HONEST

HOT TOPICS IN HIGH ENERGY ASTROPHYSICS

3 The high end of Pulsar spectra

The Crab Pulsar's Very High Energy emission: Insights from GeV to TeV Energies

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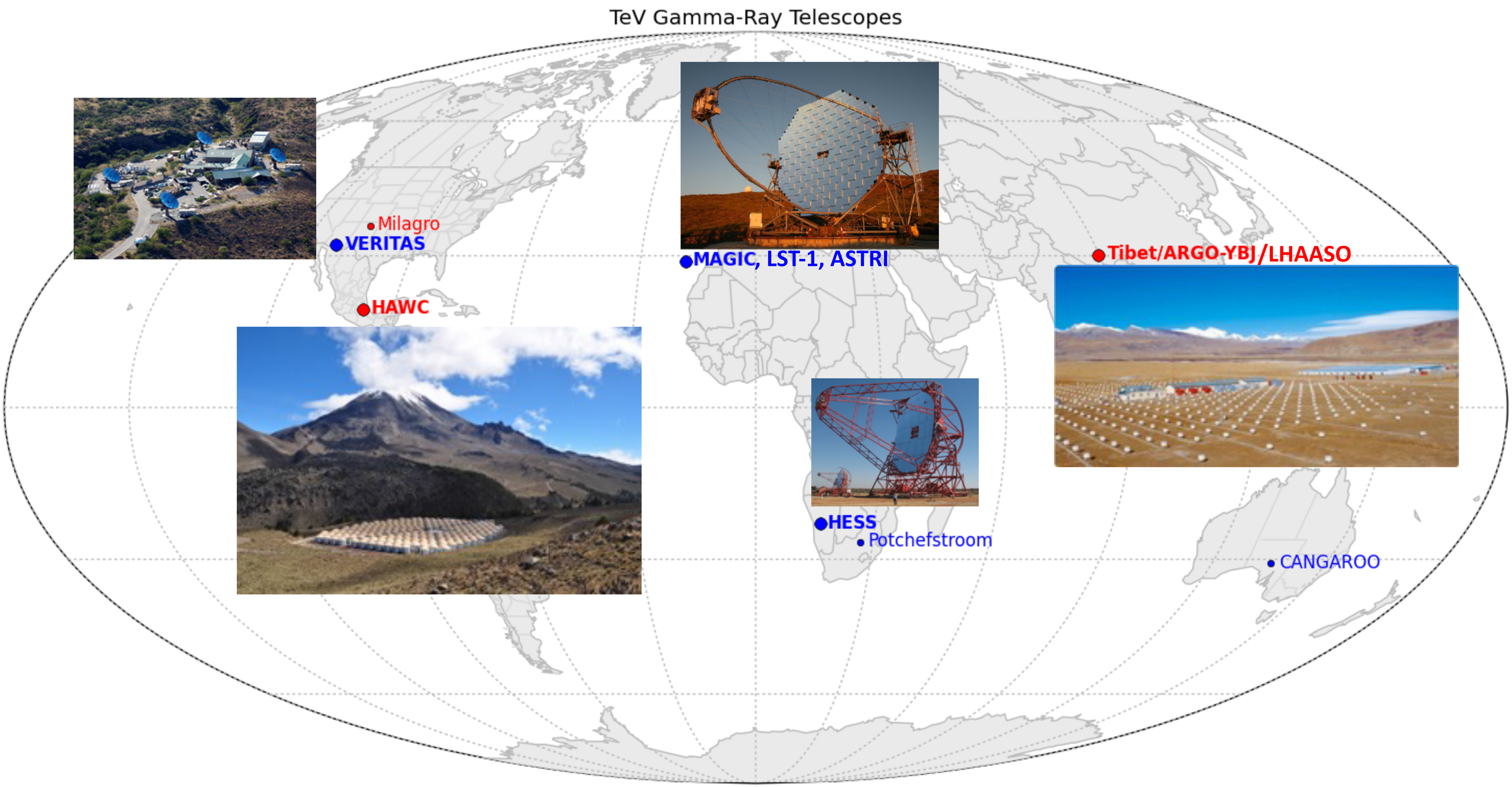
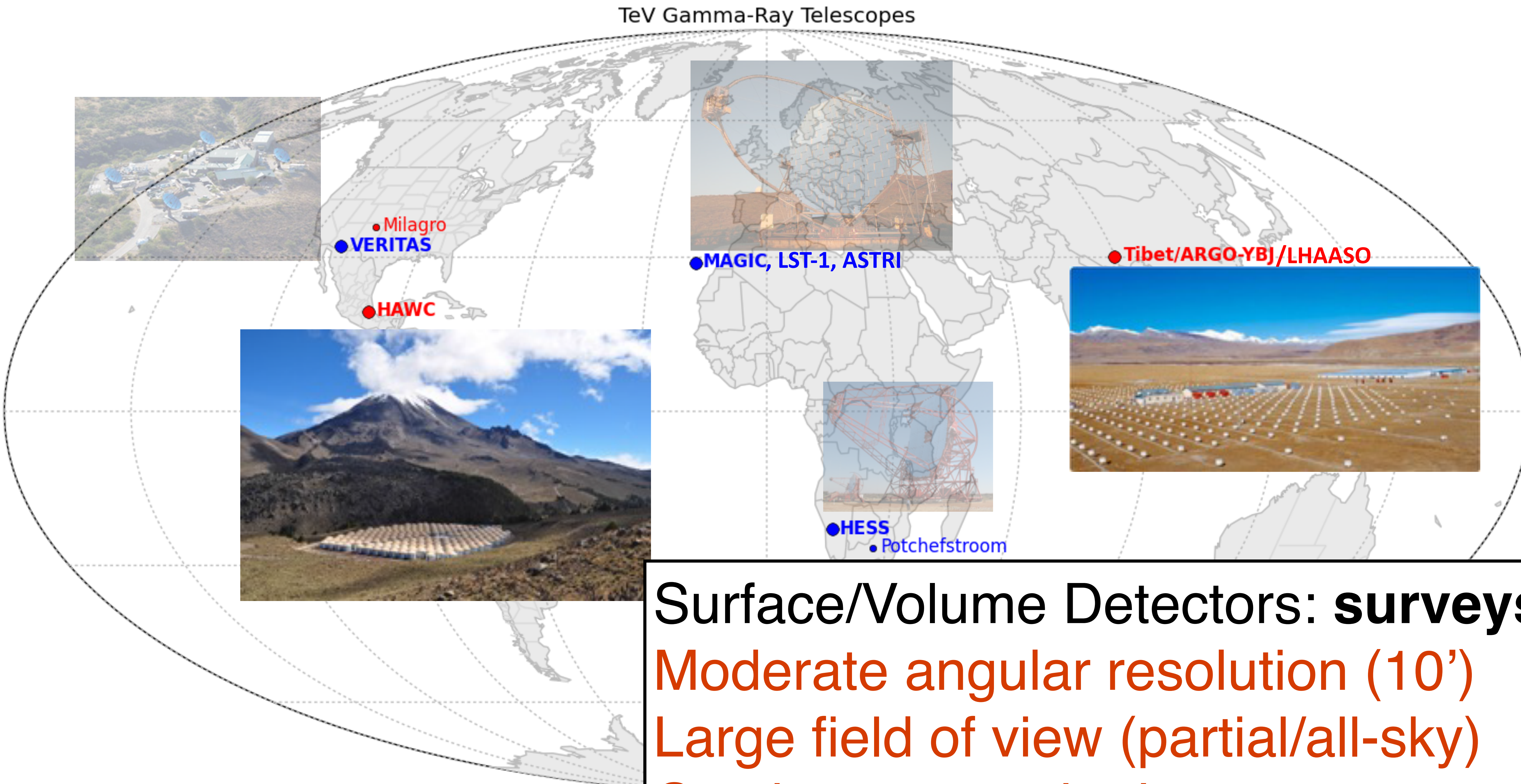
Very High Energy Gamma-ray astronomy

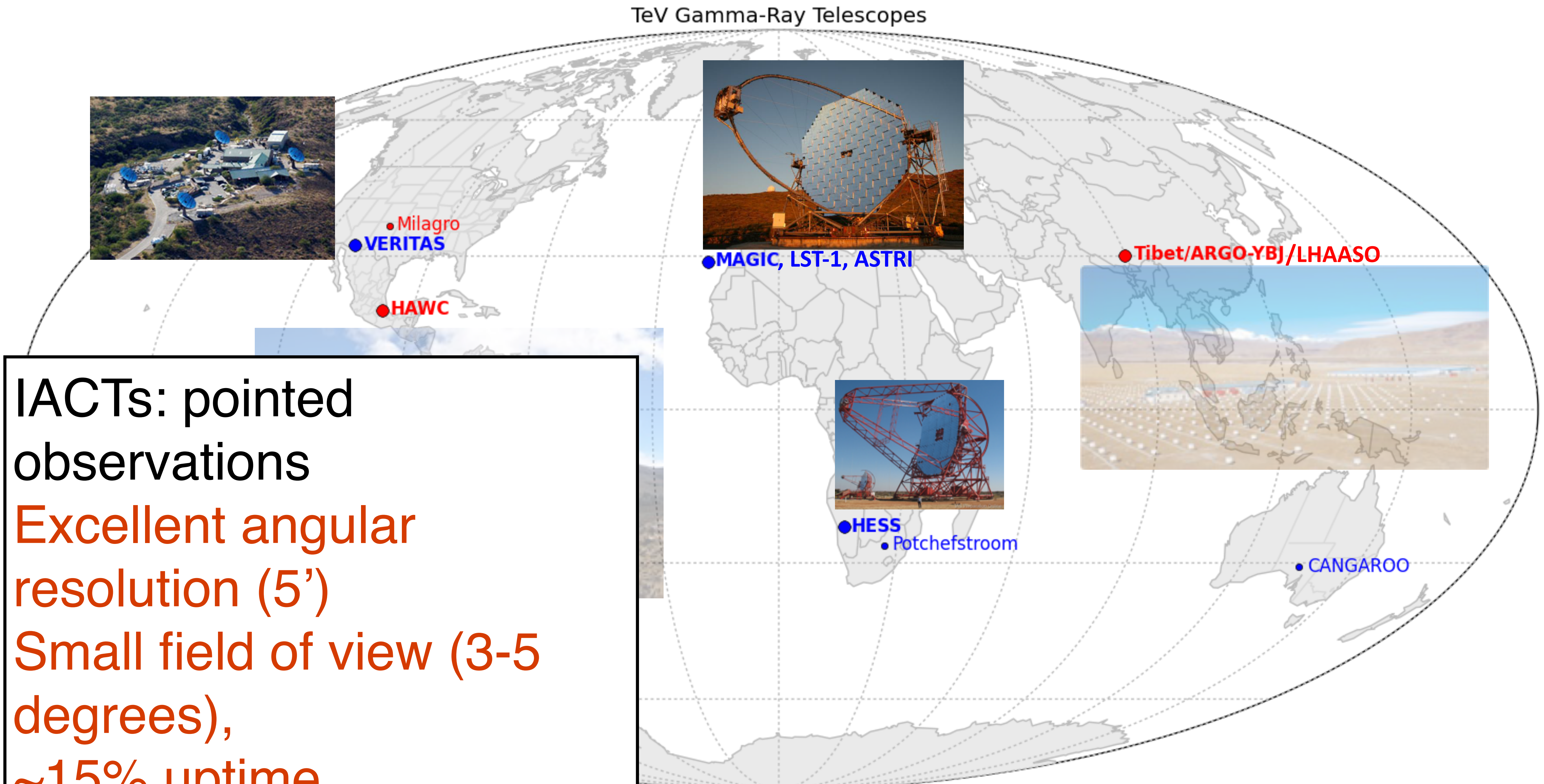


Very High Energy Gamma-ray astronomy



Surface/Volume Detectors: **surveys**
Moderate angular resolution (10')
Large field of view (partial/all-sky)
Continuous monitoring

Very High Energy Gamma-ray astronomy



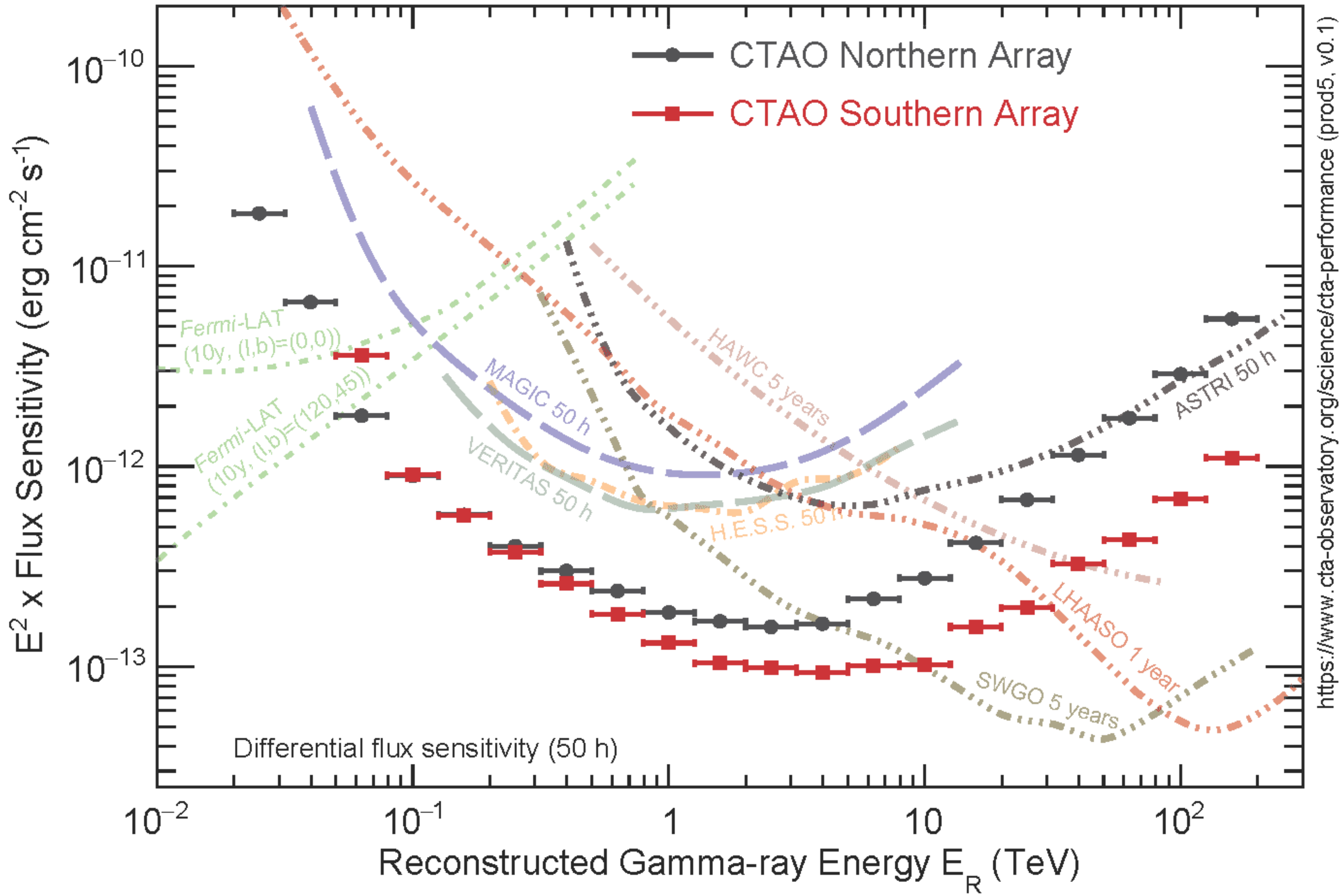
IACTs: pointed observations

Excellent angular resolution (5’)

Small field of view (3-5 degrees),

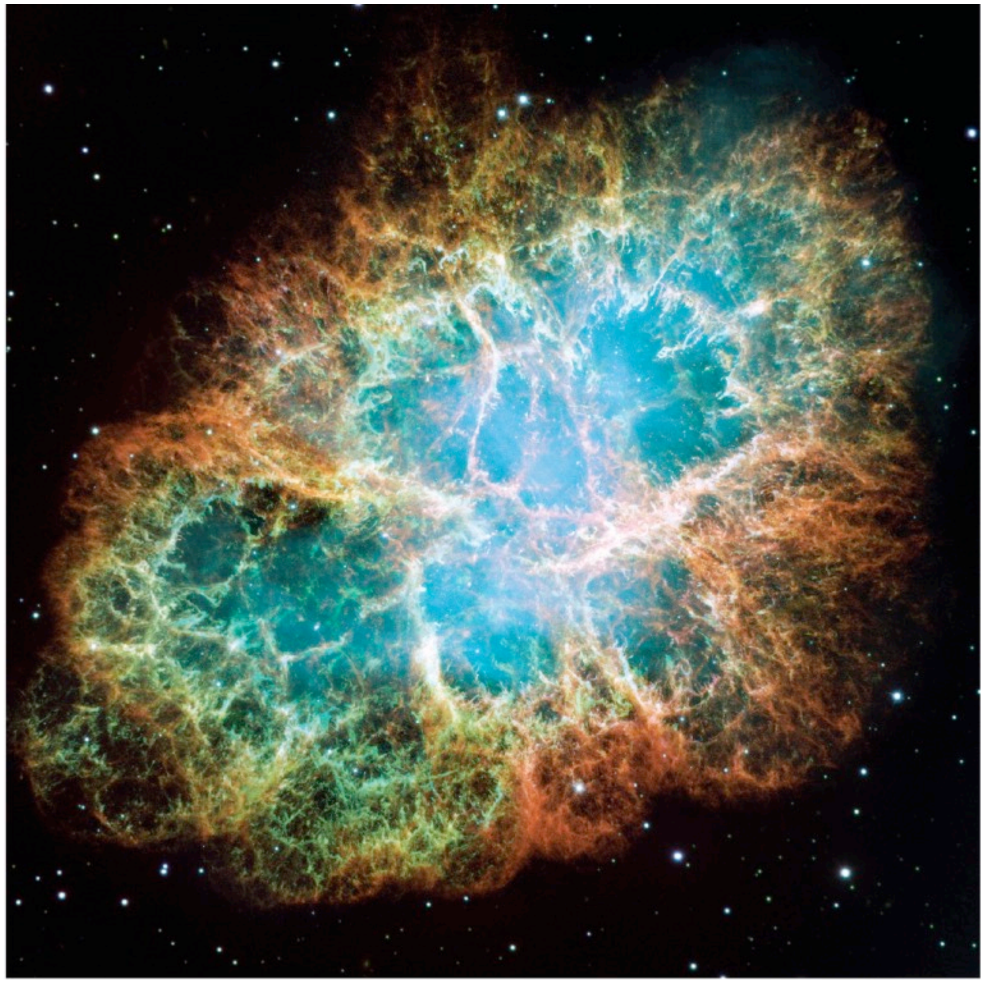
~15% uptime

Very High Energy gamma rays



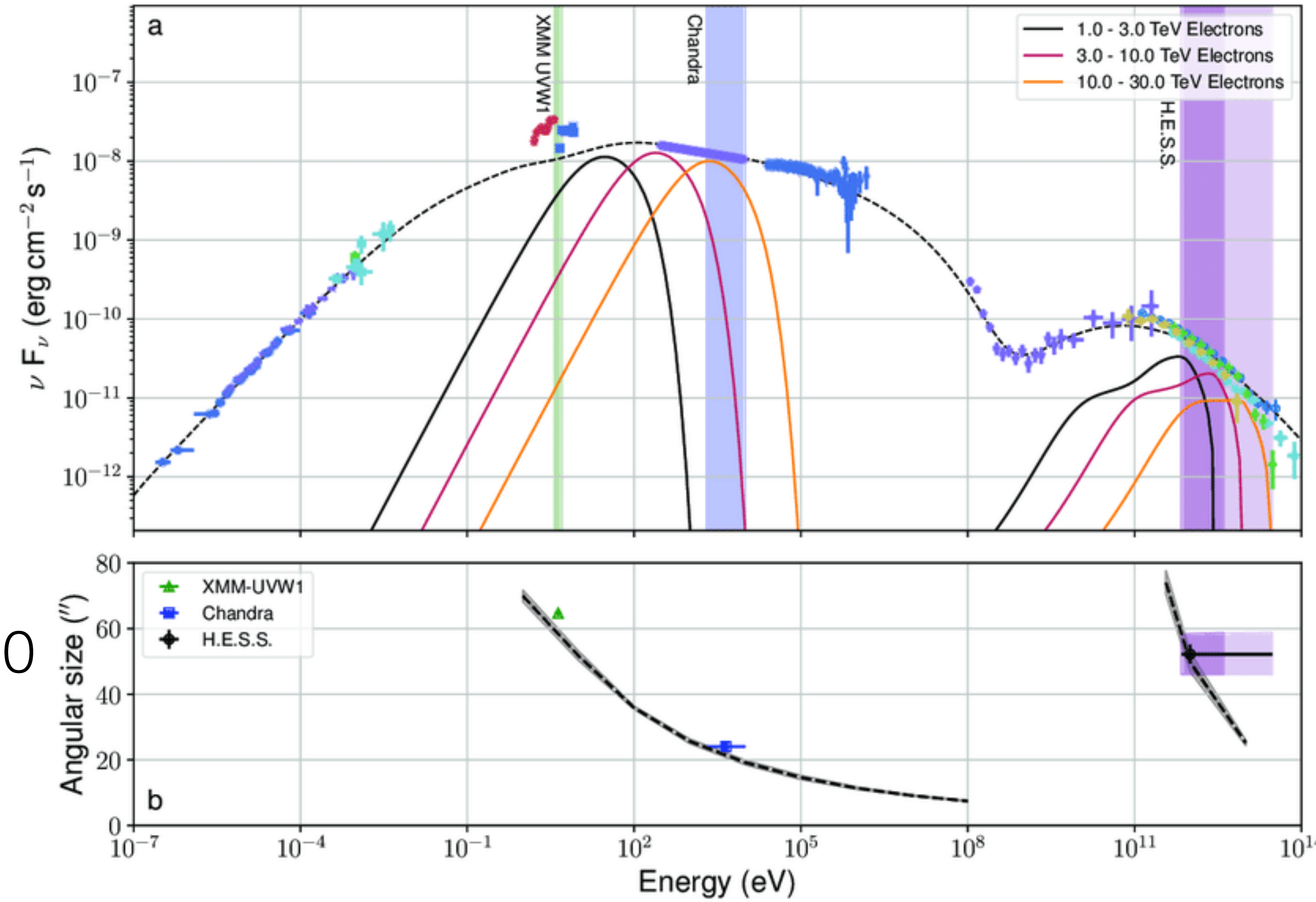
The Crab Nebula

- Remnant of the SN explosion in 1054 AD.
- Harbors one of the pulsars with highest spin-down power in the sky: PSR J0534+2200, E= 5×10^{38} erg s^{-1}
  - Distance 2 kpc.
- Strongest steady VHE gamma-ray source in the sky (standard candle), first source discovered (Whipple 1989).
- Broadband spectrum extends from radio to VHE gamma rays.
- At energies of tens of TeV we expect the spectrum to curve due to the transition to the Klein-Nishina regime.
- Variability (flares) reported by Fermi and AGILE satellites at MeV energies.



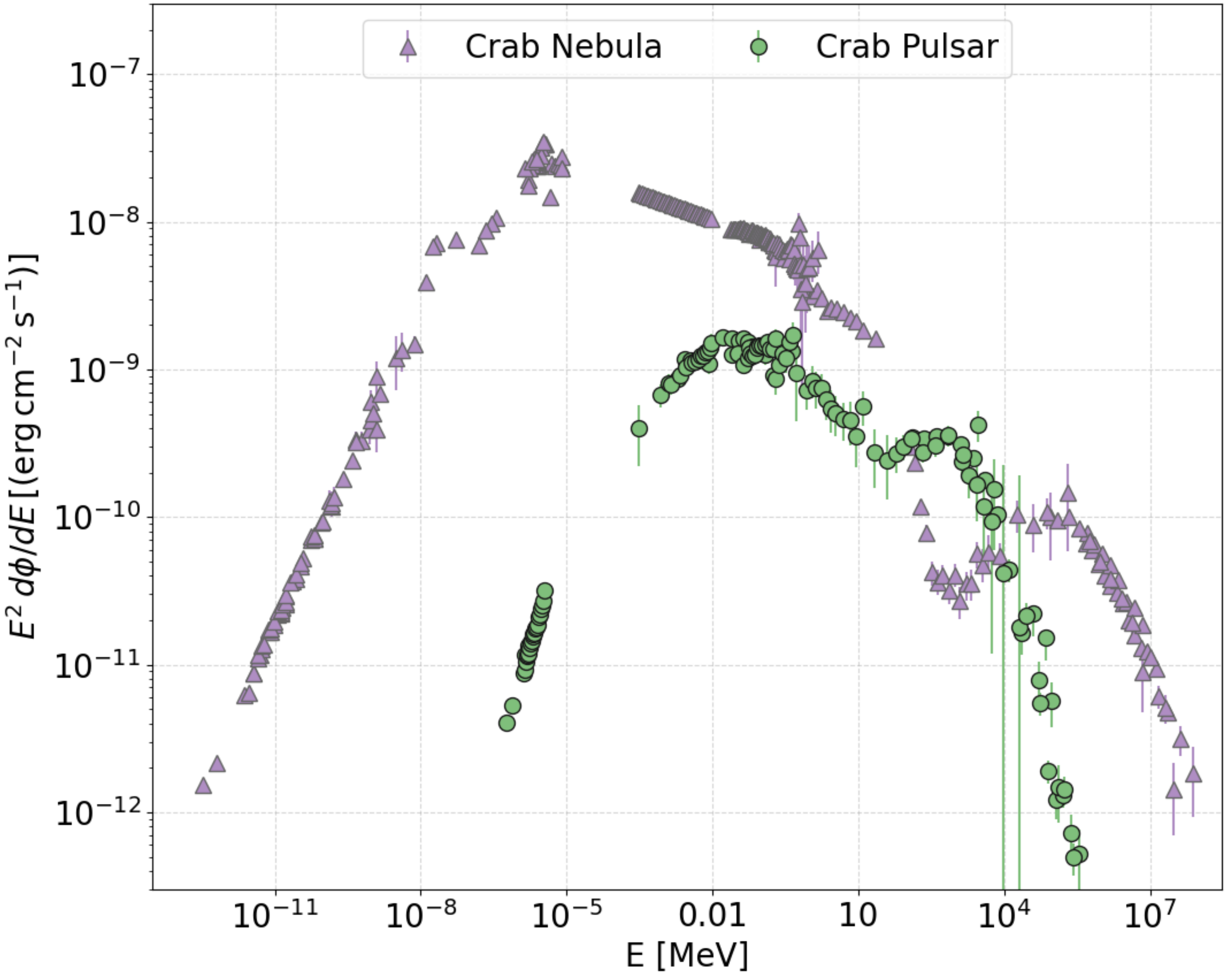
The Crab Nebula SED

- Broadband spectrum extends from radio to VHE gamma rays.
  - Extends for more than 20 decades in energy



HESS collab., Nat. Ast., 4, 167 (2020)

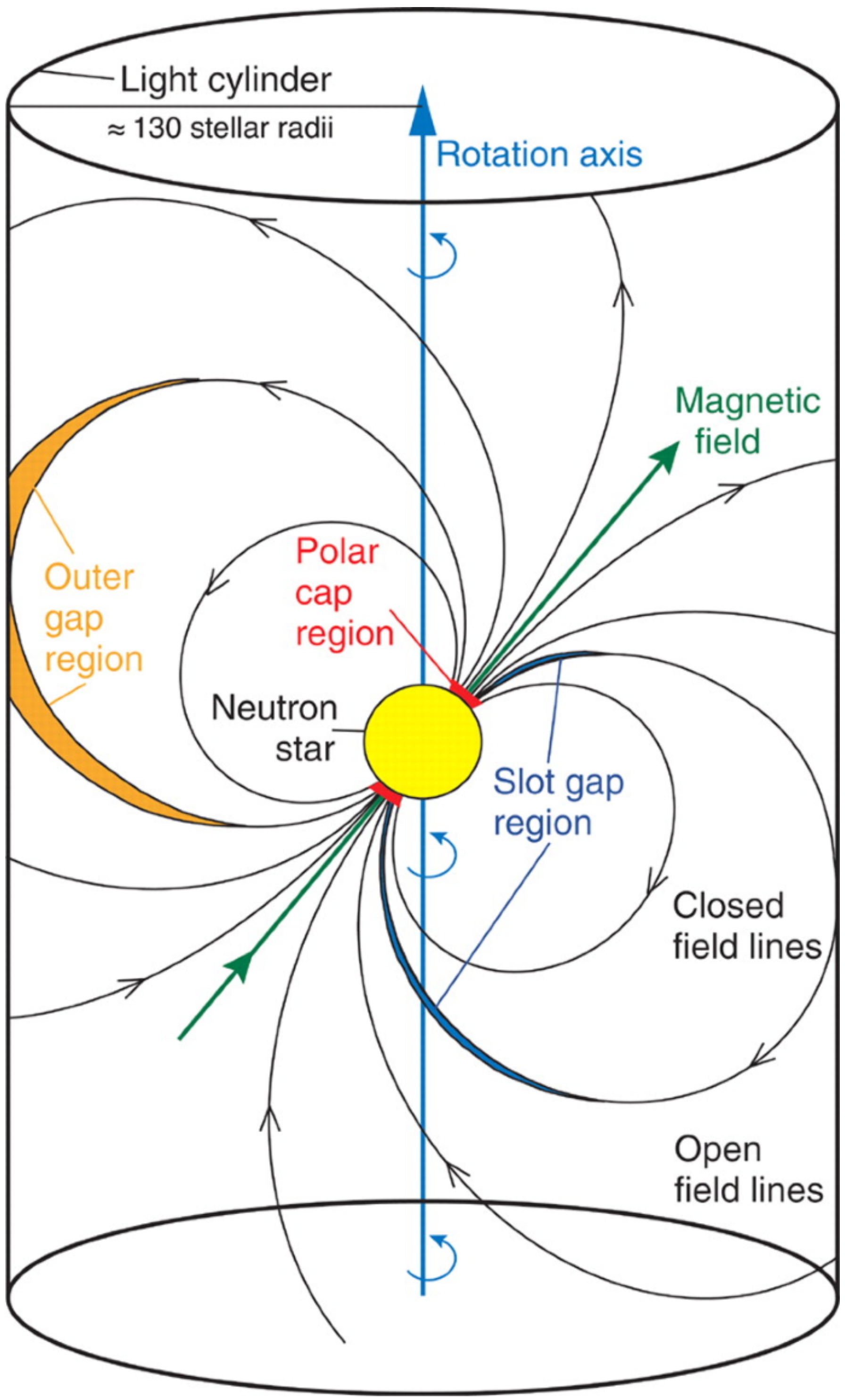
The Crab Pulsar SED



- Lower energy coverage and intensity
    - although brighter than the nebula at some energies

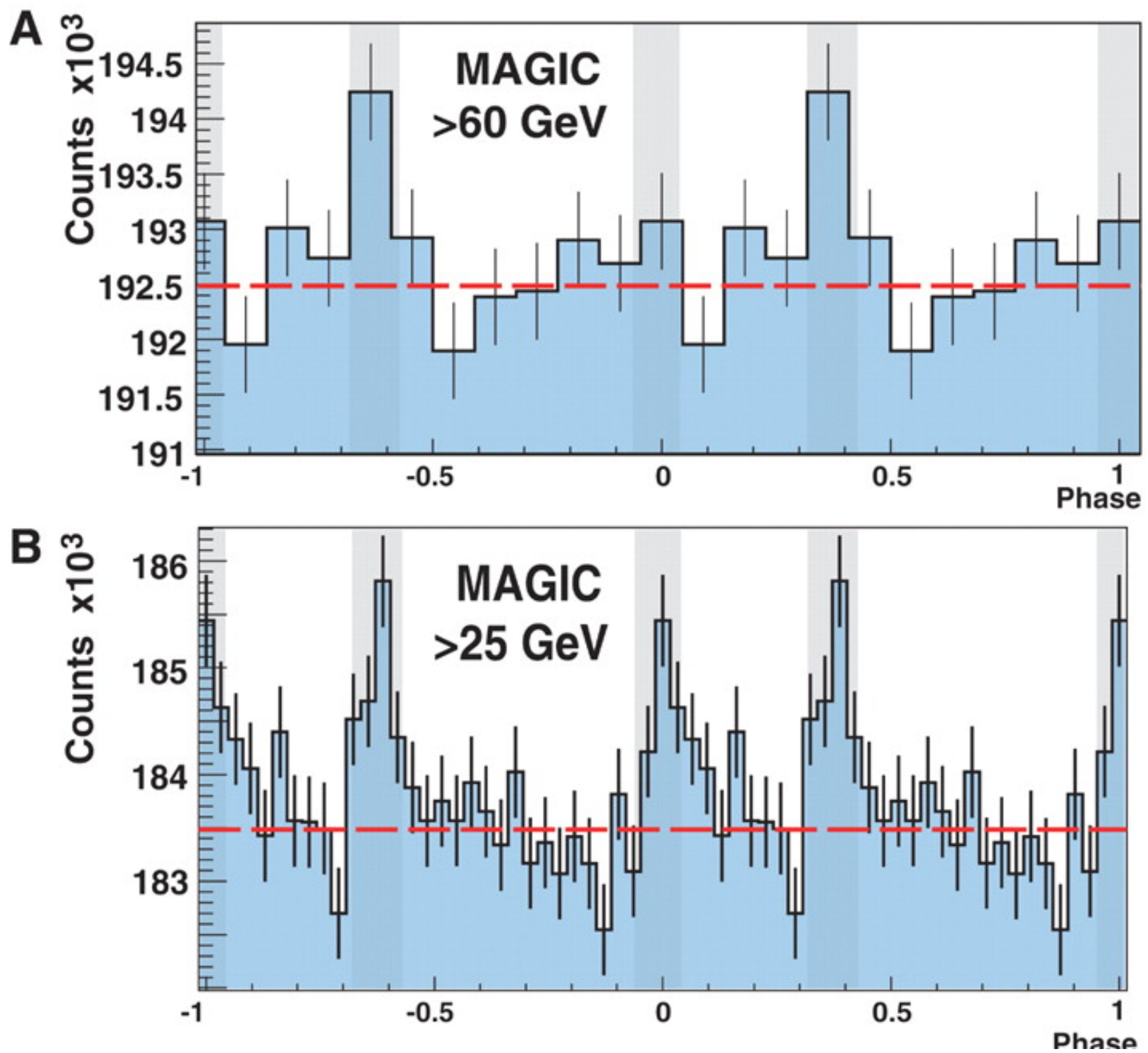
Neutron stars emission regions

- We detect pulsed emission ranging from radio to VHE gamma rays.
  - Depending on how high in energy the spectrum is reaching, the acceleration will happen in a different region
  - Polar cap models will have a sharp energy cutoff
  - Slot gap/Outer gap and wind models will have higher energy cut-offs

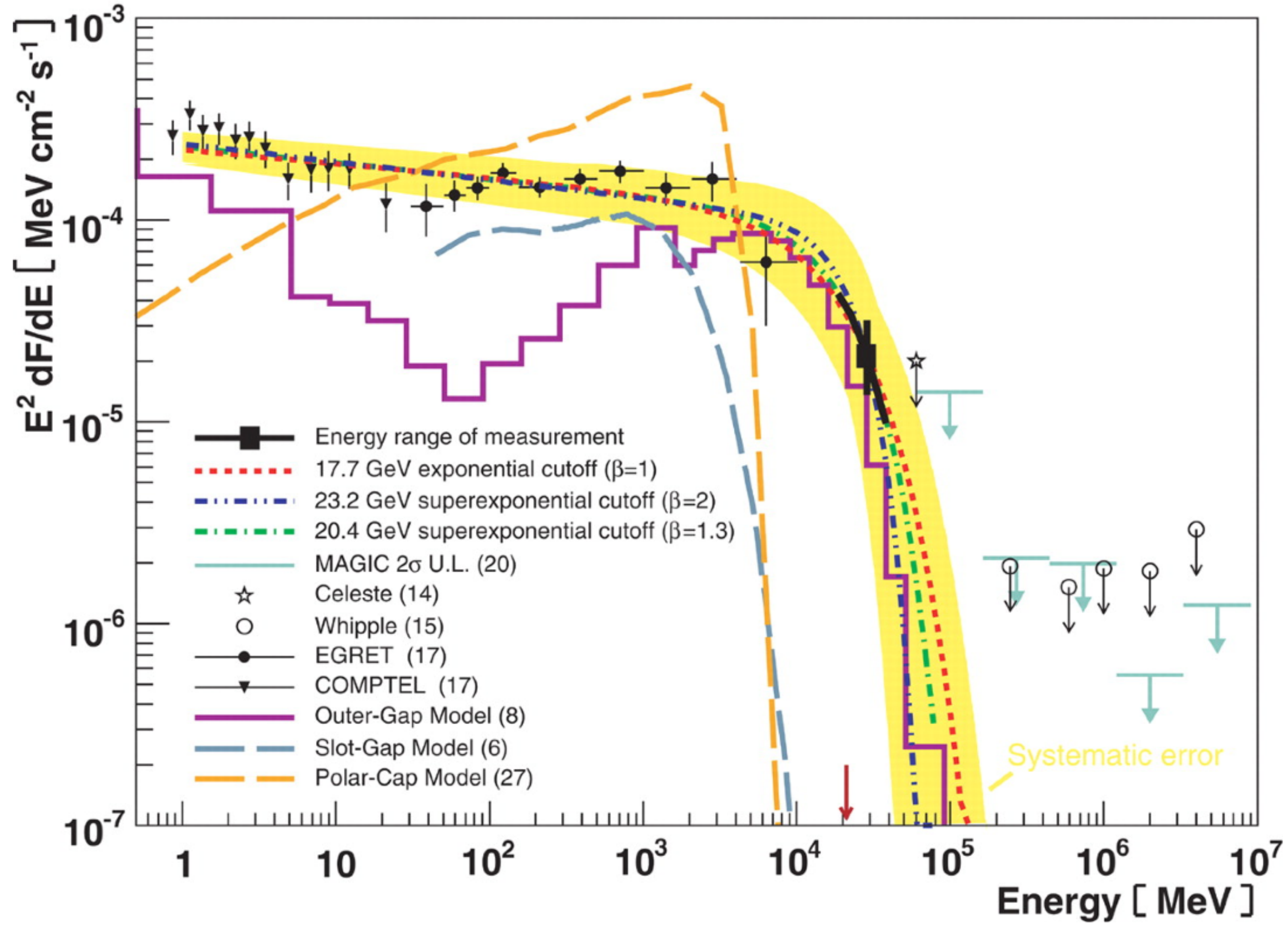


Crab Pulsar history in VHE γ rays

- MAGIC discovered pulsed gamma-ray emission above 25 GeV (Science, 2008, 322, 1221).



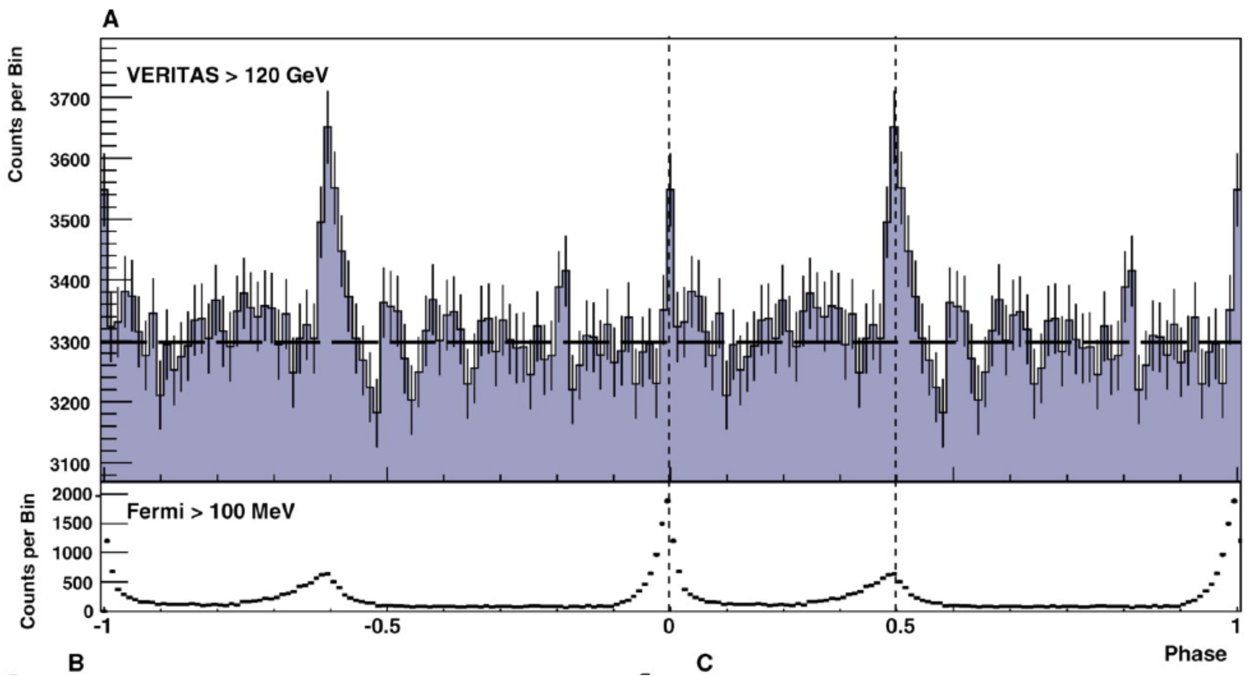
Aliu et al. (MAGIC Coll.), Science, 322 (2008)



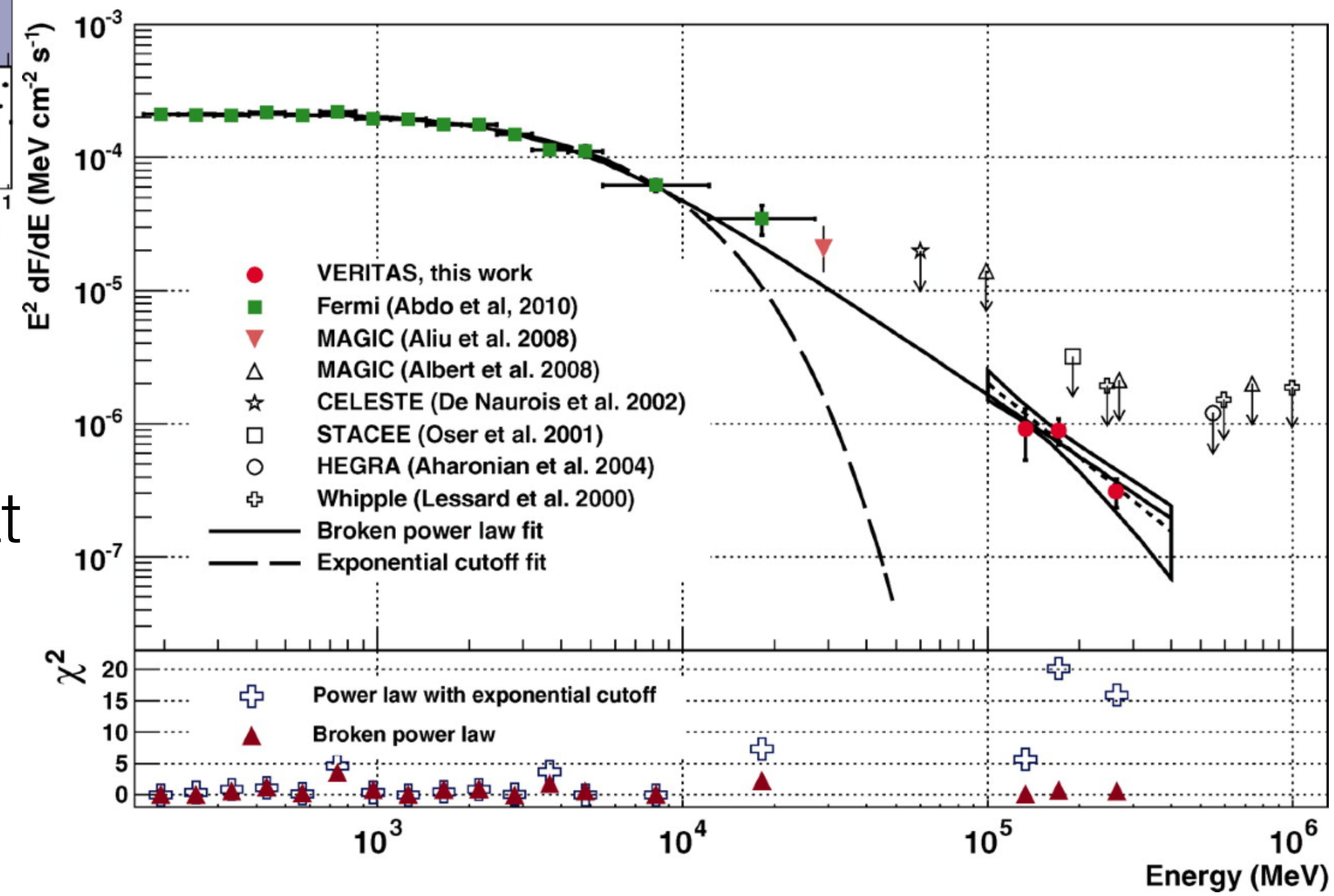
- Rules out polar cap and challenges slot gap

Crab Pulsar history in VHE γ rays

- VERITAS detected this emission above 100 GeV (Science, 2011, 334, 69)

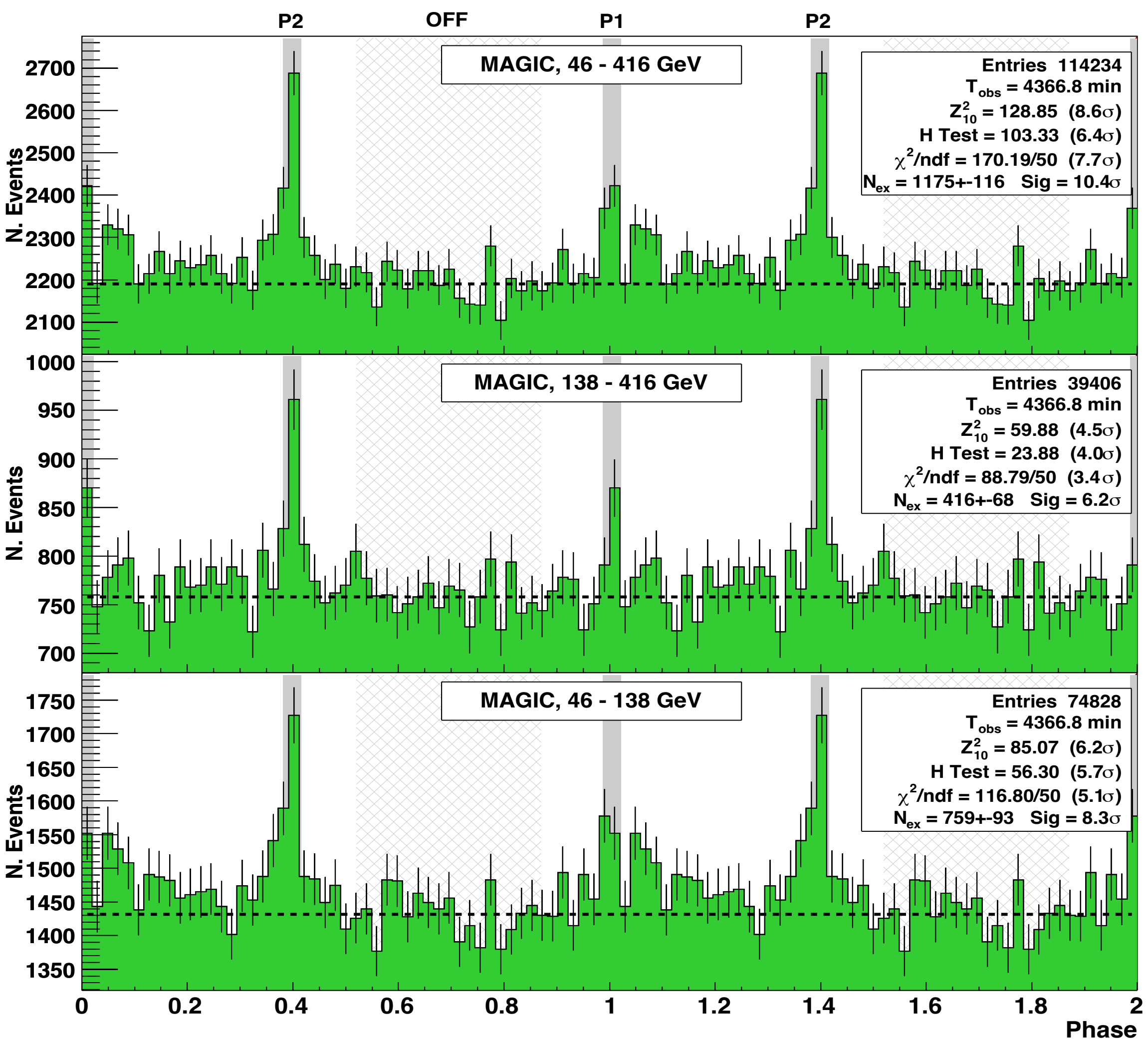


Aliu et al. (VERITAS Coll.), Science, 334 (2011)



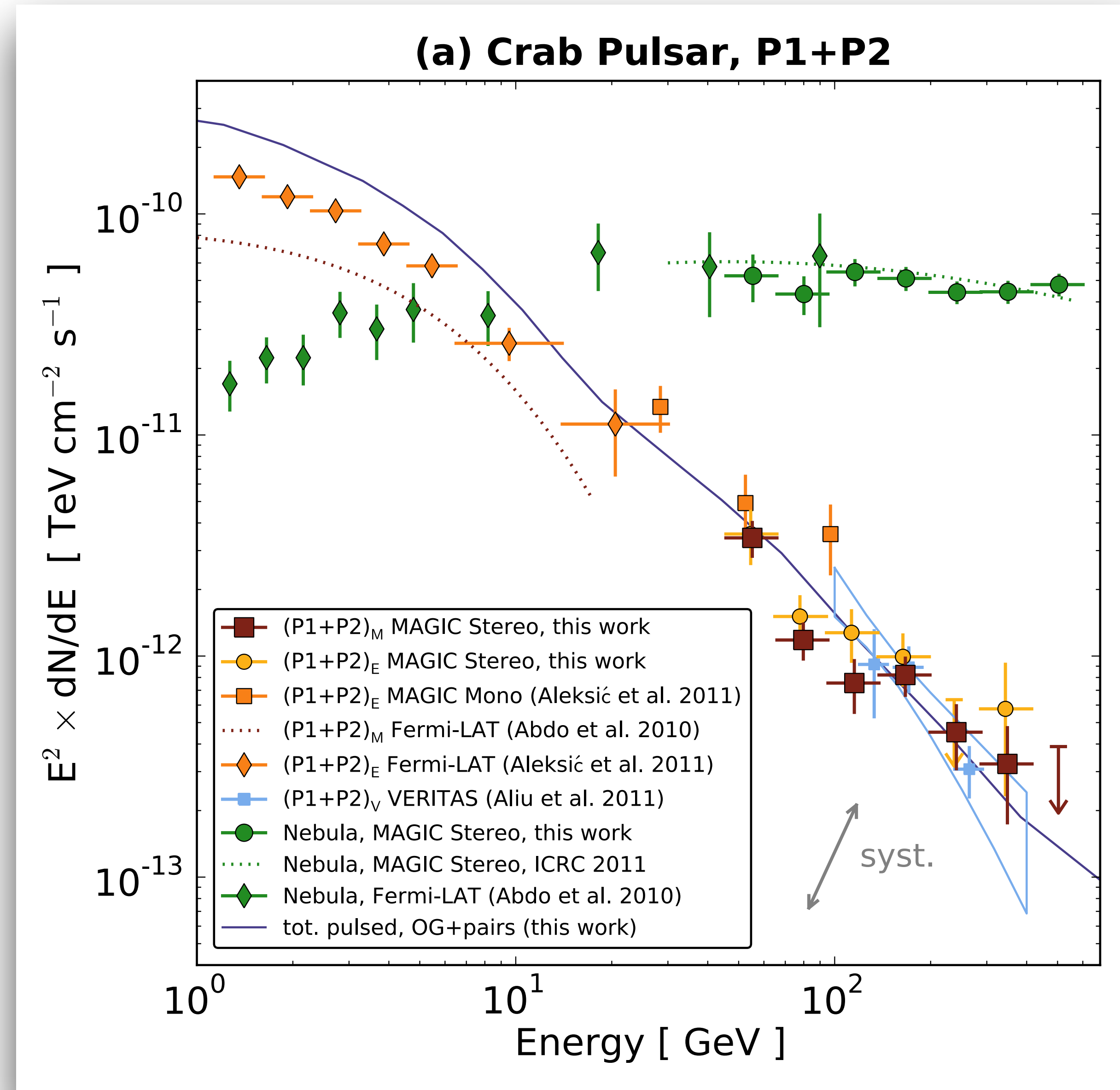
- Locates the origin of the emission at larger distances, at least further in the magnetosphere

Crab Pulsar history in VHE γ rays

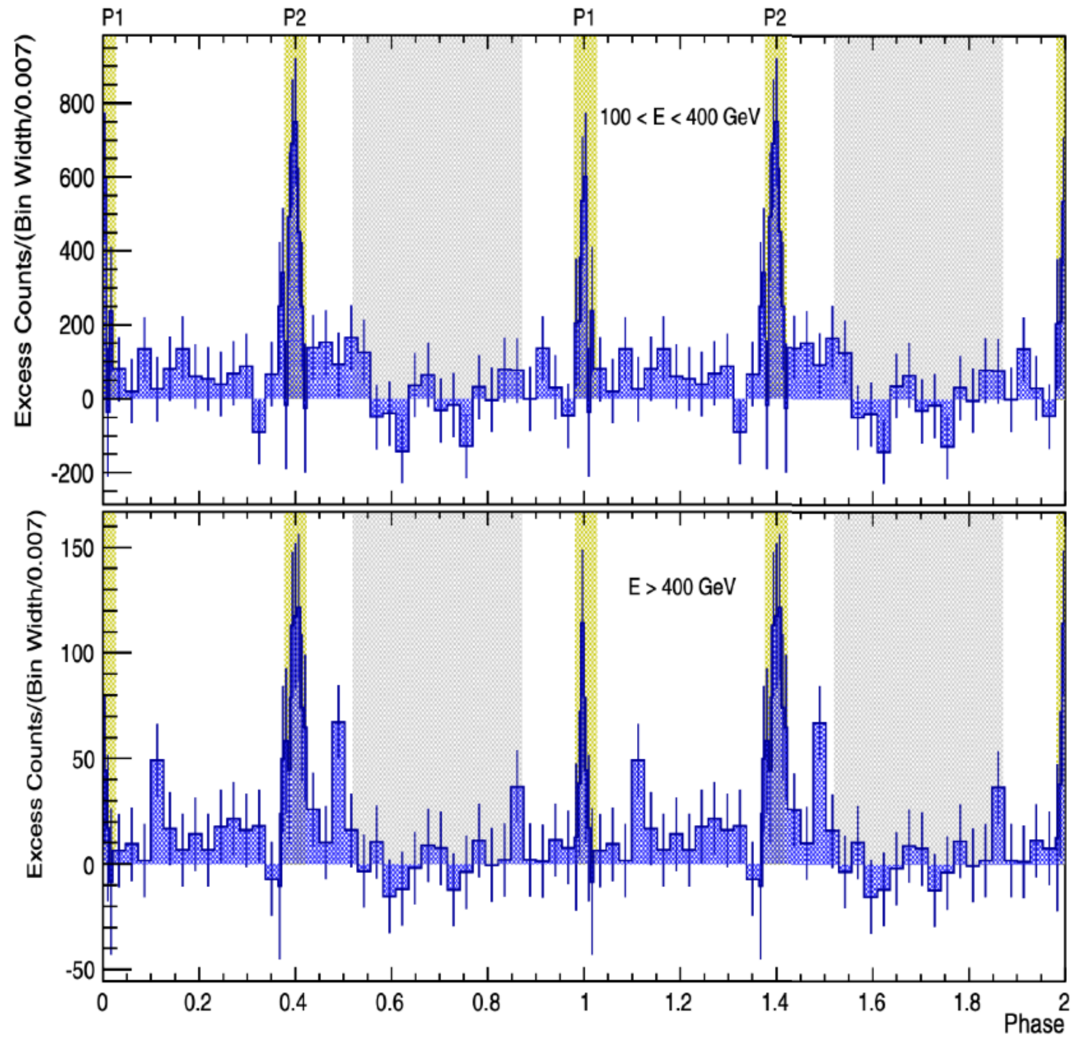


J. Aleksić et al. (MAGIC Coll.), A&A. 540 (2012) 69

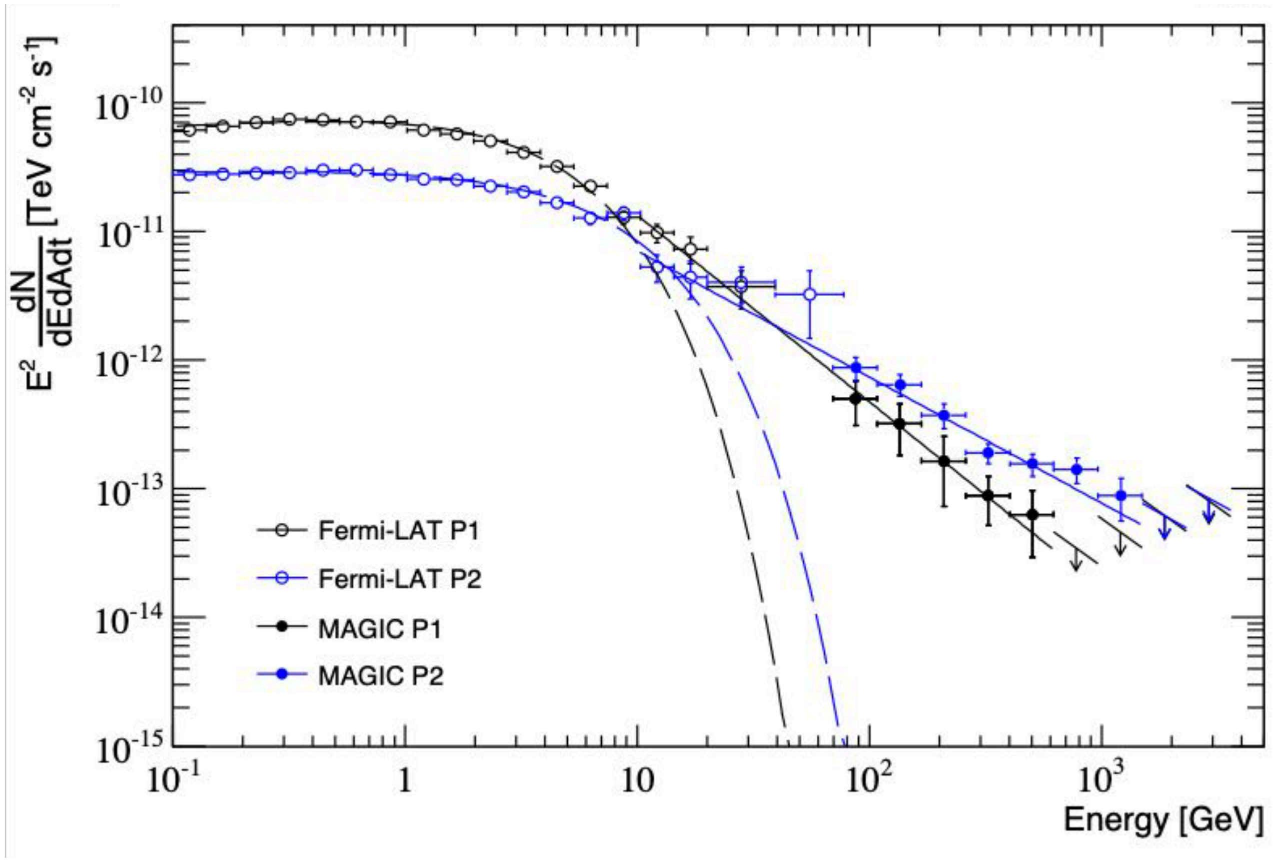
- MAGIC extended the spectrum up to 400 GeV (A&A, 2012, 540, 69) and separately measured the spectrum of P1 and P2.



Crab Pulsar history in VHE γ rays



- Discovery of emission up to TeV energies (2016).

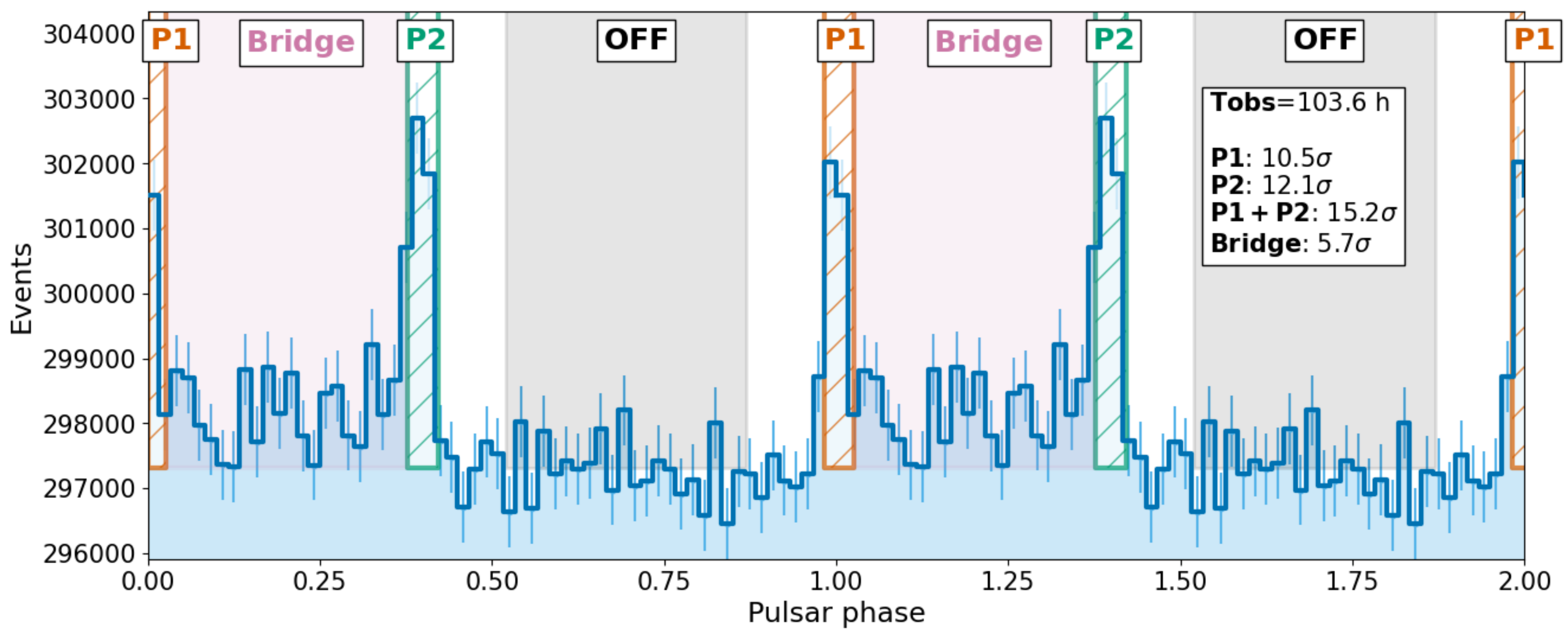


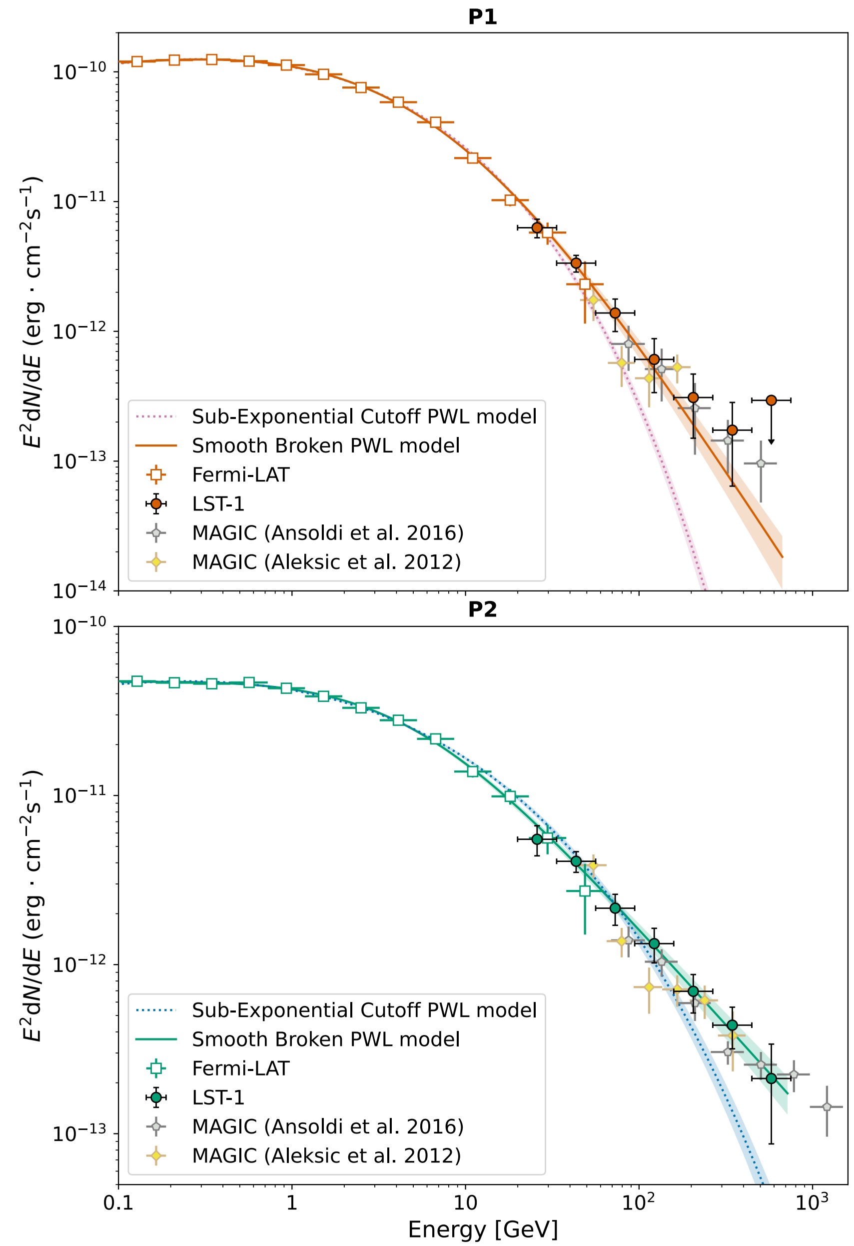
- Outer gap and wind models are the only remaining options to explain this emission

S. Ansoldi et al. (MAGIC Coll.), A&A, 585, A133 (2016)

Crab Pulsar latest results

- LST-1 of CTAO measured the spectrum from few tens of GeV up to hundreds of TeV (2024).

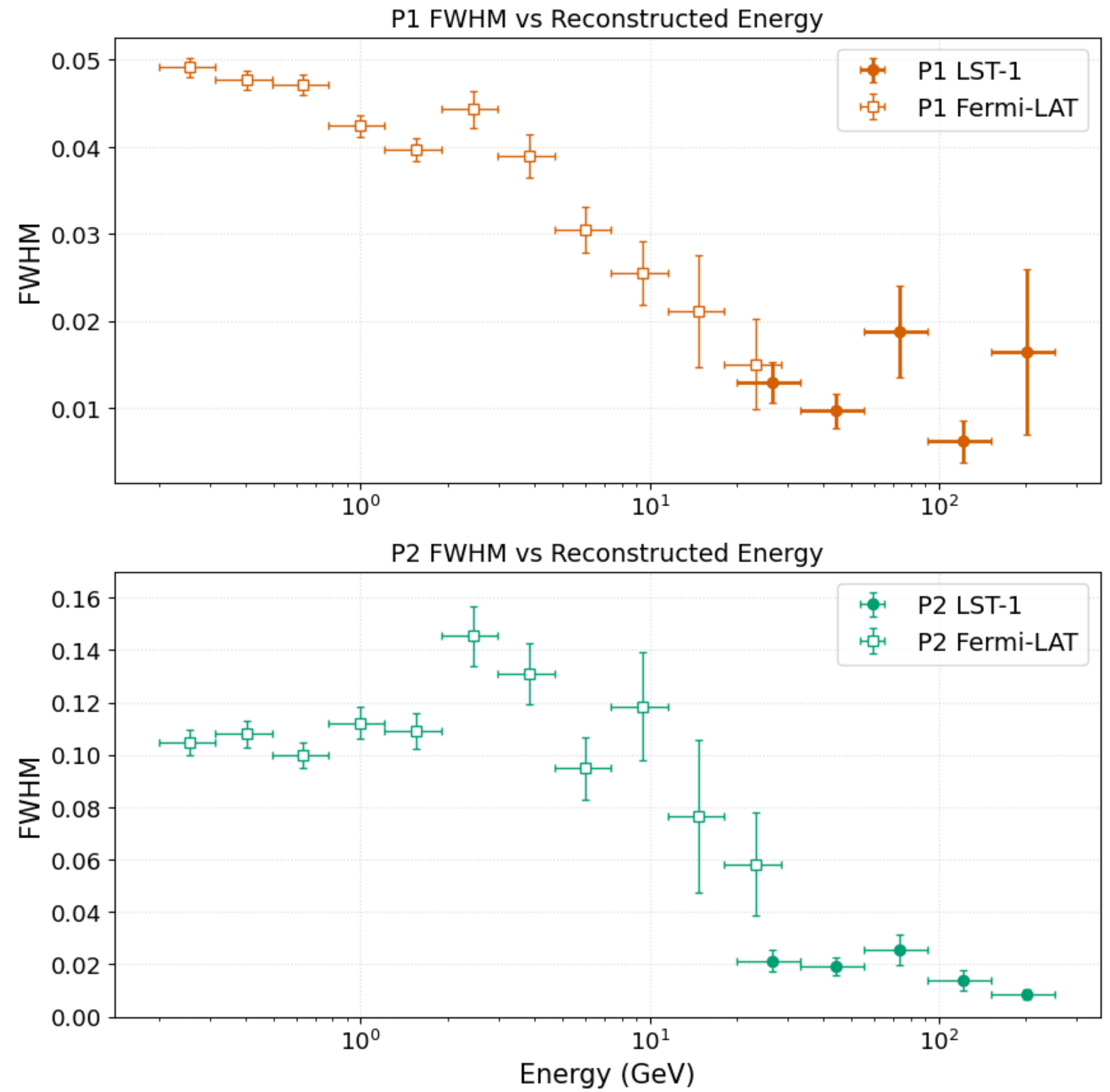




Abe et al. (LST Coll.), A&A, 690, A167 (2024)

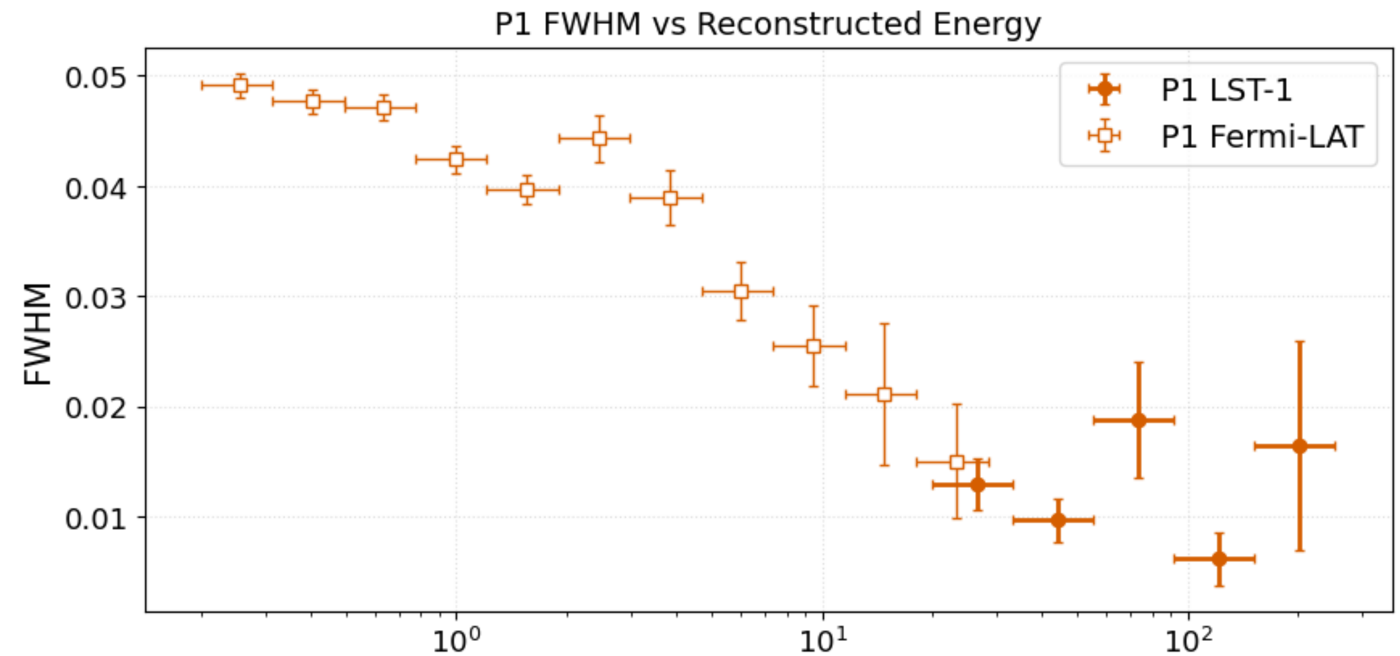
Crab Pulsar Peak Morphology

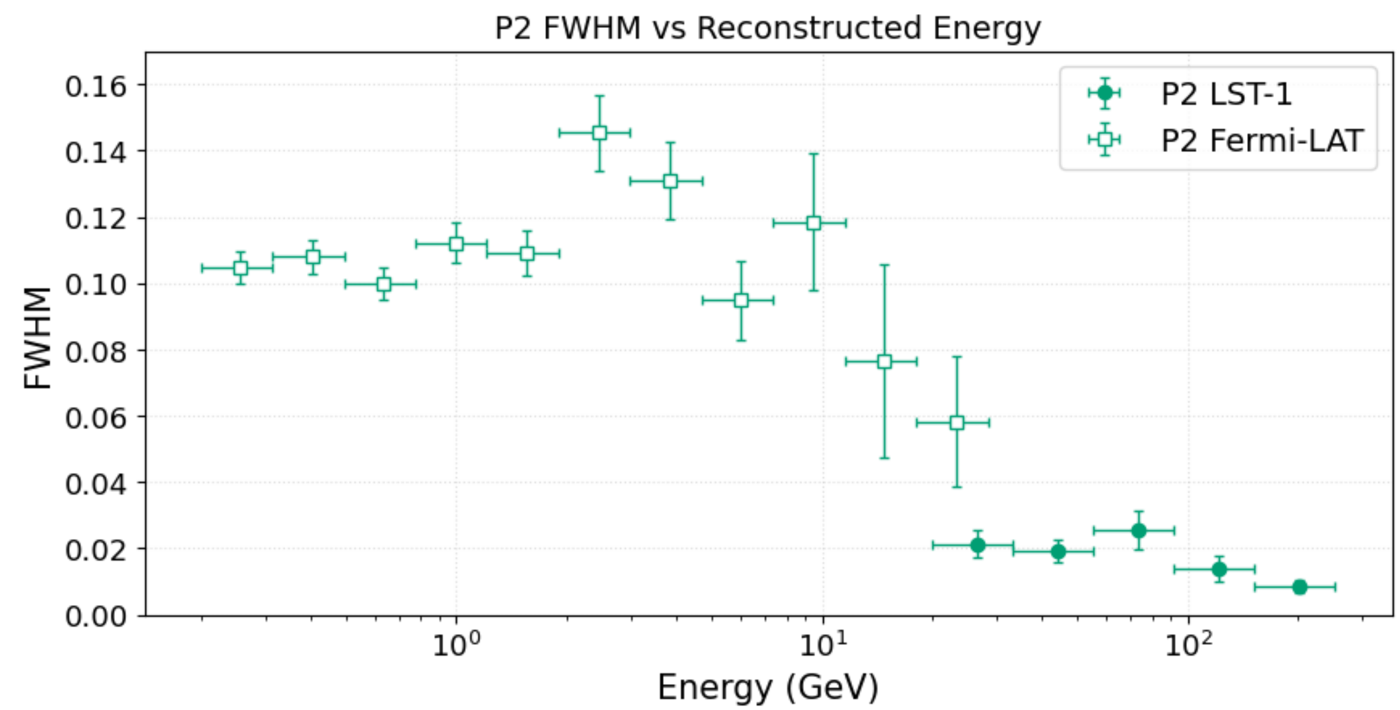
- Peak location does not significantly change
- P1 width drops until 10 GeV and no variation beyond
- P2 width decreases above 2 GeV

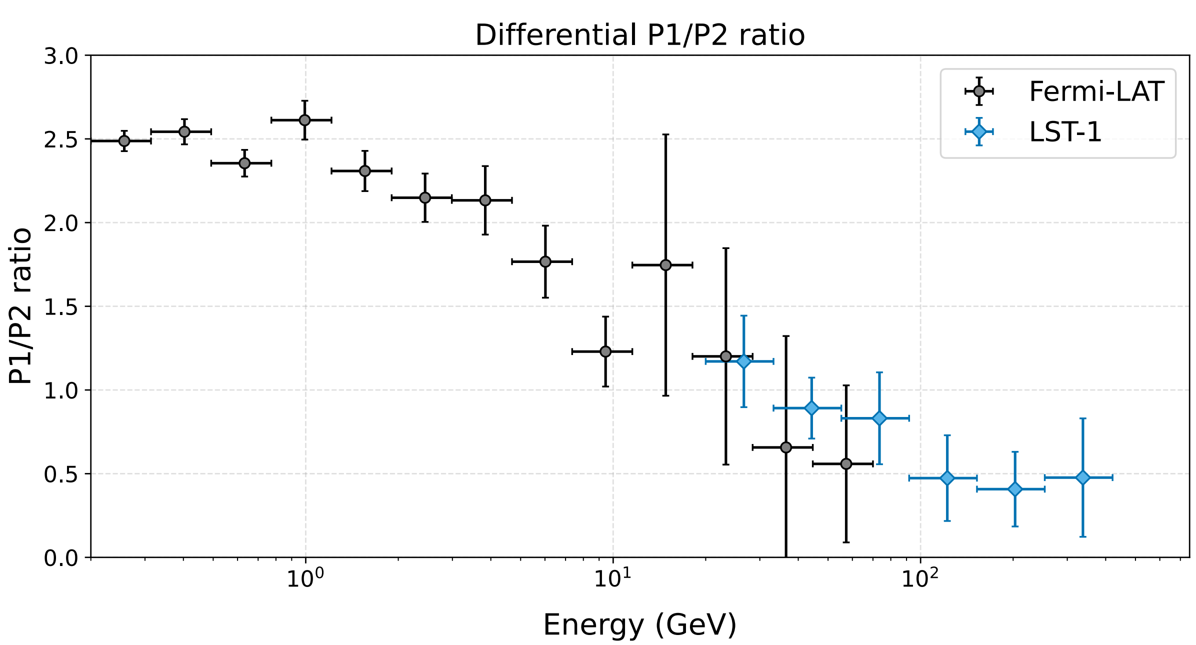


Crab Pulsar Peak Morphology

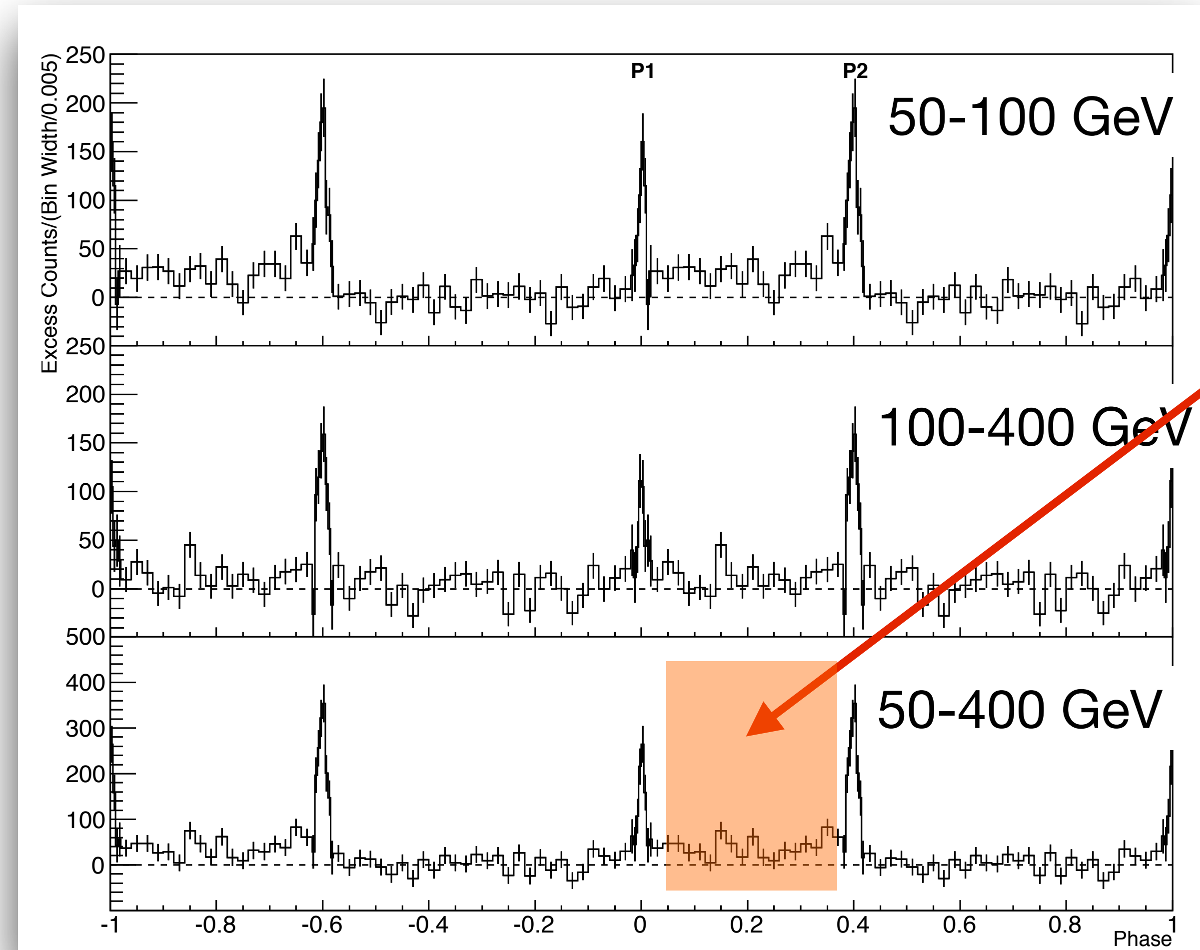
- P1/P2 ration decreases up to 100 GeV
- ~constant above that energy







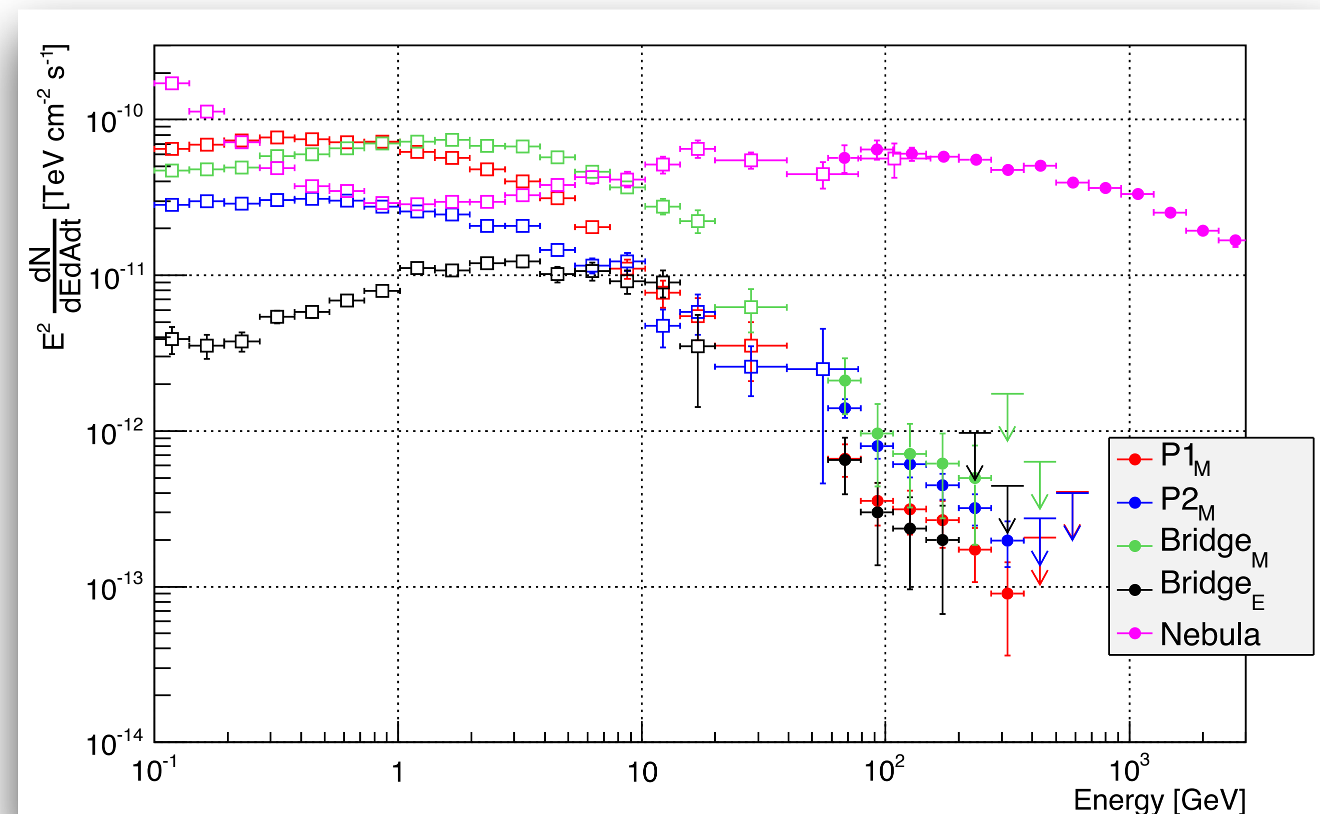
Crab Pulsar Bridge



J. Aleksić et al. (MAGIC Coll.), A&A, 565 (2014) L12

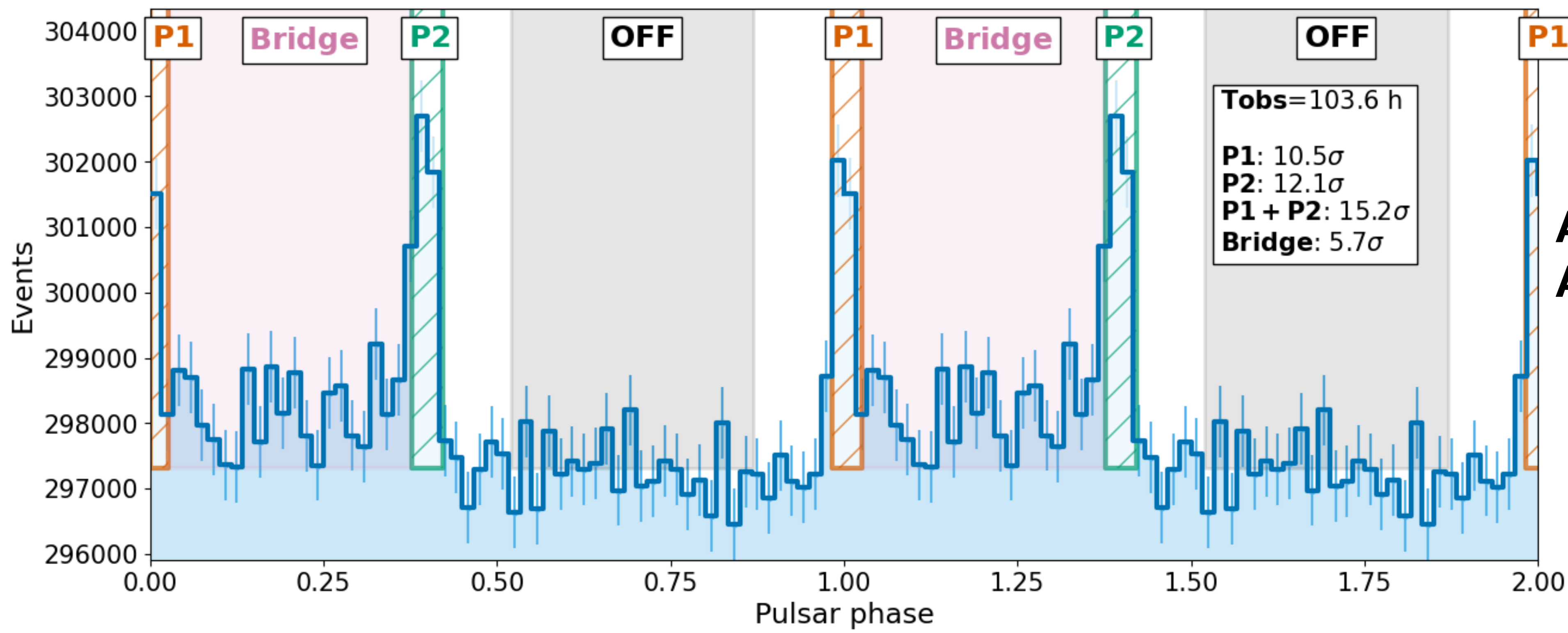
MAGIC measured for the first time VHE emission from the bridge region between the two peaks extending beyond 100 GeV

The bridge emission was significantly detected above 50 GeV



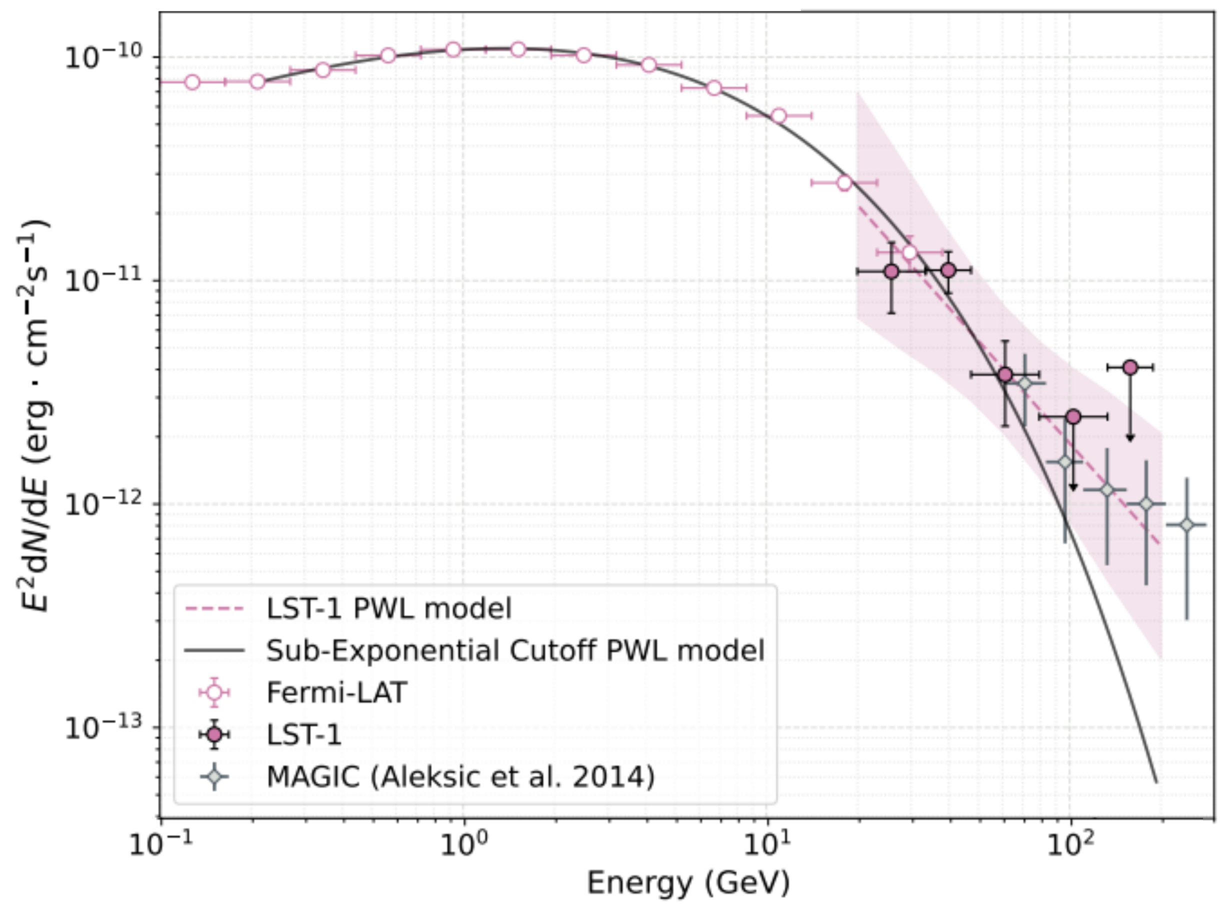
J. Aleksić et al. (MAGIC Coll.), A&A, 565 (2014) L12

Crab Pulsar Bridge

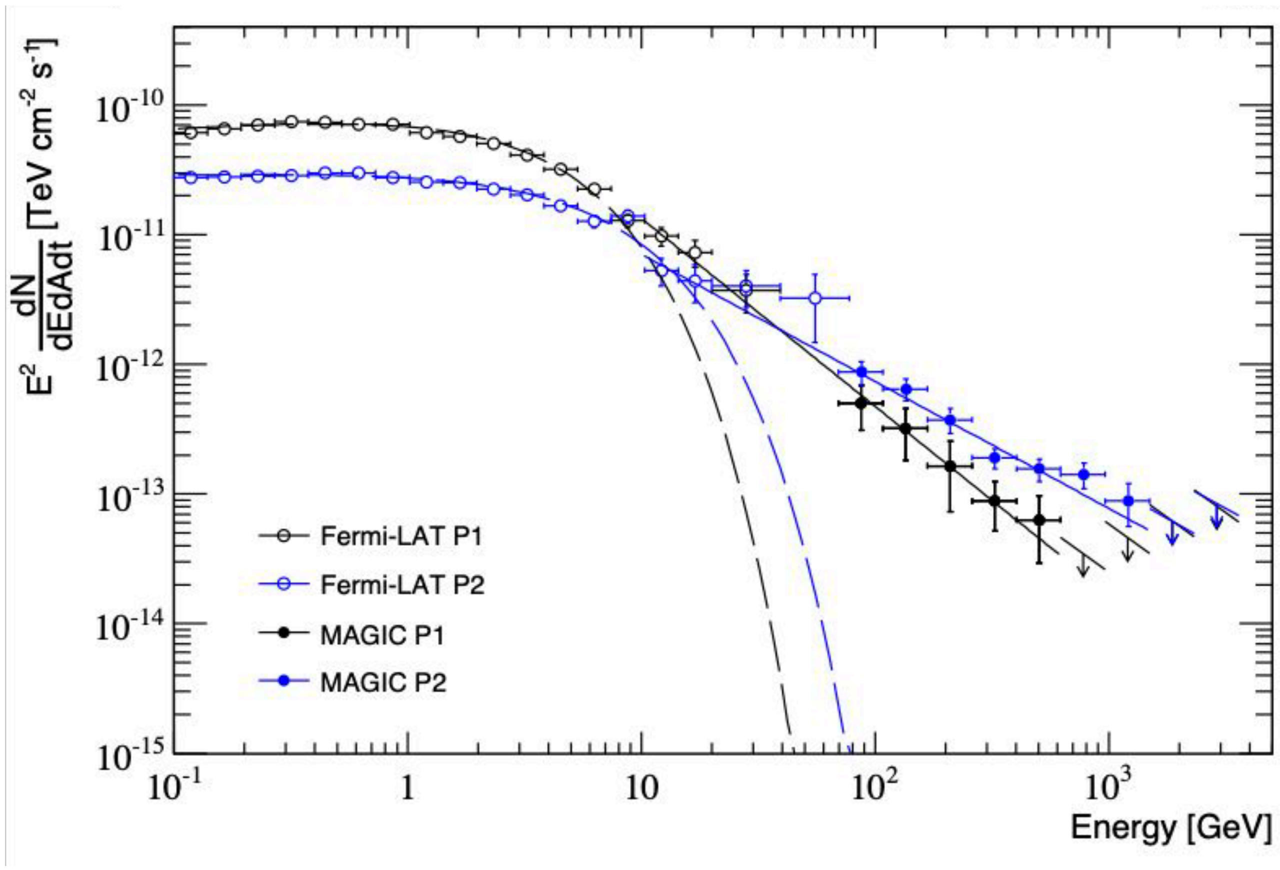


Abe et al. (LST Coll.), A&A, 690, A167 (2024)

LST-1 closed the gap at the lowest energies



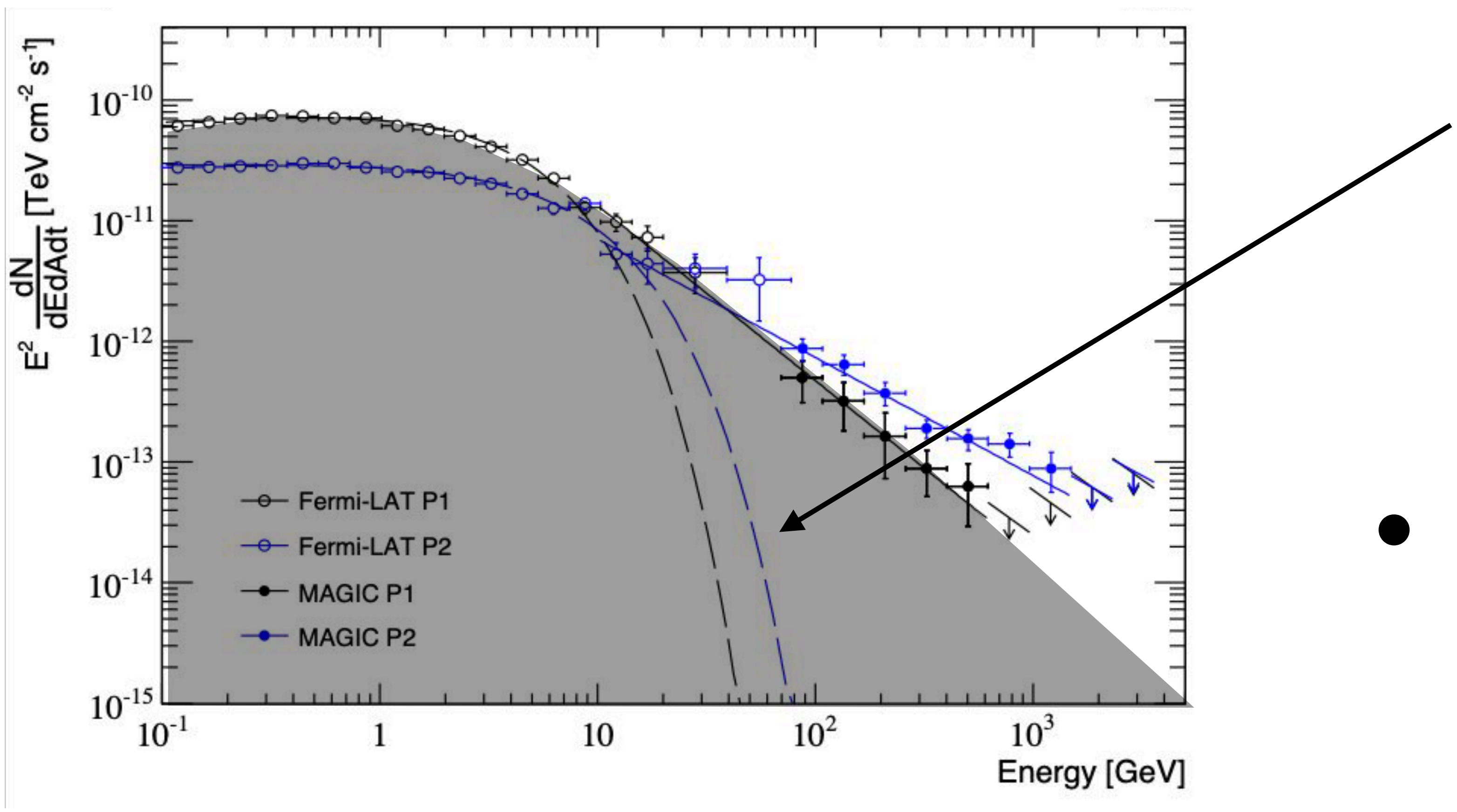
Interpretation



S. Ansoldi et al. (MAGIC Coll.), A&A, 585, A133 (2016)

- Two options to explain the VHE gamma-ray emission
  - Single component reaching TeV energies
  - Two components (below/ above ~10's of GeV)
- Not possible to reach TeV energies via synchro-curvature emission
  - IC on soft photon fields?

Interpretation



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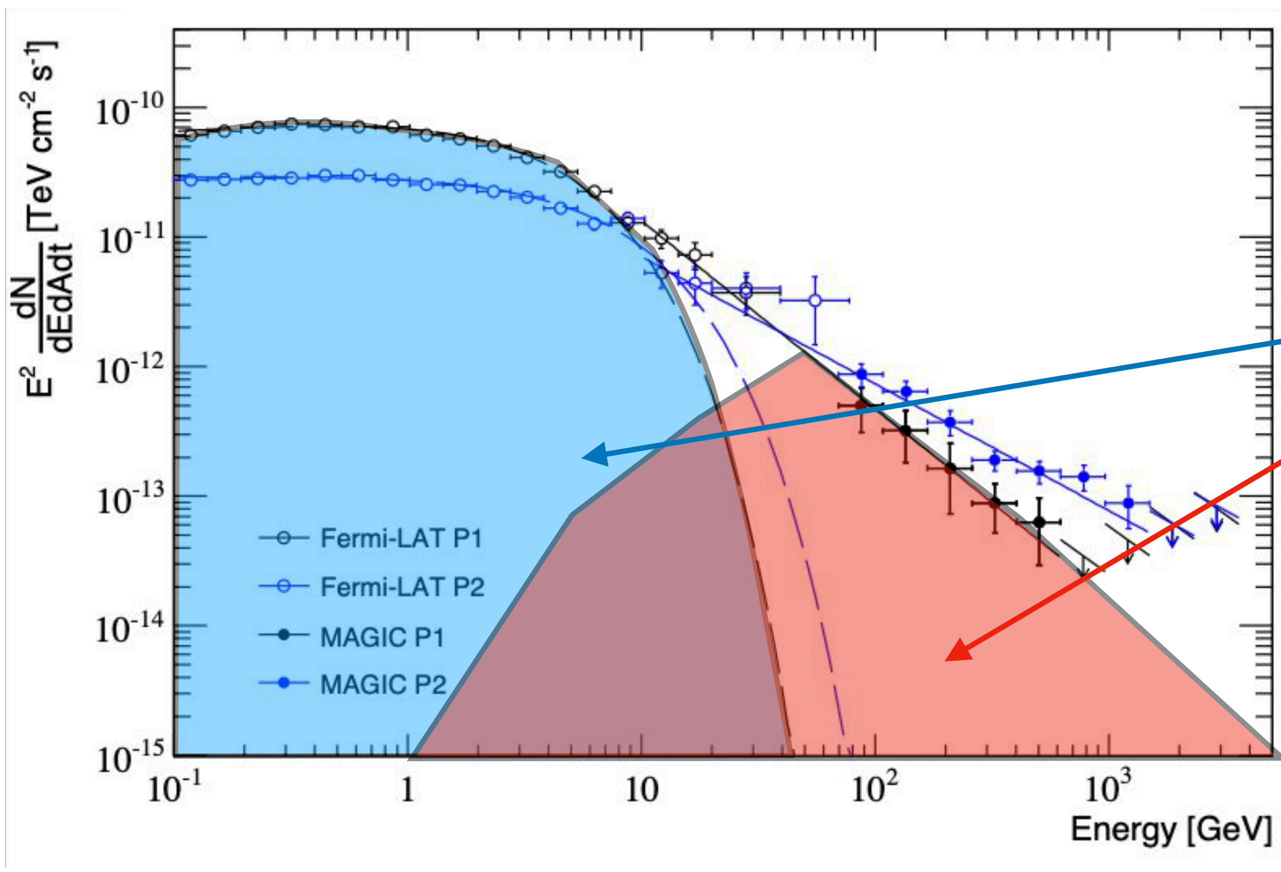

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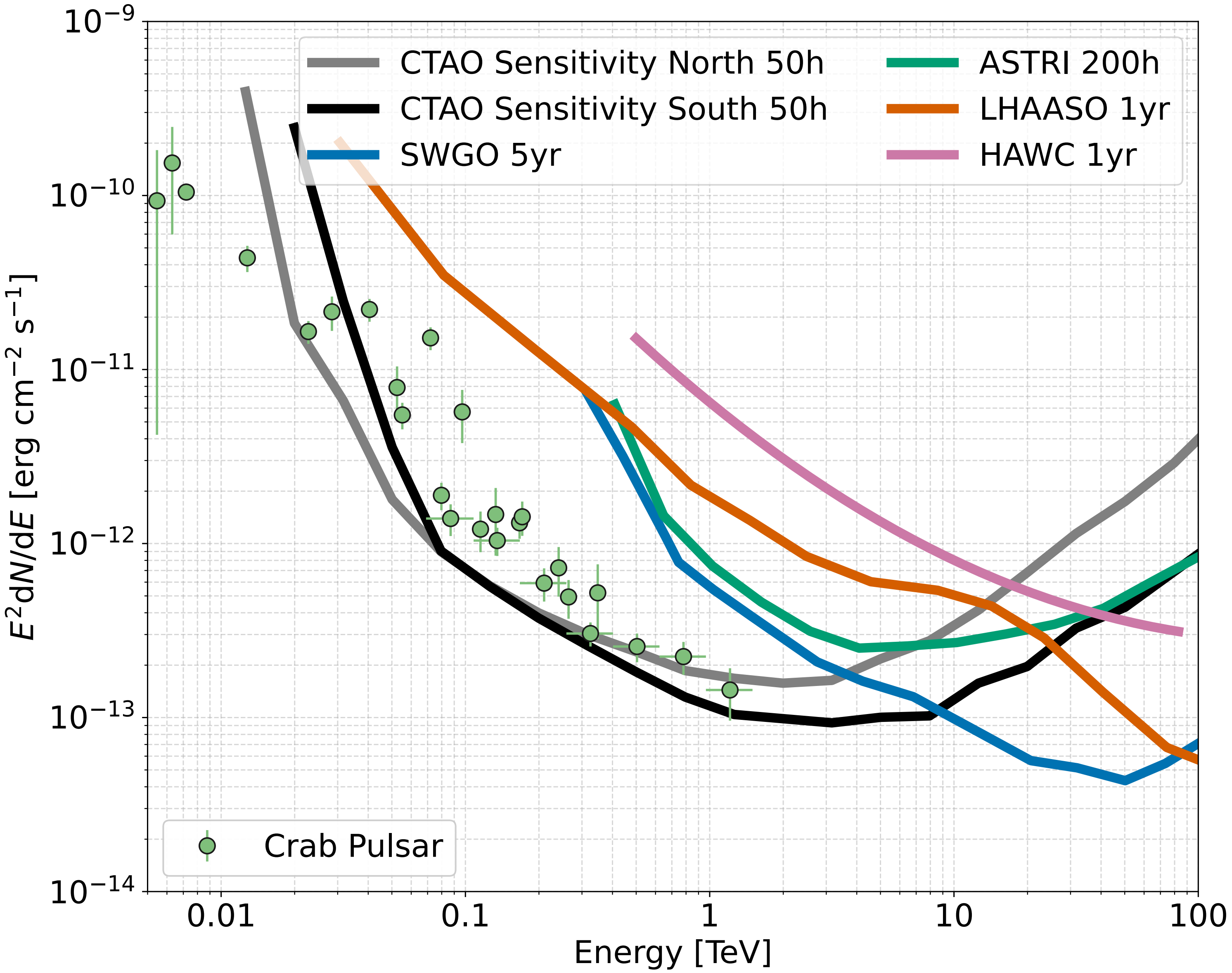
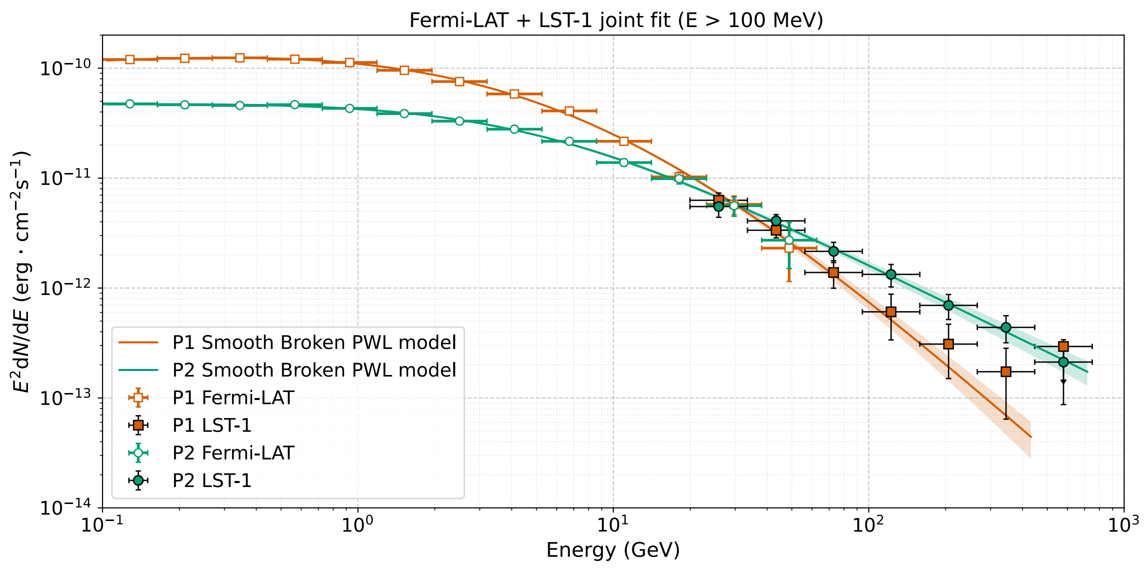
Future



- Major future facilities covering the VHE gamma-ray sky
- CTAO will perform a better measurement in the ~tens of GeV energy range
  - Will we be able to distinguish between one or two components?
- At the highest energies, CTAO remains the only facility with enough sensitivity below ~10 TeV

Summary



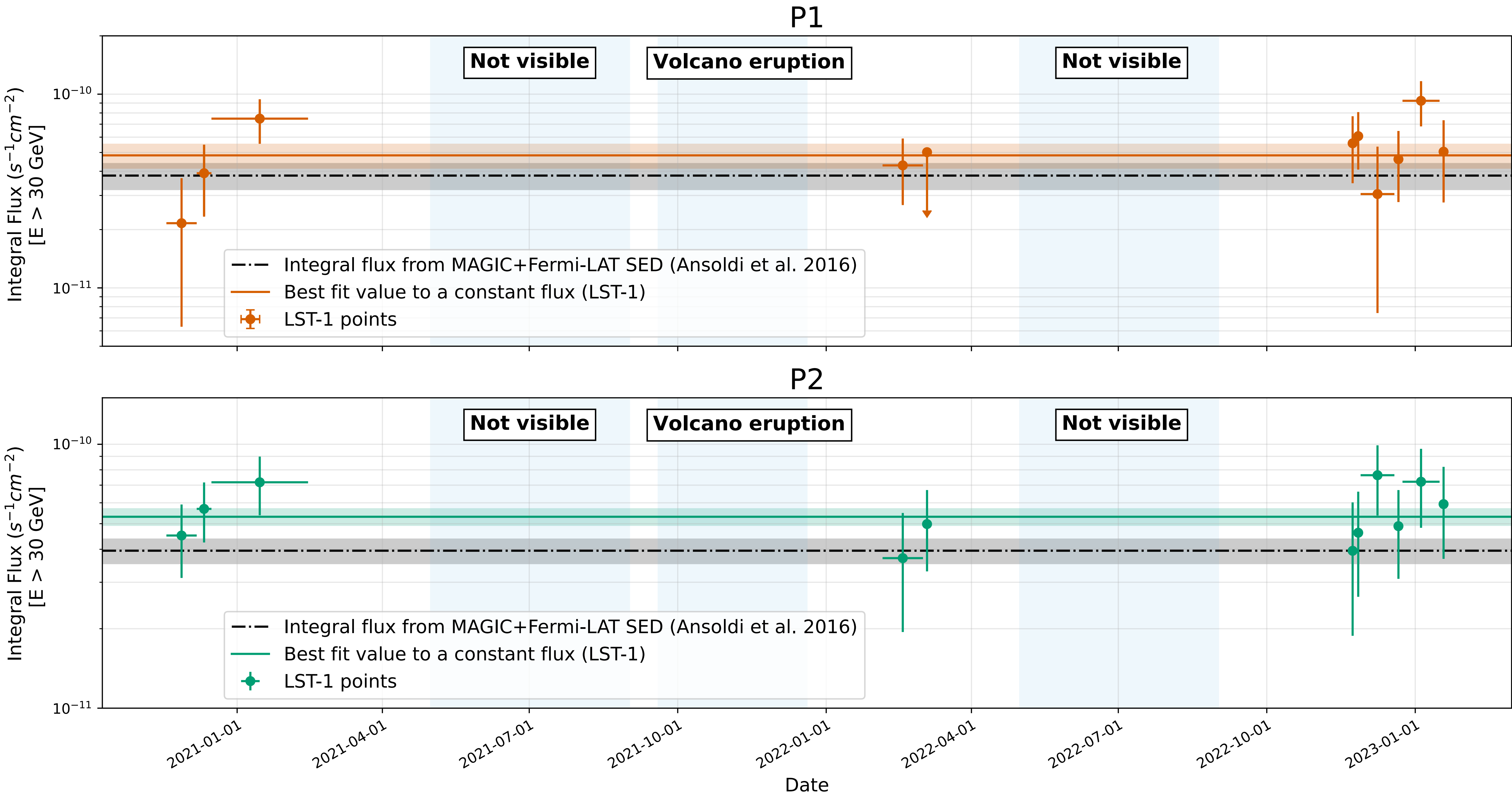
- The Crab pulsar has been an origin of surprises in the VHE gamma-ray band for more than 15 years.

- The origin of the VHE gamma-ray emission still remains an open question
  - Single component extending up to TeV energies?
  - Two components originated in different regions?

- The first pulsar measured in the multi-GeV and TeV energy range
  - Still worth studying to understand the VHE gamma-ray emission of pulsars

Thanks!

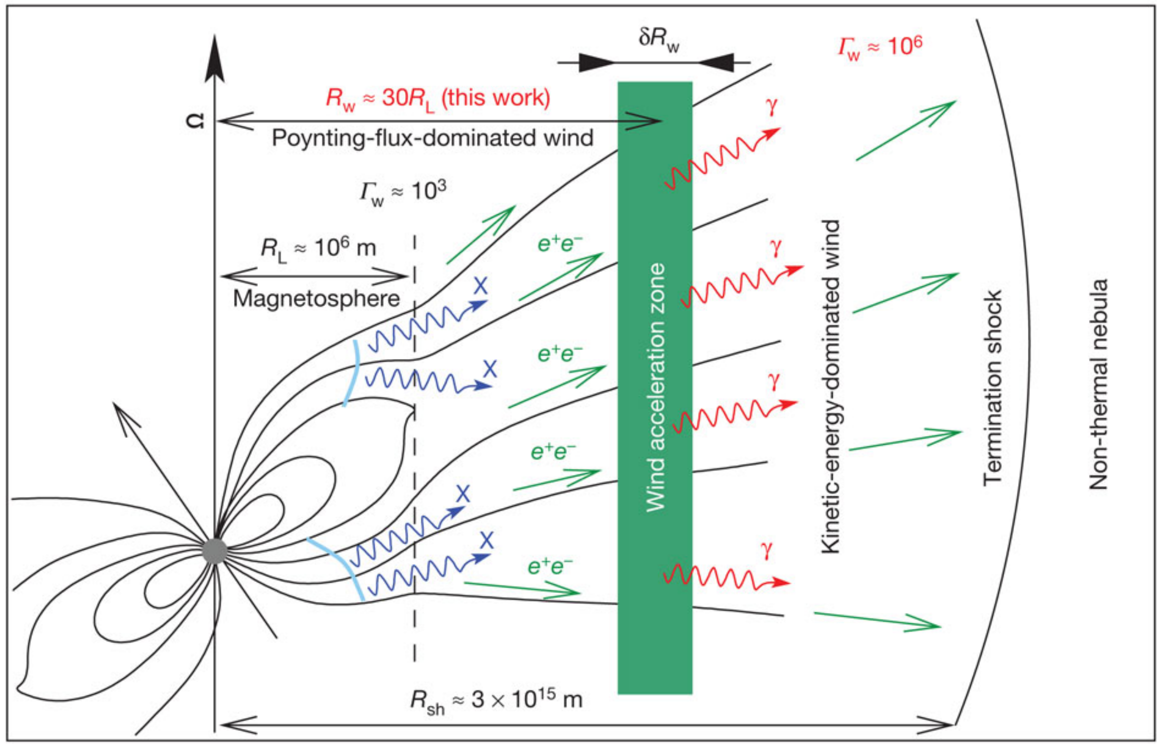
Lightcurve



P1
Not visible
Volcano eruption
Not visible
Integral Flux ($s^{-1}cm^{-2}$)
[E > 30 GeV]
10^{-10}
10^{-11}
Integral flux from MAGIC+Fermi-LAT SED (Ansoldi et al. 2016)
Best fit value to a constant flux (LST-1)
LST-1 points
P2
Not visible
Volcano eruption
Not visible
Integral Flux ($s^{-1}cm^{-2}$)
[E > 30 GeV]
10^{-10}
10^{-11}
Integral flux from MAGIC+Fermi-LAT SED (Ansoldi et al. 2016)
Best fit value to a constant flux (LST-1)
LST-1 points
2021-01-01
2021-04-01
2021-07-01
2021-10-01
2022-01-01
2022-04-01
2022-07-01
2022-10-01
2023-01-01
Date

(A couple of) VHE pulsar models

Cold ultrarelativistic wind



Aharonian, F. et al., Nature 482 (2012) 507

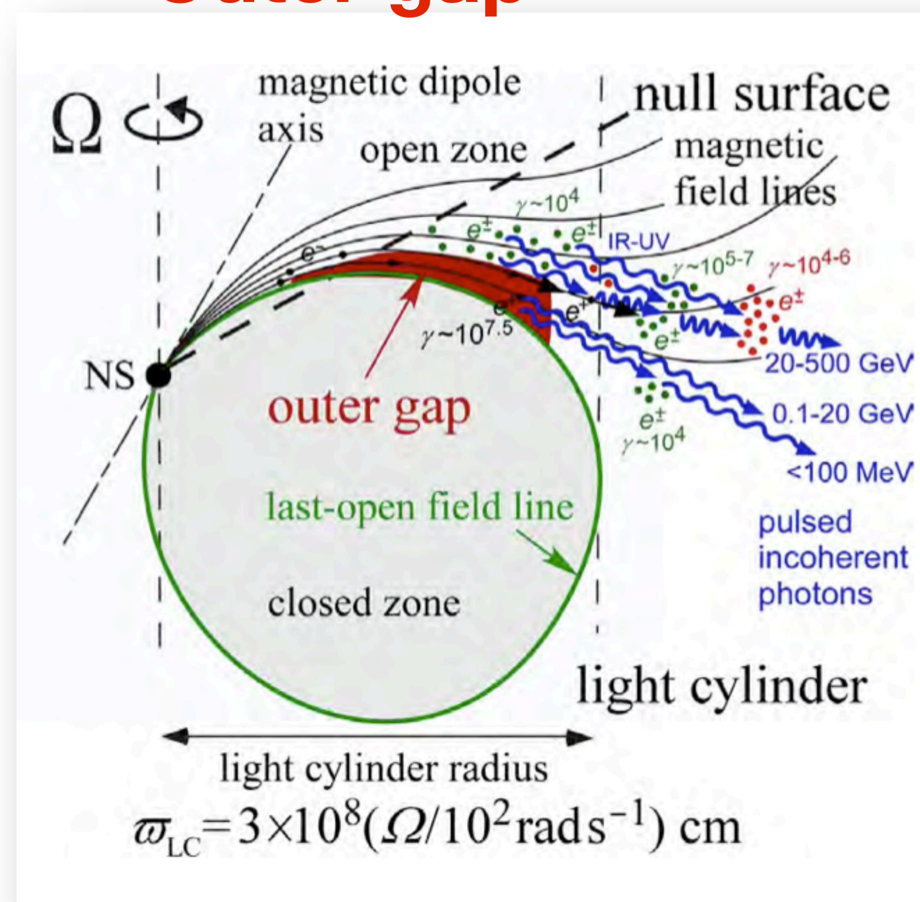
It proposes that VHE gamma-rays are produced in the wind region.

Predicts bridge emission but broader peaks than observed.

Outer gap

VHE gamma rays are produced inside the magnetosphere in an "outer gap"

It can explain the spectrum extending up to 400 GeV and also the bridge emission if the magnetic field also has a toroidal component.



Hirotani, K., ApJ, 766 (2013) 98