Gamma-ray MSP Light Curve Modeling

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on behalf of the *Fermi* LAT Collaboration and Pulsar Timing Consortium

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Strategy & Goals

Geometric Simulations:

Use vacuum, retarded dipole B-field (Deutsch '55).

Assume constant emissivity, radiation-reaction limit, curvature radiation.

R_{NS} = 10 km, I = 10^{45} g cm^2, dP/dt = 10^{-20} s s^{-1}.

Define accelerating and emitting gaps on pulsar surface as specified sets of magnetic footpoints (see Venter+ '09 & Johnson '11).

Simulate for 1.5, 2.5, 3.5, 4.5, & 5.5 ms with 1° steps in magnetic inclination (α) and viewing (ζ) angles and 2.5% polar cap opening angle.

Light Curve Fitting:

Full radiation sims. time consuming, source-specific tailoring.

Geometric models, fit many MSPs, marginalize over uncertainties introduced by simplifying assumptions.

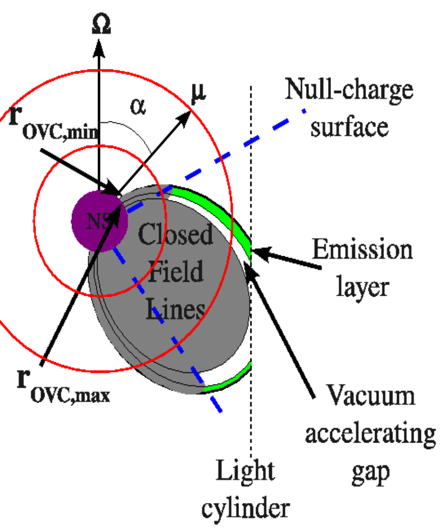
Joint radio and gamma-ray fit allows for extra, necessary constraints.

Produce confidence contours and uncertainties on other best-fit parameters.

Predict how geometry might change under different assumptions.

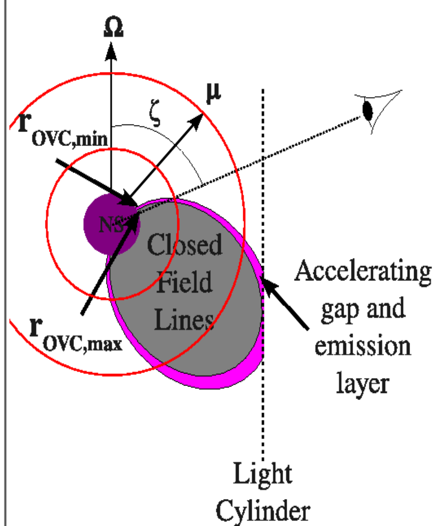
Gamma-ray Models

Outer Gap



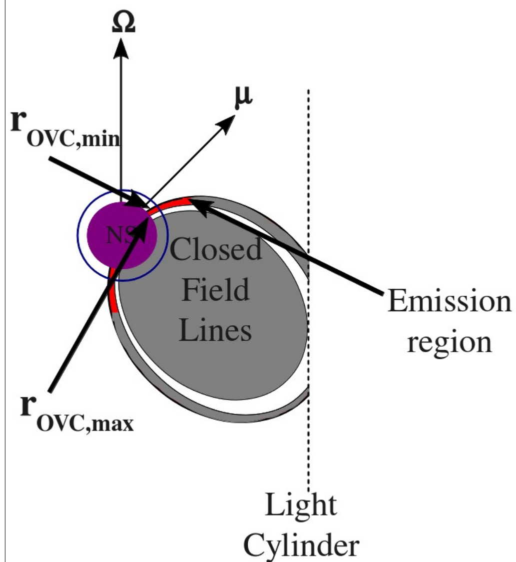
OG model
(e.g.; Cheng+ 86 & Romani & Yadigaroglu '95)

Two-Pole Caustic



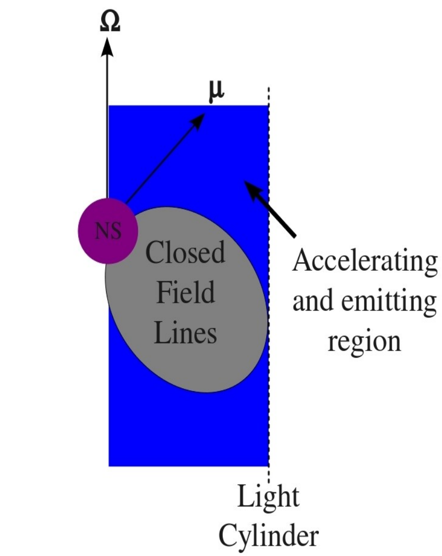
TPC model
(Dyks & Rudak '03) taken to be a geometric slot-gap (e.g.; Muslimov & Harding '04)

Low-altitude Slot Gap



(Venter+ '12) not uniform emissivity

Pair-starved Polar Cap



PSPC model
(e.g.; Harding+ '05) not uniform emissivity

MSP Model Classes

Class I: Gamma-ray peak(s) lag radio

Similar to young, non-recycled gamma-ray pulsars
Fit with TPC and OG models
Implies more pair-production than expected, offset dipoles?

Class II: Gamma-ray and radio peaks/features occur at ~ same phase

Fit with altitude-limited TPC/OG and laSG models
Implies extended radio emission region, caustic emission
Only seen in the Crab pulsar among young pulsars but 6 MSPs, why?

Class III: Gamma-ray peak(s) lead radio by ~0.2 in phase

Fit with PSPC model
Narrow gaps not formed, why?

Radio Models

Single-altitude, hollow-cone beam (with core, based on polarization) for **class I** and **III** MSPs.

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

(Kijak & Gil '03, units of R_{NS})

For **class II** MSPs use extended emission regions, co-located with gamma-ray emission regions, perhaps a combination?

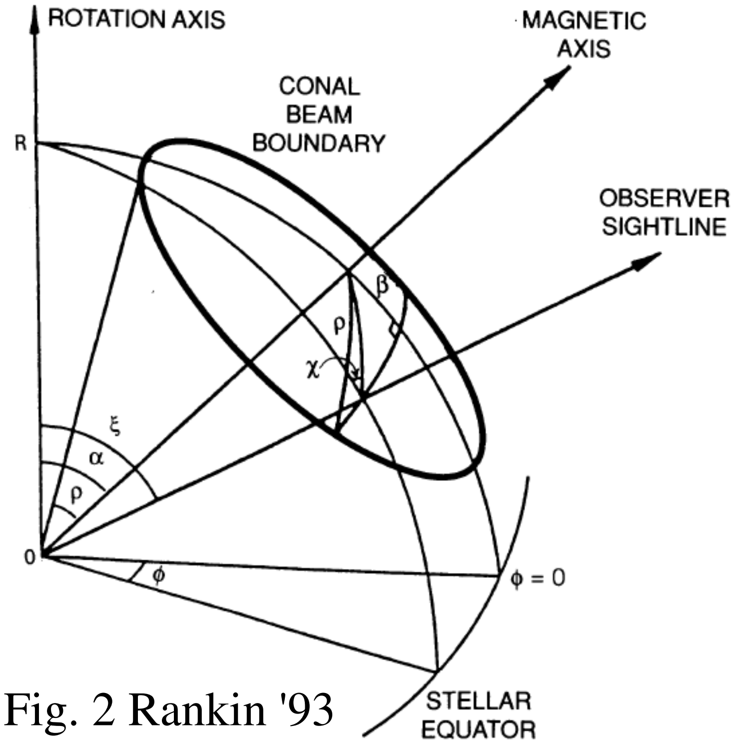
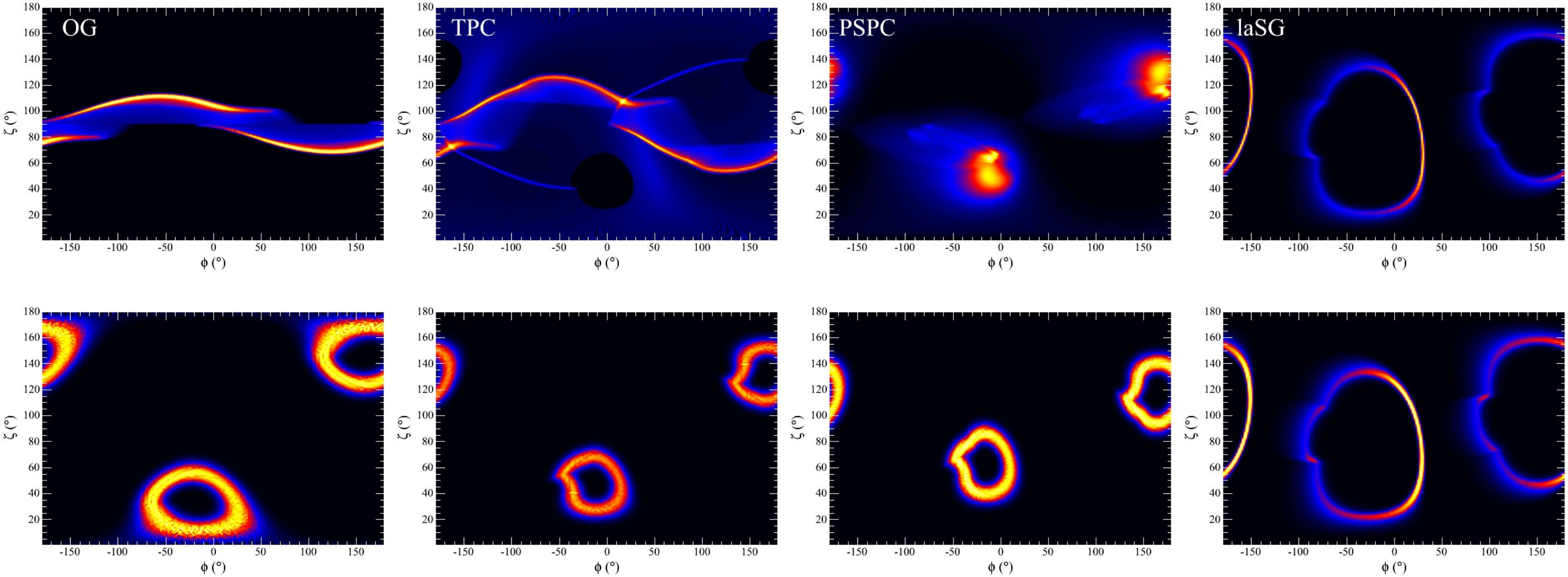


Fig. 2 Rankin '93

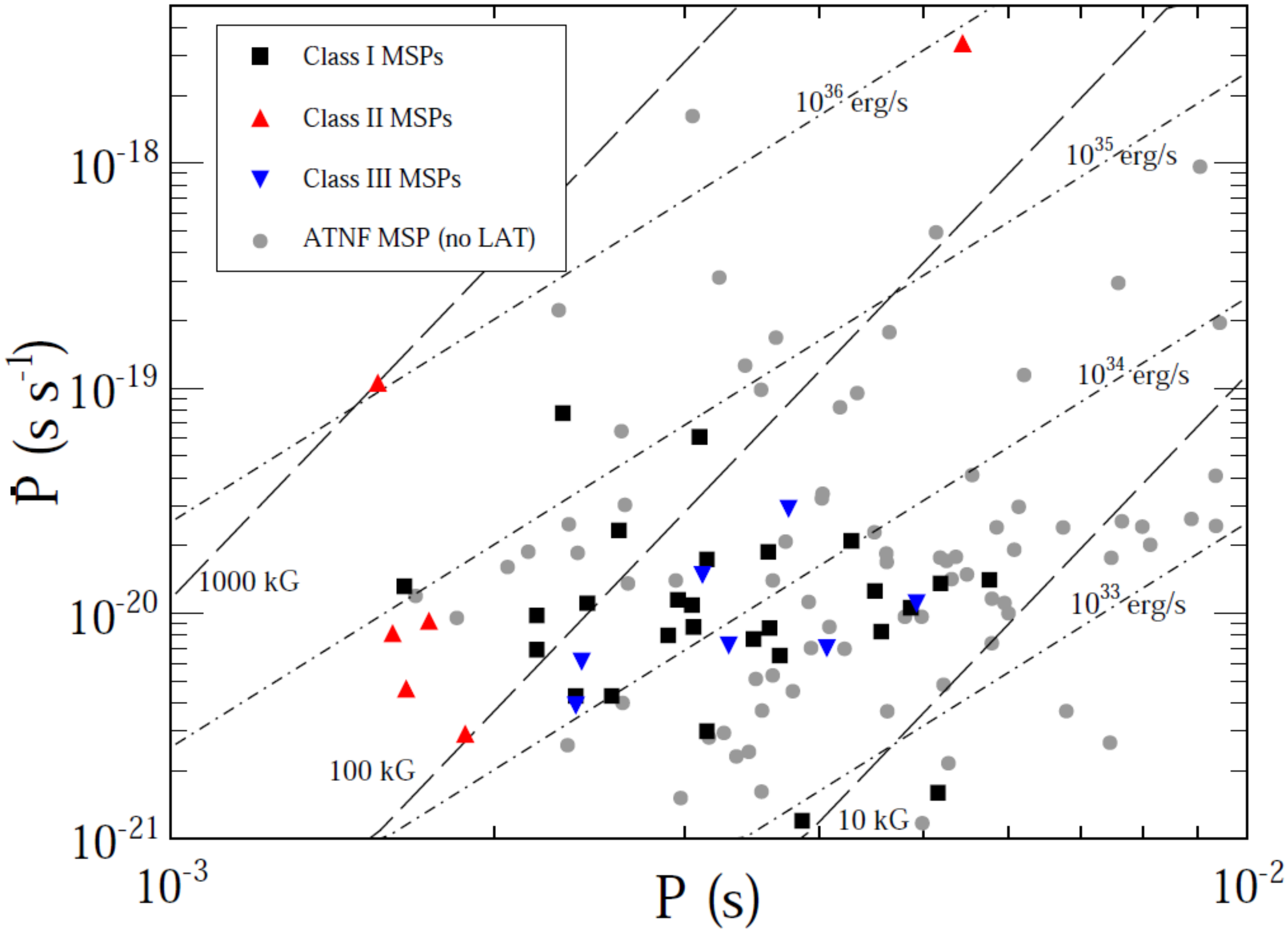
Emission Sky Maps

P = 2.5 ms, $\alpha = 30^{o}$ | **P = 3.5 ms, $\alpha = 45^{o}$** | **P = 5.5 ms, $\alpha = 60^{o}$** | **P = 1.5 ms, $\alpha = 75^{o}$**



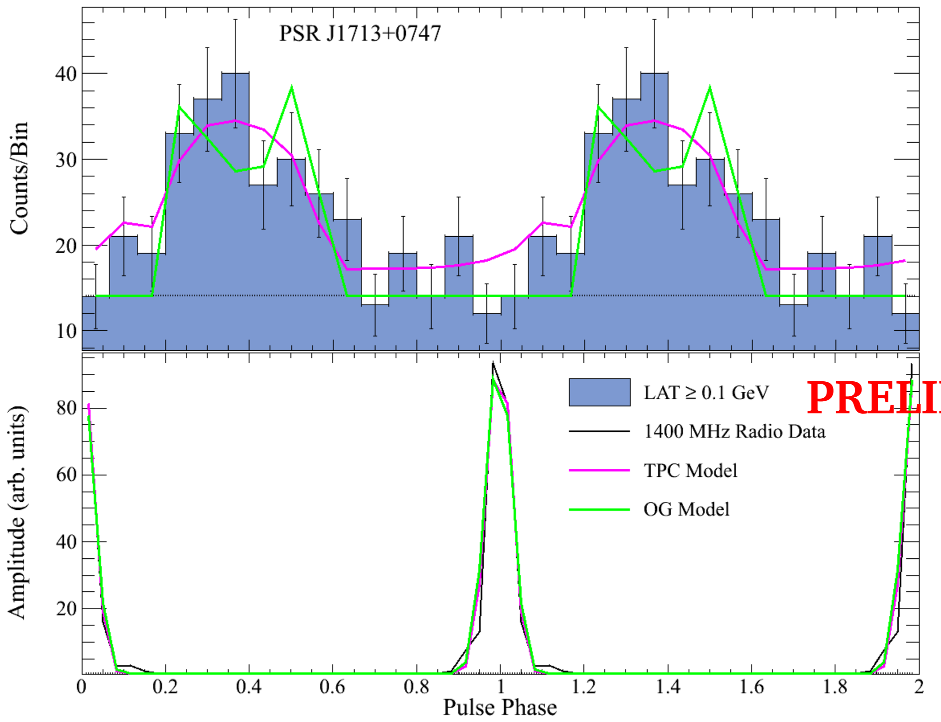
ν_{sim} = 1400 MHz | **ν_{sim} = 1400 MHz** | **ν_{sim} = 300 MHz**

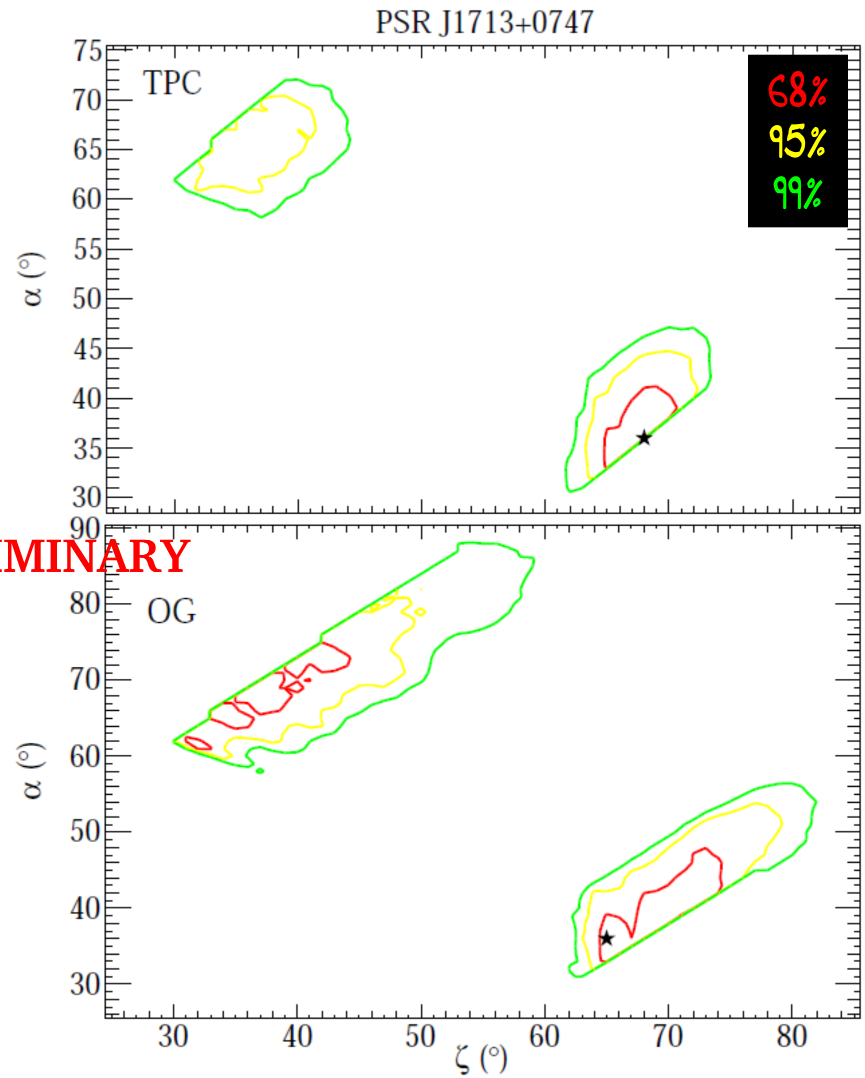
The 2PC MSP Sample



Example Fits (I)

Class I MSP, require core component, neither model significantly preferred.

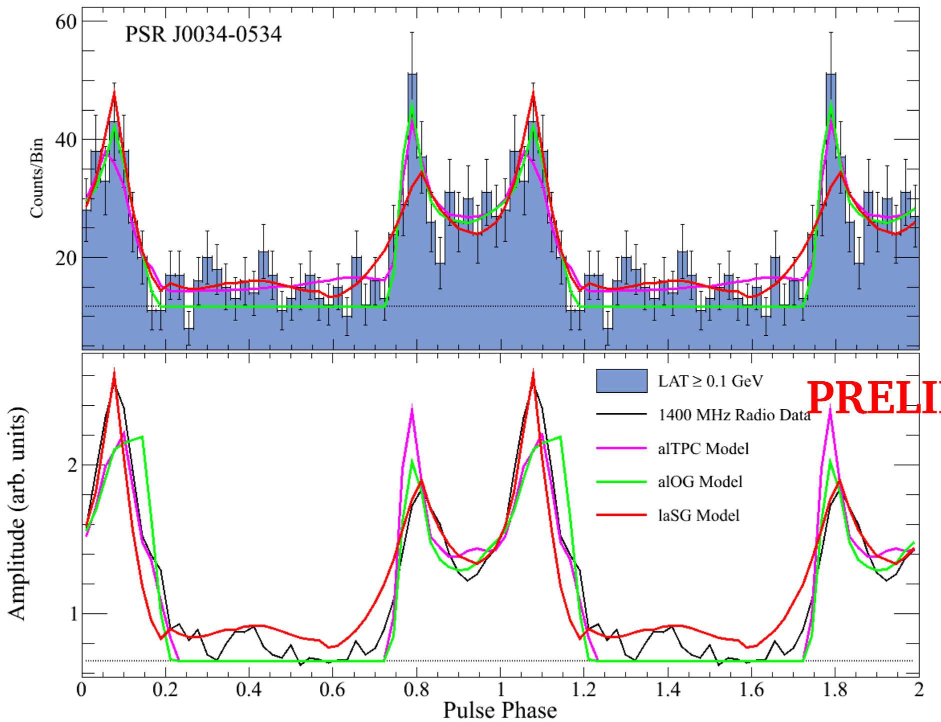




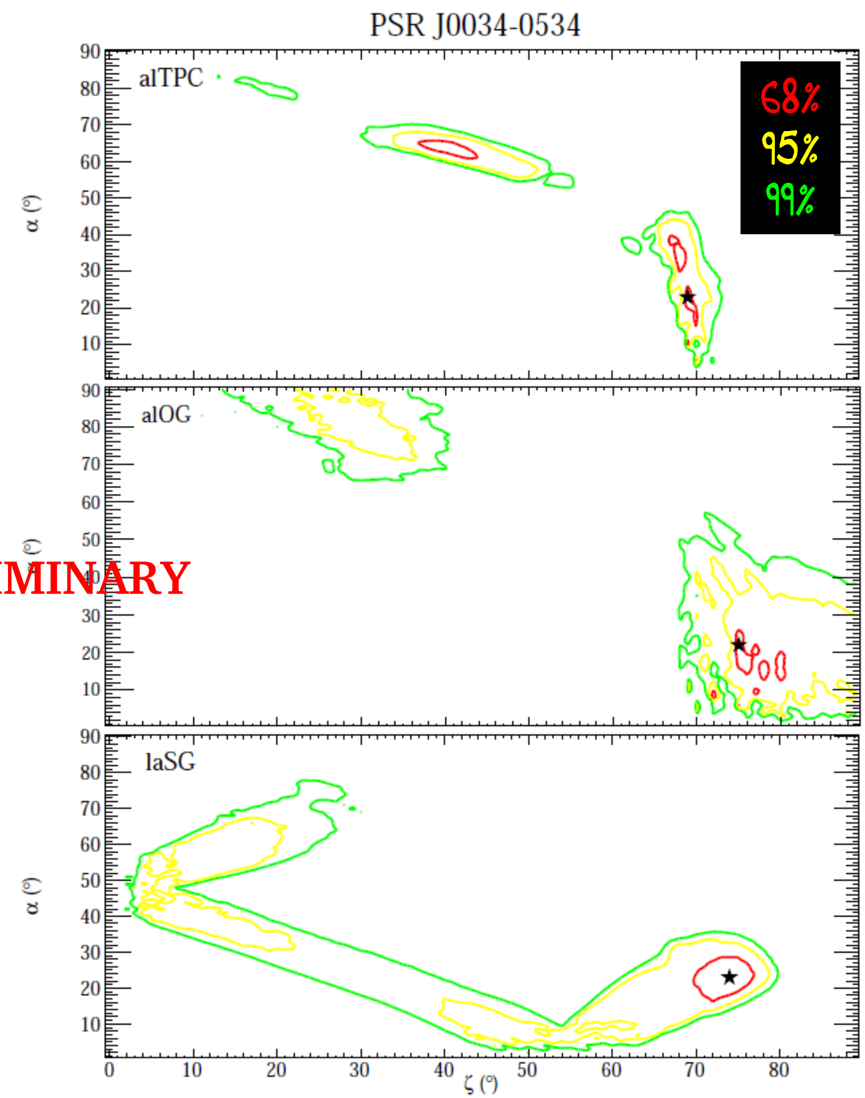
PRELIMINARY

Example Fits (II)

Class II MSP, alTPC model somewhat preferred.

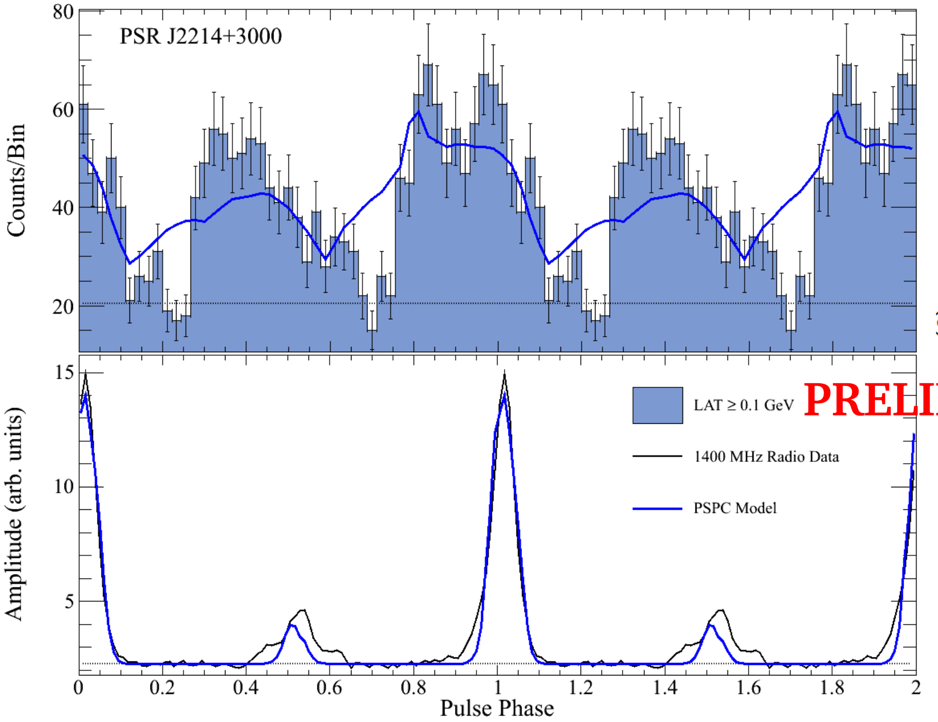


PRELIMINARY

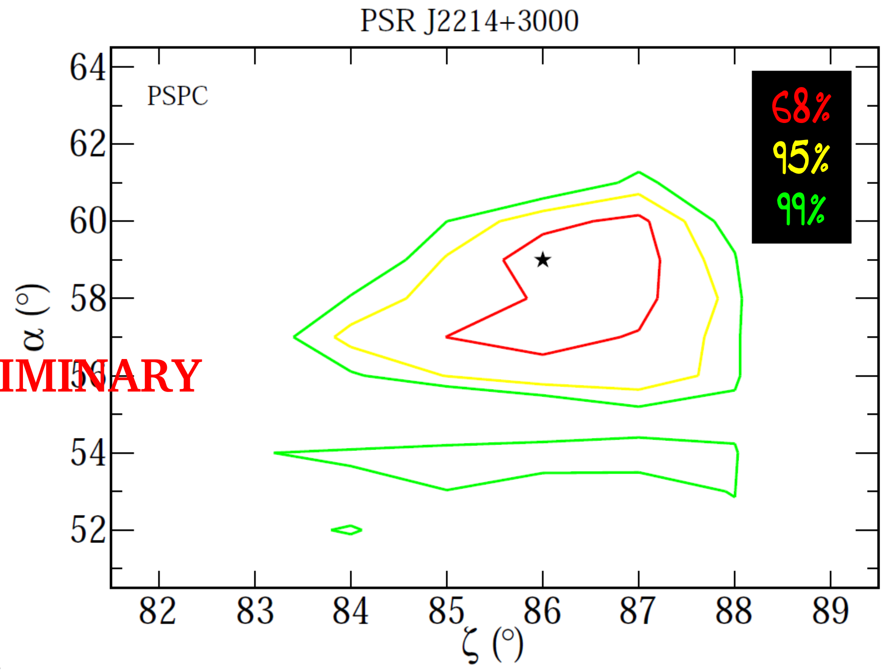


Example Fits (III)

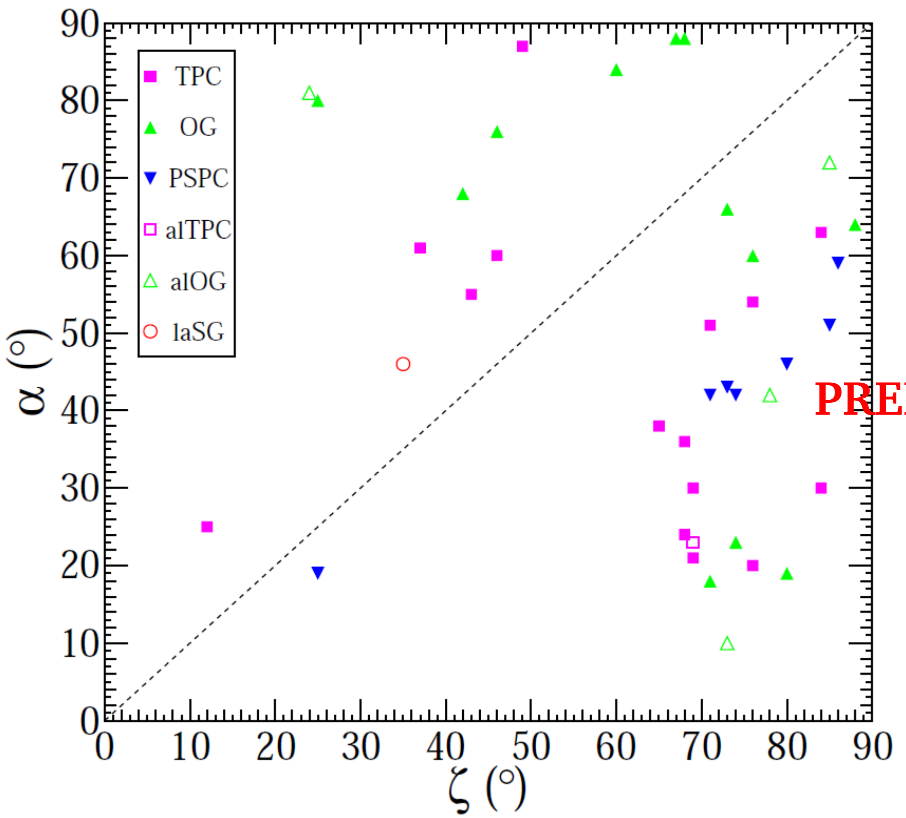
Class III MSP, phase-lag definition is tricky, but TPC and OG don't work.



PRELIMINARY



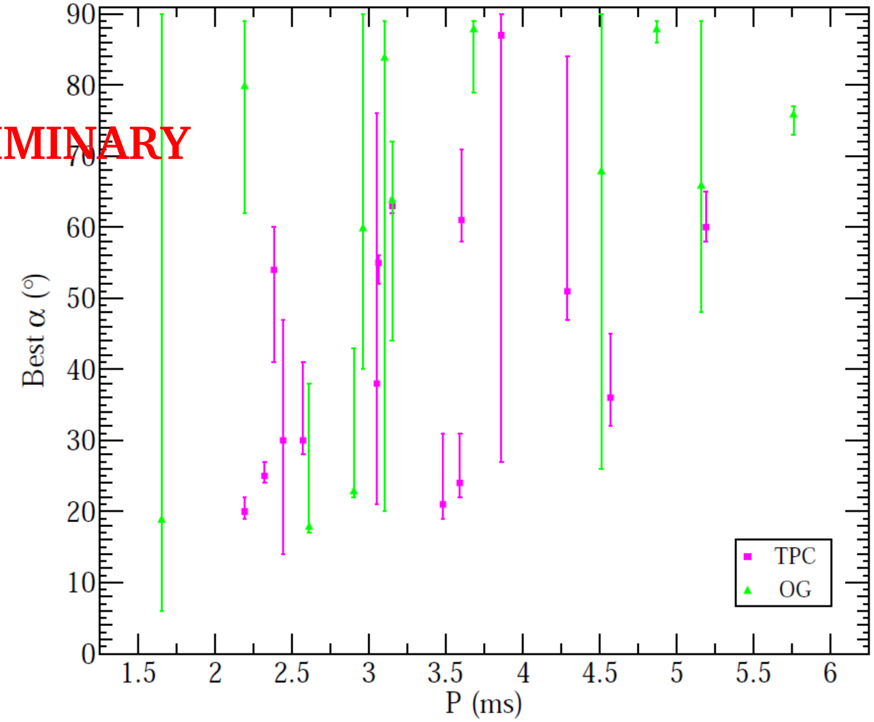
Geometry Trends



Best-fit (α,ζ), determined by lowest -ln(likelihood) for each MSP.

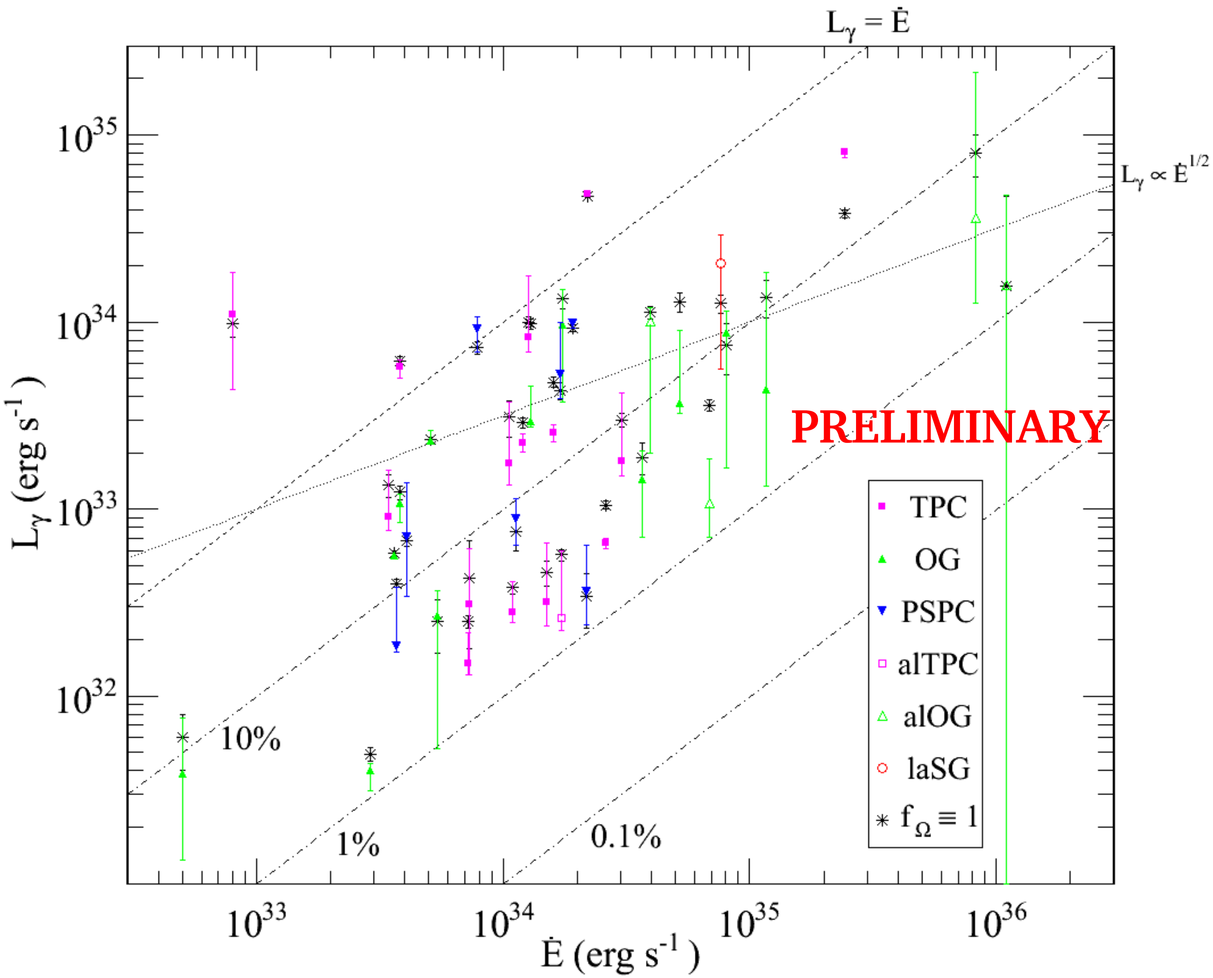
PRELIMINARY

Best-fit α vs. P for class I MSPs, uncertainties are 95% confidence level.



Likelihood differences only significantly prefer one model over the other for 7 of 27 MSPs.

Luminosity



energy flux distance

$$L_\gamma = 4\pi f_\Omega G d^2$$

beaming-correction factor

Can estimate from simulations, assumed to be 1 in 2PC.

Gamma-ray luminosity corrected for best-fit f_Ω, black stars are from 2PC, all values use statistical errors only.

Conclusions

Gamma-ray and radio light curve fits for the 40 MSPs in 2PC

- (α,ζ) confidence contours for all fits
- 27 class I—best fit by TPC (15) or OG (12)—need mix of these two models
- 6 class II—best fit by alTPC (4), alOG (4), or laSG (1)
- 7 class III—best fit by PSPC model

Trends in viewing geometry

- ζ preference near 90º
- α over all angles, possible P-dependent lower limit

Beaming-correction factor estimates

- typically ~1, a few >100% efficiency MSPs not simply due to geometry

Future

- off-set dipoles (Harding & Muslimov '11)
- finite conductivity magnetospheres
- explore higher-altitude and more complex radio beams

Acknowledgements & References

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Backup Slides

Joint Fitting

Scan over the model phase space, optimizing model normalizations at each grid point

Poisson Likelihood for gamma-ray light curve

d_i = counts in i^{th} bin

m_i = model value in i^{th} bin

$$\ln(L_\gamma) = \ln\left[\prod_i \left(\frac{m_i^{d_i}\exp\{-m_i\}}{d_i!}\right)\right]$$

χ^2 statistic for radio profile, estimate of radio error important.

σ_R = radio error est.

$$\ln(L_R) = -0.5\sum_i \left(\frac{d_i - m_i}{\sigma_R}\right)^2$$

Systematic Effects

Standard σ_R estimated as maximum value of radio light curve bins times average relative uncertainty from on-peak interval of gamma-ray light curve. If using more radio bins, σ_R decreased by ratio of gamma-ray to radio bins.

Factor of 2 change in σ_R results in < 30º change in α and/or ζ. Class II and III MSPs less strongly affected.

5% change in gamma-ray background estimate does not strongly affect geometry but can affect -ln(likelihood) value by as much as 7, need -ln(likelihood) different by at least 15 for difference to be significant.

Departing from vacuum, retarded-dipole approximation will increase predicted gamma-to-radio phase lag by up to ~0.1, accounting for this results in <10º change in α and/or ζ.