3D explosion dynamics of a critical-mass neutron star in a binary system

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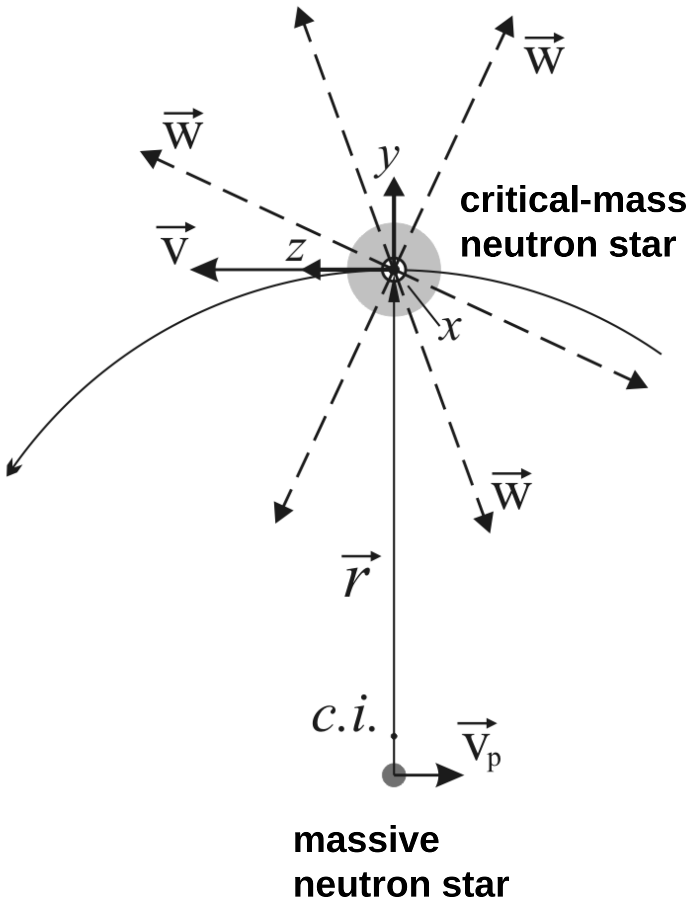
Problem statement

Imshennik V.S., Manukovskiy K.V., AstrL, 33, 2007



$$a = \frac{m^2}{M+m}\frac{G}{V_p^2} = \frac{M^2}{M+m}\frac{G}{V_{ns}^2}$$

$$[V] = \left(\frac{GM}{a}\right)^{1/2}$$

$$v = V_{ns}/[V] = \left(\frac{M}{M+m}\right)^{1/2}$$

$$w = (2\varepsilon_0/m_0)^{1/2}/[V]$$

$$\varepsilon_0 = 4.7\ MэB/nucleon$$

$$V_p = 1000\ km/s$$

$$m = 0.1 M_\odot$$

$$M/m = 18: \quad v = 0.973$$

$$w = 1.622$$

Analytical solution ($M/m \to \infty$)

Runge-Lenz vector

$$\mathbf{A} = -GM\frac{\mathbf{r}}{r} + \left(\mathbf{v} + \mathbf{w}\right) \times \mathbf{J}$$

$$A = \sqrt{\left(GM\right)^2 + 2EJ^2} = GMe \qquad \mathbf{J} = \mathbf{r} \times \left(\mathbf{v} + \mathbf{w}\right)$$

Landau L.D., Lifshitz E.M., Mechanics

Asymptotic velocity

$$\mathbf{v}_\infty = \frac{1}{e}\left[-\sqrt{2E}\,\hat{\mathbf{A}} + \left(\frac{2EJ}{GM}\right)\hat{\mathbf{J}} \times \hat{\mathbf{A}}\right] \quad \left(E > 0,\ t \to \infty\right)$$

$$\hat{\mathbf{A}} = \frac{\mathbf{A}}{A} \qquad \hat{\mathbf{J}} \times \hat{\mathbf{A}} = \frac{\mathbf{J} \times \mathbf{A}}{JA}$$

$$e^2 = 1 + \frac{2EJ^2}{\left(GM\right)^2} \quad \left(E > 0\right) \qquad 2E = \left|\mathbf{v} + \mathbf{w}\right|^2 - \frac{2GM}{r}$$

Colpi M., Wasserman I., Astrophys. J., 581, 1271(2002)

Velocity components

Isotropic explosion

$$w_x = w\sin\theta\cos\varphi$$

$$w_y = w\sin\theta\sin\varphi$$

$$w_z = w\cos\theta$$

$$v_{x\infty} = \frac{(w\sin\theta\cos\varphi)\sqrt{\Phi}}{1+\Phi\Psi}\left[w\sin\theta\sin\varphi + \sqrt{\Phi}\,(\Psi-1)\right]$$

$$v_{y\infty} = \frac{\sqrt{\Phi}}{1+\Phi\Psi}\left[\sqrt{\Phi}\Psi w\sin\theta\sin\varphi - (\Psi-1)\right]$$

$$v_{z\infty} = \frac{(v+w\cos\theta)\sqrt{\Phi}}{1+\Phi\Psi}\left[w\sin\theta\sin\varphi + \sqrt{\Phi}\,(\Psi-1)\right]$$

$$\Psi = (v+w\cos\theta)^2 + w^2\sin^2\theta\cos^2\varphi$$

$$\Phi = \left(w^2+v^2+2wv\cos\theta\right)-2$$

Energy spectrum

Velocity magnitude $$v_\infty^2 = \Phi = \left(v^2 + w^2 + 2wv\cos\theta\right) - 2$$

Critical angle $$\cos\theta_{cr} = \frac{2 - w^2 - v^2}{2wv} \qquad \sqrt{2} - v \le w \le \sqrt{2} + v$$

Energy spectrum $$f(E) = \frac{1}{\left(1 - \cos\theta_{cr}\right)wv} = \frac{2}{\left(v+w\right)^2 - 2} = const$$

Maximum energy

hyperbolic tracks

$$e_{\max}^{hyp} = \frac{1}{2}\left(v+w\right)^2 - 1$$

elliptic tracks

$$e_{\max}^{ell} = \frac{1}{2}\left(\frac{GM}{J}\right)^2 \left(e+1\right)^2 \underset{J\to 0}{\longrightarrow} \infty$$

kinetic energy

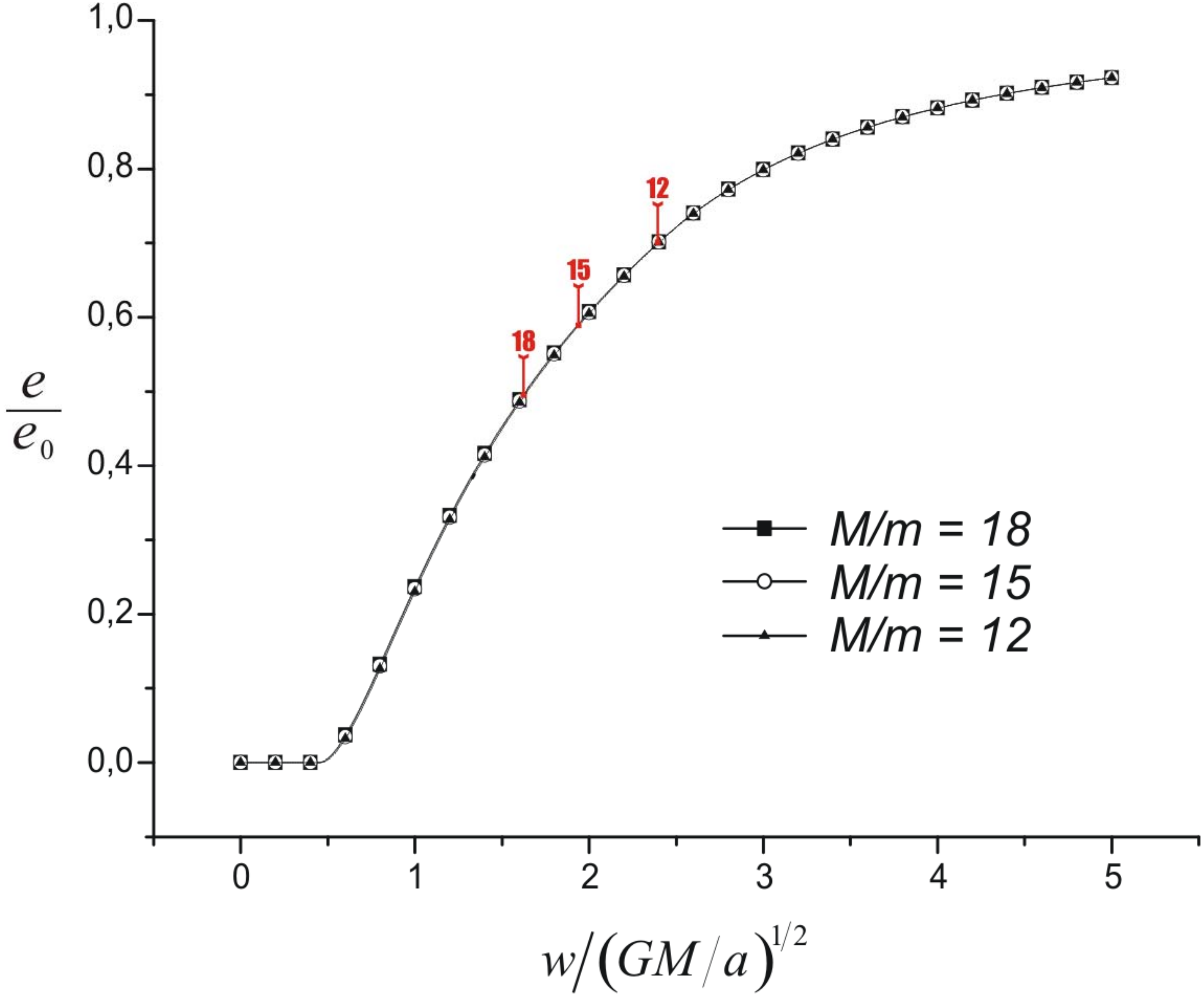
Initial energy $e_0 = \frac{m}{2}\left(\frac{GM}{a}\right)\left(v^2 + w^2\right)$

Final energy

$$e = \frac{m}{4}\left(1 - \cos\theta_{cr}\right)\left[\left(v^2 + w^2 - 2\right) + wv\left(1 + \cos\theta_{cr}\right)\right]\left(\frac{GM}{a}\right)$$

$$\begin{cases} e = \frac{m}{2}\left(\frac{GM}{a}\right)\left(v^2 + w^2 - 2\right), \quad w \geq \sqrt{2} + v \\ e = \frac{m}{16wv}\left(\frac{GM}{a}\right)\left[\left(v + w\right)^2 - 2\right]^2, \quad \sqrt{2} - v \leq w < \sqrt{2} + v \\ e = 0, \quad w < \sqrt{2} - v \end{cases}$$

Kinetic energy



Recoil momentum

$$\left(M+\Delta m\right)v_p' + \left(m-\Delta m\right)v_e = 0 \qquad \Delta m/m = \chi = \frac{1+\cos\theta_{cr}}{2}$$

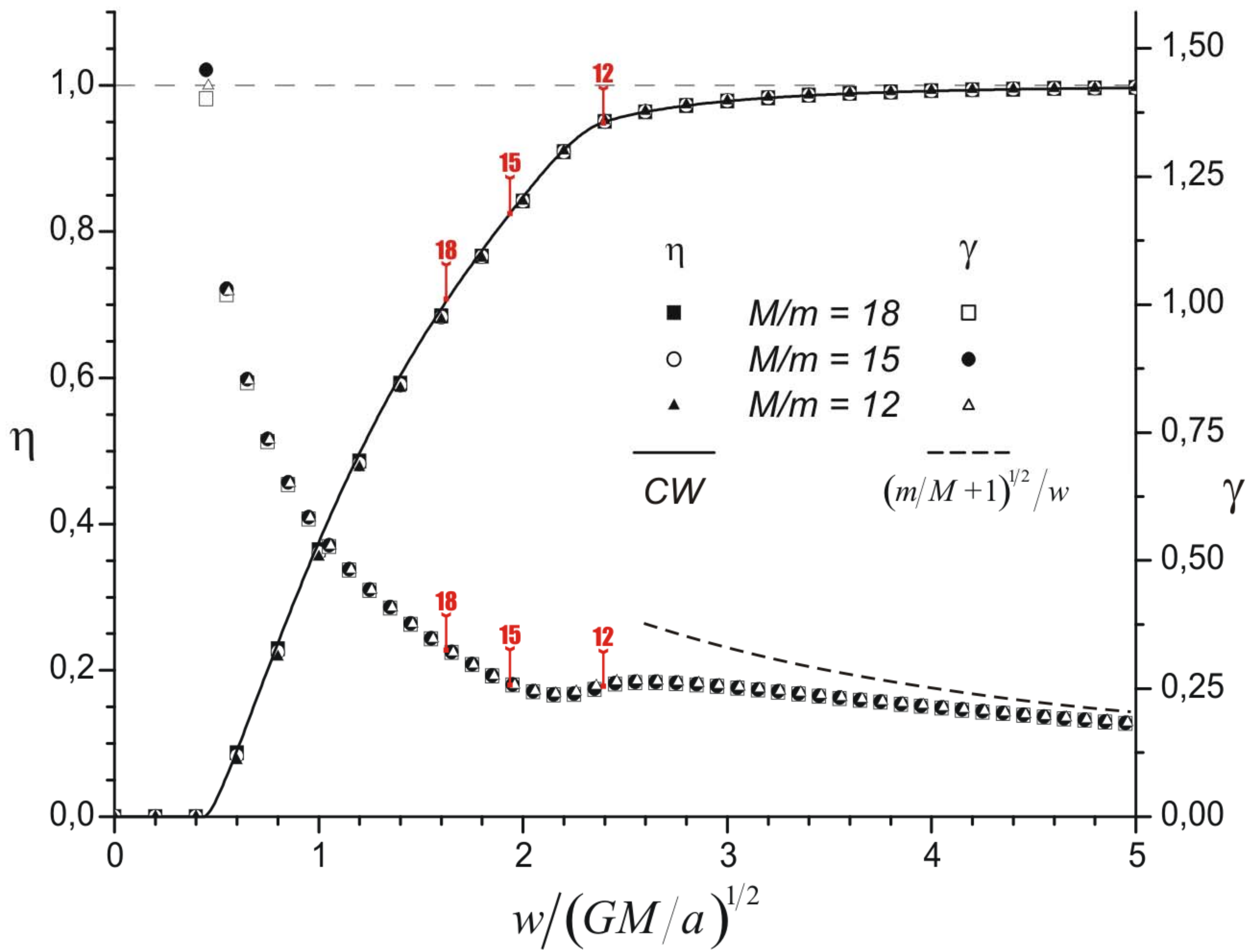
$$v_p' = \frac{1}{M/m+\chi}\left(g^2+f^2\right)^{1/2}$$

$$f = \frac{1}{4\pi}\int_0^{\theta_{cr}}\left(v+w\cos\theta\right)\Phi\sin\theta d\theta\int_0^{2\pi}\left(\frac{\Psi-1}{1+\Phi\Psi}\right)d\varphi$$

$$g = -\frac{1}{4\pi}\int_0^{\theta_{cr}}\sqrt{\Phi}\sin\theta d\theta\int_0^{2\pi}\left(\frac{\Psi-1}{1+\Phi\Psi}\right)d\varphi$$

Normalized velocity $$\eta = \frac{v_p'}{v_p} = \frac{v_p'}{\frac{m}{M}v} = \frac{1}{1+\chi\frac{m}{M}}\frac{1}{v}\left(g^2+f^2\right)^{1/2}$$

Pulsar velocity and angle of rotation



Simulation using particles

equations

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{u}_i$$

$$m_i \frac{d\mathbf{u}_i}{dt} = \mathbf{F}_i$$

$$M \frac{d\mathbf{u}_p}{dt} = -\sum_{i=1}^{N} \mathbf{F}_i$$

$$\mathbf{F}_i = \frac{G m_i M}{\left|\mathbf{r}_i - \mathbf{r}_p\right|^3} \left(\mathbf{r}_p - \mathbf{r}_i\right)$$

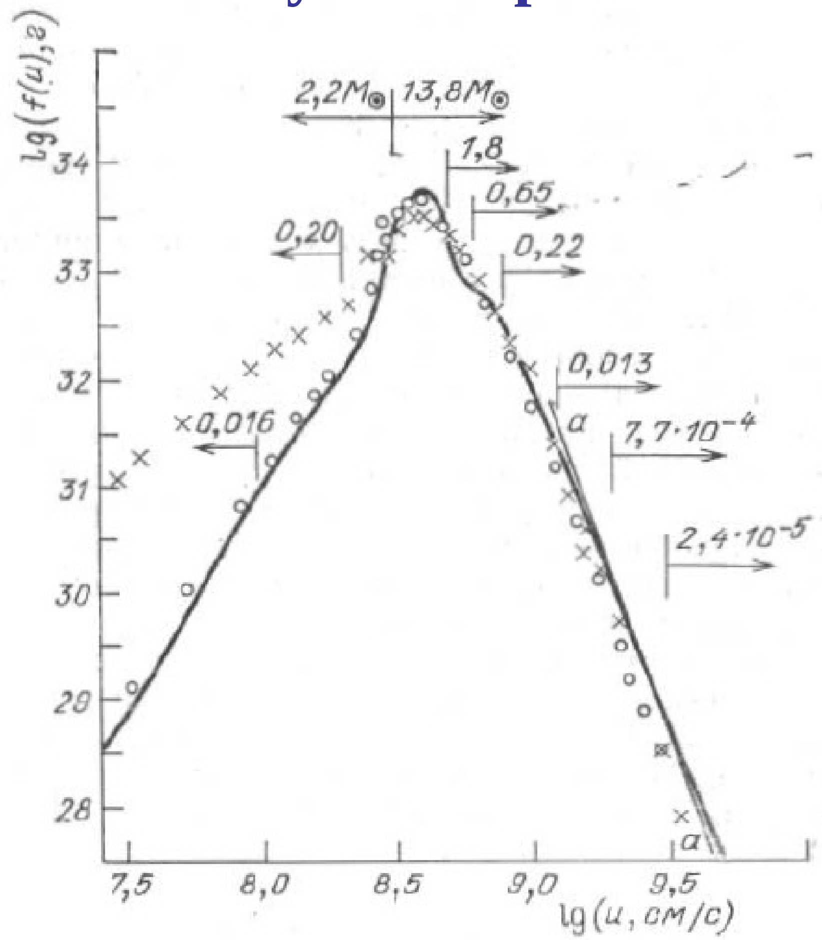
$$i = 1, .., N$$

schemes

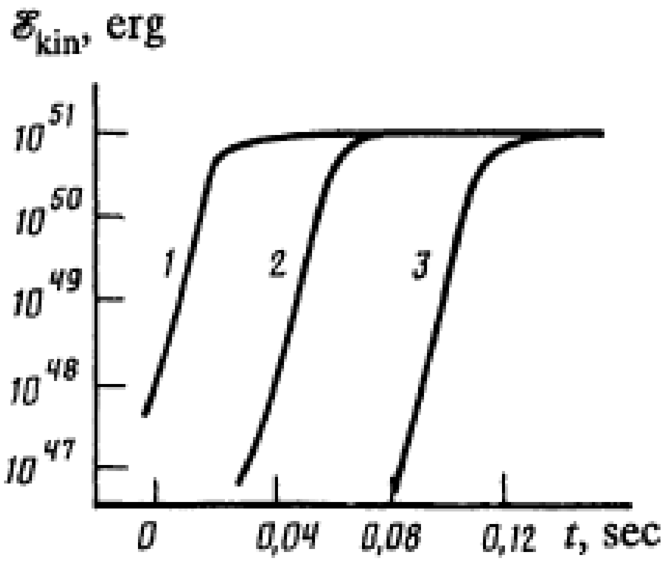
2nd-order leap-frog scheme
4th-order Runge-Kutta scheme
5th-order Runge-Kutta-England scheme
with automatic step selection

Simulation setup

Velocity radial profile



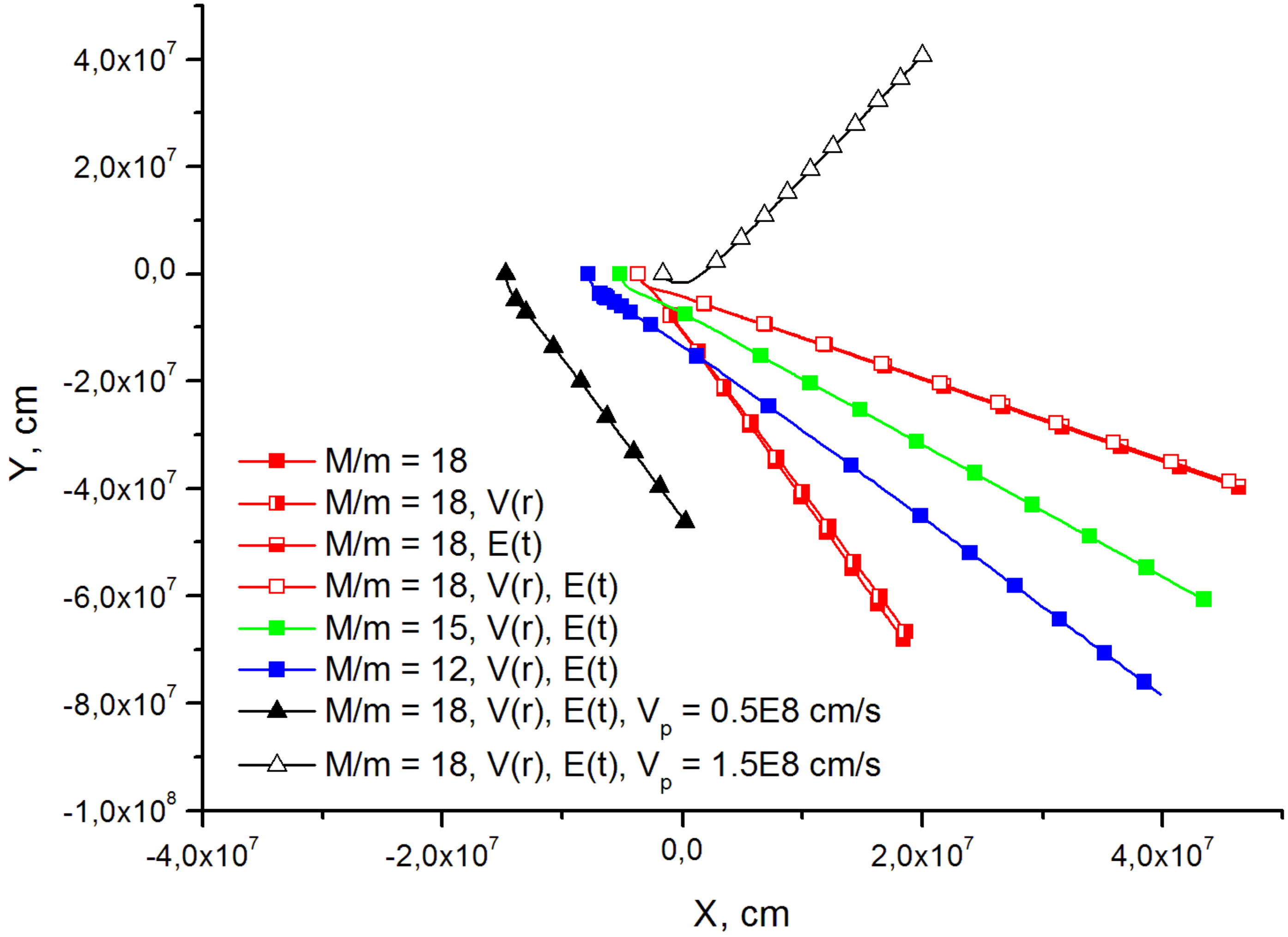
Energy release



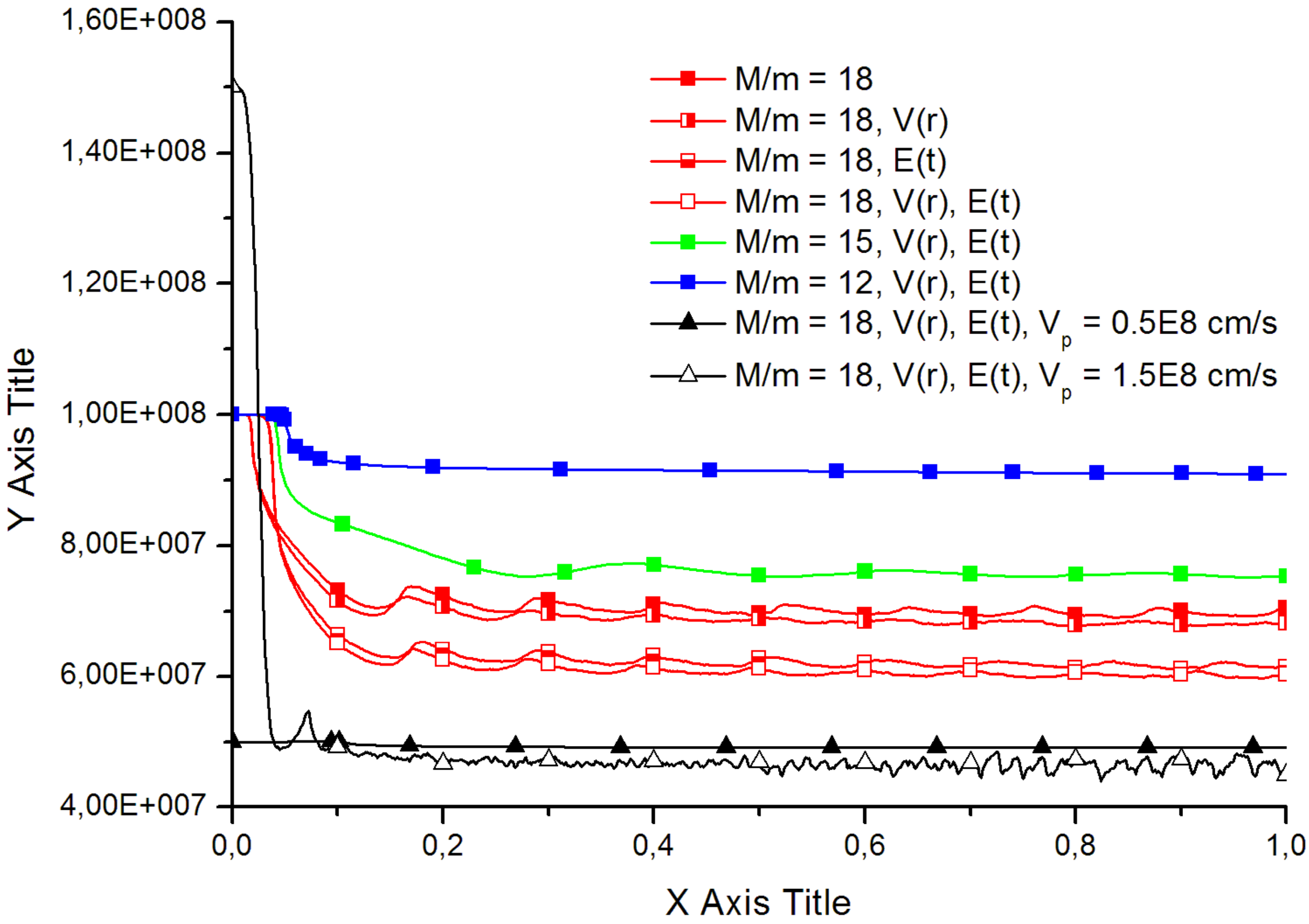
Blinnikov S.I. et al.,
Soviet Astr., 34, 1990

Imshennik, Nadyozhin,
Sov. Sci. Rev. E, 8 , 1989

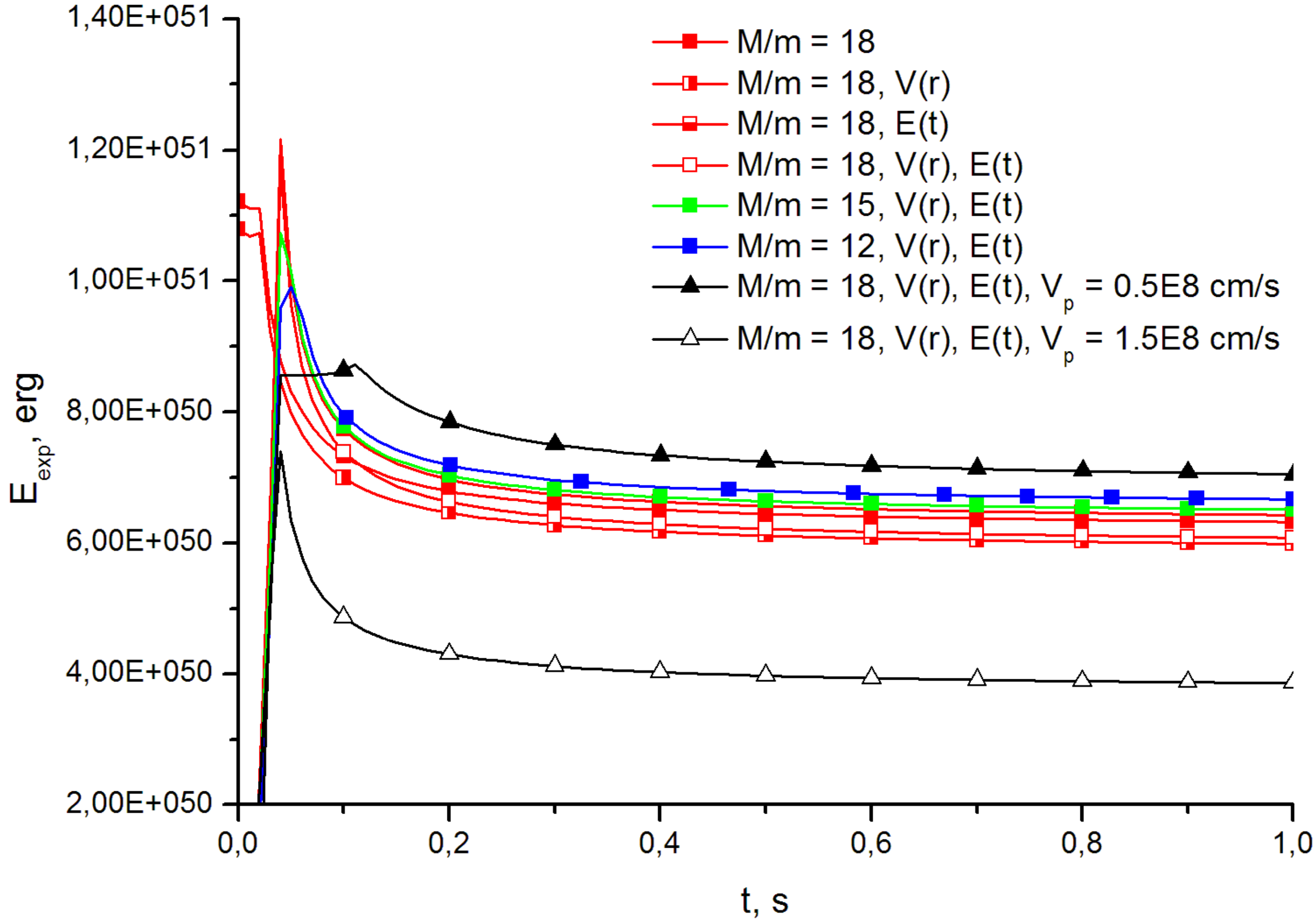
Pulsar track



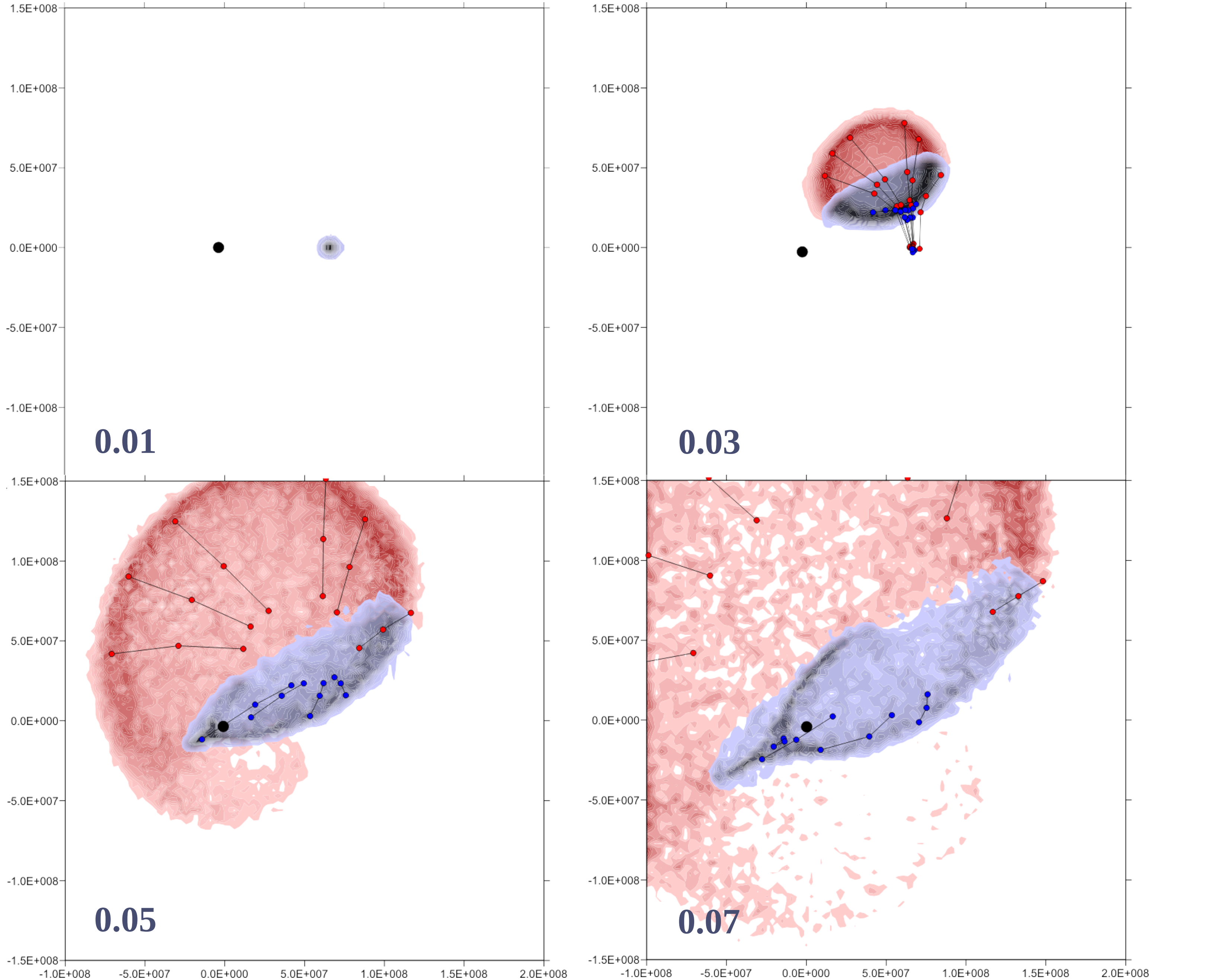
Pulsar velocity



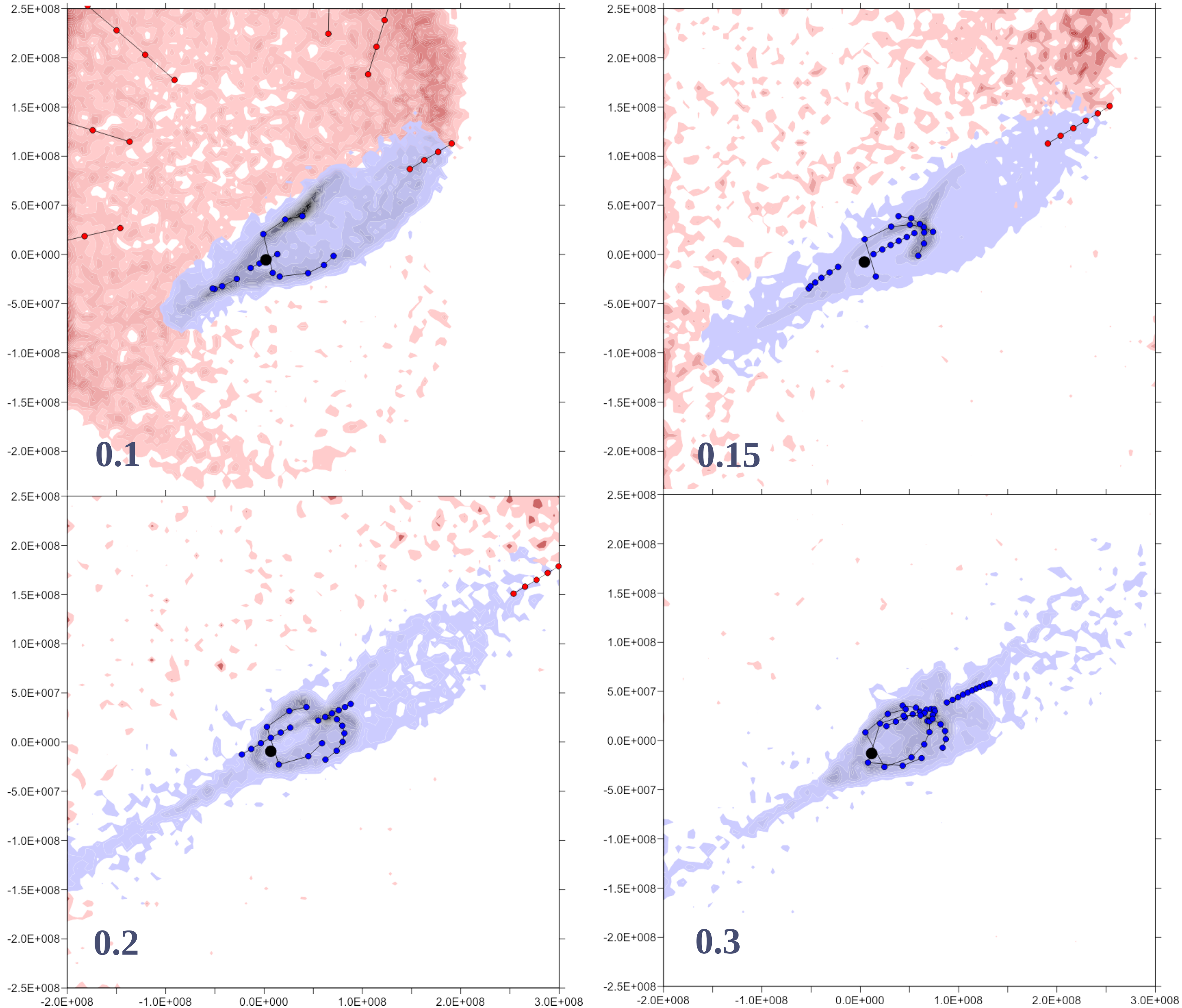
Explosion energy



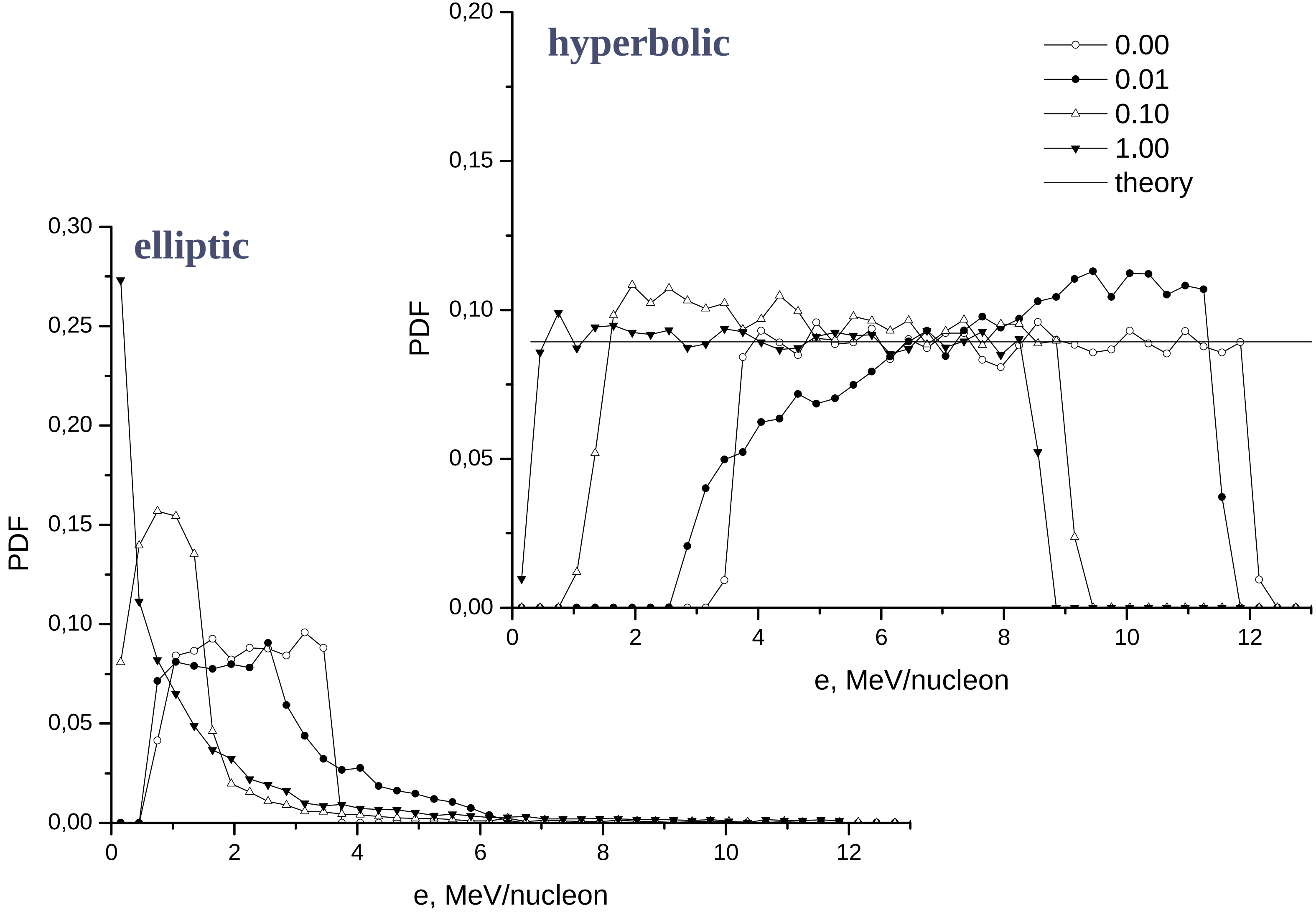
Explosion dynamics



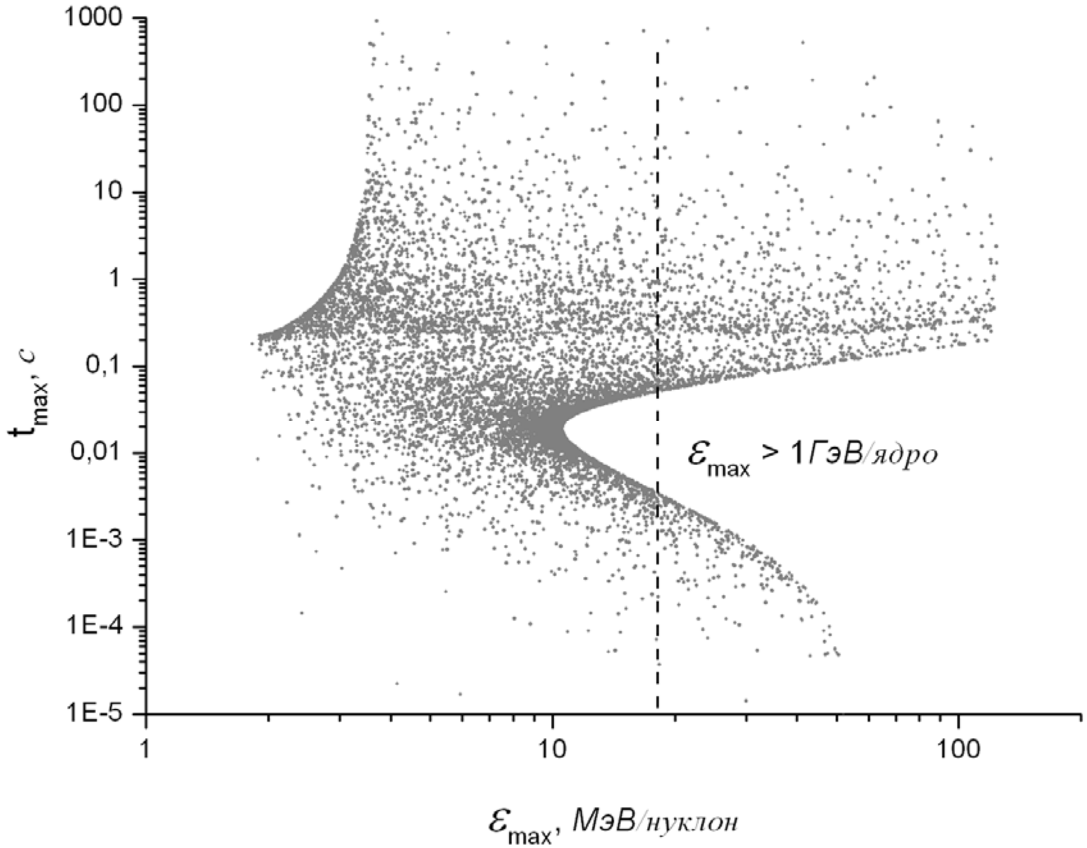
Explosion dynamics

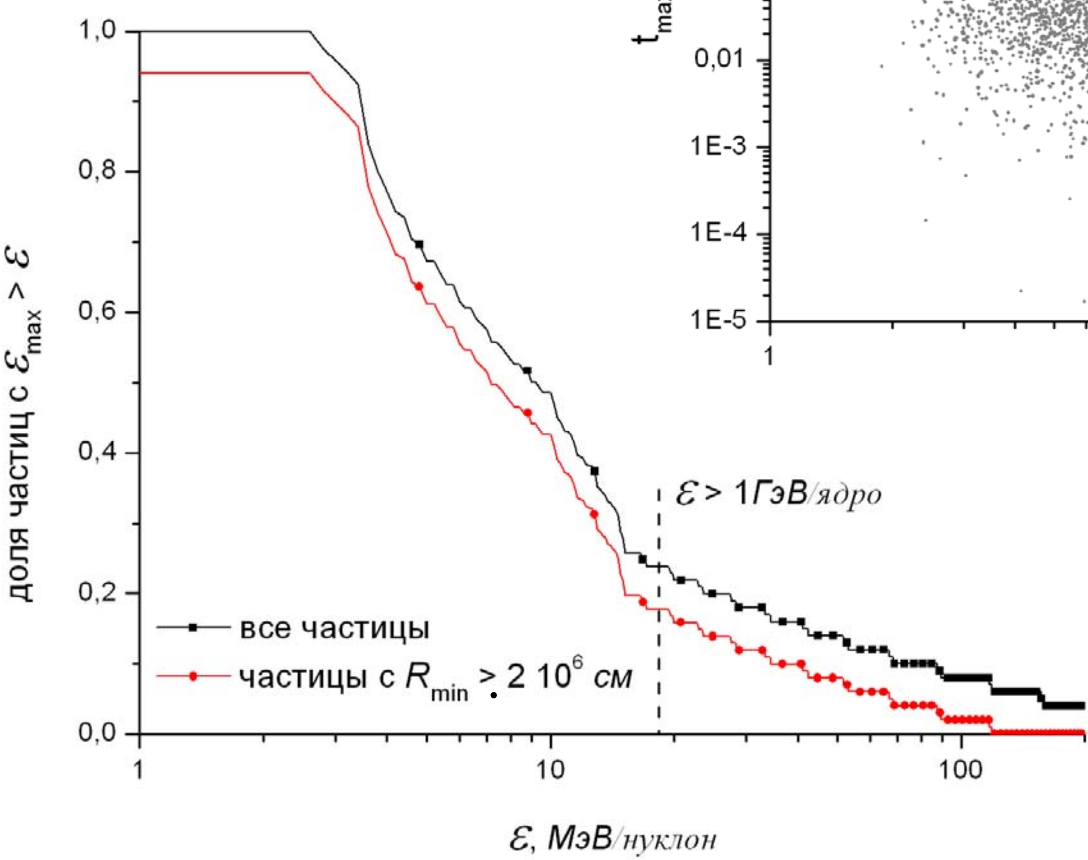


Energy spectrum



Captured matter





Muon neutrinos

$$Fe^{56} + Fe^{56} \to \pi^{\pm} + \ldots$$

$$\sigma\left(E_{Fe}\right) - ?? \quad \left(for\ E_{Fe} \geq E_{Fe\,th}\right)$$

Ryazhskaya O.G., UFN, 2007

main reaction

$$\pi^{-} \to \mu^{-} + \tilde{\nu}_{\mu} \qquad \mu^{-} + Fe^{56} \to Mn^{55} + n + \nu_{\mu}$$

$$\pi^{+} \to \mu^{+} + \nu_{\mu} \qquad \mu^{+} \to e^{+} + \nu_{e} + \tilde{\nu}_{\mu}$$