Multi-Messenger Astrophysics in the Graviational Wave Era
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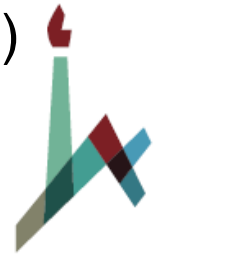
Generalized compactness limit and its application

Tatsuya Matsumoto

with Ehud Nakar (Tel Aviv), Tsvi Piran (Hebrew)
Shigeo Kimura (Tohoku), Kohta Murase(PSU) & Peter Meszaros(PSU)

Ref. Matsumoto et al. 2019a,b
Matsumoto&Piran 2019
Matsumoto+ in prep



THE HEBREW
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Outline

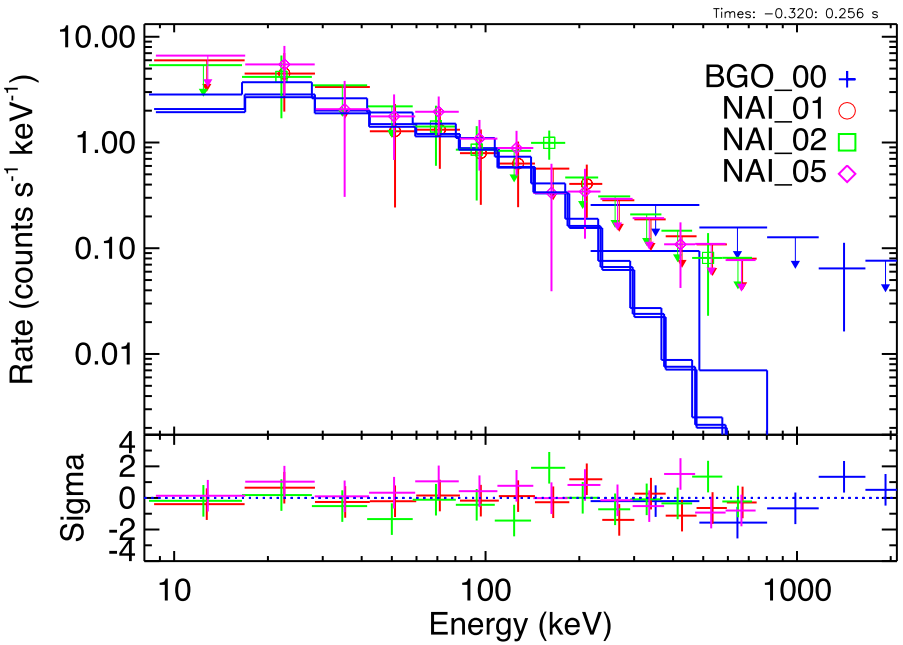
- Generalized compactness argument & GRB 170817A
- Similar events to GRB 170817A
- Other applications of compactness
- Minimal Lorentz factor of extended emissions in short GRBs

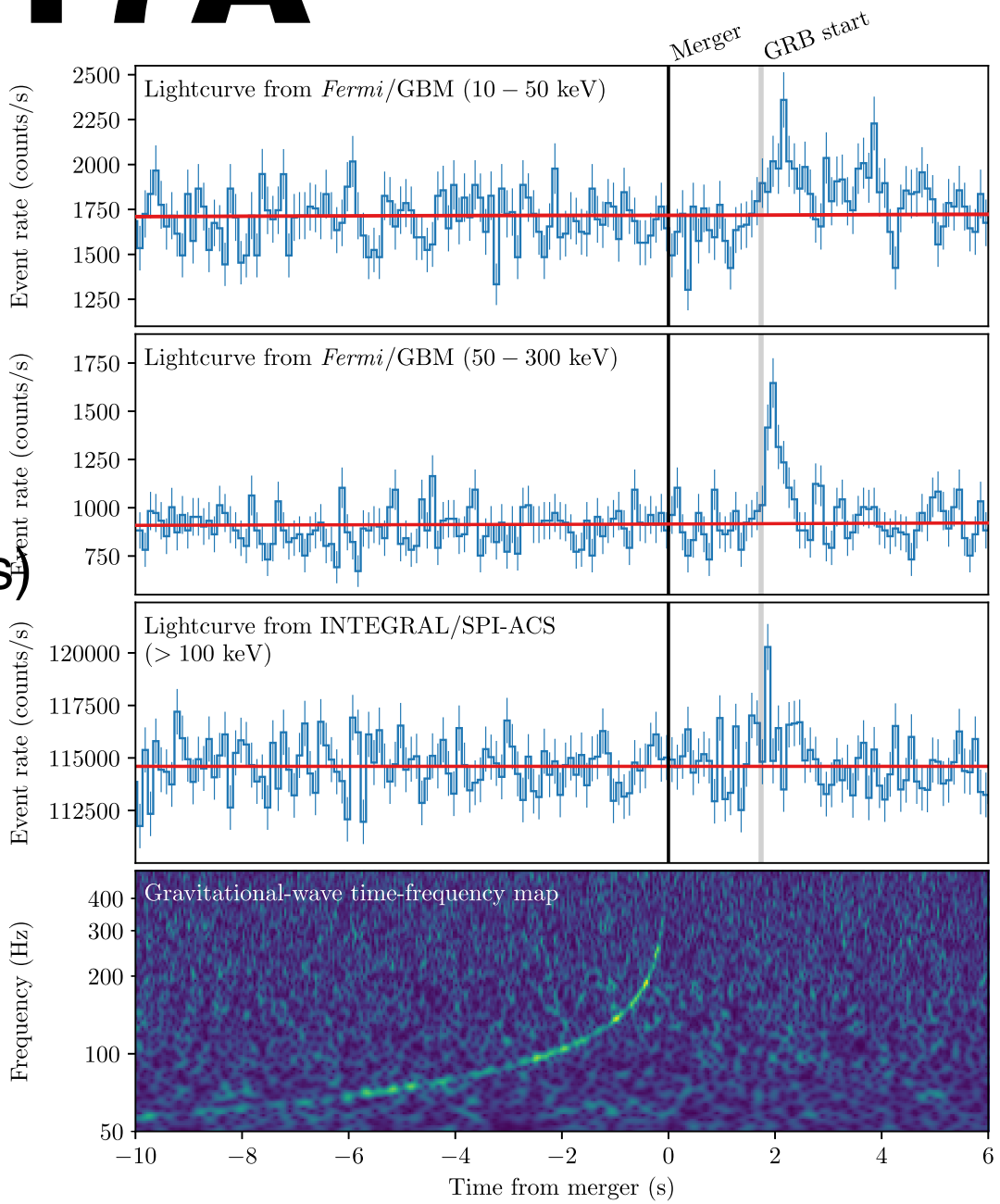
Abbott+17
Goldstein+17
Savchenko+17

GRB170817A

- $\delta t \sim 2$ s
- Power law+cut-off
- $\varepsilon_p \sim 185$ keV

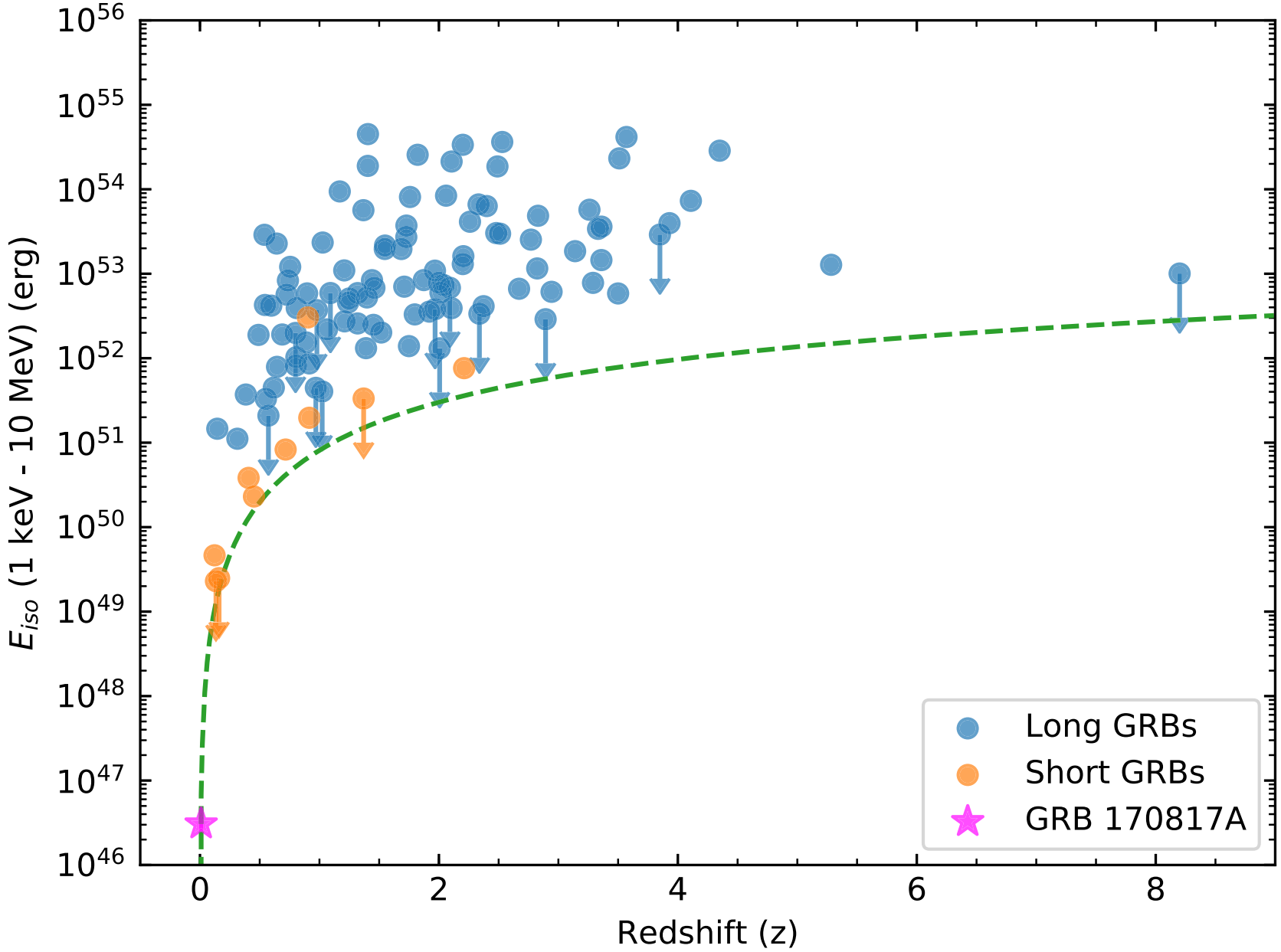
(~ 520 keV : Veres+18
Using time-resolved analysis)





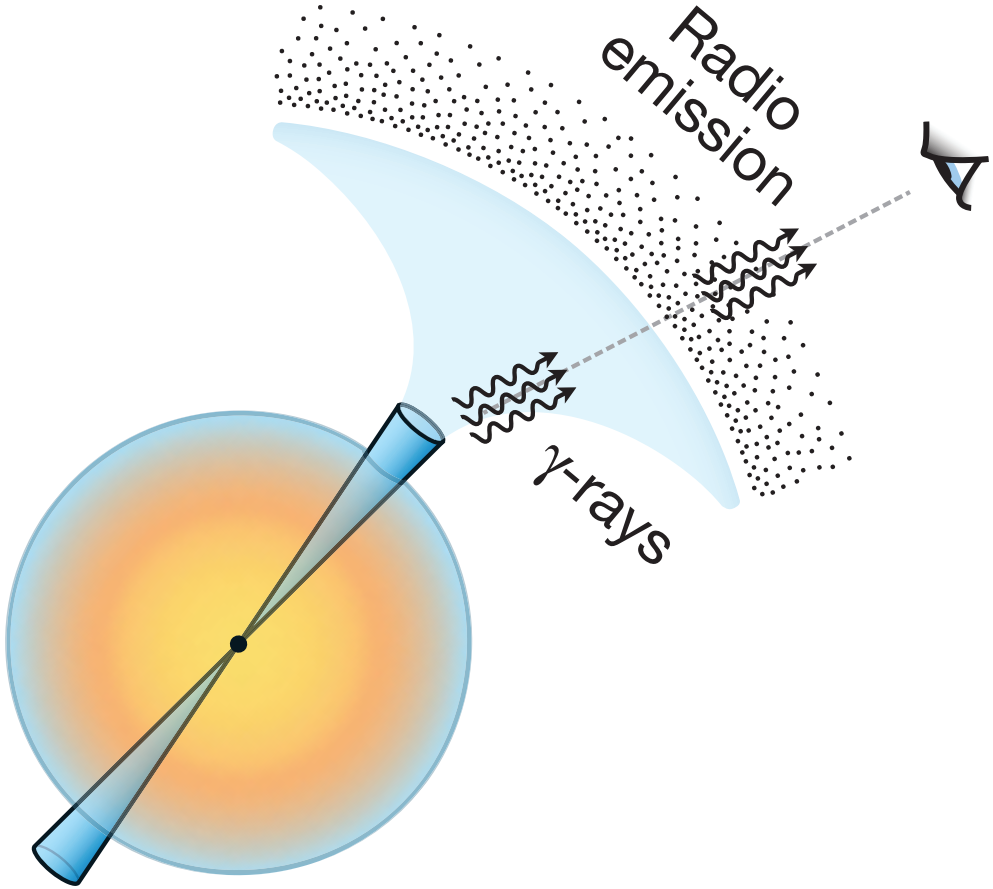
LIGO&VIRGO+17

Weakest sGRB

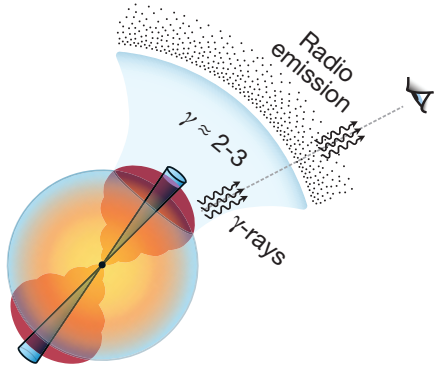


The origin of γ-rays

1) An ordinary sGRB viewed **off**-axis?



Goldstein+17,
Murguia-Berthier+17,
Ioka&Nakamura18



2) Shock breakout from a cocoon? (not the focus of this talk)

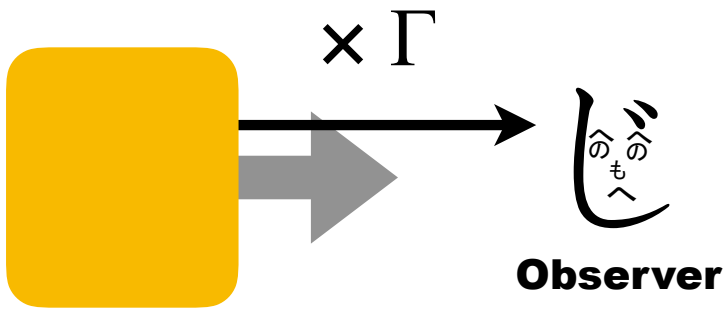
Compactness Problem

- Luminous, high-variable, non-thermal GRBs
- compact & photon dense

  => pair production : $\tau_{\gamma\gamma} \sim 10^{13}$ Ruderman75, Schimdt78

- Relativistic effects : $\tau_{\gamma\gamma} \sim 10^{13}/\Gamma^{6}$

  => $\Gamma > 10^{2}$ Piran99, Lithwick&Sari01



We generalize this analysis to off-axis sources with an arbitrary viewing angle

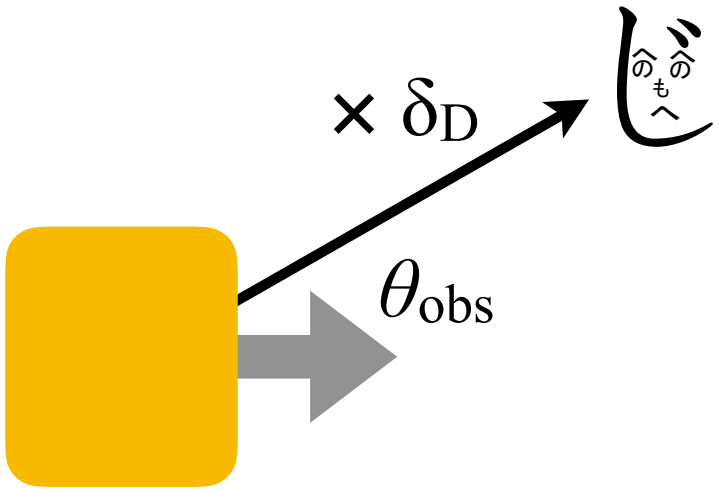
Generalization to an arbitrary viewing angle

- On axis : Γ
- General angle : Doppler factor

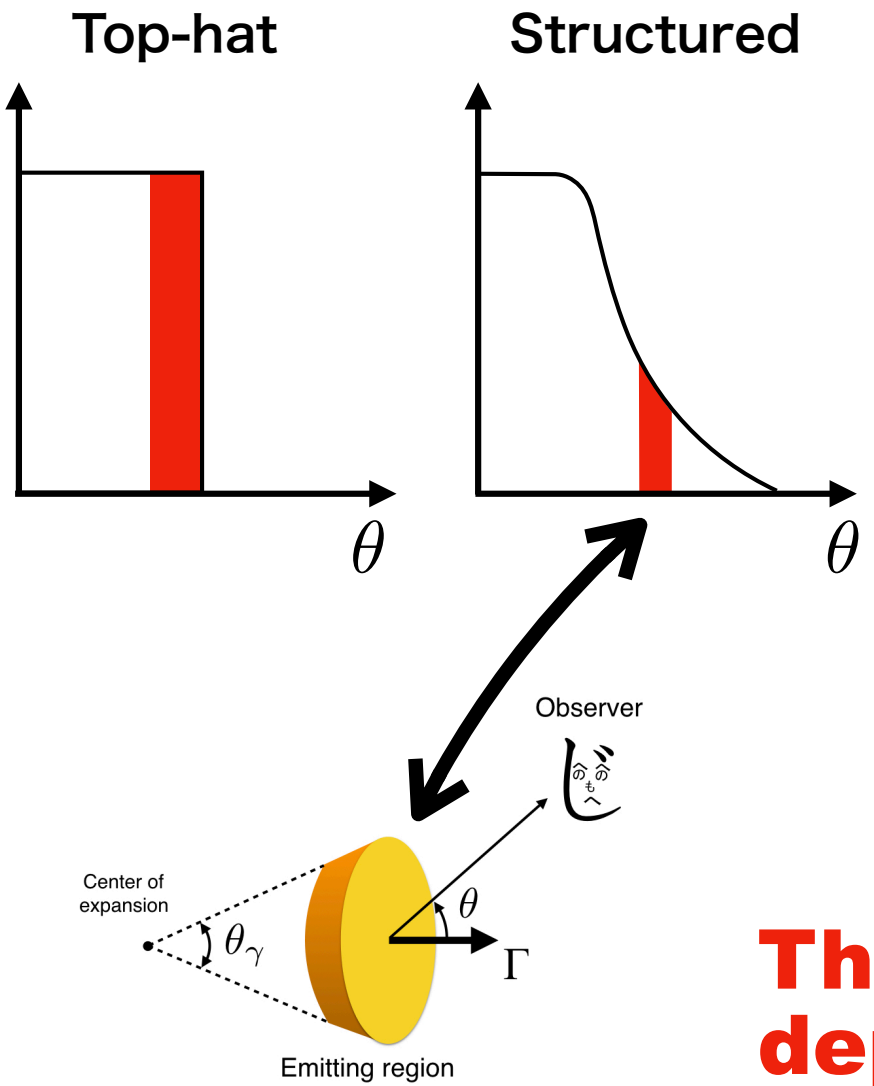
$$\delta_{\rm D} = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm obs})}$$

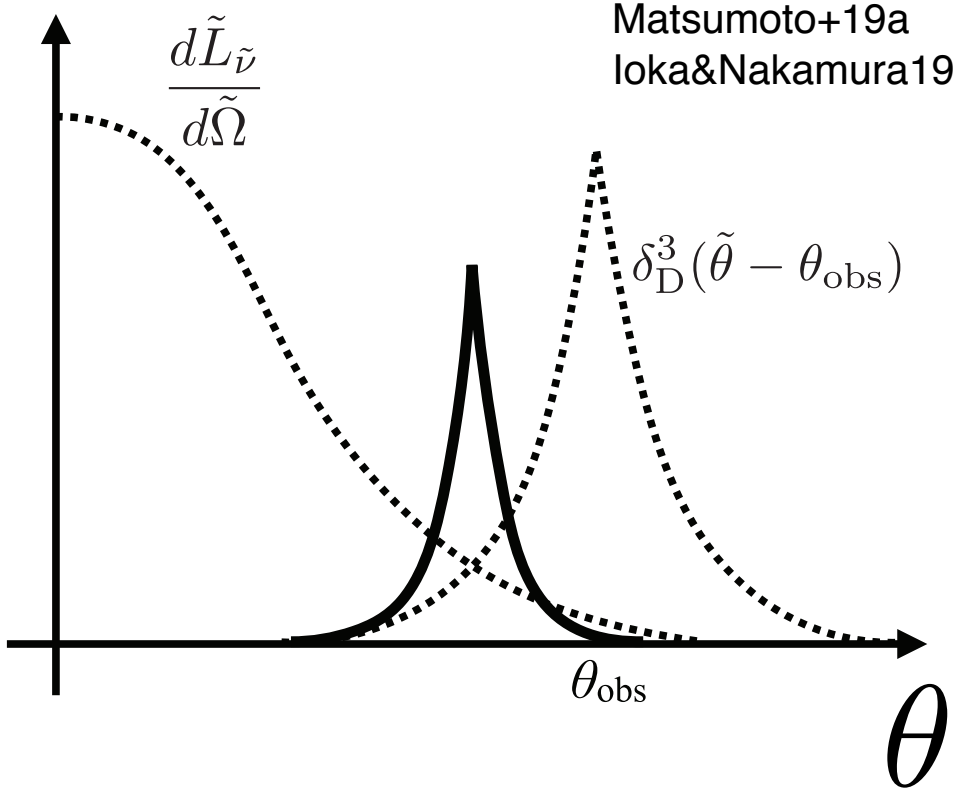
$$\Rightarrow \tau_{\gamma\gamma} \sim 10^{13}/\delta_{\rm D}^{6}$$

Limit On $\delta_{\rm D}$



Source Structure

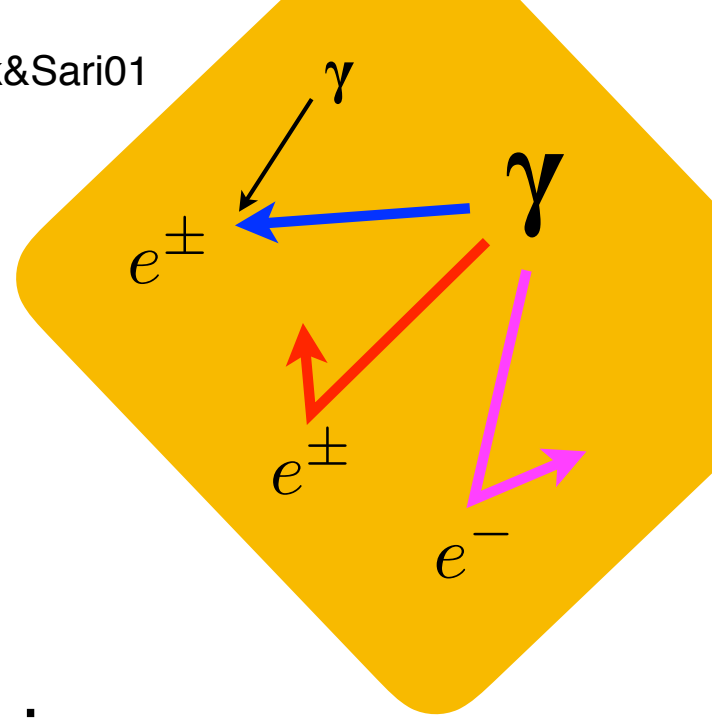




The conclusion doesn't depend on the structure!

Opacity source

Lithwick&Sari01



Limit A : Pair production

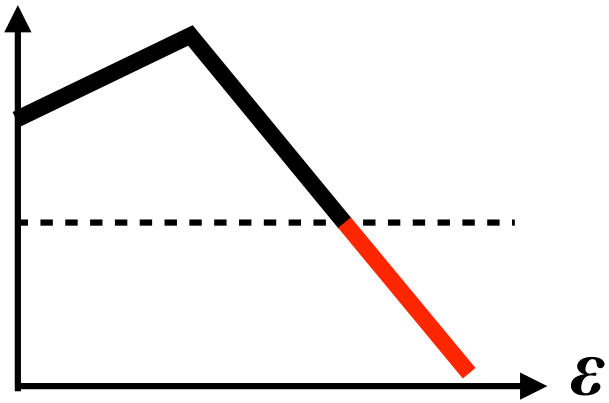
$$\varepsilon > (\delta_D m_e c^2)^2/\varepsilon_{max}$$

Limit B : Scattering by created pair

# of pair ~ # of photon $\varepsilon > \delta_D m_e c^2$

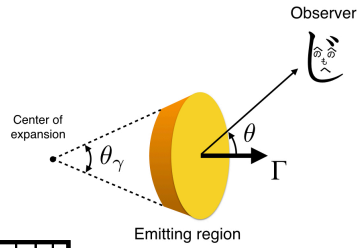
Limit C : Scattering by electron in outflow

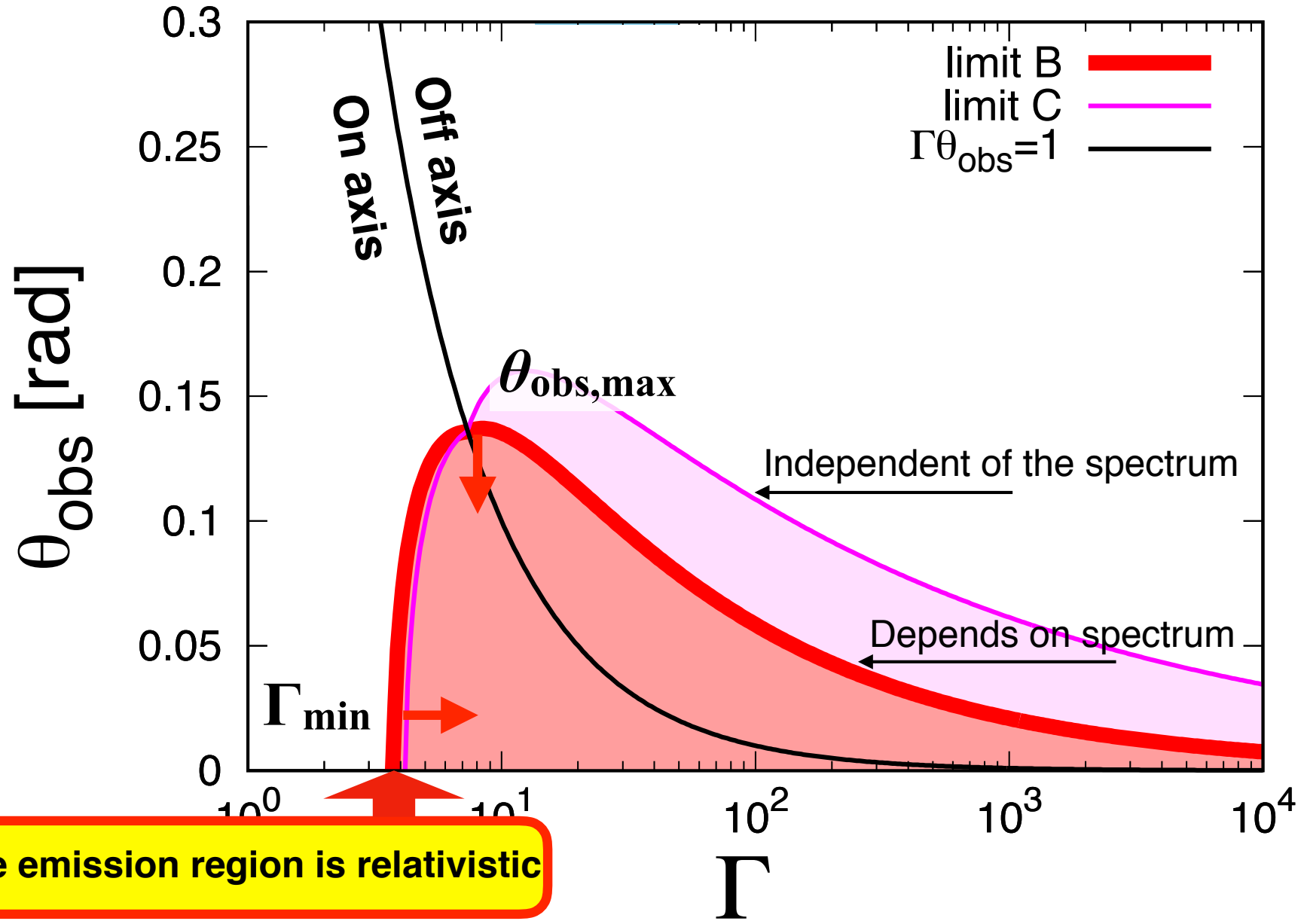
- Spectrum is extrapolated beyond observed energy



Constraint on γ-ray source in GRB 170817A

Matsumoto+19a,b
Kasliwal+17

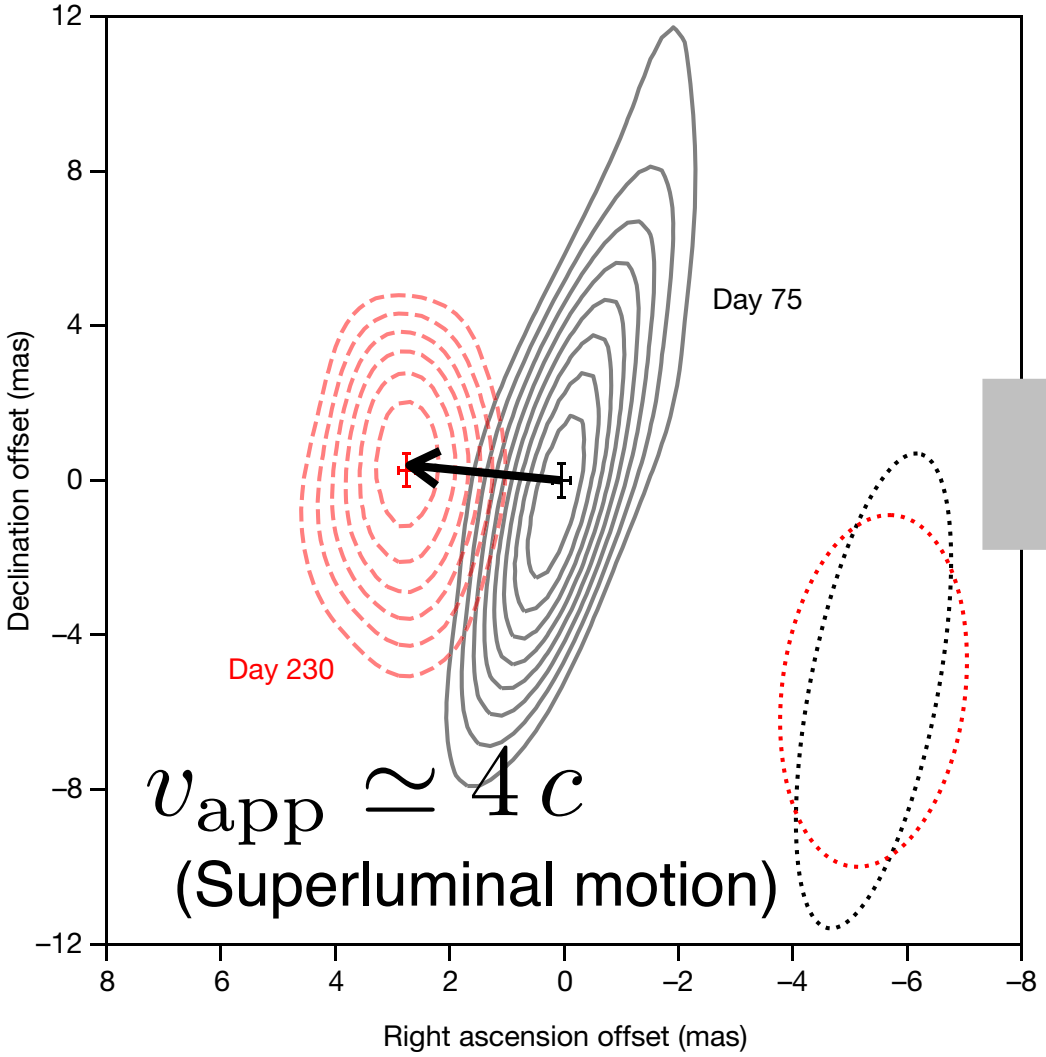


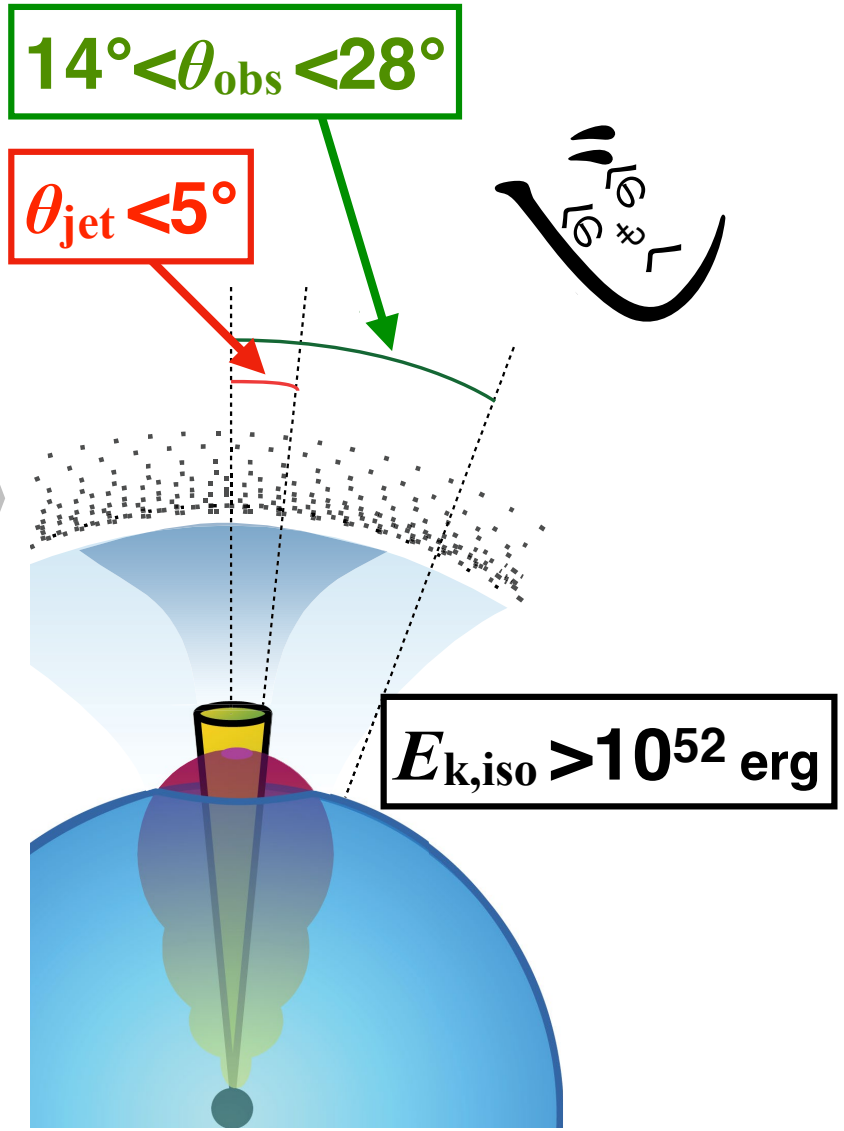


The emission region is relativistic

Mooley+18, Ghirlanda+18

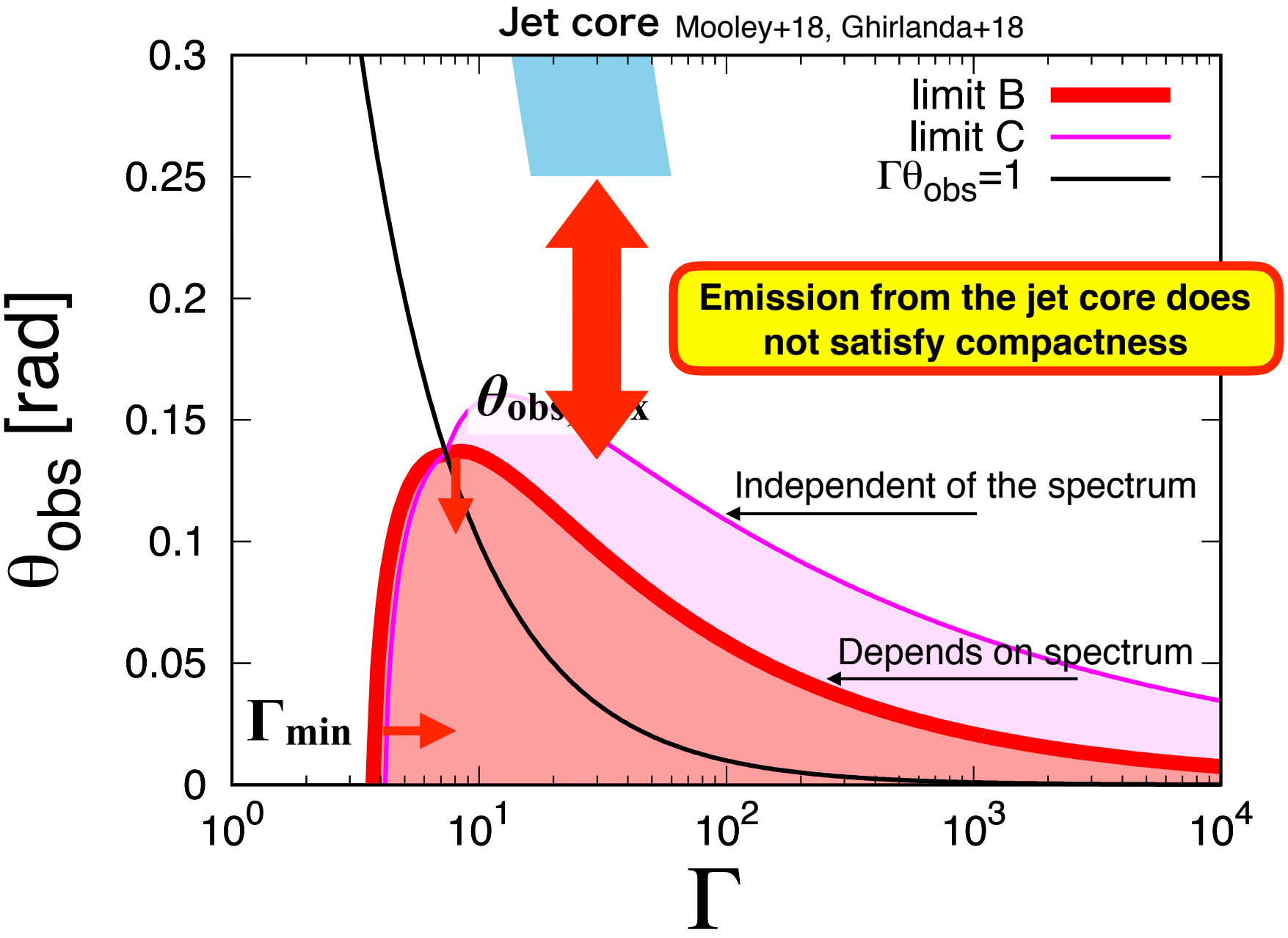
Properties of the jet



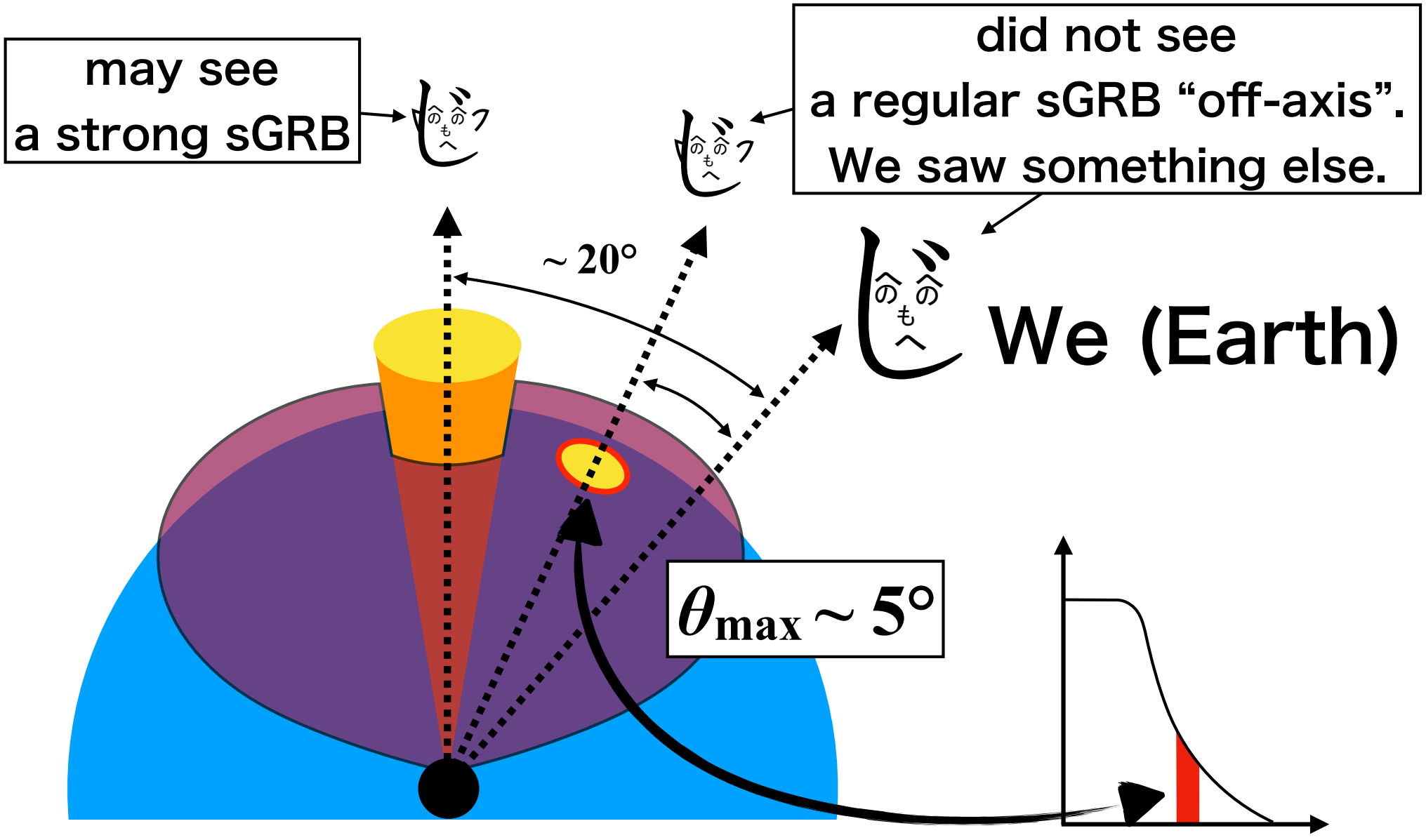


Matsumoto+19a,b

Constraint on γ-ray emission



The origin of γ-rays



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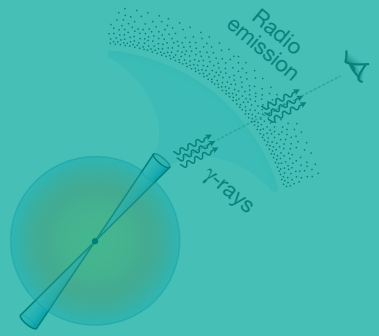
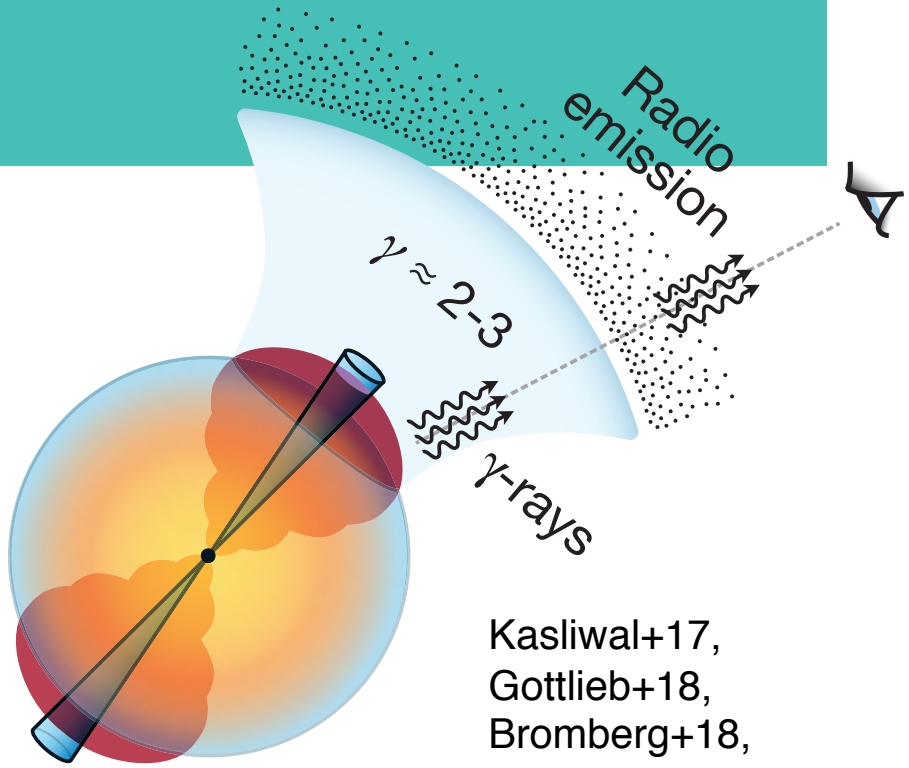


Goldstein+17,
Murguia-Berthier+17,
Ioka&Nakamura18

2) Shock breakout from a cocoon?



Kasliwal+17,
Gottlieb+18,
Bromberg+18,
Kathirgamaraju+18

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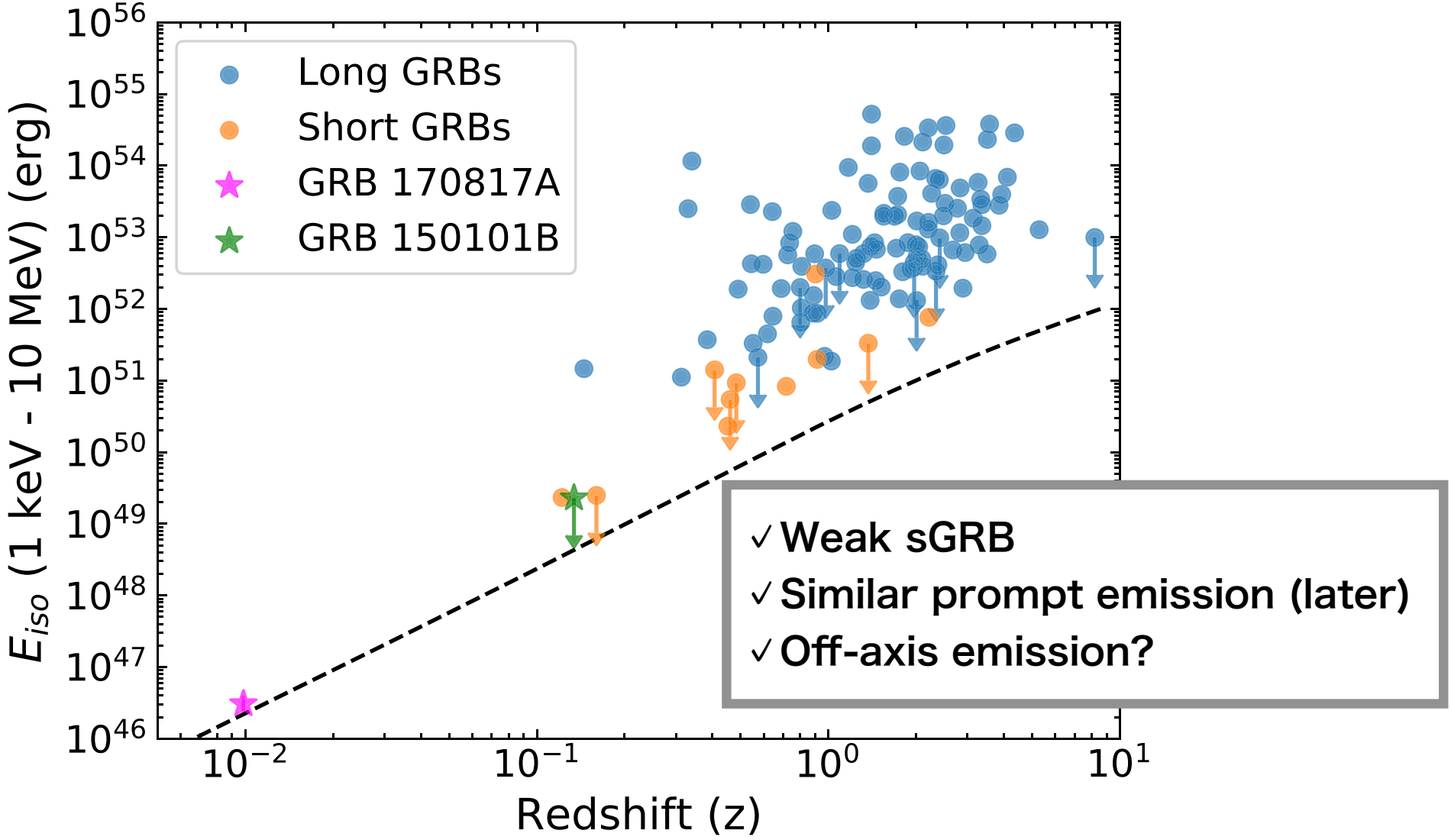
- Generalized compactness argument & GRB 170817A
- Similar events to GRB 170817A
- Other applications of compactness
- Minimal Lorentz factor of extended emissions in short GRBs

Troja+18, Burns+18

GRB 150101B
: a similar event to GRB 170817A



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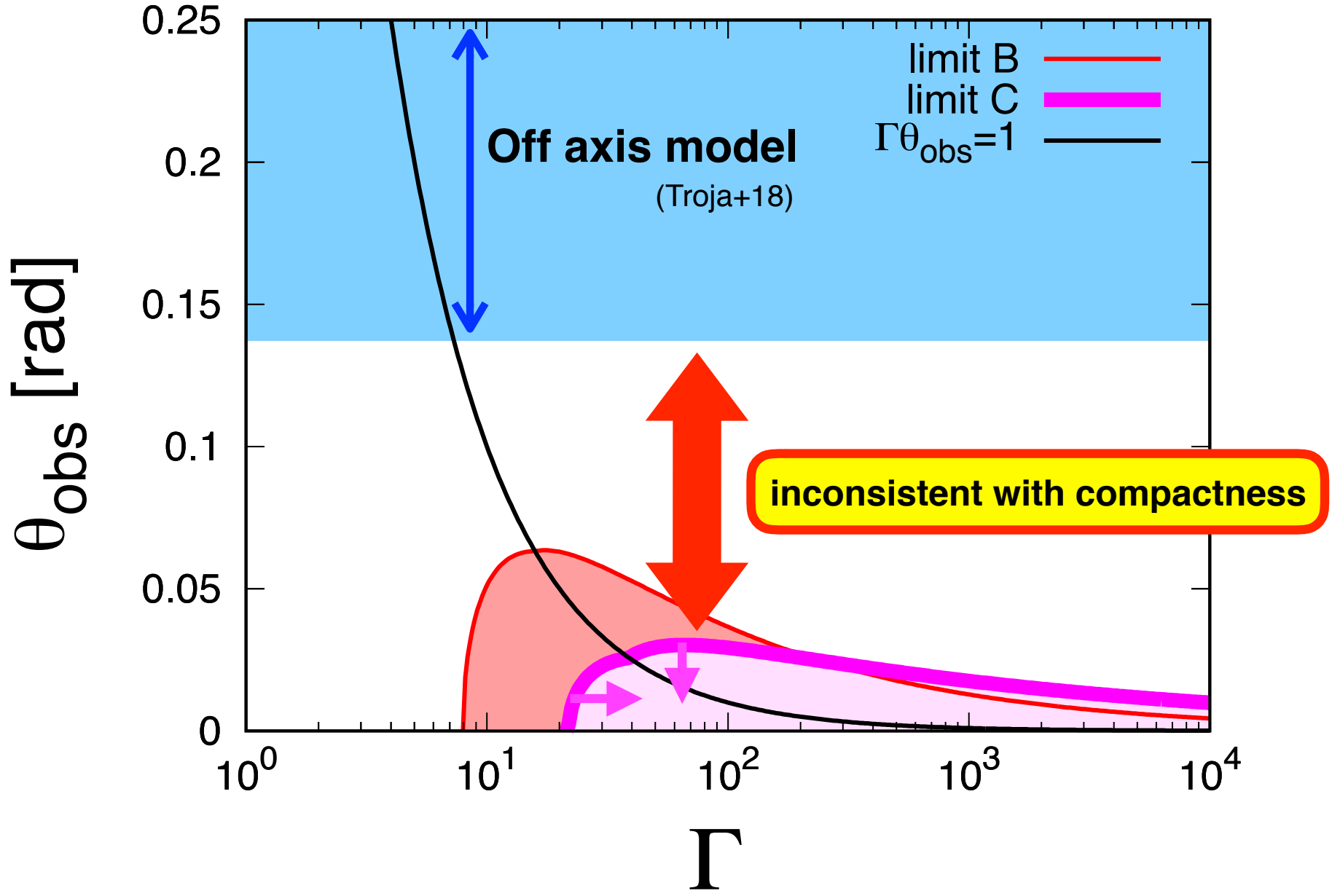
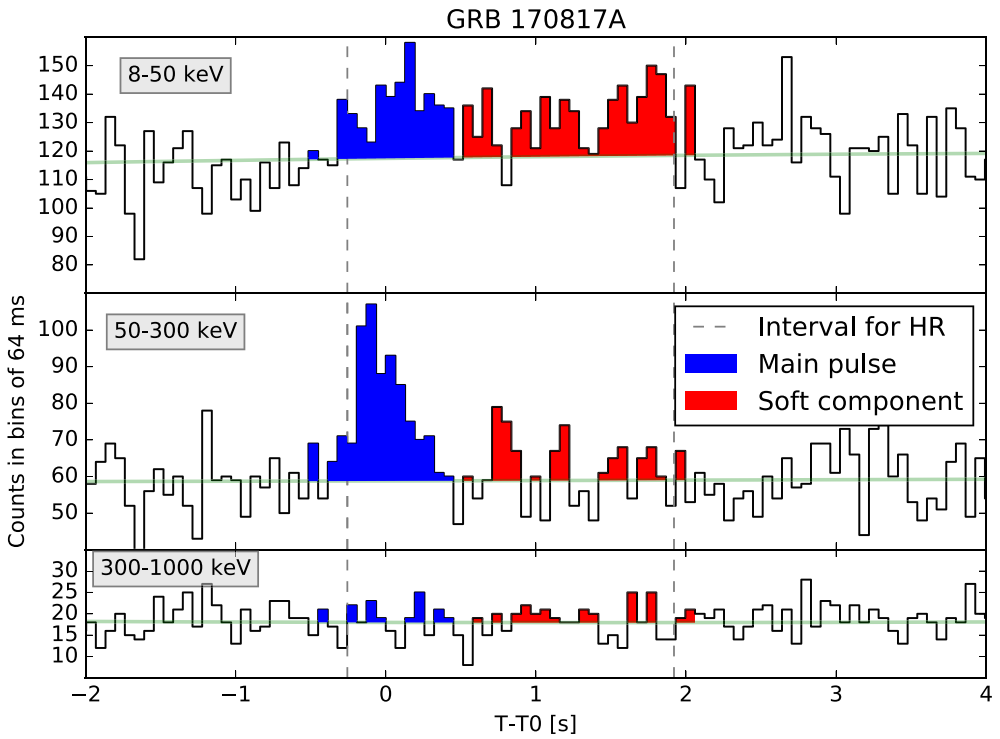
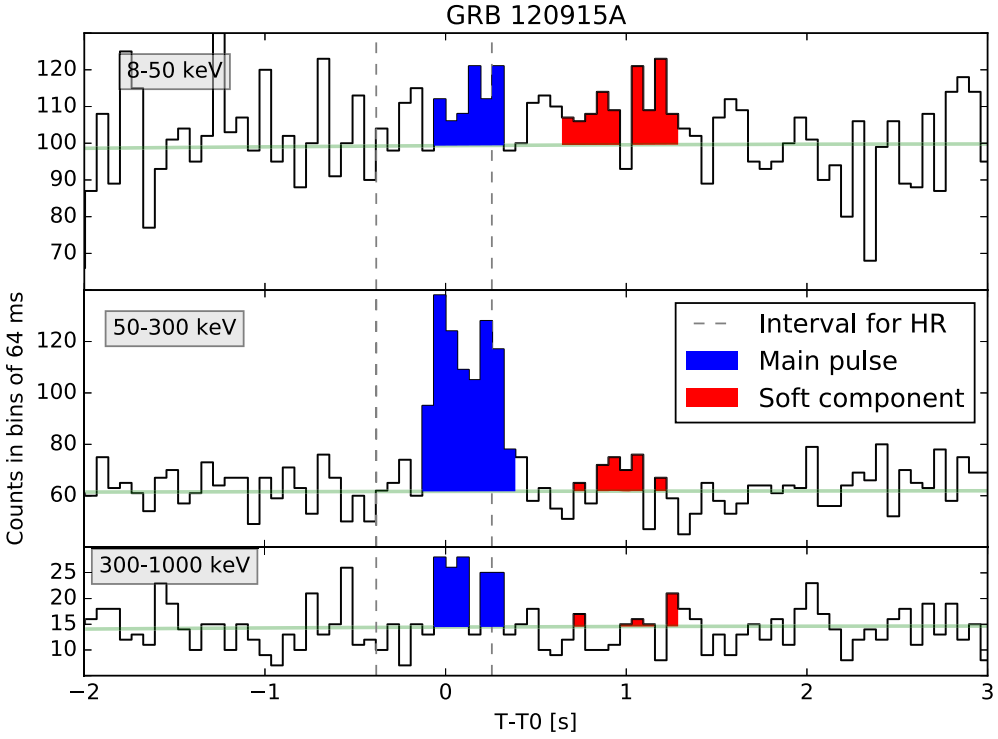
GRB 150101B



von Kienlin+19

Other similar GRBs





Selection criteria

1) a first pulse in 50-300keV
2) a soft tail in 8-50 keV
3) a discernible change in a light curve

Manual selection

11 / 395 sGRBs

in Fermi GBM 10yr catalog

von Kienlin+19

Other similar GRBs

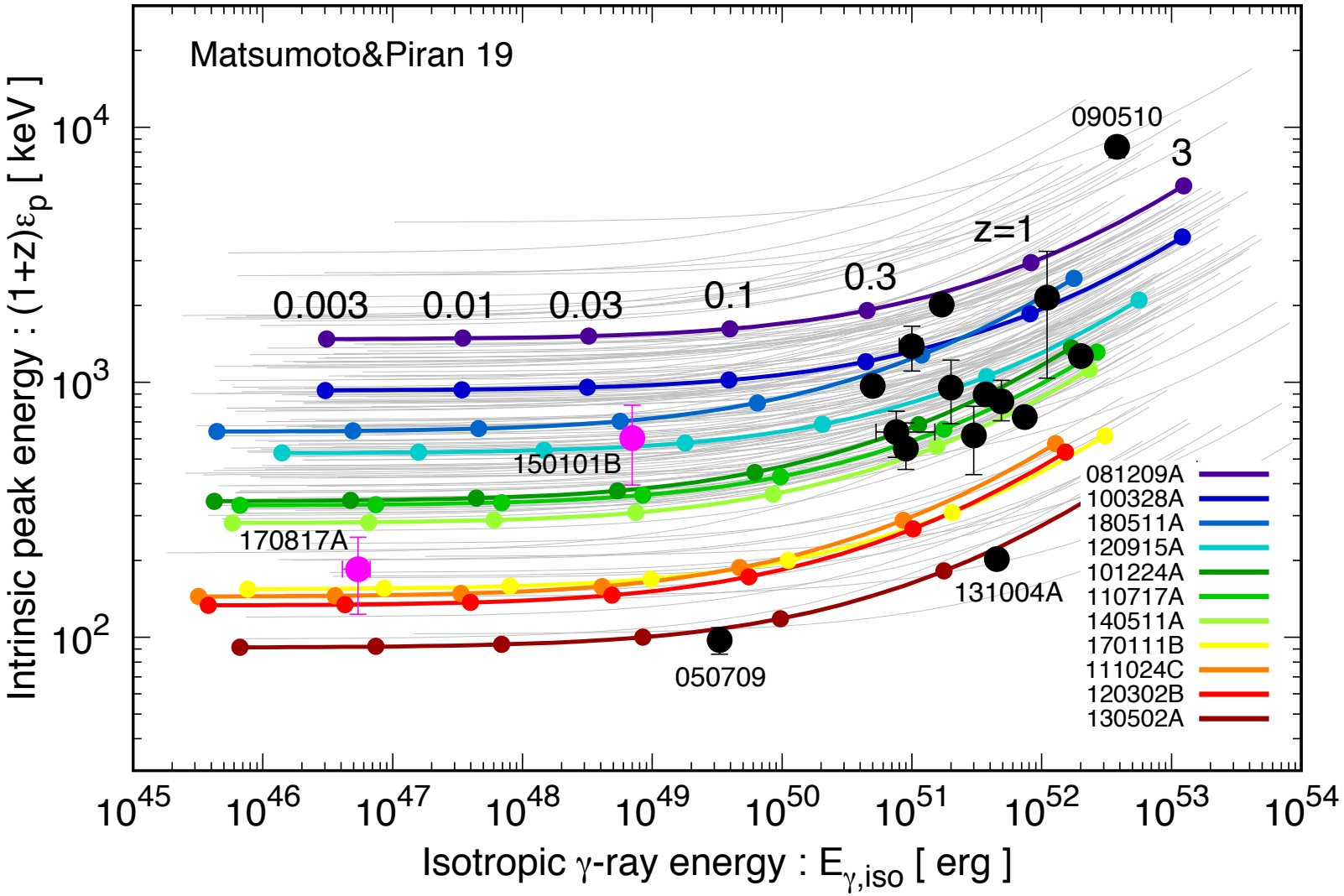
Event	Energy flux F [10^{-7} erg cm^{-2} s^{-1}]	Fluence S [10^{-7} erg cm^{-2}]	Duration δt [s]	Minimal variable timescale $\delta t_{\rm min}$ [ms]	Peak energy $\epsilon_{\rm p}$ [keV]	Spectral index α_p
GRB 081209A	40.14	15.4	0.384	< 15	1473	-0.75
GRB 100328A	33.61	15.1	0.448	< 11	927	-0.54
GRB 101224A	4.04	2.07	0.512	47	341	-1.04
GRB 110717A	25.57	3.27	0.128	11	328	-0.34
GRB 111024C	4.11	1.58	0.384	41	144	0.53
GRB 120302B	3.72	1.90	0.512	< 120	133	0.66
GRB 120915A	13.66	6.99	0.512	41	526	-0.21
GRB 130502A	2.12	3.26	1.536	221	91	-0.80
GRB 140511A	14.85	2.85	0.192	< 94	280	-0.78
GRB 170111B	7.42	3.80	0.512	< 63	154	-0.62
GRB 180511A	34.29	2.19	0.064	< 5	639	-0.61

Question:

Are they normal sGRBs?

Or are they really twins of GRB 170817A?

Are they normal sGRBs?



If z = 0.3-3 => Consistent with normal sGRBs

Cocoon shock breakout?

Closure relation:

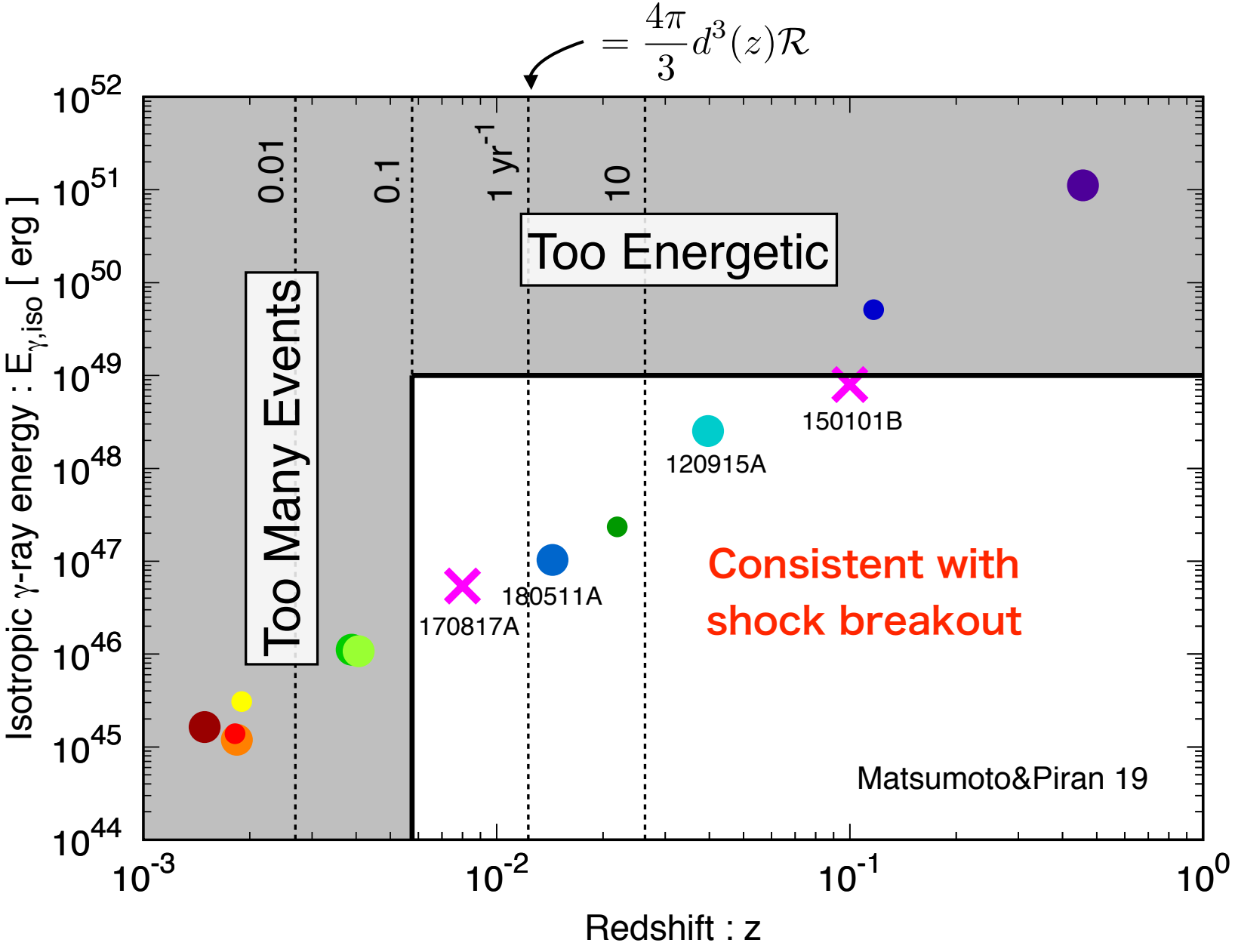
$$\delta t' \simeq 1\,\mathrm{s}\left(\frac{E_{\gamma,\mathrm{iso}}}{10^{46}\,\mathrm{erg}}\right)^{1/2}\left(\frac{\epsilon'_{\mathrm{p}}}{150\,\mathrm{keV}}\right)^{-\frac{9+\sqrt{3}}{4}}$$

Nakar&Sari12

$$\delta t = (1+z)\delta t'$$
$$\epsilon_{\mathrm{p}} = \epsilon'_{\mathrm{p}}/(1+z)$$
$$E_{\gamma,\mathrm{iso}} = 4\pi d_{\mathrm{L}}^2 S$$

$$\delta t_0^{-1} S_{-7}^{1/2} \epsilon_{\mathrm{p},150\,\mathrm{keV}}^{-\frac{9+\sqrt{3}}{4}} \simeq (1+z)^{\frac{5+\sqrt{3}}{4}}\left(\frac{d_{\mathrm{L}}(z)}{29\,\mathrm{Mpc}}\right)^{-1}$$

Cocoon shock breakout?



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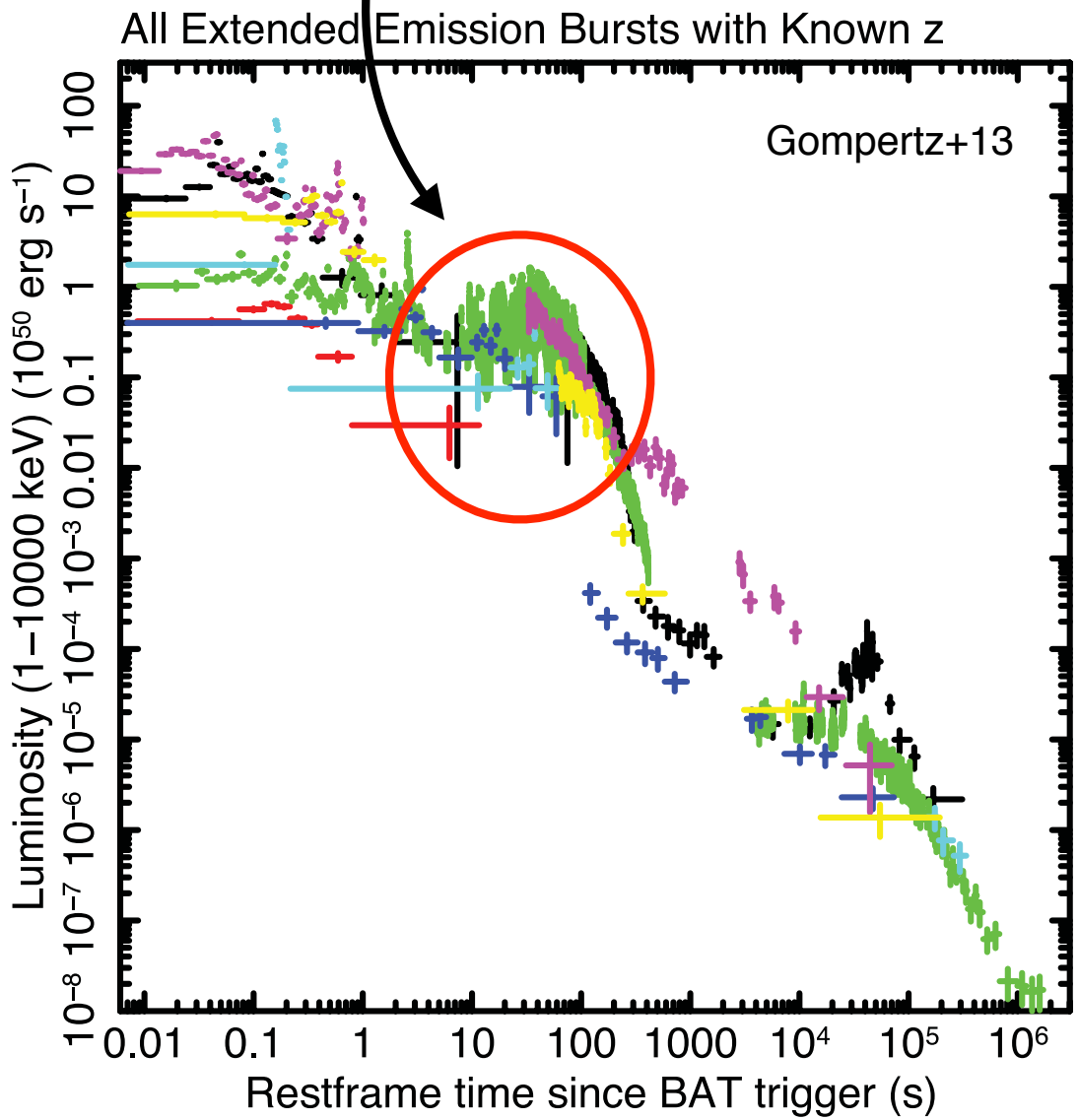
Γ_{min} of Extended Emissions in sGRBs



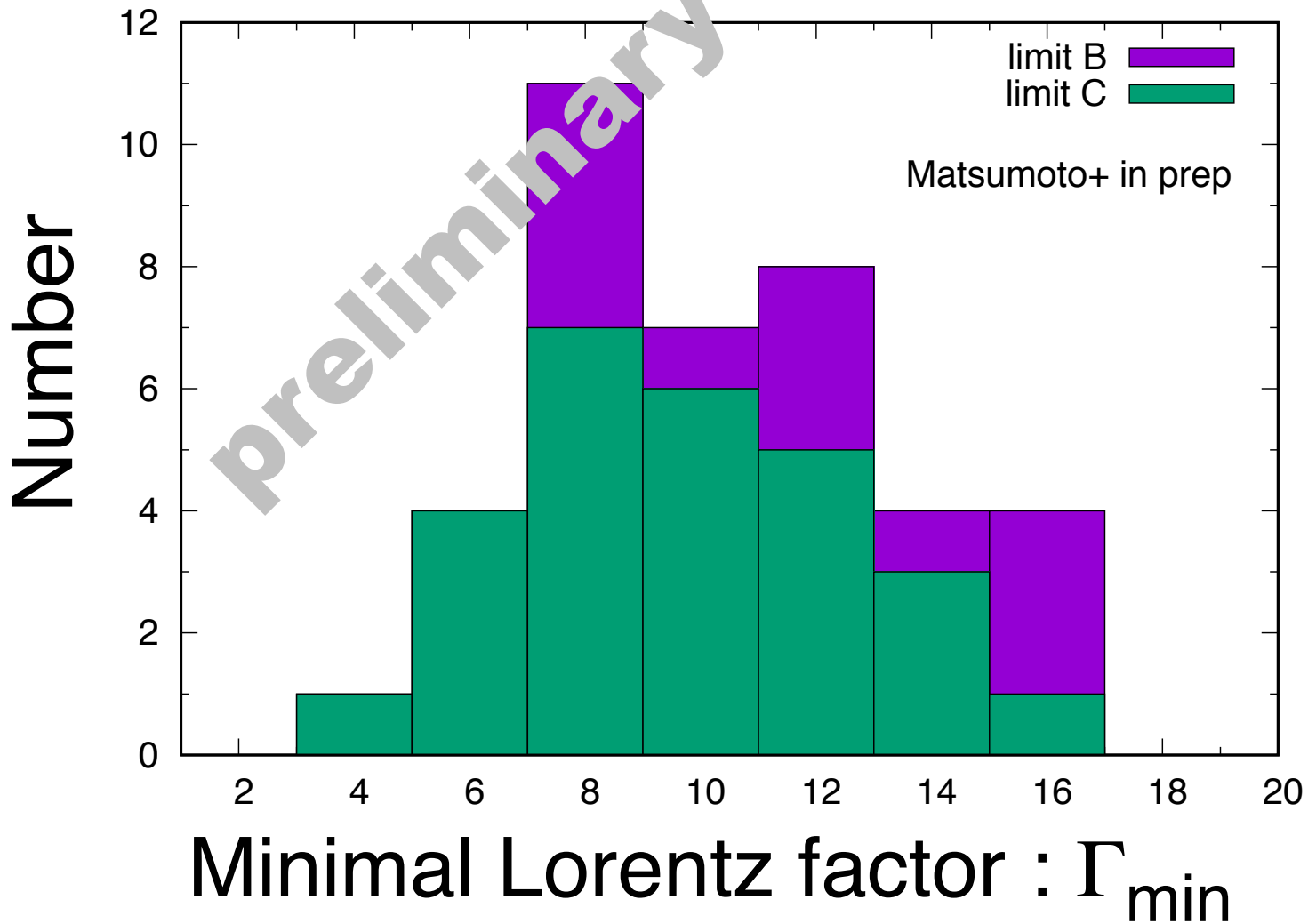
long lasting activity
of central engine
=> Magnetar? BH?

*Test of relativistic jet scenario
=> see Matsumoto&Kimura18

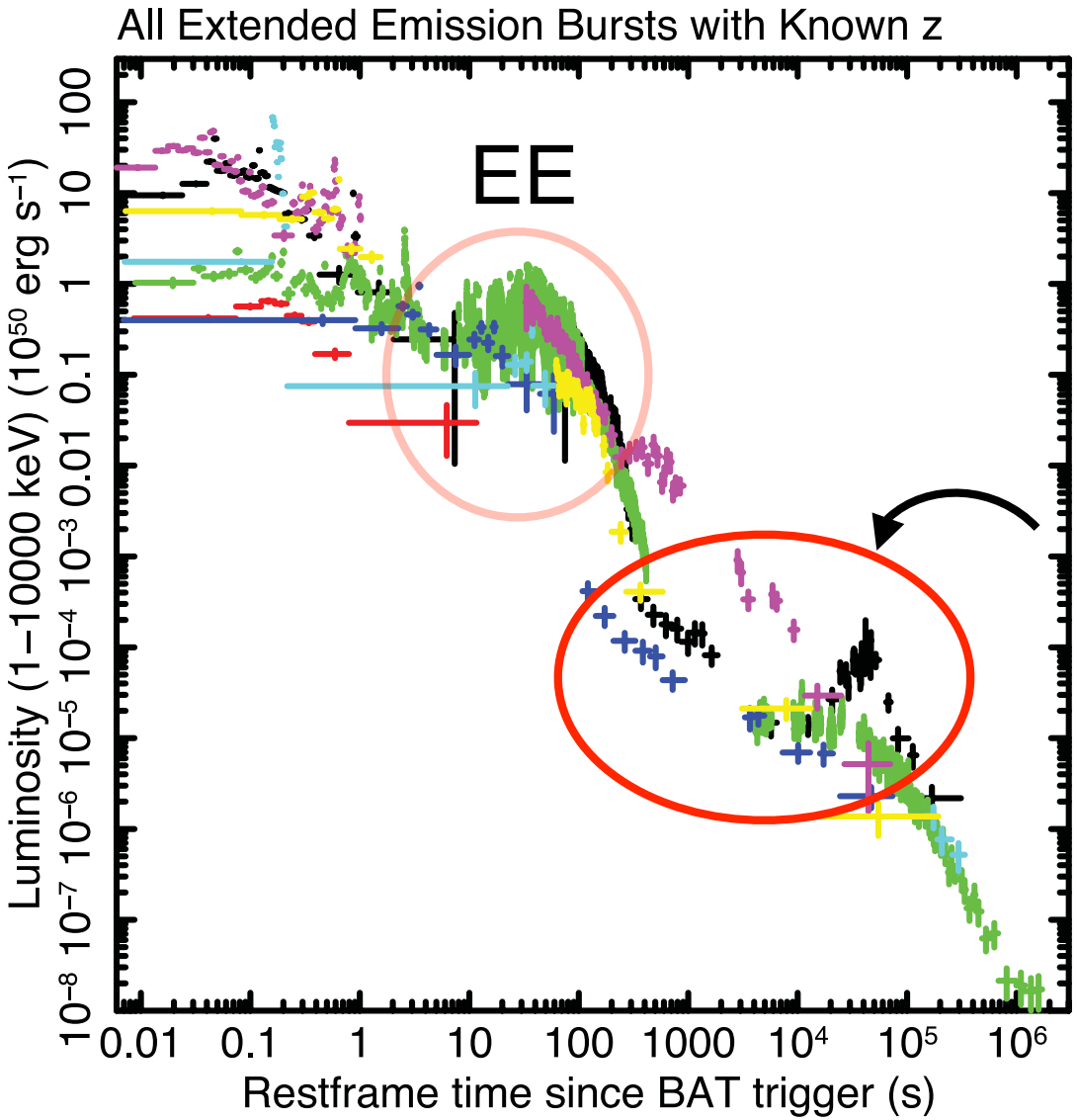
Γ_{min} of Extended Emissions

=> 39 EEs with spectrum detected by BATSE, BAT, GBM

(list in Bostanci+13,Kaneko+15)



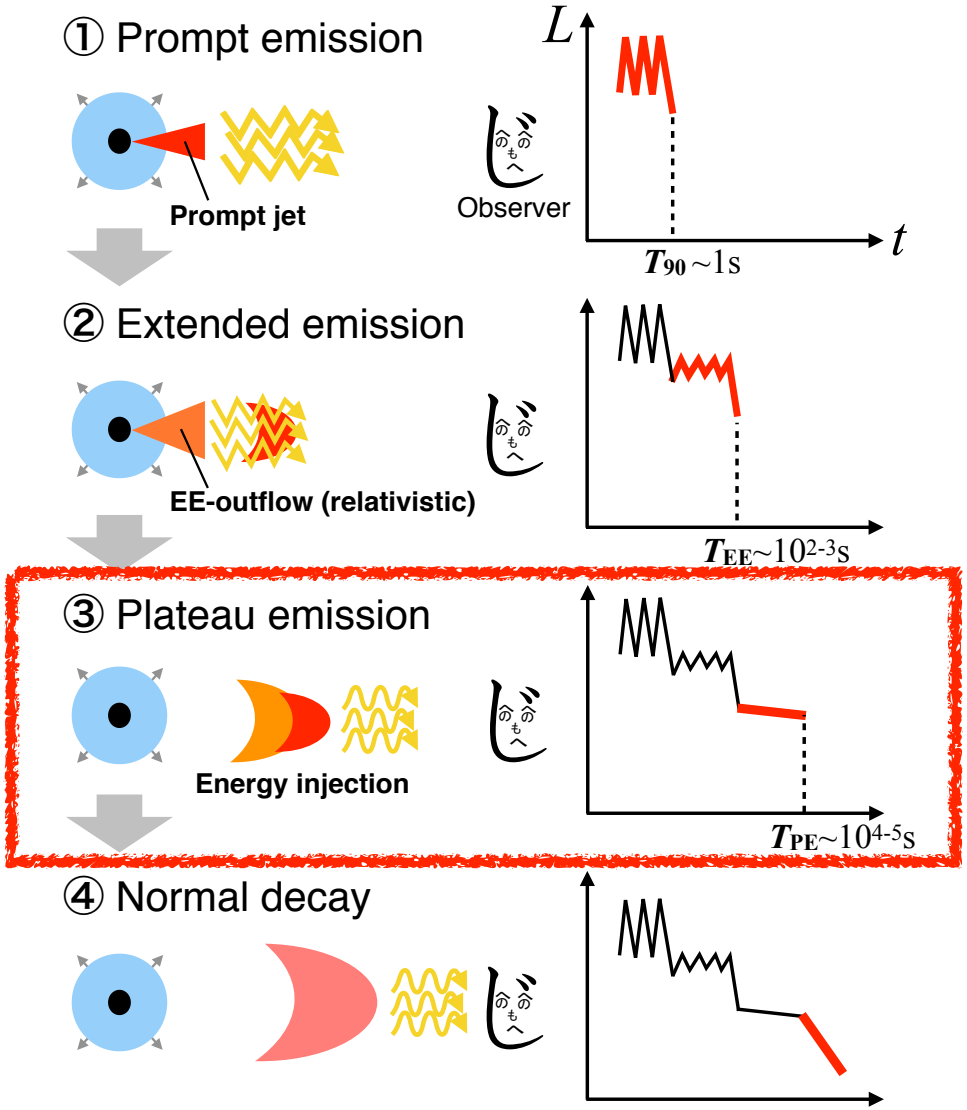
Origin of shallow decay after EE?

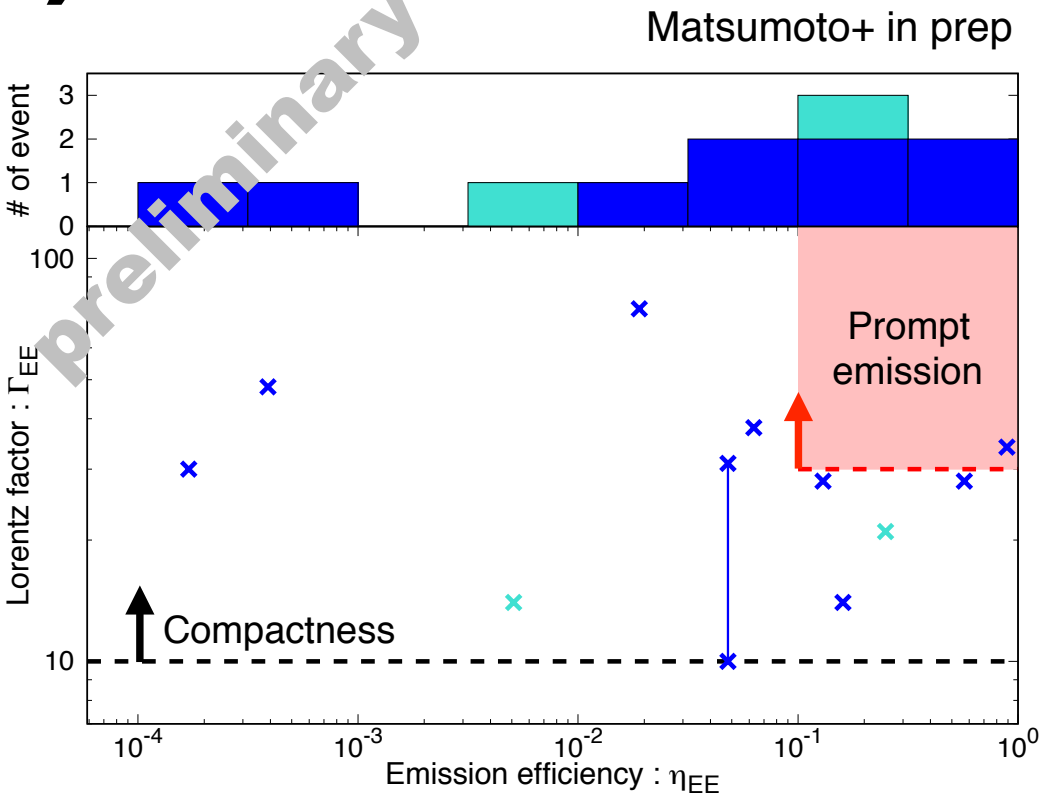


long lasting activity of central engine
=> Magnetar? BH?

Shallow decay
=> energy injection from
EE (low Γ) outflow?

Shallow decay powered by EE (low Γ) outflow





$$\eta_{\rm EE} \equiv \frac{E_{\rm EE,iso}}{E_{\rm EE,iso} + E_{\rm kin,iso}}$$

Inefficient energy dissipation?

Summary

- Generalized Compactness argument : $\Gamma_{\rm min}$, $\theta_{\rm max}$

- GRB 170817A : we did not see γ-rays from the jet core
  (the region that could have emitted a regular sGRB.)
  $\Gamma_{\rm min} > 5$, $\theta_{\rm max} <$ **0.1 rad** <-> jet core
  => another γ-ray emission mechanism is favored.
  The source is relativistic and consistent with a cocoon emission.

- Similar GRBs to GRB 170817A
  150101B : off-axis model is inconsistent with compactness
  Other events : ~2/395 events can be consistent with cocoon emissions

- Other application

  $\Gamma_{\rm min}$ ~10 of extended emissions of sGRBs => very inefficient energy dissipation?

$$\delta_{\rm D}(\theta_{\rm obs},\Gamma) \simeq \frac{2\Gamma}{1+(\Gamma\theta_{\rm obs})^2}$$

$$\theta_\gamma \leq \max\left\{\frac{1}{\Gamma}, \theta_{\rm obs}\right\}$$