PAIR PLASMA GENERATION AND PULSAR γ-RAY EMISSION

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ABSTRACT Recent progress in pulsar theoretical models points to the following picture of how the main "pulsar machine" works: pair formation in pulsars happens in bursts, the maximum pair plasma density generated during single burst does not exceed $\sim$ few $\times\, 10^5$ Goldreich-Julian densities. Pair formation bursts repeat every $\sim 30\mu$secs. γ-ray emission from polar caps should be weak and have cut-off at MeV energies.

Polar cap cascades overview

Most of the pairs in pulsar magnetosphere are created in polar cap where particles are accelerated by strong electric field, emit high energy γ-rays which are absorbed in ultrastrong magnetic field and create electron-positron pairs. The screening of the electric field in the gap happens very quickly, well before the multiplicity reaches its maximum values. Once primary particles have produced the first generation of pairs which screen the accelerating electric field, they keep moving in the regions of screened field, radiate their energy away and give rise to extensive pair cascades. Each discharge forms a pair-forming blob moving along magnetic field lines.

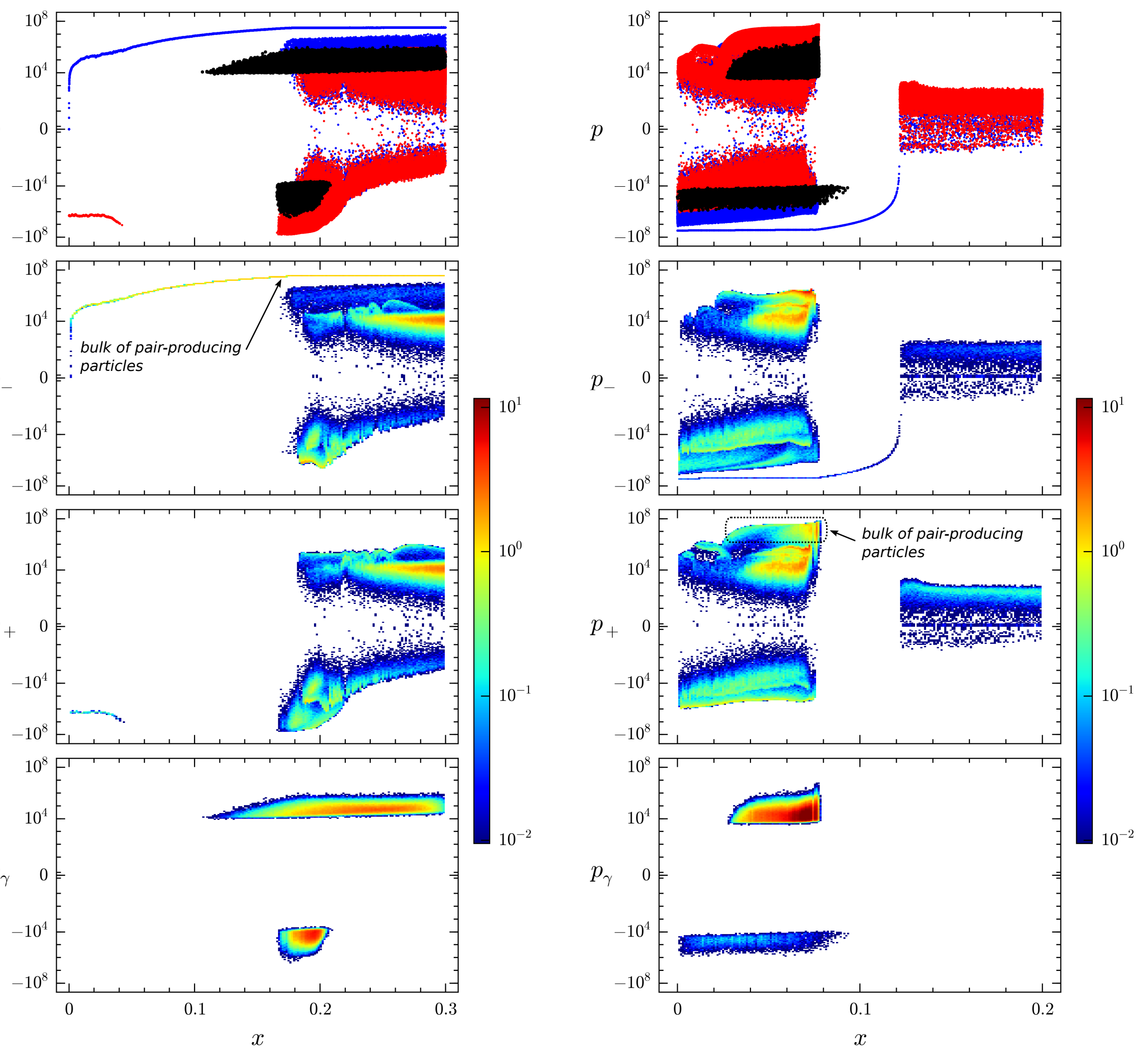

FIGURE 1: *Particle acceleration in polar caps along filed lines with different current densities. Left panels: super-GJ current, right panels: anti-GJ current. Top panels – cascade's phase space portrait: each dot is a numerical particle;* e^- *– blue,* e^+ *– red,* γ *–black. Plots beneath – particle number density* n *in phase space:* p_- *vs* x *– electrons,* p_+ *vs* x *– positrons,* p_γ *vs* x *– photons.* n *(in* $n_{\rm GJ}$*) is color-coded according to the map on the right.*

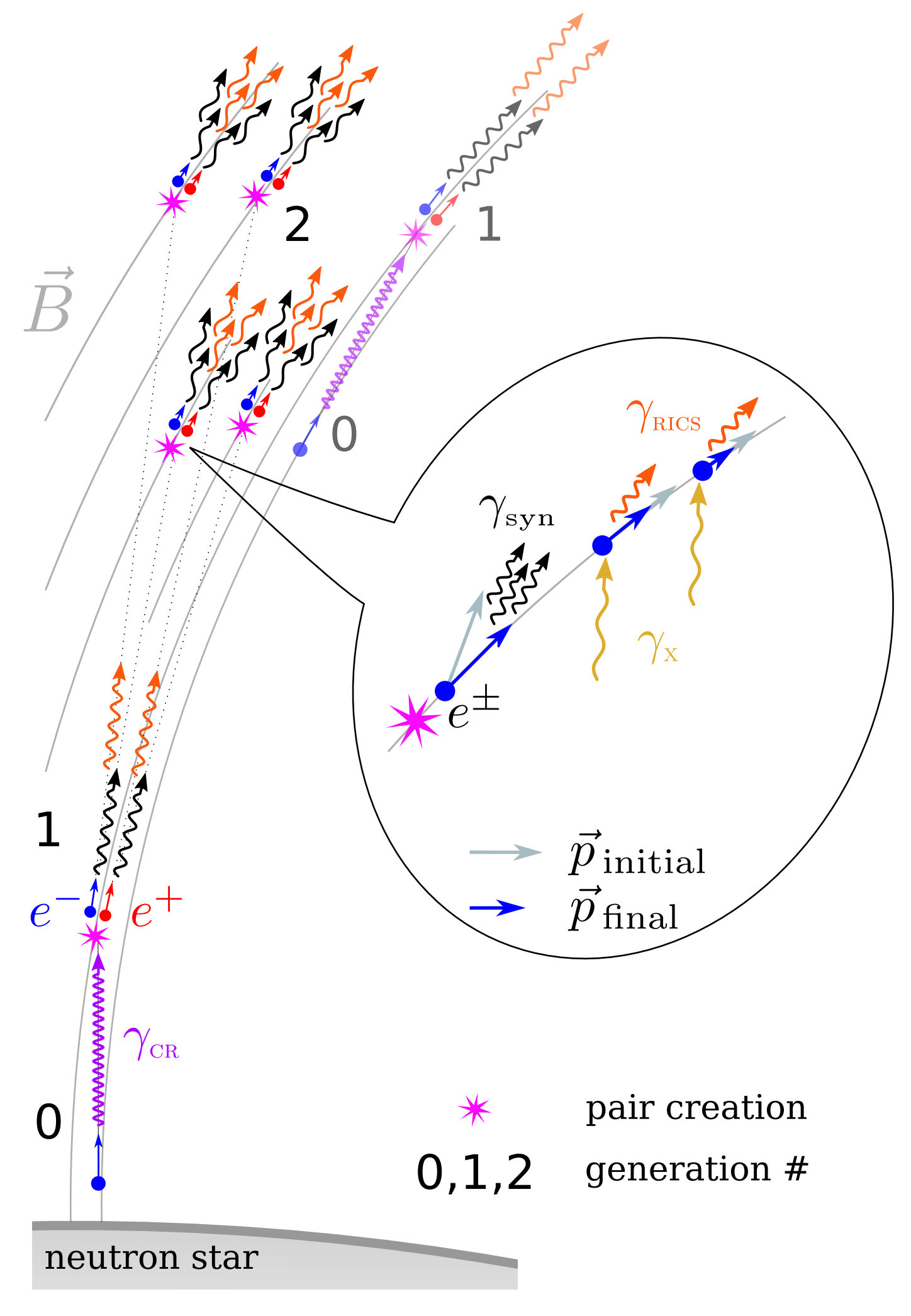

FIGURE 2: *Schematic representation of the full electron-positron cascade in the polar cap of a young pulsar with high magnetic field.*

Primary electrons emit Curvature Radiation (CR) photons $\gamma_{\rm CR}$ [generation 0]. CR photons are absorbed and each photon creates an electron-positron pair [gen 1]. At the moment of creation, these particles have finite momentum $\perp$ to $\vec{B}$ which they radiate immediately via synchrotron radiation (SR); they can also scatter thermal X-ray photons γ_X coming from the NS surface via Resonant Inverse Compton Scattering (RICS) and loose their momentum $\parallel$ to $\vec{B}$. CR photons of the secondary particles have lower energy and cannot create pairs. Gen 1 photons – $\gamma_{\rm syn}$ and $\gamma_{\rm RICS}$ are emitted tangent to $\vec{B}$ – the secondary $e^\pm$ are relativistic – and propagate some distance before acquiring the necessary angle to $\vec{B}$ and creating gen 2 pairs. These pairs in their turn radiate their perpendicular momentum via SR, and parallel momenta via RICS emitting gen 2 photons. The cascade stops at a generation where the photons energy falls below the escape energy $\epsilon_{\gamma,\,\rm esc}$.

Particle acceleration and pair creation is non-stationary – the burst of pair formation is followed by a (longer) quiet phase when accelerated field is screened by particles leaking from the pair forming plasma blob and pair formation is ceased.

Characteristics of a single burst of pair formation

Electron-positron cascade is essentially a process of splitting the energy of the primary particle into the energy of electron-positron pairs. In an ideal case, when both primary and secondary particles radiate all their energies as pair producing photons, the multiplicity κ of such cascades (the number of particles produced by each primary particle) would be

$$\kappa_{\rm max} \simeq 2\,\frac{\epsilon_{\pm,\,\rm acc}}{\epsilon_{\gamma,\,\rm esc}} = \begin{cases} 5.4\times10^5 \rho_{\rm c,7}^{-3/7} P^{-1/7} B_{12}^{6/7}, & B \lesssim 3\times10^{12}\,\mathbf{G} \\ 1.6\times10^6 \rho_{\rm c,7}^{-3/7} P^{-1/7} B_{12}^{-1/7}, & B \gtrsim 3\times10^{12}\,\mathbf{G} \end{cases} \tag{1}$$

where $B_{12} \equiv B/10^{12}$G, the radius of curvature of magnetic field lines $\rho_{\rm c,7} \equiv \rho_{\rm c}/10^7$cm; By virtue of the used approximation eq. (1) gives an upper limit on the cascade multiplicity.

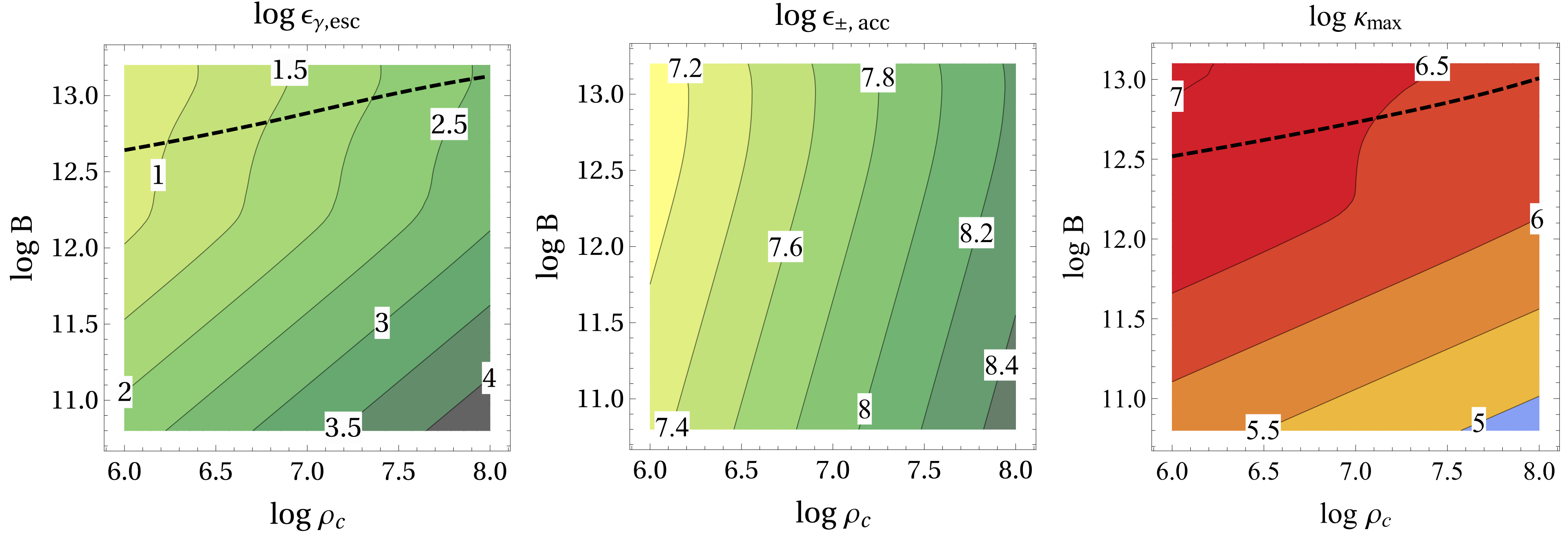

FIGURE 3: *Contour plots of the logarithms of quantities from eq. (1) as functions of the magnetic field strength and the radius of curvature of magnetic field lines. From left to right: energy of escaping photons* $\epsilon_{\gamma,\,\rm esc}$*, energy of primary particles* $\epsilon_{\pm,\,\rm acc}$*, estimate for cascade multiplicity* κ_{max} *according to eq. (1) – an upper limit on the cascade multiplicity. The dashed line is the magnetic field above which photon splitting starts affecting multiplicity.*

A detailed study of cascade kinetics which takes into account the efficiency of the energy transfer from particles to photons and back, provides the following predictions for polar cap cascade multiplicity

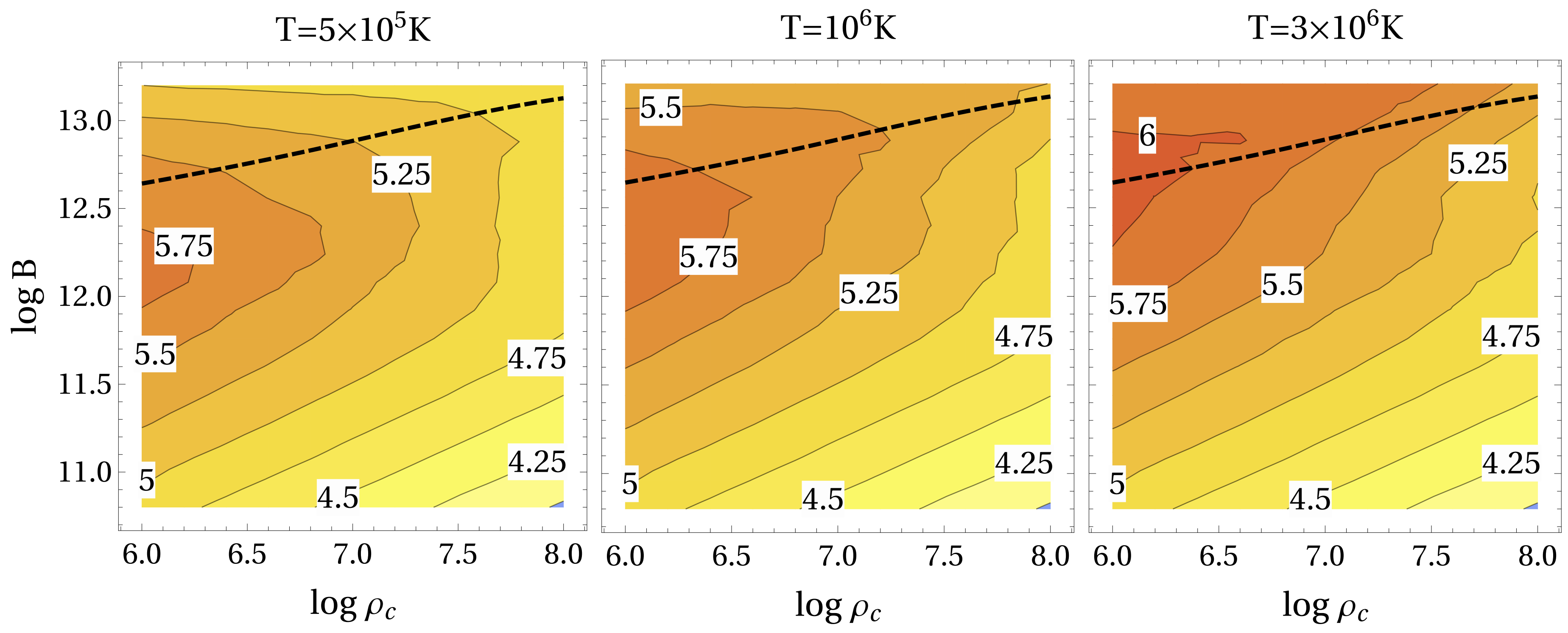

FIGURE 4: *Multiplicity of polar cap cascades: contours of* $\log\kappa$ *as a function of logarithms of curvature of magnetic field lines* ρ_c *and magnetic field strength* B *for a pulsar with* $P = 33$ *mses for three temperatures of NS surface* $T = 5\times10^5, 10^6, 3\times10^6$*K.*

Repetition rate of pair formation bursts

Repetition rate can be inferred from the data on polar cap heating. NS surface is being heated by energetic particles accelerated during the burst. During quiet phase, the polar cap is filled with low energy particles leaking from the blob where pair creation is still happening; such particles provide negligible heating. Knowing the energy output from a single pair formation burst and comparing it with the thermal X-ray flux from polar cap seen in some pulsars, it is possible to estimate the cascade repetition rate. The data point to the time between successive burst of the order of $R_{\rm NS}/c \sim 30\mu$sec.

Assuming that particle leakage from the pair forming blob stops when pair formation shuts down – what should happen ad distances of the order of $R_{\rm NS}$, where magnetic field drops by an order of magnitude – we get an estimate on the X-ray luminosity of the polar cap heated by cascades

$$L_X \sim < n\epsilon_{\rm acc} c S > \equiv f_N n_{\rm GJ}\, \epsilon_{\rm acc} c f_S\, \pi r_{\rm pc}^2 \quad f_D\,\frac{h_{\rm gap}}{R_{\rm NS}} \tag{2}$$

or numerically

$$L_X \sim f_D\, f_S\, f_N\, 2.5\times10^{16} \dot{E}^{3/7} B_{12}^{-4/7} \rho_7^{6/7} \tag{3}$$

This estimate is in a good agreement with the observational data shown on Fig. 5.

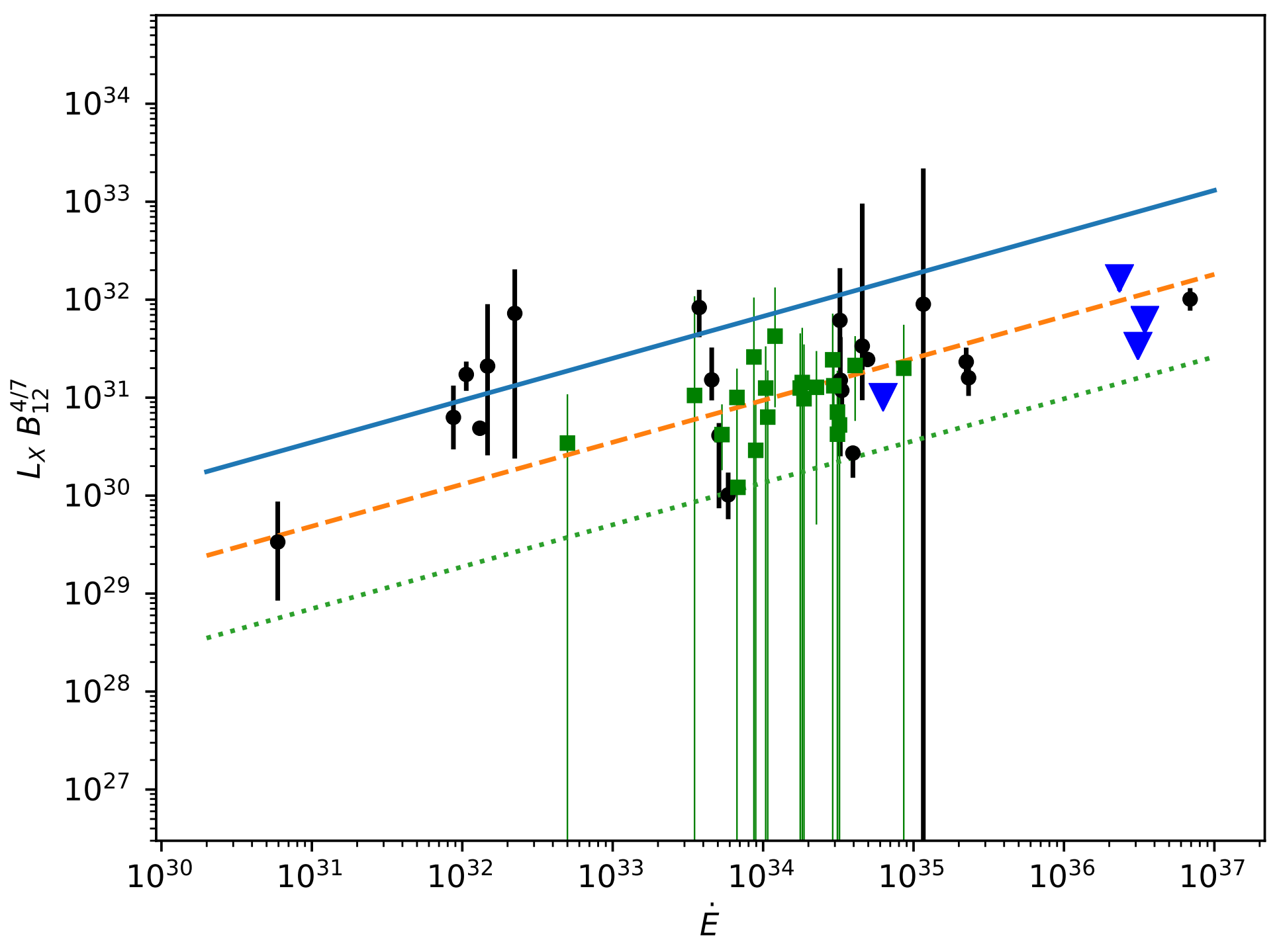

FIGURE 5: *X-ray luminosity of hot thermal spots of pulsars vs pulsar spindown rate. Lines show estimates for the luminosity of pulsar polar caps heated by cascades according to eq. (3) for different values of parameters* $f_D\, f_S\, f_N$

References: [1] A. N. Timokhin & A. Harding 2015, ApJ, **810**, 144; [2] A. N. Timokhin & A. Harding 2018, arXiv:1803.08924; [3] A. N. Timokhin & A. Harding 2018, in preparation