MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Crab: a key source in high-energy astrophysics

Roberta Zanin (MPIK)

Heidelberg, December 12, 2018

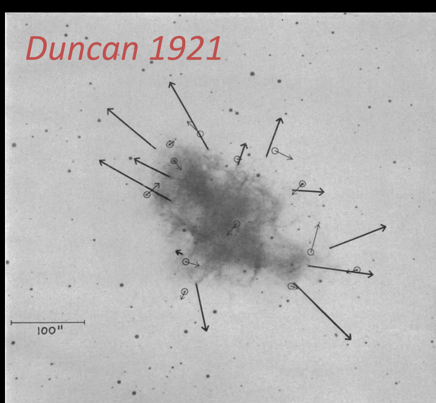
Hillas Symposium 2018

Göran Nilsson & The Liverpool Telescope

A hystorical event

- ✓ A **guest star** in the 5th month of the 1st year of Chih-ho rein (July 4th, 1054) in the South-East of Thien-Kaun (Taurus constellation) *(Duynvendak 1942)*
  - ✓ Recorded by Japanese & Pueblo people (Arizona)

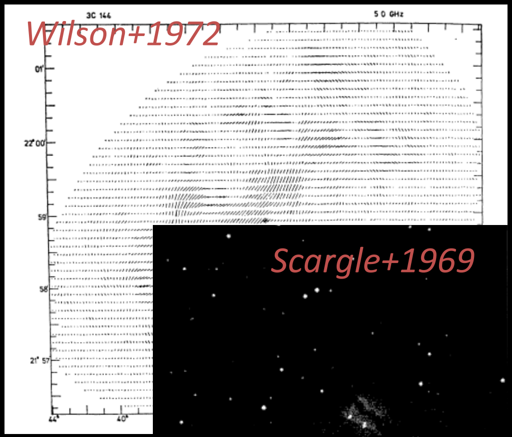
- ✓ In 1771 Messier: looking for the halley comet found M1
- ✓ In 1844 Lord Rosse: first to detect the filamentary structure

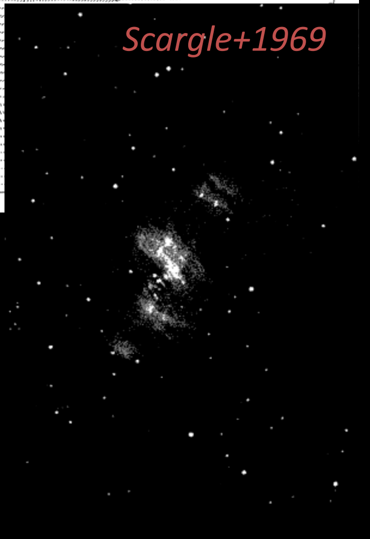


- ✓ In 1921 Lundmark: the guest star is close to NGC 1952
- ✓ In 1921 Duncan studied radial movements of NGC 1952
- ✓ NGC 1952 nebula = the guest star *(Hubble 1928)*

The impact on the high-energy astrophysics

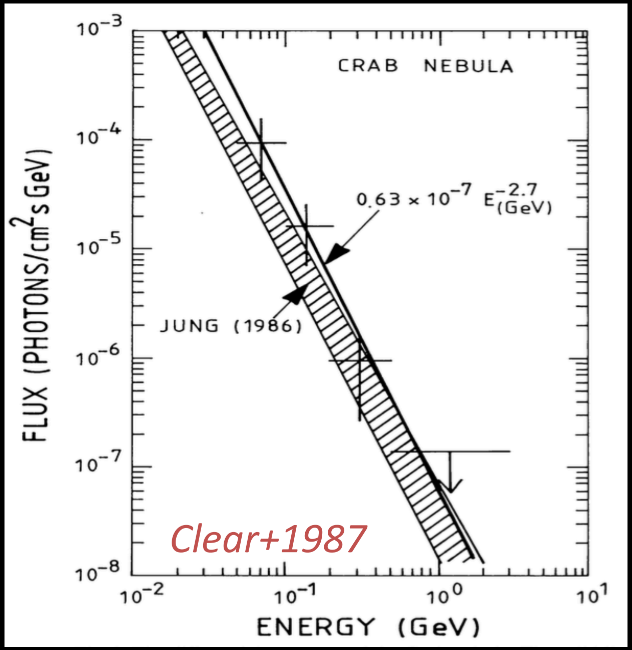
- ✓ Continuous brighter *(Baade1942)*: just few % is line emission, concentrated on filaments *(Minkosvski1942)*
- ✓ **First radio source** *(Bolton&Stanley1948)*
  - ✓ a compact radio source in the center *(Hewish&Okoye 1964; Andrew+1964)*
- ✓ Non-thermal radiation: **synchrotron** *(Shklovsky 1953)*
  - ✓ Polarization as synchrotron signature *(Gordon 1953)*
- ✓ Optical *(Dromvoski1954,Woltjer1957)* & radio *(Mayer+1957, Andrew+1967, Wright+1970,Wilson+1972…)* **polarization** varying in intensity and PA across the nebula
- ✓ Detection of the **pulsar** *(Staielin&reifenstein, Cocke1969)* associated with the central star *(Lynds1969)*
- ✓ Center of the nebula is highly dynamic & structured *(Scargle1969)*


Wilson+1972


Scargle+1969

The impact on the high-energy astrophysics

- ✓ **X-ray source** *(Bowyer+1964, Oda+1967…)* up to 500 keV → continuous emitter
- ✓ **γ-ray source** *(Lichti1980, Clear+1987…)* up to 400 MeV with COS-B in agreement with the X-ray spectrum extrapolation



The impact on the high-energy astrophysics

Modern astrophysics can be divided into two parts:
the Crab nebula one and the rest
(Shklovsky 1973)

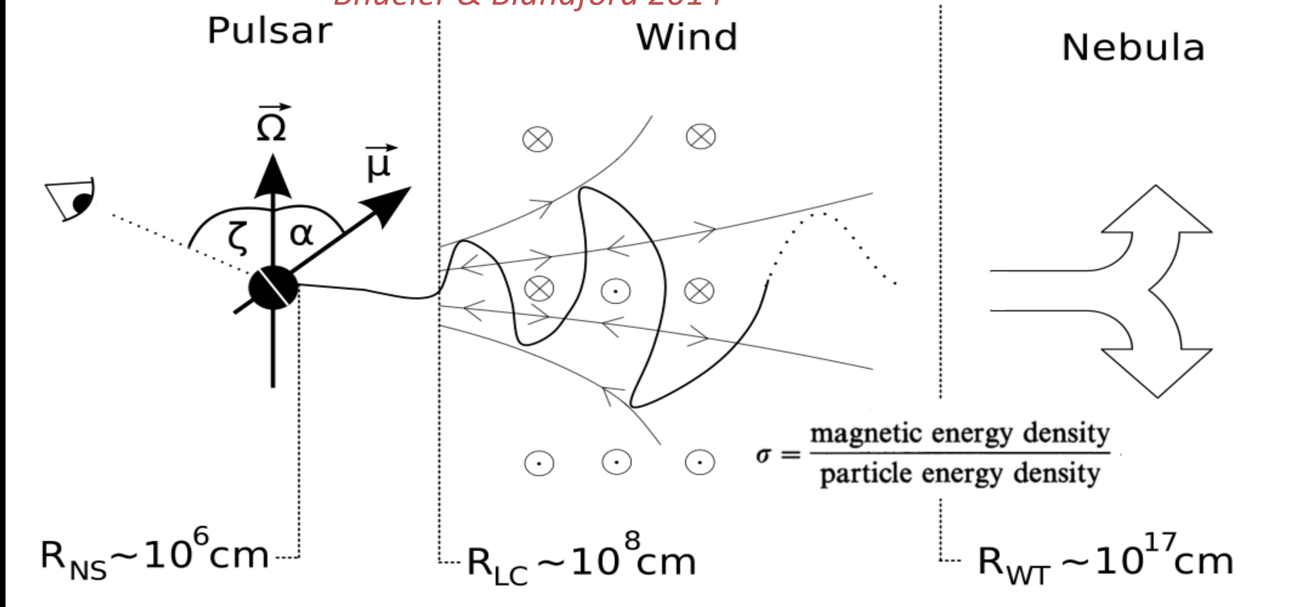
- ✓ a laboratory test case for non-thermal phenomena in general
- ✓ most of what we know about PWNe comes from the Crab nebula

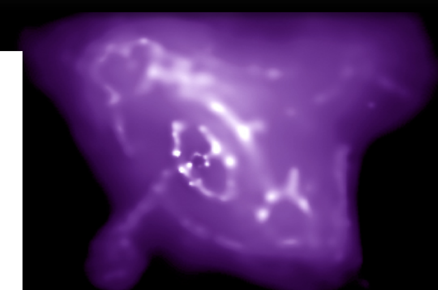
The impact on the high-energy astrophysics

Modern astrophysics can be divided into two parts: the Crab nebula one and the rest

(Shklovsky 1973)

Bhueler & Blandford 2014





Weisskopf+2000

MHD models

(Rees&Gunn1974)
Kennel&Coroniti1984)

σ = 0.001-0.003

A prominent role also in the VHE field

- ✓ **Hadronic scenario**: synchrotron as secondary product of pp → a copious gamma-ray emission from π0 decay *(Cocconi 1954)*
  the failure of the Crimea Air Cherenkov telescope called the need for a new process *(Chudakov1963)*

- ✓ **Expected** IC scattering off synchrotron photons *(Gould 1965)*
  - ✓ More realistic spatial template *(Rieke&Weekes1969)*
  - ✓ no δ approx but correct IC treatment *(Jones1965,1968)* + B~1/r + electron spectrum from synch. with constant B-field *(Grindlay&Hoffman1971)*

unambiguous conclusion despite the different approximations:
TeV emission still detectable and above COS-B extrapolation

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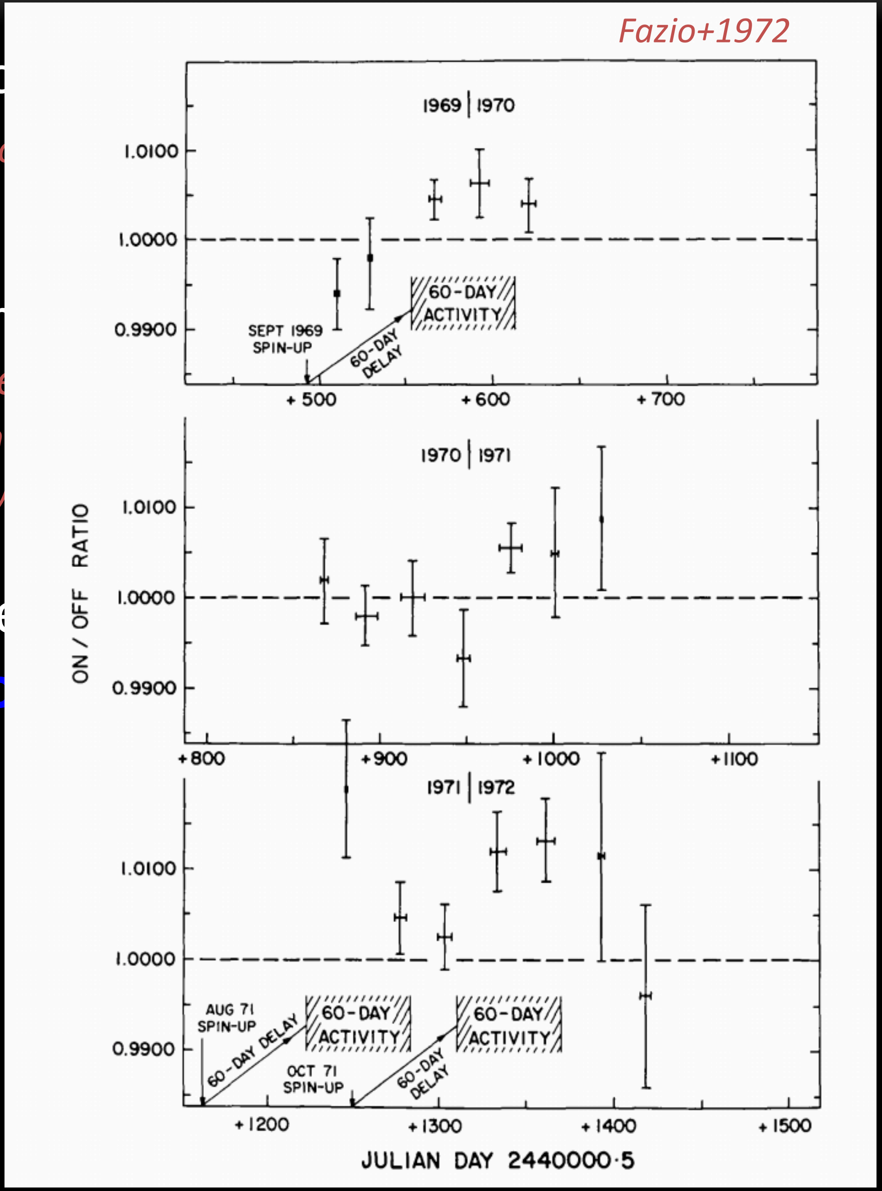
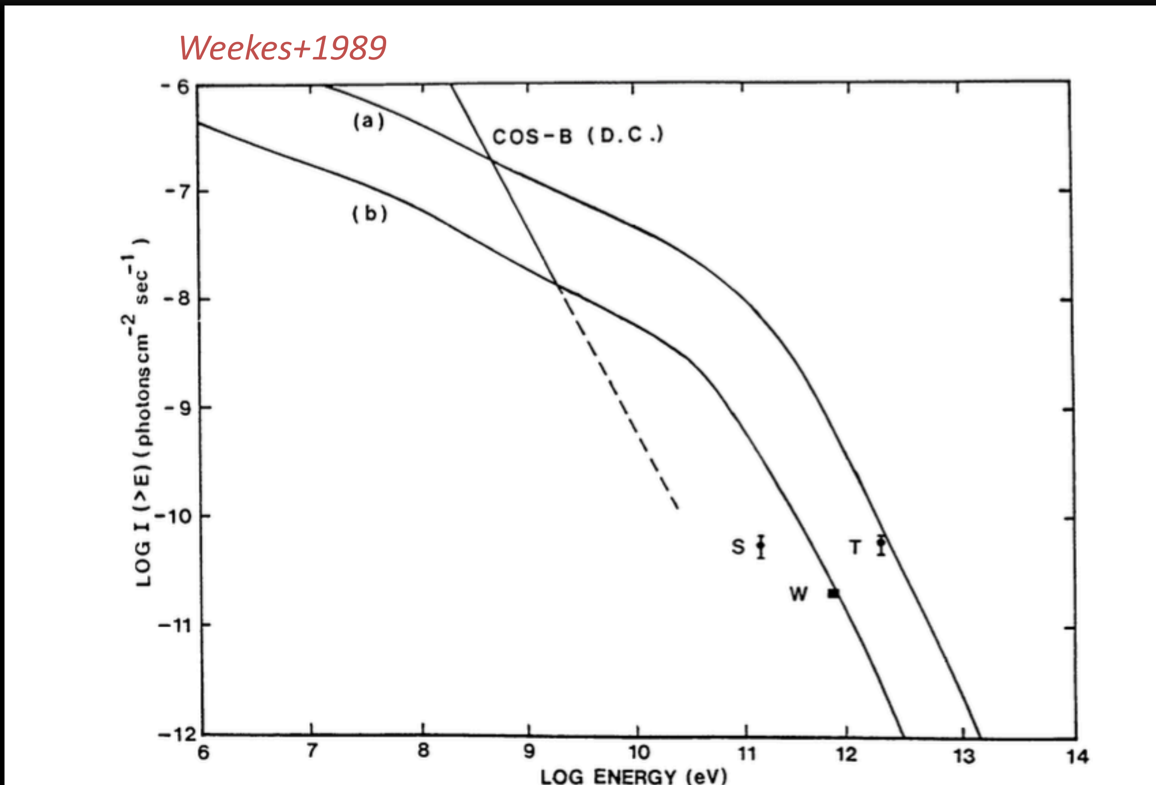
unambiguous conclusion despite the
TeV emission below COS-B (synchro

- ✓ Claims of signal hints in the 70s & 80s
  (Fazio+1972)



A prominent role also in the VHE field



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54)

need for a new process *(Chudakov1963)*

ons *(Gould 1965)*

69)

1968) + B~1/r + electron spectrum

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22.02

Detection of Very High Energy γ-rays from the Crab Nebula

C. Akerlof, J. DiMarco, H. Levy, D. Meyer, P. Radusewicz, R. Tschirhart, Z. Yama (U. Michigan), C. MacCallum (Sandia Labs)

During the period October 1988 through December 1988, a search was made for very high energy gamma rays from the direction of the Crab nebula using the atmospheric Čerenkov technique. The detector consisted of seven-fold arrays of photomultiplier tubes at the focii of two 11-meter diameter solar concentrators situated in Albuquerque, New Mexico. A DC signal was detected from the Crab nebula with a statistical significance of 5.8 σ after the application of various cuts designed to suppress the background of hadronic showers. A search for a pulsed component failed to identify a significant signal in phase with the radio pulse from the Crab pulsar. These results with a threshold energy of 200 GeV are in substantial agreement with higher energy results recently reported by the Mt. Hopkins group.

22.03

TeV Observations of the Crab Nebula with the Whipple Observatory High Resolution Imaging Gamma-ray Telescope

D.A.Lewis, R.C.Lamb, D.Macomb, G.Vacanti (Iowa State U.), P.Kwok, M.J.Lang, T.C.Weekes (Whipple Obs.), M.F.Cawley (St.Patrick's Coll., Maynooth, Ireland), D.J.Fegan, P.T.Reynolds (U. Coll. Dublin, Ireland), A.M.Hillas (U. Leeds, U.K.)

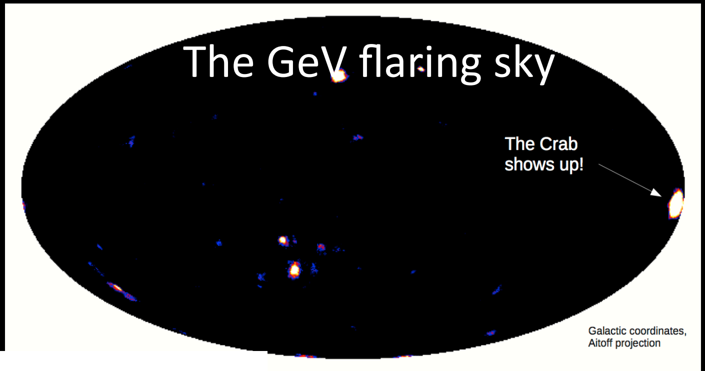
The atmospheric Cherenkov imaging technique has been established as a means of significantly enhancing the sensitivity of TeV (10^{12} eV) gamma-ray astronomy by the 9σ detection of the Crab Nebula (Weekes et al., to be published in *Ap. J.*,

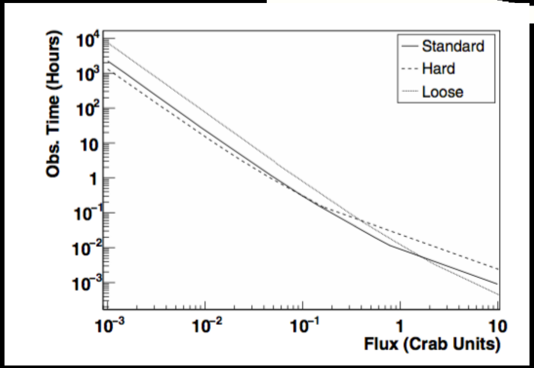
- ✓ Claims of signal hints in the 70s & 80s
  (Fazio+1972)
- ✓ First established TeV source in 1989
  (Weekes+1989, Akerlof+1989)

A prominent role also in the VHE field

… given its brightness and stability

- ✓ the **most studied TeV source**, belonging to the most common class of VHE emitters, but not the archetypal
  - ✓ keep surprising

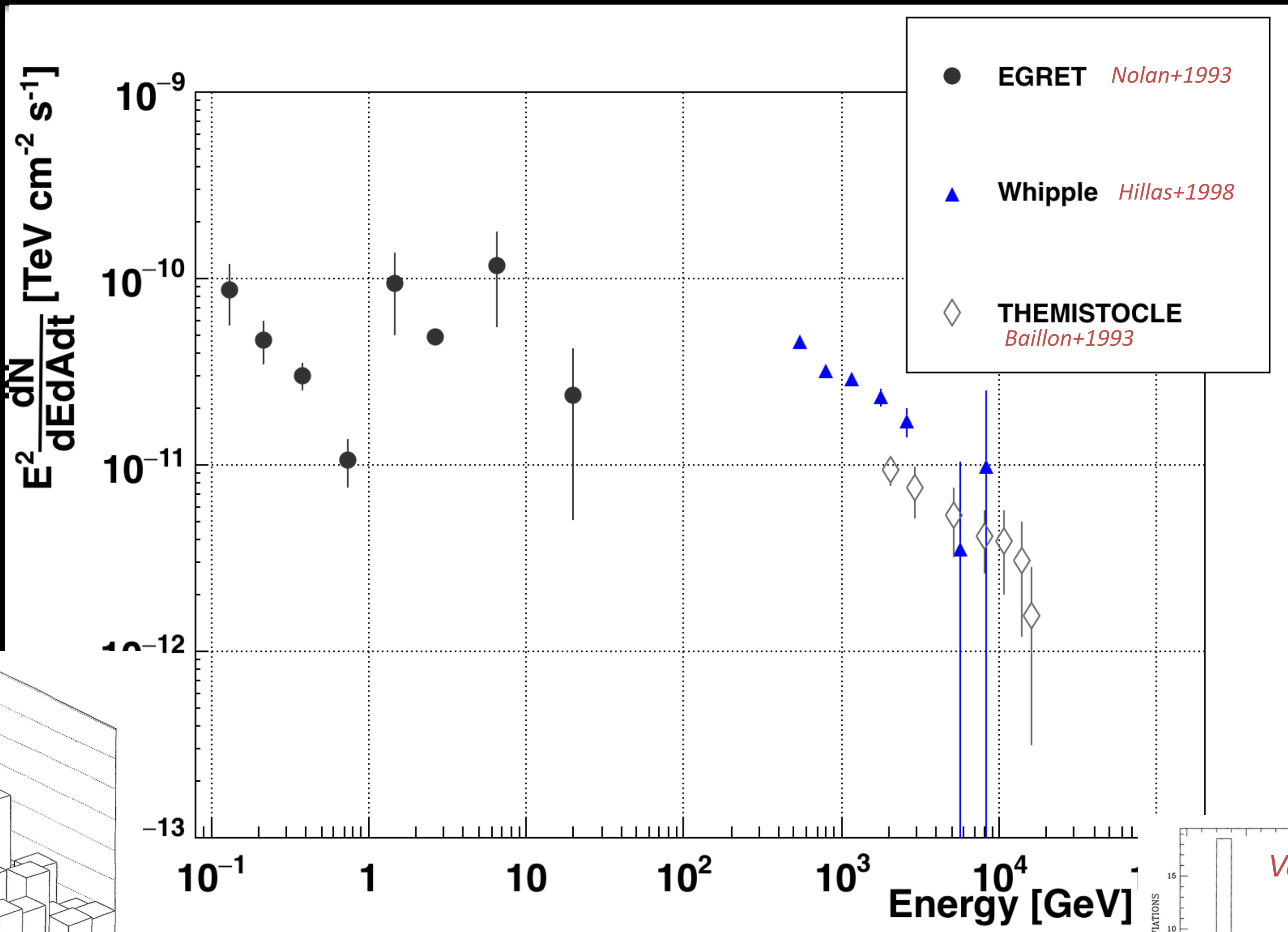


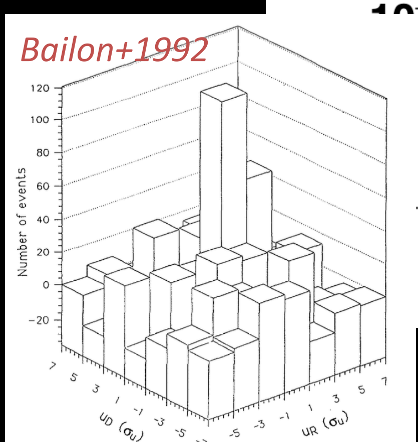


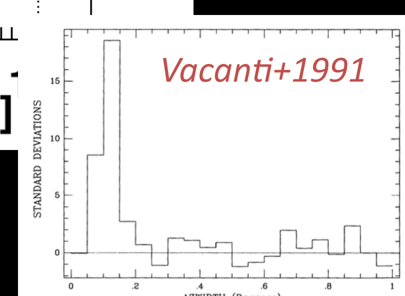
- ✓ used as **reference source**
  - ✓ visible from both Hemispheres
  - ✓ cross calibration

- ✓ first established detection of **pulsed emission** from ground

The 90s: experimental perspective







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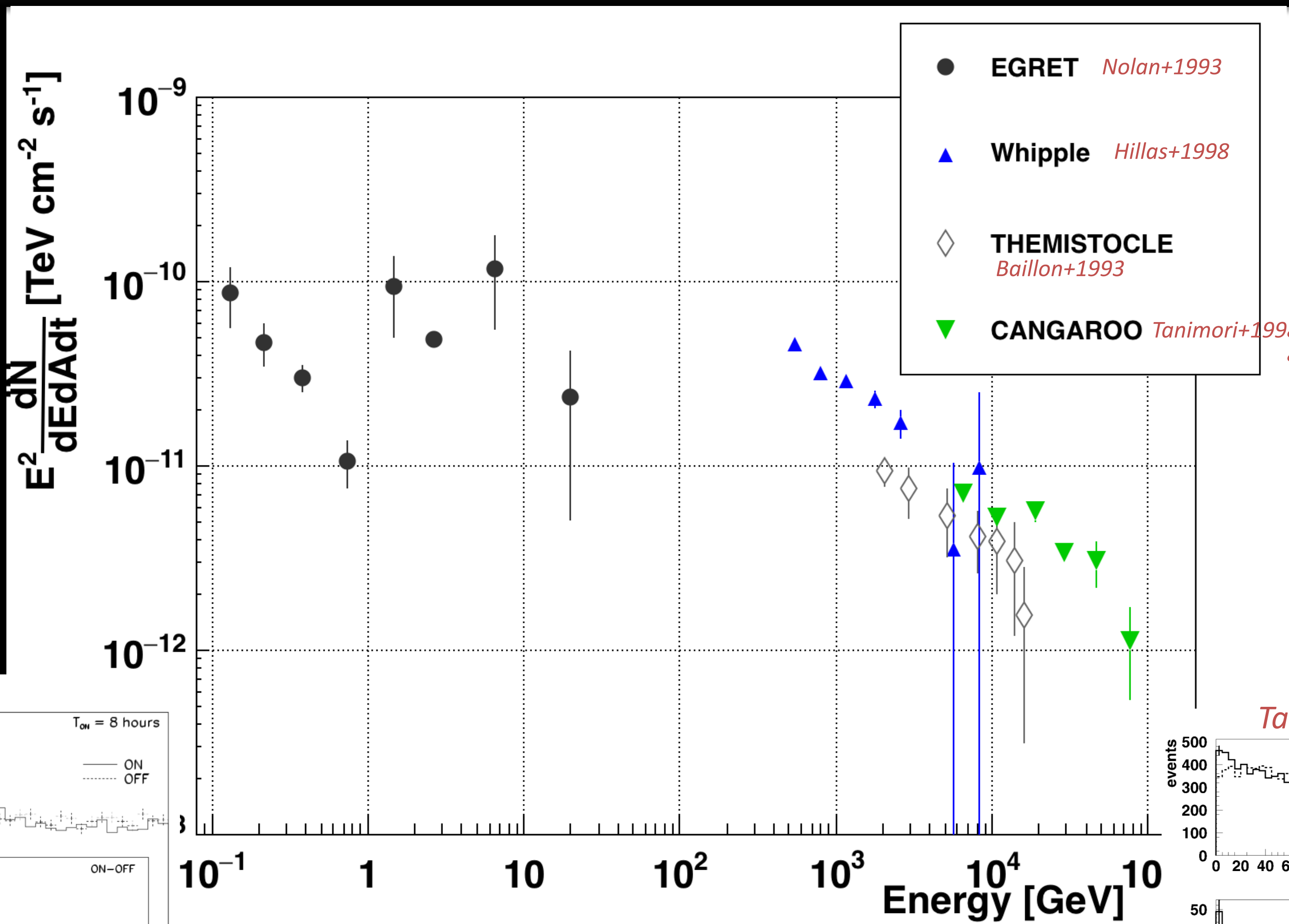

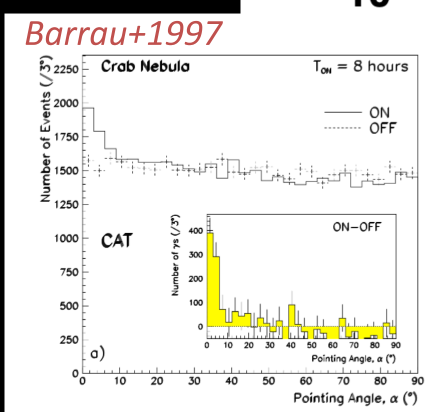

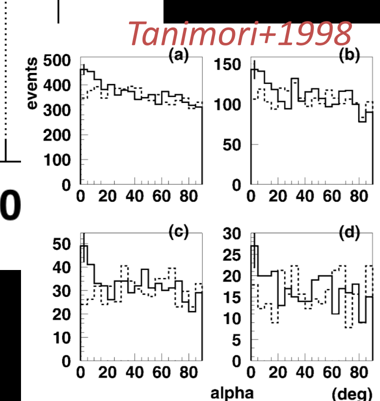

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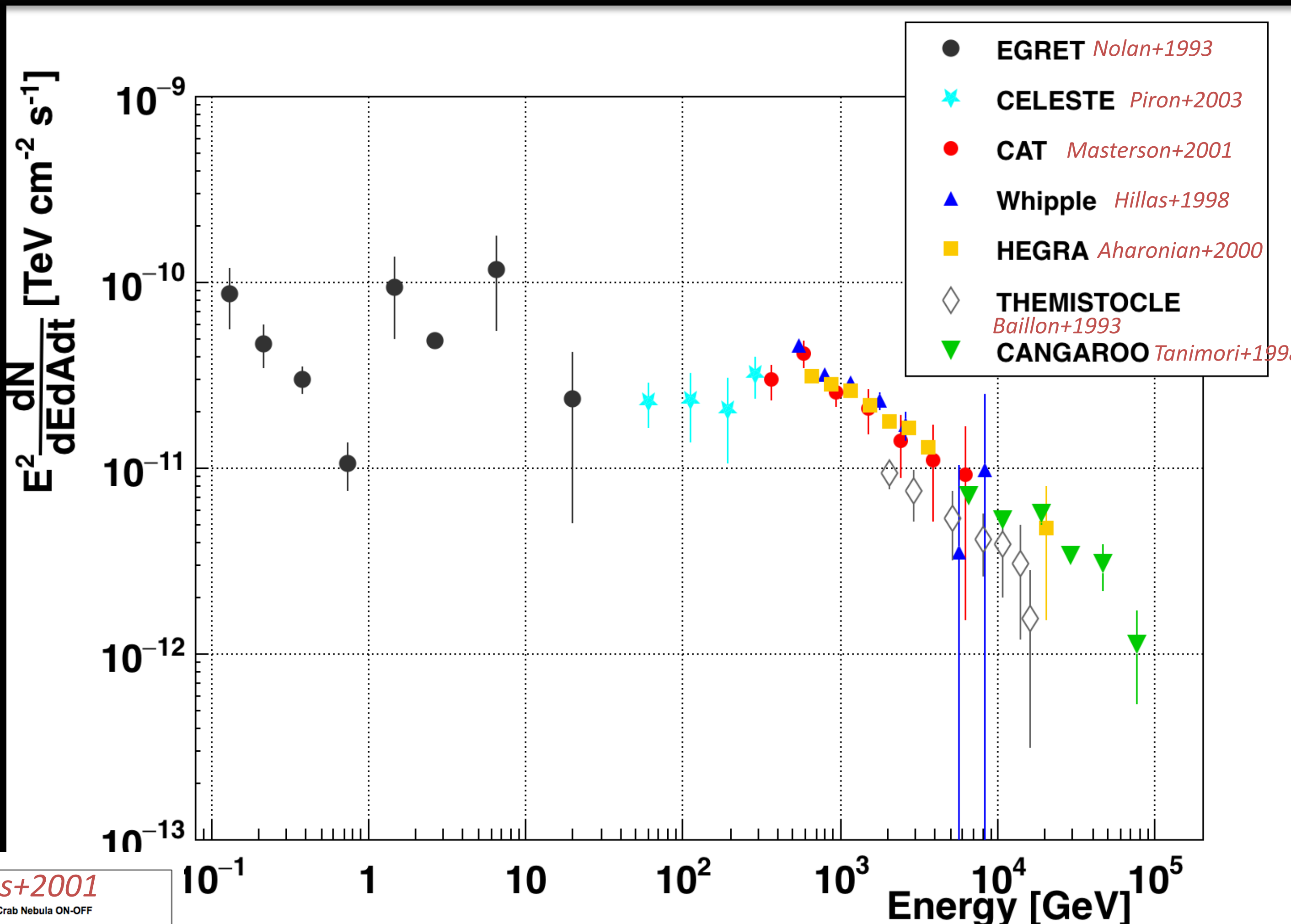
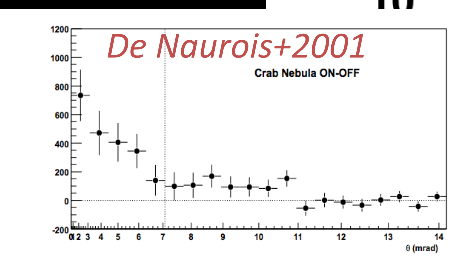
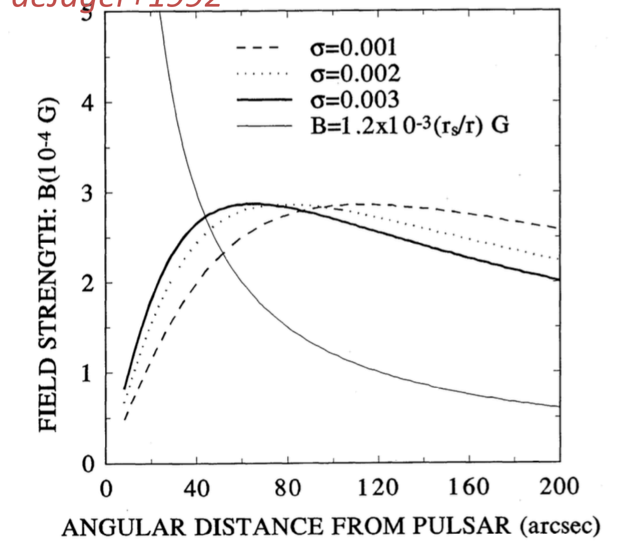


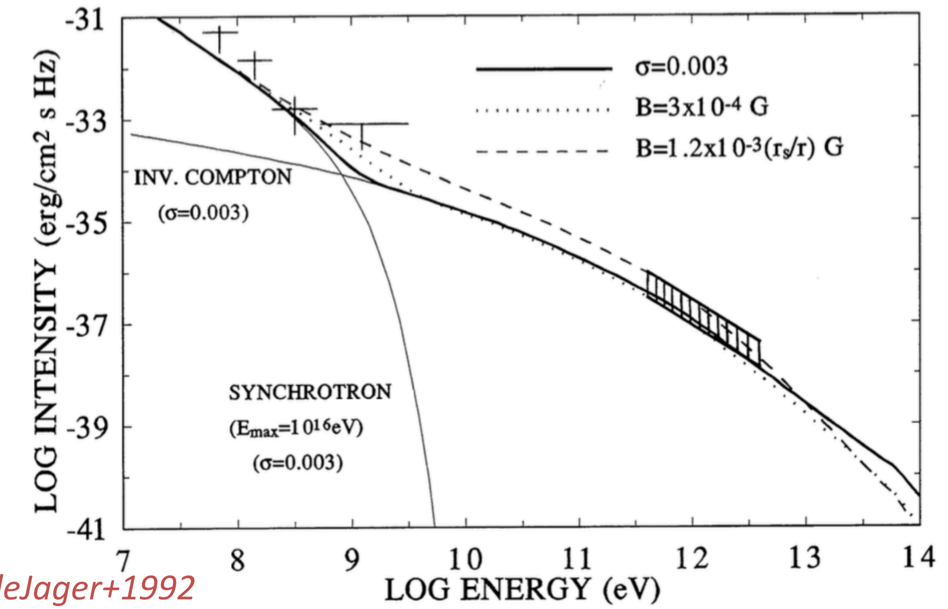


The 90s: theoretical perspective - 1

1. *deJager&Hardings1992 & deJager1996*
   - ✓ Photon fields: synchrotron + IR dust
   - ✓ IC cross section
   - ✓ Spatial resolved electron spectrum: from synch under the assumption of B distrib → B from MHD

deJager+1992

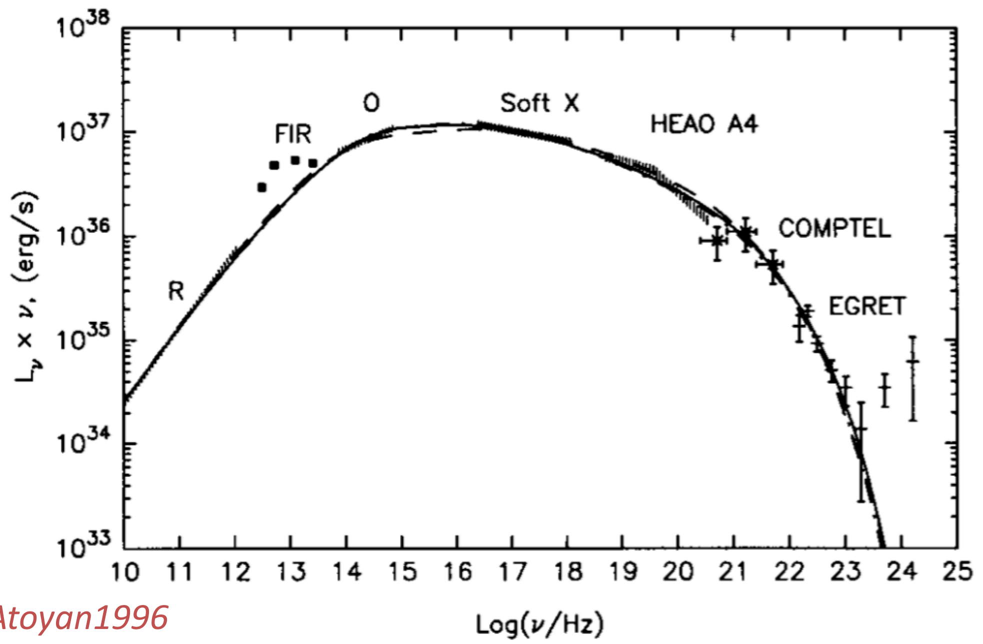




deJager+1992

The 90s: theoretical perspective - 2

2. *Atoyan&Aharonian1996*
   - ✓ Photon fields: synch + IR dust + CMB
   - ✓ Spatial resolved electron spectrum: from injection spectrum + propagation model *(KC84)*
   - ✓ 2 populations of electrons ($\alpha_{e;r}$~1.5 & $\alpha_{e;w}$~2.5 & E_{cr} =100-200 GeV)



Atoyan1996

Well fitted for σ = 0.003-0.001

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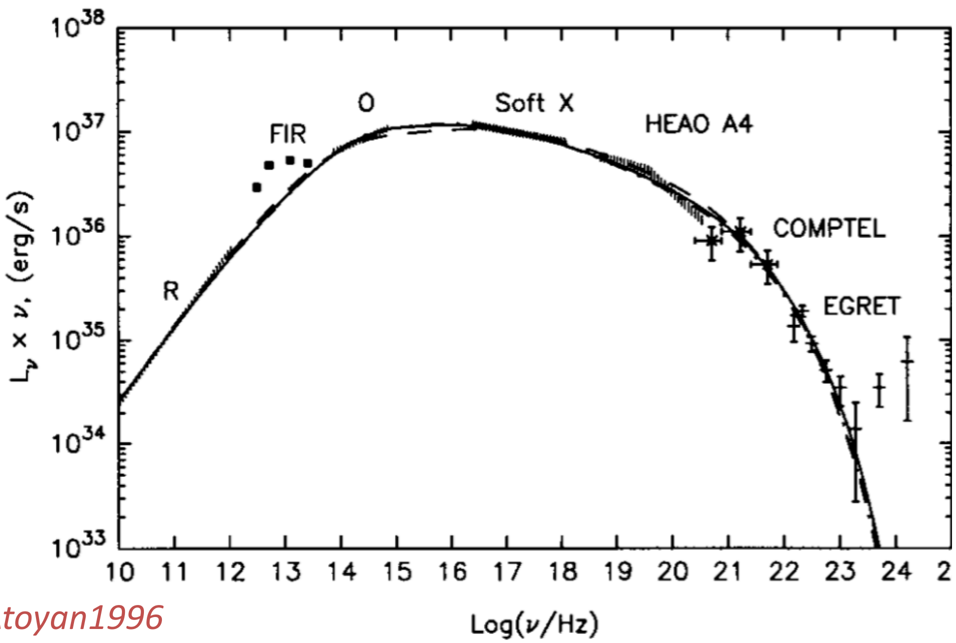

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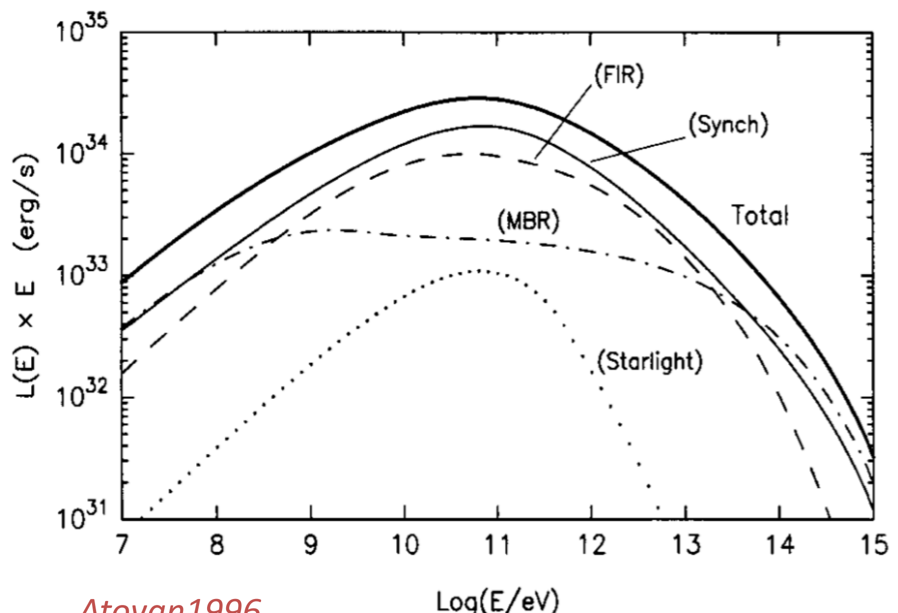

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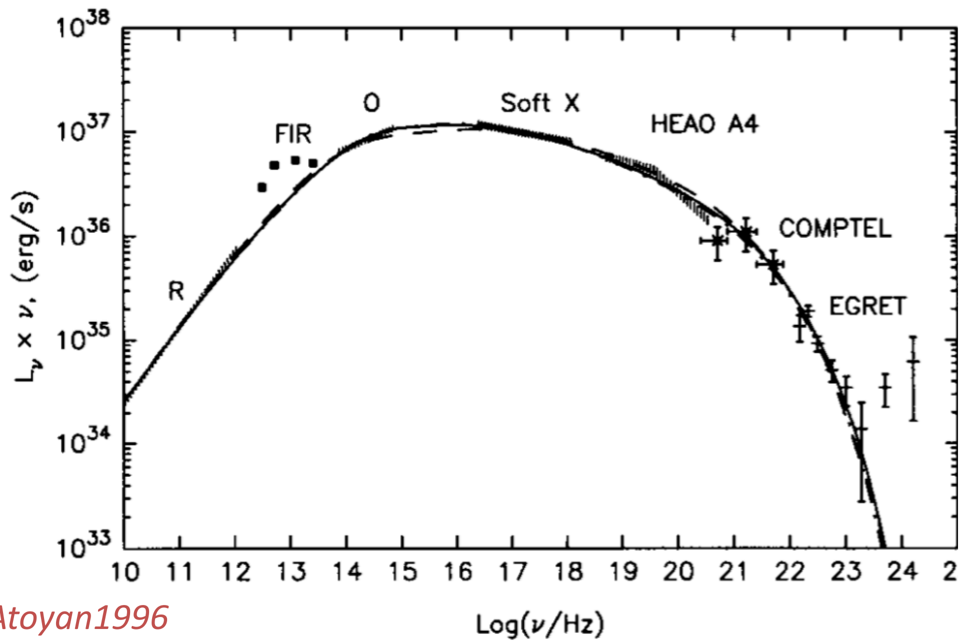

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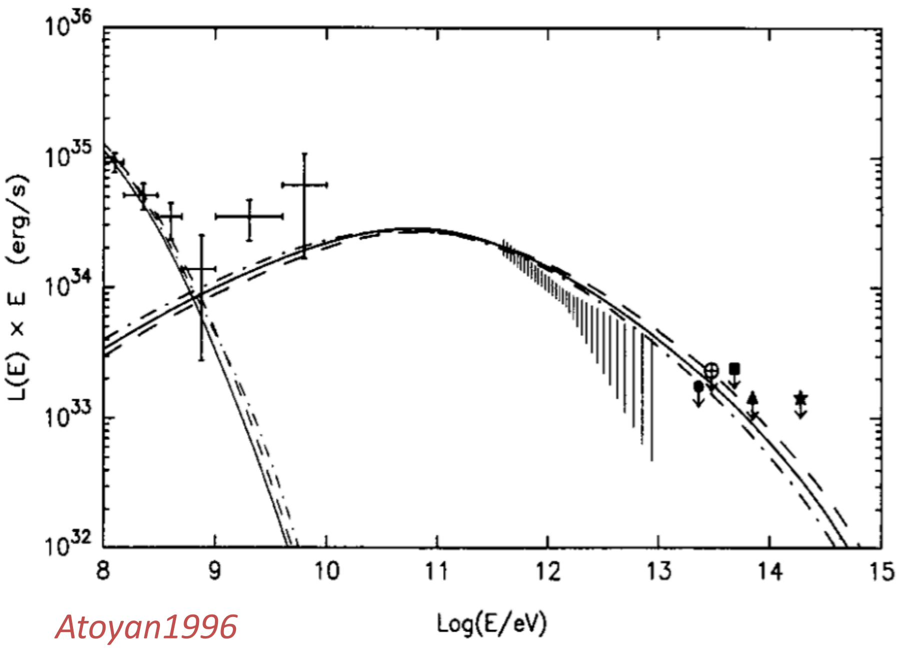

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Well fitted for σ = 0.003-0.001

for σ = 0.003-0.001 No difference in IC

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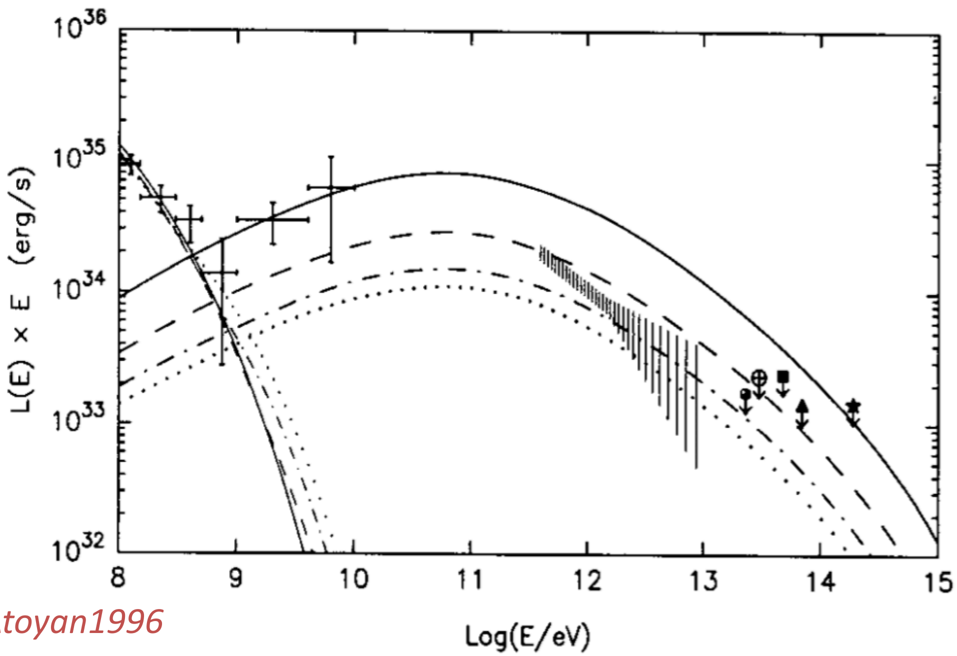

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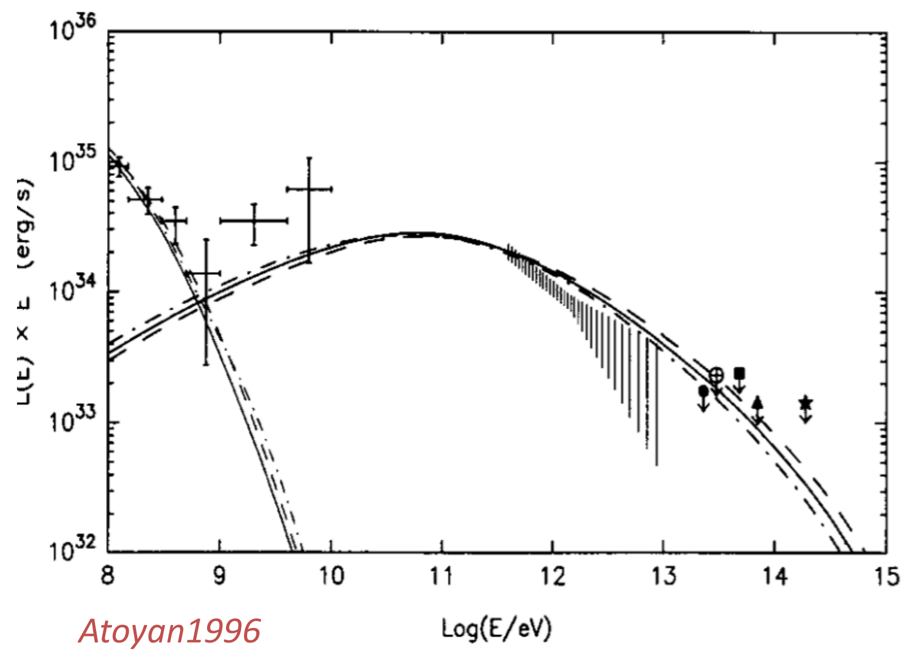


Atoyan1996

Predicted too-low GeV flux. Bo ~160-200 μG

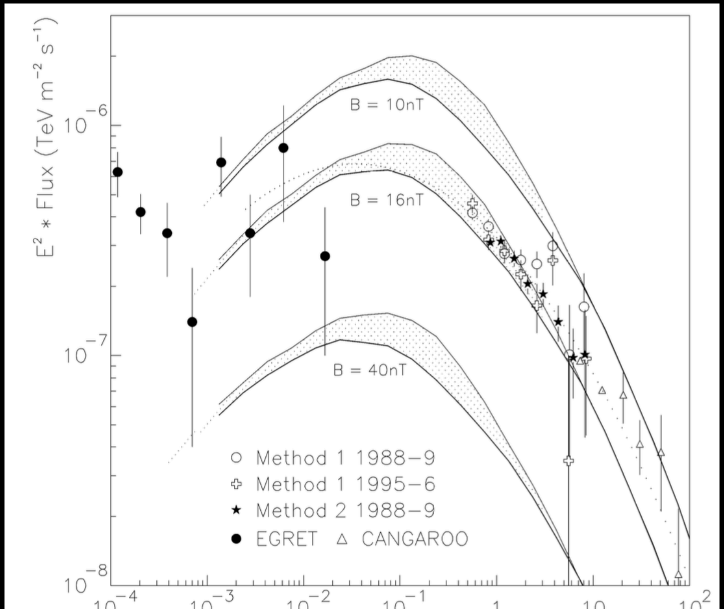
for σ = 0.003-0.001 No difference in IC

The 90s: theoretical perspective - 3

3. Hillas+1998

- ✓ When exploring a limited region of the nebula
  → B-field is constant
- ✓ PL electron spectrum & electron density Gauss distributed following the measured shrinking by fitting the synchrotron measurements
- ✓ IR + synch photon fields

B_0 @ 1 TeV 160 μG
B_0 @ 1 TeV 100-120 μG



Hillas+1998

The 90s: theoretical perspective - 3

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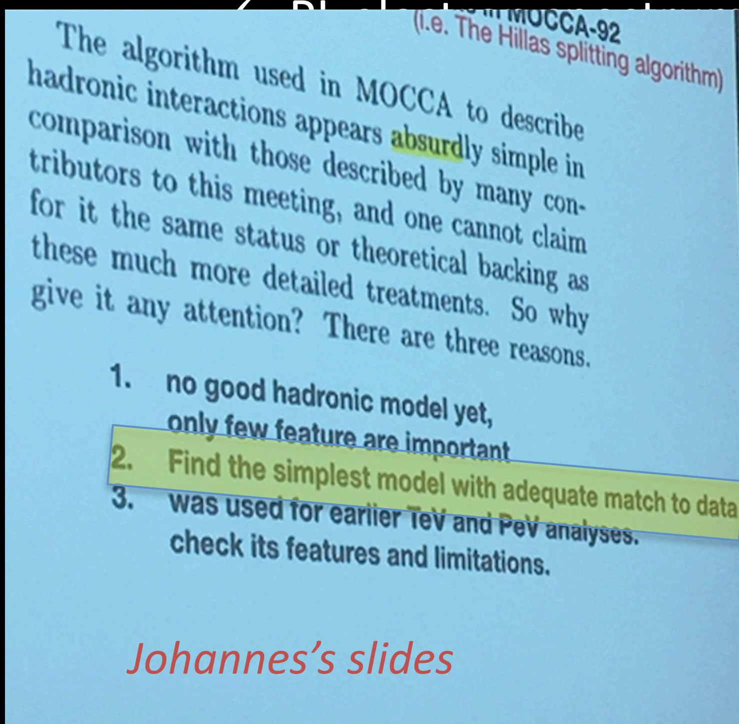
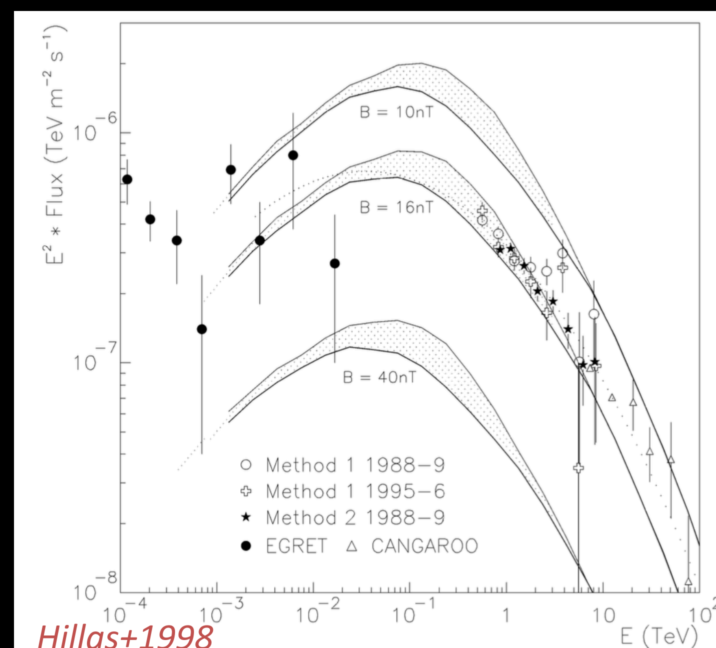
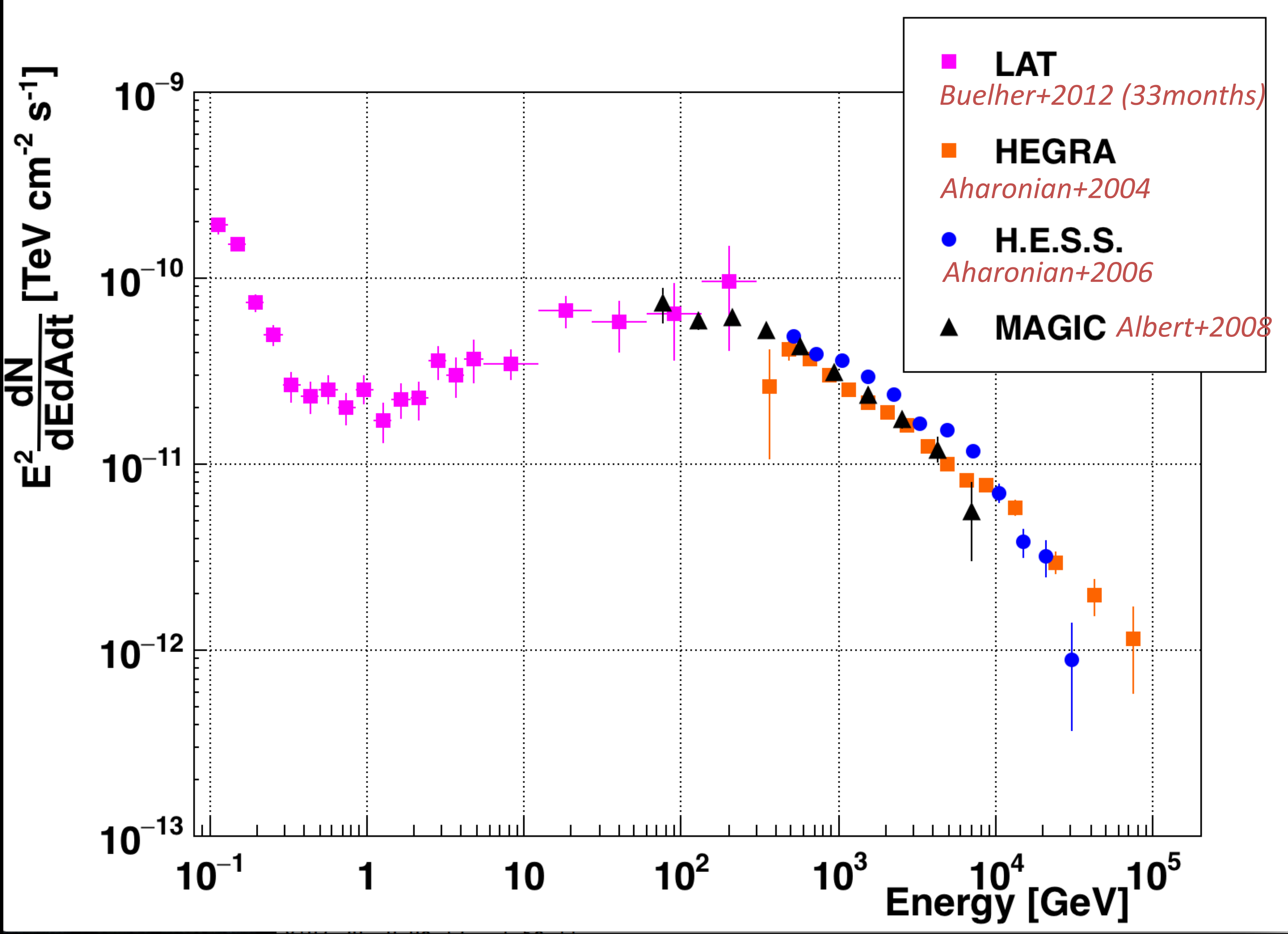




Hillas+1998

The last 15 years: the IC peak



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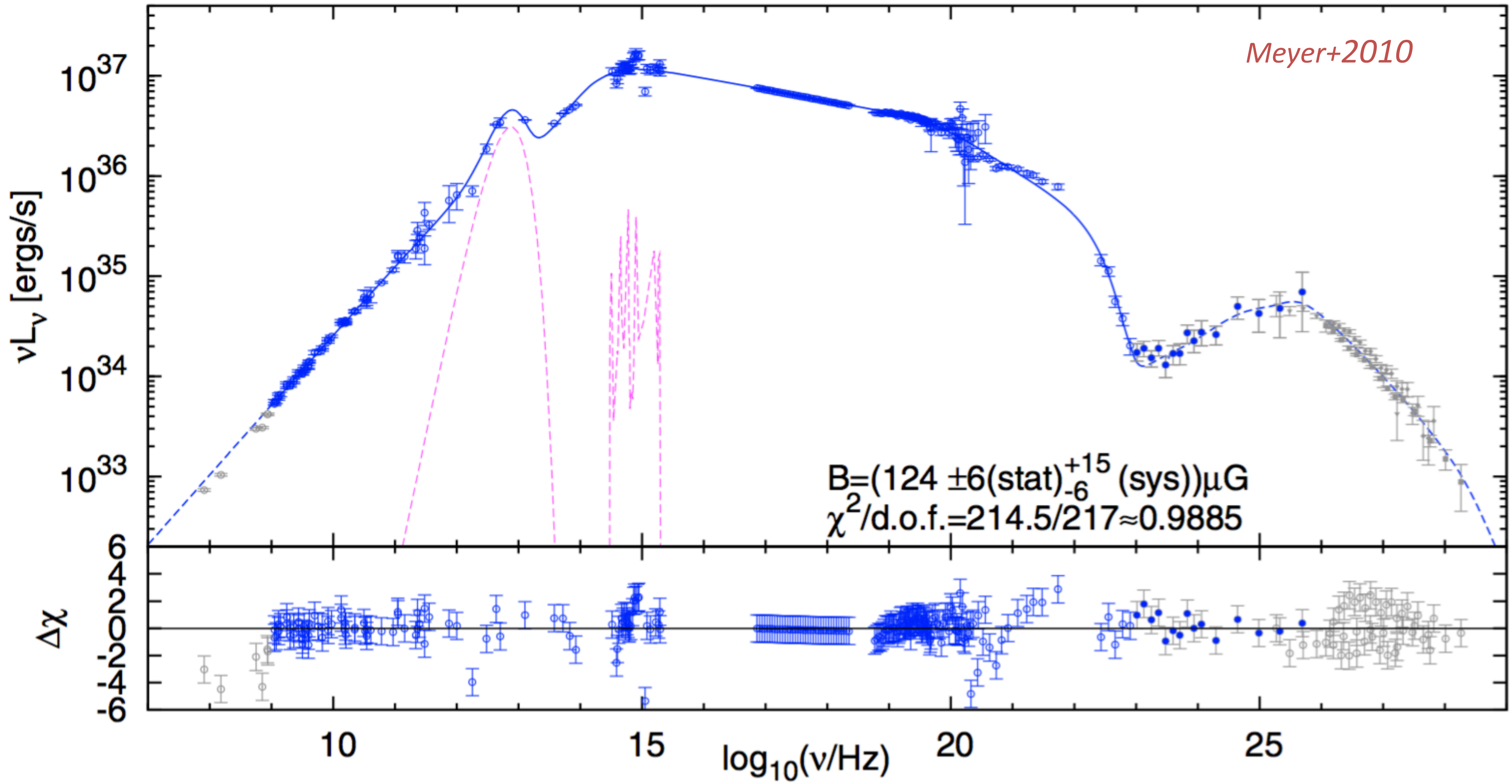
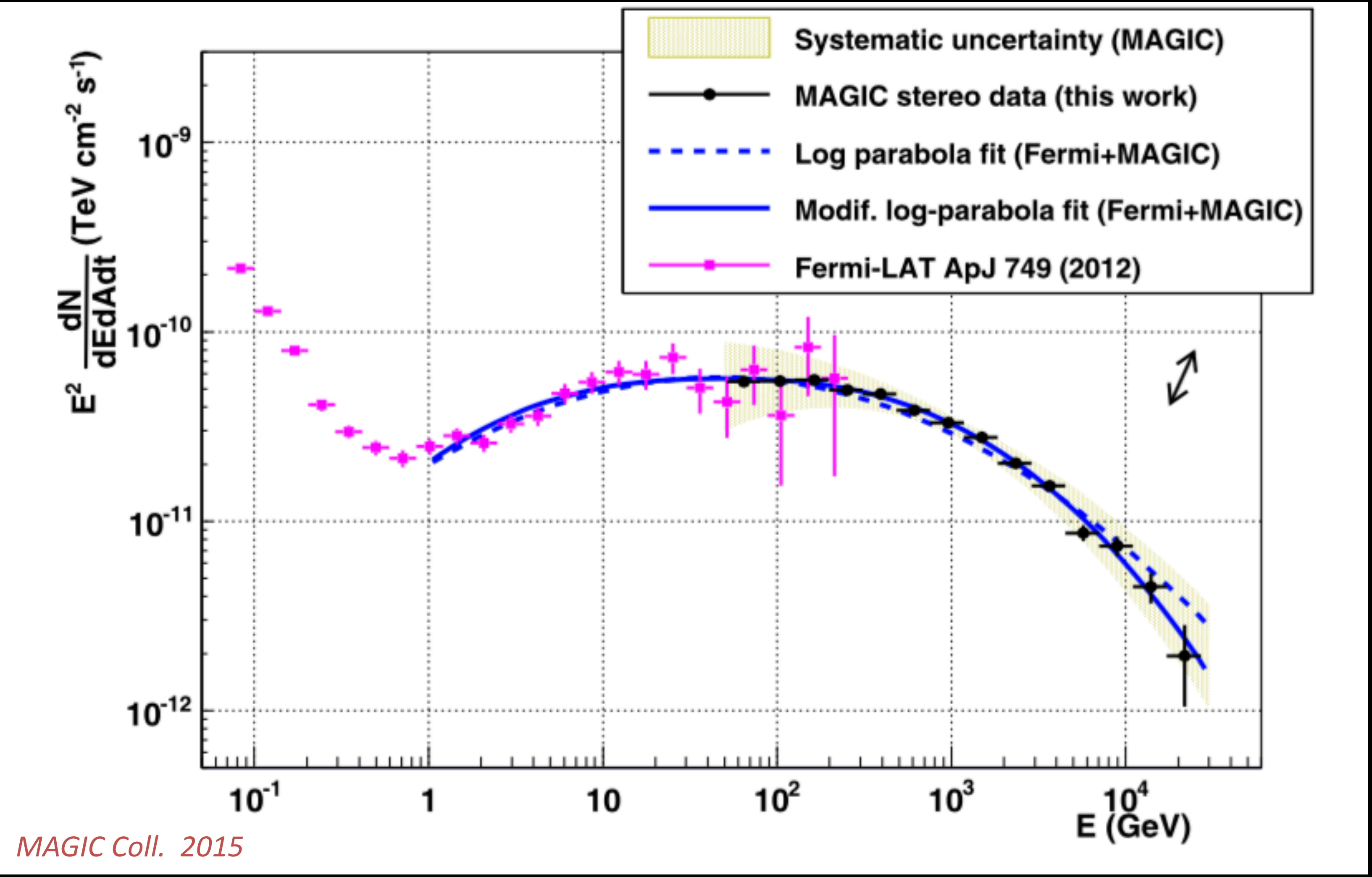


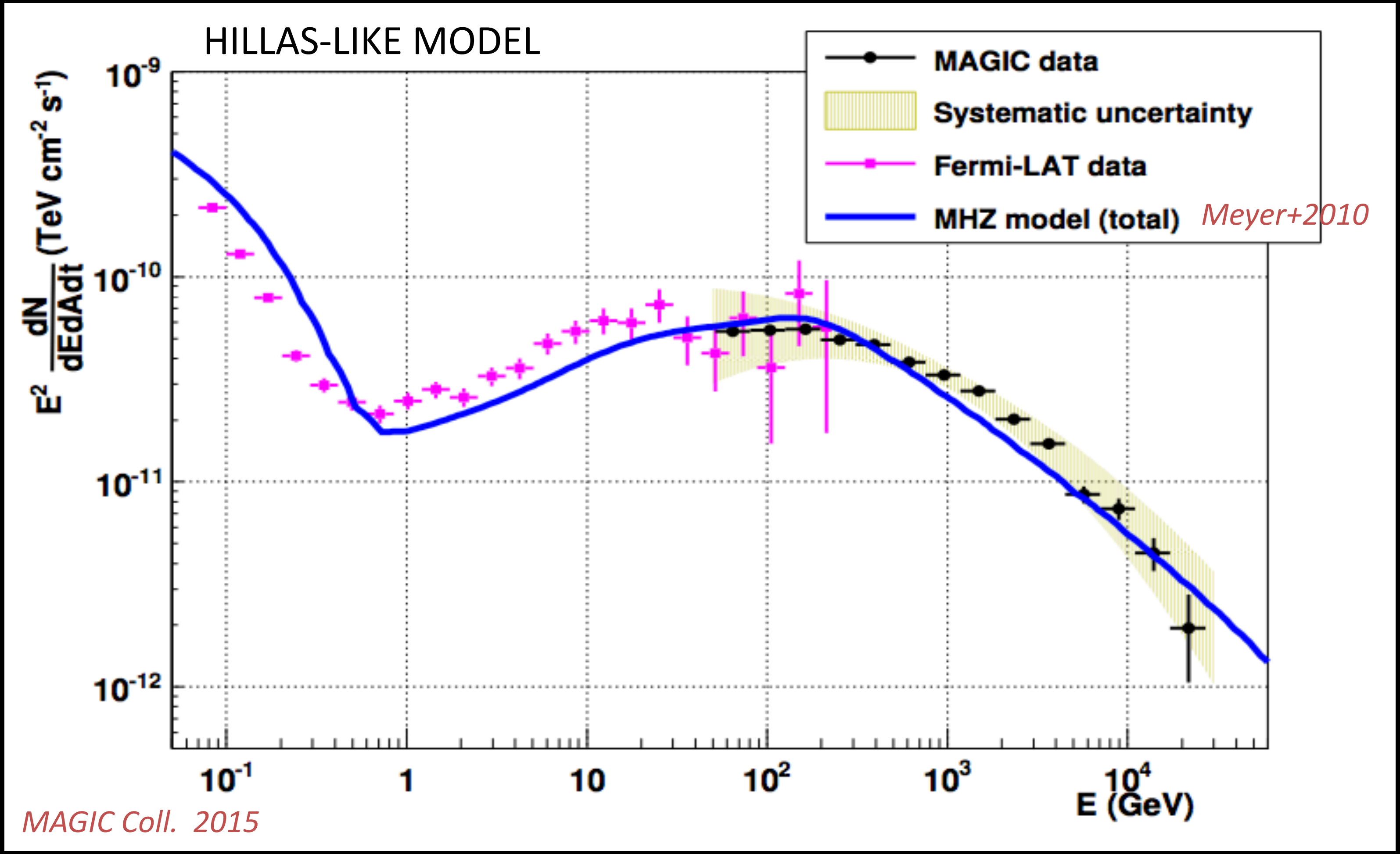
- ✓ 1MDG model (A&A-like does not provide good description of the data: spherical symmetry too simplistic (Meyer+2010)
- ✓ Simplified approach (Hillas-like) has less dof (Meyer+2010)

The last 15 years: the IC peak



A modified LogParabola (2.5 exp) is needed to fit the data → a flat peak

The last 15 years: IC peak

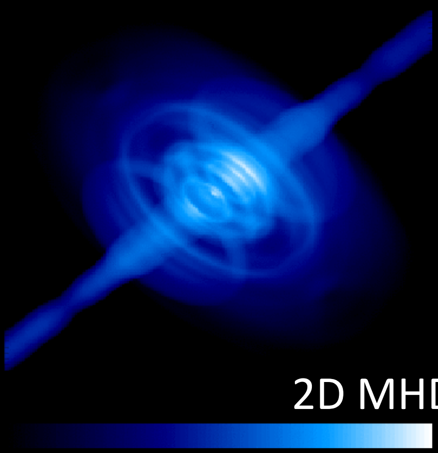


- ✓ The assumption of the homogeneity of the B-field inside the nebula is incorrect

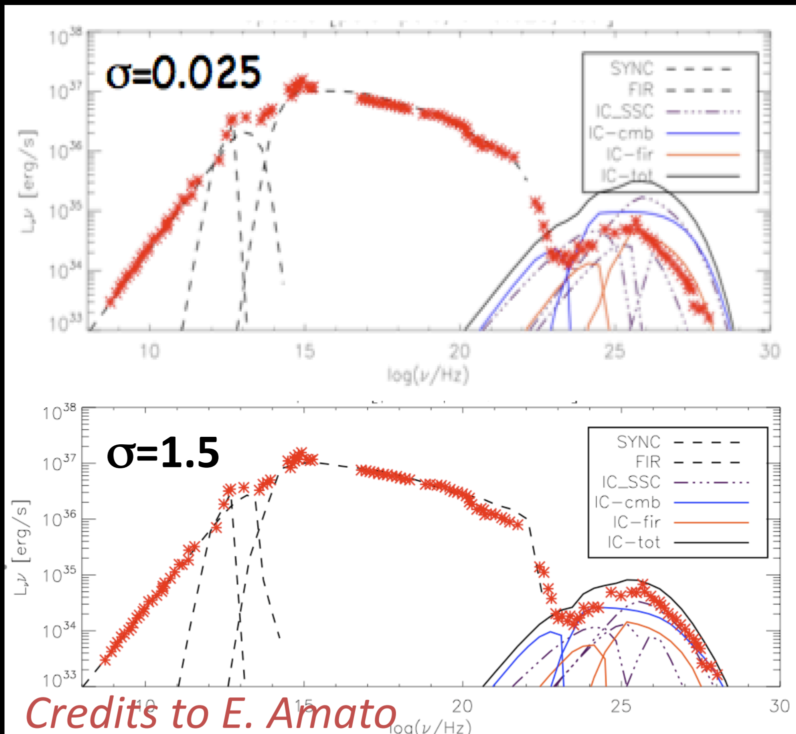
State-of-art understanding

✓ 2D MHD models reproduce the morphology and variability in the inner region *(Olmi+2016)*

Weisskopf+2000



State-of-art understanding



Credits to E. Amato

✓ 2D MHD models reproduce the morphology and variability in the inner region
but not B structure on larger scales *(Volpi+2008)*

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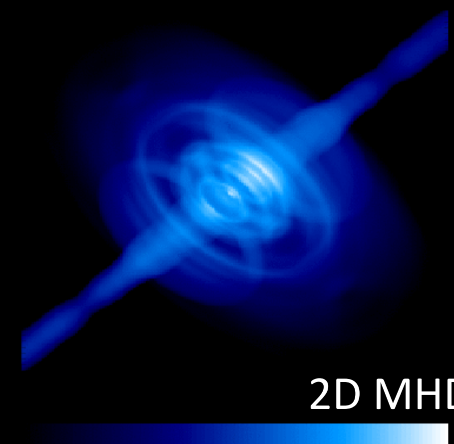
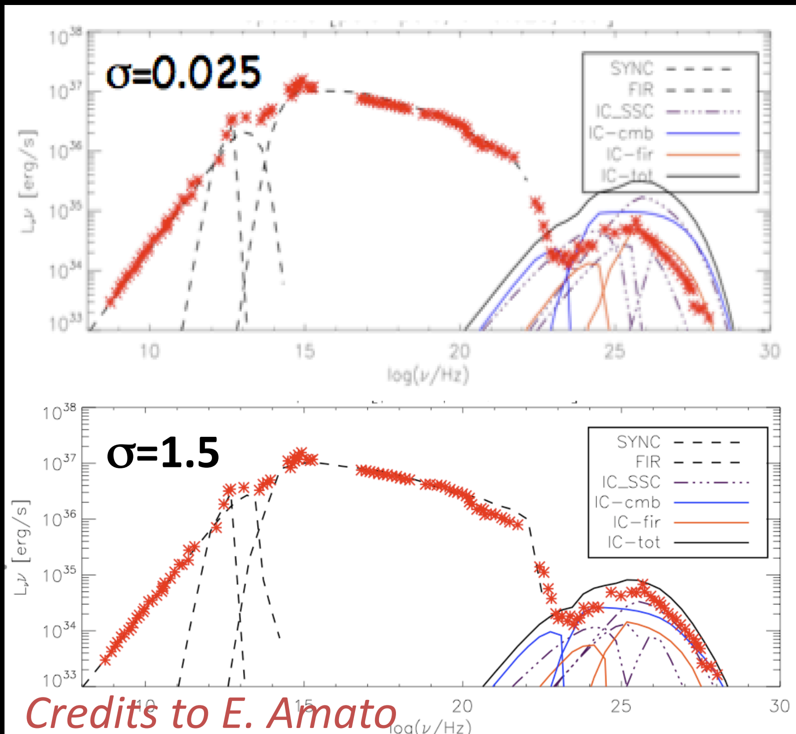


2D MHD

State-of-art understanding



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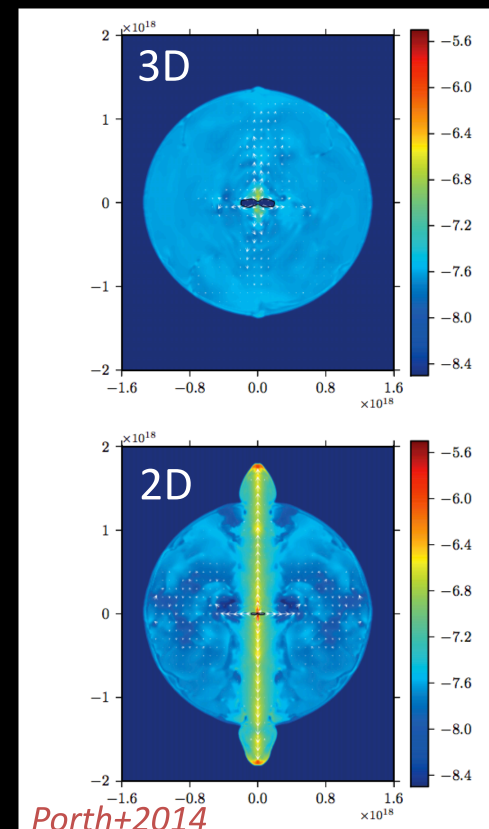


Porth+2014

- ✓ 3D MHD models allow high magnetization at the TS (σ>1) *(Porth+2013, Porth+2014)*
- ✓ 3D MDH are highly dissipative *(Porth+2014)* even though magnetic dissipation seems to become less important after 100 ys *(Olmi+2016)*
- ✓ Fermi acceleration unlike

Acceleration mechanism

wisps at different λ have distinct velocities and positions
(Bietenholz+2004, Schweizer+2013)

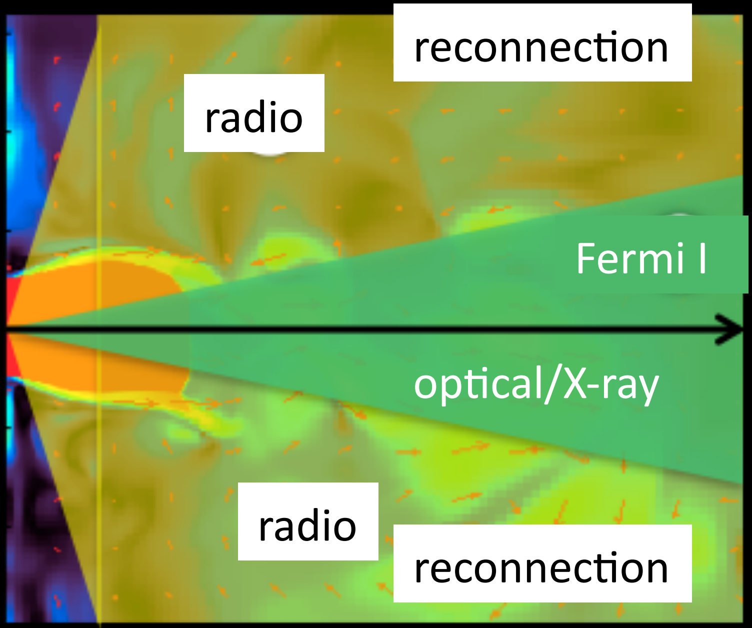
→ different mechanism at work *(Olmi+2015)*

- ✓ FERMI I
  - ✓ narrow equatorial sector (low σ)
  - ✓ optical/X-ray particles (p=2)

  (Spitkovsky2008, Sironi+2011)

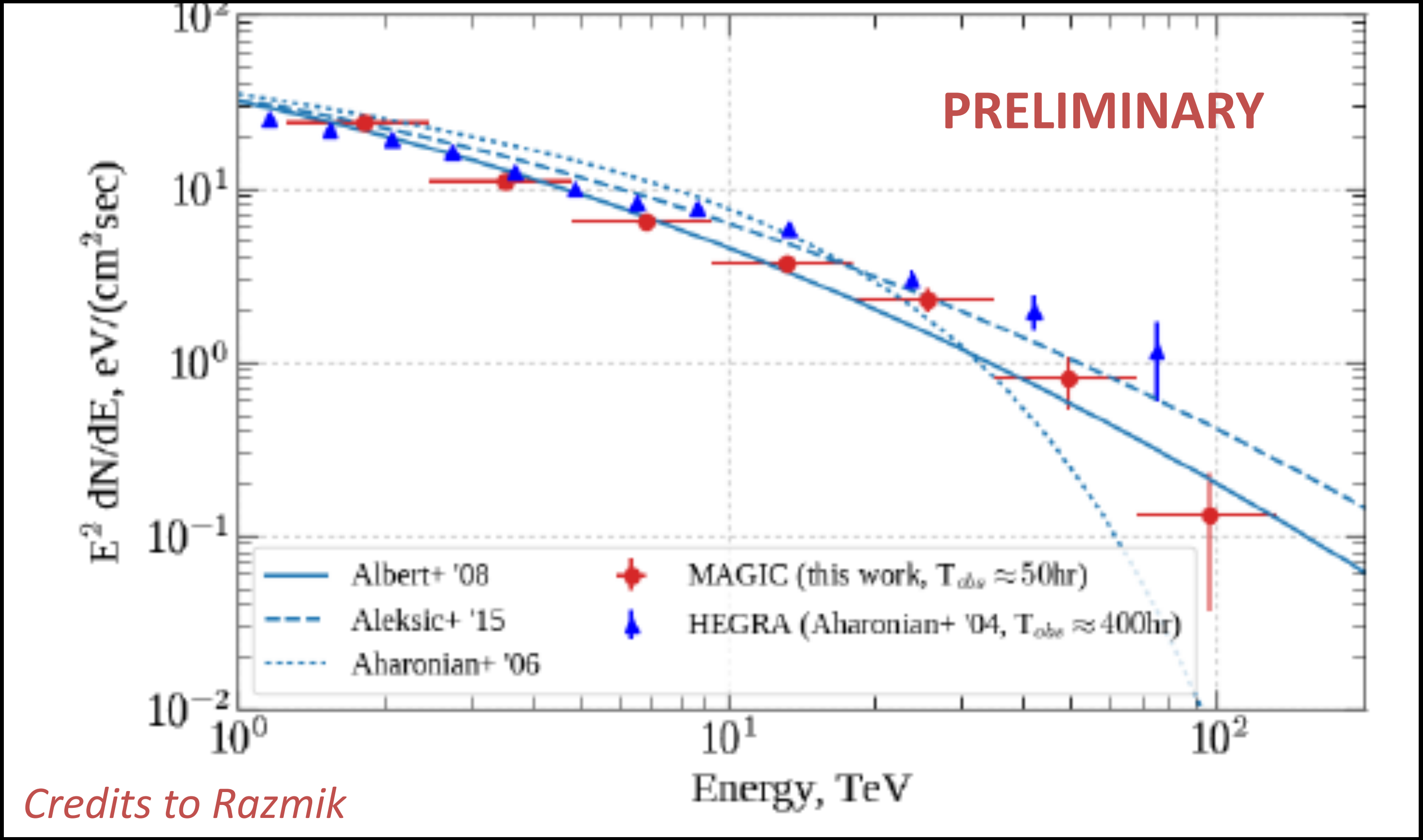
- ✓ MAGNETIC RECONNECTION
  - ✓ elsewhere (high σ)
  - ✓ radio electrons (p=1.5)

  (Lyubarsky2003, Lyubarsky+2008, Sironi+2011)



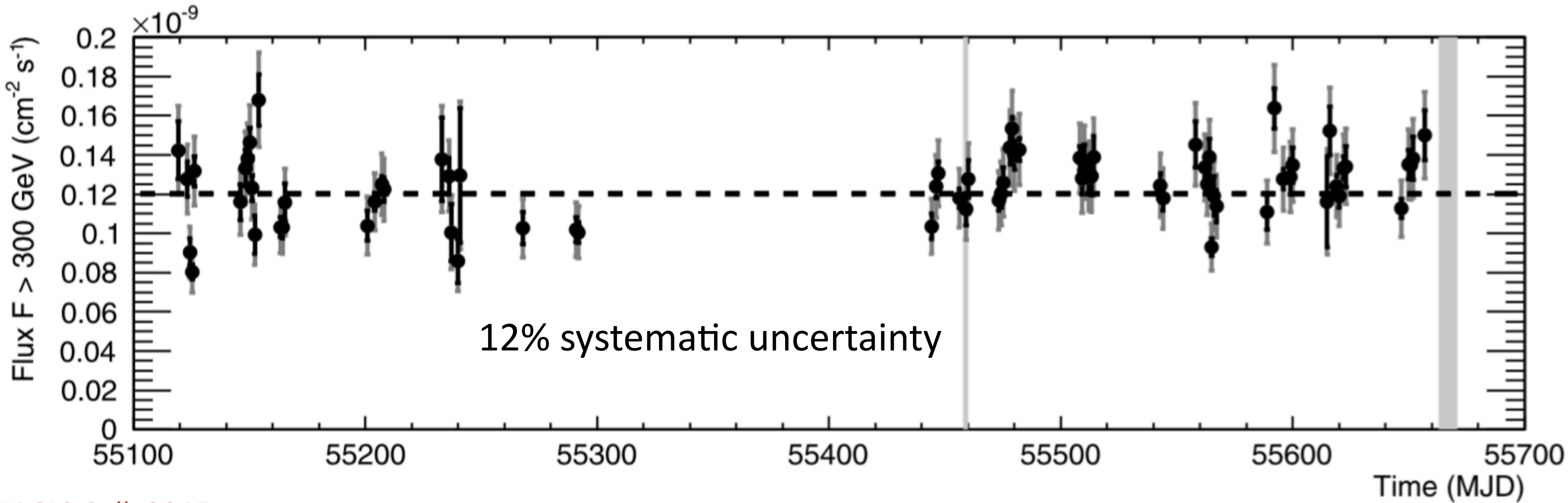
Olmi+2015

The last 15 years: the VVVHEs



✓ Observations almost at the horizon: zd 80°-90°

The last 15 years: flux variability

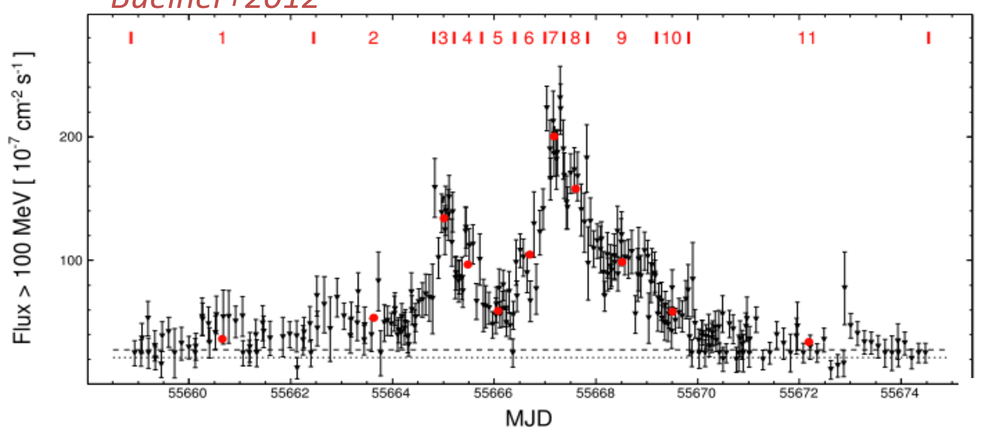


MAGIC Coll. 2015

- ✓ now searching for correlation in flux variations in simultaneous Crab observations

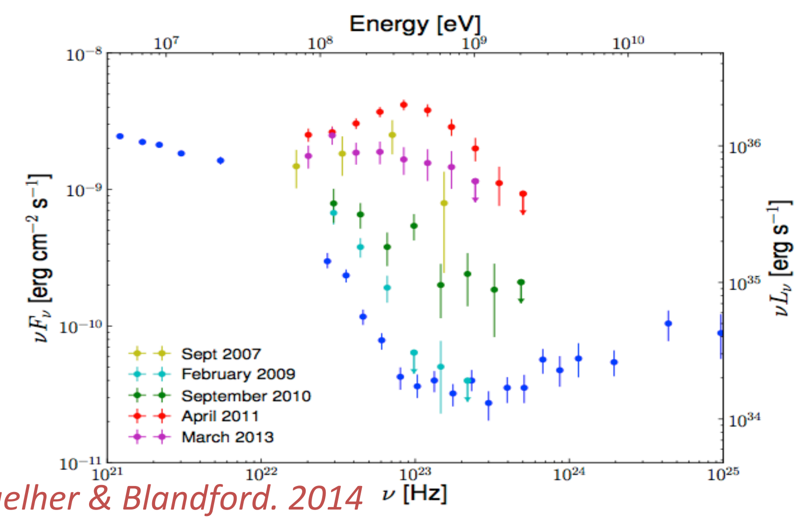
The last 15 years: GeV flares

Buelher+2012



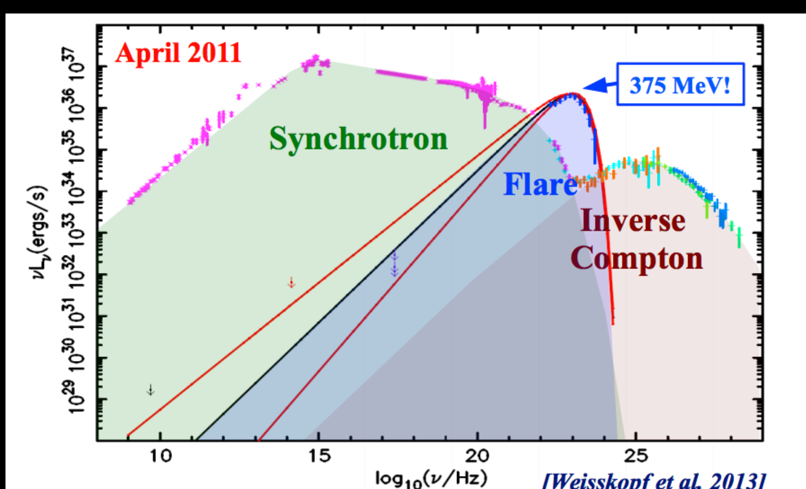
Tavani+2011, LAT2011, Buelher+2012, Mayer+13, Striani+2013

- ✓ Flux doubling in less than 8hr
- ✓ Impact emission region smaller than ct_{lare} = 0.001 pc



Buelher & Blandford. 2014

- ✓ Spectral variations, hard spectrum Γ=1.3
- ✓ Exceed the synch. critical energy

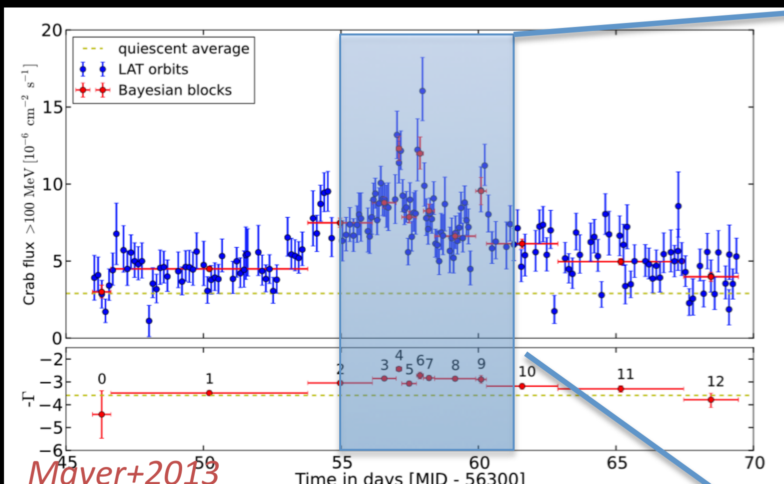


- ✓ No obvious counterpart at other wavelengthhs *(Weisskopf+2013, Rudy+2015*
- ✓ No IC enhancement *(H.E.S.S. Coll. 2014)*

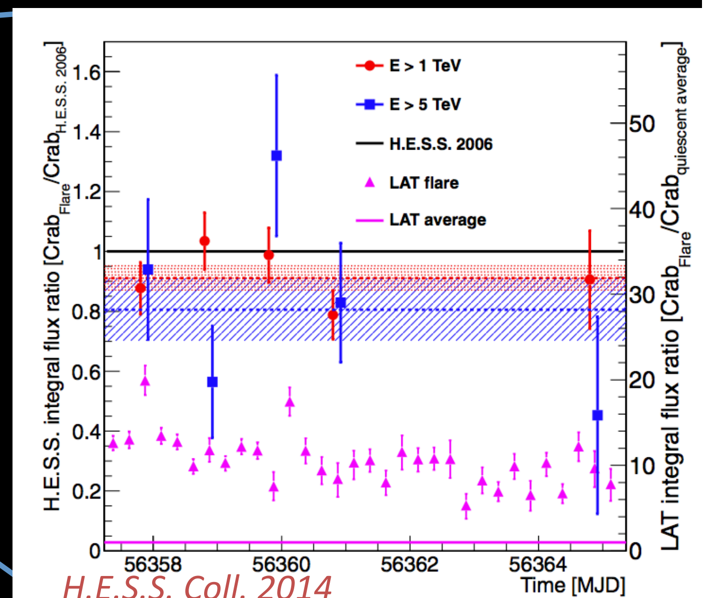
The last 15 years: GeV flares

- ✓ any counterpart for the GeV flares? Some hints by ARGO (Aielli+2010, Bartoli+2012 but no enhancement by any of the IACTs *(H.E.S.S. Coll. 2014, VERITAS Coll. 2014)*

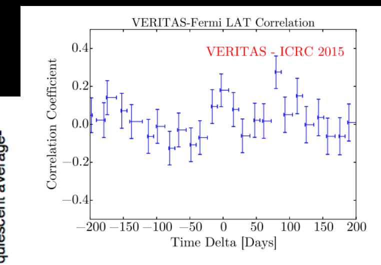
March 2013 flare



Mayer+2013



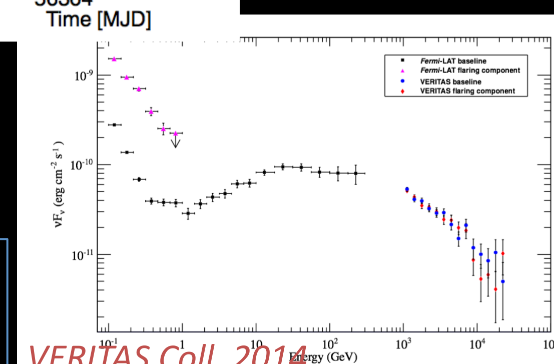
H.E.S.S. Coll. 2014



Upper limit on the Doppler factor

$$f_\nu^{IC} / f_\nu^{Syn} \propto (\delta/B)^{1+\alpha}$$

$$\delta \lesssim 100(B/122\,\mu G).$$

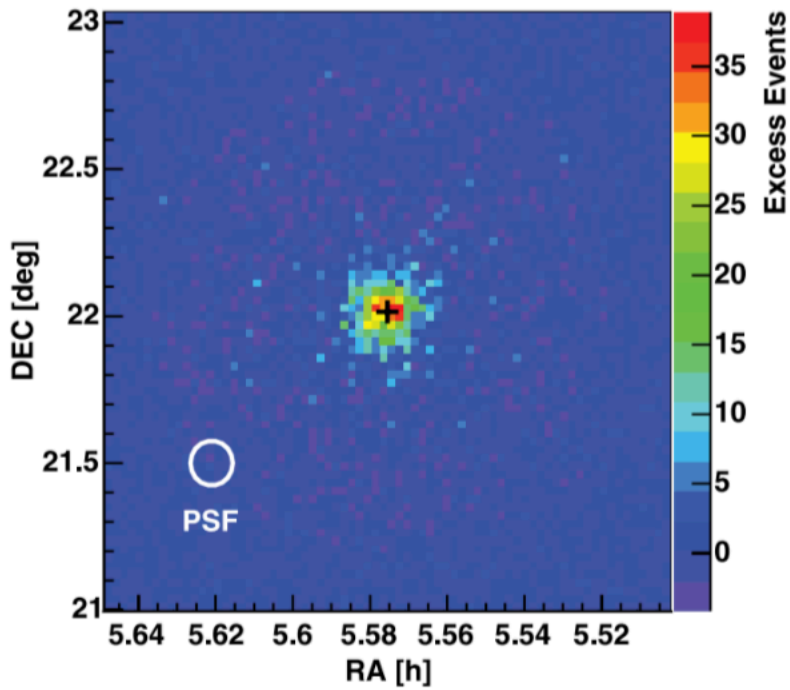


VERITAS Coll. 2014

Bykov+2012, Bednarek+2012, Clausen-Brown+2012, Komissarov+2013, Lyutikov+2016, Kirk+2018

The last 15 yr: extension

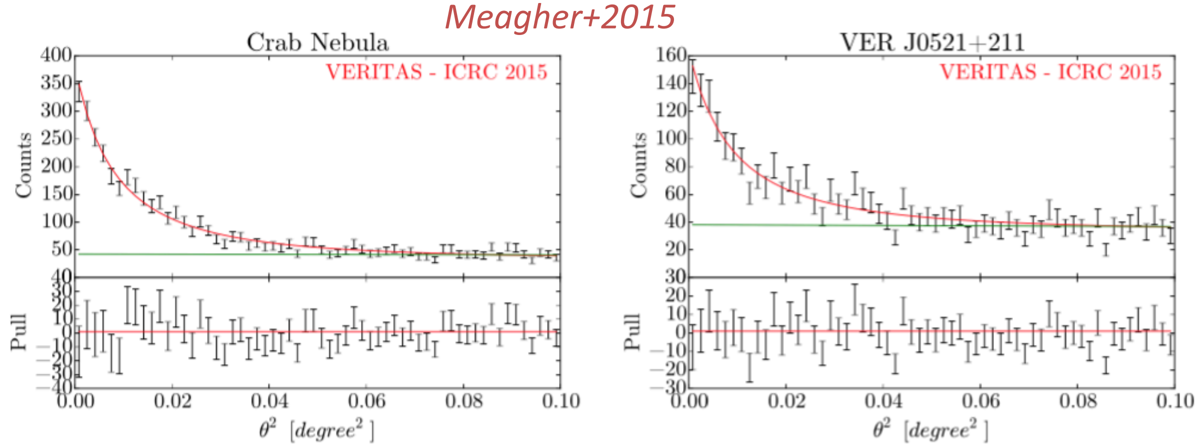
MAGIC Coll. 2008



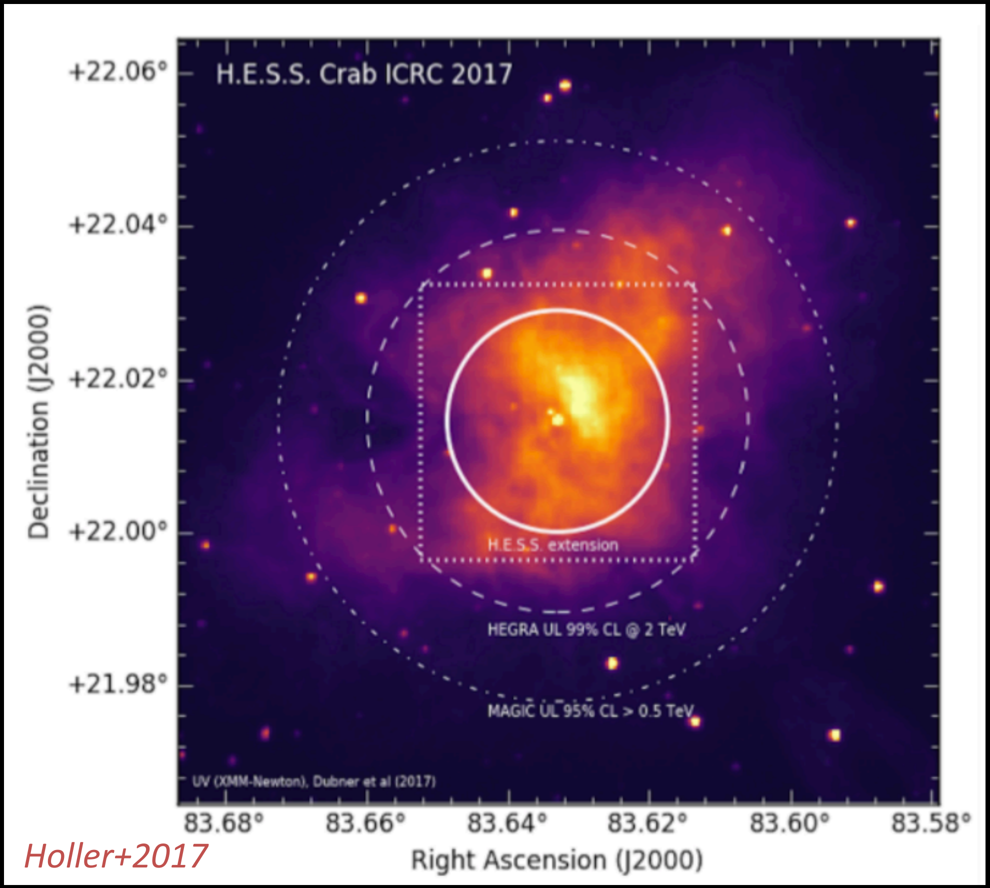
	Energy [TeV]	σ_{ext}
MAGIC	E>0.5	2.2'
HEGRA	E>5	1.7'

HEGRA Coll. 2004, MAGIC Coll. 2008

Meagher+2015

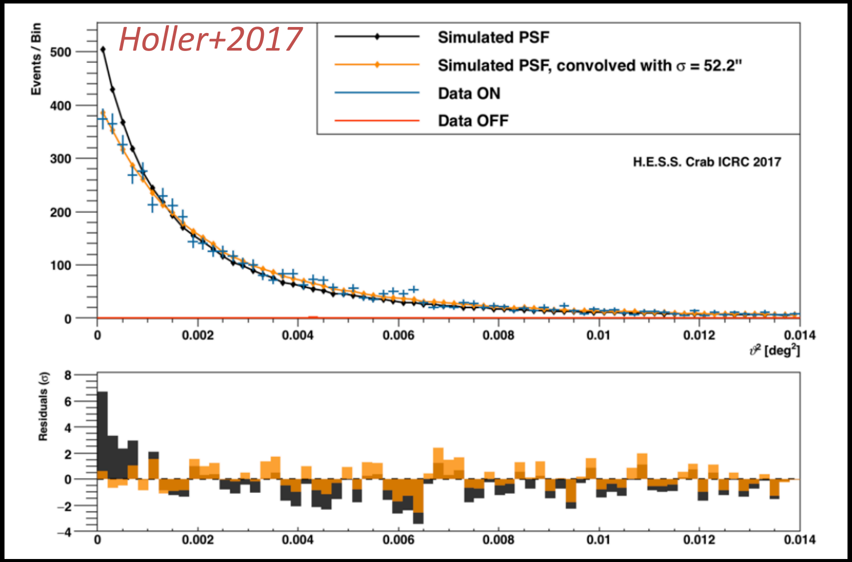


The last 15 yr: extension

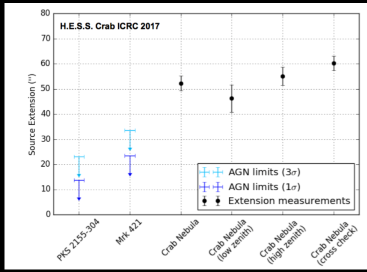


H.E.S.S. Coll. In preparation

$\sigma = 52.2'' \pm 2.9'' \pm 7.8''$ with $TS_{ext}=80$



Results compatible with 1-d MHD models (KC84, A&A96) *(Holler+2017)*



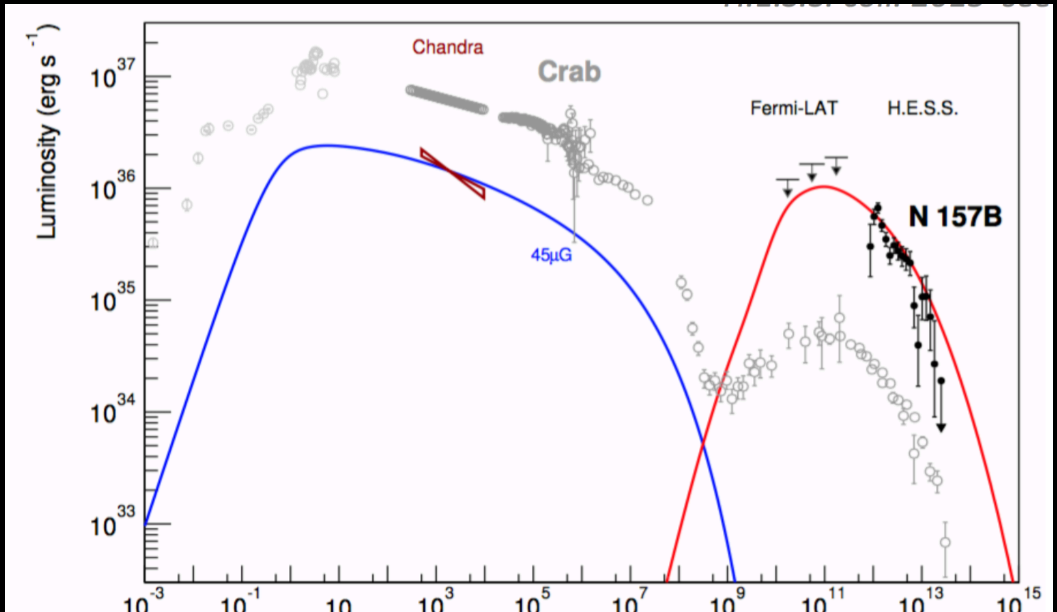
An exceptional young PWN

- ✓ Crab is a very efficient accelerator accelerating electrons up to PeV
- ✓ not an efficient γ-ray emitter

$h\nu_{cut}$ = 150 η^{-1} MeV
Crab: $h\nu_{cut}$~ 10-20 MeV → η~10

$$\frac{L_{syn}}{L_{ic}} = \frac{U_B}{U_{ph}}$$

The Crab twin in the LMC



H.E.S.S. Coll. 2015

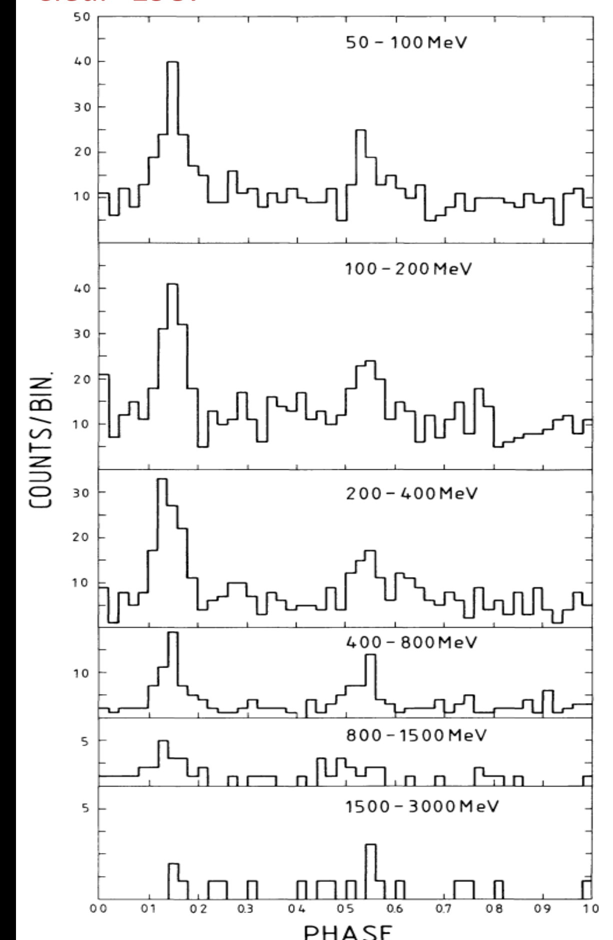
B~45μG

- ✓ also the photon field plays a role

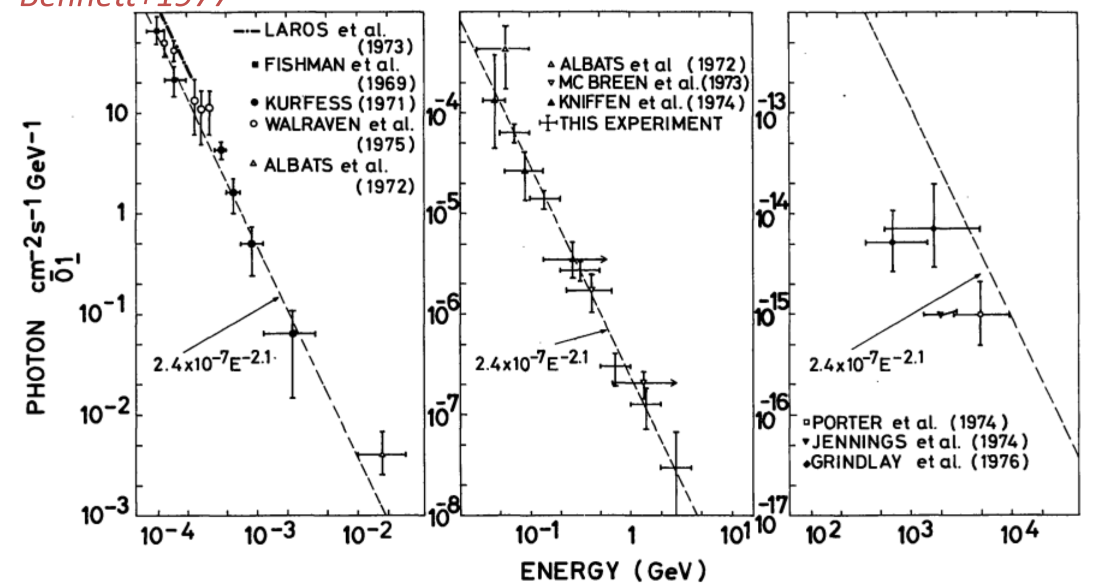
γ-ray pulsed emission

- ✓ Discovered in soft γ-rays from its discovery with baloon observations *(Browning+1971, Albatz +1972, Kinzer+1973, McBeien+1973, Parlier+1973, Graser+1982)* & with satellites SAS-2 *(Thompson+1977)*, and COS-B *(Bennett+1977, Clear+1987)*
- ✓ Results confirmed by EGRET: power-law spectrum, no emission above 4 GeV, harder bridge emission *(Nolan+1993, Ramanamurthy+1995)*

Clear+1987

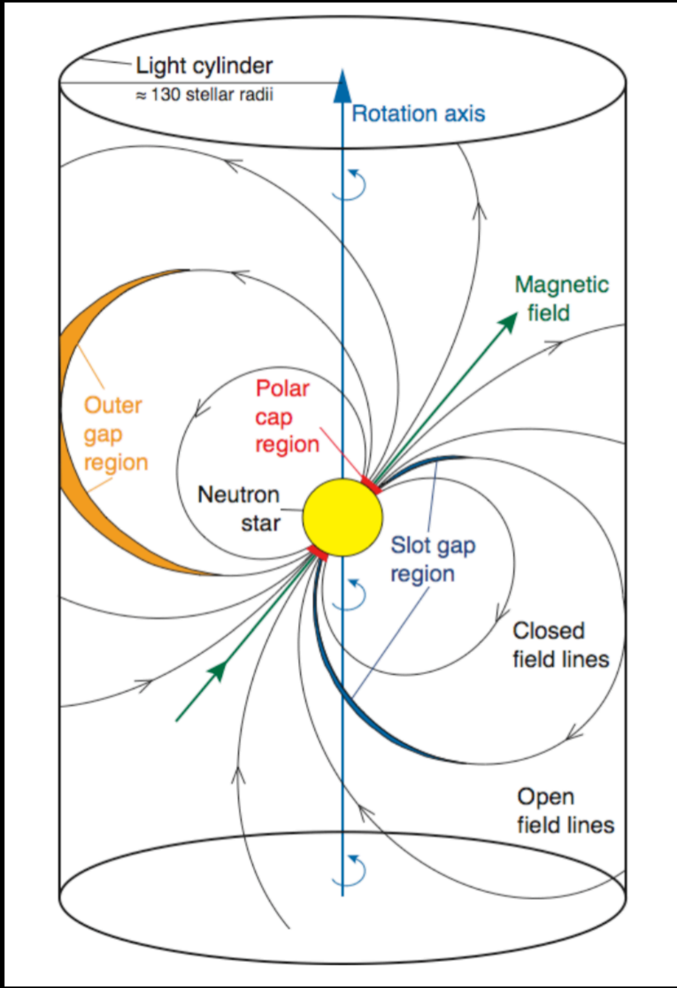


Bennett+1977



γ-ray pulsed emission: theoretical view

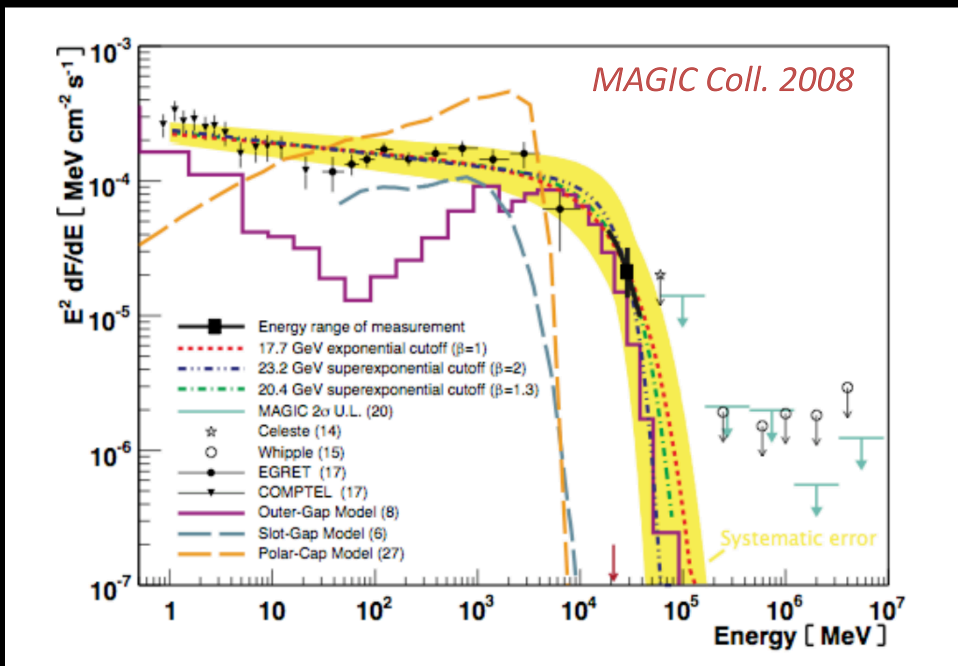
to account for particles acceleration, we need regions with deviations from the free-force conditions

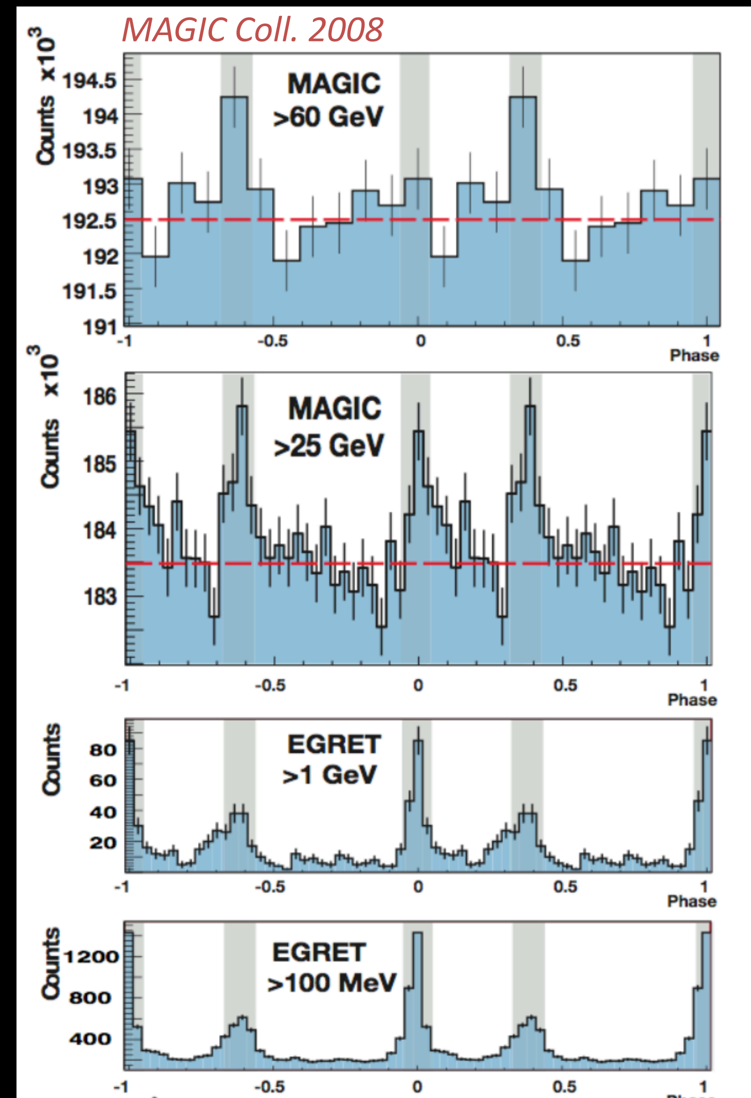


- ✓ acceleration geometries
  → regions of unscreened fields: = GAPS
  - ✓ inside the light cylinder
  - ✓ accelerated particles emit curvature radiation
    - ✓ pair production

Polar cap: *Sturrock+71, Ruderman+ 75, Harding+ 78, Daugherty+82*
Outer gap: *Cheng+86, Romani+95*
Slot gap: *Arons 83, Muslimov+ 03, 04*

Start of a new era: last 10 yr

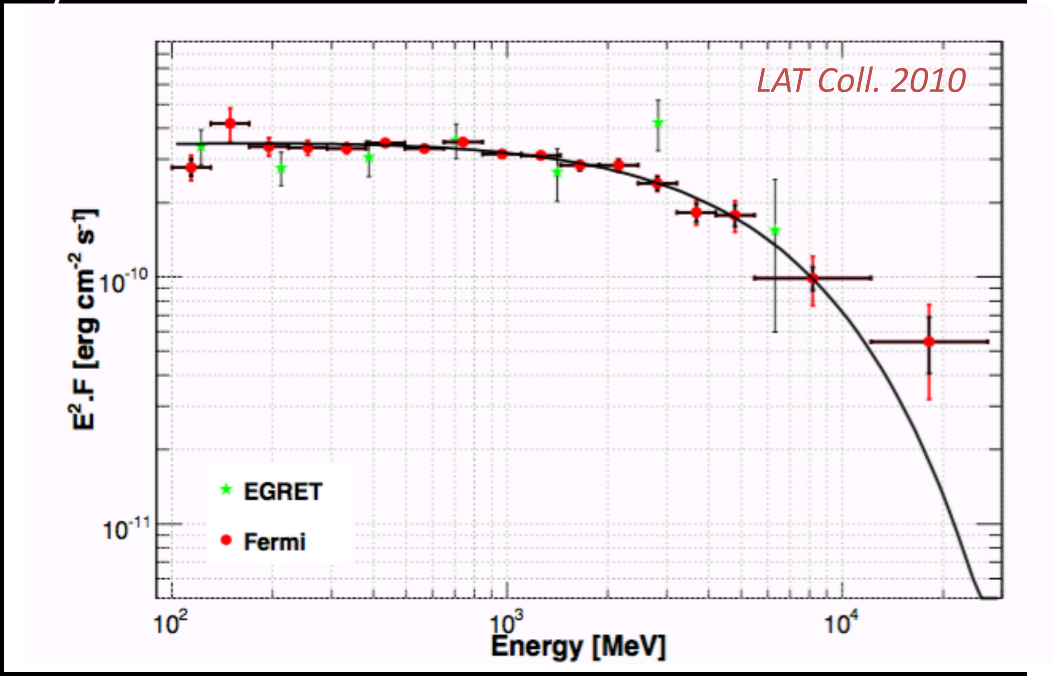


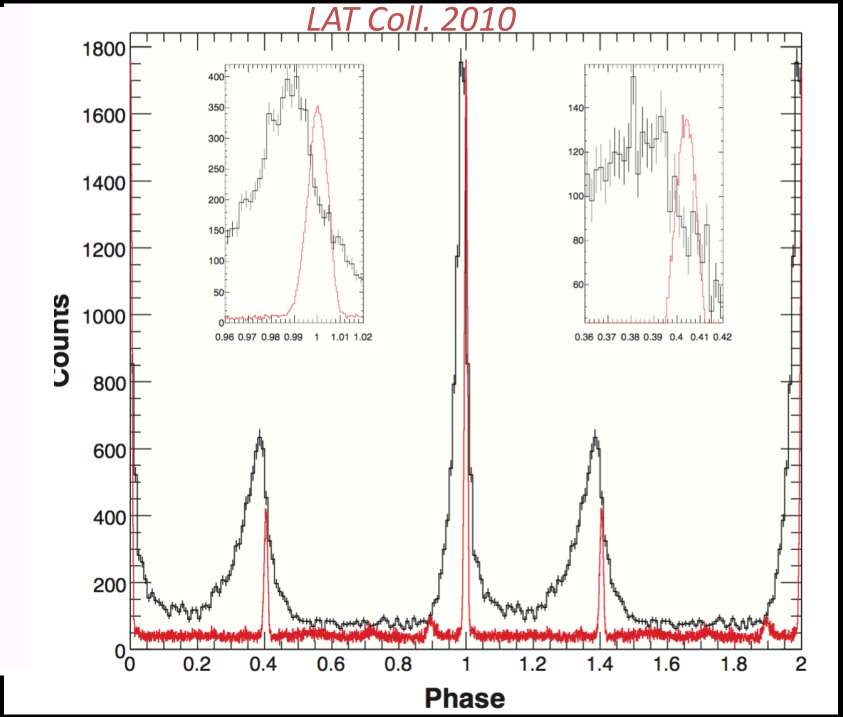


- ✓ Ecutoff ~17 GeV
- ✓ Emission in the outer magnetosphere
- ✓ Big uncertainties on the energy scales forbid to draw strong conclusions

Start of a new era: last 10 yr

1yr of Fermi-LAT data

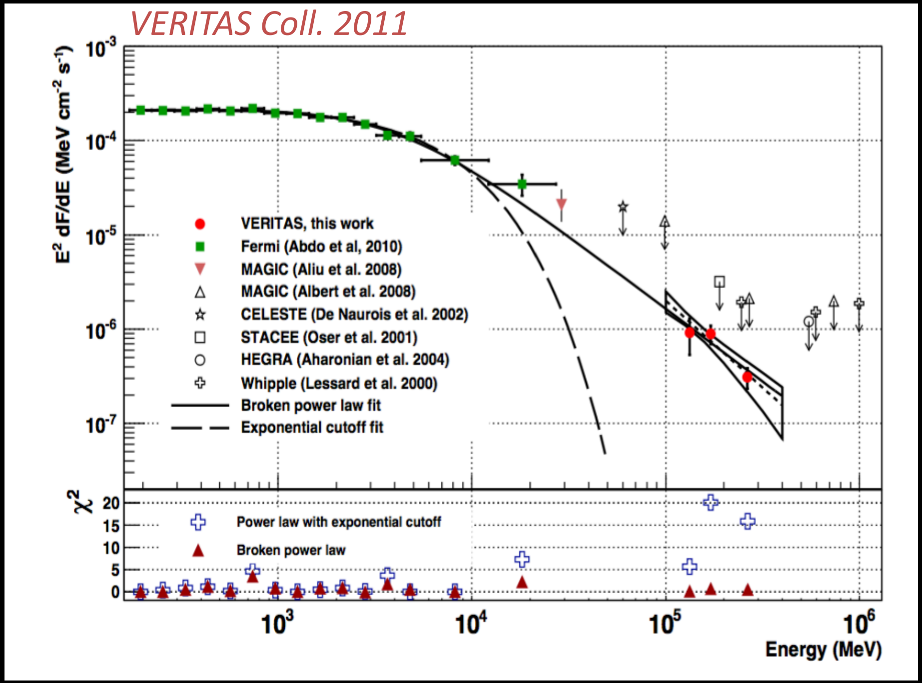




Outer gap model favored → in agreement with the results of the 200 PSRs from 2PC

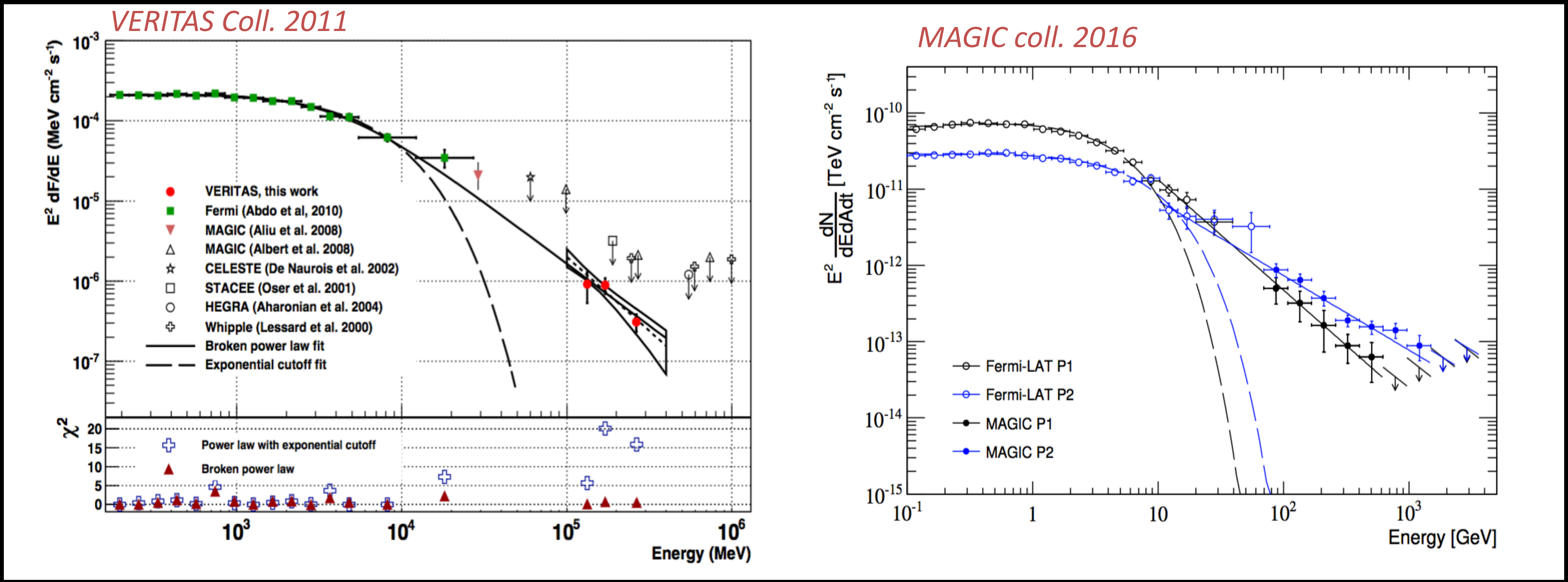
(Second pulsar catalog: LAT Coll. 2013)

Start of a new era: last 10 yr



- ✓ spectral break excluded at >6σ.

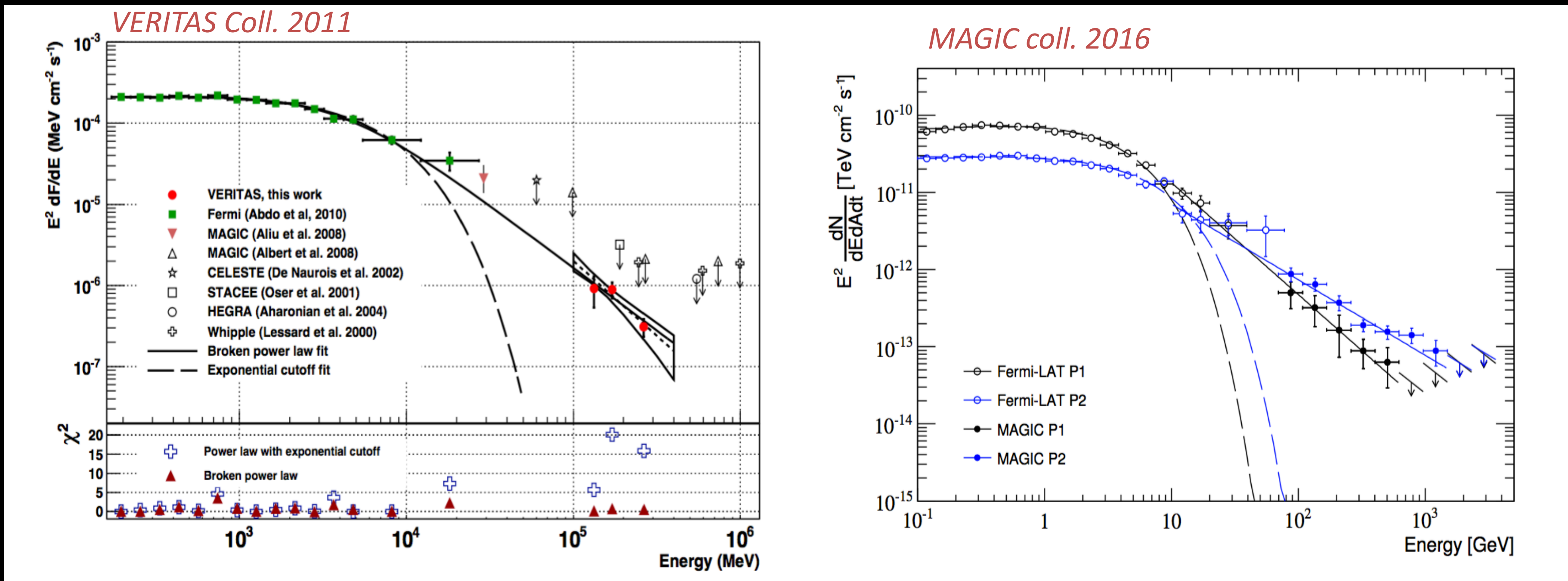
Start of a new era: last 10 yr



- ✓ spectral break excluded at >6σ.
- ✓ P2 is brighter, harder, E_{cutoff} > 700 GeV
- ✓ one single component from 10 GeV to 1 TeV?

(VERITAS 2011, MAGIC 2011, MAGIC 2012, MAGIC 2014,Richards 2015,MAGIC 2016)

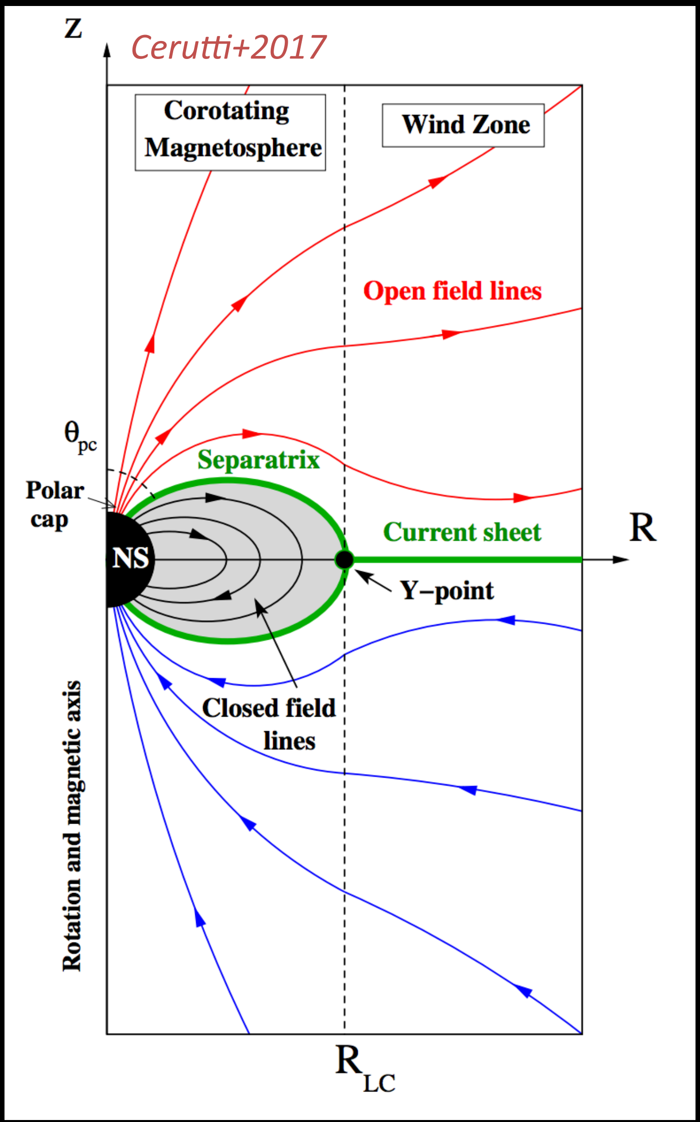
Start of a new era: last 10 yr



(VERITAS 2011, MAGIC 2011, MAGIC 2012, MAGIC 2014,Richards 2015,MAGIC 2016)

- ✓ To avoid absorption this emission must be produced close or beyond the LC
  - ✓ Twisting the B field the FF magnetosphere is more transparent than a dipole magnetosphere *(Bogovalov+2018)*
- ✓ A new mechanism? Inverse Compton inside the magnetosphere *(MAGIC 2011,Lyutikov+2012, Hirotani)* or in the pulsar wind region *(Aharonian+2012, Petri+2012, Mochol+2015)*

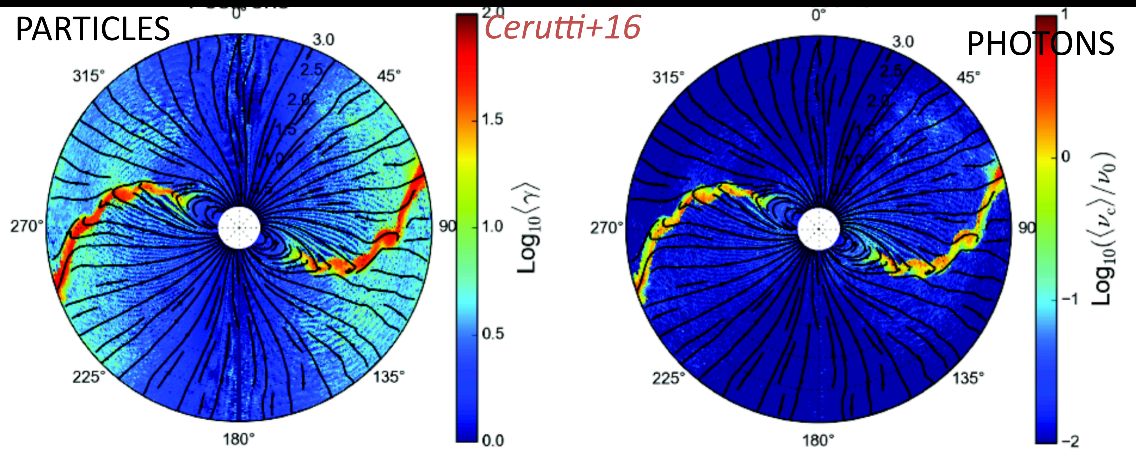
Towards a new paradigma

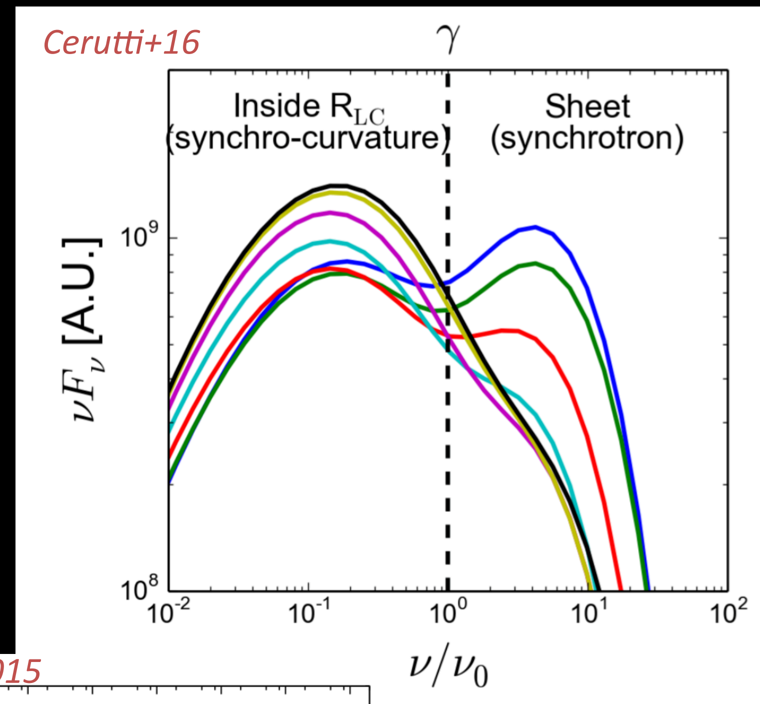


- ✓ **current sheets** *(Coroniti90, Lyubarsky96,Kirk+02)* **are important dissipative regions** *(Contopulous+99, Spitkovosky06…)*
- ✓ particle acceleration in the current sheets via **magnetic reconnection** *(Uzensky+14, Cerutti+15)*
- ✓ flux dissipation larger for α=0

- ✓ dissipative free-force → macroscopic conductivity par. *(Komissarov07,Spitkovski12,Kalapotharakos+12, Chen+14)*
- ✓ free-force-inside-Dissipative-Outside (FIDO) *(Kalapotharakos+14,Brambilla+15)*
- ✓ PIC ab-initio *(Philippov+14,15, Chen+14Cerutti+15,16)*

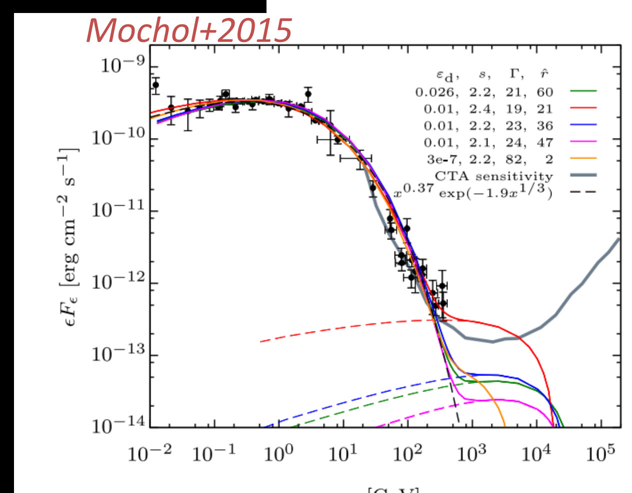
Towards a new paradigma





- ✓ **High-energy emission may also be synchrotron radiation** *(Contopoulos+2014, Cerutti+2015,2016, Contopoulos2018)*

- ✓ One would then still need a different mechanism to explain TeV emission (an example: SSC *Mochol+2015*)



Conclusions

- ✓ Crab played an exceptional role in the non-thermal astrophysics at all wavelengths, so did in the VHE astrophysics field
- ✓ Reference source used to study the instrument performance given its brightness and stability

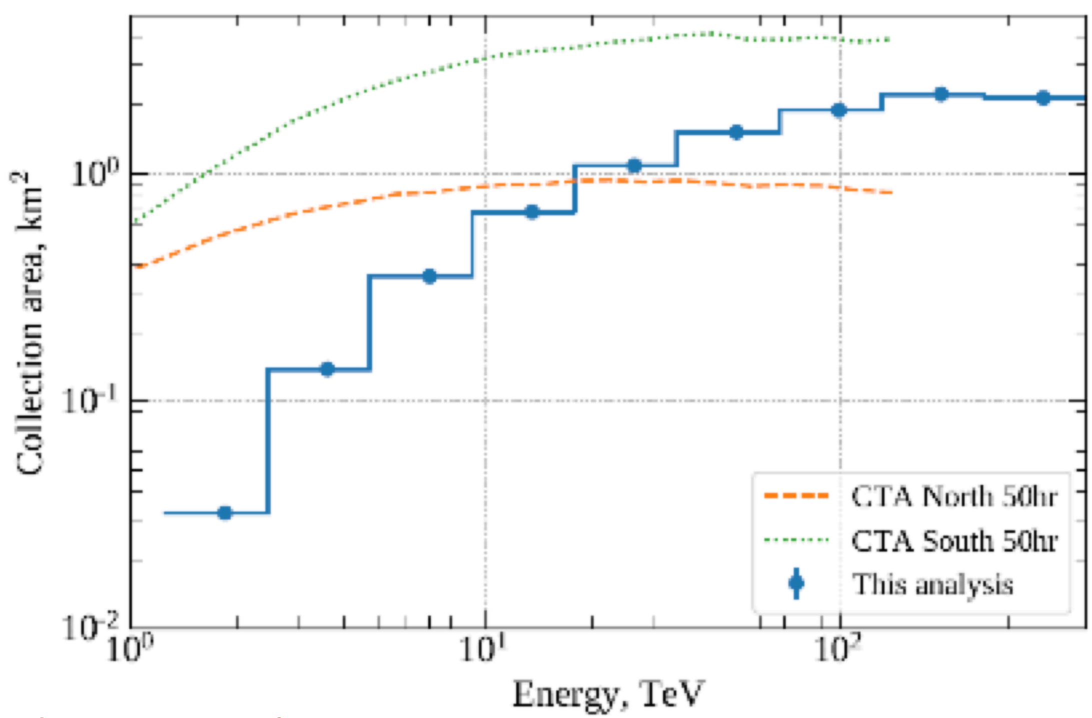
- ✓ usually referred to as archetypal PWN, not even an archetypal young PWN
  - ✓ Extreme in many respect
  - ✓ The more we dig the more it surprises us…
  - ✓ the high-precision measurements across all wavelengths make it the best laboratory to study

- ✓ Certainly an exceptional PSR, but not anymore alone at VHEs… (a new era of pulsar physics?)

looking forward to have a running CTA to discover the next surprise…

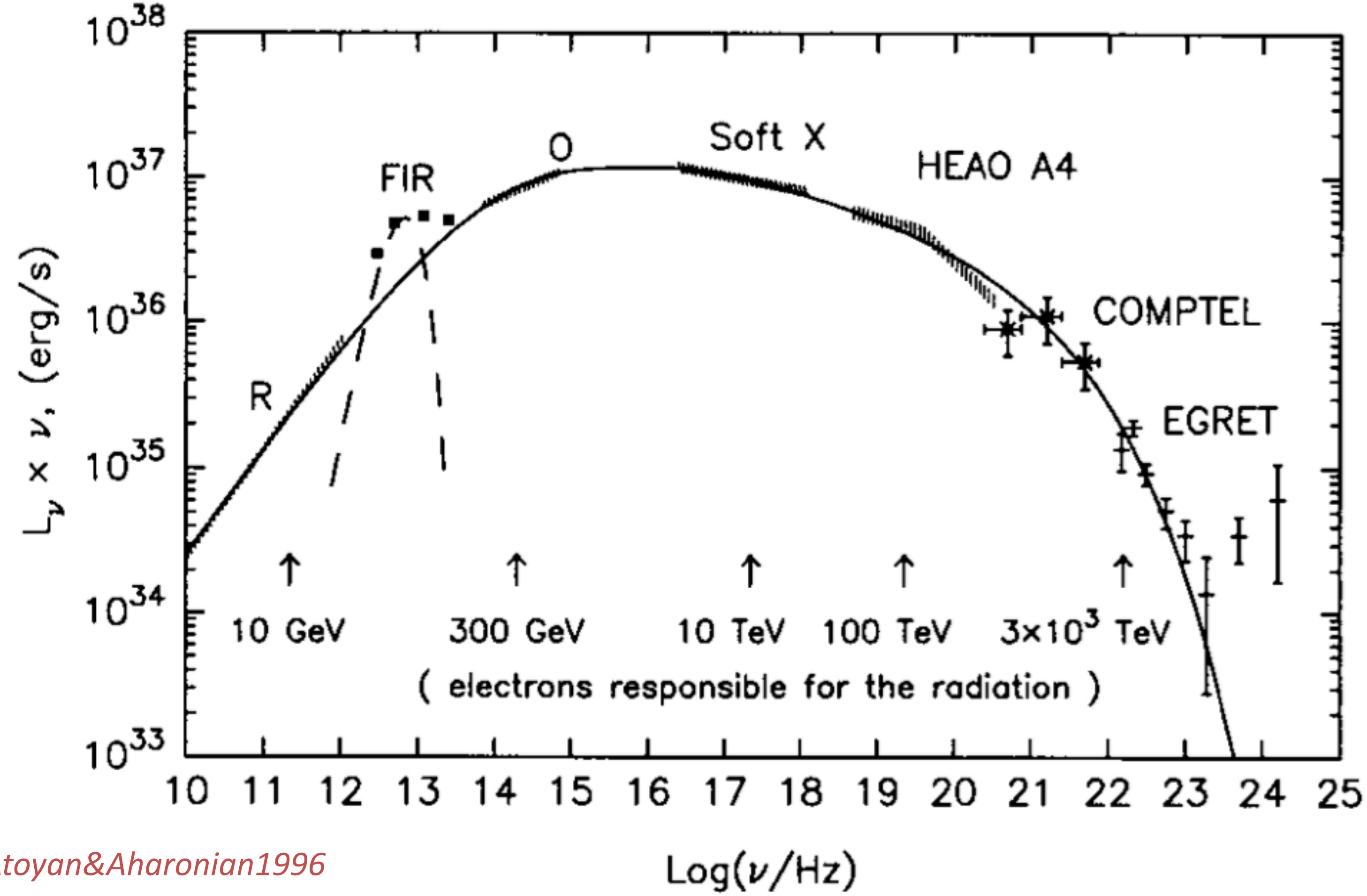
Thank you

MAGIC observations at horizon



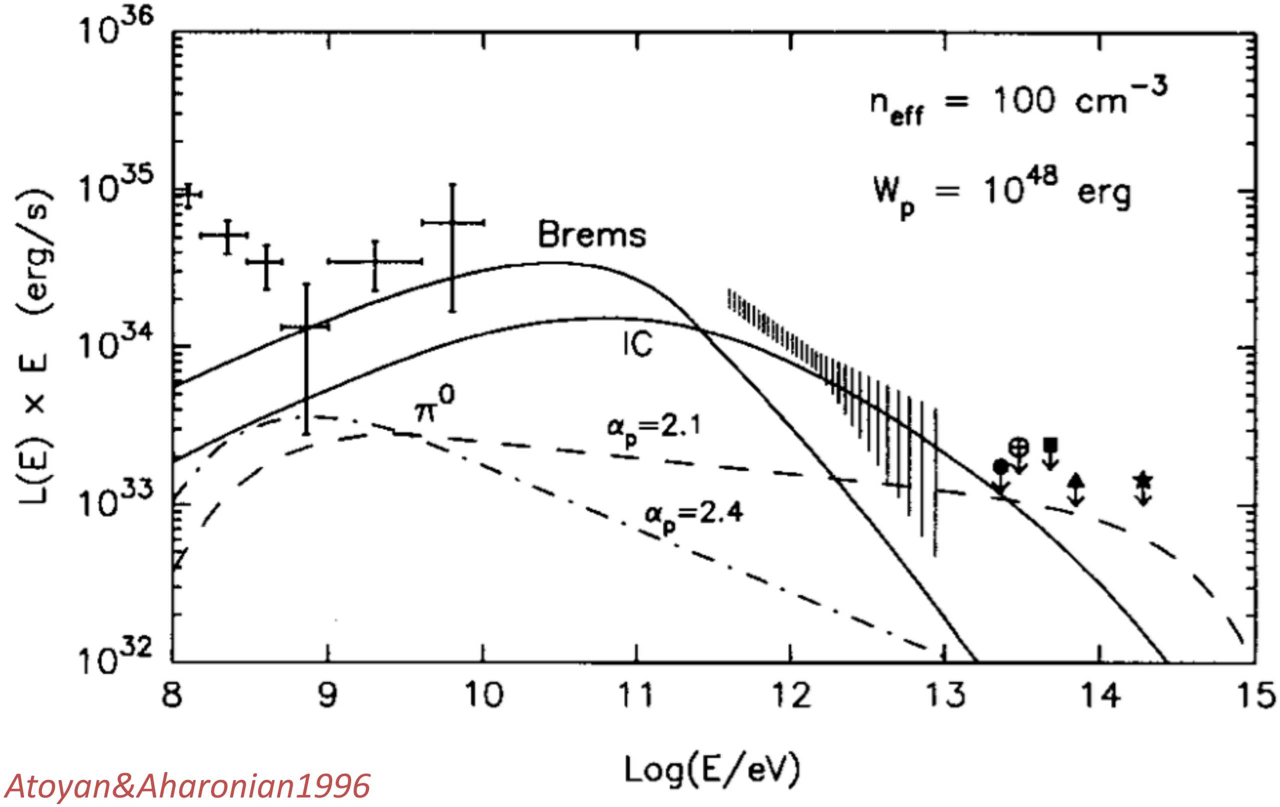
Credits to Razmik

Synchrotron emitting electrons



Atoyan&Aharonian1996

IC not enough



Atoyan&Aharonian1996

Acceleration mechanism

Crab is a PeVatron, but how/where?

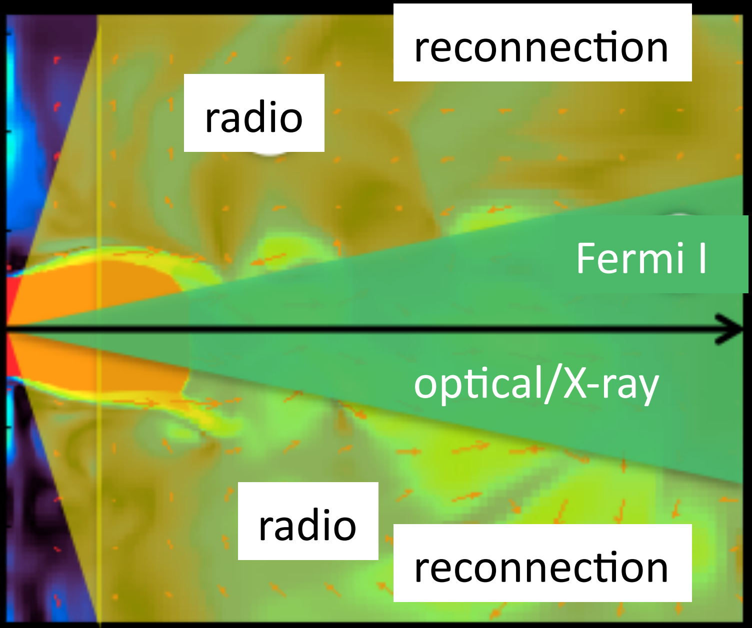
wisps at different λ have distinct velocities and positions
(Bietenholz+2004, Schweizer+2013)

→ different mechanism at work *(Olmi+2015)*

- ✓ FERMI I
  - ✓ narrow equatorial sector (low σ)
  - ✓ optical/X-ray particles (p=2)

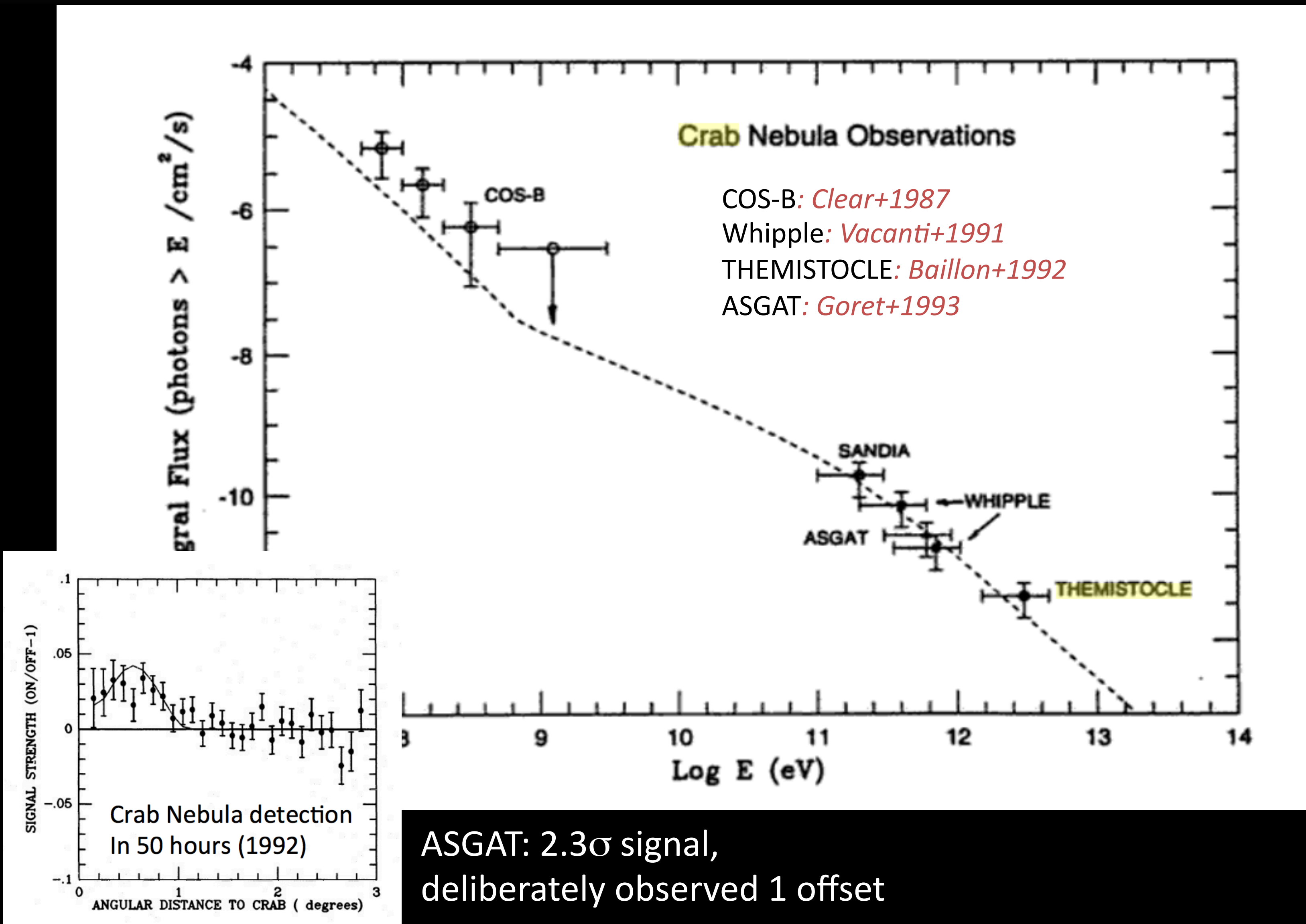
  (Spitkovsky2008, Sironi+2011)
- ✓ MAGNETIC RECONNECTION
  - ✓ elsewhere (high σ)
  - ✓ radio electrons (p=1.5)

  (Lyubarsky2003, Lyubarsky+2008, Sironi+2011)



Olmi+2015

In 1992



Crab Nebula detection
In 50 hours (1992)

ASGAT: 2.3σ signal,
deliberately observed 1 offset

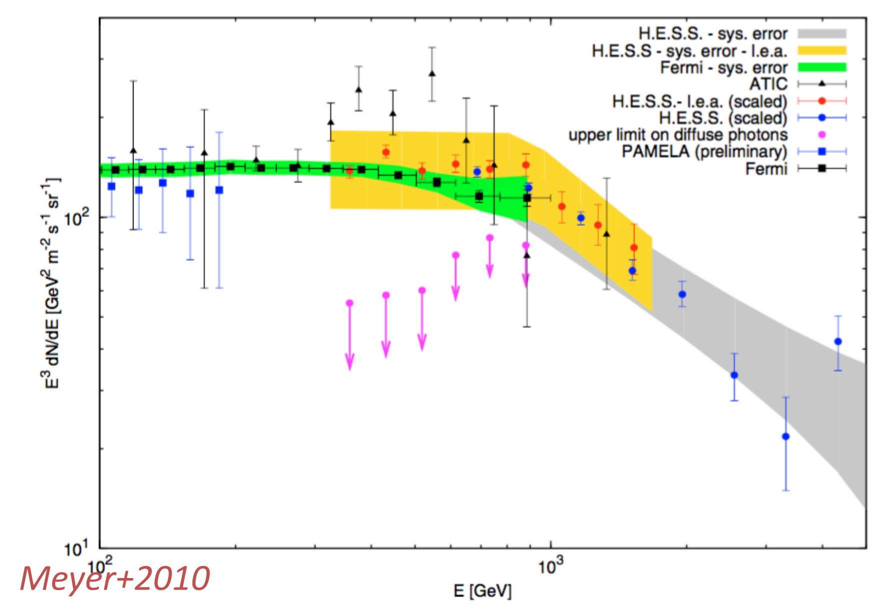
Cross calibration

$E = E_{meas}\, s_{IACT}$

s_{IACT} determined via χ^2 minimization

Instrument	Scaling factor $s_{\rm IACT}$	Stat. error Δs	$\chi^2_{\rm before}$/d.o.f.	$\chi^2_{\rm after}$/d.o.f.
Fermi/LAT	1	$+0.05 - 0.03$	–	0.49
HEGRA	1.042	± 0.005	7.652	1.046
H.E.S.S.	0.961	± 0.004	11.84	6.476
MAGIC	1.03	± 0.01	1.671	0.656

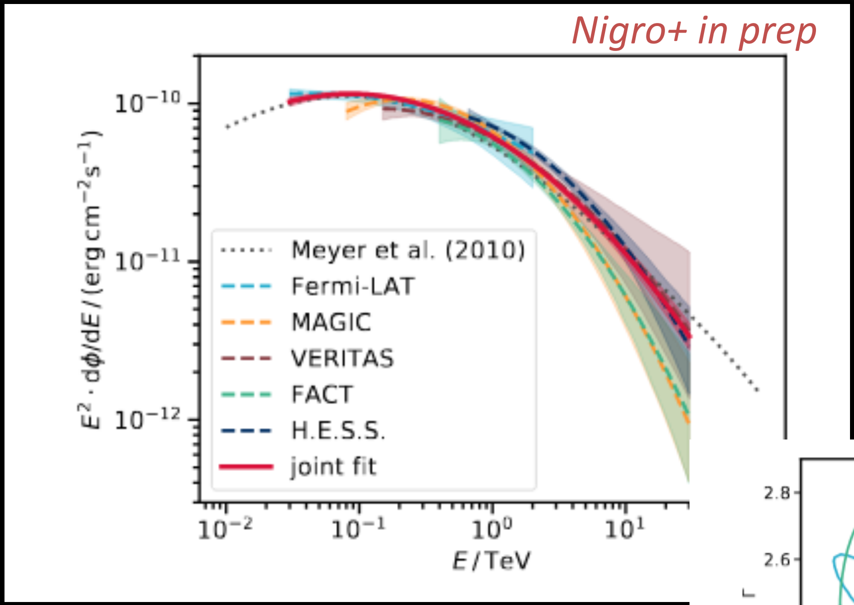
Meyer+2010



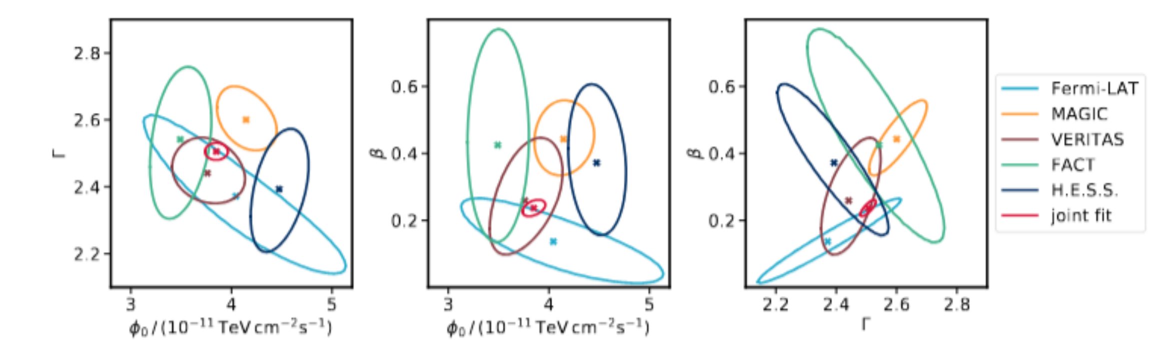
Meyer+2010

Include a constant bias in the energy estimator Gauss distributed (with sigma = syst. uncertainty of the single instrument) in the joint likelihood function *(Deminski+2017, Nigro+ in prep.)*

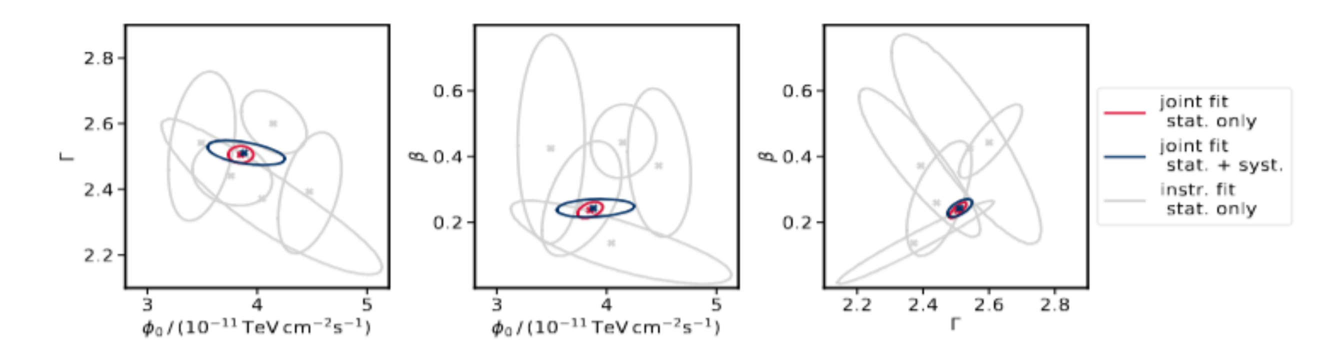
Joint-fit



Nigro+ in prep
Meyer et al. (2010)
Fermi-LAT
MAGIC
VERITAS
FACT
H.E.S.S.
joint fit
$E^2 \cdot d\phi/dE$ / (erg cm^{-2}s^{-1})
E / TeV



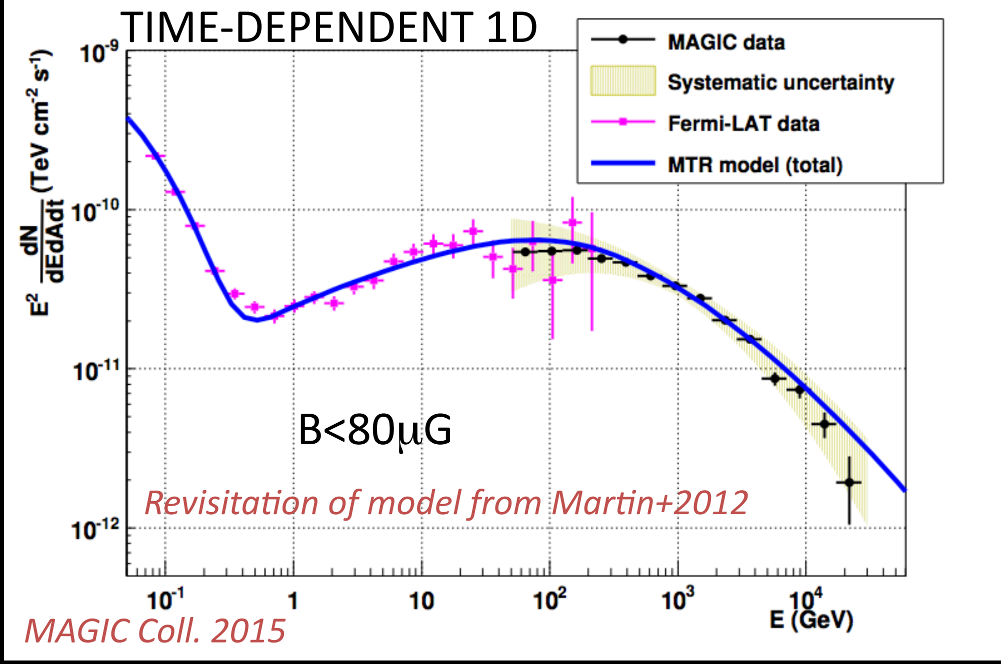
Fermi-LAT
MAGIC
VERITAS
FACT
H.E.S.S.
joint fit
ϕ_0 / (10^{-11} TeV cm^{-2}s^{-1})
Γ
β



joint fit
stat. only
joint fit
stat. + syst.
instr. fit
stat. only
ϕ_0 / (10^{-11} TeV cm^{-2}s^{-1})
Γ
β

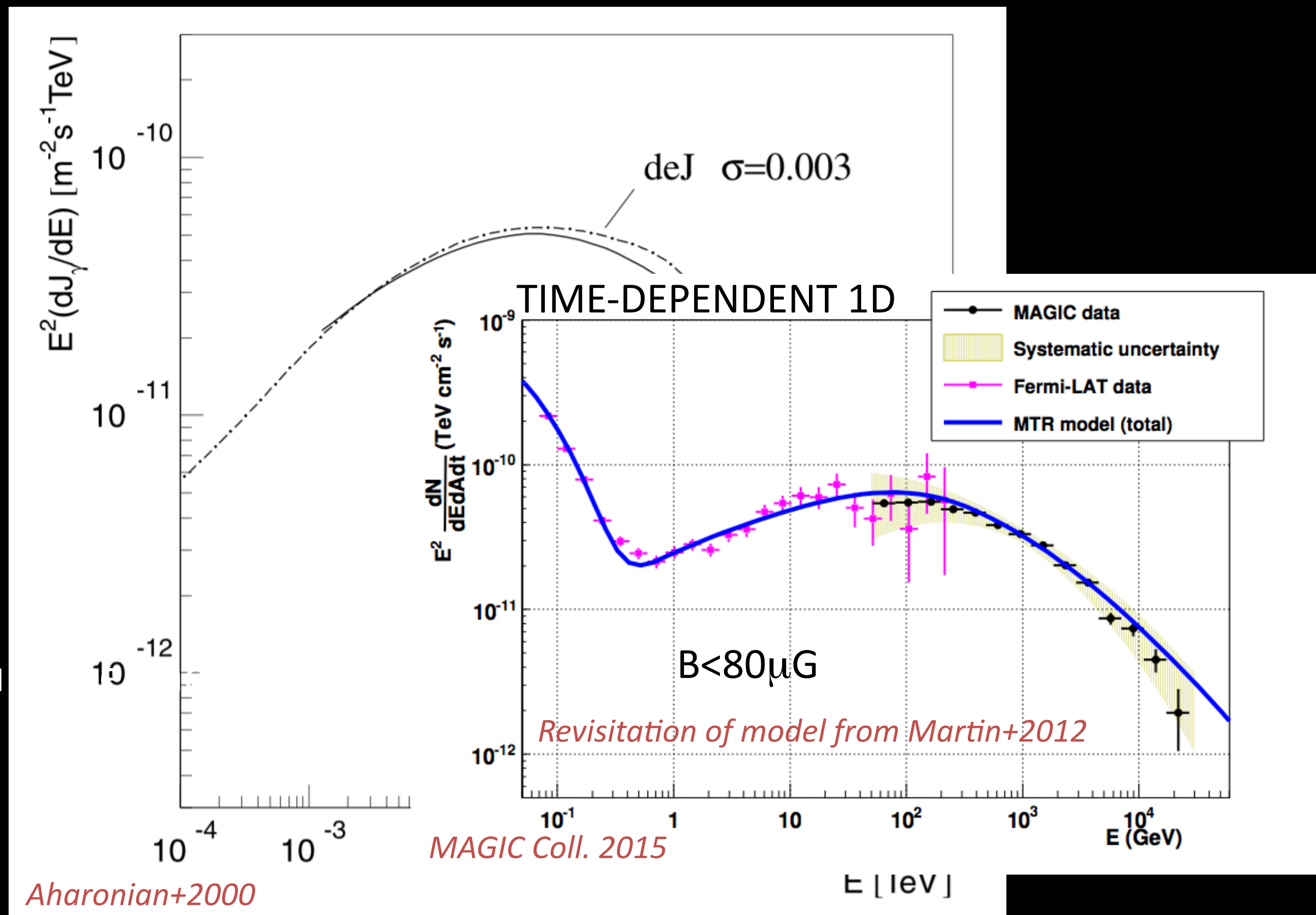
The last 15 years

This fails to account the energy-dep. morphology

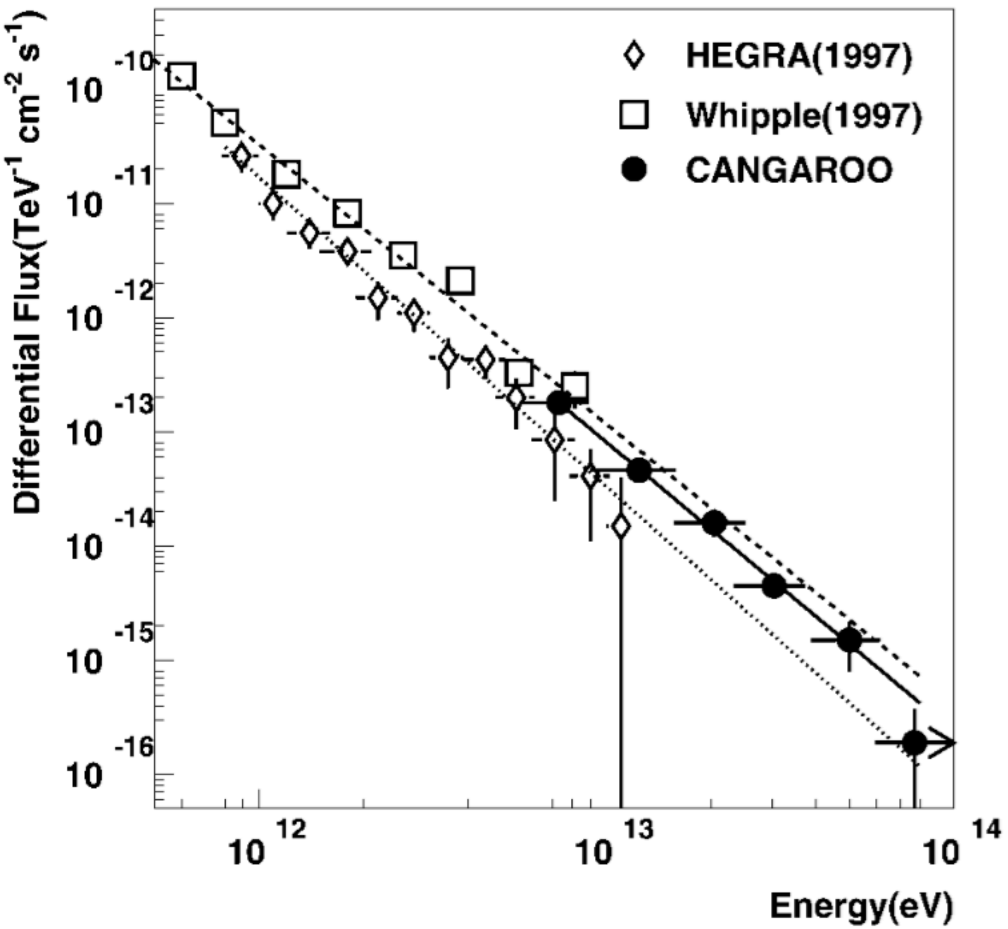


HEGRA spectral points

This fails to accou
morphology

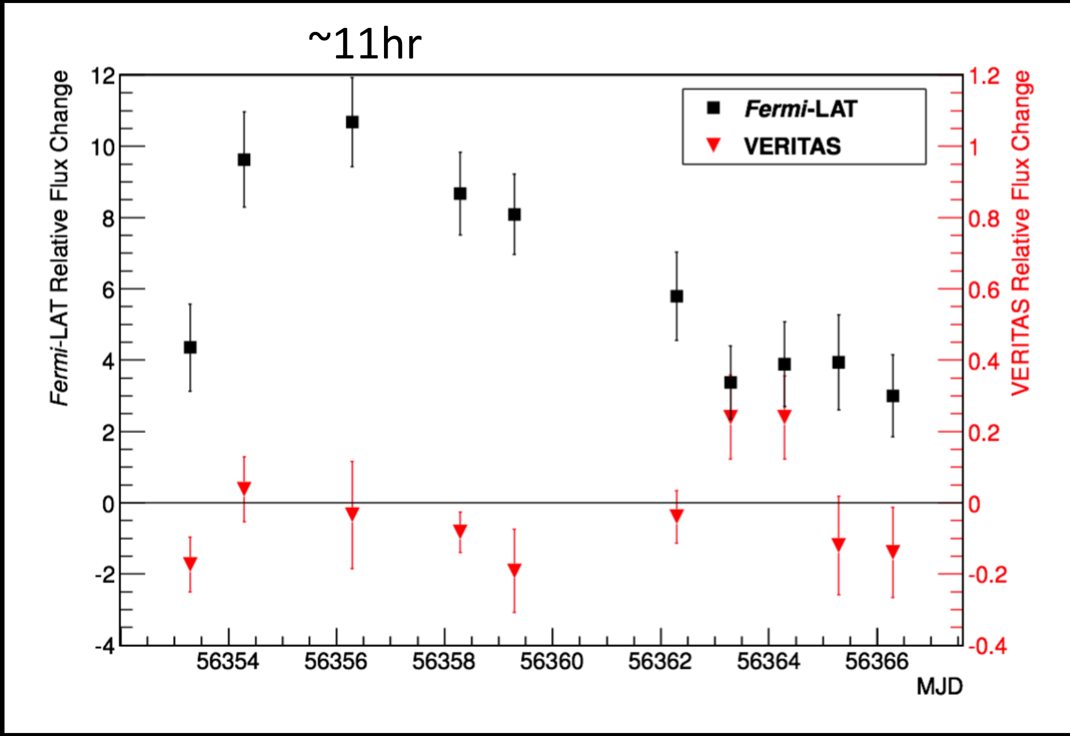


Flux discrepancies

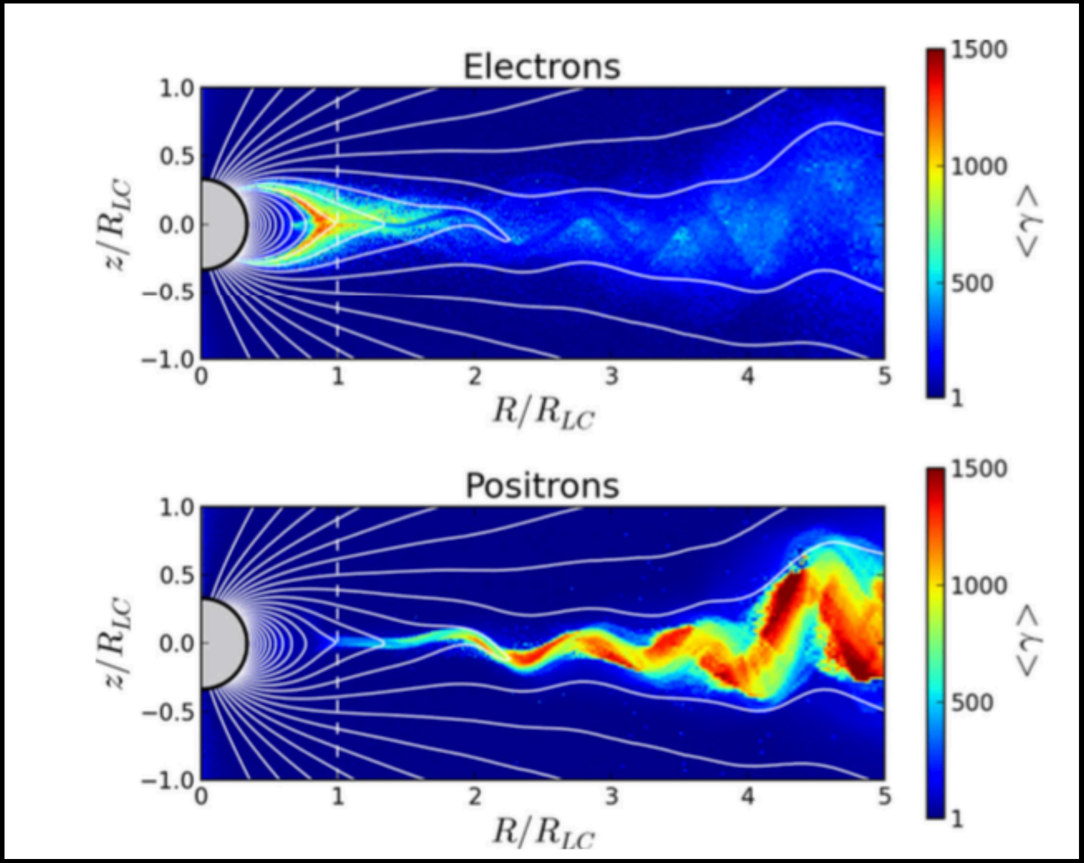


Tanimori+1998

March 2013 flare



A continuos surprise

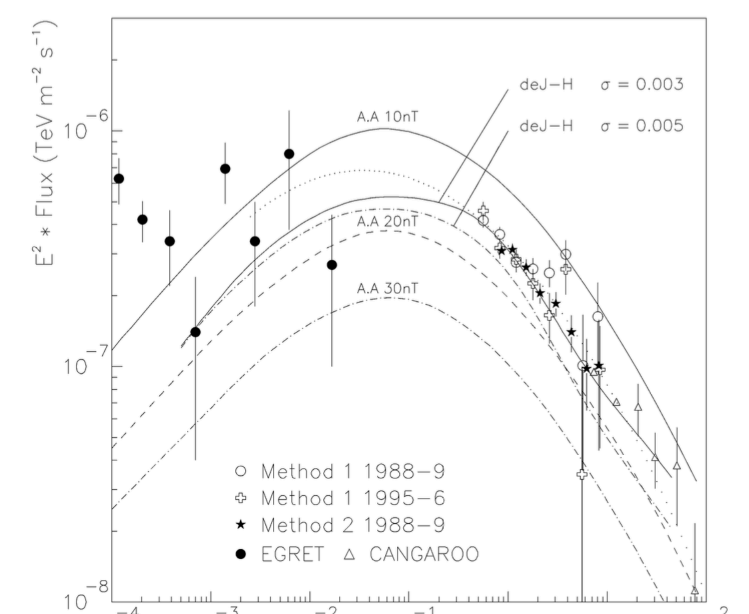


The 90s: theoretical perspective - 3

3. Hillas+1998

- ✓ TeV measurements are exploring a limited region of the nebula
  → B-field is constant
- ✓ PL electron spectrum &electron density Gauss distributed following the measured shrinking by fitting the synchrotron measurements (δ approx)
- ✓ IR photon field

B_0 @ 1 TeV 160 μG
B_0 @ 1 TeV 100-120 μG



Hillas+1998