Introduction to astroparticle physics

Part 1: Andrii Neronov

Cosmic ray physics

... direct continuation of
research started by V.Hess

Gamma-ray astronomy

.... application of particle physics
methods in astronomy

Gravitational waves

Neutrino physics

* neutrino oscillations
* high-energy neutrino astronomy

Dark matter physics

... direct continuation of
research started by F.Zwicky

Particle physics in the Early Universe

... direct continuation of research started by Gamow

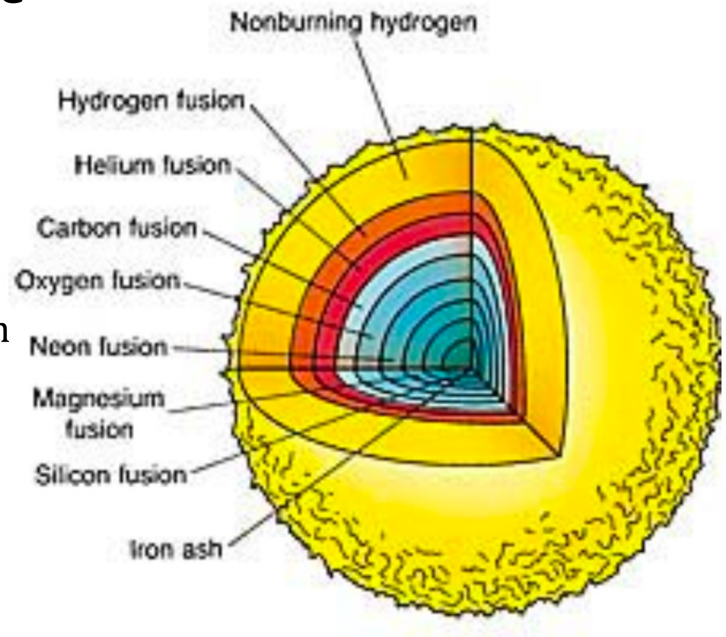
Pulsars

Black hole binaries

Gamma-ray bursts

Gravitational wave bursts

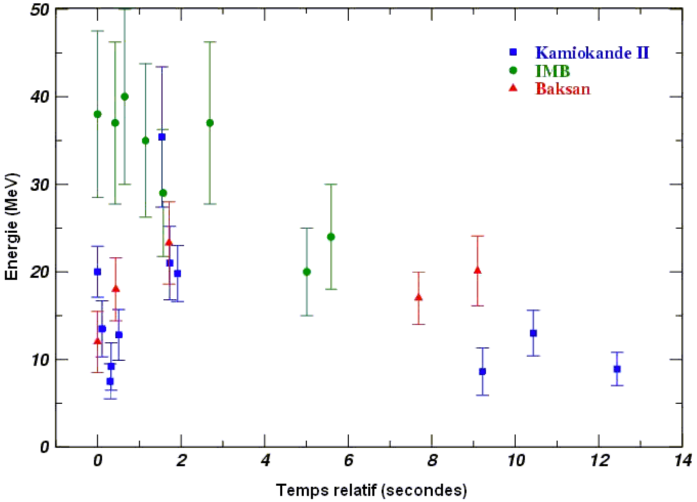
Reminder previous lecture



$$M_{Ch} = \frac{Y_e^2}{m_p^2 G_N^{\frac{3}{2}}}$$

$$R_{Ch} \sim \frac{Y_e^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} G_N M_{Ch}^{\frac{1}{3}}} \simeq 3\times10^8 \text{ cm}$$

$$\rho_{Ch} \sim \frac{M_{Ch}}{R_{Ch}^3} \simeq 10^8 \frac{\text{g}}{\text{cm}^3}$$



$$p + e^- \to n + \nu_e$$

Free neutrons do not decay, because their decay would release an electron into highly degenerate electron gas:

$$n \not\to p + e^- + \overline{\nu}_e$$

Pulsars. Neutron star magnetic field and spin

Star before the collapse had magnetic field B and rotated with the spin period $T = 2\pi/\Omega$.

Conservation of angular momentum during collapse suggests that

$$L = M\Omega R^2 \sim const$$

$$T \sim R^2$$

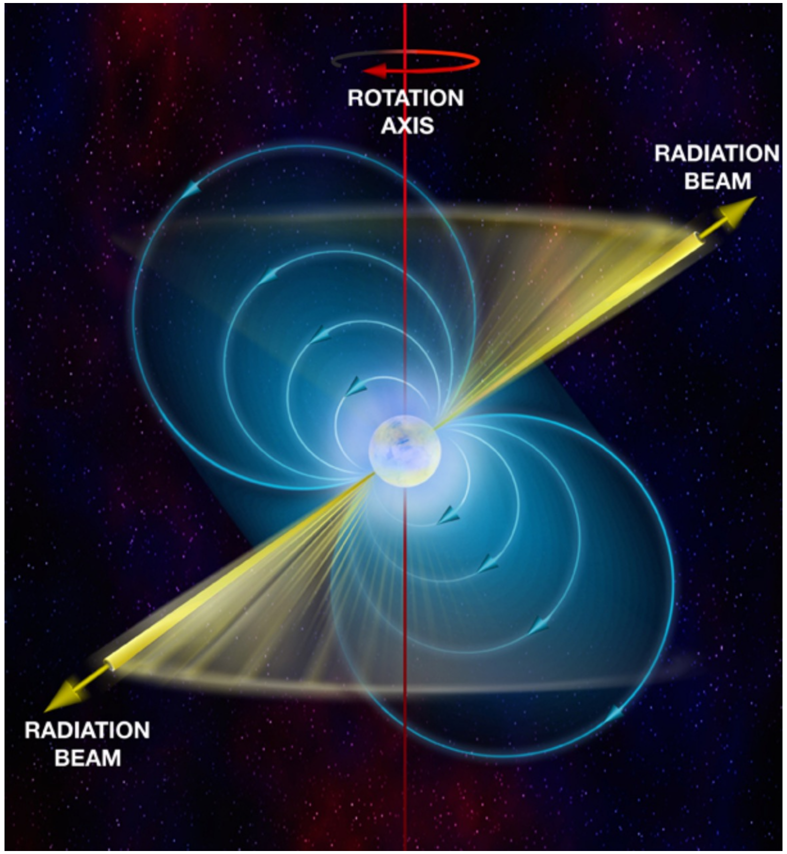
Example: the Sun rotates with period close to one month (3×10^6s). Contraction of the sun from $R \sim 10^{11}$ cm down to $R \sim 10^6$ cm would shrink the rotation period down to $\sim$ 1 ms.

Star before the collapse possessed magnetic field. Conservation of magnetic flux during the collapse suggests

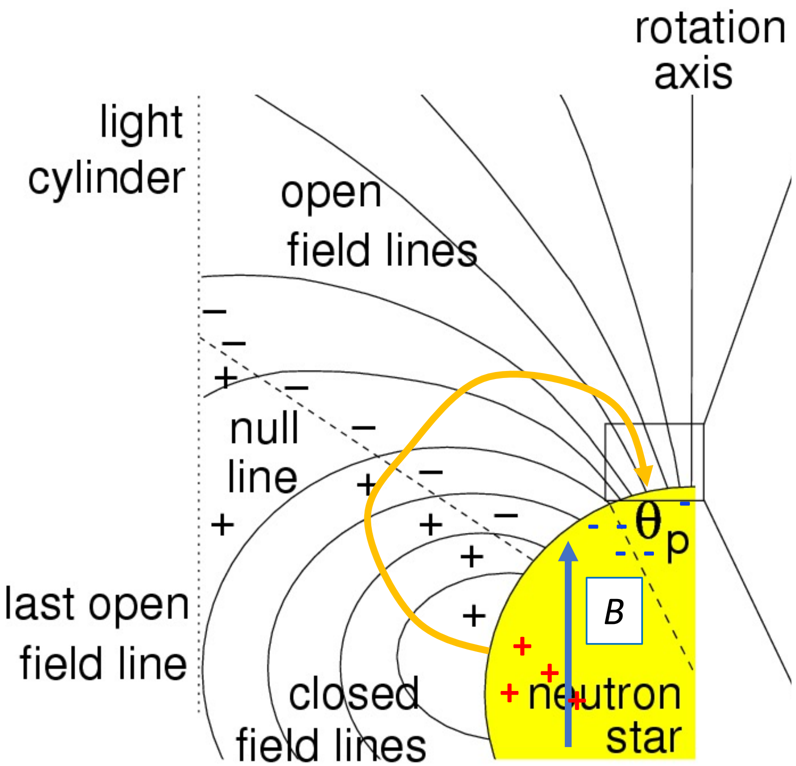
$$\Phi \sim BR^2 \sim const$$

Example. the Sun has dipole magnetic field of the orger of 1 G and up to three orders of magnitude stronger corona field. Contraction by a factor 10^5 in size would lead to magnetic field $B > 10^{10}$G.

Fast rotating magnetized neutron stars are observed as pulsars.



Neutron star as a unipolar inductor



Lorentz force acting upon free charges in the neutron star "crust" (where electrons and protons still exist)

$$\vec{F} = e(\vec{E} + \vec{v}\times\vec{B})$$
$$\vec{v} = \vec{\Omega}\times\vec{R}$$

Imagine that $\vec{E} = 0$ in an initial configuration. Tangential component of the force displaces oppositely charged particles either toward equator or toward poles.

Charge separation leads to generation of electric field which provides negative feedback that stops accumulation of charges at the poles and equator, assuring "force-free" configuration

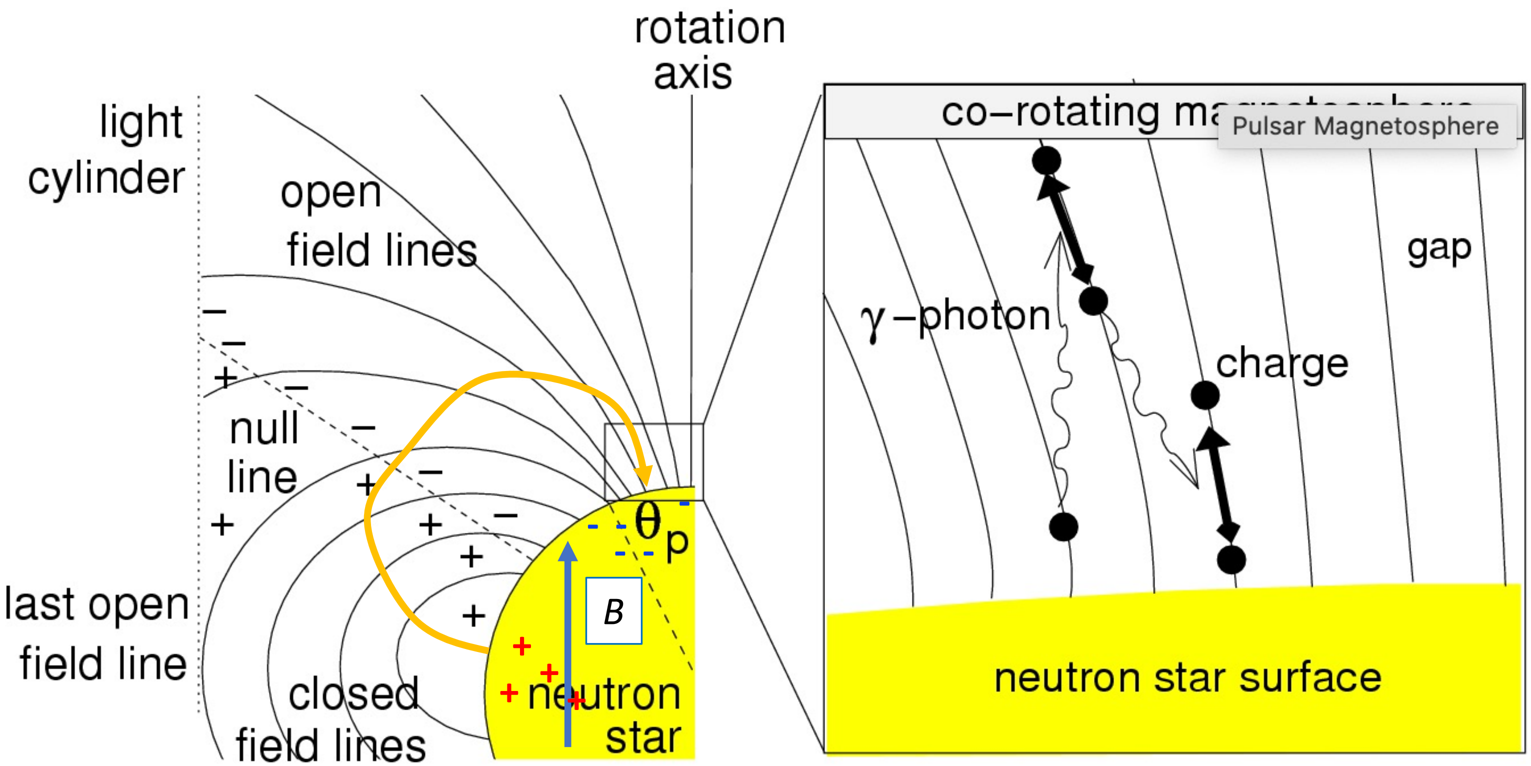
$$\vec{F} = e(\vec{E} + \vec{v}\times\vec{B})$$
$$\vec{E} + \vec{\Omega}\times\vec{R}\times\vec{B} = 0$$

at the surface of the star.

Charge separation at the surface induces quadrupole electric field outside the star. Typical electrostatic potential

$$U \sim \frac{R^2B}{T} \sim 10^{20}\left[\frac{B}{10^{12}\ G}\right]\left[\frac{R}{10^6\ cm}\right]^2\left[\frac{T}{1\ ms}\right]^{-1} V$$

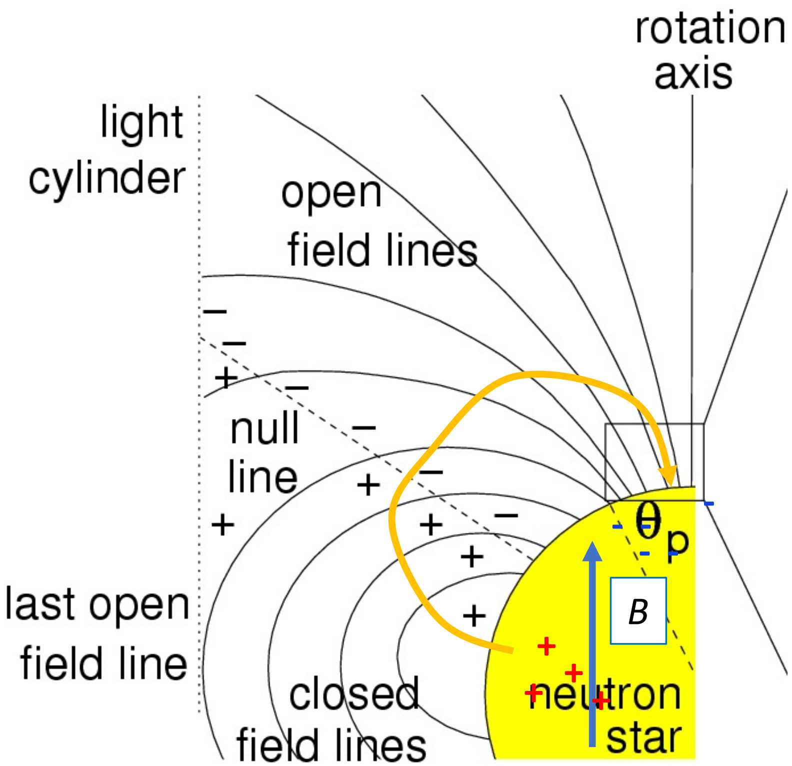
Pulsar magnetosphere



Large electrostatic potential leads to particle acceleration near the neutron star surface. High-energy electrons produce pairs in interaction with photons and magnetic field in vicinity of the neutron star. Secondary electron-positron pairs are also accelerated etc.

As a result, electron-positron plasma forms around the neutron star, creating a “magnetosphere”.

Pulsar wind



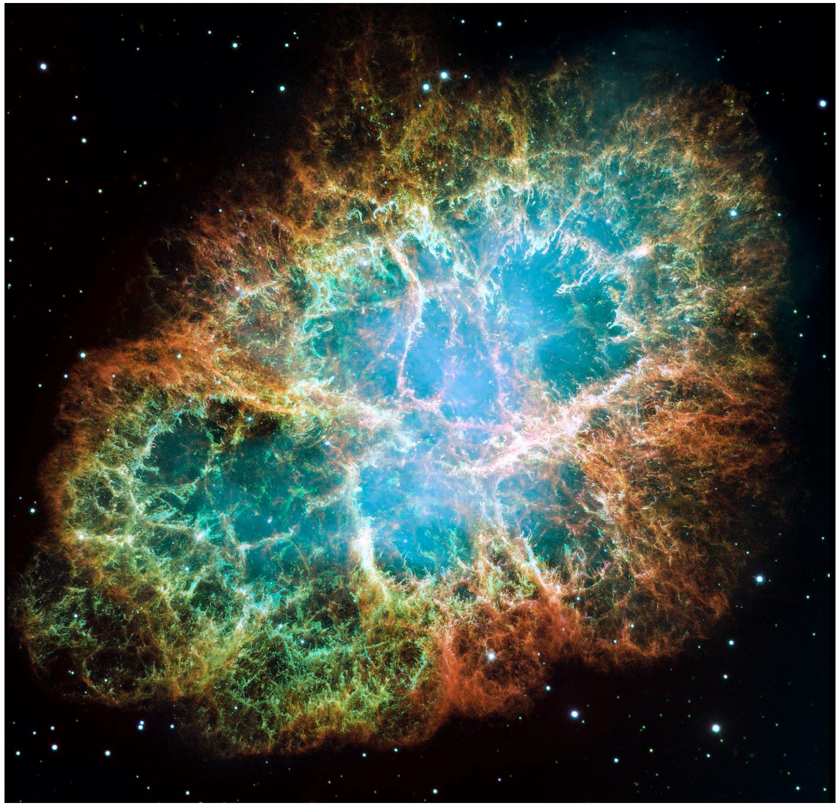
Particles in magnetosphere spiral along dipole magnetic field lines.

The magnetic field co-rotates with the neutron star.

Particles on magnetic field lines can not co-rotate beyond the distance of ”light cylinder”: the distance at which the rotation velocity is equal to the speed of light.

Plasma beyond the light cylinder escapes into a “pulsar wind”: an outflow of high-energy particles away from the neutron star.

Pulsar wind nebulae



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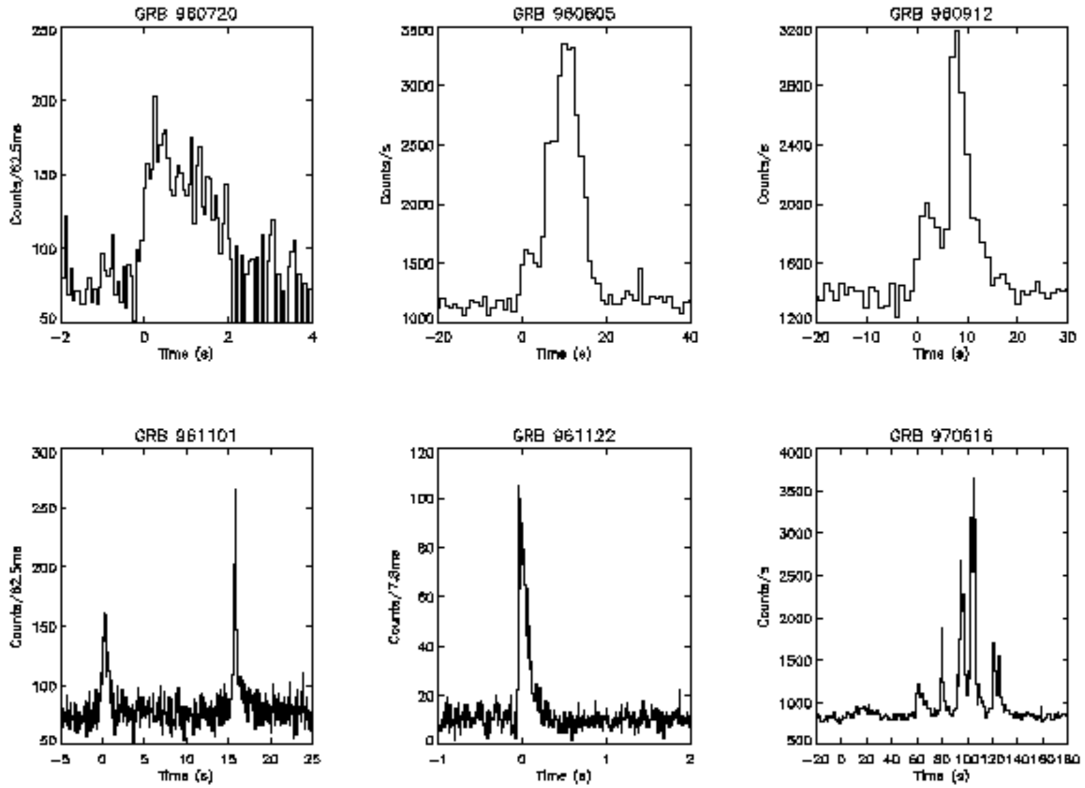
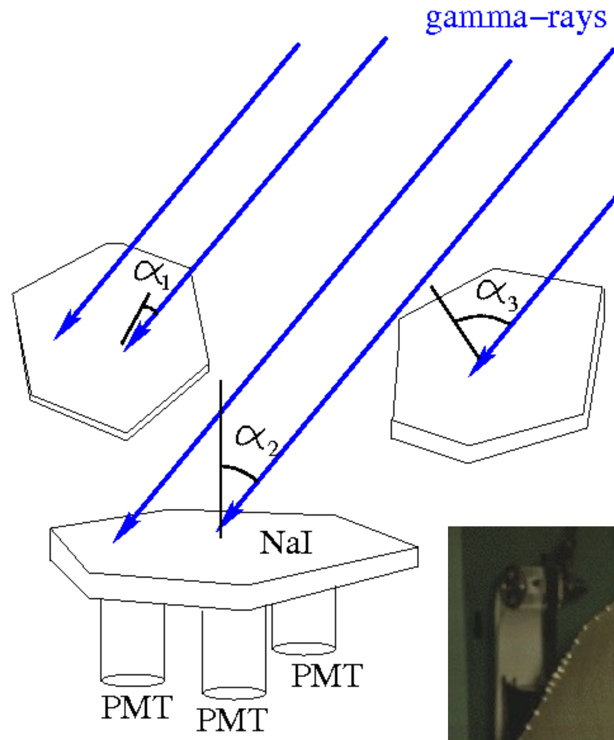
Relativistic pulsar wind is stopped at the interface with the interstellar medium. A shock is formed. Particles experience further acceleration at the shock.

High-energy electrons and positrons finally diffuse into the interstellar medium and cool emitting synchrotron and inverse Compton radiation. The synchrotron and inverse Compton “glows” are observed as a phenomenon of “pulsar wind nebulae”

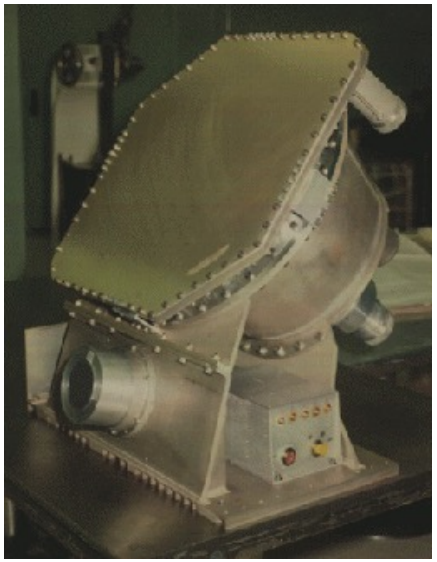
Gamma-ray bursts





Short pulses of 0.01-10 MeV gamma-rays from random directions (i.e. isotropically distributed over the full sky. ”Short” GRBs are pulses of duration <2 s. “Long” are those of duration >2 s.

Exercise: explore lightcurves of gamma-ray bursts detected with SPI-ACS detector of INTEGRAL telescope at https://www.astro.unige.ch/mmoda/ INTEGRAL telescope is operational since 2002 and most of the bright GRBs detected over the last 20 years. SPI-ACS continuously records MeV gamma-ray count rate from all the sky.



BATSE detector on board of Compton gamma-ray observatory

Relativistic outflows from collapsing stellar cores

Newly formed compact object in the core of massive star undergoing gravitational collapse starts to accrete matter of the rest of the star (if the neutrino pressure fails or “partially fails” to push the upper layers of the star into a supernova explosion.

Similar to the accreting supermassive and stellar mass black holes, the accreting black hole may “decide” top operate a particle accelerator and produce jet that may break through the collapsing matter.

Short variability time scale implies compact emission region: $R \leq ct \sim 10^{10}\left[\frac{t}{1\text{ s}}\right]$ cm. Gamma-rays with energies $E > m_e c^2$, produced by relativistic particles would not escape from a compact production region because of the pair production:

$$\lambda_{\gamma\gamma} = \frac{1}{\sigma_{\gamma\gamma} n_\gamma}; \qquad n_\gamma = \frac{L}{4\pi R^2 c\, E_\gamma}$$

$$\frac{\lambda_{\gamma\gamma}}{R} = \frac{4\pi R c\, E_\gamma}{\sigma_{\gamma\gamma} L} \sim 10^{-9}\left[\frac{R}{10^{10}\text{cm}}\right]\left[\frac{E_\gamma}{1\text{ MeV}}\right]\left[\frac{L}{10^{50}\frac{\text{erg}}{\text{s}}}\right] \ll 1$$

($\sigma_{\gamma\gamma} \sim 10^{-25}\text{cm}^2$ is the pair production cross-section). Account of Doppler effect provides solution to this “compactness problem” if the source is moving with gamma-factor $\Gamma \sim 10^3$ ($R \to \Gamma^2 ct$, $E \to \Gamma E$, $\frac{\lambda_{\gamma\gamma}}{R} \propto \Gamma^3$).