Future Gamma-Ray Observations of Pulsars and their Environments

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Outline

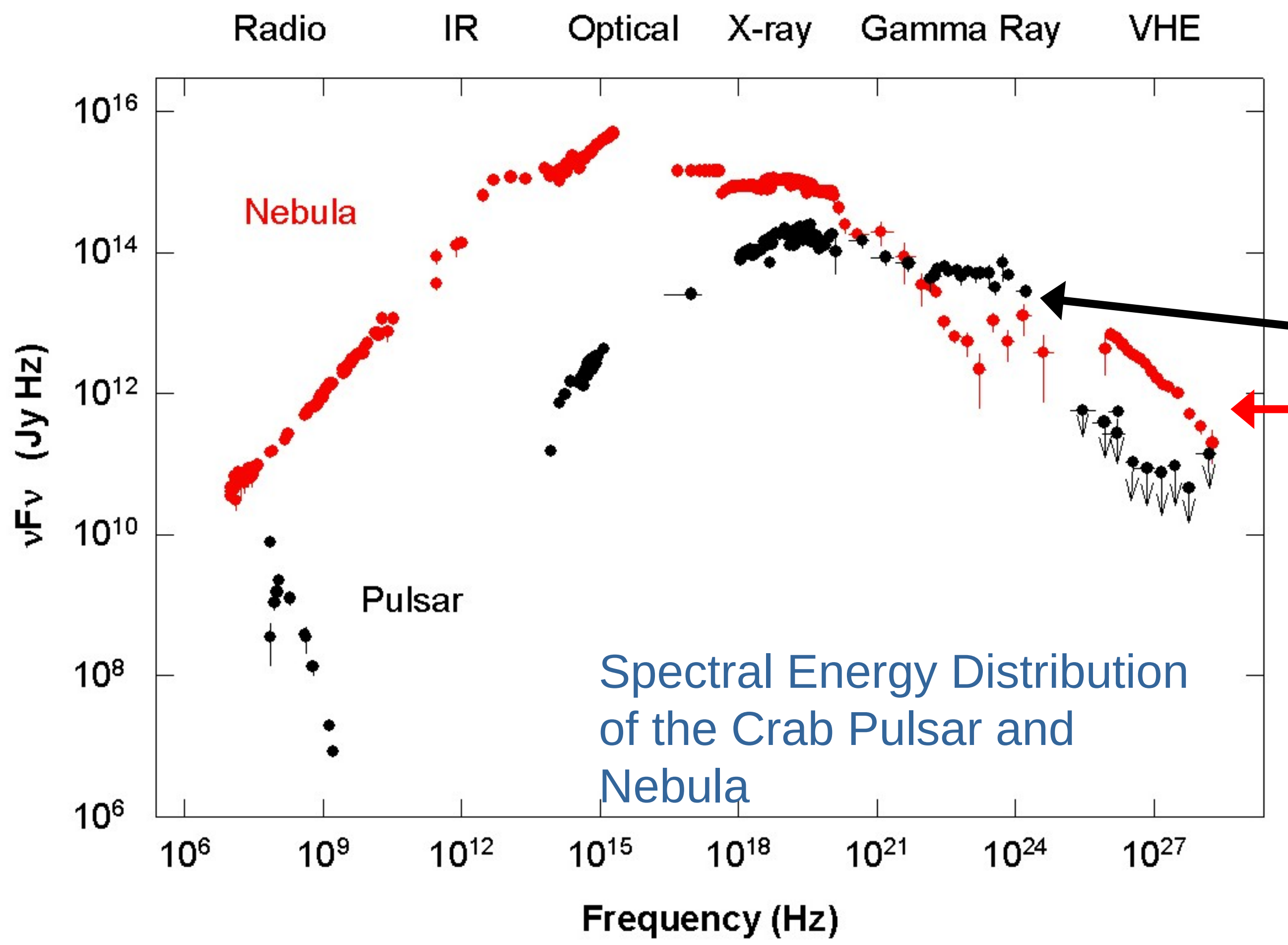
- Motivation: The role of gamma rays
- Opportunities: Status of near-future gamma-ray observatories
- GLAST: Major mission at GeV energies

MOTIVATION:

- Gamma rays are inherently associated with high-energy particles.
- Any aspect of neutron stars involving particle acceleration and interaction may be studied by gamma rays.

PULSARS AND PULSAR WIND NEBULAE

Pulsed radiation represents only a small fraction of the total energy loss from the slowdown of the neutron star. Most of the energy is carried off as a wind that can form a nebula in the pulsar's environment. Pulsars and pulsar winds can accelerate particles to high energies.



GeV and TeV gamma rays are produced by the highest-energy particles from the pulsar and the pulsar wind

Gamma rays are therefore associated with the primary acceleration and interaction processes.

SOME OPEN QUESTIONS:

- Where and how are particles accelerated?
- How do the particles interact? With what?
- Is it the same for all neutron star systems?
- How does the complex environment (frame dragging, aberration, strong magnetic and electric fields, high currents) produce the observed radiation patterns?

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SIMPLE OBSERVATIONS OF A FEW SOURCES ARE NOT GOING TO ANSWER FUNDAMENTAL QUESTIONS LIKE THESE!

TWO APPROACHES:

- **Observation-driven questions**
  - What patterns seen in present data will survive with better observations?
  - What are the implications of such patterns?
- **Theory-driven questions**
  - What predictions of current models will be borne out by new observations?
  - How will theoretical models evolve in response to improved data?

Observation: Luminosity vs. Voltage

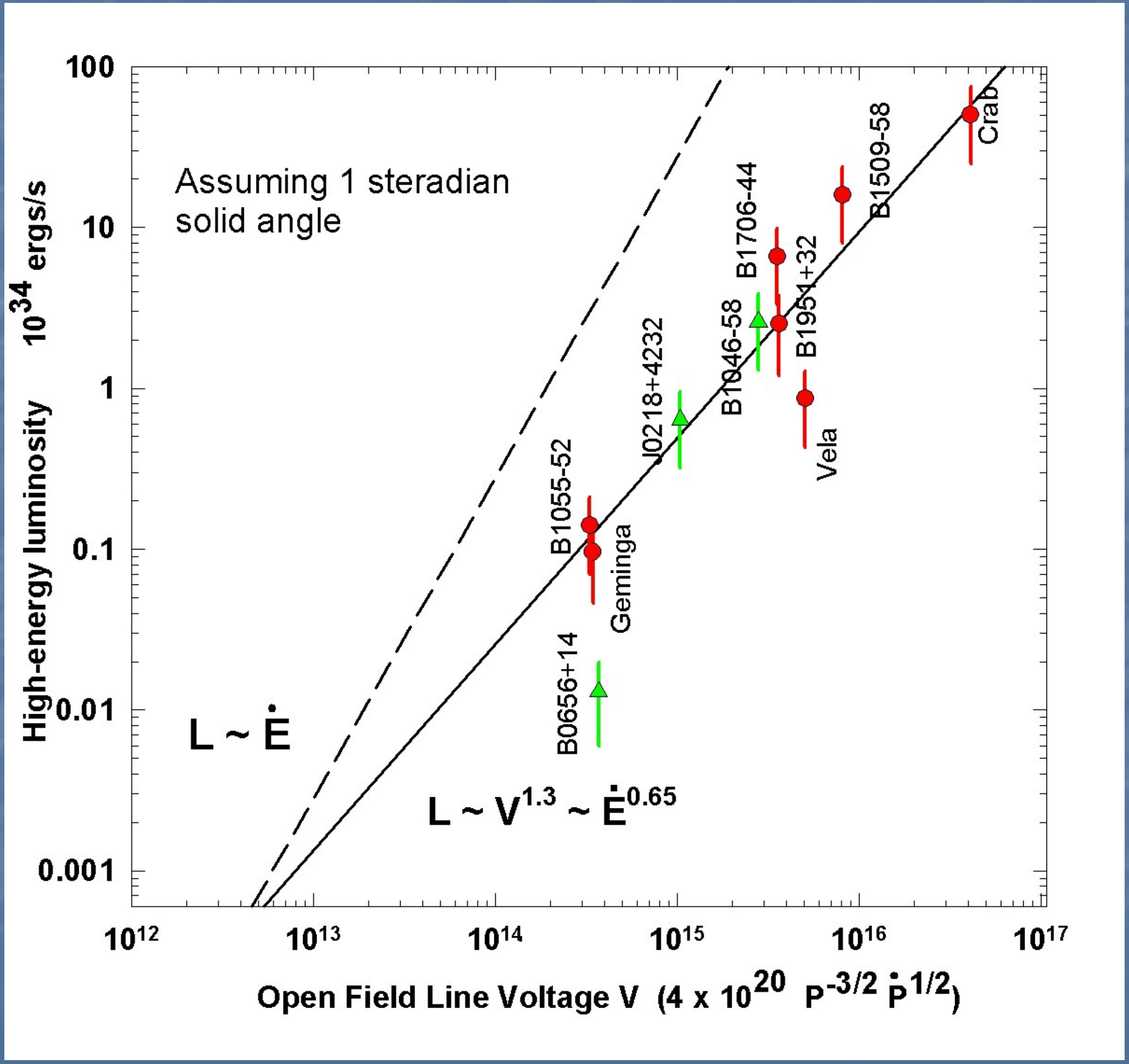
Does this trend (shown here as a fit, not a theory) hold for other pulsars?

What happens as the observed luminosity approaches the total available spin-down luminosity?

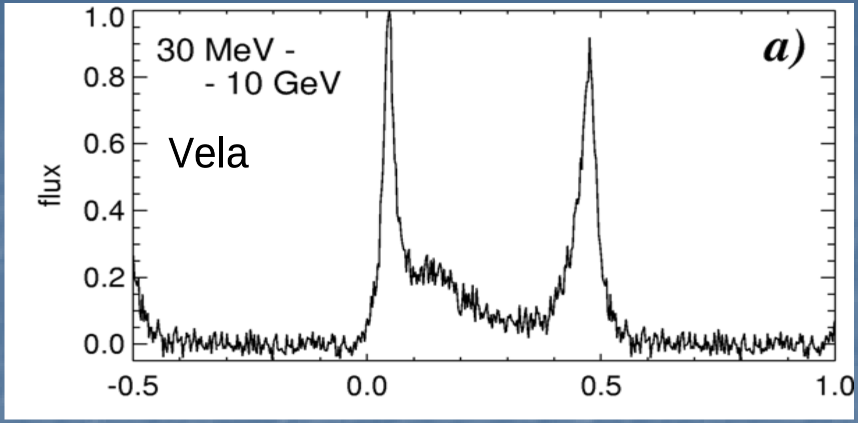
How much does the assumption of a 1 sr beaming solid angle distort the picture?

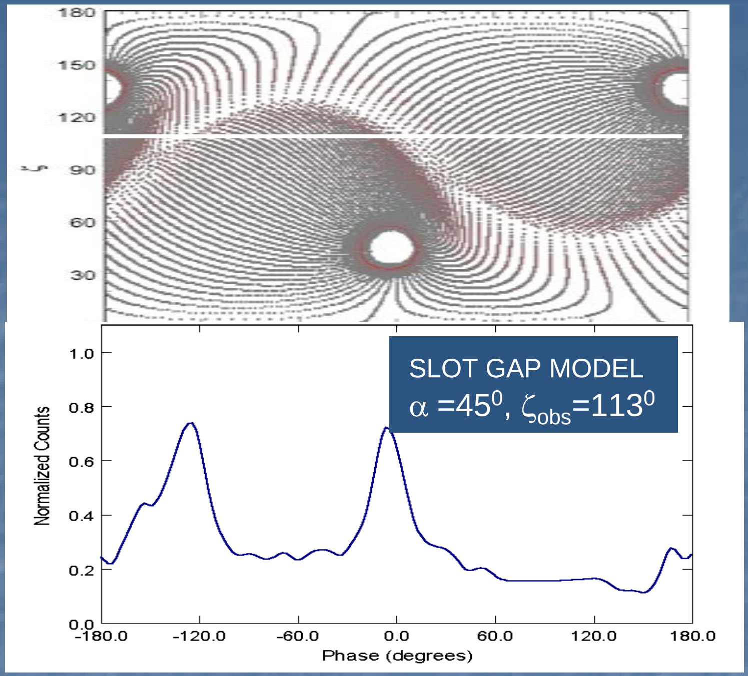
● High-confidence gamma-ray pulsars

▲ Lower-confidence gamma-ray pulsars

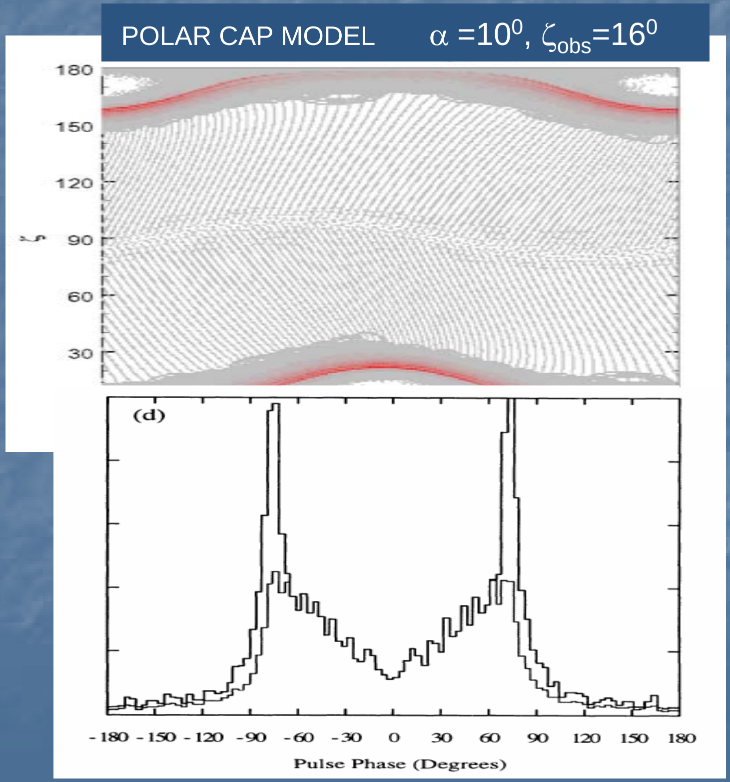


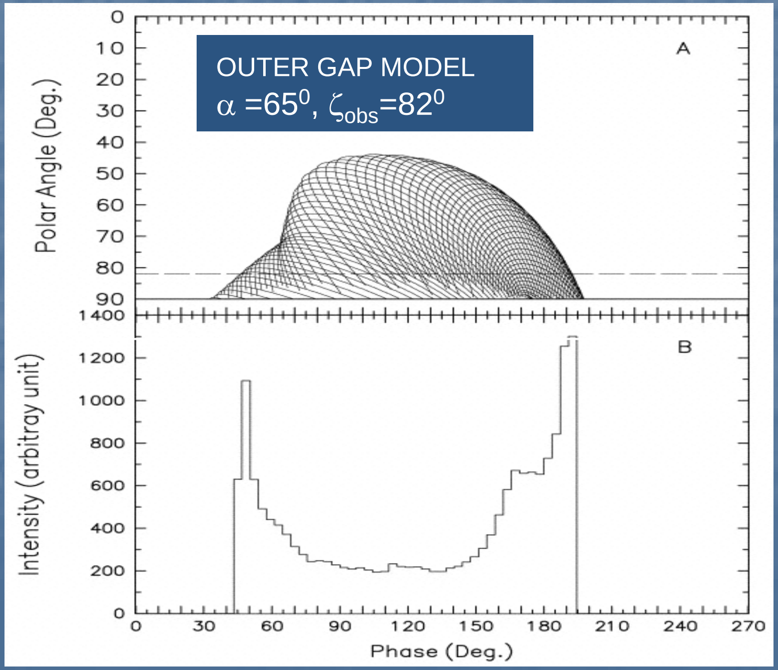
THEORY: MODEL LIGHT CURVES





Summary by Alice Harding





Which model (or variation) can explain the light curves?

OPPORTUNITIES:

A number of gamma-ray observatories will be starting or will be improved in the next few years.

- Four major Atmospheric Cherenkov Telescopes (ACT). These ground-based telescopes are most sensitive above 100 GeV. Two wide-aperture, high-altitude telescopes, sensitive at still higher energies.
- AGILE – small satellite GeV telescope
- GLAST – large satellite GeV facility

CANGAROO-III (Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback)

Four 10 meter telescopes located in Australia

Fall, 2005 – refurbished (cleaned, realigned)

Now taking data. Continuing analysis of older data.

MAGIC

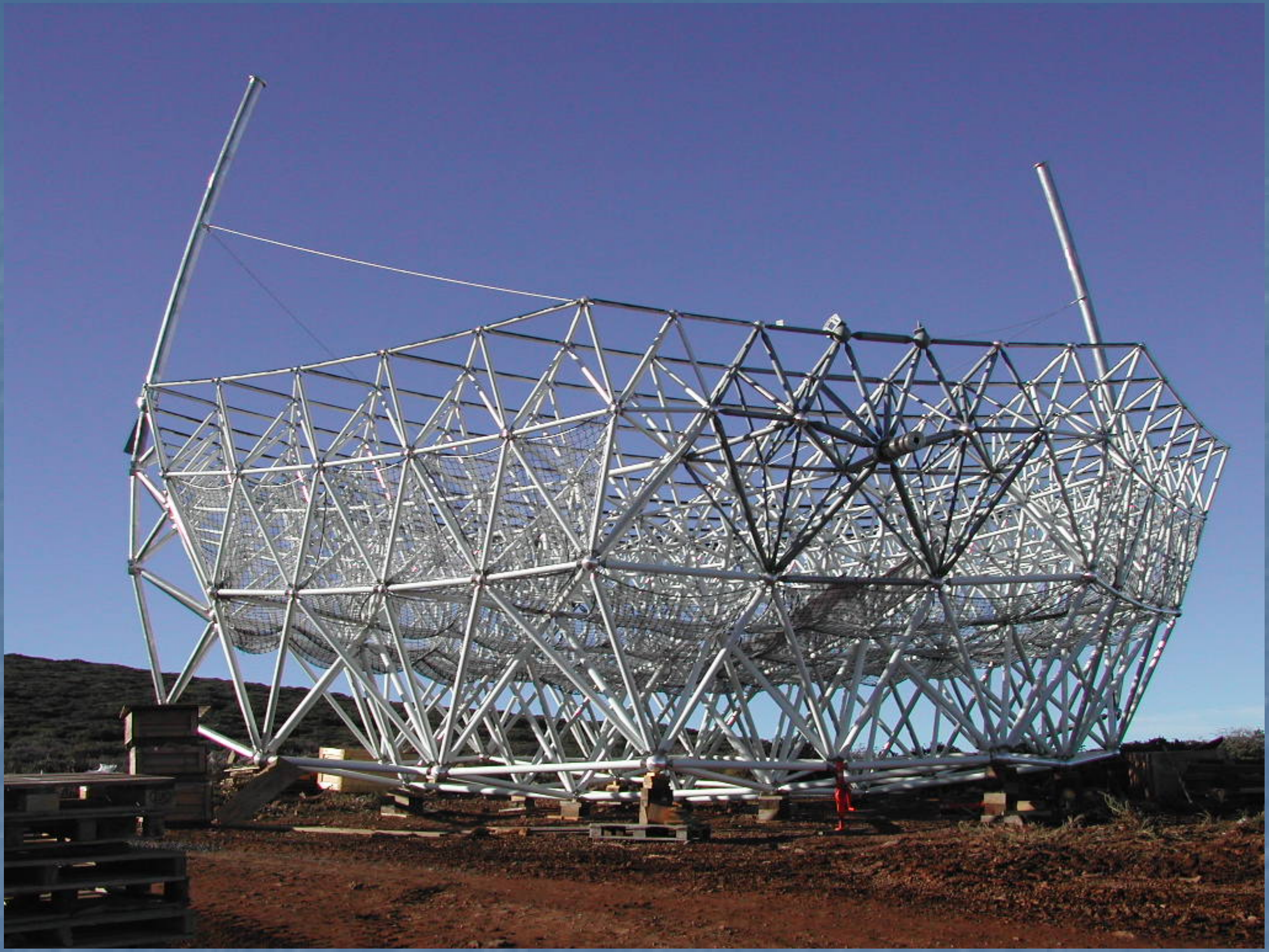
Major Atmospheric Gamma-Ray Imaging Cherenkov

One 17 meter telescope located in Canary Islands

Now taking data. Exciting results appearing.

Also ….

MAGIC-II



A second identical 17 meter telescope located 80 m away.

Under construction. Completion in 2007.

VERITAS

Very Energetic Radiation Imaging Telescope Array System

One 12 meter telescope has been operating. A second one started operation in December 2005.

Under construction…. 2 more telescopes, complete this year.

H.E.S.S. (High Energy Stereoscopic System)

Four 13 meter telescopes have been operating since 2004.

Results have been spectacular.

Near future….

H.E.S.S. II

Addition of a single 27 meter telescope.
Shown above is a simulation, not a photo.

Total collecting area will be over 1000 m^2.

Energy threshold will approach 20 GeV.

Time scale – 2008.

Mini-HAWC (High Altitude Water Cherenkov)

- MILAGRO detectors at a high-altitude site.
- Factor of 15 more sensitive than MILAGRO.
- Site search in progress. Above picture is a simulation.

ARGO-YBJ (Astrophysical Radiation Ground-based Observatory at YangBaJing)

- Resistive plate chamber detectors.
- High-altitude location (Tibet).
- Nearing completion.

NEUTRON STAR SCIENCE WITH TeV TELESCOPES - PULSARS

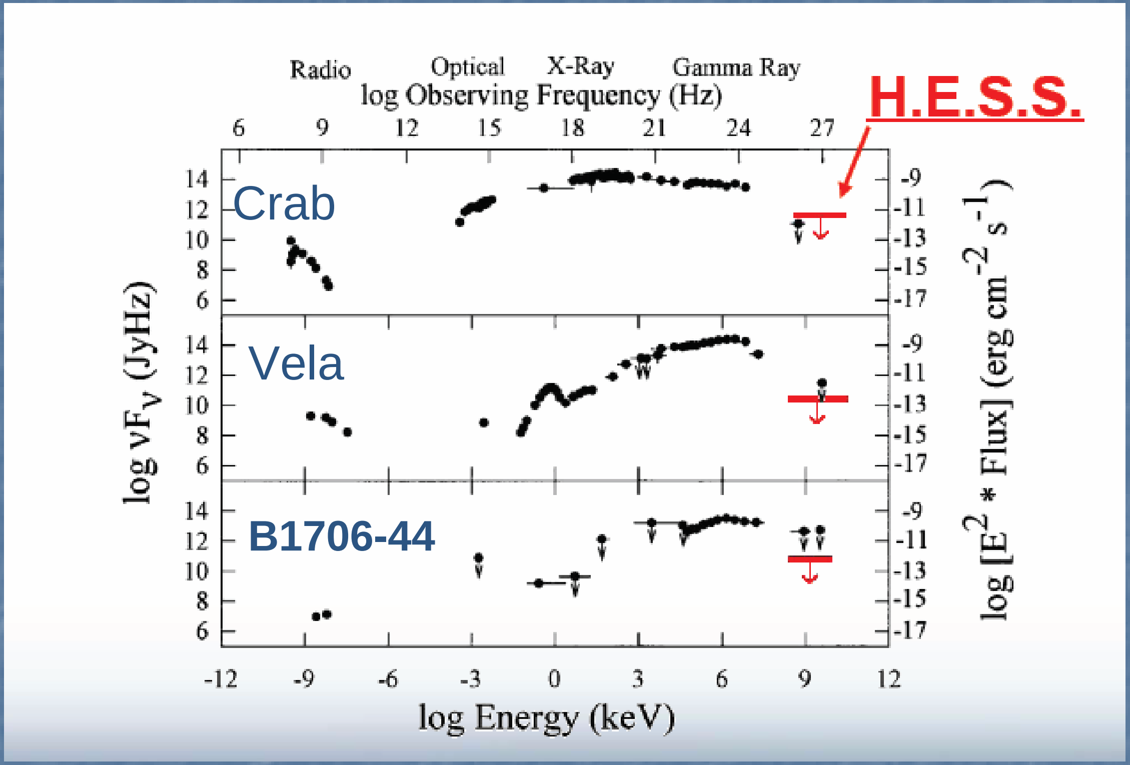
No pulsed radiation seen so far. Limits from H.E.S.S. by Schmidt (2005).

H.E.S.S-II and MAGIC-II will have significantly lower energy thresholds.

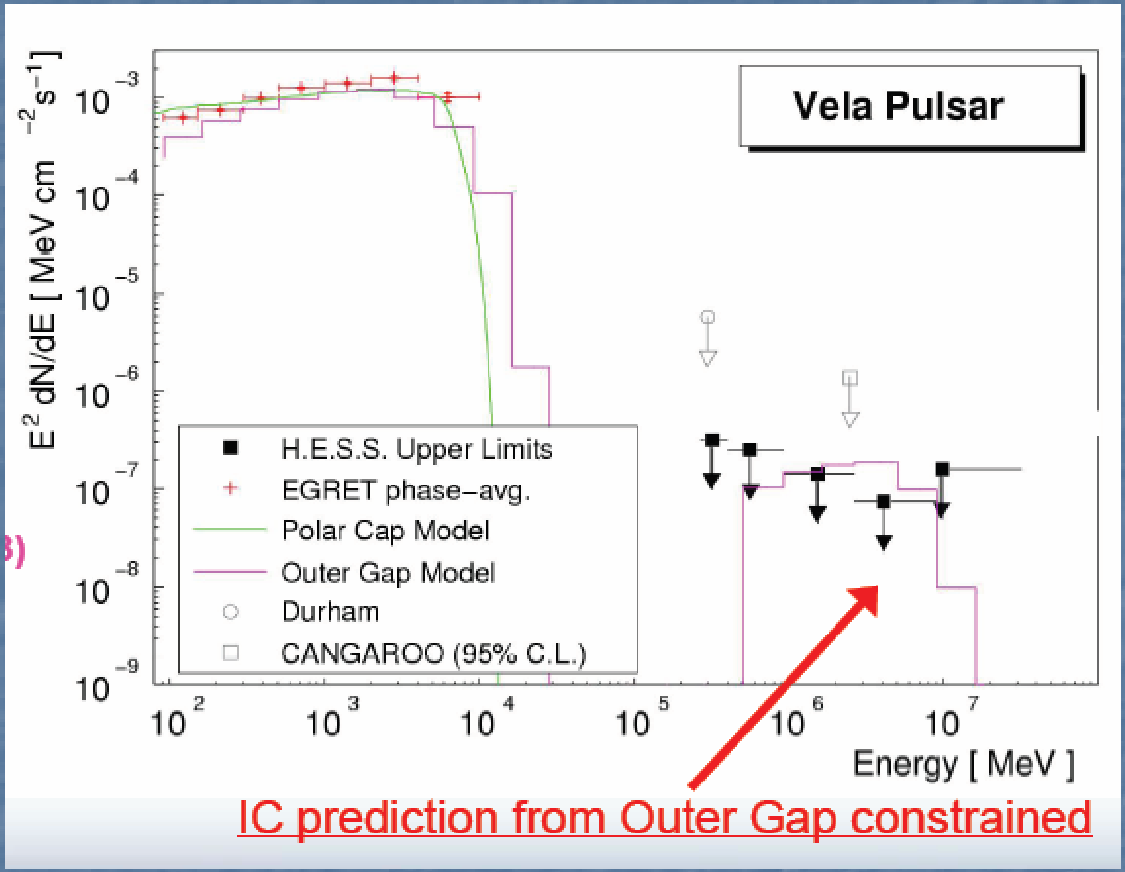
EGRET found pulsed emission above 10 GeV.

What is the upper energy limit on pulsed radiation?

How does this constrain high-energy processes?



NEUTRON STAR SCIENCE WITH TeV TELESCOPES - PULSARS



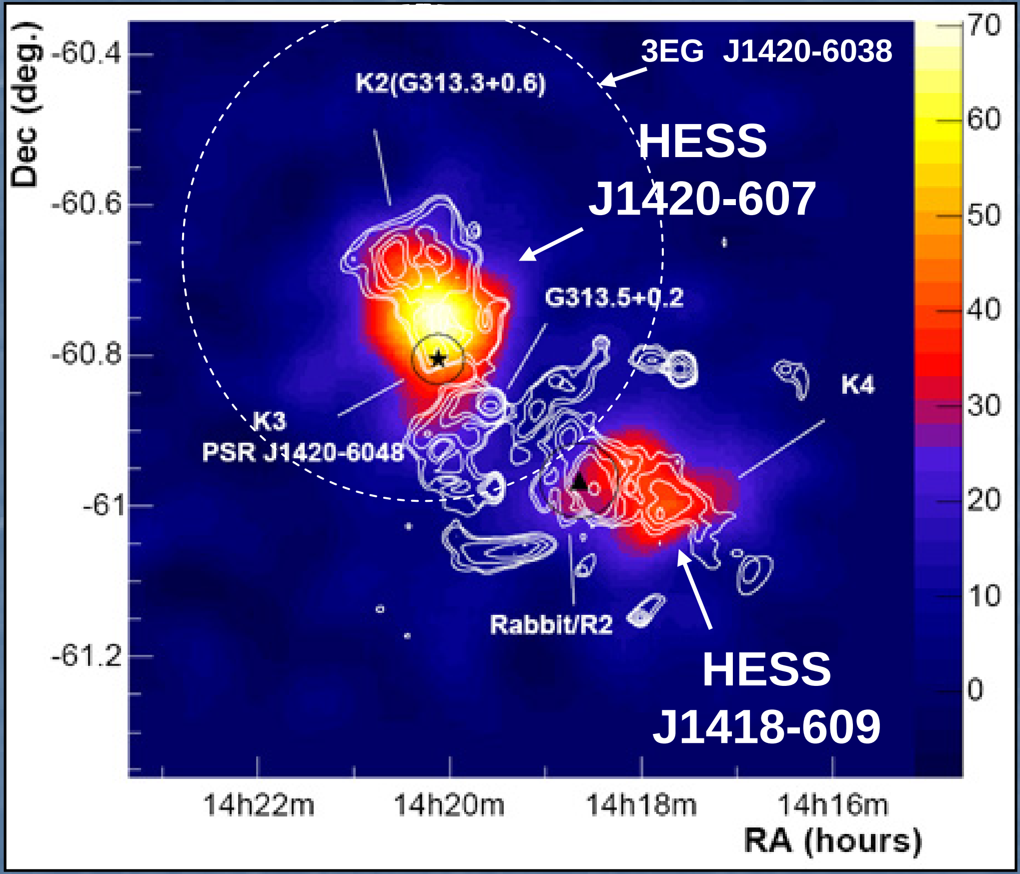
Outer gap models predict an Inverse Compton pulsed component at TeV energies.

For Vela, the H.E.S.S. results (Schmidt, 2005) just begin to constrain some models (e.g. Hirotani, 2003).

Is Vela a unique case?

How much can the outer gap model evolve to accommodate future observations?

NEUTRON STAR SCIENCE WITH TeV TELESCOPES – PULSAR WIND NEBULAE



H.E.S.S. results such as this one – the Kookaburra and the Rabbit PWN (Aharonian, 2006) – illustrate the power of TeV telescopes to see the Inverse Compton radiation produced by the pulsar wind.

Can unidentified TeV sources be used to recognize PWN and possibly pulsars?

AGILE (Astro-rivelatore Gamma a Immagini LEggero)

Italian collaboration

Currently in testing. Launch planned later this year.

Operational 2006-2008

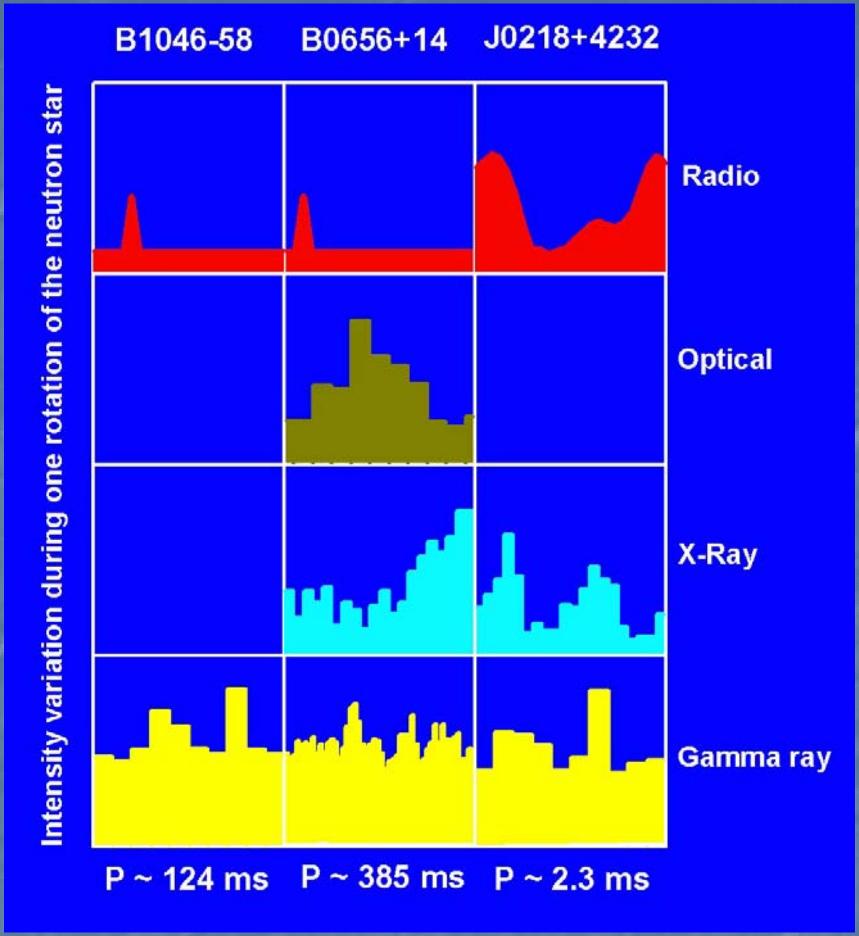
Left: AGILE instrument and spacecraft (Dec. 2005)

Pair production telescope (30 MeV – 30 GeV)

Pulsar timing and imaging

Somewhat more sensitive than EGRET

AGILE – Pulsar Science



Are these lower-confidence EGRET pulsar detections real?

How many of the new pulsars found in EGRET error boxes are gamma-ray pulsars?

Examples:

PSR J1016-5857

PSR J1015-5719

PSR J1420-6048

PSR J1637-4642

PSR J1837-0559

PSR J2229+6114

All have energy budgets consistent with EGRET sources. No timing information for EGRET era.

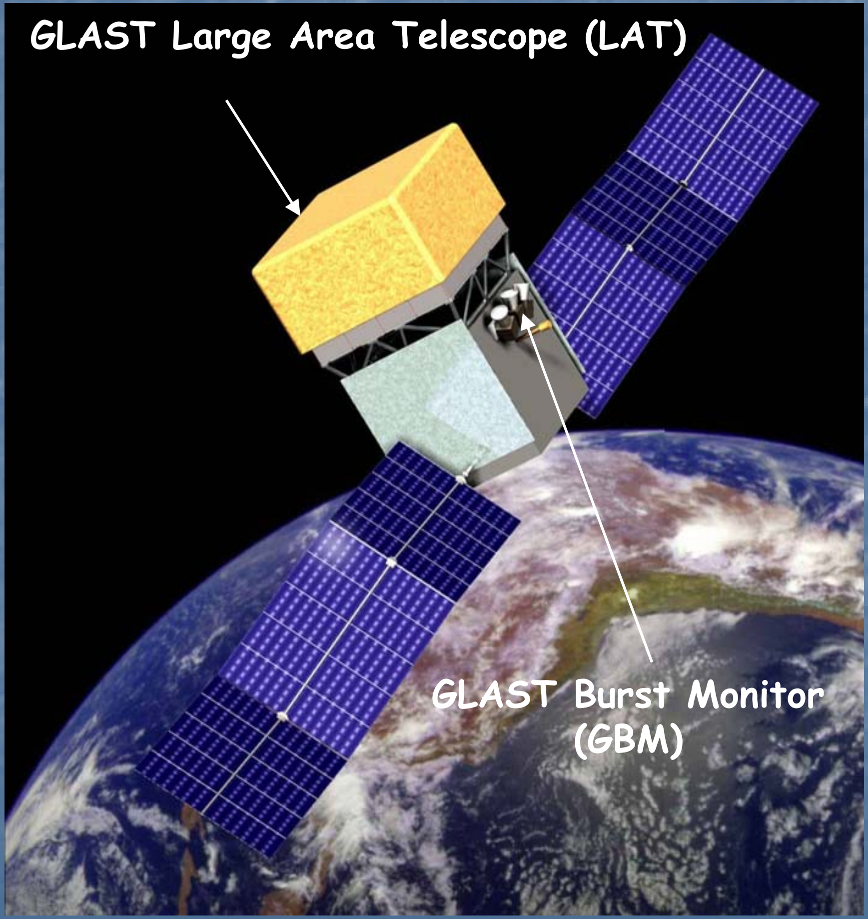
THE GAMMA RAY LARGE AREA SPACE TELESCOPE (GLAST):

GLAST will be a major observatory in the GeV energy band where some pulsars are prominent.

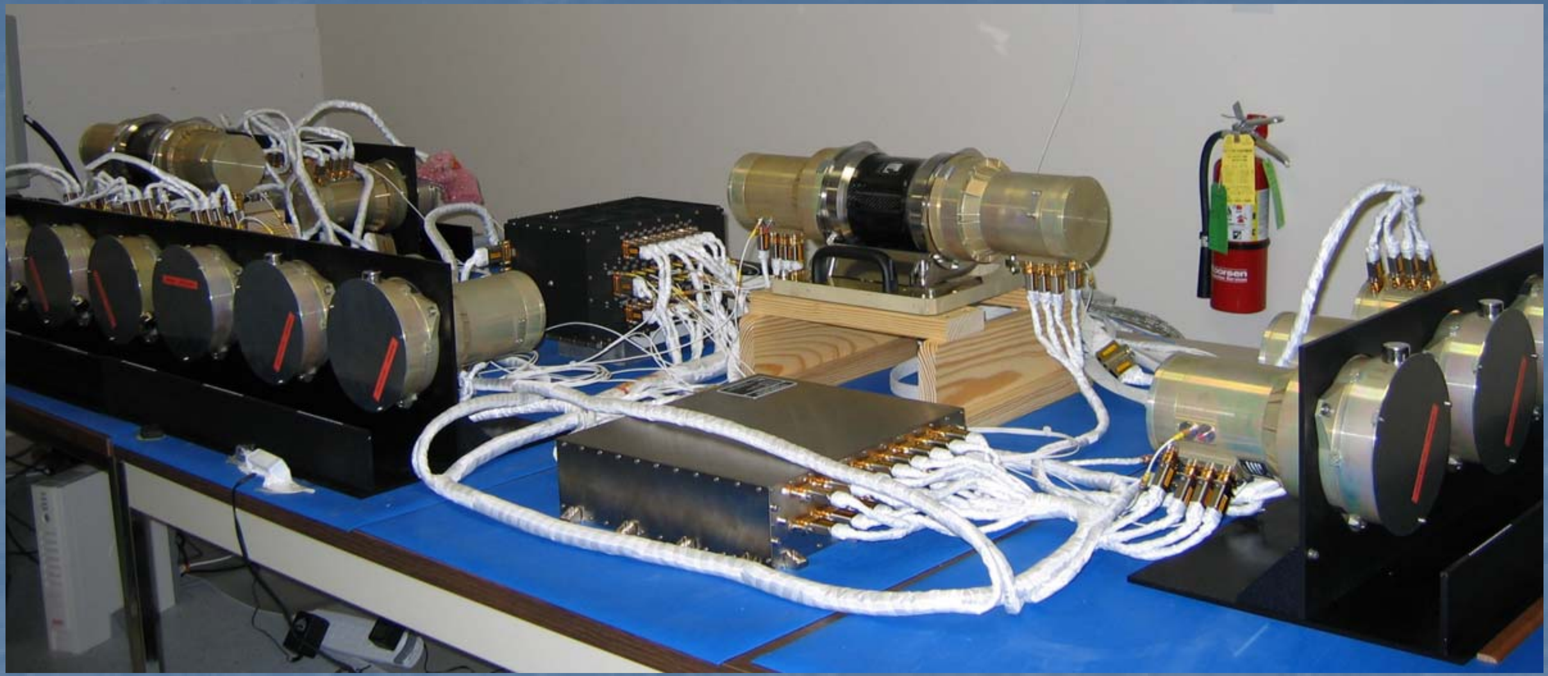
GLAST – Basic Information

GLAST: Gamma-ray Large Area Space Telescope is the observatory, not the instruments.

- **Two GLAST instruments:**
- **LAT: 20 MeV – >300 GeV (LAT was originally called GLAST by itself)**
- **GBM: 10 keV – 25 MeV**
- **Launch: Fall 2007**
- **Lifetime: 5 years minimum**

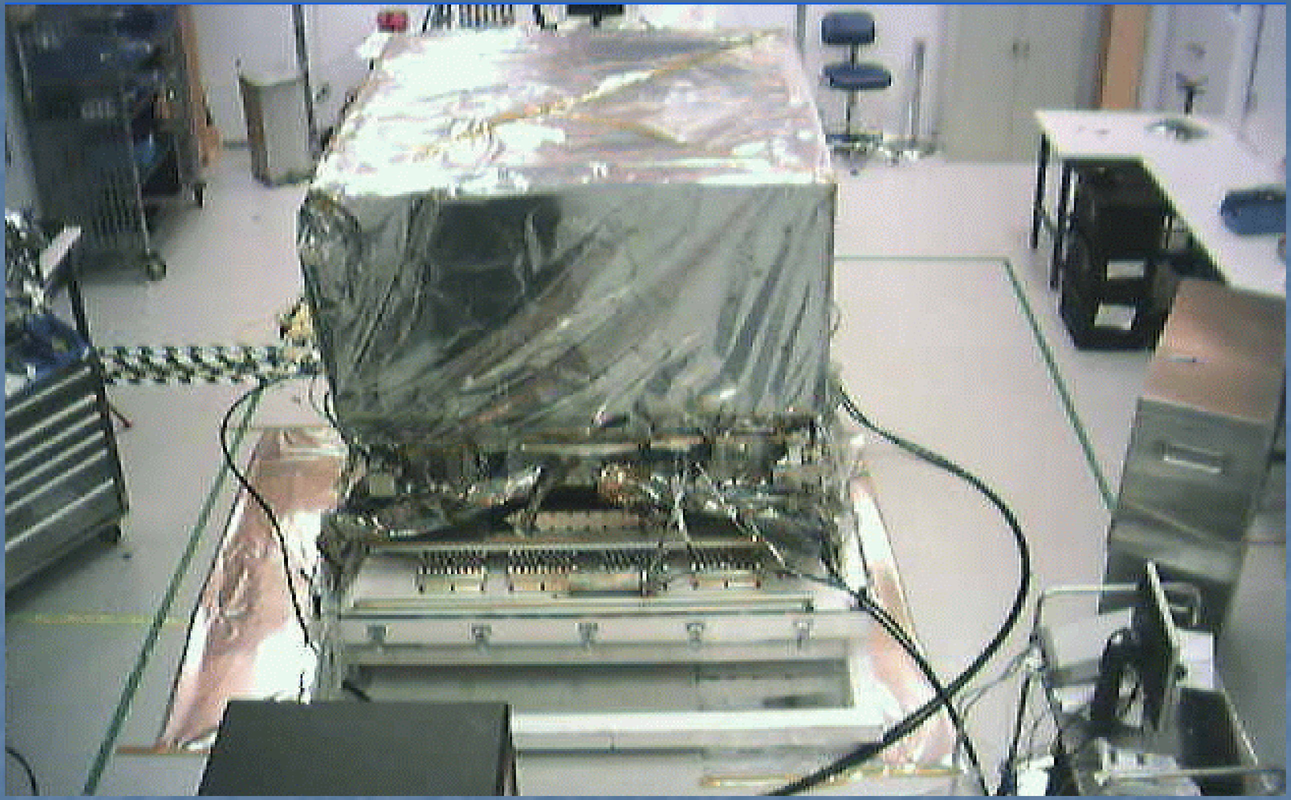


GLAST Burst Monitor (GBM)



- Successor to BATSE on the Compton Observatory.
- Flight hardware (shown above) has been delivered.
- No pulsar timing mode. GBM will detect magnetars as Soft Gamma Repeaters

GLAST Large Area Telescope (LAT)



- Successor to EGRET on the Compton Observatory.
- Significantly larger than EGRET and uses improved technology.
- Currently setting up for environmental testing.

GLAST LAT High Energy Capabilities

- **Huge FOV (~20% of sky)**
- **Scanning mode views much of the sky every day**
- **Broadband (4 decades in energy, including unexplored region > 10 GeV)**
- **Improved PSF for gamma rays (factor > 3 better than EGRET for E > 1 GeV)**
- **Large effective area (factor > 4 better than EGRET)**
- **Results in factor > 30-100 improvement in sensitivity**
- **No expendables - long mission without degradation**

LAT Science - Pulsars

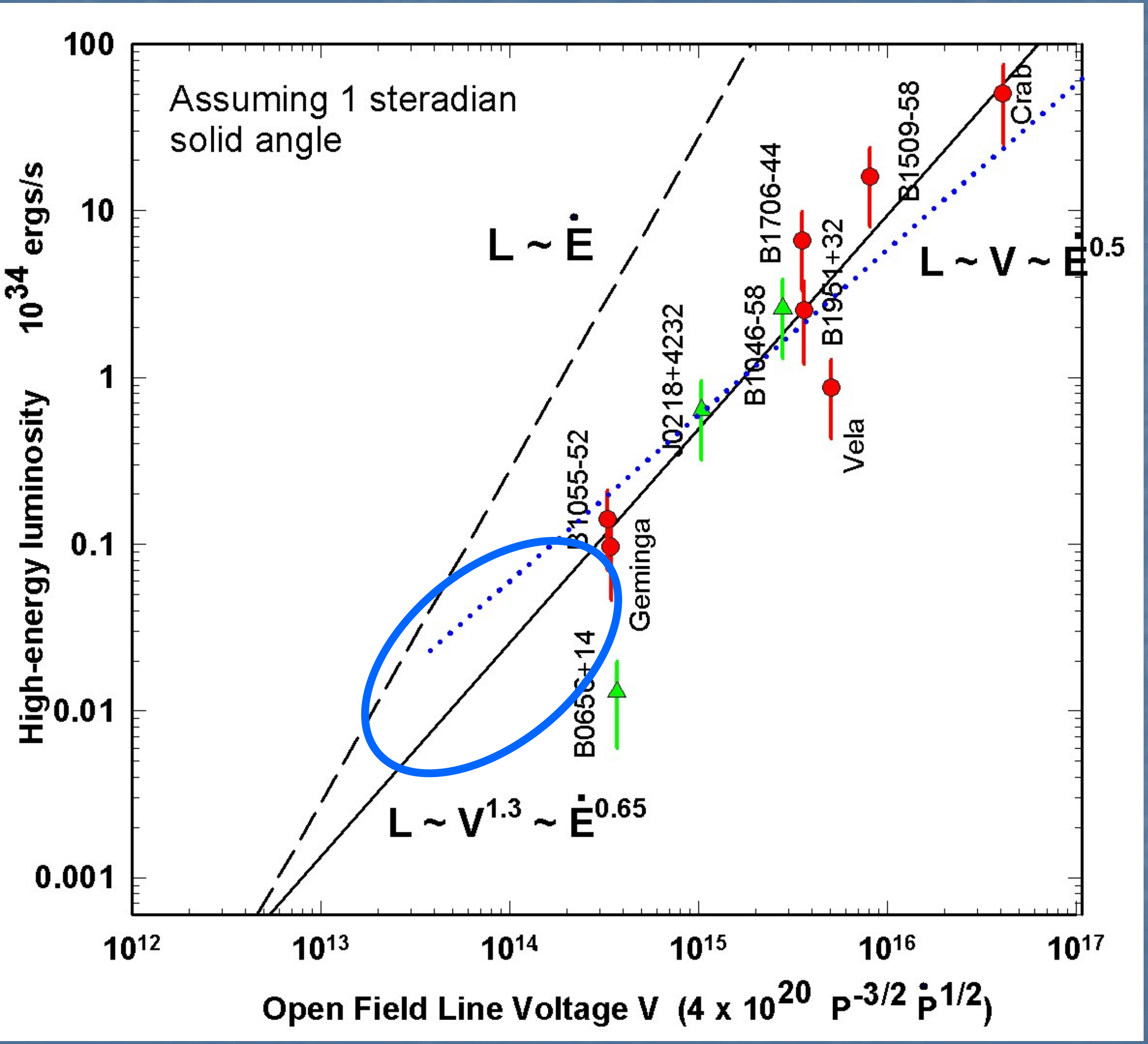
- To first order, detecting pulsed gamma radiation is limited by photon statistics.
- In two years with its scanning mode, LAT will detect 25-30 times as many photons for pulsars as EGRET did in its lifetime.
- This improvement results in detections intrinsically 25 times fainter or 5 times farther away.
- Several of the known gamma-ray pulsars are at distances of 2 kpc; therefore LAT will be able to detect some pulsars at the distance of the Galactic Center or farther.

LAT Pulsar Science: Luminosity vs. Voltage

The blue oval shows the new range that LAT will observe.

LAT will push much closer to where the gamma-ray luminosity equals the spin-down luminosity.

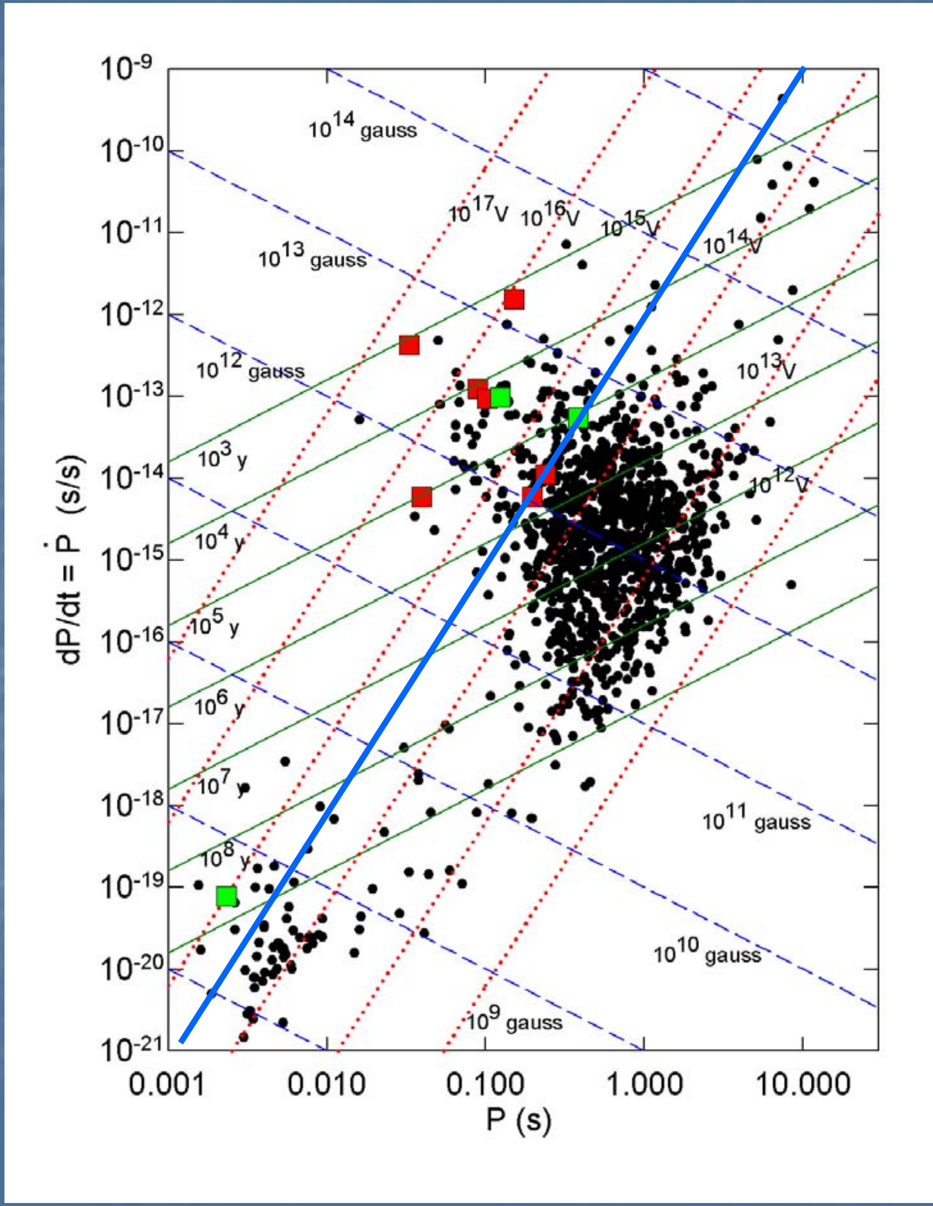
LAT observations should be able to distinguish between the empirical fit and the relationship from simple theory (shown by the dotted blue line).



LAT Pulsar Science: Pulsar Population

In the P – P-dot diagram, the heavy blue line shows the present limit for gamma-ray pulsar detections, about 4 x 10^{14} V open field line.

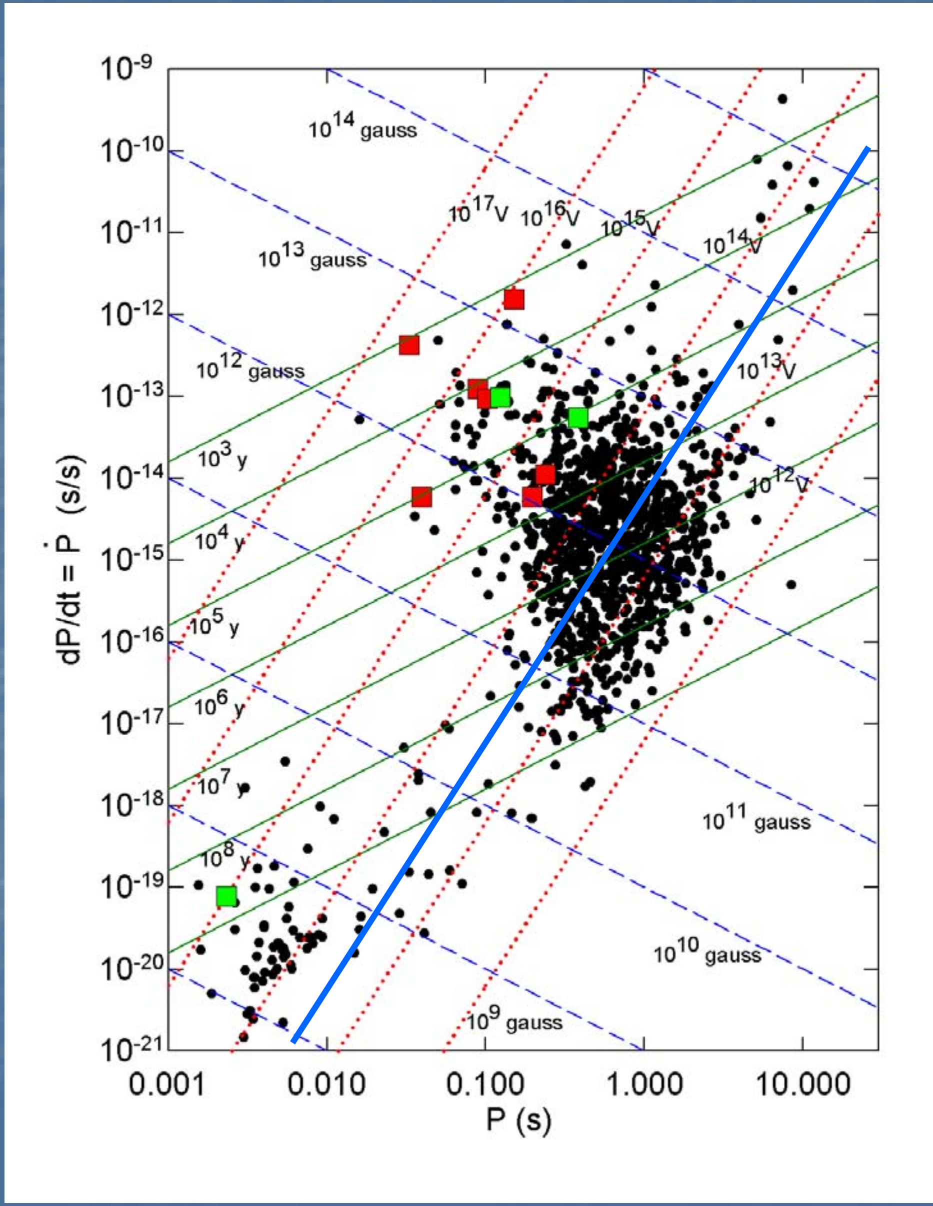
Note that not all pulsars to the left of the line are gamma-ray pulsars. The line shows a limit for accessibility, not necessarily detections.



LAT Pulsar Science: Pulsar Population

With LAT sensitivity, the line moves well into the bulk of the pulsar population.

In particular, the ms pulsars now lie almost entirely to the left of the line, in the potentially observable region, if this observational trend is valid.



LAT Pulsar Science: Highest Energies

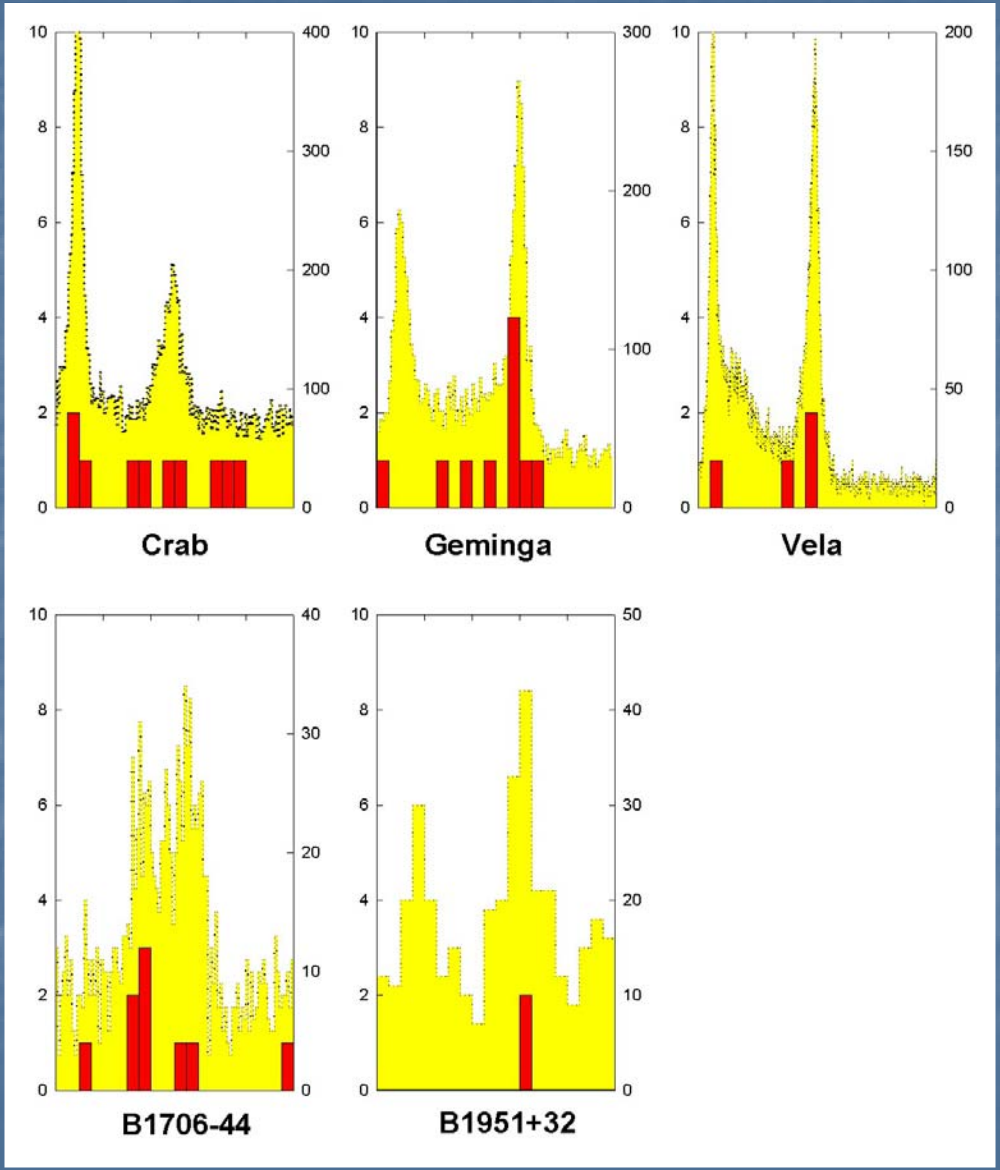
At energies above 10 GeV, LAT is at least 100 times more sensitive than EGRET.

Instead of the handful of photons seen by EGRET (red bars at right), LAT will see hundreds of photons at these energies.

Does one of the two pulses fade away with increasing energy?

What is the shape of the high-energy cutoff?

These questions may be important tests of models.

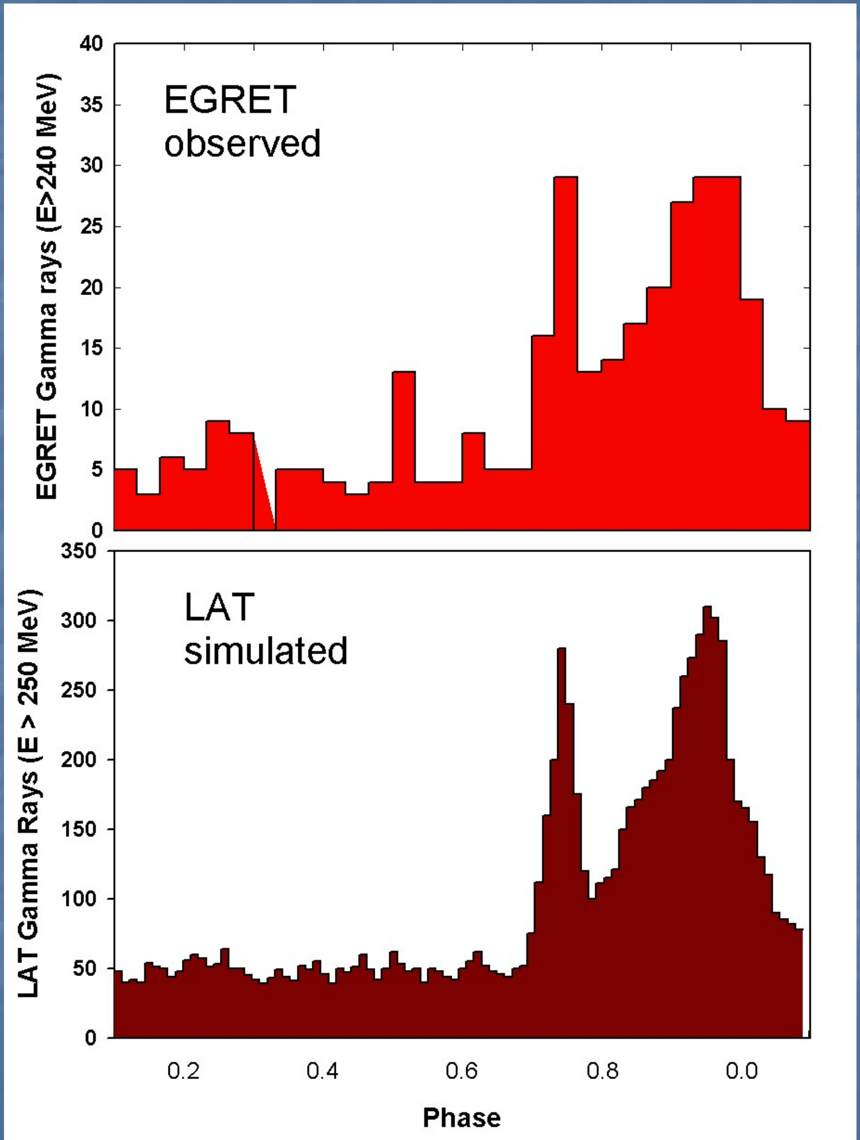


LAT Pulsar Science: Testing Models

Light Curves - Example

PSR B1055-52 light curve with EGRET provided insufficient information to compare to models.

With LAT, the statistics will allow some real tests.



LAT Pulsar Science: Testing Models

Light Curves - Example

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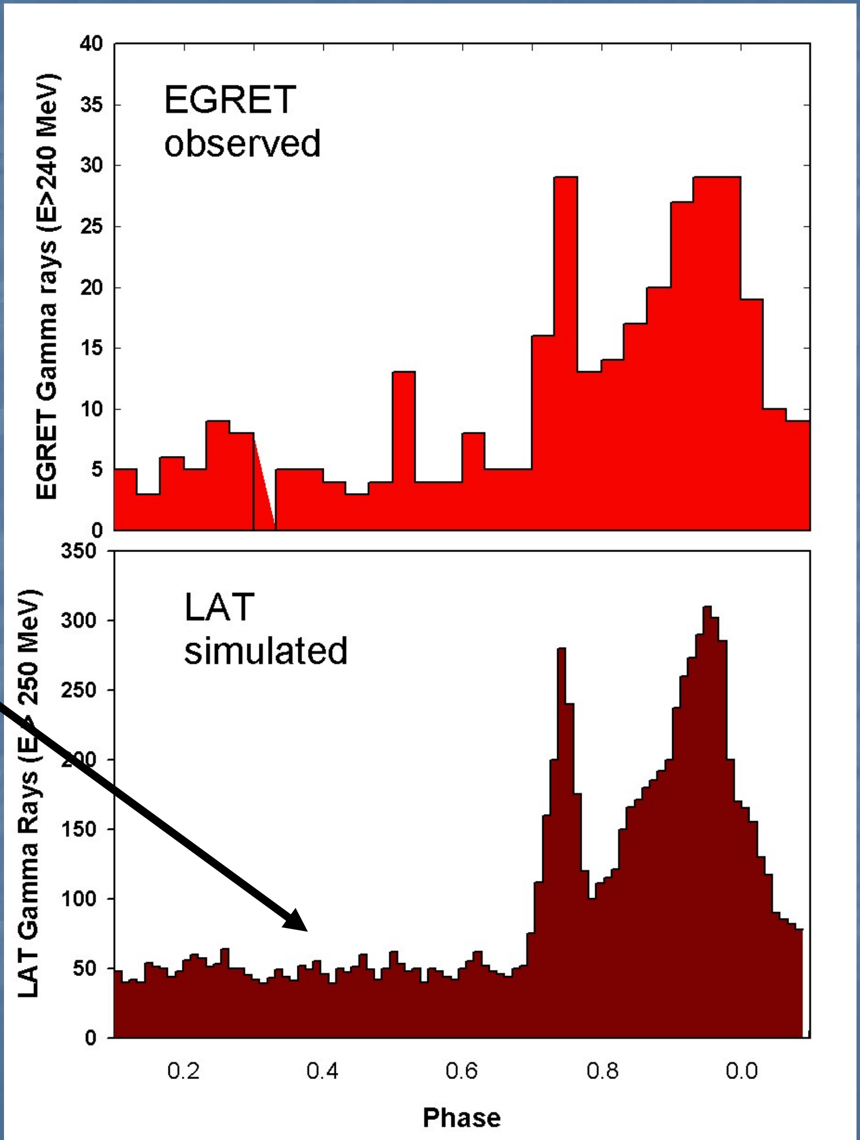
Is the emission away from the pulses associated with the source (as predicted by the slot gap) or not (predicted by outer gap)?



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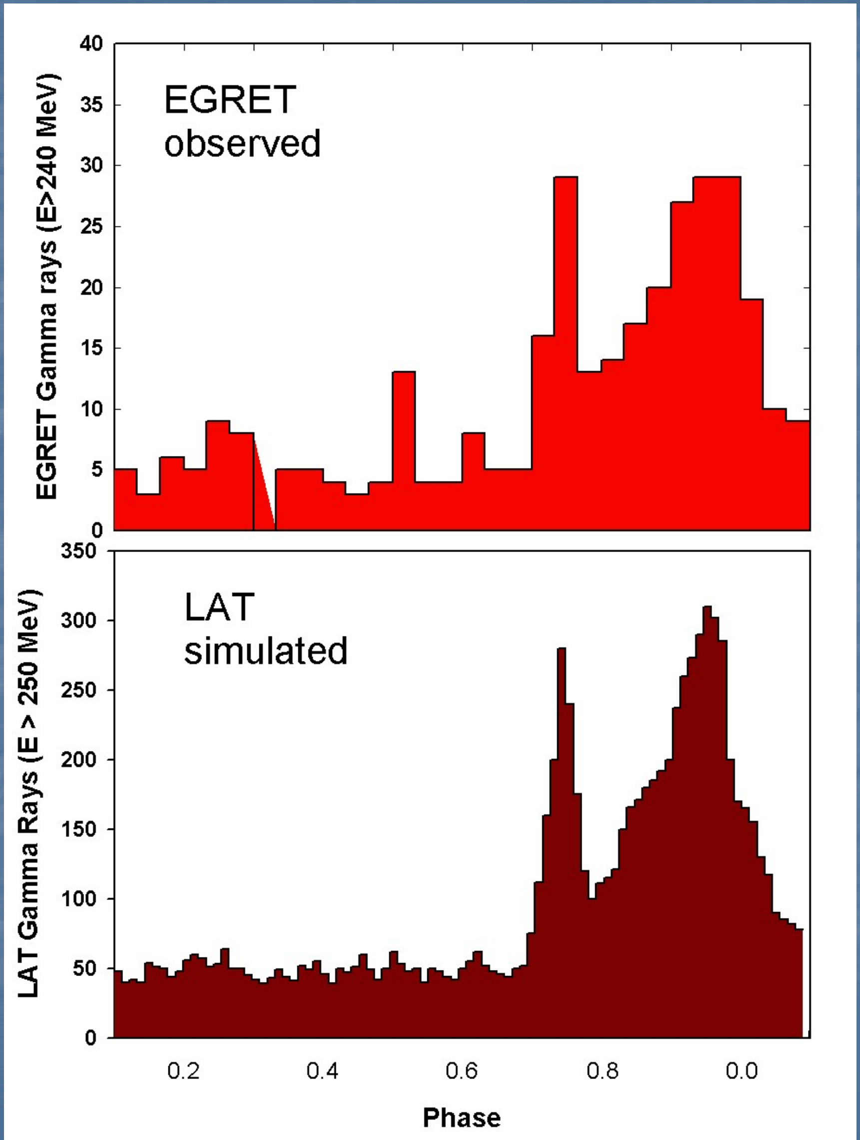
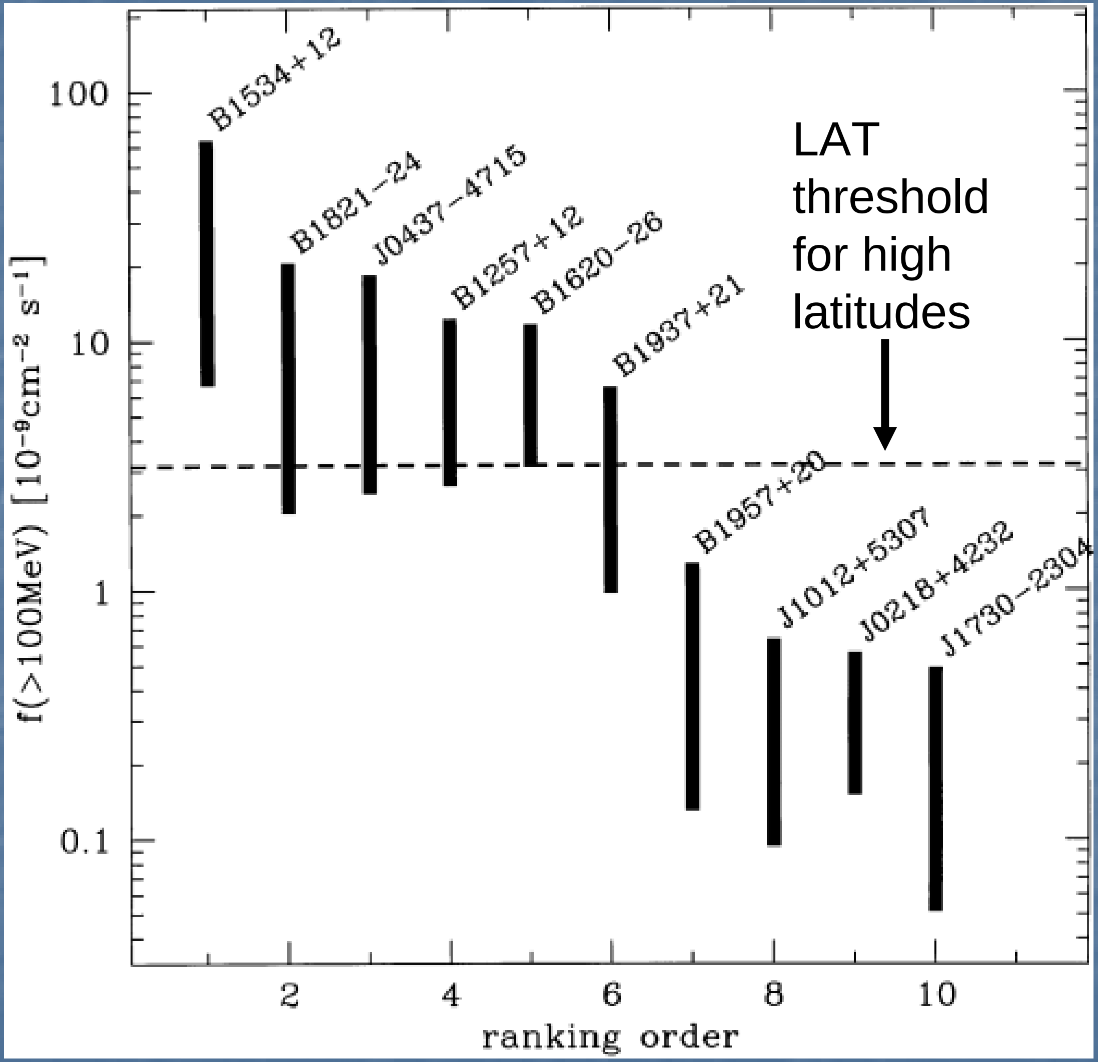
How are the pulse shapes, separation, and relationship to pulses seen at other wavelengths explained in different models?

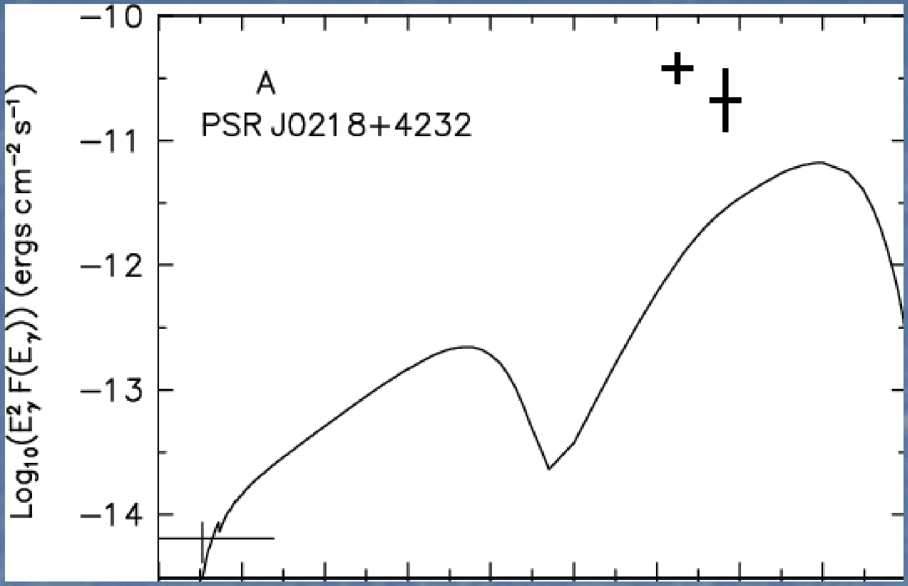


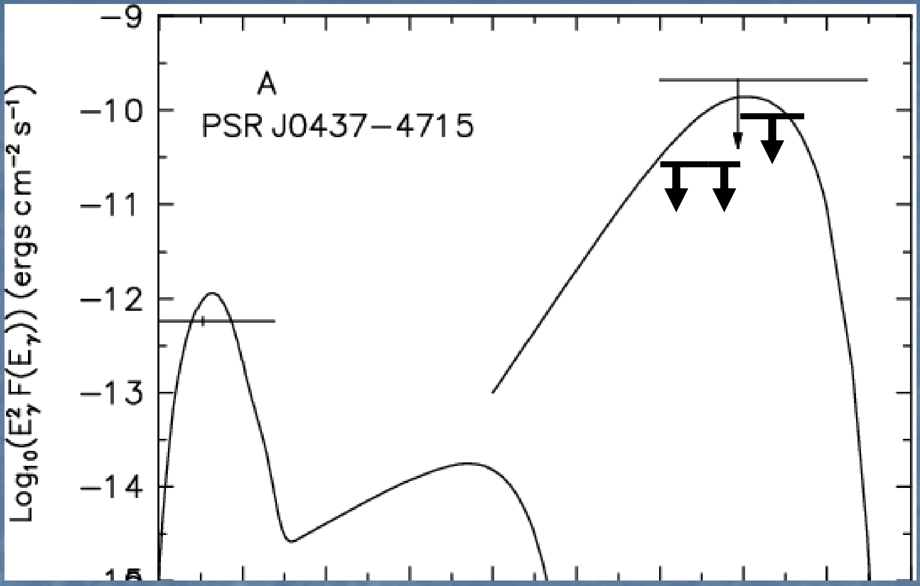
LAT Pulsar Science: MS Pulsar Theory 1

- Bulik, T., Rudak, B. & Dyks, J. (2000) extended a polar cap model for traditional pulsars to the ms regime. The dominant gamma-ray production arises from curvature radiation.
- Their predictions, shown here, are consistent with the EGRET observations only if it is assumed that J0218 was not detected.
- LAT should detect some ms pulsars in this model (but not J0218).



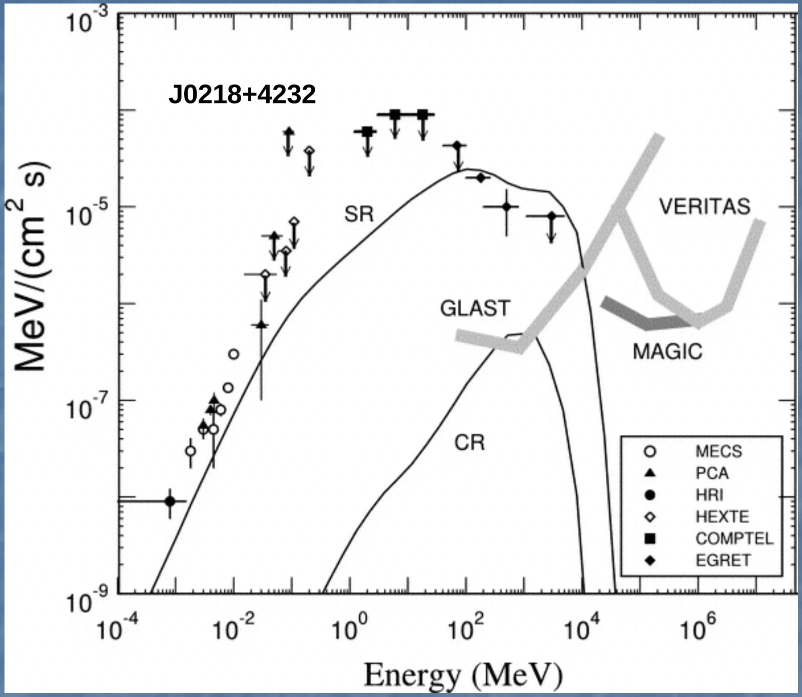
LAT Pulsar Science: MS Pulsar Theory 2

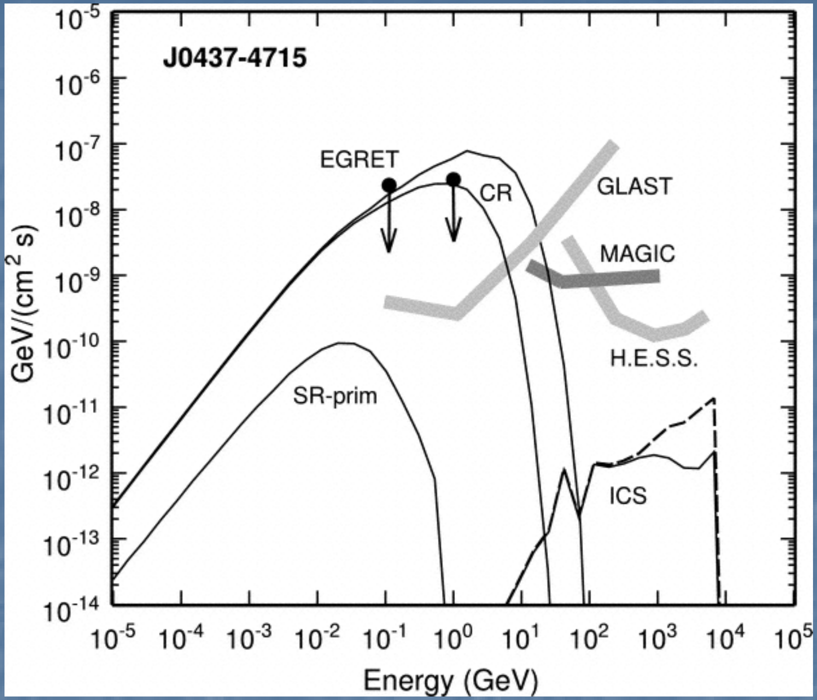




- Zhang and Cheng (2003) adapted their outer gap pulsar model to ms pulsars. The figures shown here show that this model predicts J0437 should be brighter in gamma rays than J0218 – possible if the EGRET indication of J0218 is spurious. The gamma rays in this model originate from synchro-curvature radiation.
- In this model, both pulsars should be visible to LAT, along with PSR B1821-24 and PSR J2124-3358 and possibly others.

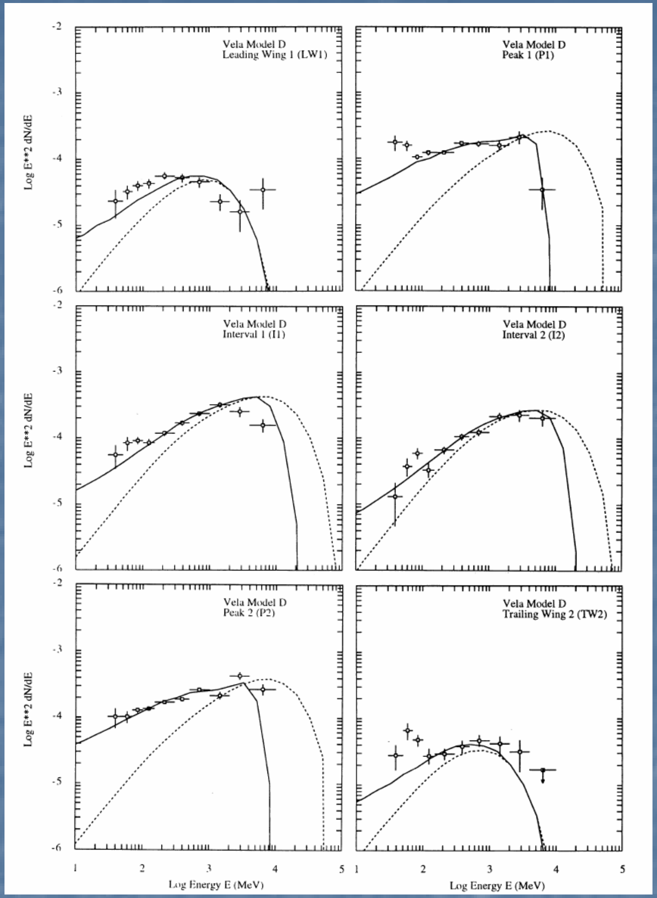
LAT Pulsar Science: MS Pulsar Theory 3



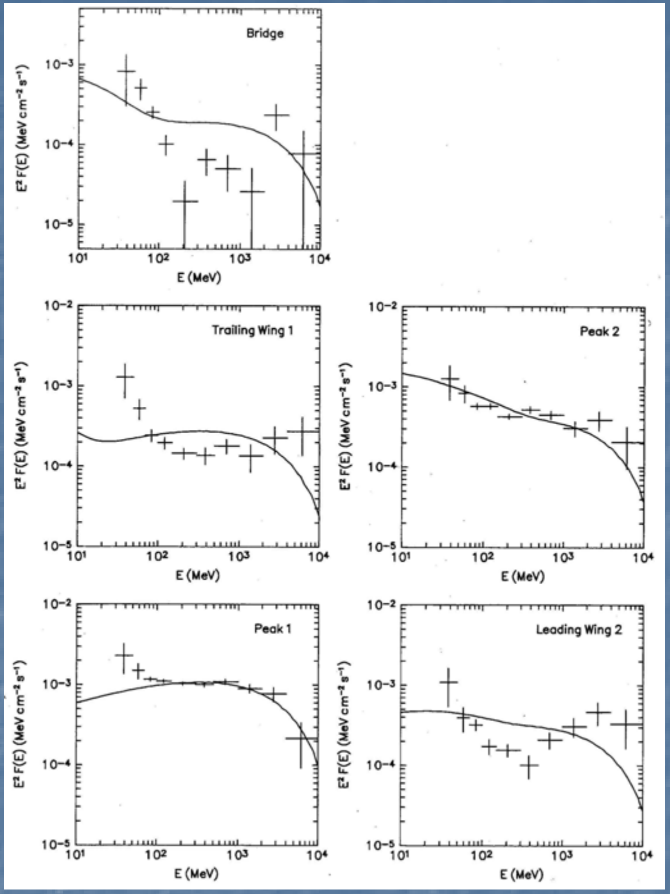


- Using a polar cap model, Harding, Usov, and Muslimov (2005) found an approach that can explain the observations. It uses cyclotron resonant absorption of radio emission to produce strong synchrotron gamma-ray emission from J0218. Other ms pulsars like J0437 are predicted to have curvature radiation just below the EGRET limits, but easily visible to LAT.
- Possible problem: this model seems to predict that EGRET should have seen some other ms pulsars and 47 Tuc.

LAT Pulsar Science: Phase-Resolved Spectra



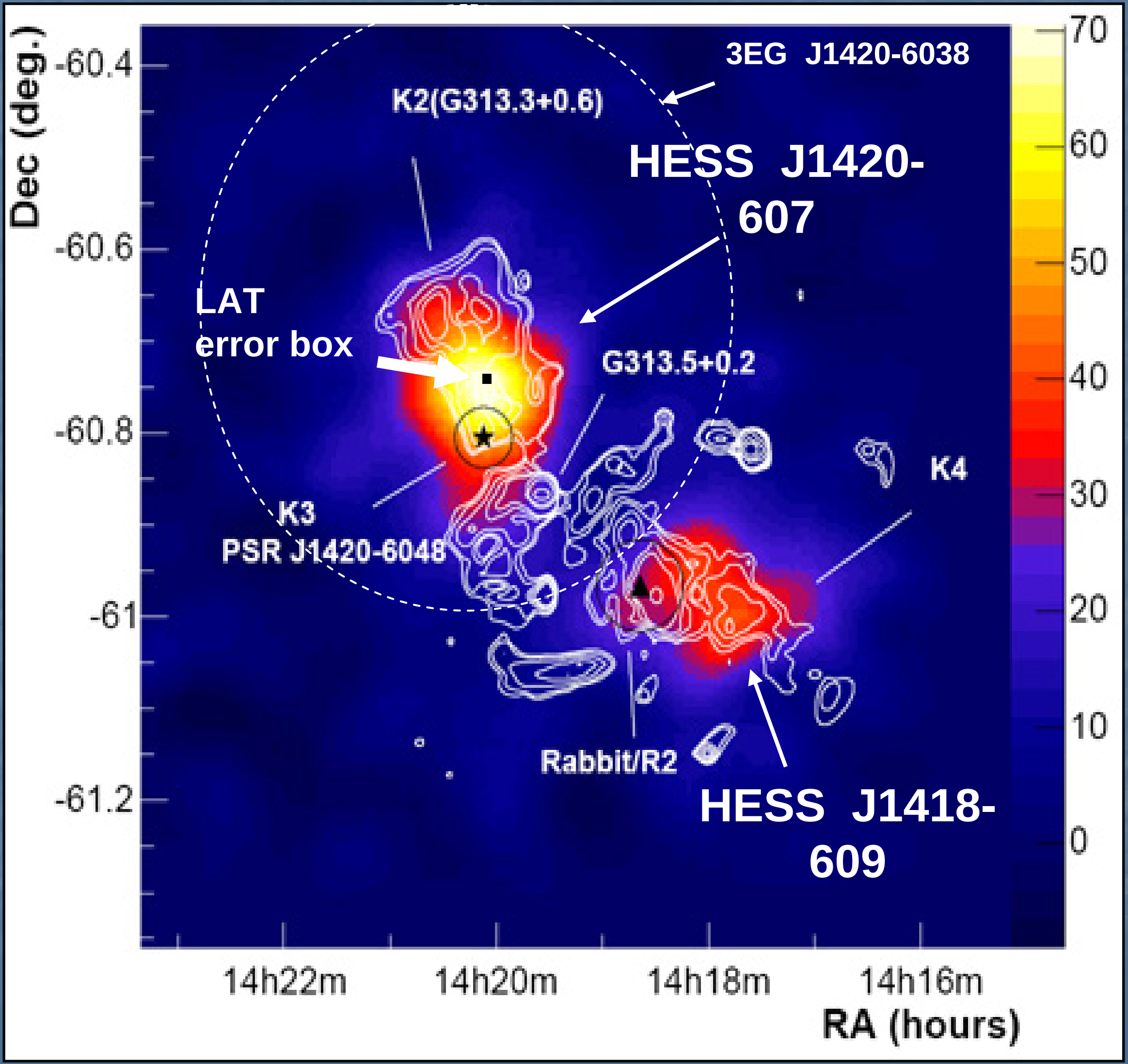
Left: Polar Cap model for Vela (Daugherty & Harding, 1996)
Right: Outer Gap model for Crab (Cheng, 2004)



Models have calculated phase-resolved spectra for some gamma-ray pulsars. Comparison with the data is largely limited by the data uncertainties.

LAT will provide high-quality phase-resolved spectra for the bright pulsars, with error bars smaller than these by about a factor of five.

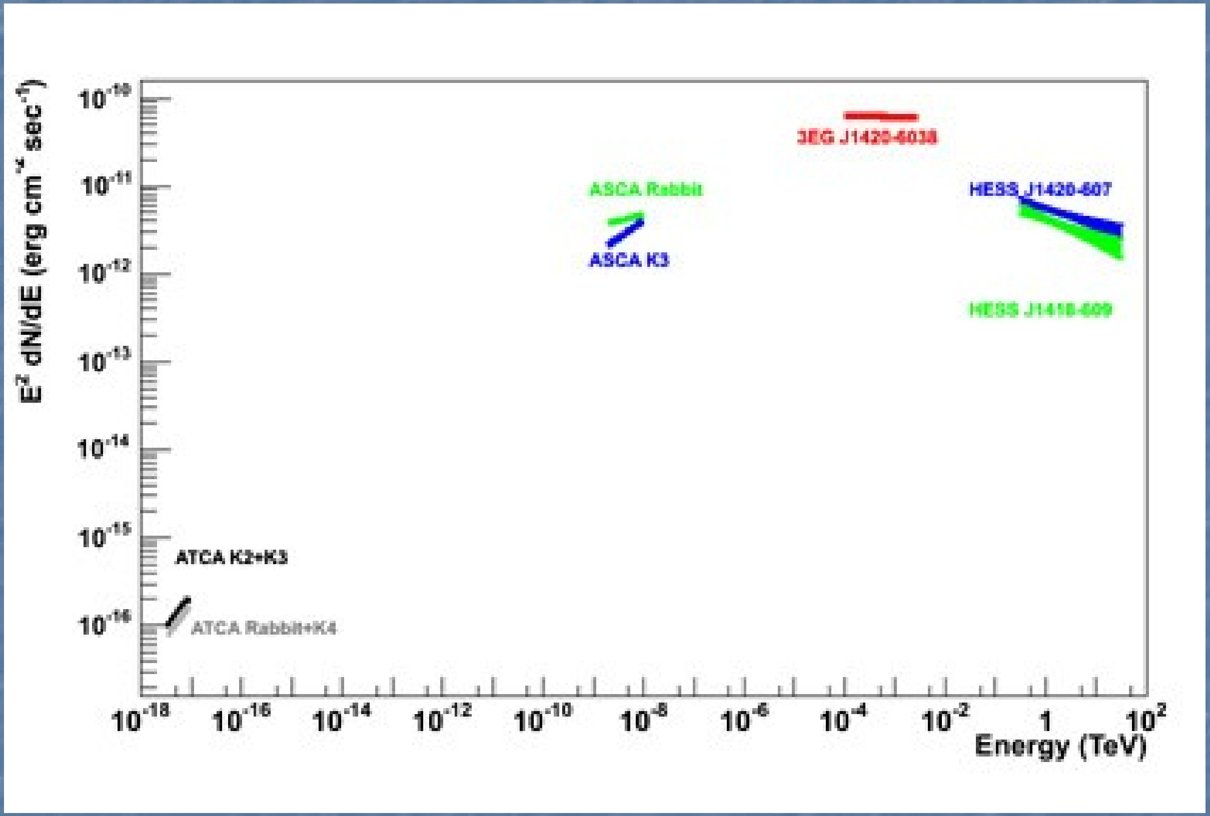
NEUTRON STAR SCIENCE WITH LAT – PULSAR WIND NEBULAE



LAT will localize the EGRET source to sub-arcmin accuracy, good enough to confirm the association with the PWN or the pulsar.

LAT will combine spatial, spectral, and timing information to help understand this complex region.

NEUTRON STAR SCIENCE WITH LAT – PULSAR WIND NEBULAE



Modeling the PWN emission to study the particle acceleration and interaction is a multiwavelength effort, as illustrated by this possible Spectral Energy Distribution summary from the H.E.S.S. Web site.

Summary

- Past results from the Compton Observatory on pulsars and emerging results from TeV telescopes like H.E.S.S. on pulsar wind nebulae provide a strong incentive to pursue gamma-ray observations of neutron stars and their environments.
- Expansions and improvements in the TeV telescope arrays will enhance their sensitivity and push energy thresholds down.
- AGILE will do some important follow-up studies for pulsars suggested but not confirmed by EGRET.
- GLAST has all-sky, high-sensitivity capabilities and plans for cooperative, multiwavelength observations of neutron stars and their surroundings. Join the fun!