How much plasma a pulsar can make

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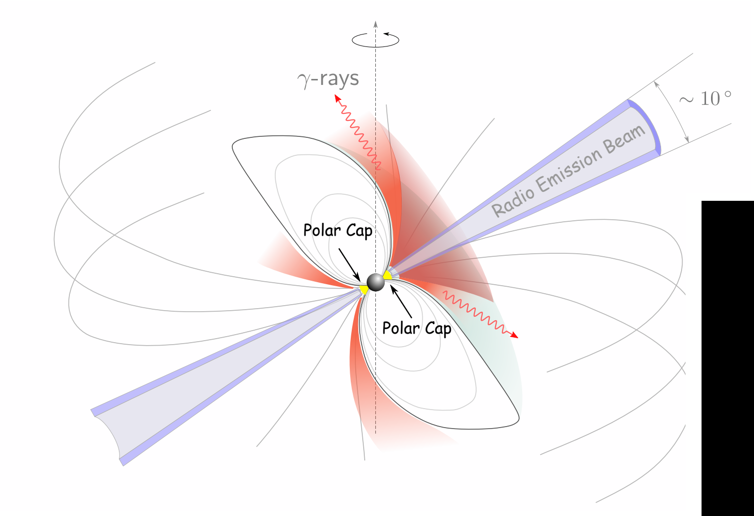
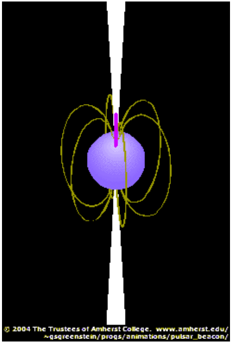
Pulsar: rapidly rotating magnet surrounded by plasma

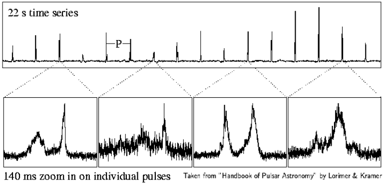
"Electric lighthouse"



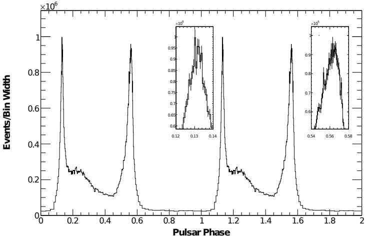


Pulsars: What we see

radio:

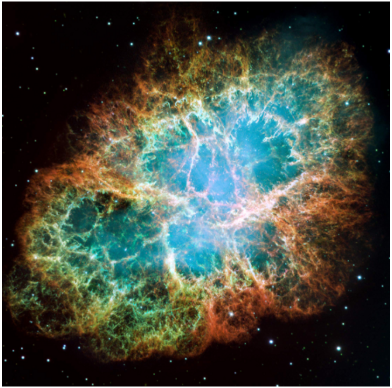


gamma:



Pulse peaks are narrow

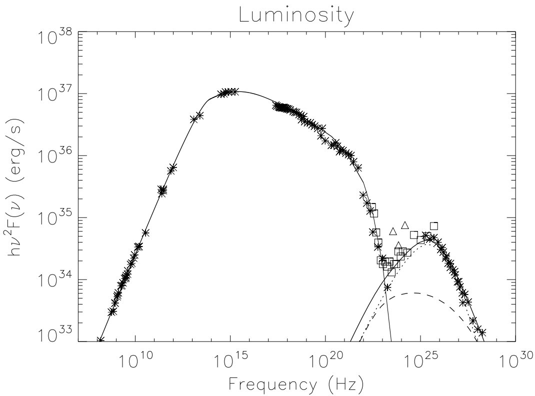
Negligible energy budget



PWNe feed by dense plasma

Energy goes there

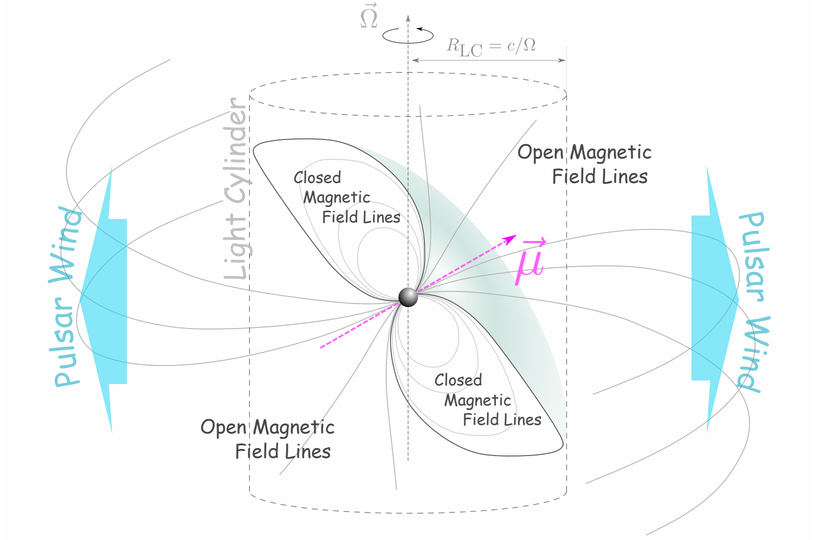
Crab Nebula Spectrum



Radio emission of PWNe suggests multiplicities well in excess of 10^5, e.g. for Crab $\kappa \sim 10^6 - 10^7$.

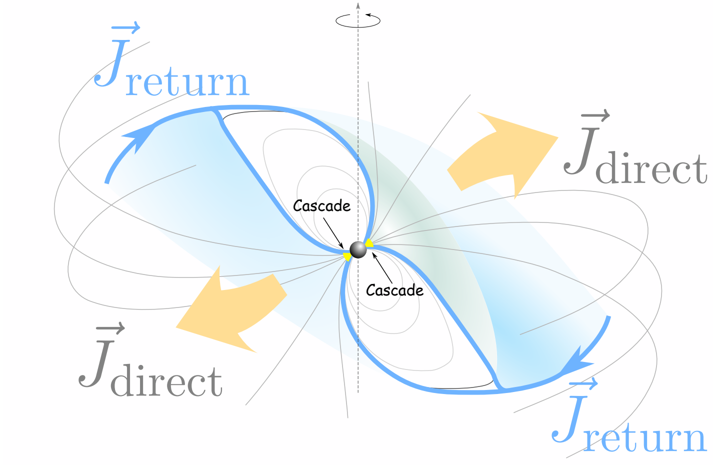
Pulsar Magnetosphere: Large scale view

"Plasma machine"



Pulsar Magnetosphere: Theorist view

Electrical generator

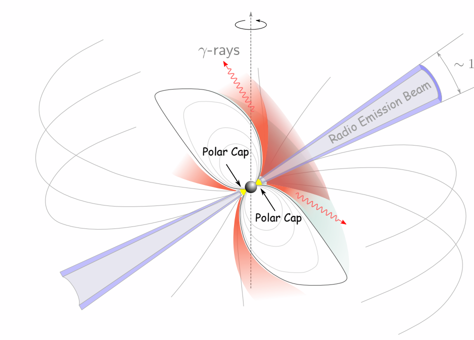


The magnetosphere is charged
characteristic charge density – “Goldrech-Julian” charge density $\eta_{\rm GJ}$.

Pair creation processes

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

Two photon pair creation
$\gamma\gamma \to e^+ e^-$
– 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.

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:

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

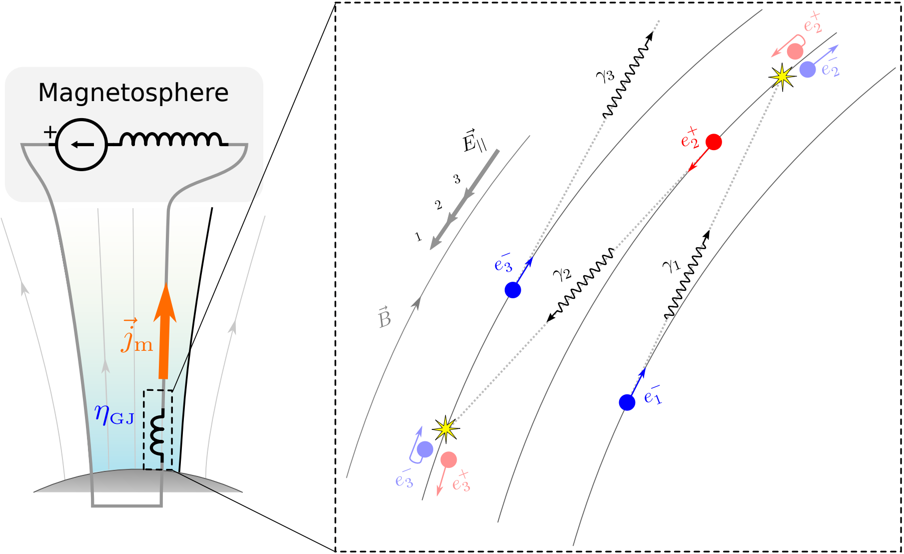
f – is the cascade efficiency.

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

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

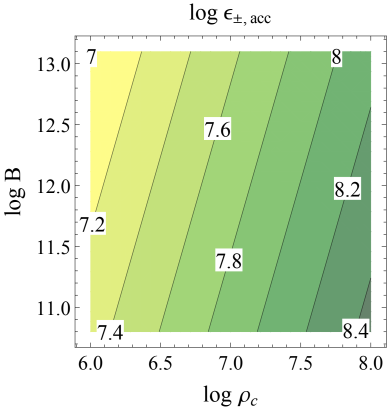
Plasma creation in the polar cap

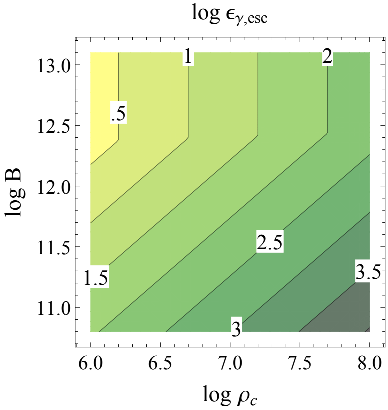
Particle acceleration is regulated by pair production



Multiplicity of polar cap cascade

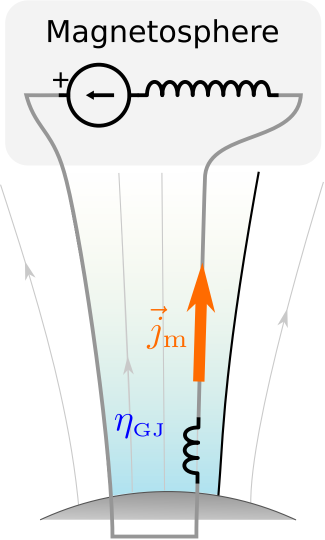
rough estimate





$$\kappa_{\rm cascade} \simeq 2\frac{\epsilon_{\rm primary}}{\epsilon_{\gamma,\,\rm esc}} \simeq 5\times10^5\ \xi_j^{1/7}\rho_{c,7}^{-3/7}P^{-1/7}B_{12}^{6/7}$$

Polar Cap Electrodynamics



Rotation of the NS

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

Twist of magnetic field lines

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

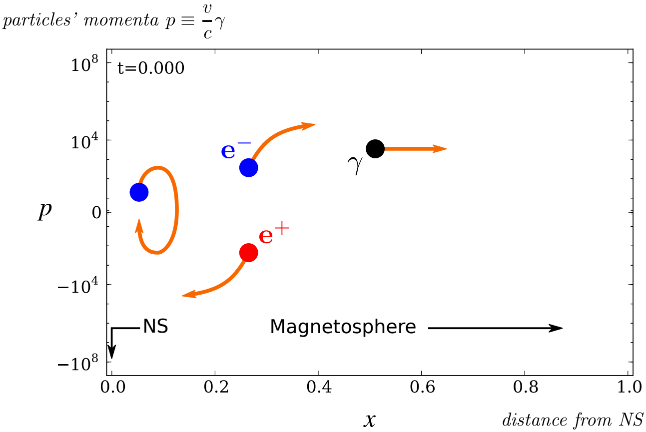
$\boldsymbol{E} = 0$ if both

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

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

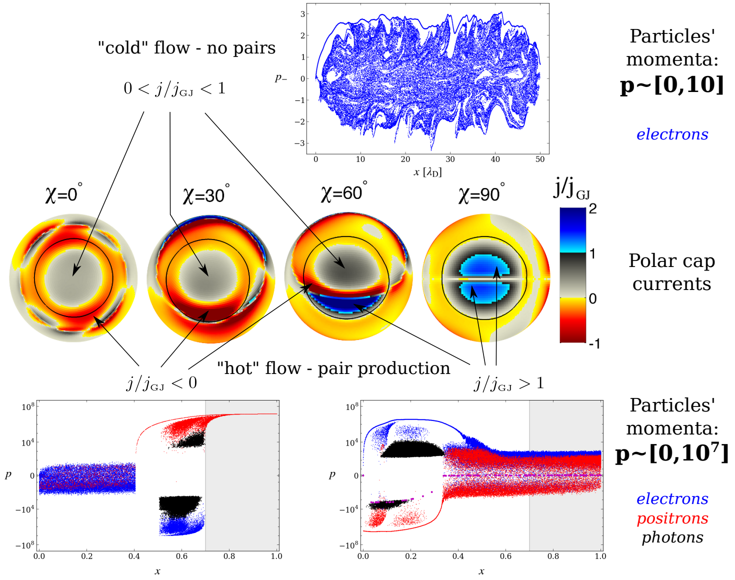
Limit cycle: series of discharges

No particles extraction from the NS



• electrons • positrons • γ-rays

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



Full cascade in young PSRs

AT & Harding '15, '16 (in prep)

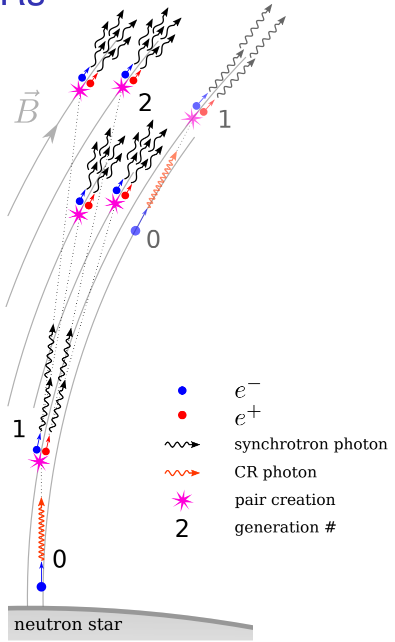
Resonant ICS Radiation

"feeds" on $\epsilon_\parallel$

Synchrotron Radiation

"feeds" on $\epsilon_\perp$

Curvature Radiation



General polar cap cascade diagram

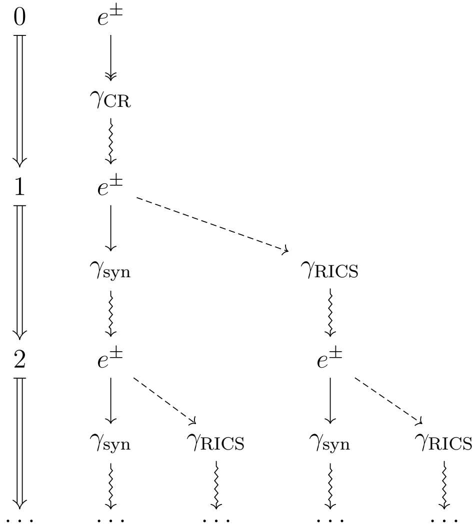
Curvature Radiation

Synchrotron cascade

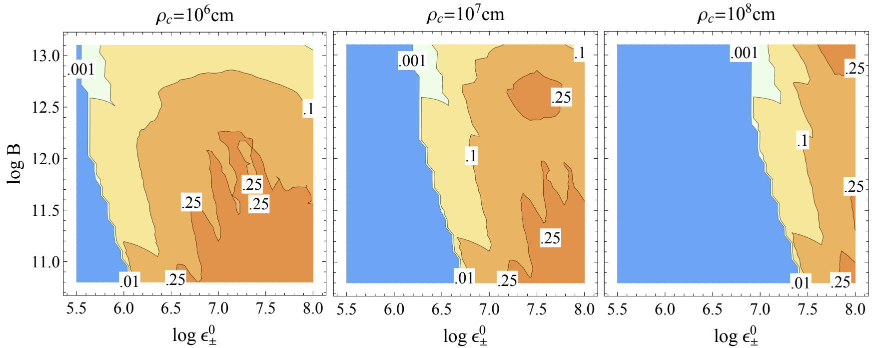
“feeds” on $\epsilon_\perp$

Resonant ICS cascade

“feeds” on $\epsilon_\parallel$

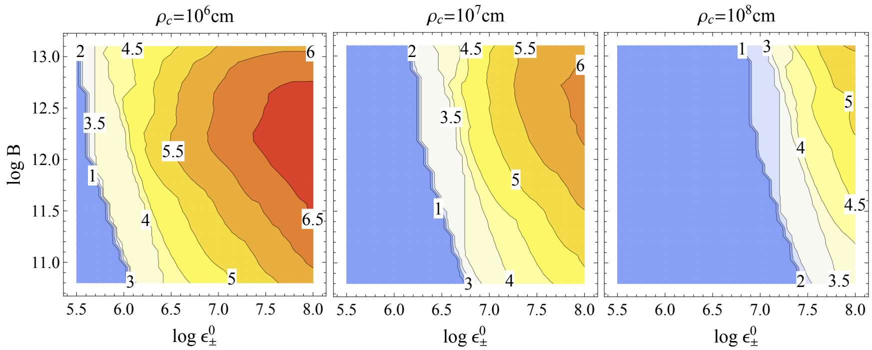


Cascade efficiency: f

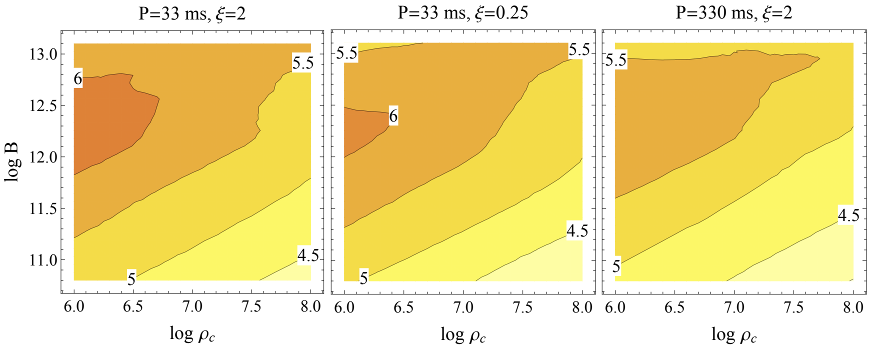


$$\kappa = 2\frac{\epsilon_p}{\epsilon_{esc}} f \, .$$

Cascade multiplicity as a function of $\epsilon_{\pm}$: log κ



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

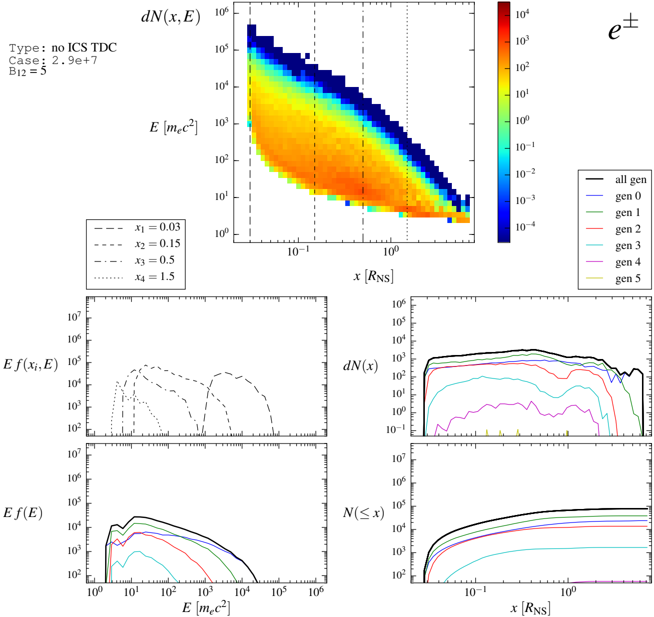


Dependence on ρ_c partially cancels out:

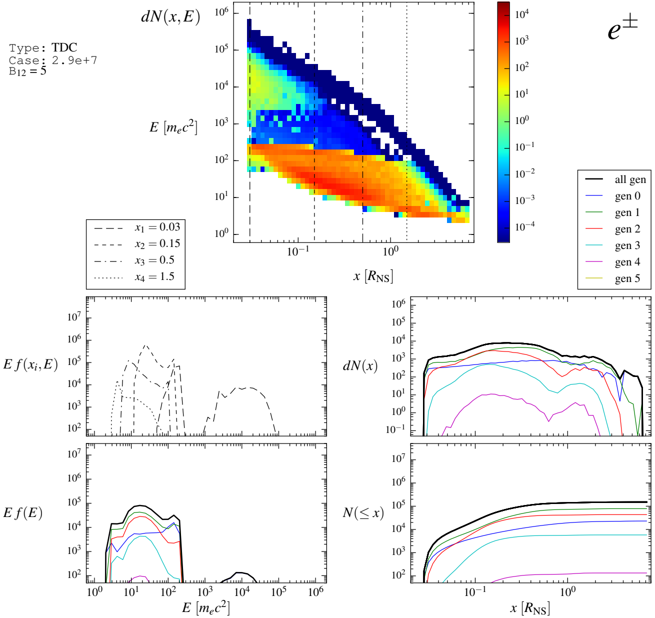
small ρ_c $\longrightarrow$ high splitting efficiency, but low primary particle energy

large ρ_c $\longrightarrow$ low splitting efficiency, but high primary particle energy

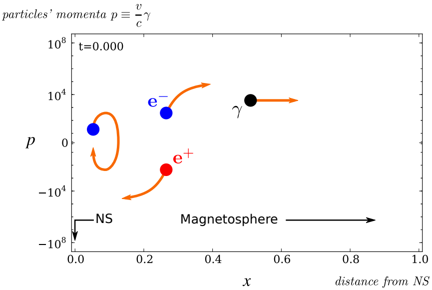
Cascade Portrait: Synchrotron Cascade



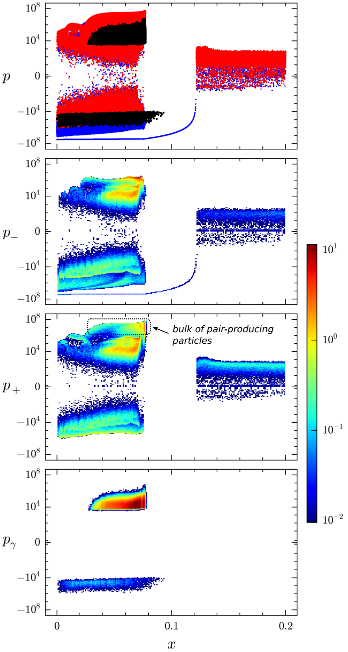
Cascade Portrait: Synchrotron-RICS Cascade



Discharge: RS flow



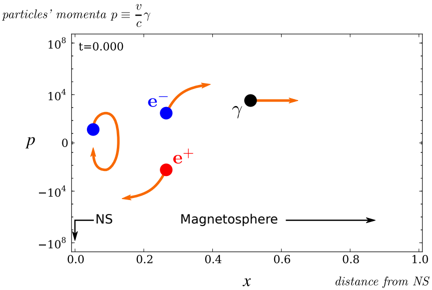
• electrons • positrons • γ-rays

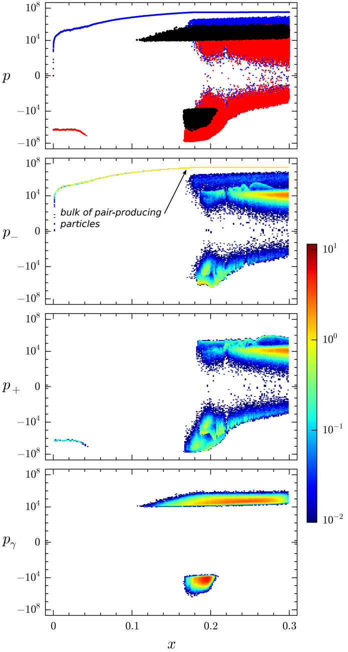


Low heating of NS surface

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: $\sim 1/\text{few}$

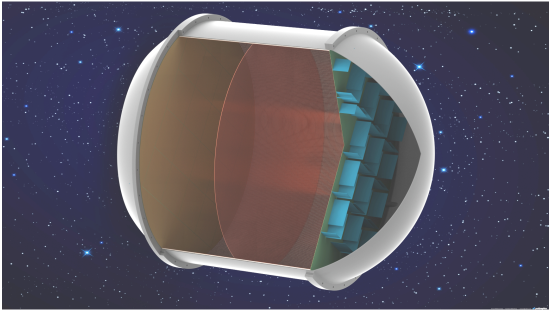
Conclusions

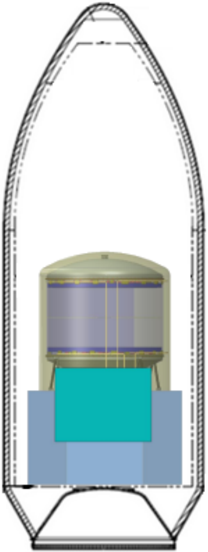
- Maximum multiplicity of polar cap cascades $\kappa \sim$ few $\times 10^5$
  - Maximum multiplicity is not sensitive to pulsar parameters
  - Pair yield is mostly determined by primary particle flux: super-GJ space charge limited flow zones should produce the highest pair yield
  - Inclinations angle should be the most important factor determining the overall pulsar pair multiplicity
- Gamma-ray emission from polar caps is at lower energies ($\sim 10 - 100$ MeV)
- Pair multiplicity is not enough to account for population of Radio emissting electrons in PWNe

Advanced **E**nergetic **P**air **T**elescope (AdEPT)

Gamma-Ray Polarimeter

Gas detector: preserves polarization information





AdEPT science: Overview

Energy Range: $2 - 500$ MeV

- Poorly explored domain
  - Detailed look at known accelerators
    - PSRs, PWNs, SNR, AGN, GRBs
  - Yet unseen accelerators
    - polar cap emission in PSRs
    - magnetars
    - new class(es) of sources
- $\pi^0 \rightarrow \gamma\gamma$ @ $E > 67.5$MeV

  π^0 - telltale signature of hadrons

  - leptonic *vs.* hadronic
  - Dark Matter

Polarization: down to 0.1% MDP

- Polarization measurements:
  - *geometry of accelerators*

  in contrast to radio band

  no propagation effects

  - *distinguishes between CR and Synchrotron*
- Strict limits on polarization:
  - *distinguishes π^0 emission*

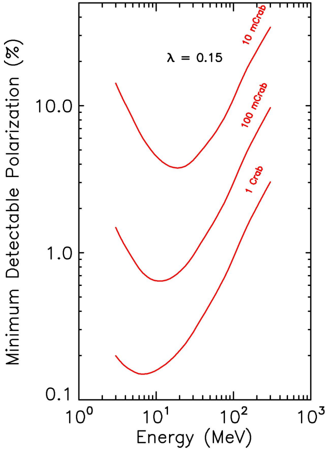
  $\pi^0 \rightarrow \gamma\gamma$ is **unpolarized**, as opposed to any leptonic process

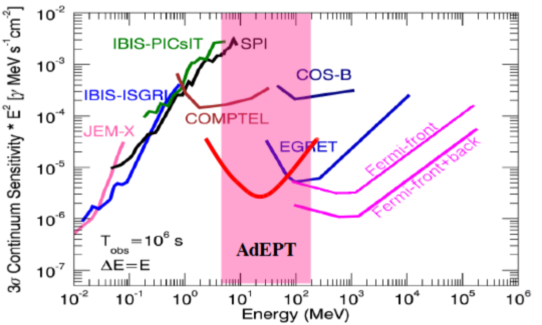
Angular Resolution: down to 0.2°

- Excellent source localization

  down to $0.2^\circ/\sqrt{N_{ph}}$
- Resolving MeV background
- Dark Matter profiles

AdEPT Characteristics





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Energy Range

Polarization Senesitivity