A theoretical model of an off-axis GRB jet

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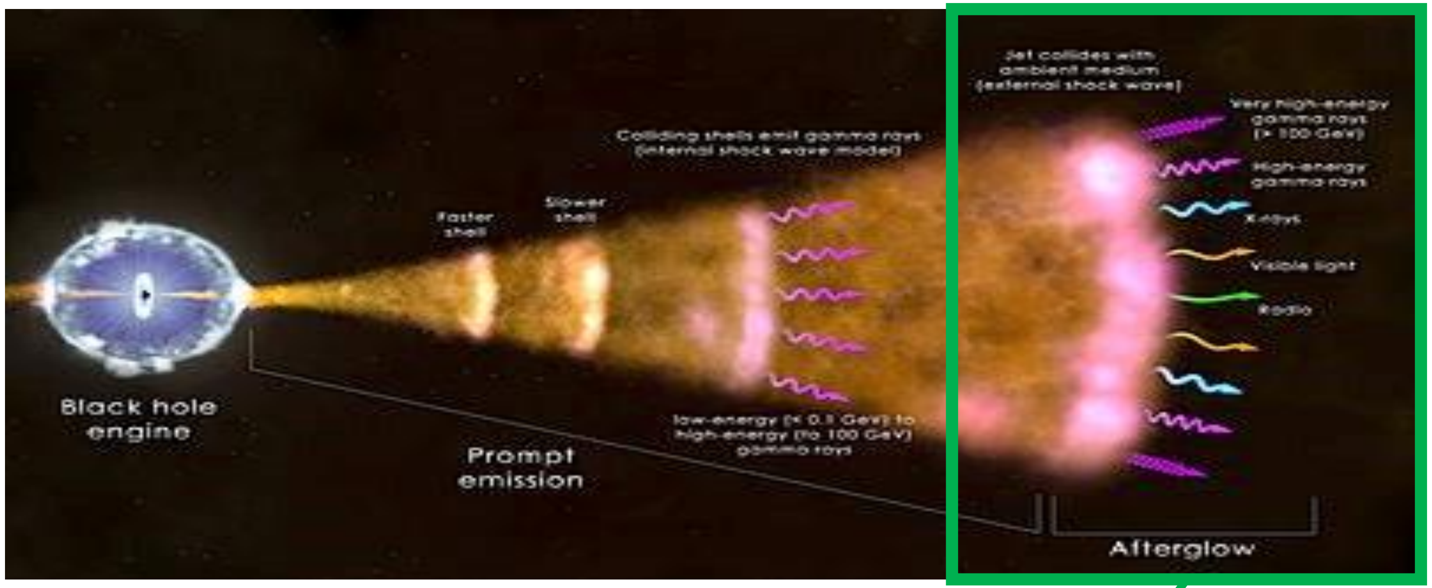
Motivation

- Link between broad-lined IC supernovae (SNe) and long duration gamma-ray bursts (lGRBs).



- Long duration gamma-ray bursts:
  - ISM: $n = \text{const}$
  - Wind: $n \propto R^{-2}$

$$n \propto R^{-k}$$

Piran, T., 1999.
Dai, Z. G. and Lu, T., 1998.

Fraija, N.,…, Betancourt Kamenetskaia, B., *et al.*, 2019.

Model: Considerations

- An off-axis top-hat jet that interacts with a stratified circumburst medium $(n = A_k R^{-k})$.

- Adiabatic evolution of the forward shock. Sari, R., Piran, T. and Narayan, R., 1998.

- Fraction of electrons accelerated by the shock front (ζ_e) considered. Synchrotron cooling is assumed. Eichler, D. and Waxman, E., 2005.

- Two phases in the afterglow's evolution: Sari, R., Piran, T. and Halpern, J.P., 1999.
  - **Relativistic phase:** Highly collimated jet out of our line of sight.
  - **Lateral expansion:** Deceleration due to interaction with medium and increase in beaming angle (enters line of sight).

Relativistic phase bulk Lorentz factor:

$$\Gamma \propto (1+z)^{-\frac{k-3}{2}} \xi^{k-3} \zeta_e^2 A_k^{-\frac{1}{2}} \theta_j^{-1} \Delta\theta^{-(k-3)} \tilde{E}^{\frac{1}{2}} t^{\frac{k-3}{2}}$$

The beaming cone of radiation grows until the jet enters on axis when $\Gamma \sim \Delta\theta^{-1}$ and the lateral expansion phase begins. This marks the jet break time.

Lateral expansion bulk Lorentz factor:

$$\Gamma \propto (1+z)^{\frac{1}{2}} \xi^{-1} A_k^{\frac{1}{2(k-3)}} \tilde{E}^{-\frac{1}{2(k-3)}} t^{-\frac{1}{2}}$$

Synchrotron Light curves

Relativistic Phase | Lateral Expansion

Fast-cooling

Relativistic Phase

$$F_\nu^{\rm syn} \propto \begin{cases} t^4\,\nu^2, & \nu < \nu_{\rm a,3}^{\rm syn}\,, \\ t^{\frac{17-8k}{3}}\,\nu^{\frac{1}{3}}, & \nu_{\rm a,3}^{\rm syn} < \nu < \nu_{\rm c}^{\rm syn}, \\ t^{\frac{26-9k}{4}}\,\nu^{-\frac{1}{2}} & \nu_{\rm c}^{\rm syn} < \nu < \nu_{\rm m}^{\rm syn}, \\ t^{\frac{32-10k-6p+kp}{4}}\,\nu^{-\frac{p}{2}}, & \nu_{\rm m}^{\rm syn} < \nu\,. \end{cases}$$

Lateral Expansion

Independent of stratification

Slow-cooling

Relativistic Phase

$$F_\nu^{\rm syn} \propto \begin{cases} t^2\,\nu^2, & \nu < \nu_{\rm a,1}^{\rm syn}\,, \\ t^{\frac{21-8k}{3}}\,\nu^{\frac{1}{3}}, & \nu_{\rm a,1}^{\rm syn} < \nu < \nu_{\rm m}^{\rm syn}, \\ t^{\frac{(p-11)k-6(p-5)}{4}}\,\nu^{-\frac{p-1}{2}}, & \nu_{\rm m}^{\rm syn} < \nu < \nu_{\rm c}^{\rm syn}, \\ t^{\frac{32-10k-6p+kp}{4}}\,\nu^{-\frac{p}{2}}, & \nu_{\rm c}^{\rm syn} < \nu\,, \end{cases}$$

$$F_\nu^{\rm syn} \propto \begin{cases} t^2\,\nu^2, & \nu < \nu_{\rm m}^{\rm syn}\,, \\ t^{\frac{14-k}{4}}\,\nu^{\frac{5}{2}}, & \nu_{\rm m}^{\rm syn} < \nu < \nu_{\rm a,2}^{\rm syn}\,, \\ t^{\frac{(p-11)k-6(p-5)}{4}}\,\nu^{-\frac{p-1}{2}}, & \nu_{\rm a,2}^{\rm syn} < \nu < \nu_{\rm c}^{\rm syn}, \\ t^{\frac{32-10k-6p+kp}{4}}\,\nu^{-\frac{p}{2}}, & \nu_{\rm c}^{\rm syn} < \nu\,. \end{cases}$$

Lateral Expansion

$$F_\nu^{\rm syn} \propto \begin{cases} t^0\,\nu^2, & \nu < \nu_{\rm a,1}^{\rm syn}\,, \\ t^{-\frac{1}{3}}\,\nu^{\frac{1}{3}}, & \nu_{\rm a,1}^{\rm syn} < \nu < \nu_{\rm m}^{\rm syn}, \\ t^{-p}\nu^{-\frac{p-1}{2}}, & \nu_{\rm m}^{\rm syn} < \nu < \nu_{\rm c}^{\rm syn}, \\ t^{-p}\,\nu^{-\frac{p}{2}}, & \nu_{\rm c}^{\rm syn} < \nu\,, \end{cases}$$

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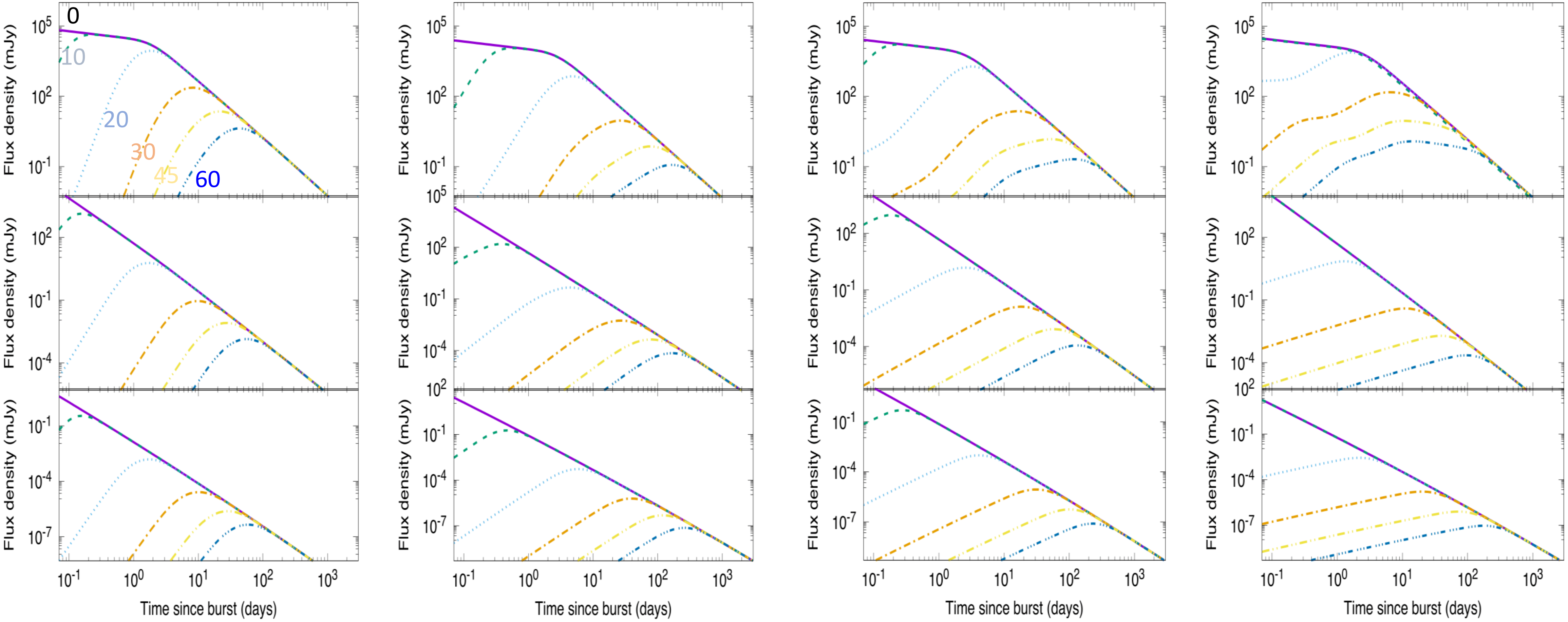
Results: expected light curves

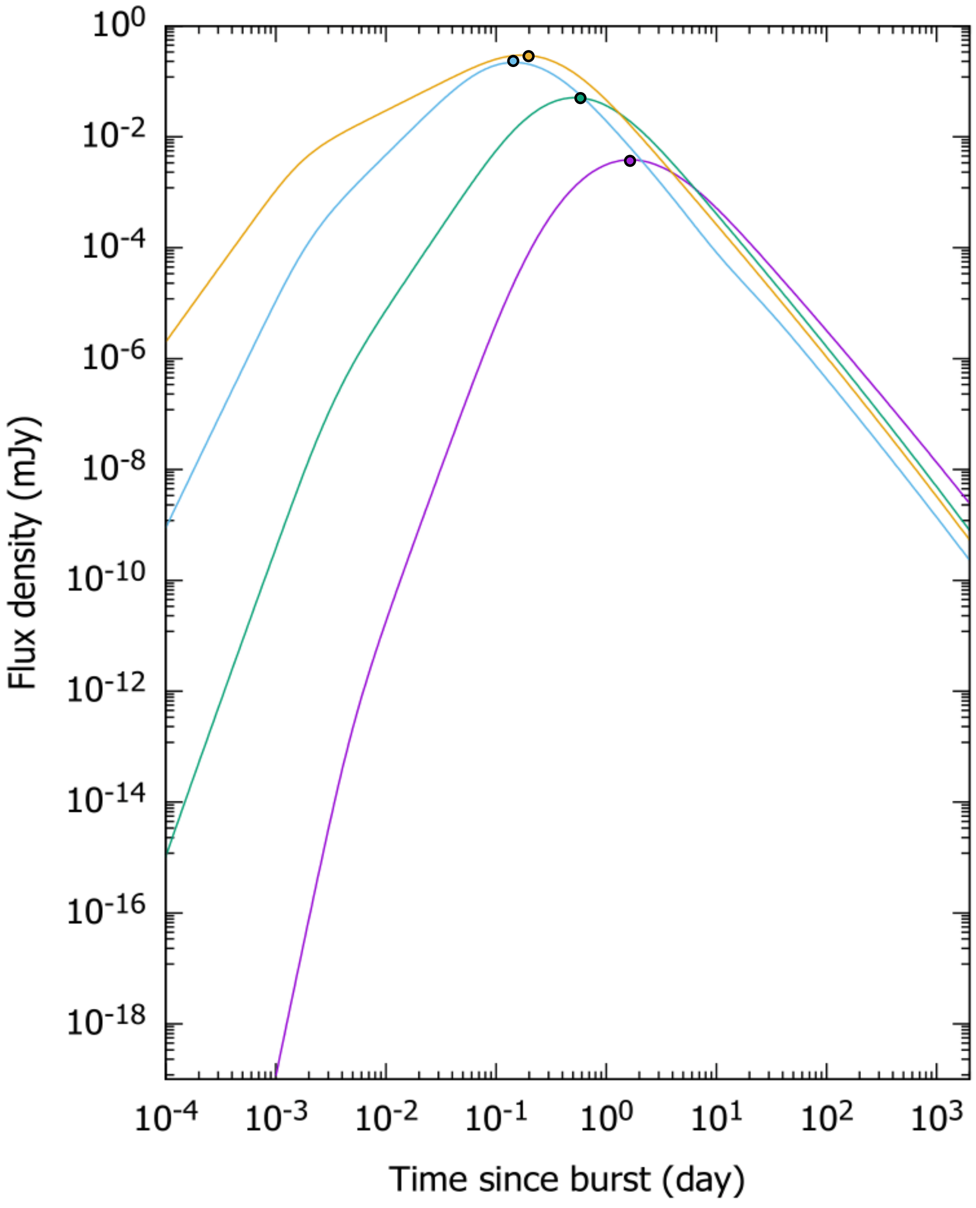
Panels from top to bottom:

- Radio (1.6 GHz).
- Optical (1 eV).
- X-ray (1 keV).

The colors correspond to the difference between the observation angle and the jet's opening angle $\Delta\theta$.



$k = 0$ $k = 1.0$ $k = 1.5$ $k = 2.0$



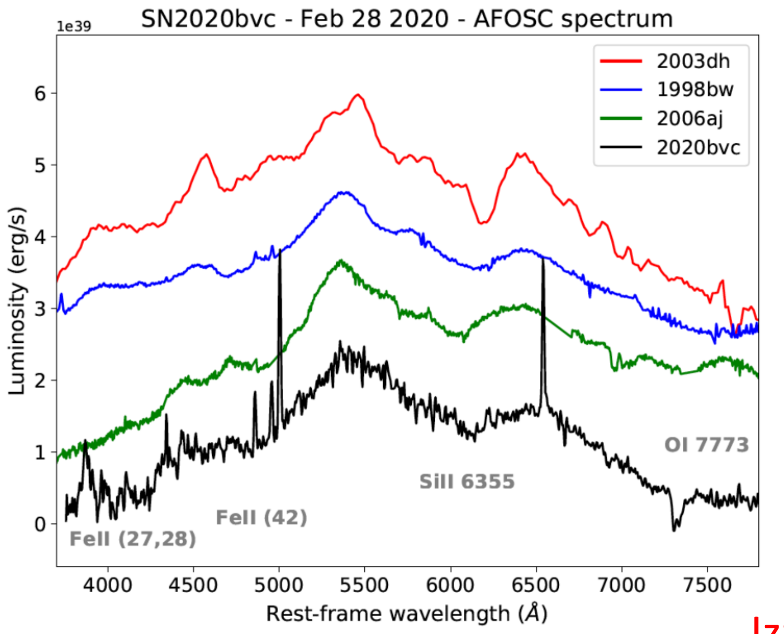
- X-ray light curves (at 1 keV).
- Different stratification parameters:
  - Purple: ISM $k = 0$
  - Green $k = 1.0$
  - Blue $k = 1.5$
  - Yellow: Wind $k = 2.0$
- Jet break time denoted by the circles on the curves.
- Behavior in the lateral expansion phase is independent of stratification.

Parameters:

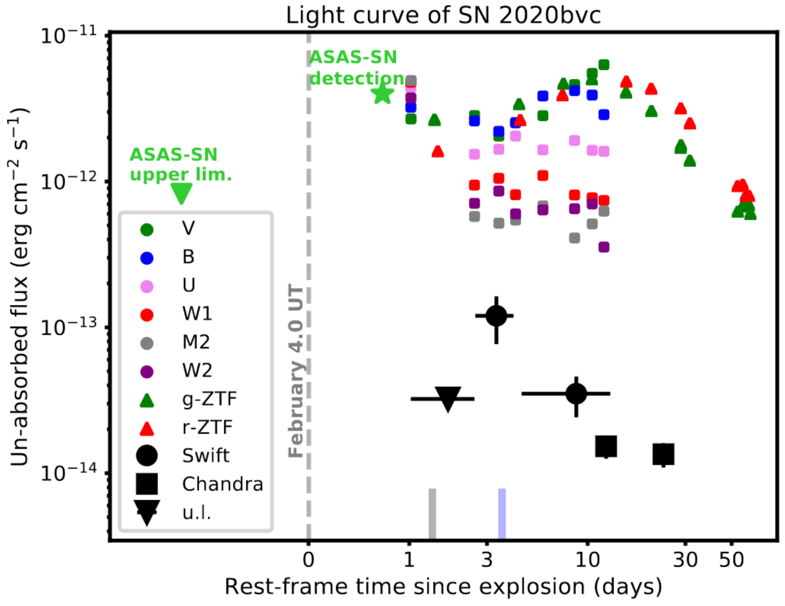
$$\tilde{E} = 10^{51}\,\mathrm{erg},\ \epsilon_{\mathrm{B}} = 10^{-2},\ \epsilon_{\mathrm{e}} = 10^{-1},\ p = 2.6,\ \zeta_e = 1,\ \xi = 1,\ \Delta\theta = 15^\circ,$$
$$\theta_j = 5^\circ \text{ and } D_z = 26.5\,\mathrm{Mpc}.$$

Application: SN 2020bvc

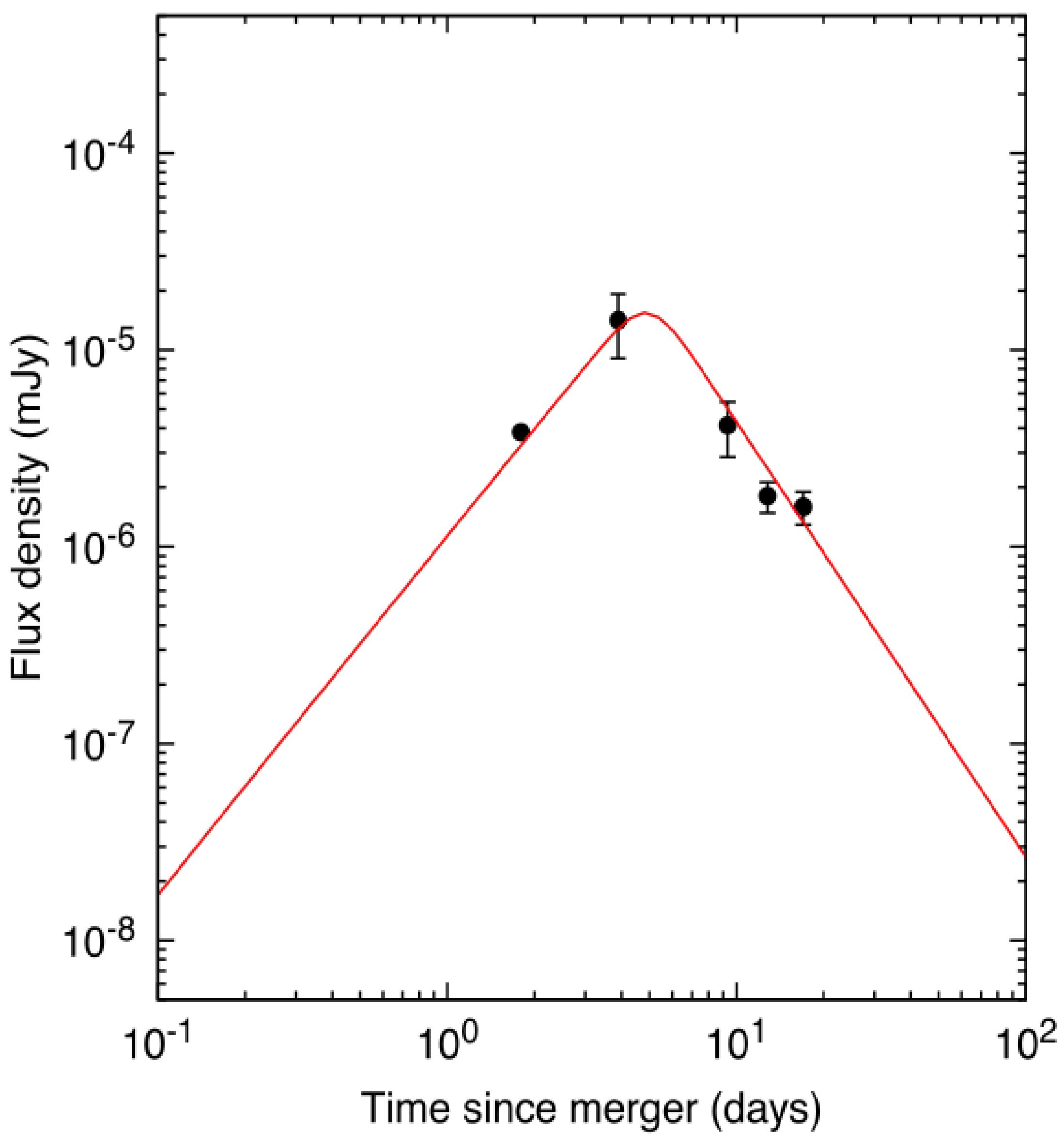
- **First detection**: February 4th, 2020 by the ASAS-SN team. Associated to galaxy UGC 09379 with $z \approx 0.025$.
- Agreement with the GRB-associated, broad-lined Ic SN 1998bw.
- It was also detected at X-ray frequencies.



Izzo, L., *et al.*, 2020.



- X-ray observations of SN 2020bvc and fit from the model in red.
- An R^{-2} model grows too slowly to account for the first two points. On the other hand, ISM grows too steeply.
- Stratification parameter $k = 1.5$.



Parameters:

$$\tilde{E} = 5.3 \times 10^{49}\,\mathrm{erg},\ \epsilon_{\mathrm{B}} = 2 \times 10^{-2},\ \epsilon_{\mathrm{e}} = 3.5 \times 10^{-3},\ A_k = 8.47 \times 10^{25}\ \mathrm{cm}^{-\frac{3}{2}},$$
$$p = 2.2,\ \zeta_e = 1,\ \xi = 1,\ \Delta\theta = 23^{\circ},\ \theta_j = 5^{\circ}\ \text{and}\ D_z = 26.5\,\mathrm{Mpc}.$$

Conclusion and summary

- A model to describe the afterglow emission of an off-axis relativistic jet has been derived.

- It considers a stratified medium $n \propto R^{-k}$, which directly influences the afterglow's evolution in the relativistic phase.

- Lateral expansion flux drops with the same power law, independent of stratification.

- SN 2020bvc X-ray flux has been successfully fitted with this model for $k = 1.5$.

Thank you for your attention!