The μeV-PeV Neutron Star Laboratory

(With some recent progress at GeV)

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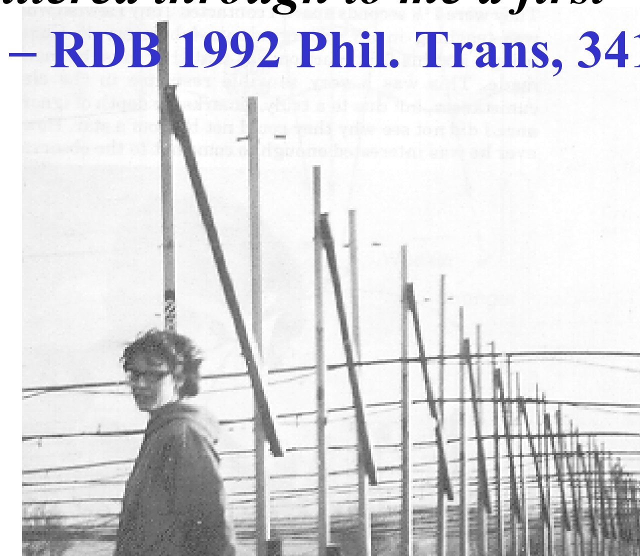
Roger B. and Neutron Stars

- **Magdalene 1967-1970**
  - **CP 1919+21 Nov '67** ***"It is perhaps hard now to communicate the excitement generated by this discovery (a fascination that filtered through to me a first-year Cambridge undergraduate at the time)…"*** **– RDB 1992 Phil. Trans, 341, 177**



- **82 Publications with Pulsar and/or Neutron Star**
- **1973 'Ghost Supernova Remnants' (Ostriker, Pacini & Rees)**
- **Many 2009 Fermi LAT publications**

Neutron Stars

- Where Astronomy meets Physics → Astrophysics
- NS as high density objects (Eγ~100eV, kT < GeV)
  - EOS constraints on $\rho>\rho_{Nucl}$ at kT << GeV
  - M/R – M from dynamics, R from surface emission
  - Cooling limits on interior condensates, superfluidity
- Radio Pulsars (Eγ ~10^{-6}eV—10^{-3}eV)
  - stable point mass clocks
  - binary dynamics, evolution
  - GR effects including intervening gravitational waves
- NS B fields: (Eγ → GeV, leptons to 30TeV, baryons?)
  - matter with B>10^{12}G
  - magnetospheres and acceleration
  - magnetars, objects with B fields near the dynamical limit
- Accretion Systems, etc. (Eγ ~keV +)
  - Thermal physics… but may be used to probe mass and photon orbits in strong gravitational fields

RDB work on Neutron Stars

- **Radio Pulsars**
  - timing models (w/ Teukolsky and others)
  - origin and evolution (w/ many, starting from Smarr)
  - Pulsar Scintillation effects (w/ Narayan)
  - Radio Emission Mechanisms (w/ Lyutikov)
  - eclipses (Various)
- **NS as high density bodies**
  - thermal emission (w/ RWR)
- **NS B fields:**
  - Biermann battery origin (w/ Hernquist)
- **Accretion Systems, etc.**
  - surface layer evolution (Konigl, Blaes, etc.)
  - starquakes (Madau, Phinney,...)

MSP: Precision Timing Industry
- MSP in GC

B=0 atm, then.
High B atm, now (Ho)

Only Limited Progress

Maybe not GRBs…
Magnetars?

ICS γ-rays from Cyg X-3 ? ('77 w/ Fabian, Hatchett)

Pulsars as Panchromatic Objects

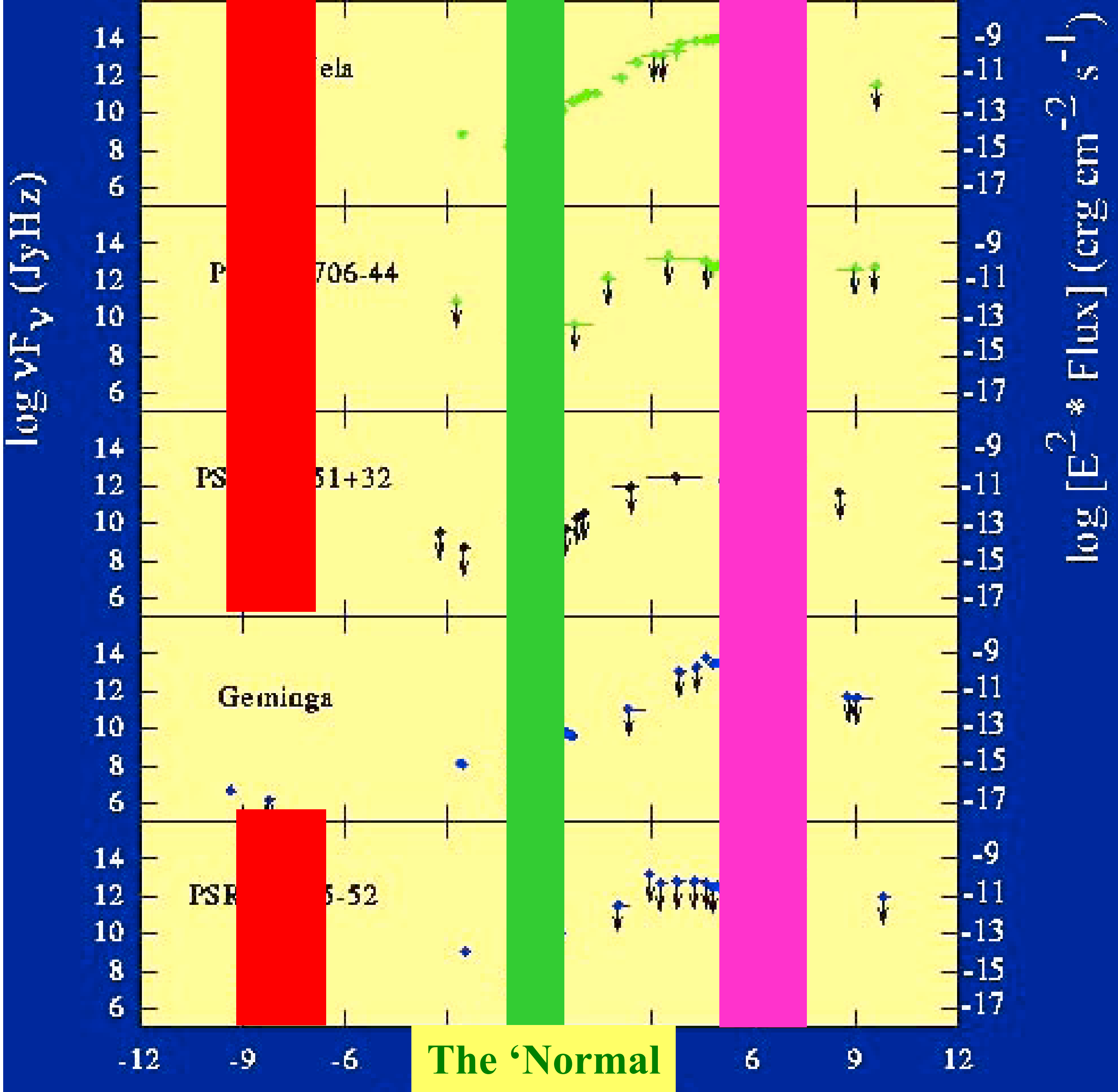
- Radio – coherent
  - the handle for precision physics
- optical/IR – synchrotron magnetospheric emission
- UV-soft X-rays
  - heat of formation
  - heat from magnetospheric backflow
- X-ray to ~MeV -- synchrotron magnetospheric emission
- MeV– 10GeV – magnetospheric curvature, (ICS?)
- >10GeV – IC from PWN beam dump
- many TeV magnetospheric, PWN termination shock e+/e-
- → PeV particles: SNR shockwave acceleration

Where's the Power??

Power νF_ν peak: GeV γ-rays

Thermal Surface Emission: ~0.1keV X-rays

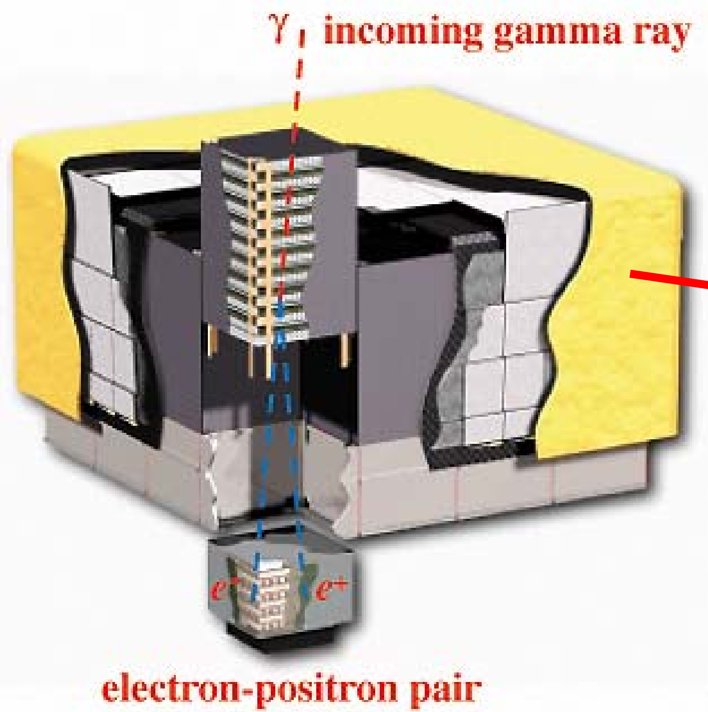
Coherent Radio Pulse: 10^{-6}-10^{-4}eV radio waves

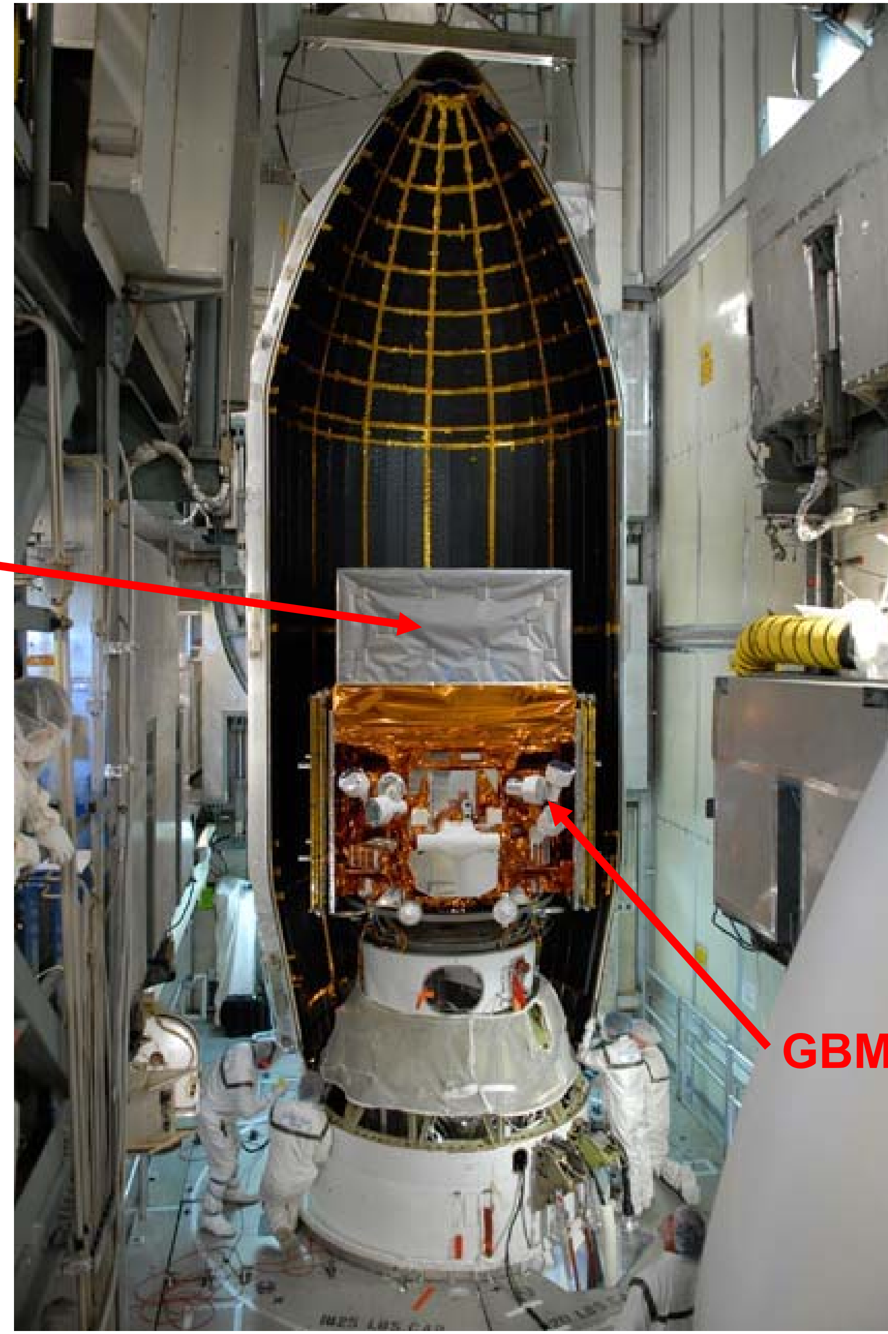


Thompson 2002

To Study the GeV Signal:

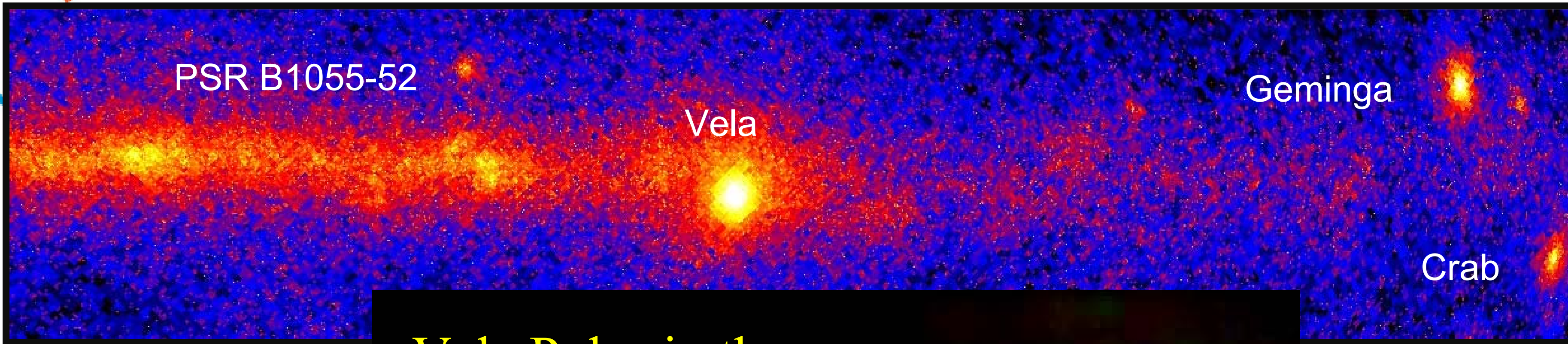
The Large Area Telescope (LAT)

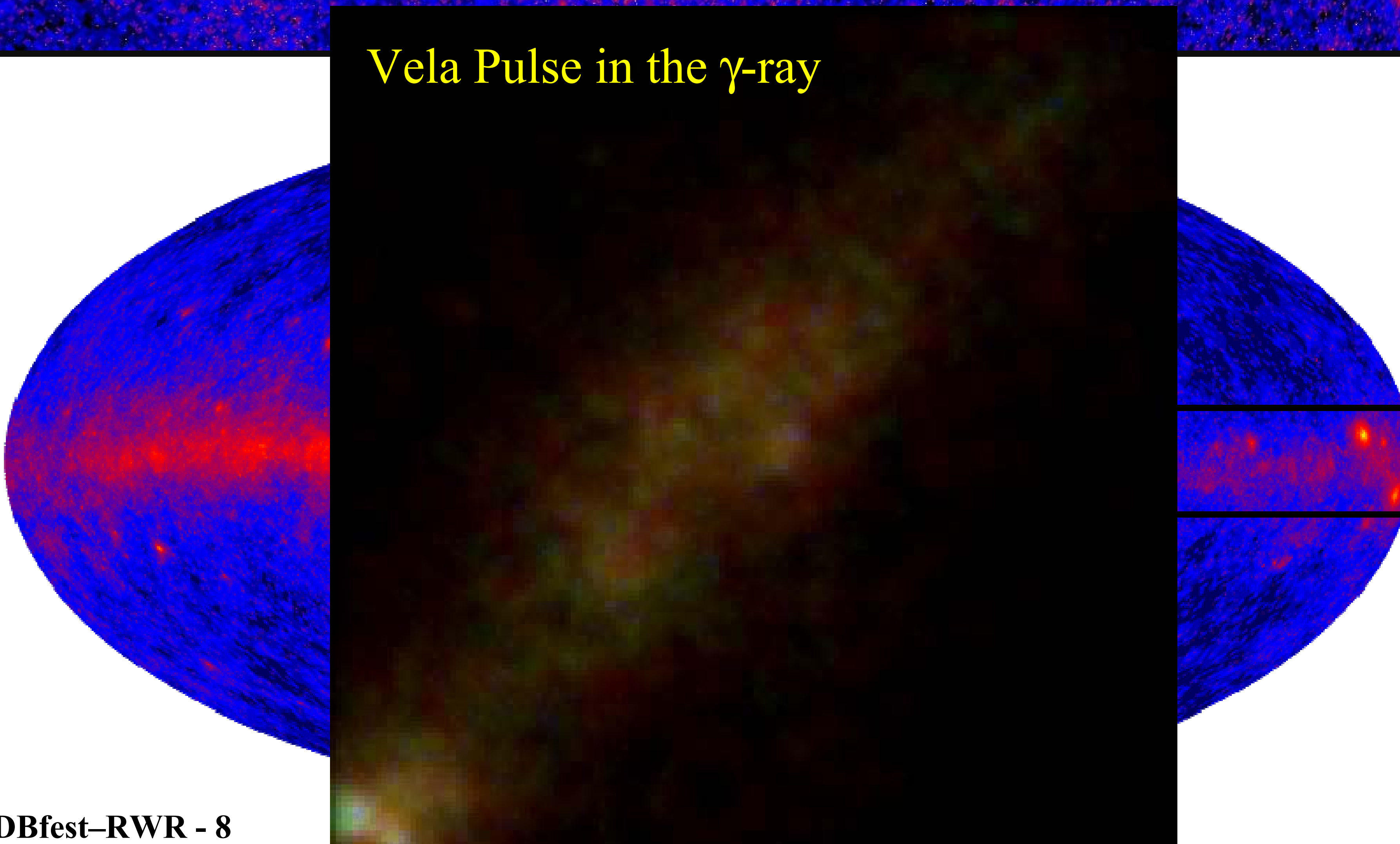




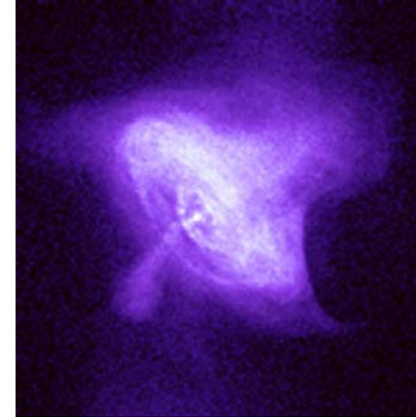
Mission	Years	$A_{eff}\Omega$(cm^{2}st)	θ_{1GeV}(deg)
EGRET	'91-'00	750	0.5
LAT	'08-	25,000	0.1

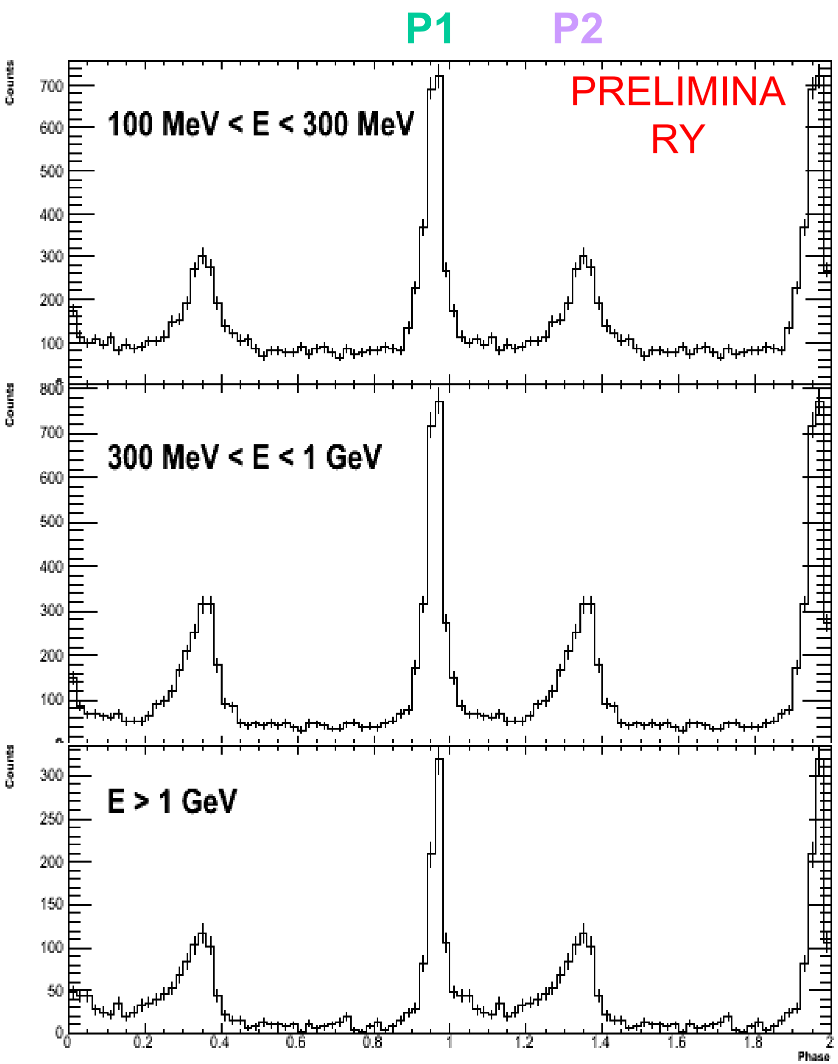
+ digital events, good sensitivity 10-100GeV, no consumables…


PSR B1055-52
Vela
Geminga
Crab


Vela Pulse in the γ-ray

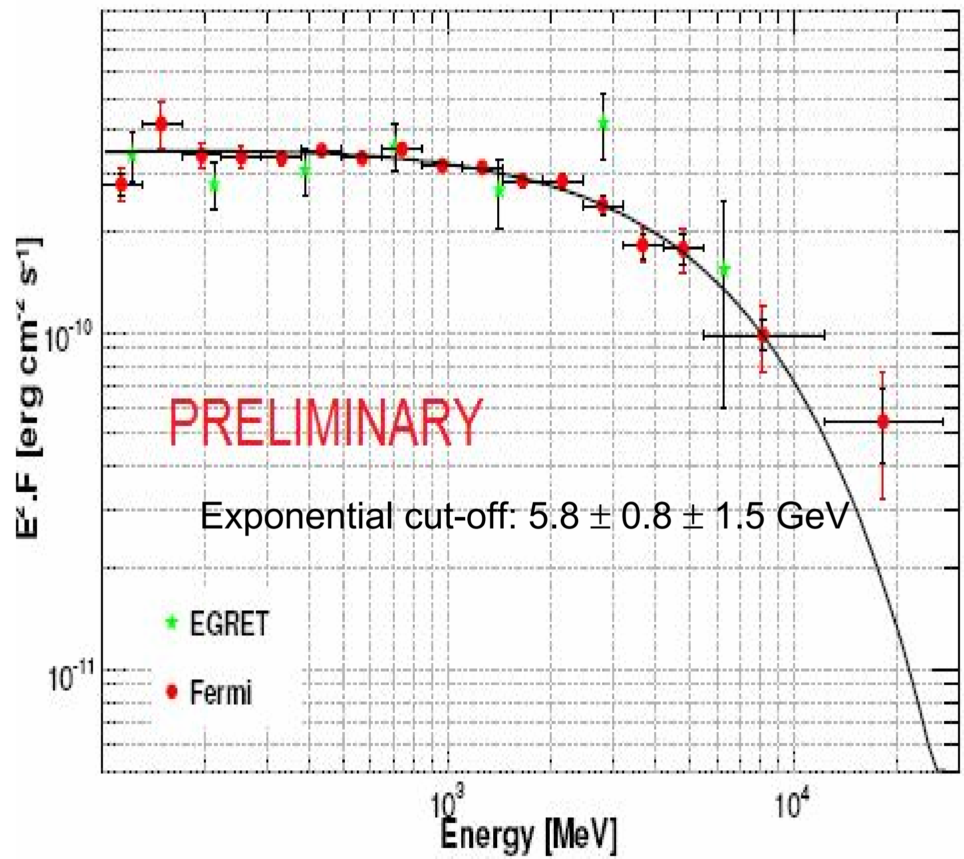
Crab Pulsar





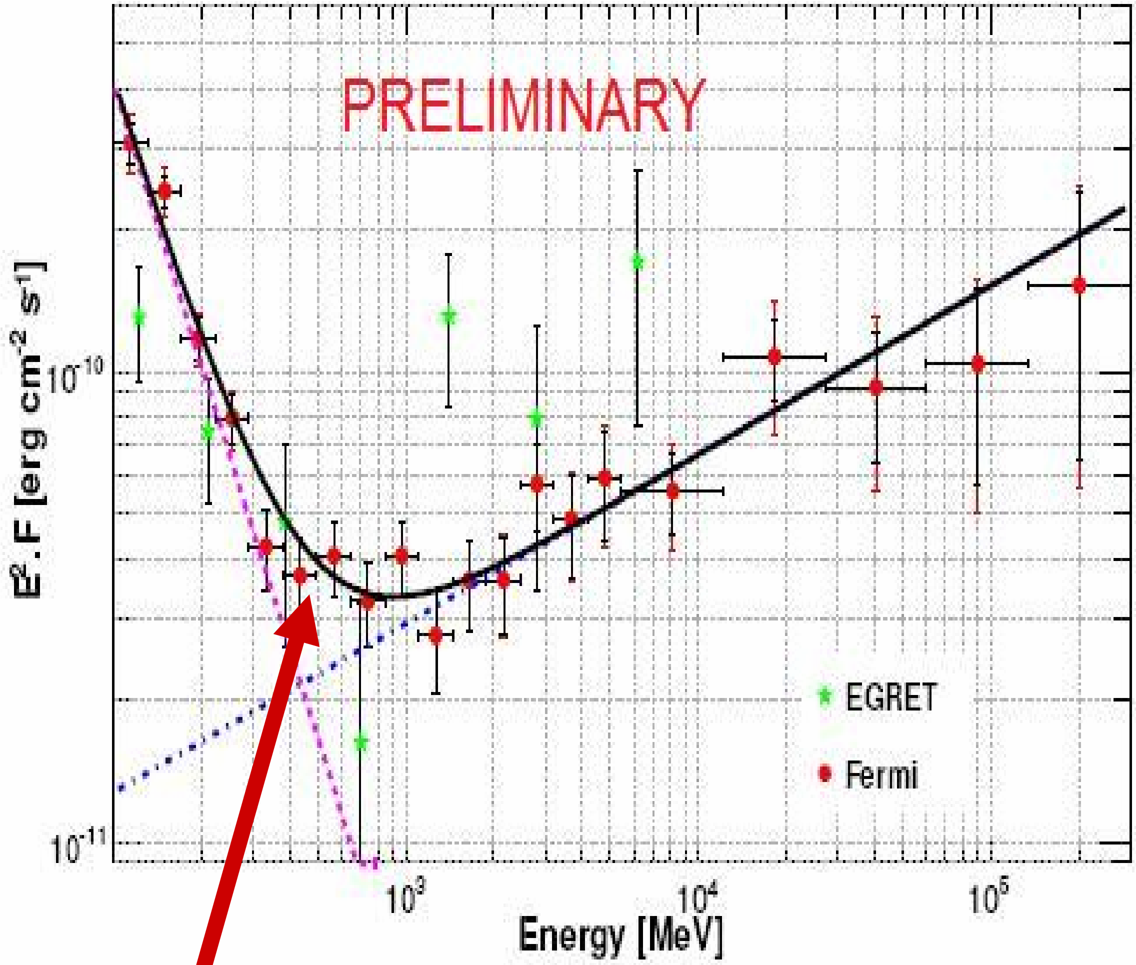
P2/P1 grows…

On-pulse spectrum.



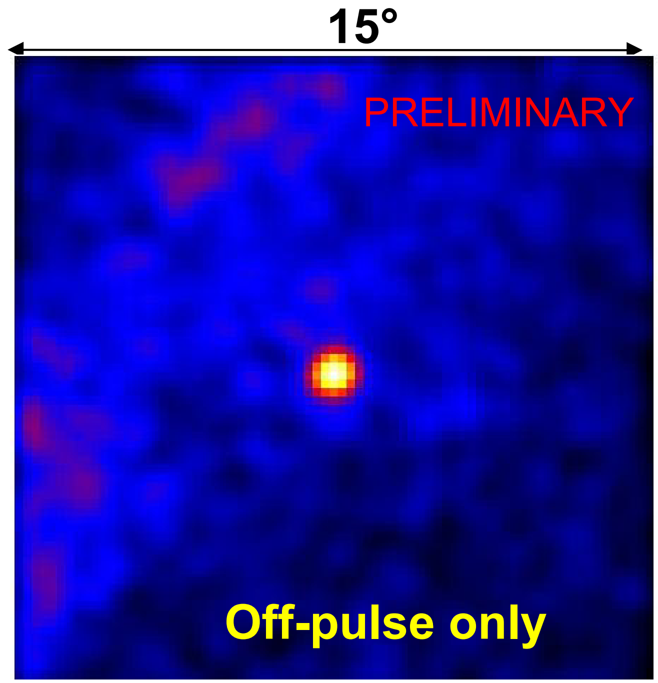
PL with ~6GeV cut-off

Crab Nebula



Off Pulse Spectrum

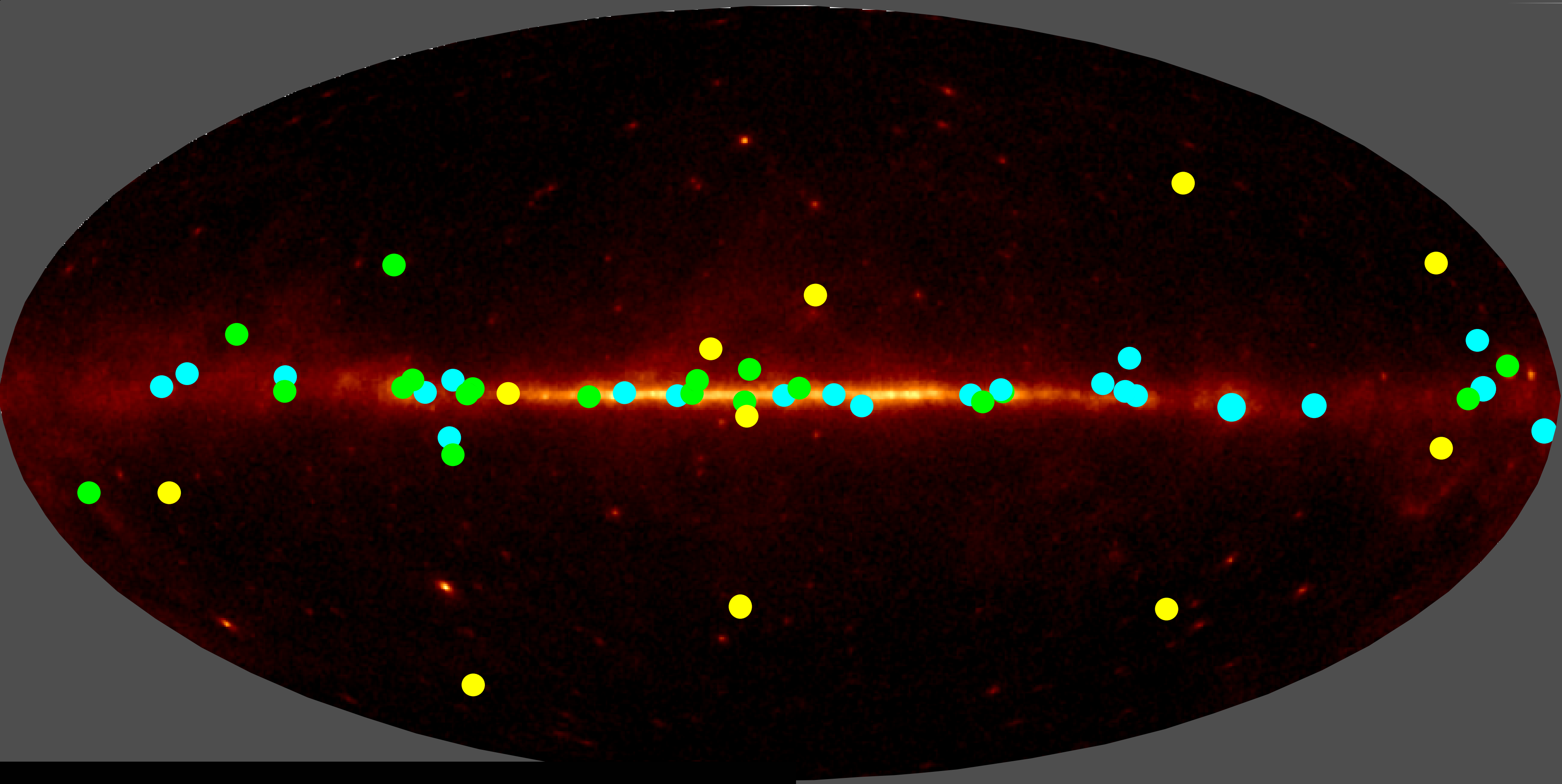
RDB: N.B. Synch photons at 0.5GeV!!



Detected at ~10σ

Grondin
Lemoine
Abdo et al ApJ sub.

The LAT Pulsar Sky



22 Radio Young Radio/γ-ray Pulsars

17 Young Pulsars Discovered in the γ-ray

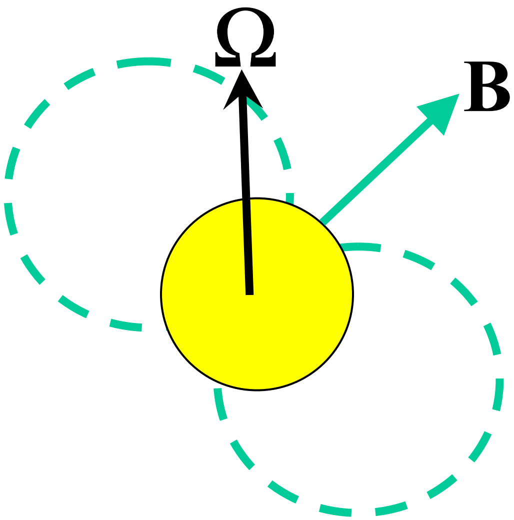
8 Millisecond γ-ray Pulsars

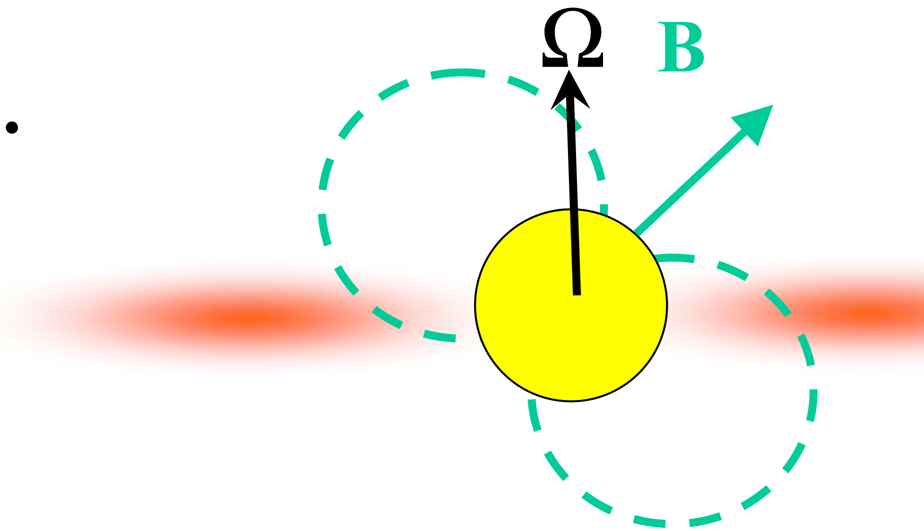
Pulses at 1/10th Real Rate

`Unipolar Inductor'

- **½ I Ω² → plasma and photons**
  - **mechanical energy of compact object rotation**
  - **Coupled through magnetic field**
  - **Poynting flux extraction, particles**
  - **High energy Radiation**
- **RDB: A surface is optional…**
- **This Radiation is**

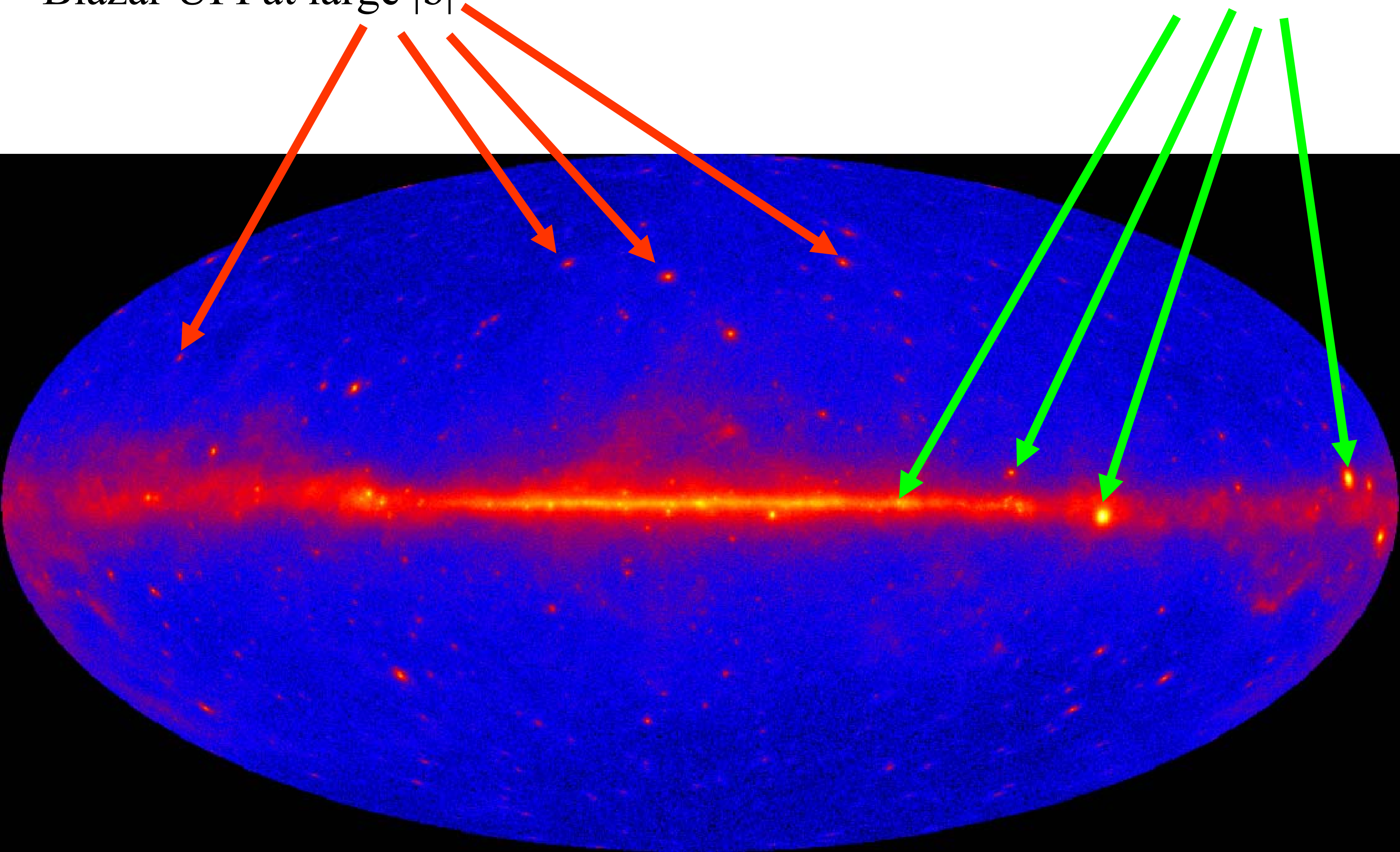
  `What Fermi Sees'
  - **(OK, the point sources…)**





The 1 year LAT sky

- Blazar UPI at large |b|
- Pulsar UPI along the plane



Interp: *Location, Location, Location*

1) Get the **geometry** right!

2) Work out the electro-dynamics

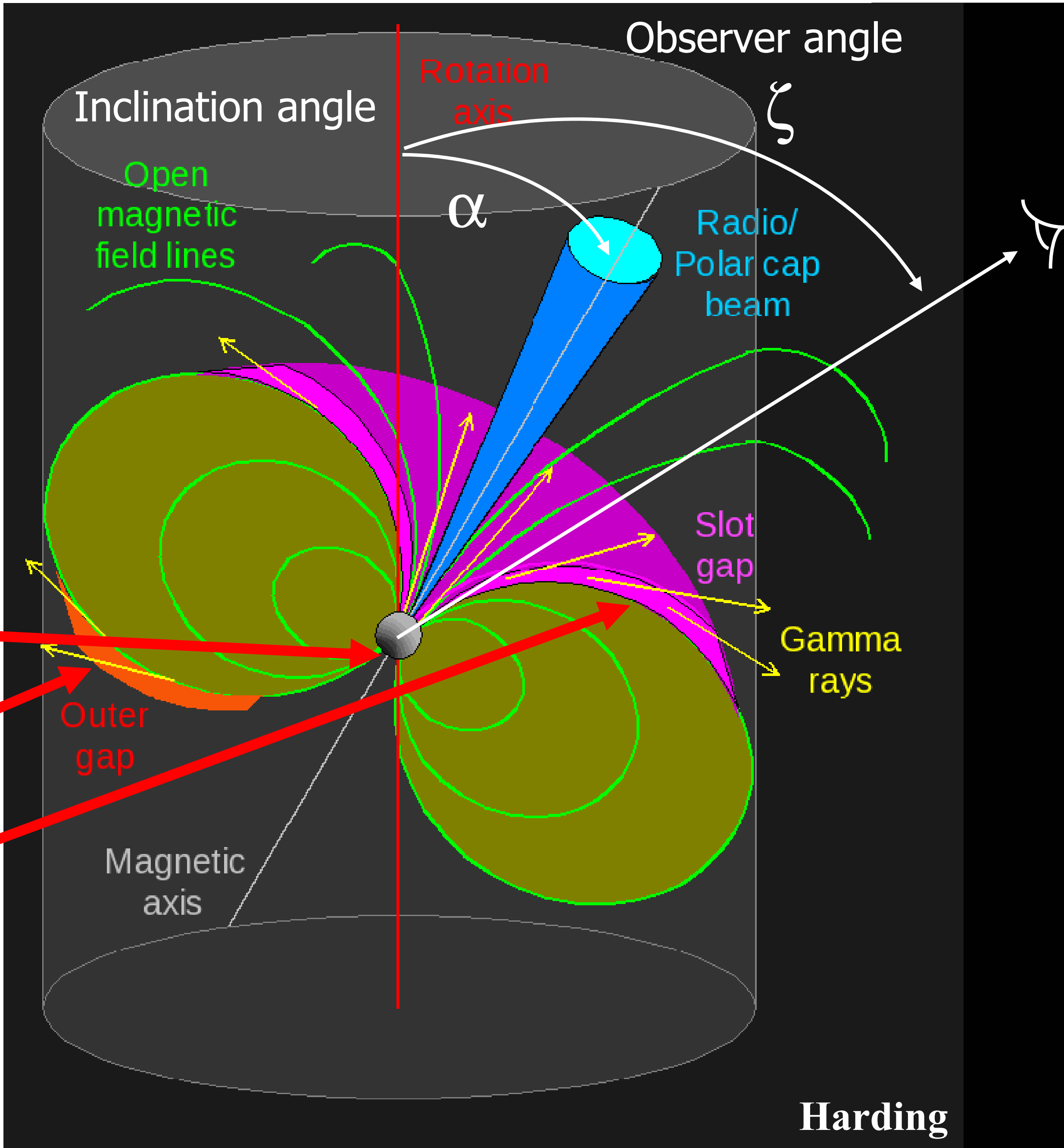
Emission Sites:

R_*, R_{LC}, $R(\Omega.B)=0$

1) Polar Cap

2) 'Outer Gap'

3) 'Slot Gap'



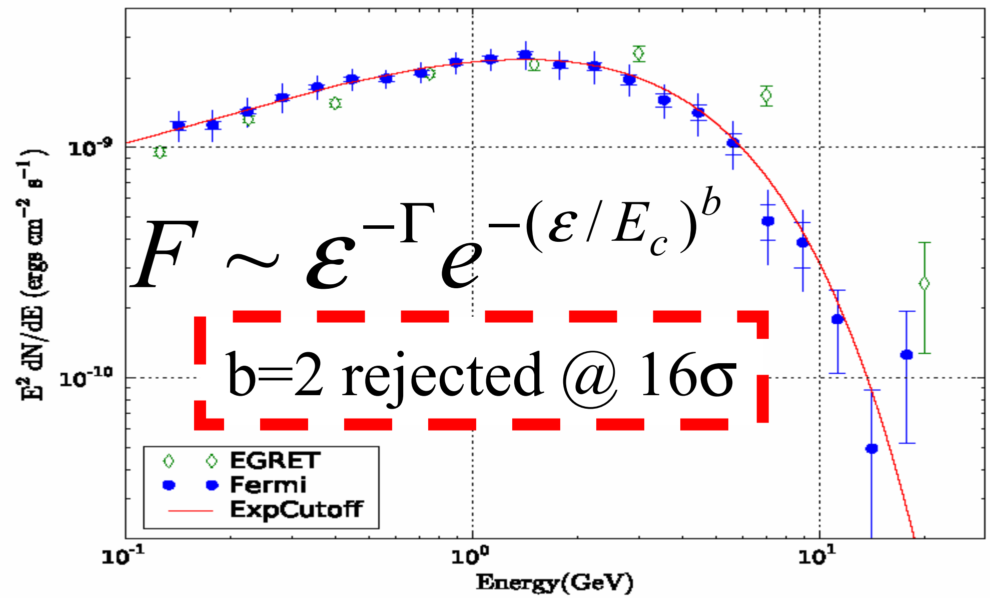
Harding

Excluding the Polar Caps

- **Beaming**
  - **Small Polar caps $\theta \sim 2P^{-1/2}/\sin\alpha$ deg -- Wide pulses only for $\alpha \sim 0$**
  - **Expect radio and γ-ray pulse to line up**
- **Physics**
  - **near surface γB → e+e-**
  - **Hyper-exponential cut-off**

$$f(\varepsilon) = A\varepsilon^{-a}\exp(-\tau_{1\gamma})$$

$$\tau_{1\gamma} \approx C(B)\exp\left[-\frac{8}{3\varepsilon B'\sin\theta}\right]$$



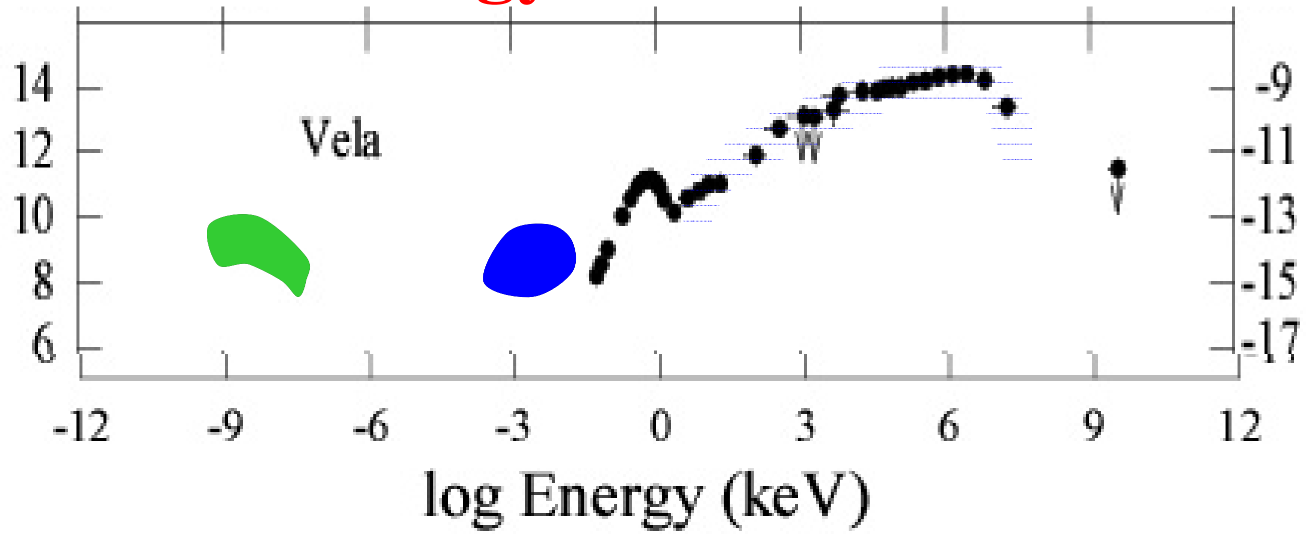
  - **Highest ε pulsed photon**

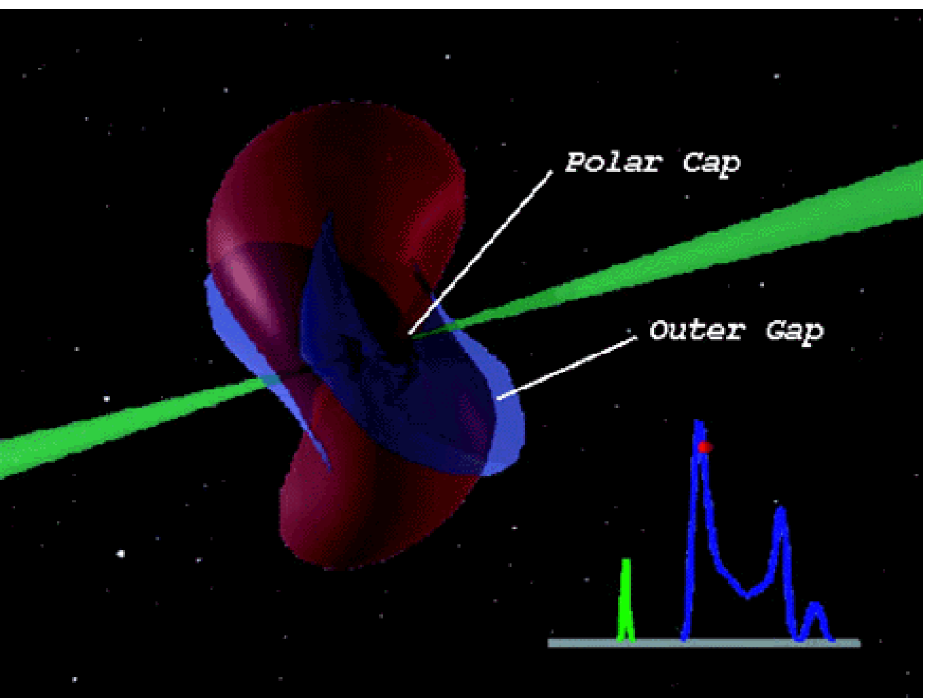
$$r/R_* \geq \left(\varepsilon_{max} B_{12} \big/ 1.76\text{GeV} \right)^{2/7} P^{-1/7}$$

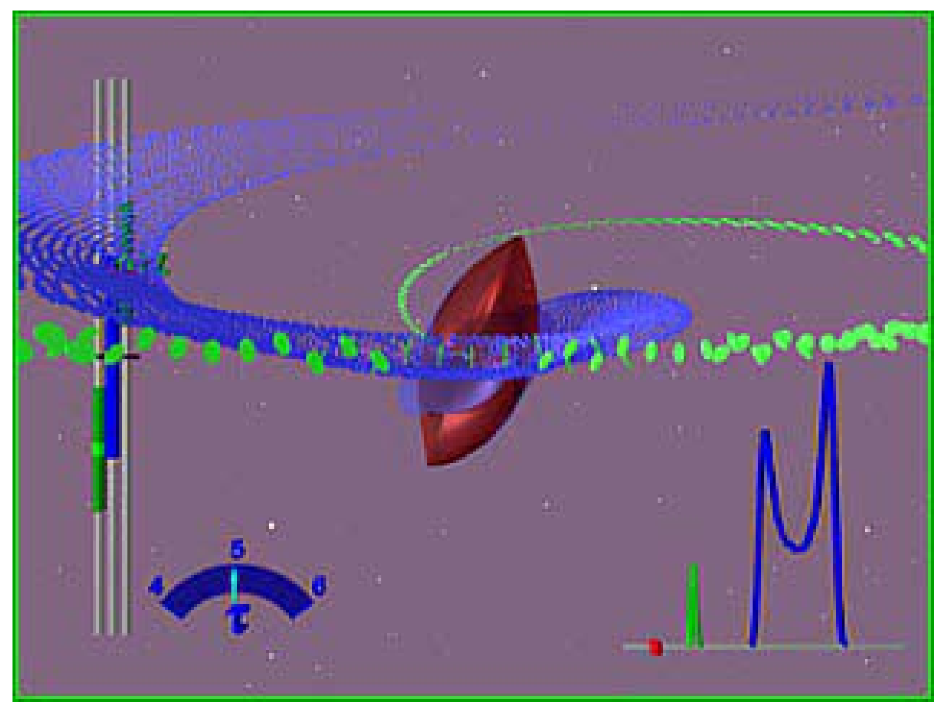
→ r > 4.5R* (LAT PSR B1706-44)
r > 6.5R* (MAGIC Crab 60GeV)

High Altitude/Energy Pairs → Radiation

- Low Altitude gap → Radio
- High Altitude → optical-γ-ray
- Basic Geometry Vacuum Models

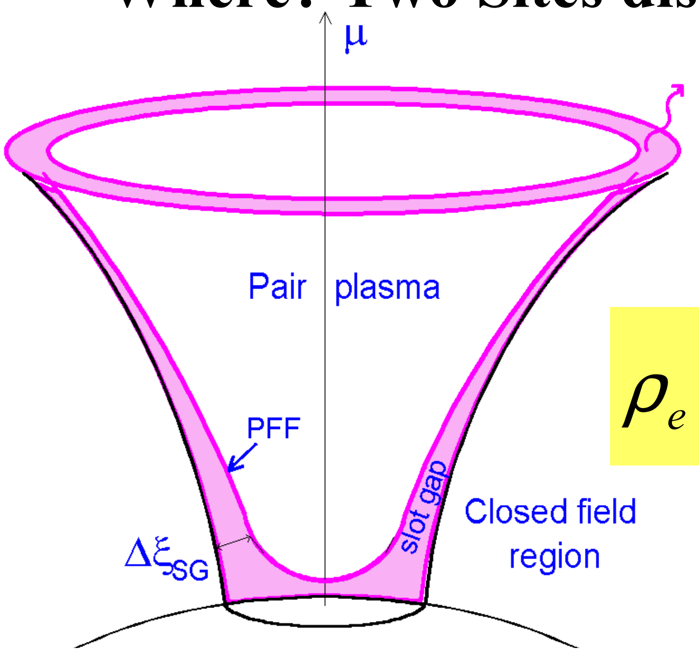




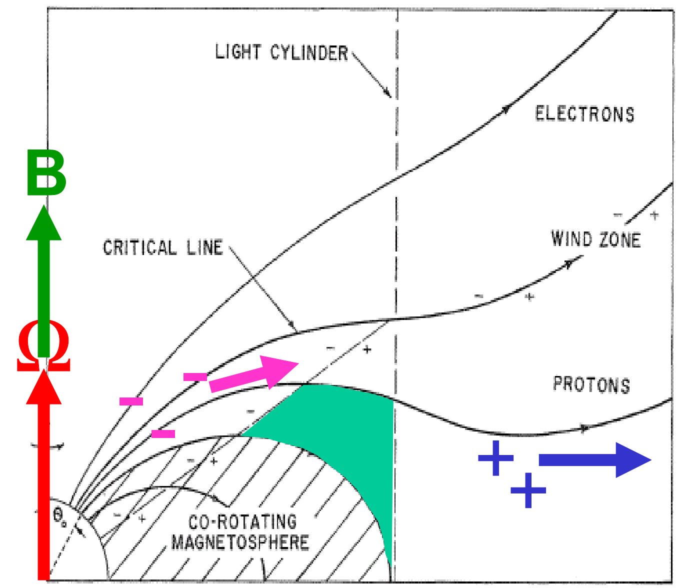


Acceleration at High Altitudes

- **Results: Wider beams, high sky coverage**
- **Dominant radiation seen is Curvature from ~10TeV e+e-**
- **How?** ***Breakdown of Force-Free Conditions***
- **Where? Two Sites discussed:**



$$\rho_e \neq -\vec{\Omega}\cdot\vec{B} \big/ 2\pi c$$



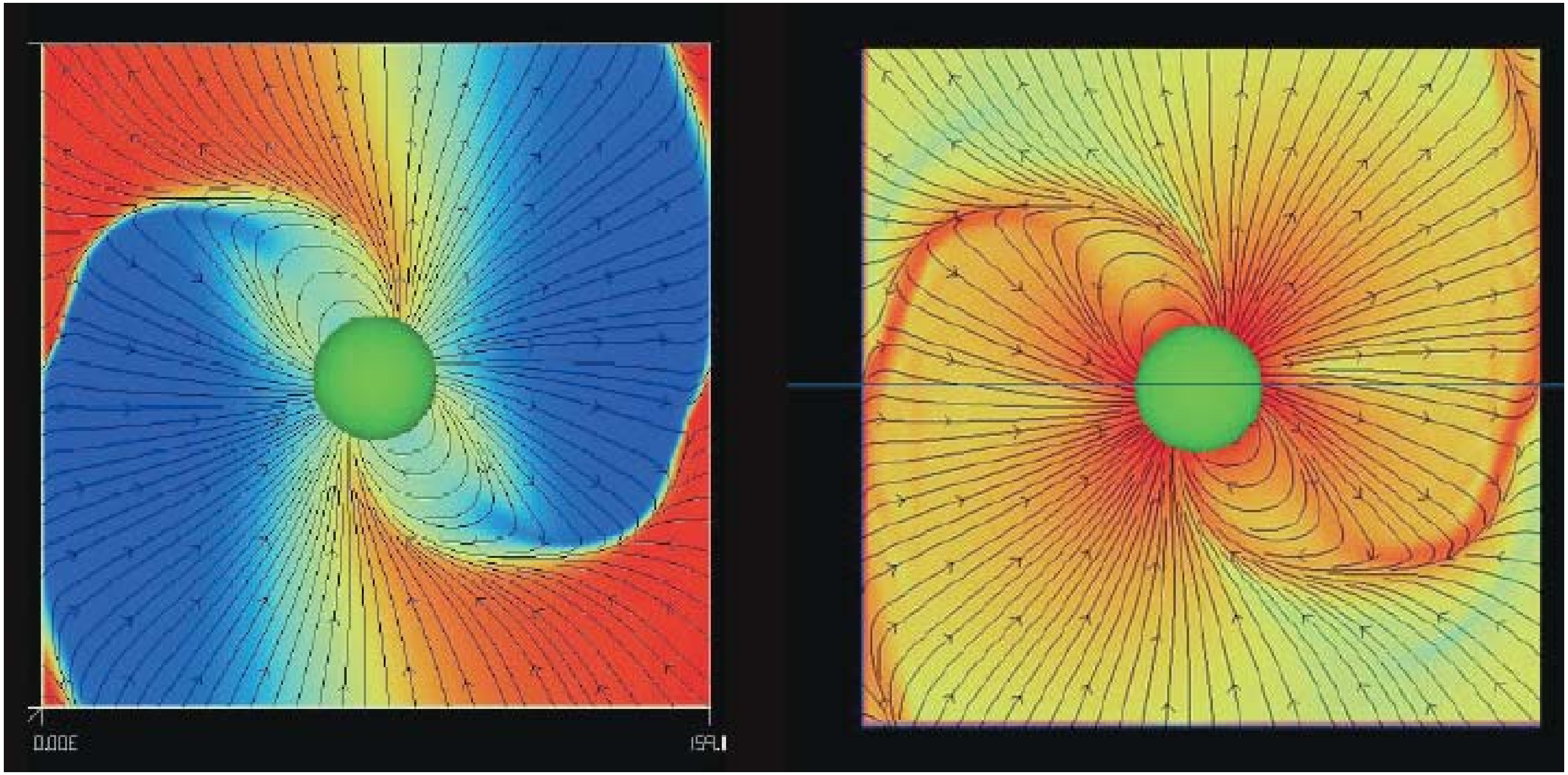
`Slot gap' (Arons '81)/Two Pole Caustic Geometry (Harding & Colleagues)
GR potential (Muslimov & Tsygan '98)

`Outer Gap' Holloway '73 → Cheng, Ho & Ruderman '86
RWR '96

Numerical Experiments

- **Computational Realizations of Completely Force-Free Magnetospheres**
  - **Nice simulations and movies (Spitkovsky 08)**

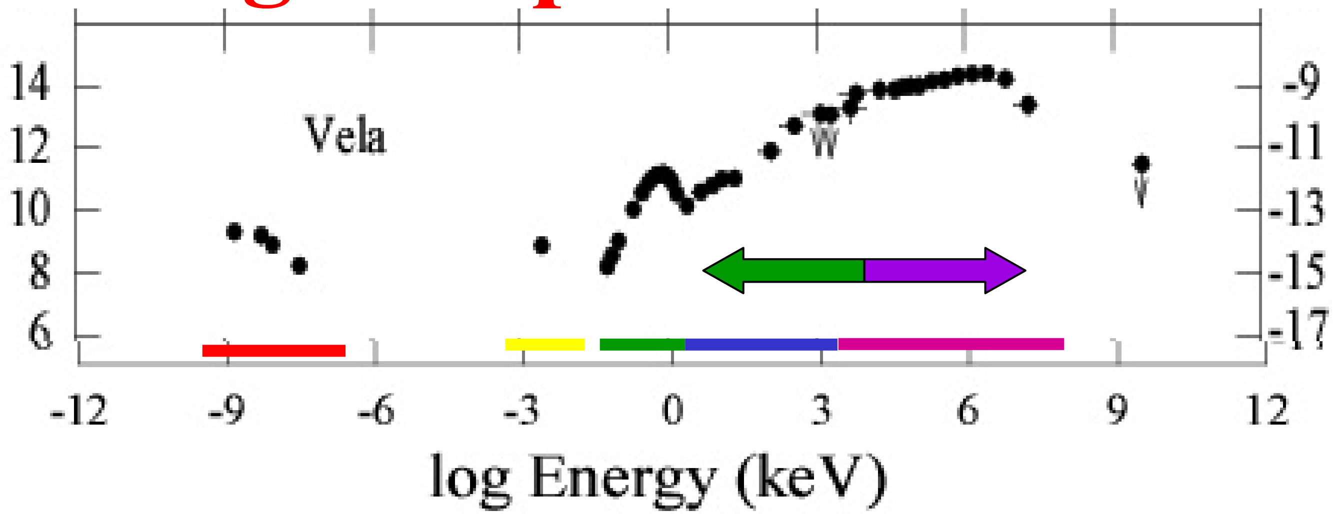
α=60^{o} Global Force Free Model



Currents

Outer Magentosphere Radiation

Radio – coherent
IR-UV, hard X – synchrotron
Soft X – thermal
GeV -- CR

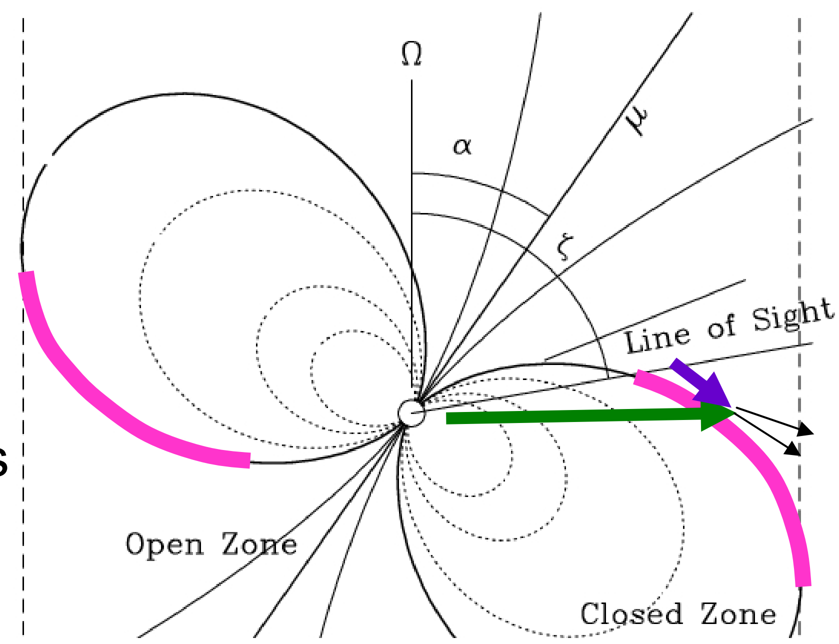


Key Point:

pair cascade from $\gamma\gamma \rightarrow e^+e^-$
w, gap potential & γ_{Max} grow until limited by Wein 'wall' of thermal surface flux:

$$\varepsilon_{\rm Th} \approx \frac{2(m_e c^2)^2}{(1-\cos\theta)\varepsilon_\gamma}$$

Few GeV E_c are natural for thermally controlled outer gaps. E_c grows as star cools

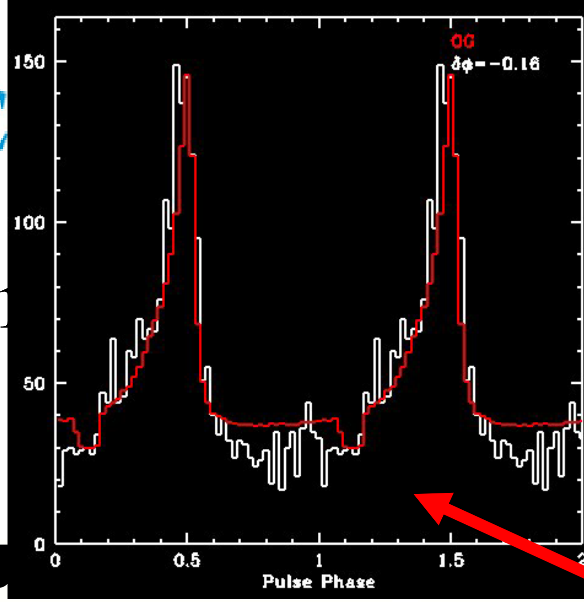


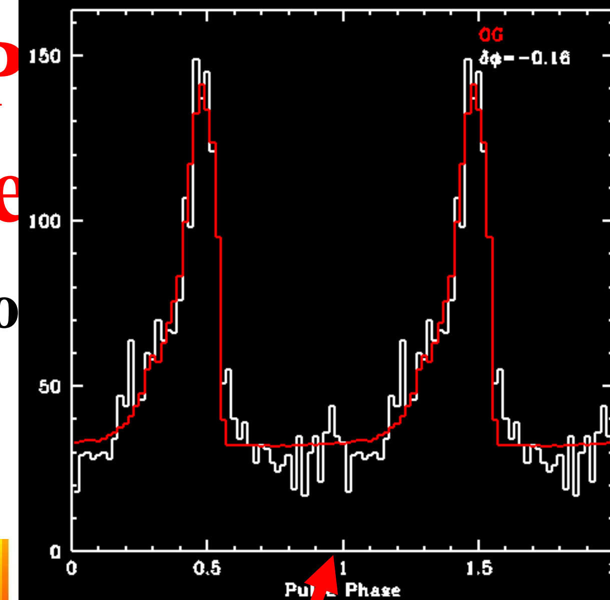
➔ **requires 10-30TeV $e^{+/-}$**

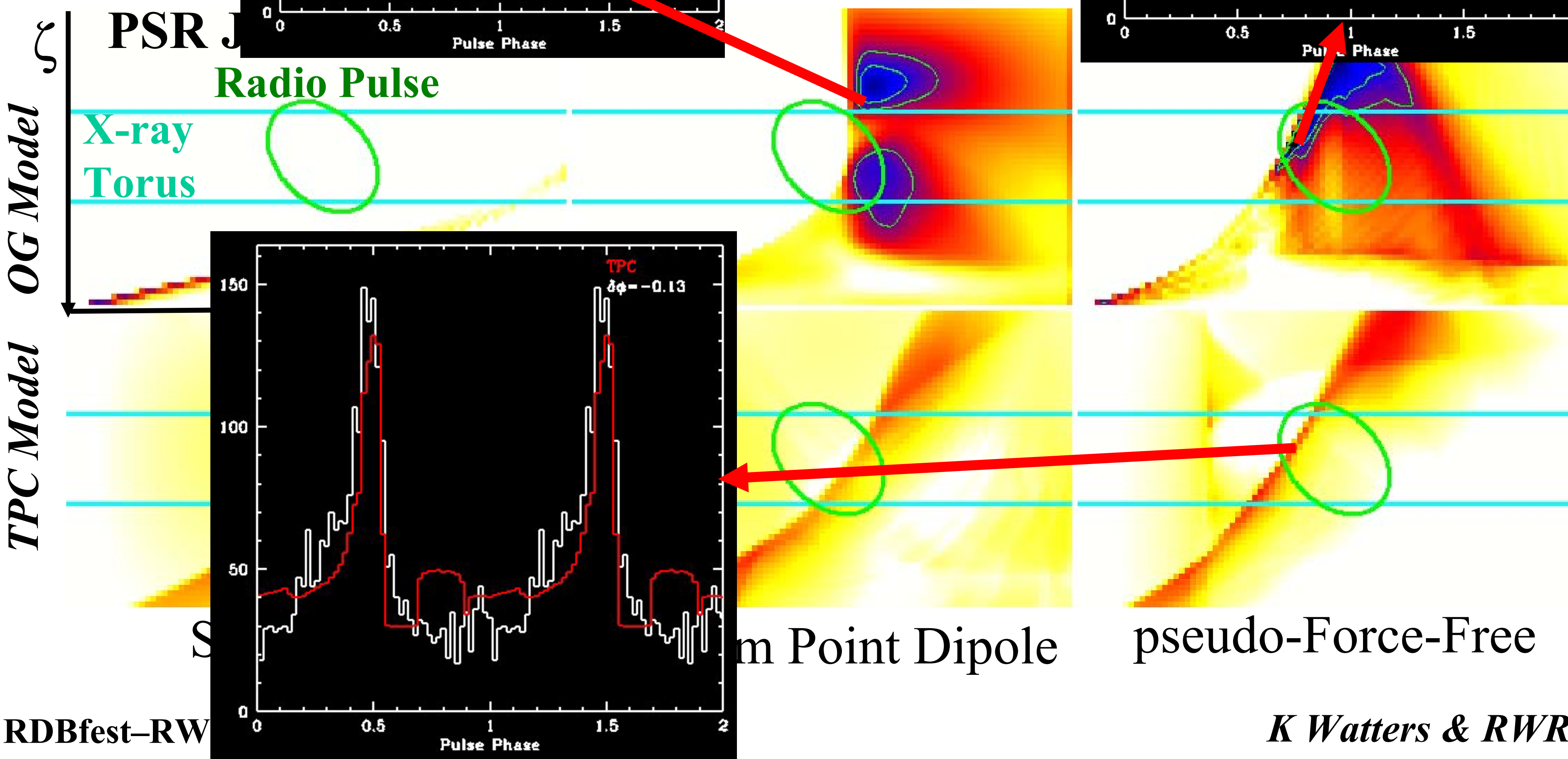
…e LAT to P…
…agnetosphe…

- Step 1 … f the acceleratio…
  - fit …

PSR J…





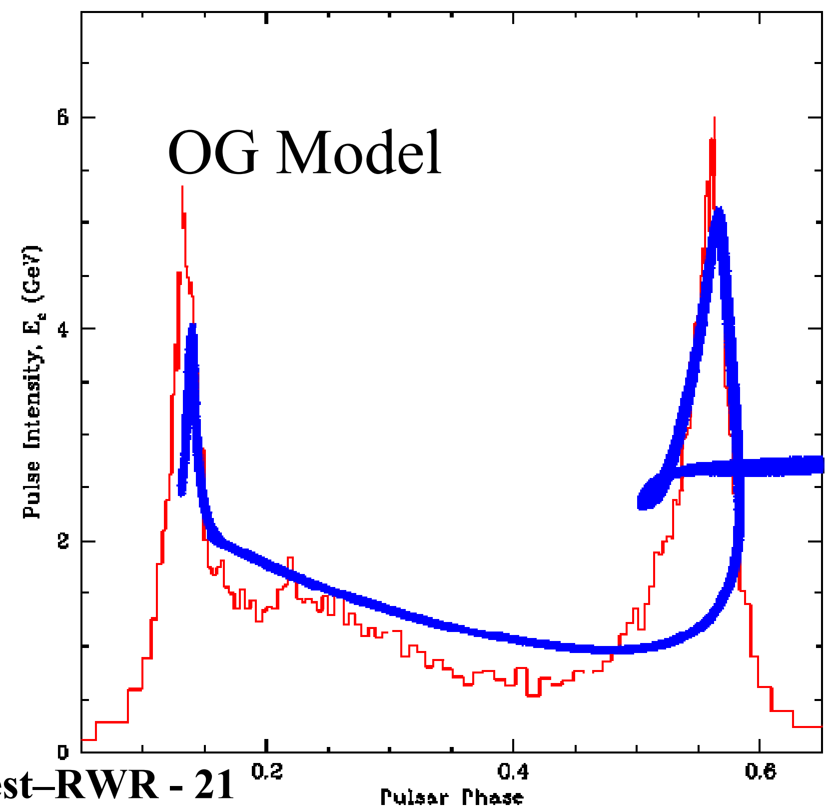


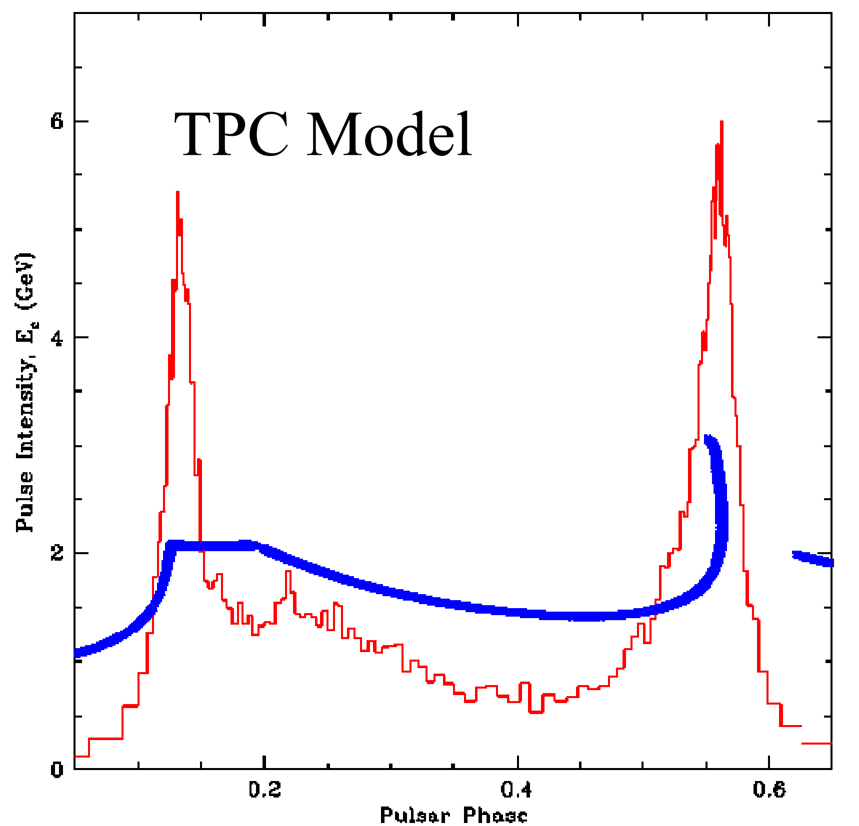
K Watters & RWR

Using the LAT to Probe Pulsar Magnetospheres

- **Step 2 - use phase-resolved <u>spectra</u> to map particle acceleration**
  - **Radiation-reaction limited CR cut-off depends on gap fields**

$$\varepsilon_c \propto \gamma^3 / \rho_c, \; \gamma \sim E_{\parallel}^{1/4} \rho_c^{1/2} \xrightarrow{E_{\parallel} \sim w/r} \varepsilon_c \sim \rho_c^{1/2} \left(s - s_{NC} / r_{LC} \right)^{-3/4} w^{3/4}$$





Conclusions

- **PSRs: charge-starved unipolar inductors**
  - **Bright γ-ray action at large altitude:**
  - **B ~1/r^3 makes this a 'simple', few parameter problem… P, B_0, α, ζ– little else → *should be solvable!***
- **With *Fermi* LAT:**
  - **We are probing the bulk energetics of the pulsar machine**
  - **→ lead on to a deeper understanding of magnetosphere electrodynamics.**

Thanks and Congratulations

- **For giving us a paradigm to think about neutron star (and many other astrophysical) problems**
- **Looking forward to continued work on UPIs and other highly magnetized systems!**

Requires
Dominant
B-fields

Roger
David
Blandford