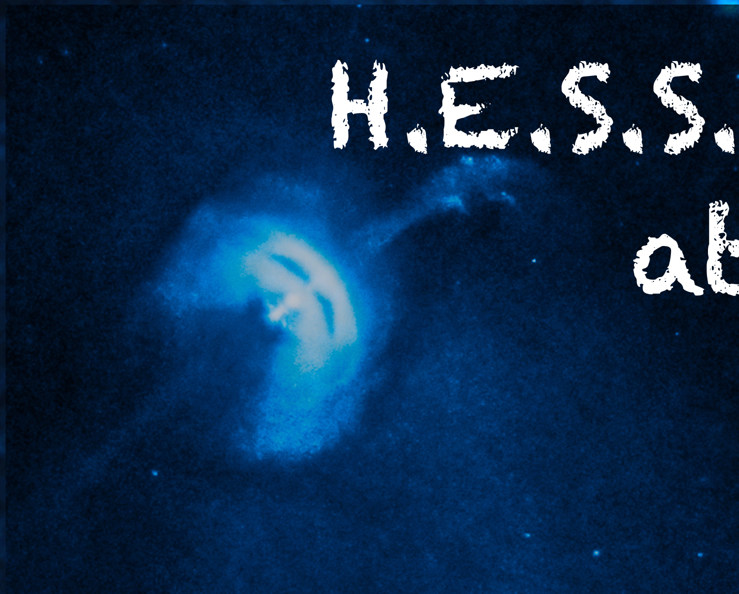
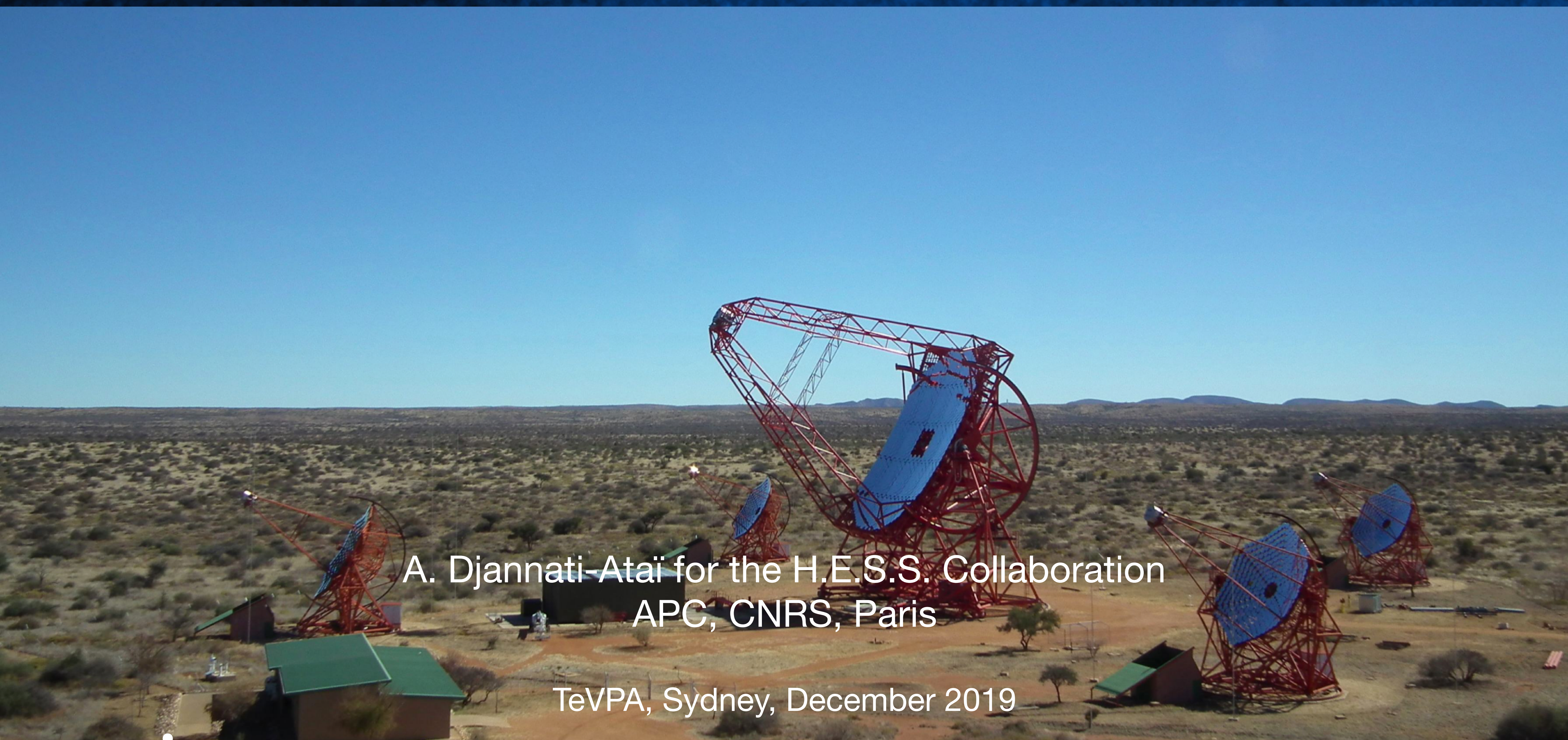
H.E.S.S. Observations of Pulsars at Very High Energies





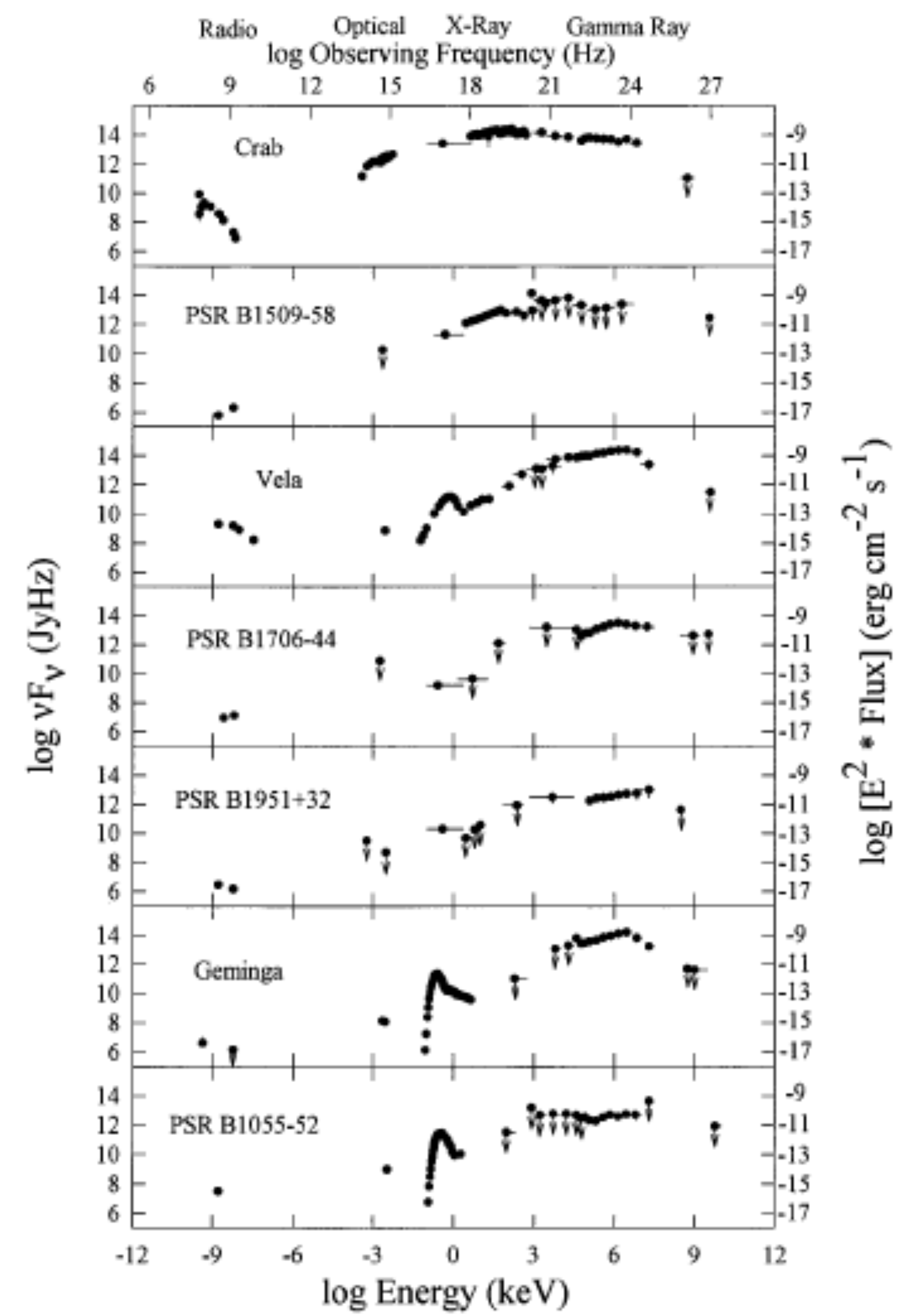
A. Djannati-Ataï for the H.E.S.S. Collaboration
APC, CNRS, Paris

TeVPA, Sydney, December 2019

EGRET Era (< 2008)

GRO: April 5th 1C991- June 4th 2000

- First discovery in 1967 : 1919+21
  [Hewish & Bell 1967]
- ATNF catalog > 2900 radio pulsars
- Crab in soft γ-rays : only 2 yrs after its discovery
  [Hillier et al. 1970]
- GeV γ-rays prior to Fermi :
  Egret/CGRO (1990's) : 7 pulsars
- X-rays : ~100 pulsars mostly thermal
- Optical : ~10 pulsars, very faint
  Mv(Crab) =16.5
  Mv(Vela) = 23.5 !
- Most of energy in GeV range
- Bump in UV-X-rays for 3 pulsars

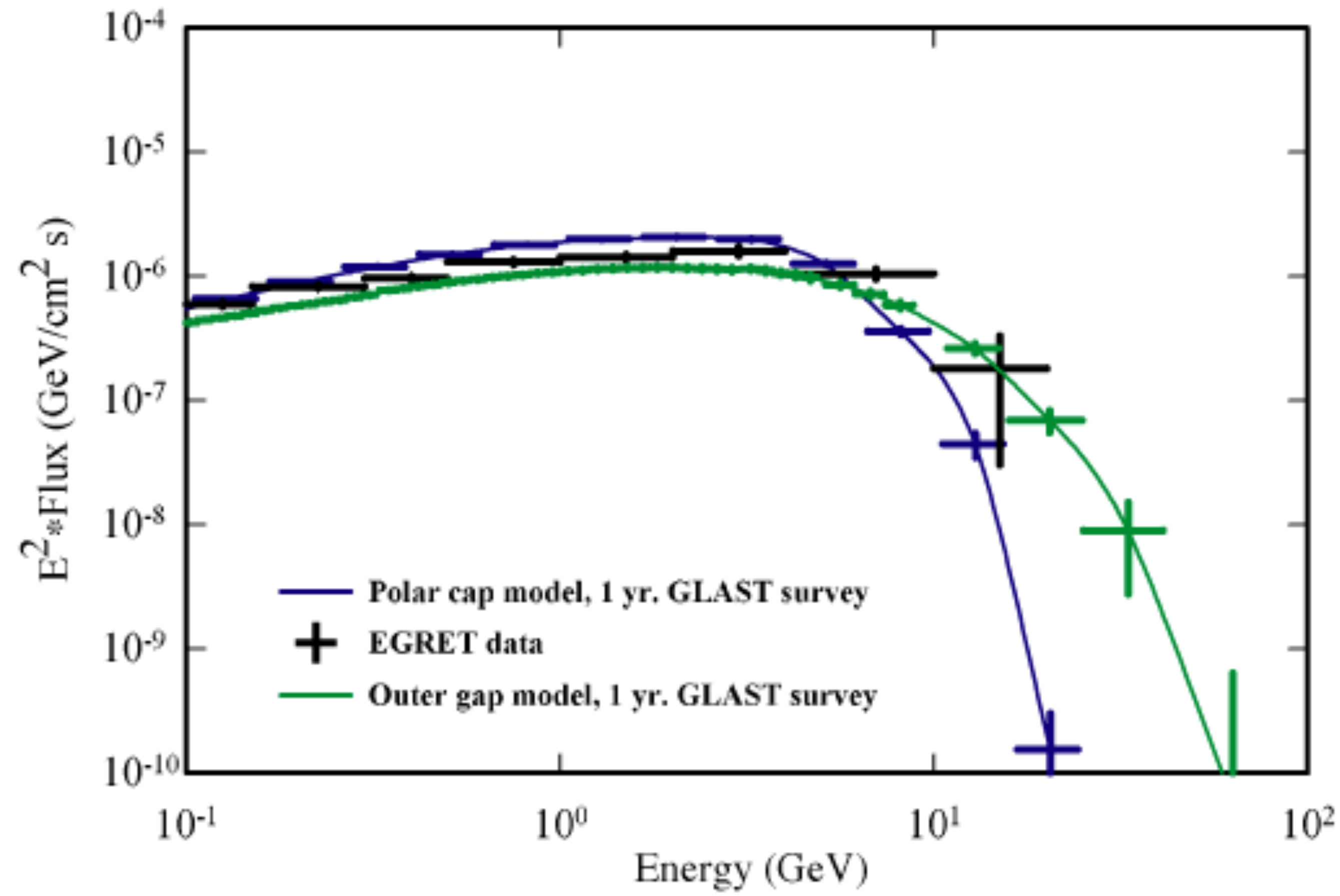


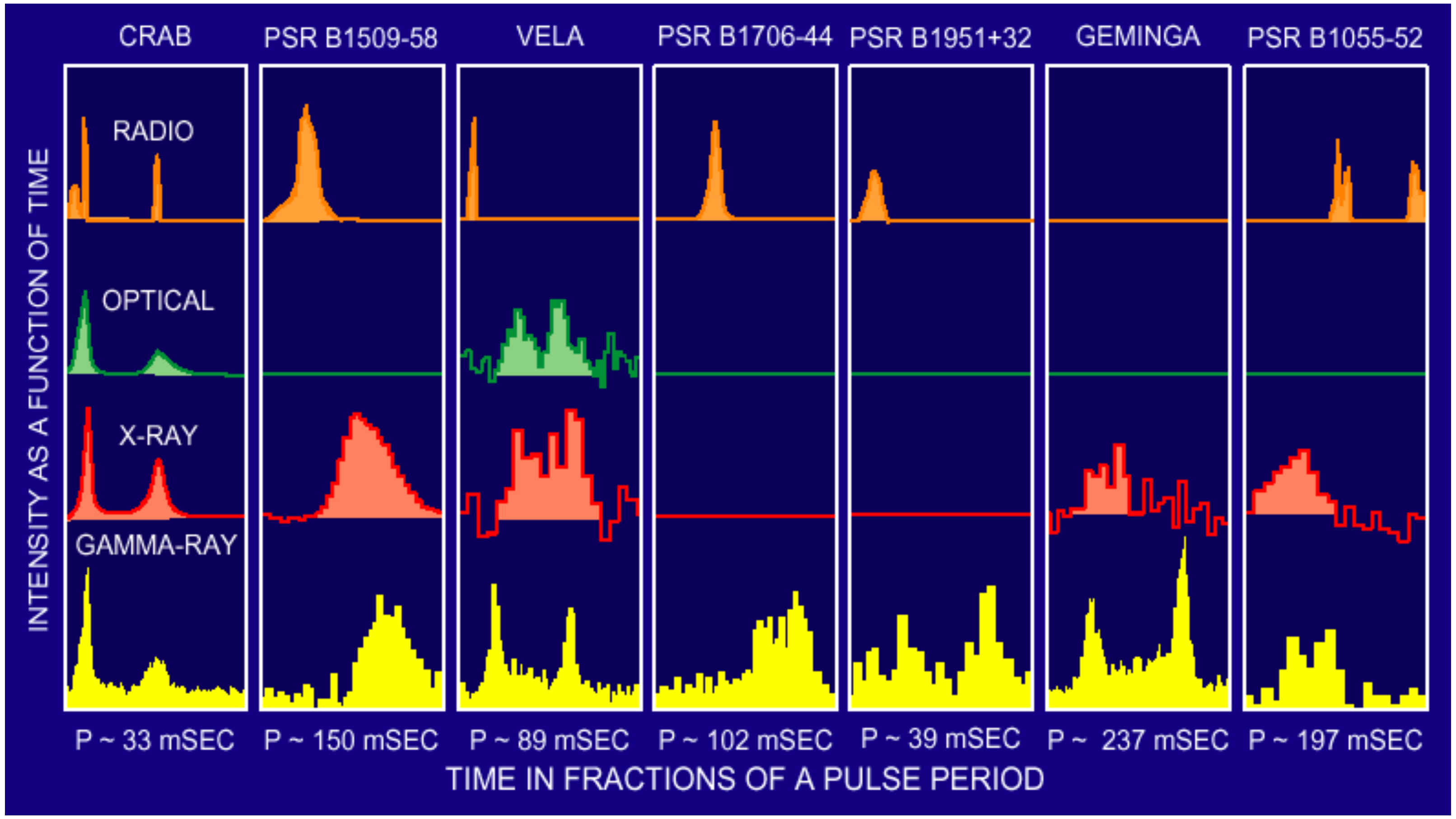
[Thompson et al. 1999]

EGRET Era (< 2008)

GRO: April 5th 1991- June 4th 2000

- 7 pulsars detected
- Polar Cap : super-exponential cut-off
- Outer/slot gaps : exponential cut-off
- Data in [1-10] GeV on brightest pulsars :
  —> not constraining





HESS searches for VHE pulsations

Data 2002-2005 [HESS collab. 2007]

H.E.S.S.

- 11 “young” isolated pulsars selected
- Except B1259-63 with a companion
- $\dot{E}/d^2 > 10^{35}$ erg/cm2/s
- (Characteristic) Ages range from 1.24 to 332 kyrs
- ~350 h of total observing time
- No significant excess found

Pulsar	Low energy cuts						Standard cuts					
PSR	N_{on}	P_{χ^2}	P_H	$P_{Z_1^2}$	$P_{Z_2^2}$	P_K	N_{on}	P_{χ^2}	P_H	$P_{Z_1^2}$	$P_{Z_2^2}$	P_K
B0531+21	8095	0.99	0.84	0.81	0.94	0.97	10622	0.51	0.56	0.63	0.25	0.66
B0833–45	7480	0.52	0.87	0.85	0.37	0.82	1156	0.79	0.92	0.90	0.98	0.88
B1259–63	16176	0.78	0.92	0.90	0.65	0.71	4535	0.29	0.25	0.18	0.46	0.23
J1420–6048	2228	0.0093	0.0031	0.072	0.007	0.0049	968	0.67	0.60	0.53	0.53	0.62
B1509–58	12481	0.37	0.81	0.77	0.70	0.89	4308	0.048	0.055	0.027	0.11	0.04
J1524–5625	2498	0.78	0.43	0.35	0.43	0.39	745	0.87	0.79	0.75	0.96	0.97
B1706–44*	–	–	–	–	–	–	391	0.02	0.82	0.78	0.85	–
J1826–1334	14497	0.71	0.46	0.38	0.57	0.62	4016	0.46	0.42	0.34	0.34	0.42
J1747–2958**	23482	0.65	0.98	0.97	0.82	0.95	6340	0.62	0.62	0.92	0.99	0.96
J1801–2451**	3230	0.035	0.22	0.15	0.42	0.21	723	0.50	0.15	0.094	0.24	0.32

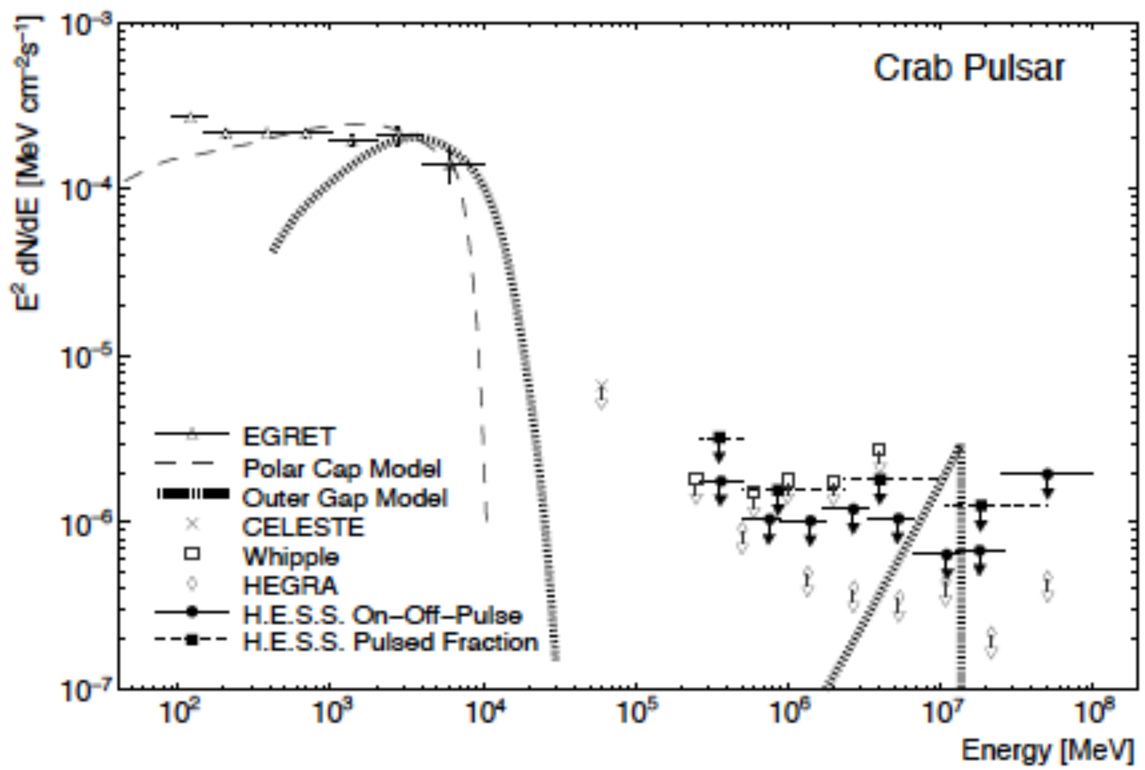
* Subject to analysis limitations (archival data, see text).

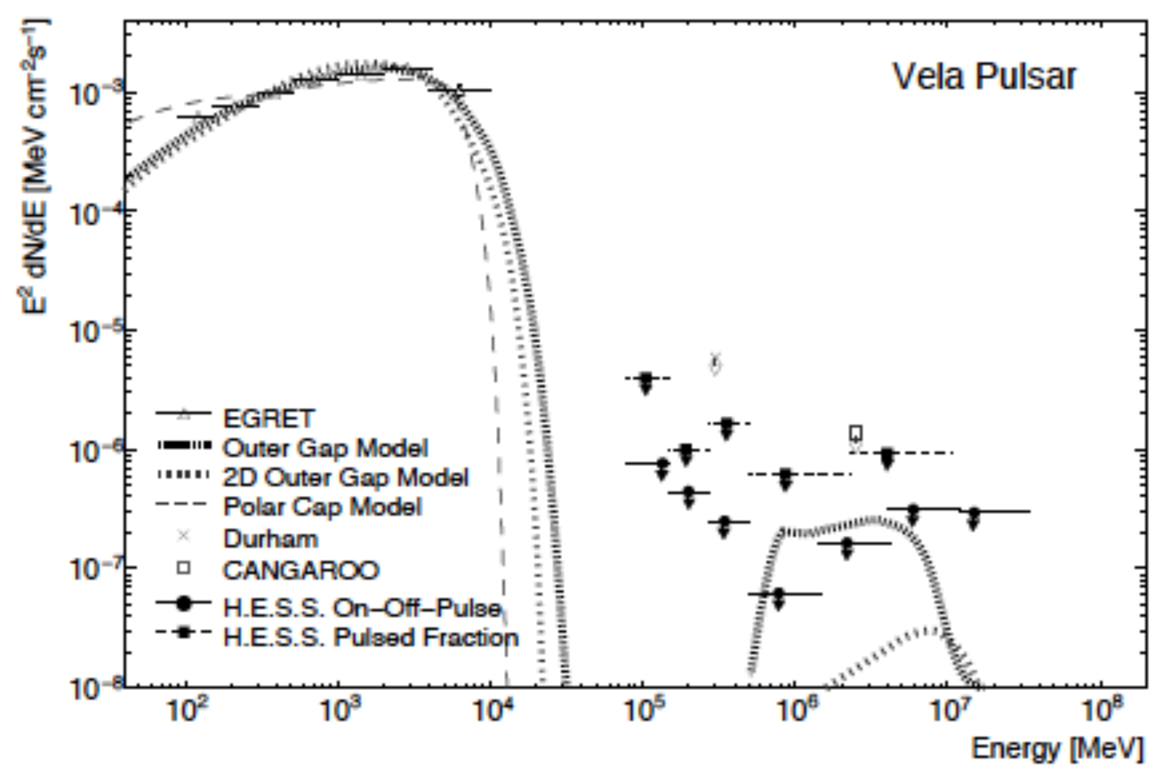
** Valid pulsar timing information was not available for all data within the H.E.S.S. data set.

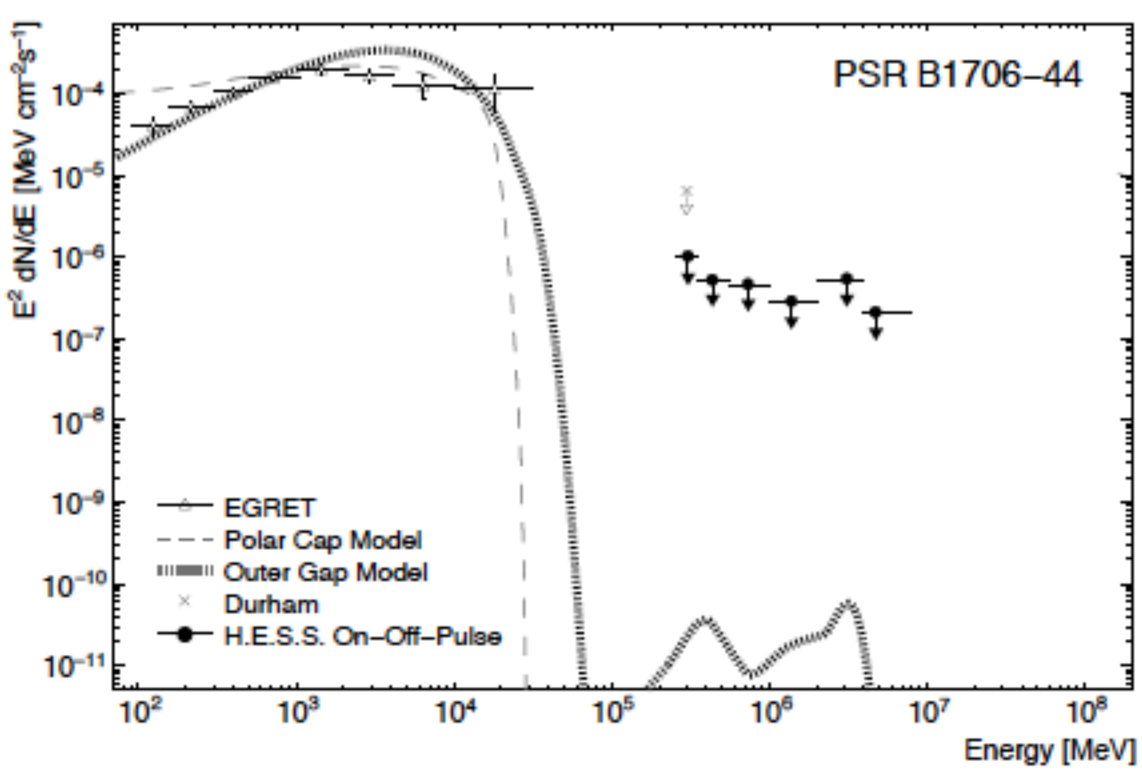
HESS searches for VHE pulsations

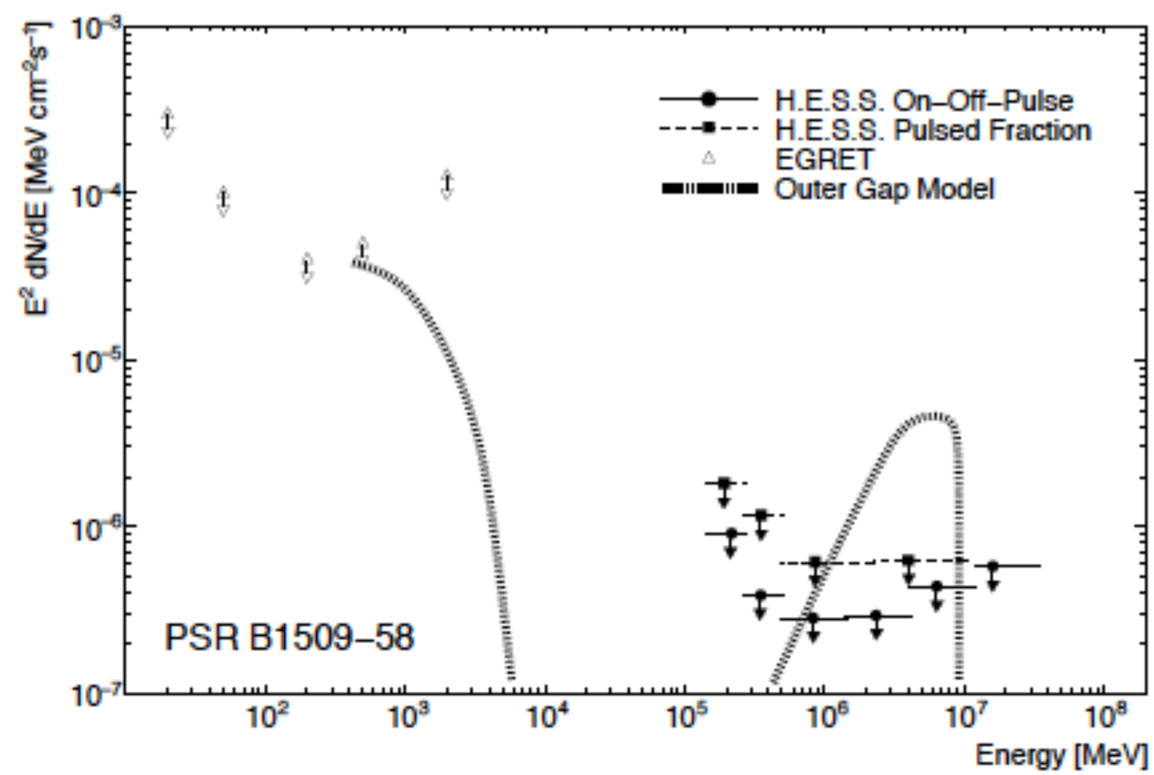
Data 2002-2005 [HESS collab. 2007]

- Constraints on OG [Dyks & Rudak]+ IC models [Hirotani et al., 2001, 2003], [Takata et al. 2006], ...





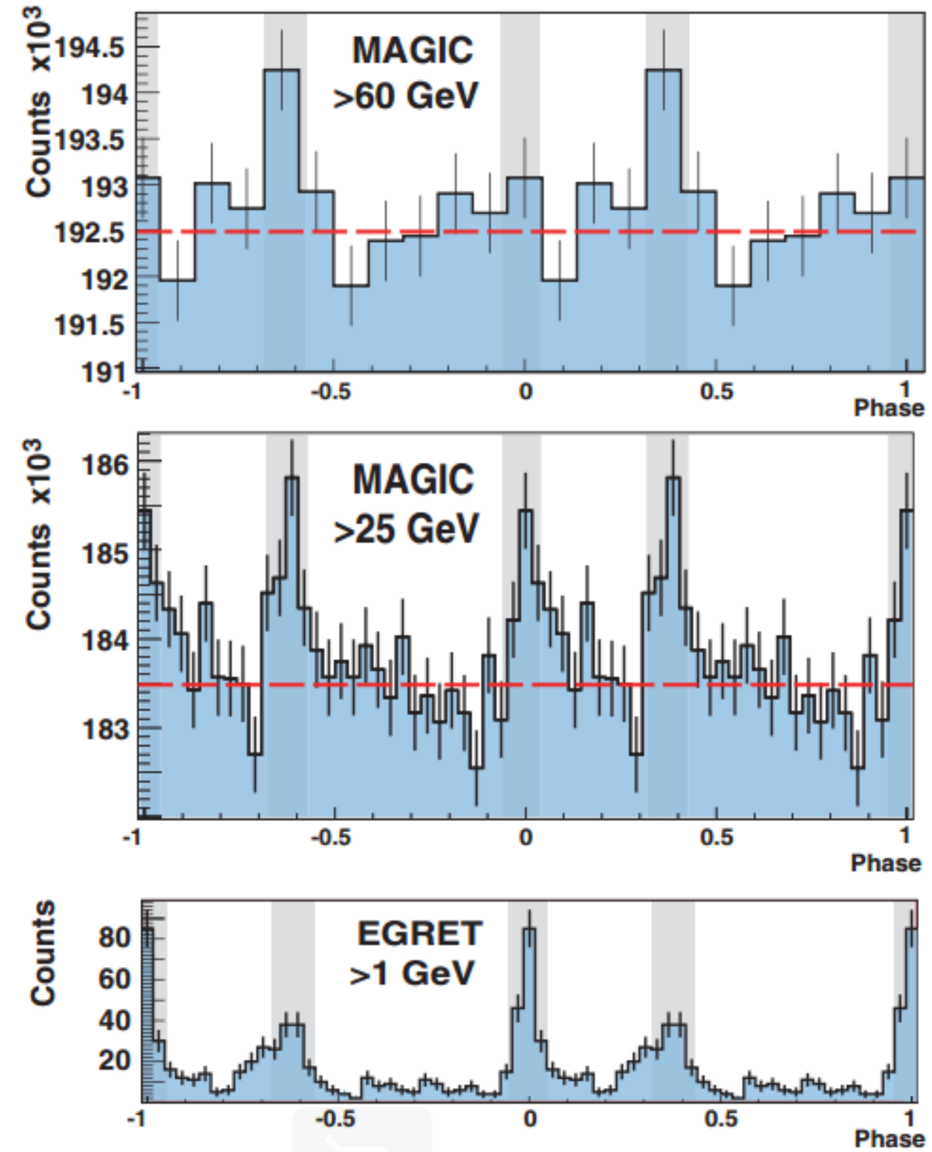




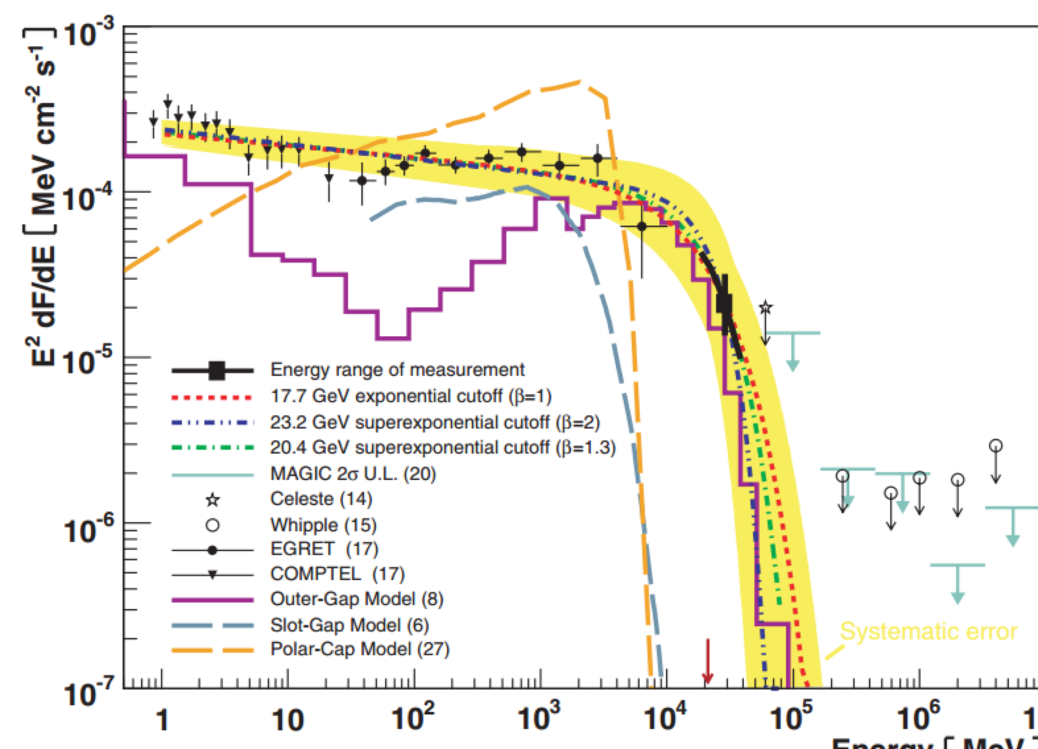
Crab : MAGIC 2008

~25 GeV [Aliu et al. 2008]

- Sept 2008 (17^{th})
  - Detection of a signal > 25 GeV !
  - 23 hours, 8500 events at 6.4 s.d. from peaks P1 and P2
  - P2 > 60 GeV : 3.4 s.d.



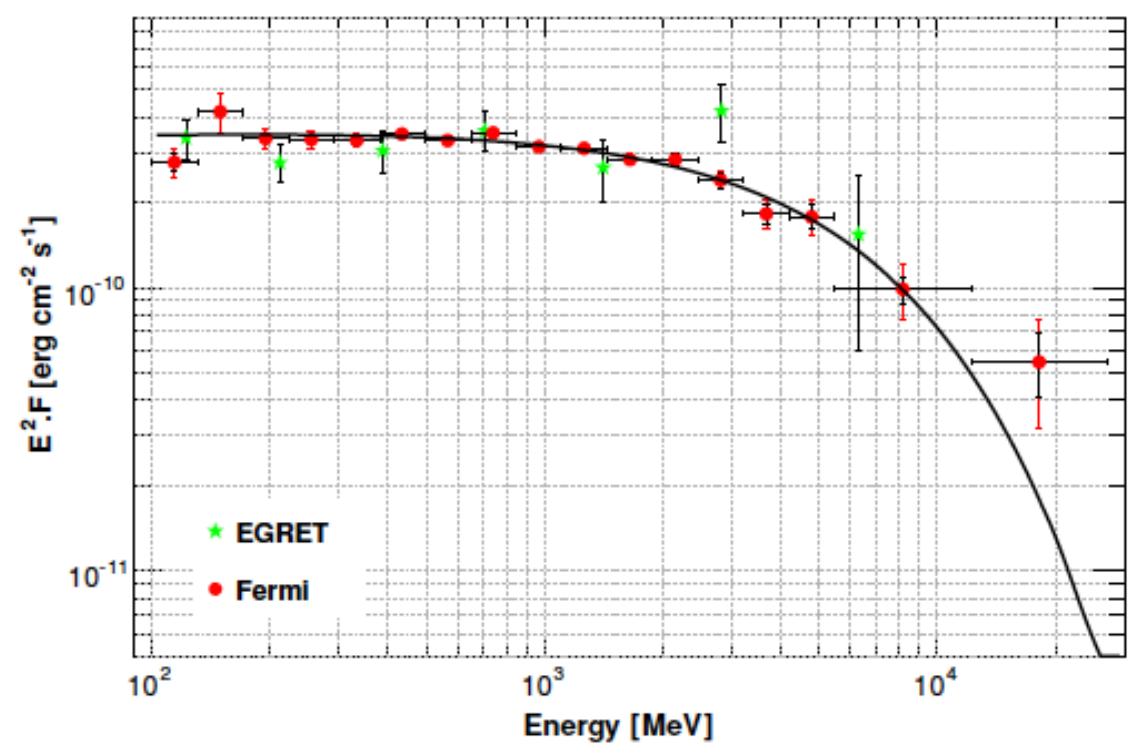
- Spectral energy distribution
- Exp-cutoff E pushed to 17.7 GeV
- Polar Cap models disfavored
- But uncertainties on energy scale forbid strong conclusions



Fermi-LAT Era (>2008)

Launch of Fermi : June 11th 2008

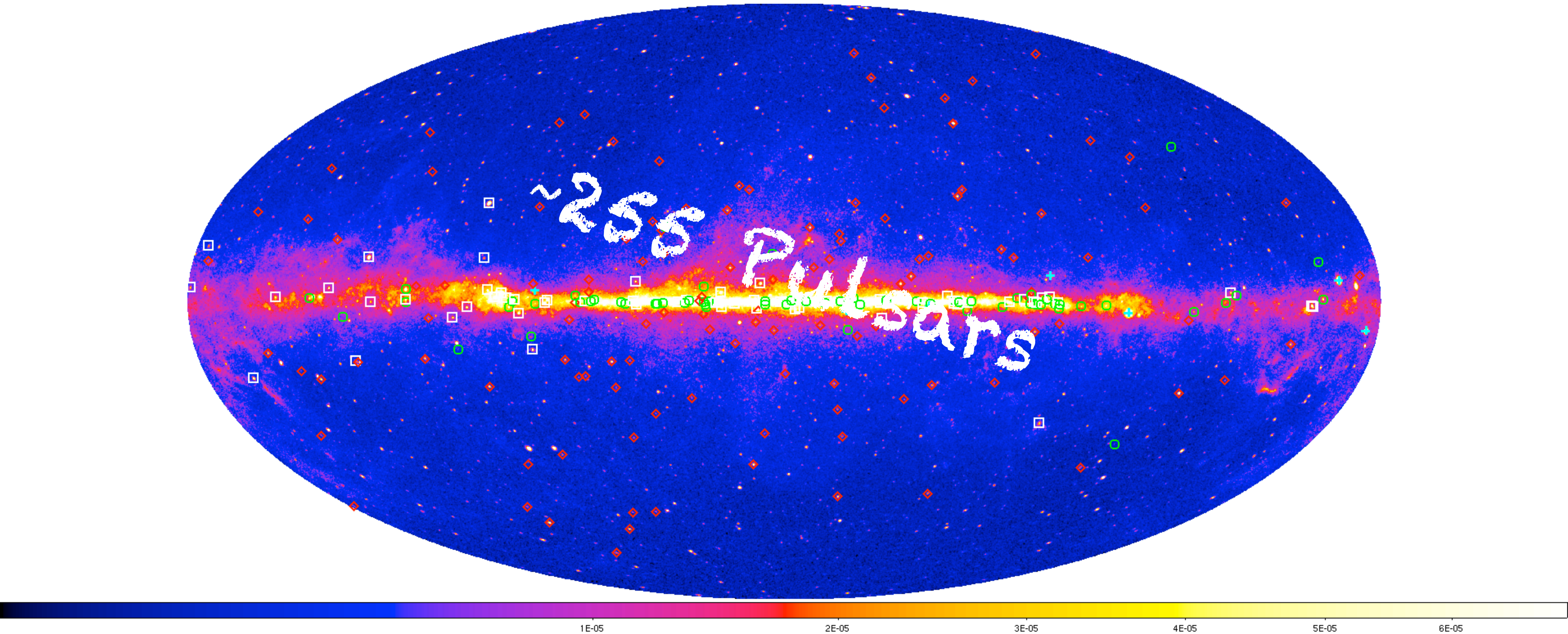
- As soon as September 2009:
- Super exponential cutoff excluded !
- Brightest pulsars (Crab, Vela) : even sub-exponential cut-off
- Cut-offs in a narrow band E_cut ~1-5 GeV
- Taken as evidence for CR
- Reasonable values for ρ_C and $E_{||}$ indeed predict E_cut in this range



- As such no hope for VHE emission, except:
  - Tails of exp-cut off in the <50 GeV range
  - New component e.g. IC à la Hirotani & Shibata OG model, but already severely constrained by HESS...

Fermi-LAT > 1 GeV sky

11 years of data

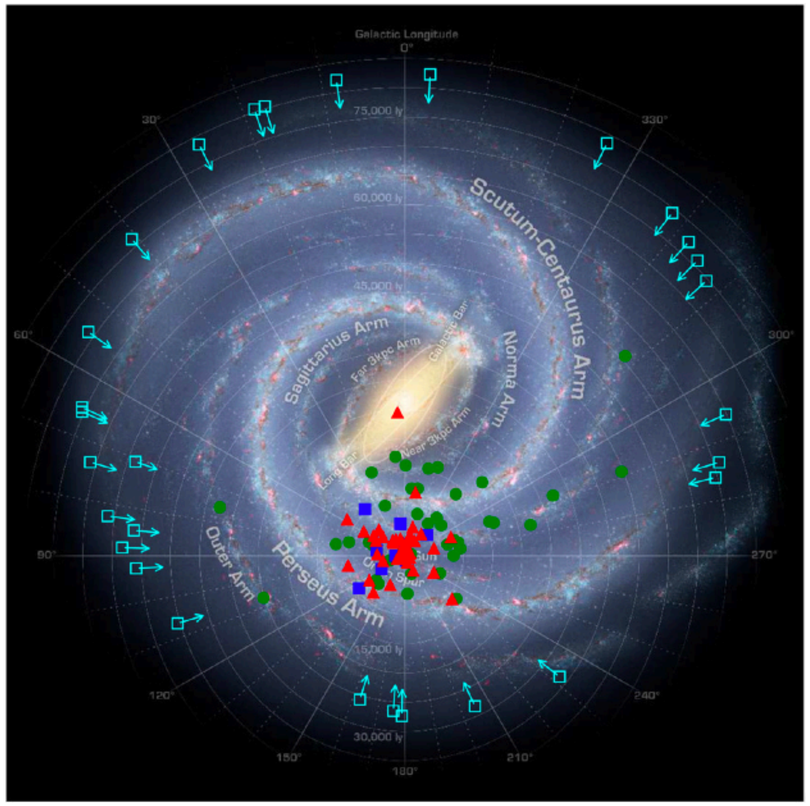


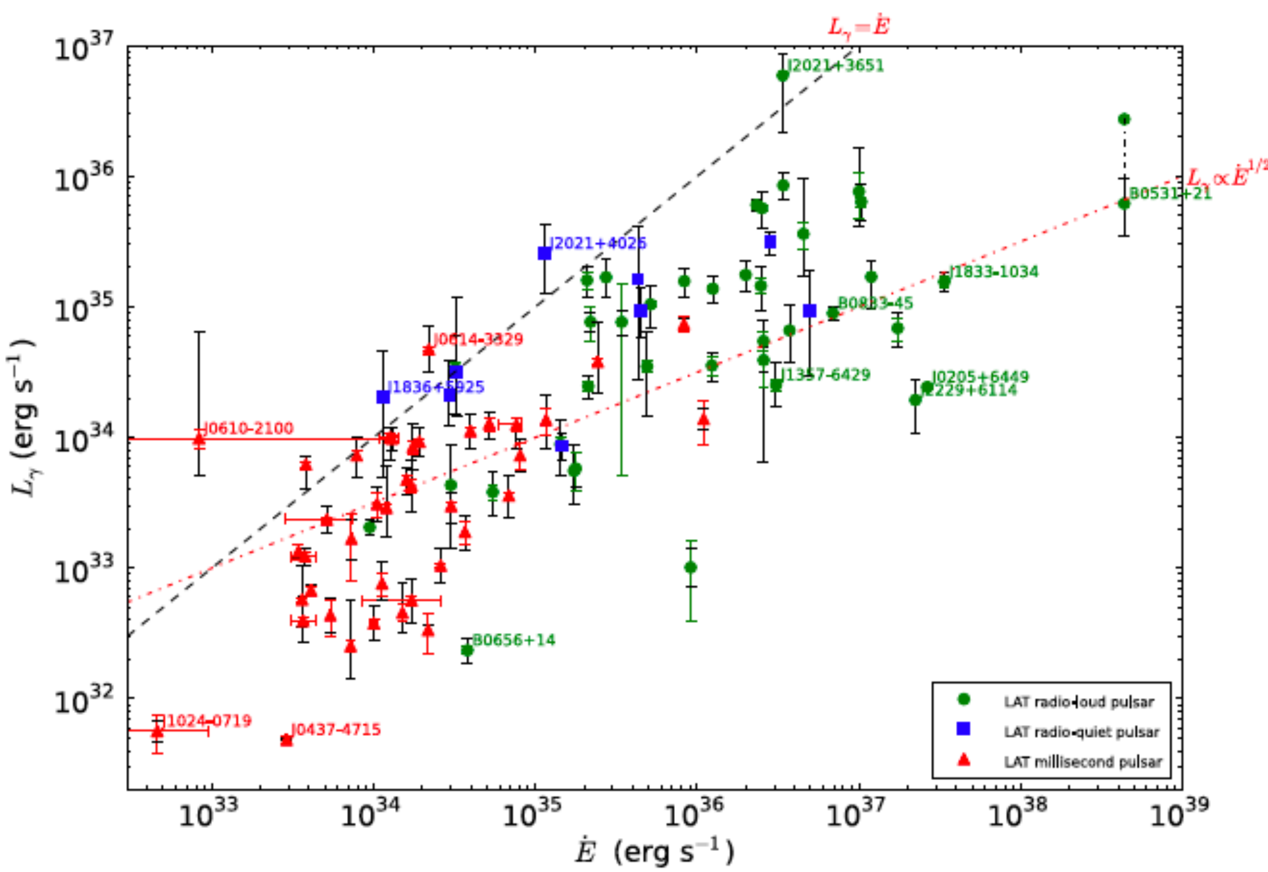
- 3PC in preparation ~255 pulsars
- 136 Young or Middle-aged
- 73 Radio-loud γ-ray (29%)
- 63 Radio-quiet γ-ray (25%)
- 119 γ-ray MSPs : 25 Isolated, 94 Binary (47%)
- 36 Black Widows (27) and Redbacks (9)
  - Public list of LAT detected pulsars :
    https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

Courtesy David Smith

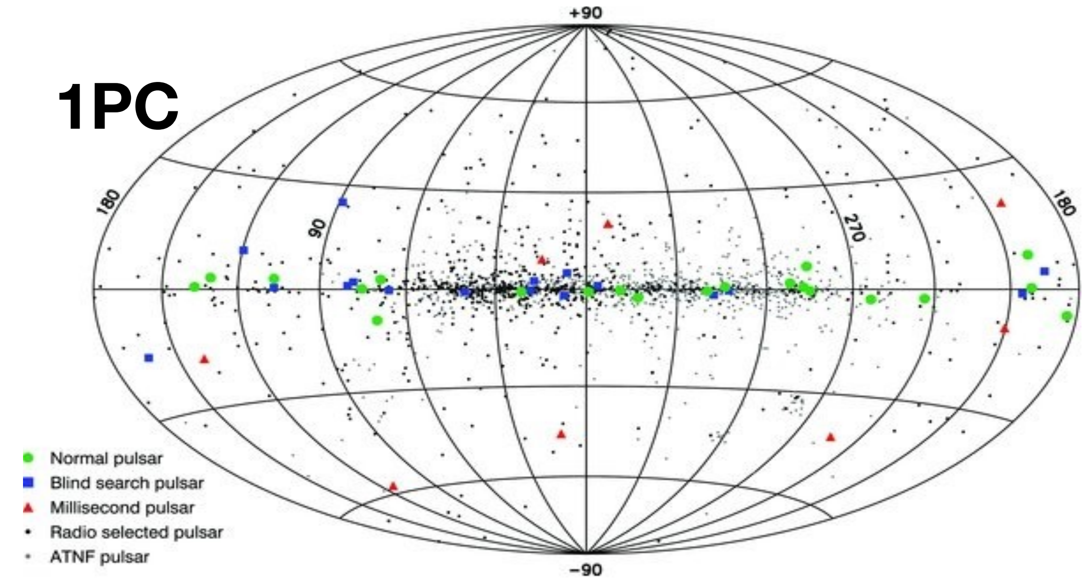
Fermi-LAT Era (>2008)

Launch of Fermi : June 11th 2008

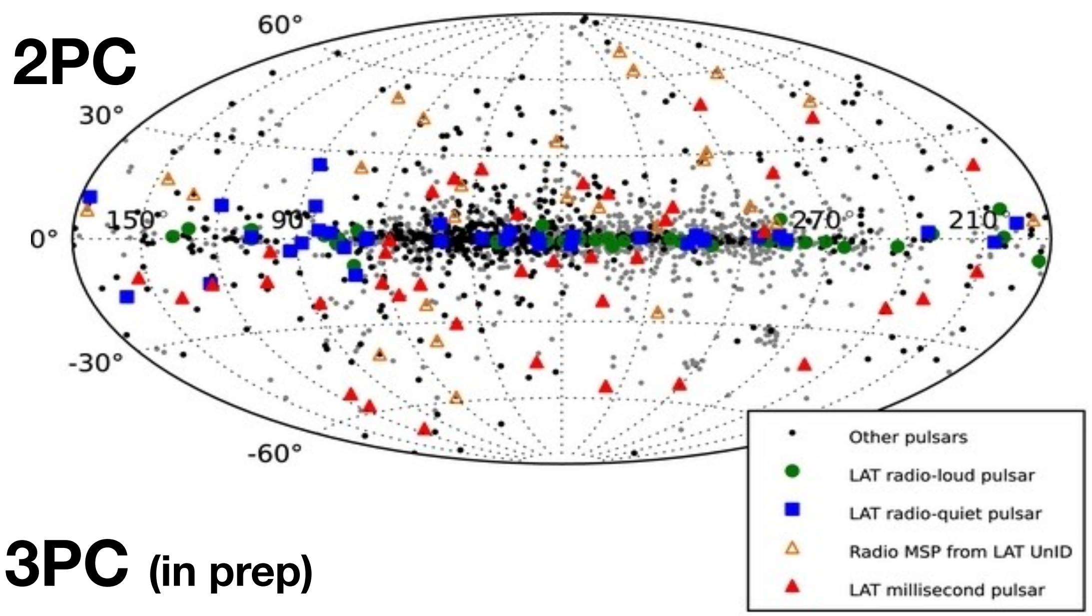




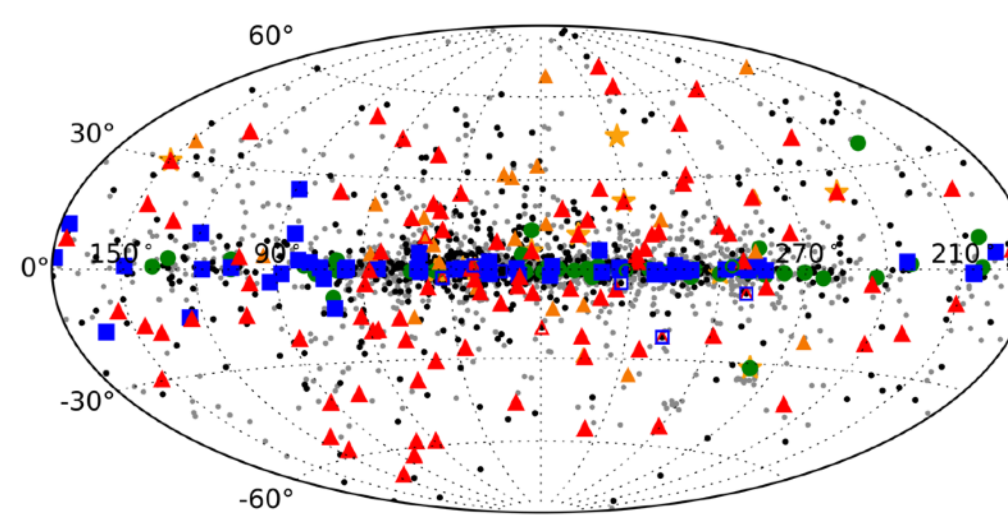
1PC



2PC



3PC (in prep)

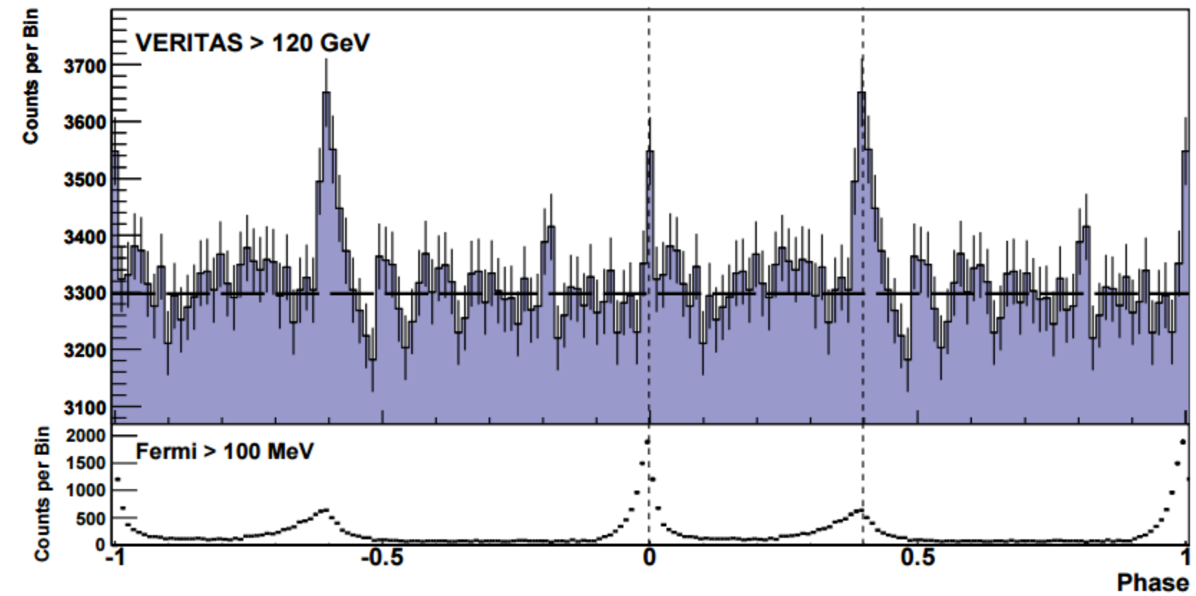


Courtesy:
David Smith & Luca Guillemot

Crab : VERITAS 2011

100-400 GeV [Aliu et al. 2011]

- **Detection of a signal in the 100-400 GeV** !
- 107 hours, 1211 events at 6.0 s.d. from peaks P1 and P2
- Confirmed by MAGIC



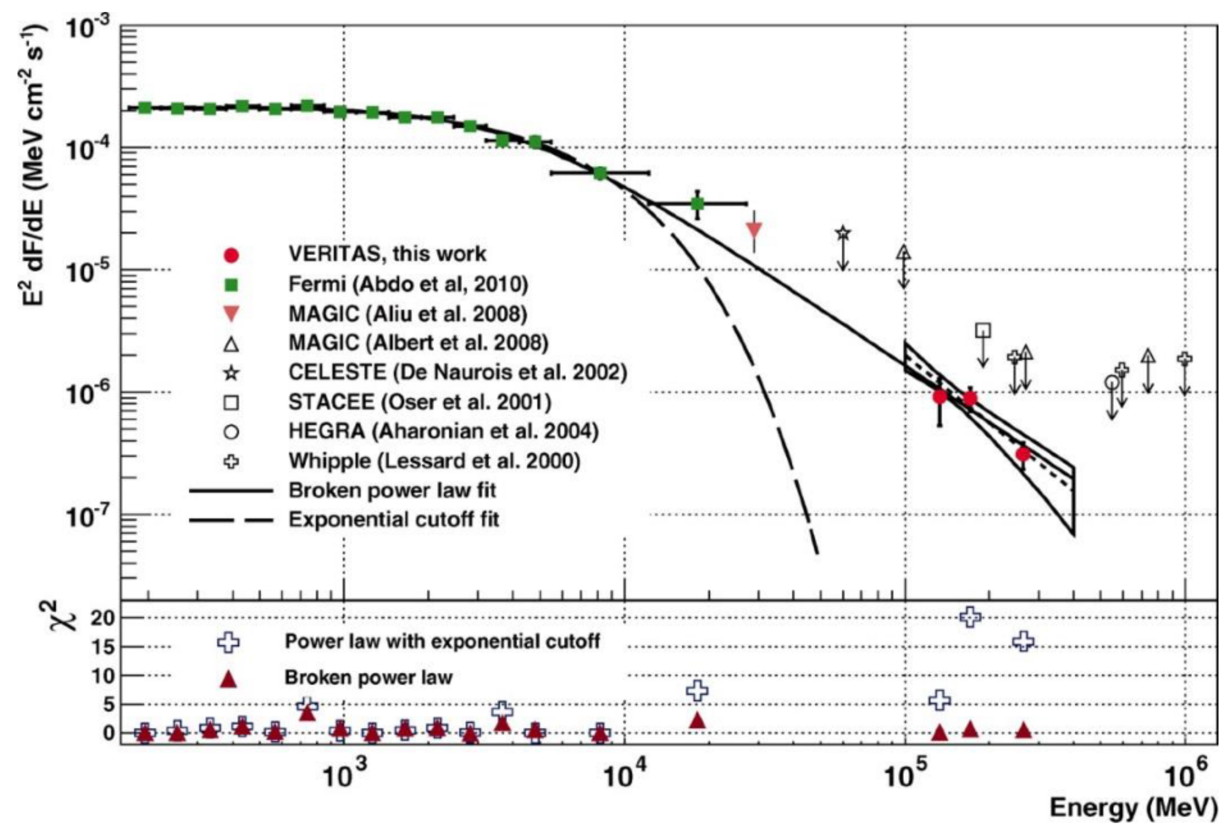
- Spectral energy distribution
- **Departure from exp-cutoff**
- **Broken power-law** :

  - Stand alone fit : $\Gamma = -3.8 \pm 0.5$
  - Combined Fermi-VERITAS fit :

    $\Gamma 1 = -1.96 \pm 0.02$

    $\Gamma 2 = -3.52 \pm 0.04$

    Assuming same component



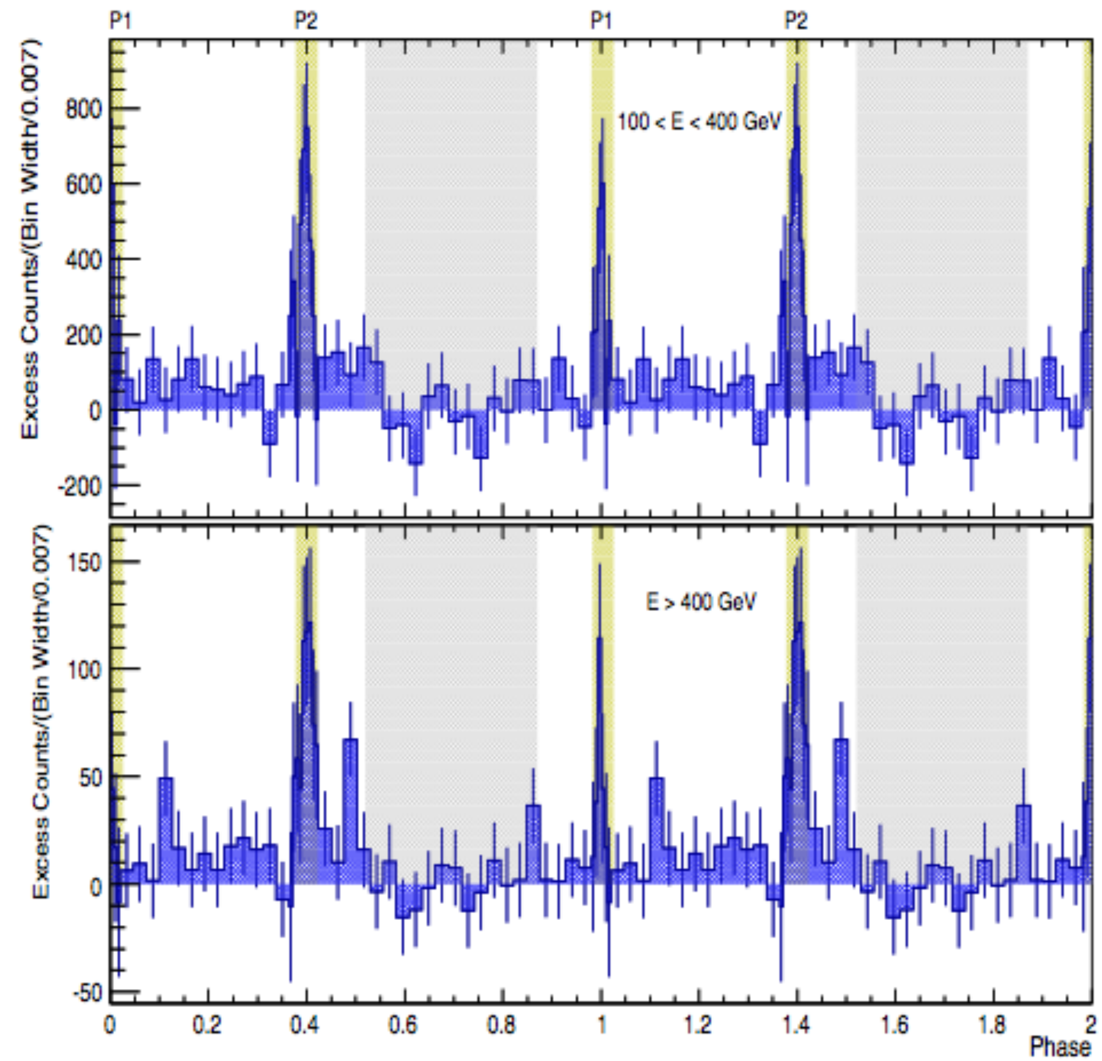
Crab : MAGIC 2016

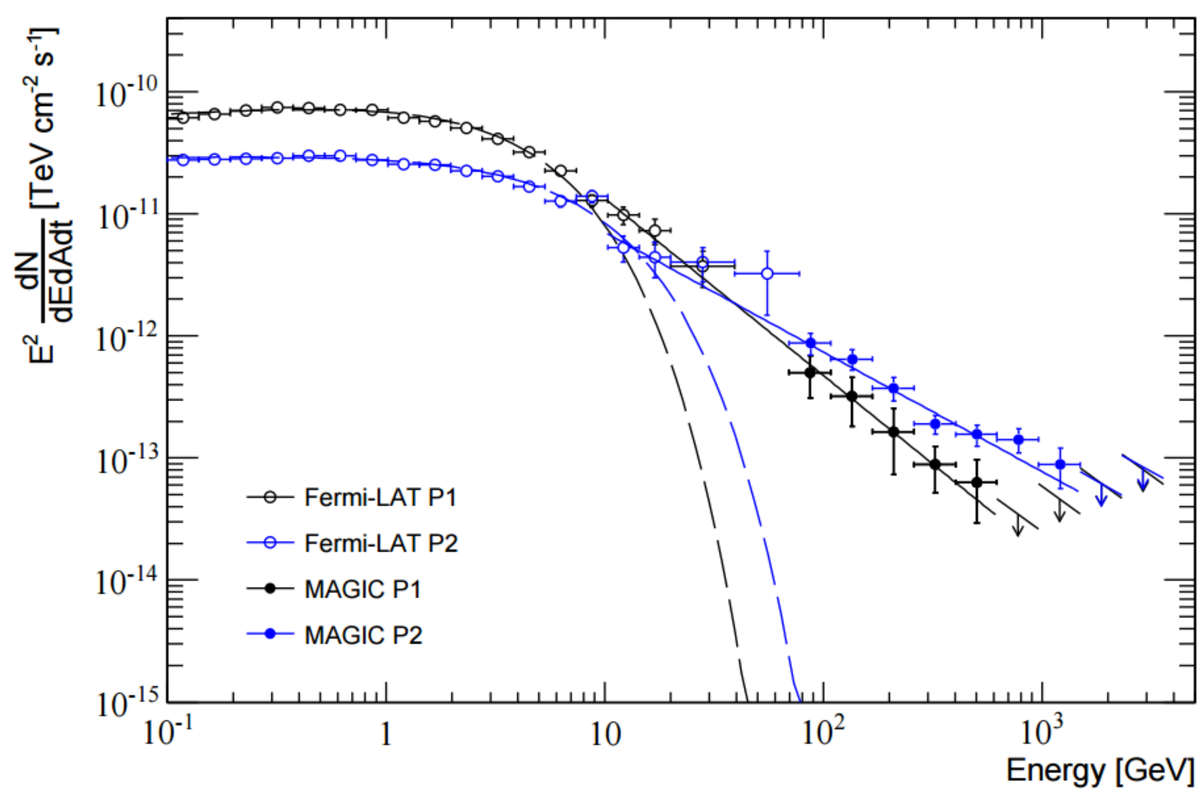
70 GeV-~1 TeV [Ansoldi et al. 2016]

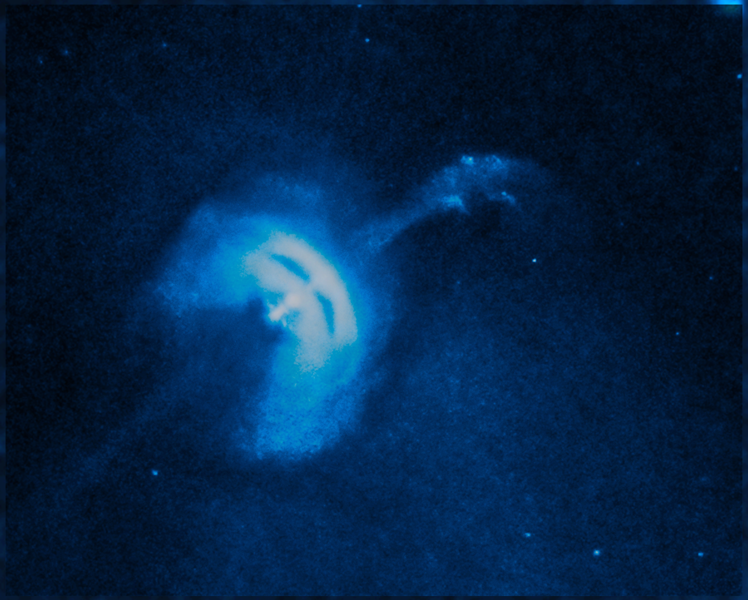
- **Extension to ~ 1 TeV**
- 320 hours!
- 100-400 GeV
- P1 : 1252 events at 2.8 s.d.
- P2 : 2537 events at 5.6.s.d.
- >400 GeV
    - P1 : 188 events at 2.2σ
    - P2 : 544 events at 6.0σ

- Spectral energy distribution
  P1 : $\Gamma = -3.2 \pm 0.4$
  P2 : $\Gamma = -2.9 \pm 0.2$
  Combined Fermi-MAGIC fit :
  P1 : $\Gamma = -3.5 \pm 0.1$
  P2 : $\Gamma = -3.0 \pm 0.1$

- In continuation of Fermi-LAT?
- **Same component?!**







H.E.S.S. Detection of the Vela PSR

Vela Pulsar detection with H.E.S.S.-II (monoscopic)

[Djannati-Ataï et al. 2016]

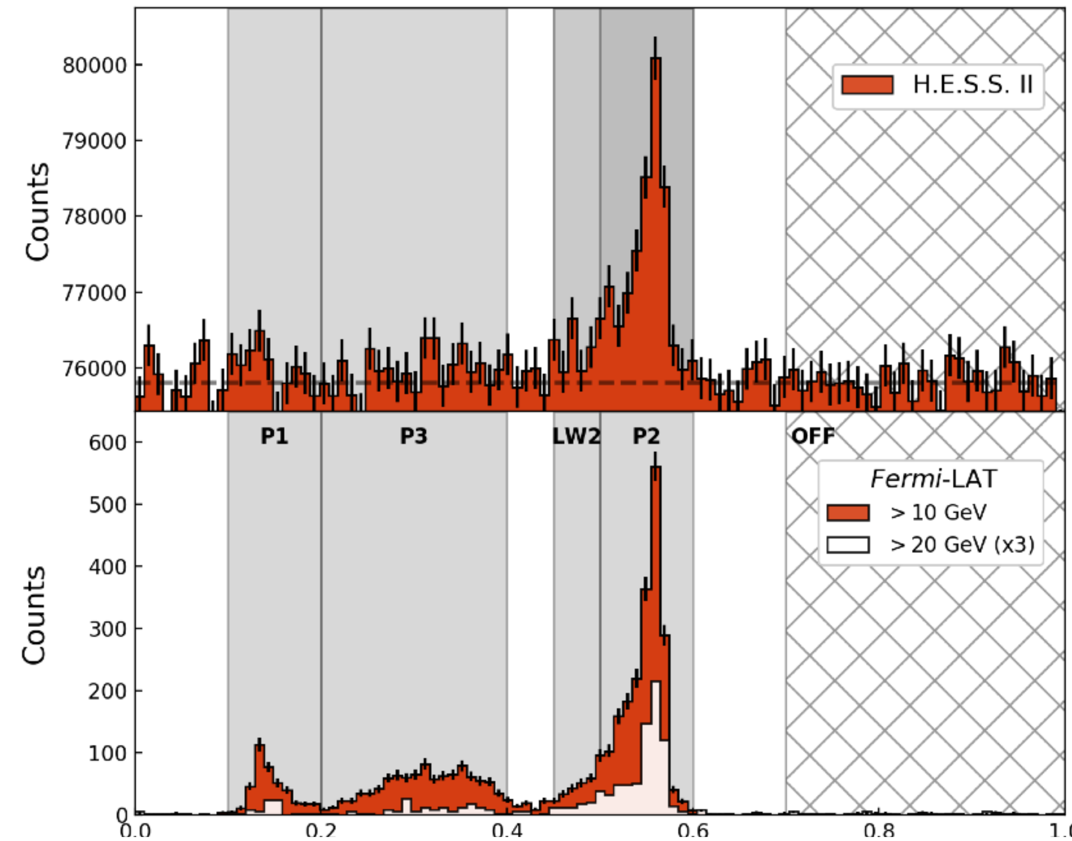
- 2012 upgrade of H.E.S.S.:
  Addition of CT5, Ø28m (eq), 600m²
- Vela pulsar: among first targets
- 40.3 h of data (2013-2015)

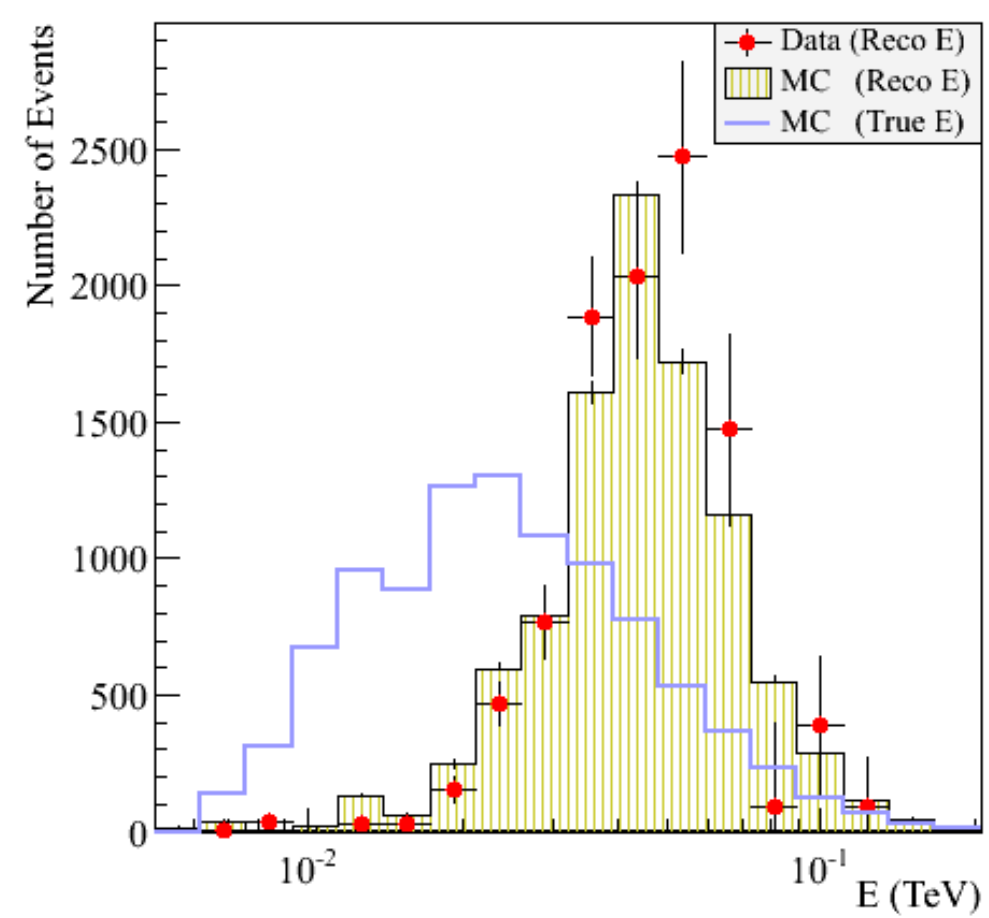
- To achieve the lowest threshold
  - Data kept only from CT5
  - Dedicated monoscopic reconstruction pipeline

- Signal of >15000 events with a significance > 15σ from the second peak P2
- Down to 10 GeV !

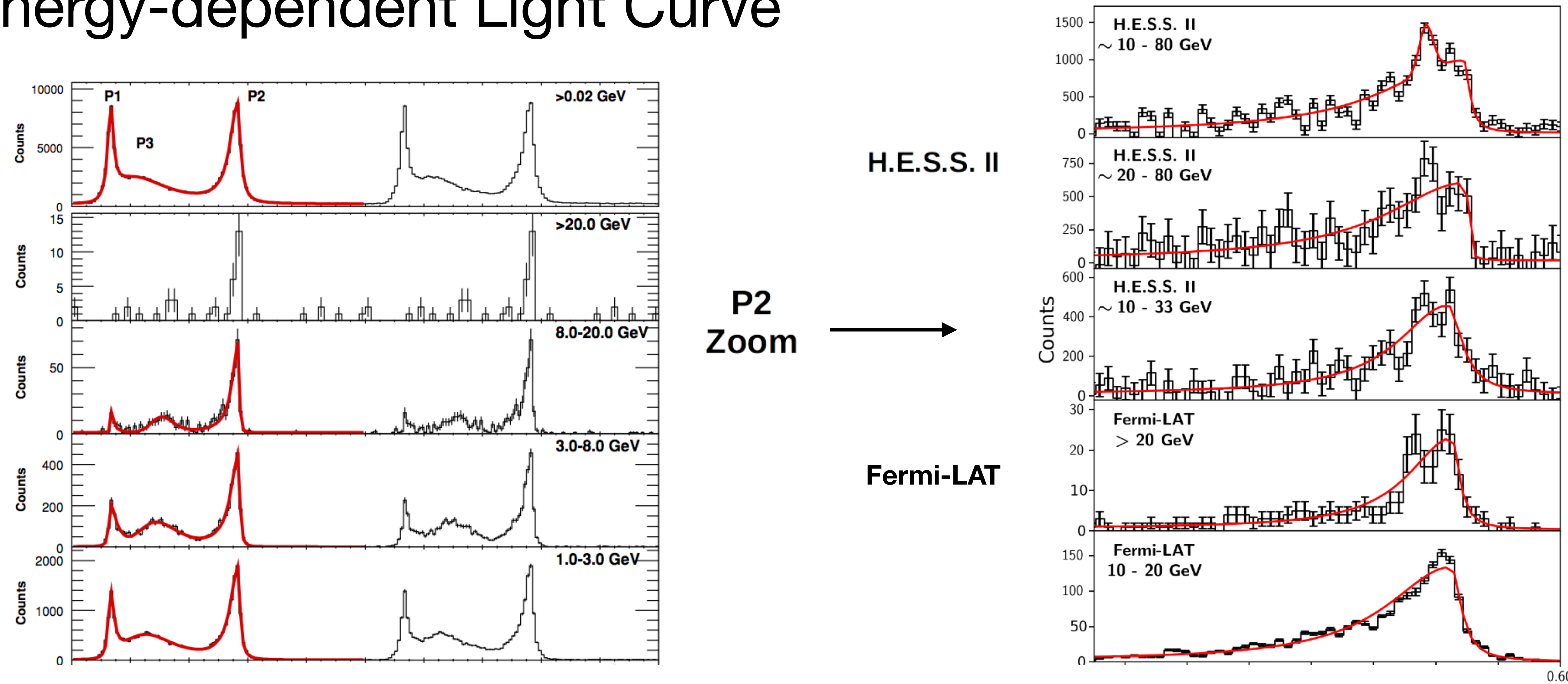
- P1, P3 show some excess but are not significant : expected from Fermi-LAT

- P1/P2 decreases with increasing E





Energy-dependent Light Curve



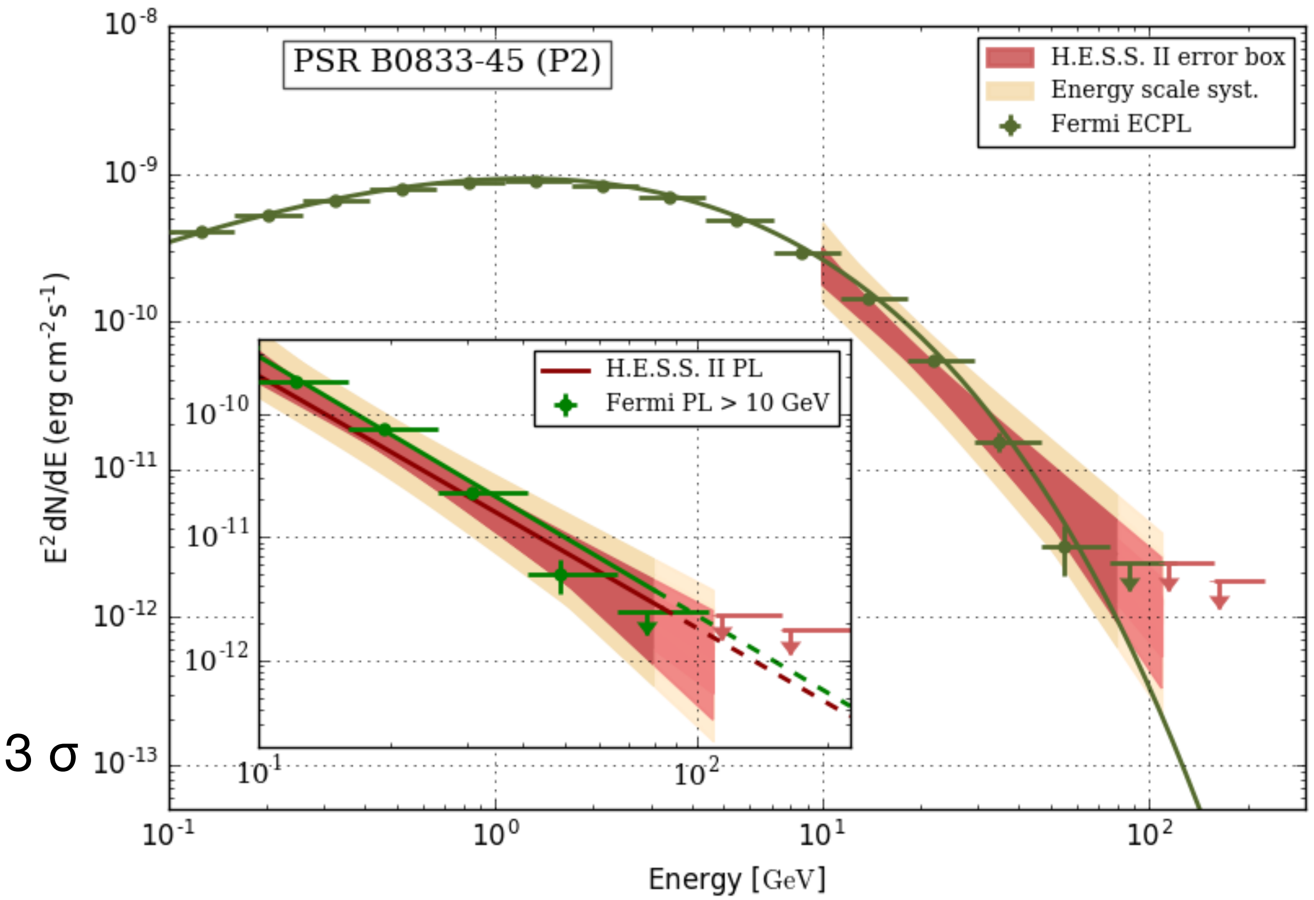
Instrument	Energy range (GeV)	$\langle E_{\mathrm{true}} \rangle$ (GeV)	ϕ_{P2} (phase units)	σ_{L} (phase units)	σ_{T} (phase units)
Fermi-LAT	1-3	1.7	0.5648 ± 0.0001	0.0327 ± 0.0002	0.0080 ± 0.00008
Fermi-LAT	3-10	4.8	0.5653 ± 0.0002	0.0323 ± 0.0004	0.0056 ± 0.0001
Fermi-LAT	10-20	13	0.5650 ± 0.0005	0.025 ± 0.001	0.0038 ± 0.0003
Fermi-LAT	>20	28	0.565 ± 0.001	0.017 ± 0.002	0.0029 ± 0.0008
H.E.S.S. II	~ 10-33	19	$0.564^{+0.001}_{-0.001}$	$0.019^{+0.003}_{-0.002}$	$0.006^{+0.001}_{-0.001}$
H.E.S.S. II	~ 20-80	42	$0.5697^{+0.0005}_{-0.0011}$	$0.031^{+0.006}_{-0.005}$	$0.0007^{+0.0015}_{-0.0007}$
H.E.S.S. II	~ 10-80	31	$0.5684^{+0.0007}_{-0.0013}$	$0.027^{+0.003}_{-0.003}$	$0.002^{+0.0014}_{-0.0008}$

Spectral Energy Distribution

- H.E.S.S. II spectrum of P2:
  power-law fit in [10-110] GeV
- *Fermi*-LAT power-law fit >10 GeV: perfect agreement
- Bound on energy scales:

$$(E_{\mathrm{LAT}} - E_{\mathrm{HESS}})/E_{\mathrm{LAT}} \leq 8\%$$

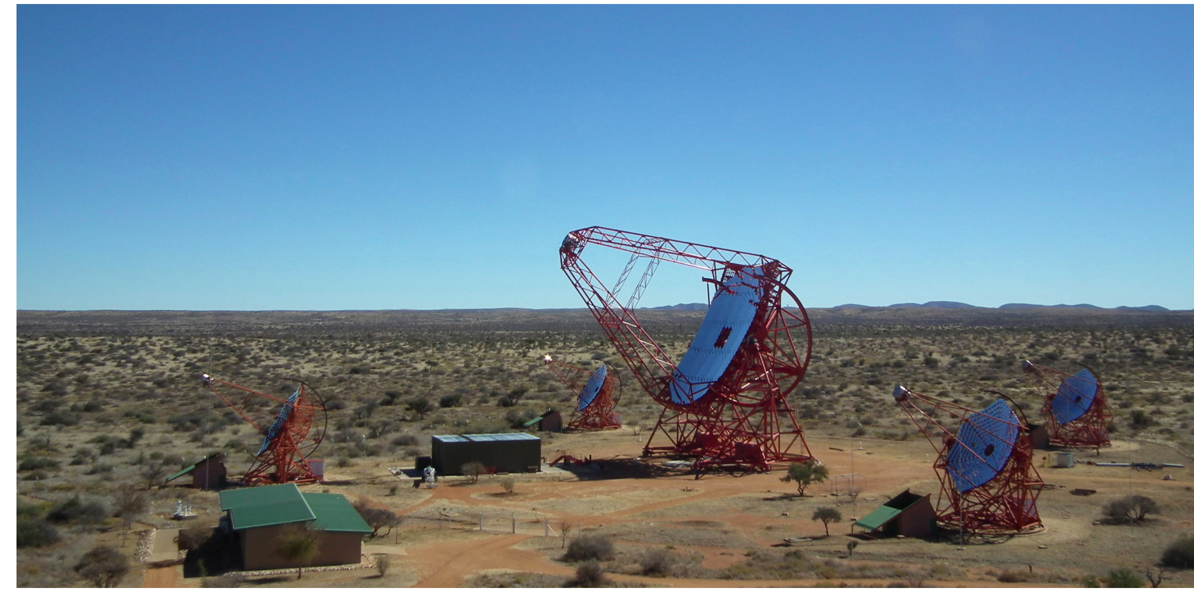
- Last significant bin: <E>=80 GeV, 909 events, 3.3 σ
- *Fermi*-LAT: > 10 GeV evidence for **curvature at 3.3 σ**
- Variation of the power-law index as a function of energy threshold
- The curved nature of P2 **is also favoured** by the H.E.S.S.II measurement at **> 3.0 σ**
- This is **at variance from the Crab pulsar** case



Instrument	Threshold	Γ
H.E.S.S. II	~ 10 GeV	4.06 ± 0.16
Fermi-LAT	10 GeV	4.10 ± 0.08
H.E.S.S. II	~ 20 GeV	5.05 ± 0.25
Fermi-LAT	10 GeV	4.80 ± 0.30

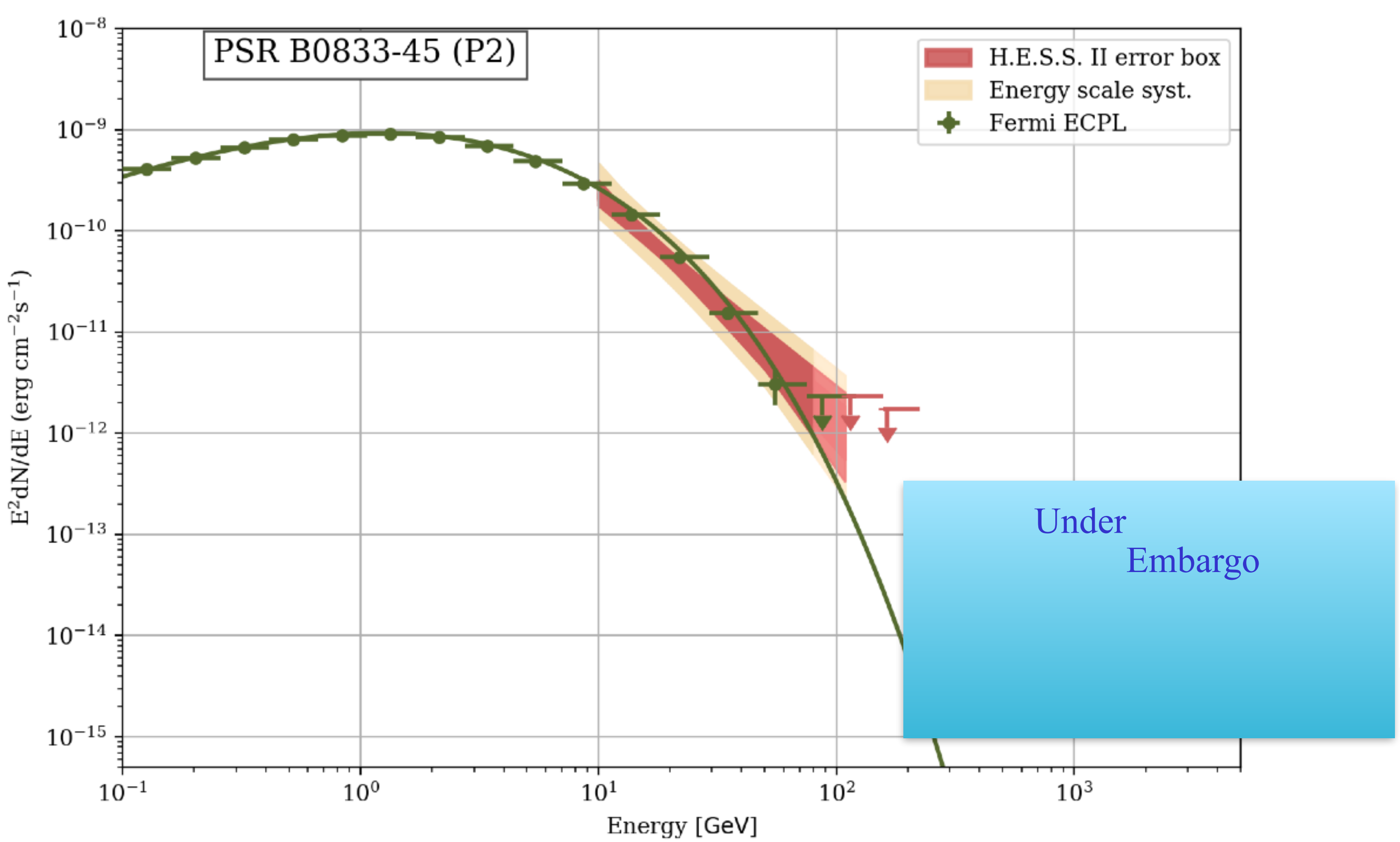
3 to > 7 TeV detection of the Vela Pulsar with H.E.S.S !

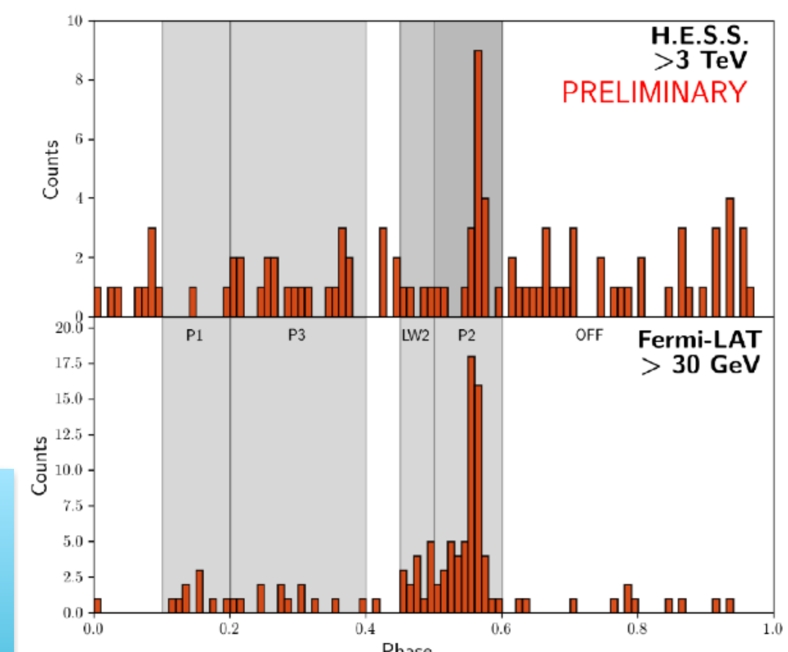
[Djannati-Ataï et al. 2017]



- Data from 2004-2016 observations
- 80 hours in stereoscopic mode:
  at least 2 telescopes among CT1-CT4

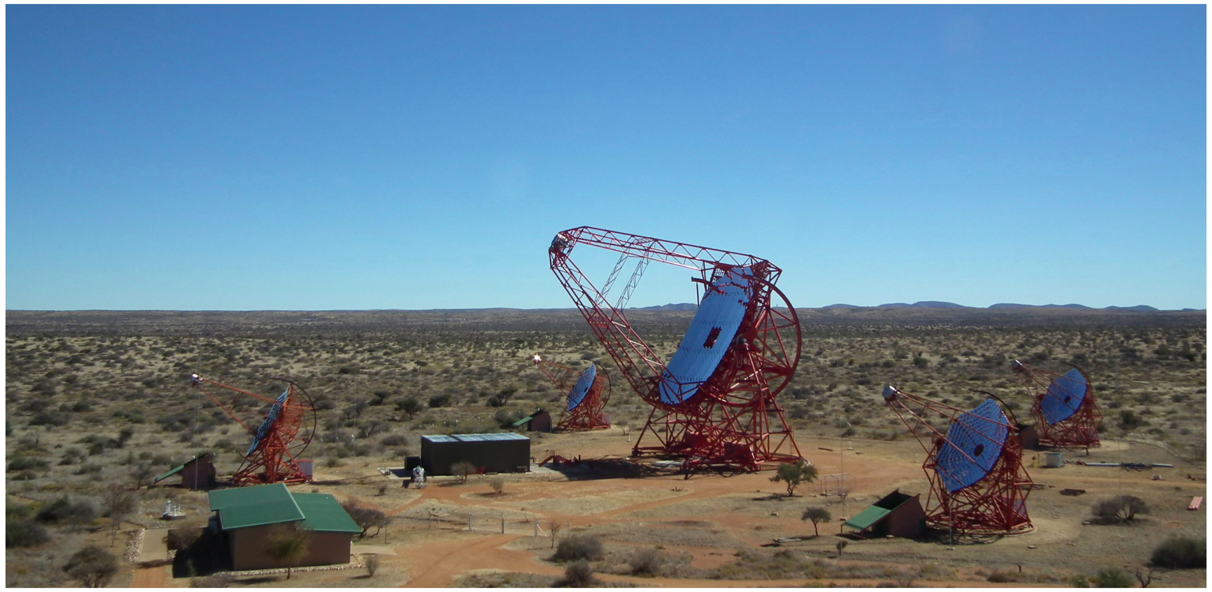
- Signal detected in the 3 to beyond 7 TeV from P2
- Stay tuned for details in the forthcoming paper



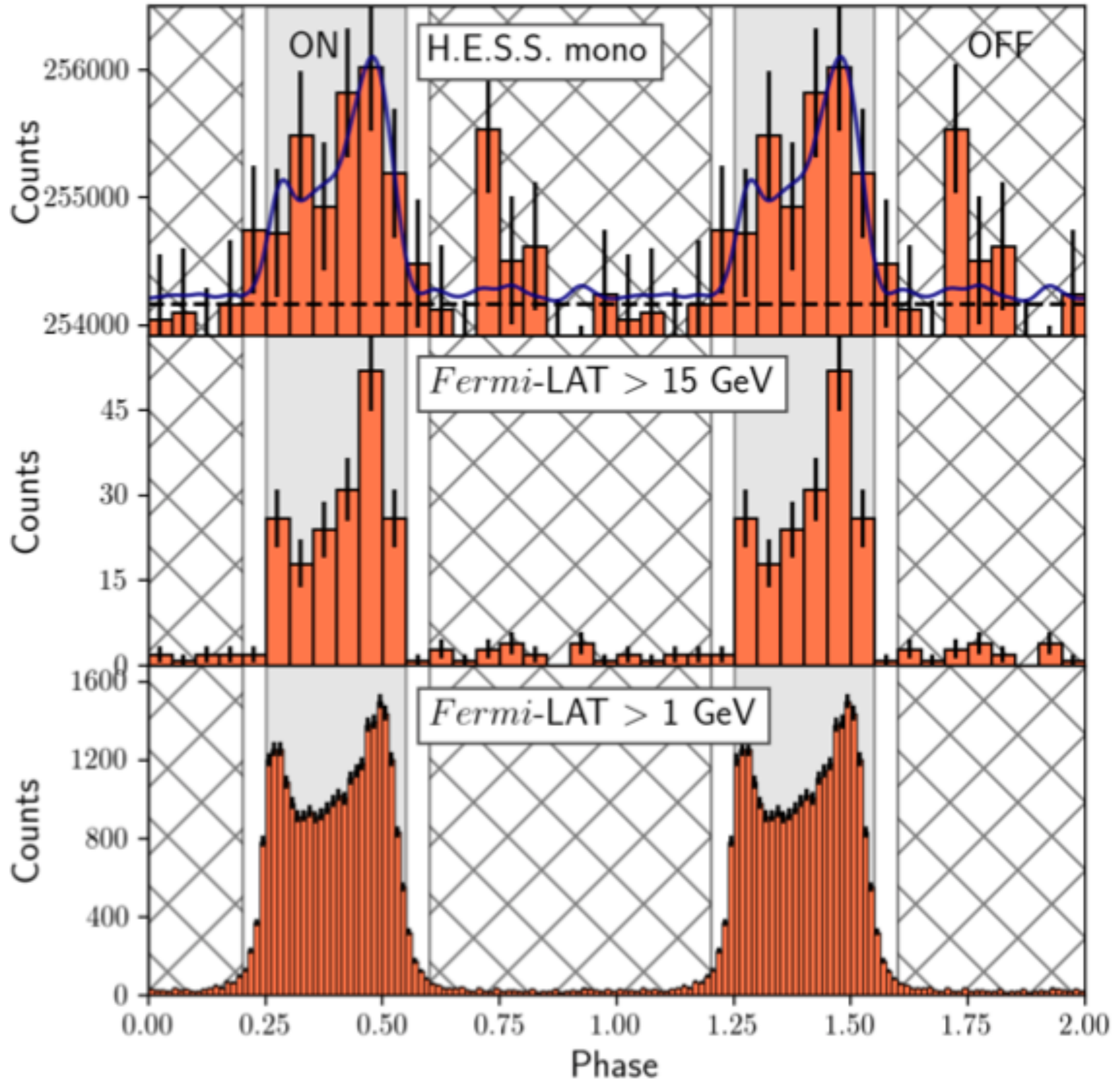


Detection of PSR B1706-44 with H.E.S.S

[Spir-Jacob, M., A.D-A et al. 2019]



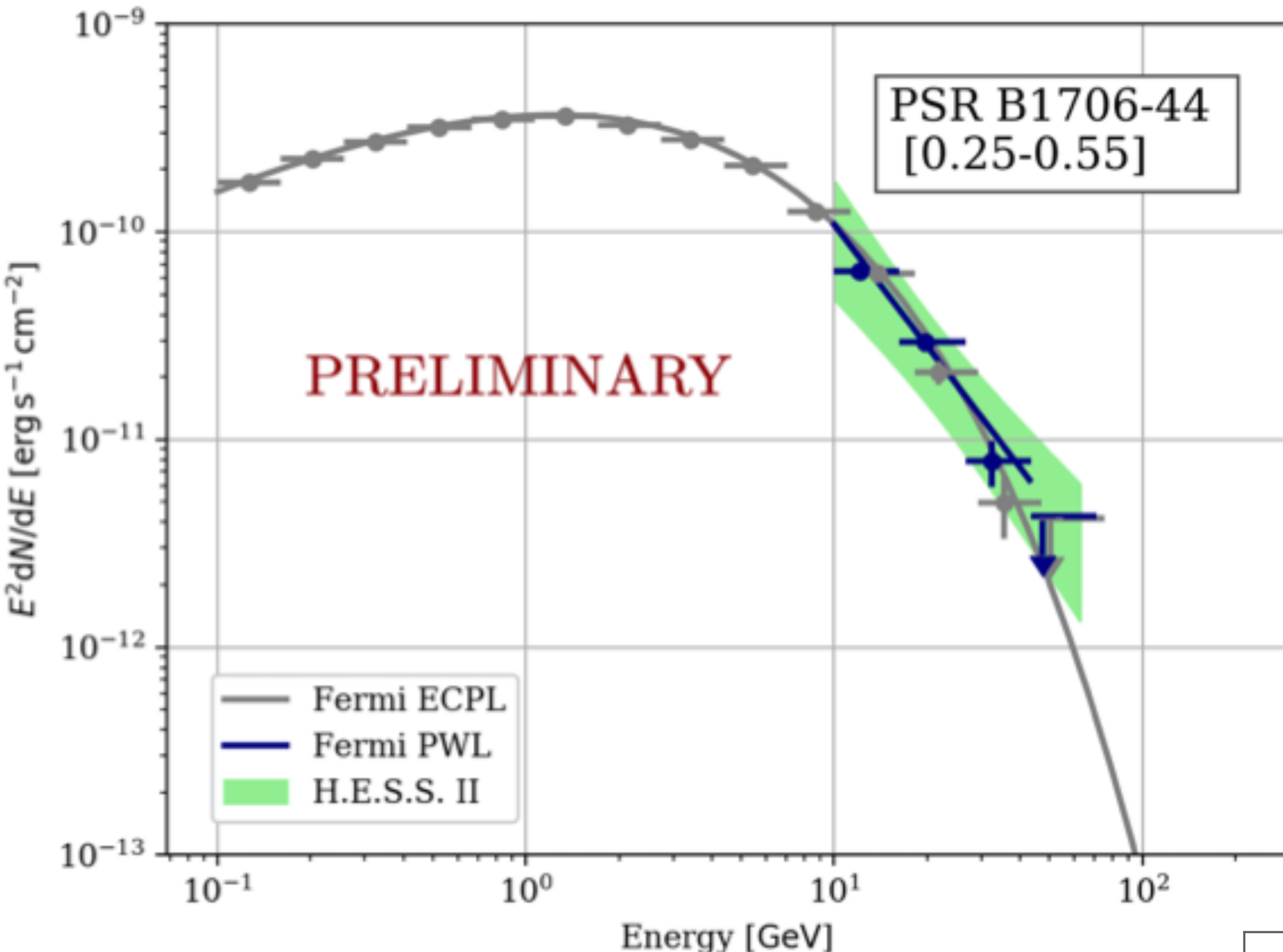
- Vela-like : Edot=3.4×10^{36} erg/s
  p= 102 ms, 17 kyrs @ 2.3 kpc *except*:
  - 3rd brightest, but ~8 times more distant
  - Light curve
- Data from 2013-2015 observations
- 42 hours in monoscopic mode with CT5
- Detected in the 10-80 GeV range



- On=[0.25-0.55] & Off = [0.6-0.2] regions based on Fermi-LAT > 15 GeV
- Pulsed excess = 7171 events
- Significance level = 4.74 σ

- Maximum likelihood ratio test based on Fermi-laT derived PDF:
- Pulsed excess = 8139 events
- Significance level = 4.6 σ

PSR B1706-44 with H.E.S.S
Phase-resolved spectrum



- Power-law fits to Fermi-LAT and HESS data yield fully compatible results with a steep spectral index ~3.8
- A significant signal of ~1000 events is detected > 70 GeV
- However, it is **not possible** to either **confirm or rule out** a **power-law behaviour** of the spectrum

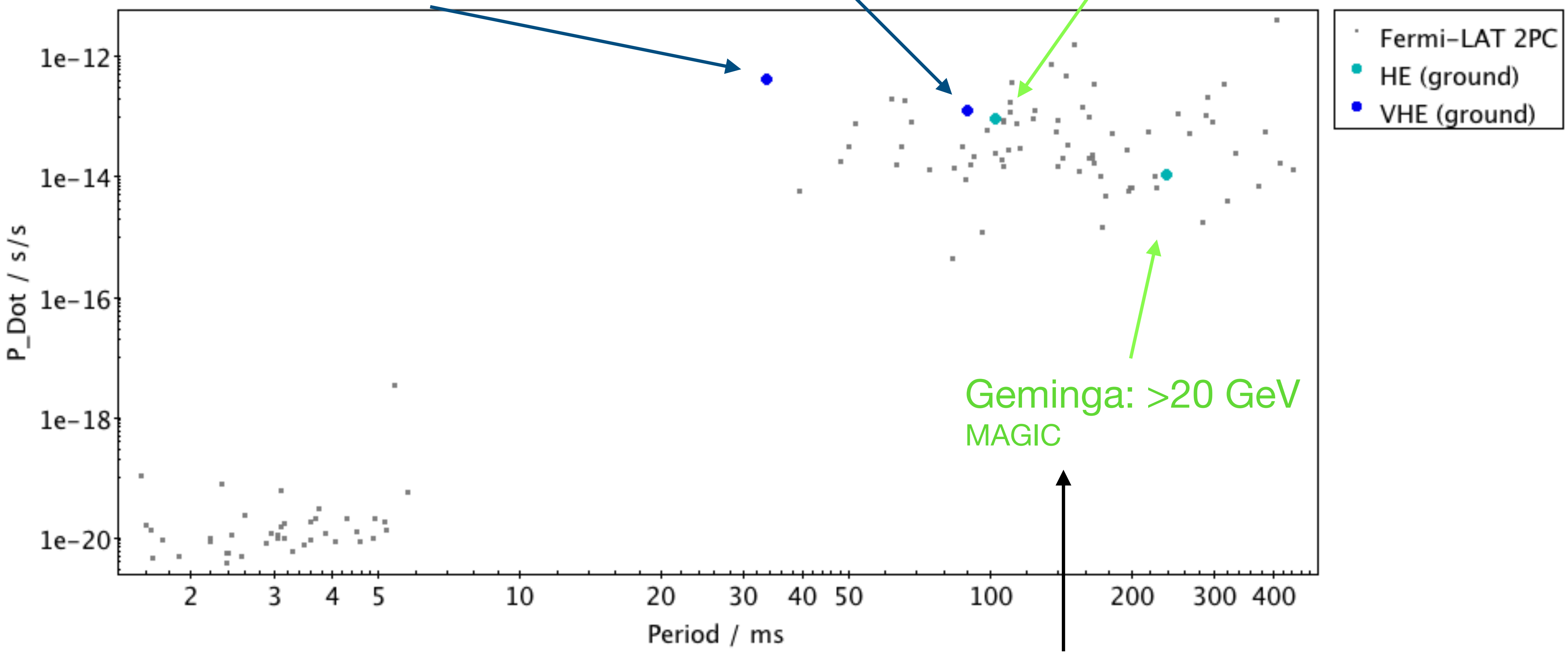
	Energy range	Index	Flux @ 20 GeV [/TeV/cm²/s]
Fermi-LAT	>10 GeV	3.9 ± 0.1	(4.4 ± 0.3)x10^{-8}
HESS	>10 GeV	3.76 ± 0.36	(4.3 ± 0.9)x10^{-8}

Four pulsars detected from ground

Crab : 400 GeV, 1 TeV
VERITAS + MAGIC, resp.

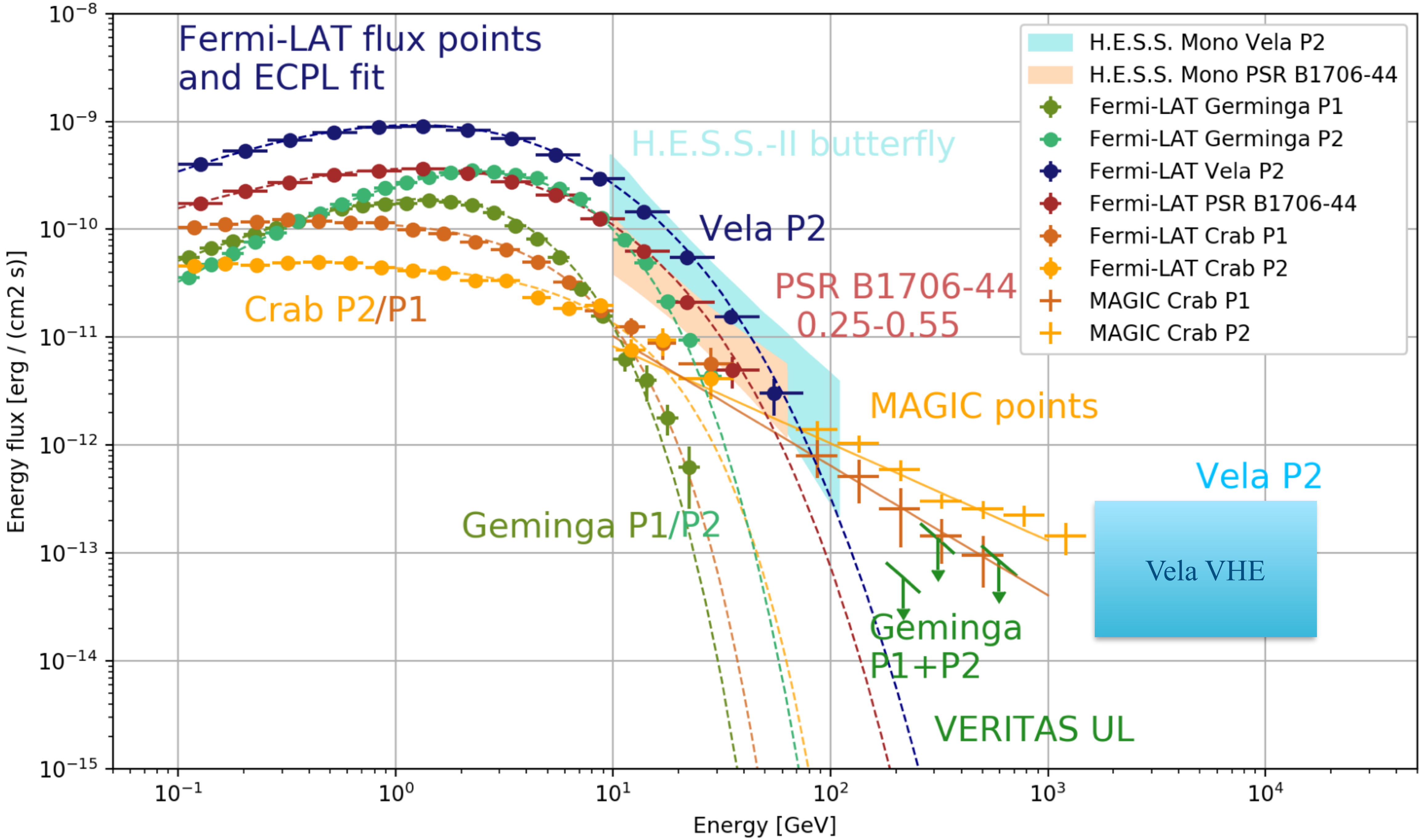
Vela : 10-80GeV
3 to > 7 TeV
H.E.S.S.

B1706-44 : 10-80GeV
H.E.S.S.



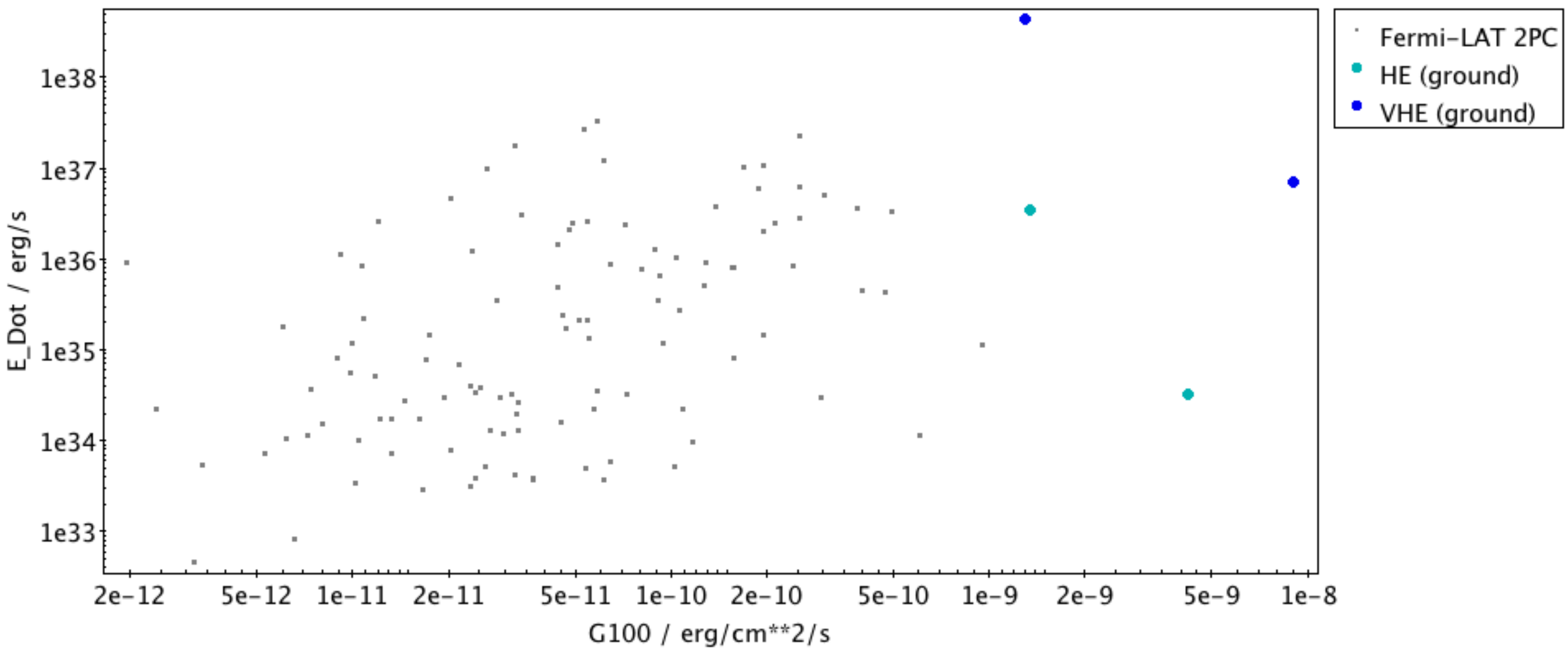
See talk by
Giovanni Ceribella

Four pulsars detected from ground



Four pulsars detected from ground

- Clearly the brightest pulsars in 2PC
- No other distinguishing parameter



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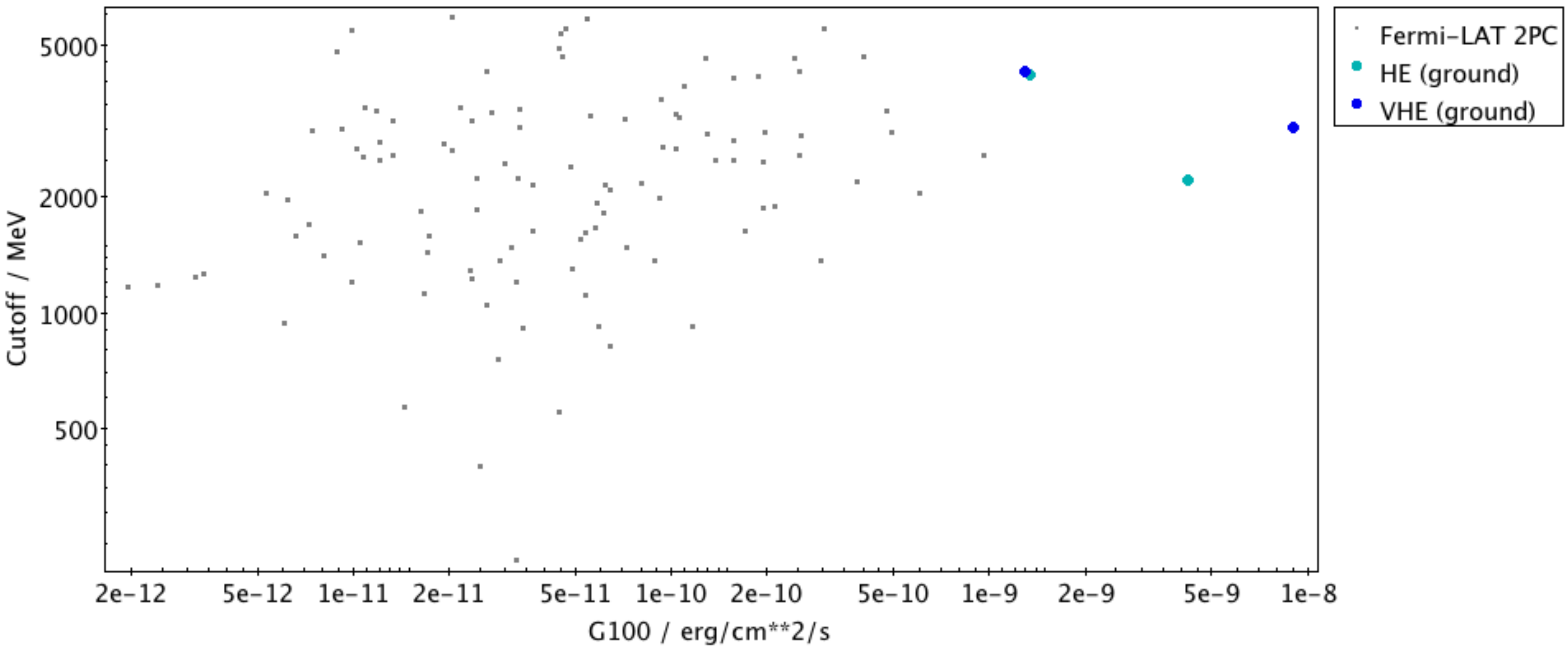

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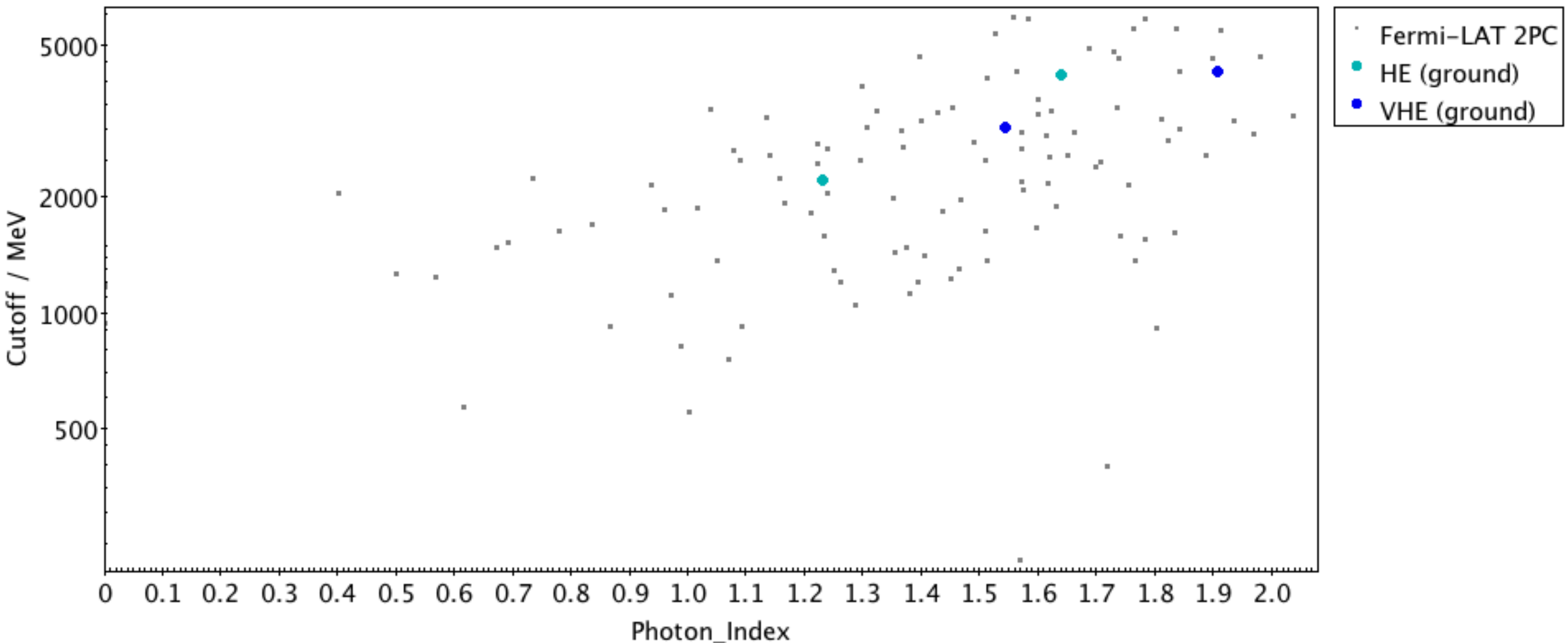


Interpretation & Models
HE + VHE

Acceleration/emission Geometries

- Polar caps
- Slot gaps
- Outer gaps
- LC to Y point
- Wind zone : inside current sheet (CS)

Accelerating force

- MHD force-free : no acceleration!
- Parallel $E_{||}$ in gaps
- Reconnection in CS

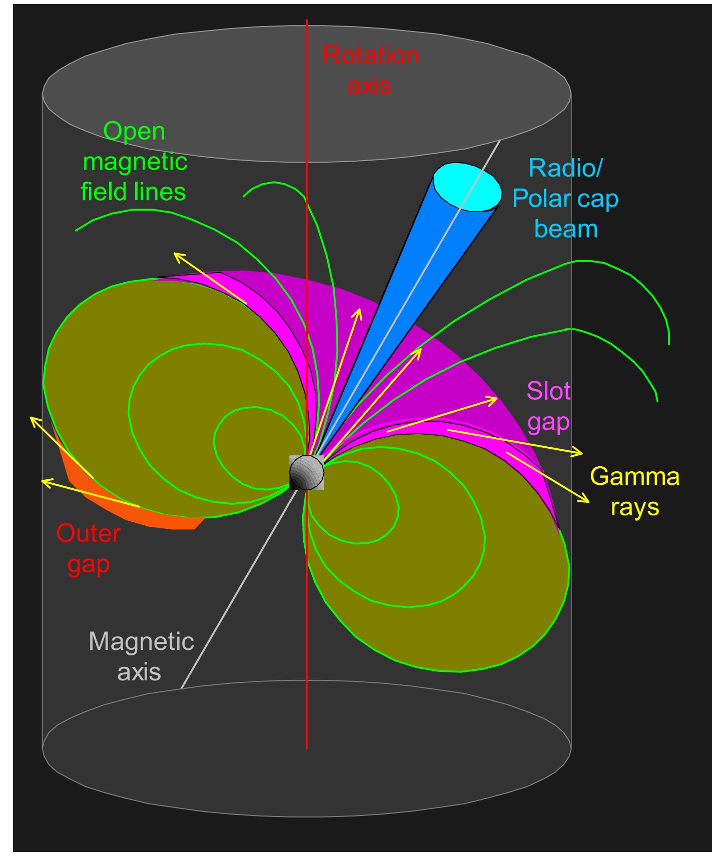
Emission mechanisms

GeV component

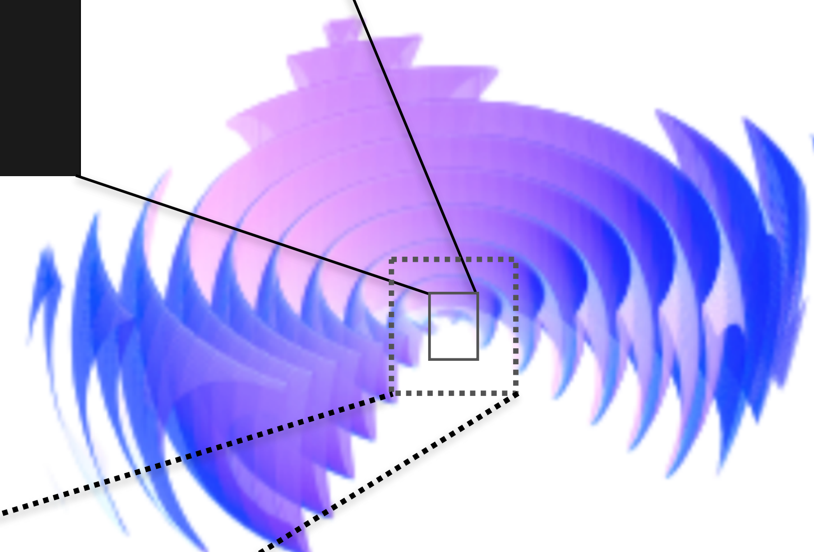
- Curvature, Synchrotron (Cyclotron)
  Synchro-Curvature?
- Within magnetosphere, close to LC or far
  in the CS? Reconnection in CS

TeV component

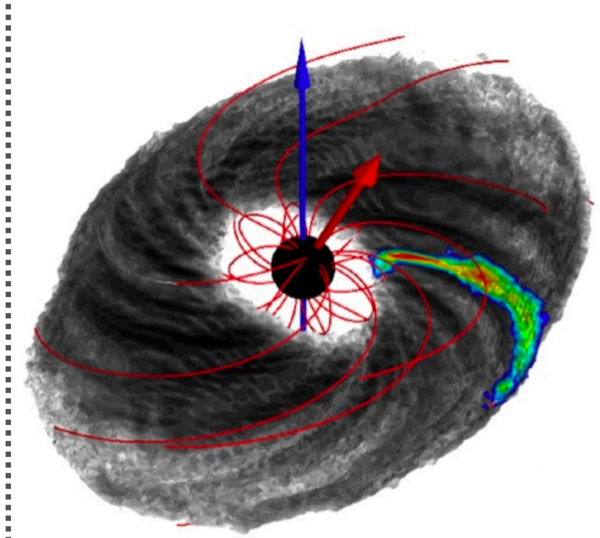
- Inverse Compton(IC)
  - SSC (Synchrotron Self Compton)?
  - IC on soft (opt- IR-far IR), X-rays?
- Within magnetosphere, close to LC or
  far in the CS?



[Many !]



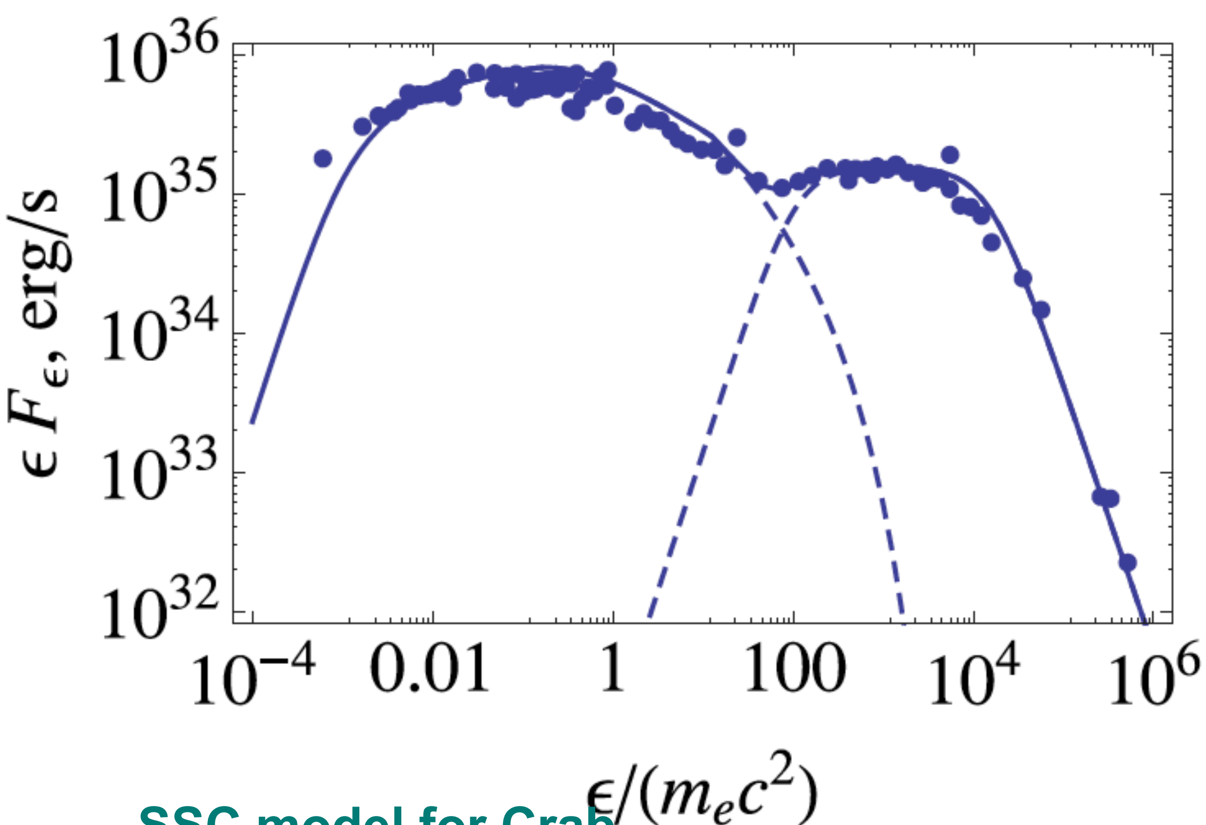
[Michel, Coroniti, Lyubarskii, Kirk, Petri +]



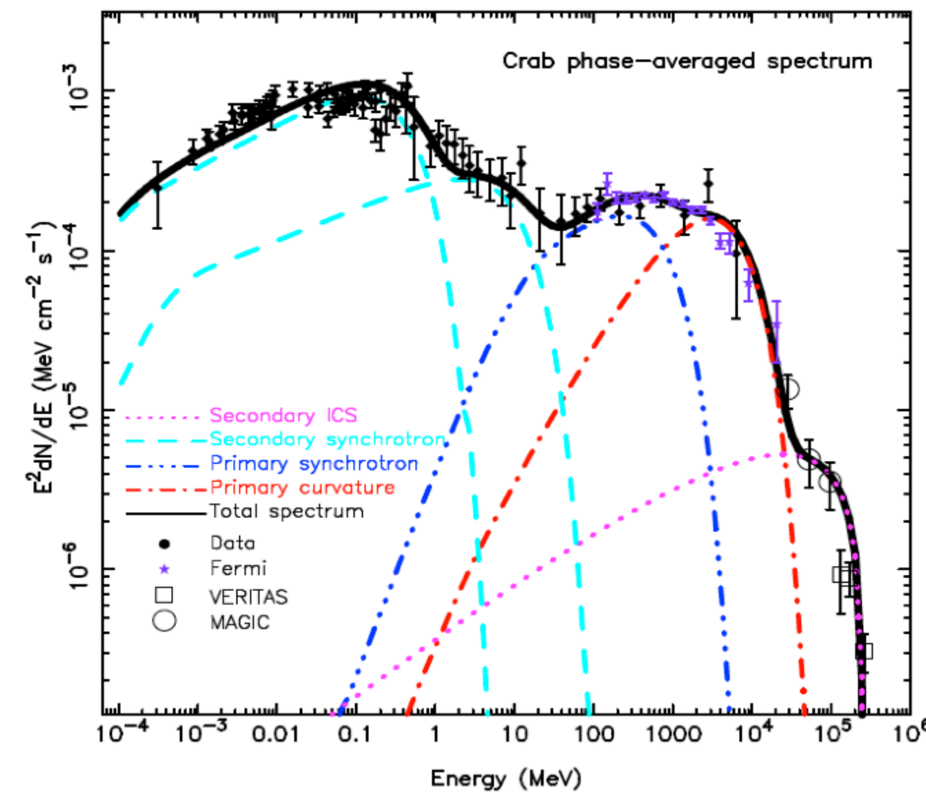
[Cerutti+ 2016,17]

Crab Emission models : $E_{||}$

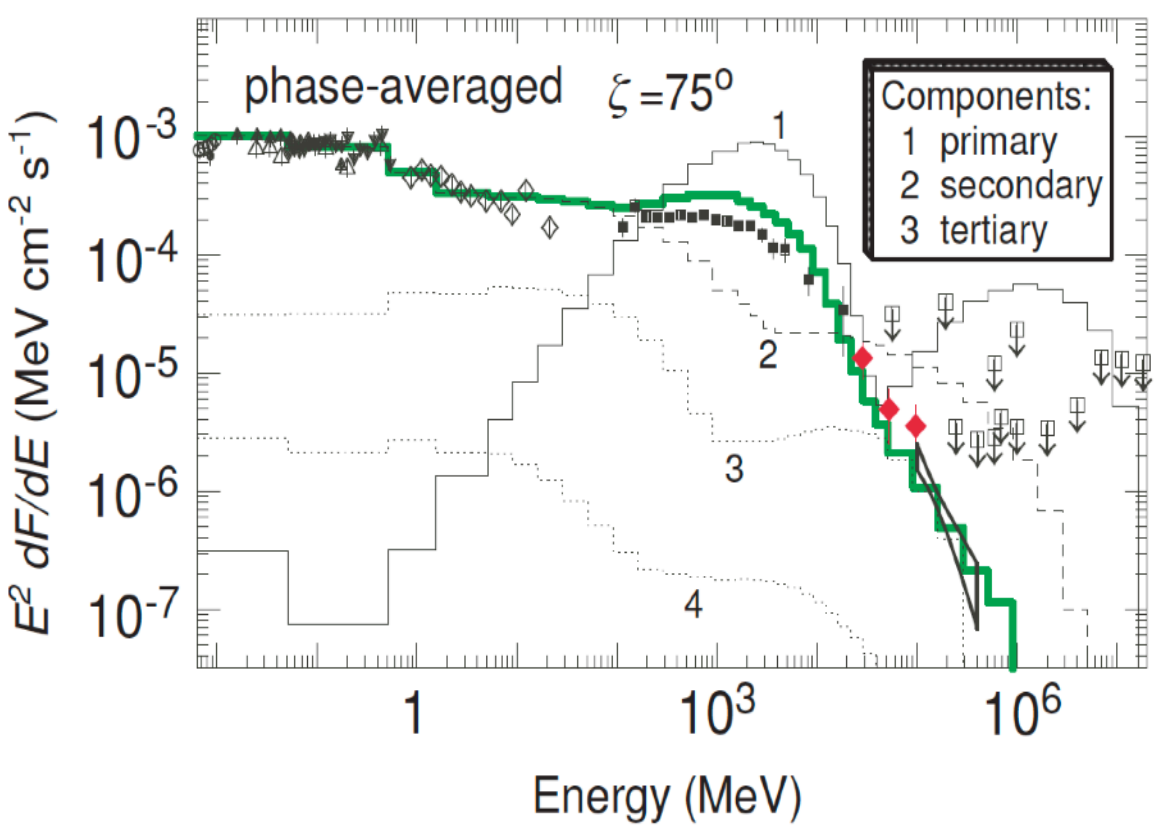
CSC model for Crab : Inverse Compton
[Lyutikov 13']



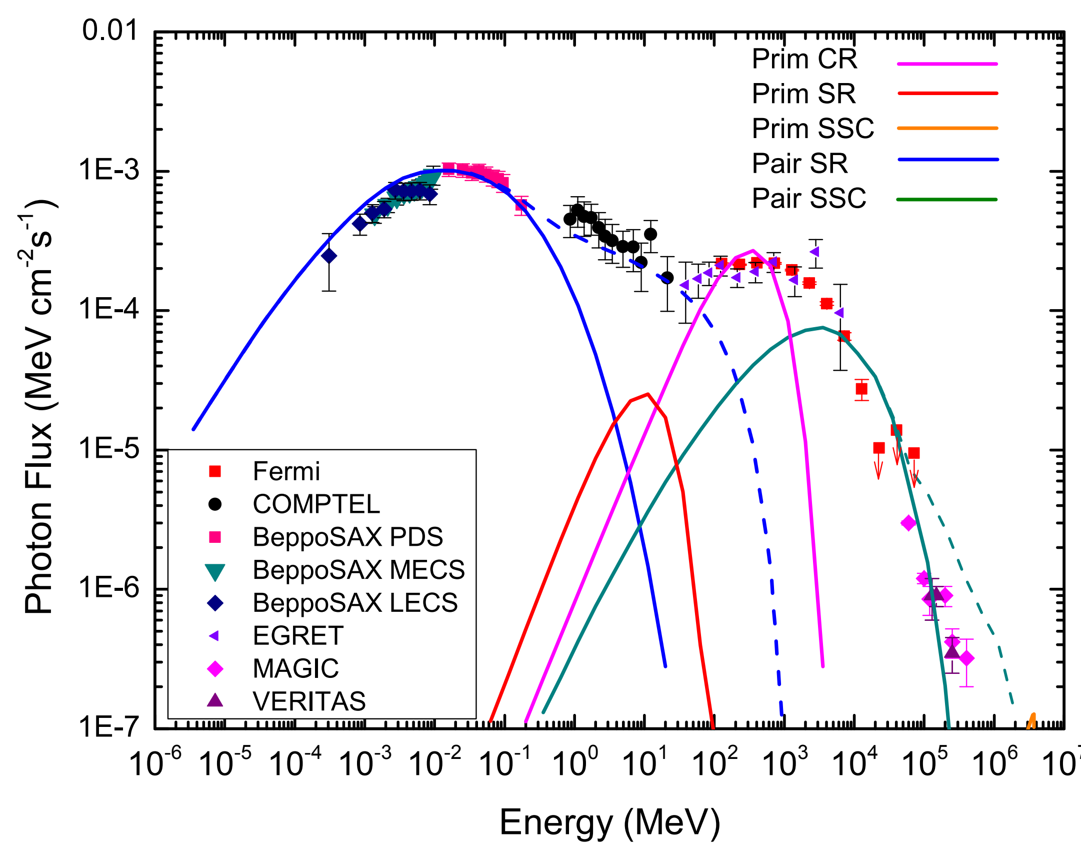
Dual annular gap
[Du et al 12']



SSC model for Crab
[Aleksic et al 11', Hirotani 13'+]



SSC model for Crab
[Kalapotharakos & Harding 15']

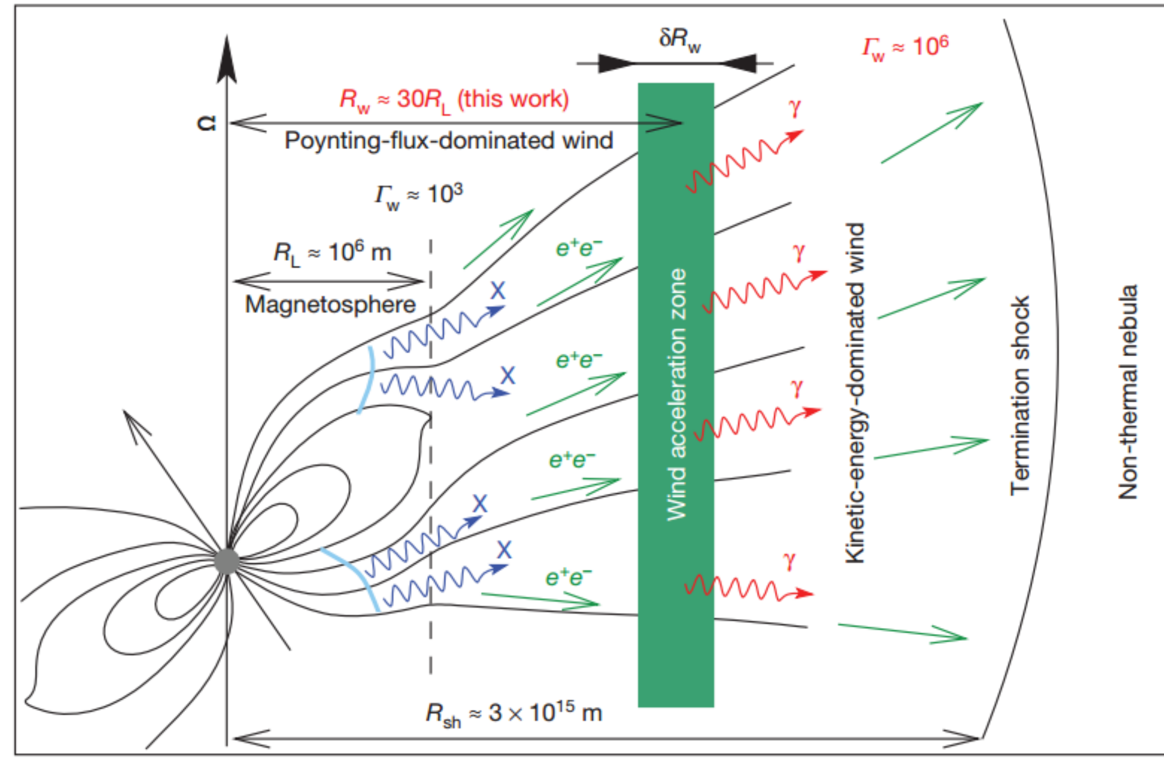


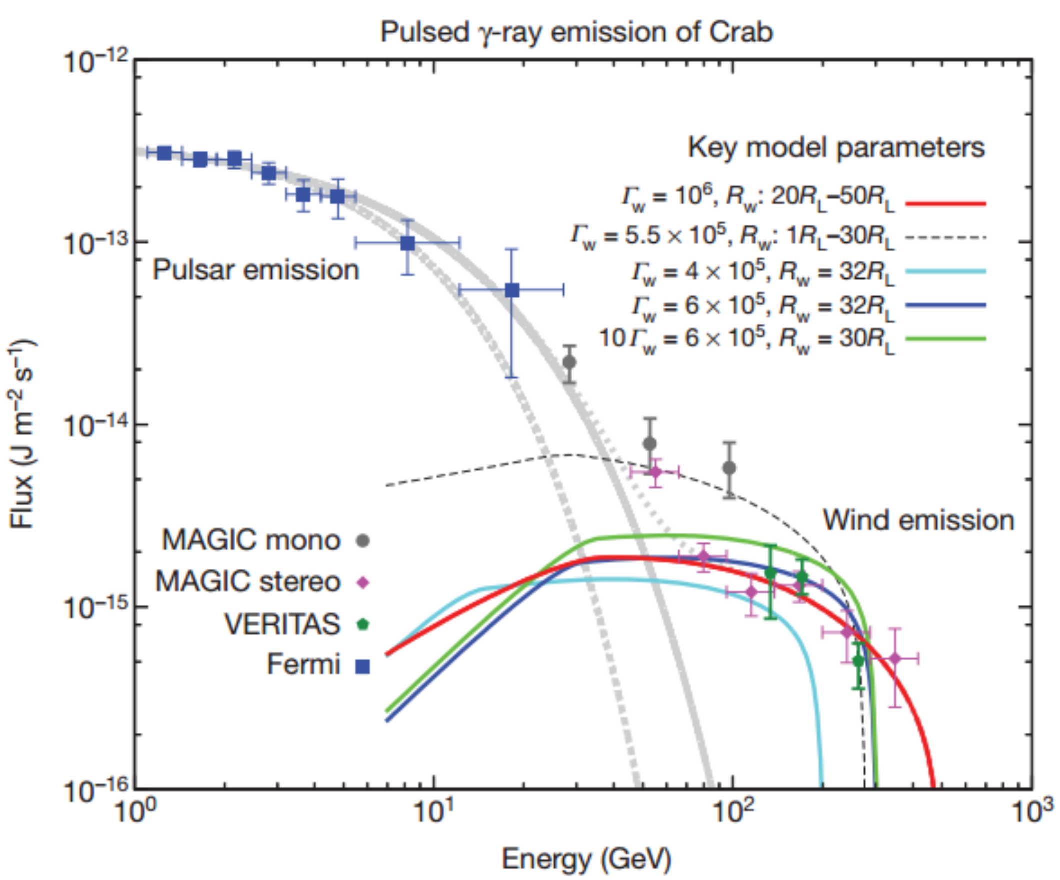
Crab Emission models: wind, $E_{||}$ + unknown

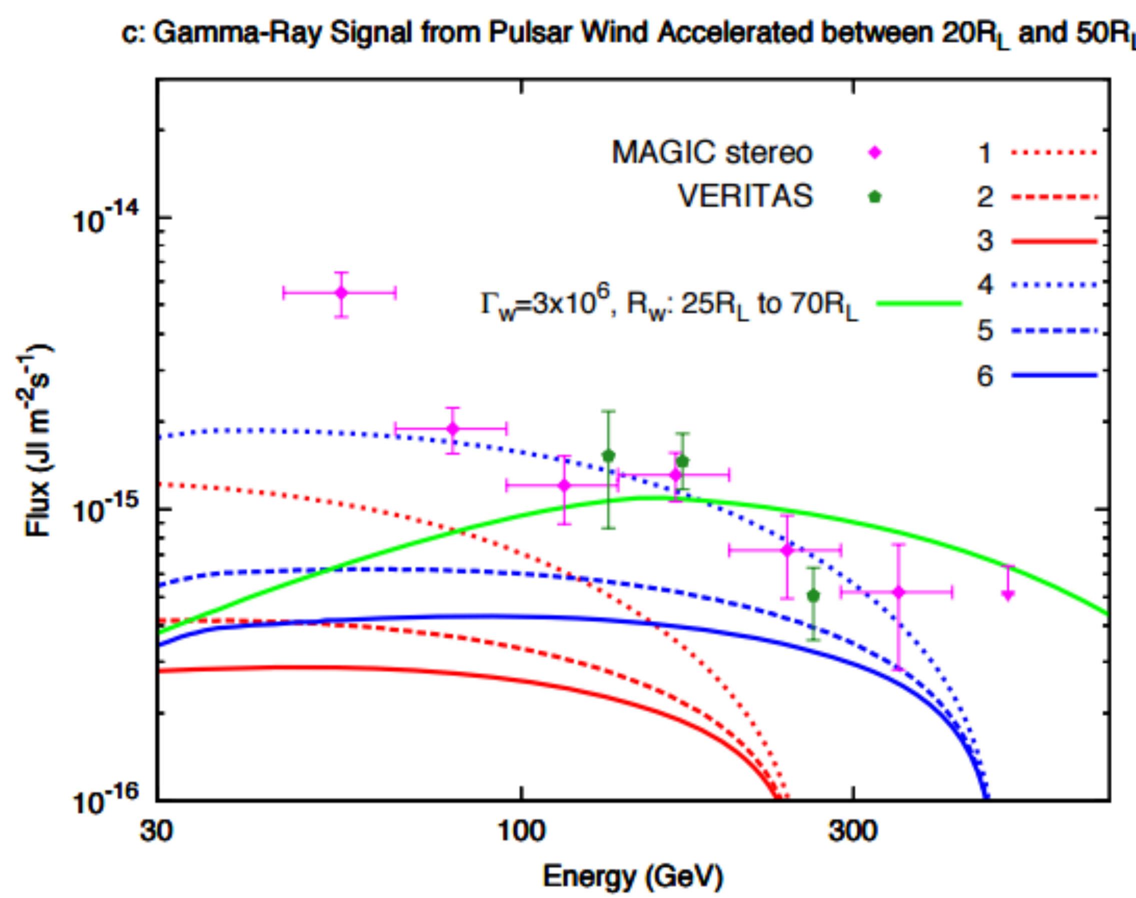
Cold wind [Aharonian et al. 2012]

- Acceleration and emission zones well beyond the Light Cylinder
- Abrupt acceleration (Γ_w ~10^5-10^6) unknown mechanism
- Inverse Compton scattering off the lower energy pulsed emission (IR, X-rays)
- Implies 2 components
- 20-50 R_LC fits the 80-400 GeV (red)

- Did survive to the extension to 1 TeV (low energies not reproduced (see Bogovalov et al 2017).
- Note: phase-averaged fit





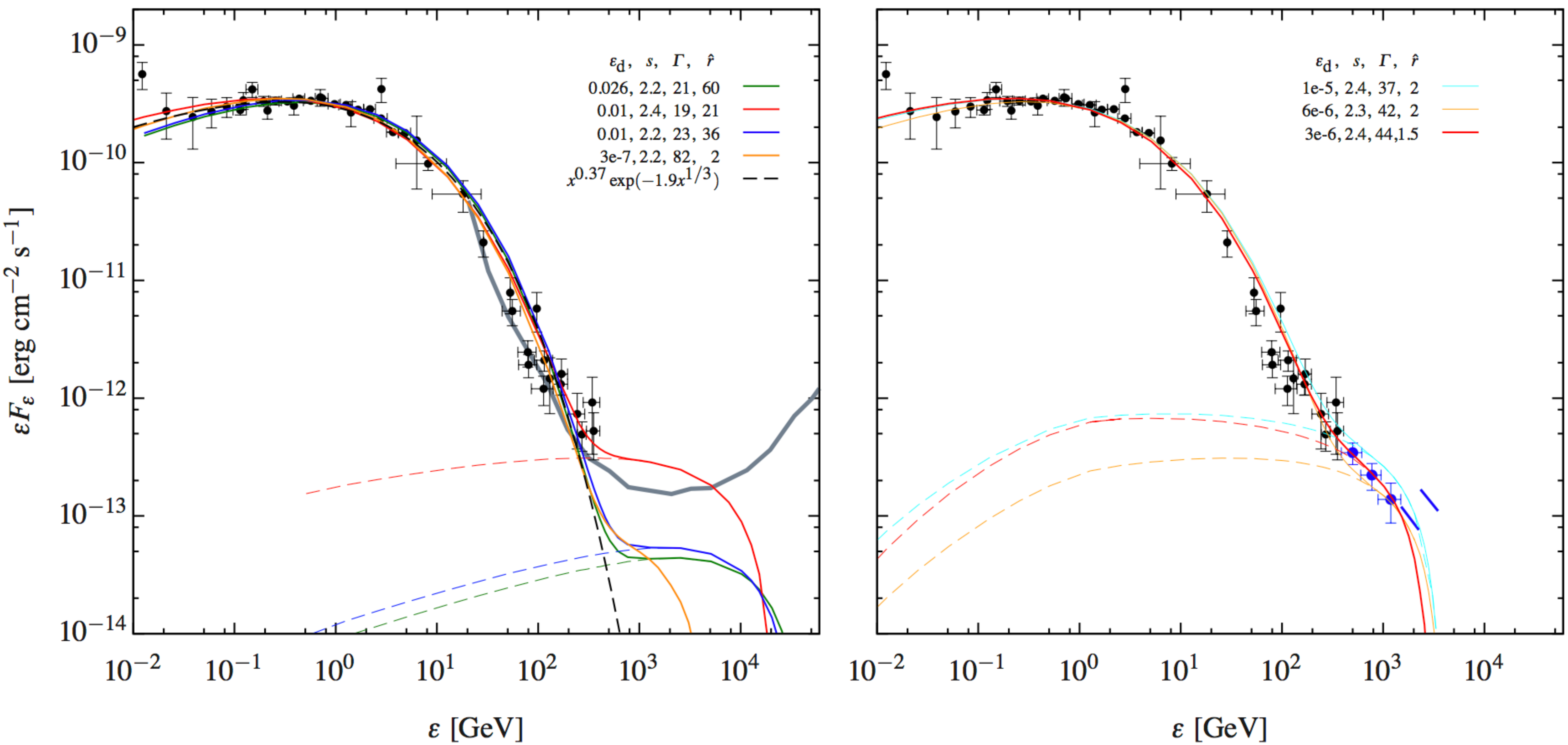


Crab Emission models : wind, reconnection

Striped wind [Arkas & Dubus 2012, Mochol & Pétri 2015, Mochol 2017]

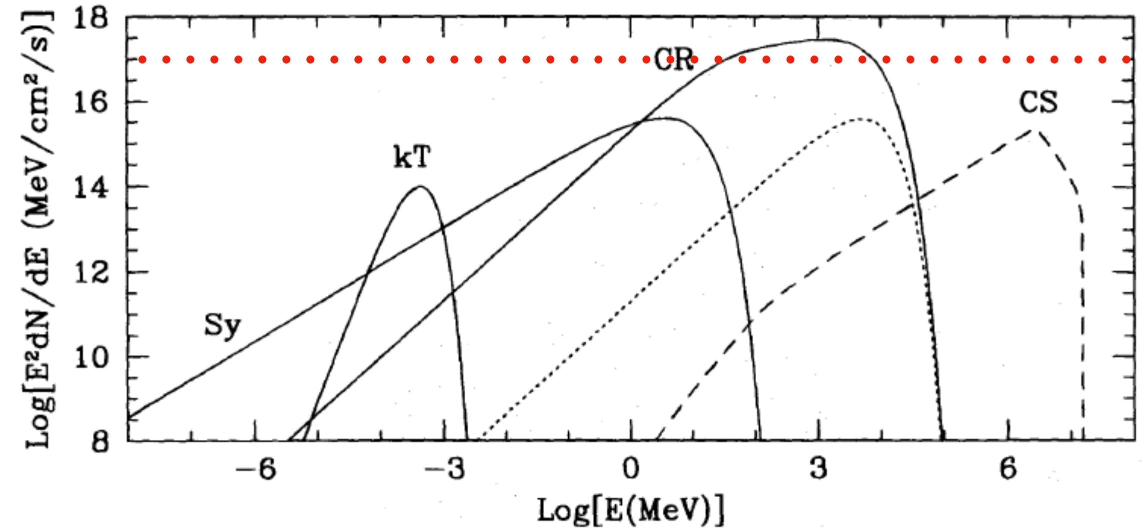
- Particle energisation within current sheet and close to the Light Cylinder
- GeV emission through synchrotron radiation in the current sheet
- A synchrotron Self-Compton component is predicted to extend beyond 1 TeV
- Young/powerful pulsars like Crab : $\Gamma_w < 100$
- Vela-like : $\Gamma_w < 50$

- Note : phase averaged fit
- Some light curve properties, e.g. thinning of peak widths with energy, remain to be reproduced
- Did survive to the extension to 1 TeV

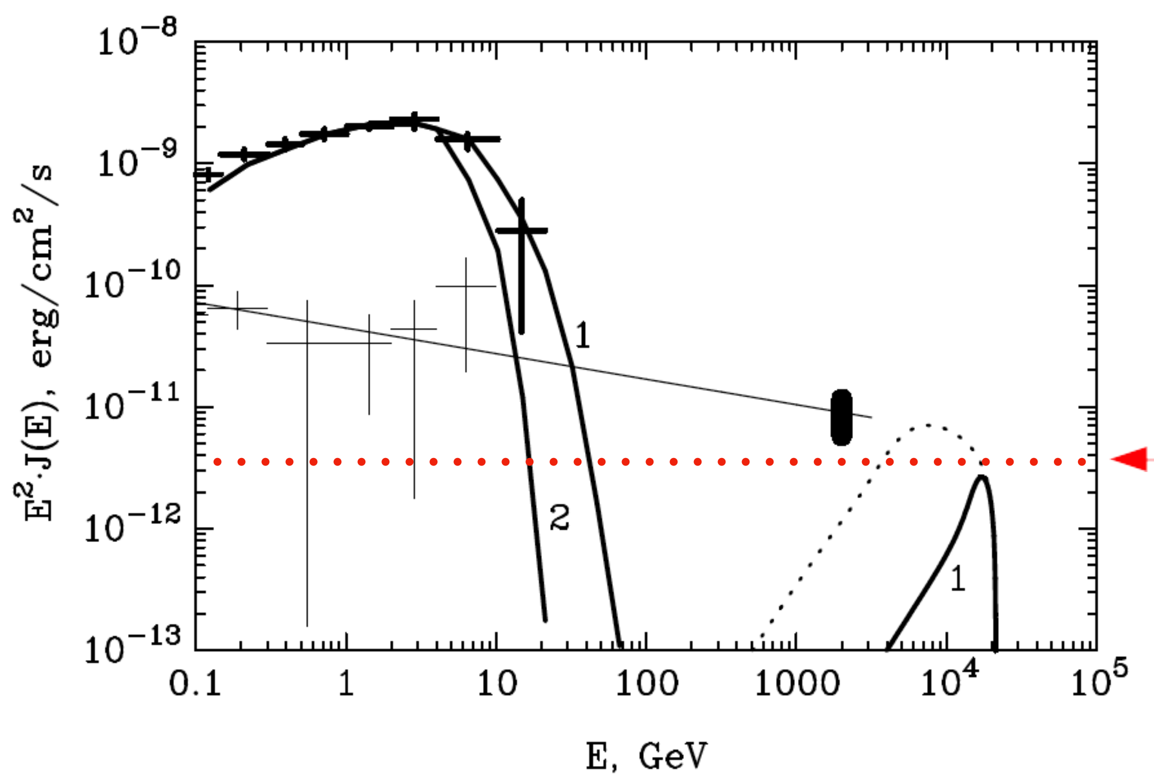


Vela VHE emission :
A second component: Inverse Compton!

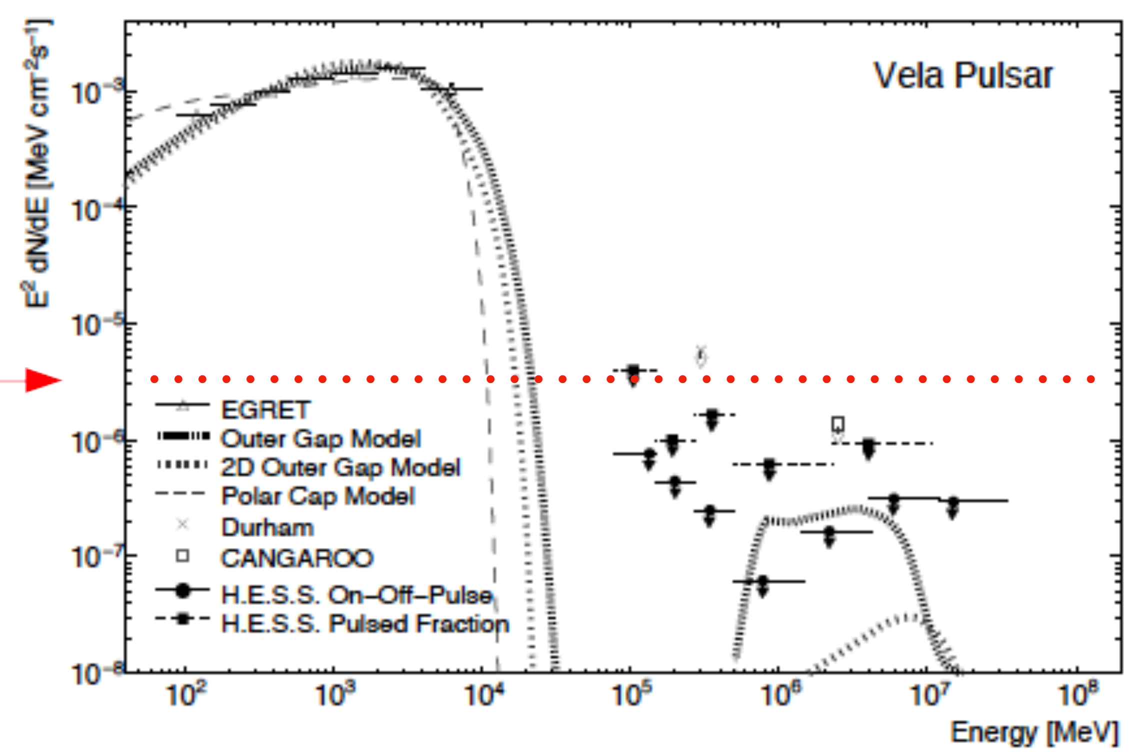
- Cheng, Ho & Ruderman (1986) :
  - IC: general considerations
- Romani 1996: IC: OG primary e⁻ + IR
- Hirotani & Shibata (2001), IC: OG primary e⁻ + IR
- Aharonian & Bogovalov (2003), IC: OG primary e⁻ + IR



Romani (1996)



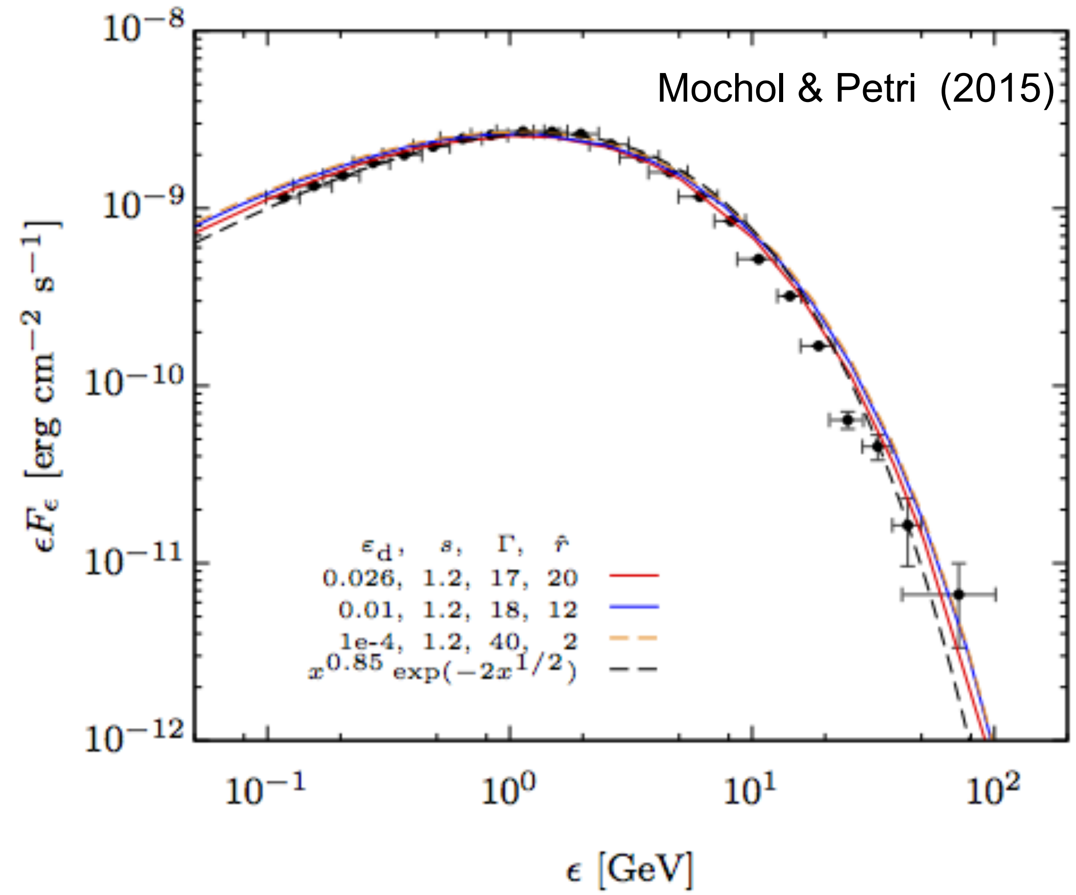
Aharonian & Bogovalov (2003)

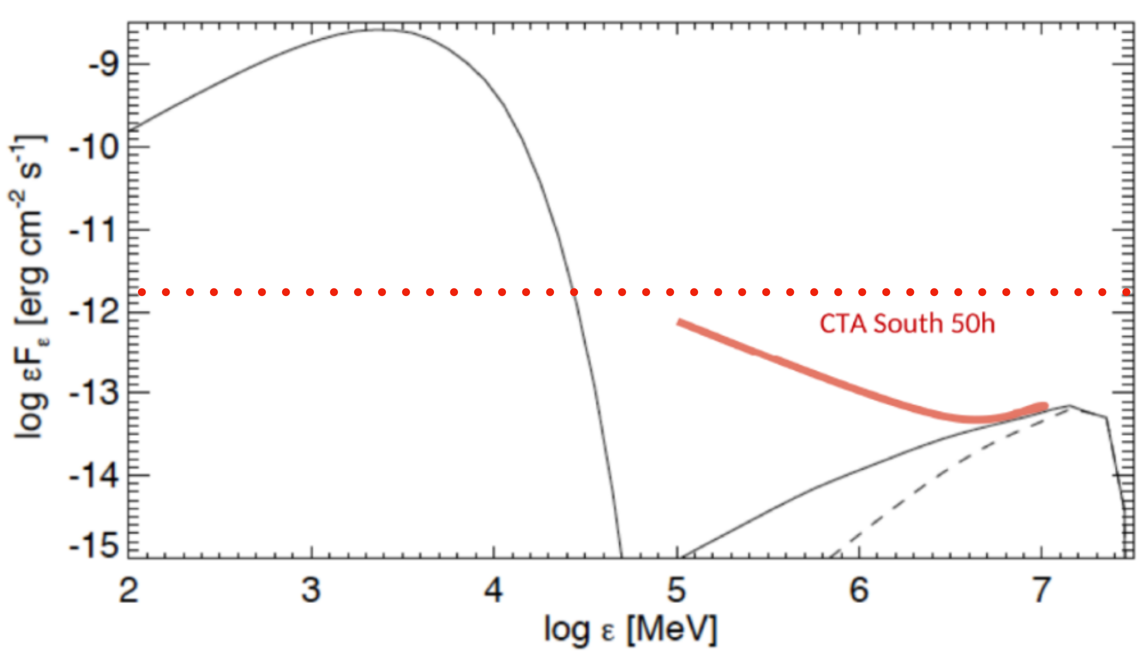


Hirotani & Shibata (2001)

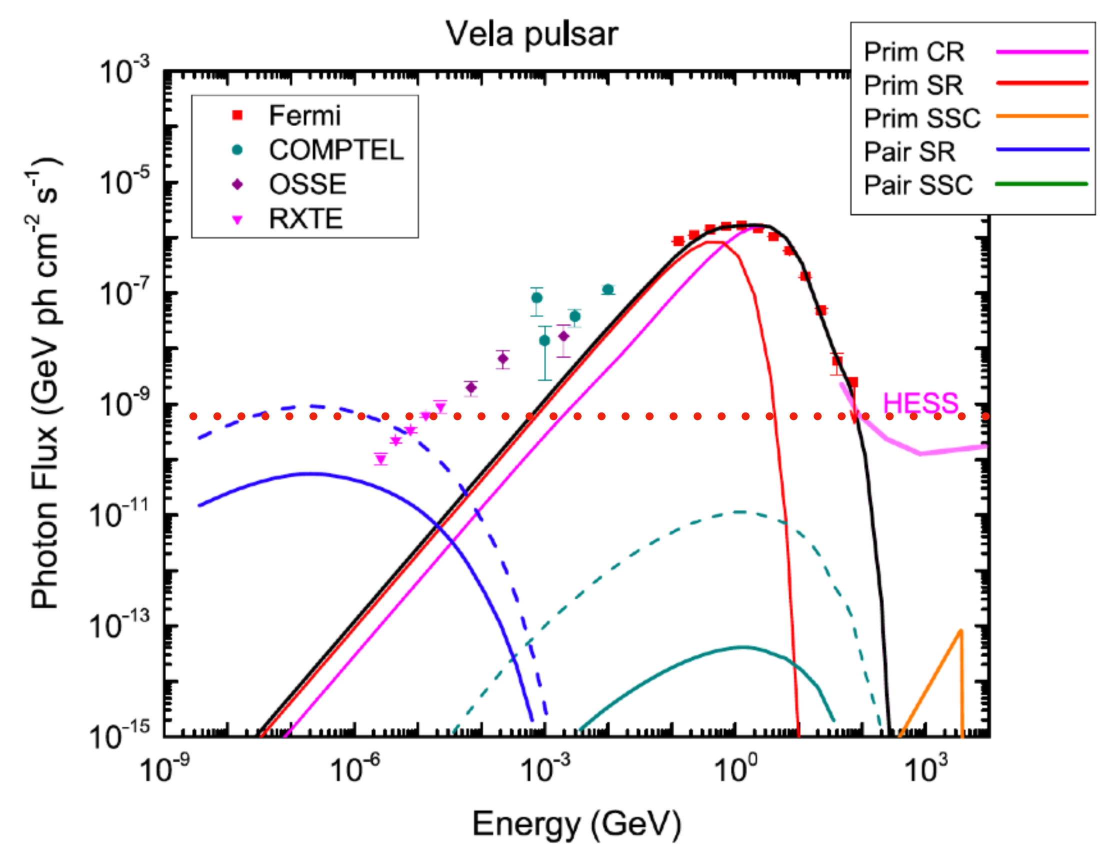
Vela VHE emission : A second component

- Mochol & Pétri (2015): SSC:
  - Striped wind/ current sheet;
    → **No component expected for Vela**
- Harding & Kalapathorakos (2015):
  - SSC from primaries and pairs inside/outside LC
    → **No component expected for Vela**
- Rudak & Dyks (2017): IC: OG primary e^- + optical/IR
  - → **phase resolved**





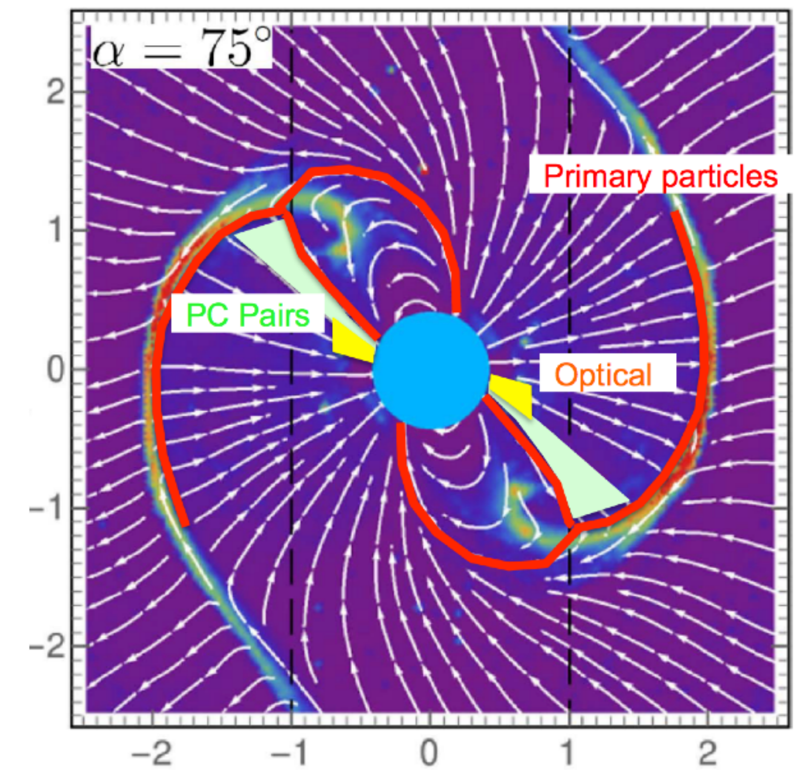
Rudak & Dyks (2017)

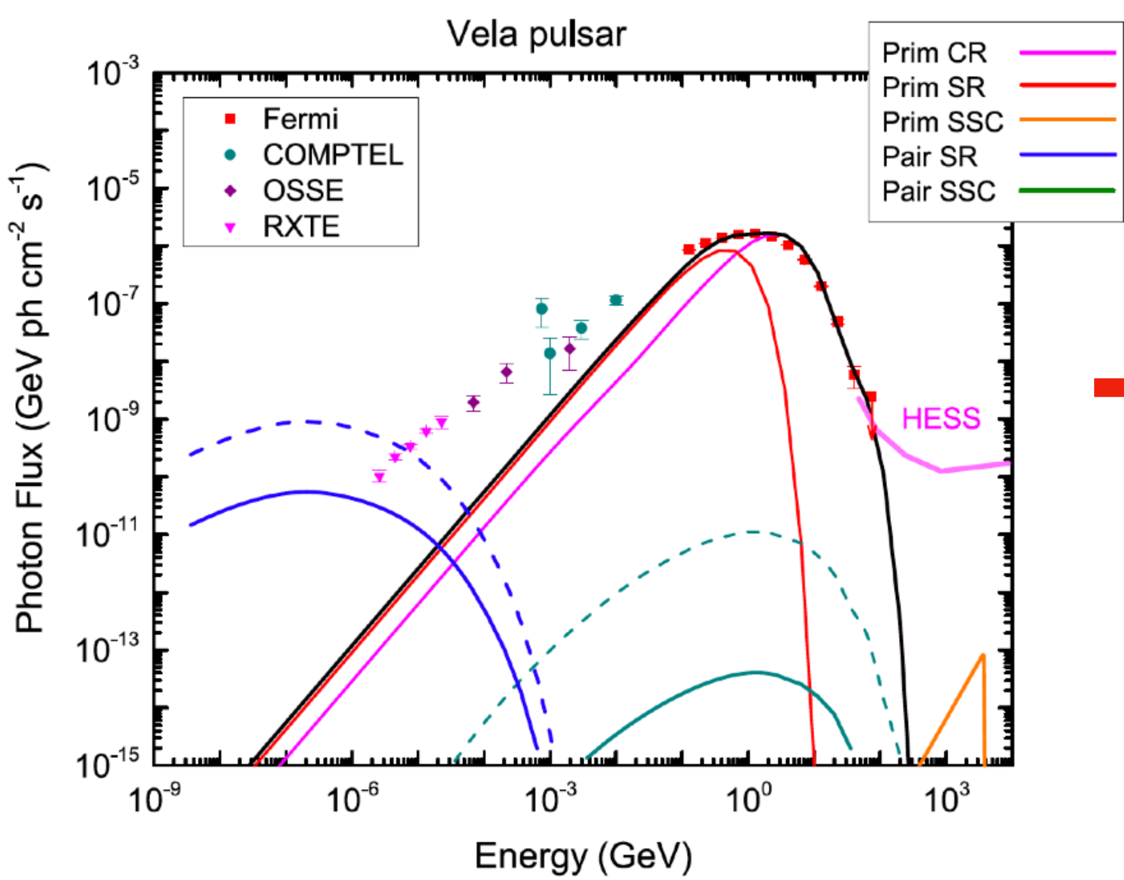


Harding & Kalapathorakos (2015)

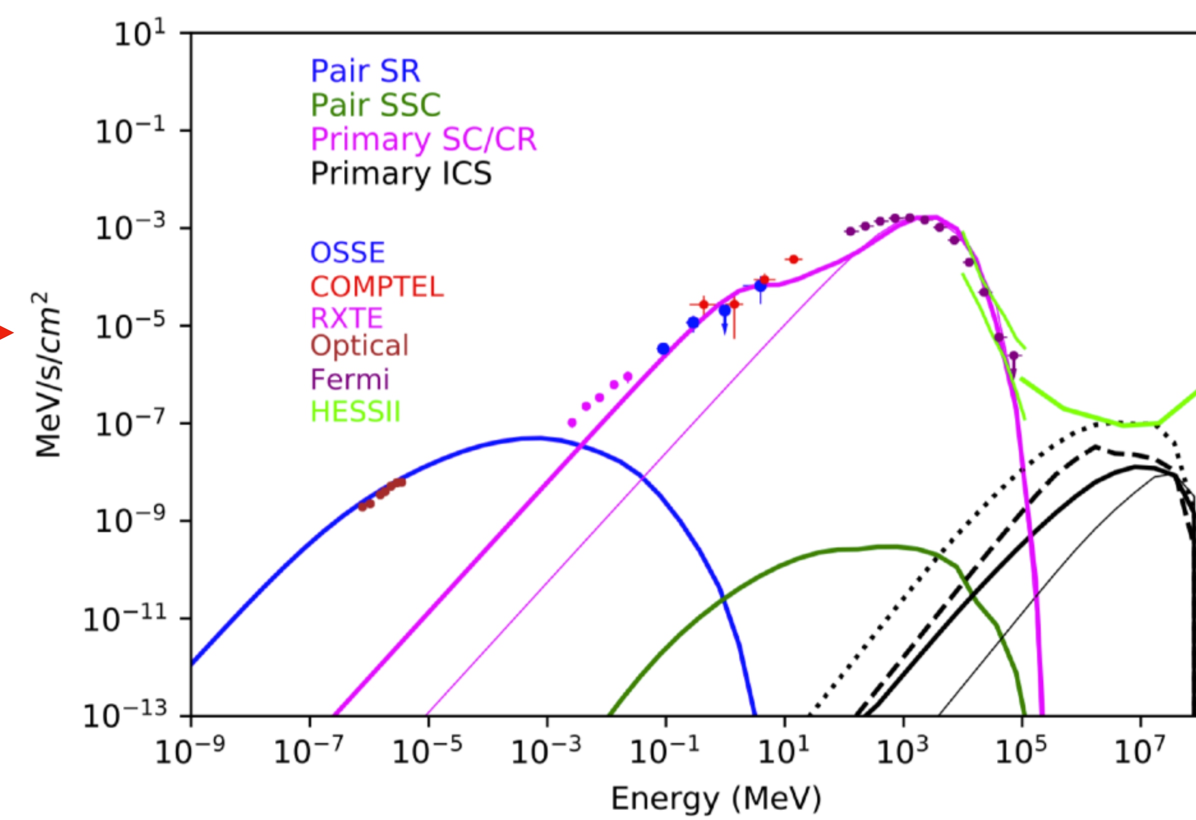
Vela VHE emission : A second component

- Harding (2018) : IC component SG primary accel. by $E_{||}$ to beyond LC + optical/IR
- Inside and outside LC, different electric field intensities
- GeV: (synchro-)curvature,
- Very very faint VHE component predicted (2015)
- VHE: IC on opt-IR from poles
- IC Flux, index, depends on target assumptions
- Fit to data points is difficult





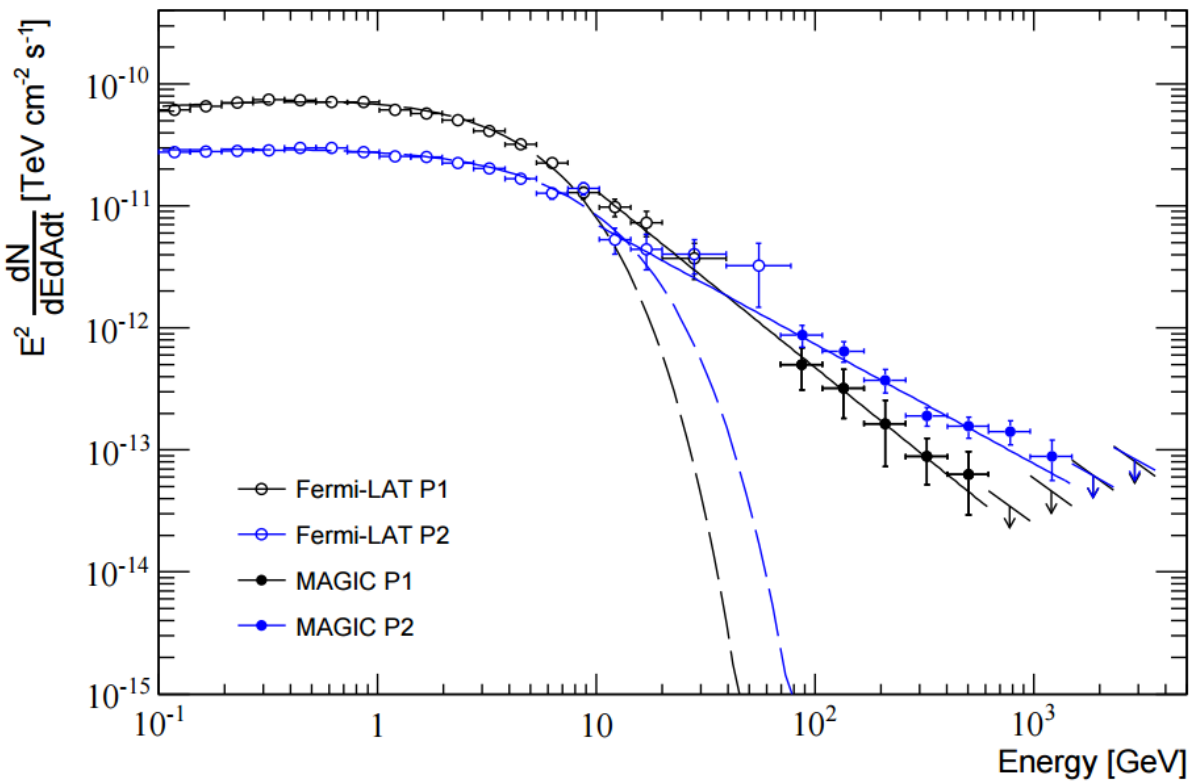
Harding & Kalapathorakos (2015)

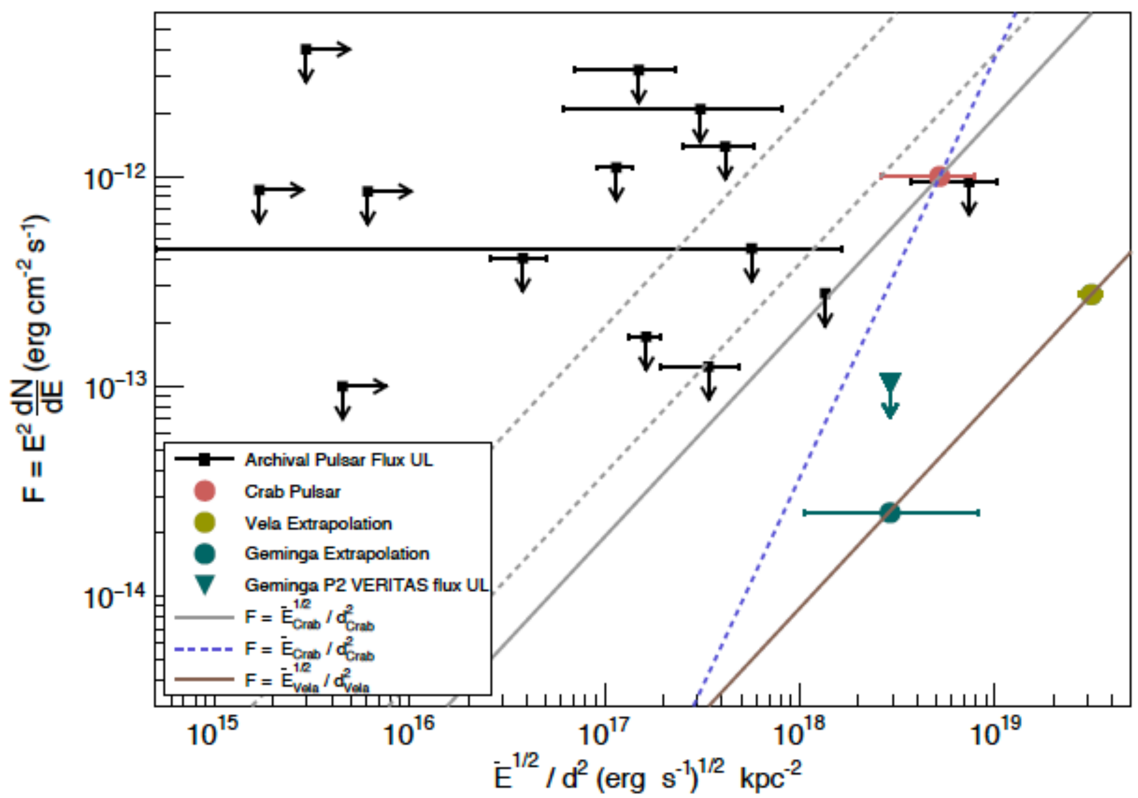


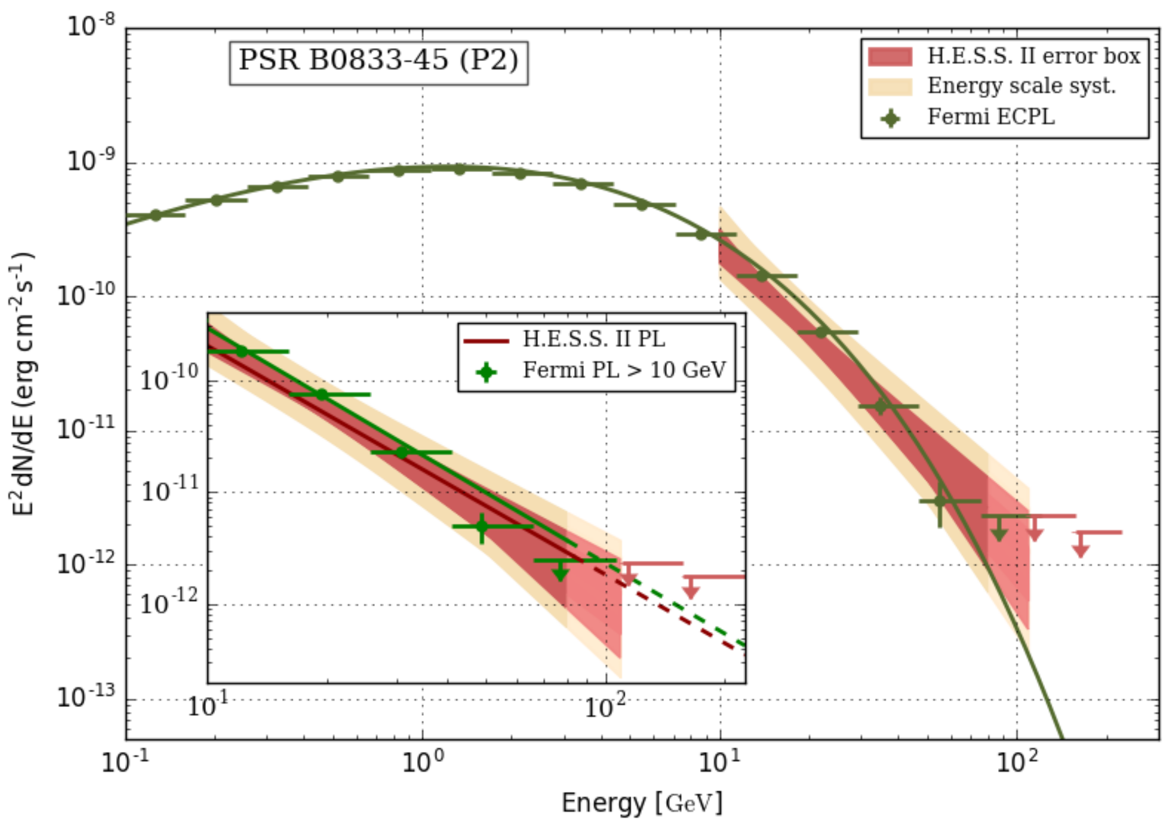
Harding et al. (2018)

Cut-off (Crab) + IC component à la Vela

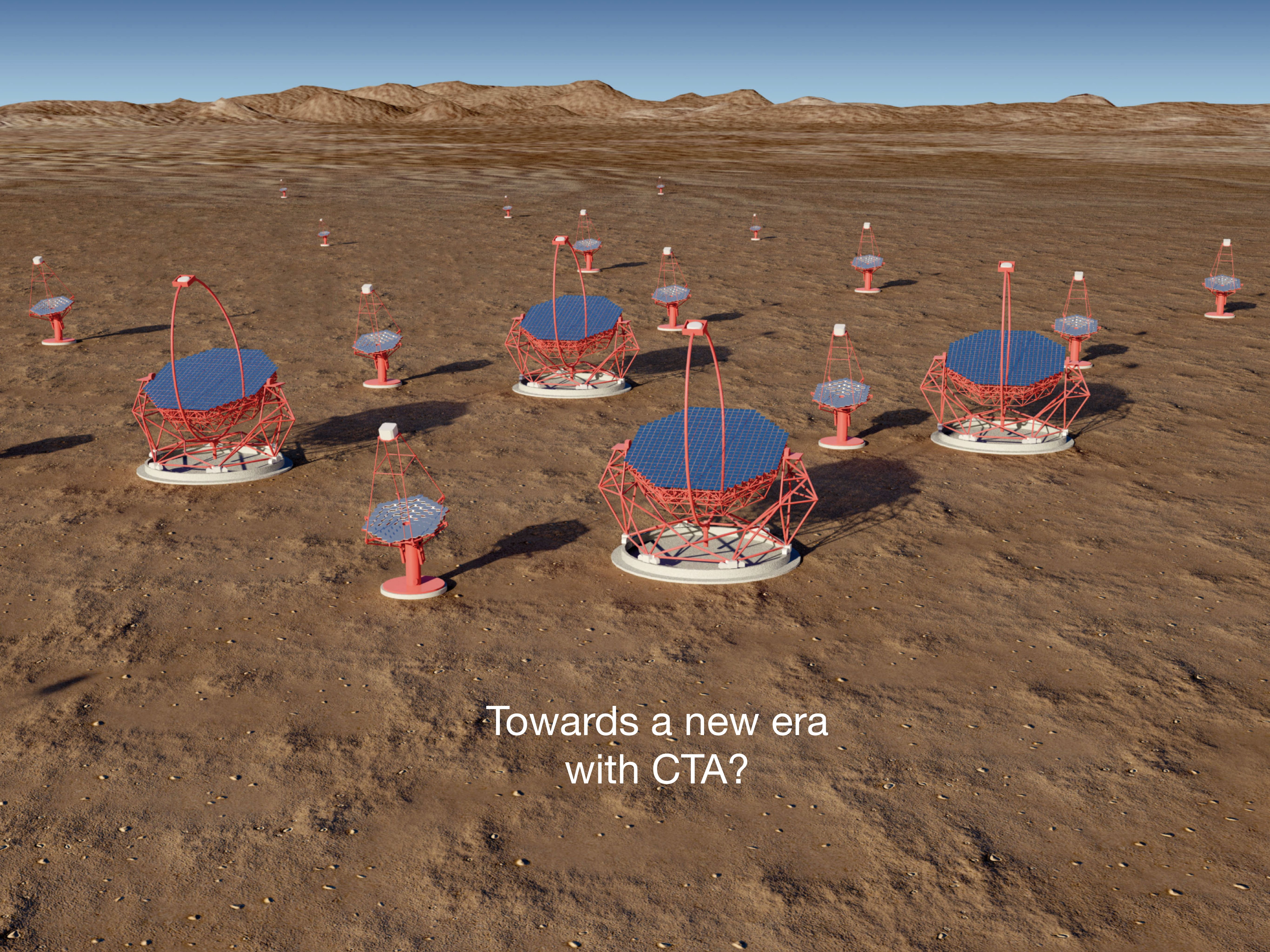
Sensitivity required ~10^{-13} erg/cm2/s



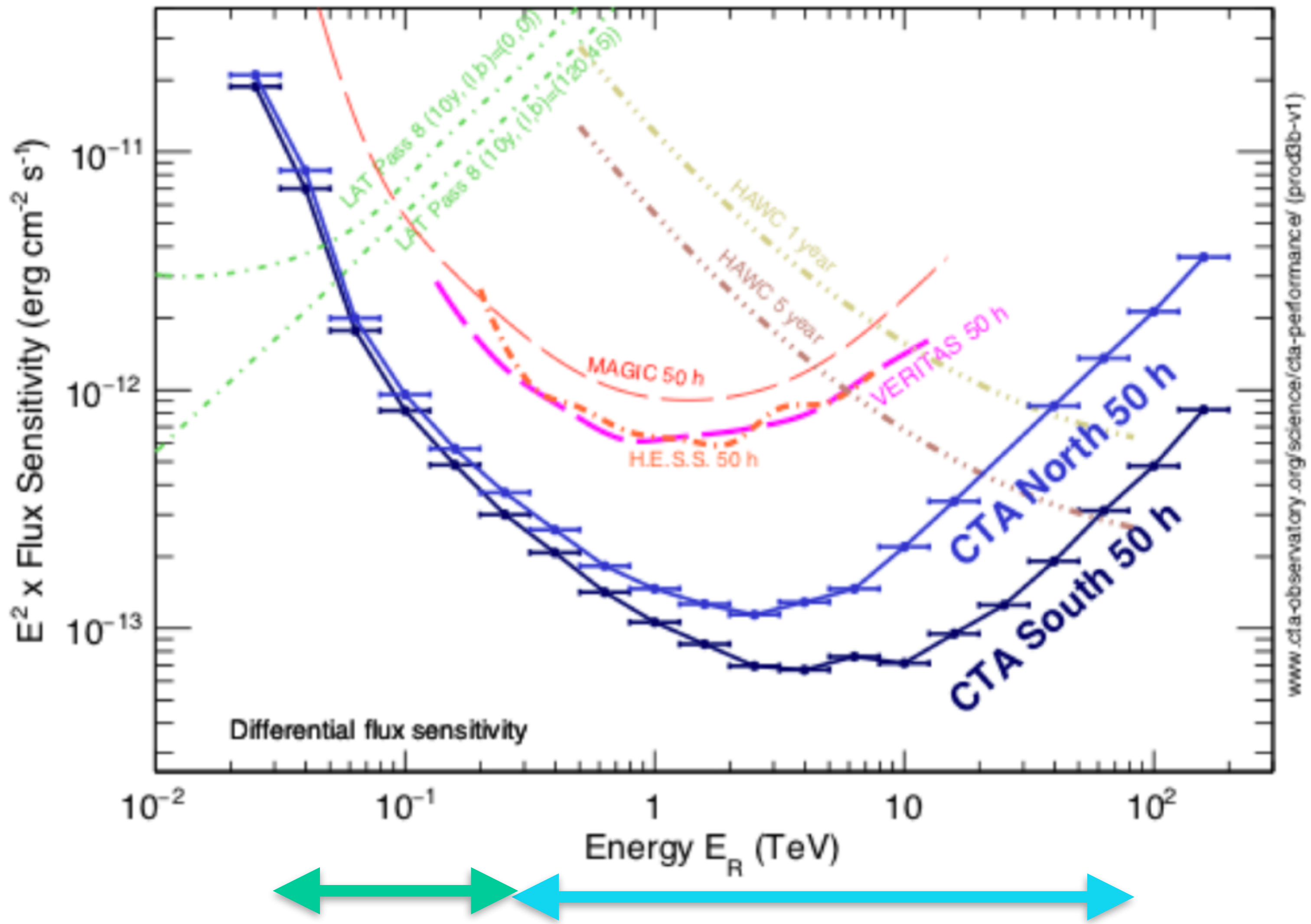




~10^{-13} erg/cm2/s


Towards a new era
with CTA?

Towards a new era with CTA?



20 to < ~300 GeV
HE component

TeV to tens of TeV
VHE component *per se*

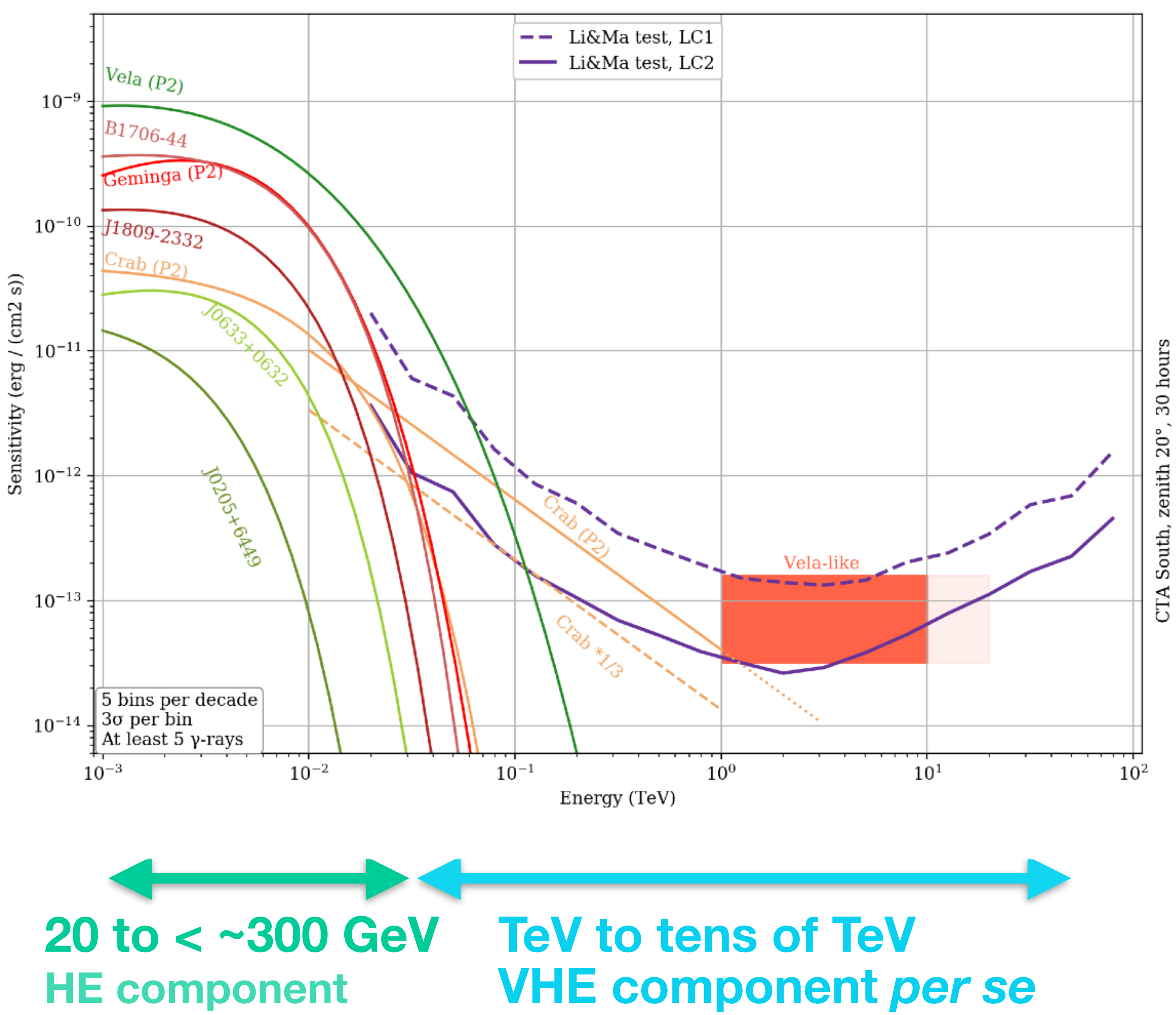
A factor of few gain in sensitivity is expected:

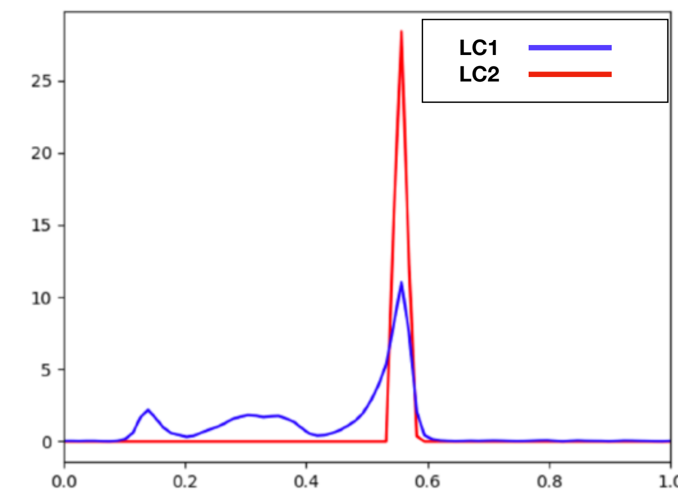
- Pulsed nature of the signal
- Depends on pulsar duty-cycle
- A lower level of background systematic error (no subtraction)

10^{-13} erg/cm2/s

Towards a new era with CTA?

- Out of > 250 Fermi-LAT pulsars expect roughly a dozen potentially interesting detections < 100 GeV, including ms pulsars in the GPS (30 h max exposure)
- Deeper dedicated observations : more sources, more physics
- Note : the importance of LST's in the South site for the HE component!
- The Vela pulsar detection in the multi-TeV range opens an exciting new perspectives for pulsar studies





10^{-13} erg/cm2/s

Summary & Perspectives

- **Four pulsars** are now detected from ground
- The young Crab, the elder Vela & PSRB 1706-44 + the “old” Geminga pulsar
- Differences!
  - Crab : GeV component extends with a power-law tail, extending to ~1 TeV
  - Vela : GeV component most probably cuts off < ~100 GeV, but second component takes over in the multi-TeV range
  - Question is still open for B1706-44 and Geminga (see talk by G. Ceribella)
  - Others?

- Current generation IACT results and observations are essential for setting the stage for pulsar physics with CTA:
  - The >10 better sensitivity of CTA will be of great importance to pulsar physics two important energy ranges :
    - TeV to tens of TeV, i.e. the “VHE component” *per se :* Vela-like psrs?
    - 20 to < 300 GeV : “HE Component”, Crab-like tail or cut-off?

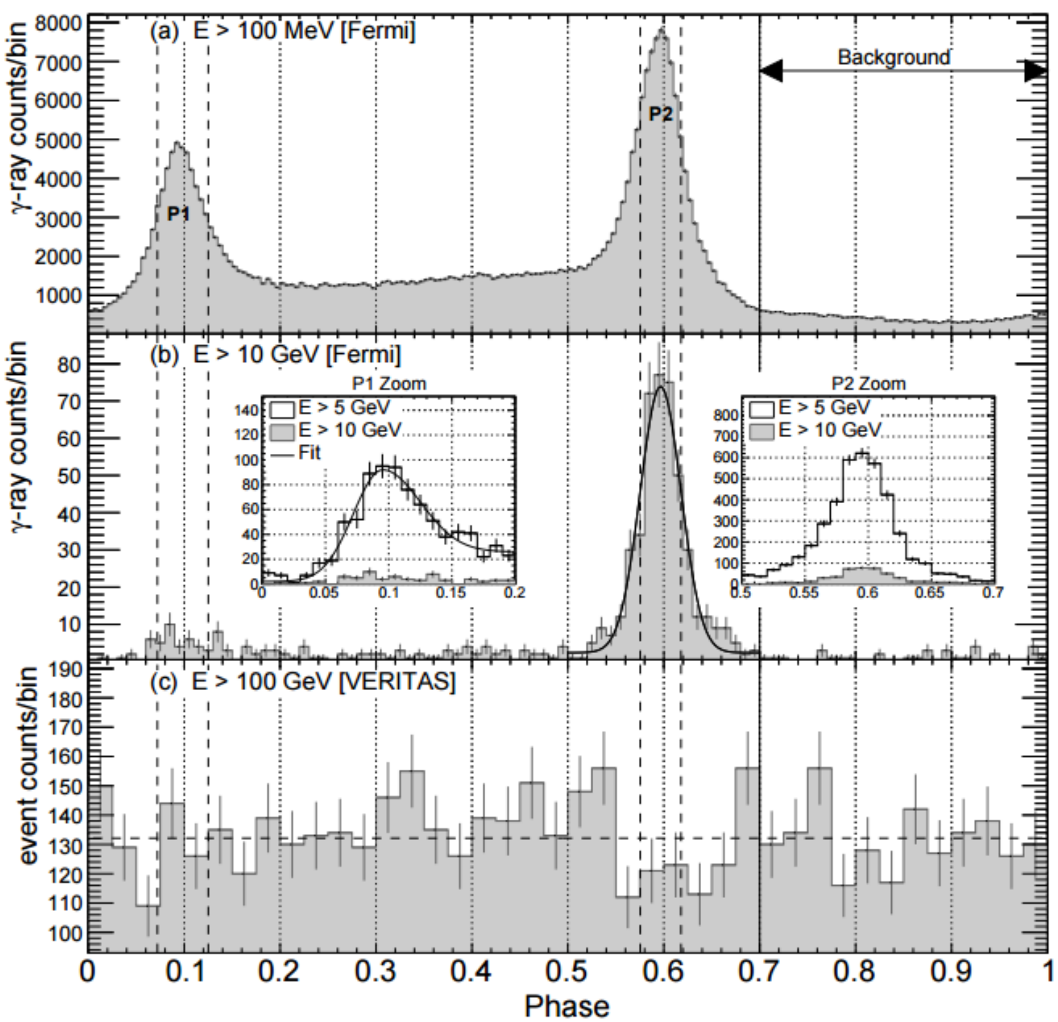
- VHE component brings in precious probes into the pulsar systems, e.g. maximum energy of acceleration and emission processes
- Crucial distinction between magnetospheric and wind-based models…

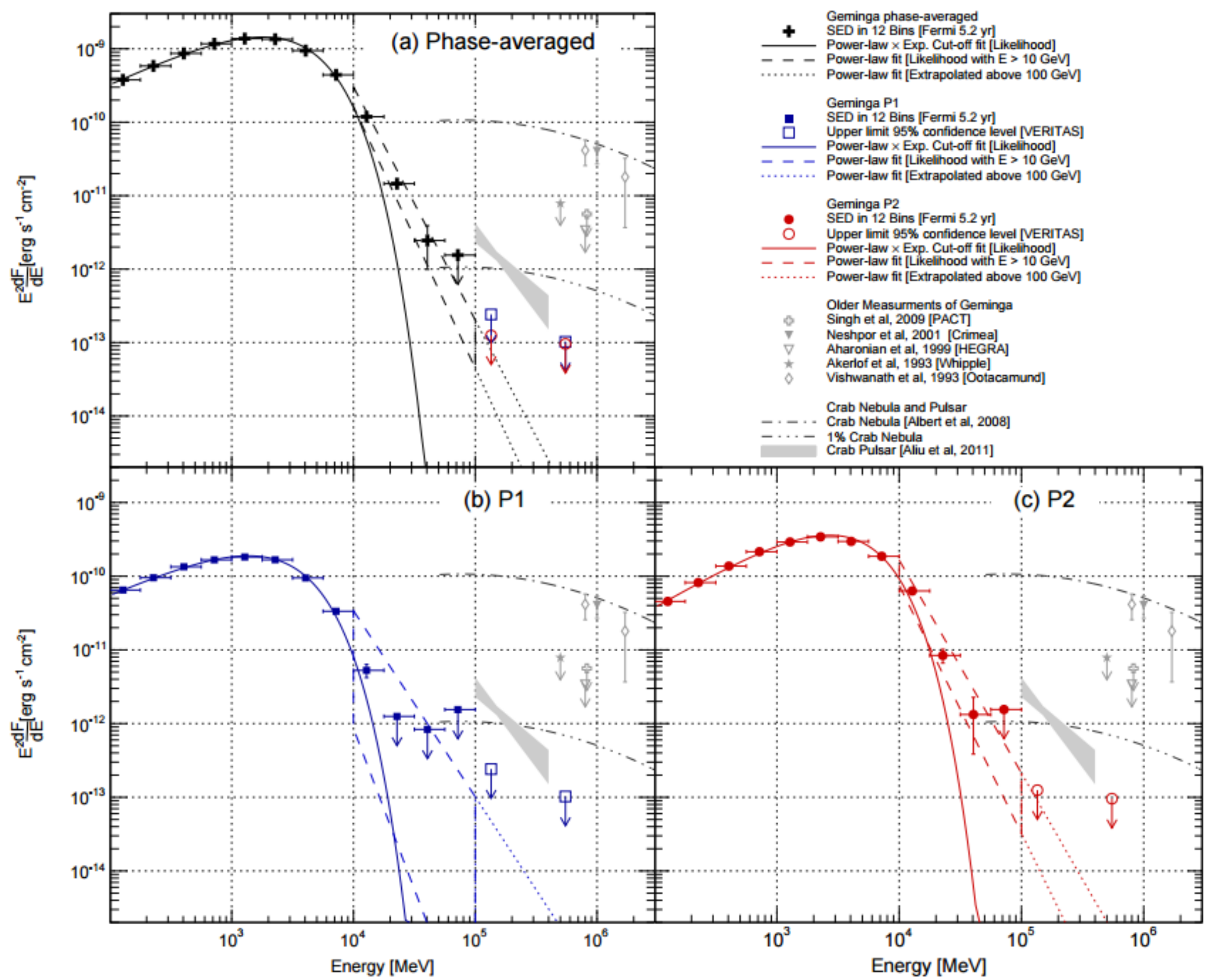
Backup

Geminga : VERITAS 2015

[Aliu et al. 2015]

- Exposure = 72 hours
- No signal > 100 GeV

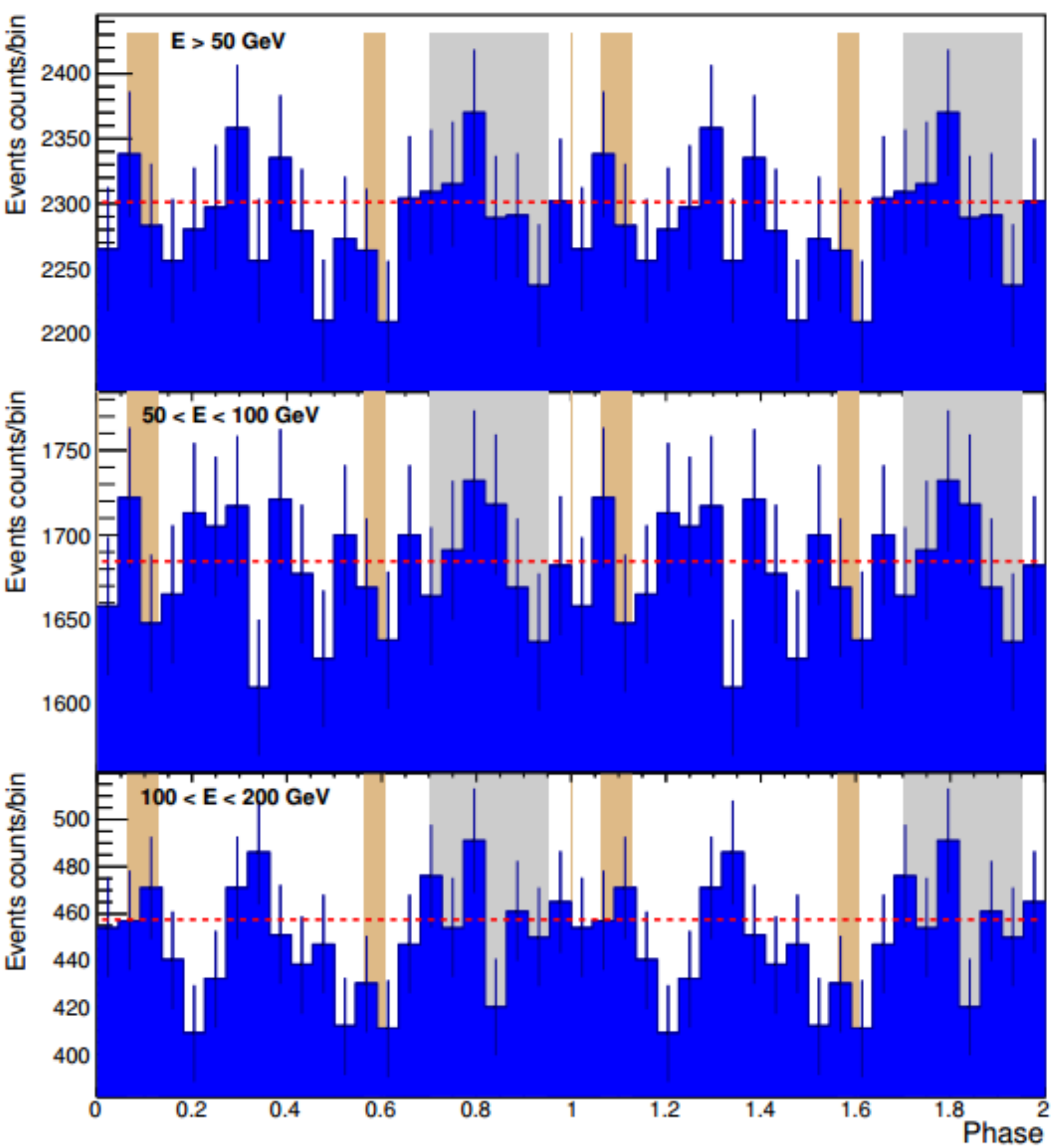


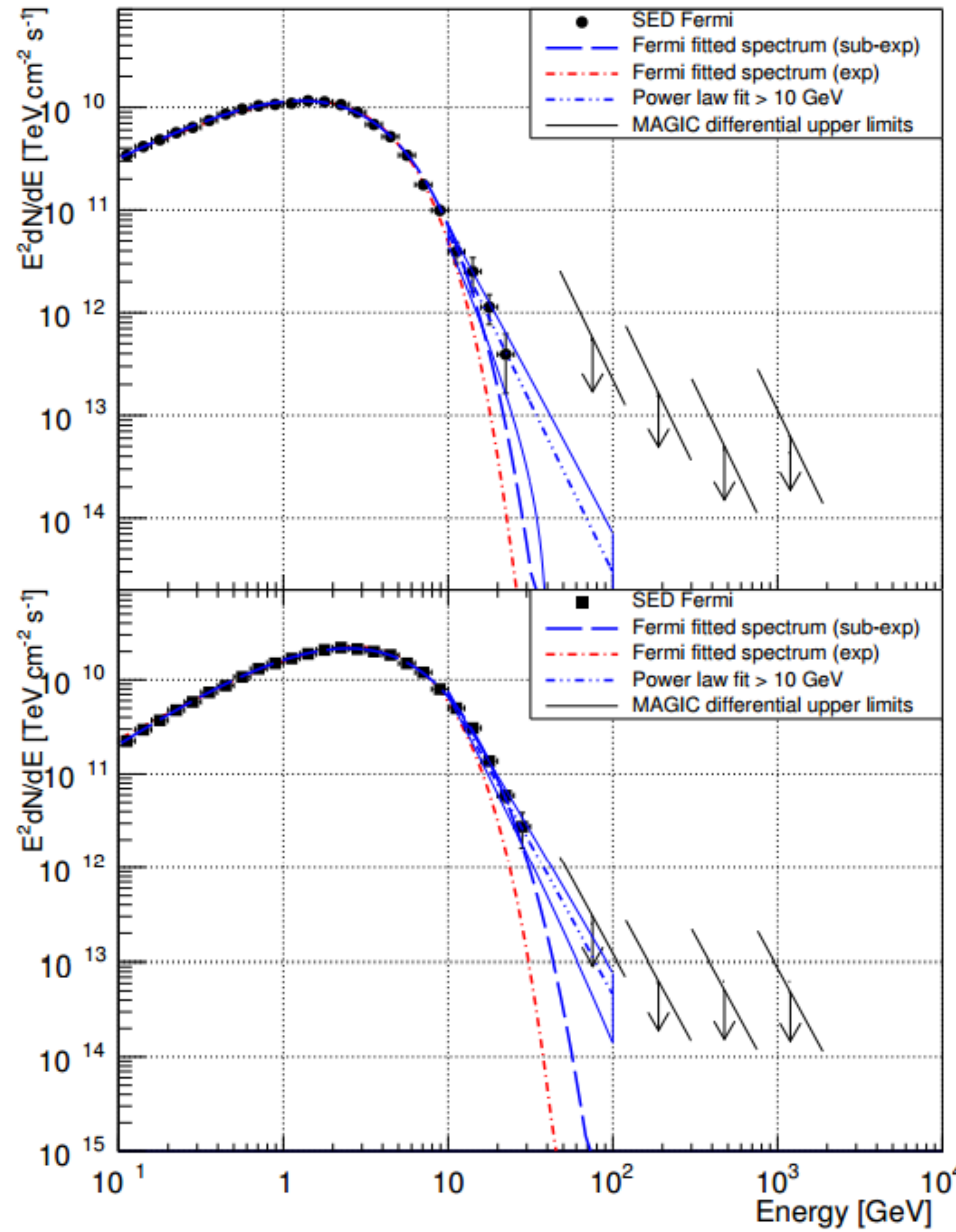


Geminga : MAGIC 2015

[Ahnen et al. 2016]

- Exposure = 75 hours
- No signal > 50 GeV

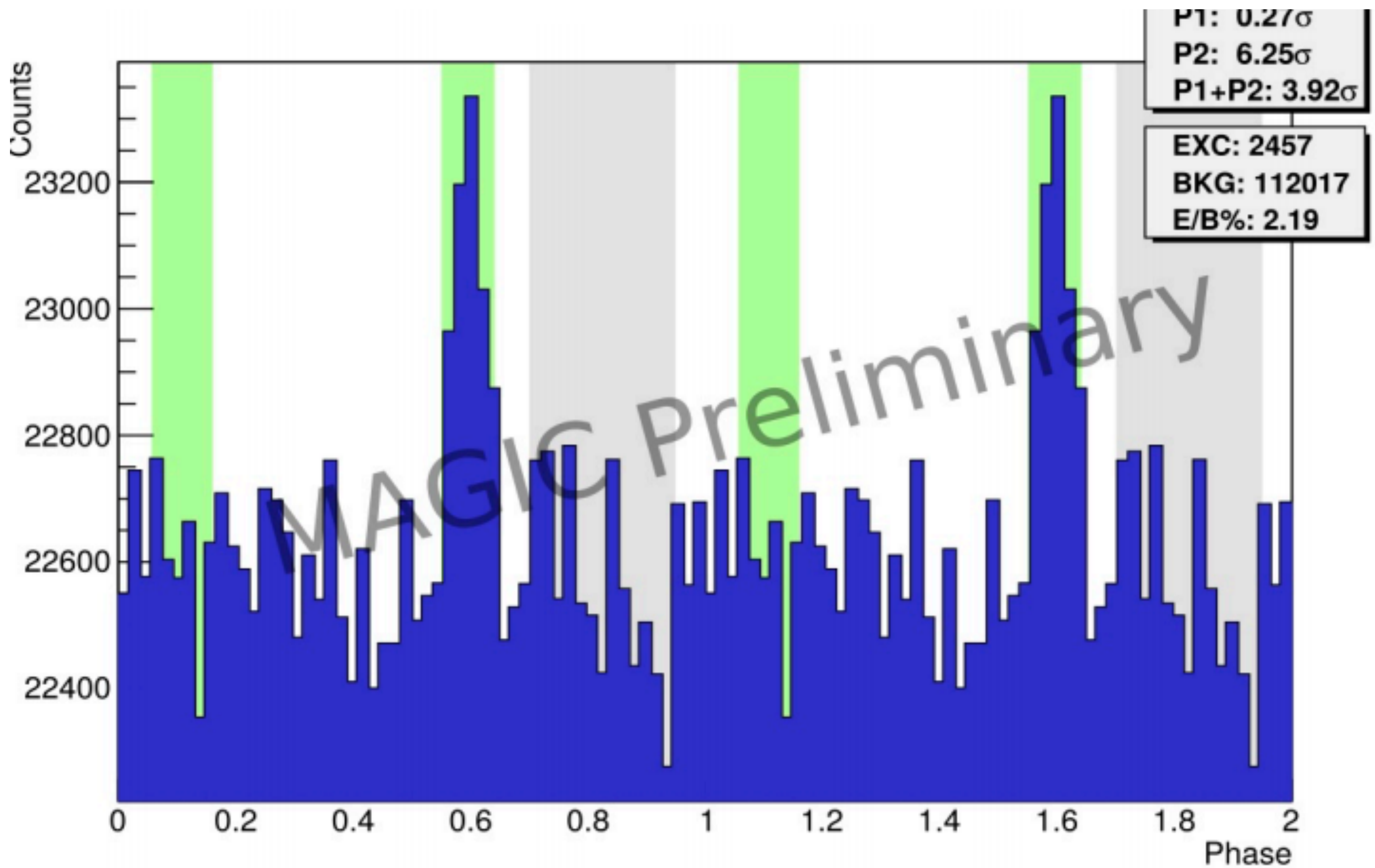




Geminga : MAGIC 2019

[Lopez, M. et al. 2019]

- Exposure = 80 hours (with dedicated low-energy trigger)
- Detection in 20-80 GeV

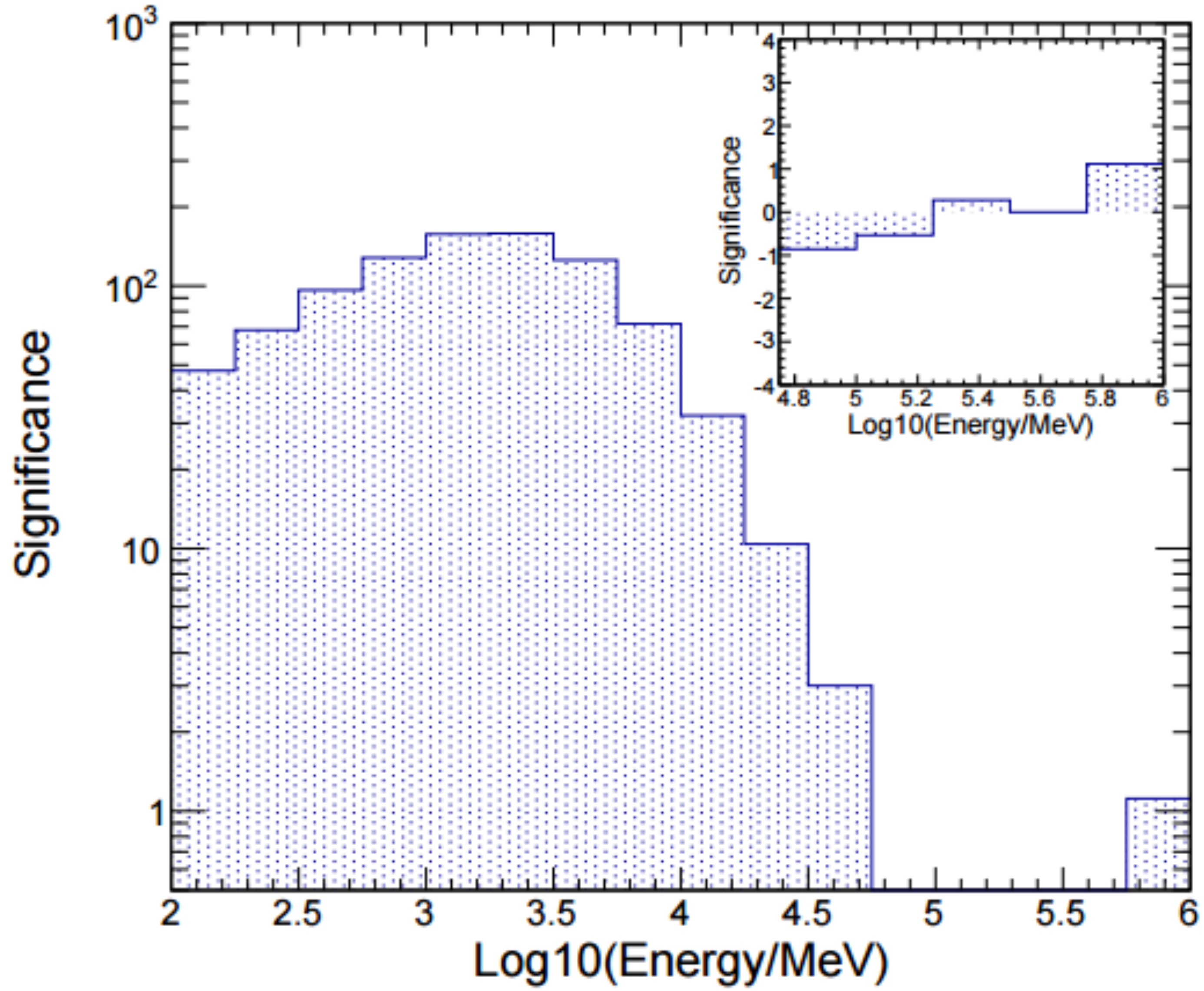


Search for > 50 GeV with Fermi-LAT

[McCann et al. 2015]

- Stacking of 115 pulsars
- Exposure = 4.2 years on average for each
- No signal > 50 GeV

- Subsets tested :
  - Young
  - MSPs
  - Still no signal



Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

- Archival data on 14 “young” and nearby pulsars
- Exposure = from 3 to 108 h
- Total exposure = 483.8 h
- 3 sets of cuts corresponding to energy threshold from 126 GeV to 1 TeV
- No signal found

Pulsar	R.A. (°)	Dec. (°)	P (s)	$\dot{P}$ (10^{-15})	$\dot{E}$ (10^{34} erg s^{-1})	Distance (kpc)	$\dot{E}/d^2$ Rank	VERITAS Exposure (hr)
J0007+7303	1.7565	73.0522	315.9	357.	44.8	1.4 ± 0.3 [170]	9	32.4
J0205+6449	31.4080	64.8286	65.7	190.	2644.	1.95 ± 0.04 [171]	3	22.2
J0248+6021	42.0776	60.3597	217.1	55.0	21.2	2.0 ± 0.2 [172]	11	45.9
J0357+3205	59.4680	32.0891	444.1	13.1	0.6	$0.5^{+0.4}_{-0.2}$ [173]	14	7.92
J0631+1036	97.8657	10.6165	287.8	104.	17.3	1.0 ± 0.2 [174]	10	2.79
J0633+0632	98.4339	6.5418	297.4	79.6	11.9	< 8.7	-	108
J1907+0602	286.9782	6.0374	106.6	86.7	282.	3.2 ± 0.3 [175]	8	39.1
J1954+2836	298.5798	28.6013	92.7	21.2	105.	< 18.6	-	5.18
J1958+2846	299.6667	28.7653	290.4	212.	34.2	< 18.5	-	13.9
J2021+3651	305.2726	36.8513	103.7	95.6	338.	$1.8^{+1.7}_{-1.4}$ [176]	4	58.2
J2021+4026	305.3781	40.4461	265.3	54.2	11.4	1.5 ± 0.4 [177]	12	20.6
J2032+4127	308.0548	41.4568	143.2	20.4	27.3	3.7 ± 0.6 [178]	15	47.9
J2229+6114	337.2720	61.2359	51.6	77.9	2231.	$0.80^{+0.15}_{-0.20}$ [179]	2	47.2
J2238+5903	339.6173	59.0624	162.7	97.0	88.8	< 12.4	-	32.5

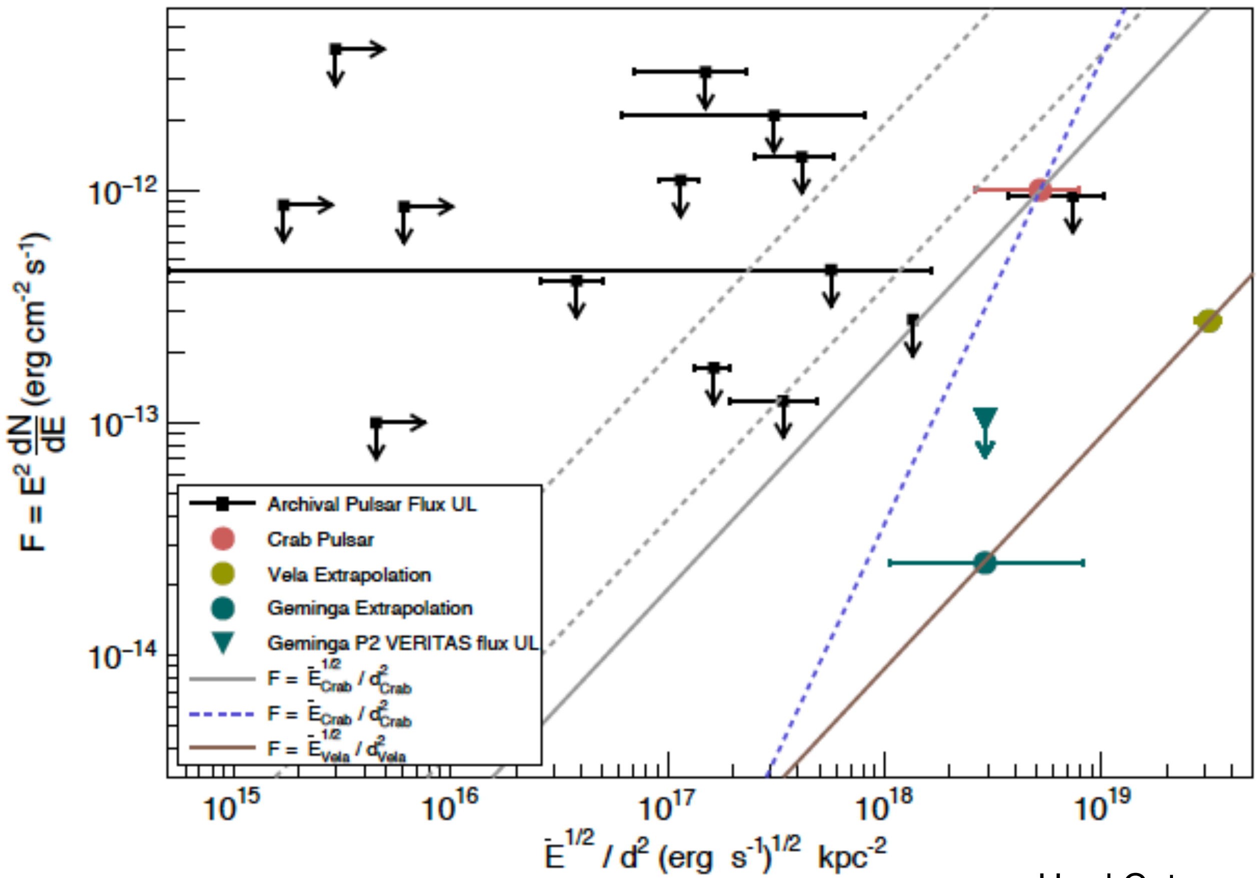
Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

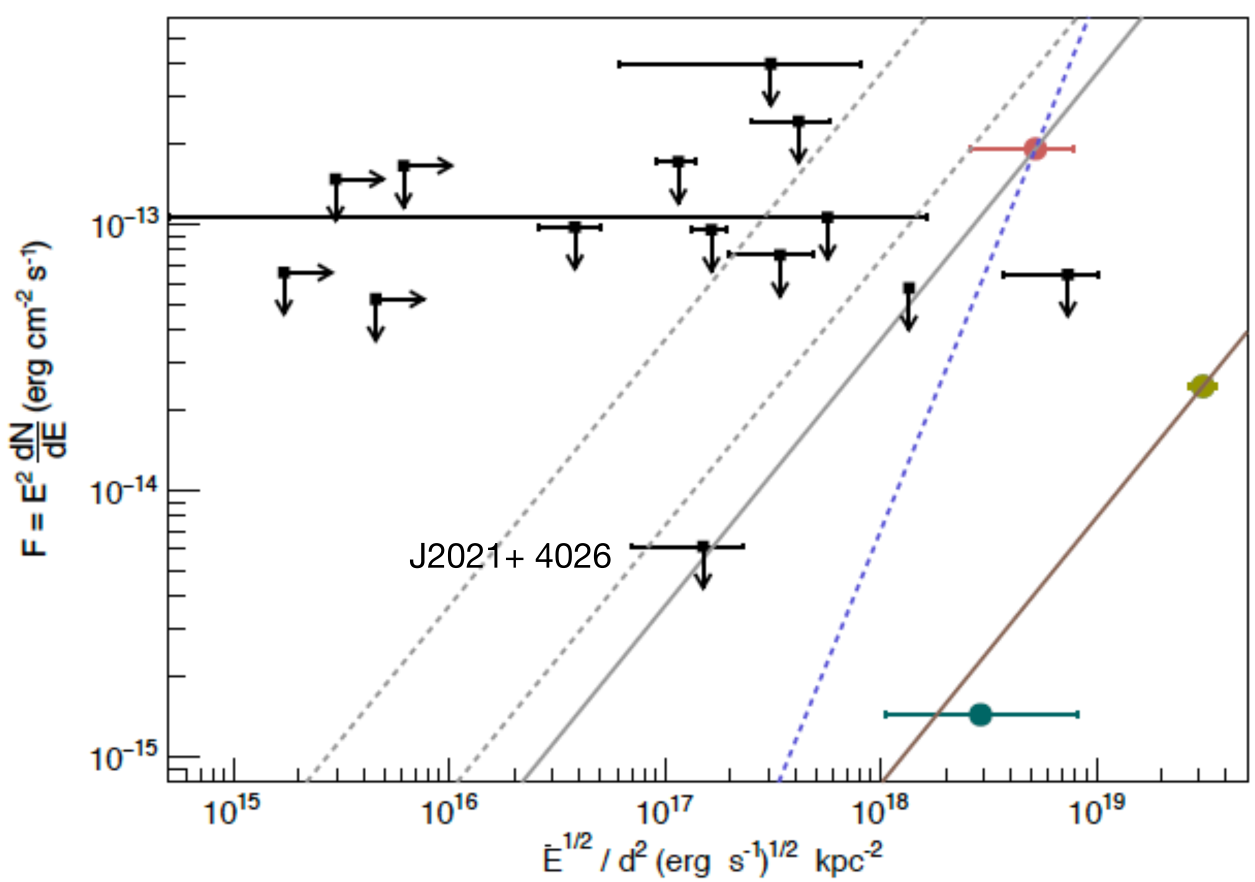
- Upper limits :
- Compared to $\sqrt{(\dot{E})}/d^2$
- Soft and Hard cuts
- Vela extrapolation is based on a power-law but which is disfavoured by HESS-II

- All limits in the range : ~10^{-12} - 10^{-13} erg/cm2/s

Soft Cuts



Hard Cuts

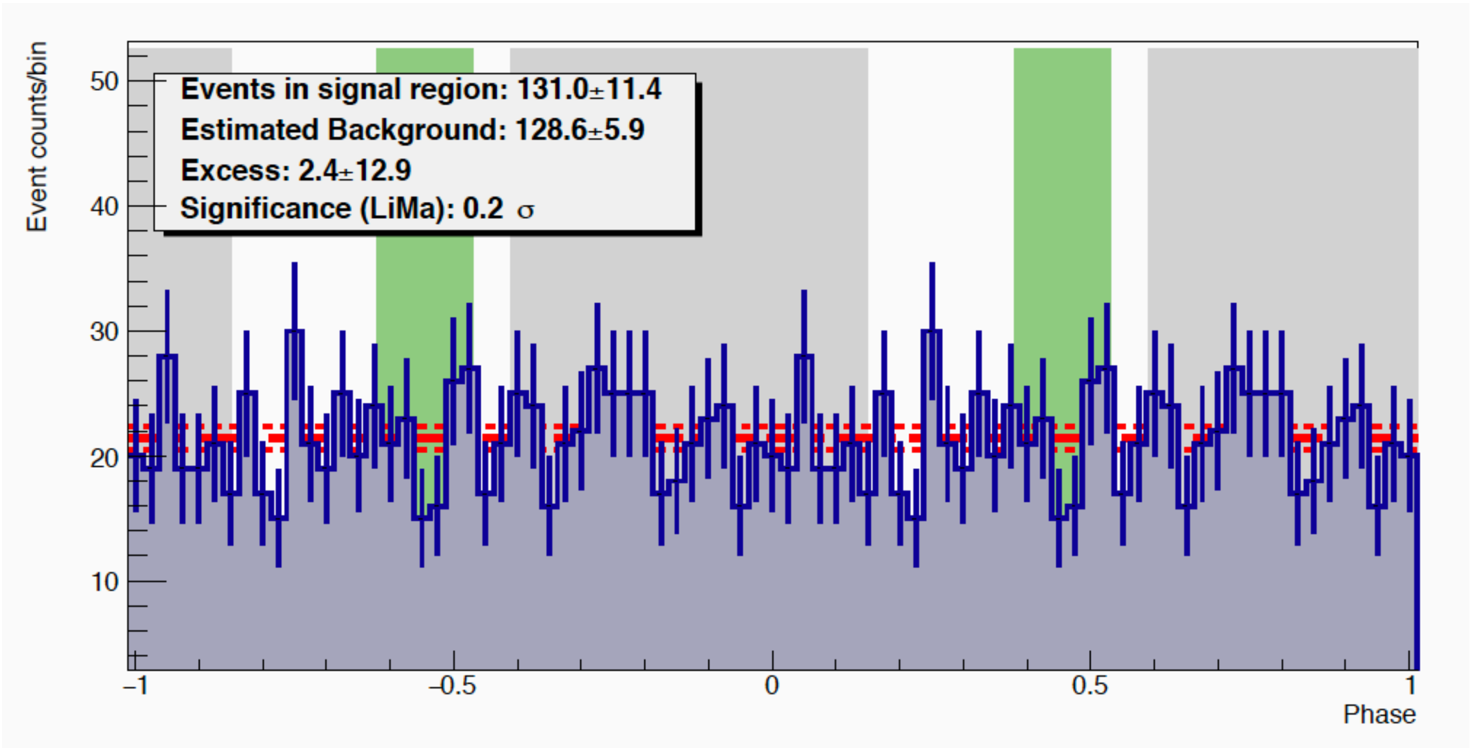


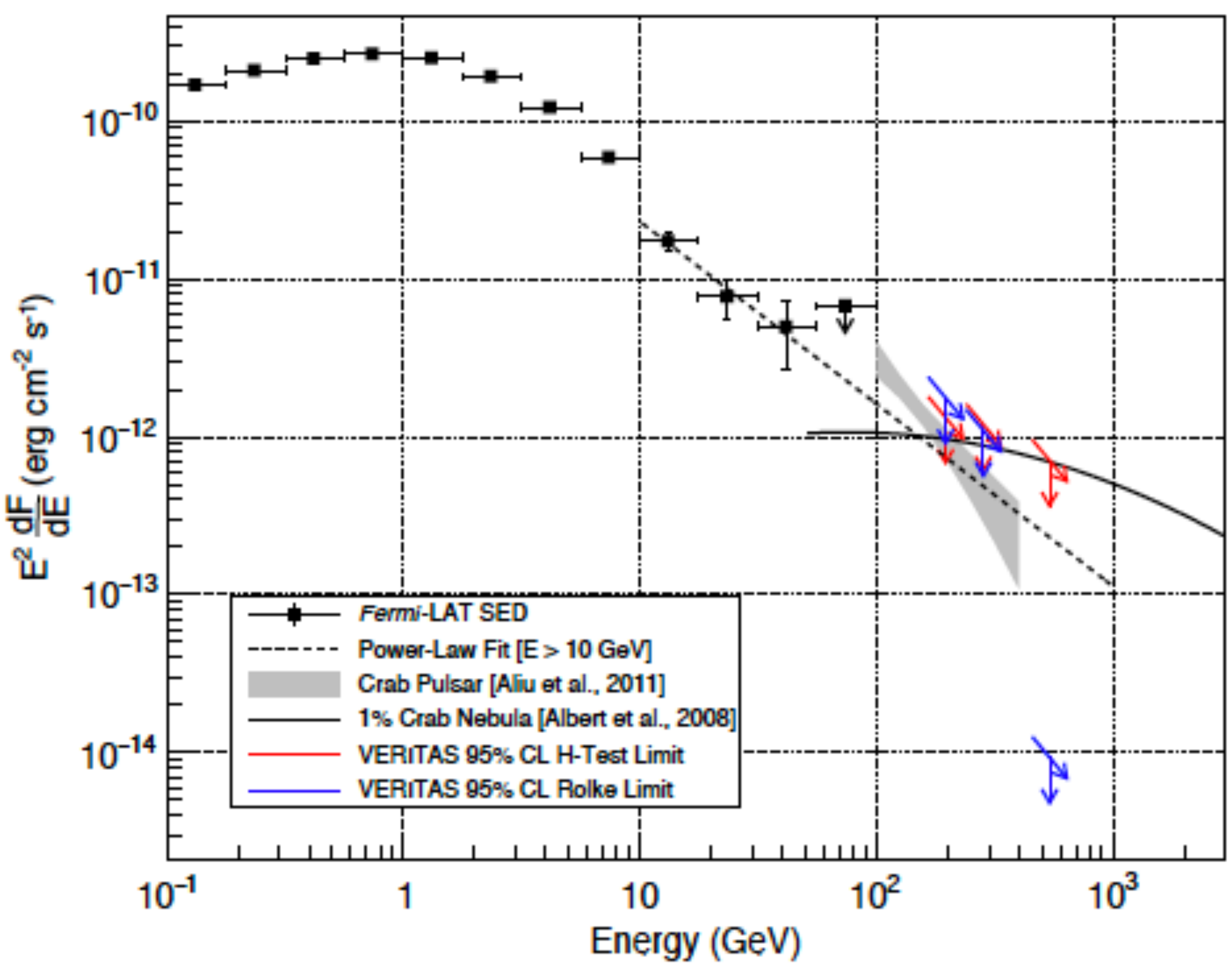
Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

- PSR J2021+ 4026
- P = 265 ms
- Dist = 1.5 +/- 0.4 kpc
- $\dot{E} = 1.14 \times 10^{35}$ erg/s
- $\dot{E}/d^2$ rank (NS) = 12
- Exposure = 20.6 hours
- Thresholds : 166, 240, 457 GeV

- Upper limits : ~10^{-12} erg/cm2/s, except @ 500 GeV ~10^{-14} erg/cm2/s -> anomaly ?



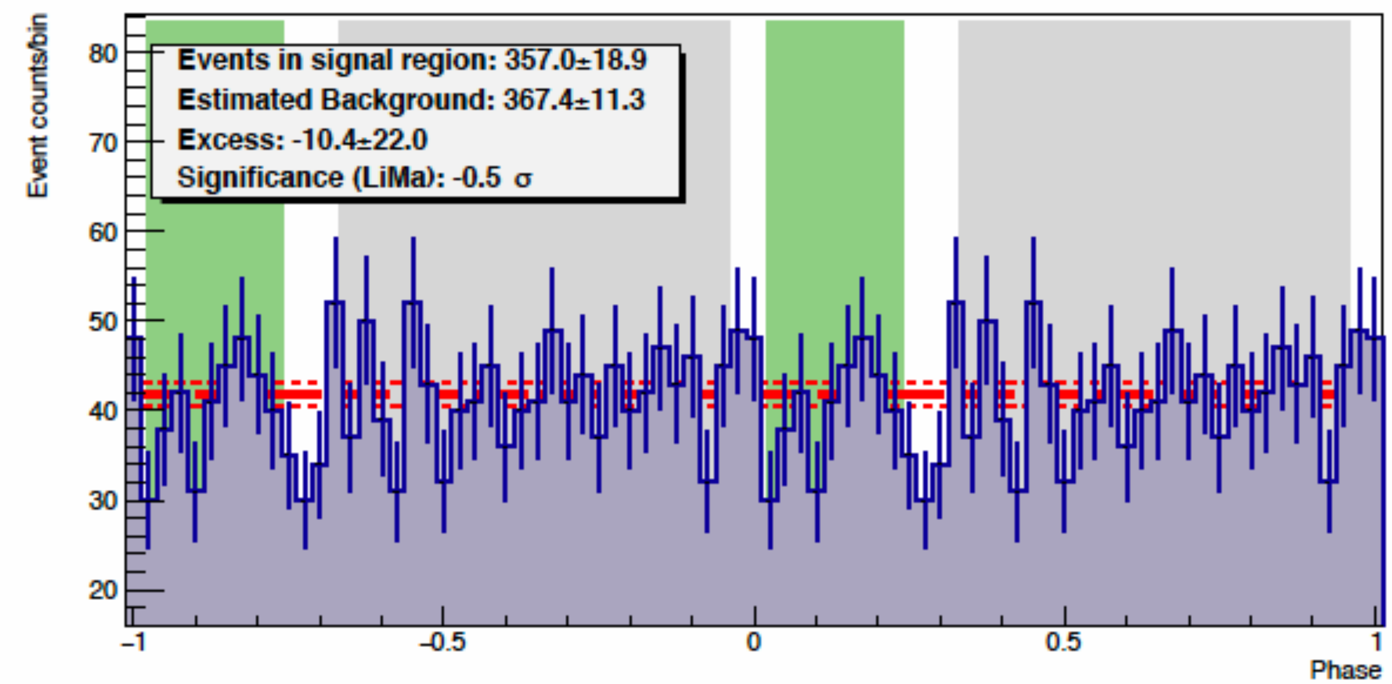


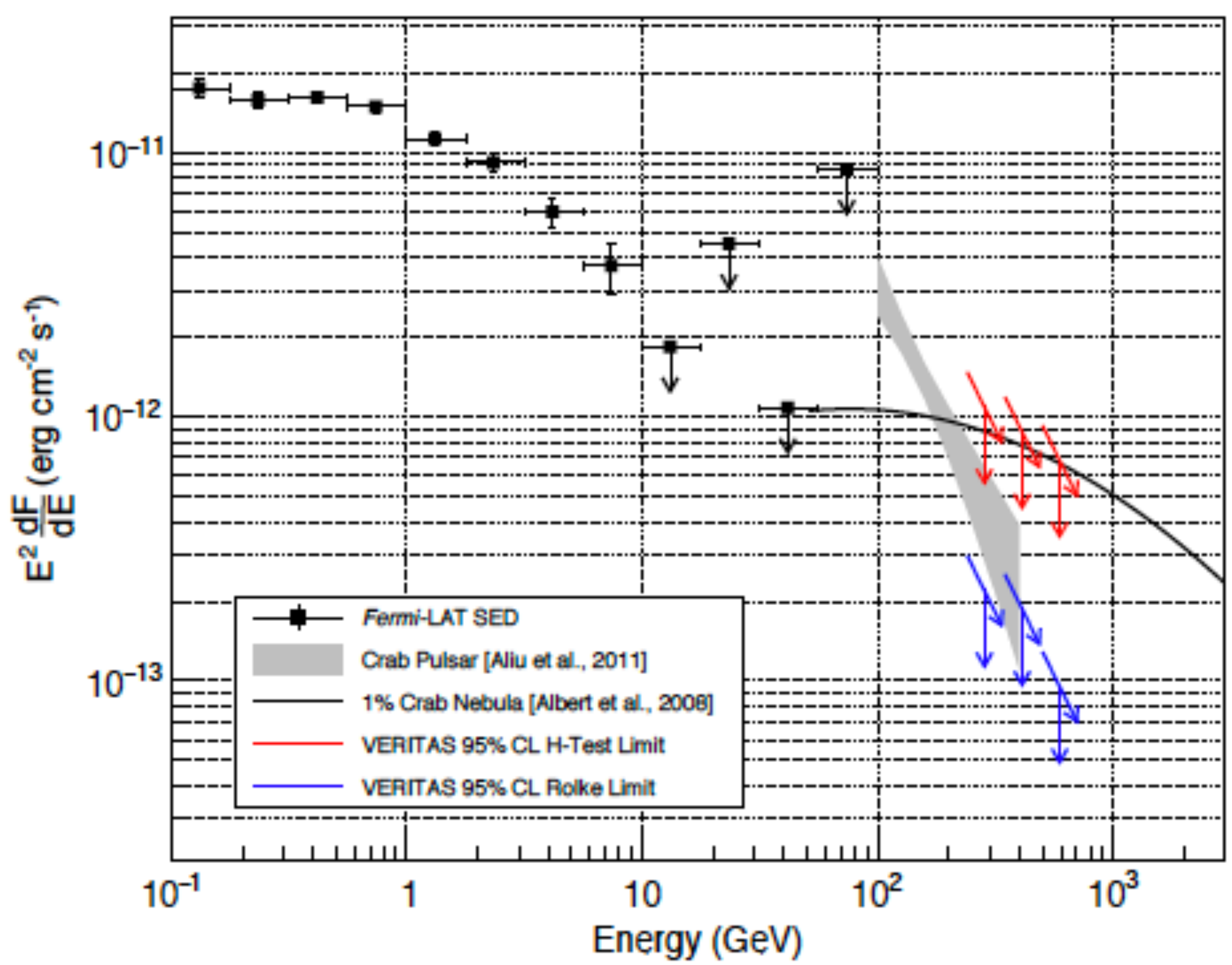
Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

- PSR J0205+ 6449
- P = 65.7 ms
- Dist = 1.95 kpc
- $\dot{E} = 2.64 \times 10^{37}$ erg/s
- $\dot{E}/d^2$ rank (NS) = 3
- Exposure = 22.2 hours
- Thresholds : 240, 347, 501 GeV

- Upper limits : ~10^{-13} erg/cm2/s





Survey of 13 pulsars with VERITAS

[Richards, et al. 2017+2018]

- PSR J2229+ 6114
- P = 51.6 ms
- Dist = 0.8 +/-0.2 kpc
- $\dot{E} = 2.23 \times 10^{37}$ erg/s
- $\dot{E}/d^2$ rank (NS) = 2
- Exposure = 47.2 hours
- Thresholds : 240, 316, 661 GeV

- Upper limits : ~ few 10^{-13} erg/cm2/s