Pulsar as plasma generator

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Workshop on Relativistic Plasma Astrophysics,
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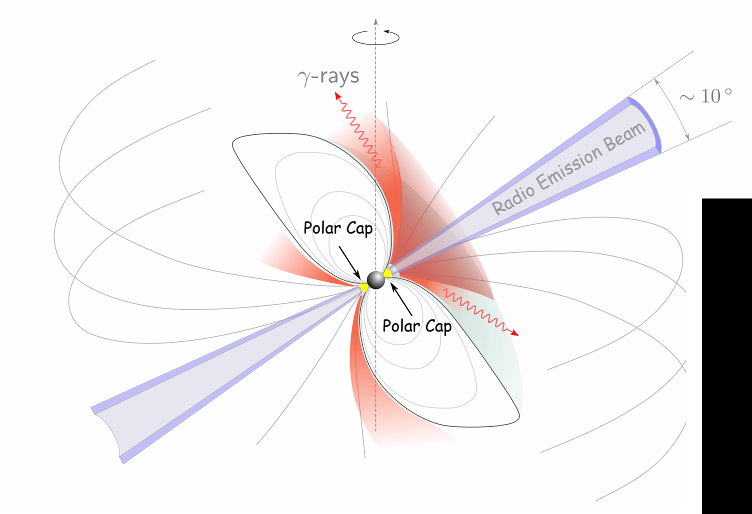
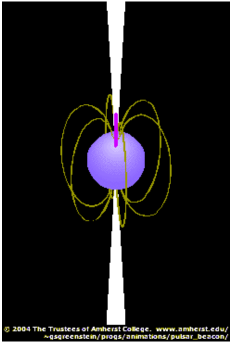
Pulsar: rapidly rotating magnetized neutron star

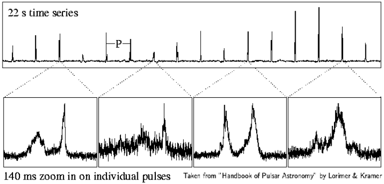
"Electric lighthouse"



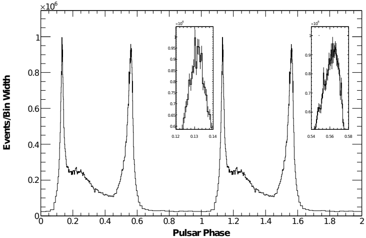


Pulsars: What we see

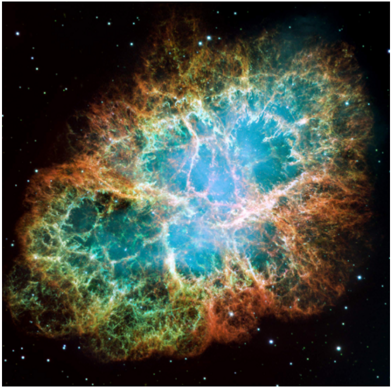
radio:



gamma:



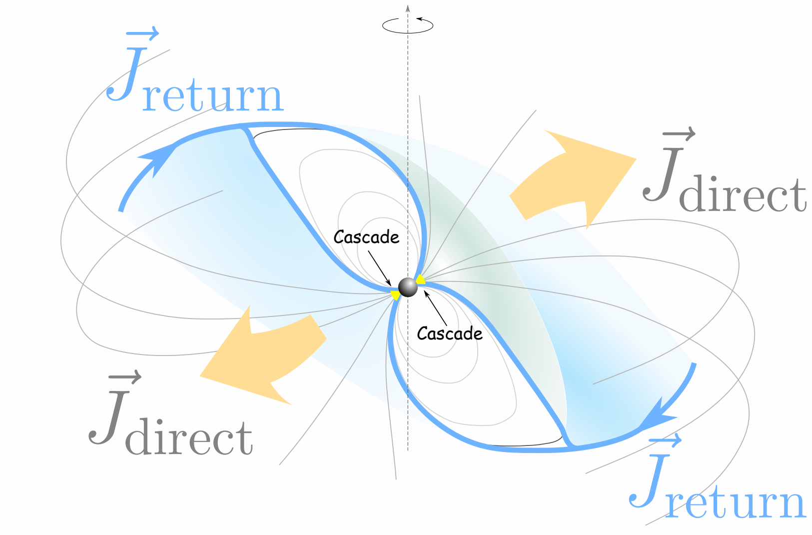
- Pulse peaks are narrow
- Negligible energy budget



- PWNe feed by dense plasma
- Energy goes there

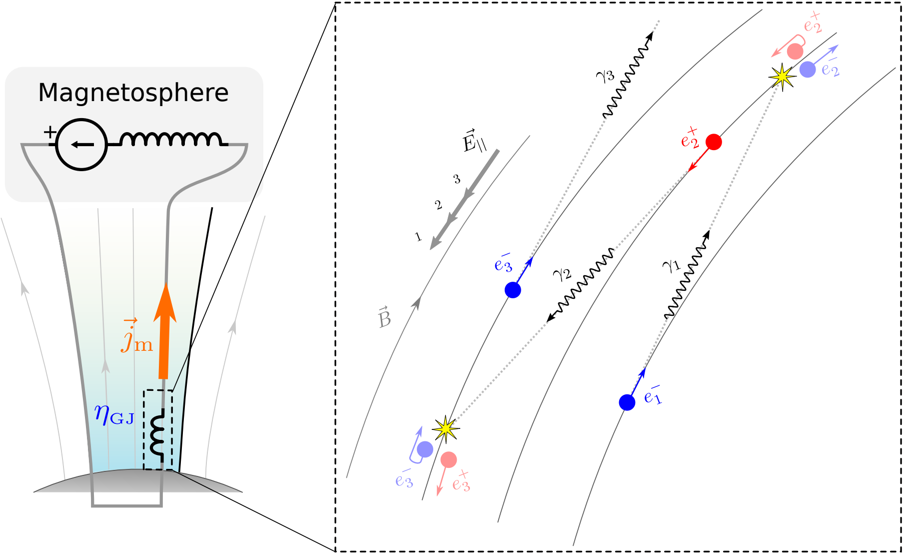
Pulsar Magnetosphere: Theorist view

The global circiut in the electrical generator



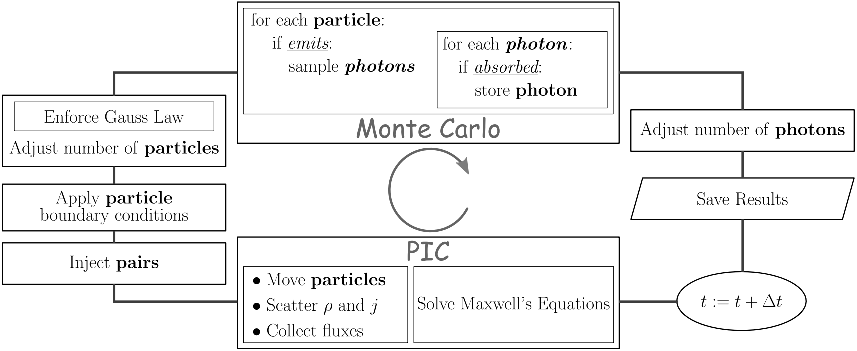
Plasma creation in the polar cap

Cascades are electromagnetically driven



Numerical code for cascace modeling *PAMINA*

*P*IC *A*nd *M*onte-Carlo code for cascades *IN* *A*strophysics



[AT 2010, AT & Arons 2013]

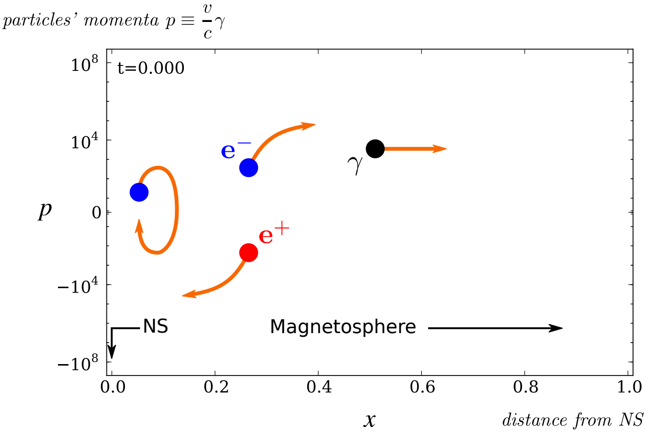
Modeling from the first principles:

Particle acceleration $\leftrightarrow$ Electric field — **Particle-In-Cell**

Particles $\rightarrow$ Photons $\rightarrow$ Particles(Pairs) — **Monte Carlo**

Limit cycle: series of discharges

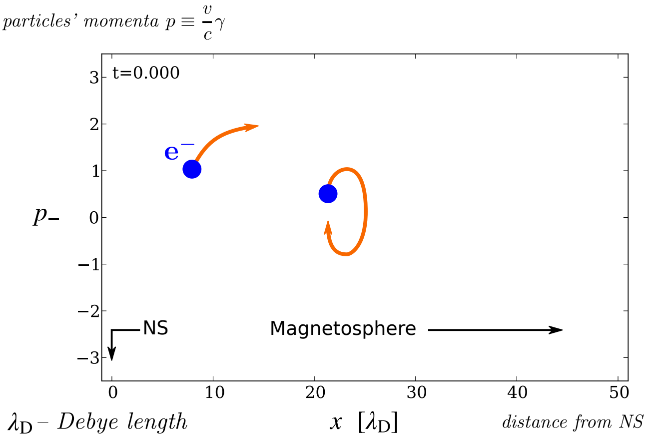
No particles extraction from the NS



• electrons • positrons • γ-rays

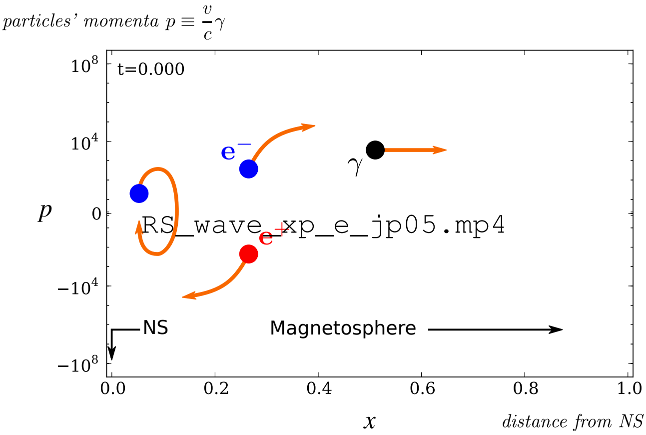
Formation of a low energetic flow for $j/j_{\rm GJ} < 1$

Free particle extraction from the NS

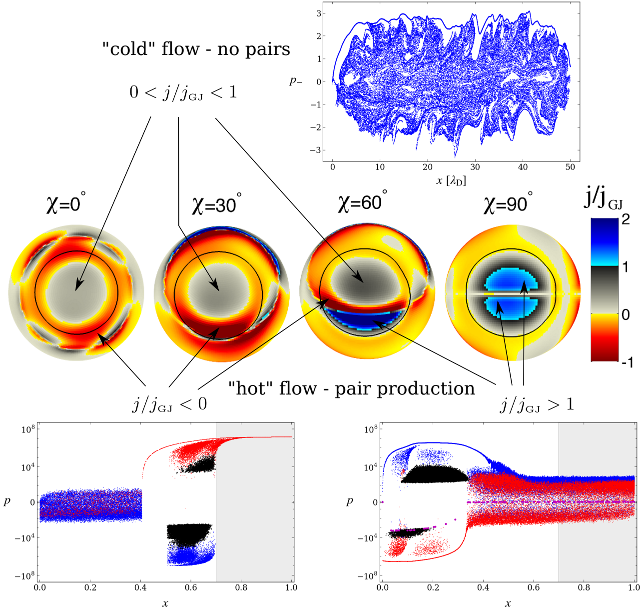


Waves during discharge

It did not escape our attention. . .



Free particle extraction from the NS



Particles' momenta:
p~[0,10]

electrons

Polar cap currents

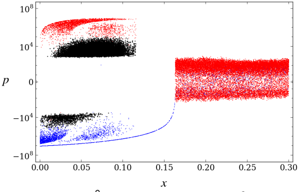
Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Particle acceleration with no particle extraction

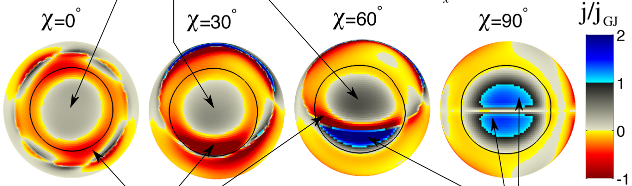
"hot" flow everywhere,
pair production:

near NS $0 < j/j_{GJ} < 1$



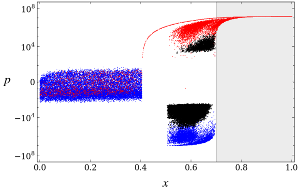
Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

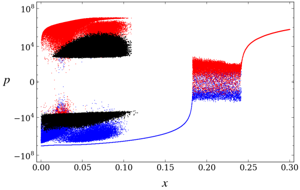


Polar cap currents

far from NS $j/j_{GJ} < 0$



near NS $j/j_{GJ} > 1$



Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Electron-positron cascade

Cascade – splitting of primary particle energy into energy of pairs

$$\kappa_{\mathrm{max}} \simeq 2\frac{\epsilon_p}{\epsilon_{\mathrm{th}}} \,.$$

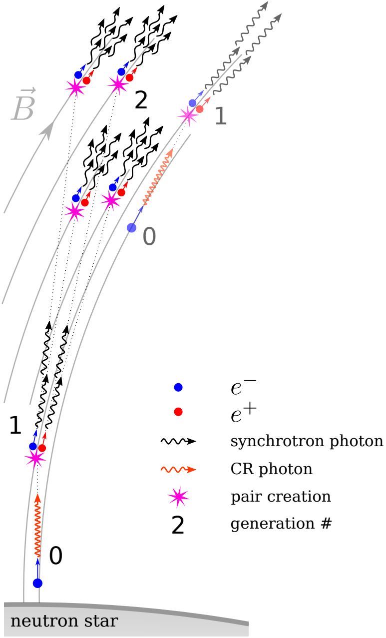
Cascade efficiencly

- flux of primary particles
- energy of primary particles
- efficiency of splitting the energy

Full cascade

Synctrotron cascade

Curvature Radiation



Photon absorption in magnetic field

$$\alpha_B(\epsilon_\gamma, \psi) = 0.23\,\frac{\alpha_f}{\lambda_C}\,\frac{B}{B_q}\,\sin\psi\,\exp\left(-\frac{4}{3\chi}\right)$$

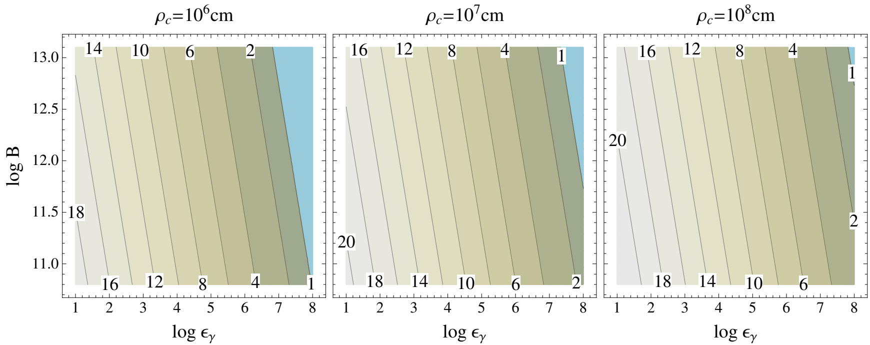
$$\chi \equiv \frac{1}{2}\,\epsilon_\gamma\frac{B}{B_q}\,\sin\psi\,,$$

$$\tau(\epsilon_\gamma, l) = \int_0^l \alpha_B(\epsilon_\gamma, \psi(s))\,ds\,,$$

In the approximation of constant magnetic, $B \approx$ const ($r \ll R_{\mathrm{NS}}$)

$$\tau(\chi) = A_B\,\frac{\rho_c}{\epsilon_\gamma^2(B/B_q)}\,\left[\frac{1}{6}\chi(3\chi - 4)\exp\left(-\frac{4}{3\chi}\right) - \frac{8}{9}\,\mathrm{Ei}\left(-\frac{4}{3\chi}\right)\right]\,.$$

$1/\chi_a : \tau(\chi_a) = 1$

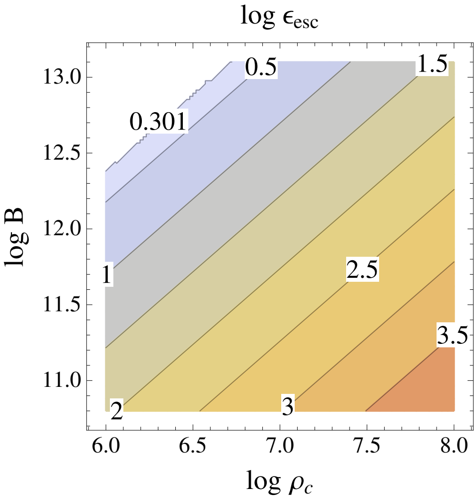


Energy of escaping photons

$$\rho_c \, \psi_a = s_{\rm esc} \, R_{\rm NS}$$

$$\epsilon_{\rm esc} = \frac{2\rho_c}{s_{\rm esc} R_{\rm NS}} \frac{\chi_a(\epsilon_{\rm esc}, B/B_q, \rho_c)}{B/B_q}$$

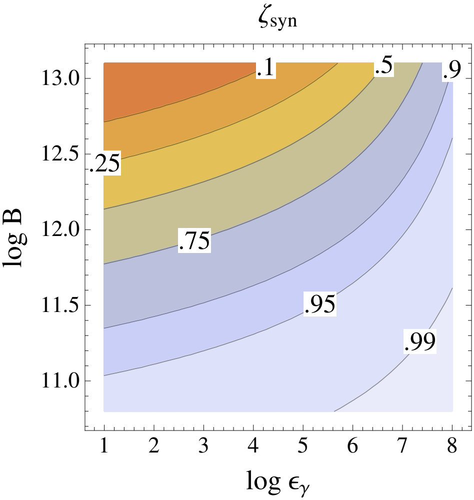
$$s_{\rm esc} \sim 1$$



Fraction of photon energy going into synchrotron radiation: $\zeta_{\rm syn}$

$$
\begin{aligned}
\epsilon_{\pm,\mathrm{F}} &= (1-\beta_{\parallel}^2)^{-1/2} \\
&\approx \epsilon_{\pm,\mathrm{I}}\left[1+(\psi_a\,\epsilon_{\pm,\mathrm{I}})^2\right]^{-1/2} \\
&= \epsilon_{\pm,\mathrm{I}}\left[1+\left(\frac{\chi_a}{B/B_q}\right)^2\right]^{-1/2}
\end{aligned}
$$

$$
\zeta_{\rm syn} = \frac{2(\epsilon_{\pm,\mathrm{I}}-\epsilon_{\pm,\mathrm{F}})}{\epsilon_\gamma}
$$



Effect of magnetic field on Synchrotron cascade

Decrease in multiplicity:

- high $B \longrightarrow$ small photon MFP, lower ψ_a, more energy in pair kinetic energy
- low $B \longrightarrow$ large escaping energy

There should be an optimum magnetic field: $B \sim 10^{12}$ G

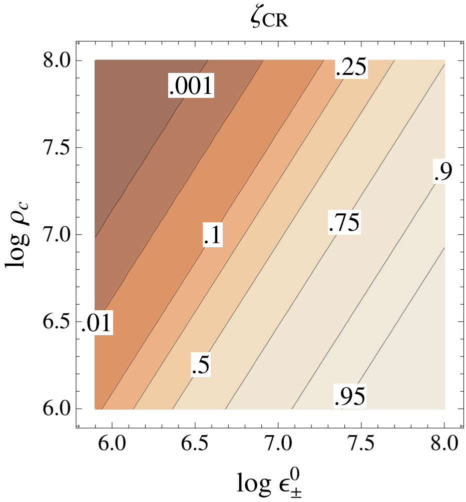
Fraction of the primary particle energy going into Curvature Radiation: ζ_{CR}

$$\frac{d\epsilon_\pm}{dt} = -\frac{2}{3}\frac{e^2}{m_e c^5}\left(\frac{c^2}{\rho_c}\right)^2 \epsilon_\pm^4$$

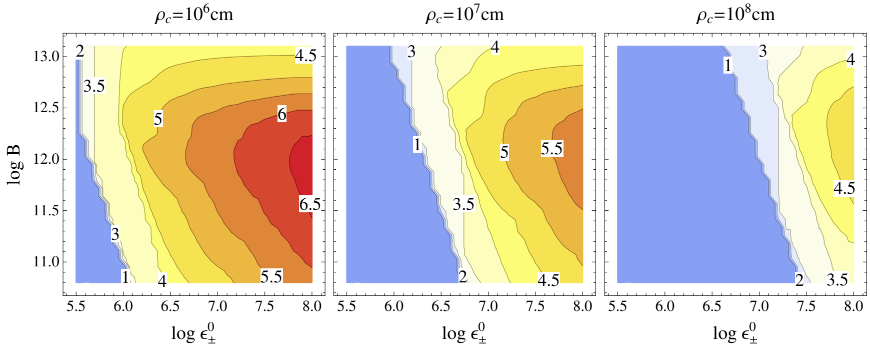
$$\epsilon_\pm(s) = \epsilon_\pm^0 \left[1 + 3H\frac{(\epsilon_\pm^0)^3}{\rho_c^2} s\right]^{-1/3}$$

$$\zeta_{\mathrm{CR}}(s_{\mathrm{CR}}) = 1 - \frac{\epsilon_\pm(s_{\mathrm{CR}})}{\epsilon_\pm^0}$$

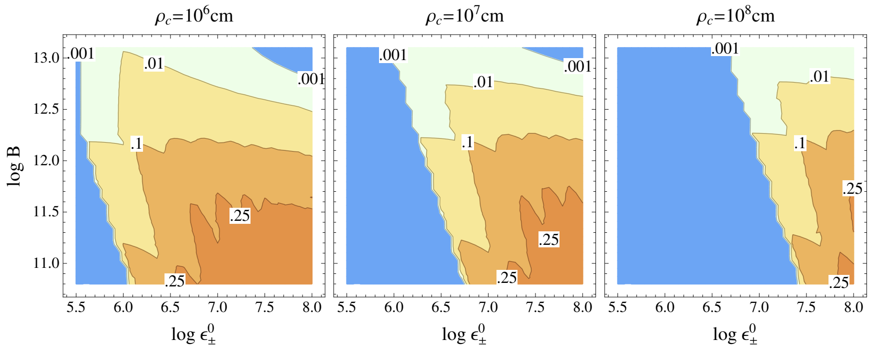
$$s_{\mathrm{CR}} \sim 1$$



Multiplicity of CR-Synchrotron cascade: log κ

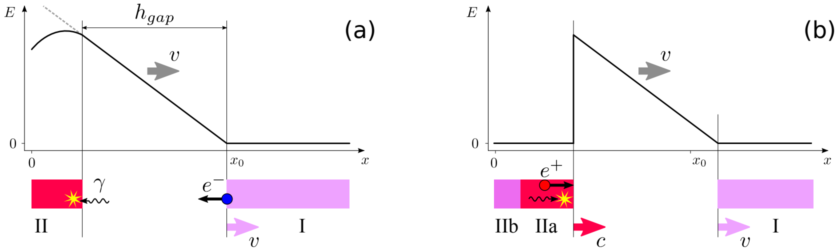


Efficiency of CR-Synchrotron cascade: κ/κ_{max}



$$\kappa_{max} \simeq 2\frac{\epsilon_p}{\epsilon_{esc}} .$$

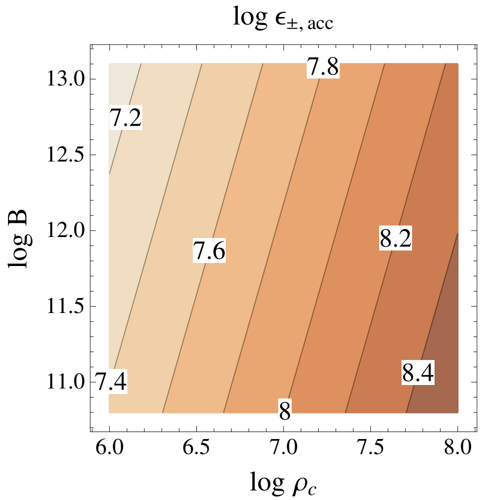
Particle acceleration

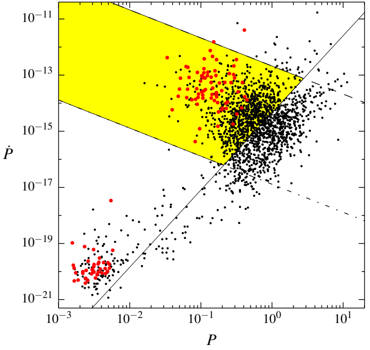


$$E(x_p) = 4\pi\eta^0_{\mathrm{GJ}}\, \xi_j\, (x_0 - x_p)\,; \qquad \xi_j \equiv \frac{j - j_{\mathrm{m}}}{j^0_{\mathrm{GJ}}}\left(1 + \frac{c}{v}\right)\,;$$

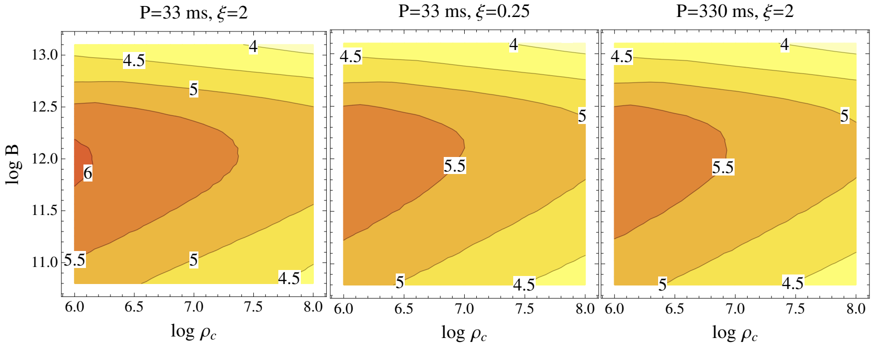
$$\epsilon_{\pm,\,\mathrm{acc}} \simeq 5 \times 10^7\, \chi_a^{2/7}\, \xi_j^{1/7}\, \rho_{c,7}^{4/7}\, P^{-1/7} B_{12}^{-1/7}$$

Energy of primary particles





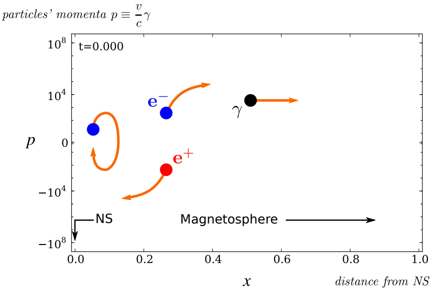
Multiplicity of polar cap cascade: $\kappa \sim 10^5$

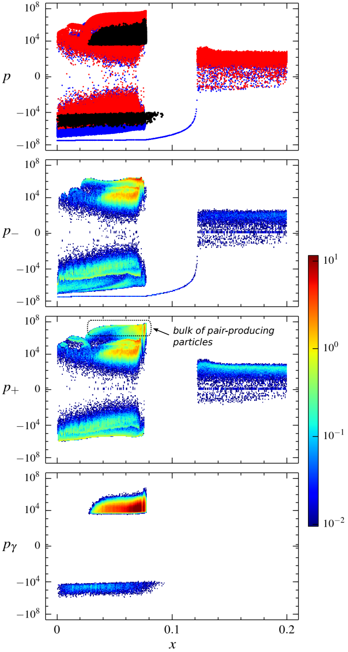


Dependence on ρ_c partially cancels out:

- small $\rho_c \longrightarrow$ high splitting efficienly, but low primary particle energy
- large $\rho_c \longrightarrow$ low splitting efficienly, but high primary particle energy

Discharge: RS flow

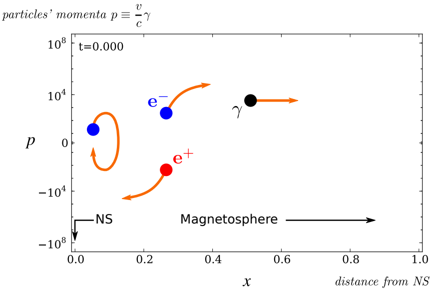


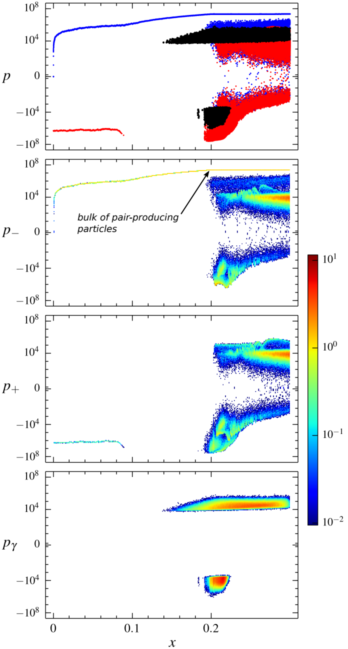


- electrons • positrons • γ-rays

- Low heating of NS surface
- Duty cycle: can be as low as $h_{\rm gap}/R_{\rm NS} \sim 1/100$ (for Crab)

Discharge: super-GJ SCLF

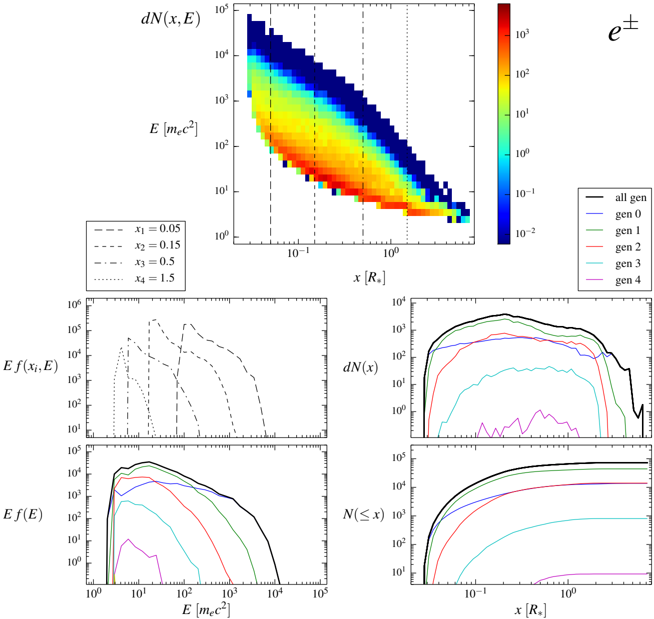




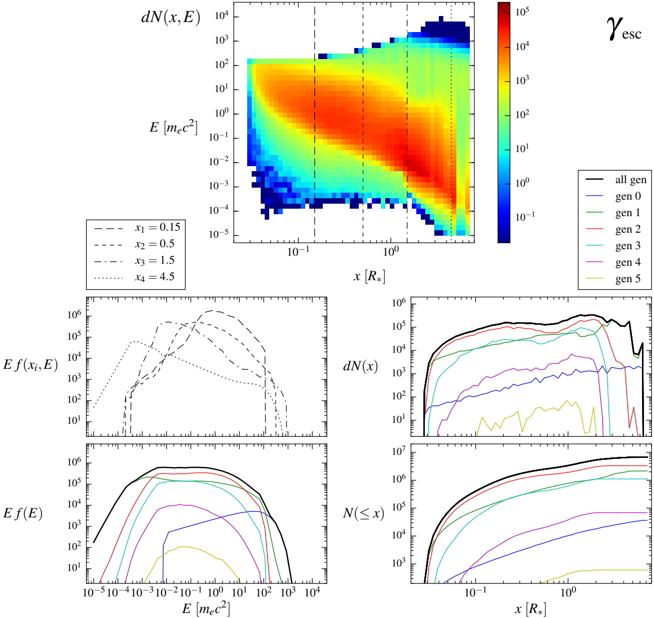
- electrons
- positrons
- γ-rays

- Low heating of NS surface
- Duty cycle: $\sim 1/\text{few}$

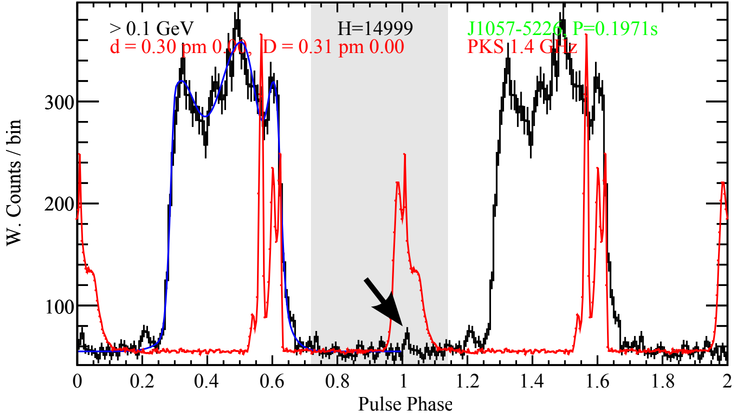
Cascade Portrait



Cascade Portrait



PSR J1057-5226: Polar cap emission?



Conclusions

- Particles can be accelearted faster and at lower altitudes
- Maximum multiplicity of polar cap cascades $\kappa \sim 10^5$
- Maximum multiplicity is not sensitive to pulsar parameters
- Plasma distribution is non-uniform
- Pair yield is mostly determined by primary particle flux: super-GJ space charge limited flow zones should produce the highest pair yield
- Gamma-ray emission from polar caps is at lower energies ($\sim 10 - 100$ MeV)

Quest for Unicorns

Unicorns DO EXISTS!