Highlights from MAGIC observations

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The extreme Universe viewed in very-high-energy gamma rays 2018
La Palma, Spain, 12.10.2018

Main VHE instruments

Main VHE instruments

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MAGIC telescope system

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

Telescopes: two D=17m
Site: La Palma (Canary Islands)
Energy range: 40 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

Recent improvements:

- at lower energies: new trigger system (SumTrigger-II);
- at higher energies: new observational strategy (Very Large Zenith angles).

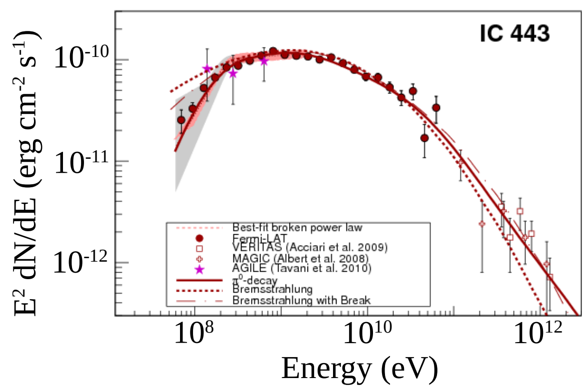
Galactic sources

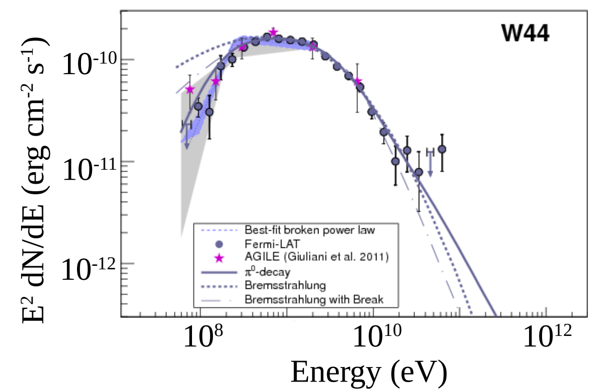
Galactic PeVatrons

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

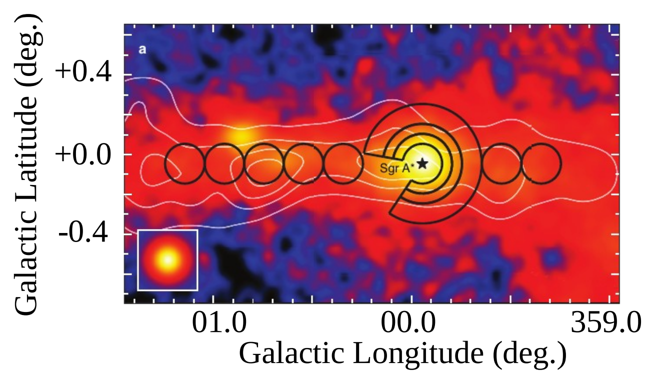


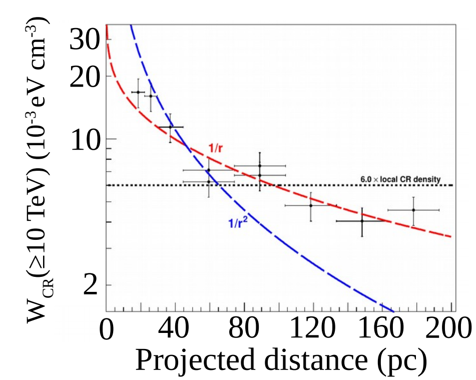


Fermi-LAT collaboration '13

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

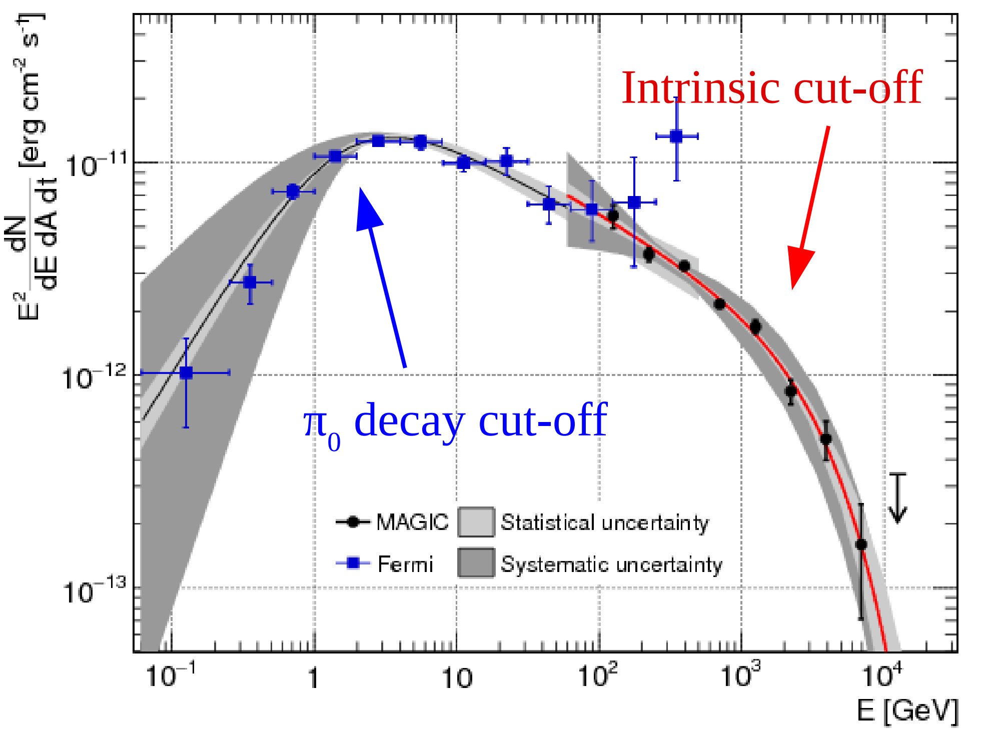
Are supernovae remants PeVatrons?

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

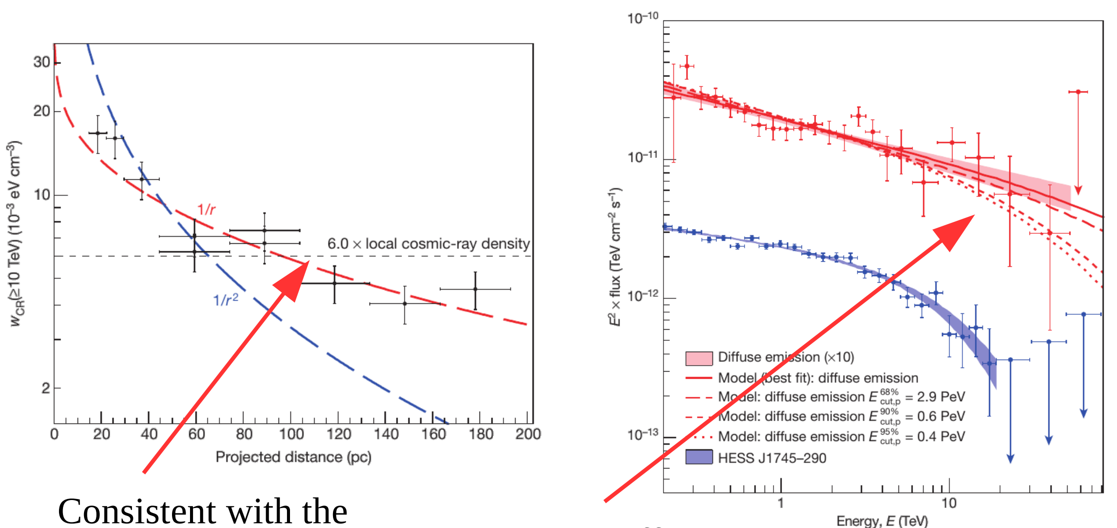


MAGIC Collaboration (2017)

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

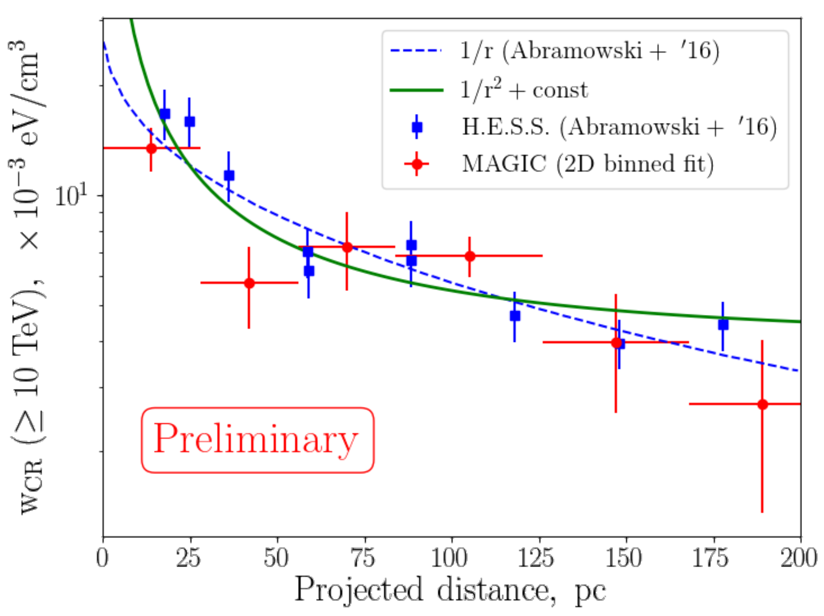
Alternative explanations proposed (Gaggero+ '17) underline the importance of the large scale CR "sea" for the firm interpretation.

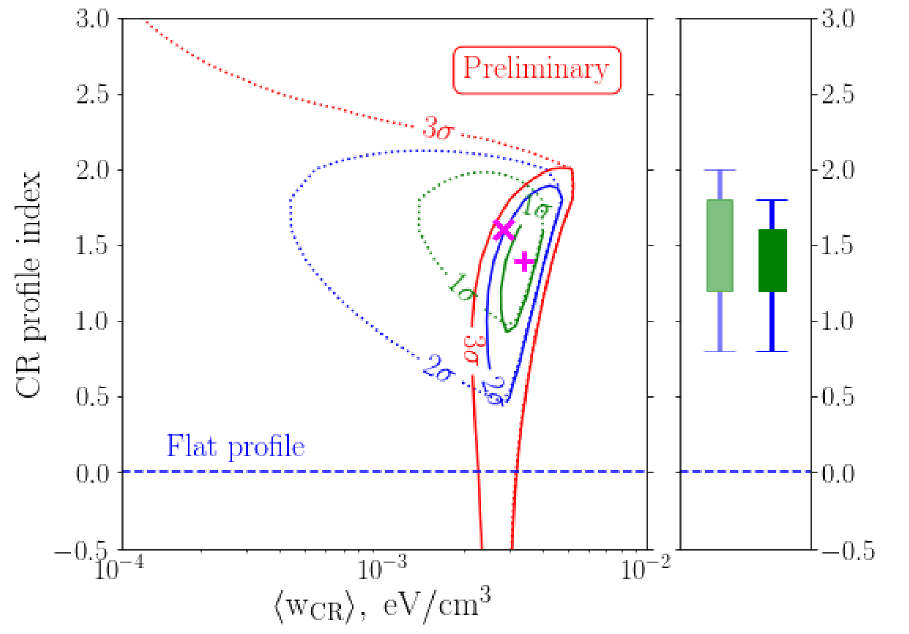
However, one of the main ingredients is the gas distribution in the central ~200 pc from the black hole.

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





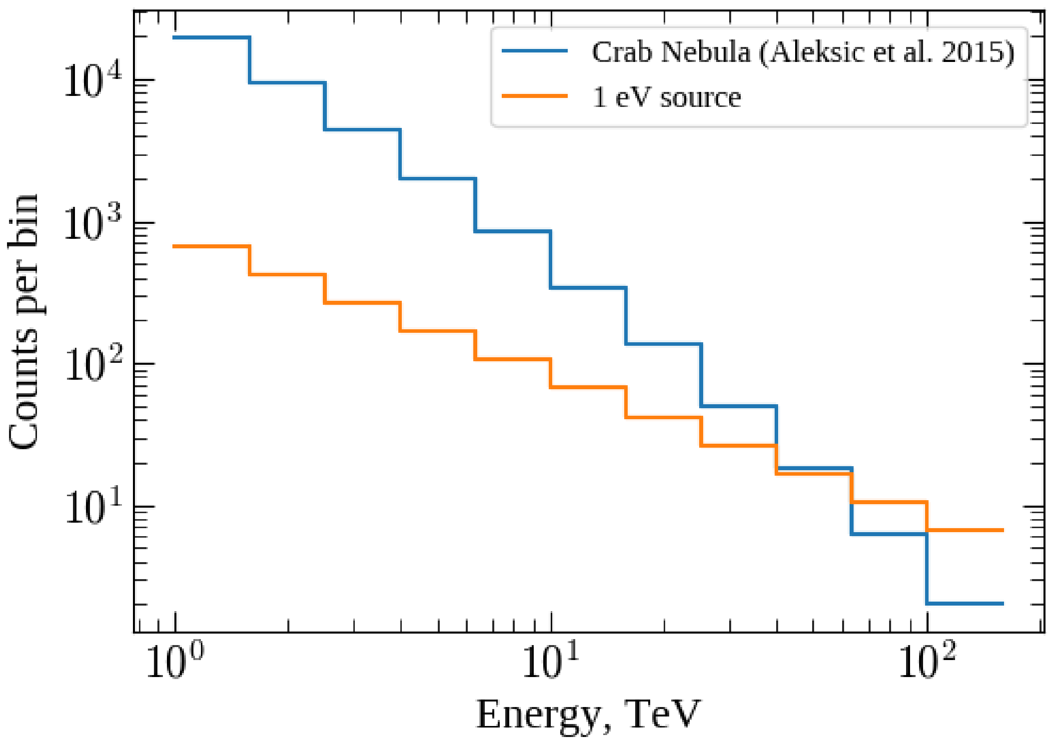
Still, the poorly know gas (target material) distribution close to the Gal. Center questions the w~r^{-1} form – other indices are also possible.

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

Detection of the >100 TeV emission

> 100 TeV emission – a signature of a PeVatron.
Main obstacle – low expected count rates.

Expected counts for A_{eff} = 1 km^2 and T_{obs}=50 hr



To keep observation time short, A_{eff} > 1 km^2 is required.

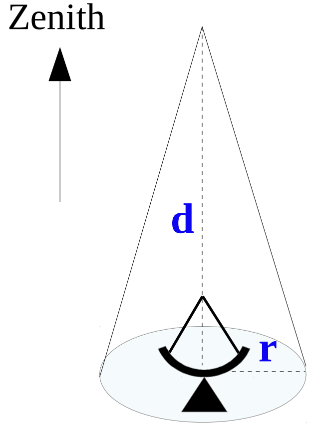
Case for CTA, but also achievable with current generation IACTs through a special observational setup.

Large zenith angle observations

Larger zenith angle observations

Vertical observations

(typical observational mode of IACTs)



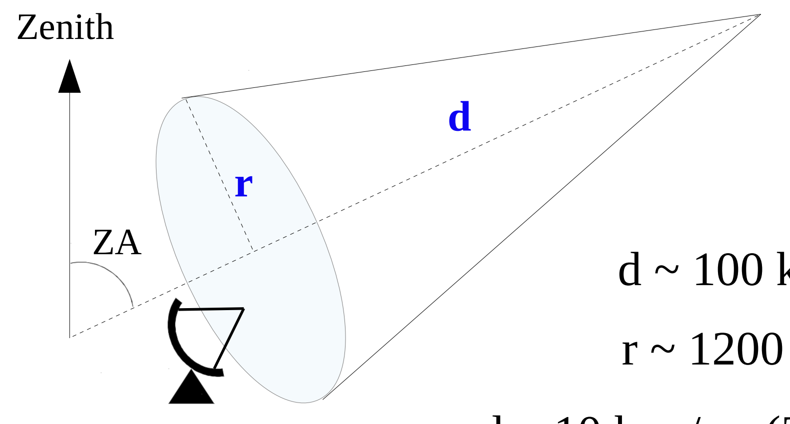
d ~ 10 km

r ~ 120 m

Usually ZA ~ [0^o; 60^o] and shower distance d ~ 10-20 km

Large zenith angle observations

(proposed setup)



d ~ 100 km

r ~ 1200 m

d ~ 10 km /cos(ZA)

ZA > 70^o

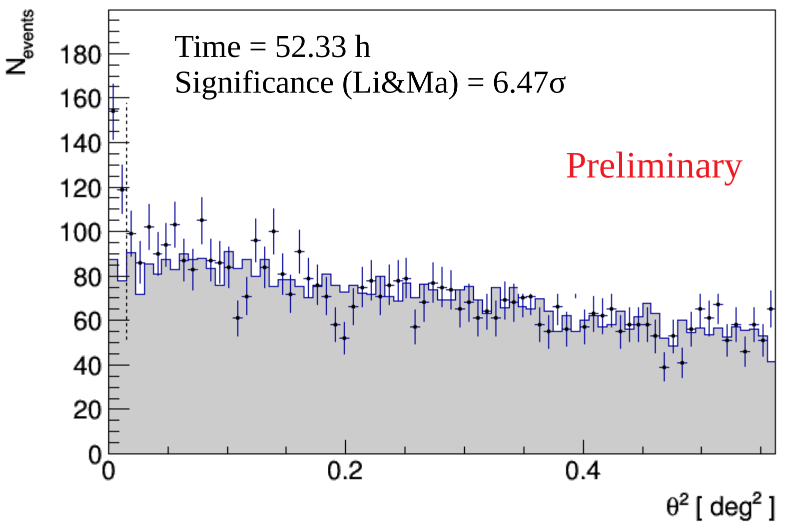
shower distance d > 50 km

Crab Nebula detection at highest energies

Approximately 50 hr of exposure (after cuts) in

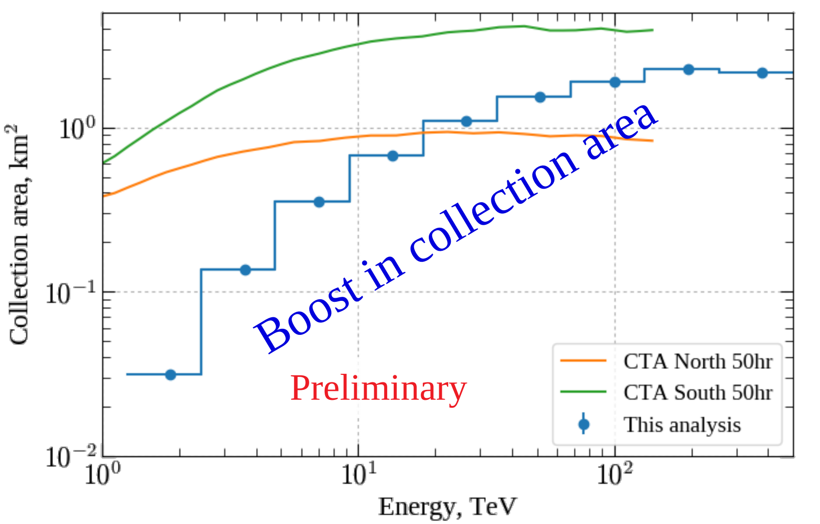
ZA range 70-80°.

Angular event distribution
> 30 TeV estimated energy



Significant signal above the highest source energy, previously measured by MAGIC (Aleksic+ '15)

Reconstructed collection area



LZA MAGIC collection area @100 TeV is comparable to CTA predictions (at 20° zenith angle).

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

Crab Nebula detection at highest energies

Approximately 50 hr of exposure (after cuts) in ZA range 70-80^{o}.

Unfolded Crab Nebula SED

Preliminary

Boost in maximal energy

Reconstructed LZA spectrum extends to ~100 TeV – comparable to HEGRA measurements, but in 8x less time.

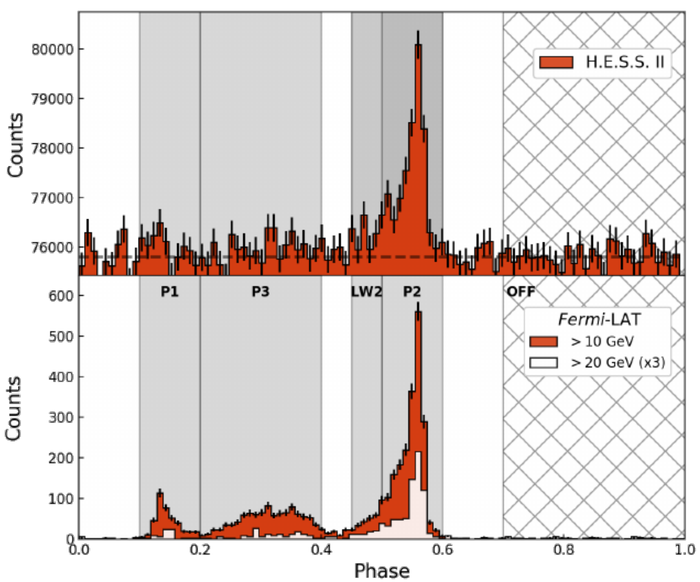
LZA SED is consistent with earlier MAGIC measurements at lower zenith angles.

Lowering the energy threshold: detecting pulsars with MAGIC

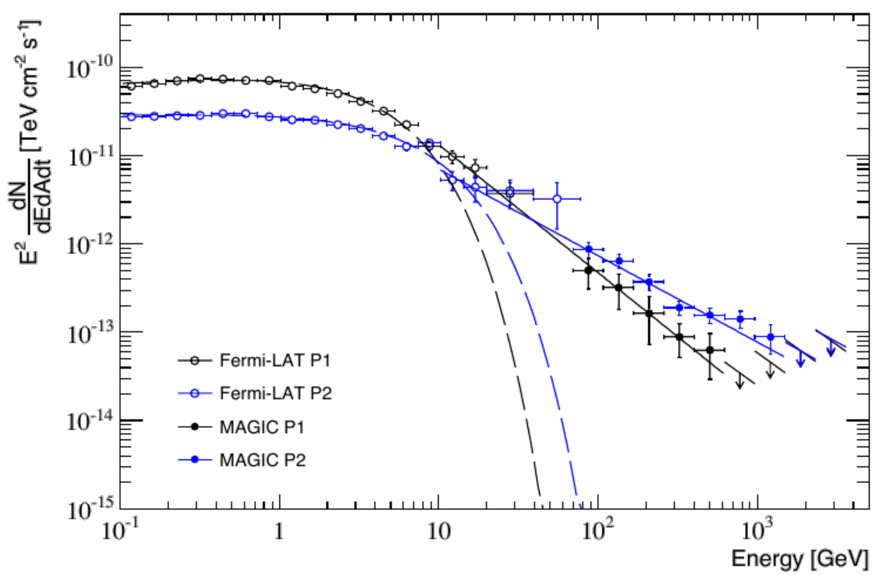
Pulsars (rotating neutron stars) typically have cut-off spectra, quenching at too low energies.

Only 2 pulsars are detected with IACTs untill recently!

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



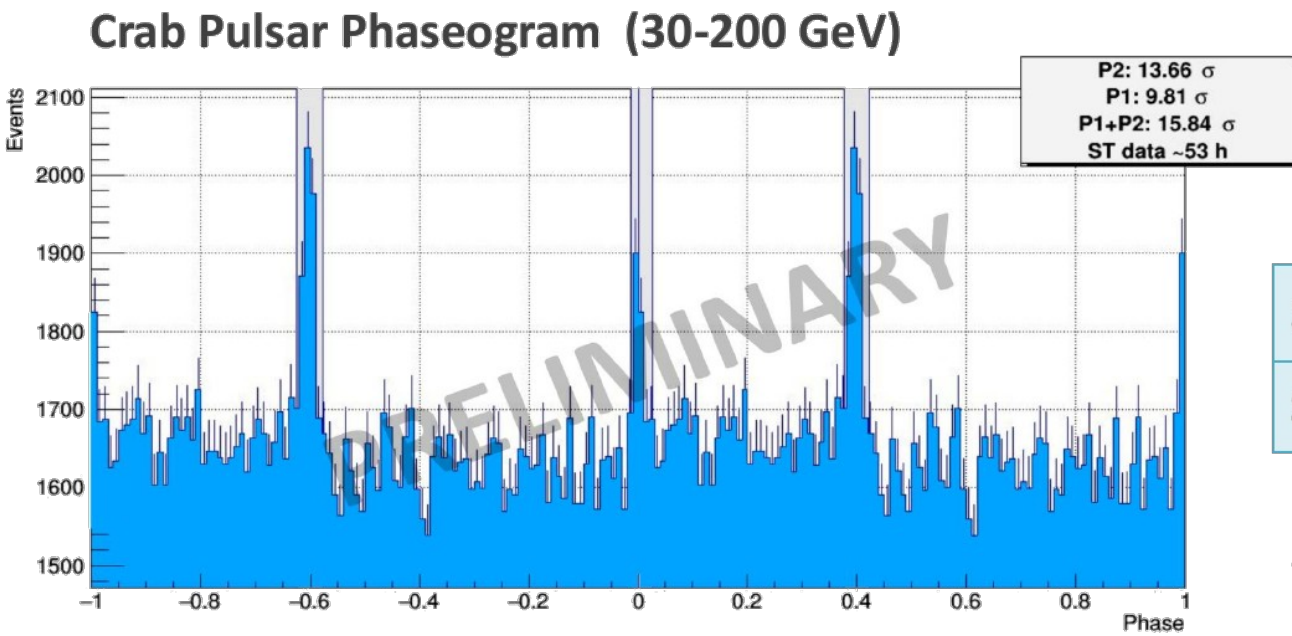
Crab pulsar spectrum
MAGIC Collaboration (2016)



Lowering the energy threshold: detecting pulsars with MAGIC

New SumTrigger-II system: stacking PMT signals.
Yields a ~30 GeV energy threshold.

→ More efficient pulsar observations.



Standard trigger	1.4 $\sigma/\sqrt{h}$
Sum-trigger-II	**2.3 $\sigma/\sqrt{h}$**

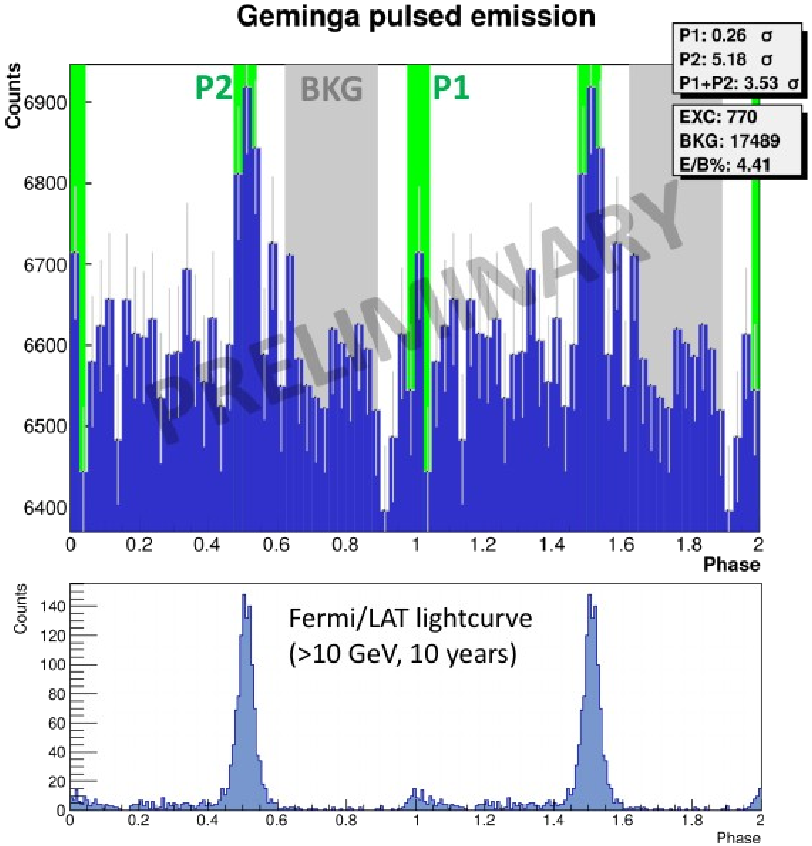
Adapted from *J. R. García, 2017*

Lowering the energy threshold: detecting pulsars with MAGIC

A new MAGIC detected pulsar: Geminga

- ~30 h of Sum-Trigger-II observations, winter 2017
- Rotational parameters derived from 10 years of Fermi/LAT data
- Clear detection of P2 (5.2σ)
- No detection of P1

→ IACT-observed pulsar family is growing.

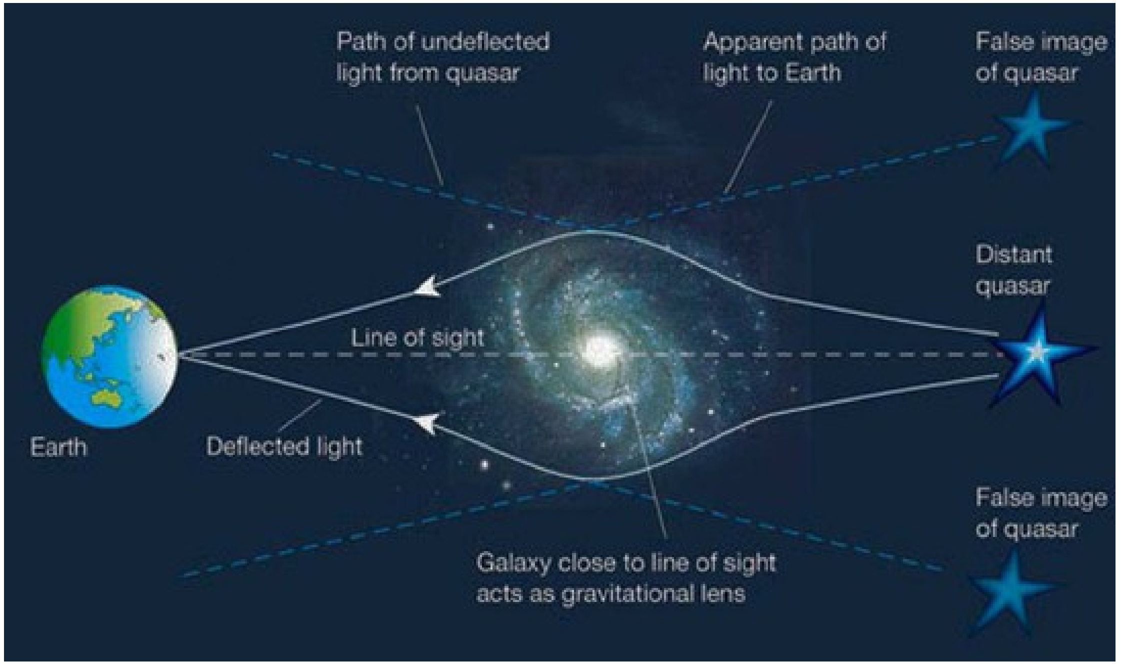


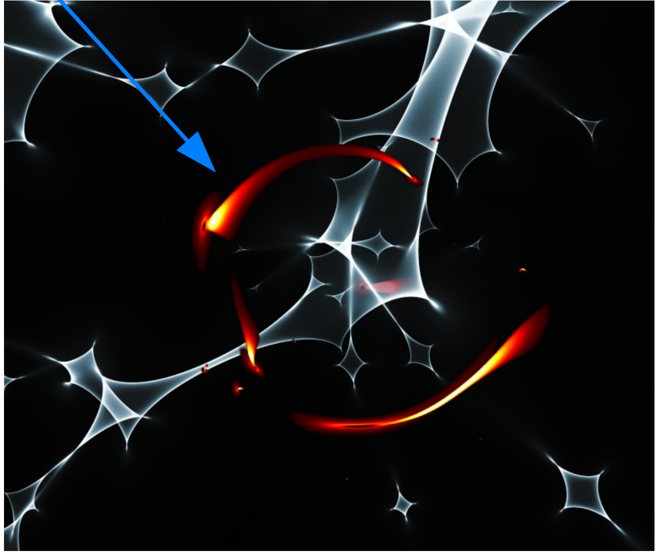
Extragalactic sources

Gravitational (micro)lensing

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

→ Image deformation / flux magnification

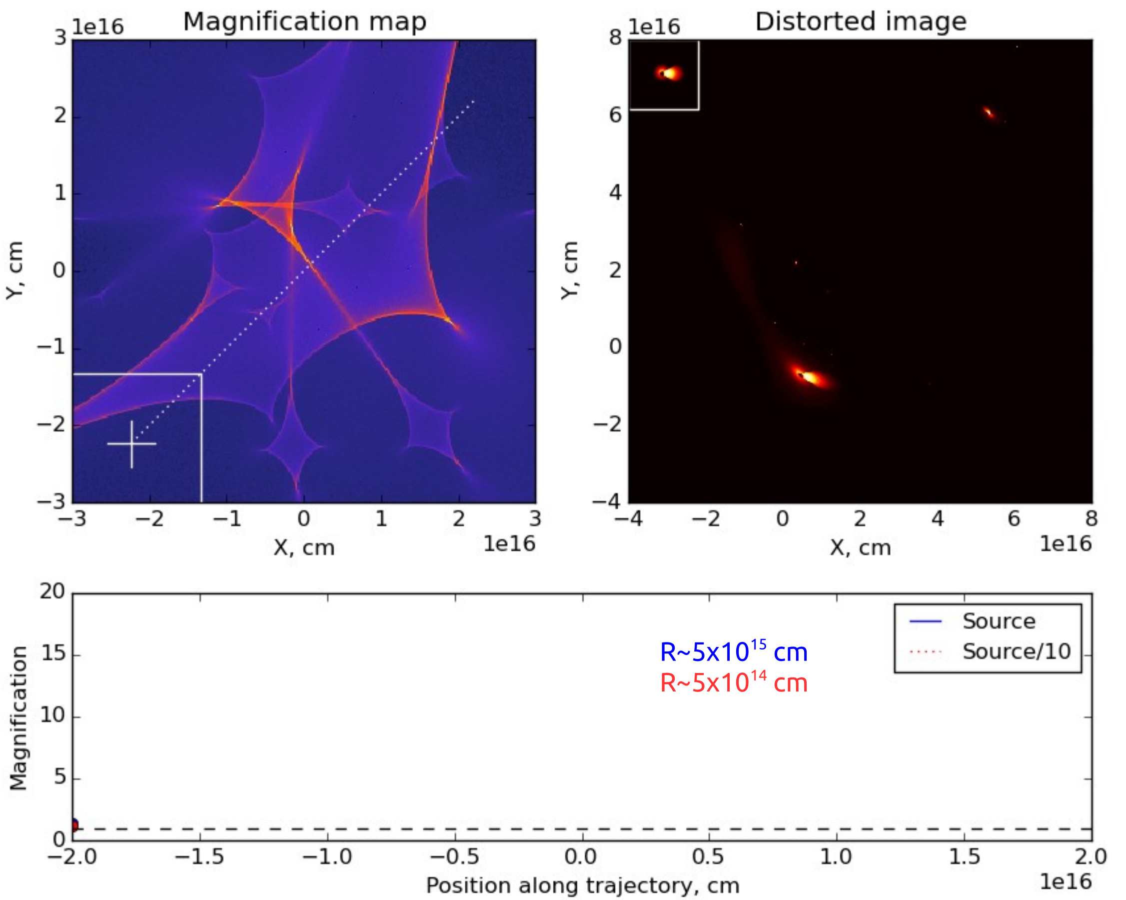




Gravitational microlensing – bending of the light due to the gravity of the stars and small-scale structures in the intervening galaxy.

→ 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.

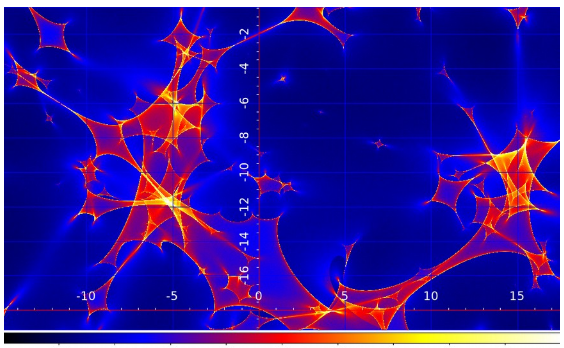
Magnification amplitude and duration depends on the source size:

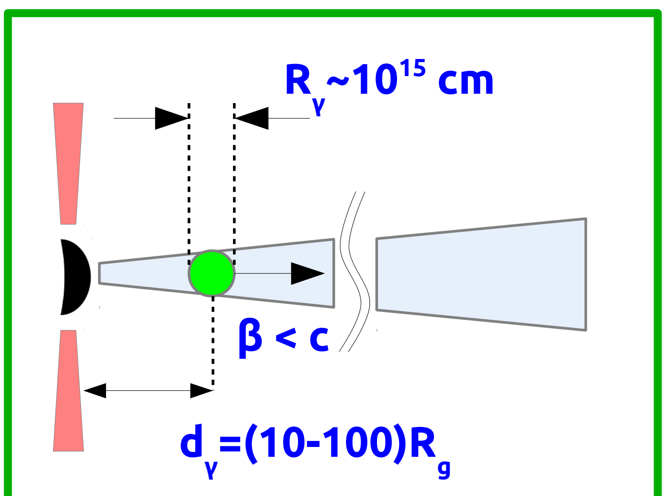
$\mu_{micro} \sim (R_E/R)^{0.5}$ and $\Delta t = R/v$

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

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

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

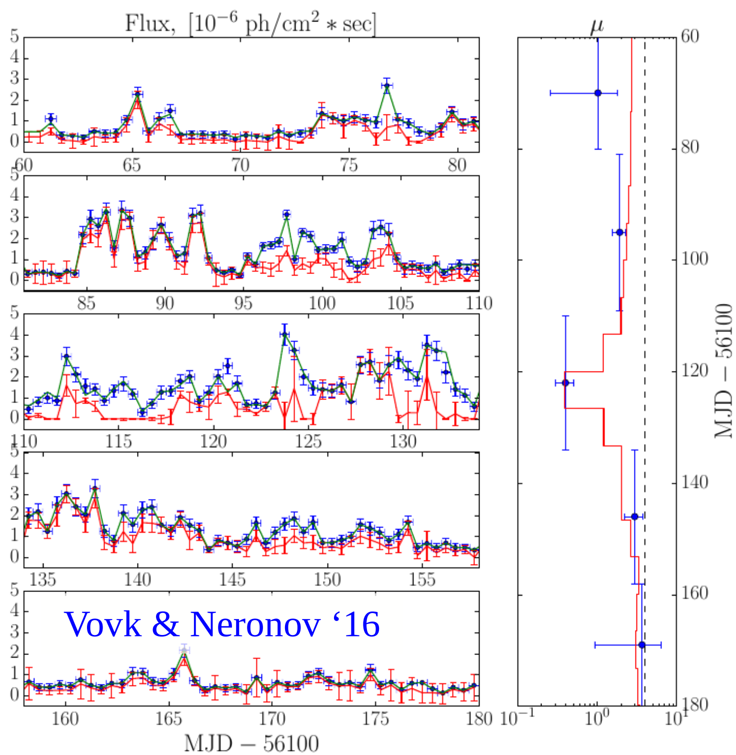
This gives a completely unique opotunity to study the details of the structure of the acceleration sites in AGNs, effectively improving the angular resolution of gamma-ray telescopes by 10^{11} times.

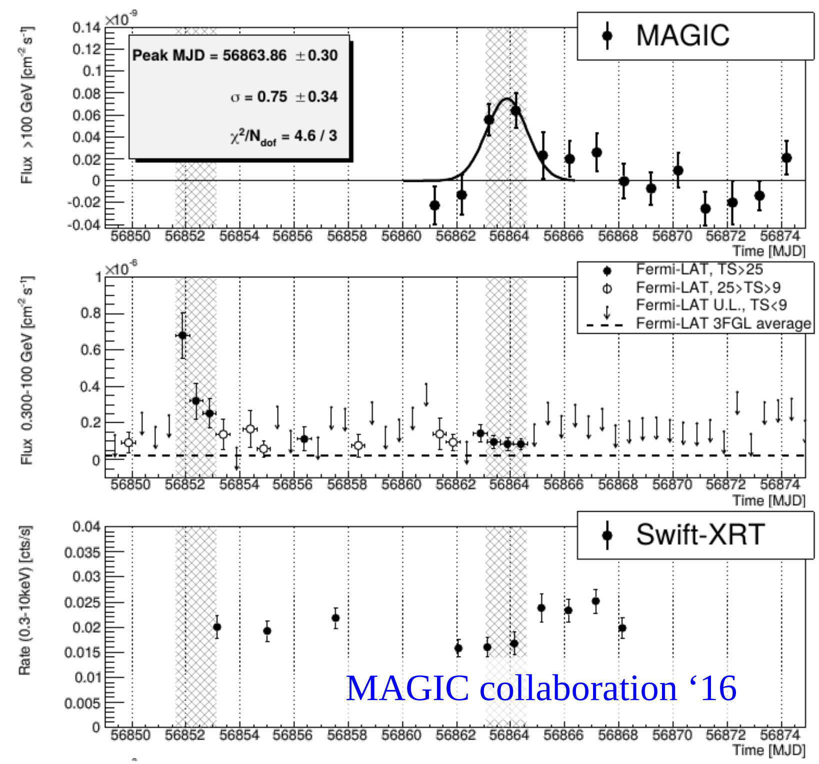
...AGN emission region angular size is that of an ant at the Moon

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

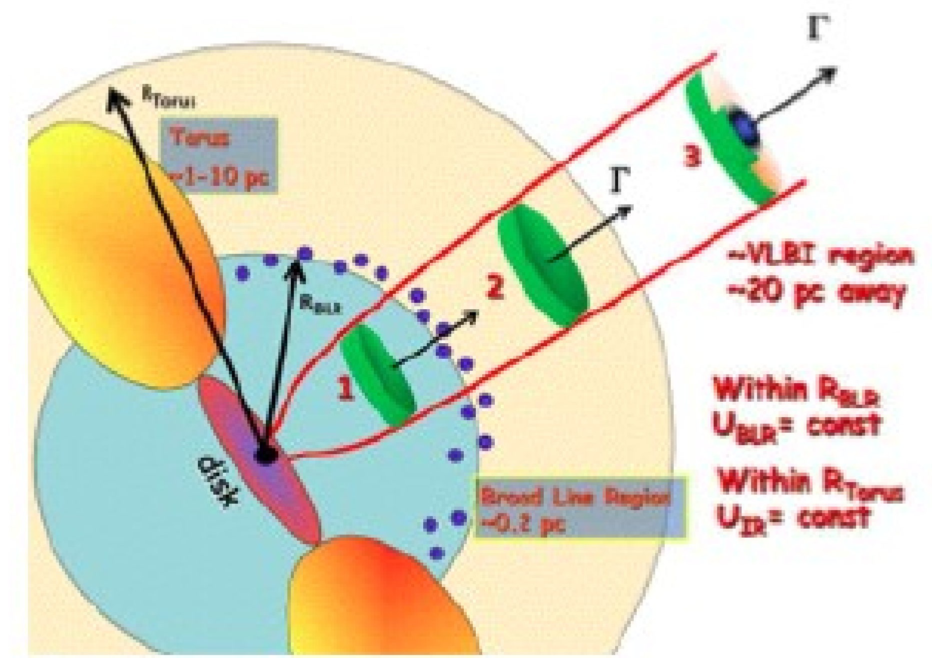
Very compact emission source, likely close to the central supermassive black hole.

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?



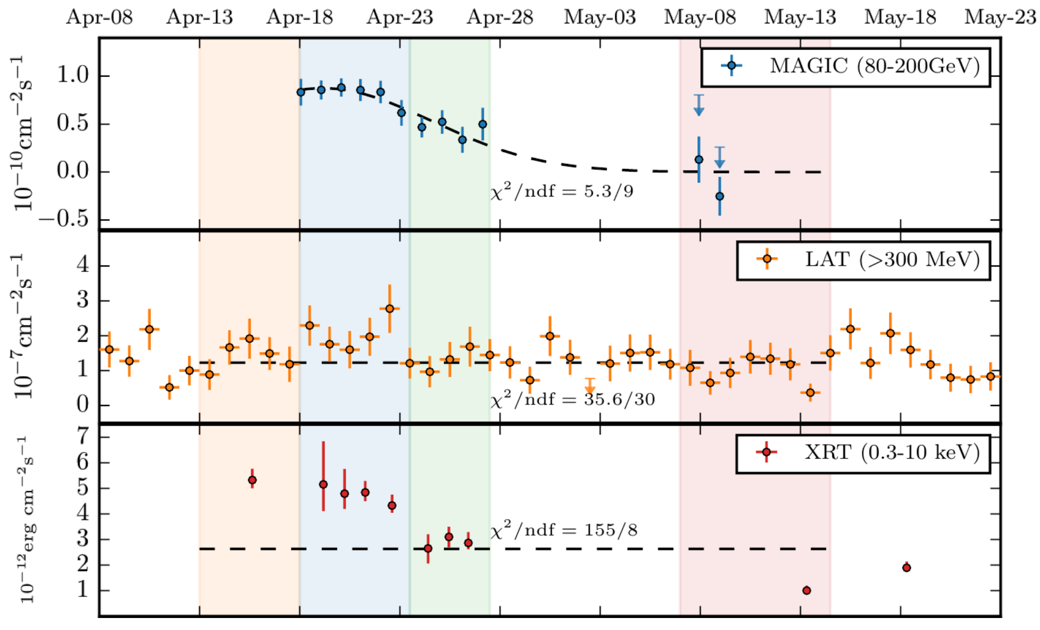
Cartoon of the possible locations of the emitting region

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)

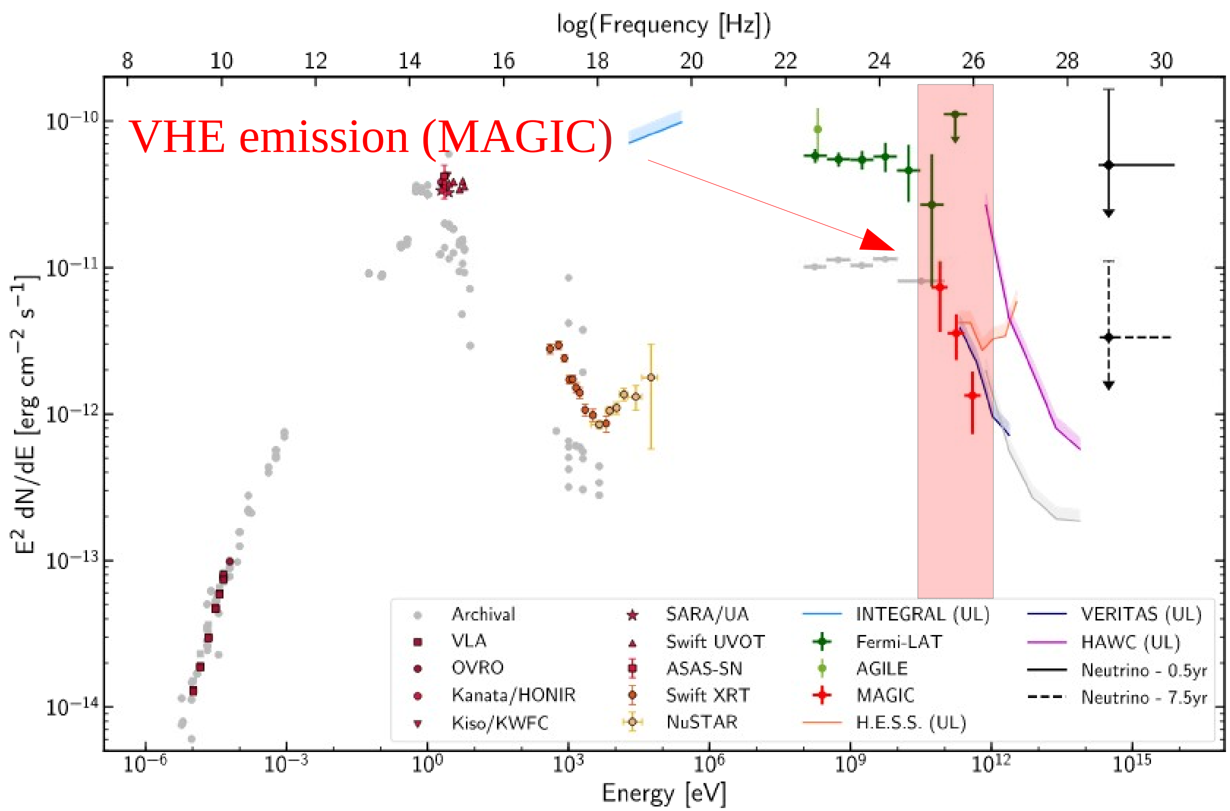
So...

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

Seems there is no common location

MAGIC detection of the neutrino source

TXS 0506+056 observations triggered by the IceCube alert EHE-170922A



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

TXS 0506+056 shows a synchrotron peak around 10^{14} Hz → classified as LBL/IBL

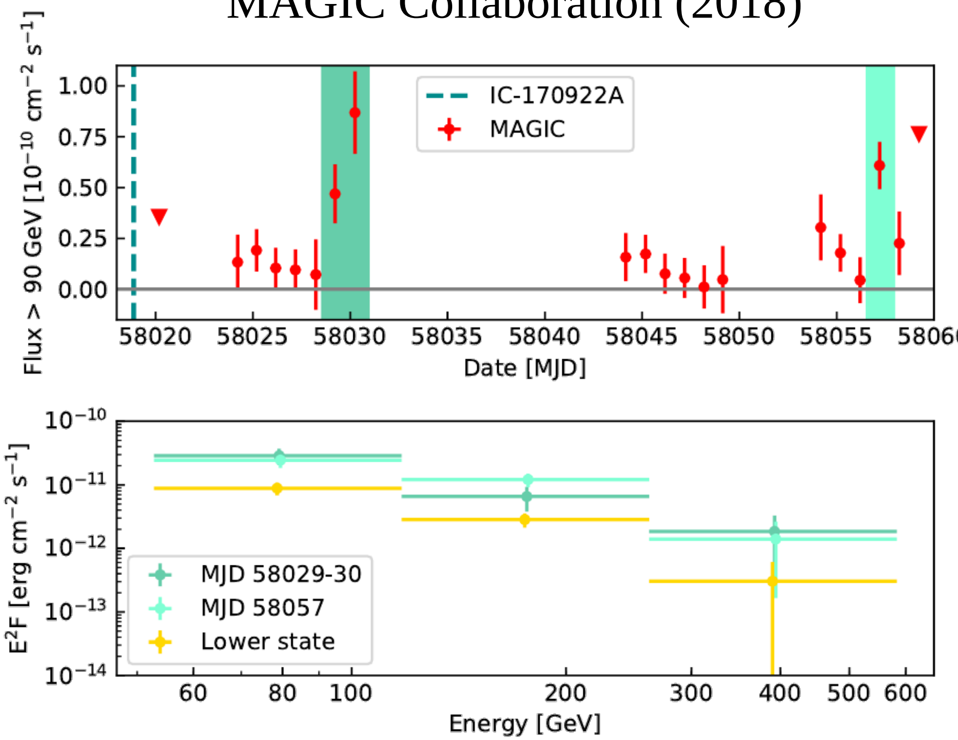
VHE gamma-ray observations allowed computation of redshift upper limits with between z=0.61 and z=0.98 at 95% CL (depending on EBL model used, Paiano+ '18)

MAGIC observations of the neutrino source

Deep (40 hr) exposure following the original event

- Two flares
- Daily time scale variabily
- No spectral changes

MAGIC Collaboration (2018)



Conclusions (overall):

- ✔ AGNs are responsible at least for a fraction of the observed astrophysical neutrino flux.
- ✔ AGNs do accelerate CRs to 10^{14}-10^{18} eV.

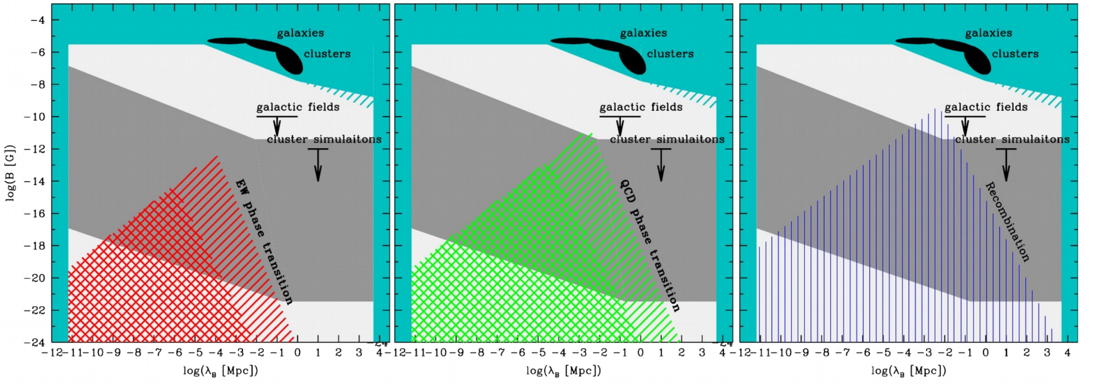
Intergalactic Magnetic Field

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: ~10^{-12}
- ✔ electroweak phase transitions: 10^{-11} G
- ✔ recombination: ~10^{-9} G

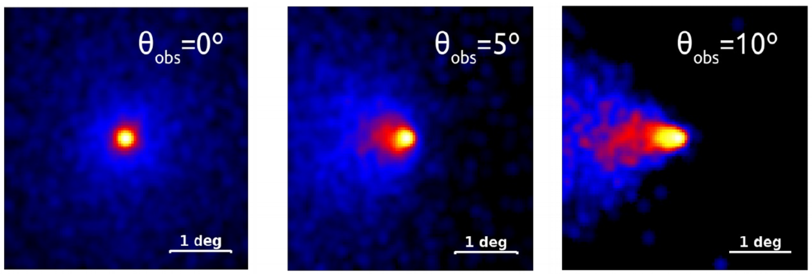


Neronov & Semikoz, '09

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

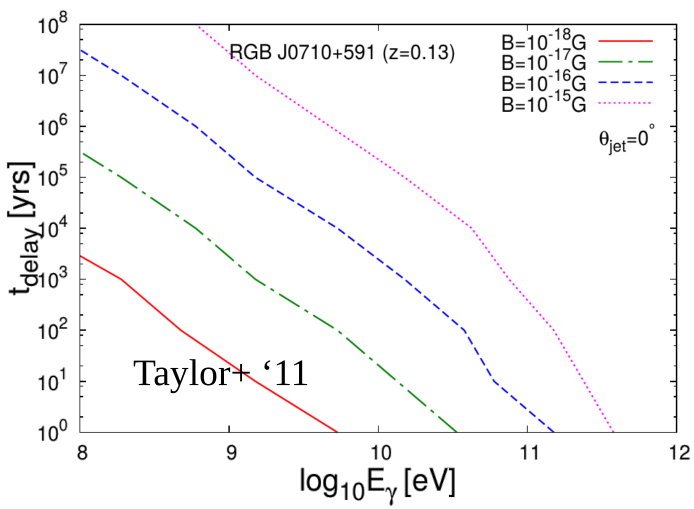
Size and shape depend on IGMF strength **and** source parameters (jet opening and orientation).

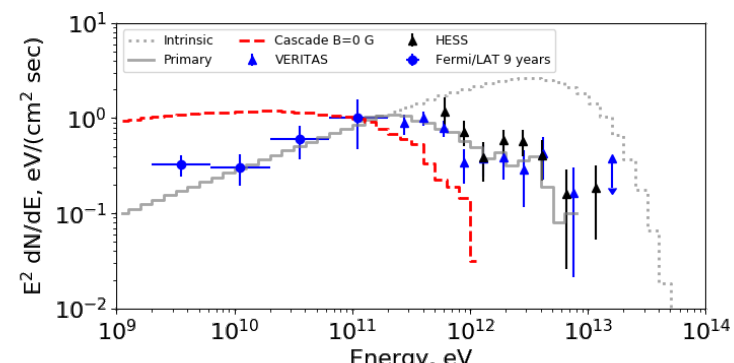
Delayed emission

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.



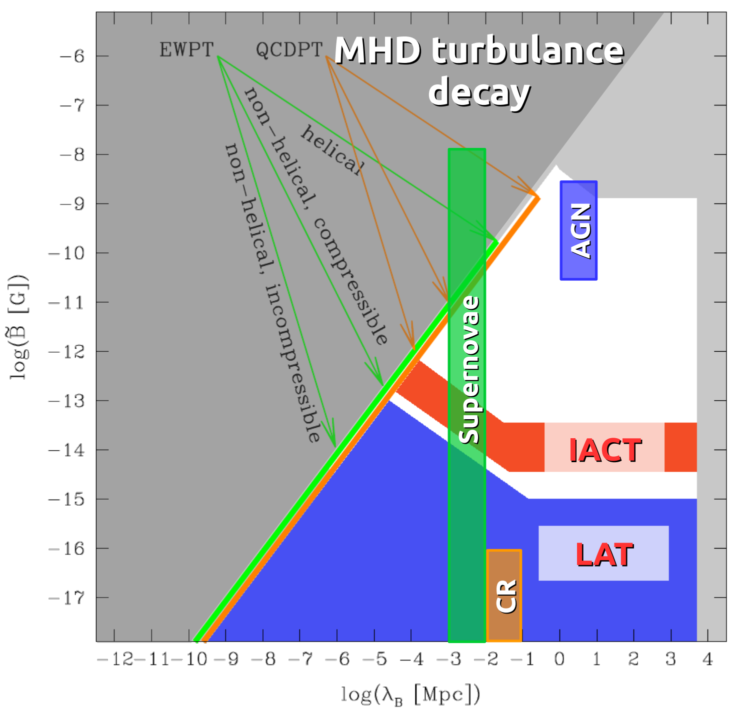


Neronov & Vovk ‘10, Tavecchio+ '10, Dermer+ ;11, Dolag+ ‘11, Taylor+ ‘11, Vovk+ ‘12, Finke+ ‘15, Aharonian+ ‘01, Aleksic+ ‘10, Abramowski+ ‘14, Archambault+ ‘17

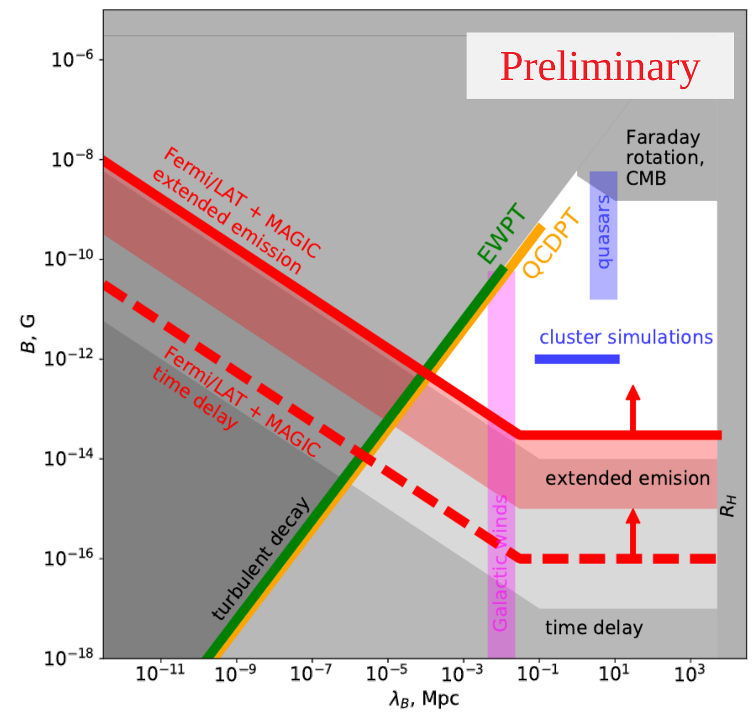
Intergalactic Magnetic Field

Recent MAGIC observations strongly constrain the IGMF parameter space

Adapted from Durrer & Neronov ‘13



MAGIC Collaboration (in prep.)



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

Summary

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

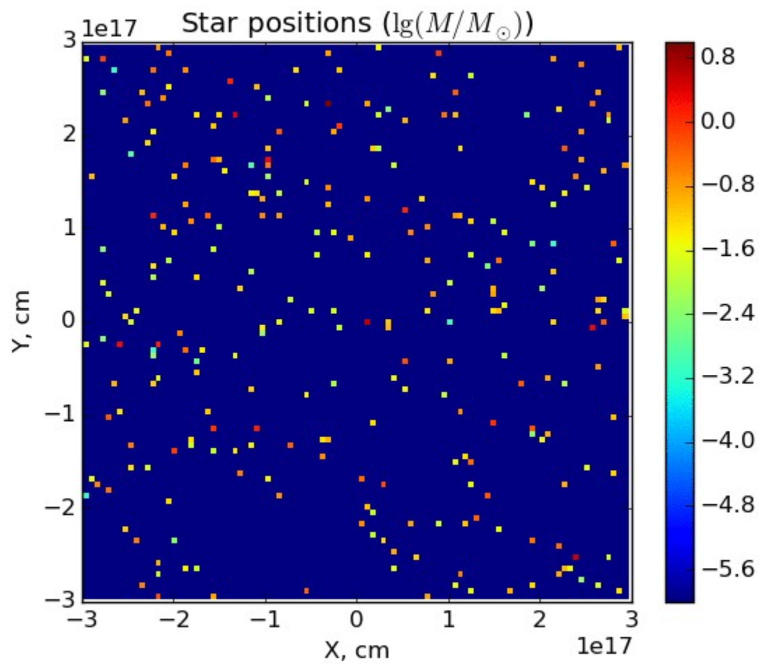
A number of prominent discoveries were not covered here due to lack of time:
- GRB detection with an IACT
- sharp spectral features in AGN gamma-ray emission
- dark matter searches
- gamma-ray binaries
- spatially-resolved supernova remnants and pulsar wind nebulae
and so on...

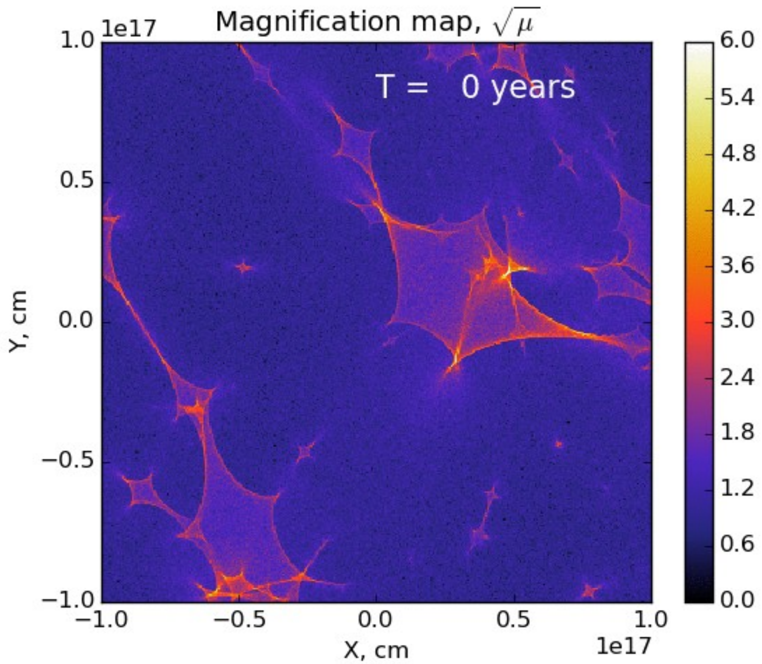
We are looking forward to joint observations with CTA/LST and synergies with upgraded LIGO/VIRGO/IceCube and others...

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

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