Counter-jet emissions from short gamma-ray bursts similar to binary neutron star merger event GW 170817/GRB 170817A

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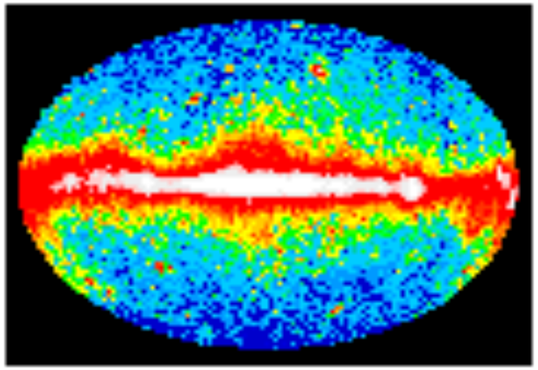
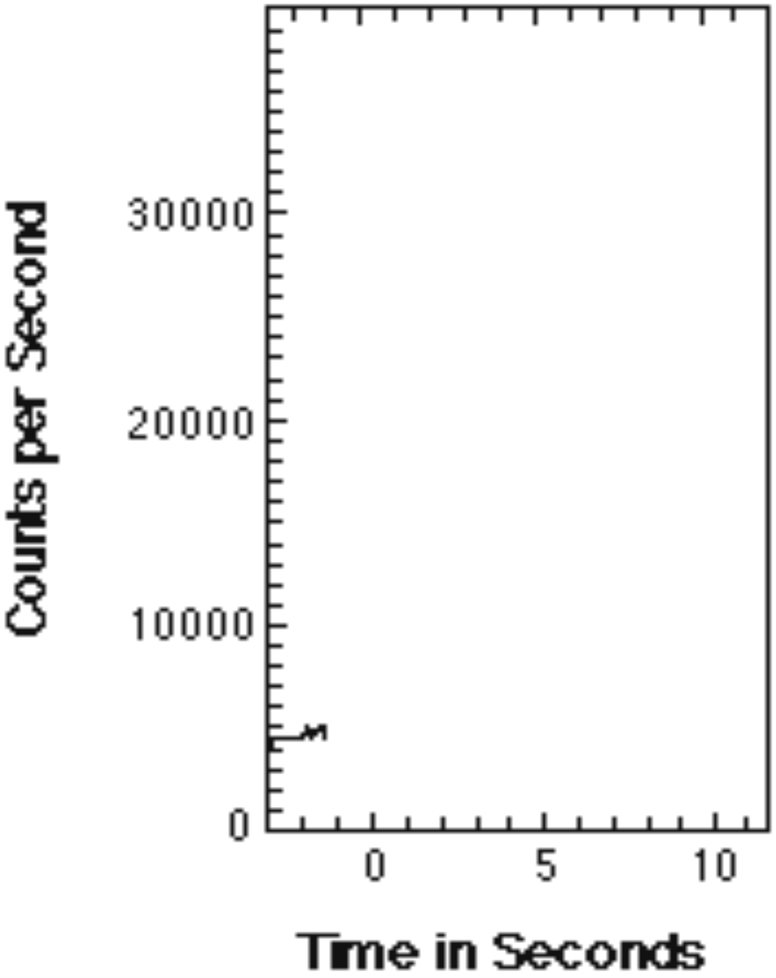
Kunihito Ioka, Takashi Nakamura (Kyoto Univ.)

Light curve of GRB

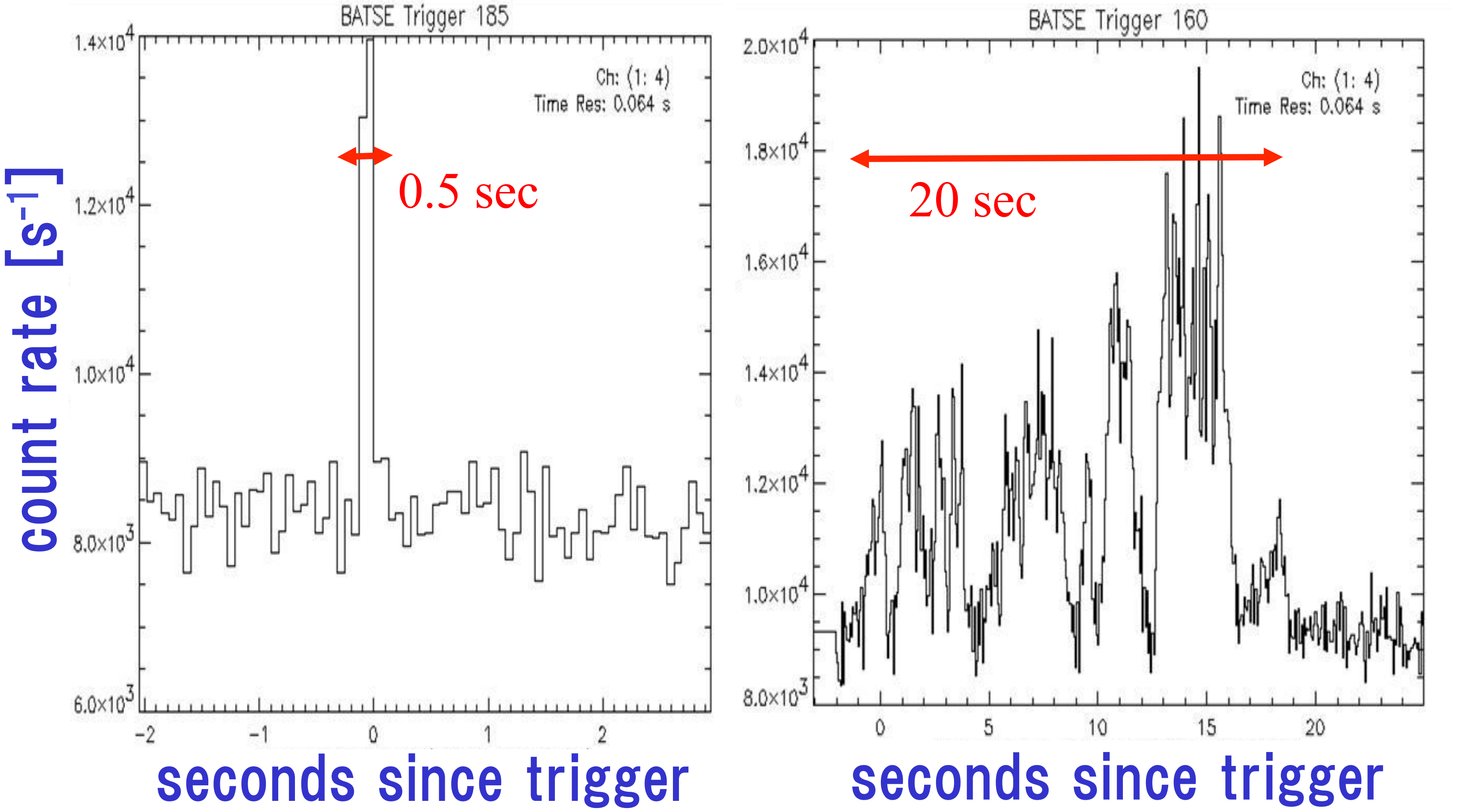
ガンマ線の全天マップ



時間変動（light curve）

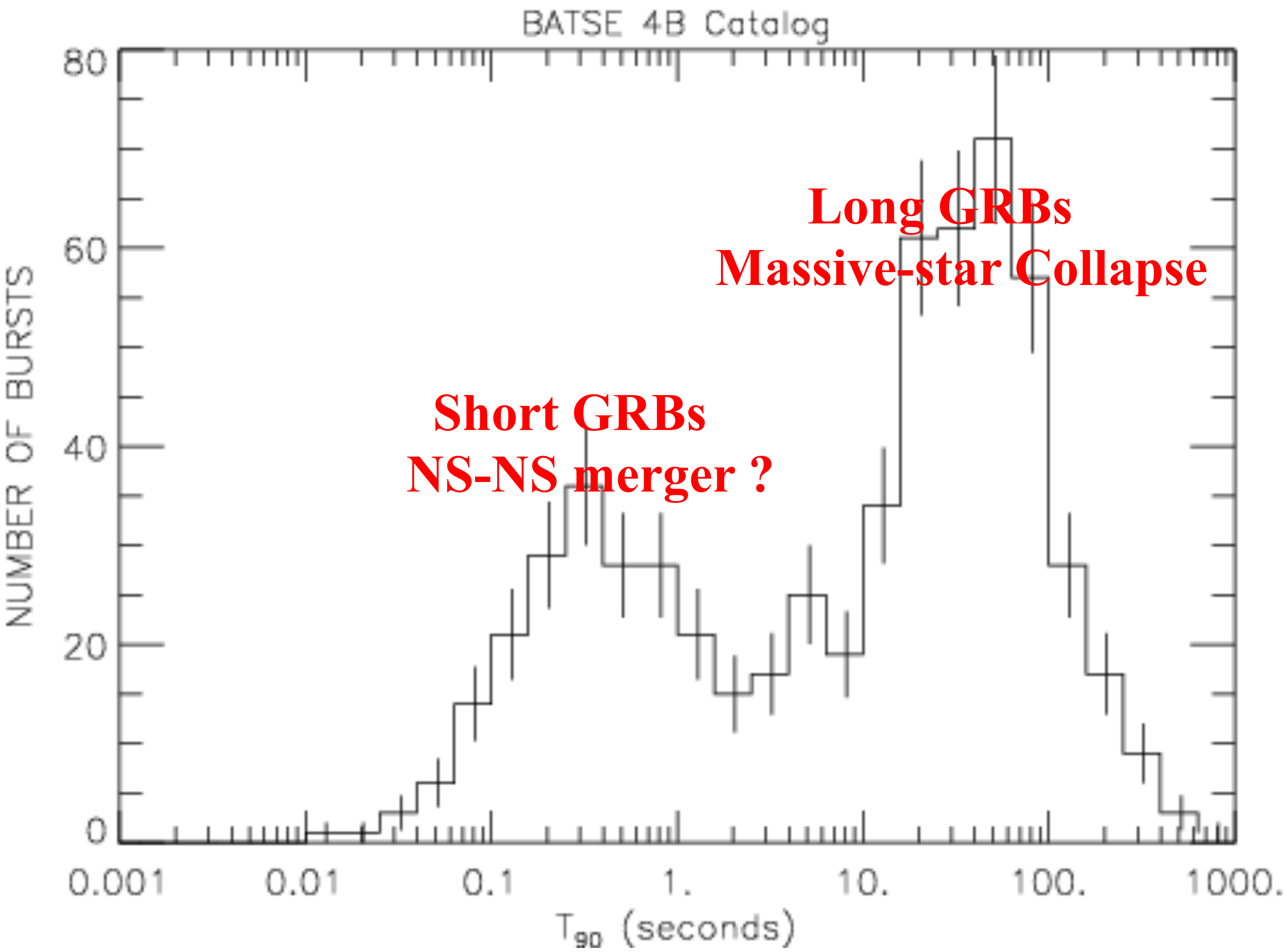


Short GRBs and Long GRBs



(From BATSE 4Br GRB catalog)

Bimodal distribution of GRB durations

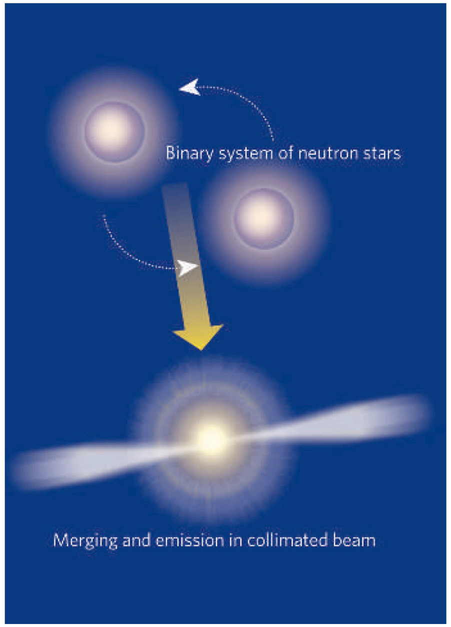


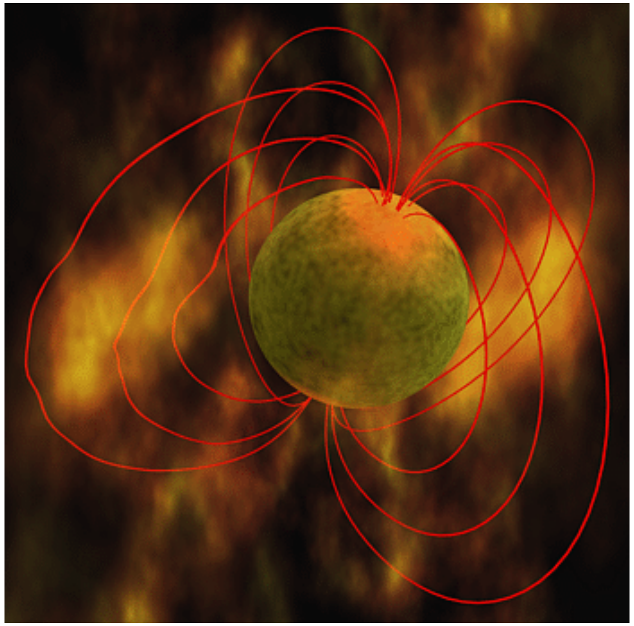
Long GRBs
Massive-star Collapse

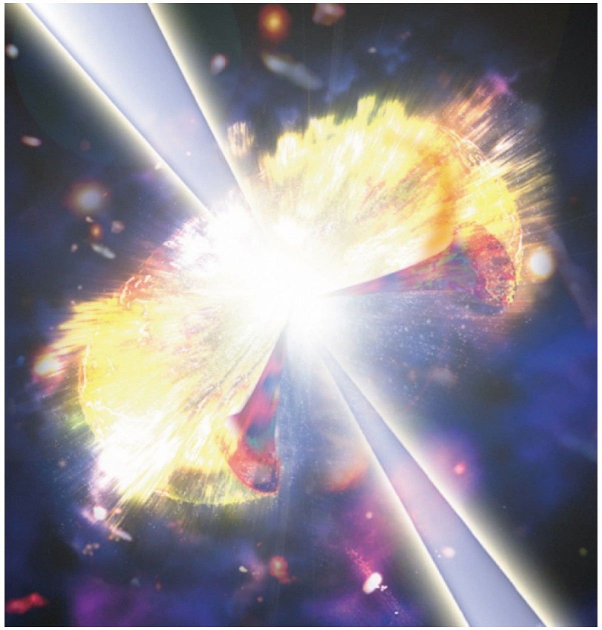
Short GRBs
NS-NS merger ?

Origin of short GRBs

1. Compact binary (NS-NS, NS-BH) merger
2. Giant flare of soft gamma repeater
3. Others ?

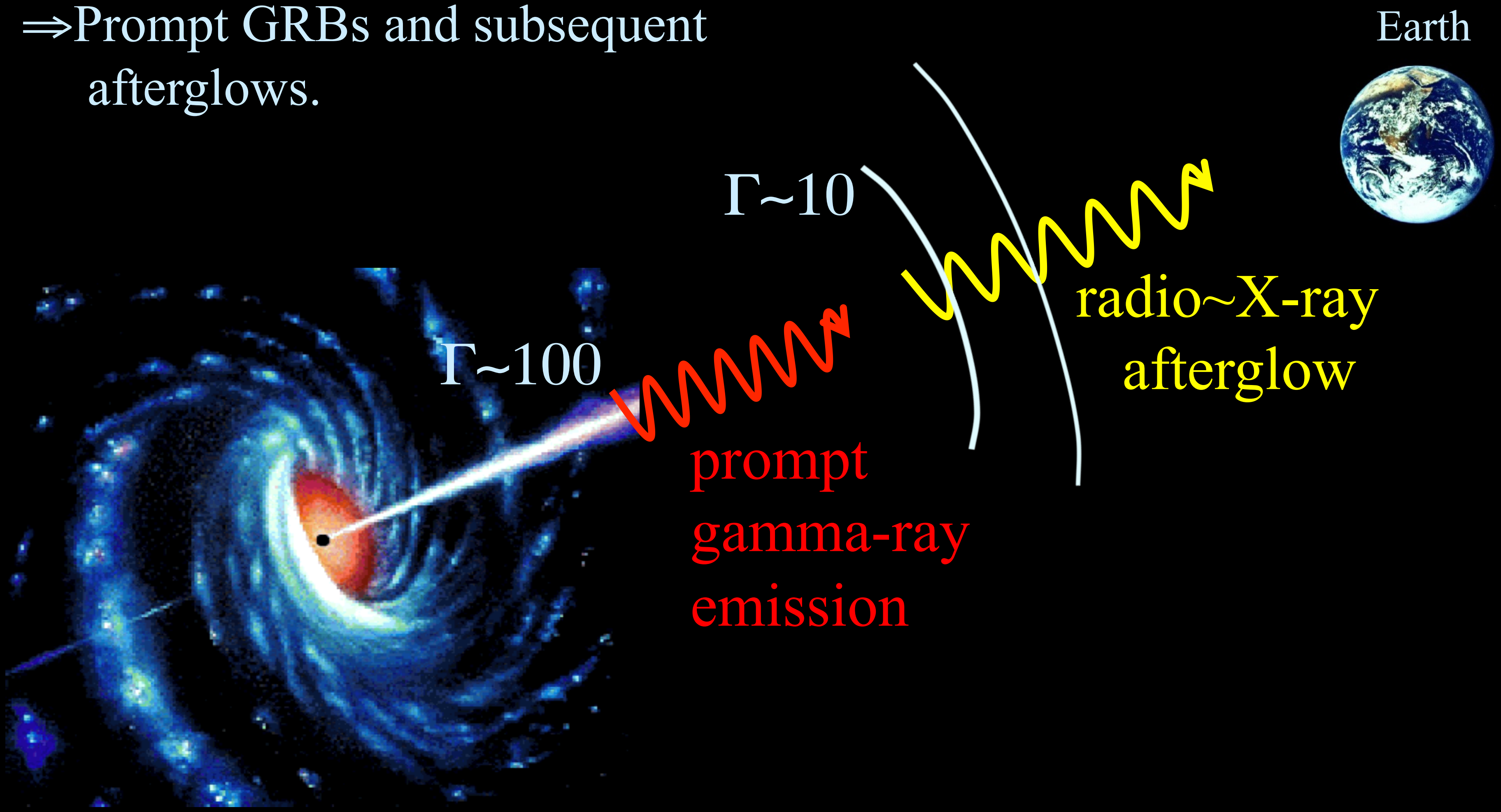






Standard model of typical GRBs:

Relativistic jets from accretion disk around BH.
⇒Dissipation of kinetic energy.
⇒Prompt GRBs and subsequent afterglows.



Energy conversion in HE astrophysics

Source energy

↓ ?

Kinetic energy

↓ Shock dissipation
Particle acceleration etc.

Thermal/Non-thermal energy

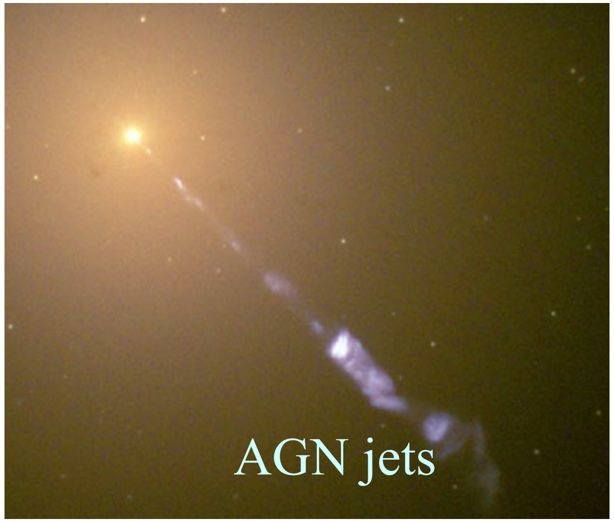
↓

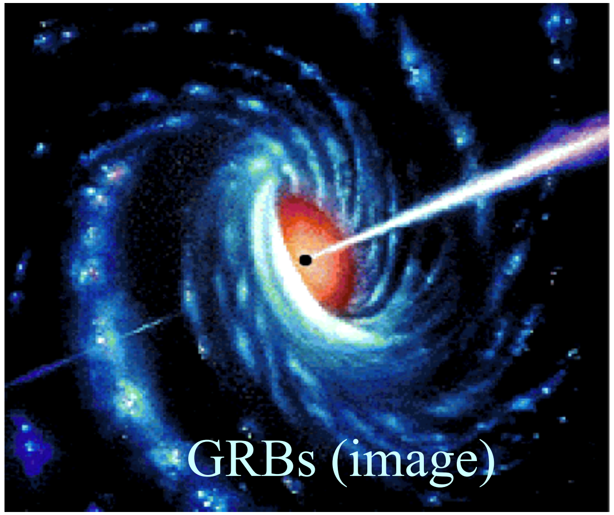
Radiation energy

Optically thick region

Optically thin region


Supernova remnants

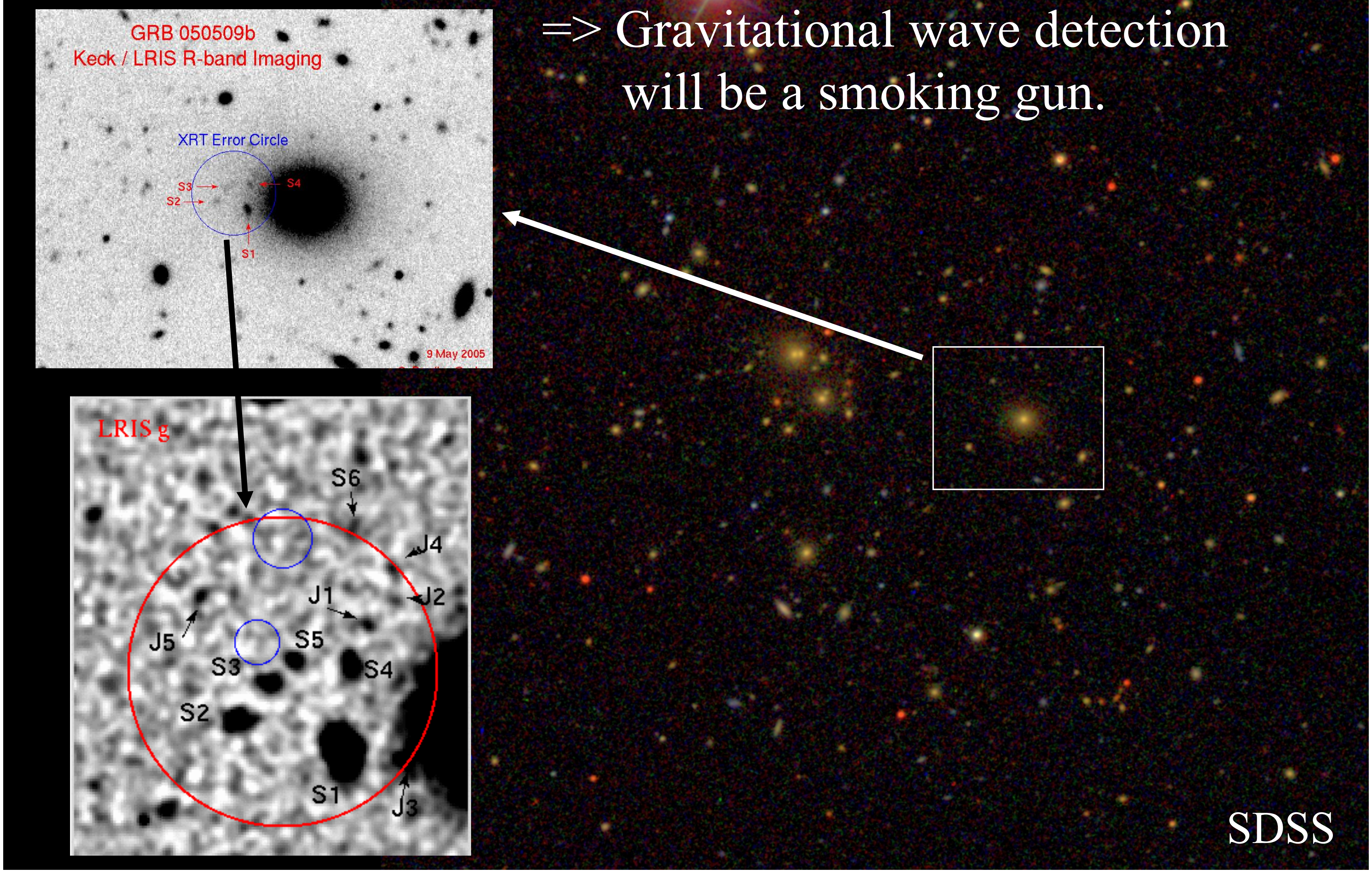

AGN jets


GRBs (image)

GRB 050509b: short GRB from the elliptical galaxy?

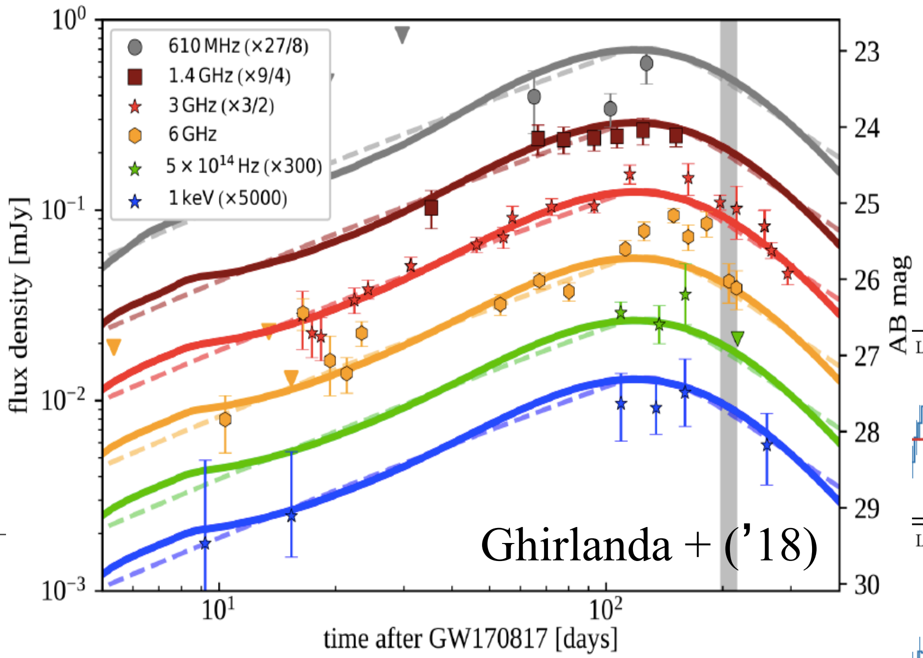
=> likely from NS-NS merger?

=> Gravitational wave detection
will be a smoking gun.

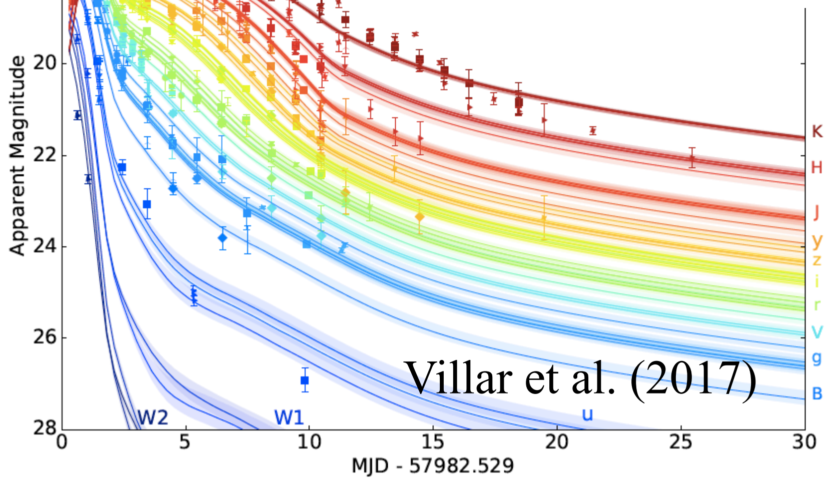


GW 170817 / GRB 170817A / AT 2017gfo / SSS17a / DLT17ck

GW, short gamma-ray burst, UV/opt/IR macronova, and radio~X afterglow.

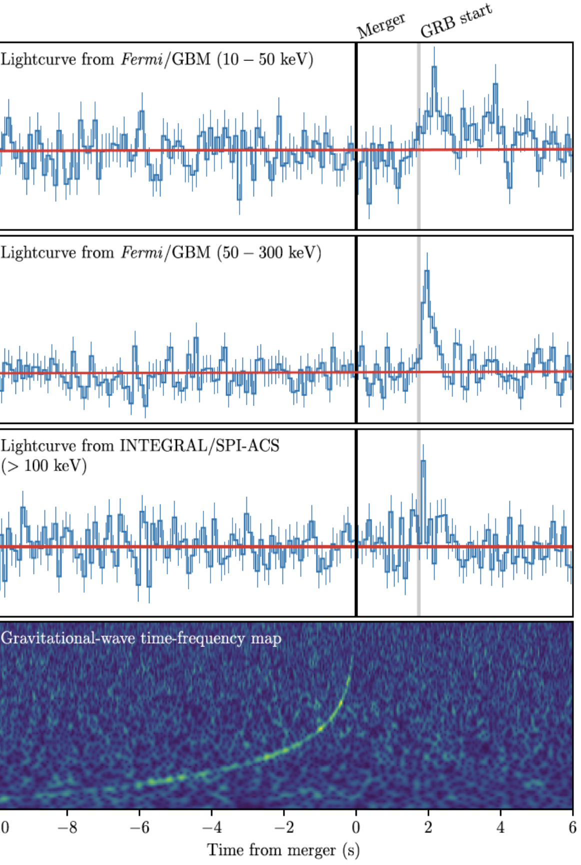


Ghirlanda + ('18)



Villar et al. (2017)

LIGO/VIRGO (2017), ApJ



GW 170817 & S-GRB 170817A

T = 0 : GW 170817

NS-NS merge: inclination angle ~25 deg.

T = 1.7 sec : short GRB 170817A.

very weak gamma-ray emission (~ 10^{-4} x typical S-GRBs)
=> off-axis jet emission, or cocoon emission?

T ~ 10 hr : kilonova (macronova) at IR/optical/UV.

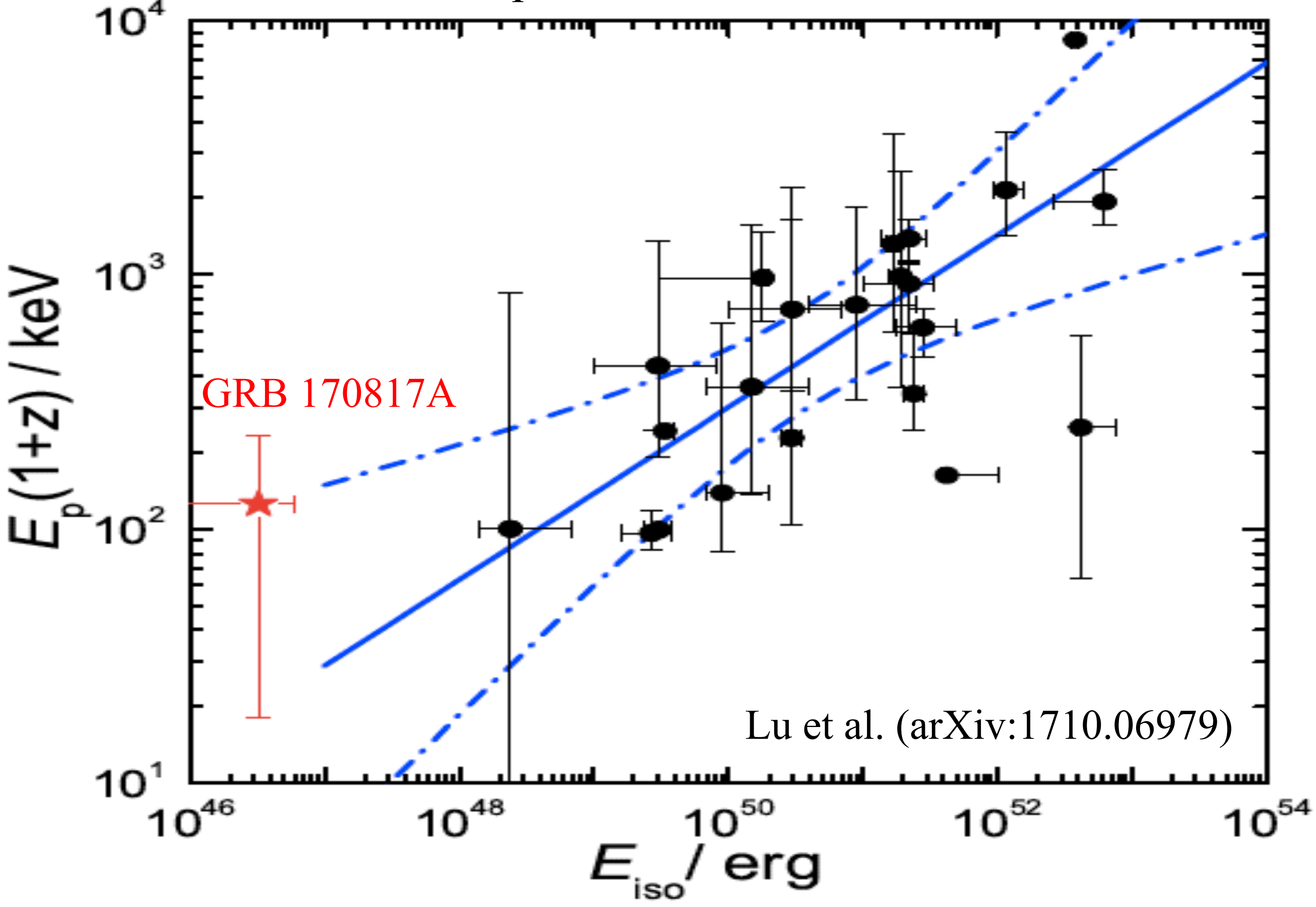
=> r-process elements synthesized.

T ~ 10~10^2 day : Afterglow at radio~X-ray.

=> relativistic jet ($\Gamma \sim 4$ at T~10^2 day, but initial Γ unknown).
why rising up to ~10^2 day? (structured jet? cocoon?)

GRB 170817A is intrinsically under-luminous, less-energetic.

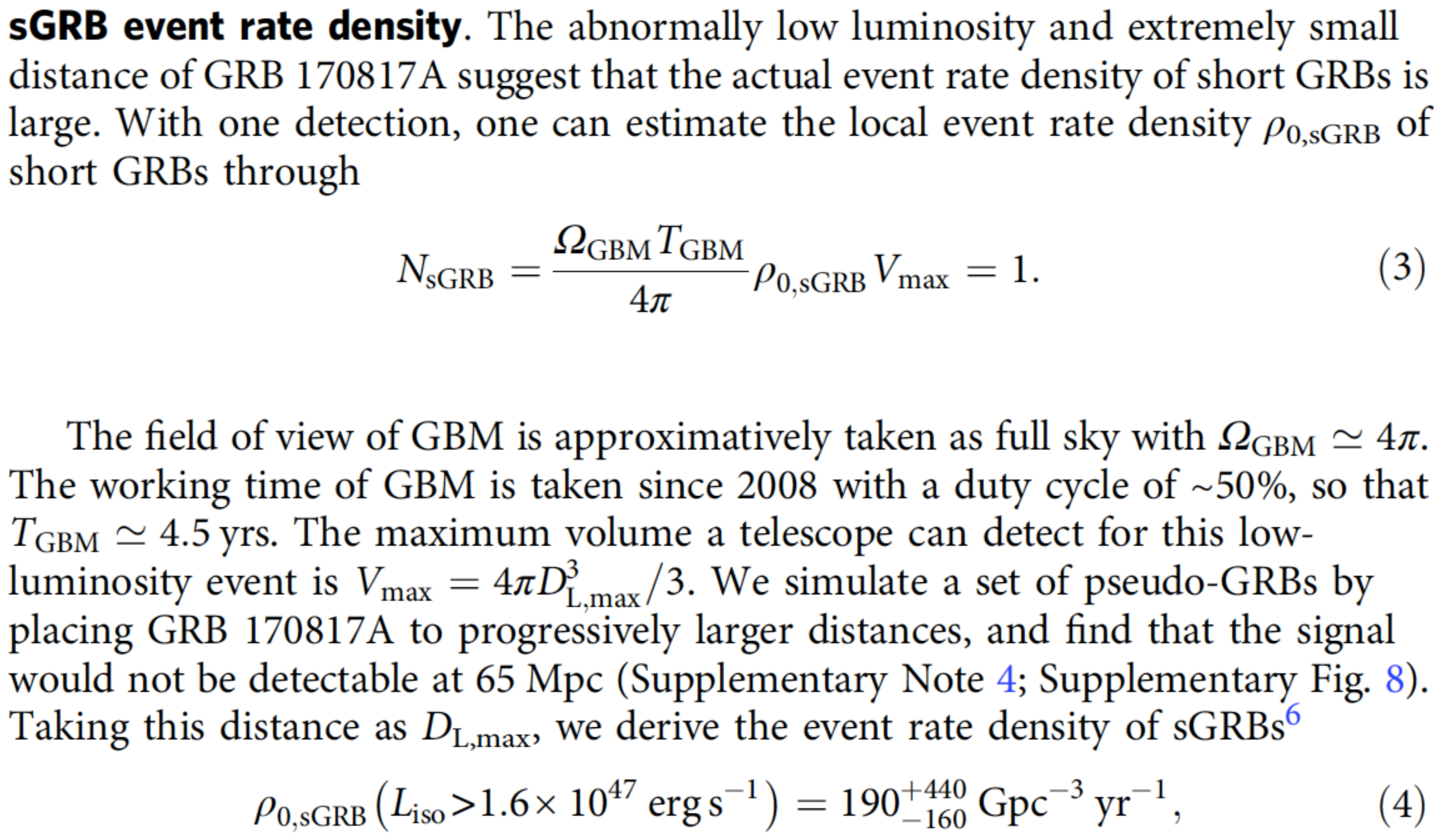
Ep- Eiso for short GRBs



Lu et al. (arXiv:1710.06979)

Fig. 10.— $E_{\rm iso}$ as a function of $E_{\rm p}$ in the burst frame for a sample of sGRB taken from Zhang et al. (2009). The red star is GRB 170817A. The solid line is the Spearman linear fit together with its 2σ confidence level.

Event rate of GRB 170817A –like GRBs ~ 200 yr $^{-1}$ Gpc^{-3}



sGRB event rate density. The abnormally low luminosity and extremely small distance of GRB 170817A suggest that the actual event rate density of short GRBs is large. With one detection, one can estimate the local event rate density $\rho_{0,\mathrm{sGRB}}$ of short GRBs through

$$N_{\mathrm{sGRB}} = \frac{\Omega_{\mathrm{GBM}} T_{\mathrm{GBM}}}{4\pi} \rho_{0,\mathrm{sGRB}} V_{\max} = 1. \tag{3}$$

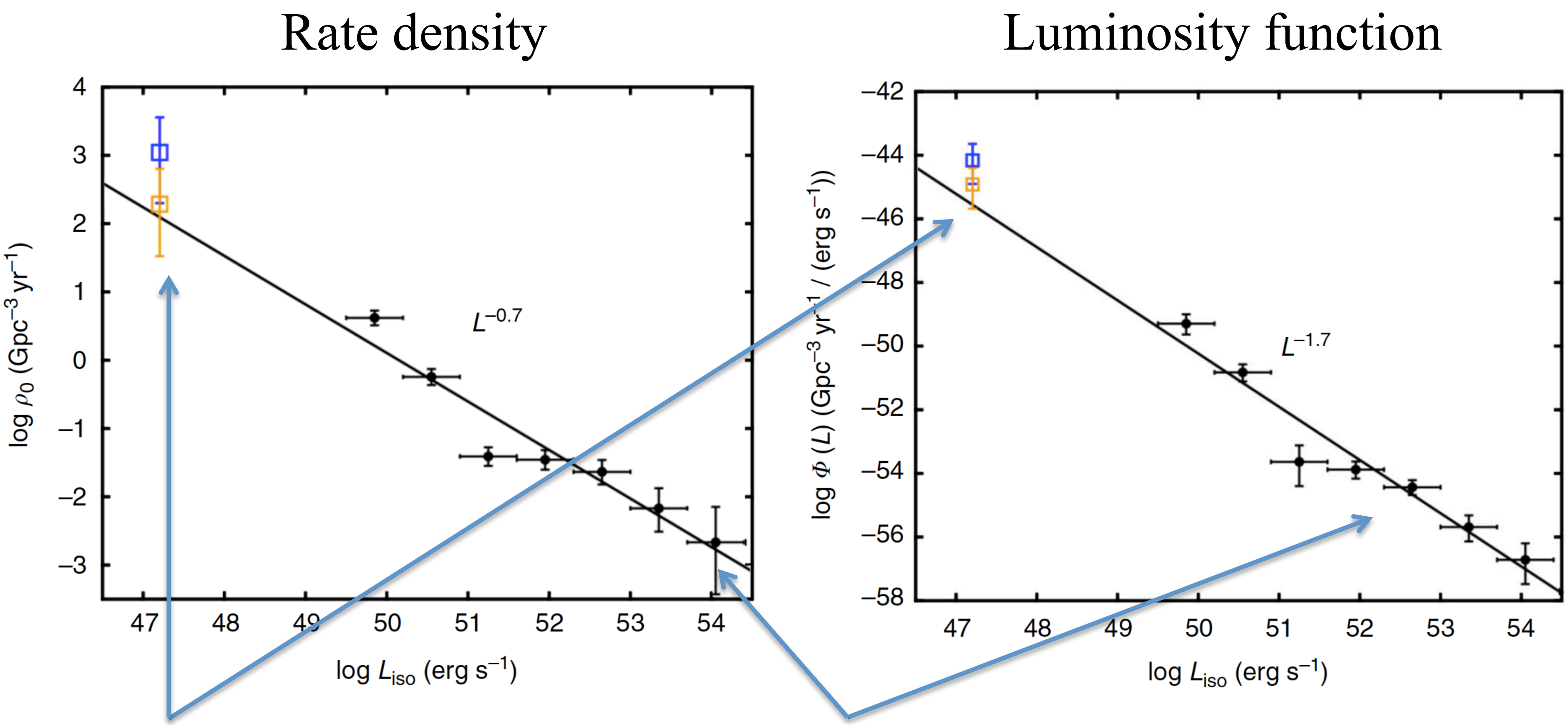
The field of view of GBM is approximatively taken as full sky with $\Omega_{\mathrm{GBM}} \simeq 4\pi$. The working time of GBM is taken since 2008 with a duty cycle of ~50%, so that $T_{\mathrm{GBM}} \simeq 4.5$ yrs. The maximum volume a telescope can detect for this low-luminosity event is $V_{\max} = 4\pi D^3_{\mathrm{L,max}}/3$. We simulate a set of pseudo-GRBs by placing GRB 170817A to progressively larger distances, and find that the signal would not be detectable at 65 Mpc (Supplementary Note 4; Supplementary Fig. 8). Taking this distance as $D_{\mathrm{L,max}}$, we derive the event rate density of sGRBs[6]

$$\rho_{0,\mathrm{sGRB}}\left(L_{\mathrm{iso}} > 1.6 \times 10^{47}\ \mathrm{erg\,s^{-1}}\right) = 190^{+440}_{-160}\ \mathrm{Gpc^{-3}\,yr^{-1}}, \tag{4}$$

cf. Event rate density for NS-NS mergers ~ $1100^{+2500}_{-910}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Zhang et al. 2018

Rate density & Luminosity function


Rate density

Luminosity function

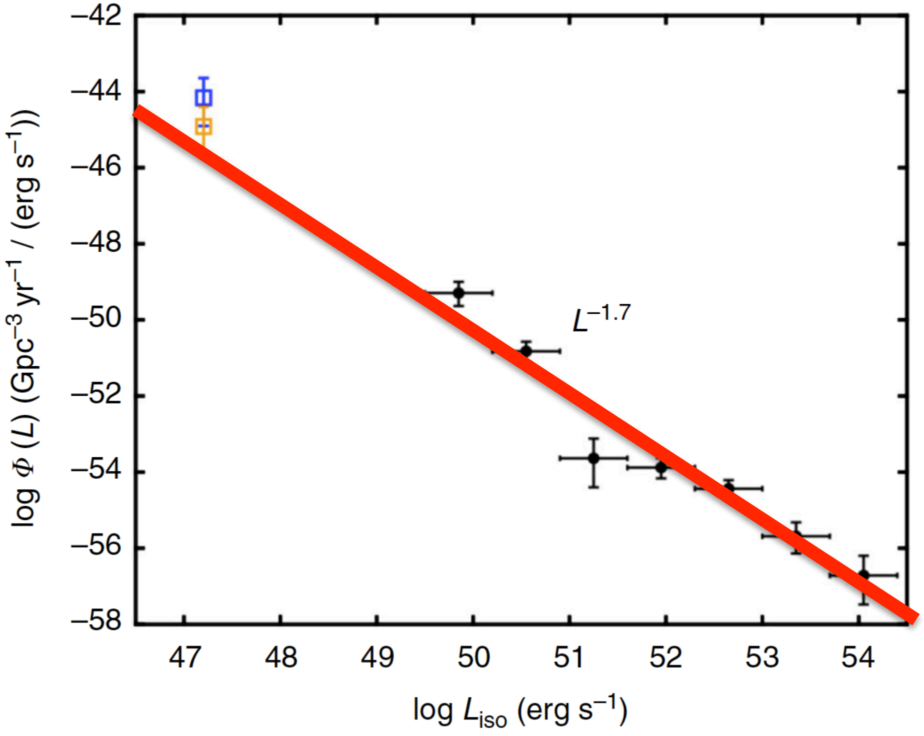
170817A-like
short GRBs

“Normal”
short GRBs

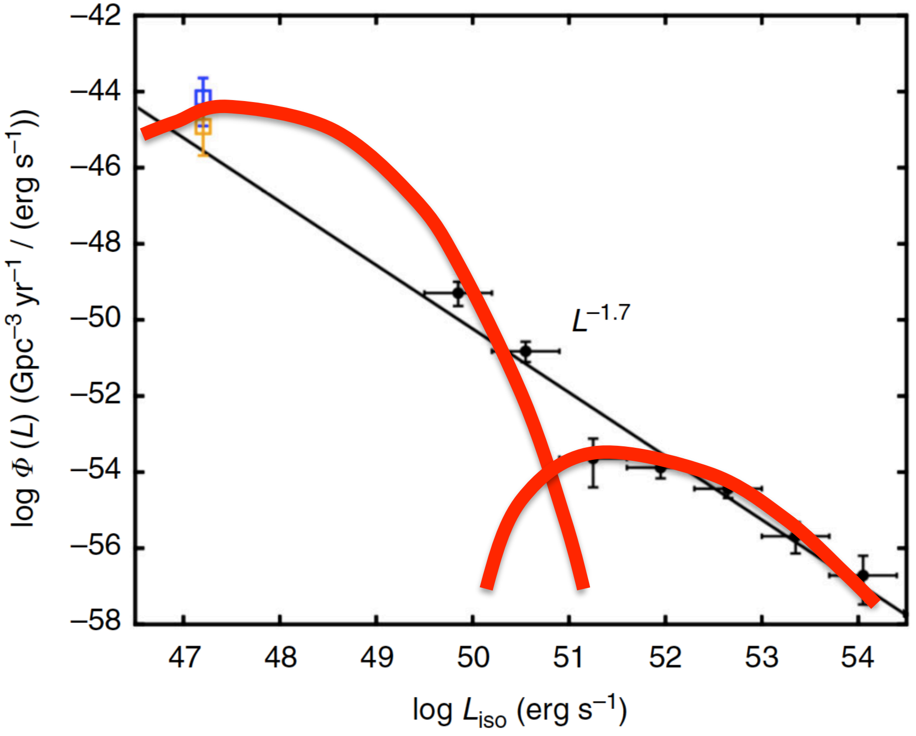
Zhang et al. 2018

Which do you like?

Single population



2 (or 3?) components



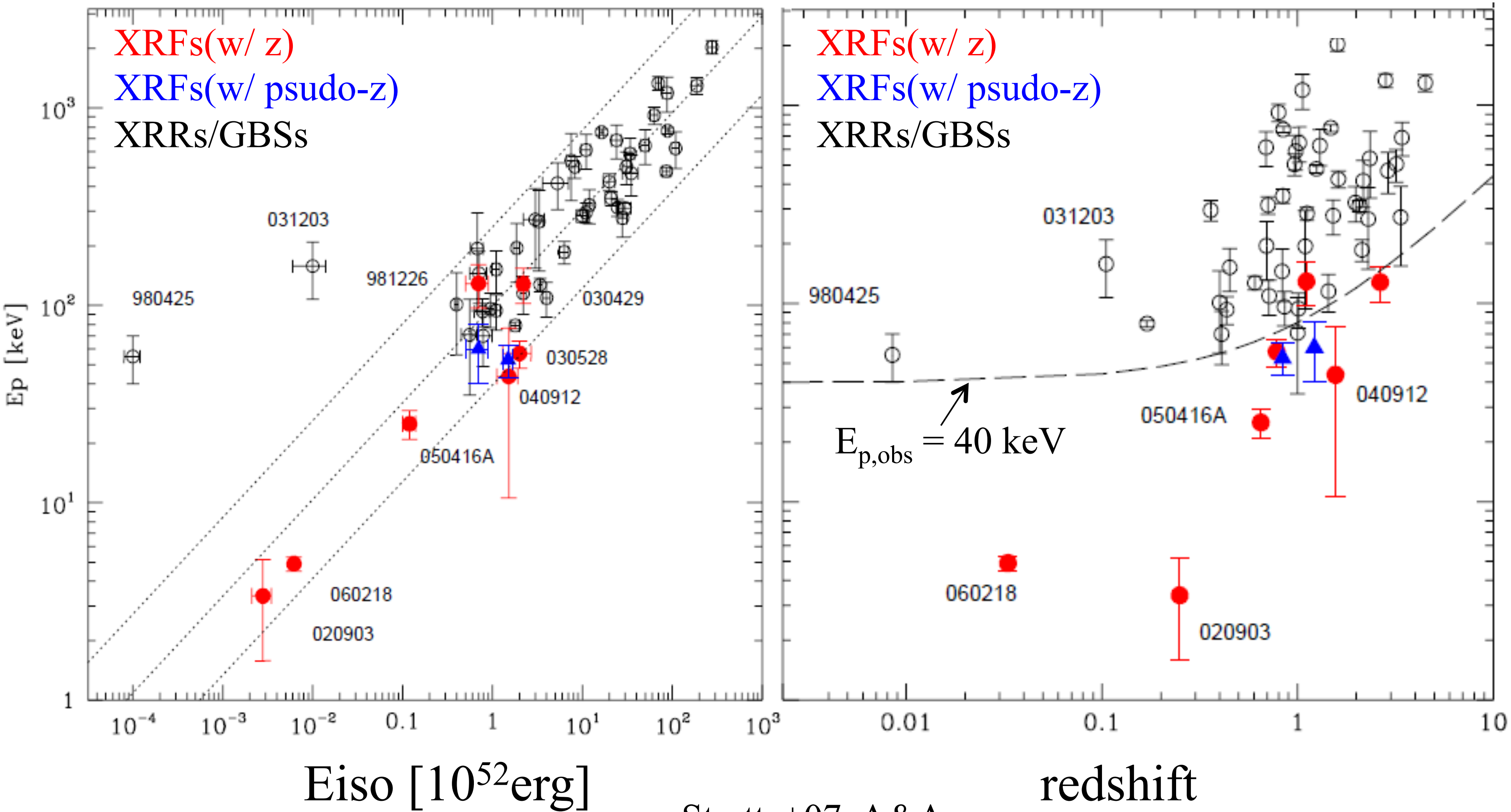
Zhang et al. 2018

Similar to GRB 980425/SN1998bw ?

The low-luminosity (long) GRB is the sub-class of LGRB.

Ep(1+z) vs. Eiso

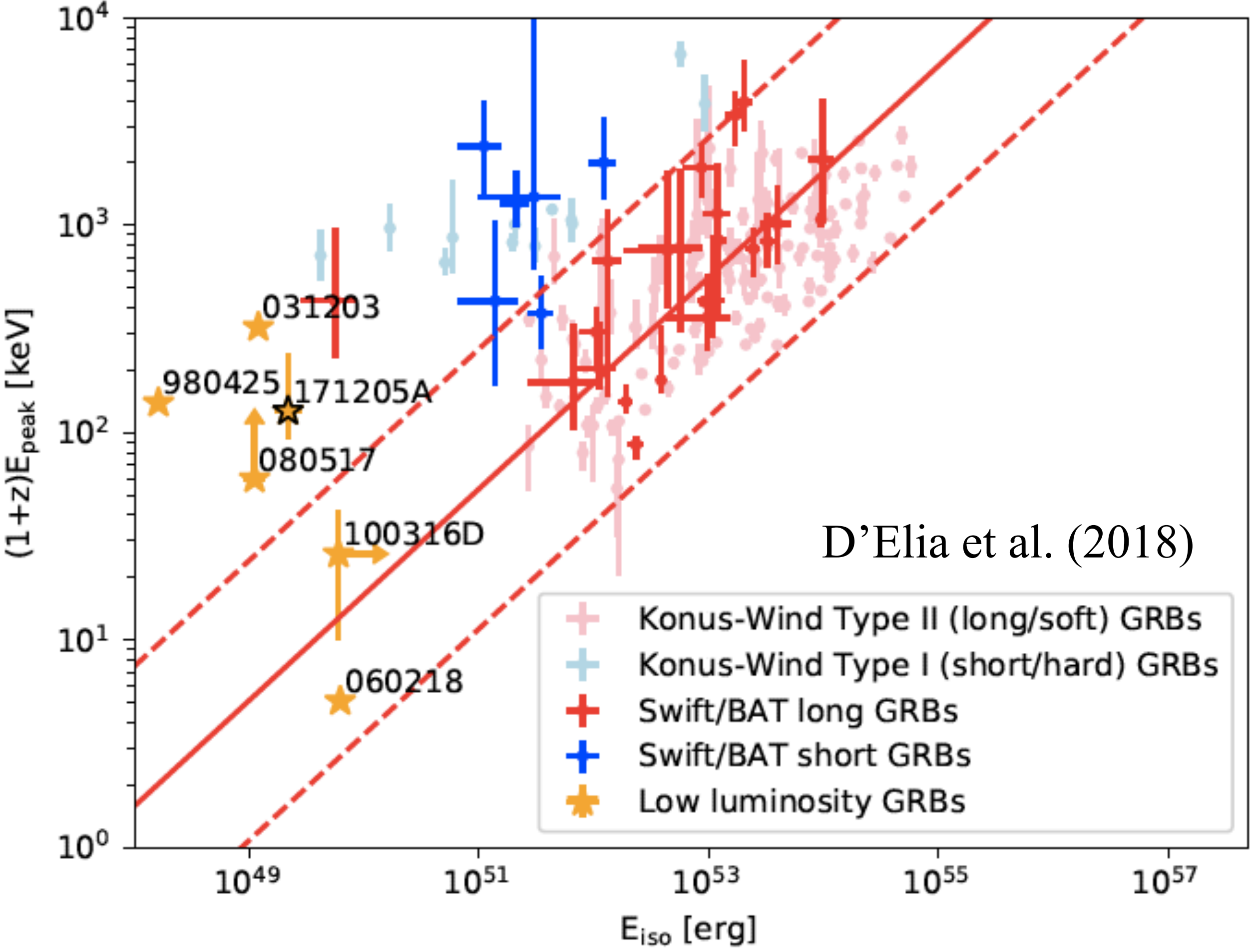
Ep(1+z) vs. z



Stratta+07, A&A

The low-luminosity (long) GRB is the sub-class of LGRB.

Ep(1+z) vs. Eiso



Observed low γ-ray luminosity of short GRB 170817A:

Two different ways of thinking

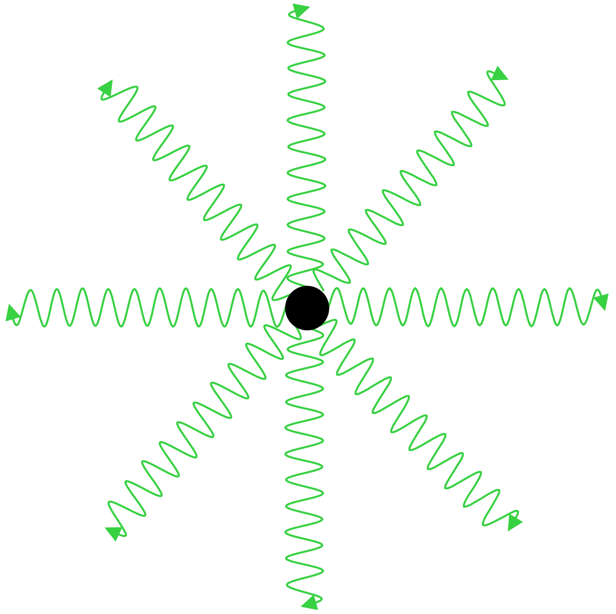
(1) GRB 170817A = (intrinsically) luminous short GRB

GRB 170817A is the same as sGRBs detected so far.
Just the viewing angle is different.
Apparently luminous short GRBs so far is seen on axis,
while GRB 170817A is viewed off-axis (Ioka & Nakamura,18).
=> All short GRBs detected so far = NS-NS merger

(2) GRB 170817A = (intrinsically) under-luminous GRB

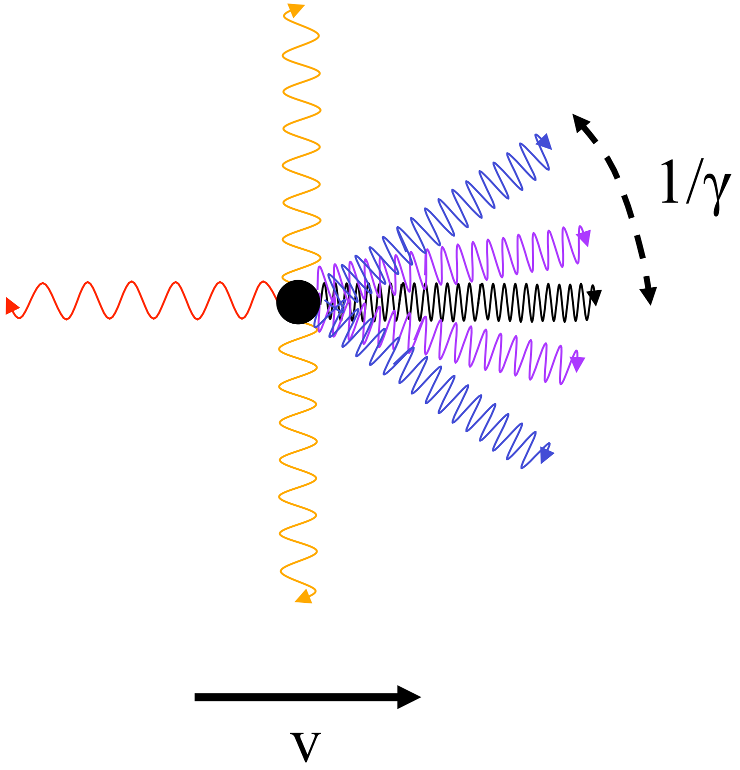
GRB 170817A is different from short GRBs so far, but
some of them (whose distance is unknown) may be the same
as GRB 170817A. (e.g., Kaliwal et al. 2018)。
=> new sub-class of short GRBs !
e.g., NS-NS or NS-BH merger ??? others ???

Relativistic beaming and Doppler effects



v = 0

(matter comoving frame)

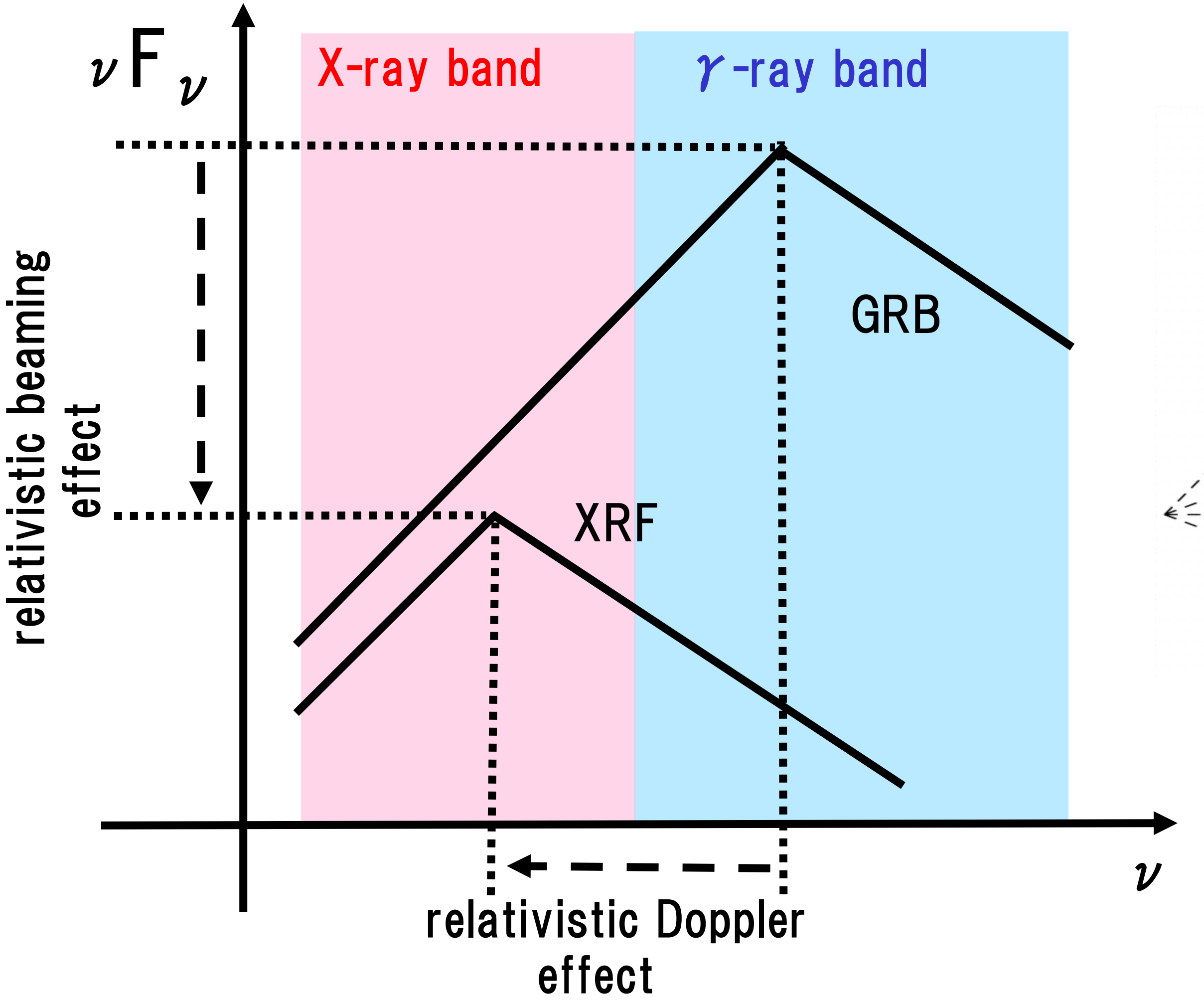


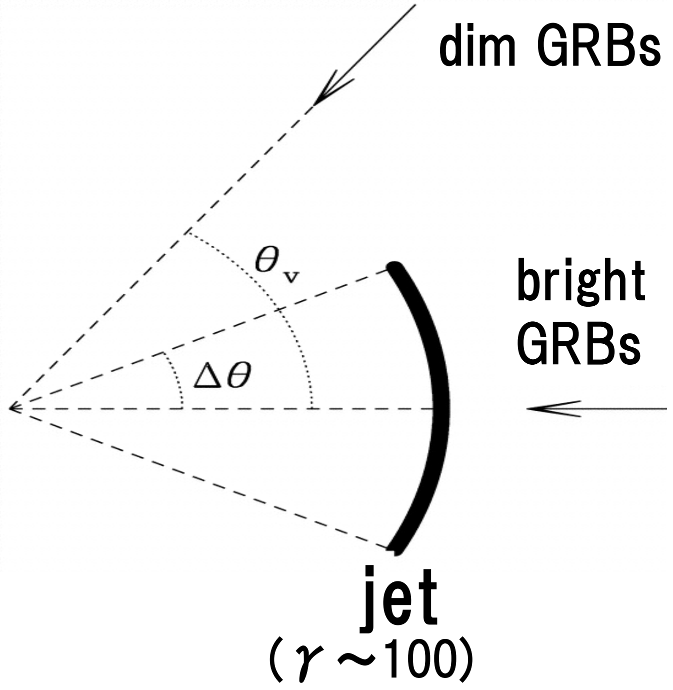
(observer frame)

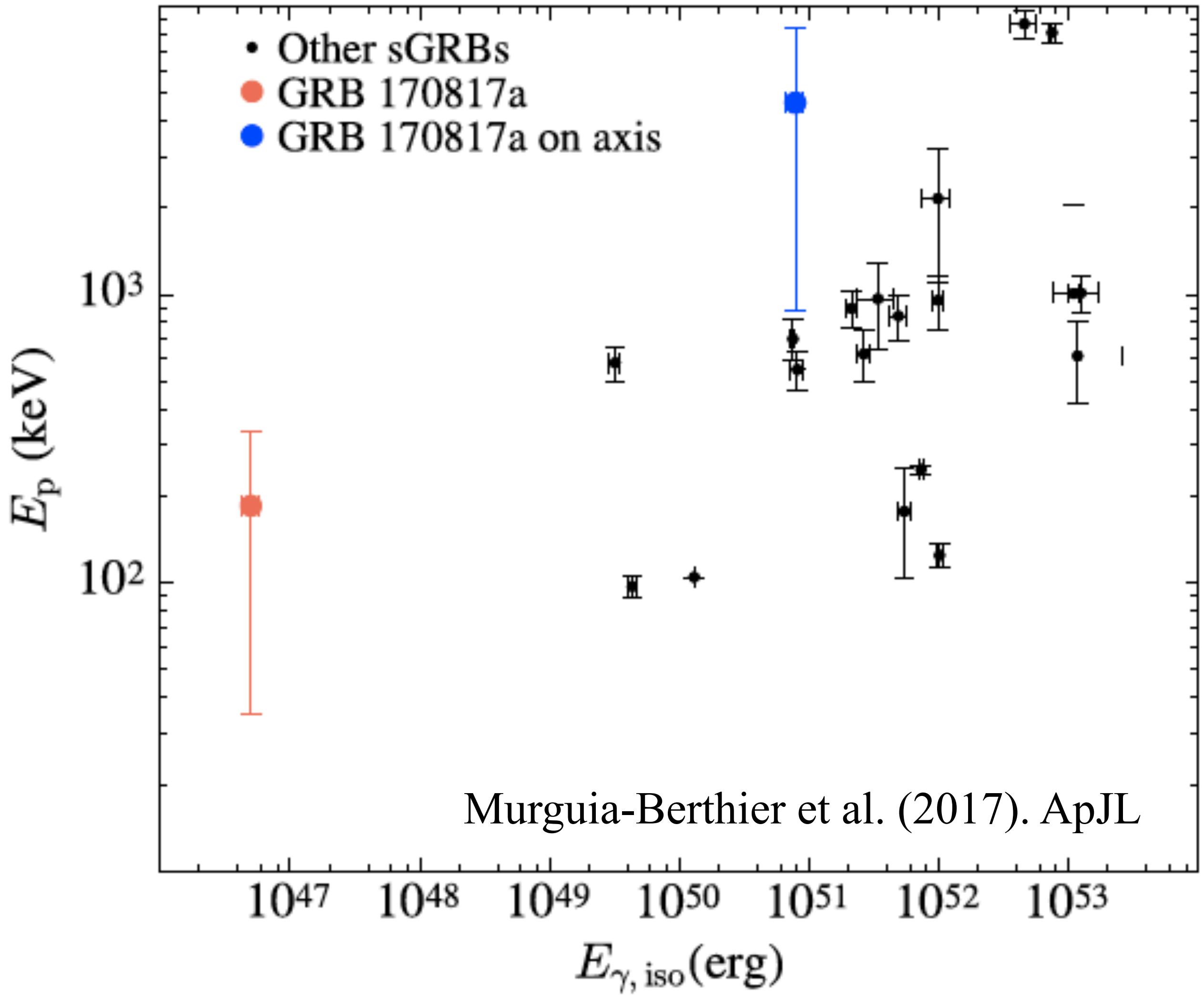
$\gamma = (1 - \beta^2)^{-1/2}$, $\beta = v/c$

Off-Axis Jet Model

The X-ray flashes (and the soft GRBs) are the typical GRBs observed from off-axis viewing angle. (Ioka & Nakamura 02; Yamazaki, Ioka & Nakamura 03,04,05)



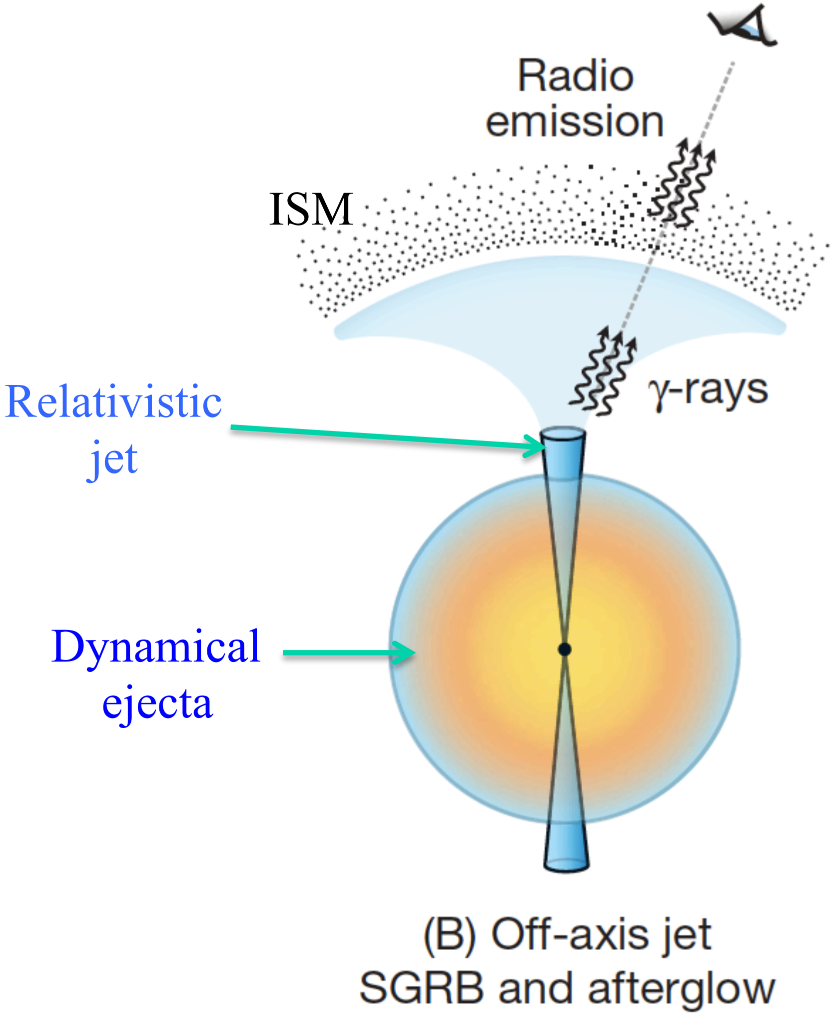




Murguia-Berthier et al. (2017). ApJL

Figure 4. Location of GRB 170817A in the E_p and $E_{\gamma,\mathrm{iso}}$ plane, from Savchenko et al. (2017) and LIGO Scientific Collaboration & Virgo Collaboration et al. (2017). Also shown is the location if GRB 170817A were on-axis under the assumption of a misaligned, sharp-edged jet. This assumes a Lorentz factor of $\Gamma \approx 50$ and $\Gamma(\theta_{\mathrm{obs}} - \theta_0) \approx 5$ (Section 4.2). The data for the other sGRBs are taken from Tsutsui et al. (2013) and D'Avanzo et al. (2014).

GRB170817A = Off-axis jets ?
Relativistic jets produce gamma and radio emission



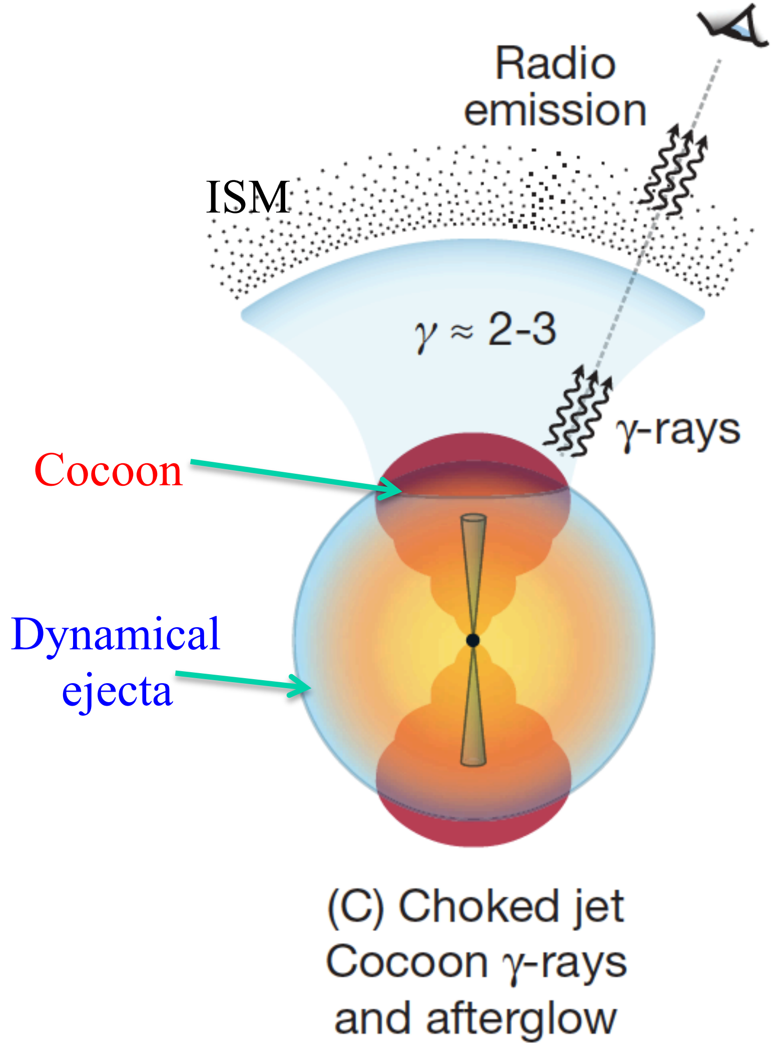
(B) Off-axis jet
SGRB and afterglow

Decelerating jet
interacts with ISM
=> radio

Mooley et al. (2018)

Alternative: Cocoon emission?

Cocoon is produced when the jet penetrates into dynamical ejecta.
(Nakar, Piran, Hotokezaka,···)



Cocoon interacts with ISM
=> radio afterglow

Shock breakout
=> gamma rays (sGRB)

Mooley et al. (2018)

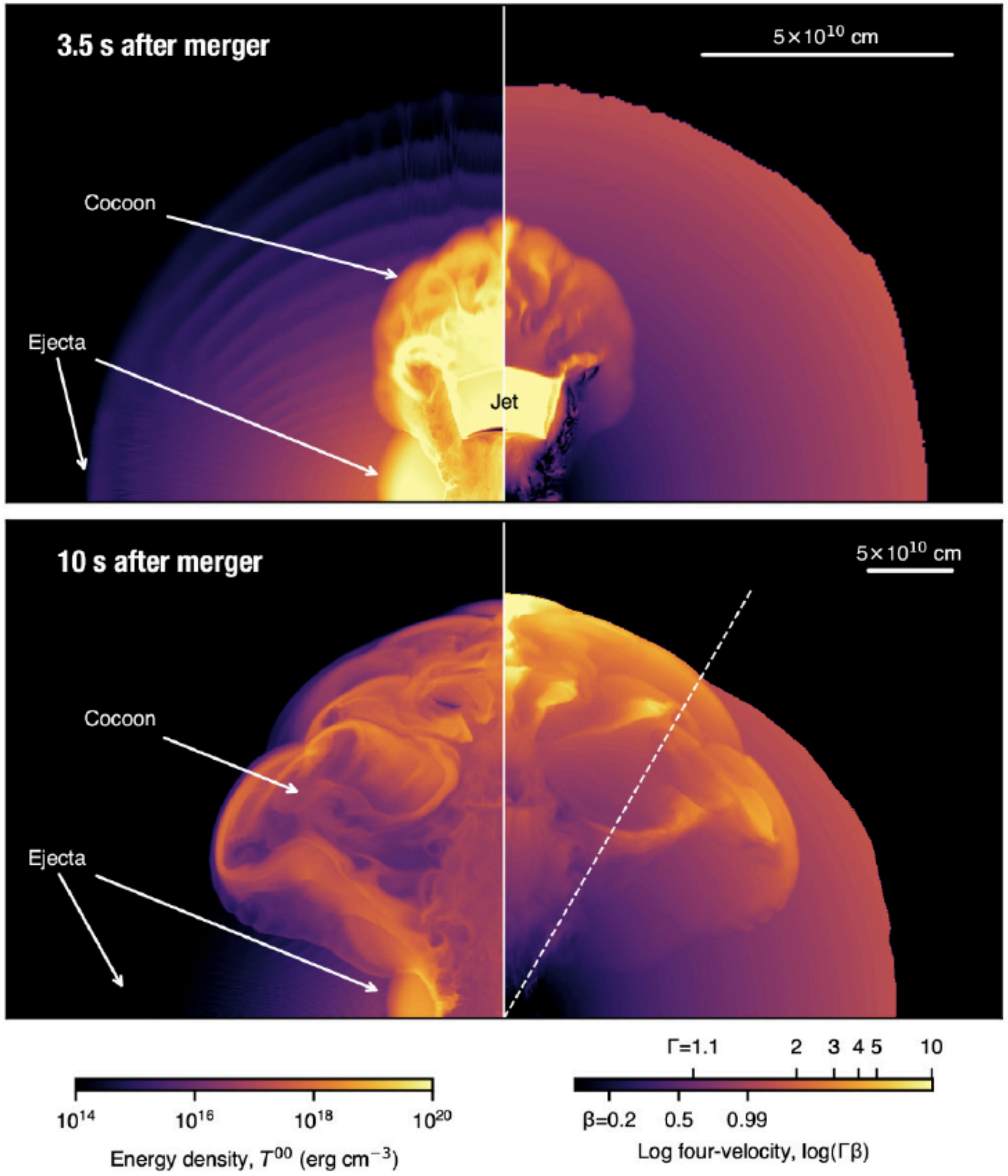
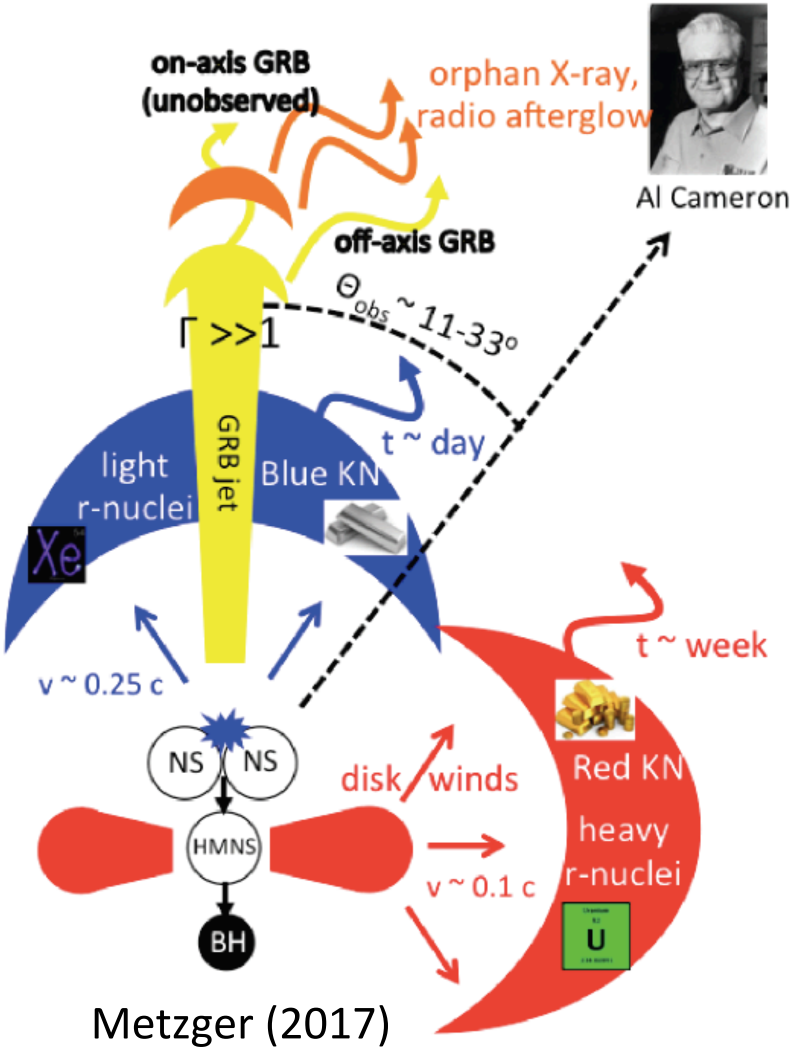


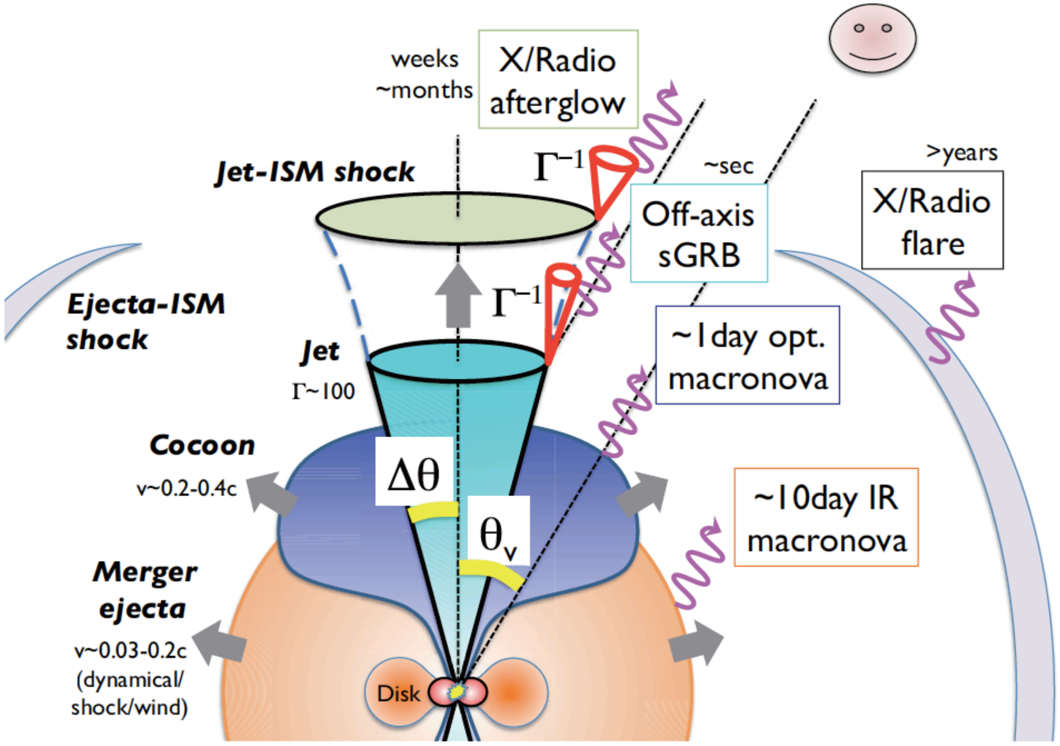
Fig. 6. Snapshots from a hydrodynamic simulation of a cocoon generated by a choked jet with emission consistent with EM170817 (see (*10*) for details). The left half-plane is color-coded by logarithmic energy density (erg cm^{-3}) and depicts the energetics. The right half-plane is color-coded by logarithmic four-velocity ($\Gamma\beta$) and depicts the kinematics. The observer is at an angle of 40°, the ejecta mass is 0.1 $M_\odot$ and the jet luminosity is 2.6×10^{51} erg s^{-1}. Based on this simulation, a bolometric light curve is calculated and shown in Fig. 2. (**A**) This snapshot is taken at 3.5 s, shortly after the jet injection stops. The jet is fully choked by 4s. (**B**) This snapshot is taken at 10 s when the cocoon breaks out. The breakout radius is 2.4×10^{11} cm which corresponds to 8 light-seconds. Thus, the delay between the observed γ-ray photons and the NS-NS merger is the difference in these times, 2 s. The Lorentz factor of the shock upon breakout is between 2 and 3.

Kasliwal+2017, Science

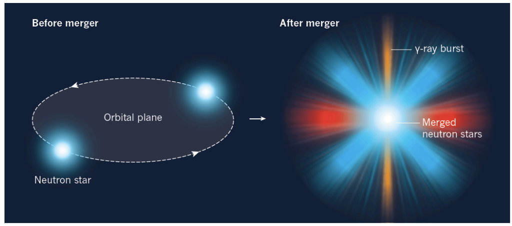
Just after LIGO press release (2017/10/17), Many papers concluded scenario (1) (GRB170817 = luminous short GRB jet viewed off-axis).

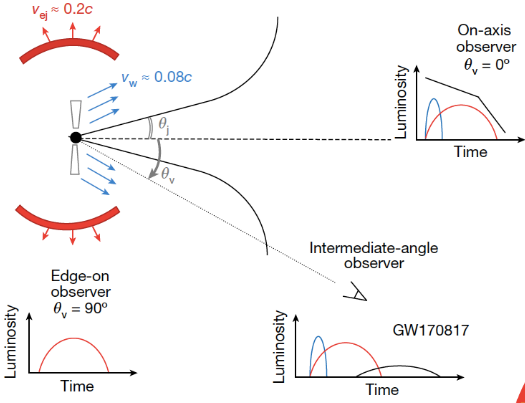


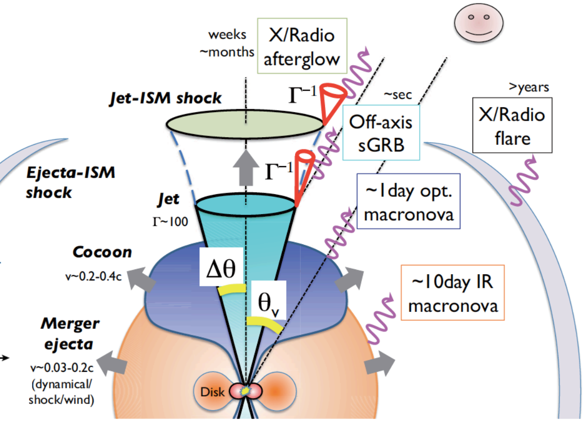
Metzger (2017)

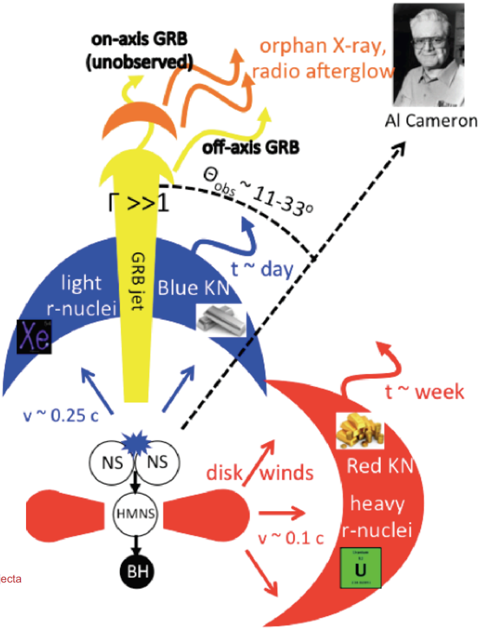


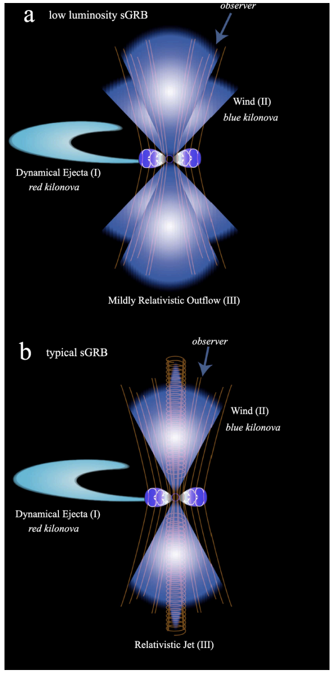
Ioka & Nakamura (2017)

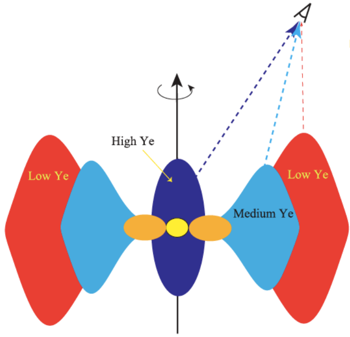

Before merger
After merger
Orbital plane
Neutron star
γ-ray burst
Merged neutron stars

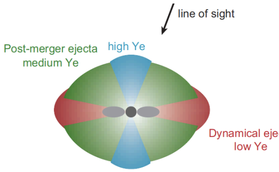

$v_{ej} \approx 0.2c$
$v_w \approx 0.08c$
θ_j
θ_v
On-axis observer $\theta_v = 0°$
Luminosity
Time
Intermediate-angle observer
Edge-on observer $\theta_v = 90°$
Luminosity
Time
GW170817
Luminosity
Time

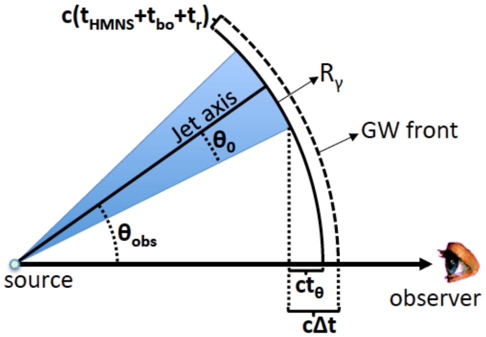

weeks ~months
X/Radio afterglow
Jet-ISM shock
Γ^{-1}
~sec
Off-axis sGRB
>years
X/Radio flare
Ejecta-ISM shock
Γ^{-1}
Jet
Γ~100
~1day opt. macronova
Cocoon
v~0.2-0.4c
Δθ
θ_v
~10day IR macronova
Merger ejecta
v~0.03-0.2c (dynamical/ shock/wind)
Disk

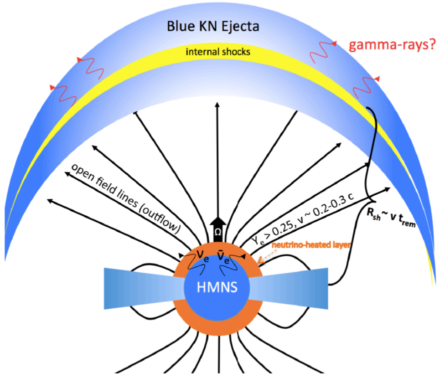

on-axis GRB (unobserved)
orphan X-ray, radio afterglow
Al Cameron
off-axis GRB
Γ >>1
Θ_{obs} ~ 11-33°
light r-nuclei
GRB jet
Blue KN
t ~ day
Xe
v ~ 0.25 c
t ~ week
NS NS
HMNS
BH
disk winds
Red KN
heavy r-nuclei
v ~ 0.1 c
U

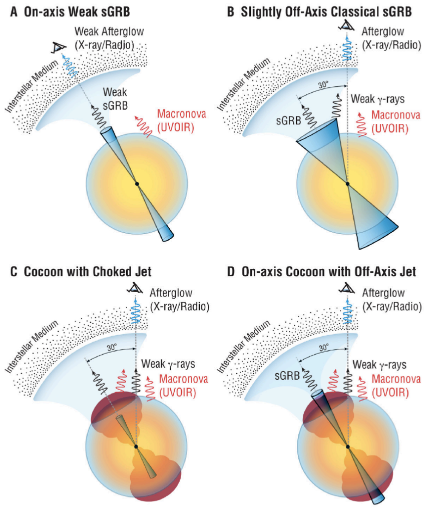

a low luminosity sGRB
observer
Wind (II)
blue kilonova
Dynamical Ejecta (I)
red kilonova
Mildly Relativistic Outflow (III)
b typical sGRB
observer
Wind (II)
blue kilonova
Dynamical Ejecta (I)
red kilonova
Relativistic Jet (III)

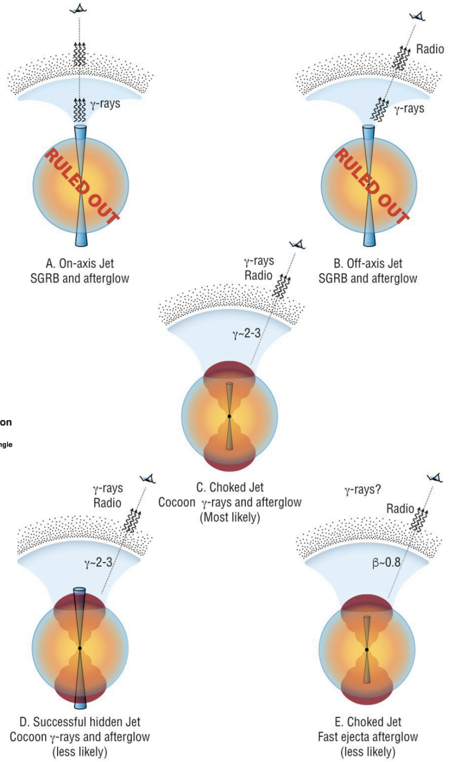

High Ye
Low Ye
Low Ye
Medium Ye

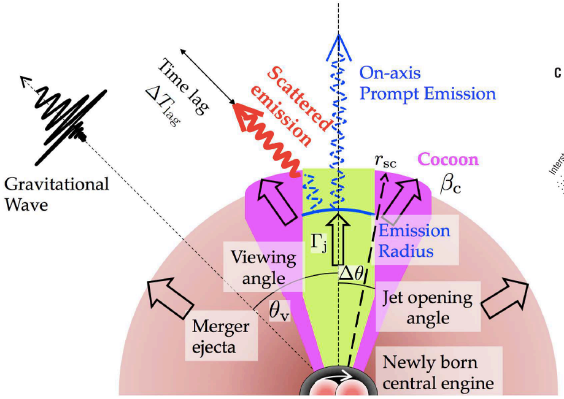

line of sight
Post-merger ejecta medium Ye
high Ye
Dynamical ejecta low Ye

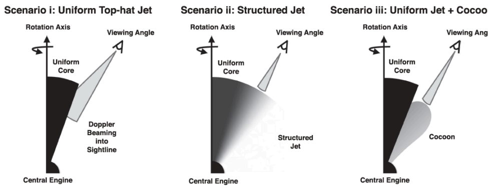

$c(t_{HMNS}+t_{bo}+t_r)$
R_γ
Jet axis
θ_0
GW front
θ_{obs}
source
observer
ct_θ
$c\Delta t$

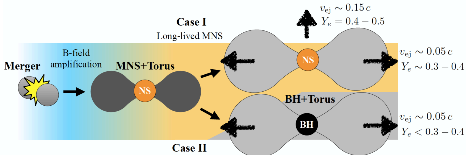

Blue KN Ejecta
internal shocks
gamma-rays?
open field lines (outflow)
$Y_e > 0.25$, v ~ 0.2-0.3 c
$R_{sh} \sim v\, t_{rem}$
neutrino-heated layer
Ω
ν_e $\bar{\nu}_e$
HMNS


A On-axis Weak sGRB
Weak Afterglow (X-ray/Radio)
Interstellar Medium
Weak sGRB
Macronova (UVOIR)
B Slightly Off-Axis Classical sGRB
Afterglow (X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
sGRB
Macronova (UVOIR)
C Cocoon with Choked Jet
Afterglow (X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
Macronova (UVOIR)
D On-axis Cocoon with Off-Axis Jet
Afterglow (X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
sGRB
Macronova (UVOIR)


γ-rays
RULED OUT
A. On-axis Jet SGRB and afterglow
Radio
γ-rays
RULED OUT
B. Off-axis Jet SGRB and afterglow
γ-rays Radio
γ~2-3
C. Choked Jet Cocoon γ-rays and afterglow (Most likely)
γ-rays Radio
γ~2-3
D. Successful hidden Jet Cocoon γ-rays and afterglow (less likely)
γ-rays?
Radio
β~0.8
E. Choked Jet Fast ejecta afterglow (less likely)


Gravitational Wave
Time lag ΔT_{lag}
Scattered emission
On-axis Prompt Emission
r_{sc}
Cocoon
β_c
Emission Radius
Γ_j
$\Delta\theta_j$
Viewing angle
θ_v
Jet opening angle
Merger ejecta
Newly born central engine


Scenario i: Uniform Top-hat Jet
Rotation Axis
Viewing Angle
Uniform Core
Doppler Beaming into Sightline
Central Engine
Scenario ii: Structured Jet
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Central Engine
Scenario iii: Uniform Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Cocoon
Central Engine

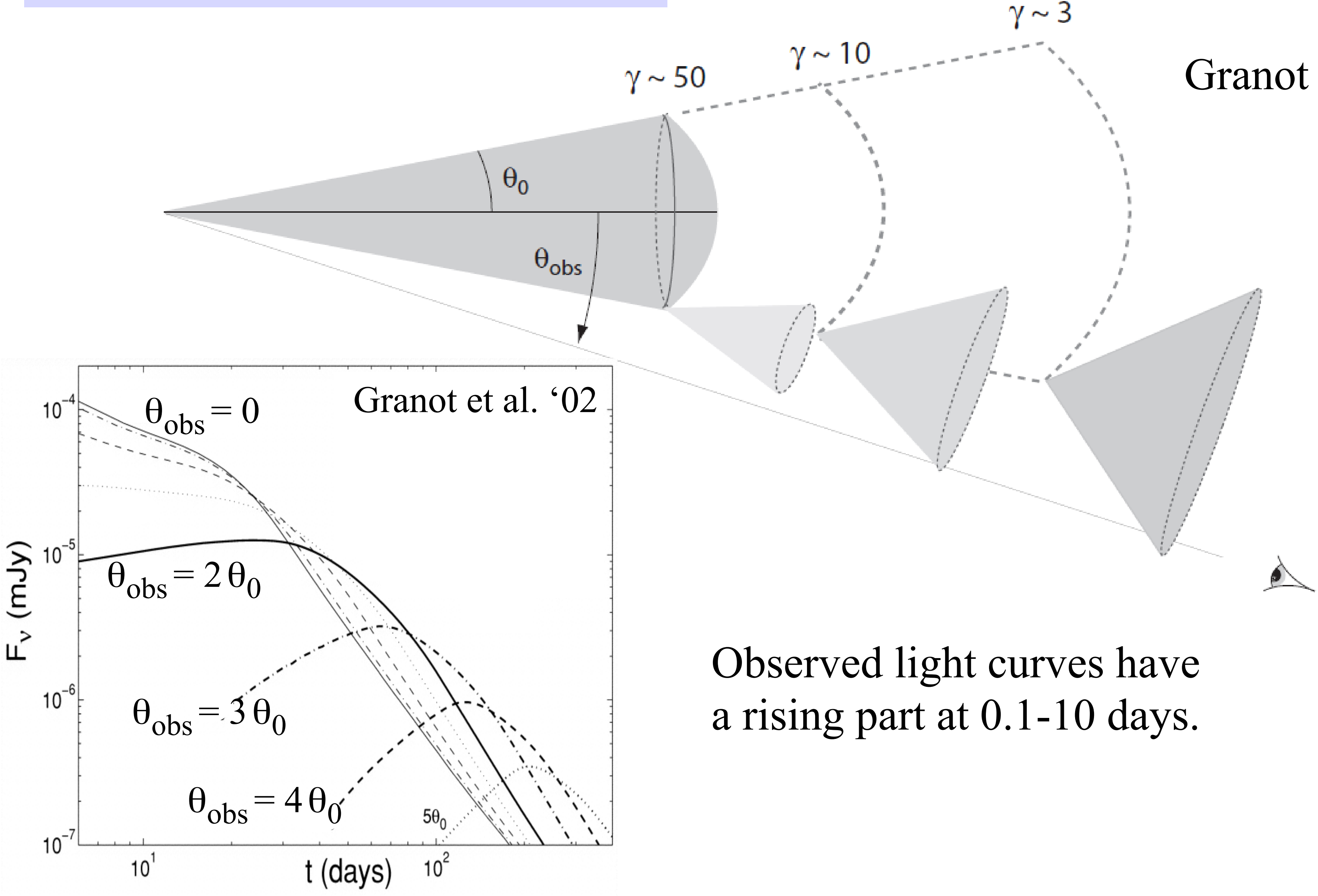

Case I
Long-lived MNS
$v_{ej} \sim 0.15\,c$
$Y_e = 0.4 - 0.5$
Merger
B-field amplification
MNS+Torus
NS
NS
$v_{ej} \sim 0.05\,c$
$Y_e \sim 0.3 - 0.4$
BH+Torus
BH
$v_{ej} \sim 0.05\,c$
$Y_e < 0.3 - 0.4$
Case II

Did GRB 170817A arise from Ultra-relativistic jets as ordinary short GRBs detected so far?

↓

Afterglows ???

Off-axis Afterglows

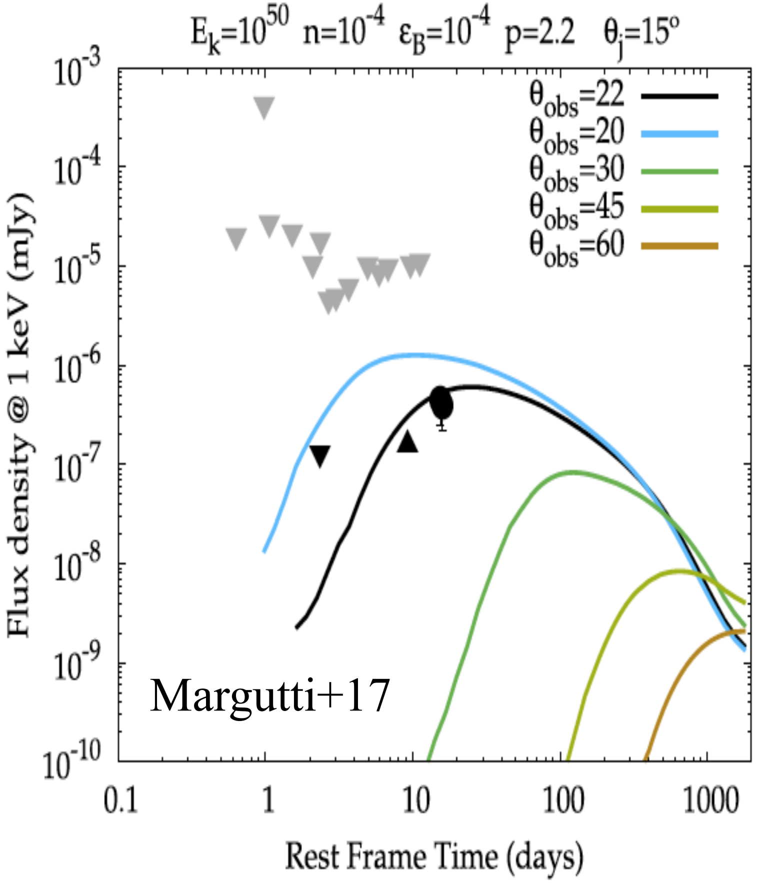


Observed light curves have a rising part at 0.1-10 days.

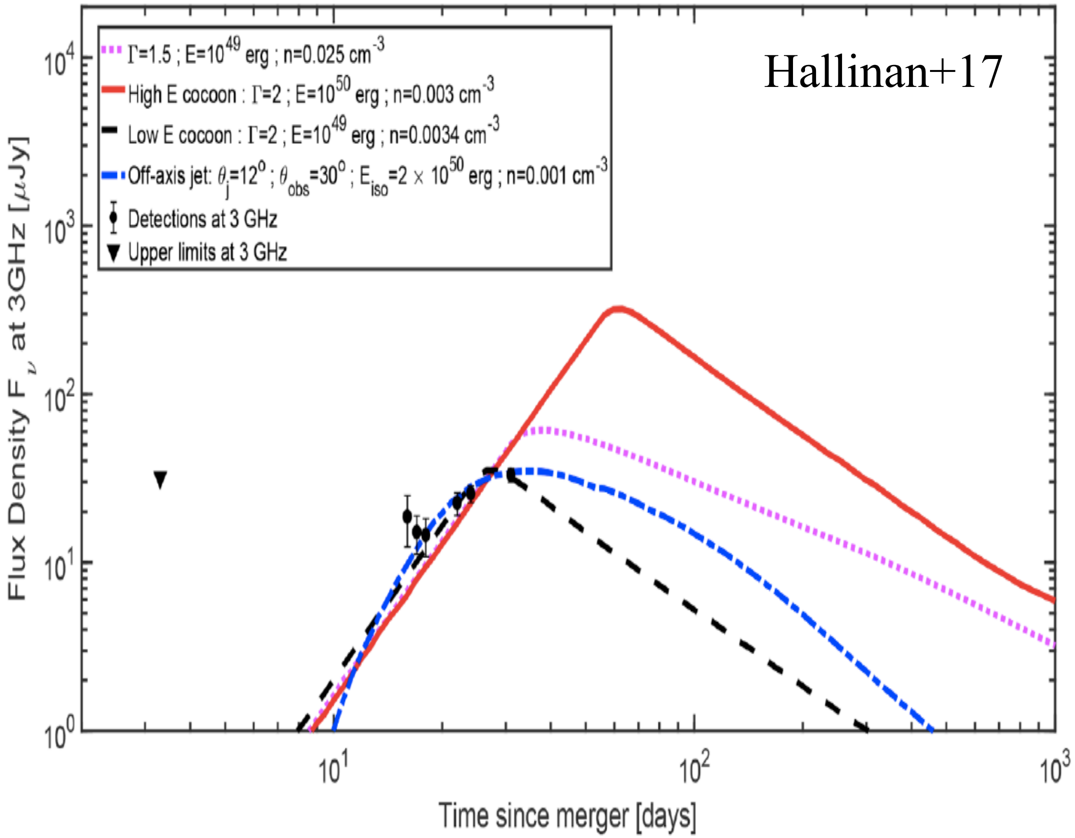
~2017.10 : afterglow light curves are consistent with either an off-axis jet or a cocoon

75 papers (Nature : 6, Science : 7) in 1 day !!

X-ray

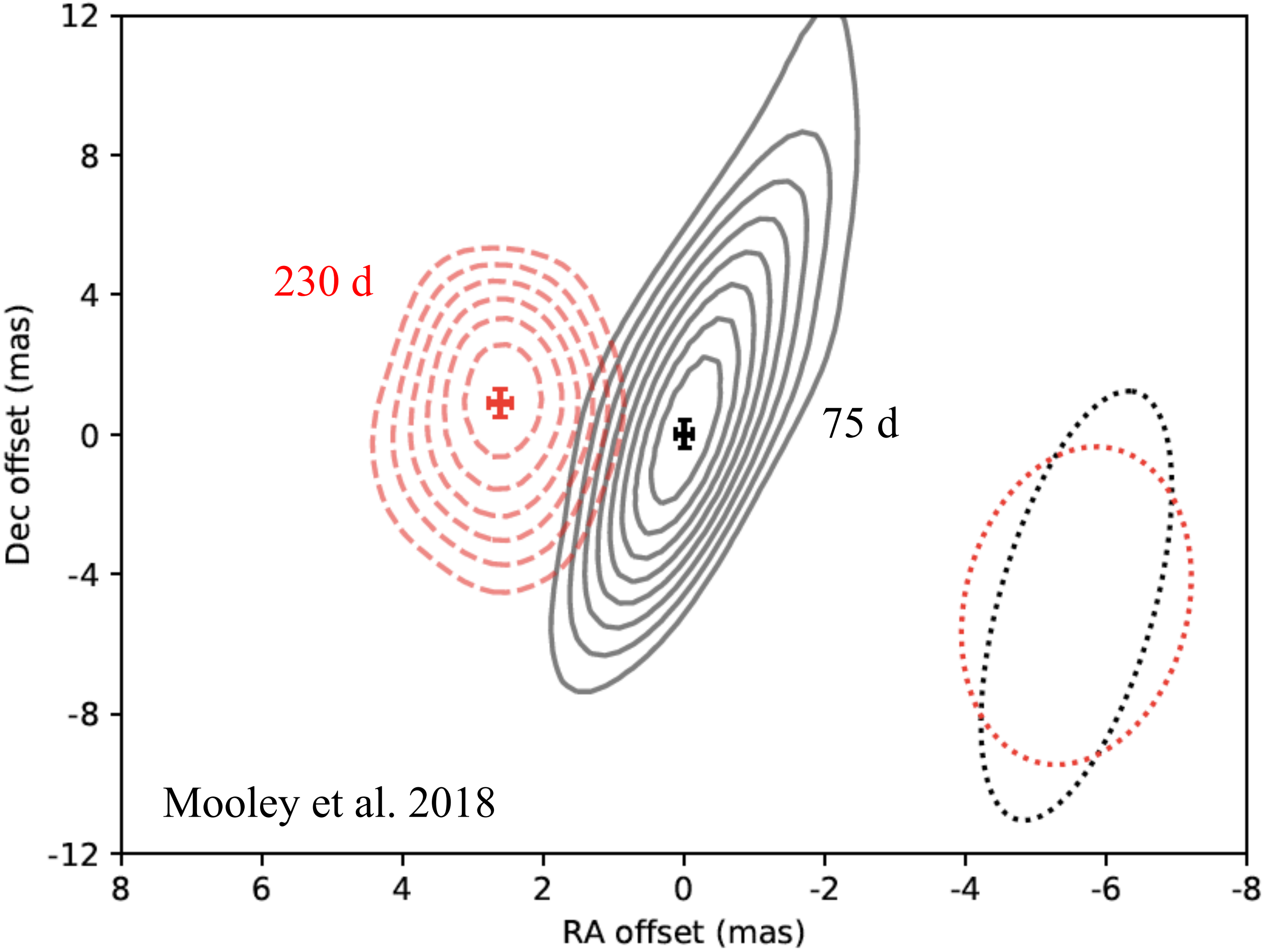


Radio



~2018.6 : Superluminal motion detected by VLBI !

Jet ($\Gamma_0 > \Gamma_{\sim 100\ \mathrm{d}} > \beta_{\mathrm{ap}} = 4$) is suggested.



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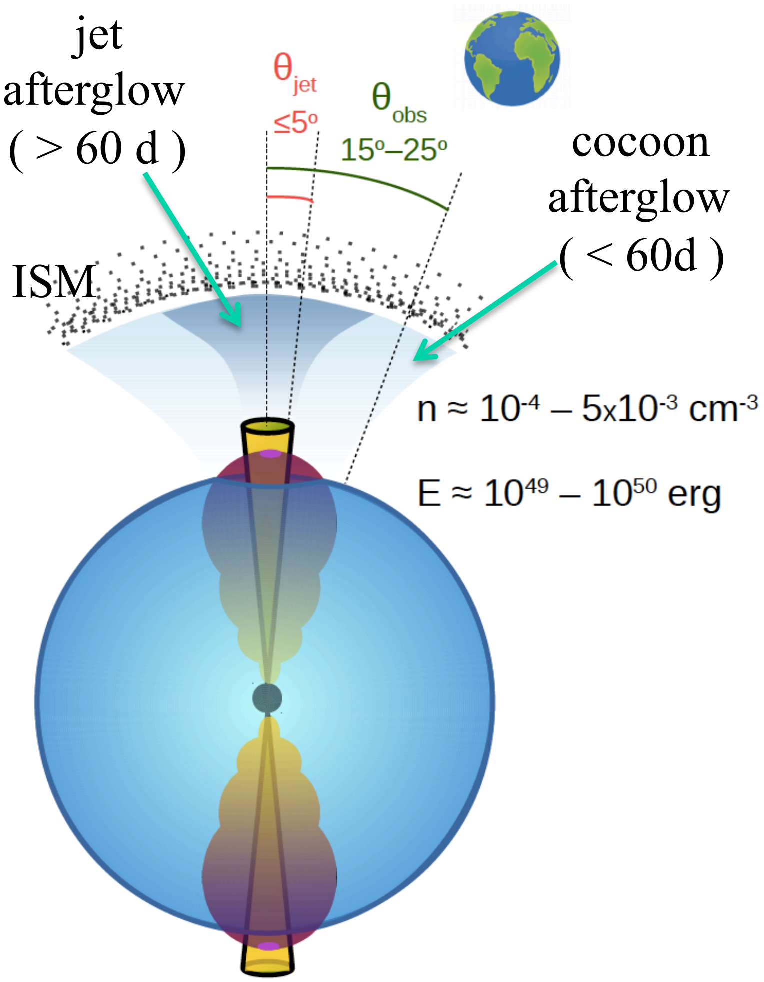


jet afterglow (> 60 d)

θ_{jet} ≤5°

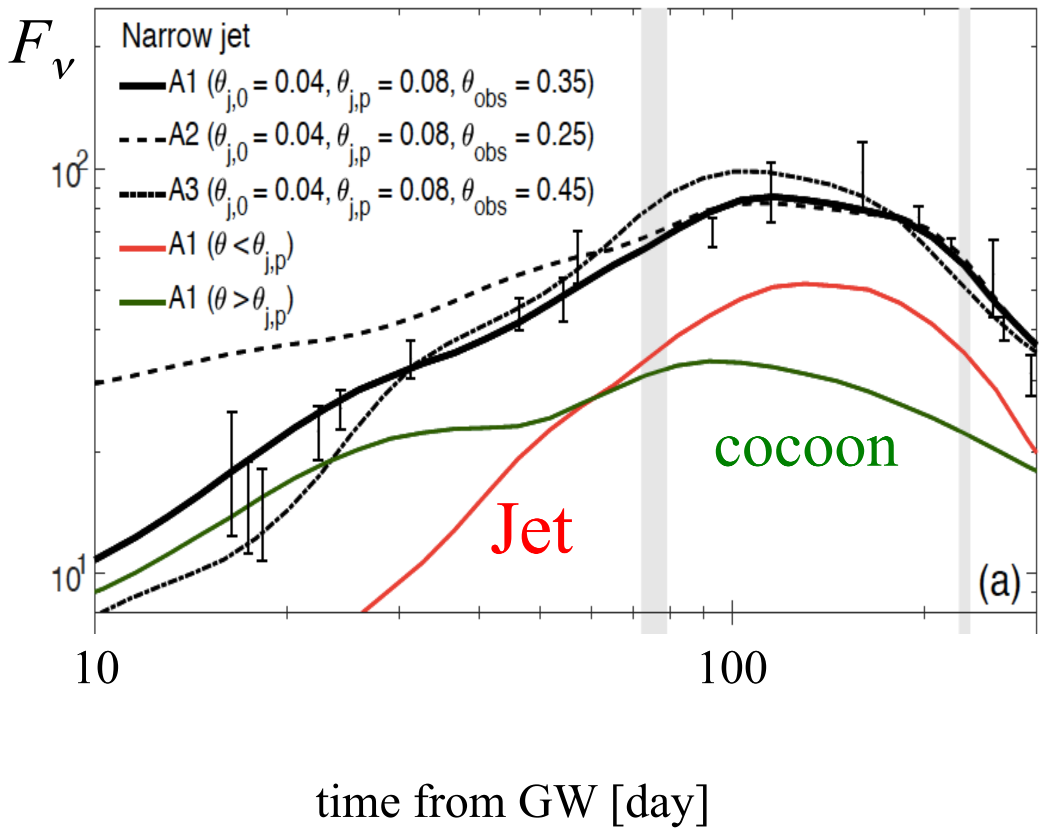
θ_{obs} 15°–25°

cocoon afterglow (< 60d)

ISM

$n \approx 10^{-4} - 5\times10^{-3}\ \mathrm{cm}^{-3}$

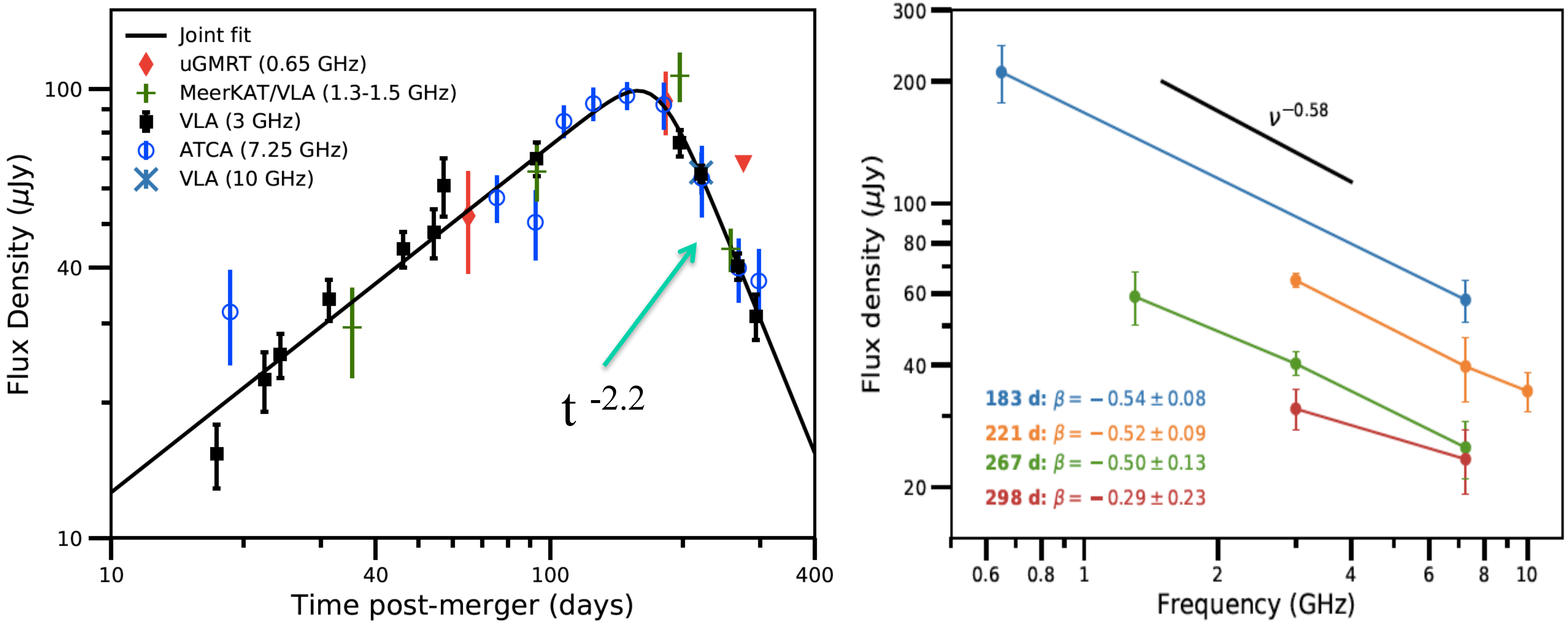
$E \approx 10^{49} - 10^{50}\ \mathrm{erg}$



Mooley et al. 2018

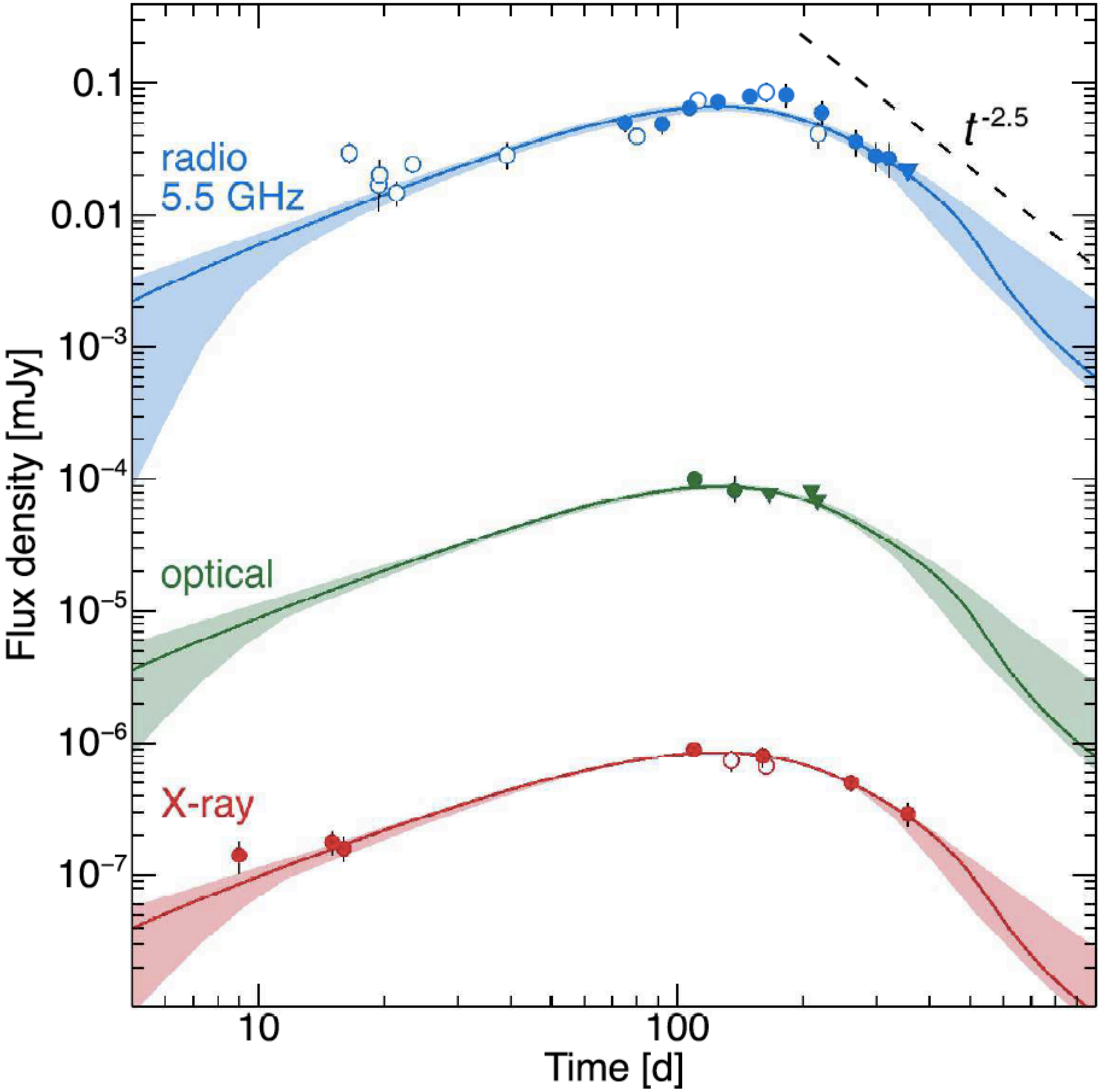
~2018.11 : Radio still declines (~ $t^{-2.2}$): signature of (decelerating) jet ?

Light curve decay ($t^{-2.2}$) and spectral slope ($\nu^{-0.58}$) are consistent with decelerating jet with electron index, p ~ 2.2.



Mooley et al. (2018)

~2018.8 : Either Cocoon or jet model can explain the observed afterglow light curves.



Theoretical curves:
Gaussian jet model

Troja et al. 2018

Motivation of our study

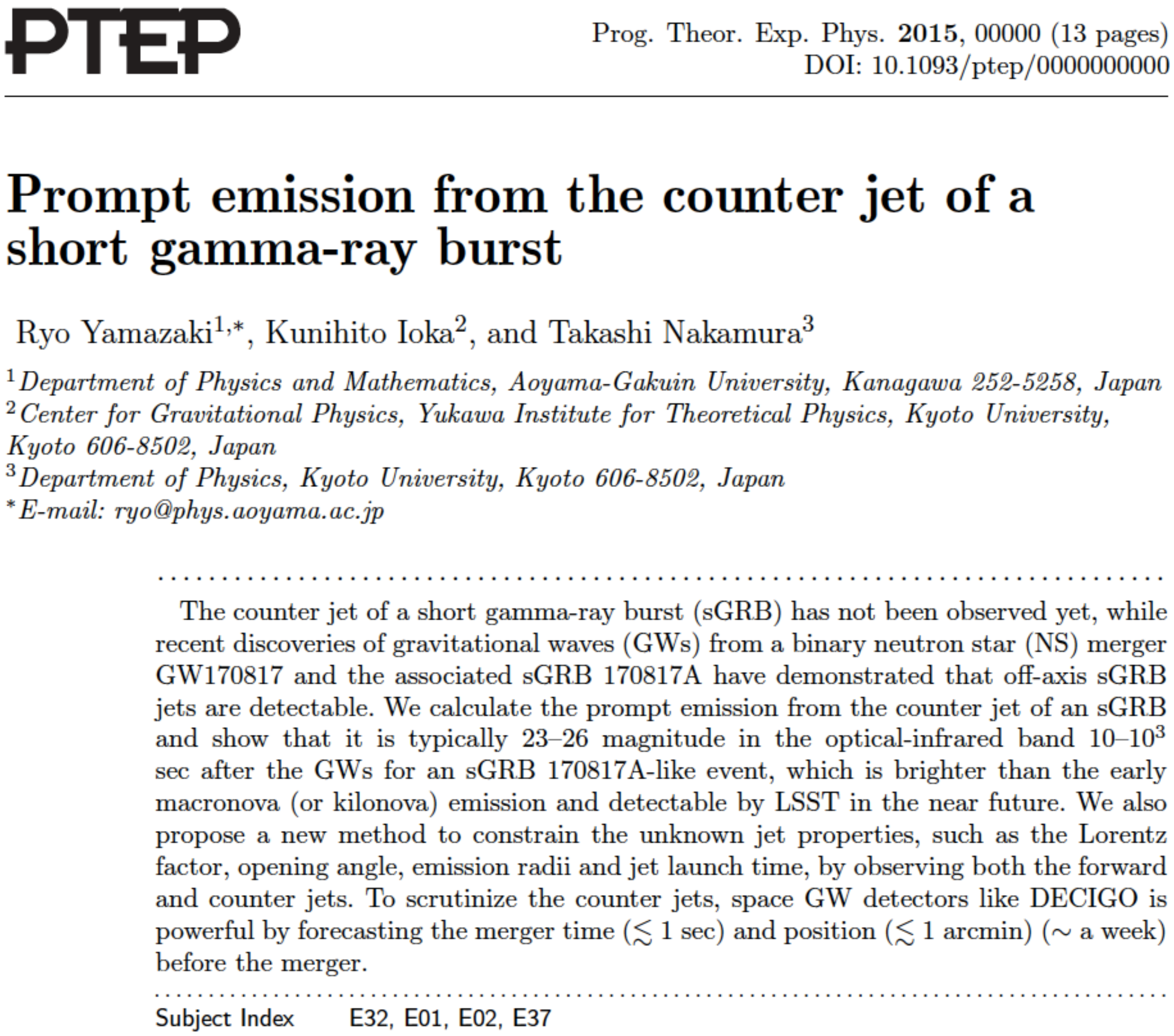
(Typical short GRBs arise from relativistic jet.)

Under-luminous short GRB 170817A
is emission from off-axis relativistic jet ($\Gamma \sim 100$) ?
(Is it the same as sGRB detected so far?)
(The origin of sGRBs is NS-NS merger?)

⇩

Detection of the counter-jet emission may be
the evidence for the relativistic jet.

Yamazaki, Ioka, Nakamura, PTEP (arXiv: 1711.06856)



PTEP
Prog. Theor. Exp. Phys. **2015**, 00000 (13 pages)
DOI: 10.1093/ptep/0000000000

Prompt emission from the counter jet of a short gamma-ray burst

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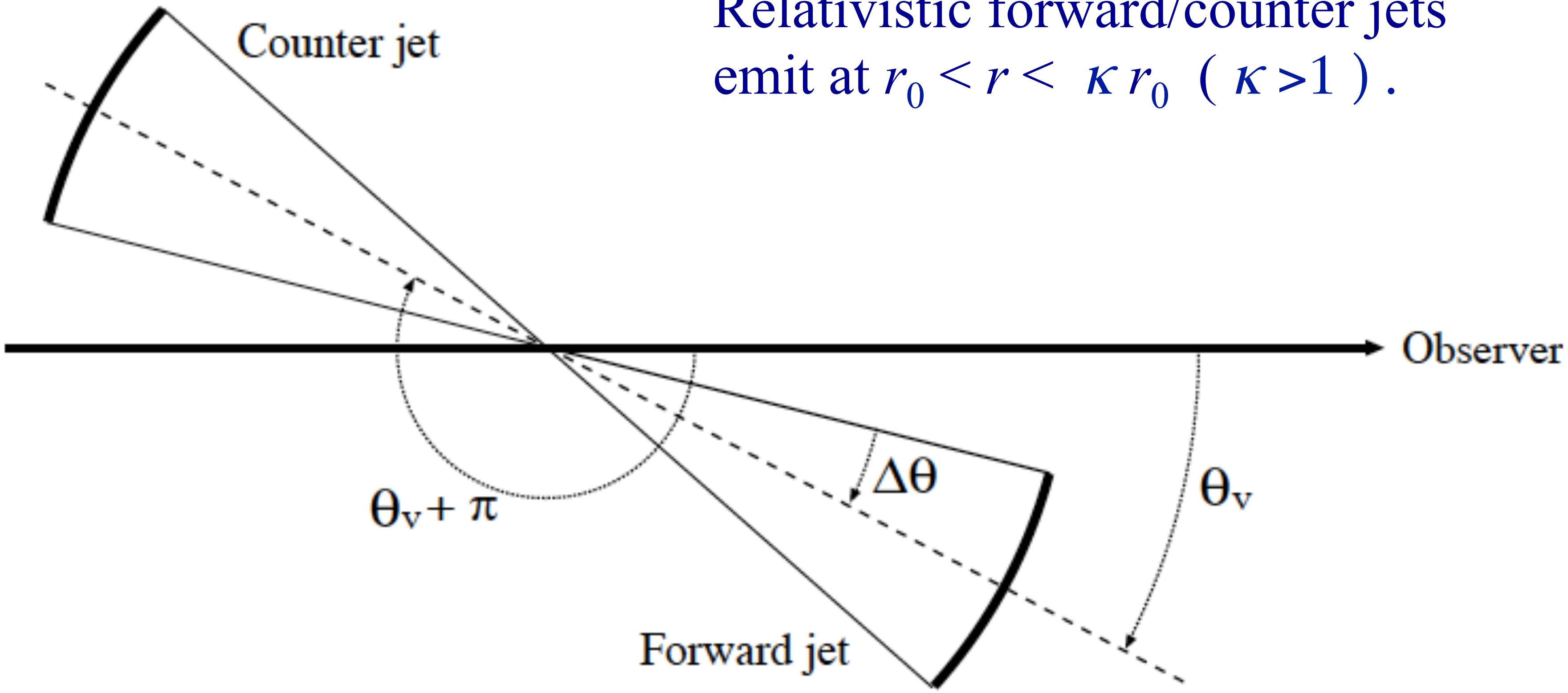
The counter jet of a short gamma-ray burst (sGRB) has not been observed yet, while recent discoveries of gravitational waves (GWs) from a binary neutron star (NS) merger GW170817 and the associated sGRB 170817A have demonstrated that off-axis sGRB jets are detectable. We calculate the prompt emission from the counter jet of an sGRB and show that it is typically 23–26 magnitude in the optical-infrared band 10–10^3 sec after the GWs for an sGRB 170817A-like event, which is brighter than the early macronova (or kilonova) emission and detectable by LSST in the near future. We also propose a new method to constrain the unknown jet properties, such as the Lorentz factor, opening angle, emission radii and jet launch time, by observing both the forward and counter jets. To scrutinize the counter jets, space GW detectors like DECIGO is powerful by forecasting the merger time ($\lesssim 1$ sec) and position ($\lesssim 1$ arcmin) ($\sim$ a week) before the merger.

Subject Index E32, E01, E02, E37

Counter-jet Emission

Relativistic forward/counter jets emit at $r_0 < r < \kappa r_0$ ($\kappa > 1$) .



Yamazaki, Ioka, Nakamura, arXiv: 1711.06856

Typical observed frequencies

Observed frequency : $\nu_{\mathrm{obs}} = \nu_0 / \gamma(1-\beta\cos\theta_{\mathrm{v}})$

Forward jet :

$\theta_{\mathrm{v}} \sim 0 \quad \Rightarrow \nu_{\mathrm{obs}} \sim \gamma\nu_0 \sim 200\ \mathrm{keV}$

Counter jet :

$\theta_{\mathrm{v}} \sim \pi \quad \Rightarrow \nu_{\mathrm{obs}} \sim \nu_0 / \gamma \sim 5\ \mathrm{eV}$

Counter jet appears in optical bands.

Observed flux from relativistically moving jets:

$$F_\nu(T) = \frac{1}{D^2}\int_0^{2\pi} d\phi \int_{-1}^{1} d\mu \int_0^{\infty} r^2 dr \, \frac{j'_{\nu'}(\Omega'_d, \boldsymbol{r}, T + r\mu/c)}{\gamma^2(1-\beta\mu)^2}$$

Emissivity in comoving frame :

$$\begin{array}{rcl} j'_{\nu'}(\Omega'_d, \boldsymbol{r}, t) & = & A(t) f(\nu') \delta[r - r_0 - \beta c(t - t_0)] \\ & \times & H(\Delta\theta - |\theta - \theta_v - \pi|) H\left[\cos\phi - \left(\dfrac{\cos\Delta\theta + \cos\theta\cos\theta_v}{-\sin\theta_v \sin\theta}\right)\right] \end{array}$$

$$A(t) = A_0 \left(\frac{t - T_0}{r_0/c\beta}\right)^{-2} H(t - \tau_j - t_0) H(\tau_j + t_e - t),$$

$$f(\nu') = (\nu'/\nu'_0)^{1+\alpha_B}[1 + (\nu'/\nu'_0)^s]^{(\beta_B - \alpha_B)/s}$$

R-band light curves from counter jet (40 Mpc)

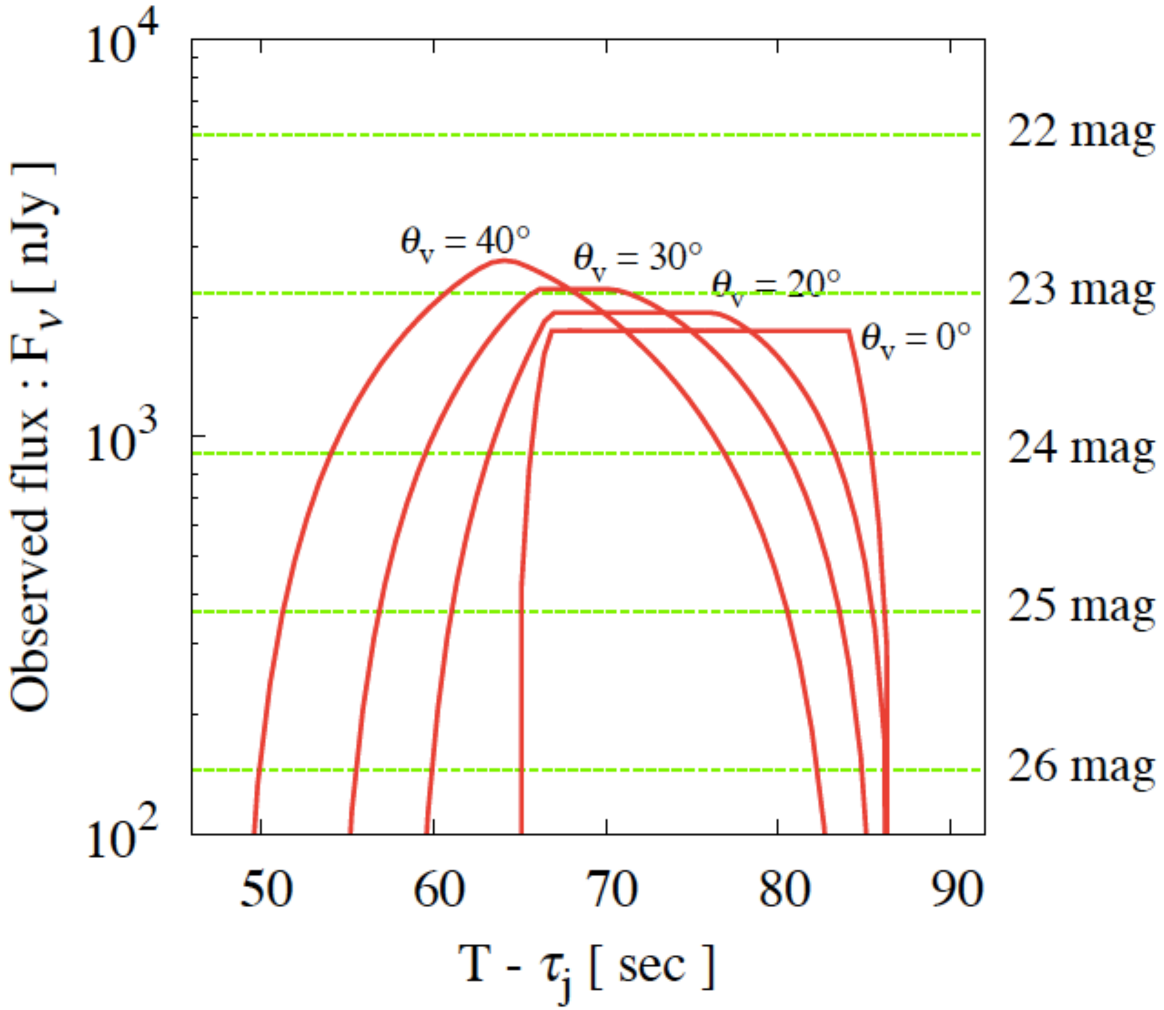


Fig. 1 Light curves of counterjet emission in the r-band for fiducial parameters ($\gamma = 100$, $\Delta\theta = 20°$, $h\gamma\nu_0' = 500\,\mathrm{keV}$, $r_0 = 1 \times 10^{12}$ cm, $\alpha_B = -1$, $\beta_B = -3$, $s = 1$, $t_0 = r_0/c\beta$, $\kappa = 1.3$, and $E_{\rm iso,on} = 8.2 \times 10^{51}$erg) with varying θ_v (= 0°, 20°, 30°, and 40°, from right to left). The source is located at $D = 40$ Mpc.

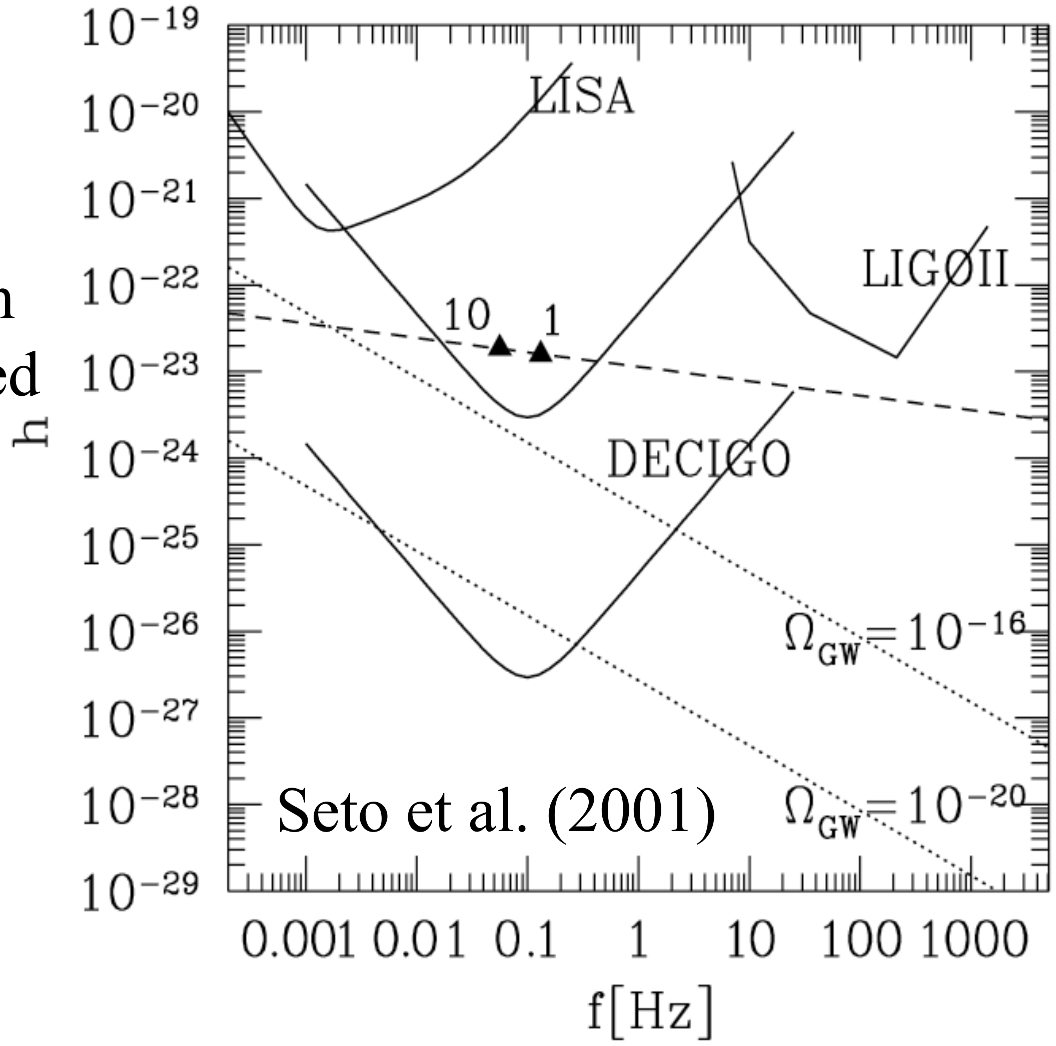
Too early?

Counter jet optical emission ~23mag in a few minutes from GW. => difficult to be observed by current telescopes.

No problem!

Seto et al. (‘01),
Takahashi & Nakamura (‘03)

DECIGO/BBO detects GWs 1-10yrs before LIGO.
→ The moment of NS-NS merger can be predicted.



Seto et al. (2001)

FIG. 1. Sensitivity (effectively S/N = 1) for various detectors (LISA, DECIGO, LIGOII, and a detector 10^3 times less sensitive than DECIGO) in the form of $h_{\rm rms}$ (solid lines). The dashed line represents evolution of the characteristic amplitude h_c for NS-NS binary at $z = 1$ (filled triangles: wave frequencies at 1 and 10 yr before coalescence). The dotted lines represent the required sensitivity for detecting stochastic background with $\Omega_{\rm GW} = 10^{-16}$ and $\Omega_{\rm GW} = 10^{-20}$ by 10 yr correlation analysis (S/N = 1).

ET (=Einstein Telescope) will also detect GW ~10-20 hrs before the merger.

Akcay et al. 2019

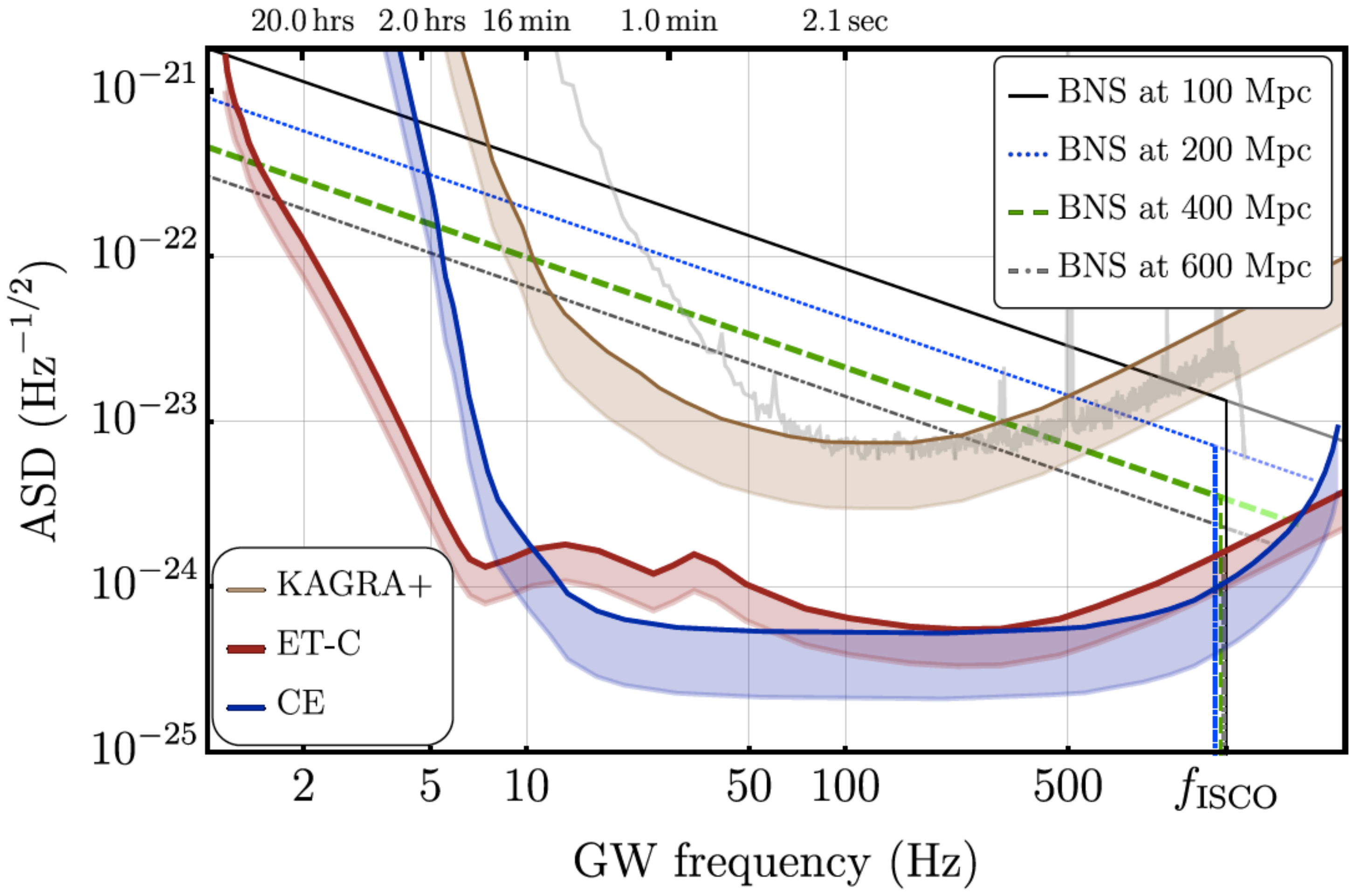


Fig. 1. $1.4M_\odot$ - $1.4M_\odot$ inspiralling BNS systems sweeping across the sensitivity band of Einstein Telescope's C configuration (thick red curve). The solid (black), dotted (blue), dashed (green), and dot-dashed lines (gray) lines are the redshift-corrected GW strains, $2\sqrt{f}\tilde{H}_{\mathrm{ET}}$, at luminosity distances of $D = 100, 200, 400, 600$ Mpc, respectively. The vertical lines with correspondingly identical patterns (colors) mark the redshifted ISCO frequencies $(1+z)^{-1} f_{\mathrm{ISCO}}$ at which point we terminate each inspiral. As the true ISCO frequency is likely larger than f_{ISCO} (Marronetti et al. 2004), the inspirals would continue to nearly 2 kHz indicated by the faded lines in the plot. We also show the sensitivity curves for Cosmic Explorer (blue) and KAGRA+ (brown) with the solid curves representing their RMS-averaged sensitivities and the bottom of each shaded region, the maximum sensitivities. The faint gray curve represents the sensitivity of Advanced LIGO during GW170817. The upper horizontal axis gives the time to merger for a BNS at 100 Mpc.

Even LIGO will detect ~10^2sec before the final merger ???

Cannon et al. (2012)

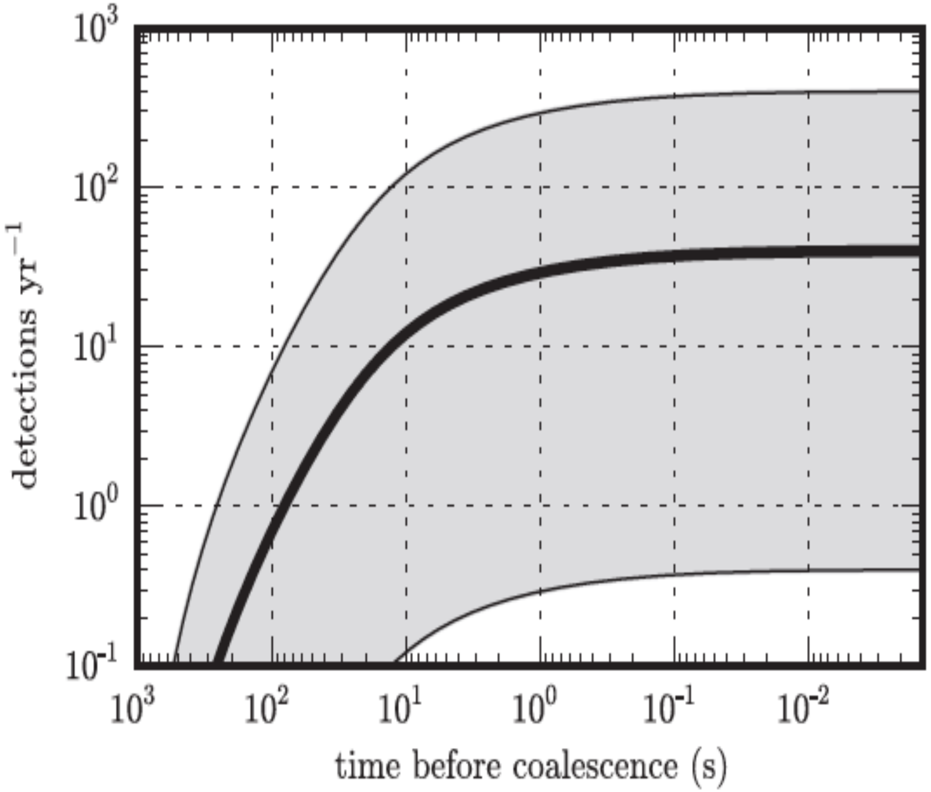


Figure 1. Expected number of NS–NS sources that could be detectable by Advanced LIGO a given number of seconds before coalescence. The heavy solid line corresponds to the most probable yearly rate estimate from Abadie et al. (2010a). The shaded region represents the 5%–95% confidence interval arising from substantial uncertainty in predicted event rates.

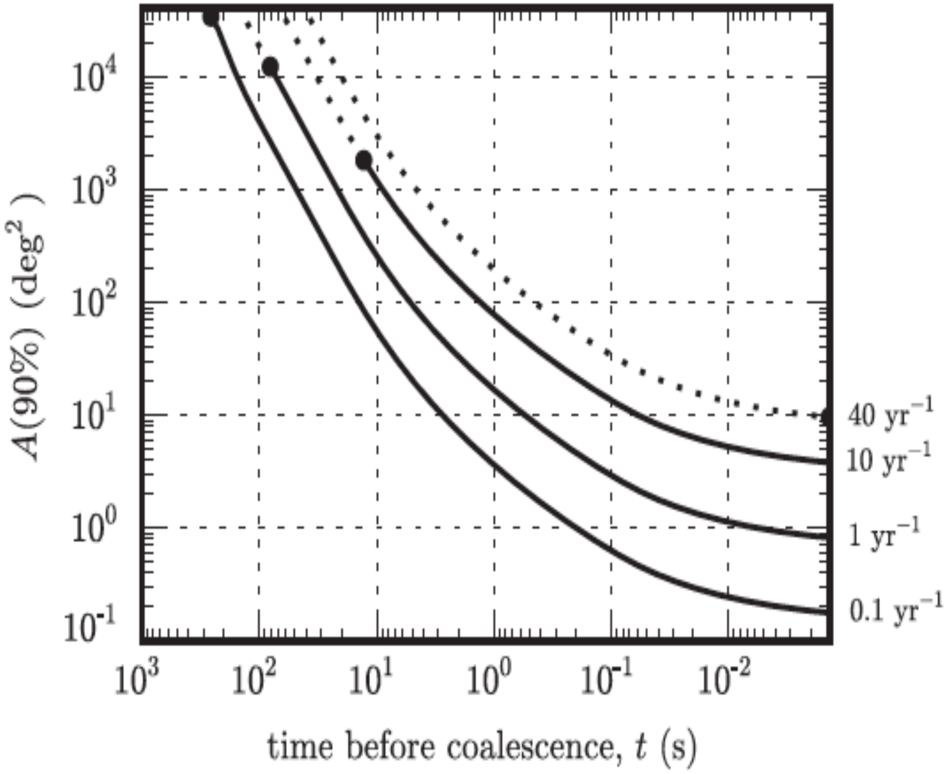


Figure 2. Area of the 90% confidence region as a function of time before coalescence for sources with anticipated detectability rates of 40, 10, 1, and 0.1 yr^{-1}. The heavy dot indicates the time at which the accumulated S/N exceeds a single-detector threshold of 8.

Summary

Ref: Yamazaki et al., PTEP (arXiv:1711.06856)

- $\Delta\theta = 20$ deg, $\theta_v = 30$ deg (Ioka & Nakamura 2017)

  Jet bulk Lorentz factor: $\gamma = 50 \sim 100$
  Emission radius $r_0 = 1\text{-}3 \times 10^{12}$cm

=>

Counter-jet optical emission:
R = 22-24 mag (at D = 40 Mpc) at a few minutes from GW.