The collimation of relativistic jets in post-neutron star binary merger simulations

Matteo **Pais**[1] (matteo.pais@mail.huji.ac.il)

Tsvi **Piran**[1], Yuri **Lyubarsky**[2], Kenta **Kiuchi**[3,4], Masaru **Shibata**[3,4]

[1]**Racah Institute for Physics**, **The Hebrew University**, Israel

[2]Physics Department, **Ben-Gurion University of the Negev**, Israel

[3]Max Planck Institute for Gravitational Physics (**Albert Einstein Institute**), Potsdam-Golm, Germany

[4]Center for Gravitational Physics and Quantum Information, **Yukawa Institute for Theoretical Physics**, **Kyoto University**, Kyoto, Japan

arXiv:2211.09135

Abstract

The gravitational waves from the binary neutron star (BNS) merger **GW170817** were accompanied by a multi-wavelength electromagnetic counterpart, which confirms the association of the merger with a short gamma-ray burst (sGRB). Afterglow observations implied that the event was accompanied by a narrow, $\sim 5^{\circ}$, and powerful, 10^{50} erg, jet. We study the propagation of a Poynting flux-dominated jet within the merger ejecta (kinematic, neutrino-driven and MRI turbulence-driven) of a neutrino-radiation-GR-MHD simulation of two coalescing neutron stars. We find that the presence of a post-merger low-density/low-pressure polar cavity, that arose due to angular momentum conservation, is crucial to let the jet break out. At the same time the ejecta collimates the jet to a narrow opening angle. The collimated jet has a narrow opening angle of $\sim 4-7^{\circ}$ and an energy of $10^{49}-10^{50}$ erg, in line with the observations of GW170817 and other sGRBs.

Simulation

- The simulation for the BNS merger (Fig. 1) is performed using a code described in **Kiuchi et al. (2022);**
- The NS is modelled with the SFHo equation of state **(Steiner et al. 2013);**
- The binary is composed of 1.2 $M_{\odot}$ and 1.5 $M_{\odot}$ NSs.
- The corresponding chirp mass is consistent with the one observed in GW 170817.
- The simulation domain is composed of 13 levels of the fixed mesh refinement (FMR) with the finest grid spacing of $\Delta x = 150$ m and size of $L \in [-37.875, 37.875]$ km;
- The merger and the subsequent black hole formation take place at ≈ 0.015 s and ≈ 0.032 s, respectively. The formed BH has a spin parameter of $a \simeq 0.65$;
- Total duration of the simulation is $\simeq 1.06$ s

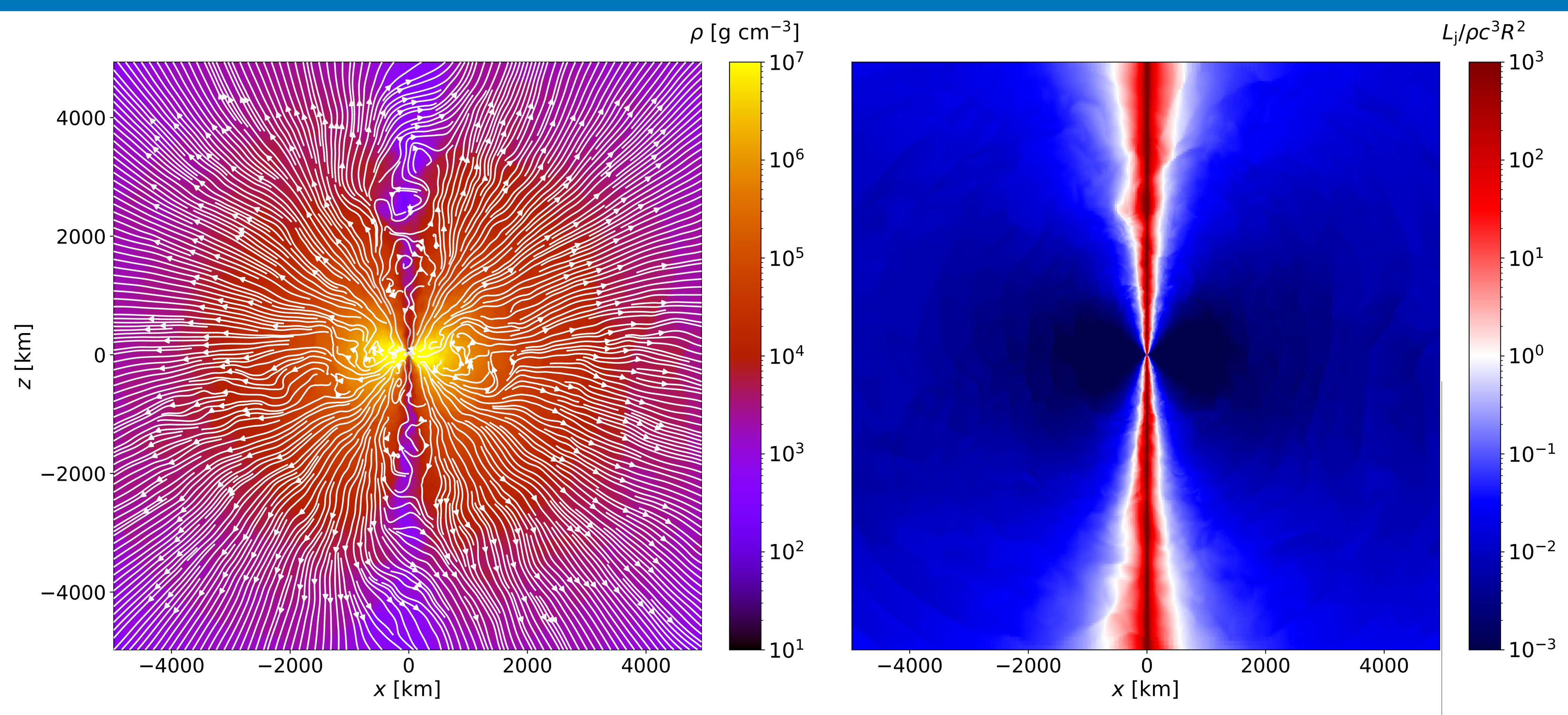

Fig 1. *Left*: Density map in a logarithmic scale of a 2D slice (x-z plane) through the center of the simulation box at t = 1 s. We superposed the velocity streamlines (white colour). *Right*: The jet parameter $\tilde{L}$ calculated for the 2D slice of the ambient density for a jet luminosity of 10^{50} erg/s.

Theory & Analysis

- As the jet propagates through the expanding ejecta it dissipates its energy in shocks that form at the jet head. Jets expand uncollimated if $\tilde{L} = L_j/\Sigma_j \rho_a c^3 \gg 1$ **(Fig. 1)**;
- If the jet is not powerful enough it may not break out from the ejecta (choked);
- Escape condition $E_{\rm jet} > E_{\rm jet,\,esc}$ (from **Gottlieb & Nakar 2022**):

$$E_{\rm jet,\,esc} \equiv 150[20]\left[\left(\frac{t_d}{t_e}\right)^2 + 2\right] E_{\rm ej}(<\theta_{\rm jet}) \times \theta_j^2 \quad \text{(Eq. 1)}$$

- Collimation condition (**Lyubarsky 2009**):

$$\frac{(B')^2}{8\pi} = \frac{1}{8\pi}\left(\frac{RB_{\varrho}}{R_L \gamma}\right)^2 = p_{\rm ext}(R,z) \qquad \text{(Eq. 2)}$$

- We calculate the contours with Eq. 2, assuming $\gamma = R/R_L$, we fit the contours and we find the relative local slope θ along the fit at the maximum height z_s of the polar funnel, where the jet is free to expand ($\tilde{L} \gg 1$). (Fig. 2)
- Using the collimation contour and varying the luminosity of the jet L_j, we are able to determine the relation between the luminosity and a desired jet opening angle θ_j. We calculate the collimation energy as $E_{\rm j,coll} = L_j \times t_e$;
- We assume no delay time between the BH formation and the jet launch in Eq. 1 ($t_d = 0$) and engine times of $t_e = 0.1$ and 1 s (Fig. 3);
- collimated jets that manage to break out from the ejecta need $E_{\rm j,esc} < E_j \leq E_{\rm j,coll}$.

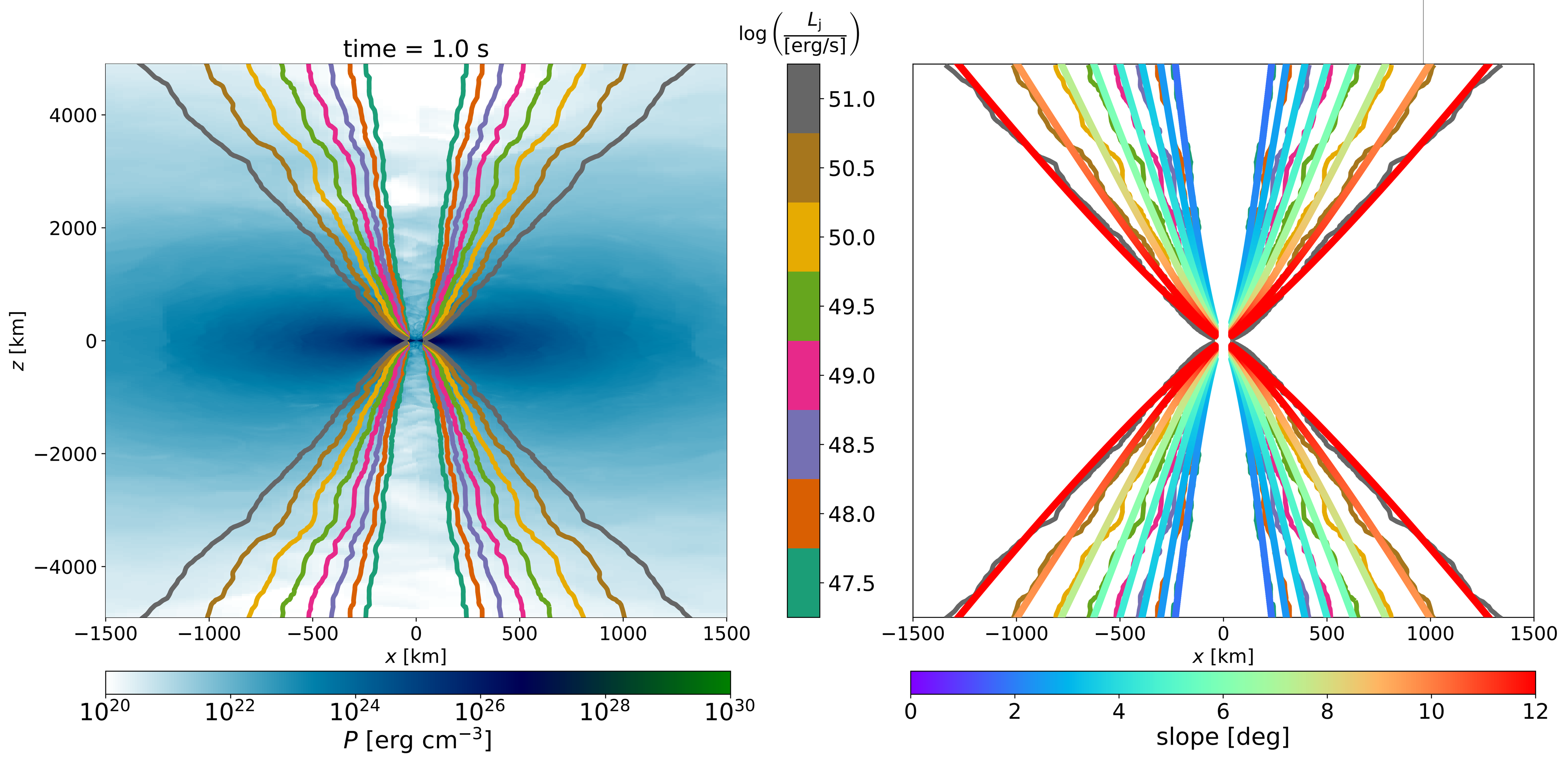

Fig 2. *Left*: Map of the thermal pressure superposed onto the collimation contours that satisfy Eq. 2. The bottom color bar shows the values of the ambient pressure while the different colours of the contour lines represent different jet luminosities L_j (vertical color bar in log scale). We fixed the light cylinder radius at $R_L = 40$ km. *Right*: Same as the left panel but superposed onto a power law fit $z = ax^b$. The horizontal color bar at the bottom of the figure represents the local slope of the curve fit (in degrees).

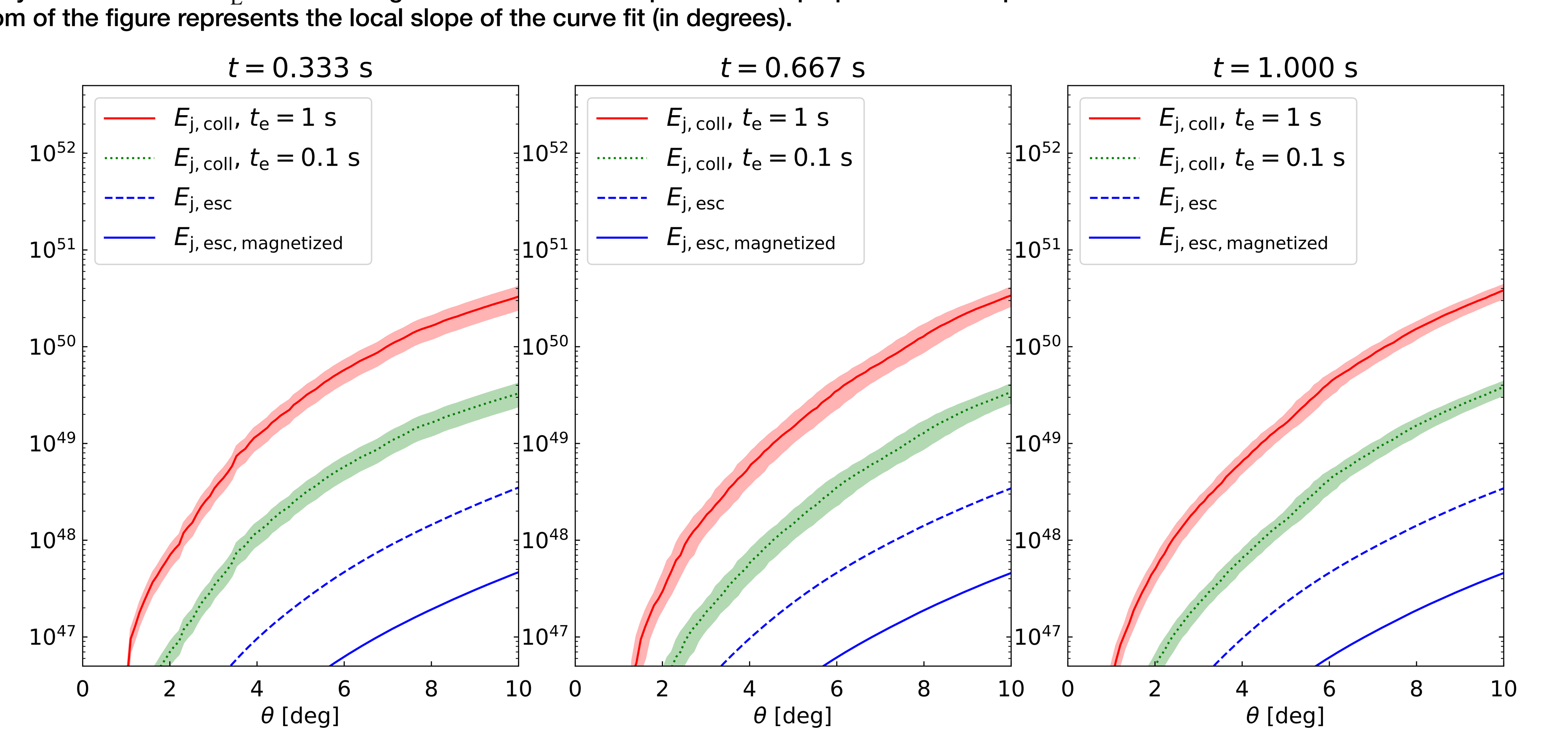

Fig 3. Escape energy, $E_{\rm j,esc}$, (blue lines) and collimation energy, $E_{\rm j,coll}$, (red and green lines) versus θ for three different snapshots at: $t = 0.33$ s (left), $t = 0.667$ s (center), and $t = 1$ s (right). The red (and green lines) are drawn varying the luminosity of the collimation contour and calculating, from the contour fit, the corresponding opening angle θ measured at $z_s = 1670$ km (left), $z_s = 3300$ km (centre), and $z_s = 5000$ km (right), which approximately represent the maximal heights of the low-density, low-pressure cavity at each snapshot, respectively. Solid blue lines represent the escape energy for magnetised jets.

Conclusions

- The values we obtain ($E_j = 10^{49-50}$, $\theta_j \simeq 4^{\circ} - 7^{\circ}$) are consistent with the observation of the afterglow light curve in combination with the superluminal motion of the jet core which estimate a powerful ($E_j = 10^{49-50}$ erg), and narrow ($\theta_j < 5^{\circ}$) conical jet;
- the jet can escape only at the poles;
- the engine operation time cannot be too short as compared to the time delay between the onset of the jet and the merger;
- Post-BNS merger ejecta anisotropic structure creates a favourable environment to successfully collimate jets in the energy range seen in sGRBs.