Highlights of VHE gamma-ray astronomy

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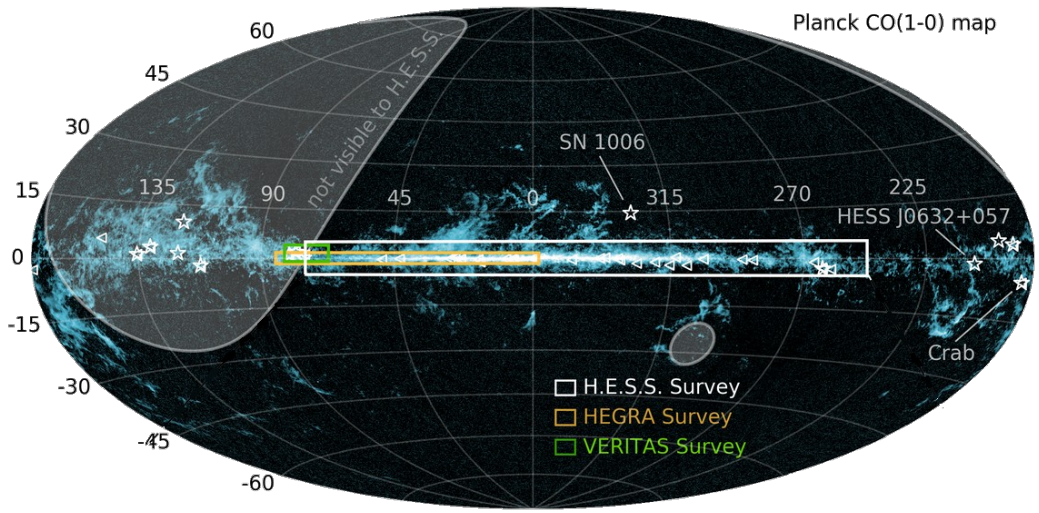
Main VHE instruments

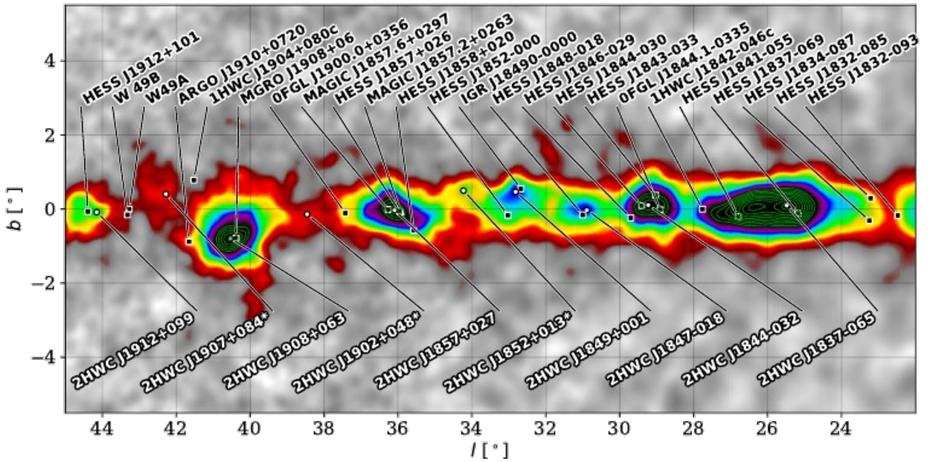
Galactic sources

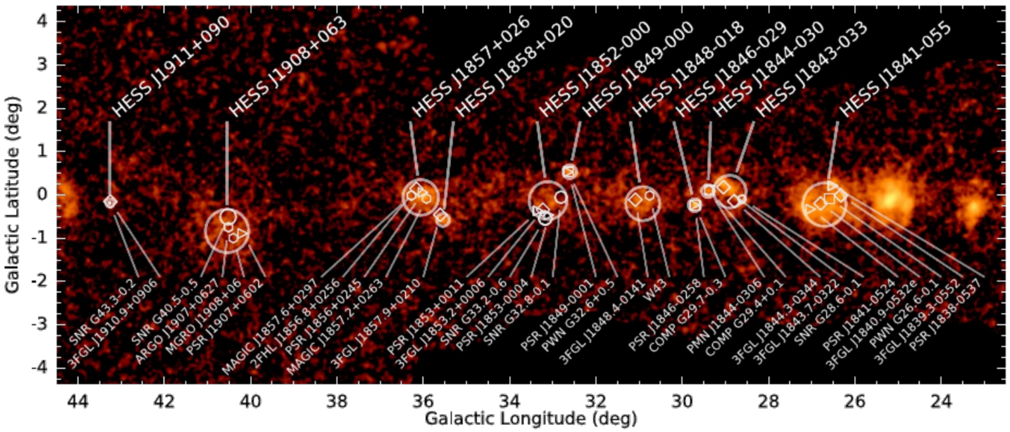
VHE sky surveys



HAWK Collaboration (2017) – 3 years of observations
H.E.S.S. Collaboration (2018) – 9 years of observations
VERITAS Collaboration (2018)

Focus on the galactic plane; a number of new sources revealed.

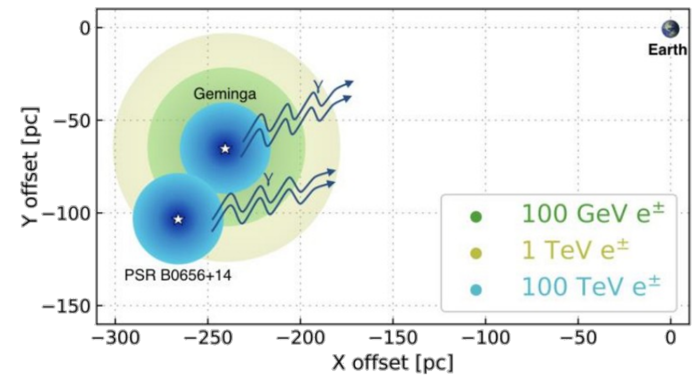


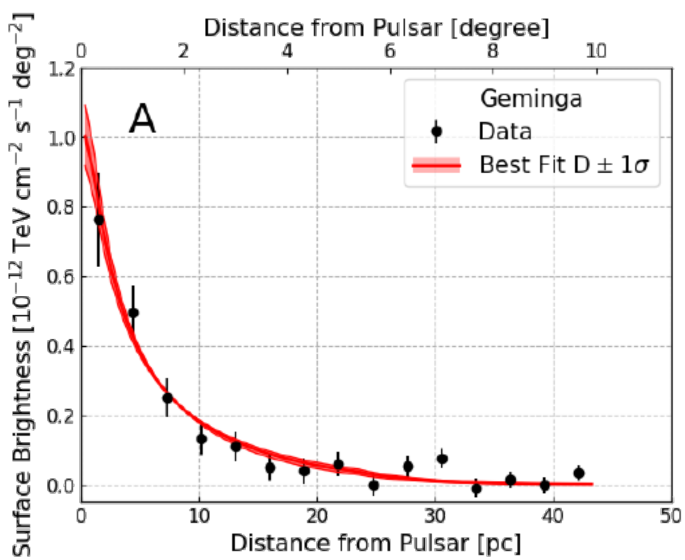


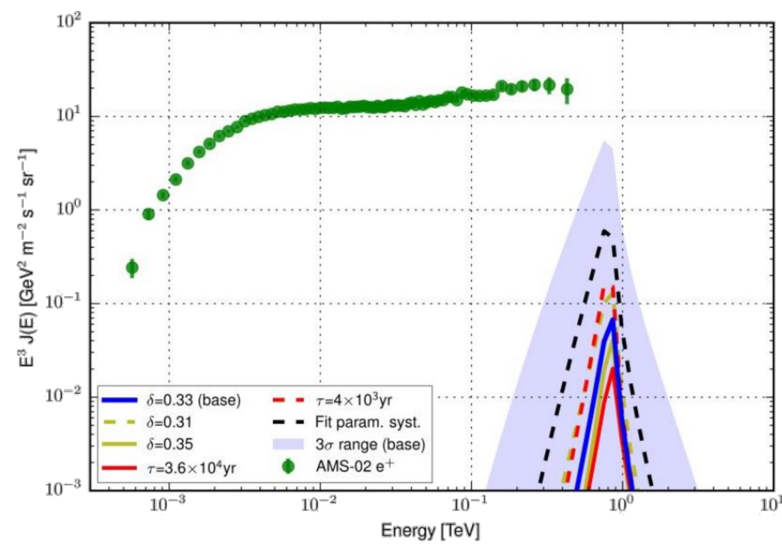
CR positron excess origin: constrains from local pulsar wind nebulae

PAMELA positron excess (Adriani+ ‘09): a local source of leptons?

HAWK observes extended leptonic halos from two local pulsars.
Estimated flux is not sufficient to explain the PAMELA excess







HAWC Collaboration, Science (2017)

CR iron spectrum measurement in the 20-500 TeV range

CR composition from 1 TeV to 100 EeV: light → heavy → light transitions.

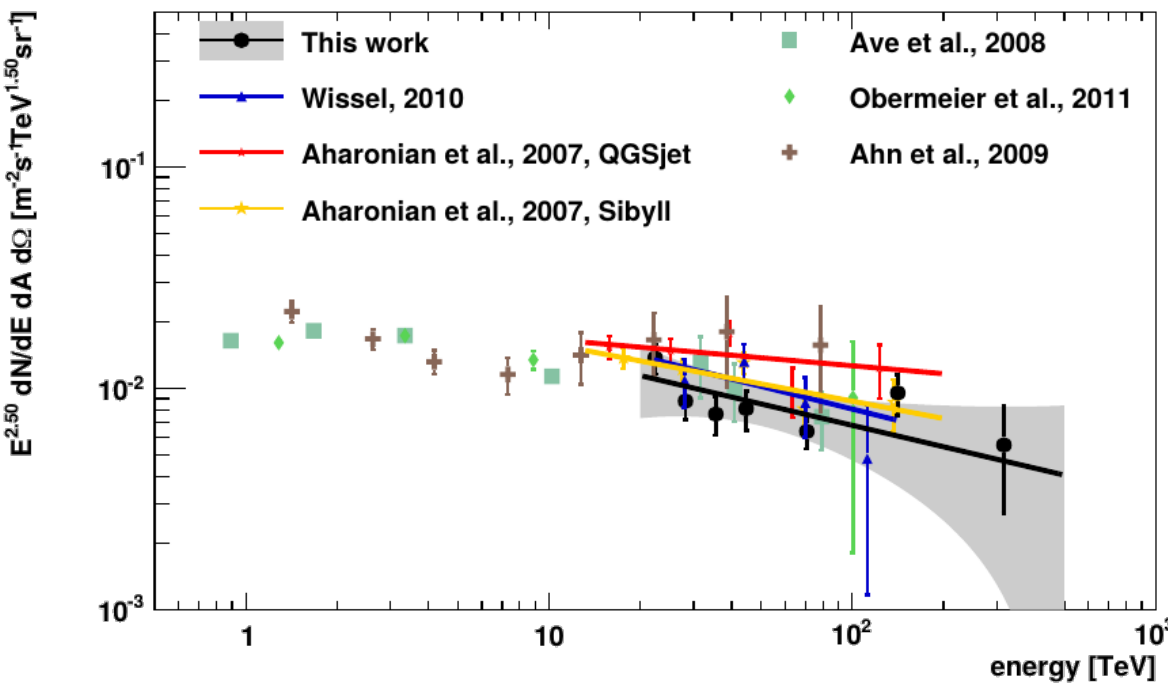
At ~PeV energies measurements are possible through observations of Extensive Air Showers (EAS).
Also ~PeV:
- possible charge-dependent cut-offs of the Galactic CR population;
- possible transition to extraglactic CR population.

Advances in analysis: composition measurements without muon detectors.

Recent VERITAS results extends IACT measurement to 0.5 PeV.

No indication for hardening or cut-off as of now, though senstivity is limited.

A pathfinder for future measurements with CTA.



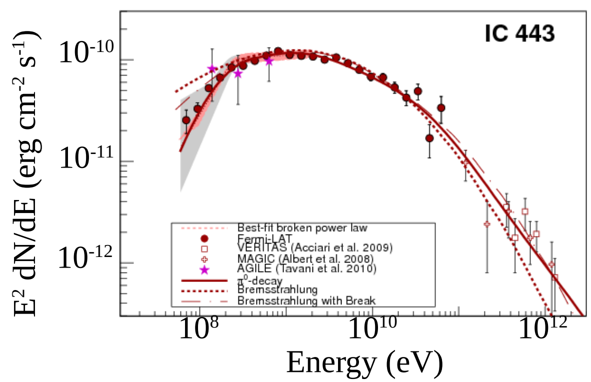
VERITAS Collaboration (2018)

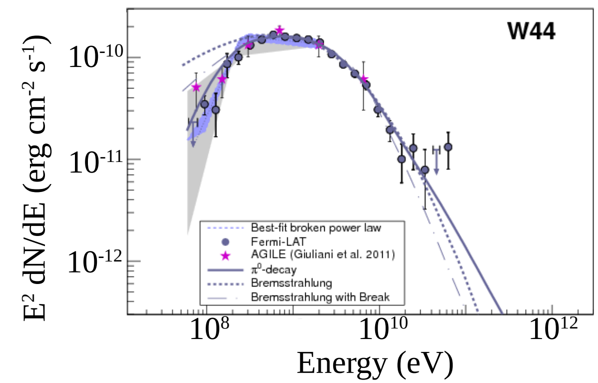
Galactic PeVatrons

Sources of the galactic cosmic rays are not known.
But there are already first identifications of cosmic ray accelerators.

Supernovae remnants were found accelerating (low-energy) protons

Main argument: spectrum at low energies

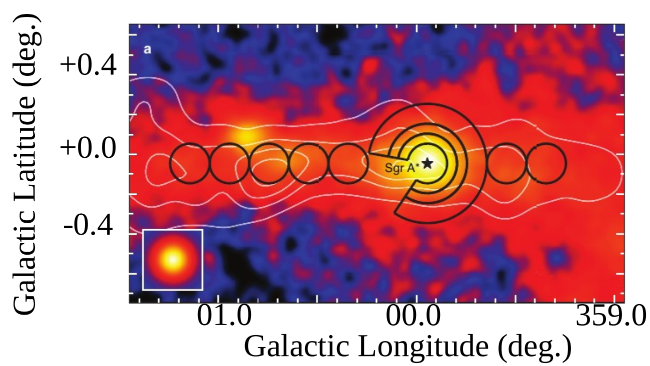


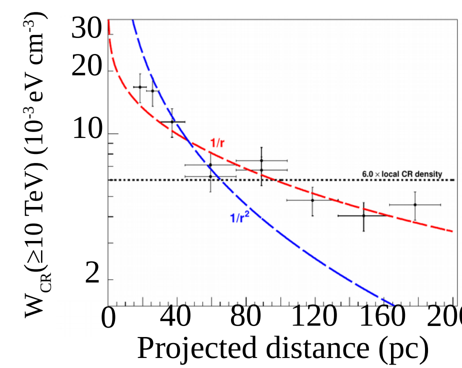


Fermi-LAT collaboration '13

Cosmic ray acceleration up to PeV energies in the Galactic Center

Main argument: morphology of emission





H.E.S.S. collaboration '16

Searching for sources of Galactic CR: Cas A supernova remnant

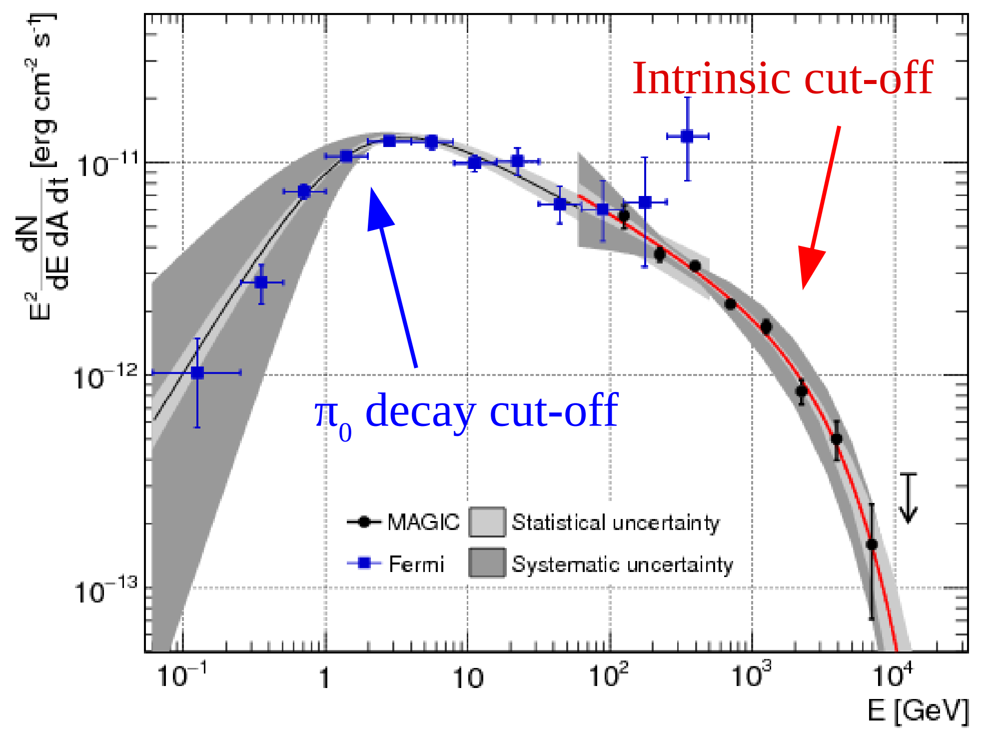
Are supernovae remants PeVatrons?

Cas A – young (~400 years old) and well-studied SNR.
Young SNRs were expected to be able to provide PeV cosmic rays.

Analysis of the deep MAGIC observations suggests the γ-ray emission is mostly hadronic.
But reveals a high-energy cut-off at ~0.01 PeV.

→ Challenging the assumption that young SNRs are PeVatrons

Cas A: MAGIC + Fermi/LAT view



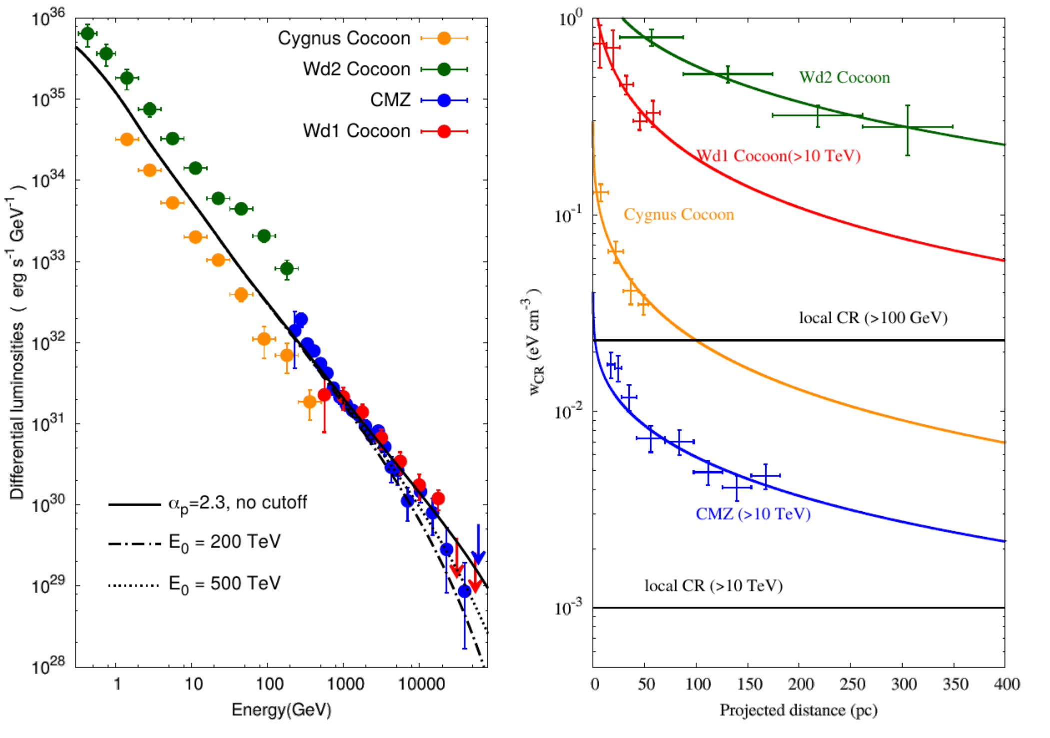
MAGIC Collaboration (2017)

Cosmic ray acceleration in massive stellar clusters

Massive stellar clusters seem to have the same w_{CR}~1/r cosmic ray density profile.

Inferred CR acceleration efficiency is 1-10% – lower than assumed for SNRs.

Measured spectra extend to 10 TeV and beyond (for SNRs its not established + cut-offs are observed).



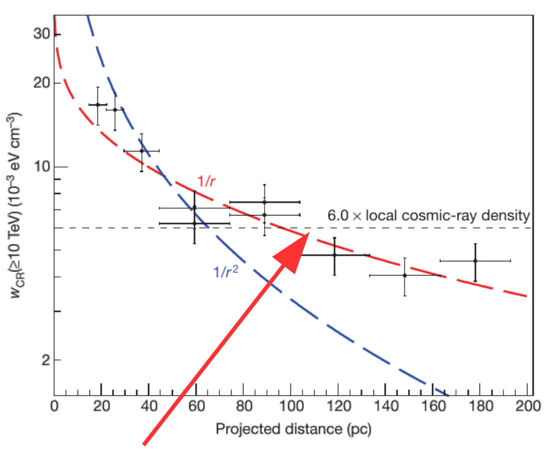
→ Viable alternative to CR acceleration in SNRs

Aharonian+, arXiv:1804.02331

A PeVatron in the Galactic Center

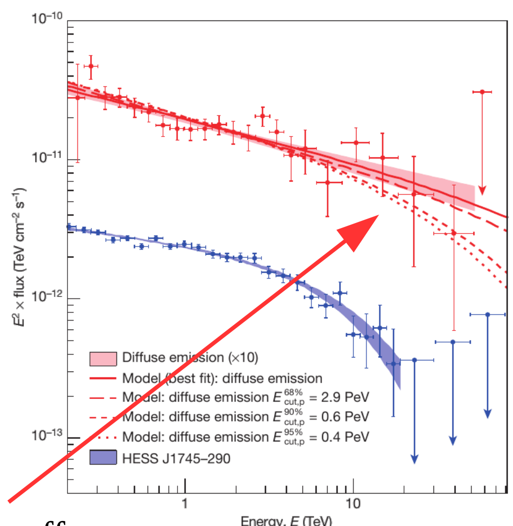
Recently the interest to the Galactic Center has increased with the discovery of a potential PeVatron there, likely associated with the SMBH.

H.E.S.S. (Abramowski+ ‘16)



Consistent with the point-like source

No cut-off



If confirmed, this provides an important milestone to the
1) identification of the galactic pevatrons
2) investigation of the CR propagation in the Galaxy

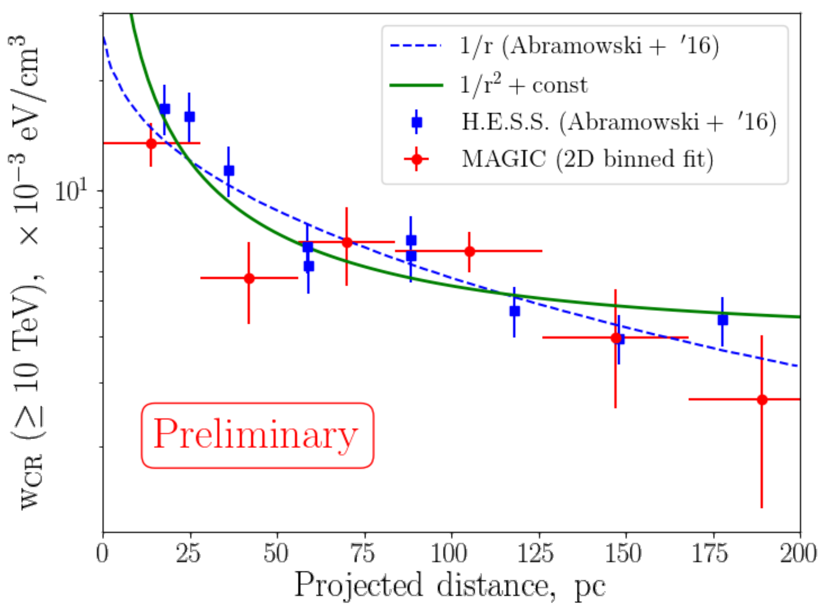
Alternative explanations proposed (Gaggero+ ‘17) underline the importance of the large scale CR “sea” for the firm interpretation.

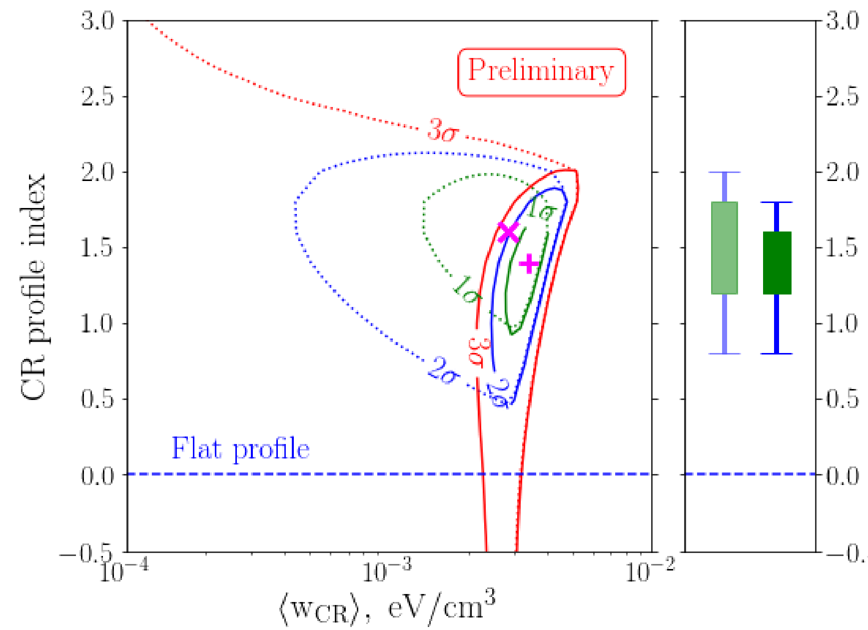
However, one of the main ingredients is the gas distribution in the central ~200 pc from the black hole.

And it is particularly difficult to get.

A PeVatron in the Galactic Center

Recent MAGIC re-observations also find a similar w~1/r CR profile, confirming H.E.S.S. results





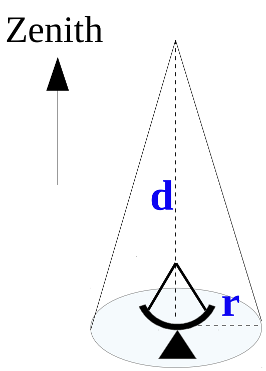
Still, the poorly know gas (target material) distribution close to the Gal. Center questions the $w \sim r^{-1}$ form – other indices are also possible.

→ More accurate radio measurements are needed to support γ-ray data.

A PeVatron hunt: large zenith angle observations

Vertical observations

typical for IACTs

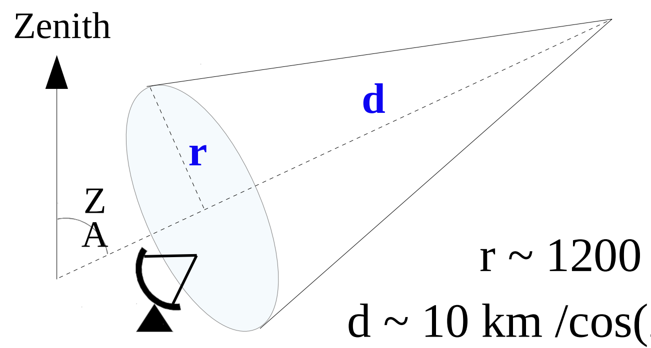


d ~ 10 km

r ~ 120 m

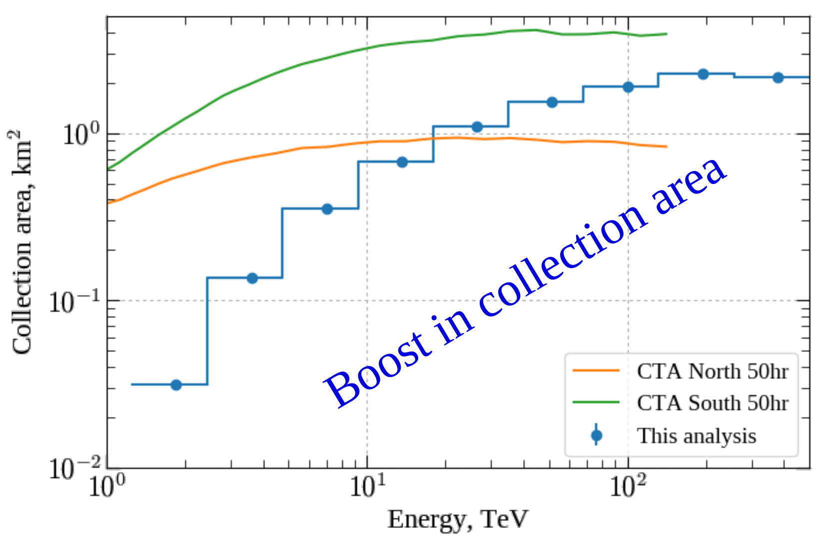
Large zenith angle observations

proposed



r ~ 1200 m

d ~ 10 km /cos(ZA) ~ 100 km

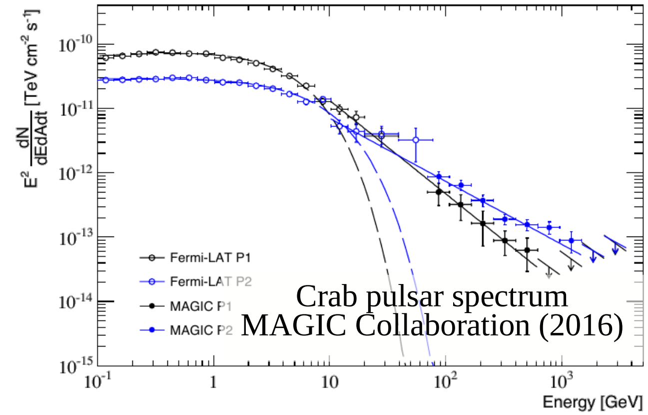


Boost in maximal energy

Lowering the energy threshold: detecting pulsars with IACTs

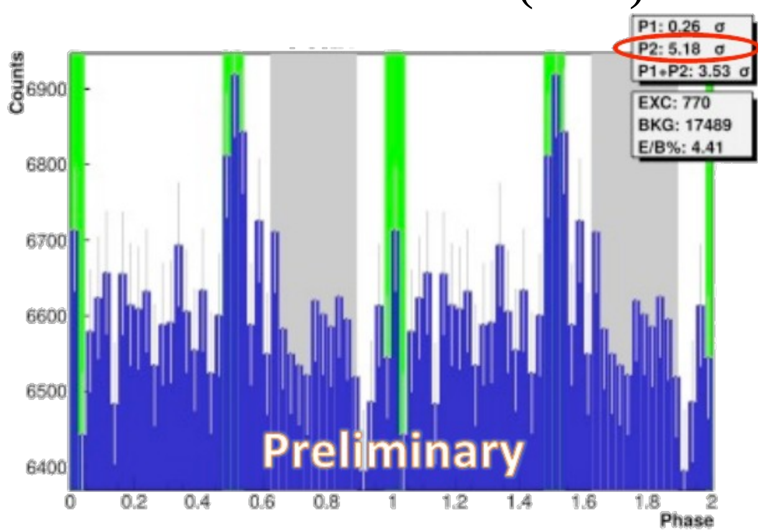
Pulsars (rotating neutron stars) typically have cut-off spectra, quenching at too low energies.

Only 3 pulsars are detected with IACTs!
(And 2 of them were detected recently)

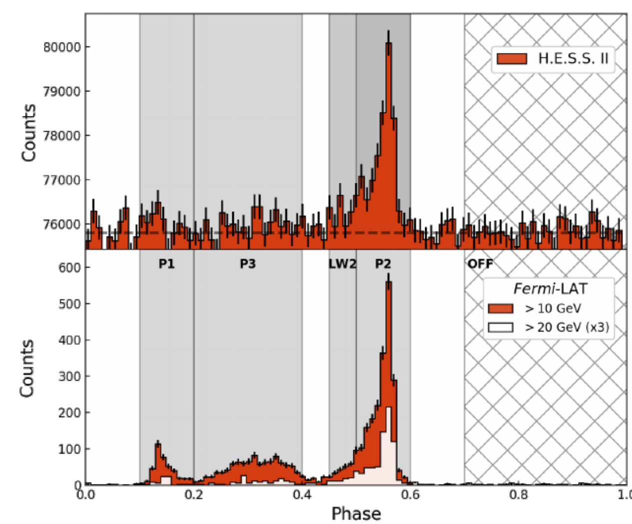


Crab pulsar spectrum
MAGIC Collaboration (2016)

Geminga pulsar
MAGIC Collaboration (2018)



Vela pulsar
H.E.S.S. Collaboration (2018)

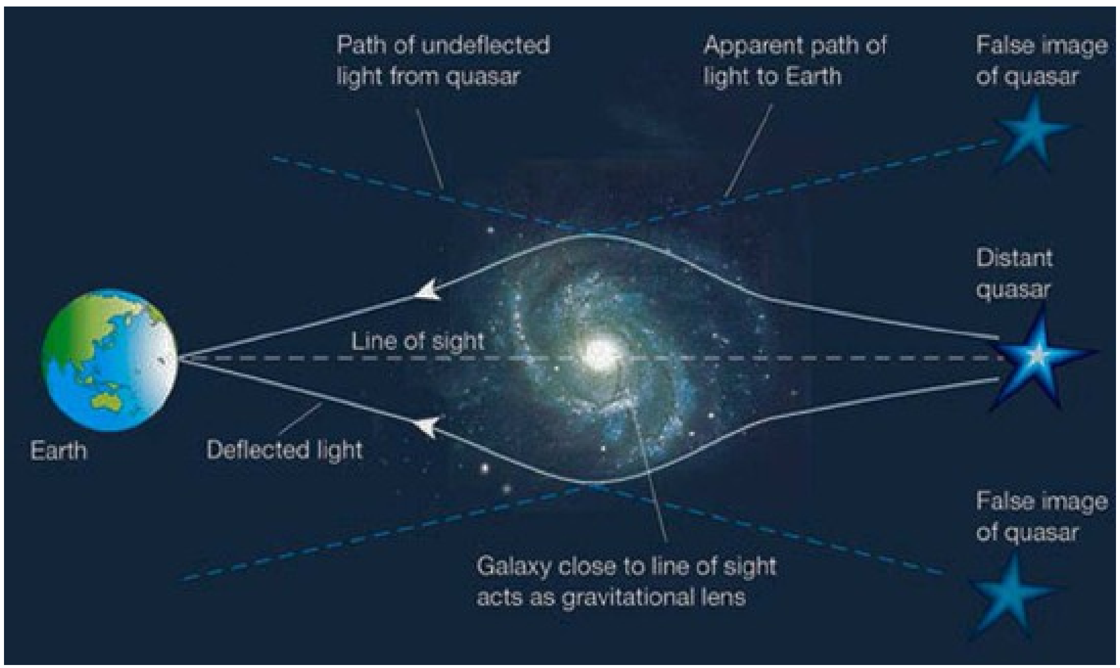


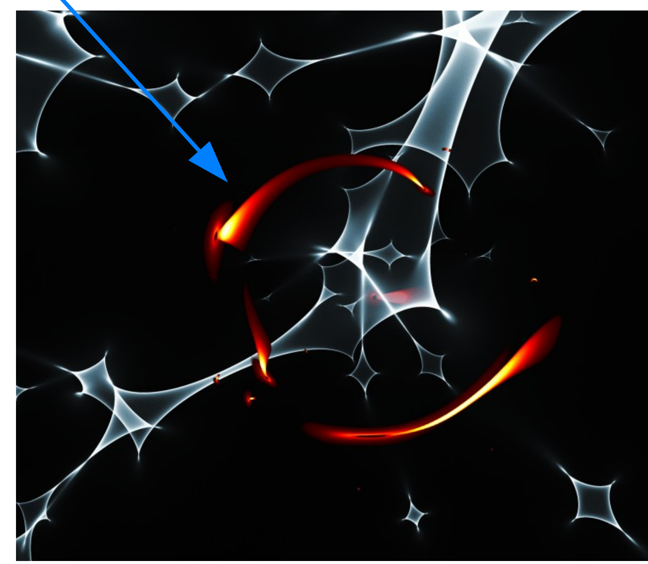
Extragalactic sources

Gravitational (micro)lensing

Gravitational lensing – bending of the light due to the gravity of the intervening galaxy.

→ Image deformation / flux magnification

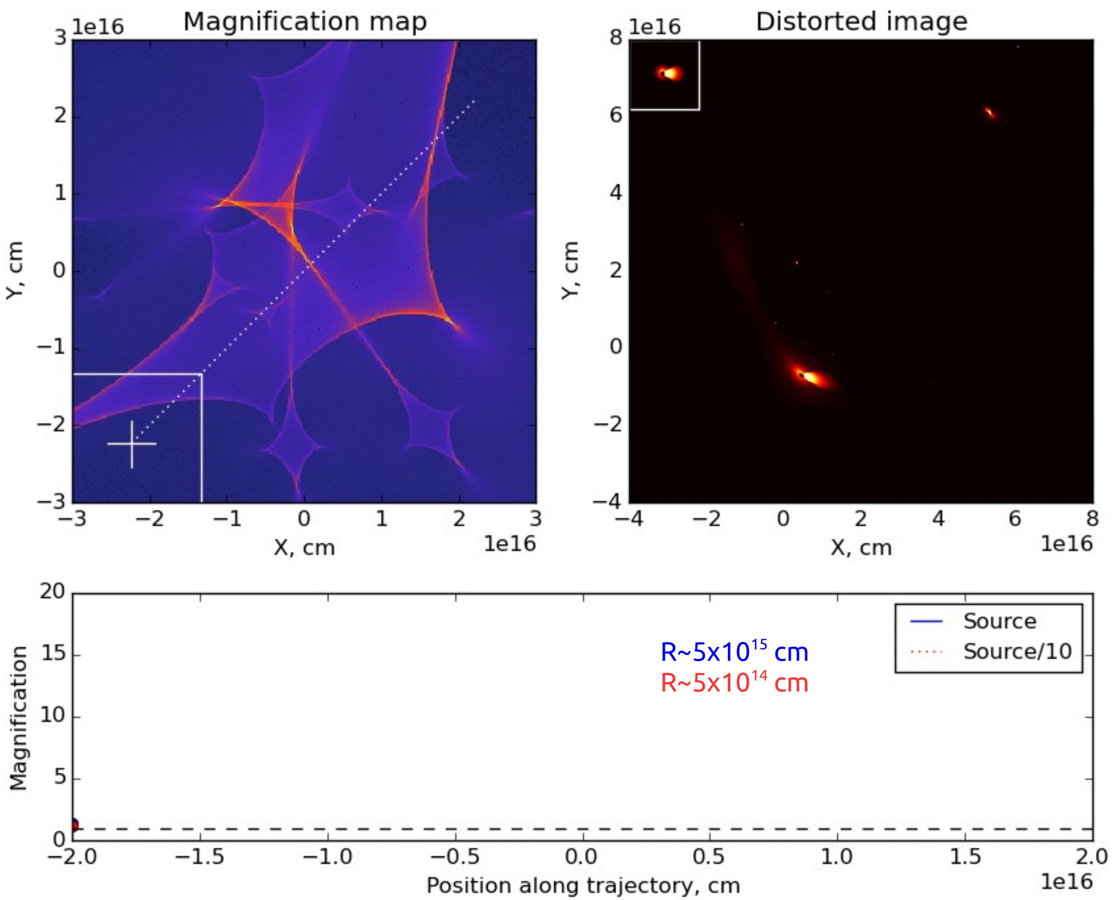




Gravitational microlensing – bending of the light due to the gravity of the stars and small-scale structures in the intervening galaxy.

→ Short-time scale flux magnification of small (!) objects only

Gravitational (micro)lensing



The lens and the source are moving with respect to each other at v~1000 km/s, leading to a constant change in magnification.

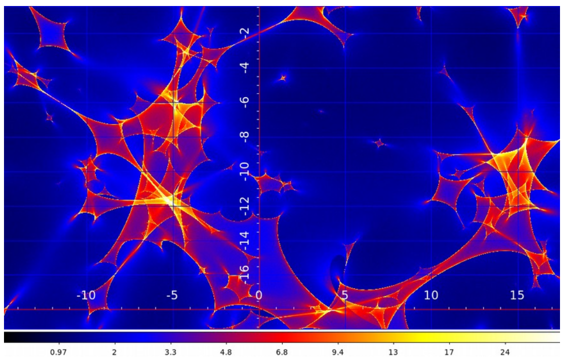
Magnification amplitude and duration depends on the source size:

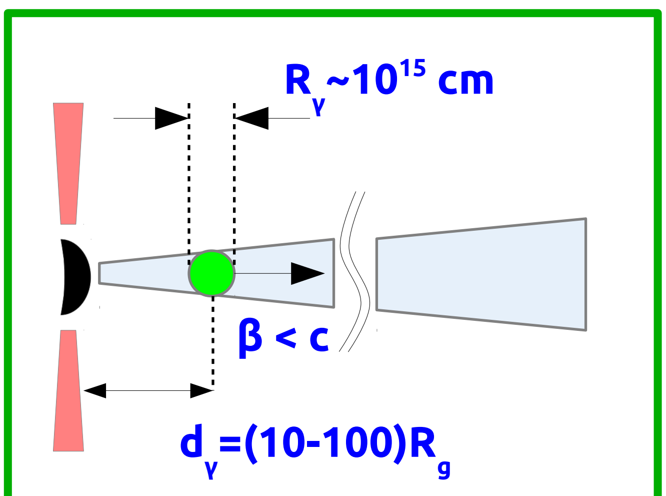
$$\mu_{micro} \sim (R_E/R)^{0.5} \text{ and } \Delta t = R/v$$

$$\mu \approx 10 \left(\frac{R}{3 \times 10^{14}\, cm} \right)^{-0.5}$$

$$\Delta t \approx 100 \left(\frac{R}{3 \times 10^{14}\, cm} \right) \left(\frac{v}{300\, km/s} \right)^{-1} days$$

Gravitational (micro)lensing





Neronov, Vovk, Malyshev ‘15

Regular observations of microlensing opens a new way to learn about the nature of AGNs:

- ✔ energy dependence of R_γ
- ✔ its variations with time
- ✔ gamma vs radio location estimates

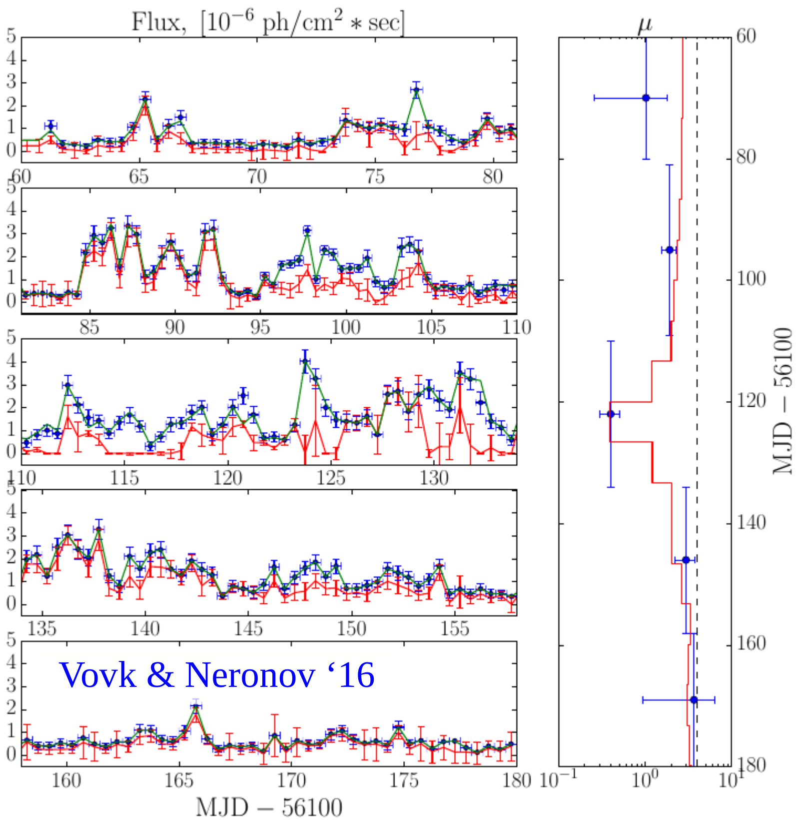
This gives a completely unique opotunity to study the details of the structure of the acceleration sites in AGNs, effectively improving the angular resolution of gamma-ray telescopes by 10^{11} times.

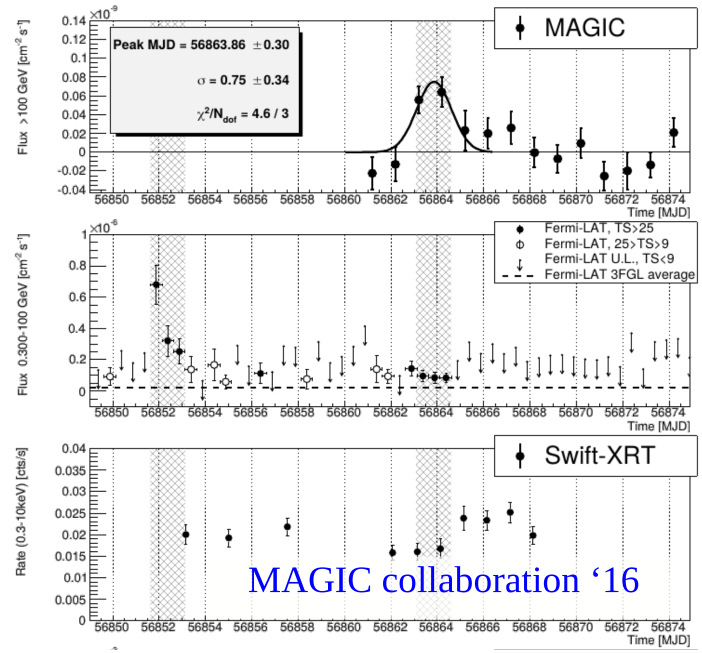
...AGN emission region angular size is that of an ant at the Moon

B0218+358: a bright lensed AGN

Redshift z=0.94 – very distant source (Universe‘s middle-age).
Microlensing is observed at GeV energies, MAGIC data at ~100 GeV may be also indicative of a magnification phenomenon.

Flaring period 1





Flaring period 2

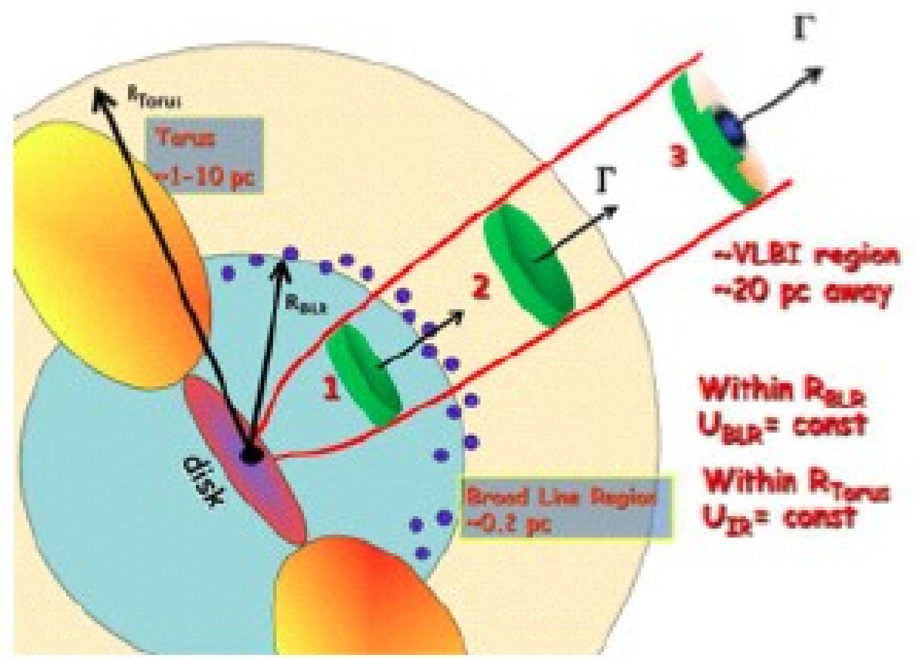
► Very compact emission source, likely close to the central supermassive black hole.

AGN emission region problem

Emission scenario:
close to central engine
OR
outside the so-called
Broad Line Region?

Close to central engine: fast variability most naturally explained, but BLR should absorb the VHE photons.

Outside BLR: where do the seed photons for inverse Compton scattering come from? How to produce the small emission region?



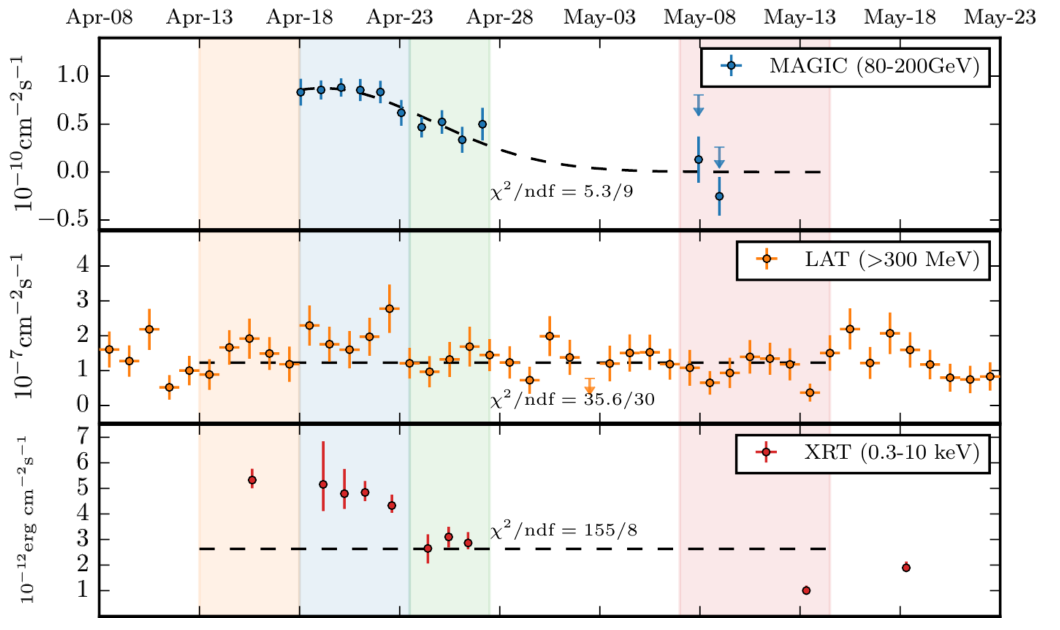
Cartoon of the possible locations of the emitting region

AGN emission region problem

In 2015 MAGIC has observed another record-breaking source (z=0.94) PKS 1441+25 in a campaign with other telescopes.

Delivers unique measurements of Extragalactic Background Light from the middle-age Universe.

Modelling suggests the emission region is outside of BLR (otherwise a strong absorption occurs).



MAGIC Collaboration + (2017)

So...

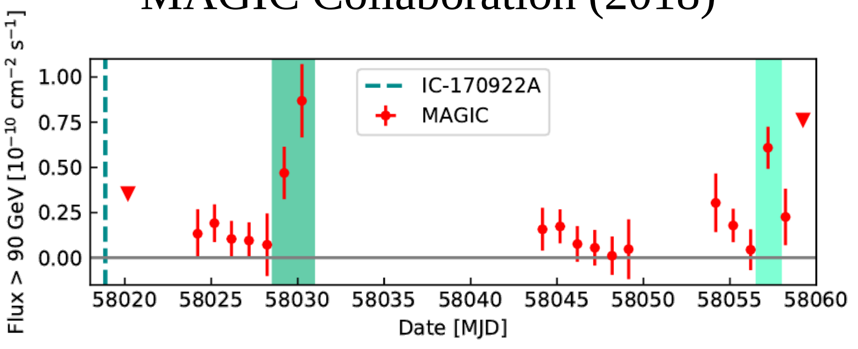
Distant emission region in some sources (absorption constraints) ⟷ Nearby emission region in other sources (microlensing detection)

Seems there is no common location

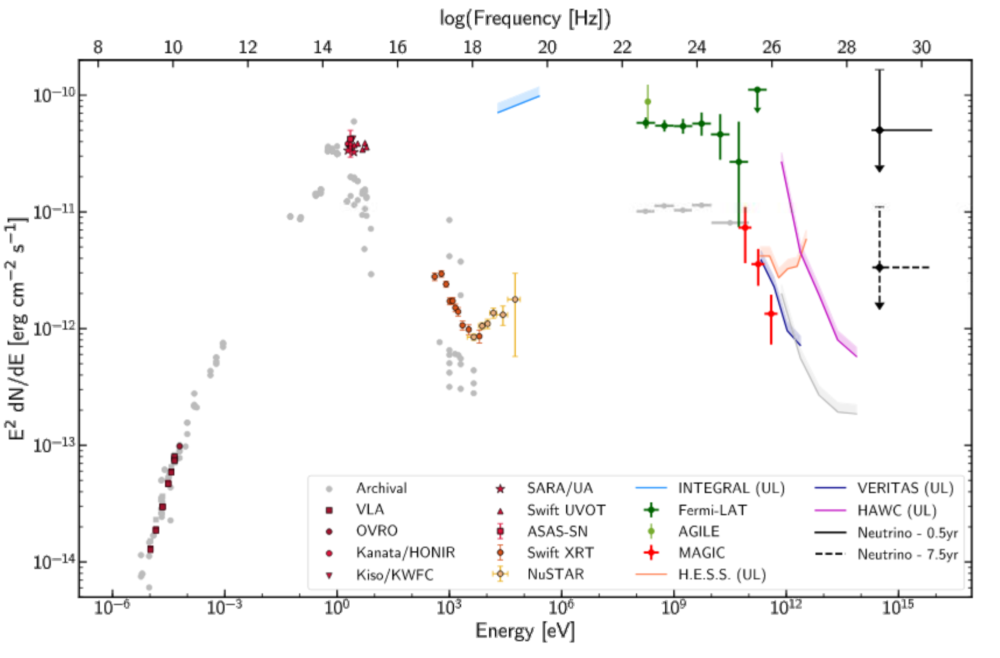
CR acceleration in AGNs

MAGIC has detected enhanced VHE emission from an AGN TXS 0506+056 during the IceCube high-energy neutrino detection in September-October 2017

MAGIC Collaboration (2018)



IceCube+Fermi/LAT+MAGIC+…, Science, (2018)



Strong indication that AGNs are responsible at least for a fraction of the observed astrophysical neutrino flux.

Also indicates that AGNs do accelerate CRs to 10^{14}-10^{18} eV.

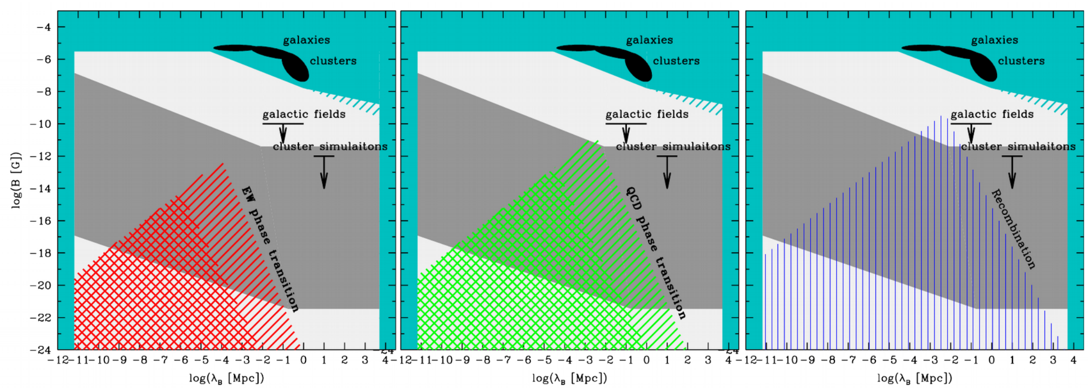
Intergalactic Magnetic Field

Physics beyond the Standard Model → large energies → astrophysics/cosmology

Suitable conditions: Early Universe. → lack of messengers → **IGMF**

Cosmological IGMF may originate from different epochs:

- ✔ QCD phase transitions: $\sim 10^{-12}$
- ✔ electroweak phase transitions: 10^{-11} G
- ✔ recombination: $\sim 10^{-9}$ G

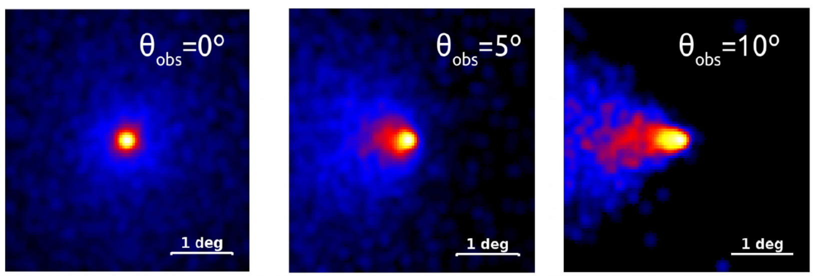


Neronov & Semikoz, '09

Detection of a cosmological IGMF may allow to learn about the conditions well before the recombination

Currently there is no other way to do this

Intergalactic Magnetic Field



"Smoking gun": extended halo

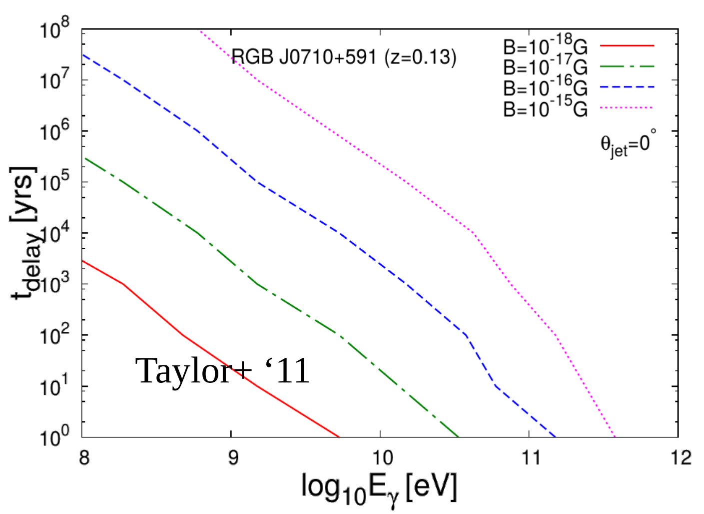
Size and shape depend on IGMF strength **and** source parameters (jet opening and orientation).

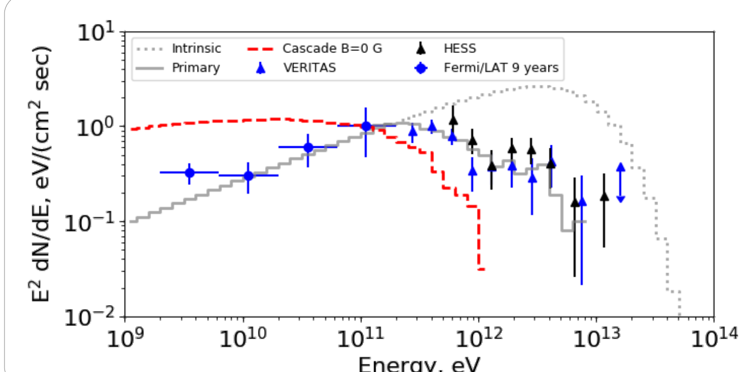
Delayed emission

The delay is set by IGMF, but light curve shape may also depend on the jet parameters.

New spectral components

Depend on IGMF, source spectrum, jet orientation.



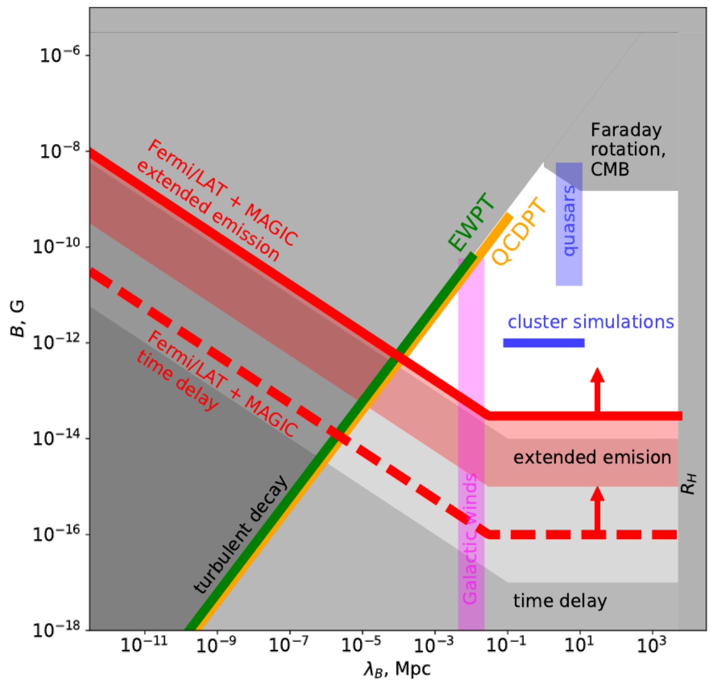


Neronov & Vovk '10, Tavecchio+ '10, Dermer+ ;11, Dolag+ '11, Taylor+ '11, Vovk+ '12, Finke+ '15, Aharonian+ '01, Aleksic+ '10, Abramowski+ '14, Archambault+ '17

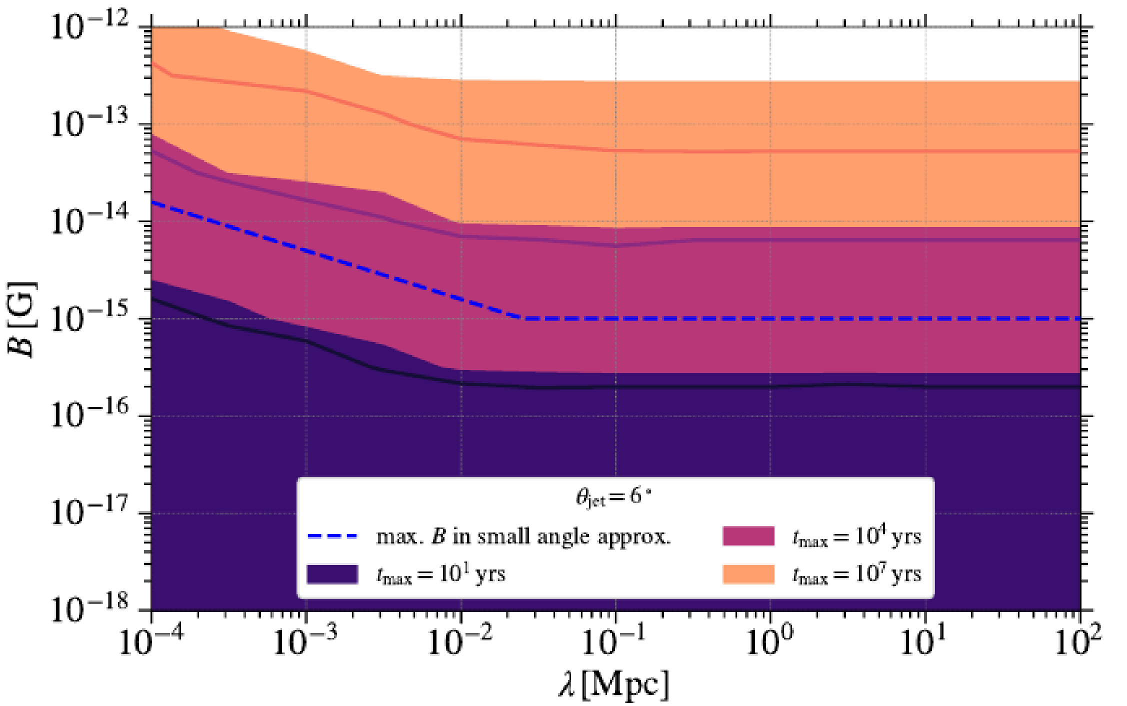
Intergalactic Magnetic Field

Recent analysis of gamma-ray data strongly constrain the IGMF parameter space

MAGIC Collaboration (in prep.)



Fermi/LAT Collaboration & Biteau (2018)



Ongoing debate on the role of plasma instabilities (Chang+ ‘12, Broderick+ ‘12, Miniati & Elyiv ‘12, Schlickeizer+ ‘12, ...)

Summary

VHE astronomy now lives its golden age:
- advances in hardware / analysis,
- many new sources discovered,
- synergies with other wavelengths / domains.

A number of prominent discoveries were not covered here due to lack of time:
- GRB detection with an IACT
- sharp spectral features in AGN gamma-ray emission
- dark matter searches
- gamma-ray binaries
- spatially-resolved supernova remnants and pulsar wind nebulae
- population studies

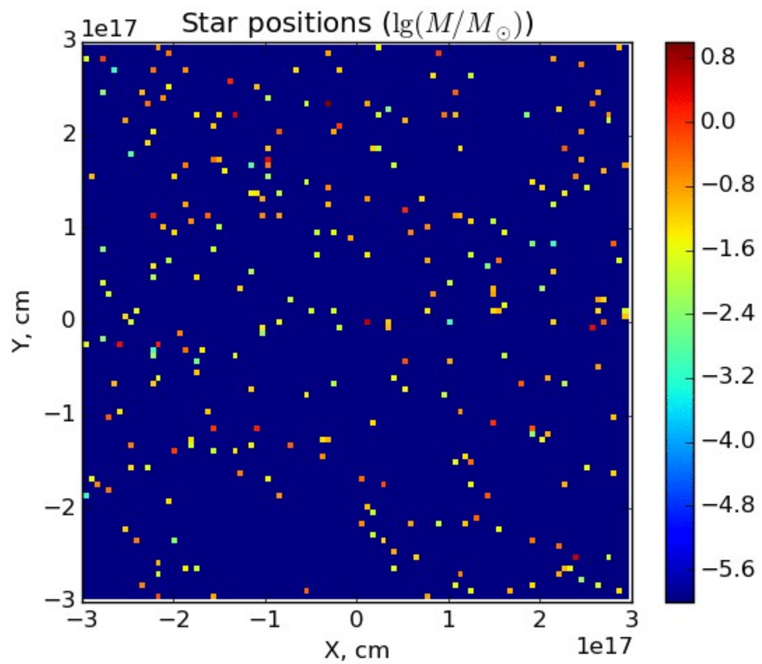
and so on...

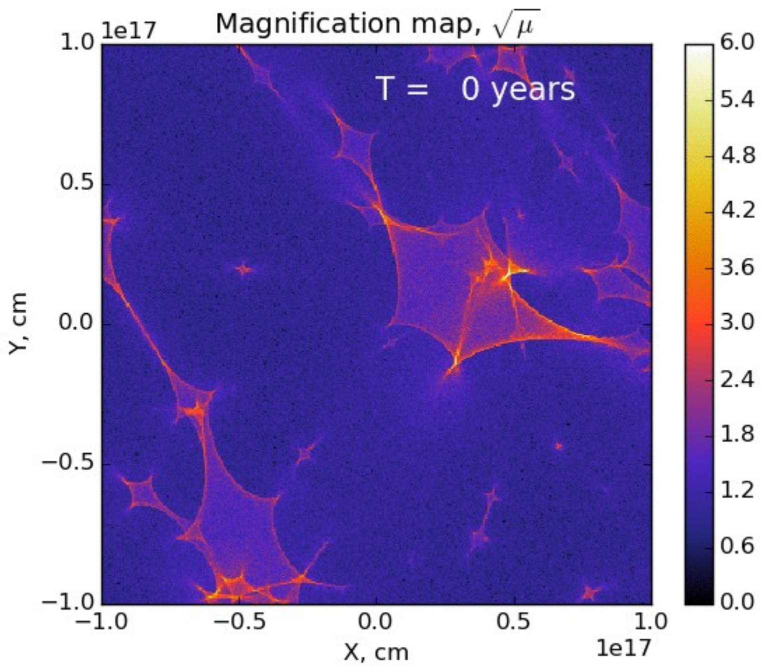
Even more discoveries can be expected from the being constructed CTA observatory and synergies with upgraded LIGO/VIRGO/IceCube and others...

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

Gravitational microlensing: dynamics of the magnification map

This magnification pattern is changing in time as the separate stars-lenses are moving with respect to each other.





However, the peculiar velocities of the stars in galaxies are typicly ~10-100 km/s and typical time scale for a change is ~10 years.
On shorter time scales the pattern can be considered stable.

Gravitational (micro)lensing