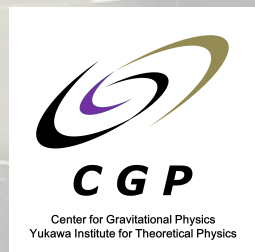
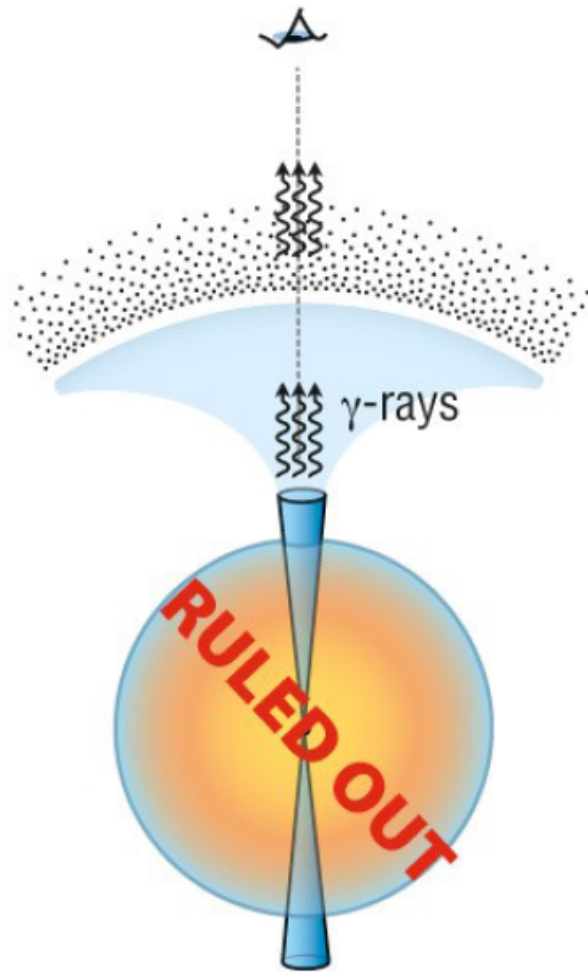


γ -Rays and Afterglow from a Short Duration Gamma-Ray Burst Jet

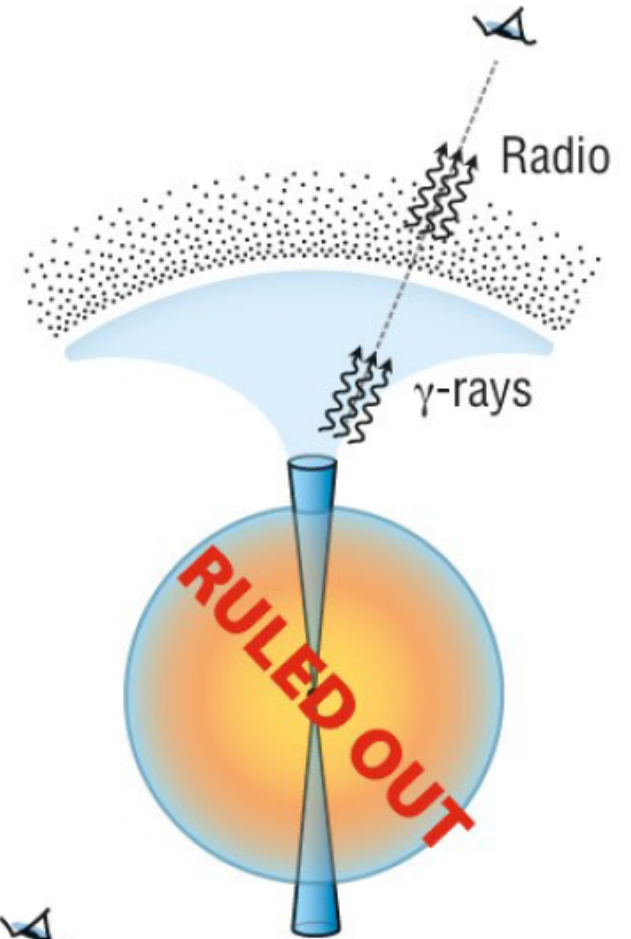
Kunihito Ioka

***(Center for Gravitational
Physics, YITP, Kyoto U.)***





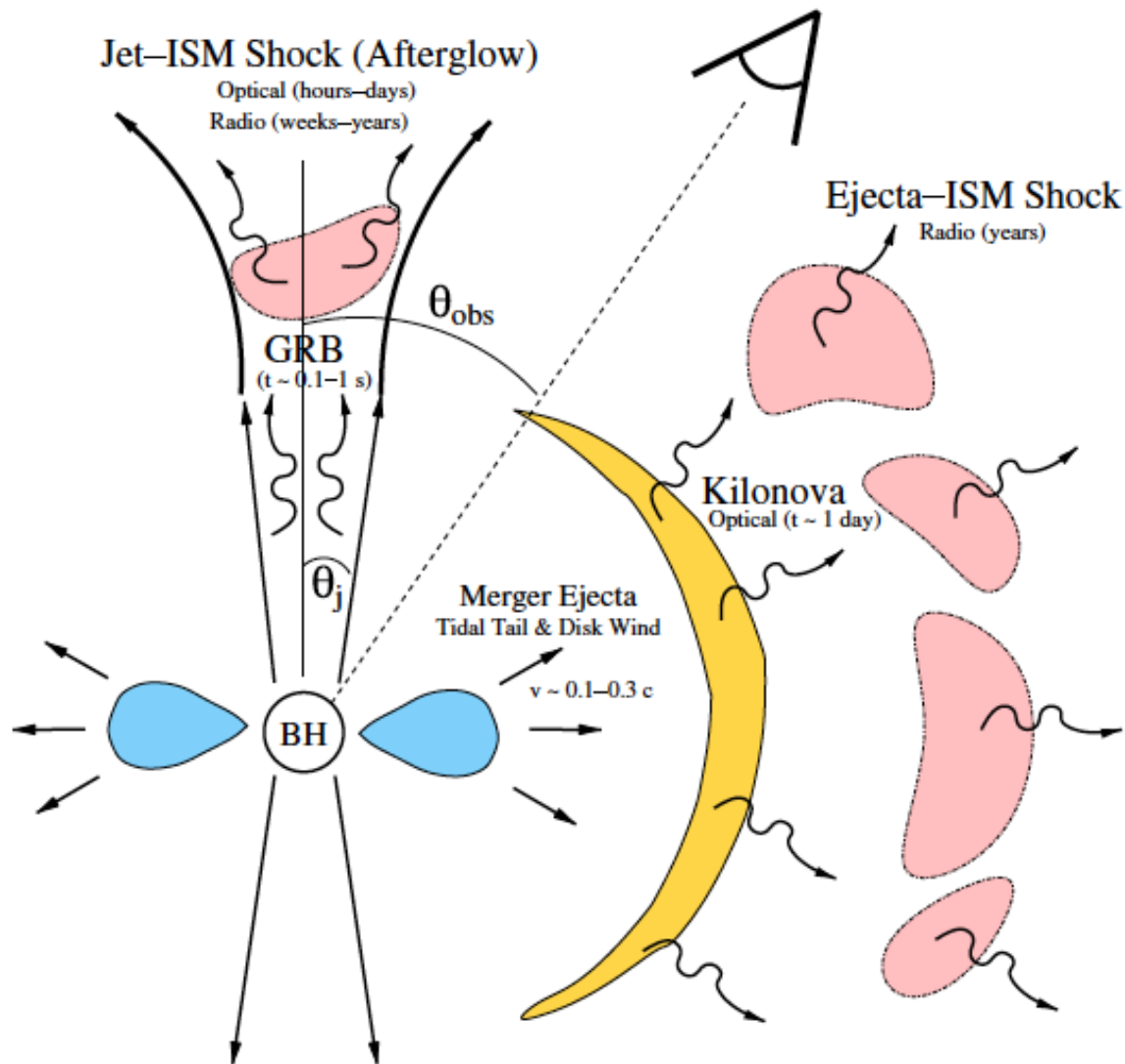
A. On-axis Jet
SGRB and afterglow



B. Off-axis Jet
SGRB and afterglow



EM Counterparts



On-axis fraction

$$\frac{2\pi(\Delta\theta)^2}{4\pi} \sim 0.01 \ll 1$$

Off-axis energy

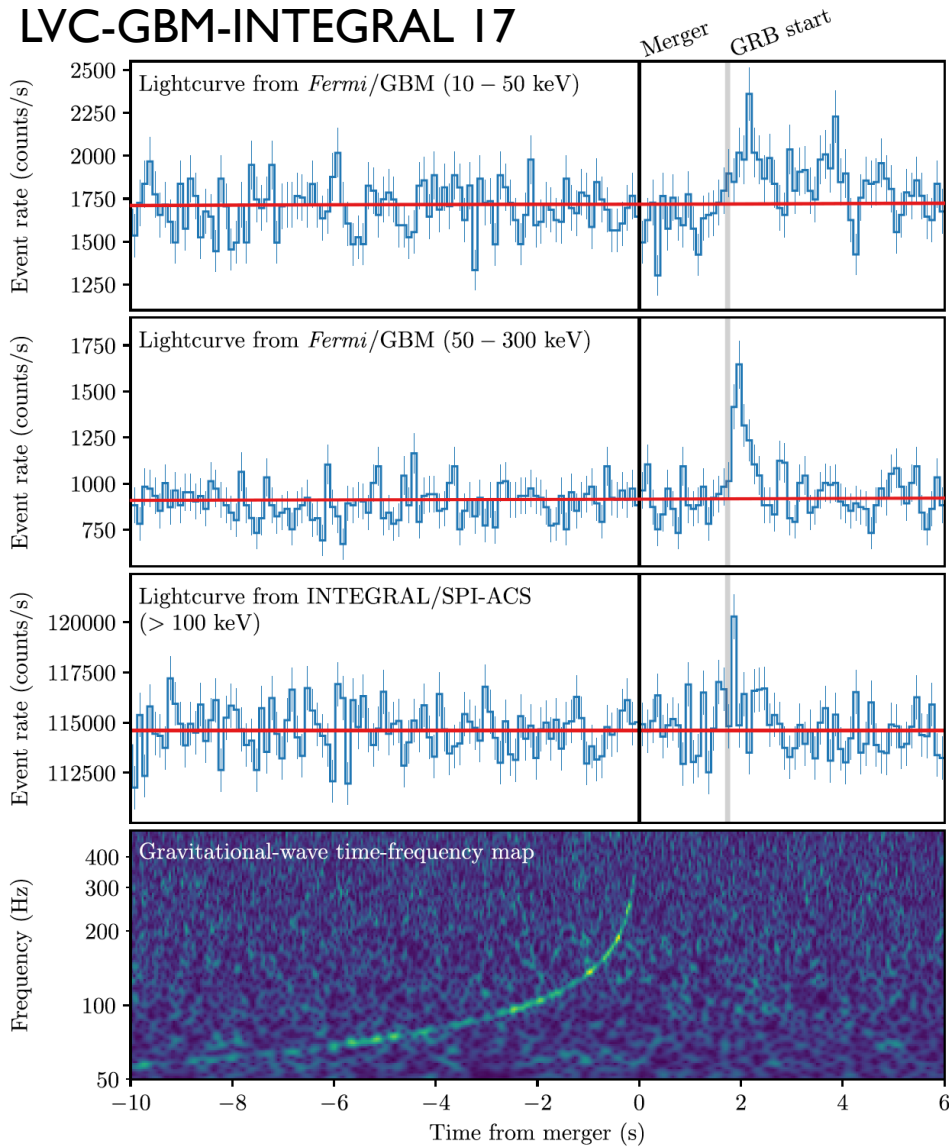
$$E_{\text{iso}} \propto \delta^3 \propto \theta_v^{-6}$$

(point source case)

Probably too dim
... but

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

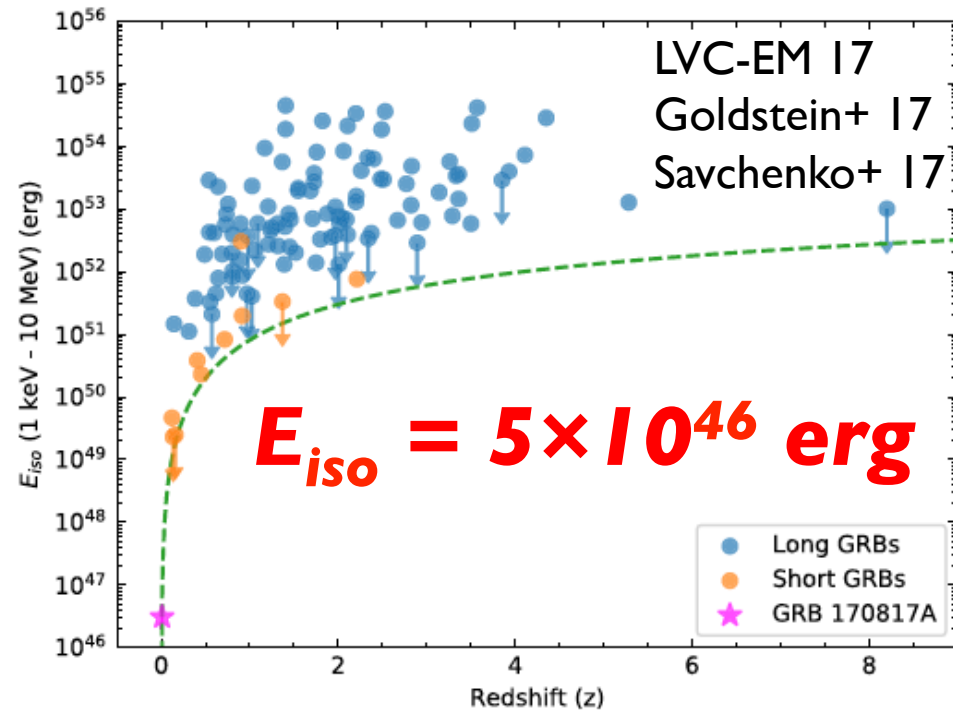


3 (of 12) GBM NaI detectors

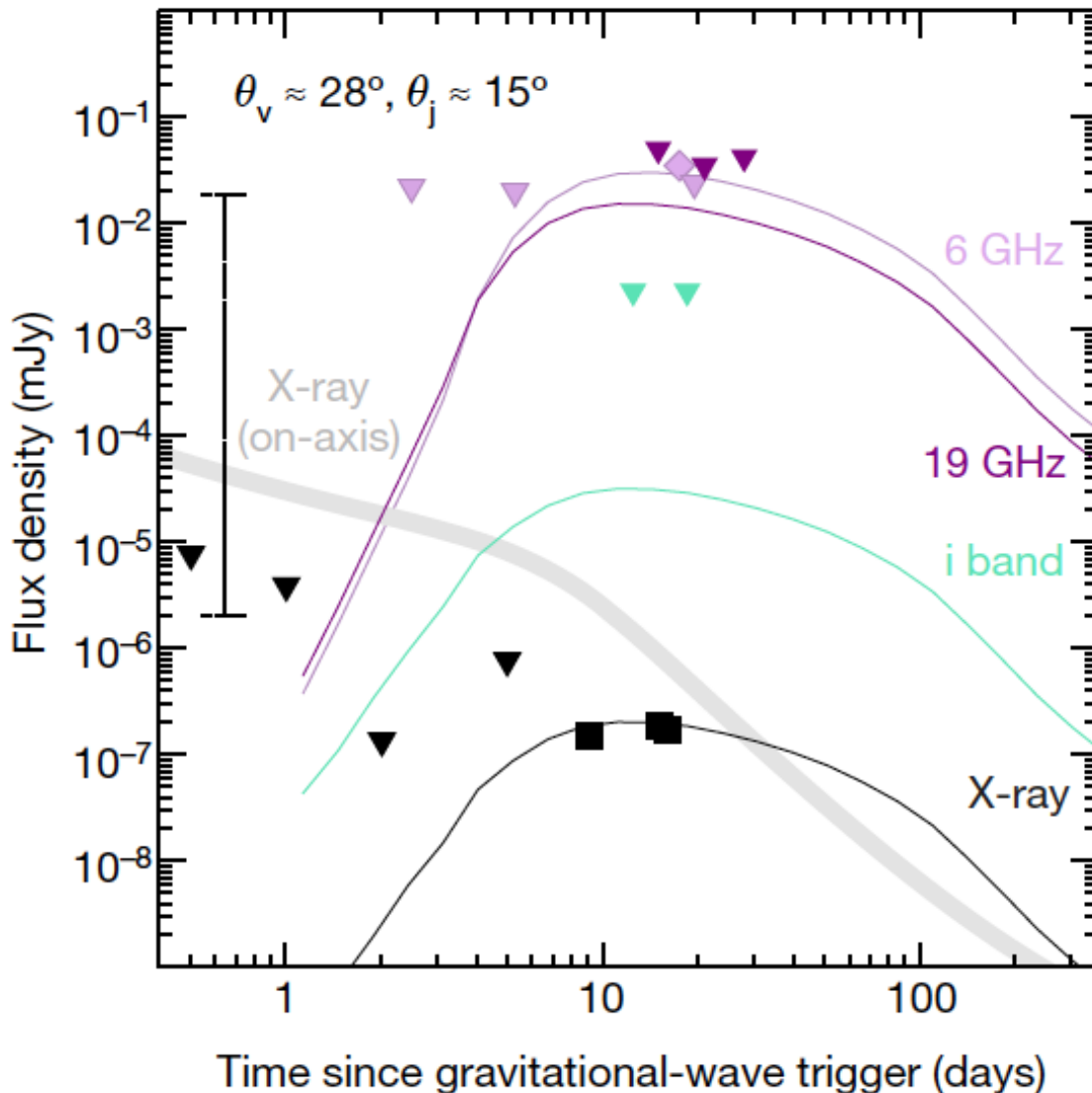
$T_0 = 1.74 \pm 0.05$ sec (68%)

$T_{90} = 2.0 \pm 0.5$ sec

Weak but Detected



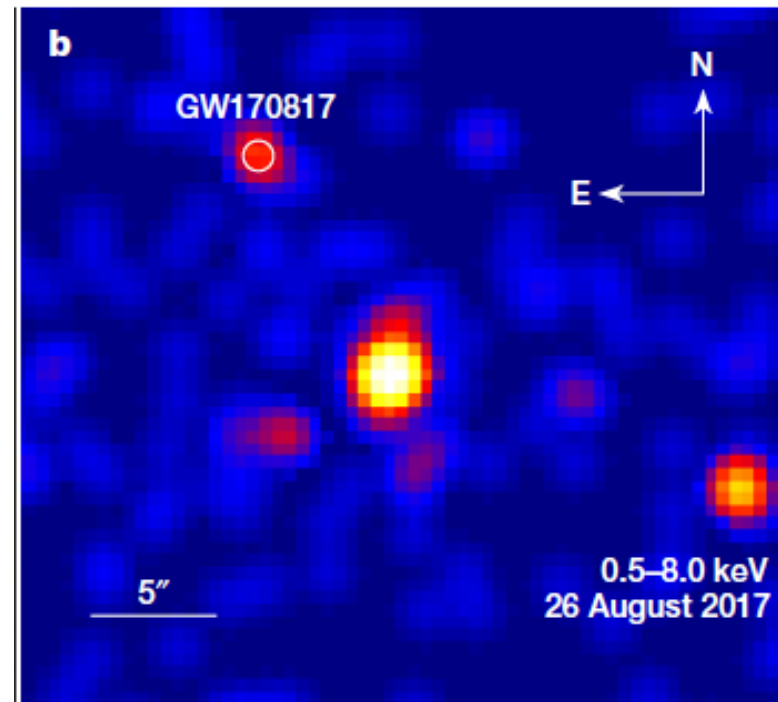
X-ray Afterglow



Chandra 50ks

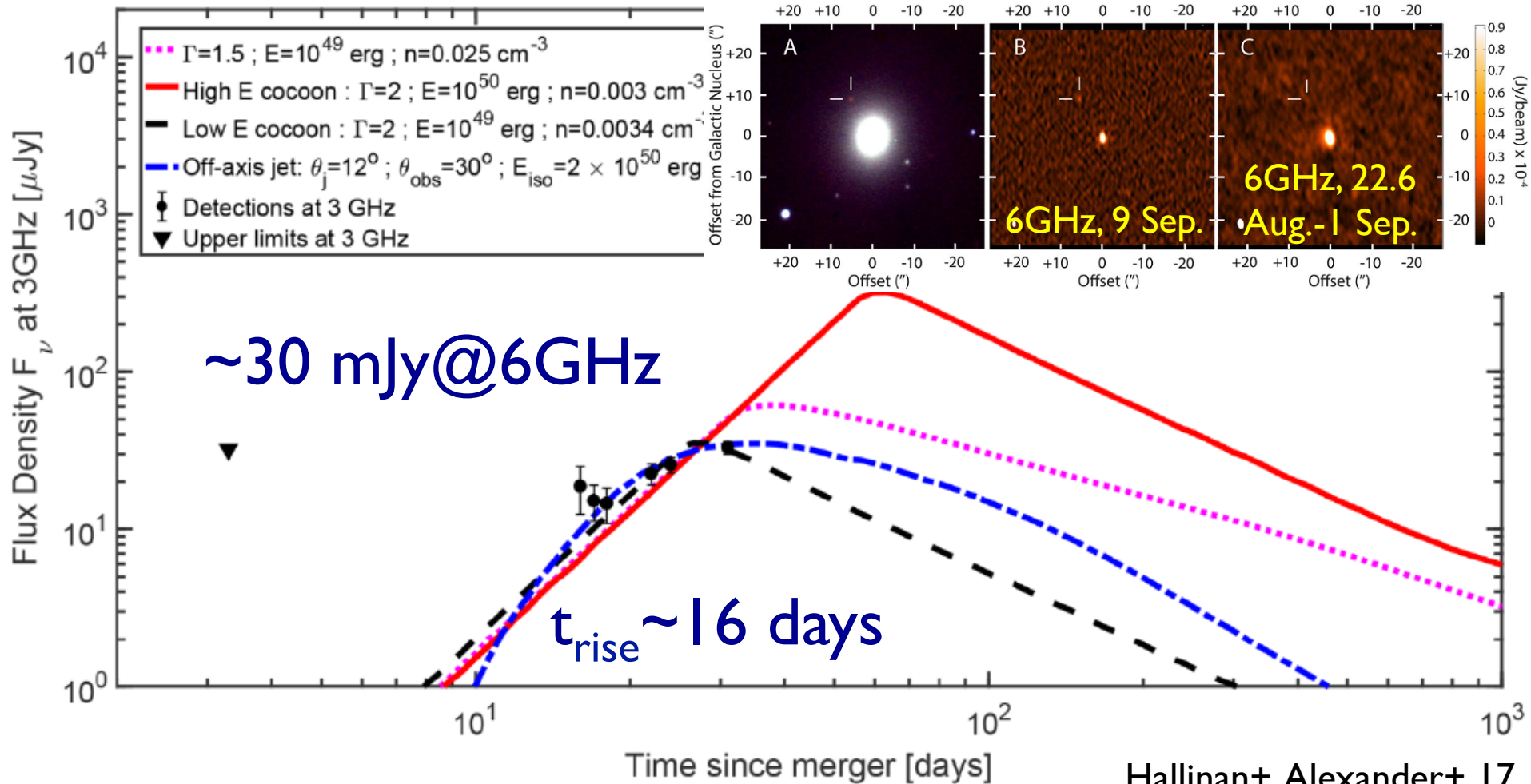
$t_{\text{rise}} \sim 9$ day

$L_{\text{X,iso}} \sim 1.1 e^{39}$ erg/s



Troja+, Margutti+, Haggard+ 17

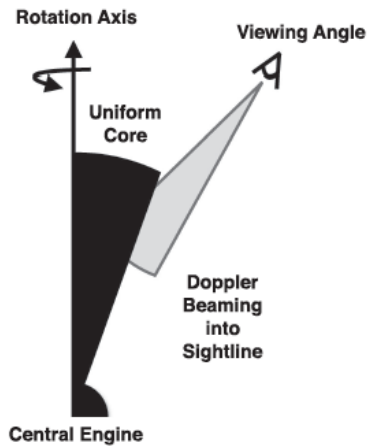
Radio Afterglow



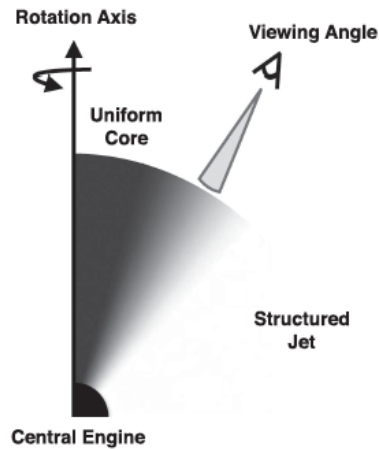
X/Radio ratio \sim Synchrotron $p=2.2$ ($\nu_m < \nu < \nu_c$)

Various Possibilities

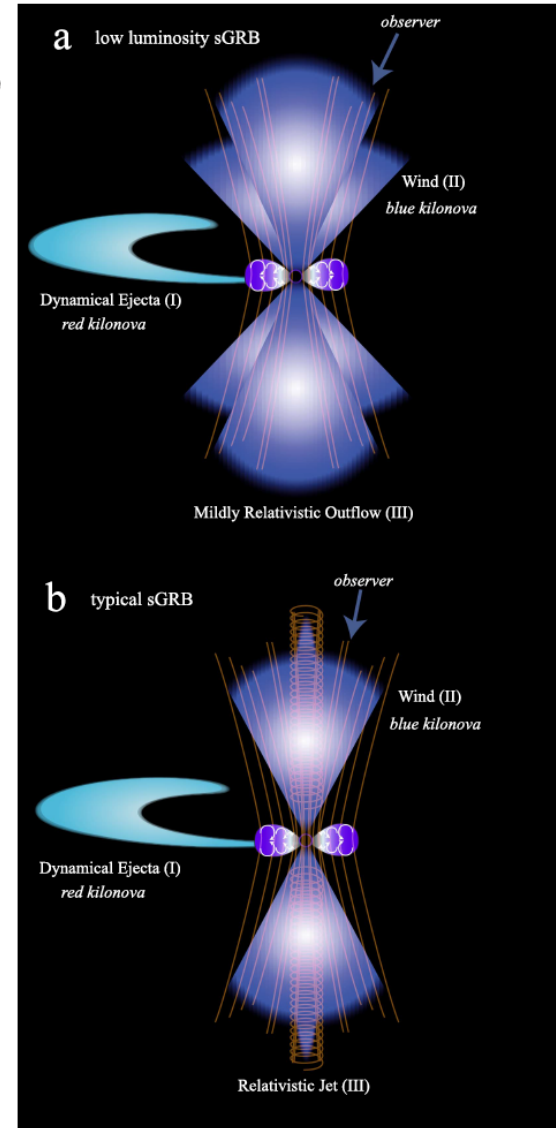
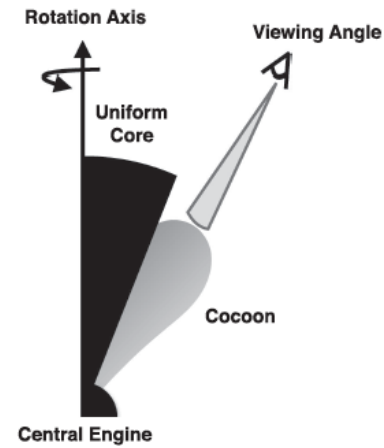
Scenario i: Uniform Top-hat Jet



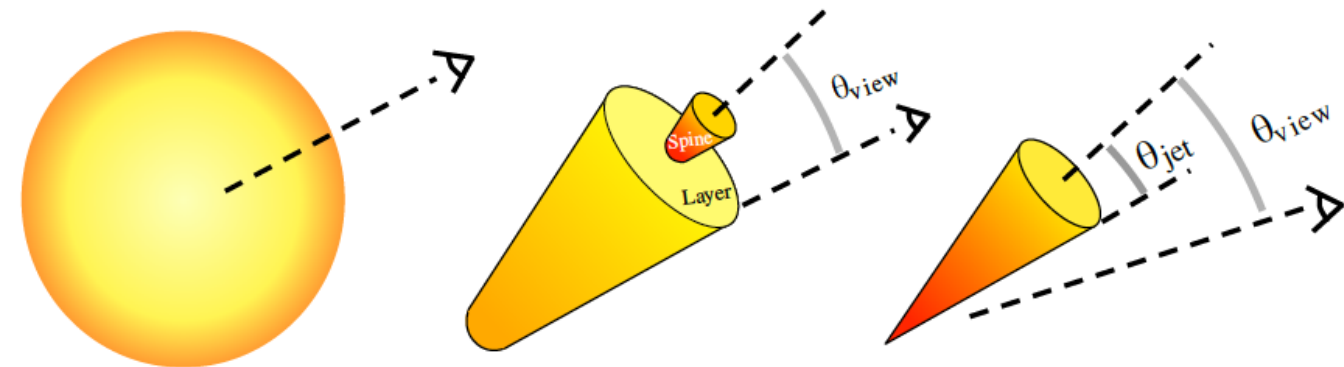
Scenario ii: Structured Jet



Scenario iii: Uniform Jet + Cocoon

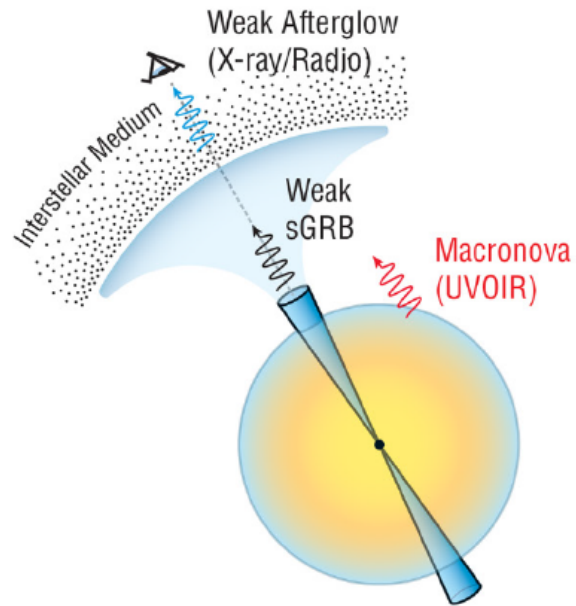
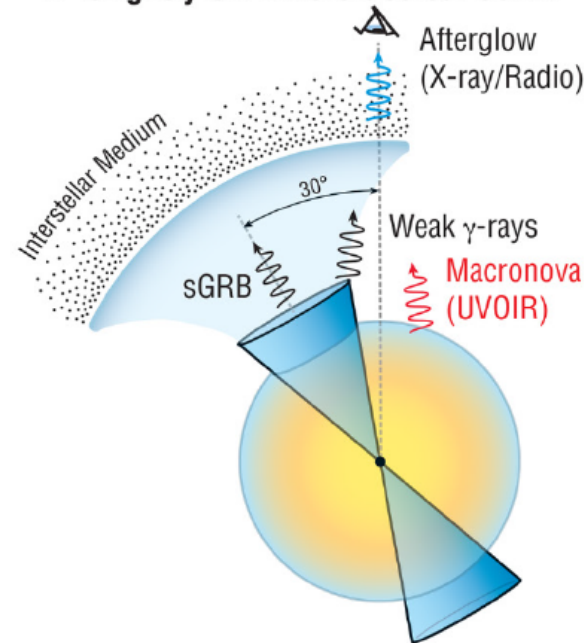
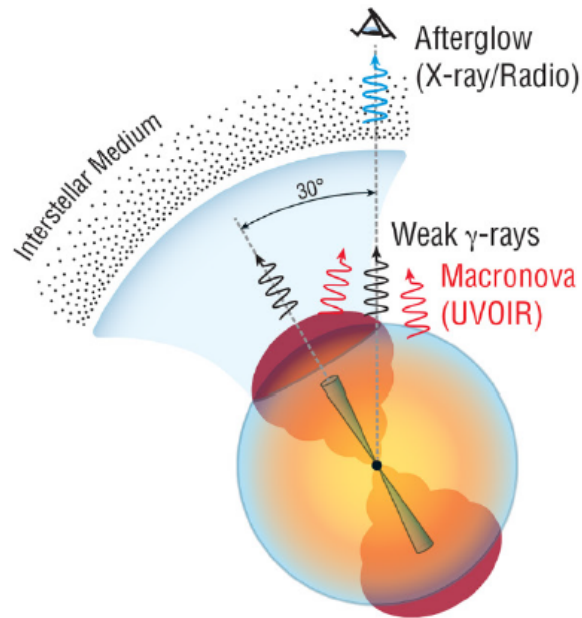
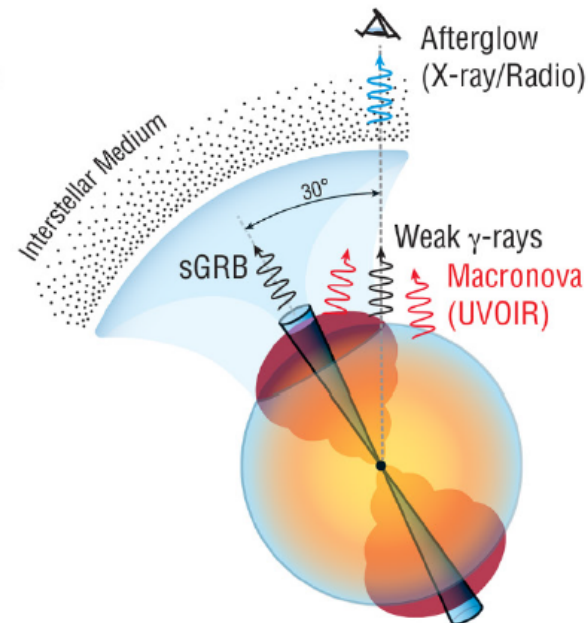


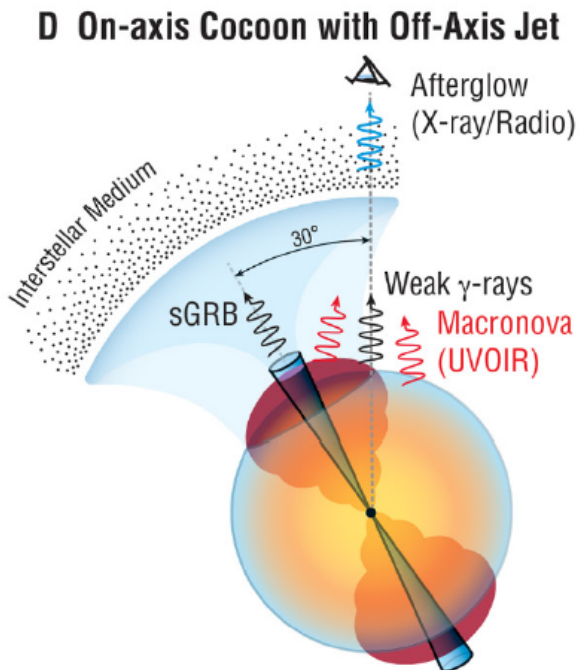
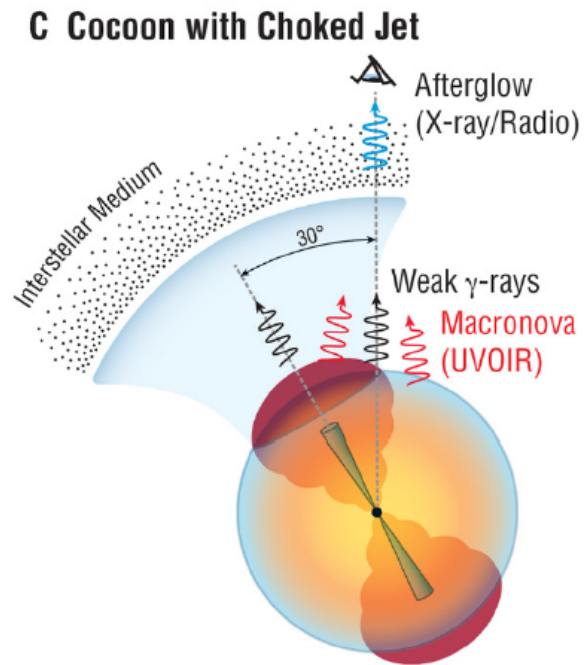
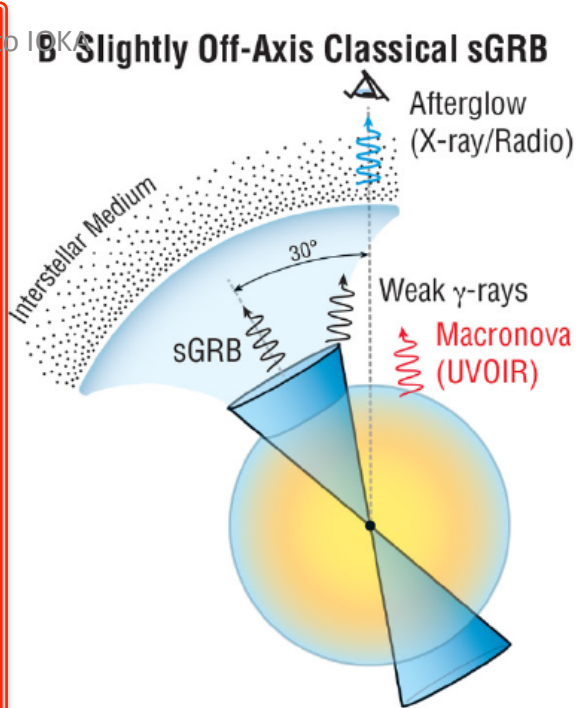
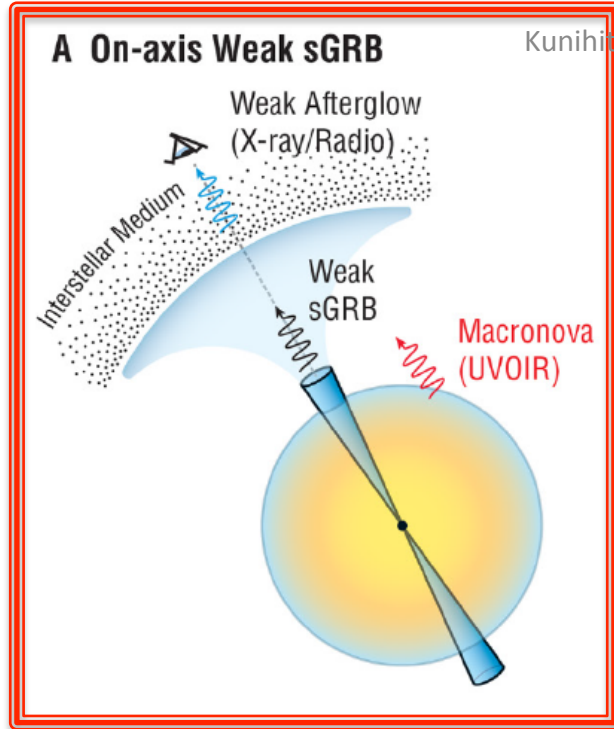
LVC-GBM-INTEGRAL 17



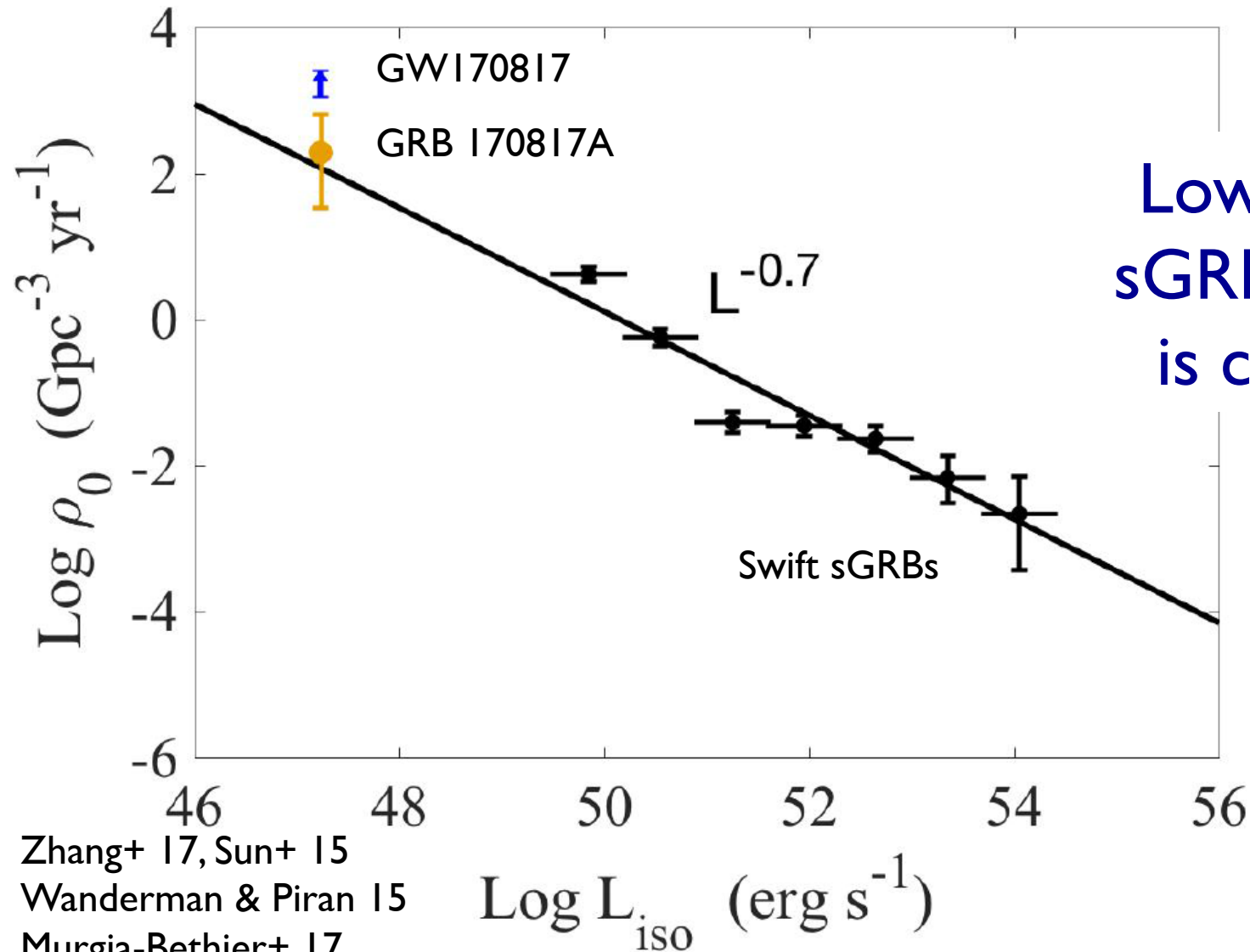
Salafia+ 17

Murguia-Berthier+ 17

A On-axis Weak sGRB**B Slightly Off-Axis Classical sGRB****C Cocoon with Choked Jet****D On-axis Cocoon with Off-Axis Jet**



Luminosity Function

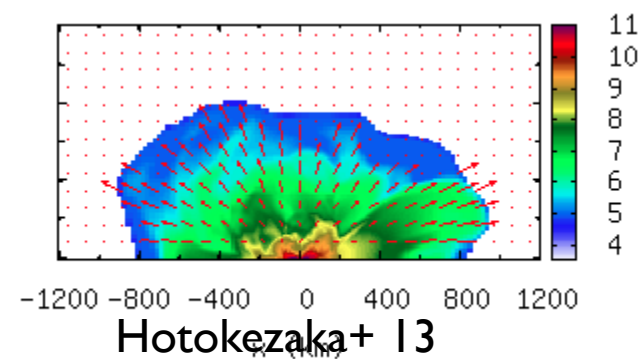
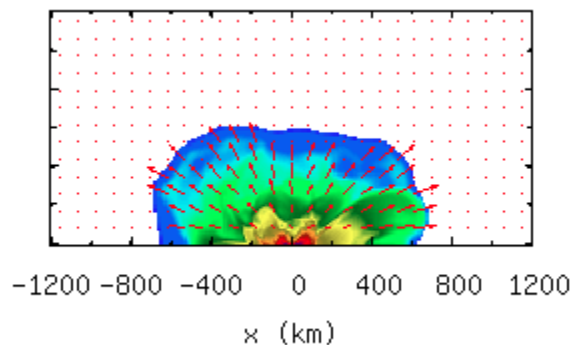
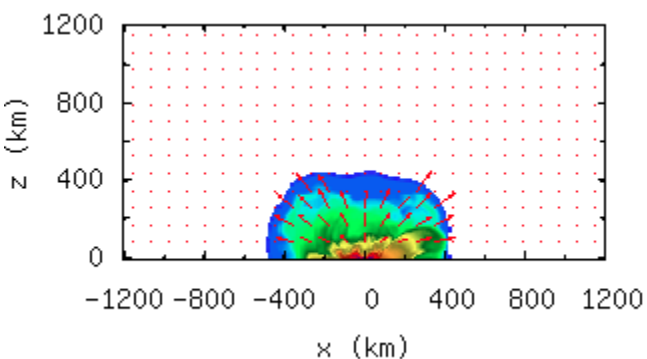
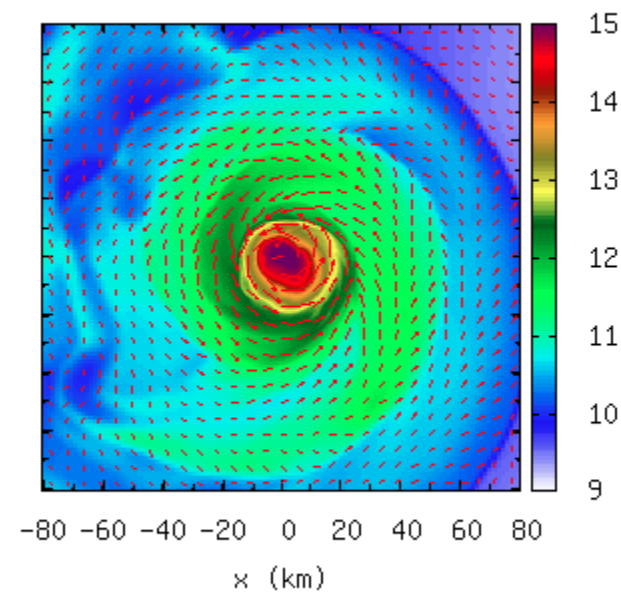
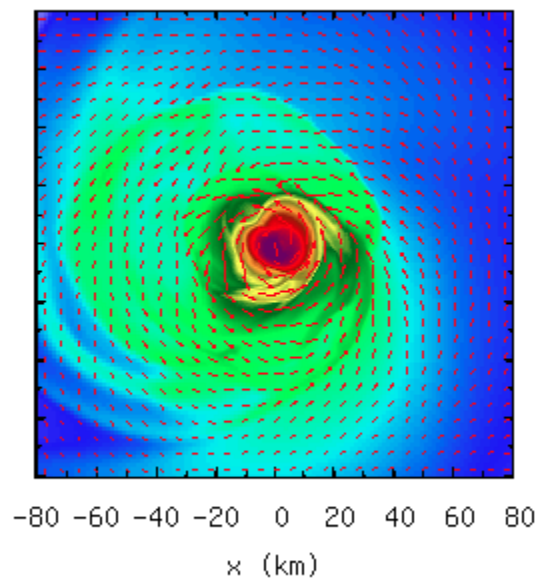
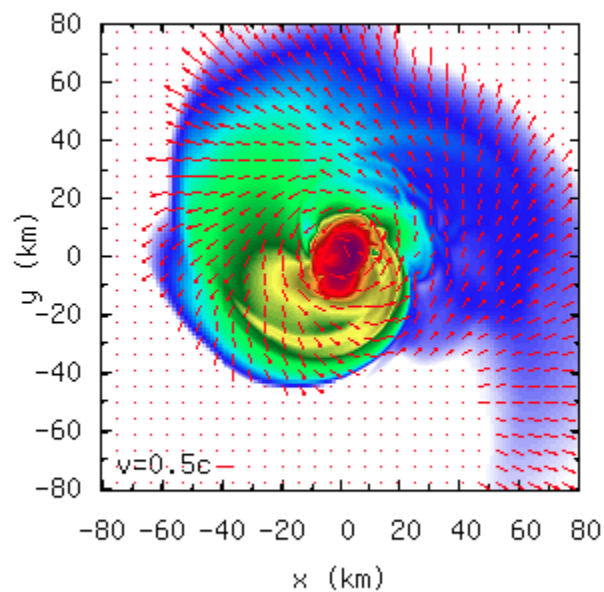


Merger Ejecta

t=11.4818 ms

t=13.0892 ms

t=14.6967 ms



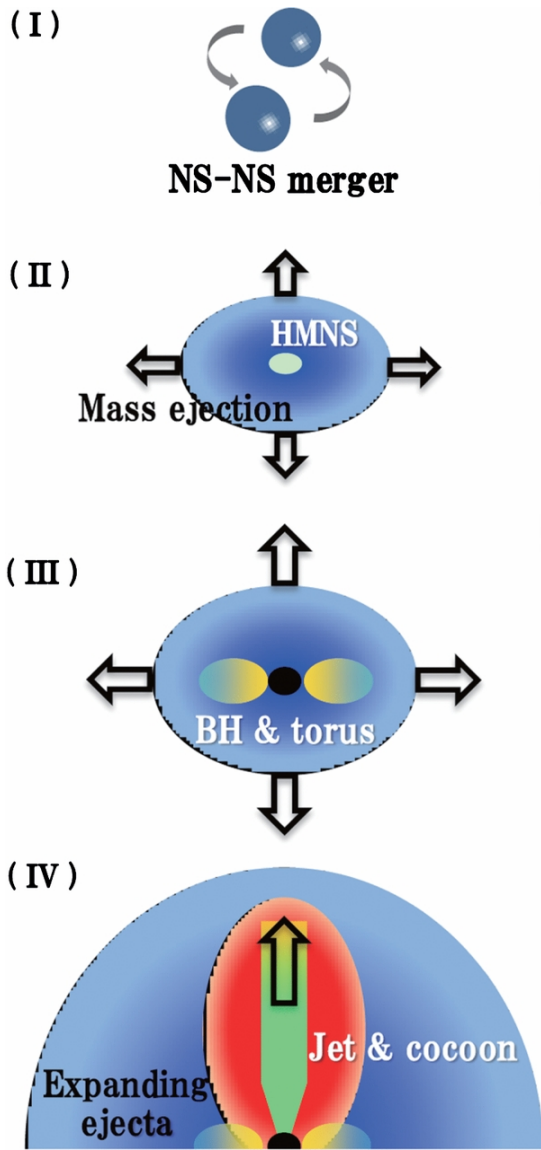
Quasi-spherical

Hotokezaka+ 13

Bauswein+ 13, Radice+ 17

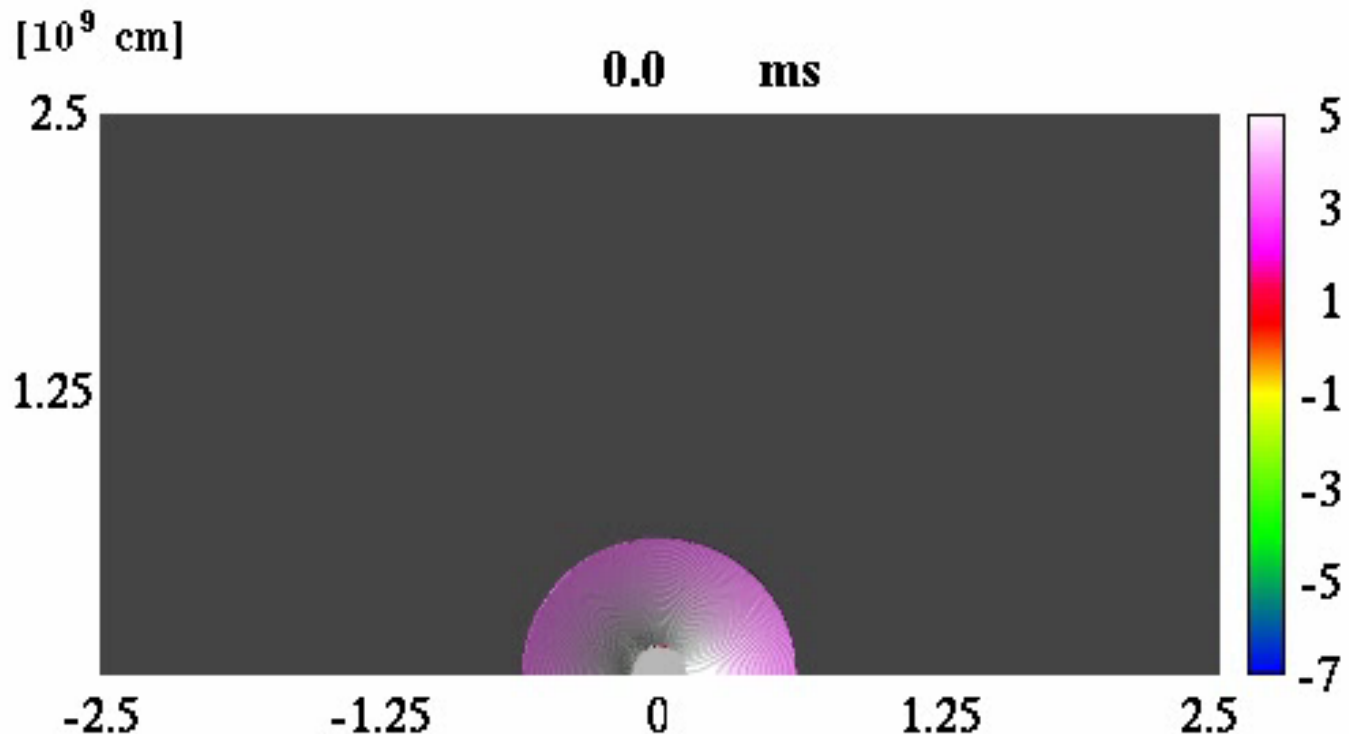
Sekiguchi+ 15, many others

Jet Breakout



Nagakura+ 14

Murguia-Berthier + 14



Similar to collapsars (long GRBs)

Weak jet $\sim 10^{46}$ erg/s cannot break out

Magnetar Giant Flare?

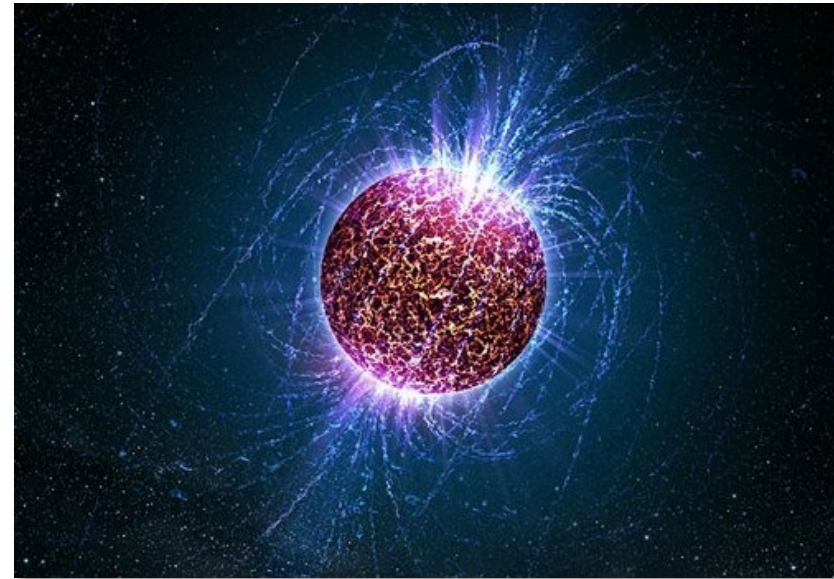
- $E_{\text{GRB 170817A}} \sim E_{\text{Giant flare}}$
- **Fireball before merger?**

$$E_0 \sim \frac{B^2}{8\pi} \frac{4\pi R_0^3}{3} \sim 10^{49} \text{ erg } B_{15}^2 R_{0,7}^3$$

$$\Gamma \sim \frac{E_0}{Mc^2} \sim \frac{R_c}{R_0} \sim 10$$

$$R_{\text{ph}} \sim \left(\frac{M\kappa}{4\pi} \right)^{1/2} \sim 10^{12.5} \text{ cm}$$

$$E_\gamma \sim E_0 \left(\frac{R_{\text{ph}}}{R_c} \right)^{-2/3} \sim 10^{46} \text{ erg}$$



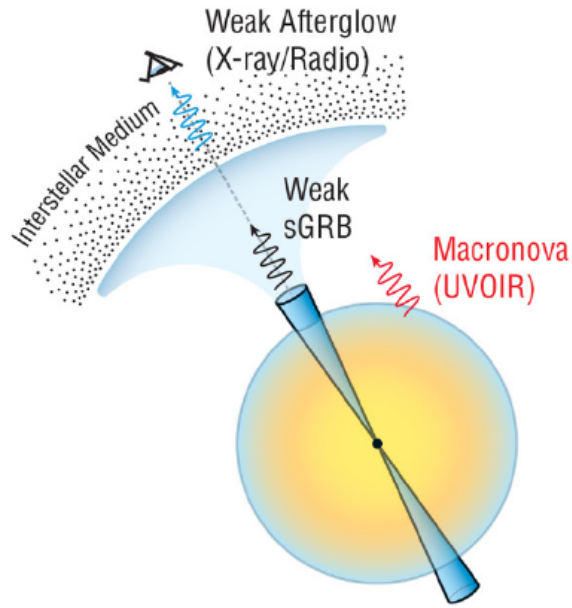
$$t_{\text{delay}} \sim t_{\text{ang}} \sim \frac{R_{\text{ph}}}{2c\Gamma^2} \sim 1 \text{ sec}$$

$$T_{\text{BB}} \sim 10 \text{ keV}$$

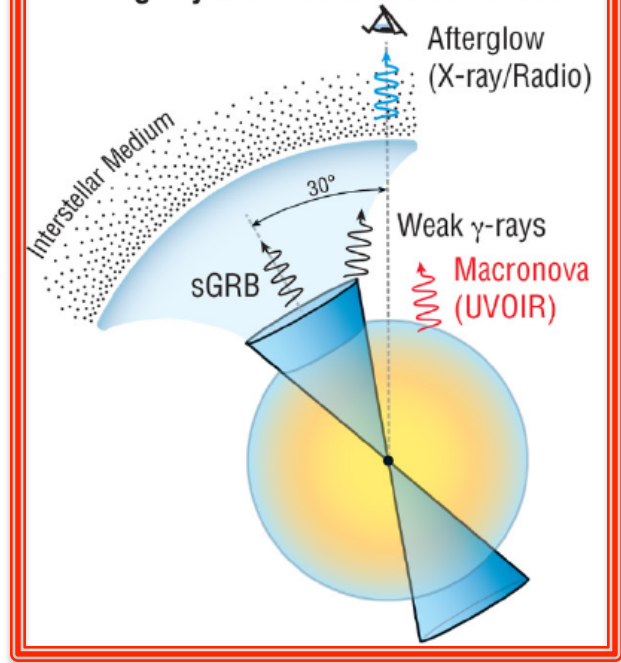
Meszaros & Rees 00
Nakar+ 05

Salafia+ 17a,b
Troja+ 10
Hansen & Lyutikov 01
KI & Taniguchi 00
Vietri 96

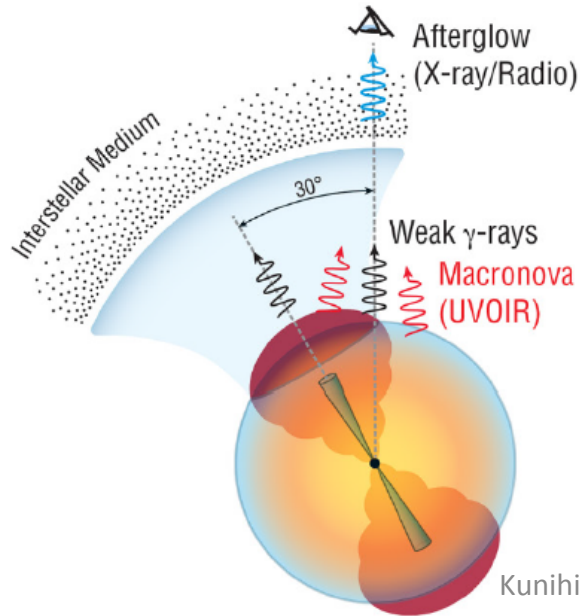
A On-axis Weak sGRB



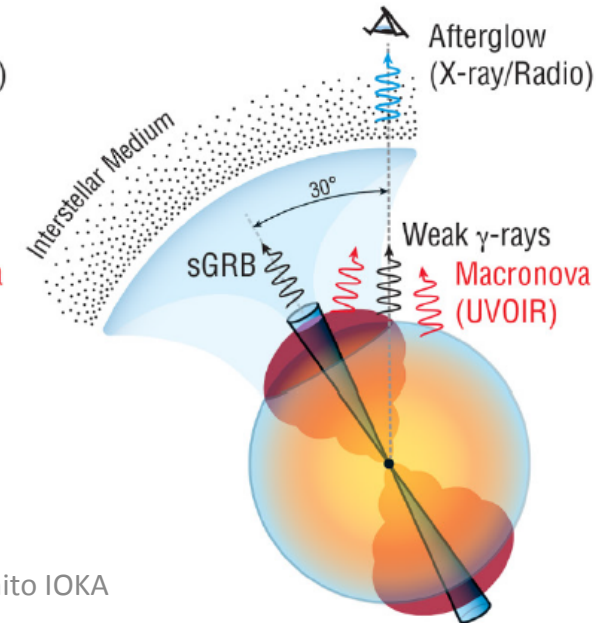
B Slightly Off-Axis Classical sGRB



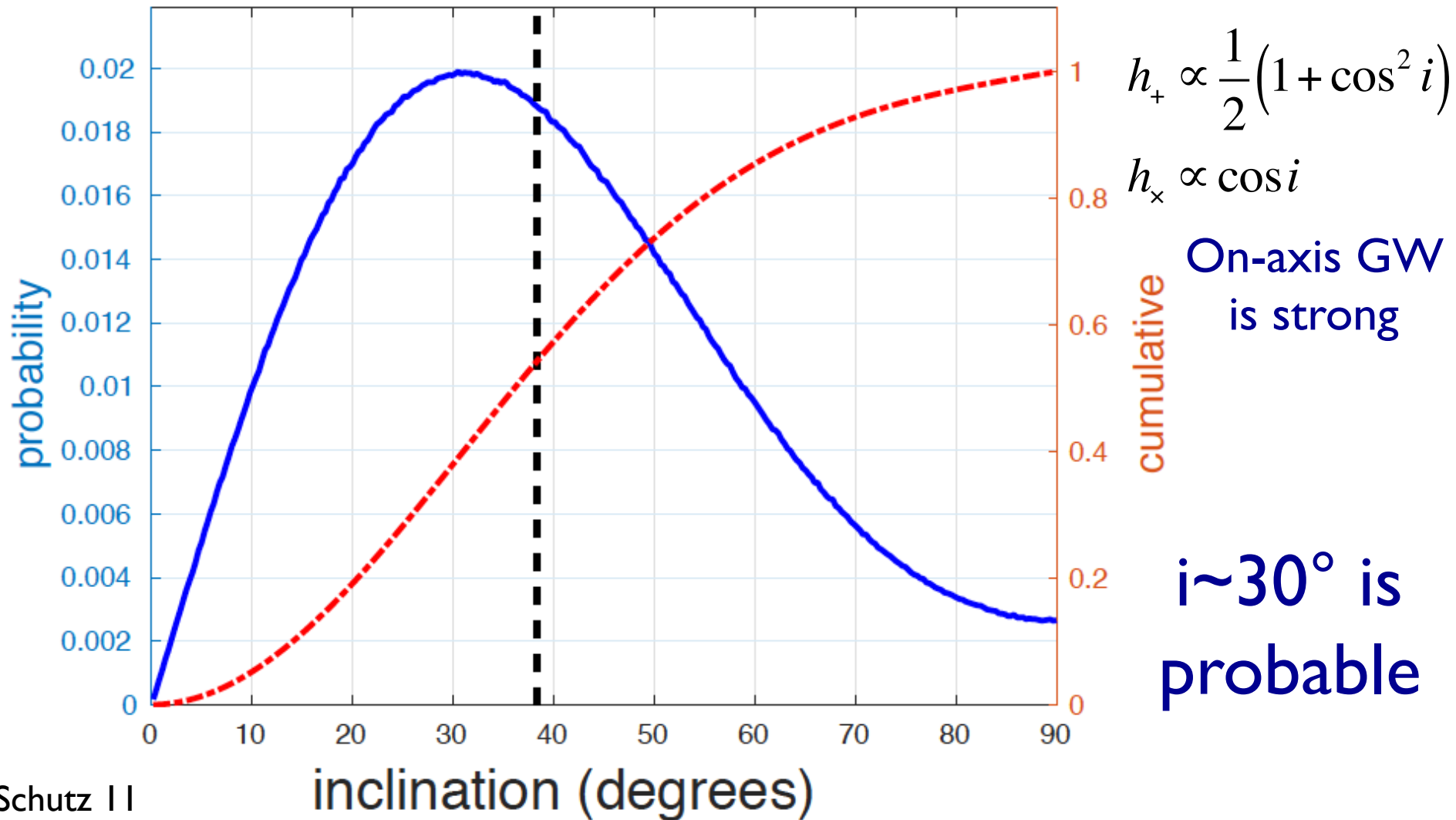
C Cocoon with Choked Jet



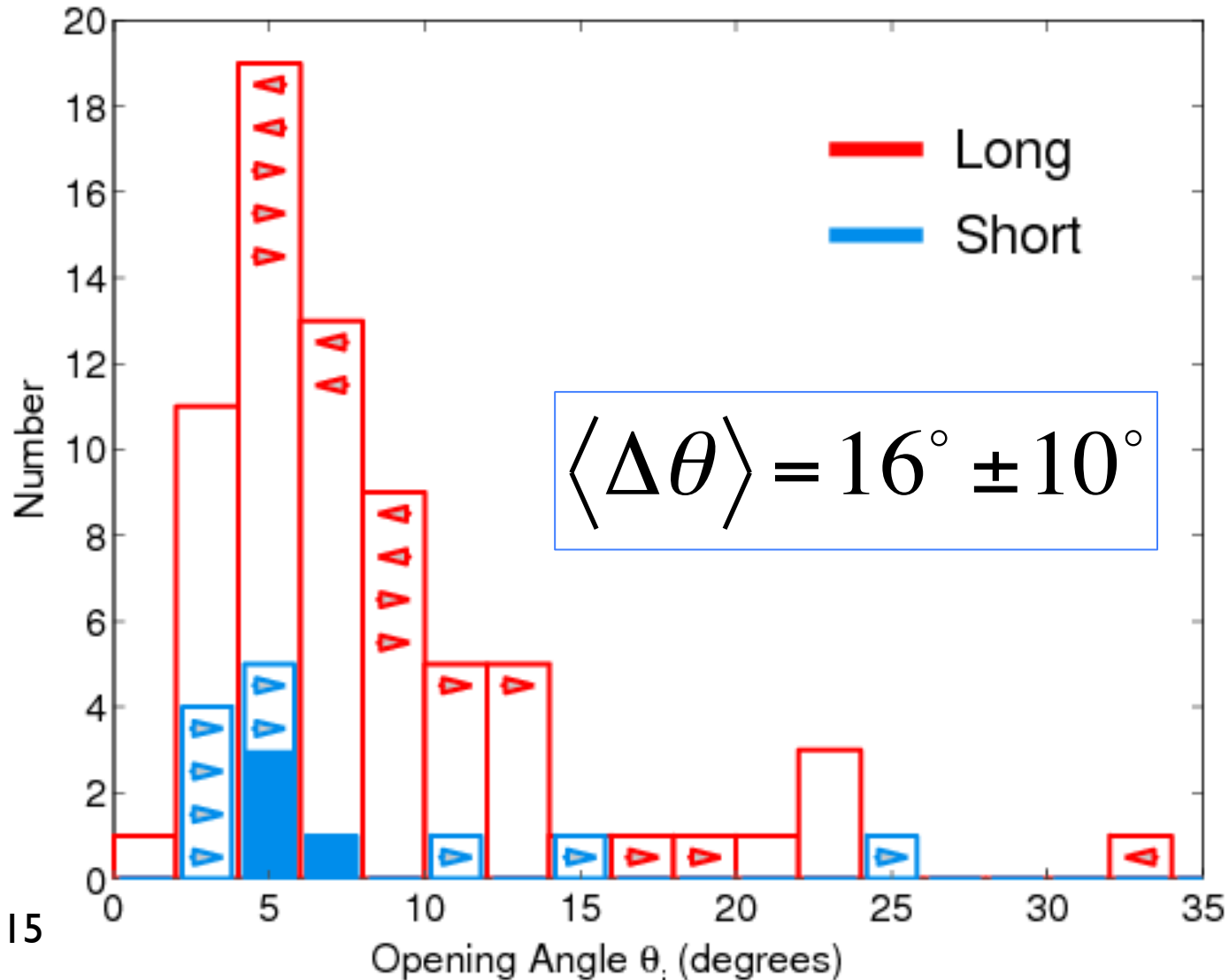
D On-axis Cocoon with Off-Axis Jet



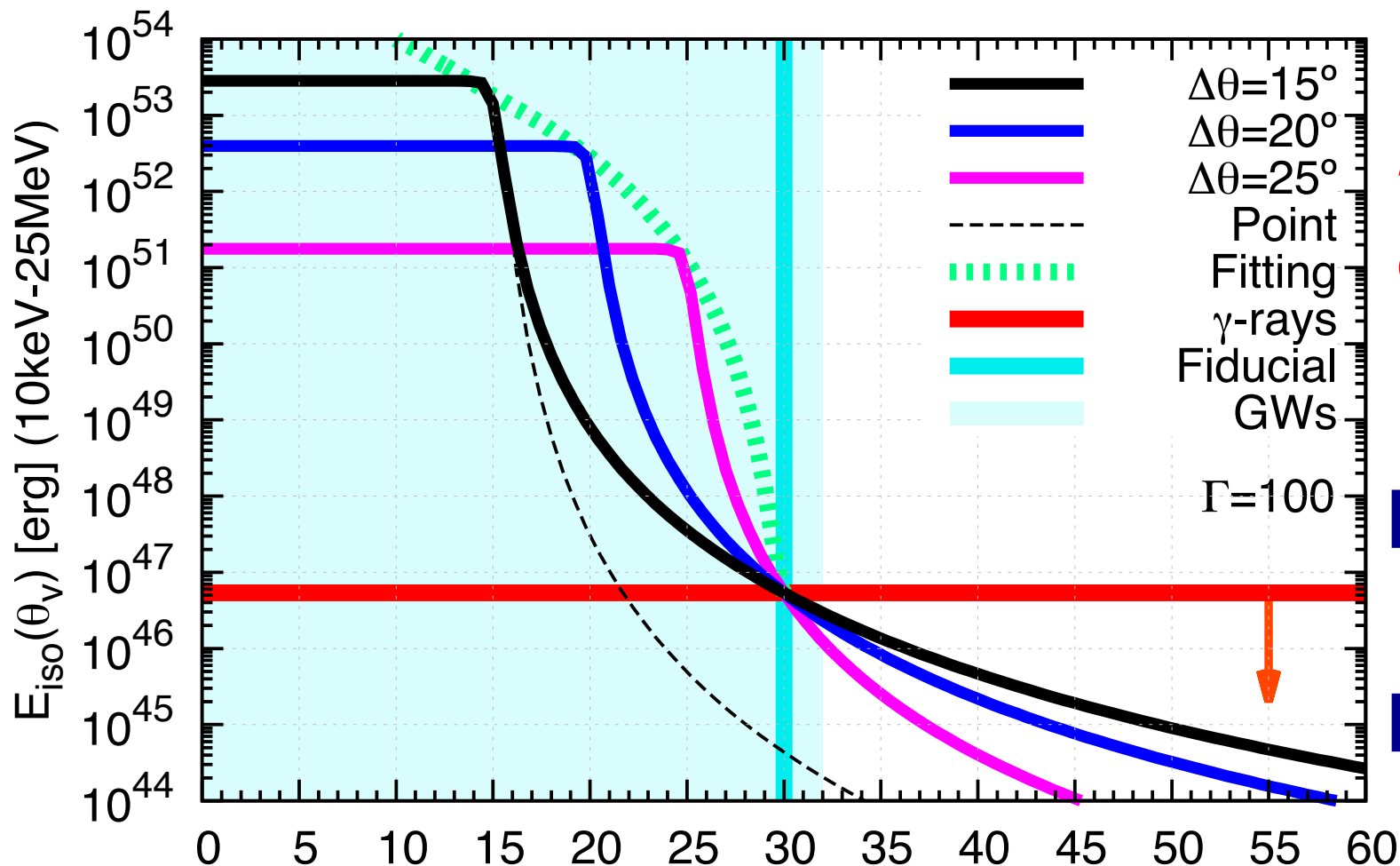
Viewing Angle Probability



Opening Angle



Off-Axis Top-hat Jet



$\theta_v \sim \Delta\theta$
 \Rightarrow **Point**
approx.
is bad

$$E_{\text{iso}} \propto \theta_v^{-6}$$

$$\downarrow$$

$$E_{\text{iso}} \propto \theta_v^{-4}$$

Off-Axis E_{iso}

$$E_{\text{iso}}(\theta_v) \propto \text{const.} \quad \text{for} \quad \theta_v < \Delta\theta,$$

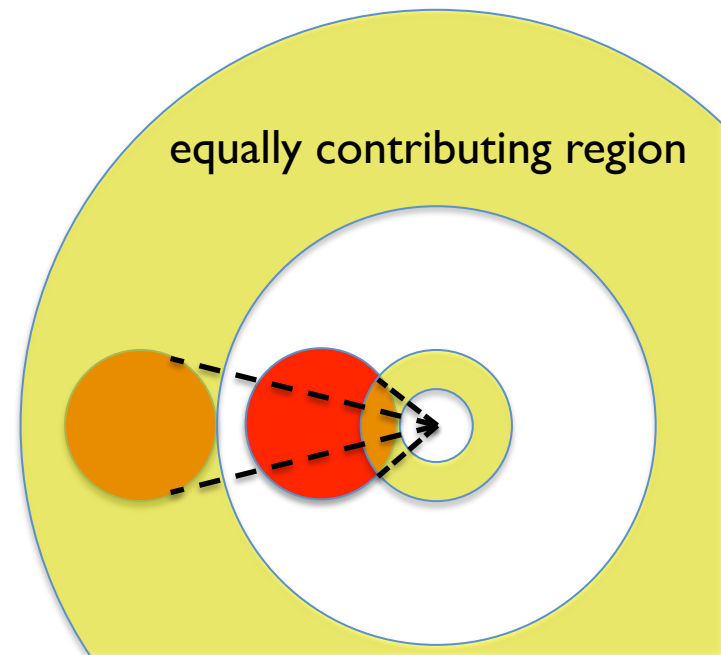
$$E_{\text{iso}}(\theta_v) \propto \tilde{\delta}(\theta_v)^2 \quad \text{for} \quad \Delta\theta < \theta_v \lesssim 2\Delta\theta,$$

$$E_{\text{iso}}(\theta_v) \propto \delta(\theta_v)^3 \quad \text{for} \quad 2\Delta\theta \lesssim \theta_v.$$

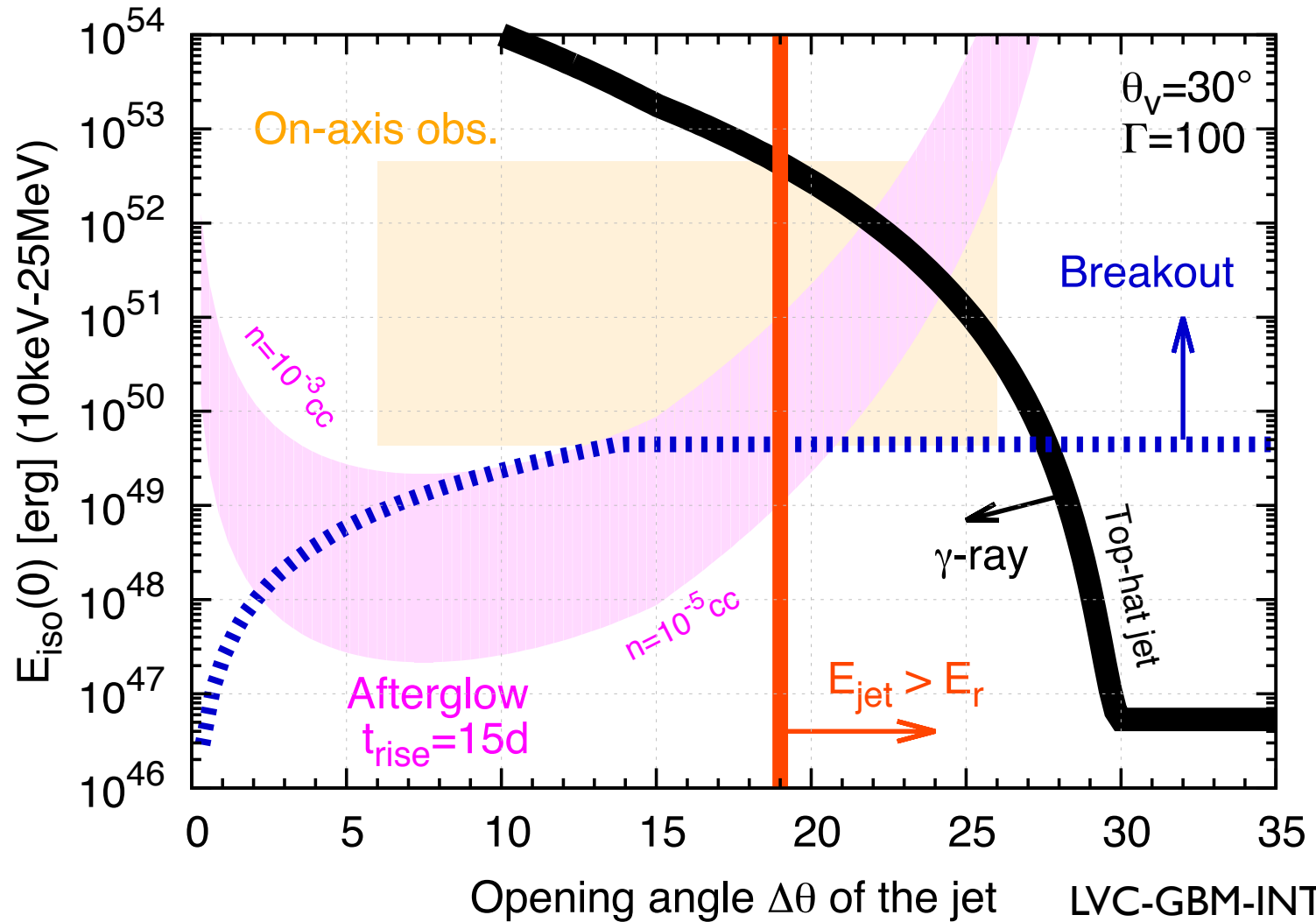
$$\tilde{\delta}(\theta_v) \equiv \frac{1}{\Gamma[1 - \beta \cos(\theta_v - \Delta\theta)]},$$

$$\delta(\theta_v) \equiv \frac{1}{\Gamma(1 - \beta \cos \theta_v)}.$$

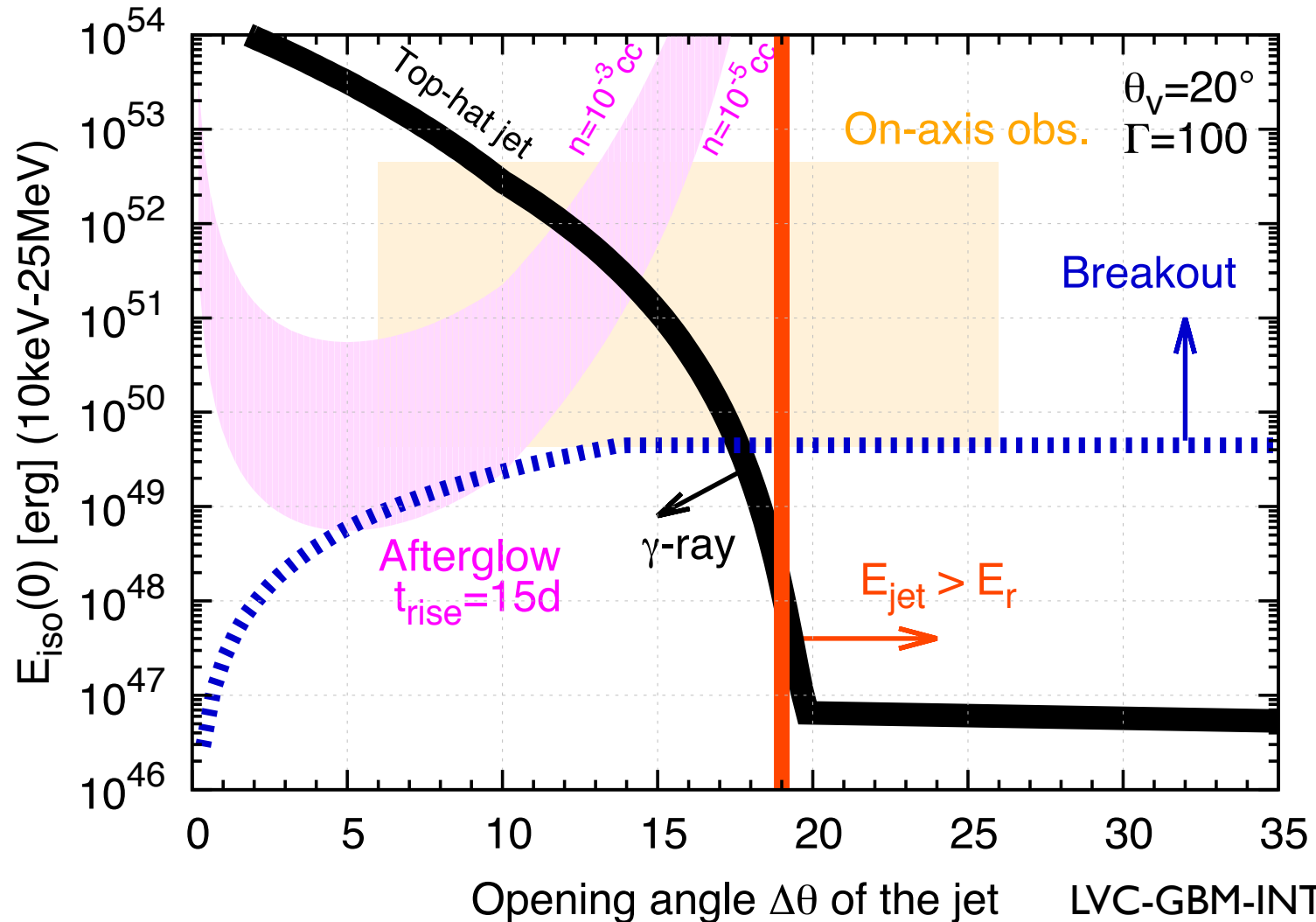
$\Delta\theta$: jet opening angle, θ_v : viewing angle



Bound on On-Axis E_{iso}



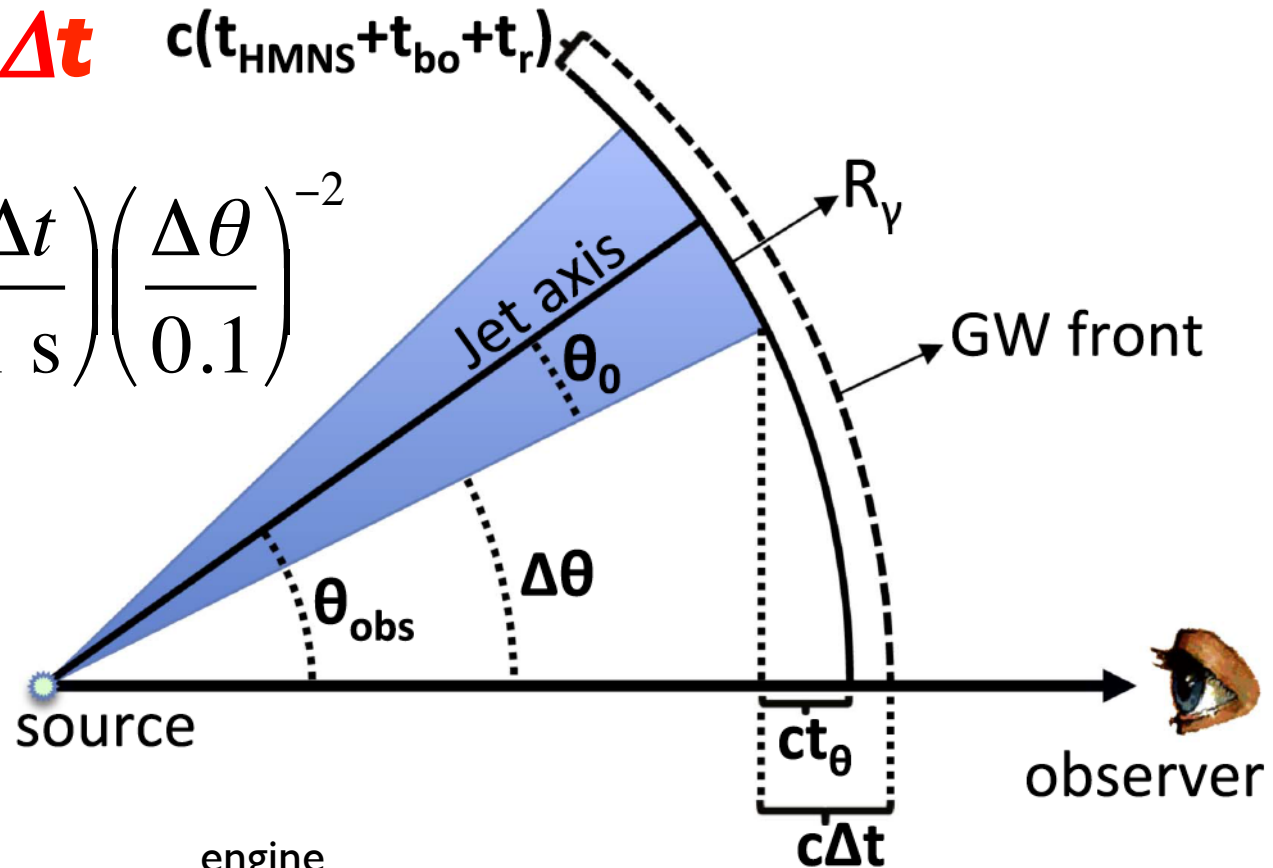
Bound on On-Axis E_{iso}



Time Scales

Time delay Δt $c(t_{\text{HMNS}} + t_{\text{bo}} + t_r)$

$$R_\gamma < 6 \times 10^{12} \text{ cm} \left(\frac{\Delta t}{1 \text{ s}} \right) \left(\frac{\Delta \theta}{0.1} \right)^{-2}$$



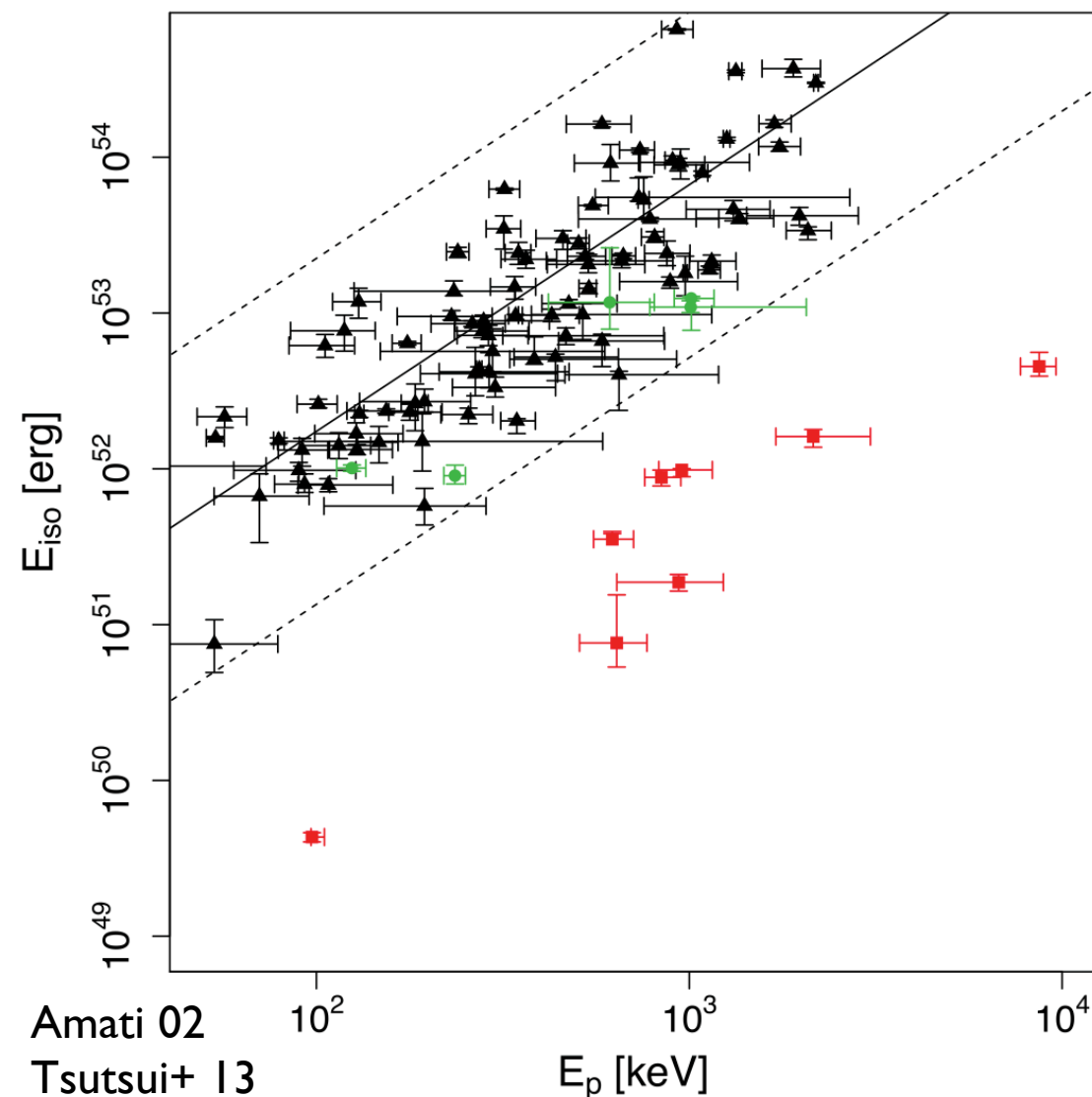
Duration

$$T_{90} \sim \max \left[t_{\text{dur}}, t_\theta \right]$$

engine
duration

Granot+ 17
KI & Nakamura 17

$E_{\text{peak}}-E_{\text{iso}}$ (Amati) Relation



$$E_{\text{iso}} \sim E_{\text{peak}}^2$$

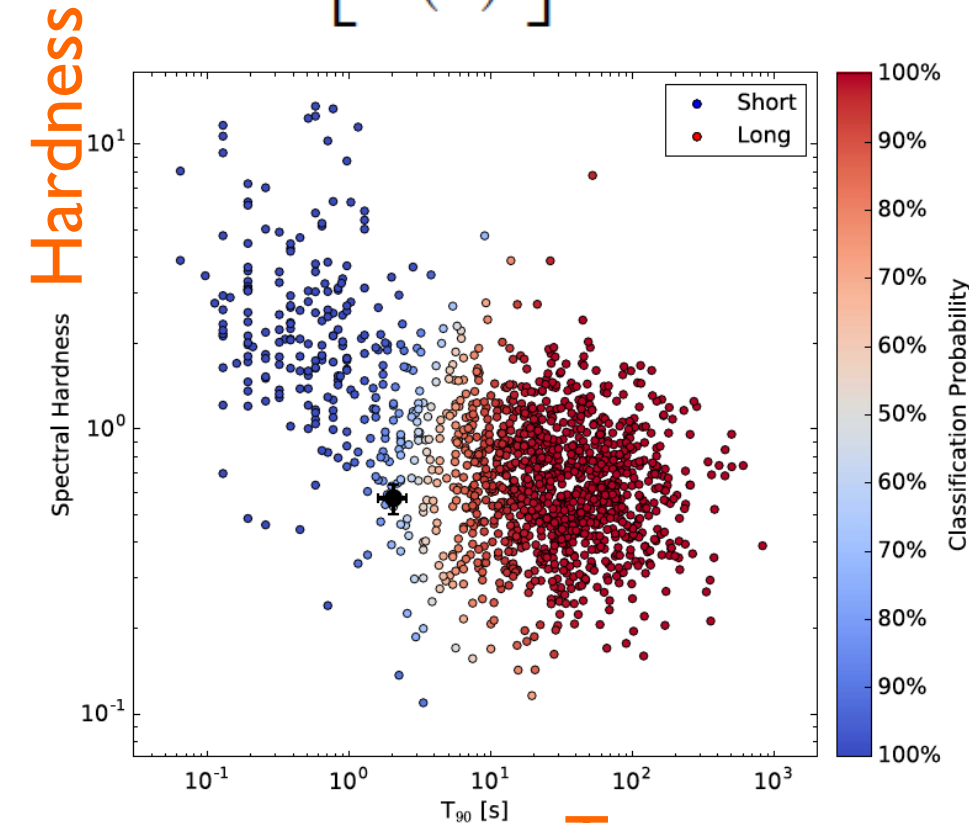
for on-axis GRBs

$$E_{\text{iso}}(\text{sGRB}) \sim E_{\text{iso}}(\text{IGRB})/100$$

Typically $E_p \sim \text{MeV}$

Spectrum

$$E_p(\theta_v) \sim \left[\frac{\tilde{\delta}(\theta_v)}{\tilde{\delta}(0)} \right] E_p(0) \sim 10 \text{ keV} \left[\frac{\Gamma(\theta_v - \Delta\theta)}{10} \right]^{-2} \left[\frac{E_p(0)}{\text{MeV}} \right],$$



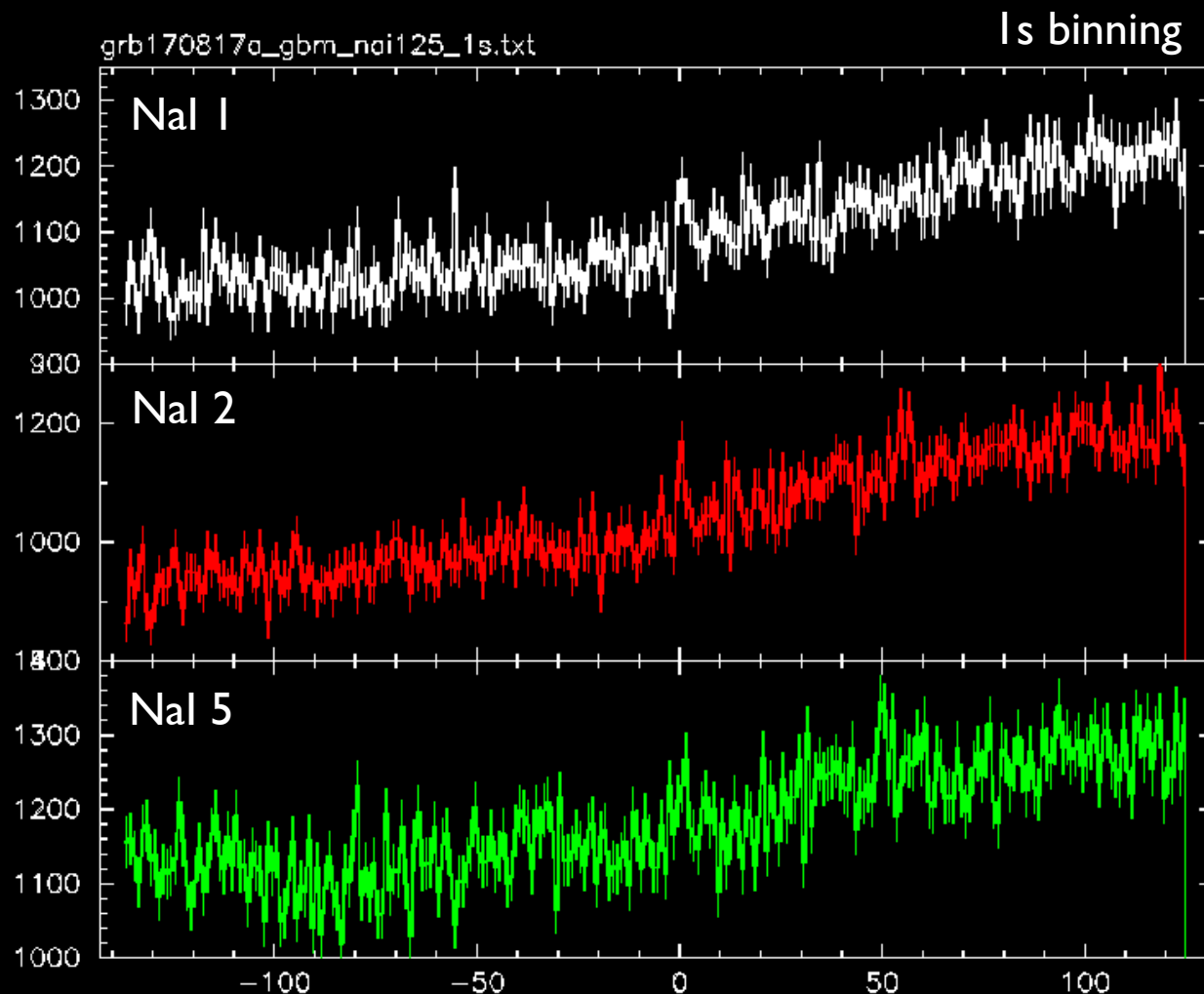
Main pulse

power law ($a = -0.62 \pm 0.40$)
 + cutoff ($E_{\text{peak}} = 185 \pm 62 \text{ keV}$)

Weak tail

34% the fluence
 of the main pulse
 $kT = 10.3 \pm 1.5 \text{ keV}$

Should be Careful?



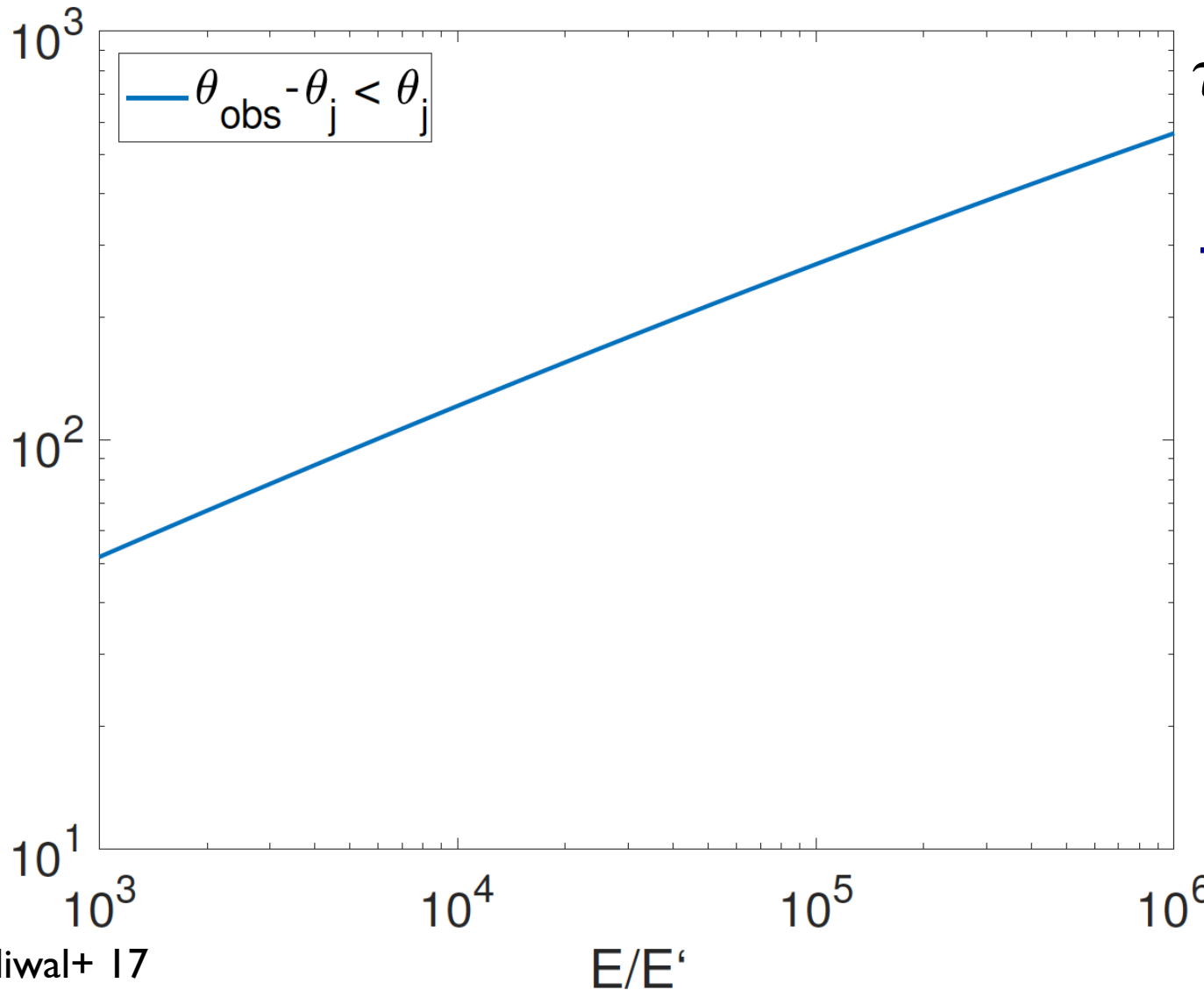
If 30% dimmer
 \Rightarrow Non-trigger

Just before
 South Atlantic
 Anomaly

$E_{\text{peak}} \sim 70\text{keV}$
 for Band fn. fit

Tip of iceberg
 effect

Compactness Problem



$$\tau_{\text{offaxis}} > \tau_{\text{onaxis}}$$

Abramowicz+ 91

This fig. is for

$$E_p = 185 \text{ keV}$$

$$\Rightarrow \Gamma > 200$$

Very strong
de-beaming

If $E_p < 185 \text{ keV}$,
the limit is
weaker

Afterglow Time Scales

Rise time $\frac{1}{\Gamma} \gtrsim \theta_v - \Delta\theta,$

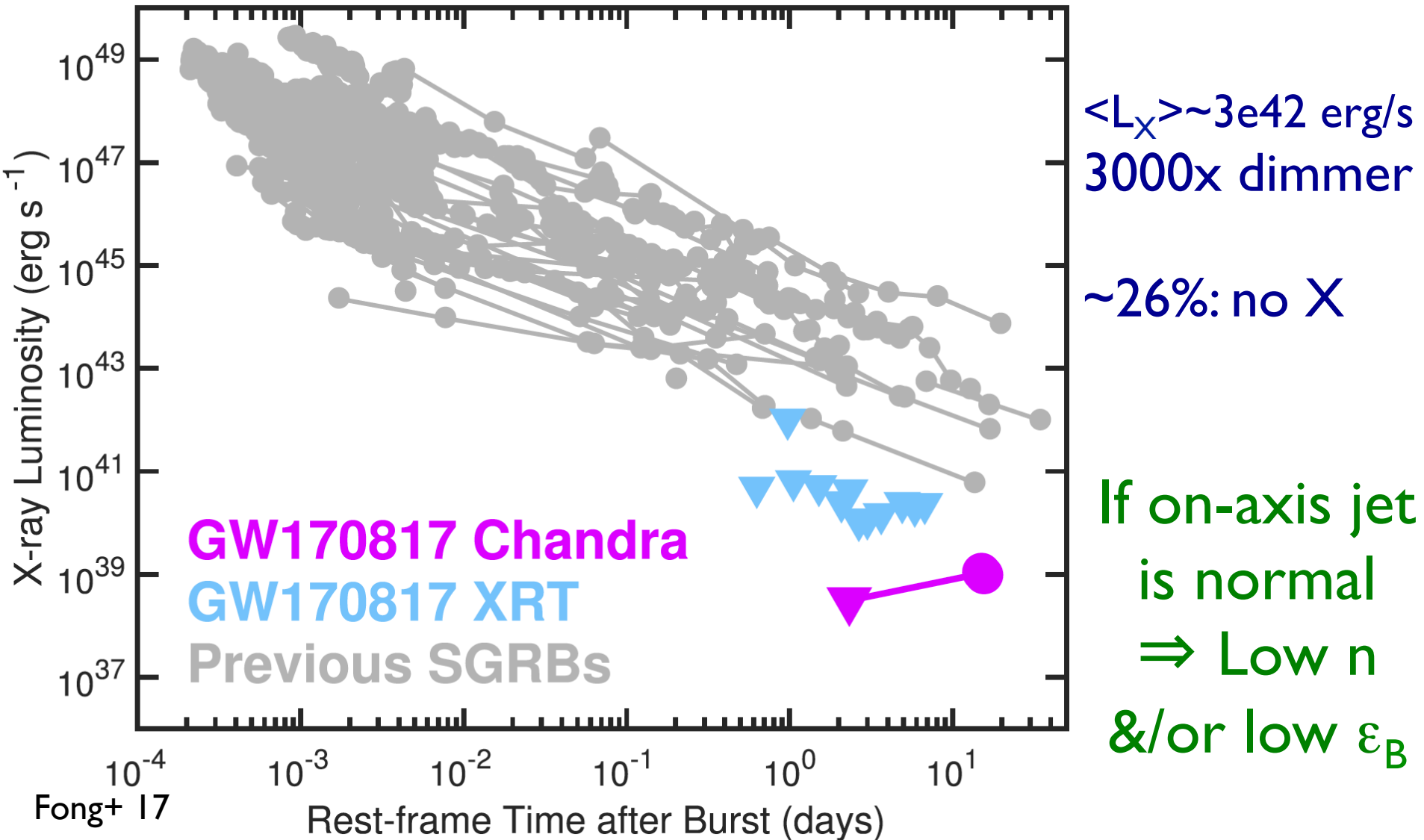
Granot+ 02
Zhang & MacFadyen+ 09

$$t_{\text{rise}} \sim 14 \text{ day} \left(\frac{\theta_v - \Delta\theta}{7^\circ} \right)^{8/3} \left(\frac{E_{\text{iso}}(0)/\epsilon_\gamma}{3 \times 10^{52} \text{ erg}} \right)^{1/3} \left(\frac{n}{10^{-4} \text{ cm}^{-3}} \right)^{-1/3}$$

Jet break time $\frac{1}{\Gamma} \sim \Delta\theta$

$$t_{\text{jet}} \sim 230 \text{ day} \left(\frac{\Delta\theta}{20^\circ} \right)^{8/3} \left(\frac{E_{\text{iso}}(0)/\epsilon_\gamma}{3 \times 10^{52} \text{ erg}} \right)^{1/3} \left(\frac{n}{10^{-4} \text{ cm}^{-3}} \right)^{-1/3}$$

X-ray Afterglow is Faint



Synchrotron Shock Model

Typical frequency and Max. flux

Sari+ 97

$$\nu_m = 2.5 \times 10^7 \text{ Hz } \epsilon_{B,-6}^{1/2} \epsilon_{e,-1}^2 E_{52}^{1/2} t_{15\text{d}}^{-3/2},$$

$$\nu_a < \nu_m < \nu < \nu_c$$

$$F_{\nu,\text{max}} = 7.2 \times 10^3 \mu\text{Jy } \epsilon_{B,-6}^{1/2} E_{52} n_{-4}^{1/2} D_{40\text{Mpc}}^{-2},$$

Expected flux

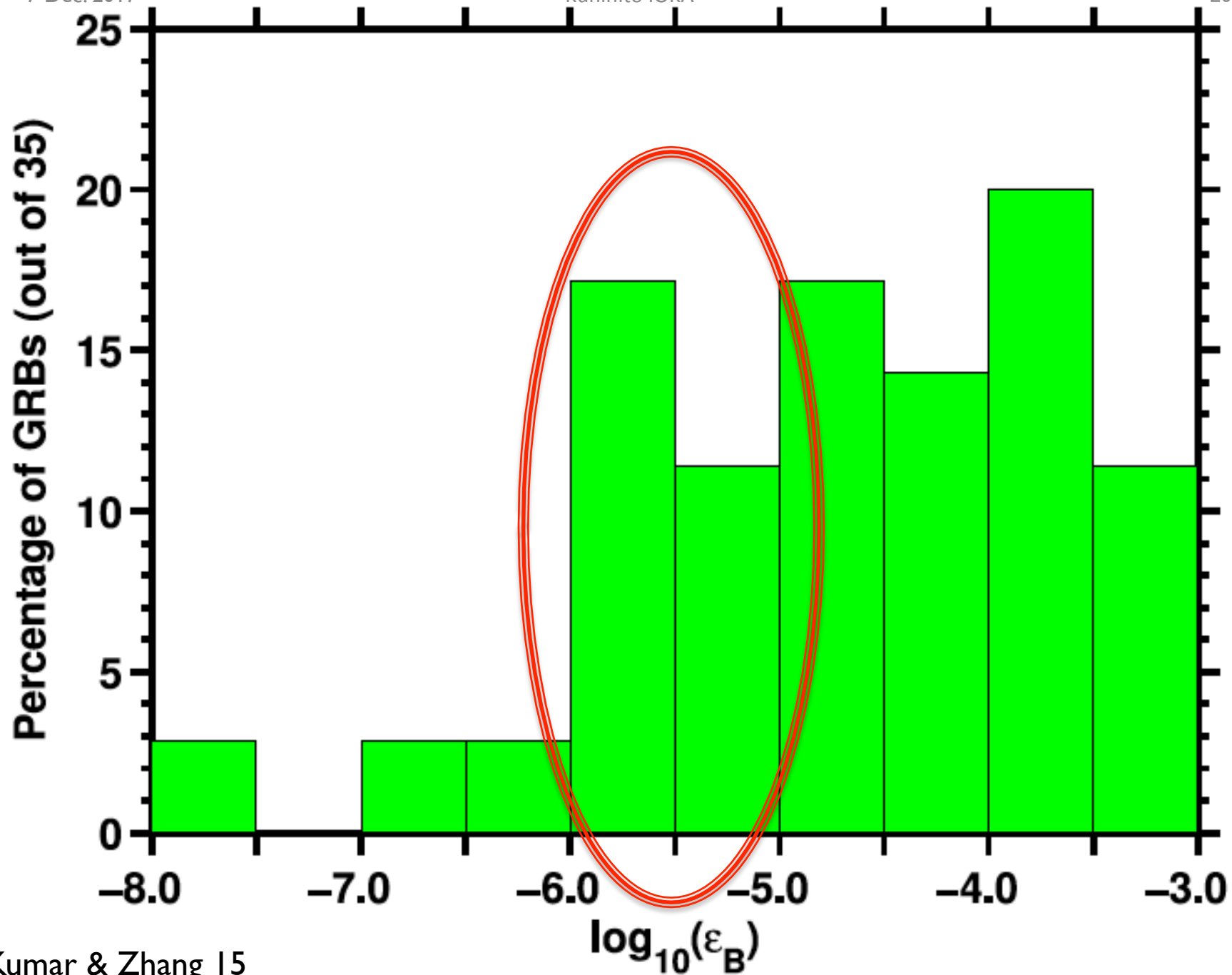
$$F_\nu = (\nu/\nu_m)^{-(p-1)/2} F_{\nu,\text{max}}$$

$$\sim 8 \times 10^2 \mu\text{Jy } \epsilon_{B,-6}^{0.8} \epsilon_{e,-1}^{1.2} E_{52}^{1.3} n_{-4}^{1/2} D_{40\text{Mpc}}^{-2} \nu_{\text{GHz}}^{-0.6} t_{15\text{d}}^{-0.9},$$

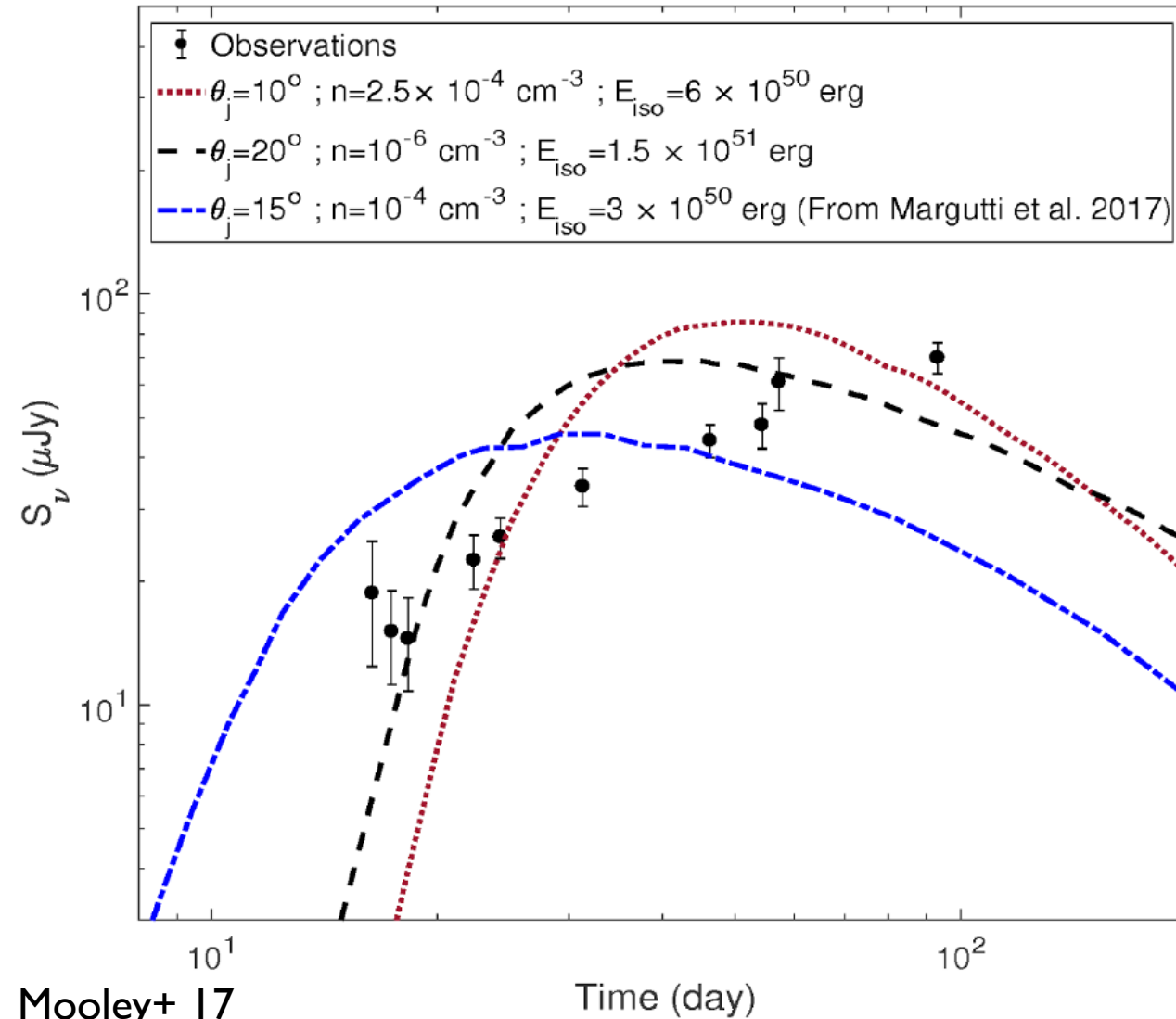
$$\nu F_\nu = 2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \epsilon_{B,-6}^{0.8} \epsilon_{e,-1}^{1.2} E_{52}^{1.3} n_{-4}^{1/2} D_{40\text{Mpc}}^{-2} \nu_{\text{keV}}^{0.4} t_{15\text{d}}^{-0.9}.$$

X/Radio \Leftrightarrow $p=2.2$ of accelerated electrons

Faint afterglows \Rightarrow Low density & low ϵ_B



Latest Radio Afterglow

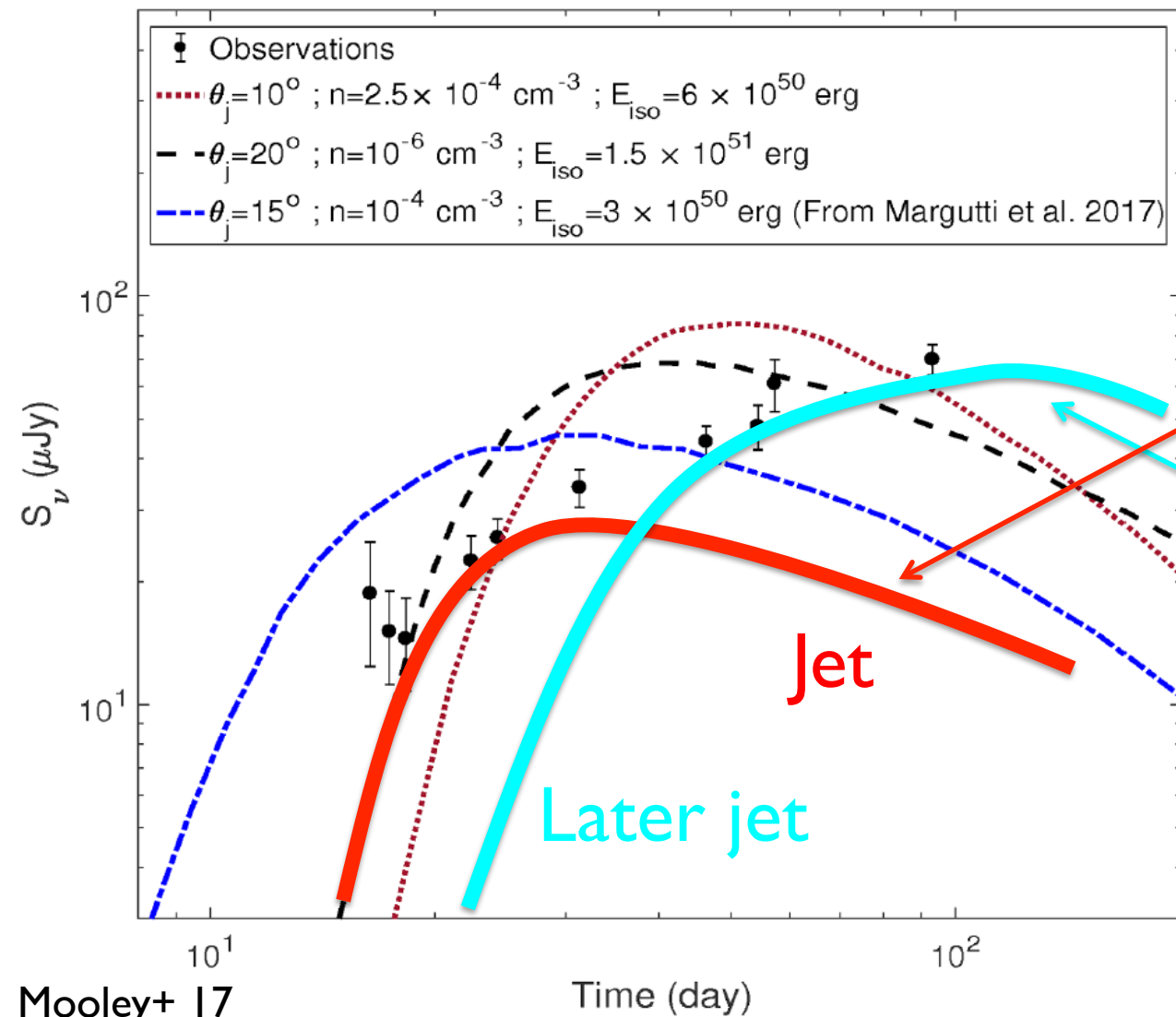


**Still rising
up to $\sim 100\text{d}$**

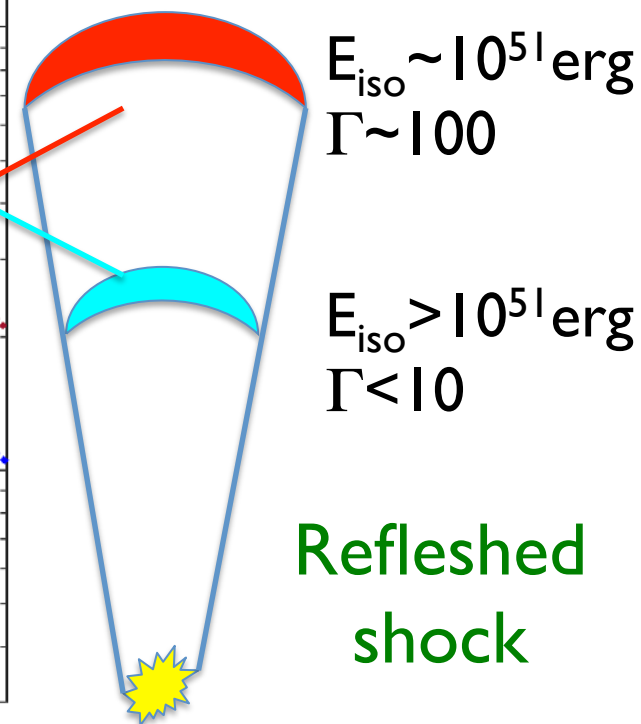
**Inconsistent
with a simple jet**

**Structured?
Refreshed?
Only Cocoon?
or Any missing?**

Off-axis Jet is Ruled Out?

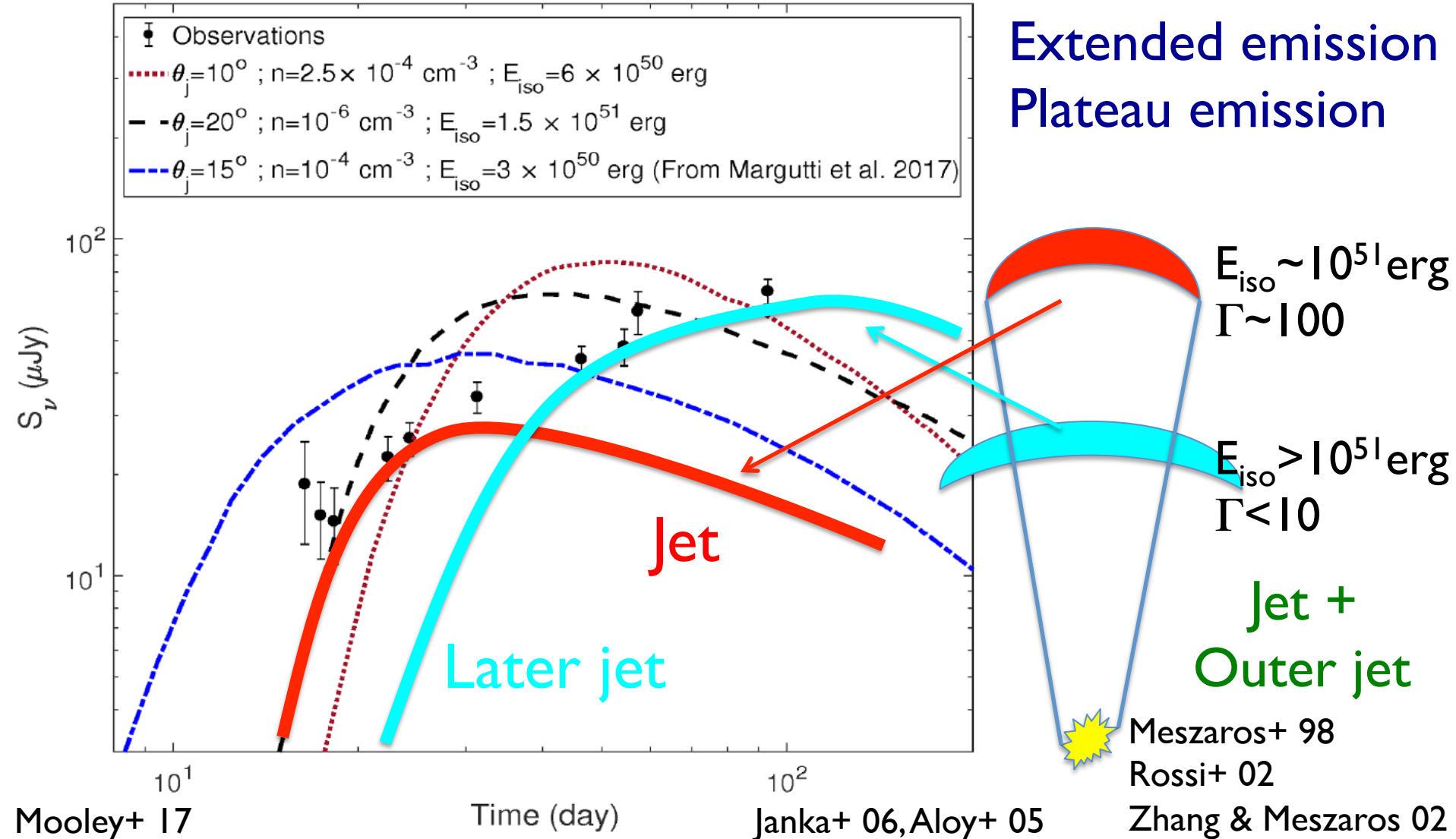


Extended emission
Plateau emission

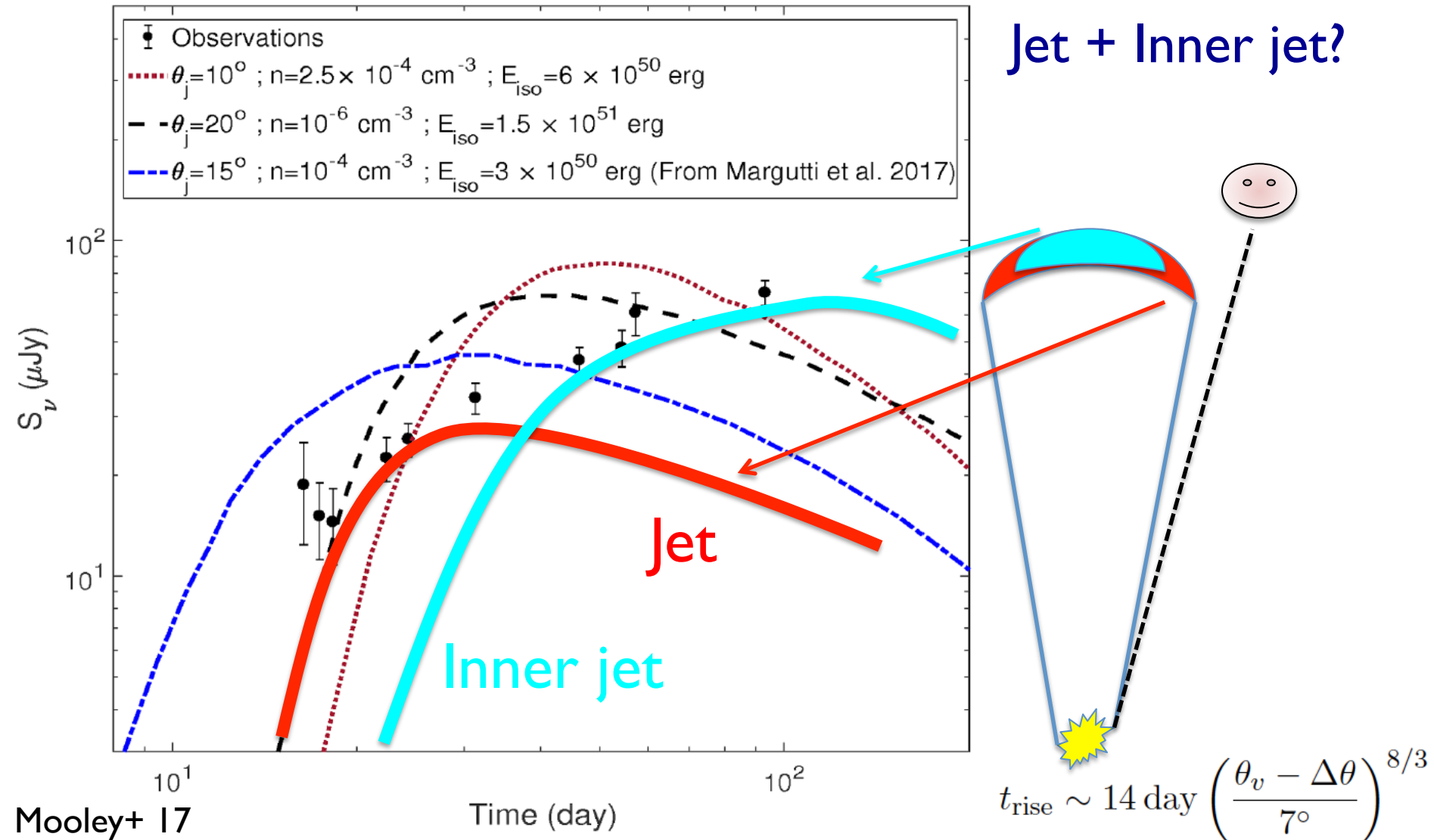


Rees & Meszaros 98

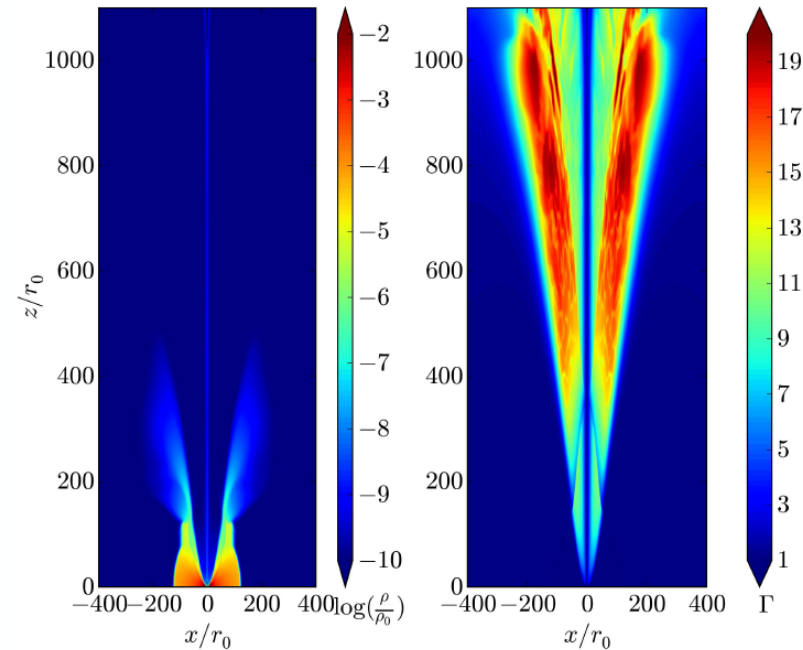
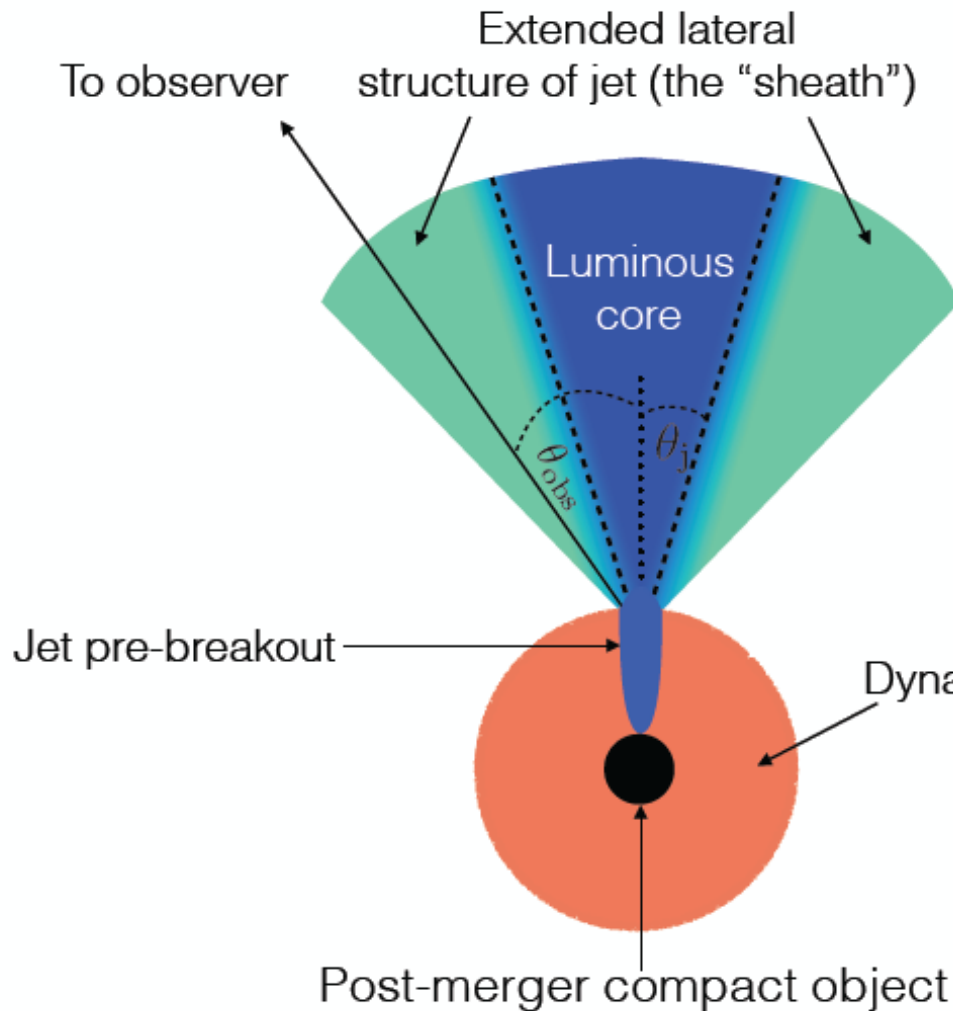
Off-axis Jet is Ruled Out?



Off-axis Jet is Ruled Out?



Structured Jet

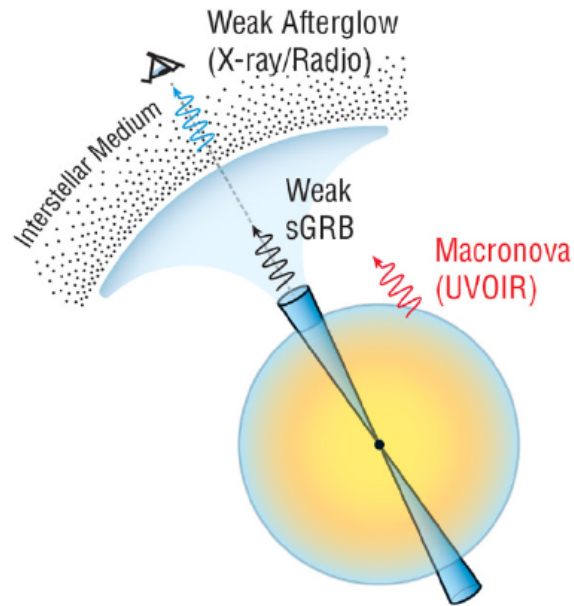
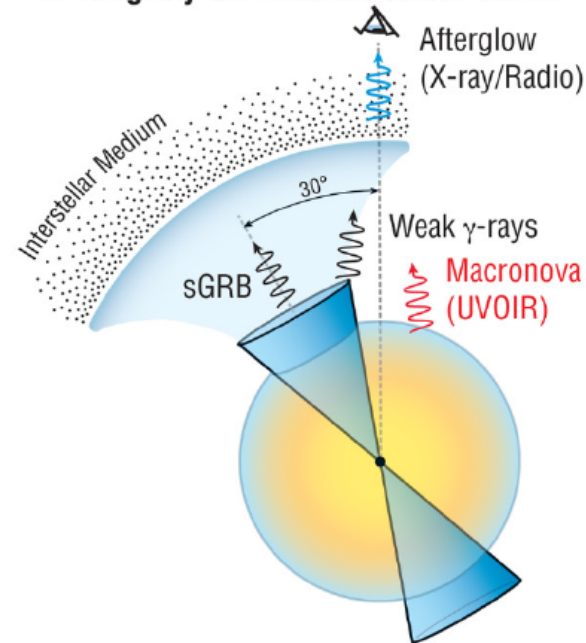
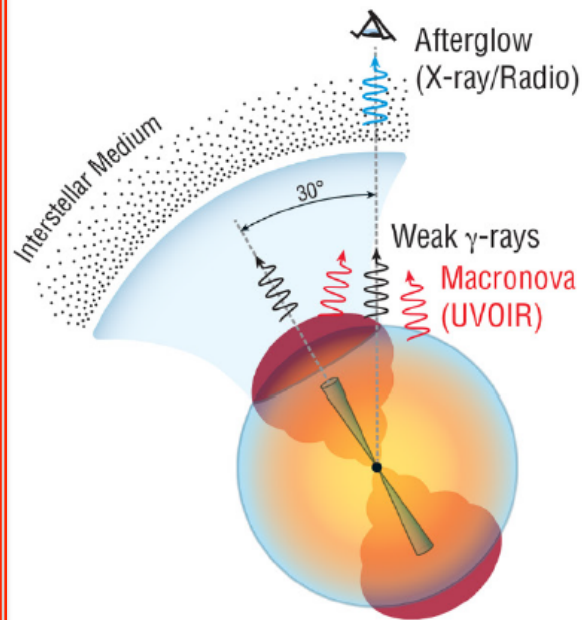
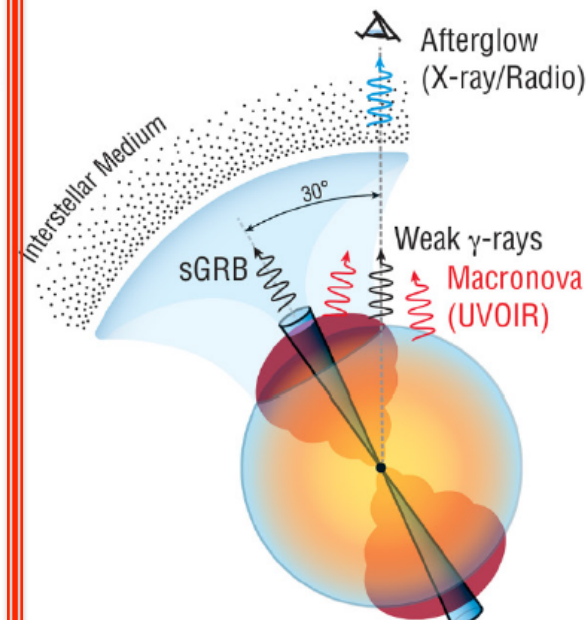


If on-axis wing is weak

\Rightarrow Breakout problem

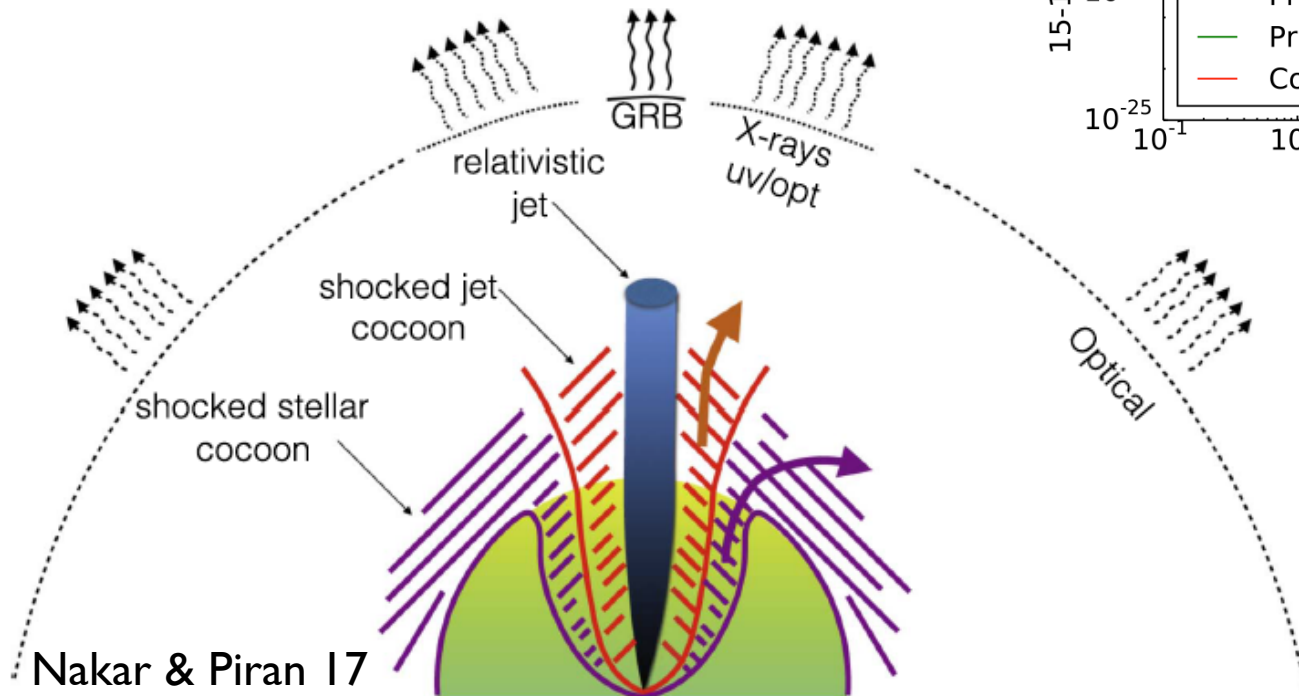
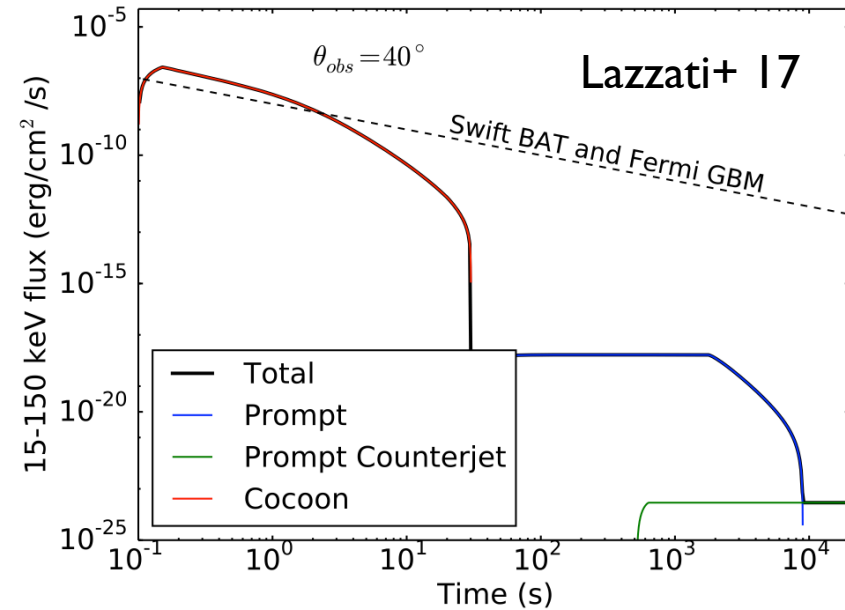
Wide $\Rightarrow \Gamma \sim 4 (\theta/15^\circ)^{-1}$

\Rightarrow Compactness prob.

A On-axis Weak sGRB**B Slightly Off-Axis Classical sGRB****C Cocoon with Choked Jet****D On-axis Cocoon with Off-Axis Jet**

Cocoon Emission

**Mildly relativistic
shock breakout
⇒ Prompt γ -rays**



+ Cooling
emission
+ Afterglow



Shock Breakout Emission

Radiation-mediated shock out of thermal equilibrium

For $\beta_s' > 0.5$, e^\pm pairs determines the opacity

$$k_B T \sim 50 \text{ keV} \quad \Gamma \sim 150 \text{ keV} \left(\frac{\Gamma}{3} \right)$$

Katz+ 10
Budnik+ 10
Nakar & Sari 12

$$t \sim \frac{R}{2c\Gamma^2} \sim 1 \text{ sec} \left(\frac{R}{5 \times 10^{11} \text{ cm}} \right) \left(\frac{\Gamma}{3} \right)^{-2}$$

**Large size
is necessary**

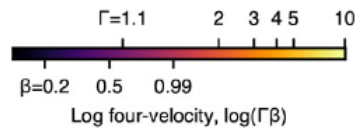
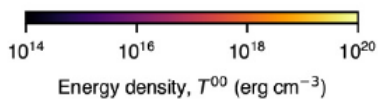
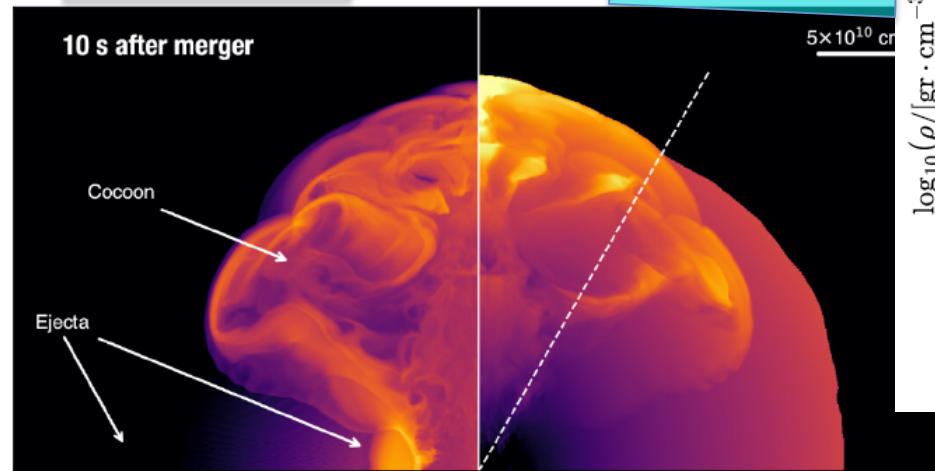
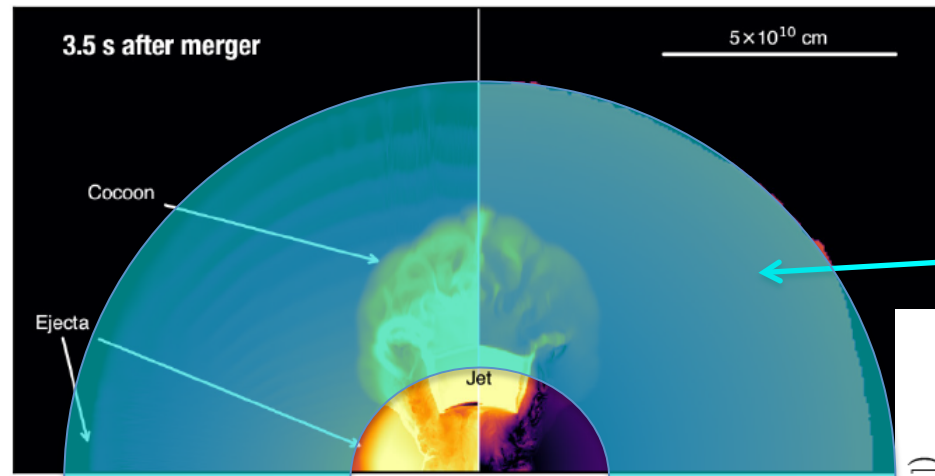
$$E_{\text{iso}} \sim \frac{1}{4} m_0 c^2 \gamma_0 \Gamma \sim 5 \times 10^{46} \text{ erg} \left(\frac{R}{5 \times 10^{11} \text{ cm}} \right)^2 \left(\frac{\Gamma}{3} \right)^{\frac{1+\sqrt{3}}{2}}$$

Satisfy a closure relation

Cooling emission \sim Soft tail

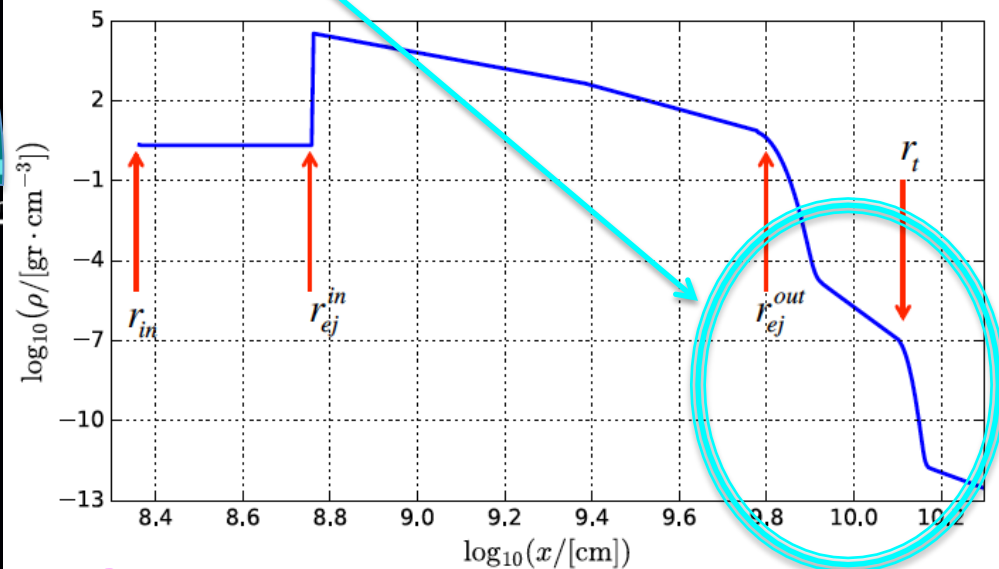
$$m_0 \sim \frac{4\pi R^2}{\kappa \beta_s'} \sim 4 \times 10^{-9} M_\odot$$

Fast Ejecta Tail



$$\beta_{ej} \approx \frac{R_{bo}}{R_{bo} + c\delta t} \sim 0.8 \gg 0.2$$

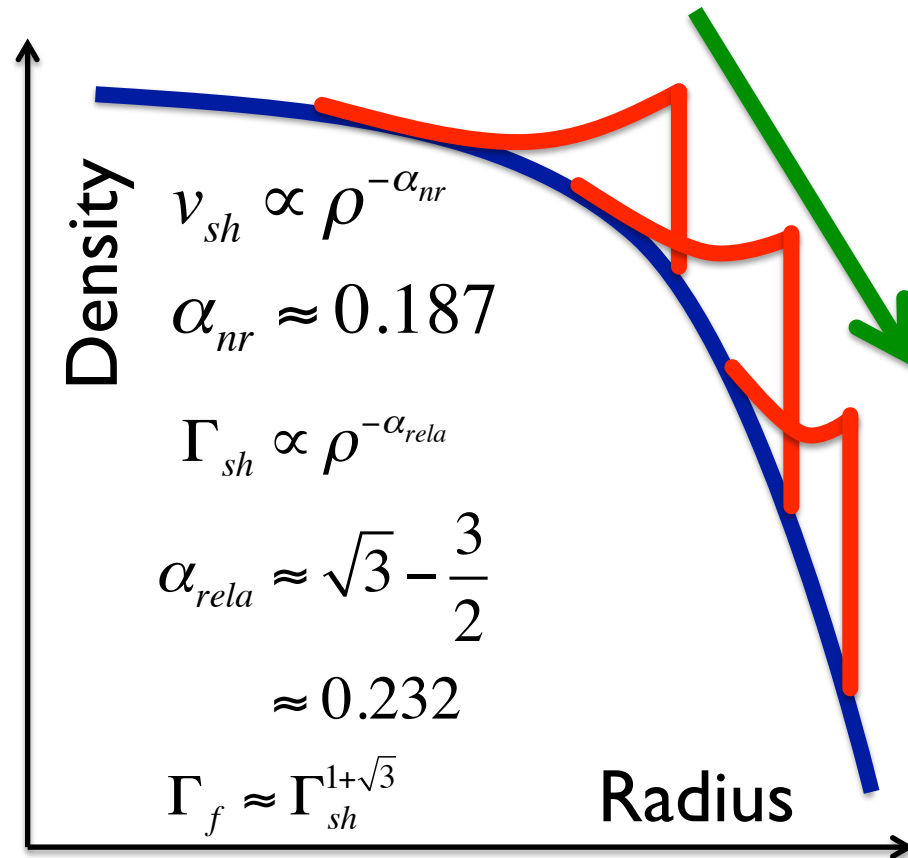
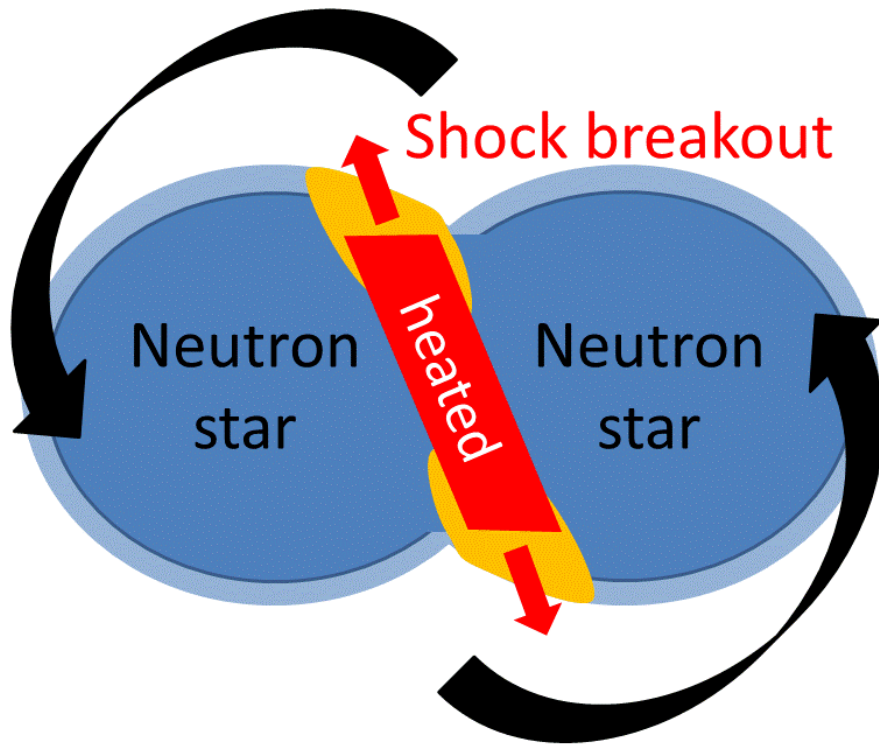
$\sim 2 \text{ sec}$



Cocoon is initially non-rela
Shock acceleration to $\Gamma \sim 3$

Kasliwal+ 17, Gottlieb+ 17, Bromberg+ 17

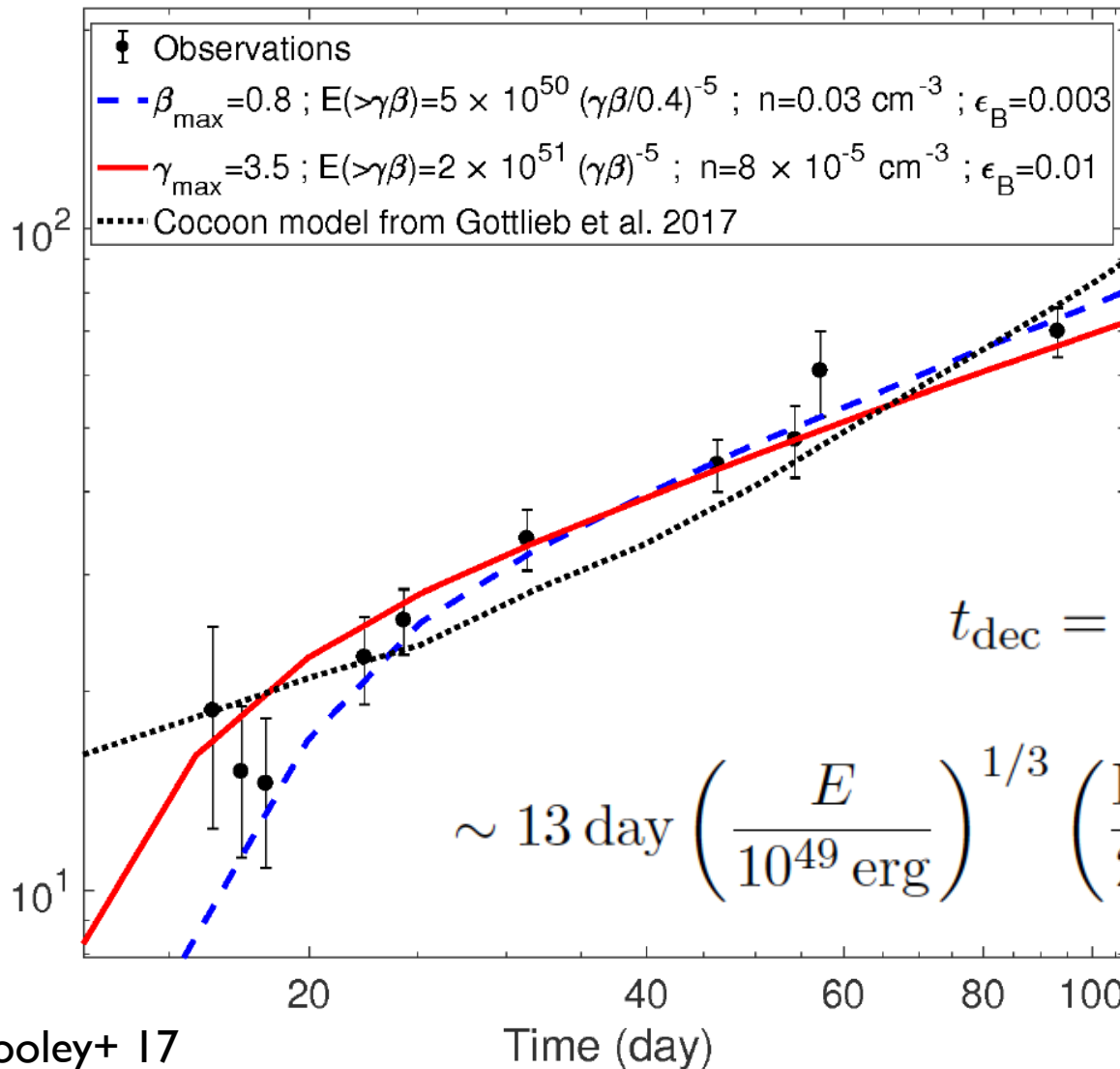
Merger Shock Breakout



Kyutoku, KI & Shibata 14
 Bauswein, Goriely & Janka 13
 Hotokezaka+ 13
 Sakurai 60, Johnson & McKee 71
 Beloborodov+ 17

Shock acceleration @surface
 up to $\sim 10^{-5} M_{\odot}$ but uncertain

Cocoon/Ejecta Afterglow



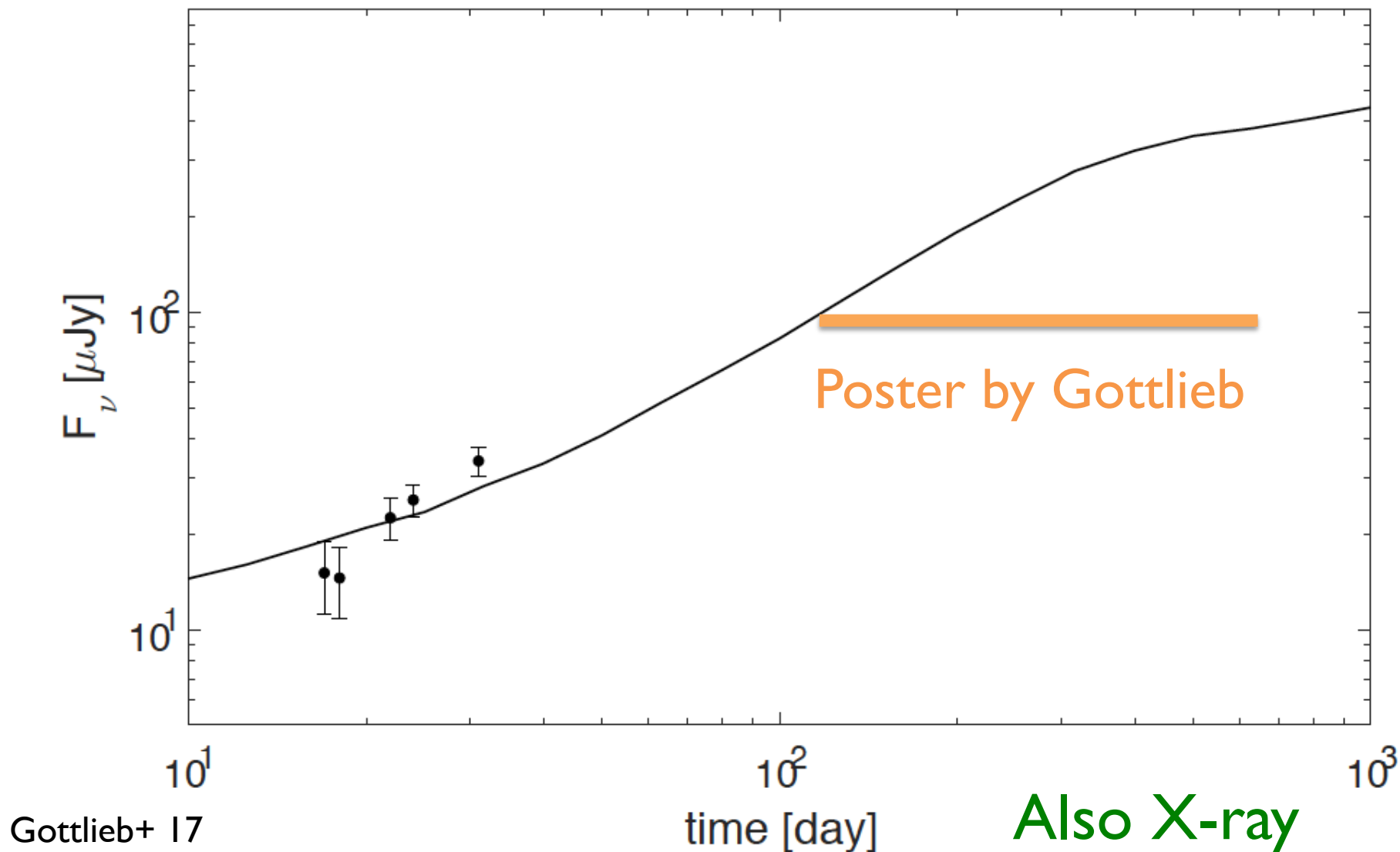
Cocoon or
Ejecta tail
interact w/ ISM

Rise time \sim
Deceleration time

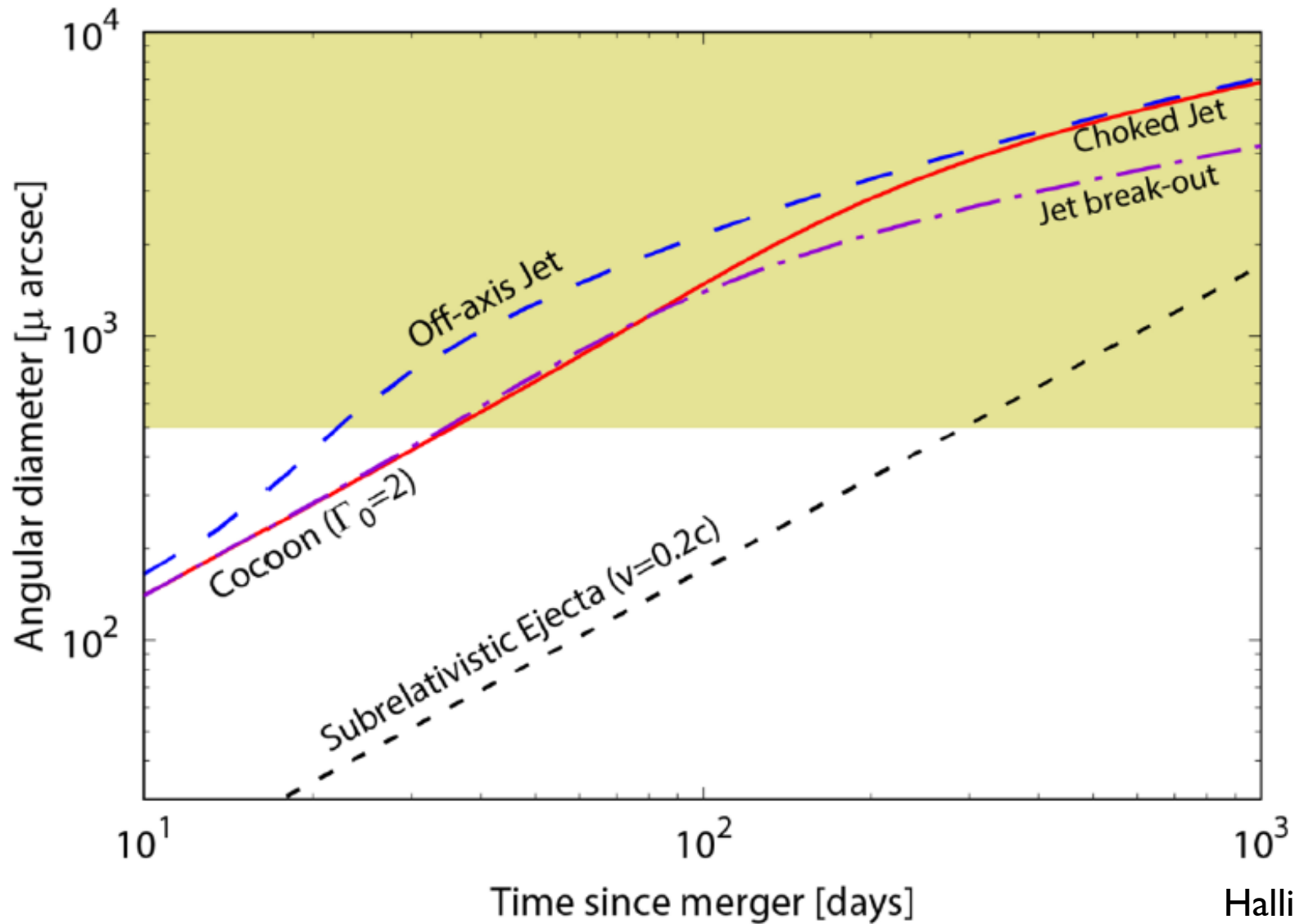
$$t_{\text{dec}} = \frac{1}{4\Gamma^2 c} \left(\frac{3E}{4\pi n m_p c^2 \Gamma^2} \right)^{1/3}$$

$$\sim 13 \text{ day} \left(\frac{E}{10^{49} \text{ erg}} \right)^{1/3} \left(\frac{\Gamma}{2} \right)^{-8/3} \left(\frac{n}{10^{-3} \text{ cm}^{-3}} \right)^{-1/3}$$

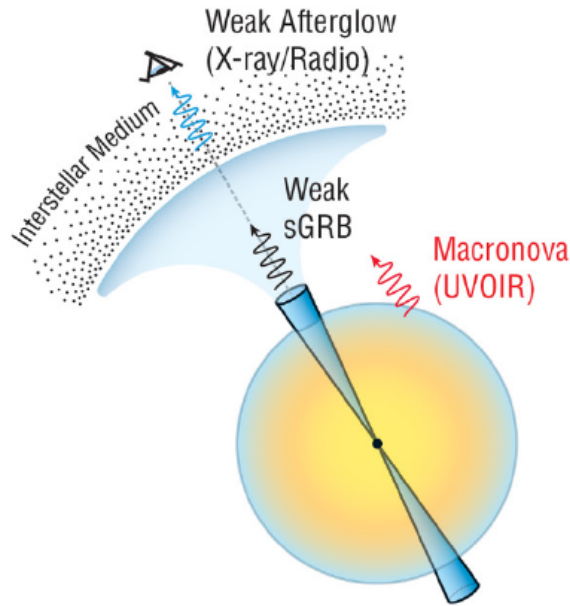
Future Radio Prediction



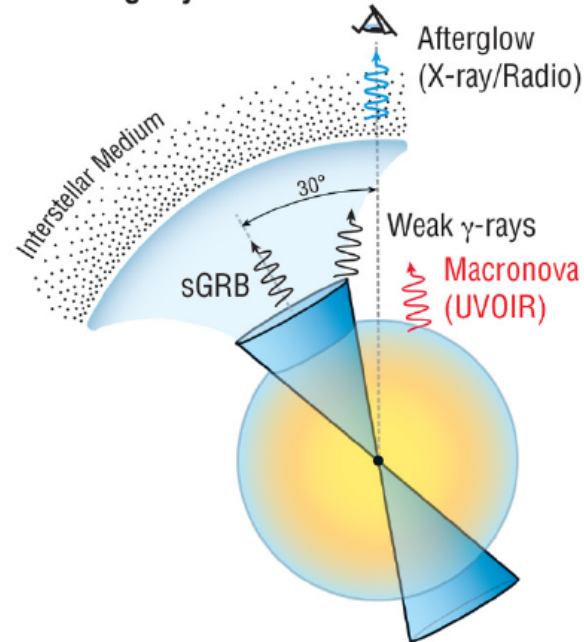
VLBI



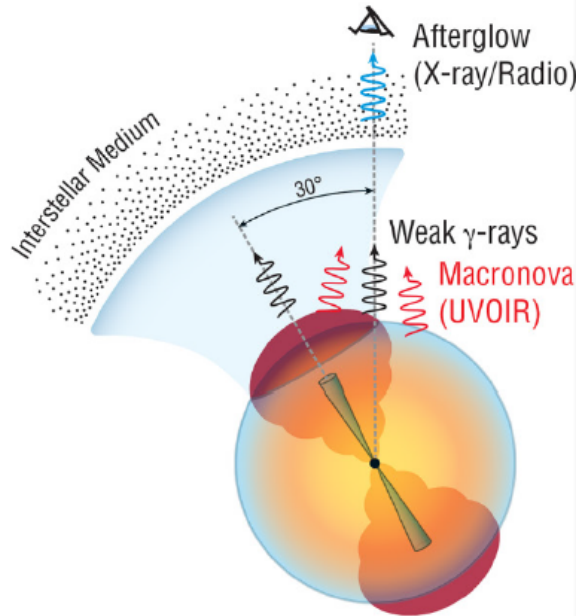
A On-axis Weak sGRB



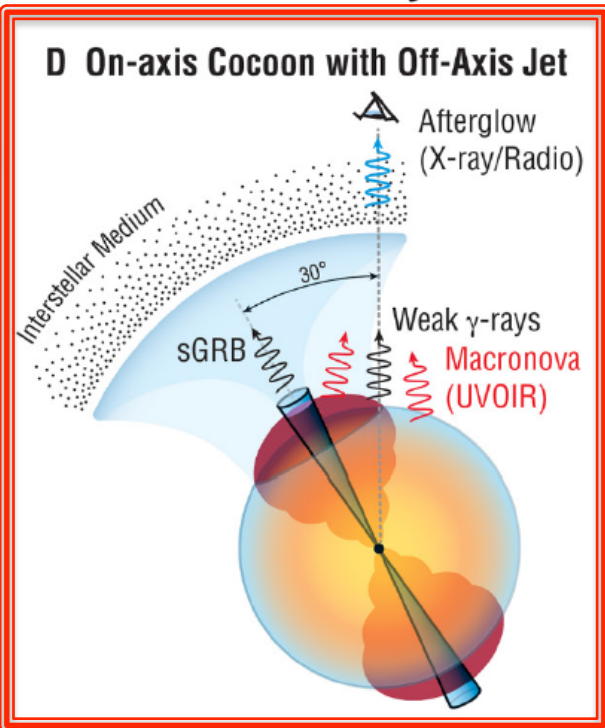
B Slightly Off-Axis Classical sGRB



C Cocoon with Choked Jet



D On-axis Cocoon with Off-Axis Jet



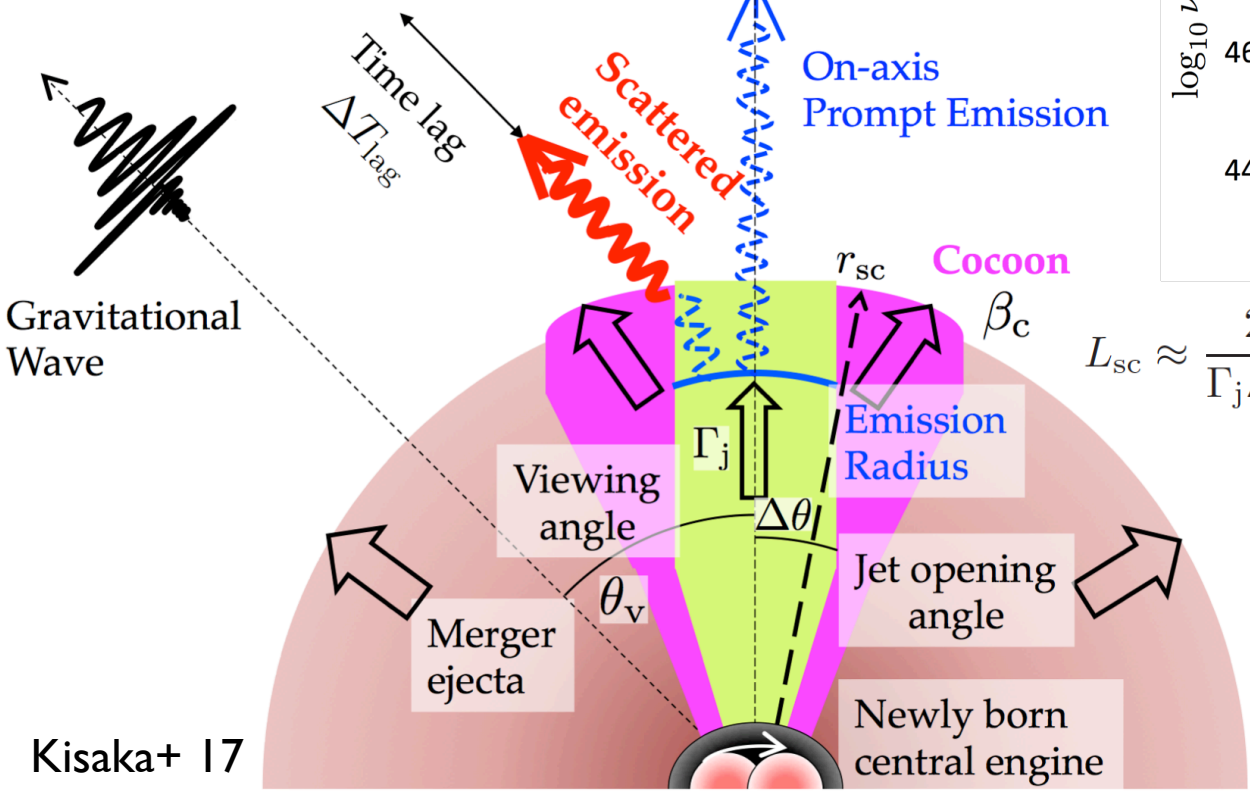
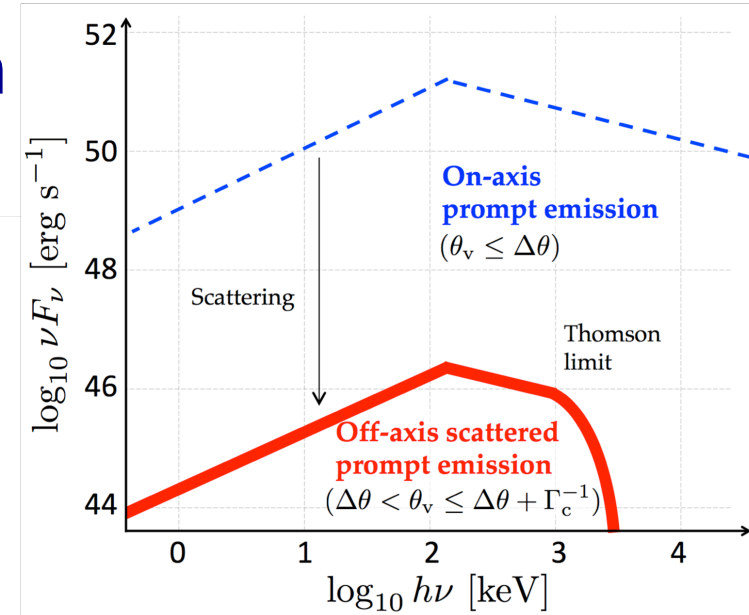
Off-axis jet emission is highly de-beamed

Scattered sGRB

Thompson scattering by cocoon

Copy spectrum w/ \sim MeV cutoff

$r_{sc} < 10^{10} - 10^{12}$ cm

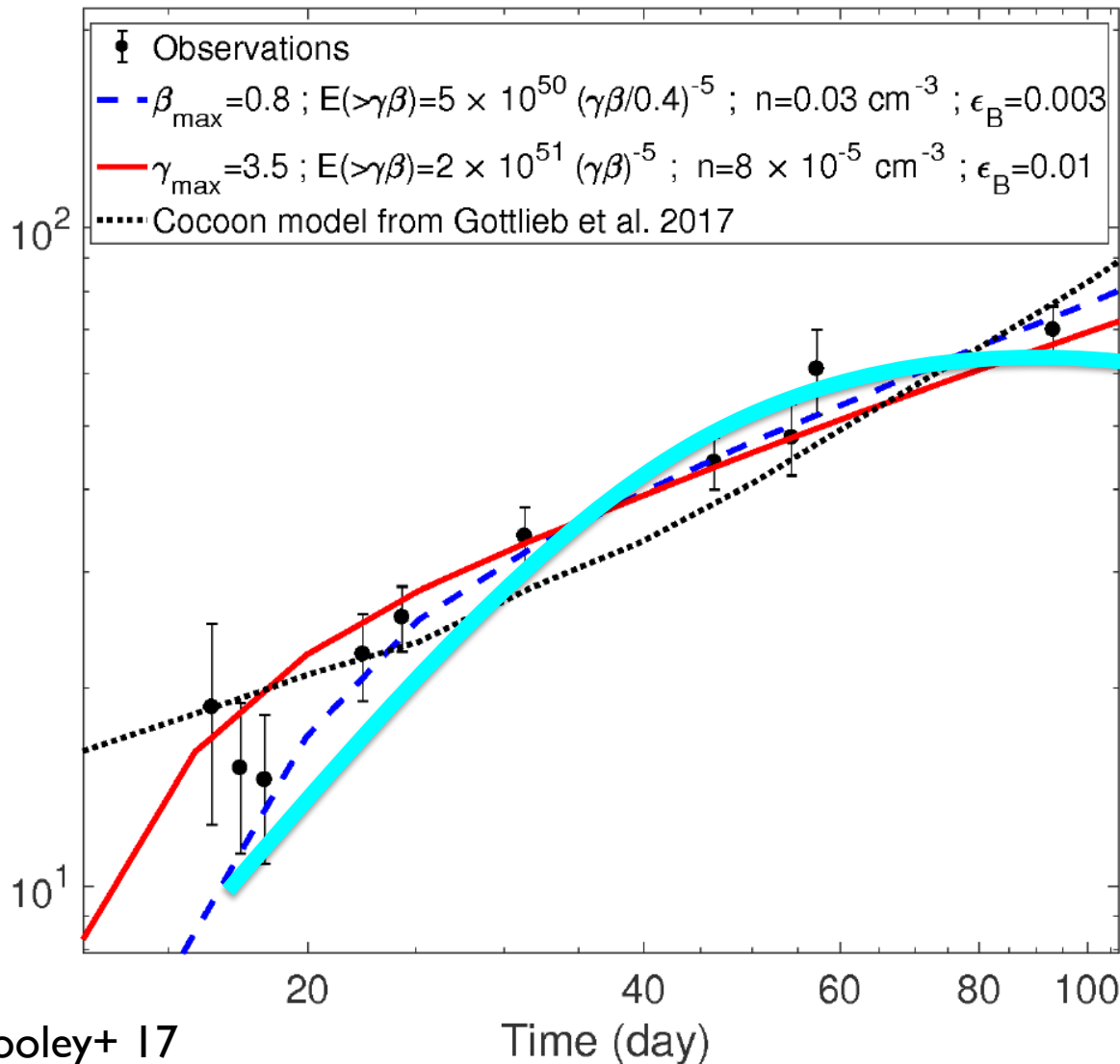


$$L_{sc} \approx \frac{2}{\Gamma_j \Delta \theta} \times \frac{t_{dur}}{T_{dur,sc}} \times \Gamma_c^2 \times \epsilon_{sc} \times \frac{\Delta \theta^2}{2} L_{iso}$$

Wide angle

$$\Delta \theta_{sc} \approx \frac{1}{\Gamma_c}$$

Afterglow Origin?



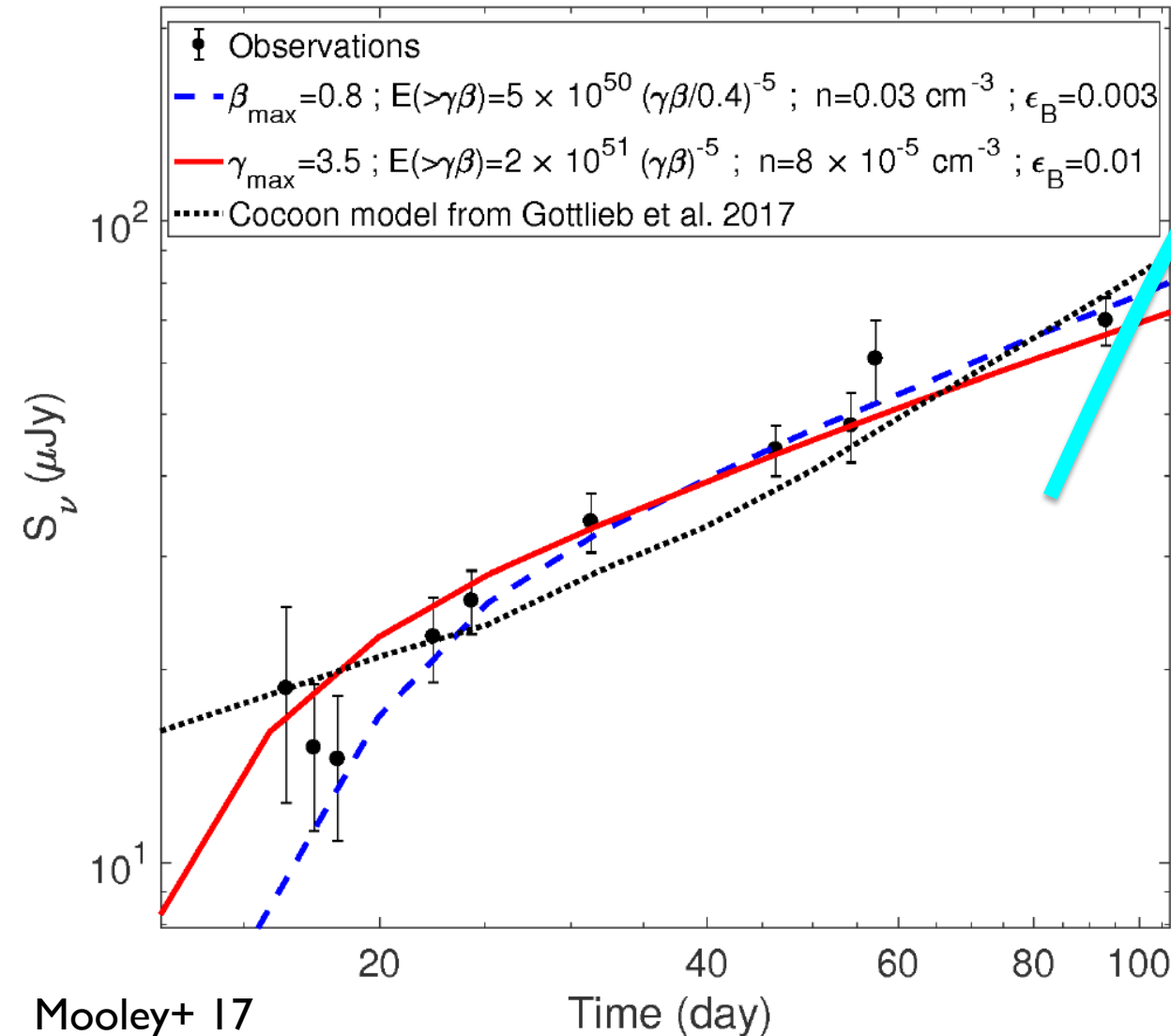
Margutti's talk
MacFadyen's talk

$$\Gamma \sim \theta_j^{-1} \quad \text{Jet break}$$

$$t_{\text{jet}} \sim 100 \text{ day} \left(\frac{\theta_j}{15^\circ} \right)^{8/3}$$

$$\times \left(\frac{E}{10^{52} \text{ erg}} \right)^{1/3} \left(\frac{n}{10^{-4} \text{ cm}^{-3}} \right)^{-1/3}$$

Afterglow Origin?



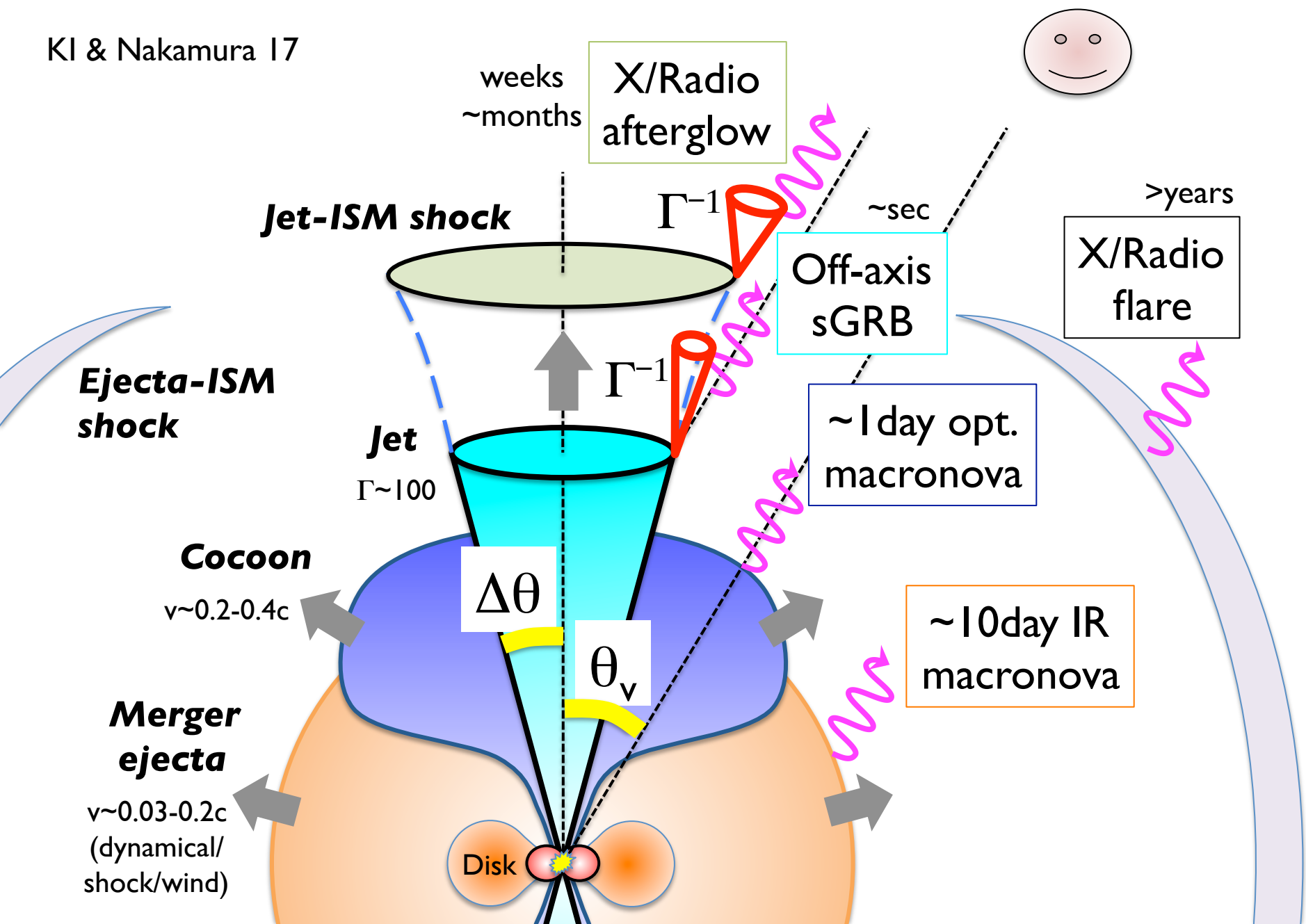
maybe
unlikely

$$\Gamma \sim \theta_j^{-1} \quad \text{Jet break}$$

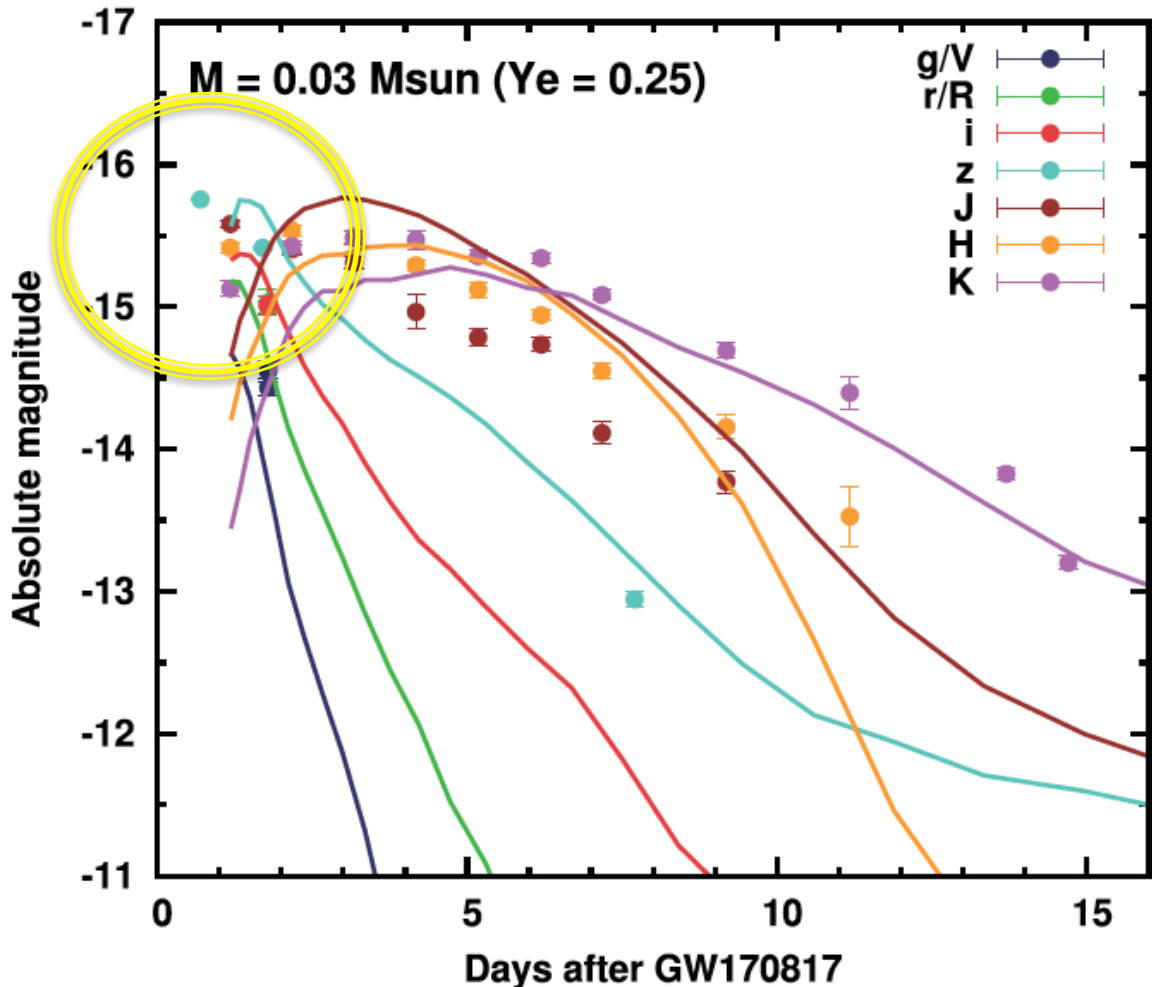
$$t_{\text{jet}} \sim 100 \text{ day} \left(\frac{\theta_j}{15^\circ} \right)^{8/3}$$

$$\times \left(\frac{E}{10^{52} \text{ erg}} \right)^{1/3} \left(\frac{n}{10^{-4} \text{ cm}^{-3}} \right)^{-1/3}$$

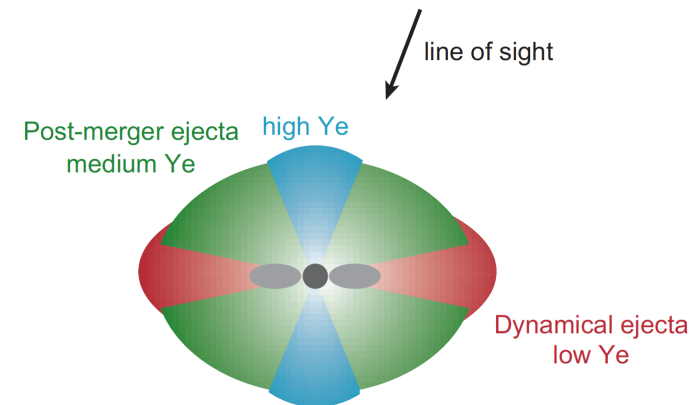
KI & Nakamura 17



Blue Macronova/Kilonova



~1 day opt.
 $T \sim 7000\text{K}$
 $L \sim 7e4 L_{\odot}$
 $\Rightarrow v \sim 0.3c$

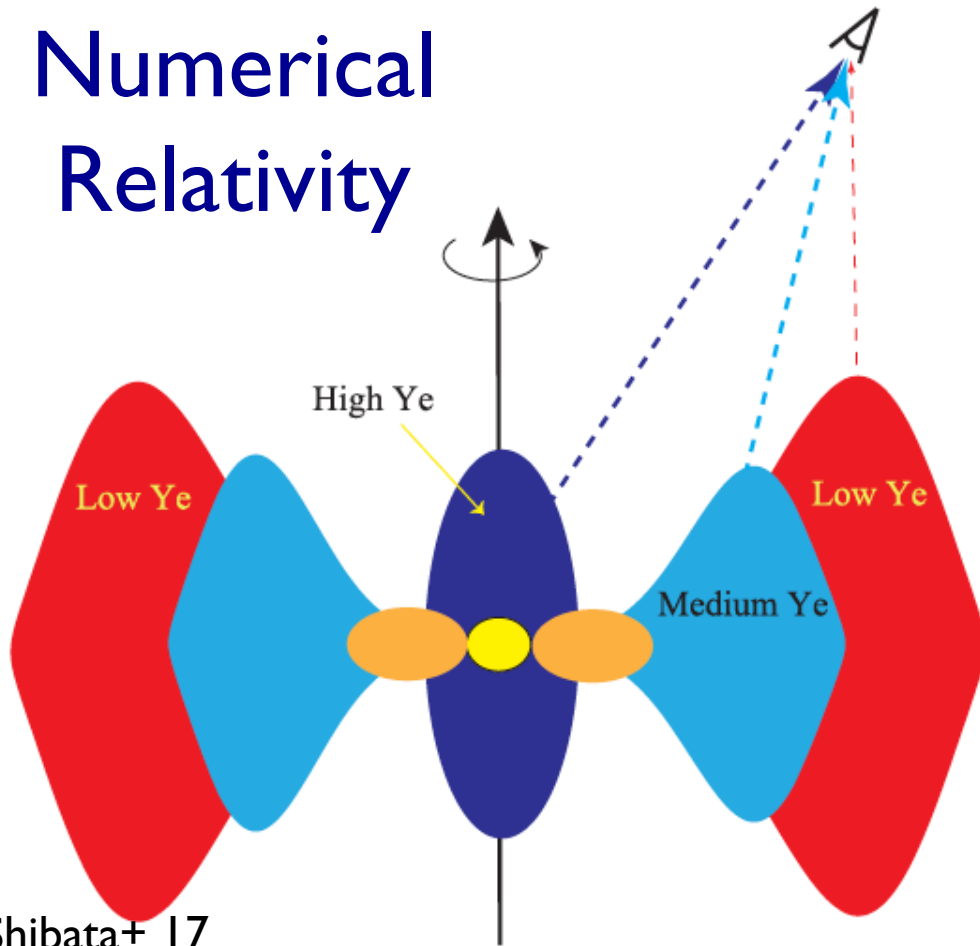


If r-process,
 $M \sim 0.02 M_{\odot}$
 $\kappa \sim 0.3 \text{ cm}^2/\text{g}$

J-GEM 17, Tanaka+ 17, Utsumi+ 17, Tominaga+ 17, Arcavi+ 17, Drout+ 17, Cowperthwaite+ 17, Villar+ 17, Kasliwal+ 17, Kasen+ 17, Smartt+ 17, Kilpatrick+ 17, Pian+ 17, Chornock+ 17, Coulter+ 17, Evans+ 17, ...

Massive Ejection?

Numerical Relativity



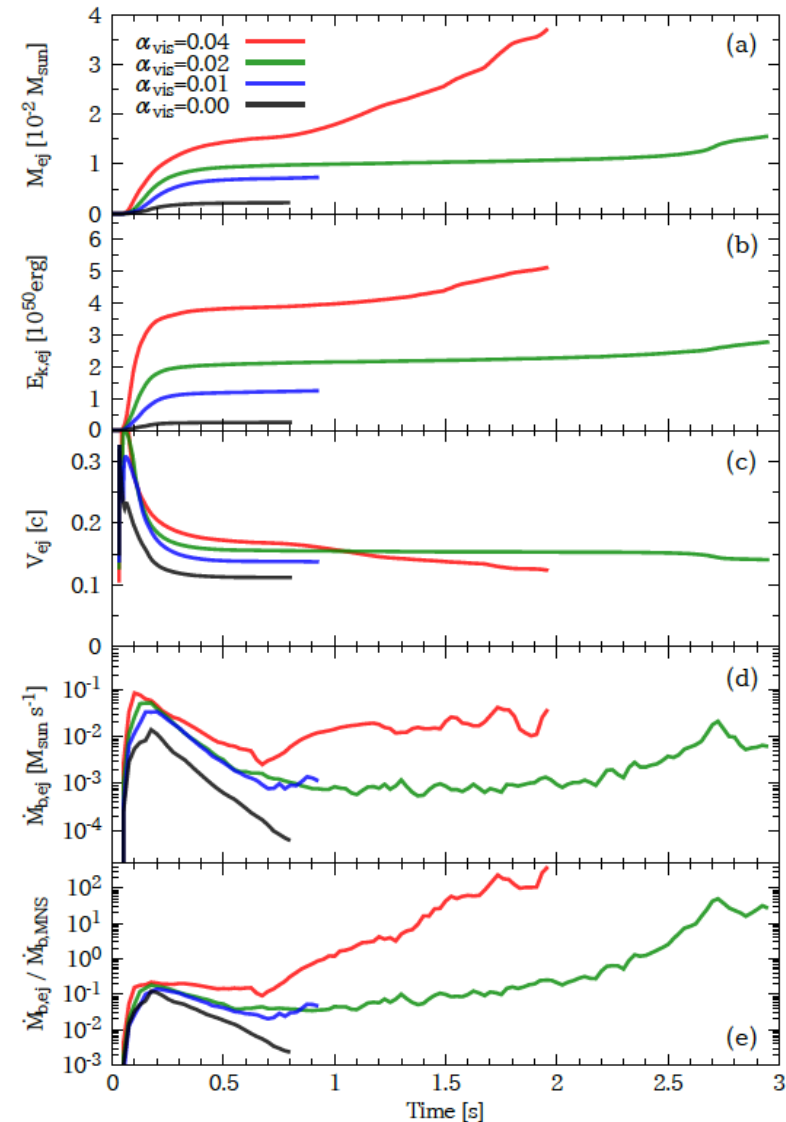
Disk outflows?

Shibata+ 17

Fujibayashi+ 17

Fernandez & Metzger 13

Just+ 15, Siegel & Metzger 17

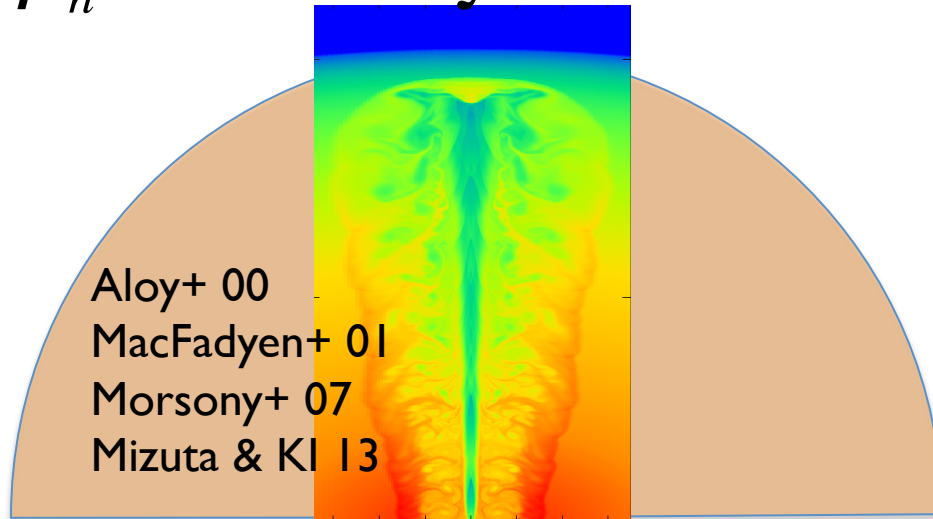


Fast & Quasi-spherical

Long GRB:

Static envelope

$\beta_h \sim$ arbitrary @Breakout



$$\beta_{\perp} \ll \beta_h / 2$$

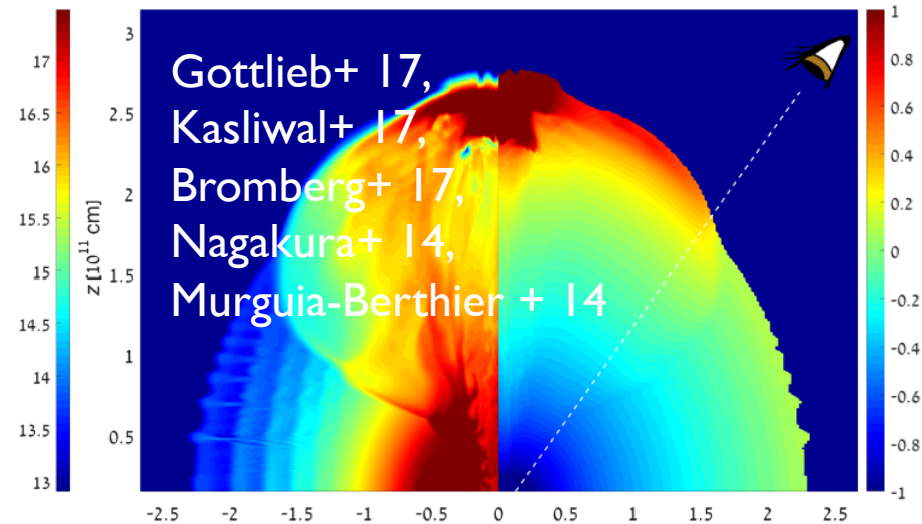
$$M_c \propto \theta_j^2$$

Analytically shown in
KI & Nakamura 17

Short GRB:

Expanding ejecta

$\beta_h \sim 2\beta_{ej}$ @Breakout



$$\beta_{\perp} \sim \beta_h / 2$$

$$M_c \propto \theta_j \quad \beta_c \sim 0.4c$$

Jet-powered Macronova

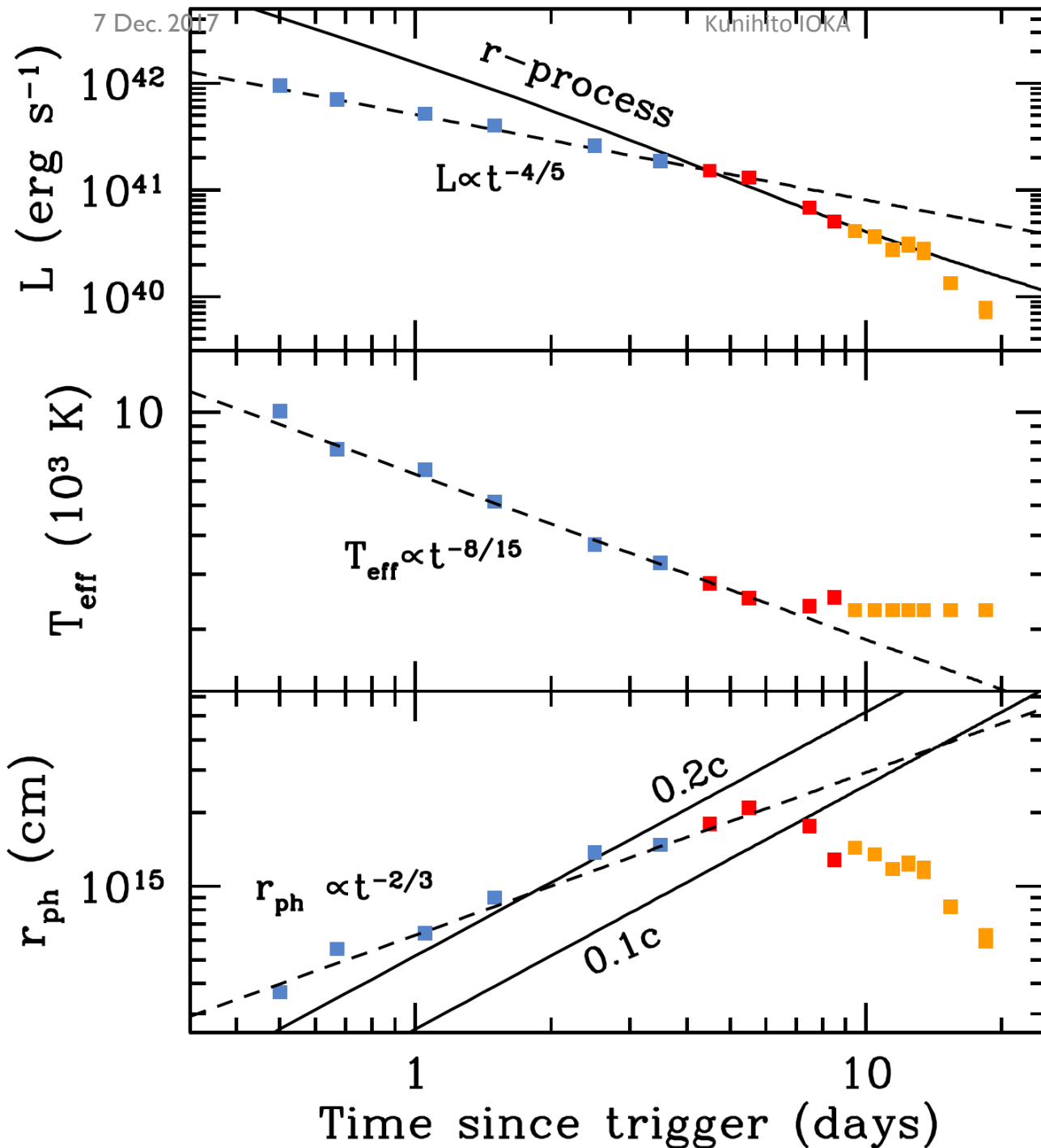
$$E_{\text{inj}} \sim 2L_j t_{\text{br}} \sim 1 \times 10^{51} \text{ erg} \left(\frac{\Delta\theta}{0.3} \right)^2 \left(\frac{\beta_e / (1 - 2\beta_e)^2}{0.2/0.6^2} \right) \left(\frac{M_e}{0.01 M_\odot} \right)$$

$$E_{\text{jet}} \sim \frac{r_{\text{br}}}{r_{\text{ph}}} E_{\text{inj}}$$

$$\sim 1.4 \times 10^{46} \text{ erg} \left(\frac{t_{\text{MN}}}{1 \text{ day}} \right)^{-1} \left(\frac{t_{\text{br}}}{2 \text{ s}} \right) \left(\frac{\Delta\theta}{0.3} \right)^2 \left(\frac{\beta_e / (1 - 2\beta_e)^2}{0.2/0.6^2} \right) \left(\frac{M_e}{0.01 M_\odot} \right)$$

$$E_r \sim \epsilon_{\text{th}} \dot{\epsilon}_r t_{\text{MN}} M_e \sim 1.7 \times 10^{46} \text{ erg} \left(\frac{t_{\text{MN}}}{1 \text{ day}} \right)^{-0.3} \left(\frac{M_e}{0.01 M_\odot} \right)$$

Even the prompt jet may power the blue macronova
 The extended & plateau emissions can add energy



Cooling emission from the cocoon

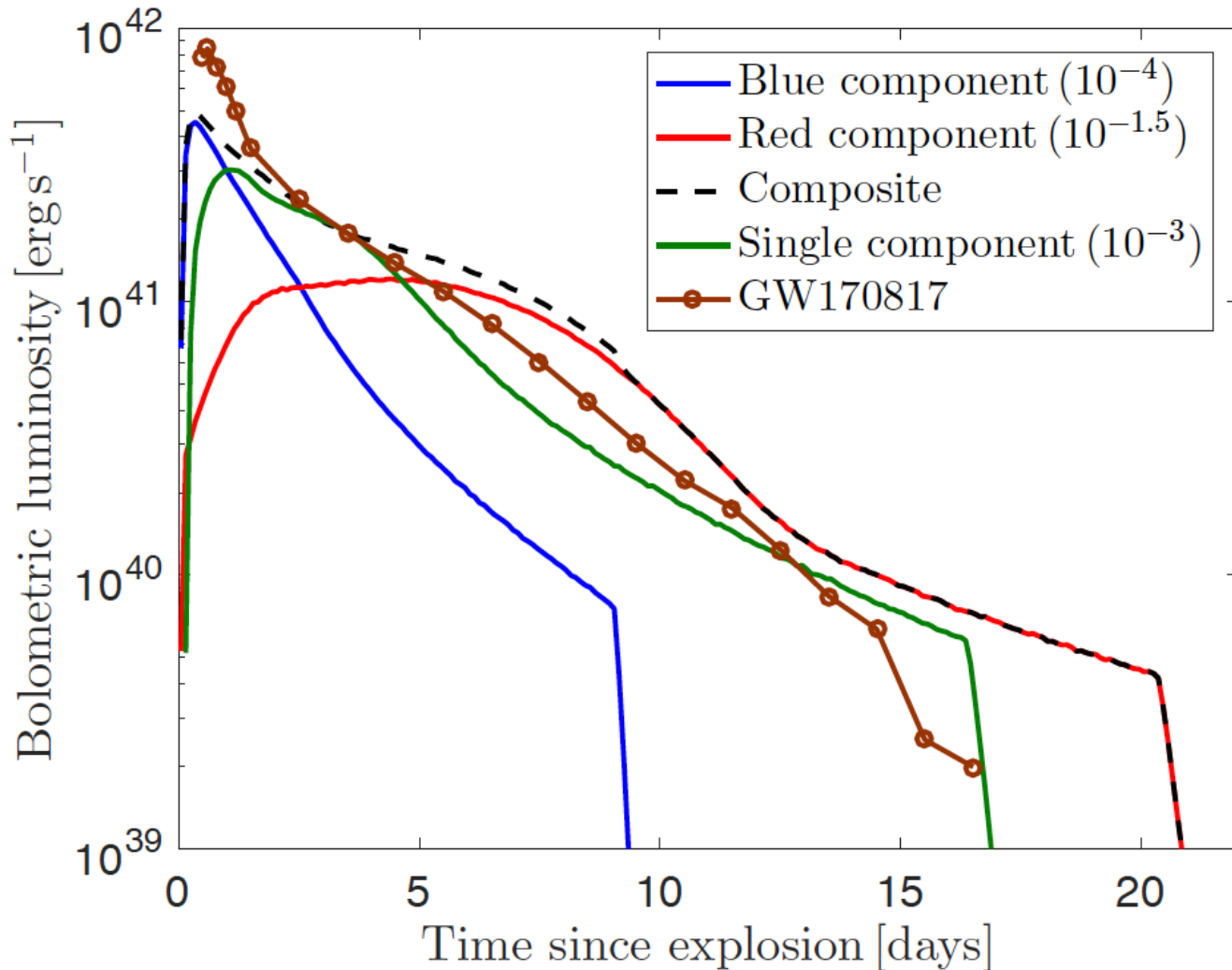
$$s = -d \ln E / d \ln v \approx 3$$

$$L \propto t^{-4/(s+2)},$$

$$T_{\text{eff}} \propto t^{1/(s+3)-1/(s+2)-1/2},$$

$$r_{\text{ph}} \propto t^{(s+1)/(s+3)},$$

Single Component?



**Structured
ejecta**

$$M_e \sim 0.05 M_\odot$$

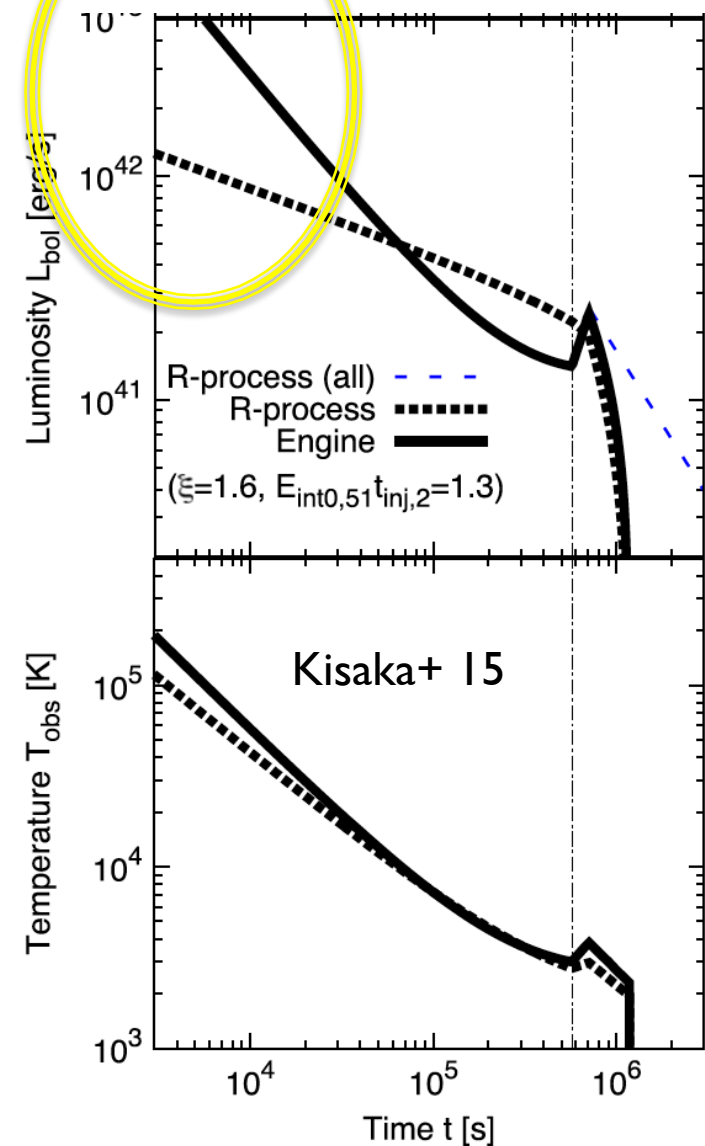
$$v(m) \propto m^{-0.6}$$

$$(0.1 < v/c < 0.3)$$

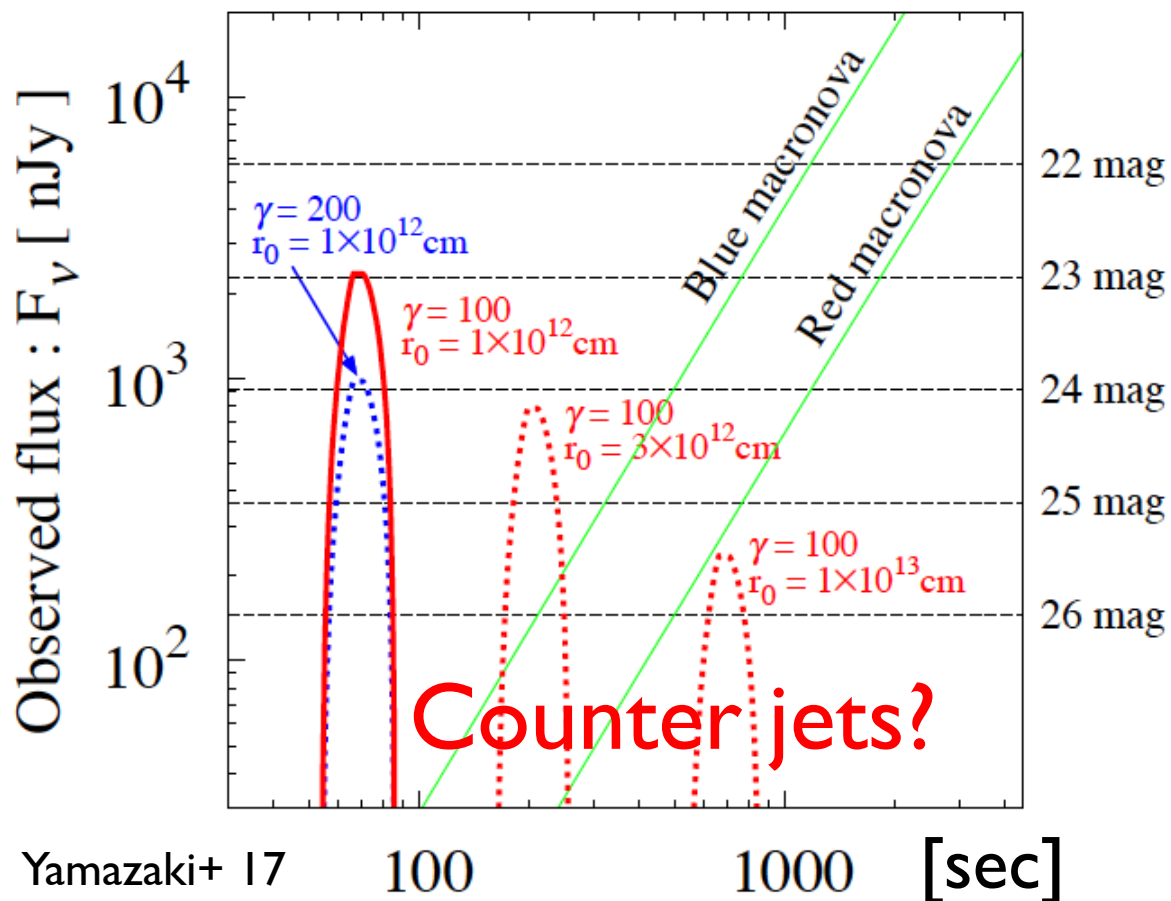
$$\frac{\kappa}{\text{cm}^2 \text{g}^{-1}} \sim 0.3 \left(\frac{t}{\text{day}} \right)^{0.6}$$

$$0.8 < T/\text{day} < 6$$

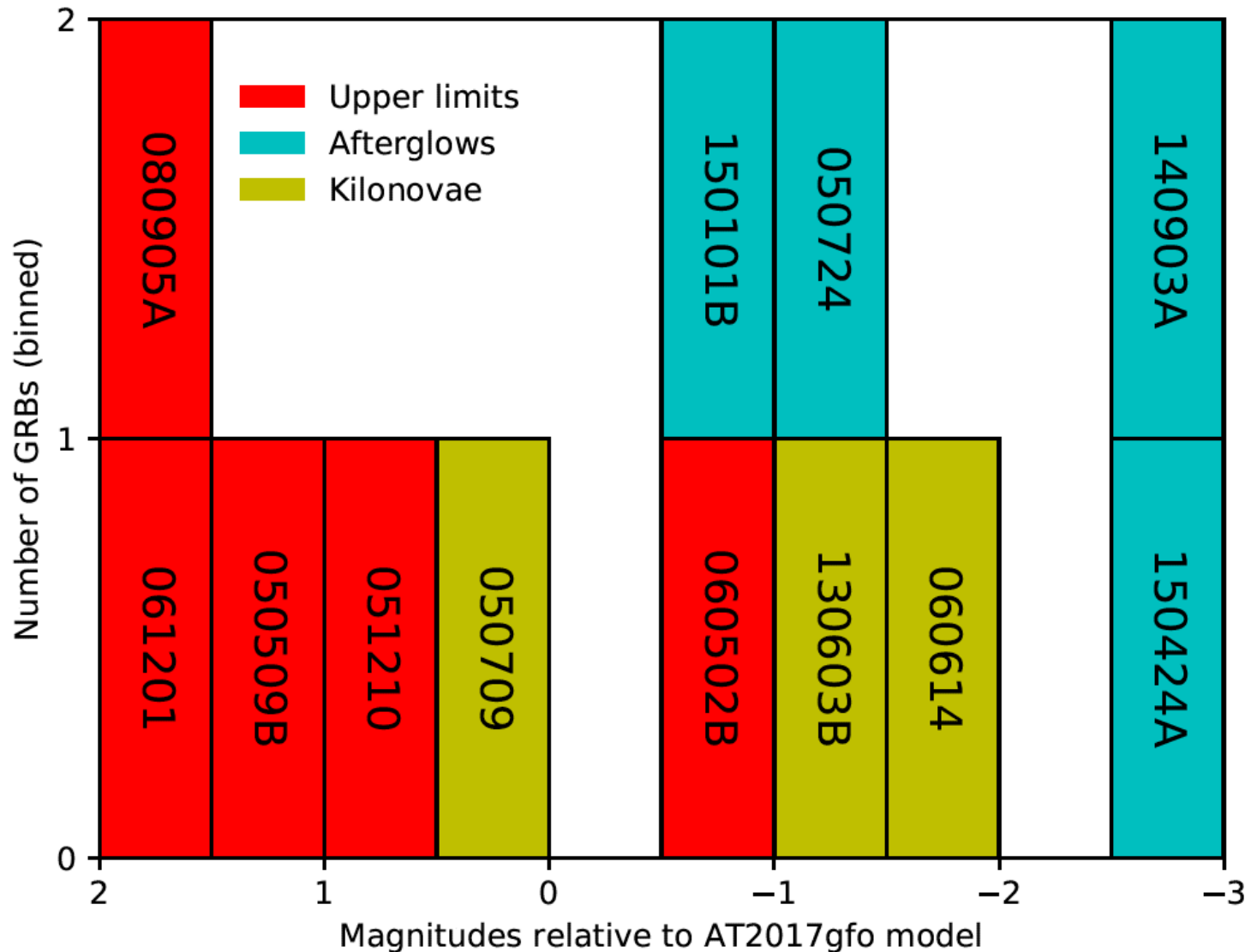
Early Macronova



r-process: $T_{BB} \sim \left(\frac{\rho \dot{\epsilon} t}{a} \right)^{1/4}$, $L \sim 4\pi R^2 \left(\frac{ct}{\kappa \rho} \right)^{1/2} \rho \dot{\epsilon}$



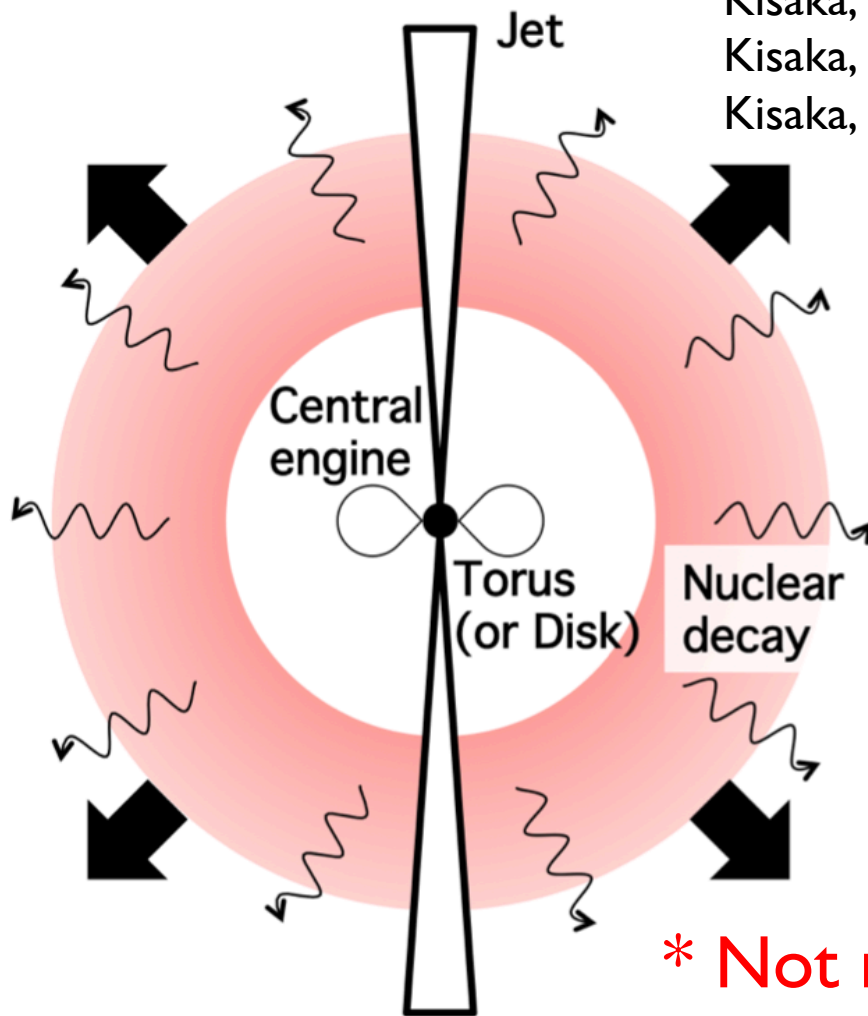
Macronova Variety



Might
suggest
jet power

Gompertz+ 17
Fong+ 17

Engine-Powered Macronova?

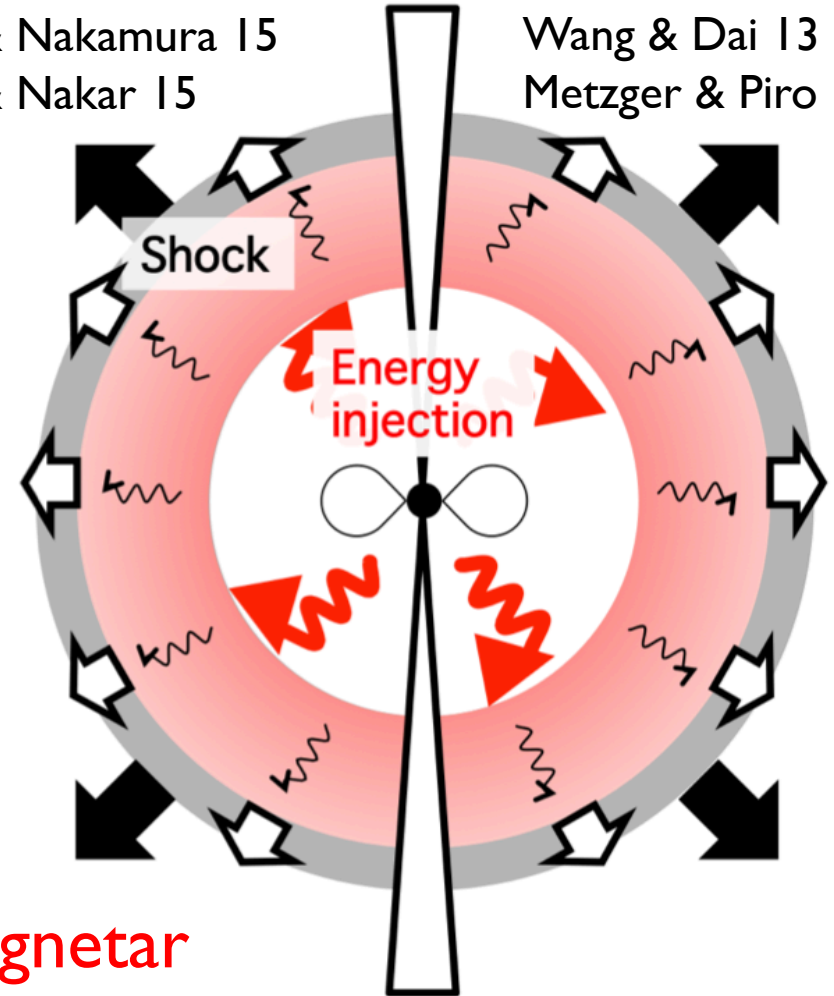


R-process model

* Not magnetar

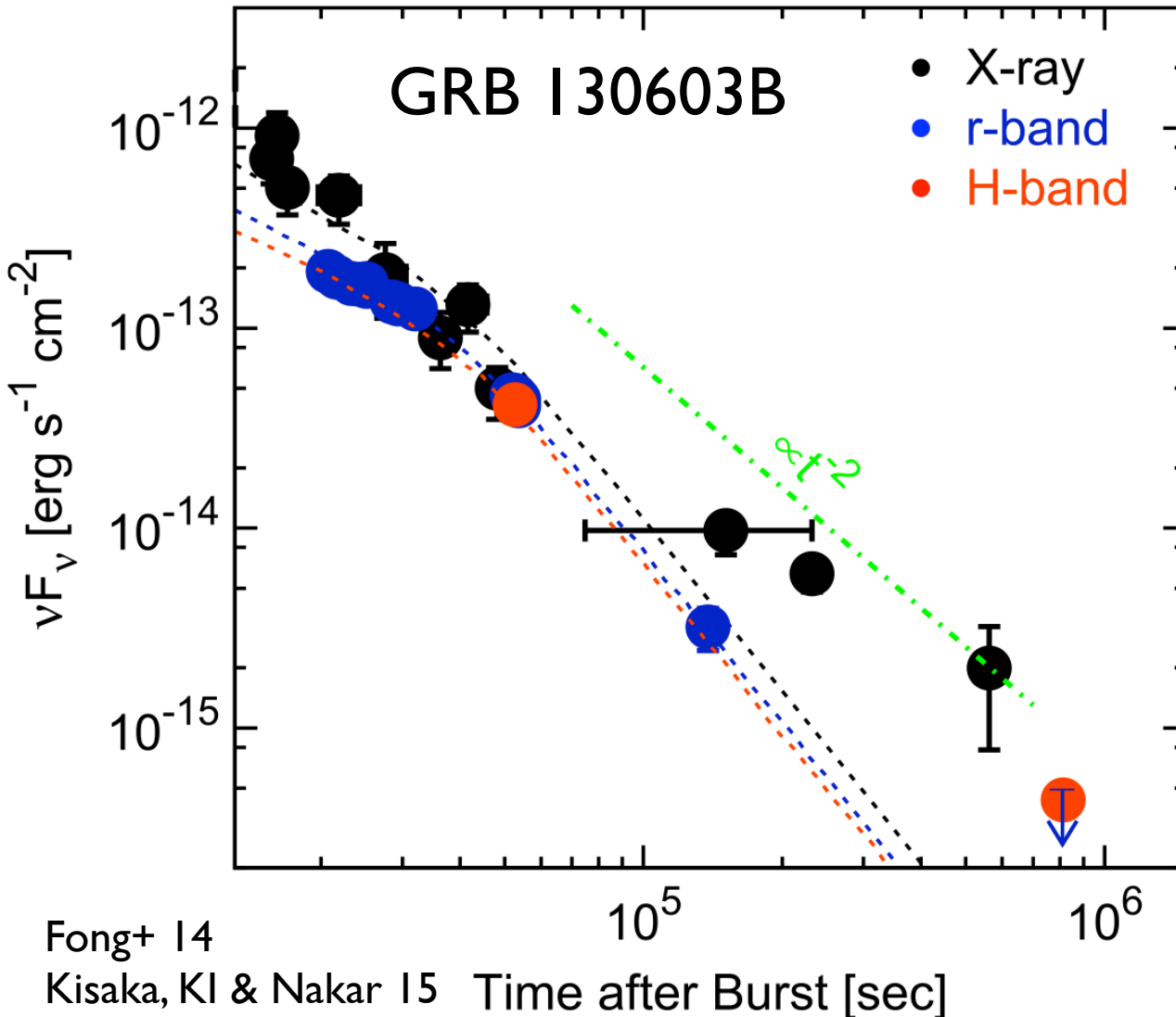
Kisaka, KI & Takami 14
 Kisaka, KI & Nakamura 15
 Kisaka, KI & Nakar 15

Yu+ 13
 Wang & Dai 13
 Metzger & Piro 14



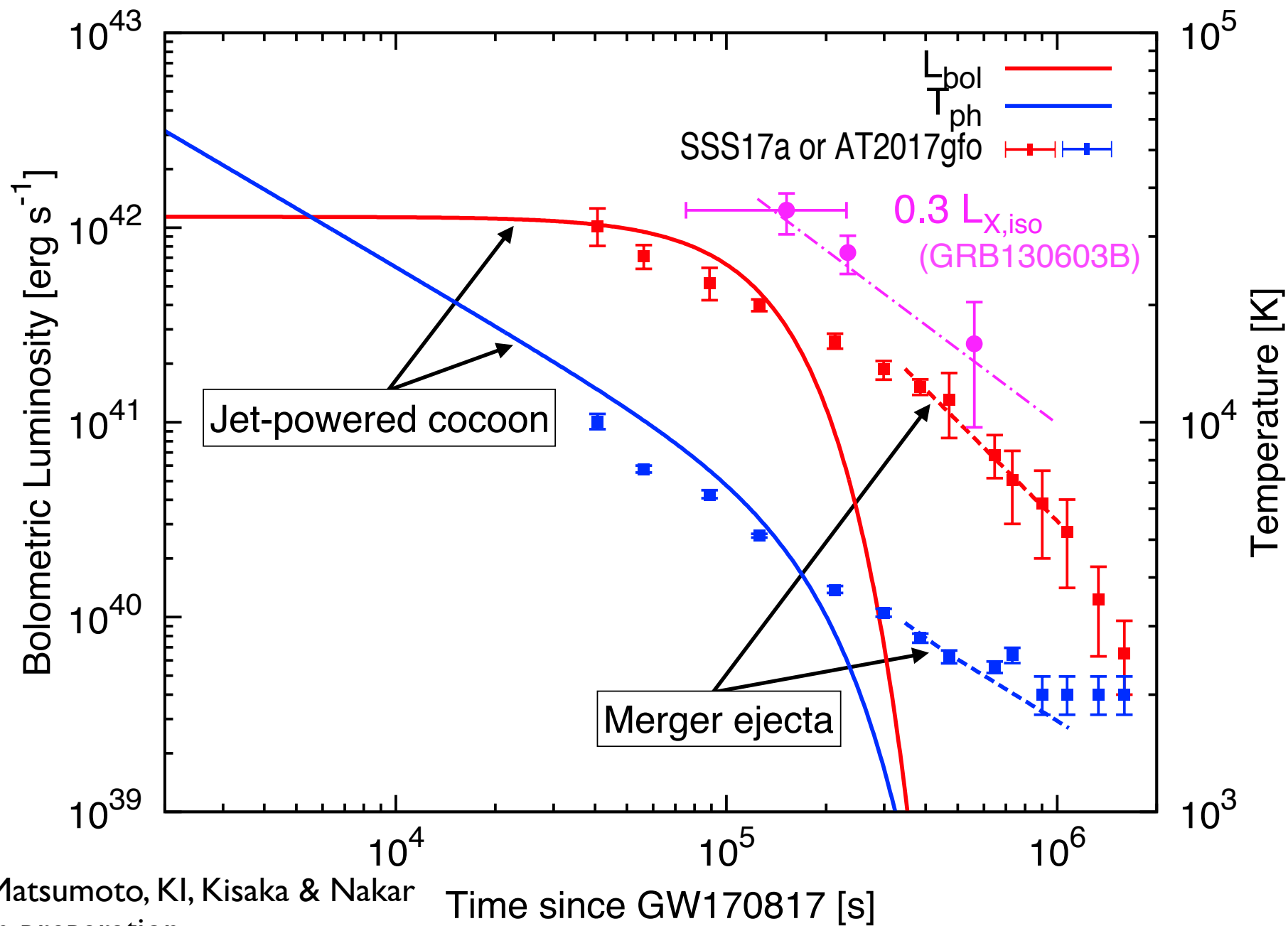
Engine model

X-ray Powered?

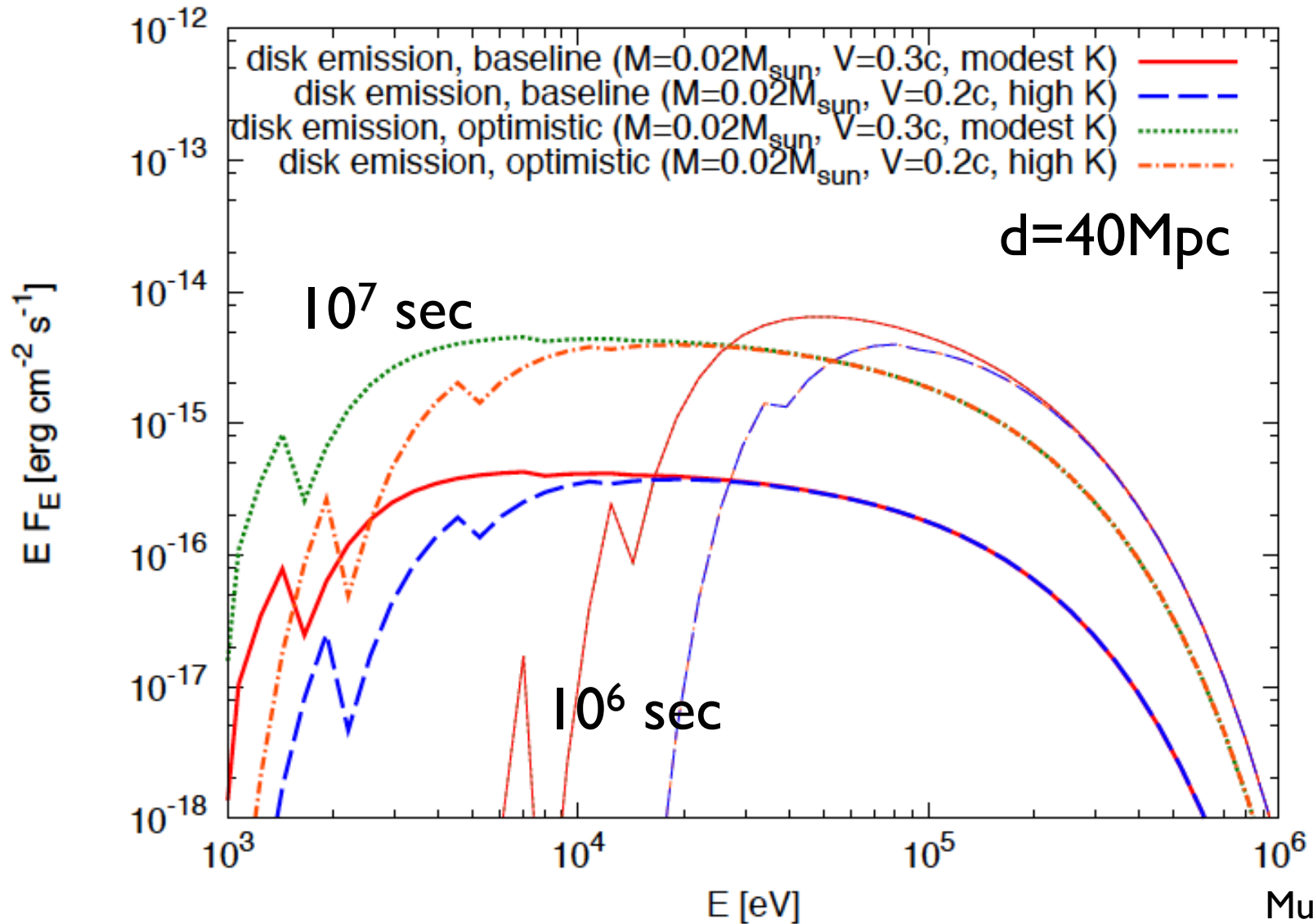


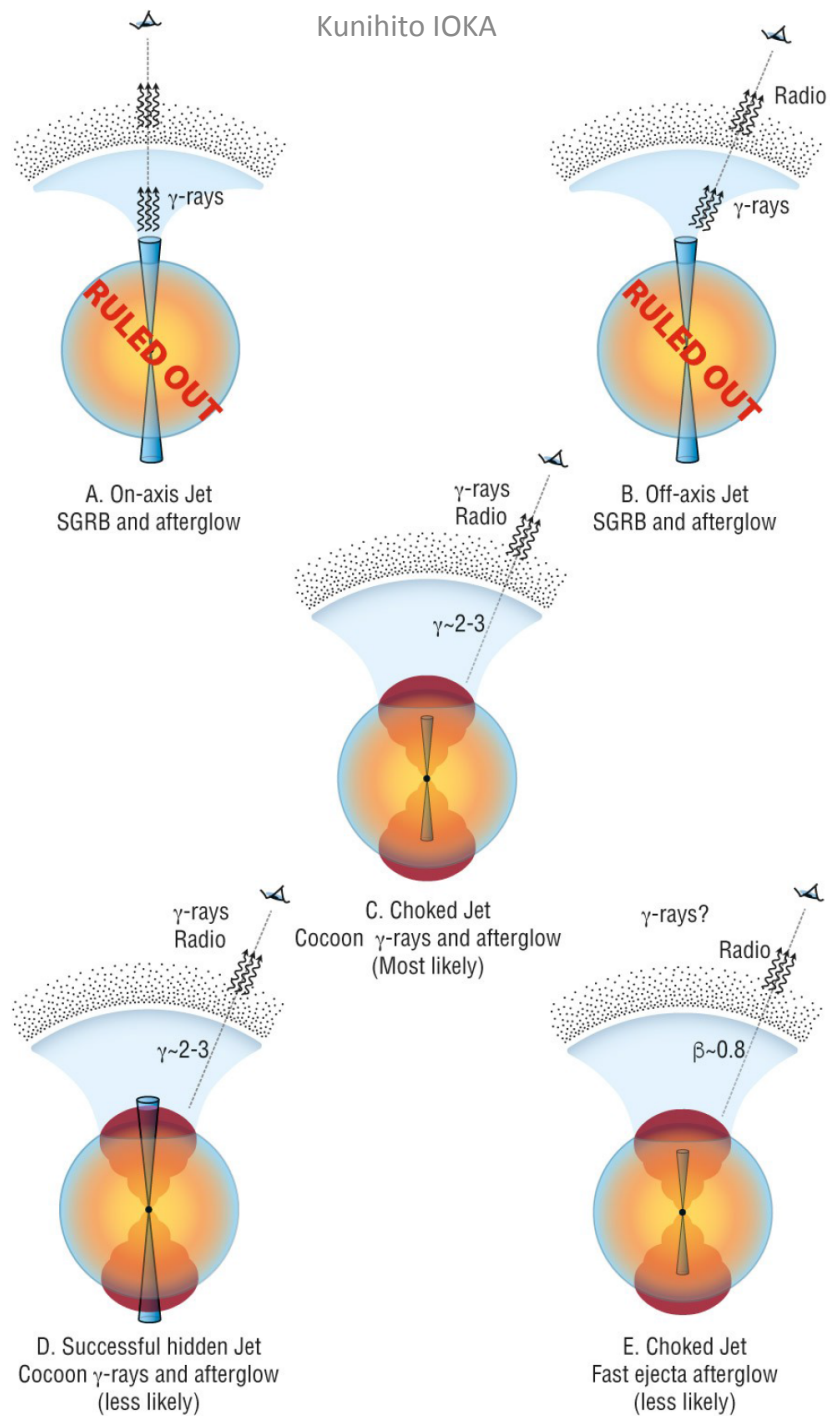
Macronova @IR
 ≈ X-ray excess
Same origin?

X-ray
 ⇒ Ejecta
 ⇒ Thermalized
 ⇒ Infrared
 as reprocessed

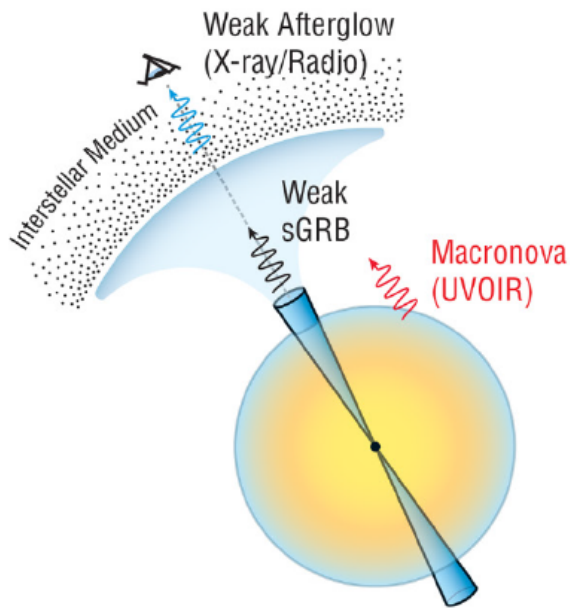


X-raying sGRB Engine



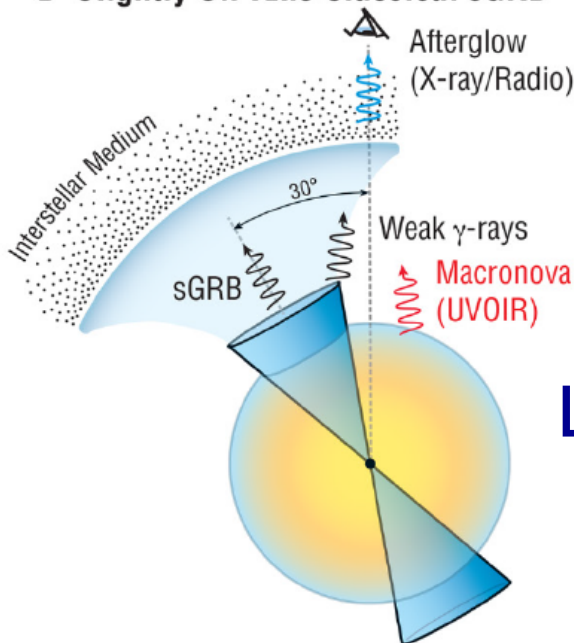


A On-axis Weak sGRB



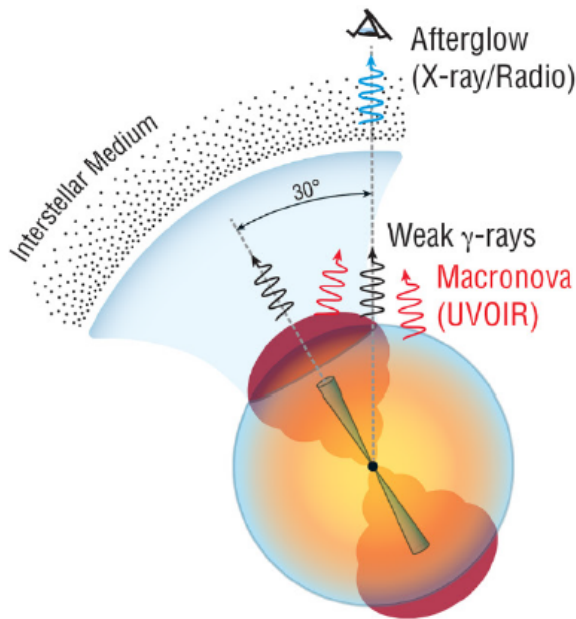
Magnetar before merger?

B Slightly Off-Axis Classical sGRB



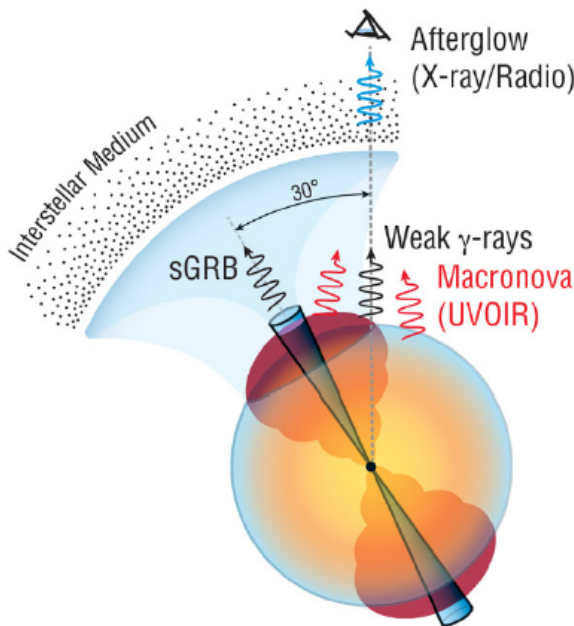
Spectrum? Low density? Afterglow?

C Cocoon with Choked Jet



Ejecta tail?

D On-axis Cocoon with Off-Axis Jet



Scattered? Afterglow?

Radio & X Radio size Early MN

Thank

You