Jet in Electromagnetic Counterparts to GW170817?

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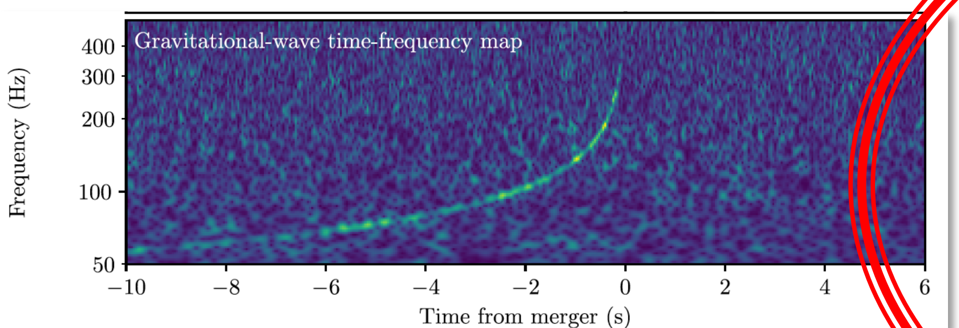
With Takashi NAKAMURA, …

Contents

- ***sGRB 170817A from an off-axis jet***
  - A top-hat jet is not perfect
  - Spectral problem
- ***Off-axis emission of a structured jet***
  - We are likely observing a jet side-profile
  - Not an on-axis outflow, not a jet core, but middle
  - Both off-axis emission & structure are essential
  - The jet side has been observed for the first time
  - No compactness problem
  - Predict Yonetoku outliers

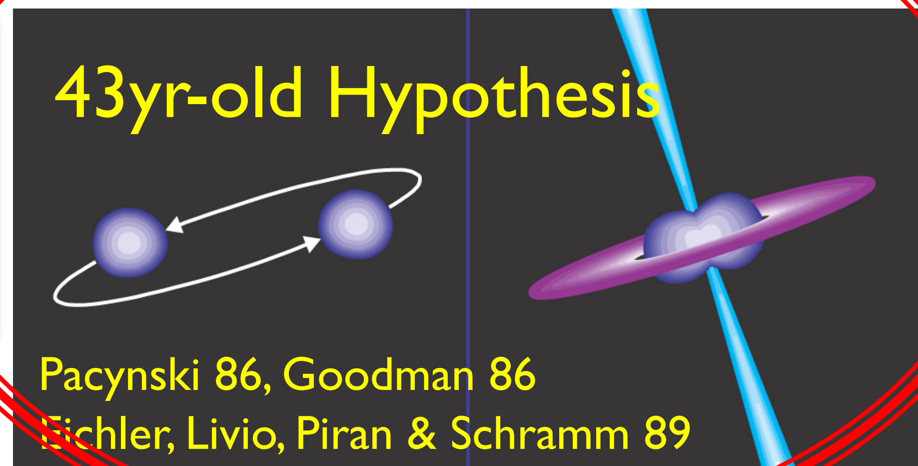
GW170817

1st GW from NS²



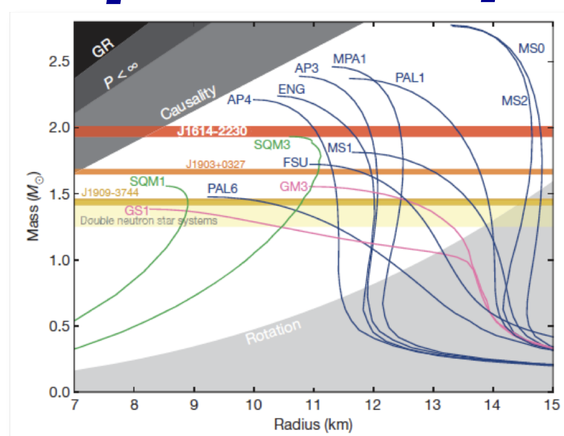
~100 sec chirp ⇒ NS-NS

NS² = Short GRB?



R-process elements

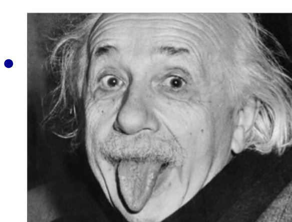
Equation of state



Relativity,

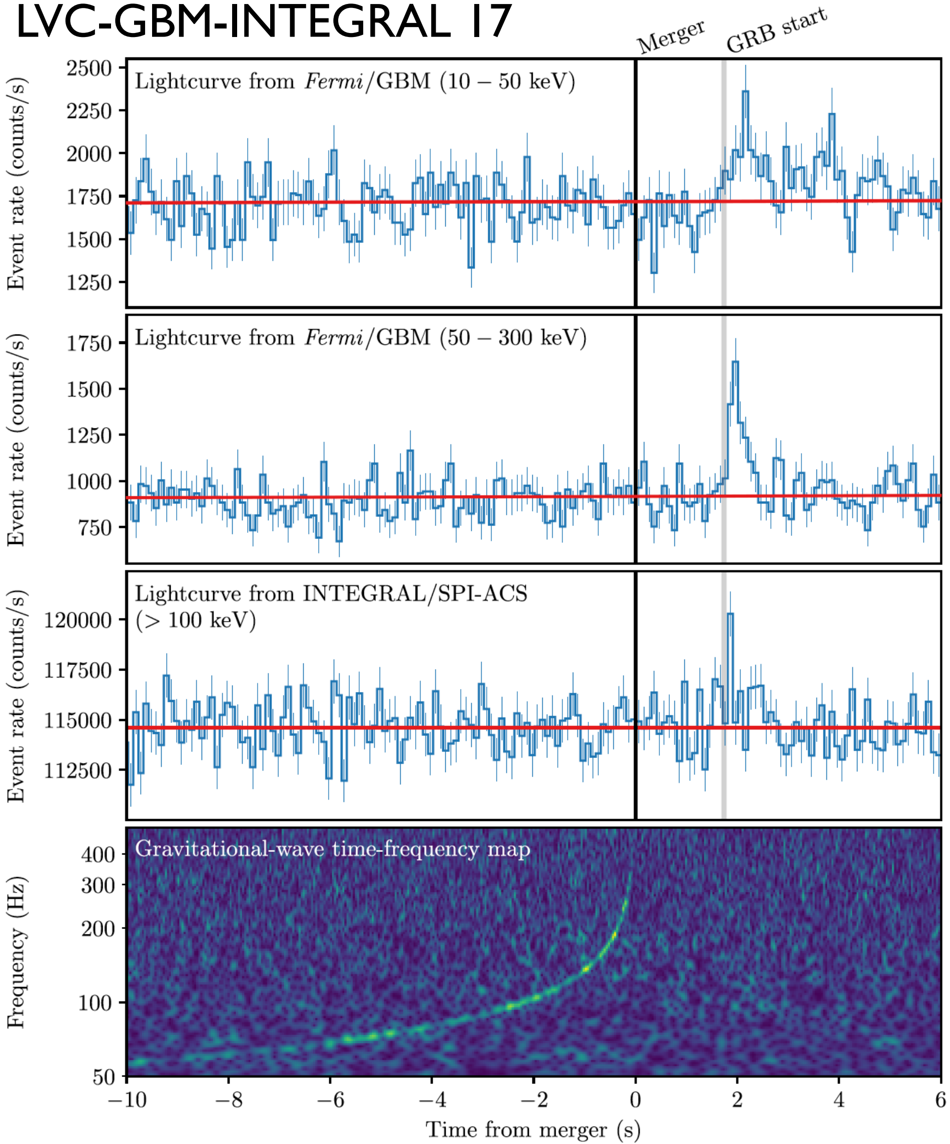
Cosmology,

…



GW170817 & sGRB 170817A

LVC-GBM-INTEGRAL 17

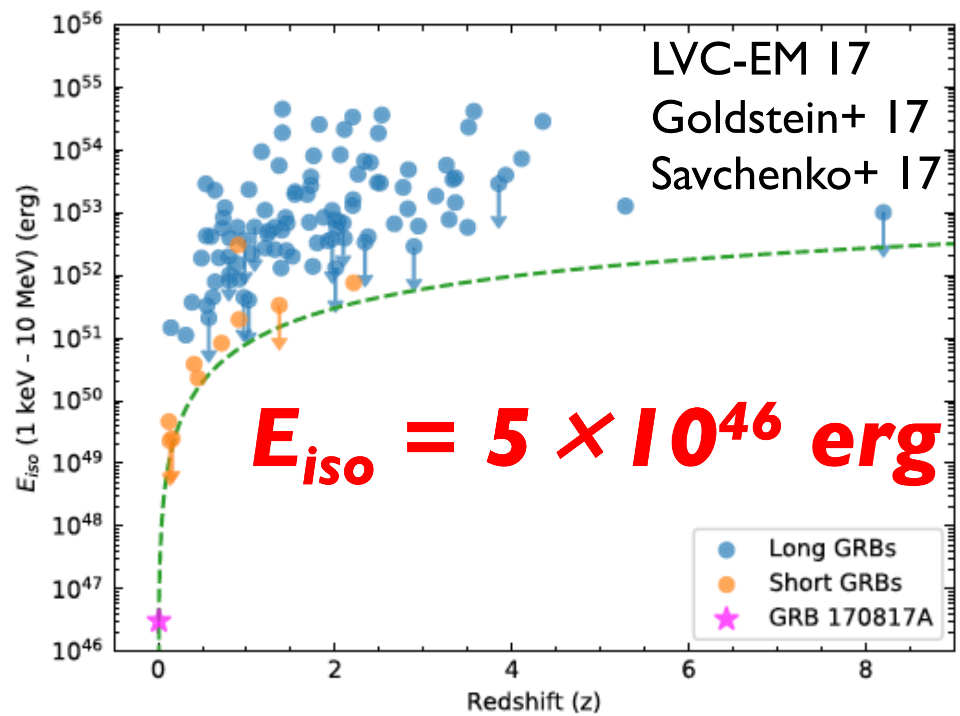


3 (of 12) GBM NaI detectors

T_0=1.74±0.05 sec (68%)

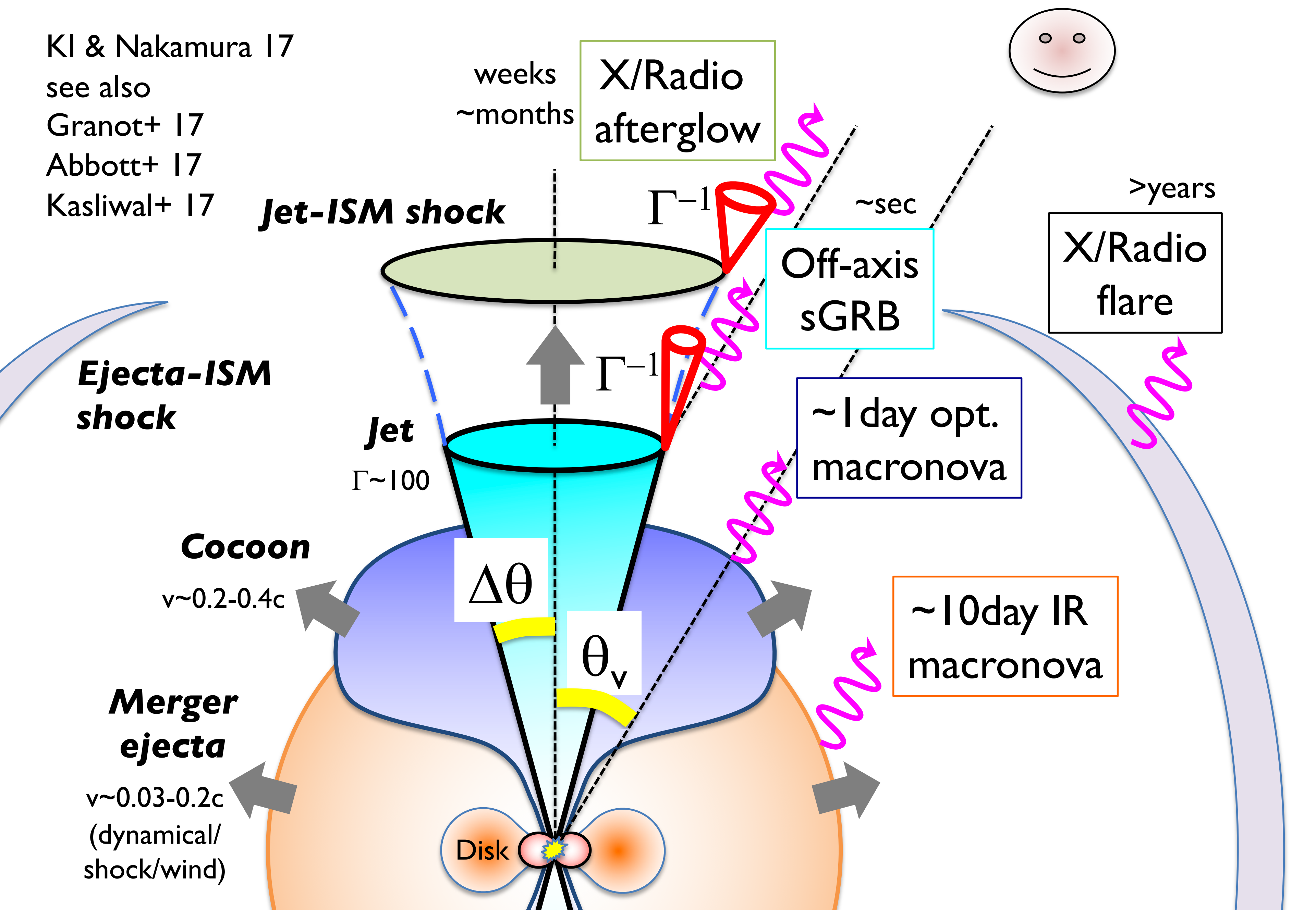
T_{90}=2.0±0.5 sec

But very weak

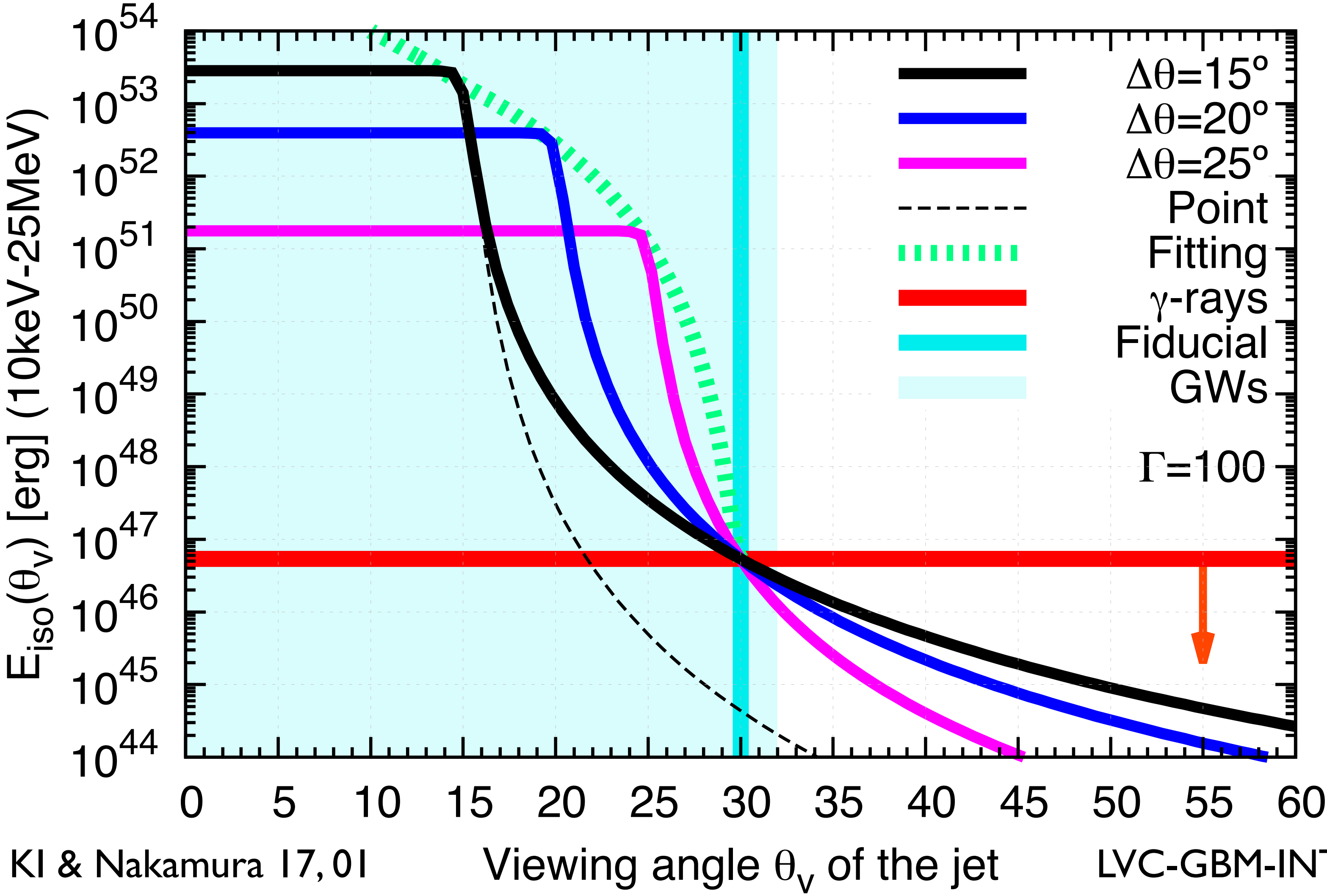


$E_{iso} = 5 \times 10^{46}$ erg

KI & Nakamura 17
see also
Granot+ 17
Abbott+ 17
Kasliwal+ 17



Off-Axis Jet



$\theta_v \sim \Delta\theta$

⇒ **Point approx. is bad**

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

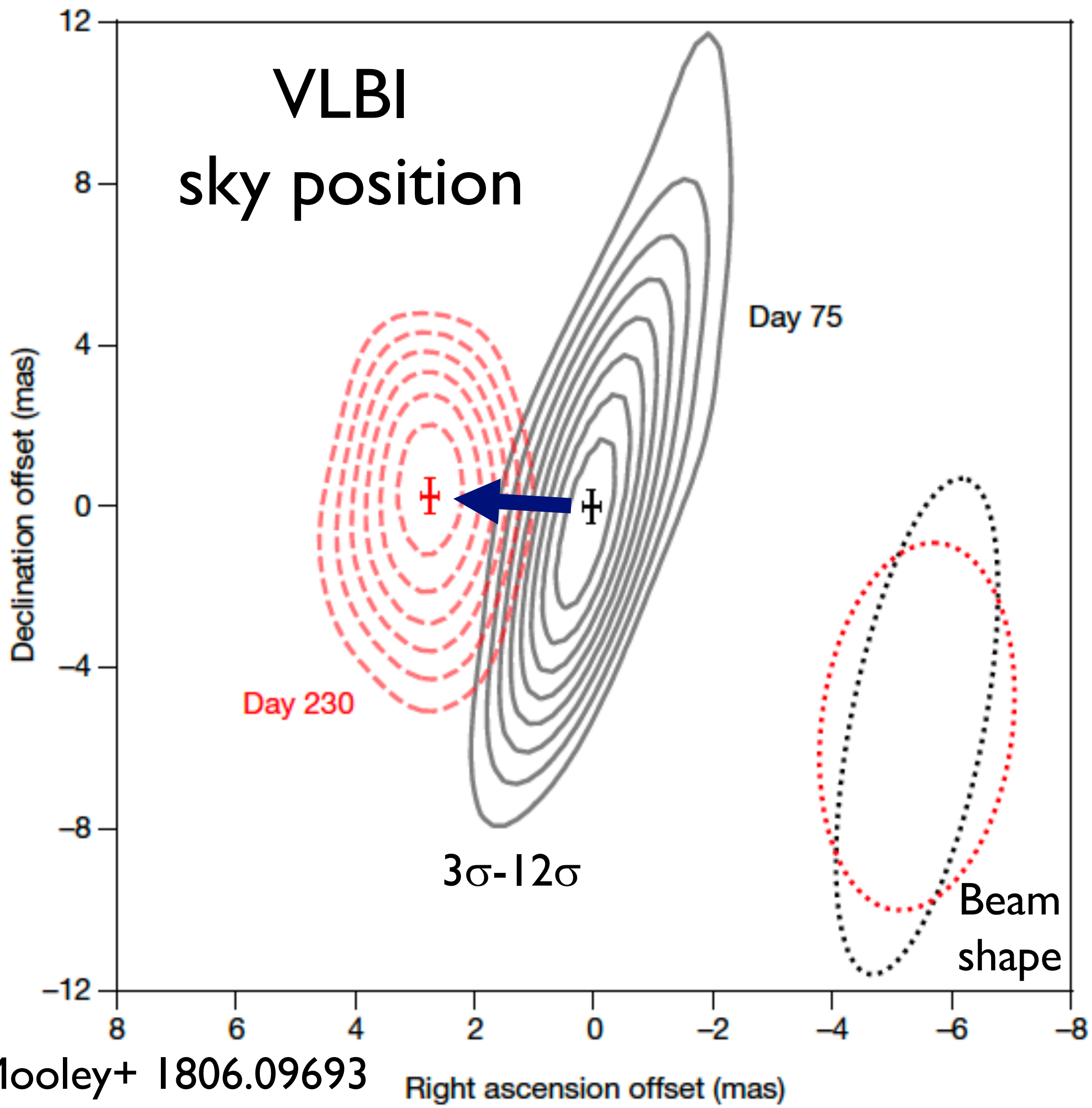
↓

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

KI & Nakamura 17, 01
Yamazaki, KI & Nakamura 02, 03, 04

LVC-GBM-INTEGRAL 17
Granot+ 17, Kasliwal+ 17

Superluminal Motion



Mooley+ 1806.09693

v_{app}~4.1 ±0.5 c!

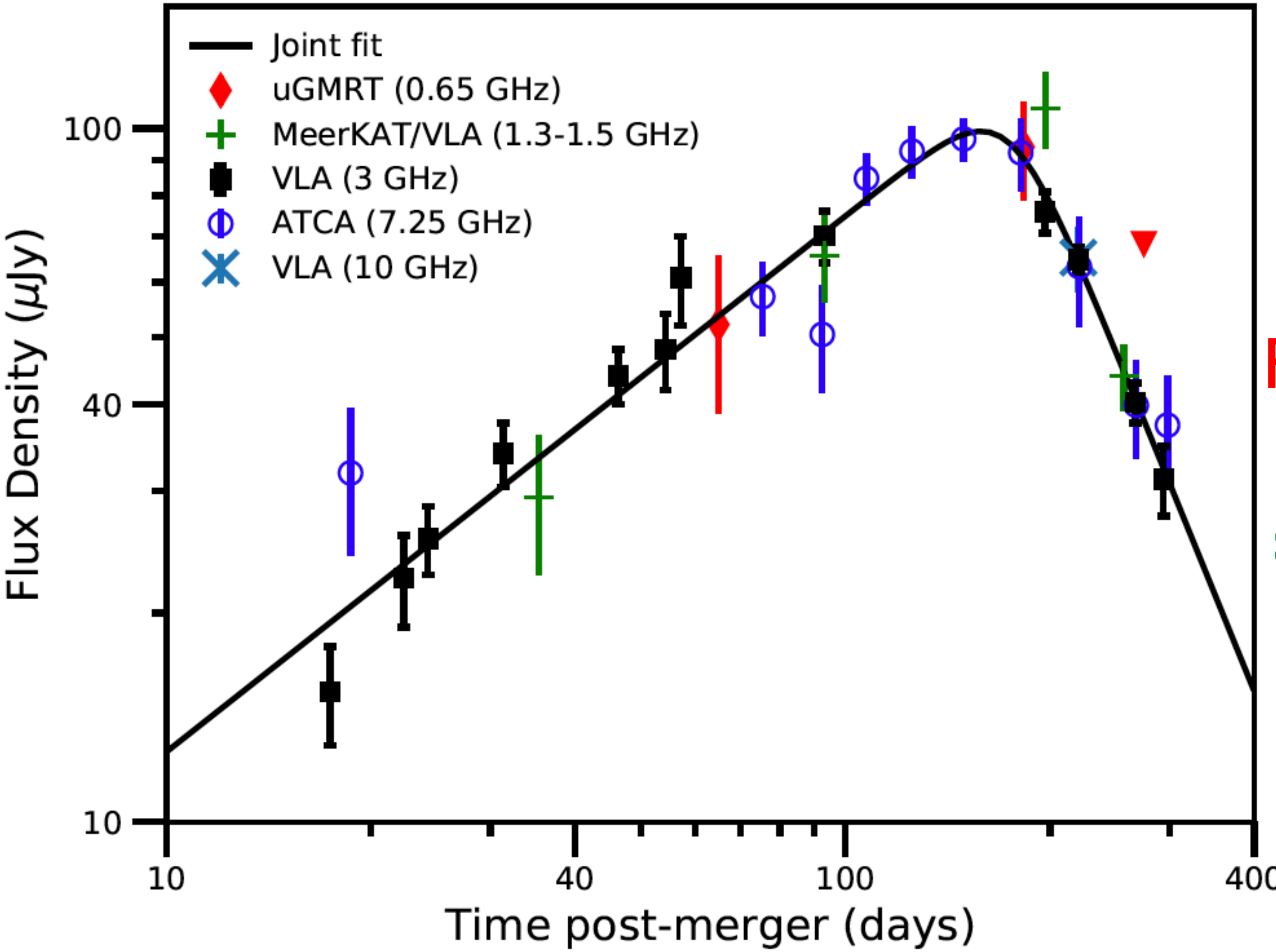
Unresolved

R<0.2pc(1mas),
<2pc(10mas)

Not consistent with a spherical source

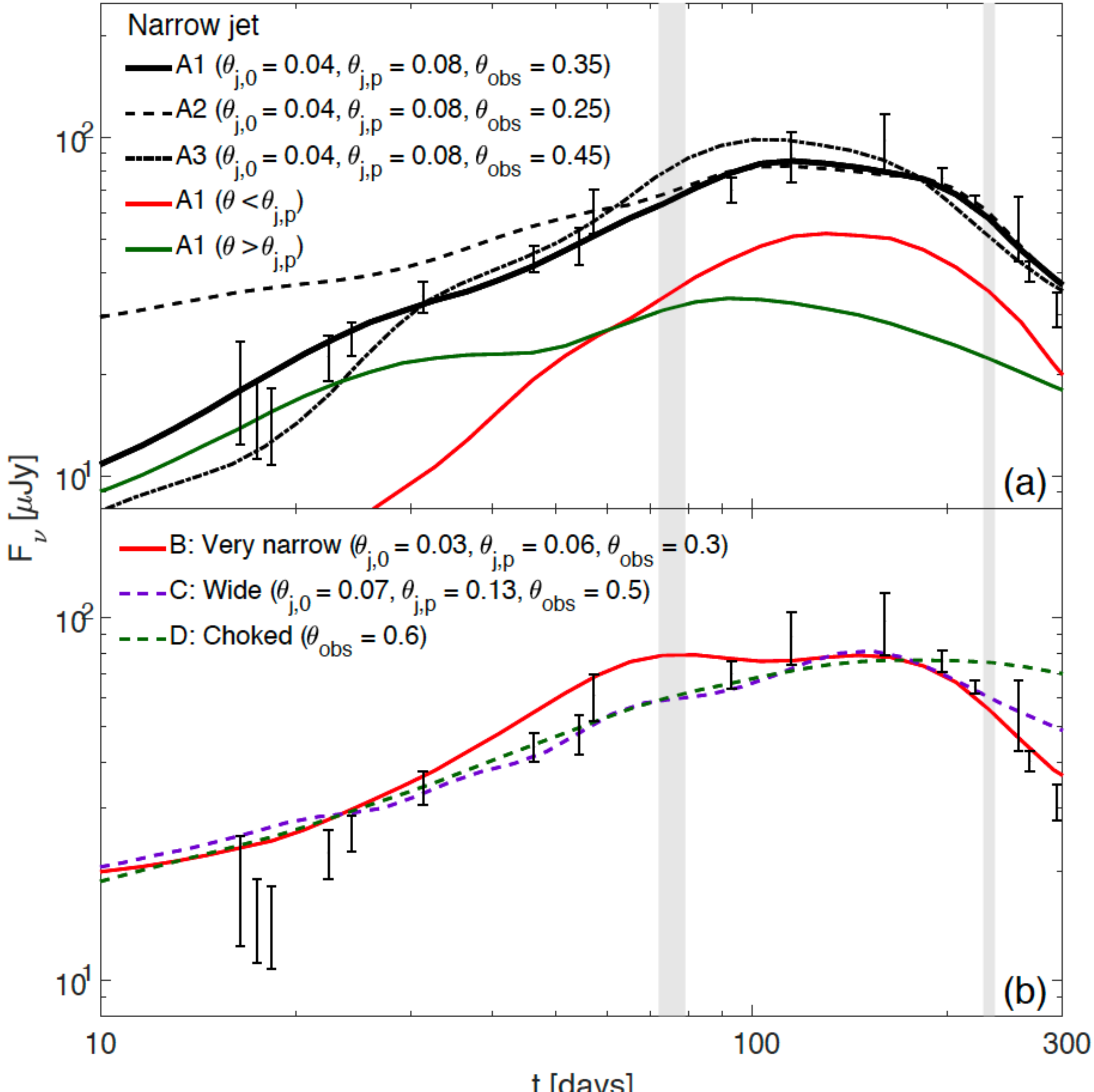
Γ~4 at t~t_{peak}

Turnovers in Afterglows



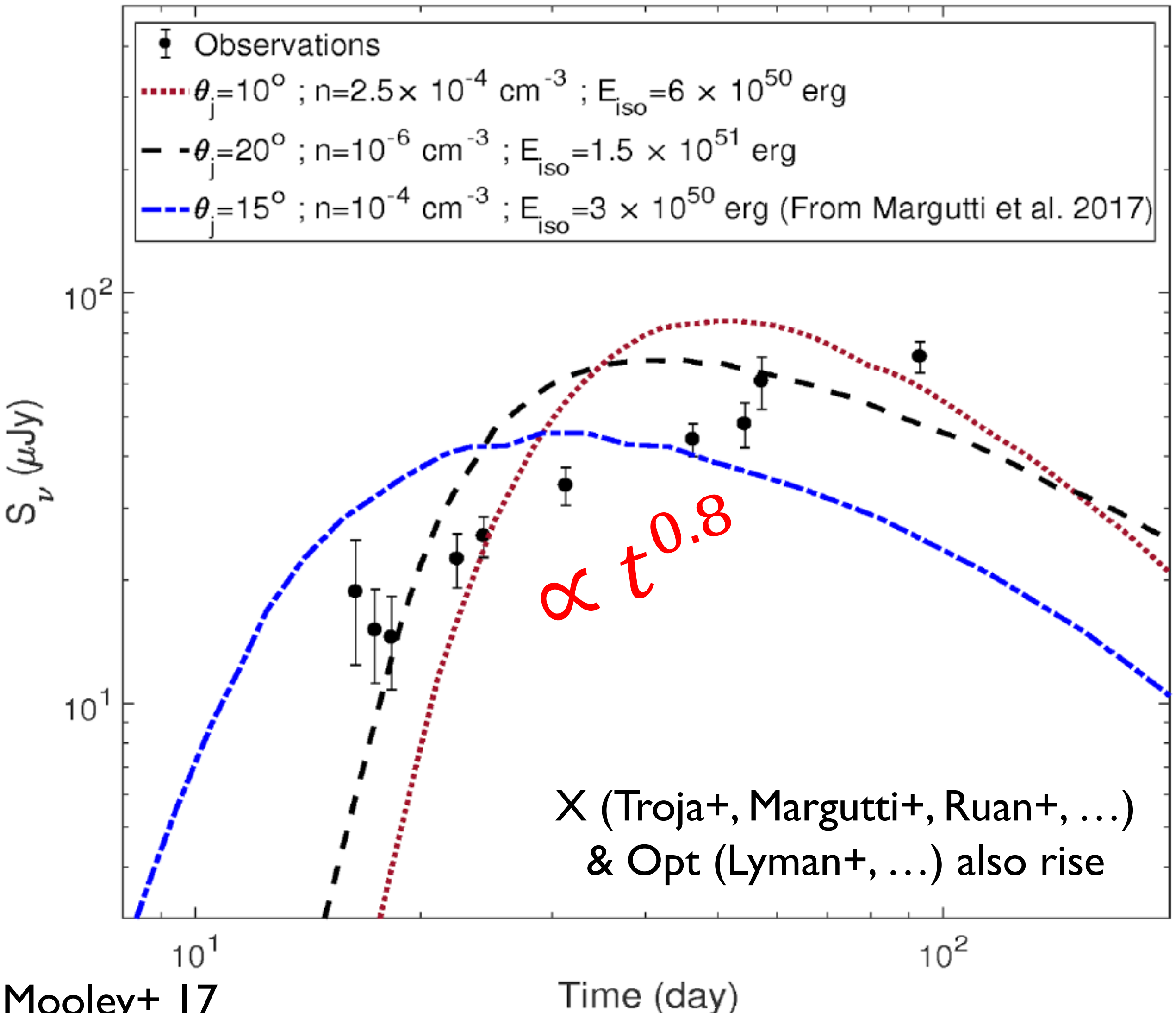
Afterglow theory predicts $F_\nu \sim t^{-p}\ \nu^{-(p-1)/2}$ for a jet as observed (p~2.2)

Mooely+ 18


Narrow jet
A1 (θj,0 = 0.04, θj,p = 0.08, θobs = 0.35)
A2 (θj,0 = 0.04, θj,p = 0.08, θobs = 0.25)
A3 (θj,0 = 0.04, θj,p = 0.08, θobs = 0.45)
A1 (θ < θj,p)
A1 (θ > θj,p)
(a)
B: Very narrow (θj,0 = 0.03, θj,p = 0.06, θobs = 0.3)
C: Wide (θj,0 = 0.07, θj,p = 0.13, θobs = 0.5)
D: Choked (θobs = 0.6)
(b)
Fν [μJy]
10^2
10^1
10
100
300
t [days]

Mooley+ 18

Slowly Rising Afterglow



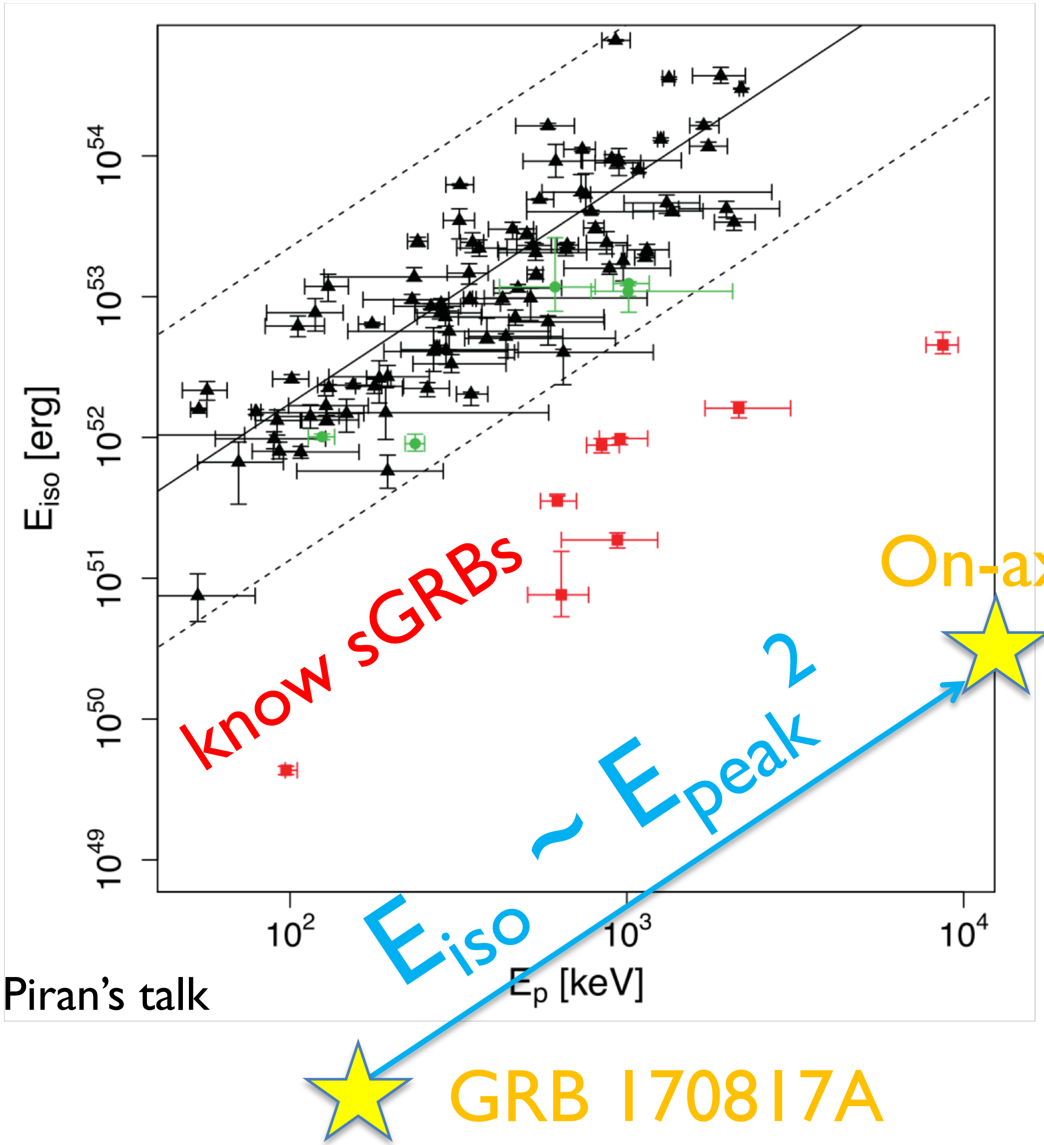
Mooley+ 17

Slowly rising up to ~150d

Inconsistent w/ top-hat jet

Energy injection polar or radial

E_{peak}-E_{iso} (Amati) Relation



Piran's talk

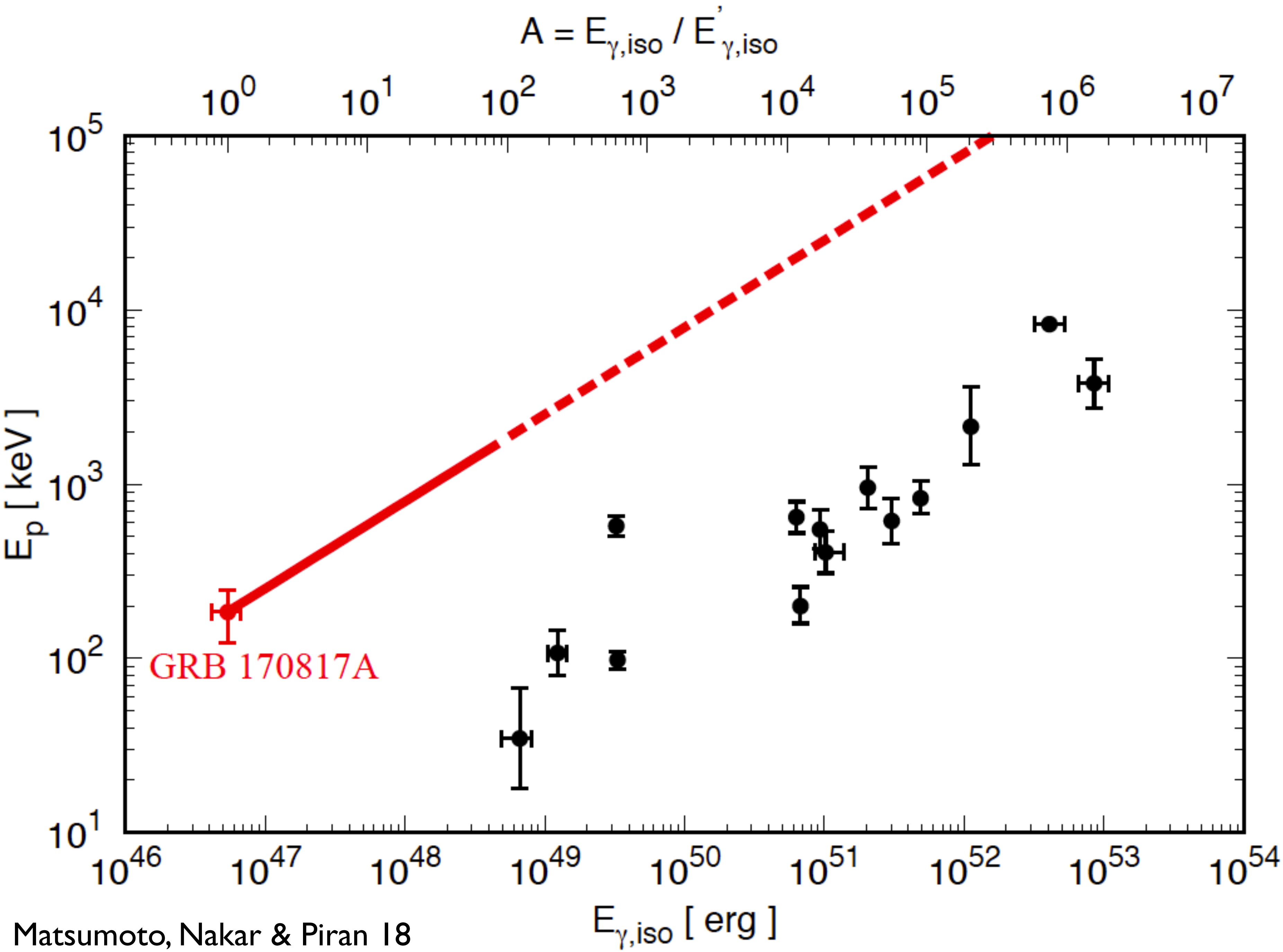
$E_{iso} \propto \theta_v^{-4}$, $E_{peak} \propto \theta_v^{-2}$
for $\theta_v \sim \Delta\theta$

Off-axis to on-axis

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

E_{peak}^{on}>10MeV?? inconsistent with the known GRBs

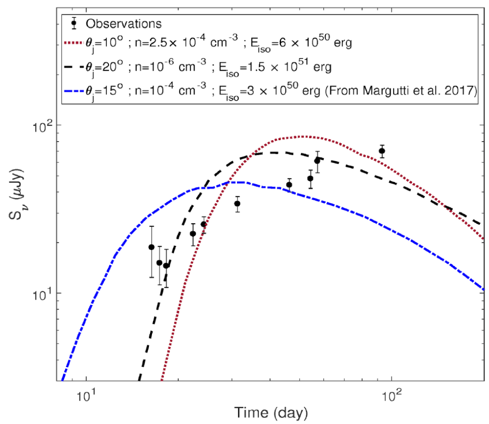
Tsutsui+ 13, Amati 02, Yonetoku+ 04



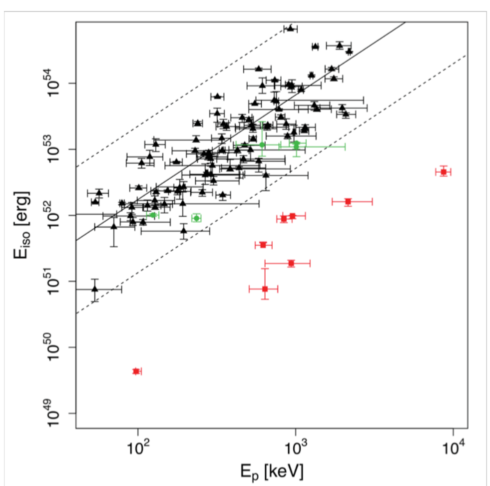
Matsumoto, Nakar & Piran 18

A Top-hat Jet is Imperfect

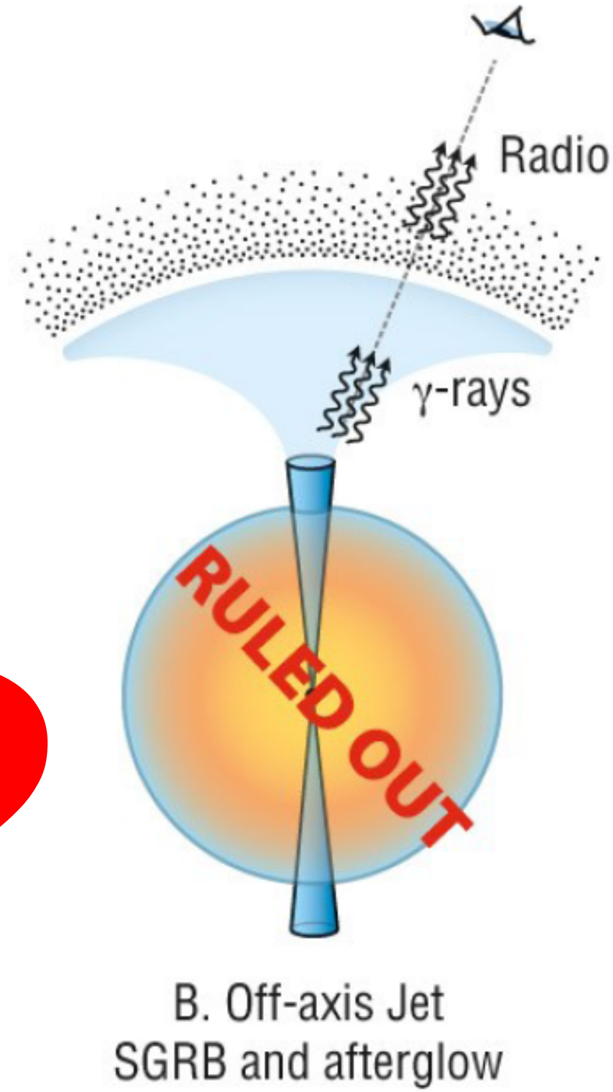
- ***Rising afterglow***



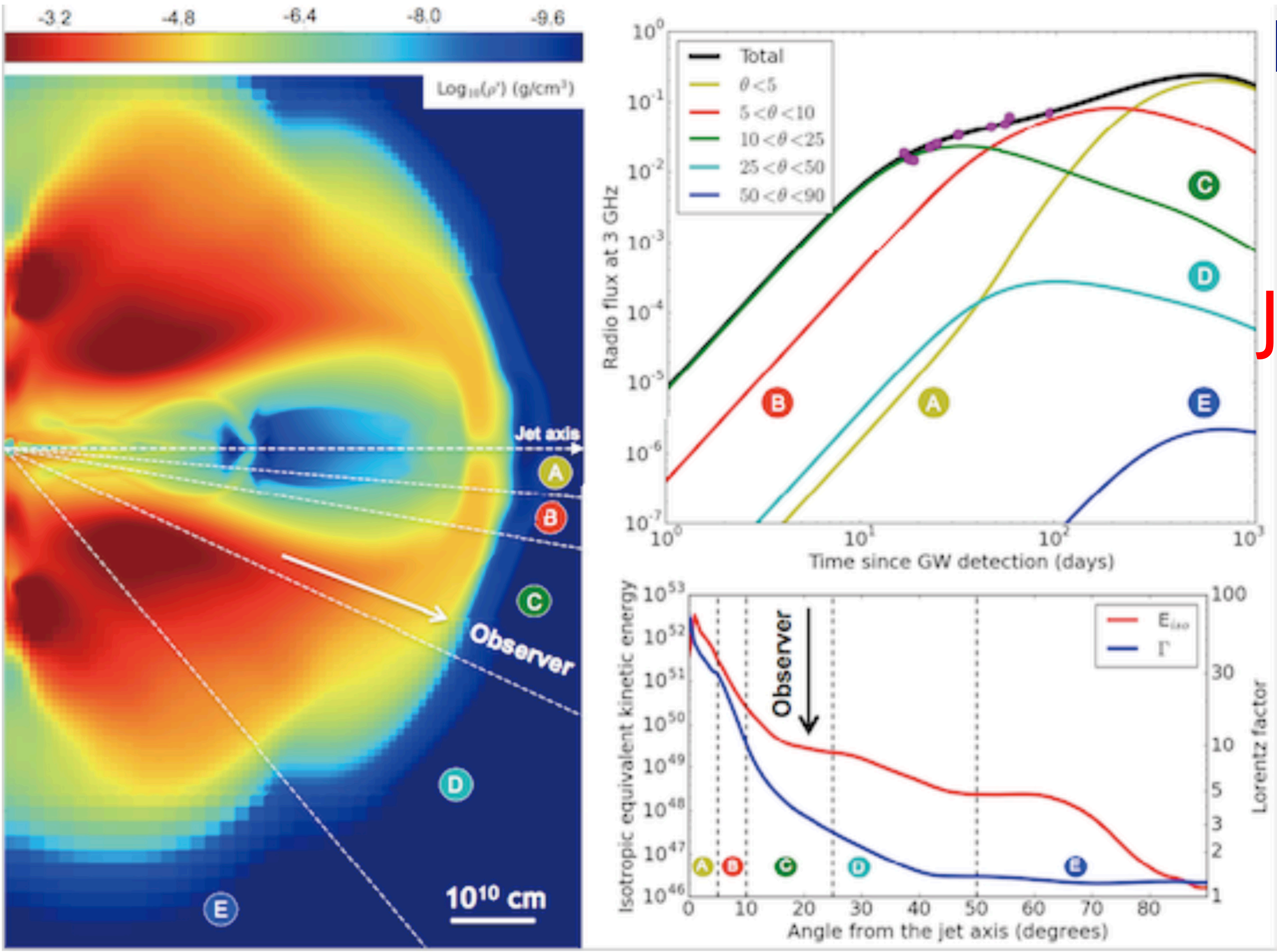
- ***E_{peak}***



?



Structured Jet



Polar energy injection

Jet + Coccon
Jet + ISM
Intrincially structured

Lazzati+ 17
Margutti+ 18
D'Avanzo+ 18
Lyman+ 18
Alexander+ 18
Xie+ 18, …

Structured Jet

Margutti+ 18
Lazzati+ 17
D'Avanzo+ 18
Lyman+ 18
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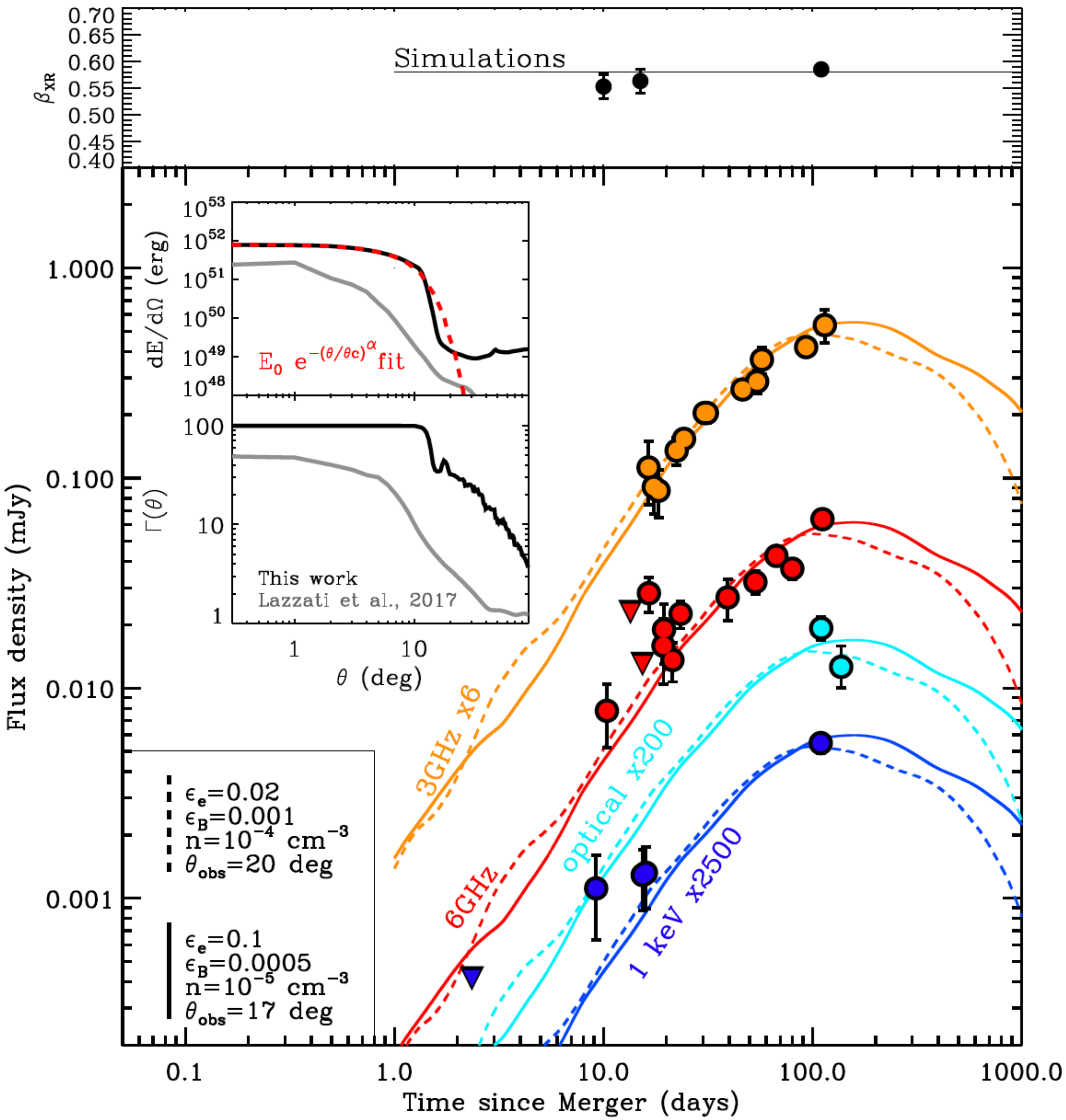
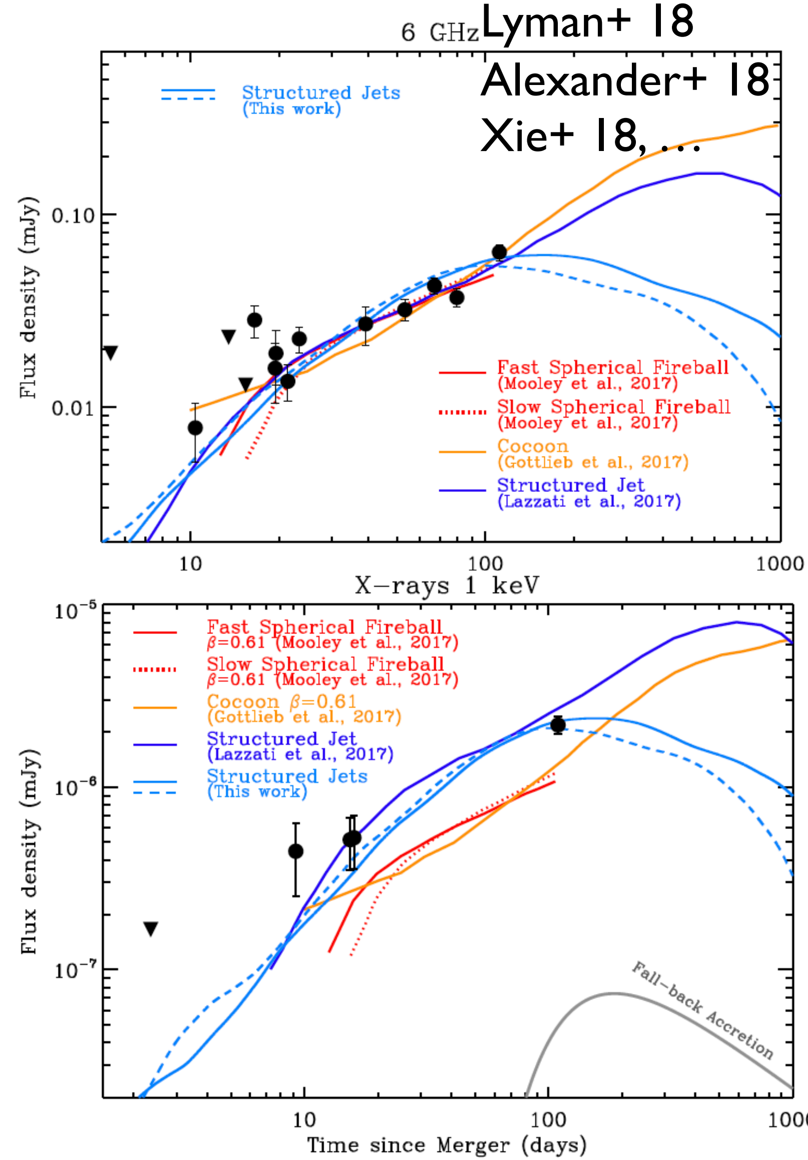
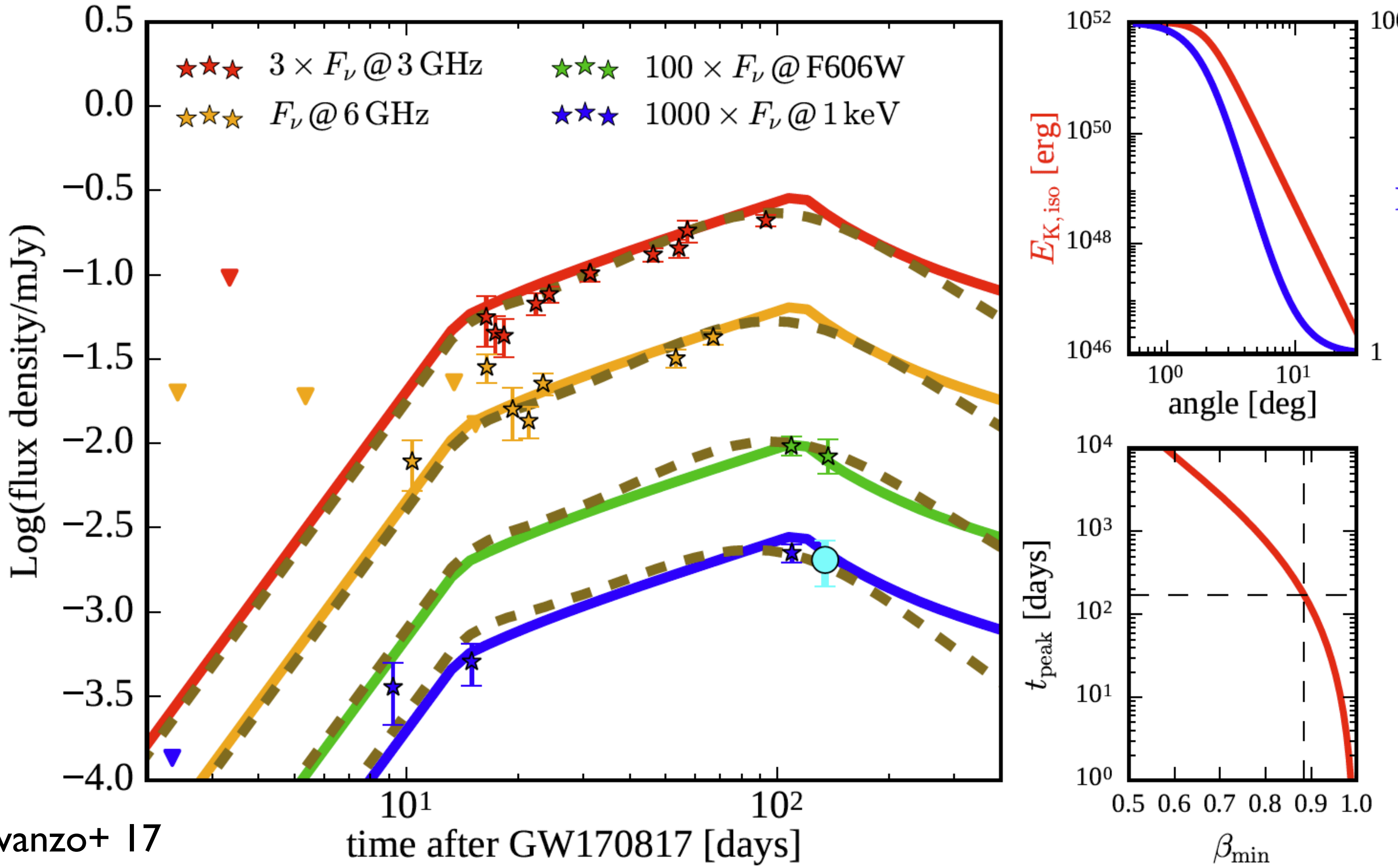




Power-Law Jet?

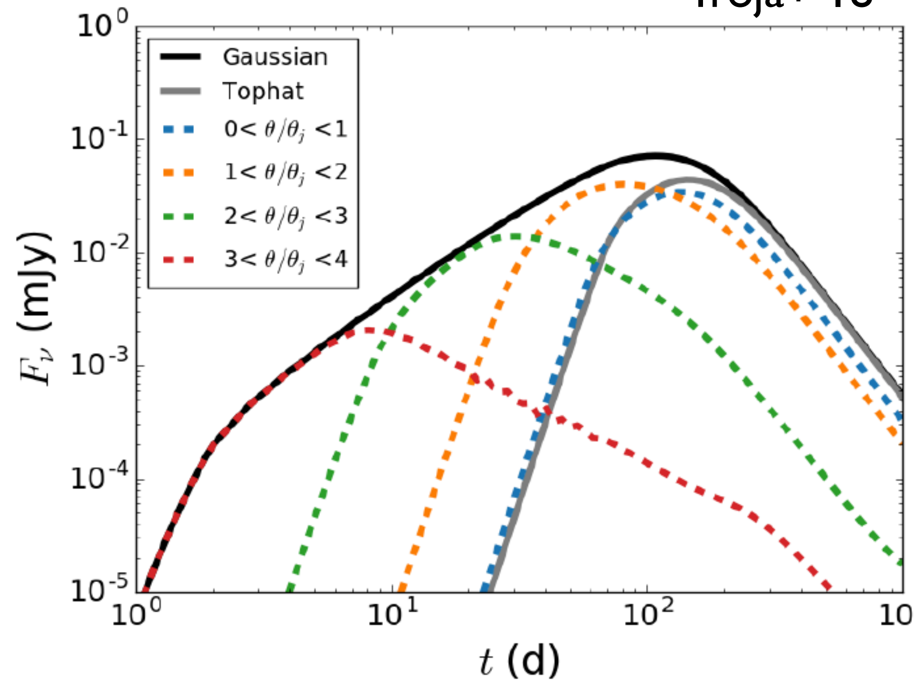
$F_\nu(t) \propto \nu^{0.6} t^{0.7}$ ⇨ e spectrum: $p \approx 2.2$



D'Avanzo+ 17

Gaussian Jet?

Troja+ 18



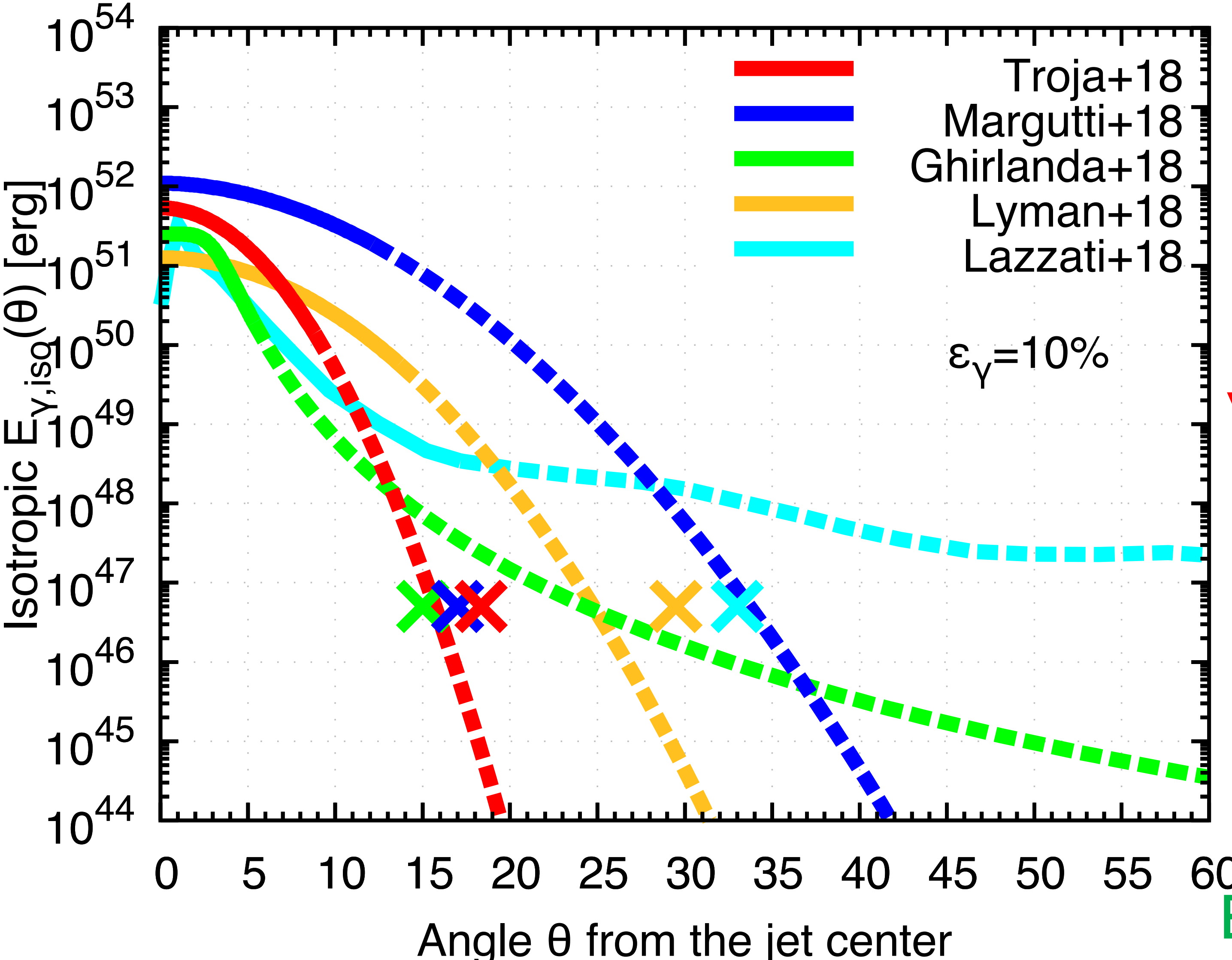
$$E(\theta) = E_0(-\theta^2/2\,\theta_c^2)$$

Table 2. Constraints on the Gaussian jet and Cocoon model param distribution with symmetric 68% uncertainties (ie. the 16% and 84% q

	Jet		Jet+GW+Planck			
Parameter	Med.	Best-fit	Med.	Best-fit		
θ_v	$0.51^{+0.20}_{-0.22}$	0.79	$0.32^{+0.13}_{-0.13}$	0.51		
$\log_{10} E_0$	$52.50^{+1.6}_{-0.79}$	54.39	$52.73^{+1.30}_{-0.75}$	56.93	$52.52^{+1.4}_{-0.71}$	56.93
θ_c	$0.091^{+0.037}_{-0.040}$	0.146	$0.057^{+0.025}_{-0.023}$	0.079	$0.076^{+0.026}_{-0.027}$	0.079
θ_w	$0.55^{+0.65}_{-0.22}$	0.63	$0.62^{+0.65}_{-0.37}$	0.44	$0.53^{+0.70}_{-0.24}$	0.44
$\log_{10} n_0$	$-3.1^{+1.0}_{-1.4}$	-3.8	$-3.8^{+1.0}_{-1.3}$	-6.4	$-3.24^{+0.91}_{-1.3}$	-6.4
p	$2.155^{+0.015}_{-0.014}$	2.159	$2.155^{+0.015}_{-0.014}$	2.170	$2.155^{+0.015}_{-0.014}$	2.170
$\log_{10} \epsilon_e$	$-1.22^{+0.45}_{-0.80}$	-0.73	$-1.51^{+0.53}_{-0.89}$	-1.37	$-1.31^{+0.46}_{-0.78}$	-1.37
$\log_{10} \epsilon_B$	$-3.38^{+0.81}_{-0.45}$	-3.50	$-3.20^{+0.92}_{-0.58}$	-1.27	$-3.33^{+0.82}_{-0.49}$	-1.27
$\log_{10} E_{tot}$	$50.26^{+1.7}_{-0.69}$	52.72	$50.16^{+1.1}_{-0.67}$	54.75	$50.19^{+1.41}_{-0.65}$	54.75

$\log_{10} u_{\rm min}$	$-2.2^{+1.9}_{-1.9}$	-2.9
$\log_{10} E_{\rm inj}$	$54.7^{+1.6}_{-2.7}$	52.4
k	$5.62^{+0.93}_{-1.1}$	5.3
$\log_{10} M_{\rm ej}$	$-7.6^{2.1}_{-1.7}$	-9.5
$\log_{10} n_0$	$-5.2^{+2.2}_{-2.0}$	-6.5
p	$2.156^{+0.014}_{-0.014}$	2.157
$\log_{10} \epsilon_e$	$-1.33^{+0.93}_{-1.3}$	-0.36
$\log_{10} \epsilon_B$	$-2.5^{+1.5}_{-1.1}$	-0.4
$\log_{10} E^*_{tot}$	$52.84^{+0.97}_{-1.3}$	51.00

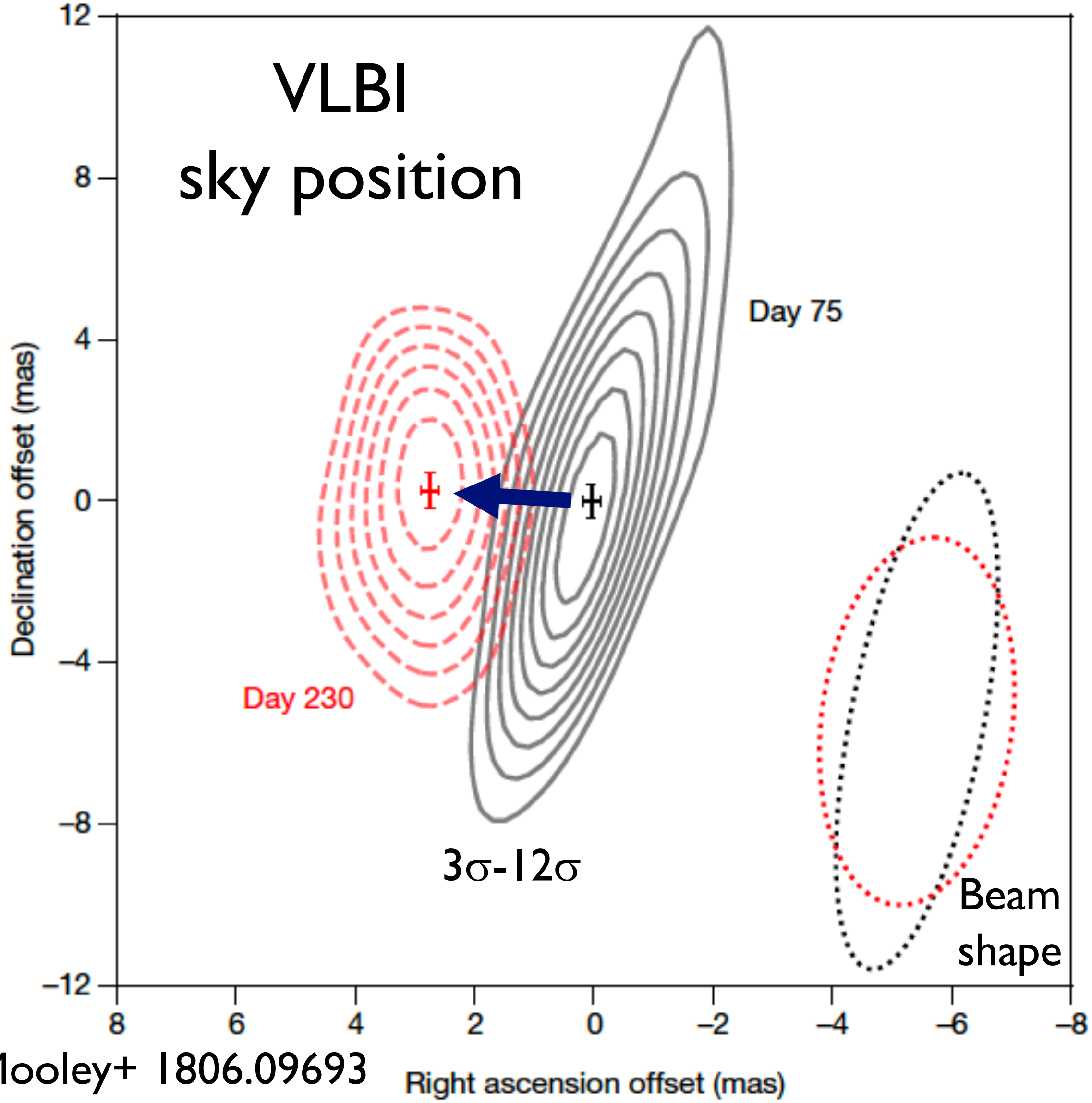
Afterglow vs. Prompt



Some AG models are not consistent with prompt

Typically, radiative efficiency ε_γ~10-50% & $E_{GRB} \propto E_{afterglow}$

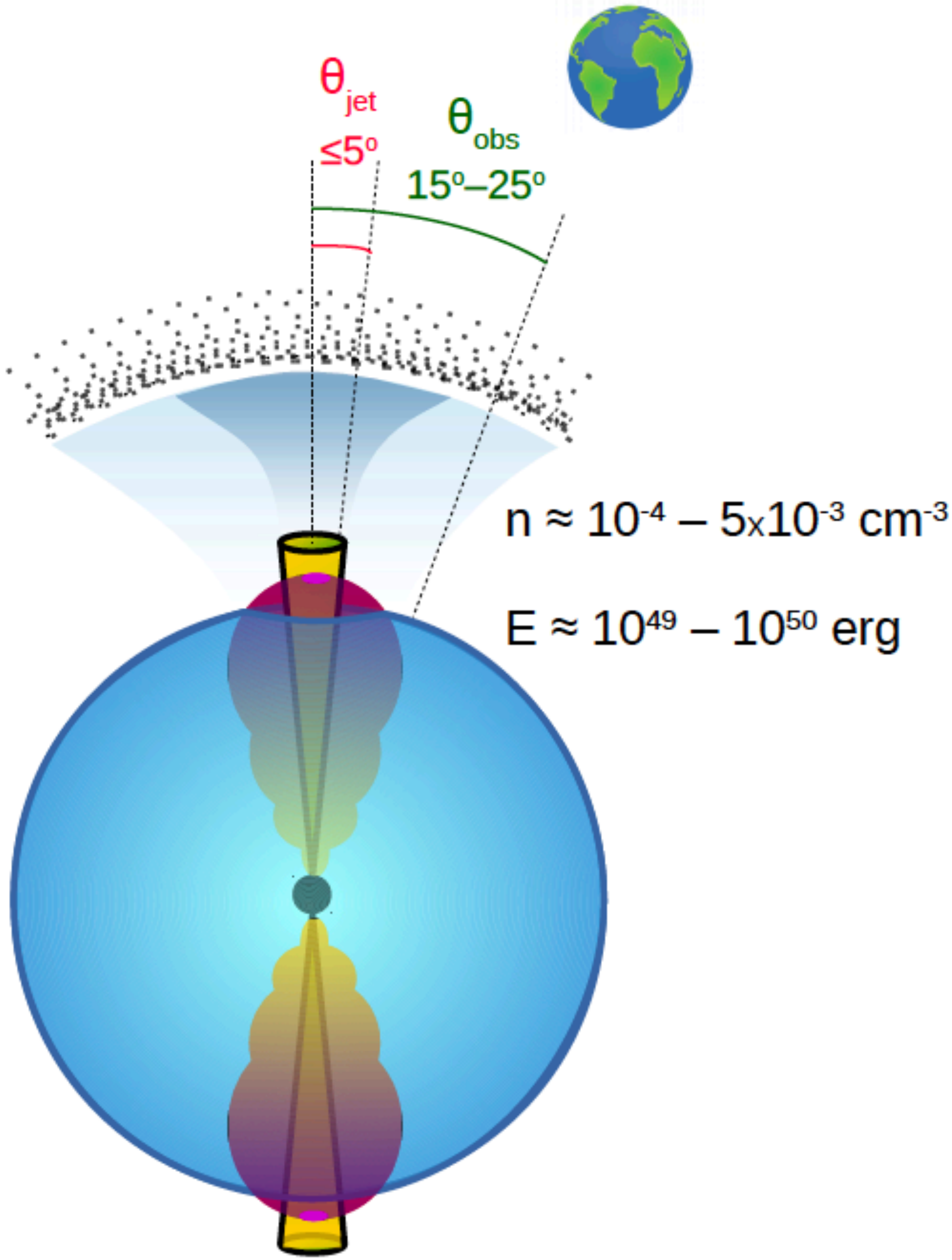
VLBI → Viewing Angle



Mooley+ 1806.09693

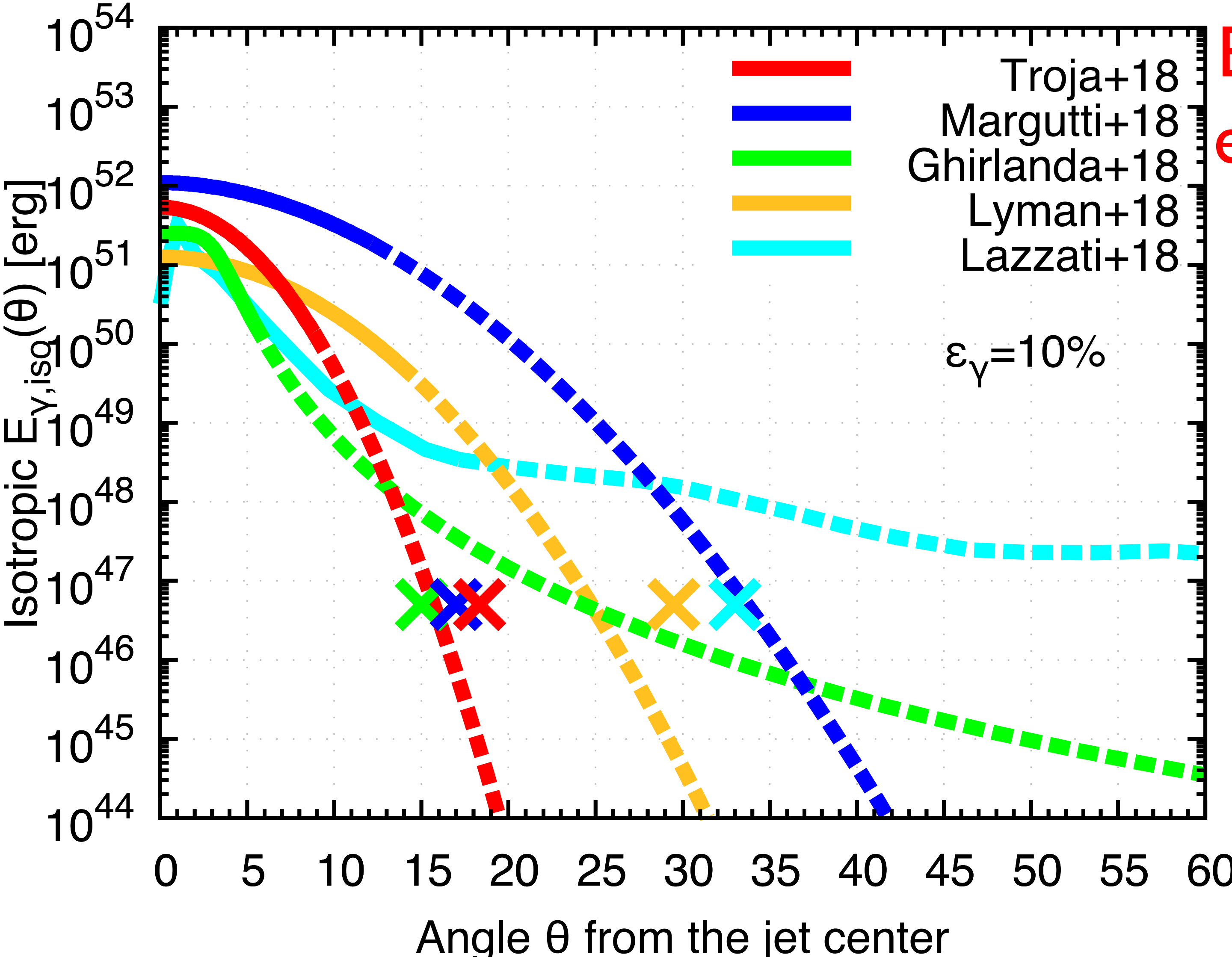
v_{app}~4.1 ±0.5 c at t~t_{peak}

θ_v~c/v_{app} ~0.25 ~15-25°



Mooley+ 18

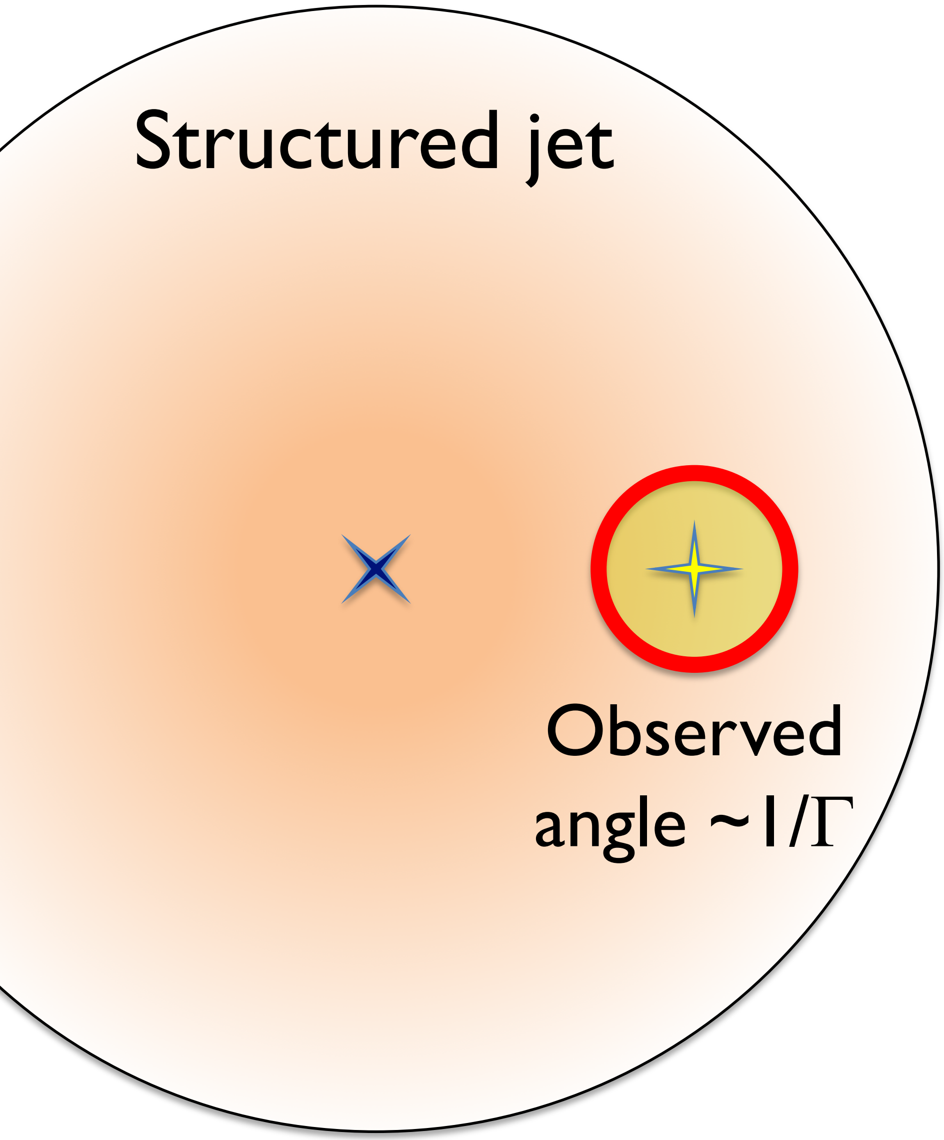
Afterglow vs. Prompt



But generally exponentially decreasing profile is necessary

1. Radiative efficiency is very low
2. Structure is wrong

Reconstruction Concept



Synchrotron shock model

Loretnz factor $\Gamma(t)$

$$\Gamma(t) \approx 4 \left(\frac{F_\nu}{20\mu\mathrm{Jy}}\right)^{\frac{1}{6+2p}} \left(\frac{\nu_{\rm obs}}{3\,\mathrm{GHz}}\right)^{\frac{p-1}{12+4p}} \left(\frac{t}{10\,\mathrm{d}}\right)^{-\frac{3}{6+2p}}$$

$$\times \epsilon_{e,-1}^{-\frac{p-1}{6+2p}} \epsilon_{B,-2}^{-\frac{p+1}{24+8p}} \left(\frac{n}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-\frac{p+5}{24+8p}} \left(\frac{d}{40\,\mathrm{Mpc}}\right)^{\frac{1}{3+p}}$$

Total energy $E_{obs}(t)$

$$E_{\rm obs}(t) \approx 2\times 10^{47}\,\mathrm{erg} \left(\frac{F_\nu}{20\mu\mathrm{Jy}}\right)^{\frac{3}{3+p}} \left(\frac{\nu_{\rm obs}}{3\,\mathrm{GHz}}\right)^{\frac{3(p-1)}{2(3+p)}} \left(\frac{t}{10\,\mathrm{d}}\right)^{\frac{3p}{3+p}}$$

$$\times \epsilon_{e,-1}^{-\frac{3(p-1)}{3+p}} \epsilon_{B,-2}^{-\frac{3(p+1)}{4(3+p)}} \left(\frac{n}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-\frac{3-p}{4(3+p)}} \left(\frac{d}{40\,\mathrm{Mpc}}\right)^{\frac{6}{3+p}}$$

Nakar & Piran 18

Unknown: n, ε_B (, ε_e~0.1)

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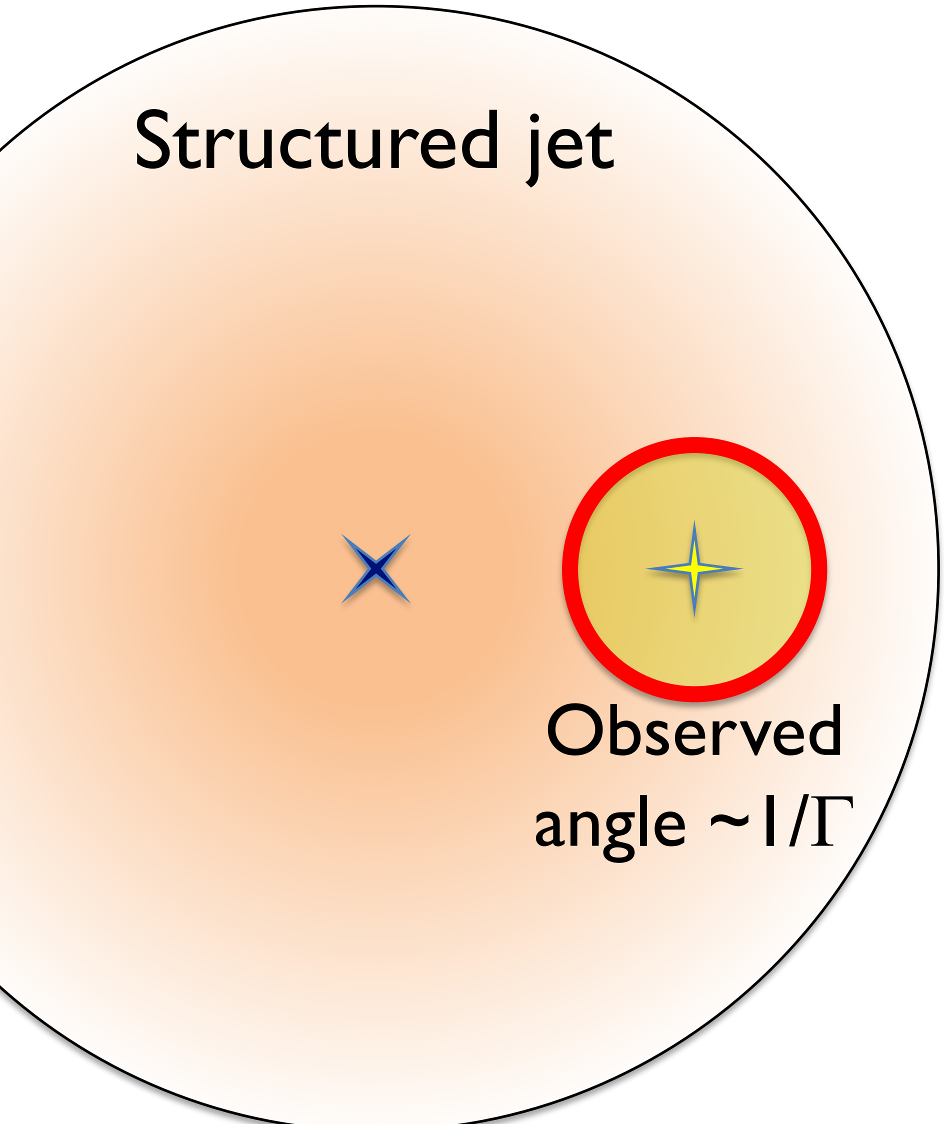

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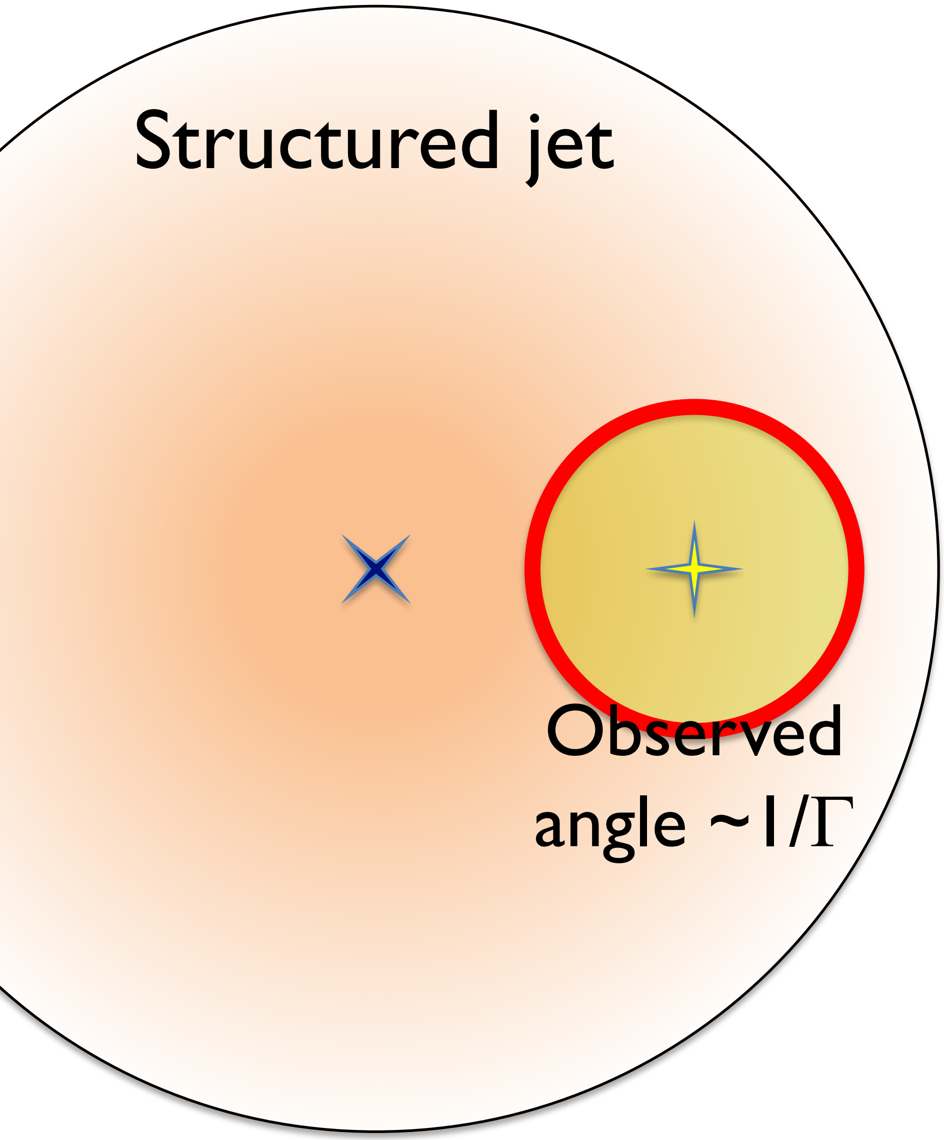

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Nakar & Piran 18

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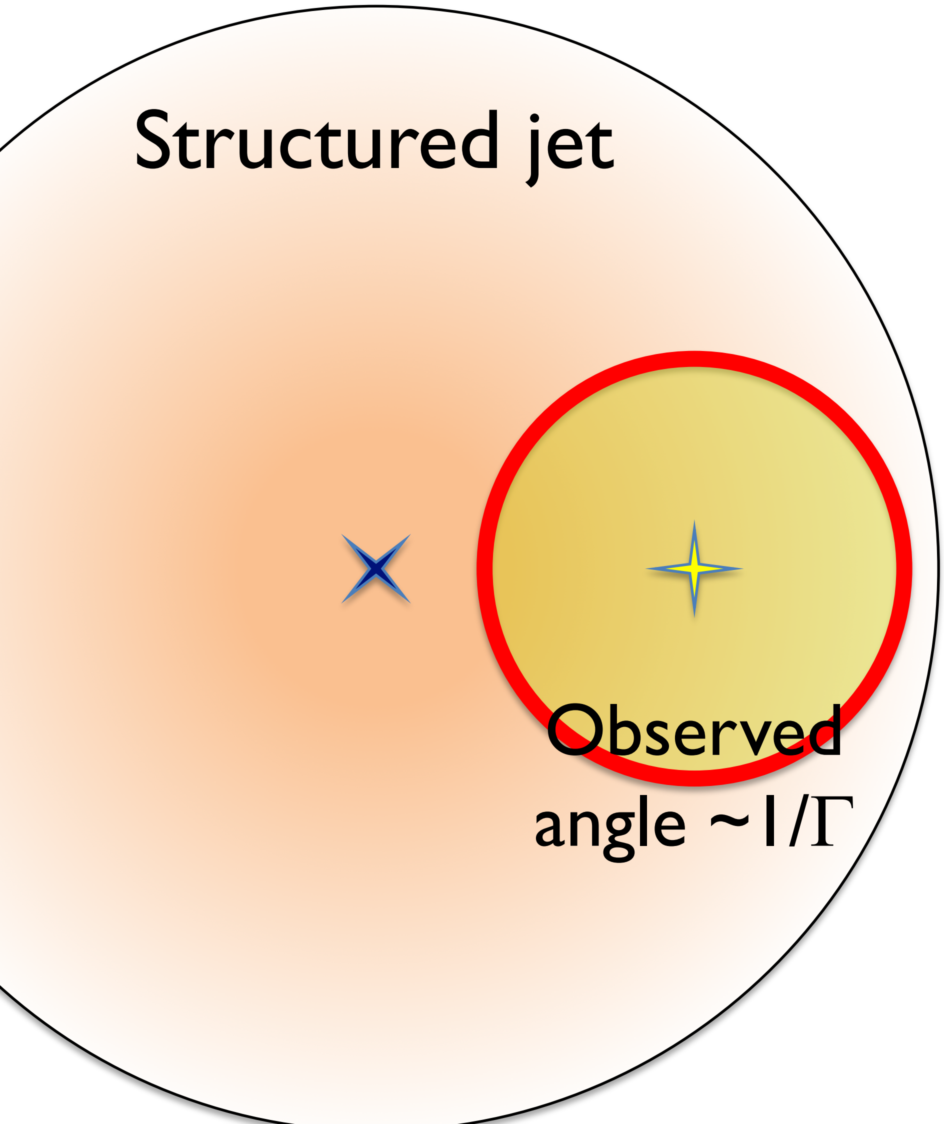

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Nakar & Piran 18

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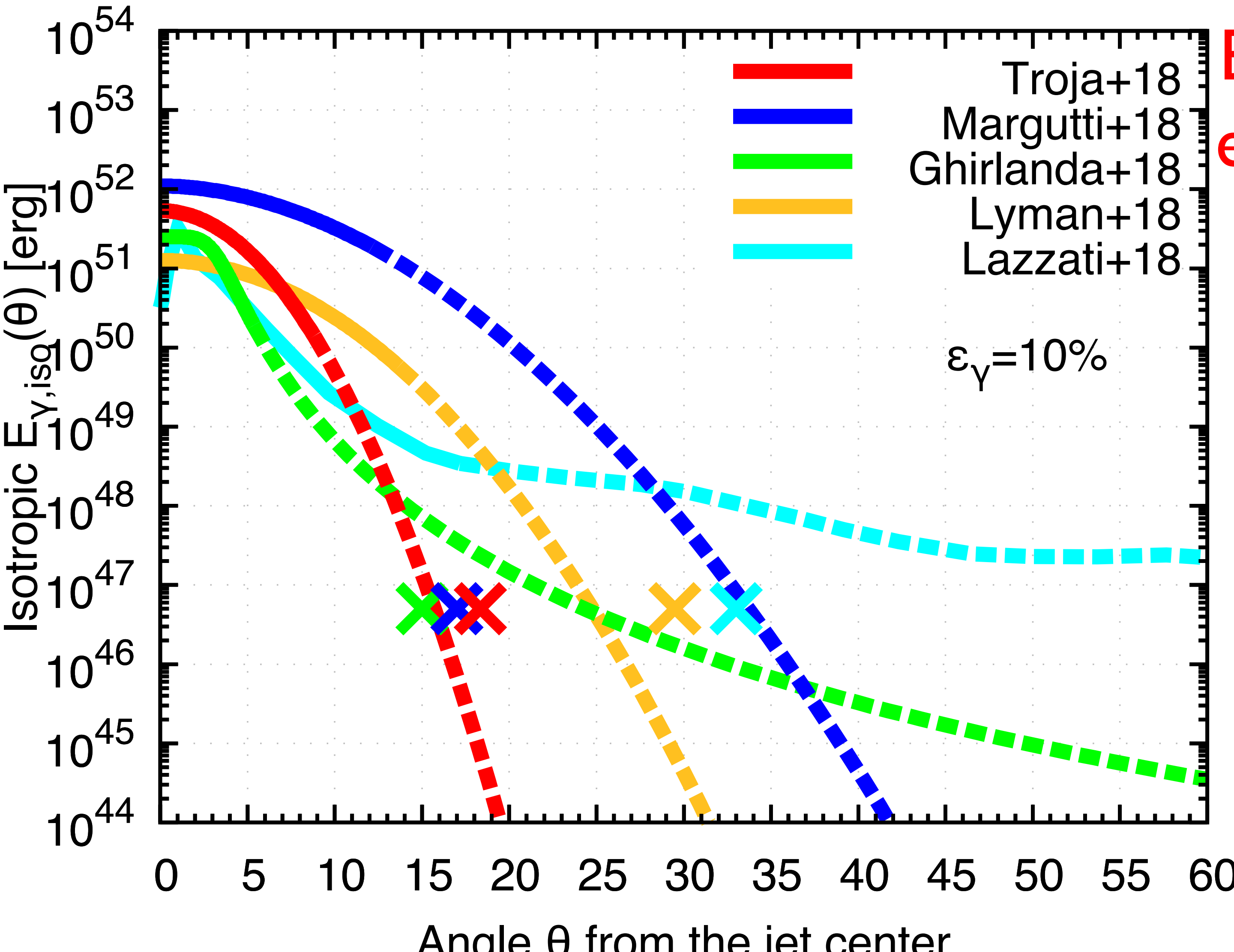
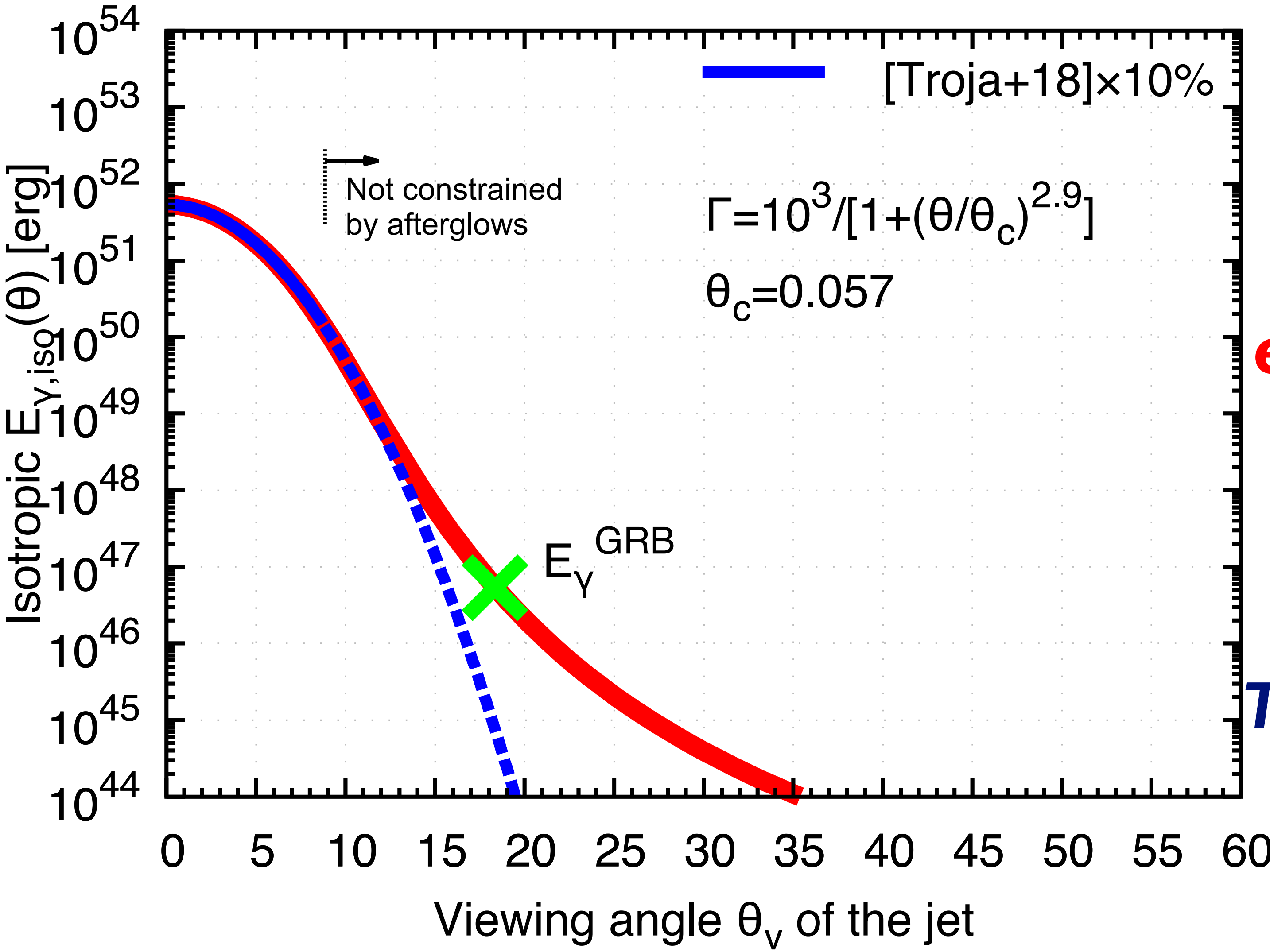
Afterglow vs. Prompt



But generally exponentially decreasing profile is necessary

1. Radiative efficiency is very low
2. Structure is wrong

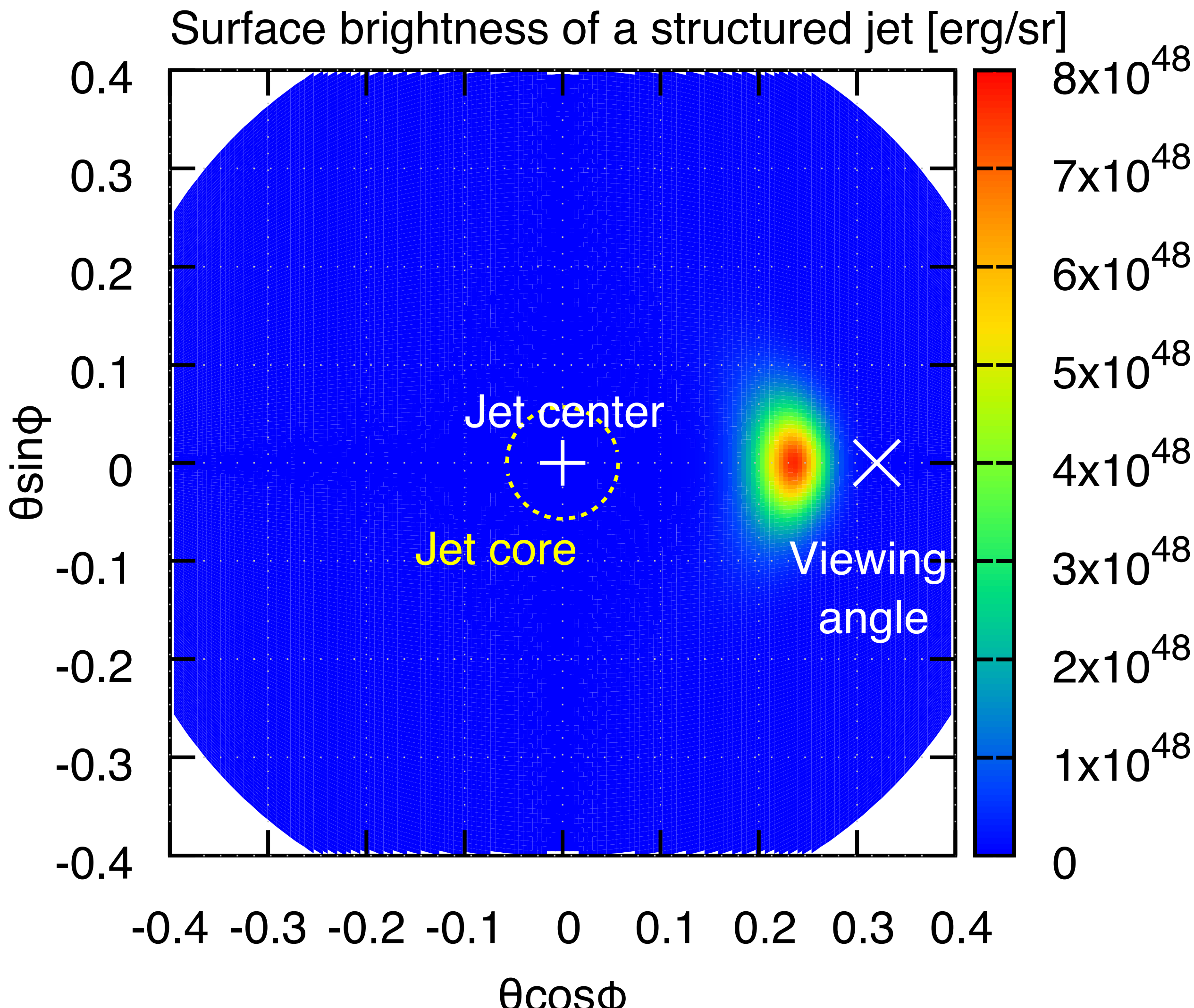
Off-Axis Emission



Quasi-Gaussian emission is always exceeded by off-axis emission

The jet profile, not jet core, is essential

Surface Brightness

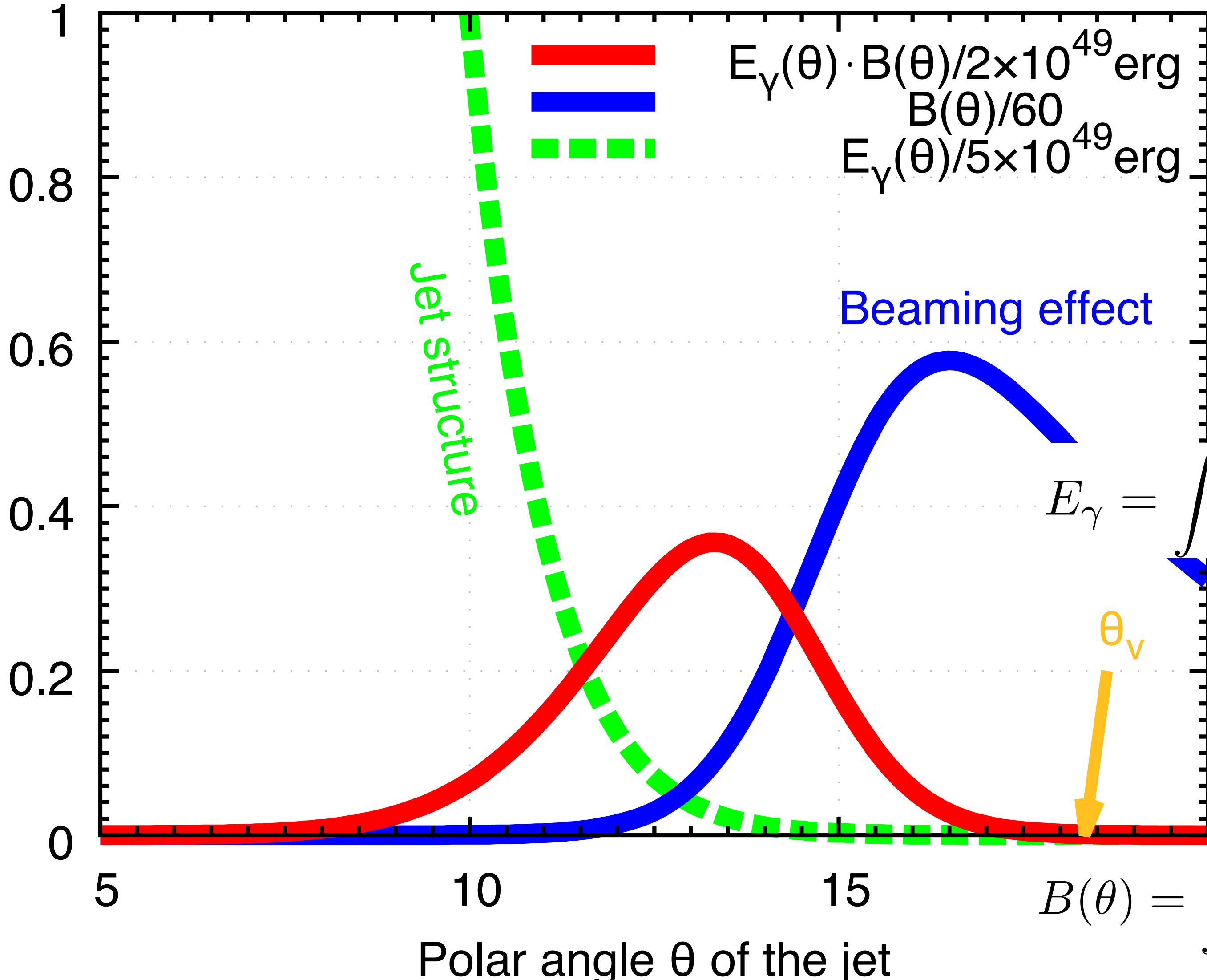


$$E_{\gamma,\mathrm{iso}} = \int \frac{d\Omega}{4\pi} \frac{E_\gamma(\theta)}{\Gamma^4 (1-\beta\cos\theta_\Delta)^3}$$

$$\cos\theta_\Delta = \sin\theta\cos\phi\sin\theta_v + \cos\theta\cos\theta_v$$

Most emission comes from the jet edge outside the core & not on-axis

Jet Structure + Beaming



Decaying E + Rising beaming

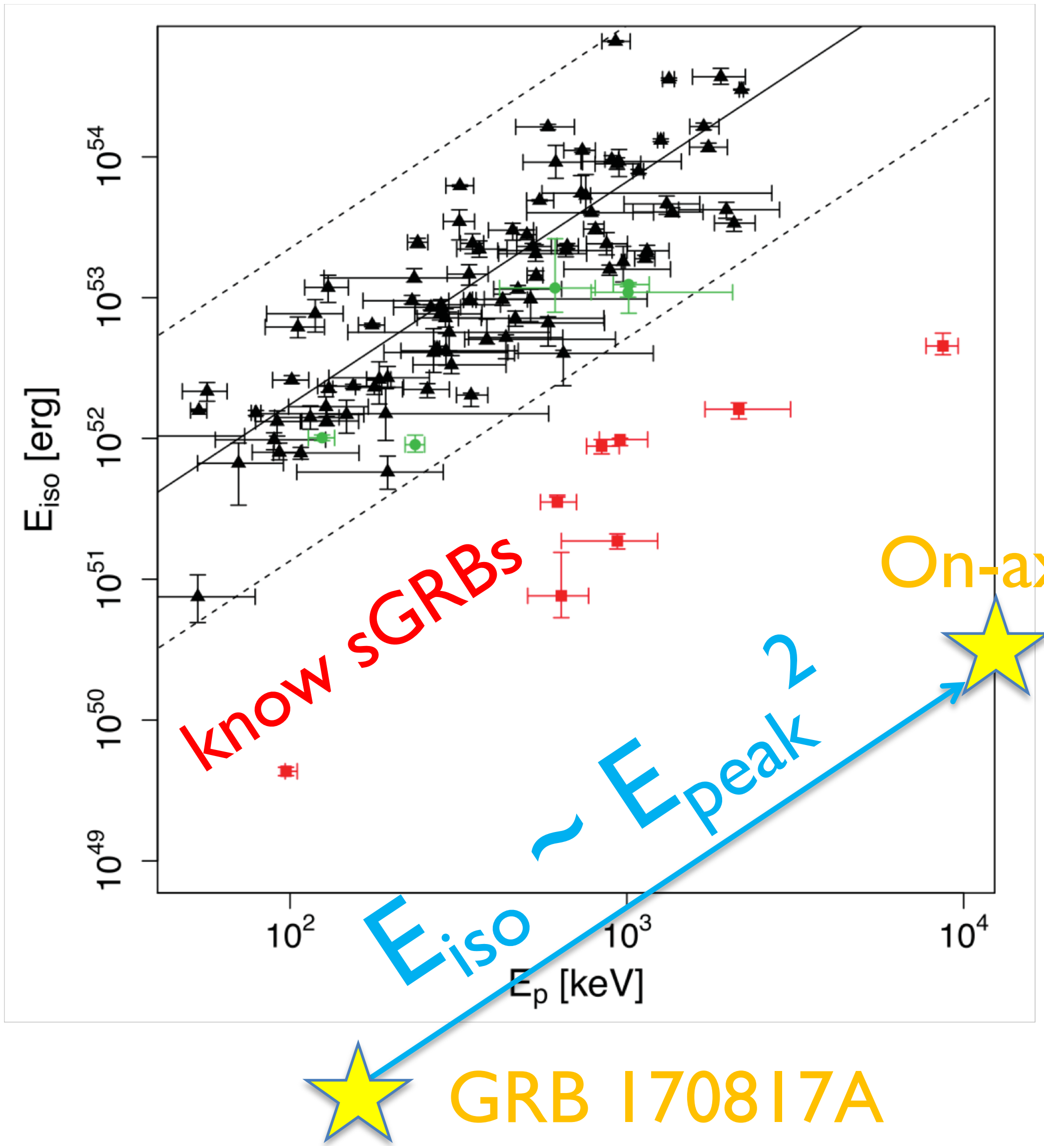
= Peak in the jet edge

$$E_\gamma = \int \frac{d(\cos\theta)}{2} \epsilon_\gamma E(\theta) \cdot B(\theta)$$

Jet Structure   Beam-ing

$$B(\theta) = \int \frac{d\phi}{2\pi} \frac{1}{\Gamma^4 (1-\beta\cos\theta_\Delta)^3}$$

E_{peak}-E_{iso} (Amati) Relation



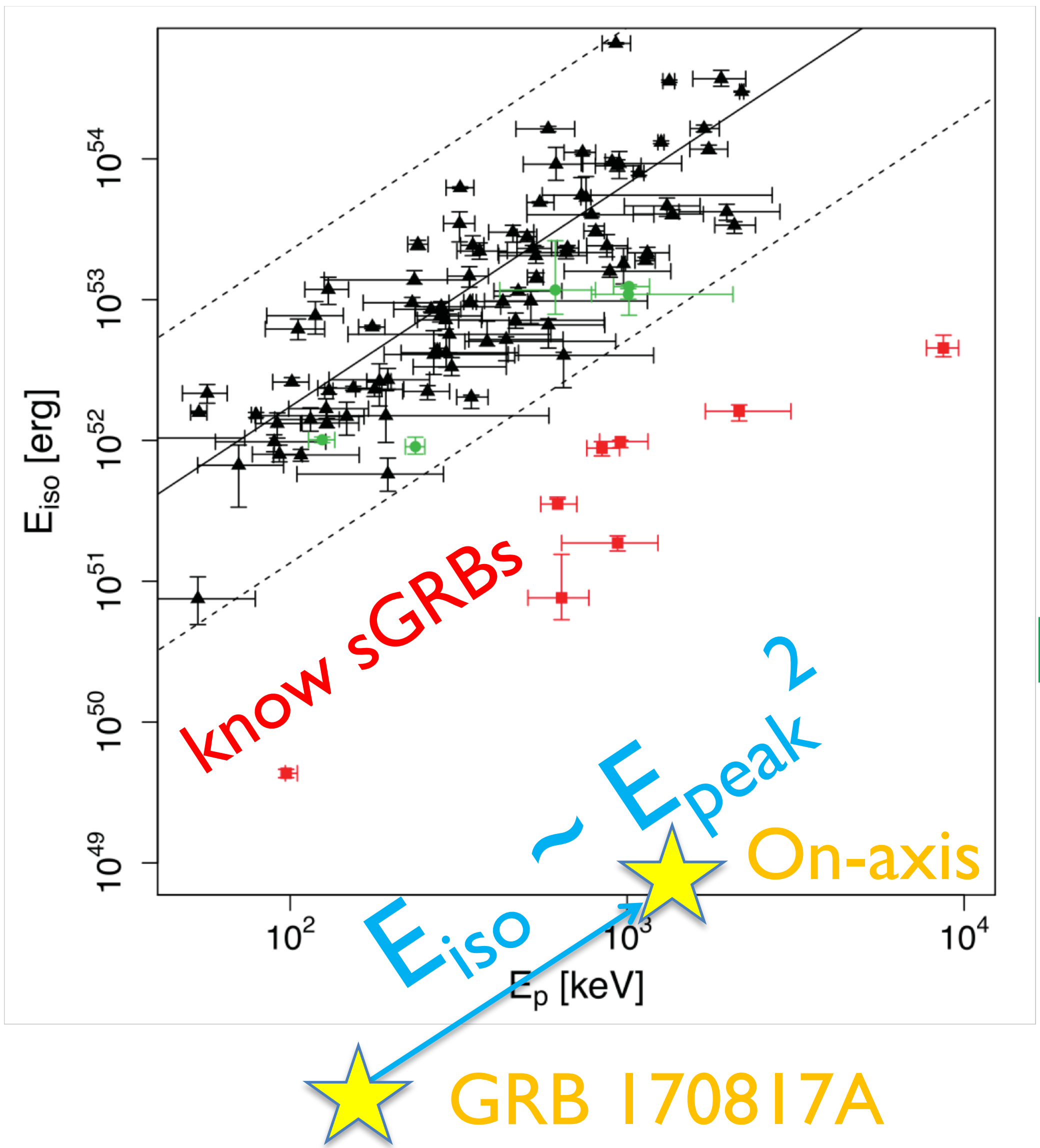
$E_{iso} \propto \theta_v^{-4}$, $E_{peak} \propto \theta_v^{-2}$
for $\theta_v \sim \Delta\theta$

Off-axis to on-axis
$E_{iso} \sim E_{peak}^{2}$

$E_{peak}^{on} > 10$ MeV?? inconsistent with the known GRBs

Tsutsui+ 13, Amati 02, Yonetoku+ 04

E_{peak}-E_{iso} (Amati) Relation



Small $\Gamma \Rightarrow$ Mild E_p

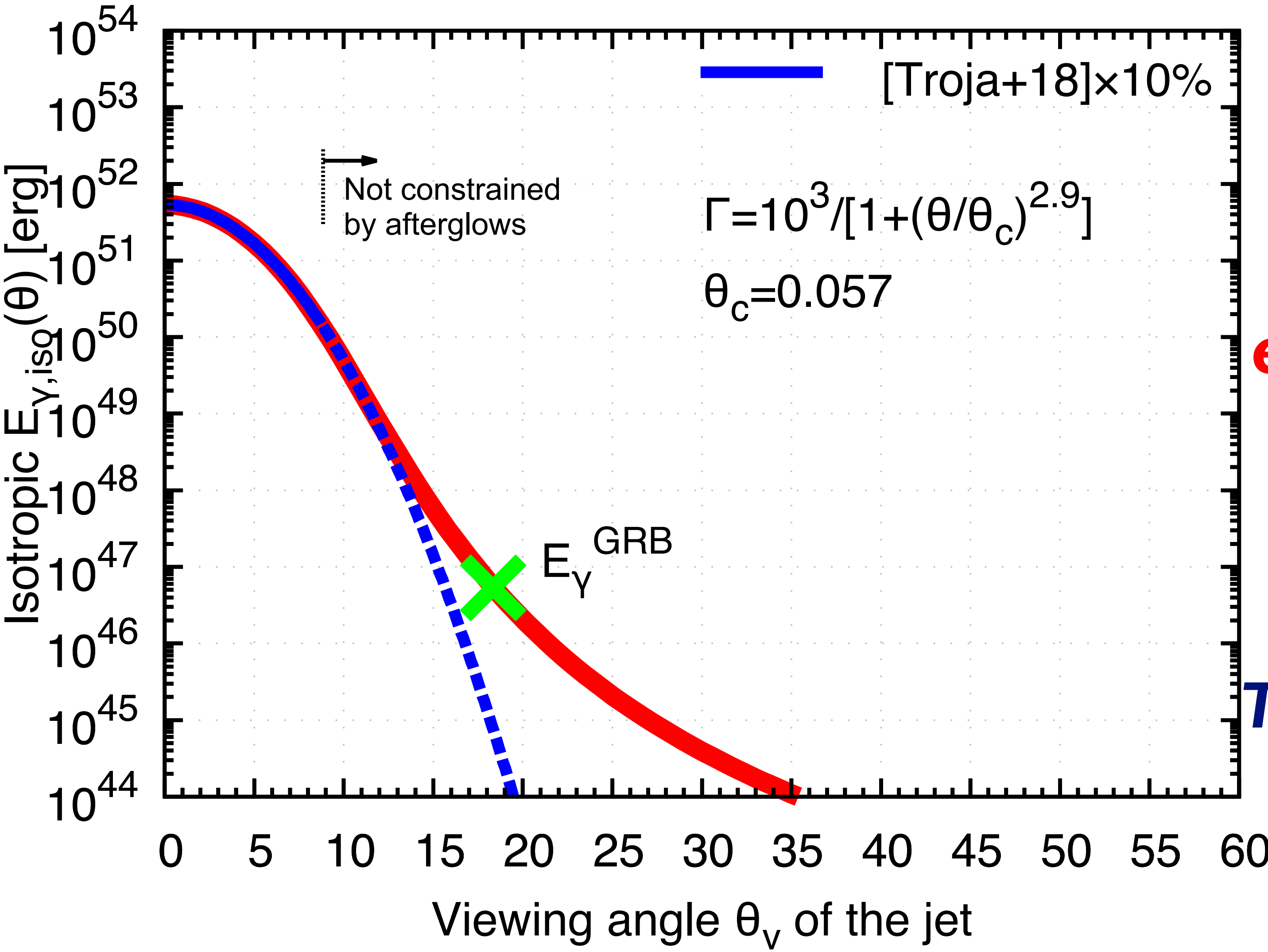
Edge is faint & sharp
$\Rightarrow$ has not observed

Keep $E_{GRB} \propto E_{afterglow}$

No compactness problem

Tsutsui+ 13, Amati 02, Yonetoku+ 04

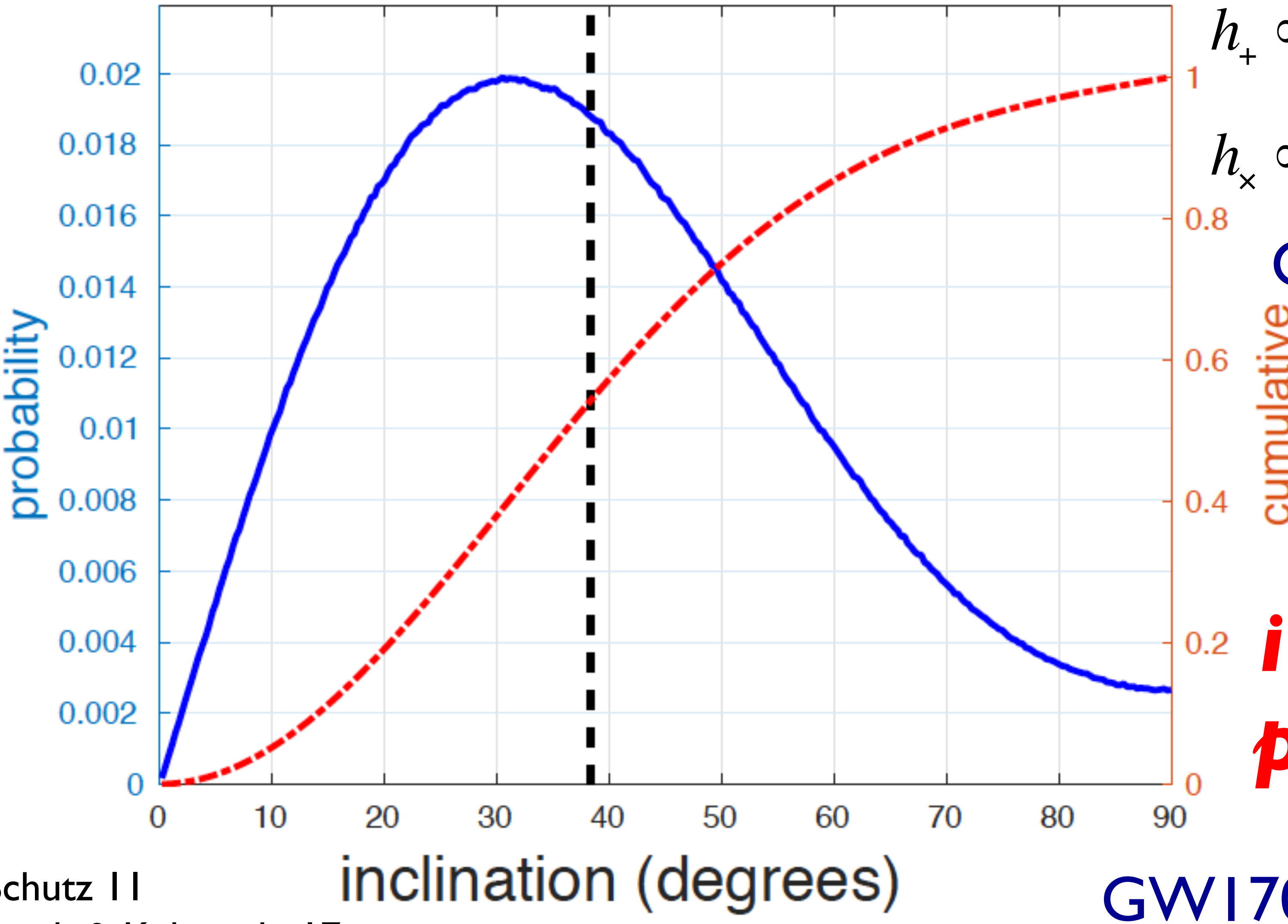
Future Prospects



Quasi-Gaussian emission is always exceeded by off-axis emission

The jet profile, not jet core, is essential

Viewing Angle Probability



$$h_+ \propto \frac{1}{2}\left(1+\cos^2 i\right)$$

$$h_\times \propto \cos i$$

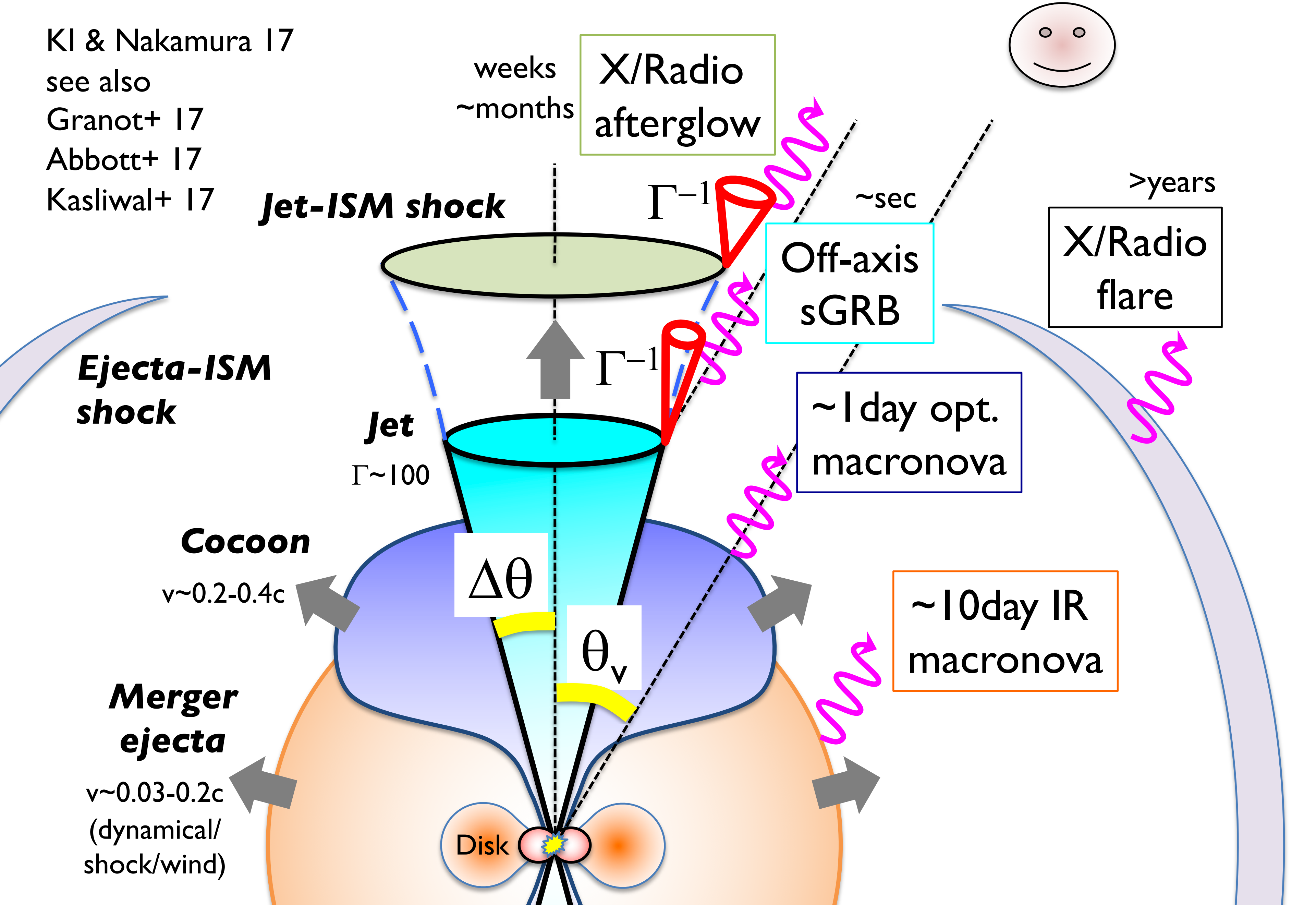
On-axis GW is strong

i~30° is probable

Schutz 11
Lamb & Kobayashi 17

GW170817: i<~30°

KI & Nakamura 17
see also
Granot+ 17
Abbott+ 17
Kasliwal+ 17



Contents

- ***sGRB 170817A from an off-axis jet***
  – A top-hat jet is not perfect
  – Spectral problem
- ***Off-axis emission of a structured jet***
  – We are likely observing a jet side-profile
  – Not an on-axis outflow, not a jet core, but middle
  – Both off-axis emission & structure are essential
  – The jet side has been observed for the first time
  – No compactness problem
  – Predict Yonetoku outliers

Almost top-hat

Thank You