



[http://www.earthtimes.org/newsimage/nebula-gamma-rays\\_910.jpg](http://www.earthtimes.org/newsimage/nebula-gamma-rays_910.jpg)



# High-energy pulsar models: Developments and new questions

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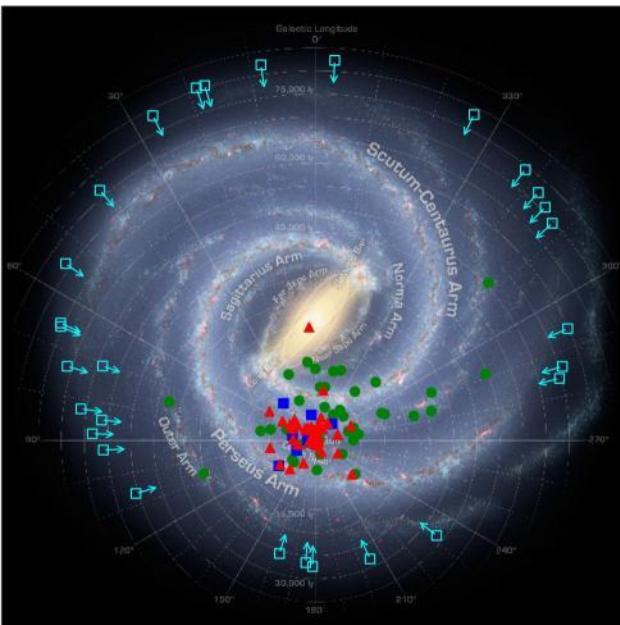
*The Fast and the Furious: Energetic Phenomena in Isolated Neutron Stars,  
Pulsar Wind Nebulae and Supernova Remnants, 22 - 24 May 2013, Madrid, Spain*

# HE Pulsars - a Diverse Population

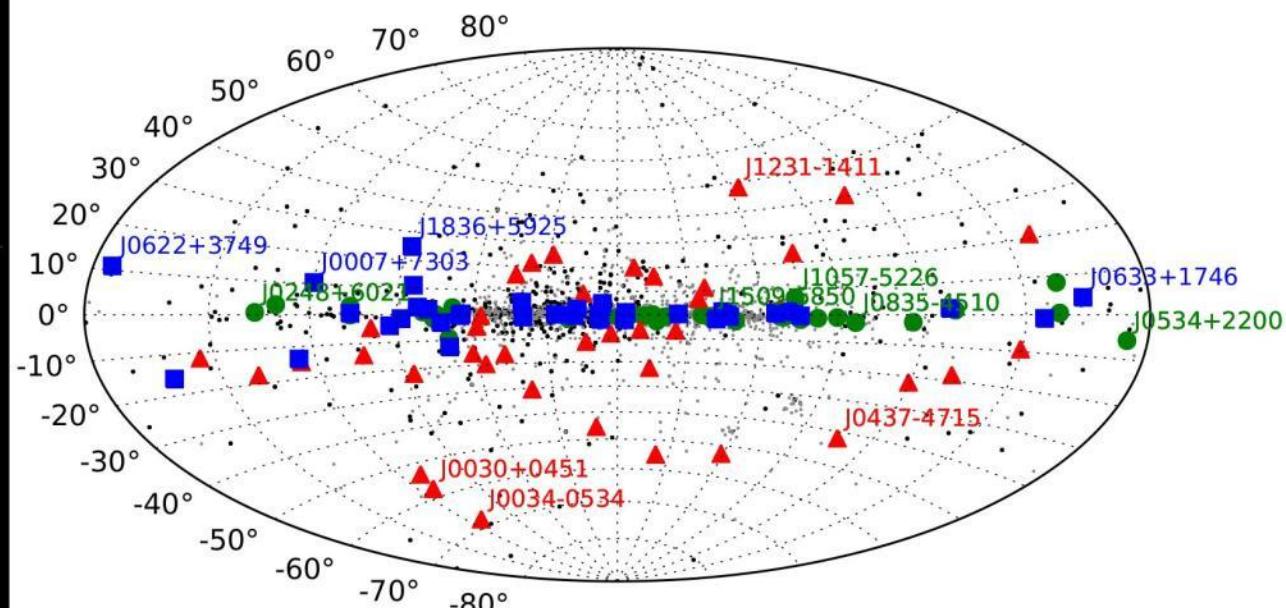
## *Fermi LAT 2<sup>nd</sup> Pulsar Catalog (2PC)*

- 117 high-confidence  $> 0.1$  GeV pulsars
- 3 years of *Fermi* LAT data
- 50% of these discovered by *Fermi*!
- 3 even groups: MSPs, young RLPs, young RQPs

See D Smith's talk



Preliminary

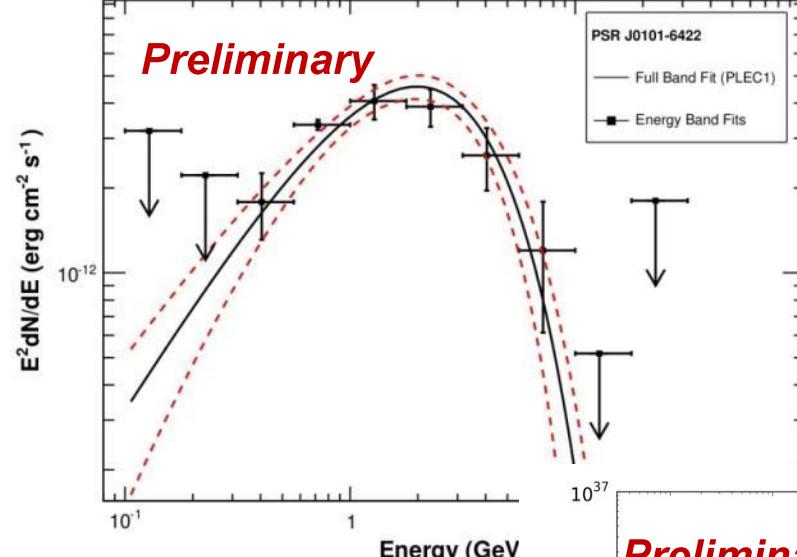
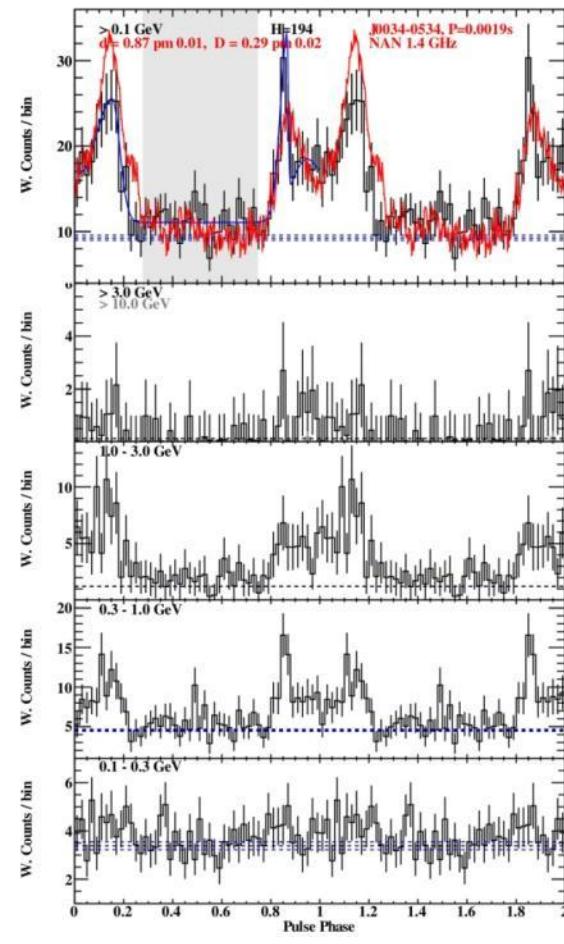


Preliminary

# HE Pulsars - a Diverse Population

## Fermi LAT 2nd Pulsar Catalog (2PC)

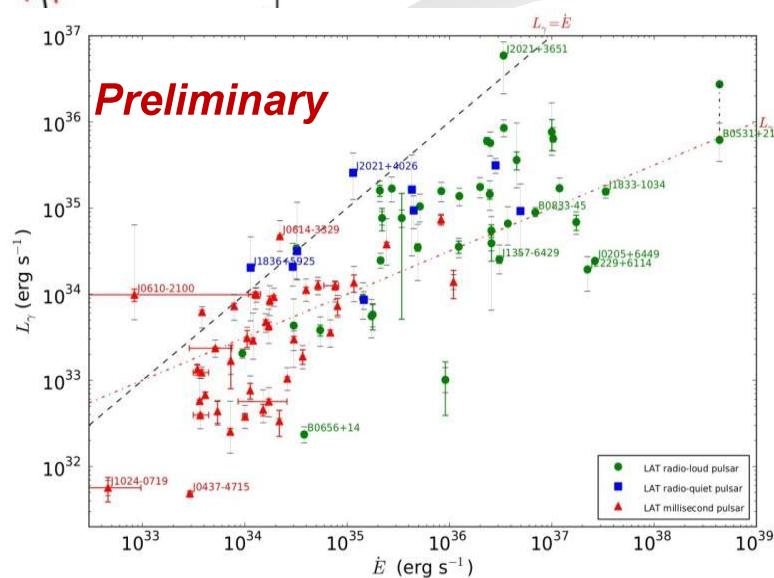
- Multiband profiles
- Energy spectra



- Off-peak emission
- Unseen pulsars

See D Smith's talk

- Luminosities

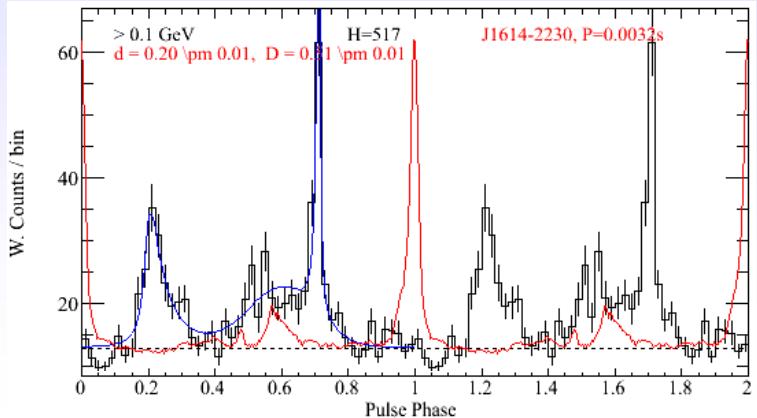


Preliminary

# Light Curve Classes

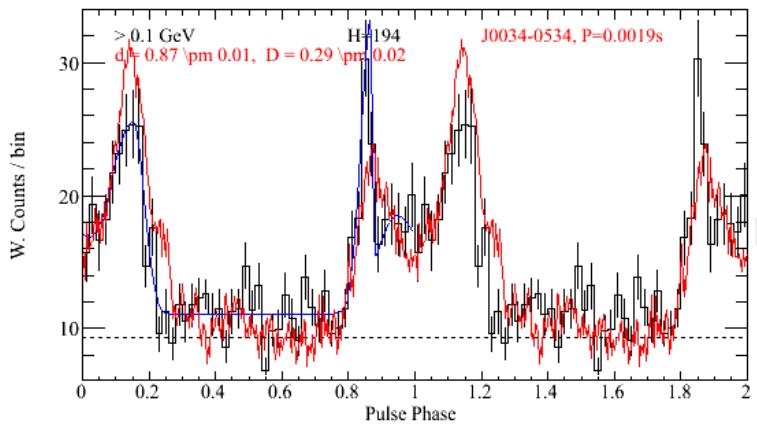
## 1. $\gamma$ -ray peak(s) **lag** main radio peak

- Young pulsars & MSPs
- “Class I”



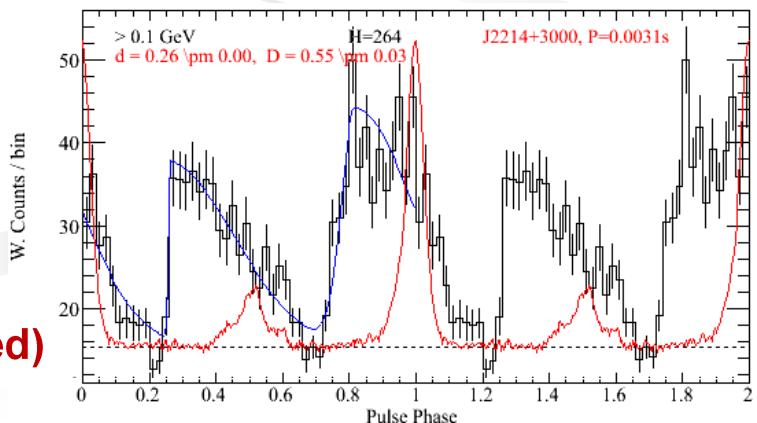
## 2. $\gamma$ -ray peaks **aligned** with radio peaks

- *Nearly* exclusive to MSPs
- “Class II”



## 3. $\gamma$ -ray peak(s) **lead** main radio peak(s)

- Exclusive to MSPs
- “Class III”



# Magnetospheric Structure

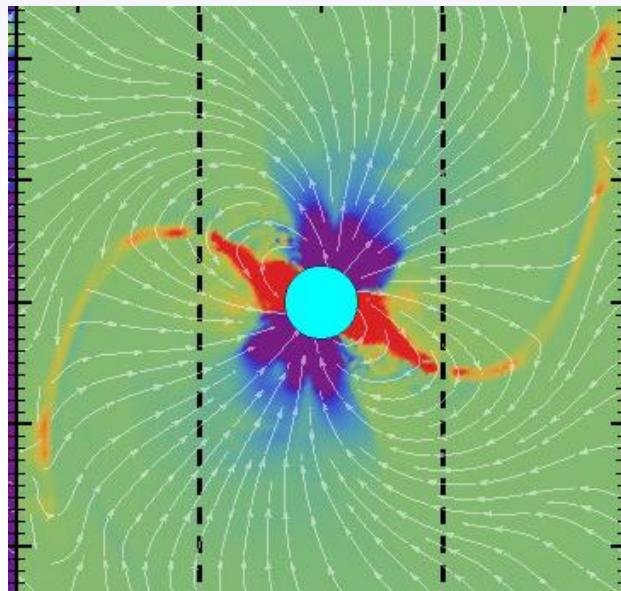
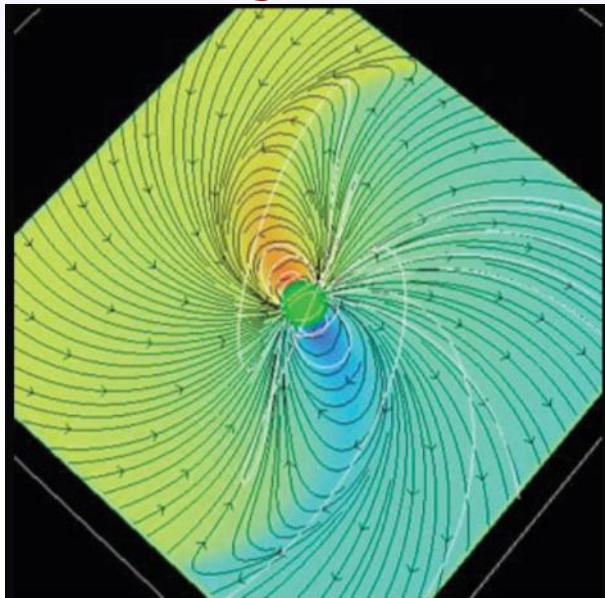


# Different Regimes

Vacuum retarded dipole (VRD)

(Deutsch 1955)

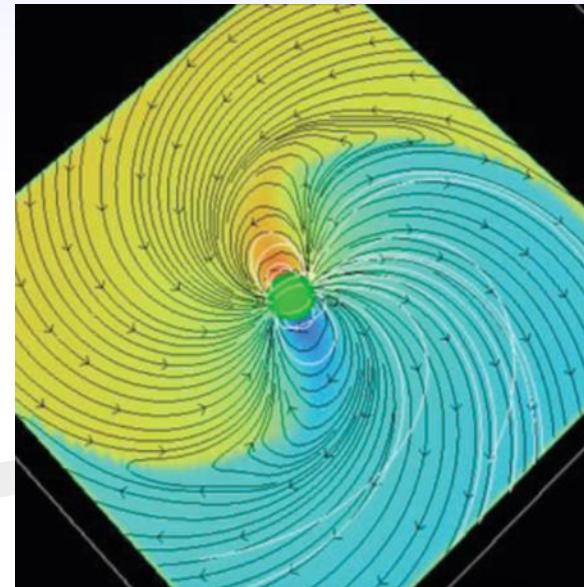
No charges, no currents



Force-free magnetosphere

(Spitkovsky 2006)

No particle acceleration



Non-ideal MHD magnetosphere  
(Kalapotharakos et al. 2011, Li et al. 2011)

Charges, currents + acceleration!

$$\vec{E} \cdot \vec{B} = 0$$

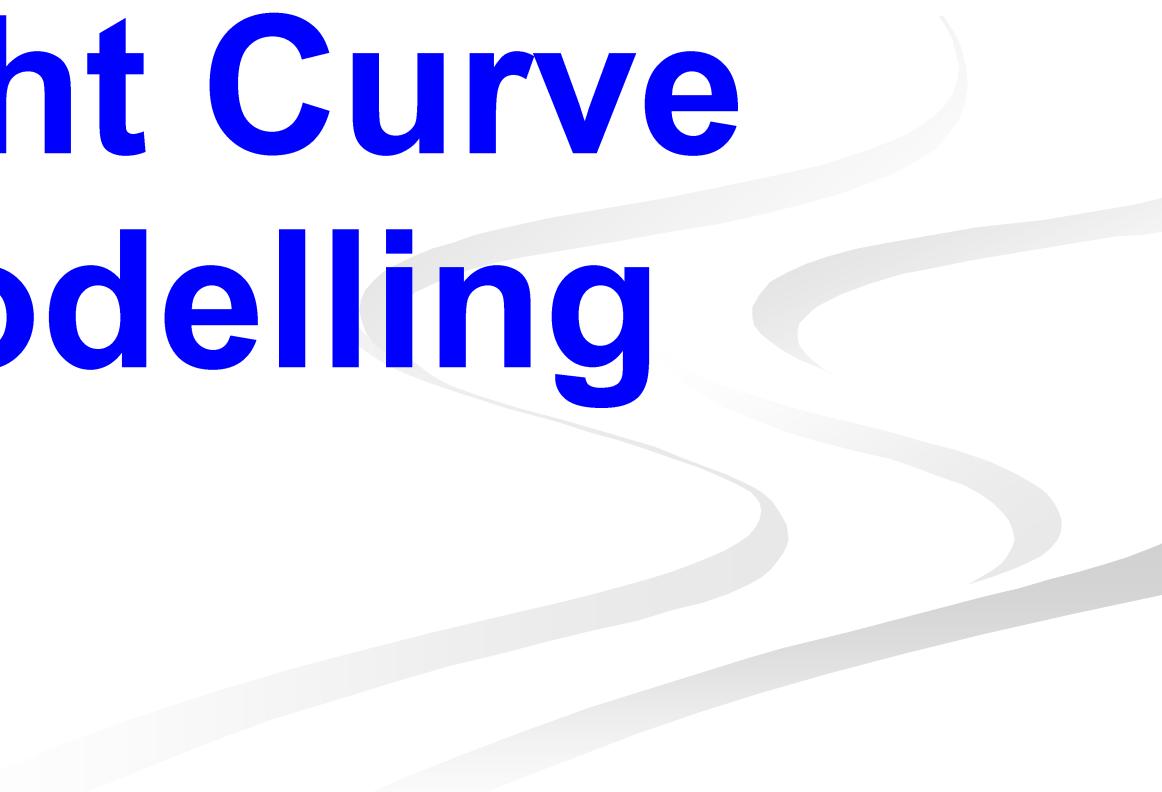
Filled with plasma

$$\vec{E} \cdot \vec{B} \neq 0$$

$$E_{||} = 0$$

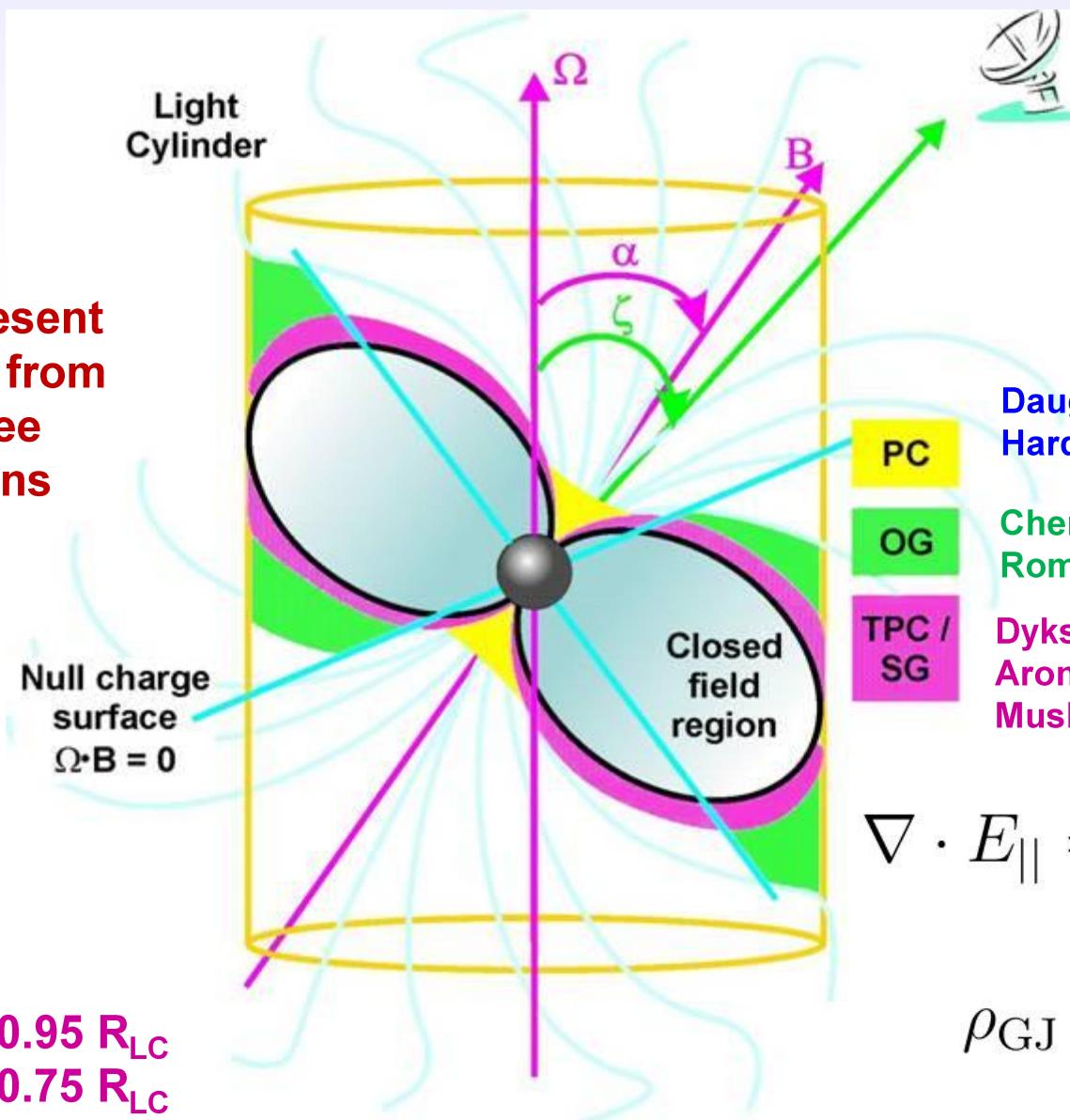
**$\gamma$ -ray light curves and phase-resolved spectroscopy will help to constrain  $B$**

# Geometric Light Curve Modelling



# Traditional Accelerator Geometries

Gaps represent deviations from force-free conditions

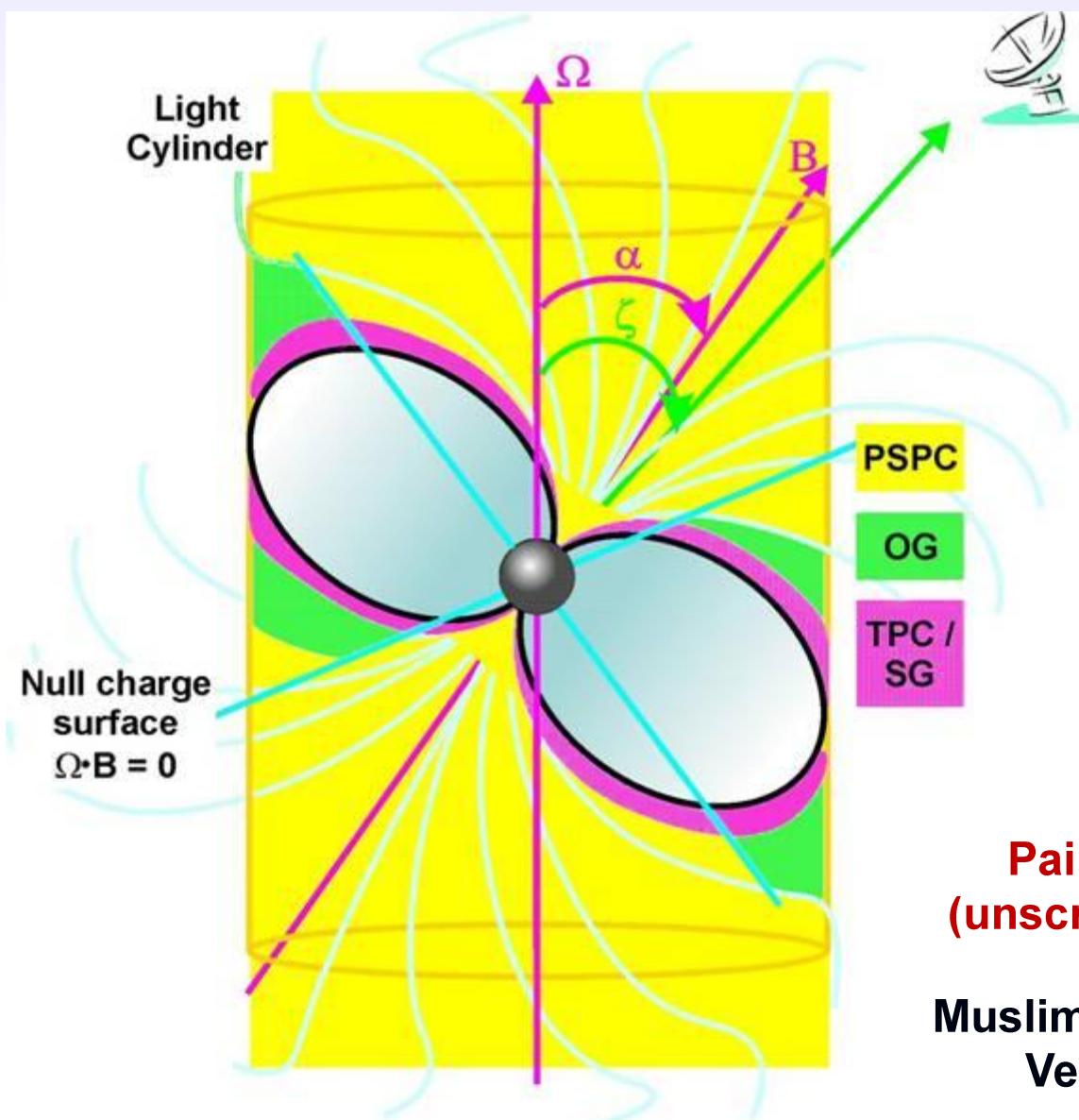


$$\nabla \cdot E_{||} = -4\pi (\rho - \rho_{GJ})_{||}$$

$$\rho_{GJ} \approx -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

SG:  $r_{cyl} < 0.95 R_{LC}$   
TPC:  $r_{cyl} < 0.75 R_{LC}$

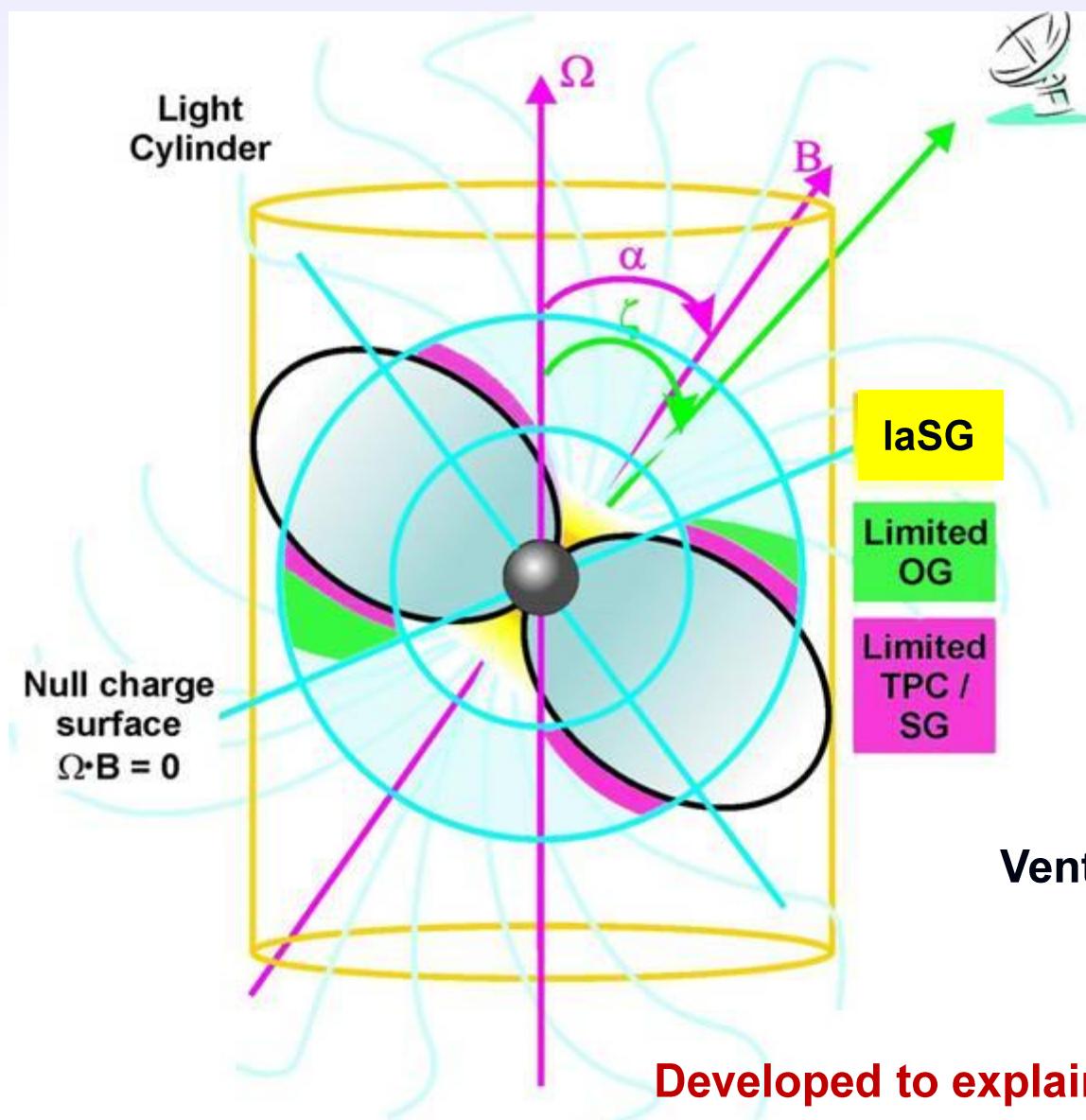
# PSPC Geometry



Pair-starved case  
(unscreened PC model)

Muslimov & Harding (2004)  
Venter et al. (2009)

# Altitude-Limited Geometries



# Radio Beam Geometry

Single-altitude conal radio beam

Harding et al. (2007); Gonthier (2004)

Model of Arzoumanian, Chernoff & Cordes (2002) – 400 MHz; Kijak & Gil (2003)

Frequency-dependent cone width of Mitra & Deshpande (1999)

**Total flux:**  $S(\theta, \nu) = F_{\text{cone}} e^{-(\theta - \bar{\theta})^2 / \omega_e^2}$

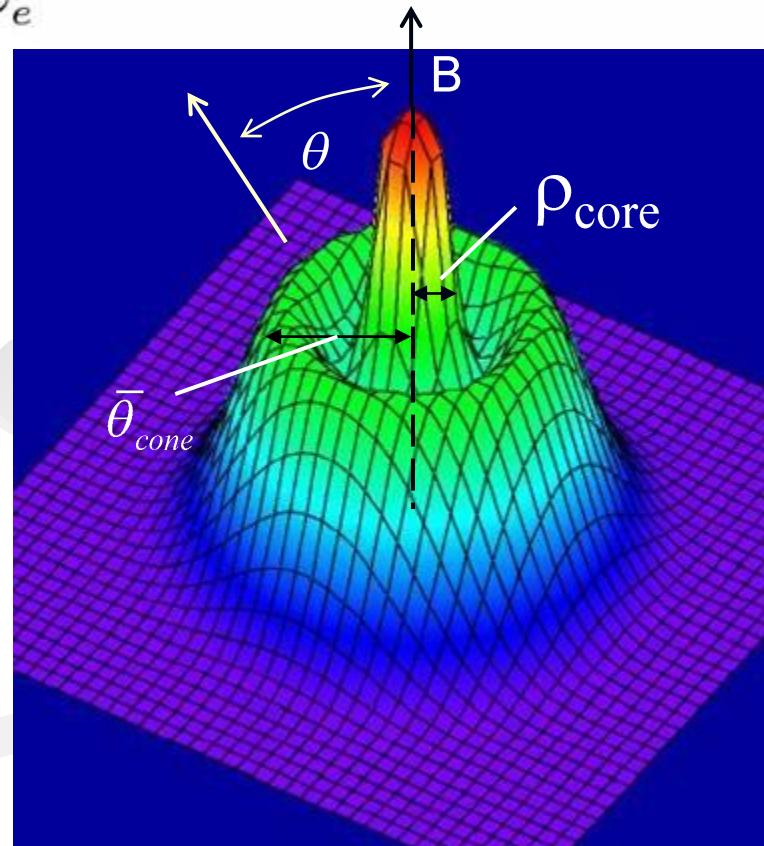
**Cone radius:**  $\rho_{\text{cone}} = 1.24^\circ r_{\text{KG}}^{0.5} P^{-0.5}$

**Cone position**  $\bar{\theta} = (1.0 - 2.63 \delta_w) \rho_{\text{cone}}$

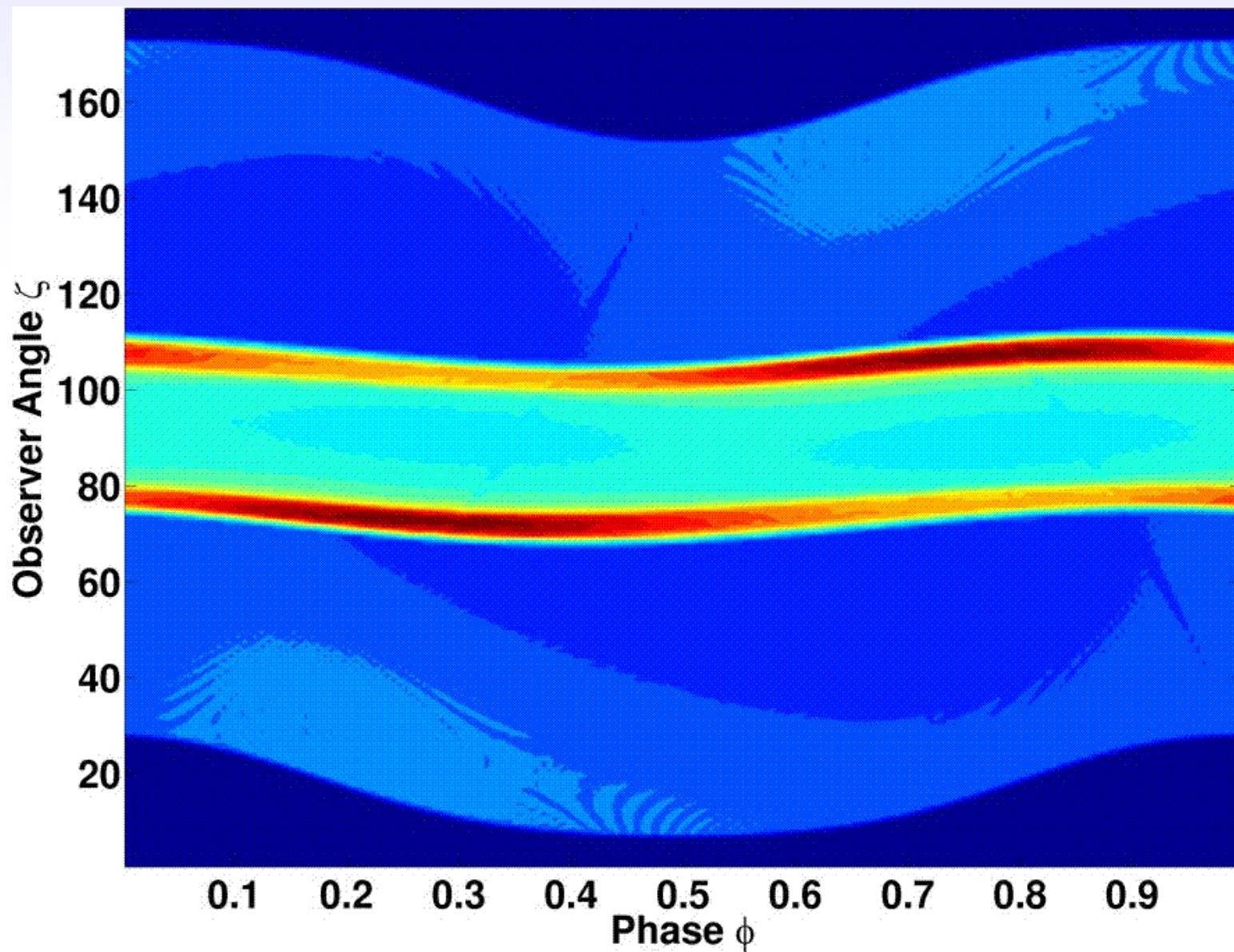
**Cone width:**  $w_e = \delta_w \rho_{\text{cone}}$

**Emission altitude:**

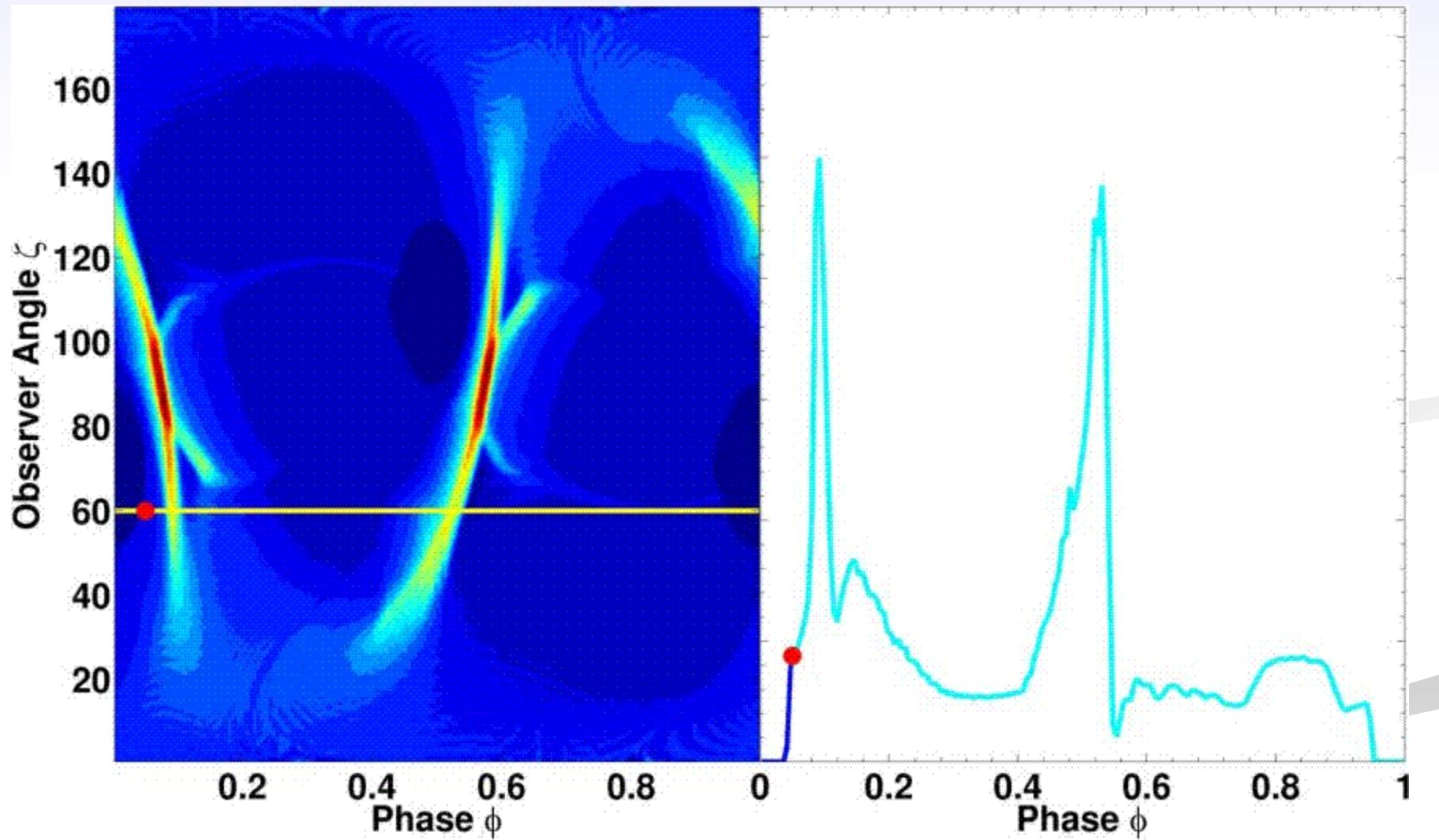
$$r_{\text{KG}} \approx 40 \left( \frac{\dot{P}}{10^{-15} \text{ s s}^{-1}} \right)^{0.07} P^{0.3} \nu_{\text{GHz}}^{-0.26}$$



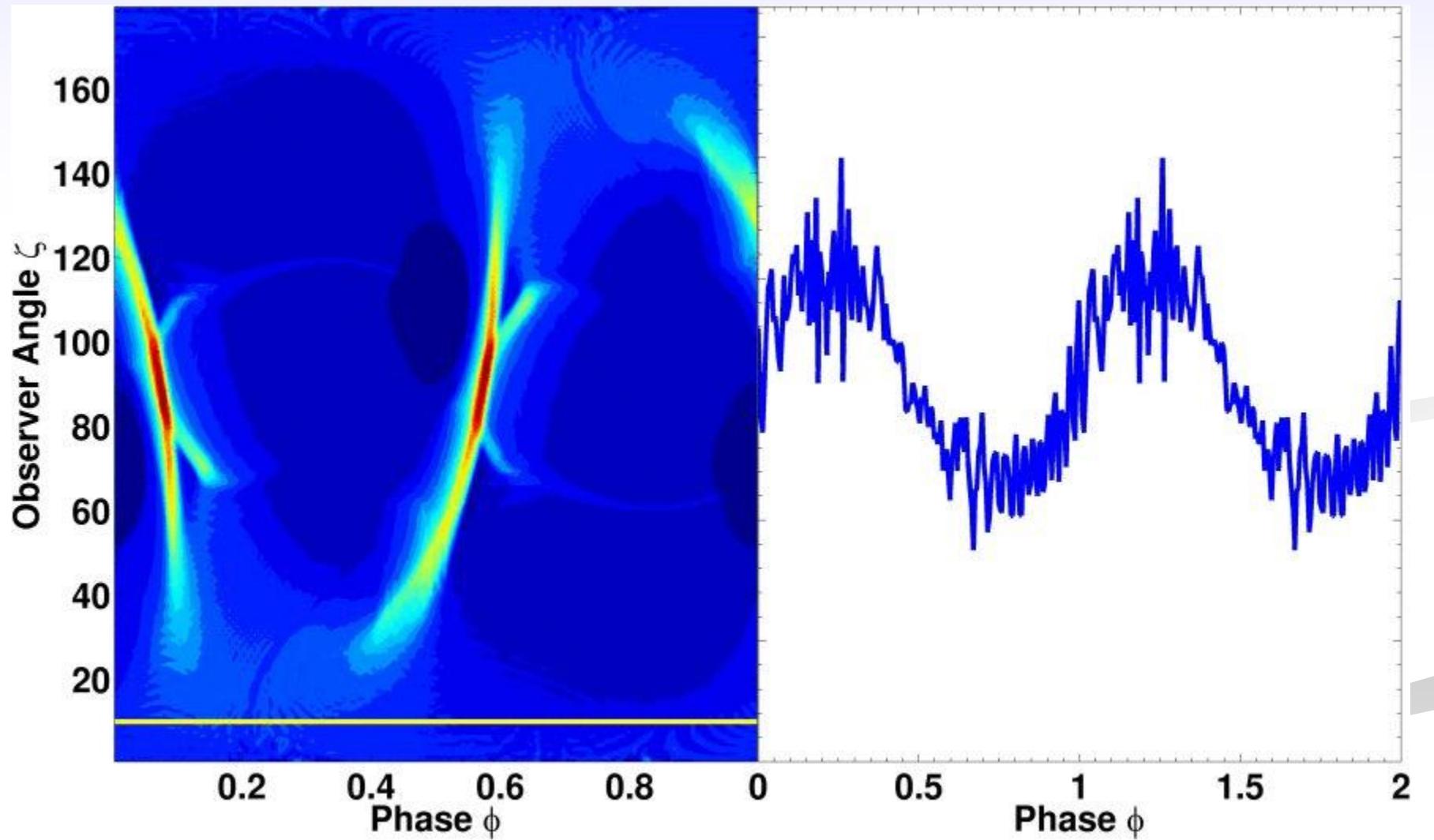
# TPC Phaseplot as Function of $\alpha$



# Light Curve Calculation



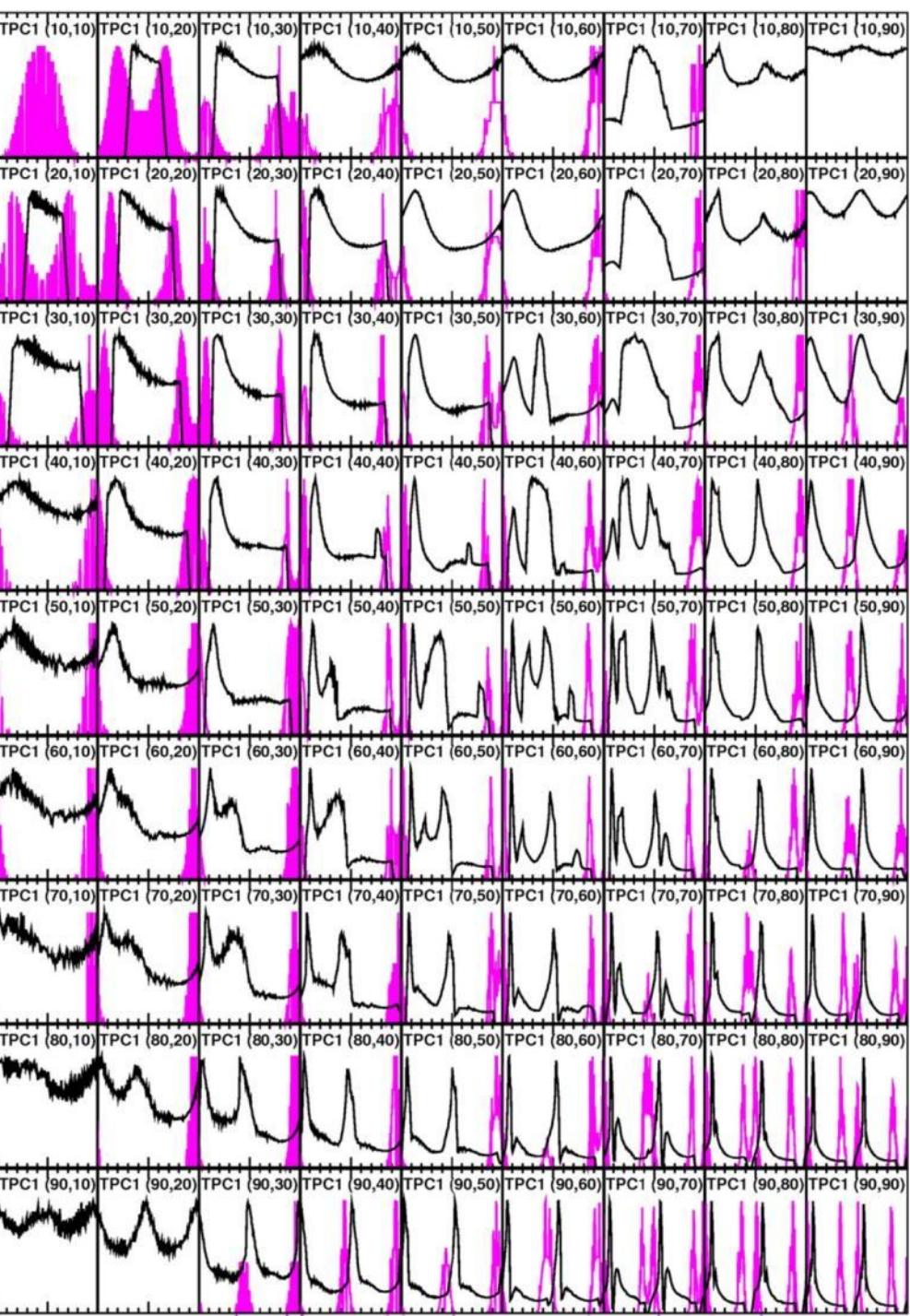
# Light Curves as Function of $\zeta$



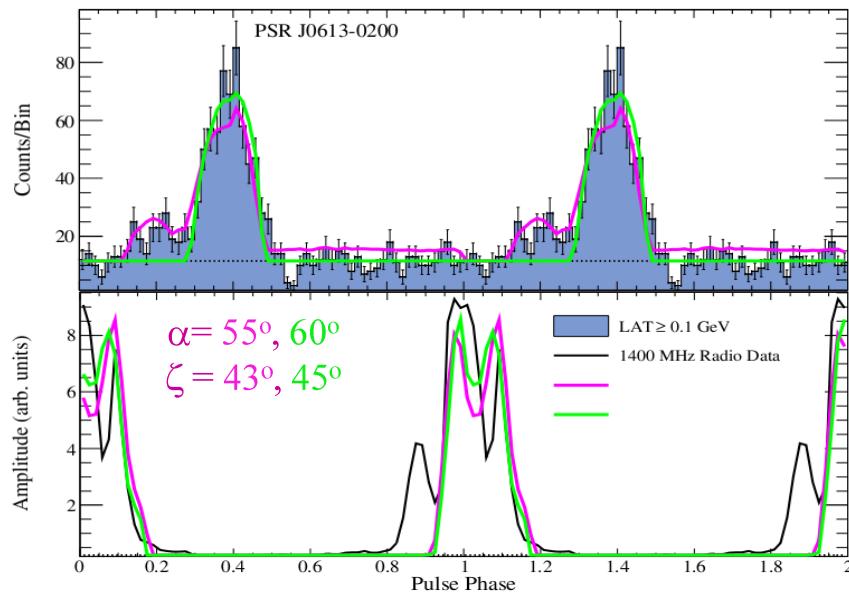
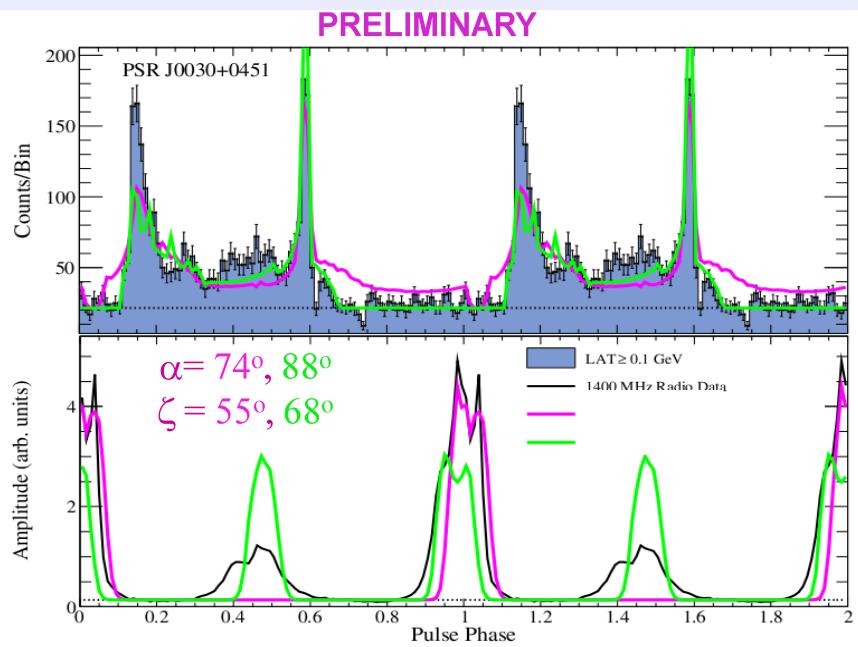
# Atlas of Light Curves $(\alpha, \zeta)$

Venter et al. (2009)

Radio  
 $\gamma$ -ray

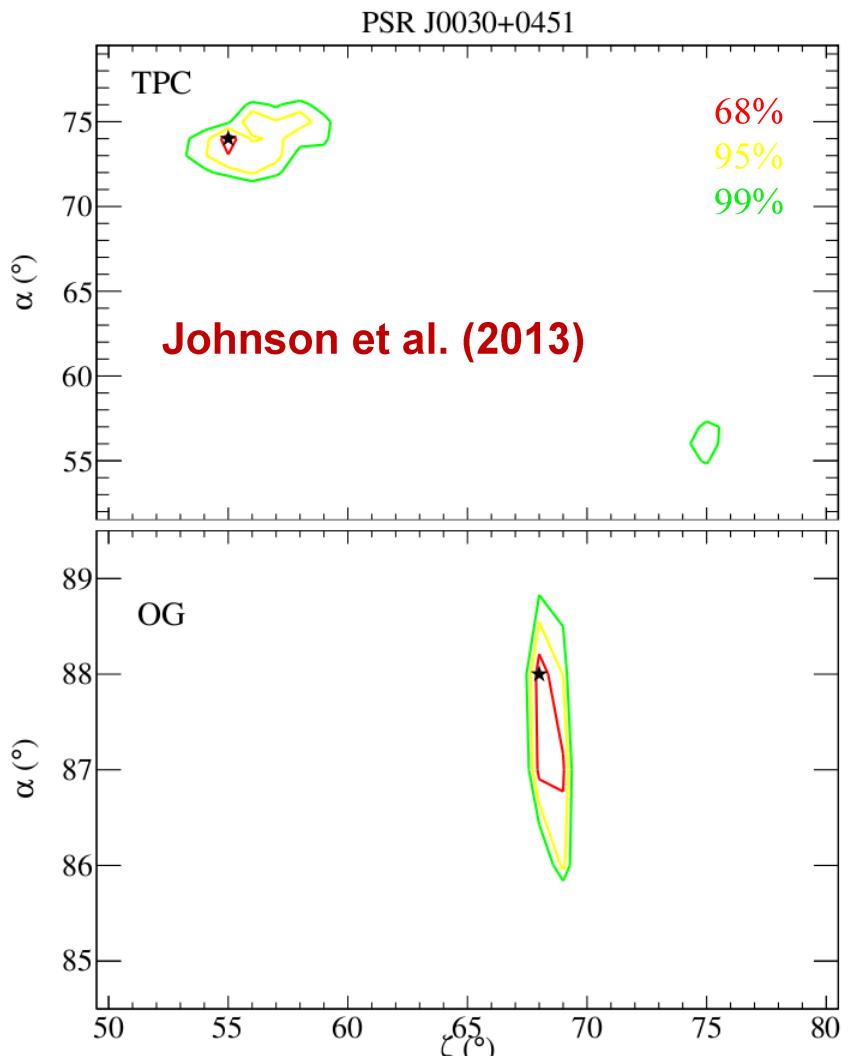


# Example Best-fit MSP Profiles



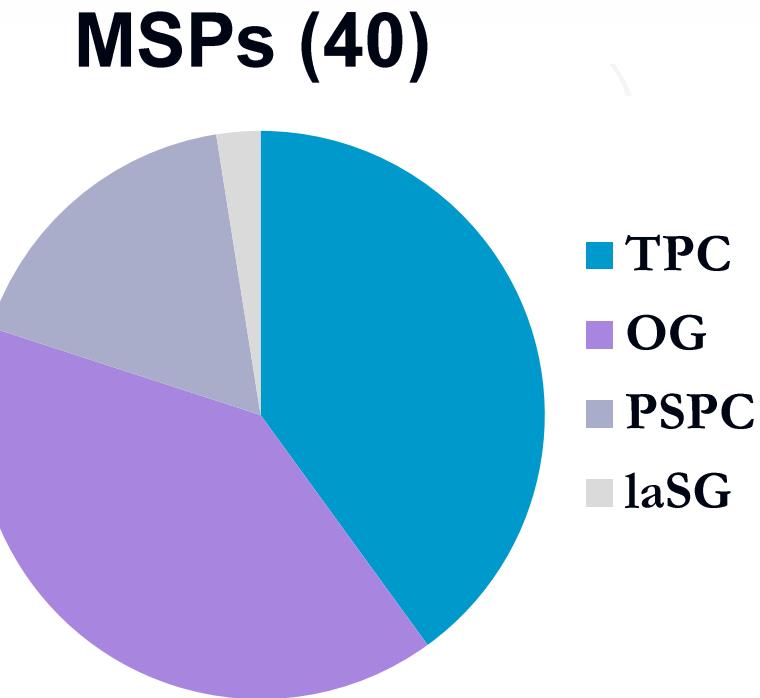
Outer gap and Two-pole caustic models

**“Class I”**



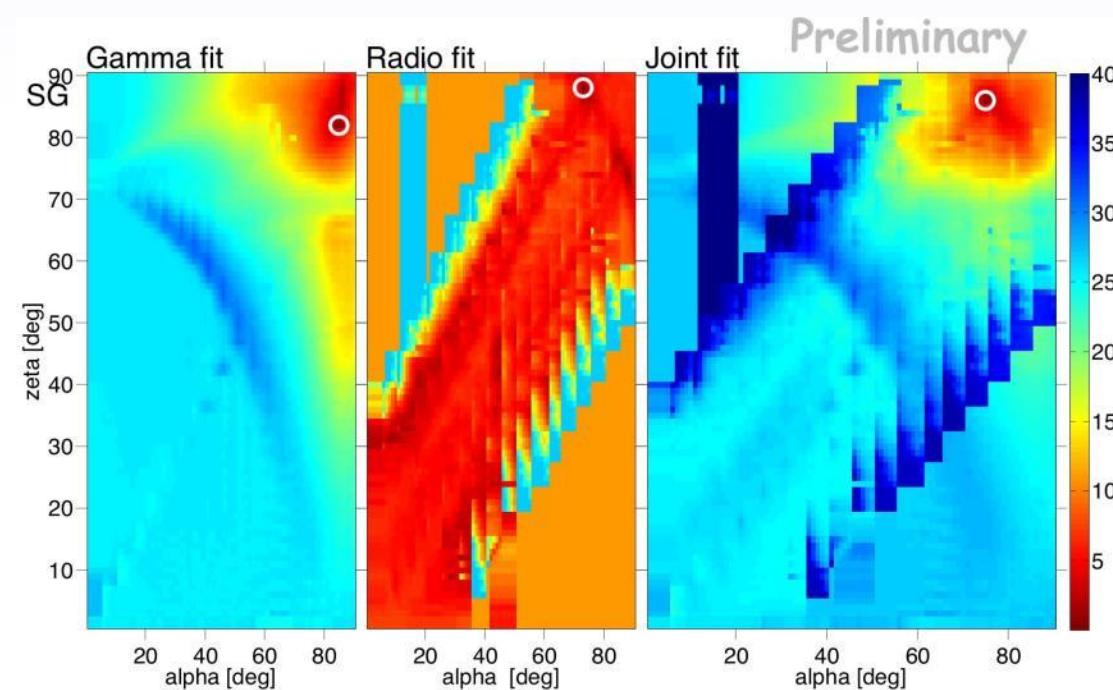
# MSPs: Geometric LC Fitting

- **$\gamma$ -ray and radio LC fits for 40 MSPs in 2PC** (Johnson et al. 2013)
  - ✓ 27 class I – best fit by TPC (15) or OG (12); need mix of these two models
  - ✓ 6 class II – best fit by aITPC (1), aIOG (4), or laSG (1)
  - ✓ 7 class III – best fit by PSPC model
- **Classes**
  - ✓ No clear separation of classes
  - ✓ Class II – low  $P$ ; Class III – low  $B_{LC}$
- **Trends**
  - ✓ Broad distribution of  $\alpha$ , larger  $\zeta$
  - ✓ Larger  $\alpha$  for OG: visibility
  - ✓ TPC: smaller  $\alpha$  for larger Edot  
(larger  $|\beta|$ )
  - ✓ Class II emission altitudes: Radio more limited, higher up, contained within  $\gamma$ -ray region (within errors)
  - ✓ Clustering around  $\eta = 10\%$ ;  
 $L_g \sim \text{Edot}$ ;  $f_\Omega < 1$  for TPC / OG

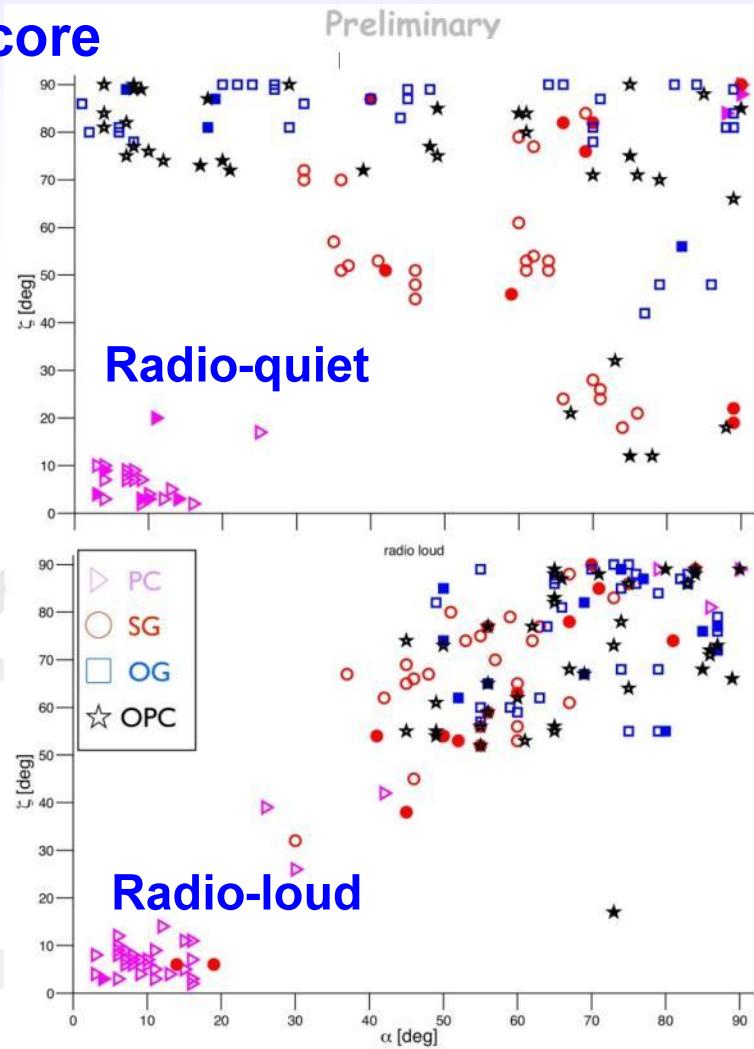


# Young Pulsars: Geometric LC Fits

- 78 young pulsars from 2PC (36 RQ + 40 RL)
- $\gamma$ -ray: PC, SG, OG, 1PC; Radio: cone + core
- Joint fits

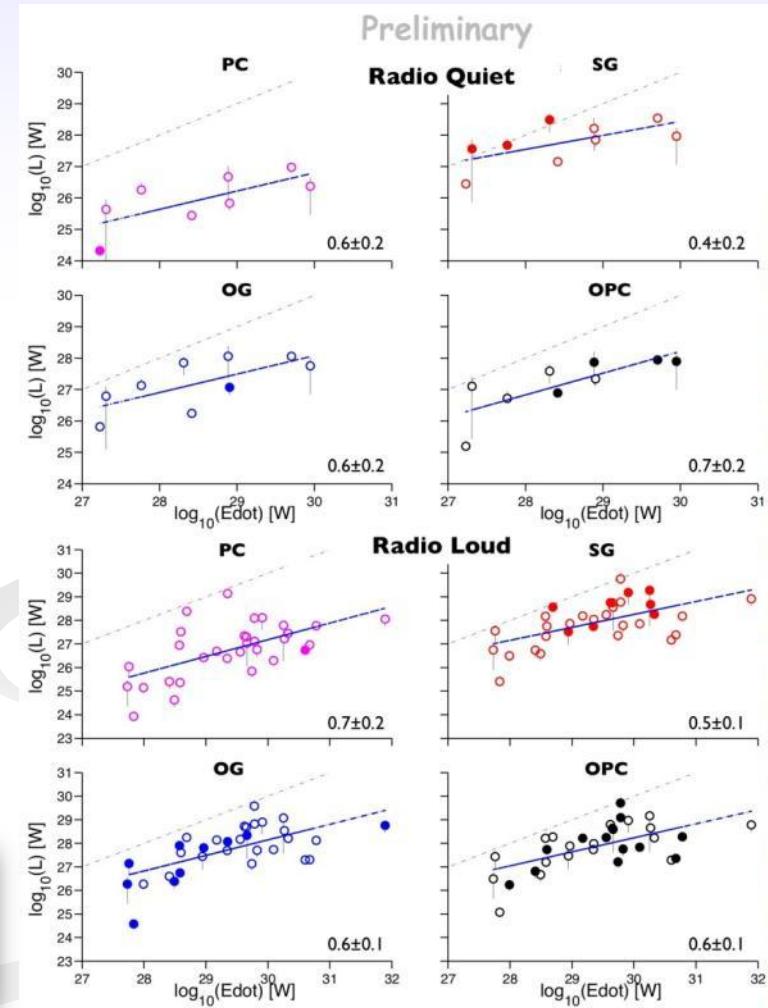
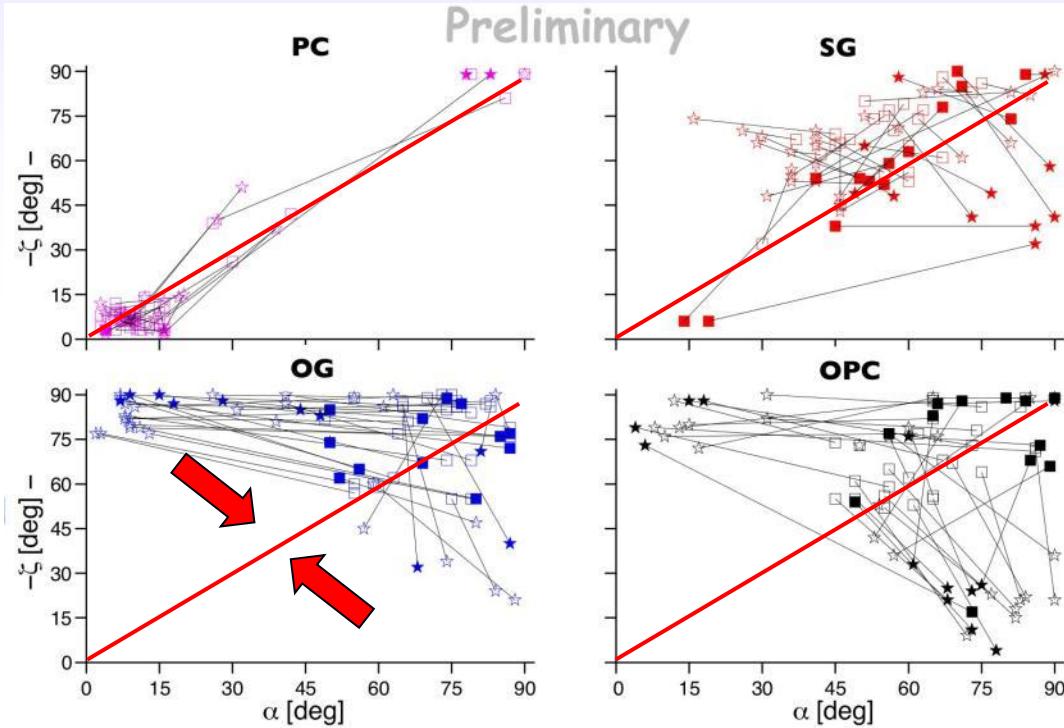


- PC: low  $\alpha$  and  $\zeta$
- Outer-magnetosphere: high  $\alpha$  and  $\zeta$



# Young Pulsars: Geometric LC Fits

- $\gamma$ -ray only vs.  $\gamma$ -ray + radio LC fits: Underestimation of  $\alpha$  and  $\zeta$



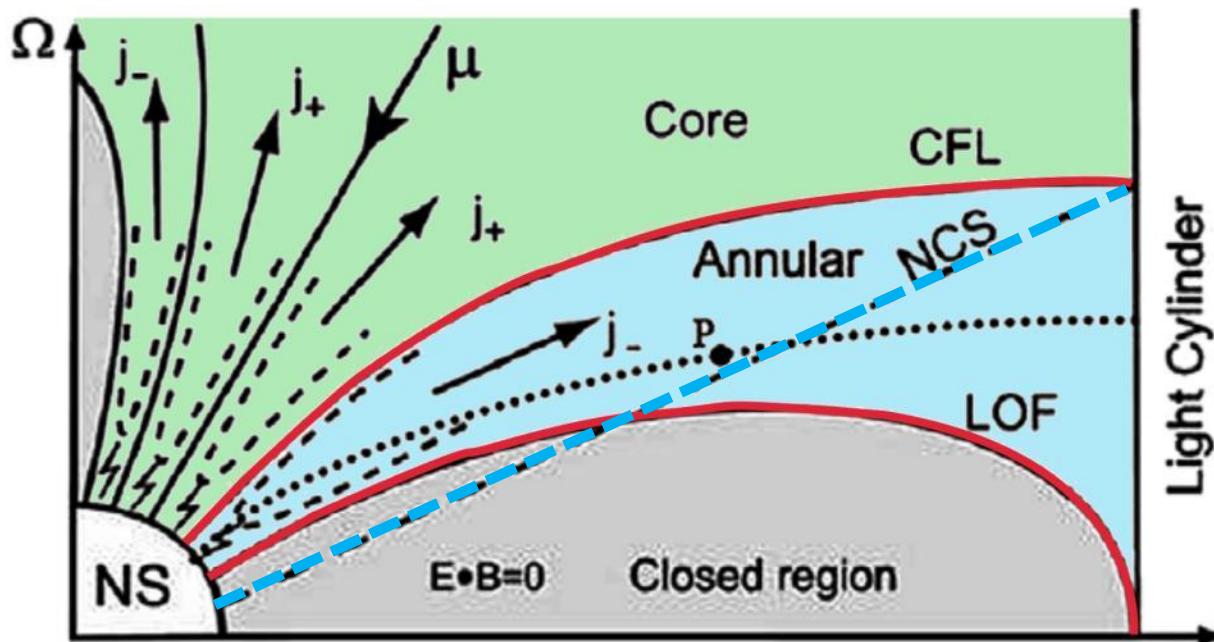
- $f_\Omega$  values:  
PC low; SG ~ 1; OG ~ 0.5 – 0.8; OPC ~ 0.8 – 0.9

$$f_\Omega = \frac{\int_0^\pi \sin \zeta d\zeta \int_0^{2\pi} n(\phi, \zeta) d\phi}{2 \int_0^{2\pi} n(\zeta_{\text{obs}}, \phi) d\phi}$$

- $L_\gamma \sim Edot^{0.5}$

- PC : SG : OG = 16% : 39% : 45% - need some “hybrid” geometry

# Annular Gap Geometry

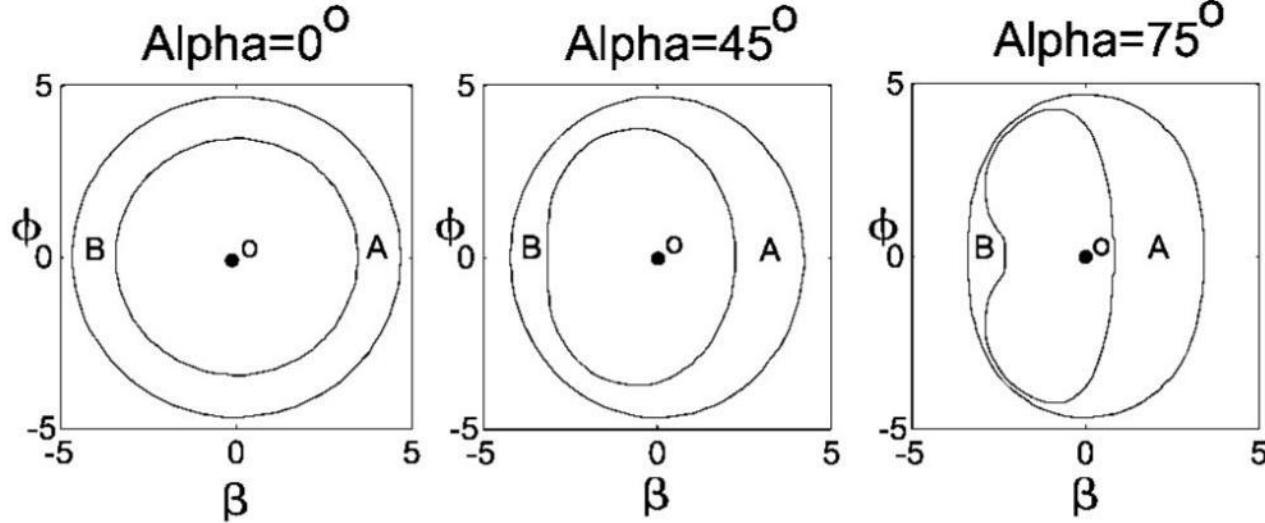


Gaussians for emissivity in longitudinal (peaking close to NCS) and transverse directions

Intermediate-altitude, single-pole model

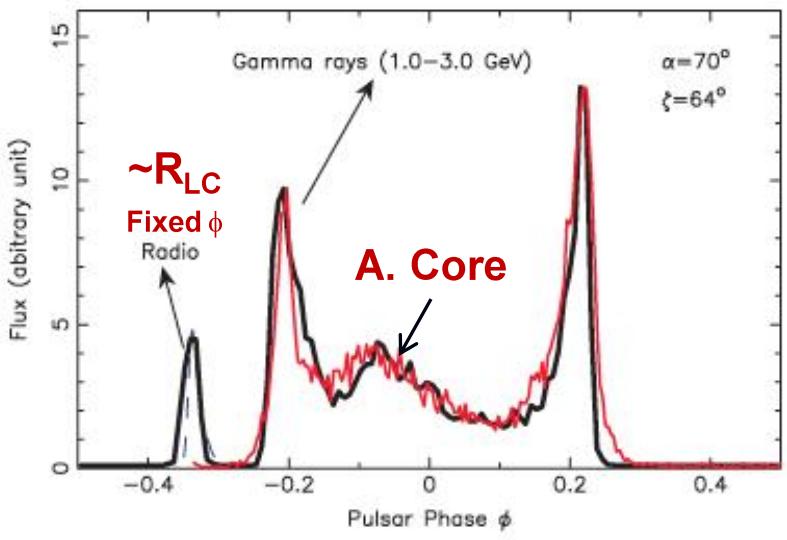
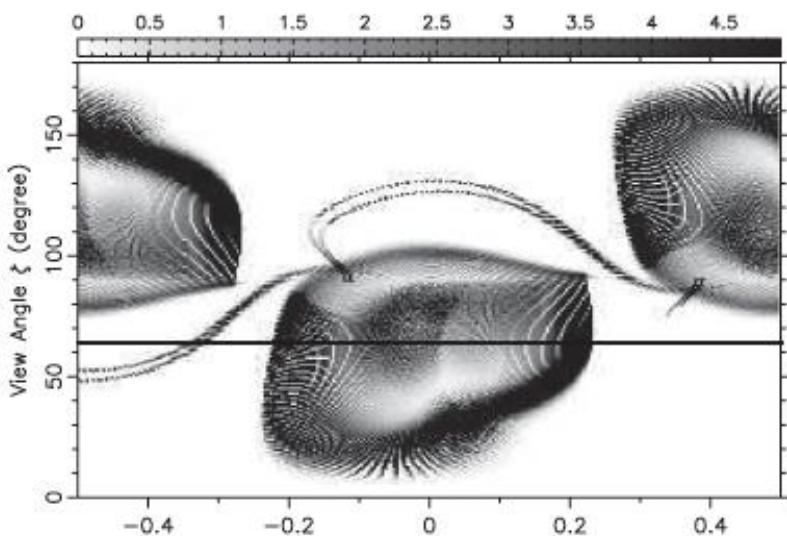
Qiao et al. (2004, 2007)  
Du et al. (2010)

(Striped wind: see talk by Pétri)

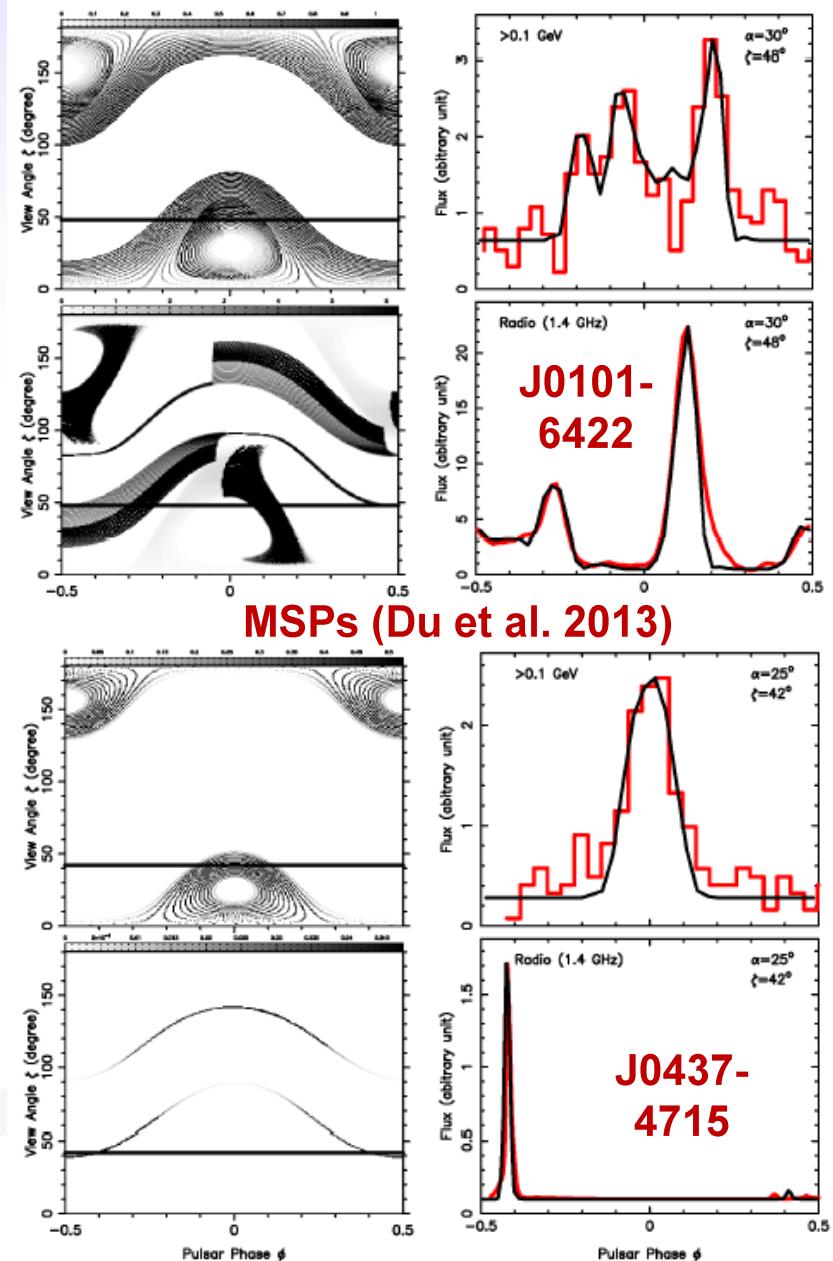


# Annular Gap Model LC Fits

Core + annular gap  
(altitude-dependent)



Vela (Du et al. 2011)

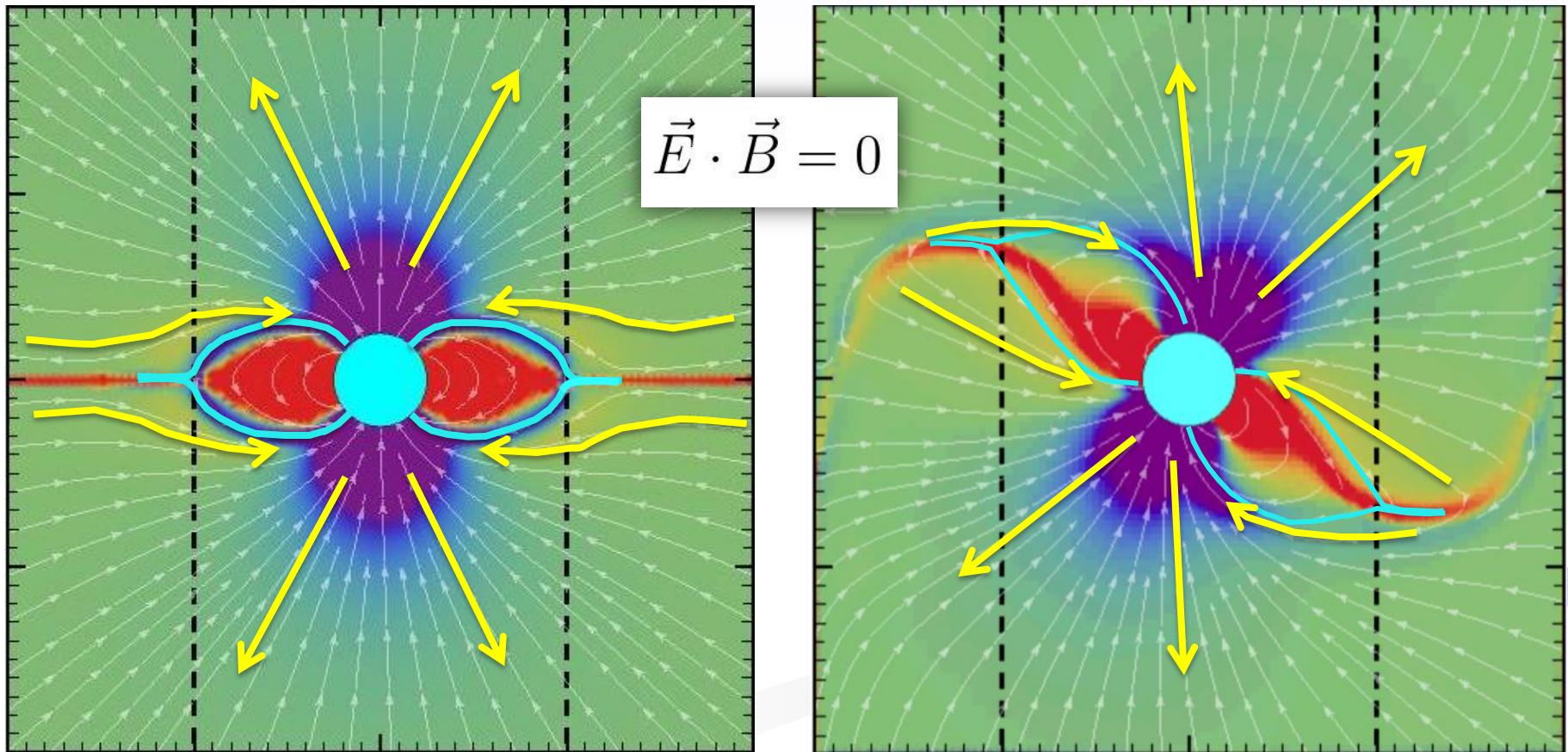


# **Global magnetospheres: Force-free solutions**

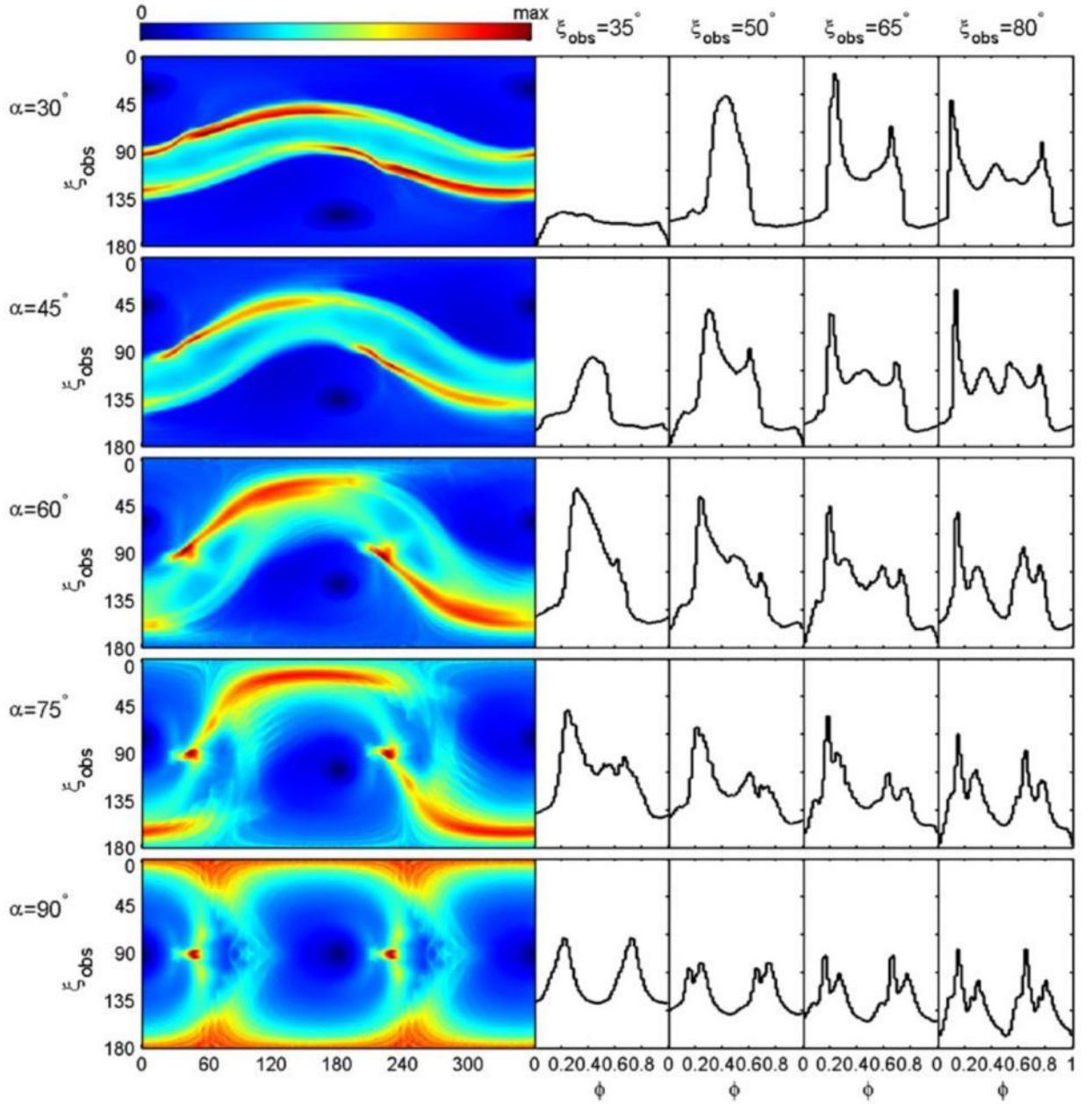
# Force-Free Magnetic Field Solutions

- Contain open and closed field regions (blue lines)
- Contain different signs of charge
- Global current flows out of polar regions and returns along equatorial current sheet (yellow arrows)

Contopoulos et al. (1999)  
Spitkovsky (2006)  
Timokhin (2006)



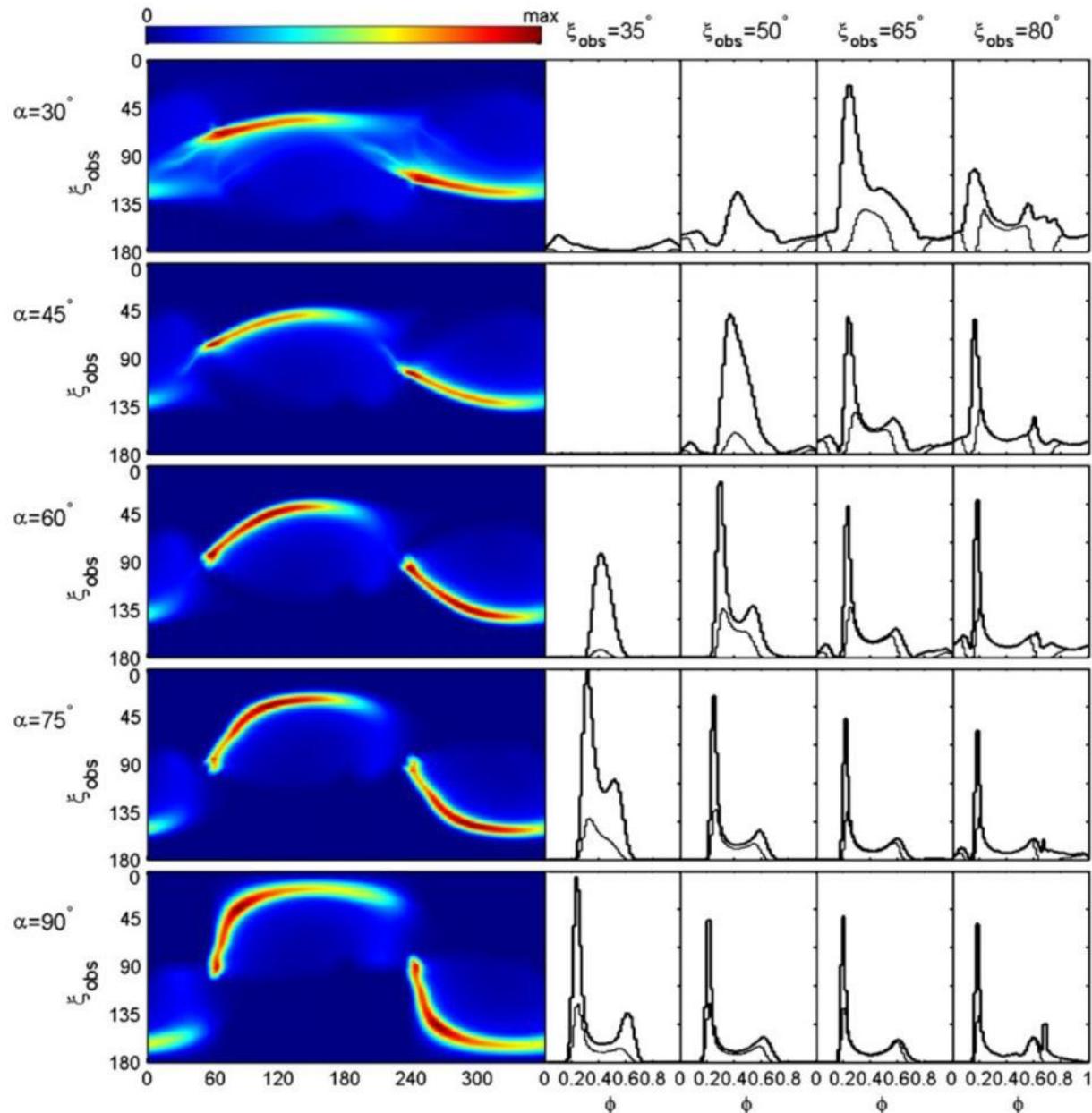
# LCs in TPC / Force-Free Magnetic Field



- PC larger than in vacuum retarded dipole
- Suppresses caustic formation in inner magnetosphere
- Not many double-peak profiles

Bai & Spitkovsky (2010)

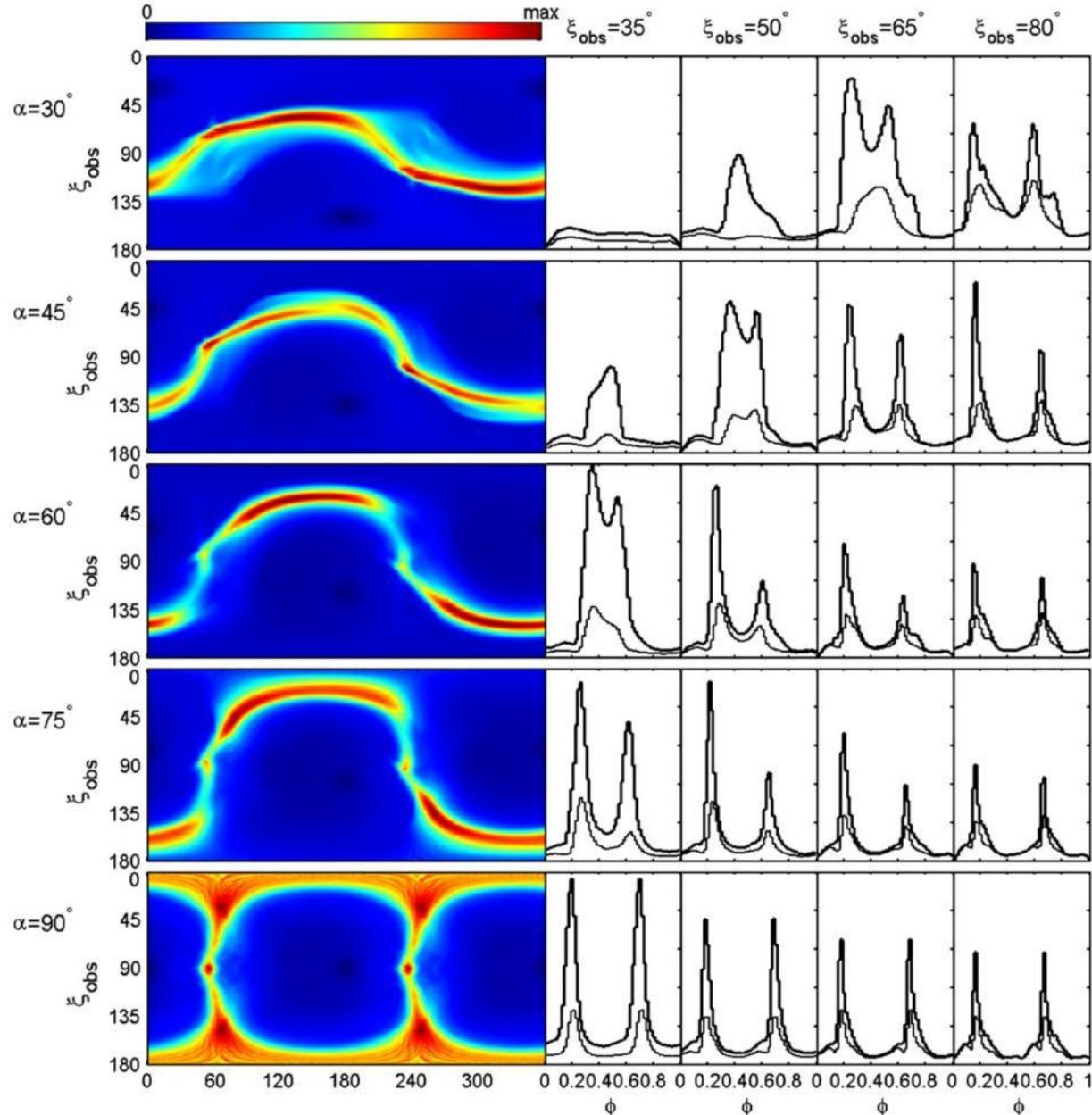
# LCs in OG / Force-Free Magnetic Field



- A large fraction of open field lines does not cross the null charge surface
- Only single-peaked profiles produced under general conditions

Bai & Spitkovsky (2010)

# LCs in SL / Force-Free Magnetic Field



- Separatrix layer model:  $\gamma$ -ray emission originates on thin layer on open field lines just inside separatrix (current sheet) that bounds open flux tube

- Two strong caustics due to “sky map stagnation” (since force-free solution asymptotically approaches split monopole)

Bai & Spitkovsky (2010)

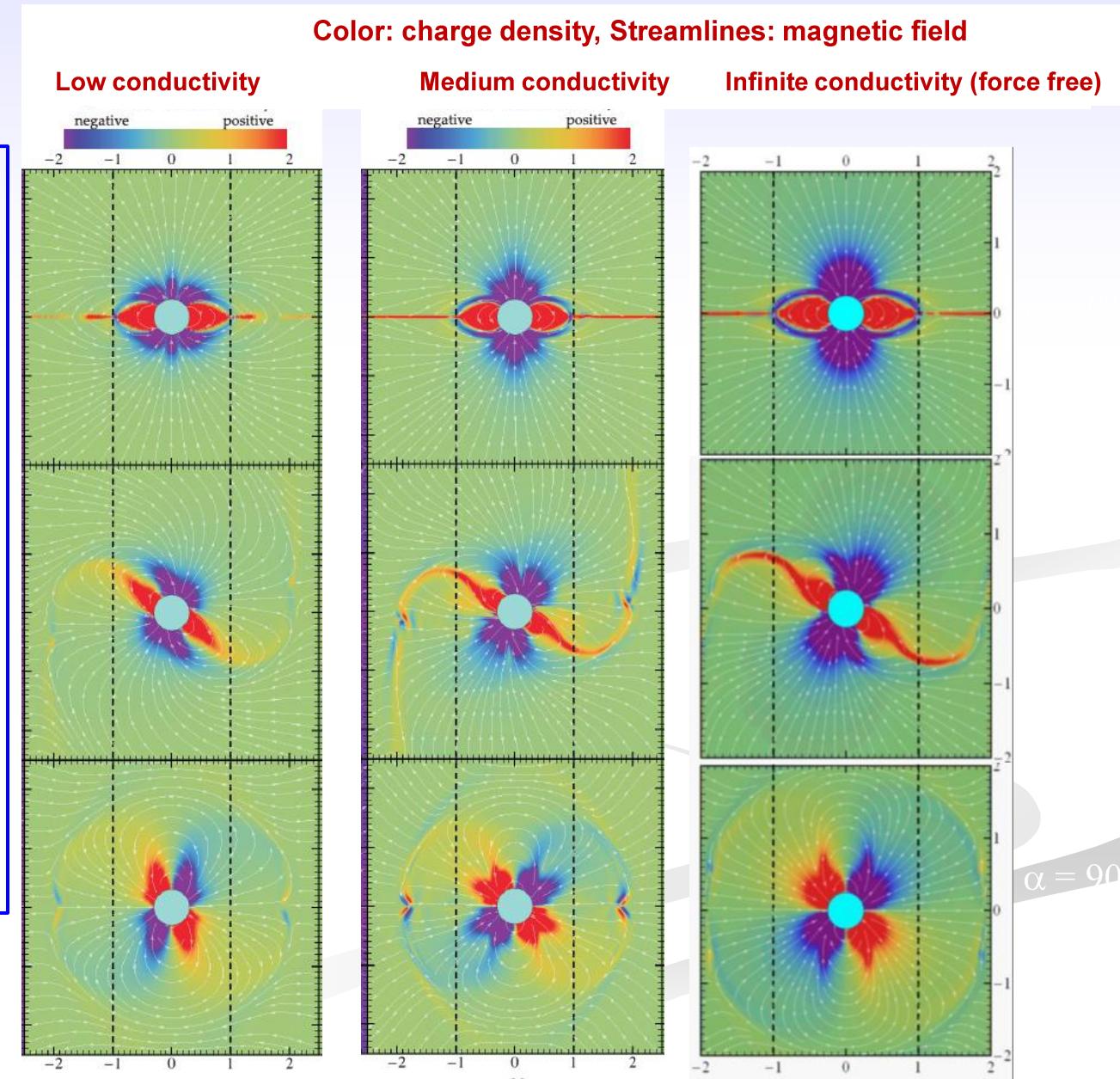
# Global magnetospheres: Dissipative solutions



# Magnetospheres with Finite Conductivity

As conductivity increases:

- Charge and current density increase
  - Current sheet becomes stronger
  - Field lines become straighter
  - Spin-down power increases

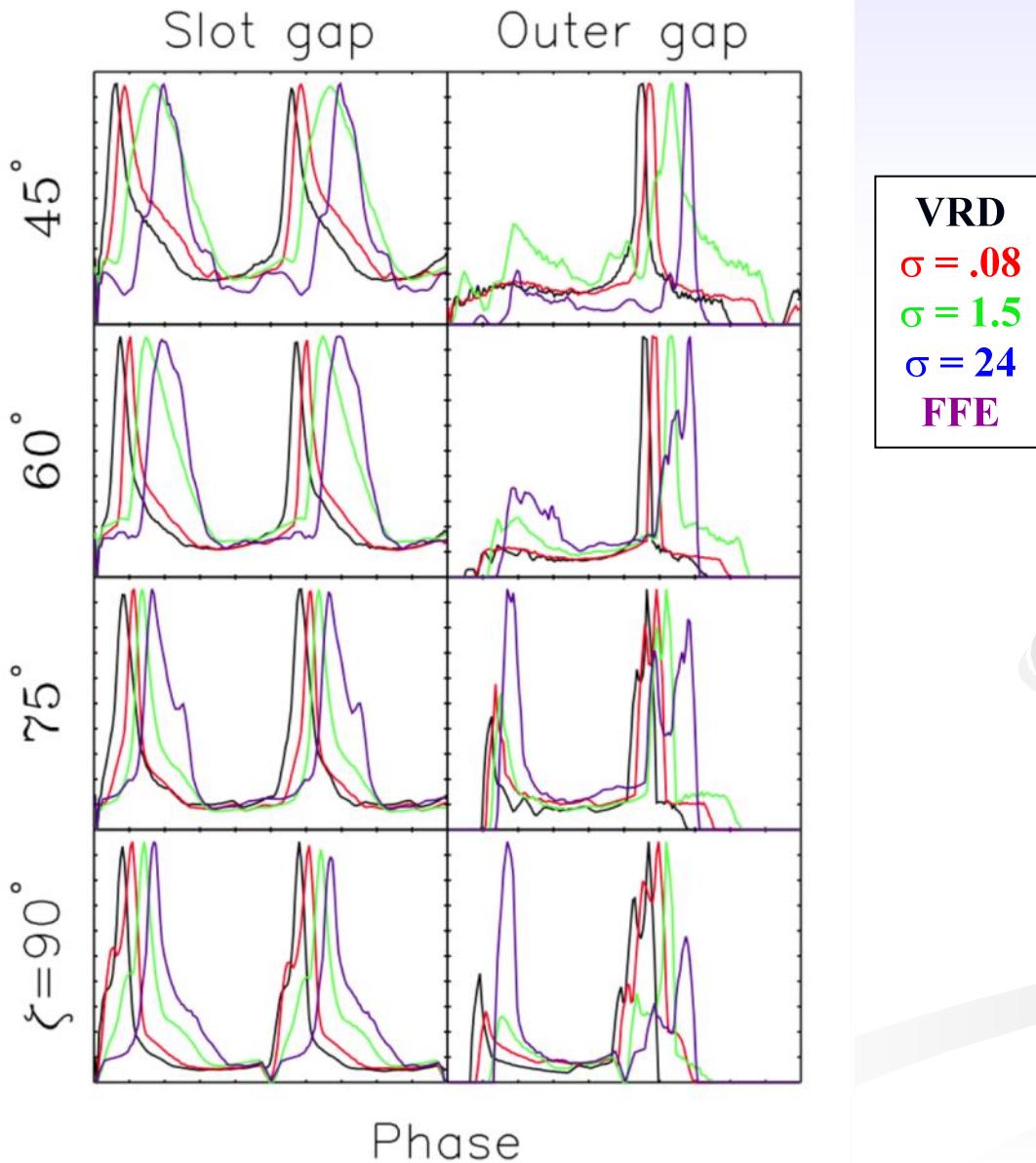


Kalapotharakos, Kazanas,  
Harding & Contopoulos  
(2012)

# LCs from Resistive Magnetospheres

$$\alpha = 90^\circ$$

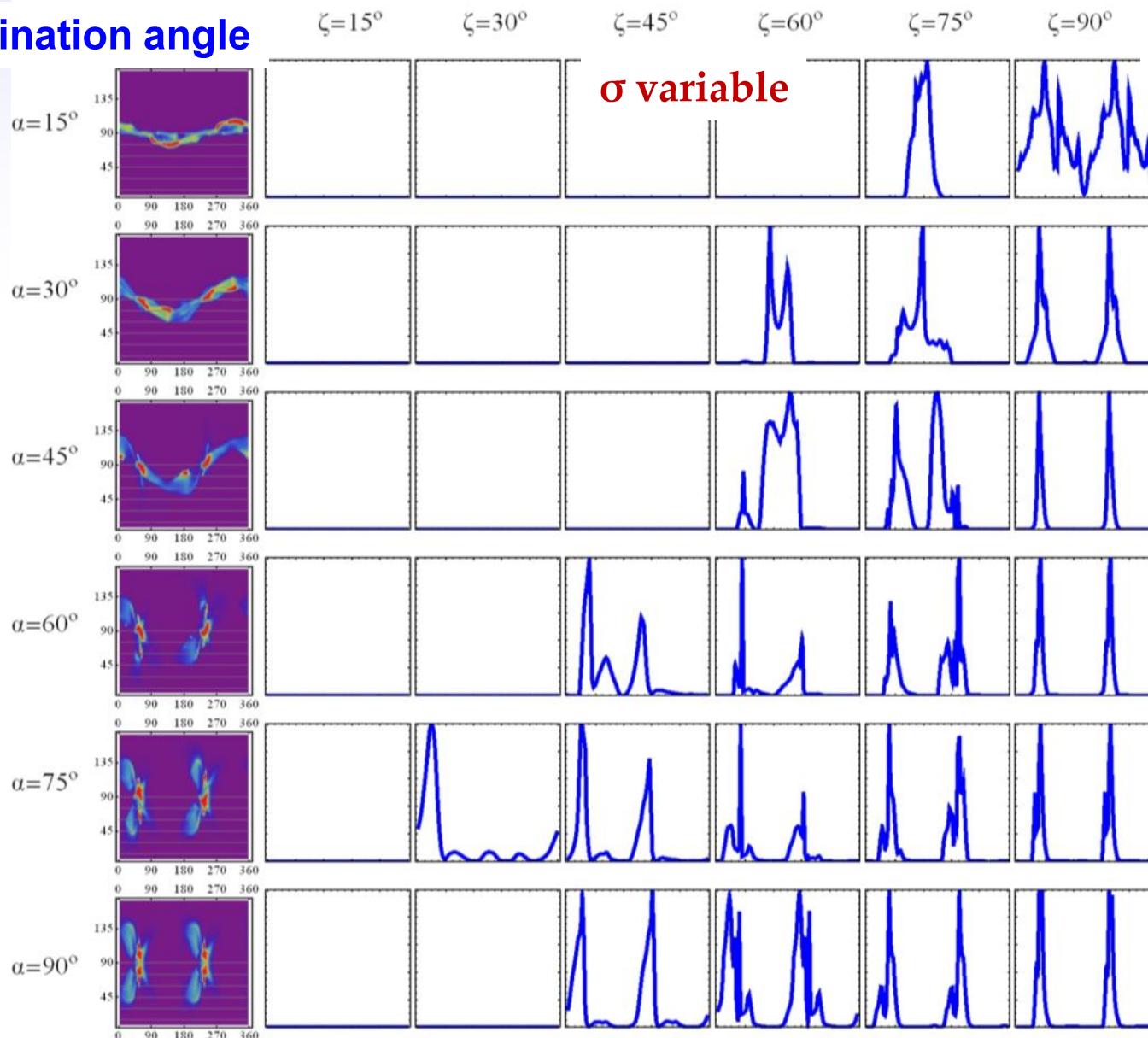
Kalapotharakos et al. (2012)



- The resistive solutions of lowest  $\sigma$  are closest to the VRD
- Distinct progression in LC shapes as  $\sigma$  increases
- Increasing  $\sigma$ : the peaks are shifted to larger phase; broadening
- Highest  $\sigma$  – value closest to FF case

# LCs from Dissipative Magnetospheres

$\alpha$ : inclination angle



$\sigma$  variable

$\zeta$ : observer angle

$E_{\parallel} = 0$  below  
 $r = 0.9 R_{LC}$

Most emission  
from current  
sheet near light  
cylinder

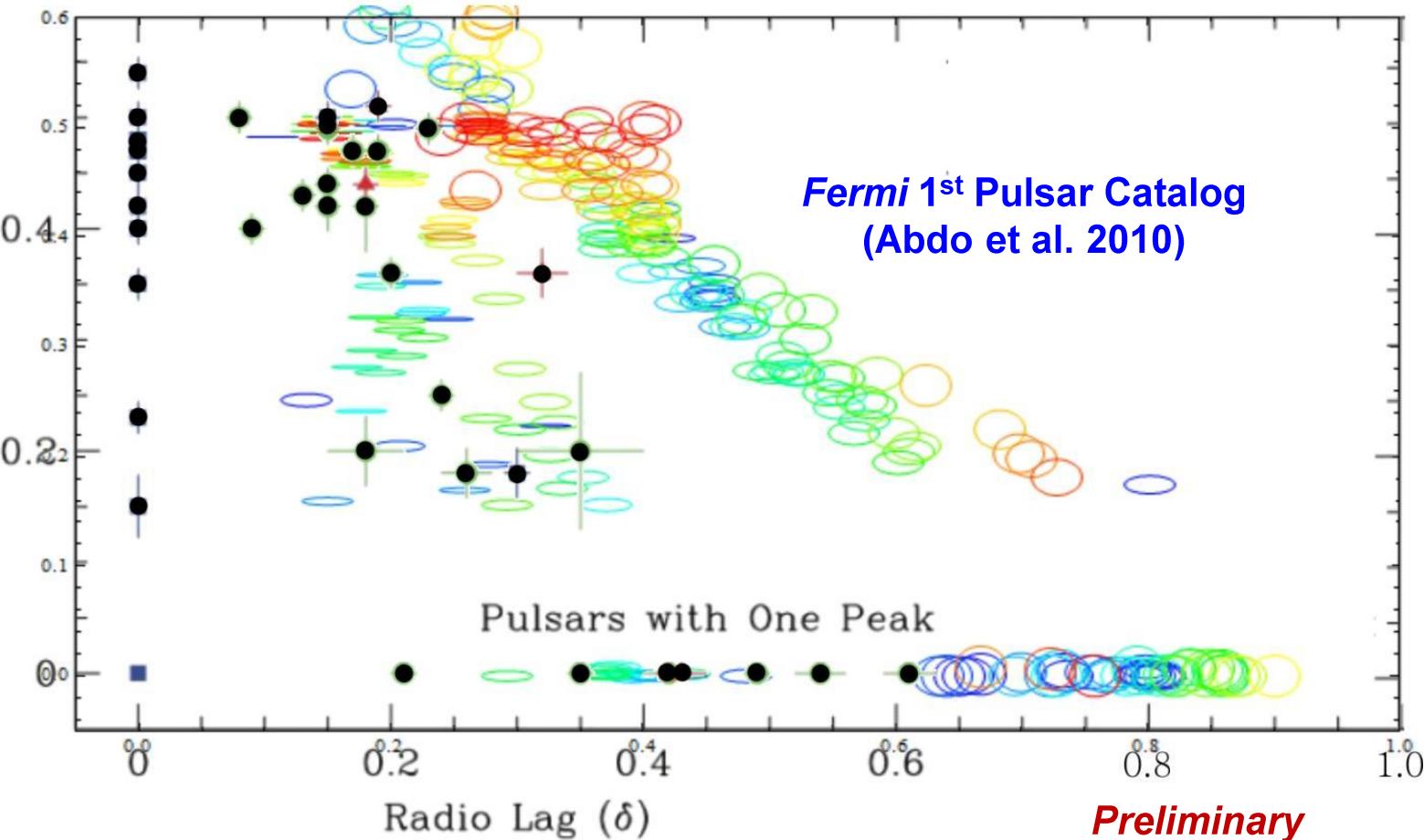
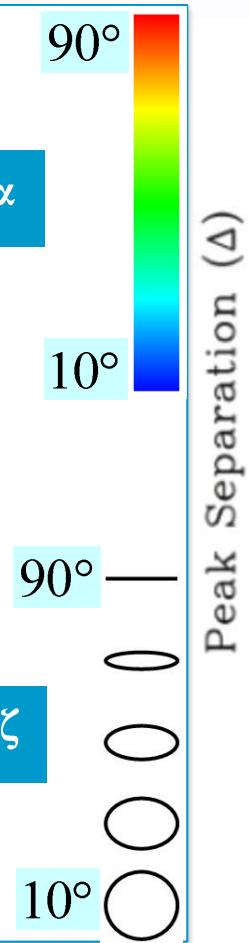
Kalapotharakos  
et al. (2013)

# $\Delta$ - $\delta$ Trend Revisited

Force-free

Kalapotharakos et al. (2013)

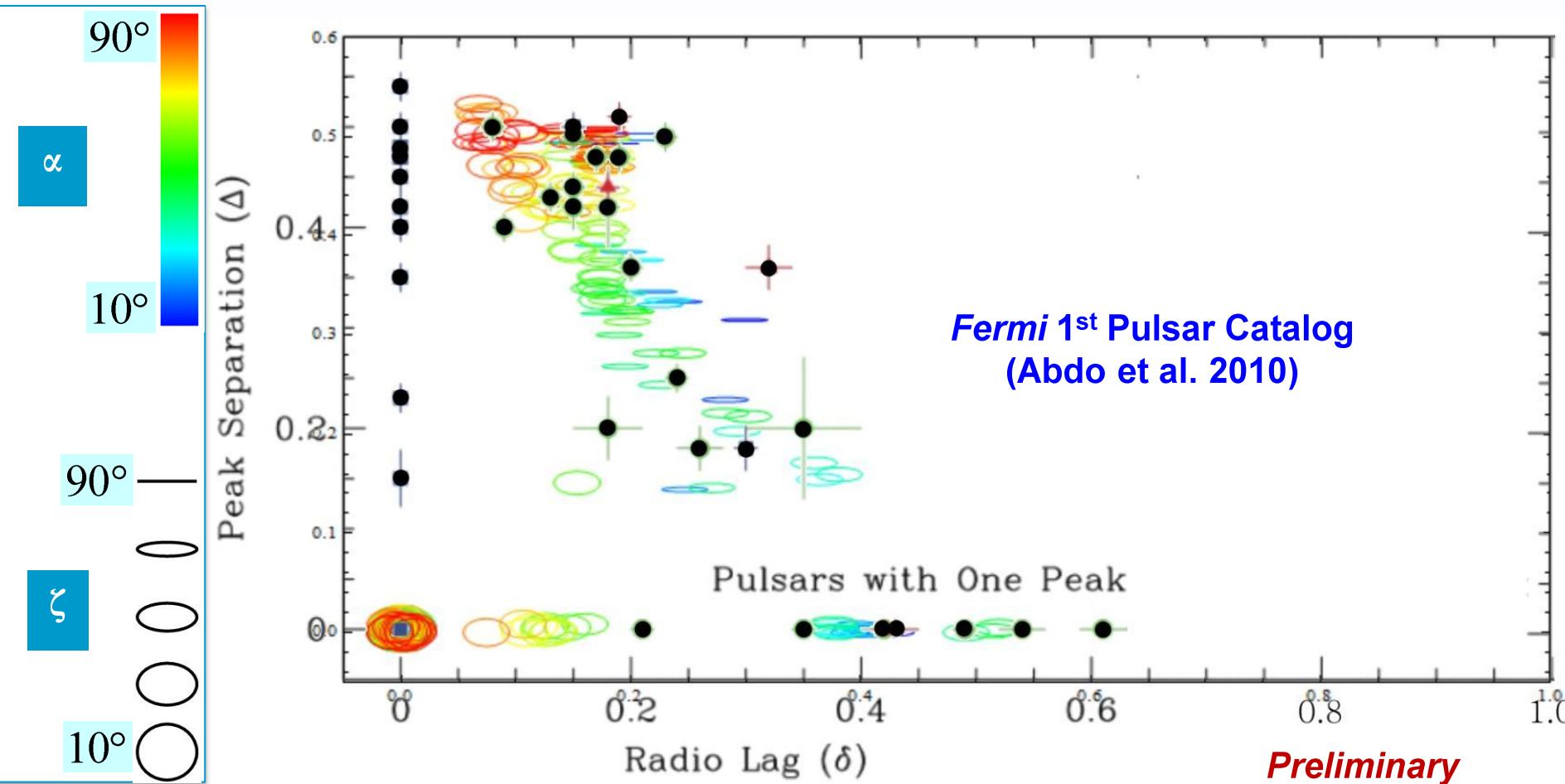
Fermi 1<sup>st</sup> Pulsar Catalog  
(Abdo et al. 2010)



# $\Delta$ - $\delta$ Trend Revisited

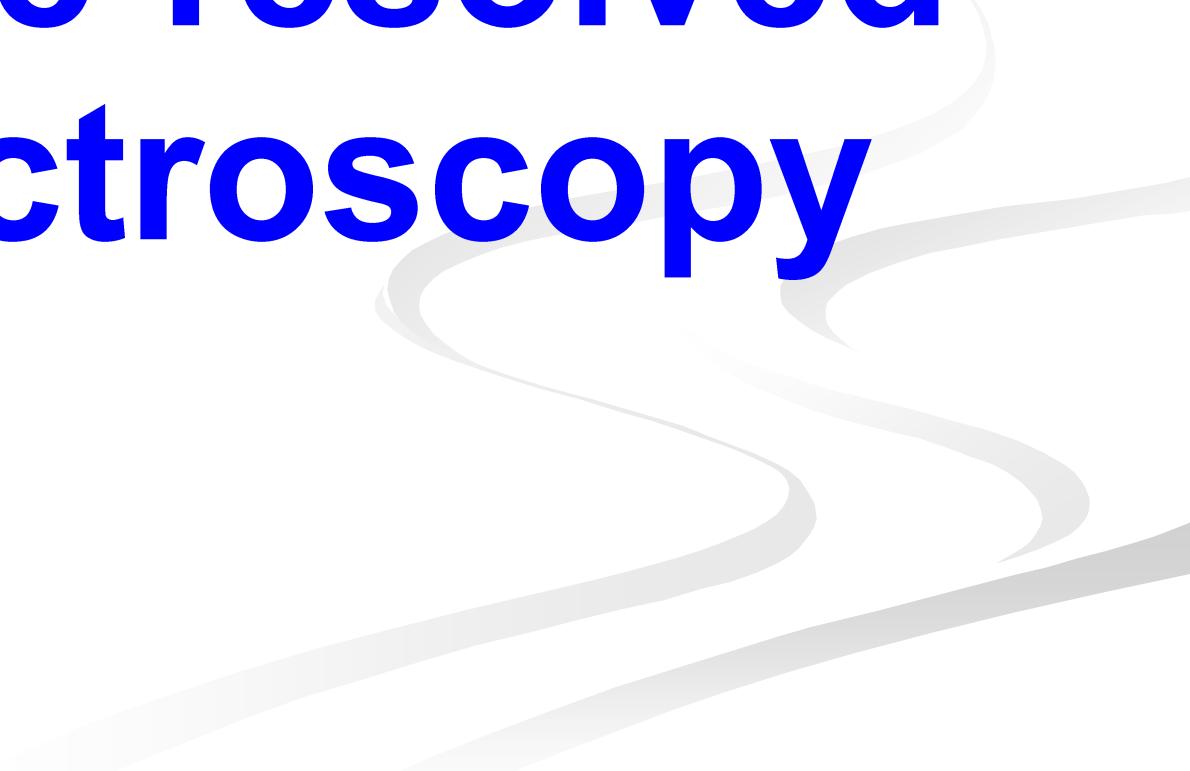
$r < 0.9 R_{LC}$ : force-free  
 $r > 0.9 R_{LC}$ : finite, high  $\sigma$

Kalapotharakos et al. (2013)



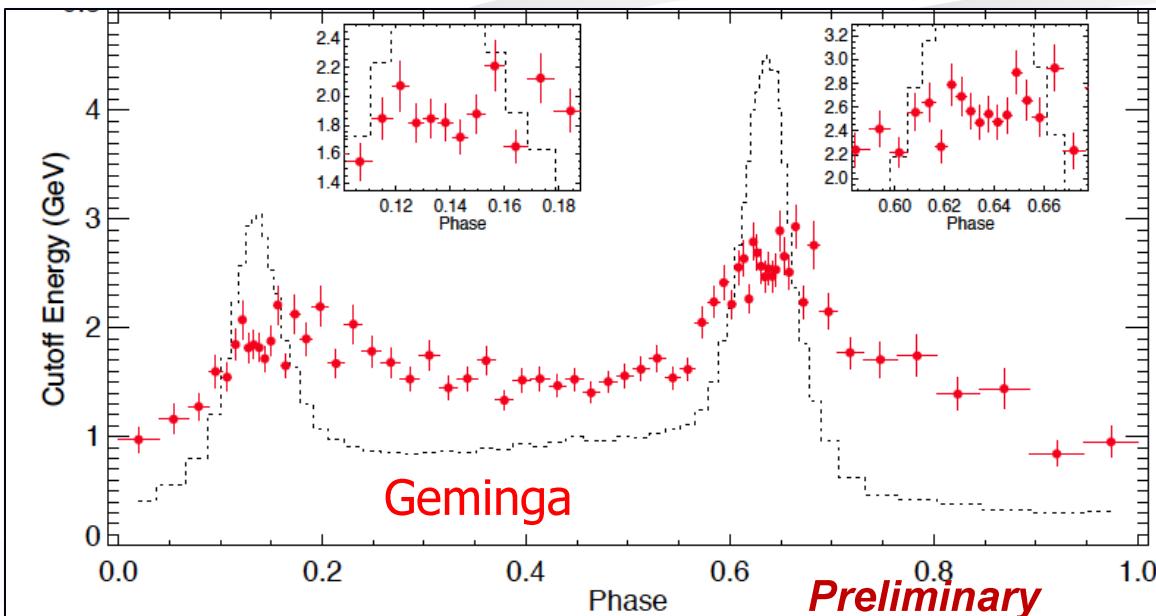
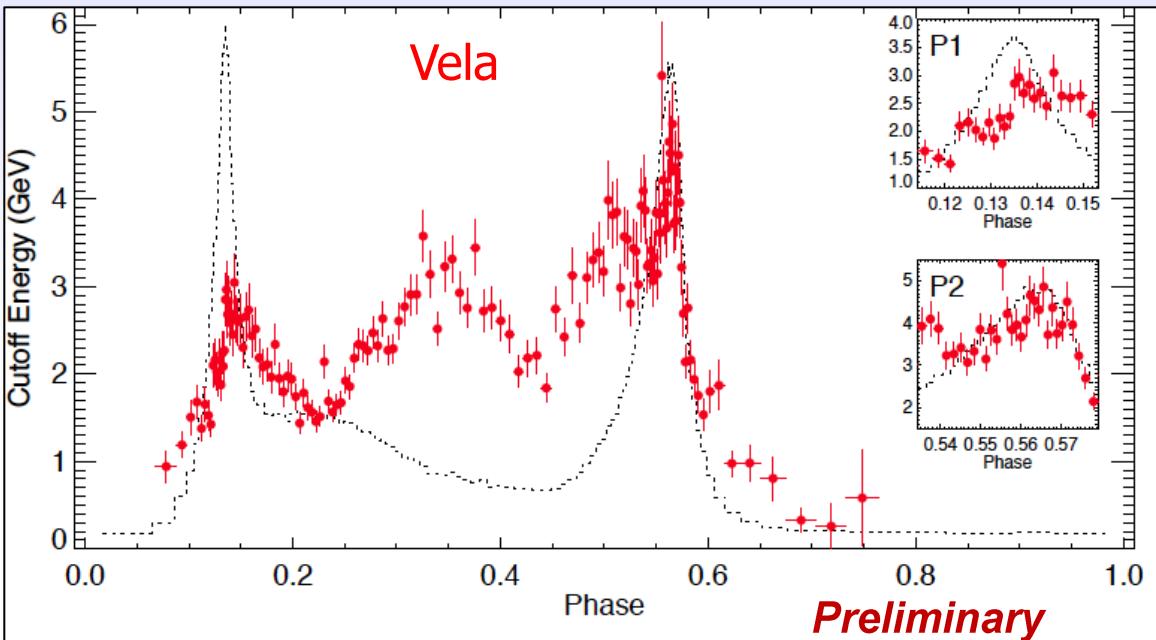
Preliminary

# Phase-resolved Spectroscopy



# Phase-resolved Spectroscopy

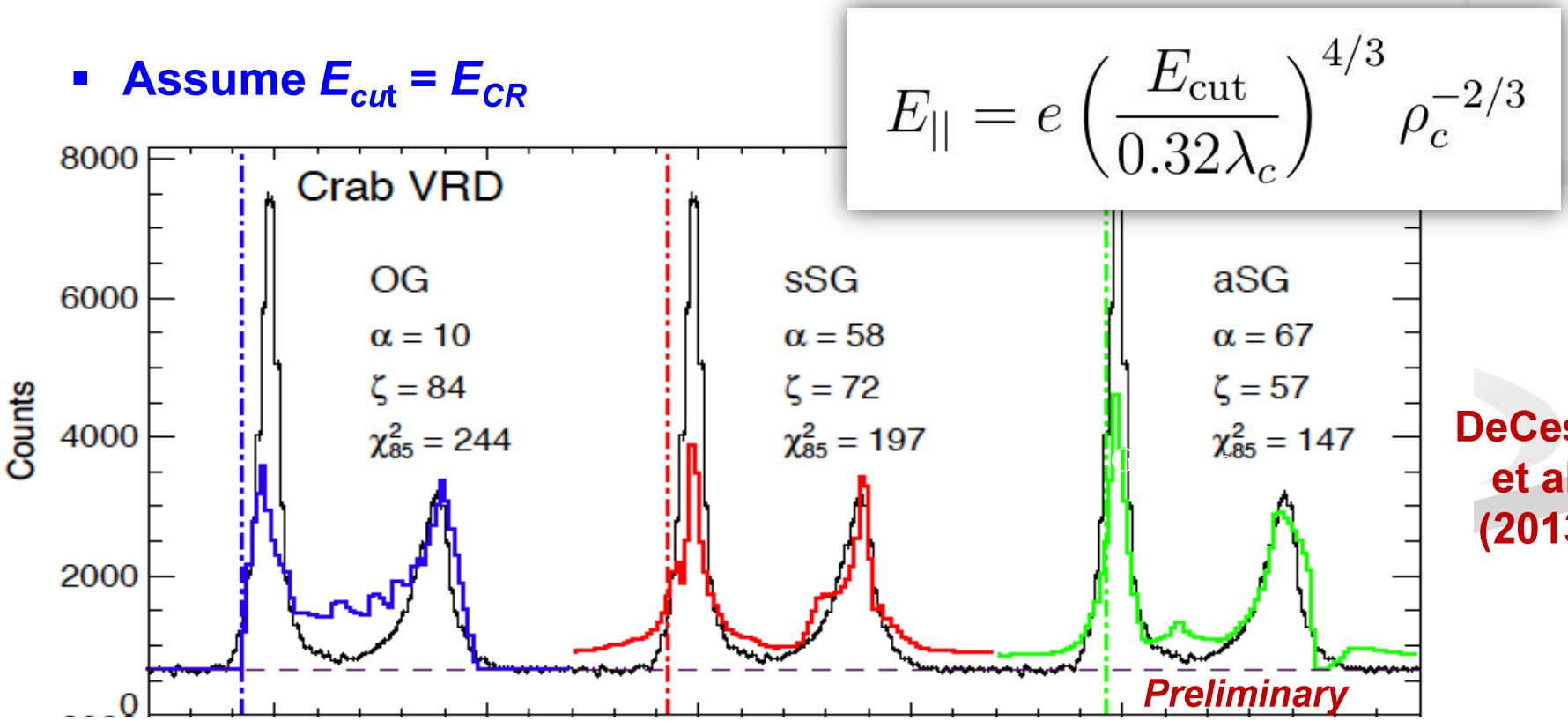
- Vela & Crab: peaks softer than bridge
- P2 has higher  $E_{cut}$  than P1
- “Dipping” behaviour of  $E_{cut}$  in Geminga’s peaks, P1 of Crab; rising of  $E_{cut}$  in Vela’s peaks
- Reflecting local changes in  $B$ ,  $\rho_c$  or  $E_{||}$ ?



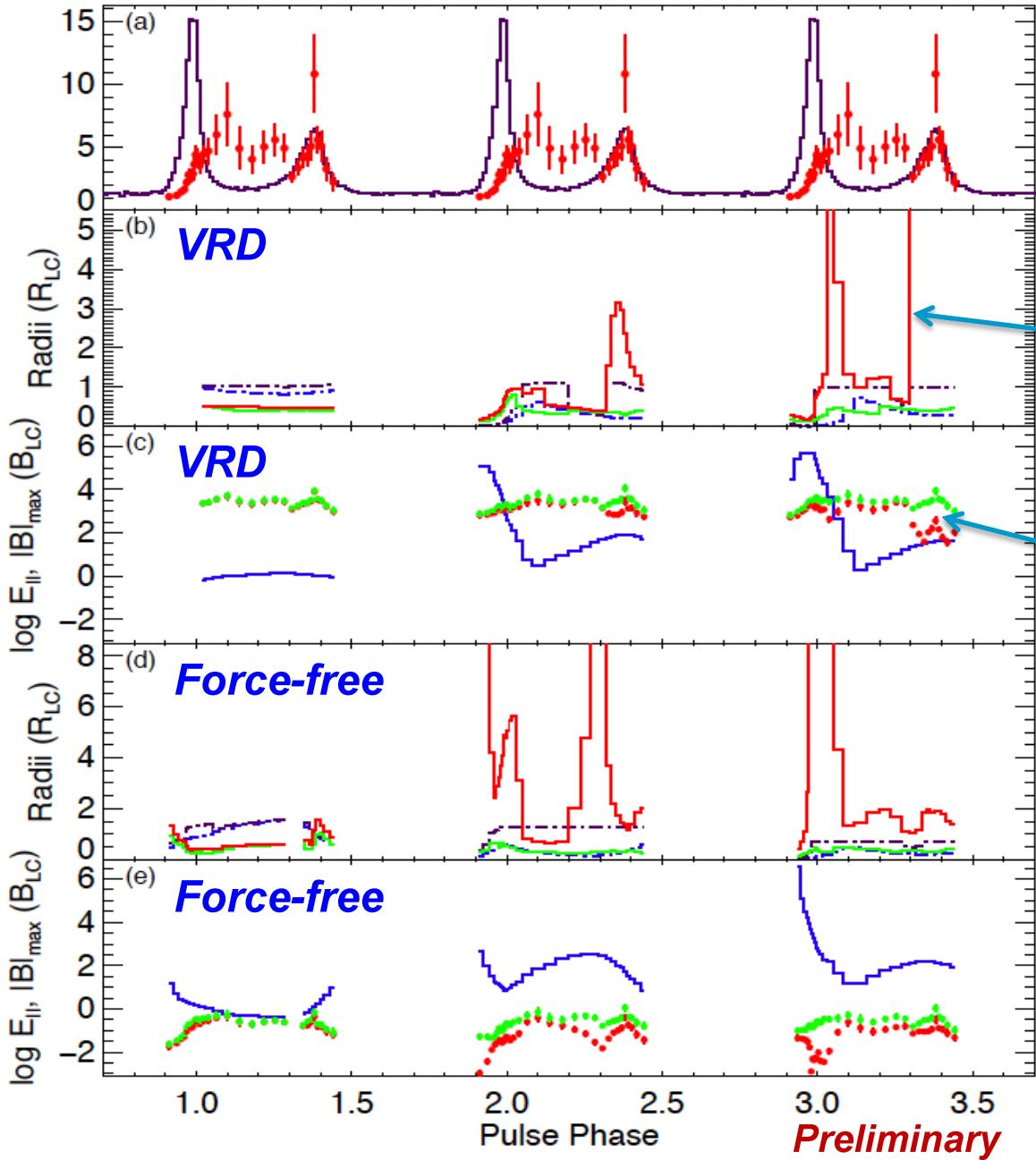
# Phase-resolved Spectroscopy

Does  $E_{cut}$  variation map magnetic field curvature vs. phase?

- Find  $E_{cut}(\phi)$  from phase-resolved spectroscopy
- Find  $\rho_c(\phi)$  from LC fitting (force-free and VRD  $B$ -fields)
- Assume balance of acceleration and radiation losses
- Assume  $E_{cut} = E_{CR}$



# Crab: Constraining $E_{\parallel}$

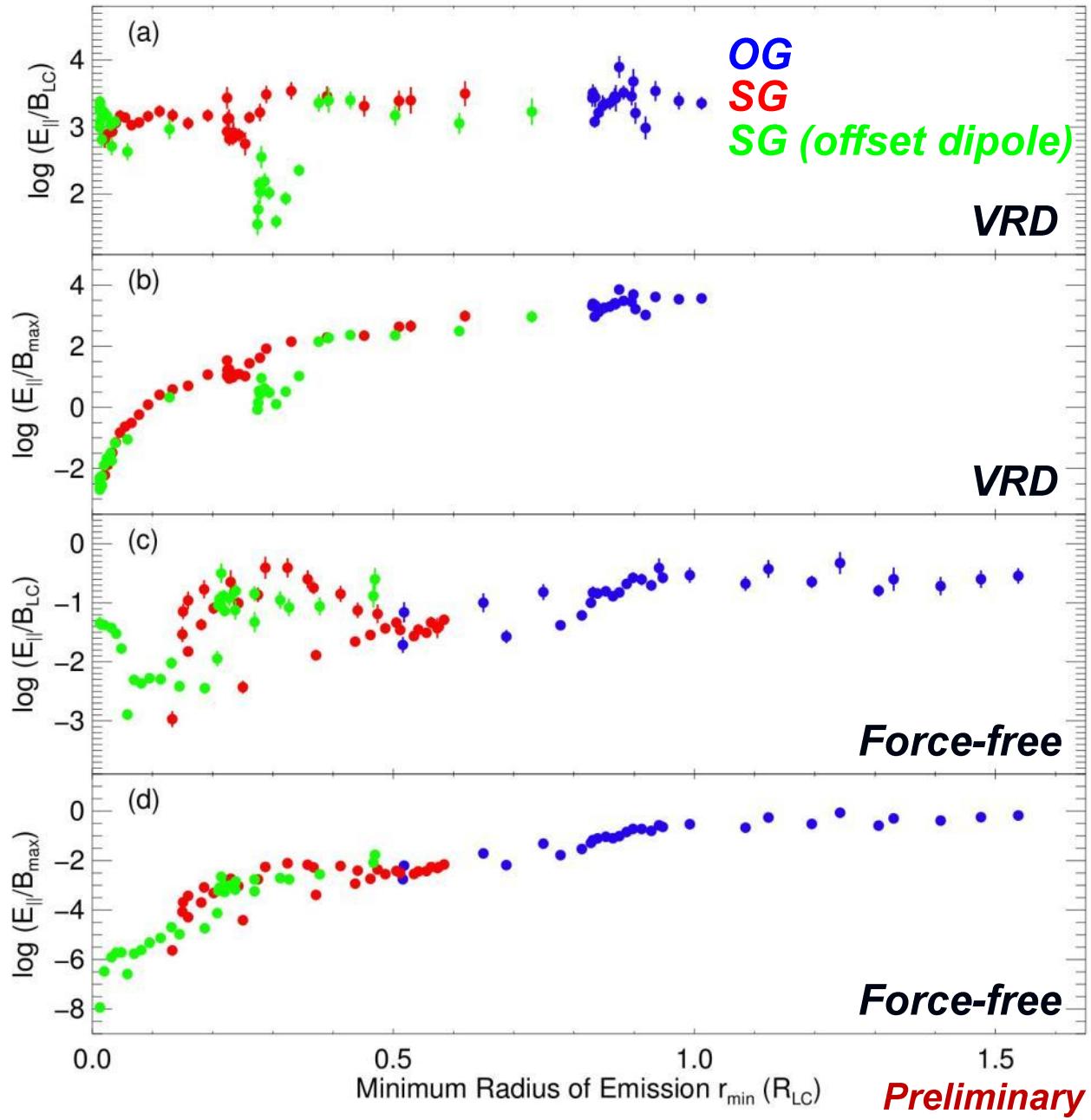


Maximum / minimum  $\rho_c$   
Maximum / minimum  
emission radii

Maximum / minimum  $E_{\parallel}$

DeCesar et al. (2013)

# Crab: Constraining $B$



$E_{\parallel}/B_{max} > 1$  not physical

$E_{\parallel} > B$  for VRD but larger radii of curvature (straighter field lines) and larger  $B$  near LC give  $E_{\parallel} < B$  for FF

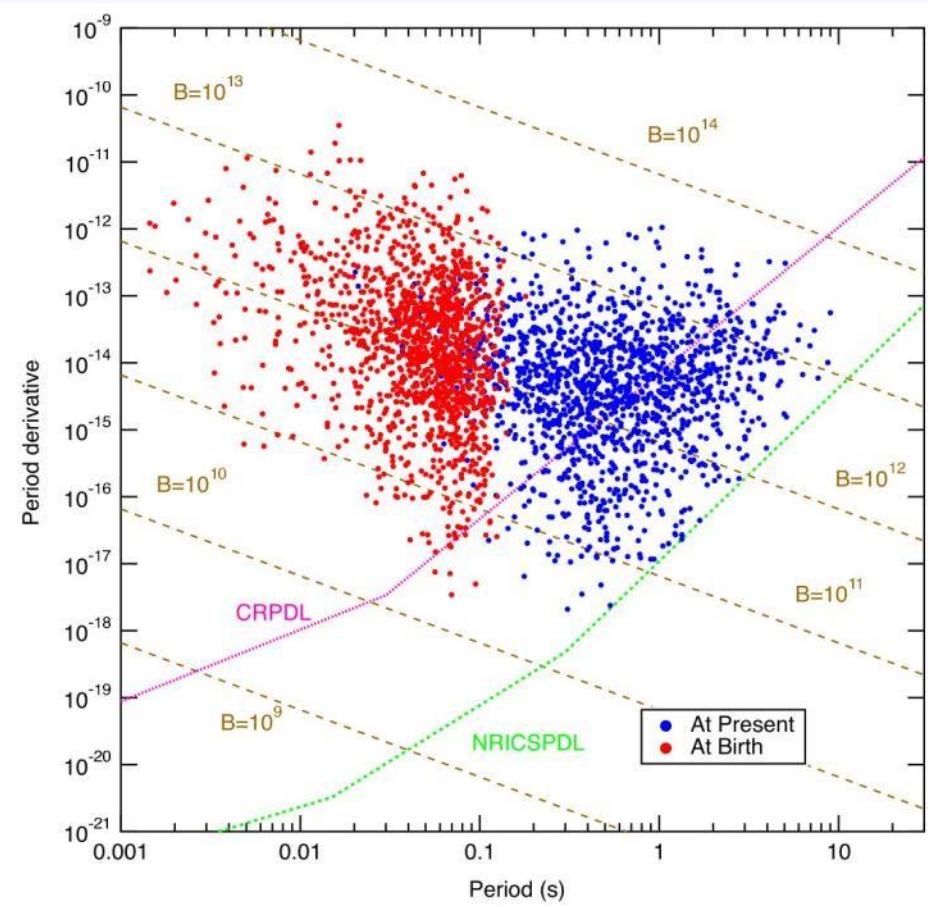
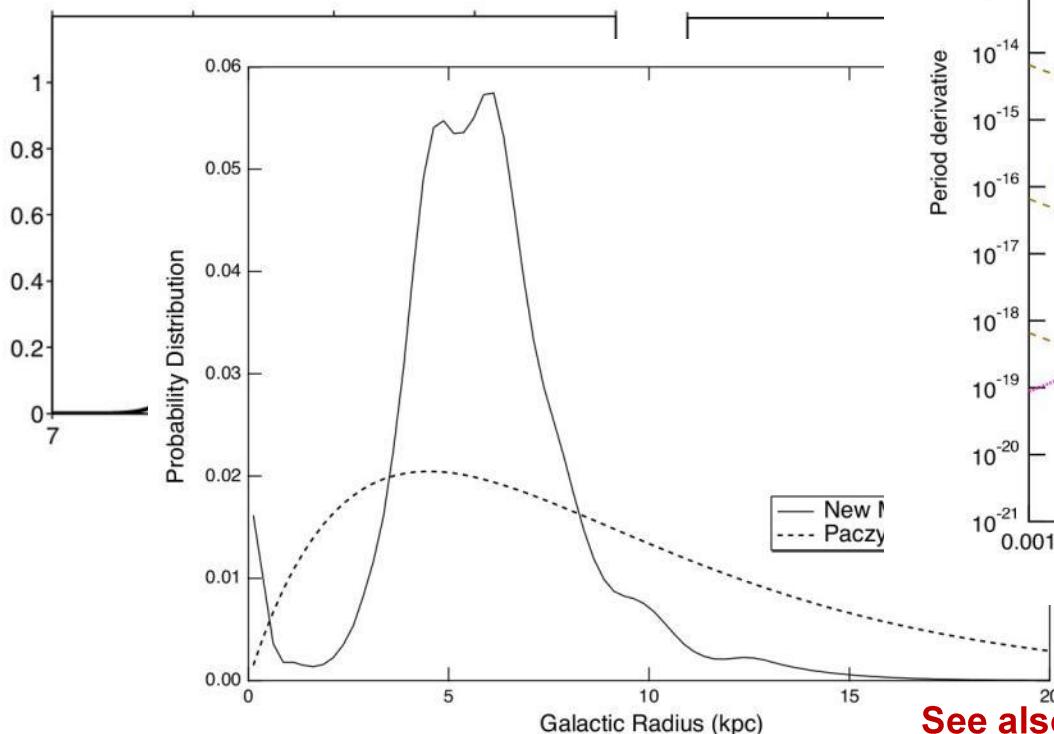
Preliminary

# Population Synthesis



# Initial Population Setup

- Comparing collective properties using population synthesis
- EOS; birth  $B$  and  $P$  distributions
- Magnetic field decay
- Birth position, kick velocity
- Evolve to obtain  $P$ ,  $P_{dot}$ , position, velocity

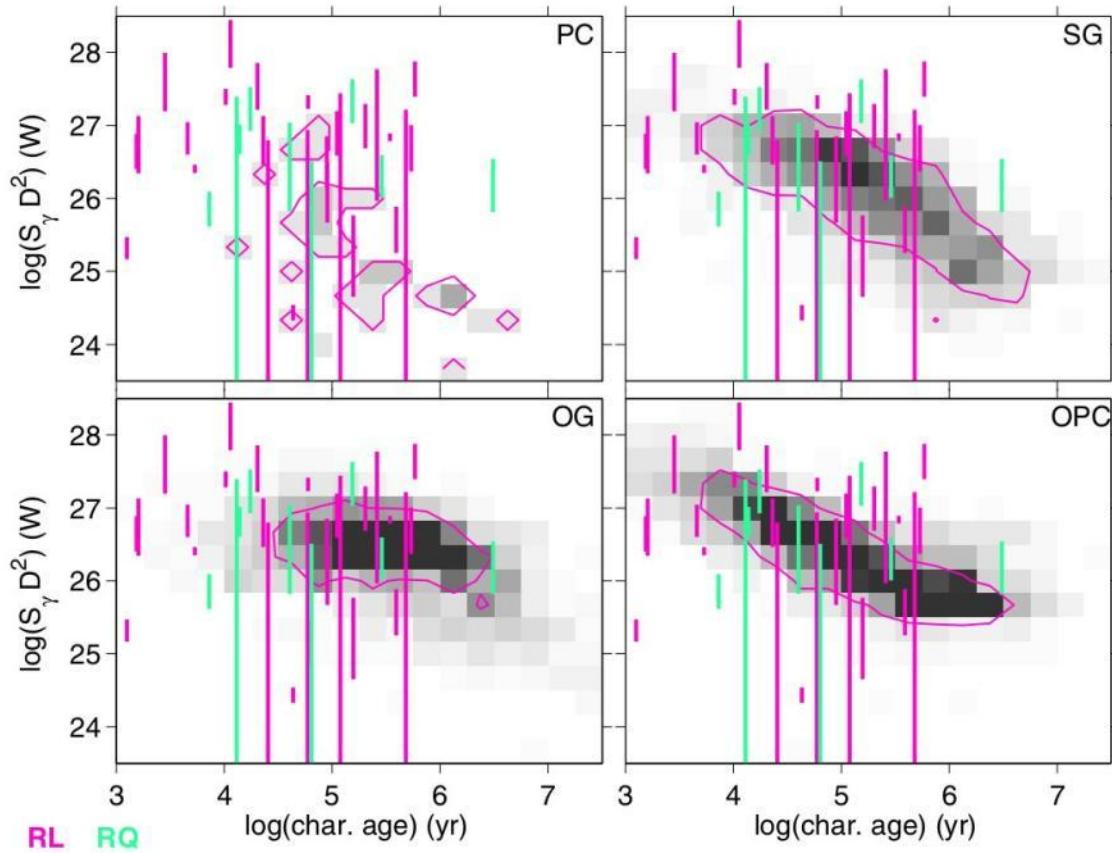


Pierbattista et al. (2012)

See also Watters & Romani (2011), Takata et al. (2011)

# Geometry, Luminosity, Detection

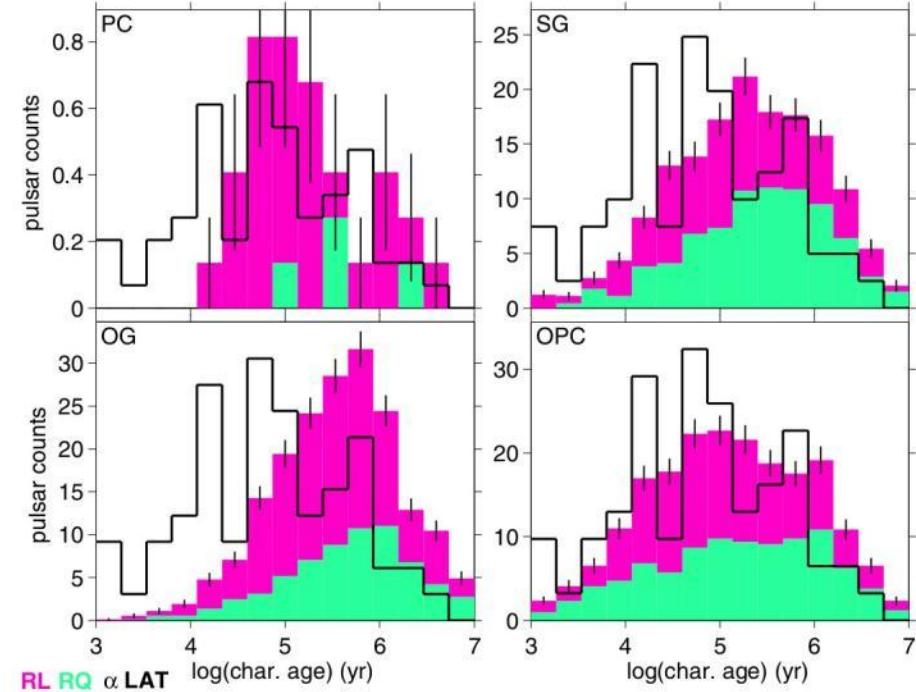
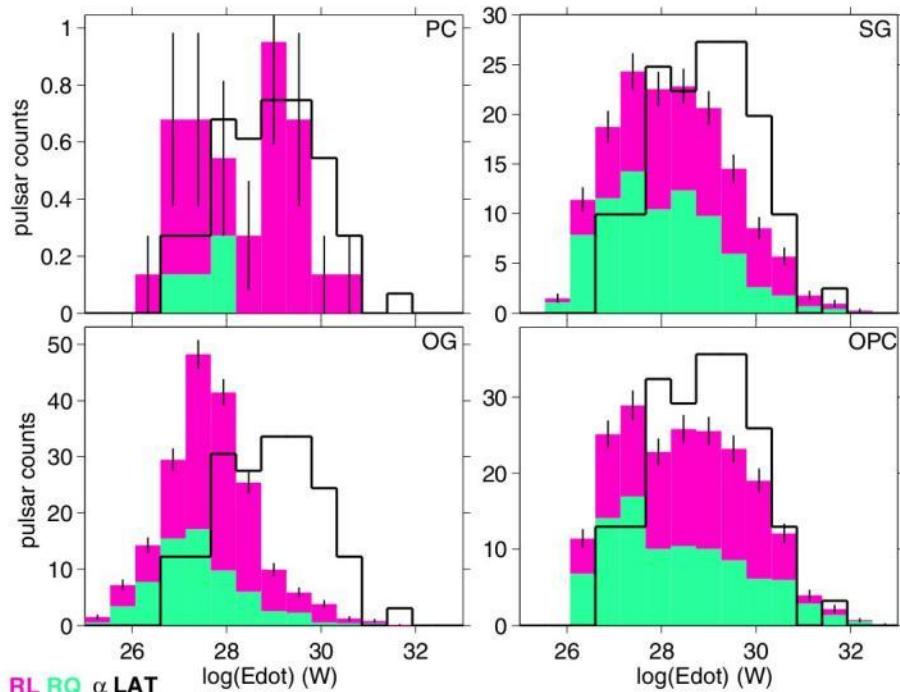
- Radio core + conal beam; Geometrical gaps: PC, SG, OG, OPC
- Particle luminosity prescription ( $L_\gamma \sim w$  or  $w^3$ ); gap widths
- Detection sensitivities
- Efficiency ( $L_\gamma = \varepsilon L_p$ ): OG ~ 1; SG ~ 10 (V or I); PC ~ 1, OPC ~ 0.5



Pierbattista et al. (2012)

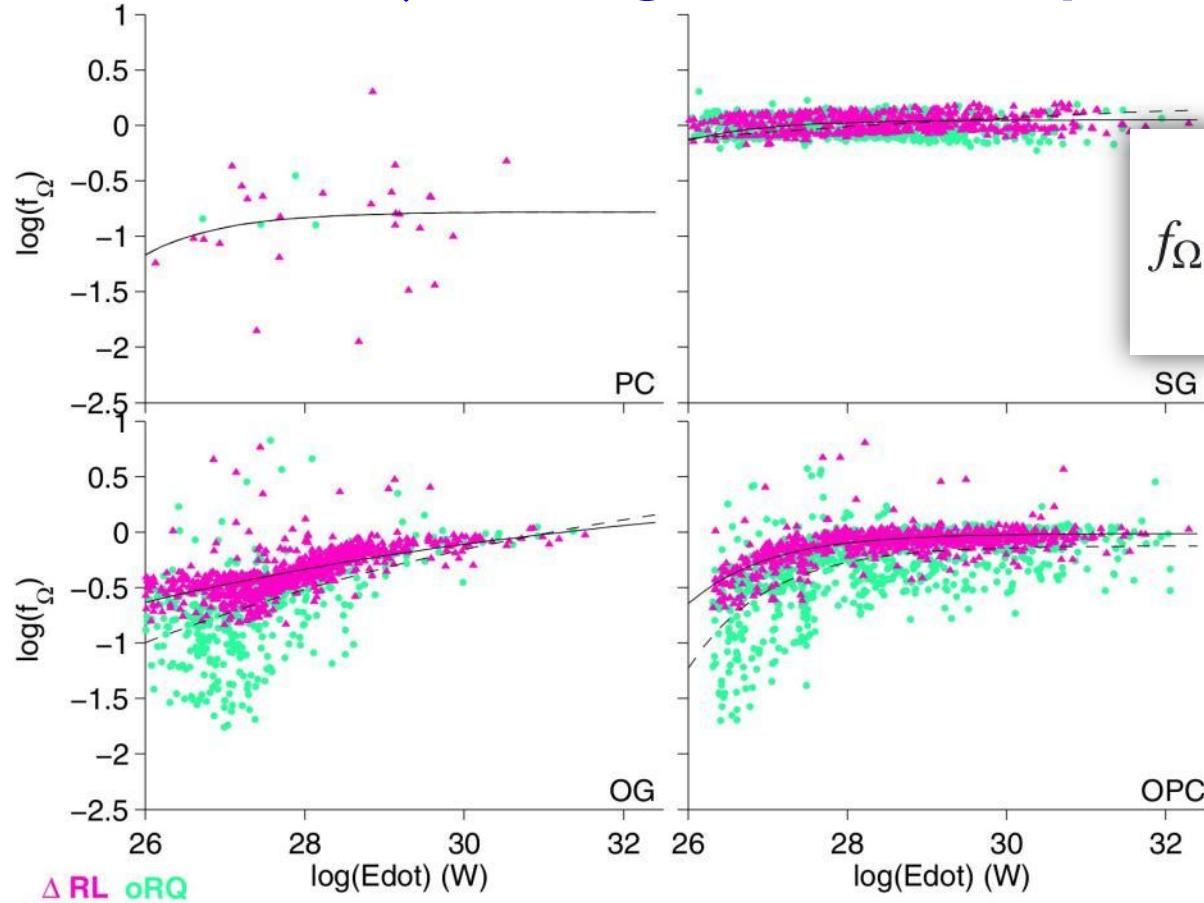
# Spin-down Luminosity Distribution

- All models underpredict number of pulsars with  $Edot > 3e35$  erg/s and  $t < 100$  kyr
- Predicted population too old and faint
- Evolution modelling needs to be revised



# Beaming Correction Factor

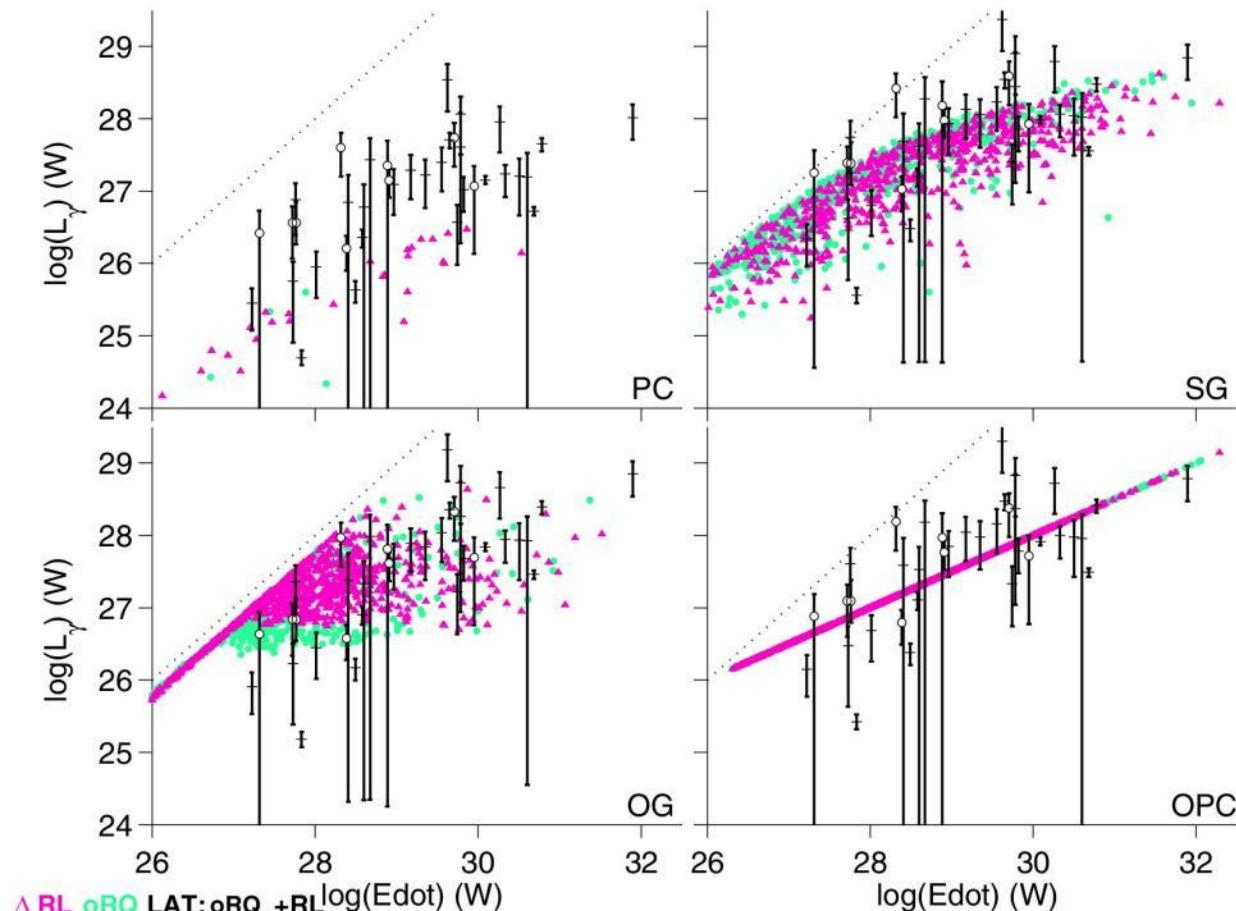
- Small decrease in  $f_\Omega$  with age /  $\dot{E}$ : smaller PC
- RQ more dispersed; lower  $f_\Omega$ : larger  $\beta$  (?)
- SG: slight gap evolution with age; radiation large beam
- OG / OPC:  $\gamma$ -beam goes toward spin equator



$$f_\Omega = \frac{\int_0^\pi \sin \zeta d\zeta \int_0^{2\pi} n(\phi, \zeta) d\phi}{2 \int_0^{2\pi} n(\zeta_{\text{obs}}, \phi) d\phi}$$

# $L_\gamma$ vs. Spin-down Luminosity

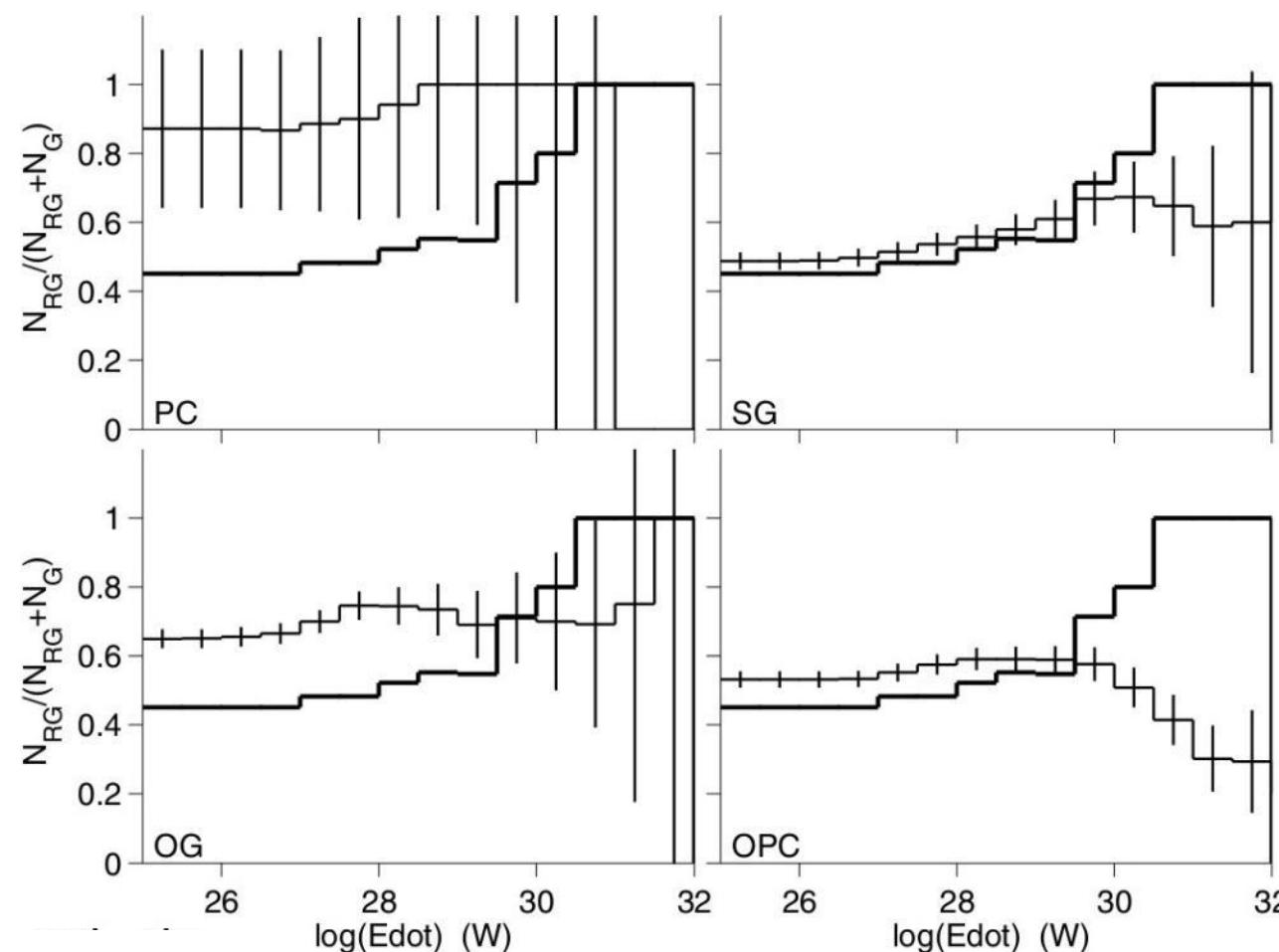
- Large dispersion in  $L_\gamma$  vs. spin-down: cannot discriminate between models
- PC model not luminous enough
- Break in  $Edot^{0.5}$  trend for PC / SG (ineffective screening at low  $Edot$ )
- OG: w saturation at low  $Edot$
- Scatter:  $f_\Omega$ , w( $P$ ,  $Pdot$ ,  $\alpha$ )



Pierbattista et al. (2012)

# Radio-loud vs. Radio-quiet Pulsars

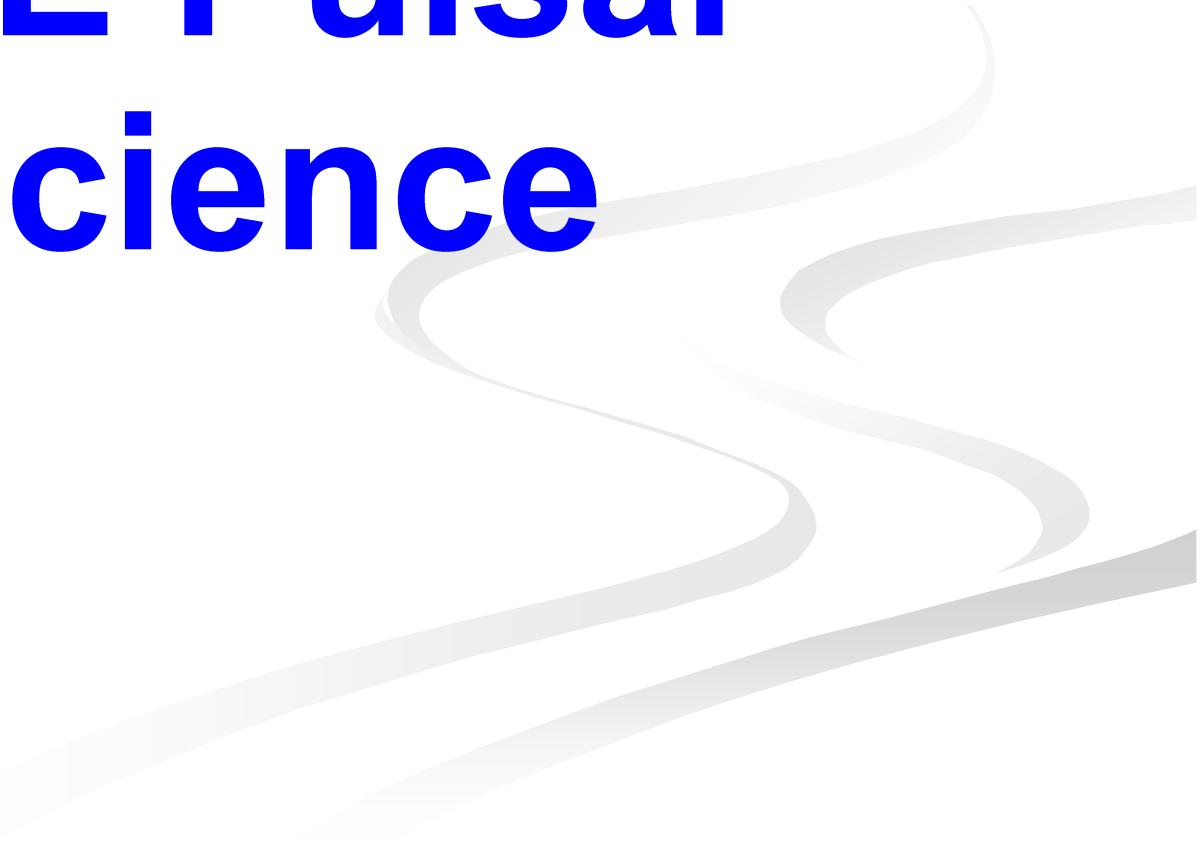
- Cumulative distribution of radio-loud vs. total number of pulsars with  $E\dot{o}$
- PC: ~constant due to small beams



- All models underpredict this fraction at high  $E\dot{o}$
- Broader radio beams at higher altitudes for young pulsars?

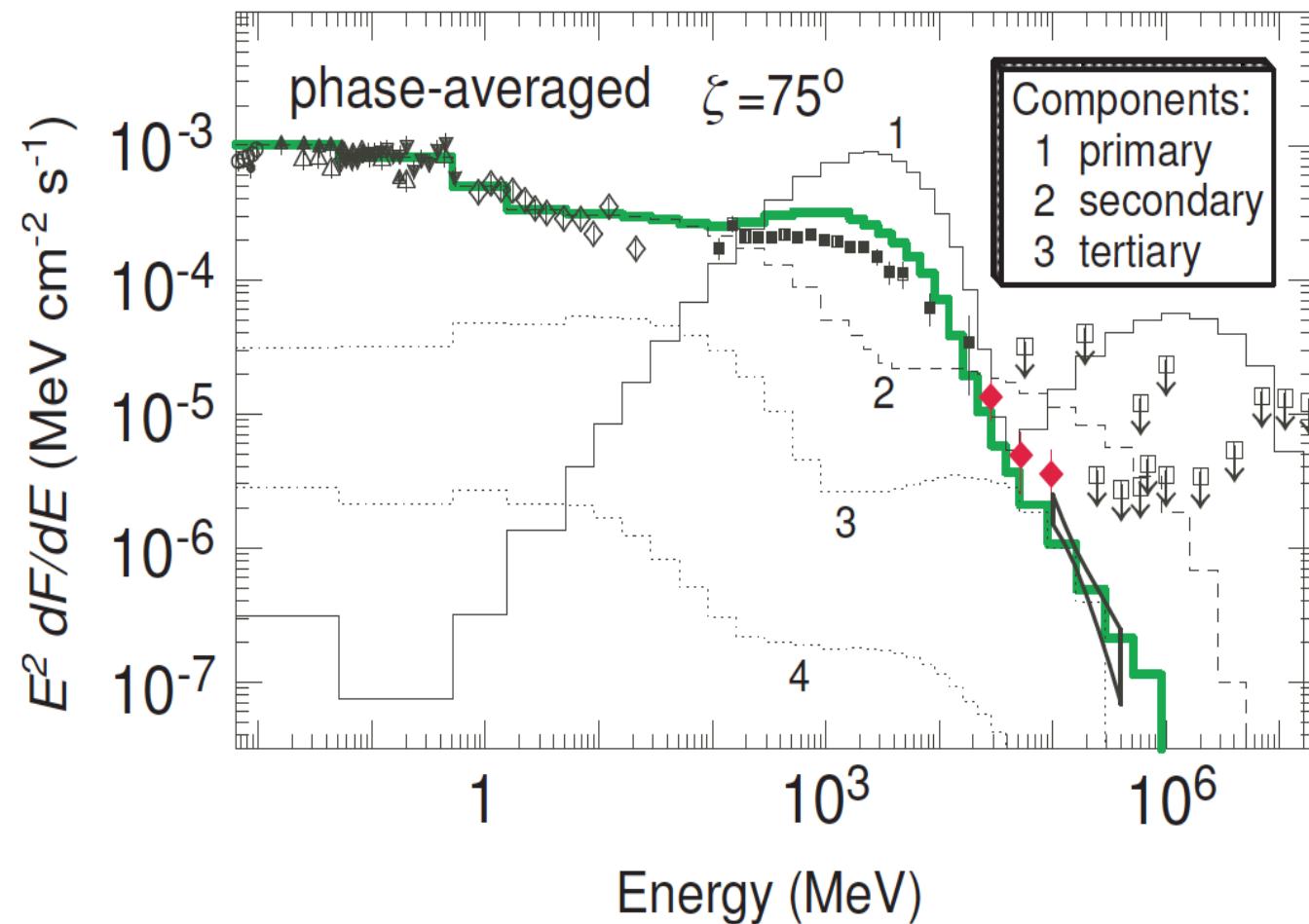
Pierbattista et al. (2012)  
Ravi et al. (2010)

# VHE Pulsar Science



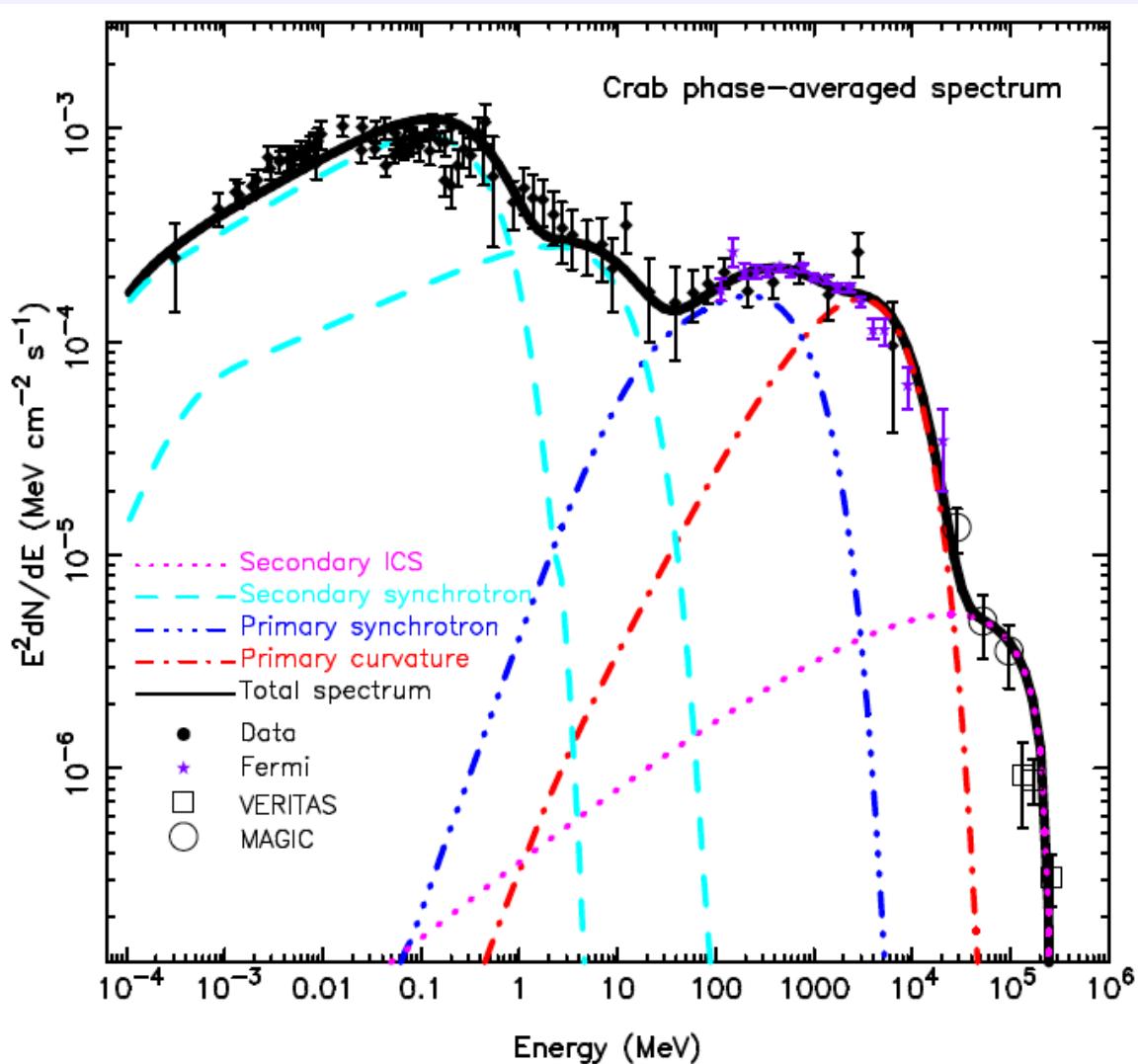
# Crab Pulsar > 100 GeV

Hirotani outer gap (Aleksic et al. 2011)



- VHE Emission is SSC from pairs
- Uncertain: B-geometry, pairs, SR emissivity
- Possibility of structure in HE spectrum

# Crab Pulsar > 100 GeV

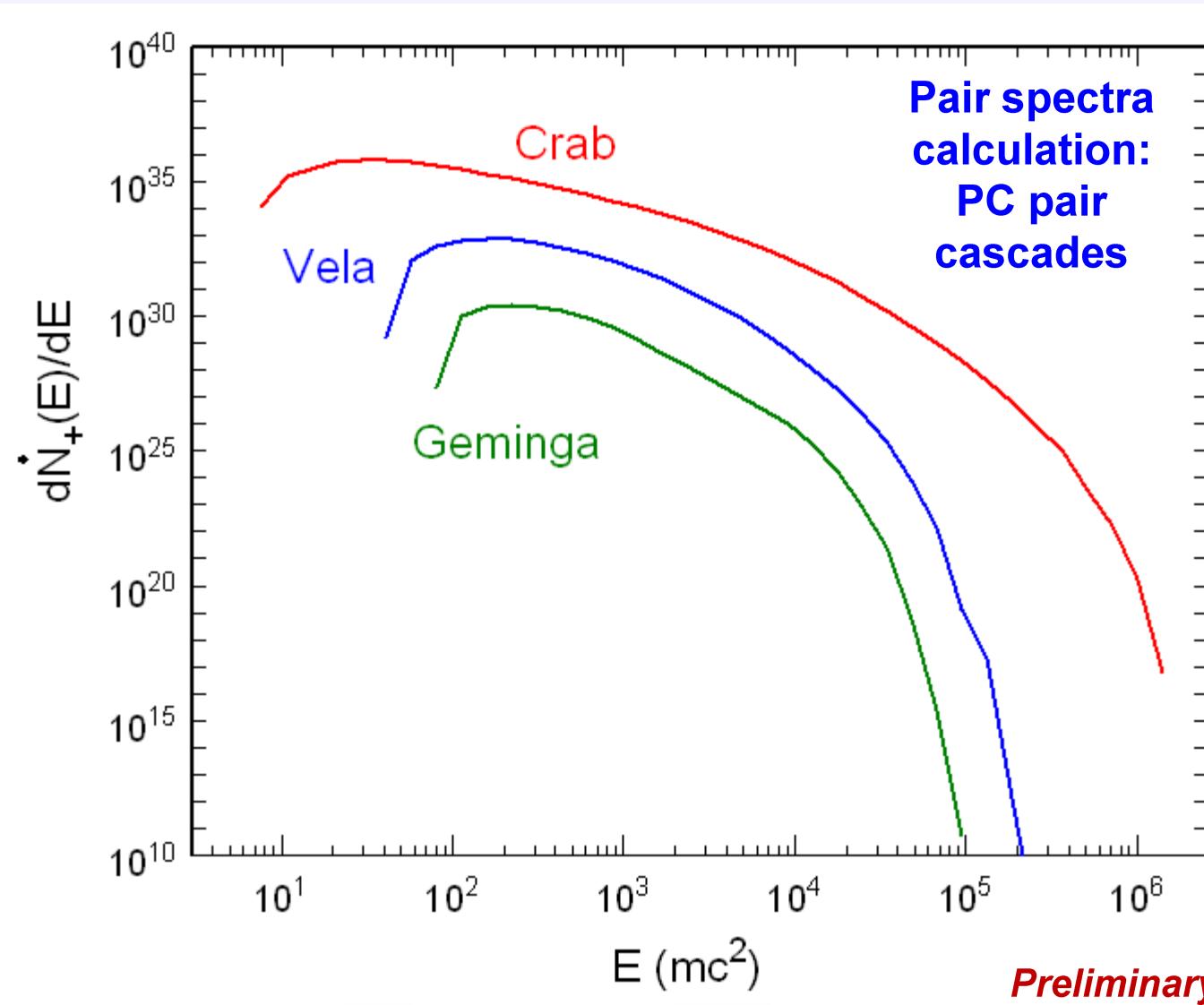


Annular gap  
(Du et al. 2012)

- Primaries: CR, SR
- Secondaries:  
SR (x2), SSC
- Approximations  
include PL for 2 pair  
spectral components,  
soft-photon SR field;  
No GR effects

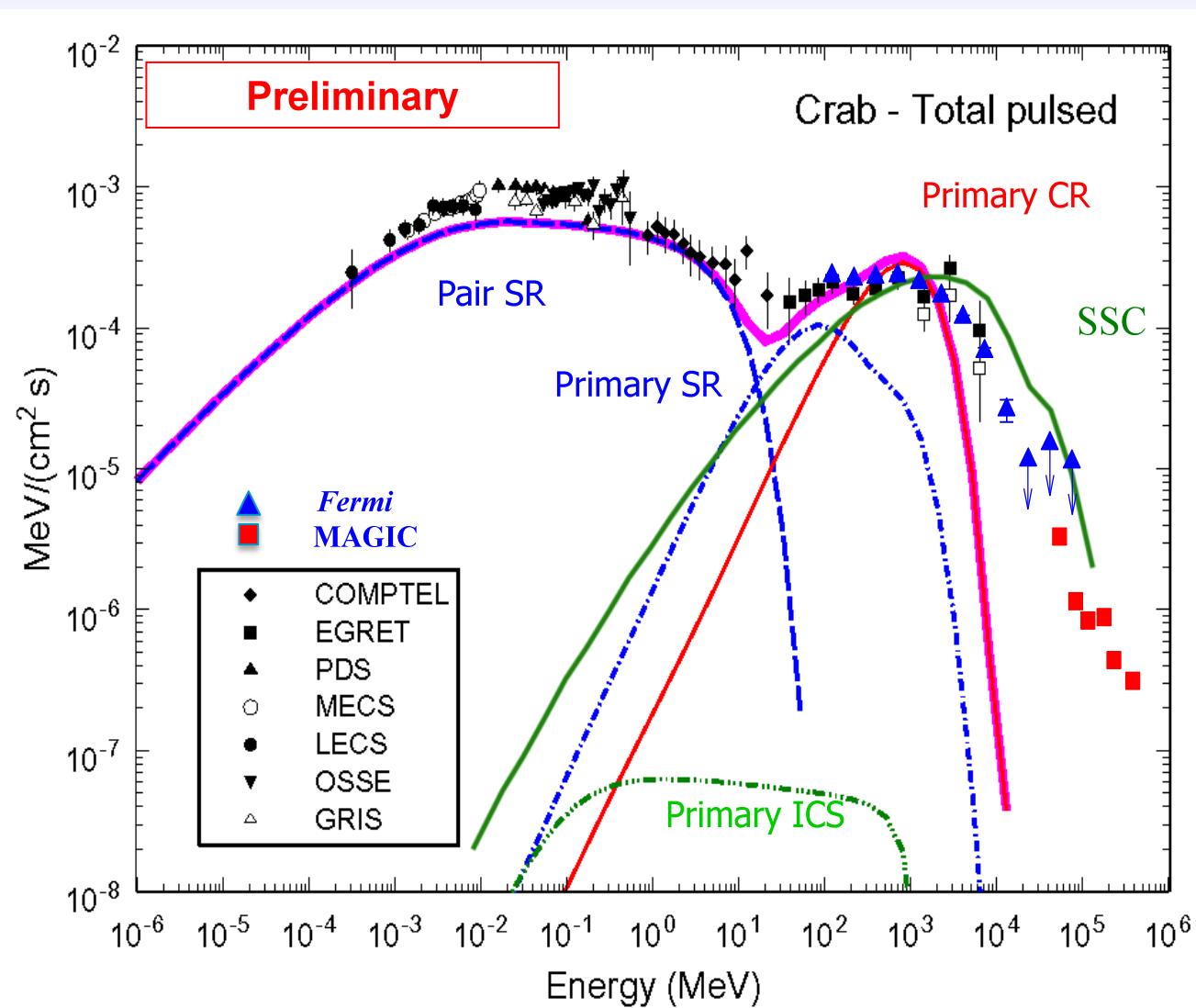
# Crab Pulsar > 100 GeV

Slot gap model (Harding 2013)



# Crab Pulsar > 100 GeV

Slot gap model (Harding 2013)



Preliminary

# (Some) Open Questions

- Rich variety in newly-detected  $\gamma$ -ray pulsar population
- No overall best-fit geometrical model – may point to hybrid / new geometry
- Preliminary trends seen between geometric / spectral and pulsar parameters
- Force-free vs. conductive magnetospheres – Preferred magnetospheric structure? Current sheet? Magnetic reconnection?
- Behaviour of spectral parameters with phase
- Population synthesis: lack of high- $\dot{E}$  pulsars? Prescription of  $L_\gamma$ ? Beaming? Evolutionary history of pulsars?
- Origin of pulsed TeV photons

# THANK YOU!



*“You have done wonderful things; Your counsels of old are faithfulness and truth” (Is. 25:1b)*