Diverse jet structures consistent with the off-axis afterglow of GRB 170817A

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KT & Ioka (2021), arXiv:2007.13116
KT & Ioka (2020), arXiv:1912.01871

Neutron Star Merger GW170817

EM counterparts

short GRB
GRB 170817A

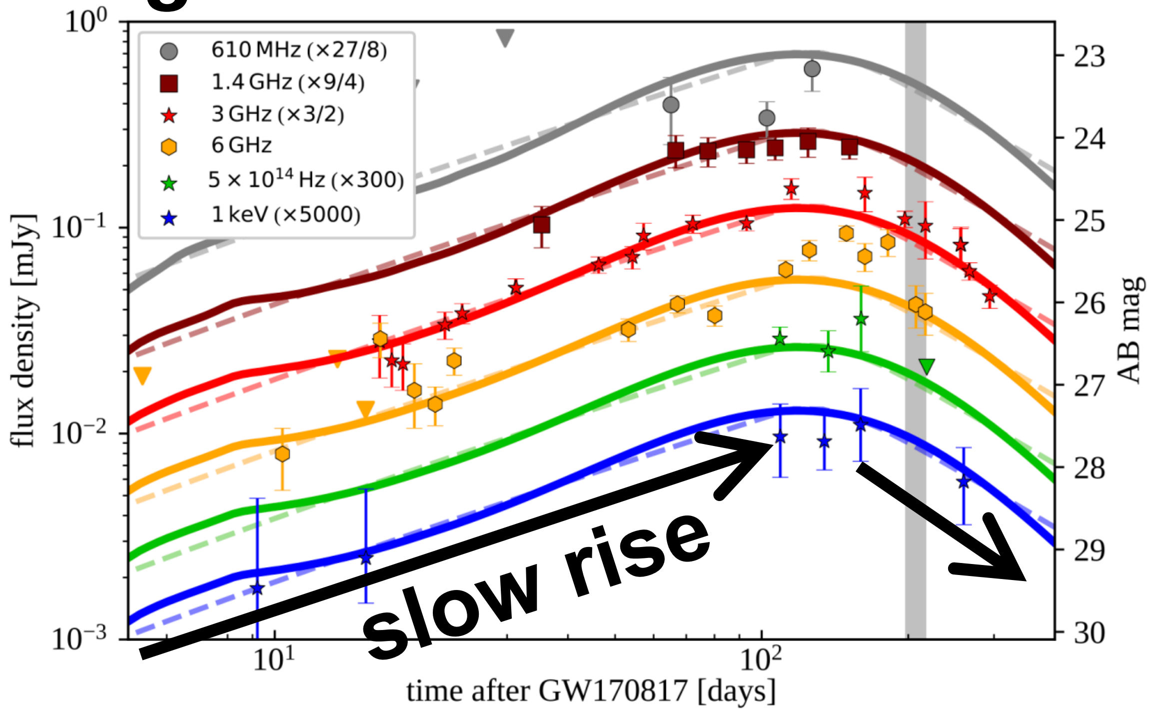
GRB afterglow（radio, optical, X-ray）

kilonova（optical, IR）

picture: from LIGO website

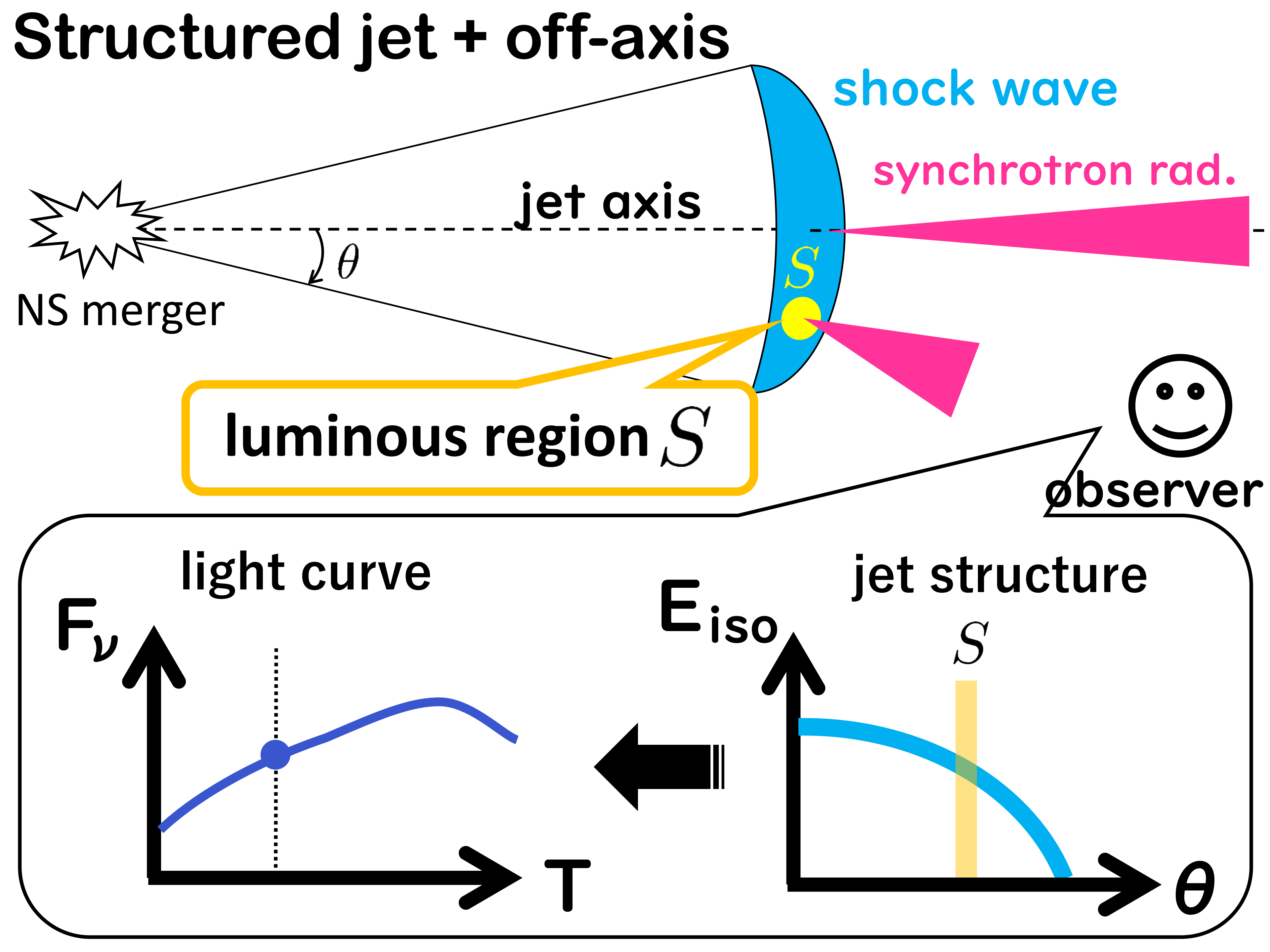
Afterglow of GRB170817A

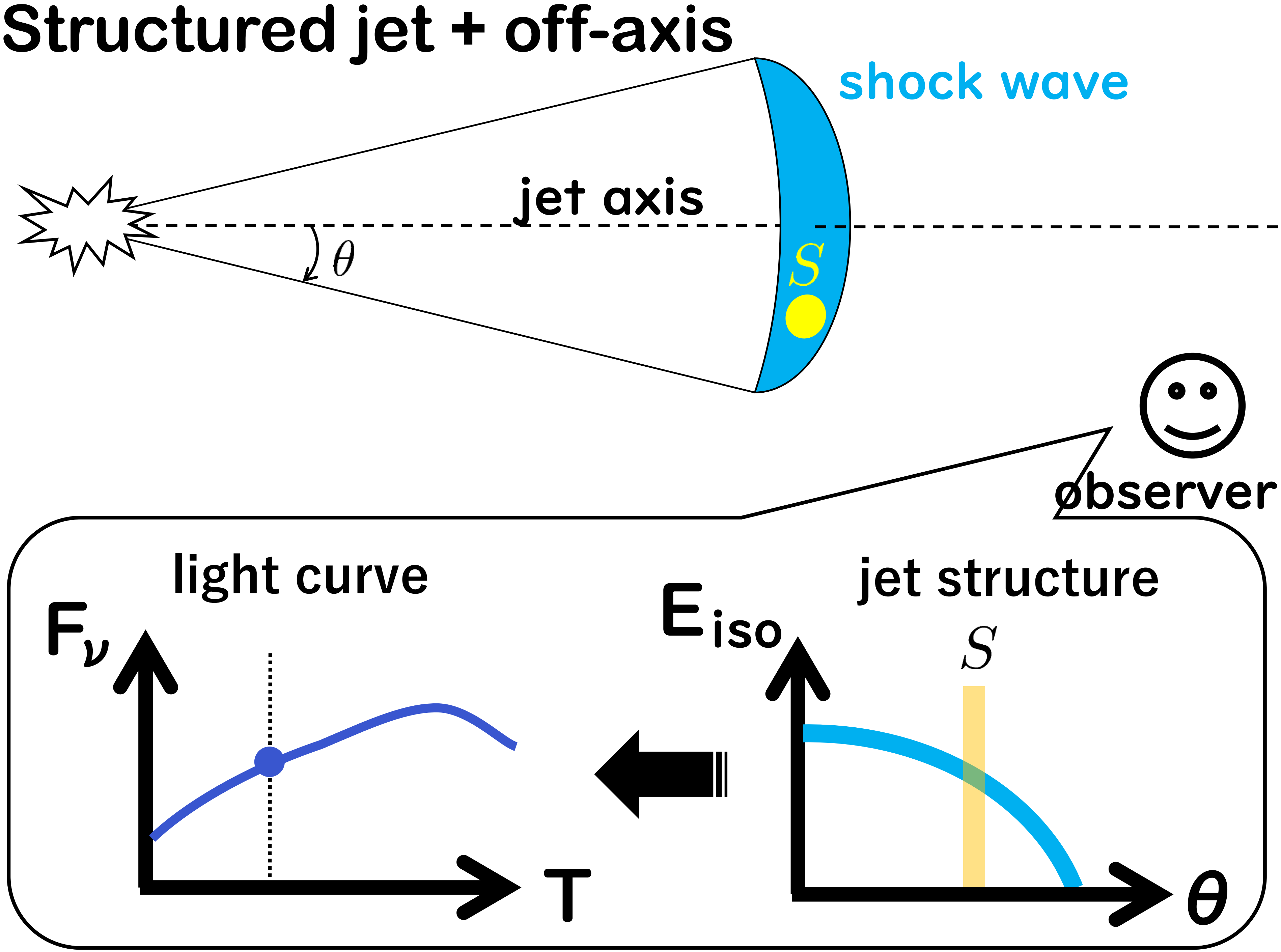
(Ghirlanda+19)



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

➡ **Synchrotron from a relativistic jet**


Structured jet + off-axis
shock wave
synchrotron rad.
jet axis
θ
NS merger
S
luminous region S
observer
light curve
F_ν
T
jet structure
E_{iso}
S
θ



Structured jet + off-axis
shock wave
jet axis
θ
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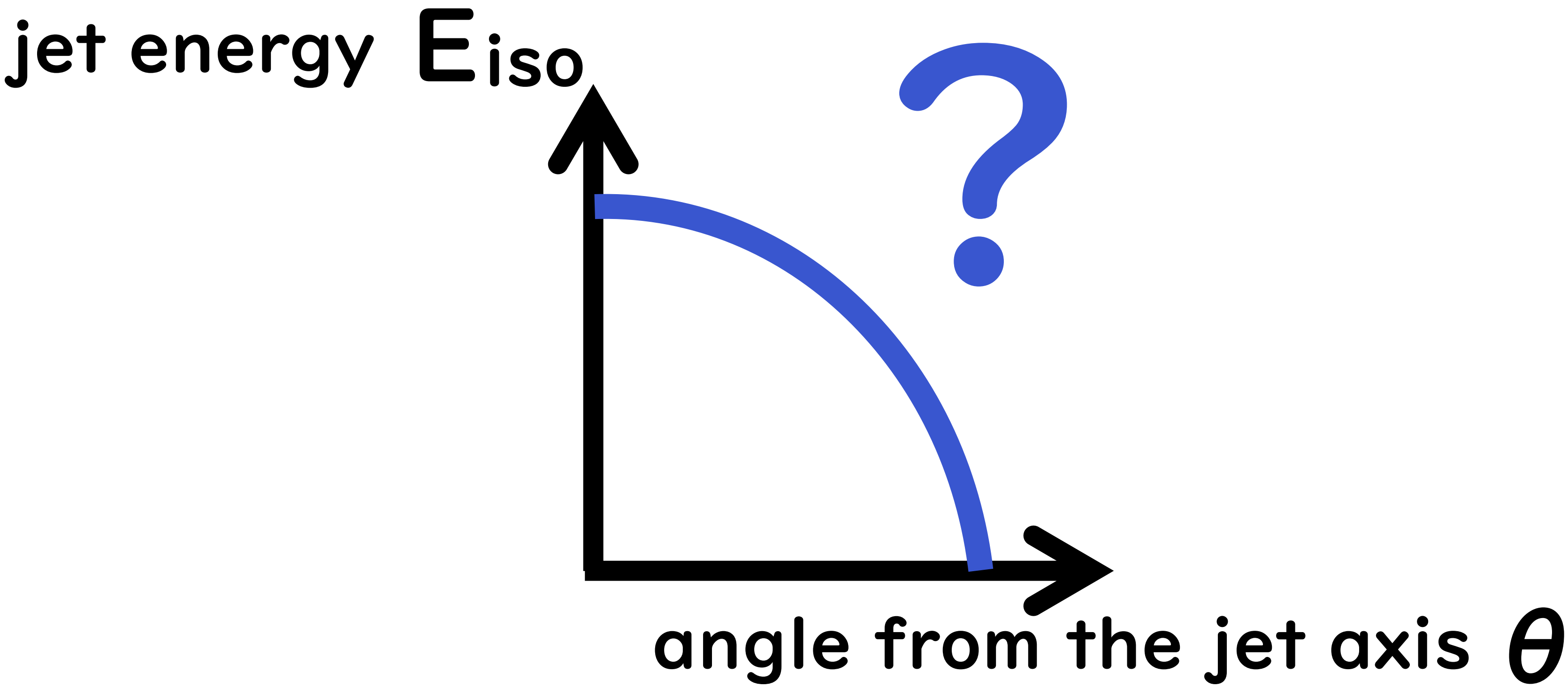
What is the jet structure?



Previous studies *assume* a power-law or a Gaussian.

(D'Avanzo+18, Ghirlanda+19, Lyman+18, Resmi+18, Troja+19, 20…)

Our motivation: Are there *other possible structures* that can explain the observed afterglow light curve?

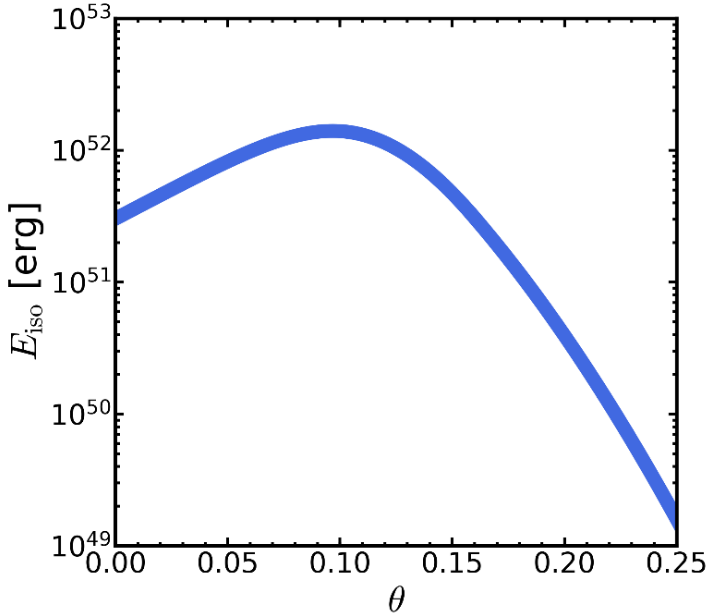
Yes!

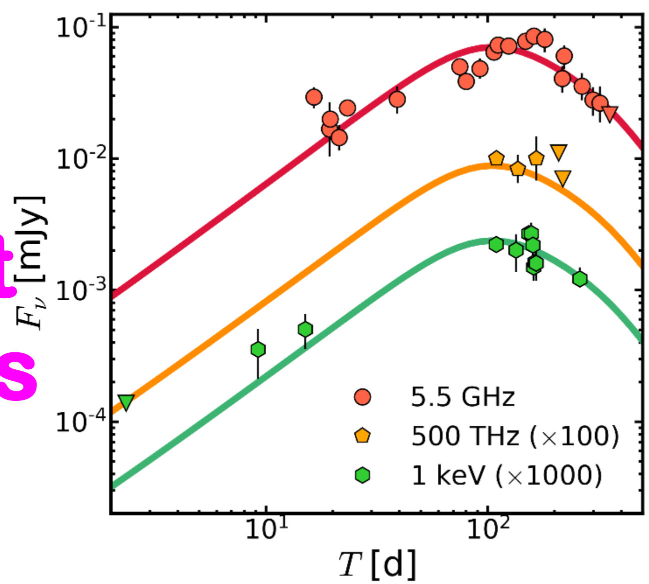
New jet structures

$$E_{\mathrm{iso}}(\theta)$$

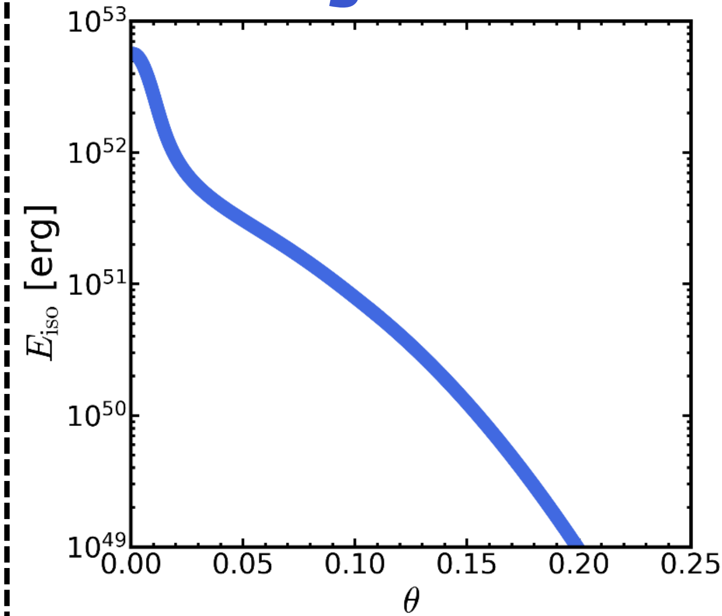
consistent light curves

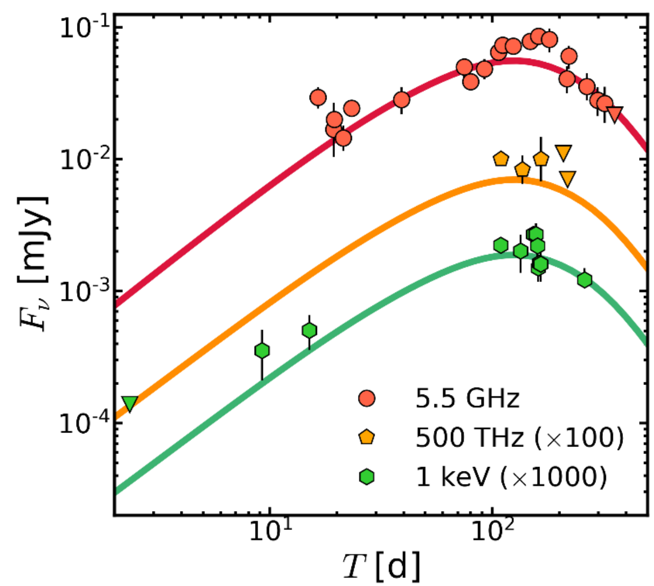
Hollow-cone jet



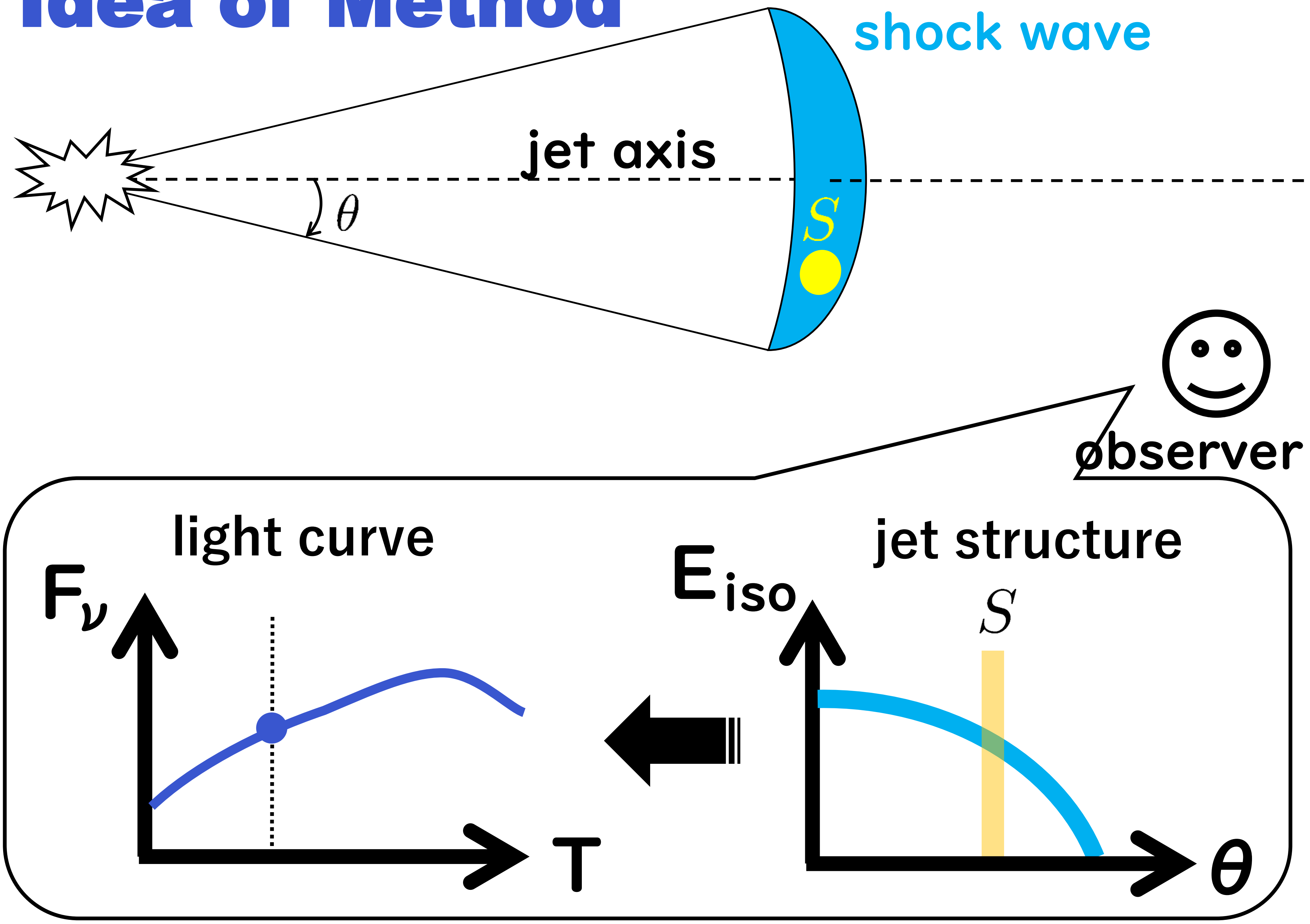


Spindle jet

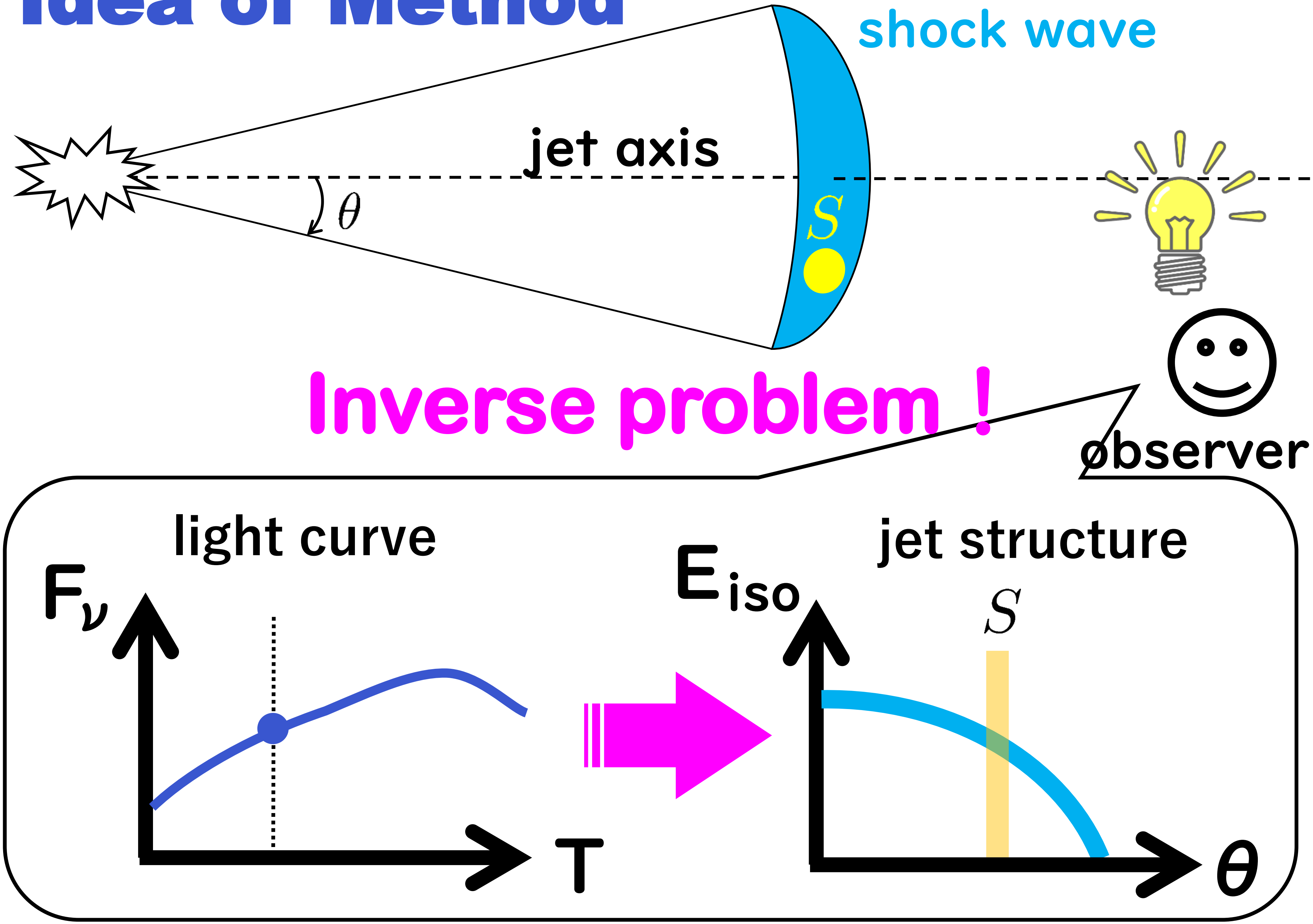




Idea of Method



Idea of Method



Basic eq. (van Eerten+10) Assumptions：axi-sym., cold uniform ISM

$$F_\nu(T) = \frac{1}{4\pi D^2}\int_{\theta>\theta_S} \mathrm{d}\Omega\, R^2\Delta R \left.\frac{\epsilon'_{\nu'}}{\Gamma^2(1-\beta\mu)^2}\right|_{t=t(T,\Omega)}$$

Integrate the luminous shock surface

Synchrotron emissivity (+relativistic beaming effects)

Sari+98

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

n_o : ISM density

ε_B ε_e : phenomenological params.

p : electron power-law index

Shock dynamics

Blandford & McKee 76

$$\Gamma_{\rm sh}\beta_{\rm sh} \sim \sqrt{\frac{17E_{\rm iso}}{8\pi n_0 m_{\rm p} c^5}}\, t^{-3/2}$$

Thin shell approx.

$$\Delta R = R/12\Gamma^2(1-\beta_{\rm sh}\mu)$$

$$F_\nu(T) = \int_{\theta>\theta_S(T)} f(E_{\rm iso}(\theta), n_0, \varepsilon_{\rm B}, \varepsilon_{\rm e}, p, \theta_{\rm v})\mathrm{d}\Omega$$

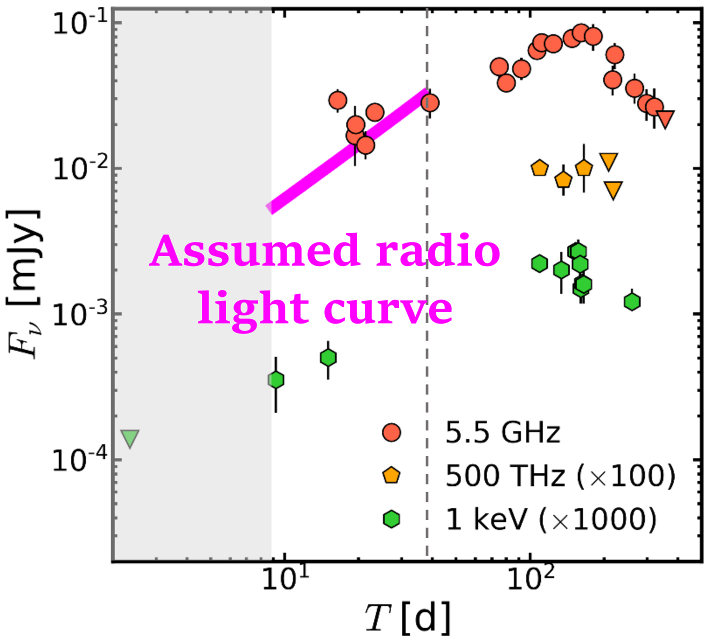
viewing angle

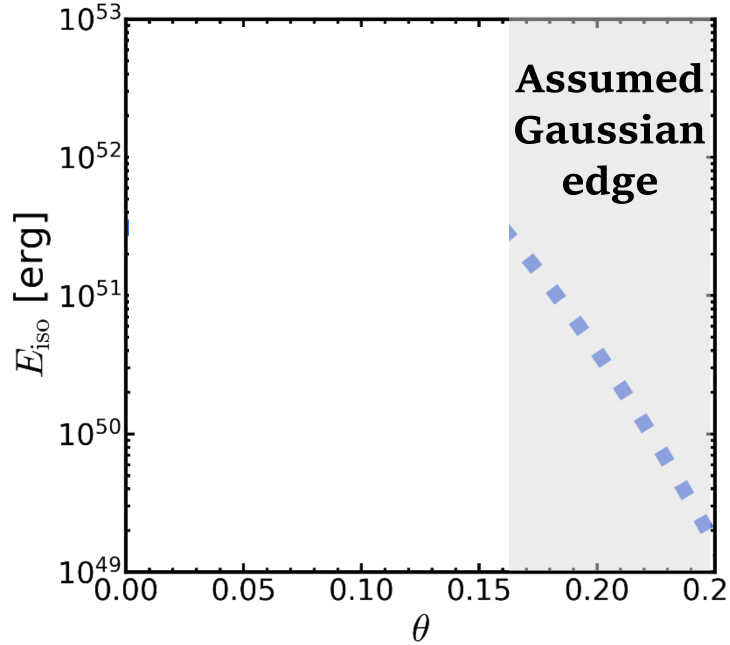
O.D.E. for inversion

$$\frac{\mathrm{d}E_{\rm iso}}{\mathrm{d}\theta_S} = g(F_\nu(T), n_0, \varepsilon_{\rm B}, \varepsilon_{\rm e}, p, \theta_{\rm v})$$

[See KT & Ioka (2020,2021) for the function g]

Results Hollow-cone jet





Assumed slope of the radio light curve

$$\boxed{\frac{\mathrm{d}\log F_\nu}{\mathrm{d}\log T} = a(T - T_0) + 1.22 \quad (a > 0,\ T_0 = 9\ \mathrm{d})}$$

convex downward (concave)

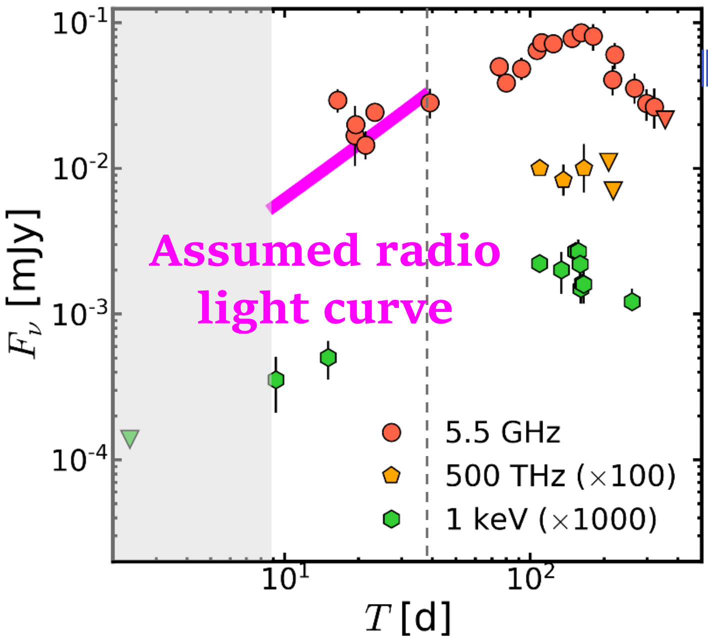
$\varepsilon_{\rm B} = 4.1 \times 10^{-5}$

$n_0 = 10^{-3}\ \mathrm{cm}^{-3}$ (cf. $n_0 < 9.6 \times 10^{-3}\ \mathrm{cm}^{-3}$: Hajela+19)

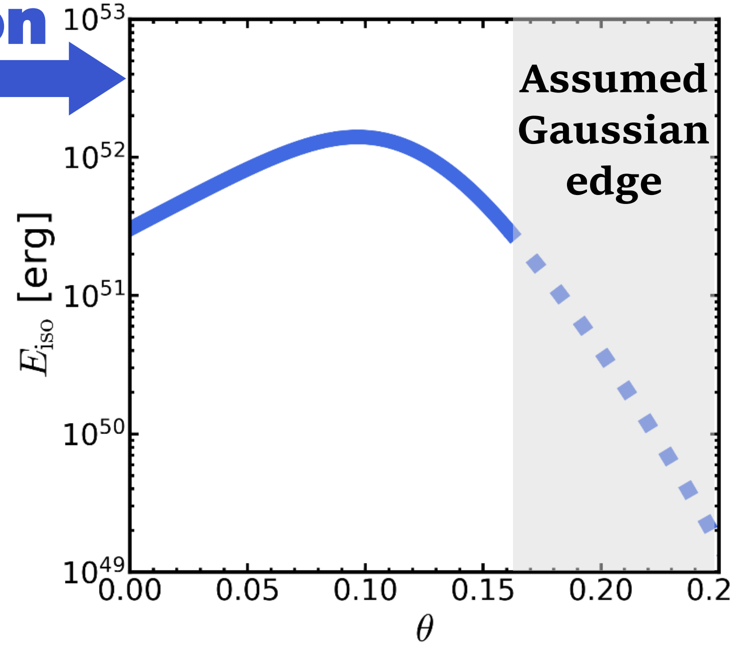
$\varepsilon_{\rm e} = 0.1 \quad \theta_{\rm v} = 0.387 = 22.2^\circ$

$p = 2.17 \quad D = 41\ \mathrm{Mpc}$

Results Hollow-cone jet



Inversion



Assumed slope of the radio light curve

$$\boxed{\frac{\mathrm{d}\log F_\nu}{\mathrm{d}\log T} = a(T - T_0) + 1.22 \quad (a > 0,\ T_0 = 9\ \mathrm{d})}$$

convex downward (concave)

$\varepsilon_{\mathrm{B}} = 4.1 \times 10^{-5}$

$n_0 = 10^{-3}\ \mathrm{cm}^{-3}$ (cf. $n_0 < 9.6 \times 10^{-3}\ \mathrm{cm}^{-3}$: Hajela+19)

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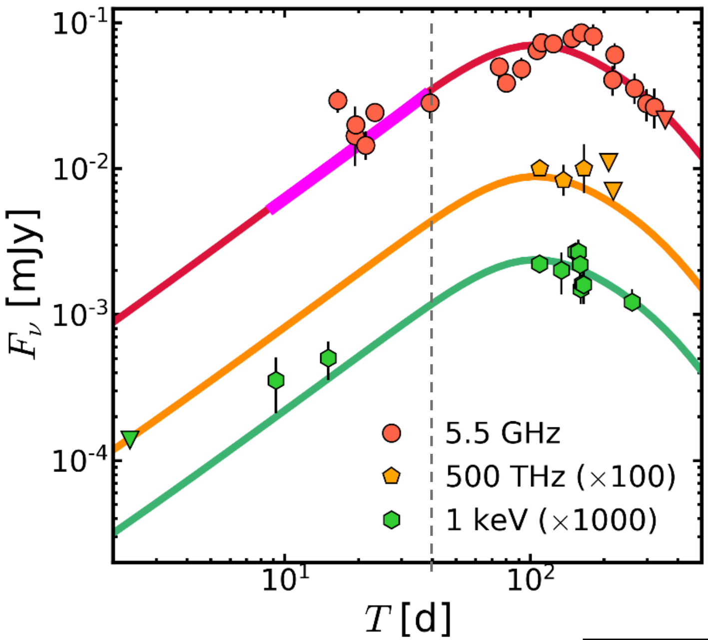
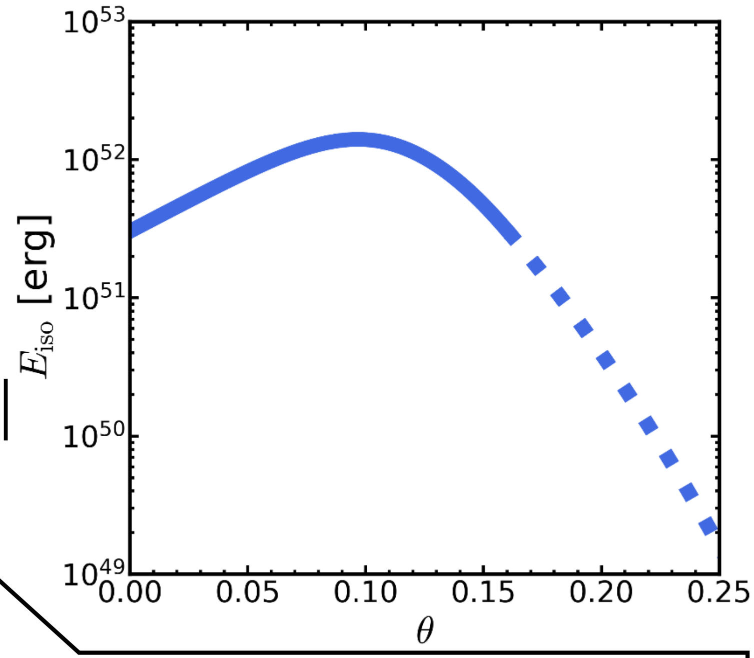
Results Hollow-cone jet





Generate the radio, optical, X-ray light curves from the reconstructed jet structure

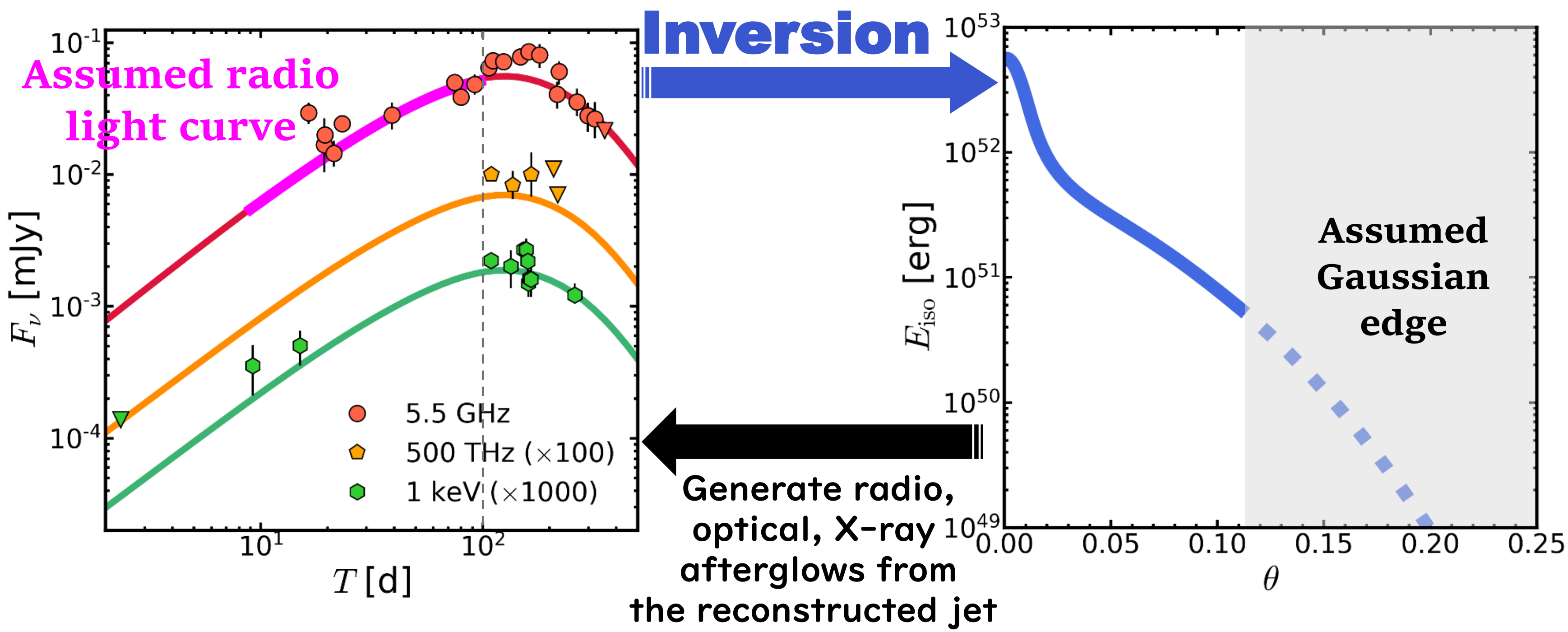
$$\varepsilon_{\rm B} = 4.1 \times 10^{-5}$$

$$n_0 = 10^{-3}\ {\rm cm}^{-3}$$ (cf. $n_0 < 9.6 \times 10^{-3}\ {\rm cm}^{-3}$: Hajela+19)

$$\varepsilon_{\rm e} = 0.1 \quad \theta_{\rm v} = 0.387 = 22.2^\circ$$

$$p = 2.17 \quad D = 41\ {\rm Mpc}$$

Results Spindle jet



Assumed slope of the radio light curve

$$\frac{\mathrm{d}\log F_\nu}{\mathrm{d}\log T} = a(T - T_0) + 1.22 \quad (a < 0,\ T_0 = 9\ \mathrm{d})$$

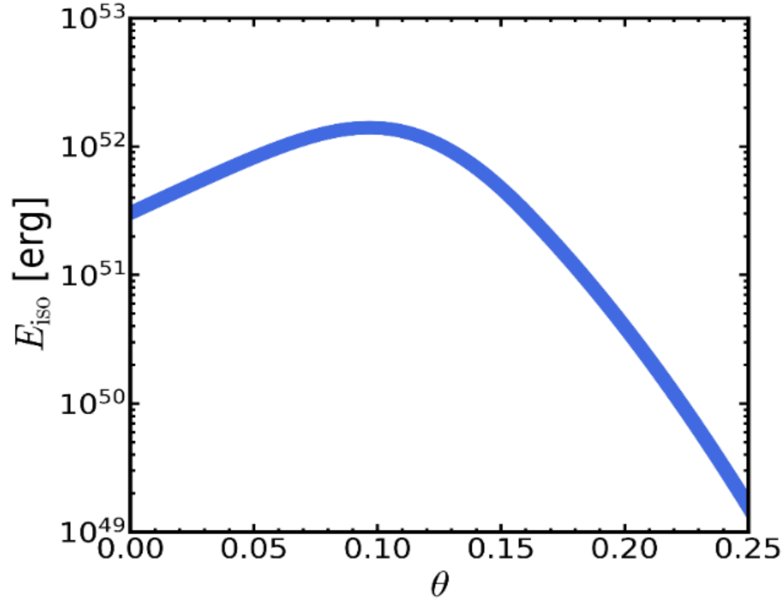
convex upward

(cf. convex downward for the hollow-cone jet)

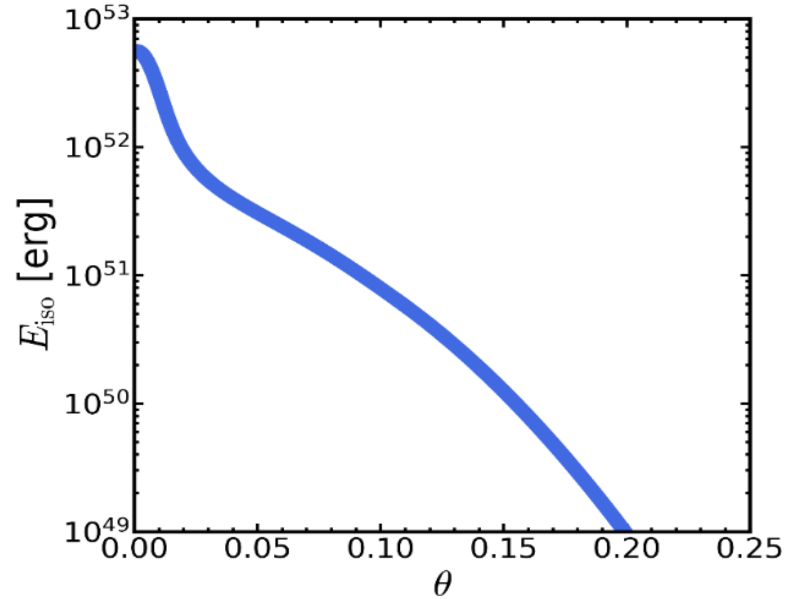
$$\varepsilon_{\rm B} = 6.6 \times 10^{-4}$$

The other parameter values are the same as those for the low-cone jet

Hollow-cone jet



Spindle jet



The hollow-cone and spindle jets are also a candidate consistent with GRB 170817A as well as a power-law and Gaussian jets.

If a similar GRB takes place in a denser environment, the afterglow can be more luminous.

(cf. $n_0 < 9.6 \times 10^{-3}\ \mathrm{cm}^{-3}$: Hajela+19)

→ We could pin down the GRB jet structure.

Summary

Idea of inversion

off-axis GRB afterglow light curve
→ jet structure

New jet candidates of GRB 170817A

Hollow-cone jet & Spindle jet
are also consistent
(as well as a power-law or Gaussian)

Future prospect

If a similar GRB takes place
in a denser environment,
the afterglow can be more luminous
→ We could pin down the GRB jet structure