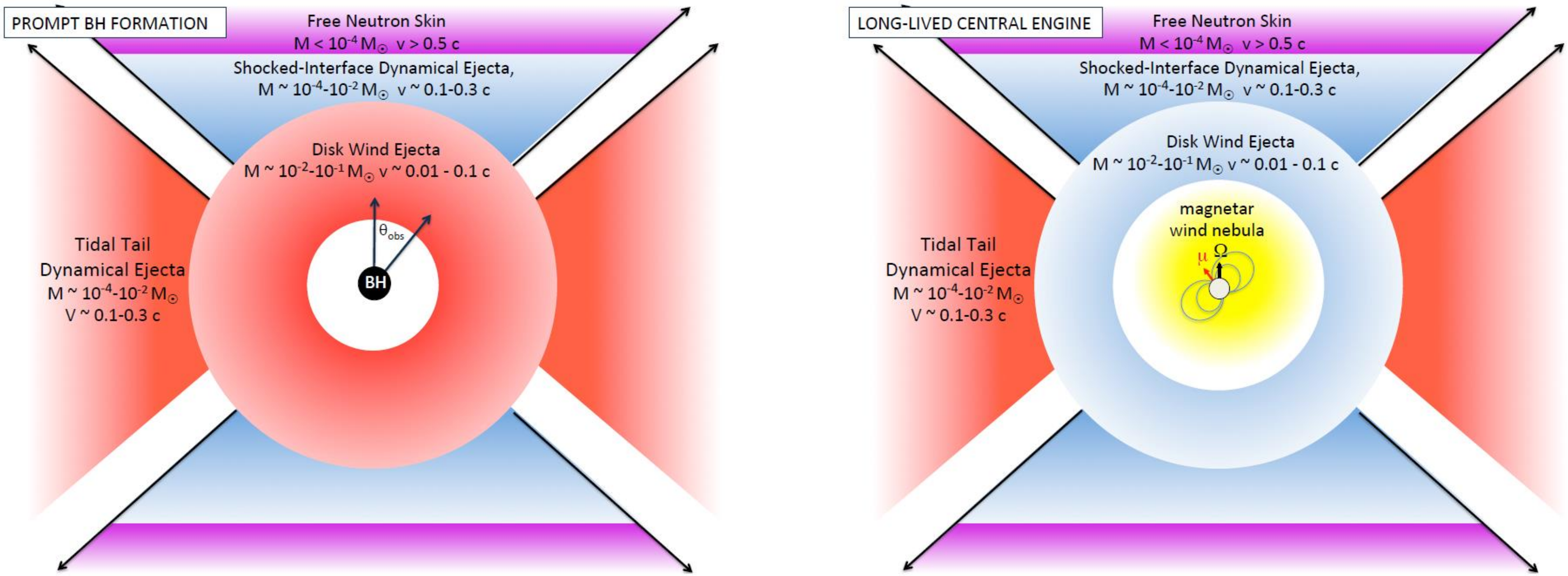


Bartos et al. (2013)

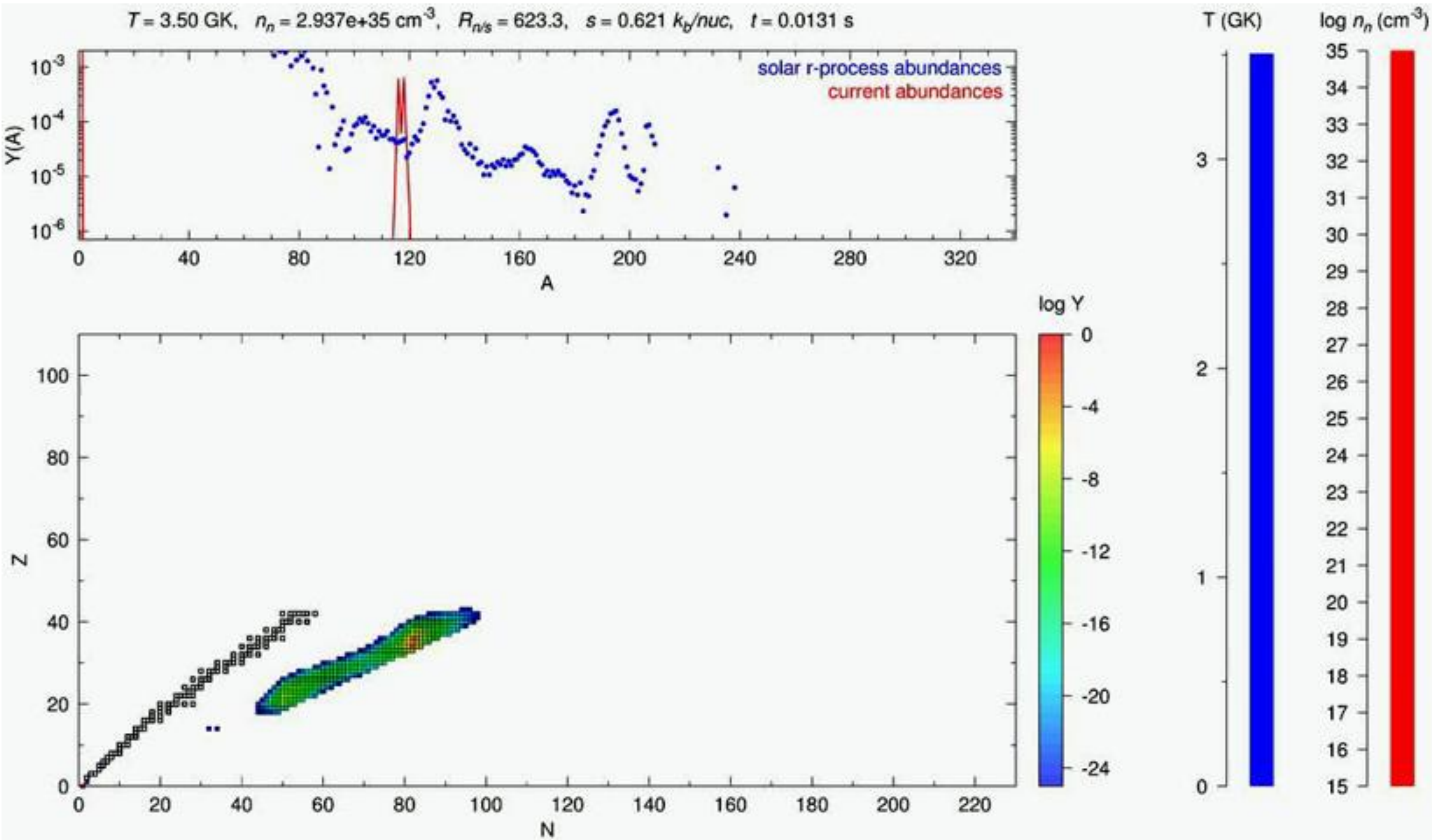
Binary neutron star mergers



Radice et al.



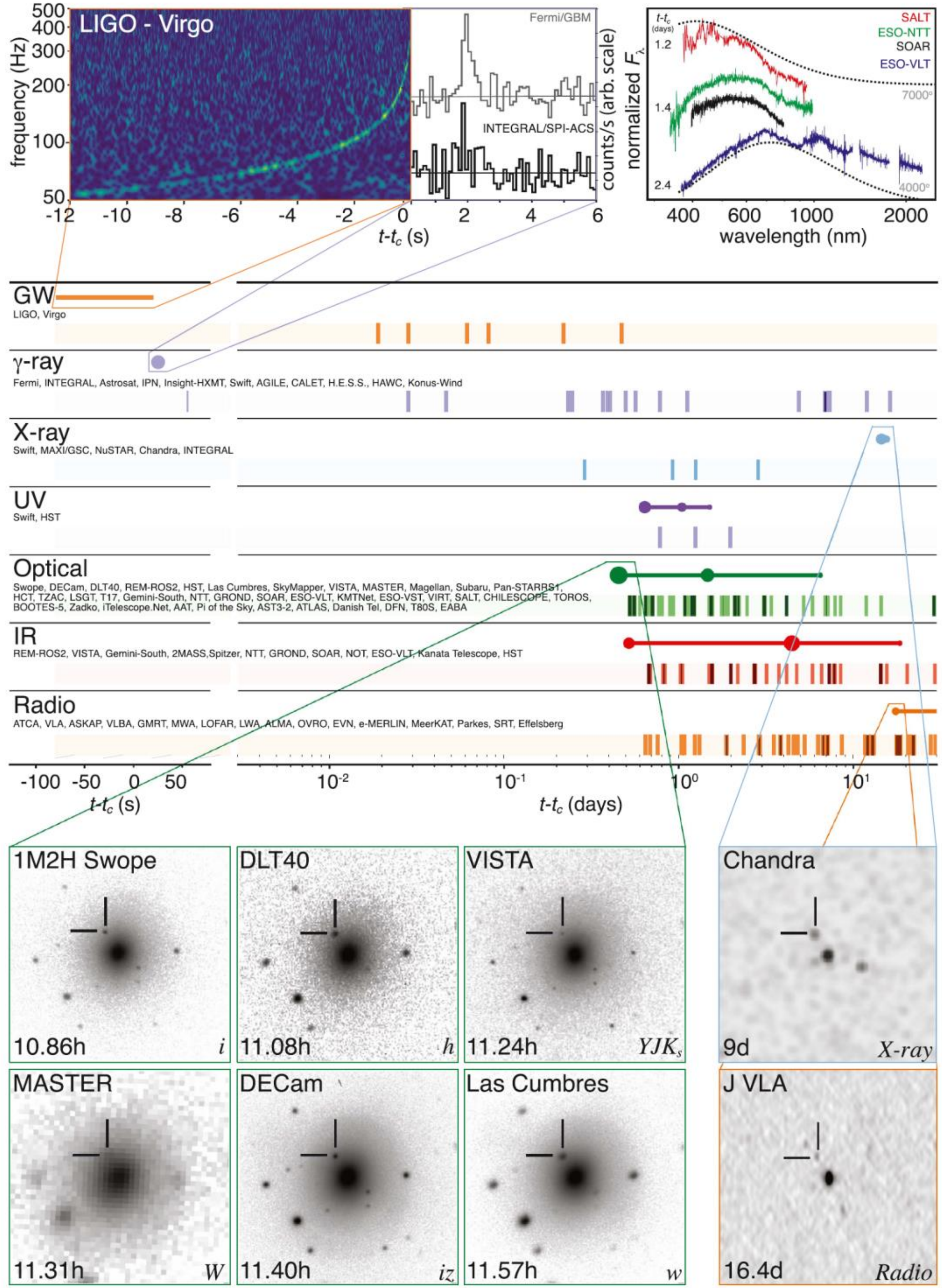
Metzger (2016)



https://www.youtube.com/watch?v=T44B9j3Vzxw

Energy deposition by r-process

Entering the era of multi-messenger astronomy



Abott et al. (2017)

$$t_{lc} \approx \left(\frac{3\kappa M}{4\pi c v}\right)^{\frac{1}{2}} \approx 2.7\,\text{days} \times \left(\frac{M}{0.01M}\right)^{\frac{1}{2}} \left(\frac{v}{0.1c}\right)^{-\frac{1}{2}} \left(\frac{\kappa}{1\,\text{cm}^2\,\text{g}^{-1}}\right)^{\frac{1}{2}} \quad (2)$$

The characteristic luminosity of the kilonova is approximately equal to the radioactive heating rate at this escape timescale

$$L_{lc} \approx M\varepsilon_{nuc}(t_{lc}) \approx 5\times10^{40}\,\text{erg}\,\text{s}^{-1} \times \left(\frac{M}{0.01M}\right)^{1-\frac{\alpha}{2}} \left(\frac{v}{0.1c}\right)^{\frac{\alpha}{2}} \left(\frac{\kappa}{1\,\text{cm}^2\,\text{g}^{-1}}\right)^{-\frac{\alpha}{2}} \quad (3)$$

A larger ejecta mass produces a brighter and longer-lasting kilonova; a higher velocity gives a brighter and briefer kilonova.

Observable signatures of heavy element formation

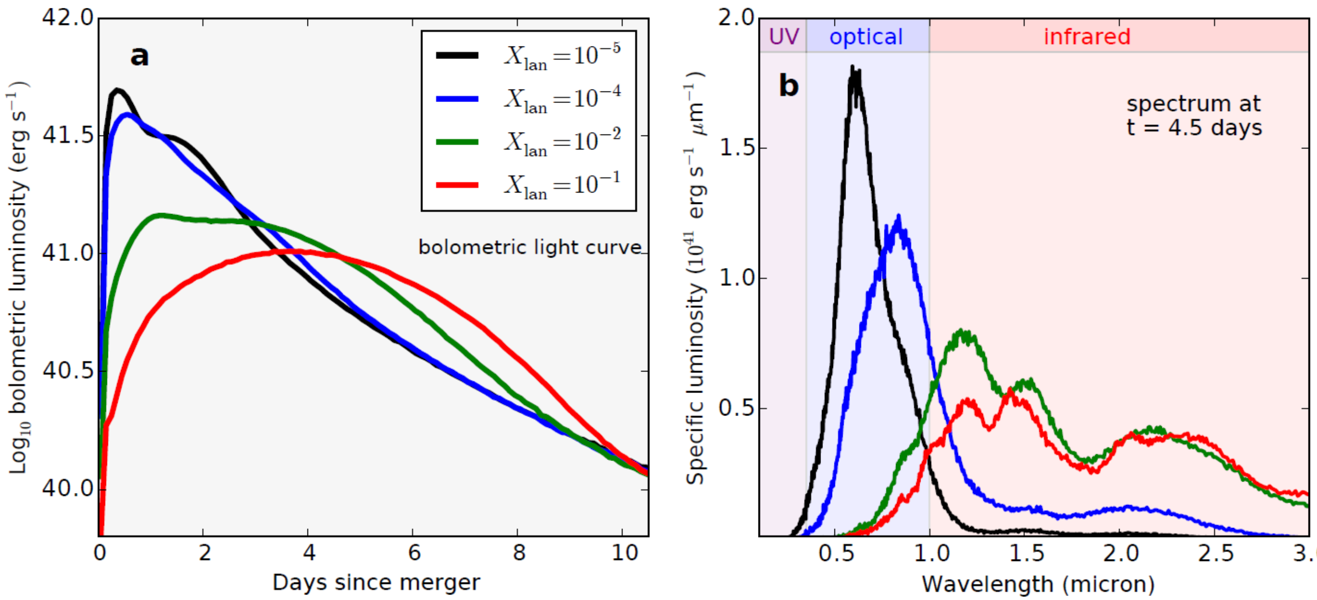
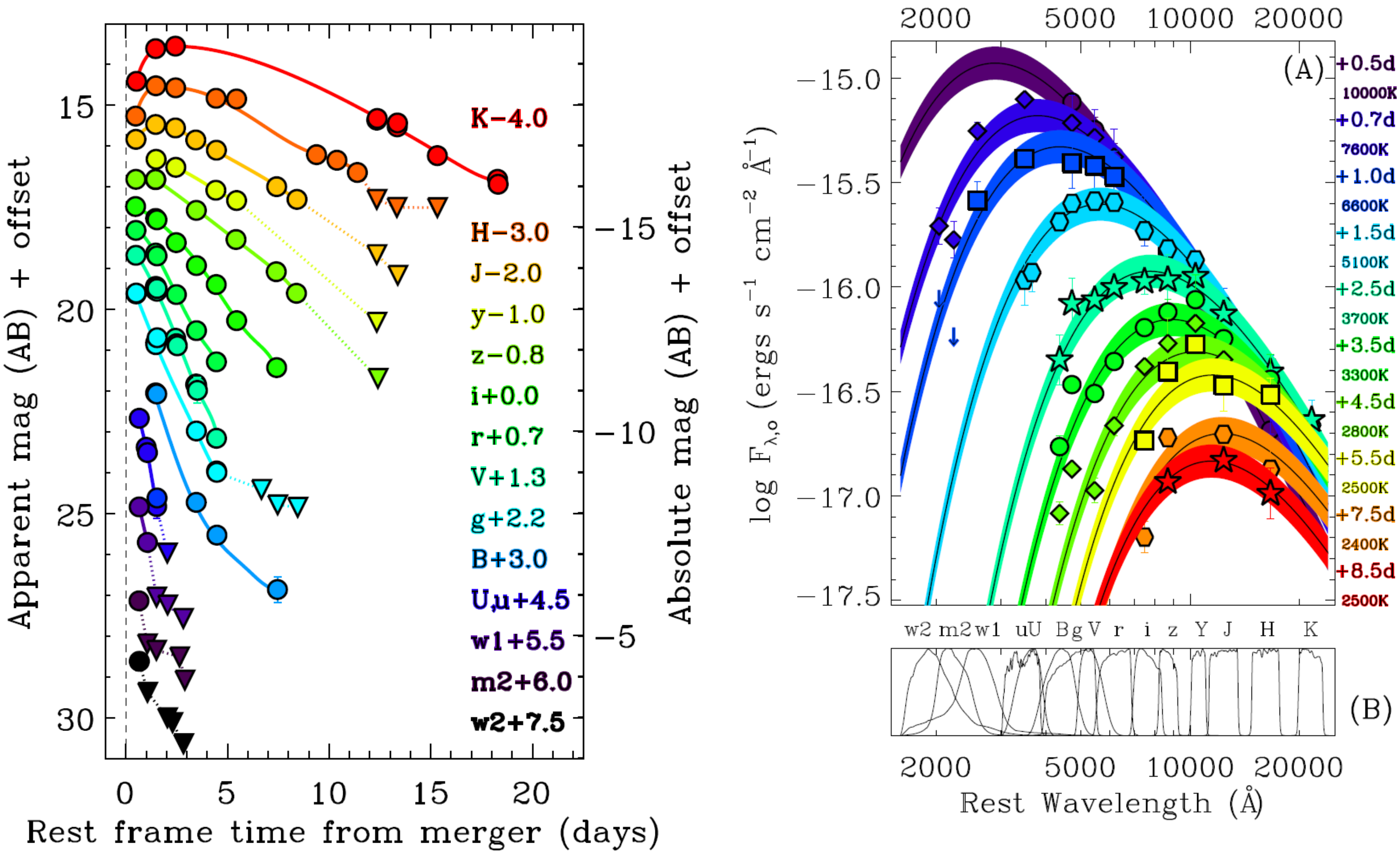


Figure 2 | Models of kilonovae demonstrating the observable signatures of r-process abundances. All models have an ejecta mass $M = 0.05M_\odot$ and velocity $v_k = 0.2c$, but different mass fractions of lanthanides X_{lan}. **a**, Model bolometric light curves. If the ejecta is composed primarily of heavier r-process material ($X_{lan} \geq 10^{-2}$) the opacity is higher, resulting in a longer diffusion times and longer duration bolometric light curves. **b**, Model spectra as observed 4.5 d after the mergers. The higher lanthanide opacities of the heavy r-process materials obscure the optical bands and shift the emission primarily to the infrared.

Kasen et al. 2017

Observations of GW170817



Drout et al. (2017)

What can we learn from a spectrum of kilonova?

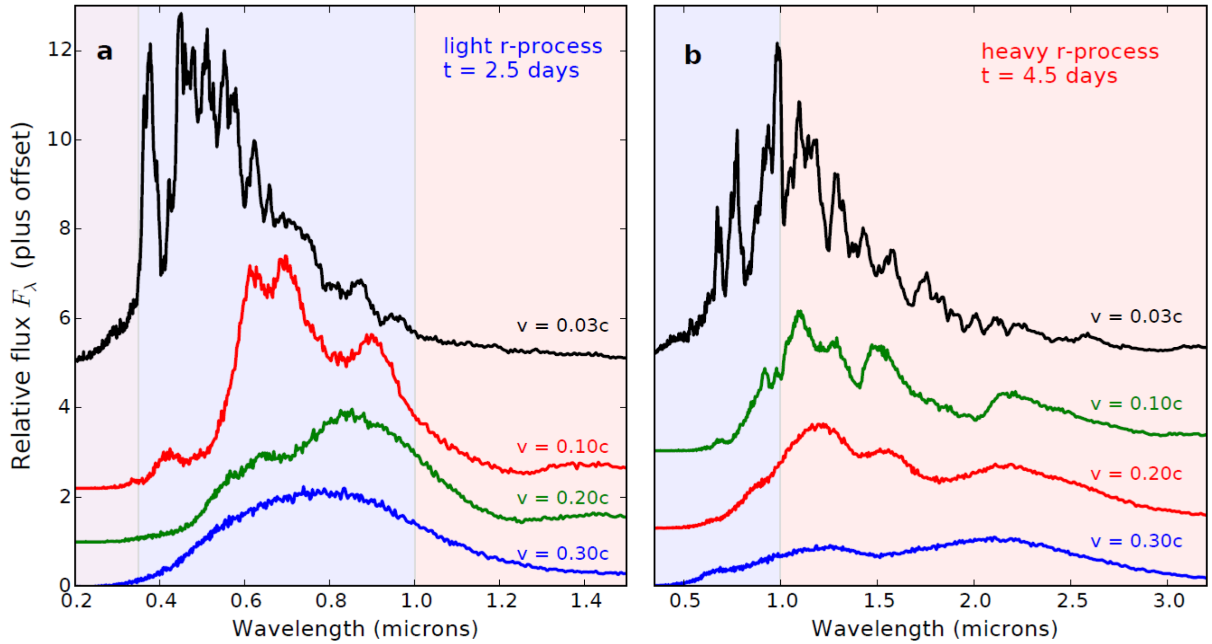


Figure 3 | Models of kilonovae demonstrating the spectral diagnostics of the ejecta velocity. The models all have ejecta mass $M = 0.03M_\odot$. **a**, Spectra of models composed of light r-process material ($X_{lan} = 10^{-4}$) observed 1.5 d after the merger. Modest ejecta velocities ($v_k = 0.03c$, typical of supernovae) produce conspicuous absorption spectral features. At higher velocities ($v_k = 0.1c$–$0.2c$) the features are broadened and blended, while for $v_k = 0.3c$ the spectra are essentially featureless. The optical spectra of AT 2017gfo were featureless, implying a high-velocity, approximately $0.3c$ component of light r-process ejecta. **b**, Spectra of models composed of heavy r-process material ($X_{lan} = 10^{-2}$) observed 3.5 d after the merger. The infrared spectra of AT 2017gfo showed broad peaks, implying a lower-velocity, approximately $0.1c$ component of heavy r-process ejecta.

Kasen et al. (2017)

What can we learn from a spectrum of kilonova?

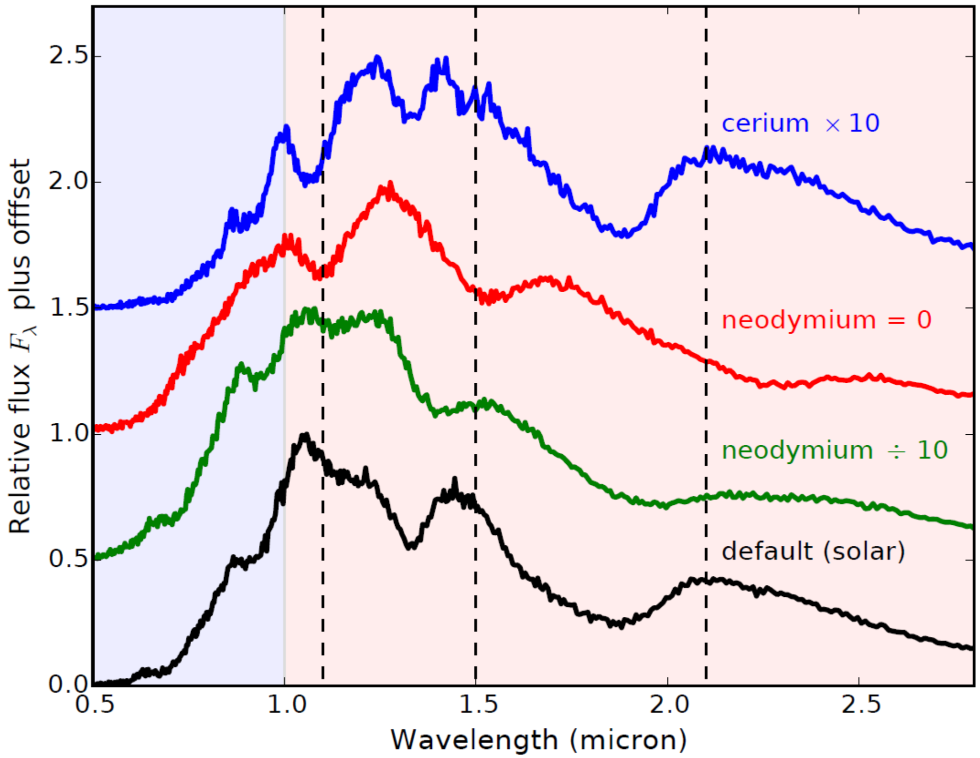
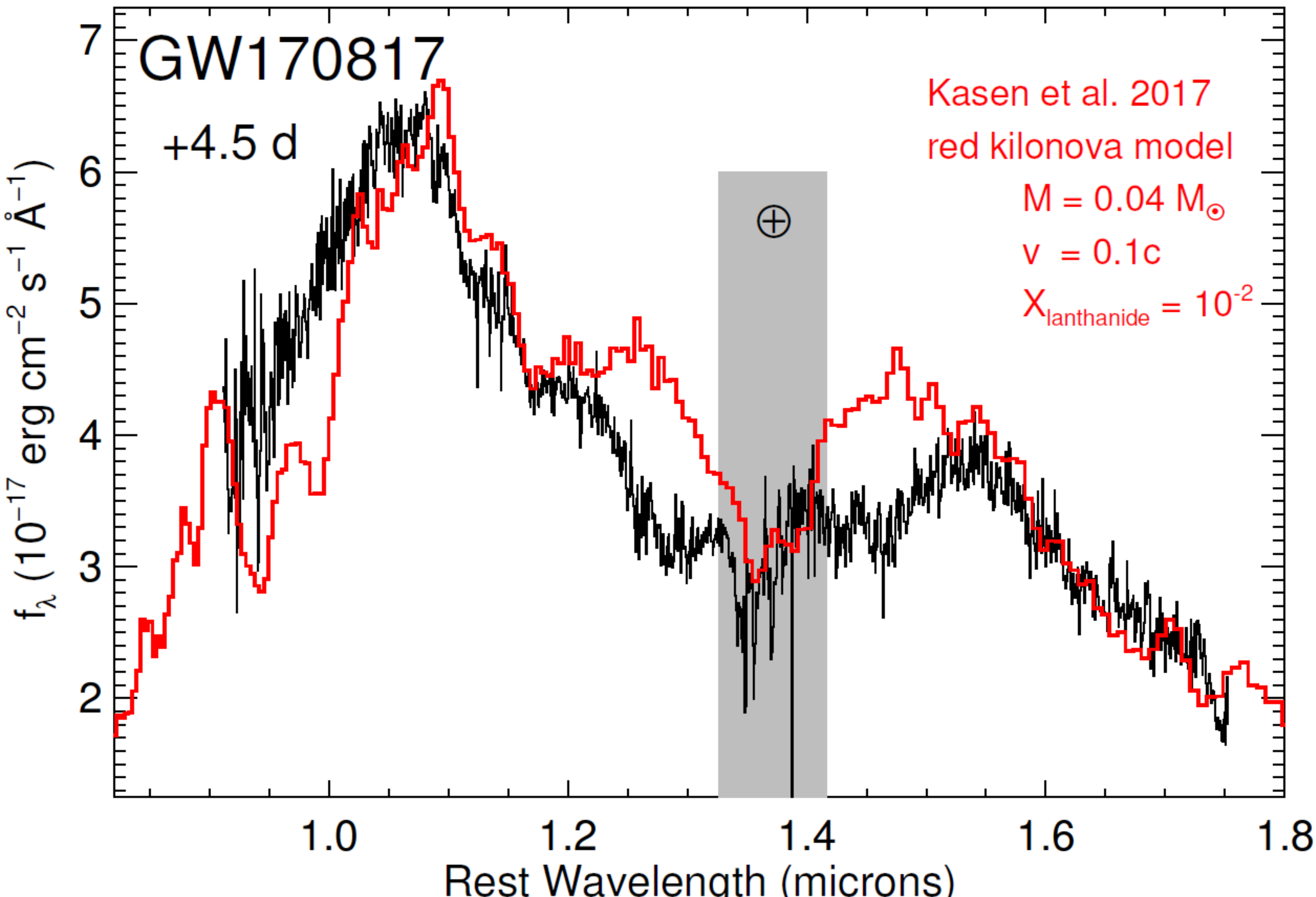


Figure 4 | Models demonstrating how kilonova spectral features probe the abundance of individual r-process elements. The spectral peaks in the models are blends of many lines, primarily those of the complex lanthanide species. The default model shown (parameters $M = 0.04M_\odot$, $v_k = 0.15c$, $X_{lan} = 10^{-1.5}$) uses a solar distribution of lanthanides, and has spectral peaks near 1.1 μm, 1.5 μm and 2.0 μm (marked with dashed lines). These features are mainly attributable to neodymium ($Z = 60$) given that reducing or removing this species changes the feature locations. However, other lanthanides such as cerium ($Z = 58$) also affect the blended peaks. Uncertainties in the current atomic line data sources limit hinder spectral analysis, but with improved atomic inputs a more detailed compositional breakdown is within reach.

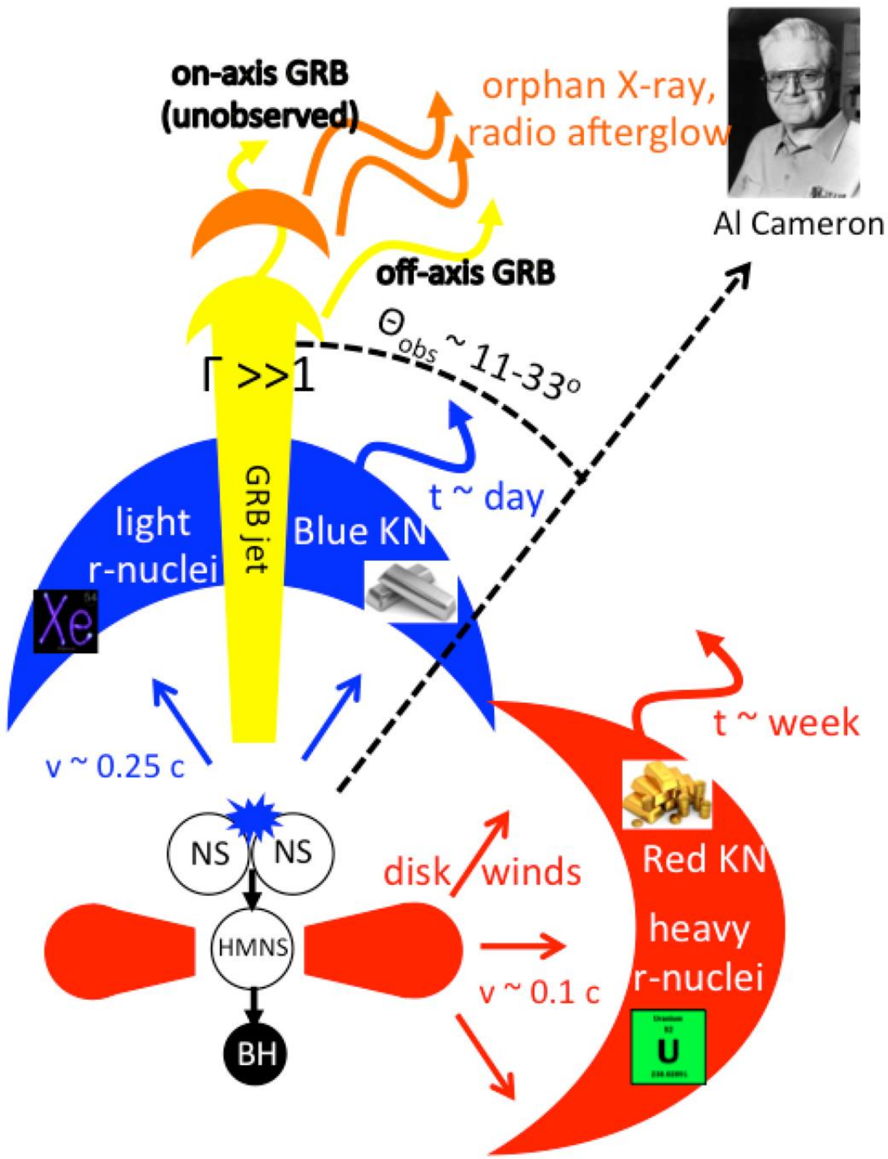
Kasen et al. (2017)

Observations of GW170817



Chornock et al. 2017

What did we see in GW170817?



Metzger 2017

- What is the luminosity and duration of the transient from the destruction of Thor’s hammer?

- Can we detect signatures of clashing superheros with LSST?