The Case for

# “Engine Powered” Over r-Process Powered Blue Kilonova


**Hamid Hamidani**

**With:**

**Masaomi Tanaka, Shigeo Kimura, Gavin P. Lamb, & Kyohei Kawaguchi**



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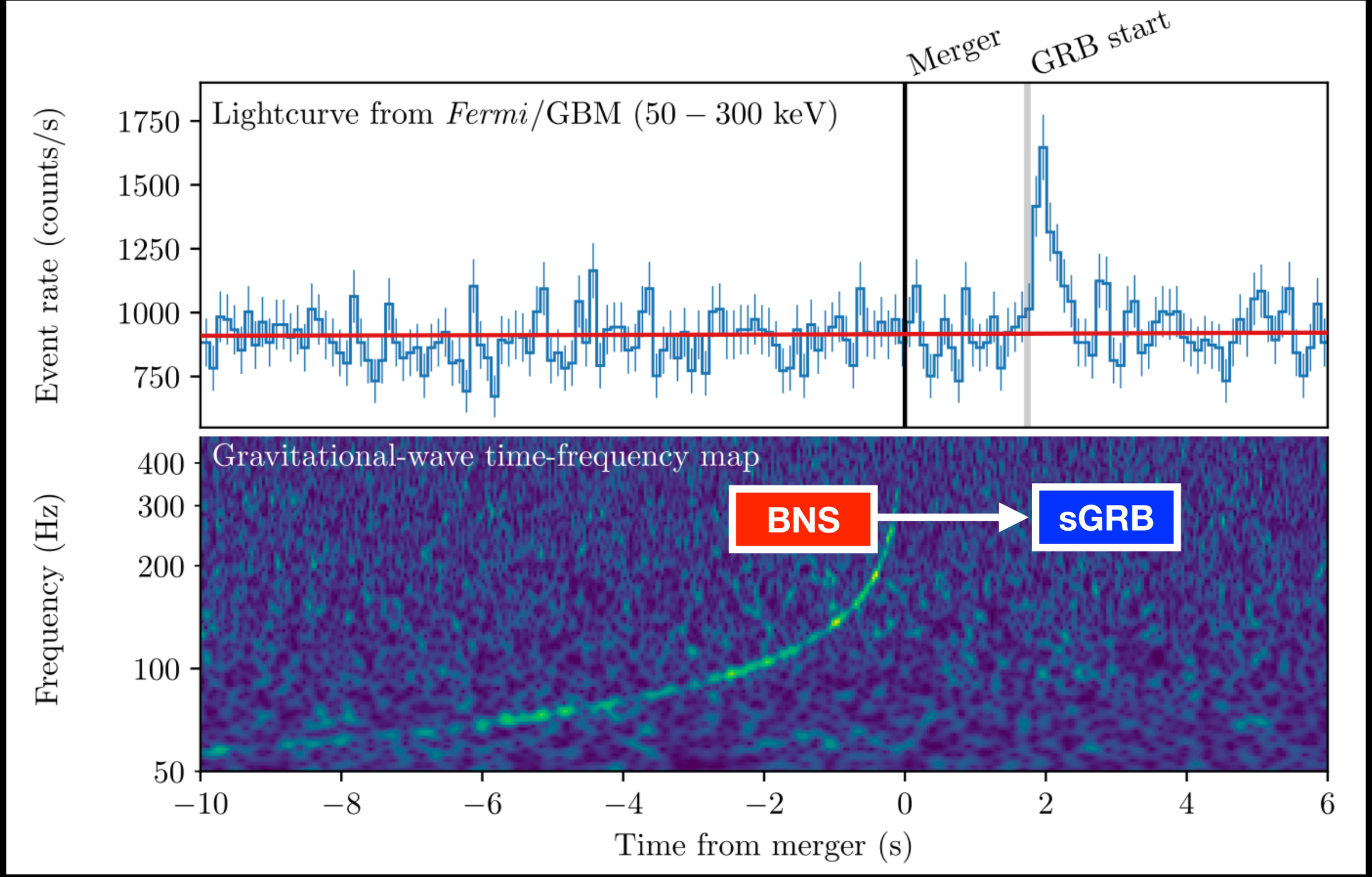
# NS mergers [& sGRBs]

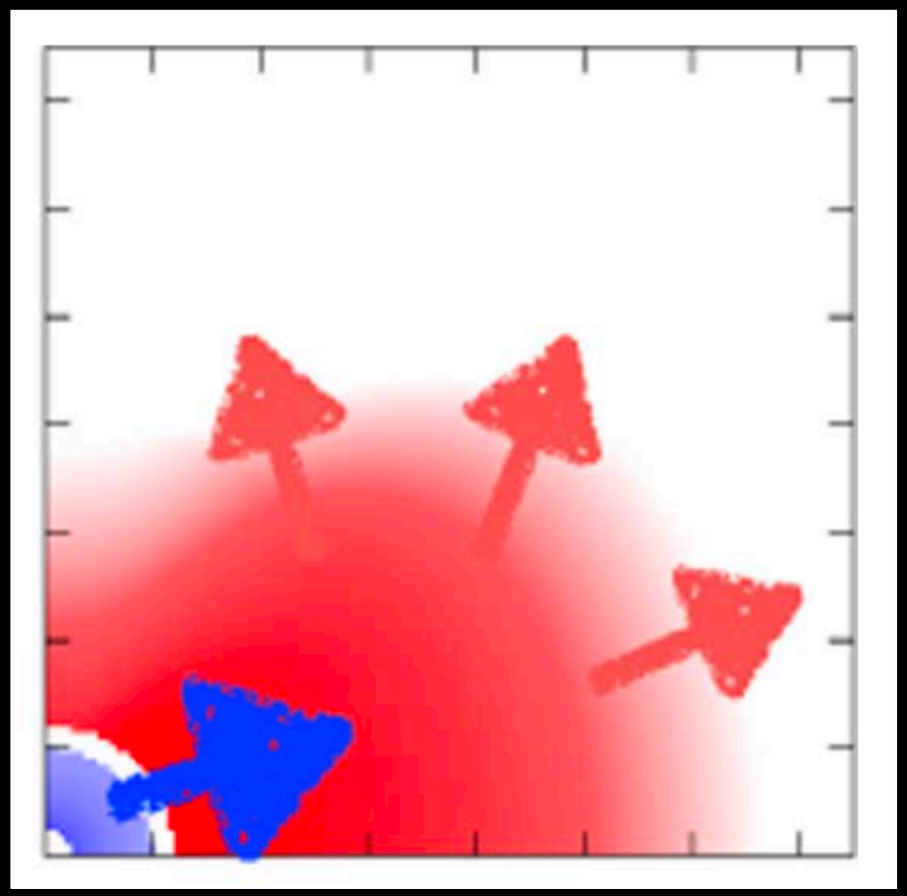



**See talks by: Tanaka-san & Kido-kun**

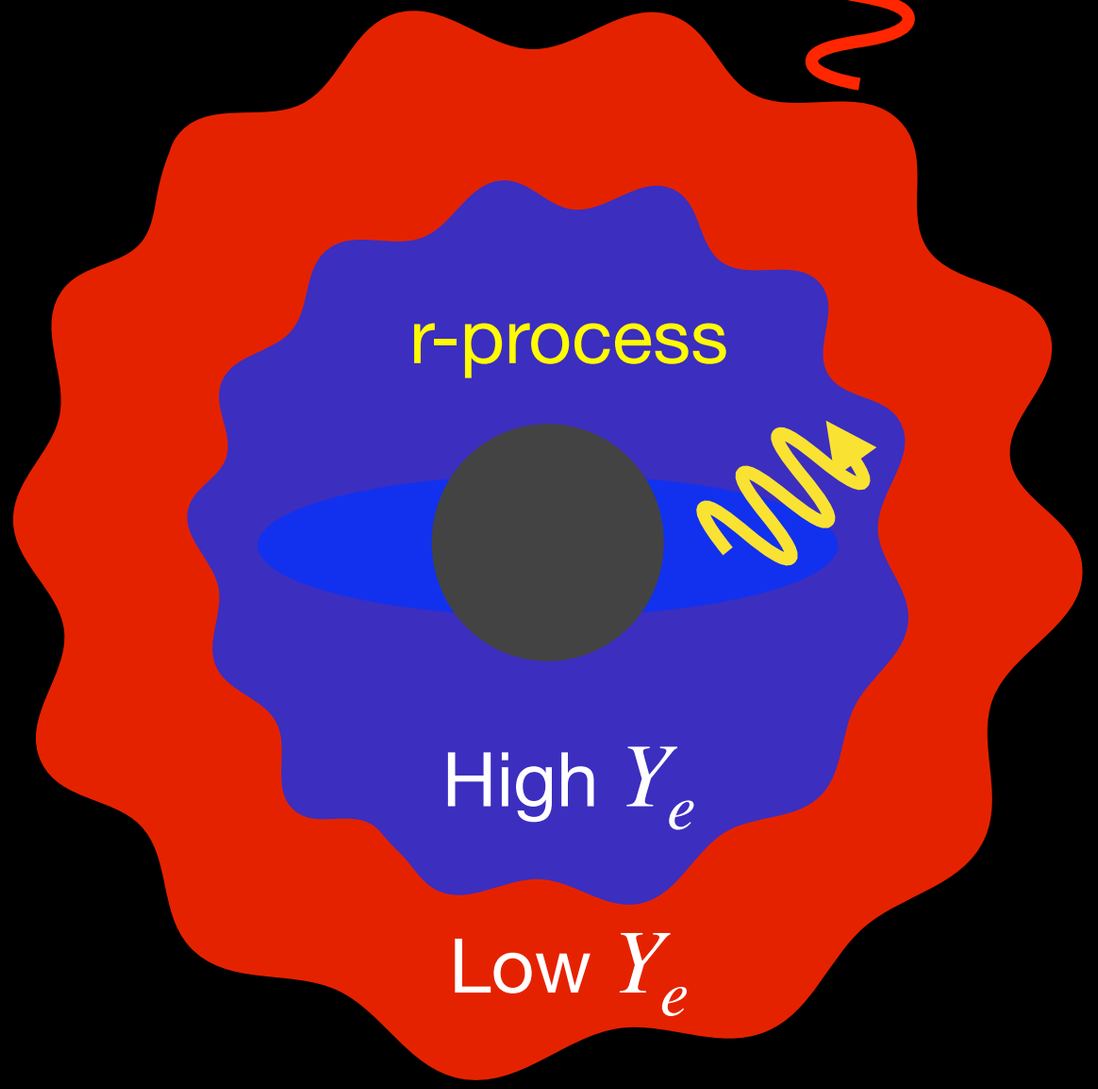
Credit: Abbott et al. 2017

# Basic Concept [r-Process Kilonova]

Credit: Kawaguchi+20



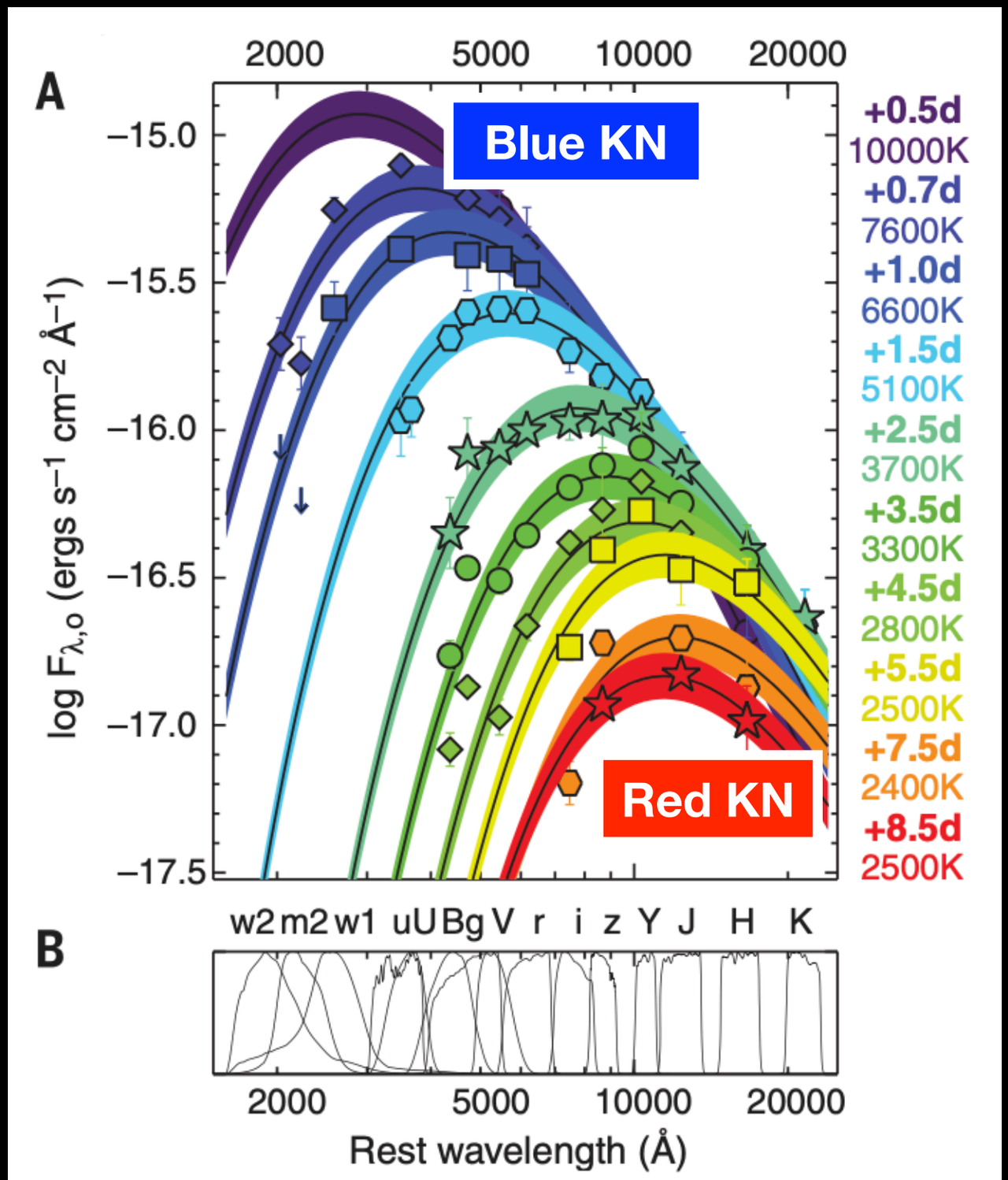
Red KN?

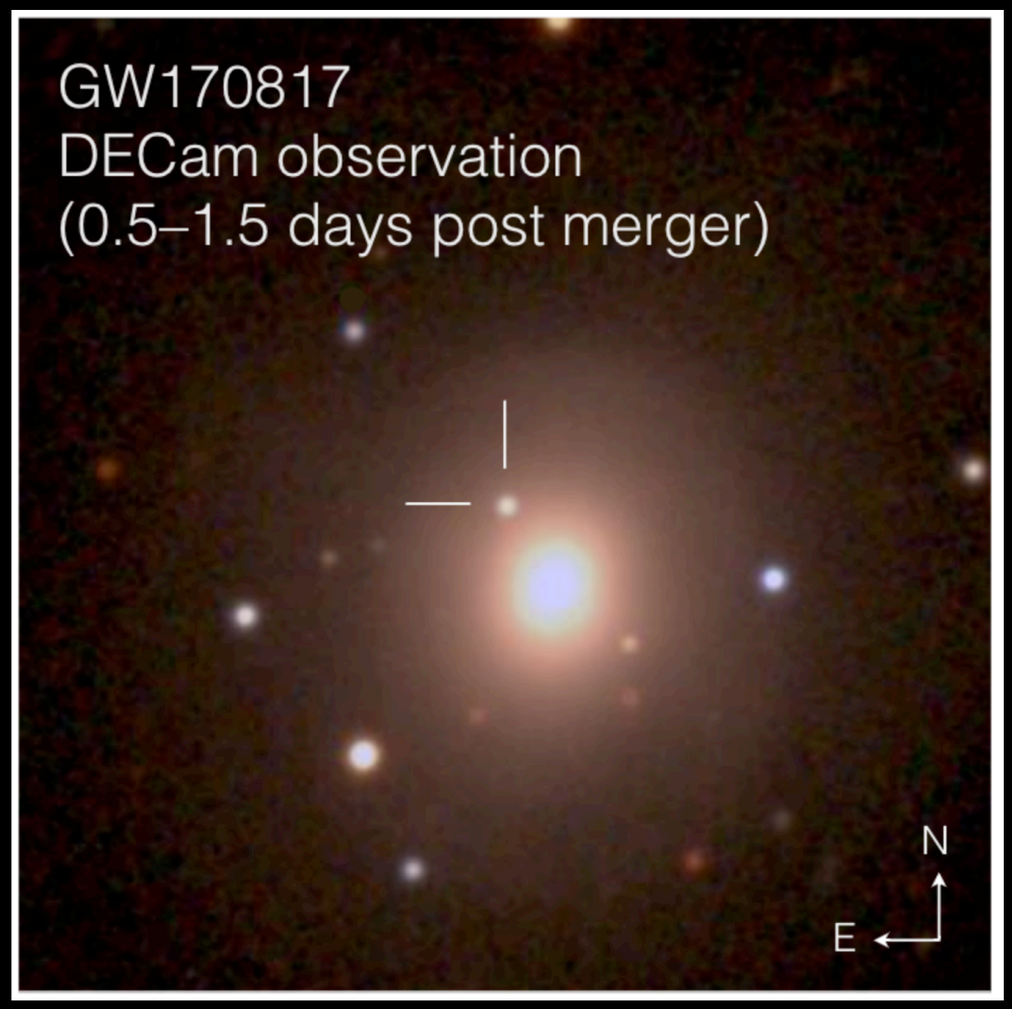



**See: Masaomi-san's Talk, & Kitamura-san's poster.**

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

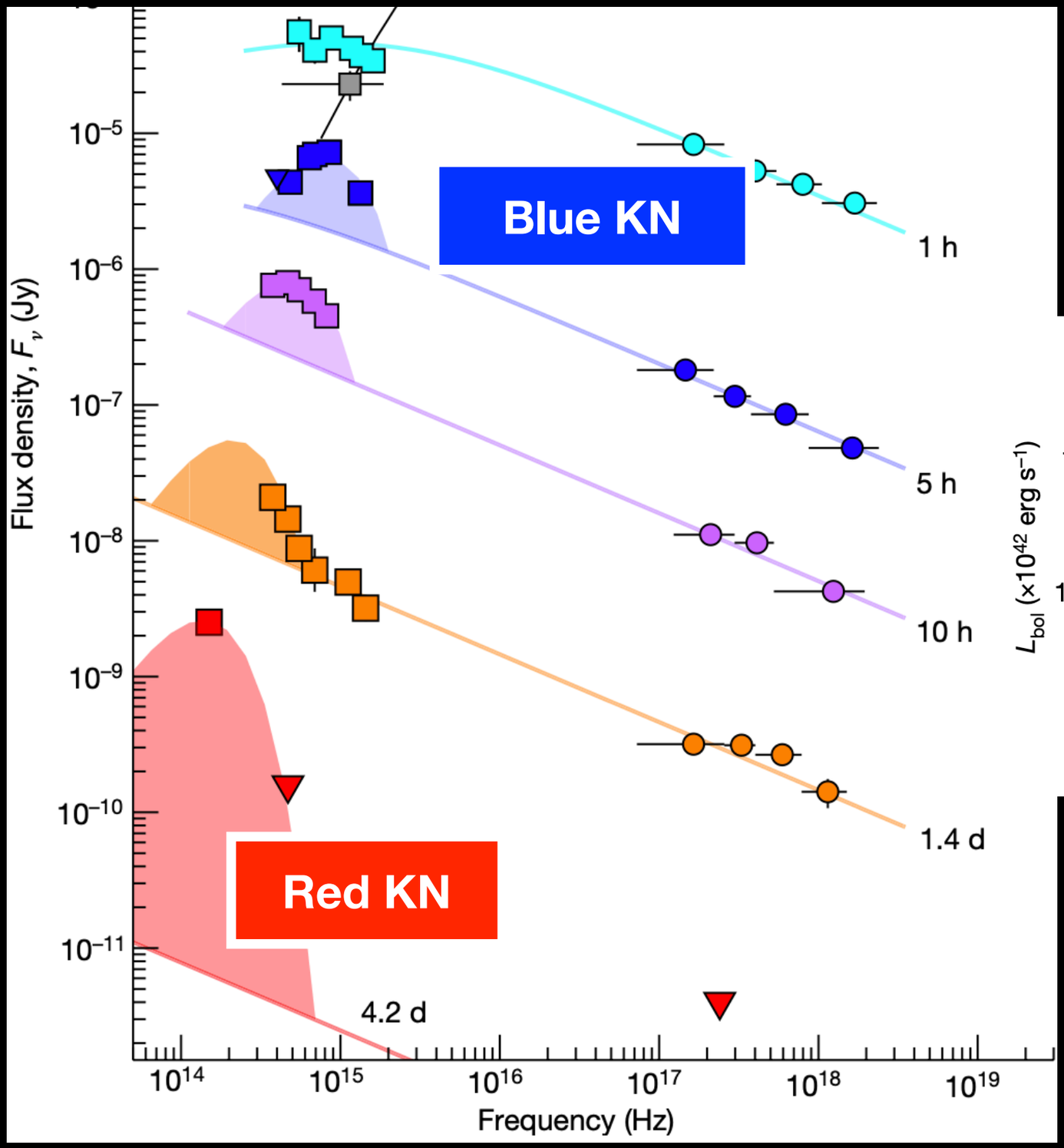
# Blue kilonova [GW170817]

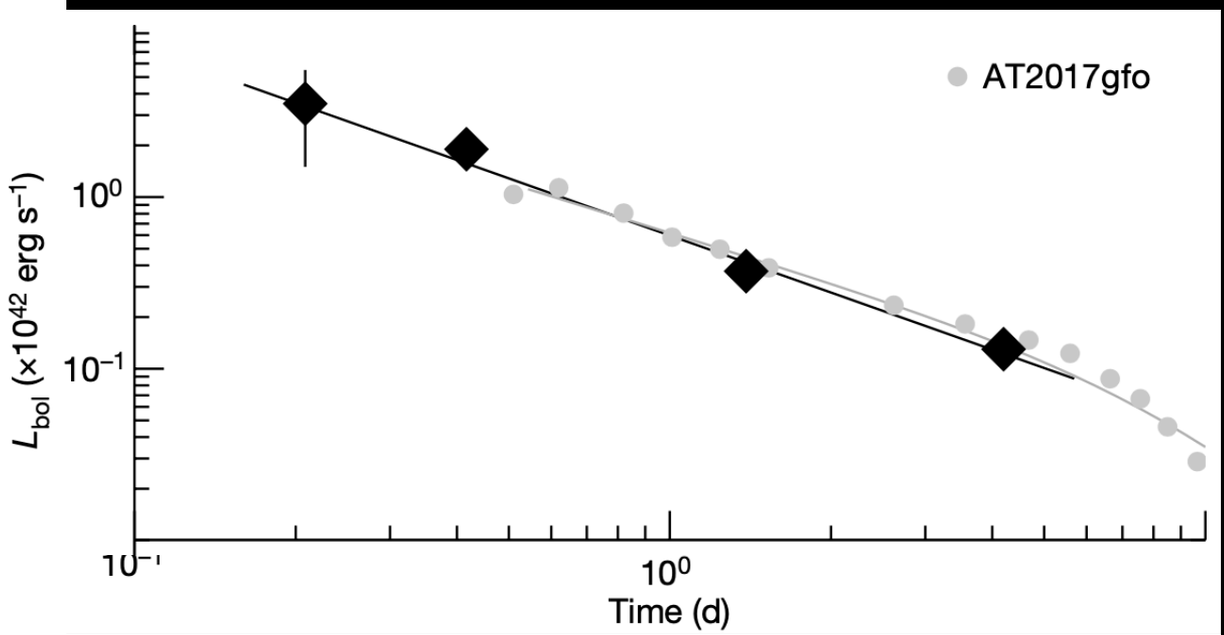



Credit: Soares-Santos et al. and DES Collaboration; Drout et al. 2017

# A new Blue KN [GRB211211A]



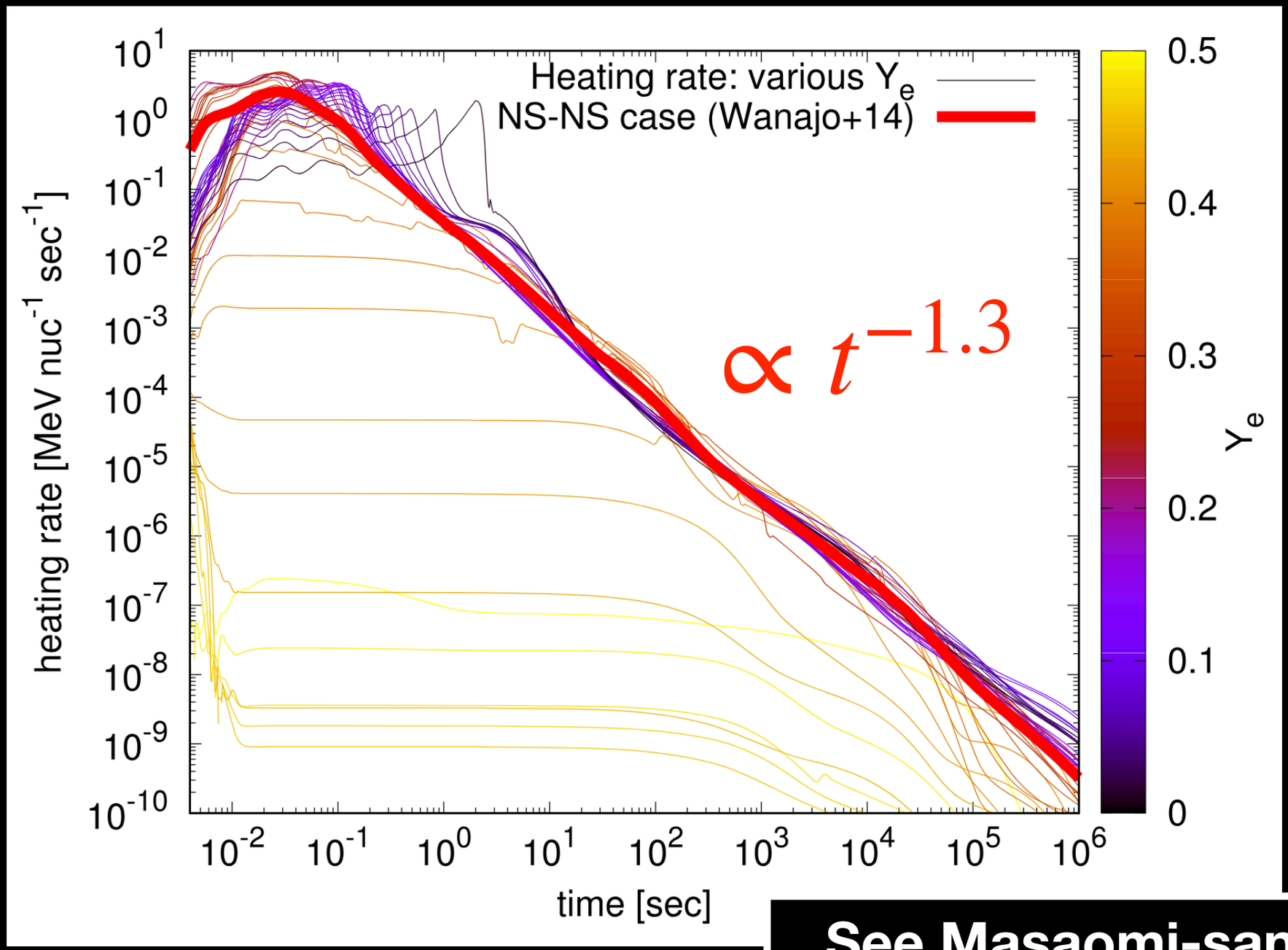




**Earliest, Brightest KN to date!**

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

# Q: What’s the origin the early blue KN?

# R-process [deposition]




Credit: Zaq+2021; Wanajo+2014

**See Masaomi-san's Talk**

# Analytic KN Model

Homologous: $\rho \propto \beta^{-n}$

Deposition rate: $\dot{\varepsilon} = \dot{\varepsilon}_0 \left( \frac{t}{1\,\mathrm{d}} \right)^{-1.3}$, $\dot{\varepsilon}_0 = 2 \times 10^{10}\,\mathrm{erg\,g^{-1}s^{-1}}$,

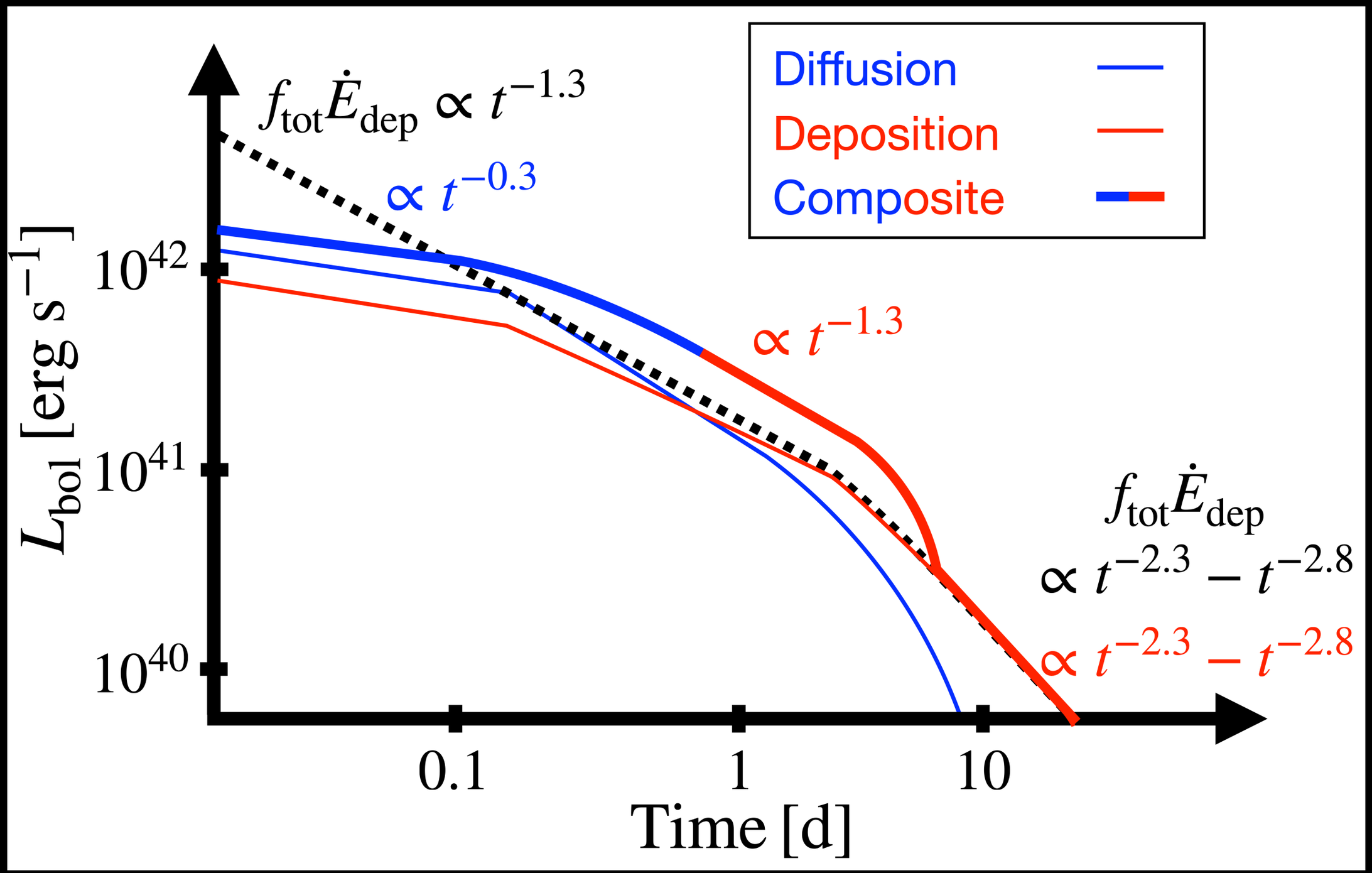
Thermalization: $f_{tot} = f_\beta(t, M_e)$

Diffusion shell: $\tau = \frac{c}{(v_\mathrm{m} - v_\mathrm{d})}$

Grey opacity: $\kappa = \mathrm{Const}\,.$

Total luminosity: $L_{\mathrm{KN}}(t) = \underbrace{L_{\mathrm{KN}}(<\beta_\mathrm{d}, t)}_{\textbf{Diffusion}} + \underbrace{L_{\mathrm{KN}}(\geqslant \beta_\mathrm{d}, t)}_{\textbf{Deposition}}$

# Time evolution




Credit: HH+24

# Early time evolution [r-p KN]

At early times $L_{\rm KN}(t) \approx L_{\rm KN}(<\beta_{\rm d}, t) = \dfrac{\Delta E_{\rm i}(<\beta_{\rm d}, t)}{\Delta t}$

$$\frac{\partial E_{\rm i}(<\beta_{\rm d}, t)}{\partial t} = -\frac{E_{\rm i}(<\beta_{\rm d}, t)}{t} + f_{\rm tot}(t)\dot{E}_{\rm dep}(<\beta_{\rm d}, t)$$

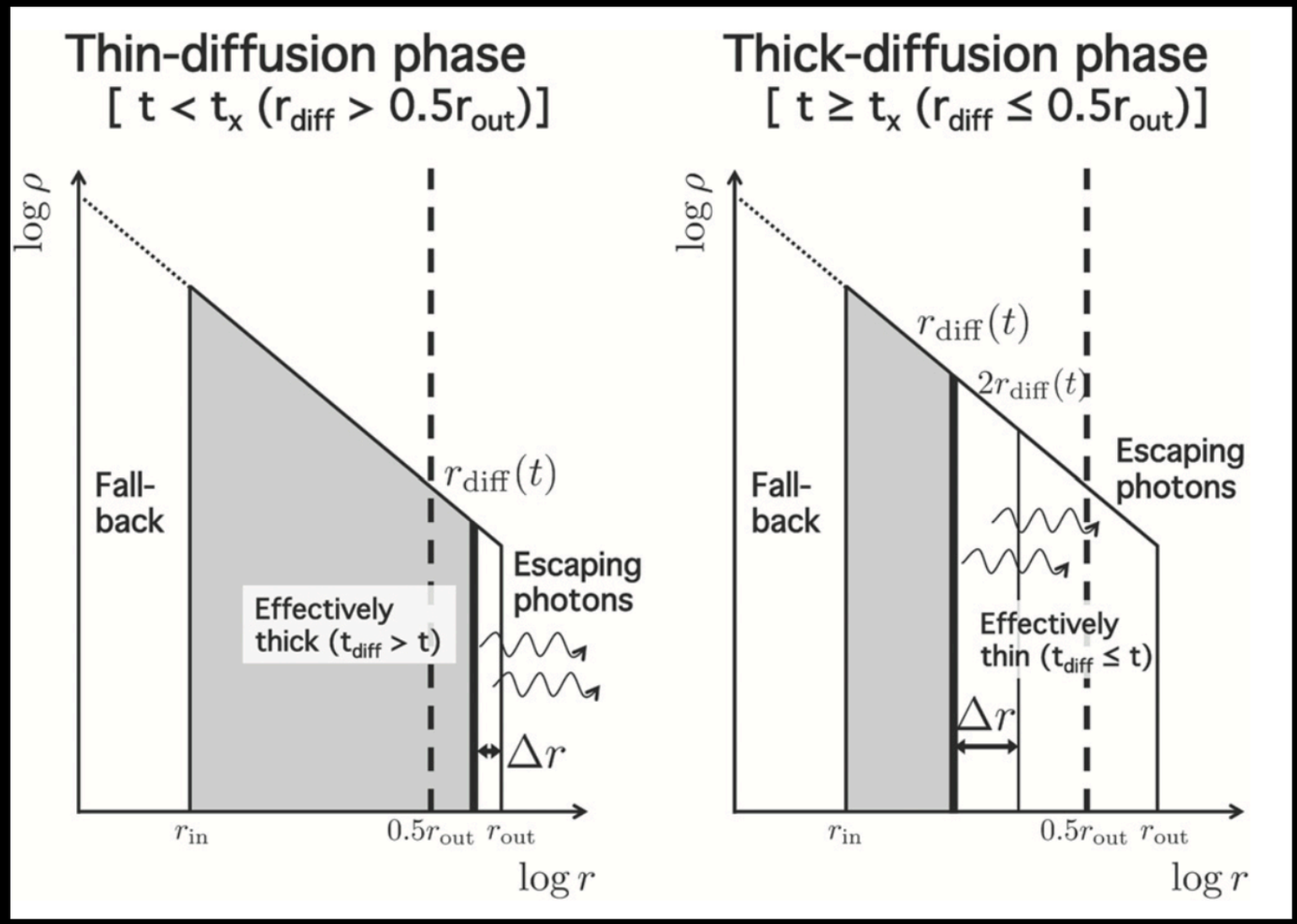
$$\Delta M_{\rm e}(<\beta_{\rm d}, t) = \rho(\beta_{\rm m}, t)\Delta V \propto \Delta t \quad \& \quad f_{tot}(t) \sim 0.7$$

$$\begin{aligned} E_{\rm i}(<\beta_{\rm d}, t) &= \frac{1}{t}\int_0^t f_{\rm tot}(t)\dot{E}_{\rm tot}(<\beta_{\rm d}, t) t dt \\ &\propto t^{1-k} f_{\rm tot}(t) M_{\rm e}(<\beta_{\rm d}, t) \\ &\propto t^{2-k} \end{aligned}$$

$$L_{\rm KN}(t) \approx \frac{\Delta E_{\rm i}(<\beta_{\rm d}, t)}{\Delta t} \propto t^{-0.3}$$

**Credit: Kisaka+15; HH+24**

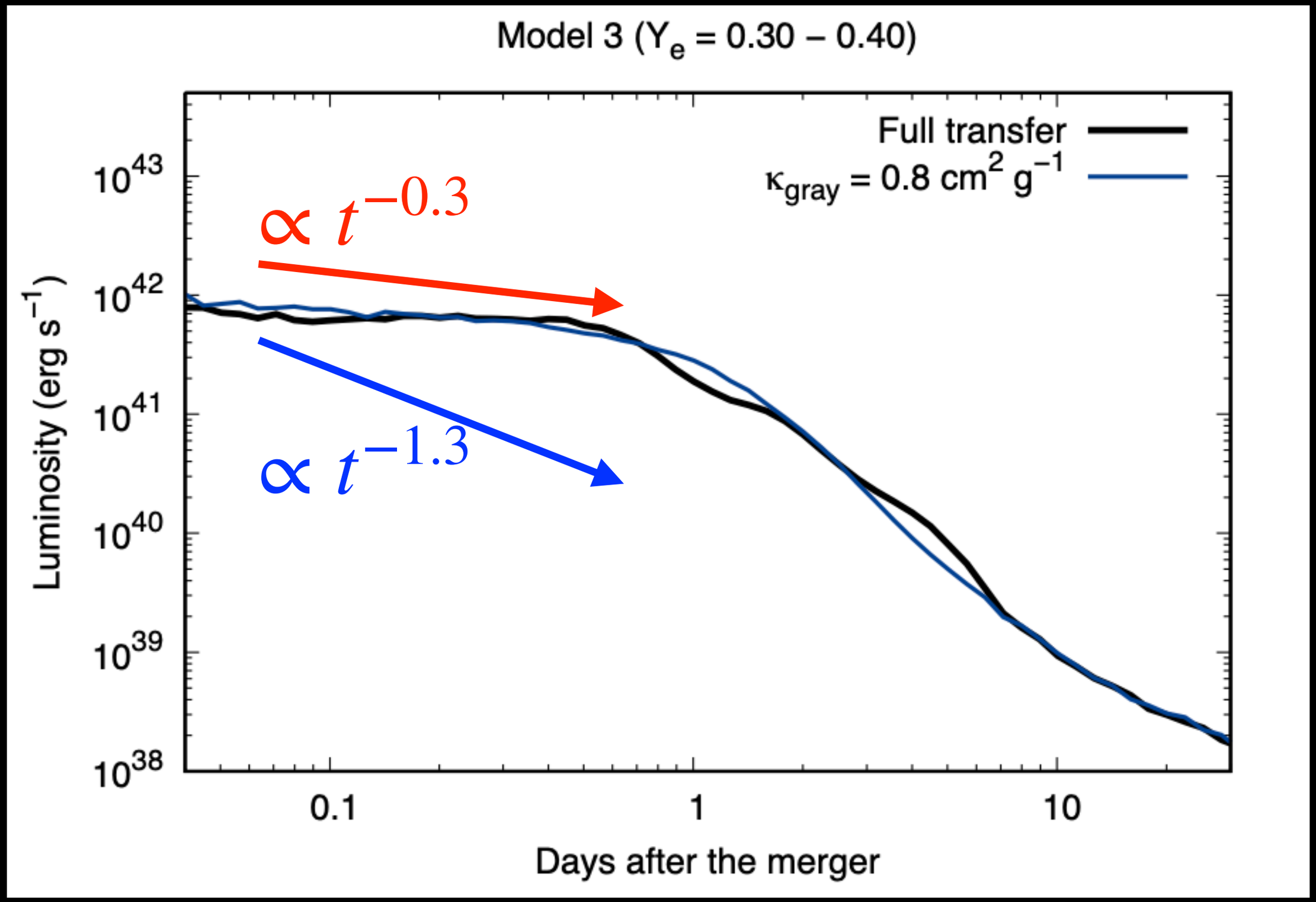
# Early time evolution [r-p KN]




$$L_{\rm bol} \sim 4\pi r_{\rm out}^2 \Delta r \rho(t, v_{\rm max}) \dot{\epsilon}$$
$$\propto \kappa^{-1/2} M_{\rm ej}^{1/2} v_{\rm min}^{\frac{\beta-3}{2}} v_{\rm max}^{\frac{4-\beta}{2}} t^{1-\alpha}.$$

Credit: Kisaka+2015

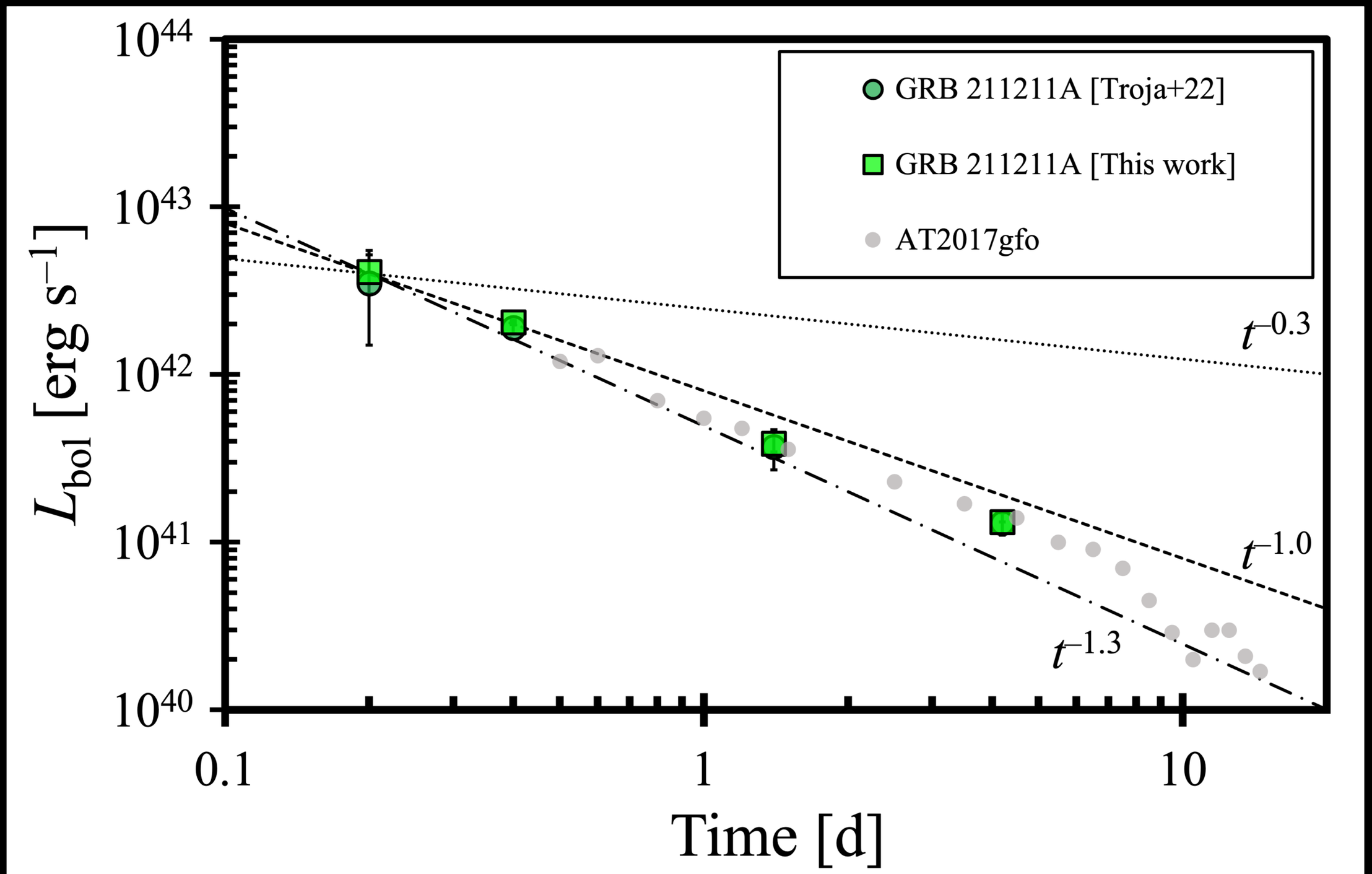
# In RT simulations




Credit: Banerjee+24

# Light curve [GRB211211A]

Credit: HH+24



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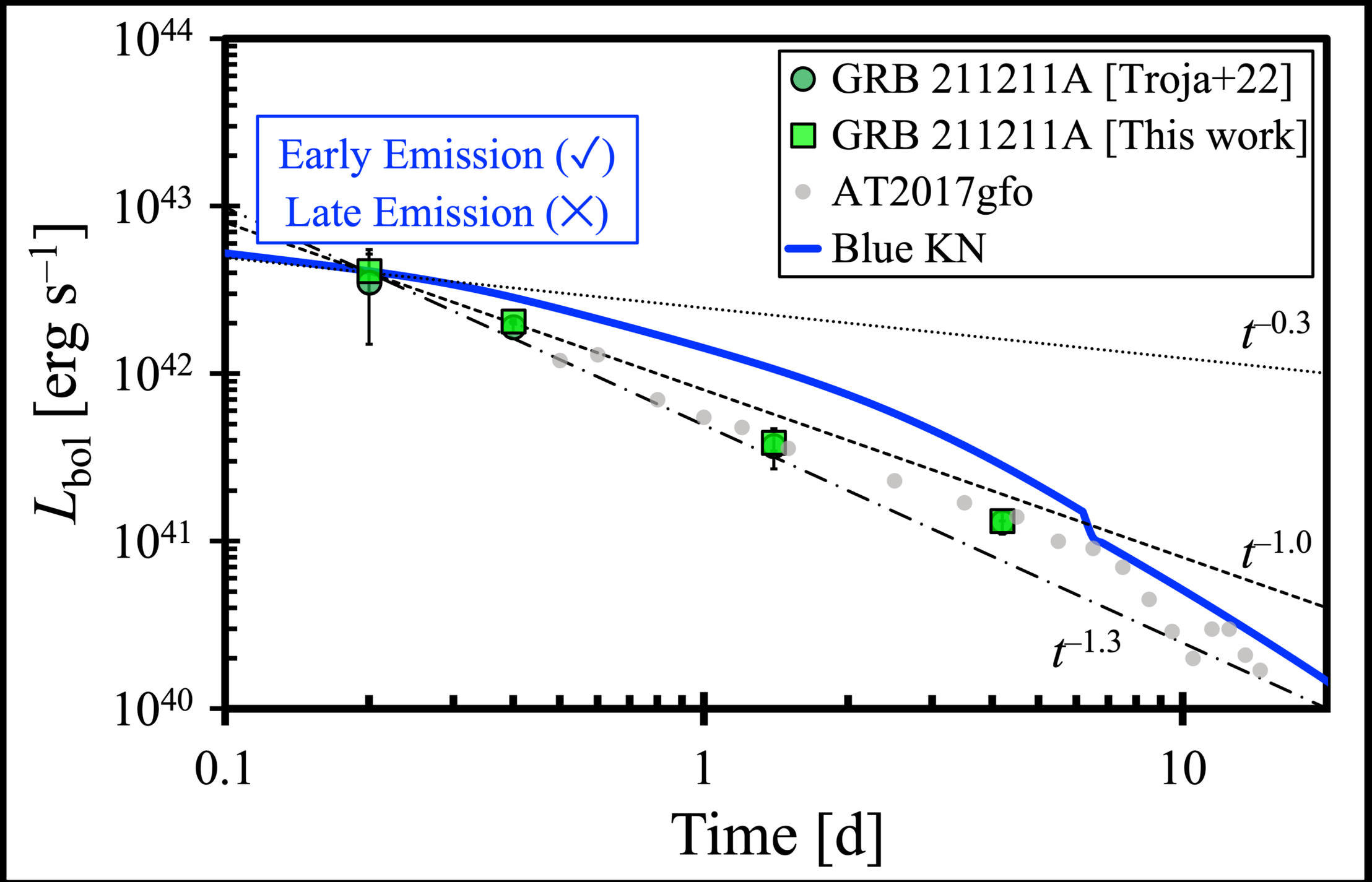

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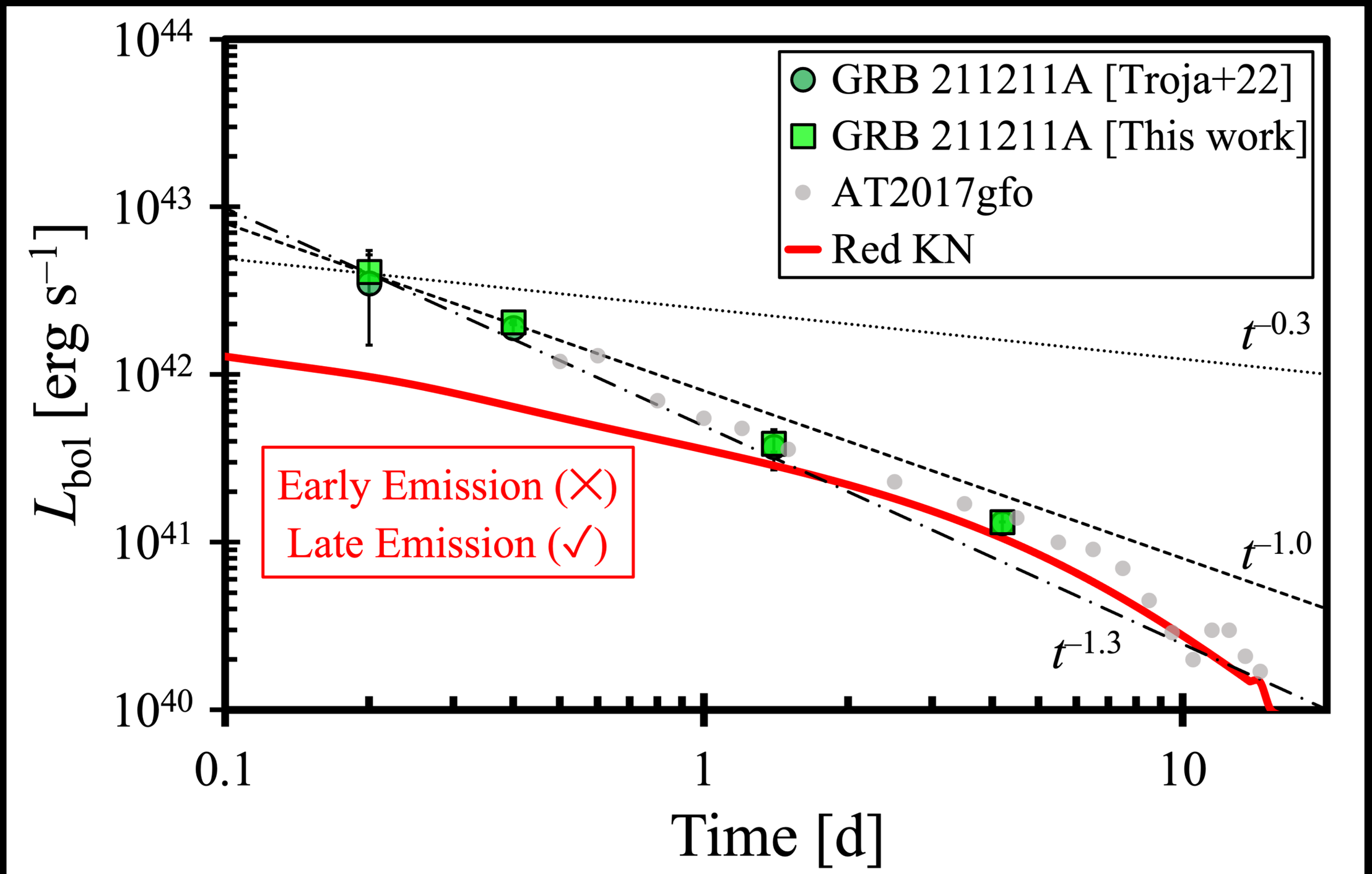

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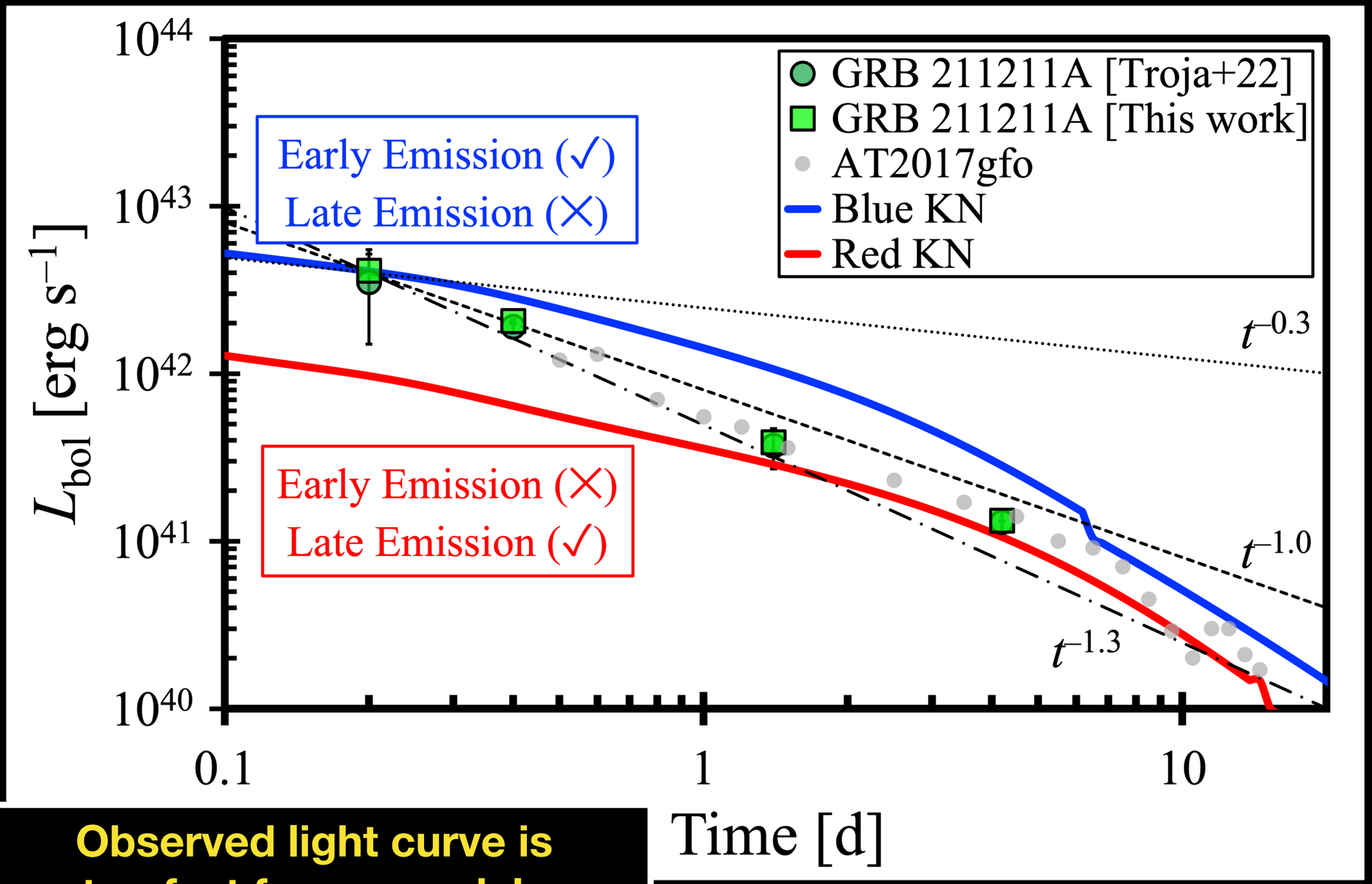
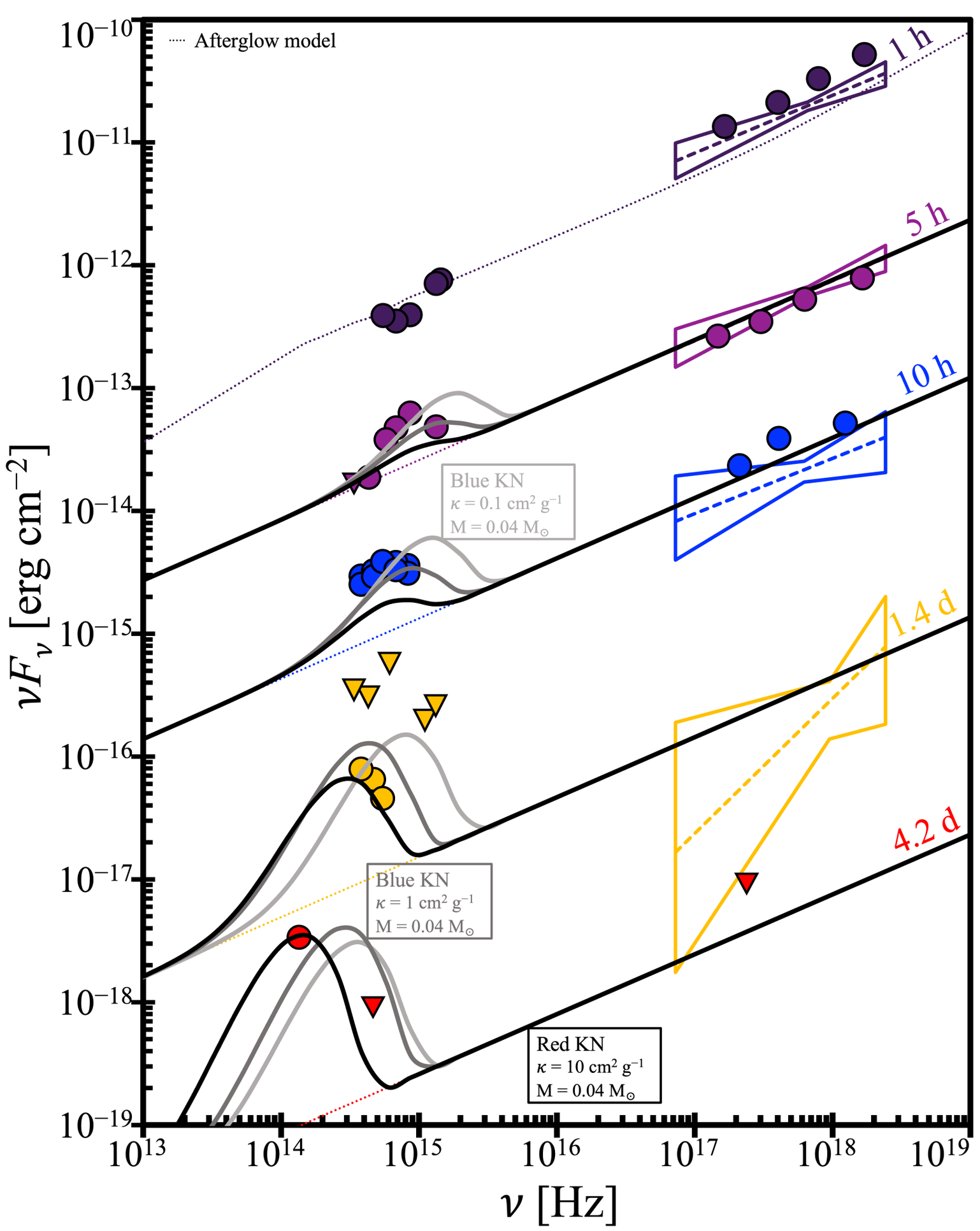



**Observed light curve is too fast for r-p models**

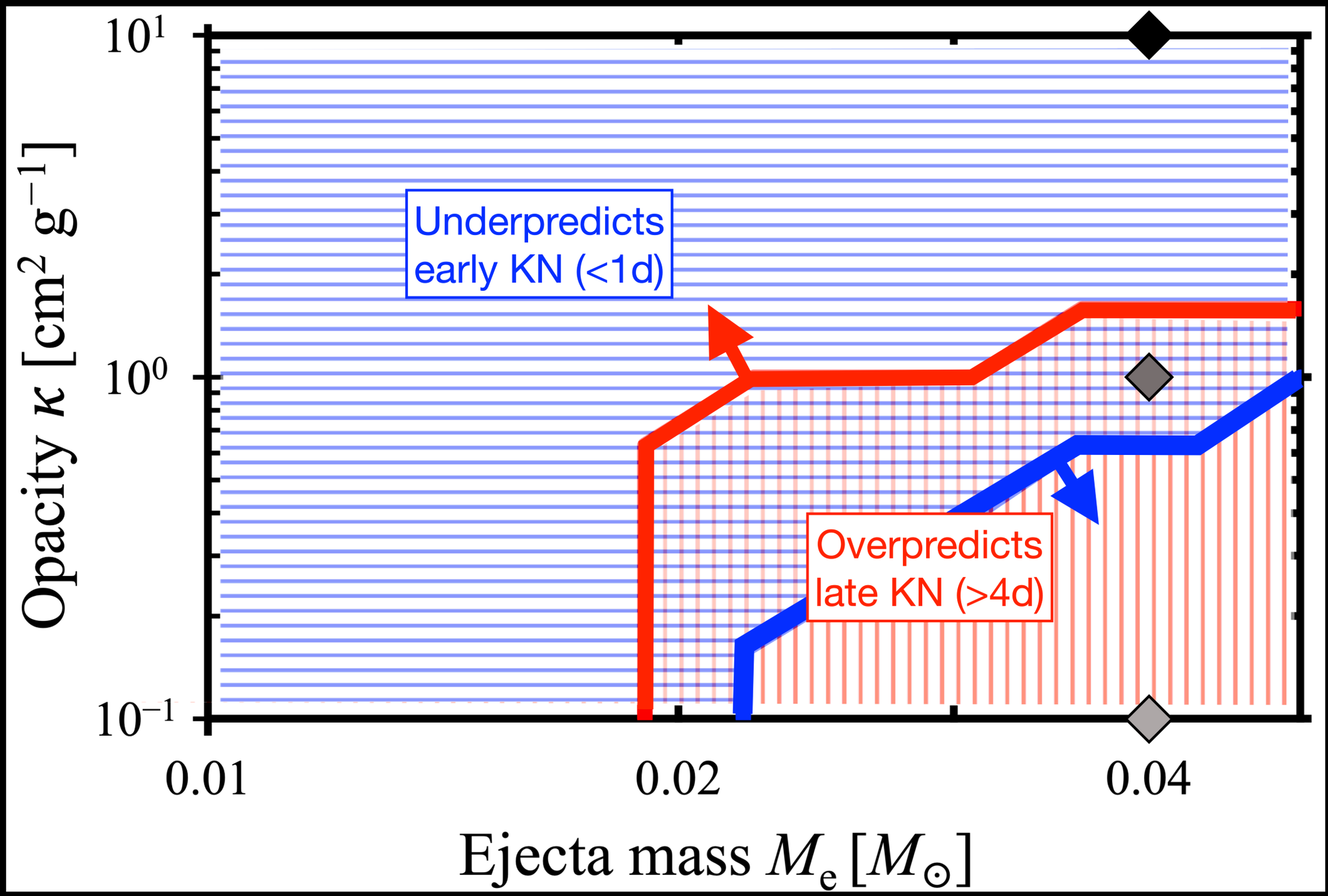
# Failure of r-p Model

**r-p KN cannot explain the SED…**

Credit: HH+24



# Difficult with r-p…



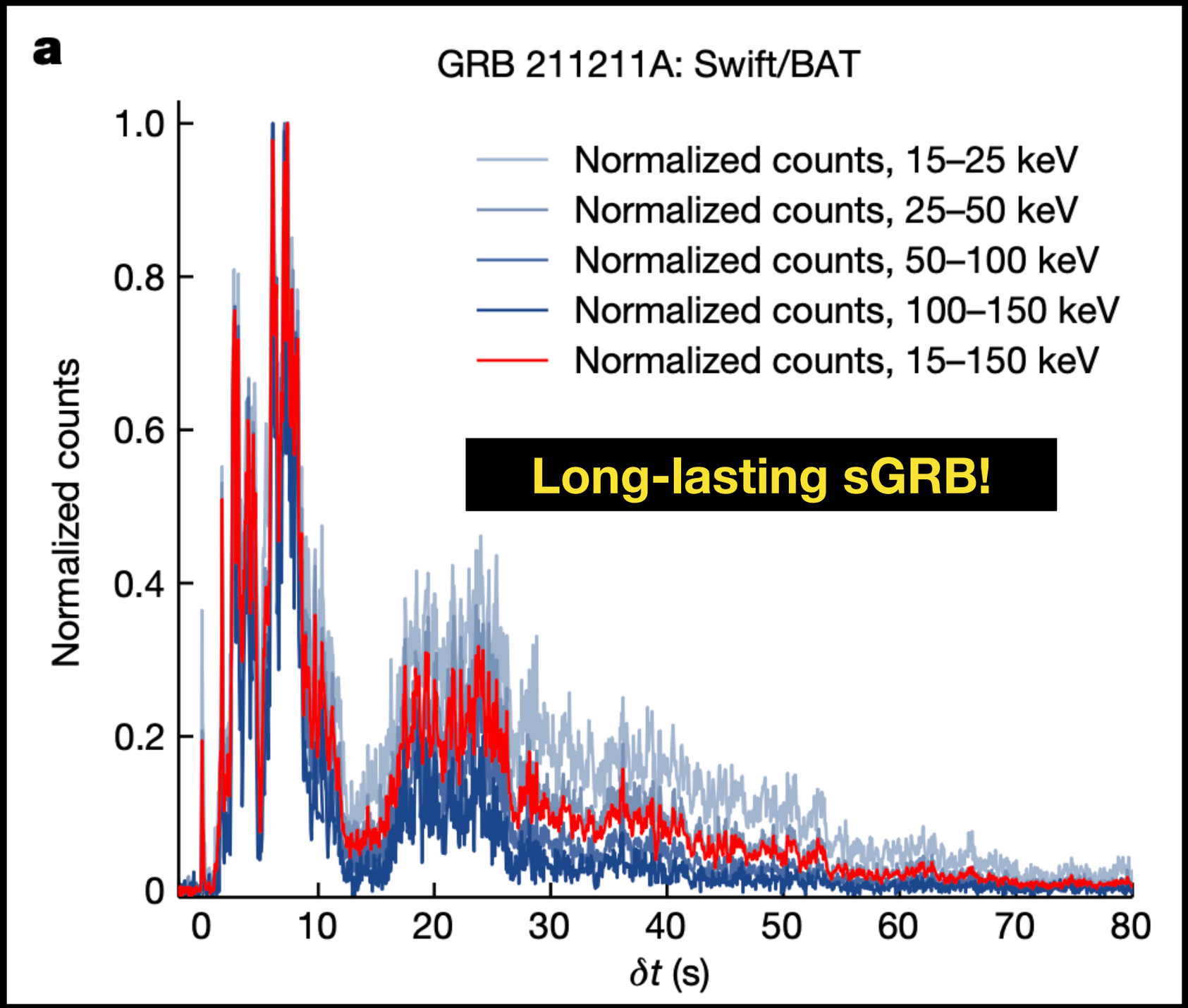

**No valid parameter space**

# Recap

- Difficult to explain the blue KN with r-process heating
- Observed KN time evolution is too fast for r-p models

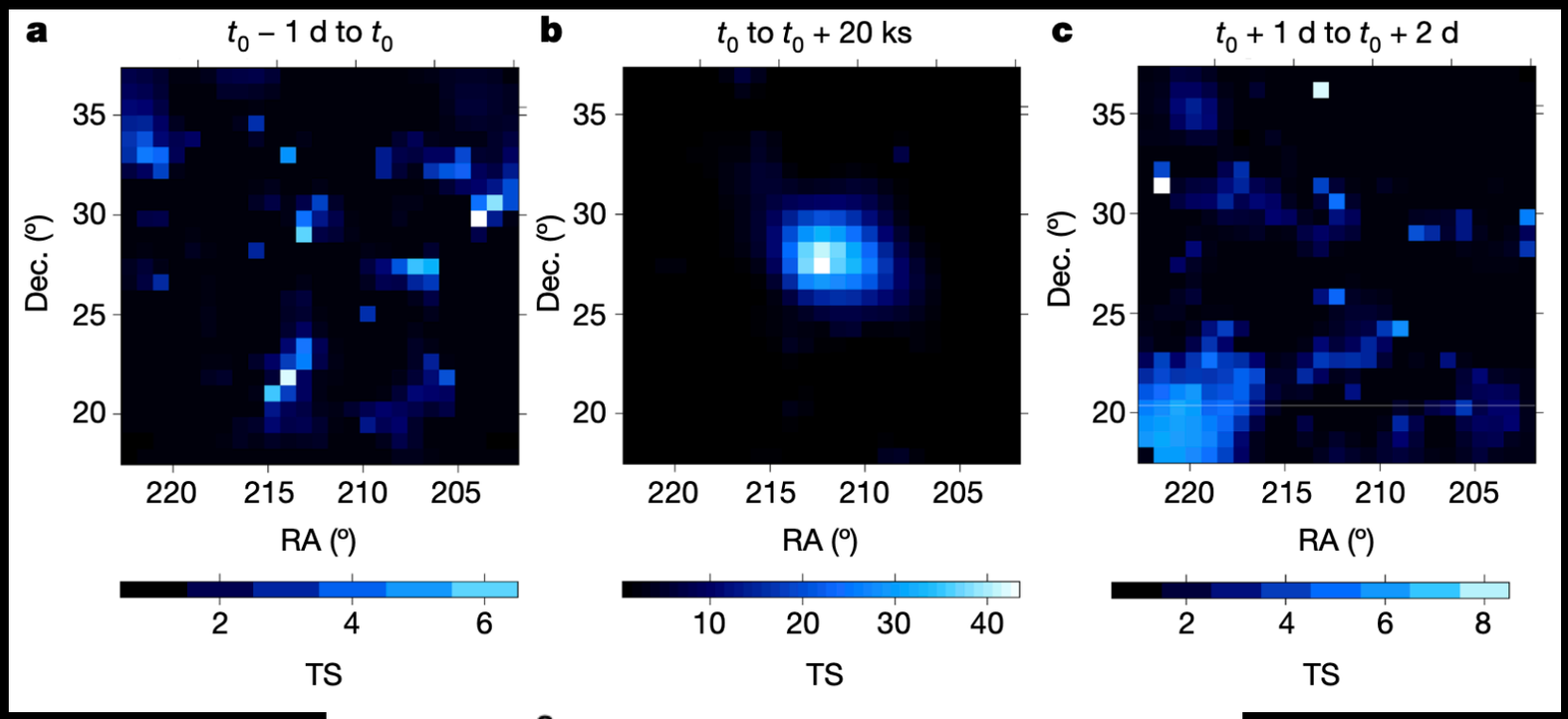
**Q: What's the alternative?**

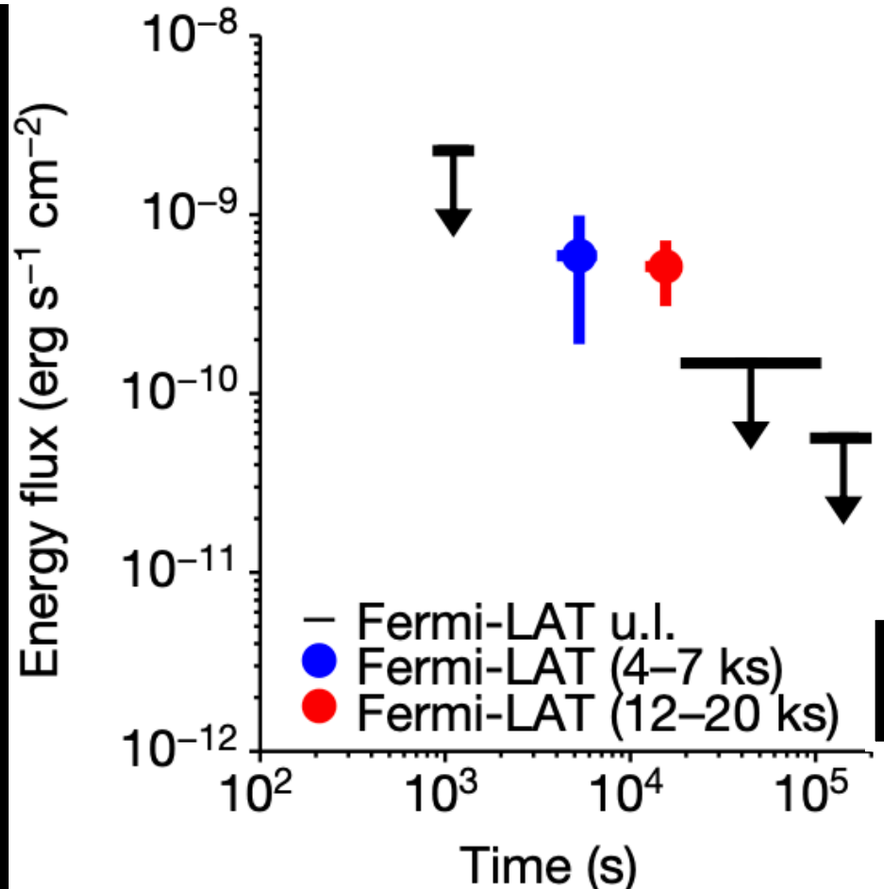
# GRB 211211A [long BNS?]

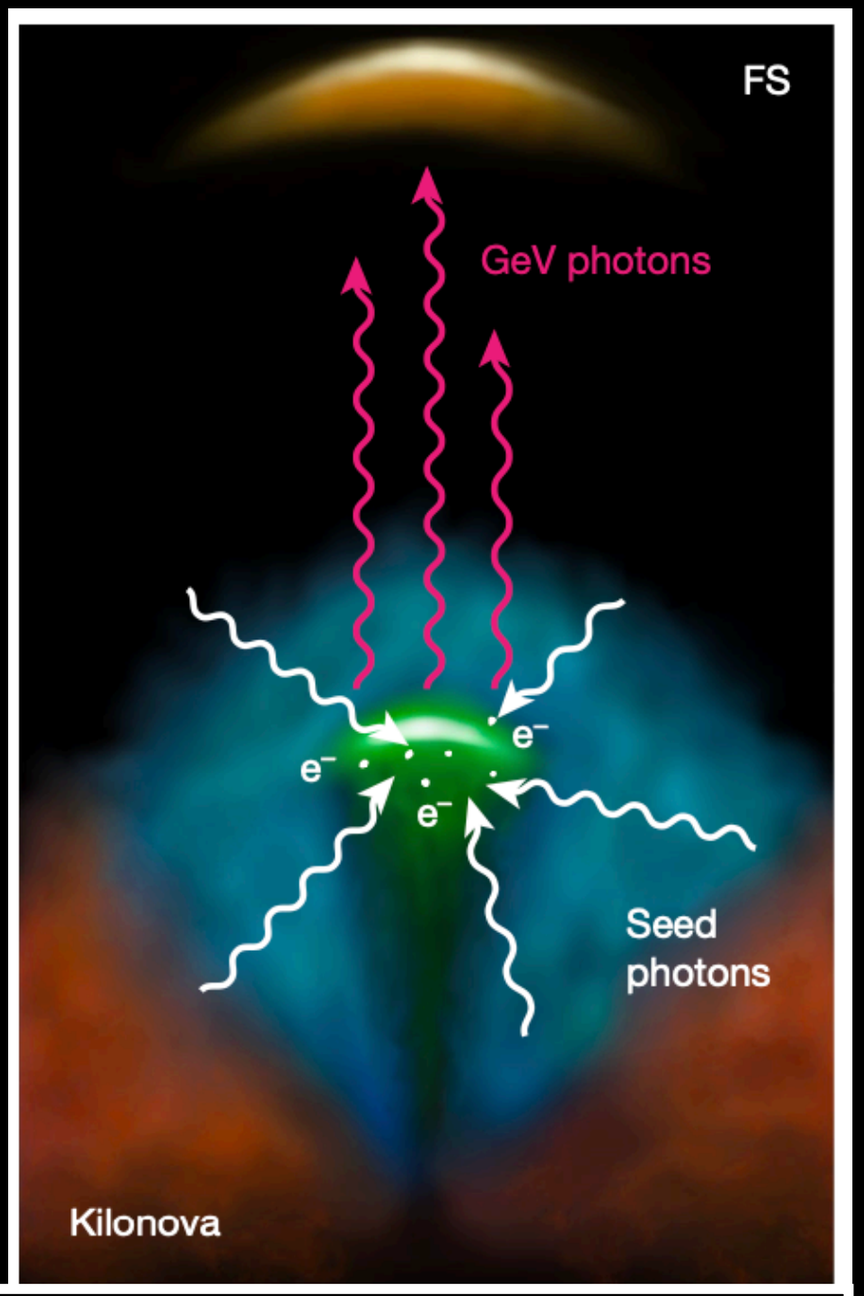



Credit: Rastinejad et al. 2022

# GRB211211A [GeV emission]



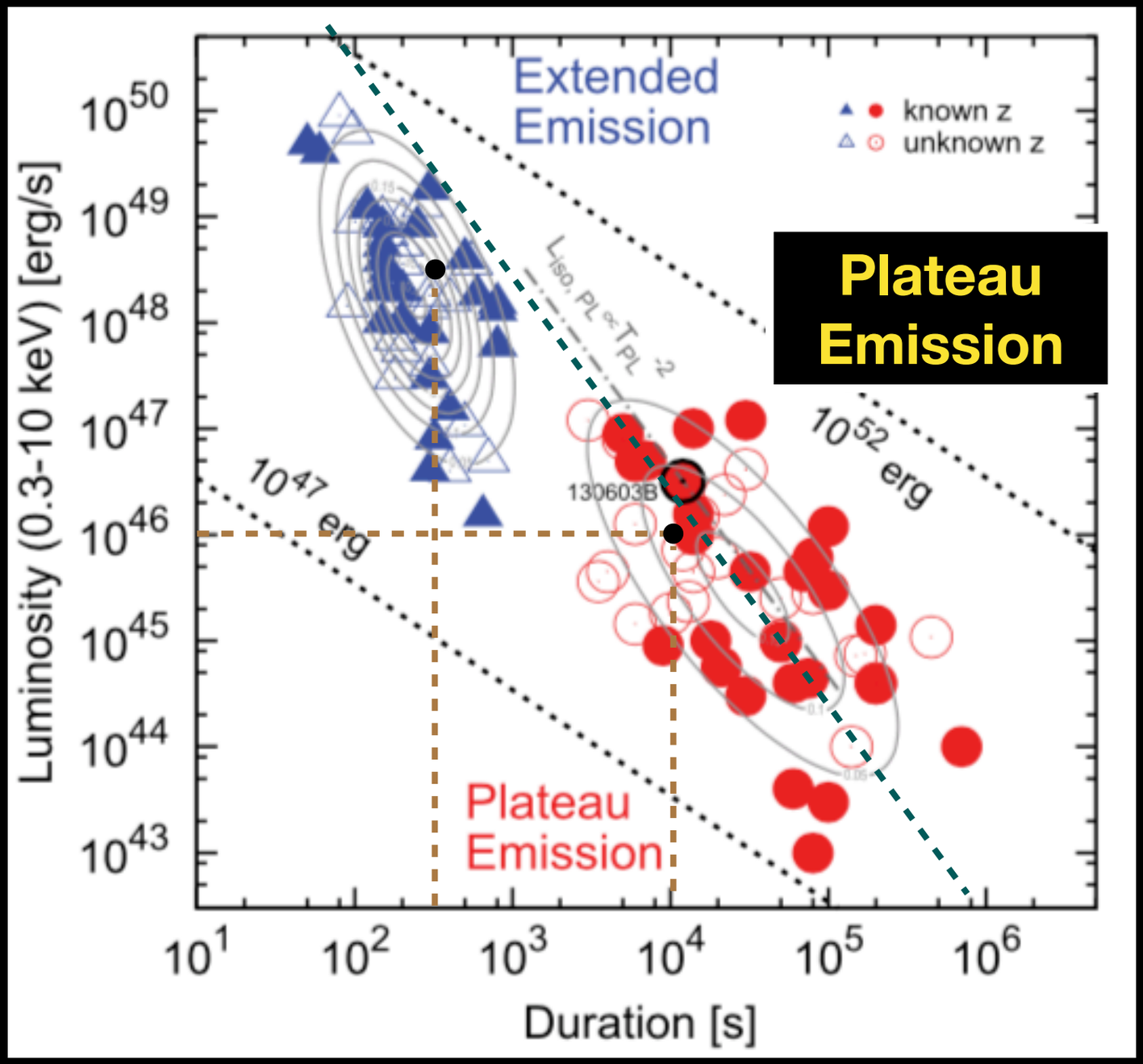




**$\sim 10^{46}$erg/s low power jet at $\sim 10^4$ s**

Credit: Mei et al. 2022

# Late engine activity




Credit: Kisaka et al. 2017

(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; $\gamma$ – 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

# Engine powered emission

$$L_{CE} \approx \underline{3 \times 10^{42}\ \mathrm{erg\ s^{-1}}} \left(\frac{\theta_0}{7.5^\circ}\right)^2 \left(\frac{L_{iso,0}}{10^{47}\ \mathrm{erg\ s^{-1}}}\right) \left(\frac{t_b}{4.7 \times 10^3\ \mathrm{s}}\right) \left(\frac{\kappa}{10\ \mathrm{cm^2\ g^{-1}}}\right)^{\frac{p-2}{2}} \left(\frac{M_c}{4 \times 10^{-2} M_\odot}\right)^{\frac{p-2}{2}} \underline{\left(\frac{t_{obs}}{5\ \mathrm{h}}\right)^{-p}}$$

$[p \sim 1 - 2]$

# Why brighter w/ the late jet?

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

2. The system is expanding

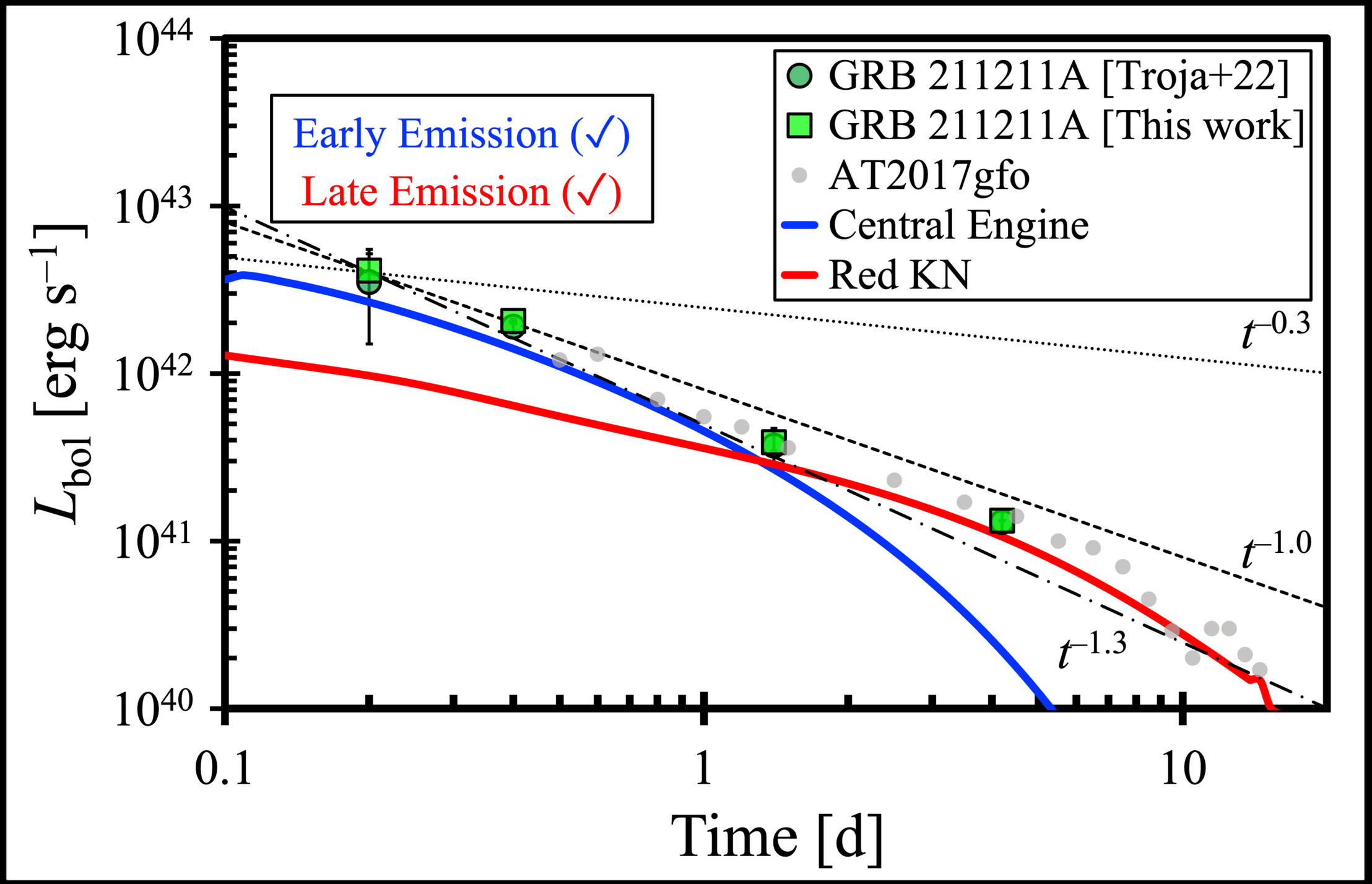
e.g., Prompt jet (breakout) timescale $1$ s

- 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**

# GRB211211A

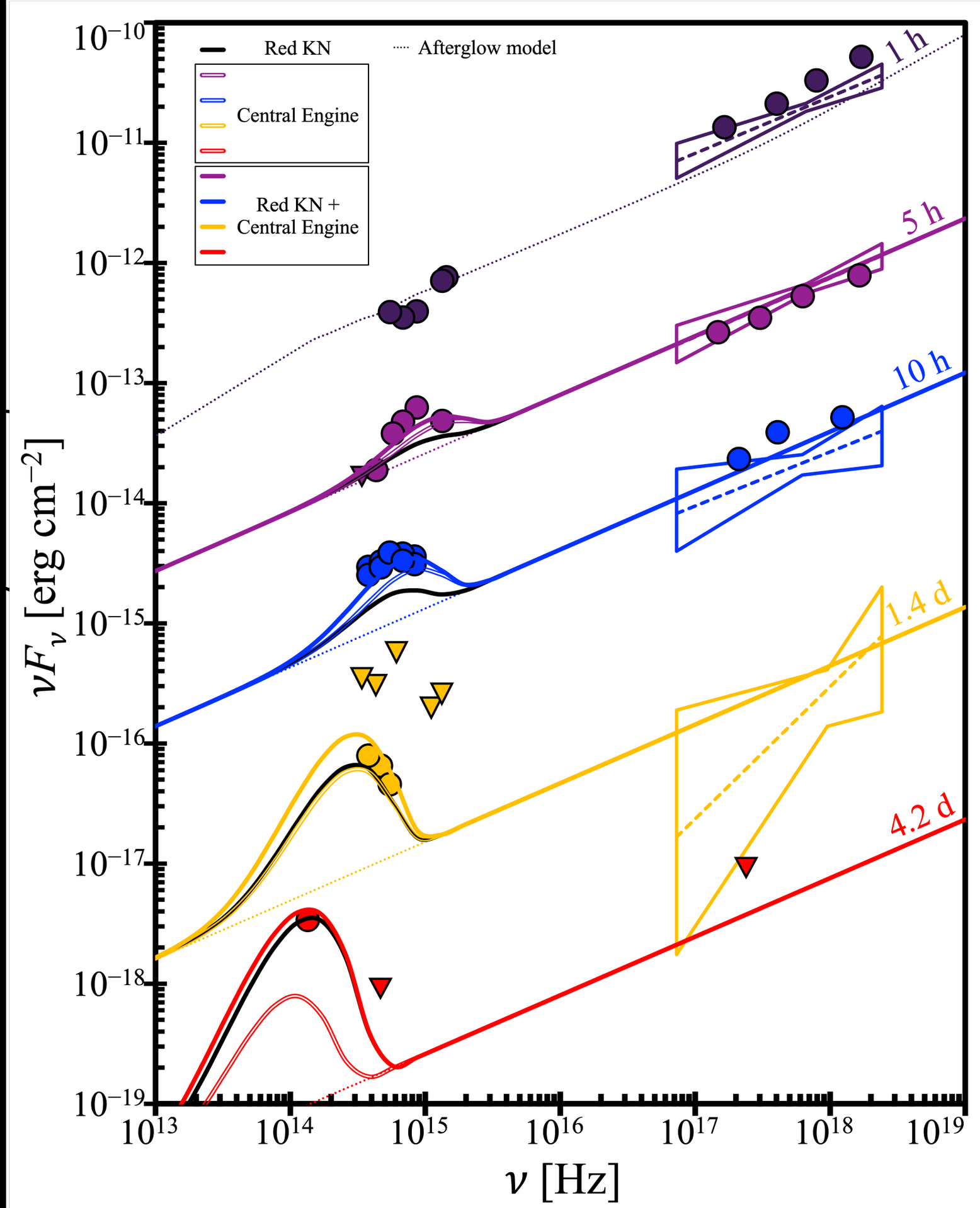
Credit: HH+24



# Success of CE Model

**CE KN can explain the SED…**

Credit: HH+24



# Summary

**R-process powered KN struggles**
at explaining the observed fast time evolution of the blue KN

**Low-power plateau like jet can explain the blue KN**
both the time evolution and the SED

**With only one component!**
an effective red component (realistic considering re-process)

**Supports observations of late GeV & plateau emission**
suggesting that GRB engines continue to be active

**Future early KN observations are encouraged**
to reveal more about the central engine of GRBs

(C)

**Prompt +**
**Extended/Plateau emission**
**(~1-$10^4$ seconds; $\gamma$ – X-ray)**

Prompt jet
Late jet

Late jet-heated:
Escaped cocoon
Trapped cocoon

Ejecta

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

**Trapped cocoon**
**"blue kilonova-like"**
**(~day; UV – Opt)**

**Red kilonova**
**(~week; Opt –IR)**

Credit: HH+24