GW 170817 / GRB 170817A の Counter jet の放射について

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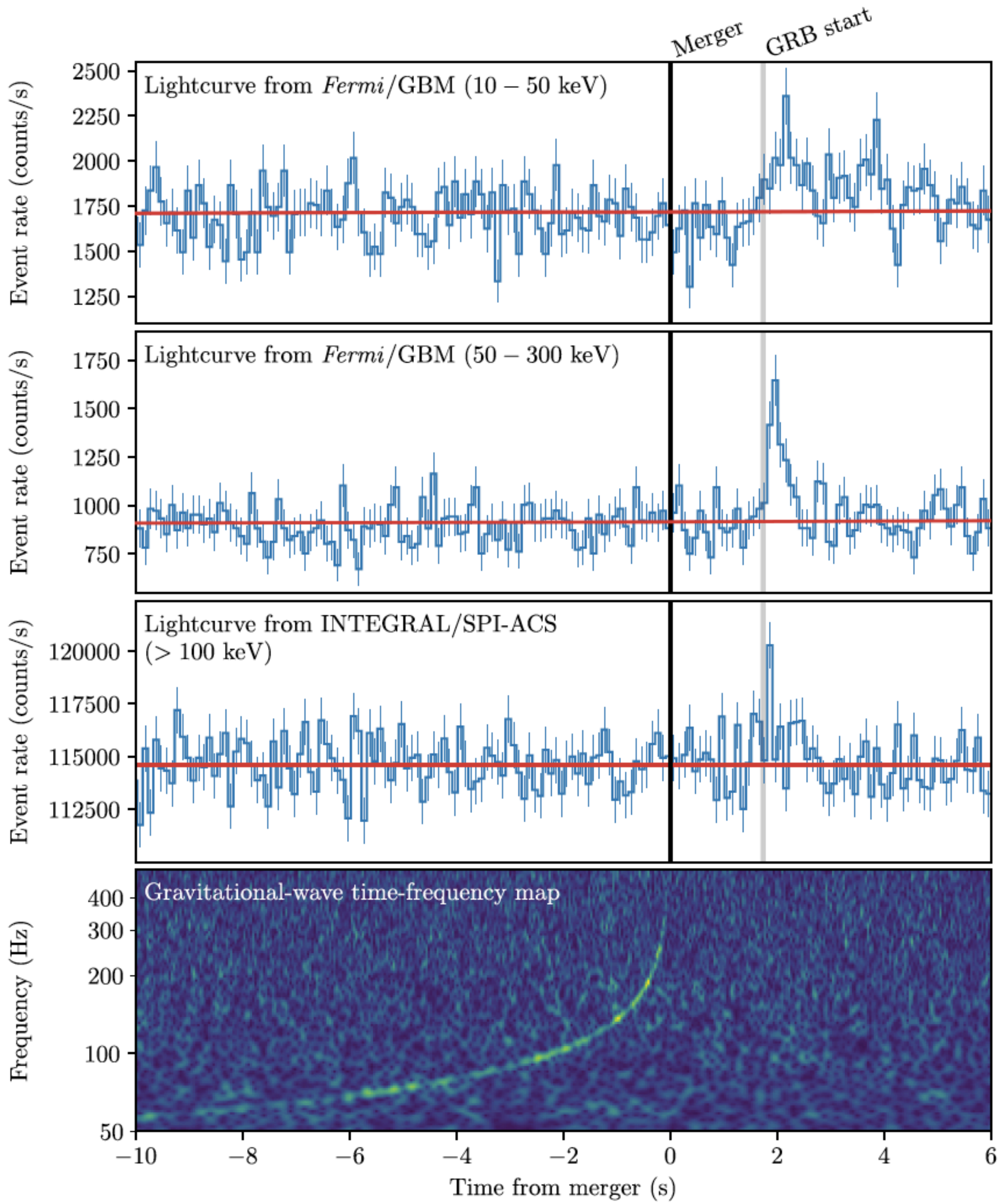
GW170817 / GRB 170817A

LIGO/VIRGO (2017), ApJ

GWから1.7秒後に10^{47}ergのガンマ線バースト



Ep- Eiso for short GRBs

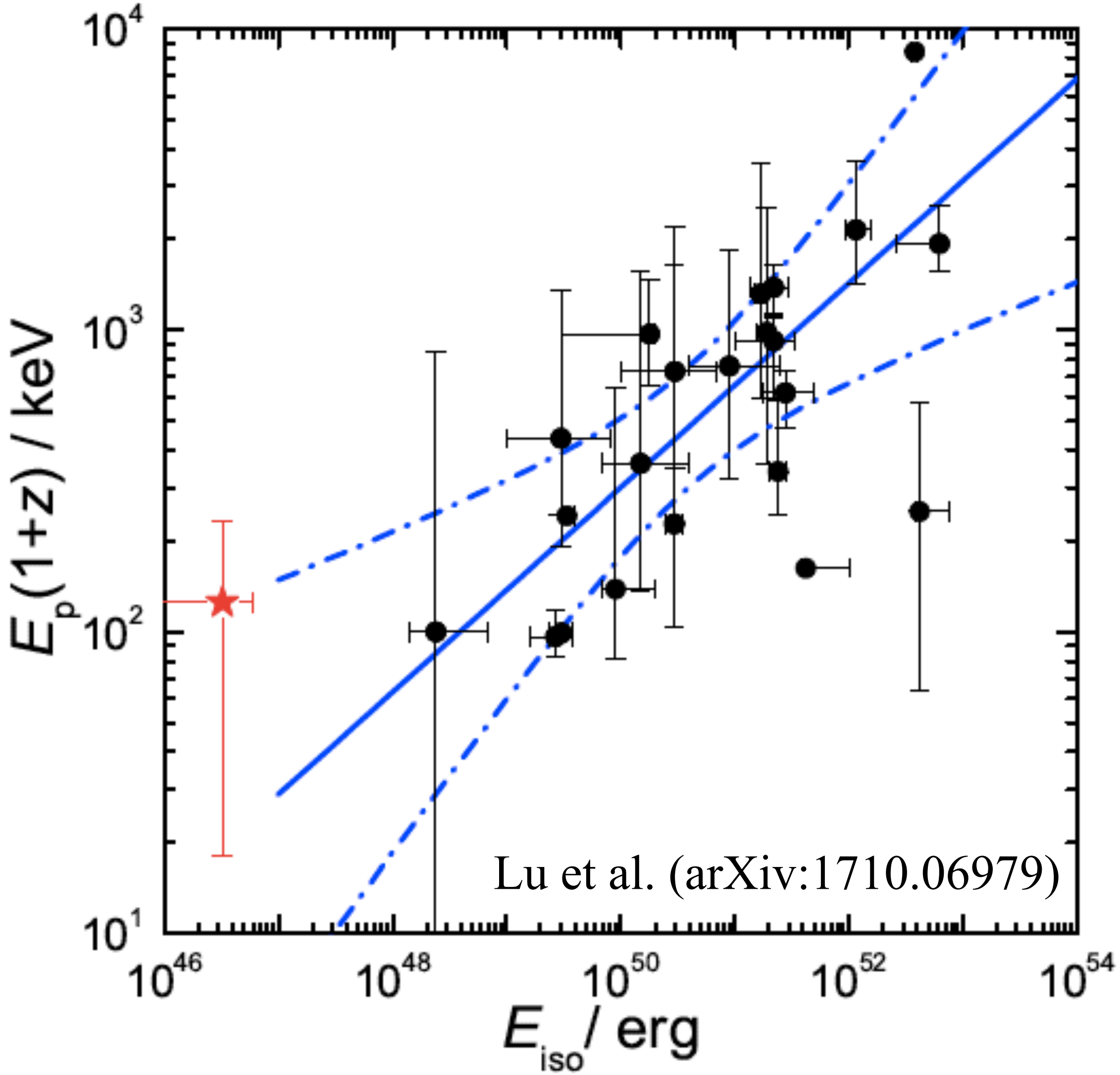
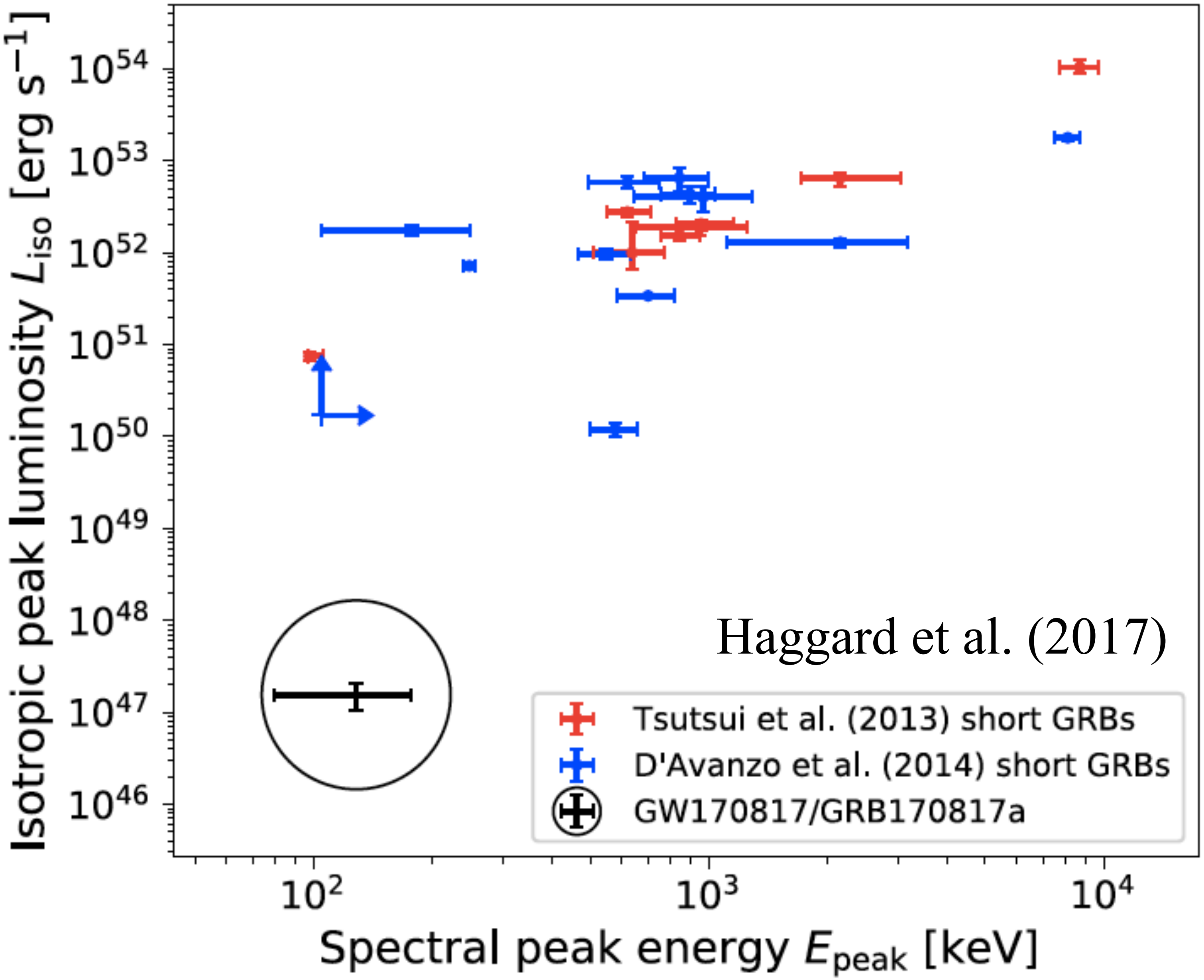


Fig. 10.— $E_{\rm iso}$ as a function of $E_{\rm p}$ in the burst frame for a sample of sGRB taken from Zhang et al. (2009). The red star is GRB 170817A. The solid line is the Spearman linear fit together with its 2σ confidence level.

Ep- Liso for short GRBs



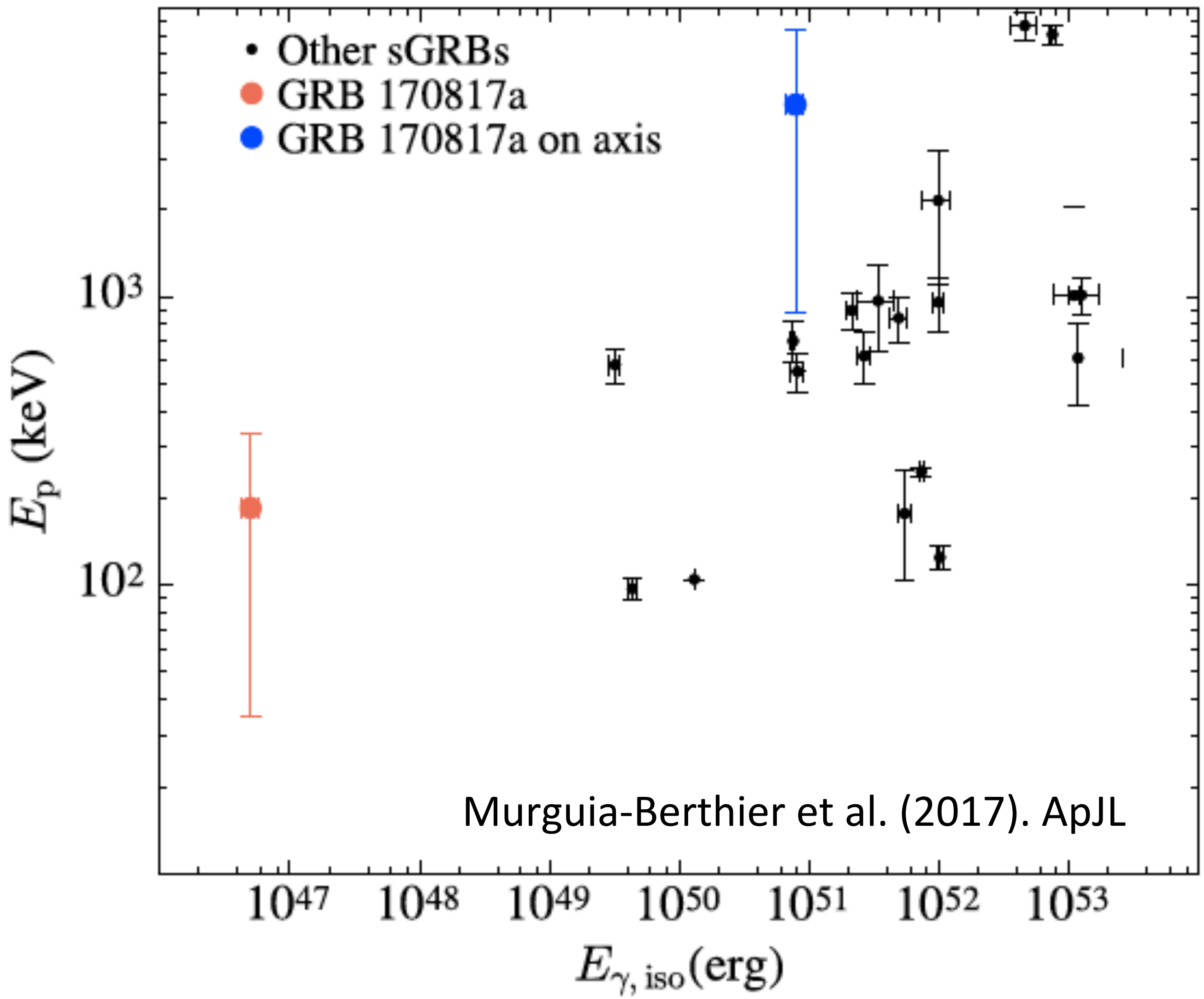
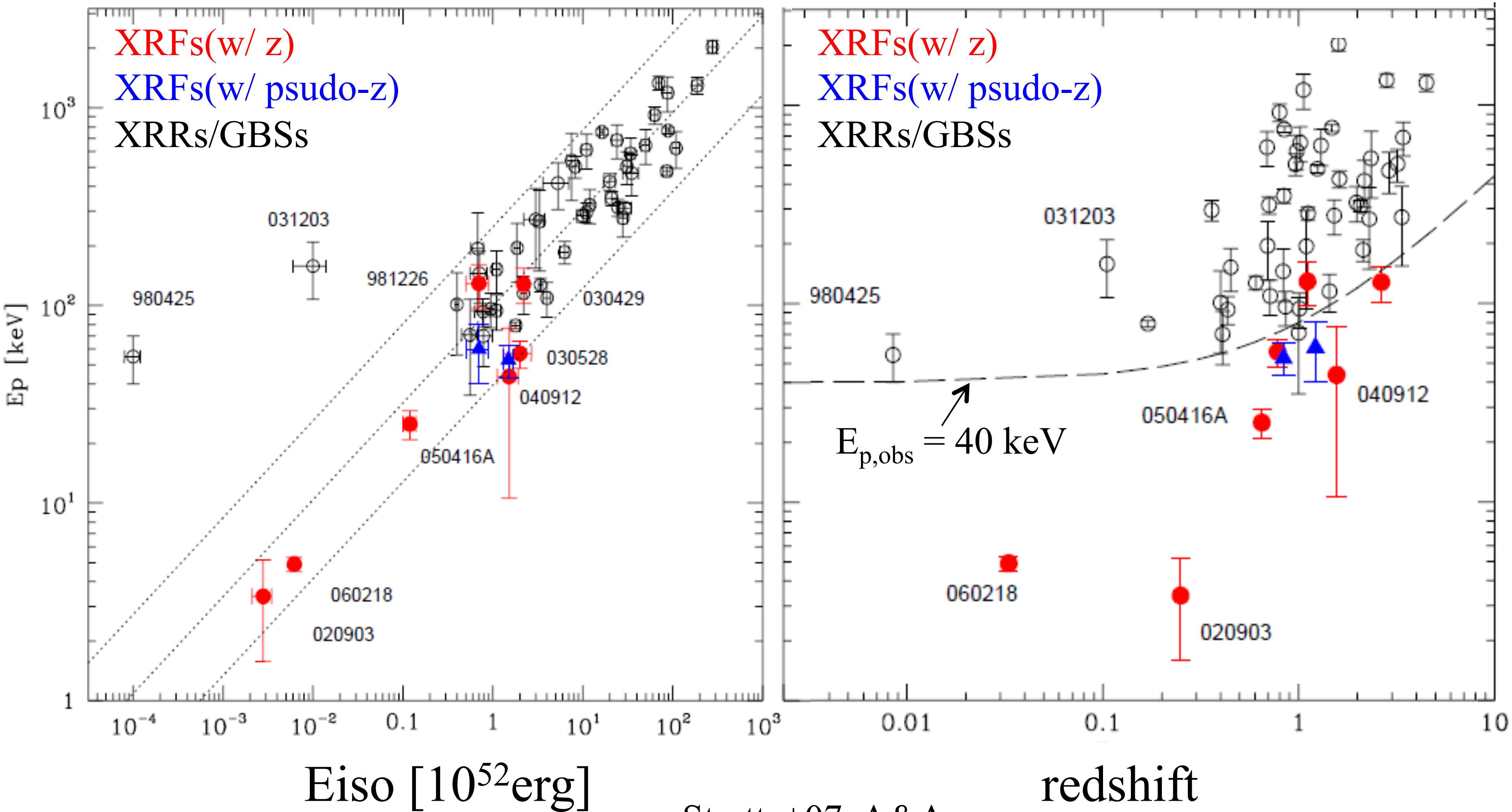


Figure 4. Location of GRB 170817A in the E_{p} and $E_{\gamma,\mathrm{iso}}$ plane, from Savchenko et al. (2017) and LIGO Scientific Collaboration & Virgo Collaboration et al. (2017). Also shown is the location if GRB 170817A were on-axis under the assumption of a misaligned, sharp-edged jet. This assumes 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).

GRB 980425/SN1998bw とよく似た状況？

Low-luminosity GRBs というsubclassの確立.

Ep(1+z) vs. Eiso　　Ep(1+z) vs. z

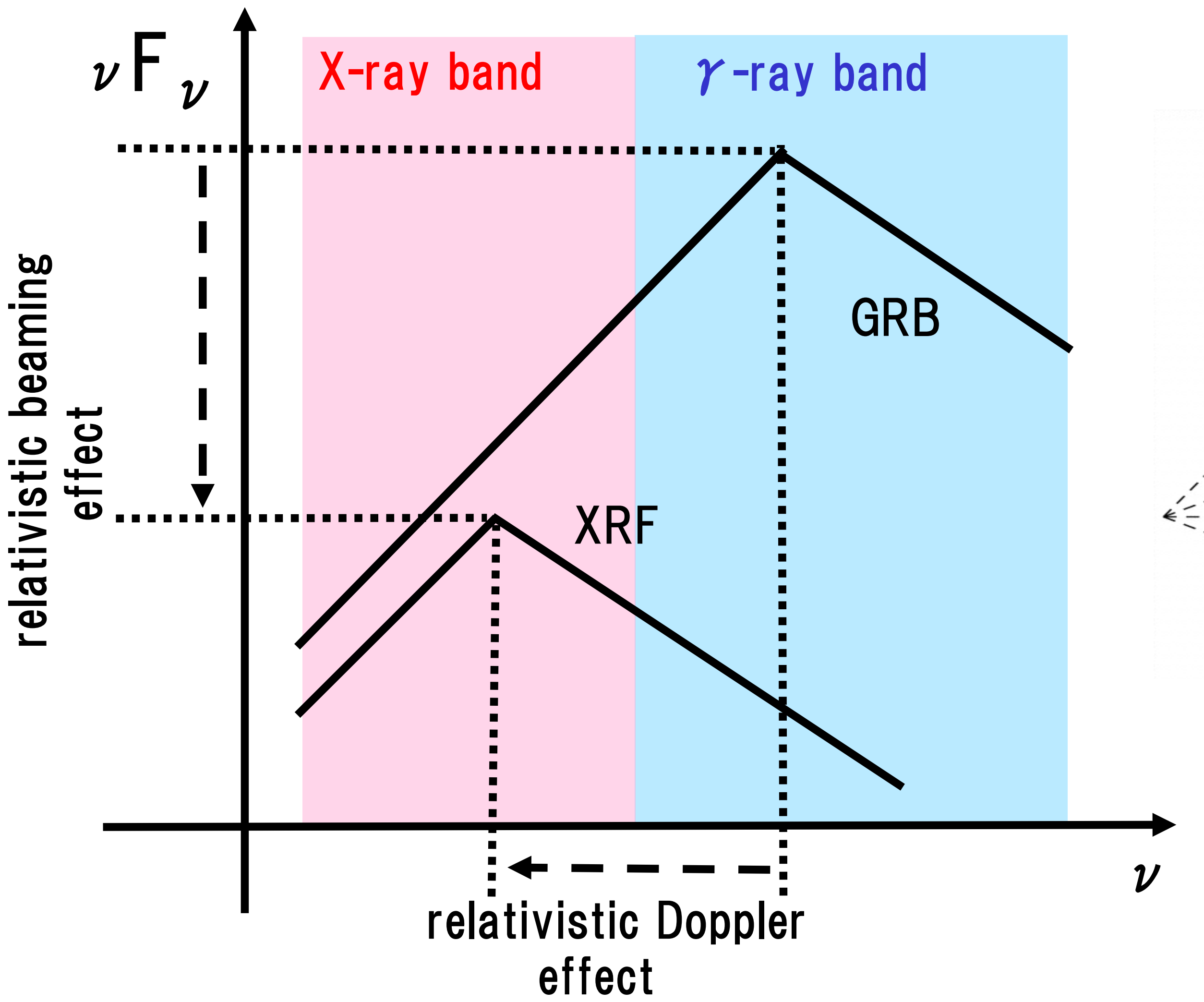


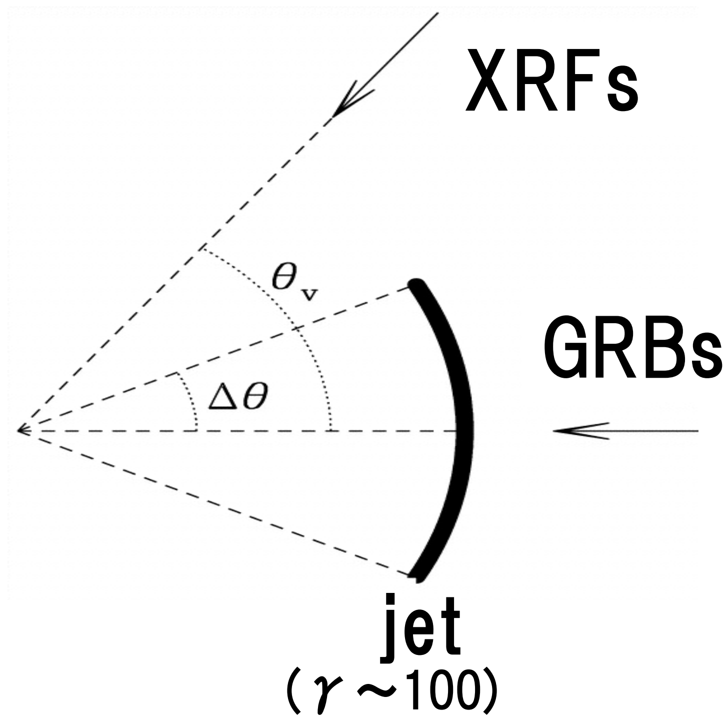
Stratta+07, A&A

Off-Axis jet model

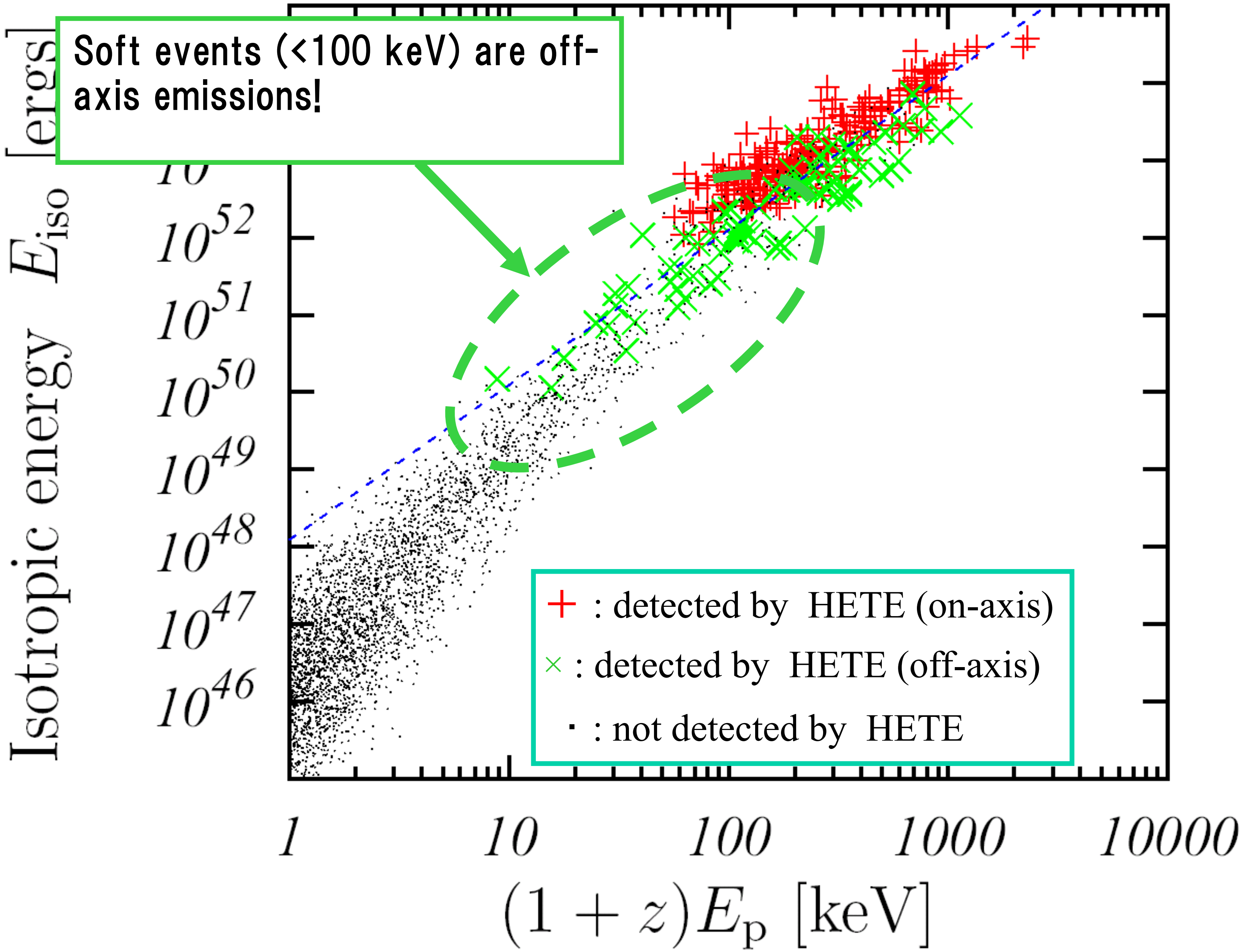
Off-Axis Jet Model of XRFs

The X-ray flashes (and the soft GRBs) are the typical GRBs observed from off-axis viewing angle.



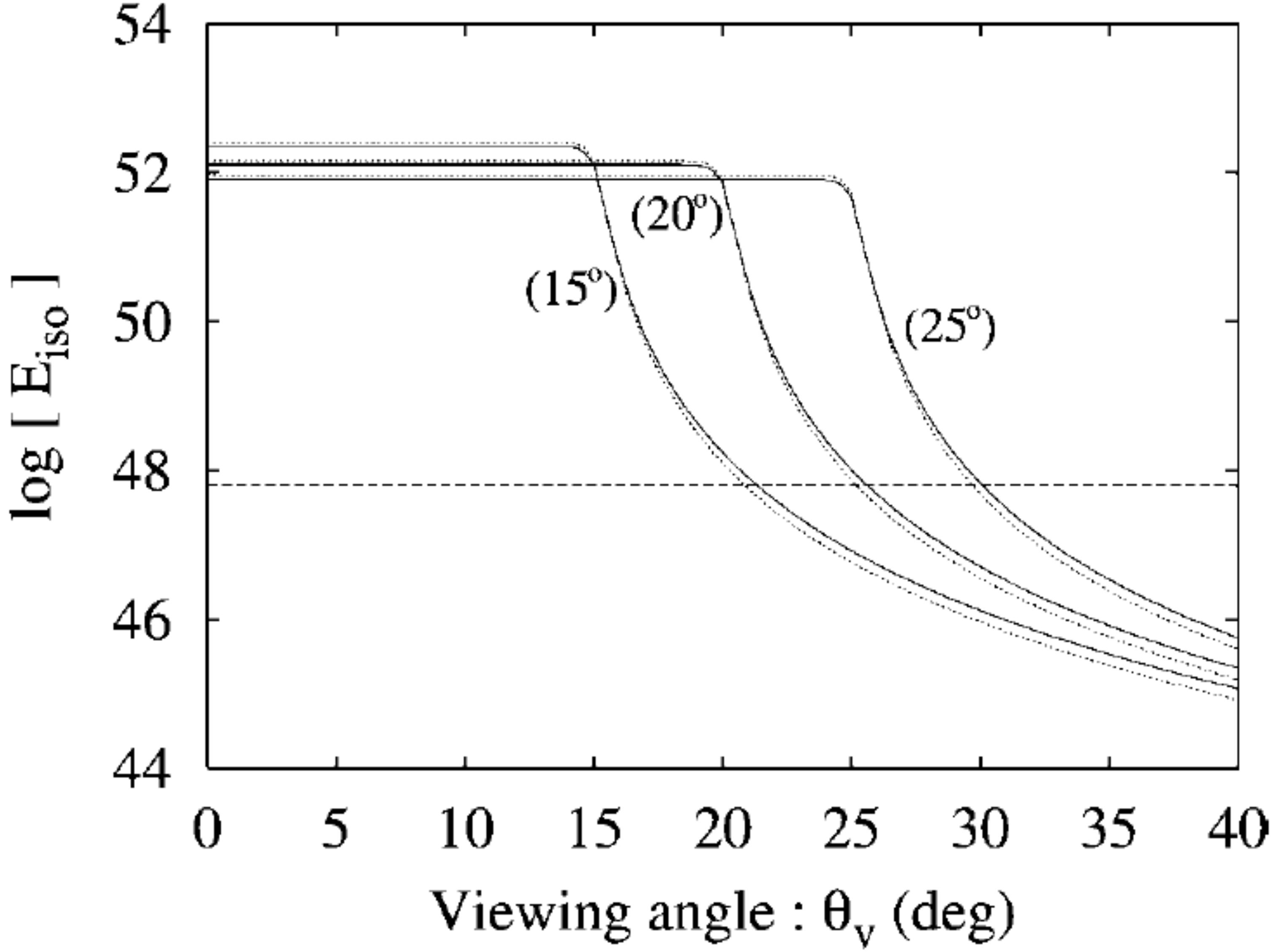


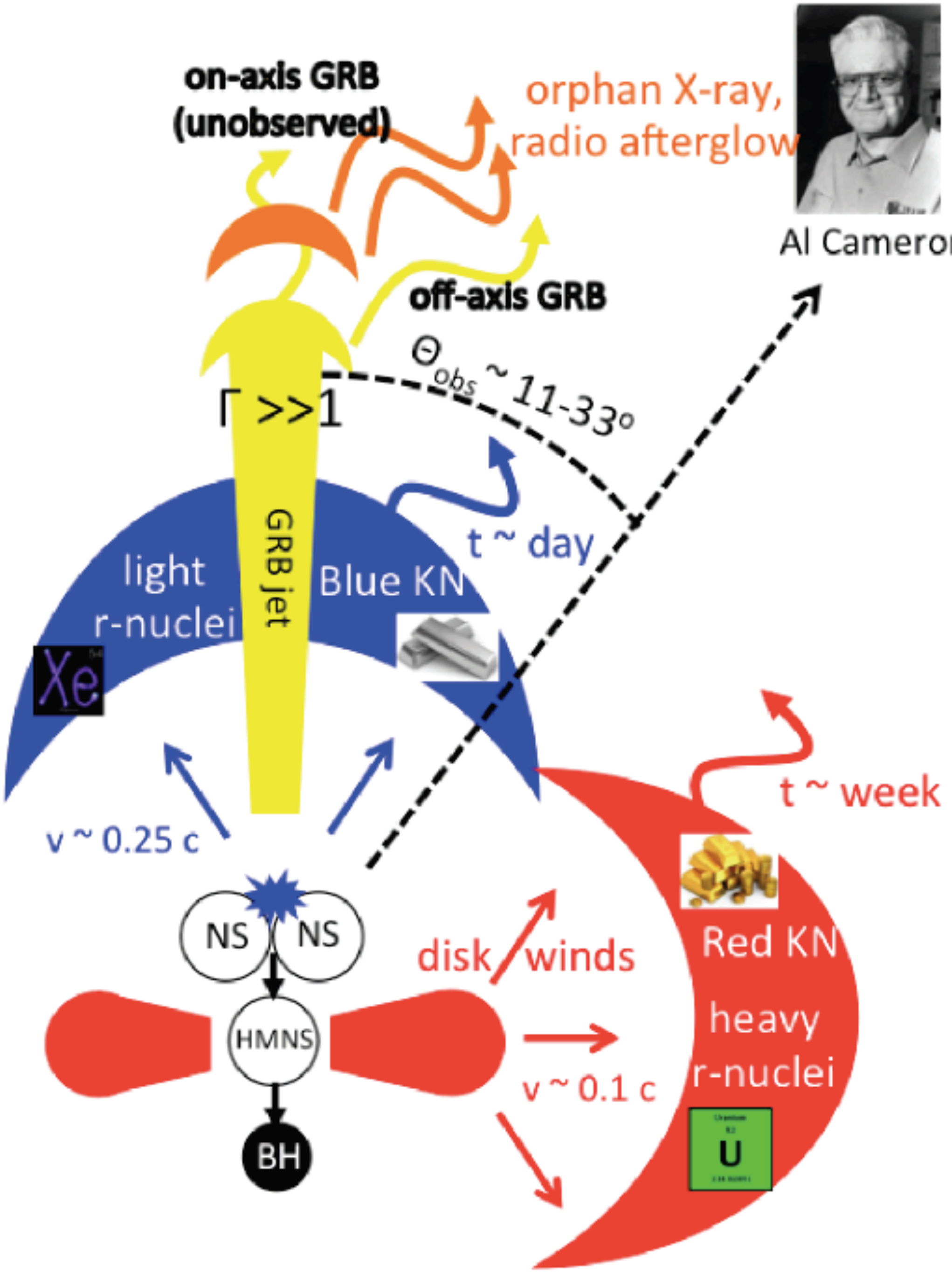
Off-axis model で $Ep - E_{iso}$ 関係を説明



GRB 980425 = off-axis GRB?

Yamazaki, Yonetoku, Nakamura (2003)

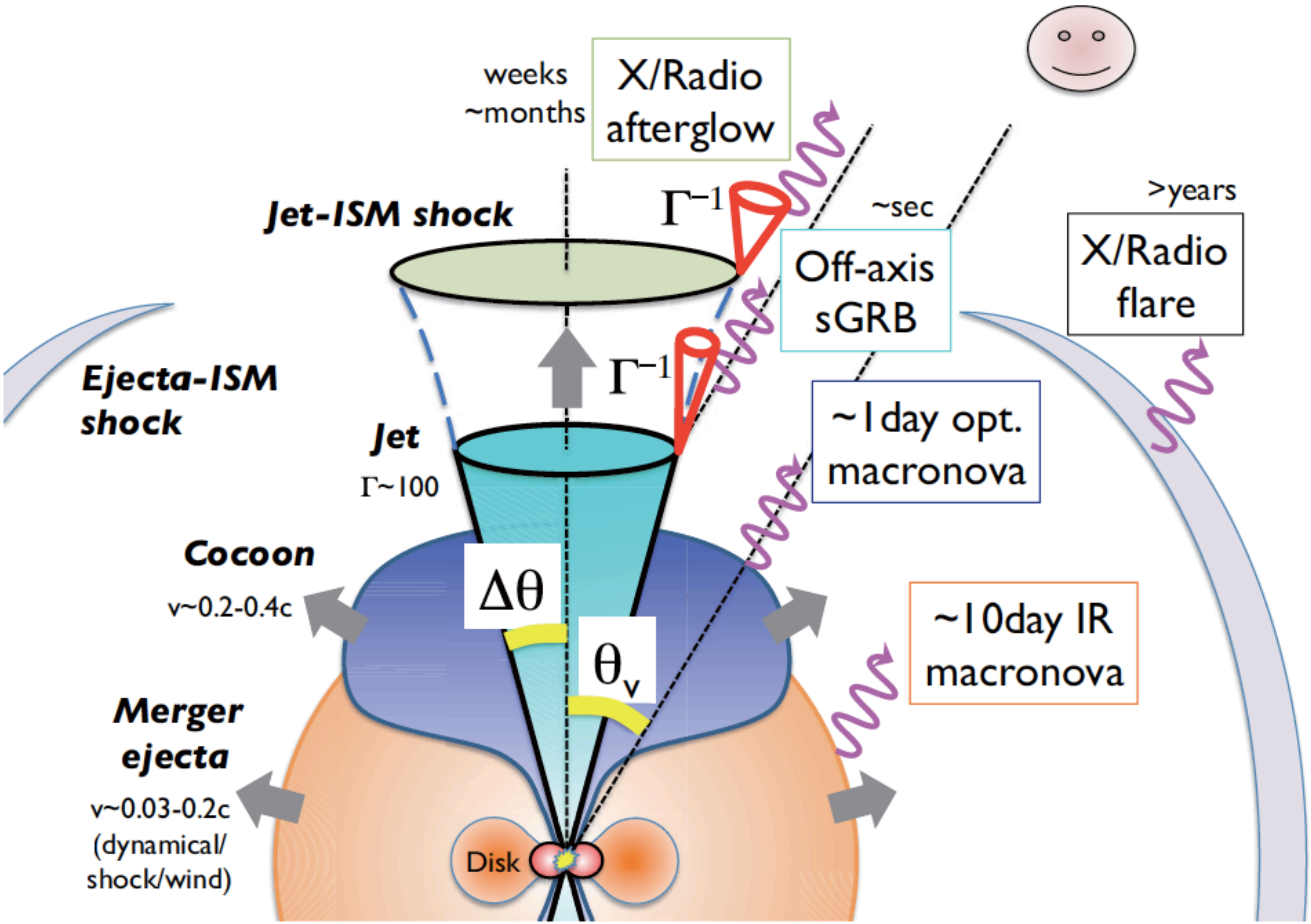




Al Cameron

Alastair Cameron (1925-2005):
r-processの研究をした人

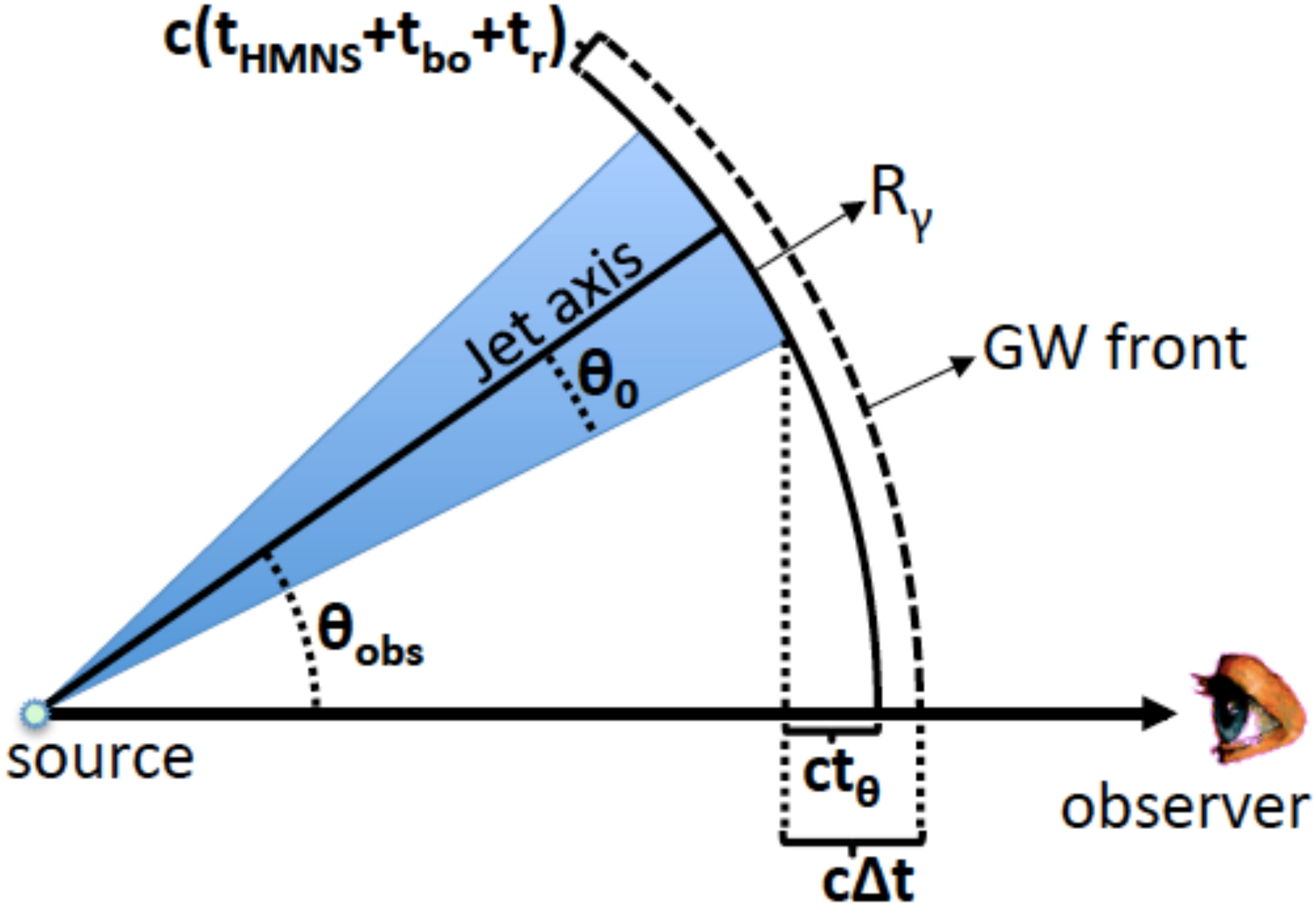
Metzger (2017)

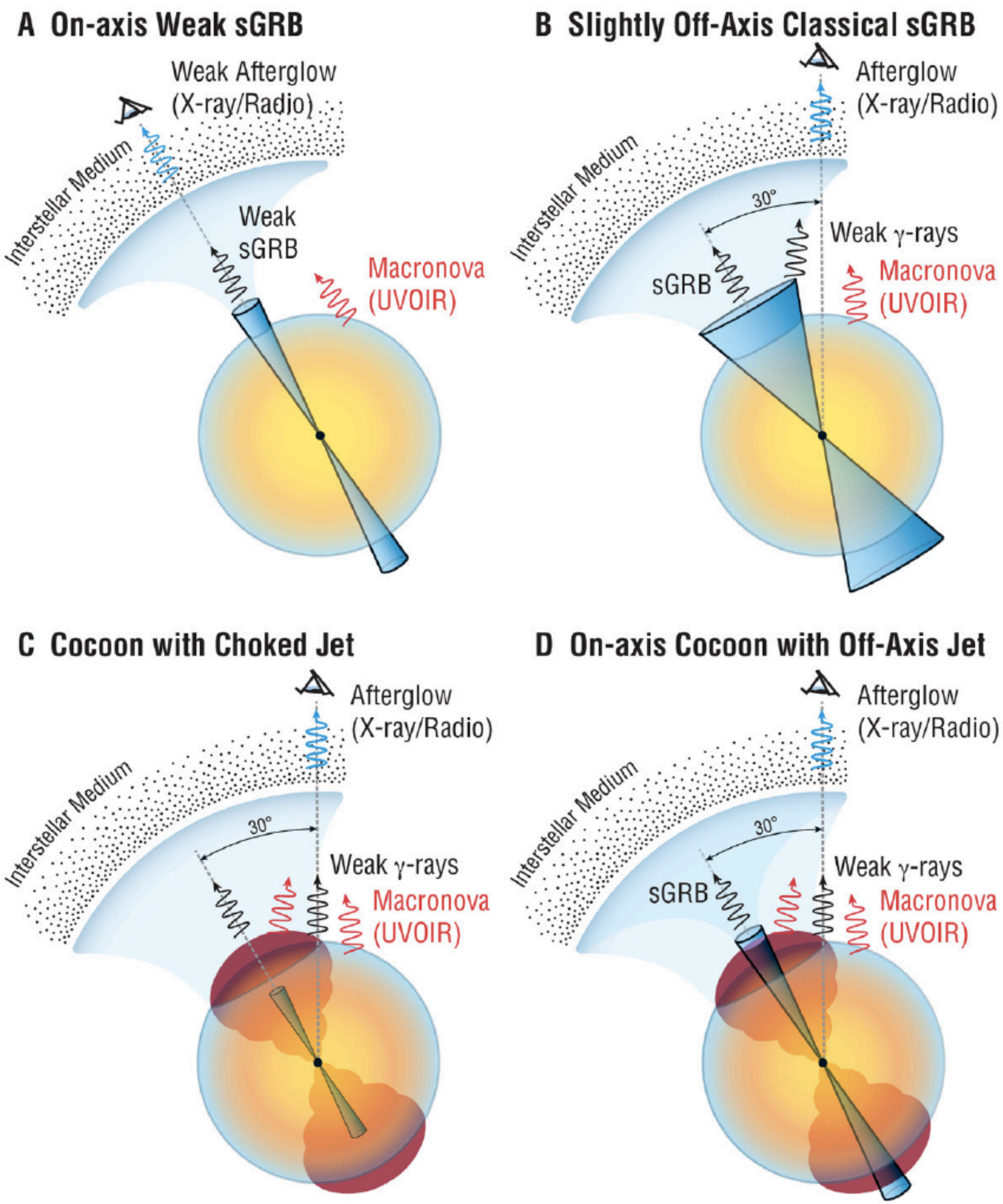


Ioka & Nakamura (2017)

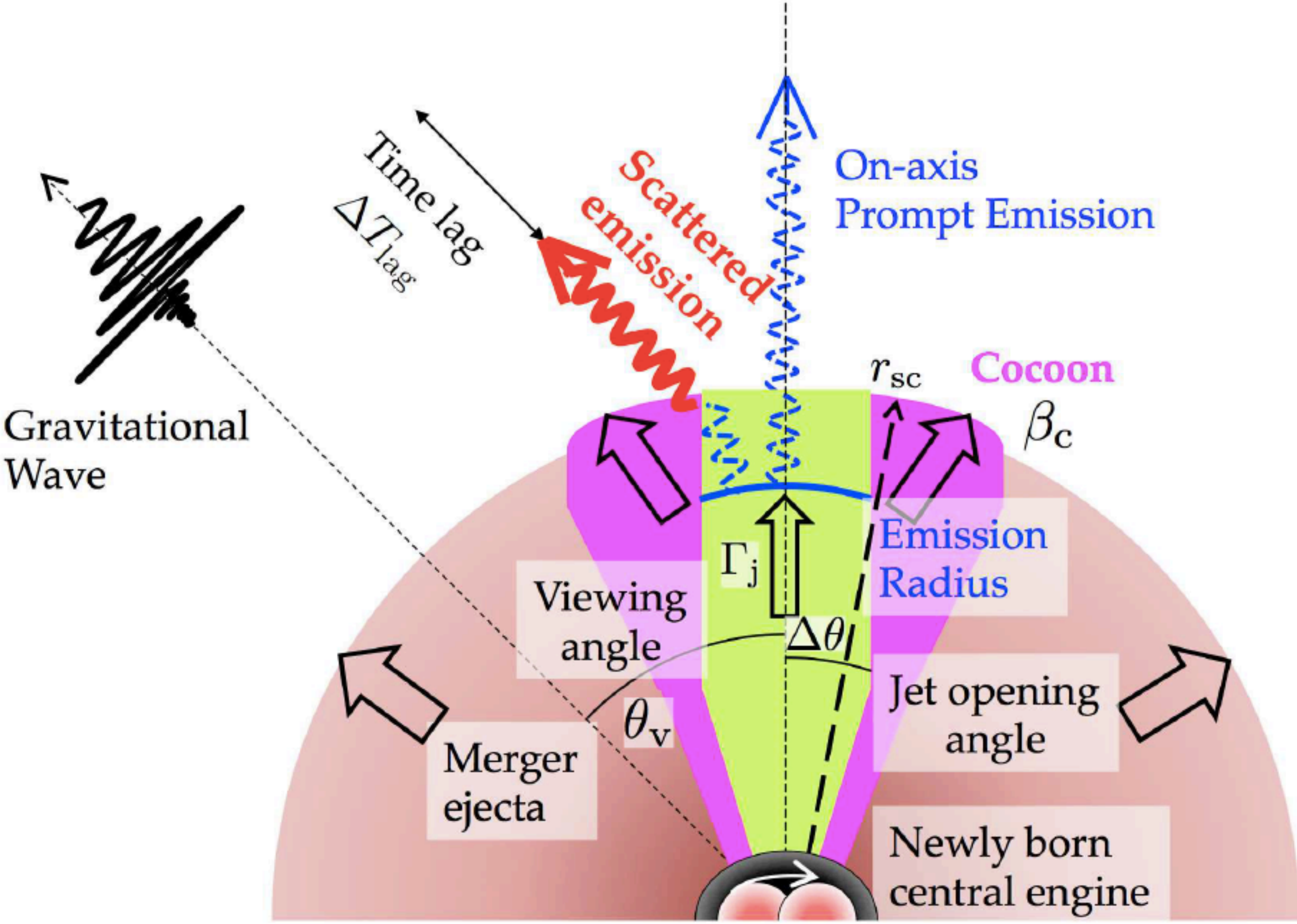
Granot et al. (2017): Constraints from arrival time difference of GW and γ.

$$R_\gamma < \frac{c\Delta t}{1-\cos(\Delta\theta)} \approx \frac{2c\Delta t}{\Delta\theta^2} = 6\times 10^{12}\left(\frac{\Delta t}{1\ \mathrm{s}}\right)\Delta\theta_{-1}^{-2}\ \mathrm{cm}$$





Kasliwal et al. (2017), Science



Kisaka et al. (2017)

Isotropic outflow説もある
（Asano’s talk, Salafia+2017, giant flare説）

Short GRBのoff-axis jet model の証拠は得られるか？

⇩

Counter-jet Emission ?

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DELAYED FLASHES FROM COUNTERJETS OF GAMMA-RAY BURSTS

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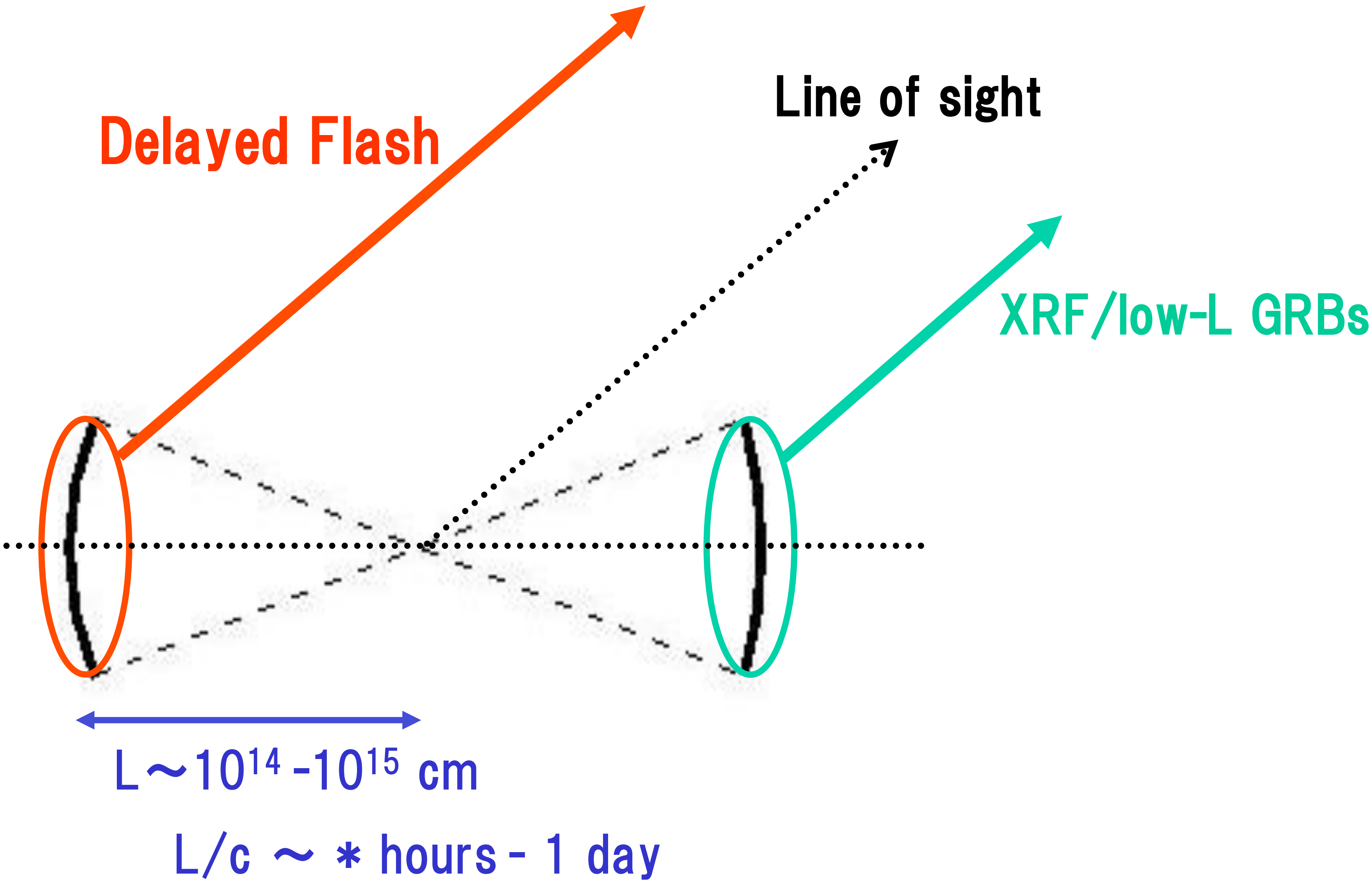
ABSTRACT

If X-ray flashes are due to the forward-jet emissions from gamma-ray bursts (GRBs) observed at large viewing angles, we show that a prompt emission from a counterjet should be observed as a "delayed flash" in the UV or optical band several hours to a day after the X-ray flash. The Ultraviolet and Optical Telescope on *Swift* can observe the delayed flashes within $\sim$13 Mpc, so that (double-sided) jets of GRBs can be directly confirmed. Since the event rate of delayed flashes detected by *Swift* may be as small as $\sim 6 \times 10^{-5}$ events yr^{-1}, we require more sensitive detectors in future experiments.

Subject headings: gamma rays: bursts — gamma rays: theory

Prediction of Jet Model : Delayed Flash



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

$\theta_v \sim 0 \Rightarrow \nu_{obs} \sim 200$ keV : GRB

$\gamma\theta_v \sim 10 \Rightarrow \nu_{obs} \sim 2$ keV : X-ray flash

$\theta_v \sim \pi \Rightarrow \nu_{obs} \sim 5$ eV : Delayed flash

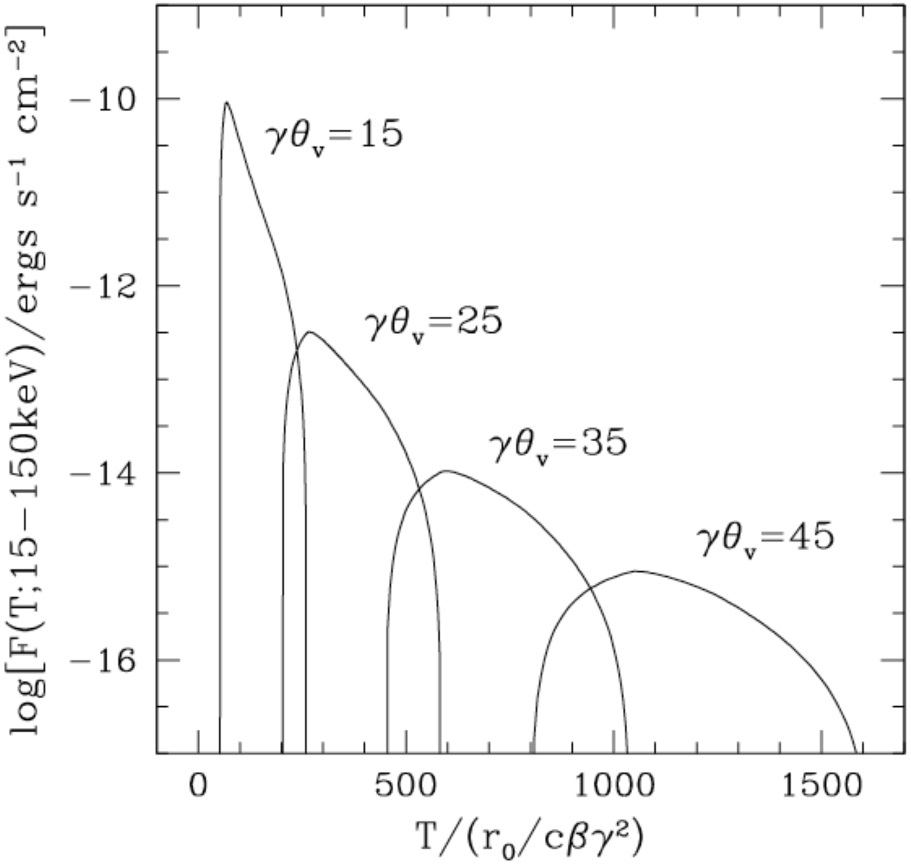


FIG. 1.—Light curves of the XRF as a function of the normalized observed time $T/(r_0/c\beta\gamma^2)$, where we adopt $r_0/\beta c\gamma^2 = 1$ s. We choose $\gamma\Delta\theta = 5$, $\alpha_B = -1$, $\beta_B = -3$, $\gamma\nu'_0 = 200$ keV, and $D = 1$ Gpc. The flux is proportional to D^{-2}.

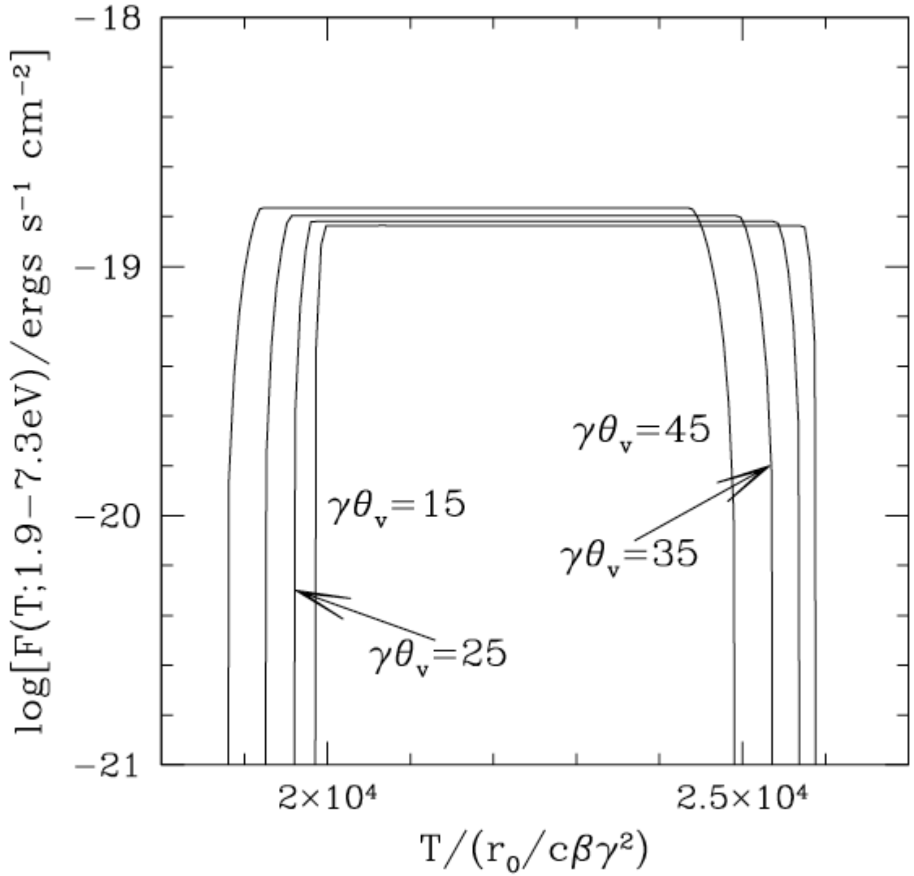


FIG. 2.—Light curves of the DF as a function of the normalized observed time $T/(r_0/c\beta\gamma^2)$, where we adopt $r_0/\beta c\gamma^2 = 1$ s. We choose $\gamma = 100$, $\gamma\Delta\theta = 5$, $\alpha_B = -1$, $\beta_B = -3$, $\gamma\nu'_0 = 200$ keV, and $D = 1$ Gpc. Our jet model predicts that the flux of the DF be almost constant ($F \sim 2 \times 10^{-19} D_{\rm Gpc}^{-2}$ ergs s $^{-1}$ cm^{-2}) with both the observed time and the viewing angle.

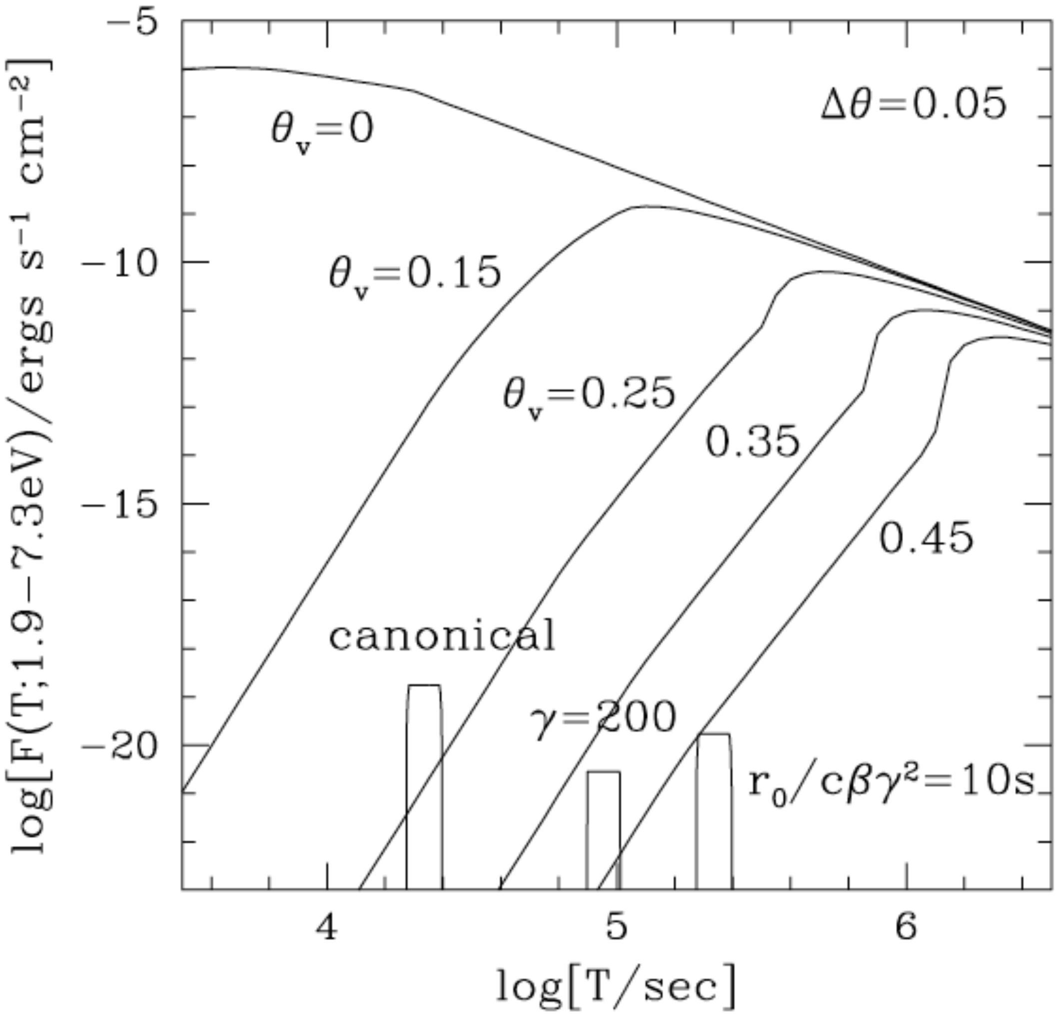


FIG. 3.—Light curves of the XRF afterglow in the UV band, shown by varying the viewing angle θ_v. We fix parameters as $\Delta\theta = 0.05$, $n = 1\ \mathrm{cm}^{-3}$, $p = 2.25$, $E = 2 \times 10^{54}$ ergs, $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, and $D = 1$ Gpc. Boxes represent the light curves of the DF in the same band. We choose a canonical set of parameters as $\gamma = 100$ and $r_0/\beta c\gamma^2 = 1$ s. The light curve of the DF does not depend so much on the viewing angle θ_v. For comparison, we show the light curves of the DF with one of the fiducial parameters changed. Note that all the flux is proportional to D^{-2}, and the flux and the duration of the DF are proportional to $(r_0/\beta c\gamma^2)^{-1}$ and $r_0/\beta c\gamma^2$, respectively.

Counterjet emission of short GRBs

Yamazaki, Ioka, Nakamura, arXiv: 1711.06856

PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (13 pages)
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Prompt emission from the counter jet of a short gamma-ray burst

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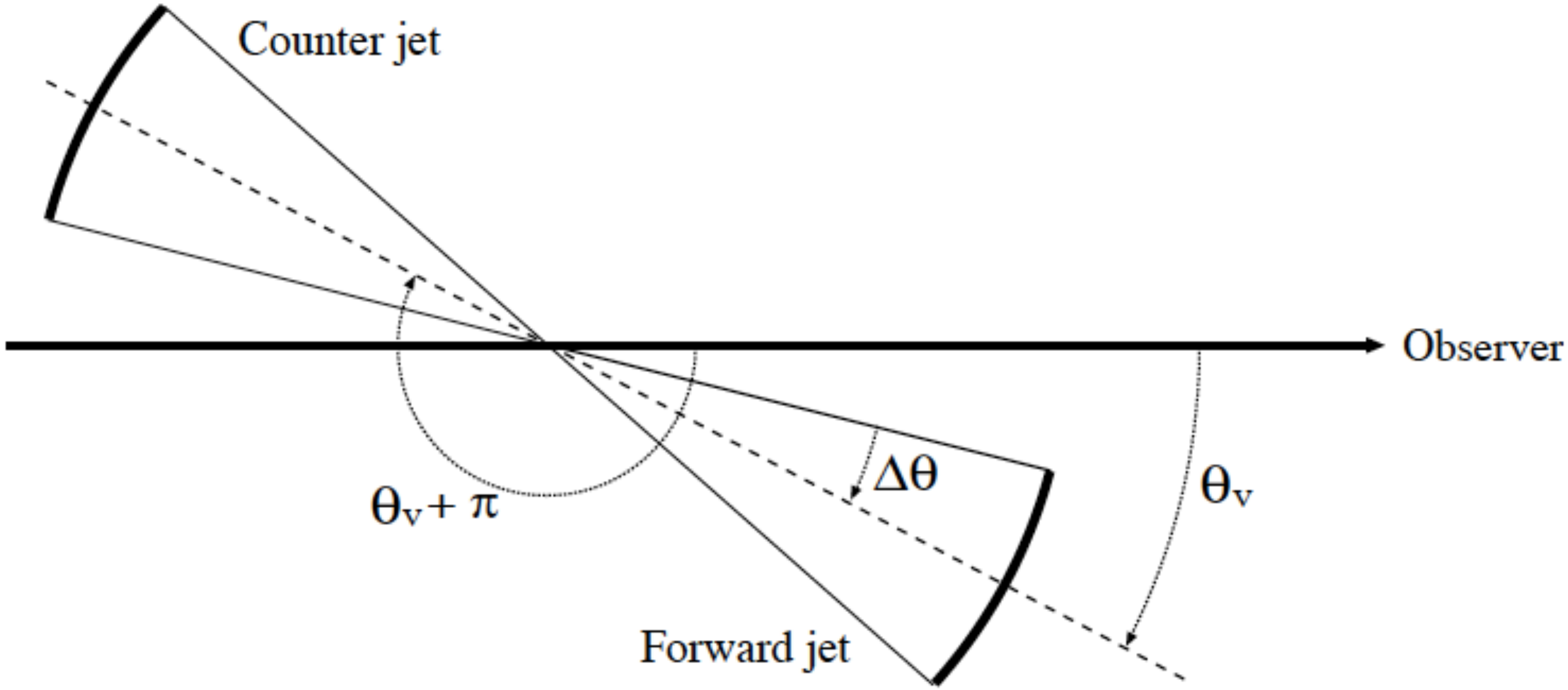
The counter jet of a short gamma-ray burst (sGRB) has not been observed yet, while recent discoveries of gravitational waves (GWs) from a binary neutron star (NS) merger GW170817 and the associated sGRB 170817A have demonstrated that off-axis sGRB jets are detectable. We calculate the prompt emission 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



Time coordinate, t, and Observer time, T

Time coordinate in Lab frame	
$t = 0$	GW emission ends.
$t = \tau_j$	Relativistc jets are launched from $r = 0$.
$t = \tau_j + t_0$	Jet emissions start.
$t = \tau_j + t_e$	Jet emissions end.

Observer time	
$T = 0$	GW detection ends.
$T = T^{(f)}_{\text{start}}$	Forward-jet emission starts.
$T = T^{(c)}_{\text{start}}$	Counter-jet emission starts.
$T = T^{(f)}_{\text{end}}$	Forward-jet emission ends.
$T = T^{(c)}_{\text{end}}$	Counter-jet emission ends.

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

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

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

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

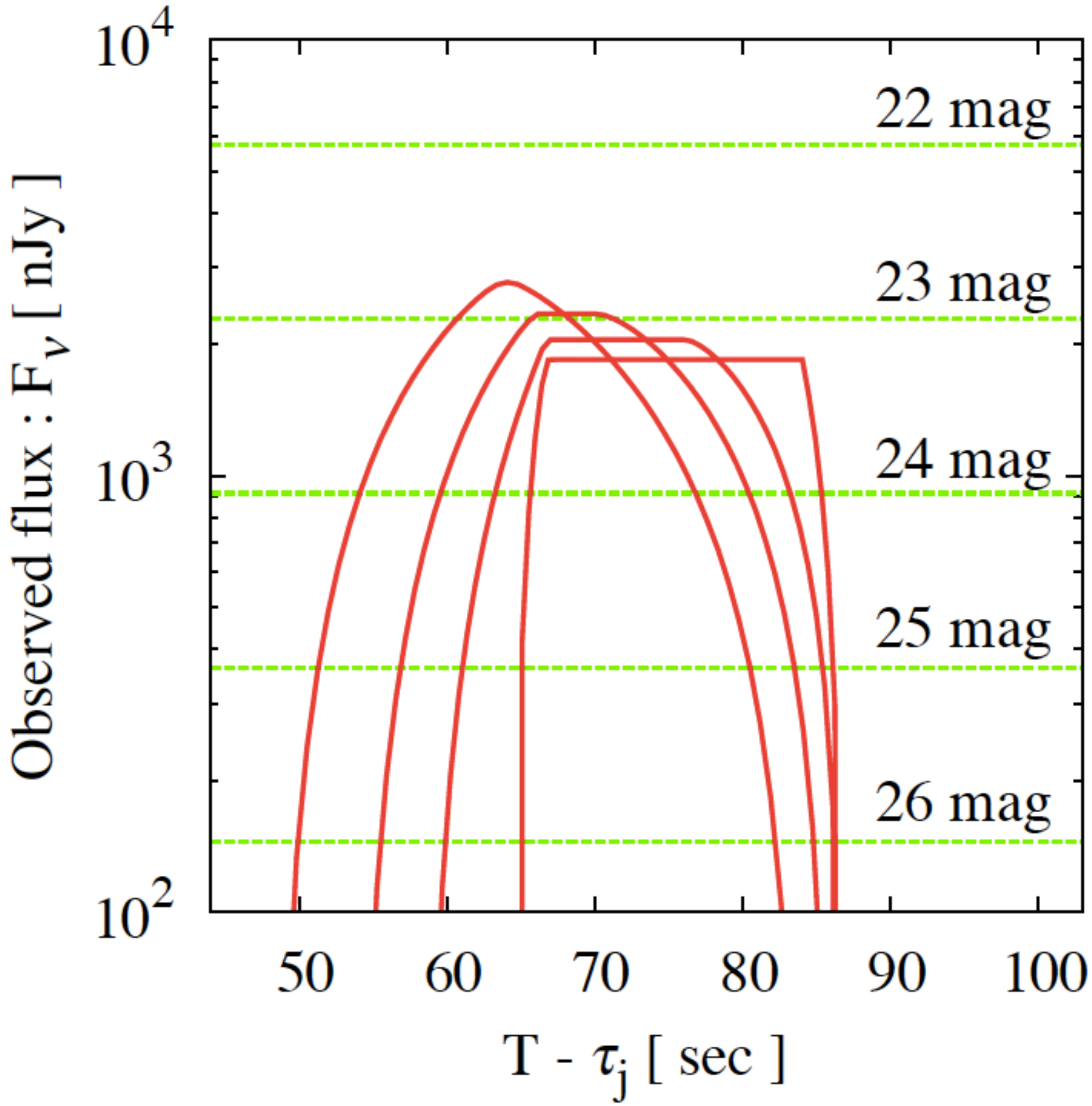


Fig. 1 Light curves of counterjet emission in the r-band for fiducial parameters ($\gamma = 100$, $\Delta\theta = 20°$, $h\gamma\nu'_0 = 500\,\mathrm{keV}$, $r_0 = 1 \times 10^{12}\,\mathrm{cm}$, $\alpha_B = -1$, $\beta_B = -3$, $s = 1$, $t_0 = r_0/c\beta$, $\kappa = 1.3$, and $E_{\mathrm{iso,on}} = 8.2 \times 10^{51}\mathrm{erg}$) with varying θ_v ($= 0°$, $20°$, $30°$, and $40°$, from right to left). The source is located at $D = 40$ Mpc.

T_{start} and T_{end} of counter-jet emission

For, $\gamma >> 1$, $\theta_v < 1$, $\Delta\theta < 1$, and $\theta_v > \Delta\theta$,

$$T^{(c)}_{\rm start} - \tau_j = \frac{2r_0}{c}\left[1 - \frac{(\theta_v + \Delta\theta)^2}{4}\right],$$

$$T^{(c)}_{\rm end} - \tau_j = \frac{2\kappa r_0}{c}\left[1 - \frac{(\theta_v - \Delta\theta)^2}{4}\right],$$

Pulse starting time and ending time constrains viewing geometry and the emission radius.

Too early?

No problem!

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

DECIGO/BBOができれば
LIGOで検出する1-10年前に
NS-NS mergerの方向と場所
を予言可能。

それまで長生きしよう！

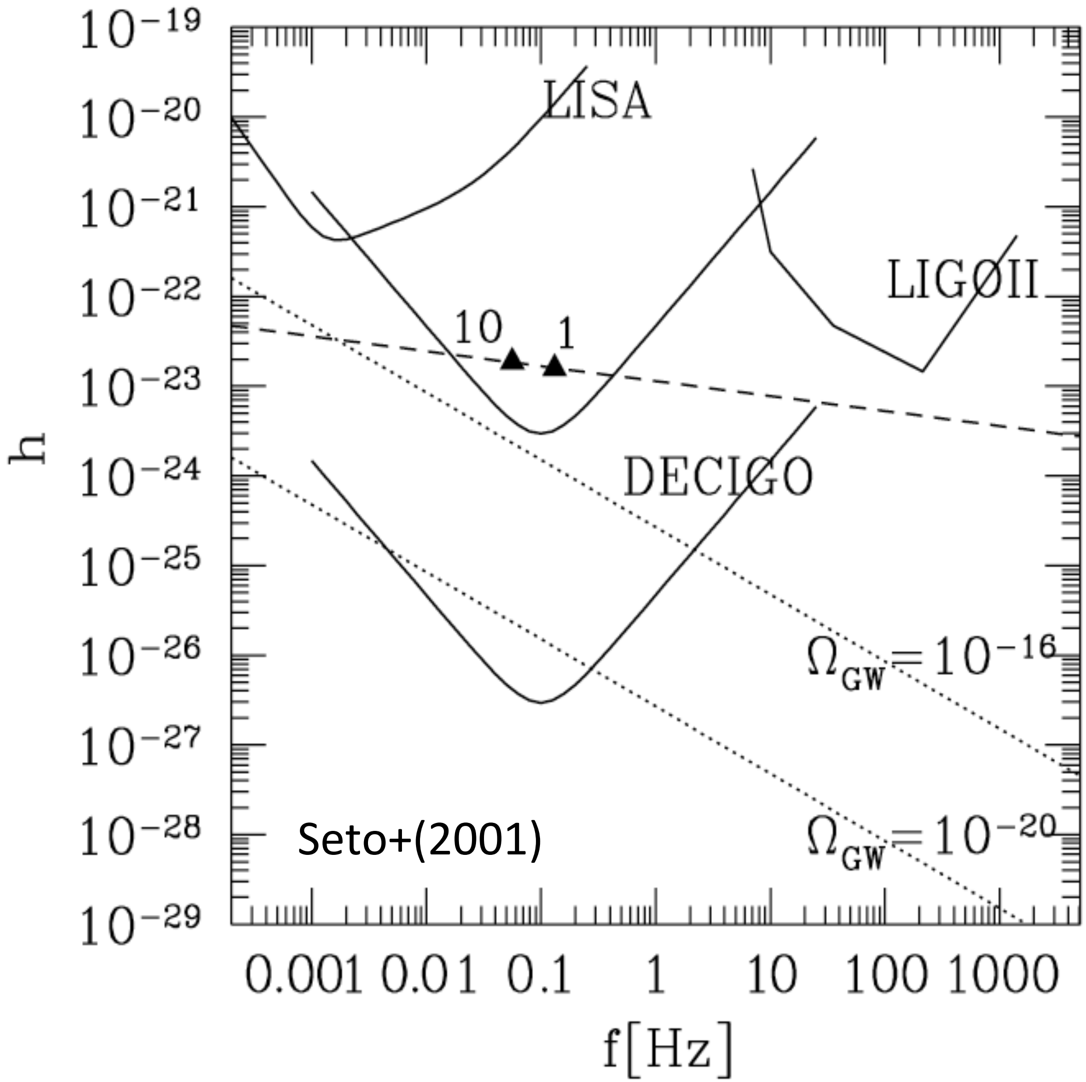


FIG. 1. Sensitivity (effectively S/N = 1) for various detectors (LISA, DECIGO, LIGOII, and a detector 10^3 times less sensitive than DECIGO) in the form of h_{rms} (solid lines). The dashed line represents evolution of the characteristic amplitude h_c for NS-NS binary at $z = 1$ (filled triangles: wave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

Early Macronova Emission

Kisaka et al. (2015), "thin-diffusion" regime

Nuclear heating rate: $\dot{\varepsilon}_r(t) = 2 \times 10^{10}(t/1\,\mathrm{day})^{-1.3}\ \mathrm{erg\ s^{-1} g^{-1}}$

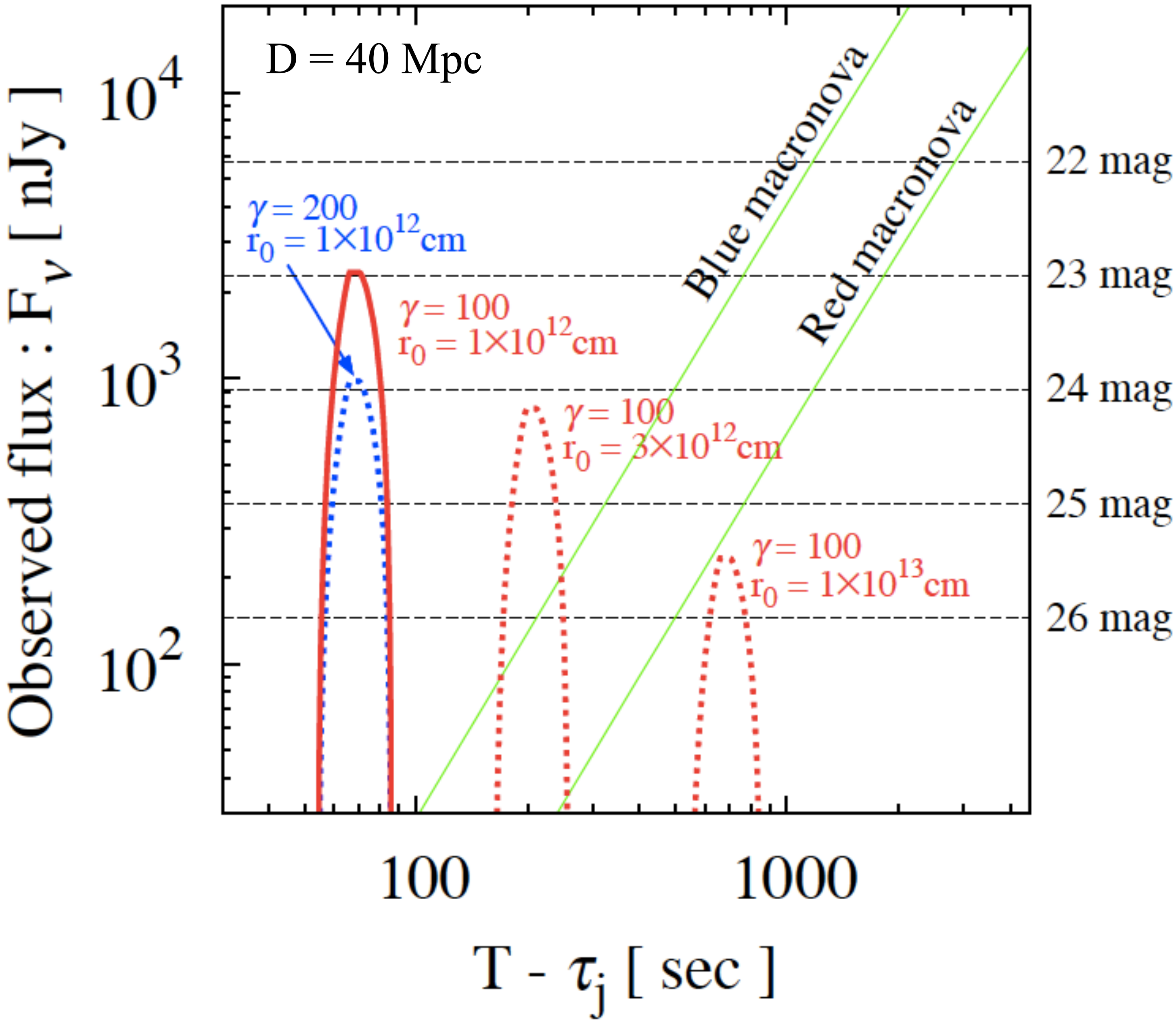
Blackbody temperature: $T_{\rm BB}(t) \approx \left(\frac{\epsilon_{\rm th}\dot{\varepsilon}_r(t)t\rho(t, v_{\rm max})}{a}\right)^{1/4}$

Bolometric luminosity:

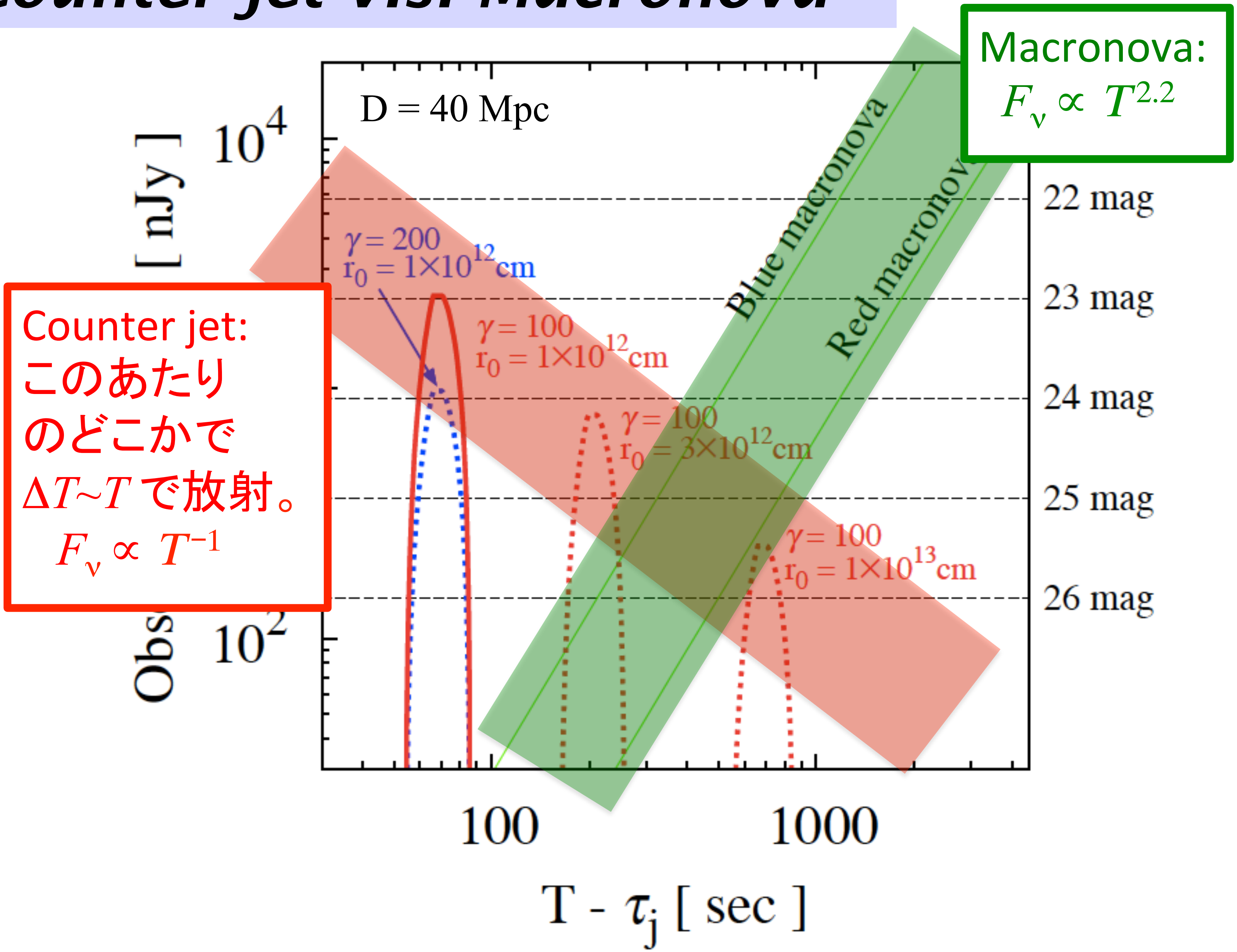
$$
\begin{aligned}
L_{\rm bol}(t) &\approx 4\pi(v_{\rm max}t)^2\left(\frac{ct}{\kappa\rho(t, v_{\rm max})}\right)^{1/2}\rho(t, v_{\rm max})\epsilon_{\rm th}\dot{\varepsilon}_r(t) \\
&= 1.5 \times 10^{42}\ \mathrm{erg\ s^{-1}}\left(\frac{\kappa}{10\ \mathrm{cm^2\ g^{-1}}}\right)^{-1/2}\left(\frac{M_{\rm ej}}{0.03M_\odot}\right)^{1/2} \\
&\quad \times \left(\frac{v_{\rm min}}{0.1c}\right)^{0.25}\left(\frac{v_{\rm max}}{0.4c}\right)^{0.25}\left(\frac{t}{10^2\ \mathrm{s}}\right)^{-0.3},
\end{aligned}
$$

(for heating rate $\dot{\varepsilon} \propto T^{-1.3}$ and ejecta profile : $\rho_{\rm ej} \propto t^{-3}v^{-3.5}$)

Counter-jet v.s. Macronova



Counter-jet v.s. Macronova



(Non-rela) macronova (kilonova) ejecta の残光放射は10-1000secでは暗い。

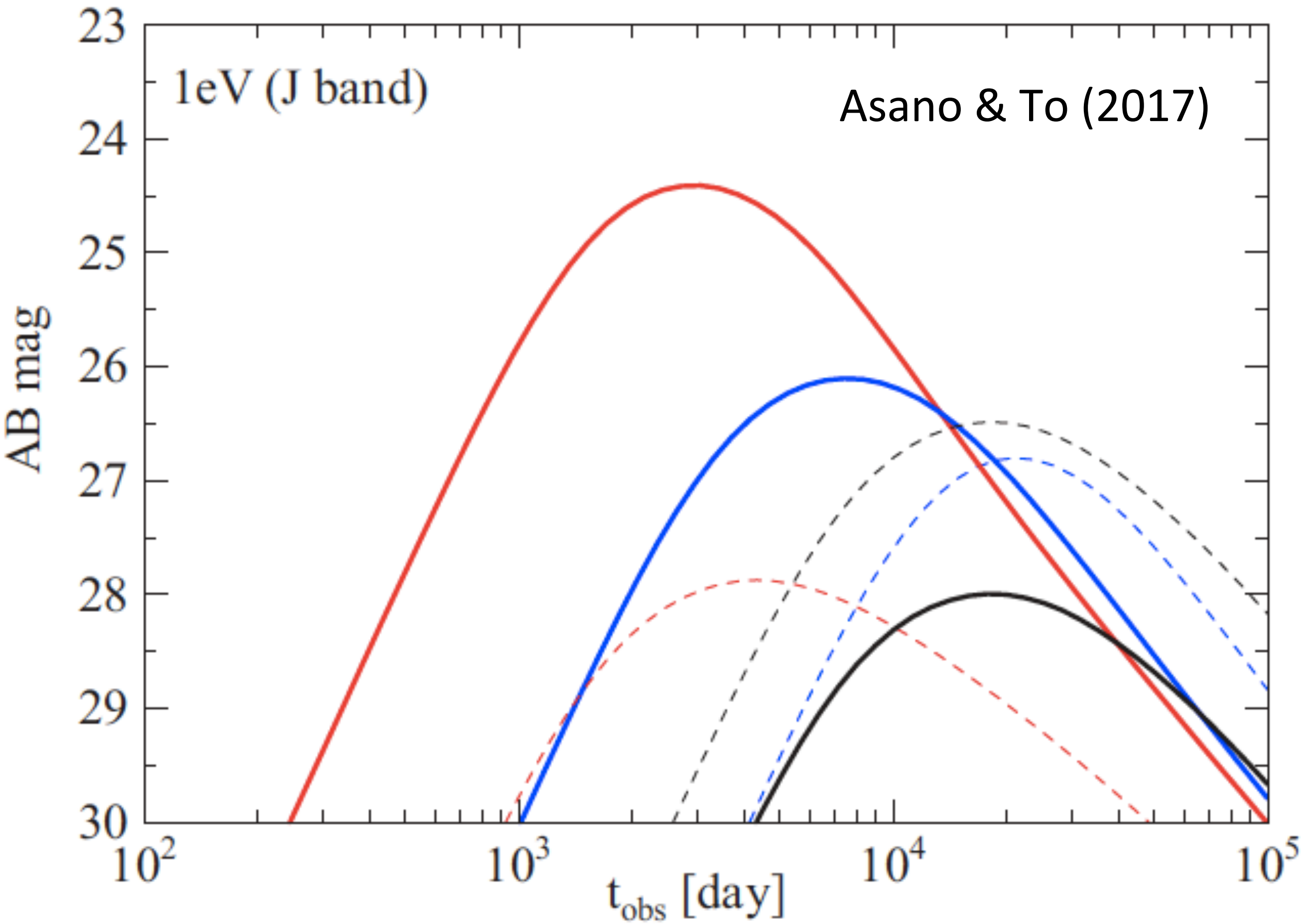


FIG. 2.— IR (1eV, J band) lightcurves for the model A (red, solid), A' (red, dashed), B (blue, solid), B' (blue, dashed), C (black, solid), and C' (black, dashed).

Forward jet のoff-axis残光は10-1000 secでは暗い？

memo: D = 40Mpcでは、R-bandで、
νL_ν =10^{39}erg/s ⇔ F_ν ~ 1000 nJy

Granot et al. (2017)

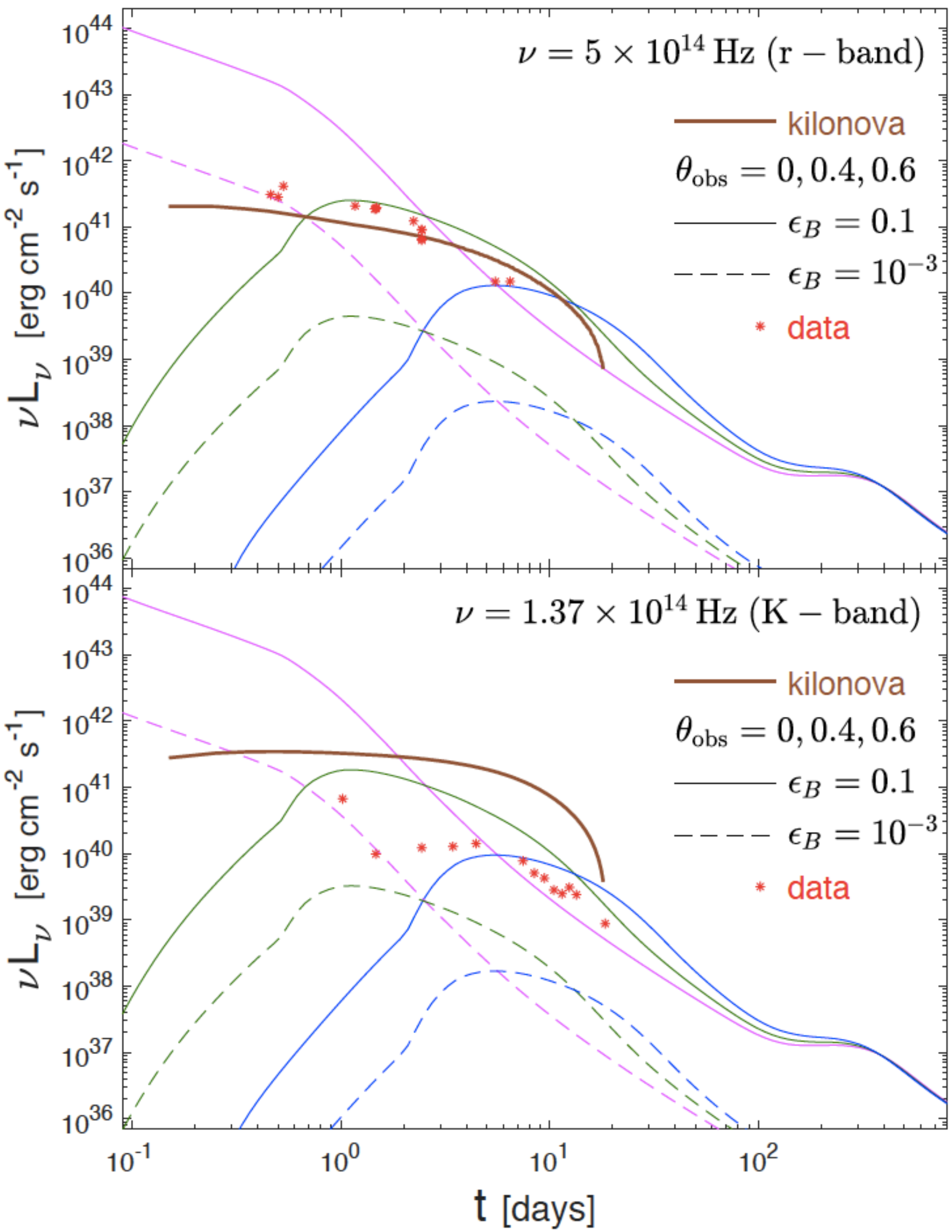


Figure 1. Comparison of optical (*upper panel*) and IR (*lower panel*) data (*red asterisks*) for GRB 170817A to theoretical models (Kasen, Fernandez & Metger 2015, with t_{HMNS} = 300 ms) for emission from a kilonova (*brown thick line*) and afterglow emission from a GRB jet observed from different viewing angles (θ_{obs} = 0, 0.4, 0.6 in magenta, dark green, and blue, respectively) and for two different values of the magnetic field equiprtition value (ϵ_B = 0.1, 10^{-3} in solid and dashed lines, respectively) while the other parameters are fixed to their fiducial values ($E = 10^{49}$ erg, $p = 2.5$, $n_0 = 1$, $\epsilon_e = 0.1$, $\theta_0 = 0.2$), based on relativistic hydrodynamic simulations (see §§ 6 and 7 for details).

Forward jetの残光は、Bulk Lorentz factorが小さいと（下の例では=80）、
初期でも明るくなる可能性がある。

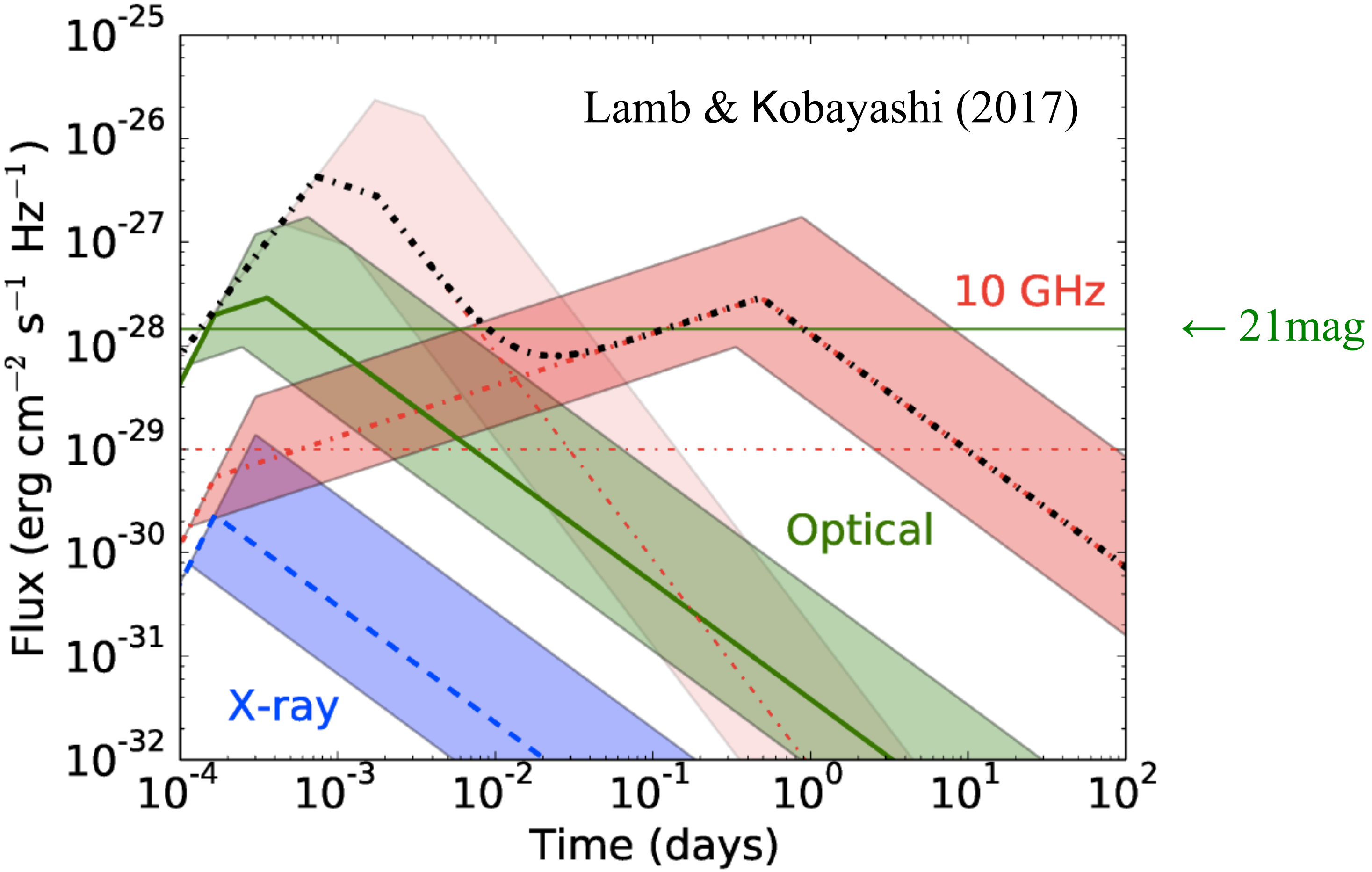


Figure 1. Afterglow lightcurves for a jet with an isotropic γ-ray energy of 4.0×10^{46} erg, a γ-ray efficiency of $\eta = 0.4$, a jet bulk Lorentz factor $\Gamma = 80$, in an ambient medium of $n = 0.009$ cm^{-3} with microphysical parameters $\varepsilon_B = 0.01$ and $\varepsilon_e = 0.1$, and a luminosity distance of 40 Mpc. The blue dashed line shows the X-ray afterglow, the green solid line shows the optical afterglow, and the red dashed-dotted line shows the 10 GHz radio afterglow. The shaded regions indicate the lightcurve for an efficiency $0.1 \leq \eta \leq 0.7$. The reverse shock is important at radio frequencies, the 10 GHz reverse shock is shown as a thin dash-dotted red line and faint shaded region for the range of jet energies considered; the forward and reverse shock lightcurve at 10 GHz is shown as a thick black dashed-dotted line. The the red dashed horizontal line indicates the 1μJy limit, the green horizontal dashed line indicates $m_{AB} \sim 21$ magnitude, and lower-limit of the y-axis is the X-ray sensitivity ~ 0.4 μCrab at 4 keV

Useful formulae

Counter-jet emission (optical band) :

$$F_\nu \propto \frac{E_{\rm iso,\,on}^{(SGRB)}}{r_0 \gamma^2} \nu^{1+\alpha_B}$$

$$T_{\rm start} \sim T_{\rm end} \sim \Delta T \sim \frac{2r_0}{c}$$

Early macronova (T<<10^4sec) :

$$F_\nu \propto \frac{v_{\rm max}^{2.875}}{\kappa^{1/2} M_{\rm ej}^{1/4} v_{\rm min}^{0.125}} T^{2.175} \nu^2$$

for heating rate : $\dot{\varepsilon} \propto T^{-1.3}$

ejecta profile : $\rho_{\rm ej} \propto t^{-3} v^{-3.5}$

Parameter determination

6 Model parameters : γ, $\Delta\theta$, θ_V ,
r_0 , r_e (emission radii),
τ_j = t (jet launch) – t (GW end)

5 observables: θ_V (<= GW analysis) ,
T_{start} , T_{end} (<= forward jet)
T_{start} , T_{end} (<= counter jet)

GRB spectrum + Amati (Yonetoku) relation
=> (Off-axis model Doppler factor) = $\gamma\,[1-\beta\cos(\theta_V\text{-}\Delta\theta)]$

5 observables & 1 relation to determine 6 model parameters.

Parameter determination 2

２つのジェットをほぼ真横 ($\theta_V \sim \pi / 2$) からみているとき、

$$
\begin{aligned}
T^{(\mathrm{f})}_{\mathrm{start}} - \tau_j &= \frac{r_0}{c\beta}\left[1 - \beta \sin(\delta\theta_v + \Delta\theta)\right], \\
T^{(\mathrm{f})}_{\mathrm{end}} - \tau_j &= \frac{r_e}{c\beta}\left[1 - \beta \sin(\delta\theta_v - \Delta\theta)\right], \\
T^{(\mathrm{c})}_{\mathrm{start}} - \tau_j &= \frac{r_0}{c\beta}\left[1 + \beta \sin(\delta\theta_v - \Delta\theta)\right], \\
T^{(\mathrm{c})}_{\mathrm{end}} - \tau_j &= \frac{r_e}{c\beta}\left[1 + \beta \sin(\delta\theta_v + \Delta\theta)\right].
\end{aligned}
$$

$$(\theta_v = \pi/2 - \delta\theta_v \text{ with } 0 \leq \delta\theta_v < 1)$$

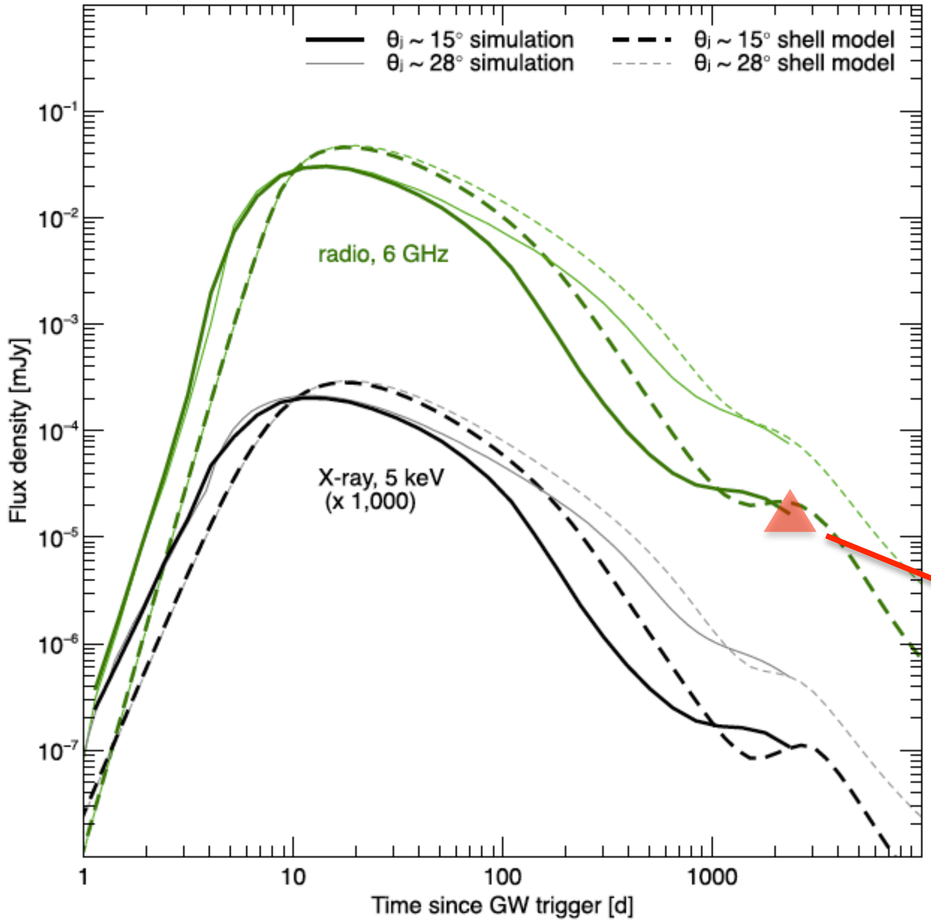
$$\rightarrow \qquad \tau_j = \frac{T^{(\mathrm{c})}_{\mathrm{end}} T^{(\mathrm{f})}_{\mathrm{start}} - T^{(\mathrm{c})}_{\mathrm{start}} T^{(\mathrm{f})}_{\mathrm{end}}}{(T^{(\mathrm{c})}_{\mathrm{end}} - T^{(\mathrm{c})}_{\mathrm{start}}) - (T^{(\mathrm{f})}_{\mathrm{end}} - T^{(\mathrm{f})}_{\mathrm{start}})}$$

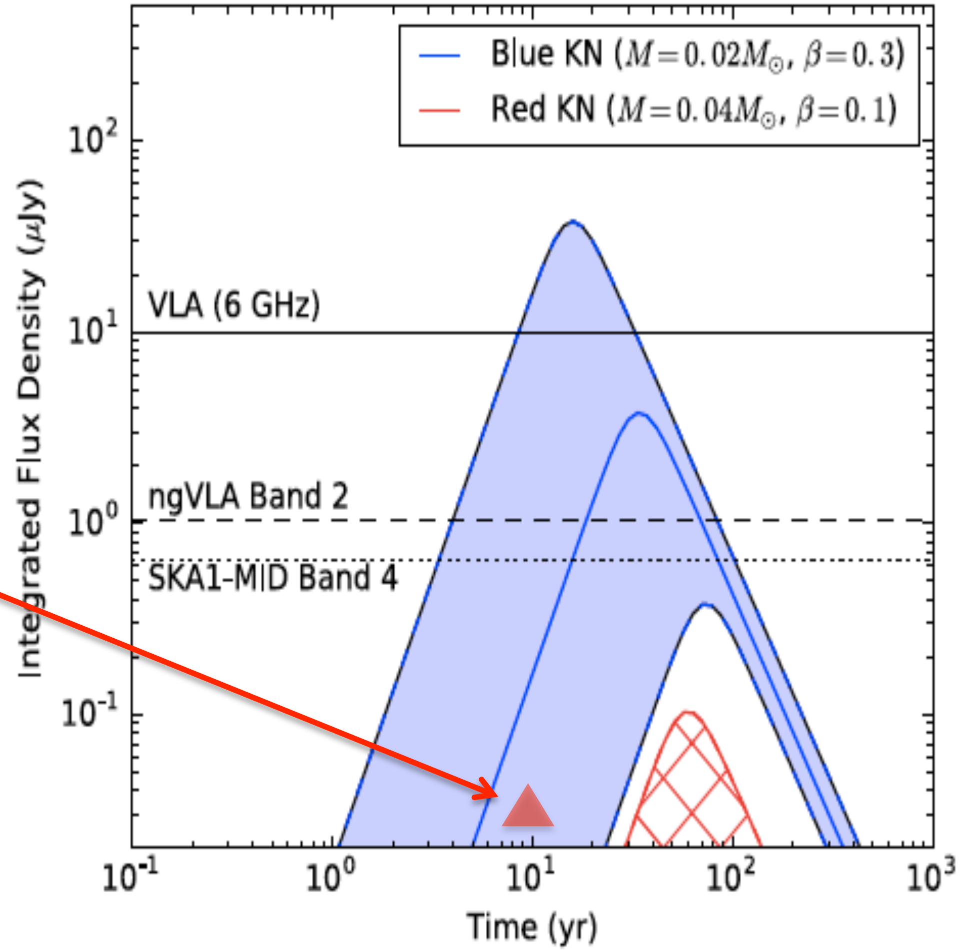
となり、GW放射終了からジェットが出るまでの時間差がわかるかも！

Radio afterglow?

Forward/counter jets

Macronova dynamical ejecta





Troja et al. (2017)

Alexander et al. (2017)

Summary

・$\Delta\theta$ = 20 deg, θ_v = 30 deg (Ioka & Nakamura 2017) のとき、

Jet bulk Lorentz factor: γ = 50 〜200
Emission radius r_0 = 1-3 x 10^{12}cm

であれば、

GW (merger) から 1~10分後くらいに
R = 22-24 mag (at D = 40 Mpc)

のcounter-jet emission が見えるかもしれない。

・気長に待ちましょう。

cf. GRB 980425やGRB 031203といったLow-luminosity GRBs
は当時は20年に一度のイベントと言われたが、なぜか
その後、似たようなものがいくつか受かってしまった。