# Probing the particle acceleration at trans-relativistic shocks with GRB afterglows

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# Neutron Star Merger GW170817

## EM counterparts

short GRB
GRB 170817A

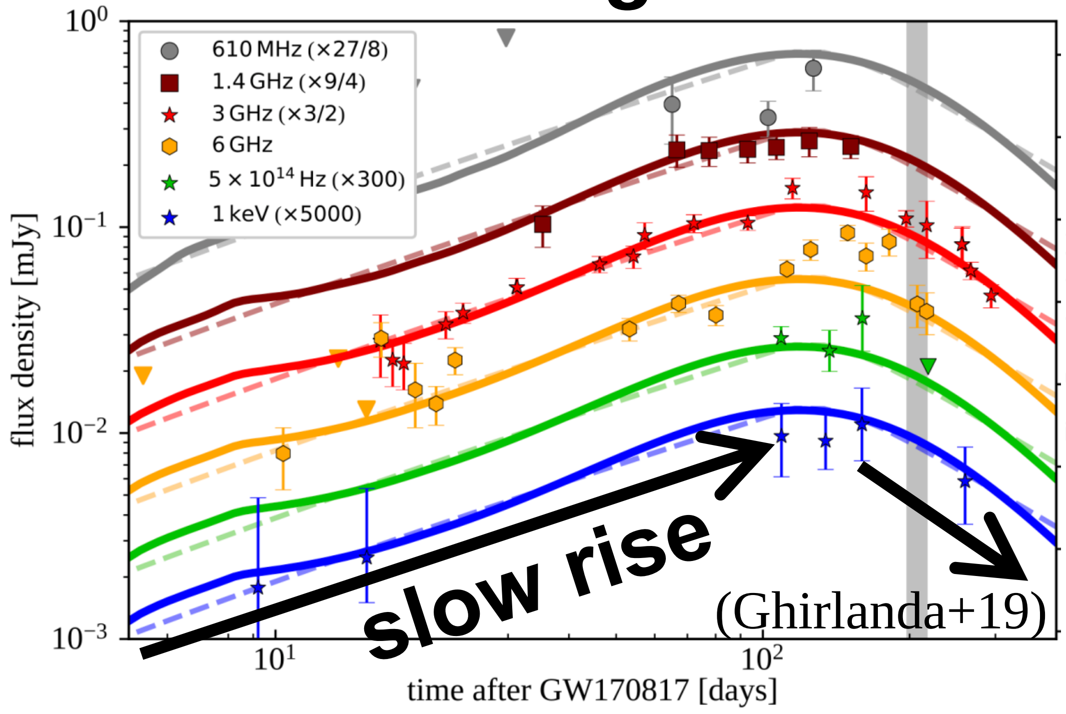
kilonova（optical, IR）

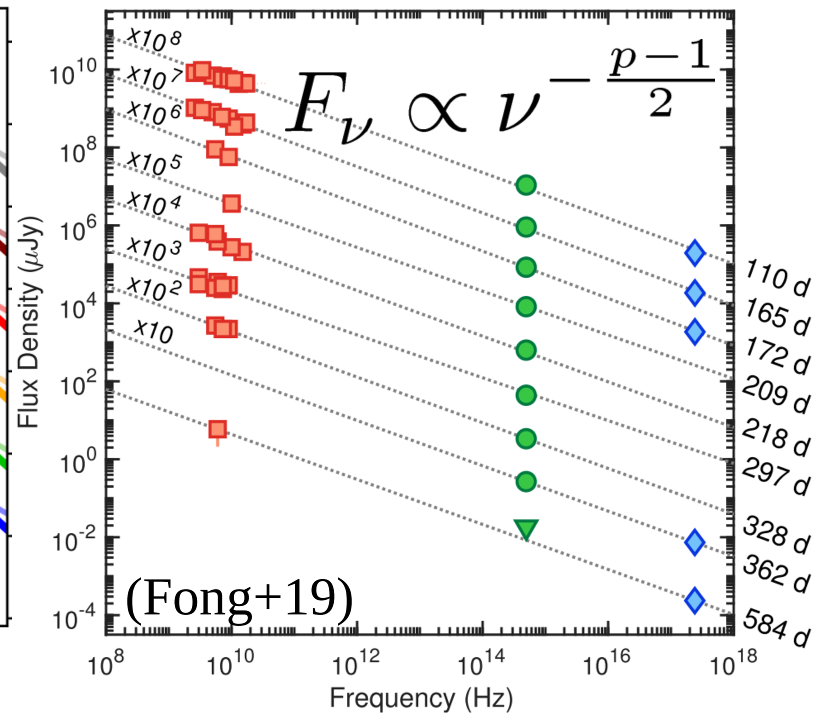
GRB afterglow（radio, optical, X-ray）

# Multi-Messenger Astronomy!

picture: from LIGO website

# Afterglow of GRB170817A



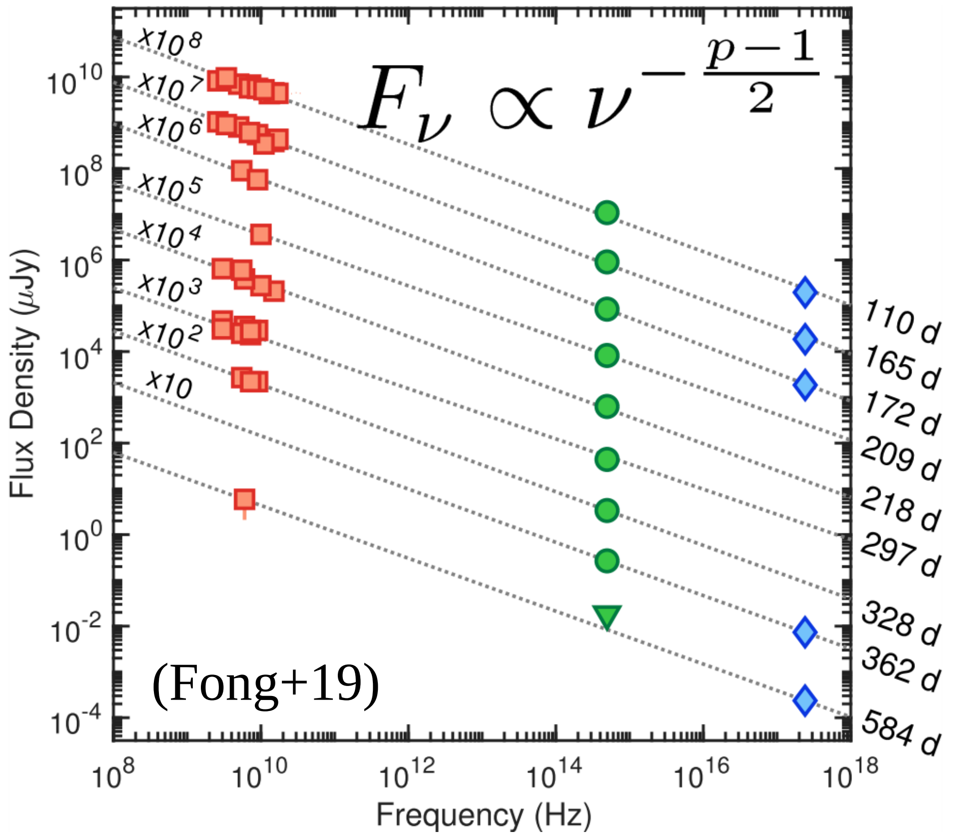

- **slow rising & rapid decline after the peak**
- **single power-law spectrum**
- **super-luminal motion of a compact source detected by VLBI**

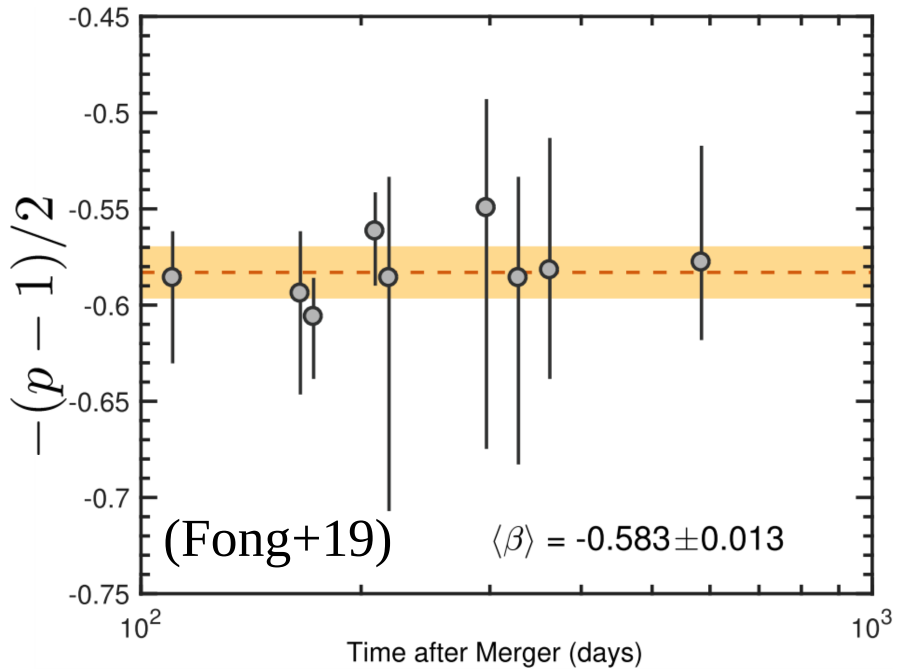
⇒

* **Synchrotron radiation from a relativistic jet**

* **The jet is structured and is viewed from off-axis.**

# Spectrum: a single power-law from radio to X-ray



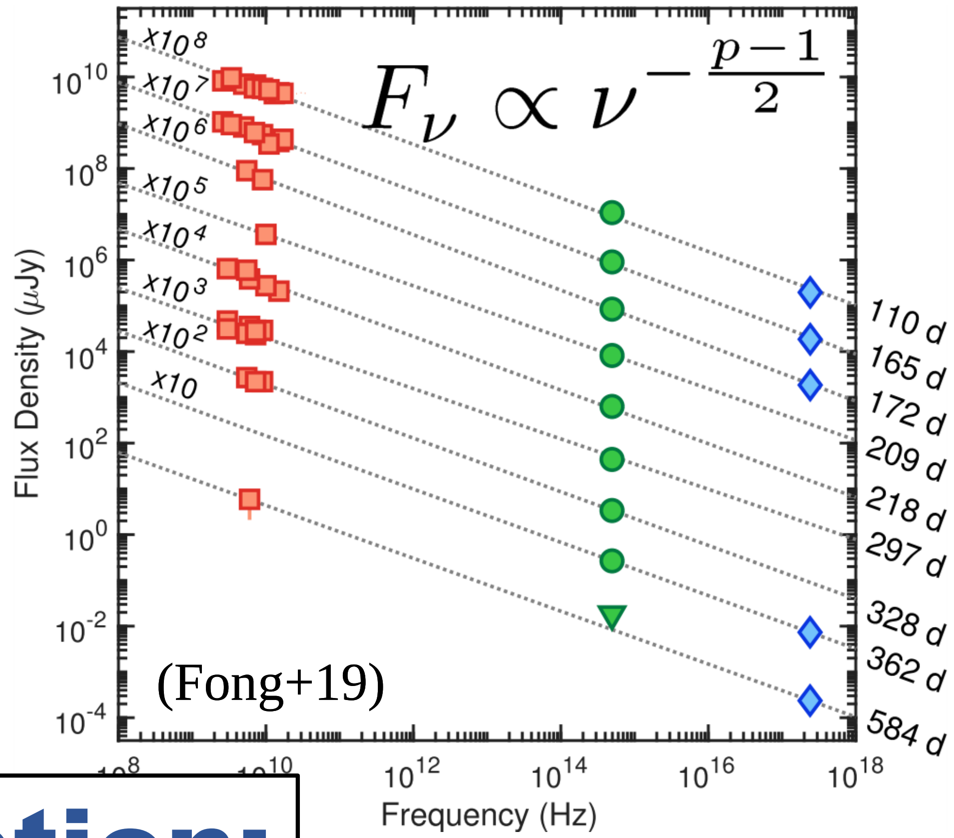

It is consistent with *p* = const.
But, the obs. errors are large.

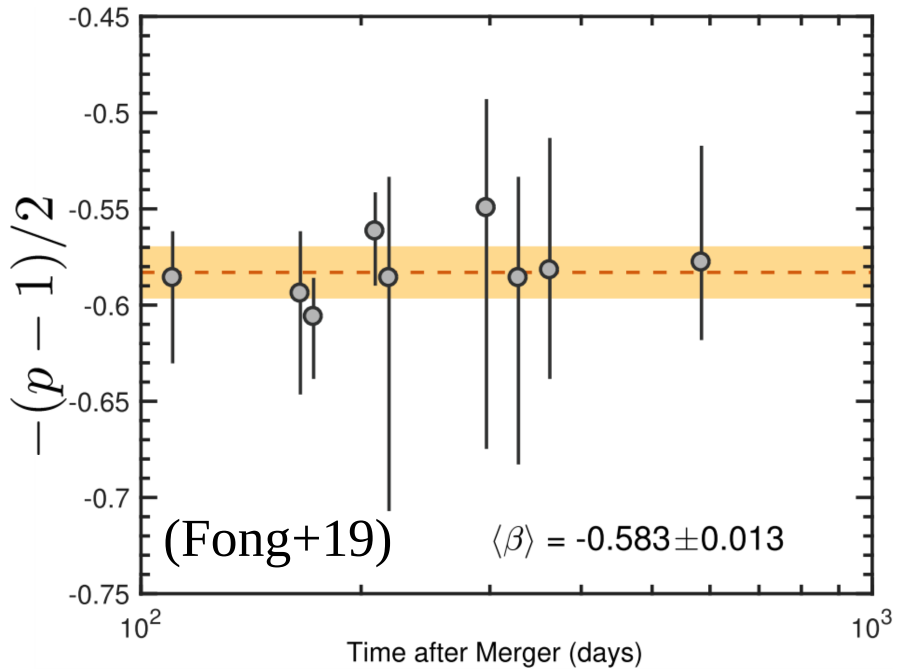
**Indeed, the observation is still consistent if we use a particle acceleration model in which *p* changes with the shock speed.** (KT et al. in prep.)

**p: energy spectral index of the accelerated electrons**

$$f(E)\mathrm{d}E \propto E^{-p}\mathrm{d}E$$

# Spectrum: a single power-law from radio to X-ray

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But, the obs. errors are large.

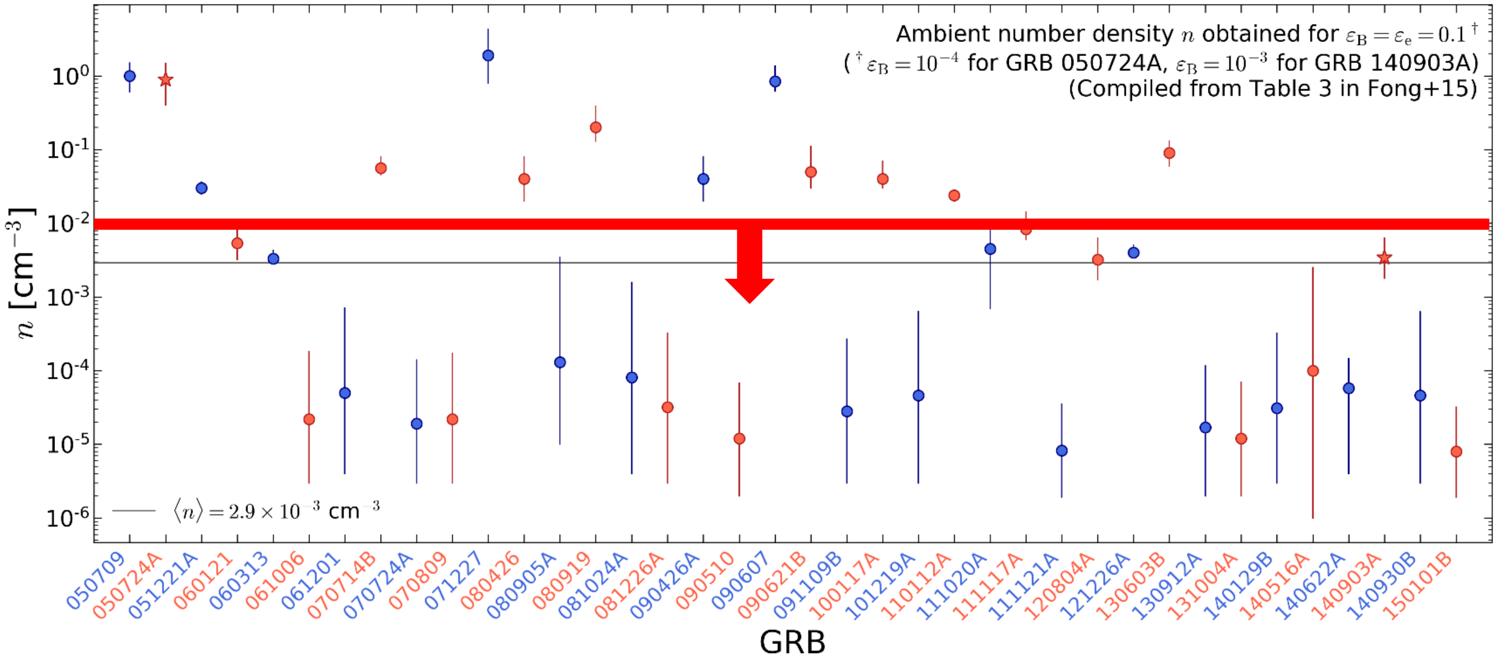
**Question:**

**Can we obtain the evolution of *p* more precisely in future observations of off-axis GRB afterglows?**

# Motivation:

1. Short GRBs can take place in a dense environment.
   Afterglow fluxes become larger for denser ISM.

**ISM number density in short GRBs**



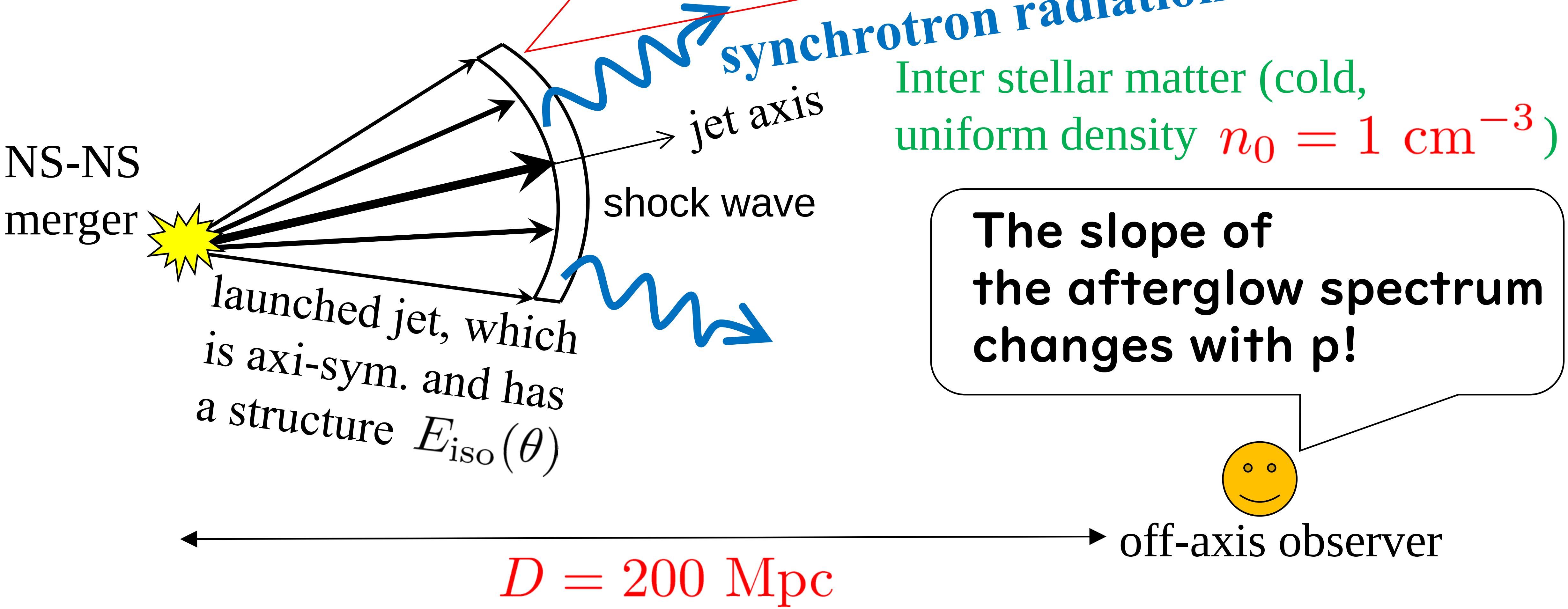

upper limit for GRB 170817A (Hajela+19)

2. Afterglows of nearby (D< 200 Mpc) off-axis short GRBs will be detected as a counterpart of gravitational wave signals.

# Method

# Off-axis afterglow model:

**Electrons are accelerated at the forward shock.**
**We assume an acceleration model** $p = p(\Gamma_{\rm sh})$



# Observed afterglow flux (Sari+98, Granot+99, van Eerten+10)

$$F_\nu(T) = \frac{1}{4\pi D^2}\int \mathrm{d}\Omega\ \mu R^2 \frac{\epsilon'_{\nu'}(1-e^{-\tau_\nu})}{\alpha'_{\nu'}\Gamma^3(1-\beta\mu)^3}\Bigg|_{t=t(T,\Omega)}$$

Local synchrotron emission

$\epsilon'_{\nu'}(E_{\rm iso}, n_0, \varepsilon_B, \varepsilon_e, p)$ : emissivity

$\alpha'_{\nu'}(E_{\rm iso}, n_0, \varepsilon_B, \varepsilon_e, p)$ : absorption coefficient

$p=p(\Gamma_{sh})$ : electron power-law index

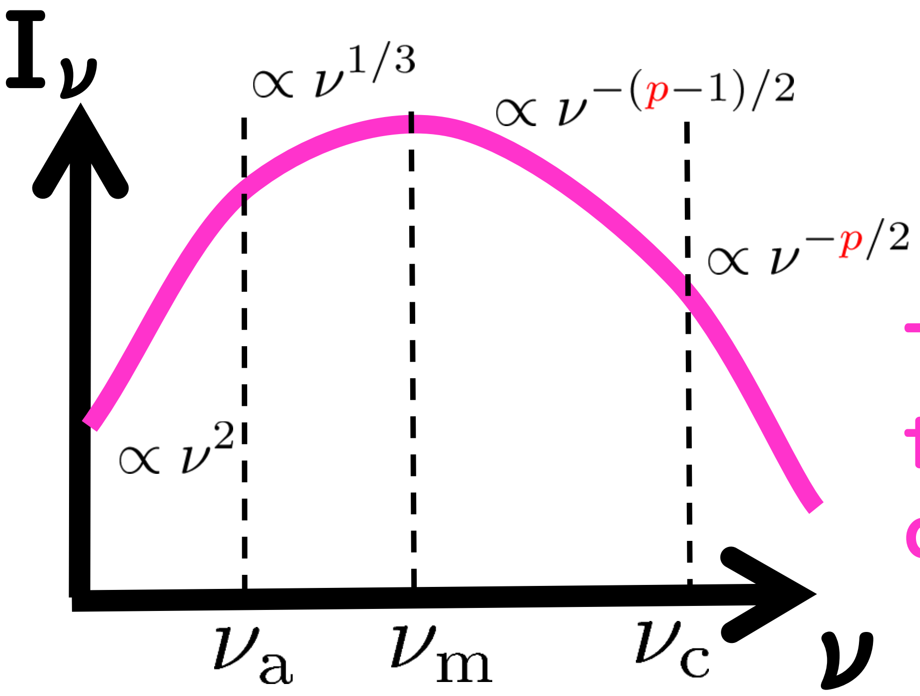
$n_o$ : ISM number density

$\varepsilon_{\rm B}$ : energy conversion fraction to B-field

$\varepsilon_{\rm e}$ : energy conversion fraction to e-accel.

$\tau_\nu$ : optical depth

$\mu$ : cosine of the angle btw. the radial direction and the line of sight




The shape of the spectrum depends on $p$

Shock dynamics model

- Each segment expands as if it were a portion of a spherically expanding shell.
- Blandford & McKee 1976 (Rela. regime) + Sedov & Taylor (Non-rela regime)
- Thin shell approximation

# Particle acceleration model

*As an example,* we use the model of Keshet & Waxman (2005):

* parallel shock
* isotropic diffusion
* Relativistic effects

$$p = \frac{3\beta_u - 2\beta_u\beta_d^2 + \beta_d^3}{\beta_u - \beta_d} - 2$$

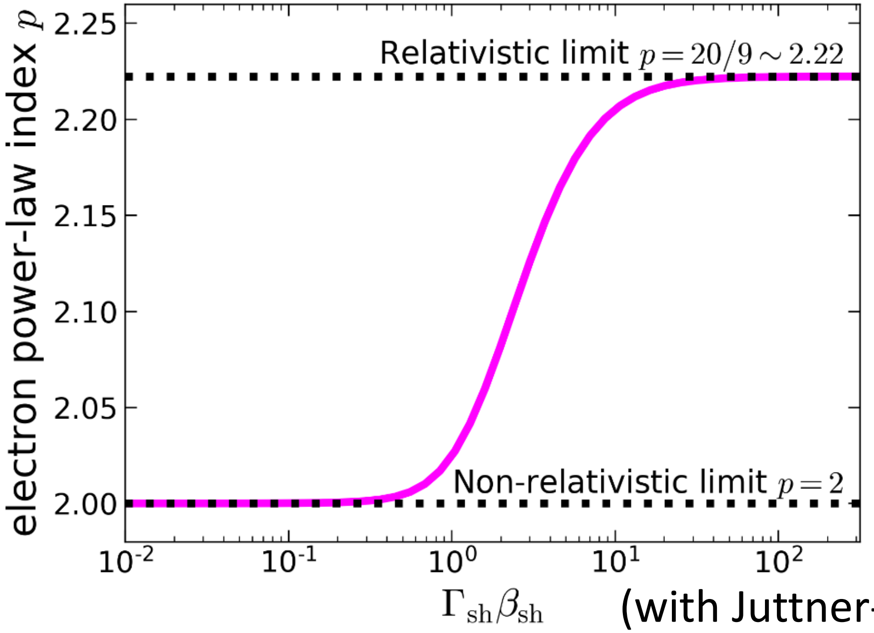
$\beta_{u,d}$ : shock upstream& downstream speeds measured at the shock rest frame

Relativistic limit:

$$p \to 2.22 \ (\Gamma_{\rm sh} \to \infty)$$

Non-relativistic limit:

$$p \to 2 \ (\Gamma_{\rm sh} \to 1)$$



(with Juttner-Synge EoS)

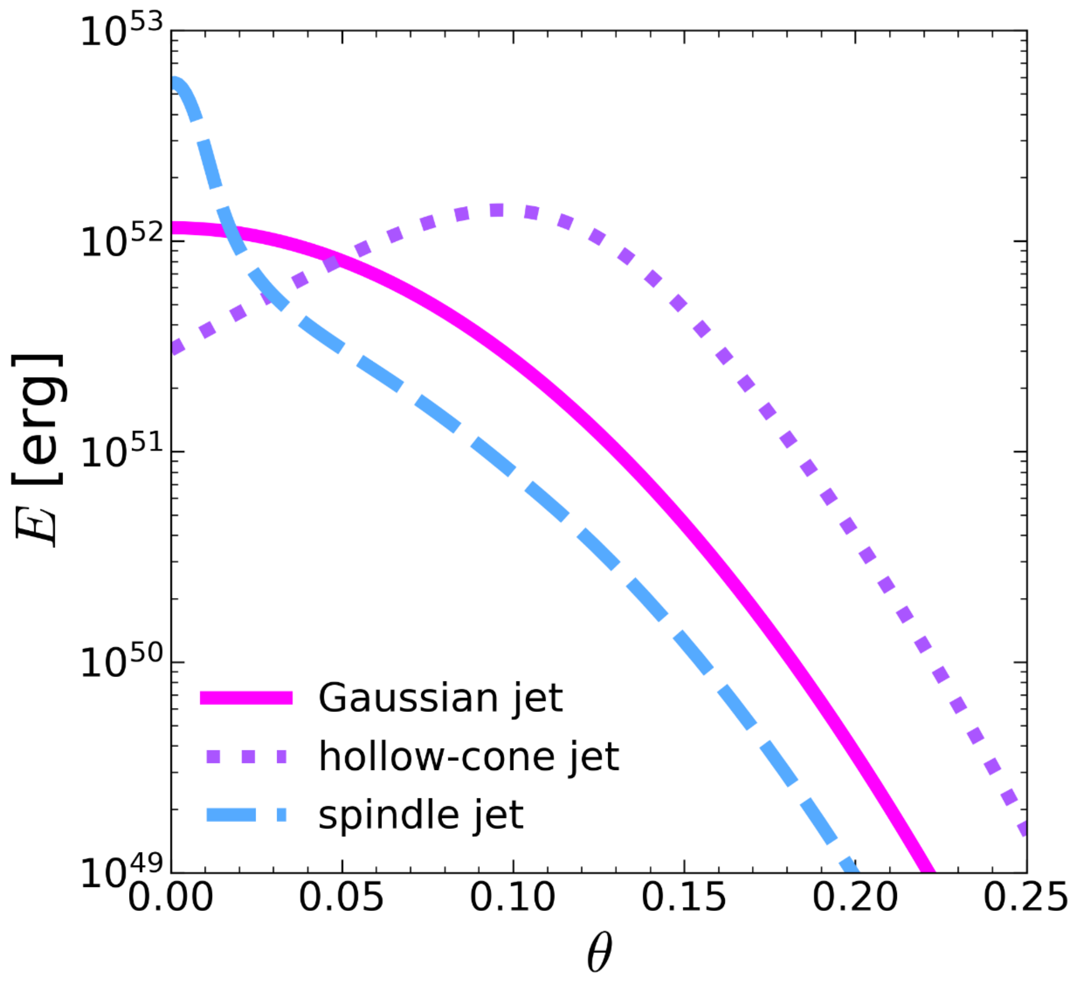
* This model is consistent with the afterglow spectra of GRB 170817A. (KT et al., in prep.)

# Jet structures and afterglow parameters

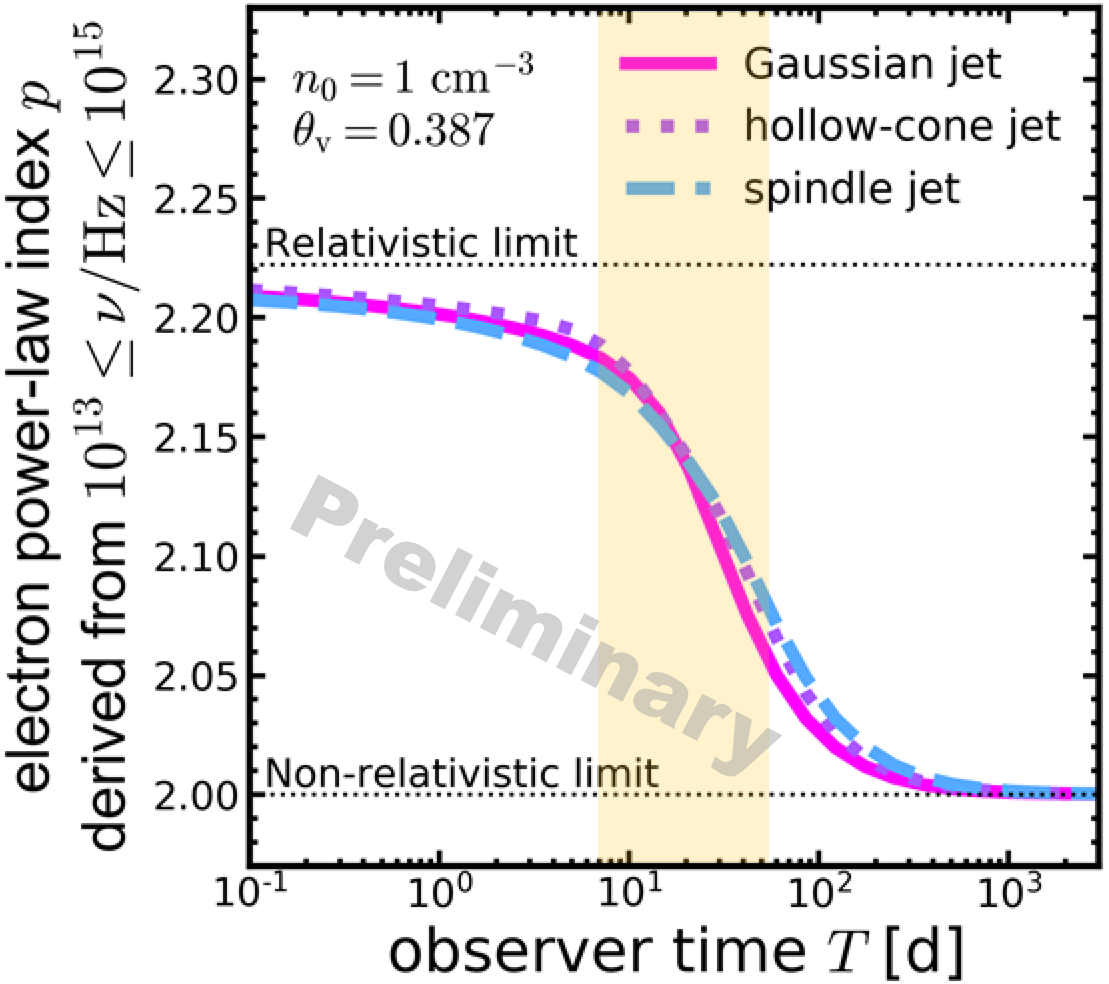
We apply three jet structures that are consistent with the afterglow of GRB 170817A.
(KT & Ioka 2021)

The values of afterglow parameters $\varepsilon_{\rm B}, \varepsilon_{\rm e}$ are the same as those used for GRB 170817A.

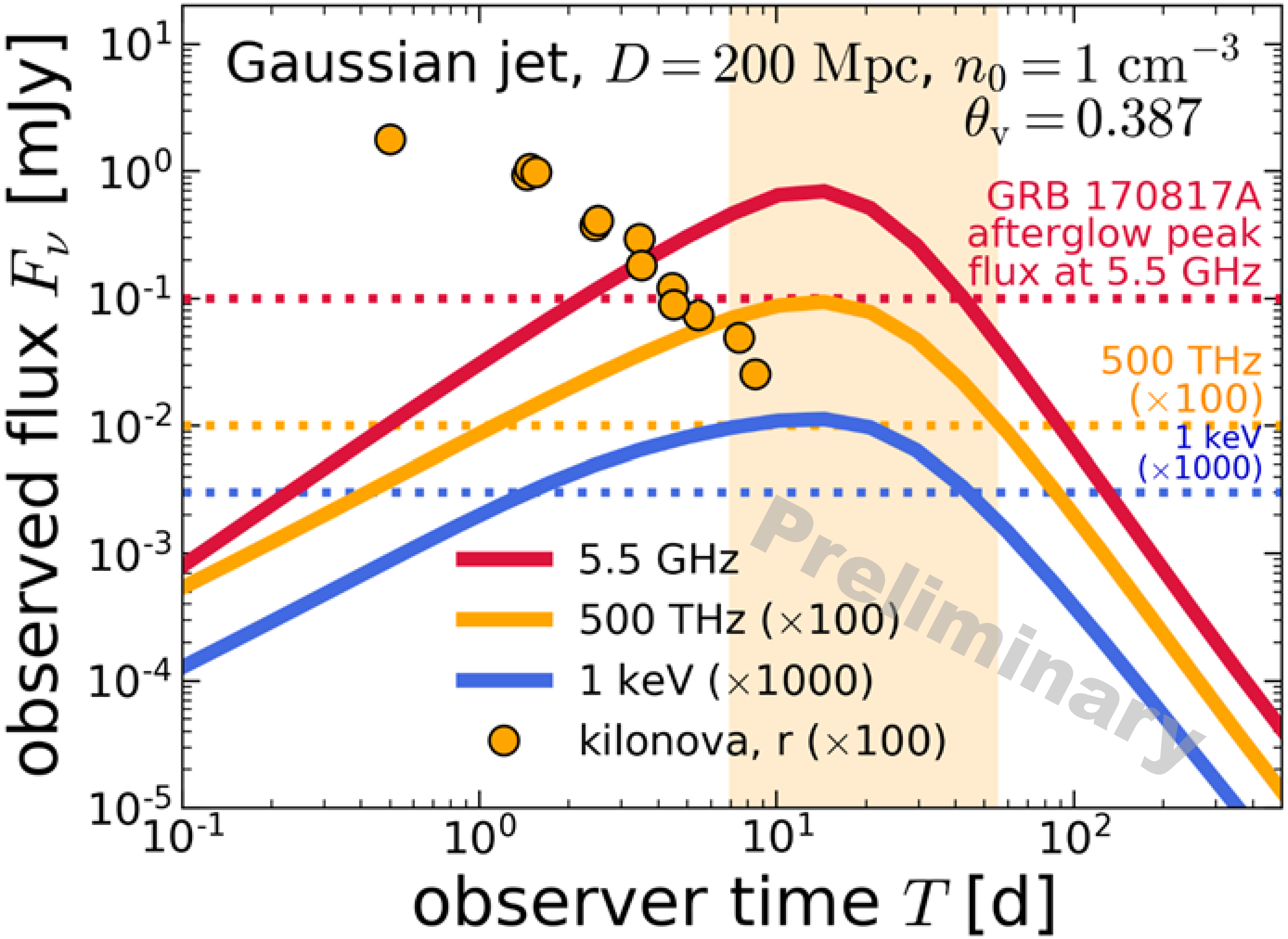
The viewing angle is changed in the range of $0.25 \leq \theta_{\rm v} \leq 0.5$



Electron power-law index *p* derived from the spectral slope

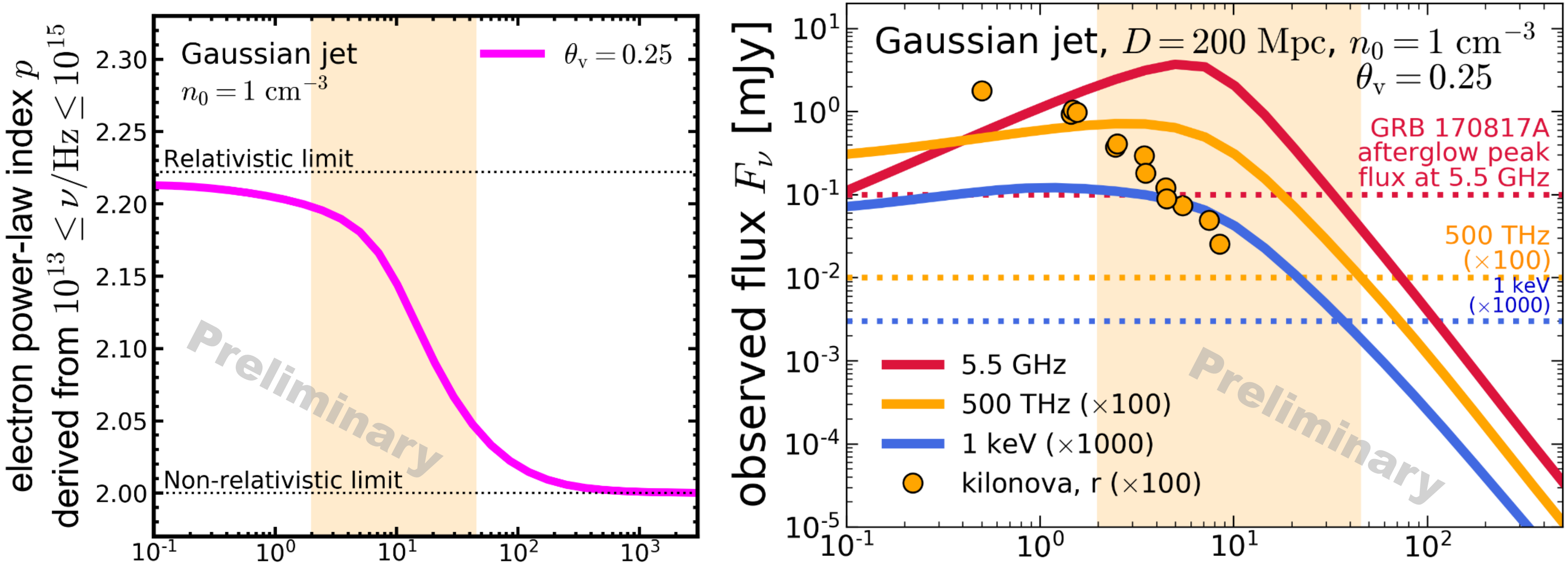



# Afterglow light curves

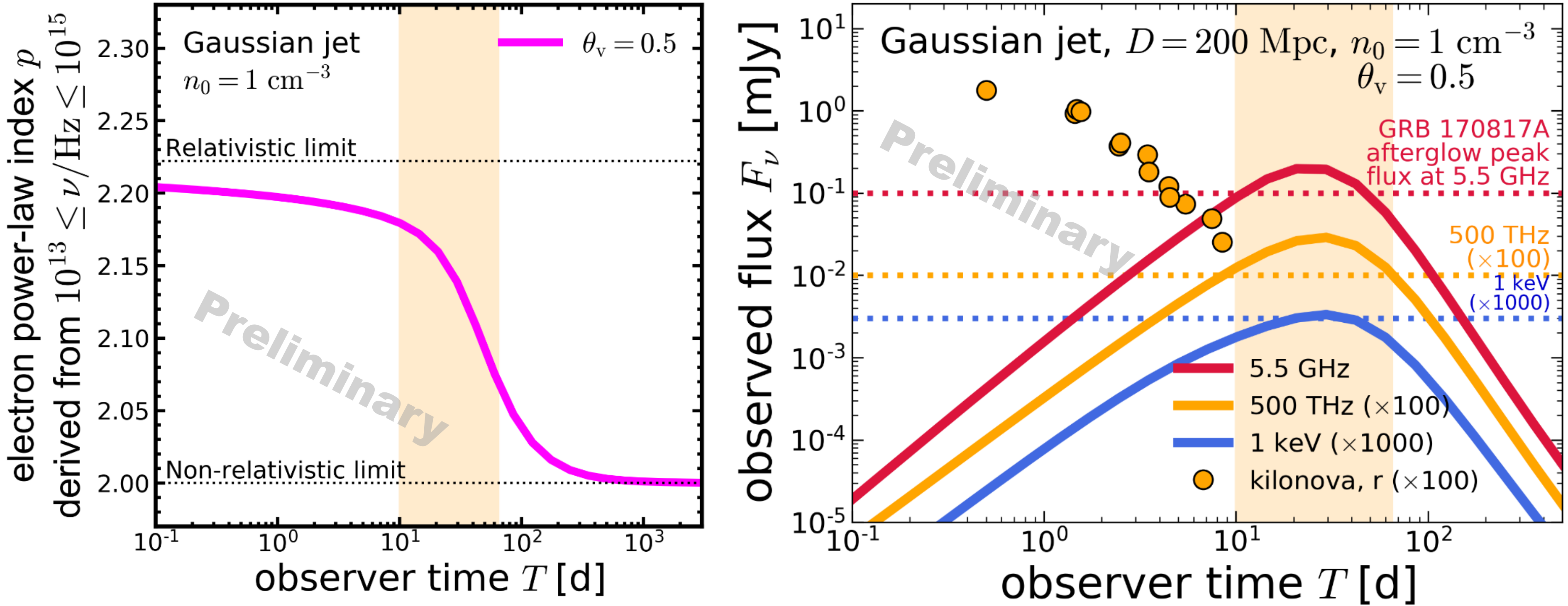



**The transition phase of *p* could be observed!**

Smaller viewing angle




Larger viewing angle



# Summary & Conclusion

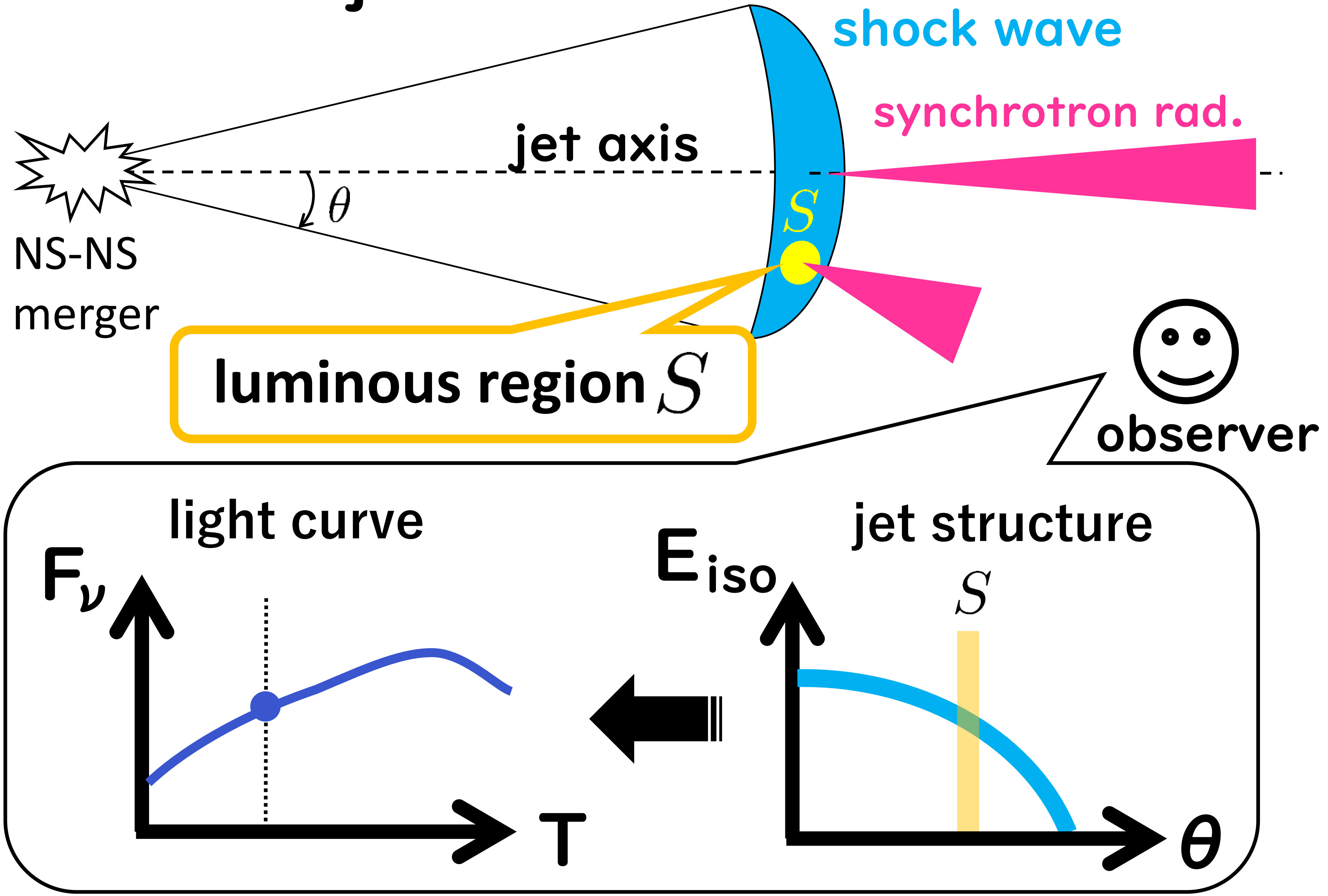
Off-axis GRBs similar to GRB 170817A, but with

- larger ISM density: $n_0 = 1\ \mathrm{cm}^{-3}$
- larger luminosity distance: $D = 200\ \mathrm{Mpc}$
- viewing angle: $0.25 \leq \theta_{\mathrm{v}} \leq 0.5$

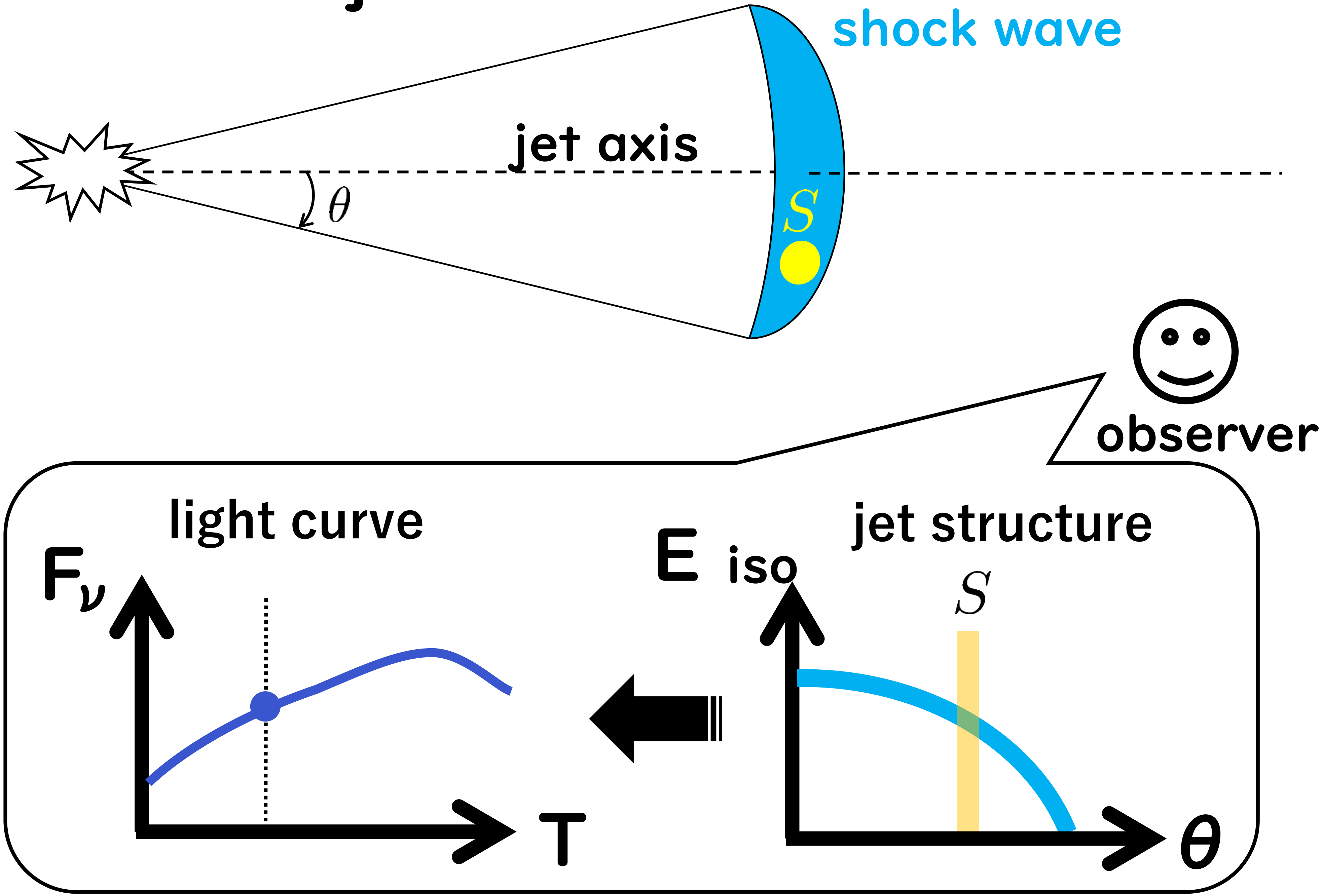
➡ The transition of the electron power-law index p from relativistic to non-relativistic regimes would be more clearly observable than in GRB 170817A in the timescale from days to several tens of days.

# Backup

# Structured jet + off-axis



# Structured jet + off-axis

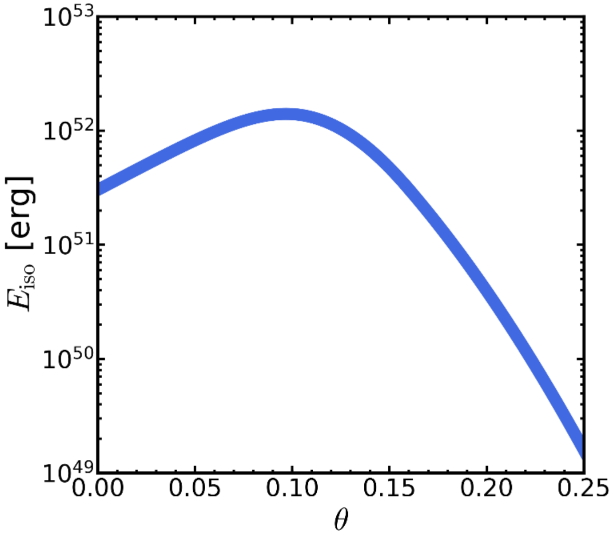


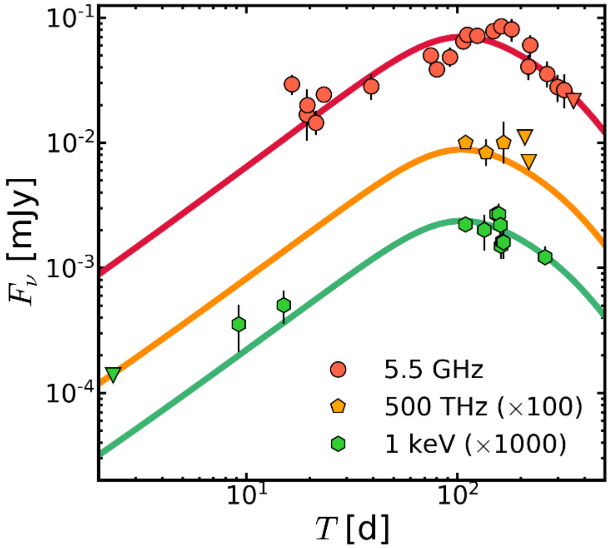
# Diversity of the possible jet structures (KT & Ioka 2020, 2021)

## Jet structure

## Afterglow light curve

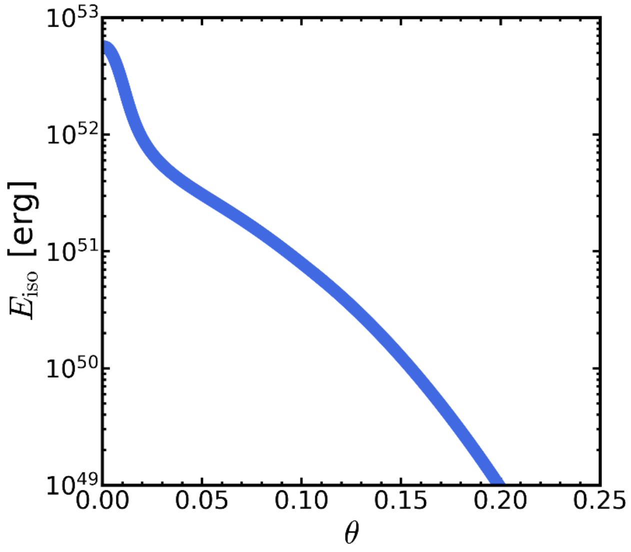
**Hollow-cone jet**

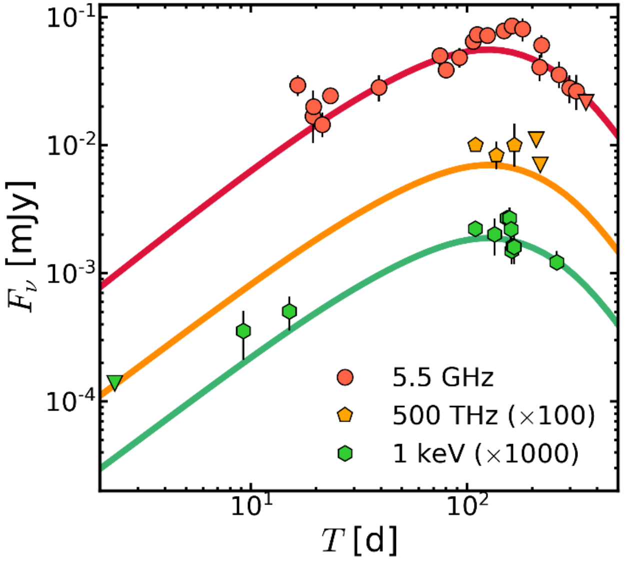



consistent with the observations!

**Spindle jet**




consistent with the observations!

Gaussian jets and power-law jets are also candidates.