Optical and infrared constraints on r-process ejecta mass and abundances from kilonovae

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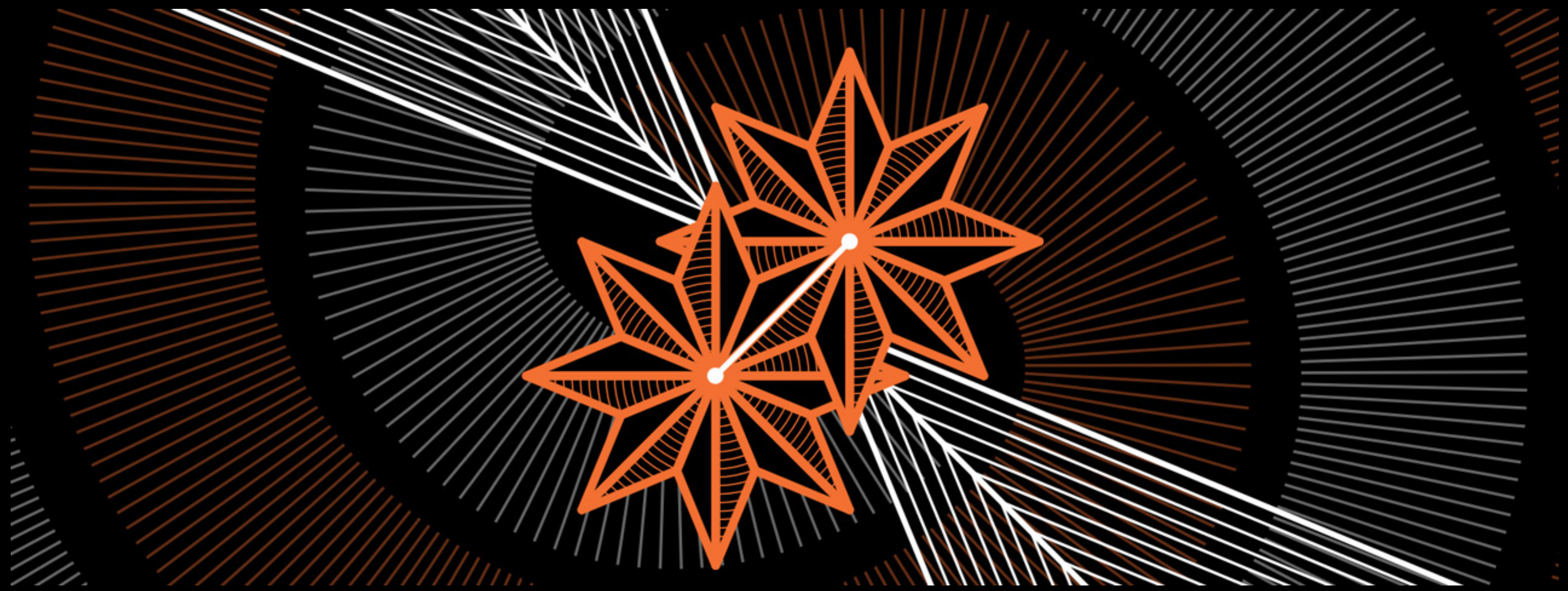


In collaboration with: R. Foley, D. Coulter, M. Drout, J. Rastinejad, W. Fong, A. Rest, A. Piro, E. Ramirez-Ruiz, D. Kasen, I. Arcavi, D. Sand, and others

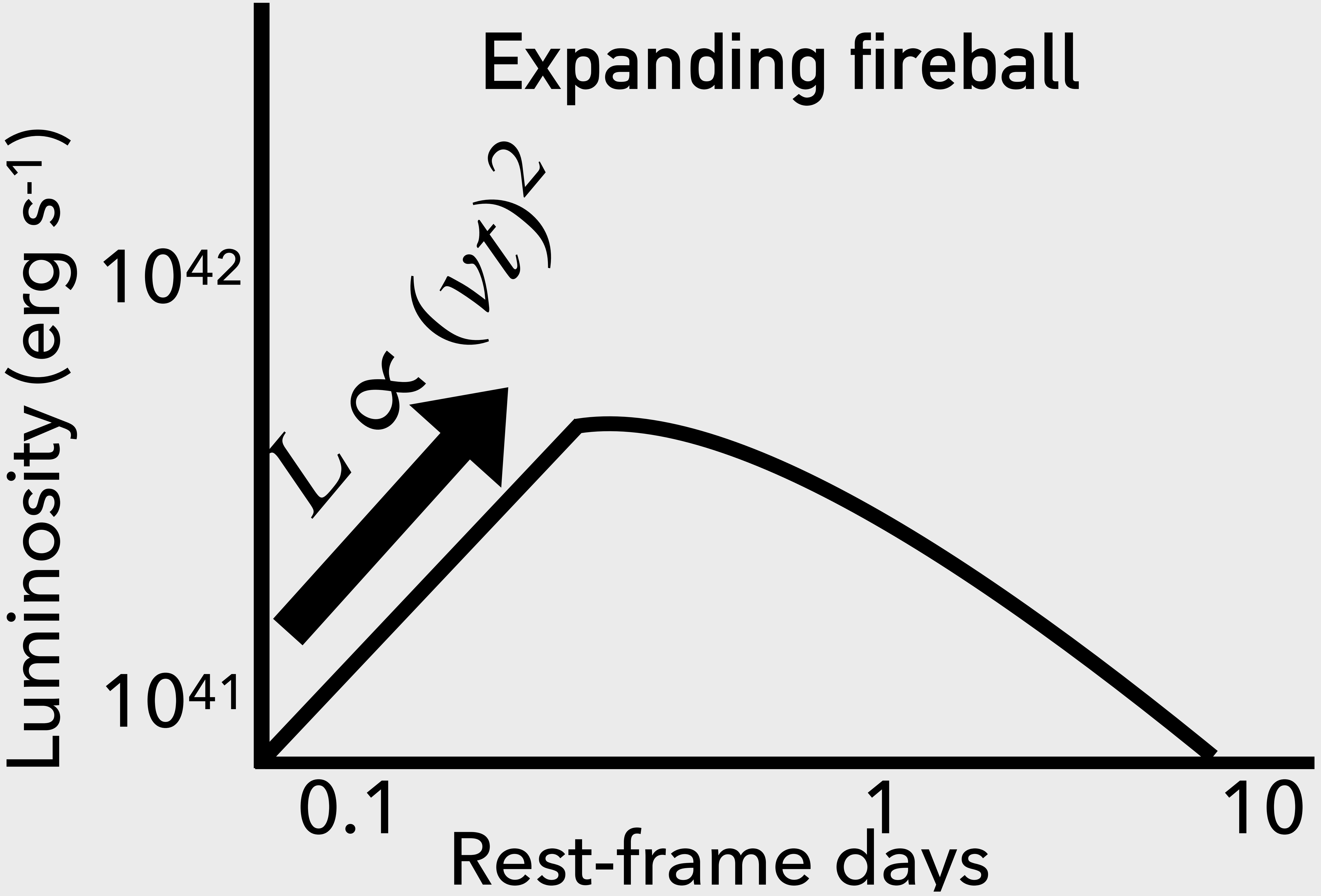
Outline

* How do we know kilonova ejecta are dominated by r-process species?
* Constraints on kilonovae from GRBs + GW
    * GRB-discovered kilonovae - statistical properties and outliers
    * GW170817 and limits on BNS/NSBH from O3
* The r-process during O4 with JWST

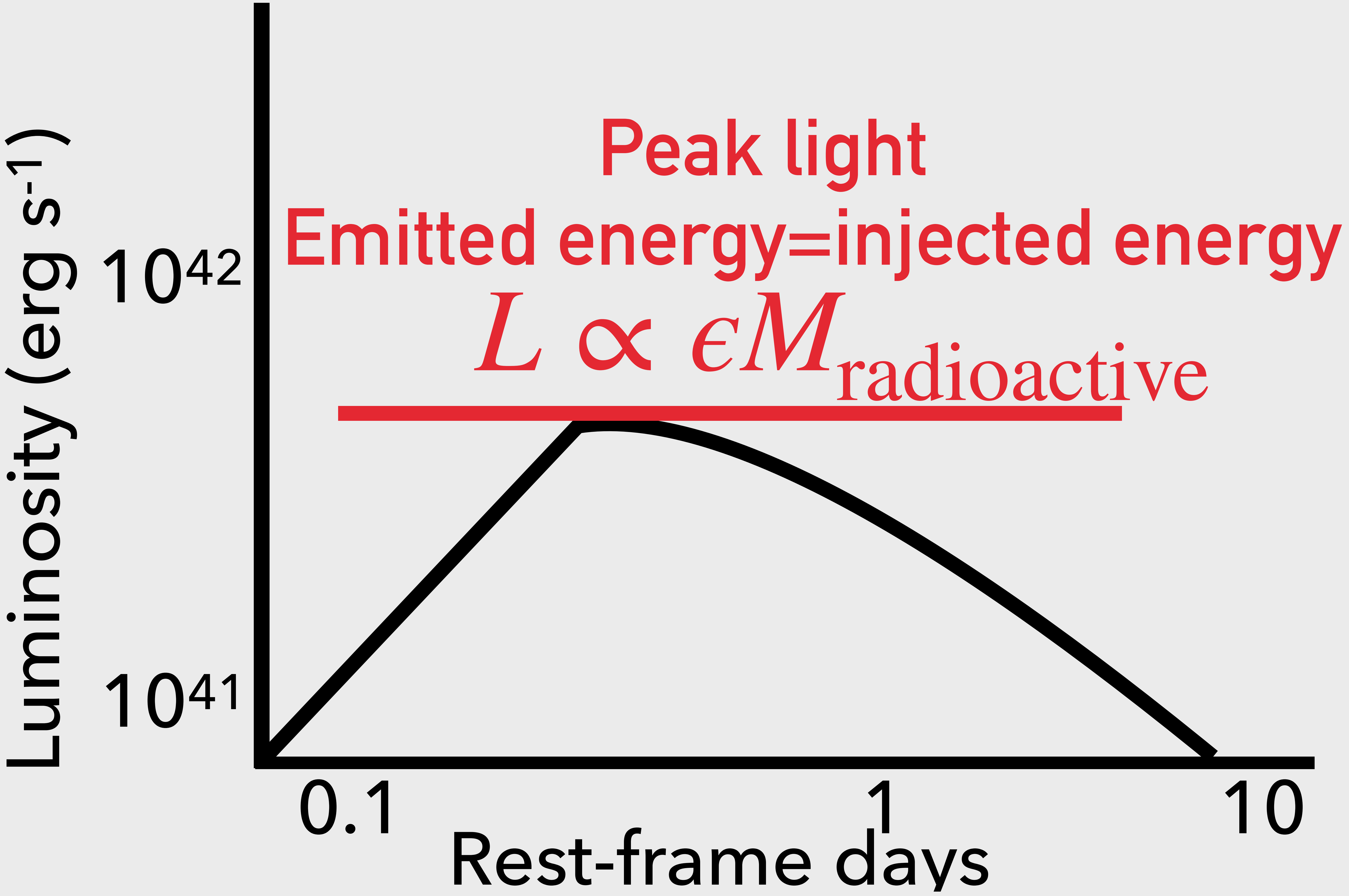
Signatures of the r-process

* Opacity (talks by Mattia Bulla, Ryan Foley, and others)
  * Notably work by: Kasen+2013, ApJ 774, Kasen+2015, MNRAS 450, Metzger+2014, MNRAS 441, Tanaka+2013, ApJ 775
* Heating rate (talk by Matthew Mumpower - ^{254}Cf!)
  * Wu+2019, PhRvL 122, Metzger+2010, MNRAS 406, Just+2015, MNRAS 448, Roberts+2011, ApJ 736
* Spectral features (talk by John Ruan)

Light curve properties of kilonovae: Arnett's law



Light curve properties of kilonovae: Arnett's law



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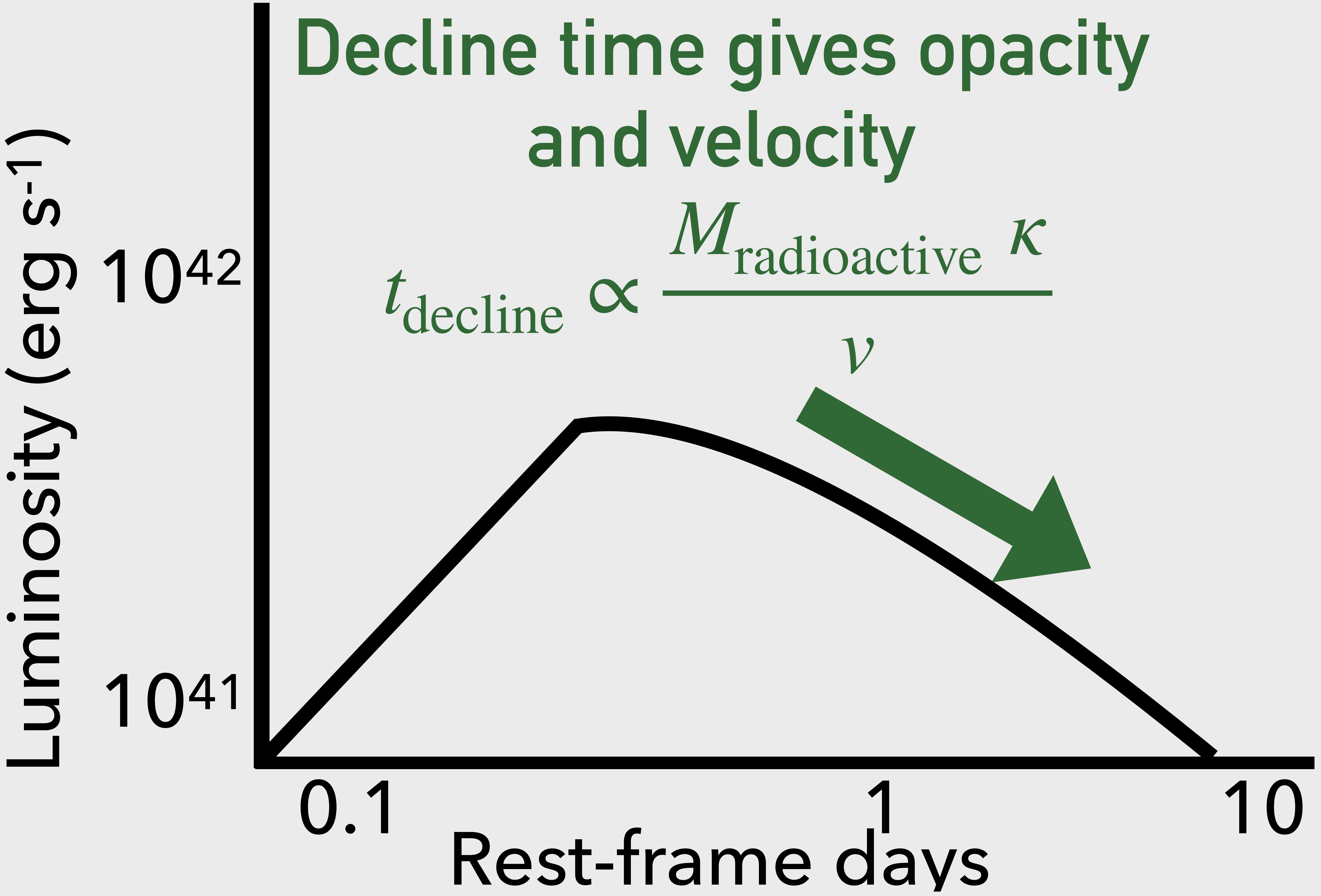


$$t_{\text{decline}} \propto \frac{M_{\text{radioactive}}\ \kappa}{v}$$

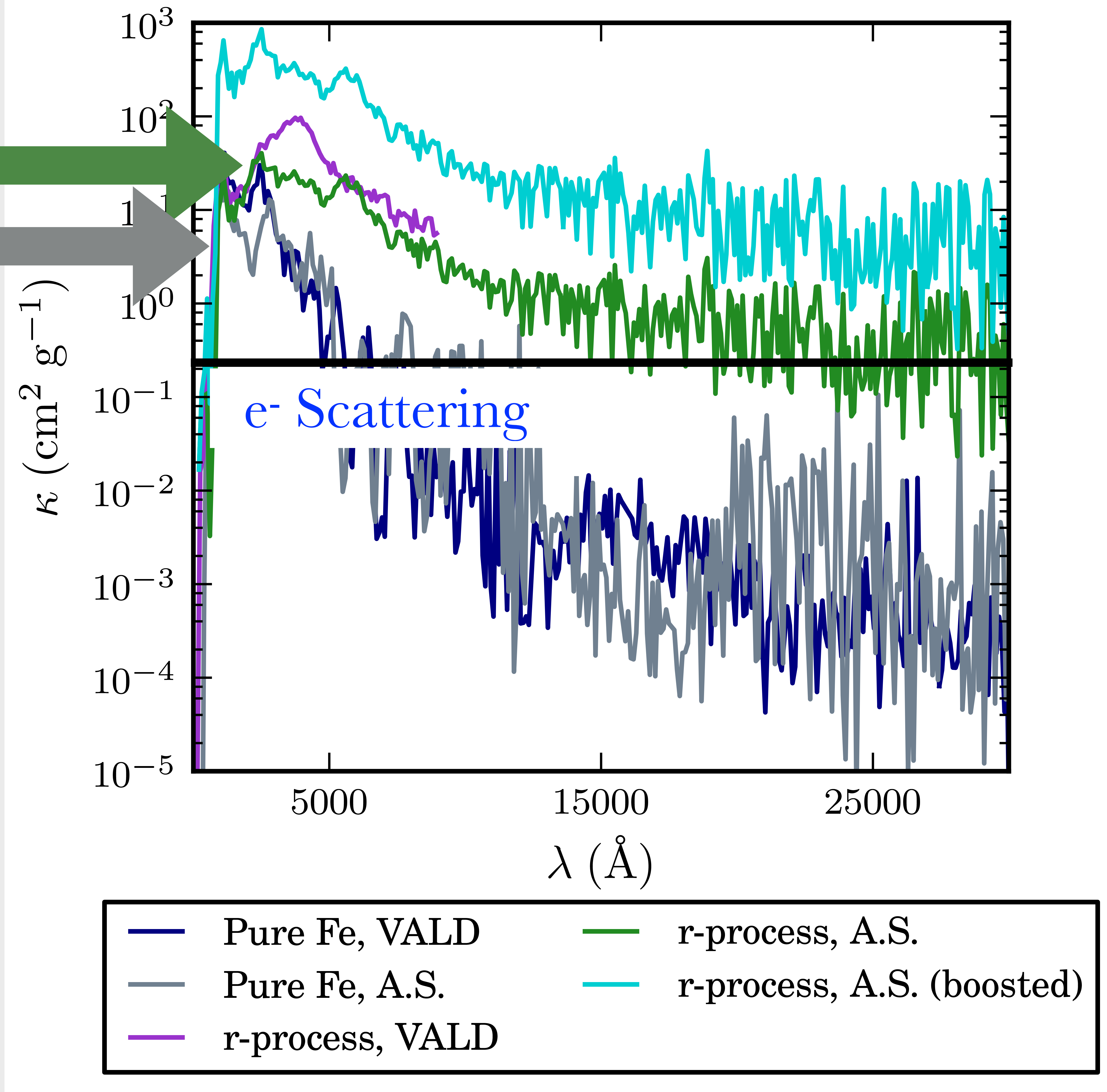
$$L \propto \epsilon(t) M (vt)^2 \exp(-\frac{tv}{M\kappa})$$

Evidence for the r-process: opacity

r-process opacities (5-10 $cm^2\ g^{-1}$)

Iron-like opacities (~1 $cm^2\ g^{-1}$)

"Smoking gun" signature of kilonovae: they are red (except when they're not), short-lived transients

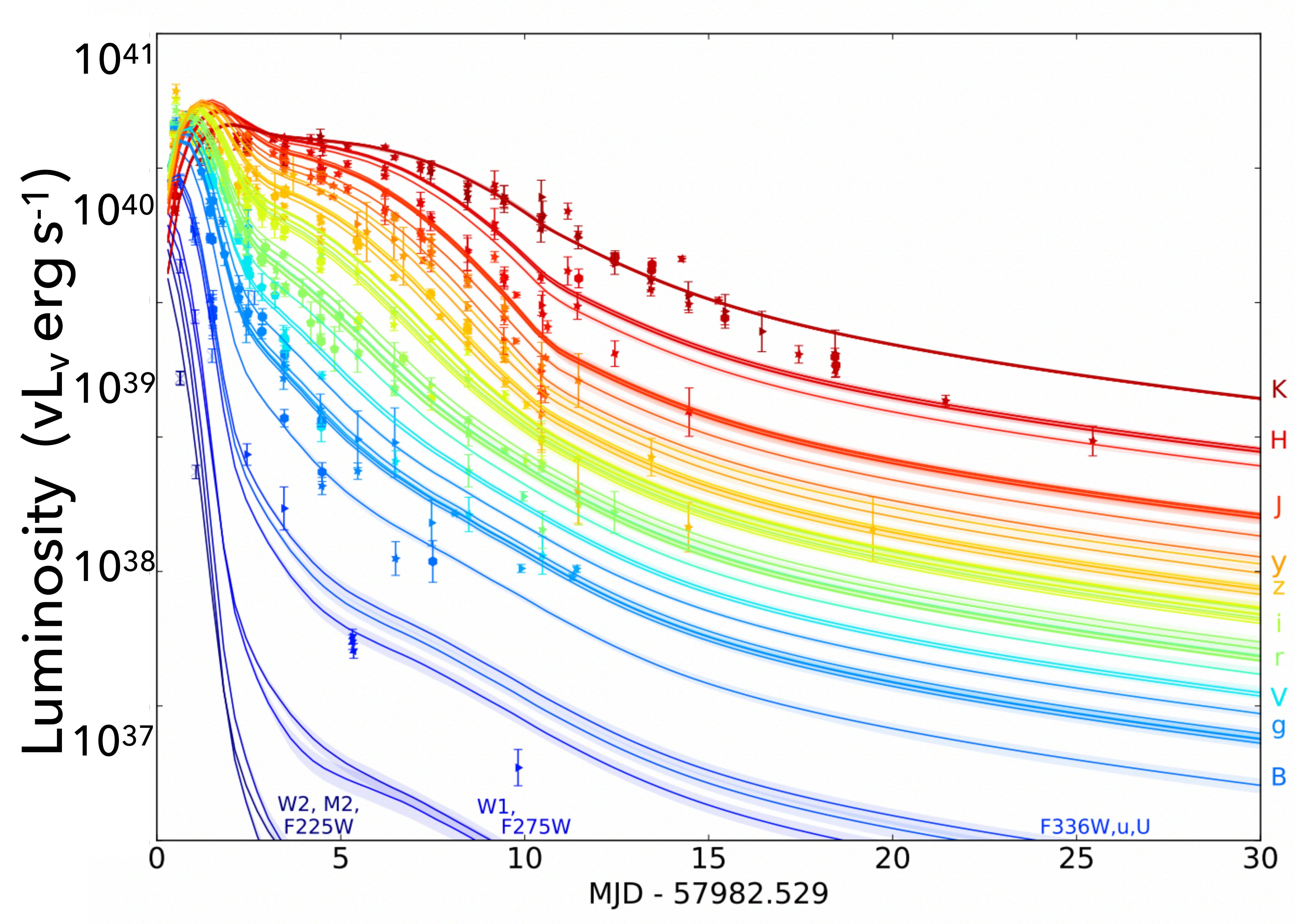


Barnes & Kasen (2013)

Light curve properties of kilonovae: Arnett's law

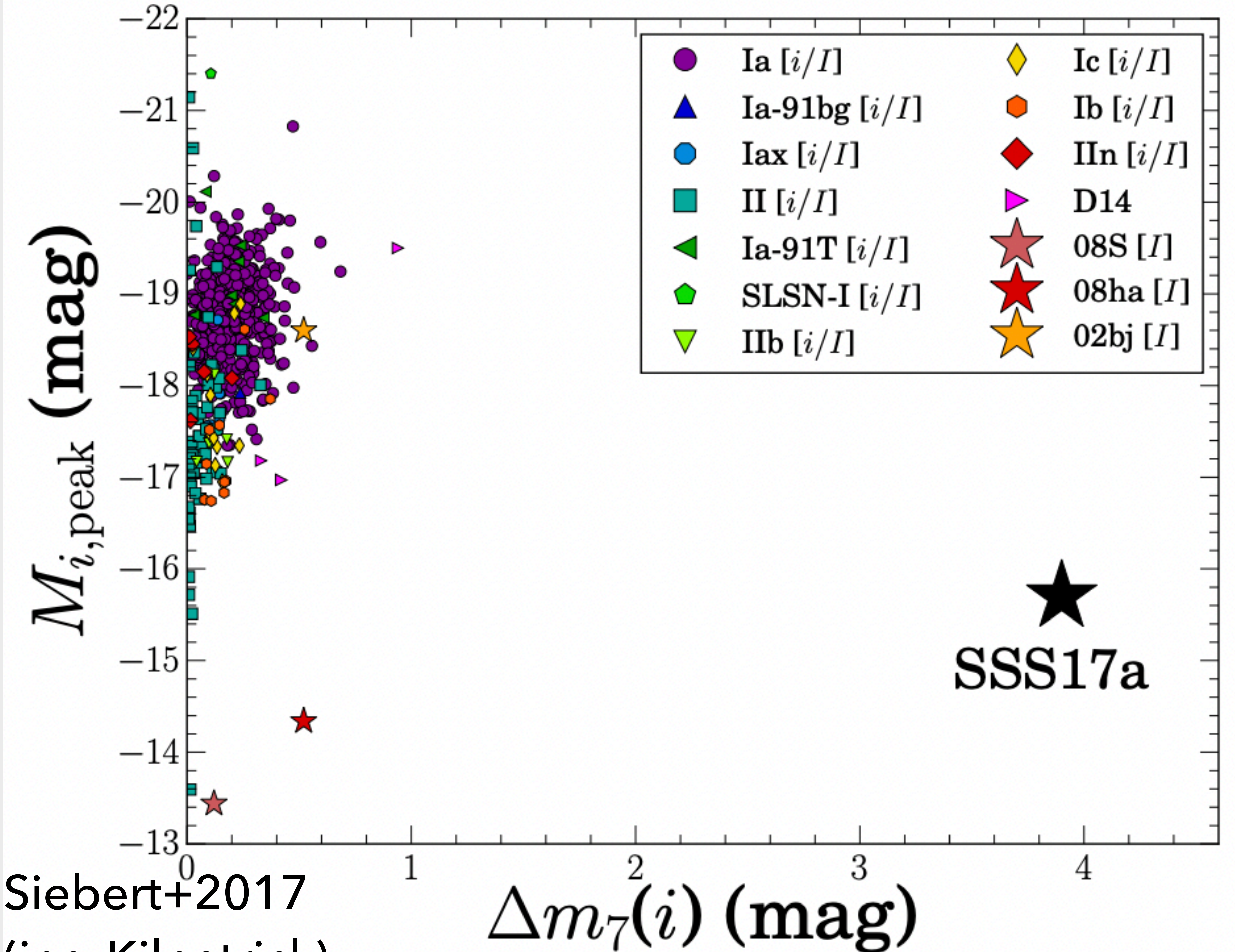
Kilonovae match very closely the prescription implied by Arnett's law, enabling constraints on:

* Mass
* Velocity
* Opacity
* Viewing angle

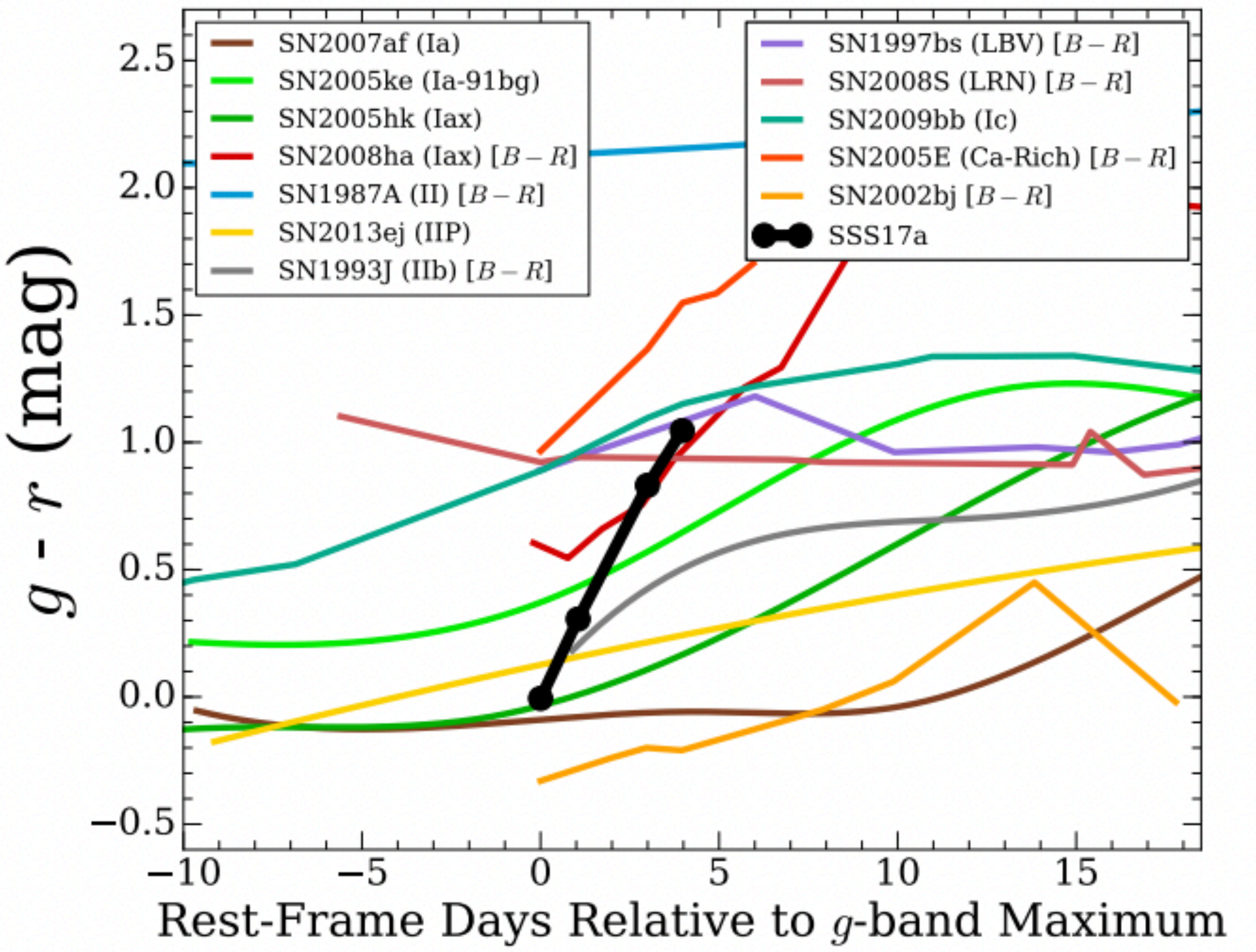


Villar+2017 (Arnett-like MCMC model)

Evidence for the r-process: opacity

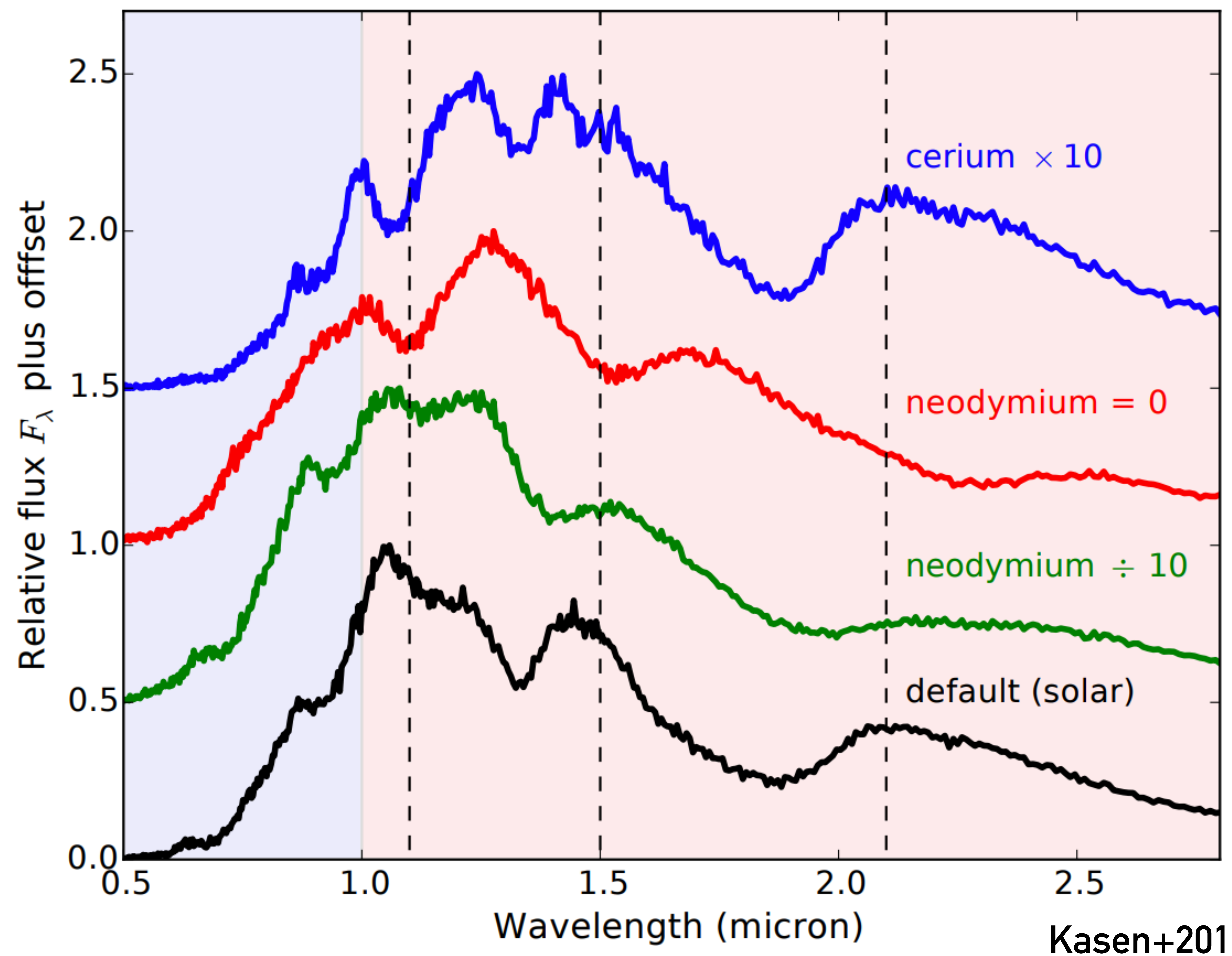


Siebert+2017
(inc. Kilpatrick)



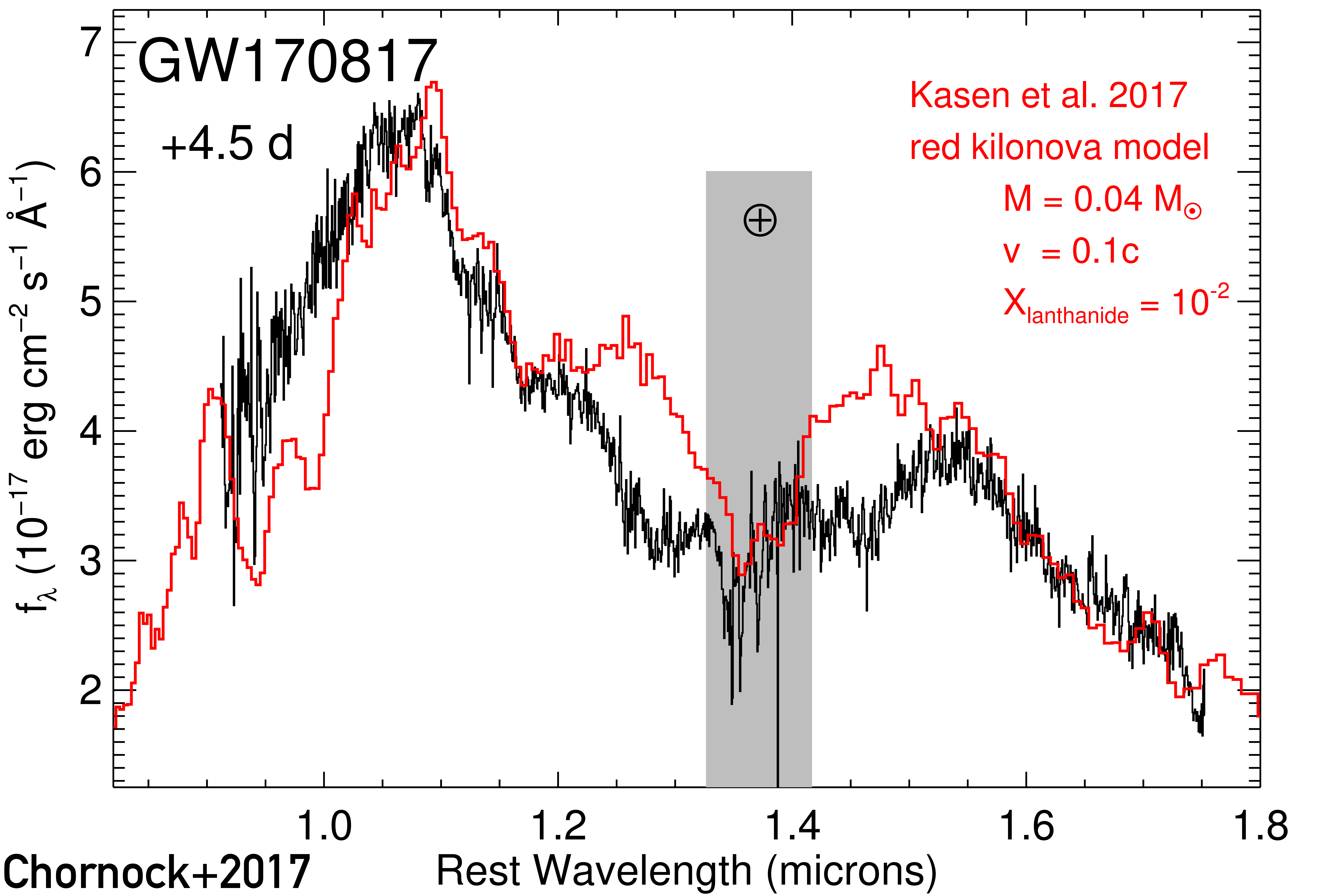
The kilonova needs to have 1) low ejecta mass, 2) near-relativistic, and 3) an extremely high opacity component

Evidence for the r-process: spectral profile



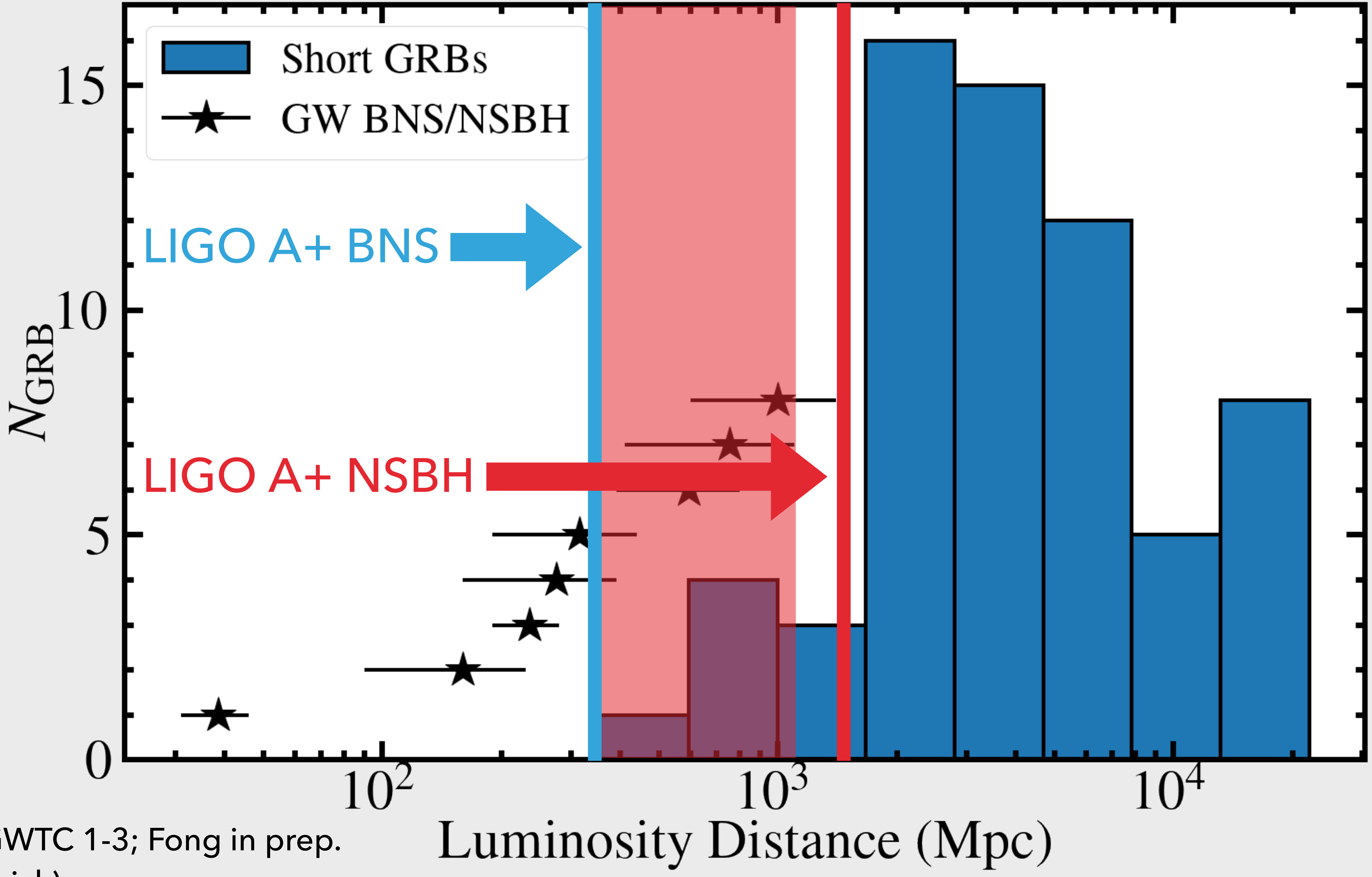
Kasen+2017

Evidence for the r-process: spectral profile

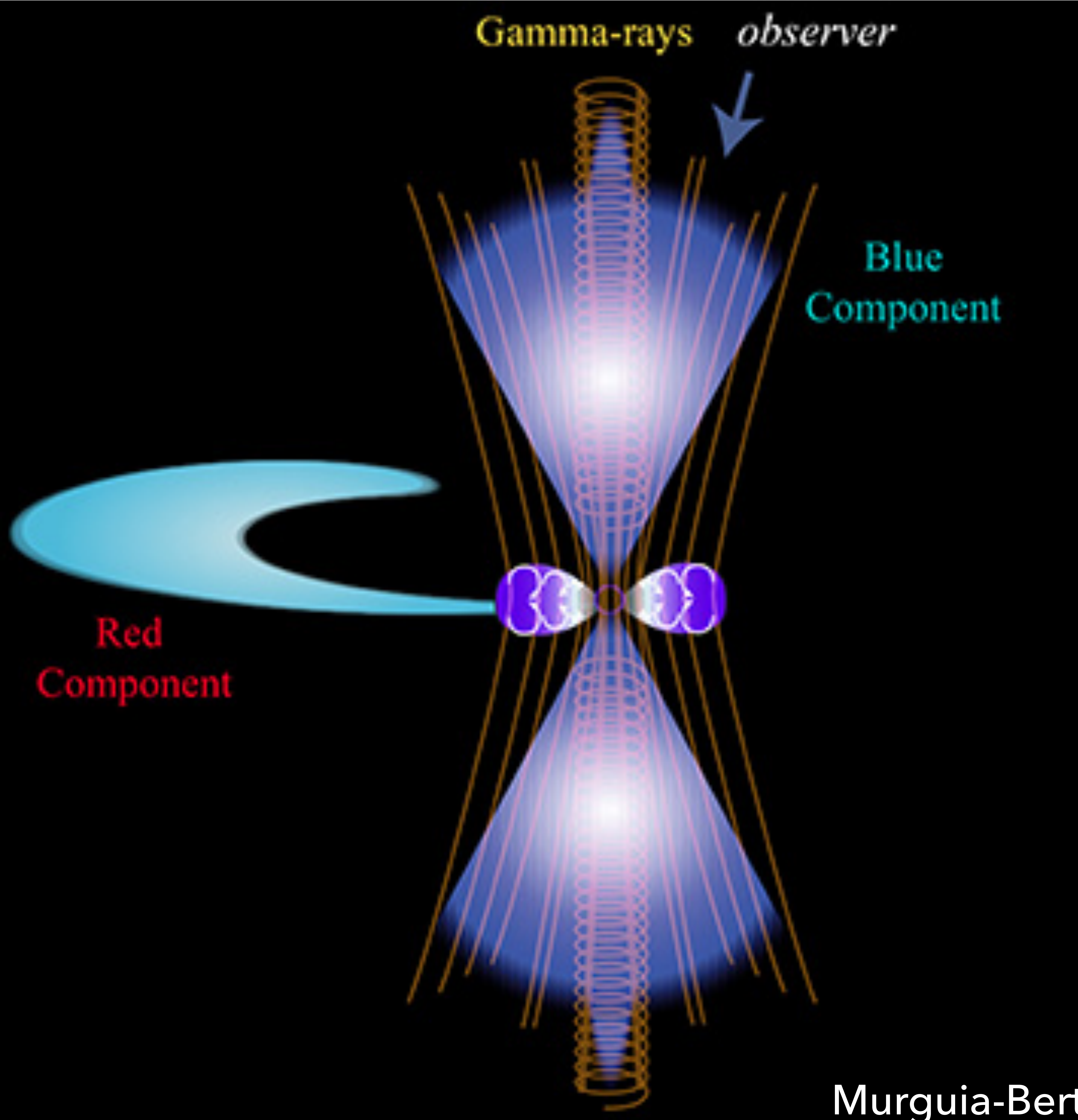


Chornock+2017

Comparing GW and GRB-targeted kilonovae



Sources: GWTC 1-3; Fong in prep.
(inc. Kilpatrick)

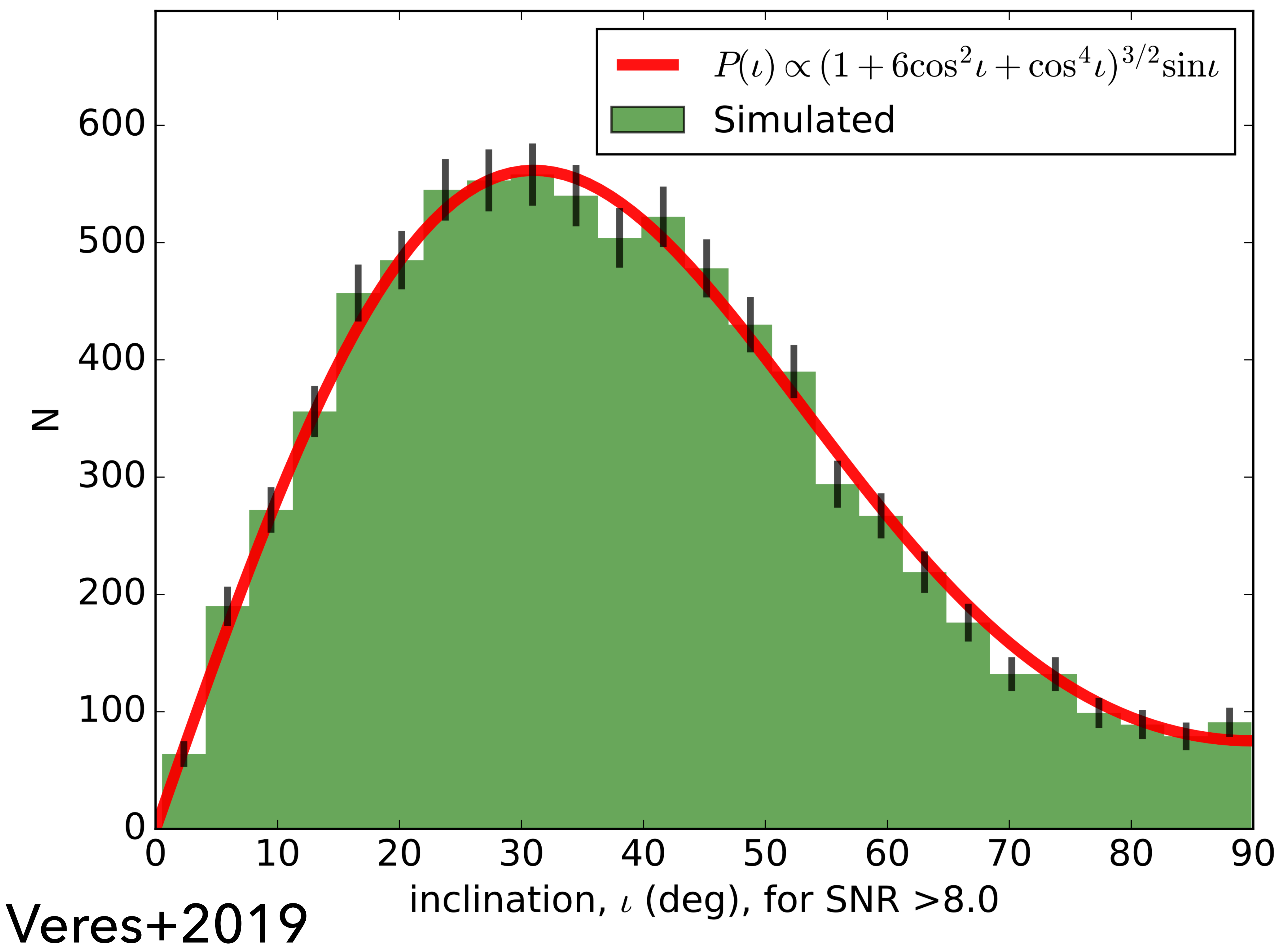


Murguia-Berthier, Kilpatrick, +2017

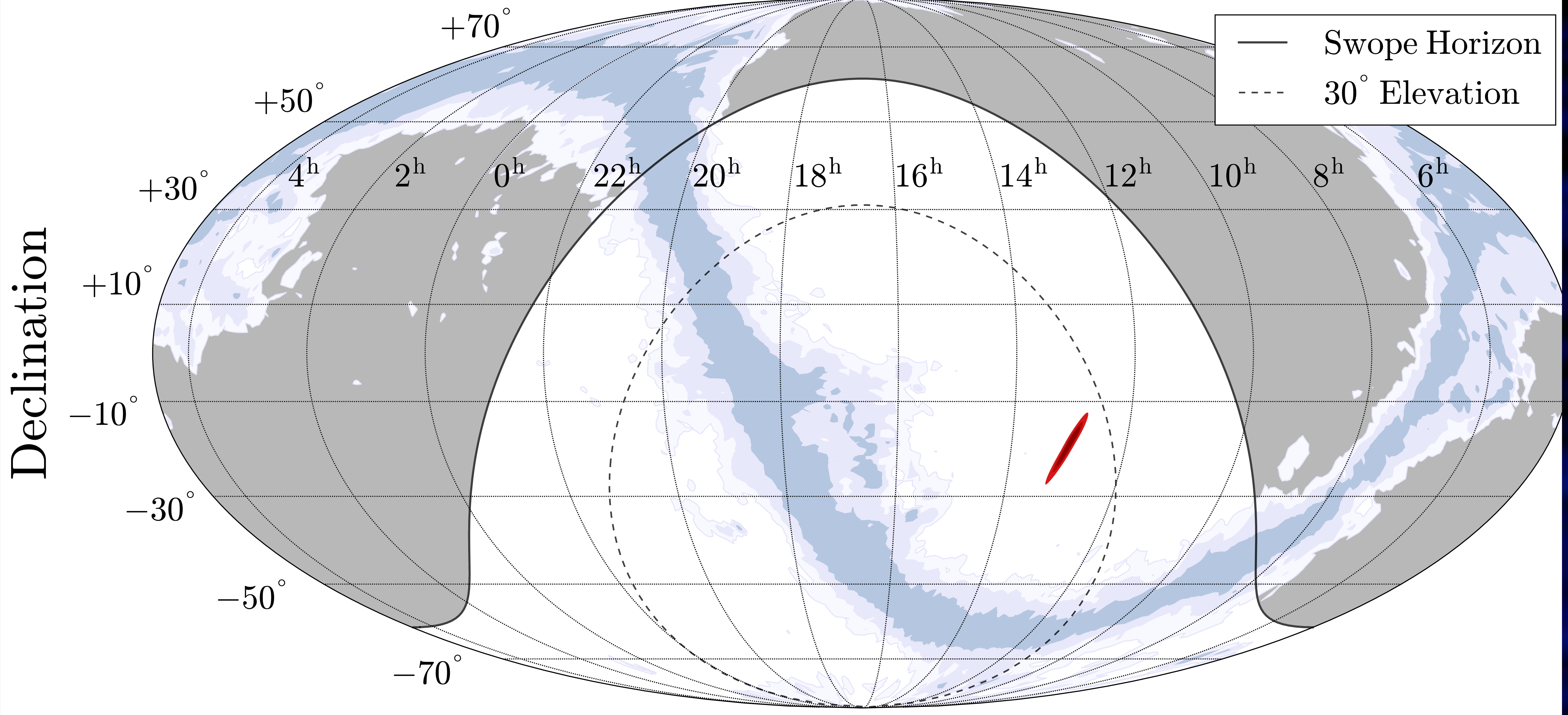
Viewing angle

GRBs always viewed pole-on

Viewing angle is arbitrary for GW, inclination effects favor ~30 deg



Veres+2019

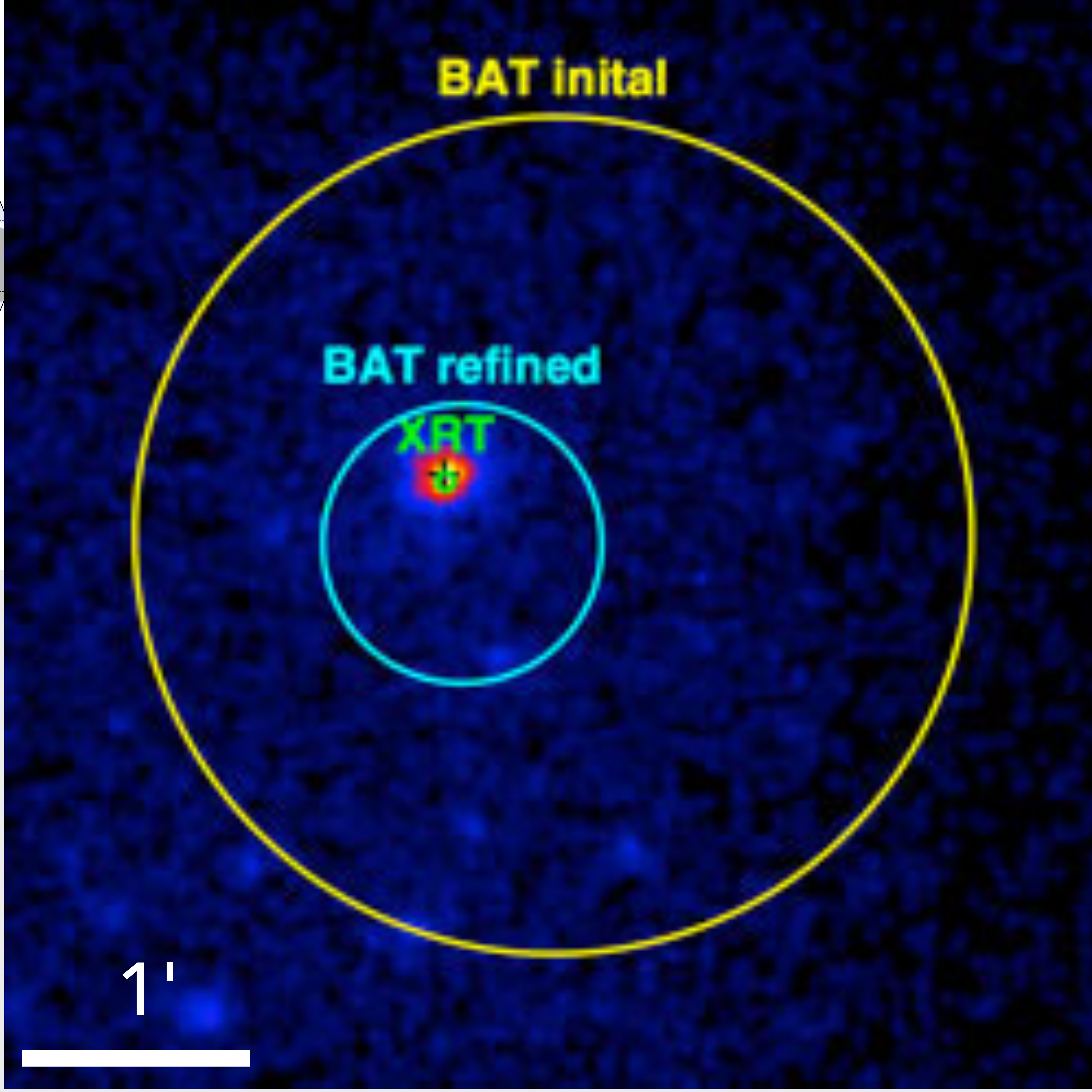


Coulter+2017

Localization

GW require significant follow up for localization even in the best cases (few x10 deg²)

Short GRBs are frequently localized immediately, enabling deep constraints on kilonova emission

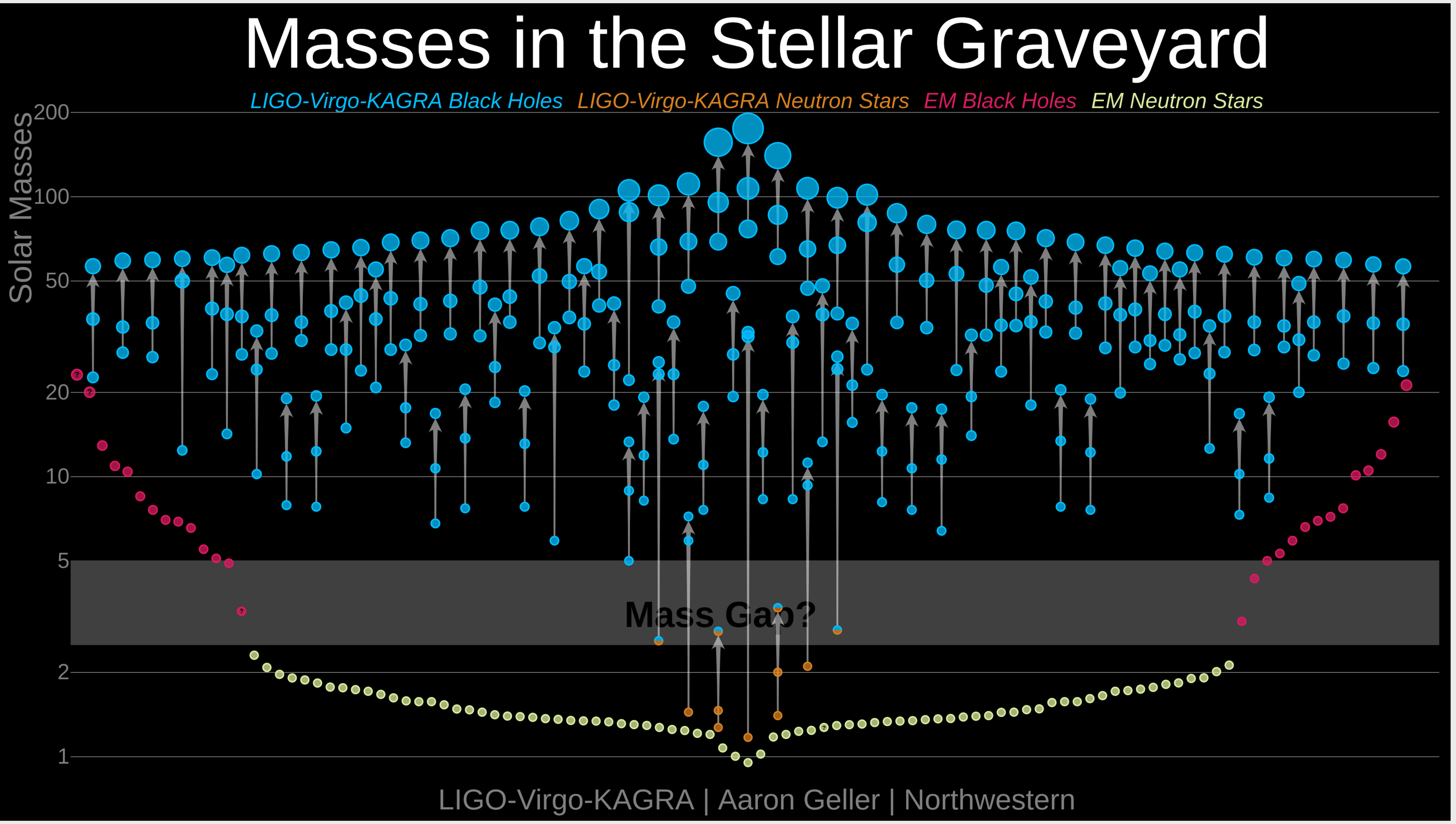


GRB060614A, Gehrels+2006

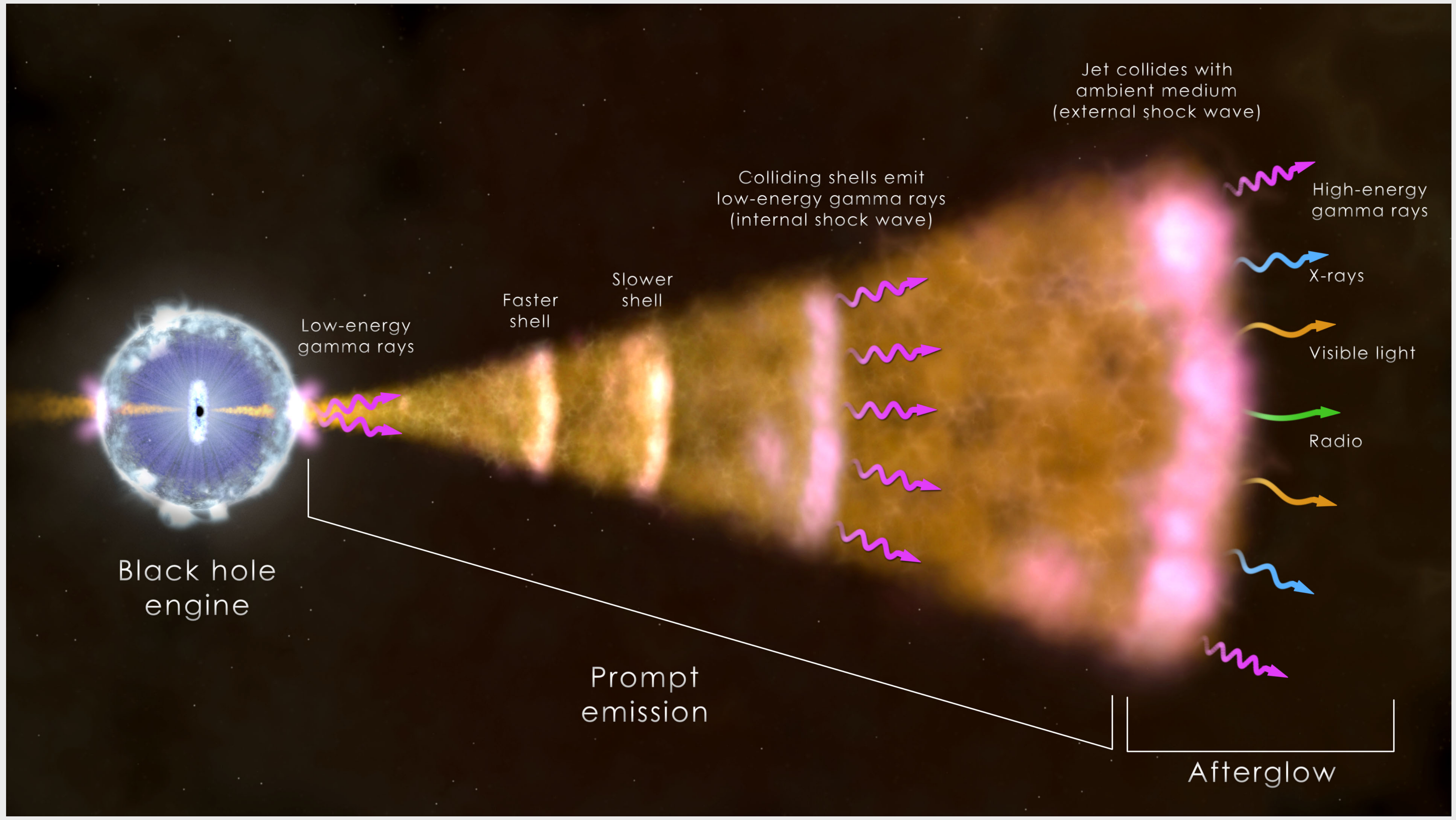
Classification

GW provides key information about the mass of the merger that can be used to predict the emergence and luminosity of a kilonova counterpart

Short GRBs require neutron star matter, but can theoretically be produced by BNS and NSBH mergers (see Just+2015, Kyutoku+2015, Foucart+2018, Shibati+2019)



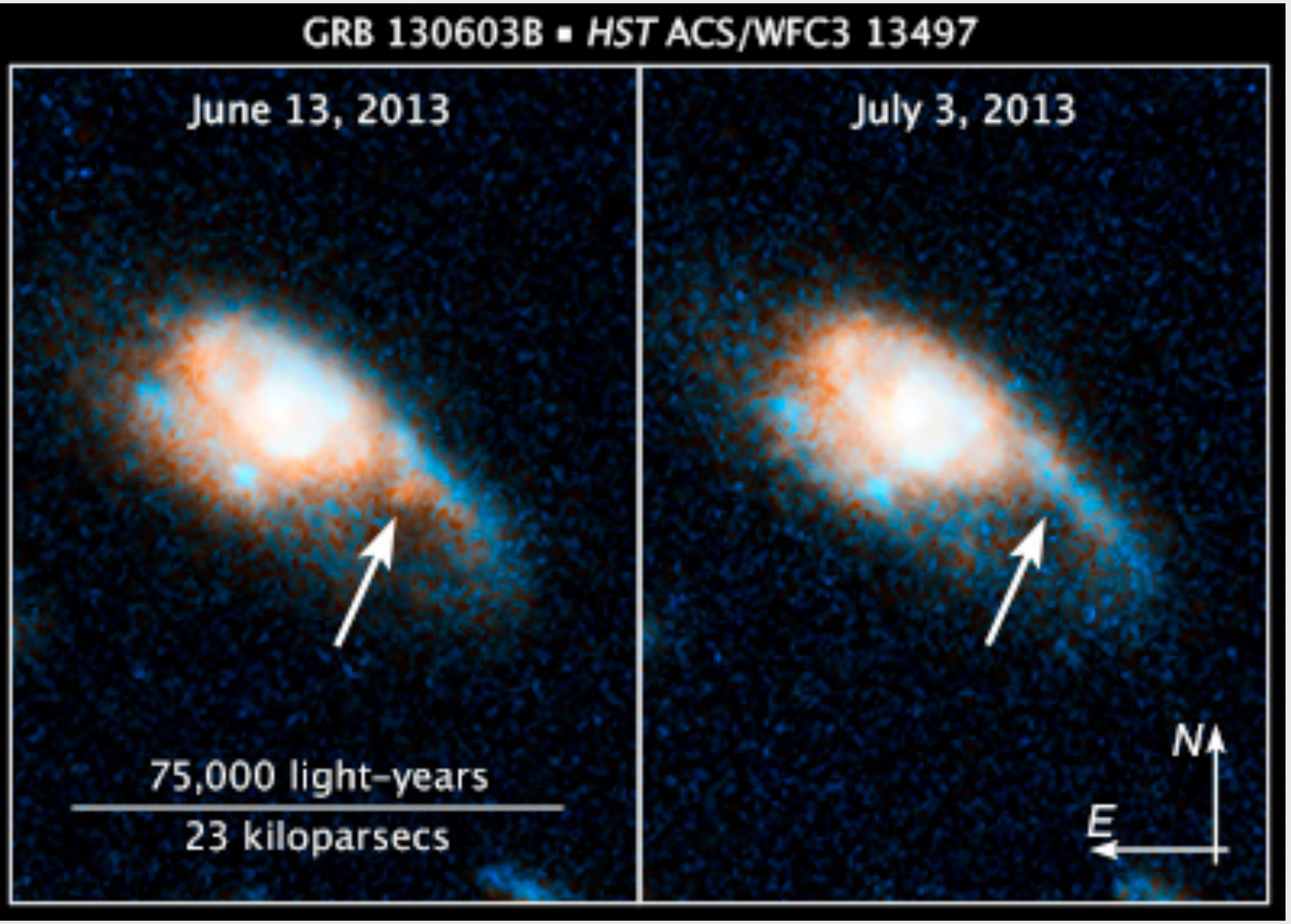
LIGO-Virgo-KAGRA / Aaron Geller / Northwestern



Credit: NASA/Swift

GRB-targeted kilonovae

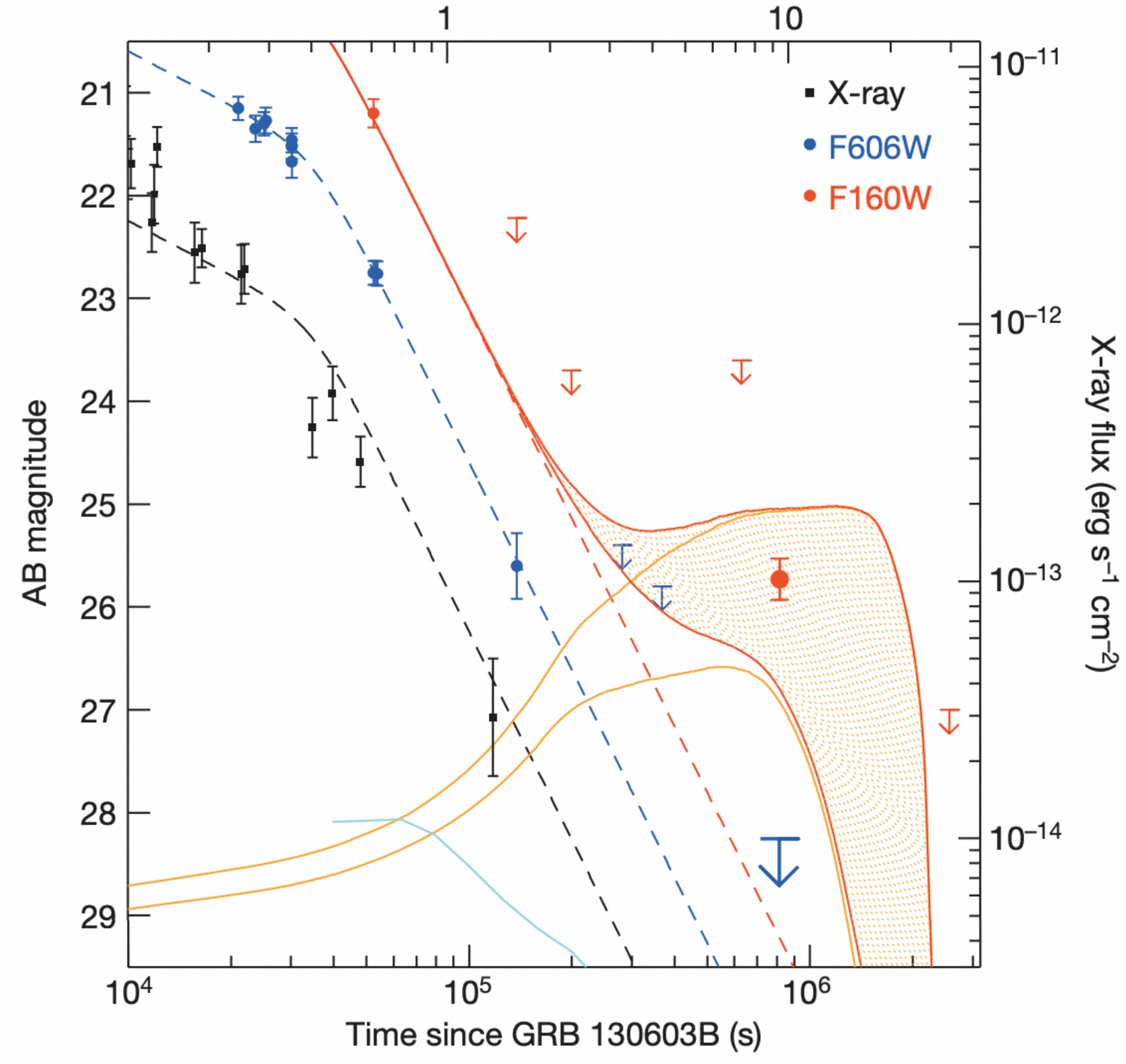
Kilonovae from GRBs: the "infrared excess"



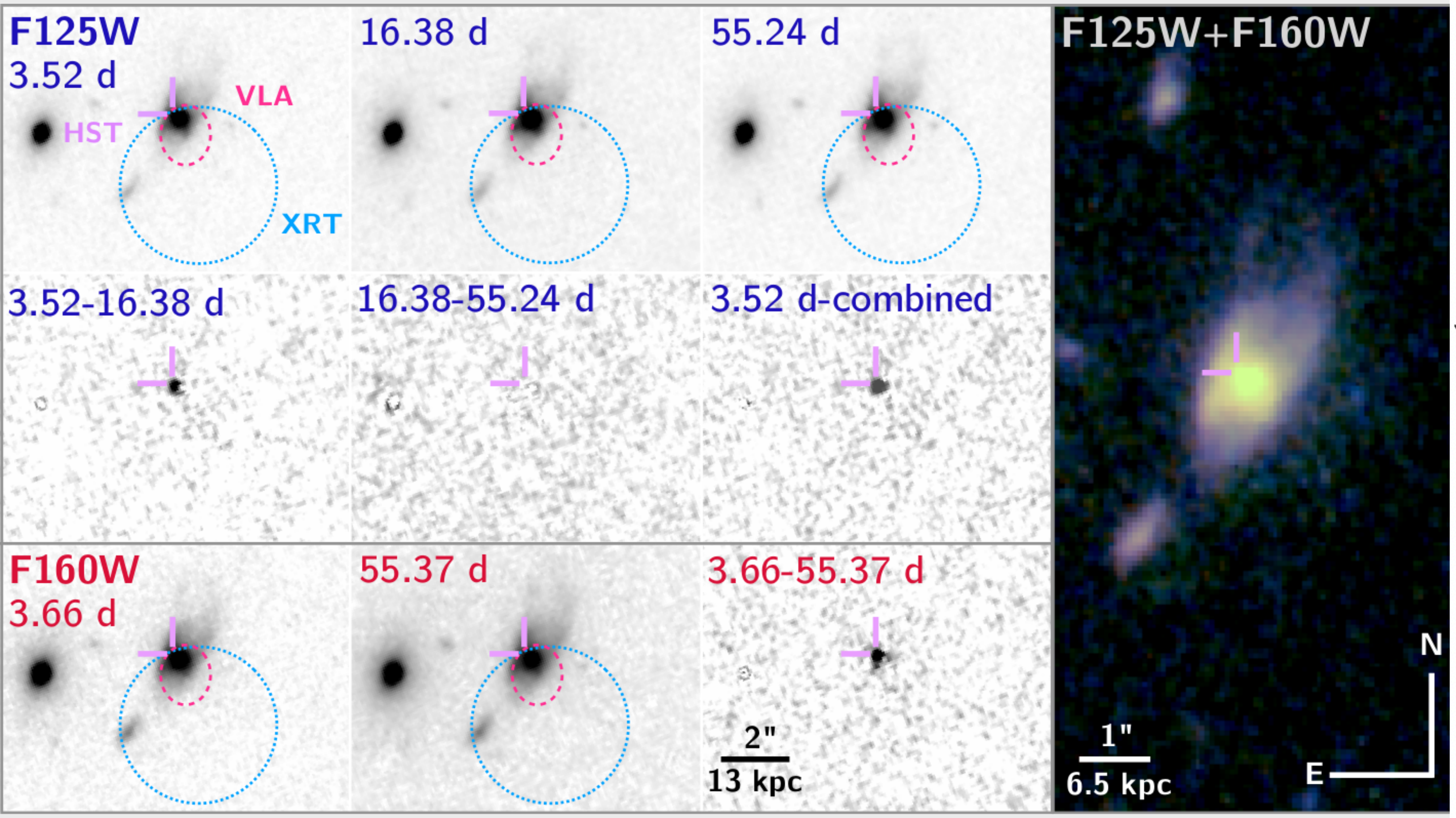
Tanvir+2013

GRB130603B - first clear example of a kilonova candidate.

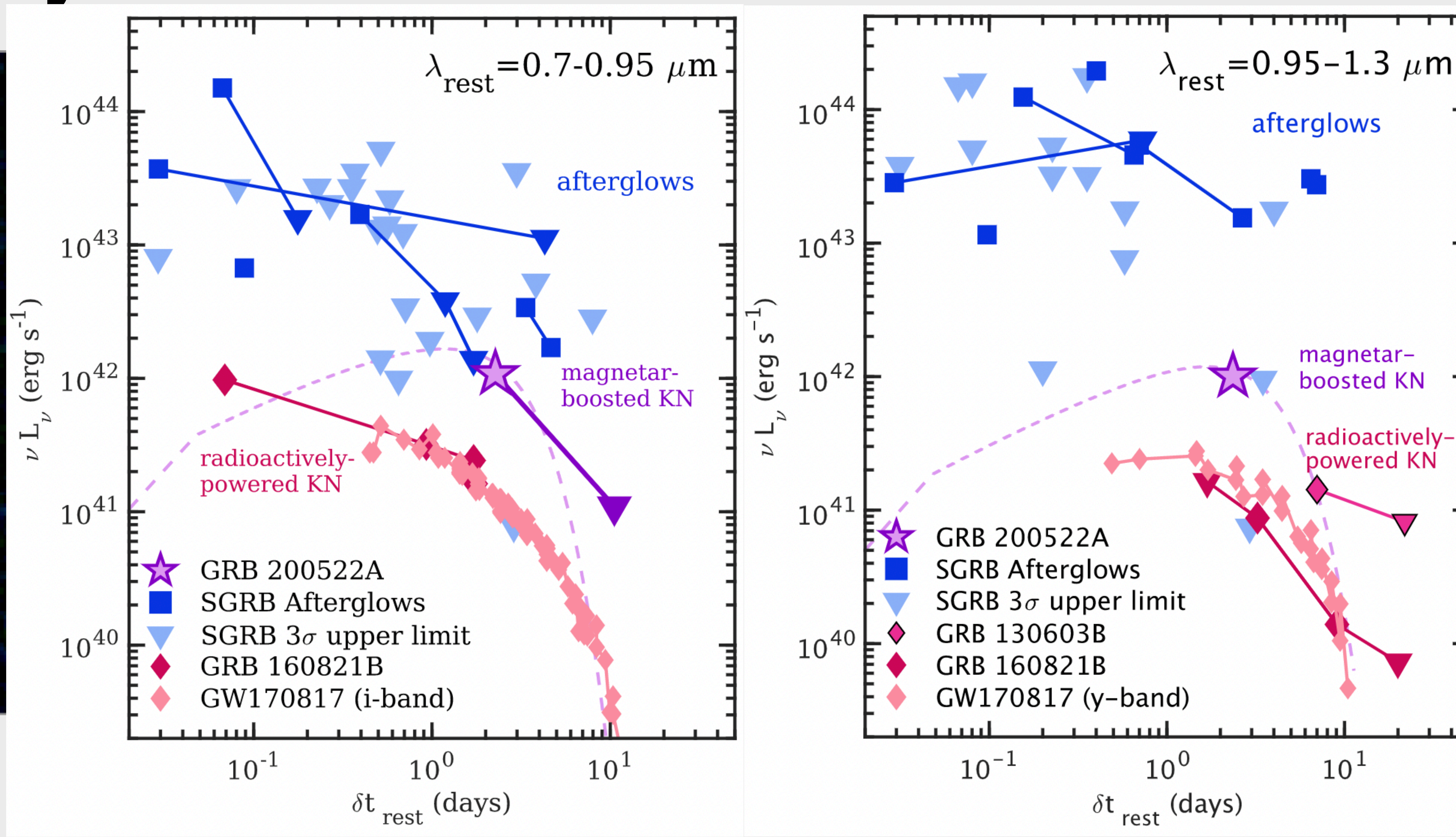
Dynamical ejecta mass of ~0.04 M⊙



GRB 200522A: an extremely luminous kilonova



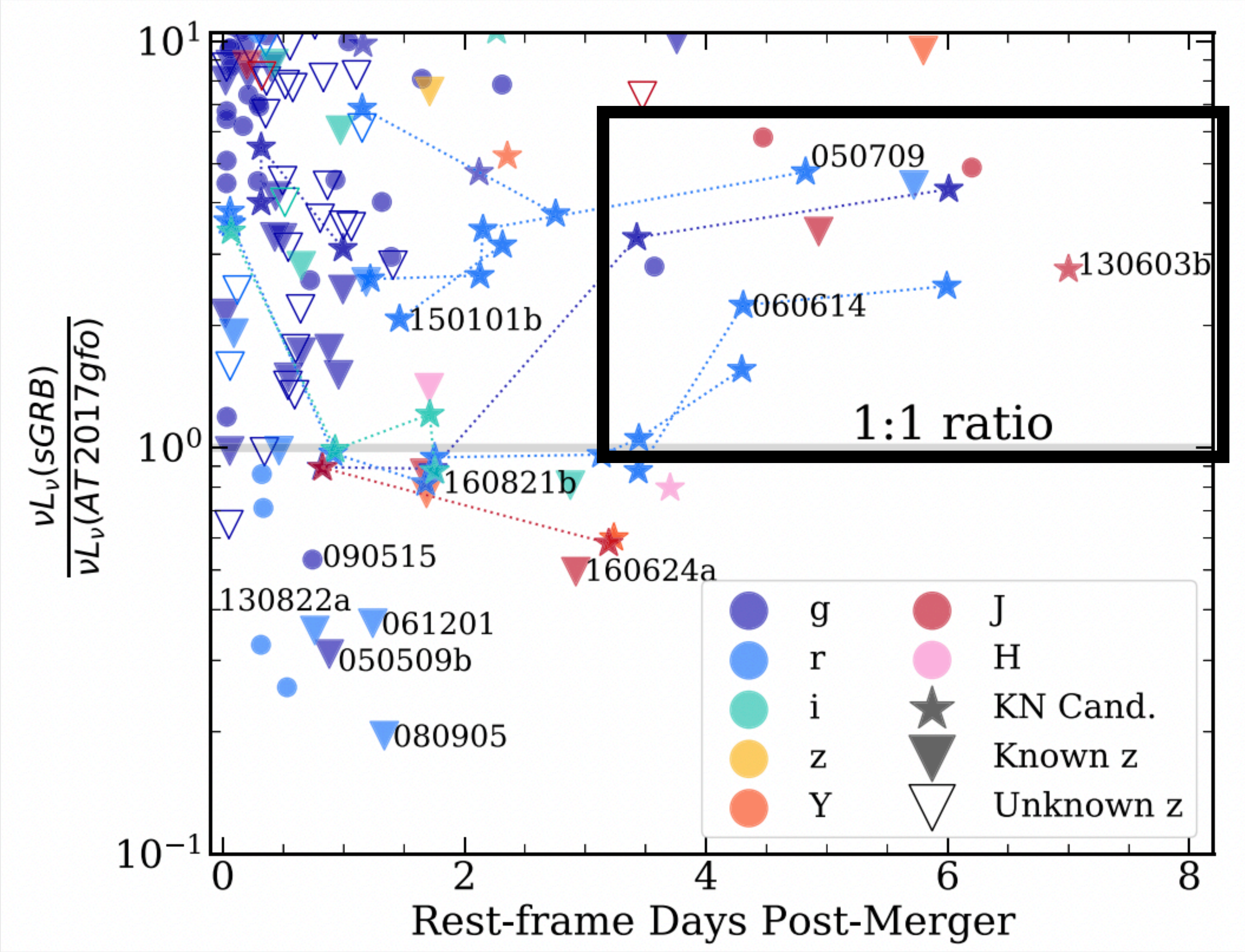
Fong+2021 (inc. Kilpatrick)



One of the highest redshift kilonova candidate detections in a z=0.55 galaxy.

Optical and IR component on timescales of ~3 days are ~10x brighter than GW170817

GRB-targeted kilonovae: populations



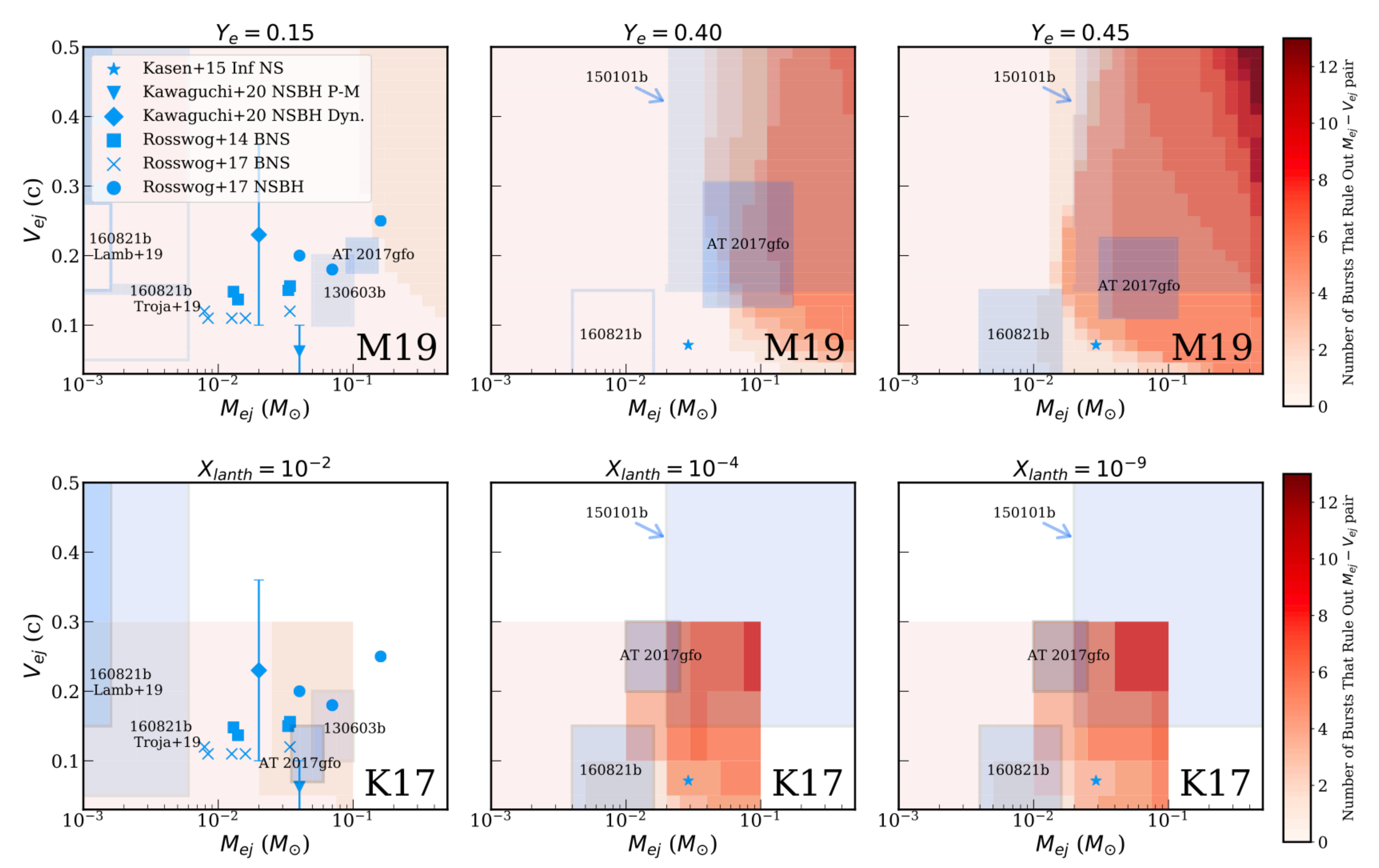
Significant population of sources with long-lived, relatively blue emission at several days post-merger

This is too luminous to be consistent with afterglow emission - population of high ejecta mass kilonovae?

Rastinejad, Fong, Kilpatrick+2021

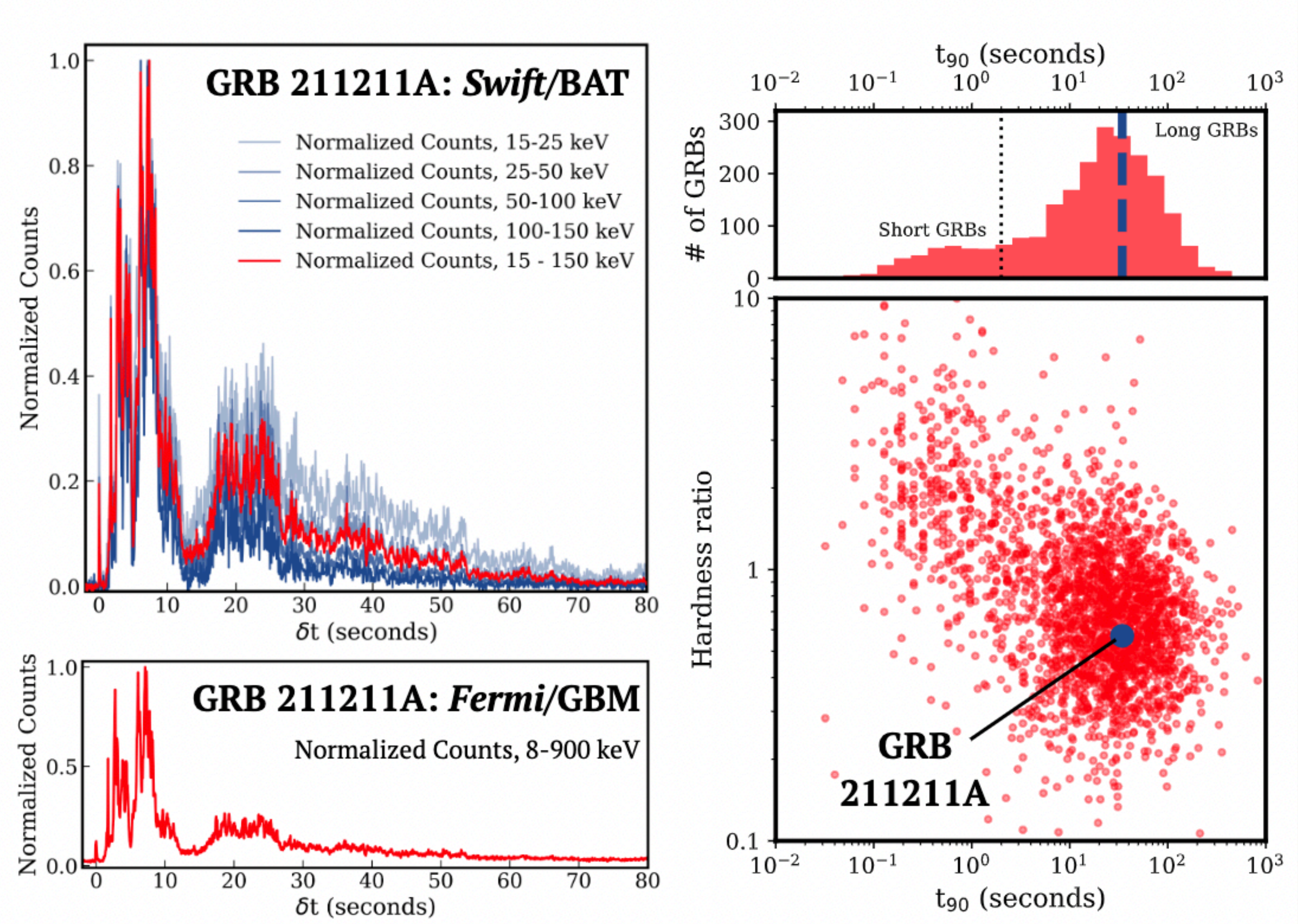
GRB-targeted kilonovae: populations

Rastinejad, Fong, Kilpatrick+2021



We are more sensitive to bluer emission, but some low Y_e, high-lanthanide models are ruled out at ~0.05-0.1 $M_\odot$

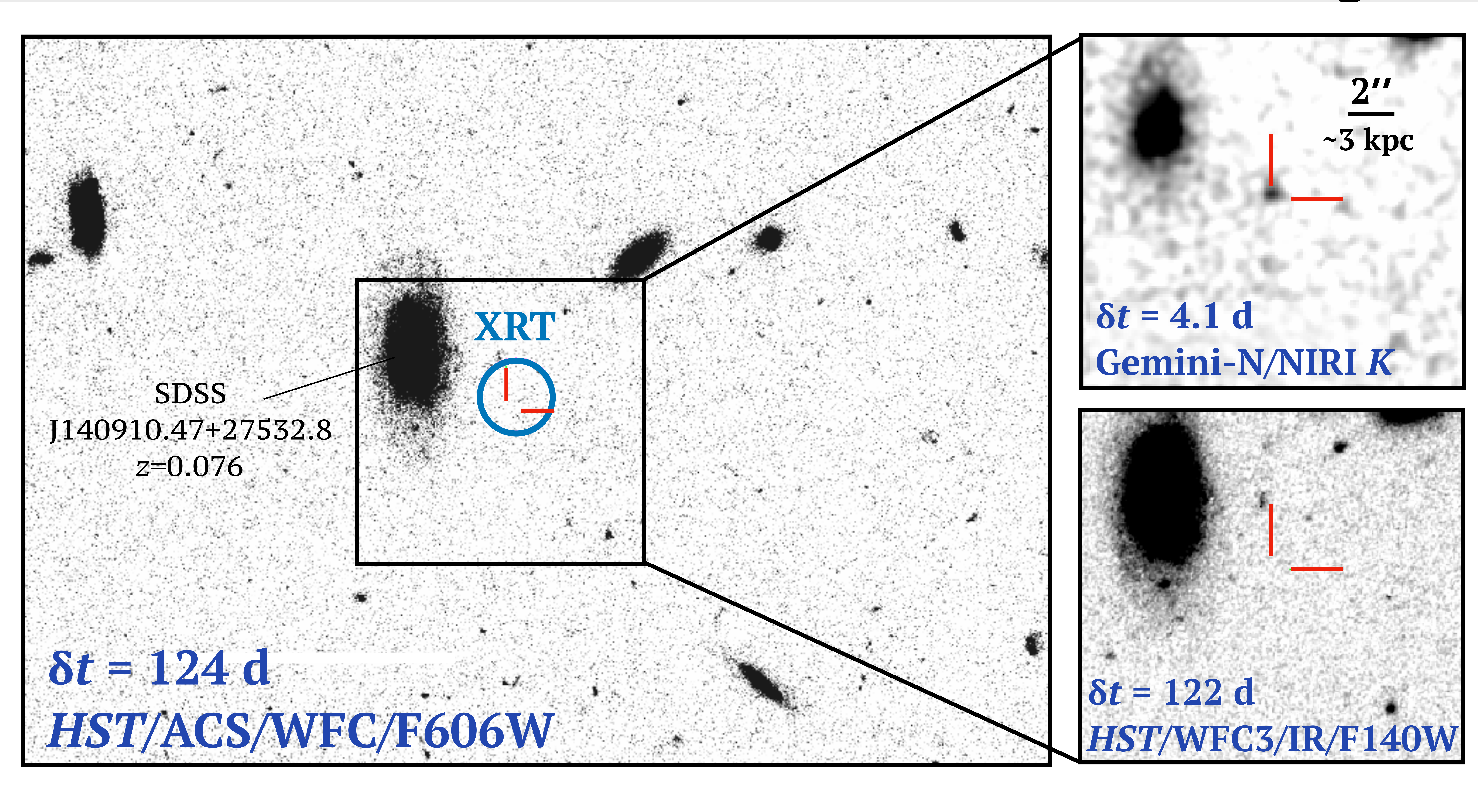
GRB 211211A: a kilonova associated with a long GRB?



Rastinejad+2022
(inc. Kilpatrick)

GRB with duration 51s shows infrared excess consistent with kilonova in most likely host galaxy (z=0.076)

GRB 211211A: a kilonova associated with a long GRB?



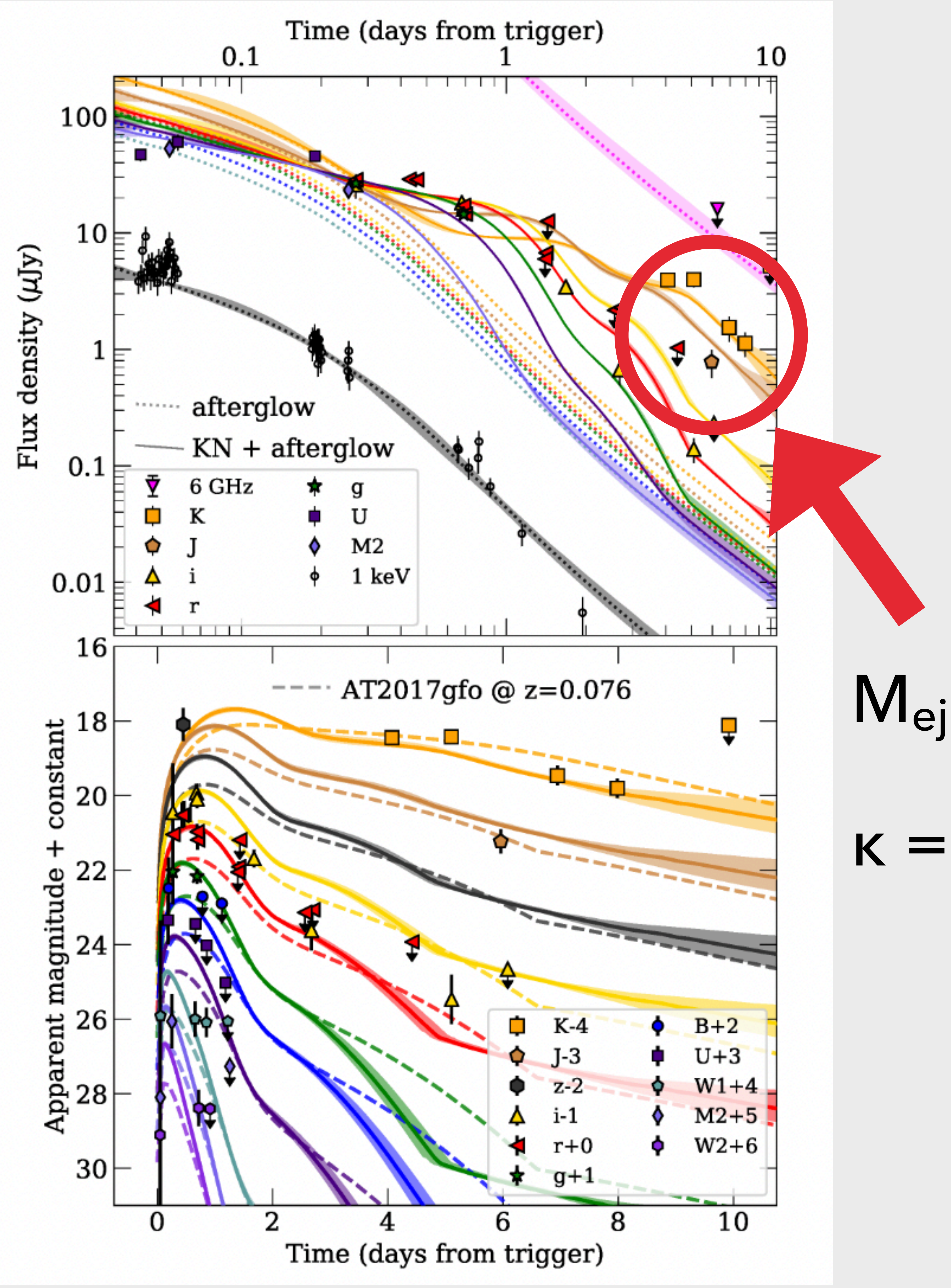
Association with a galaxy at z=0.076 - no clear background galaxy to high redshift

GRB 211211A: a kilonova associated with a long GRB?

Clear infrared excess observed in K-band

Consistent with a kilonova nearly identical to GW170817

At z=0.076 (~350 Mpc), this is near the limit of visibility for LIGO A+ and inclination is not favorable

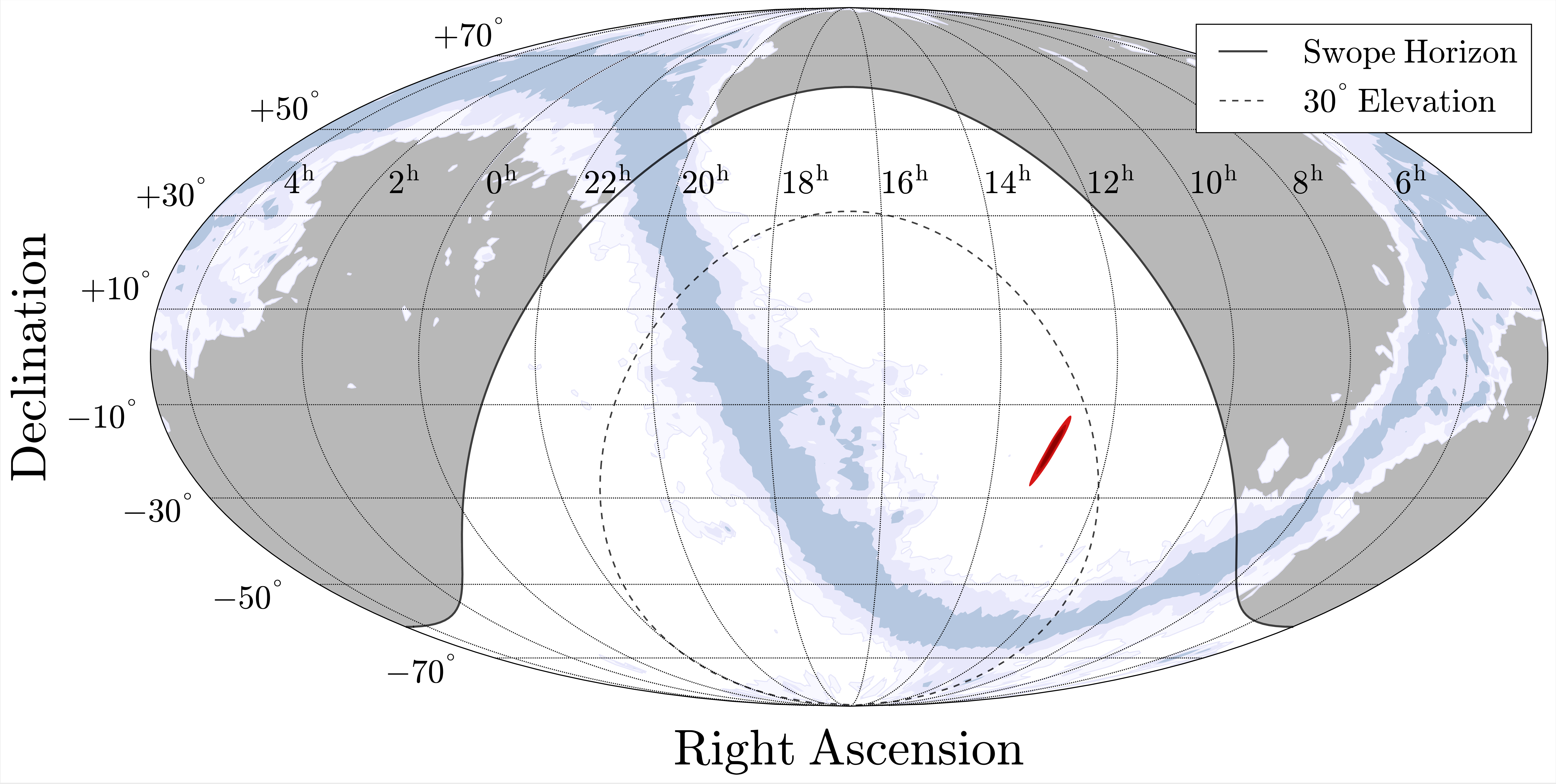


$M_{ej} = 0.03\ M_{\odot}$

$\kappa = 10\ cm^2\ g^{-1}$

GW-targeted kilonovae

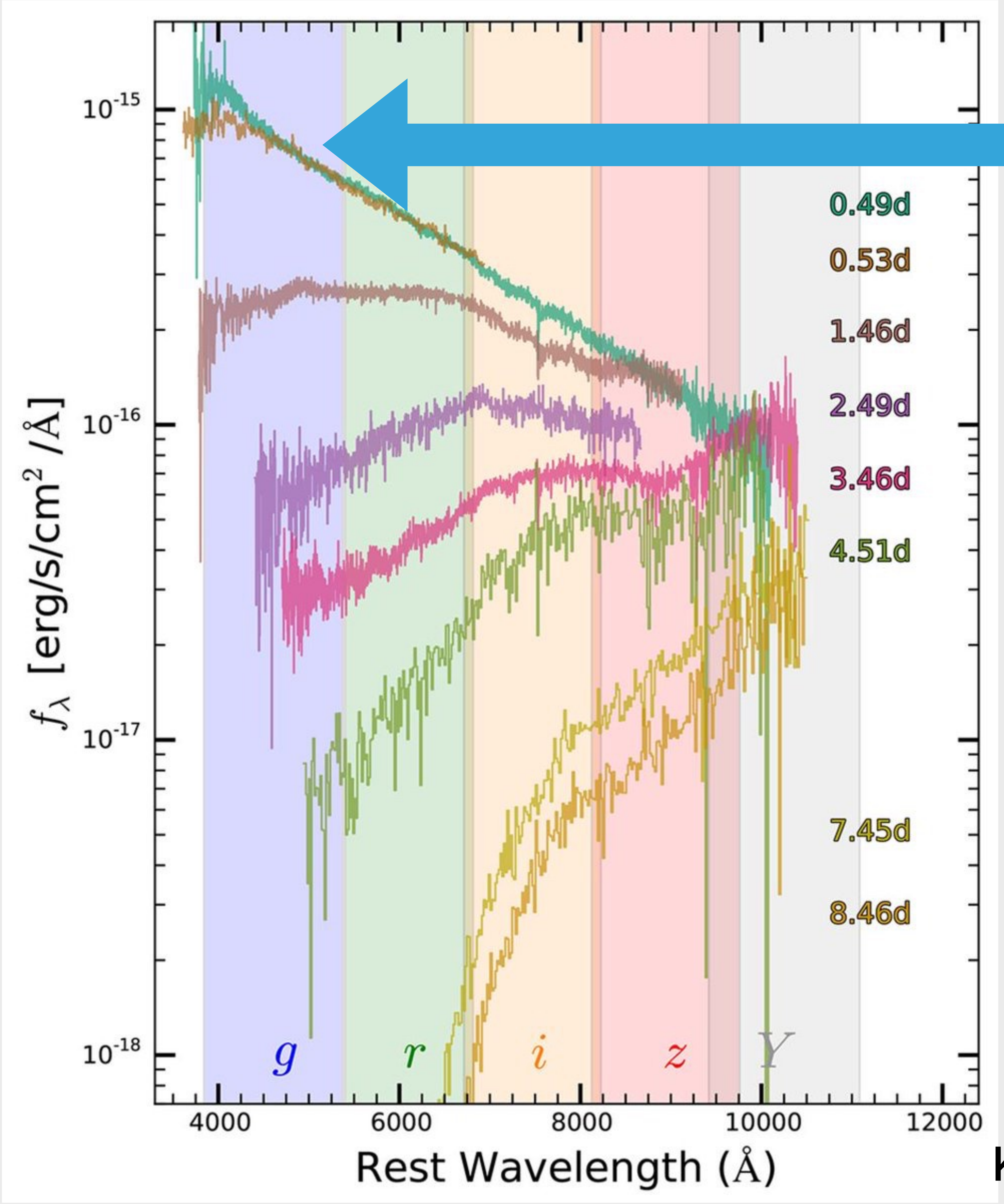
GW-targeted kilonovae: GW170817



GW-targeted kilonovae: GW170817

The kilonova to GW170817 discovered in i-band, but extremely blue

GW-targeted kilonovae: GW170817



Kilpatrick+2017

Extremely blue component confirms neutrino-driven outflow

The peak of the energy distribution shifted beyond 9000 Å in <5 days

GW-targeted kilonovae: GW170817

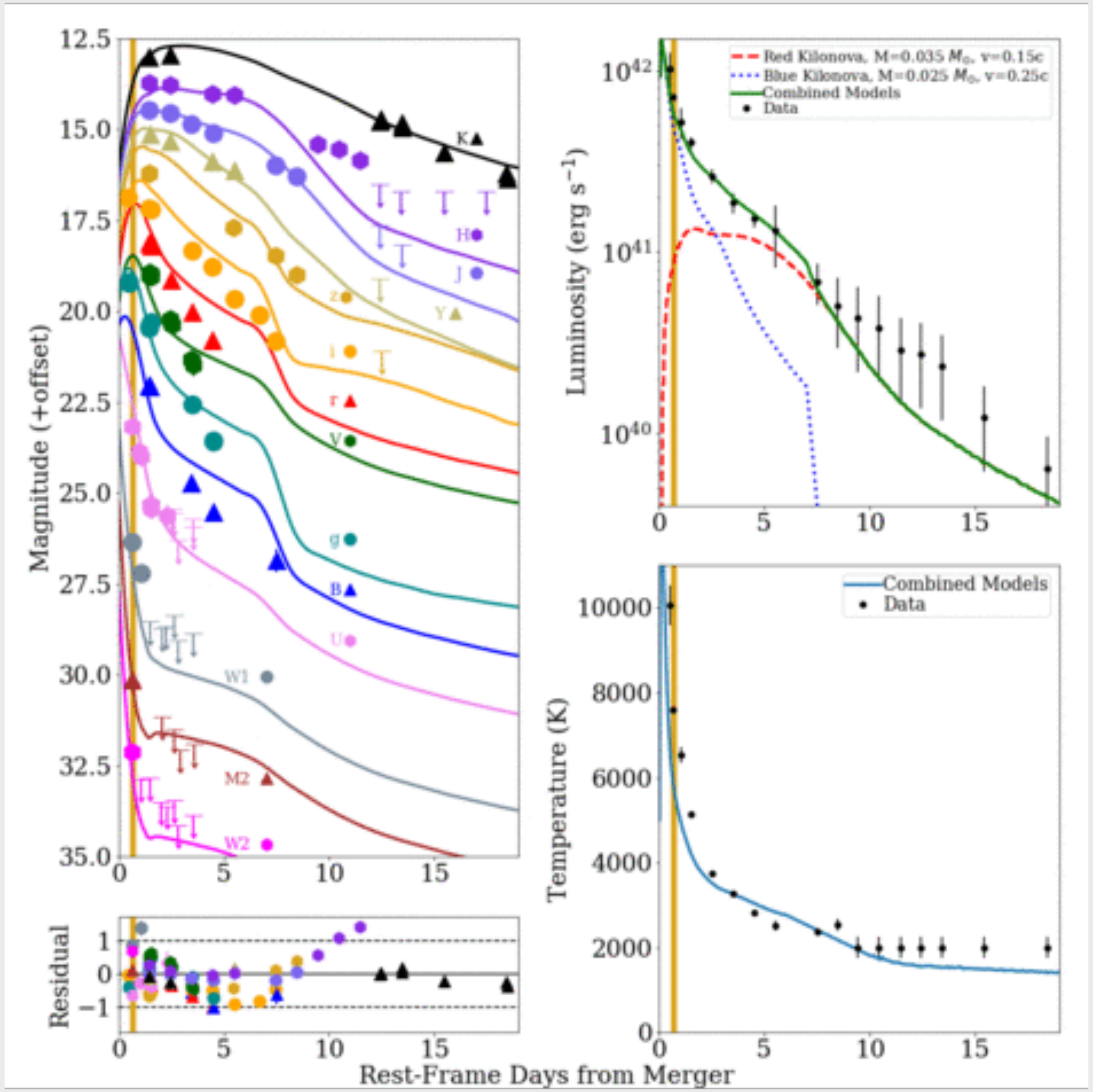
"Blue" kilonova:

$\kappa = 1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, 0.025 $M_\odot$

"Red" kilonova:

$\kappa = 10\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, 0.035 $M_\odot$

Kilpatrick+2017



GW-targeted kilonovae: GW170817

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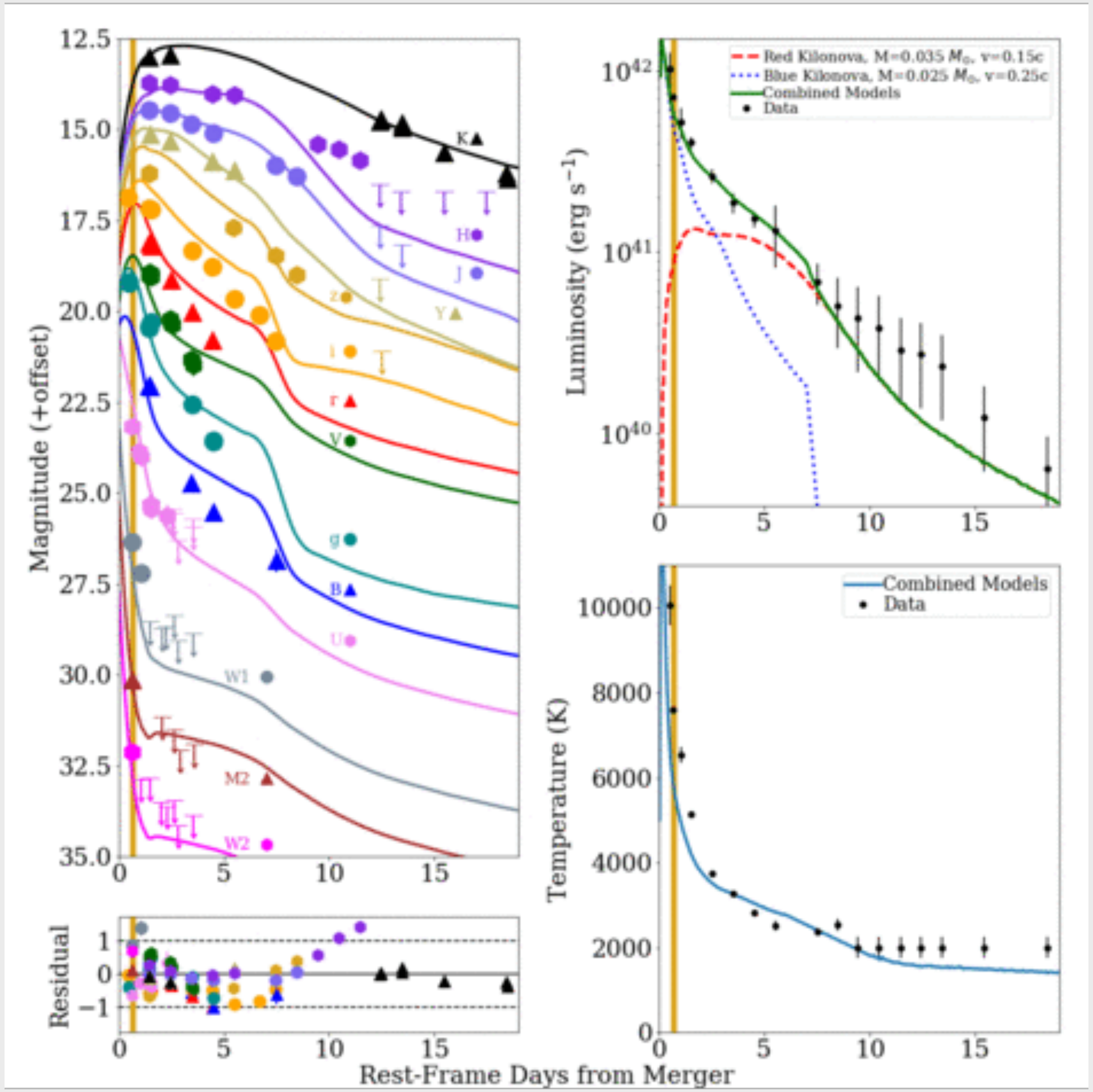
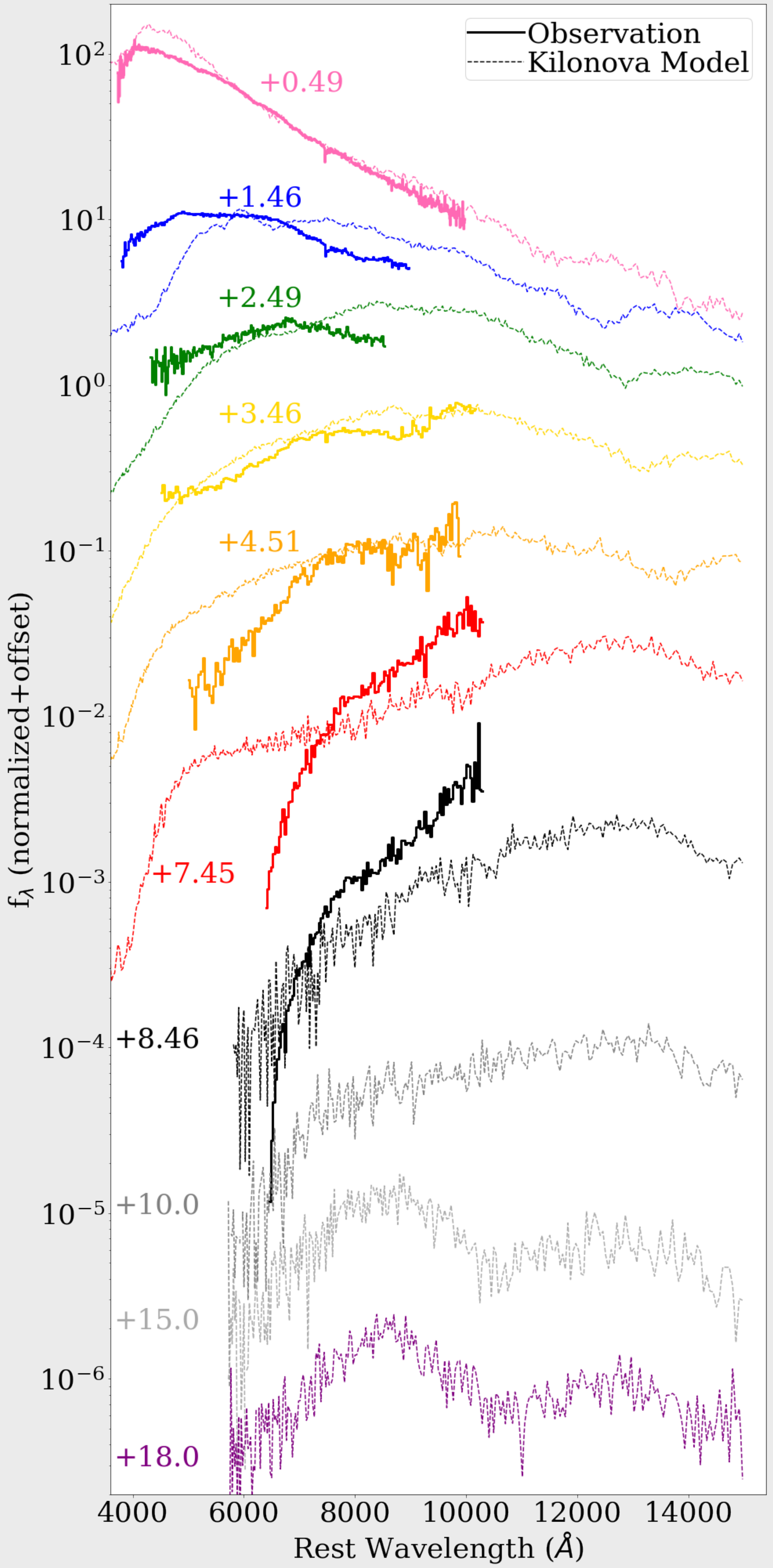
Kilpatrick+2017



GW-targeted kilonovae: GW170817

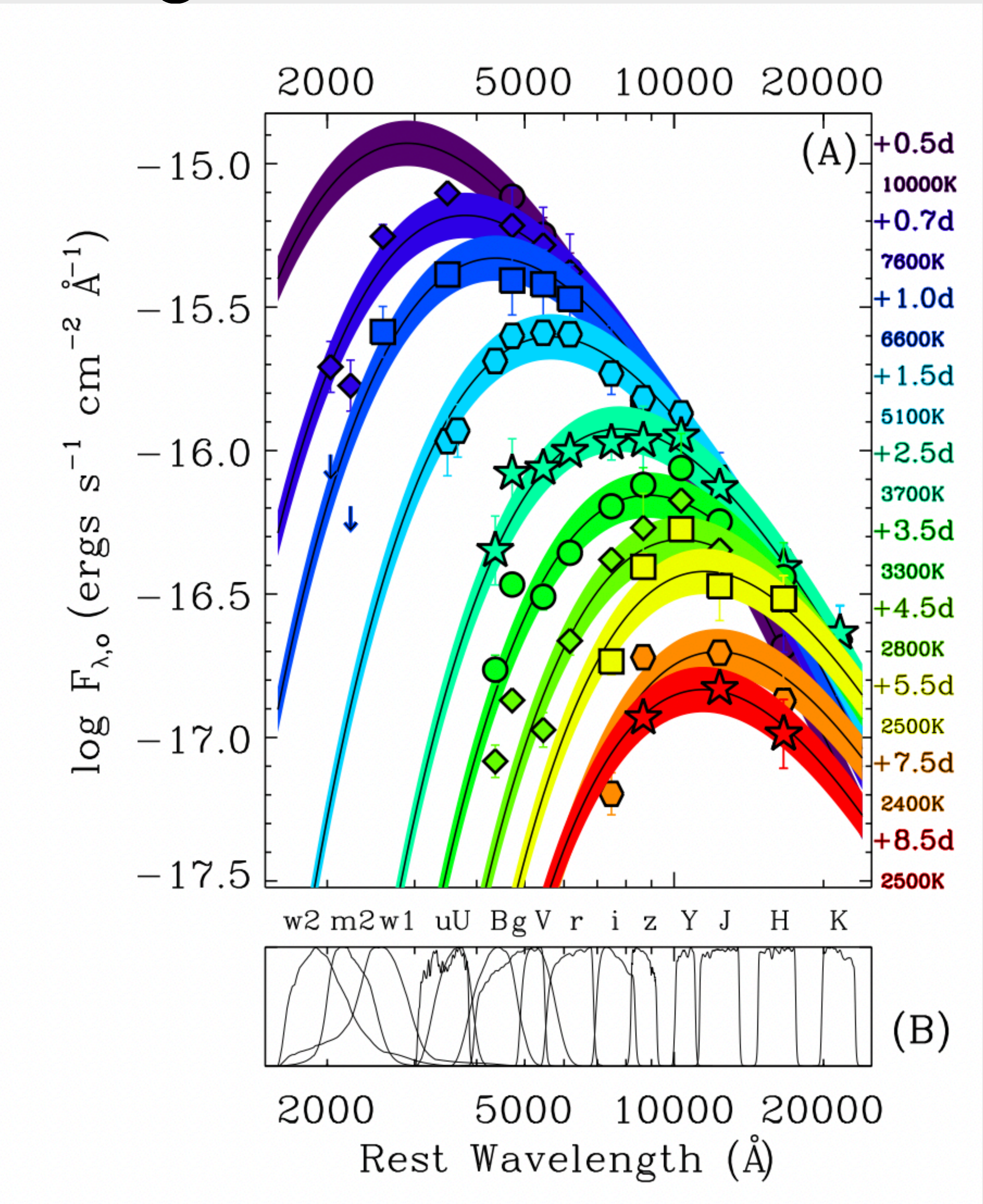
Large divergences in the spectral slope and observable features over time

The statistical power for constraining r-process abundances is large, but the theory is extremely challenging

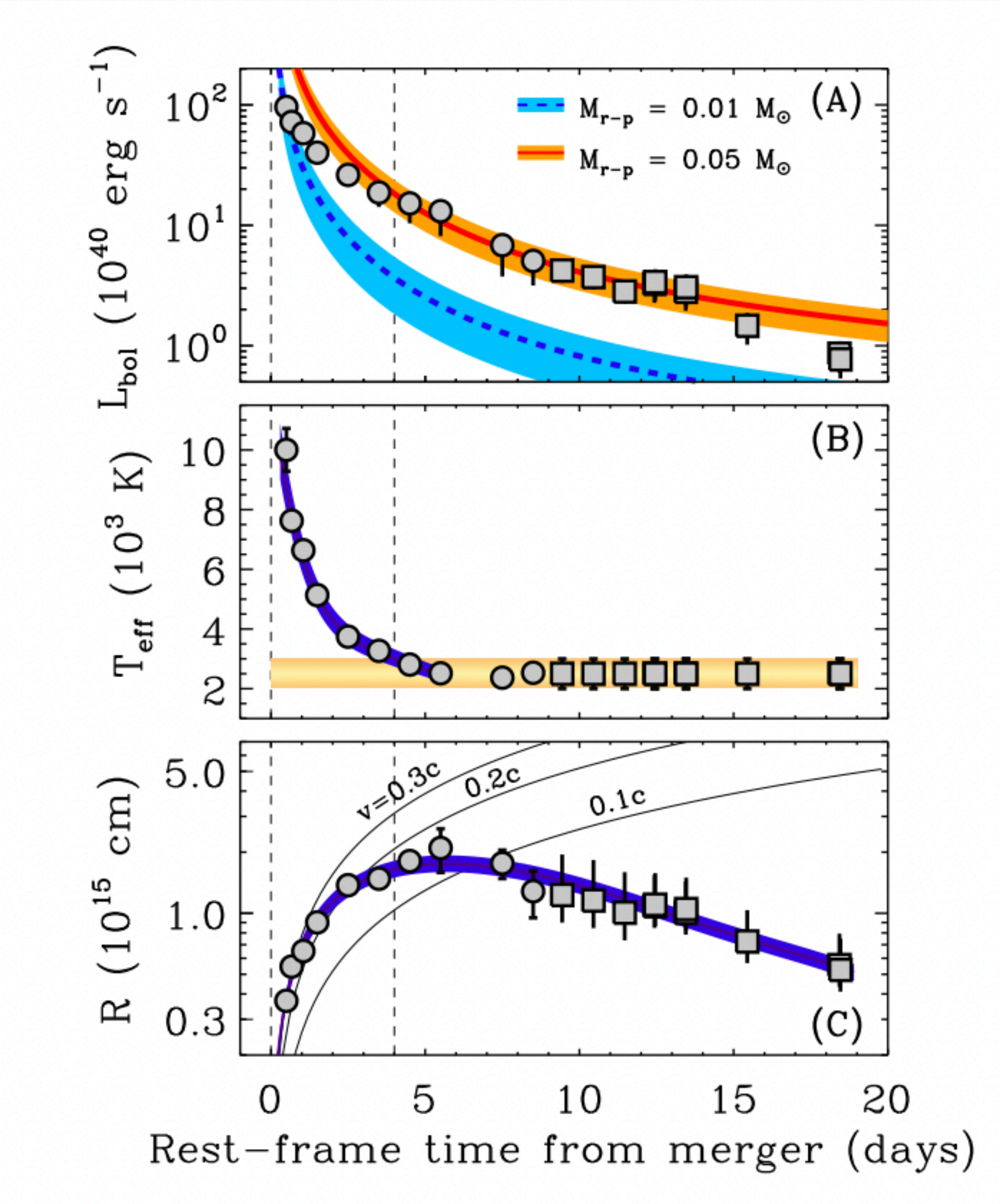


Kilpatrick+2017

GW-targeted kilonovae: GW170817

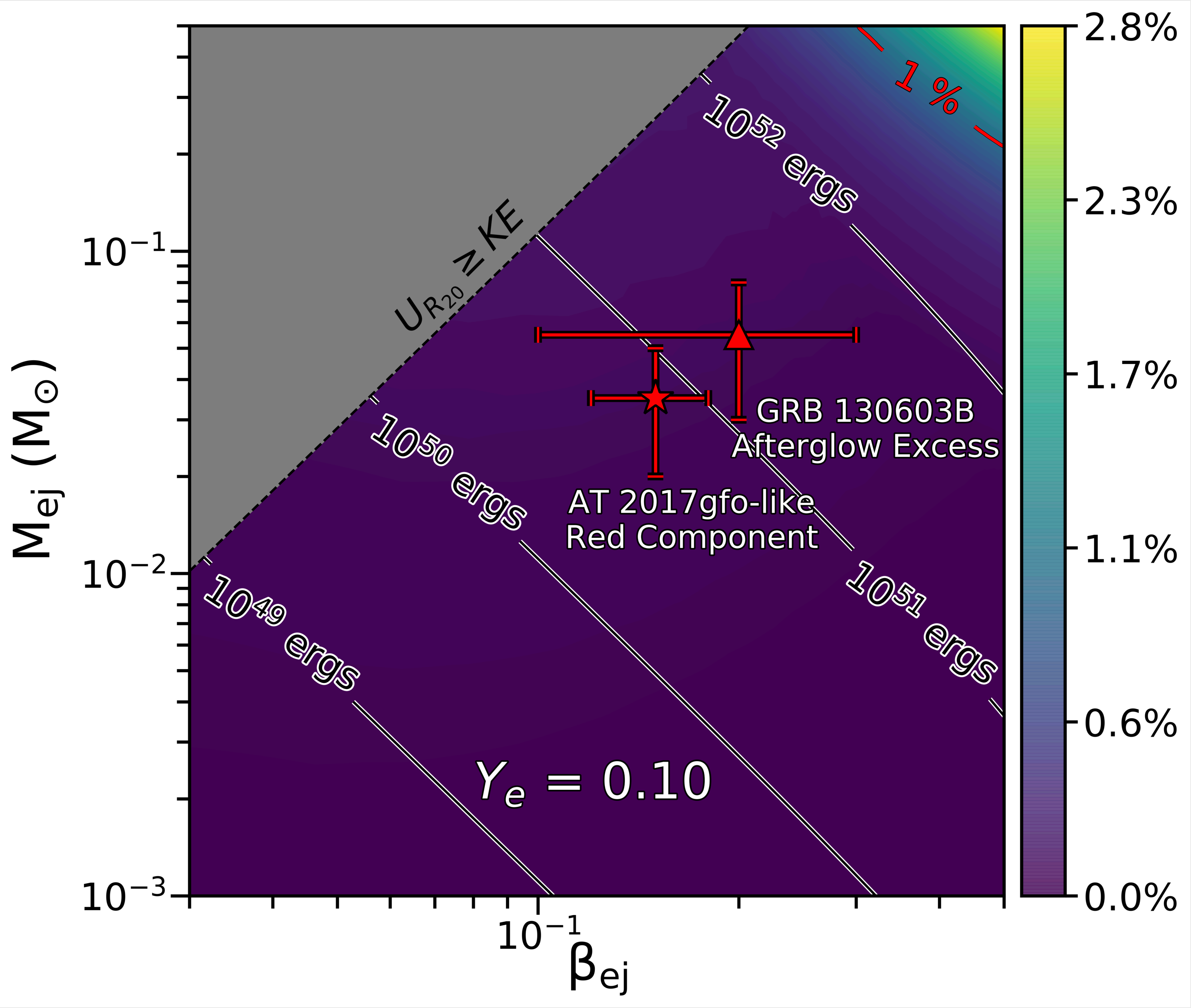


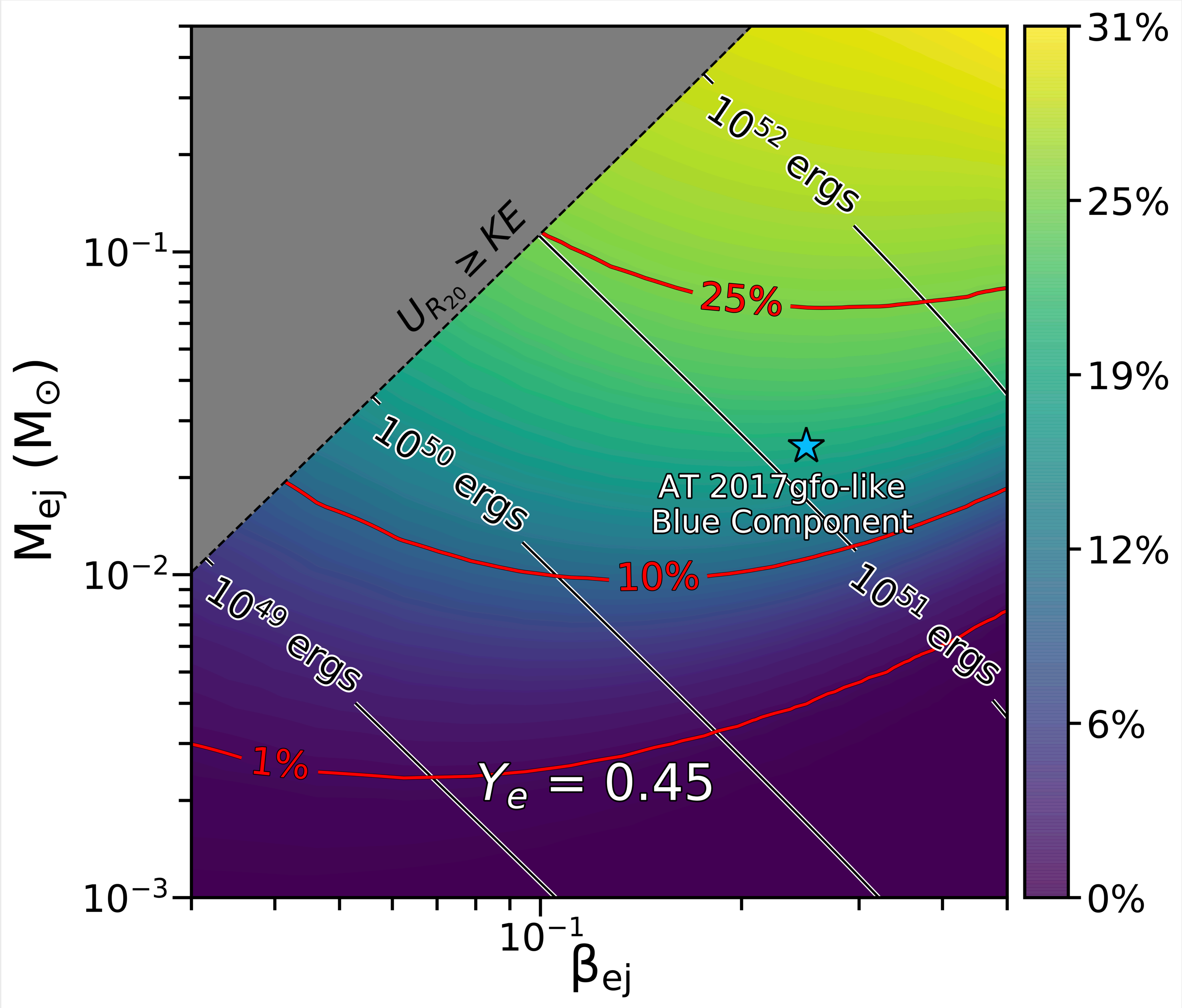
Drout+2017 (inc. Kilpatrick)



GW-targeted kilonovae: O3 BNS and NSBH mergers

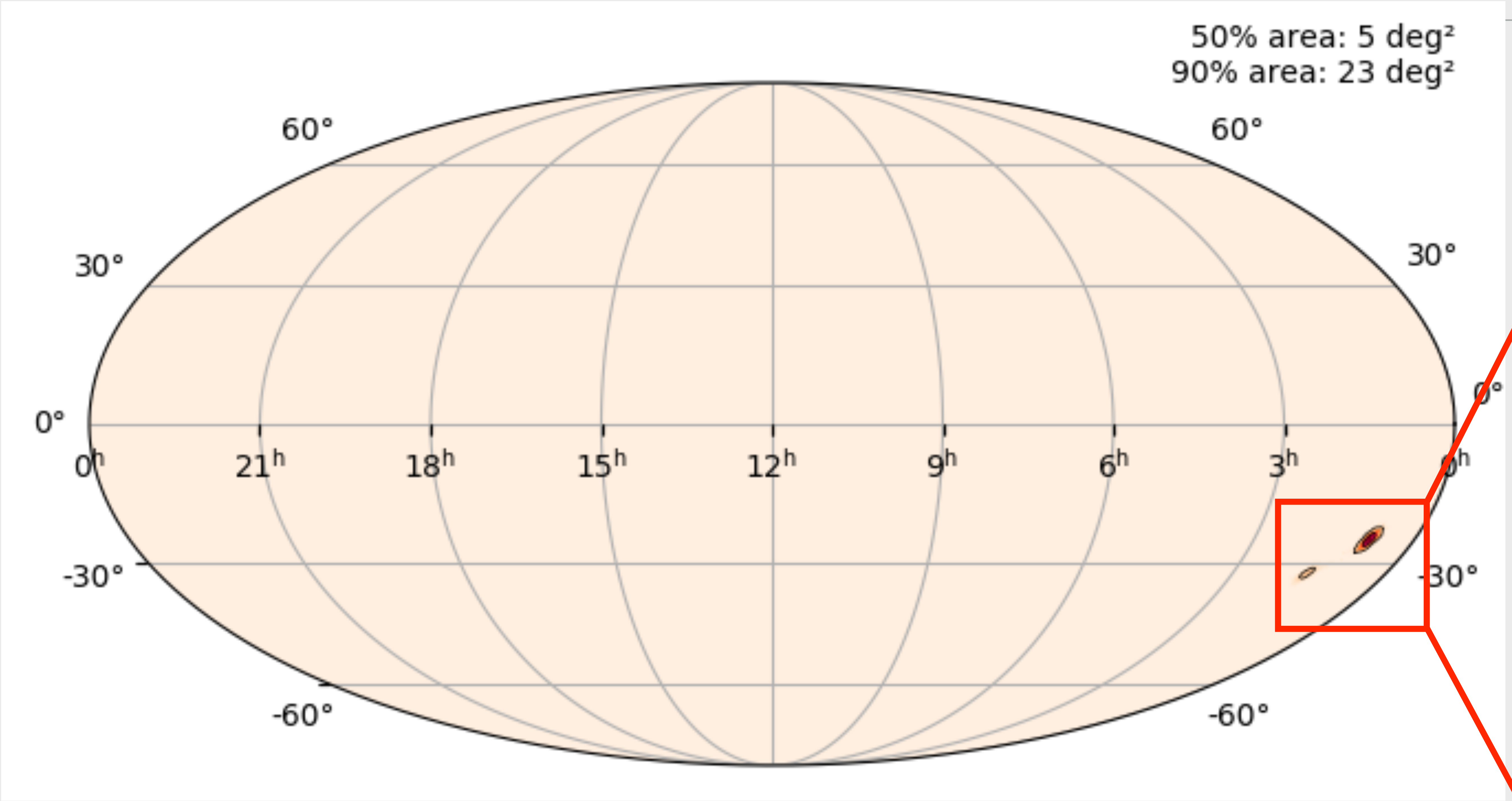
GW190425 (BNS), GW200105 (NSBH), GW200115 (NSBH)

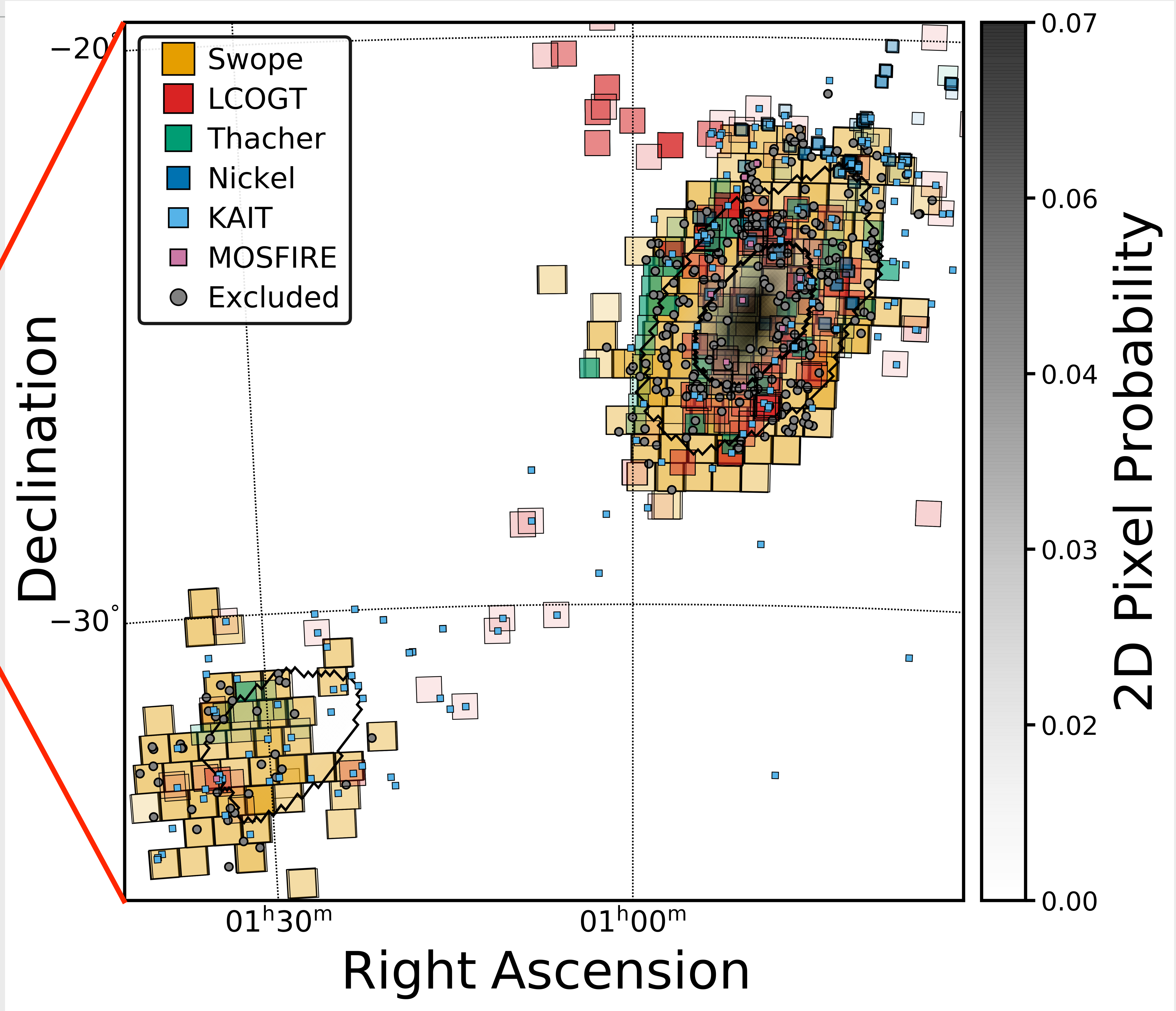




Coulter+in prep. for GW190425 from all follow up

Black Hole/Neutron Star Merger GW190814





A 23.2 + 2.6 $M_\odot$ black hole and neutron star(?) merger at ~250 Mpc

Best localized GW event yet: extremely promising for search and follow up!

Kilpatrick et al. 2021

Black Hole/Neutron Star Merger GW190814

$$r_{\text{tidal}} \approx \left(\frac{M_{BH}}{M_{NS}}\right)^{1/3} R_{NS}$$

$$r_{\text{ISCO}} = \frac{6GM_{BH}}{c^2}$$

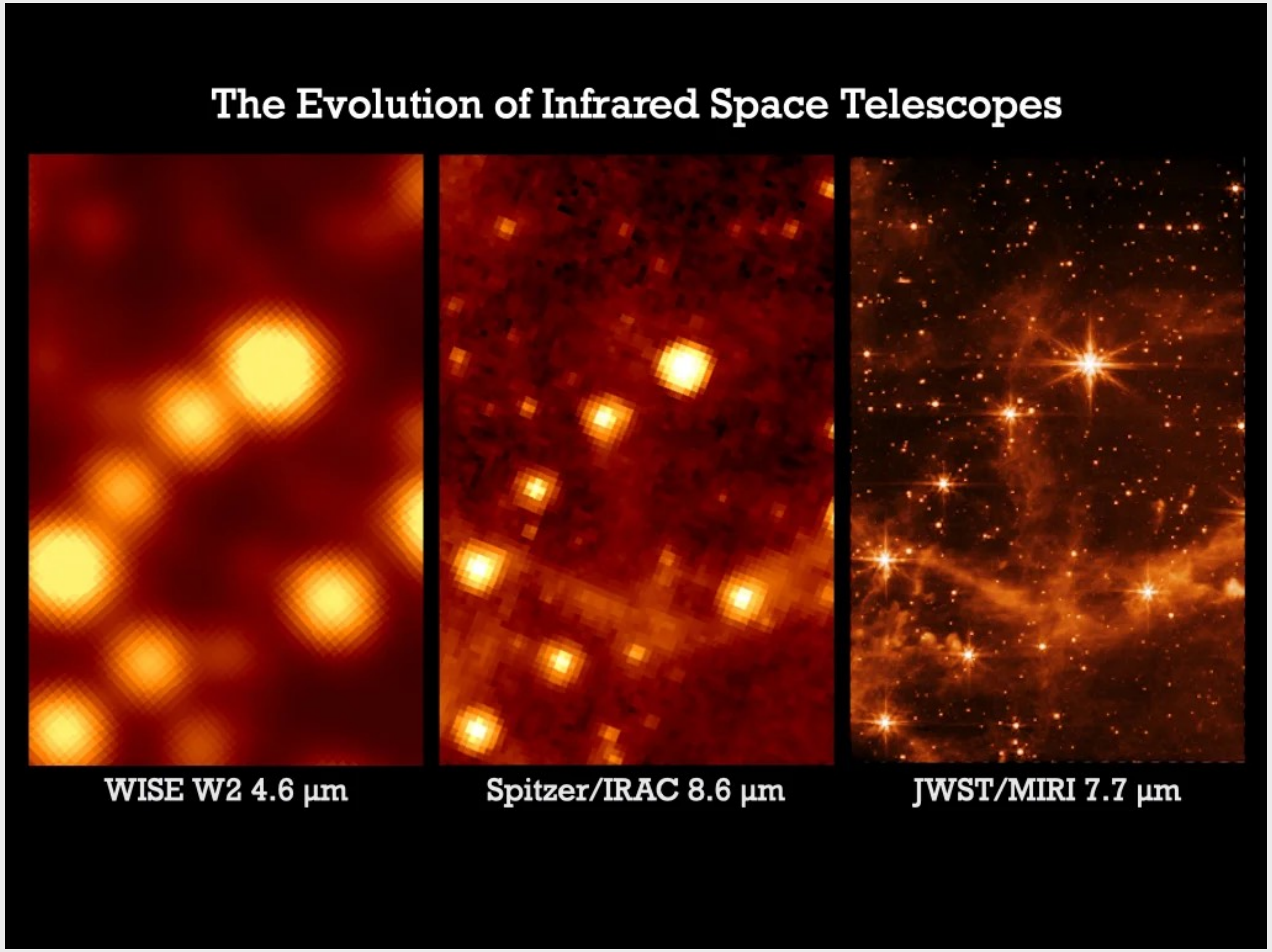
$$\frac{r_{\text{tidal}}}{r_{\text{ISCO}}} \propto M_{BH}^{-2/3} M_{NS}^{-1/3} R_{NS} > 1$$

Condition to produce a kilonova - requires a low-mass black hole or stiff equation of state

BH larger than ~6-10 $M_\odot$ will produce no ejecta even for the most massive, largest NS

Kyutoku+2015

Gravity Collective/GW04 JWST Program

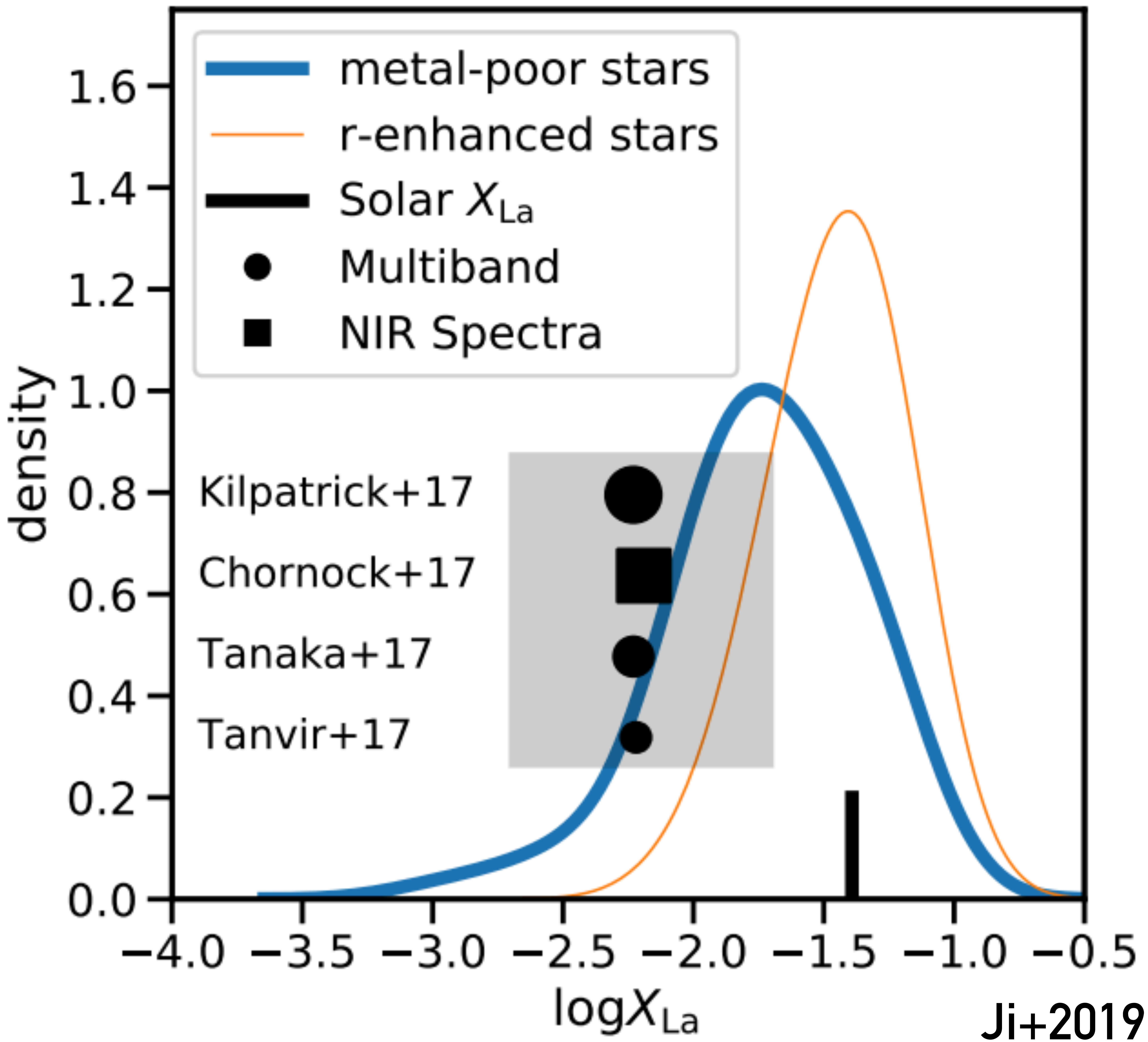


Credit: NASA/
ESA/JPL/Caltech

Significant triggered follow up with JWST is planned for kilonovae discovered from GRBs and GW events during O4

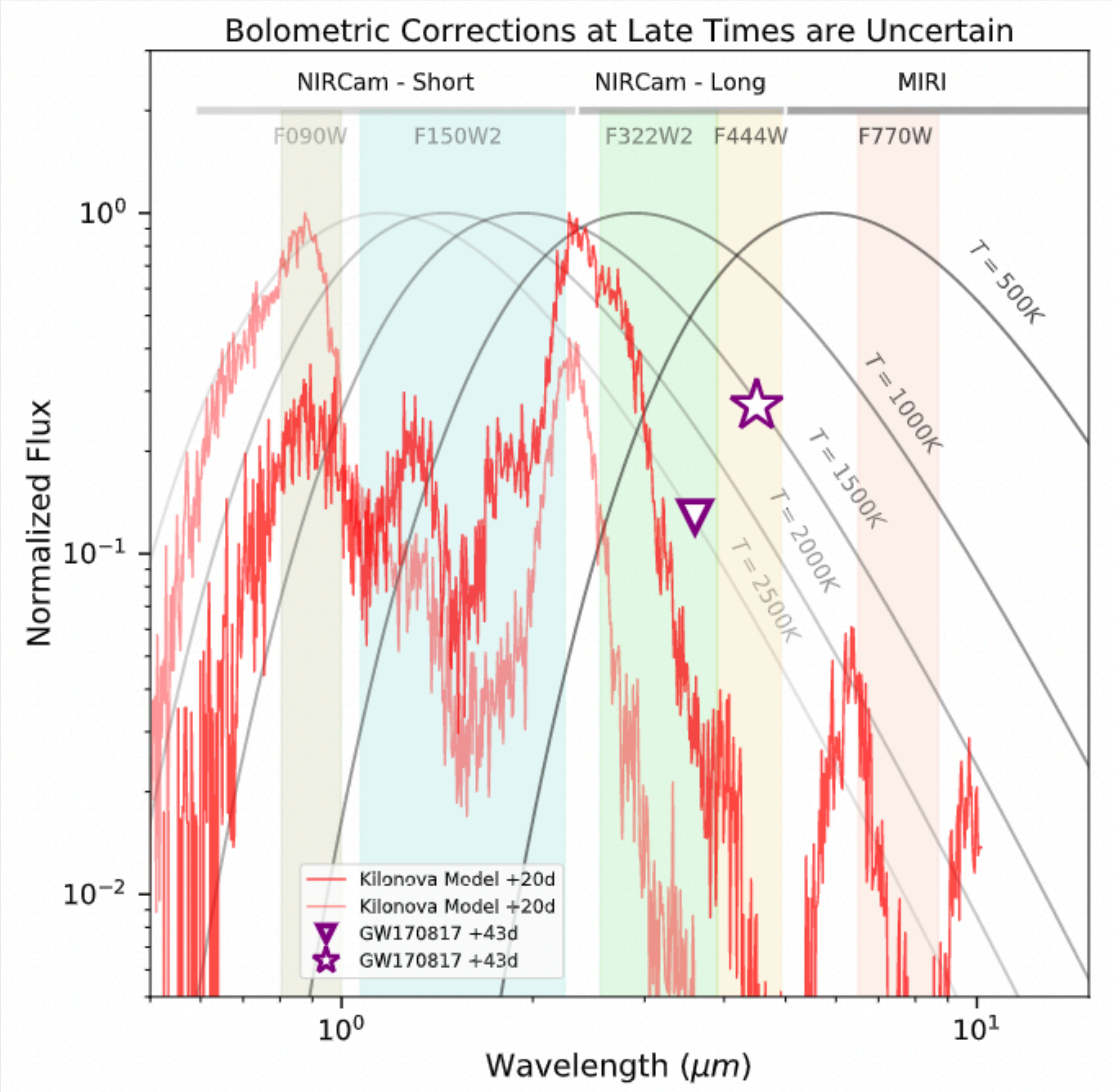
Do BNS and NSBH mergers produce a range of r-process yields?

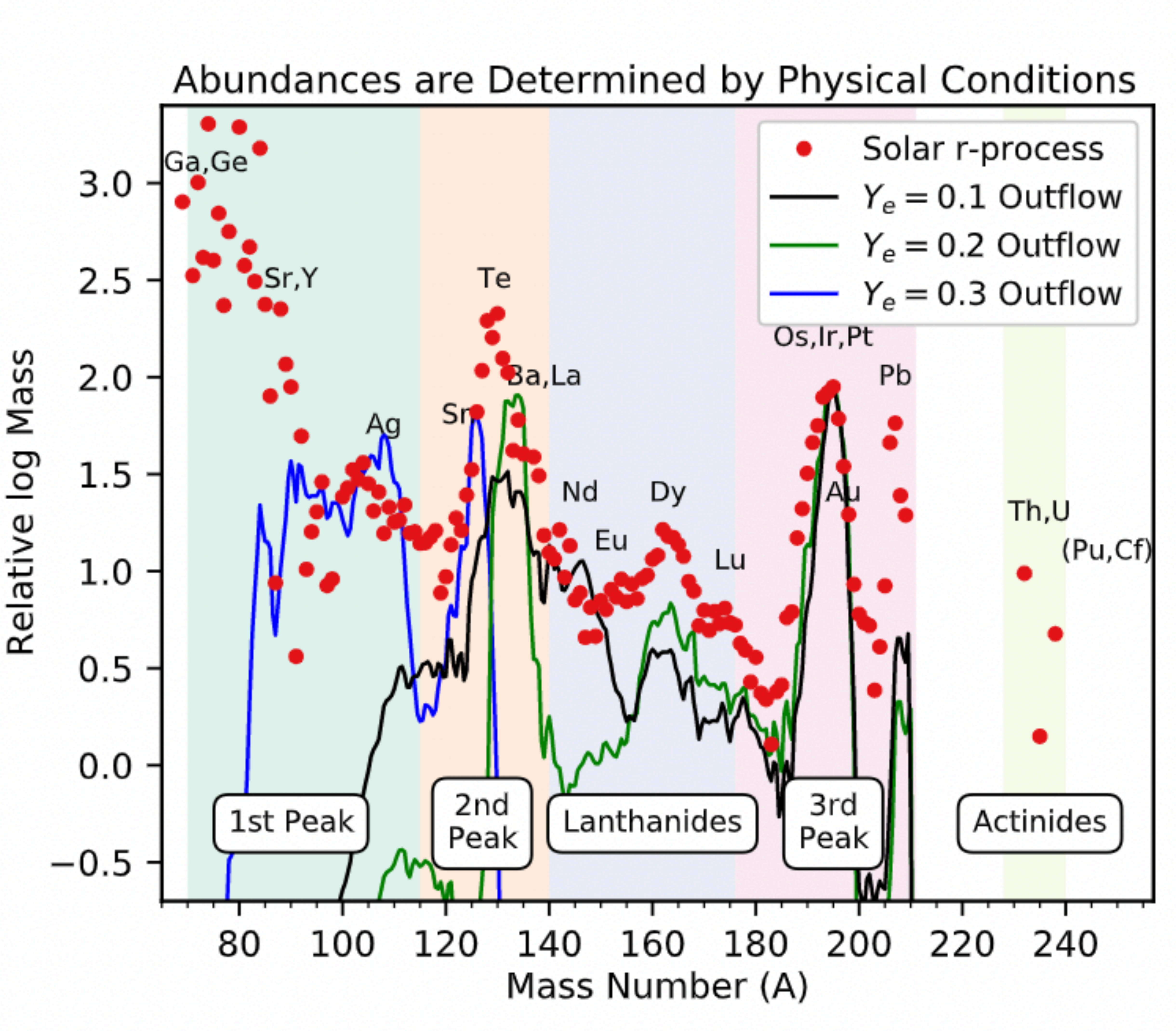
In what ways can we uniquely constrain the abundances of O4 kilonovae with JWST?



Ji+2019

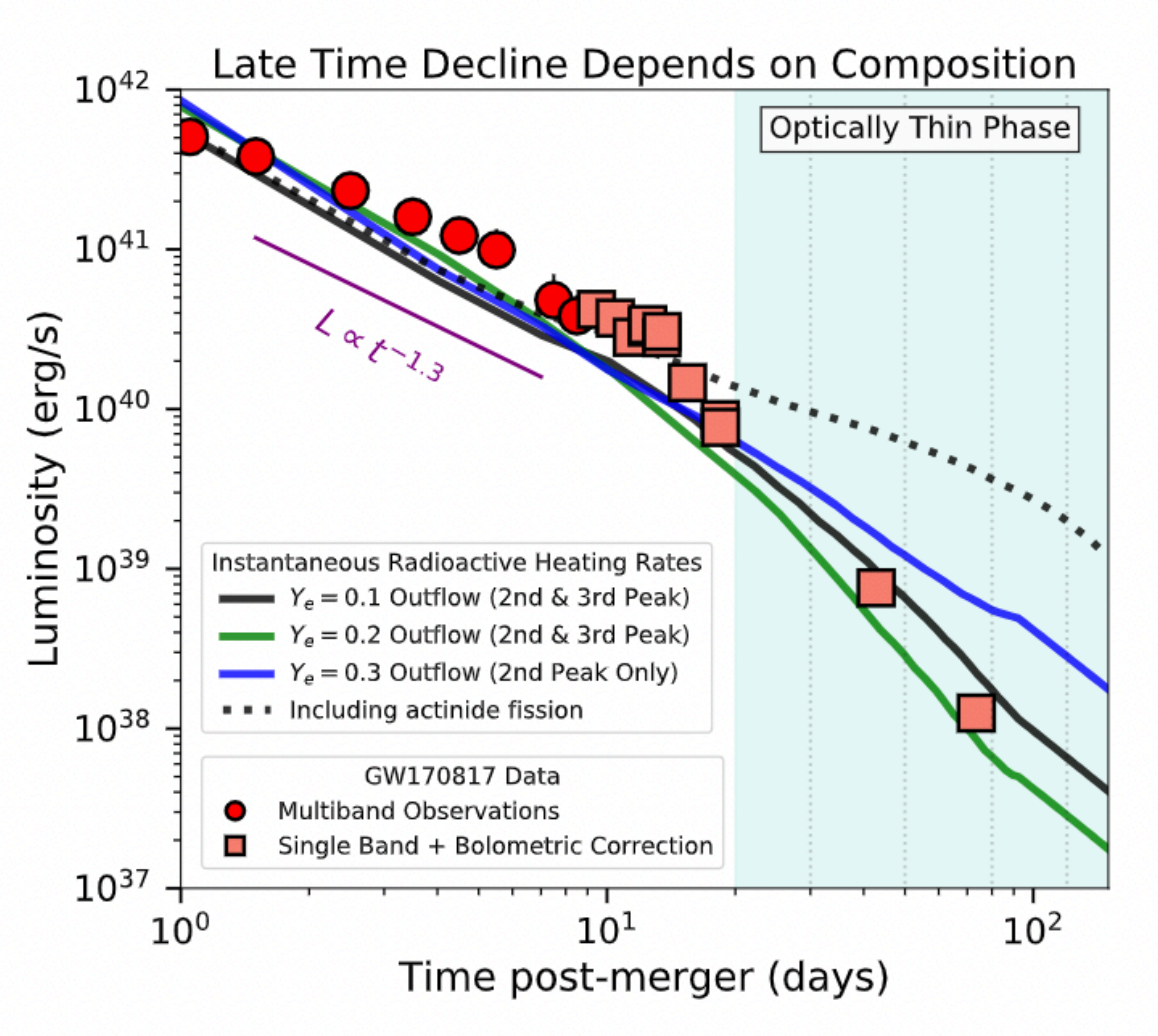
Gravity Collective/GW04 JWST Program





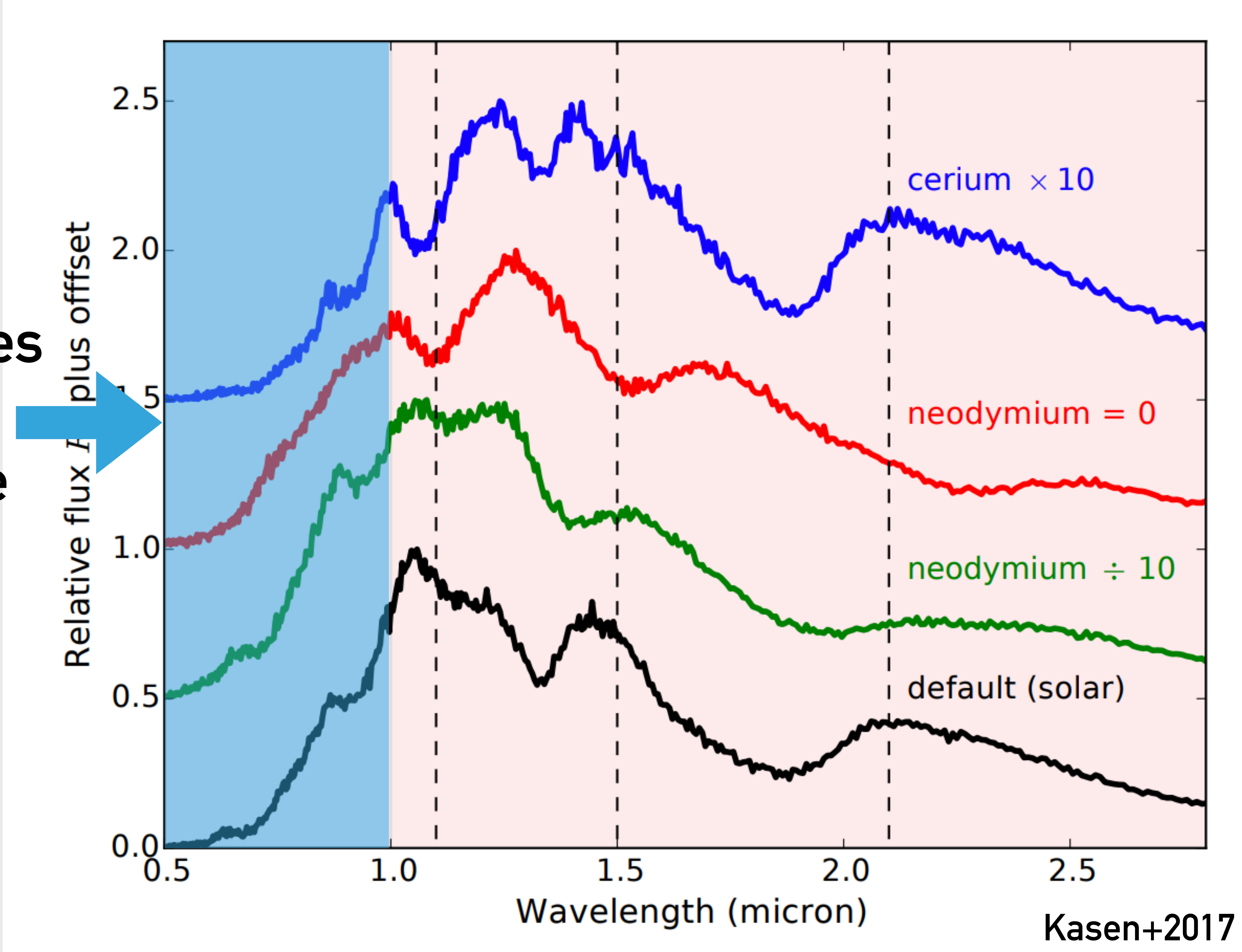
Late-time kilonova emission depends on heating rate from slowly-decaying ($t_{1/2} > 10$ day) elements - but are we getting all of the flux?

Gravity Collective/GW04 JWST Program



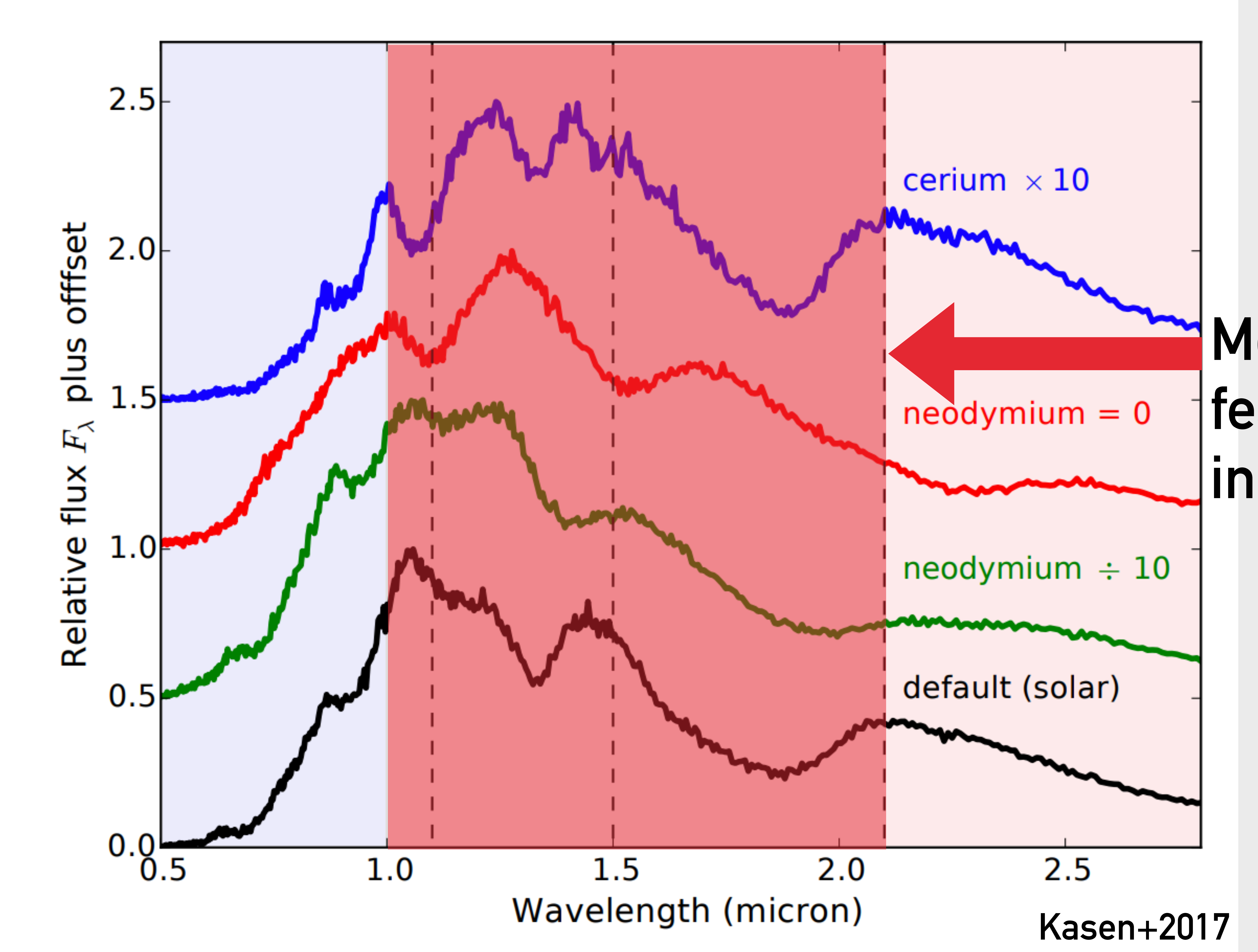
Gravity Collective/GW04 JWST Program

Few differences in abundance patterns in the optical



Kasen+2017

Gravity Collective/GW04 JWST Program



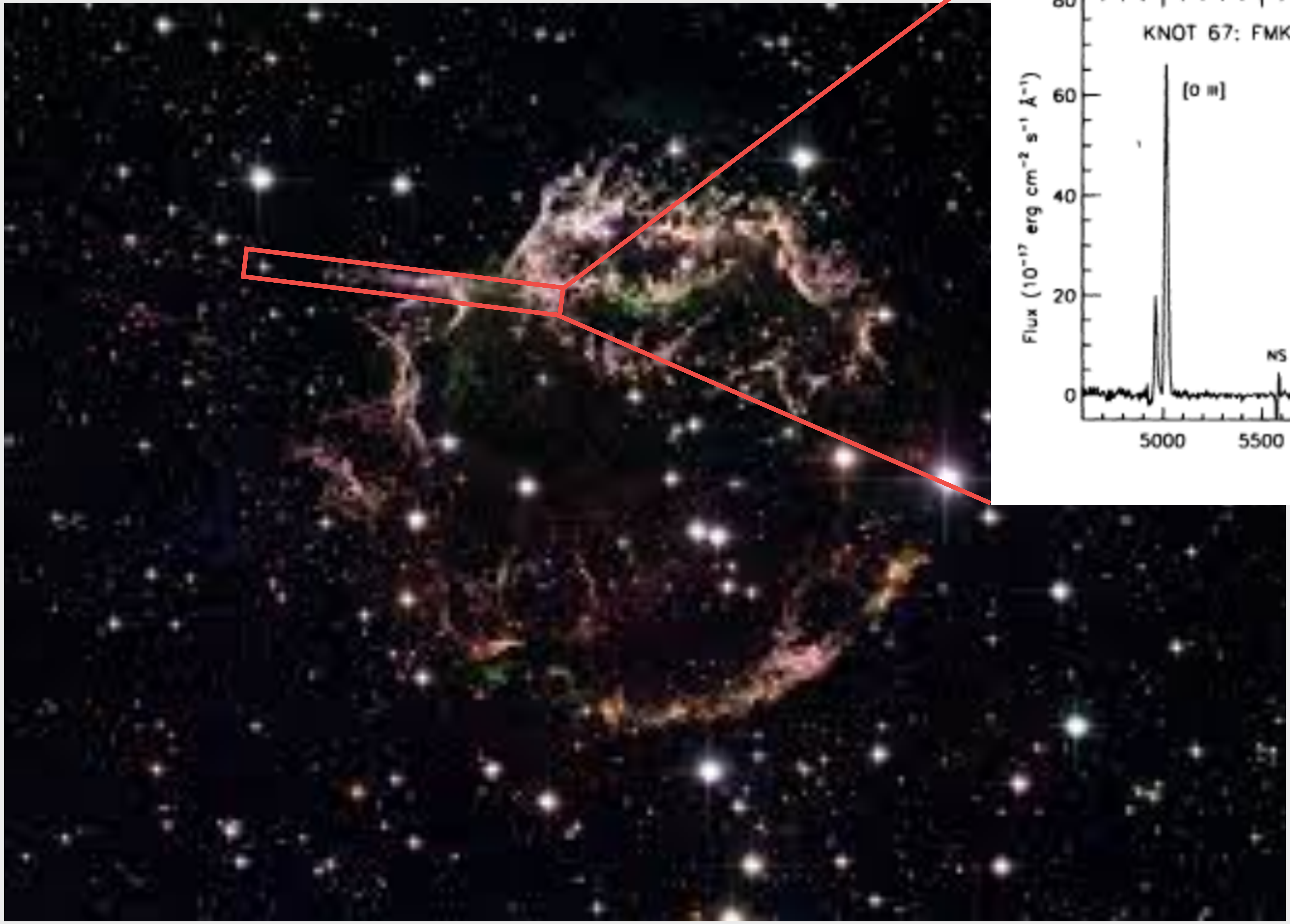
Most spectral features arise in near-infrared

Gravity Collective/GW04 JWST Program

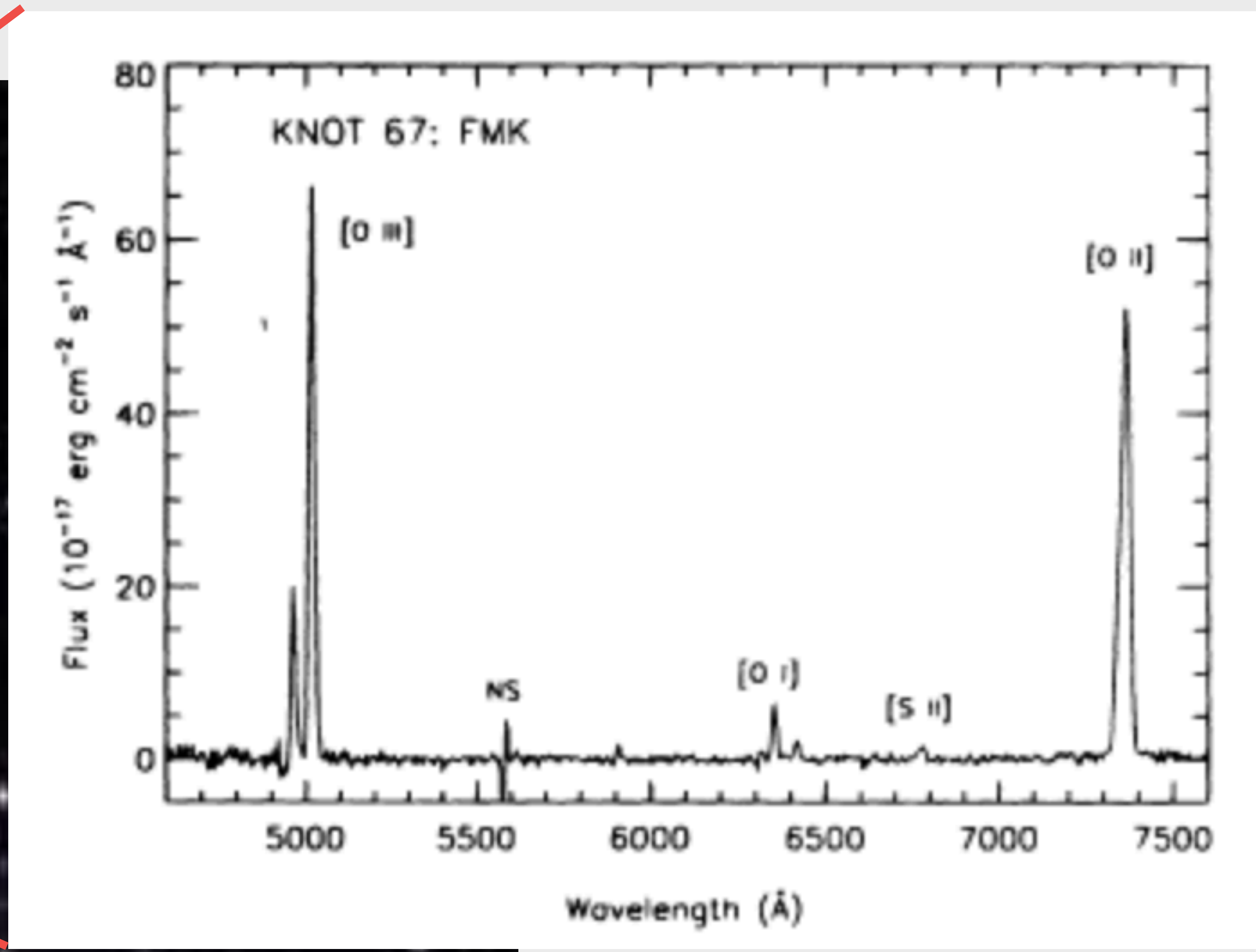
Cassiopeia A
Credit: ESA/NASA

$$t_{\rm thin} = 30\ {\rm days} \left(\frac{M_{\rm ej}}{0.05\ M_\odot}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.15\ c}\right)^{-1} \left(\frac{\kappa}{5\ {\rm cm^2\ g^{-1}}}\right)^{1/2}$$

Gravity Collective/GW04 JWST Program



Cassiopeia A
Credit: ESA/NASA

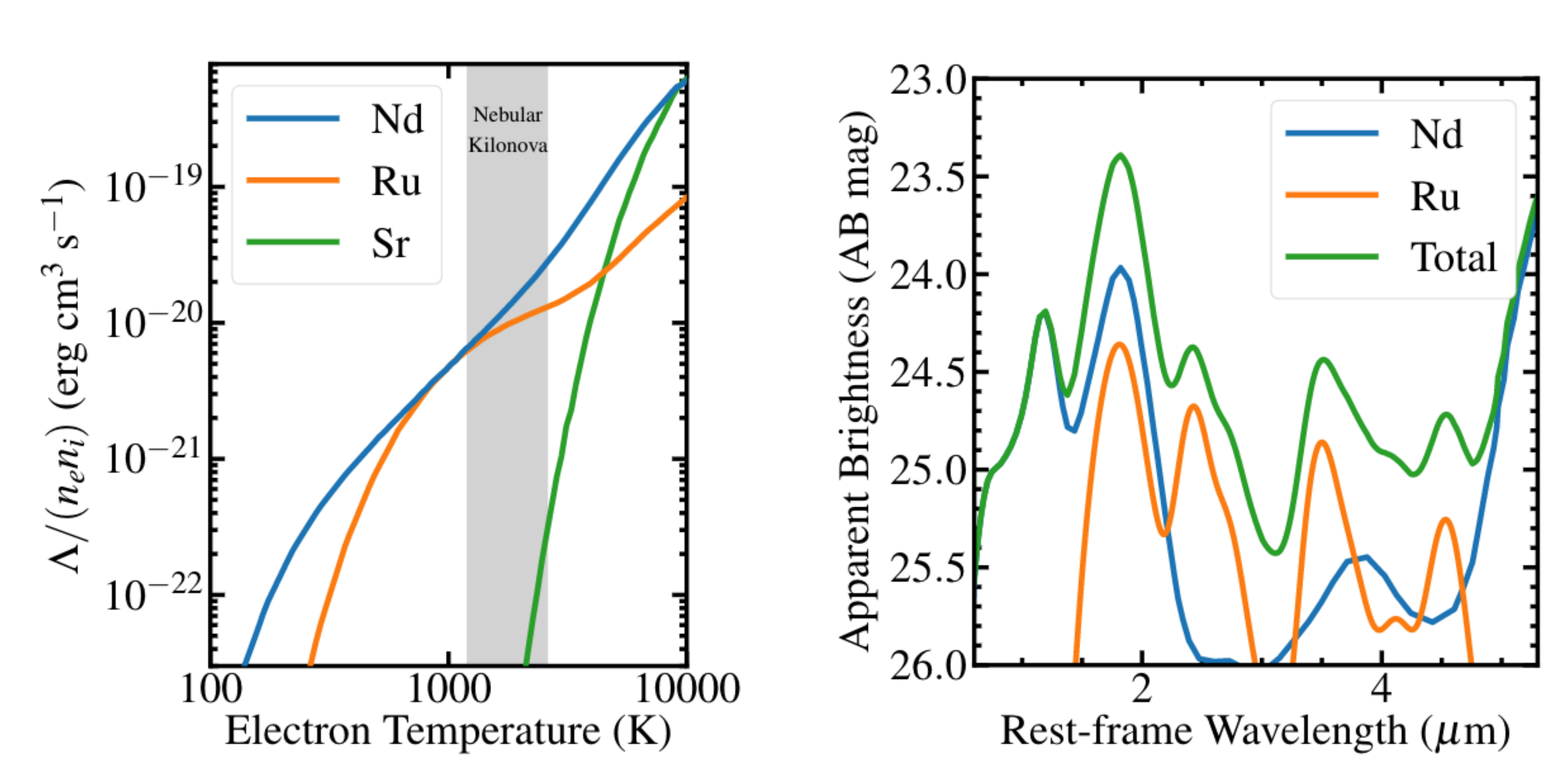


Fesen+1996

$$t_{\rm thin} = 30 \text{ days} \left(\frac{M_{\rm ej}}{0.05\ M_\odot}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.15\ c}\right)^{-1} \left(\frac{\kappa}{5\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{1/2}$$

Gravity Collective/GW04 JWST Program

Based on models from Hotokezaka+



We can directly measure the abundances of specific elements using JWST

Conclusions

Our constraints on the r-process are dominated by bulk indicators of r-process material, especially opacity, but much more information could be obtained using the full range of spectral data we have

GRB and GW kilonovae can provide complementary information - GRB samples larger, poorer sampling, at one viewing angle, larger distances and GW samples smaller, more detailed data, at a range of viewing angles, smaller distances

New infrared facilities, especially JWST, will revolutionize discovery and follow up of both GRB and GW-discovered kilonovae