Pevatron studies with MAGIC LZA observation

Ie. Vovk
ICRR, The University of Tokyo

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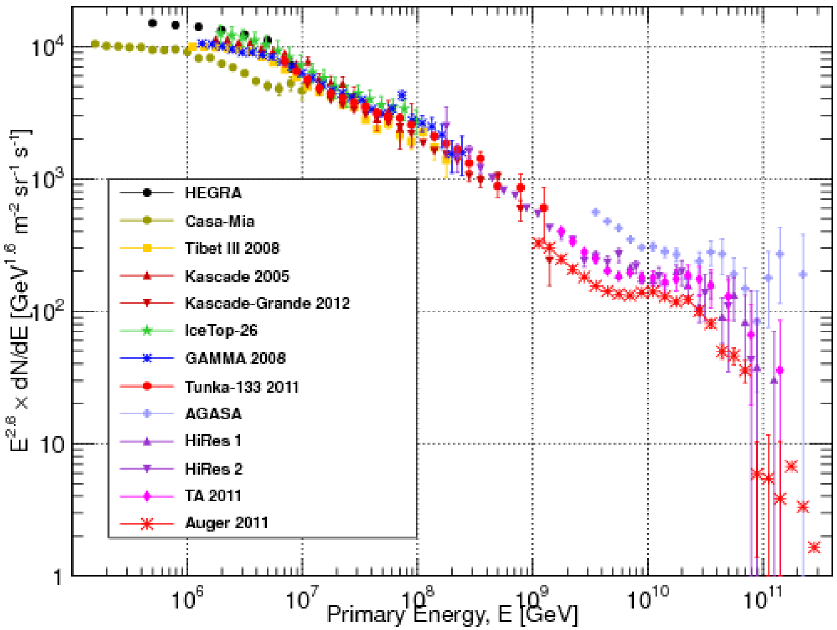
Galactic PeVatrons

Cosmic rays below the “knee” (~10^{15}-10^{17} eV) are generally believed to be of Galactic origin.

Several source populations were brought forward as parents:

- SNRs (e.g Ginzburg & Syrovatskii ‘64, Aharonian+ ‘12, Hillas 2005)
- pulsars and PWNe (e.g. Neronov & Semikoz ‘12)
- OB-associations (e.g. Bykov & Fleishman ‘92, Aharonian+ ‘18)



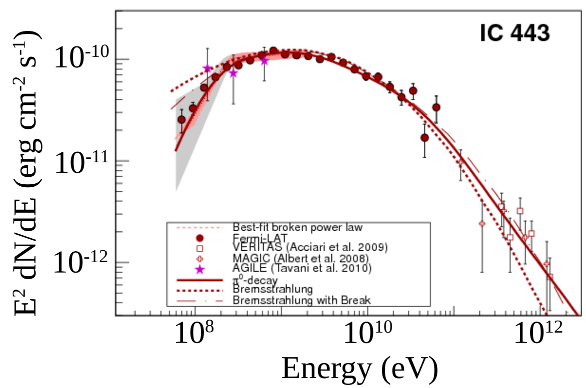
Gaisser+ '13

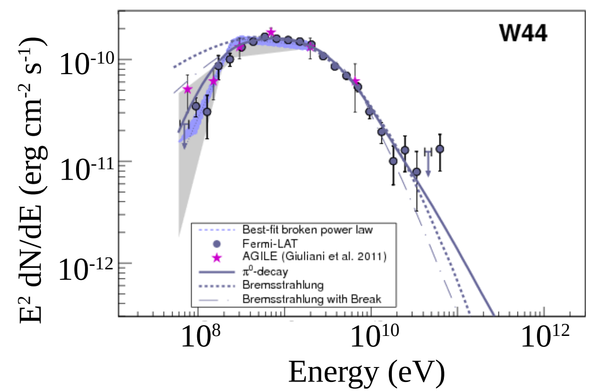
Possible PeVatrons: first indications

First identifications of cosmic ray accelerators

Supernovae remnants were found accelerating (low-energy) protons

Main argument: spectrum at low energies

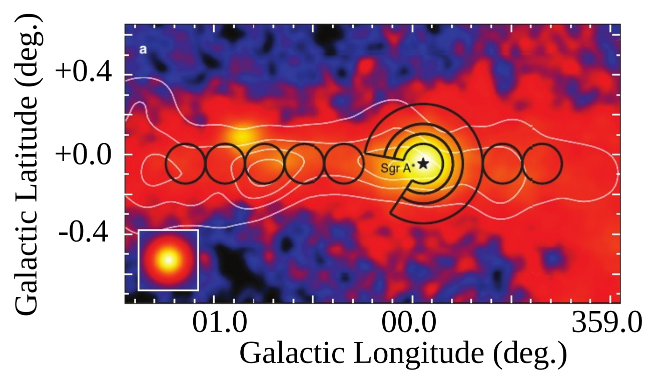


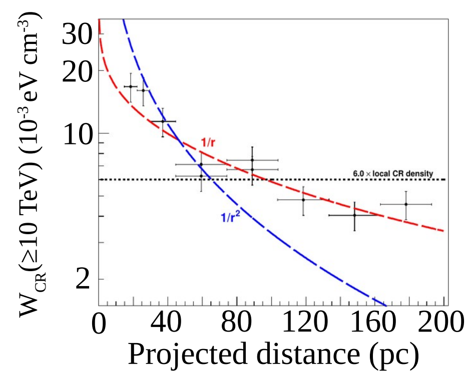


Fermi-LAT collaboration '13

Cosmic ray acceleration up to PeV energies in the Galactic Center

Main argument: morphology of emission

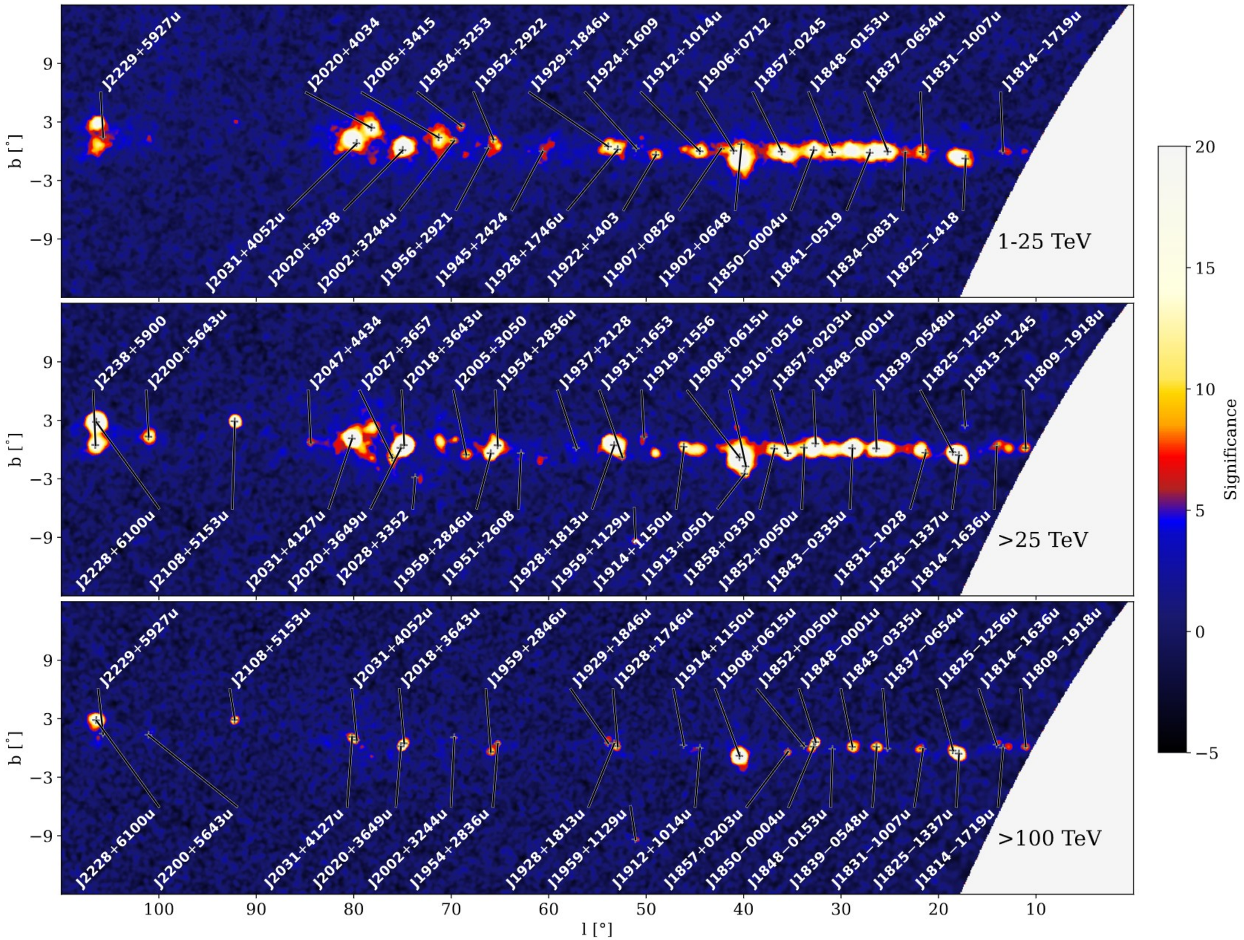




H.E.S.S. collaboration '16

Possible PeVatrons: LHAASO view

The First LHAASO Catalog of Gamma-Ray Sources



Cao ‘23

43 UHE sources (E >100 TeV)

20% of UHE sources peak >100 TeV

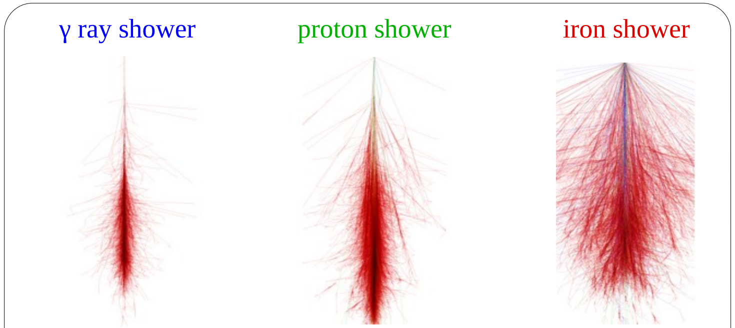
Many more UHE sources may be in a southern sky, not accessible to LHAASO

Hadronic PeVatrons – target for further deep source-by-source or class-by-class analysis

Morphological studies with IACTs with superior angular resolution

IACTs and VHE shower detection technique

Atmosphere as a detector medium



E=1 TeV. Credit: CORSIKA website

Imaging Atmospheric Cherenkov Telescopes (IACTs)

- detect: Cherenkov light from secondaries
- location: below the shower
- observations: pointing
- collection area: light pool size

Lower energy threshold
Better angular resolution

Can IACTs get this?

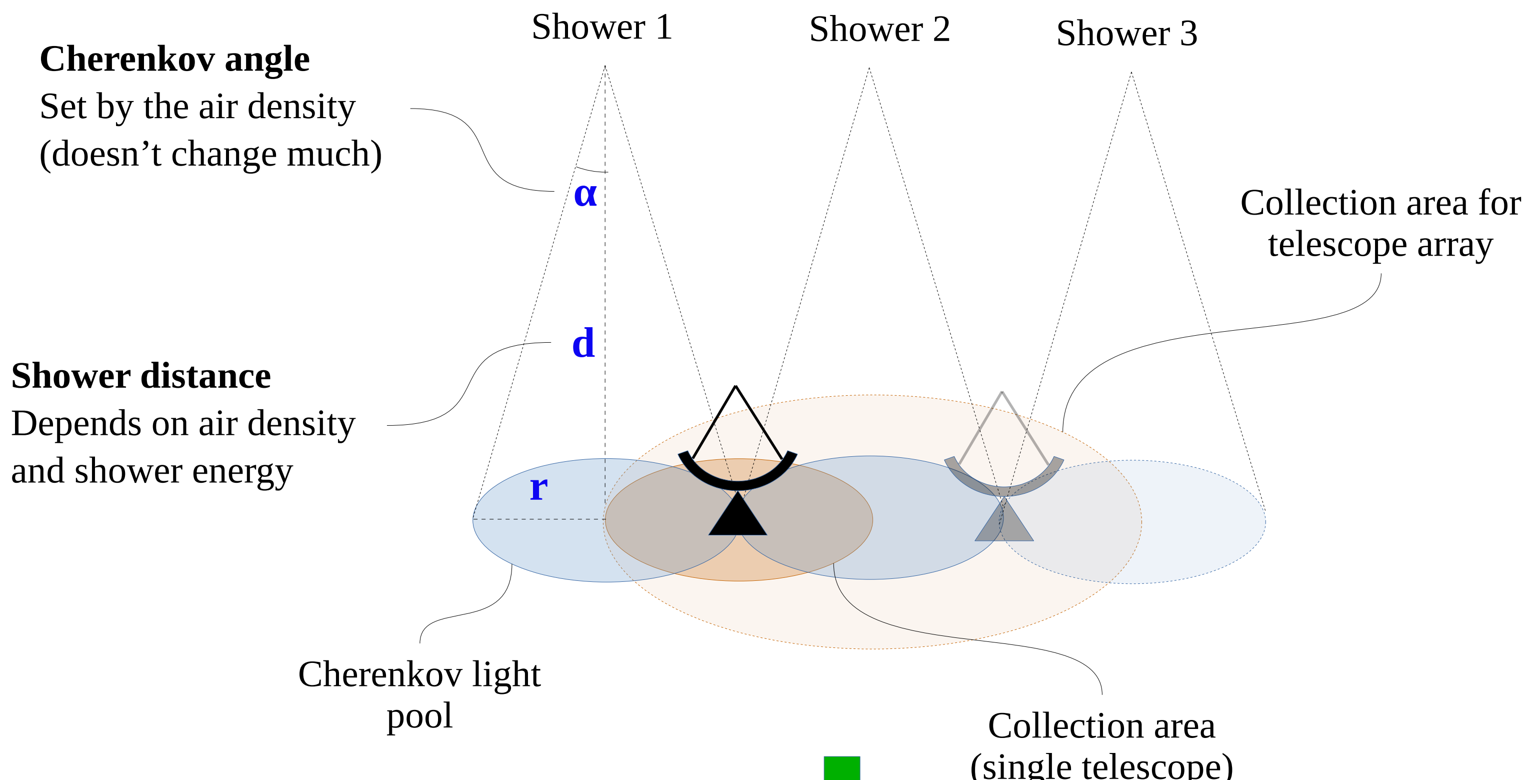
Surface arrays

- detect: secondaries
- location: submerged into the shower
- observations: all-sky
- collection area: array area

Larger collection area / exposure

IACT collection area

Collection area of the IACTs is determined by the cherenkov light pool size

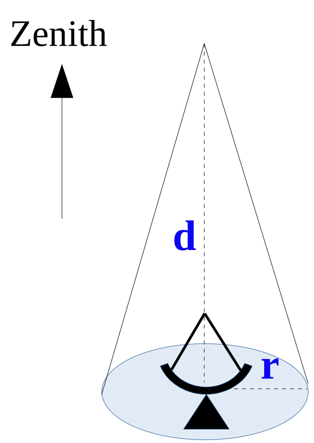


Increasing the collection area:
- more telescopes
- increasing distance to shower

Larger zenith angle observations

Vertical observations

(typical observational
mode of IACTs)

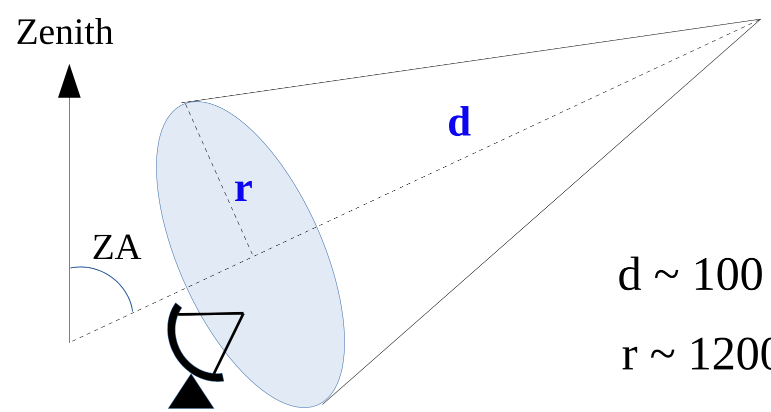


d ~ 10 km

r ~ 120 m

Usually ZA ~ [0⁰; 60⁰] and shower distance d ~ 10-20 km

Large zenith angle observations



d ~ 100 km

r ~ 1200 m

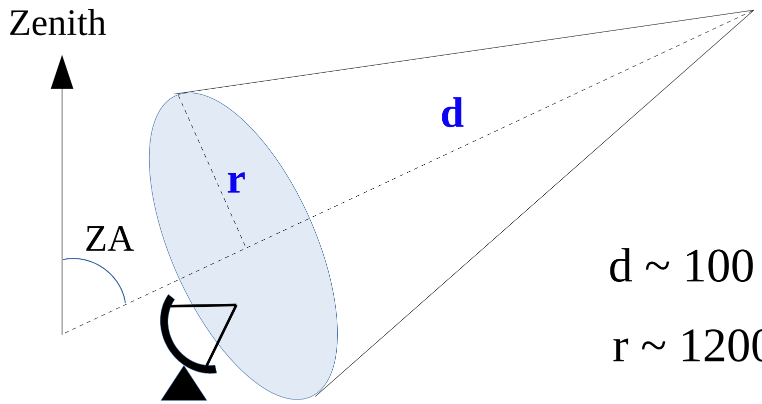
d ~ 10 km /cos(ZA)

ZA > 60^0-70^0
shower distance d > 50 km

Larger zenith angle observations

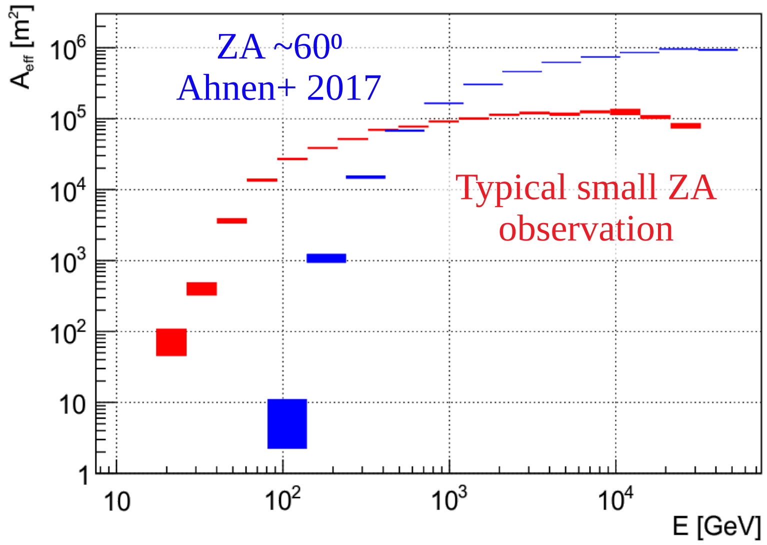
Originally proposed by Konopelko+ ‘99

Observations performed at ZA~60⁰ demonstrate a boost in A_{eff} at high energy end. (e.g. Ahnen+ 2017).

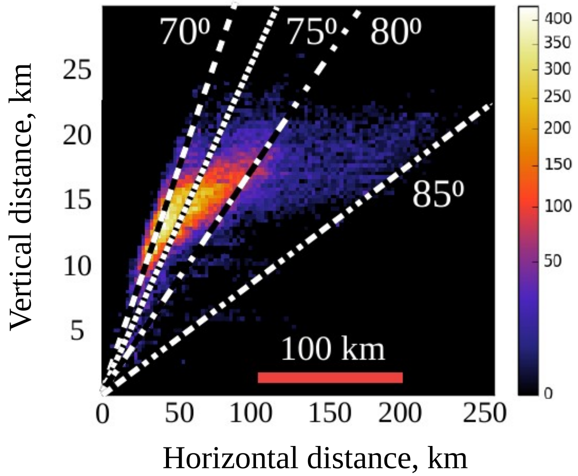


d ~ 100 km

r ~ 1200 m



Cherenkov emission location (MC)

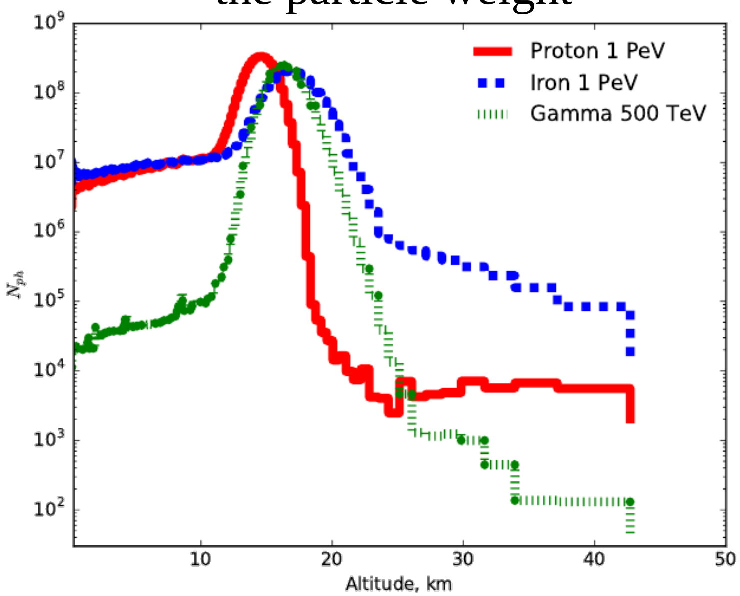


EAS development at large zenith angles

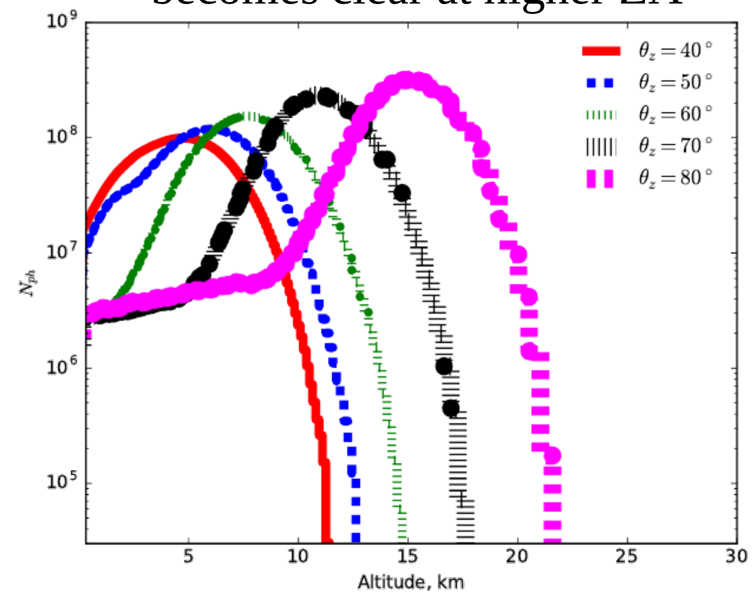
Neronov+ '16

Electrons in EAS cool over ~0.1-1 km path.
Muons require ~20-500 km to loose their energy.

Muon richness increases with the particle weight



Muon contribution develops gradually, becomes clear at higher ZA



High zenith angle observation may enable measurements of muon "tail" also with IACTs.

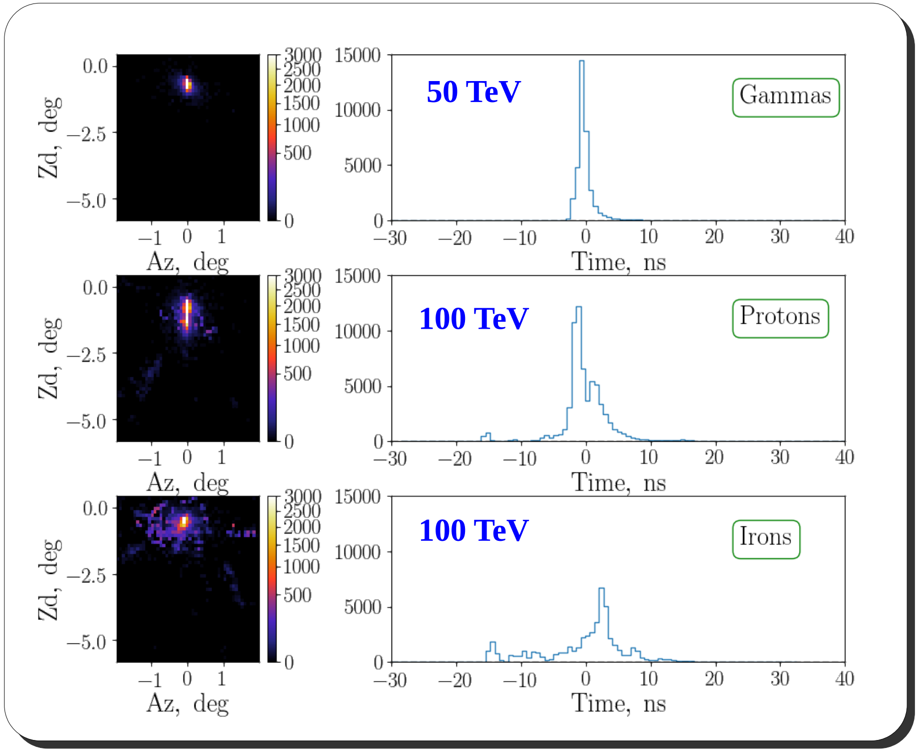
Imaging and timing of LZA EAS

Neronov+ ‘16

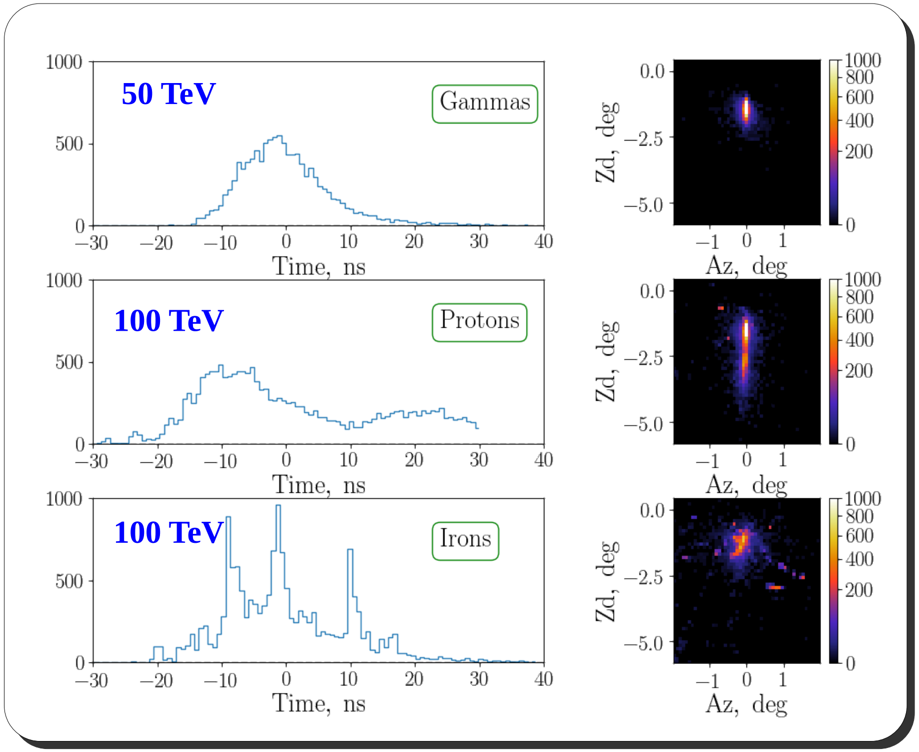
Another profound difference of the high-ZA showers is their longitudinal (temporal) evolution (Neronov+ ‘16)

Impact parameter (@ ZA=70°)

0.5 km



1.0 km



Towards the EAS composition measurement with LZA data

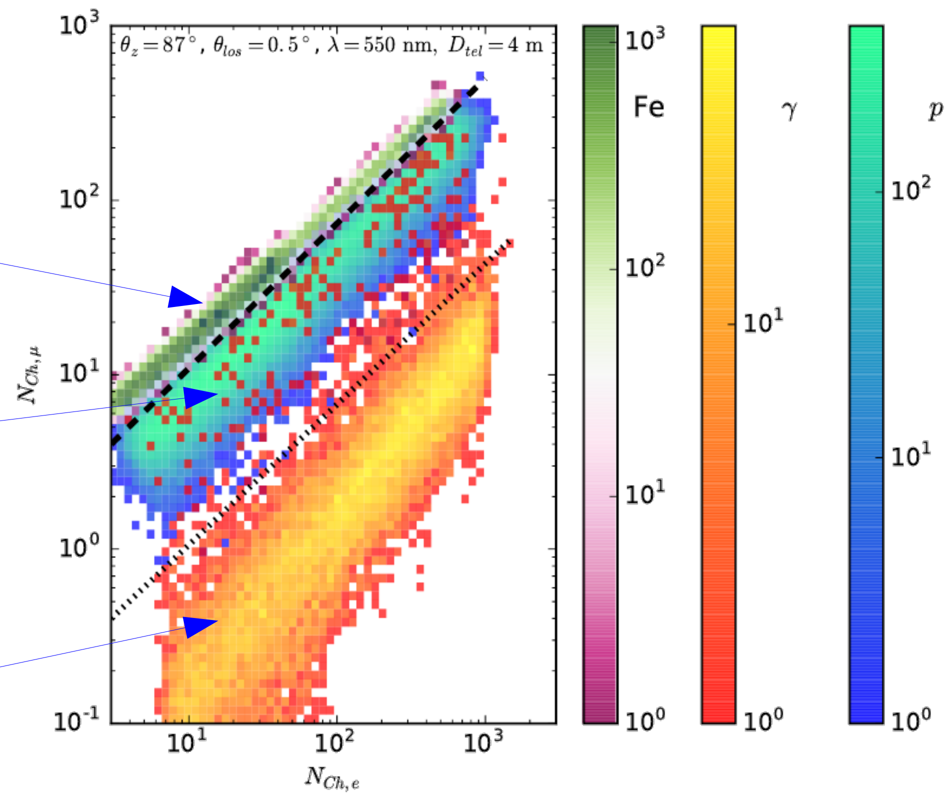
Neronov+ '16

Muons richness → primary's identity

Iron

Protons

Gamma rays



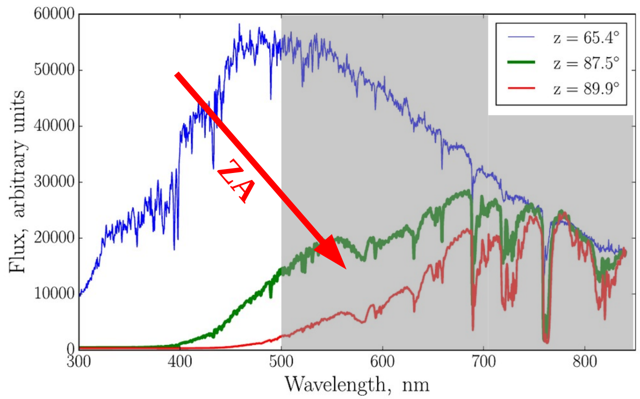
N_μ and N_e can be estimated from data using the extended (leading) and core (delayed) emission

→ Potential boost in g/h separation in sub-PeV energy range

Added complexity of LZA observations

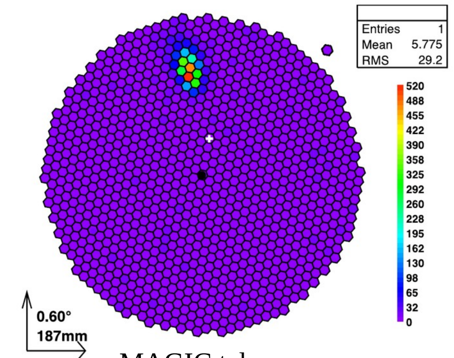
Mirzoyan+ '20

Light absorption



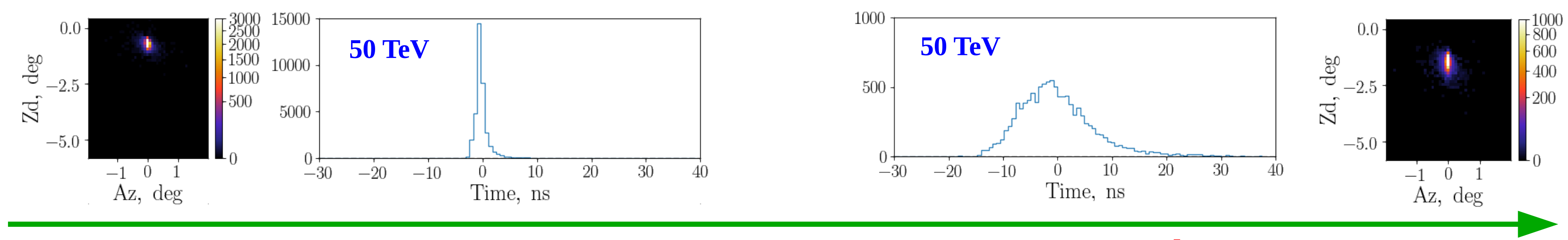
- Larger light absorption:
  higher energy threshold.
- Smaller shower images:
  degradation of parameter reconstruction.
- Longer lasting showers:
  possible issues when recording data.

Smaller image size



MAGIC telescope
E=144 TeV @ZA=78 deg

Longer lasting showers from larger impact distances



0.5 km

1.0 km

Impact distance

Neronov+ '16

MAGIC telescope system

Stereoscopic system of 2 IACTs, located at La Palma, Spain

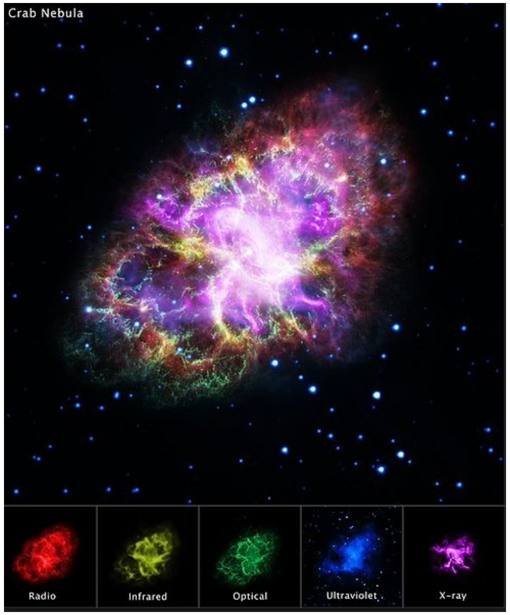
Telescopes: two D=17m
Site: La Palma (Canary Islands)
Energy range: 30 GeV – above 50 TeV
Resolution: 0.07º-0.14º (0.1-1 TeV)
Sensitivity: 0.6% Crab units (integral)
Field of view: 3.5 deg

Observes all kinds of sources:
AGNs, GRBs, novae, gamma-ray binaries, pulsars and pulsar wind nebulae etc.

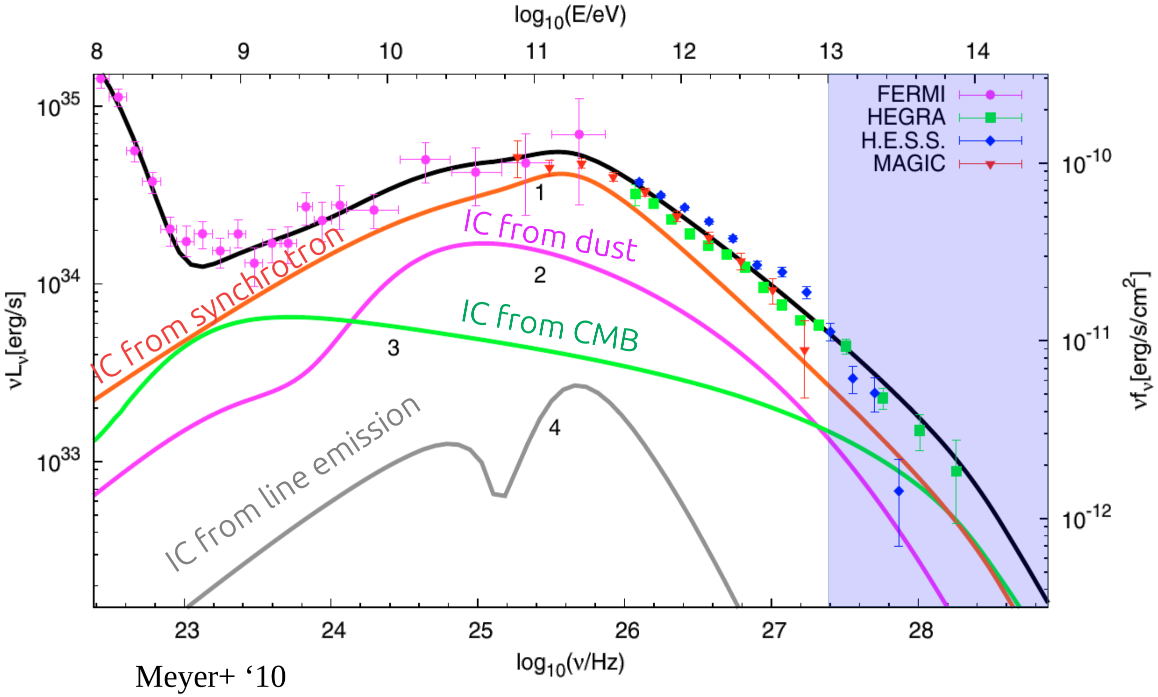
LZA observations of selected sources, including Crab Nebula and Galactic Center

Crab Nebula: leptonic PeVatron

Nearby (d ~ 2 kpc), young (age ~ 1ky), powerful (L_{sd}~5x10^{38} ergs/s), magnetized (B~100 μG)



Credit: NASA, STScI



Meyer+ ‘10

Multiple electron populations argued
(Atoyan & Aharonian ‘96).
VHE emission is extended (H.E.S.S. Collaboration ‘20)
PeV photons detected (LHASSO Collaboration ‘21)

GeV-TeV emission is produced by several competing mechanisms.
Multiple electron populations (“radio”, “wind”, possibly “flare”).

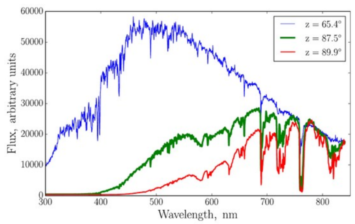
Hadronic contribution in >10 TeV range?
(Atoyan & Aharonian ‘96, Bednarek & Protheroe ‘97, Amato+ ‘03)

MAGIC LZA observations of Crab Nebula

MAGIC Collaboration ‘20
Mirzoyan+ ‘20

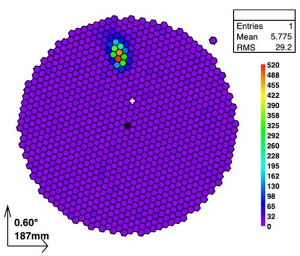
Crab Nebula – VHE «standard candle»

Thorough VLZA measurements systematics study

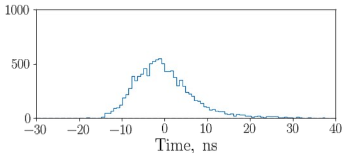


Strong light absorption:

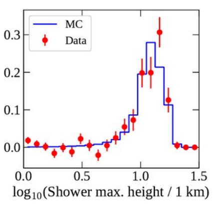
- optical CCD cameras to measure star brightness within FoV
- dedicated VLZA data correction procedure for transmission
- adaptive data cuts



Reduced EAS image size: defocused mirrors: worse reconstruction, but enabled triggering on smaller EAS images



Increased EAS duration: reduced the DAQ sampling speed to record showers longer



Reconstruction: dedicated MC accounting for the Earth curvature, two independent reconstruction techniques

...and many more checks (pointing, MC to data mismatch, lidar, Az dependence)

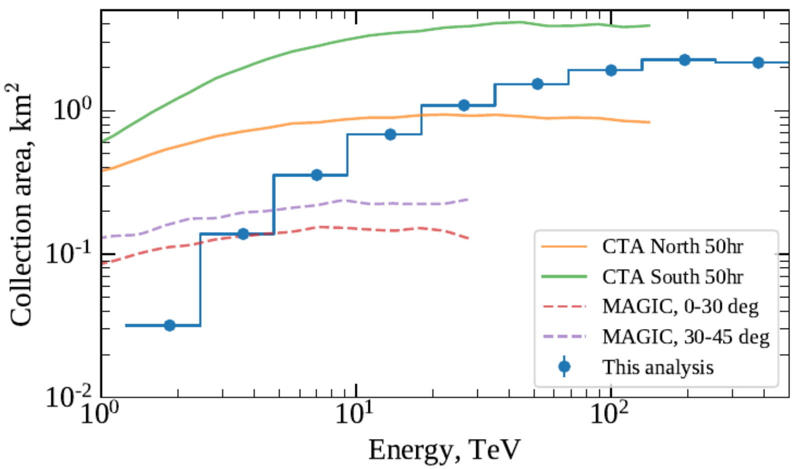
MAGIC LZA detection of Crab Nebula @ 100 TeV

MAGIC Collaboration '20

First LZA observations in the range ZA=70-80⁰

Addressing the associated systematics:
atmosphere transmission, defocused imaging, small image size

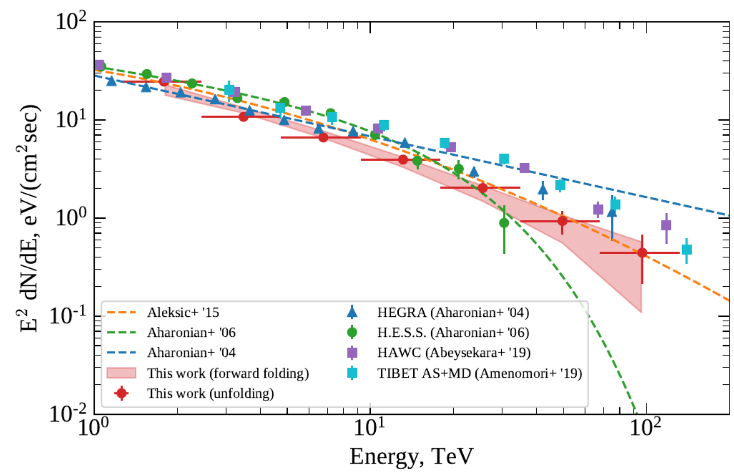
Reconstructed collection area



A_{eff} @100 TeV is comparable to CTA predictions (at 20° zenith angle).

http://www.cta-observatory.org/science/cta-performance/ (version prod3b-v1)

Reconstructed SED

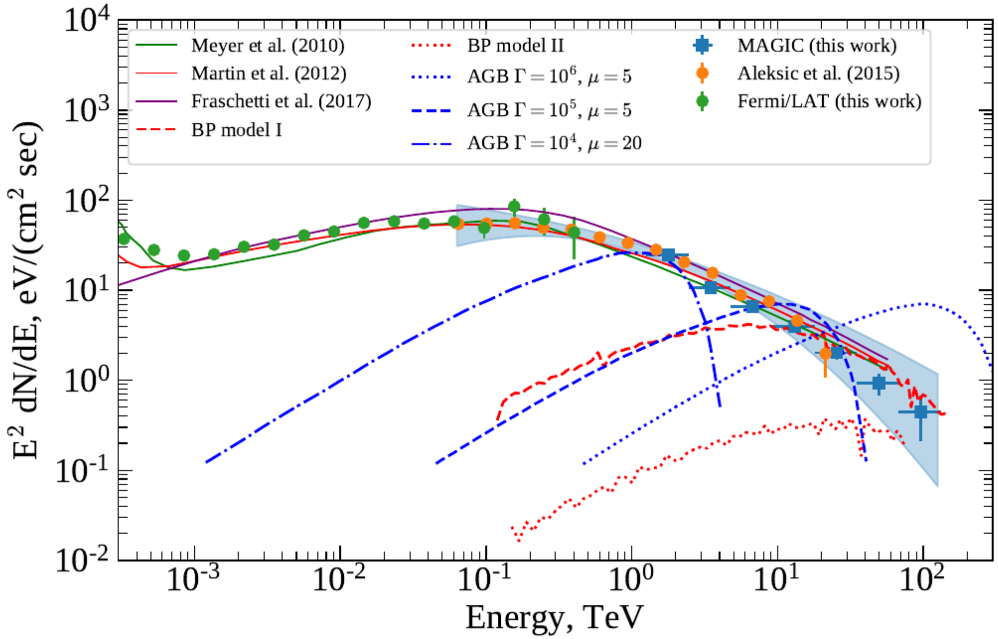


- larger E_{max} : 30 TeV → 100 TeV (compared to Aleksic+ '15)
- 8x shorter observation time compared to earlier HEGRA measurements (Aharonian+ '04)

"Pathfinder" for future CTA observations

Constraining the hadronic contribution

MAGIC Collaboration '20



Accelerated electrons ≡ accelerated protons (likely)

Nuclei can be (1) ripped from the pulsar surface, (2) accelerated on shock wave(s) resulting from the wind or (3) accelerated during the magnetic re-connection events.

Interactions may be ~10 fold intensified in the nebula filaments.

Tested models from Bednarek & Protheroe (1997) and Amato+ (2003)

→ No obvious contribution from hadronic component.

LHASSO measurements should be even more constraining.

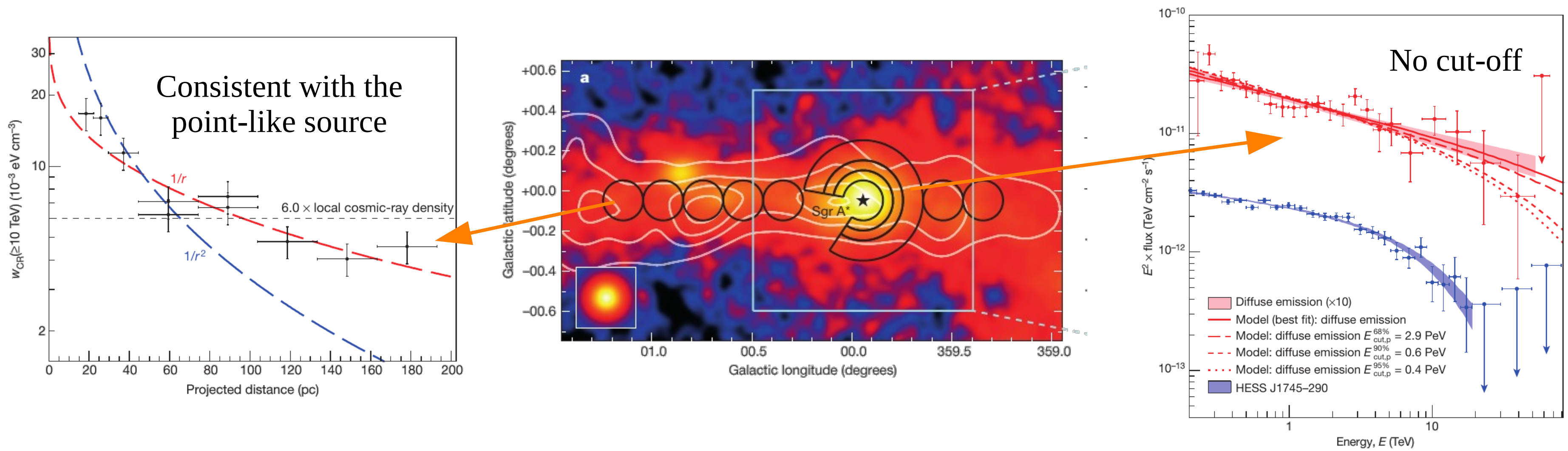
Demonstration of the LZA observations potential in extending the IACT energy range.

Galactic Center PeVatron

Abramowski+ ‘16

Possible PeVatron detected by H.E.S.S. in the Galactic center, likely associated with the SMBH.

Alternative explanations proposed (Gaggero+ ‘17) underline the importance of the large scale CR sea for the firm interpretation.



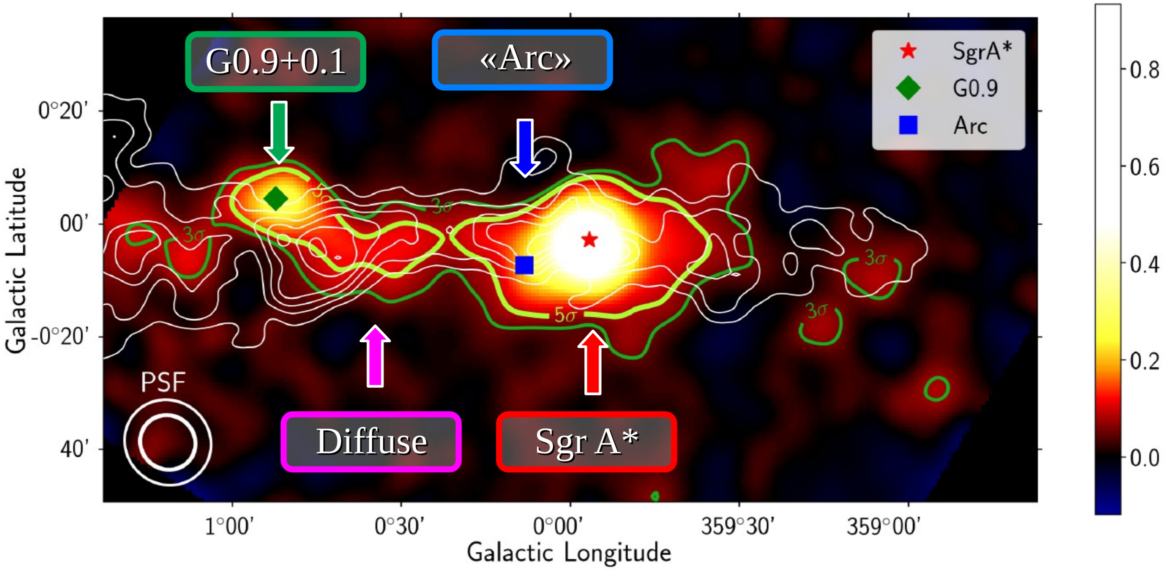
However, one of the main ingredients is the gas distribution in the central ~200 pc from the black hole.

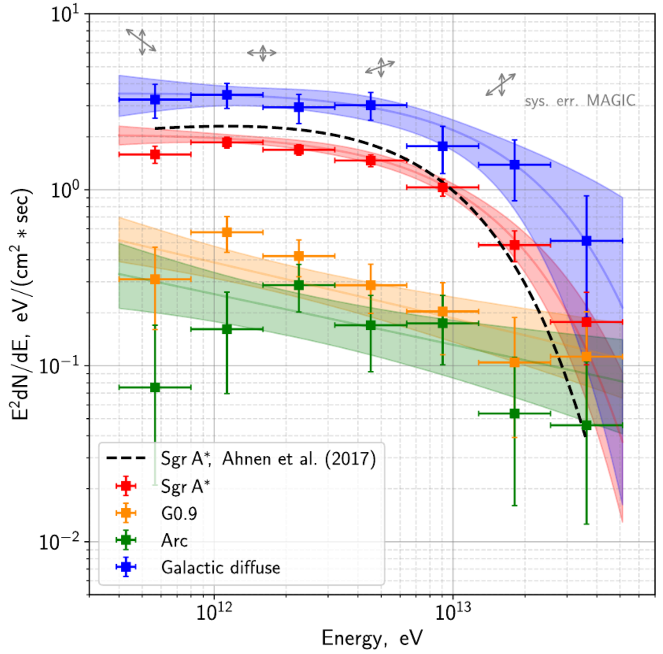
Galactic Center – VLZA source for MAGIC, and we benefit from the boost in A_{eff} to compensate for the smaller obs. time compared to H.E.S.S.

MAGIC LZA view of Gal. Center region

Ahnen+ ‘17
MAGIC Collaboration ‘20

More than 100 hr of observations up to 2017 (and there are more)
3D analysis (spatial + energy; Vovk+ ‘18)





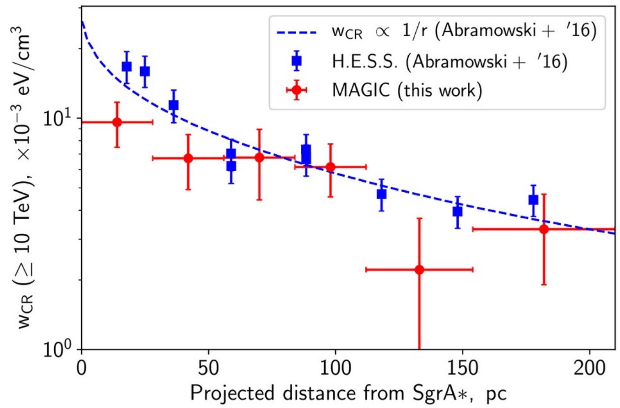
Diffuse emission detected at 17σ, multiple other point-like sources > 1 TeV

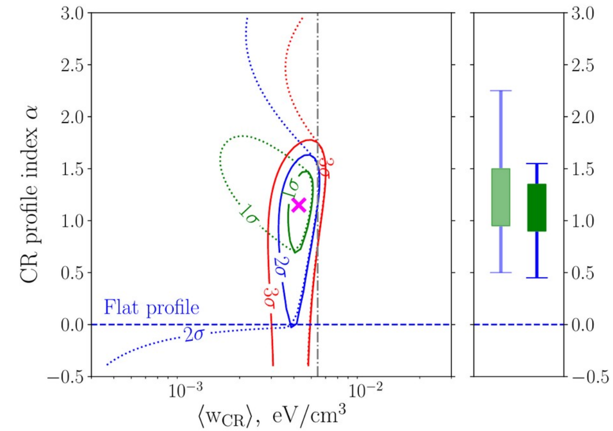
The diffuse component spectrum is best described with power law with cut-off.
The spectrum of the “Arc” (Archer+ ‘16, Ahnen+ ‘17, Abdalla+ ‘17) is consistent with Γ~2.2 power law.

MAGIC LZA view of Gal. Center region

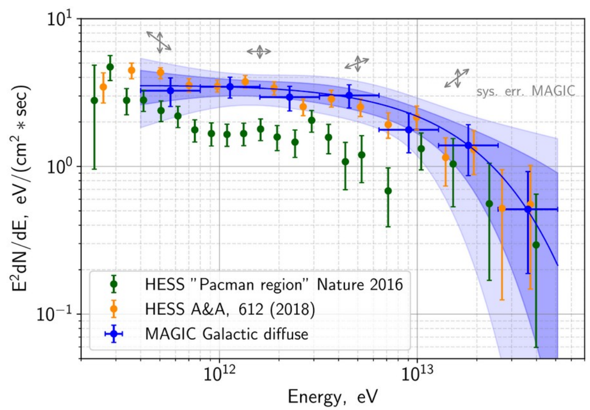
MAGIC Collaboration ‘20

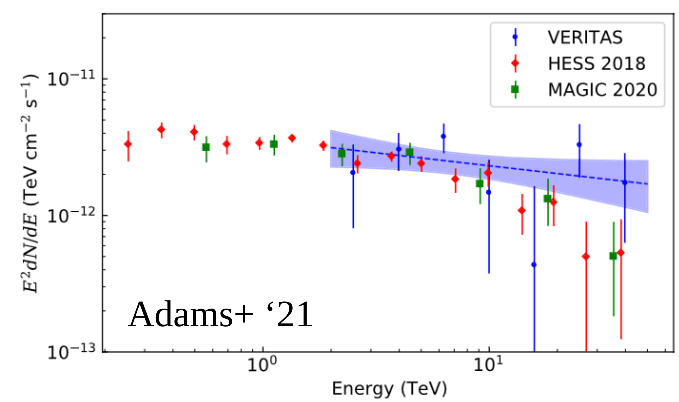
- similar 1/r CR scaling as found by H.E.S.S.
- develop a 3D model of the gas around GC:
  - confirm 1/r scaling is compatible with the data
  - strong systematics: need more accurate gas distribution measurements to reliably measure CR profile





- Diffuse emission spectrum compatible with H.E.S.S. and VERITAS results
- indication for a cut off at $E_{cut} = 18^{+59}_{-10}$ TeV





Would be interesting to revisit the region with larger exposure and joining all IACTs together (also CTA/LST-1)

Summary

Large zenith angle observations – a challenging, but promising novel way to perform >100 TeV observations with IACTs.

It's been a big effort in MAGIC collaboration to make them work – we've learned a lot about merits and limitations (small pixels, longer read-out, auxiliary atmosphere monitoring, reconstruction adjustments).

MAGIC employed LZA mode to observe several possible PeVatrons and Crab Nebula + Galactic Center analysis demonstrate we can get competitive results. We have not yet explored the full potential of VLZA observations yet, though.

Expect to get more of interesting results from further collaboration with CTA/LST(s).