# 連星中性子星合体から得られる電磁波放射の理論解釈

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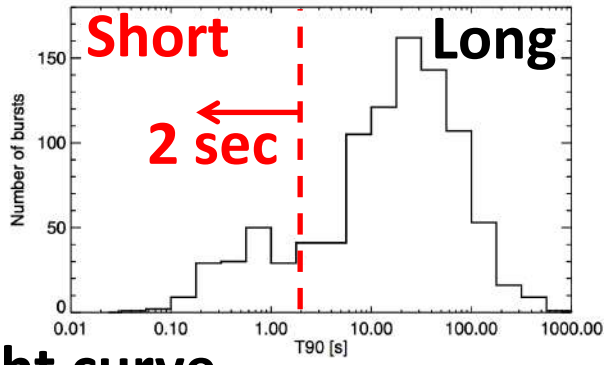
# Short Gamma-ray Bursts

- **Radiation energy :** ~ $10^{50}$ - $10^{51}$ erg (isotropic)
- **Duration :** ~ $10^{-2}$ - 2 sec
- **Event rate :** ~ $10^{3}$ $Gpc^{-3}$ $yr^{-1}$
- **Jet opening angle :** ~ 16° ±10° (Fong+ 15)

- **Duration distribution**

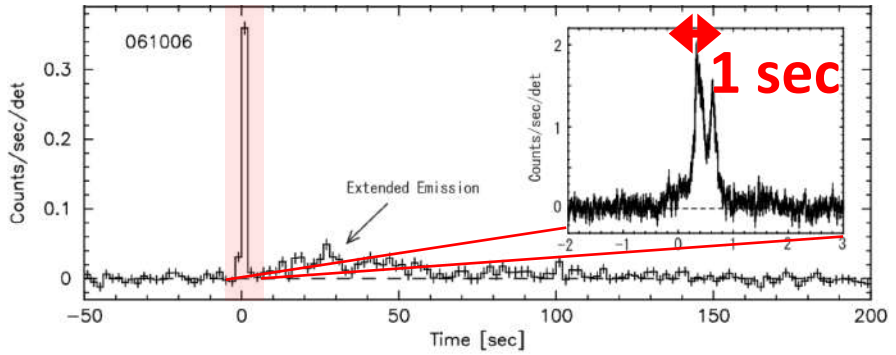
2nd Fermi/GBM Catalog (50-300keV)

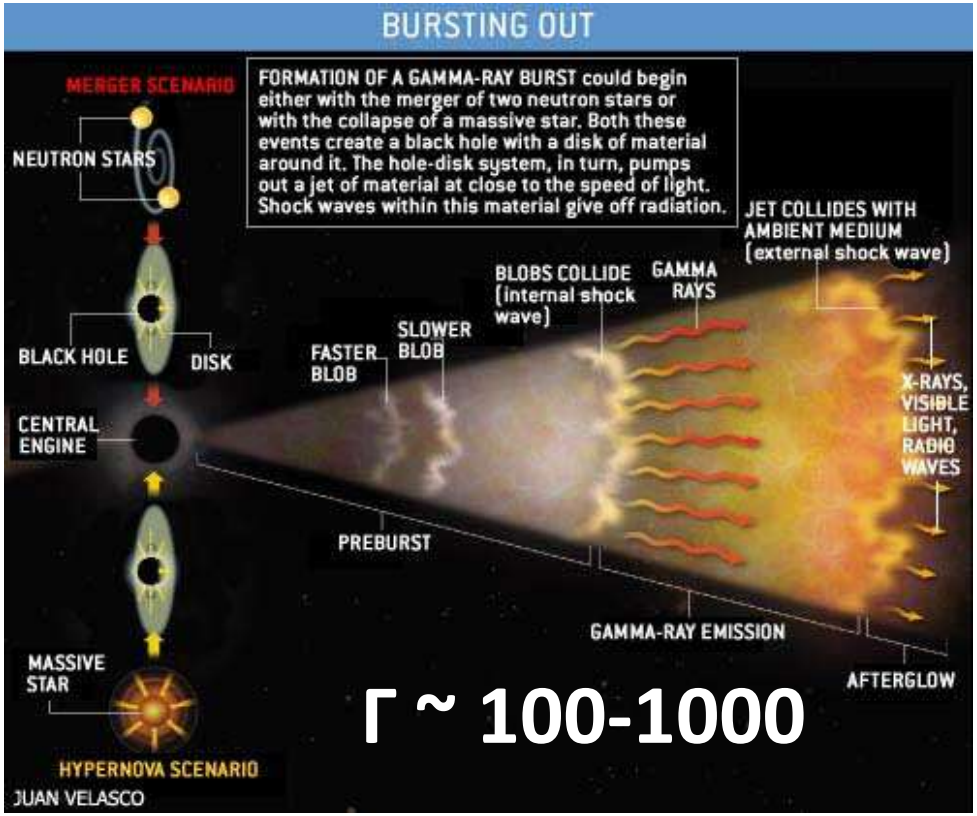



- **Light curve**

100 sec

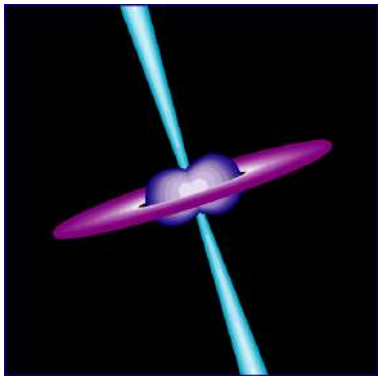
Norris & Bonnell 06



# Short GRB = NS Merger?

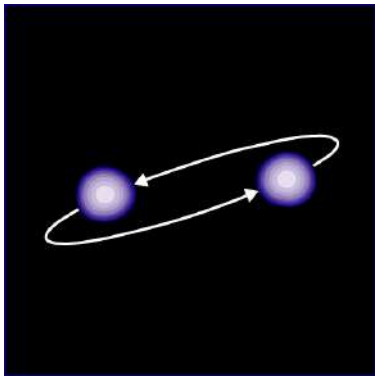
## Short GRBs



- Isotropic energy
  ~ $10^{50}$ – $10^{51}$ erg
- Variability timescale
  < 1 ms
- Event rate
  ~ $10^{3}$ $Gpc^{-3}$ $yr^{-1}$
- No association with SNe
- Wide variety of the hosts
- Low-density environment

… (e.g., Berger 14)

## NS mergers



- Maximum energy
  ~ $10^{53}$ erg
- Radius
  ~ $10^{6}$ cm → ~ 0.1 ms
- Merger rate
  ~ $10^{2}$ - $10^{3}$ $Gpc^{-3}$ $yr^{-1}$
- Merger time
  ~ 0.1 - 10 Gyr

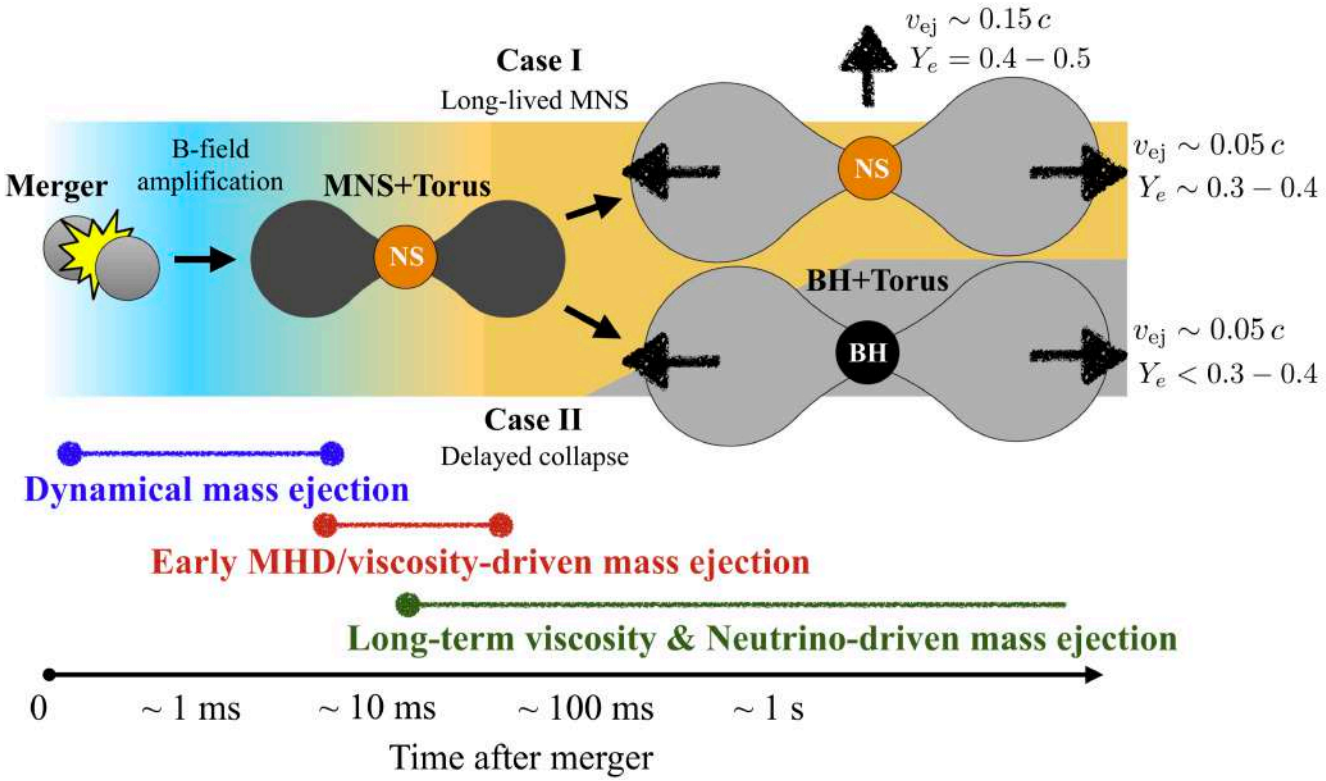
**No smocking-gun evidence**

# Merger Ejecta

## Properties of merger ejecta

Fujibayashi+ 18
See also Fernandez+ 19

| Type of Ejecta | Mass ($M_\odot$) | $V_{\rm ej}/c$ | $Y_e$ | Direction | Duration |
|---|---|---|---|---|---|
| Dynamical ejecta | $O(10^{-3})$ | $\sim$0.2 | 0.05–0.5 | $\theta \gtrsim 45°$ | $t - t_{\rm merge} \lesssim$ 10 ms |
| Early viscosity-driven ejecta | $\sim 10^{-2}(\alpha_{\rm vis}/0.02)$ | $\sim 0.15 - 0.2$ | 0.2–0.5 | $\theta \gtrsim 30°$ | $t - t_{\rm merge} \lesssim$ 0.1 s |
| Late-time viscosity-driven ejecta (polar) | $\sim 10^{-3}$ $(t_\nu/{\rm s})$ | $\sim$0.15 | 0.4–0.5[a] | $\theta \lesssim 30°$ | $t - t_{\rm merge} \sim t_\nu \sim$ 10 s |
| Late-time viscosity-driven ejecta (equatorial) | $\gtrsim 10^{-2}$ | $\sim$0.05 | 0.3–0.4[a] | $\theta \gtrsim 30°$ | $t - t_{\rm merge} \sim$ 1–10 s |

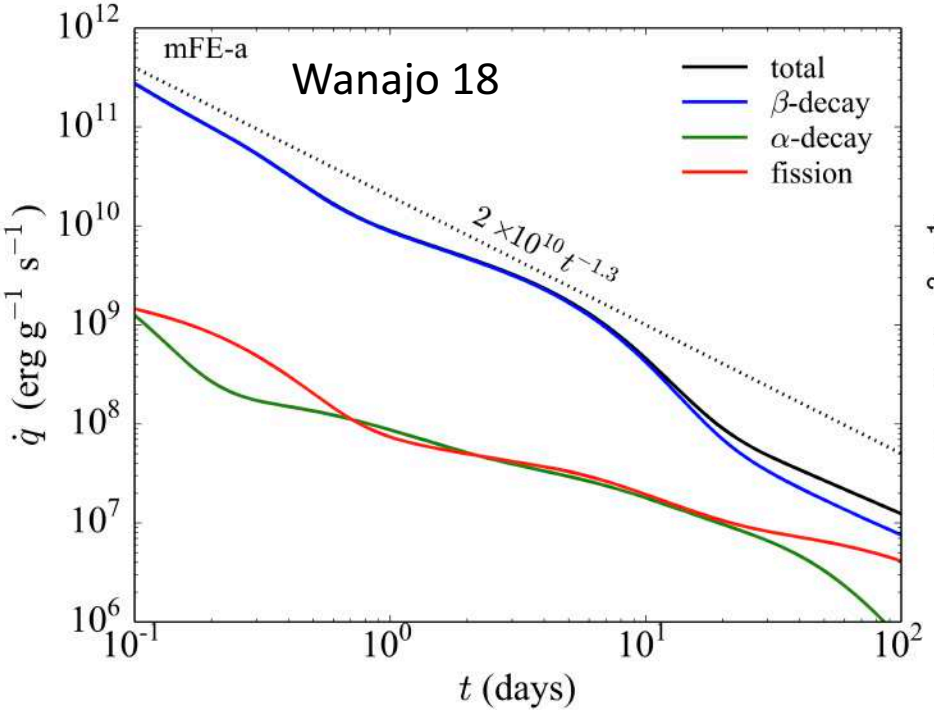



$$M_{\rm dyn} \sim 10^{-3} - 10^{-2} M_\odot, \quad M_{\rm acc} \sim M_{\rm wind} \sim 0.01 - 0.1 M_\odot$$

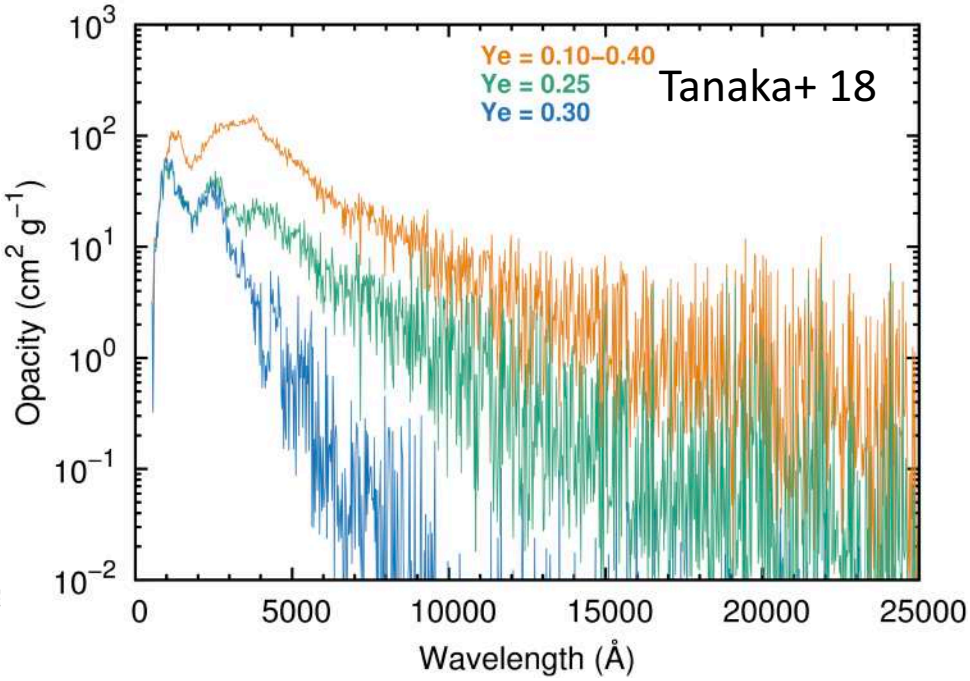
# *r*-process nucleosynthesis

## Neutron rich ejecta → rapid neutron capture process

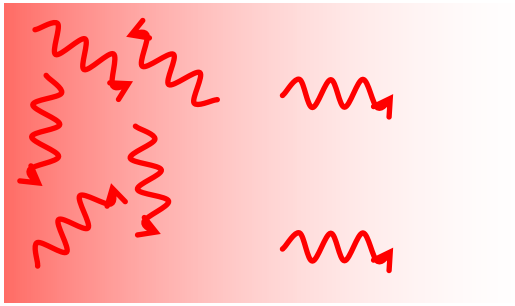
### Radioactive heating




### Opacity κ

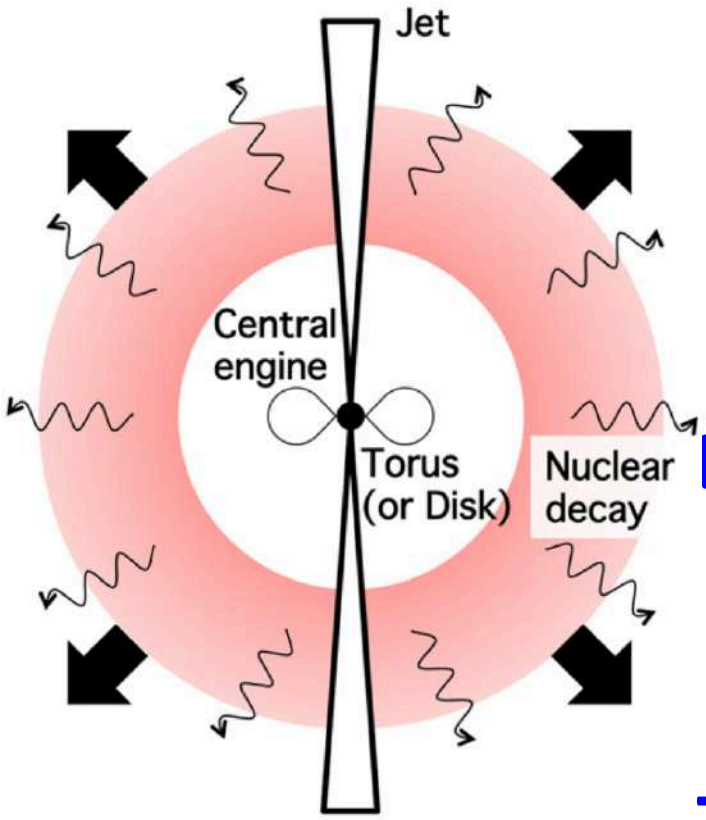



**Optical depth** $\tau = \int \kappa \rho dr$



# Macronova/Kilonova

Li & Paczynsky 98
Kulkarni 05




SK, Ioka & Takami 15

## Timescale

$$t_{\rm diff} \sim \tau \frac{r}{c} \sim t$$

$$t_{\rm peak} \sim 7 \left(\frac{M_{\rm ej}}{0.05 M_\odot}\right)^{1/2} \left(\frac{\kappa}{10 {\rm cm}^2 {\rm g}^{-1}}\right)^{1/2} \times \left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2} {\rm day}$$

## Luminosity

$$\dot{\epsilon} \sim 2 \times 10^{10} \left(\frac{t}{1{\rm day}}\right)^{-1.3} {\rm erg\ g^{-1} s^{-1}}$$

$$L \sim \dot{\epsilon} M_{\rm ej} \sim 10^{41} \left(\frac{M_{\rm ej}}{0.05 M_\odot}\right) \left(\frac{t}{7{\rm day}}\right)^{-1.3} {\rm erg\ s^{-1}}$$

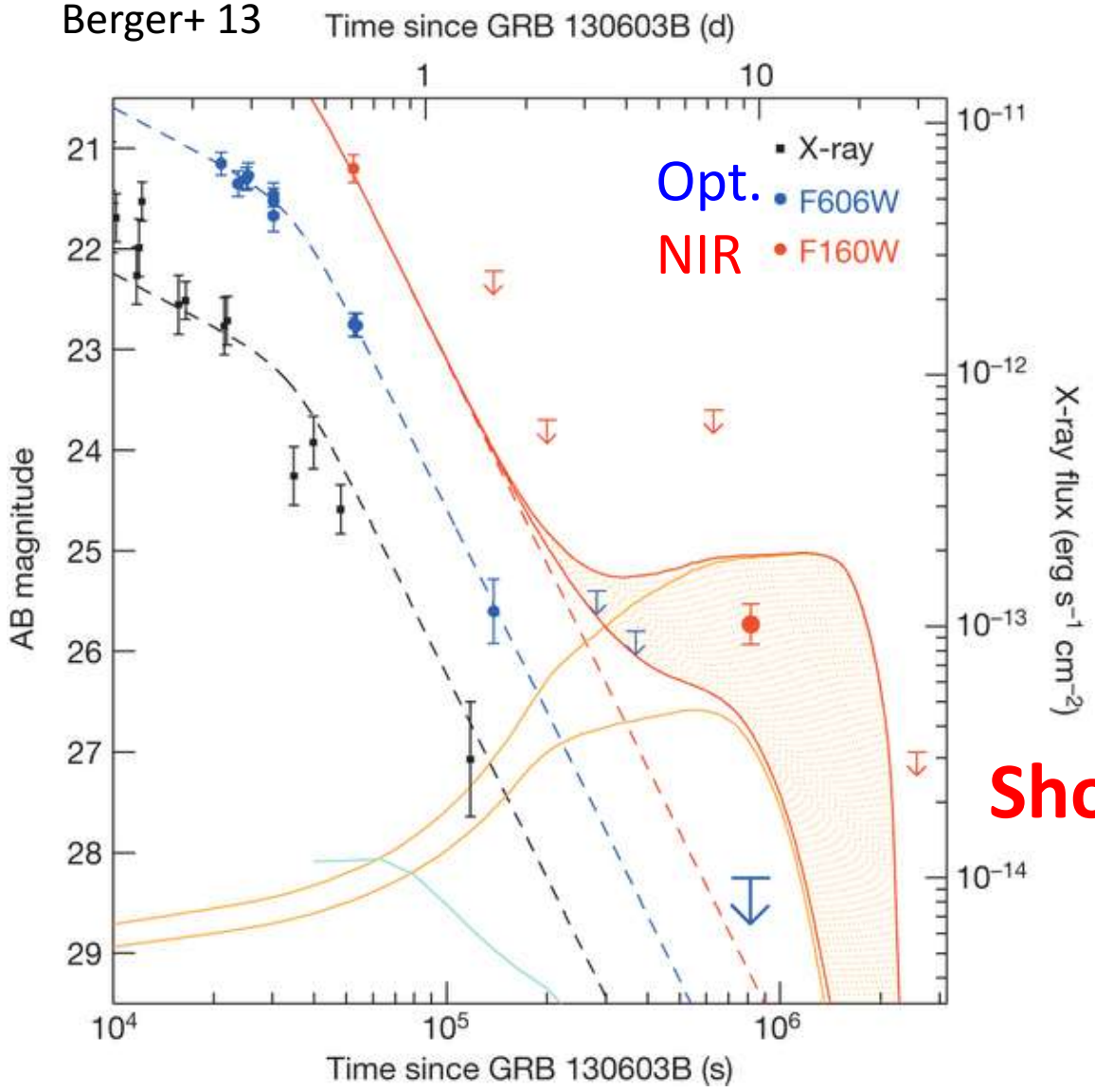
## Temperature

$$L \sim 4\pi r^2 \sigma_{\rm SB} T^4$$

$$T \sim 3 \times 10^3 \left(\frac{M_{\rm ej}}{0.05 M_\odot}\right)^{1/4} \times \left(\frac{v_{\rm ej}}{0.1c}\right)^{-1/2} \left(\frac{t}{7{\rm day}}\right)^{-1/2} {\rm K}$$

# GRB 130603B

Tanvir+ 13
Berger+ 13




**t ~ 7 day**

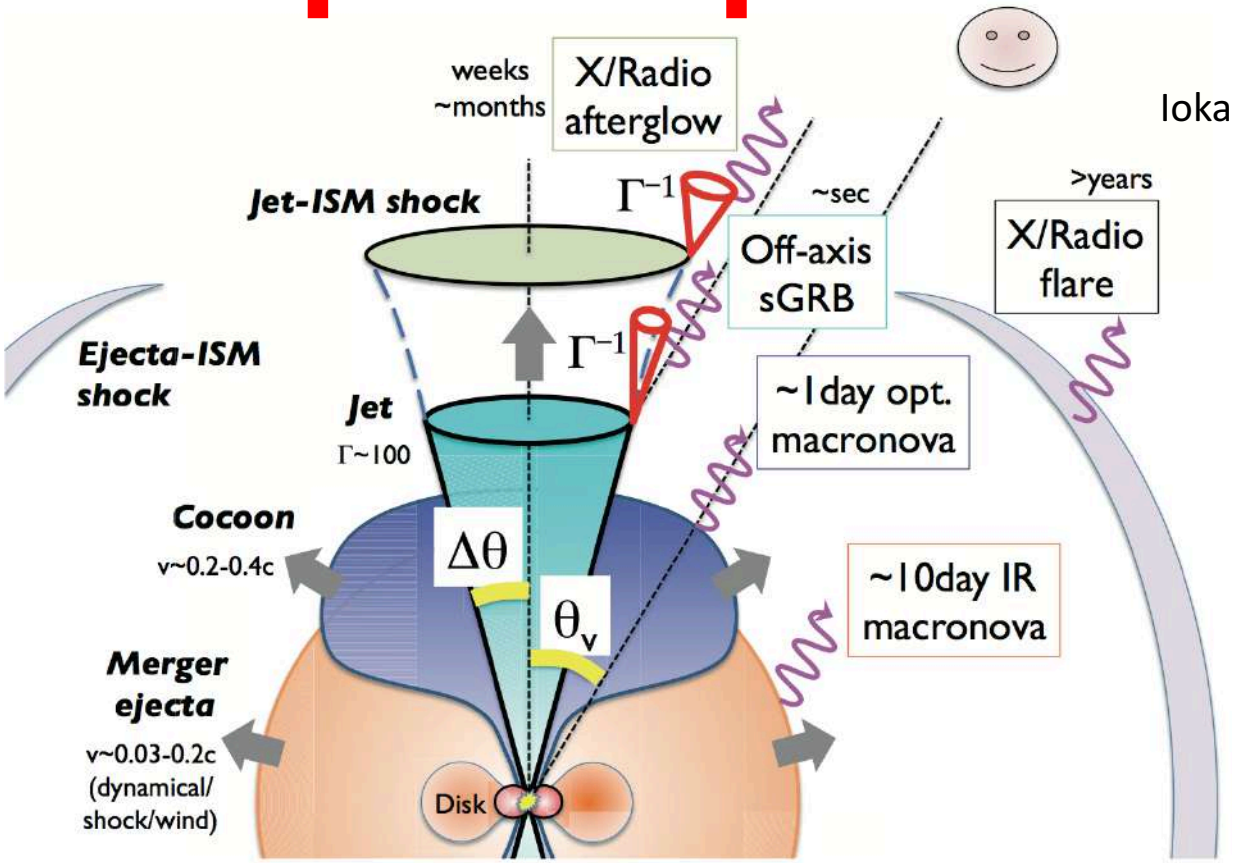
**$L_{NIR}$ ~ $10^{41}$erg/s**

**T < 4000 K**

($m_r$-$m_j$ ≥ 2.5)

**Short GRB = NS merger?**

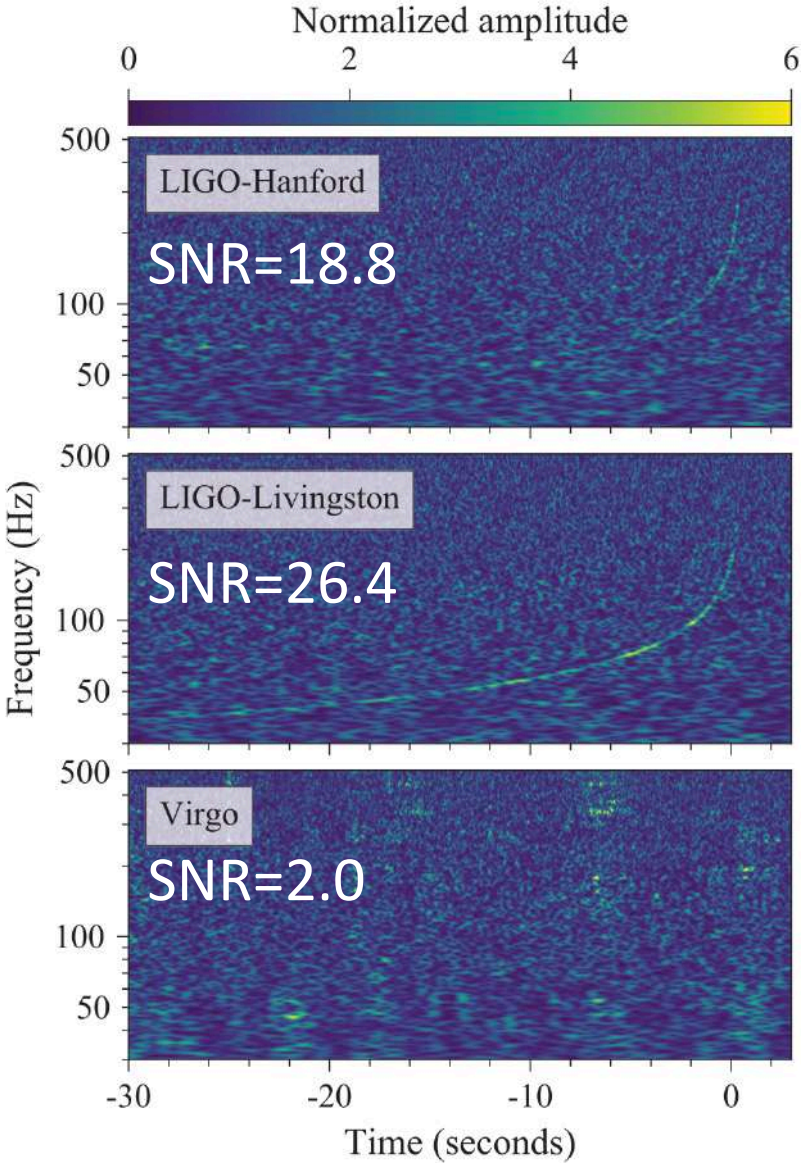
# Expected picture




Ioka & Nakamura 18

- **NS or BH formation**
- **Relativistic jet** (Short GRB)
- **Mass ejection** (Macronova/Kilonova)
- ***r*-process nucleosynthesis** (Macronova/Kilonova)

# GW170817 = Binary NS merger




Abbott+ 17

SNR : 32.4

Localization : 31 $deg^2$ (5 hr after)

Distance : ~ 40 Mpc

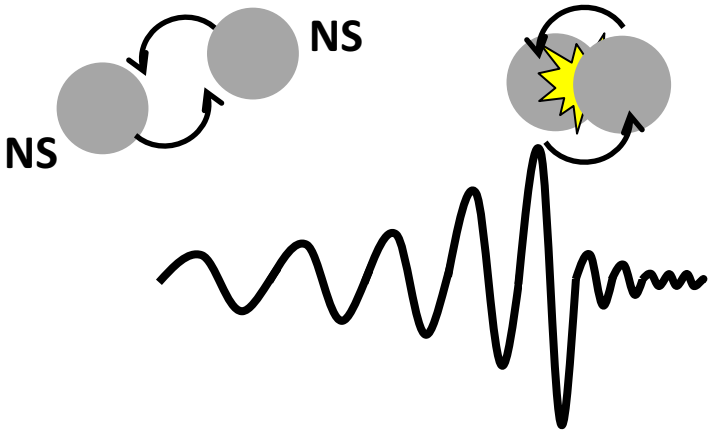
Viewing angle : < 32°

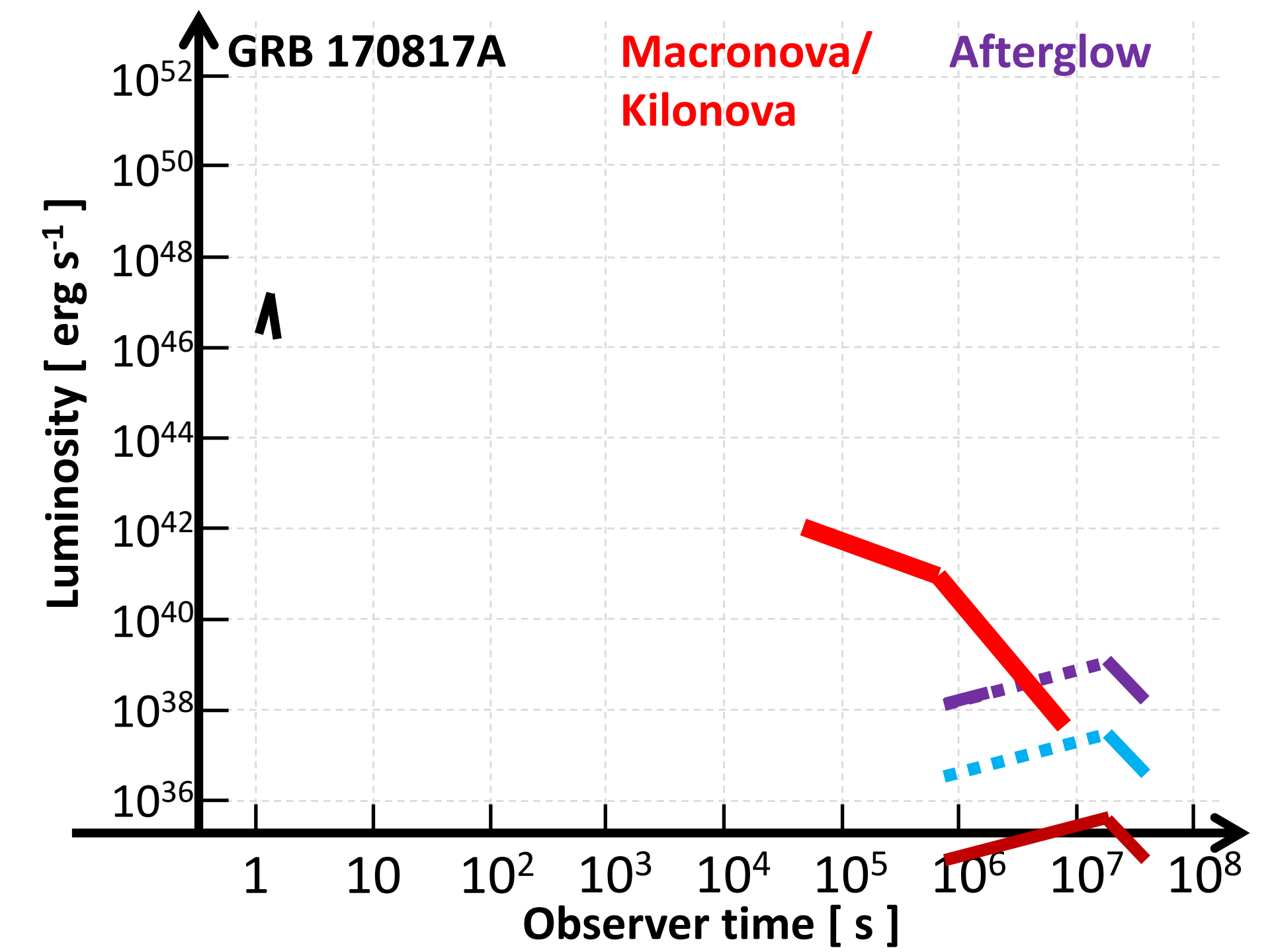
Total mass : $2.74^{+0.04}_{-0.01}$ Msun

NS mass : 1.17 – 1.60 Msun

NS radius : < 13 km

Merger rate : $1540^{+3200}_{-1220}$ $Gpc^{-3}yr^{-1}$

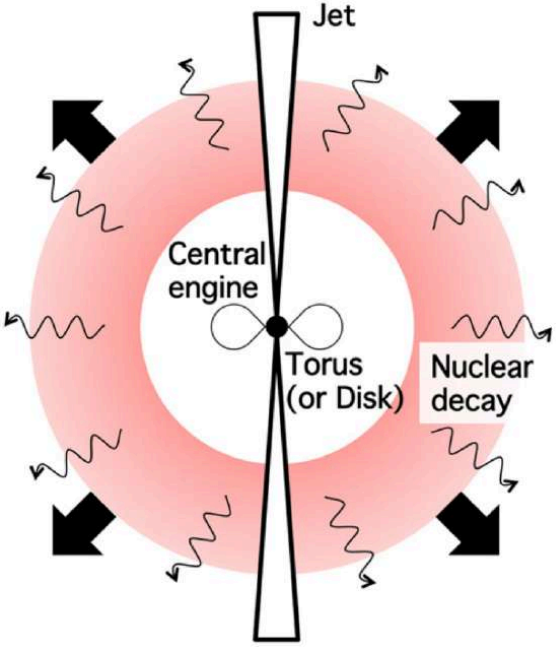



GRB 170817A
Macronova/
Kilonova
Afterglow
Luminosity [ erg s-1 ]
10^52
10^50
10^48
10^46
10^44
10^42
10^40
10^38
10^36
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Observer time [ s ]

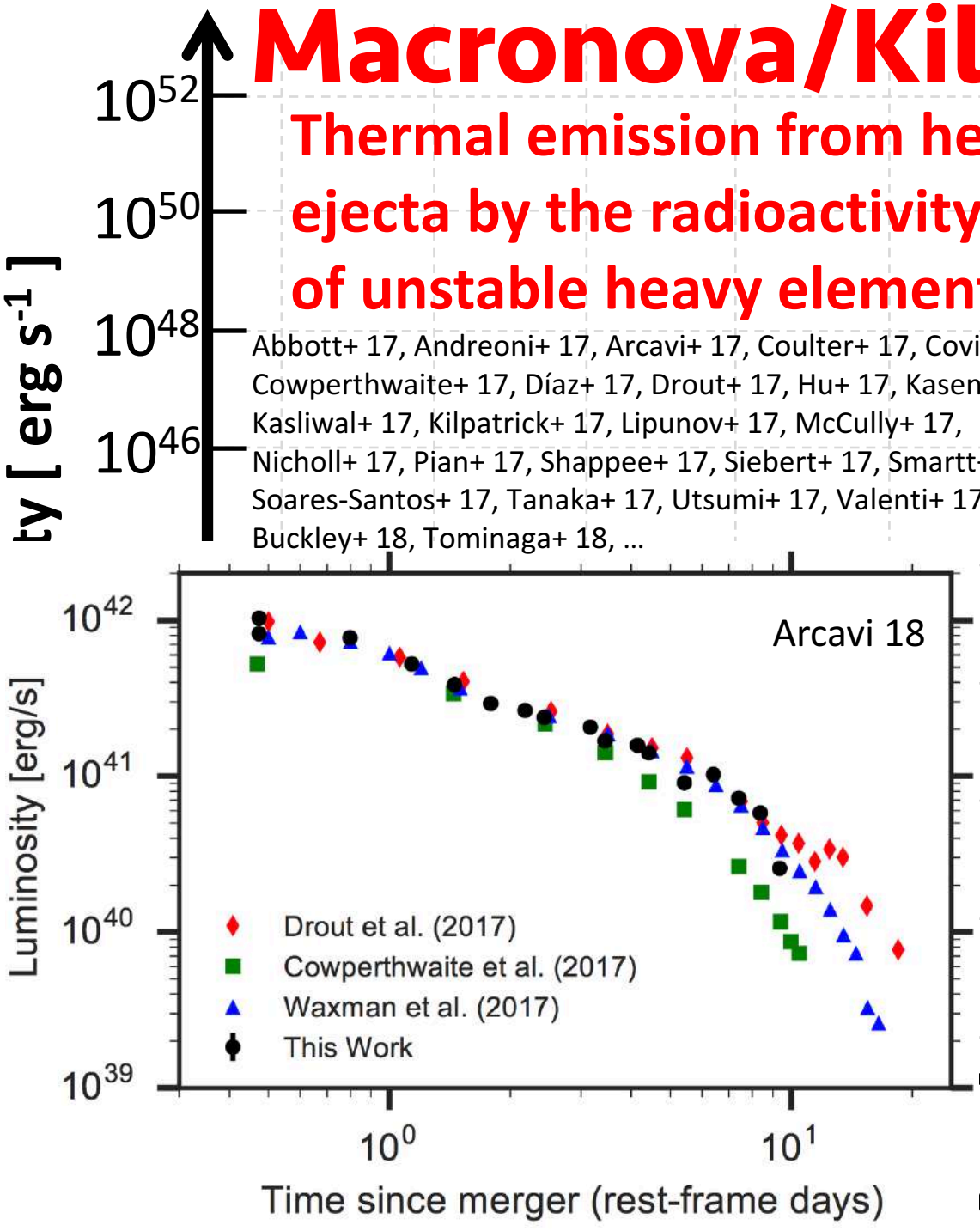
# Macronova/Kilonova

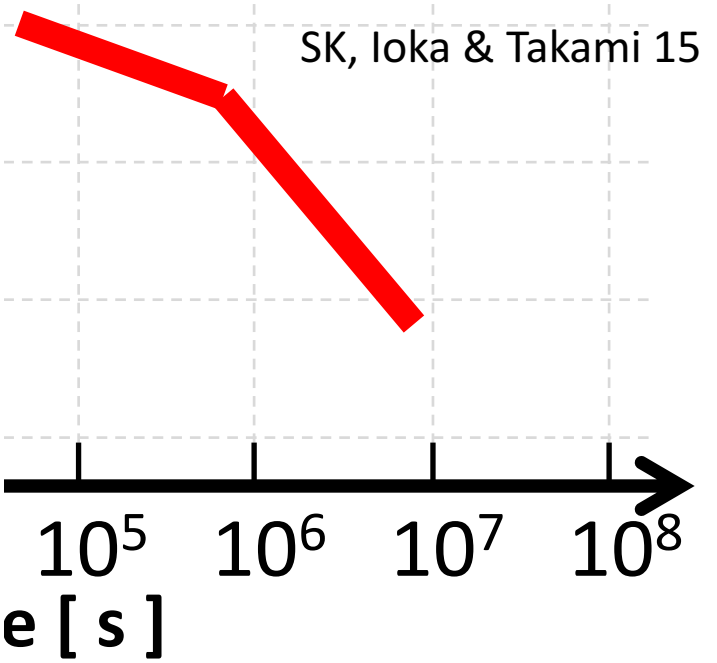
## Thermal emission from heated ejecta by the radioactivity of unstable heavy elements.

Abbott+ 17, Andreoni+ 17, Arcavi+ 17, Coulter+ 17, Covino+ 17, Cowperthwaite+ 17, Díaz+ 17, Drout+ 17, Hu+ 17, Kasen+ 17, Kasliwal+ 17, Kilpatrick+ 17, Lipunov+ 17, McCully+ 17, Nicholl+ 17, Pian+ 17, Shappee+ 17, Siebert+ 17, Smartt+ 17, Soares-Santos+ 17, Tanaka+ 17, Utsumi+ 17, Valenti+ 17, Buckley+ 18, Tominaga+ 18, …



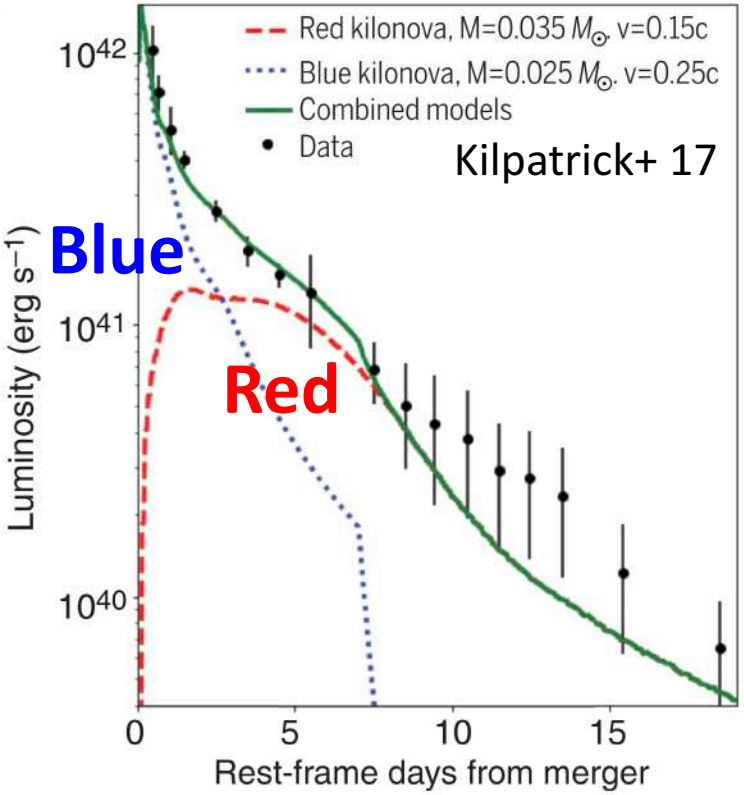

SK, Ioka & Takami 15



# SSS17a / AT2017gfo

## A binary NS merger is accompanied with macronova/kilonova → Mass ejection




### Blue Macronova

$t_{peak}$ ~ 1 day  $M_{ej}$ ~ 0.025 Msun

T ~ $10^4$ K  v ~ 0.25c

L ~ $10^{42}$ erg s$^{-1}$  $X_{lan}$ ~ $10^{-6}$ - $10^{-4}$ (Ye > 0.3)

### Red Macronova

$t_{peak}$ ~ 10 day  $M_{ej}$ ~ 0.035 Msun

T ~ 2000 K  v ~ 0.15c

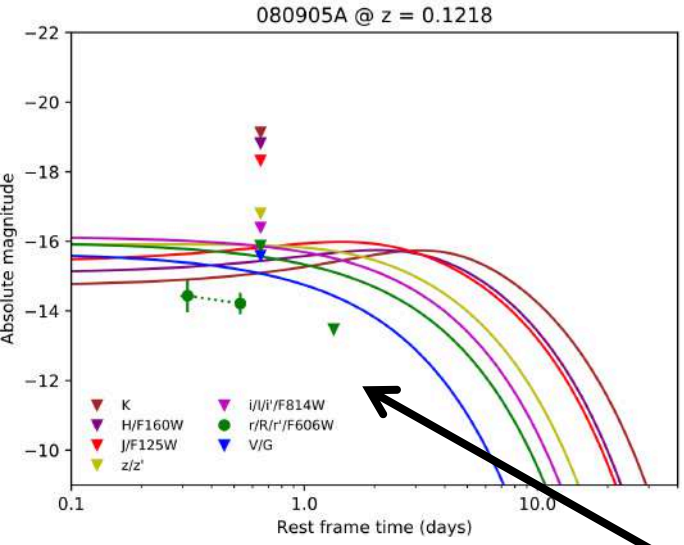
L ~ $10^{41}$ erg s$^{-1}$  $X_{lan}$ ~ $10^{-2}$ (Ye ~ 0.25)

Ejecta mass and rate are consistent with the Galactic *r*-process element enrichment.

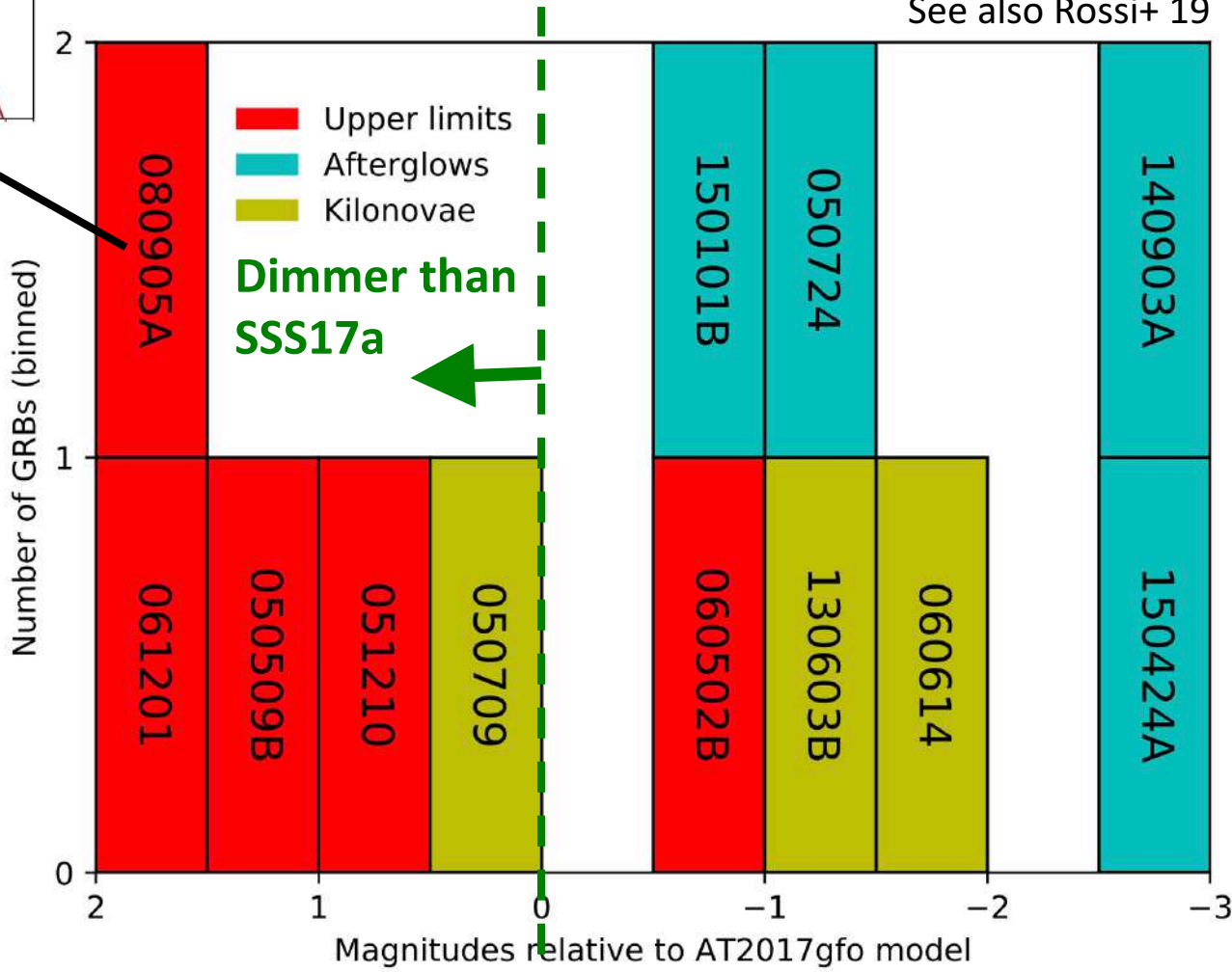
# Macronova Diversity

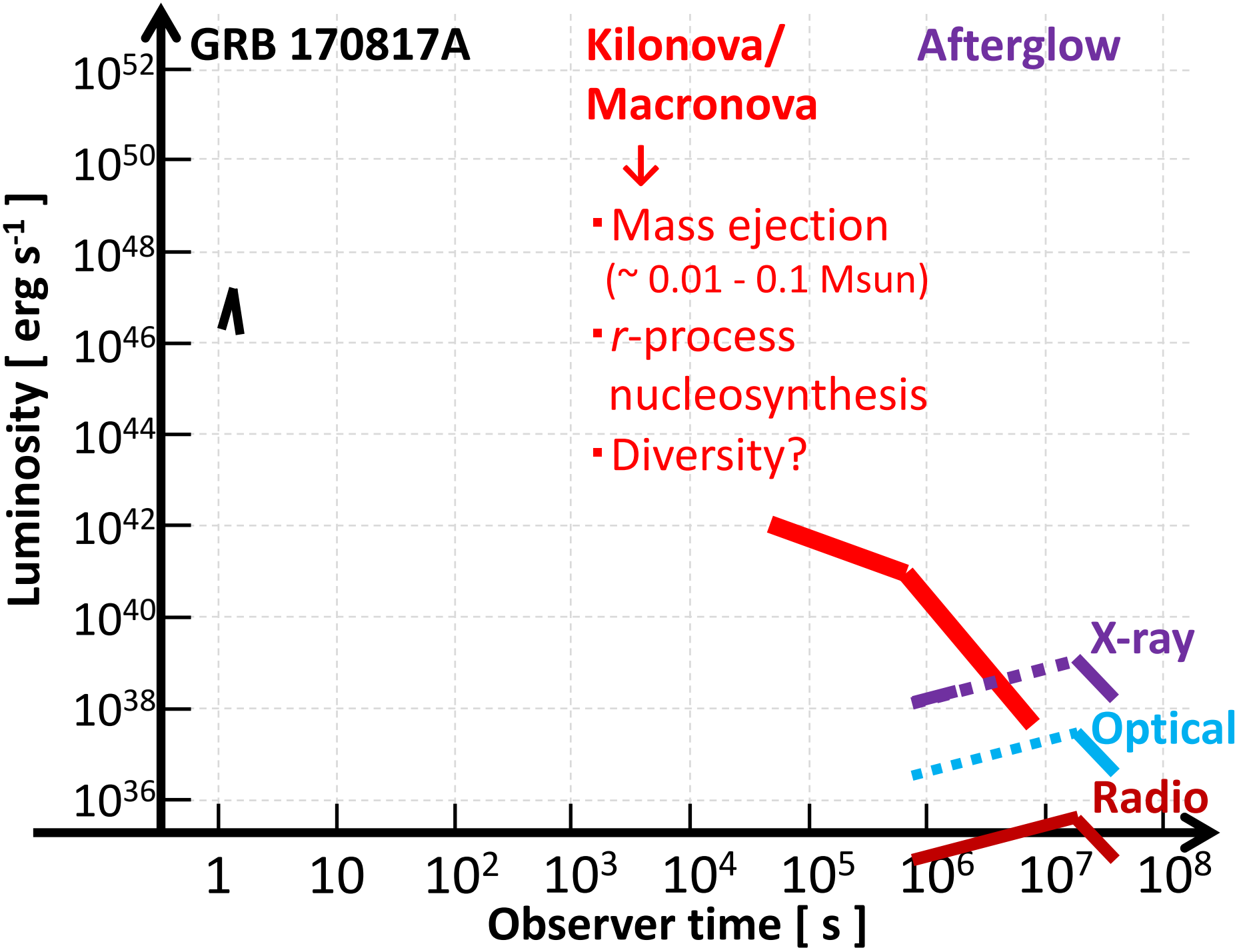
**Macronova properties have diversity despite the similar conditions expected in NS-NS mergers.**

Gompertz+ 18
See also Rossi+ 19



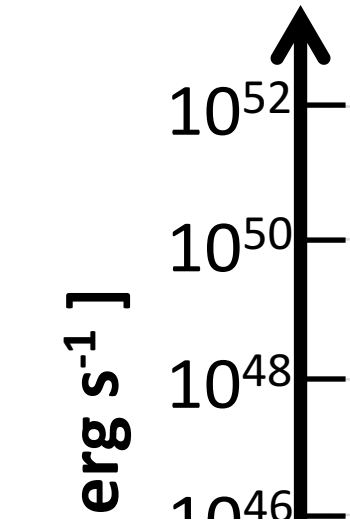

- Fate of a remnant?
  (e.g., direct collapse to BH)
- BH-NS merger?
- Different energy source?

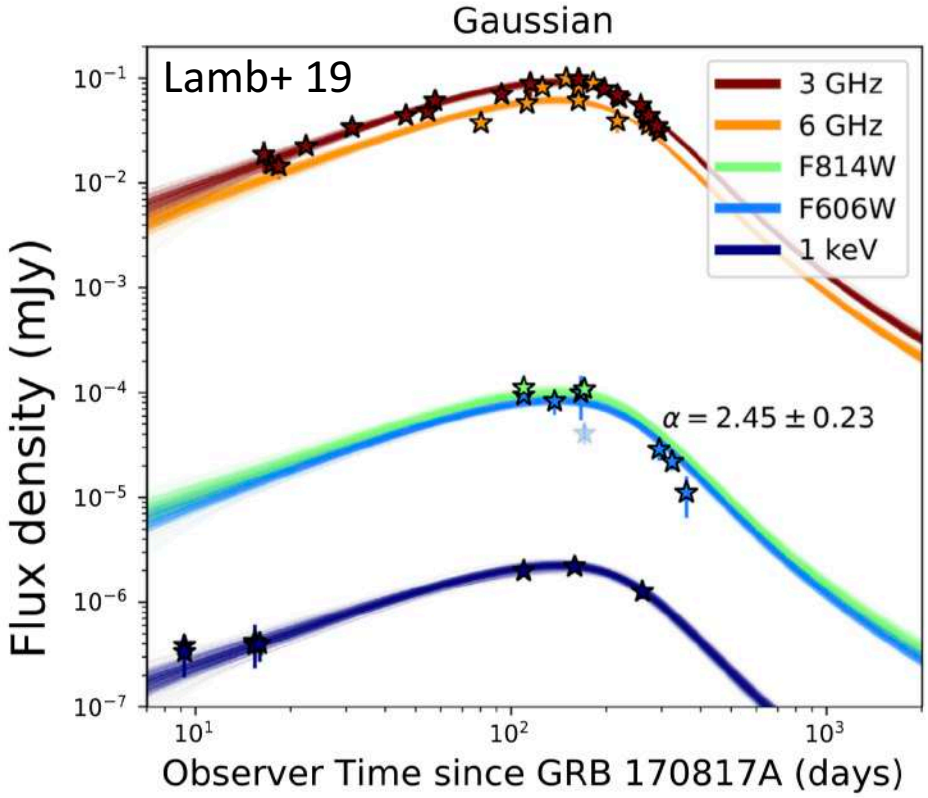


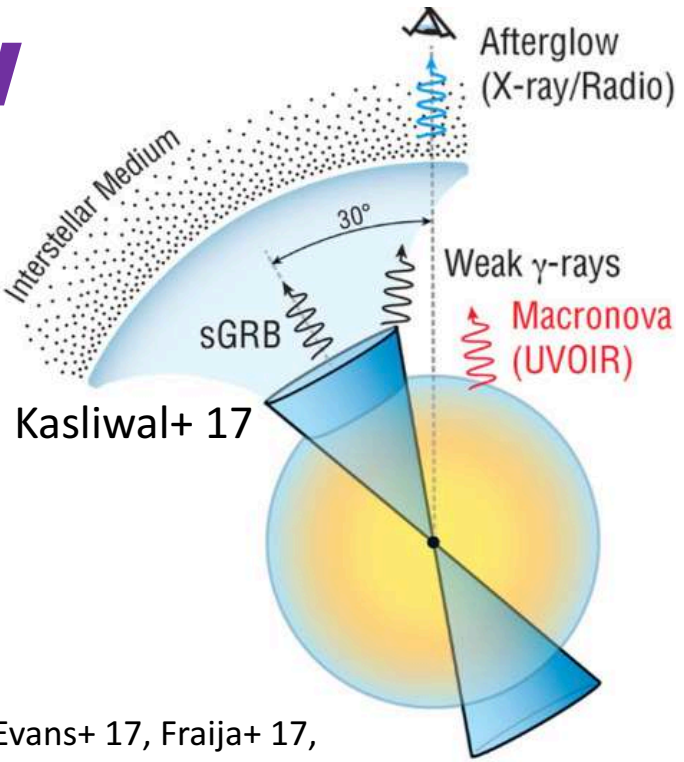

GRB 170817A
Kilonova/
Macronova
Afterglow
↓
・Mass ejection
(~ 0.01 - 0.1 Msun)
・r-process
nucleosynthesis
・Diversity?
X-ray
Optical
Radio
Luminosity [ erg s-1 ]
10^52
10^50
10^48
10^46
10^44
10^42
10^40
10^38
10^36
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Observer time [ s ]

# Afterglow

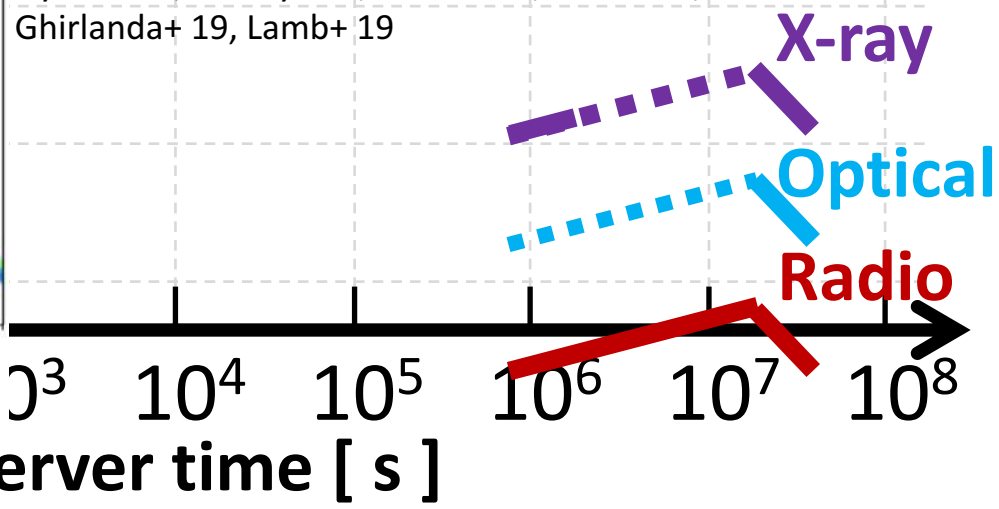
**The synchrotron emission arising from the interaction of an outflow with the surrounding ISM.**



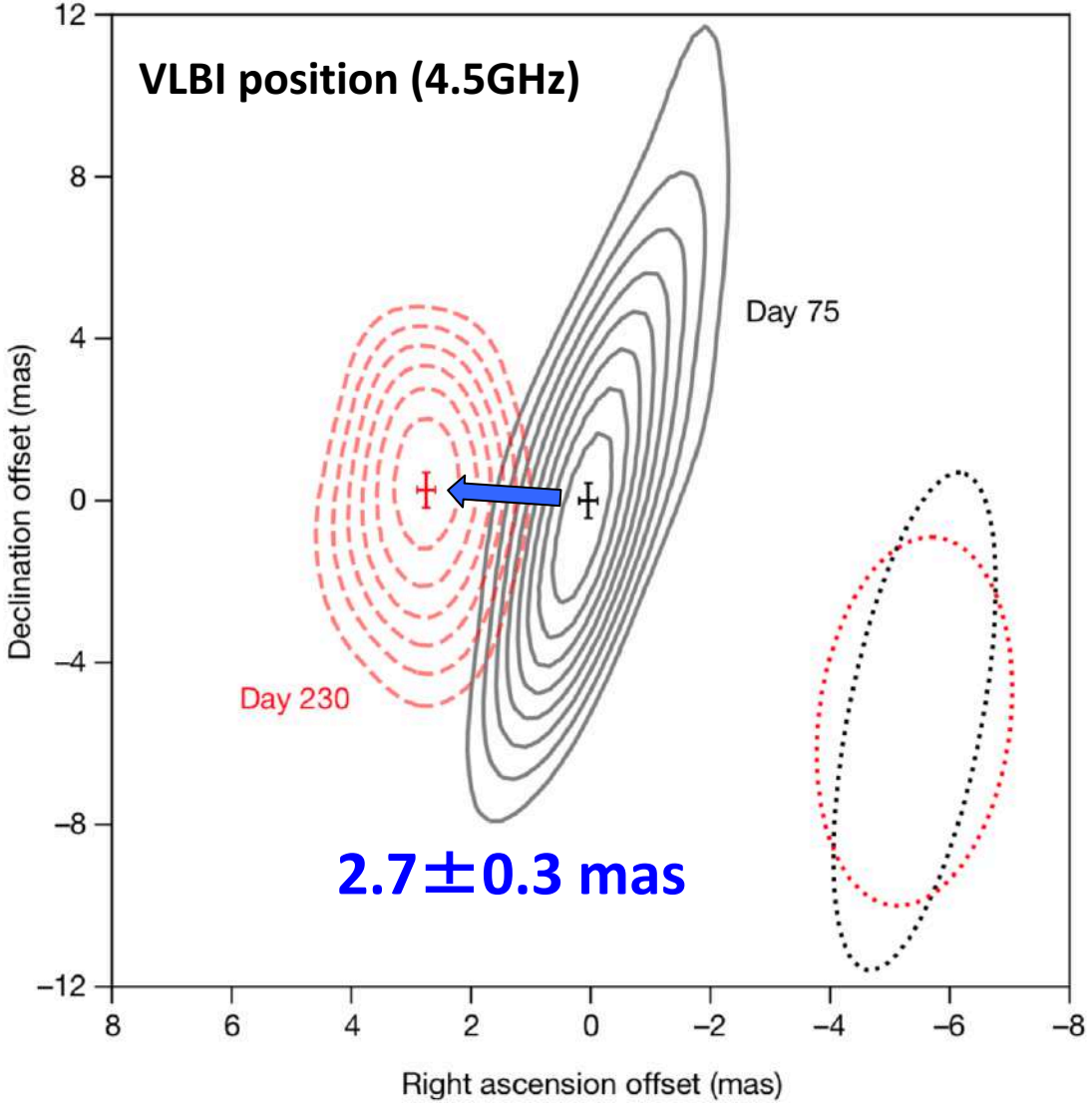

Alexander+ 17, 18, Evans+ 17, Fraija+ 17, Haggard+ 17, Hallinan+ 17, Kim+ 17, Margutti+ 17, 18, Troja+ 17,18, D'Avanzo+ 18, Dobie+ 18, Lyman+ 18, Mooley+ 18a, 18b, Nynka+ 18, Pooley+ 18, Resmi+ 18, Ruan+ 18, Ghirlanda+ 19, Lamb+ 19



# Relativistic jet in GW170817

## Superluminal motion = relativistic collimated jet

Jet opening angle < viewing angle → off-axis event

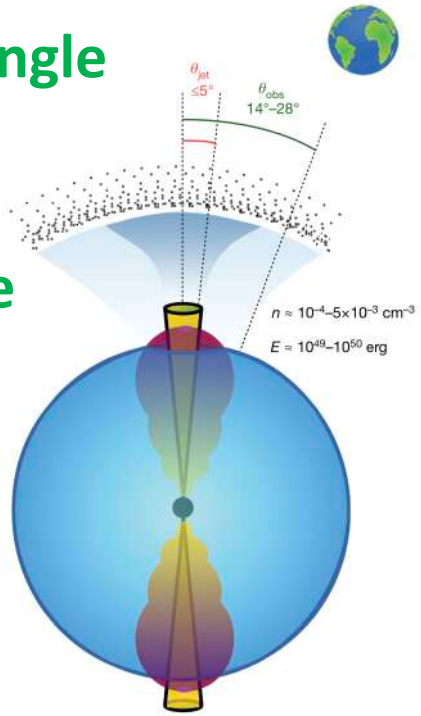



- **Unresolved source**
- **Apparent velocity**

  $\beta_{app} = 4.1 \pm 0.5 \rightarrow \Gamma \sim 4$
- **Jet opening angle**

  $\theta_j \leq 5^\circ$
- **Viewing angle**

  $\theta_v \sim 20^\circ$




Mooley+ 18a
Ghirlanda+ 19

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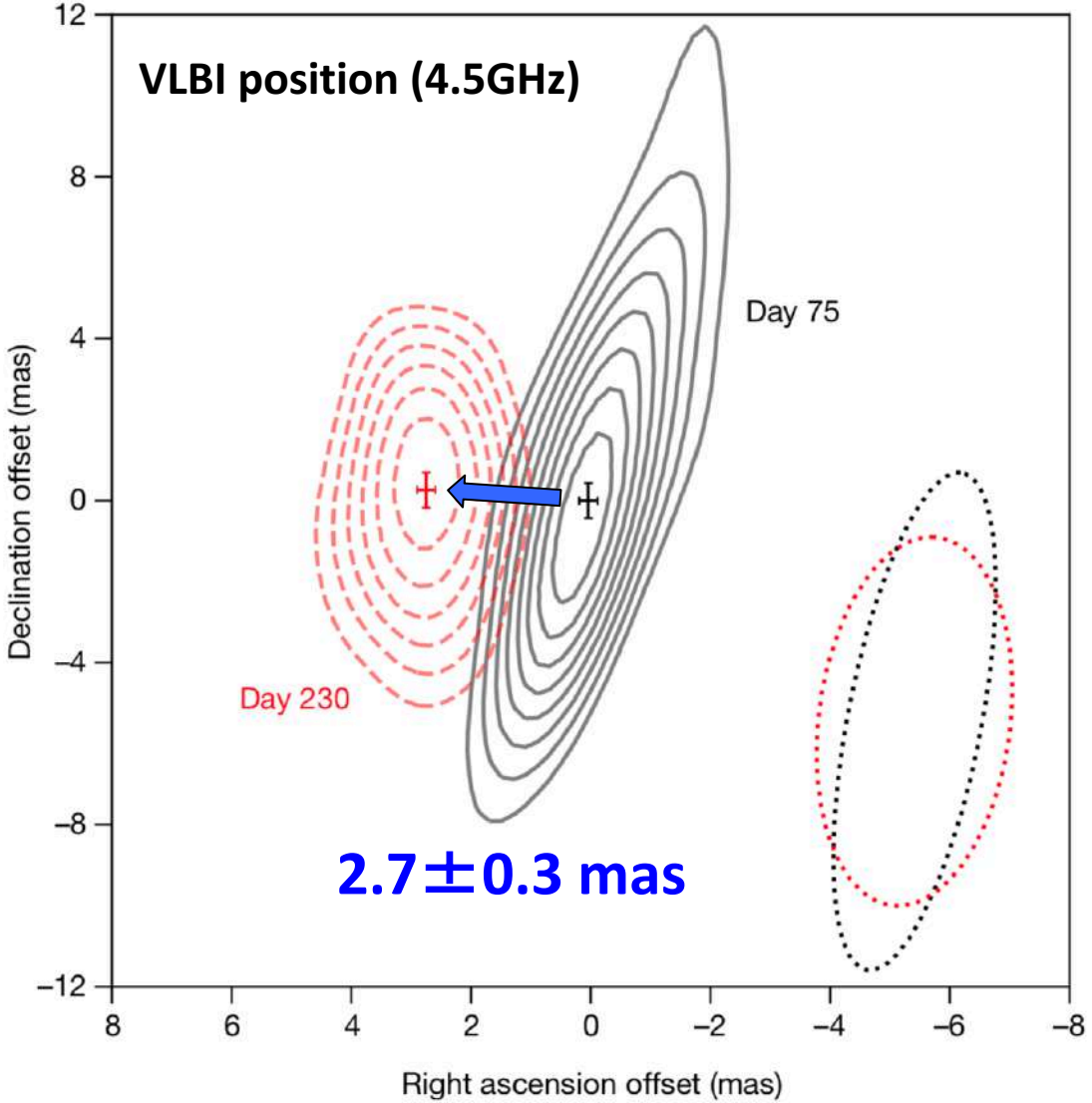
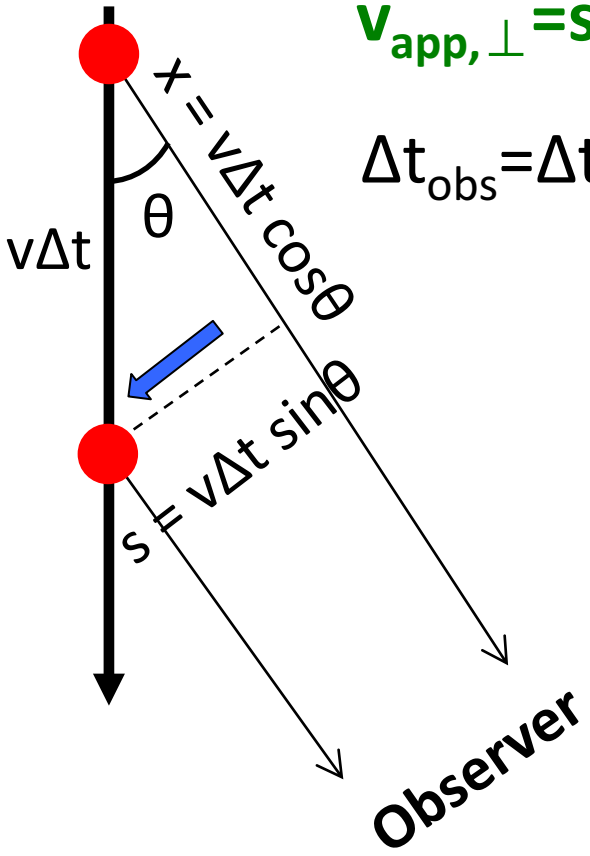



$v_{app,\perp} = s/\Delta t_{obs}$

$\Delta t_{obs} = \Delta t - x/c$

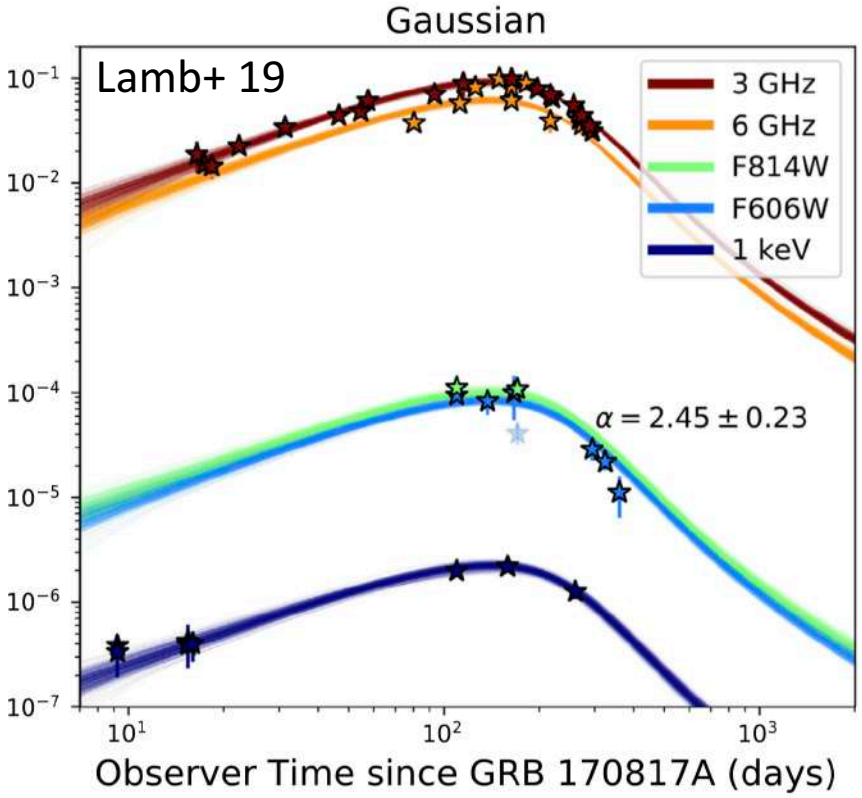
Mooley+ 18a
Ghirlanda+ 19

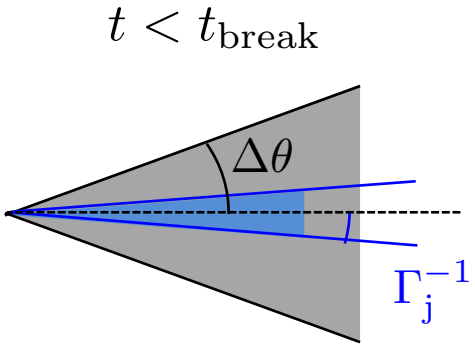
# Jet Break

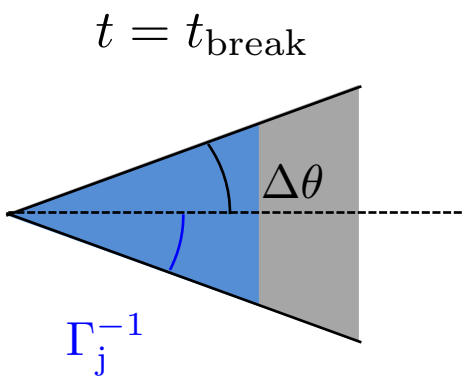
エネルギーが
Consistentで

**Jet break time** $\Gamma_{\rm j}^{-1} \sim \Delta\theta$

$$t_{\rm break} \sim 230\ {\rm day} \left(\frac{\Delta\theta}{20^\circ}\right)^{8/3} \left(\frac{E_{\rm iso}/\epsilon_\gamma}{3\times10^{52}{\rm erg}}\right)^{1/3} \left(\frac{n_{\rm ism}}{10^{-4}{\rm cm}^{-3}}\right)^{-1/3}$$



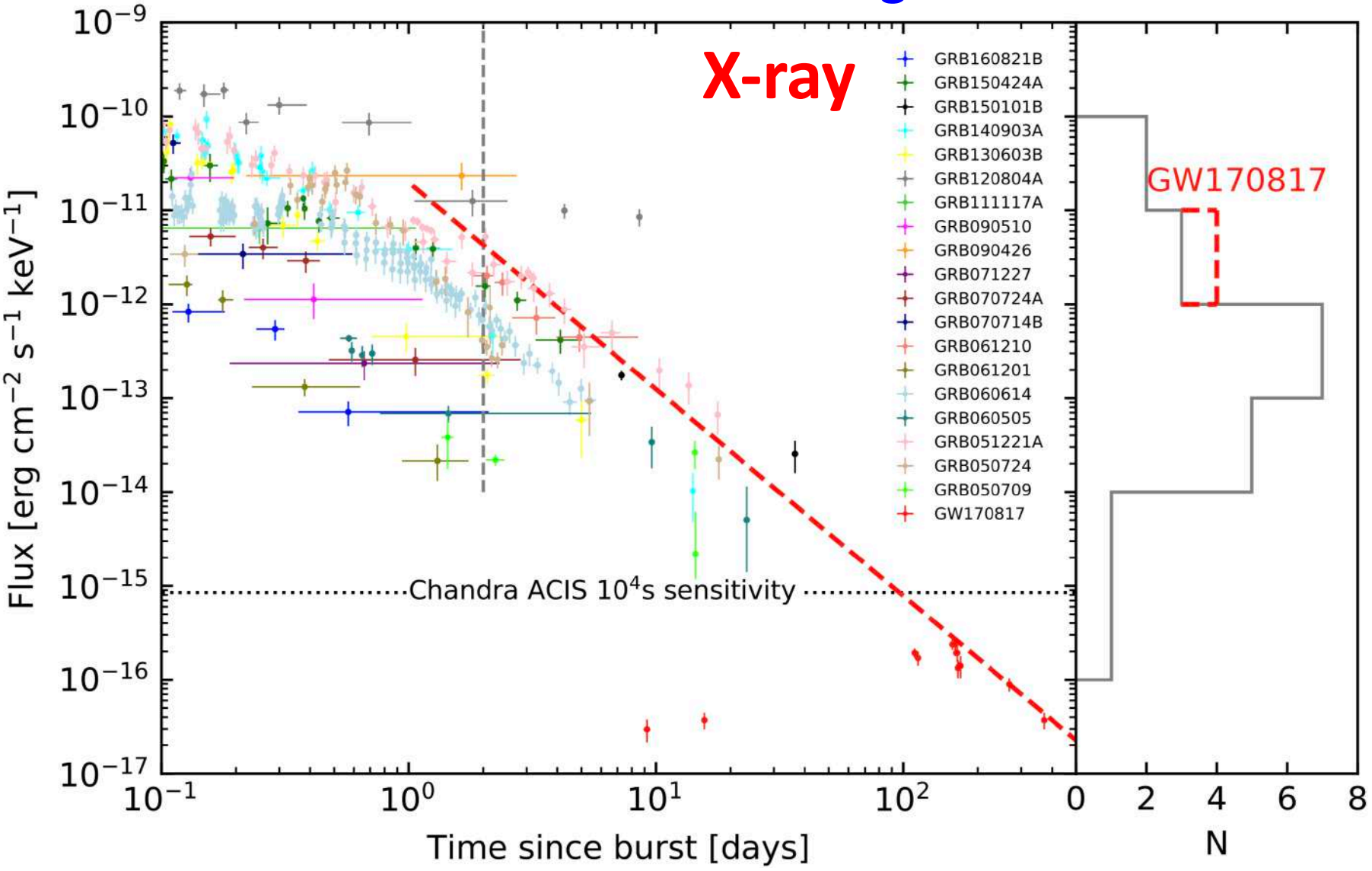



# GRB 170817A afterglow

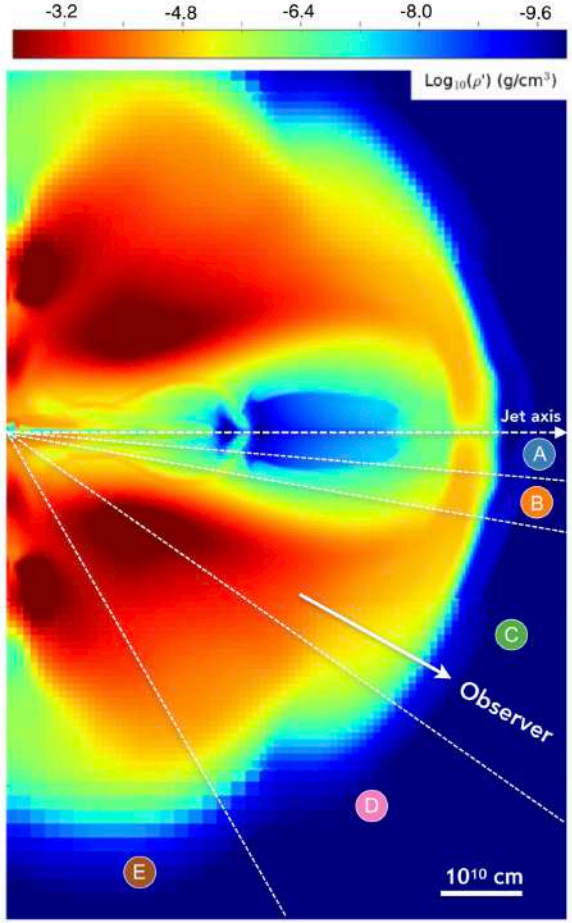
**The decaying curve is consistent with other short GRB afterglows.**

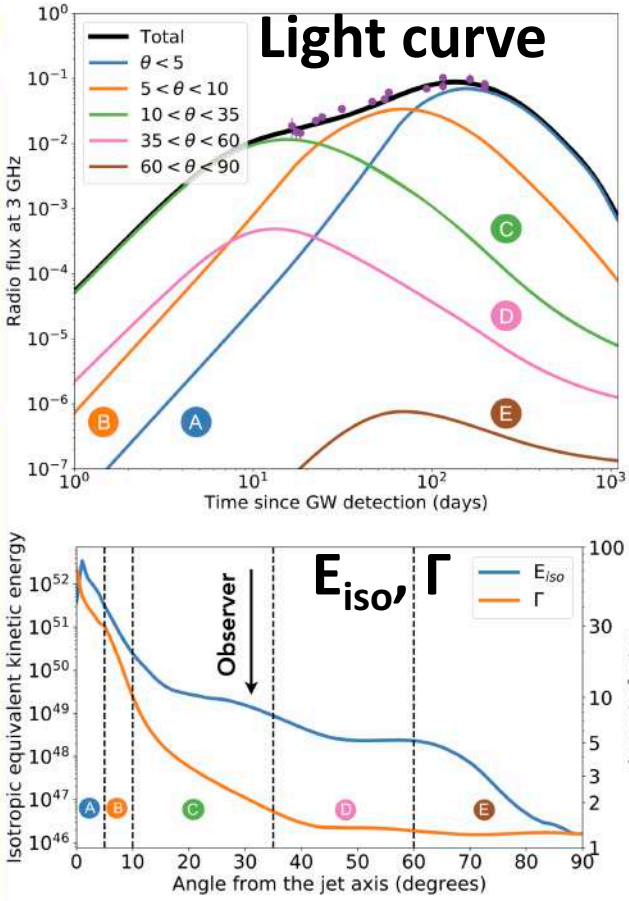
Duan+ 19



# Relativistic jet in GW170817

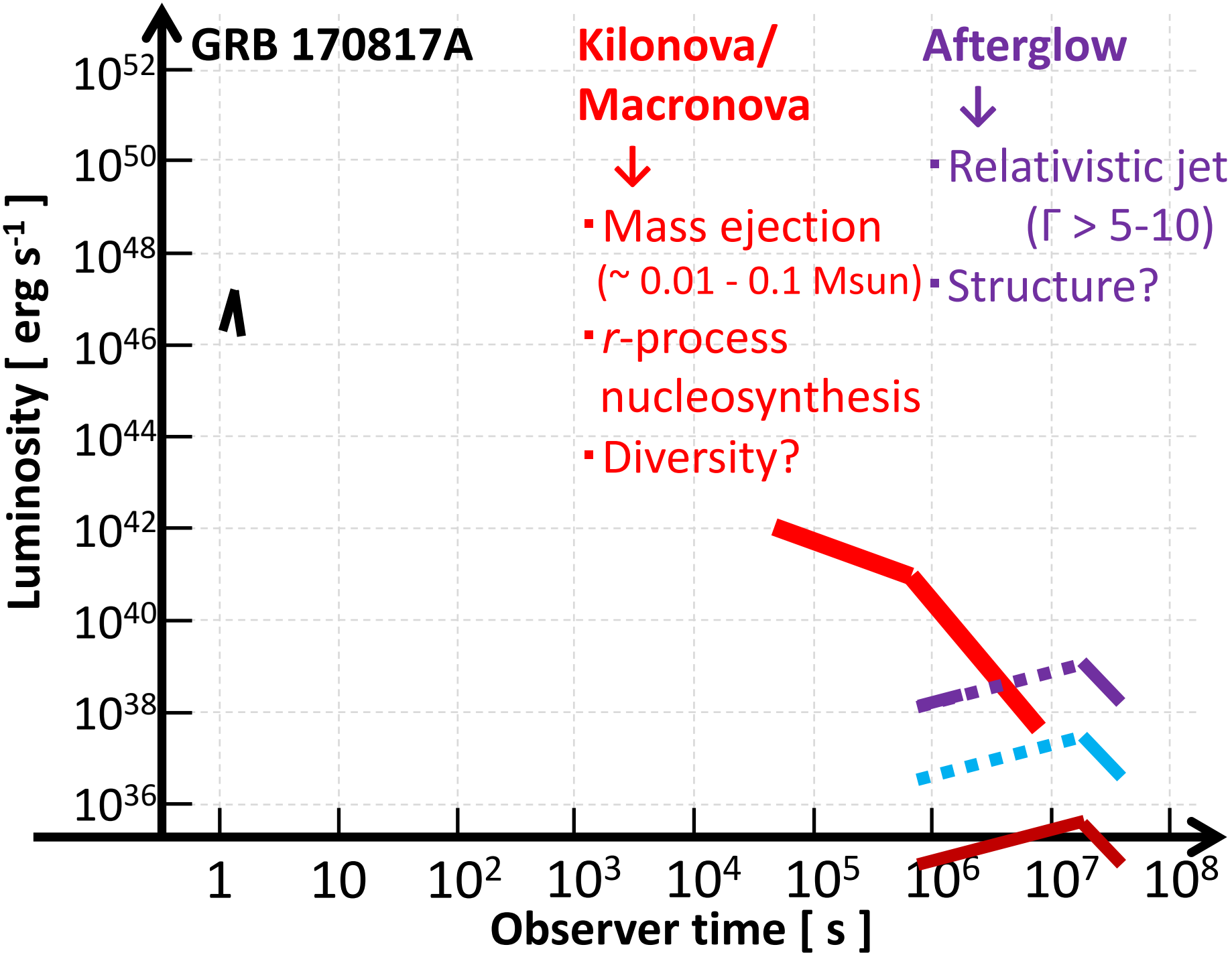
## Jet with a specific structure can reproduce the light curve.




Lazzati+ 18

- **Light curve**
  $F_\nu \propto t^{0.8}$ $(t < t_{break})$
  $F_\nu \propto t^{-2.2}$ $(t < t_{break})$
- **Break time**
  $t_{break} \sim 160$ day
- **Isotropic kinetic energy**
  $\sim 10^{51} - 10^{53}$ erg
- **Bulk Lorentz factor**
  $> 5$-$10$
- **Ambient density**
  $\sim 10^{-2} - 10^{-4}$ cm$^{-3}$


GRB 170817A
Kilonova/
Macronova
Afterglow
Relativistic jet
(Γ > 5-10)
Mass ejection
(~ 0.01 - 0.1 Msun)
Structure?
r-process
nucleosynthesis
Diversity?
Luminosity [ erg s-1 ]
10^52
10^50
10^48
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10^44
10^42
10^40
10^38
10^36
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Observer time [ s ]

# GRB 170817A

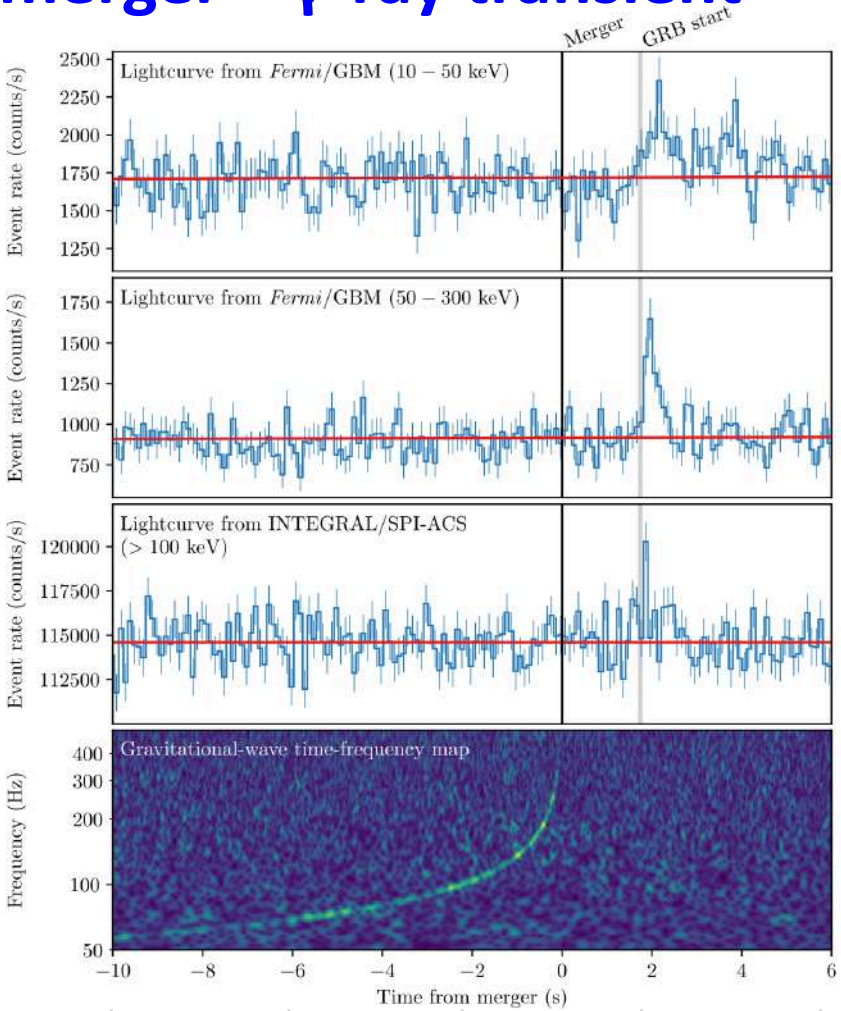
**NS merger = γ-ray transient**

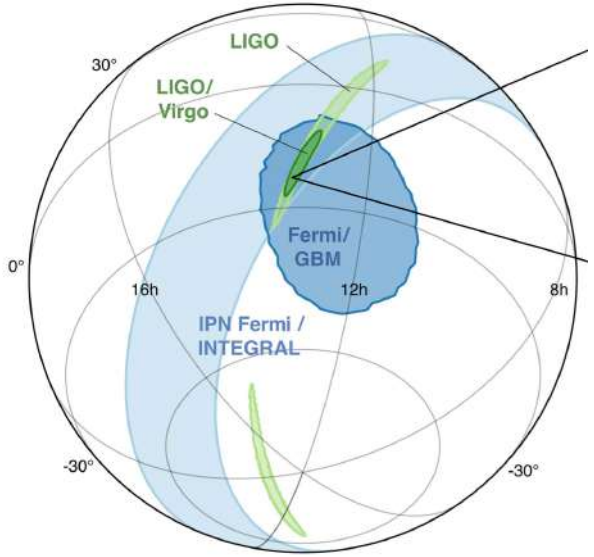
$T_{dur}$ : ~ 2 s

$T_{delay}$ : ~ 1.7 s

$E_{\gamma,\,iso}$ : ~ $5 \times 10^{46}$ erg

$E_p$ : ~ $185 \pm 62$ keV



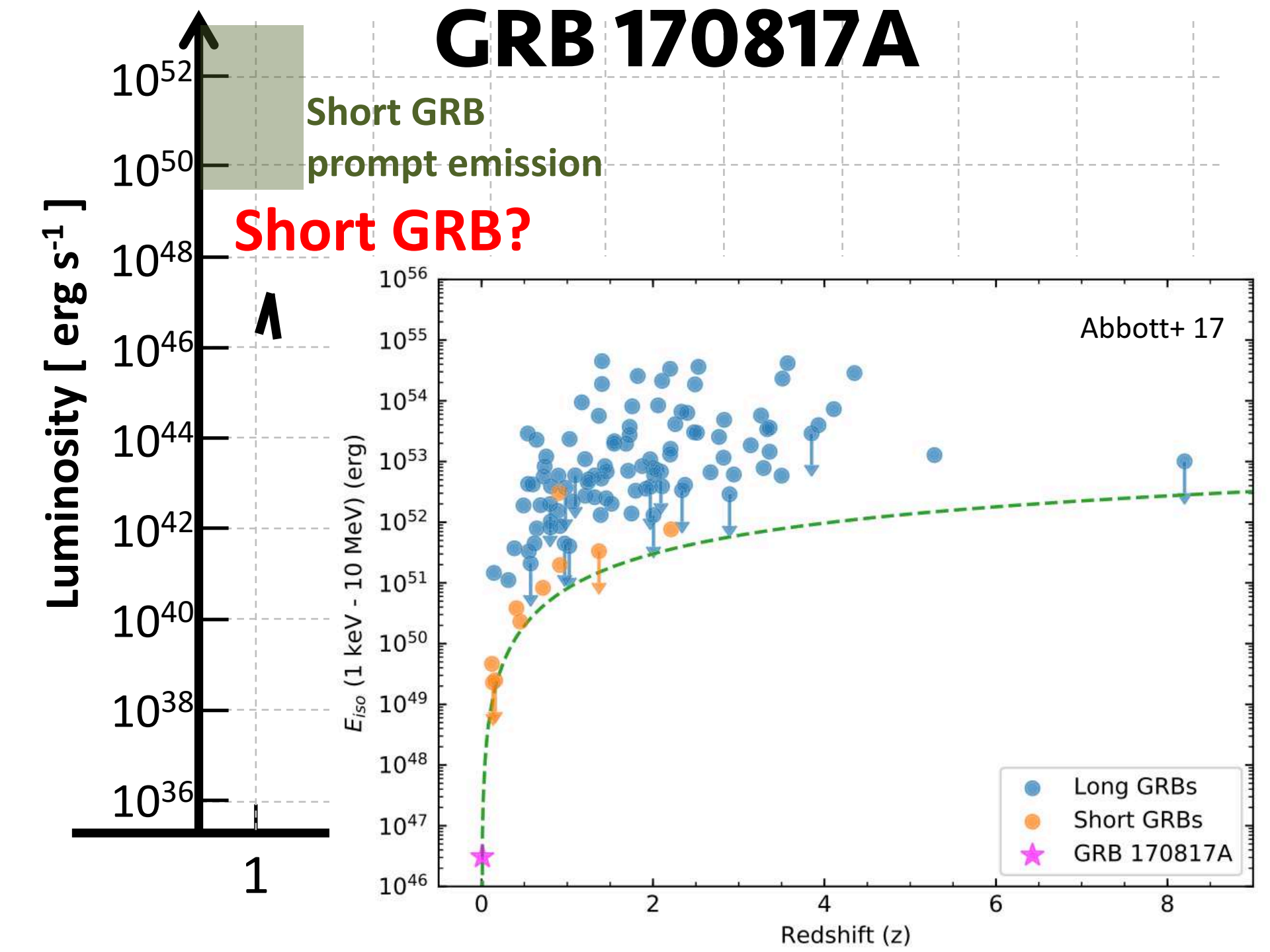

Luminosity [ erg $s^{-1}$ ]

$10^{52}$ $10^{50}$ $10^{48}$ $10^{46}$ $10^{44}$ $10^{42}$ $10^{40}$ $10^{38}$ $10^{36}$

1 10 $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$

Observer time [ s ]

# GRB 170817A


Short GRB
prompt emission
Short GRB?
Luminosity [ erg s$^{-1}$ ]
$10^{52}$
$10^{50}$
$10^{48}$
$10^{46}$
$10^{44}$
$10^{42}$
$10^{40}$
$10^{38}$
$10^{36}$
1
Abbott+ 17
$E_{iso}$ (1 keV - 10 MeV) (erg)
$10^{56}$
$10^{55}$
$10^{54}$
$10^{53}$
$10^{52}$
$10^{51}$
$10^{50}$
$10^{49}$
$10^{48}$
$10^{47}$
$10^{46}$
0
2
4
6
8
Redshift (z)
Long GRBs
Short GRBs
GRB 170817A

# GW170817/GRB 170817A/SSS17a

**NS merger :**

- **Mass ejection**

  ($M_{ej}$ ~ 0.01 - 0.1 $M_{sun}$, $v_{ej}$ ~ 0.1 - 0.3 c)

- ***r*-process nucleosynthesis**

  ($<X_{lan}>$ ~ 0.01)

- **Relativistic jet**

  ($\theta_{jet}$ ~ 5°, $\Gamma$ > 5 - 10, $E_{iso}$ ~ $10^{51}$ - $10^{53}$ erg)

- **Off-axis γ-ray emission**

  ($E_{iso,\gamma}$ ~ $10^{46}$ - $10^{47}$ erg, $E_p$ ~ 200 keV, $T_{dur}$ ~ $T_{delay}$ ~ 2 sec)

**Open questions :**

- Diversity of macronovae?
- Origin of off-axis γ-ray emission?
- Jet structure?

# GW170817/GRB 170817A/SSS17a

**NS merger :**

- **Mass ejection**

  ($M_{ej}$ ~ 0.01 - 0.1 $M_{sun}$, $v_{ej}$ ~ 0.1 - 0.3 c)

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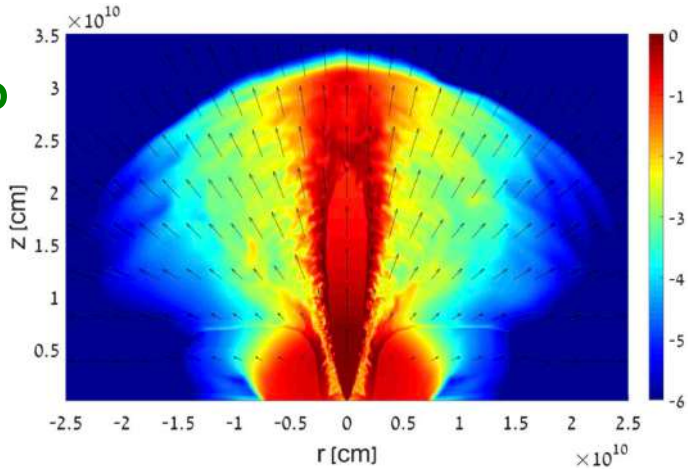
**Open questions : → Jet-ejecta interaction**

- Diversity of macronovae?
- Origin of off-axis γ-ray emission?
- Jet structure?




Gottlieb+ 18

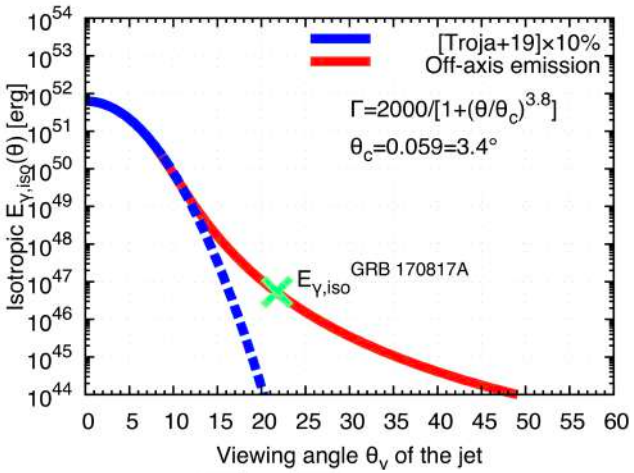
# GRB 170817A γ-ray emission model

**Energy density  Four-velocity**

- **Cocoon shock breakout**

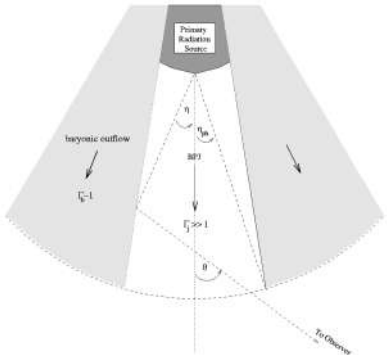
  Kasliwal+ 17, Gottlieb+ 17, Bromberg+ 17

http://www.astro.tau.ac.il/~ore/nakar-jets.html




- **Short GRB off-axis emission**

  Ioka & Nakamura 01, 18, 19, Murguia-Berthier+ 17b, Abbott+ 17, Kim+17, Lamb & Kobayashi 17, Granot+ 17



- **Scattered short GRB**

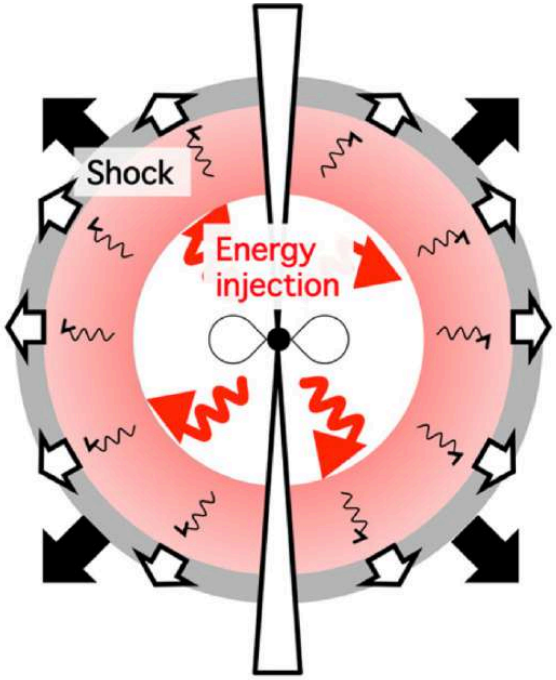
  SK, Ioka, Kashiyama & Nakamura 18

Eichler & Levinson 99

# Engine-powered macronova

Relativistic jet could heat the ejecta due to the jet-ejecta interaction.

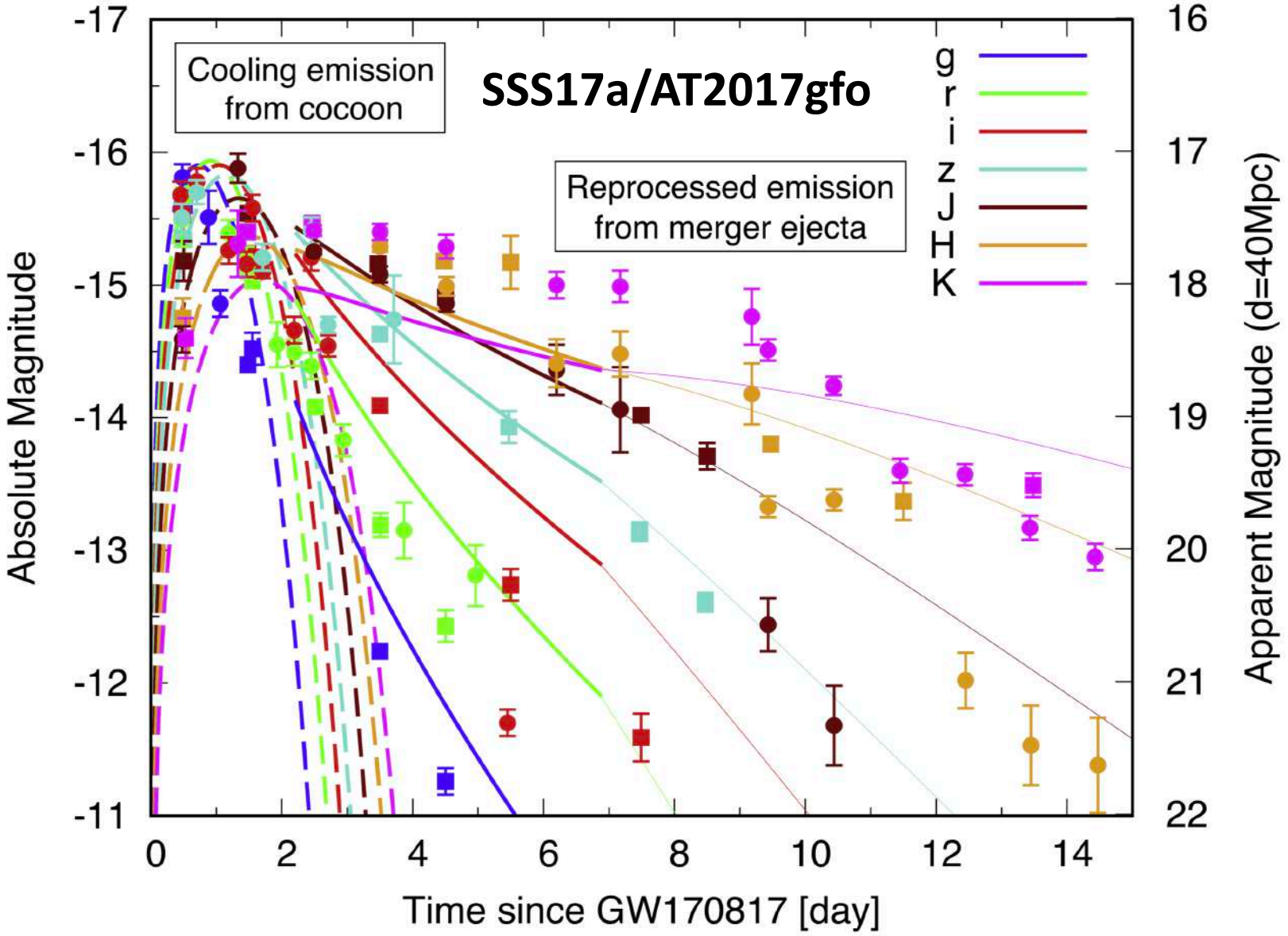
→ **Diversity?**



# Engine-powered macronova

Matsumoto, Ioka, SK & Nakar 18

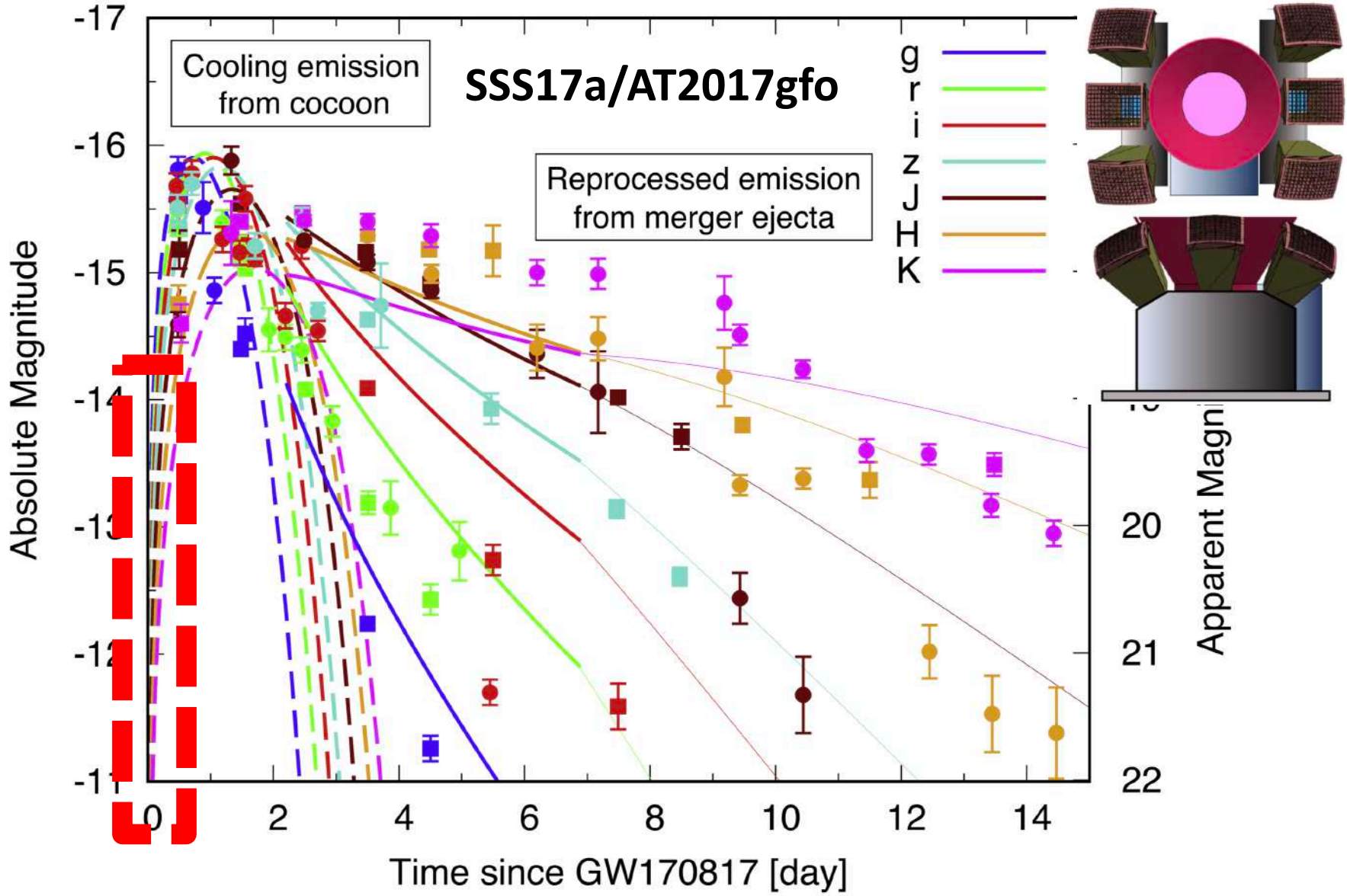
## Engine-powered model can reproduce the light curve.



# Engine-powered macronova

Matsumoto, Ioka, SK & Nakar 18

## HiZ-GUNDAM 22mag (2.0-2.5μm) ($10^4$ s)



# Summary

**NS merger :**

- **Off-axis γ-ray emission**

  ($\theta_{obs}$ ~ 20° ~ 4$\theta_{jet}$, $E_{iso,\gamma}$ ~ $10^{46}$ - $10^{47}$ erg, $E_p$ ~ 200 keV, $T_{dur}$ ~ $T_{delay}$ ~ 2 sec)

- **Mass ejection**

  ($M_{ej}$ ~ 0.01 - 0.1 $M_{sun}$, $v_{ej}$ ~ 0.1 - 0.3 c)

- ***r*-process nucleosynthesis**

  ($<X_{lan}>$ ~ 0.01)

- **Relativistic jet**

  ($\Gamma$ > 5 - 10, $E_{iso}$ ~ $10^{51}$ - $10^{53}$ erg)

**Open questions :** → **Jet-ejecta interaction**

- Origin of off-axis γ-ray emission?
- Jet structure?
- Diversity of macronovae?

**Because of large uncertainties and varieties of the central engine activities, the energy deposition rate and opacity are required to distinguish the energy sources.**