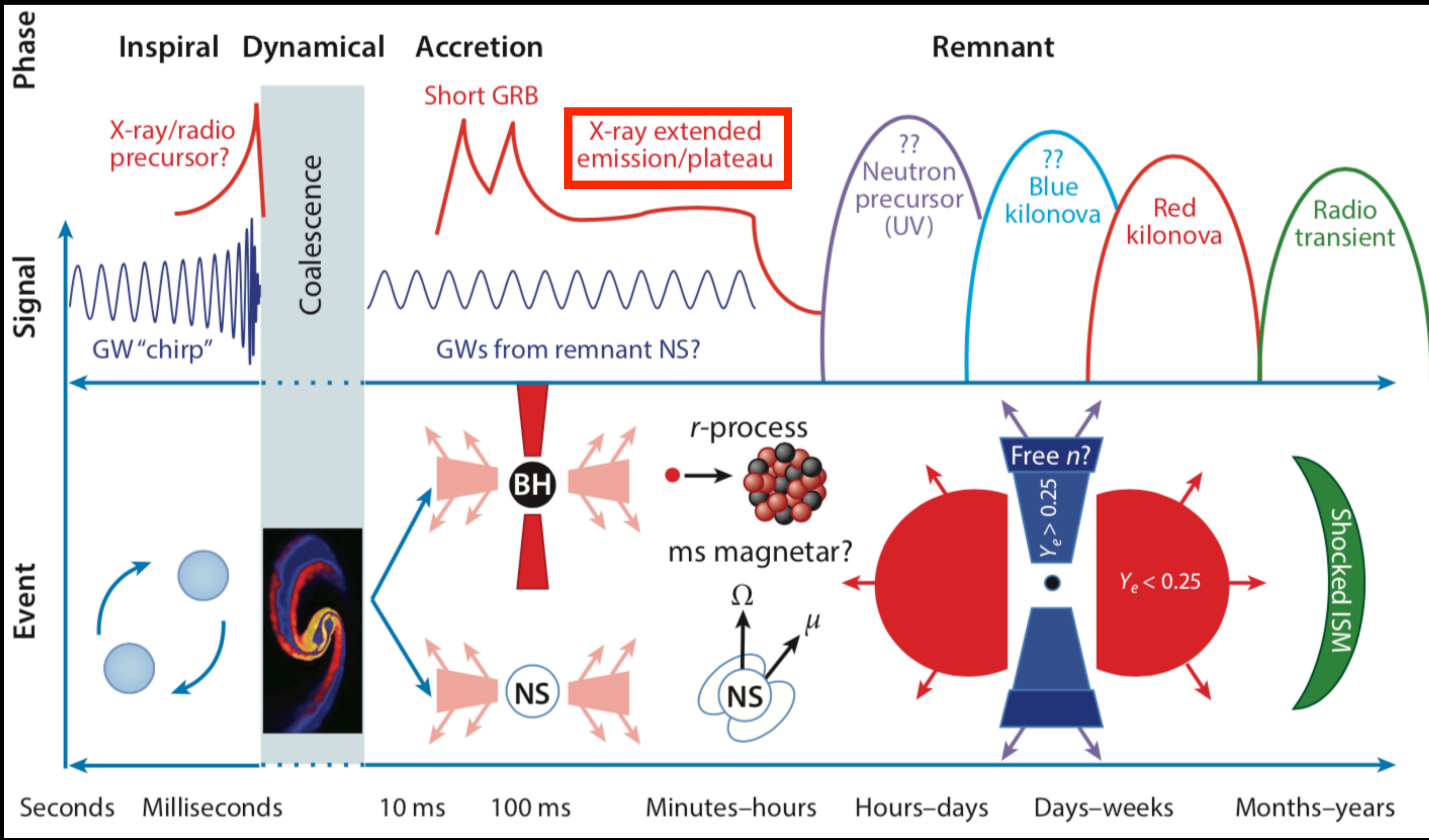
# Jet propagation and Cocoon Emission in Neutron Star Mergers and GW170817

**Hamid Hamidani, Kunihito Ioka, & Kenta Kiuchi**

**YITP long-term workshop**
**Multi-Messenger Astrophysics in the Gravitational Wave Era**
**September 24 - October 25 2019**

# BNS Merger & Multi-Messenger Astronomy

Credit: Fernandez Metzger 2016

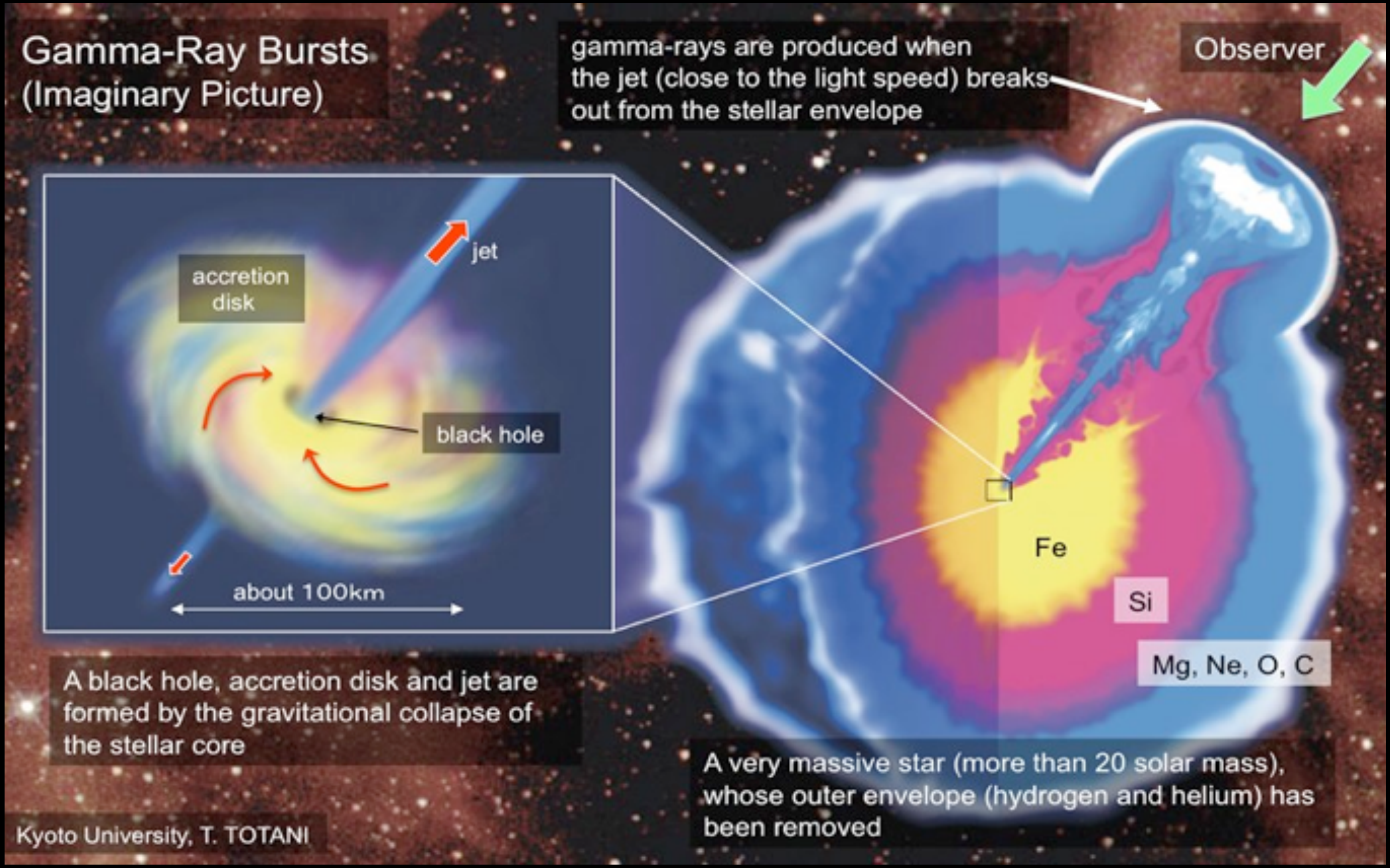



Numerical Relativity

This study

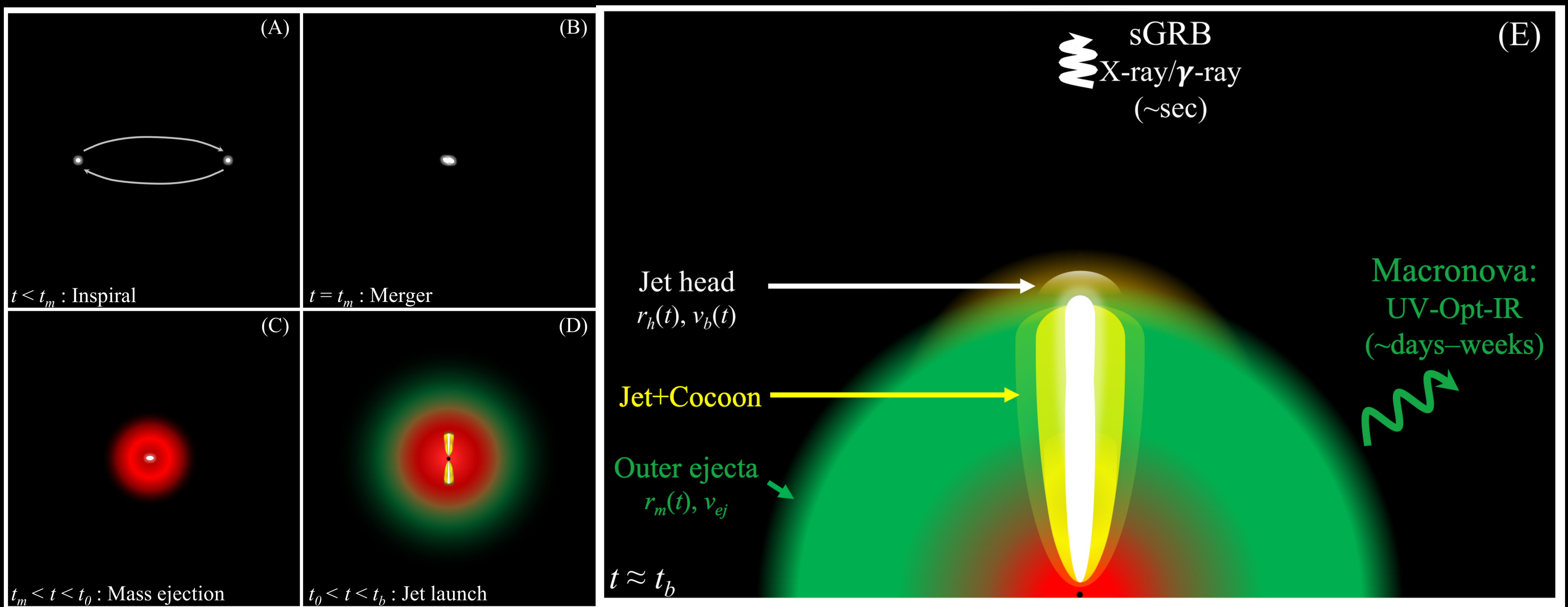
Late Observations

# Jet propagation (collapsar)




Credit: T.Totani

# Jet Propagation (BNS merger)



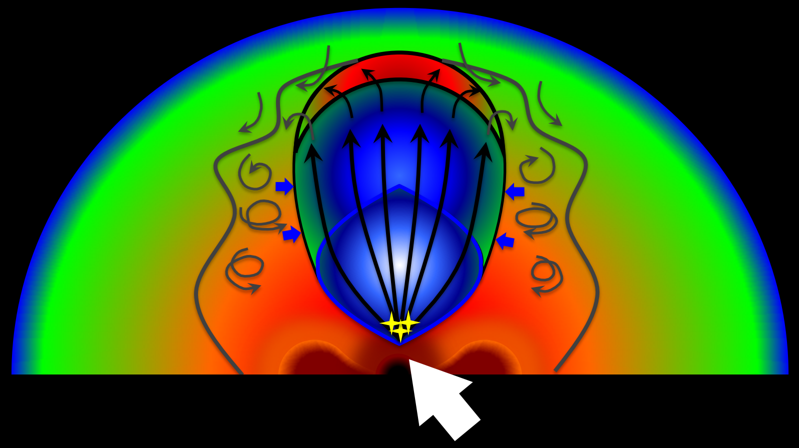

Credit: Hamidani Kiuchi Ioka 2019

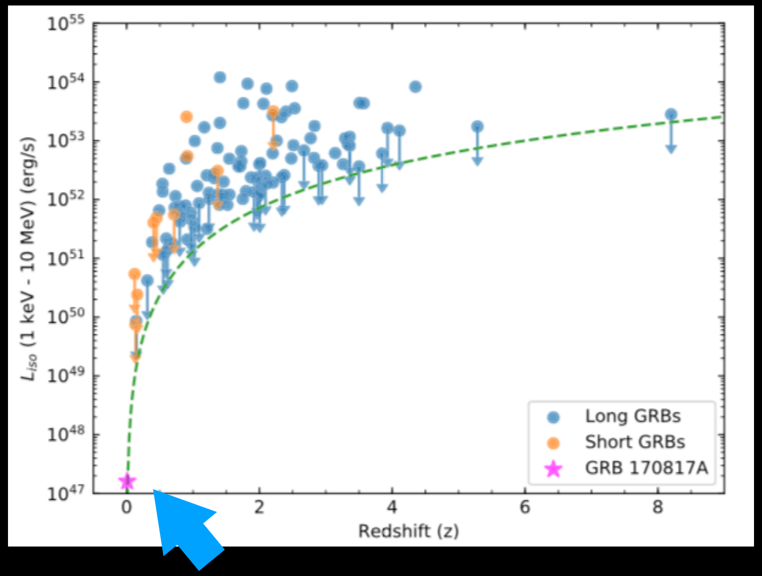
# Motivation

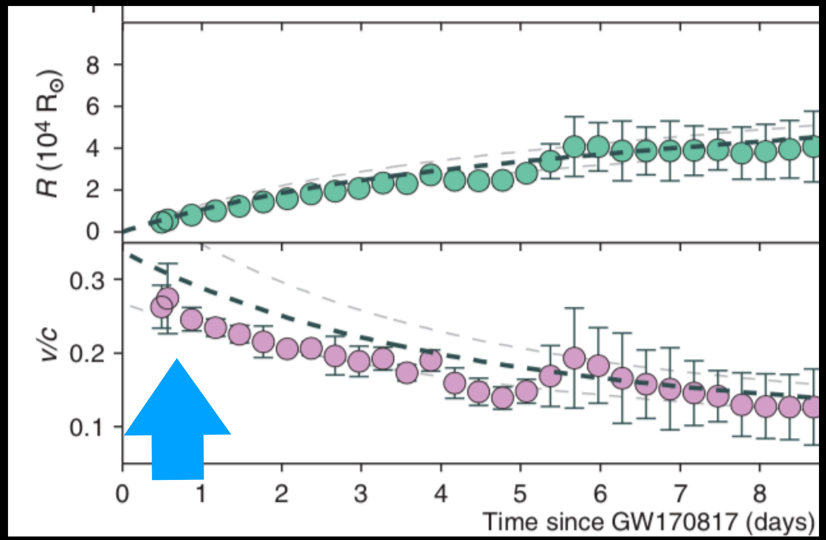
- **Any Information on GW170817's Engine?**
  i.e., power, opening angle, etc.

- **Is GRB170817A A Typical sGRB?**
  i.e., the origin of its faintness?

- **Any Cocoon's EM Counterparts?**
  i.e., its luminosity, magnitude, peak time, etc.



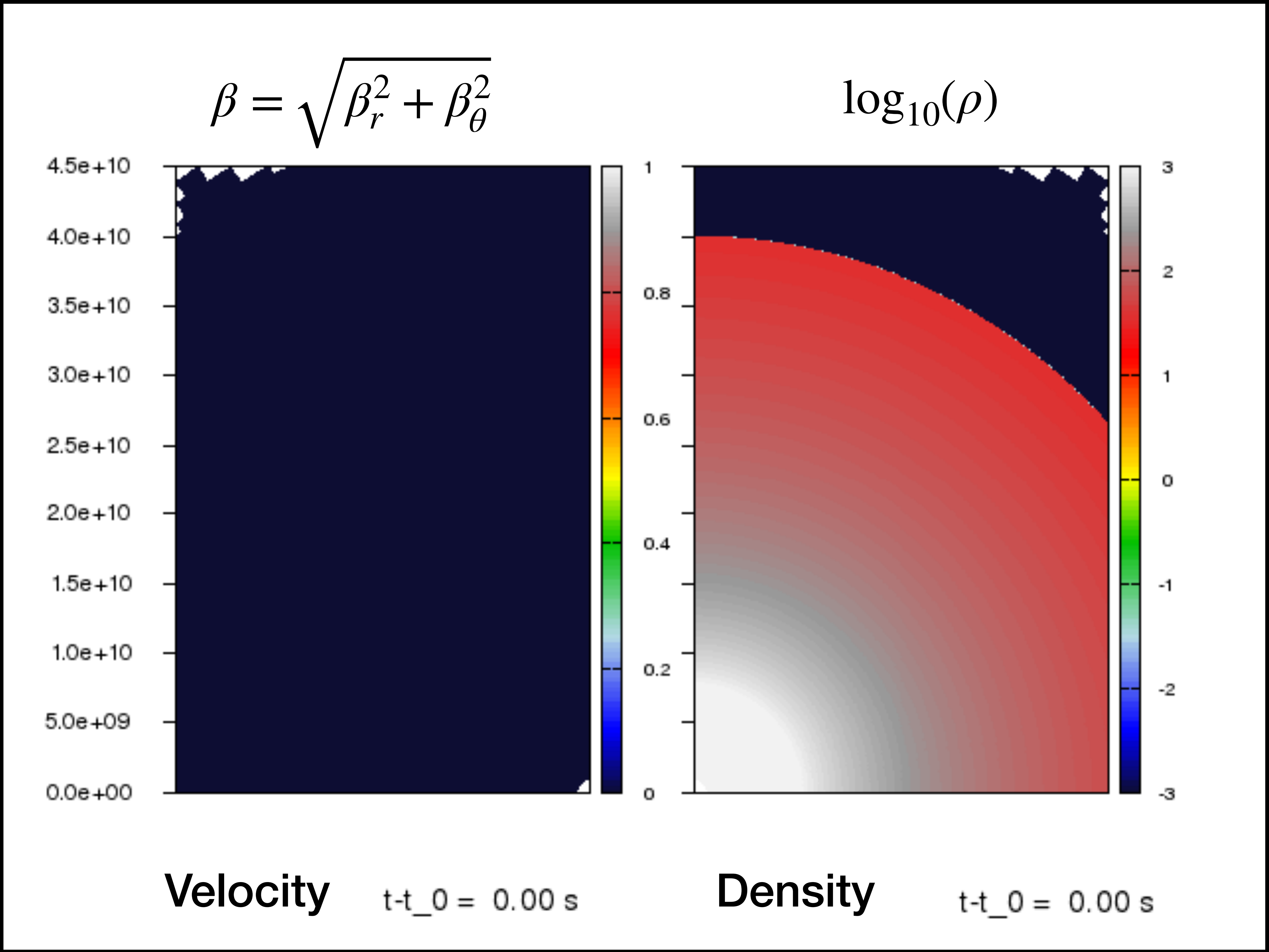



**Credit: LIGO/FERMI17; Kasliwal+17 & Hamidani+17**

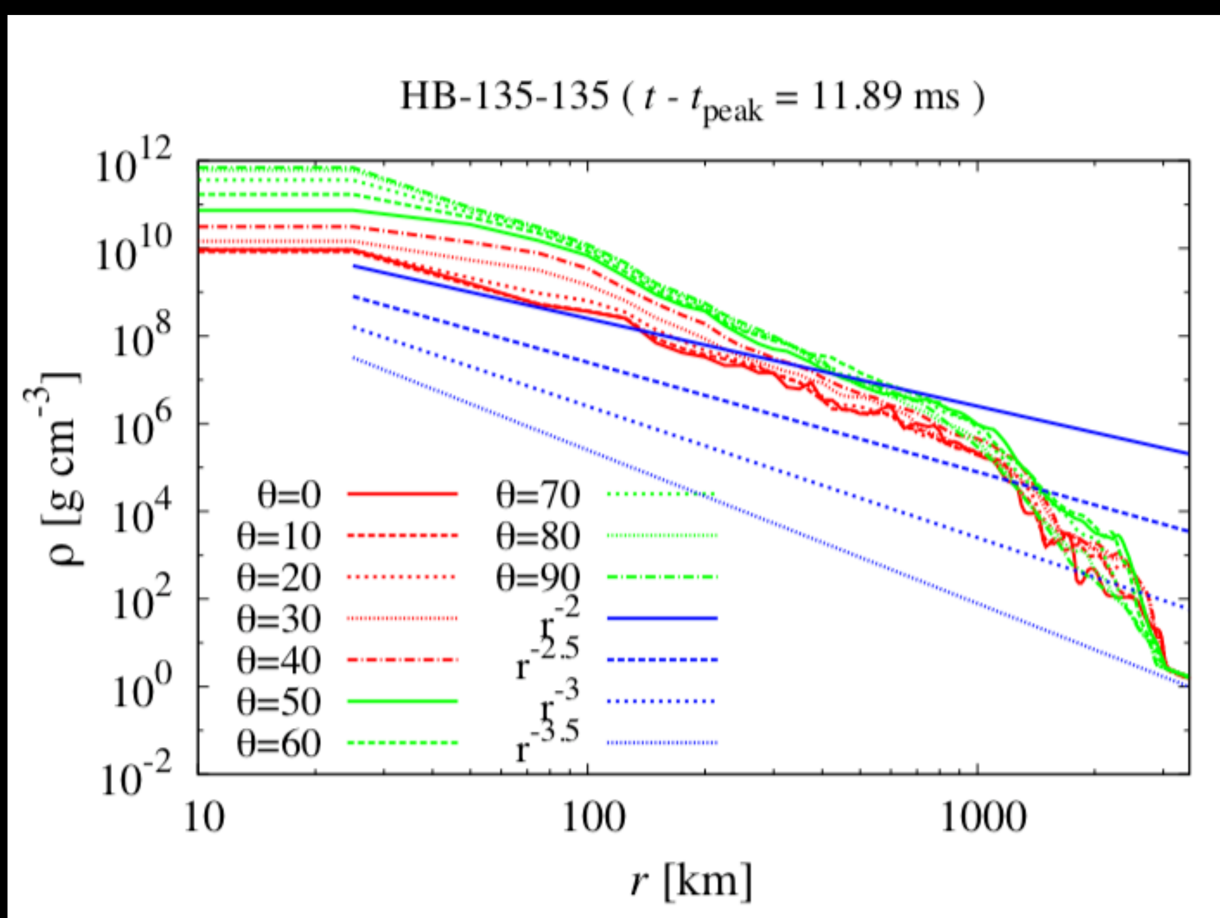
# Step I:
# Hydrodynamical Simulations For Jet Propagation

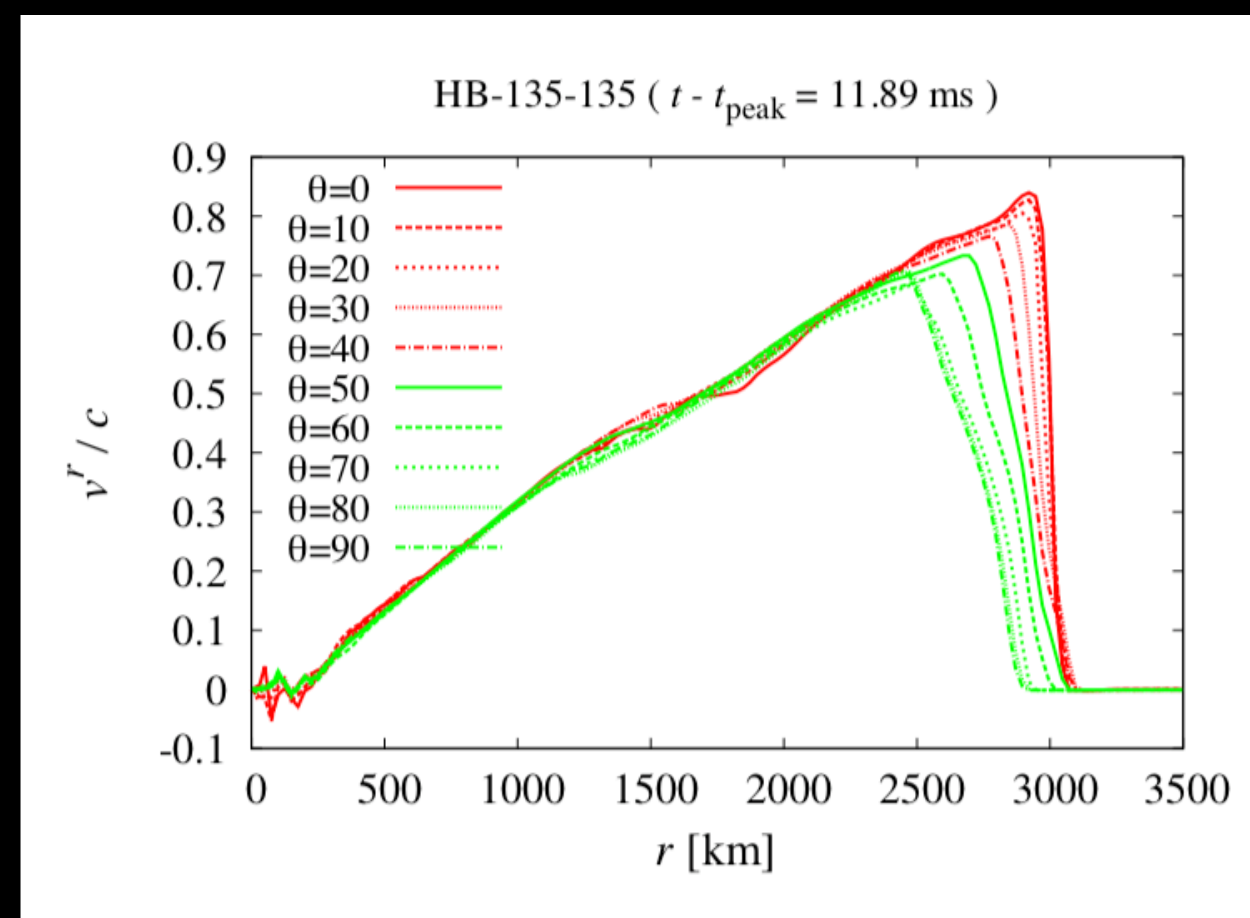
# Numerical Simulations (Collapsar)



# Hints From
# Numerical Relativity Calculations of NSM

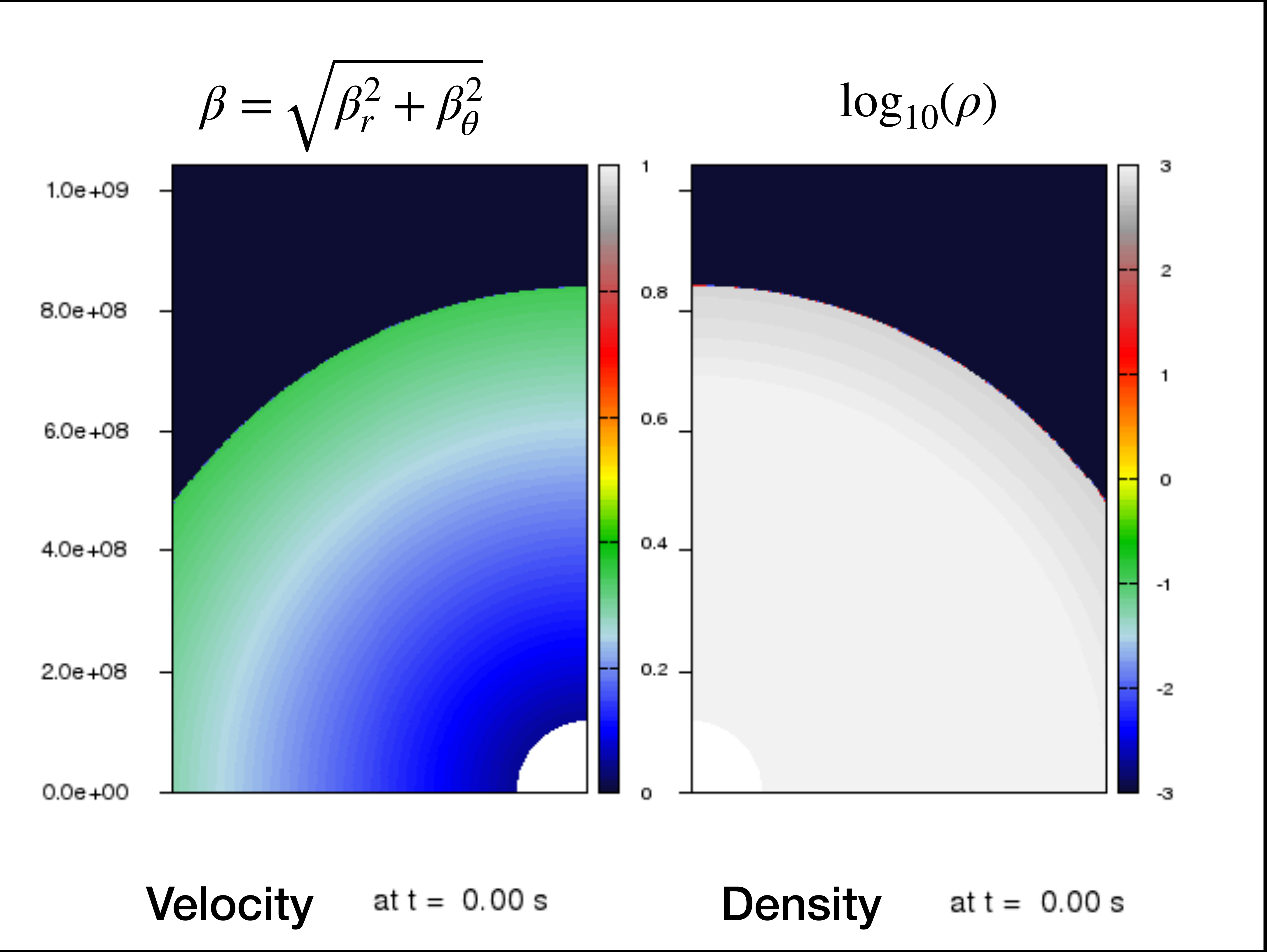
- **Crucial information no the first moments after the merger:** i.e, Density profile, Velocity profile




**Credit: Kiuchi+ 2017**

# Hydrodynamical Simulations (BNS merger)



# Step II:
# Analytic Modeling of Jet Propagation

# Analytic Modeling of Jet Propagation

## Ram Pressure Balance

$$h_j \rho_j c^2 \Gamma_j^2 \beta_j^2 + P_j = h_e \rho_e c^2 \Gamma_e \beta_e^2 + P_e$$

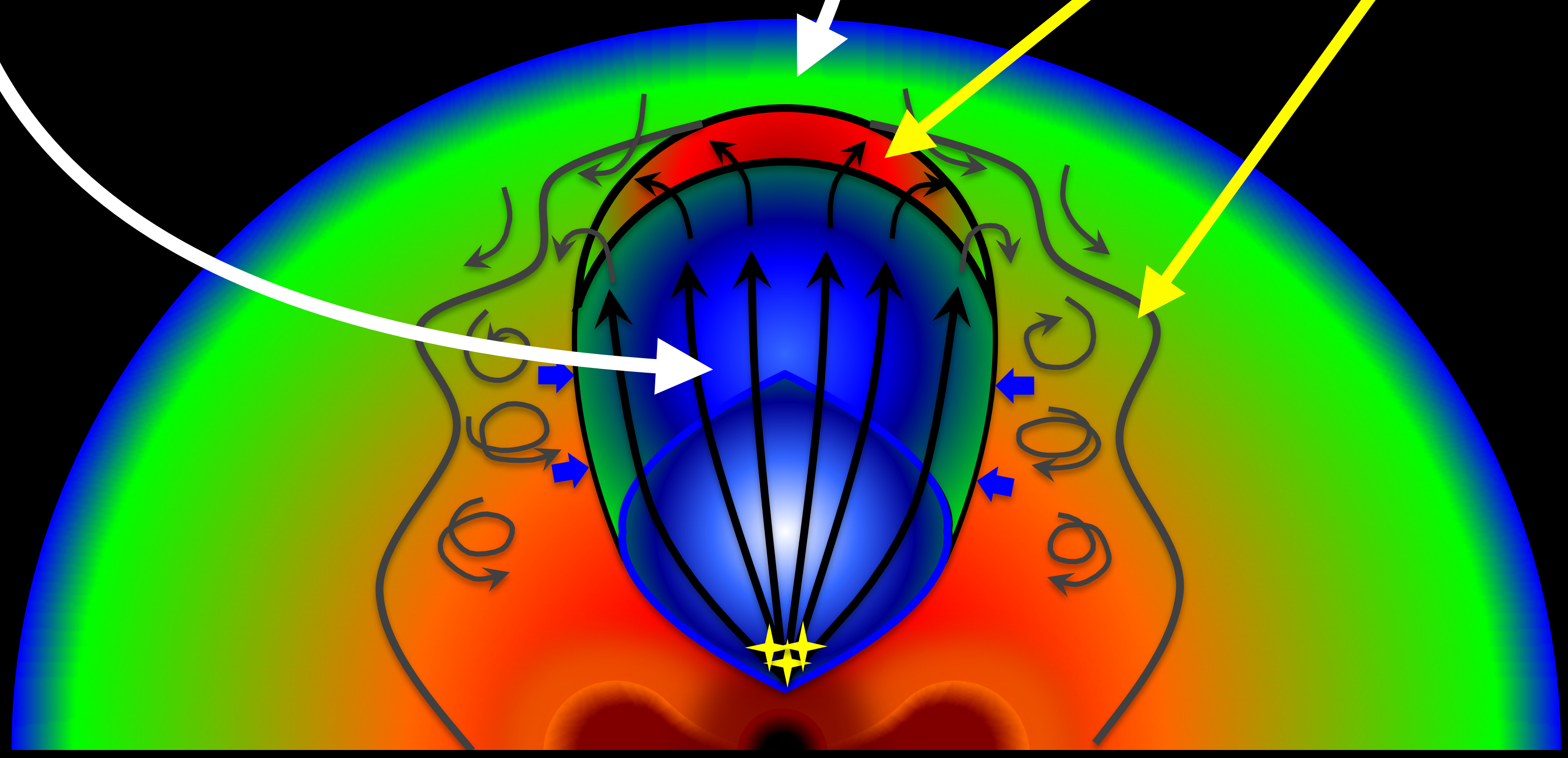
Engine

Ejecta

**Gives:**

**Jet head motion**

**Cocoon (*E*, *M*, <v>)**



**As in:**
**Bromberg+11**
**Mizuta+13**
**Harrison+18**
**etc.**

**Credit: Hamidani+17**

# Analytic Modeling: The Key Equations

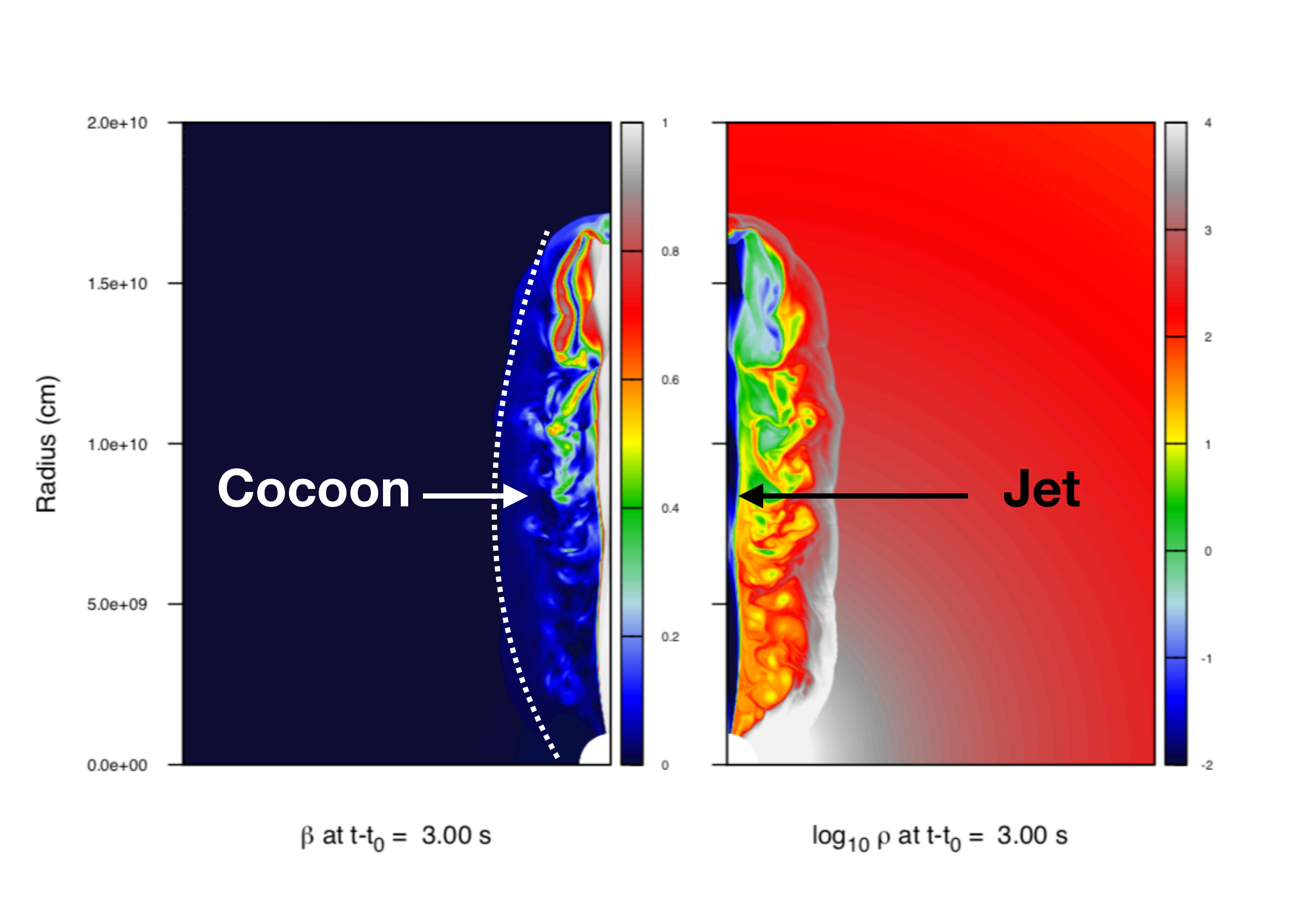
**Based on Bromberg et al. 2011 (also Nakar Piran 2016):**

$$r_c \approx \chi c \left\langle \beta_\perp \right\rangle (t - t_0)$$

$$\left\langle \beta_\perp \right\rangle = \sqrt{\frac{P_c}{\left\langle \rho_a(t) \right\rangle c^2}}$$

$$P_c = \frac{E_{in}}{3V_c} = \eta \frac{L_j \left(1 - \left\langle \beta_h \right\rangle\right)(t - t_0)}{2\pi r_c^2 r_h(t)}$$

$$\Sigma_j(t) = \pi r_h^2(t) \theta_j^2(t) = \frac{L_j \theta_0^2}{4cP_c}$$



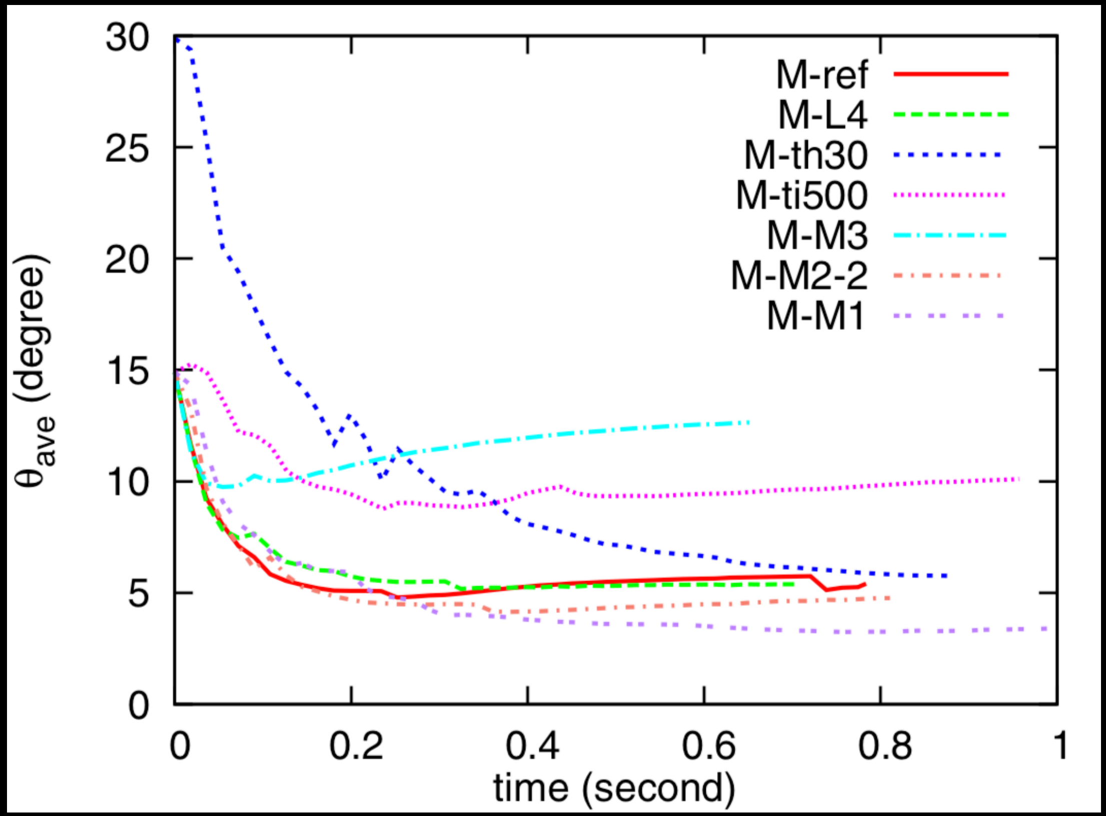

Credit: Hamidani+19

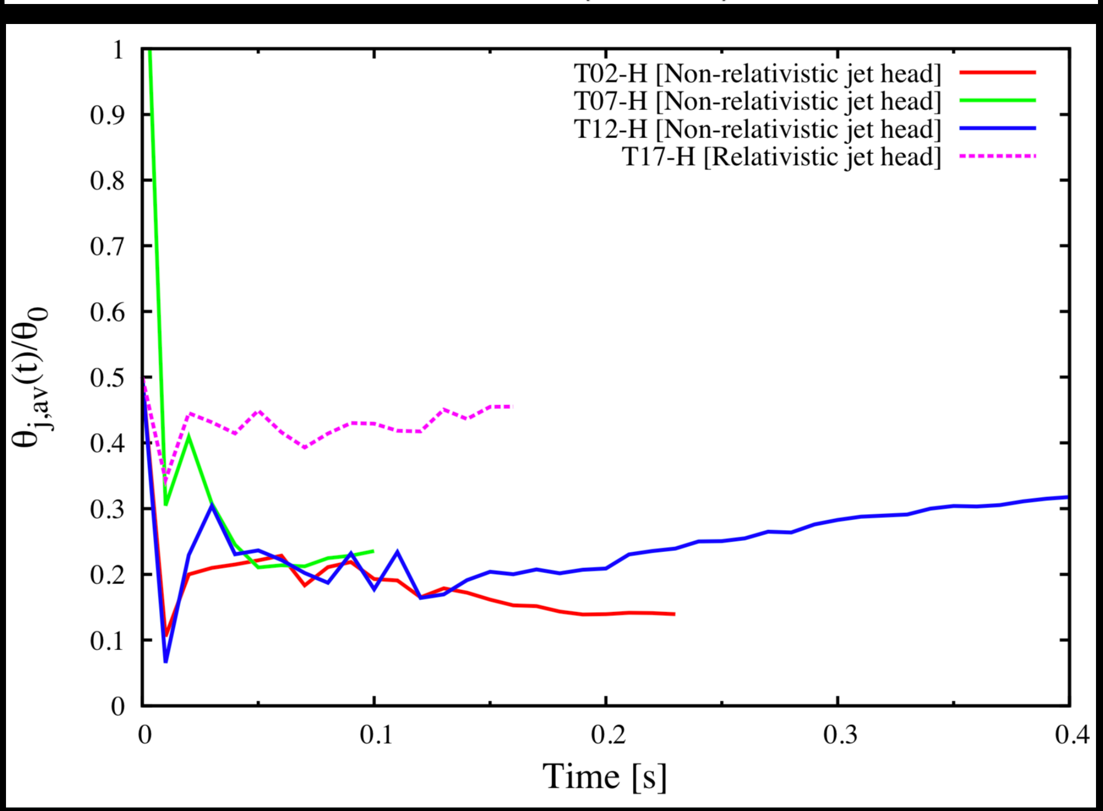
# The Opening Angle of The Jet

$$\frac{\theta_j(t)}{\theta_0} = \left[\frac{f_r^2}{\eta}\frac{L_j}{6M_{ej}c^2v_{ej}}\right]^{\frac{1}{4}}\left[\frac{r_h(t)}{r_m(t)}\right]^{\frac{n-3}{4}}\left[r_m(t) - r_{m,0}\right]^{\frac{1}{4}} \propto t^{1/4}$$

**We approximate:**

$$\theta_j(t) \equiv \theta_j$$




**Credit: Nagakura+14 & Hamidani+19**

# Equation of Motion:

$$\frac{dr_h(t)}{dt} = Ar_h(t)^{\frac{n-2}{2}}$$

**Static medium**

$$\frac{dr_h(t)}{dt} + \left(-\frac{v_{ej}}{r_m(t)}\right) r_h(t) = Ar_m(t)^{\frac{3-n}{2}} r_h(t)^{\frac{n-2}{2}}$$

**Expanding medium**

$$A = \sqrt{\left(\frac{r_{m,0}^{3-n} - r_0^{3-n}}{(3-n)r_{m,0}^{3-n}}\right)\left(\frac{4L_j}{\theta_j^2 M_{ej} c}\right)} \propto \theta_j^{-1} \sim$$ **Constant**

**Hamidani+19**

# The Breakout Time

**Static Medium case (i.e. Collapsar):**

$$t_b - t_0 \simeq 4.61s \left(\frac{M_{ej}}{14M_\odot}\right)^{\frac{1}{2}} \left(\frac{r_m}{4\times 10^{10}\textbf{cm}}\right)^{\frac{1}{2}} \left(\frac{L_{iso,0}}{5\times 10^{52}\ \textbf{erg s}^{-1}}\right)^{-\frac{1}{2}} \left(\frac{\frac{3-n}{(4-n)^2}}{1/4}\right)^{\frac{1}{2}} \left(\frac{N_s}{2/5}\right)^{-1} \left(\frac{f_j}{14}\right)^{-1}.$$

**Expanding medium case (i.e. BNS mergers):**

$$t_b - t_0 \simeq 0.173s \left(\frac{M_{ej}}{0.002M_\odot}\right)^{\frac{1}{2}} \left(\frac{r_{m,0}}{10^9\textbf{cm}}\right)^{\frac{1}{2}} \left(\frac{L_{iso,0}}{10^{51}\textbf{erg s}^{-1}}\right)^{-\frac{1}{2}} \left(\frac{\frac{(3-n)}{(4-n)^2}}{1/4}\right)^{\frac{1}{2}} \left(\frac{N_s}{2/5}\right)^{-1} \left(\frac{f_j}{5}\right)^{-1}$$

$$+0.077s \left(\frac{M_{ej}}{0.002M_\odot}\right) \left(\frac{v_{ej}}{0.346c}\right) \left(\frac{L_{iso,0}}{10^{51}\textbf{erg s}^{-1}}\right)^{-1} \left(\frac{\frac{(3-n)}{(4-n)^2}}{1/4}\right) \left(\frac{N_s}{2/5}\right)^{-2} \left(\frac{f_j}{5}\right)^{-2}$$ **(for n<3)**

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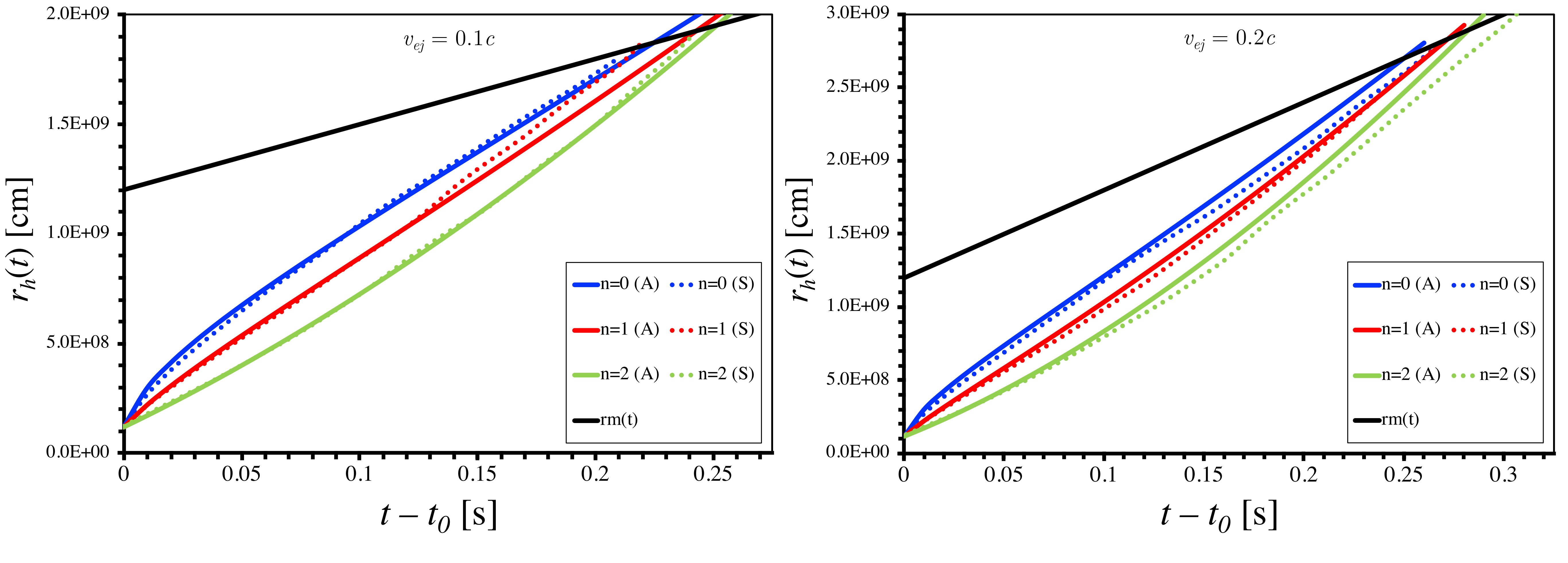
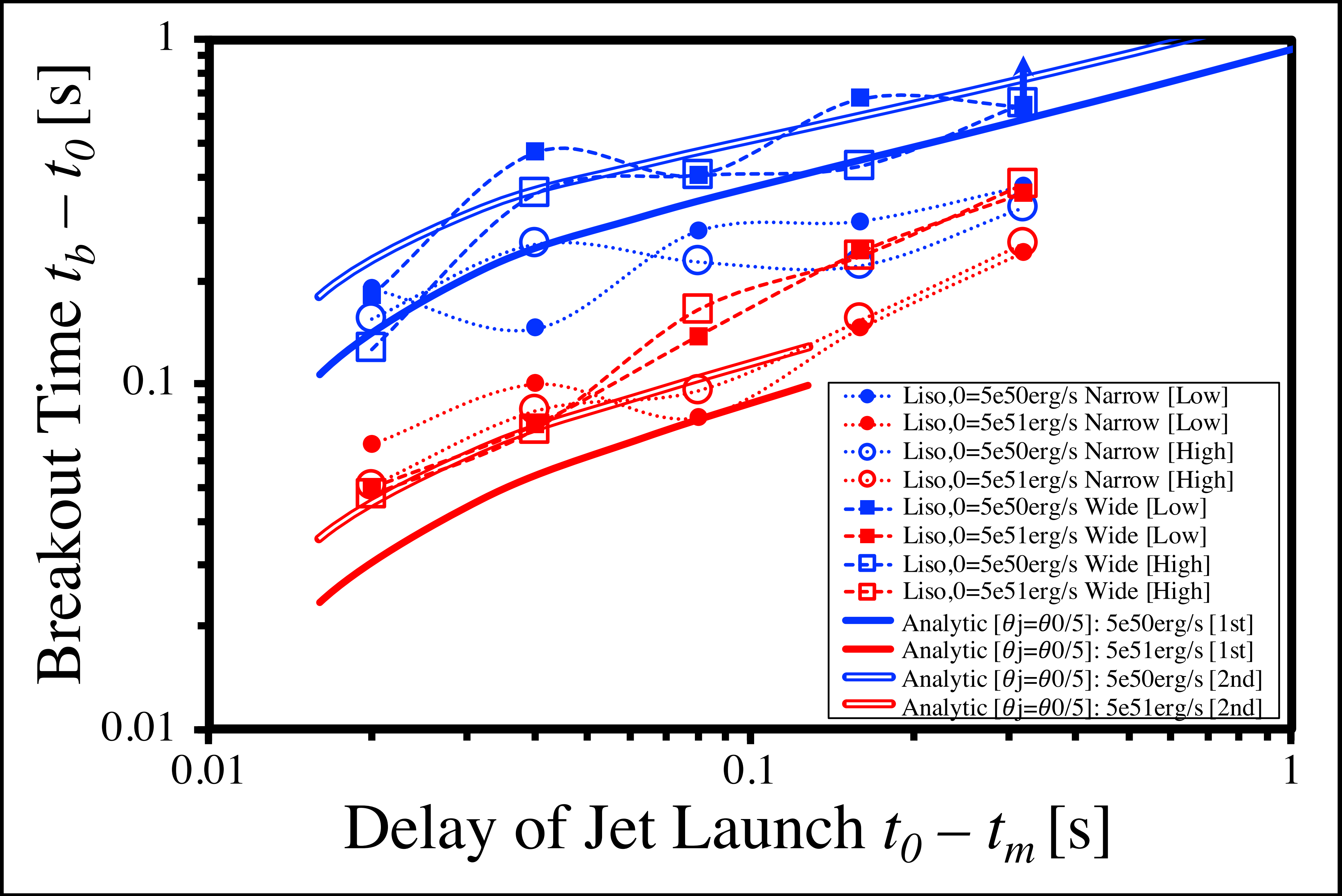
# Analytic Vs. Numerical Results



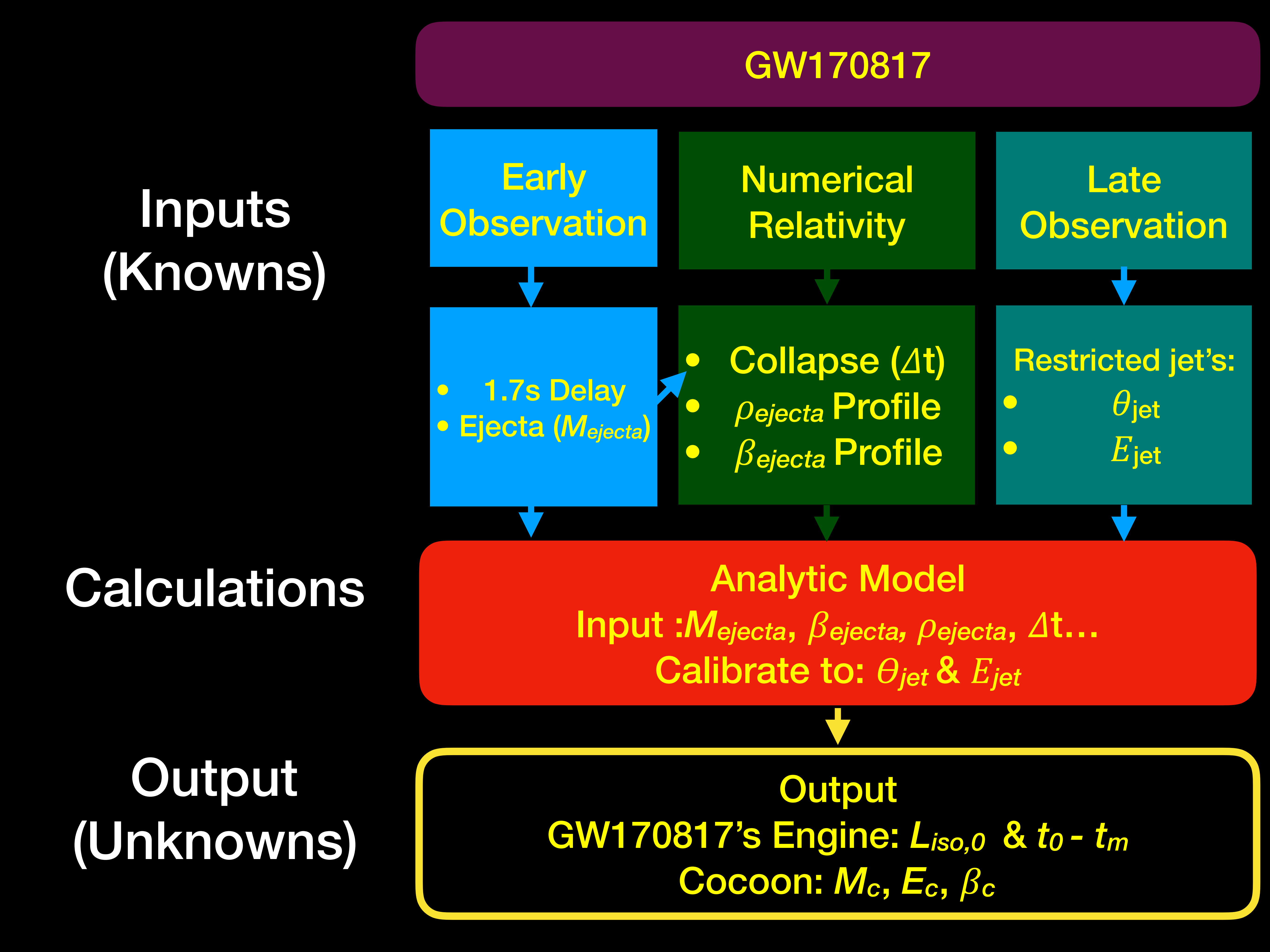

Credit: Hamidani+19

# Analytic Vs. Numerical Results

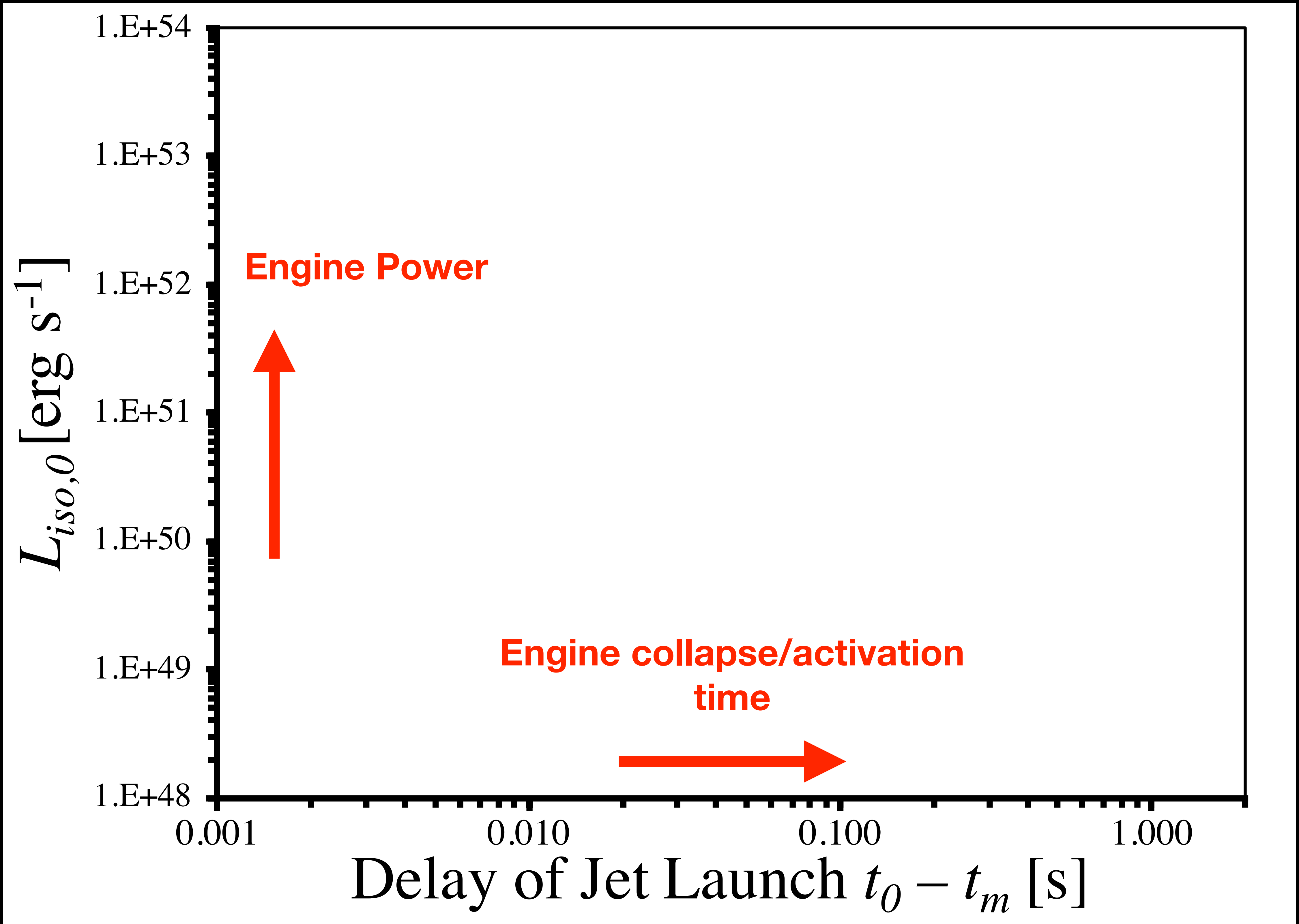


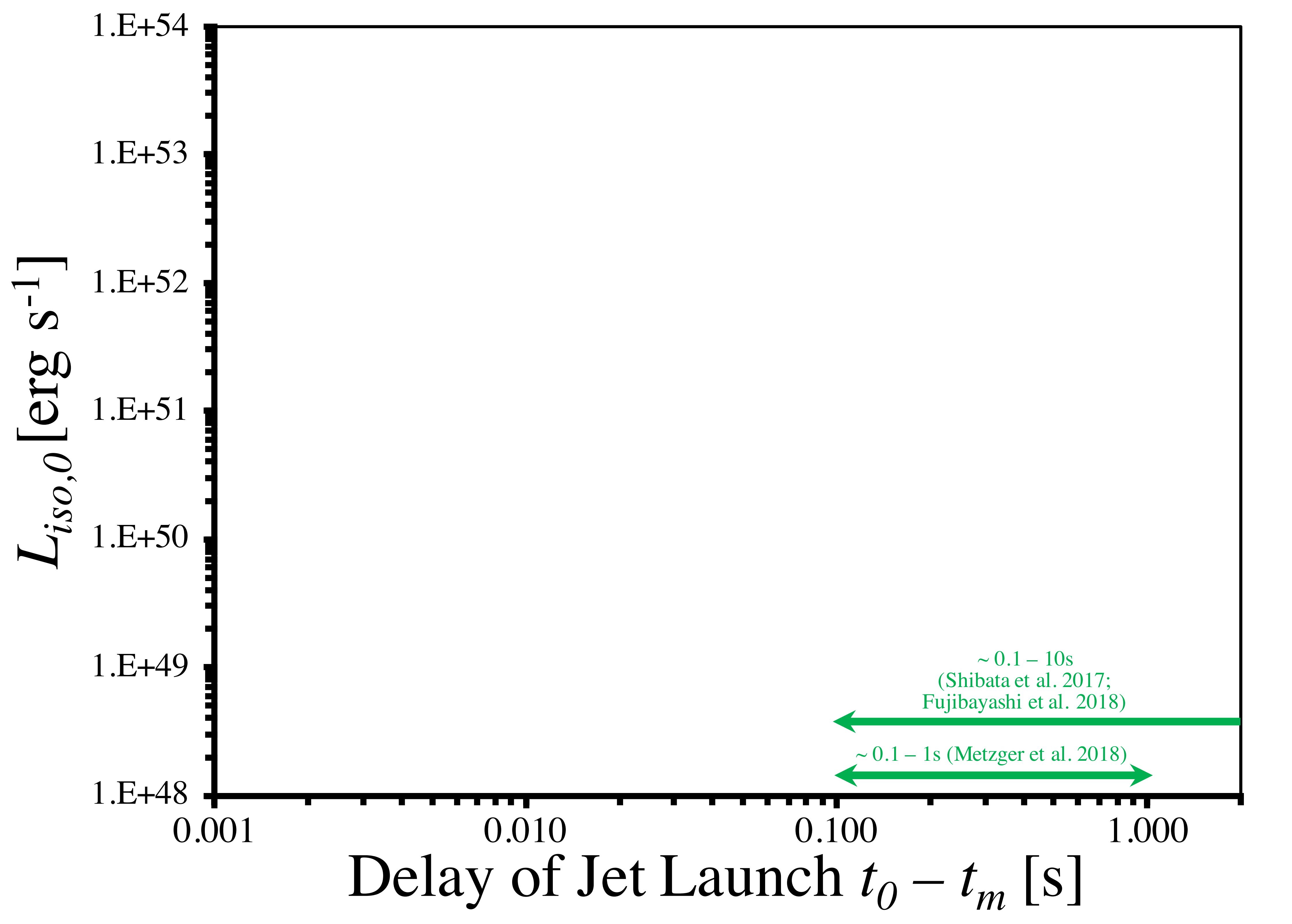

**Credit: Hamidani+19**

# II. Application for GW170817's Engine


GW170817
Inputs (Knowns)
Early Observation
Numerical Relativity
Late Observation
• 1.7s Delay
• Ejecta ($M_{ejecta}$)
• Collapse ($\Delta$t)
• $\rho_{ejecta}$ Profile
• $\beta_{ejecta}$ Profile
Restricted jet's:
• $\theta_{\rm jet}$
• $E_{\rm jet}$
Calculations
Analytic Model
Input :$M_{ejecta}$, $\beta_{ejecta}$, $\rho_{ejecta}$, $\Delta$t…
Calibrate to: $\theta_{jet}$ & $E_{jet}$
Output (Unknowns)
Output
GW170817's Engine: $L_{iso,0}$ & $t_0$ - $t_m$
Cocoon: $M_c$, $E_c$, $\beta_c$

# Results I:
## GW170817's Engine



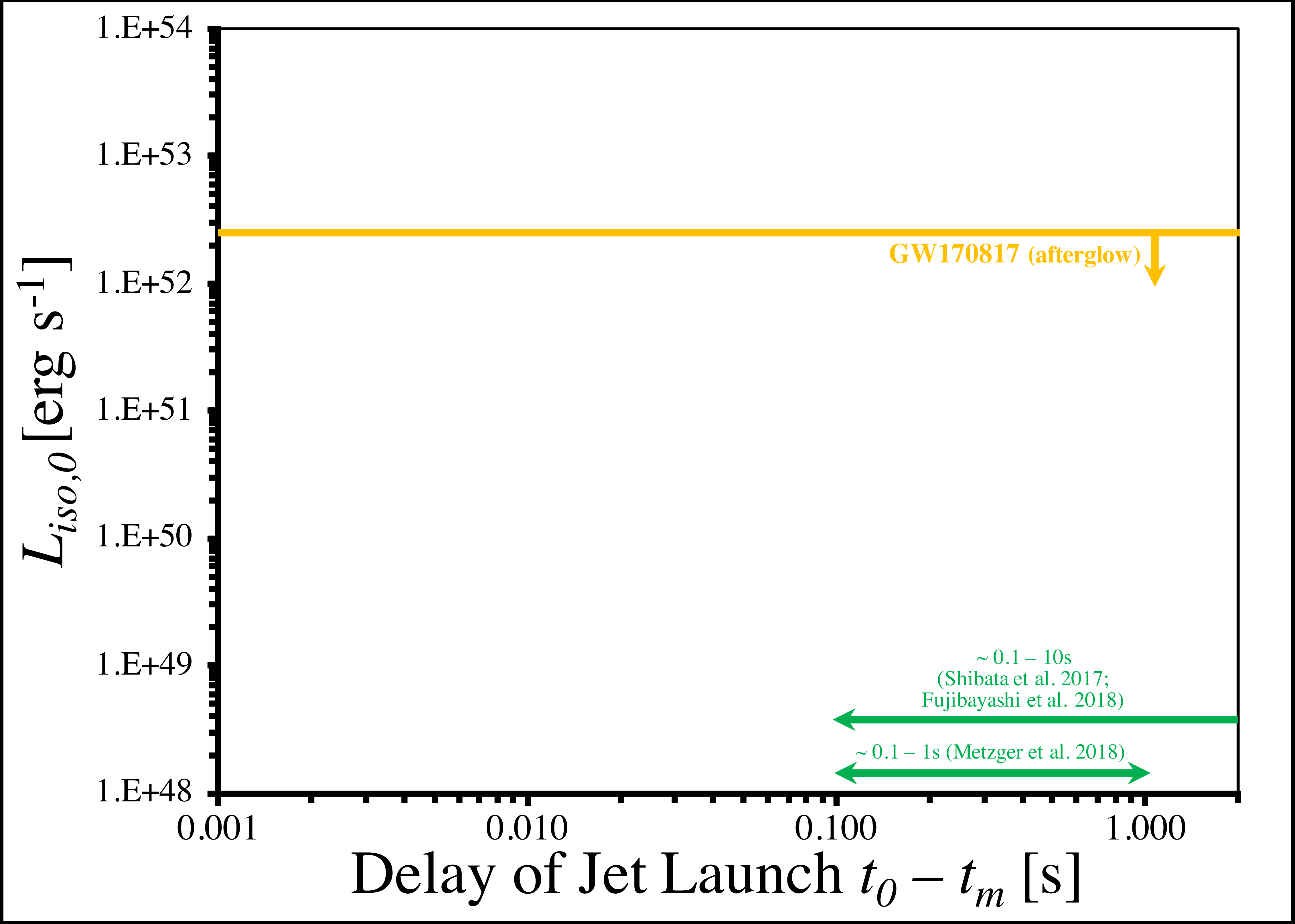


1.E+54
1.E+53
1.E+52
1.E+51
1.E+50
1.E+49
1.E+48
$L_{iso,0}$ [erg s$^{-1}$]
~ 0.1 – 10s
(Shibata et al. 2017;
Fujibayashi et al. 2018)
~ 0.1 – 1s (Metzger et al. 2018)
0.001
0.010
0.100
1.000
Delay of Jet Launch $t_0 - t_m$ [s]

$E_{iso} \leqslant 10^{53} erg$

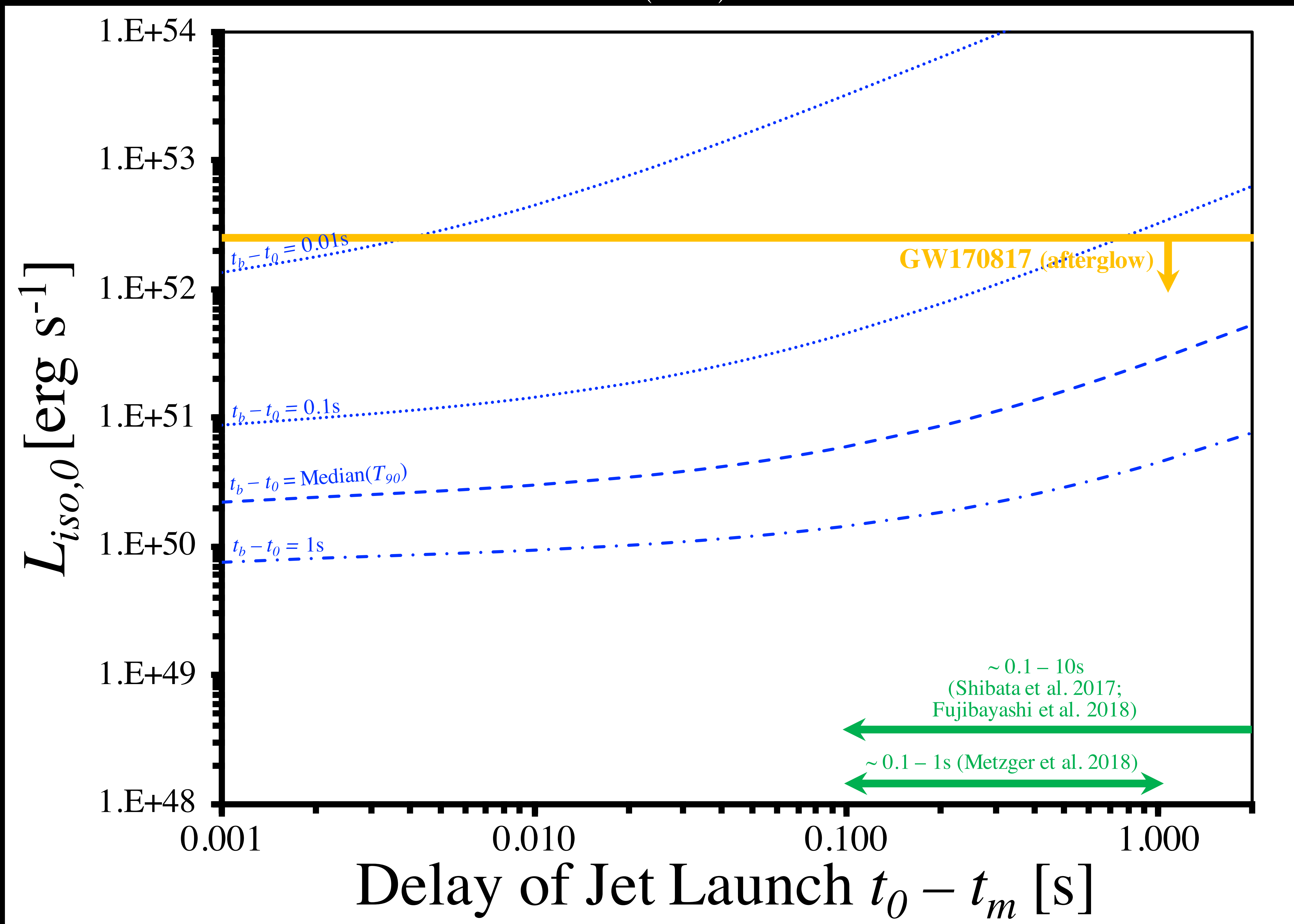
**Mooley+18 & Ghirlanda+18**

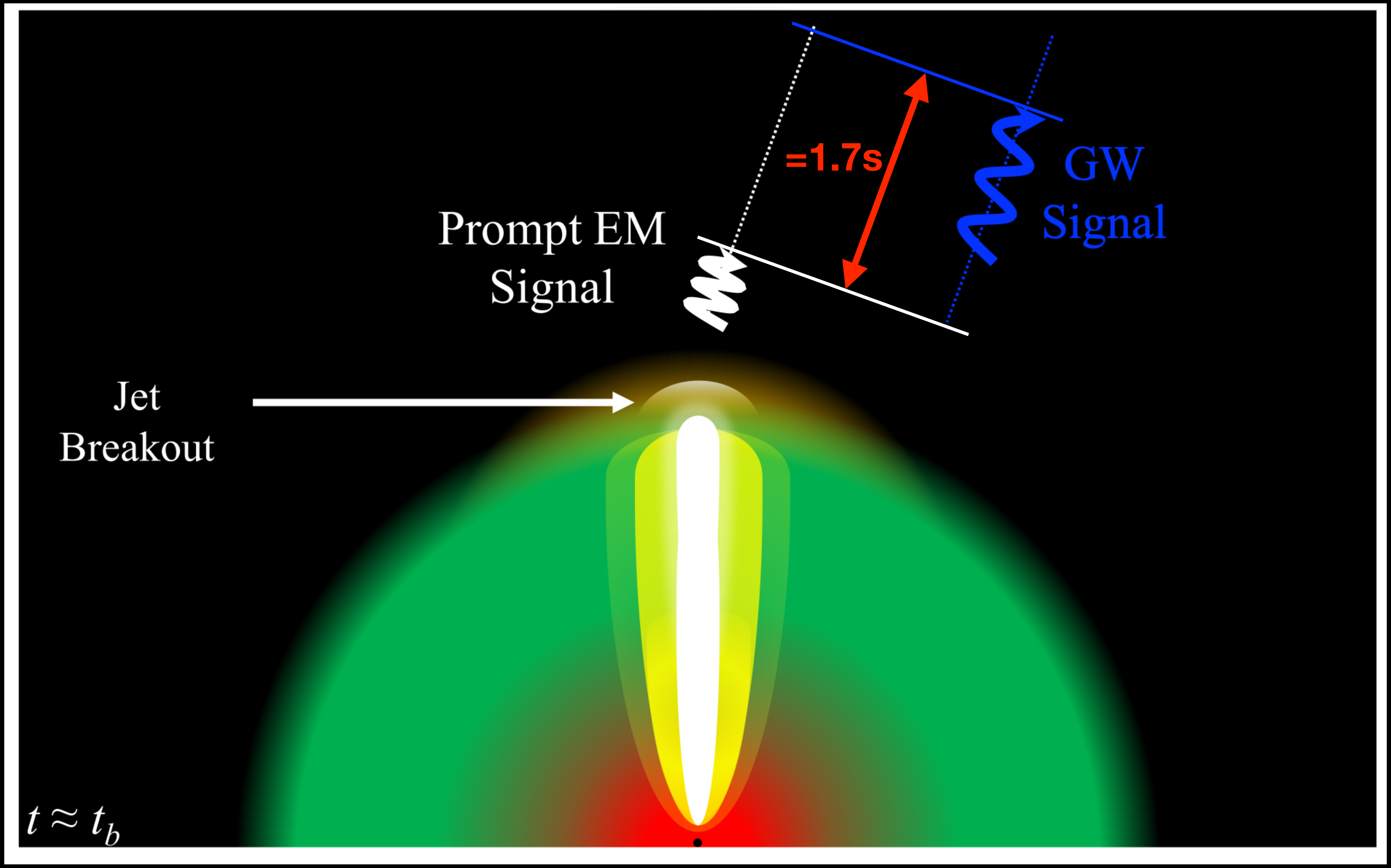
$\epsilon_\gamma \leq 50\,\%$ $\theta_f \sim \theta_0/2$



$$t_b - t_0 \simeq 0.173s \left(\frac{M_{ej}}{0.002M_\odot}\right)^{\frac{1}{2}} \left(\frac{r_{m,0}}{10^9\,\mathrm{cm}}\right)^{\frac{1}{2}} \left(\frac{L_{iso,0}}{10^{51}\,\mathrm{erg\ s^{-1}}}\right)^{-\frac{1}{2}} \left(\frac{\frac{(3-n)}{(4-n)^2}}{1/4}\right)^{\frac{1}{2}} \left(\frac{N_s}{2/5}\right)^{-1} \left(\frac{f_j}{5}\right)^{-1}$$

$$+0.077s \left(\frac{M_{ej}}{0.002M_\odot}\right) \left(\frac{v_{ej}}{0.346c}\right) \left(\frac{L_{iso,0}}{10^{51}\,\mathrm{erg\ s^{-1}}}\right)^{-1} \left(\frac{\frac{(3-n)}{(4-n)^2}}{1/4}\right) \left(\frac{N_s}{2/5}\right)^{-2} \left(\frac{f_j}{5}\right)^{-2}$$

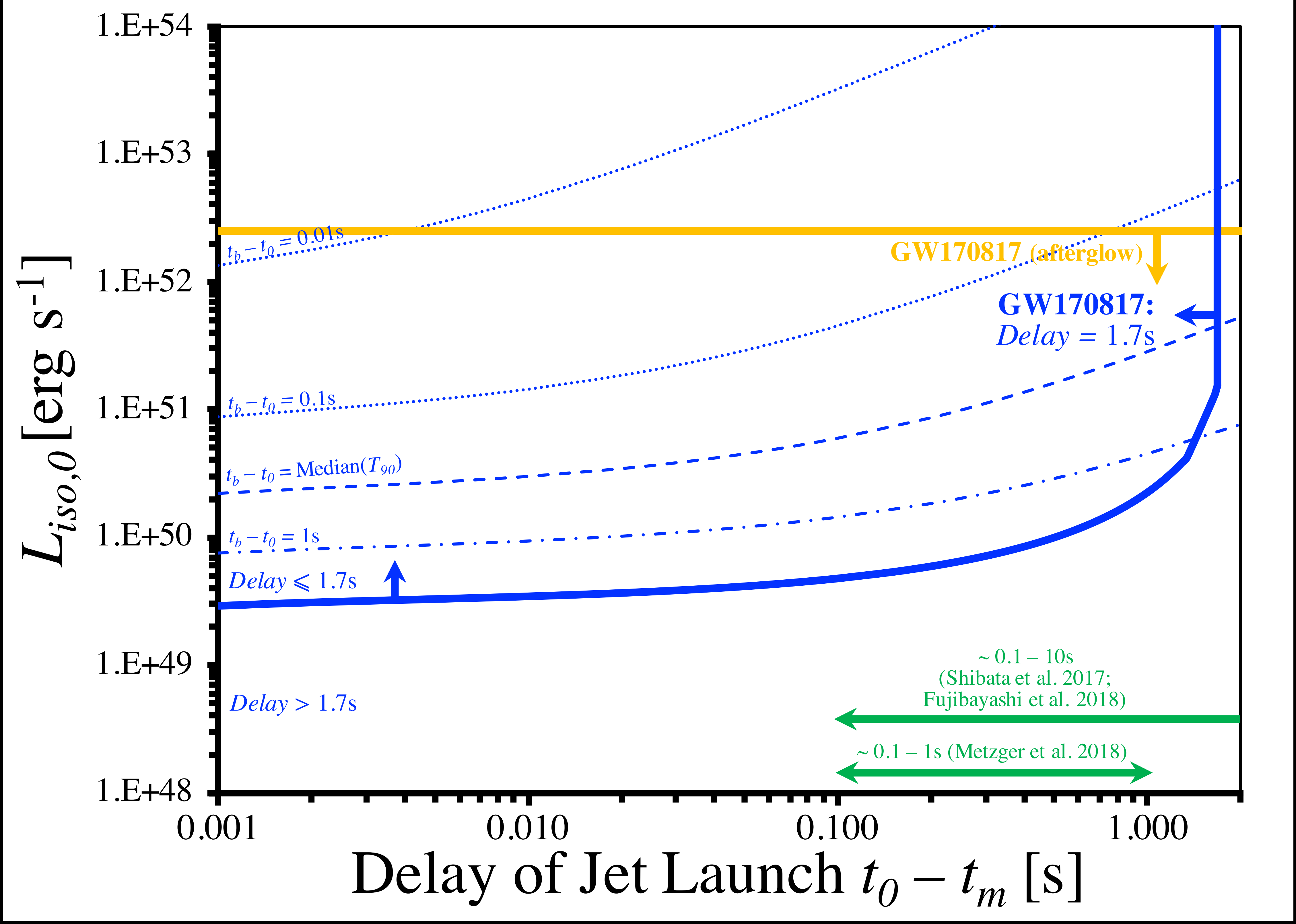




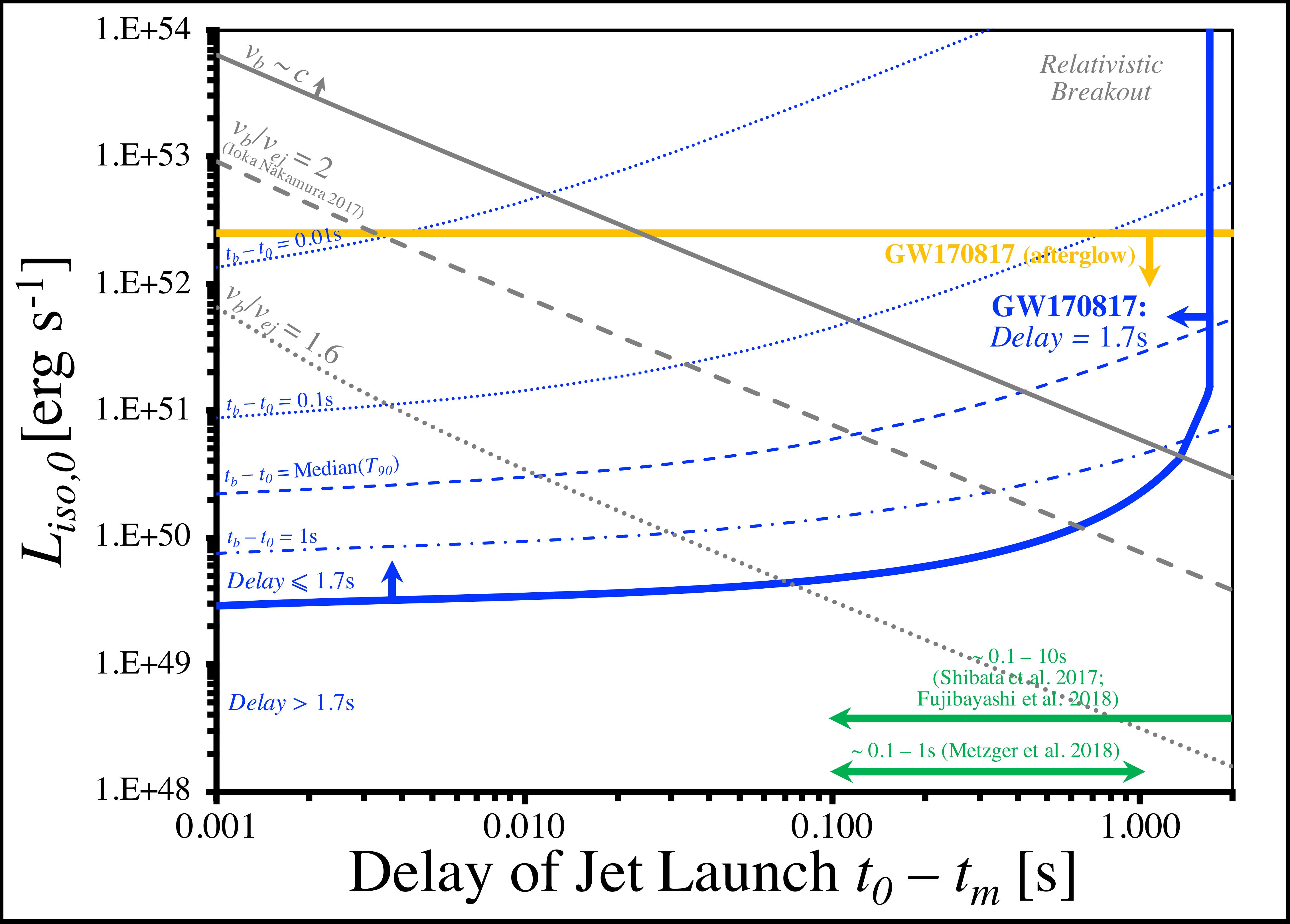

$$1.7 = \left(t_b - t_m\right) - R_b \cos\theta_v / c + x$$

$$t_b - t_m \leqslant \frac{1.7}{1 - \left(v_{ej}/c\right)\cos\theta_v}$$

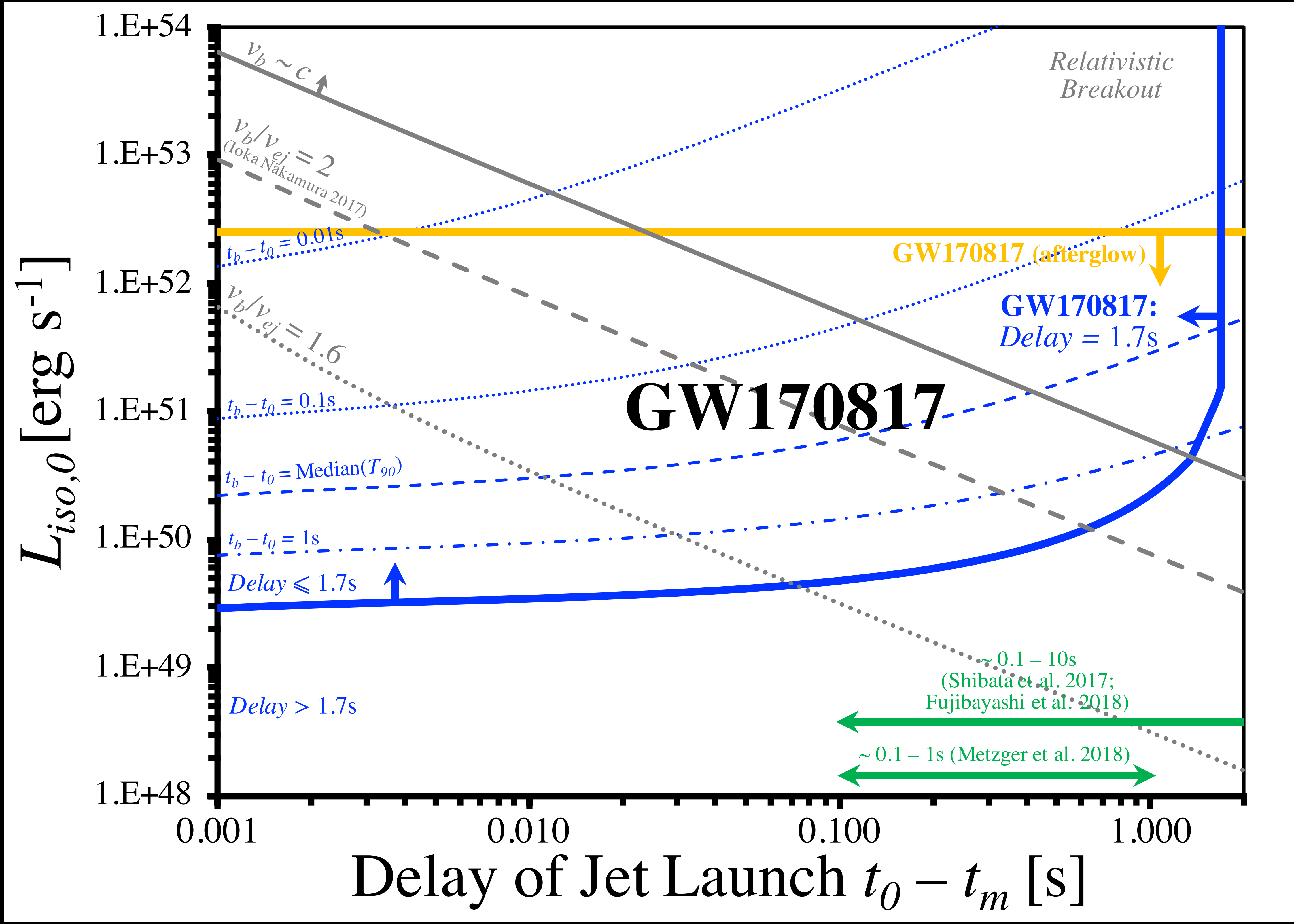
$$1.7 = (t_b - t_m) - R_b \cos\theta_v / c + x \quad \Rightarrow \quad t_b - t_0 \leqslant \frac{1.7}{1 - (v_{ej}/c)\cos\theta_v} - (t_0 - t_m)$$



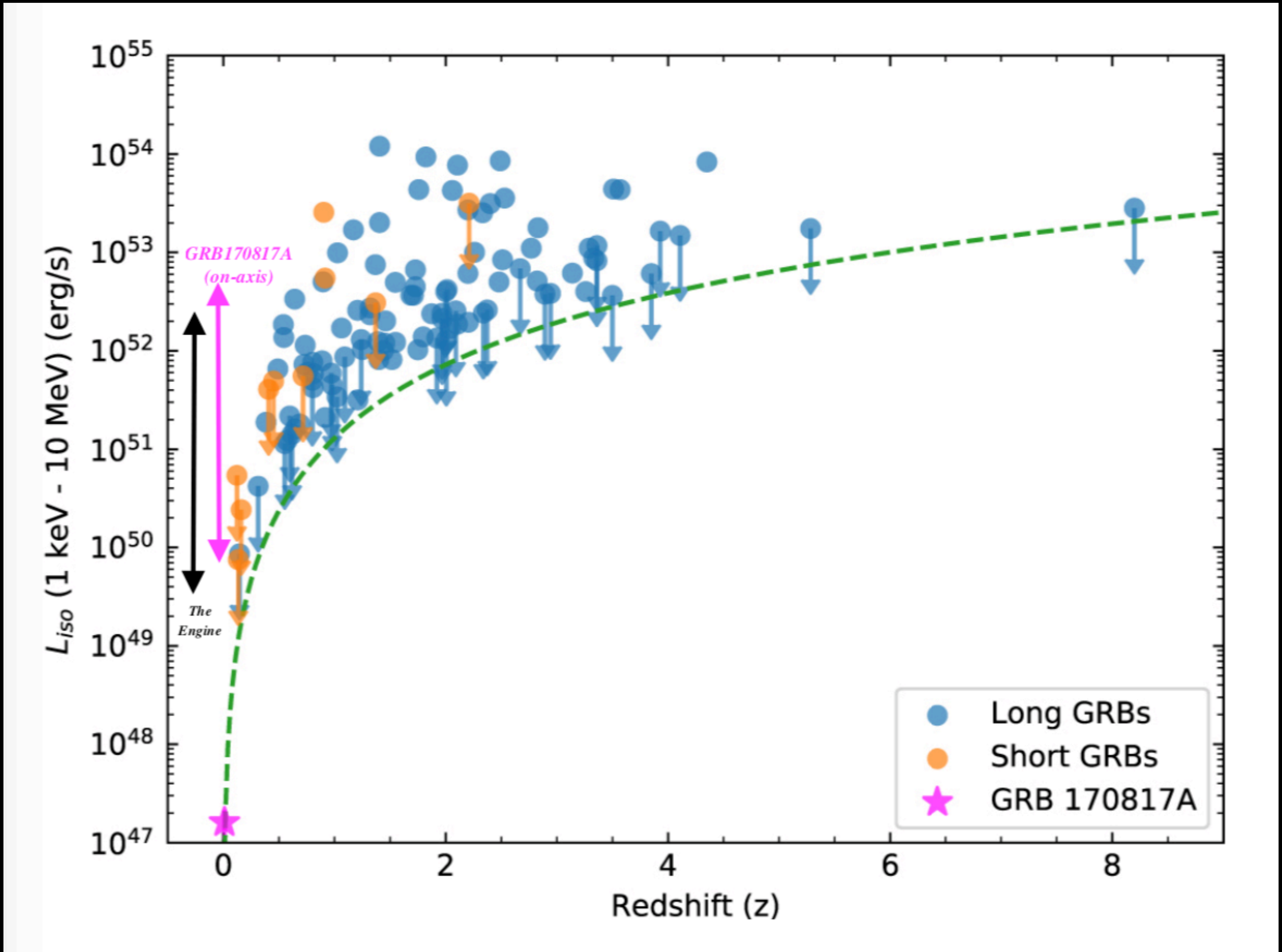
$$v_b = A\sqrt{R_b} + v_{ej}$$



# Results I:
## GW170817's Engine



# GRB170817A: Why so faint?




Credit: Fermi/LIGO+17 & Hamidani+19

# II. Application for GW170817's Cocoon

# Modeling The Cocoon

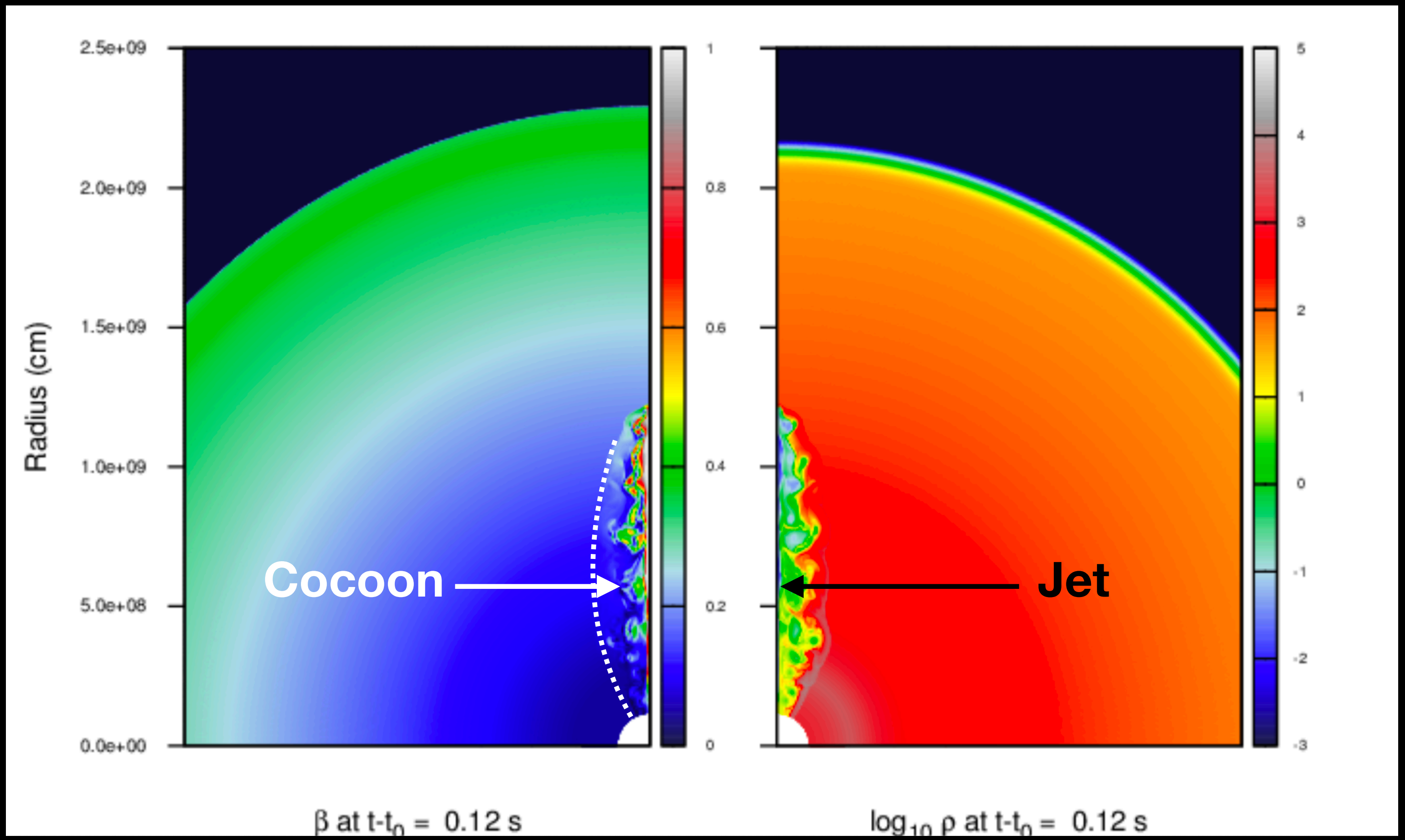
**Approximations on the cocoon:**

$$E_{in} = L_j(t_b - t_0 - R_b/c)$$

$$E_{in} = 3P_cV_c$$

$$E_c = E_{in} + E_{k,e}$$

$$E_c \approx \frac{1}{2}M_c(c\left\langle\beta_c\right\rangle)^2$$

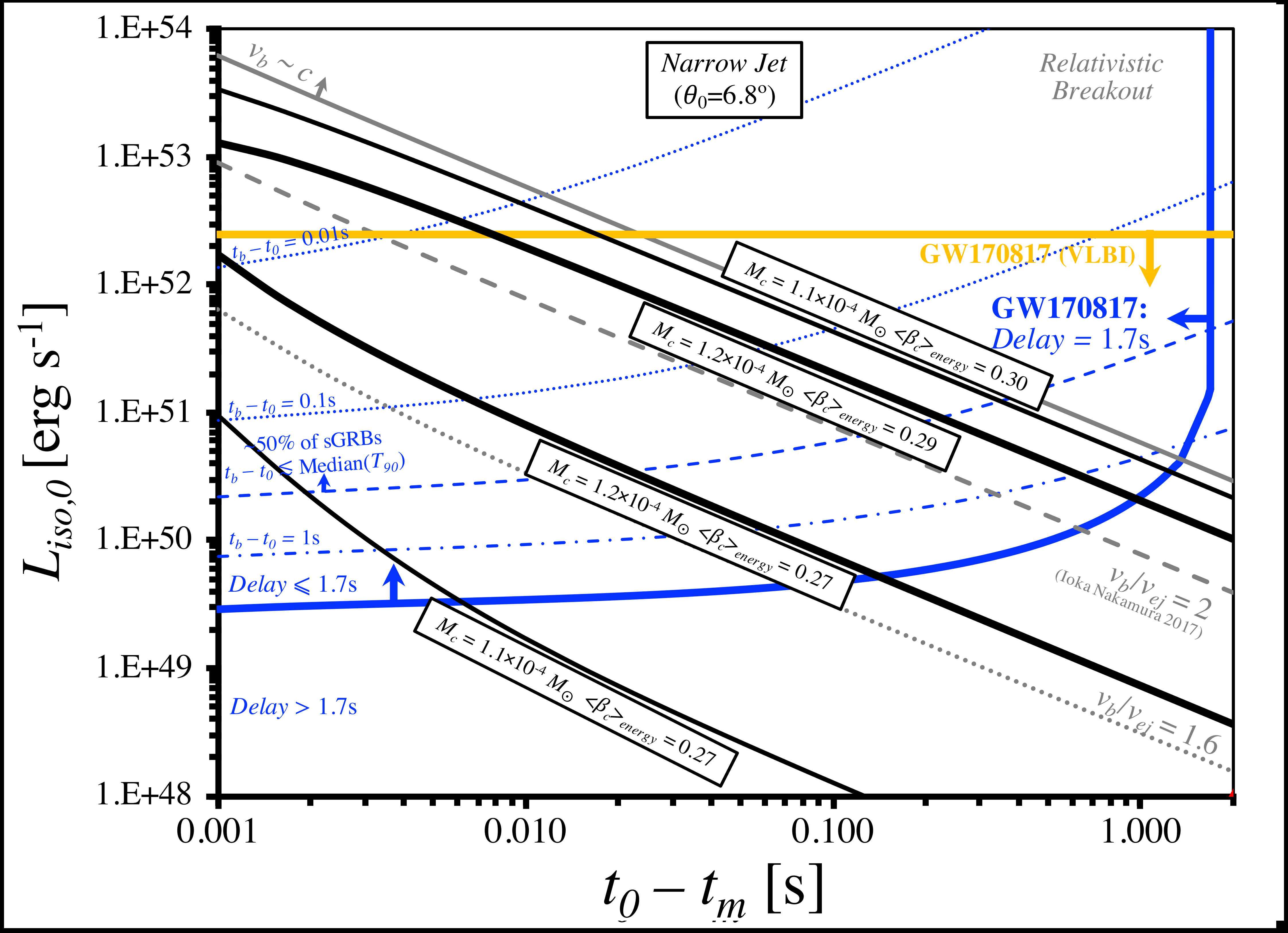



**Gives:**

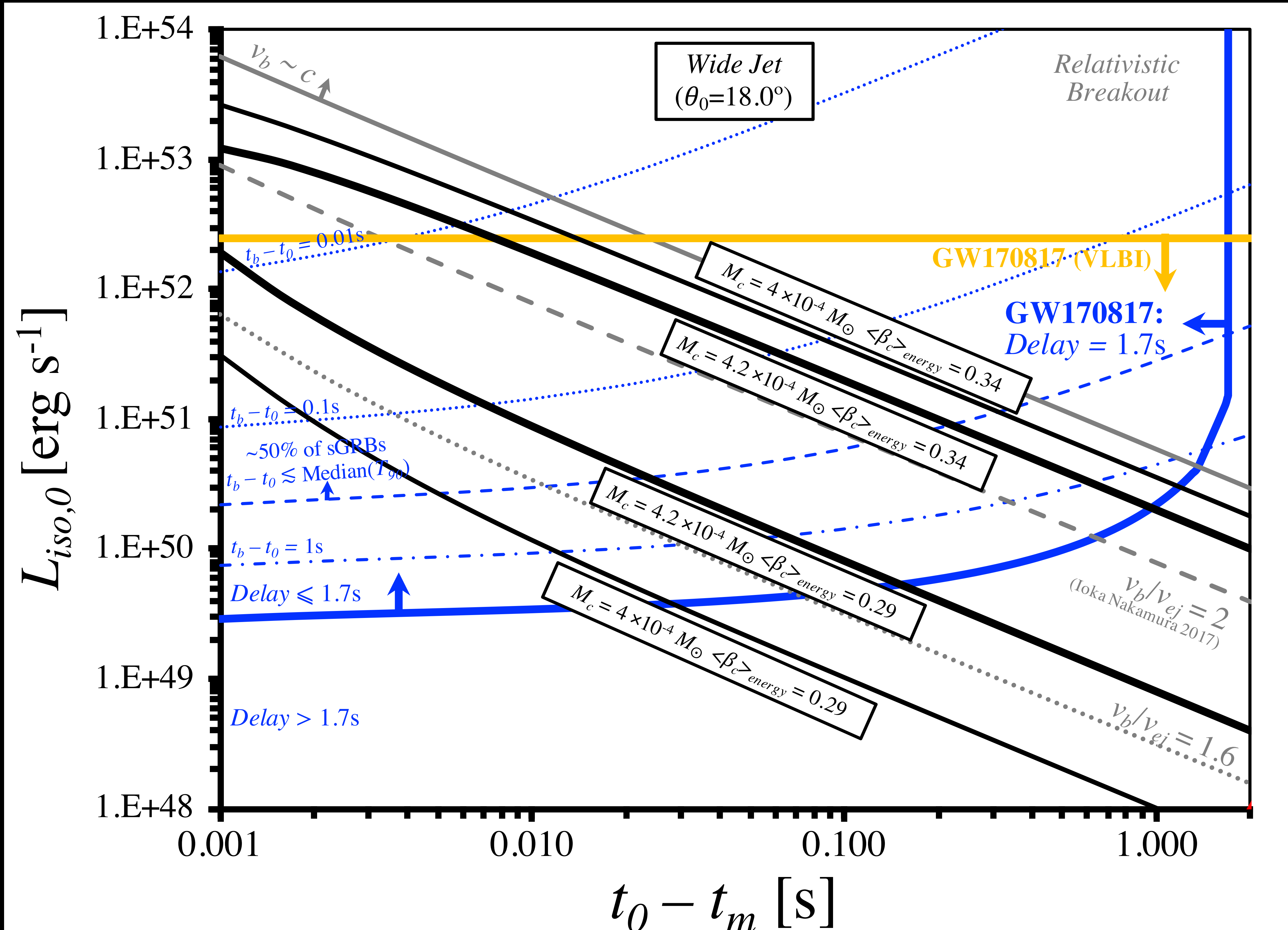
$$E_c, M_c, \& \left\langle\beta_c\right\rangle$$

**Hamidani+19 in prep**

# Results I:
# GW170817's Cocoon

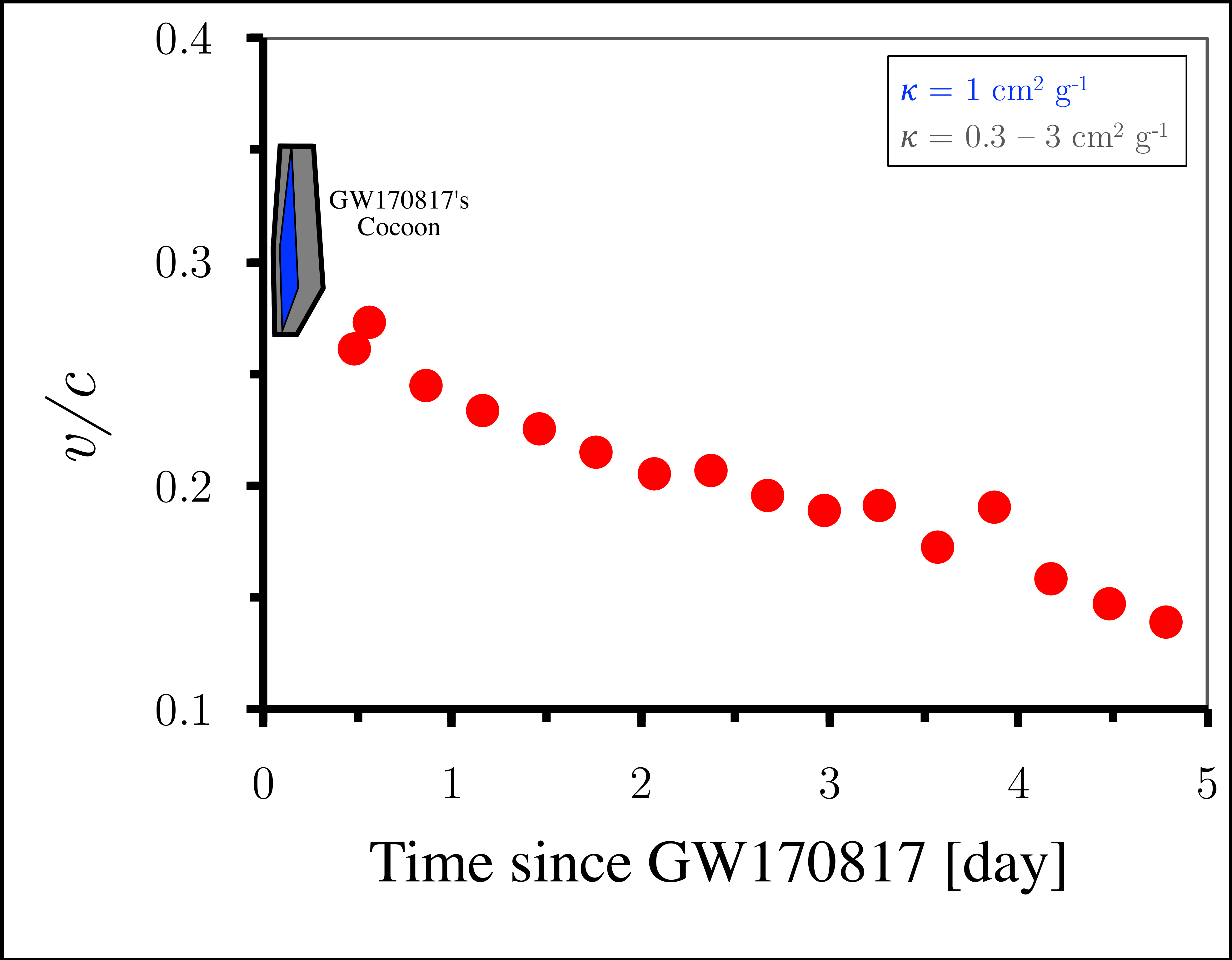


# Results I:
## GW170817's Cocoon

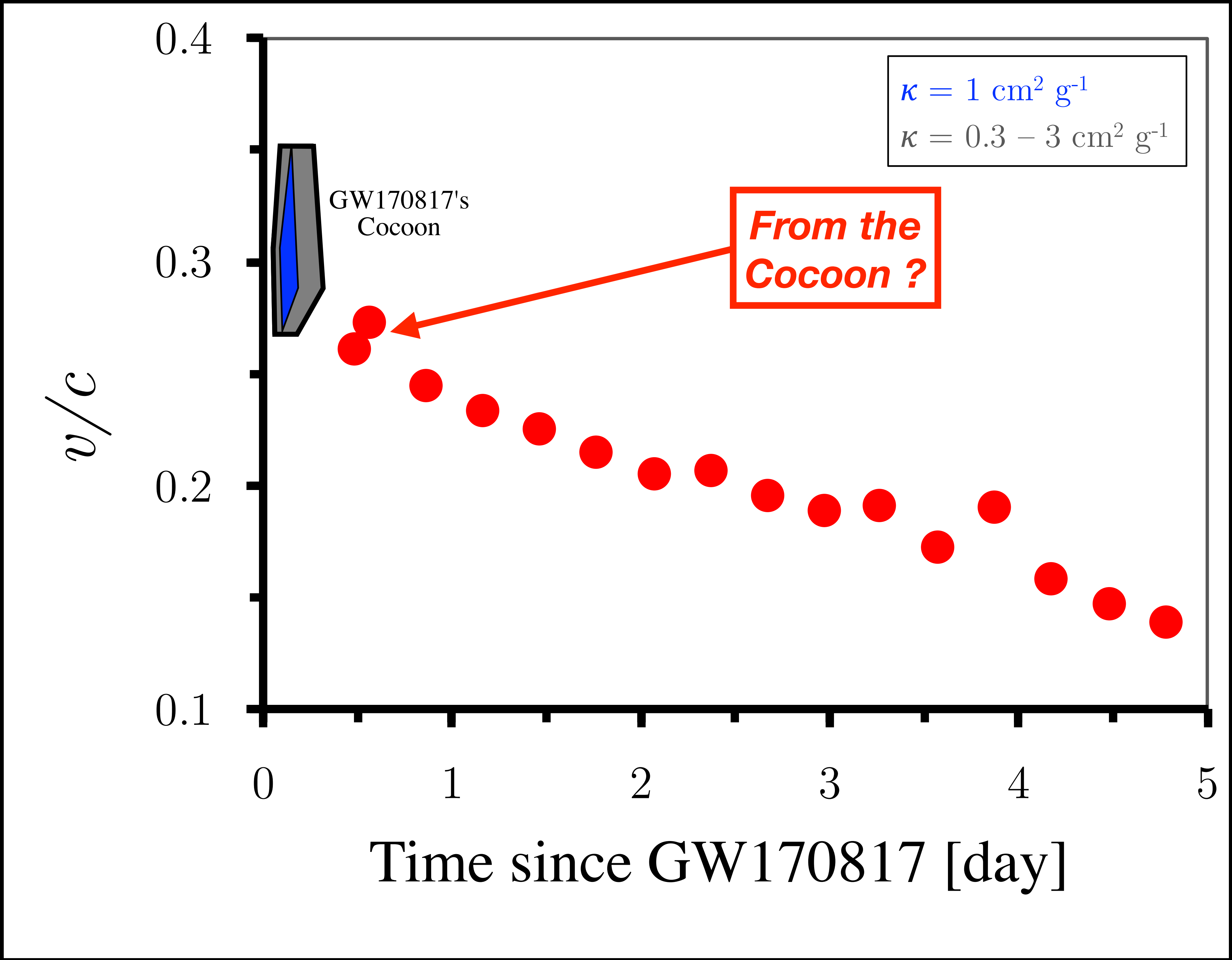


# The EM Counterparts & The Cocoon

# Photospheric Velocity

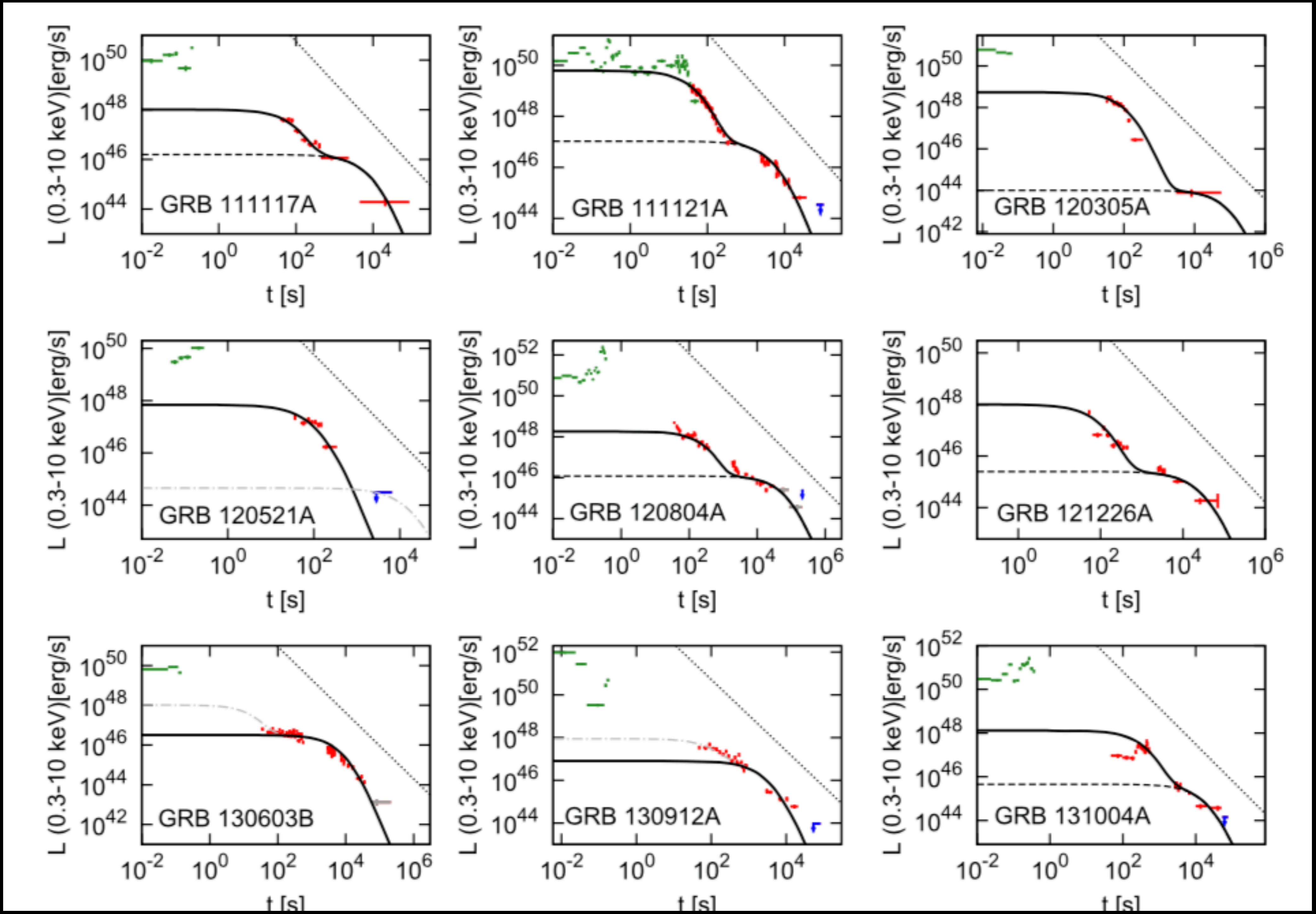


# Photospheric Velocity



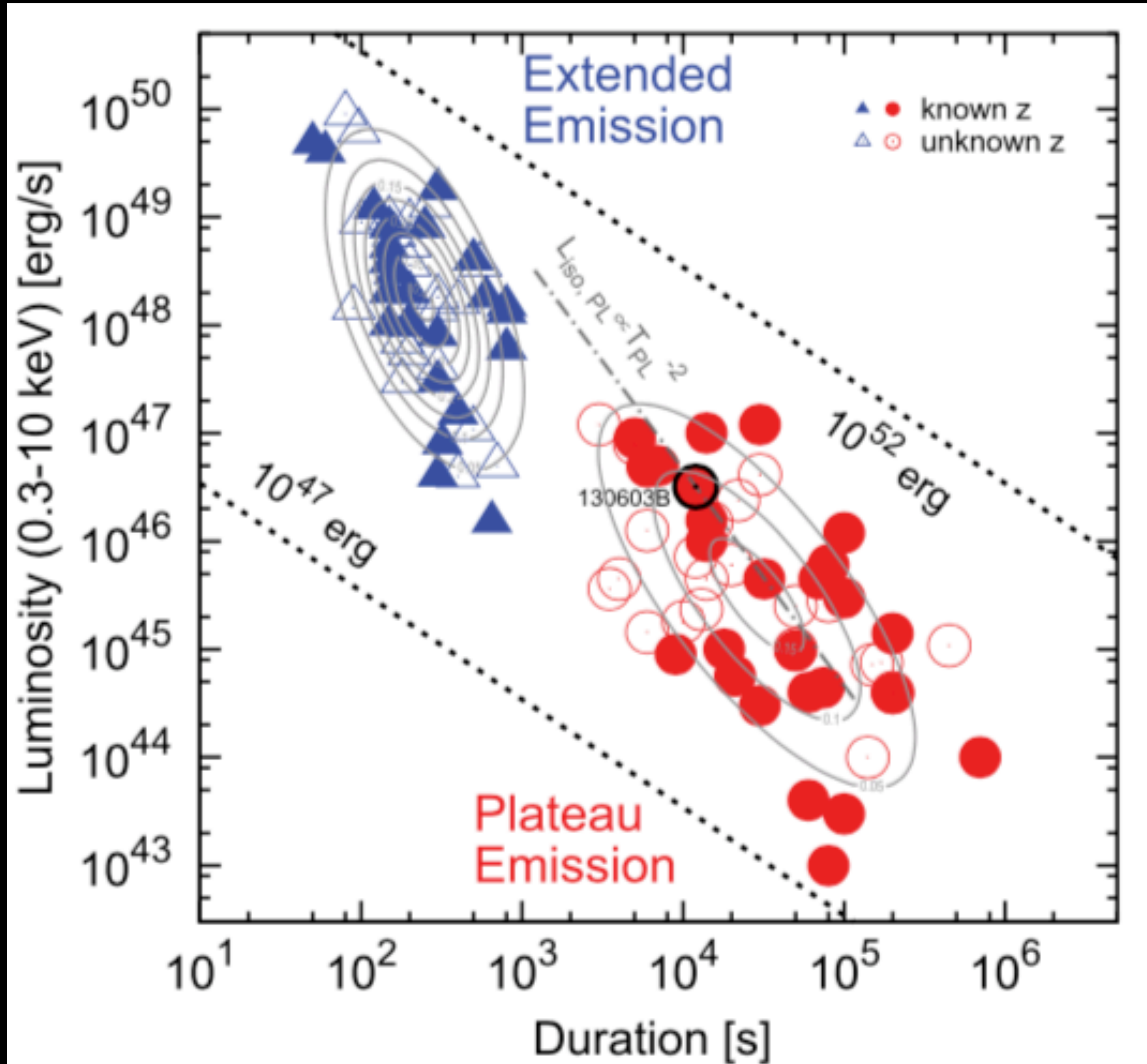
# Late Time Engine Activity
# & Potential EM Counterparts

# EE, and Plateau Emission




Kisaka+17

# EE, and Plateau Emission

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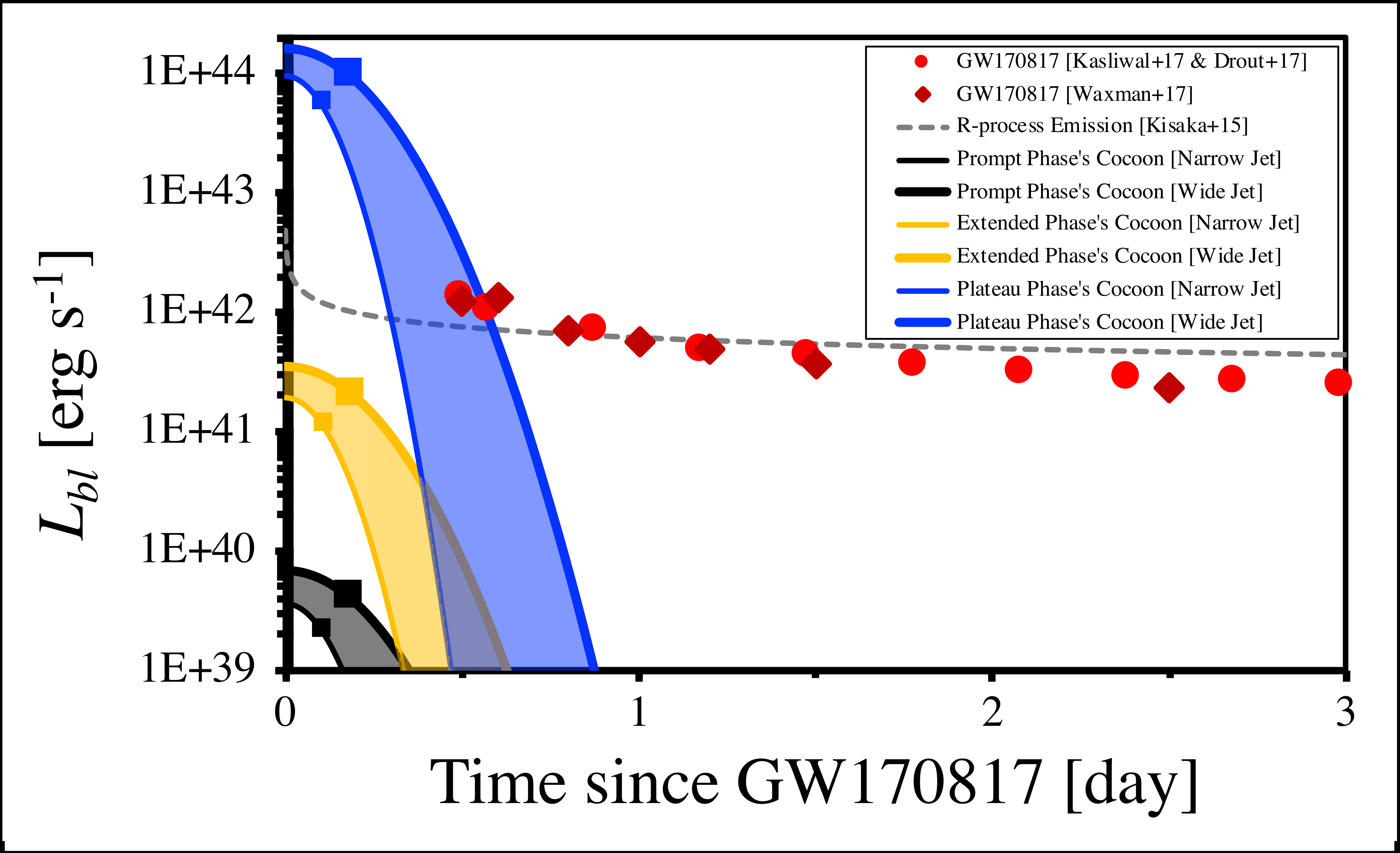
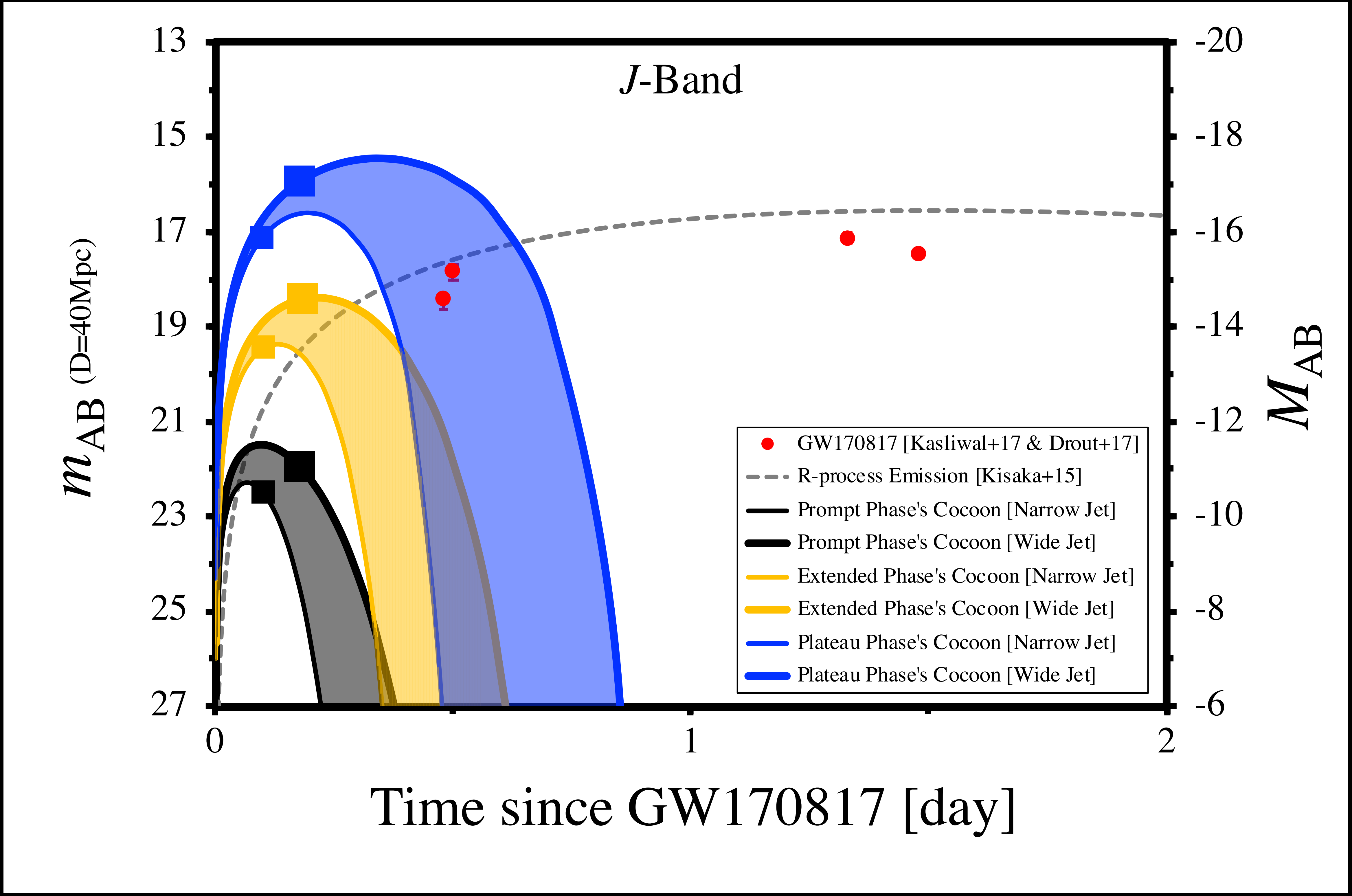
# The Different Cocoons

## (Preliminary)



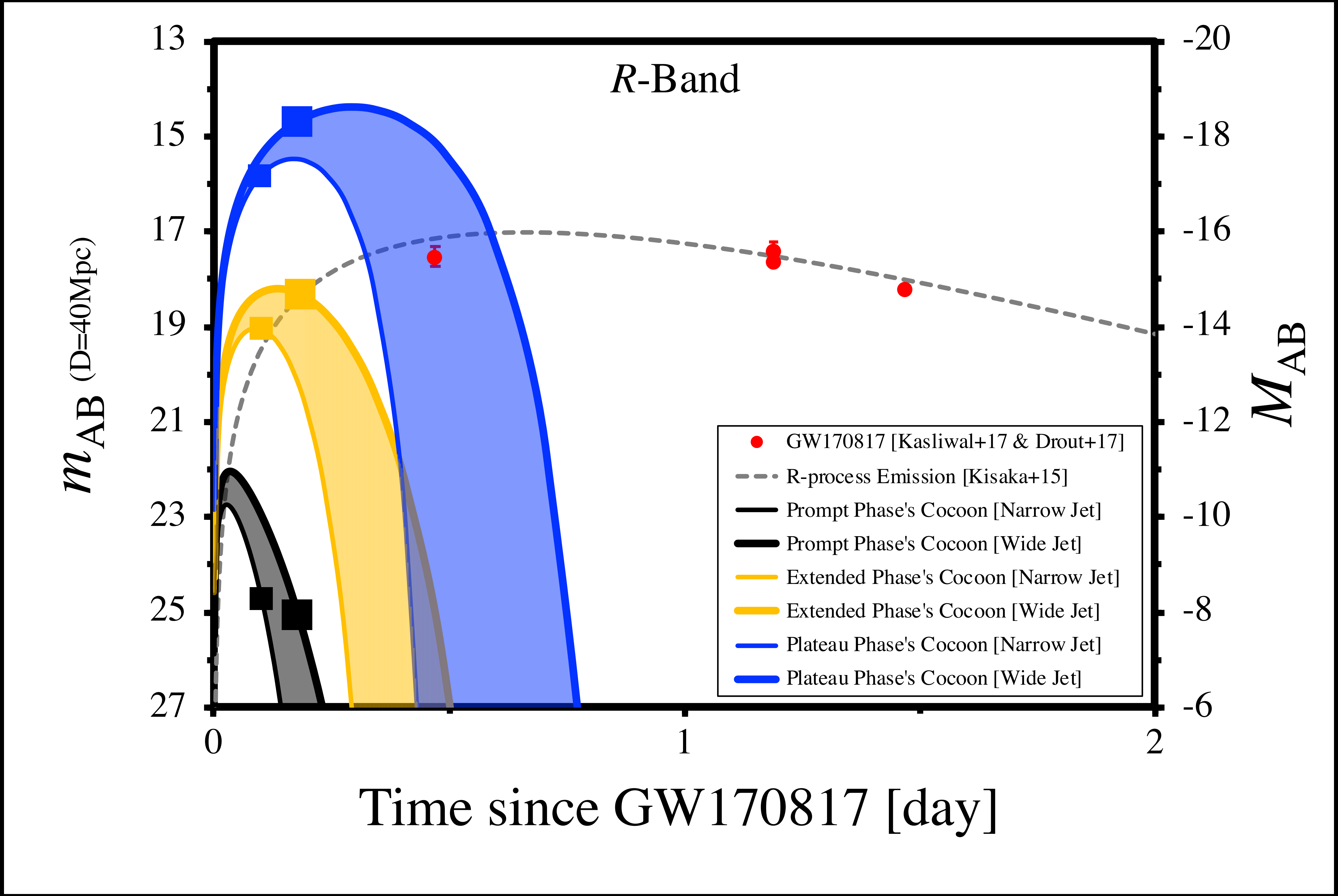

**HH+19 in prep**

# The Cocoon Can Outshine r-Process
## (Preliminary)



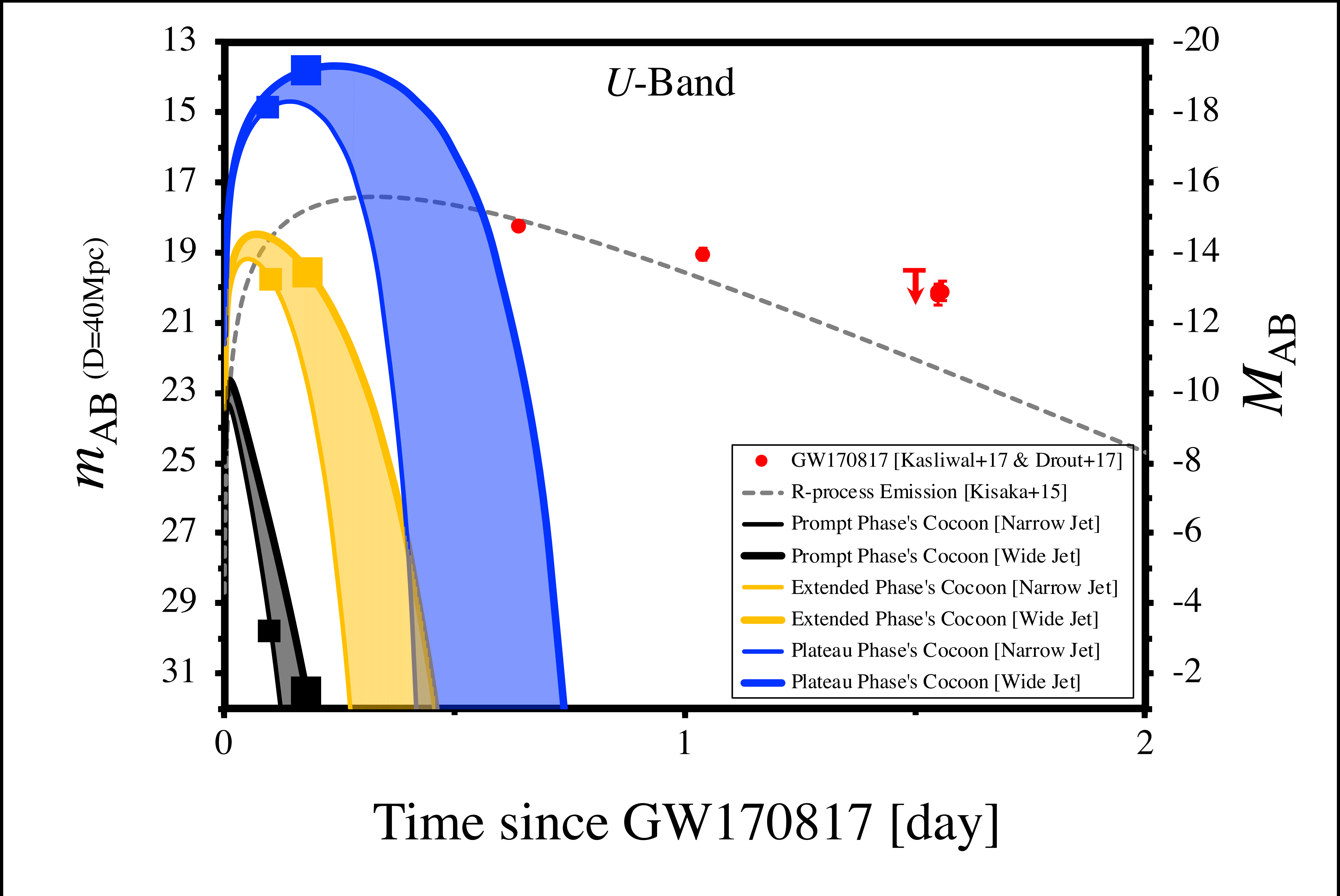

HH+19 in prep

# The Cocoon Can Outshine r-Process
## (Preliminary)




**HH+19 in prep**

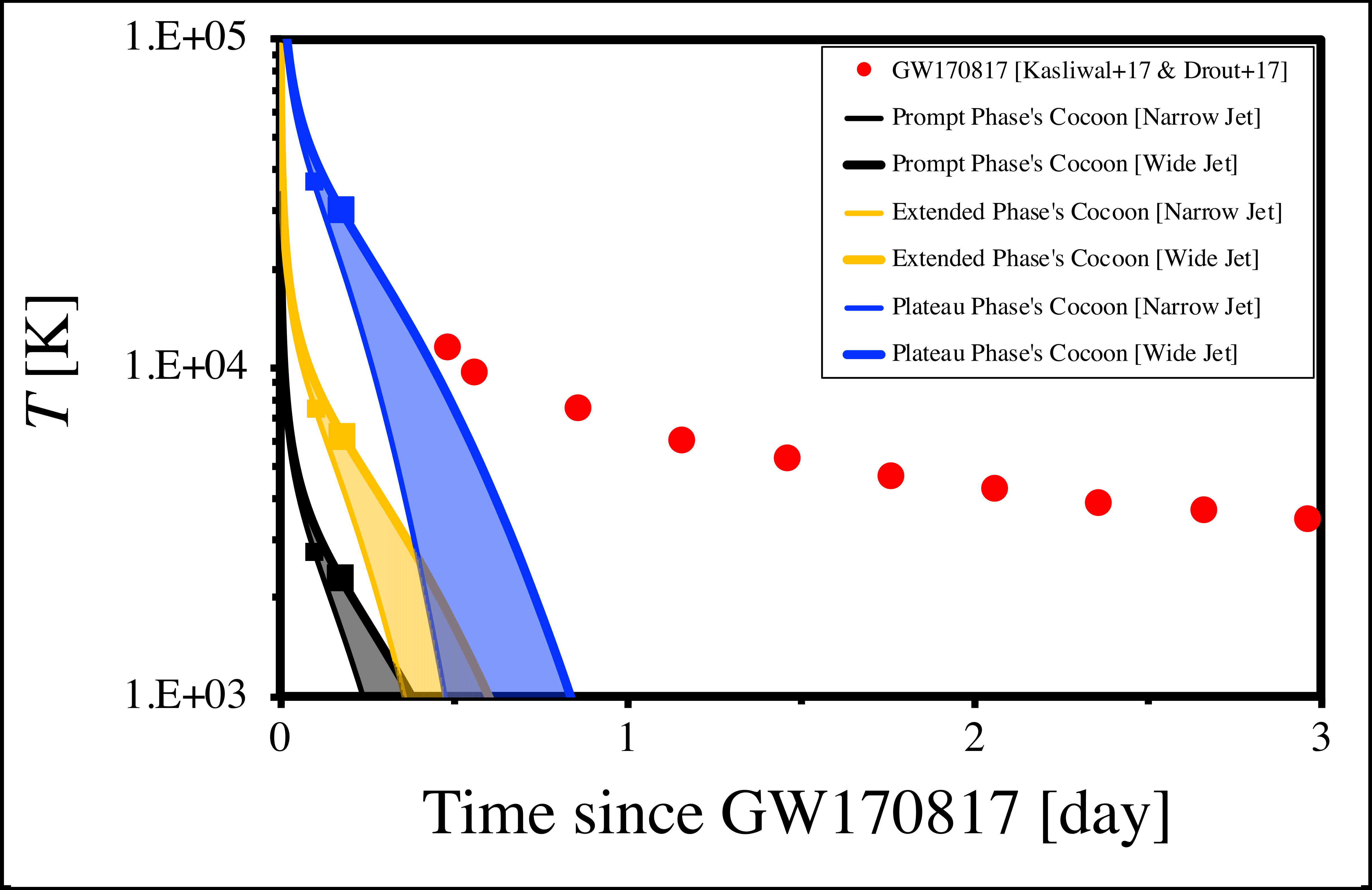
# The Cocoon Can Outshine r-Process
## (Preliminary)




HH+19 in prep

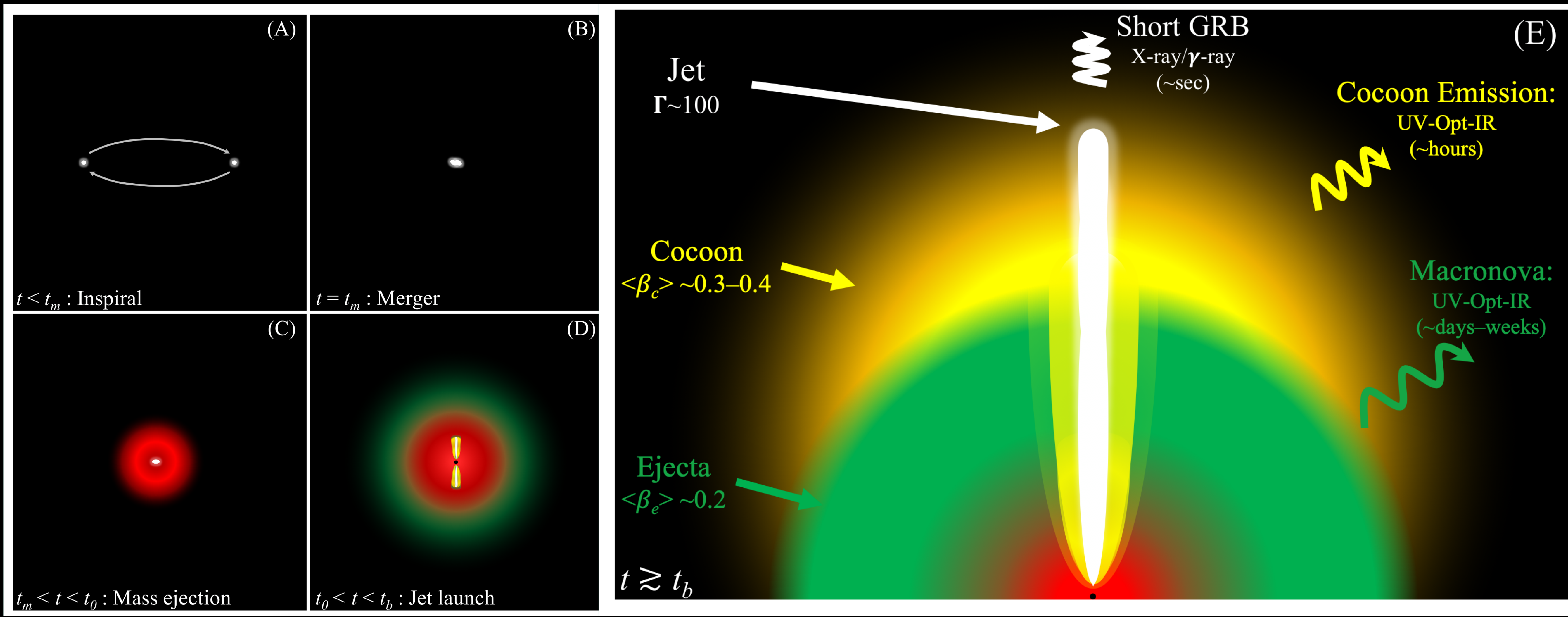
# Temperature & Color of the Cocoon

## (Preliminary)




**HH+19 in prep**

# One Prediction




HH+19 in prep

# Summary

**Analytic modeling of jet head motion**
in an expanding medium (i.e. BNS mergers)

**The Cocoon outshines r-process**
likely to have contaminated the early macronova in GW170817

**Large Opening Angles for the central engine**
are excluded

**Prediction of A Bright Early Counterparts** to peak and outshine r-process in the first a few hours [considering the EE/PL emission from the engine].
Expected to be revealed by future prompt followup Observations.