Late Engine Activity: An Alternative Scenario for the Blue Kilonova

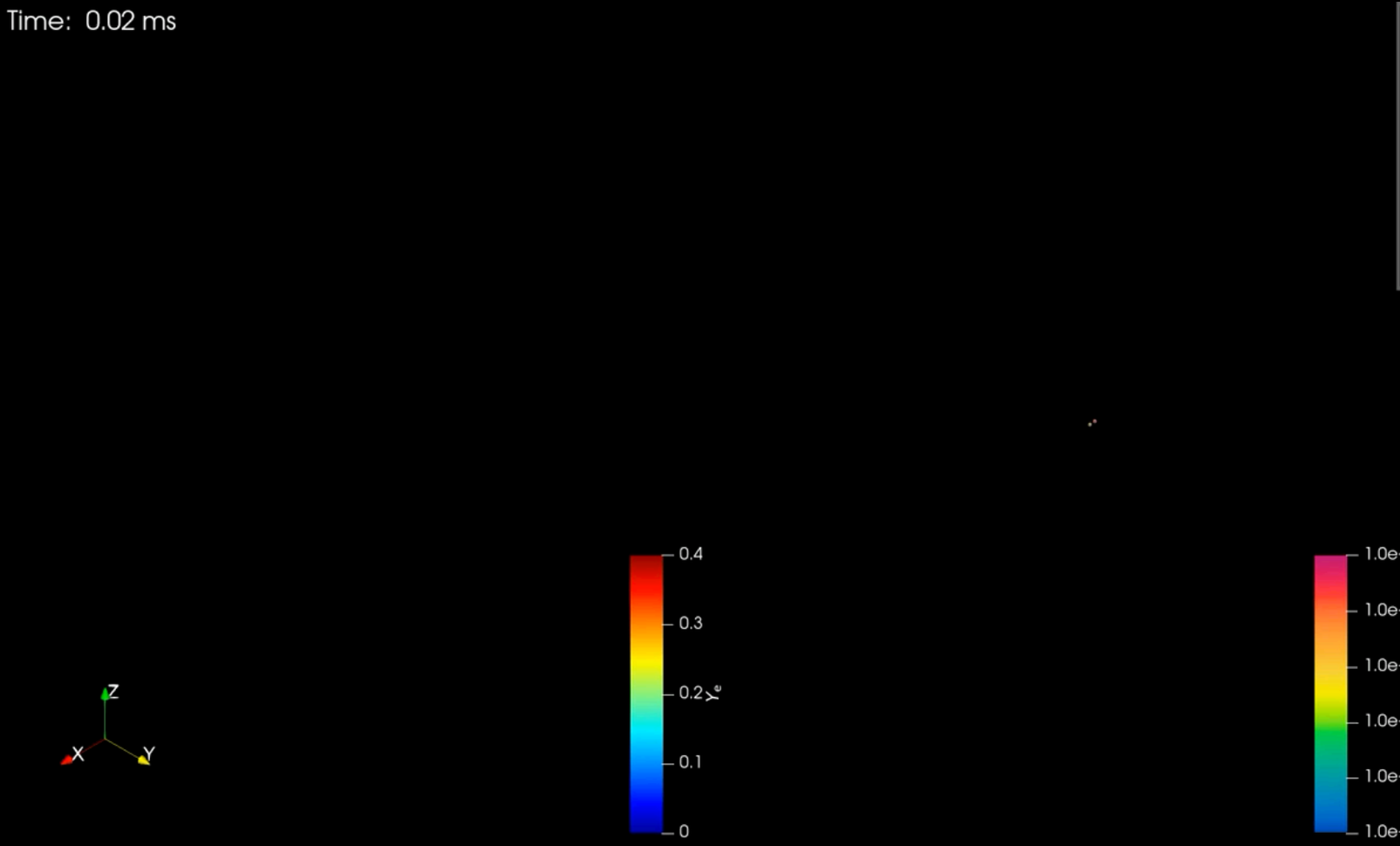
Hamid Hamidani, Shigeo Kimura, Masaomi Tanaka, & Kunihito Ioka

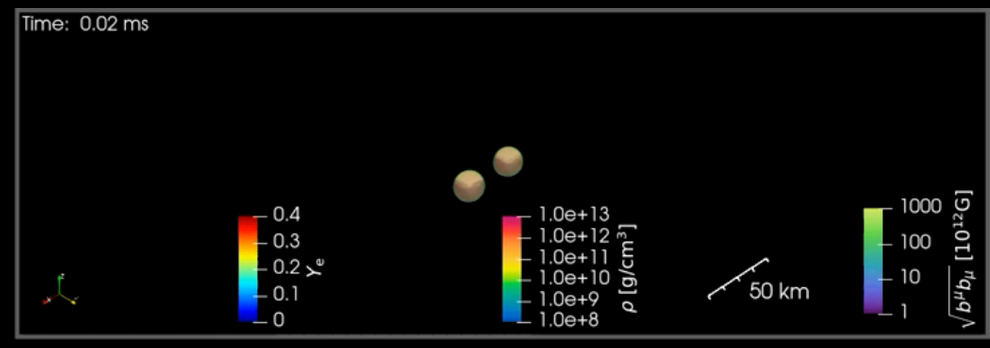
Based on:
https://arxiv.org/abs/2312.06286
https://arxiv.org/abs/2406.14366

GRBs and central engine powered transients - December 2-6, 2024, Mexico

Theory

Neutron Star Merger

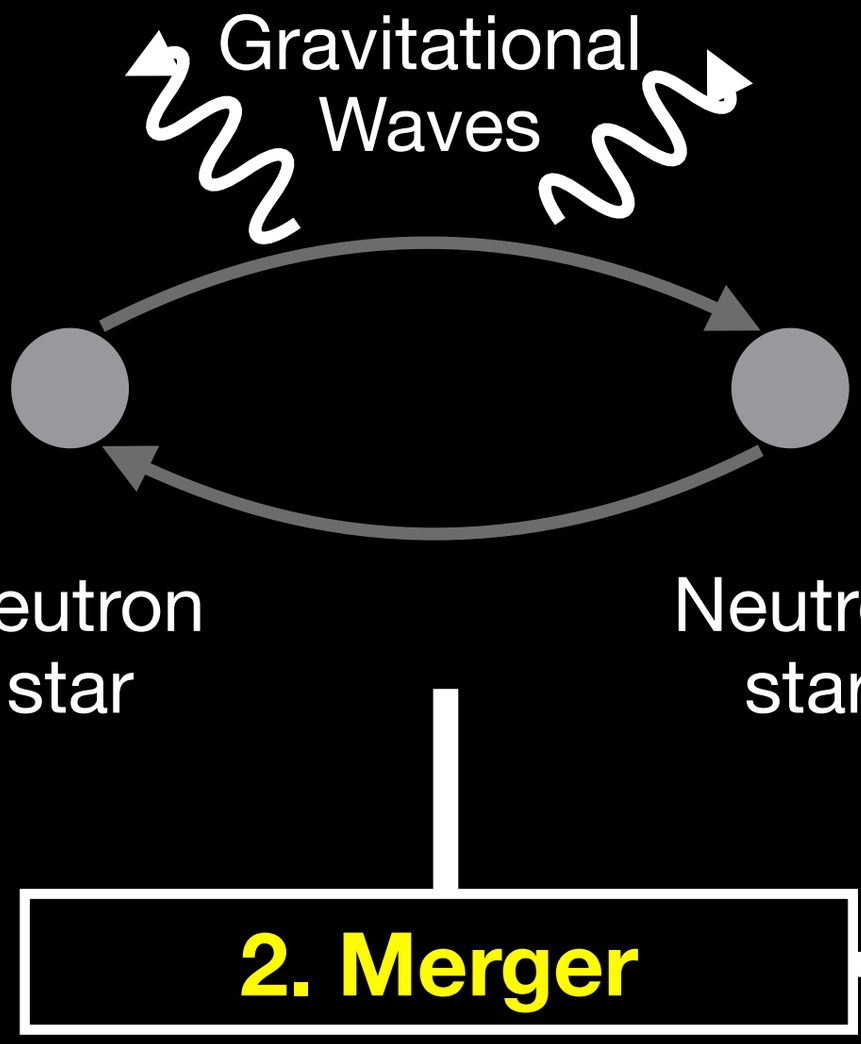




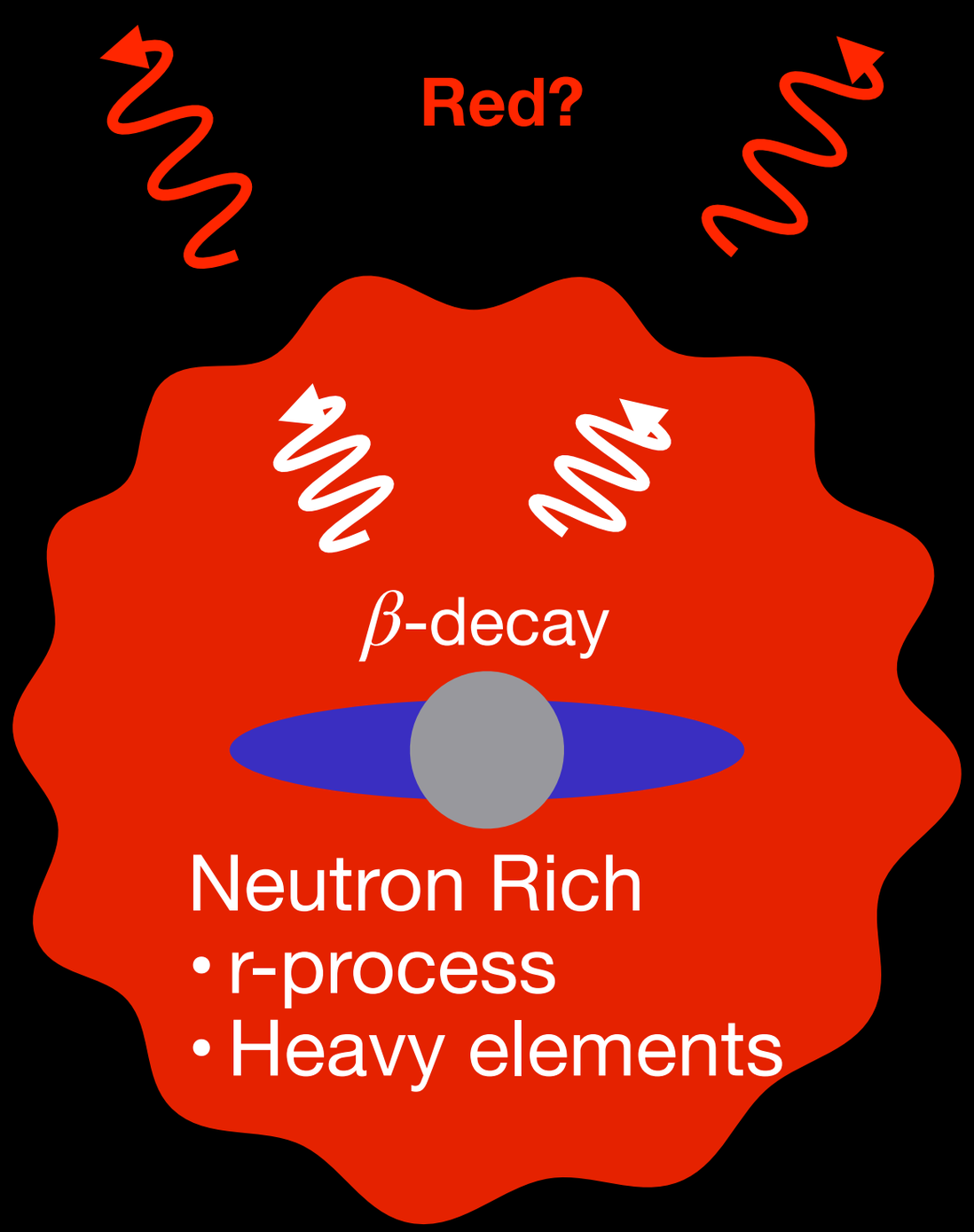
Neutron rich **Mass ejection** **Jet launch**

Credit: Kota Hayashi (Max Planck Institute for Gravitational Physics)

1. Binary Neutron Star

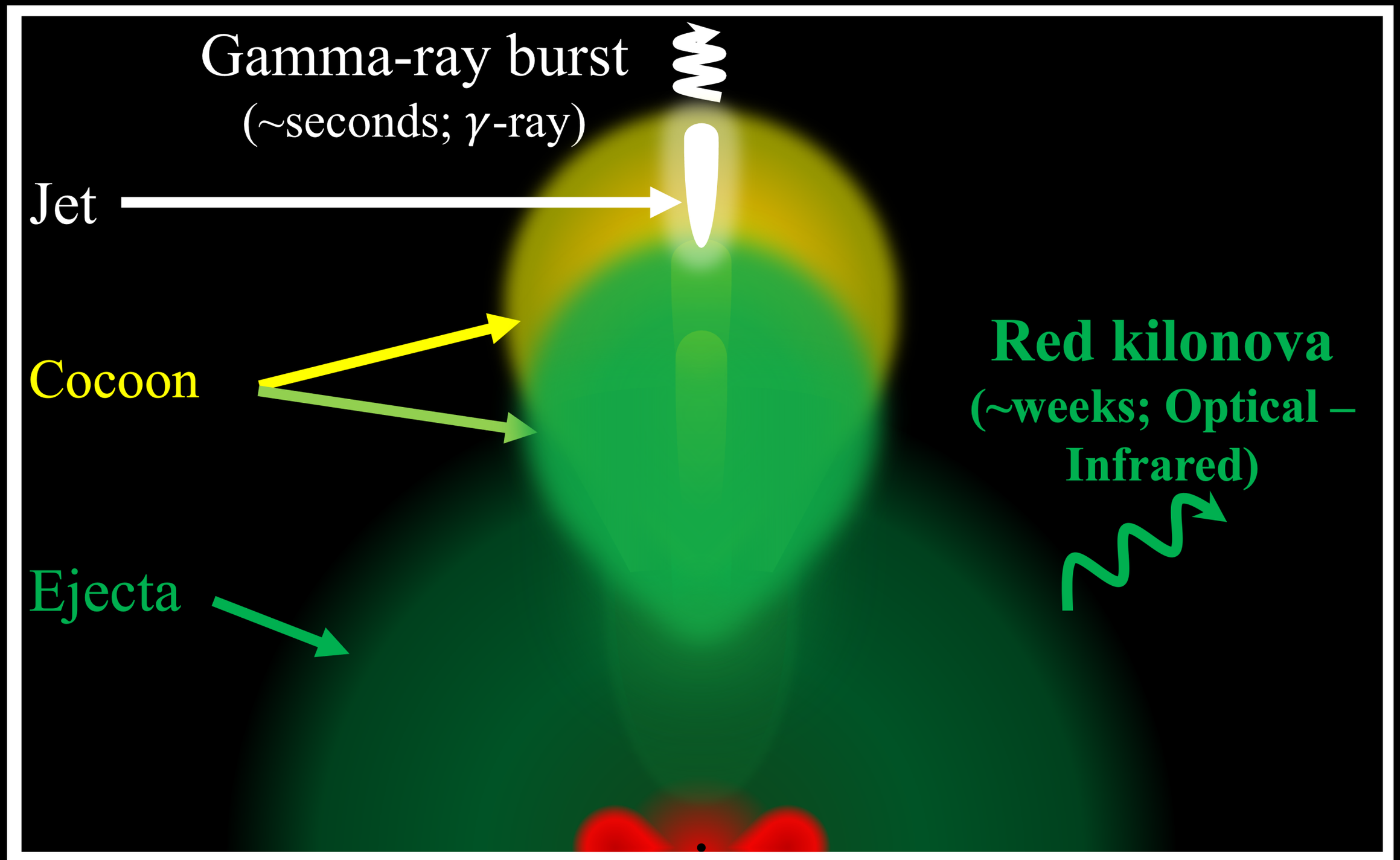


3. Kilonova



Late emission: $L_{KN} \propto M_e$

Old Paradigm [sGRBs & KN]

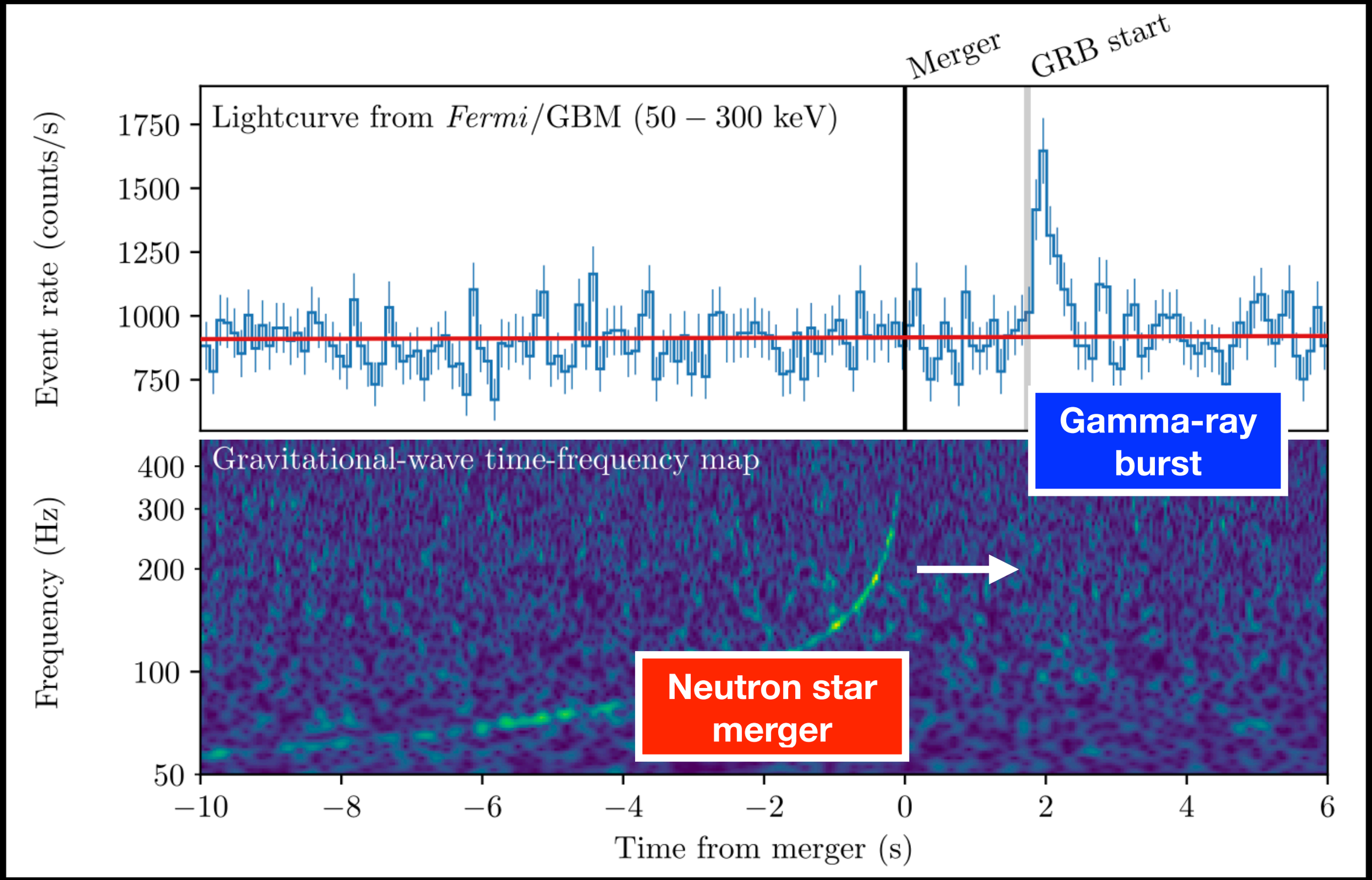


Credit: Hamidani et al. in 2023

Observation

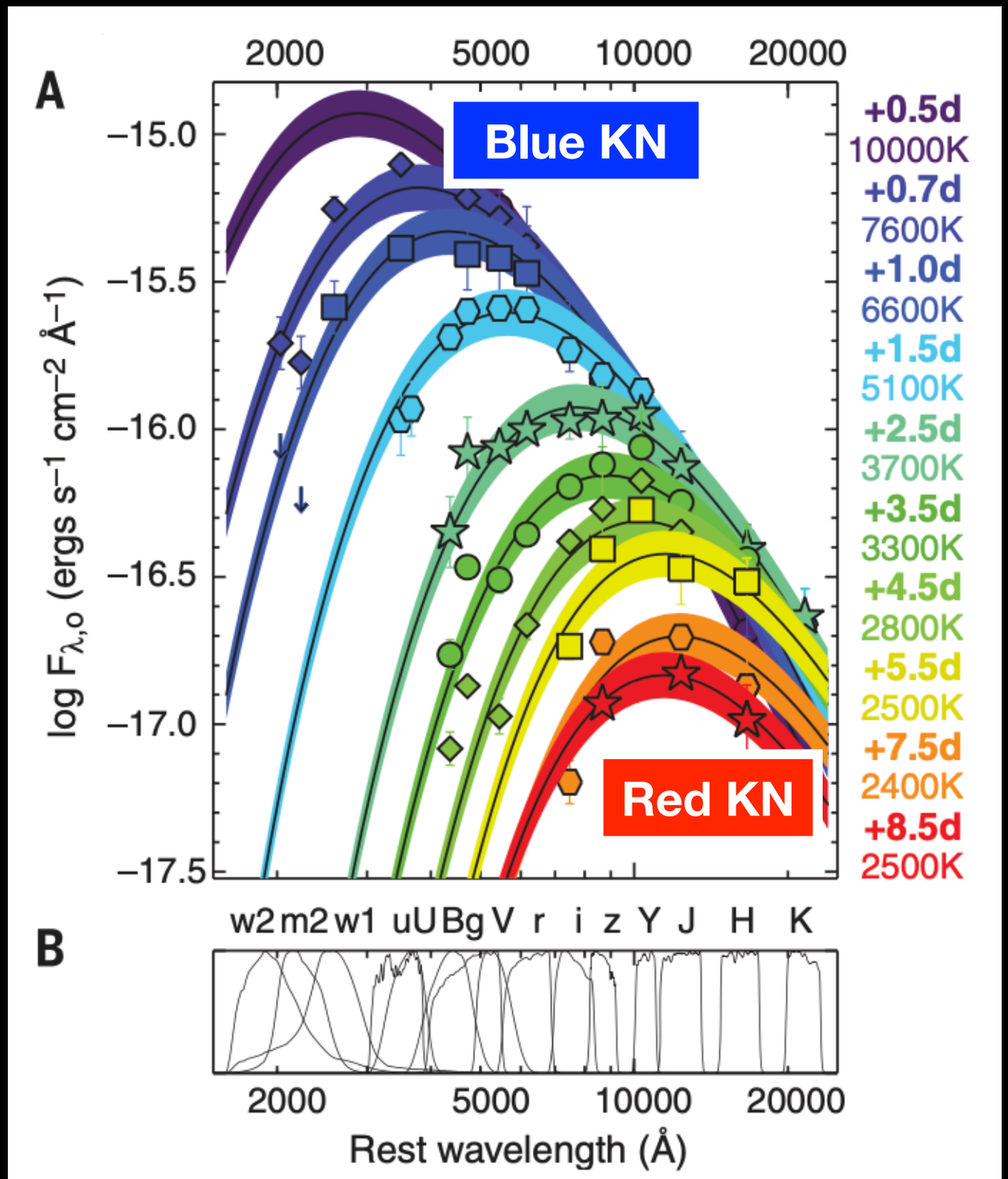
1. Surprisingly blue early KN
2. Late engine activity

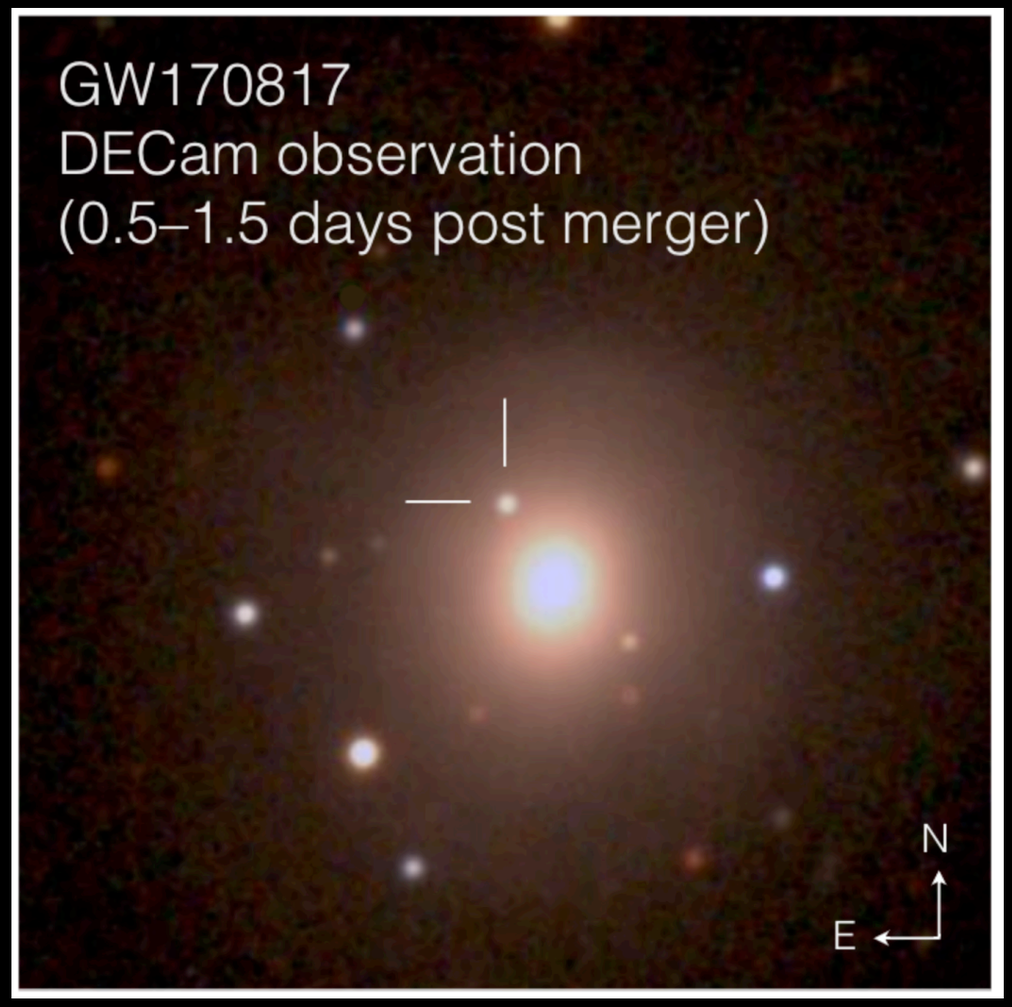
GW170817 [& GRB170817A]



Credit: Abbott et al. 2017

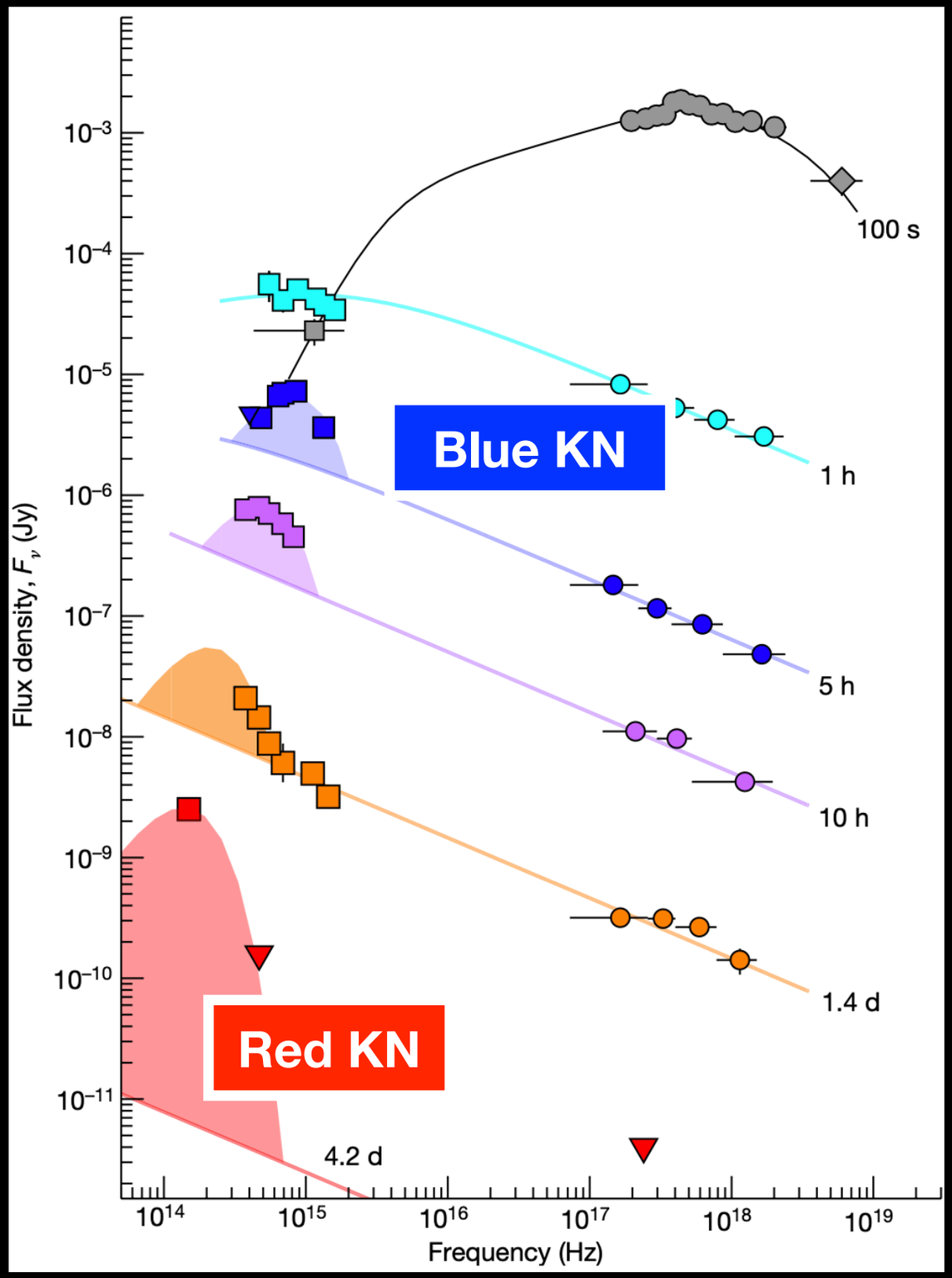
Fact 1: Blue kilonova [GW170817]

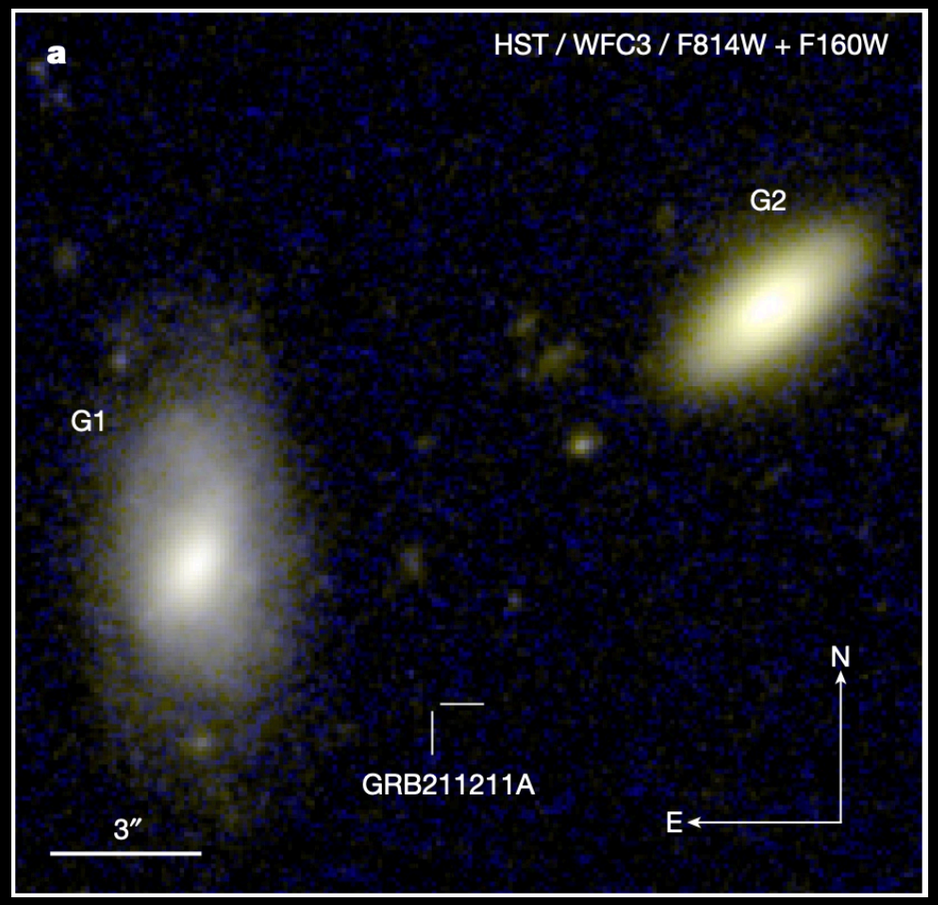




Credit: Soares-Santos et al. and DES Collaboration; Drout et al. 2017

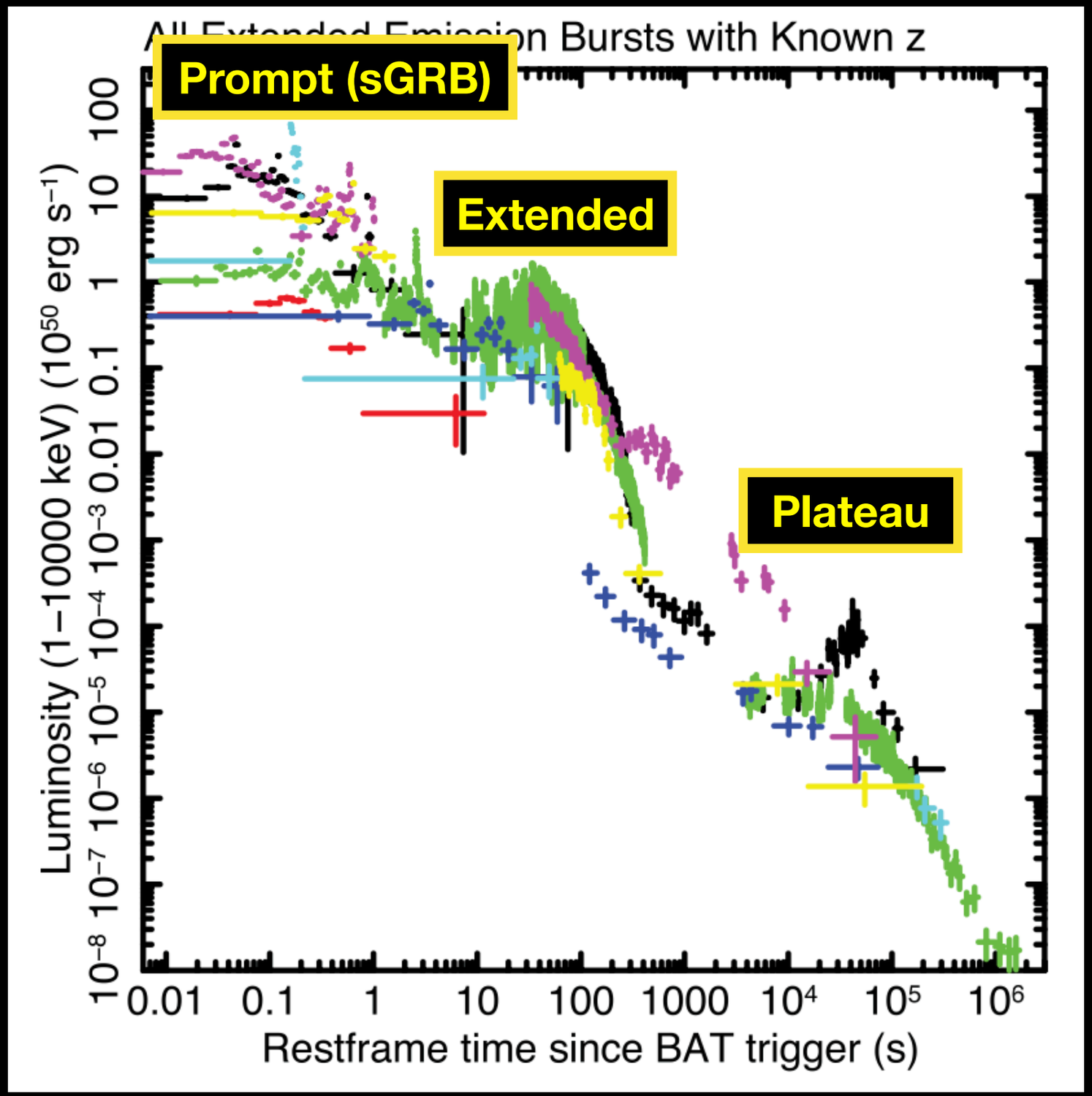
Fact 1: Blue kilonova [GRB211211A]





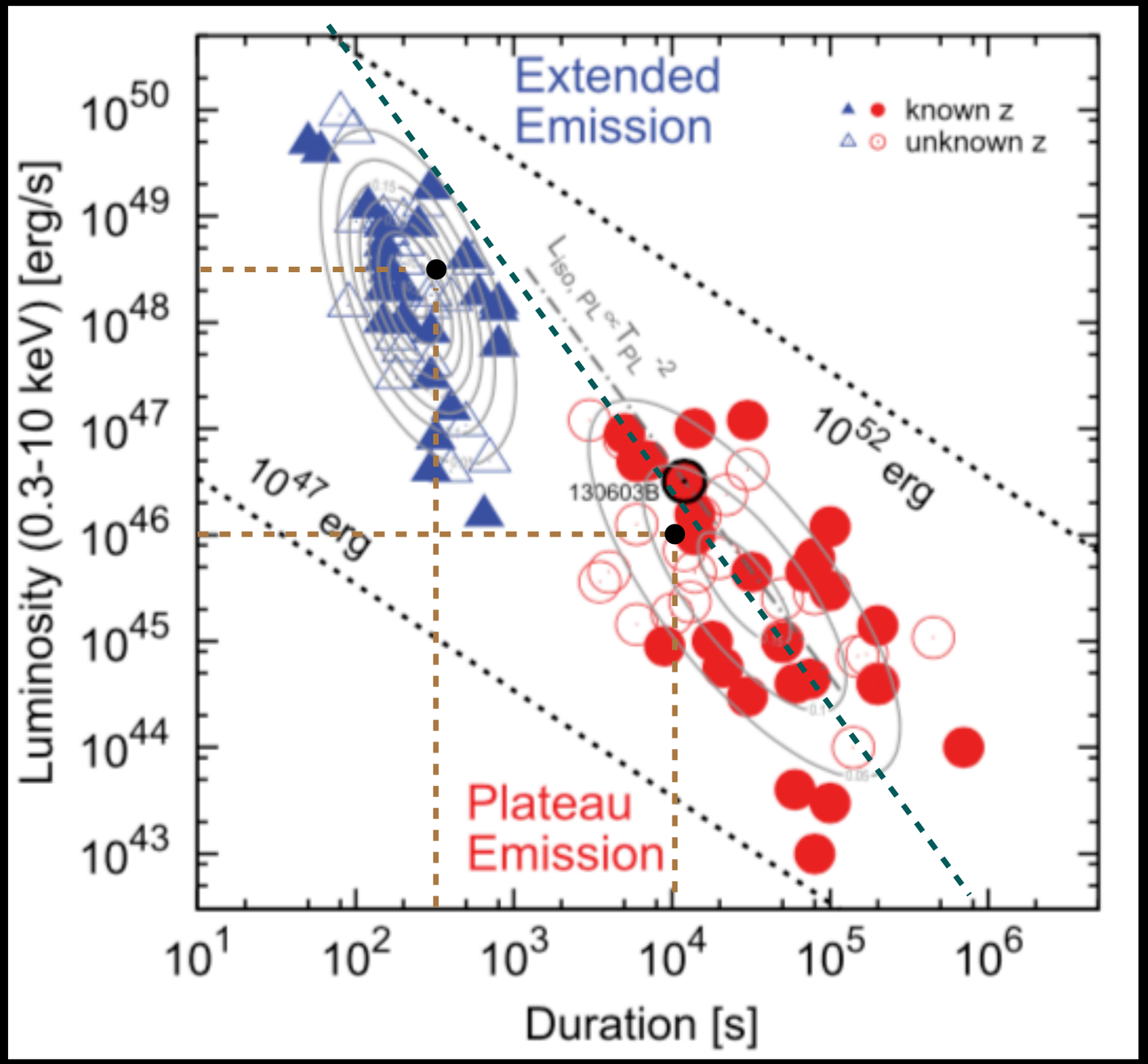
Credit: Troja et al. 2022; Rastinejad et al. 2022

Fact 2: Late engine activity



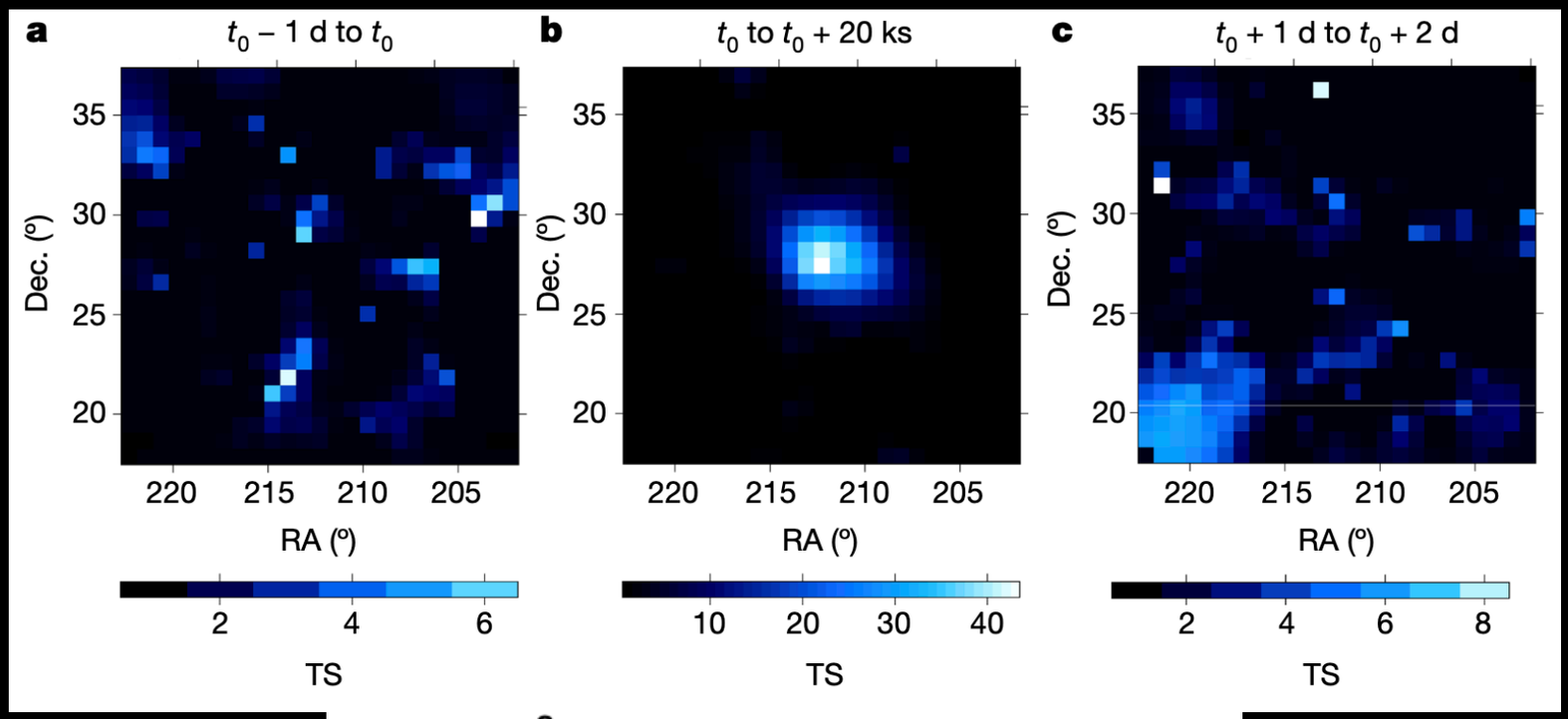
Credit: Gompertz et al. 2012

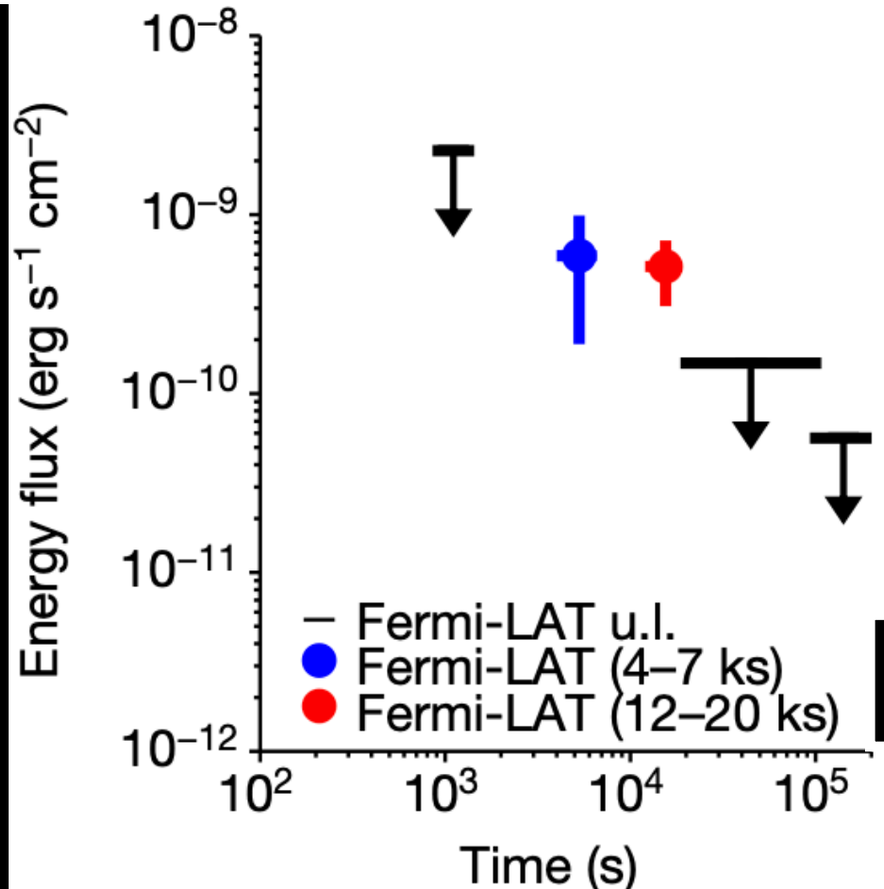
Fact 2: Late engine activity

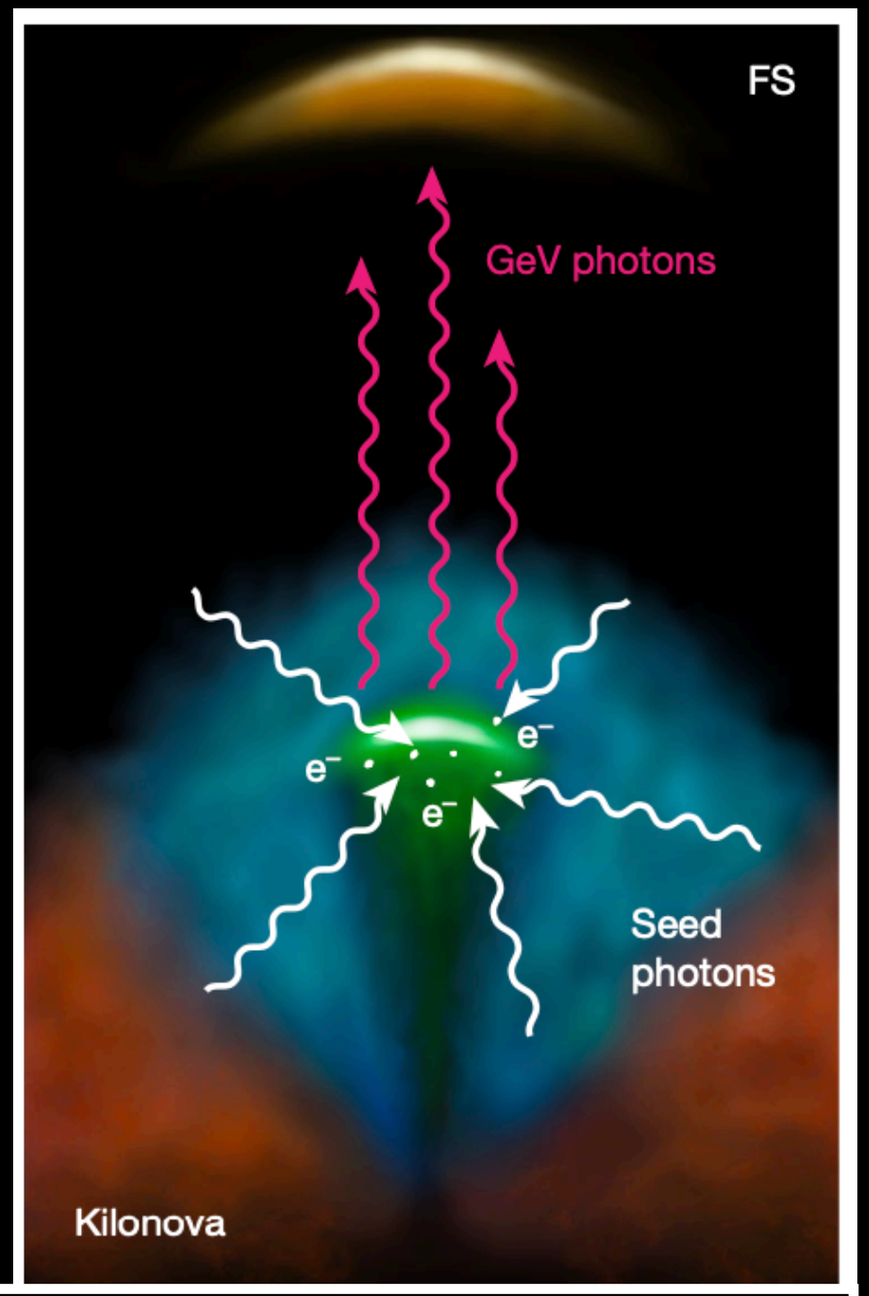


Credit: Kisaka et al. 2017

Fact 2: Late engine activity [in GeV]







$\sim 10^{46}$erg/s low power jet at $\sim 10^4$ s

Credit: Mei et al. 2022

Motivation:
How does such late engine activity affect the KN?

(A)

Gravitational Waves

NS NS

$t \sim -100 - 0$ s:
Inspiral & merger

(B)

Merger ejecta

Prompt jet

$t \sim 0 - 1$ s:
Mass ejection & prompt jet

(C)

Prompt +
Extended/Plateau emission
(~1-10^4 seconds; γ – X-ray)

?

Prompt jet
Late jet

Late jet-heated:
Escaped cocoon
Trapped cocoon

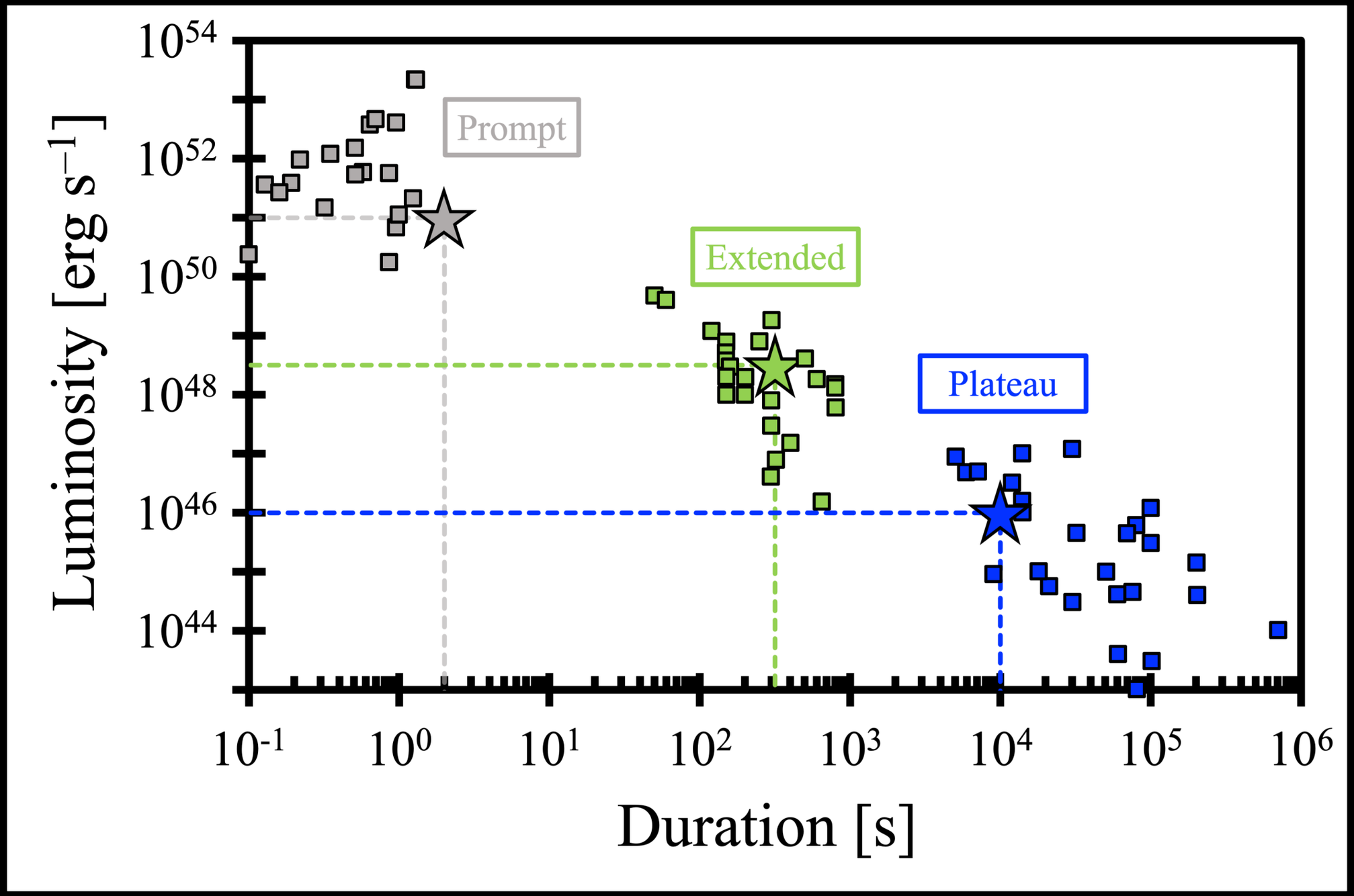
Ejecta

Red kilonova
(~week; Opt –IR)

$t \sim 10 - 10^4$ s:
Late jet breakout

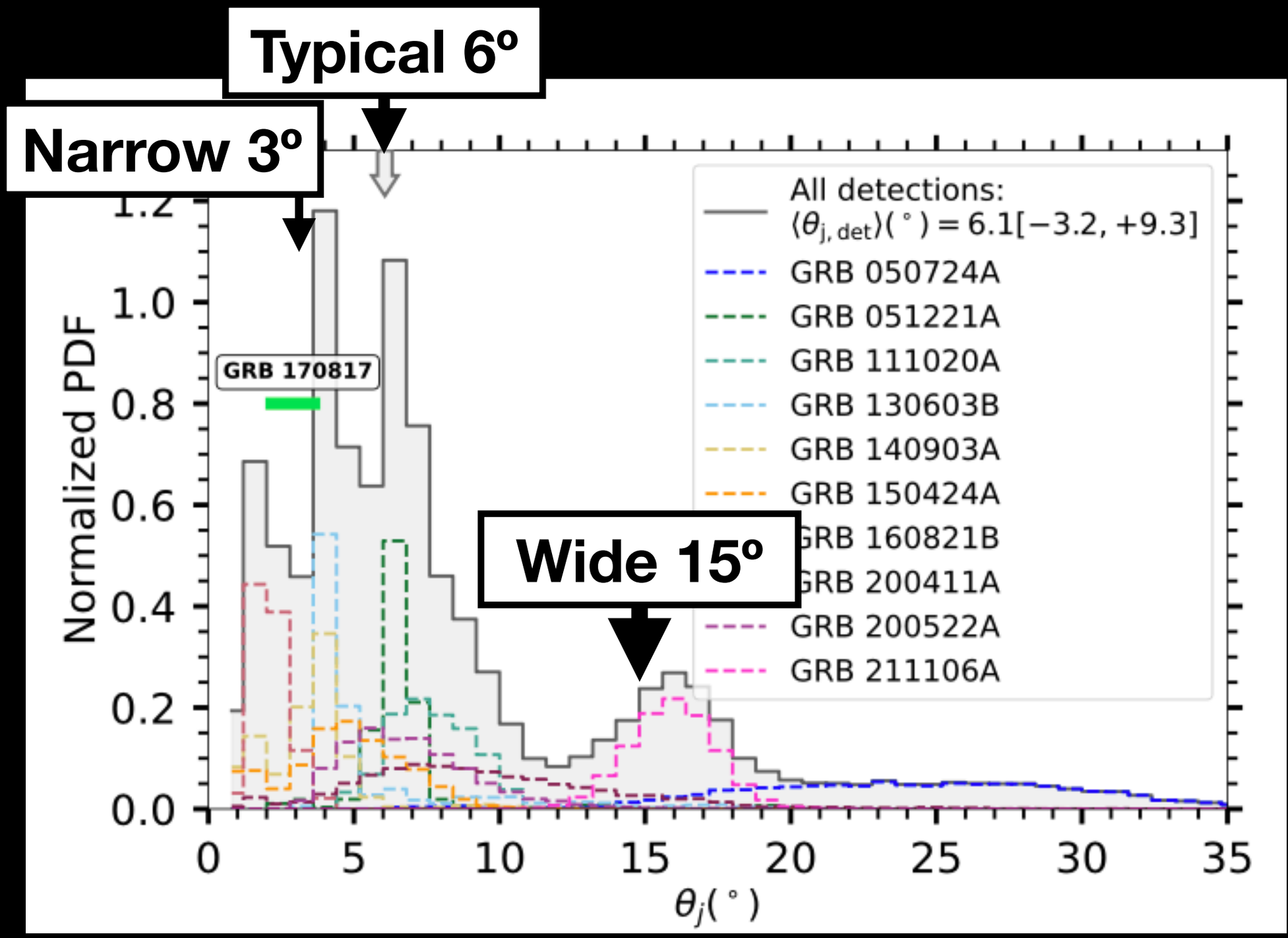
Credit: Hamidani et al. in 2024

Observations: t & L



Credit: Hamidani et al. in 2024

Observations: θ_{jet}



Credit: Escorial et al. 2023

Analytic jet breakout time

$$t_b \sim 18\ \mathrm{s} \left(\frac{\beta_m}{0.35}\right)^2 \left(\frac{M_e}{0.05 M_\odot}\right) \left(\frac{\theta_0}{6^\circ}\right)^2 \left(\frac{L_{iso,0}}{10^{49.5}}\right)^{-1}$$

AT2017gfo; GRB211211A

sGRBs

Three engine phases:

Prompt ($\sim 10^{53}$ erg/s)

Extended ($\sim 10^{49}$ erg/s)

Plateau ($\sim 10^{47}$ erg/s)

Three jet models:

Narrow ($\theta_0 = 3^\circ$)

Typical ($\theta_0 = 6^\circ$)

Wide ($\theta_0 = 15^\circ$)

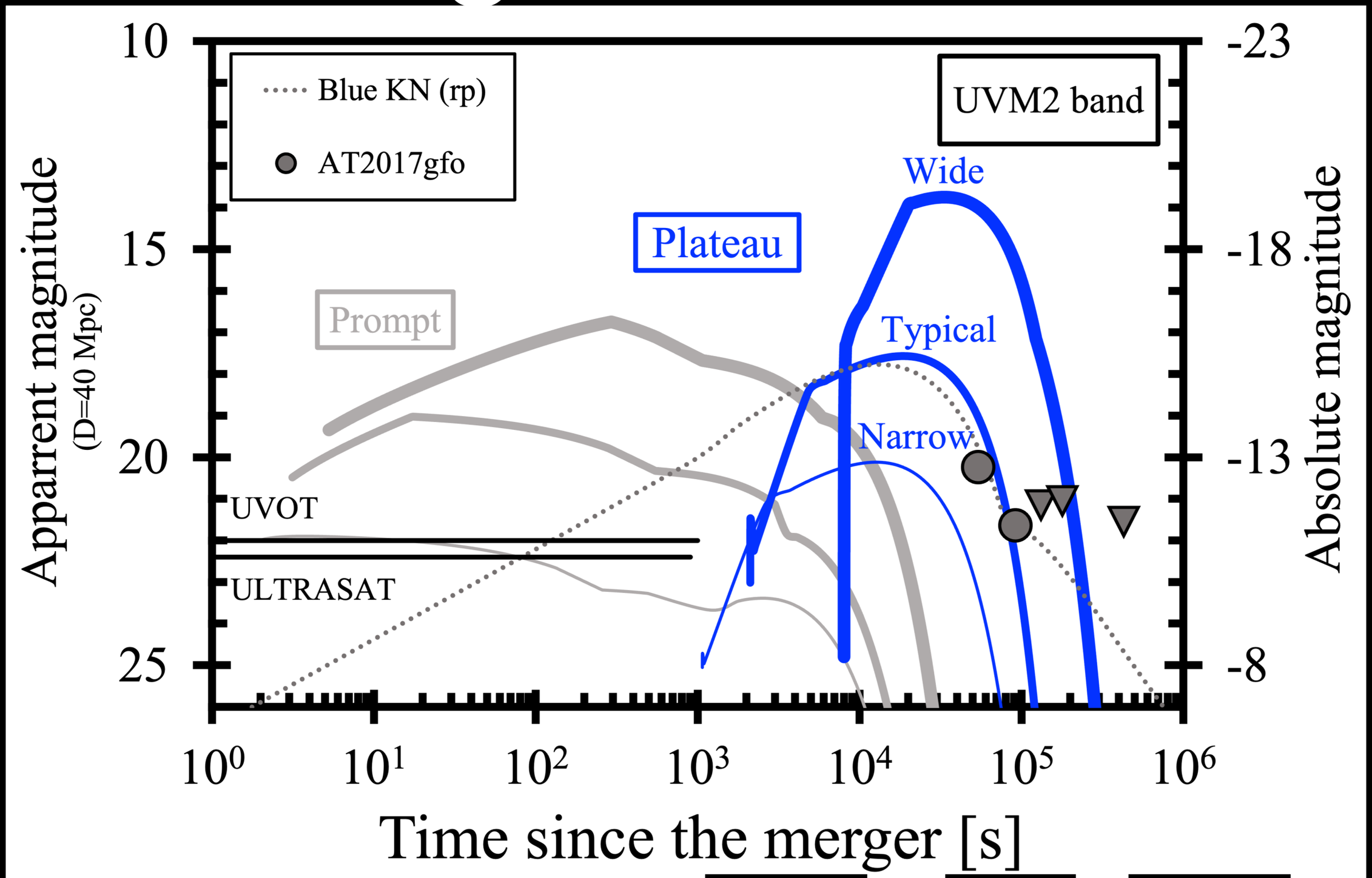
Cooling emission

$$L_{bol}^{cocoon} \approx 5 \times 10^{42} \mathrm{ergs}^{-1}$$

$$\left(\frac{\theta_0}{6^\circ}\right)^2 \left(\frac{\eta_X L_{iso,0}}{10^{46}\mathrm{ergs}^{-1}}\right) \left(\frac{t_b}{3\times10^3\ \mathrm{s}}\right) \left(\frac{\kappa}{1\ \mathrm{cm}^2\ \mathrm{g}^{-1}}\right)^{\frac{p-2}{2}}$$

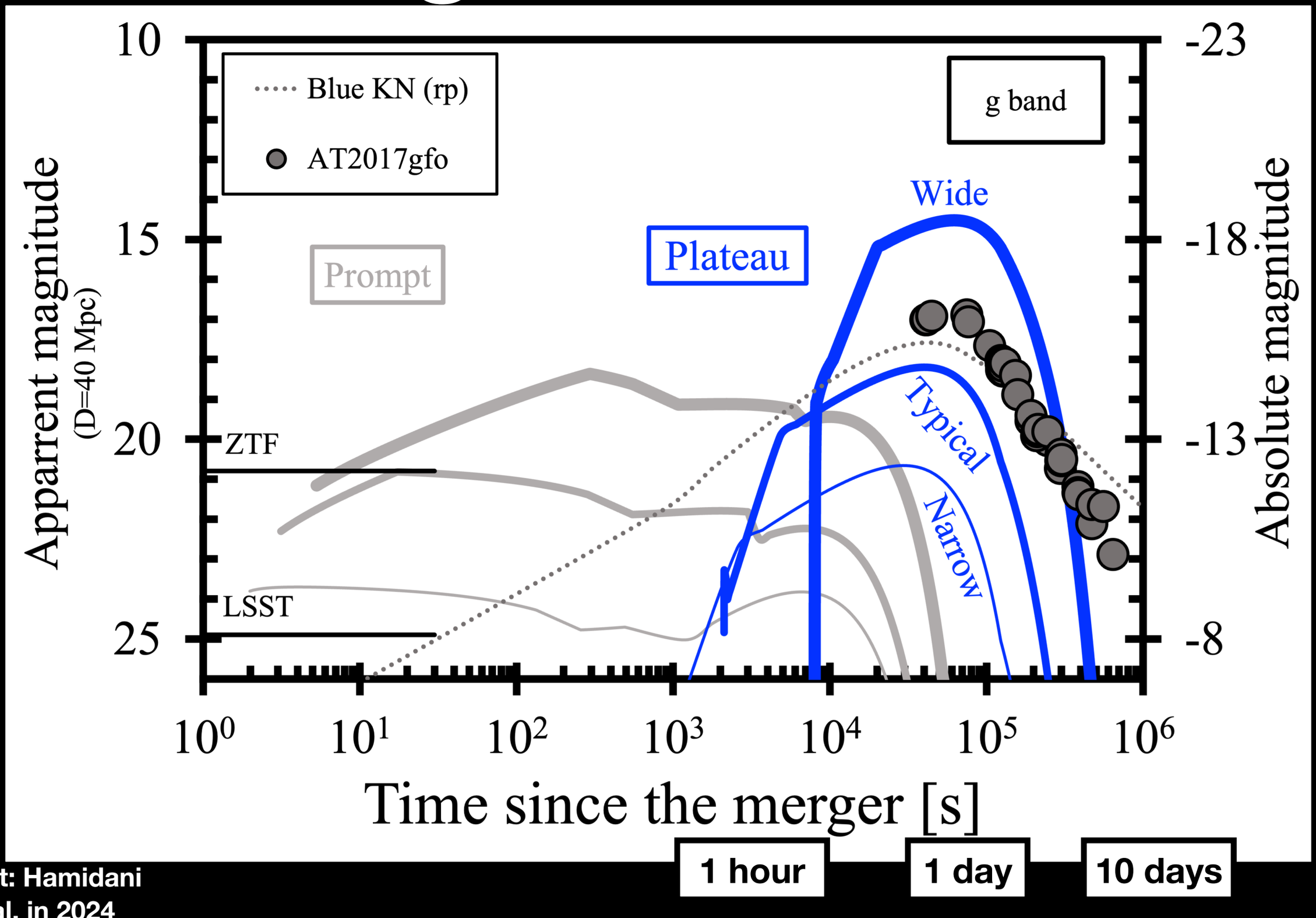
$$\left(\frac{M_c}{4\times10^{-3}M_\odot}\right)^{\frac{p-2}{2}} \left(\frac{t_{obs}}{6\times10^3\ \mathrm{s}}\right)^{-p} \qquad [p \sim 2]$$

Magnitudes [UV]



Credit: Hamidani et al. in 2024

Magnitudes [Opt]



Credit: Hamidani et al. in 2024

Why brighter w/ the late jet?

1. Blue KN peaks at ~ 1 day ($\sim 10^5$ s)

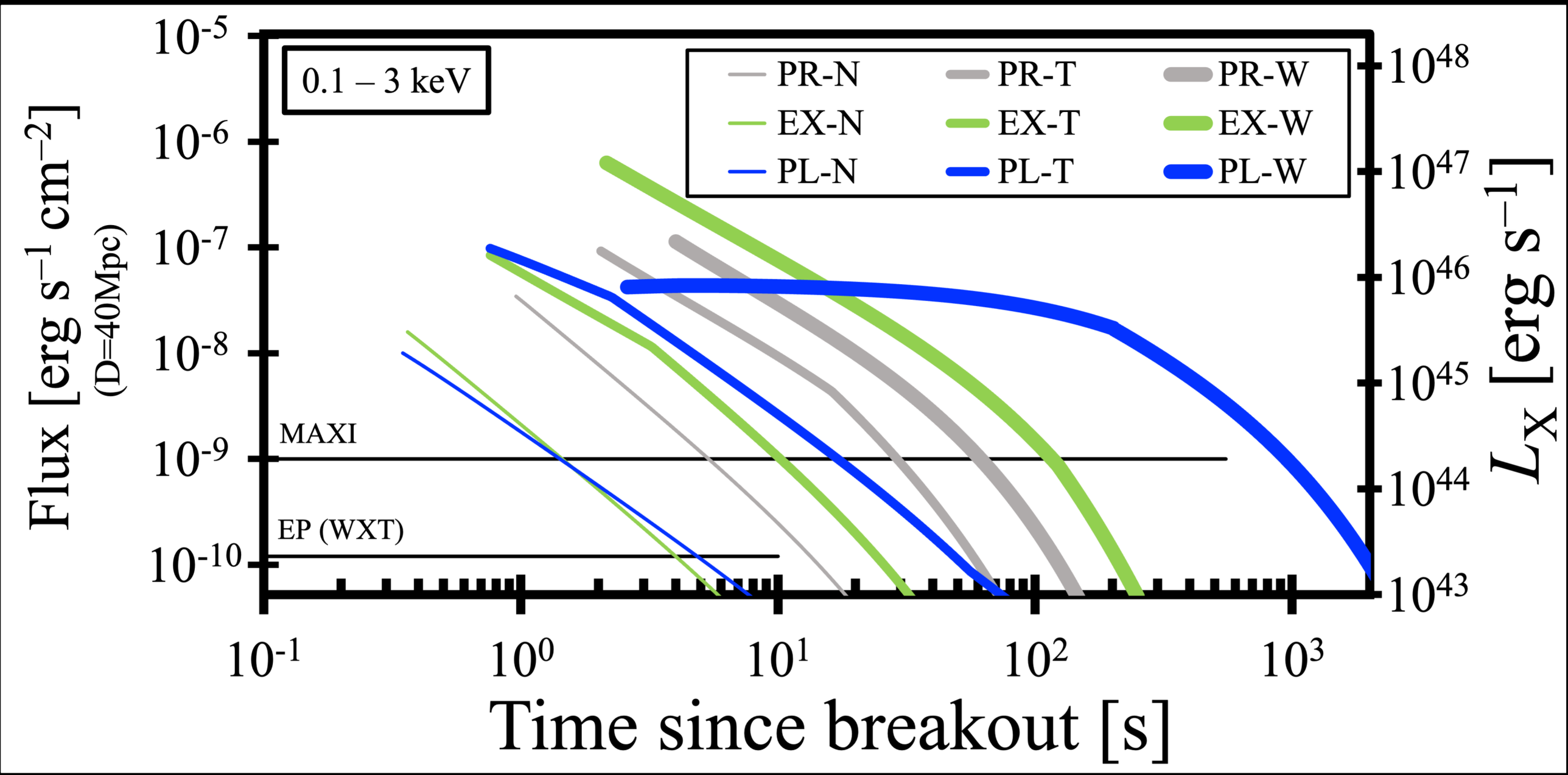
2. The system is expanding

e.g., Prompt jet (breakout) timescale 1 s

- By $\sim 10^5$ s the volume ($\propto t^3$) is 10^{15} times larger!
  - Adiabatic cooling $\propto V^{-\frac{1}{3}} \propto t^{-1}$
  - i.e., only $\sim 10^{-5}$ of prompt jet's energy remains (to be radiated)

$1\,\%$ **of the jet energy injection** $\sim 10^4$ **s later**
$\Rightarrow \sim 10^2$ **times brighter cooling emission**

Prediction: Thermal soft X-ray [off-axis & failed sGRBs]

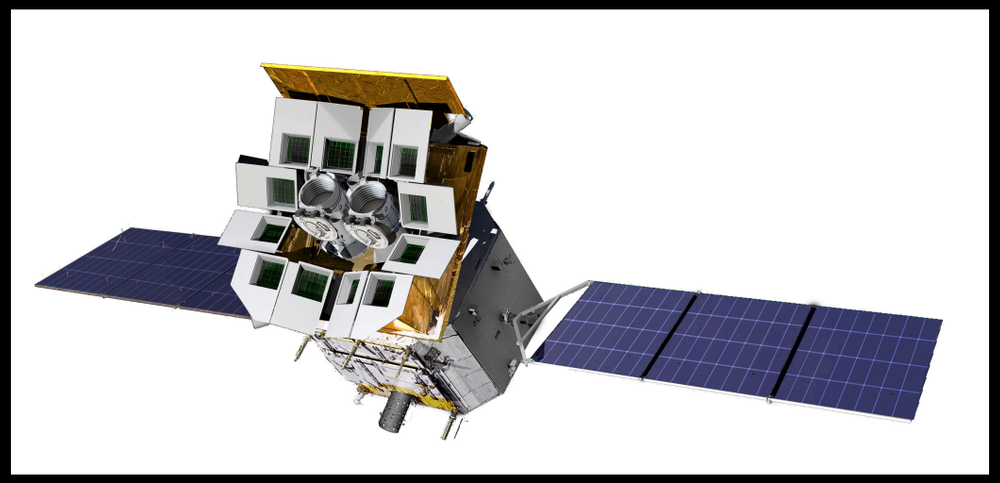


Credit: Hamidani et al. in 2024

Detection rate [in $0.1-3$ keV]

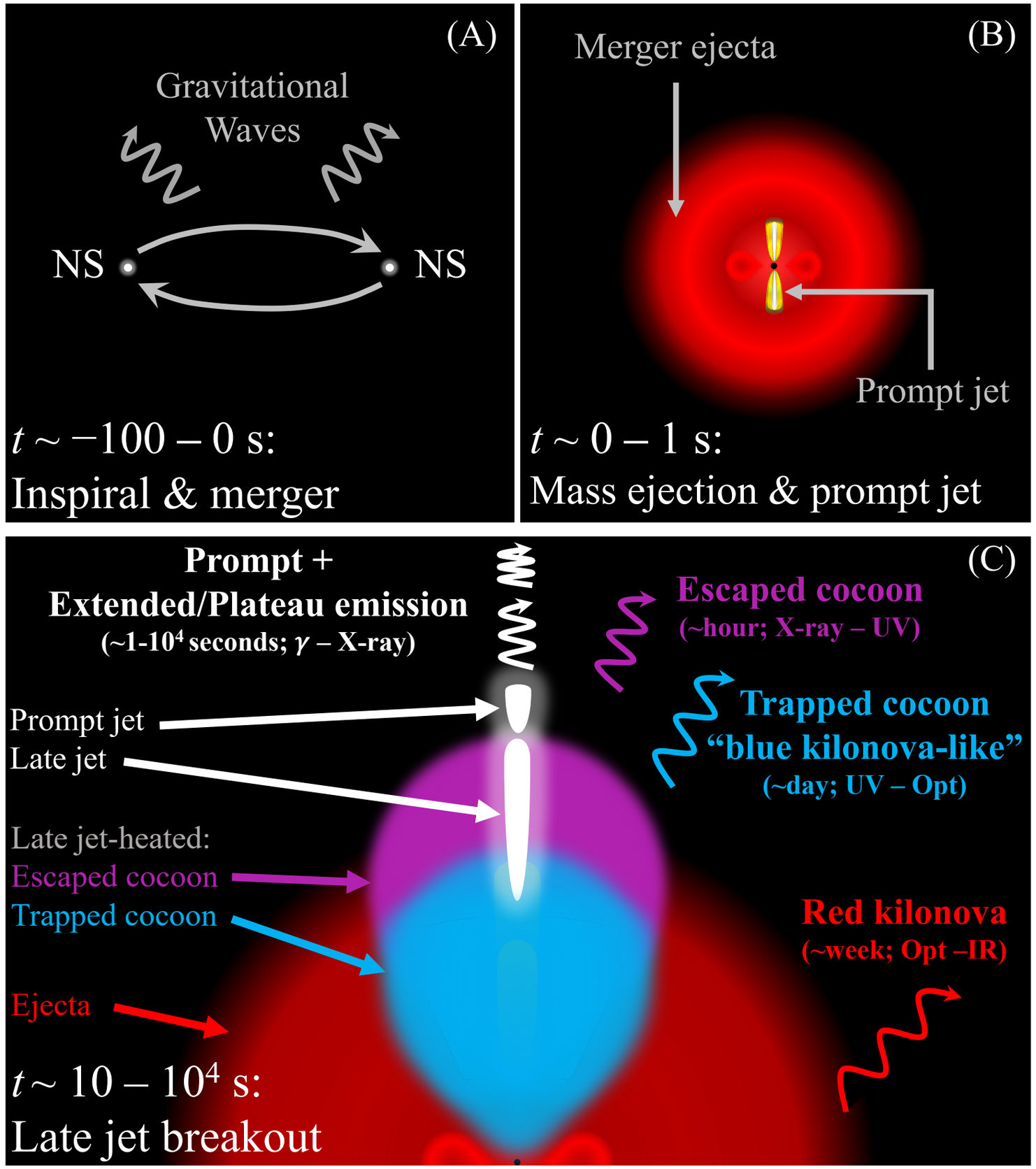
$$R_{X,\,\textbf{cocoon}} \sim 2.1^{+3.2}_{-1.6} \times \left[\frac{D}{1\ \mathrm{Gpc}}\right]^{3} \mathrm{yr}^{-1}$$

1. Expected for off-axis & failed sGRB events!
2. Perhaps, some of EP's recent faint X-ray events?



Credit: EP

New Paradigm



Credit: Hamidani et al. in 2024

Summary

Late engine activity is ubiquitous in sGRB
extended emission & plateau emission

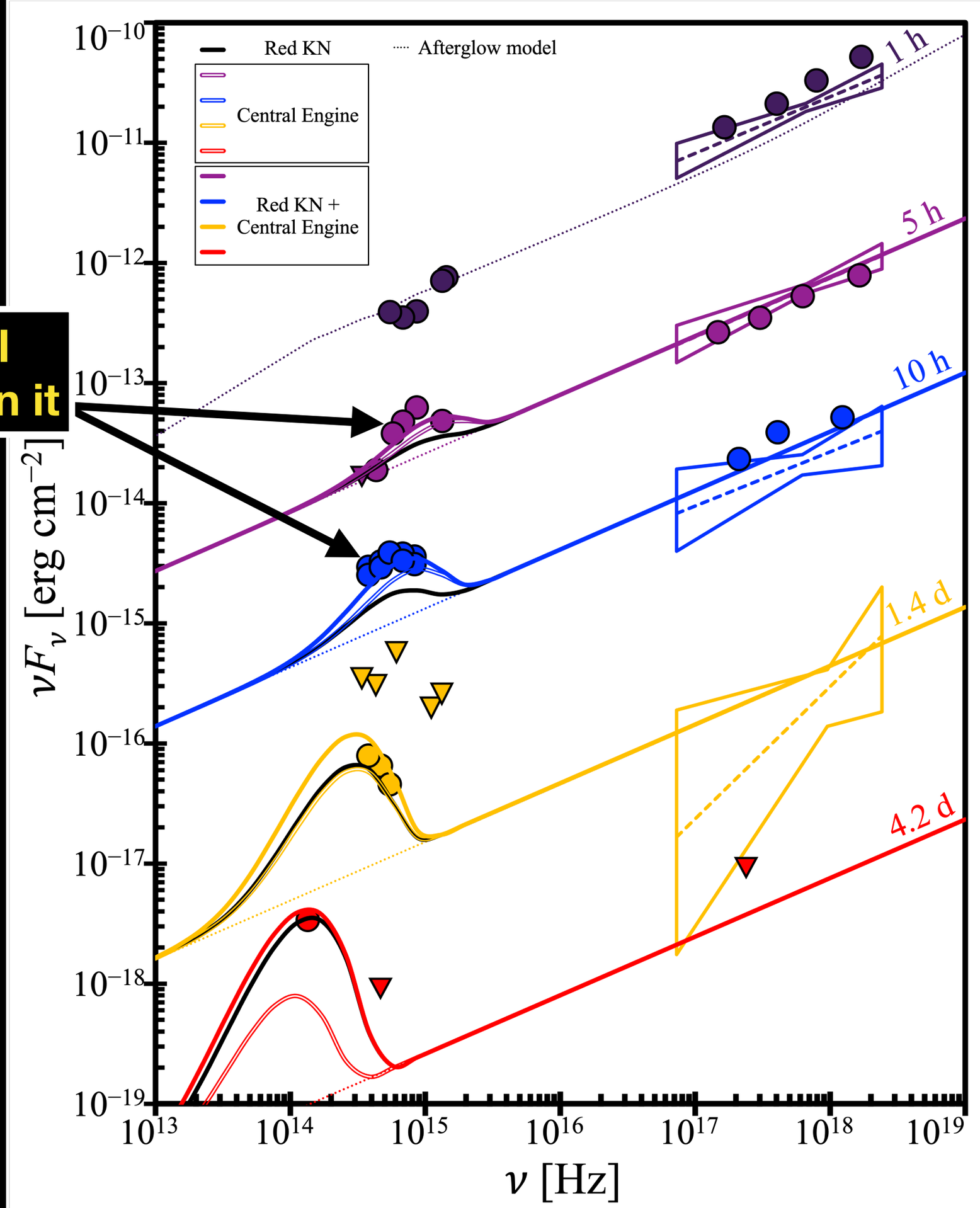
With late engine shock heating is much more effective
$\sim 10^2$ times; due to the heating at larger radius, hence much less effective adiabatic cooling.

Predict an X-ray transient from the late jet/outflow
Detectable with with Einstein Probe $\sim 1/\mathrm{yr}$ for off-axis & failed sGRBs!

Future early follow-up observations are key
$\lesssim$ day follow-up observations of GW-sGRB events will be decisive

GRB211211A's early Blue KN

Only the central engine can explain it



Credit: Hamidani et al. 2024