Modelling the Light Curves of *Fermi* LAT Millisecond Pulsars

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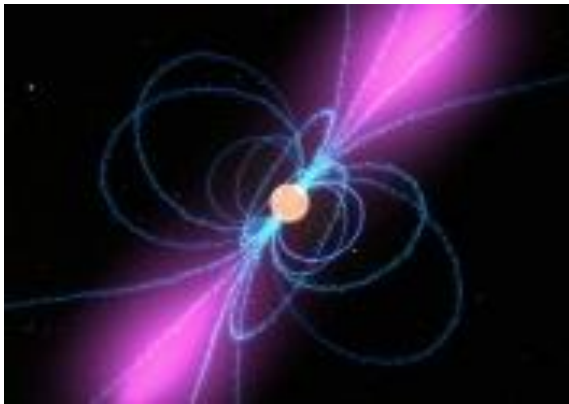
Why MSPs are Special

- **Smaller light cylinders: Radio emission beams at relatively higher altitudes**

- **Radio beams wider: Visible for larger impact angle $|\beta| = \zeta - \alpha$**

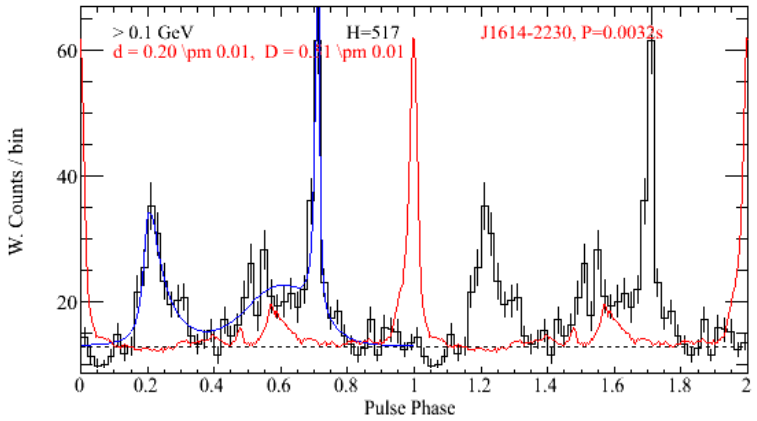
- **More complicated B-field structure: Relatively more diverse profiles?**

- **More massive: Increased E-field?**



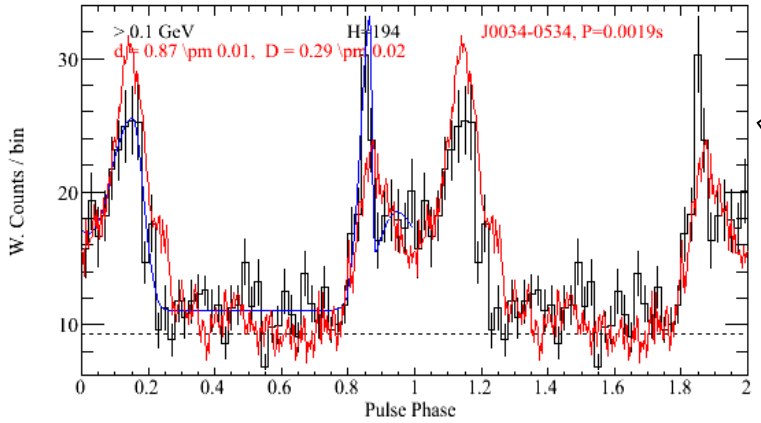
Millisecond Pulsar Profile Types

1. γ-ray peak(s) lag main radio peak
   - Similar to young pulsars
   - **"Class I"**
2. γ-ray peaks aligned with radio peaks
   - *Nearly* exclusive to MSPs
   - **"Class II"**
3. γ-ray peak(s) lead main radio peak(s)
   - Exclusive to MSPs
   - **"Class III"**

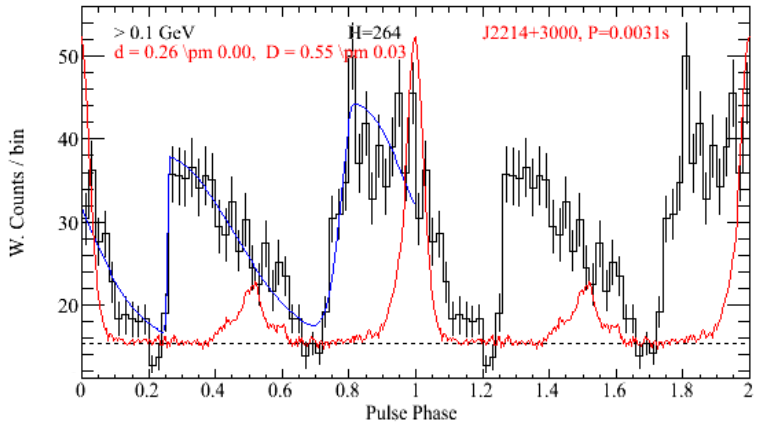


2nd *Fermi* LAT Pulsar Catalog (Abdo et al. 2013)

(See talk of P. Ray)

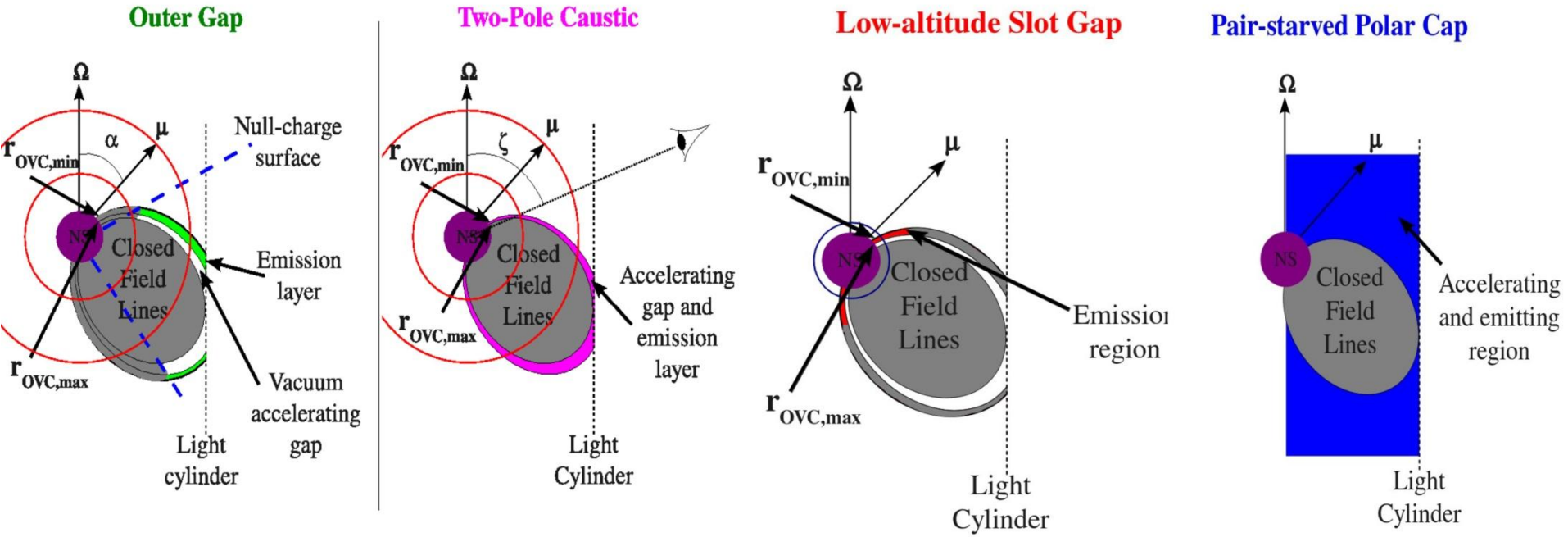


PRELIMINARY



Johnson et al. (2013)

Accelerator / Emission Geometries



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

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

(different from Watters et al. 2009)

laSG model (Venter+ '12) not uniform emissivity

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

Radio Emission Geometries

Single-altitude, hollow-cone beam (with core based on polarization) for MSPs with gamma-ray peaks lagging radio (**class I**) or gamma-ray leading radio by ~0.2 in phase (**class III**).

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

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

For MSPs with gamma-ray and radio peaks at (nearly) same phase (**class II**), use extended emission regions, co-located with gamma-ray emission regions (either laSG or altitude-limited TPC/OG (alTPC/OG) models).

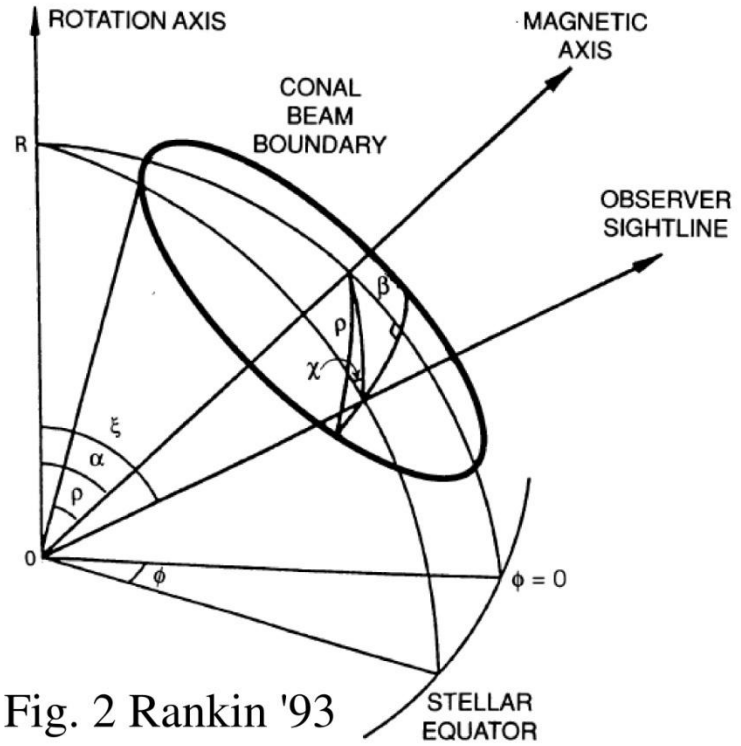
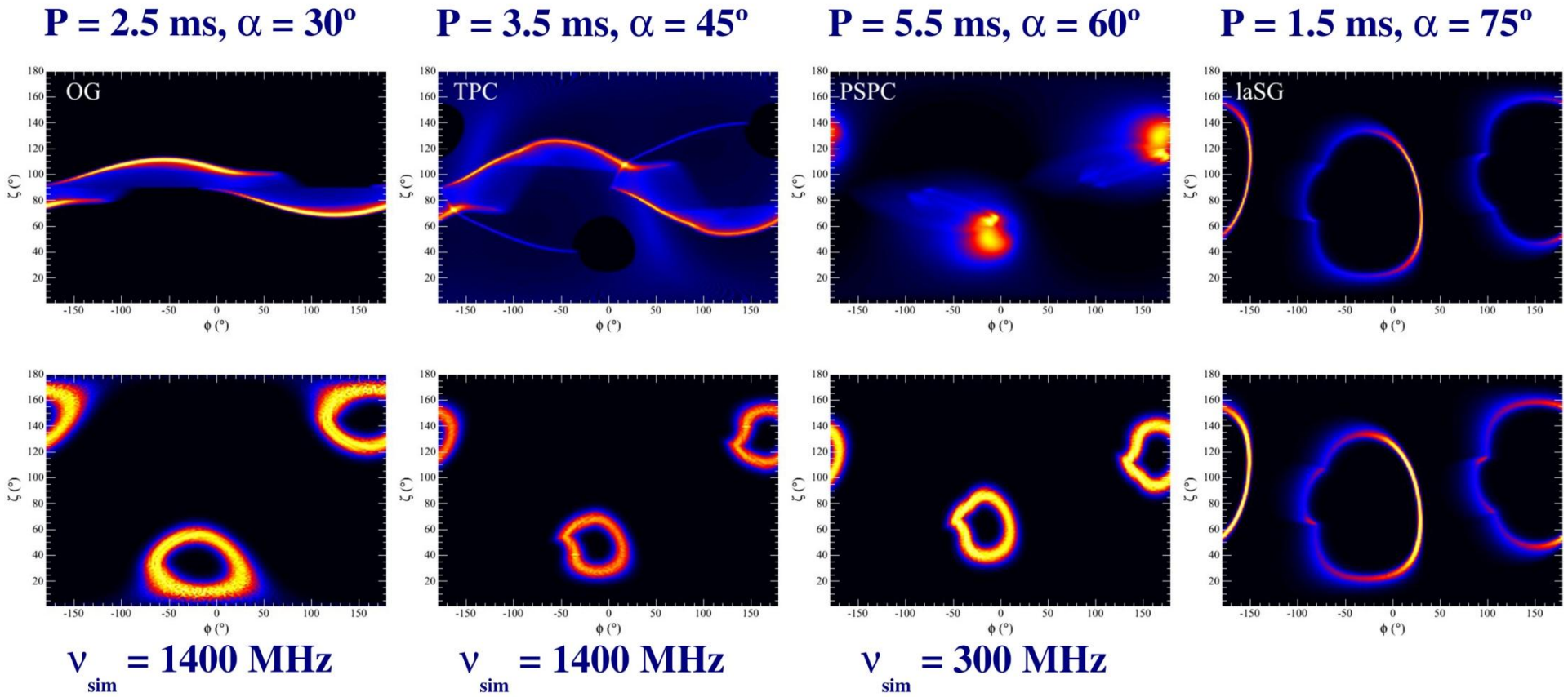


Fig. 2 Rankin '93

Sky Distribution of Intensity



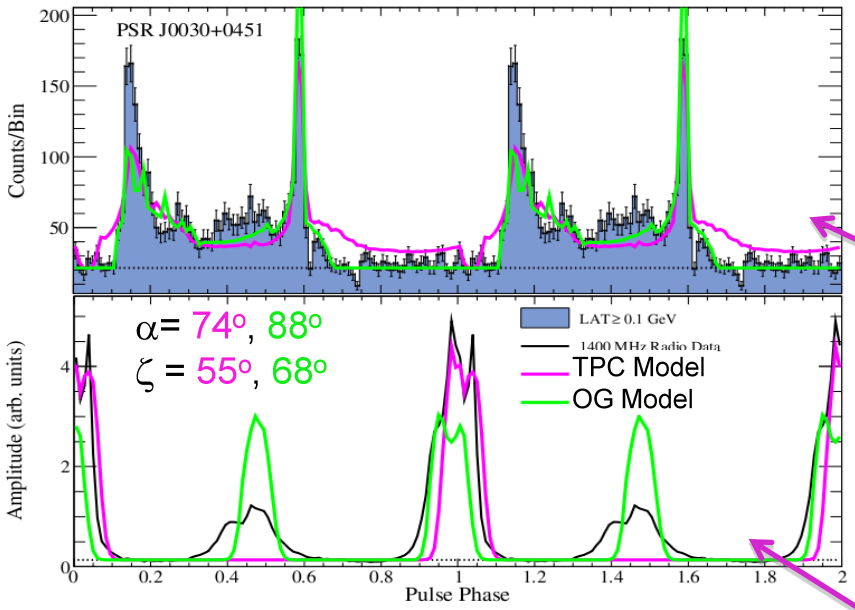
- Retarded dipole field (Deutsch 1955)
- Constant emissivity in corotating frame
- Grid of model parameters
- Find best joint radio / γ-ray fits using log(likelihood)

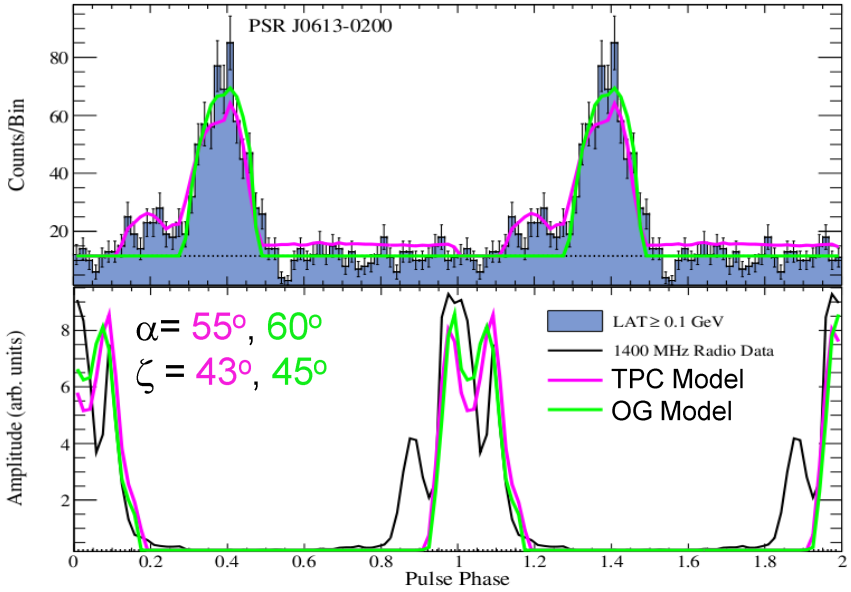
Modelling MSP γ-ray and Radio Profiles

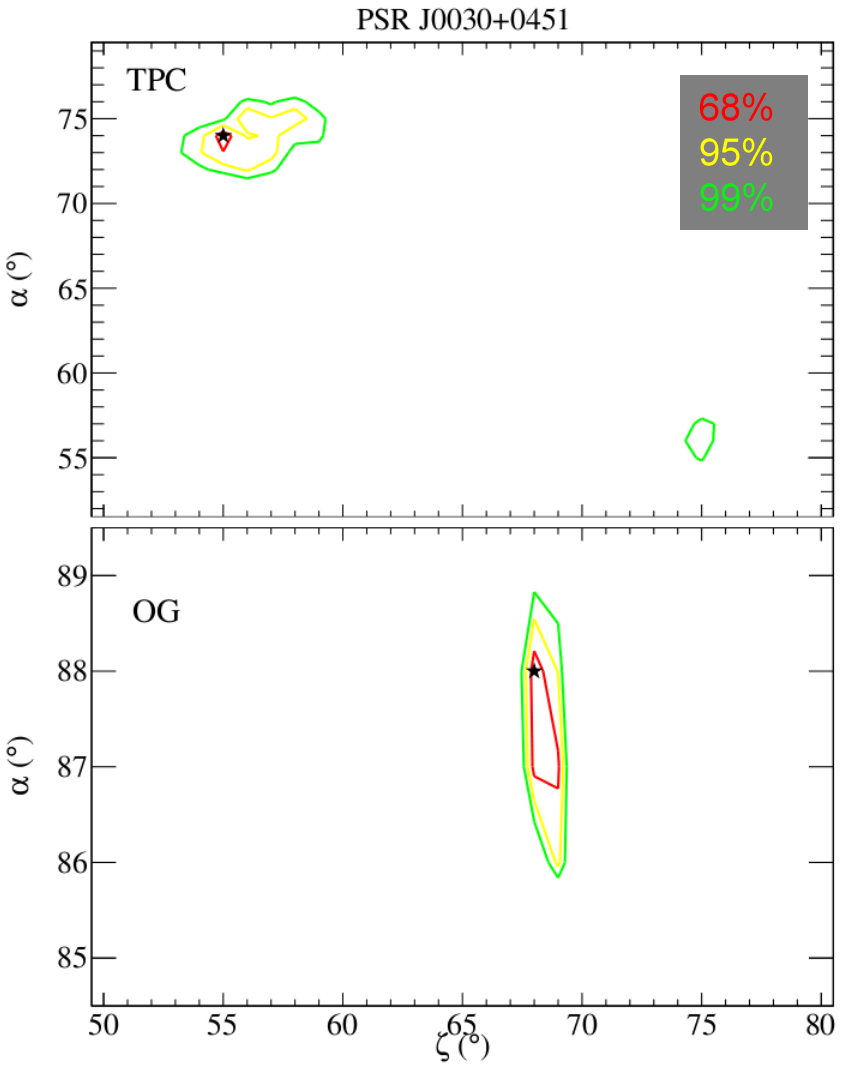
Johnson et al. (2013) — **Outer gap** and **Two-pole caustic** models

PRELIMINARY

"Class I"





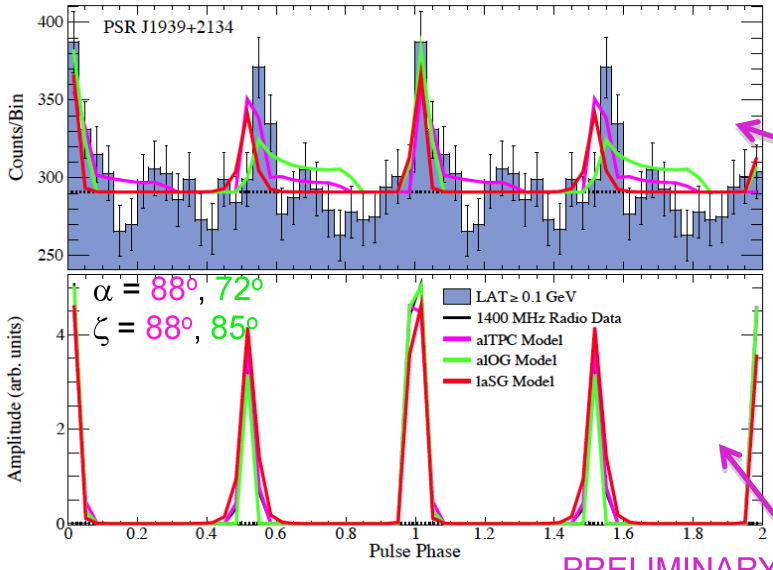


Maximum Likelihood Fits of Aligned MSPs

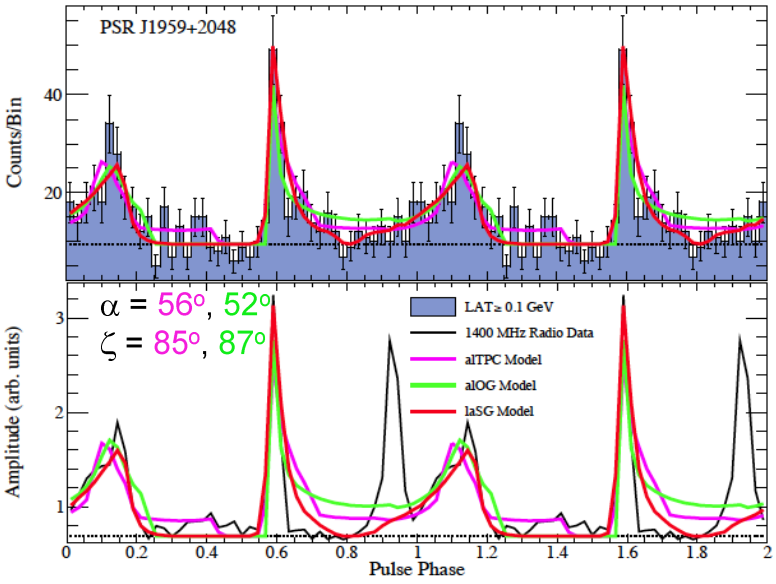
Johnson et al. (2013)

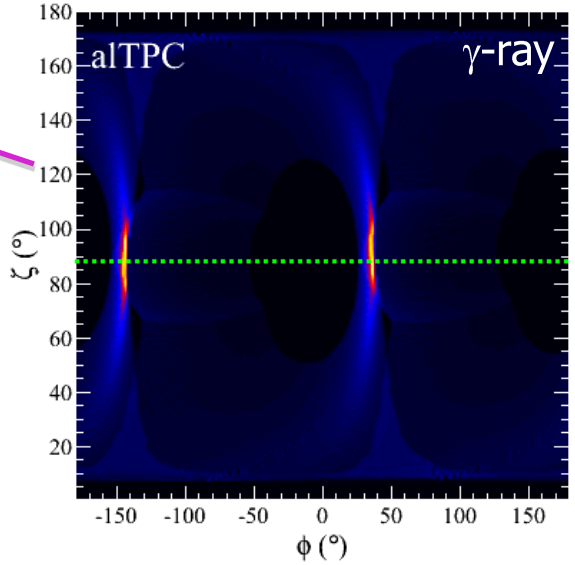
Altitude-limited Two-pole caustic, Outer Gap and Low-altitude Slot Gap

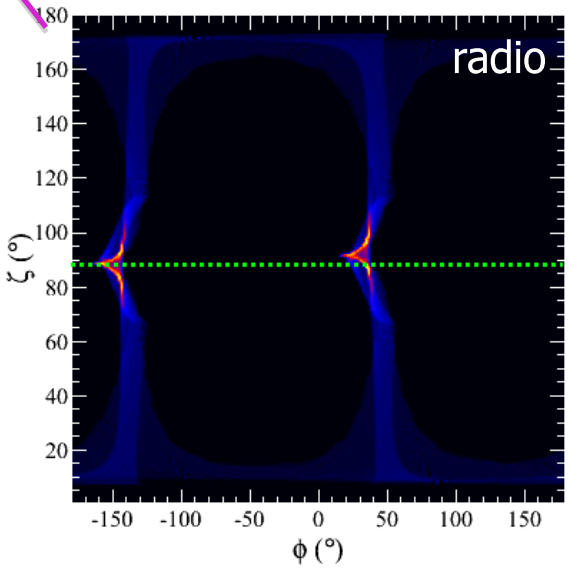
"Class II"



PRELIMINARY







γ–ray and radio emission both *caustic* but with different altitude ranges:

$R^{\gamma}_{min} = R_{ns}, R_{ncs}$

$R^{\gamma}_{max} = 0.85, 0.8\ R_{LC}$

$R^{r}_{min} = 0.75, 0.9\ R_{LC}$

$R^{r}_{max} = 0.95, 1.05\ R_{LC}$

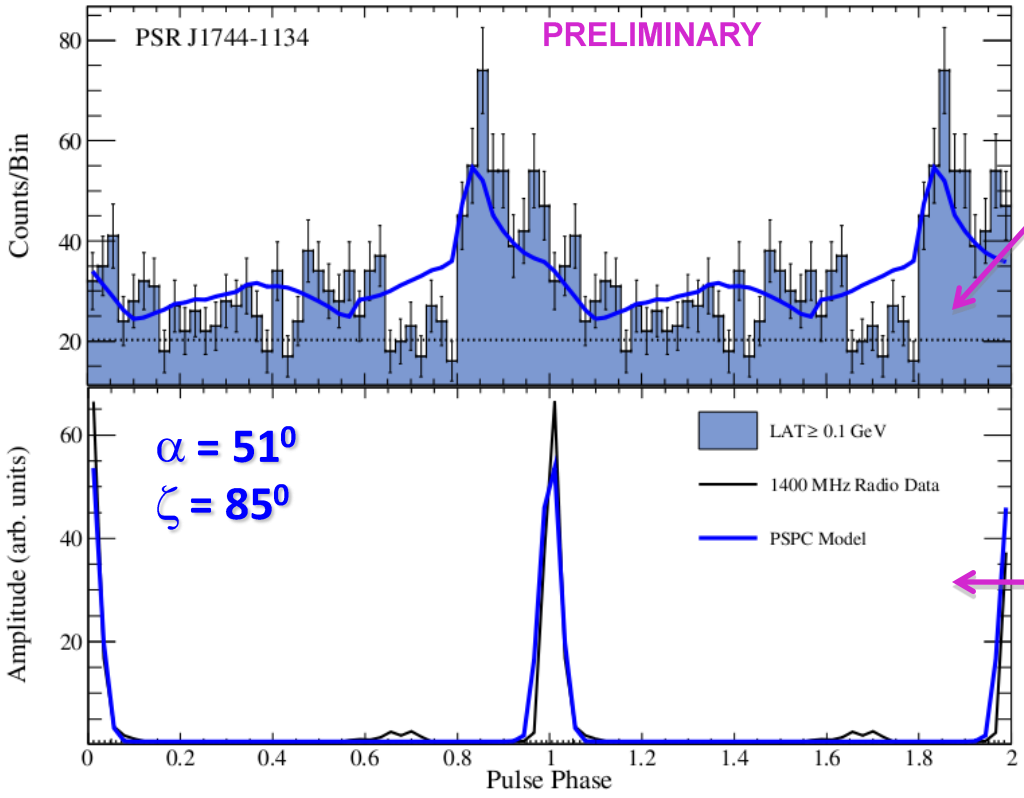
~ 0% radio polarization consistent with caustic emission

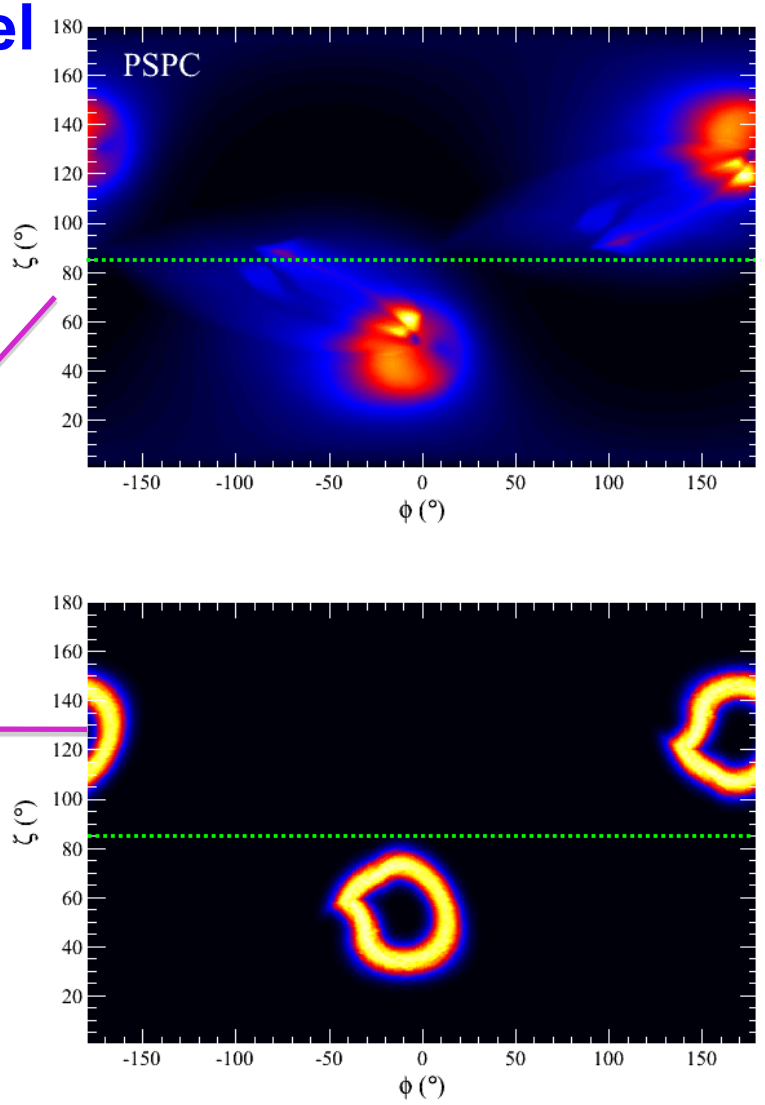
Modelling MSP γ-ray and Radio Profiles

Johnson et al. (2013)

"Class III"

Pair-starved polar cap (PSPC) model

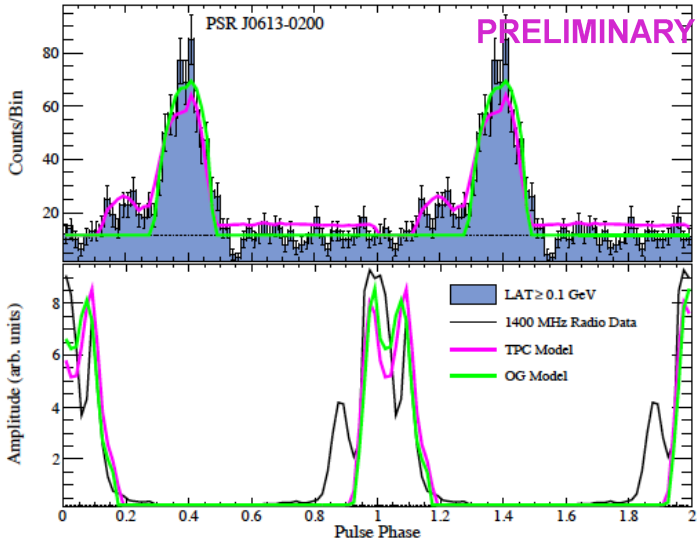


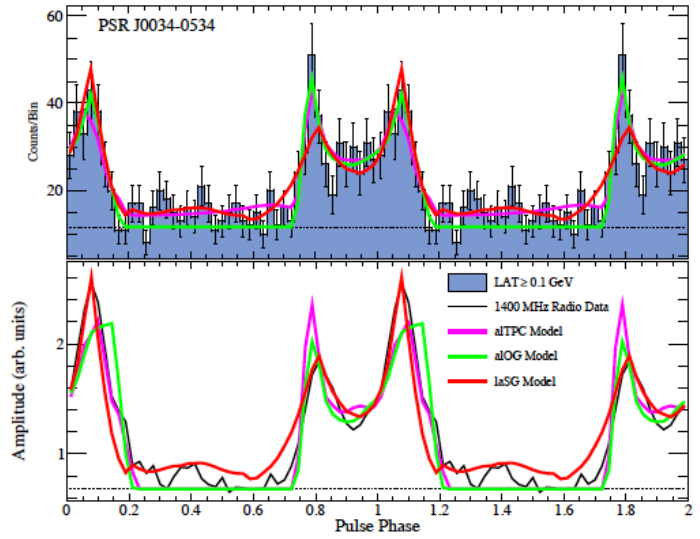


MSP Pulsar Light Curve Fits

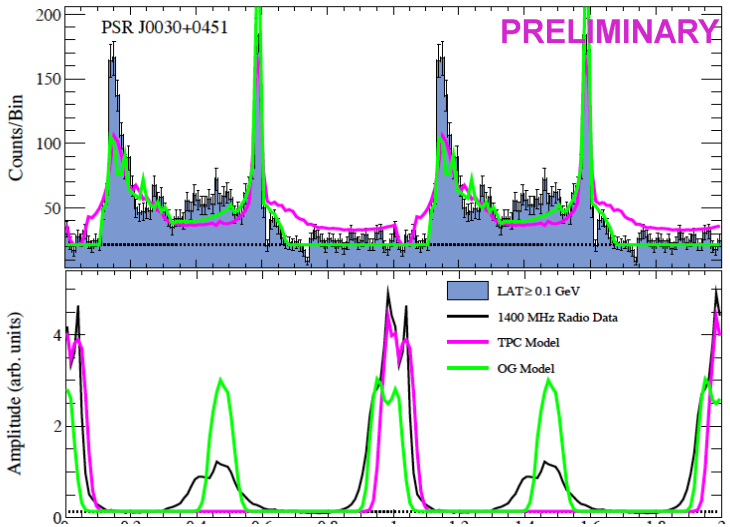
Johnson et al. (2013)

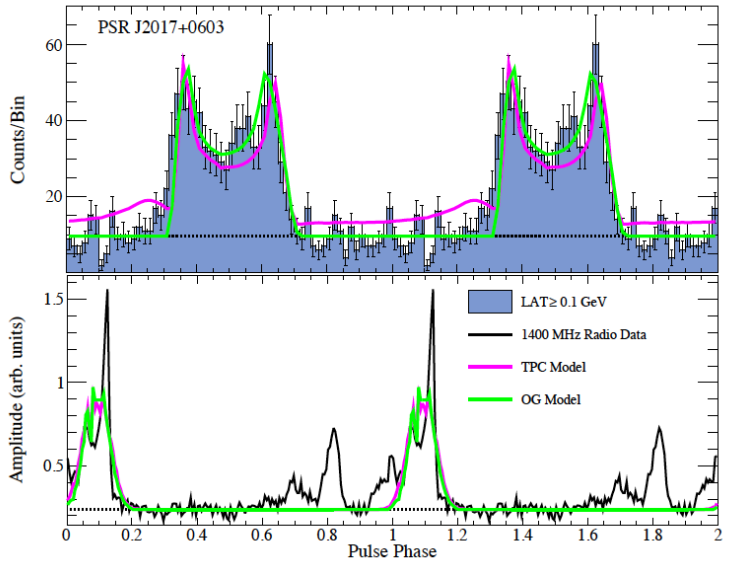
Two-pole caustic better fits LCs with off-peak emission





Outer gap better fits LCs with no off-peak emission



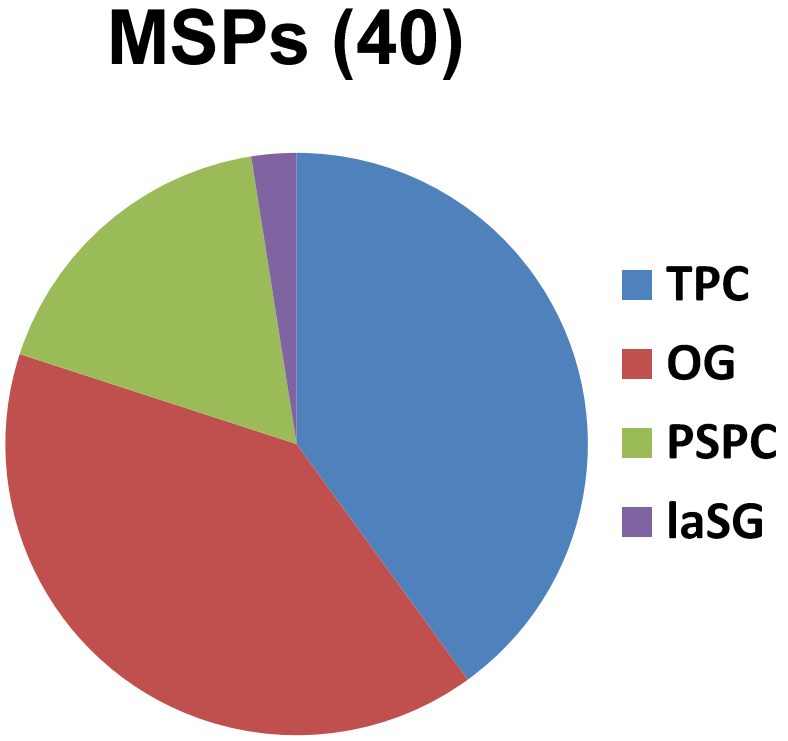


Fermi MSP Light Curve Best Fits

Results of fits for all MSPs in Second Pulsar Catalog (2PC)
- **No model best fits all light curves**
- **Two-pole caustic and outer gap geometry fit comparable %**

Systematic Bias Checks

- **Radio uncertainty (x2): changes in α, ζ < 30° (less for class II & III)**
- **γ-ray background level (5%): small effect in -ln(L): may change best-fit model**
- **Increasing radio lag (0.1): changes in α, ζ < 10°**



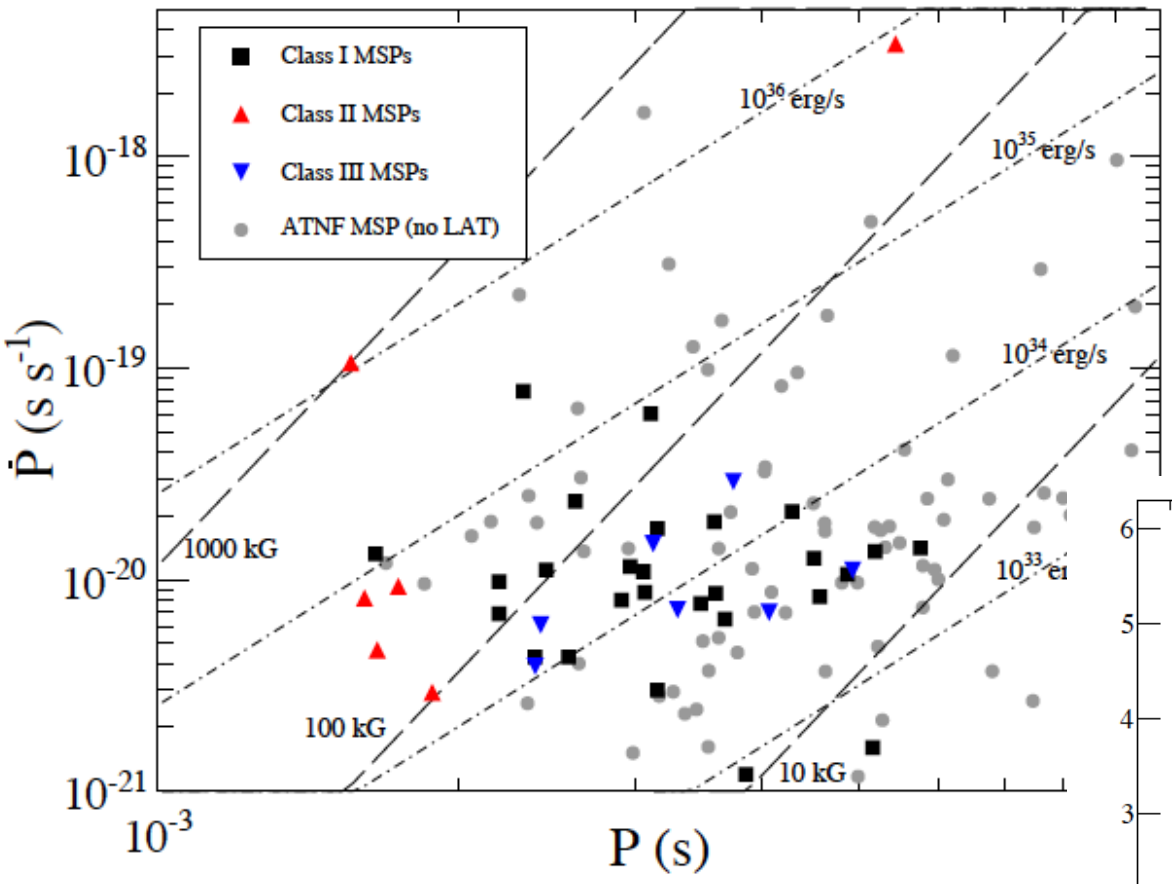
Johnson et al. (2013)

Which MSPs are Pair-Starved? Aligned?

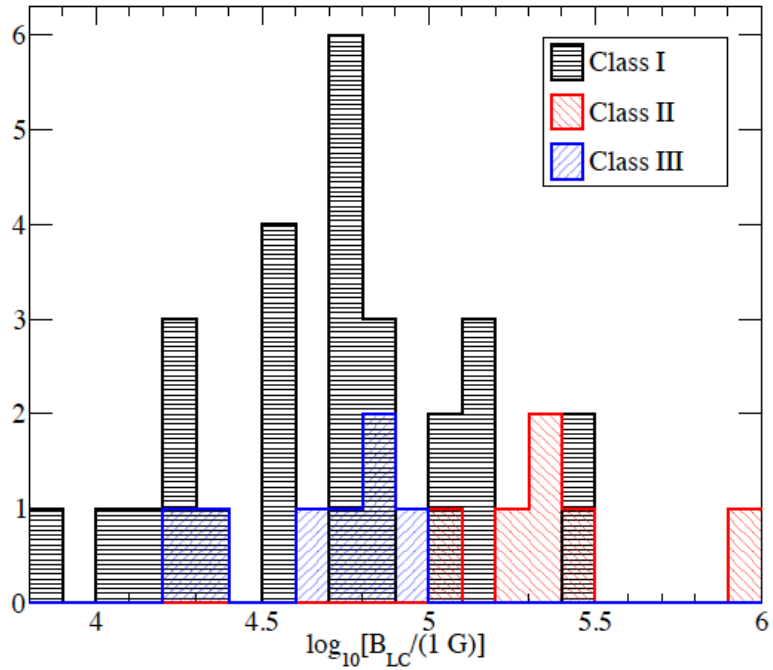
Class I –
standard OG or TPC

Class II –
aligned γ-ray/radio

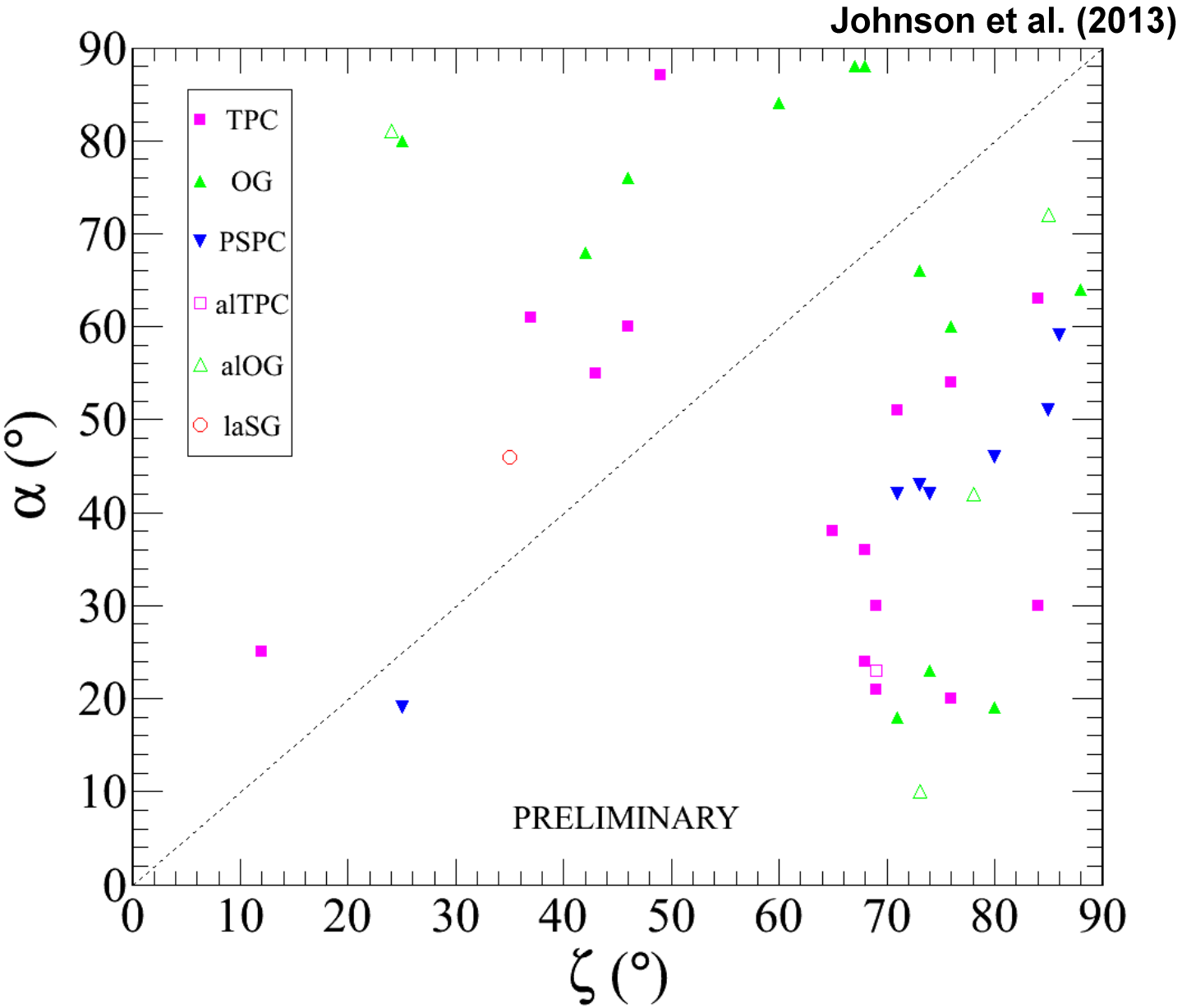
Class III –
pair starved polar cap (PSPC)



Johnson et al. (2013)

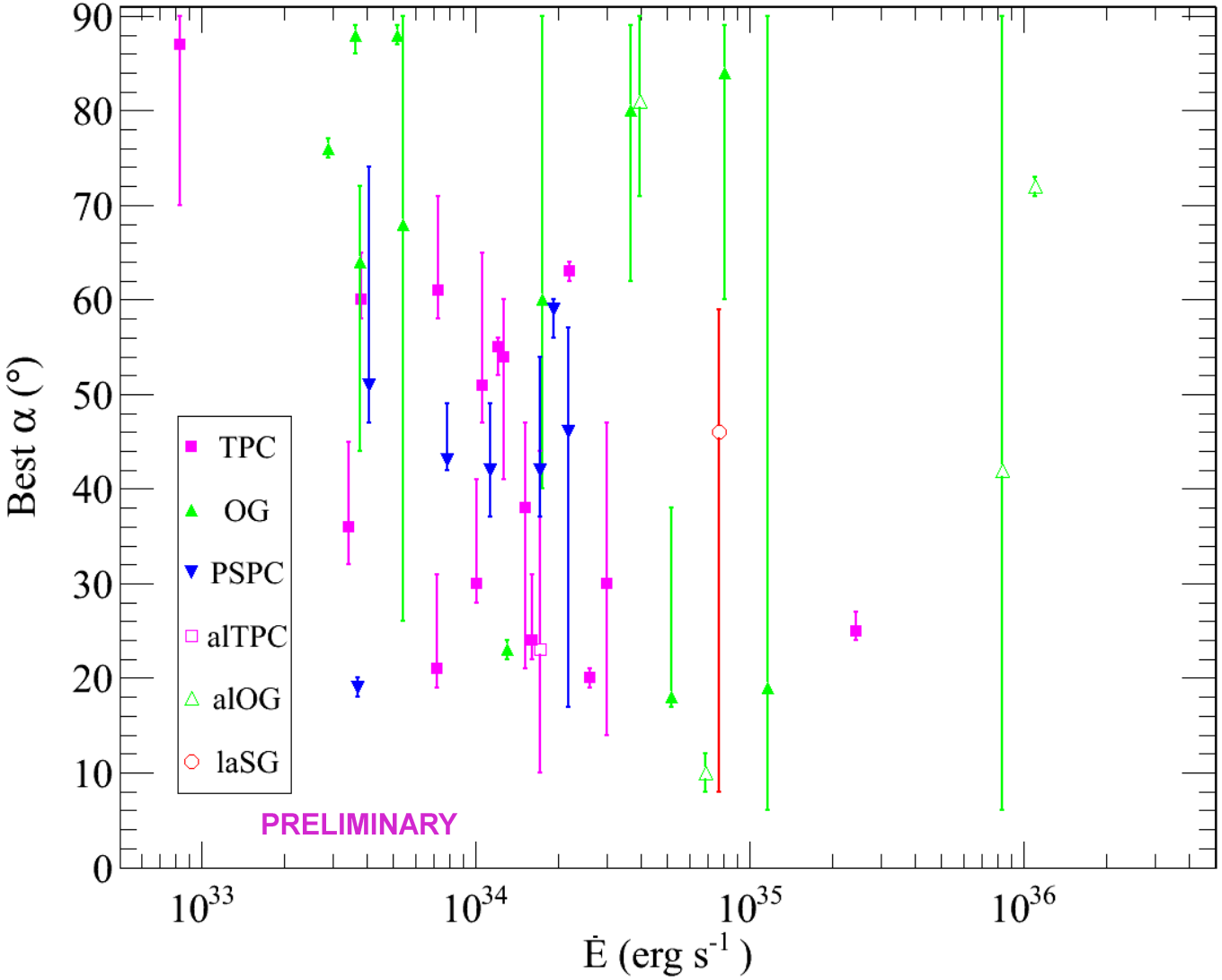


Best-fit Inclination vs. Observer Angle



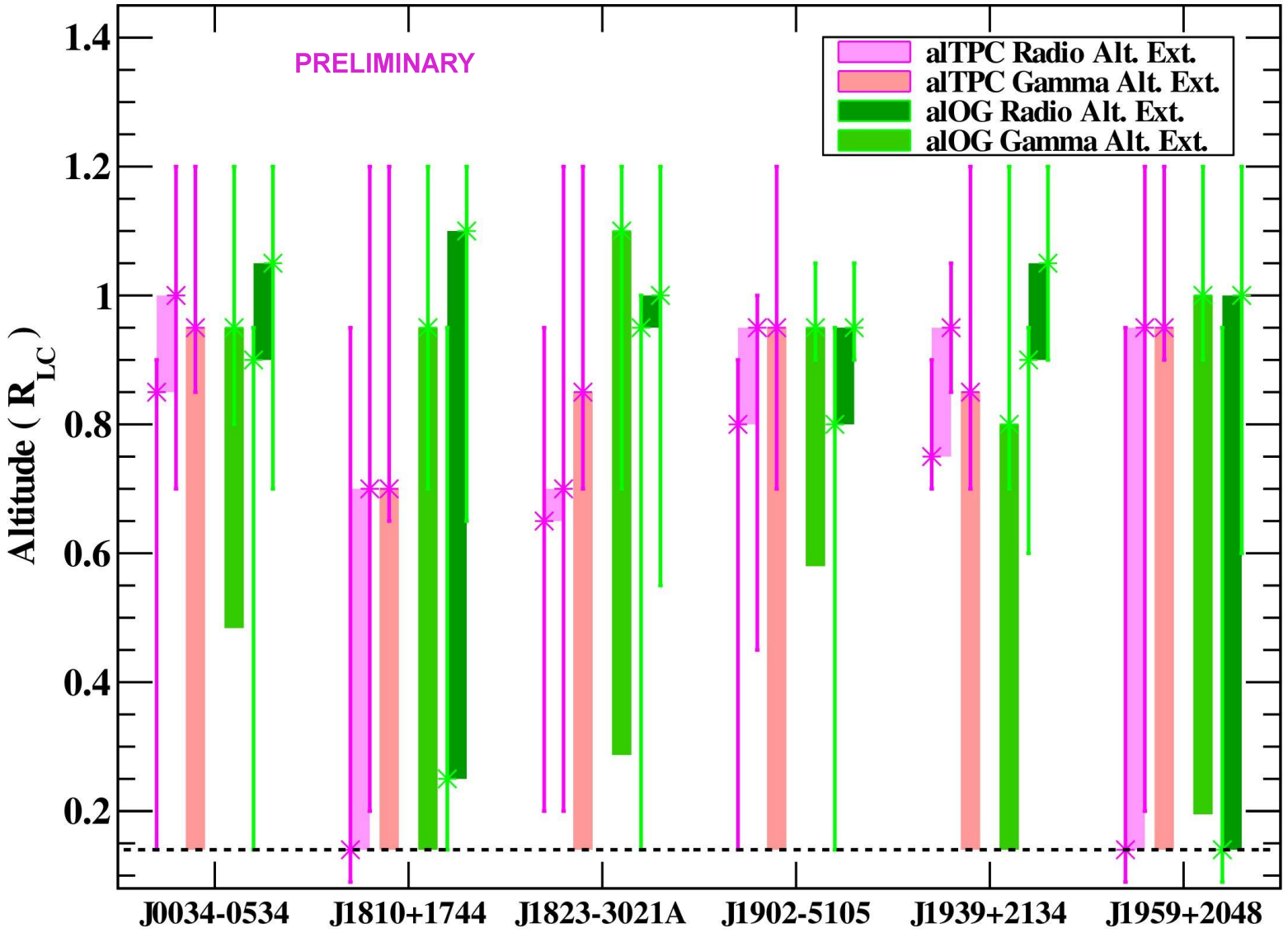
Best-fit Inclination vs. Spindown

Johnson et al. (2013)



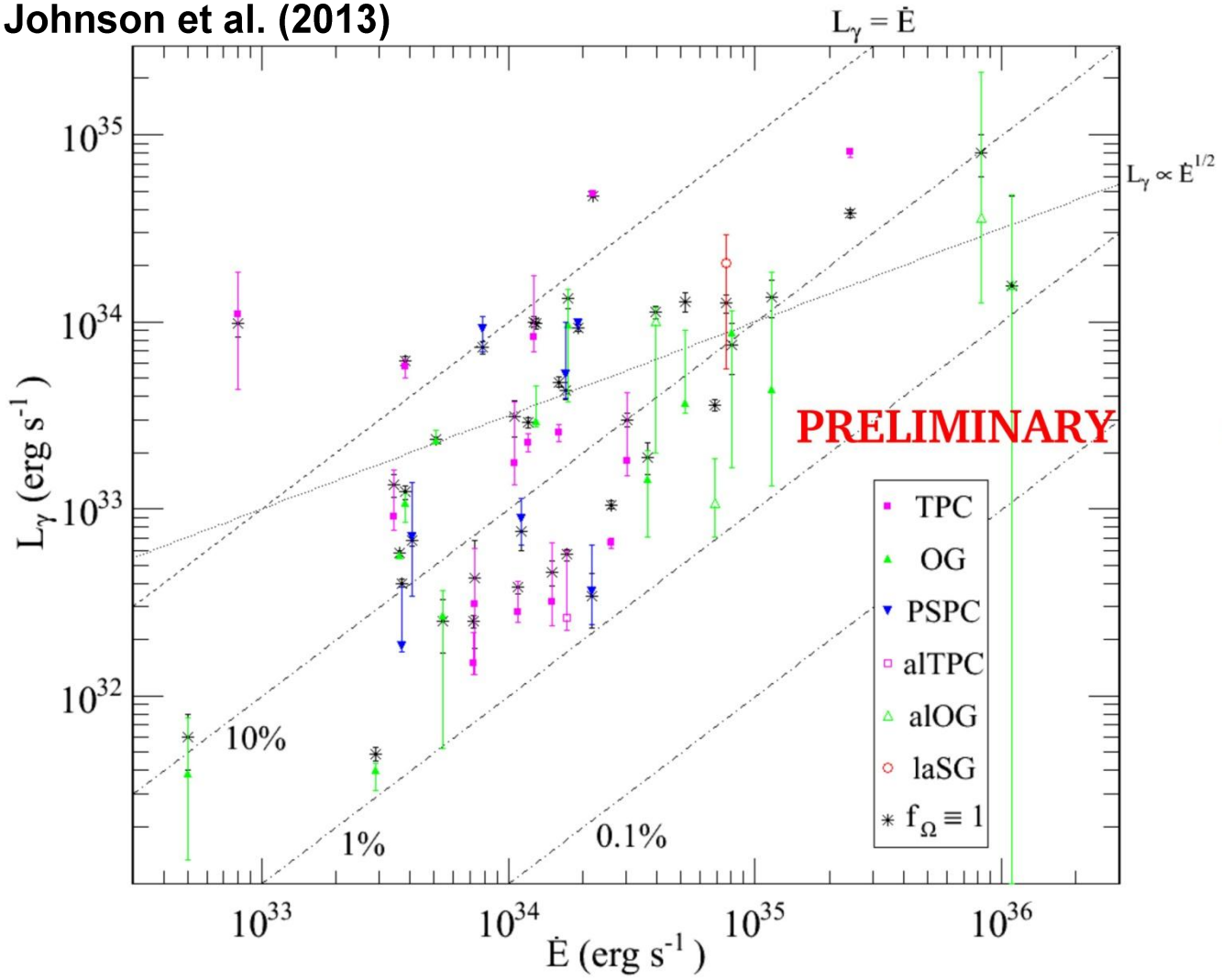
Class II: Maximum and Minimum Altitudes

Johnson et al. (2013)



γ-ray Luminosity vs. Spindown Power

Johnson et al. (2013)



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.

Average f_Ω

TPC (std only):	**0.76**
OG (std only):	**0.72**
PSPC:	**1.03**
alTPC:	**0.86**
alOG:	**0.62**
all TPC (std + al):	**0.78**
all OG (std + al):	**0.70**
laSG:	**1.8**

L_γ* corrected for best-fit *f_Ω

*** *f_Ω* = 1 from 2PC**

Conclusions

- **γ-ray and radio light curve fits for 40 MSPs in 2PC**
  - ✓27 class I – best fit by TPC (15) or OG (12); need mix of these two models
  - ✓6 class II – best fit by alTPC (1), alOG (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 α, clustering at larger ζ (caustics)
  - ✓Larger α for OG: visibility
  - ✓TPC: smaller α for larger Edot (larger $|\beta|$; wider radio beams)
  - ✓Class II emission altitudes: Radio more limited, higher up, contained within γ-ray region (within errors)
  - ✓Clustering around η = 10%; L_γ ~ Edot; $\langle f_\Omega \rangle$ < 1 for TPC / OG
- **Future**
  - ✓New B-field geometries (offset dipoles; finite conductivity magnetospheres)
  - ✓Higher-altitude and more complex radio beams

THANK YOU!

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"The heavens are Yours, and Yours also the earth;
You founded the world and all that is in it" (Ps. 89:11 NIV).