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Unraveling the Emission Geometry of the *Fermi* Millisecond Pulsars

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(astro-ph:0911.0872v1)
Second Fermi Symposium, Washington, DC
2 – 5 November 2009

New Gamma-ray MSPs

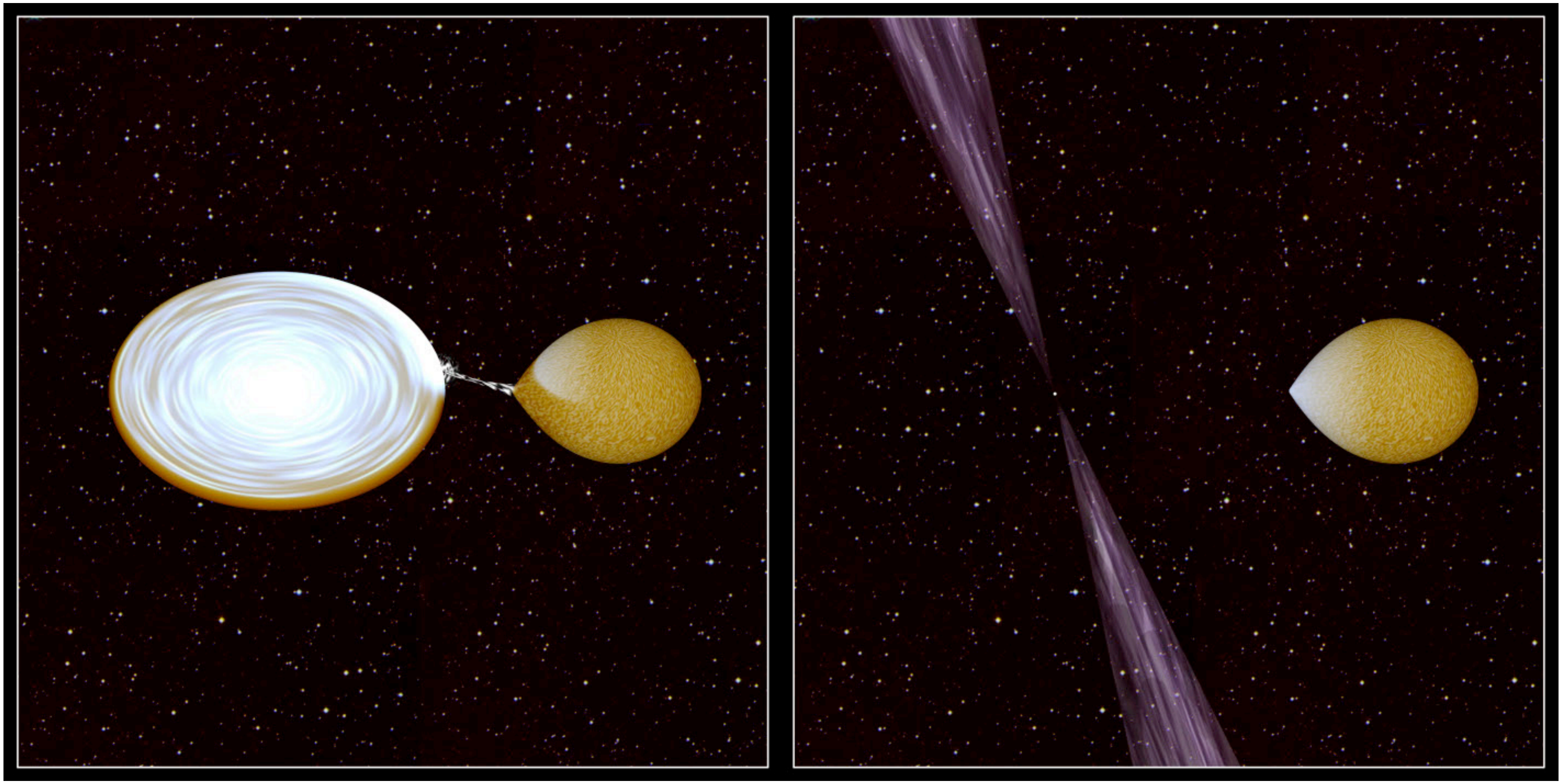
Name	P (ms)	$\dot{P}$ (10^{-20})	Distance (kpc)	Age (10^9 yr)	$\dot{E}_{\rm rot}$ (10^{33} erg s^{-1})	B_0 (10^8 G)
J0030+0451	4.865	1.01	0.300 ± 0.090	7.63	3.47	2.04
J0218+4232	2.323	7.79	2.70 ± 0.60	0.47	245	4.31
J0437−4715	5.757	1.39	0.156 ± 0.002	6.55	2.88	2.87
J0613−0200	3.061	0.915	0.48 ± 0.14	5.31	12.6	1.69
J0751+1807	3.479	0.755	0.62 ± 0.31	7.30	7.08	1.64
J1614−2230	3.151	0.397	1.30 ± 0.25	12.6	5.01	1.13
J1744−1134	4.075	0.682	0.470 ± 0.090	9.47	3.98	1.69
J2124−3358	4.931	1.21	0.25 ± 0.13	6.47	3.98	2.47
J0034-0534	**1.877**	**0.259**	**0.54 (+ 0.22 - 0.14)**	**11.5**	**15.5**	**0.706**

Abdo et al. 2009, Science, 325, 848

Venter et al. (2009) *(astro-ph:0911.0872v1)*

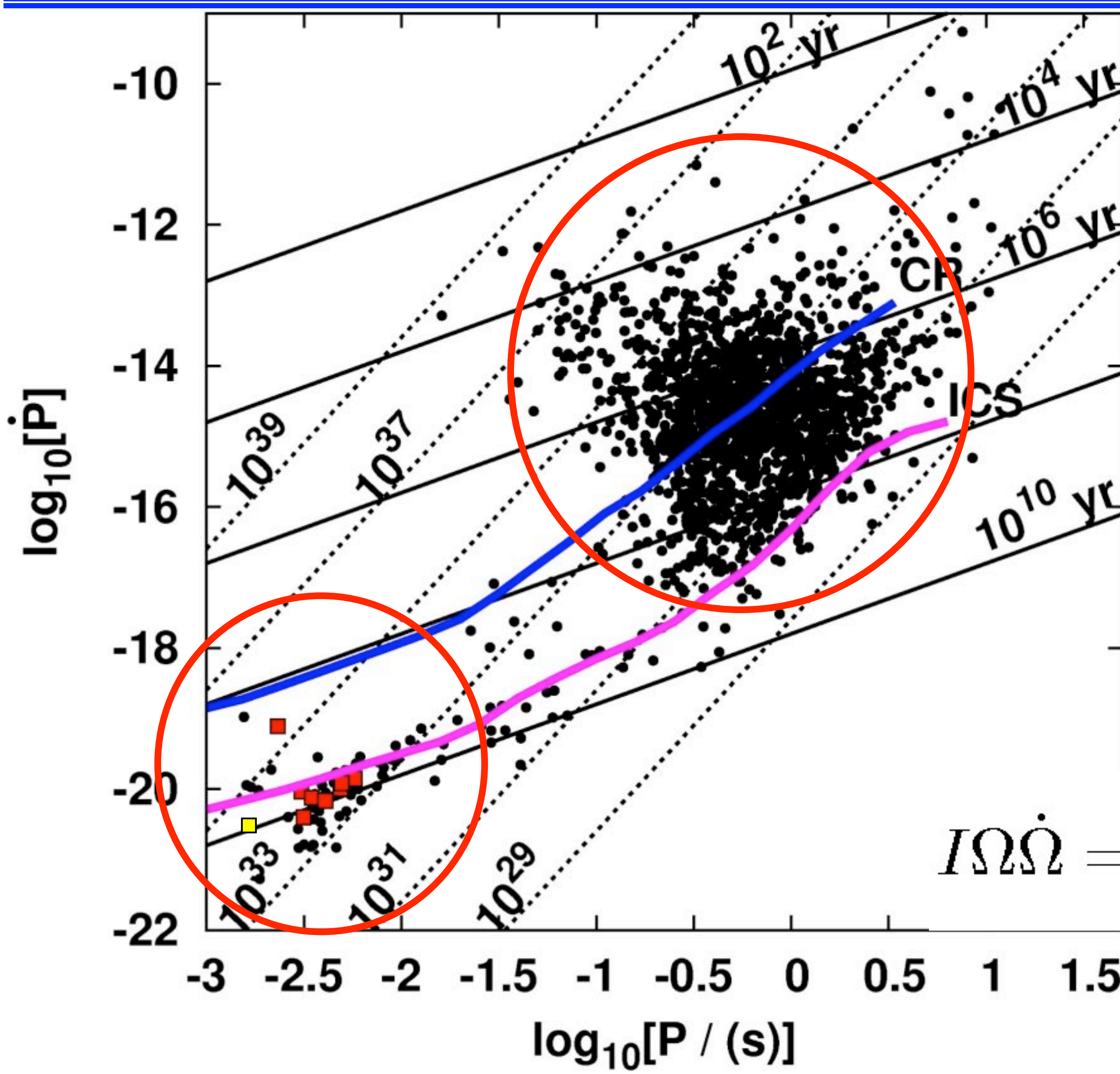
Abdo et al. 2009, in preparation (see talk of L. Guillemot)

'Recycled' Pulsars



Alpar et al. (1982)
Archibald et al. (2009)
http://www.mcgill.ca/channels/announcements/item/?item_id=106788

Millisecond Pulsars



$$\Omega_f \sim \Omega_i \left(\frac{R_i}{R_f}\right)^2$$

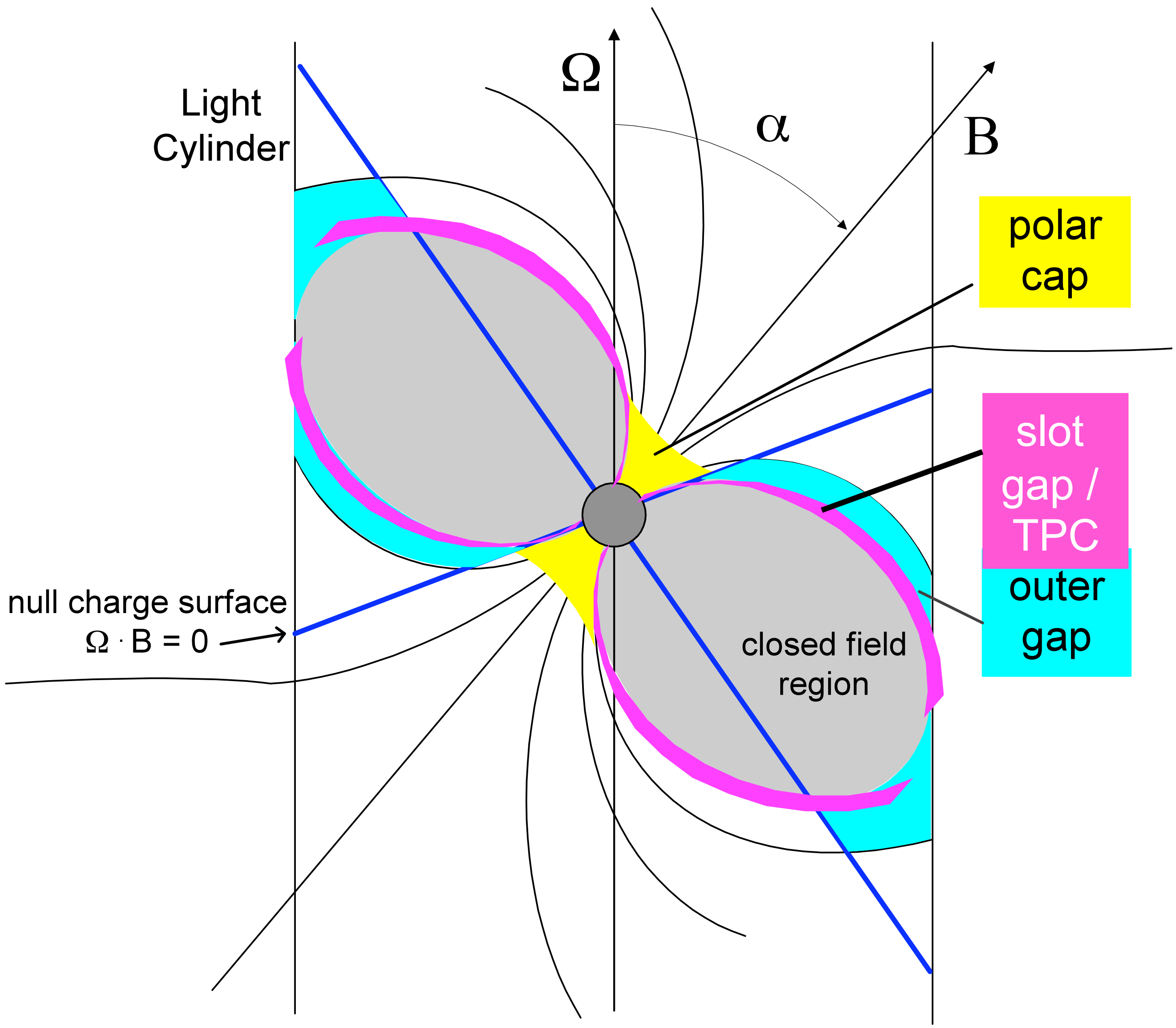
$$B_f \sim B_i \left(\frac{R_i}{R_f}\right)^2$$

$$B_0 \sim 3 \times 10^{19} \sqrt{P\dot{P}}$$

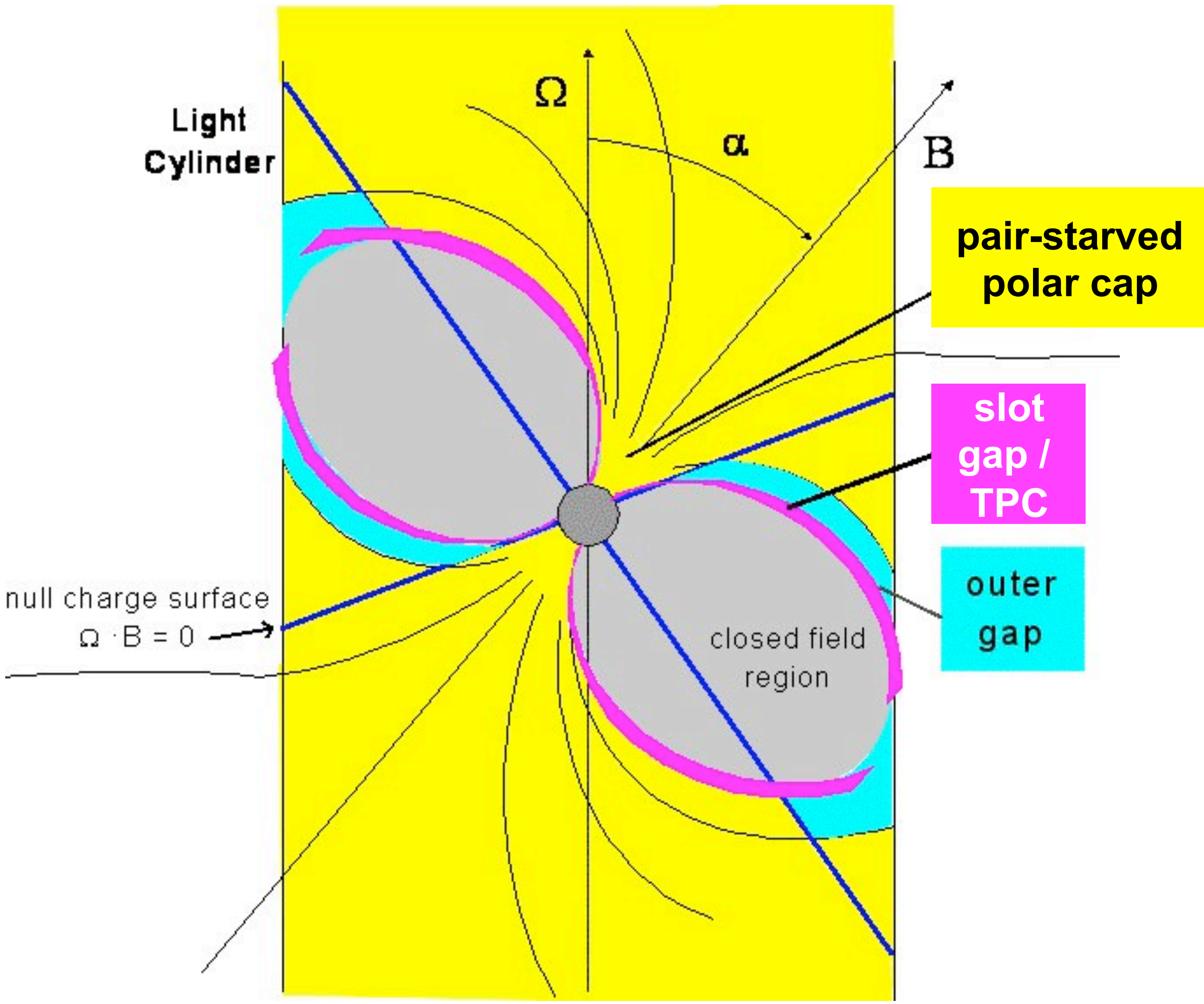
$$\tau \approx \frac{P}{2\dot{P}}$$

$$I\Omega\dot{\Omega} = -\frac{2}{3c^3}\mu^2 \sin^2(\alpha)\Omega^4$$

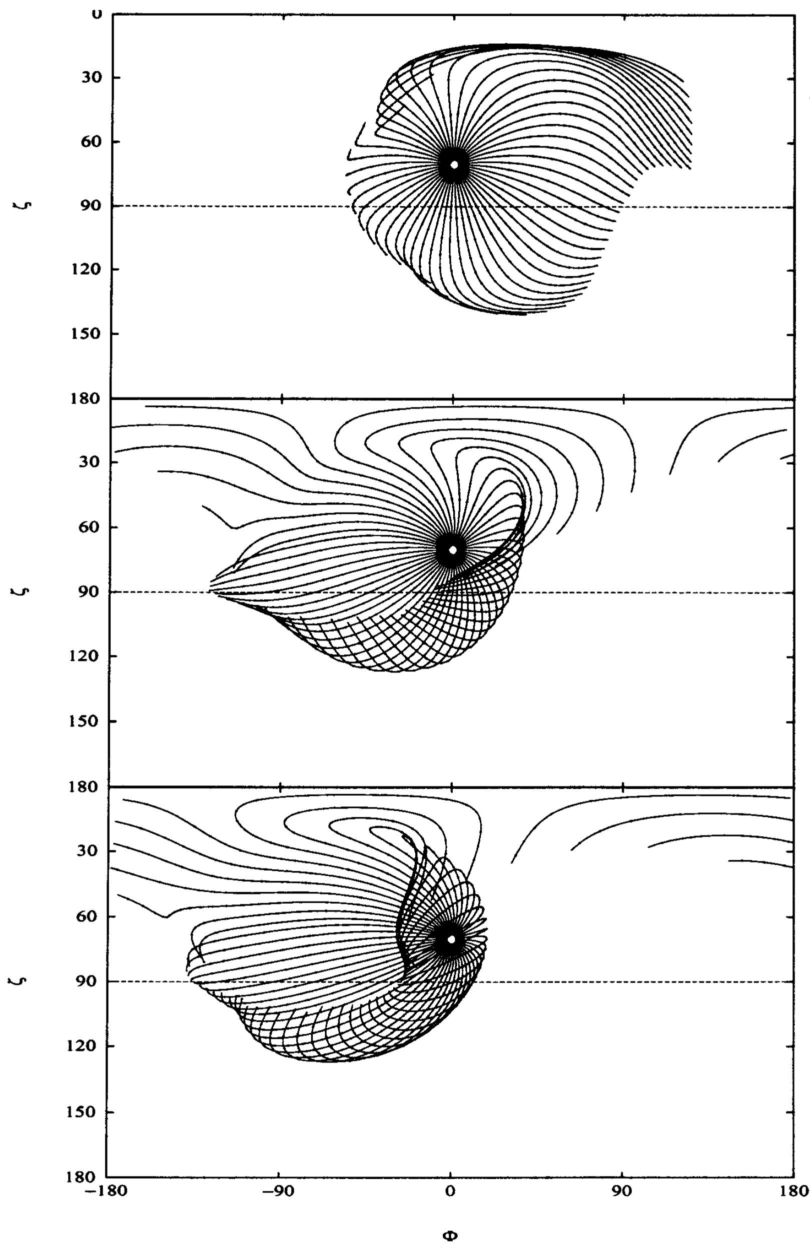
Standard Accelerator Geometries



Accelerator Geometries



SR Effects & Retardation



Sweepback only …

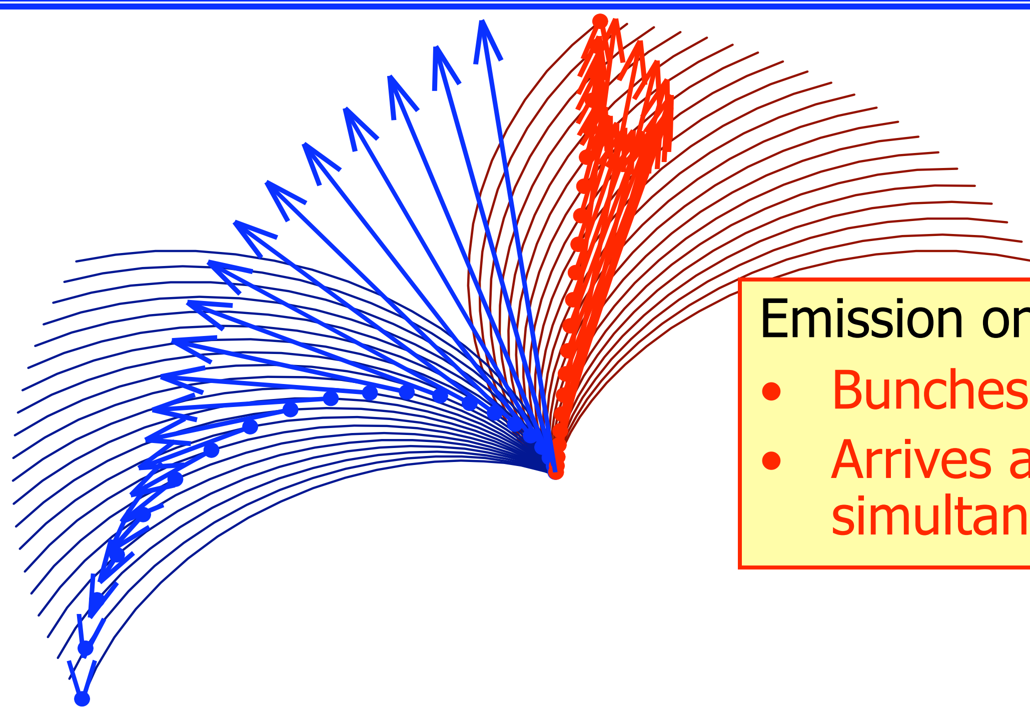
Projected field lines from single pole

plus aberration …

… and travel time delay

Yadigaroglu (1997)

Formation of Caustics



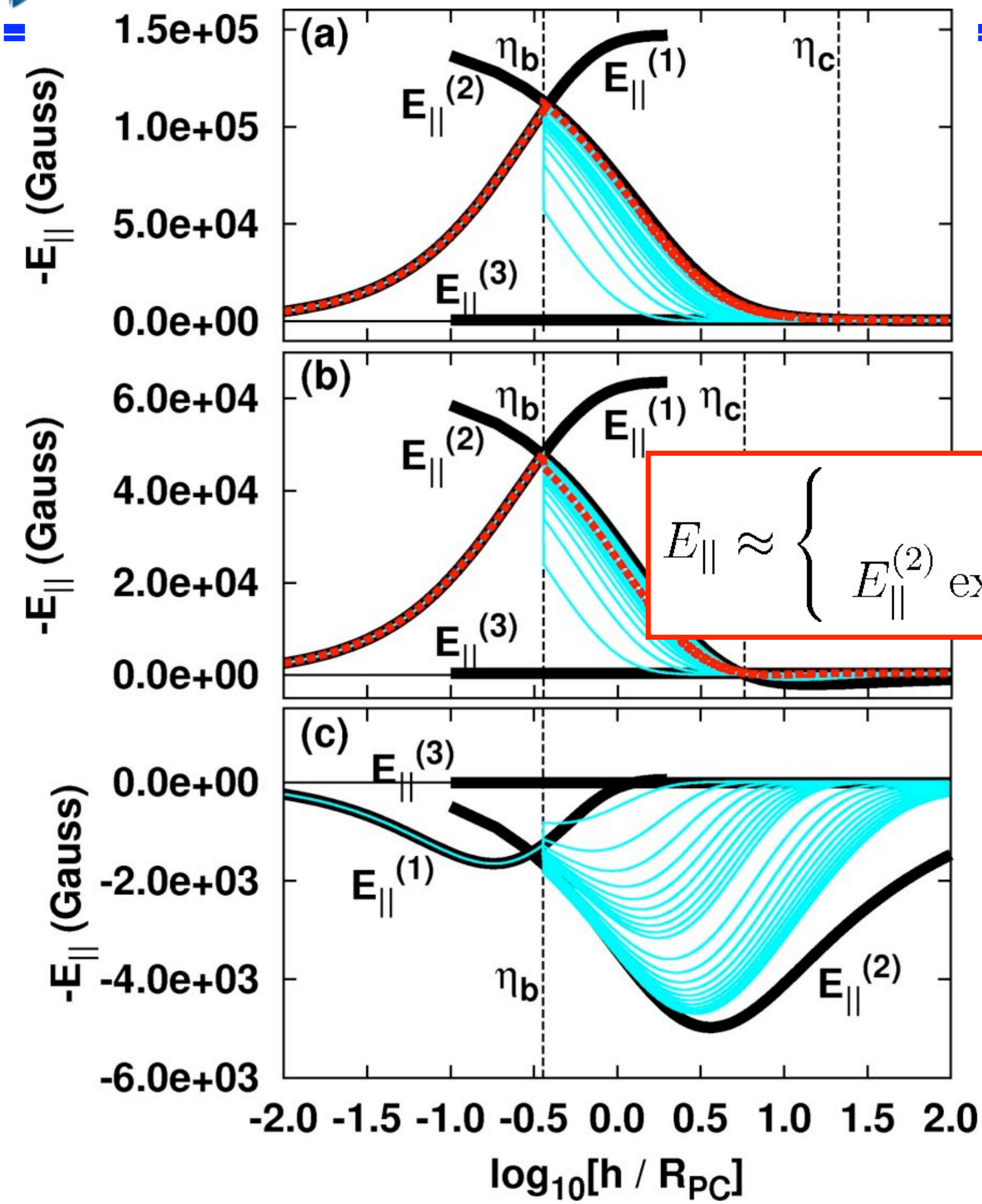
Emission on trailing field lines
- Bunches in phase
- Arrives at inertial observer simultaneously

Emission on leading field lines
- Spreads out in phase
- Arrives at inertial observer at different times

Caustic emission
- Dipole magnetic field
- Outer edge of open volume

(Observed: Static & retarded dipole, for $\xi <= 1$)

PSPC E-field: Matching of Solutions



Matching Criteria:

- $E_{||}$ matching for $E_{||}^{(2)} < E_{||}^{(3)}$
- $E_{||} \rightarrow E_{||}^{(3)}$
- $E_{||} < 0$

$$E_{||} \approx \begin{cases} E_{||}^{(1)}, & \eta \leq \eta_b \\ E_{||}^{(2)} \exp\left[-(\eta - 1)/(\eta_c - 1)\right] + E_{||}^{(3)}, & \eta > \eta_b \end{cases}$$

Pair-starved case (unscreened PC model)

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

Radio Beam Geometry

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

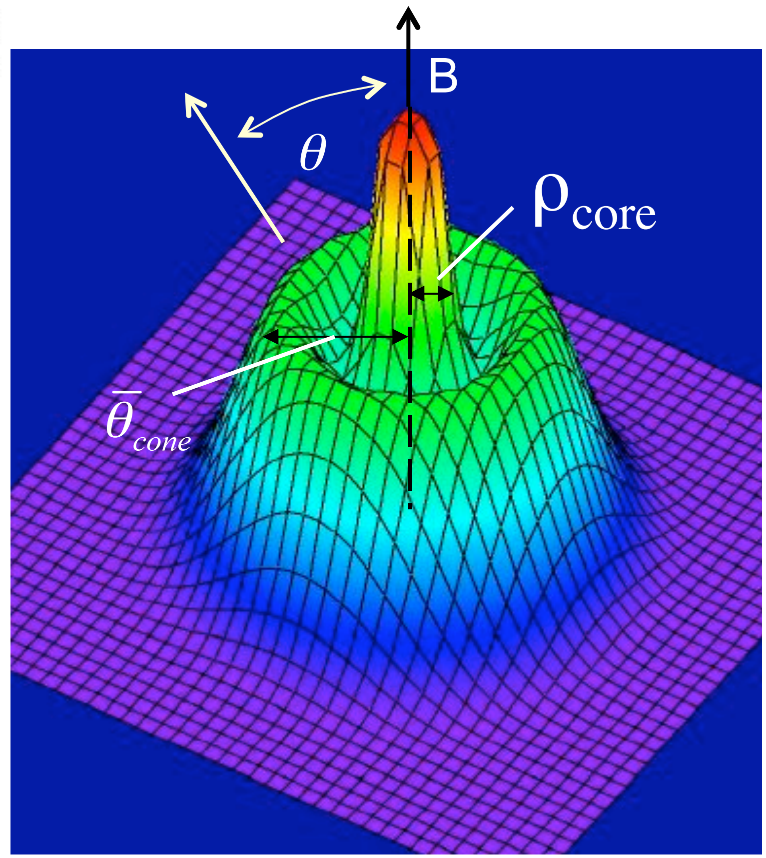
Cone radius: $\rho_{\rm cone} = 1.24^\circ \, r_{\rm KG}^{0.5} \, P^{-0.5}$

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

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

Emission altitude:

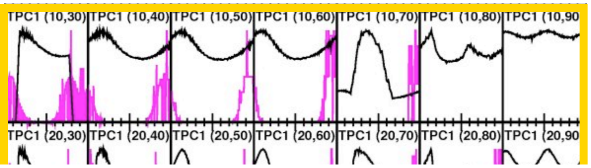
$$r_{\rm KG} \approx 40 \left(\frac{\dot{P}}{10^{-15}{\rm s\,s^{-1}}} \right)^{0.07} P^{0.3} \nu_{\rm GHz}^{-0.26}$$

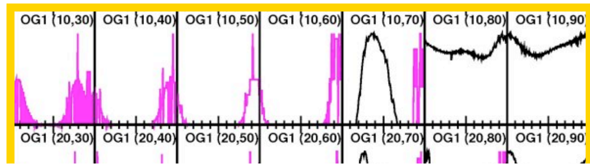


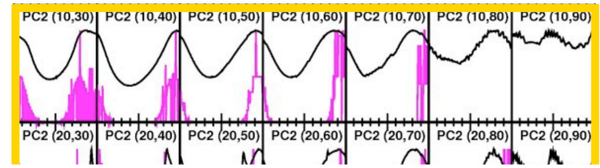
RESULTS: MSP Light Curves

(P = 2, 3, 5 ms; various α, ζ)

TPC1 | **OG1** | **PSPC**

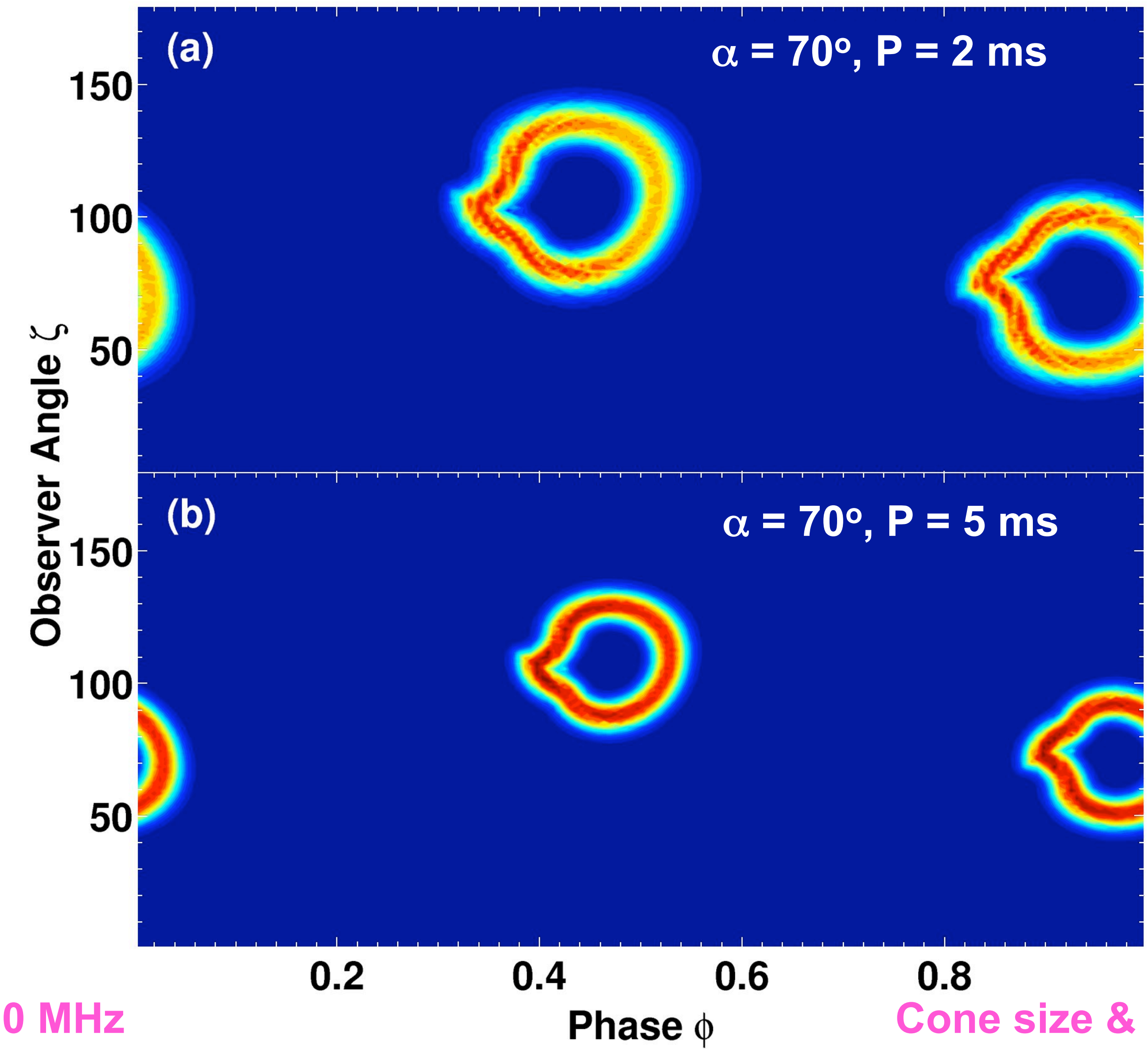






Abbreviation	r_{ovc}	w	δr_{ovc}	Azimuthal bins	Description
TPC1	[0.90, 1.00]	0.10	0.005	180	Geometric TPC Model
TPC2	[0.95, 1.00]	0.05	0.005	180	Geometric TPC Model
TPC3	[0.80, 1.00]	0.20	0.005	180	Geometric TPC Model
TPC4	[0.60, 1.00]	0.40	0.005	180	Geometric TPC Model
TPC5	[1.00, 1.00]	0.00	0.005	180	Geometric TPC Model
OG1	[0.95, 1.00]	0.05	0.005	180	Geometric OG Model
OG2	[0.90, 0.90]	0.00	0.005	180	Geometric OG Model
OG3	[1.00, 1.00]	0.00	0.005	180	Geometric OG Model
PC1	[0.00, 1.00]	1.00	0.005	180	Geometric PC Model
PC2	[0.00, 1.00]	1.00	0.005	180	Radiation PSPC Model

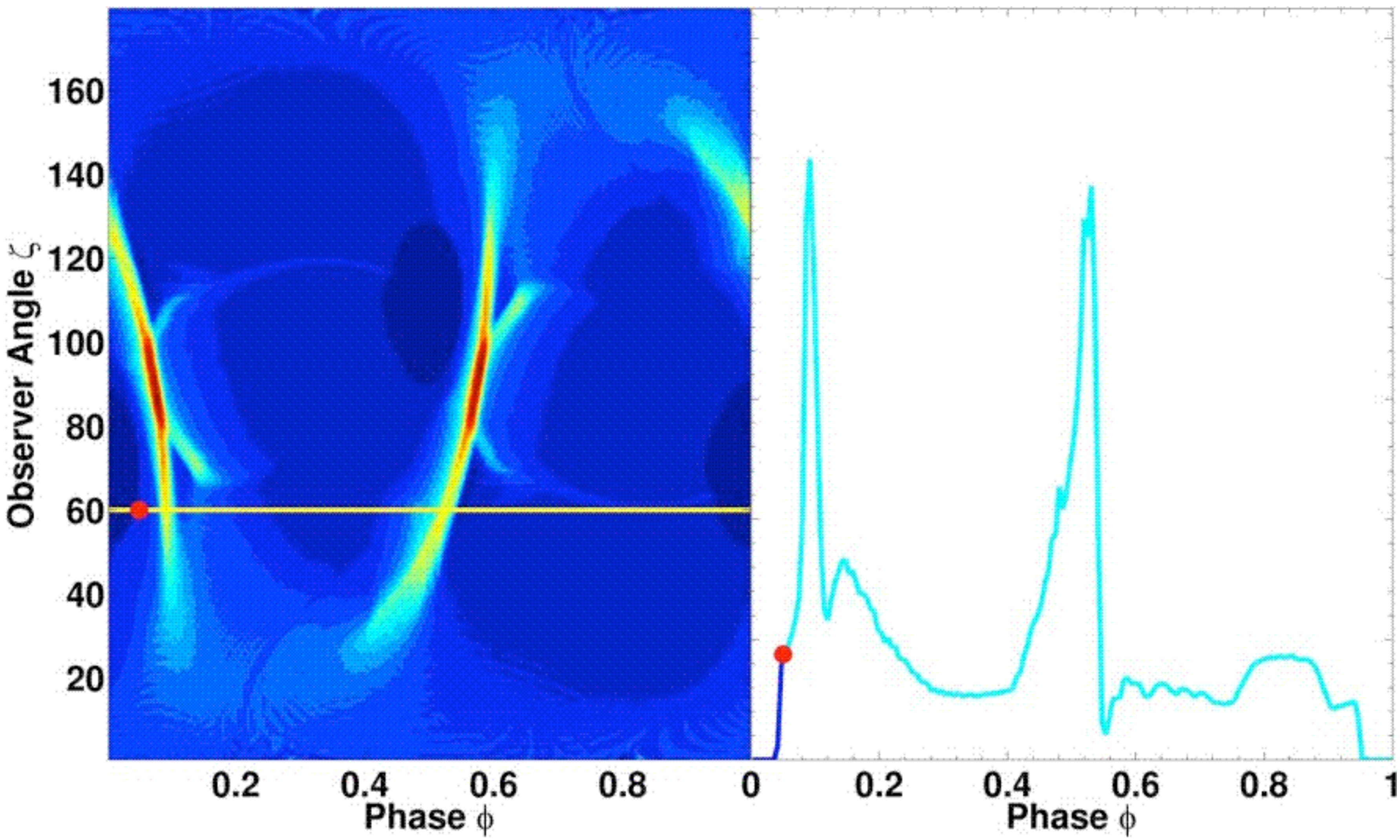
Radio Beam Geometry



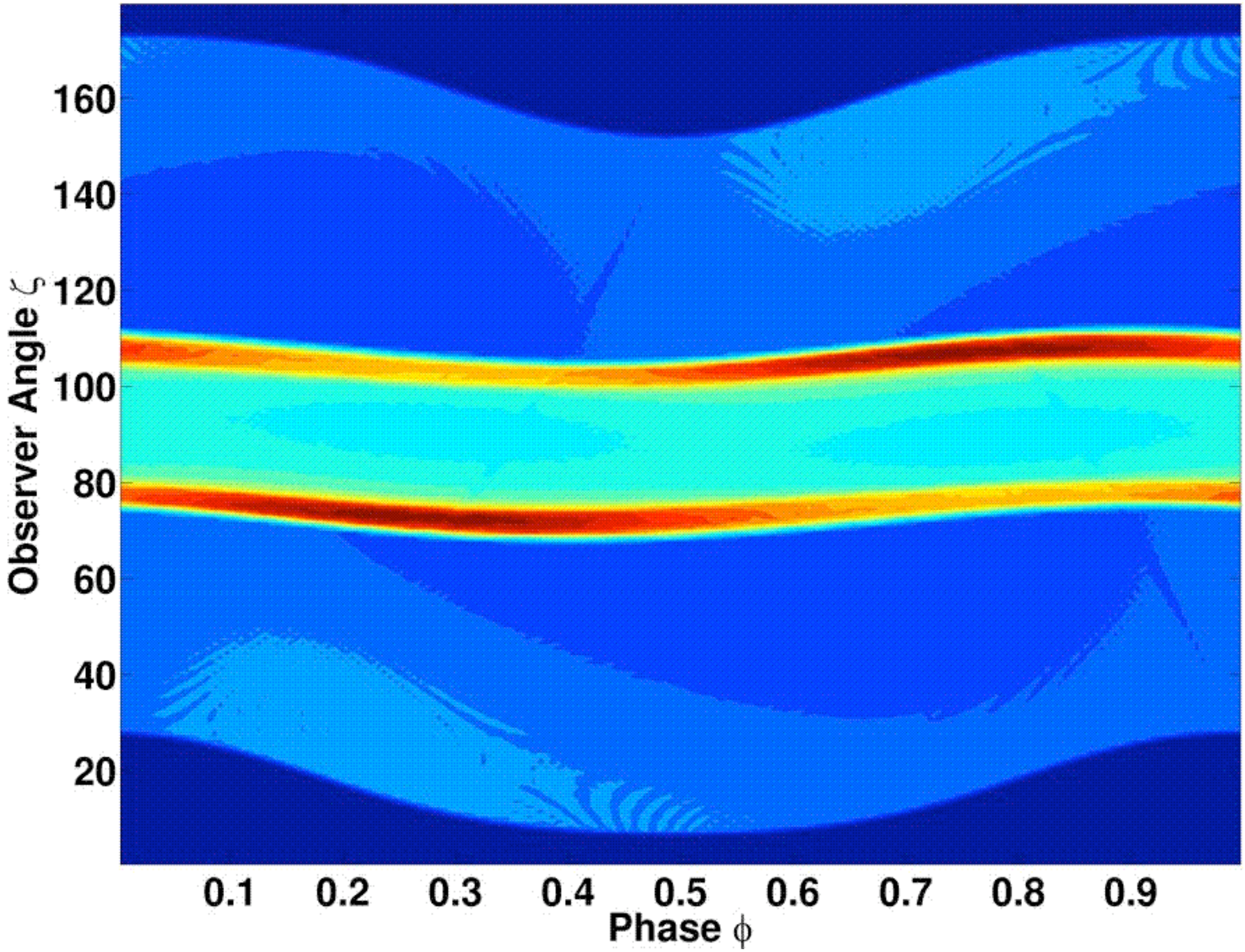
Radio @ 1400 MHz

Cone size & width ~ $P^{-0.35}$

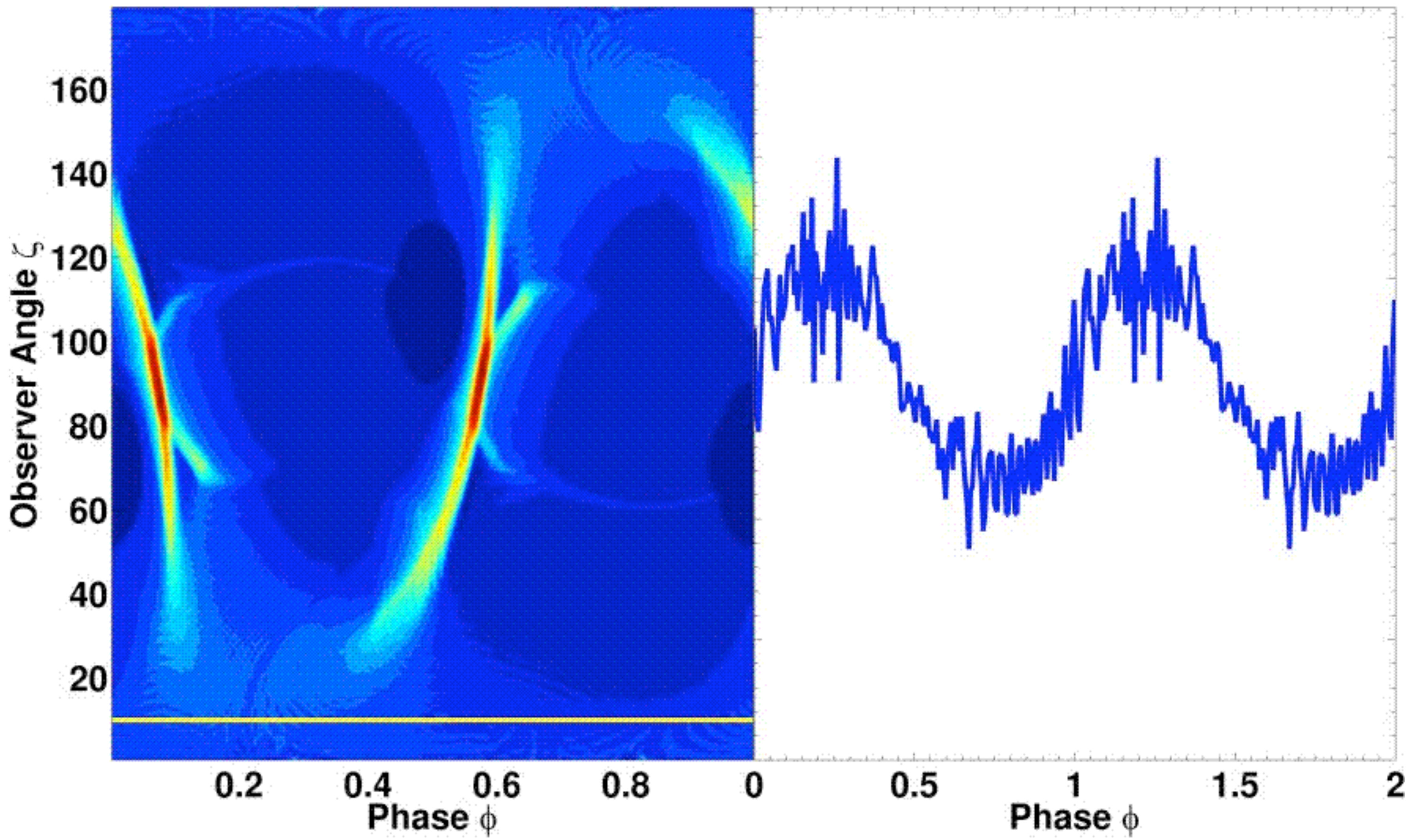
Light Curve Calculation



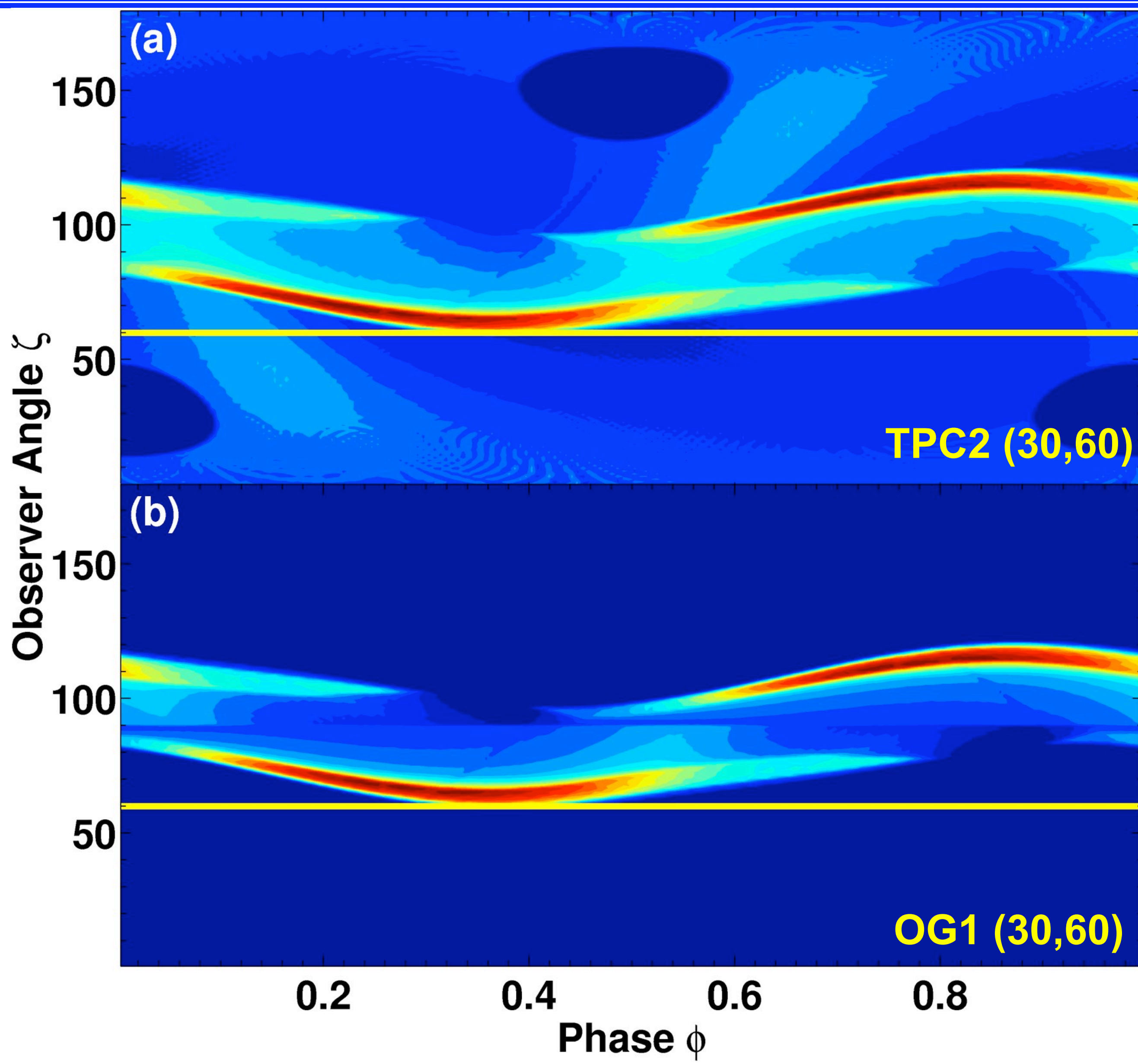
TPC Phaseplot as function of α



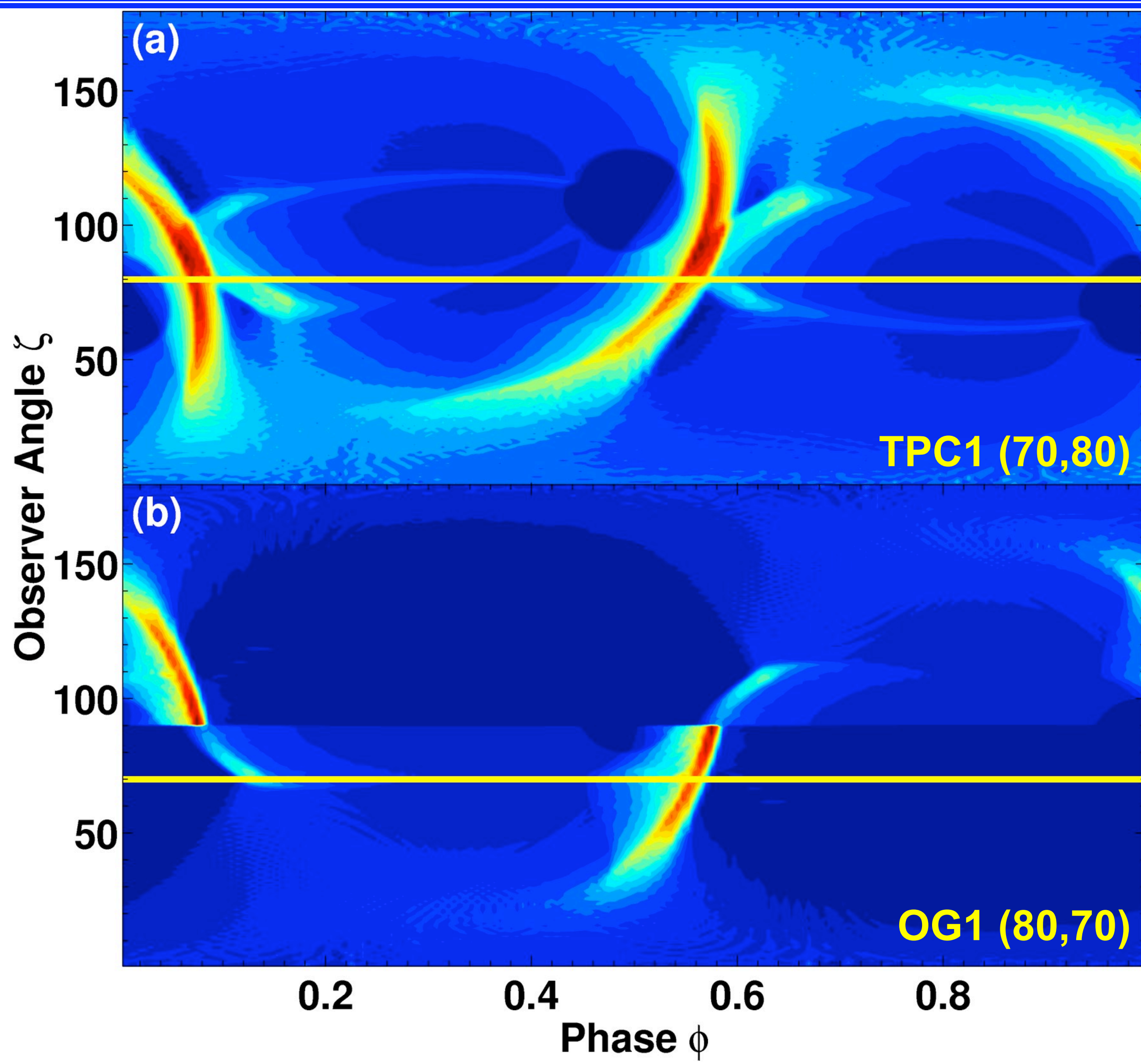
Light Curves as function of ζ



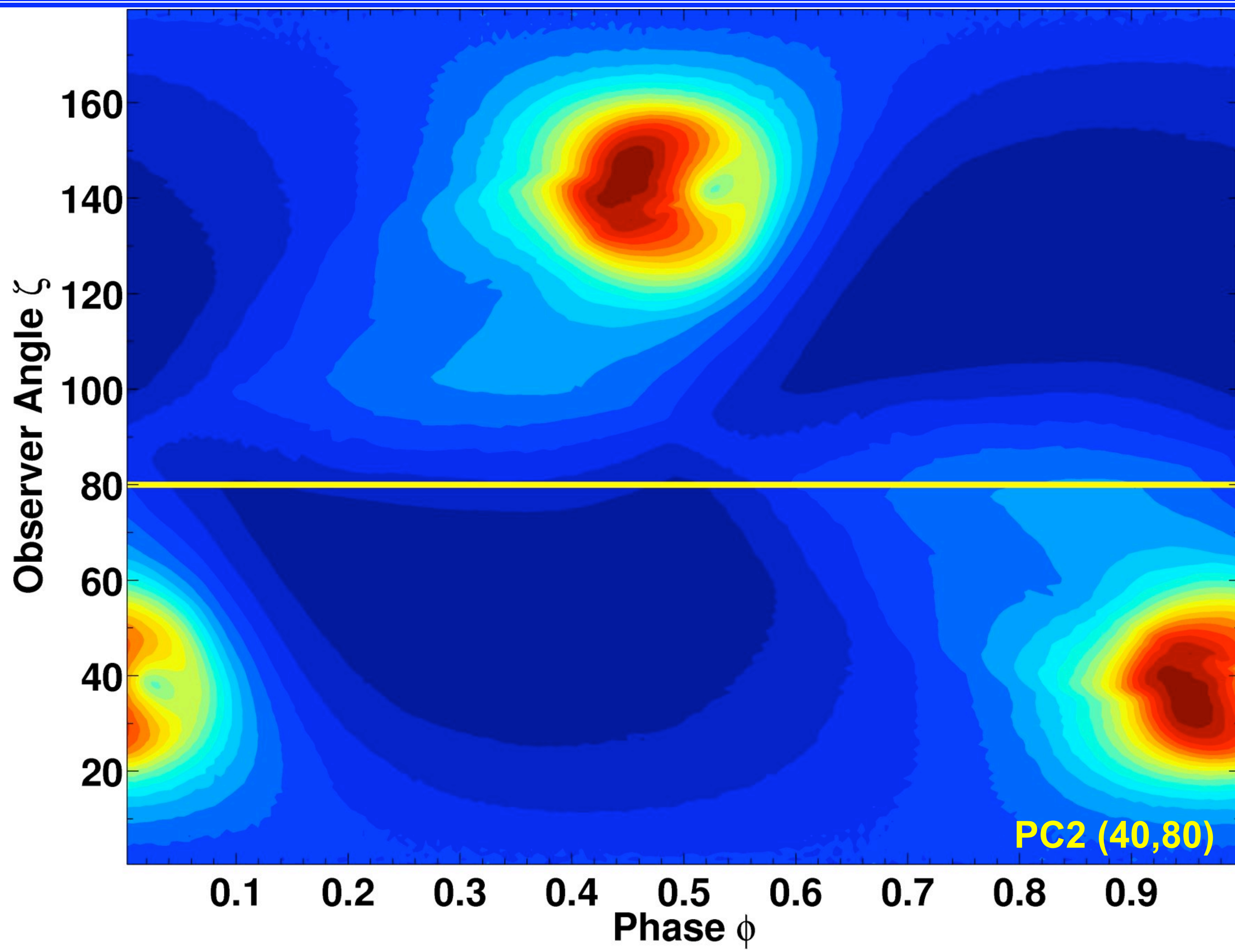
E.g. TPC & OG, $\alpha = 30^o$



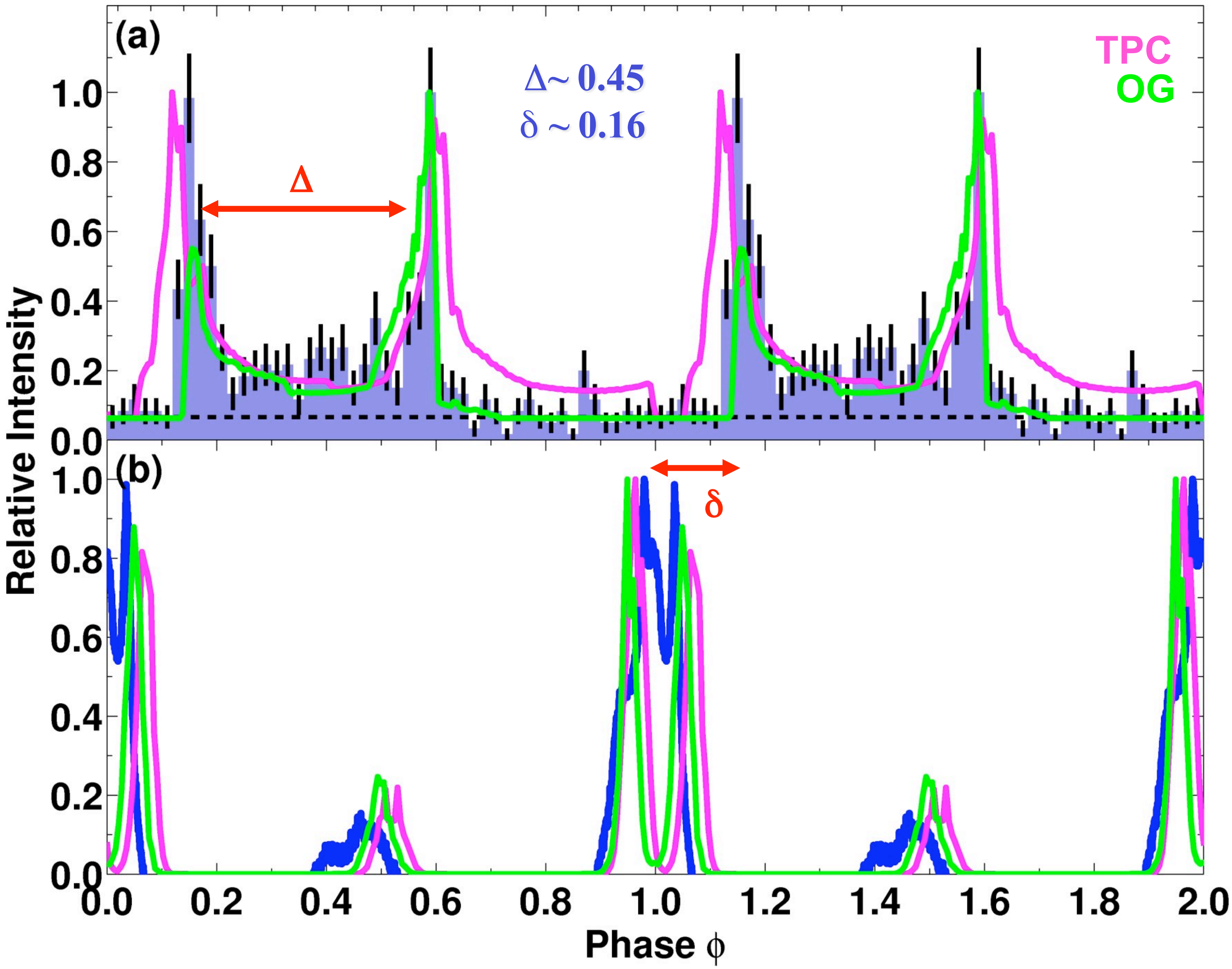
E.g. TPC & OG, α = 70º, 80º



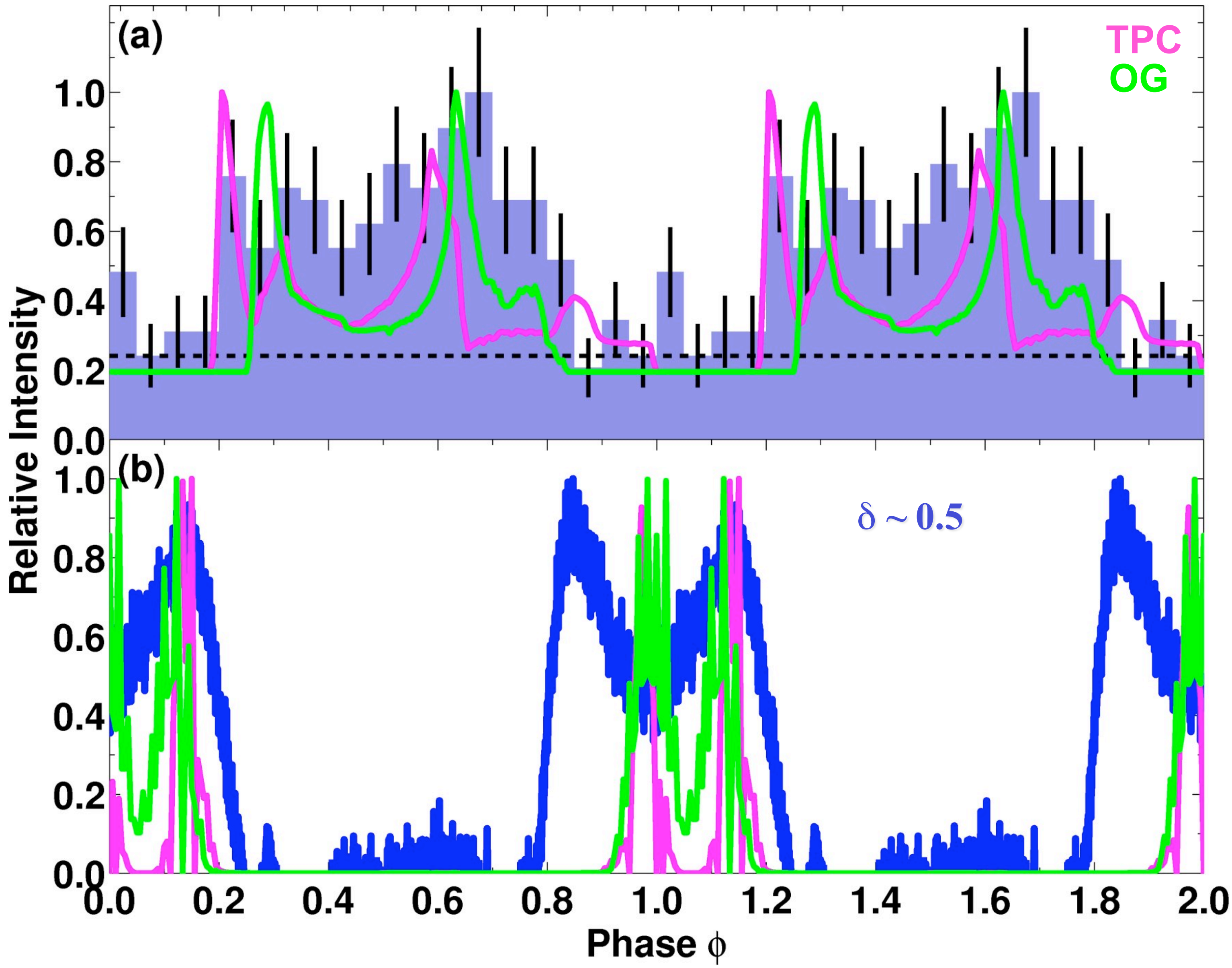
E.g. PSPC, α = 40°



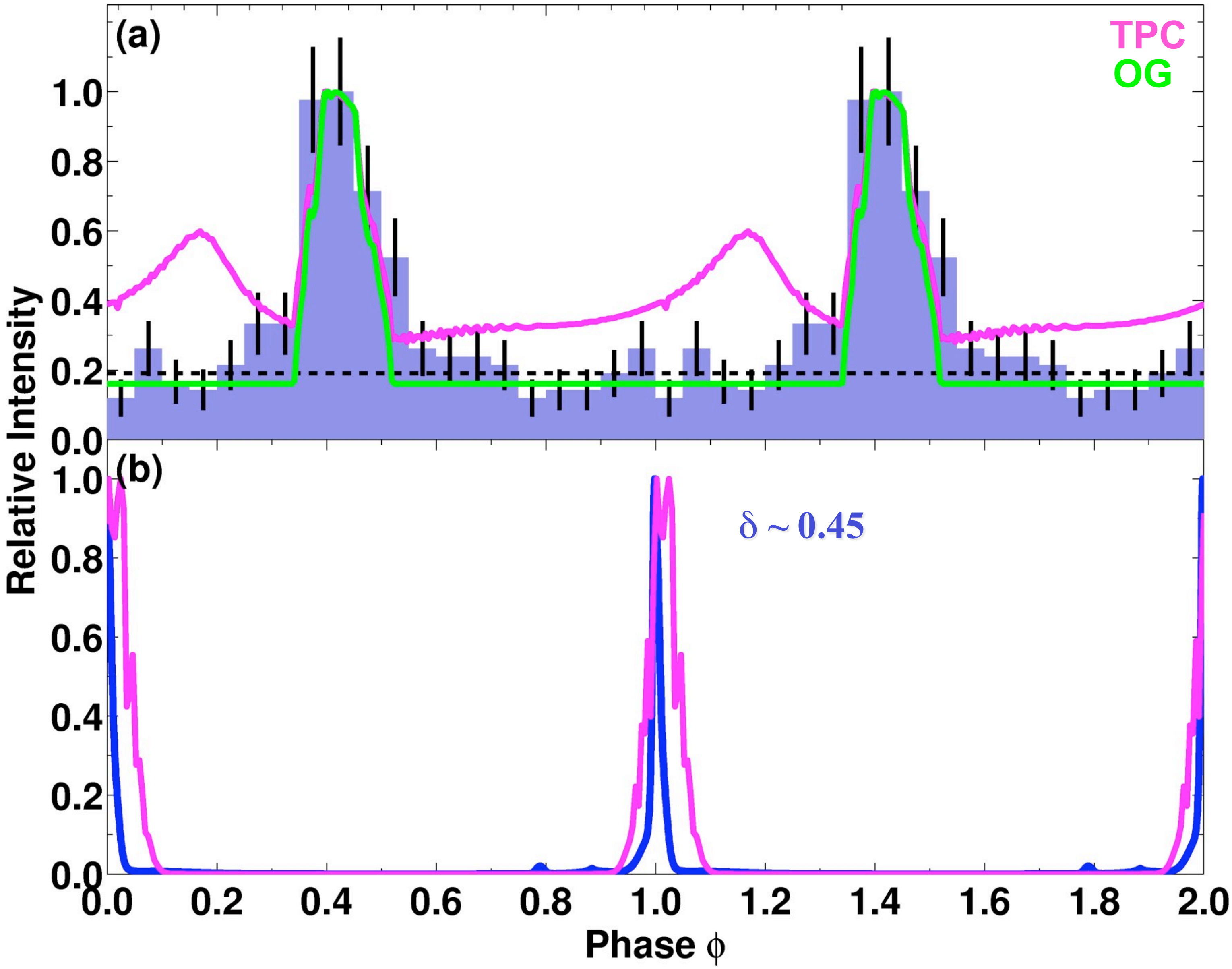
PSR J0030+0451



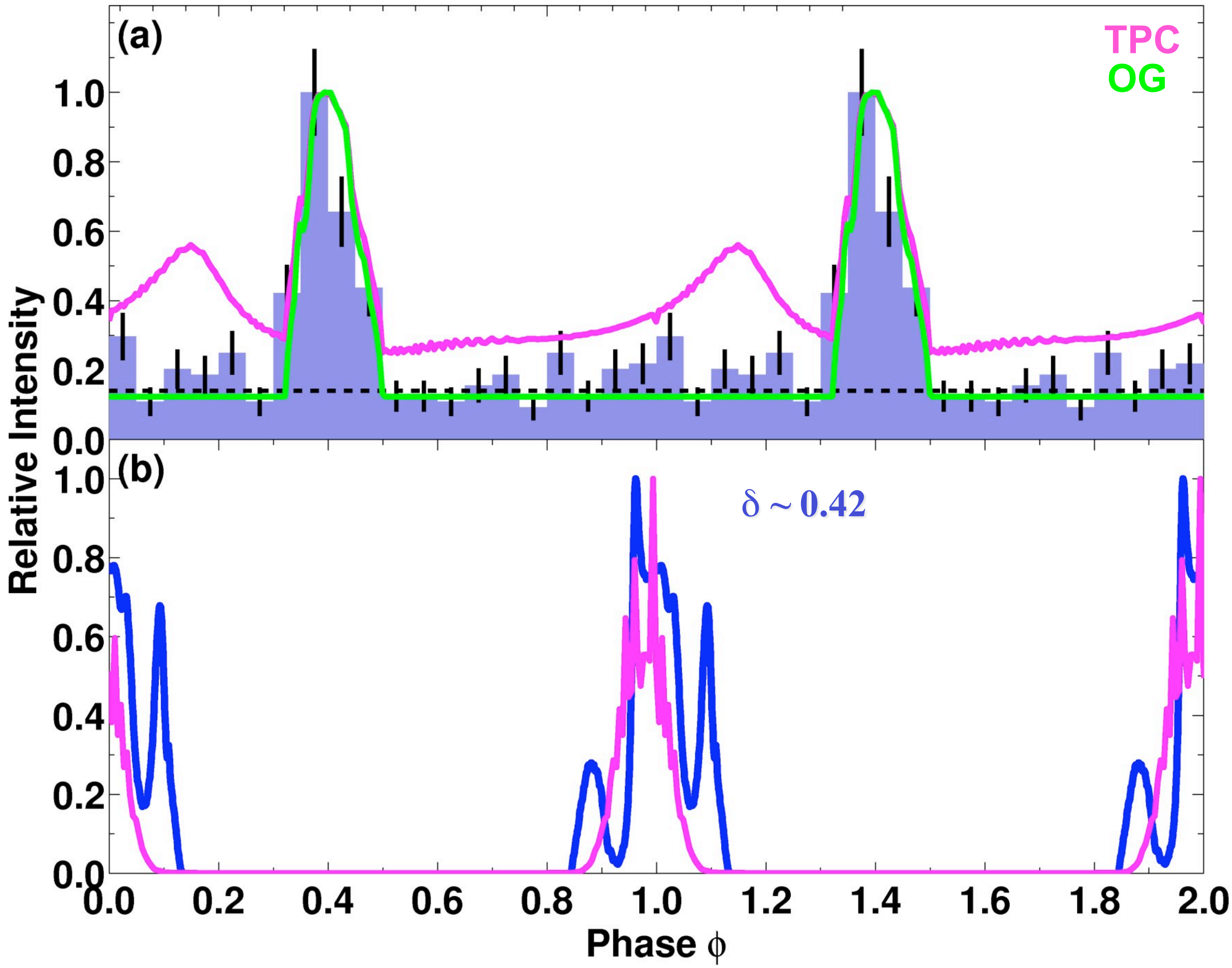
PSR J0218+4232



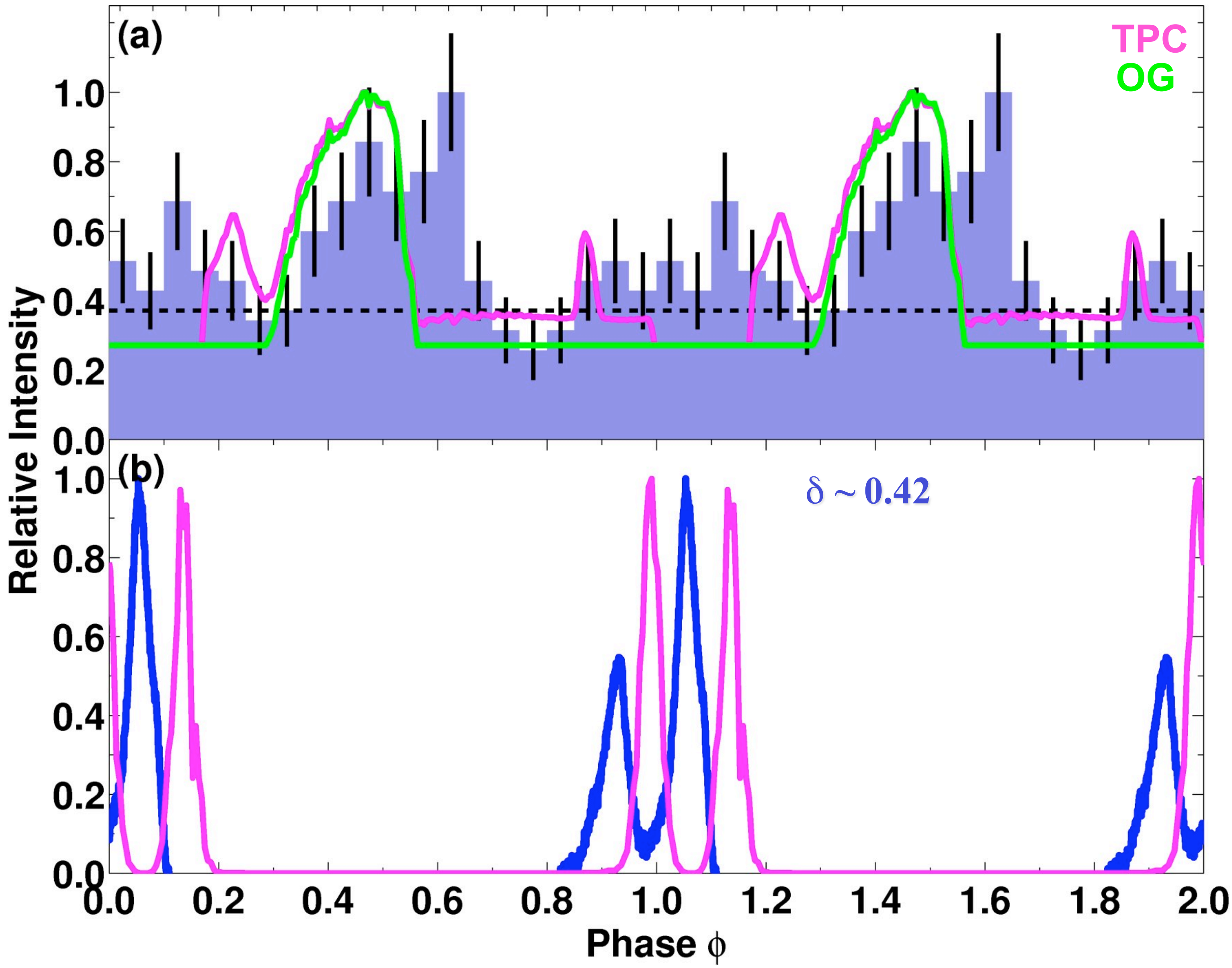
PSR J0437-4715



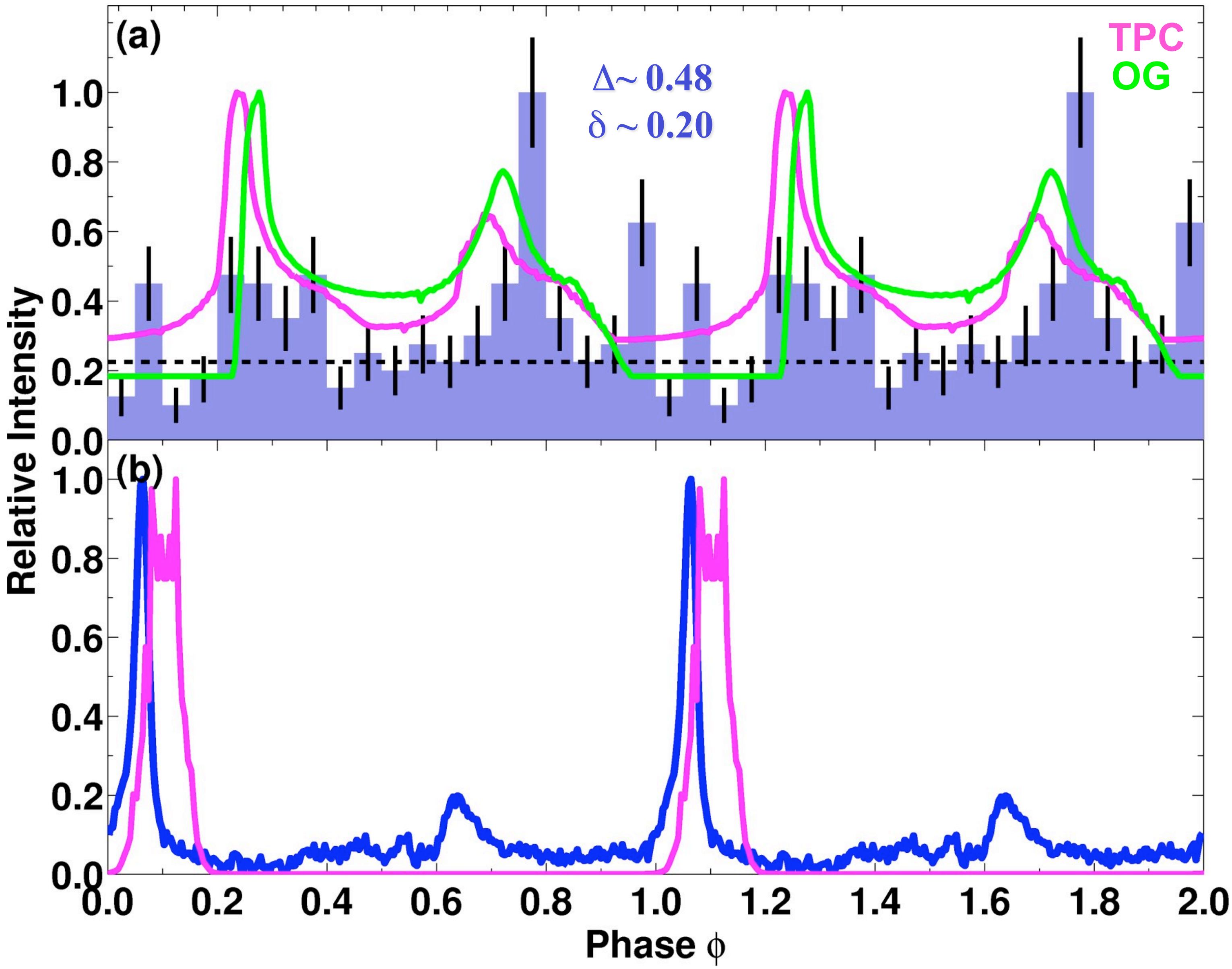
PSR J0613-0200



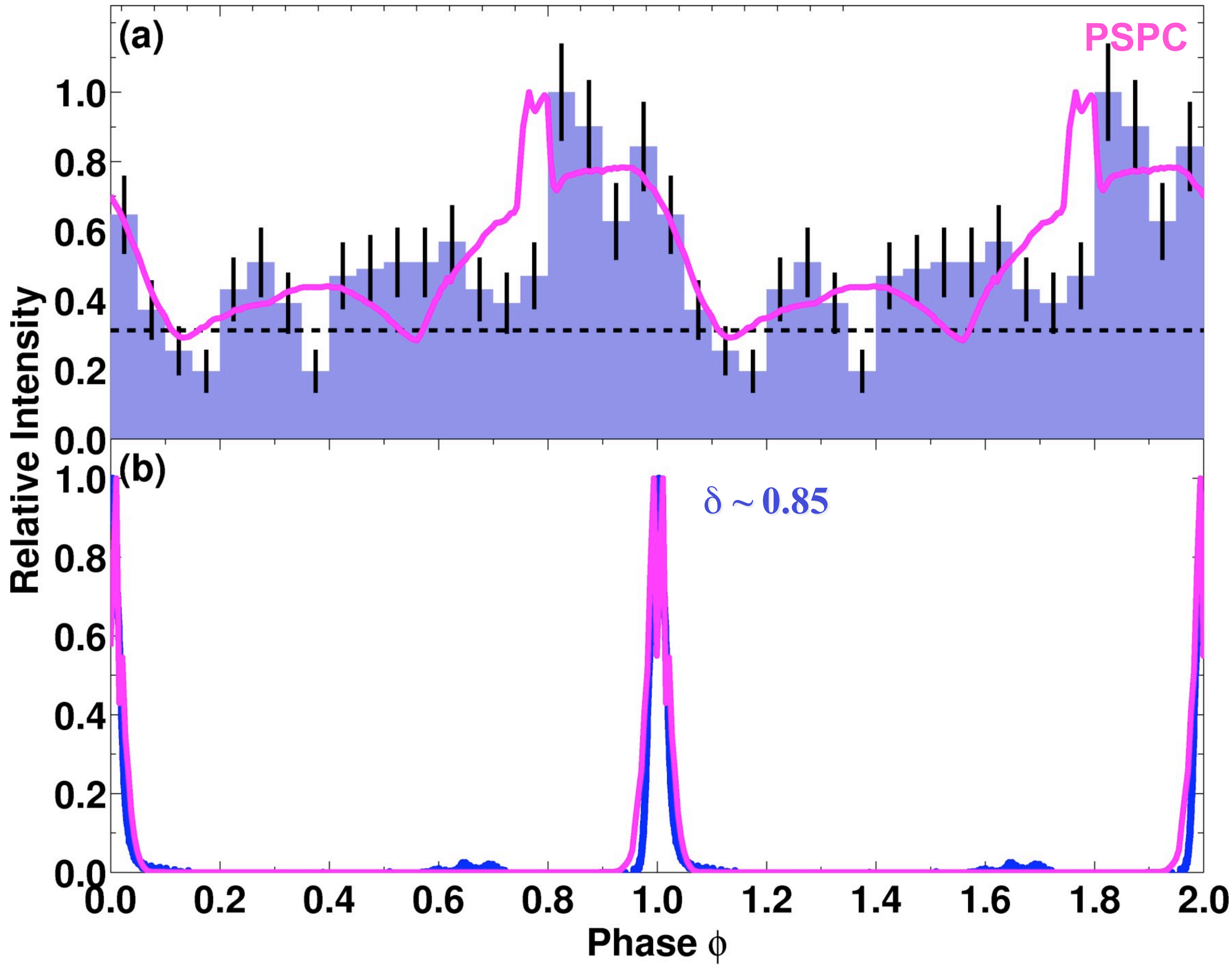
PSR J0751+1807



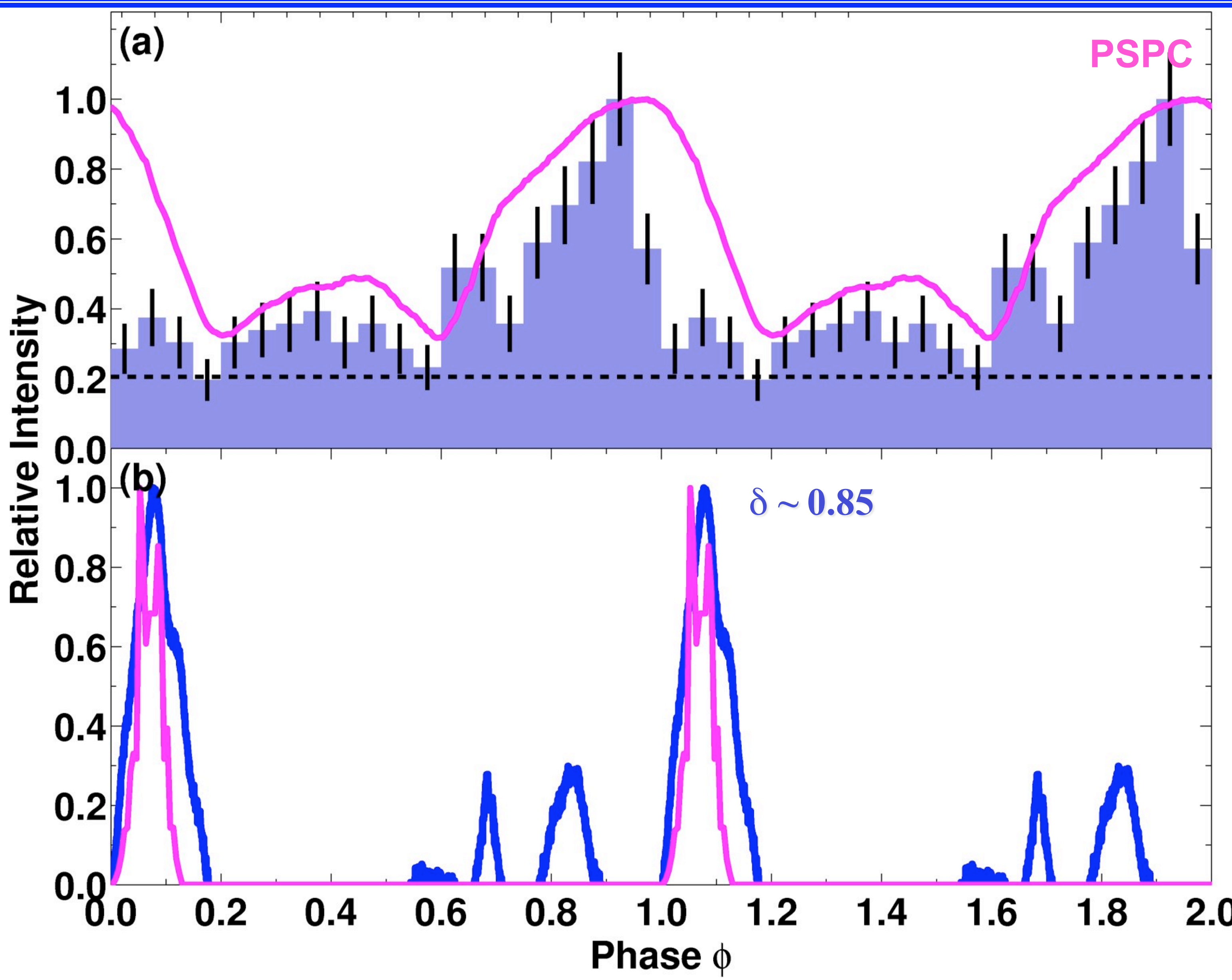
PSR J1614+2230



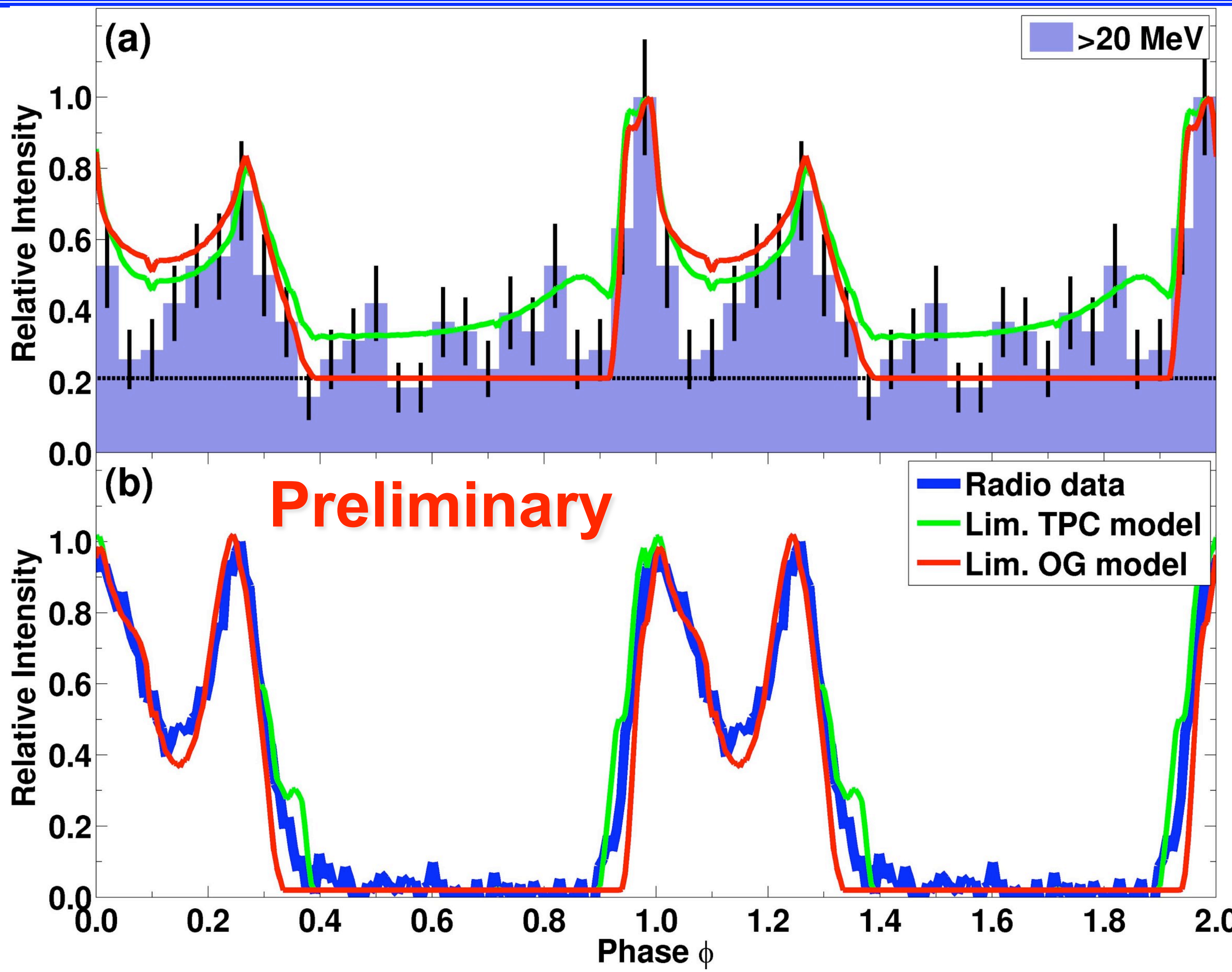
PSR J1744-1134



PSR J2124-3358



PSR J0034-0534



Fits of α and ζ

Name	$\alpha_{\rm TPC}$ (°)	$\zeta_{\rm TPC}$ (°)	$\alpha_{\rm OG}$ (°)	$\zeta_{\rm OG}$ (°)	$\alpha_{\rm PSPC}$ (°)	$\zeta_{\rm PSPC}$ (°)	$\alpha_{\rm radio}$ (°)	$\zeta_{\rm radio}$ (°)
J0030+0451	70	80	80	70	...	...	~ 62	~ 72
J0218+4232	60	60	50	70	...	...	~ 8	~ 90
J0437−4715	30	60	30	60	...	...	20 − 35	16 − 20
J0613−0200	30	60	30	60	...	...	small β	...
J0751+1807	50	50	50	50	...	...	...	...
J1614−2230	40	80	40	80	...	...	...	...
J1744−1134	...	...	...	...	50	80	...	...
J2124−3358	...	...	...	...	40	80	20 − 60 (48)	27 − 80 (67)
J0034 –0534	**30**	**70**	**30**	**70**				

Conclusions

- Pulse shape + lag: outer magnetospheric (high-altitude) emission (OG / SG / unscreened PC)
  - Unexpected implication: screening / pair cascades
  - We need to find new ways of creating pairs in low-spin-down magnetospheres (Compactness, Larger $E_{||}$, smaller ρ_c, larger B)
- Exclusive differentiation between PSPC vs. TPC / OG models
  - OG / SG: gamma trails radio with large lag
  - PSPC: radio has small lag w.r.t. gamma
- f_Ω: < 4 (~1); extended emission (wide beaming angle)
- Few radio-quiet MSPs expected: larger radio beam widths than for canonical pulsars
- Reasonable agreement with parameters inferred from MSP polarization measurements

Future Work

- Using full acceleration models to study gamma-ray:
  - Spectra (phase-resolved & phase-averaged)
  - Luminosities / Efficiencies
  - Light curves
- Constrain electrodynamical quantities & B-field structure
- Population studies
- Compare Galactic Field and Globular Cluster MSP properties?

THANKS!

"He stretches out the north over empty space; He hangs the earth on nothing."
(Job 26:7 NKJ)