Inverse reconstruction of jet structure from off-axis gamma-ray burst afterglows

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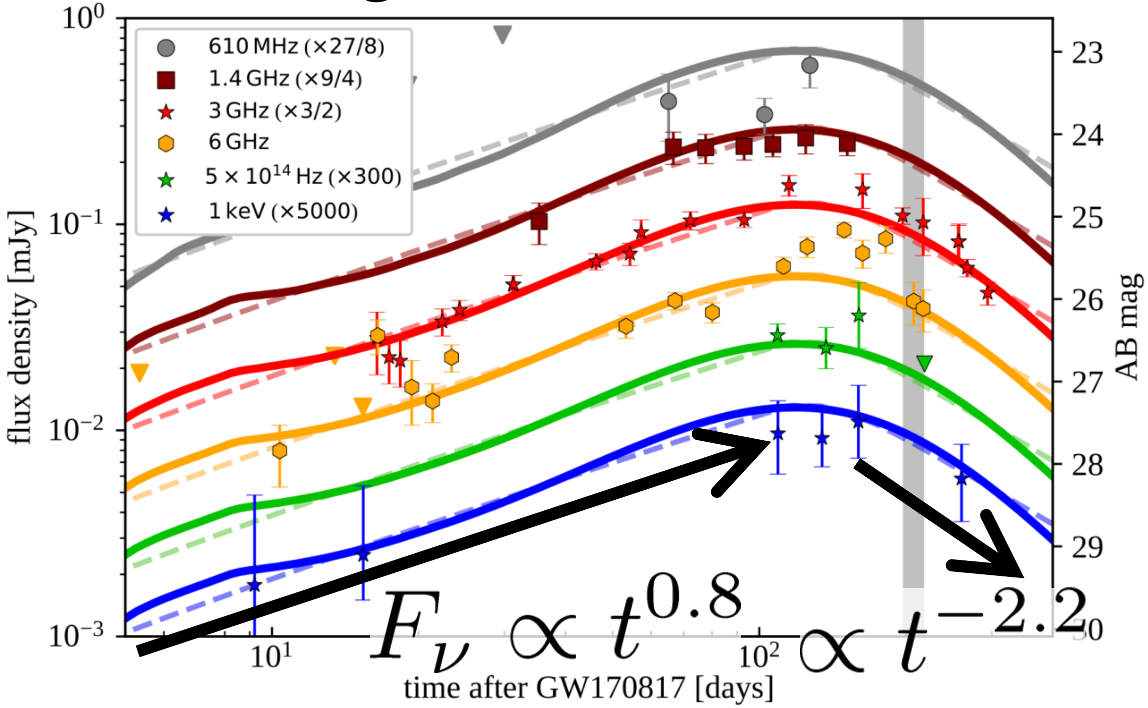
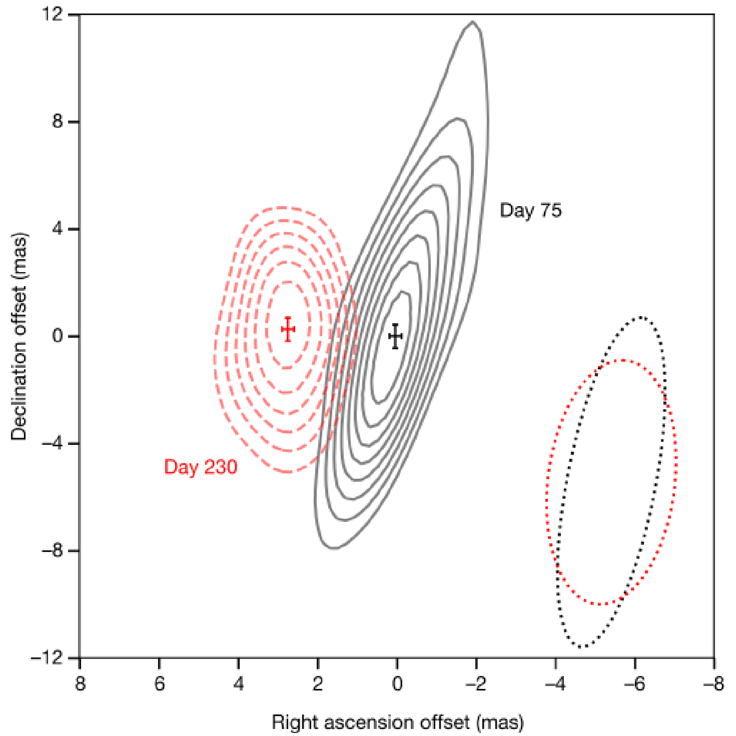
KT & Ioka (2019) arXiv:1912.01871

Artist conception of the moment two neutron stars collide.

The afterglow of GRB170817A



(Ghirlanda+19, Mooley+18b)



(Mooley+18a)

- Slowly-rising afterglow light curve
- Rapid decline of the afterglow after the peak
- Super-luminal apparent motion

➡ **We saw a structured jet from off-axis.**

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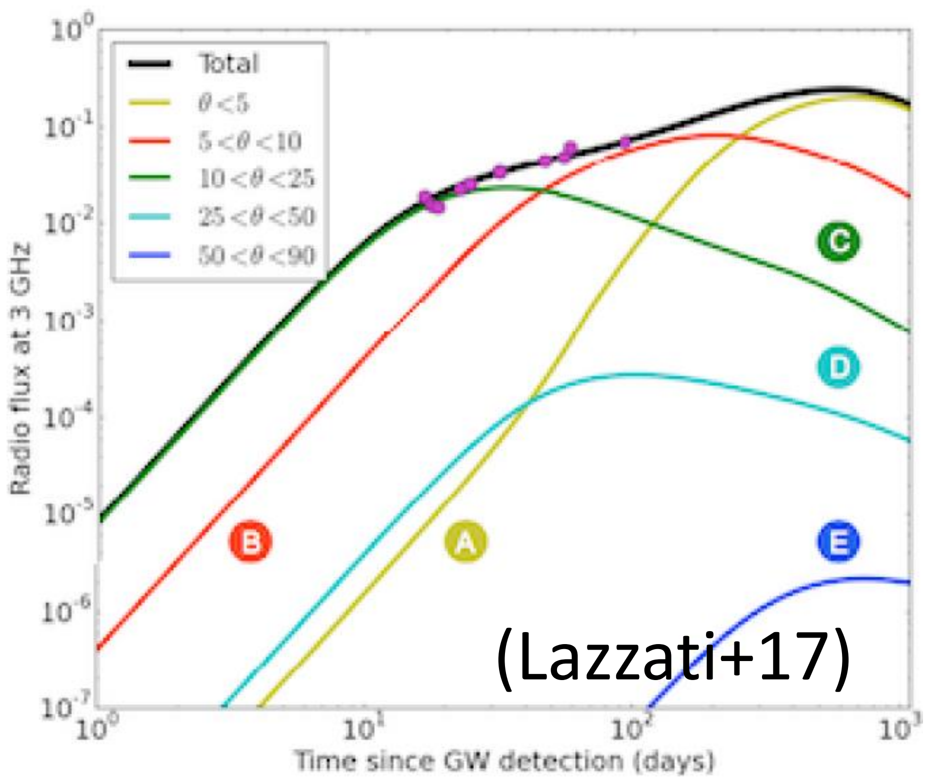
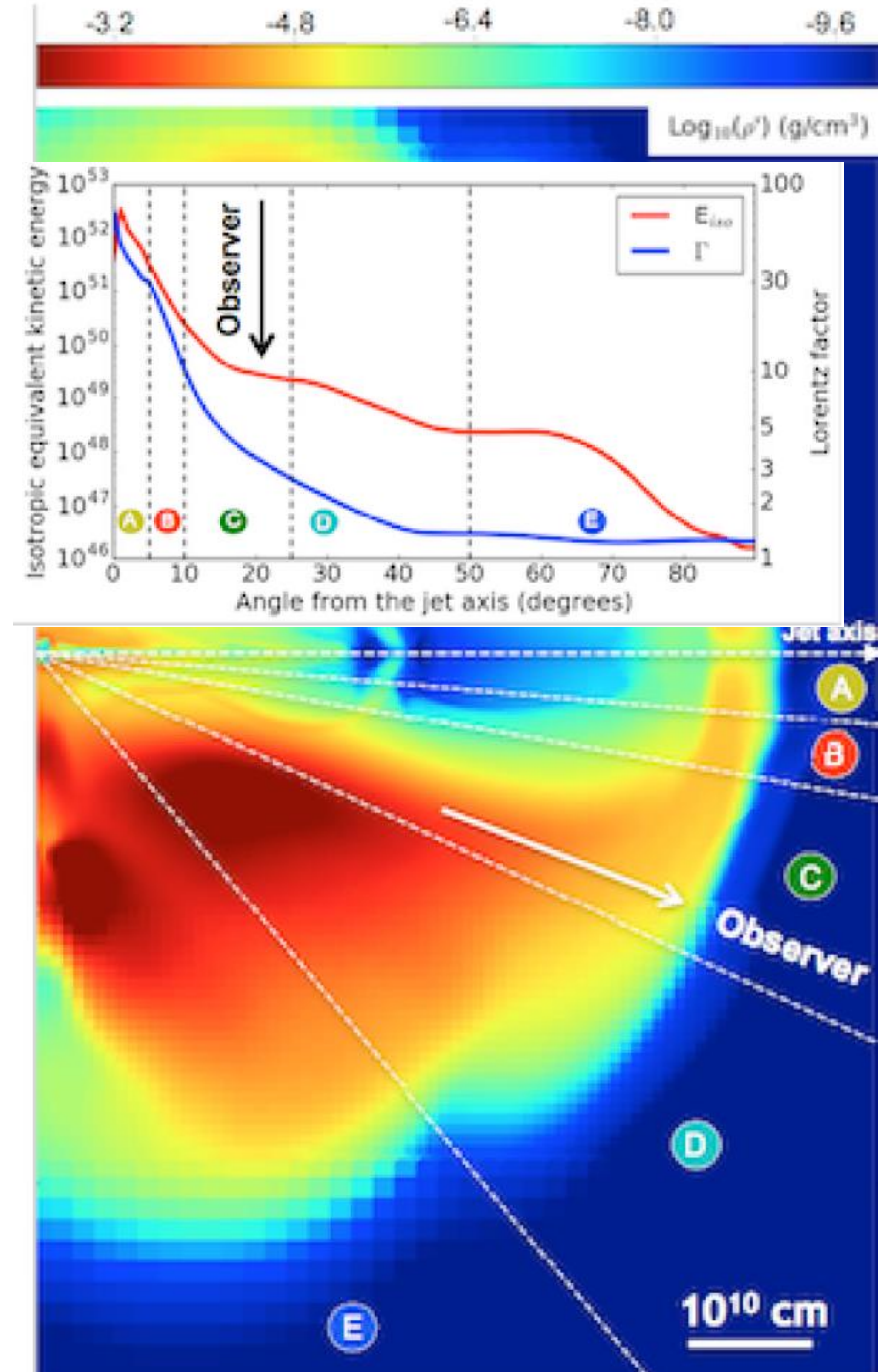
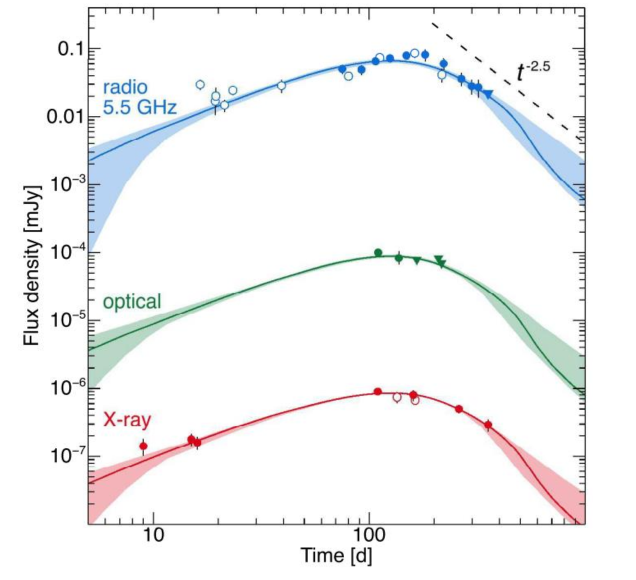


(Lazzati+17)



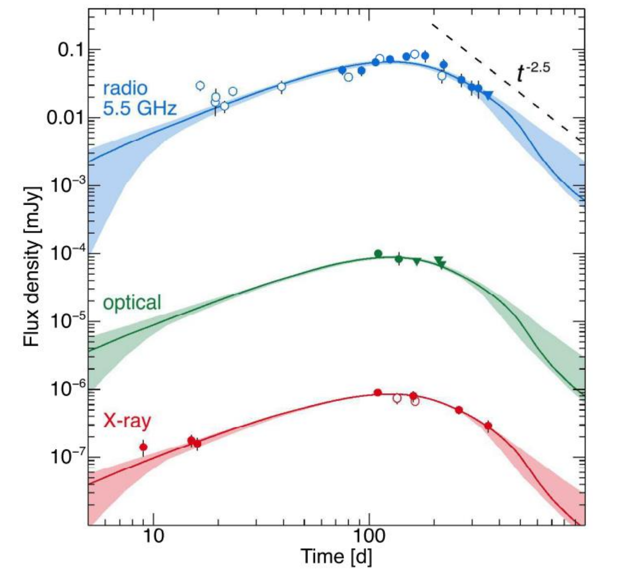
Previous studies (e.g., Troja+19, Ghirlanda+19)

$$E(\theta) = E_{\rm c} \exp\left(-\frac{\theta^2}{2\theta_{\rm c}^2}\right)$$



This study

$$E(\theta) = ?$$



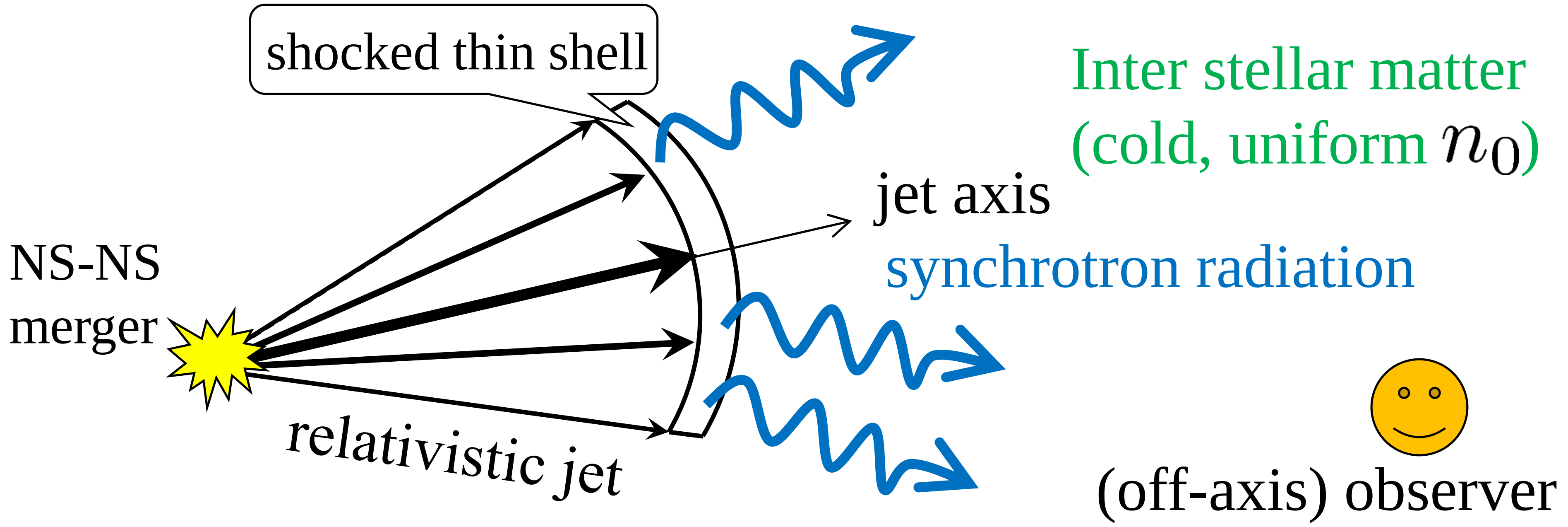
Inverse problem

Method

A novel method to inversely reconstruct $E(\theta)$

A model of structured jets

(Troja+19, van Eerten+10)



The jet energy has an angle dependence: $E = E(\theta)$

Each segment expands as if it were a portion of a spherically expanding shell (e.g., Kumar & Granot 2003):

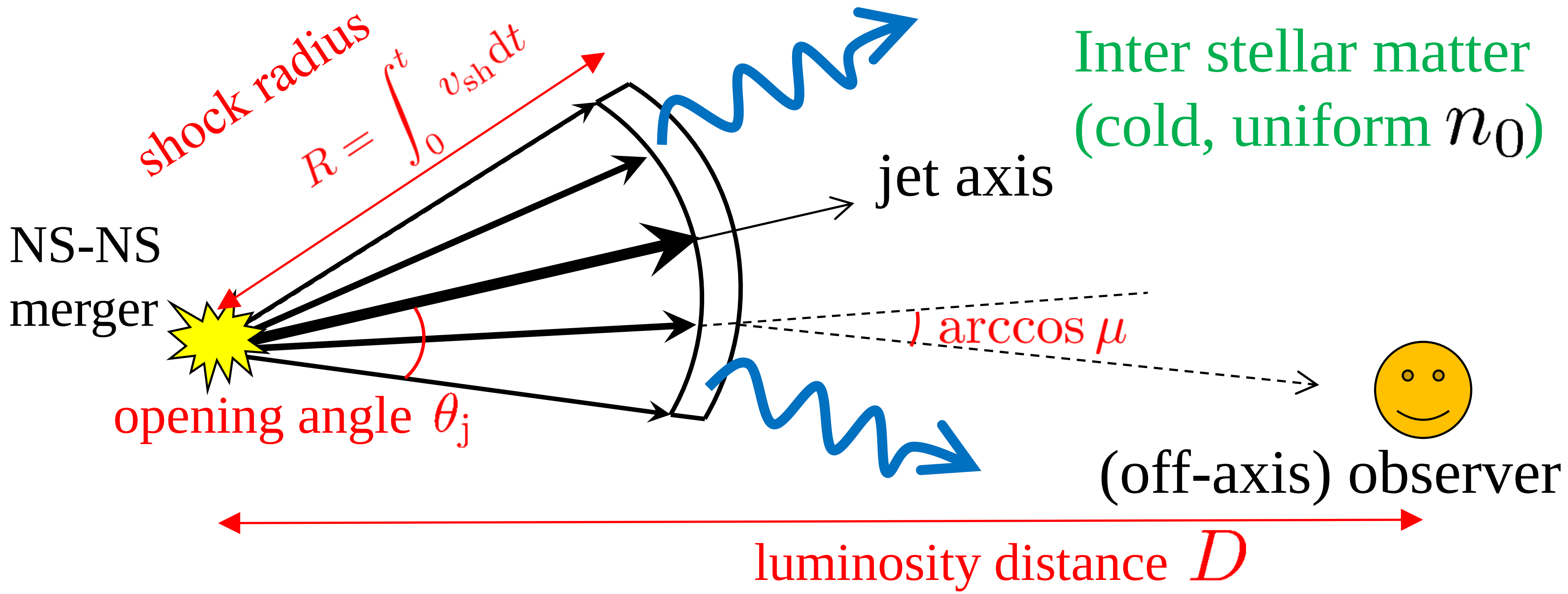
$$\Gamma_{\rm sh}\beta_{\rm sh} \sim \sqrt{\frac{17E(\theta)}{8\pi n_0 m_{\rm p} c^5}}\, t^{-3/2}$$

(cf. Blandford-McKee 1976)

The synchrotron emissivity is given by the standard model of Sari+98: $\epsilon'_{\nu'} = \epsilon'_{\nu'}(n_0, \varepsilon_B, \varepsilon_e, p)$

A model of structured jets

(Troja+18, van Eerten+10)



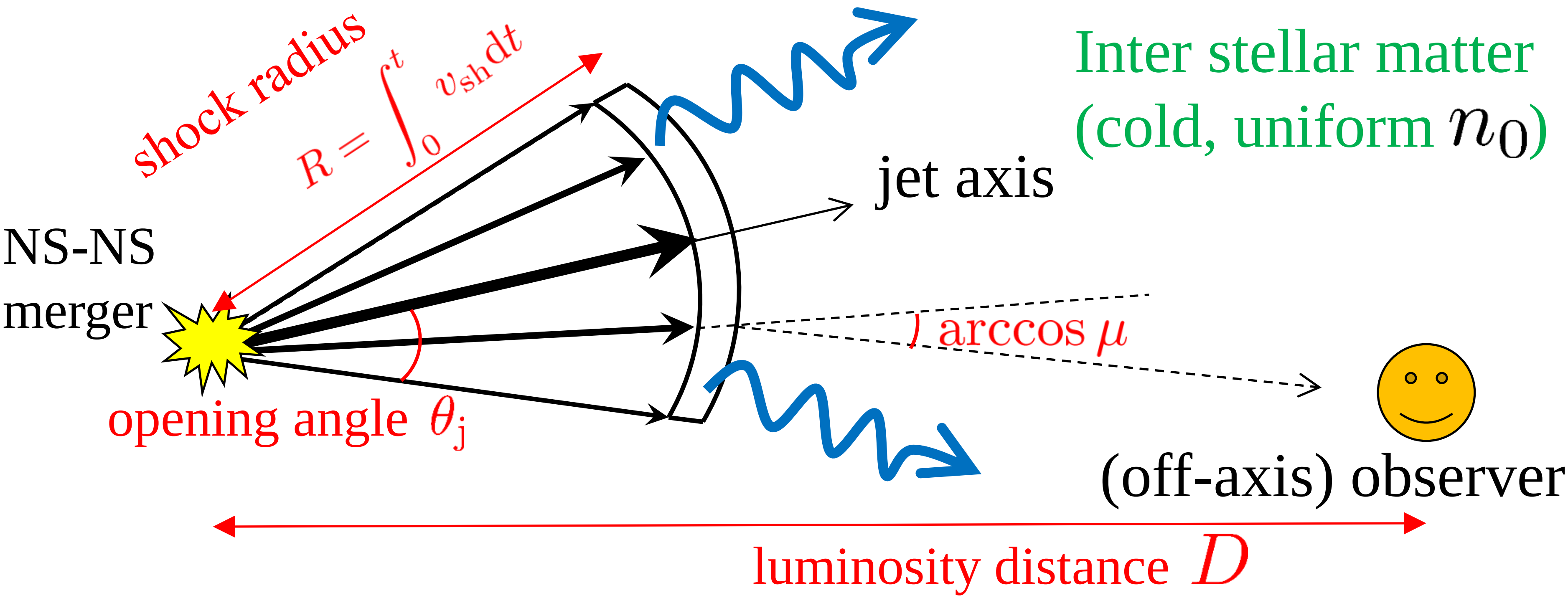
The observed flux density at T:

$$F_\nu(T) = \int_0^{\theta_j} d\theta \int_0^{2\pi} d\phi \, \frac{\sin\theta R^3 \epsilon'_{\nu'}}{4\pi D^2 \cdot 12\Gamma^4 (1-\beta\mu)^2 (1-\beta_{\rm sh}\mu)}\bigg|_{t=T+\frac{R\mu}{c}}$$

Complicated function of $E(\theta)$

A model of structured jets

(Troja+18, van Eerten+10)



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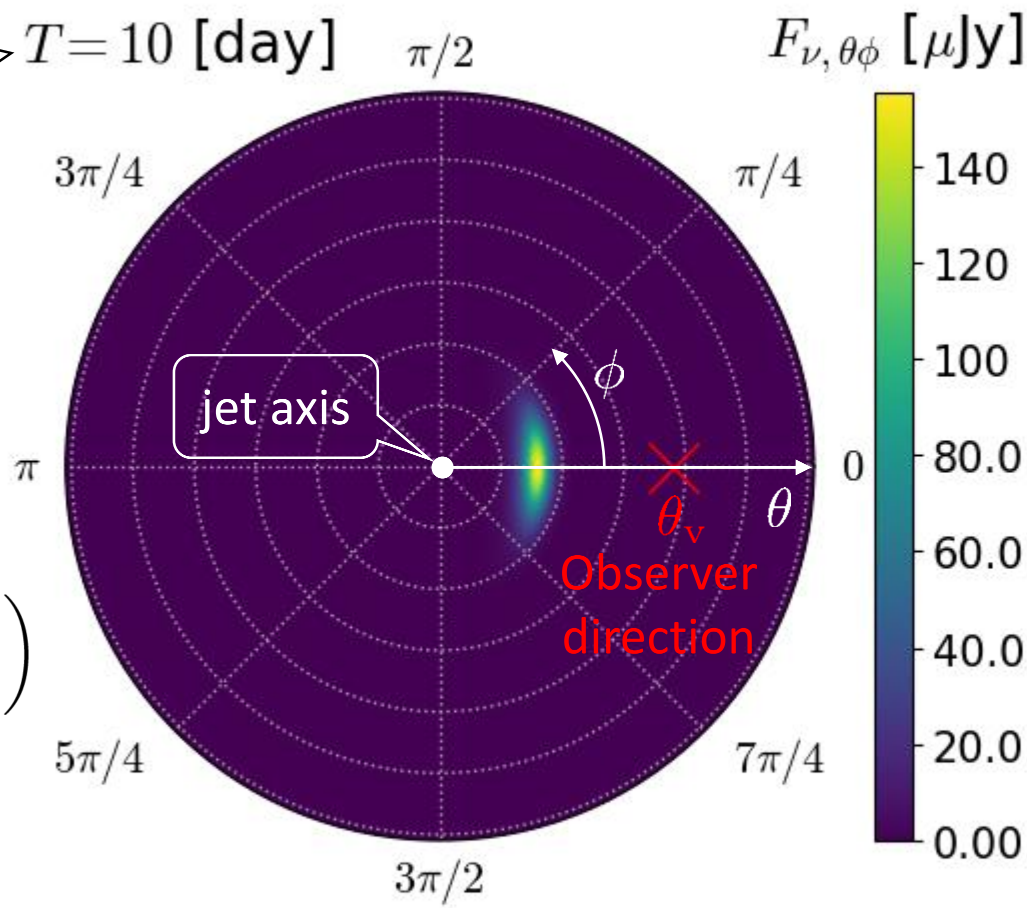
How to reconstruct?

Complicated function of $E(\theta)$

$$F_\nu(T) = \int_0^{\theta_j} d\theta \int_0^{2\pi} d\phi \, \underbrace{\frac{\sin\theta R^3 \epsilon'_{\nu'}}{4\pi D^2 \cdot 12\Gamma^4 (1-\beta\mu)^2 (1-\beta_{\rm sh}\mu)}\Bigg|_{t=T+\frac{R\mu}{c}}}_{\equiv F_{\nu,\theta\phi}}$$

Observer time after the merger



For a Gaussian jet:

$$E(\theta) = E_{\rm c} \exp\left(-\frac{\theta^2}{2\theta_{\rm c}^2}\right)$$

$$E_{\rm c} = 10^{52.5} \text{ erg}$$

$$\theta_{\rm c} = 0.0565$$

Only a limited region contributes to the observed flux (Why?)

$$F_\nu(T) = \int_0^{\theta_j} d\theta \int_0^{2\pi} d\phi \left. \frac{\sin\theta R^3 \epsilon'_{\nu'}}{4\pi D^2 \cdot 12\Gamma^4 (1-\beta\mu)^2 (1-\beta_{\rm sh}\mu)} \right|_{t=T+\frac{R\mu}{c}}$$

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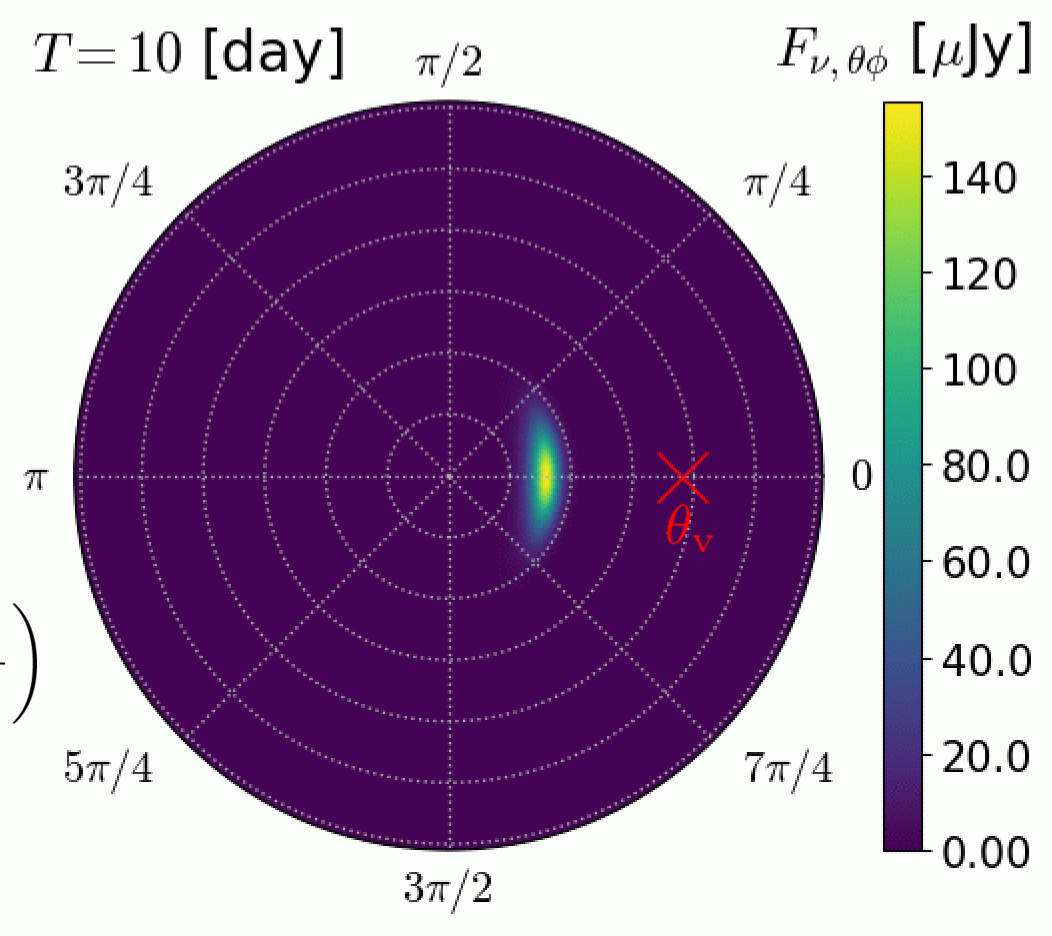

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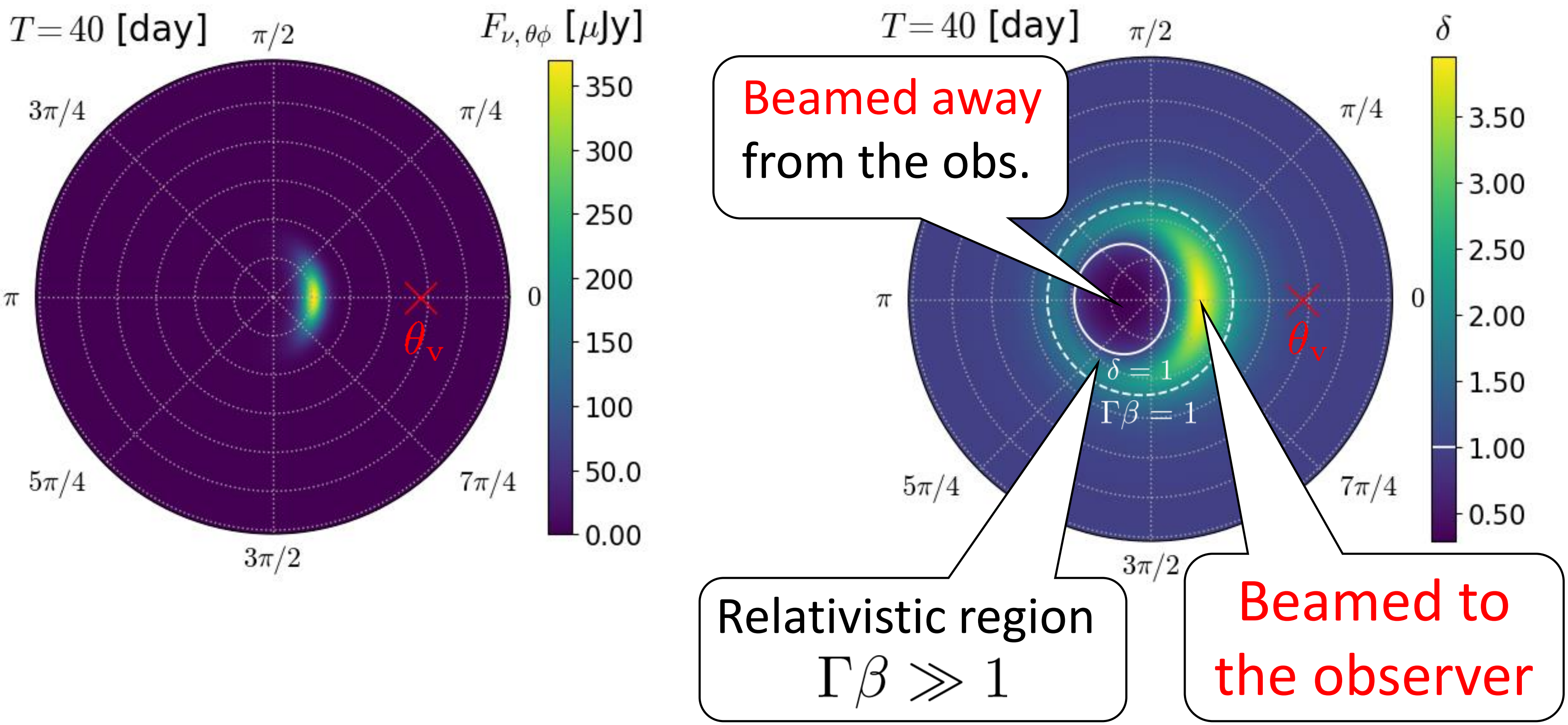
The contributing region gradually approach the jet axis, as the time passes. (Why?)

Contribution to the flux strongly related Beaming factor

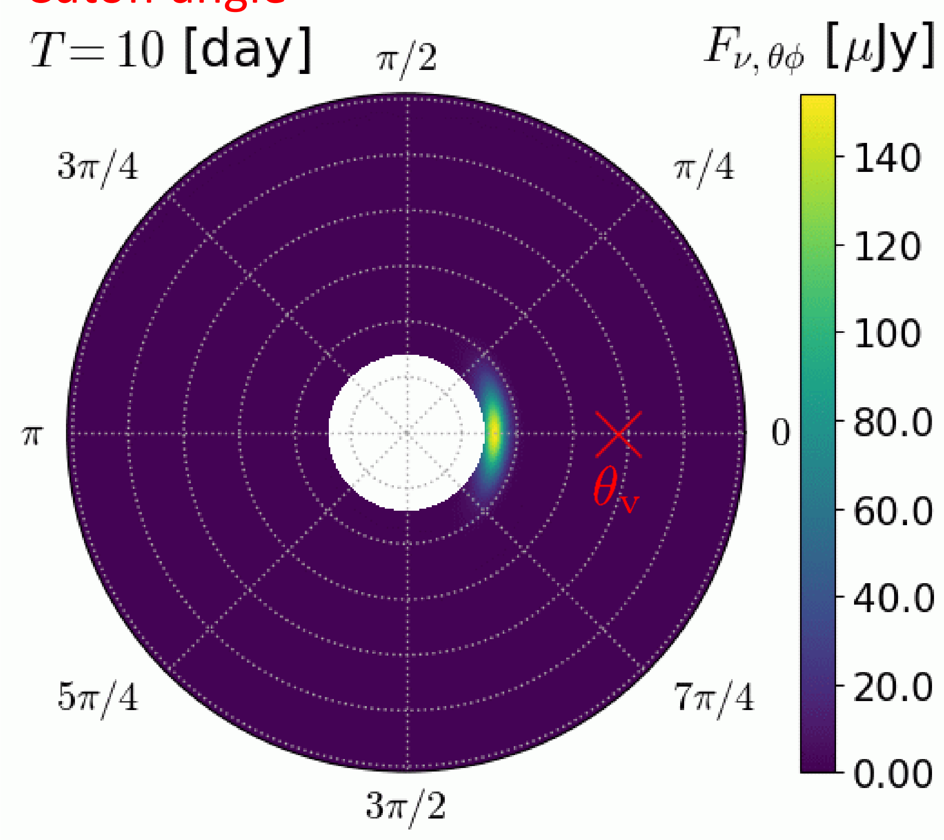
$$F_{\nu,\theta\phi} \propto E(\theta)^{\frac{3p+5}{10}} \delta^{\frac{2(10-p)}{5}} \sin\theta \qquad \delta = \frac{1}{\Gamma(1-\beta\mu)}$$



The contributing region gradually approach the jet axis as the jet is decelerated, due to beaming effects.

$$F_\nu(T) = \int_{\Theta(T)}^{\theta_j} d\theta \int_0^{2\pi} d\phi F_{\nu,\theta\phi}\Big|_{t=T+\frac{R\mu}{c}}$$

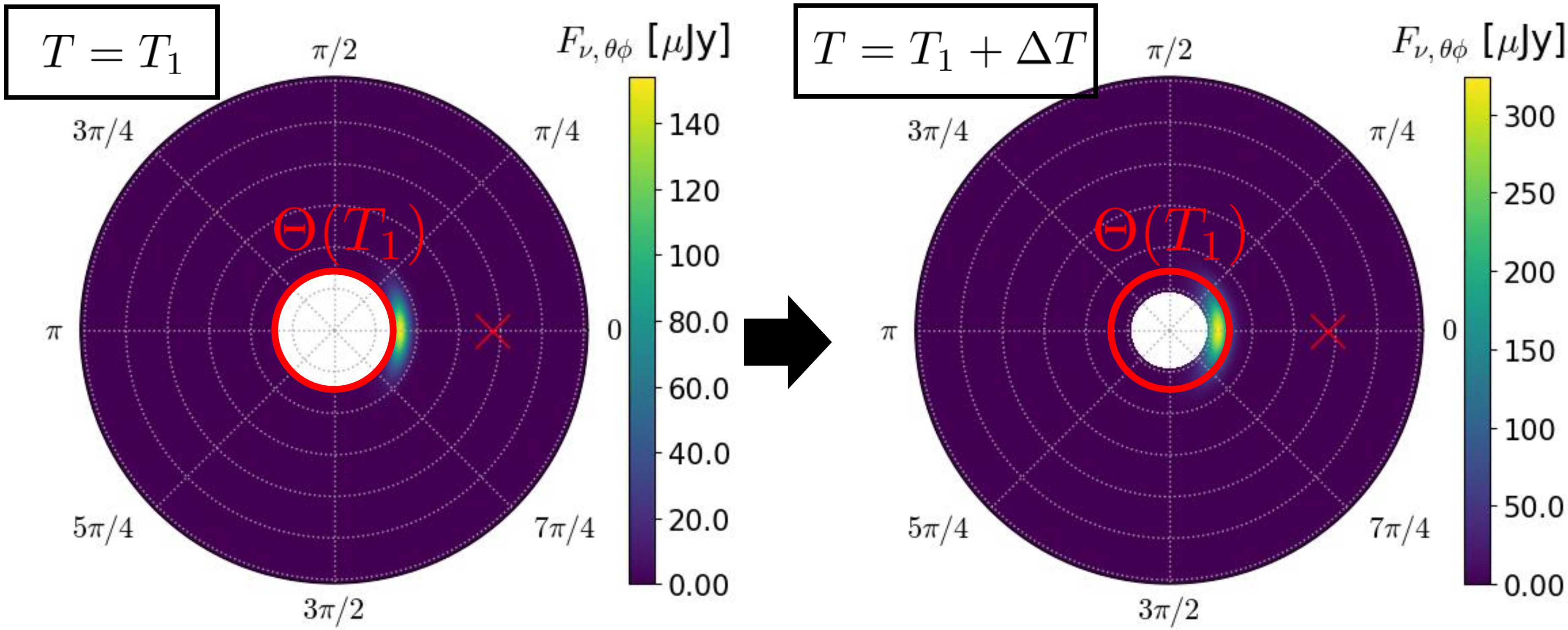
Cutoff angle



General expression for the cutoff angle:

$$\Theta = \theta_\mathrm{v} - 28\left(\frac{\pi n_0 m_\mathrm{p} c^5}{17 \cdot 57^3}\right)^{1/8} E^{-1/8}(\Theta) T^{3/8}$$

n_0 : ambient matter number density

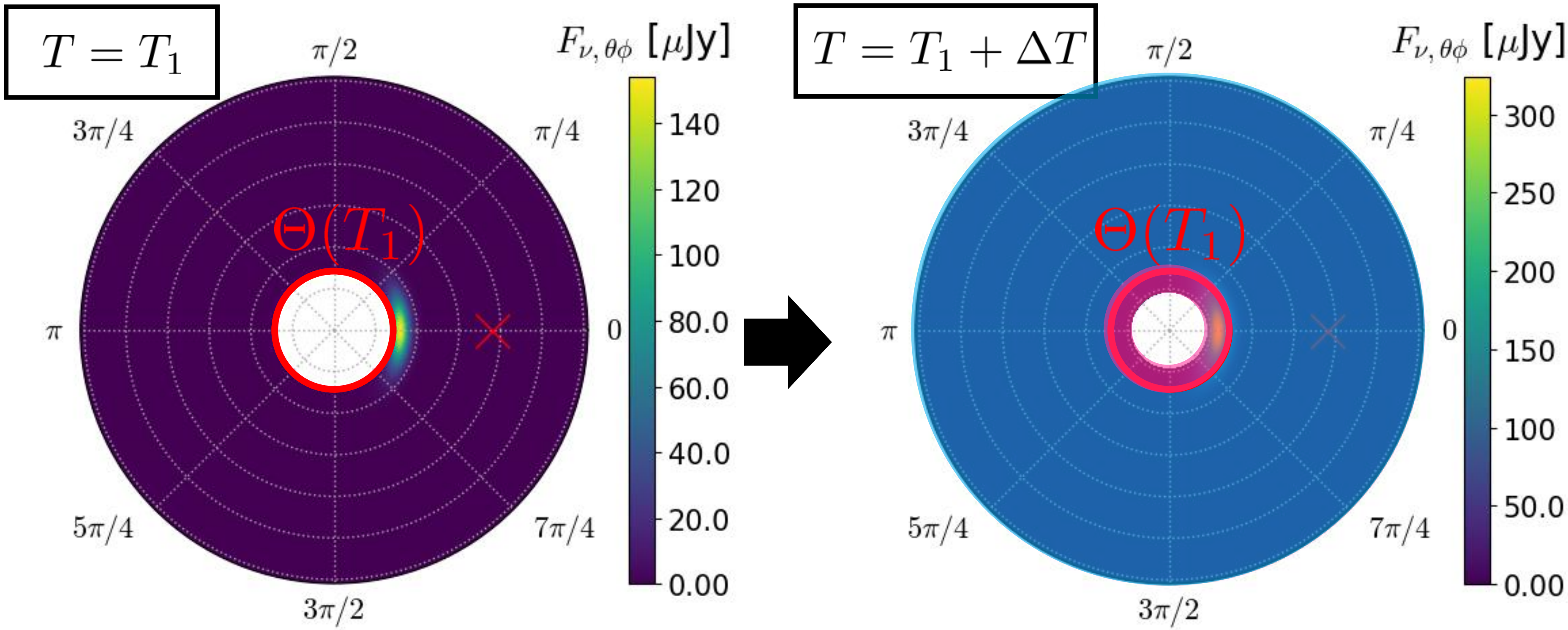


All the contributions to the observed flux $F_\nu(T_1 + \Delta T)$

— Contribution from the region that has been seen before: $\theta \geq \Theta(T_1)$

= Contribution from $\Theta(T_1 + \Delta T) \leq \theta < \Theta(T_1)$

containing the information on the energy distribution for $\Theta(T_1 + \Delta T) \leq \theta < \Theta(T_1)$



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Inversion Formula:

$$\frac{\mathrm{d}\ln E}{\mathrm{d}\Theta} = \frac{8}{\theta_{\mathrm{v}} - \Theta} - \frac{3\dfrac{K(T,\Theta;E(\Theta))}{F_\nu(T)}}{\dfrac{\mathrm{d}\log F_\nu}{\mathrm{d}\log T}(T) - \displaystyle\int_\Theta^{\theta_{\mathrm{j}}} \mathrm{d}\theta \frac{K(T,\theta;E(\theta))}{F_\nu(T)} \frac{\mathrm{d}\log K}{\mathrm{d}\log T}(T,\theta;E(\theta))}$$

Change rate of the observed flux

Subtracted contribution from the ever-seen region

where **K** is defined by

$$F_\nu(T) = \int_{\Theta(T)}^{\theta_j} \mathrm{d}\theta \int_0^{2\pi} \mathrm{d}\phi F_{\nu,\theta\phi}\Big|_{t=T+R\mu/c} \equiv \int_{\Theta(T)}^{\theta_j} \mathrm{d}\theta K(T,\theta;E(\theta))$$

Boundary condition (*assumption*):

$$E(\theta) \ \text{for} \ \Theta(T_0) \le \theta \le \theta_{\mathrm{j}}$$

jet truncation angle

The cutoff angle at a given initial time

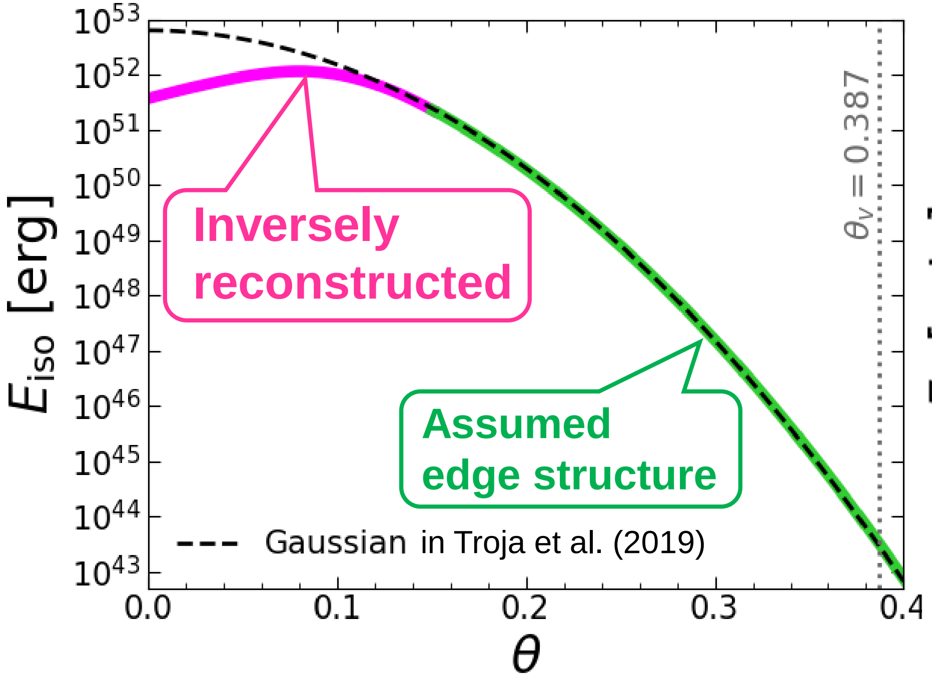
The jet structure is uniquely reconstructed by integrating the inversion formula from $\Theta(T_0)$ to $\Theta = 0$ (the jet axis).

Results

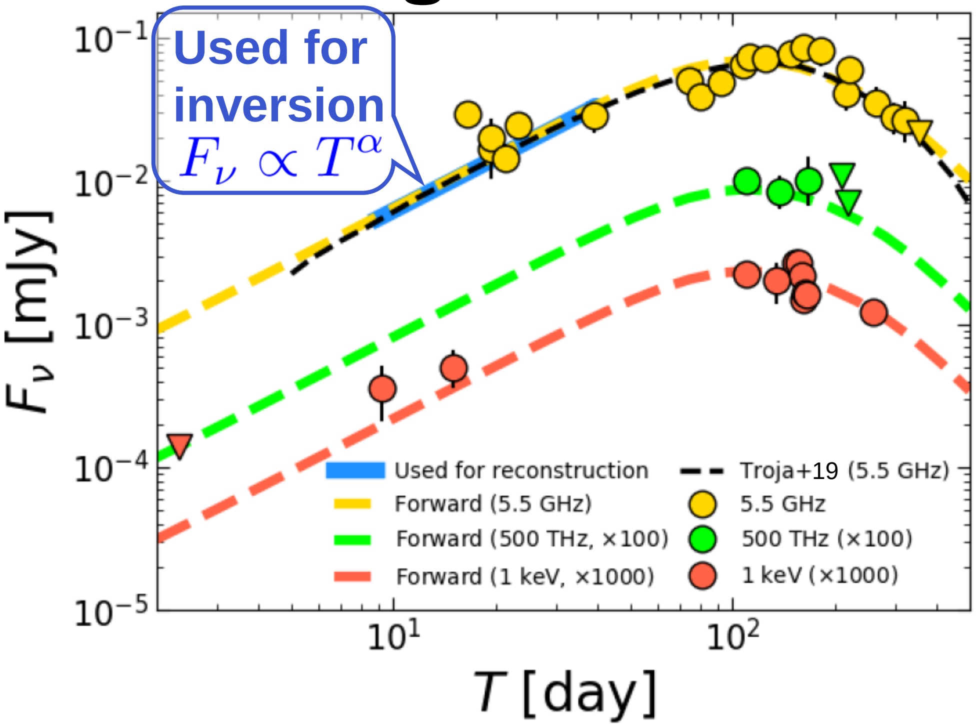
A non-trivial jet structure obtained by our method

Non-trivial Result : Hollow-cone structure

Jet Structure



Light Curve



Parameters:

$$n_0 = 10^{-3.01}\ \mathrm{cm}^{-3},\ \varepsilon_B = 10^{-3.56}\ \varepsilon_e = 10^{-1.39},\ p = 2.17,$$

$$\theta_\mathrm{v} = 0.387,\ D = 41\ \mathrm{Mpc},\ \theta_\mathrm{j} = 0.61$$

Possible origin of hollow-cone structures (only naïve consideration)

Jet acceleration mechanism?

If the jet is launched by the Blandford-Znajek mechanism, the energy flux around the jet axis is low ($F_E \propto \sin^2 \theta$).
(e.g., McKinney 2006, Tchekhovskoy+ 2008,)

Structure created through the interaction with the ejecta during the propagation or at the shock breakout?

Some numerical simulations show the jet structure can be a hollow-cone type.
(e.g., Zhang et al. 2006, Mizuta & Ioka 2013)

Summary

- We developed **a novel method to inversely reconstruct jet structures from off-axis GRB afterglows.**
  - Our method **does not assume the functional form** of E(θ).
  - Our method **uniquely** obtains E(θ) for a given afterglow light curve and given parameters.
- We found that a **hollow-cone jet structure** can be consistent with GRB170817A afterglow.
- The method can be **applicable to future off-axis GRB afterglows**.