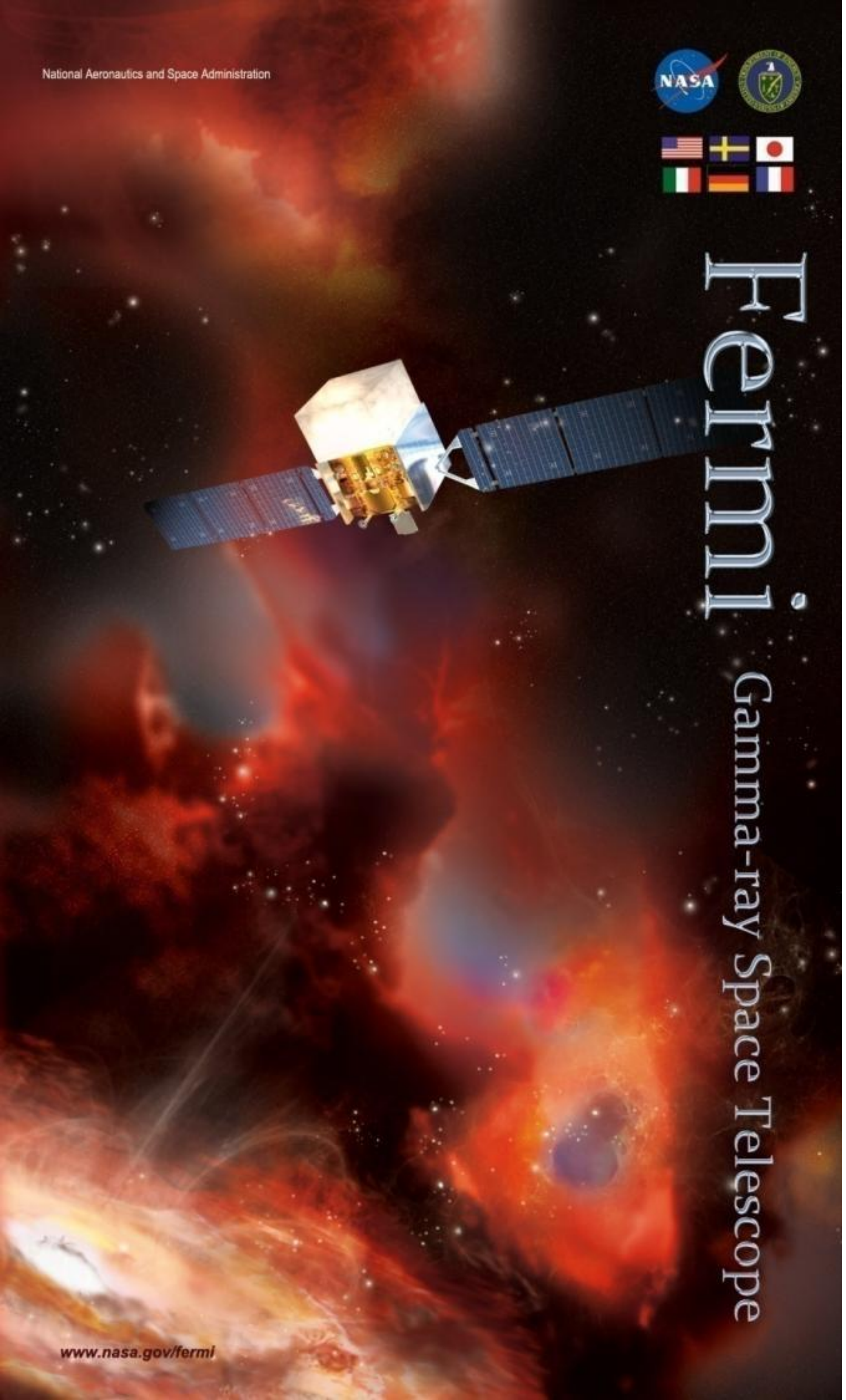

Geometry: The *Sine Qua Non* For Understanding the Pulsar Magnetosphere (and Gamma-ray Emission)

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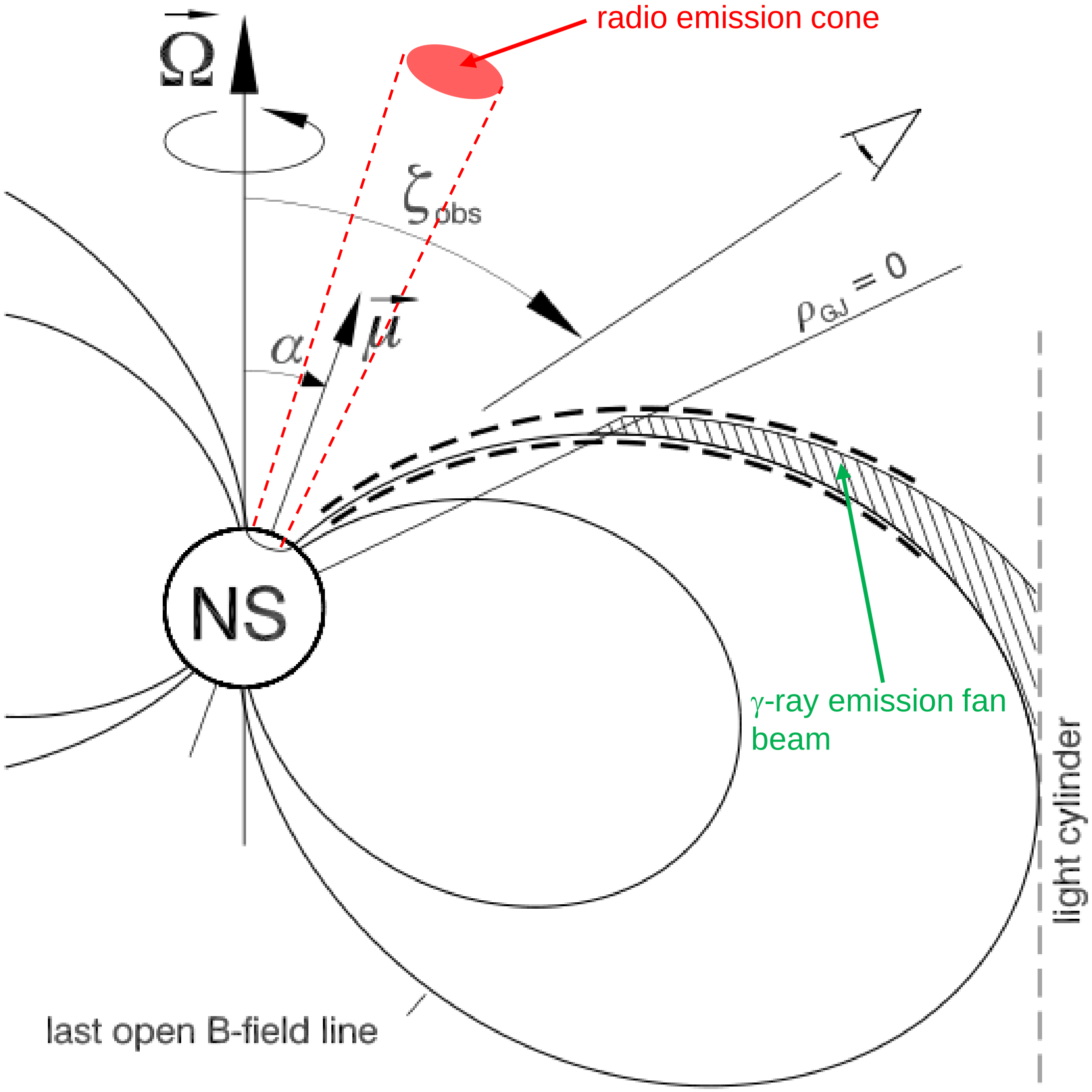
Parkes' 50th Birthday Party,
Parkes Telescope,
November 2nd, 2011

Pulsars In A Nutshell, OR Pulsars Are Easy, Right?



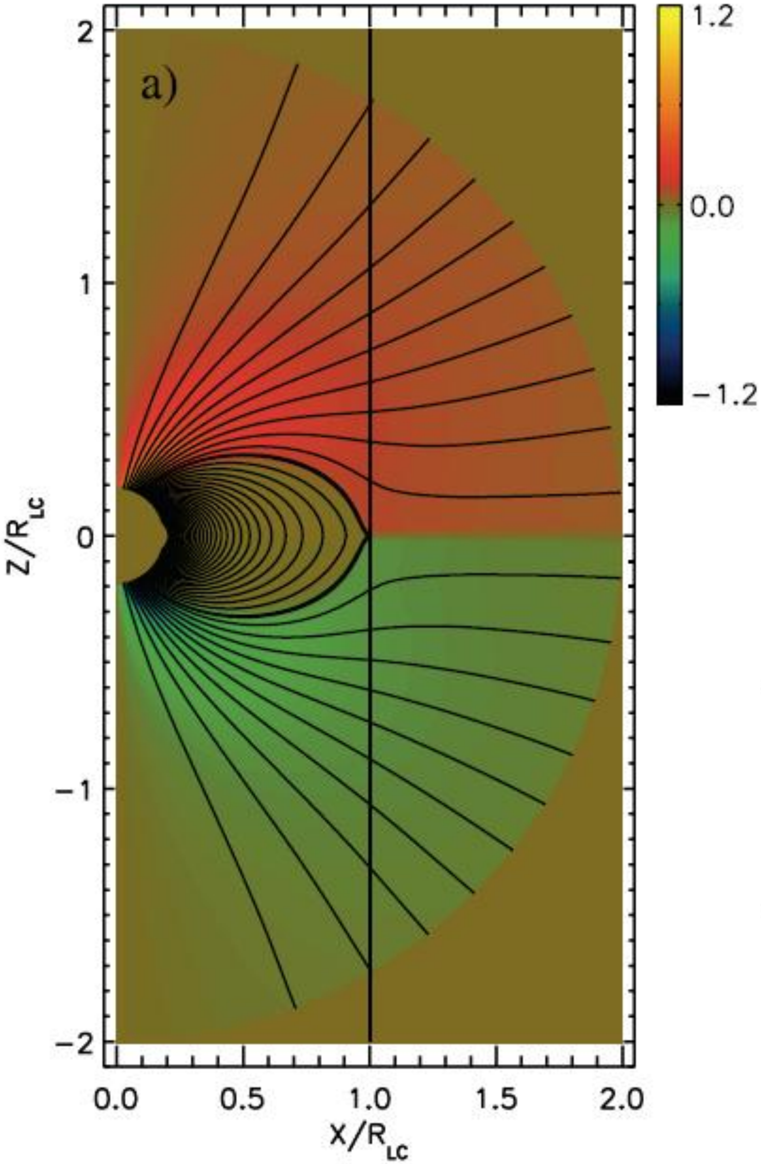
- Neutron stars dominated by dipole field…
- so all intrinsic physics should be determined by α, the magnetic inclination to the spin axis…
- and all observed properties should be determined by ζ, the inclination of the observer to the spin axis.

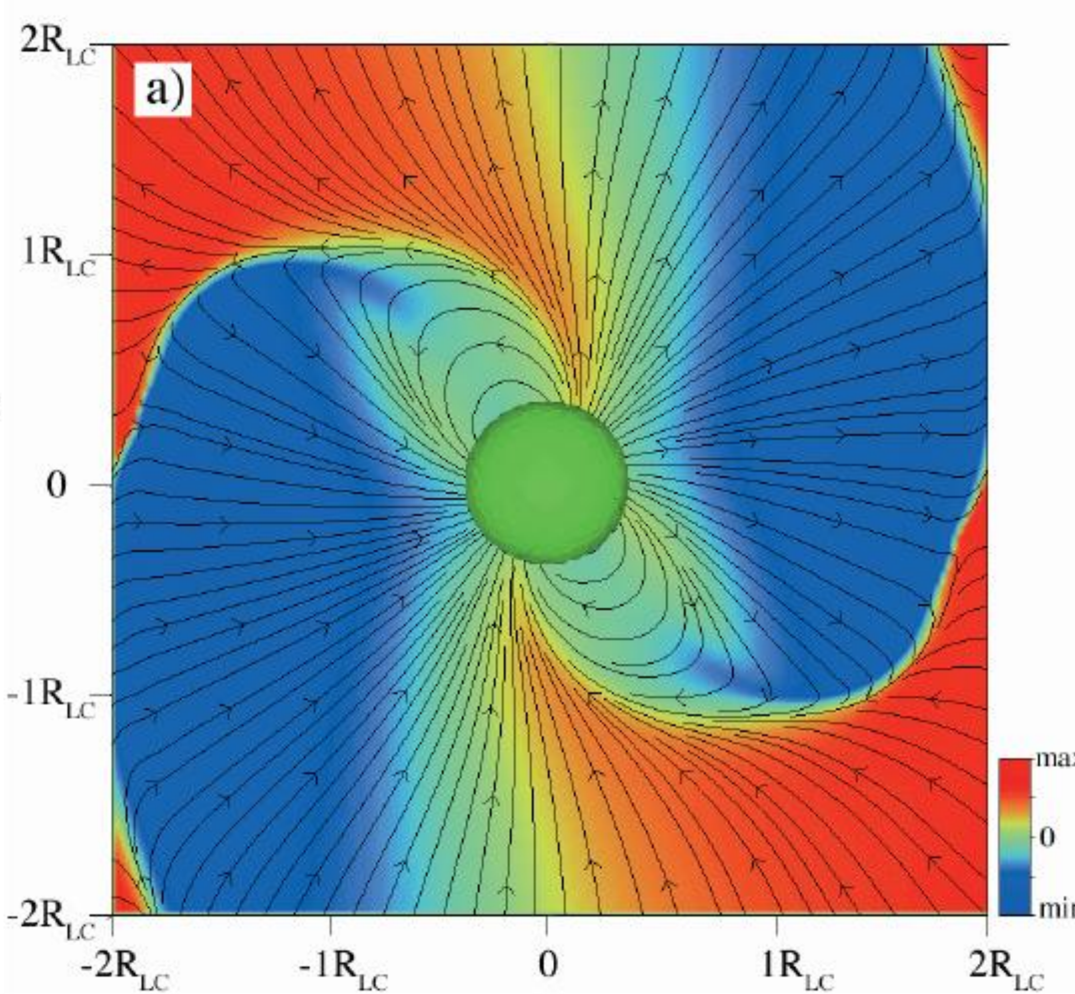
Alas. The "Pulsar Problem":

- After 40+ years, the global structure of electromagnetic fields and currents in pulsars is still uncertain.
  - Recent force-free MHD solutions are perhaps correct at first order.
  - Getting gamma-ray emission correct is an important part in solving the problem.
    - Gamma-ray efficiency can be >10%; must appreciably affect global structure.
      - E.g. Kramer+ 2006, radio emission (indicating presence of particle acceleration) changes spindown rate by 50%

- But, we are living in special times:
  - Numerical prowess improving rapidly; simulate (iteratively?) a real pulsar?
  - Gamma-ray observations probe pulsar population for first time.

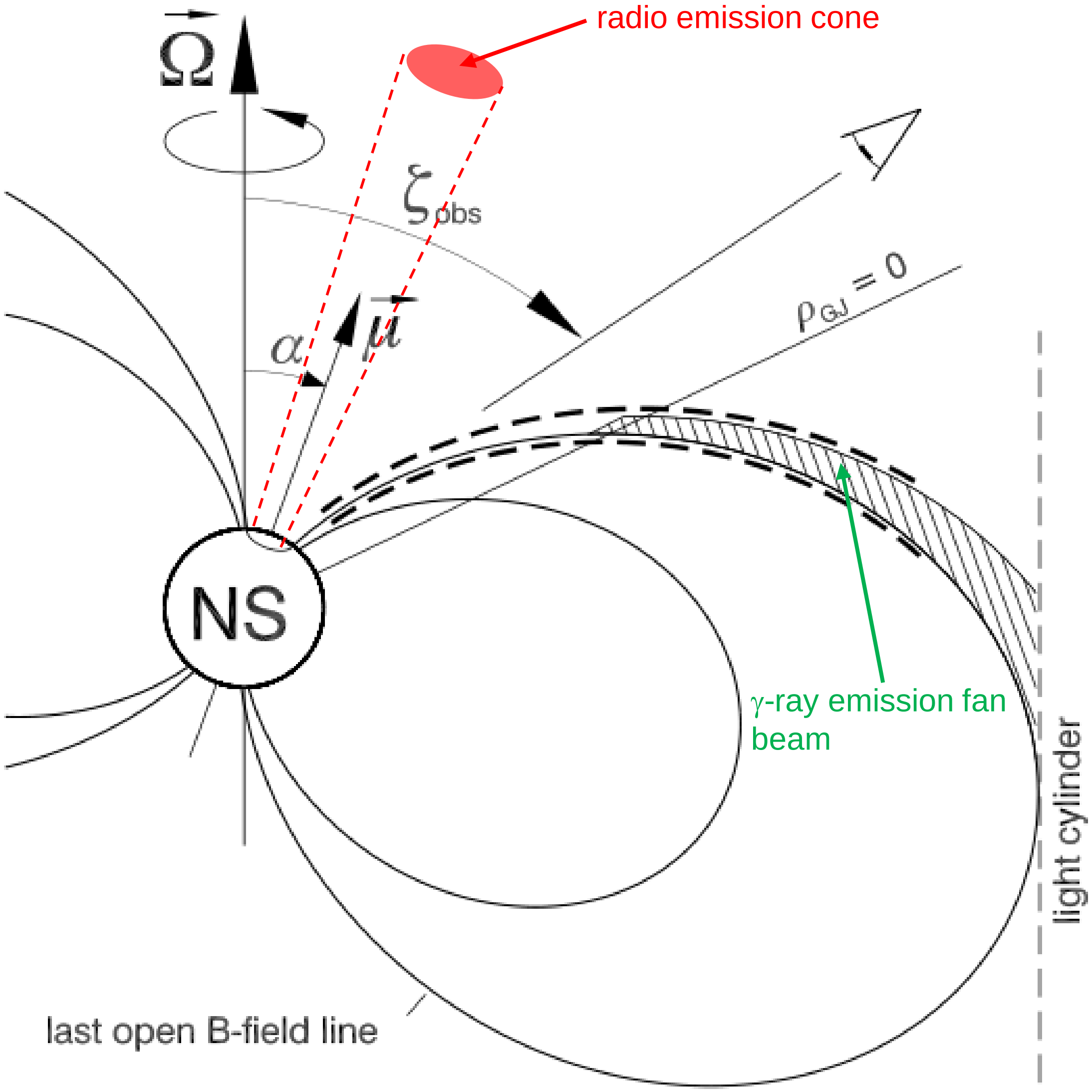
FFMHD results





Contopoulos, ApJ 1999
Spitkovsky, ApJ 2006

A closer look at "Geometry"



Polar Cap (PC)

- Harding, ApJ 1982

Outer Gap (OG)

- Cheng, Ho, Ruderman, ApJ 1986
- Romani ApJ 1996

Slot Gap (SG) / Two-pole Caustic (TPC)

- Muslimov & Harding, ApJ 2004
- Dyks & Rudak, ApJ 2003

Controlling parameters are α and ζ, viz. GEOMETRY.

All of above models can be expressed with a general gap geometry, e.g.

- R_max
- ϖ_max
- s_min
- θ_min, θ_max

Getting Physics From Simple Models

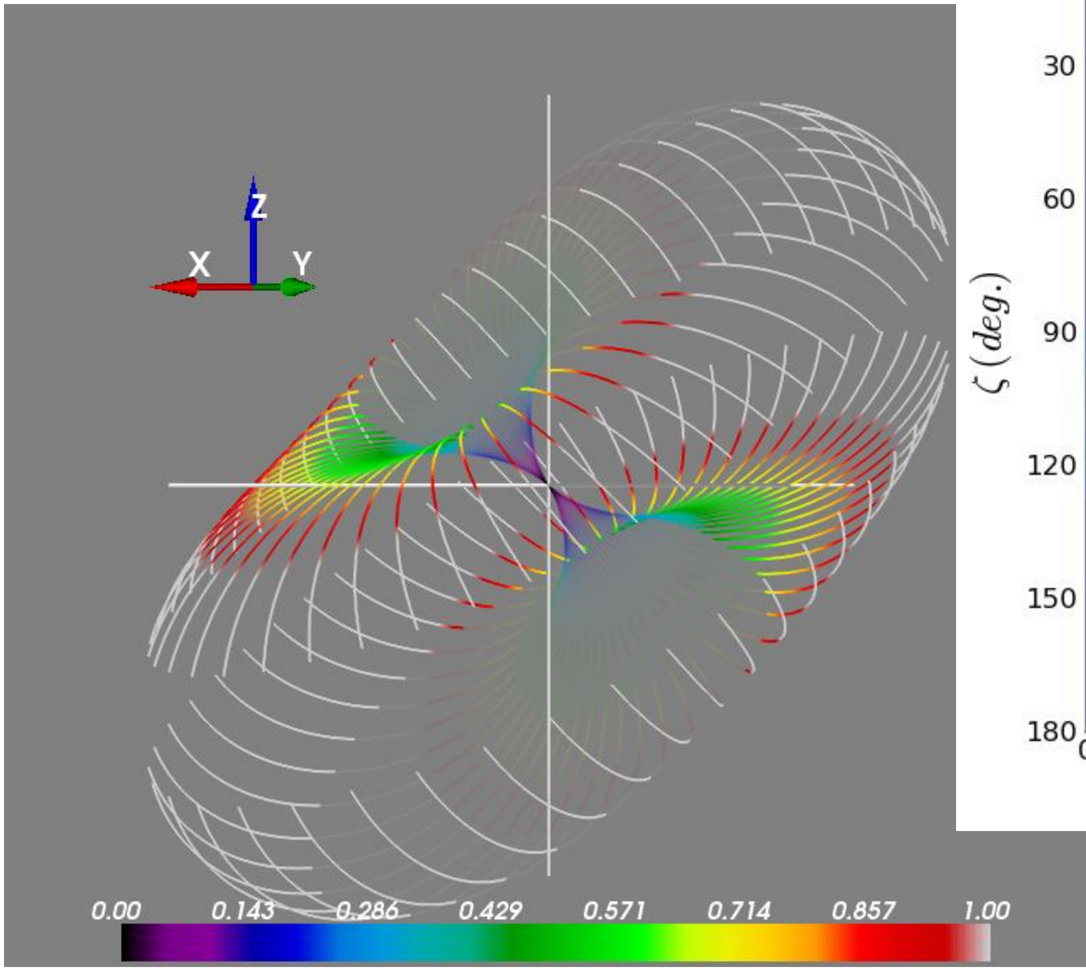
- Geometry + assumed magnetic field go a long way to predicting gamma-ray light curves and spectra. Goal is to measure properties of magnetosphere without having to put in hard, largely “unknown” physics.
  - All you need to do is add a prescription for the emitting volume and its emissivity.
  - Next, adapt your prescription (including geometry) to fit the data and try to extract :
    - The shape of the emitting region
      - gives information about the electrodynamic processes in play, has implications for the observability of pulsar population. (Different electrodynamic models predict radically different efficiencies for a given emitting volume; large emitting volumes → greater sky coverage.)
    - Looking at gamma-ray spectrum gives (nearly) direct measurement of the local accelerating field.

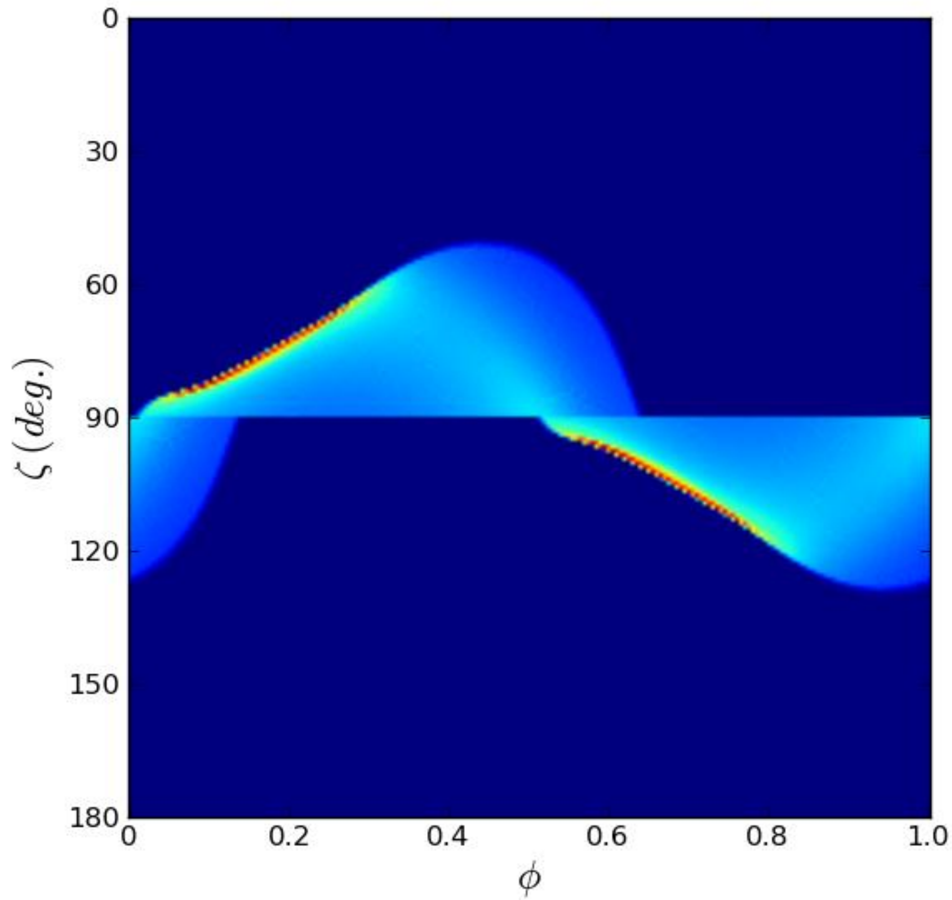
The Pulsar Solution (?)

- LAT Gamma-ray Pulsar "Revolution":
  - 88+ gamma-ray pulsars detected by LAT.
    - Greatly enabled by efforts of radio colleagues!
  - Detailed light curves for brightest.

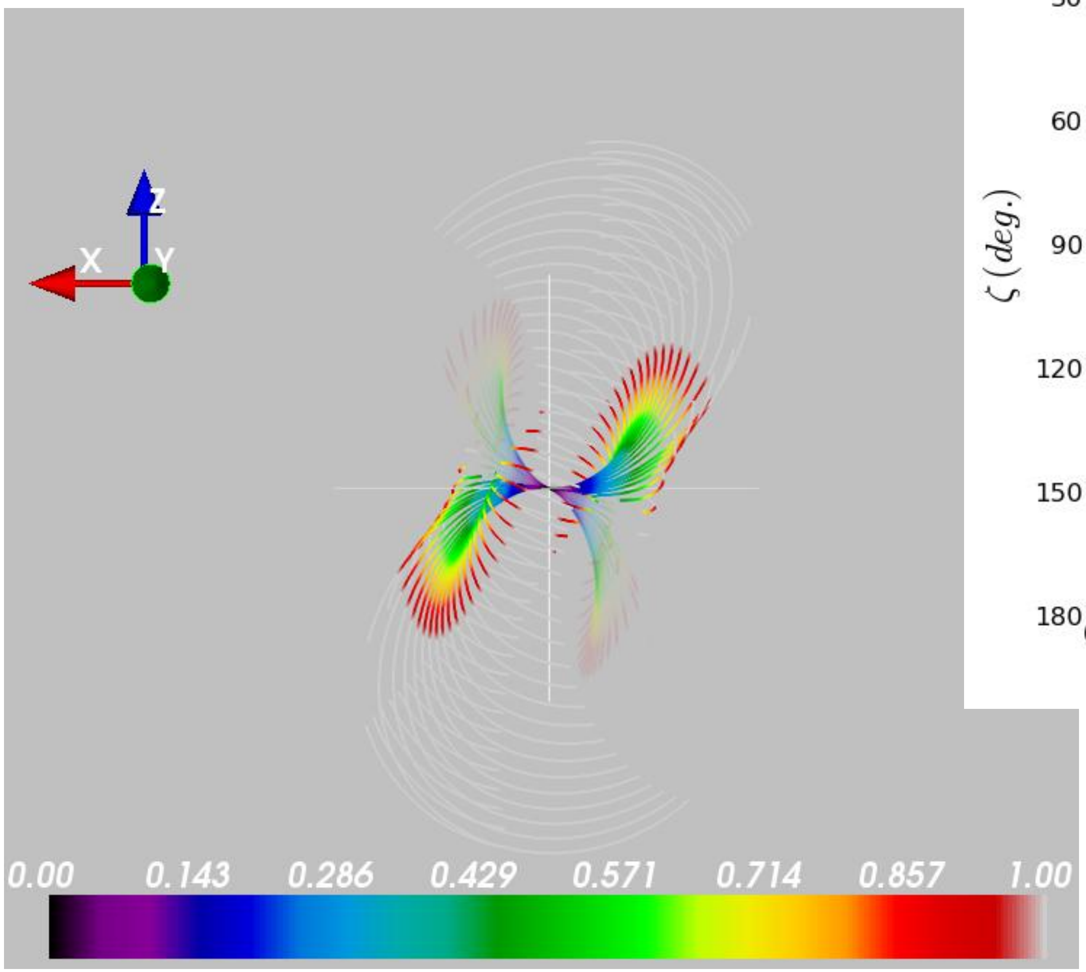
- The Hope: with a population this large, we don't need to know the geometry for individual pulsars. We just use the best fit and assume that the geometry will "average out" as we sample many viewing and magnetic geometries. This leaves the non-geometric parameters (gap shape, emissivity, etc.) this large population will allow us to "marginalize" over the random viewing/magnetic geometry and explore physical trends. Make some progress in understanding pulsar emission!

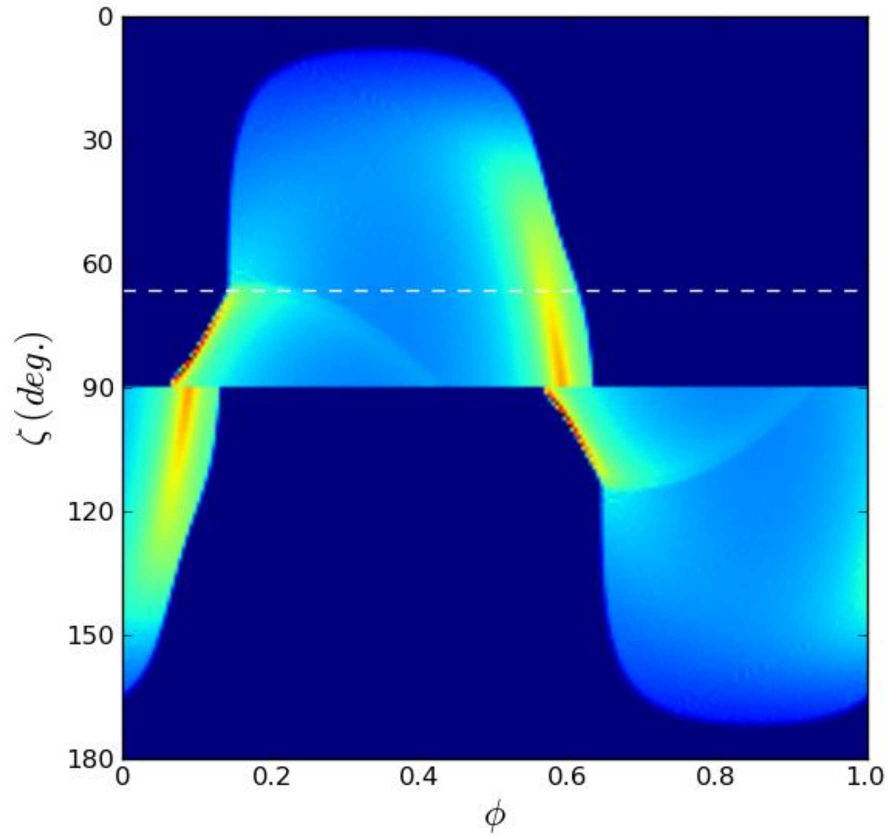
Quick Example – "Static" B-field @ 45 deg.



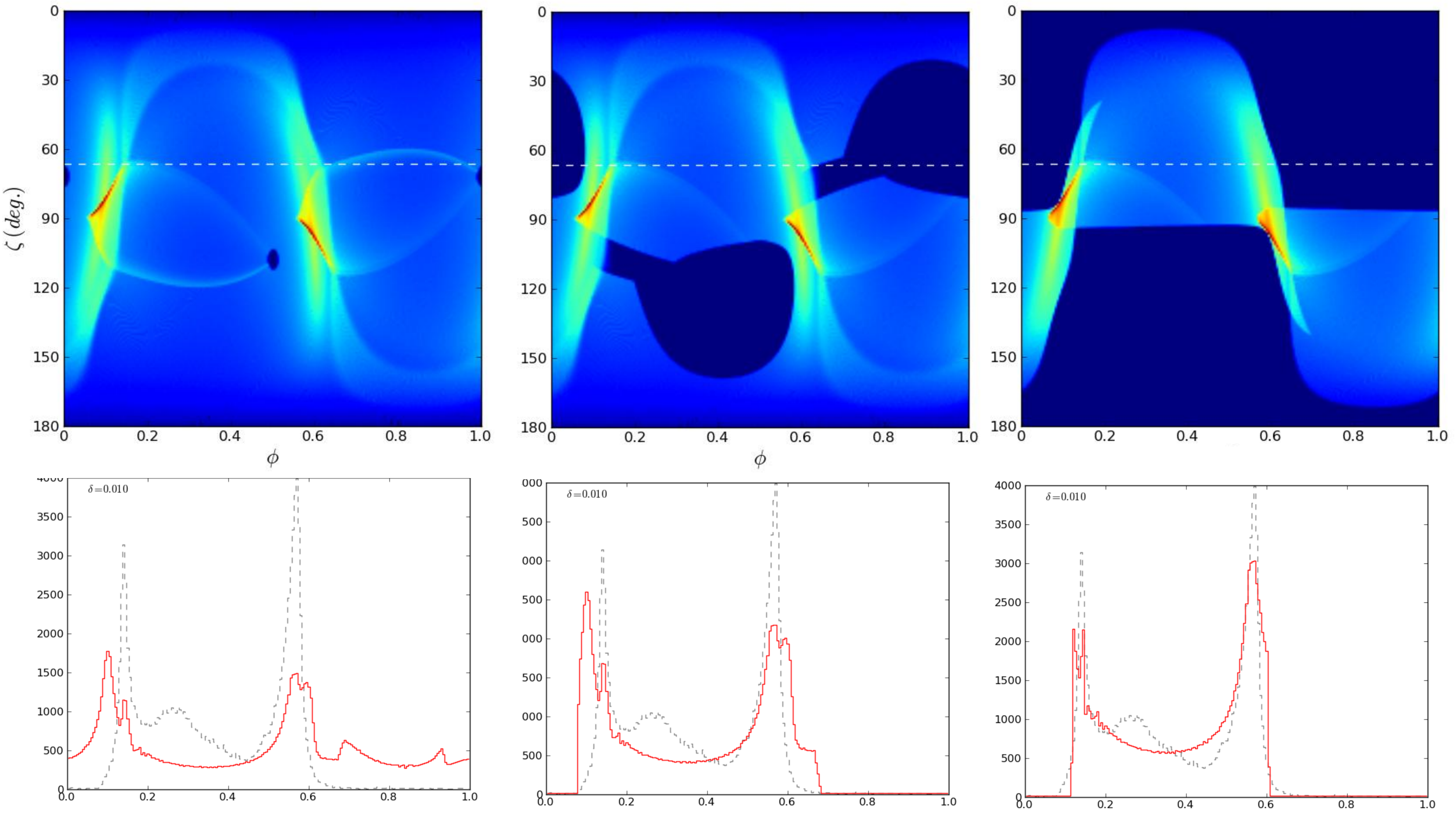


“Vela” – Retarded Dipole, $\alpha = 72$ deg.

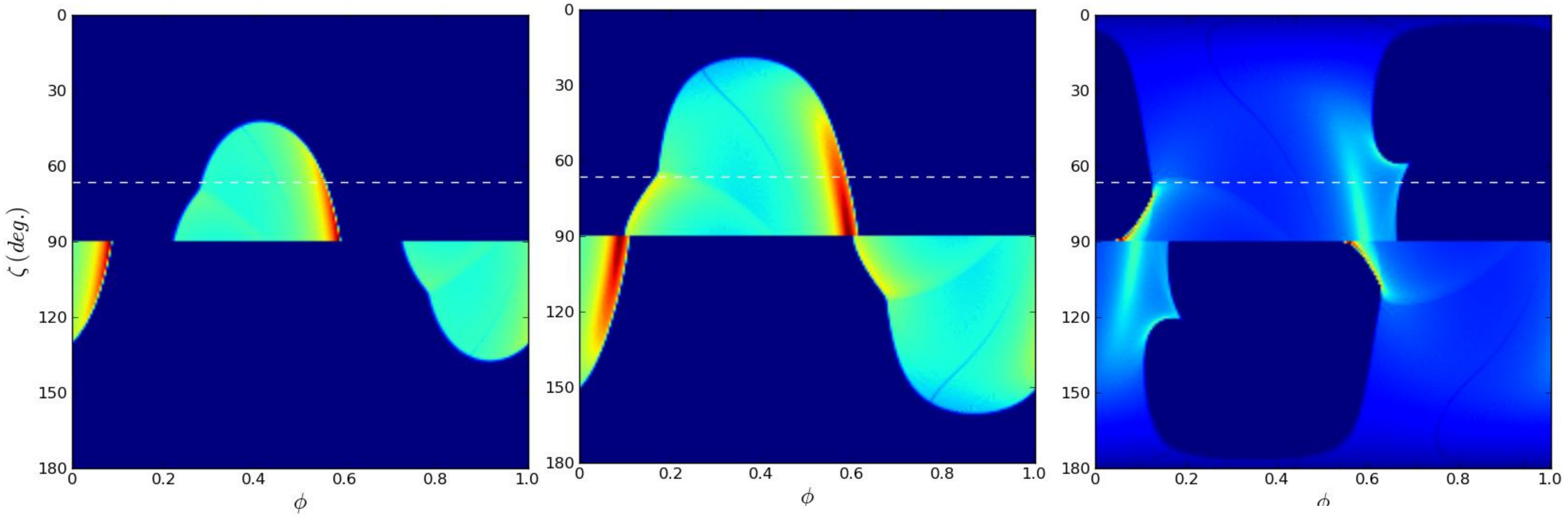


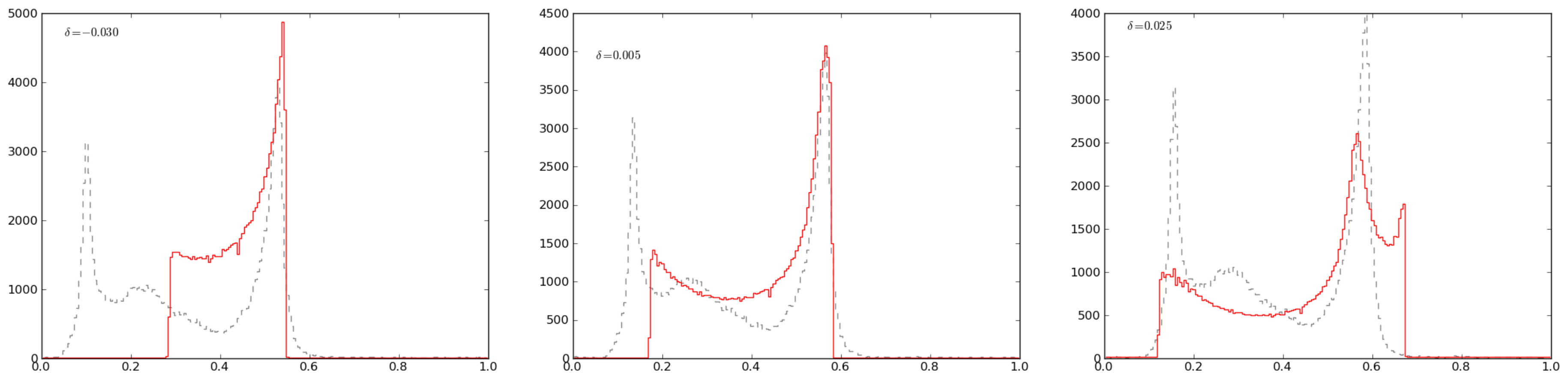


Characterizing the Gap – minimum altitude

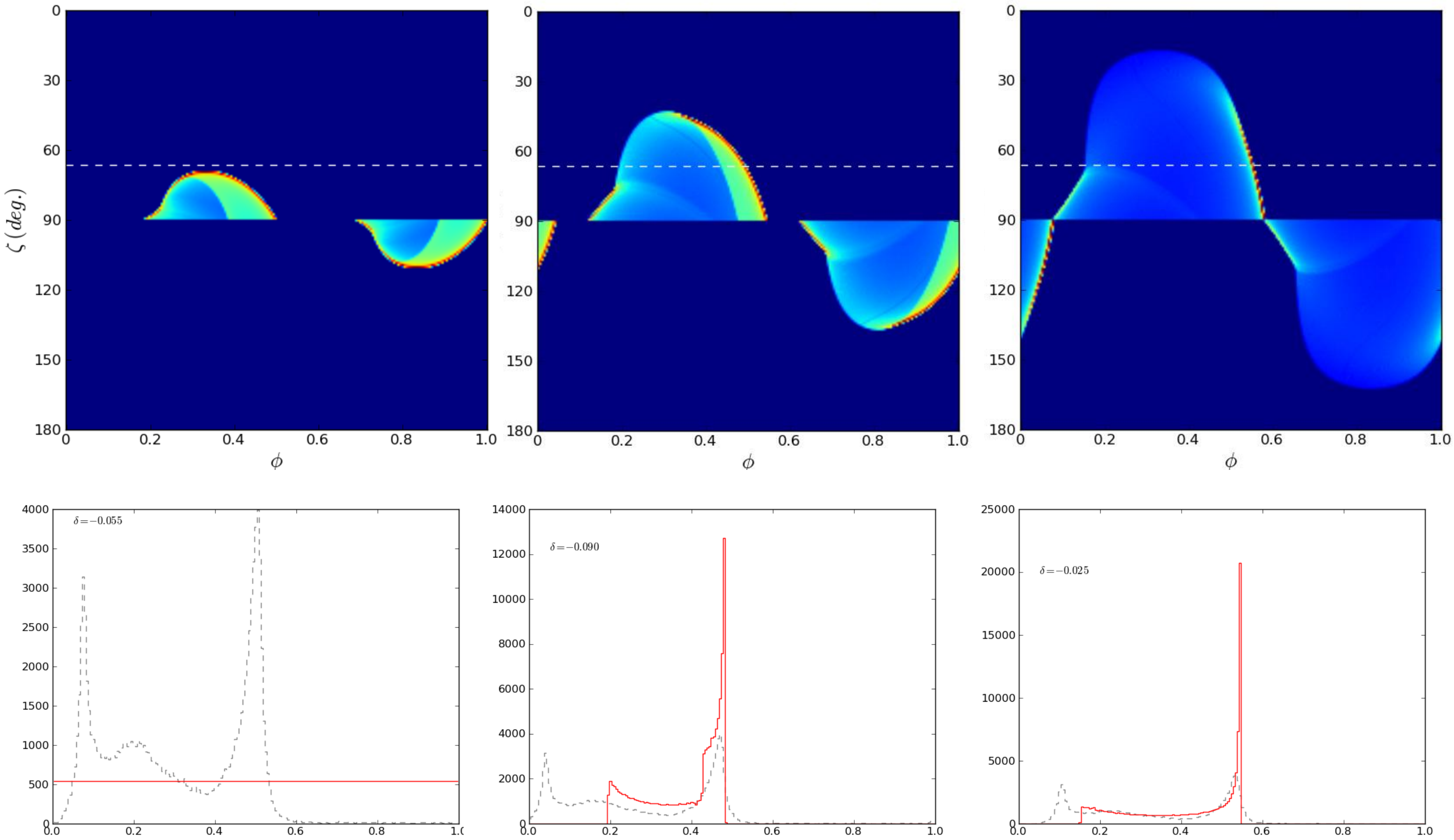


Characterizing the Gap – maximum altitude

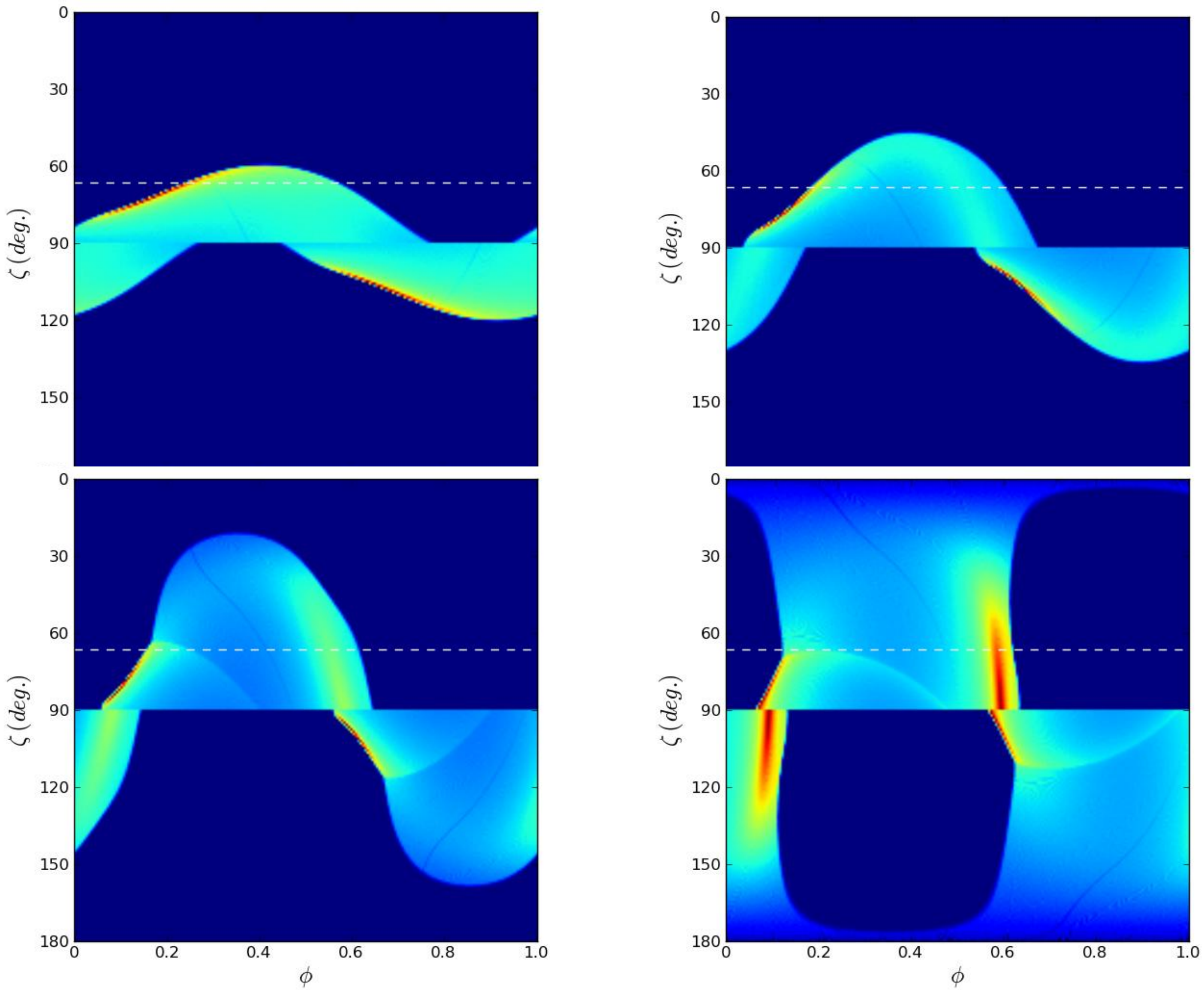




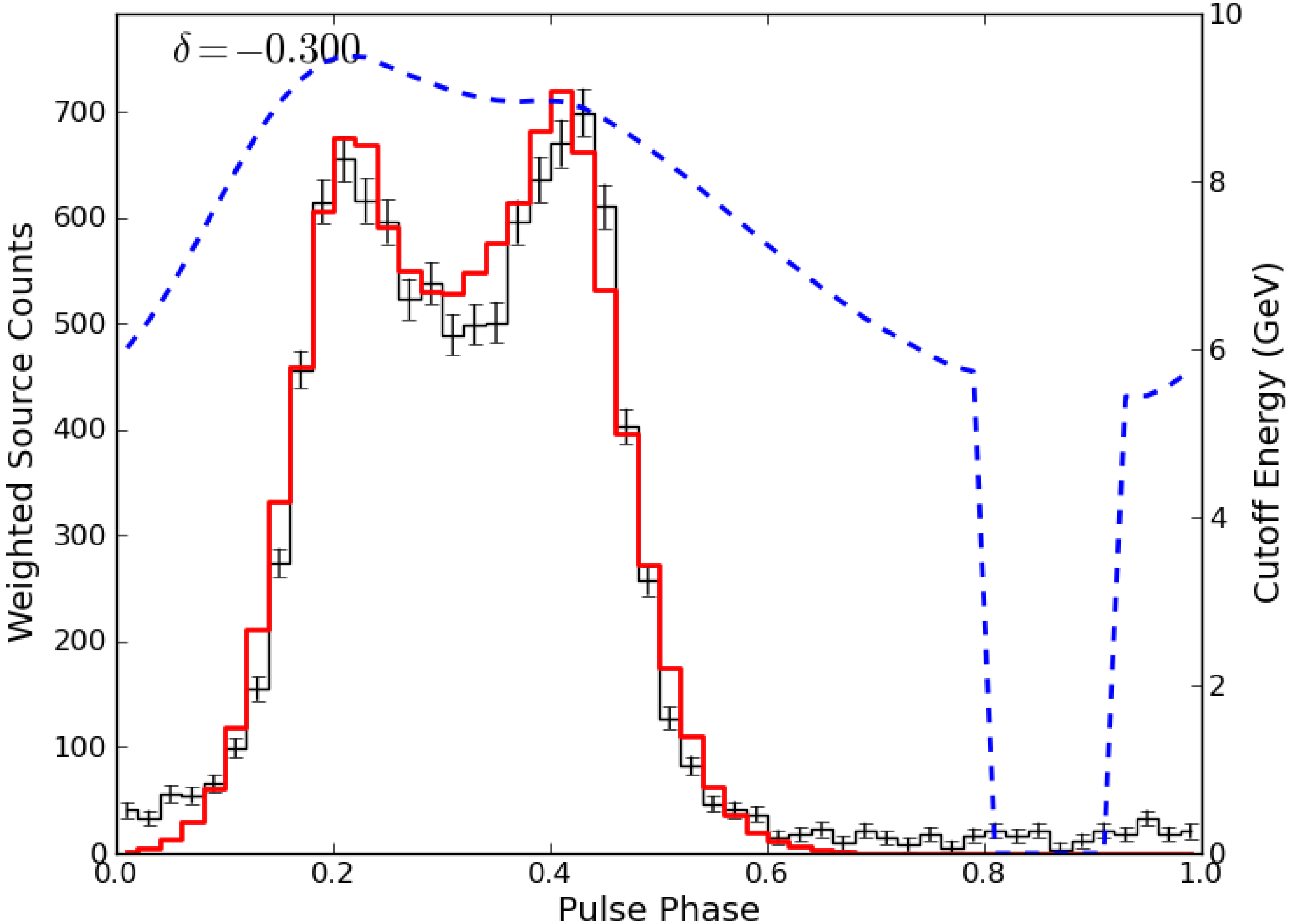
Characterizing the Gap – the "gap width"



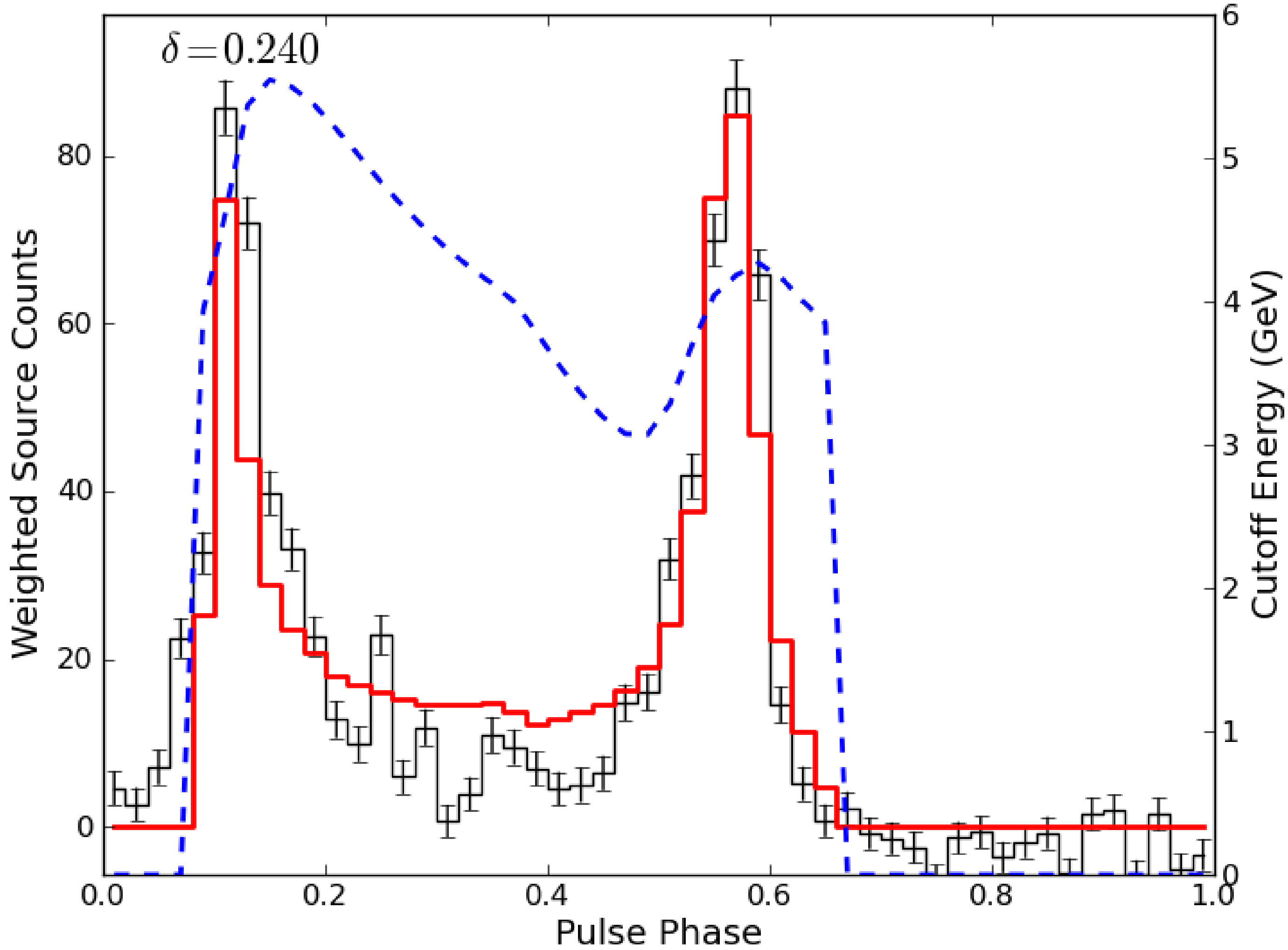
Varying The Magnetic Inclination (α)



Some Results

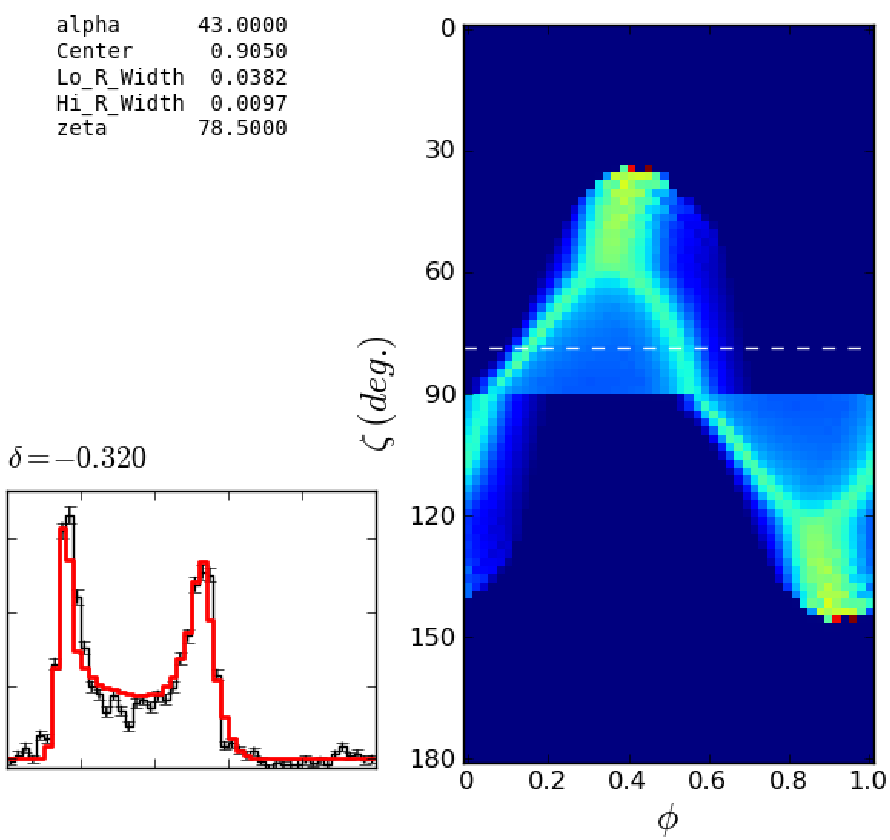


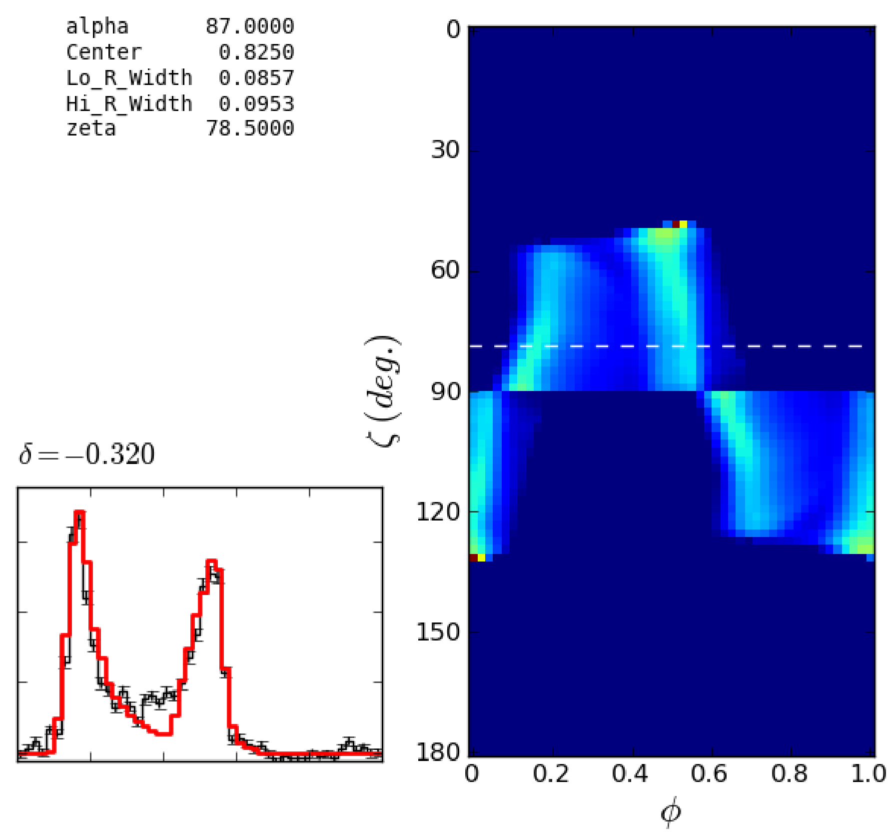
Some Results



Back to Problems (With Degeneracy)

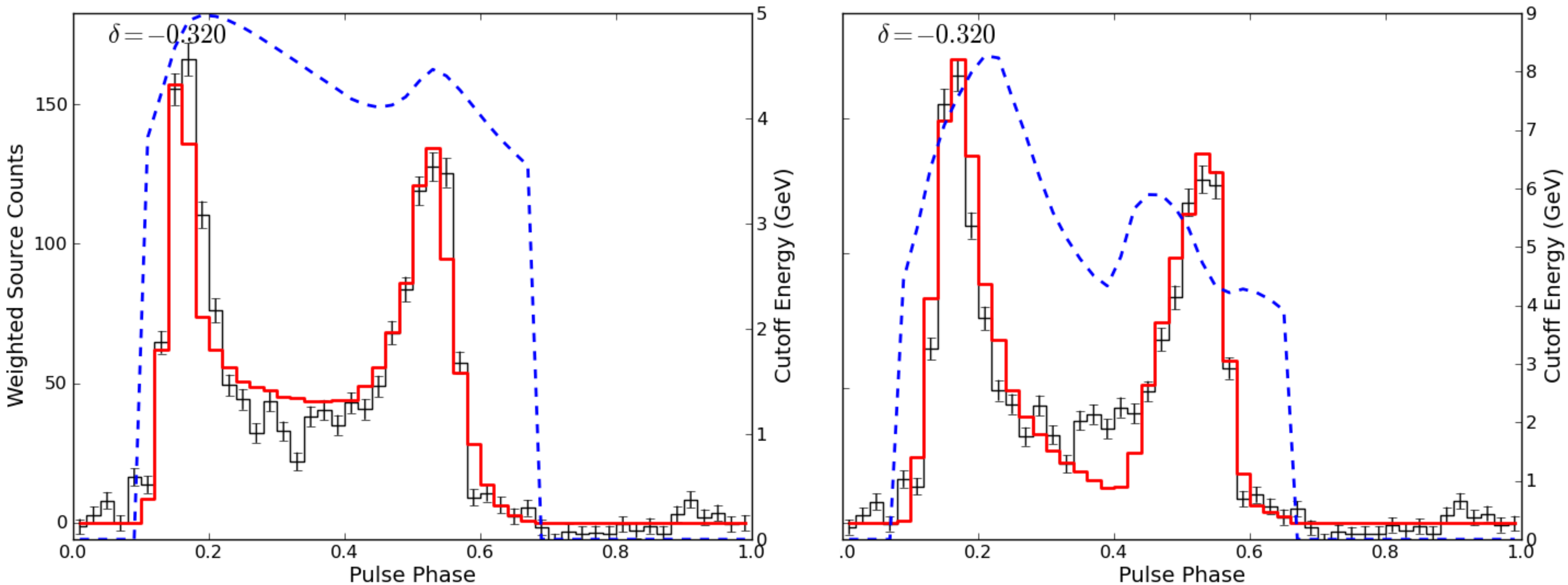
- Fits are good! Now, the dramatic dependence on geometry will make emissivity/volume/electric field easy to determine!
  - Alas.





Poor: LAT Spectra

- Using LAT data, compare expectations for spectra.
  - Some pulsars do predict dramatically different spectra under different geometries.
- But this is quite model-dependent, possibly circular…



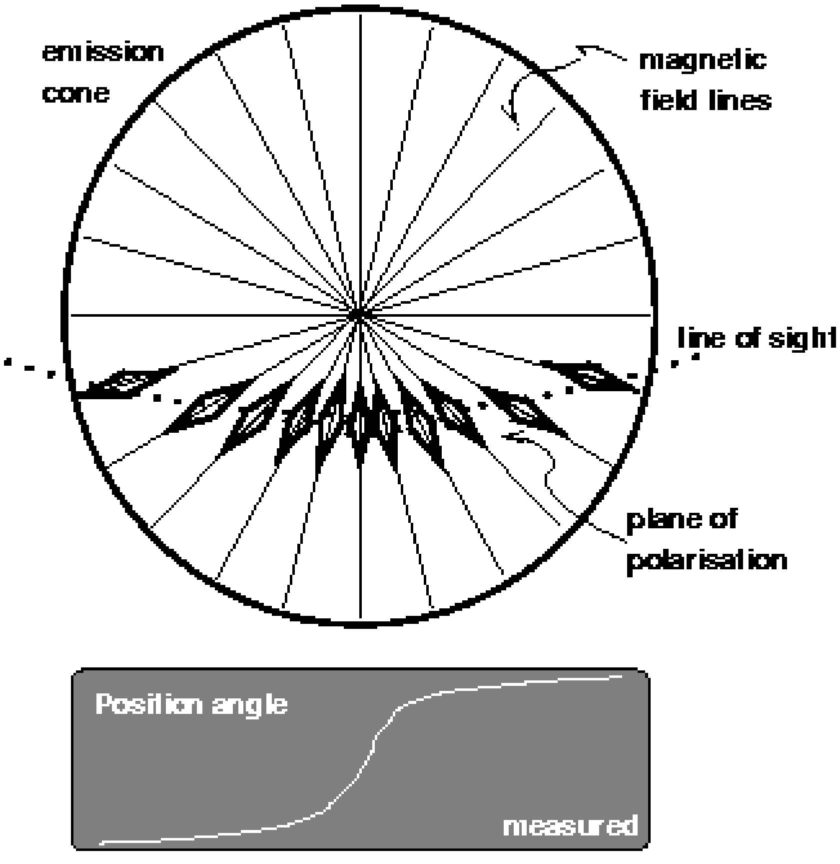
Better: Radio Beam Visibility

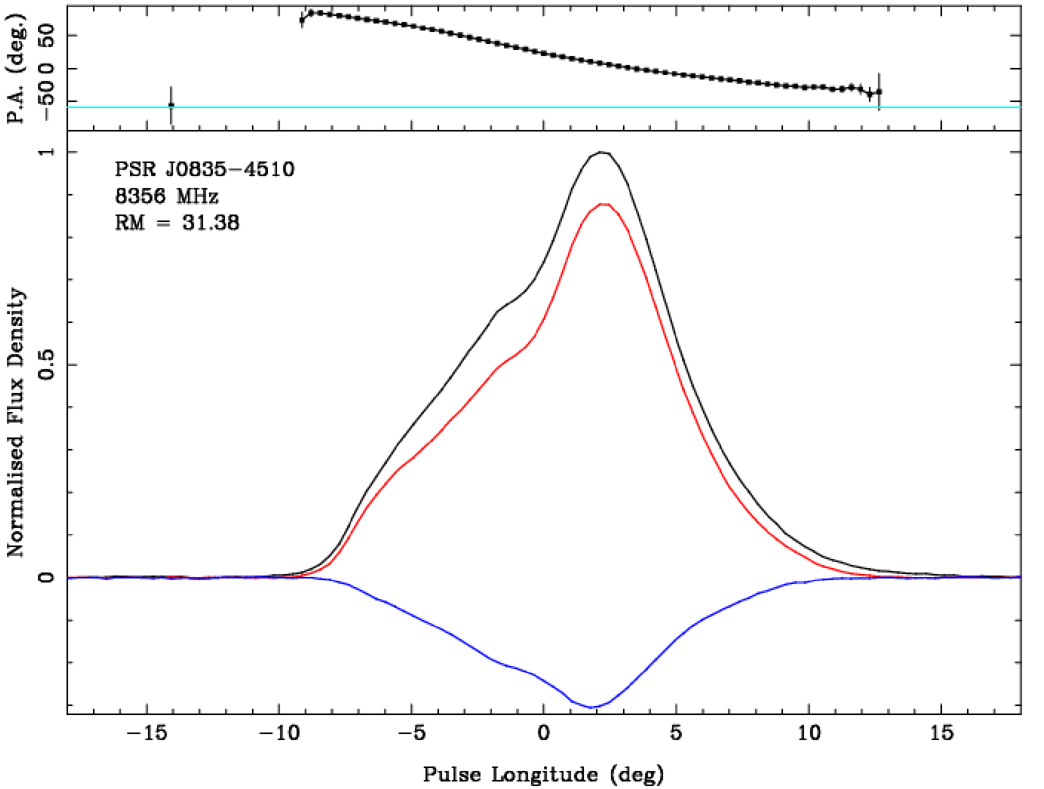
- Crude (but robust): do we see it?
  - $|\beta| \equiv |\alpha - \zeta|$ not too large (depends on pulsar period, emission height)
- Less crude (and robust): do we see an interpulse?
  - $\alpha \sim \zeta \sim 90$ deg.
  - Unfortunately a small slice of phase space.
- Constraining but fraught:
  - Assume radio beam fills open zone; then, given pulse width, gives acceptable contour in α/ζ plane.
  - Depends fairly strongly on whether one uses, e.g. W_{10} or W_1.
  - Affected by scattering.

Best: Radio Polarization

- At low altitude, (ignoring multipolar field structure, GR), relativistic corrections not important → magnetic field a static dipole.
- Particles must flow along field lines; fixes plane of polarization relative to magnetic field, fixes position angle sweep.
  - First noted in the seminal but hard-to-find Radhakrishan & Cooke, 1969.
- Observing polarization on enough field lines, i.e. by observing the position angle as a function of phase, uniquely determines α and ζ.
  - In practice, low polarization fraction (though many gamma-ray pulsars are highly polarized, see Weltevrede & Johnston 2008), multiple components, and limited duty cycle give large contours.
- Careful treatments require model of magnetic field and ray tracing to determine shape of polar cap.
  - This also applies to previous arguments for beam shape.

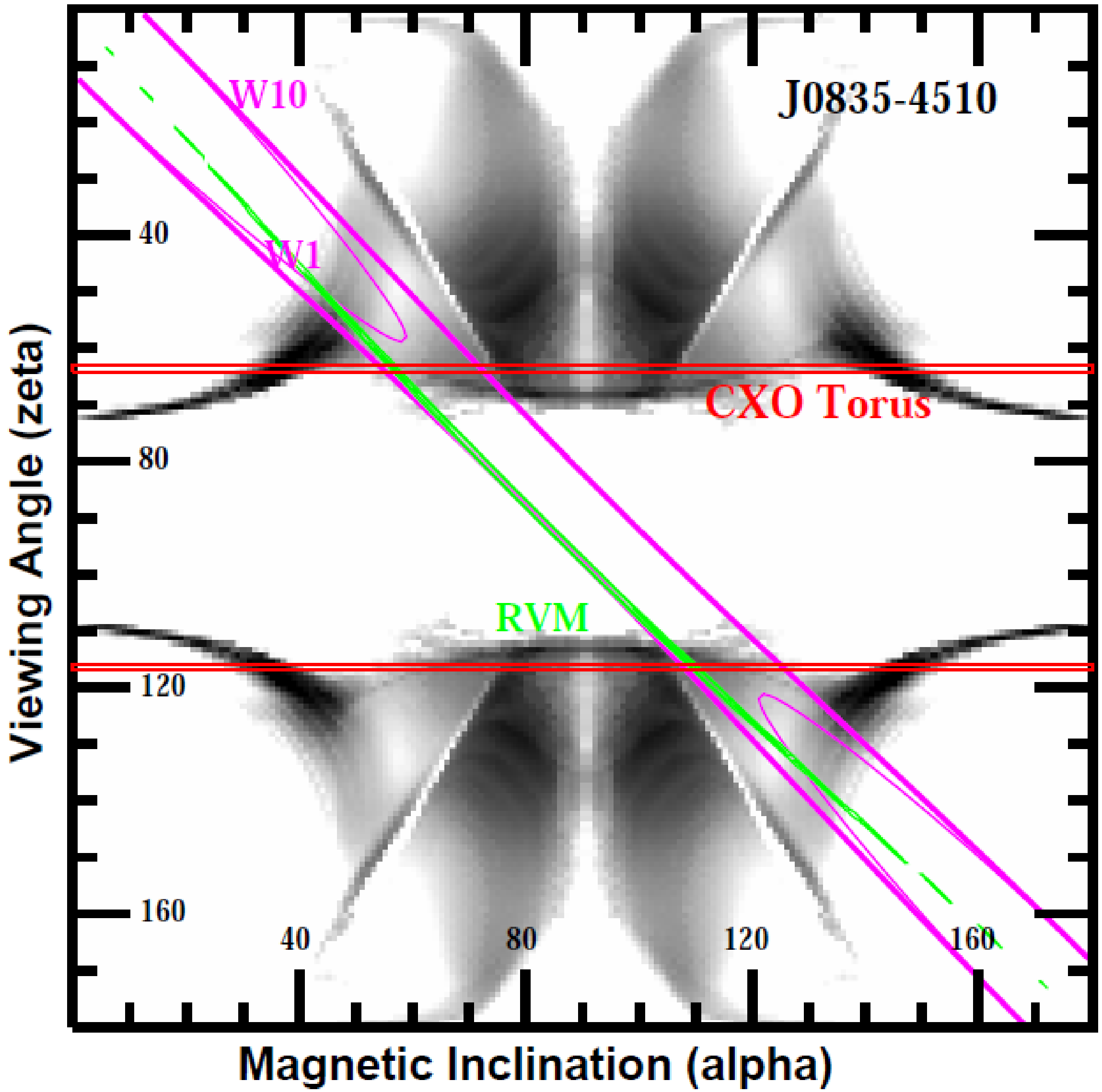
From Lorimer & Kramer

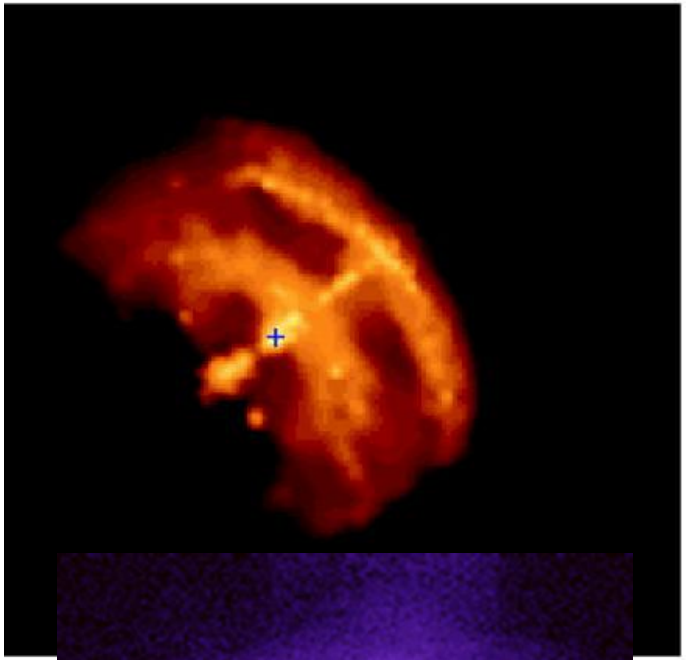


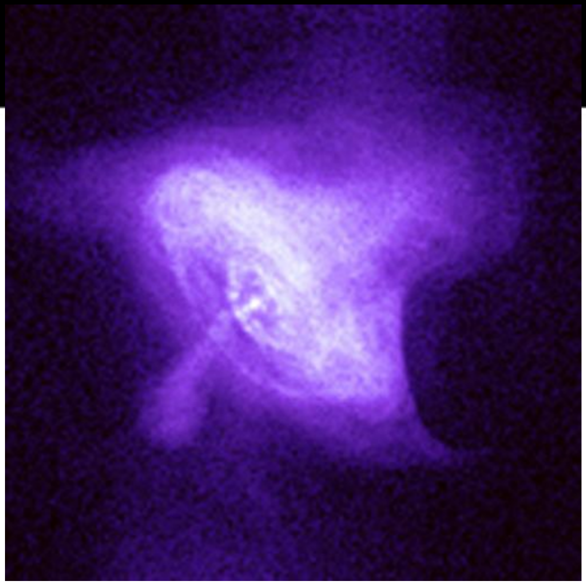


(a)

Putting It All Together







Summary and Plans

- Largely, geometric models with vacuum fields do a decent job reproducing LAT light curves.
  - Too good! Can't get geometry out without putting more physics in.
  - But external constraints can help.
    - Need high S/N polarization profiles from Parkes, GBT, AO...
- The beautiful future:
  - Try FFMHD field.
  - Put in electrodynamics.

  Iterate towards a physical model.

  - Implement joint fitting for radio-loud pulsars.
    - Need good S/N Full Stokes for all (if possible!) radio-loud pulsars – go Parkes!
    - And good model for radio emission.
- Timing is perfect since the second LAT pulsar catalog is coming!

Two Frameworks - (1) Charge-separated Magnetosphere

Goldreich & Julian, ApJ 1969

- Rotating poloidal B-field induces a poloidal E-field.
  - $E \cdot B$ at surface great enough to liberate electrons and positrons; acceleration along field lines.
- Equilibrium configuration screens the accelerating field.
  - $E \cdot B = 0 \rightarrow \rho_{GJ} \propto \Omega \cdot B$.
  - This level of (charge separated) plasma is dynamically unimportant, so magnetic field still resembles dipole.
- Provides a nice motivation for particle acceleration:
  - If ρ_{GJ} is somewhere depleted, the unscreened electric field can accelerate particles to extremely high energies.
- Problems:
  - Isn't actually a global solution to Maxwell's equations.
  - Unclear how currents are distributed.

Two Frameworks - (2) Force-free MHD

- “MHD” ignoring particle inertia (mostly justified inside LC).
- Achieves $E \cdot B = 0$ through screening by dense, mostly-neutral plasma.
- Such a plasma is expected to be produced in the pair cascades that produce gamma rays, and its existence is implied by PWNe.
- Within last decade, axisymmetric (BVP) and 3D evolutionary (FDTD) solutions of FFMHD equations have been computed.
- Gives global distribution of currents and fields, but:
  - Since $E \cdot B = 0$ is enforced explicitly, cannot accelerate particles
- This picture is likely correct at first order, but needs a way to incorporate particle acceleration.
  - Especially for older pulsars, the particle acceleration will be a significant perturbation (dominate?) the FF solutions. Gamma rays are the key to it.

LAMPE

- "Likelihood Analysis of Models of Pulsar Emission"
  - I'm not very good at acronyms either.
- Provide a framework for mapping theory to data in an optimal and (hopefully) painless way.
- C++ backbone with a Python interface (Boost.Python rocks)
- Everything designed to be modular:
  - Magnetic Field
  - Field Line Tracer
  - Emissivity
  - Observables
  - Likelihood (for various data sets)
  - Fitter / Parameter space explorer
- To be released publically when ~complete – if you're dying to model some pulsar emission and can't wait, email me for a copy.