Pulsar High Energy Emission Models: What Works and What Doesn't

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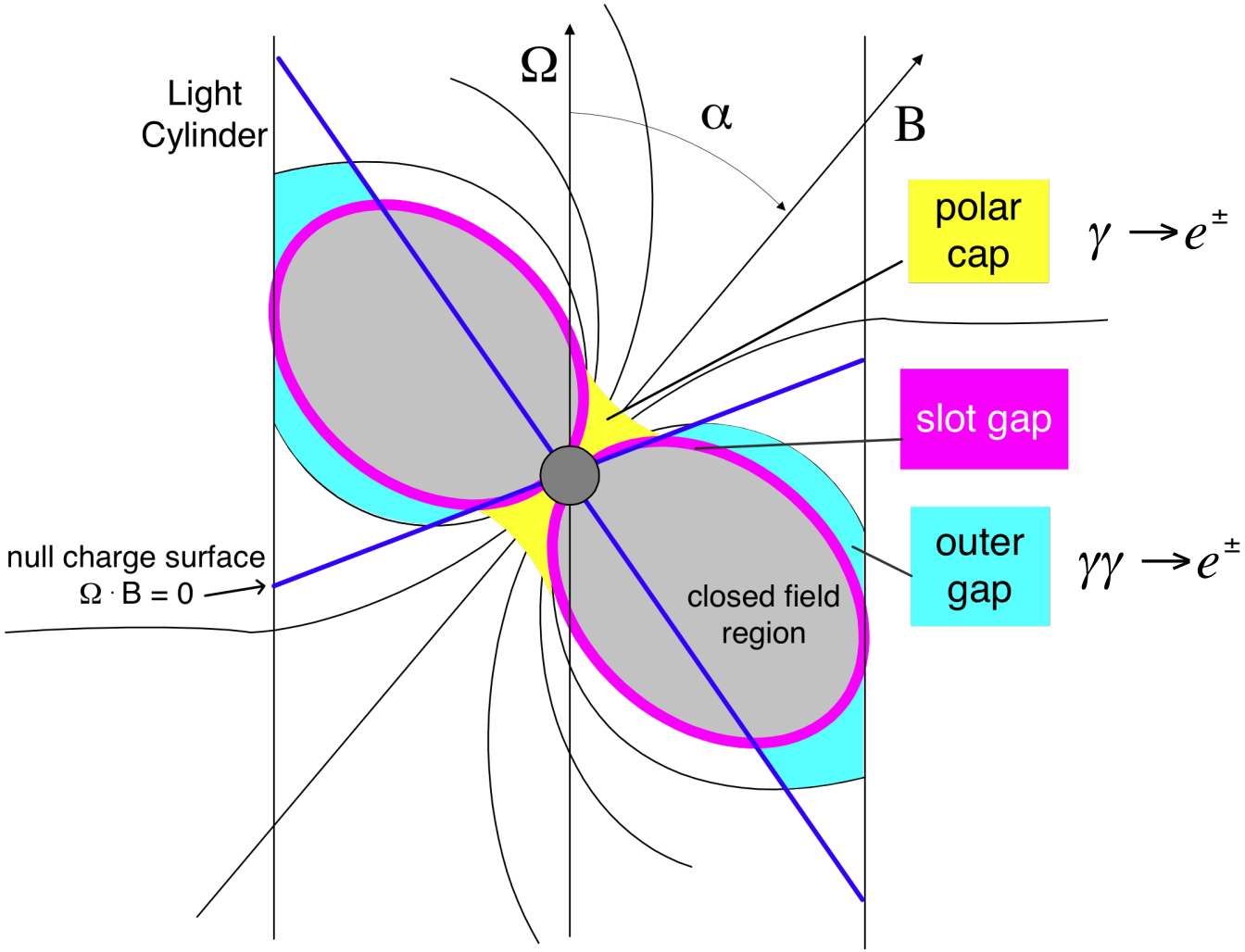
- "Standard" outer magnetosphere models - successes
- Shortcomings of the models
- Next steps?

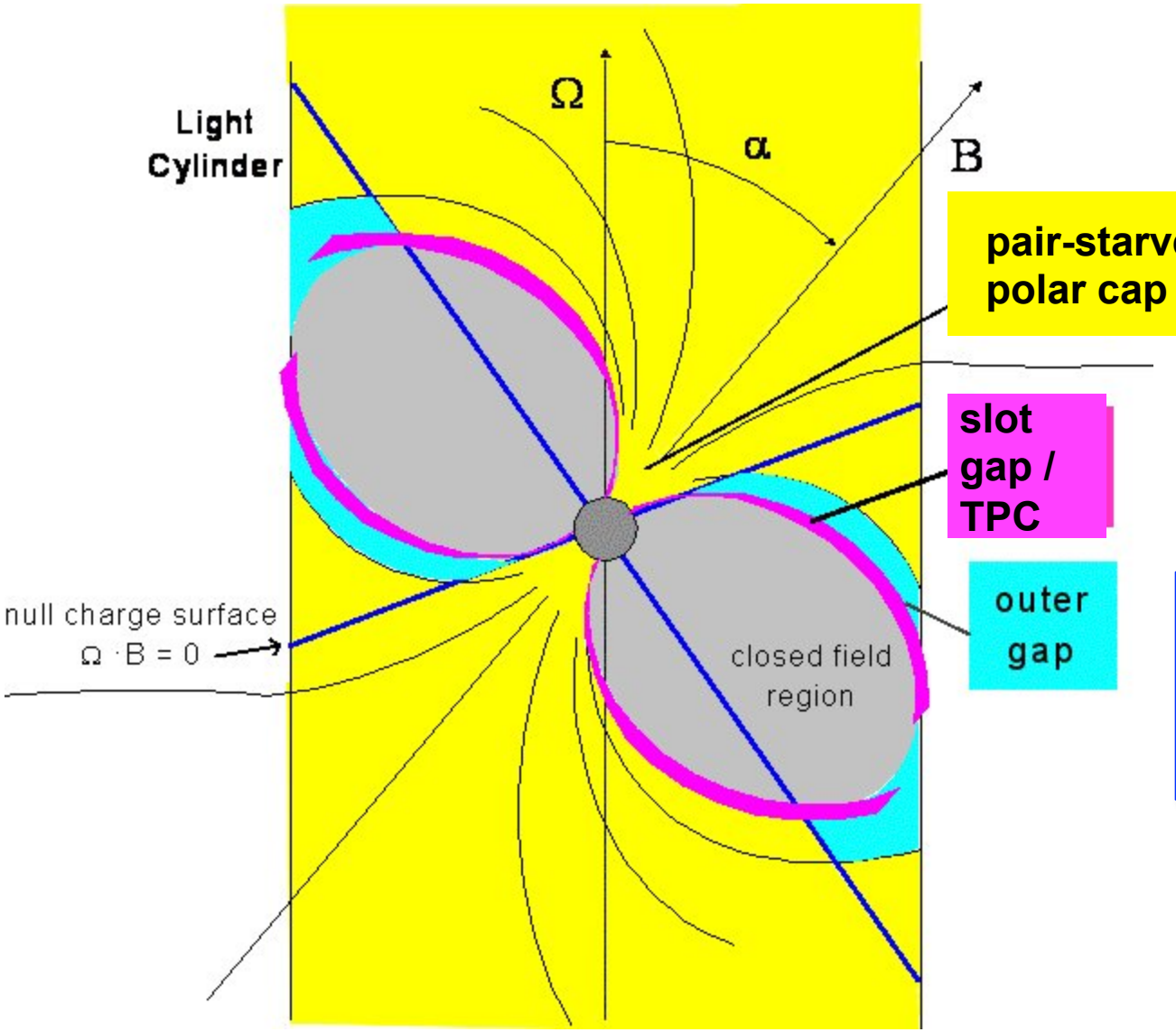
“Standard” outer magnetosphere models - successes

- Outer gap, slot gap and separatrix layer models can roughly produce observed gamma-ray light curves – but require thin emission layers
- Predicted cutoff energies for curvature radiation roughly match observed cutoff energies
- Variation of curvature radius similar to phase resolved cutoff energies

Pulsar accelerator geometries

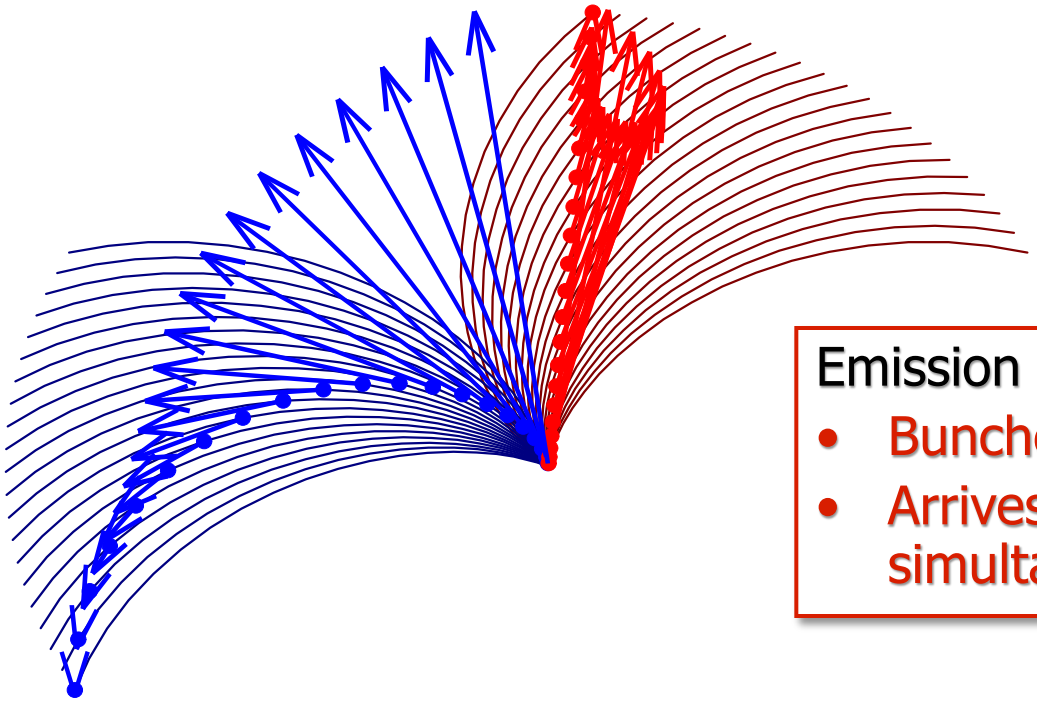


Accelerator Geometries



Narrow accelerators require screening of E field by pairs

Formation of caustics



Emission on trailing field lines

- Bunches in phase
- Arrives at inertial observer simultaneously

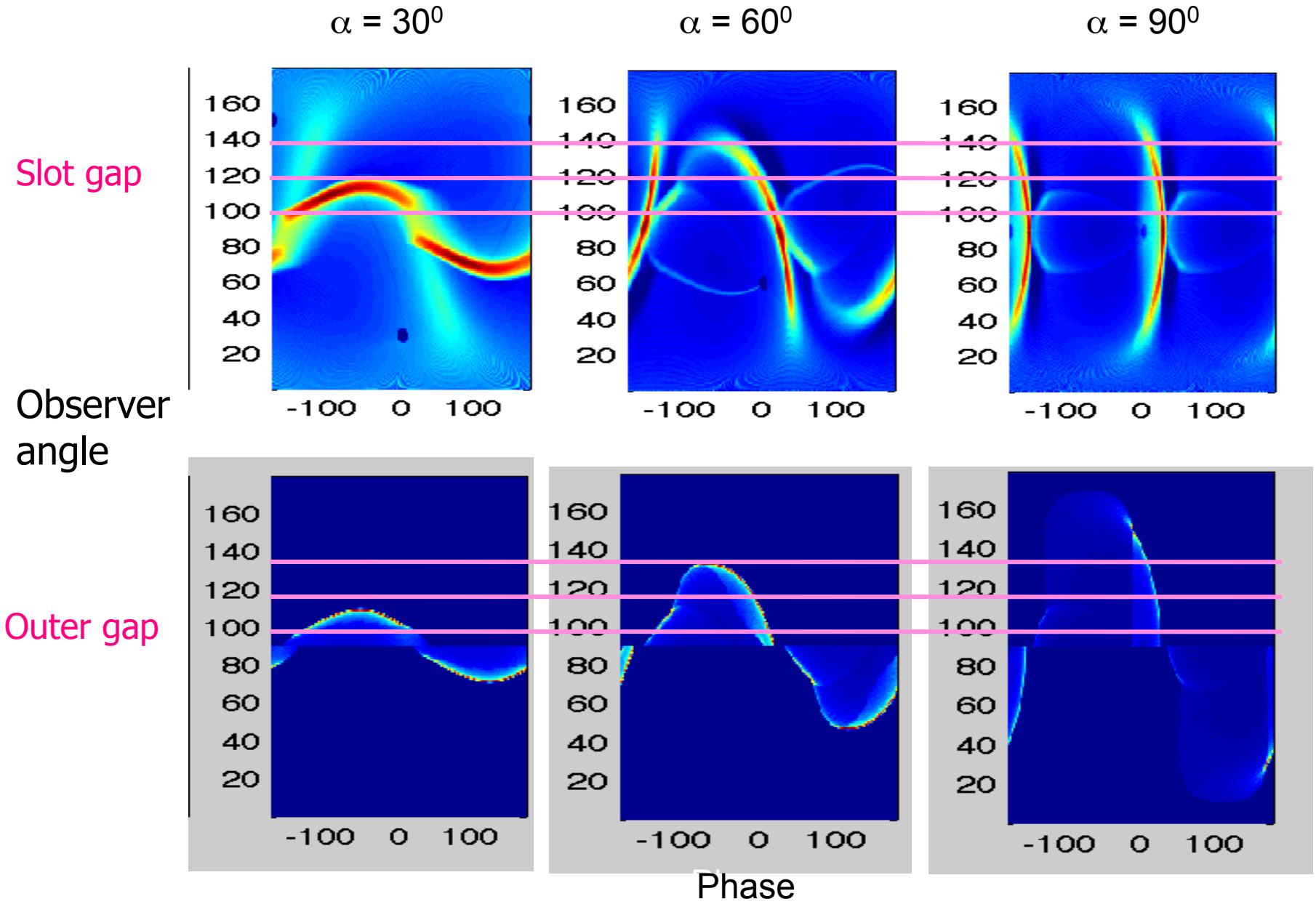
Emission on leading field lines

- Spreads out in phase
- Arrives at inertial observer at different times

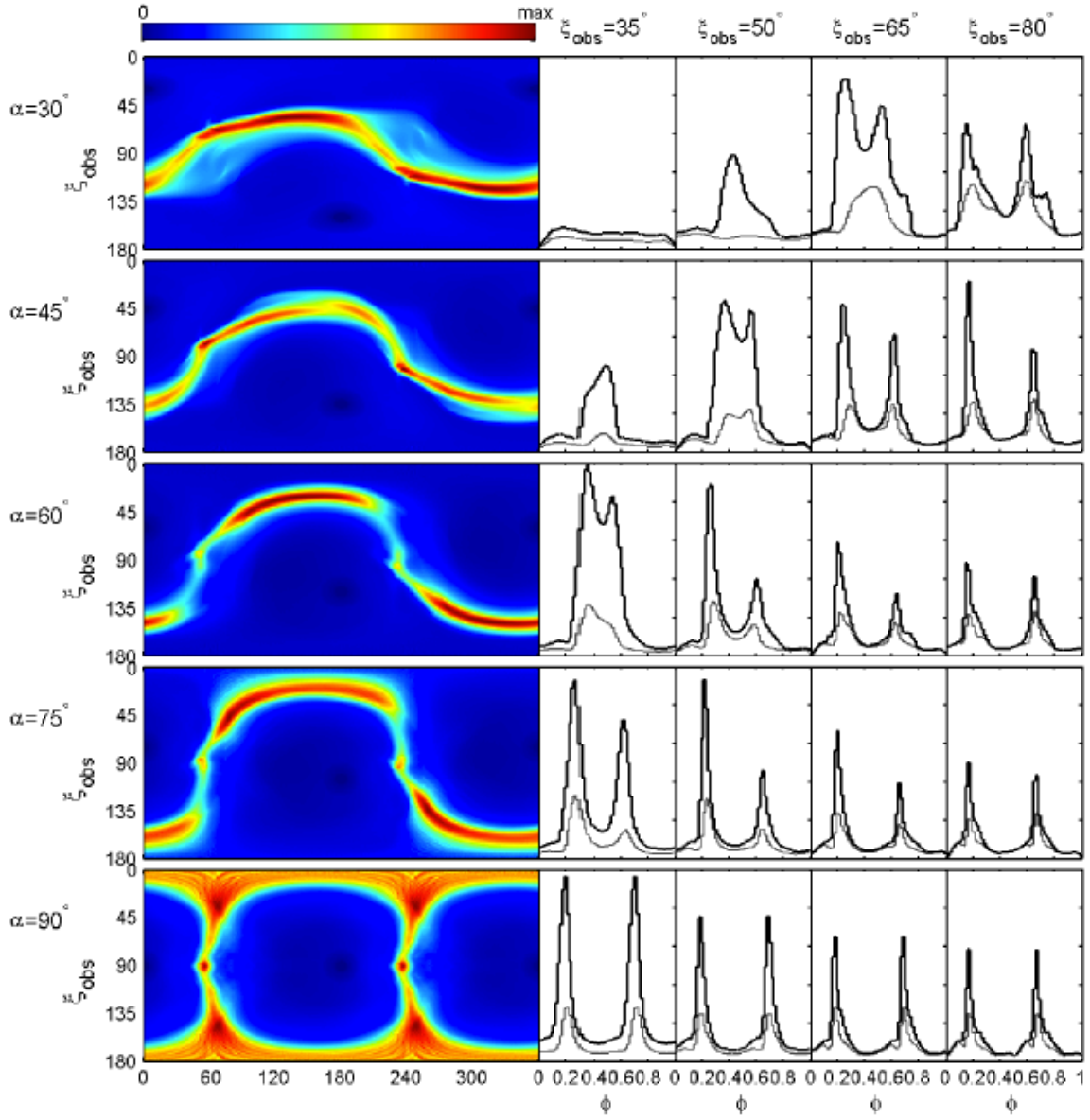
Caustic emission

- Photons emitted parallel to dipole magnetic field
- Aberration and time-of-flight delays
- Trailing outer edge of open volume

Sky distribution of intensity

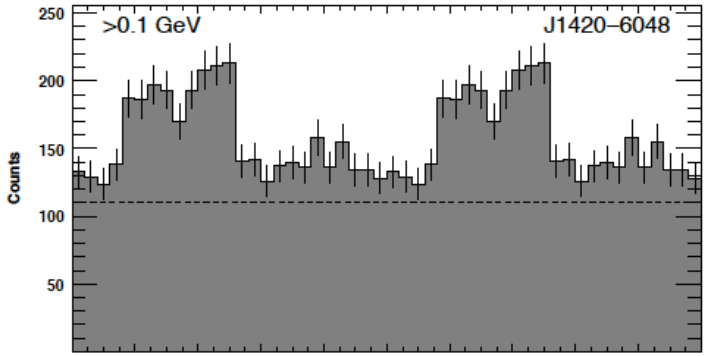


Light curves in force-free geometry



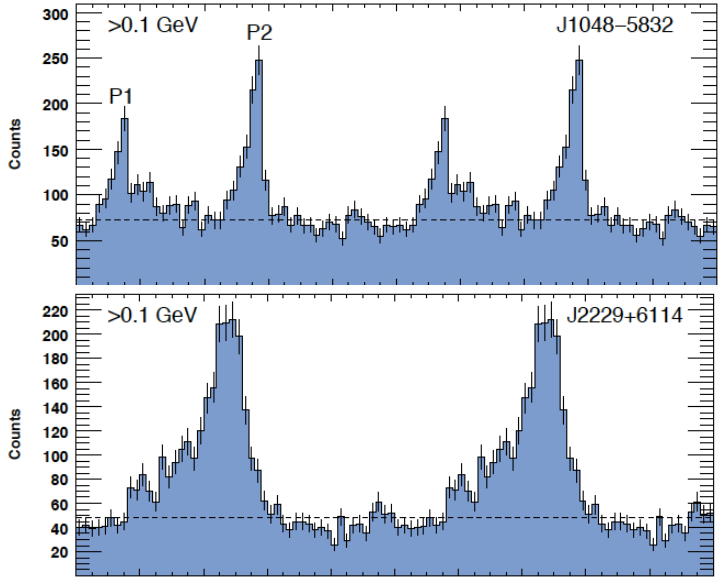
Bai & Spitkovsky 2010

Young Radio-loud Pulsars



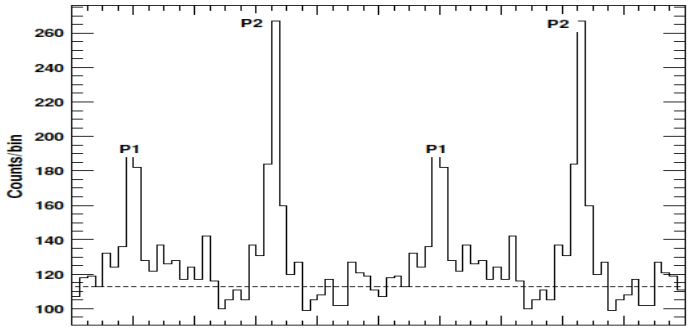
PSR J1420-6048

(Weltevrede et al., ApJ 2009 submitted)

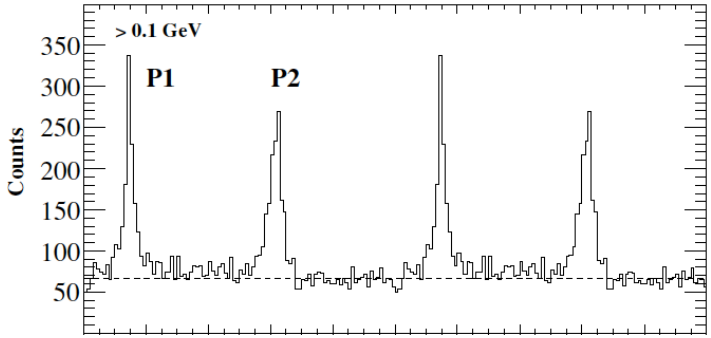


PSR J1048-5832 & J2229+6114

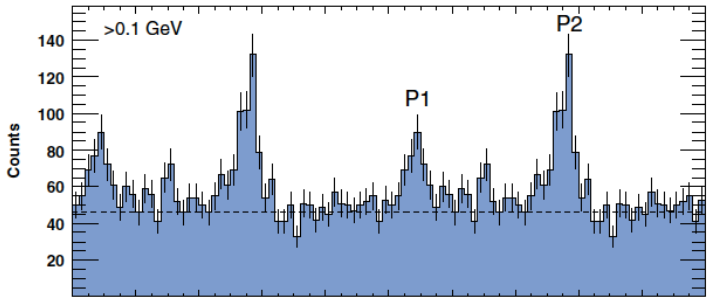
(Abdo et al., ApJ 2009 accepted)



PSR J1028-5819 (Abdo et al., ApJL 695, 72, 2009)



PSR J2021+3651 (Abdo et al., ApJ 700, 1059, 2009)



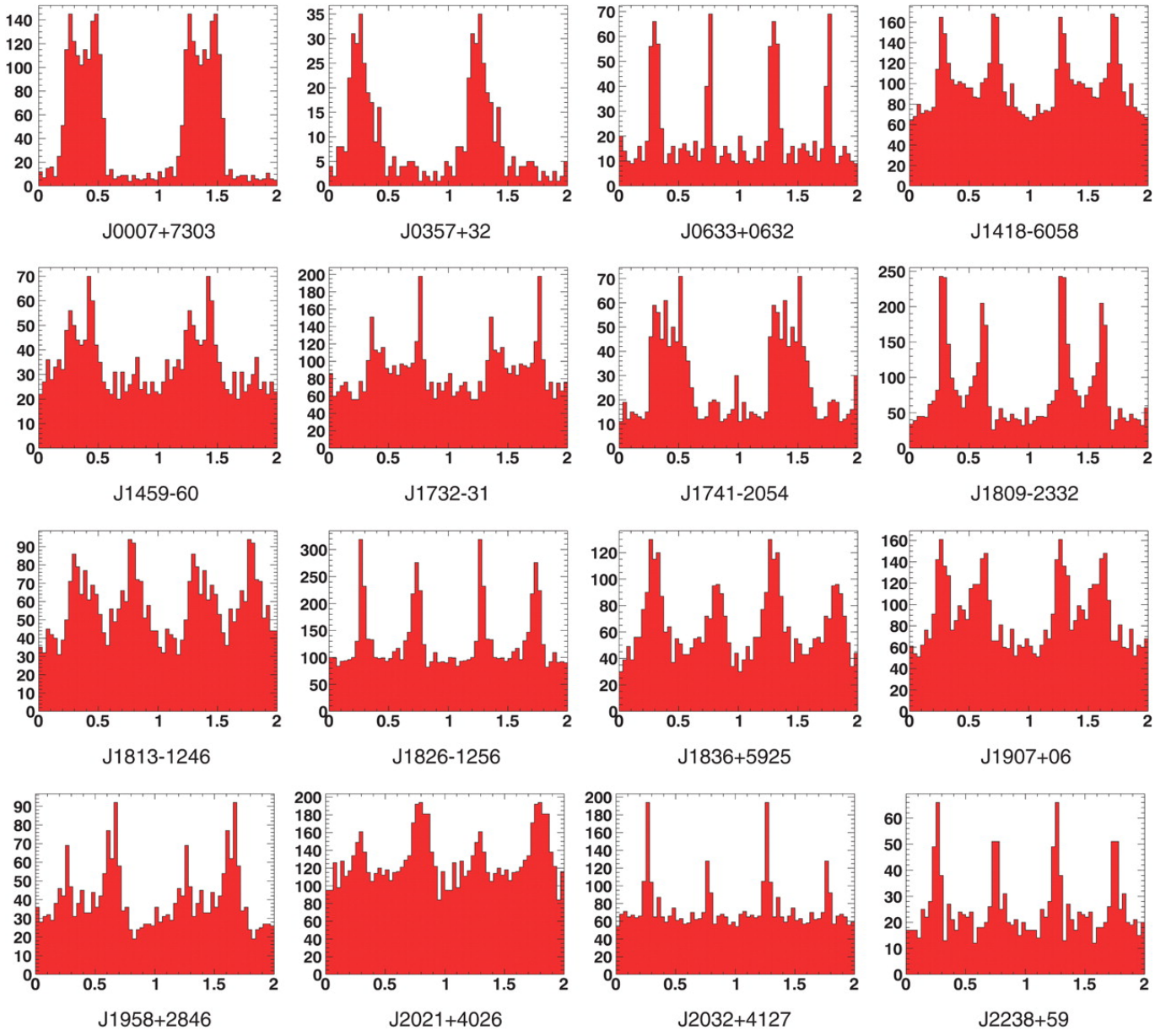
PSR J0205+6449 (Abdo et al., ApJL 699, 102, 2009)

16 Pulsars Found in Blind Searches

After 4 months of data taking, 16 pulsars were found with blind search technique!

(Abdo et al., Science 325, 840, 2009).

13 were unidentified sources for EGRET

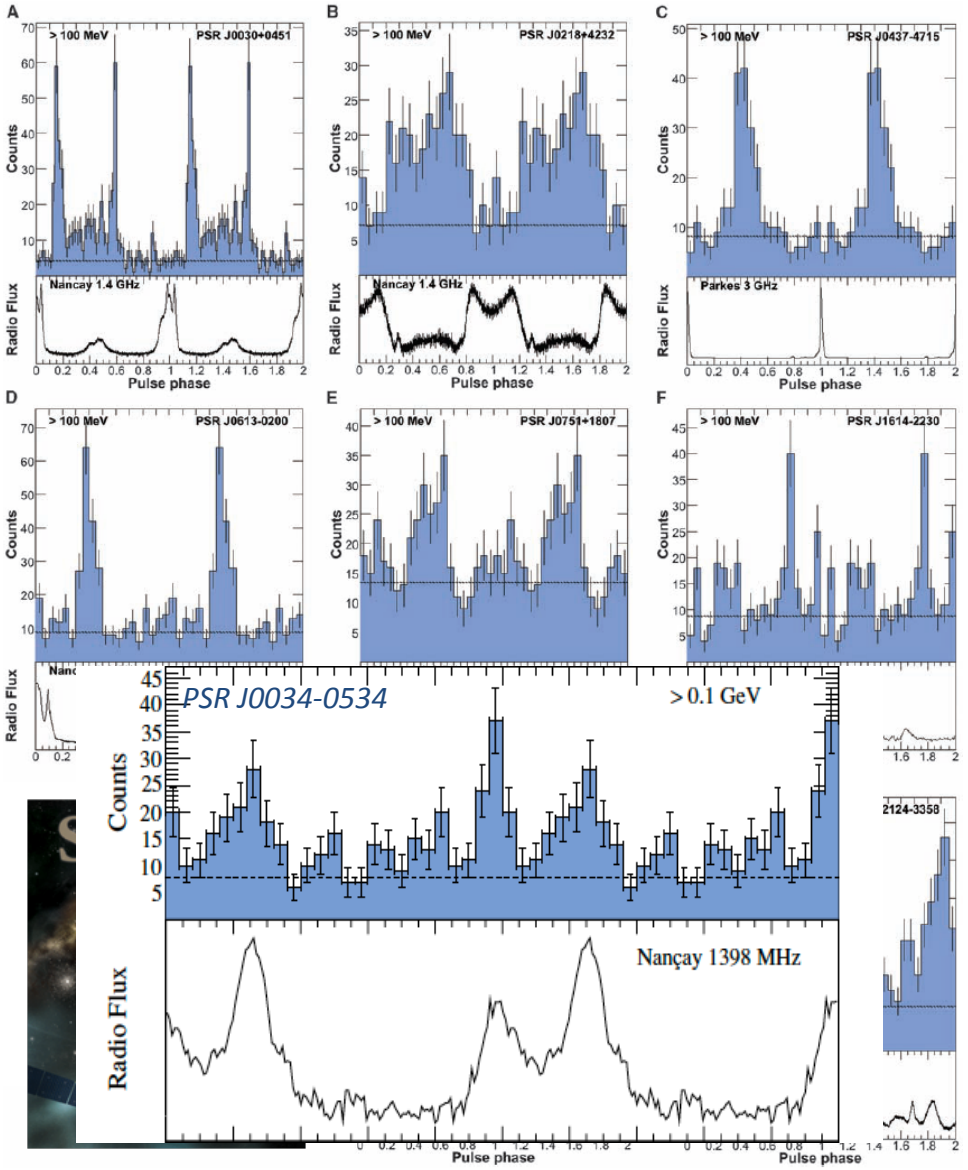


Radio-loud millisecond pulsars

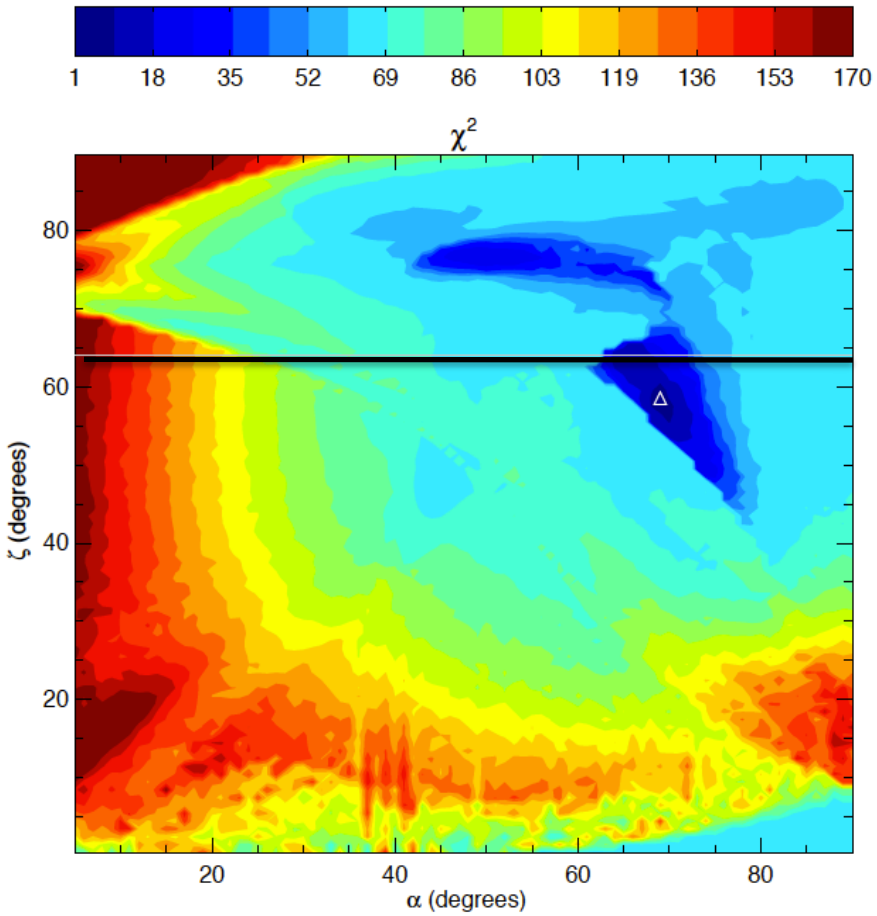
Fermi LAT detected pulsed gamma-ray emission from J0030+0451, making it the first firm detection of an MSP in gamma rays (Abdo et al., ApJ 699, 1171, 2009).

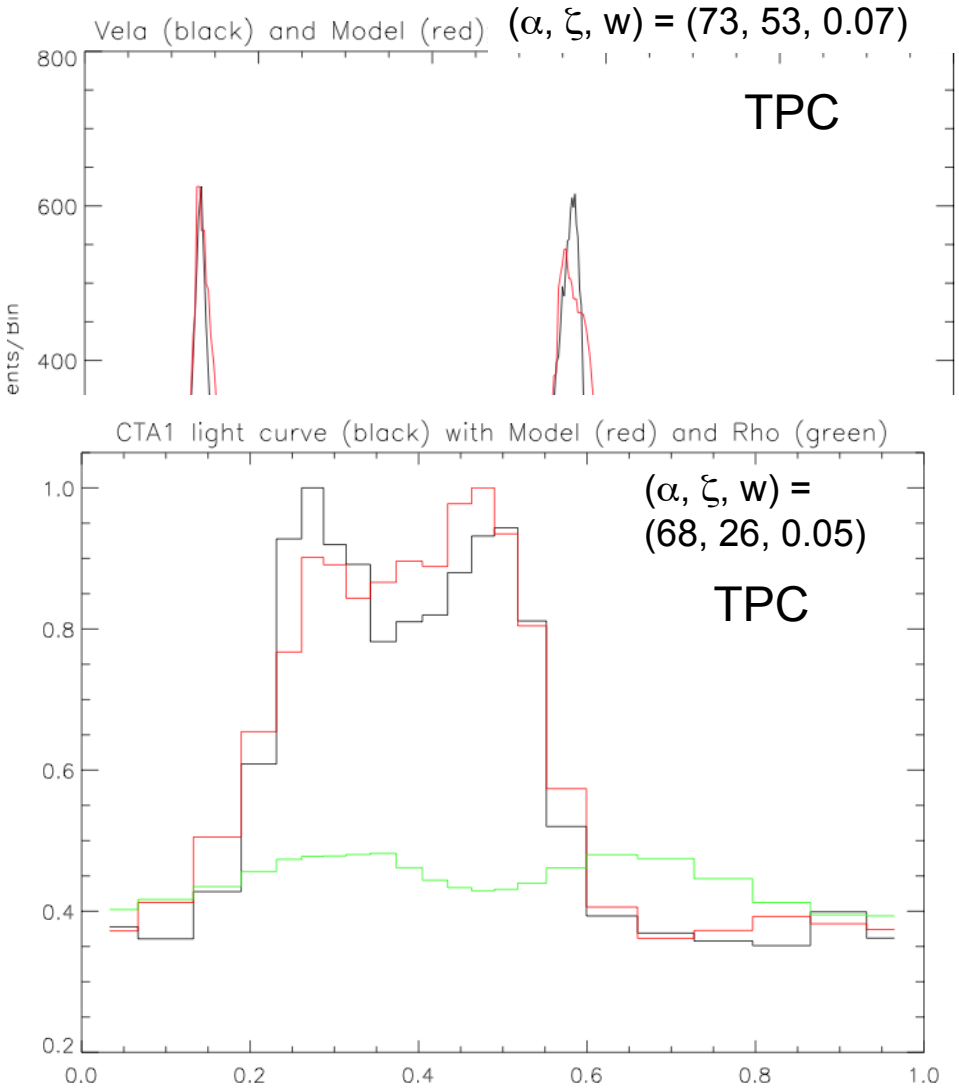
After 9 months of data taking, the LAT had detected 8 gamma-ray MSPs (Abdo et al. Science 325, 848, 2009).

For the first time, a population of gamma-ray MSPs has been observed.



Modeling young pulsar light curves

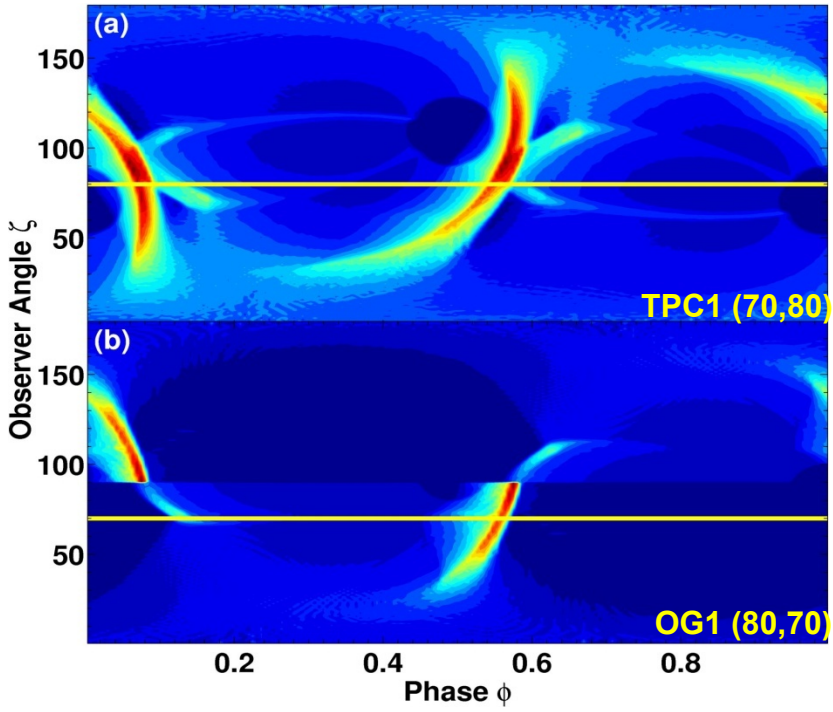


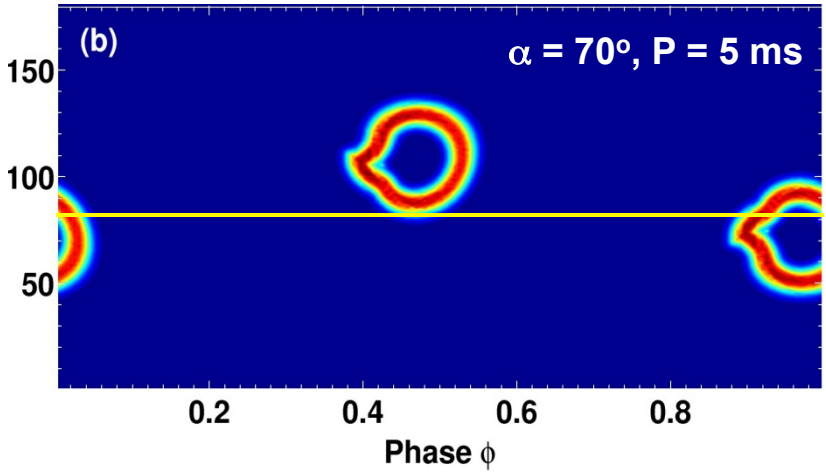


Decesar et al., in prep.

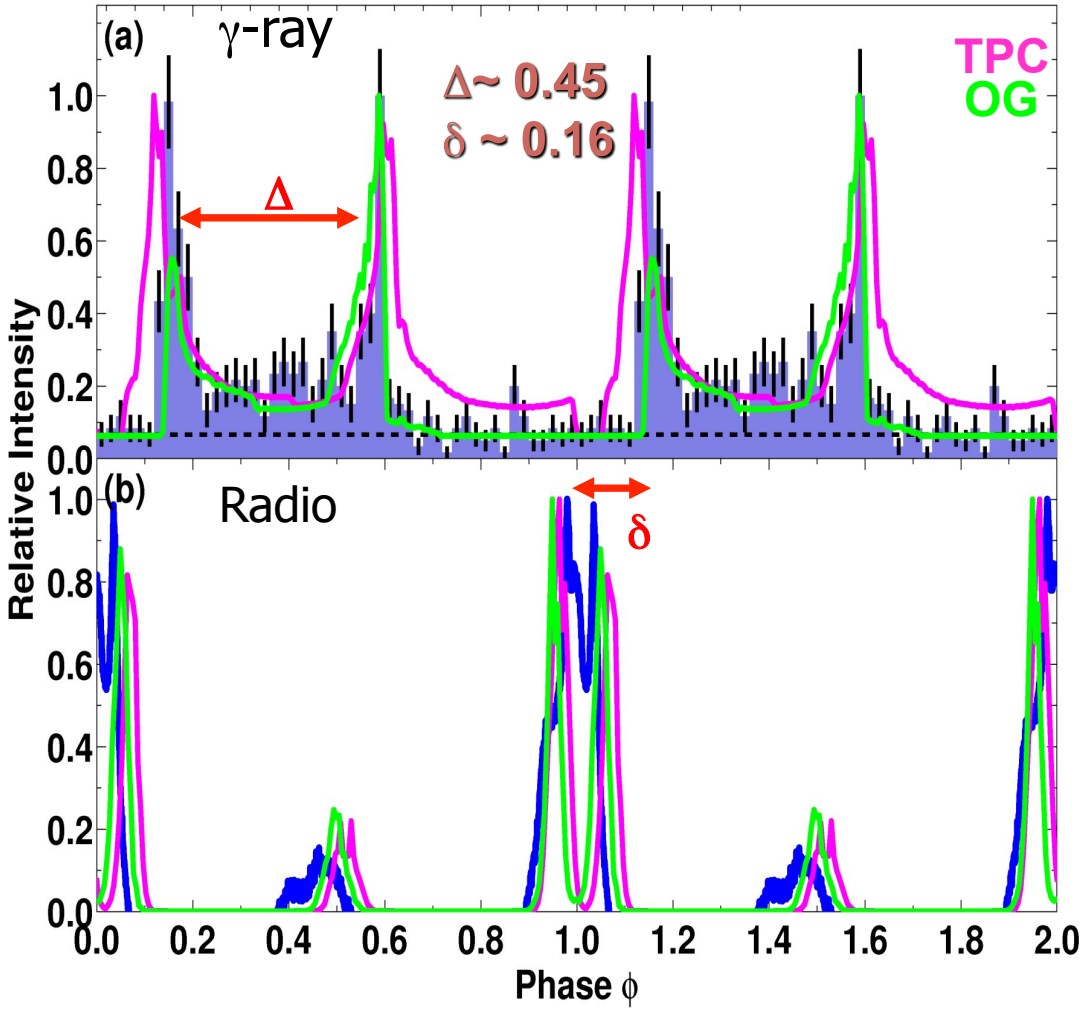
Modeling MSP Light Curves

Venter, Harding & Guillemot 2009

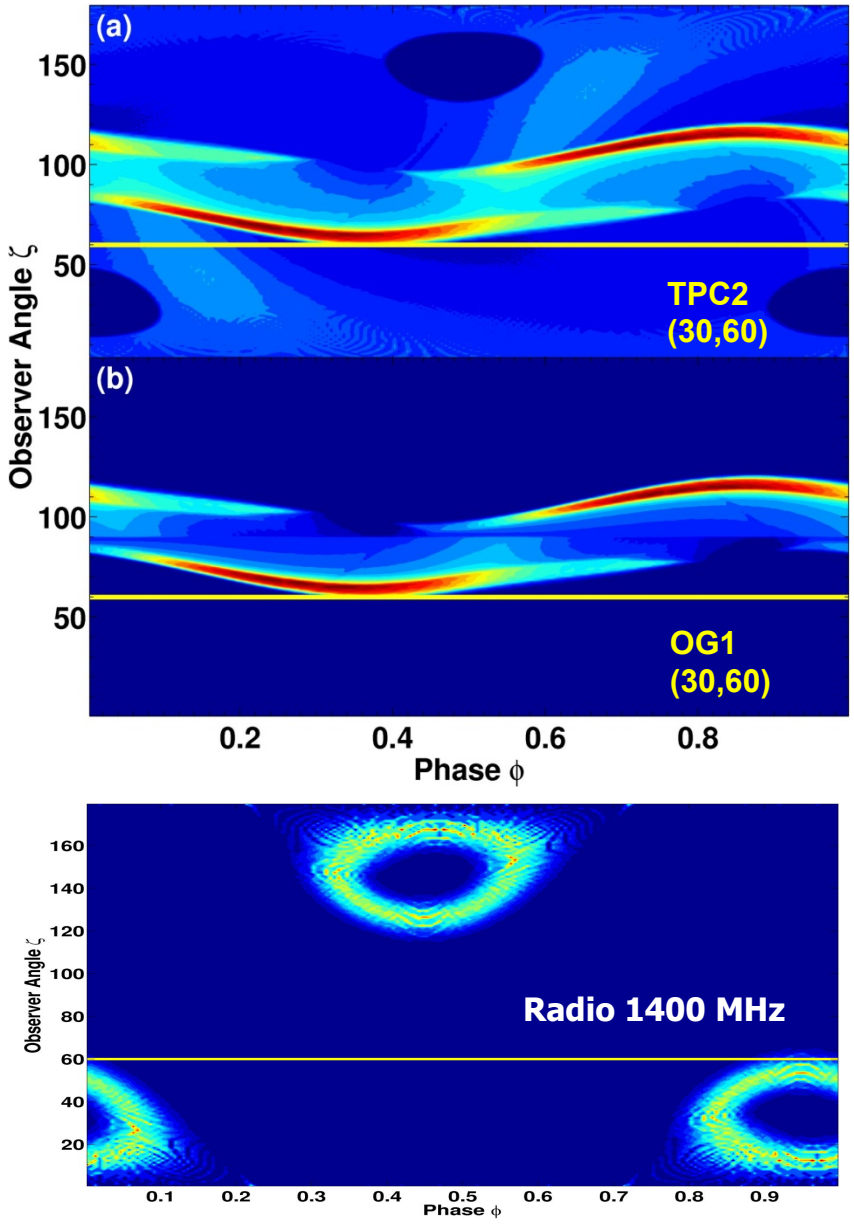




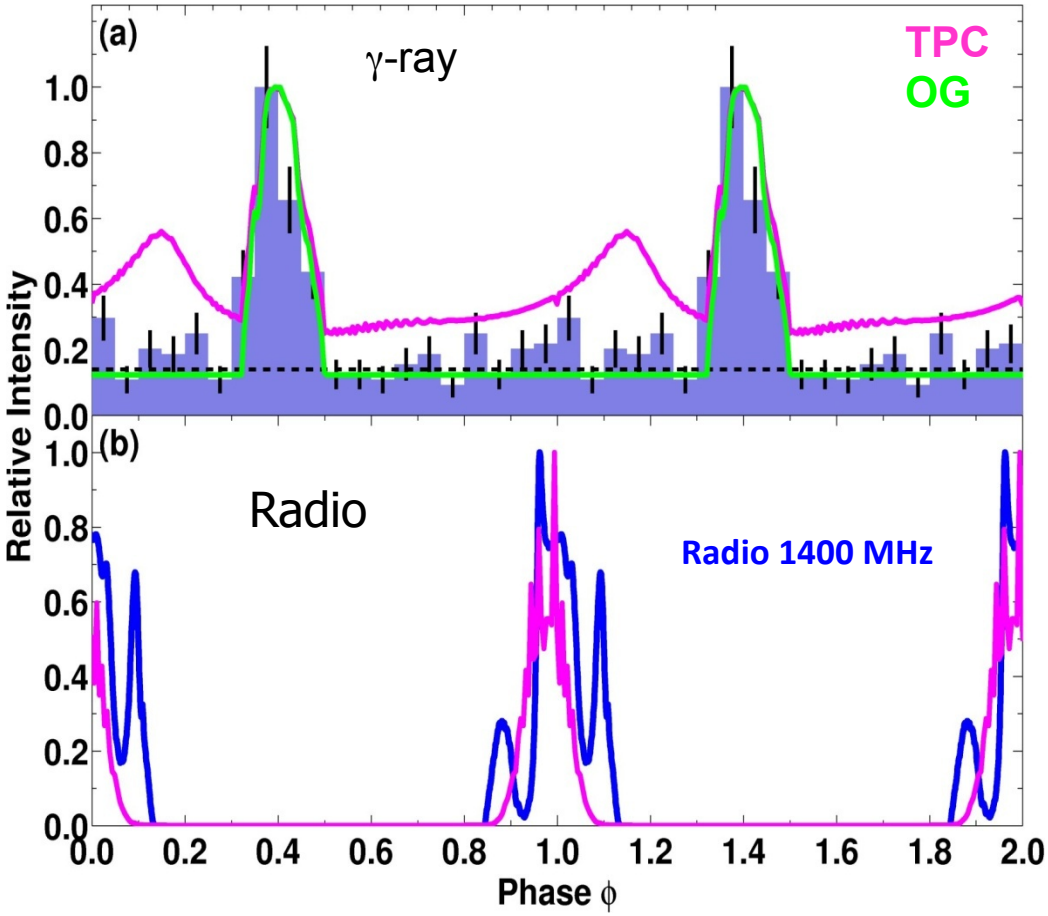
PSR J0030+0451



PSR J0613-0200



$\alpha = 30^0, \zeta = 60^0$



Predicted CR cutoff energies roughly match observed cutoff energies

- Balance CR losses with acceleration gain

$$eE_{\parallel} = \dot{\gamma}_{CR} = \frac{2e^2\gamma^4}{3\rho_c^2}$$

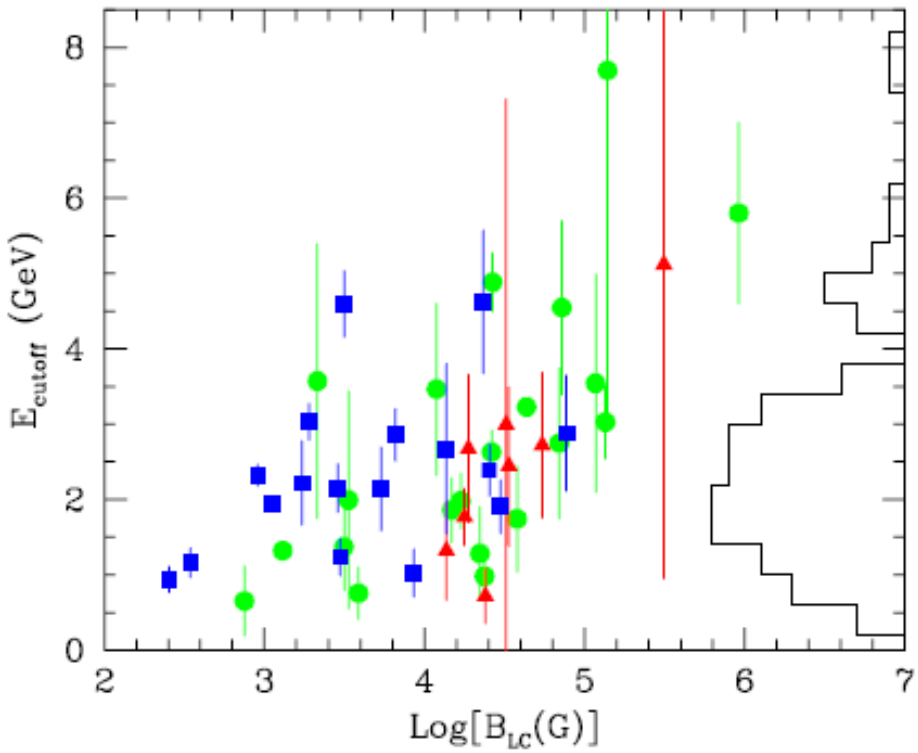
- Steady-state Lorentz factor

$$\gamma_{CRR} = \left(\frac{3}{2}\frac{E_{\parallel}\rho_c^2}{e}\right)^{1/4} \approx 2\times10^7$$

$$E_{\parallel} \sim w^2 B_{LC}$$

- Curvature radiation peak energy:

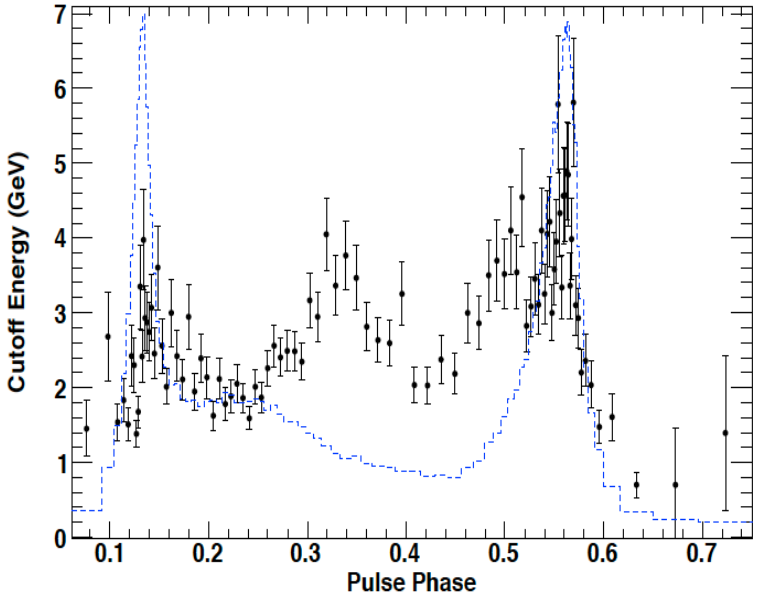
$$\varepsilon_{CR} = \frac{2}{3}\frac{\lambda\!\!\!^{-}_c \gamma_{CRR}^3}{\rho_c} = \left(\frac{3}{2}\right)^{7/4}\left(\frac{E_{\parallel}}{e}\right)^{3/4}\lambda\!\!\!^{-}_c \rho_c^{1/2} \approx 3\ GeV$$



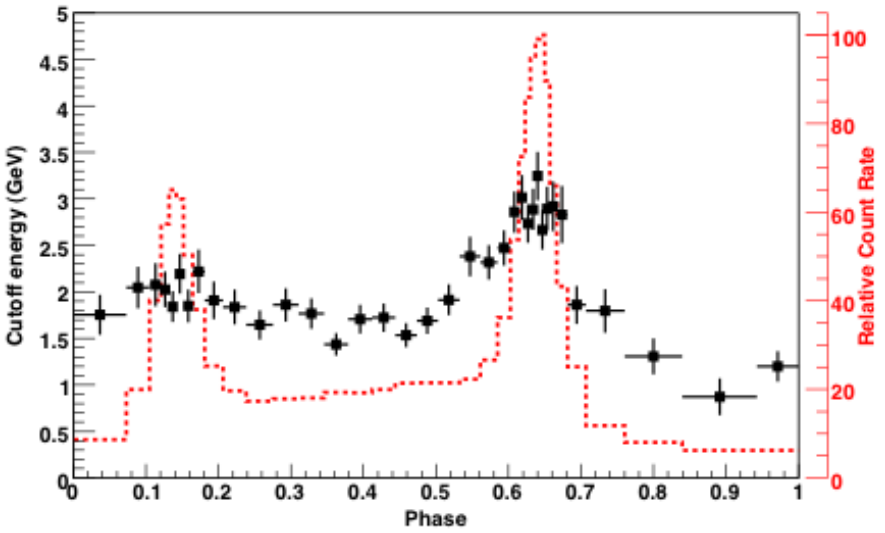
Observed cutoff energies show remarkably small spread

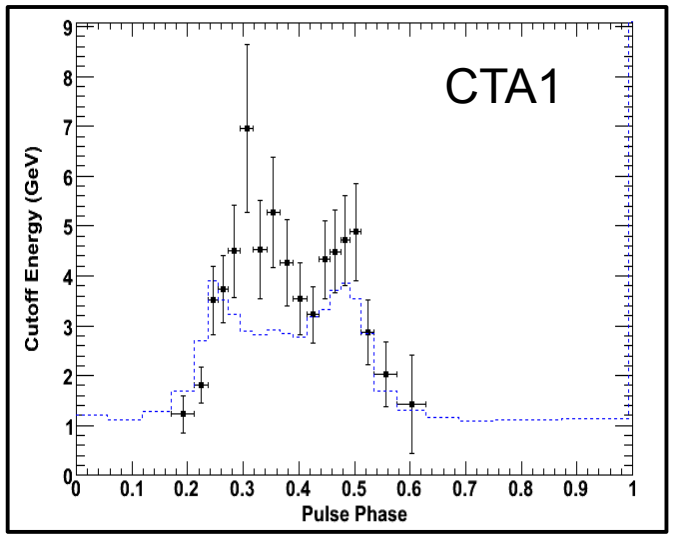
Phase resolved cutoff energies

Vela

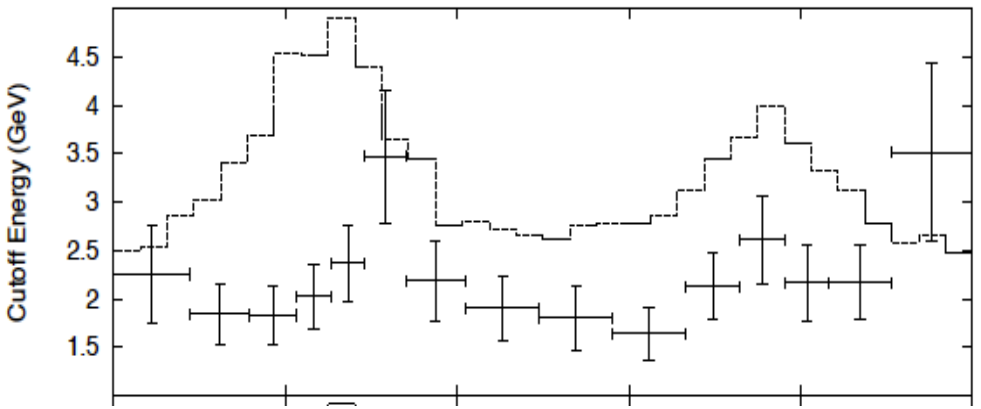


Geminga



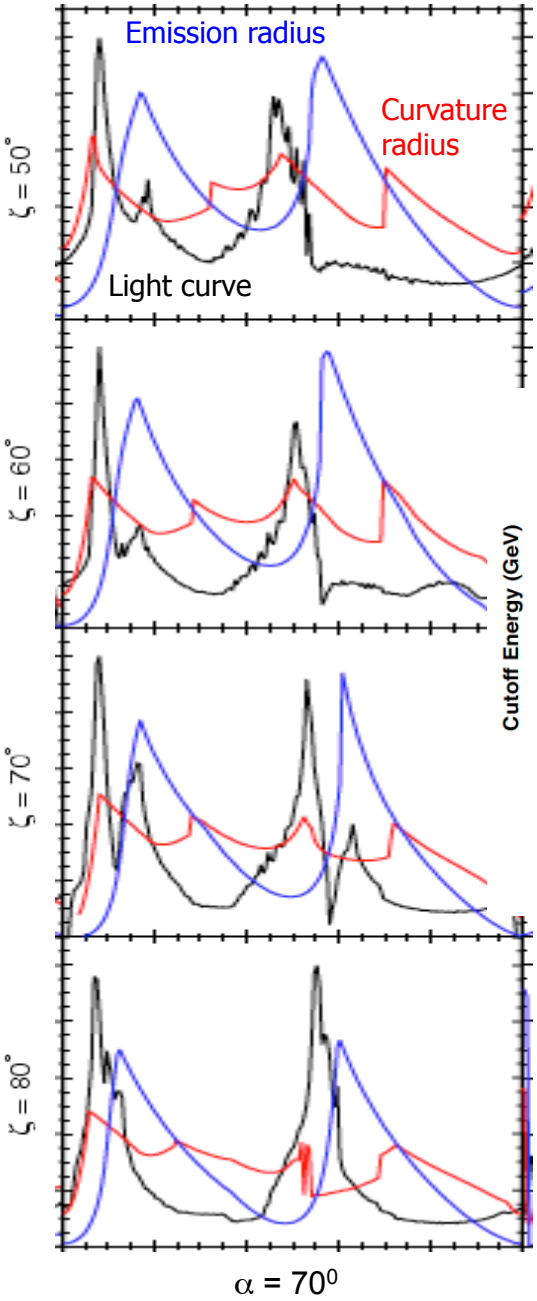


J1836+5925



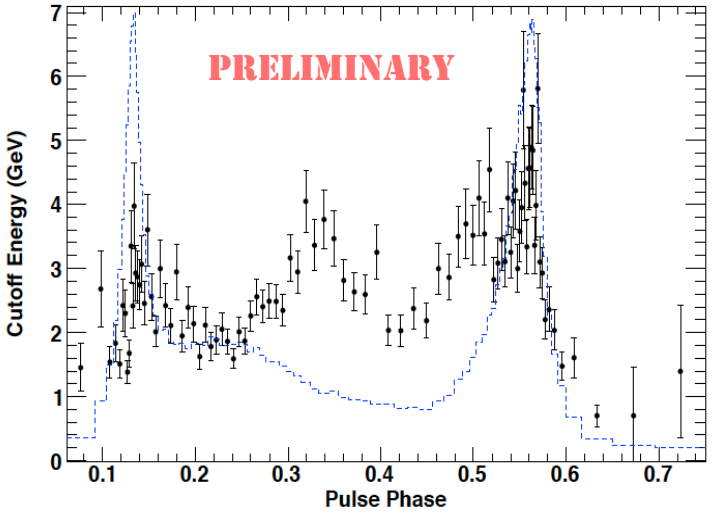
Model variation of emission, curvature radius

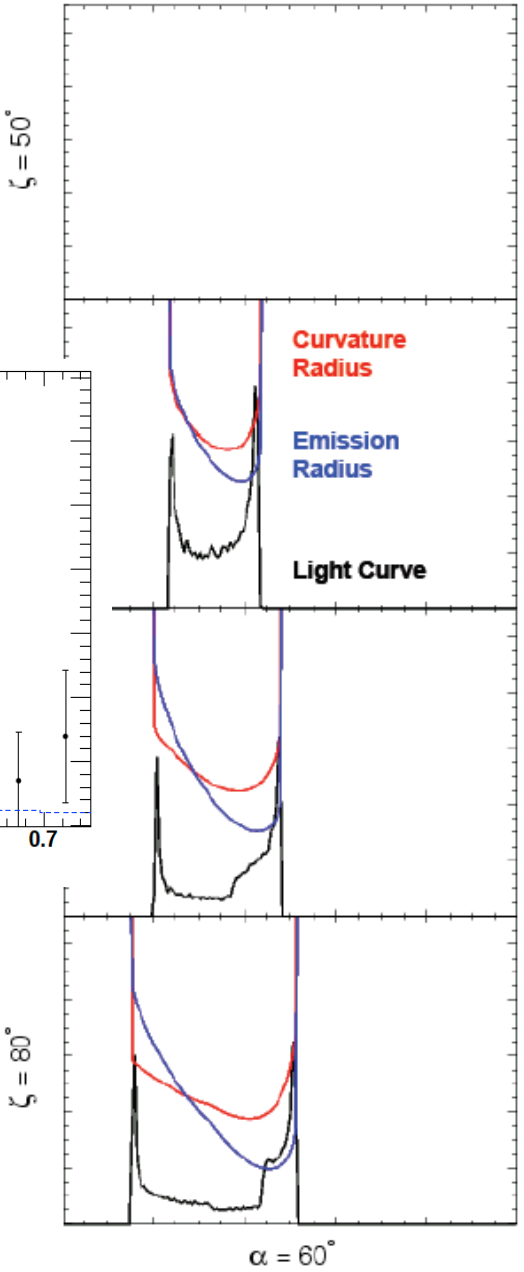
DeCesar et al., in prep.



Examples

- Two-pole caustic model (Romani & Yadigaroglu 1995) with vacuum retarded dipole field





Shortcomings of the models

- Energetics

$L_\gamma = \dot{n}\ \gamma mc^2$ too small for both slot gap and outer gap models by a factor of 5 – 10 (for narrow gap widths)

- Lack of sufficient pairs –

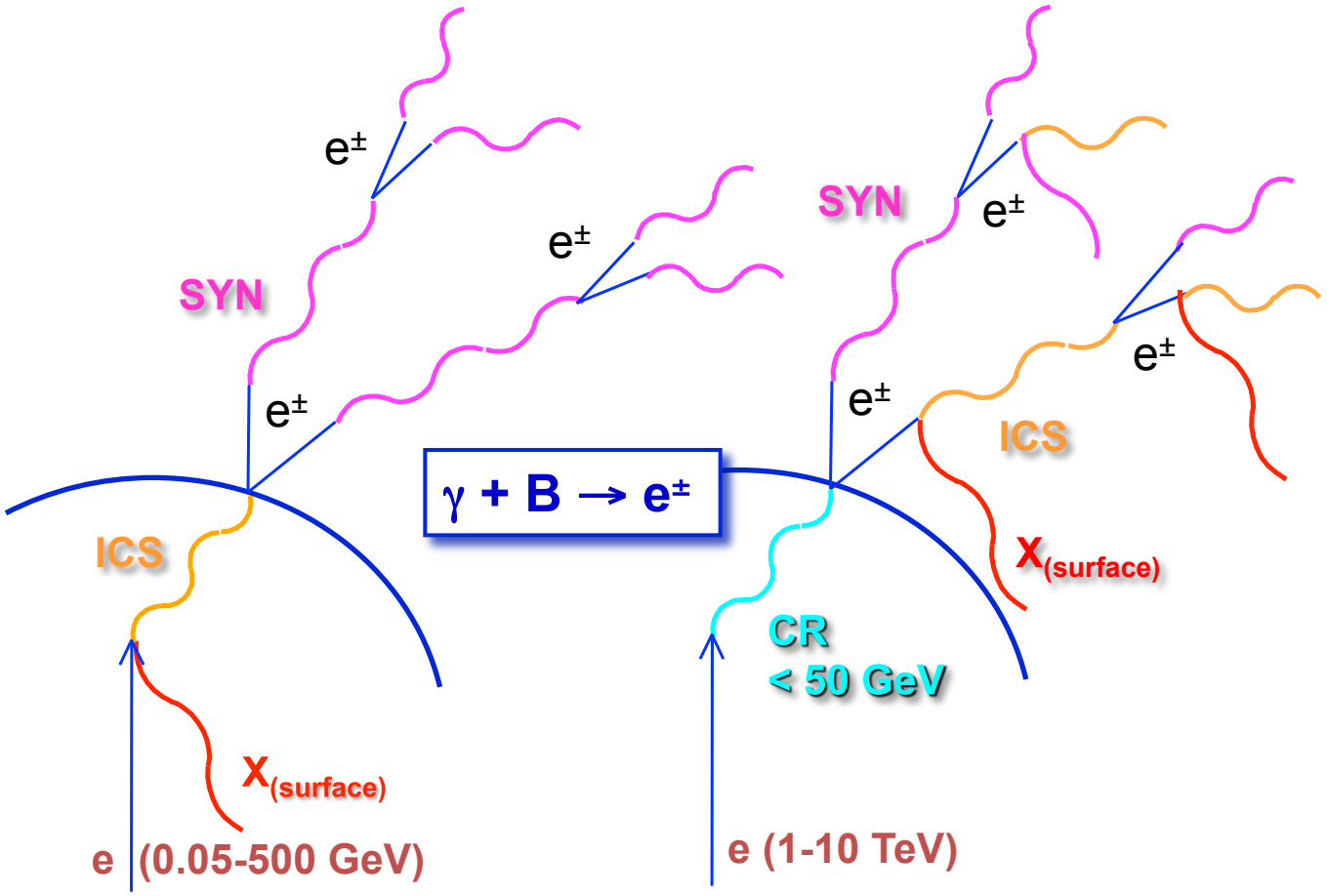
for either PWNe: Crab nebula requires ~10^{40} s^{-1} particles

→ pair multiplicity ~ 10^6

or MSPs with narrow gaps emission

- Dipole field geometry and lack of current closure

Polar cap pair cascades



near the surface
not efficient screening
$N_{e2}/N_{e1} = 10^{-3}$-10^{2}

Sturner & Dermer '94

Hibschmann & Arons '01

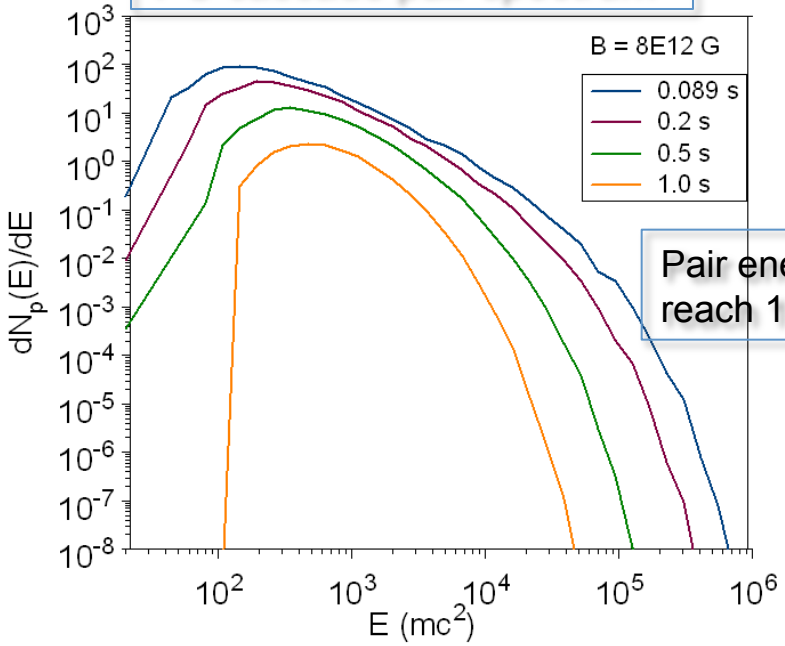
higher above the surface
$E_{//}$ screening
$N_{e2}/N_{e1} = 10$-10^{5}

Daugherty & Harding '82

Zhang & Harding '00

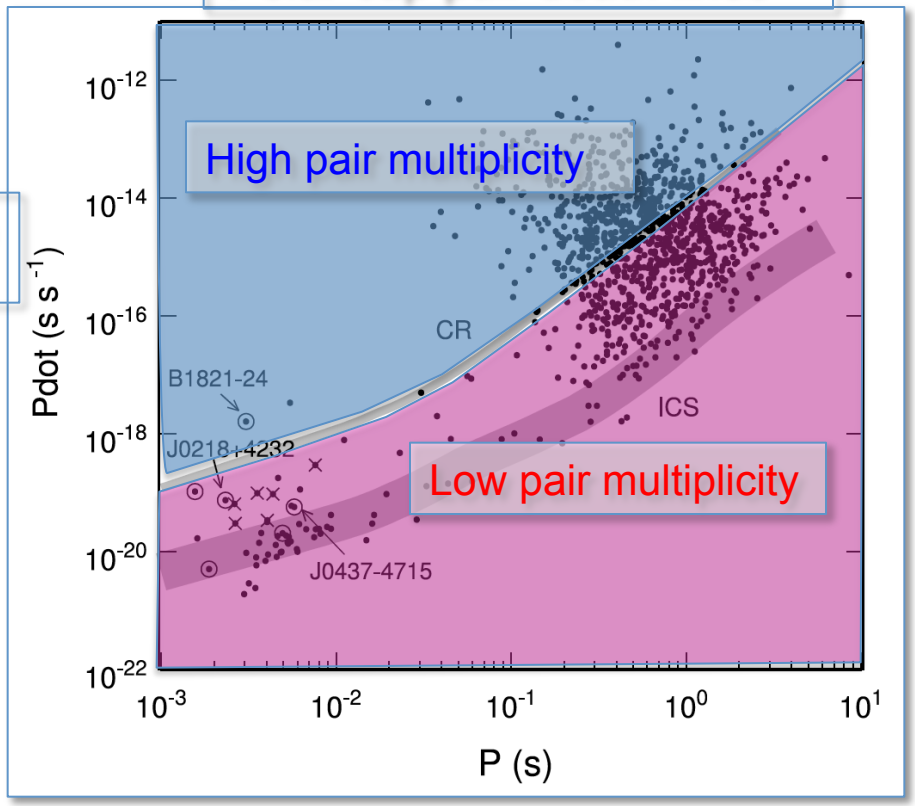
Pulsar pair cascades

PC cascade pair spectrum

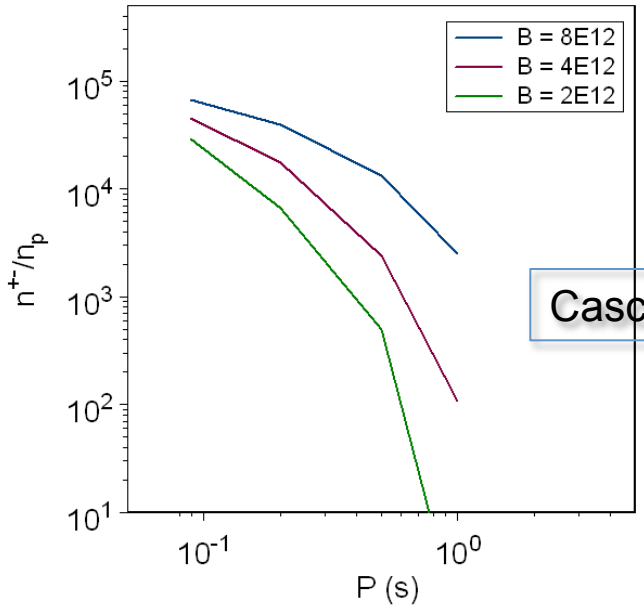


Pair energies can reach 100 GeV

Polar cap pair death lines



Harding & Muslimov 2002,
Harding et al. 2005

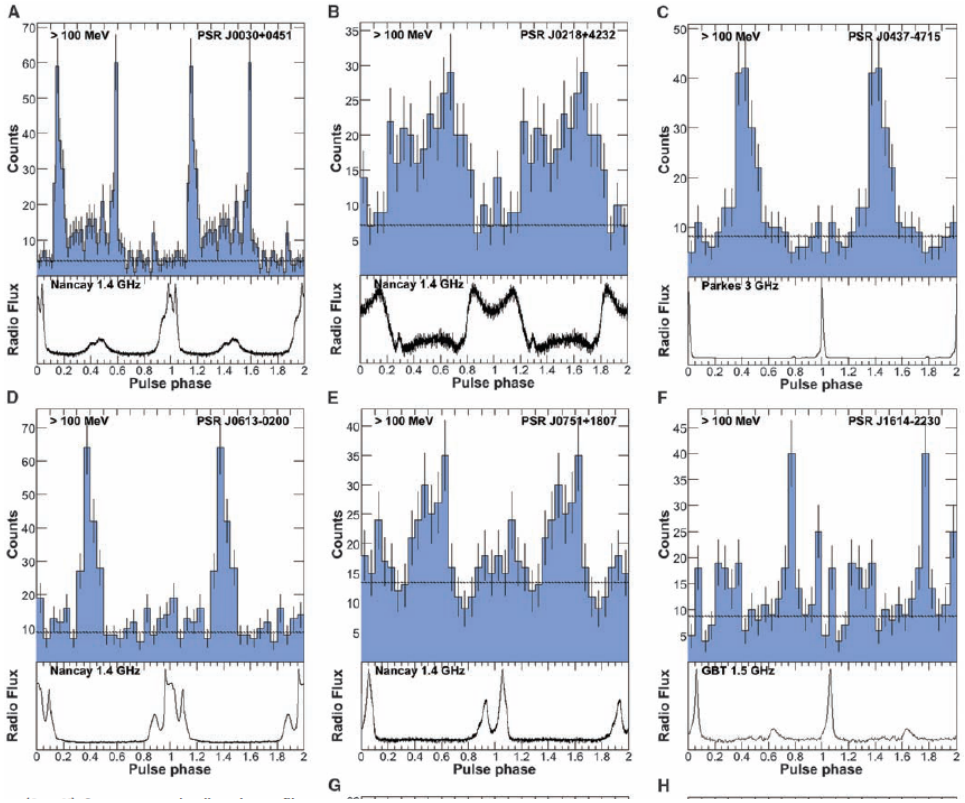


Cascade pair multiplicity

Above/below CR pair death line –
high/low pair multiplicity (for dipole field)

What about millisecond pulsars?

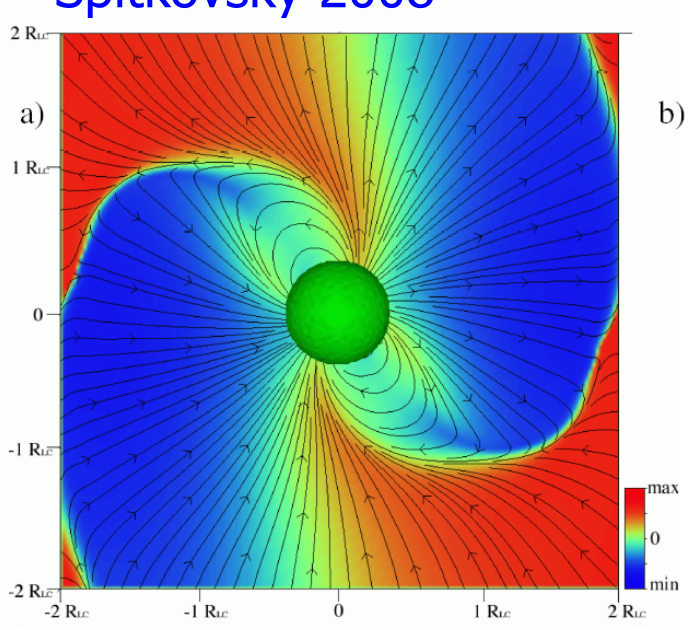
- Many detected by Fermi
- Pair cascades in dipole fields not expected to have high multiplicity → 'pair starved'
- But gamma-ray light curves show narrow peaks, not in phase with radio → narrow acceleration gaps



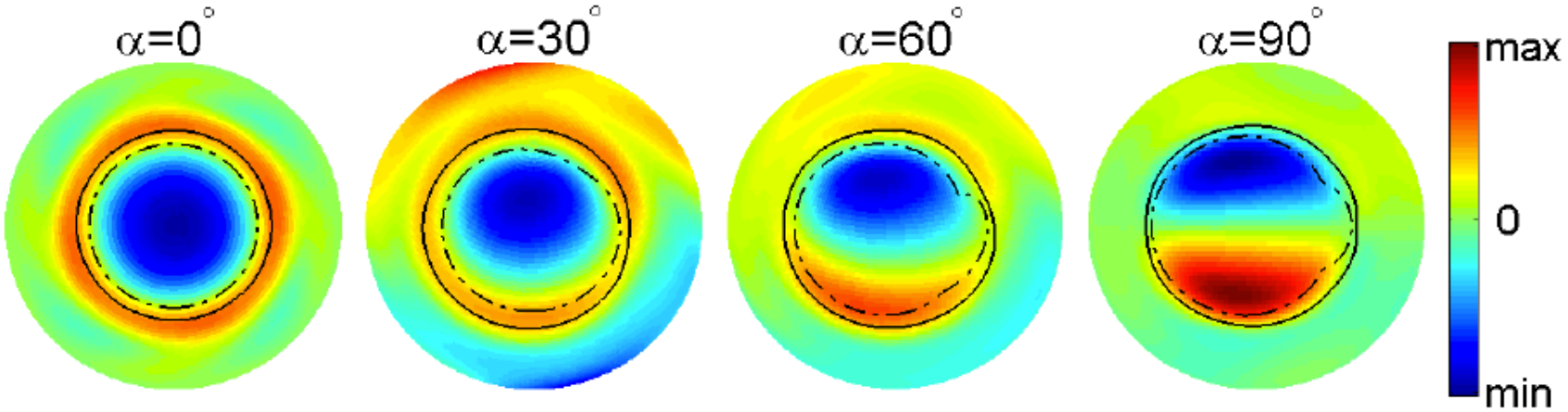
Field geometry and current closure

- Emission models assume retarded vacuum dipole field
- Emission models ignore current closure
- Force-free current is not the same as $\rho_{GJ}c$ assumed by models

Force-free magnetosphere
Spitkovsky 2008

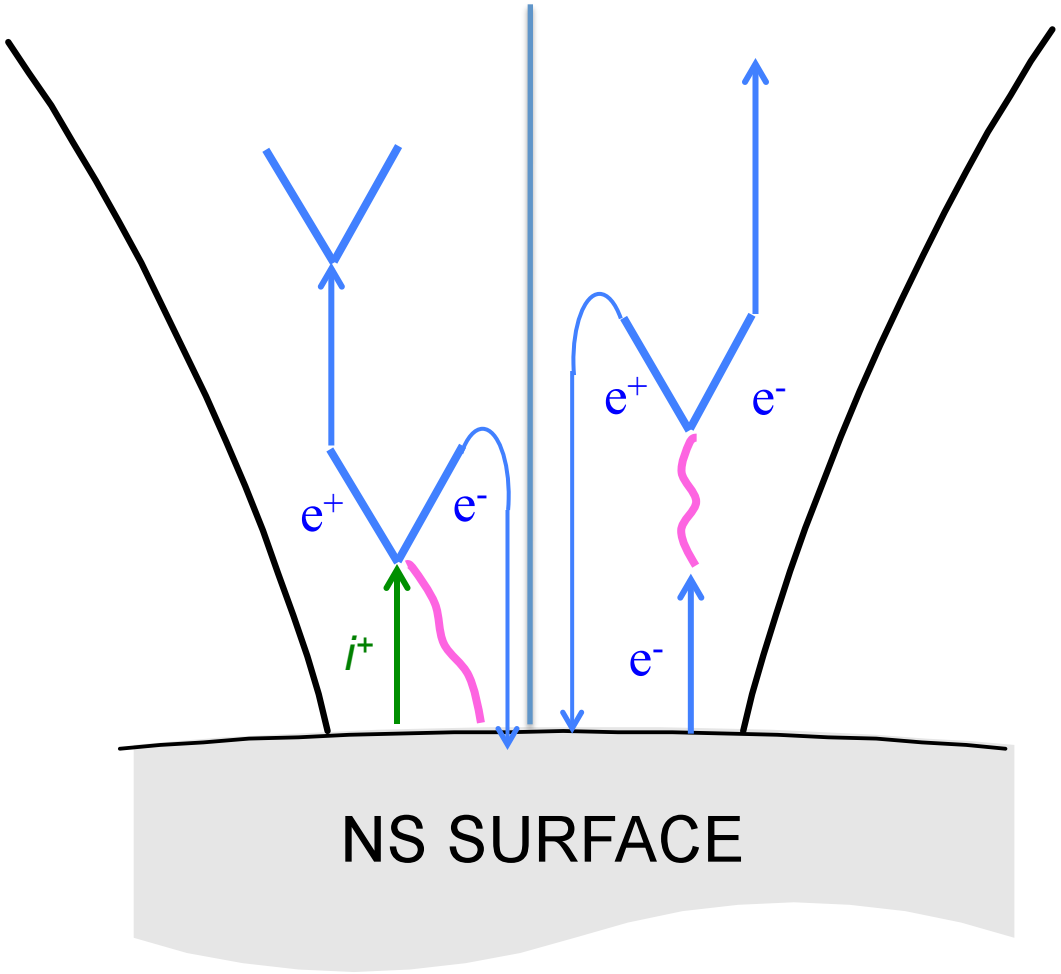


Bai & Spitkovsky 2010



Next steps

- Understand acceleration in self-consistent global geometry? (not likely anytime soon!)
- Accelerate both signs of charge above polar cap?



- Space-charge limited ion (as well as electron) acceleration
- Lorentz-boosted pair production *(Cheng & Ruderman 1977)*
- Positrons initiate pair cascade

Questions

- How do MSPs (and maybe all pulsars) produce higher pair multiplicities?
- How do polar cap pair cascades link to global magnetosphere currents (and what happens when pulsars are pair-starved)?
- How do thin gaps produce observed gamma-ray luminosity?