Radio and Gamma-Ray Beams from Pulsars

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Summary

- Pulse profiles – doubles and interpulses
- High Edot pulsars – radio and high-energy emission
- Radio and γ-ray beaming

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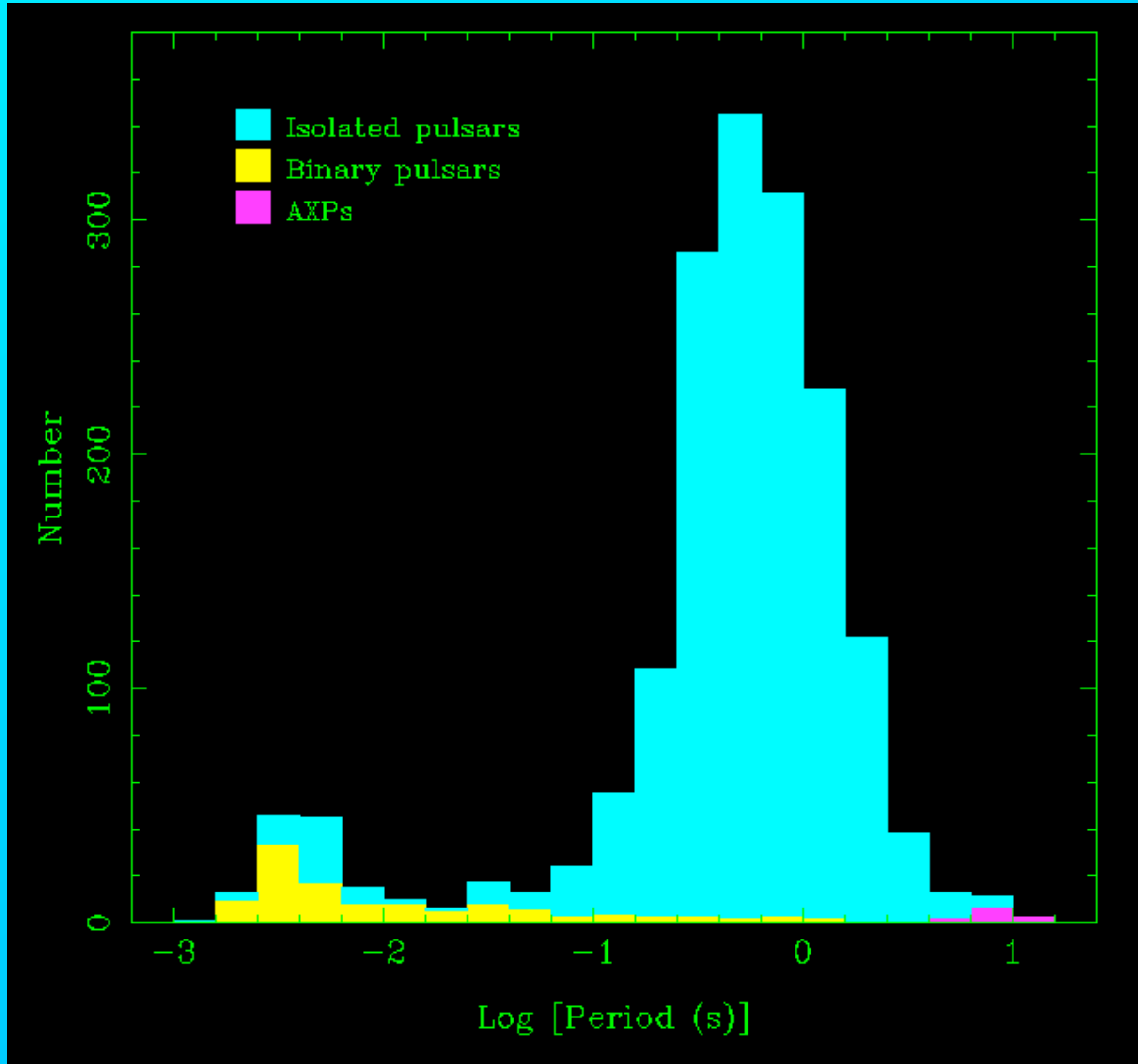
Spin-Powered Pulsars: A Census

- Currently 1880 known (published) pulsars
- 1754 rotation-powered disk pulsars
- 179 in binary systems
- 182 millisecond pulsars
- 108 in globular clusters*
- 13 AXP/SGR
- 20 extra-galactic pulsars

* Total known: 140 in 26 clusters
(Paulo Freire's web page)



Data from ATNF Pulsar Catalogue, V1.40 (www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)

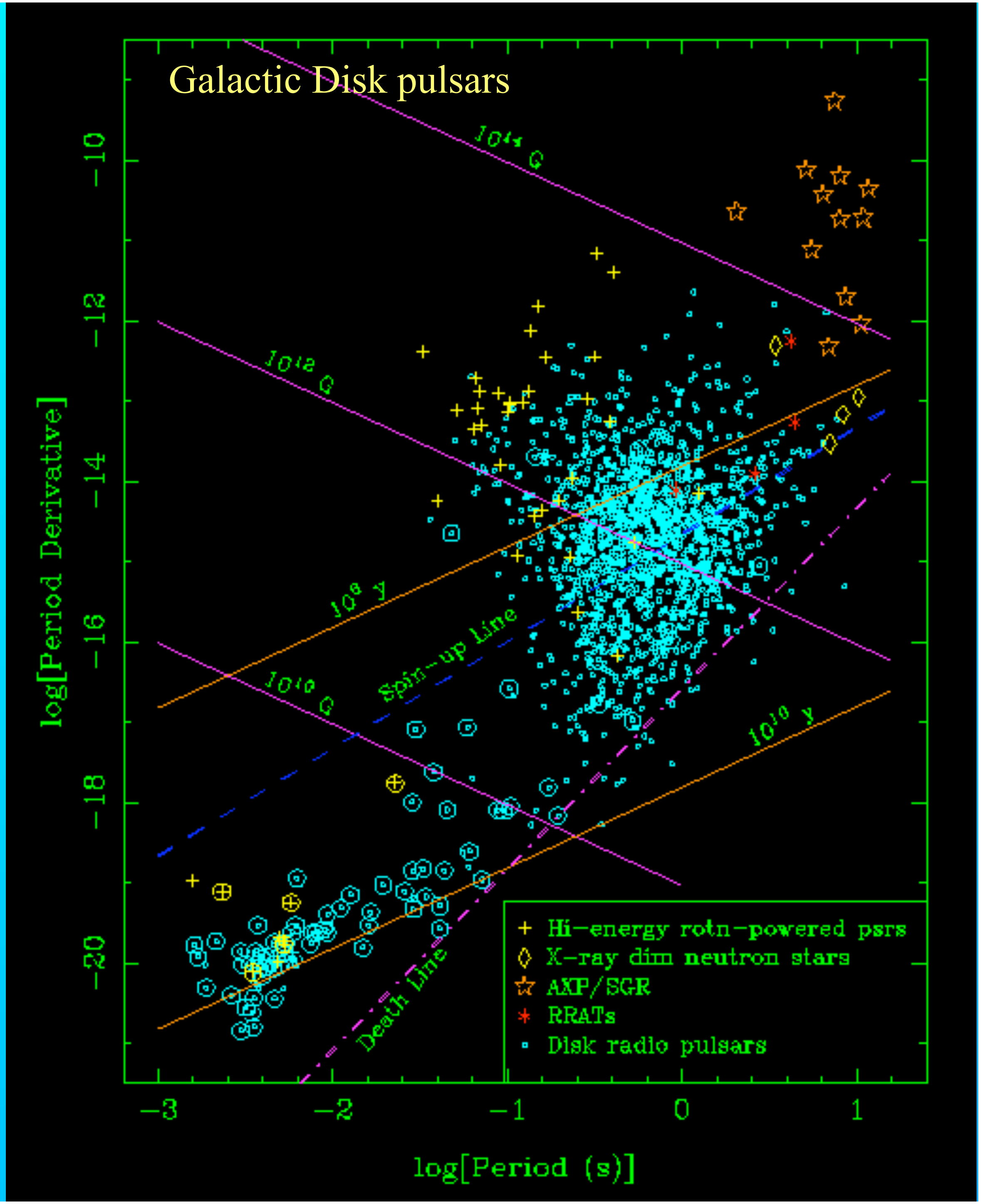
The P – $\dot{P}$ Diagram

P = Pulsar period

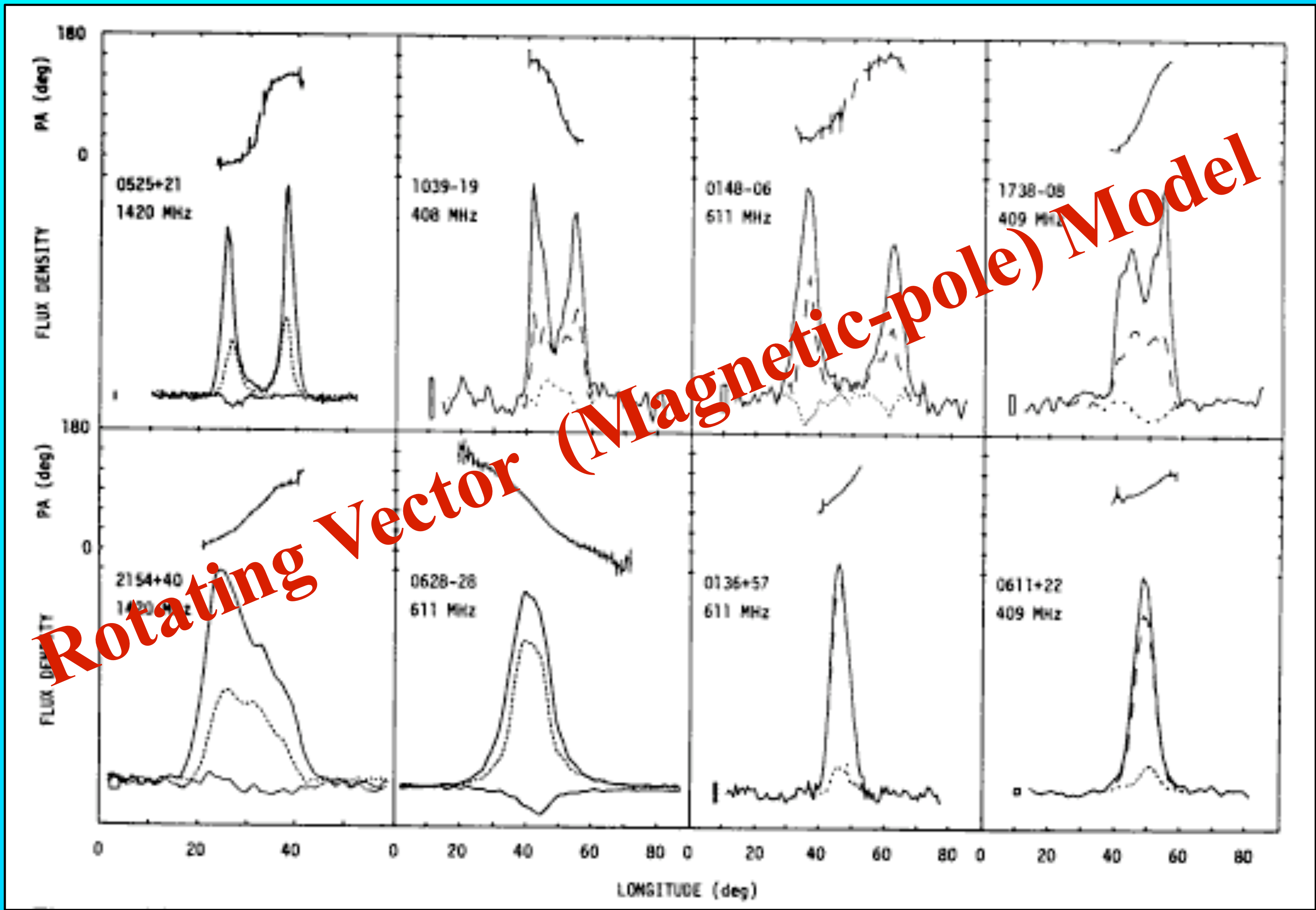
$\dot{P}$ = dP/dt = slow-down rate

- For most pulsars $\dot{P} \sim 10^{-15}$
- MSPs have $\dot{P}$ smaller by about 5 orders of magnitude
- Most MSPs are binary, but few normal pulsars are
- $P/(2\dot{P})$ is an indicator of pulsar age
- Surface dipole magnetic field $\sim (P\dot{P})^{1/2}$

Great diversity in the pulsar population!

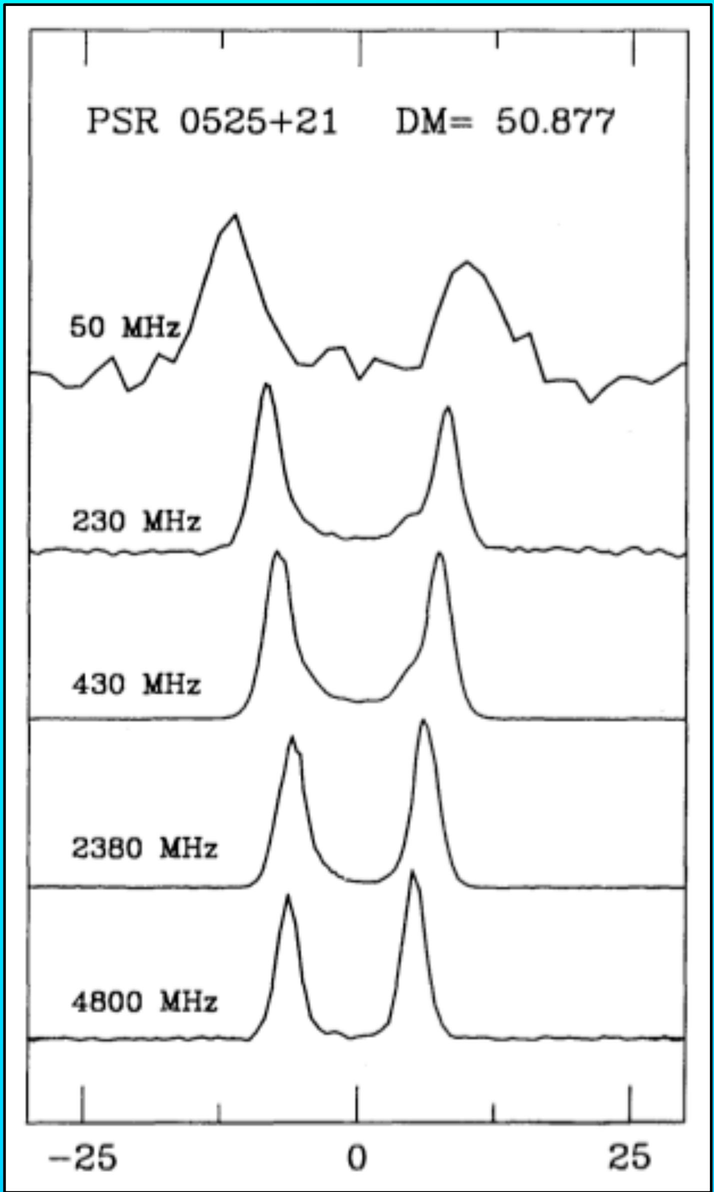


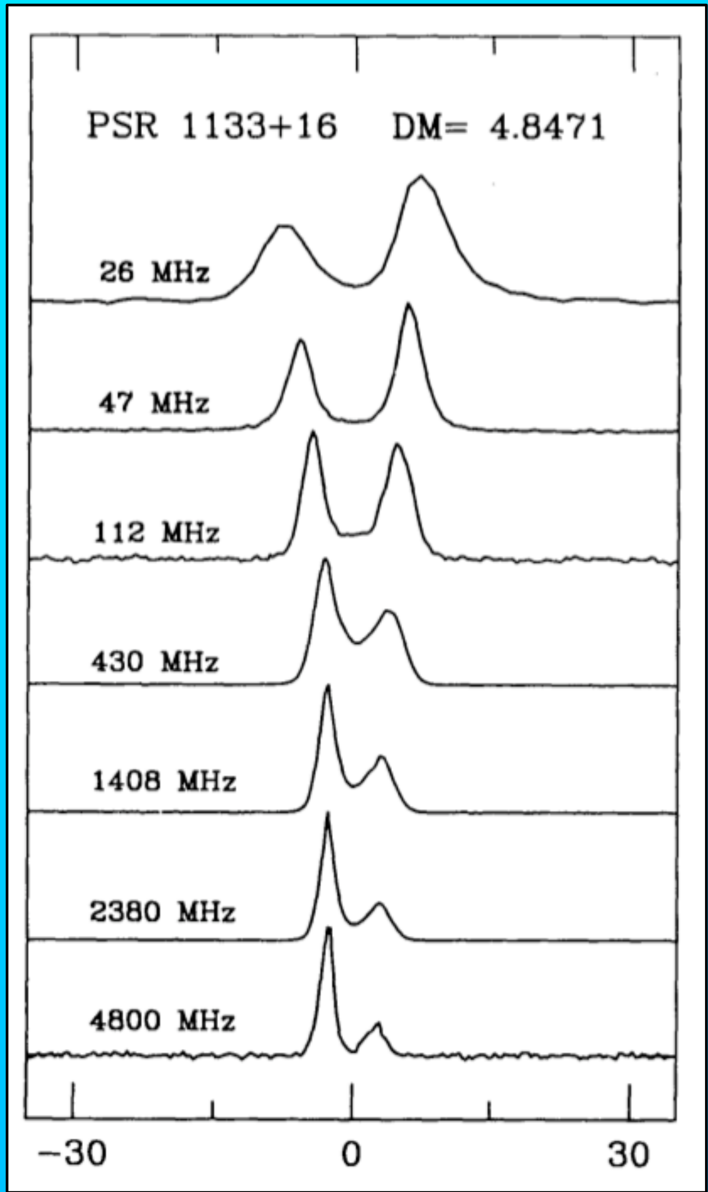
Radio Mean Pulse Profiles – "Normal" Pulsars



(Lyne & Manchester 1988)

Radius to Frequency Mapping



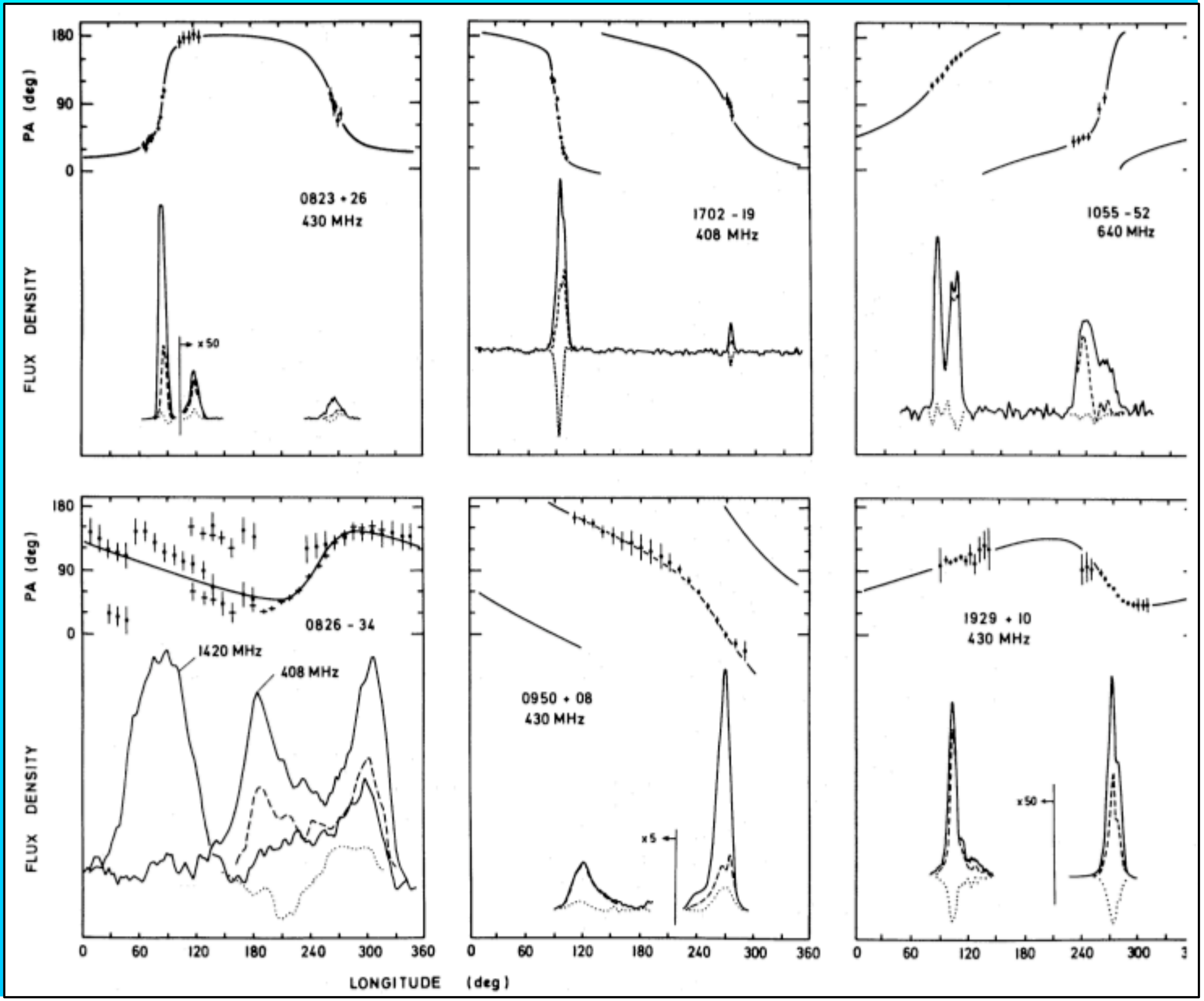


(Phillips & Wolszczan 1992)

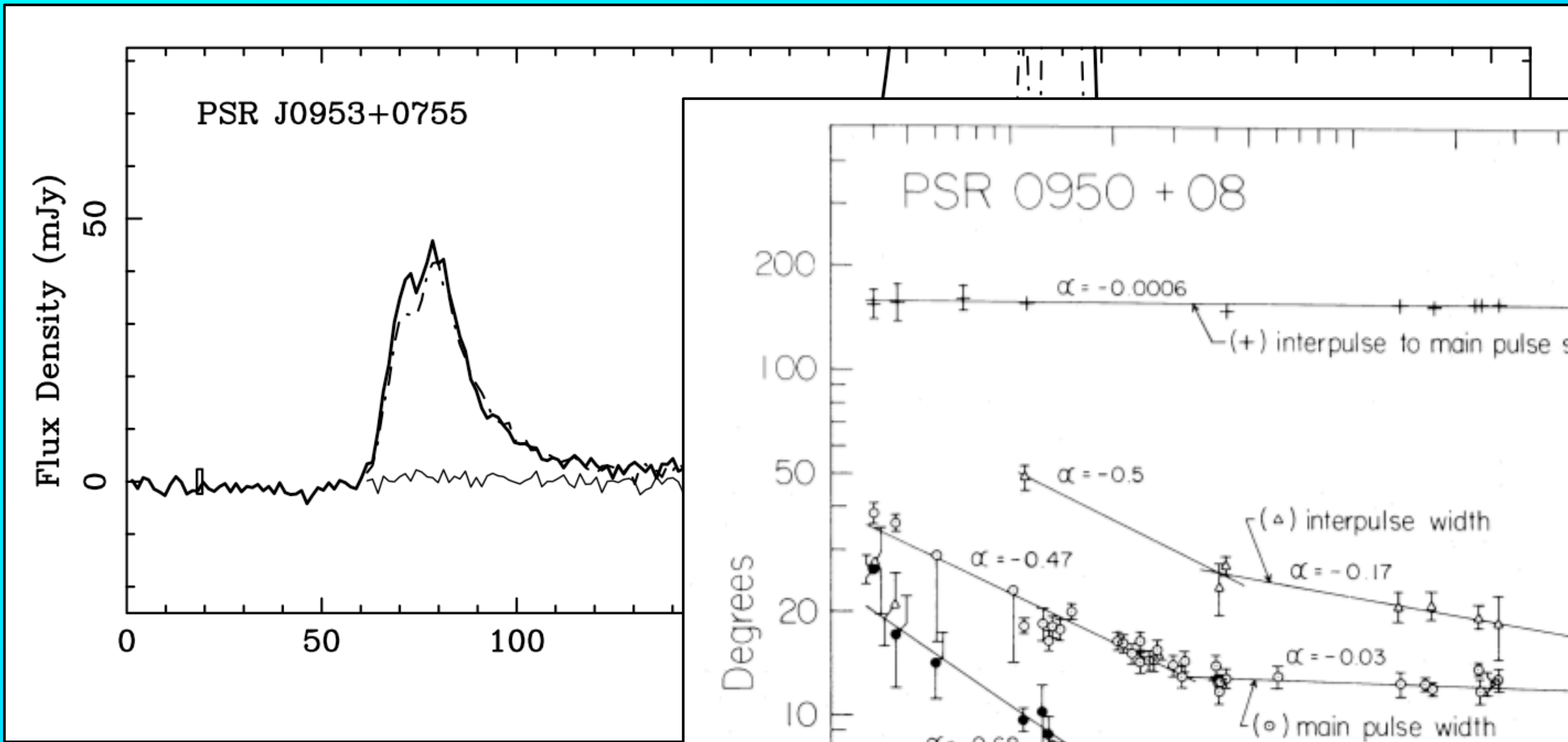
Interpulses

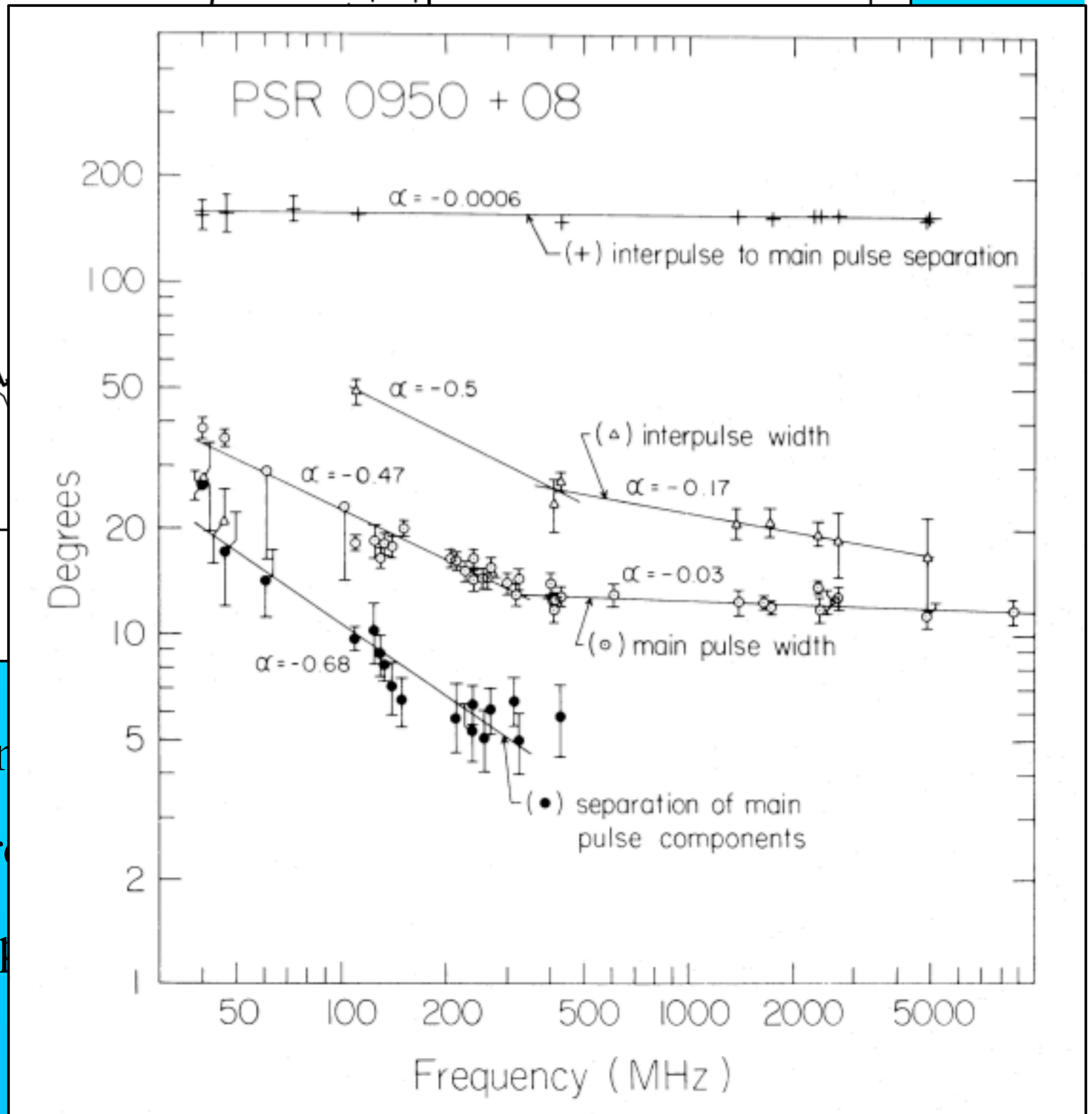
- Seen mostly in young short-period pulsars
- Some close to 180^{o} separation, e.g., B1702-19
- Others less, e.g., B0950+08

(Lyne & Manchester 1988)



PSR B0950+08



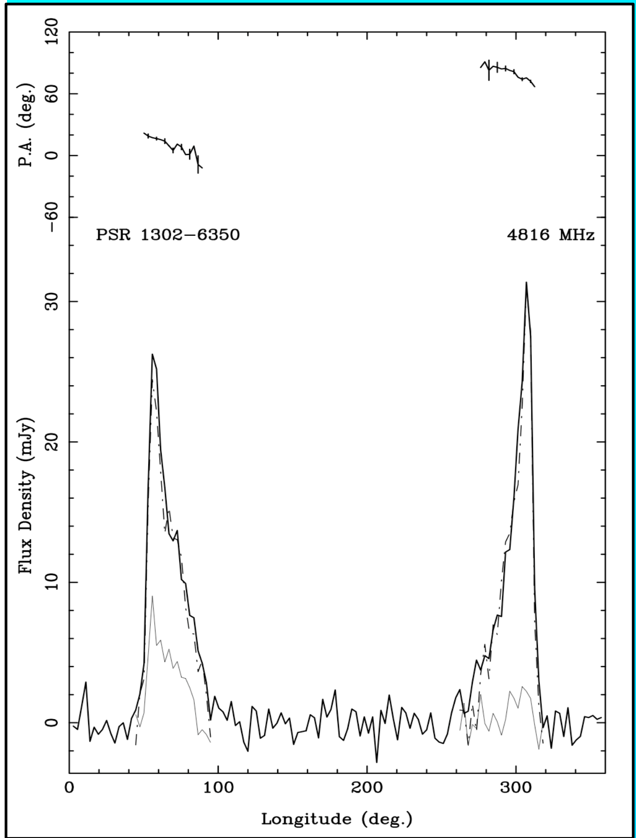


- Wide saddle-shaped profile - fro
- Nearly-aligned normal double pr
- But main-pulse – "interpulse" se

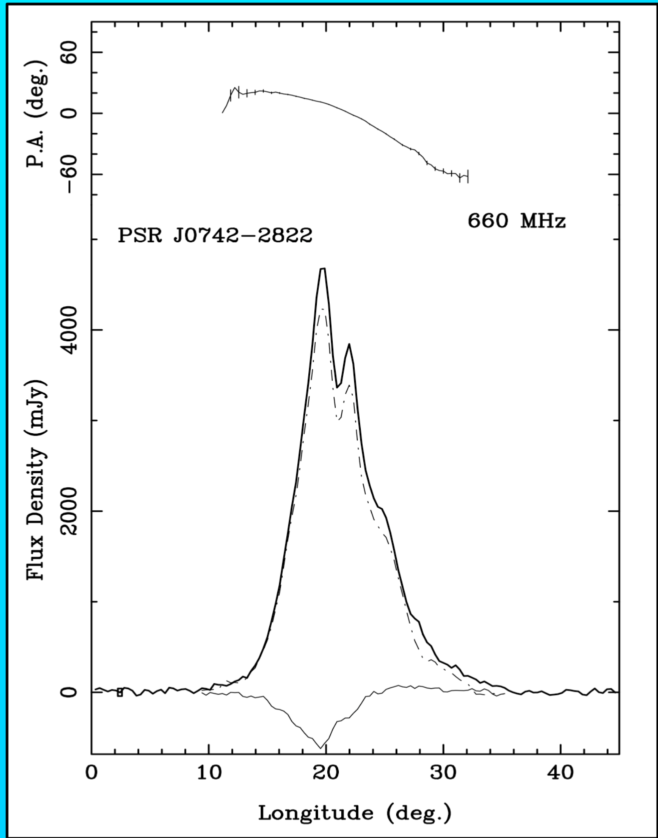
(Hankins & Cordes 1981)

Young Highly Polarised Pulsars

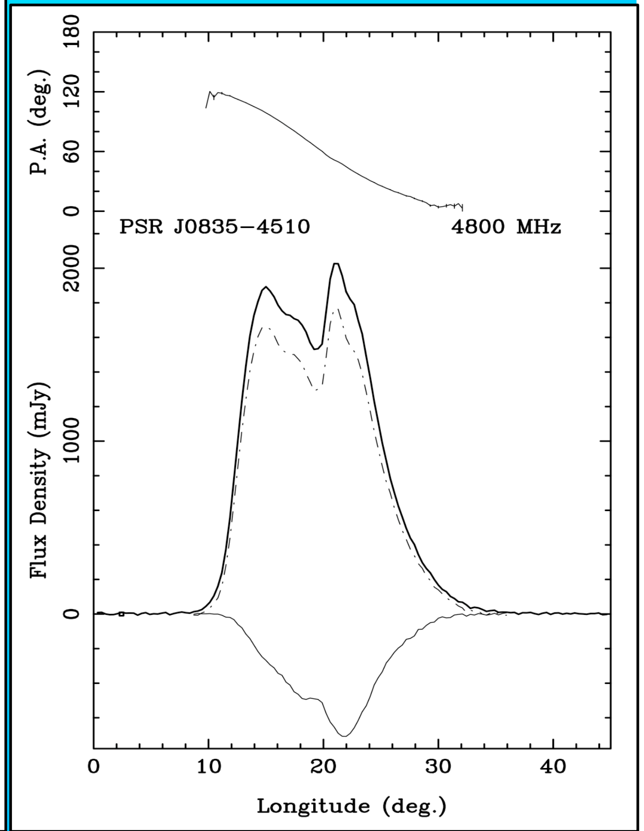
B1259-63



B0740-28



B0833-45 (Vela)



- PSR B1259-63 similar: wide double, frequency-independent spacing, nearly 100% linearly polarised
- Other young, high-Edot pulsars also highly polarised – look like leading component of wide double profile

The Crab Pulsar

• Interpulse with 145° spacing from main pulse – at all frequencies

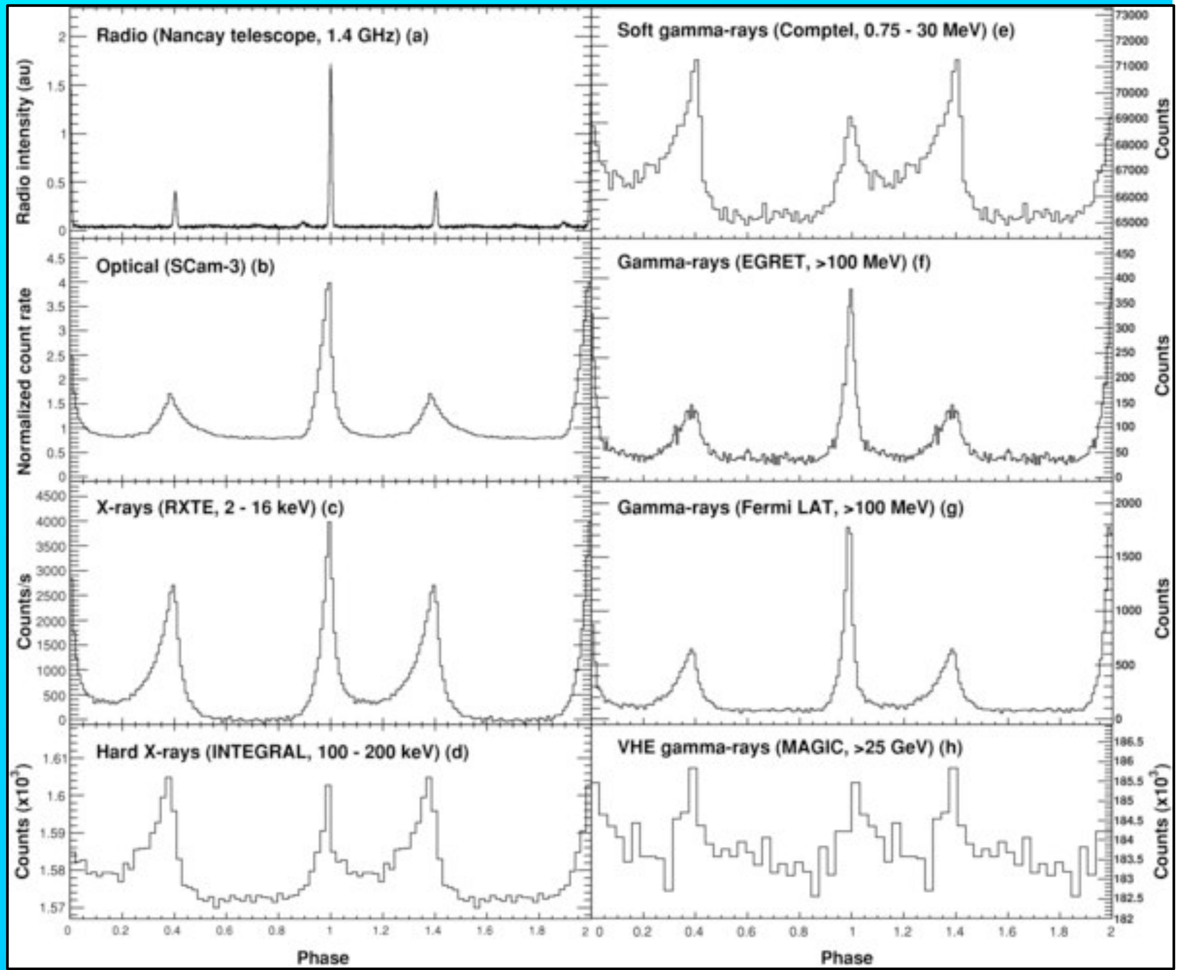
• High-energy pulse profile has wide-double shape

• Radio main, interpulse nearly aligned with HE peaks (trail by 200 μs) – must have common emission location

• Profile shape & γ-ray spectral cutoff imply emission from outer magnetosphere

• Radio precursor is 100% linearly polarised – similar to radio from young high-Edot psrs

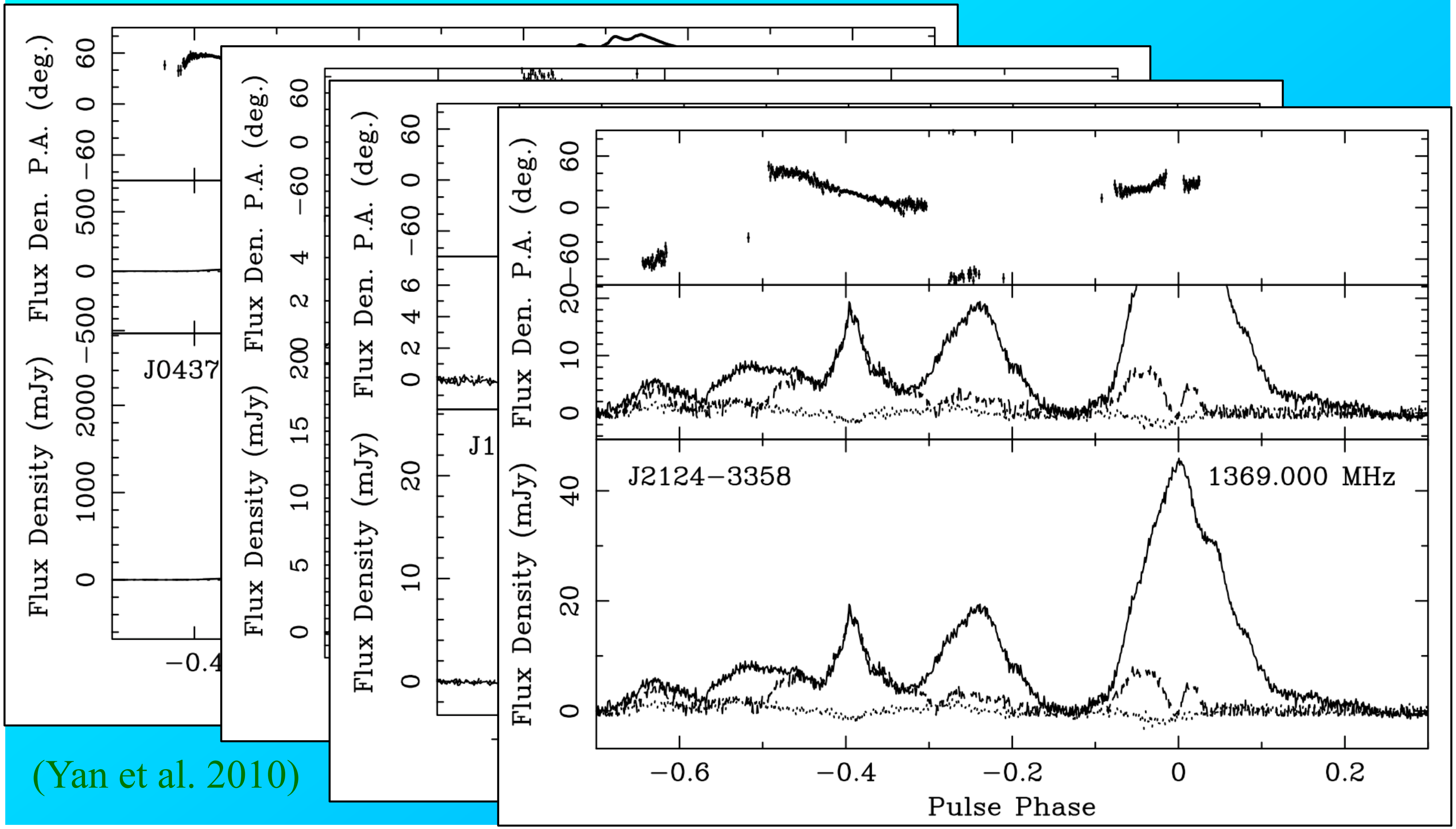
• Radio main and interpulse composed of “giant” pulses



(Abdo et al. 2010)

Millisecond Pulsars

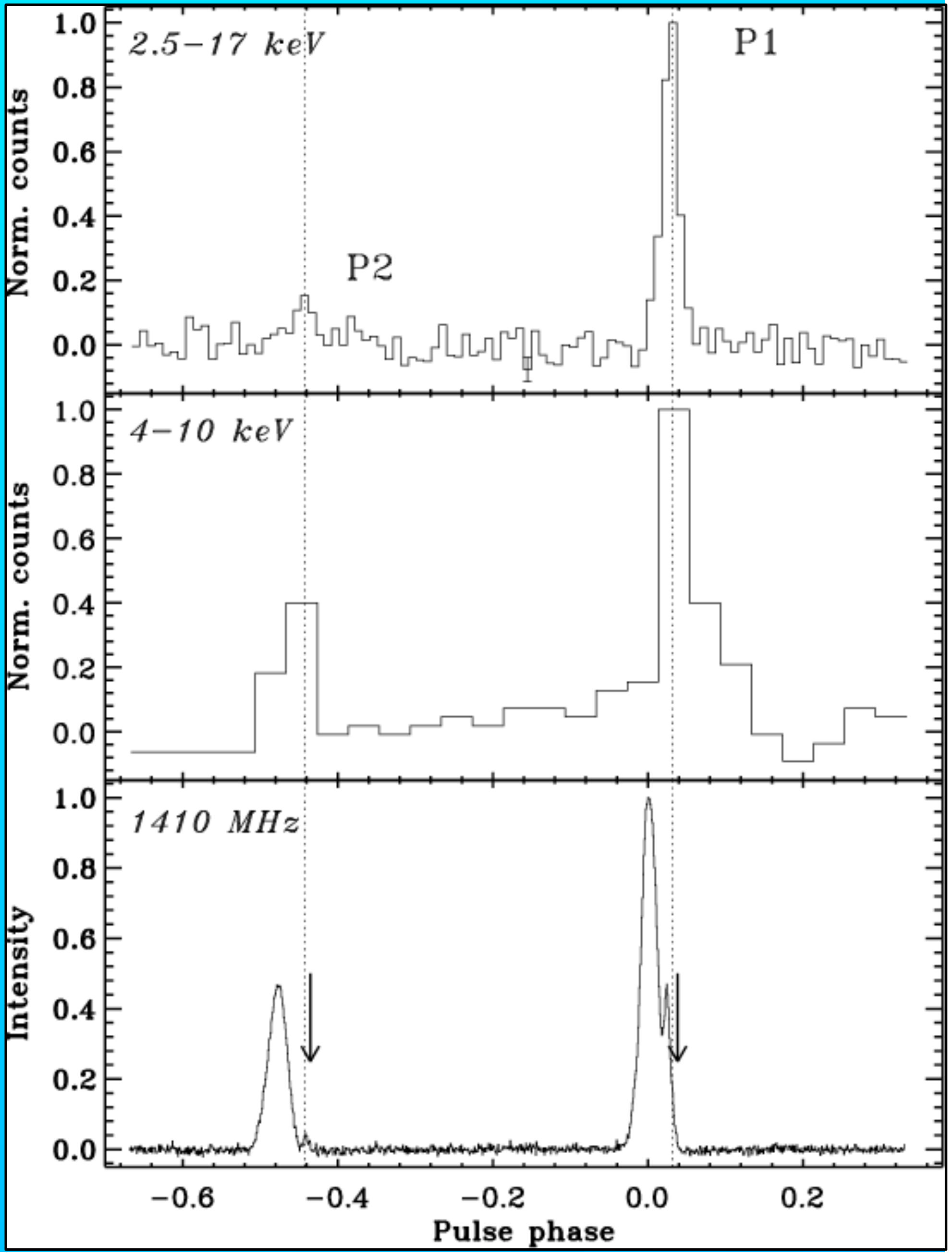
- Wide, complex profiles! Non-RVM PA variations
- Can't be low-altitude emission from polar field lines



(Yan et al. 2010)

PSR B1937+21

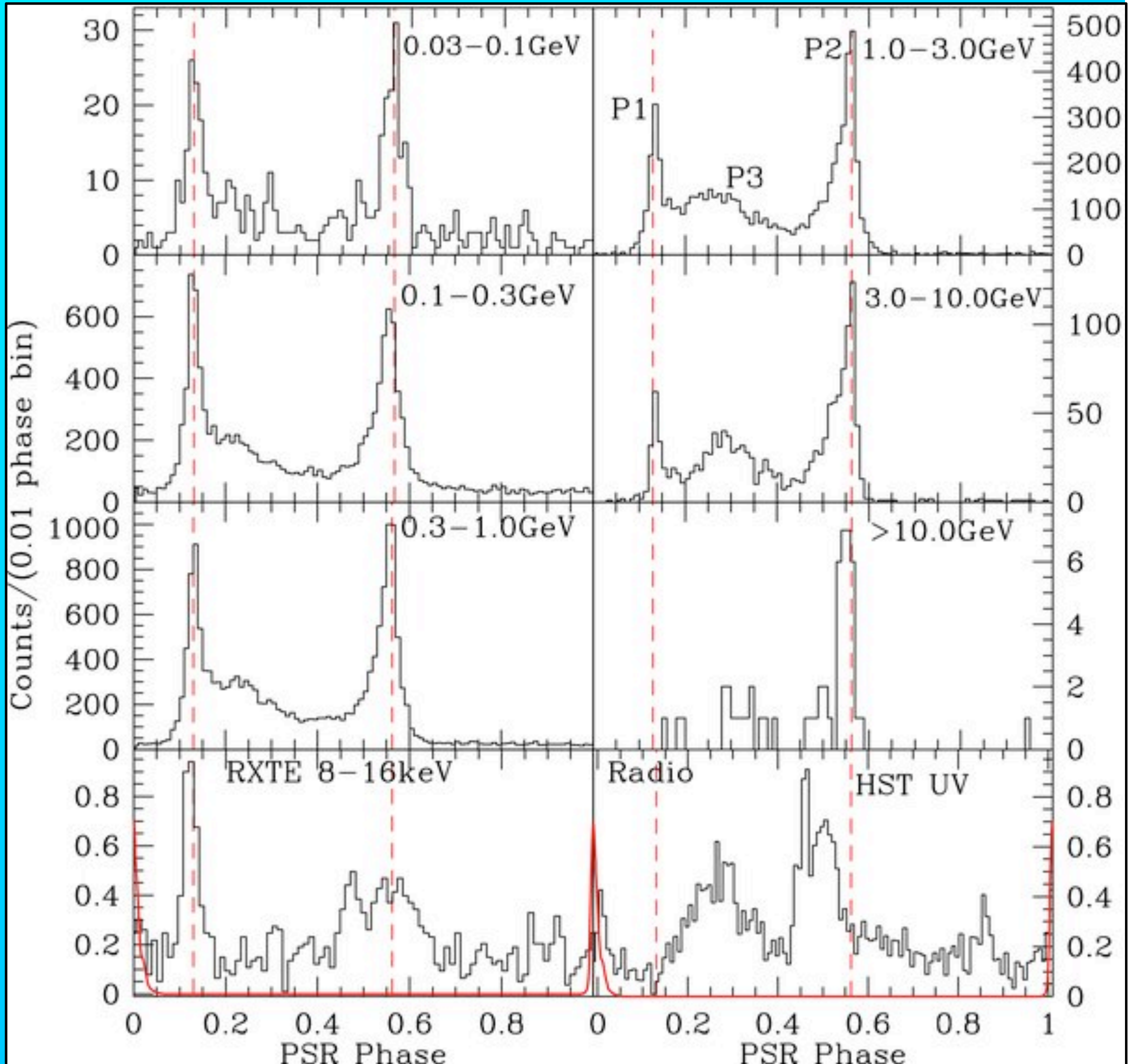
- First MSP – 1.6 ms period
- Radio main-interpulse separation very close to 180^o
- Giant radio pulses observed, trailing both peaks
- Hard X-ray pulses aligned with radio giant pulses
- Also outer-magnetosphere emission (?)



(Takahashi et al. 2001)

The Vela Pulsar

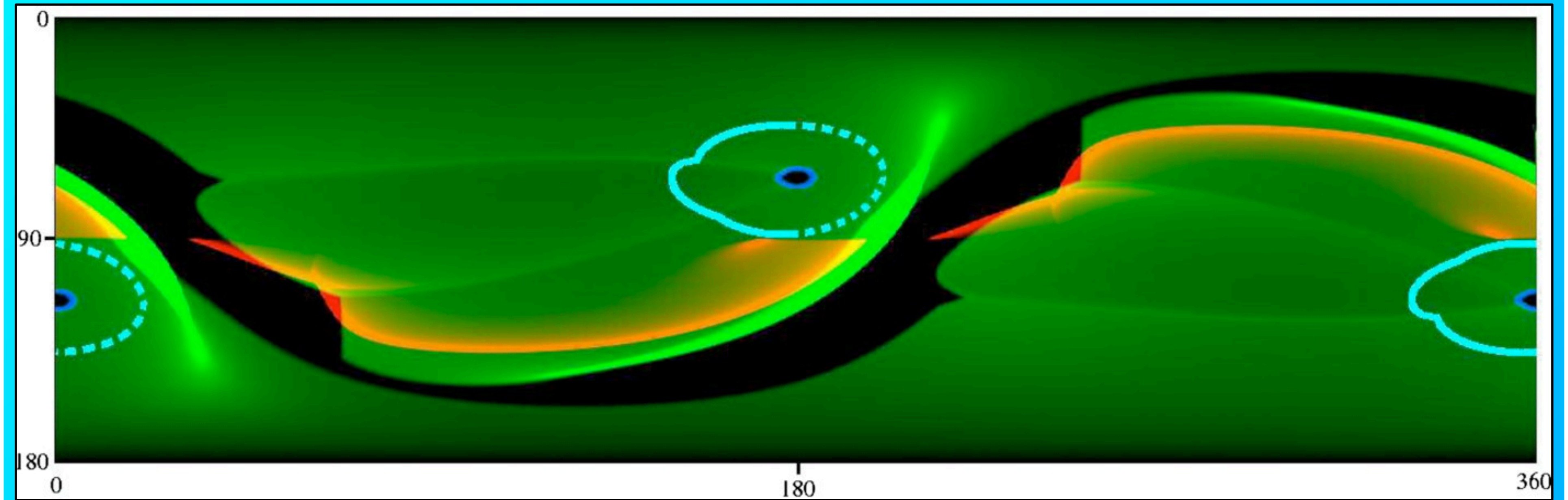
- Wide double γ-ray profile, main peaks (P1, P2) separated by ~ 0.43 periods
- P1 lags radio pulse by ~ 0.13 periods
- UV profile peaks lie between γ-ray peaks
- Most other young γ-ray emitters have similar pulse morphology
- Consistent with outer-magnetosphere emission



(Abdo et al. 2009)

Modelling of γ-ray pulse profiles

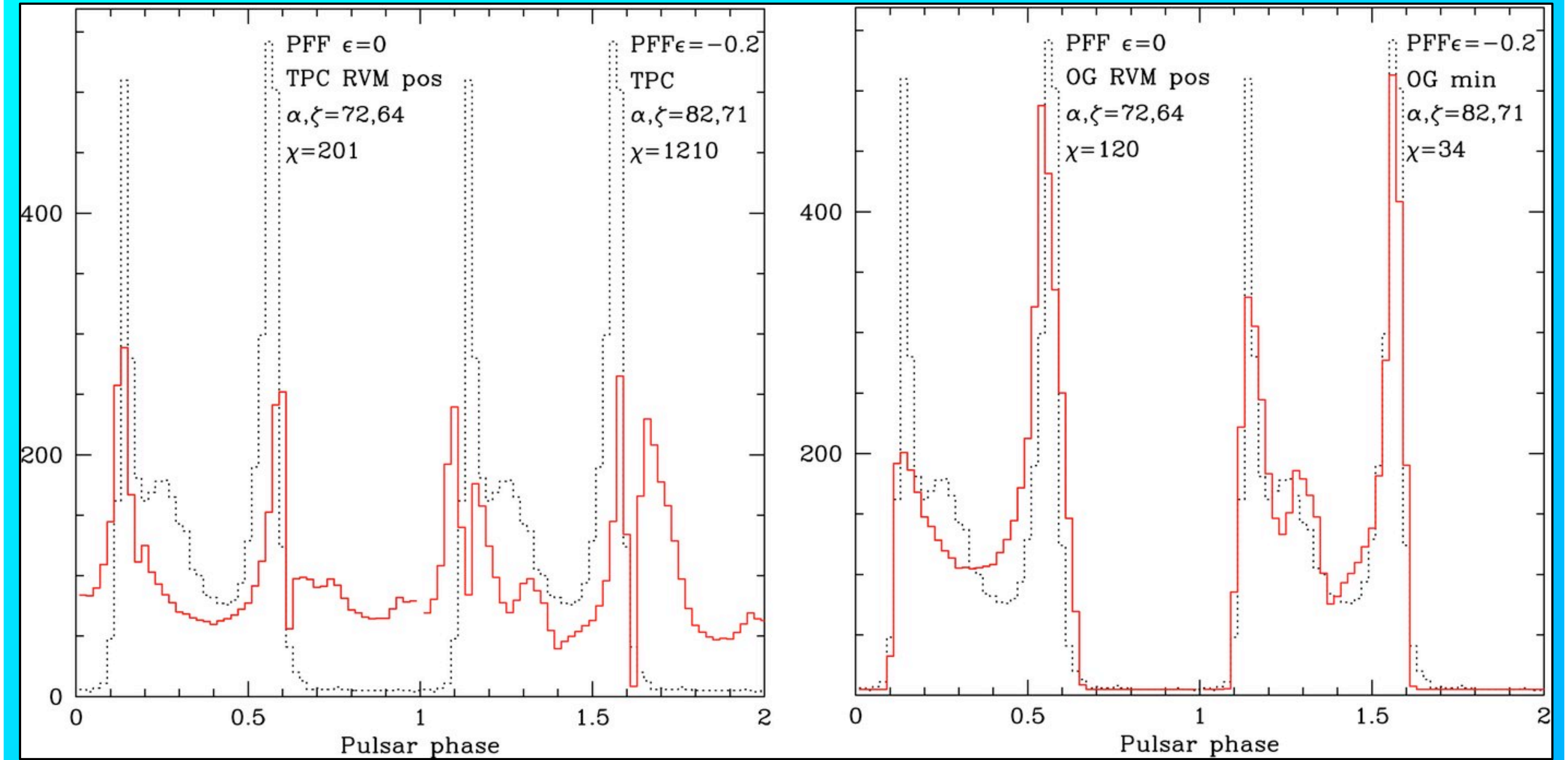
- Two main models:
  - ➢ Outer-Gap model
  - ➢ Slot-Gap or Two-Pole Caustic model



- OG model in red
- TPC model in green
- 500 km altitude PC emission (radio) in aqua

(Watters et al. 2009)

Vela γ-ray Profile Fits

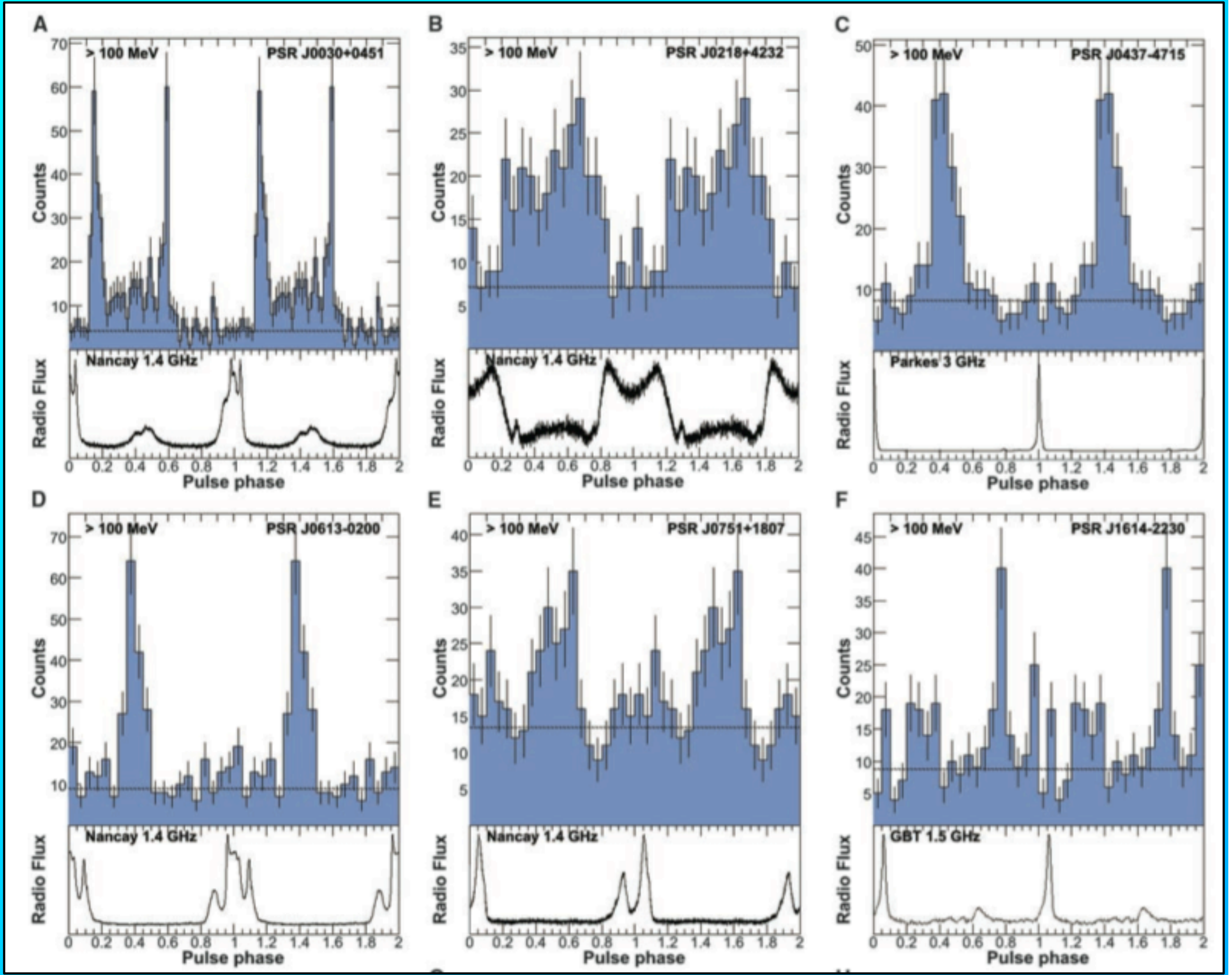


- Constrained by known inclination angle of rotation axis (X-ray torus)
- Best fit for OG model

(Romani & Watters 2010)

Fermi MSP Profiles

- Generally similar γ-ray pulse morphology and relationship to radio profiles as for young pulsars
- Implies that emission region(s) also in outer magnetosphere

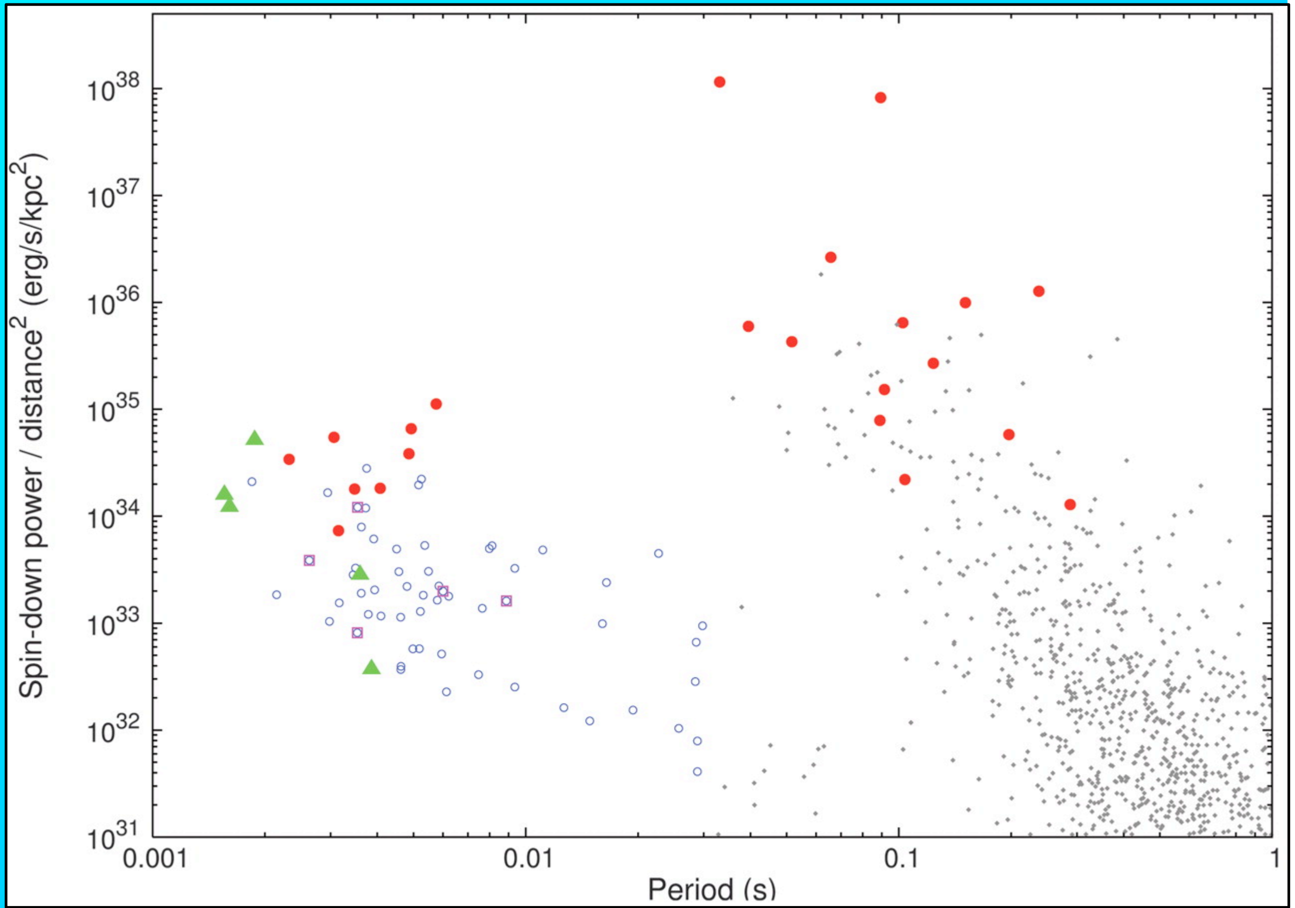


(Abdo et al. 2009)

Edot/d^2 – Period Dependence

- Radio-selected sample
- Most high Edot/d^2 pulsars have detected γ-ray pulsed emission, for both young pulsars and MSPs
- Some high Edot/d^2 pulsars have no detected γ-ray emission
- Implication:

For these pulsars, the radio beams and γ-ray beams have comparable sky coverage



(Abdo et al., 2009)

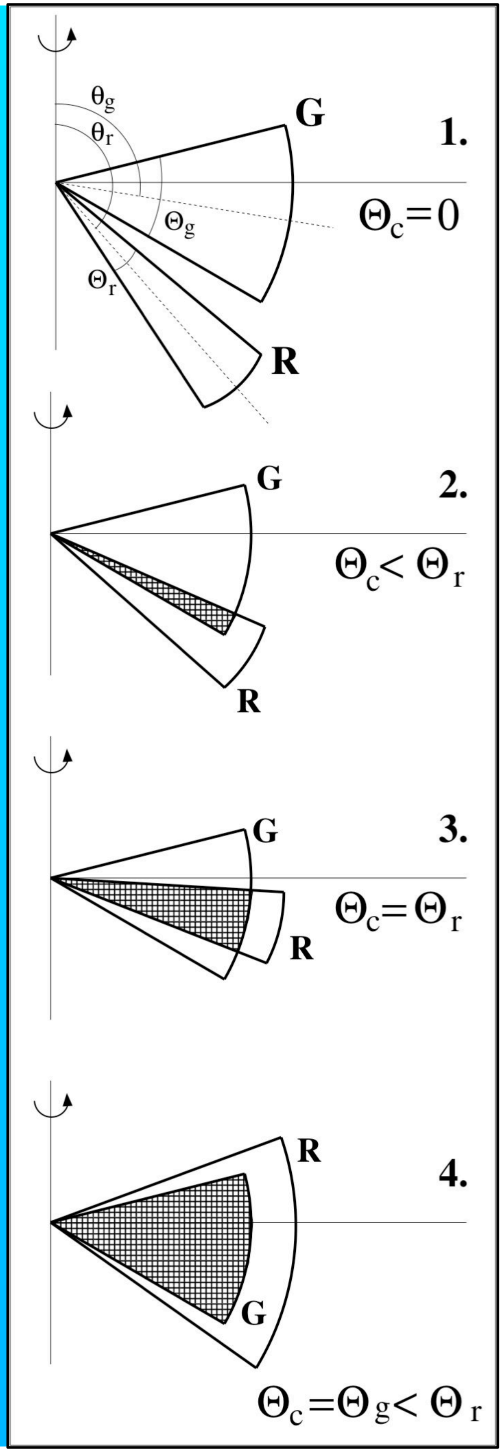
- γ-ray pulses detected: red dot
- γ-ray point source: green triangle

Radio and γ-ray Beaming

- Approximate sky coverage by "top-hat" fan beams (integral over ϕ of two-dimensional beam pattern)
- Θ_r and Θ_g are equivalent widths of radio and γ-ray beams respectively
- Θ_c is the angular width of the overlap region
- For a random orientation of rotation axes:
  - ➢ the relative number of pulsars detectable in band i is proportional to Θ_i
  - ➢ the relative number of pulsars detectable in both bands is proportional to Θ_c

In all cases $\Theta_r >= \Theta_c$

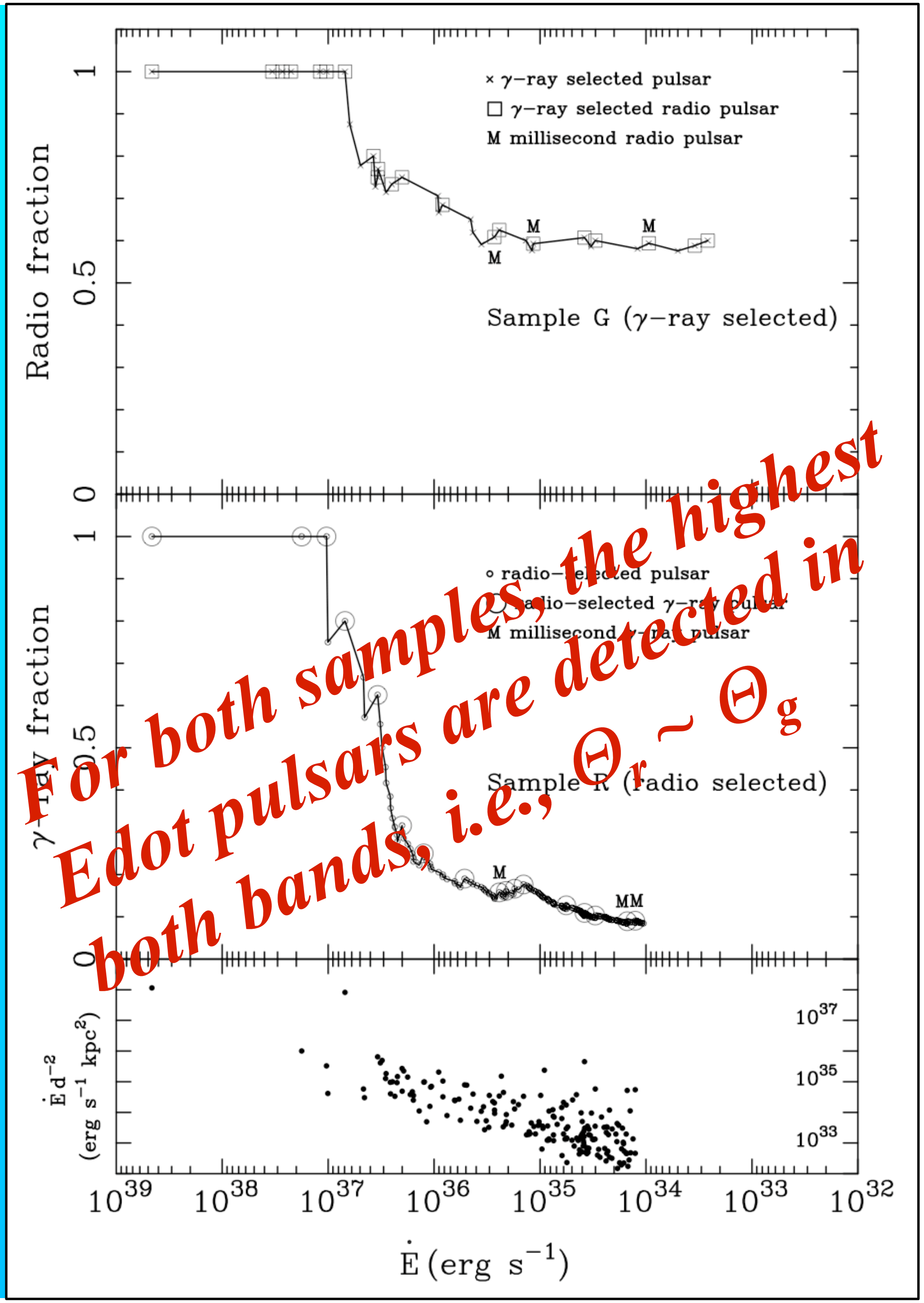
(Ravi, Manchester & Hobbs 2010)



Radio – γ-ray Beaming

- Two samples:
  - G: All pulsars found (or that could be found) in the Fermi 6-month blind search (Abdo et al. 2010)
  - R: High Edot radio pulsars searched by LAT for γ-ray emission (Abdo et al. 2010)
- Fraction of G and R samples with Edot > given value observed at **both** bands plotted as function of Edot
- 20/35 Sample G pulsars detected in radio band
- 17/201 Sample R pulsars detected in γ-ray band

(Ravi, Manchester & Hobbs 2010)



Radio – γ-ray Beaming

- For the highest Edot pulsars, $\Theta_r >\sim \Theta_g$
- This implies that the radio beaming fraction f_r is comparable to or greater than the γ-ray beaming fraction f_g
- For OG and TPC models, $f_g \sim 1.0$
- For lower Edot Sample G pulsars, $f_r >\sim 0.57$ – includes several MSPs
- Even high-altitude radio polar-cap models (e.g., Kastergiou & Johnston 2007) are unlikely to give $f_r >\sim f_g \sim 1$
- Therefore …

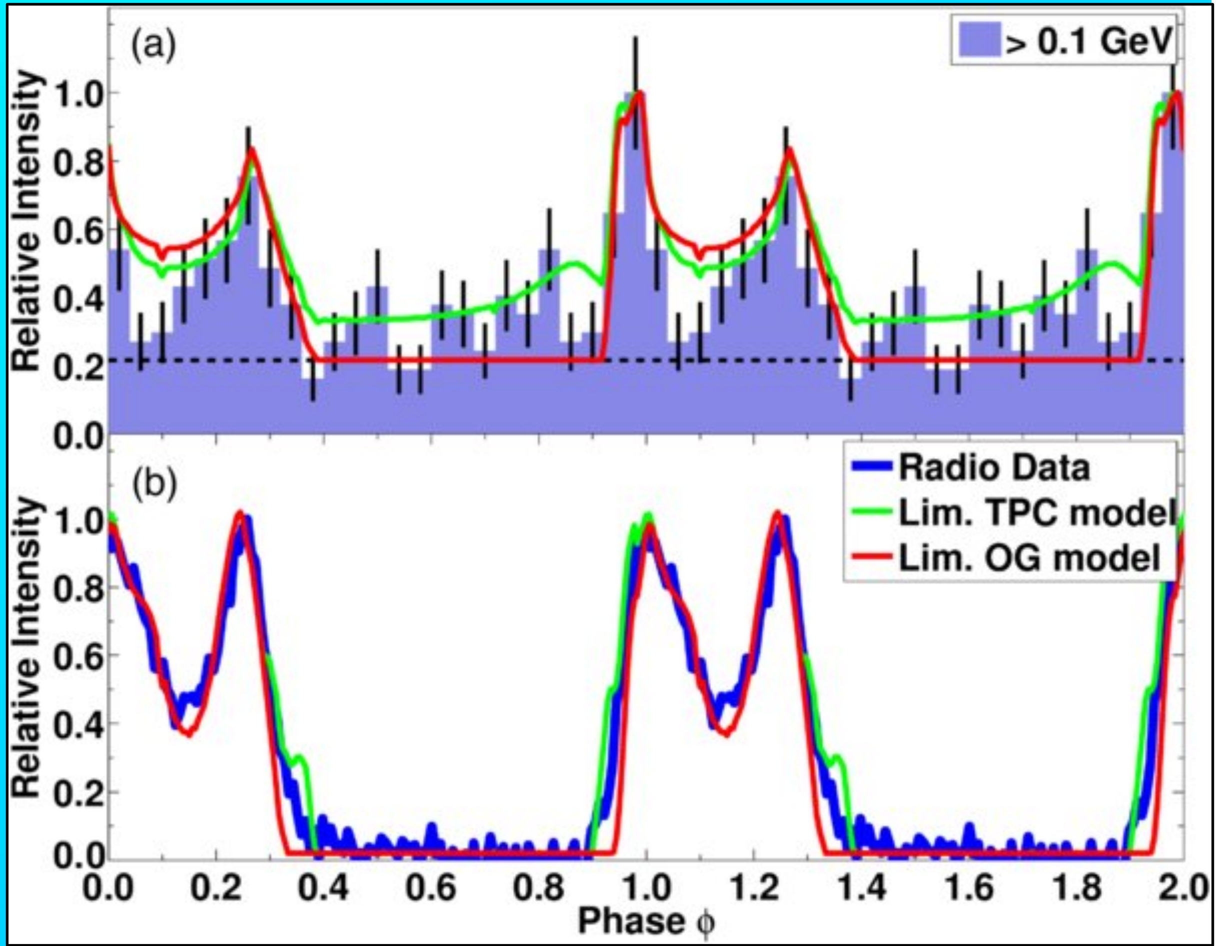
➢ ***For high Edot pulsars, it is probable that the radio emission region is located in the outer magnetosphere***

➢ ***Radio pulse profiles are formed in a similar way to γ-ray profiles with caustic effects important***

(Manchester 2005, Ravi et al. 2010)

More:

- Recent *Fermi* detection of pulses from MSP PSR J0034-0534
- Radio and γ-ray pulse profiles virtually identical and aligned
- This result gives strong support to the idea that radio and γ-ray emission regions are co-located, at least in some cases



(Abdo et al. 2010)

- But most radio and γ-ray pulse profiles are not identical
- Some high-Edot/d^2 radio pulsars are not (yet) detected by *Fermi*
- Both radio and γ-ray emission regions are in the outer magnetosphere, but not co-located, e.g., γ-ray emission may be OG, radio emission TPC

Summary and Questions

• Radio emission from young, high-Edot pulsars has different properties compared to that from older "normal" pulsars – wide profiles, interpulses, very high linear polarisation

• MSPs also have very wide profiles

• Giant pulse emission is closely connected to HE emission

• Almost all of the highest Edot pulsars are seen in both radio and γ-ray bands

• More than half of the γ-ray-selected sample also have radio pulsed emission

• For high Edot pulsars, the radio and γ-ray beams have comparable sky coverage

• For high Edot pulsars the radio emission region is approximately co-located with the γ-ray emission region in the outer magnetosphere

• **Where and how is the radio emission from high Edot pulsars generated?**

• **How does the radio emission mechanism evolve to "normal" PC emission?**

• **Is there an outer gap?**