Young Pulsars and Fermi

A Match Made in the Heavens

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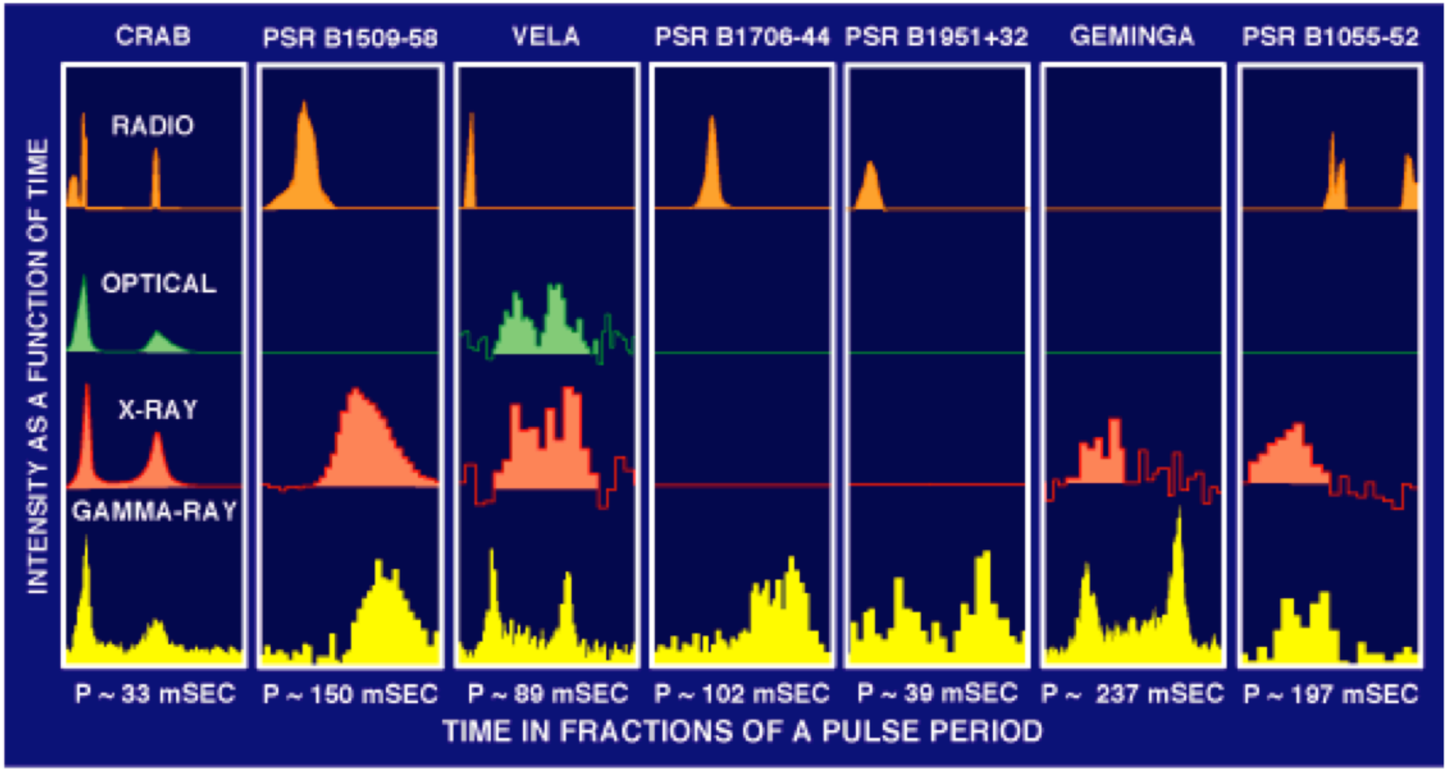
summarizing the efforts of many

(LAT Team, Pulsar Timing Consortium, Pulsar Search Consortium, bosonic observers and theorists)

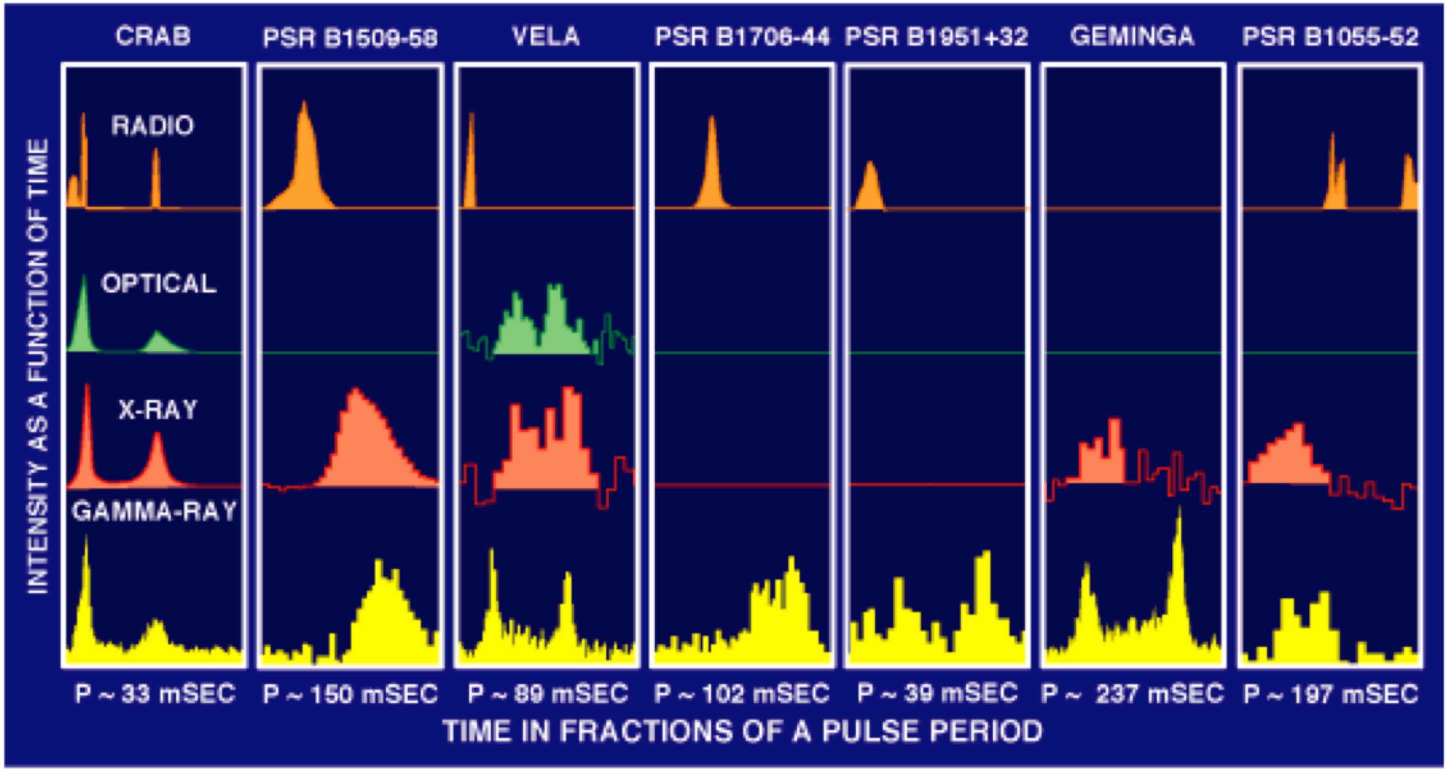
Life Before Fermi

- Radio-loud young pulsars: 6
- Radio-quiet young pulsars: 1
  - Blind search pulsars: 0
- Fermi pulsar *Science* papers: 0



The Promise of Fermi

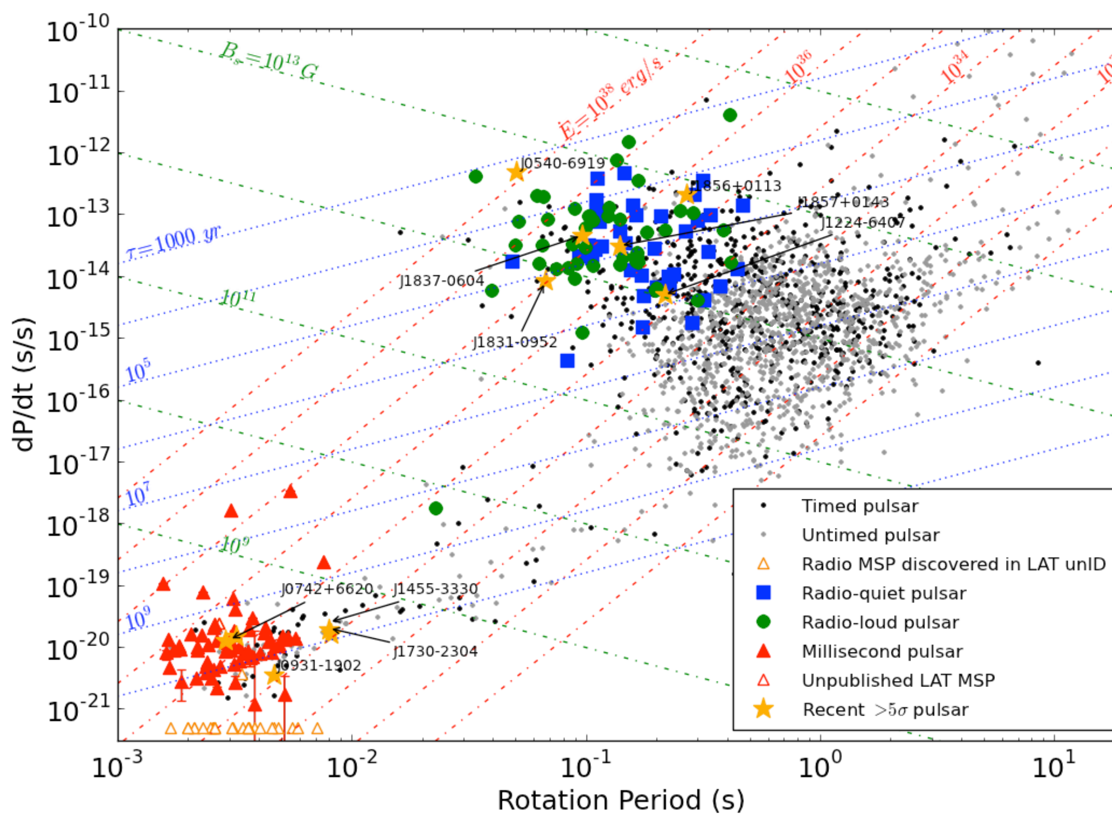
- **Gamma-ray beam clearly different from radio beam**
- **Radio coherent, tiny efficiency; gamma rays incoherent, dominate emission**



Promise (Partially) Fulfilled

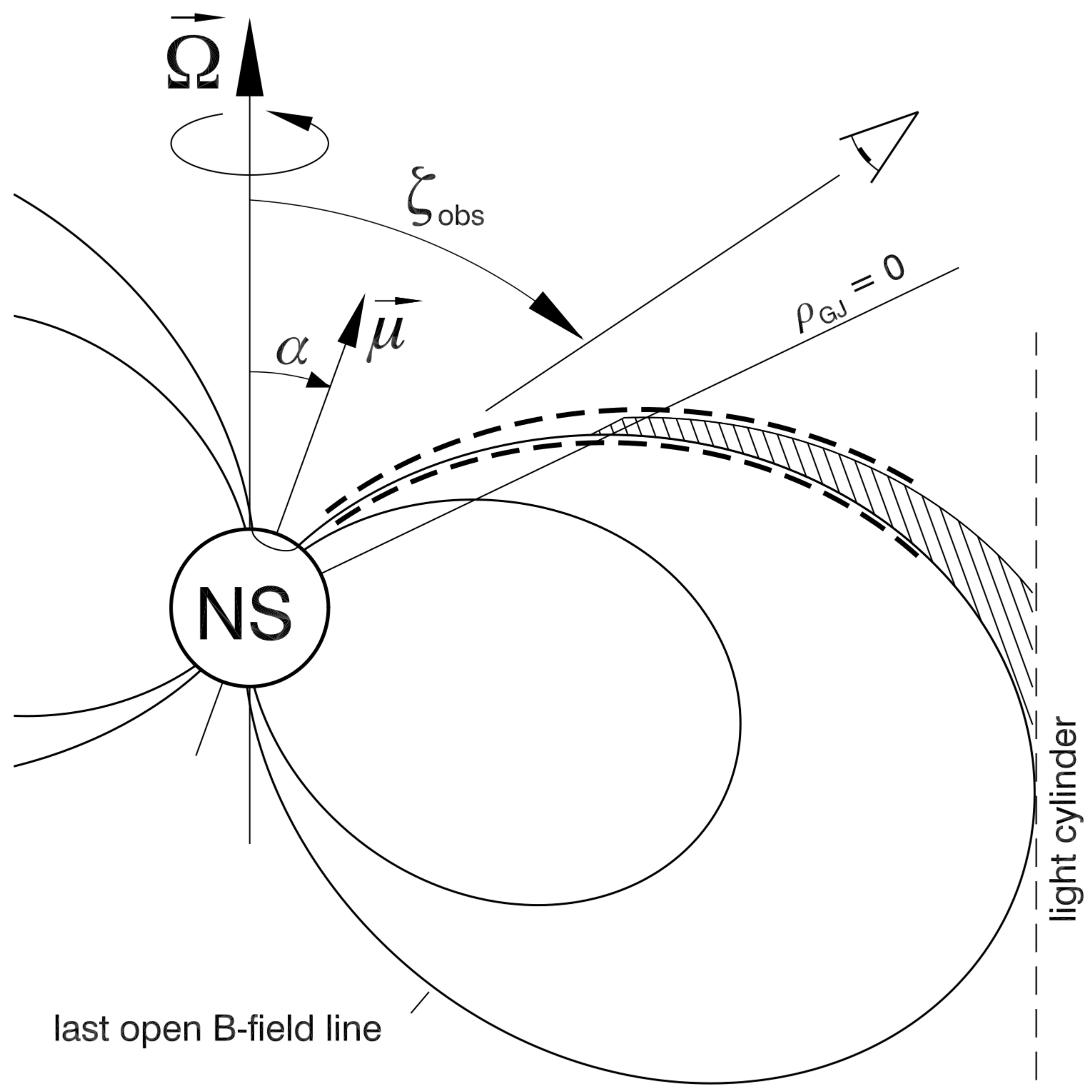
- Radio-loud young pulsars: 50*
- Radio-quiet young pulsars: 40*
- Fermi pulsar *Science* papers: 7

- Millisecond Pulsars: 71
  - Viva la revolution!
  - See EF's poster 7.02 and Anne Archibald talk.
  - But MSPs are *complicated.*



Keep It Simple: A Physical Cartoon

- Prominent models vary in detail/ consistency of physics, but primary distinction is GEOMETRY.
- Given a magnetic field, fairly robust and distinct predictions.
- But see talk by Andrey Timokhin!



Dyks & Rudak 2003

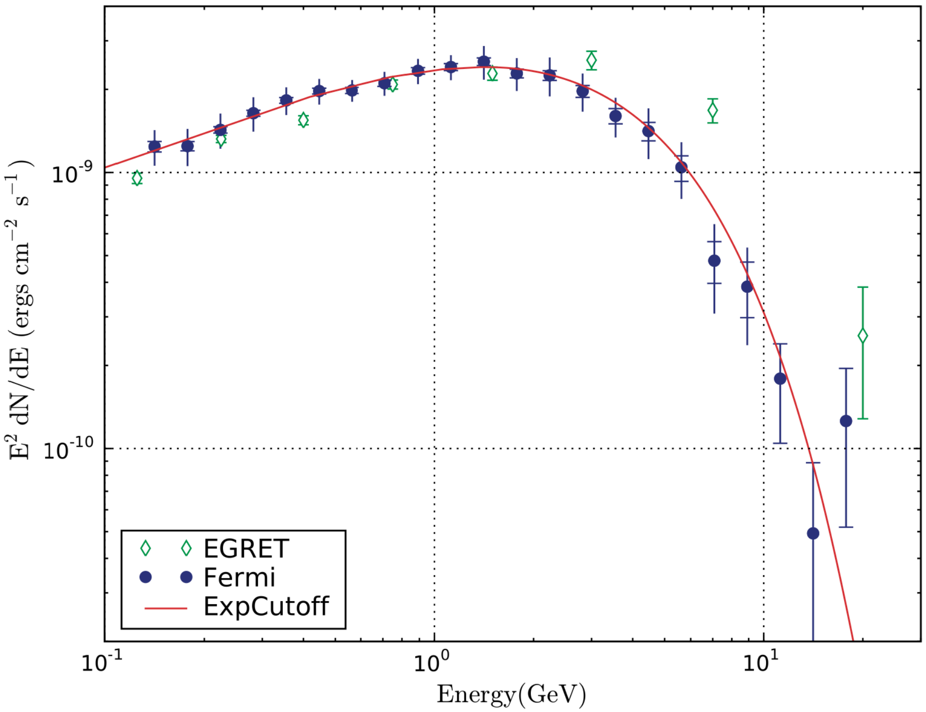
Physics from a Cartoon

- This picture gets us a long way in figuring out the bulk properties of the magnetosphere and in doing population syntheses.
  - Gamma rays come from the outer magnetosphere.
  - Gamma ray and radio beams come from similar altitude for young pulsars.
  - The beams evolve “orthogonally” with age.
- Three lines of evidence:
  - Spectral shapes.
  - Light curve modeling.
  - Population synthesis / statistics.

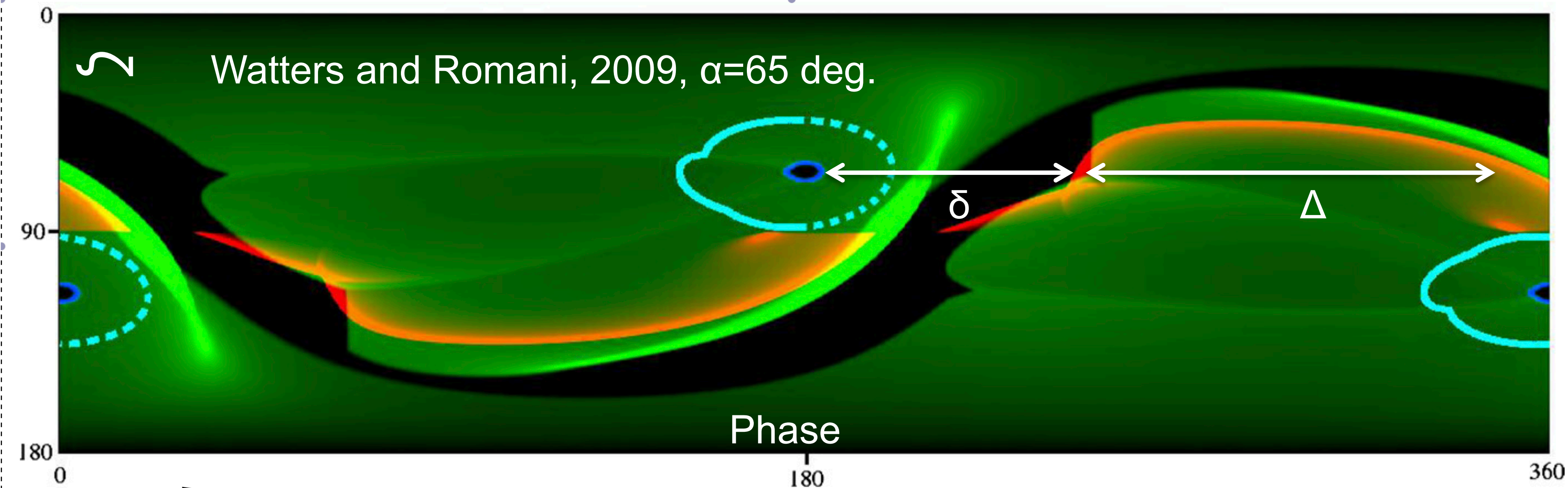
Vela and Friends

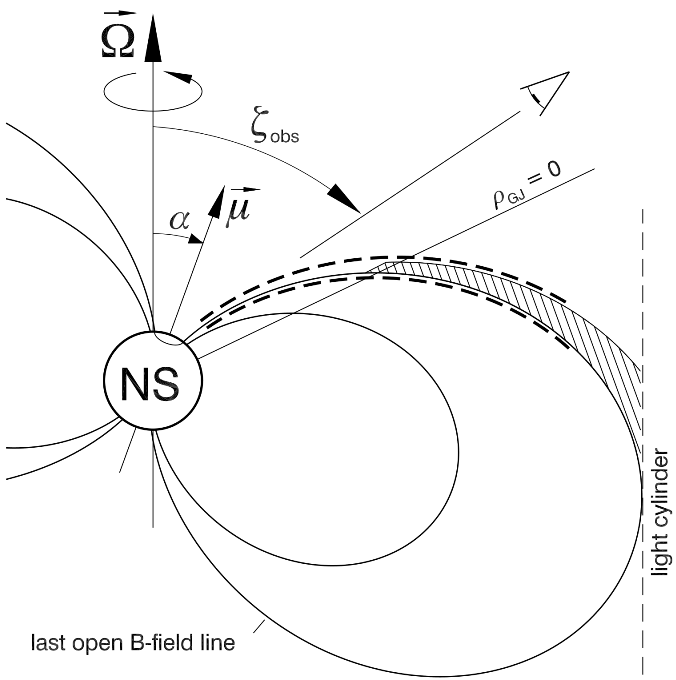
- **Low-altitude (~few NS radii) GeV gamma rays absorbed by strong magnetic field → strong "hyperexponential cutoff"**
  - **See Story & Baring (2014) for updated calculations.**

- **One of first LAT results:**
  - **Vela spectrum consistent with power law + exponential cutoff, rules out polar cap origin**
  - **In fact, "subexponential", but let's not get ahead of ourselves.**



Light Curve Modeling



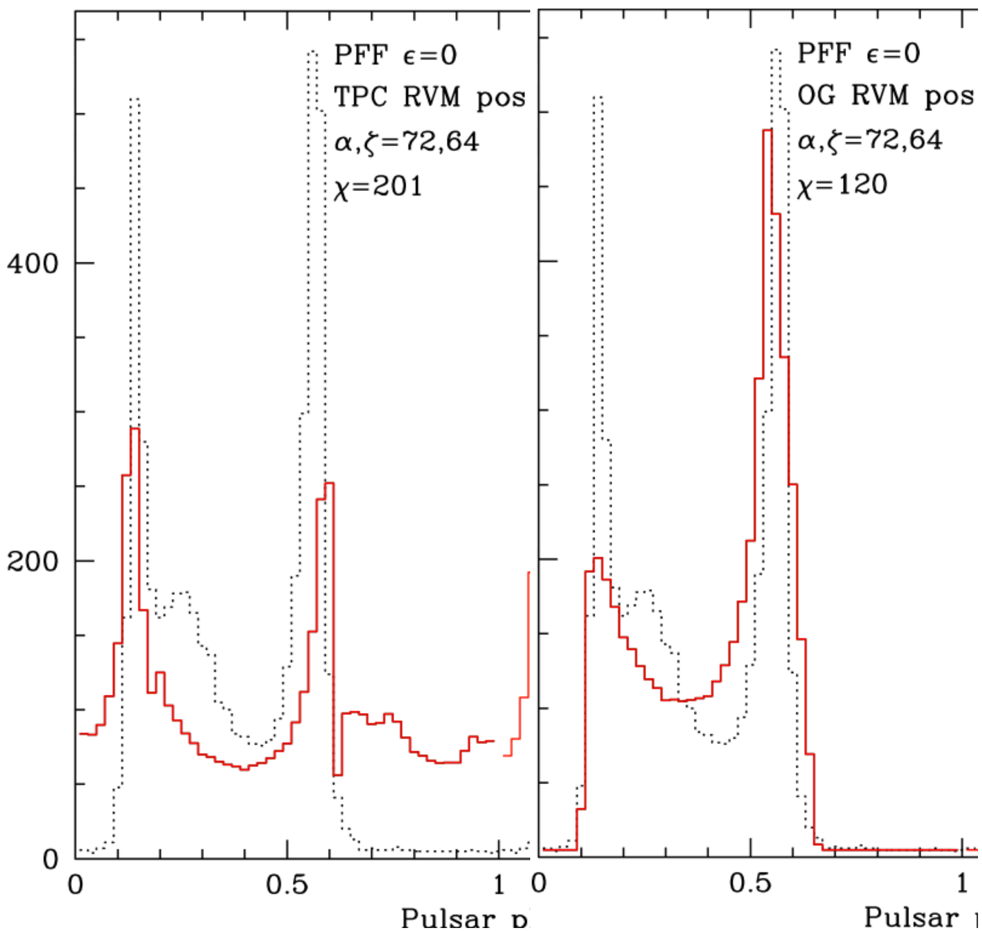


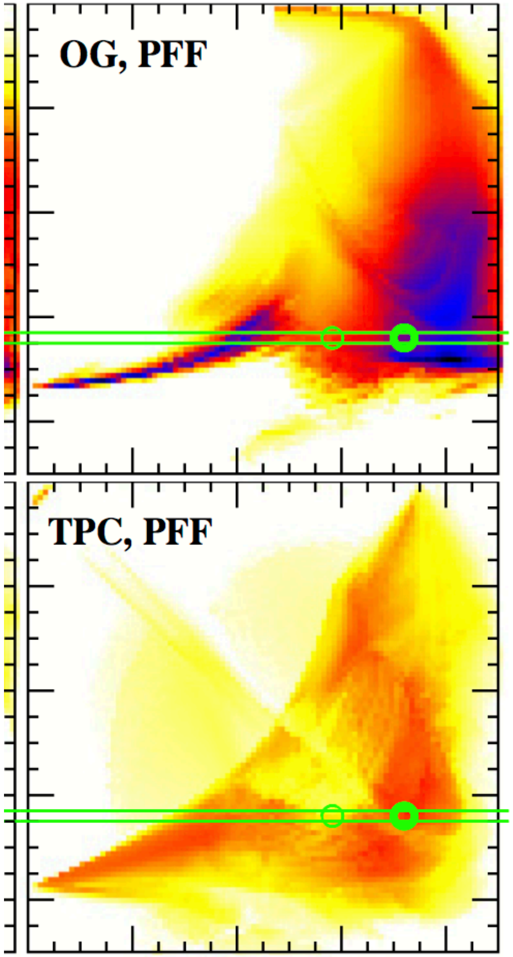
- **Reminder: don't try to capture detailed physics, just pick out the gross features of emission region and beam shapes.**
  - **Guidance for future models.**
  - **Adequate for population synthesis.**

Light Curves

See Simon Johnston's talk!

Romani & Watters (2010)

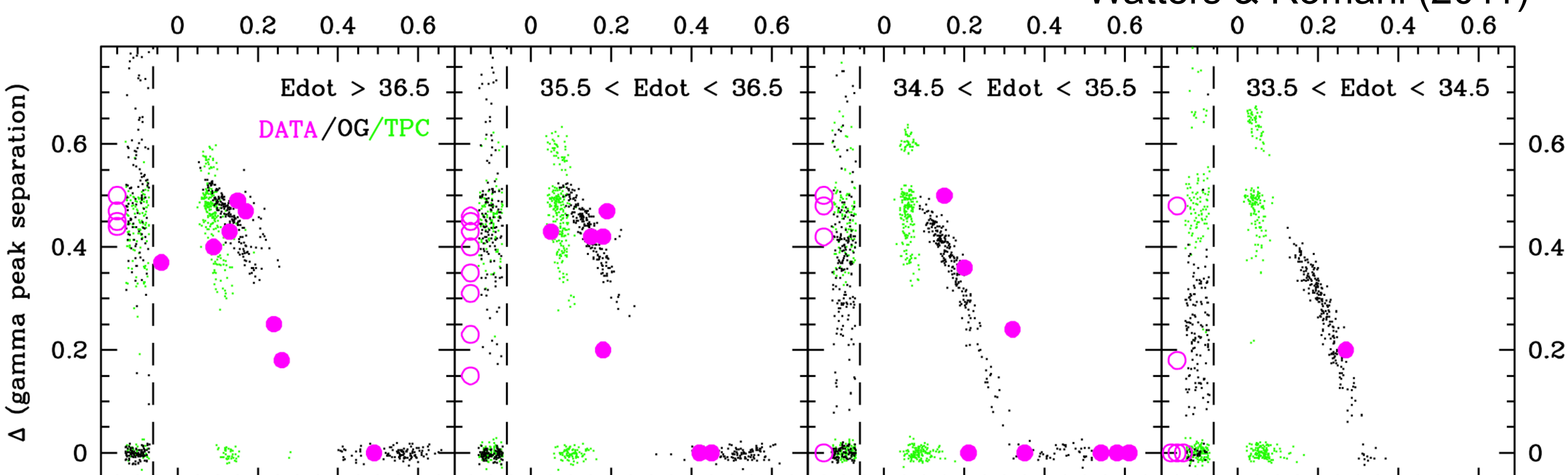




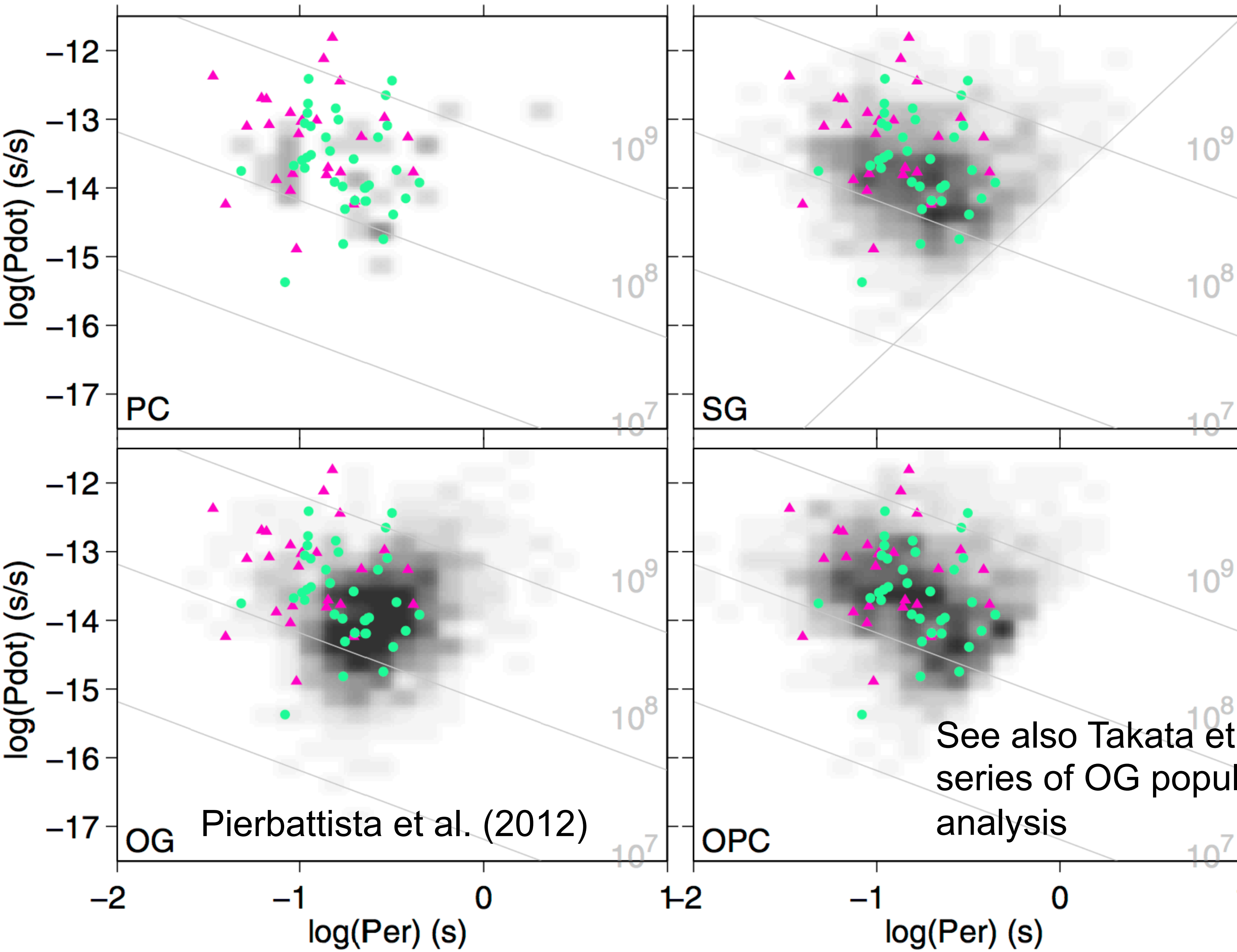
Population Synthesis

- Simulate neutron star birth rate, spindown, distribution, magnetic field orientation, etc.
- Assume model of radio and gamma-ray emission and compute observables:
  - Number of detections for given sensitivity (RL vs. RQ)
  - Distribution of luminosities
  - Light curve shapes (e.g. δ/Δ)
- Powerful but very model dependent!

Watters & Romani (2011)



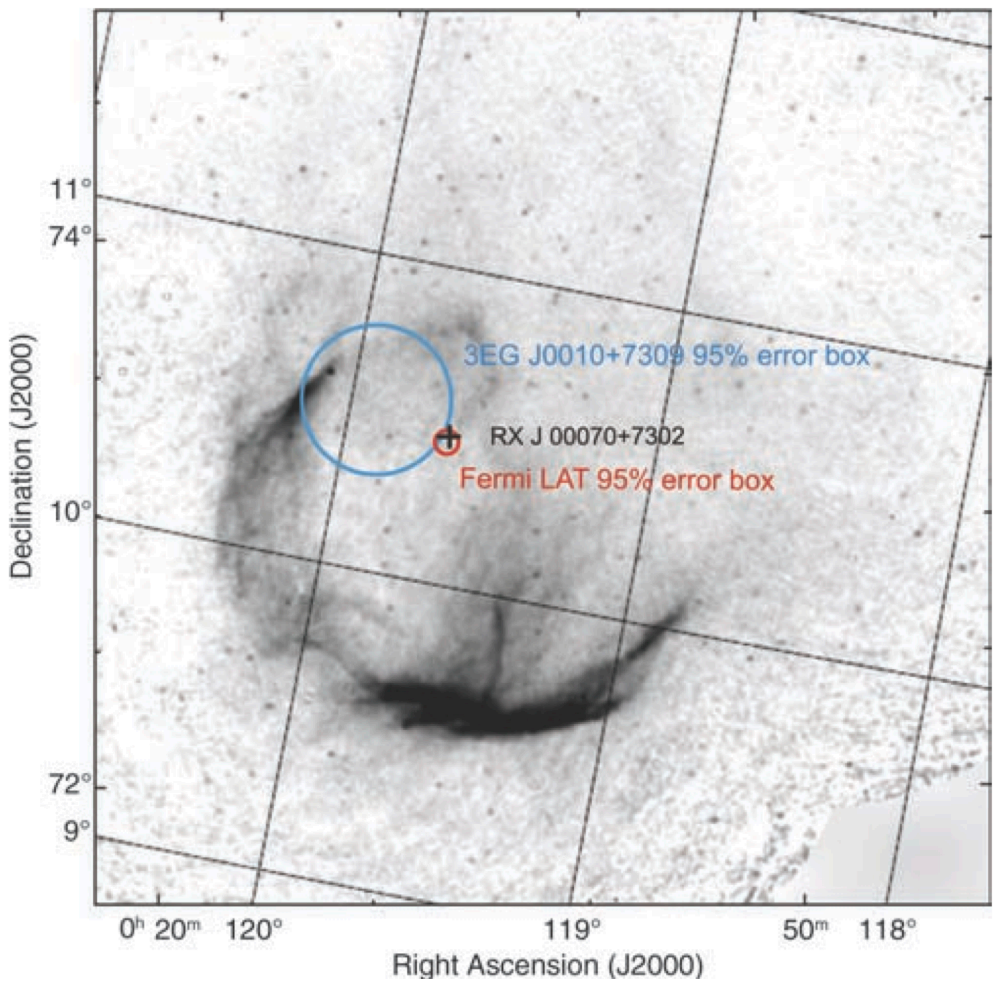
Population Synthesis

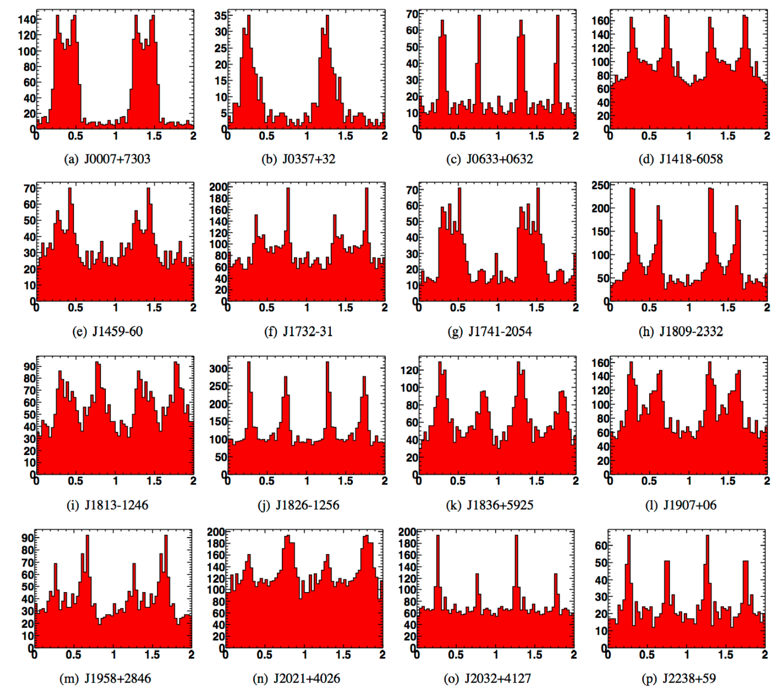


See also Takata et al. series of OG population analysis

Population Synthesis Needs Sources: Blind Searches

- **A great success story of Fermi!**
  - **Instrument performance, smart people, and fast computers.**

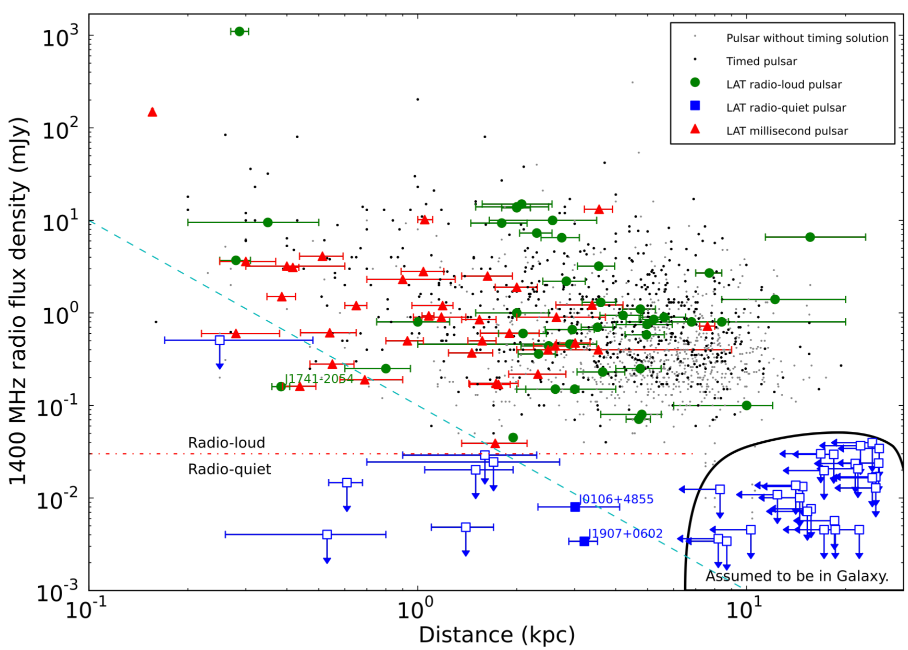


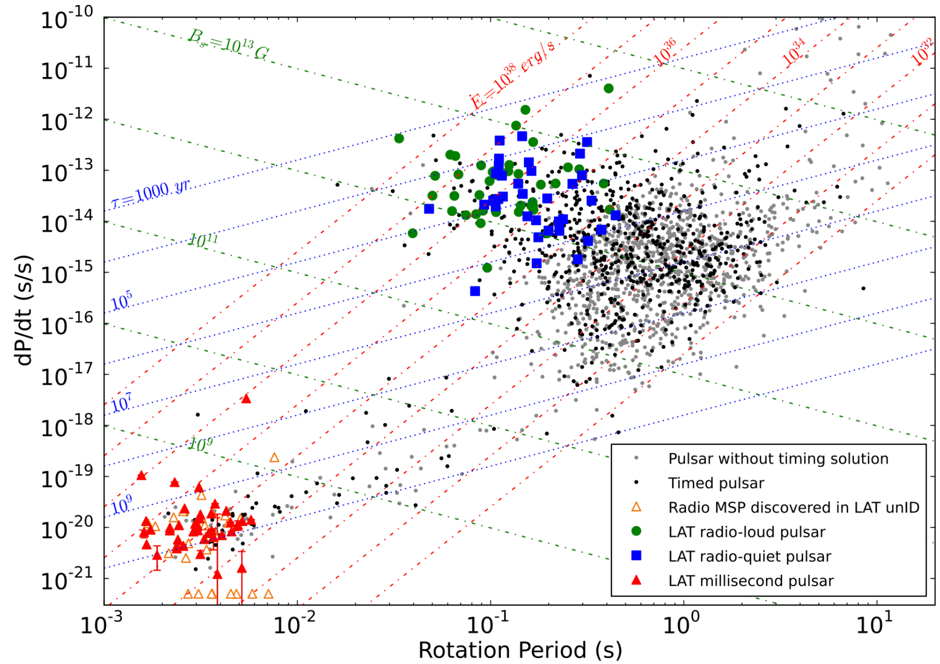


Abdo et al. 2008, 2009

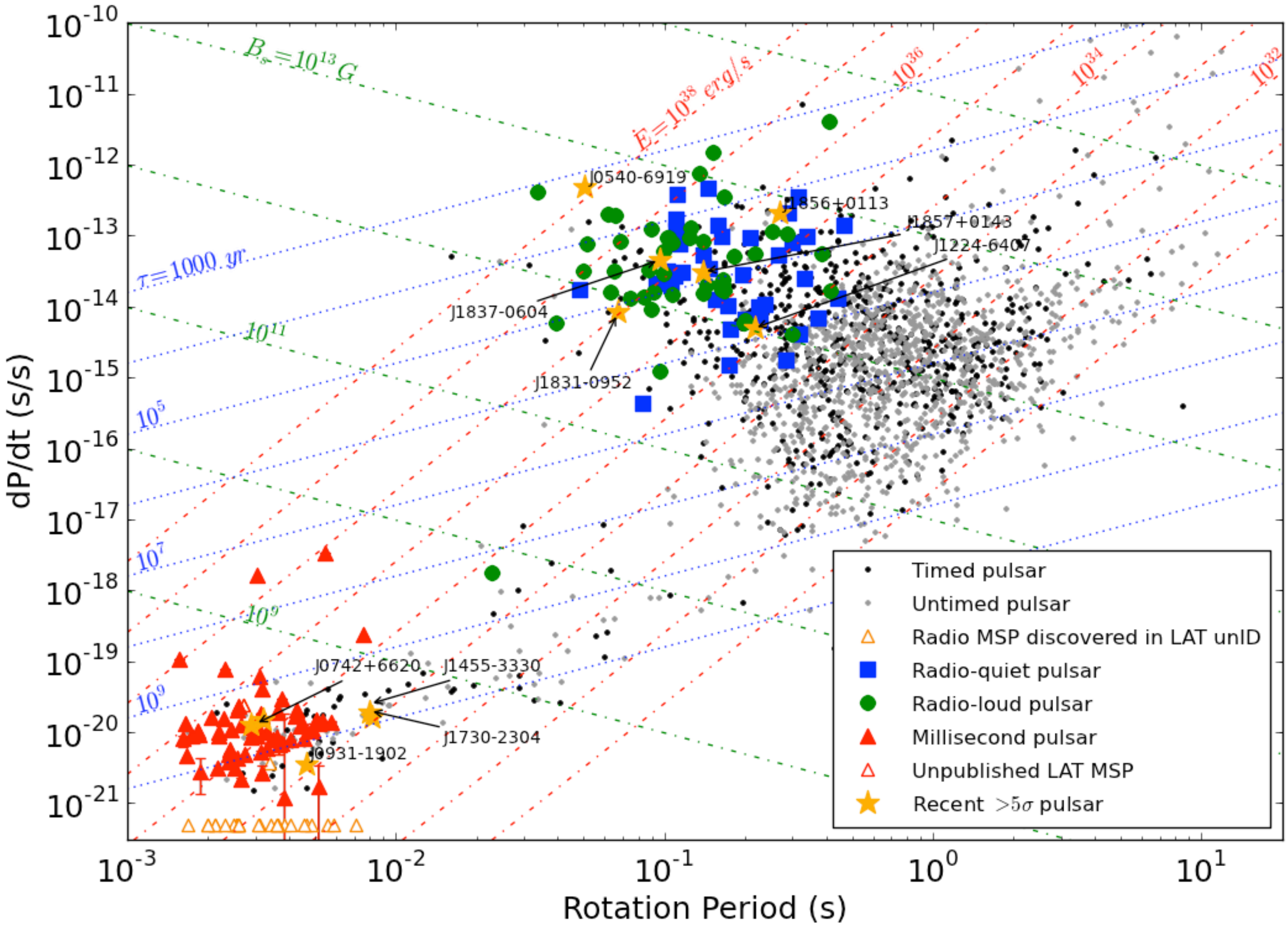
Pushing Deeper

- "Semicoherent" algorithms and Einstein@HOME power a second wave of blind search detections.
- Clear divergence in population thanks to PTC and PSC:
  - PTC: Fermi detects most high-Edot pulsars.
    - See talk and poster 7.06 from Helene Laffon.
  - PSC: Most low-Edot Fermi pulsars are radio quiet.



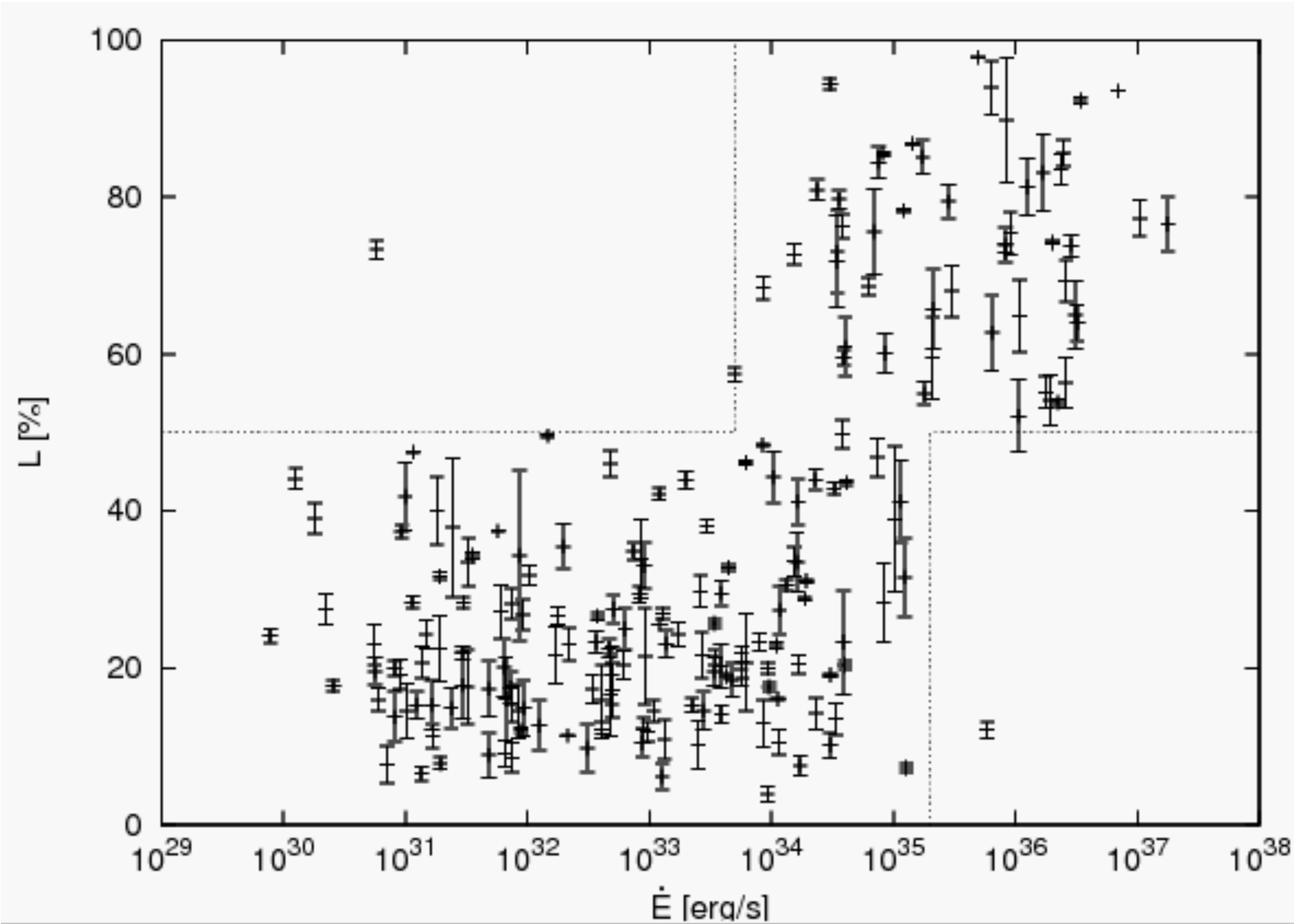


Zooming In



dP/dt (s/s)
Rotation Period (s)
$B_s = 10^{13}\,G$
10^{11}
10^{9}
$\dot{E} = 10^{38}\ erg/s$
10^{36}
10^{34}
10^{32}
$\tau = 1000\ yr$
10^{5}
10^{7}
10^{9}
J0540-6919
J1856+0113
J1857+0143
J1224-6407
J1837-0604
J1831-0952
J0742+6620
J1455-3330
J1730-2304
J0931-1902
Timed pulsar
Untimed pulsar
Radio MSP discovered in LAT unID
Radio-quiet pulsar
Radio-loud pulsar
Millisecond pulsar
Unpublished LAT MSP
Recent $>5\sigma$ pulsar

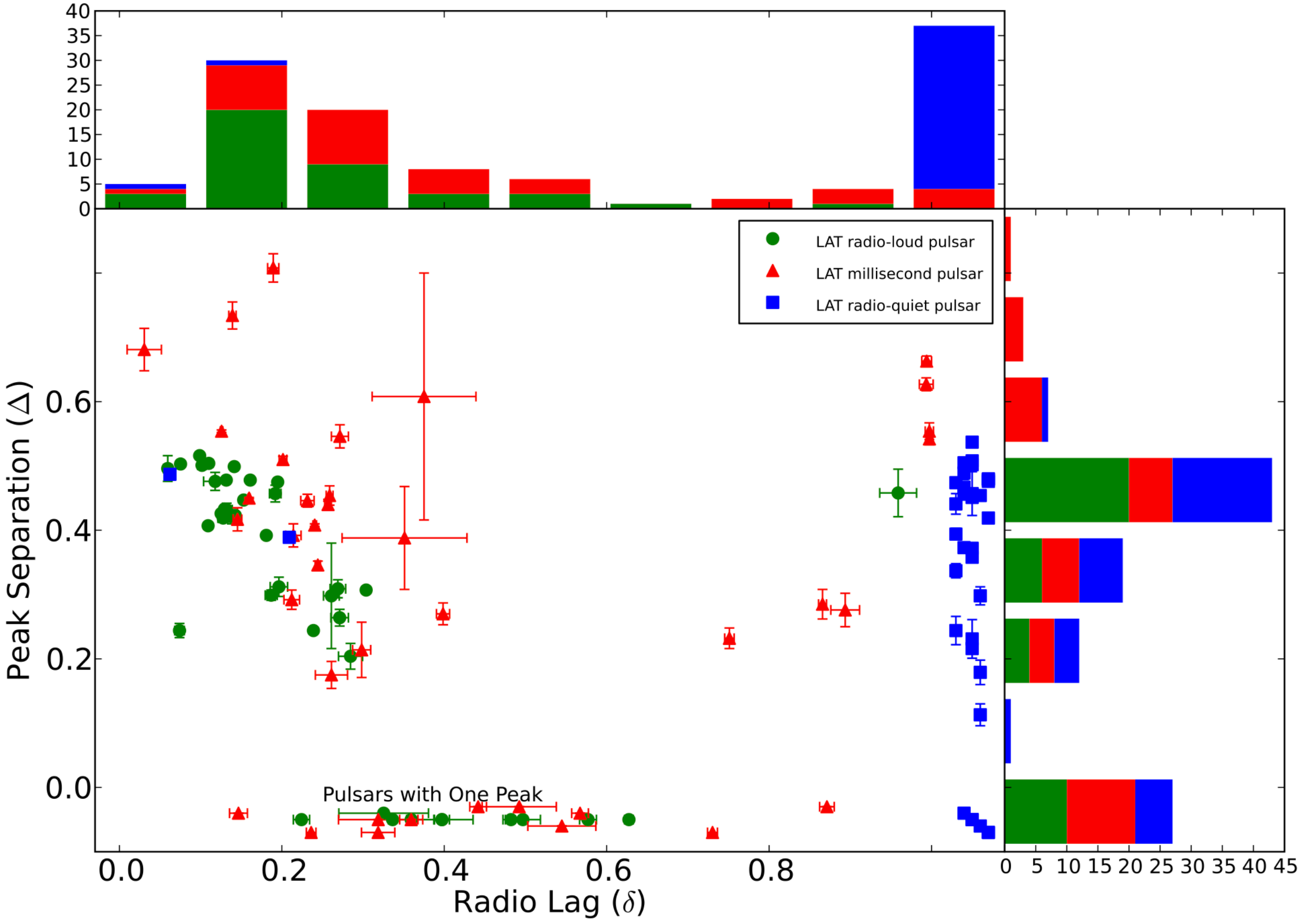
Reality Check – Multiwavelength Evidence?



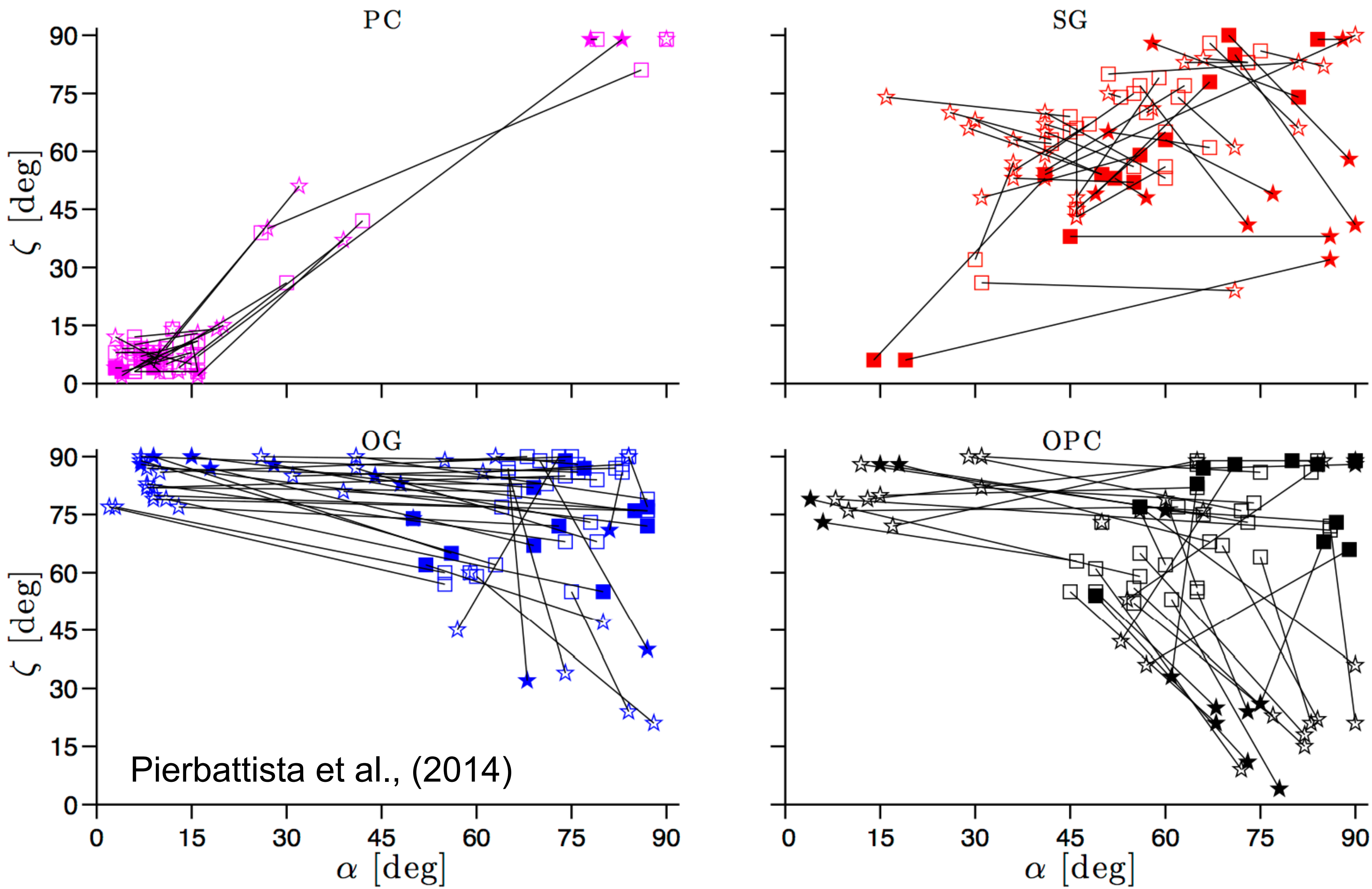
Weltevrede & Johnston (2008)

The 2nd Fermi Pulsar Catalog

- Spectra, energy-resolved, phase-aligned light curves for 117 pulsars – huge effort!
  – Plenty of ammunition to challenge models!



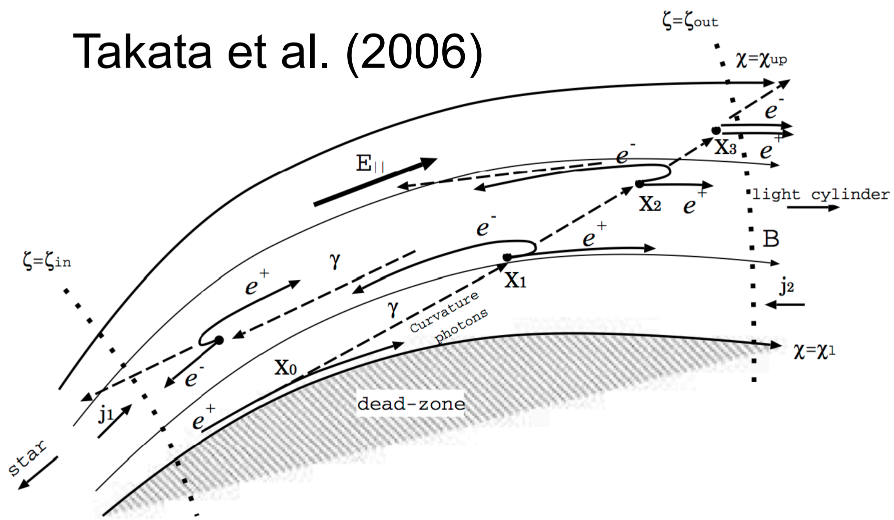
The End of Innocence

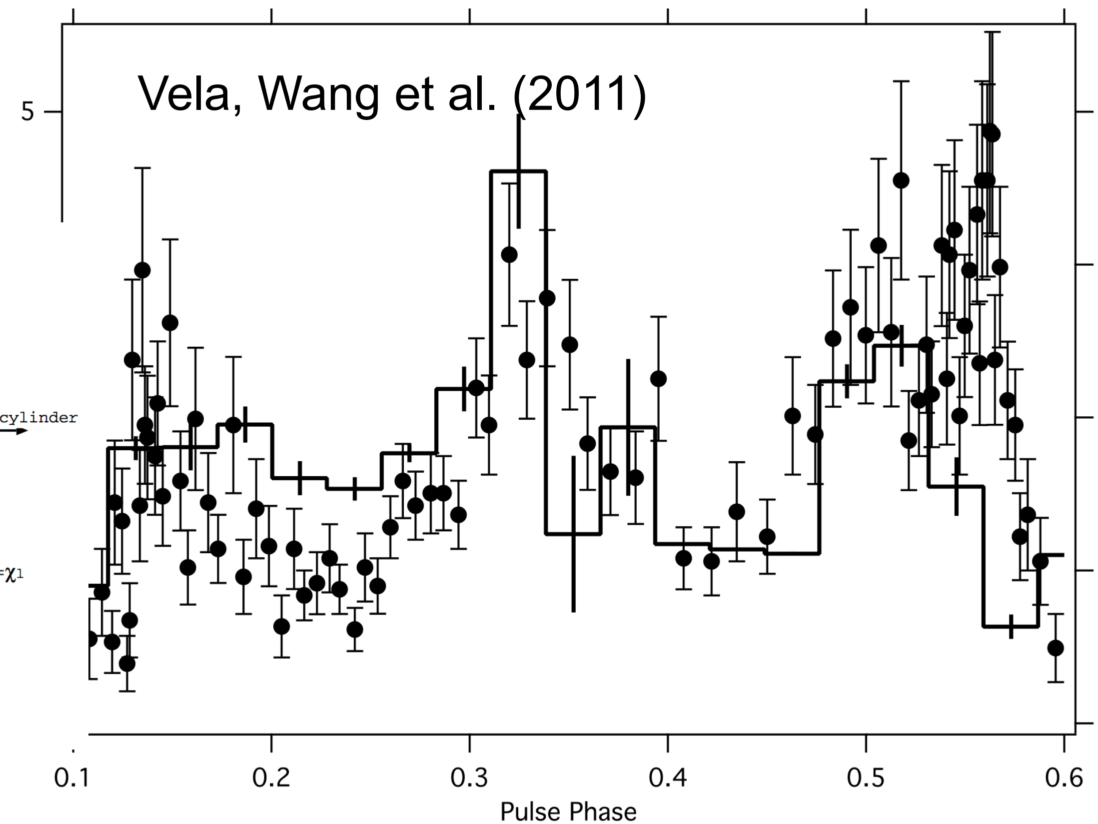


Microphysics: Confronting Spectra

- **Geometric models offer limited predictive power for spectra.**
- **One approach: assume boundary conditions and solve microphysics of resulting gap.**
  - **But light curves remain a challenge.**

Takata et al. (2006)

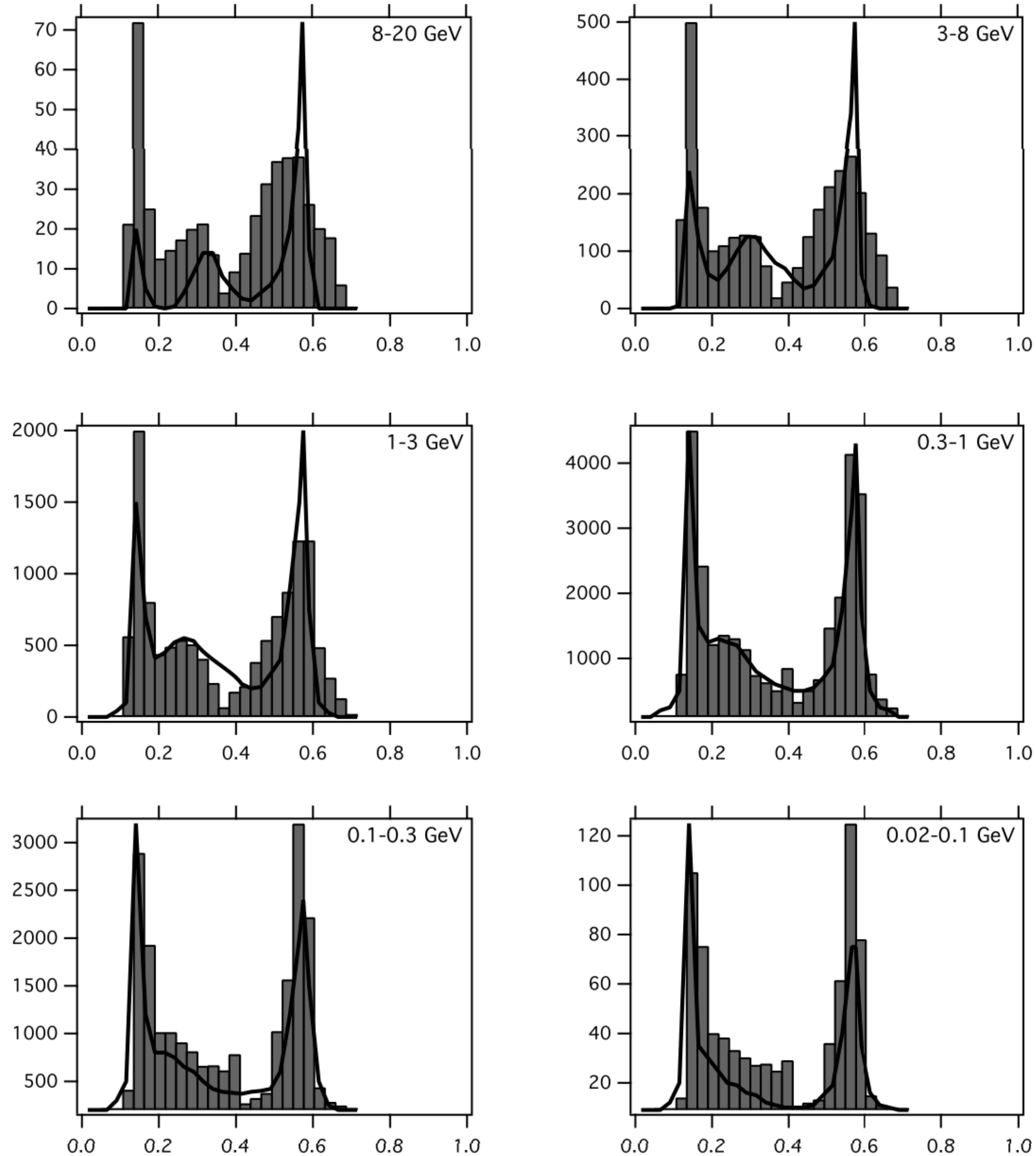




Microphysics: Confronting Spectra

Vela, Wang et al. (2011)

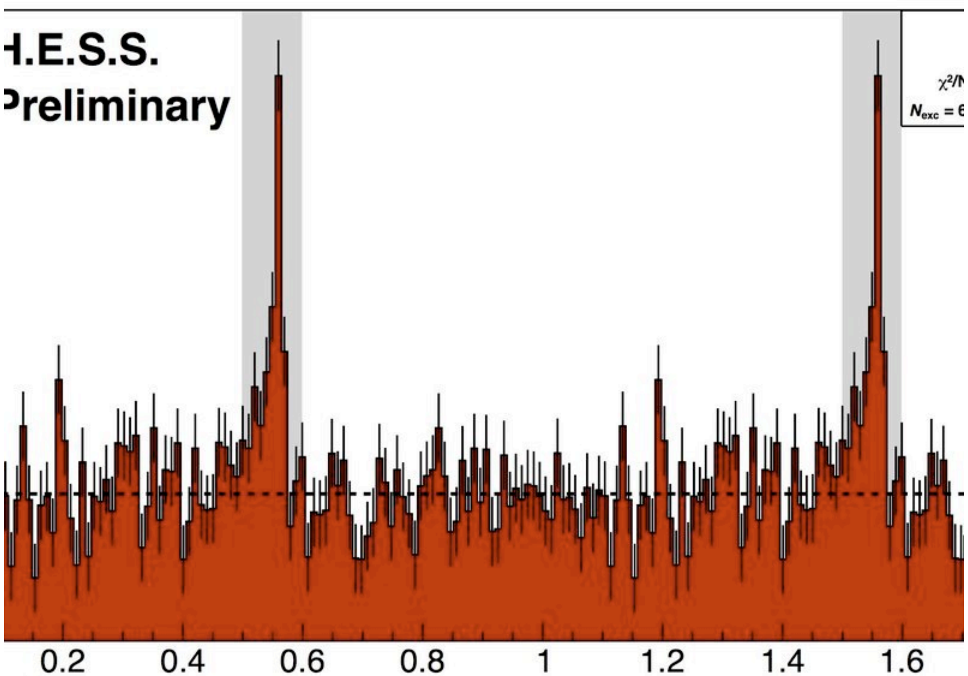
See also, e.g., “annular gap” computations of Du et al.

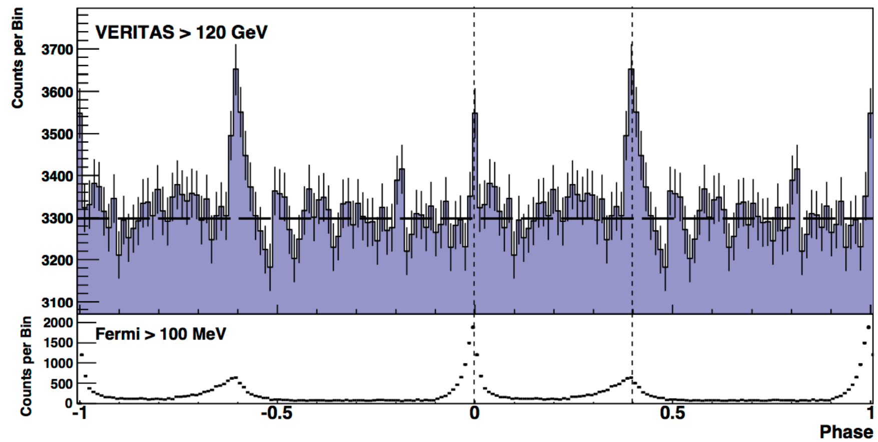


Microphysics: Confronting Spectra

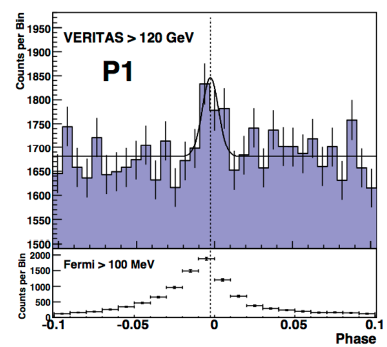
- **Is curvature radiation the whole story?**
- **Crab emission to 400 GeV → inverse Compton**
  - **See e.g. papers by Lyutikov, and modifications to OG model**
- **Aharonian/Petri models here?**

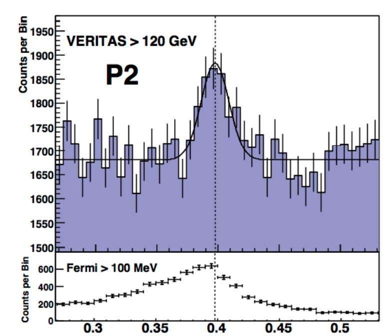
See posters 7.08 (MR), 7.09 (PSP)





Aliu et al. (2011)



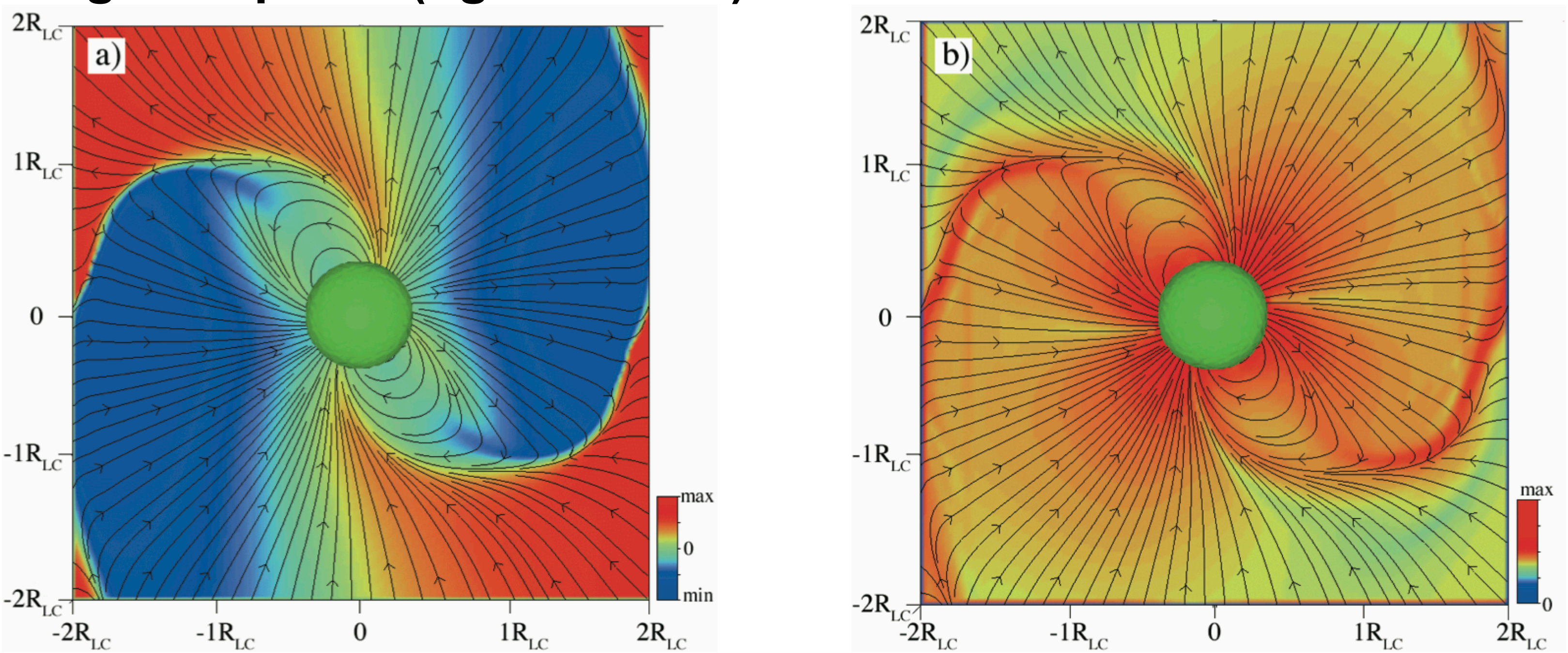


Macrophysics: Confronting Light Curves

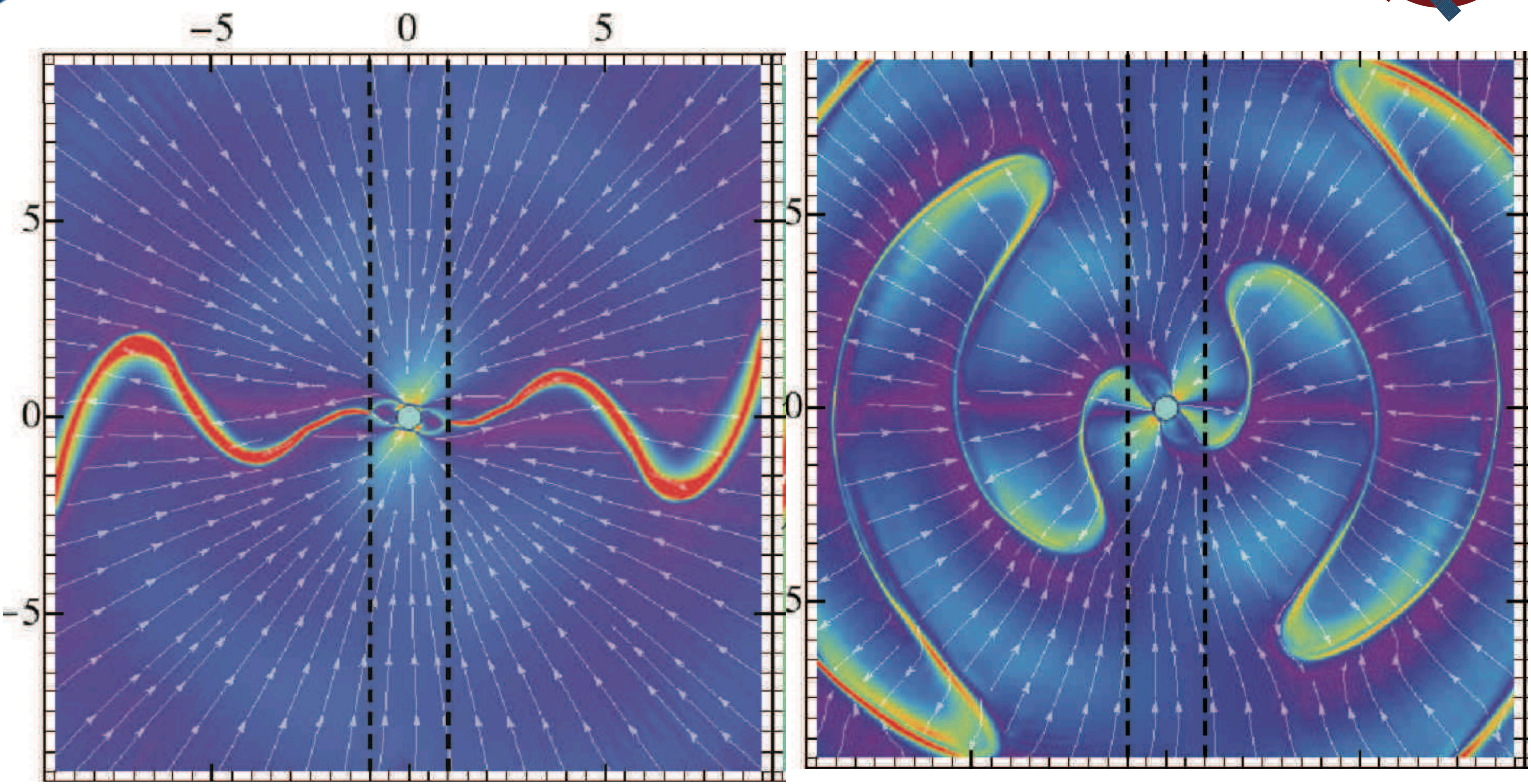
- If gamma-ray emission does come from outer magnetosphere, this is precisely where assumptions about the magnetic field are most important!
  - Plasma effects on field line sweepback, modified particle trajectories, reconnection (!)
  - So perhaps it's no surprise geometric models fail with a Fermi-quality sample.
- Thus, crucial to study effect of magnetosphere assumptions on gamma-ray observables.
  - See e.g. Bai & Spitkovsky (2010)

Force-free Magnetospheres

- Contopoulos et al. (1999) numerically solve axisymmetric (static) force-free magnetosphere.
  - Currents flow out (in) of open zone above polar cap and return in a current sheet through equator and into rim of polar cap.
- Spitkovsky et al. (2006) numerically solve oblique force-free magnetosphere (figure below).



Force-free Magnetospheres



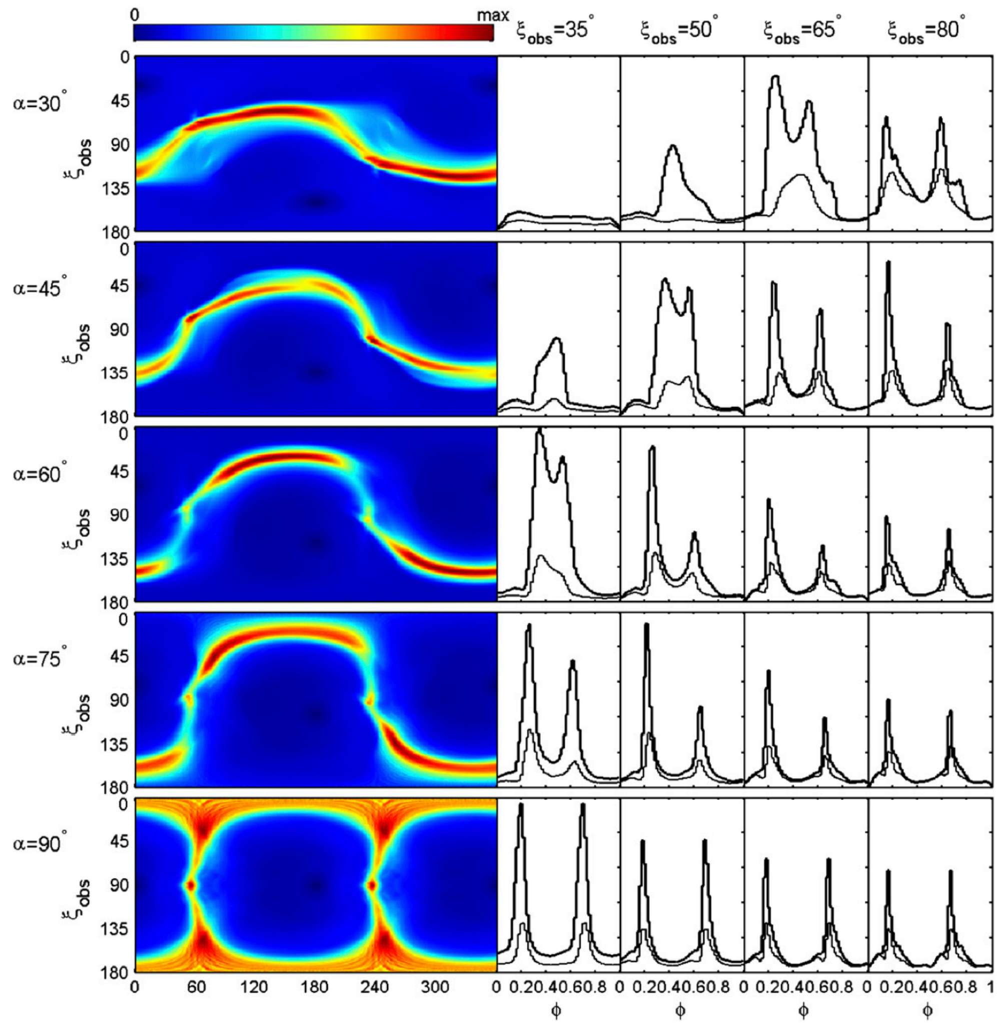
α = 15 deg.   α = 60 deg.

Current density, Kalapotharakos et al. (2012)

FF Light Curve Modeling

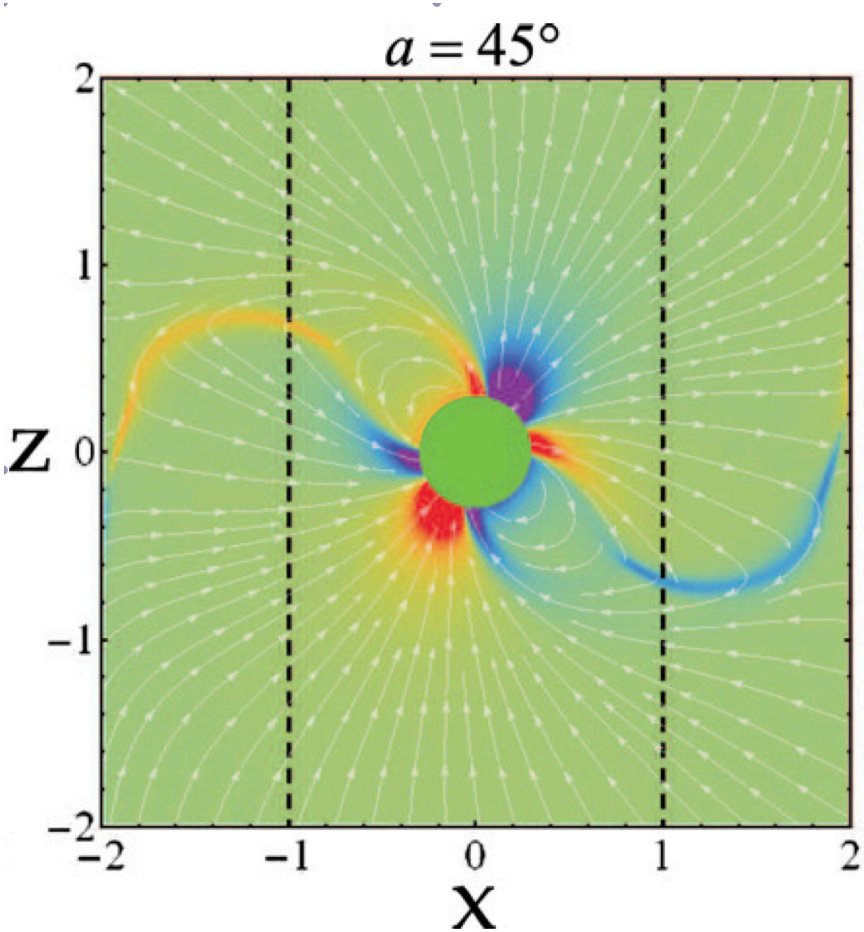
- **Magnetosphere perhaps more realistic, but selection of illumination regions ad hoc, thus “FF TPC”, “FF OG”, “FF AG”, “FF SL”, etc.**

Bai & Spitkovsky, (2010)



Dissipative Magnetospheres

- **Ideally, put in microphysics to compute particle production and currents self-consistently. Too hard! Instead, use good ol' Ohm's Law. Gives parallel electric field, though "by hand".**



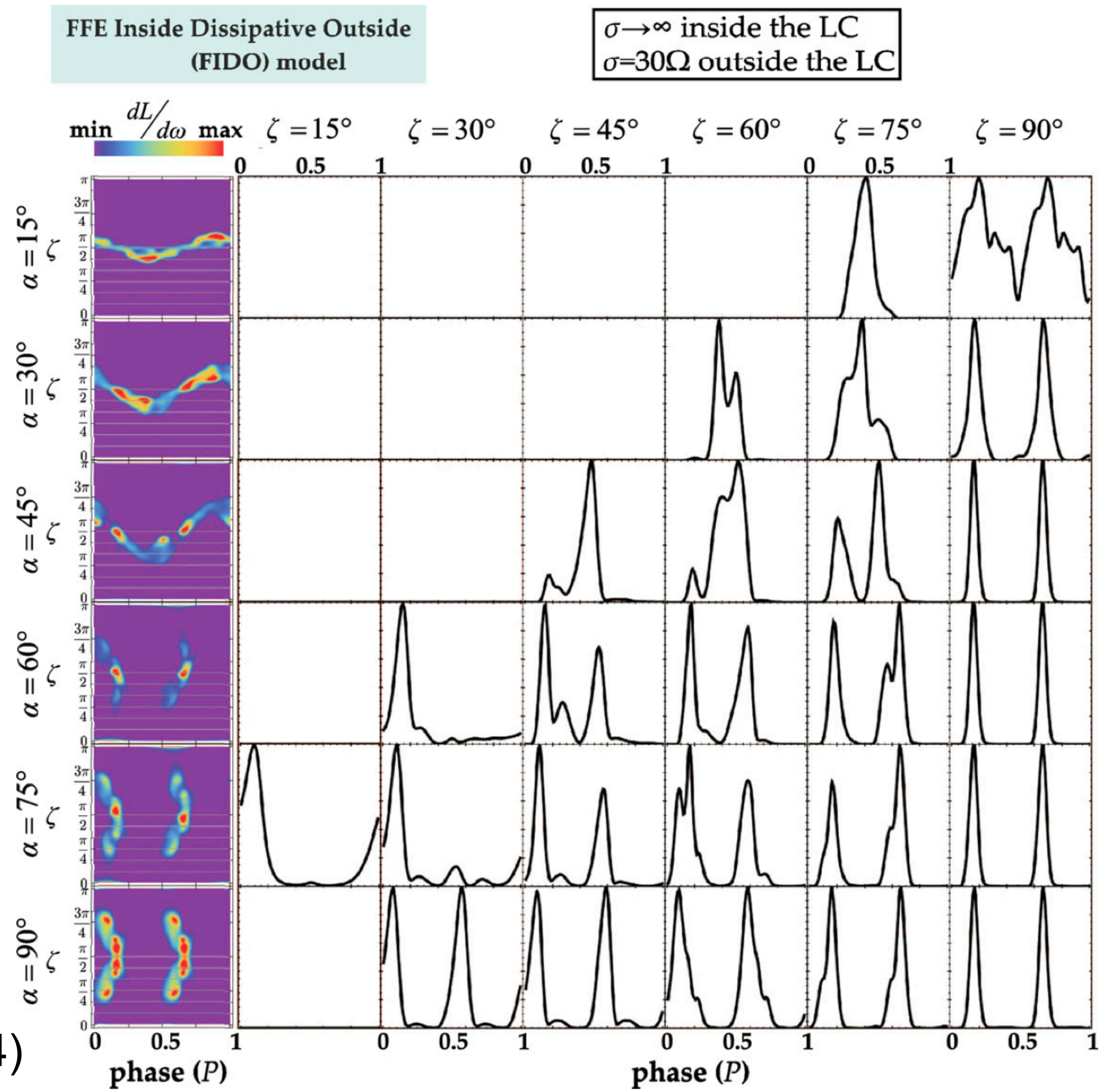
Parallel electric field,
high conductivity magnetosphere,
Kalapotharakos et al. (2014)

High altitude emission, and
emission from outside the LC!
(C.f., e.g., Petri (2012))

See poster 7.04 by CK!

Dissipative Magnetosphere LC Modeling

- **Compute trajectories and Lorentz factors consistently.**
- **Freedom in conductivity, choice of particle injection.**

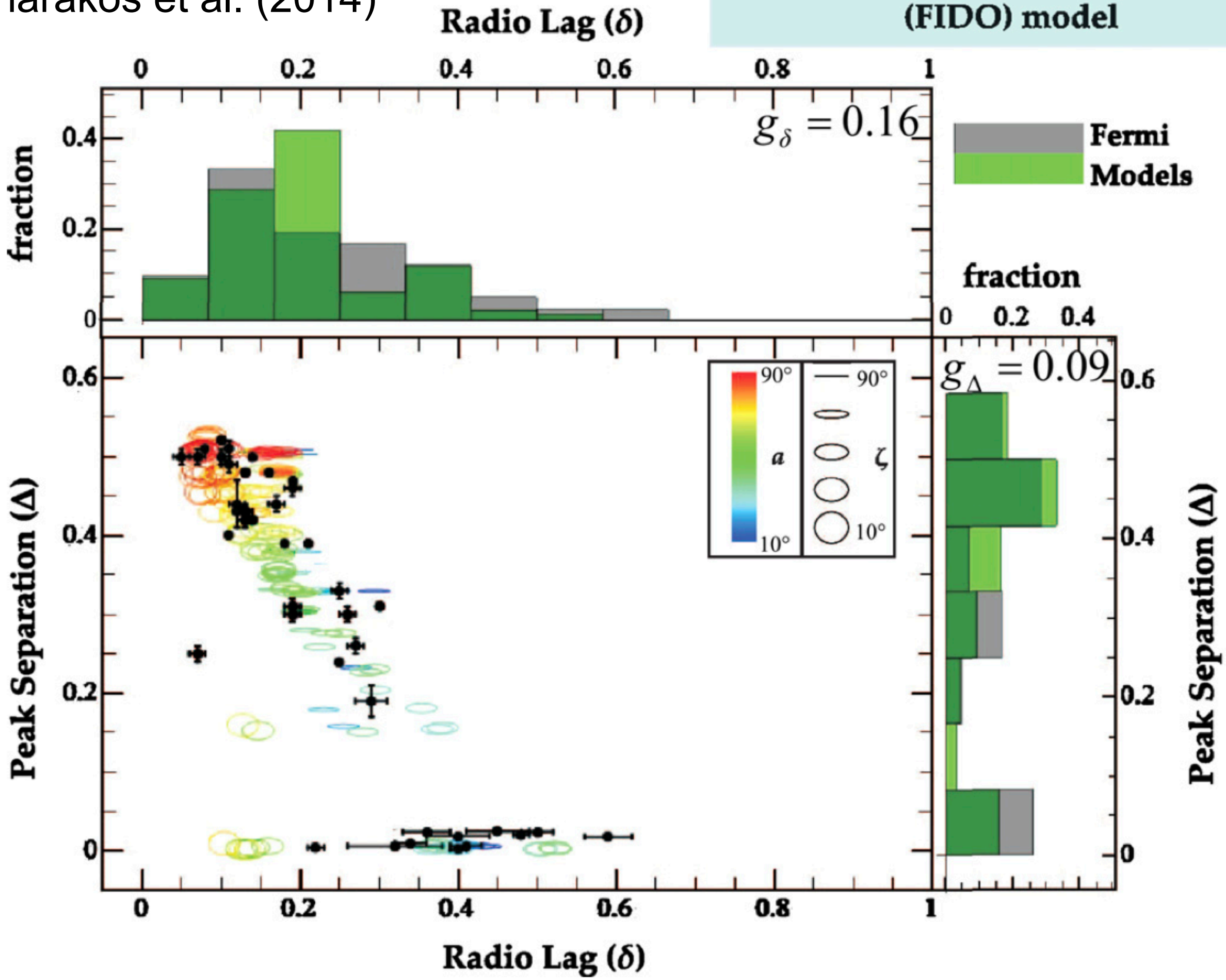


Kalapotharakos et al. (2014)

Comparison with 2PC

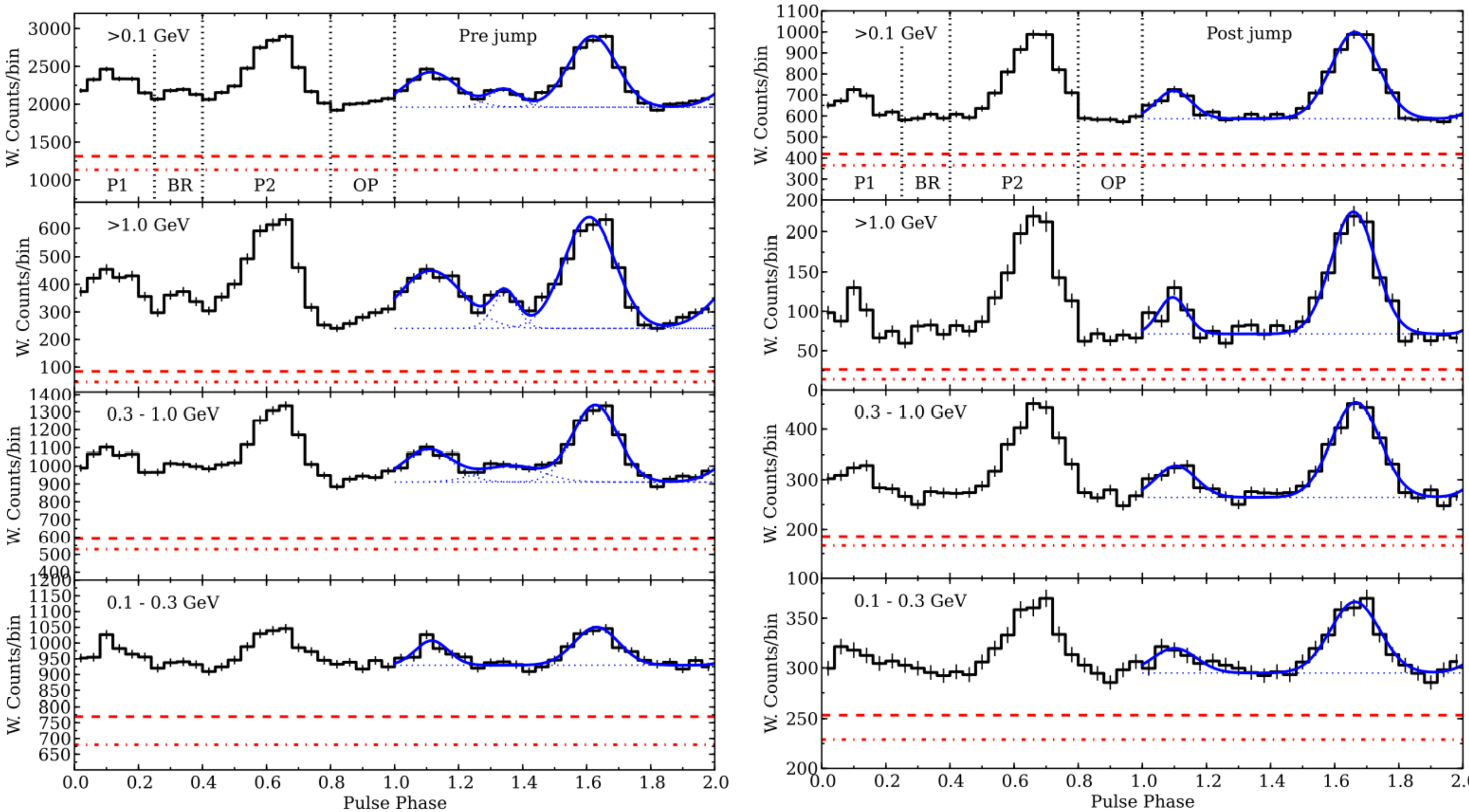
Kalapotharakos et al. (2014)

FFE Inside Dissipative Outside (FIDO) model



J2021+4026: Fermi Joins the Mode Switching Party

- **Mode switches a hot topic! Lyne et al. (2010), Hermsen et al. (2013); clues to pulsar timing noise, magnetosphere?**

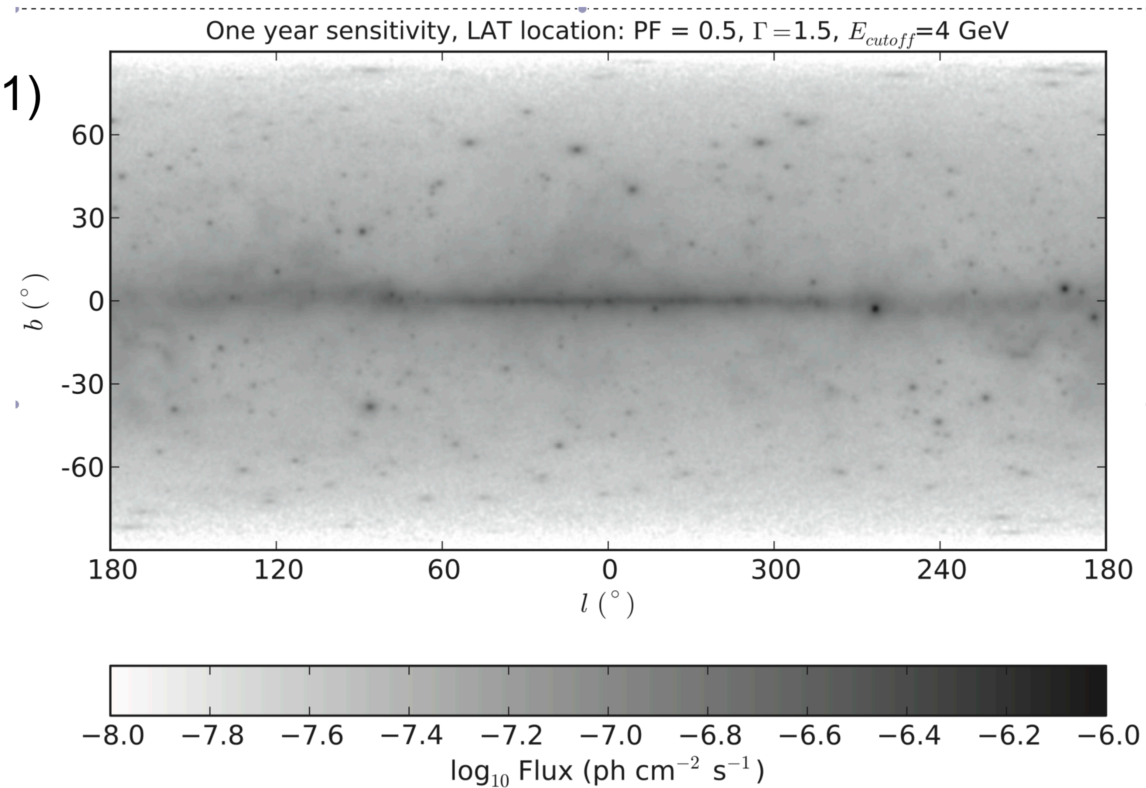


Allafort et al. (2013)

Desperately Needed To-Dos

- **New blind searches to take advantage of GC pointing**
- **Thorough understanding of selection function**
  - **Population synthesis lagging behind light curve modelling.**
  - **Contribution to diffuse and dark matter?**
- **Get macrophysics and microphysics together.**

Dormody et al. (2011)



The Beautiful Future

- **Pass 8:**
  - **Explore <100 MeV pulsar emission; polar caps?**
  - **Build science case for MeV mission.**
  - **Push to >10 GeV to connect with IACTs.**
- **Phase-resolved spectroscopy for fainter pulsars: ~t**

- **The Third Pulsar Catalog**
- **The next pulsar *Science* paper?**
  - **PC emission?**
  - **Mode-switching RL pulsar?**
  - **GC pulsar?**
  - **Young binary?**