On the physics of pair plasma generation in pulsars

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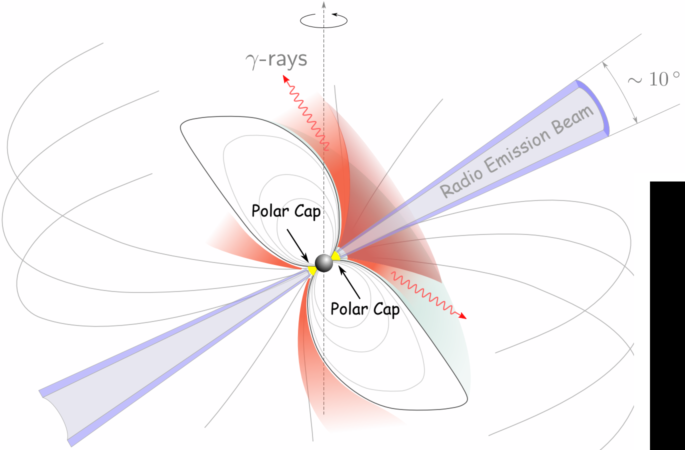
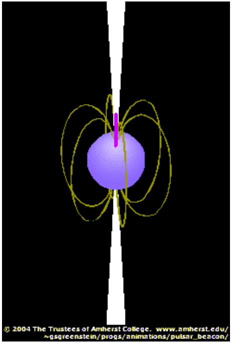
Pulsar: rapidly rotating magnet surrounded by plasma

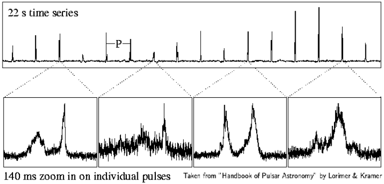
"Electric lighthouse"



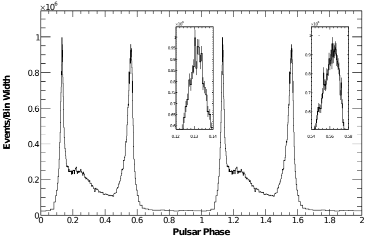


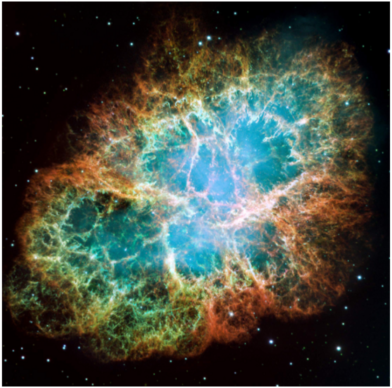
Pulsars: What we see

radio:



gamma:





Pulse peaks are narrow

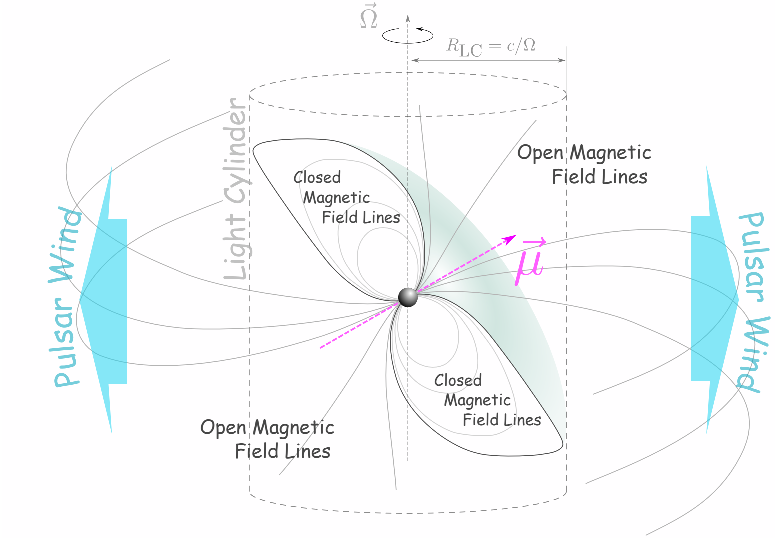
Negligible energy budget

PWNe feed by dense plasma

Energy goes there

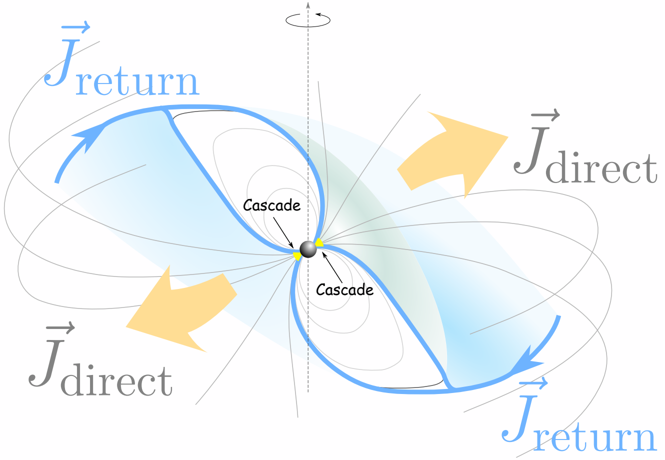
Pulsar Magnetosphere: Large scale view

“Plasma machine”



Pulsar Magnetosphere: Theorist view

Electrical generator

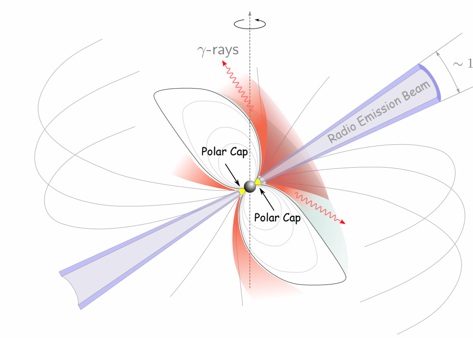


The magnetosphere is charged
characteristic charge density – "Goldrech-Julian" charge density $\eta_{\rm GJ}$.

Pair creation processes

Sinlge photon pair creation in strong magnetic field
$\gamma B \rightarrow e^+ e^-$
– close to the NS

Two photon pair creation
$\gamma\gamma \rightarrow e^+ e^-$
– outer magnetosphere

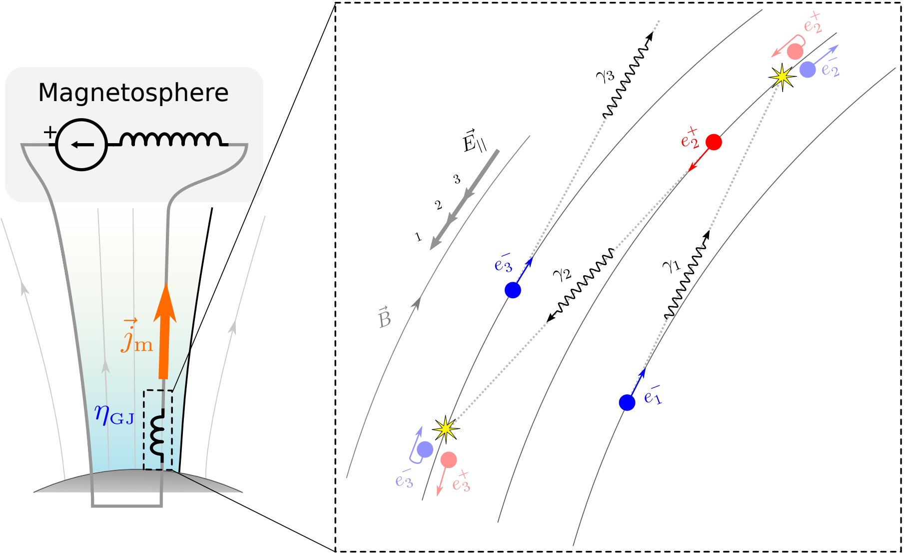


The outer magnetosphere is transparent to gamma-rays up to few GeV, $\epsilon_{\rm esc} \sim 10^4 mc^2$.

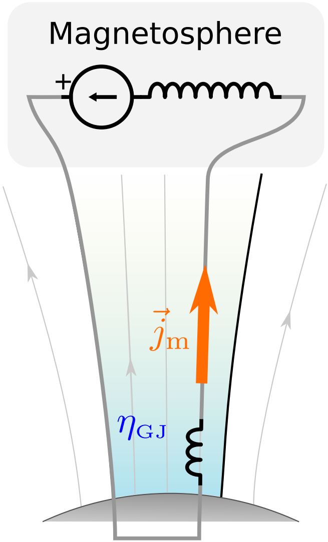
Very high multiplicity can be produces only close to the NS.

Plasma creation in the polar cap

Particle acceleration is regulated by pair production



Polar Cap Electrodynamics



Rotation of the NS

$$\nabla \cdot \boldsymbol{E} = 4\pi(\eta - \eta_{\rm GJ})$$

Twist of magnetic field lines

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} j + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

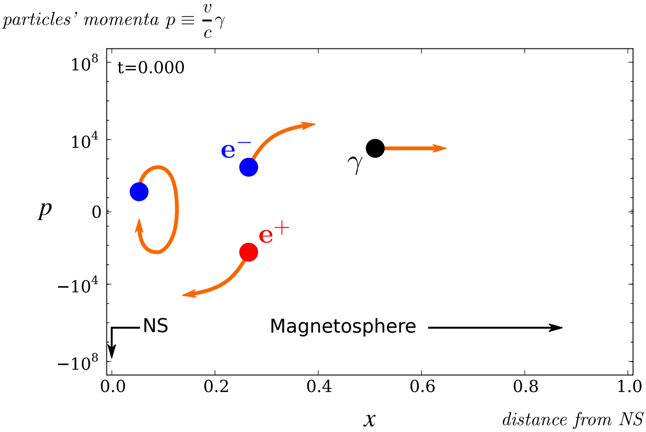
$\boldsymbol{E} = 0$ if both

$$\eta = \eta_{\rm GJ}$$

$$j = j_{\rm m} \equiv \frac{c \nabla \times \boldsymbol{B}}{4\pi}$$

Limit cycle: series of discharges

No particles extraction from the NS



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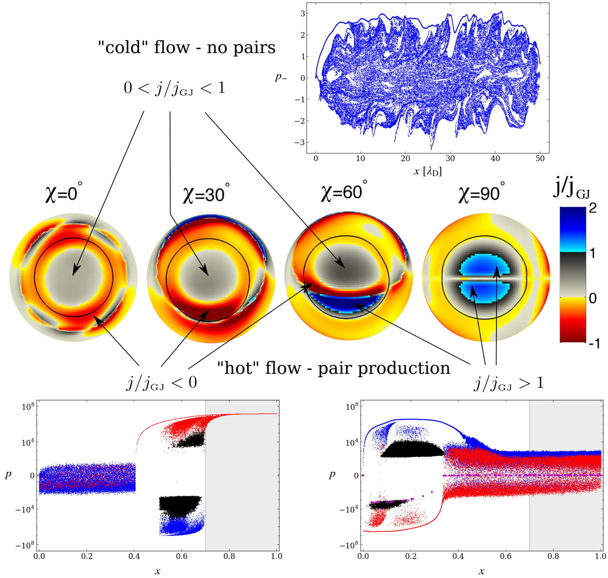
Free particle extraction from the NS (AT & Arons'13)



Particles' momenta:
p~[0,10]

electrons

Polar cap currents

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

electrons
positrons
photons

Electron-positron cascade is splitting of primary particle's energy into energy of pairs

Multiplicity is the number of particles created in cascade per single primary particle:

$$\kappa_{\mathrm{cascade}} \simeq 2 \frac{\epsilon_{\mathrm{primary}}}{\epsilon_{\gamma,\,\mathrm{esc}}} f \,.$$

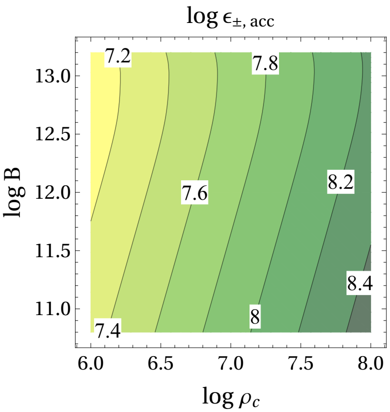
f – is the cascade efficiency.

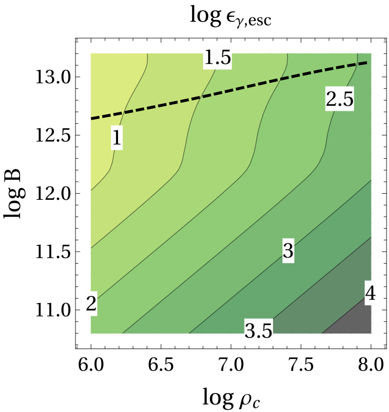
For pulsars multiplicity is excess of plasma density relative to the Goldrech-Julian number density:

$$\kappa_{\mathrm{PSR}} \simeq 2 \frac{n_{\mathrm{plasma}}}{n_{\mathrm{GJ}}} \,.$$

Multiplicity of polar cap cascade

rough estimate

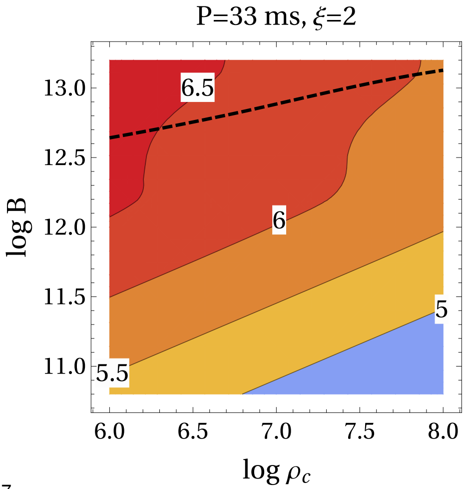




$$\kappa_{\mathrm{cascade}} \simeq 2\frac{\epsilon_{\mathrm{primary}}}{\epsilon_{\gamma,\,\mathrm{esc}}}$$

Multiplicity of polar cap cascade

rough estimate



$\kappa_{\max} = 5.4 \times 10^5 \rho_{c,7}^{-3/7} P^{-1/7} B_{12}^{6/7}$

for $B \gtrsim 3 \times 10^{12}$G

$\kappa_{\max} = 1.6 \times 10^6 \rho_{c,7}^{-3/7} P^{-1/7} B_{12}^{-1/7}$

Full cascade in energetic PSRs

AT & Harding ’15, ’18a

Resonant ICS Radiation

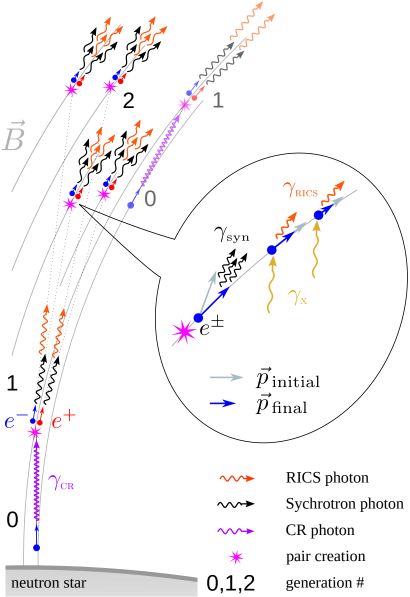
“feeds” on $\epsilon_{\|}$

Synchrotron Radiation

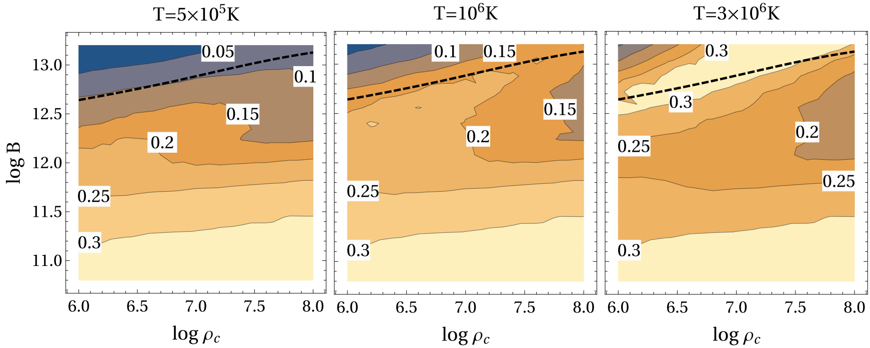
“feeds” on $\epsilon_{\perp}$

Curvature Radiation

“feeds” on $\epsilon_{\|}$

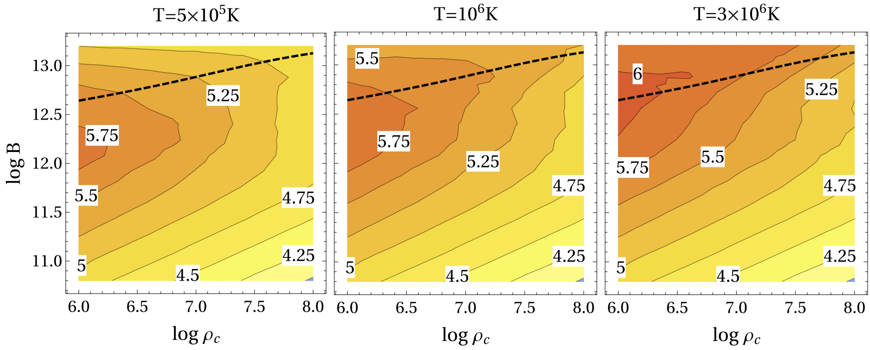


Cascade efficiency: *f*



$$\kappa = 2\frac{\epsilon_p}{\epsilon_{esc}} f\,.$$

Multiplicity of the polar cap cascade: $\kappa \sim$ few $\times\, 10^5$



κ weakly depends on pulsar period

The higher the NS temperature, the larger the κ at high B

Cascade Graphs for $\rho_c = 10^7$cm

Cascades do not have a lof of generations

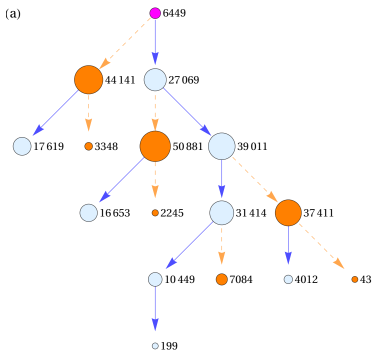


Figure: Cascade graphs for cascades in pulsars with $P = 33$ms, $\rho_c = 10^7$cm, $T = 10^6$K, and the following magnetic field strengths: (a) $B = 10^{12.5}$G, (b) $B = 10^{12}$G, (c) $B = 10^{11.5}$G.

Cascade Graphs for $\rho_c = 10^{7.9} \approx 7.94 \times 10^7$cm

Cascades do not have a lof of generations

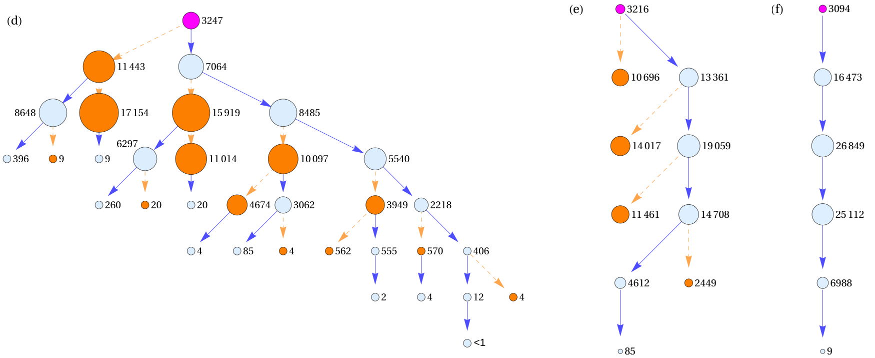
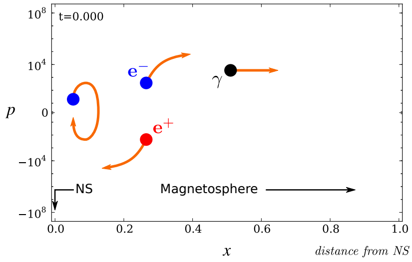


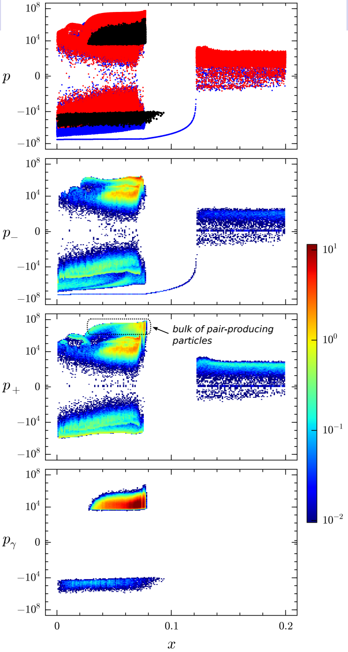
Figure: Cascade graphs for cascades in pulsars with $P = 33$ms, $\rho_c = 10^{7.9} \approx 7.94 \times 10^7$cm and the following magnetic field strengths: (d) $B = 10^{12.9}$G, (e) $B = 10^{12.5}$G, (f) $B = 10^{12}$G.

Discharge: RS flow

particles' momenta $p \equiv \frac{v}{c}\gamma$



distance from NS



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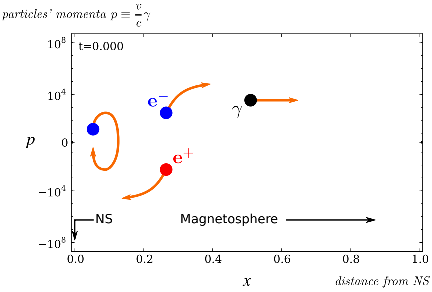
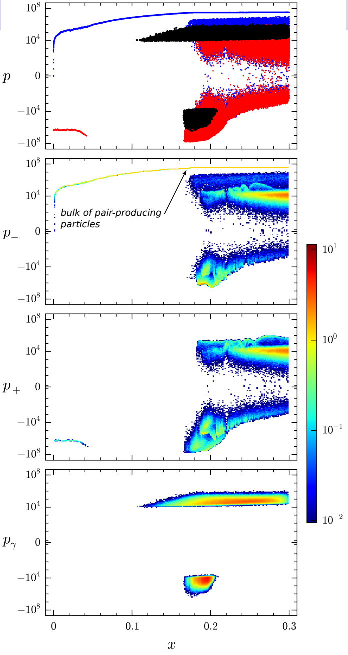
Discharge: super-GJ SCLF





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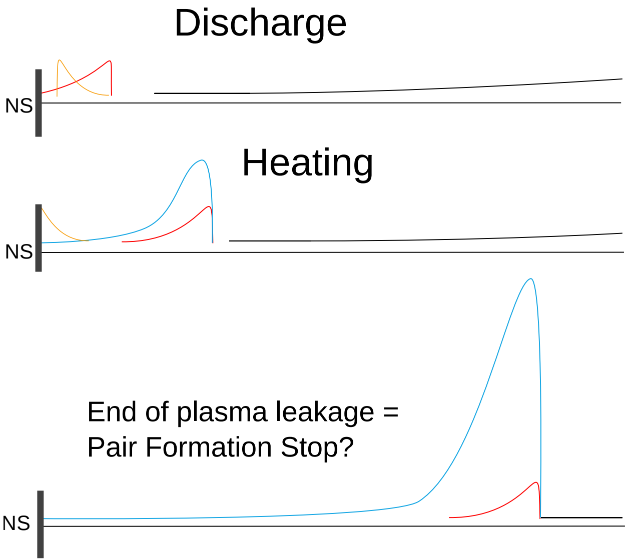
Cascade Repetition Rate



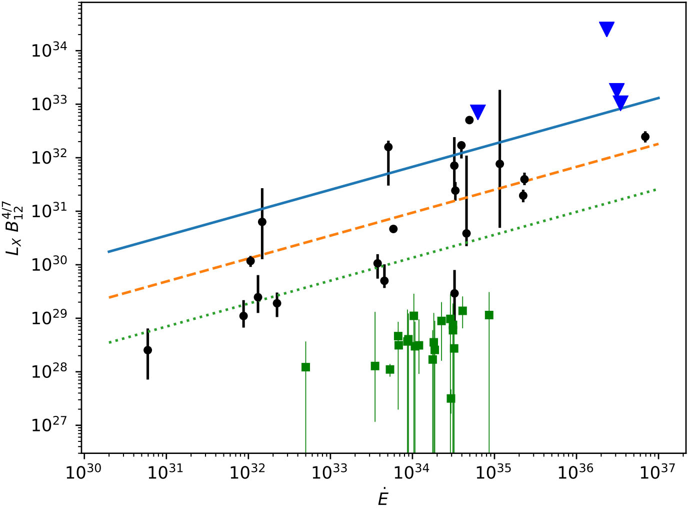
Heating of NS surface by pair cascades

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

$$L_X \sim f_D f_S f_N \, 2.5 \times 10^{16} \dot{E}^{3/7} B_{12}^{-4/7} \rho_7^{6/7}$$

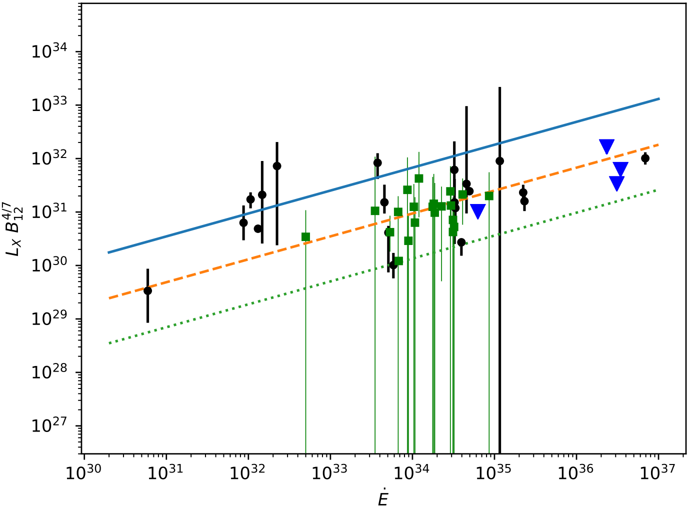
(AT & Harding 2018b, in preparation)

$L_X \, B^{4/7}$ vs $\dot{E}$



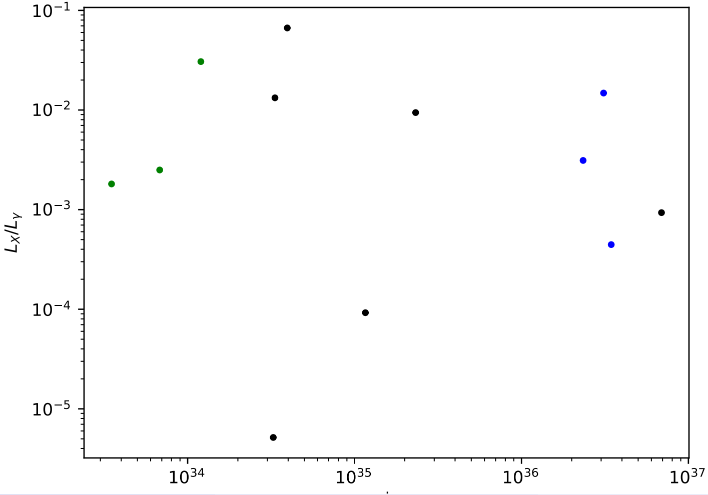
preliminary

$L_X B^{4/7}$ vs $\dot{E}$ corrected for r_{hot}/r_{pc}



preliminary

L_X/L_γ: observed PSR γ ray emission is not due to cascades in the outer magnetosphere



Conclusions

Maximum cascade multiplicity in a single burst $\kappa \sim$ few $\times 10^5$

Maximum multiplicity is not sensitive to pulsar parameters

Cascade duty cycle seems to be $\sim h_{\rm gap}/R_{\rm NS}$

Fermi does not see polar caps because the emission is very weak.