

VERITAS Observations of the Crab Pulsar

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The Crab Pulsar

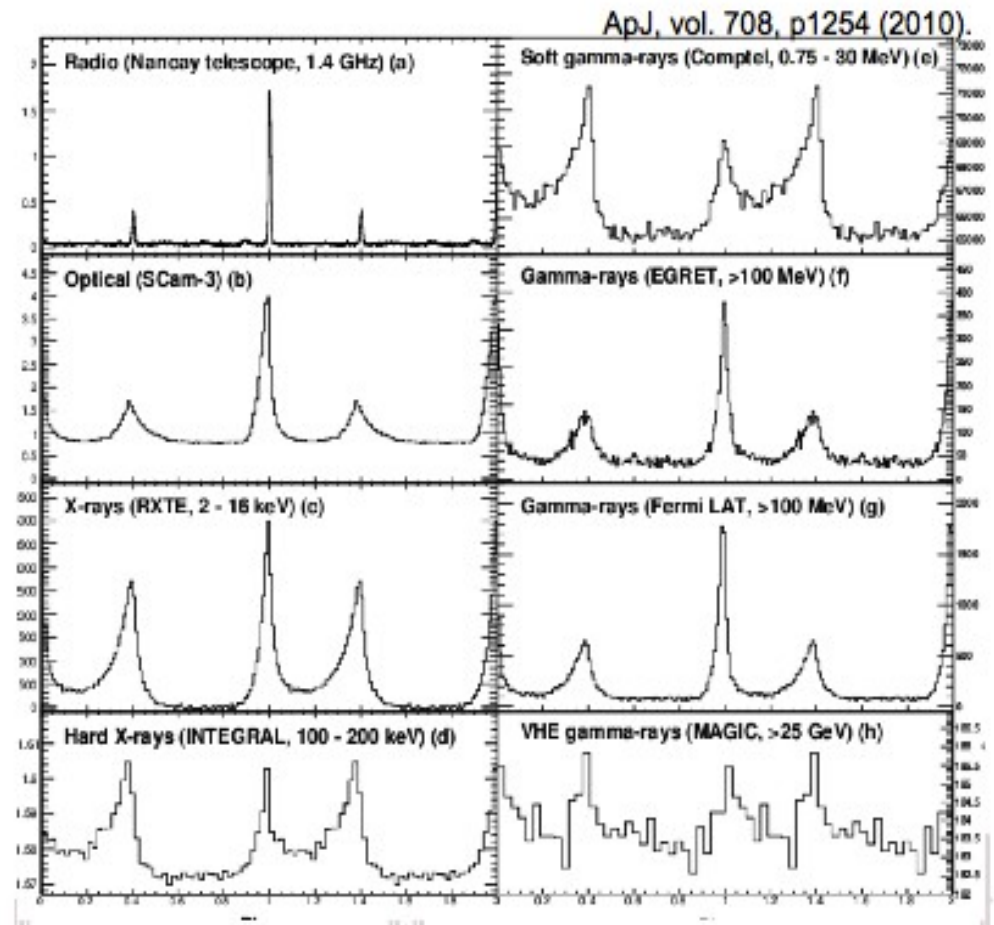
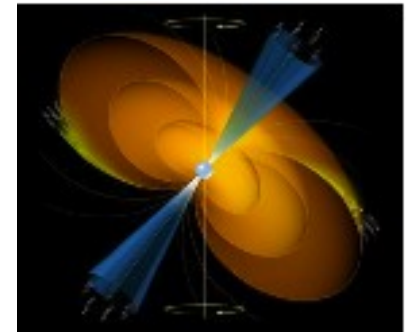
Remnant of supernova
observed in 1054 A.D.

Bright FERMI Source

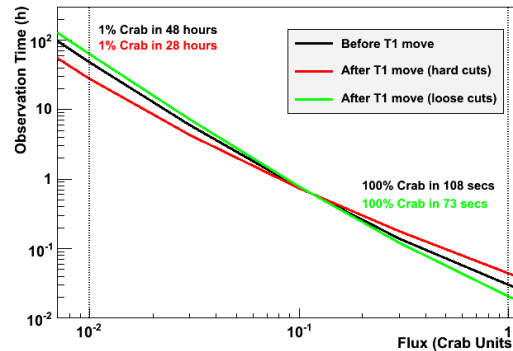
Pulsar statistics:

- Period: 33ms
- Spin down age: 1.2kyr
- Distance: 2kpc
- Spin down power:
 4.6×10^{38} ergs/s

Powers the VHE standard
candle, the Crab Nebula



VERITAS



Very Energetic Radiation Imaging Telescope Array
System

Employs ~100 scientists in five countries

Full Array Operations since fall 2007

Four 12m Davies-Cotton Telescopes in Southern AZ

Move of T1 in Summer 2009

Performance:

- Sensitivity: 1% Crab Nebula Flux in ~25hrs
- Energy Range: 0.1-30TeV ($\Delta E/E \sim 20\%$)
- PSF: 0.1deg (68% containment)
- FOV: 3.5 deg

See Highlight talk by N. Galante

The Crab Pulsar in Gamma-Rays

Fermi-LAT:

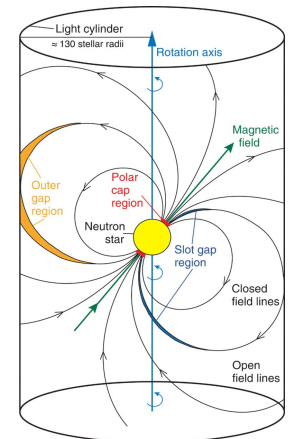
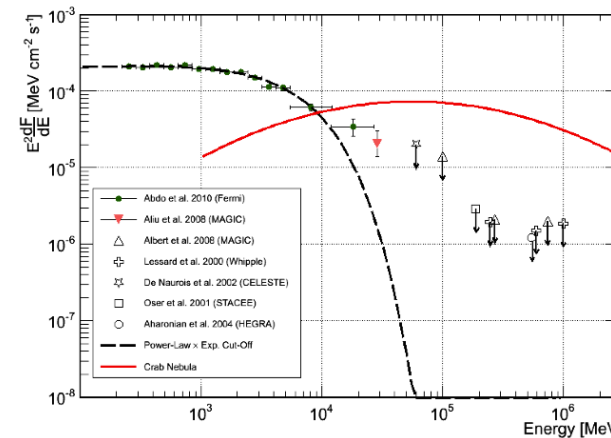
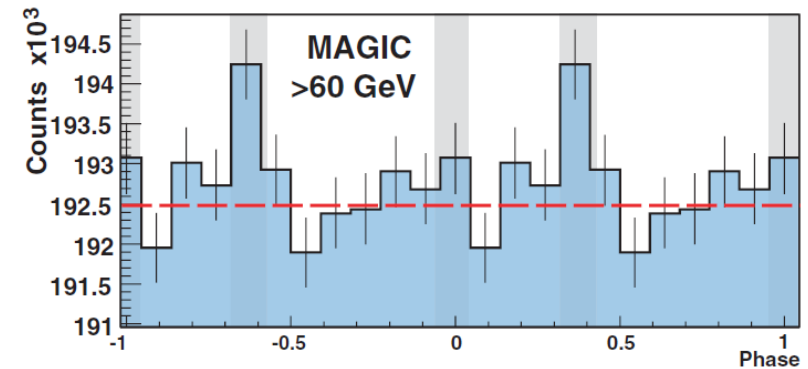
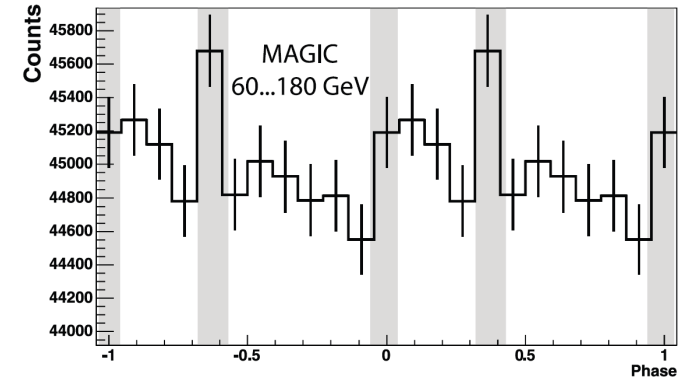
- Spectral break at ~ 5 GeV

MAGIC:

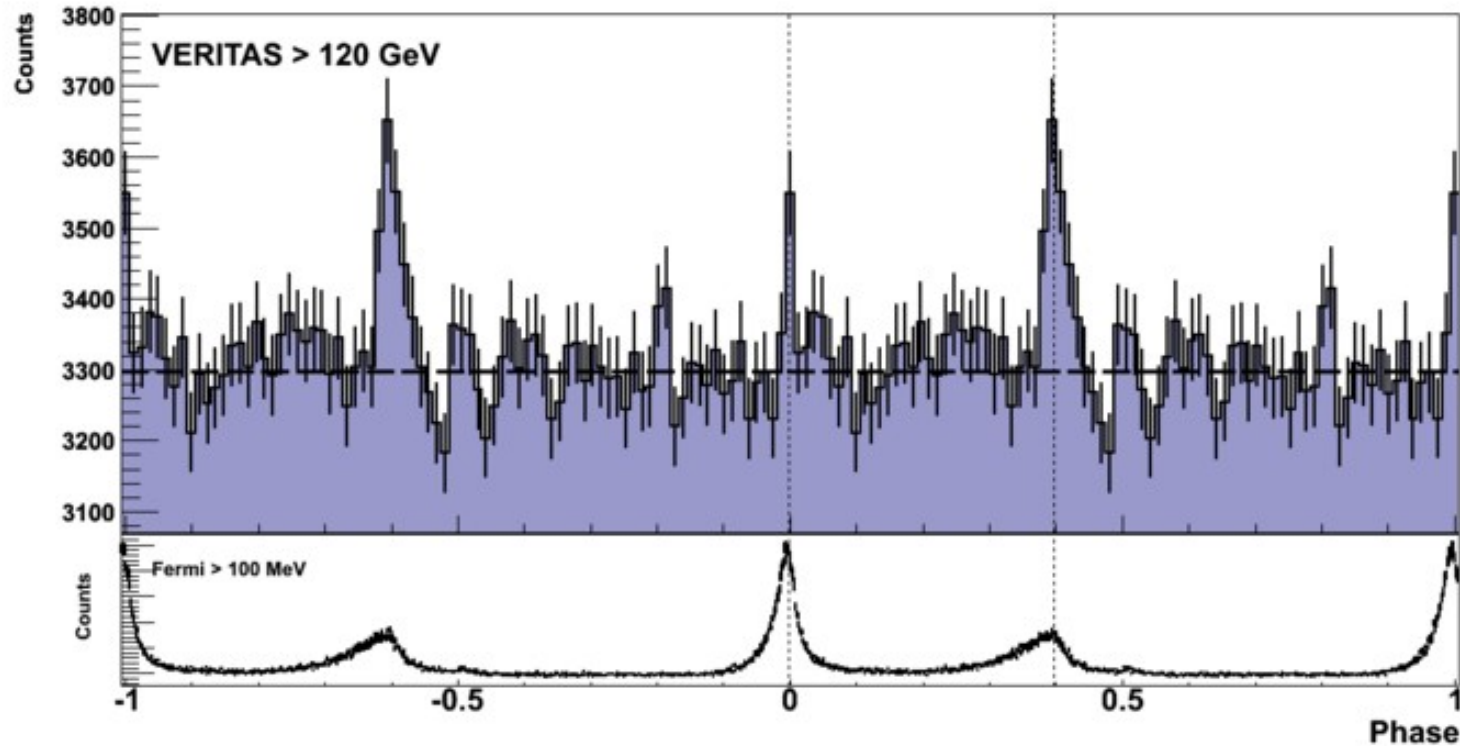
- Detection at 25 GeV (Aliu et al, 2008)
- Hints of pulsations above 60 GeV (Albert et al, 2008, Aliu et al, 2008)

Common Wisdom:

- Spectral Break is a exponential cutoff
- Curvature Radiation the is favored gamma emission process (outer gap model)
- Emission comes from ~ 6 stellar radii from Pulsar



Pulse Profile: 2007-2011



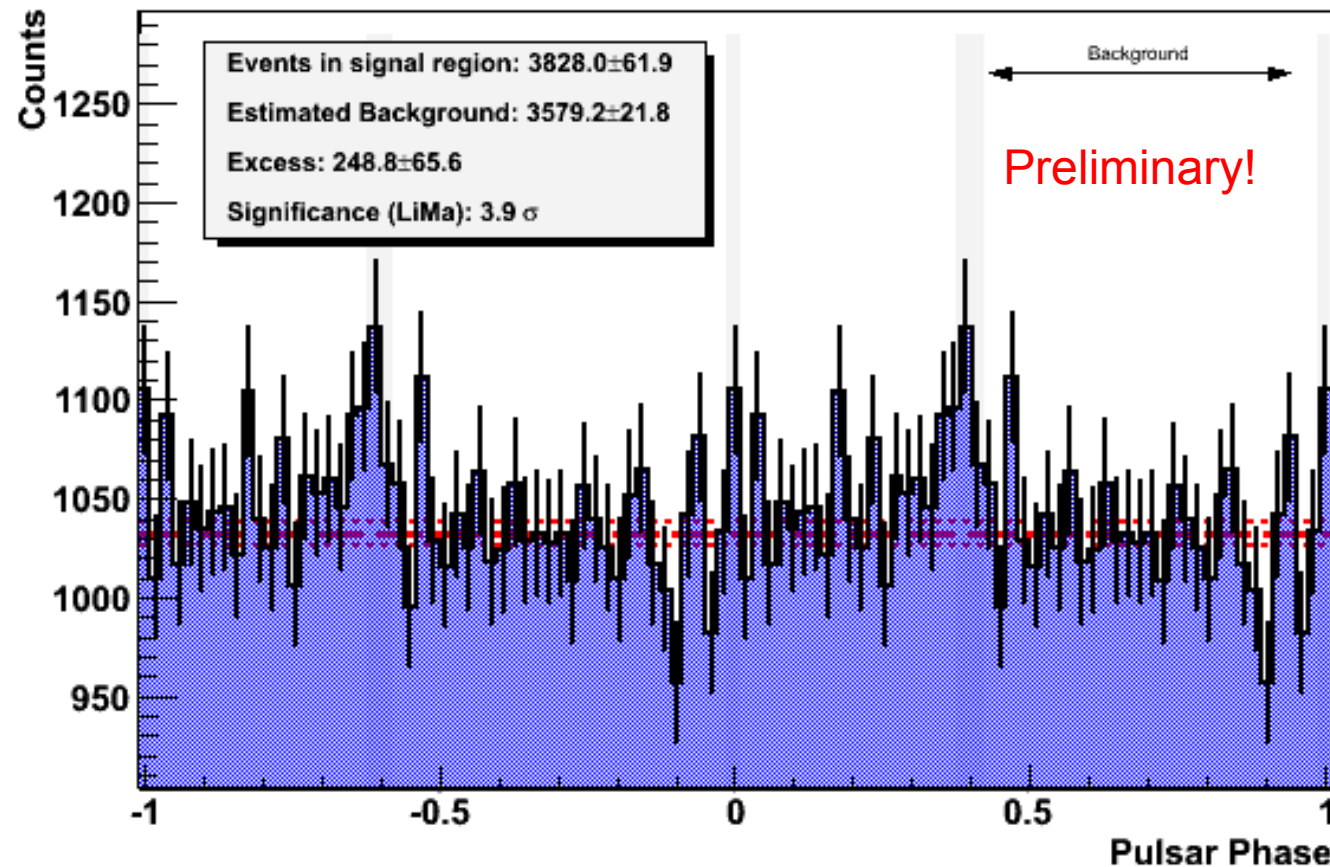
Data:

- VERITAS Collab., 2011
- 107 hours observation time
- 0.5deg Wobble observations
- Zenith < 25deg

Analysis:

- Two independent analysis packages
- Phase-folded from Jodrell Bank timing ephemeris
- H-test value of 50 \rightarrow 6σ
- Li & Ma Significance of 8.8σ

Pulse Profile: 2011-2012



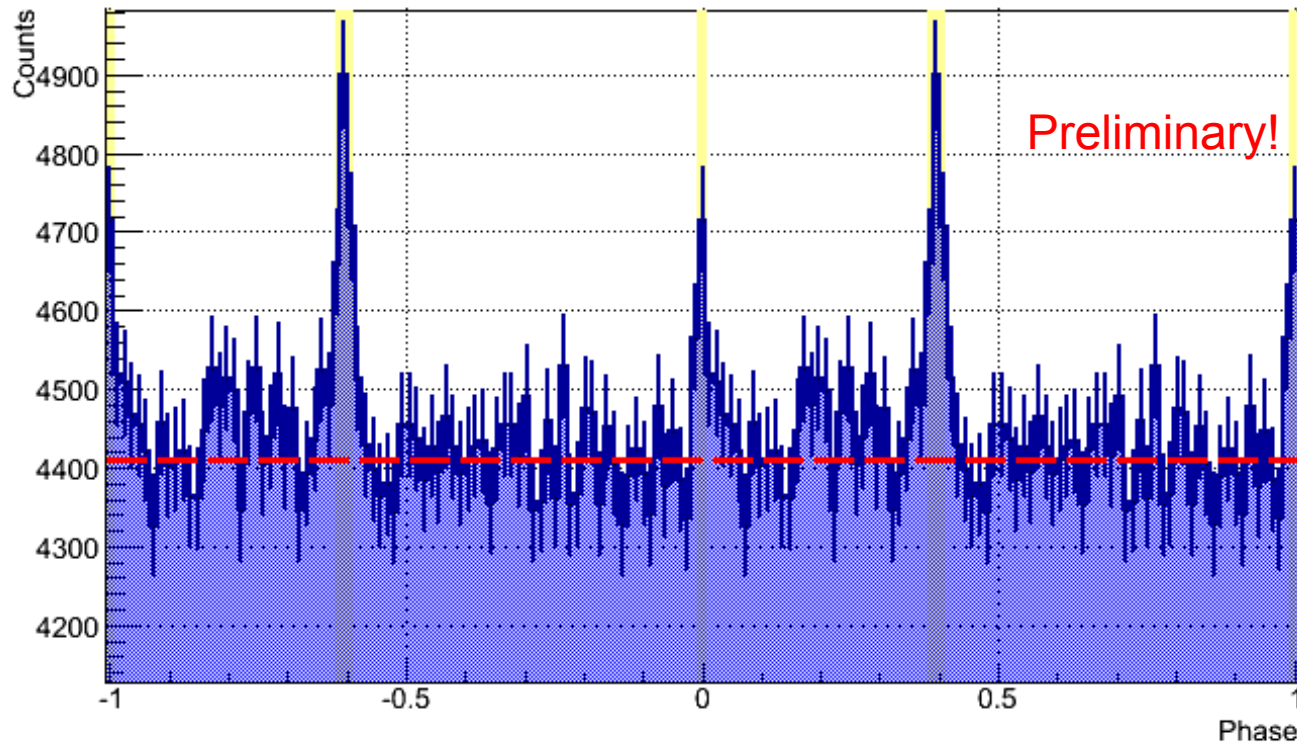
Preliminary results

~20hrs of low Zenith observations this season

3.9σ using Li & Ma significance

Pulse Profile: 2007-2012

Crab Pulsar with VERITAS 2007-2012



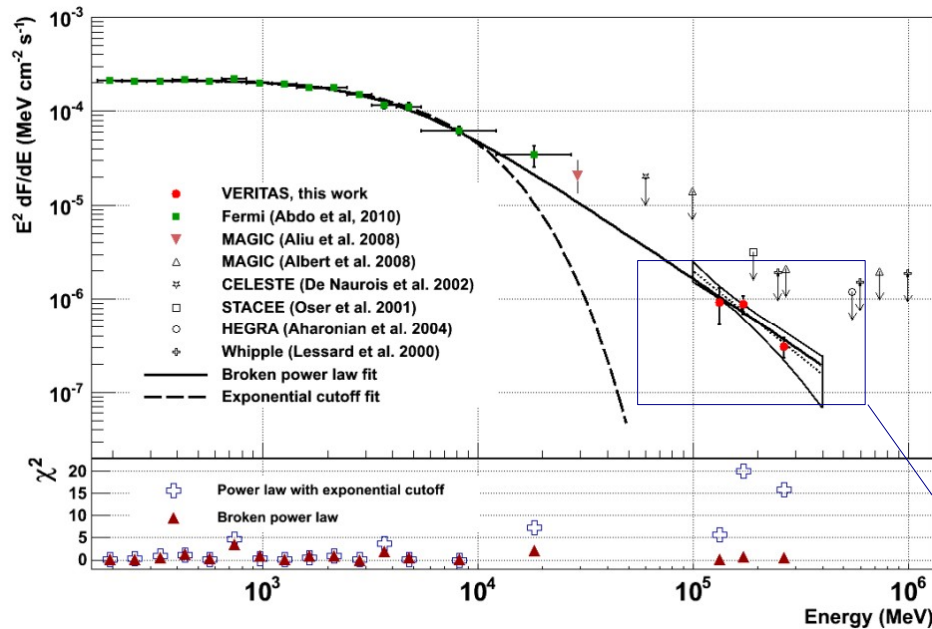
Preliminary results

~130hrs total observation time

10.7 σ using Li & Ma significance

1514 \pm 145 total pulsed excess events in P1 and P2

Spectrum



2007-2011 data

VERITAS fit combined excess of P1 + P2 to $dN/dE = N_0(E/150 \text{ GeV})^{-\Gamma}$

$$N_0 = (4.6 \pm 0.6_{\text{stat}} +2.4_{\text{sys}} -1.4_{\text{sys}}) \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\Gamma = 3.8 \pm 0.5_{\text{stat}} \pm 0.2_{\text{sys}}$$

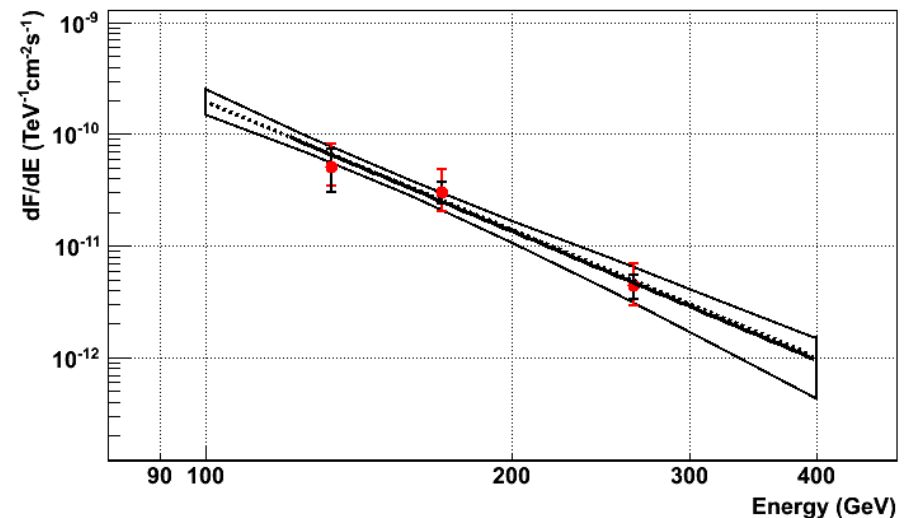
MAGIC data released in 2011 confirm VERITAS measurements (MAGIC Collab. & K. Hirotani (2011))

χ^2 fit of combined FERMI + VERITAS SED
excludes exponential cutoff: 67.8/16 dof $\rightarrow 5.6\sigma$

Good fit of combined SED with smooth broken
power law

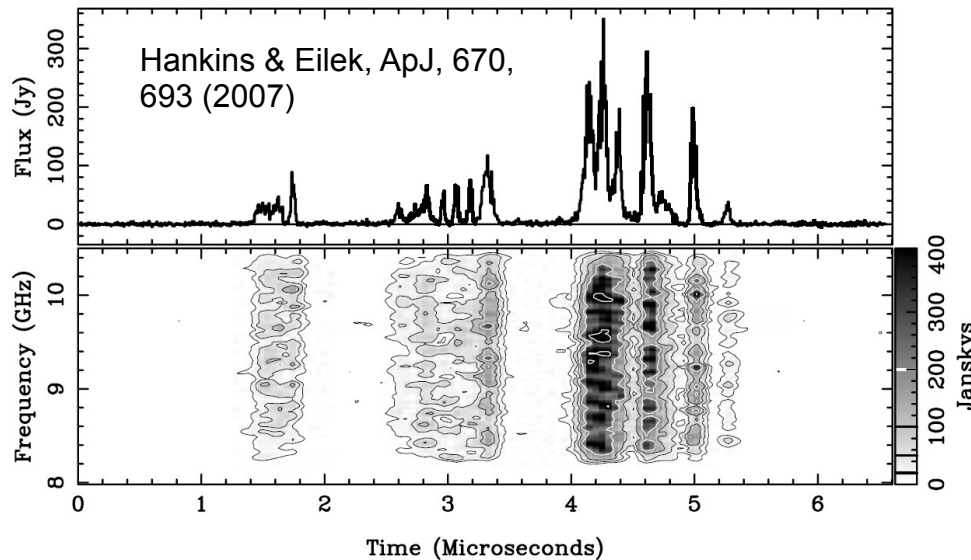
Possible Explanations of VHE emission:

- IC scattering of UV/X-ray photons by secondary leptons (Lyutikov, Otte & McCann (2011))
- Acceleration of Pulsar Wind outside of light cylinder surface IC scattering X-ray photons (Aharonian, Bogovalov & Khangulyan (2012))



Giant Radio Pulses (GRPs)

Main Pulse GRPs: Succession of narrow broadband pulses



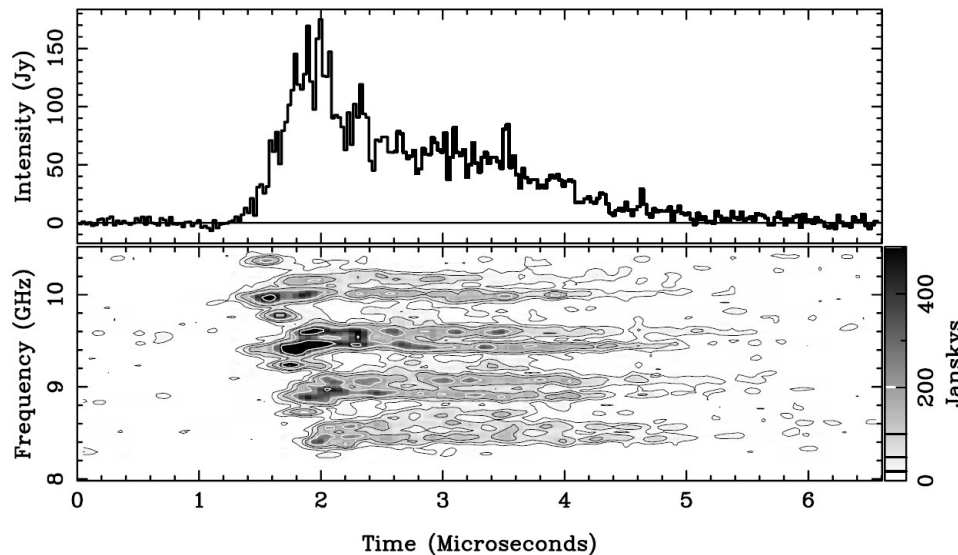
Giant pulses are distinguished by a number of characteristic features:

They possess a very high flux density relative to average radio pulses

Seen in only ~10 pulsars

The energy distribution of GPs follows a power-law

IP GRPs: Single wide pulse occupying frequency bands



GPs have a short pulse time-scale compared to the average pulse.

Model of Lyutikov (2007) predicted the behavior of the Inter pulse GRPs for the Crab with electrons with Lorentz factors of 10^8 in the outer magnetosphere

– Enhanced Gamma-Ray emission?

GRP Correlation Search

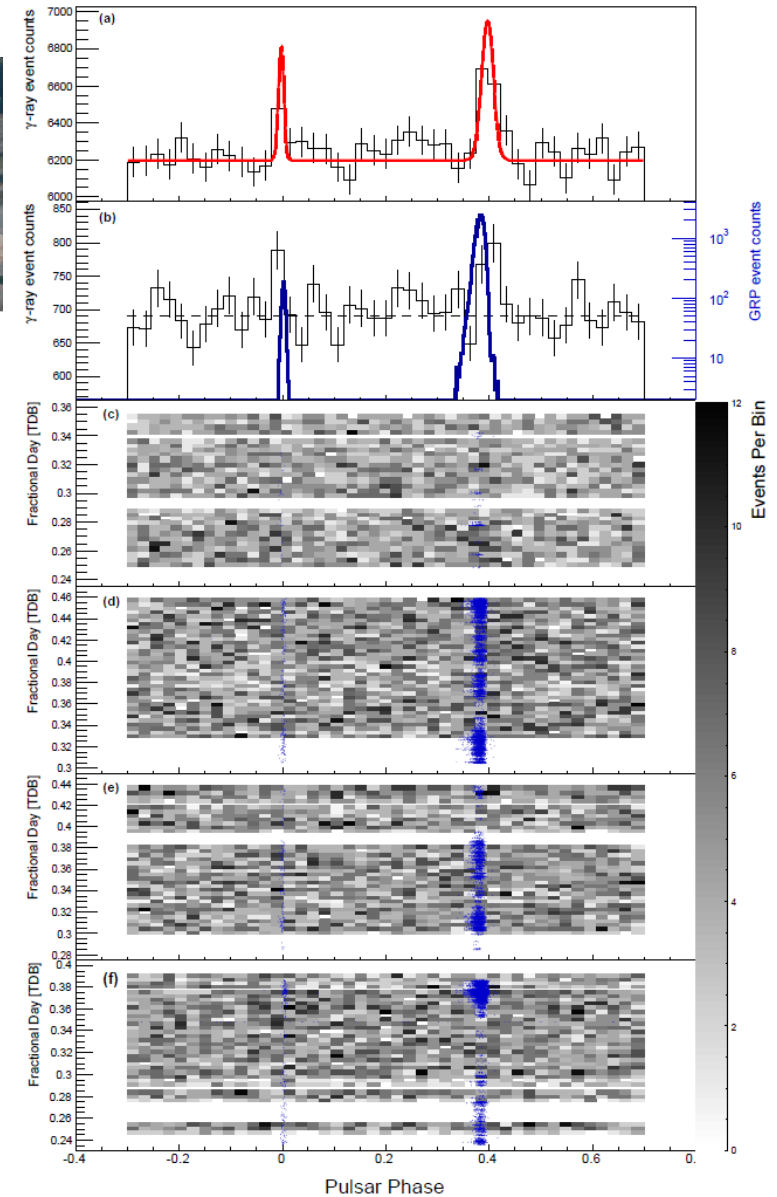


Four nights of simultaneous exposure with VERITAS and the Green Bank Telescope (GBT)

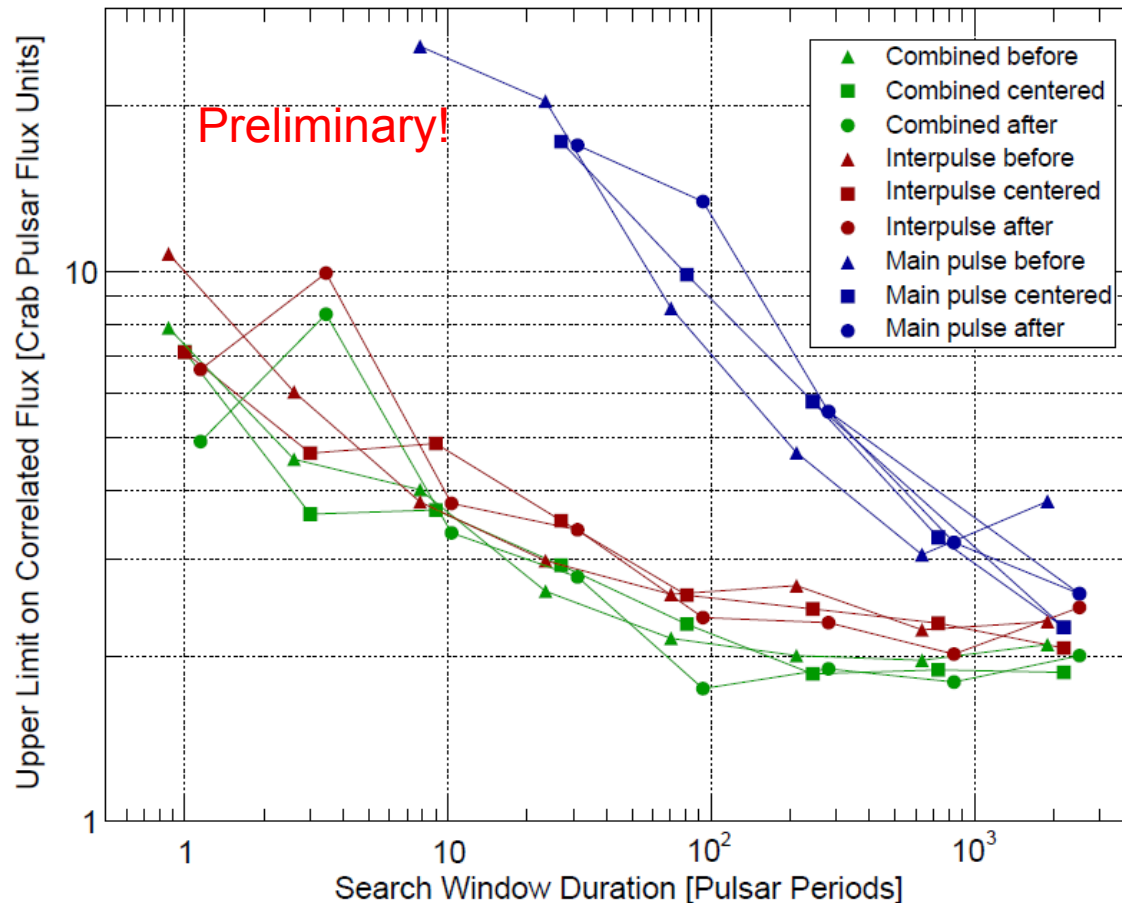
11.6 hrs exposure, 18780 GRPs found (15366 overlap with VERITAS exposure)

Looked for enhancement in VERITAS pulsar signal at times lagging, coincident and following GRP arrival time

Date [MJD]	# GRPs	# GRPs Overlap	# γ -ray Candidates	T Overlap [min]	Center Freq. [MHz]	Δ samp. [μ s]
54829	280	150	5566	138.365	8832	40.96
55153	7813	5937	8738	200.232	8900	3.2
55158	3771	3243	7928	182.881	8900	3.2
55180	6916	6036	7861	180.107	8900	3.2
Total	18780	15366	30093	701.585		



GRP Search Results: Upper Limits



Preliminary results!

UL values for IP and combined searches are 5-10 times the average pulsar flux on single period time-scales

Limits are much weaker on MP searches since the number of MP GRPs at 8.8 GHz is ~30 times lower than the number of IP GRPs

Limit values are pretty close to Fermi limits.

Models of GRP emission provide no quantitative guidance. It's difficult to cast our limits in to some physical pulsar/GRP parameter space.

Search for Lorentz Invariance Violations with the Crab Pulsar

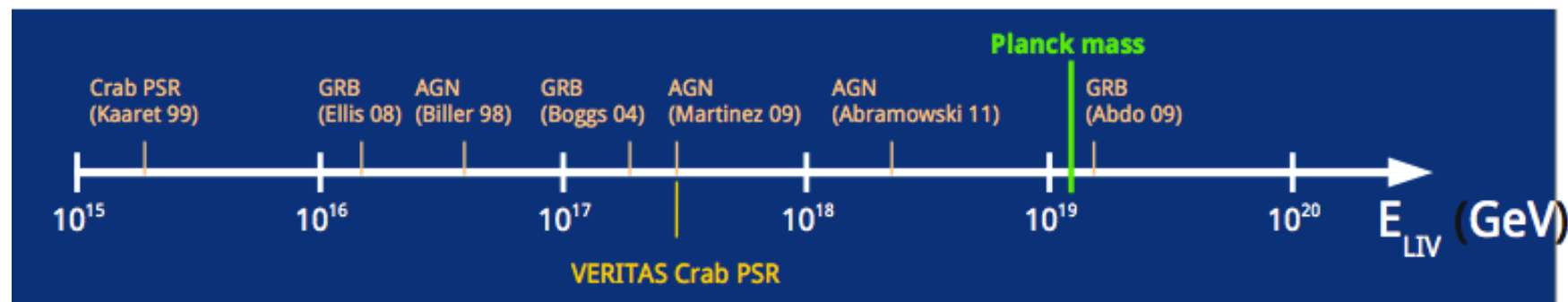
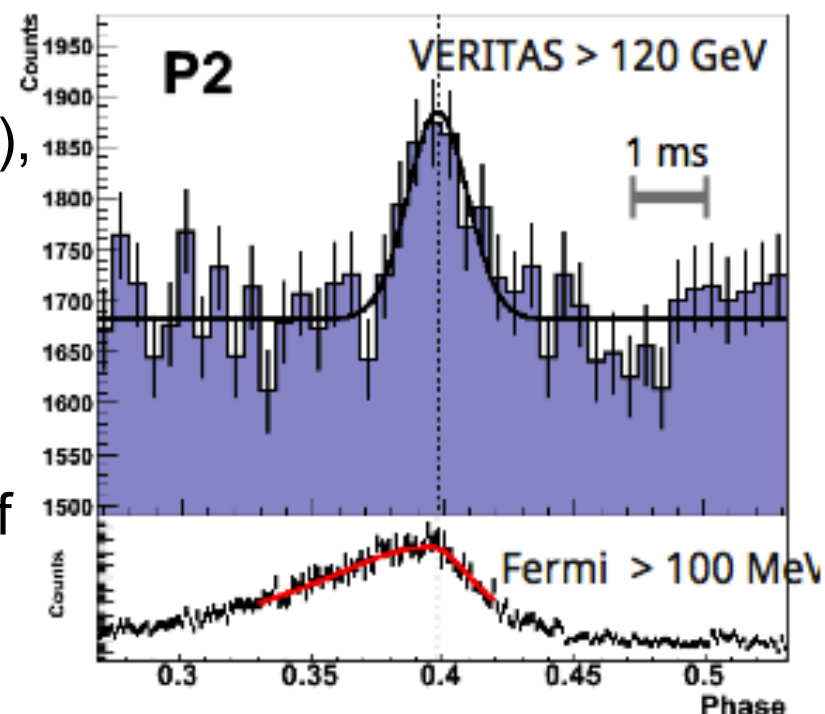
N. Otte, ICRC 2011, Preliminary

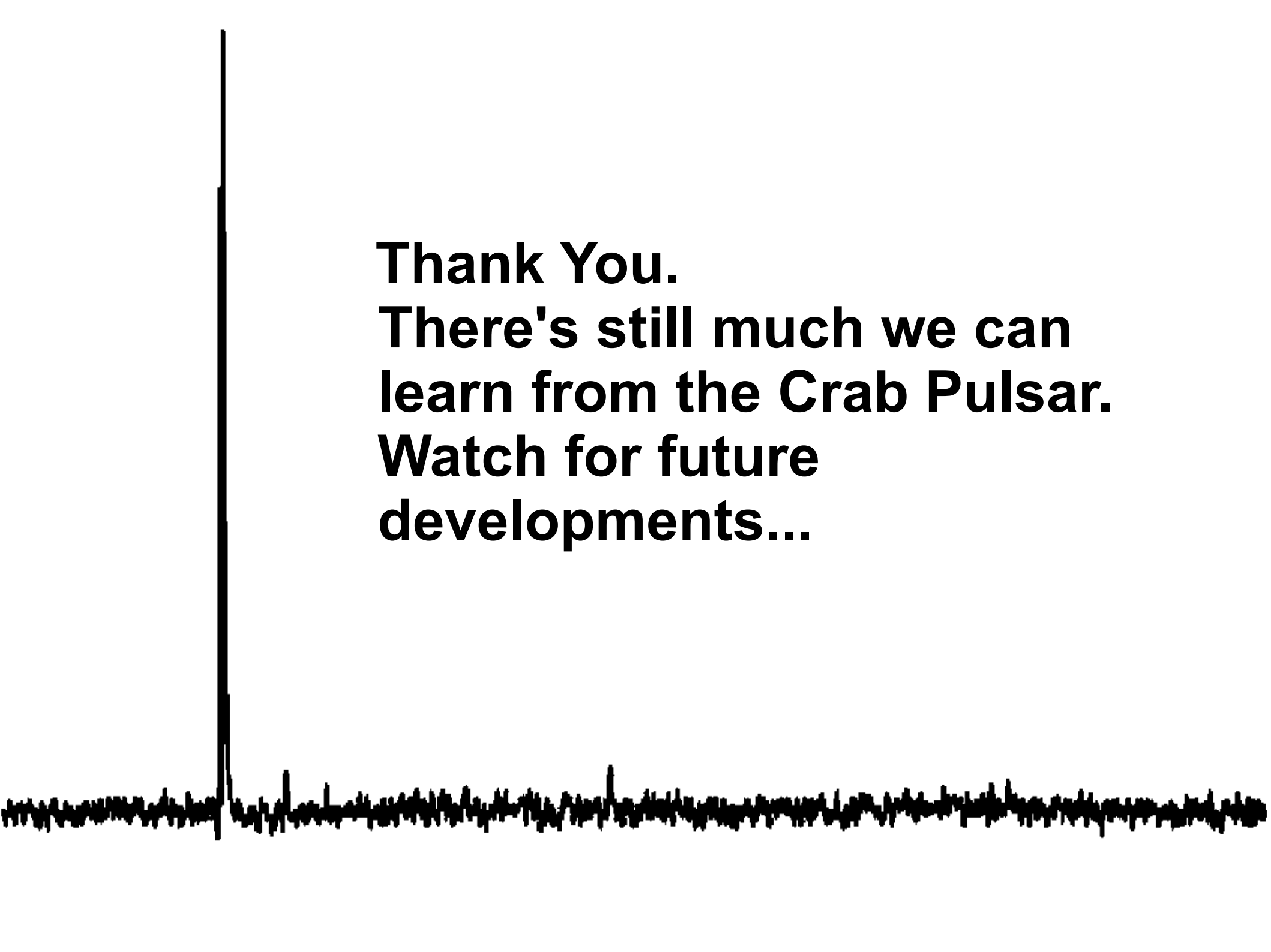
Quantum Gravity suggests: $c = c_0(1-(E/E_{\text{LIV}})^n)$,
where $n = 1, 2$ & $E_{\text{LIV}} \sim M_{\text{pl}}$

Effects small, requires fast variability, high energies and astronomical distances

Limit calculated from P2 peaks differences of FERMI and VERITAS

$E_{\text{LIV}} > 3 \times 10^{17} \text{ GeV}$ for the linear term





**Thank You.
There's still much we can
learn from the Crab Pulsar.
Watch for future
developments...**