ショートガンマ線バースト

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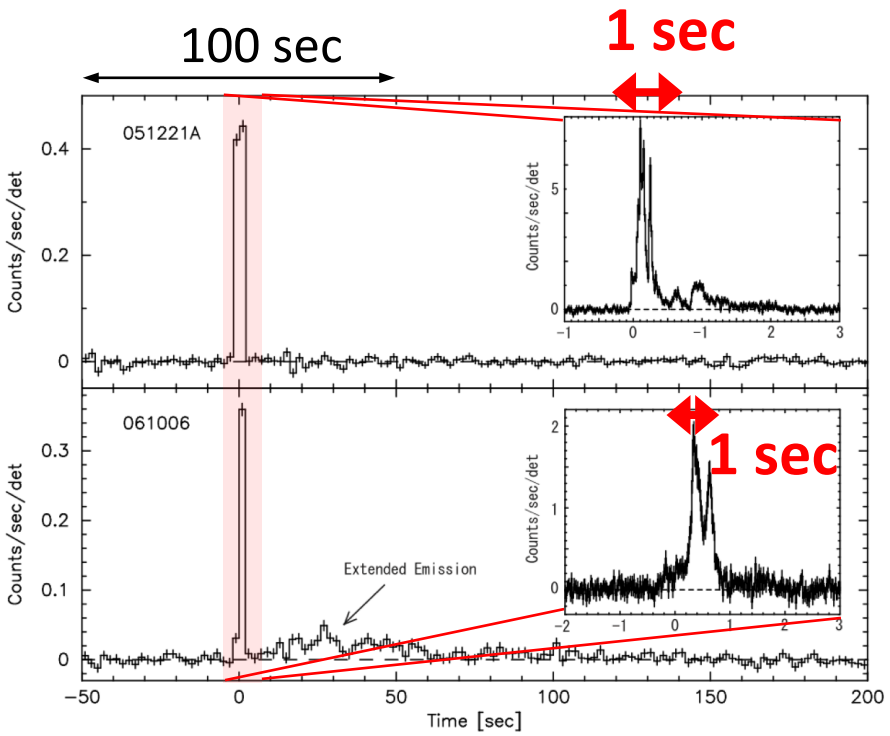
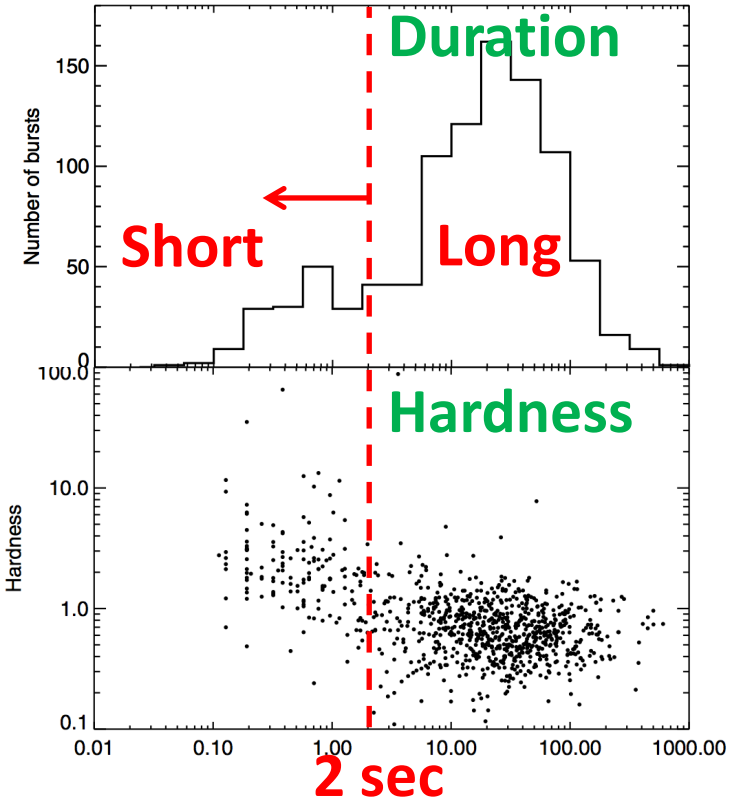
Short Gamma-ray Bursts

- 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)

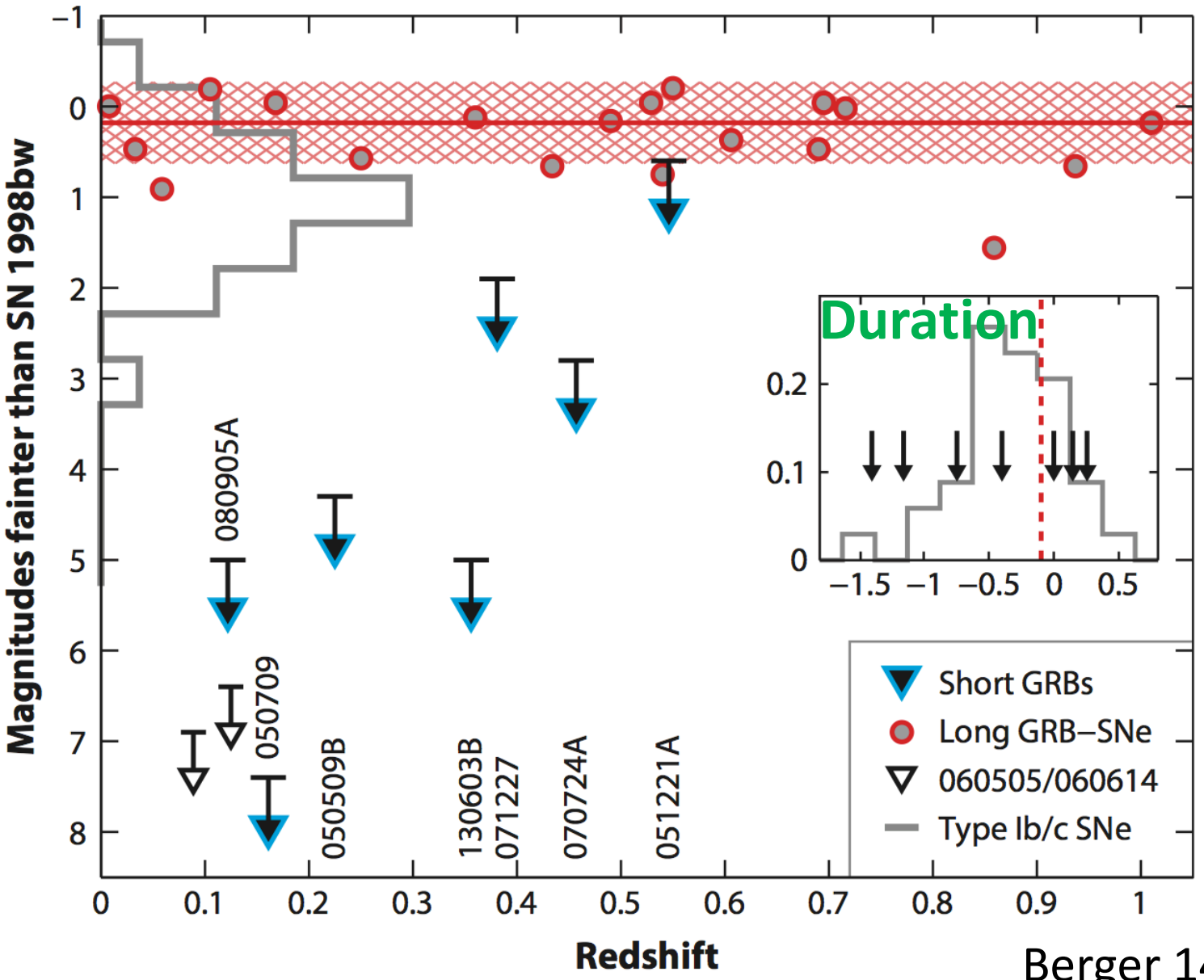


Norris & Bonnell 06

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



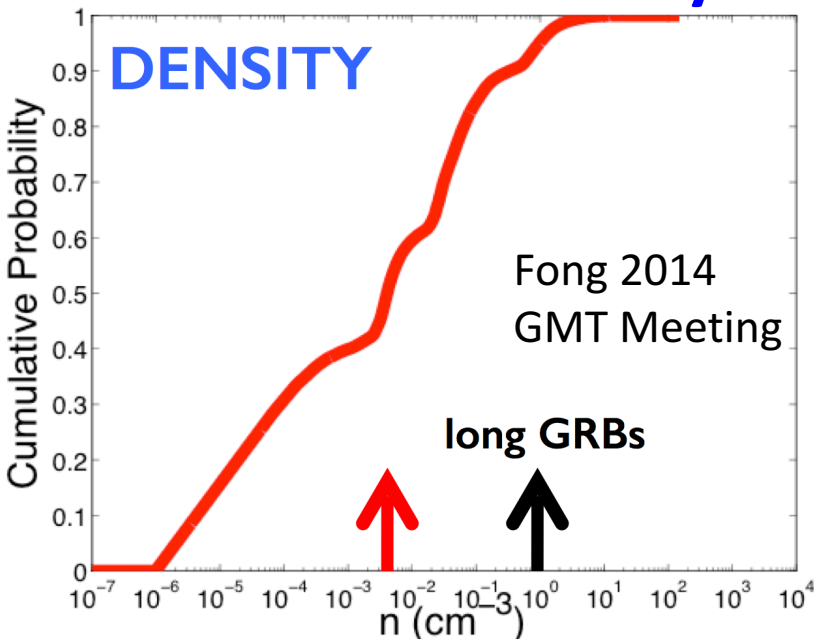
Lack of supernova association



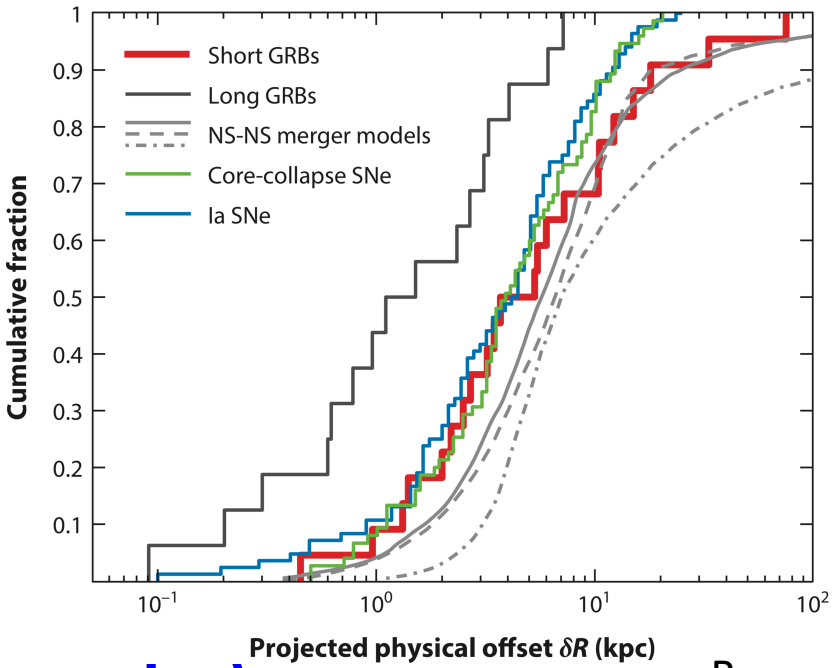
Berger 14

Environments

Circumburst density

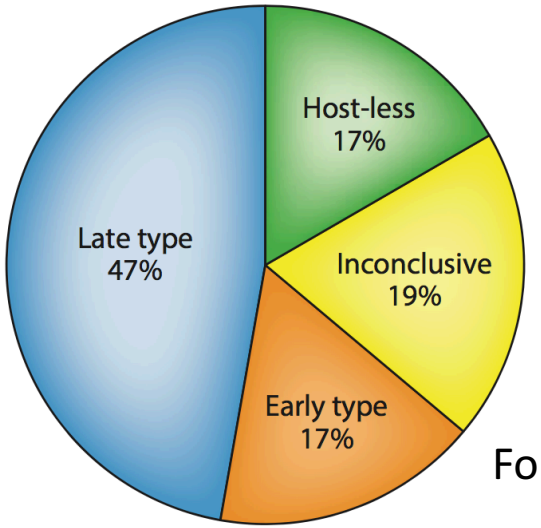


Offset distribution



Berger 14

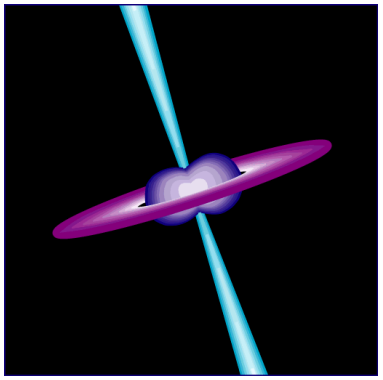
Host galaxy (36 samples)



Fong+ 13

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

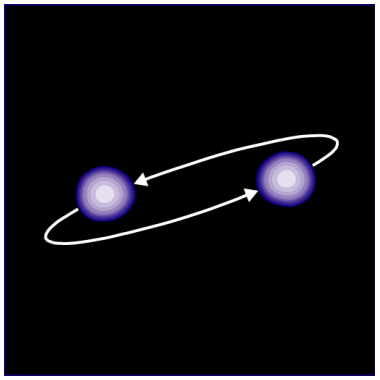
Wide variety of the hosts

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

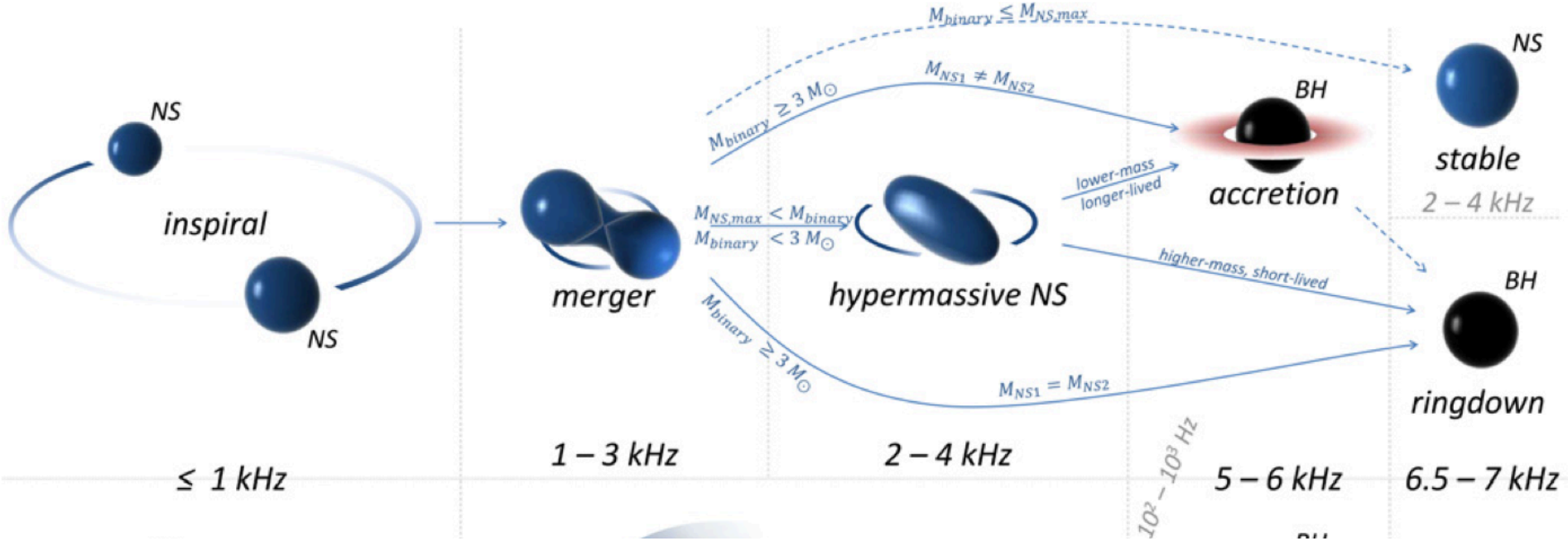
~ 0.1 - 10 Gyr

Post-merger activities

- NS or BH formation
- Relativistic jet launching
- Mass ejection
- Fallback
- Accretion and wind
- Magnetic field amplification
- *r*-process nucleosynthesis

BH or NS formation

Bartos+ 13



$M < M_{max}$: Stable NS

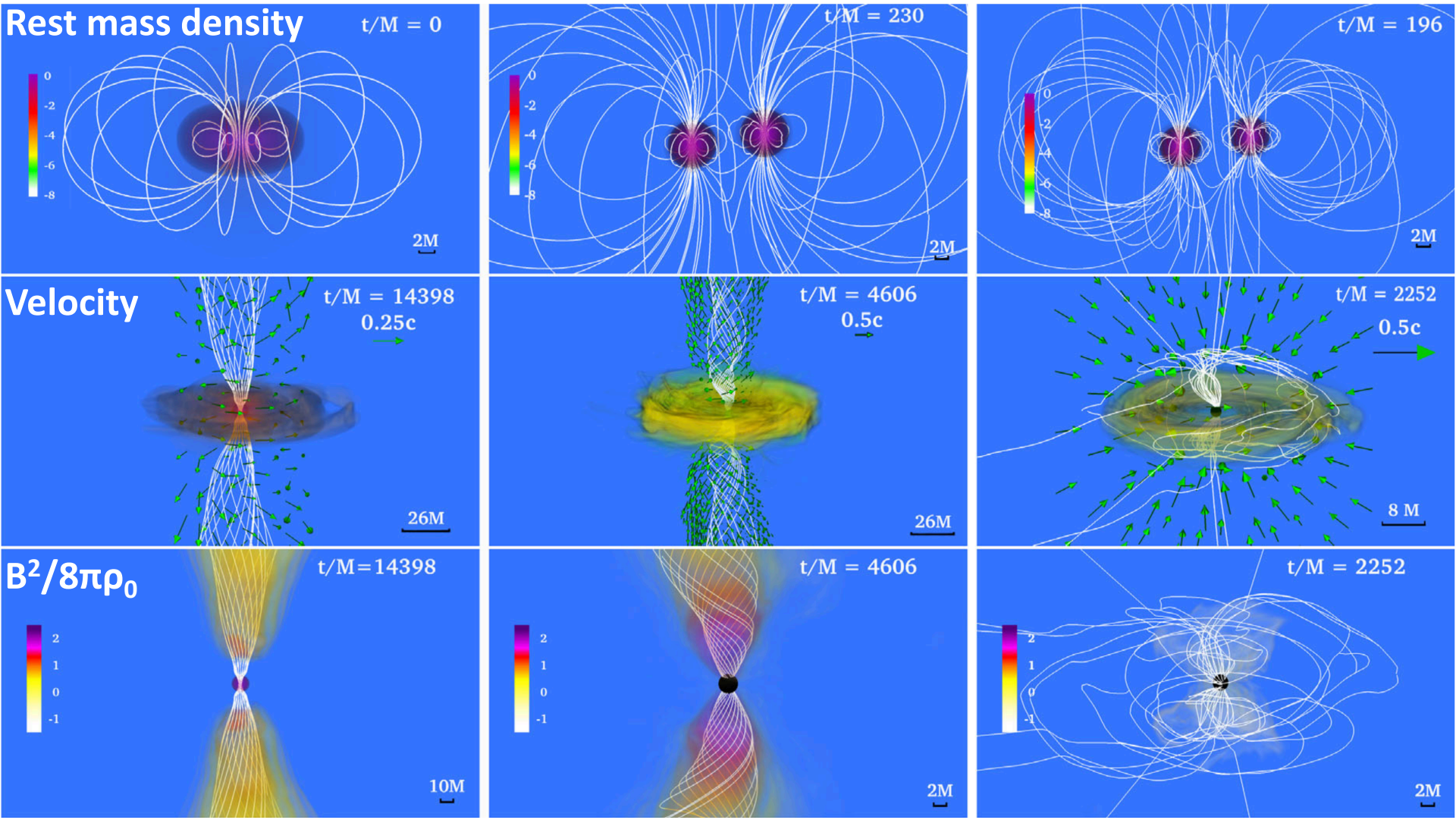
$M_{max} < M < kM_{max}$: HMNS → BH (or BH + disk)

$M > kM_{max}$: BH

$1.4 < k < 1.7$ Hotokezaka+ 11

Relativistic jet launching

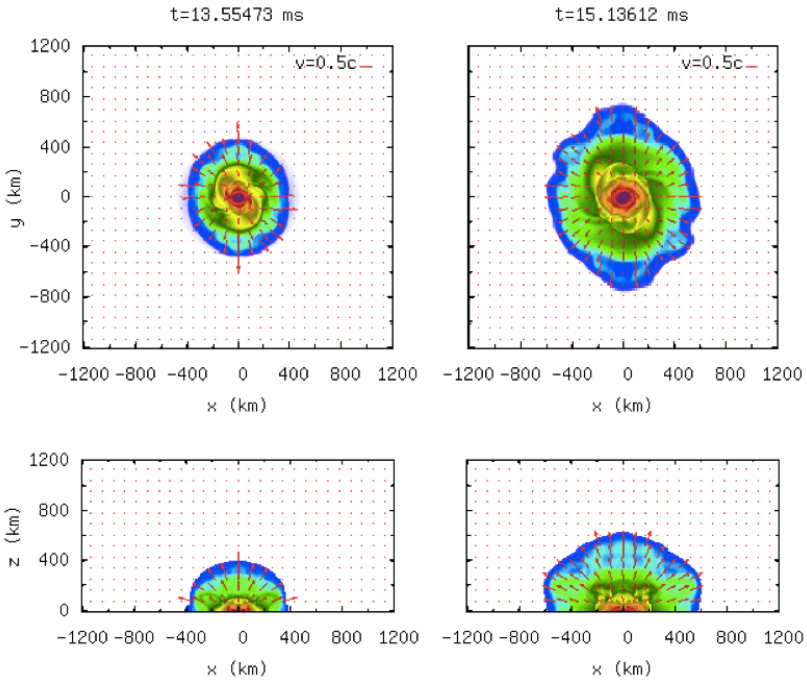
Ruiz+ 18



$L \sim 10^{51}$ erg s^{-1}

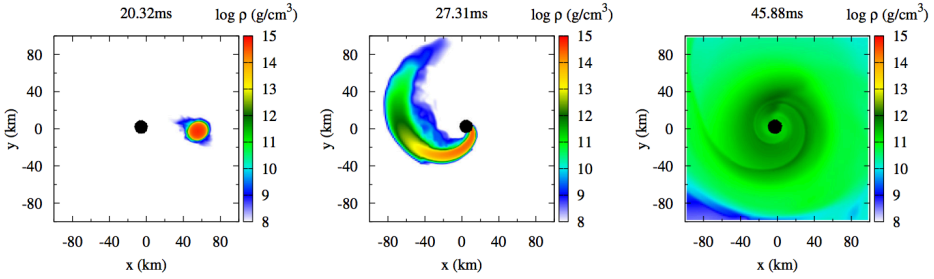
Mass ejection (dynamical ejecta)

NS-NS binary merger



Hotokezaka+ 13

BH-NS binary merger



Kyutoku+ 15

Bounded mass

$$M_{\rm d} \sim 10^{-1} M_\odot$$

Ejecta mass

NS-NS: $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_\odot$

BH-NS: $M_{\rm ej} \lesssim 10^{-1} M_\odot$

Ejecta velocity

$$v_{\rm ej} \sim 0.1 - 0.3c$$

Fallback

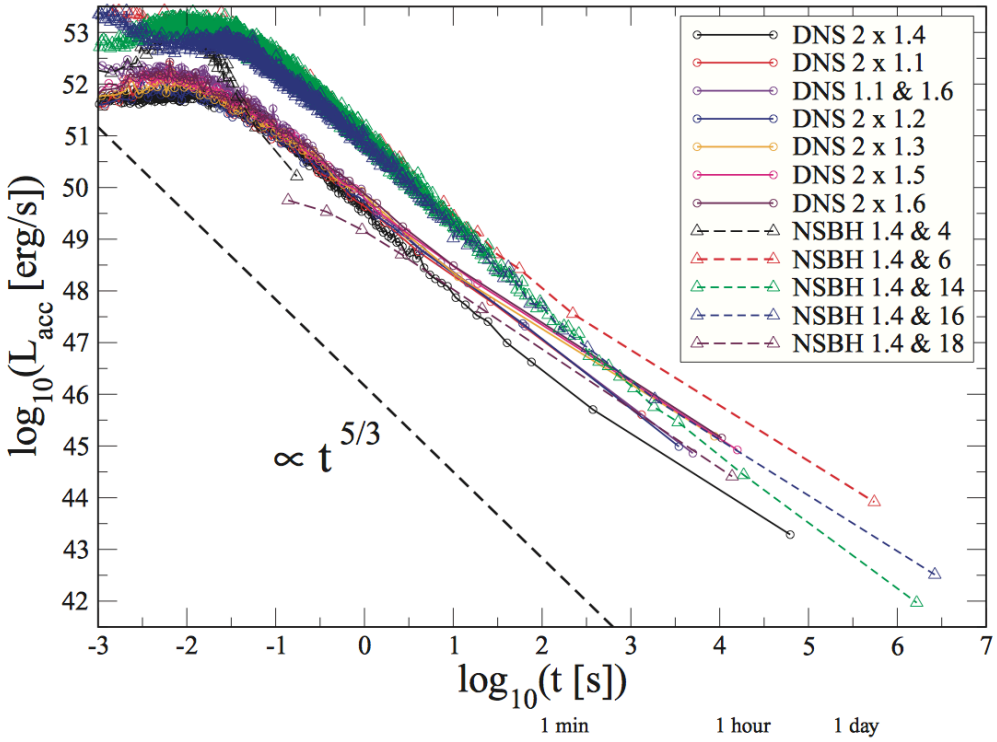
- **Free-fall timescale**

$$t_{\rm ff} = \frac{1}{\sqrt{G\rho}} \sim 10^{-4}{\rm s}\ M_{0.5}^{-1/2} r_6^{3/2}$$

r_d : disk radius
H: scale height

- **Accretion timescale**

$$t_{\rm acc} \sim \frac{t_{\rm ff}}{\alpha}\left(\frac{r_{\rm d}}{H}\right)^2 \sim 10\ {\rm s}\ \alpha_{-2}^{-1} M_{0.5}^{-1/2} r_{\rm d,7}^{3/2} \left(\frac{H}{r_{\rm d}}\right)_{-1}^{-2}$$



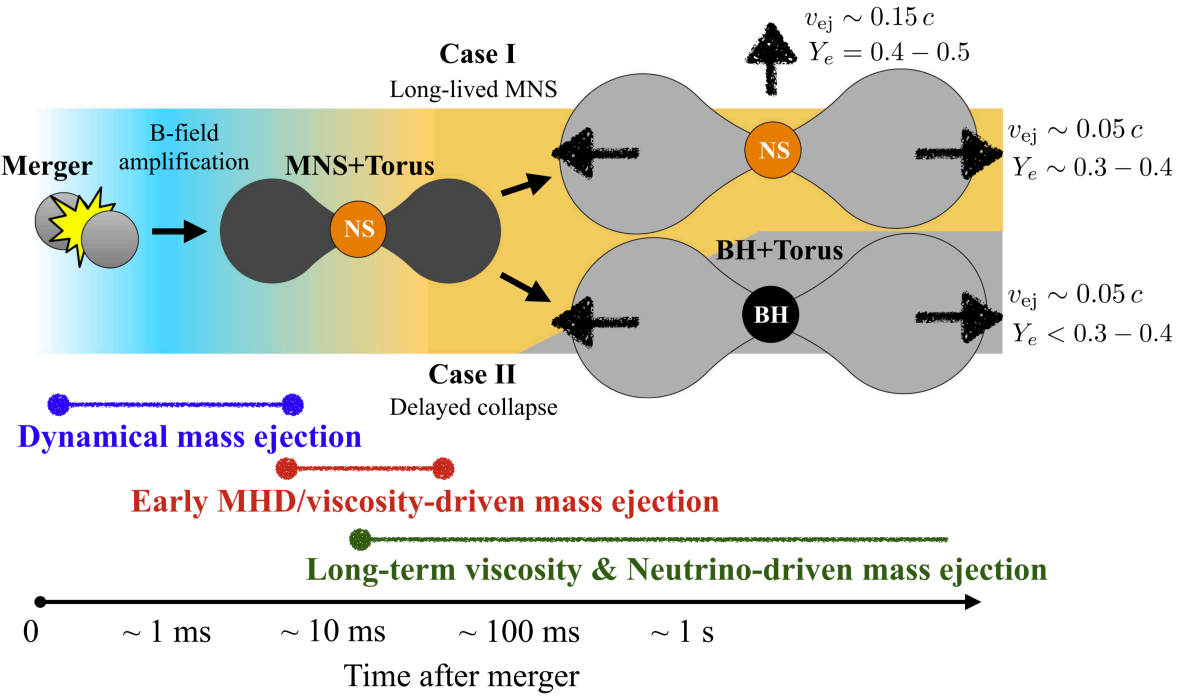
Rosswog 07

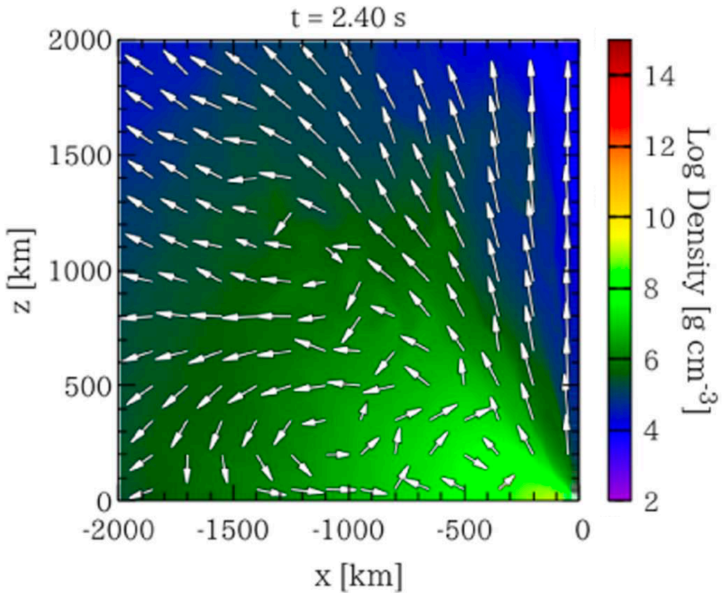
Accretion and wind (viscous ejecta)

Properties of 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

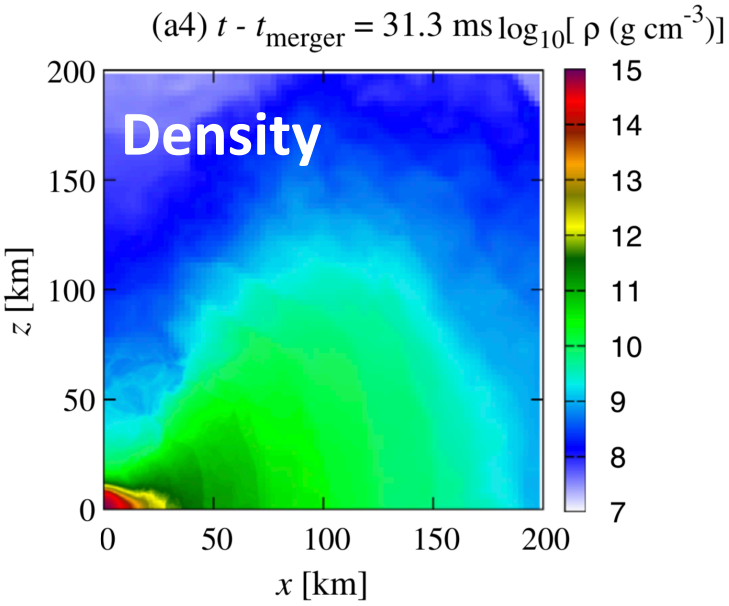


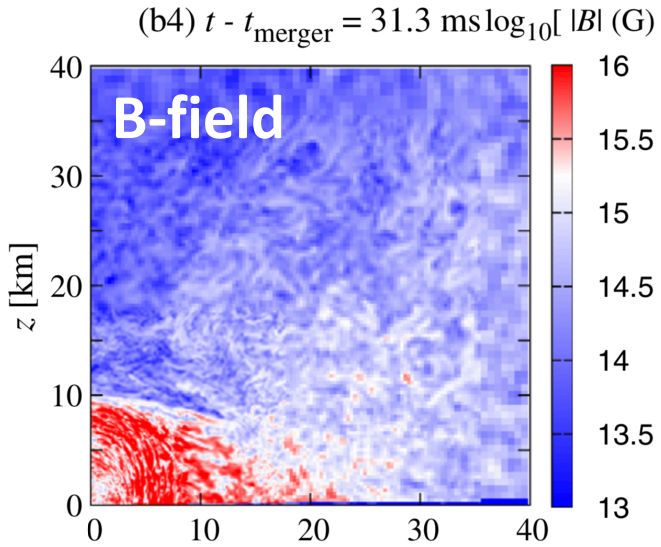


$$M_{\rm acc} \sim M_{\rm wind} \sim 0.01 - 0.1 M_\odot$$

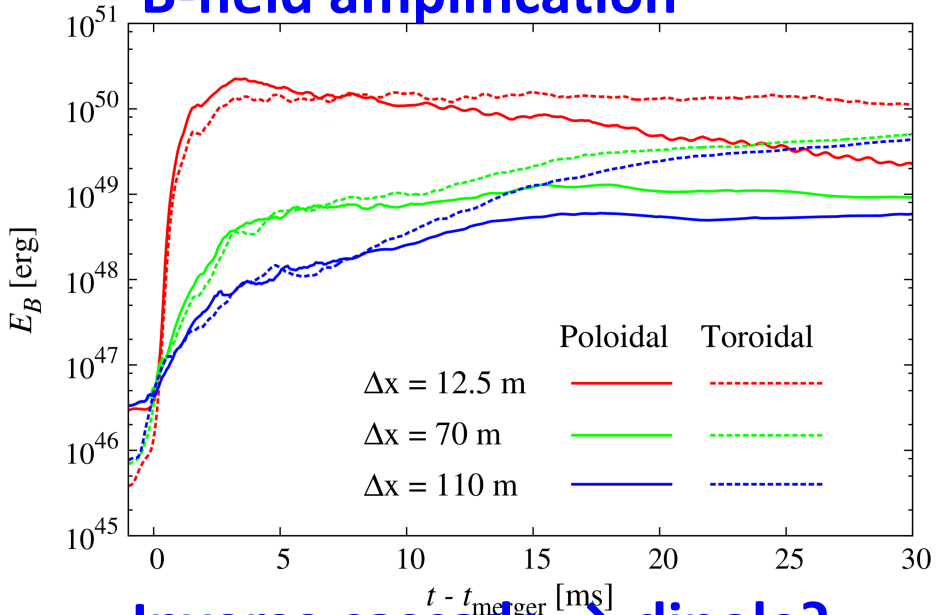
Magnetic field amplification

Kiuchi+ 18

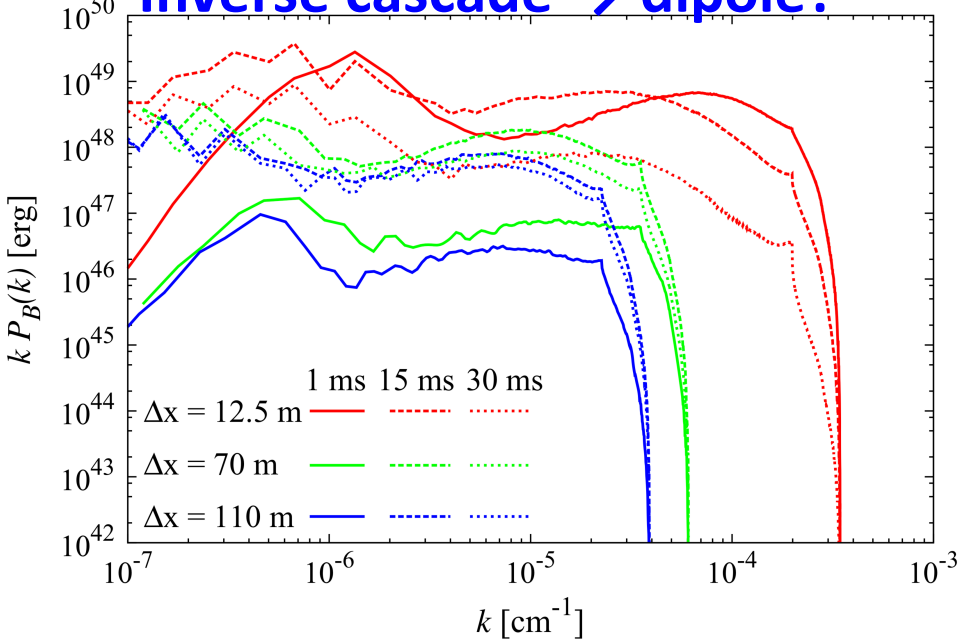




B-field amplification



Inverse cascade → dipole?

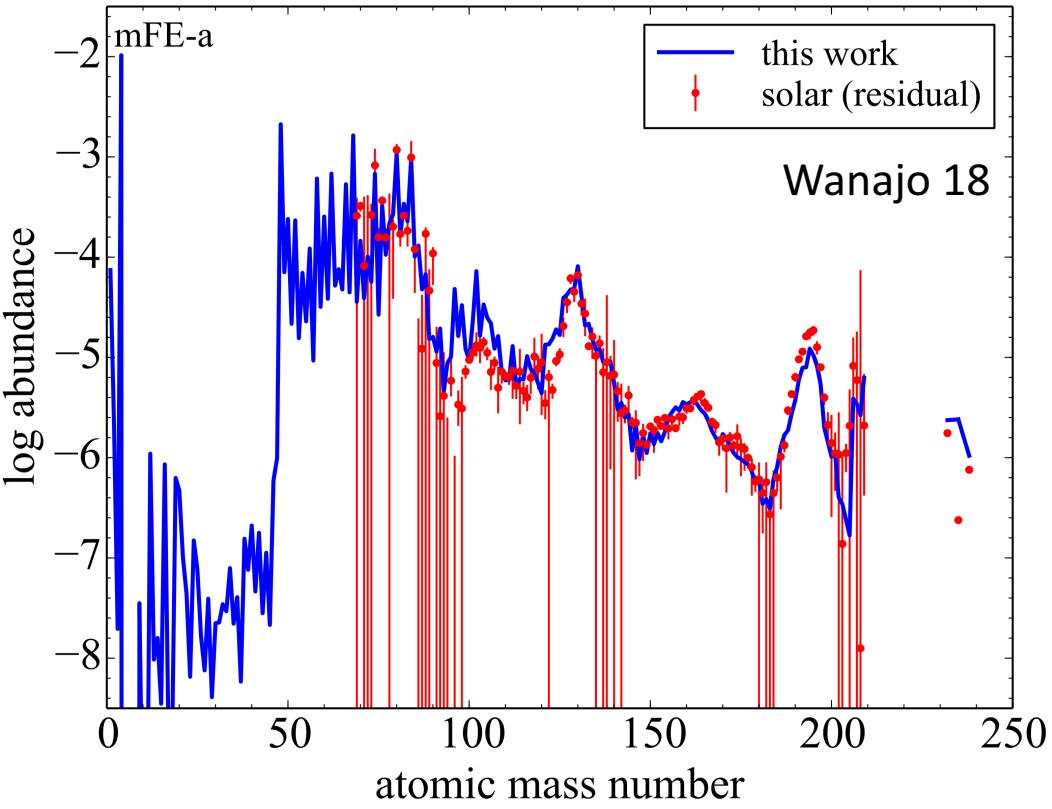


r-process nucleosynthesis

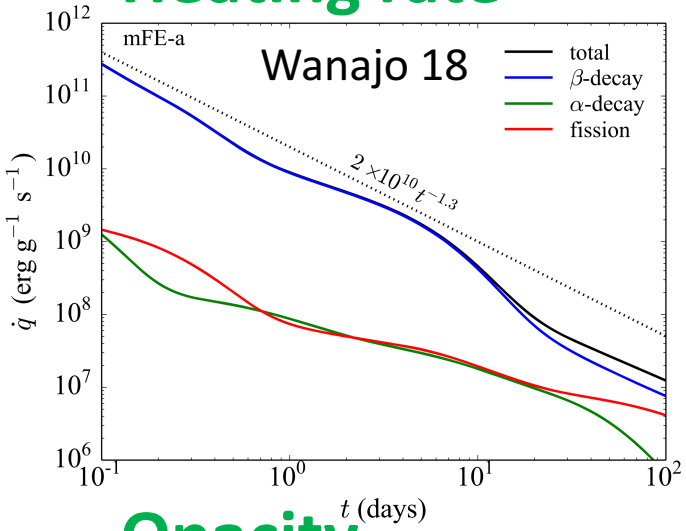
Neutron rich ejecta → rapid neutron capture process

(beta decay time >> neutron capture time)

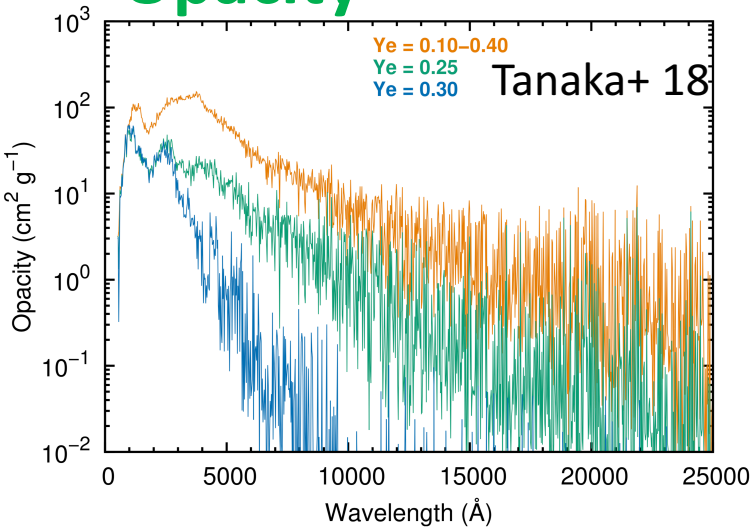
Mass fraction



Heating rate



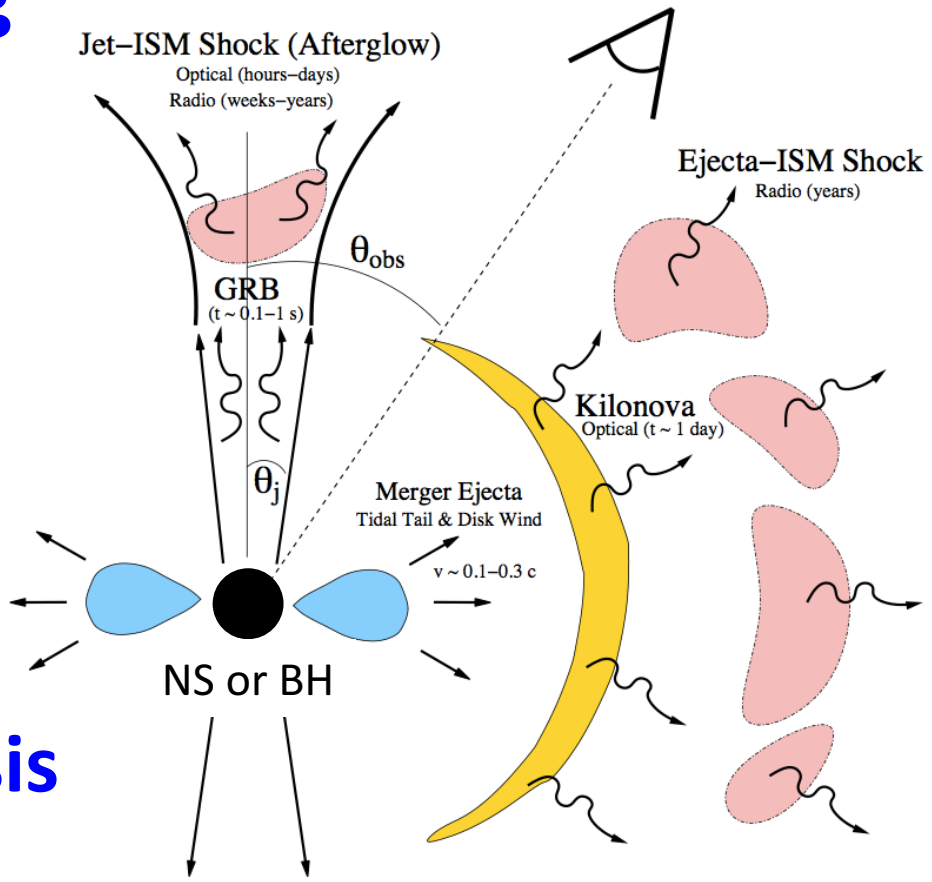
Opacity



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

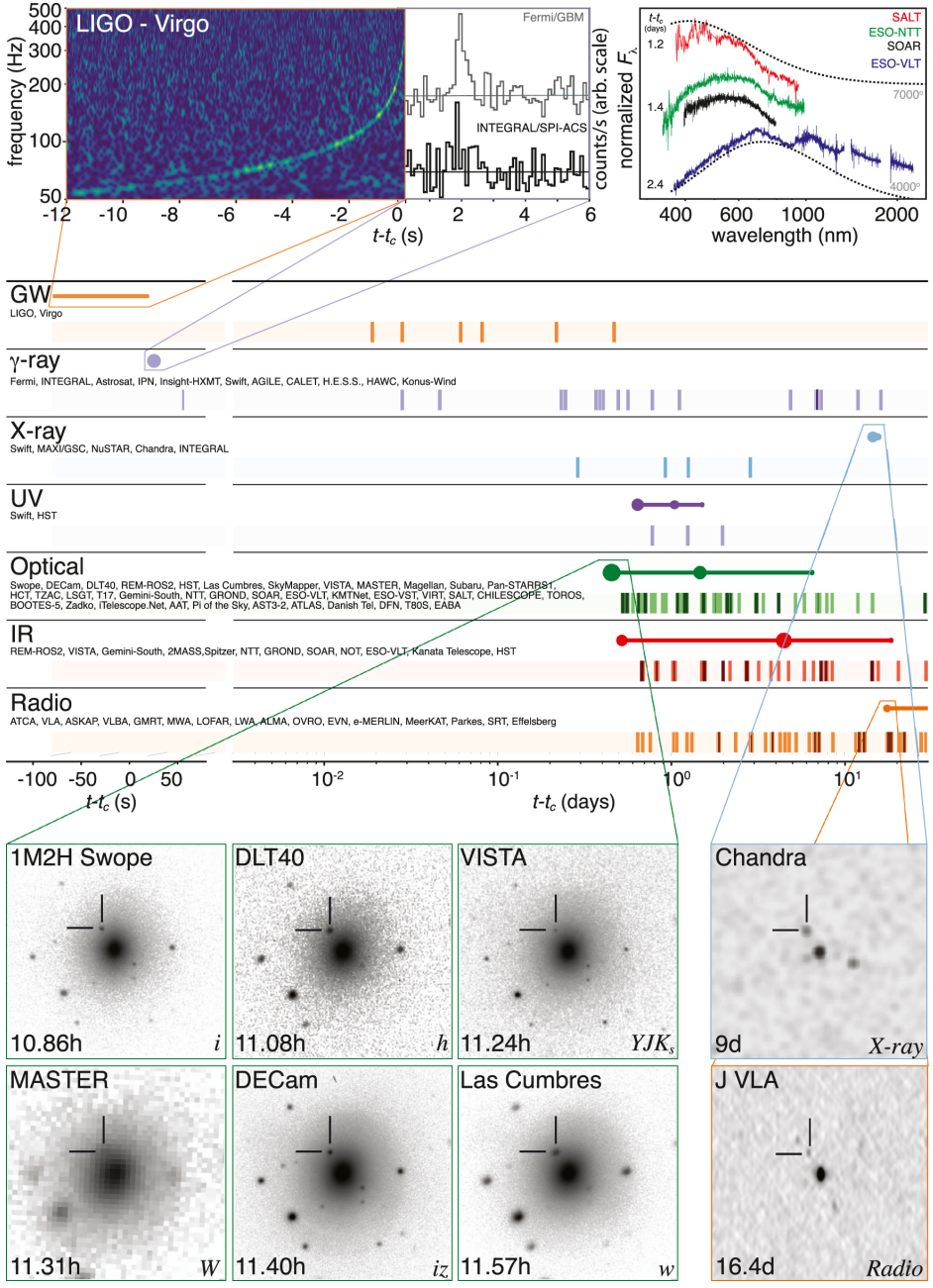
Post-merger activities

- NS or BH formation
- Relativistic jet launching
- Mass ejection
- Fallback
- Accretion and wind
- B-field amplification
- *r*-process nucleosynthesis



Metzger & Berger 12

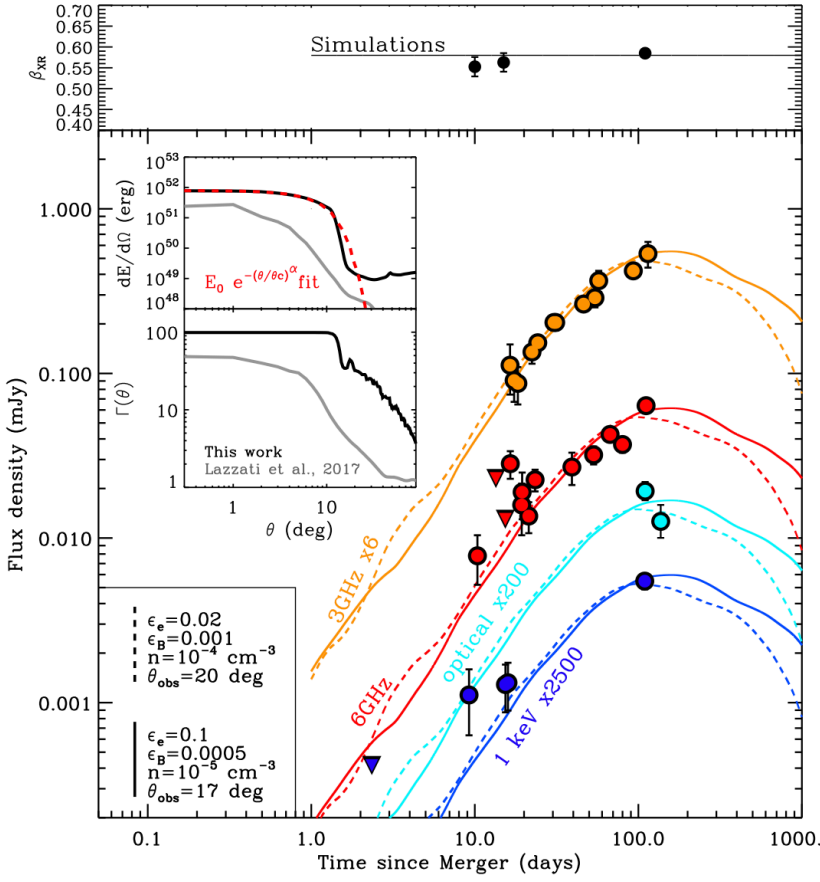
GW170817/GRB 170817A/SSS17a



Abbott+ 17

Mluti-messenger Astronomy

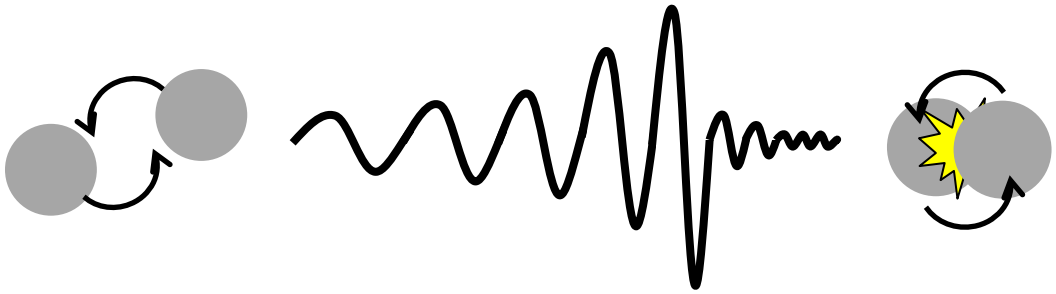
Margutti+ 18



Summary : GW170817

17 Aug. 2017 12:41:04 UTC GW detection (LIGO × 2 + Virgo)

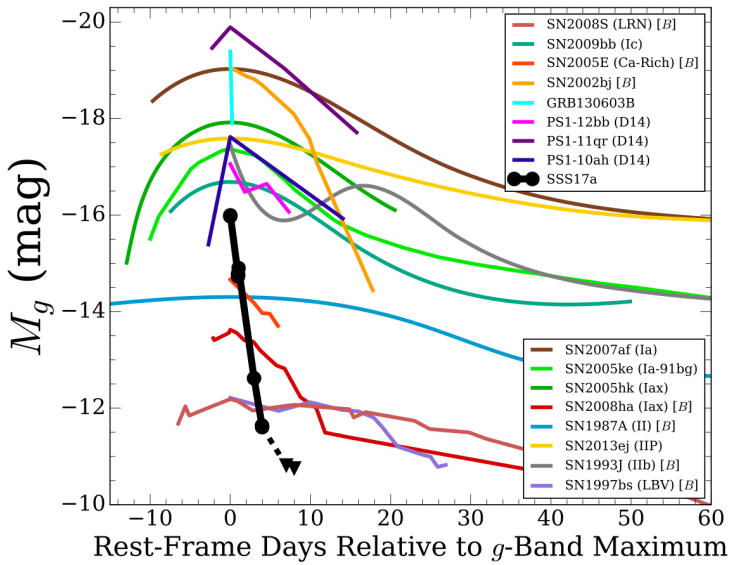
S/N :	32.4
Localization :	31 deg^2 (5 hr after)
Distance :	~40 Mpc
Viewing angle :	< 32° (depending on H_0)
Total mass :	$2.74^{+0.04}_{-0.01}$ Msun
NS mass :	1.17 – 1.60 Msun ($\|\chi_z\|$<0.04)
NS radius :	< 13 km
Merger rate :	1540^{+3200}_{-1220} $Gpc^{-3}yr^{-1}$

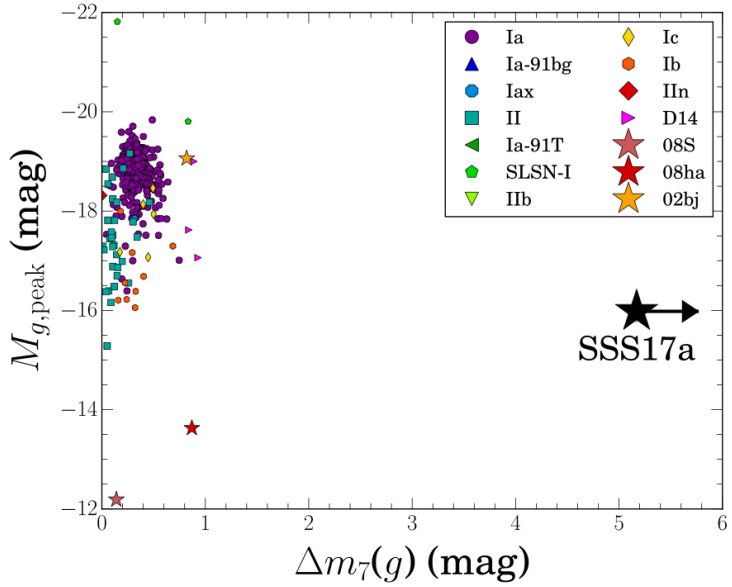


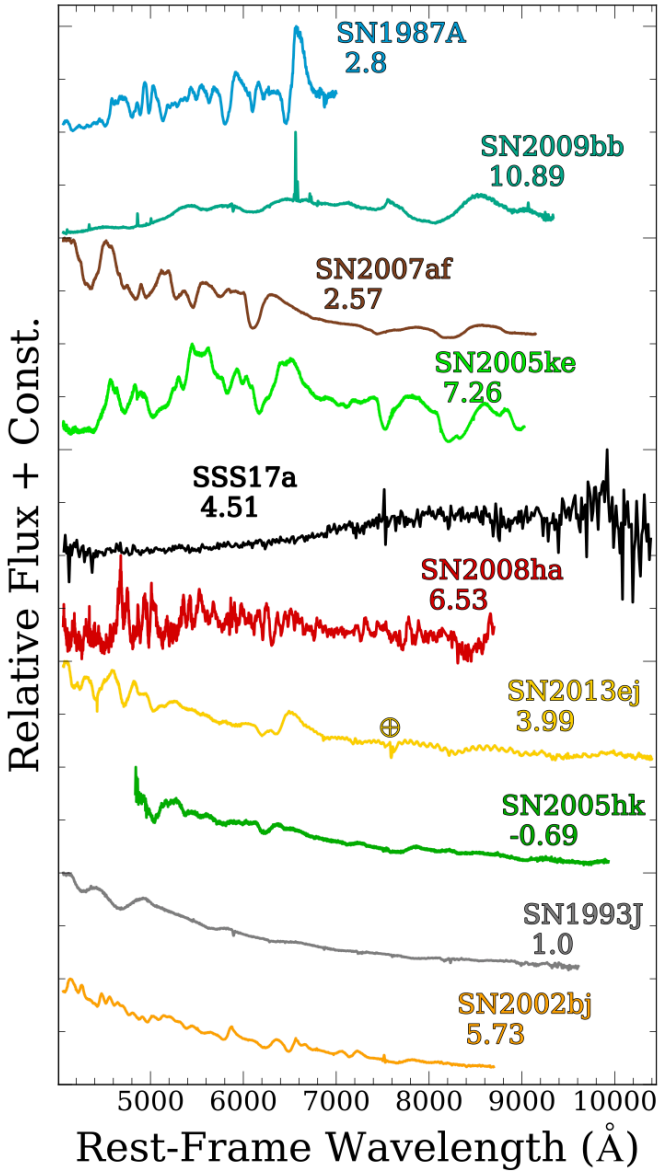
SSS17a (AT2017gfo)

Rapidly evolving transient, clearly different from SNe.

Siebert+ 17







Summary : SSS17a (AT2017gfo)

Confirmed that binary NS mergers are accompanied with kilonovae.

Timescale : ~ 0.5 - 10 day
Luminosity : ~ 10^{40} - 10^{42} erg s^{-1}
Temperature : T ~ 2×10^{3} - 10^{4} K

→ Ejecta mass : ~ 0.05 Msun
Ejecta velocity : v ~ 0.1 - 0.3 c
Lanthanoid fraction : ~ 0.01

- Multi-component ejecta? (blue and red)
- Ejecta mass and rate are consistent with the Galactic *r*-process element enrichment.
- The massive ejecta mass indicates the formation of hypermassive NS transiently.

Post-merger activities

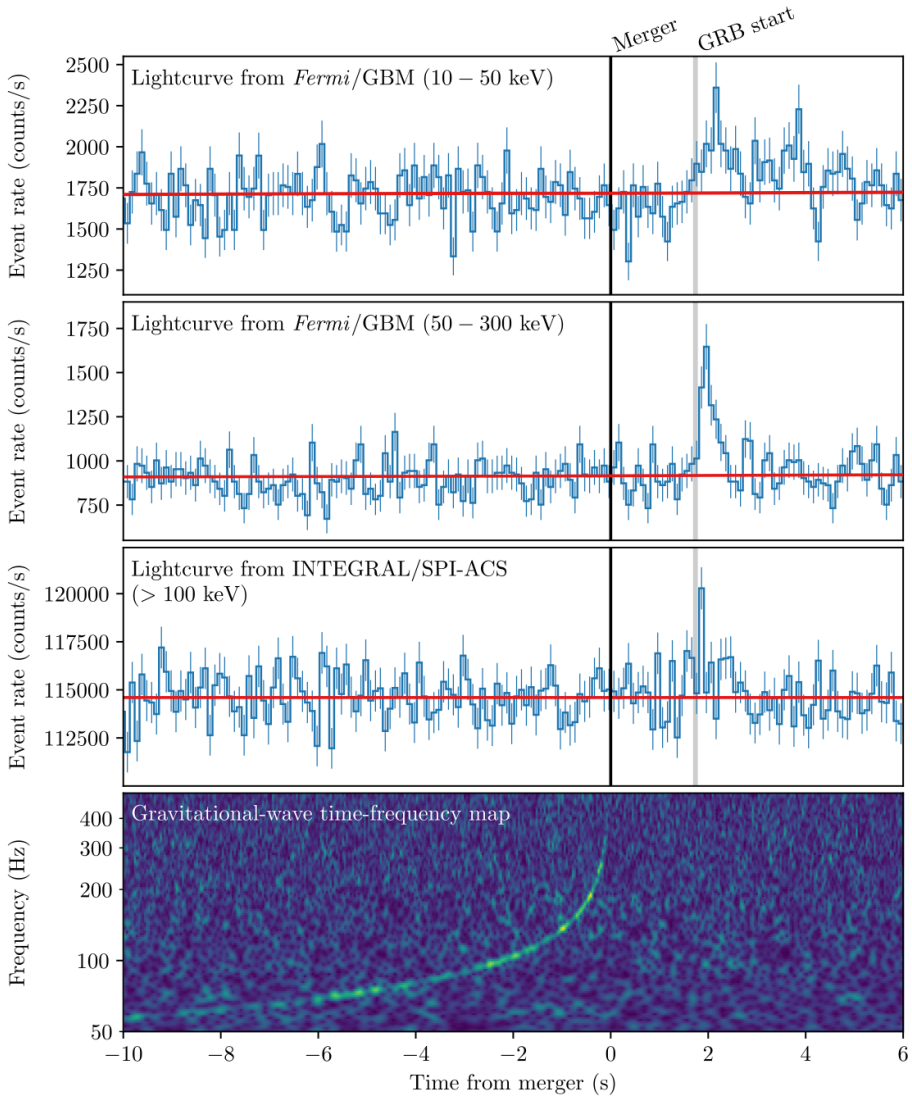
- NS or BH formation
- Relativistic jet launching
- Mass ejection
- Fallback
- Accretion and wind
- Magnetic field amplification
- *r*-process nucleosynthesis

GRB 170817A

Abbott+ 17
Goldstein+ 17
Savchenko+ 17

Fermi/GBM independently reported a γ-ray transient.

Binary NS merger = γ-ray transient

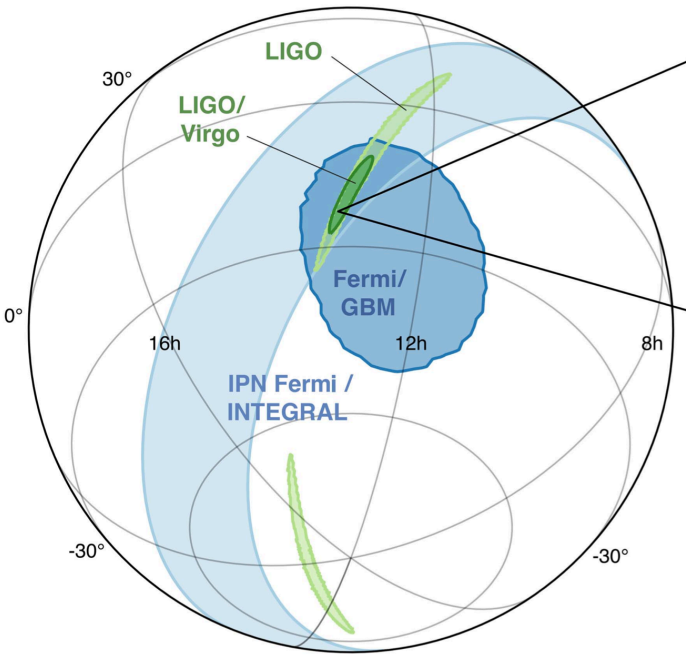


Duration : ~ 2 s

Time delay : ~ 1.7 s

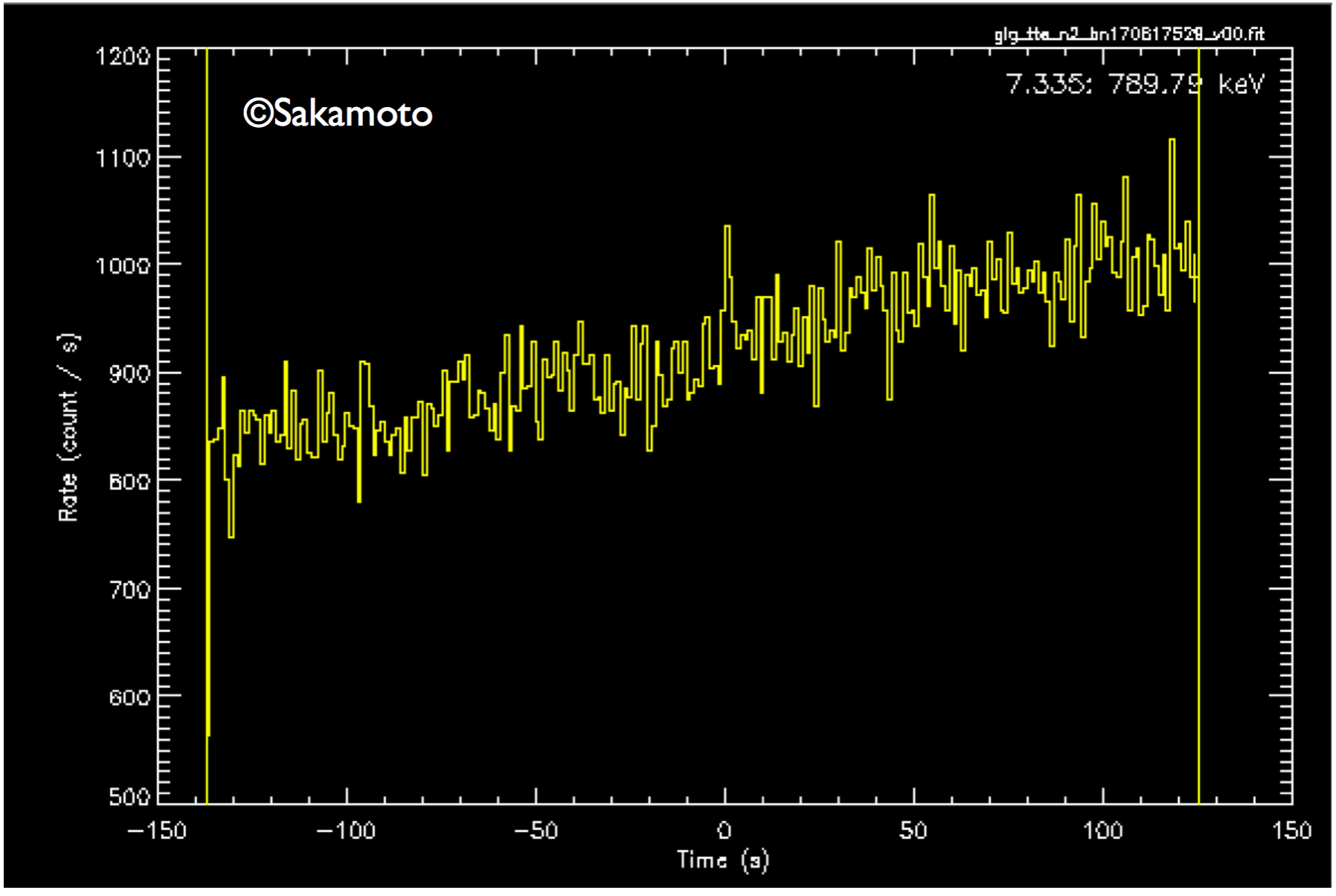
Radiation energy : ~ 5×10^{46} erg

Peak energy : ~ 185 ± 62 keV



Real signal?

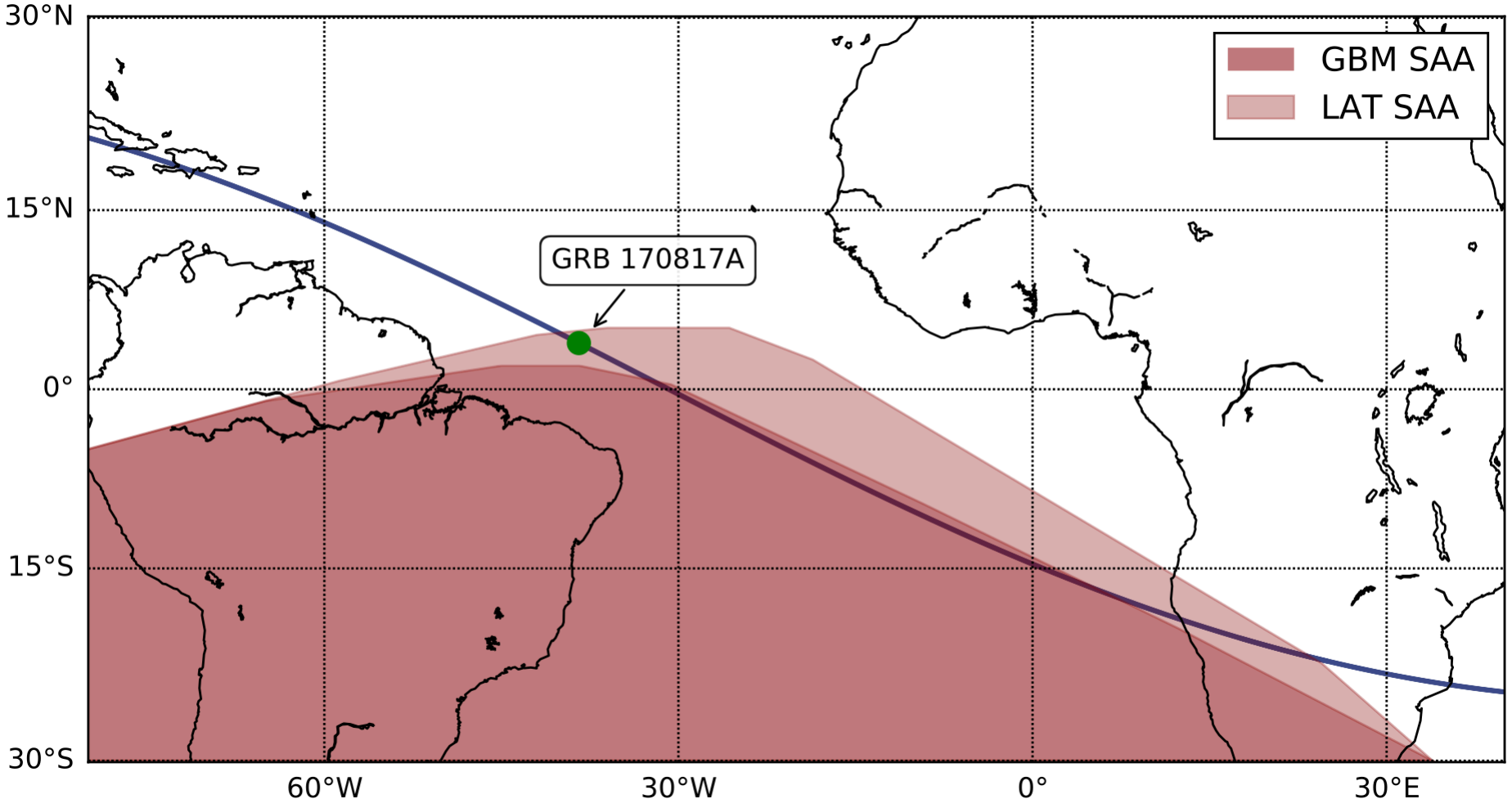
Fermi/GBM data



Real signal?

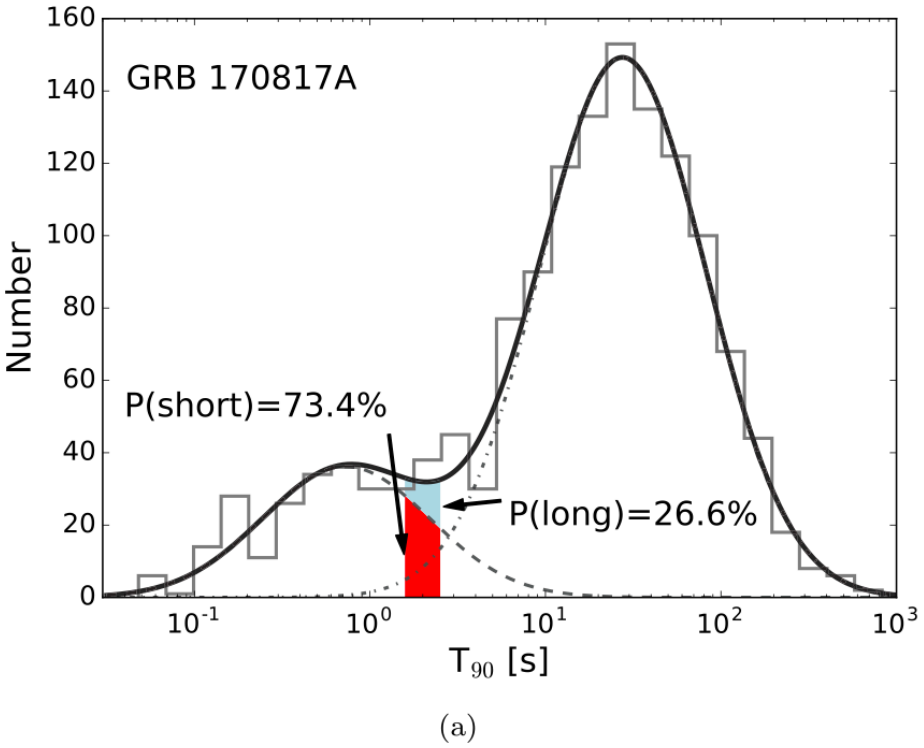
Goldstein+ 17

South Atlantic Anomaly



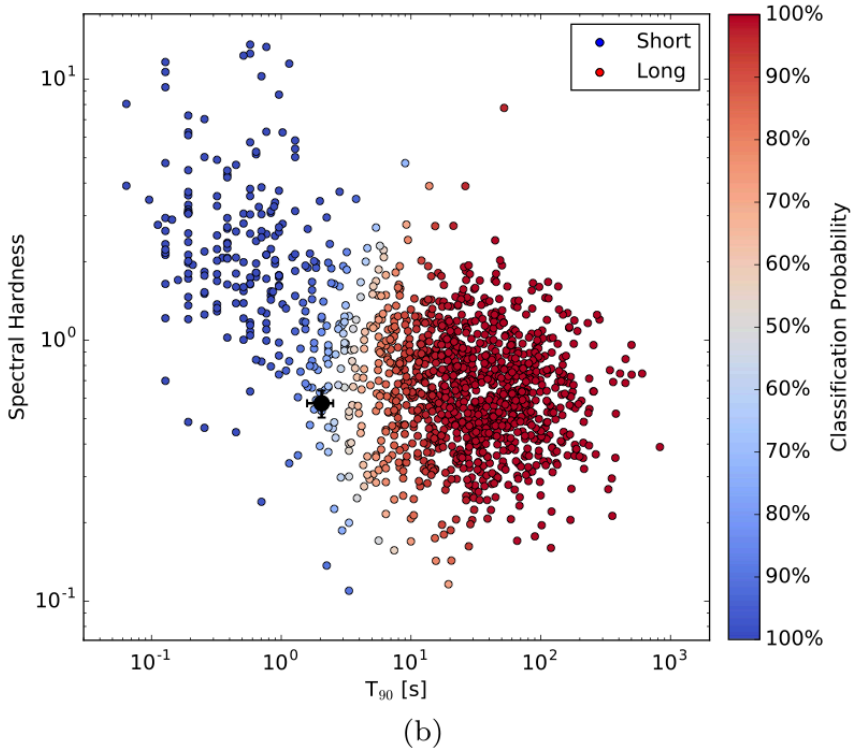
GRB 170817A = Short GRB?

Duration



(a)

Hardness



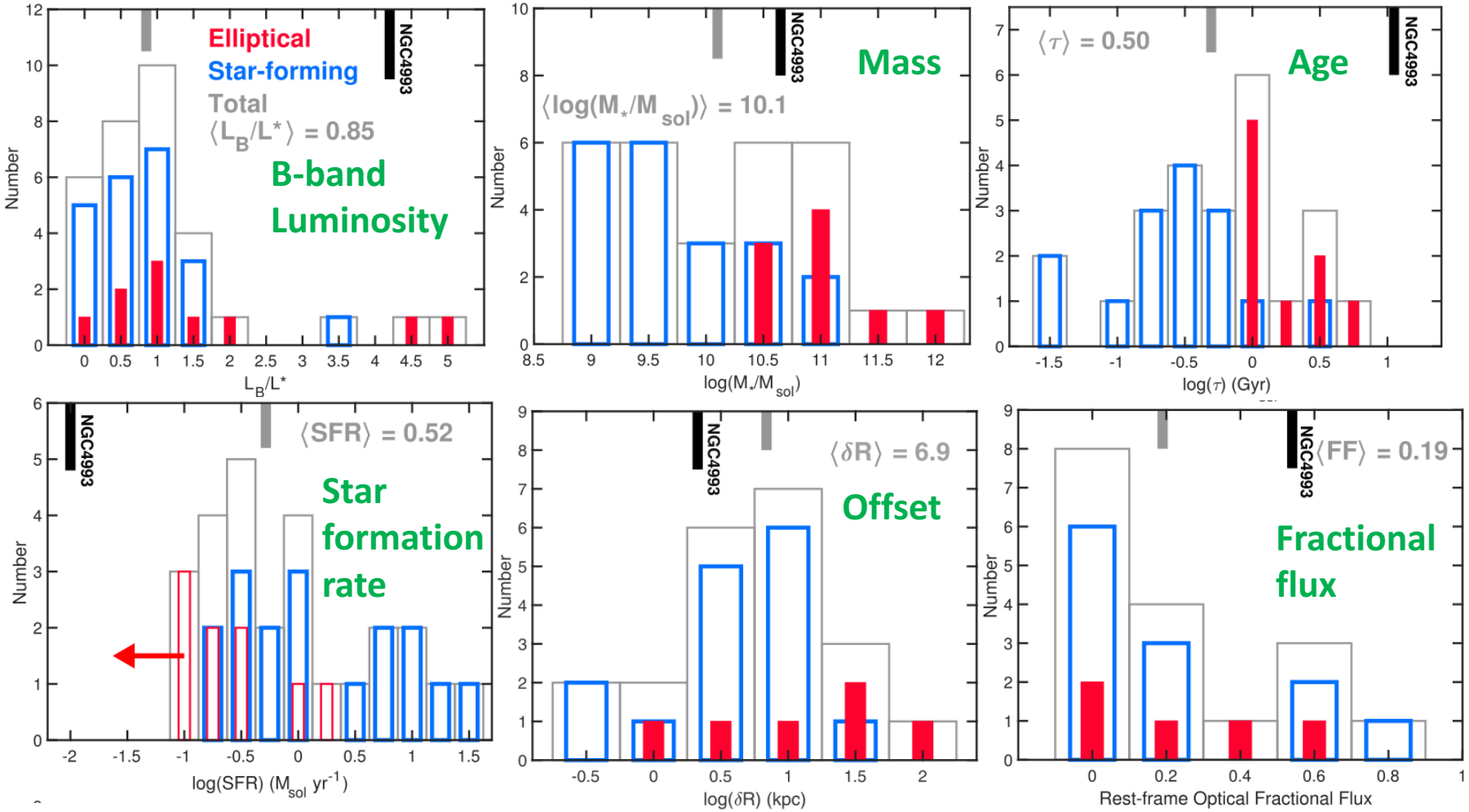
(b)

Goldstein+ 17

Typical short GRB?

GRB 170817A = Short GRB?

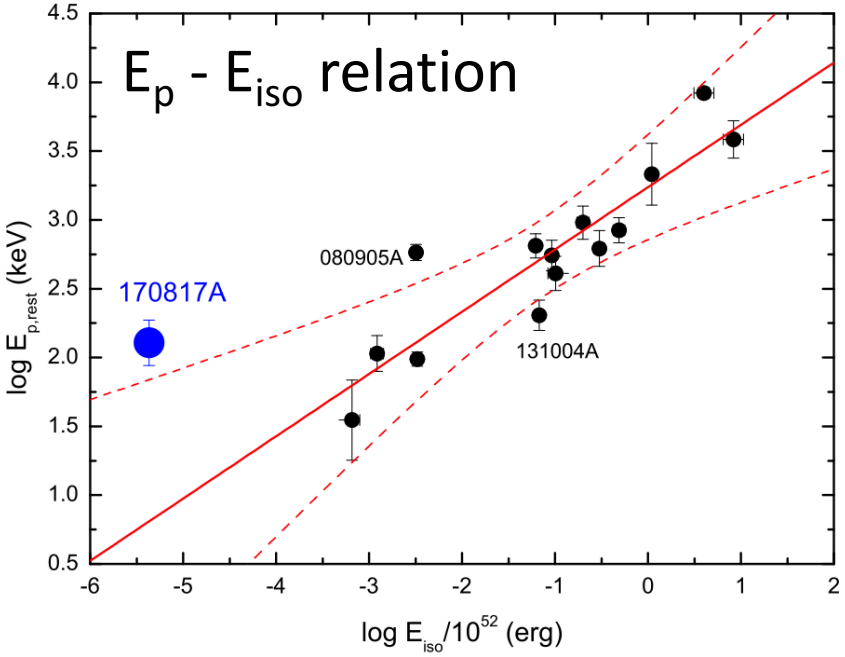
Properties of the host galaxy are also consistent with those of other short GRBs.

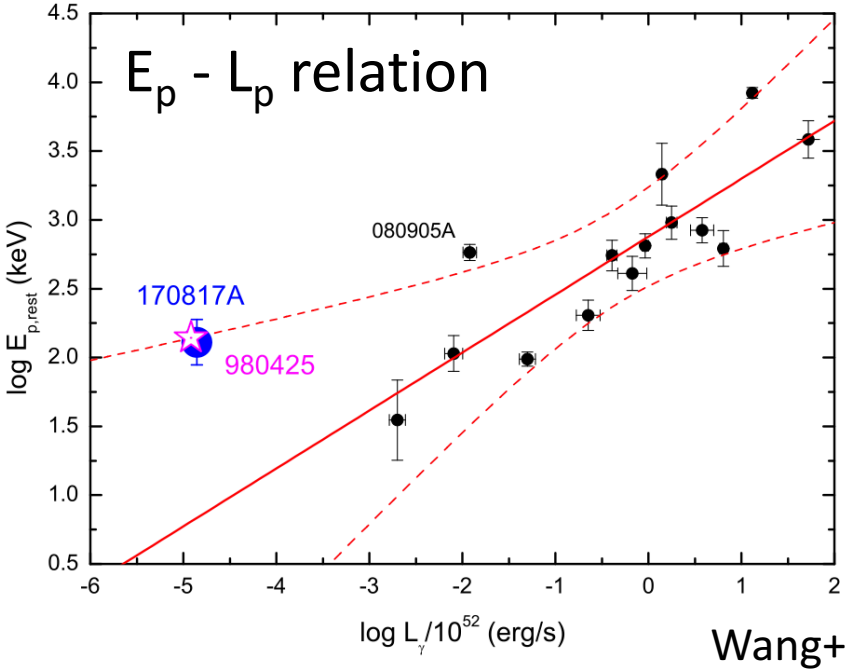


Fong+ 17

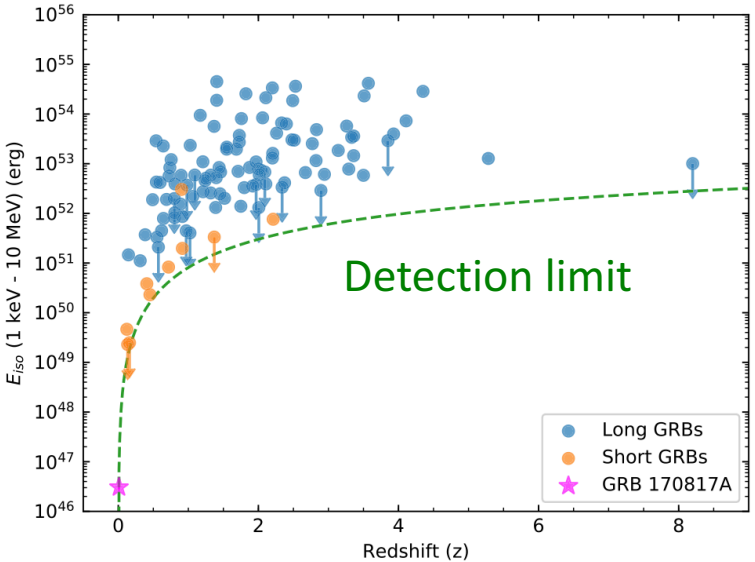
GRB 170817A = Short GRB?

Typical peak energy, but much lower radiation energy.





Wang+ 17

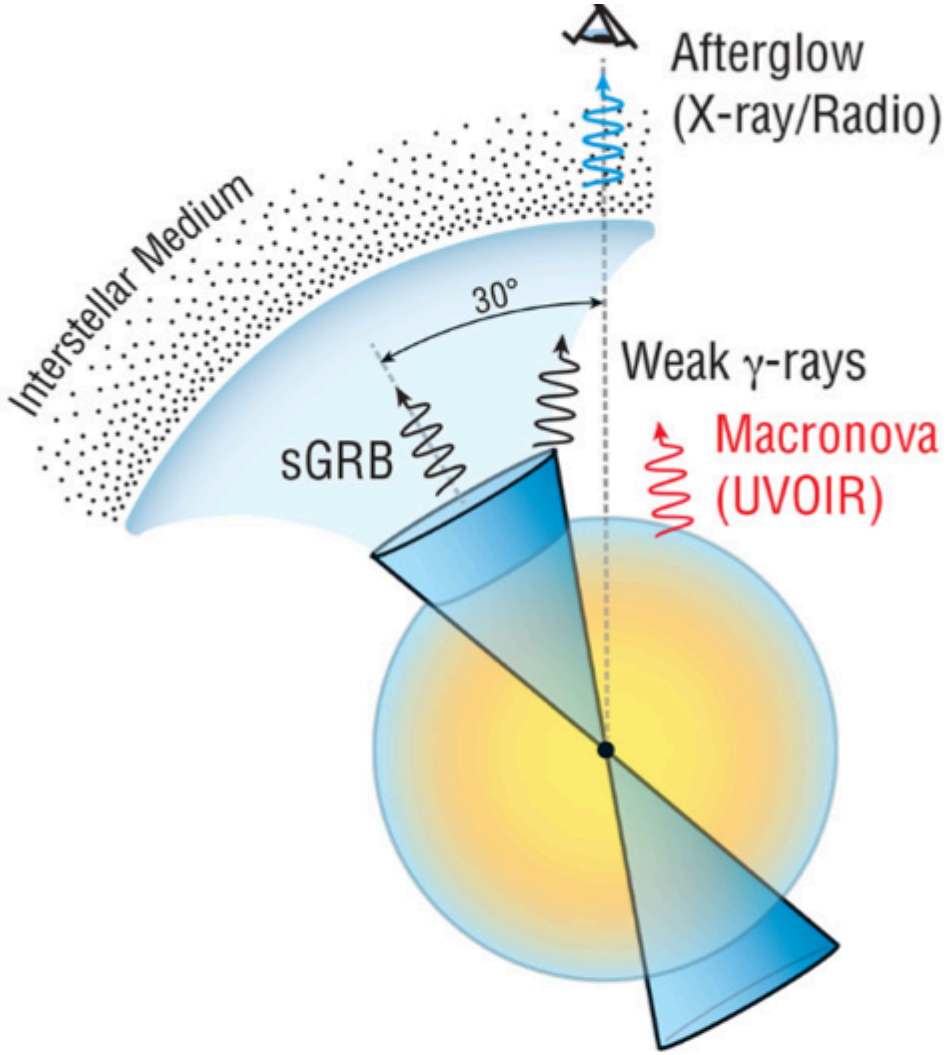


Not an on-axis jet with Γ ~ 100?

Abbott+ 17

GRB 170817A afterglow

The synchrotron emission arising from the interaction of a jet or a cocoon with the surrounding ISM.



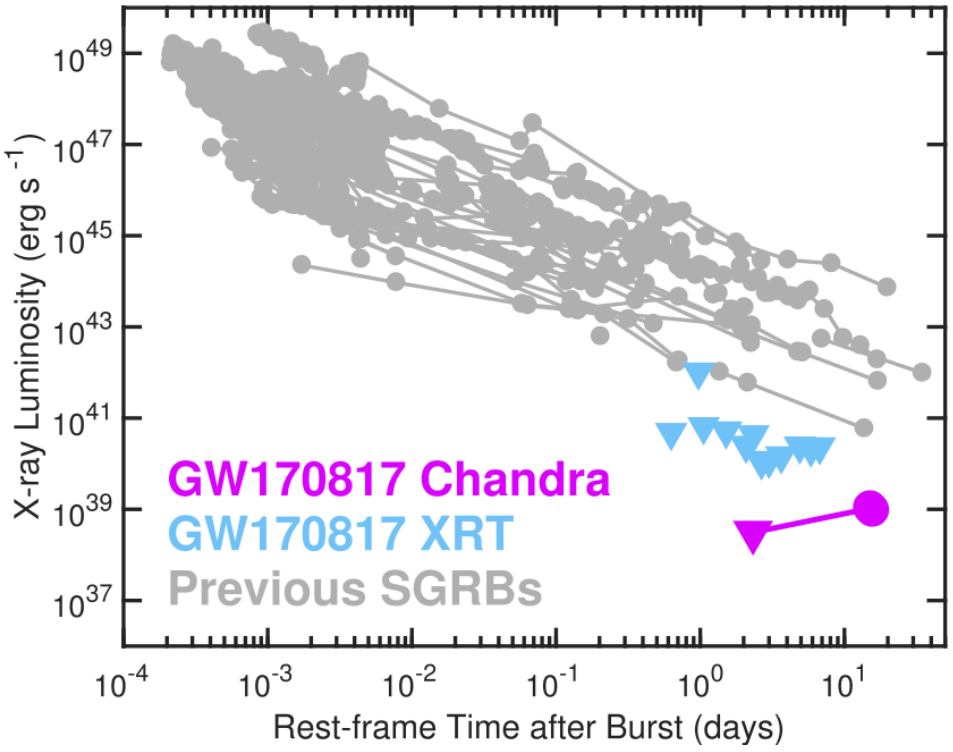
Kasliwal+ 17

Early afterglow (< 20 days)

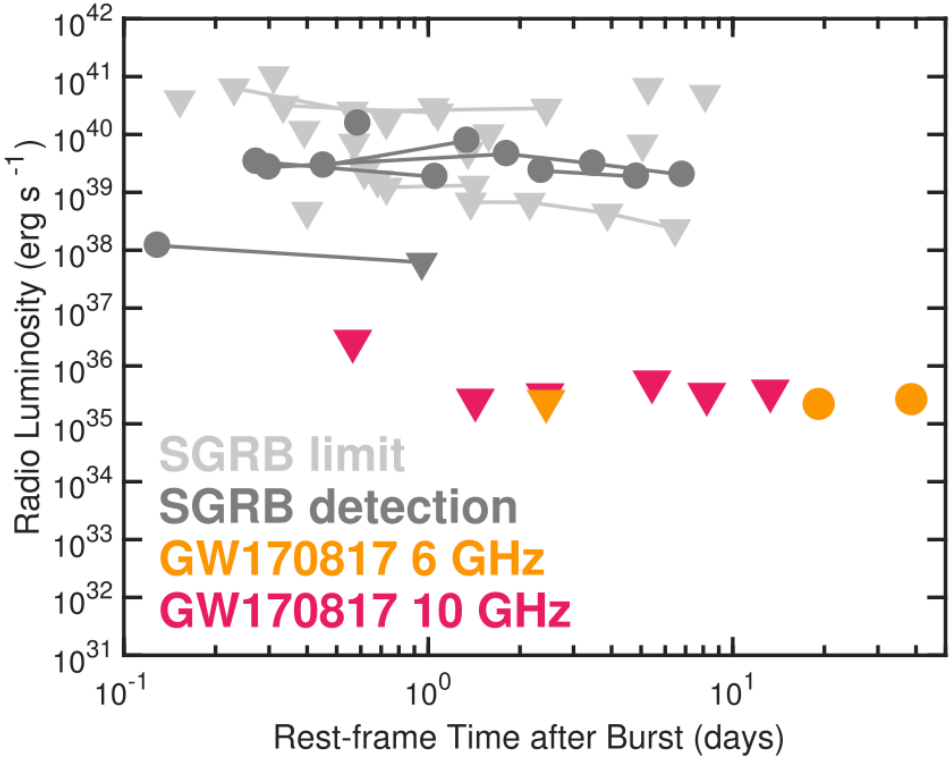
Non-detection of the early afterglow emission (< 10 day).

→ Not an on-axis jet with Γ ~ 100 !!

X-ray



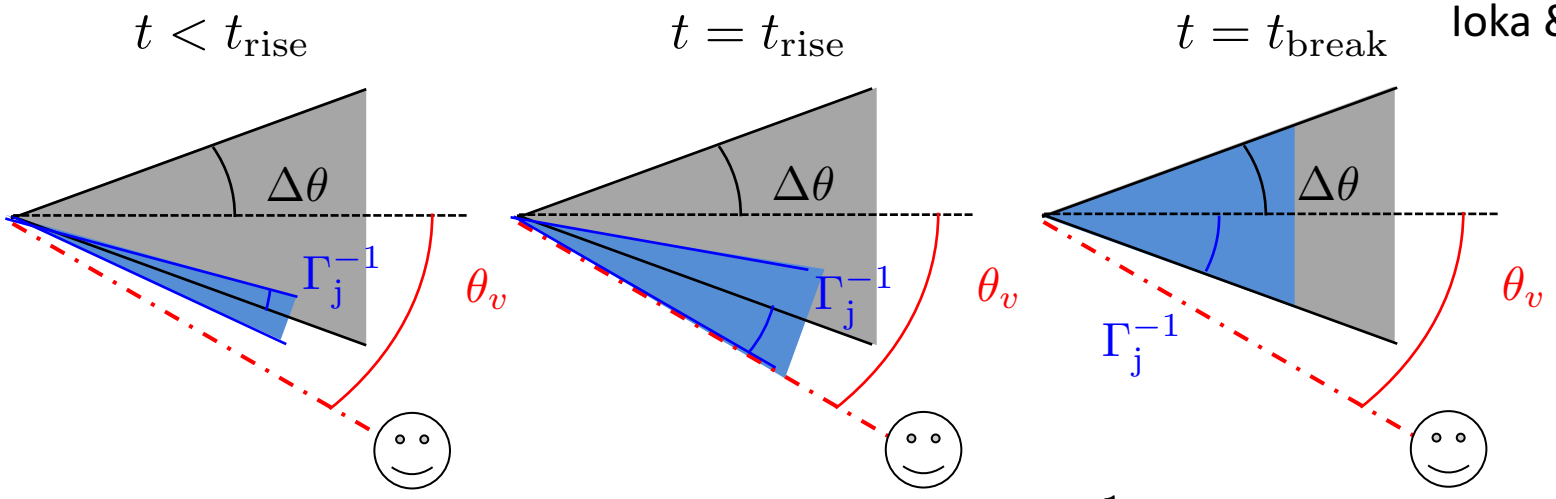
Radio



Fong+ 17

Afterglow timescale

Ioka & Nakamura 18



Rise time

$$\Gamma_{\rm j}^{-1} \sim \theta_v - \Delta\theta$$

$$t_{\rm rise} \sim 14\ {\rm day} \left(\frac{\theta_v - \Delta\theta}{7^\circ}\right)^{8/3} \left(\frac{E_{\rm iso}/\epsilon_\gamma}{3\times10^{52}{\rm erg}}\right)^{1/3} \left(\frac{n_{\rm ism}}{10^{-4}{\rm cm}^{-3}}\right)^{-1/3}$$

Jet break time

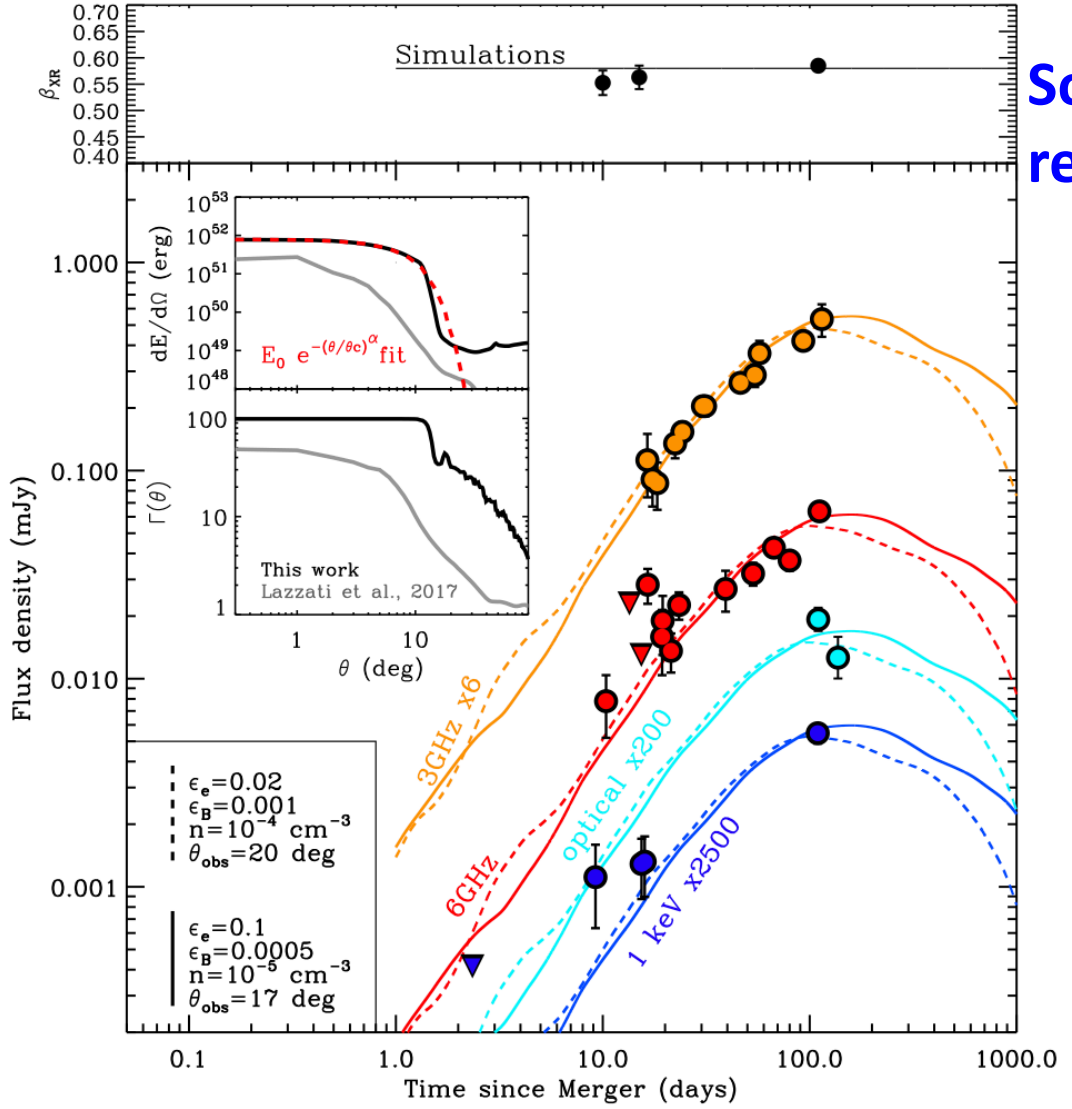
$$\Gamma_{\rm j}^{-1} \sim \Delta\theta$$

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

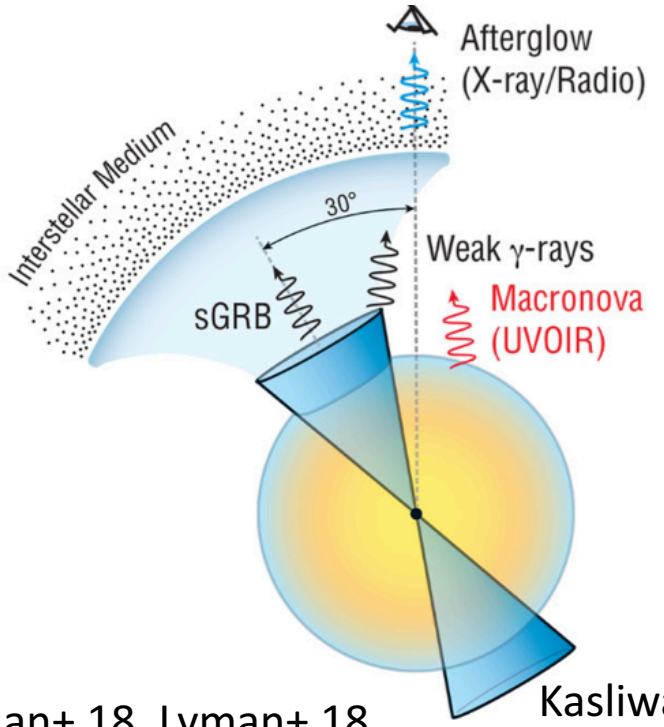
$E_{\rm kin} \sim E_{\rm iso}/\epsilon_\gamma \uparrow$ $t_{\rm break} \uparrow$

GRB 170817A afterglow

The synchrotron emission arising from the interaction of a jet or a cocoon with the surrounding ISM.



Some structured jet models could reproduce the observations.

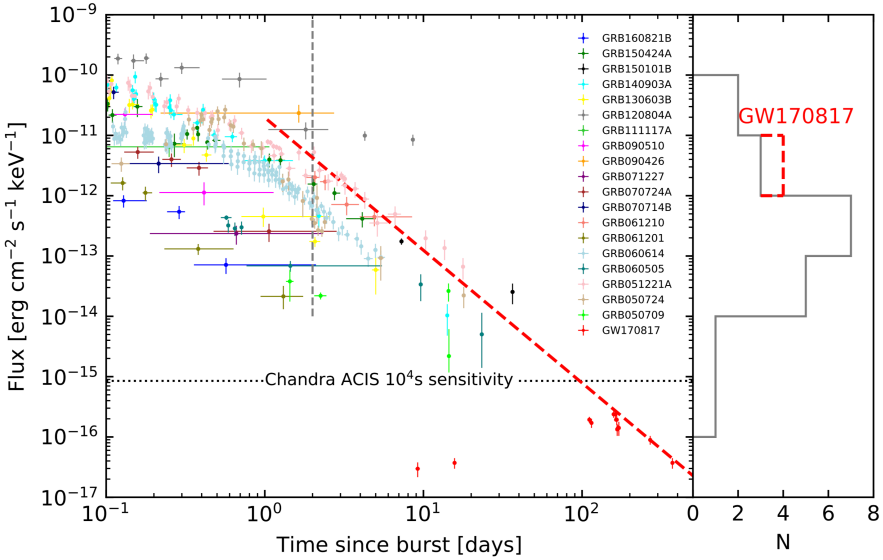


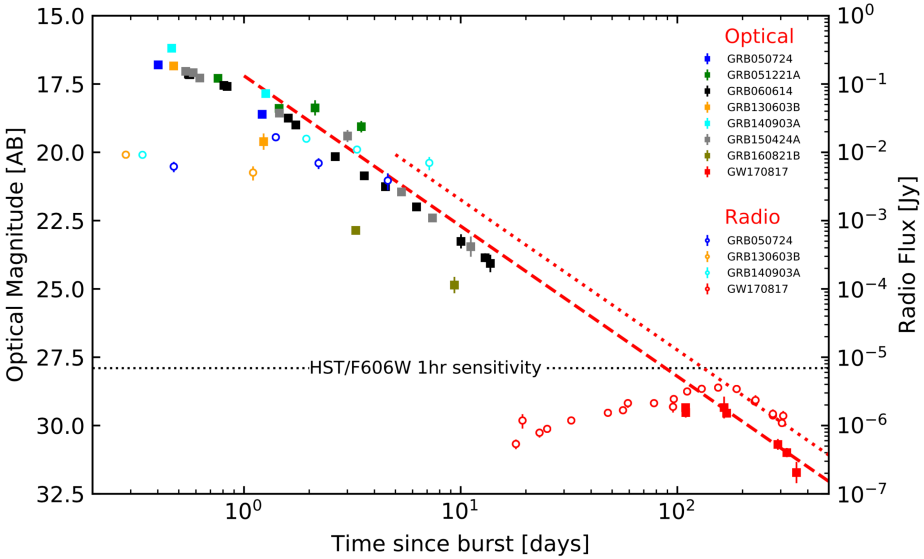
Kasliwal+ 17

Ruan+ 18, Lyman+ 18, Margutti+ 18, D'Avanzo+ 18, Troja+ 18

GRB 170817A afterglow

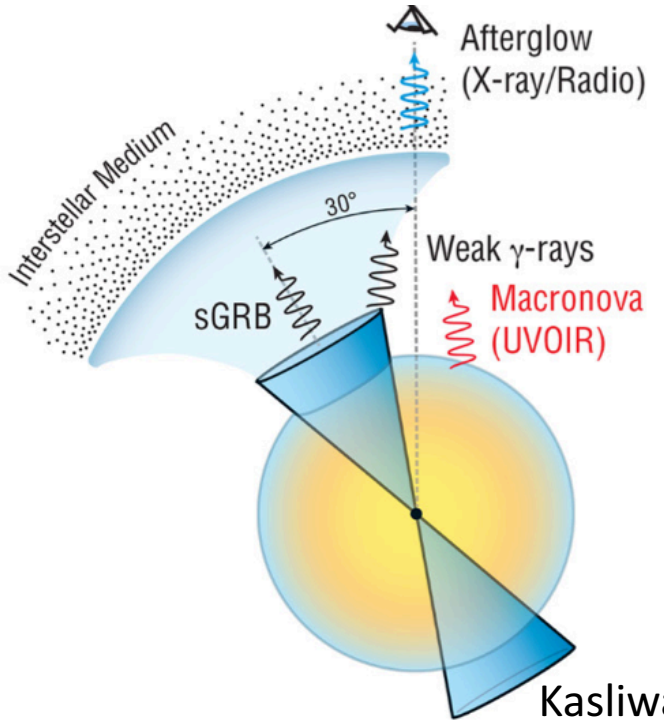
The synchrotron emission arising from the interaction of a jet or a cocoon with the surrounding ISM.





Duan+ 19

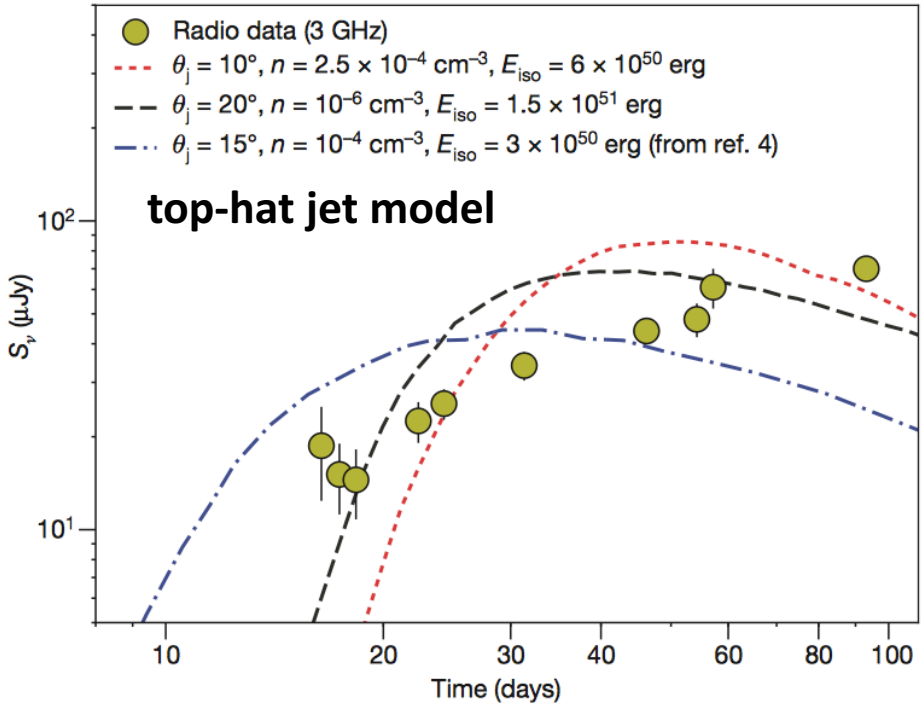
The decaying curve is consistent with other short GRB afterglows.



Kasliwal+ 17

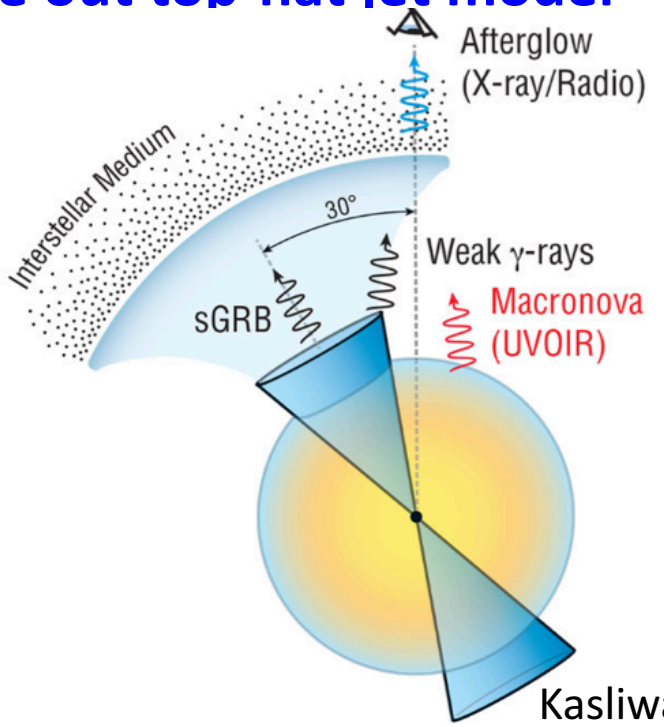
GRB 170817A afterglow

The synchrotron emission arising from the interaction of a jet or a cocoon with the surrounding ISM.



- **A steady rise in the light curve of $S \propto t^{0.8}$**

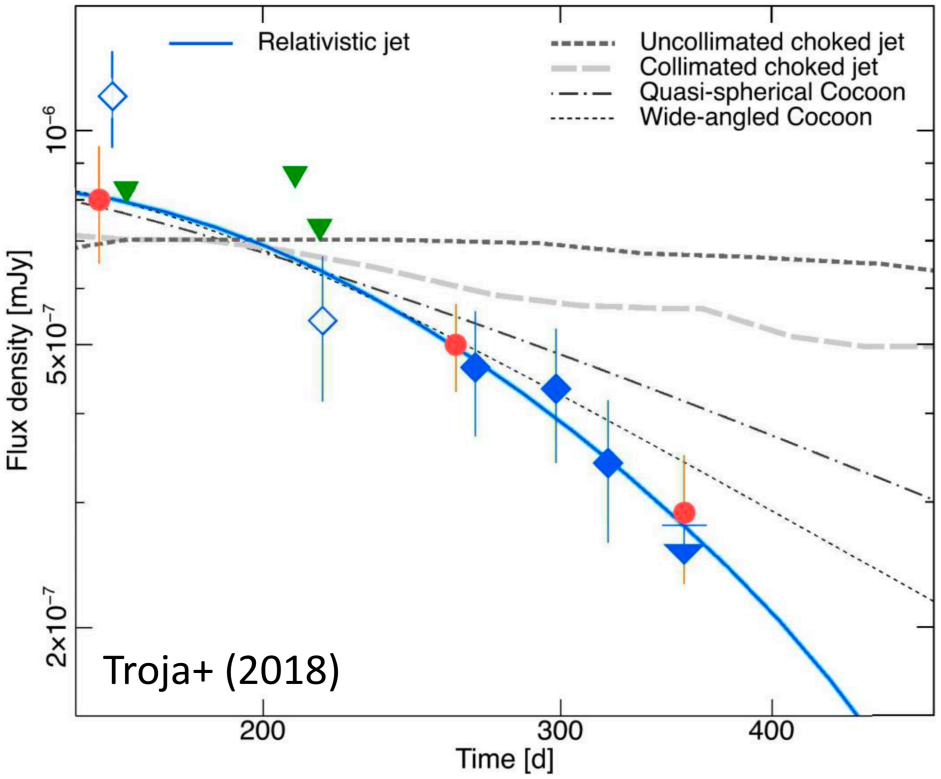
→ Rule out top-hat jet model



Kasliwal+ 17

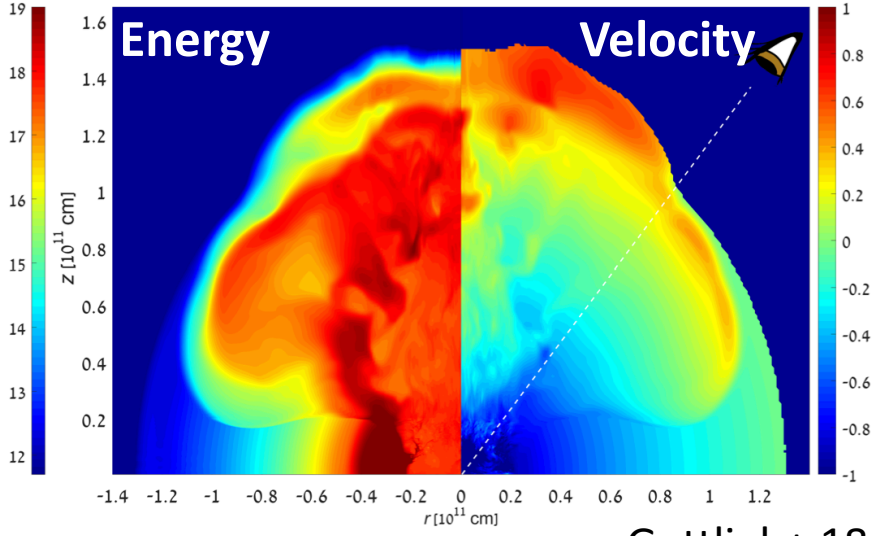
GRB 170817A afterglow

The synchrotron emission arising from the interaction of a jet or a cocoon with the surrounding ISM.



- **Turnover in Radio, optical, and X-ray light curves at ~ 160 days**
- **No evidence of synchrotron cooling break**

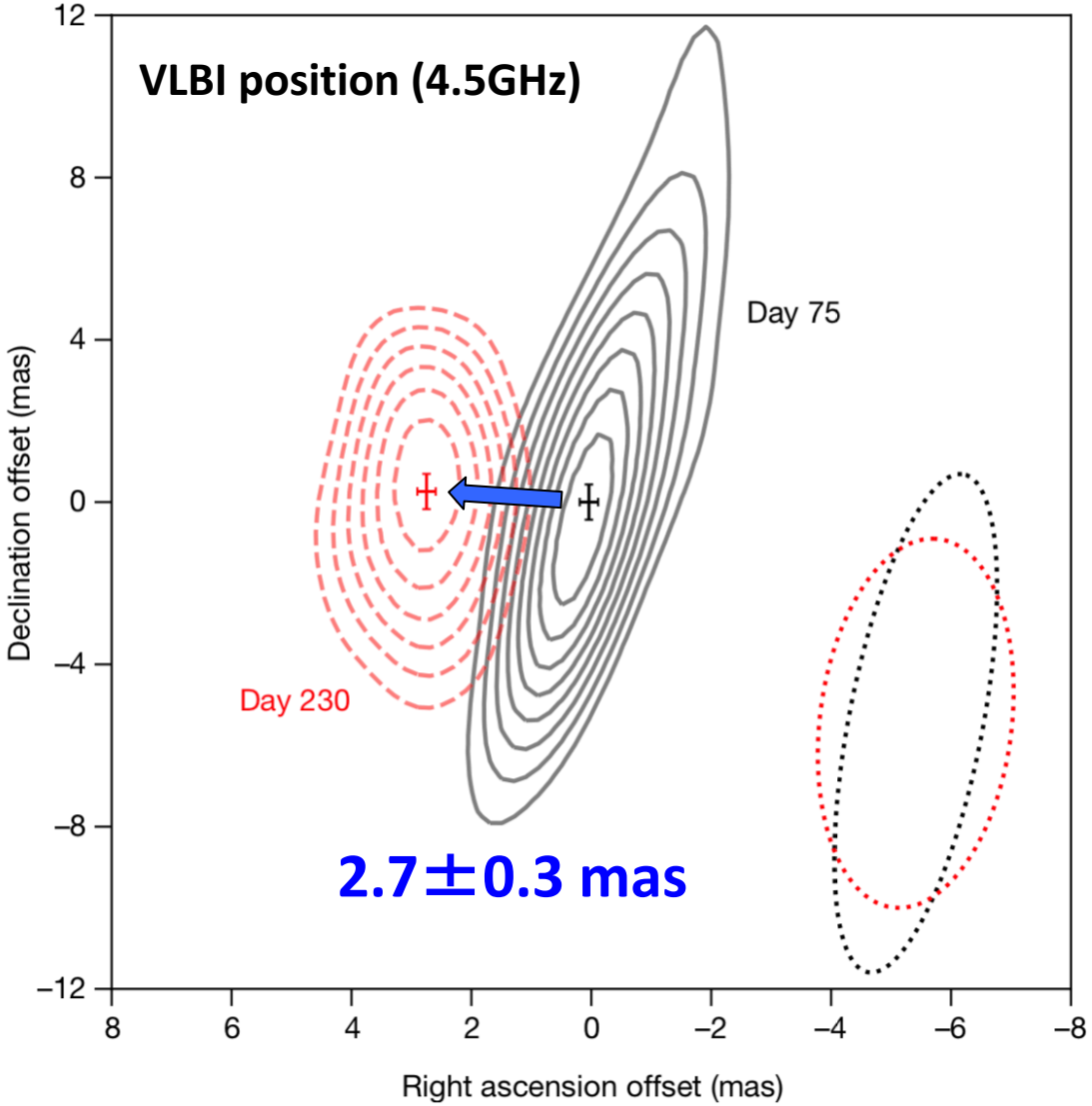
→ **Rule out some cocoon and dynamical ejecta models**



Gottlieb+ 18

Relativistic jet in GW170817

Superluminal motion = relativistic collimated jet
Jet opening angle < viewing angle → off-axis event



- Unresolved source
- Apparent velocity
  $\beta_{app} = 4.1 \pm 0.5$
- Jet opening angle
  $\theta_j \leq 5^\circ$
- Viewing angle
  $\theta_v \sim 20^\circ$

Mooley+ 18a

Summary : GRB 170817A

- **γ-ray detection**

  (E_{iso} ~ 10^{47} erg, T_{dur} ~ 2 s, T_{delay} ~ 1.7 s)

  → **Binary NS merger = γ-ray transient**

  Note : the detection significance is not so high.

- **Afterglow light curve**

  ($E_{kin,iso}$ ~ 10^{51} - 10^{53} erg, n ~ 10^{-4} - 10^{-2} cm^{-3}, p ~ 2.2)

  [$S \propto t^{0.8}$ ($t < t_{break}$), $S \propto t^{-2.2}$ ($t < t_{break}$), t_{break} ~ 160 day]

  Superluminal motion

  (β_{app} ~ 4, $\theta_j < 5^\circ$, θ_v ~ 20°)

  → **Relativistic jet (Γ > 5-10) with some energy distribution.**

No direct evidence of the occurrence of short GRB.

Post-merger activities

- NS or BH formation
- Relativistic jet launching
- Mass ejection
- Fallback
- Accretion and wind
- Magnetic field amplification
- *r*-process nucleosynthesis

GRB 170817A γ-ray emission model

- **Short GRB off-axis emission**

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

- **Scattered short GRB**

  SK+ 18

Typical short GRB for an on-axis observer.

- **Low-luminosity short GRB**

  Murguia-Berthier+ 17b, Zhang+ 17

- **Cocoon shock breakout**

  Kasliwal+ 17, Gottlieb+ 17, Bromberg+ 17

New phenomena.

Magnetar giant flare?

Salafia+ 18, Tong+ 18

Summary

Short GRB = NS Merger?

NS merger : Mass ejection
r-process nucleosynthesis
Relativistic outflow
γ-ray transient?

Prospects : Prompt emission properties (E_p – E_{iso} plot)
Macronova energy sources
Long-lasting components