The MAGIC legacy to next generation of IACTs: results and prospects

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Vulcano workshop 2014
Frontier Objects in Astrophysics and Particle Physics
May 18-24, 2014

Some recent highlights of MAGIC & prospects… legacy in a few years

KEEP
CALM
I'M
NOT
DEAD YET

J. Cortina (IFAE Barcelona)

Vulcano workshop 2014
Frontier Objects in Astrophysics and Particle Physics
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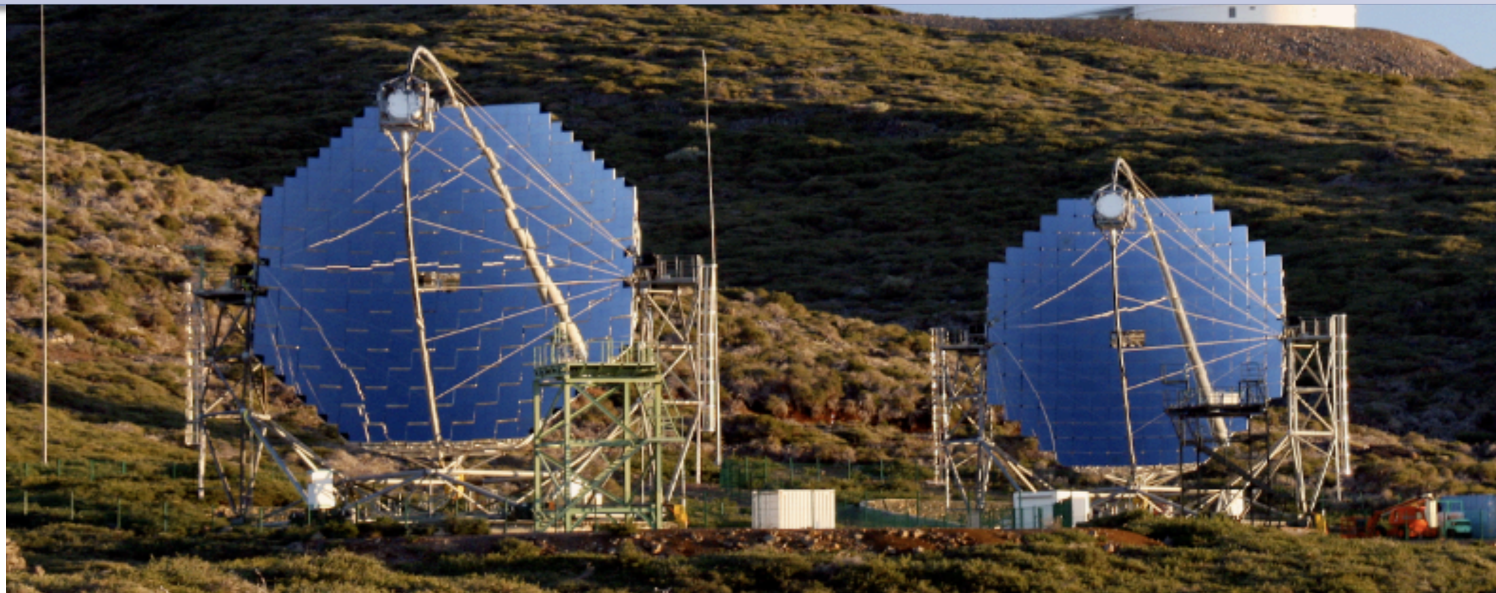
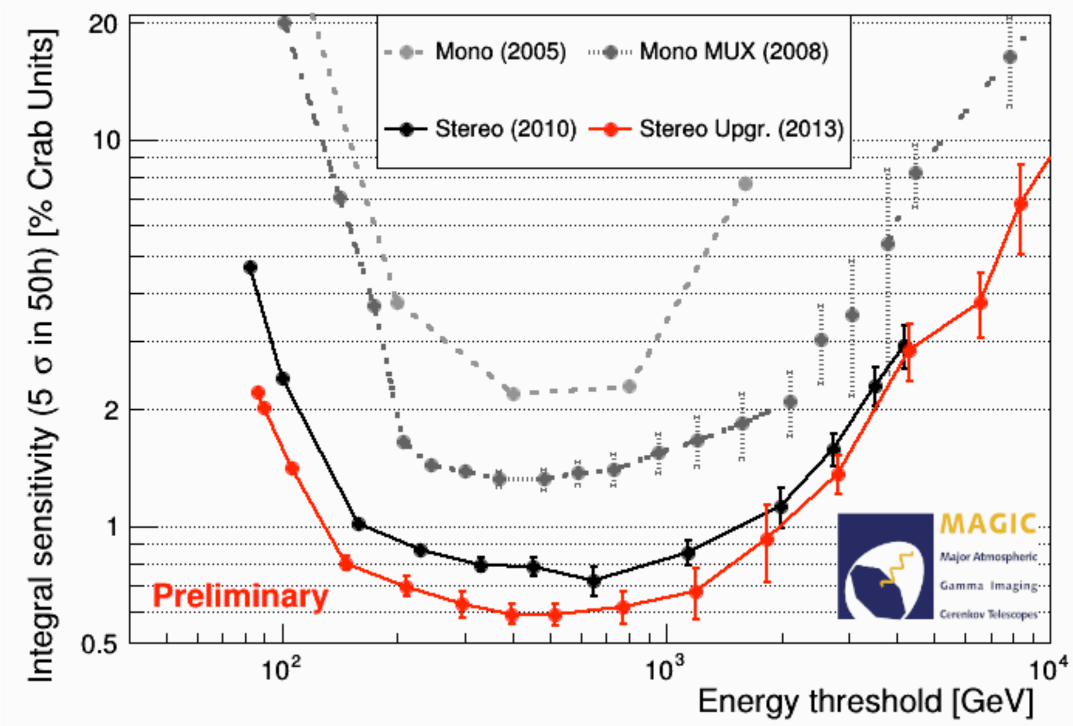
10th anniversary of MAGIC

- Collaboration of Germany, Spain, Italy (INFN+INAF)… Located in La Palma, Spain.
- Single telescope (MAGIC-I) finished in 2004: at the time largest IACT ever built (17m Ø), i.e. lowest energy threshold. Ultralight carbon fiber frame and mirrors for fast repositioning (<20 secs/180°)



- MAGIC telescope array: stereo observations down to 50 GeV since 2009.
- Upgrade of both telescopes readout and camera of M1 finished on 2012.

Current performance



- Best flux sensitivity around 400 GeV: 0.6% Crab.
- Angular resolution: 0.1° at 100 GeV ➔0.07° at 1 TeV
- Energy resolution: 20% at 100 GeV ➔ 15% at 1 TeV.

- A new trigger for even lower trigger threshold ("analog trigger" or "sumtrigger") is under commissioning.
- Two papers with technical description and performance of upgrade MAGIC about to be submitted.

Extragalactic VHE γ-ray physics: not only blazars

To make my case clear: I won't mention a single blazar…

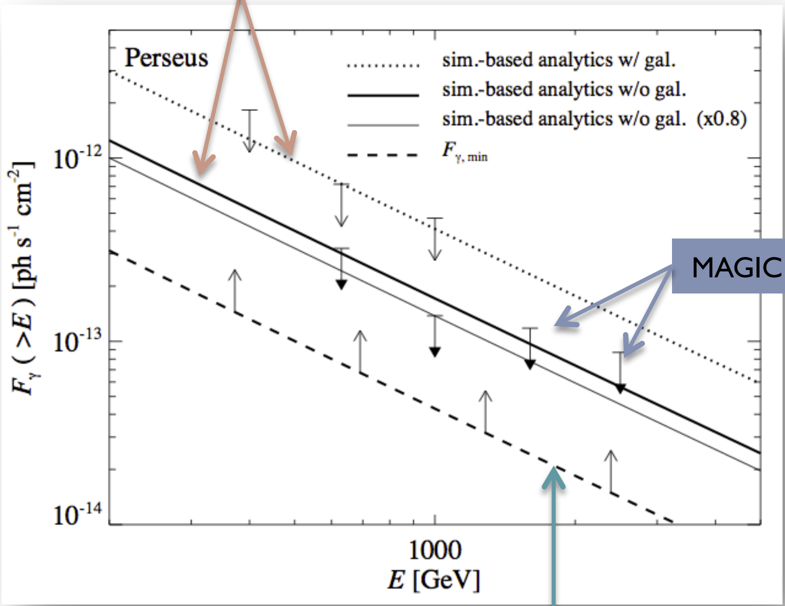
Perseus cluster of galaxies

Clusters of galaxies

- Clusters of galaxies are the largest bound structures in our Universe. They are young: still forming now.
- Huge energy budget is available from gravitational potential of infalling gas (10^{15} $M_{\odot}$, 10^{61}-10^{63} erg).
- Observed synchrotron emissions in centers of clusters (Kempner et al. 2004) come from CR electrons, which are probably accompanied by 100x more CR protons (because protons are easier to accelerate –as observed in our own galaxy).
- CR electrons may actually come from CR protons. In any case, we would very much like to measure the density of CR protons inside cluster and CR protons produce γ-rays through π^0 decay.

Perseus cluster: MAGIC results

Cosmological hydrodynamical simulations with/without galaxies

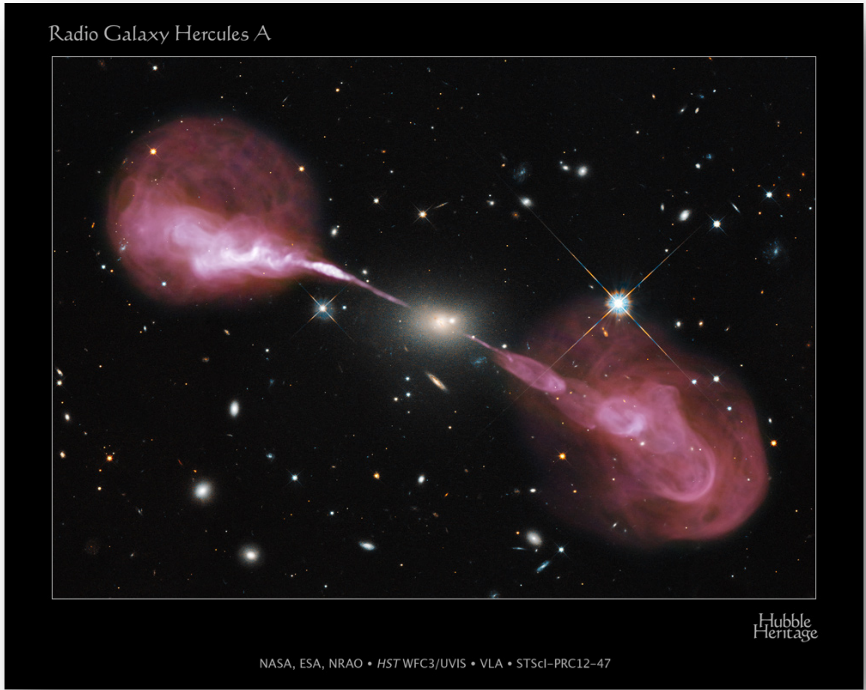


Absolute minimum gamma flux assuming electrons come from protons

- Perseus was selected because it's nearby (78 Mpc), so very bright in X-rays, and shows a massive cool core and radio mini-halo.
- No detection after 85 hours of observations (2009-2011, MAGIC Coll., A&A 541, 99 (2012)). We set Upper Limits at E>600 GeV.
- We compare to simulations and to absolute minimum possible flux: at the limit of simulations and only factor 3 above UL.
- Allows to calculate ratio of pressure of CR and pressure of thermal component in cluster: $\langle P_{CR}\rangle/\langle P_{thermal}\rangle$=0.77%-11.6%.
- Allows to set lower limit on magnetic field in center of cluster: B>4-9 μG.

Radiogalaxies

Radiogalaxies

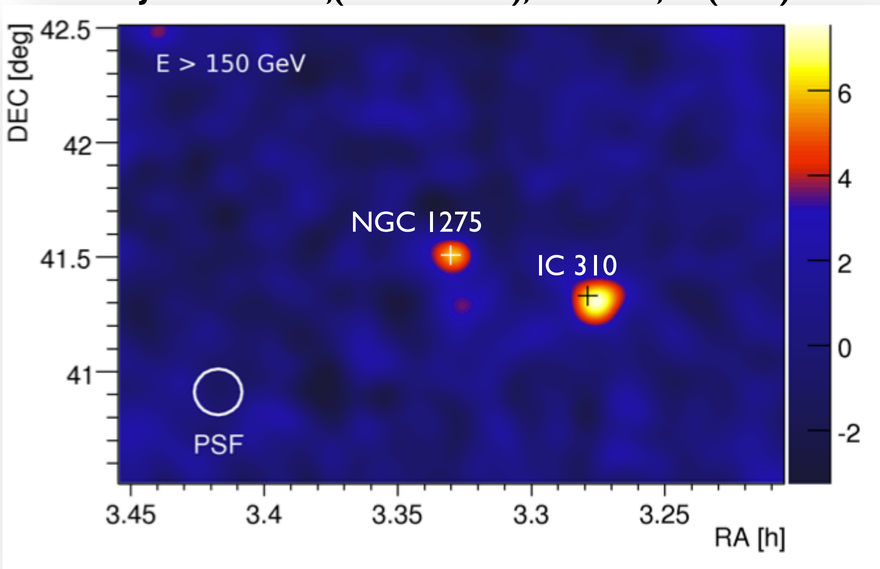


- Radiogalaxies (active galaxies displaying a radio jet) generate CR (electron or proton) bubbles in the intergalactic medium.
- Same process injects magnetic field into intracluster medium.
- Total injected energy is huge (10^{60}-10^{61} erg): some % of total energy of accretion into central supermassive black hole (Kronberg et al, ApJ 560 (2001) 178).
- Relativistic electrons produce synchrotron which can be studied using radiotelescopes. But the same electrons can produce VHE gammas through Inverse Compton, so IACTs provide complementary information.

Radiogalaxies

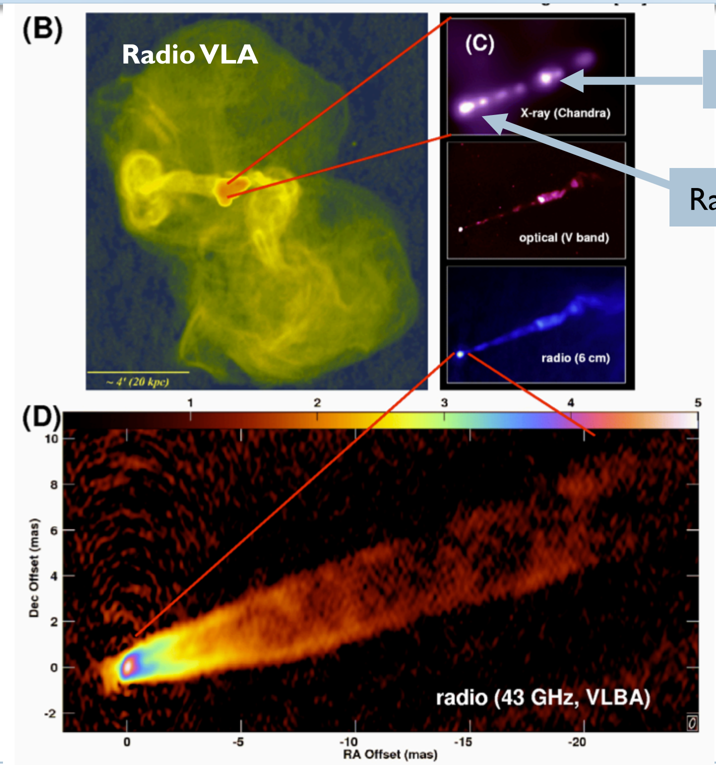
- Radiogalaxies are interesting because:
  - Emission is not so strongly beamed, ie the jet is not so aligned with the line of sight like in blazars.
  - They are nearby objects, i.e. we can study them in more detail.
- IACTs have discovered **four radiogalaxies** at VHE: Cen-A, M87, NGC 1275 and IC 310
- MAGIC has discovered the last two sources.
- They actually happen to be in the same field of view. Not so surprising because they belong to a cluster of galaxies: Perseus.

J. Aleksić et al.,(MAGIC Coll.), A&A. 541, 99 (2012)

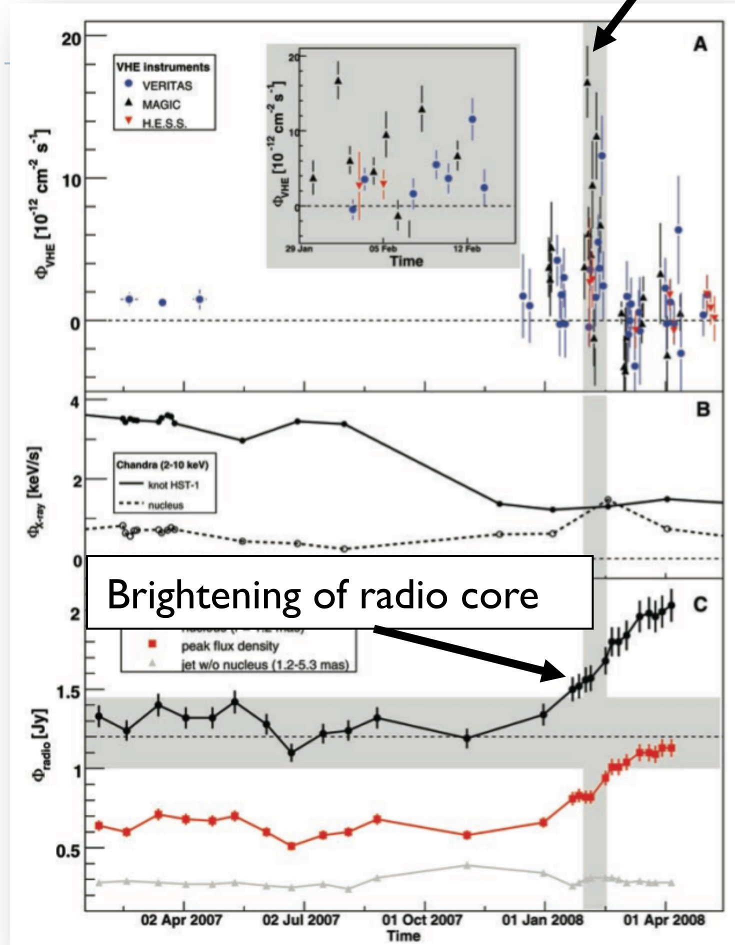


Radiogalaxies: M87

- MAGIC, together with HESS and VERITAS, has studied one of the other VHE radiogalaxies: M87.
- M87 is so close to us (17 Mpc) that many features in the jet can be resolved.
- Flux variations then allow to identify the source of the VHE emission.



M87 Flare at VHE



MAGIC+VERITAS+HESS: Science 325 (2009) 444

Small problem: further observations do not show the same pattern! (ApJ. 746, 151 (2012)) Different emission regions??

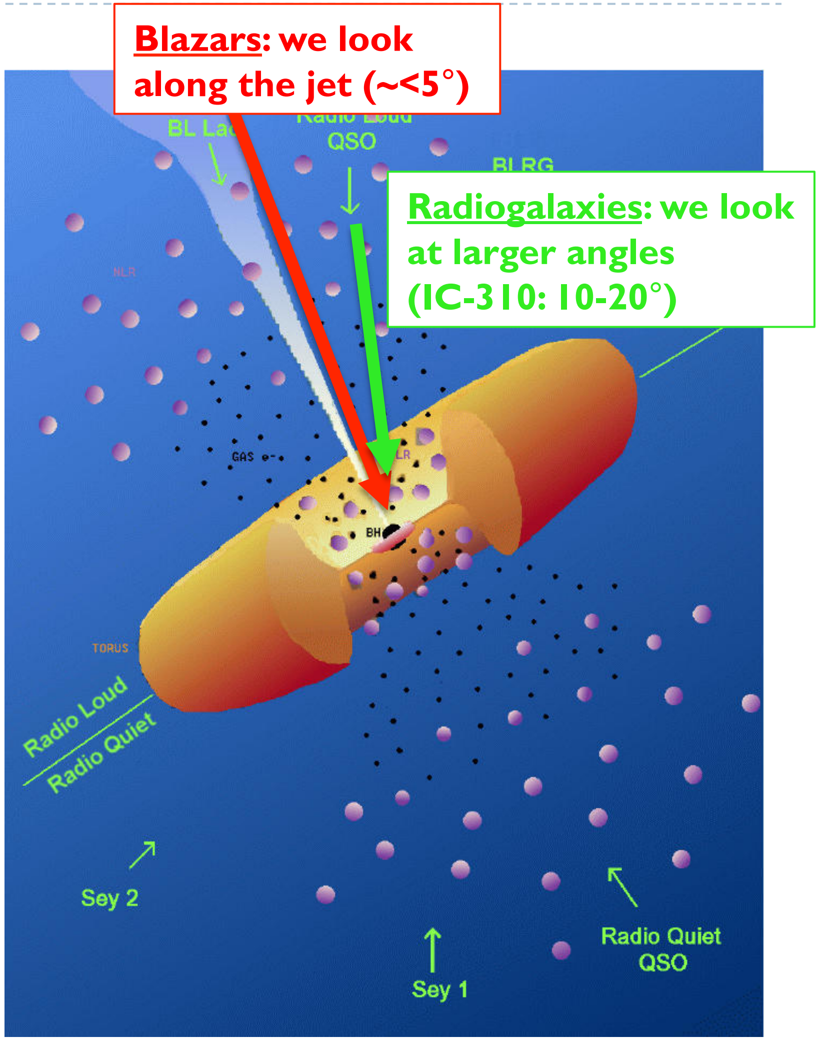
Radiogalaxies: IC 310

- Discovered at VHE by MAGIC (ApJ, 723 (2010) L207) during observations of Perseus.
- Reobservation during flare in 2011 (A&A 563 (2014) A91): variable from day to day, source is **FAST!**
- Third observation during flare in 2012: observed variability timescale of (9.5±1.9)min (Gaussian σ) and large-amplitude flickering with doubling time scales down to 1 min. **EVEN FASTER!**

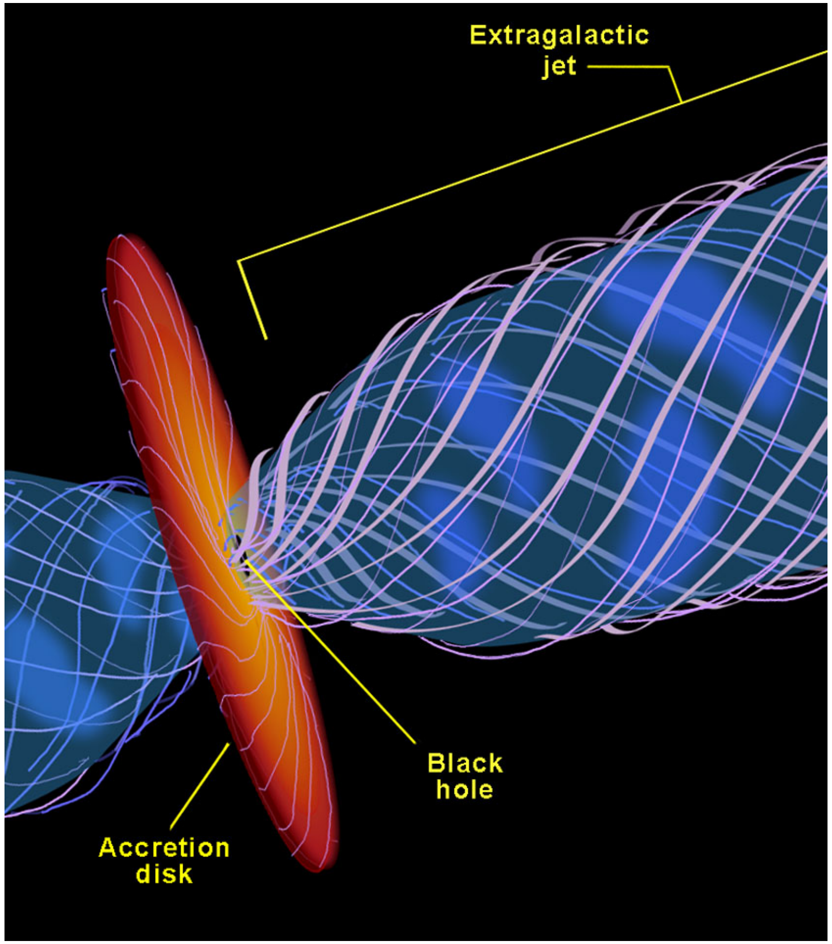
Plot removed from presentation

Radiogalaxies: IC 310

- 1 min flickering scale corresponds to <25% of the **event horizon** light-crossing time (R_{eh}) for $M_{BH}=2{\cdot}10^8\ M_\odot$
- Smallest feature resolved in AGN with radio interferometry: ~10 R_{eh}
- VHE blazars Mrk 501 and PKS 2155–304 show equally fast variations but variability t= R_emission (1+z) / (c δ), but they are blazars. For IC-310 the angle of the jet to the line-of-sight has been estimated to be in the range of 10–20° and a Doppler factor of δ=3 – 4, while blazars have δ ~50.



Radiogalaxies: IC 310

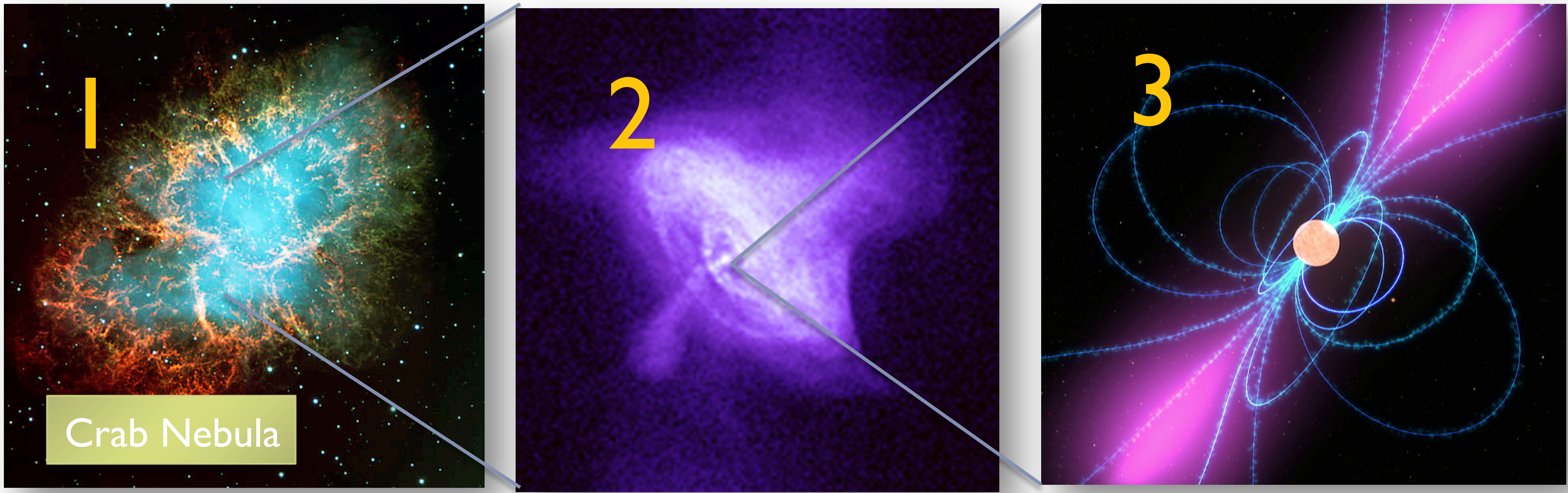


- An emission region smaller than 25% of the **event horizon** light-crossing time is very hard to explain with any model:
  1. Shocks in the jet ("standard model"): the shock is probably as big as the jet. How can the jet be collimated to a size < event horizon?
  2. Minijets in the jet: small plasmoids moving faster inside the jet? But if a minijet points to us, there must be many others pointing elsewhere. Adding all together: huge luminosity.
  3. Jets shortly hitting stars or clouds? Crossing times and pp cooling times are typically longer.
- We may have found an explanation, but you have to wait for the paper…

Pulsars and pulsar wind nebulae

Surprise at VHE: PWN all over the place

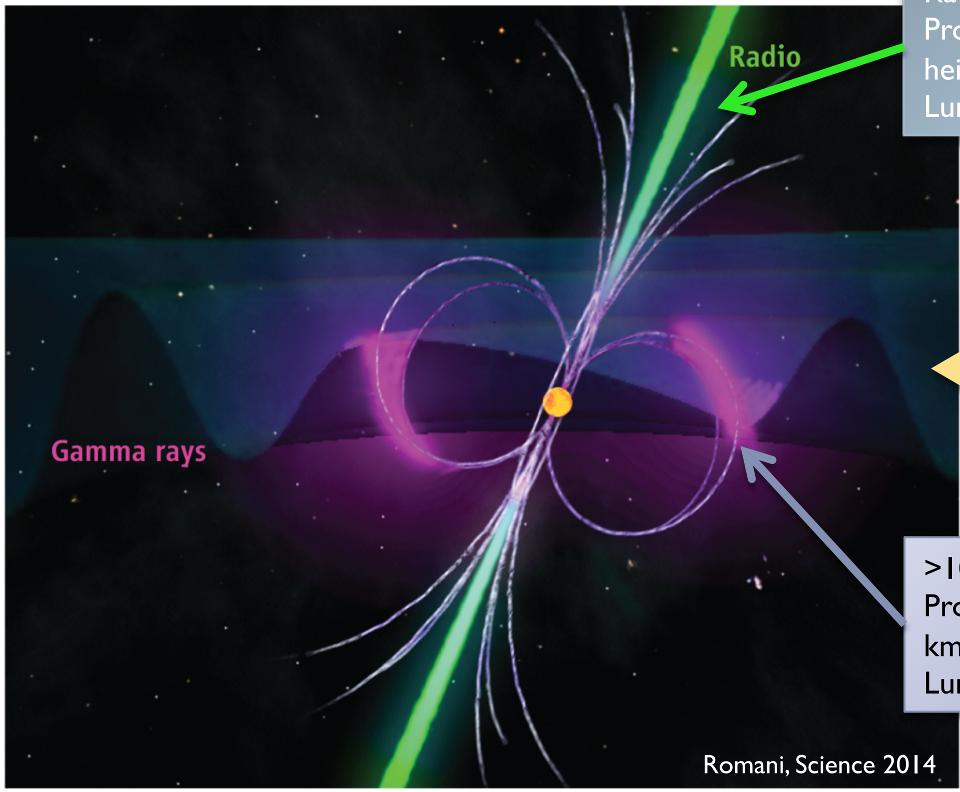
The largest population of sources in the HESS galactic plane survey are Pulsar Wind Nebula.



Optical+X-ray images | X-ray: Chandra | Artist's view

Pulsars

- Energetically speaking pulsars are **cosmic ray sources** = they spend most of their energy in accelerating particles. Photons, especially E<100 MeV, are a "sideshow".



Radio, optical, X:
Produced near the star (<~10 km height) at the polar cap.
Luminosity <1% Pulsar spindown power

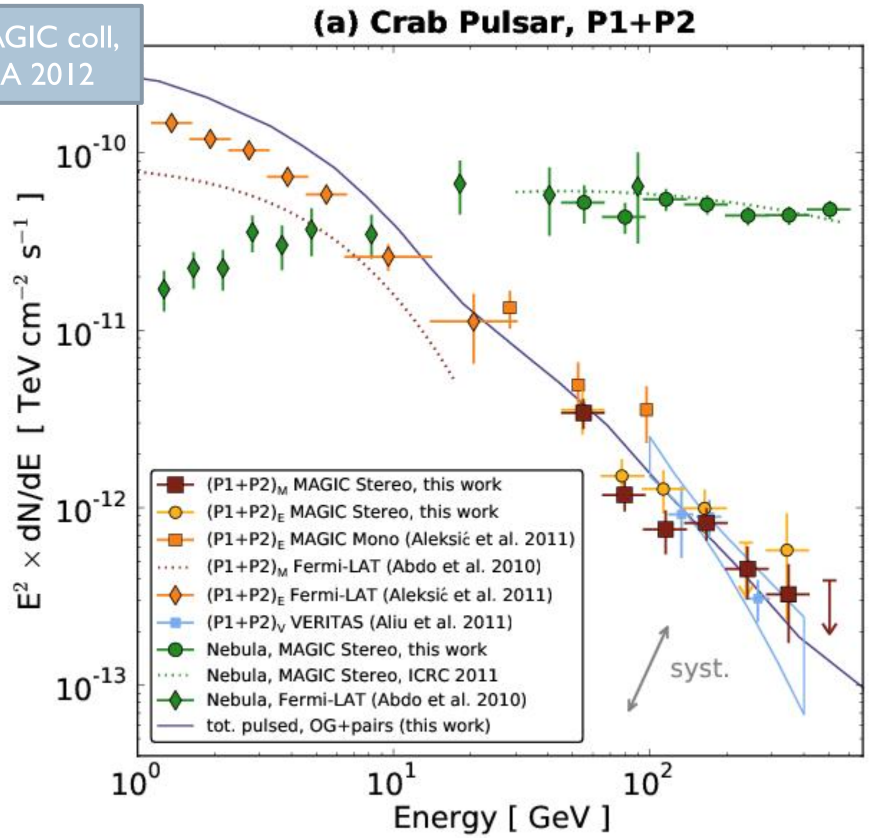
A wind of ~MeV electrons flows away from the star and eventually develops into a "pulsar wind nebula".
Particle Luminosity ~10% spindown power

>100 MeV gammas (Fermi, IACTs):
Produced near the light cylinder (~1000 km height) at the outer gaps.
Luminosity ~10% spindown power

VHE γ-rays from pulsars

- At VHE we study the particles with the highest energy which the pulsar is able to accelerate.

MAGIC coll, A&A 2012

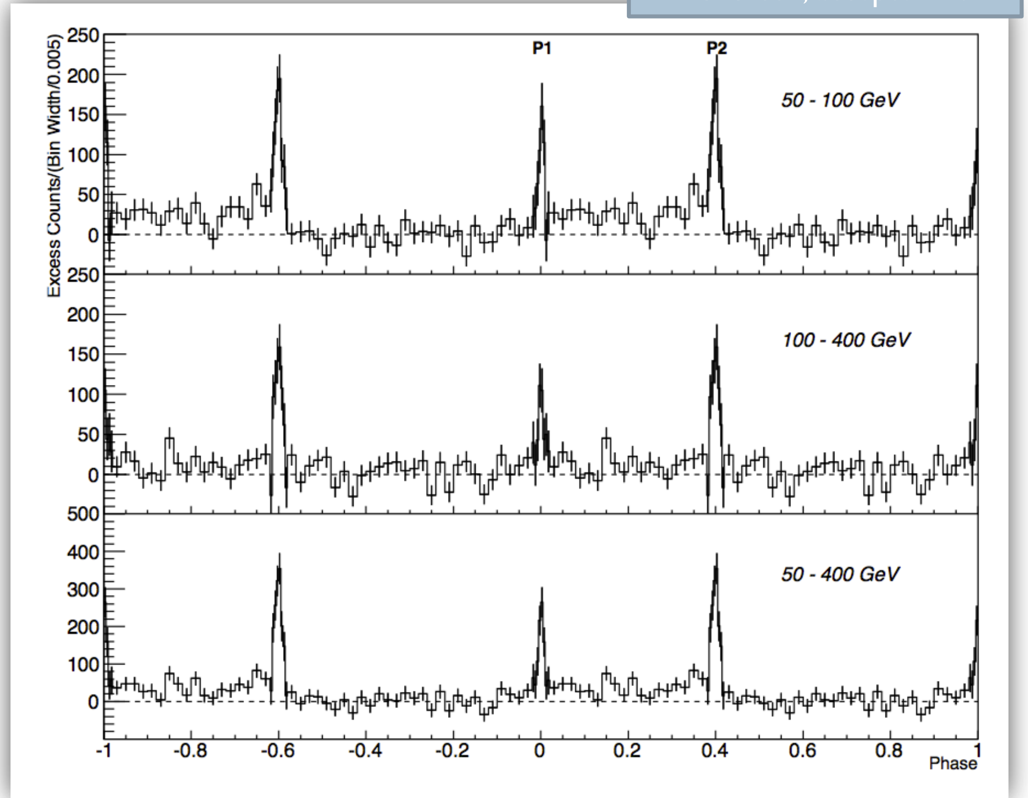


1. MAGIC discovers emission >25 GeV from the Crab pulsar (Science 2008).
2. VERITAS discovers extension >100 GeV (Science 2011).
3. Some months later: MAGIC measures both peaks up to 400 GeV (A&A 2012).
4. MAGIC discovers that "bridge" extends >100 GeV (A&A 2014).

VHE γ-rays from pulsars

- The light curve contains a wealth of information

MAGIC coll, accepted A&A



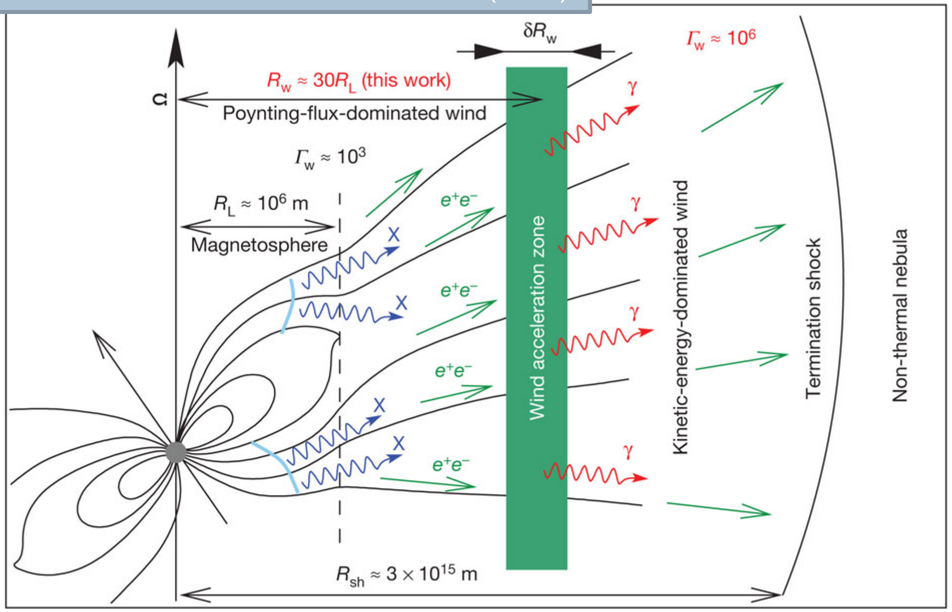
1. Both peaks P1 and P2 are present even at 100-400 GeV.
2. They are very narrow.
3. A bridge is visible at >50 GeV with >6 sigma significance.

Can we explain the VHE phenomenology?

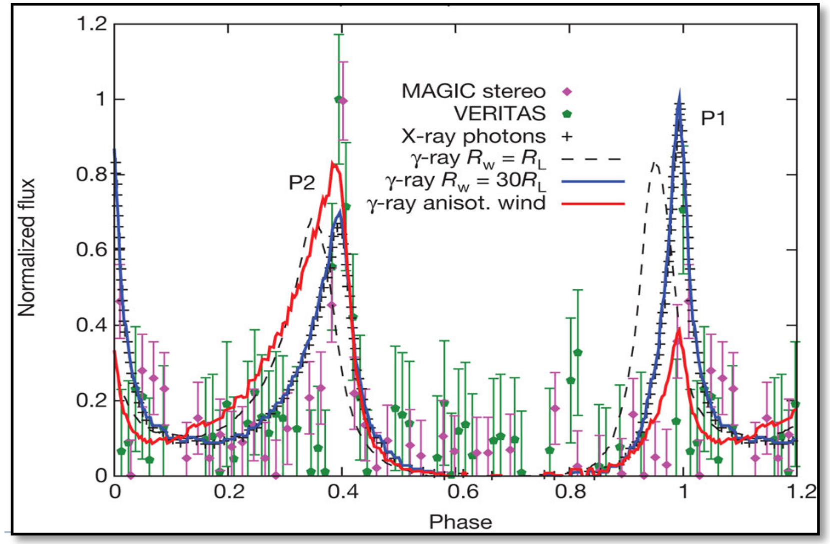
- I can't possibly mention all models. Will zoom on 2 of them.

1

Aharonian et al, Nature 482, 507–509 (2012)

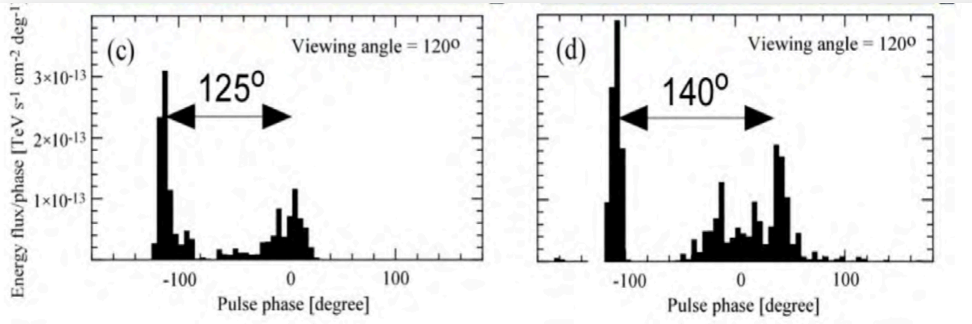


- Proposes VHE γ-rays are not produced inside the magnetosphere but in the wind region.
- If true, VHE allows to study the wind, which is totally dark at other wavelengths.
- Predicts a bridge but much broader peaks.



Can we explain the VHE phenomenology?

- VHE would be produced inside the magnetosphere in an "outer gap".
- VHE photons produced by Inverse Compton on synchrotron photons (SSC).
- Can explain extension to 400 GeV.
- Can explain bridge if magnetic field is not only poloidal, but has also a toroidal component.
- Field lines bend at the edge of the magnetosphere: new discovery.

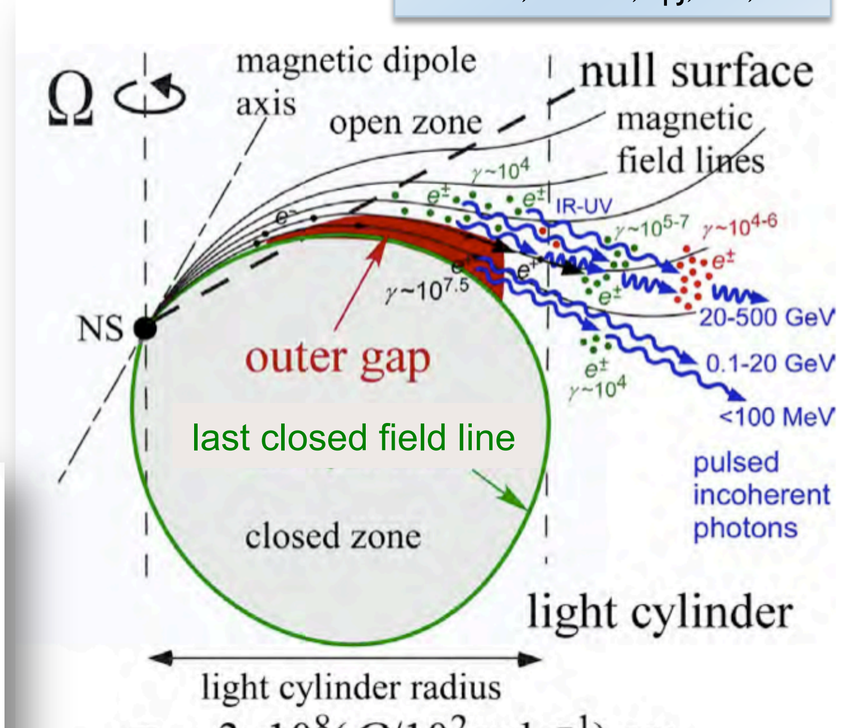


(almost) simple Dipole

Added toroidal component

2

Hirotani, K. 2011, ApJ, 733, L49
Hirotani, K. 2013, ApJ, 766, 98



$\varpi_{LC} = 3\times10^8(\Omega/10^2 \mathrm{rad\,s^{-1}})$ cm

PWN, the Monsters: 3c58 and Crab

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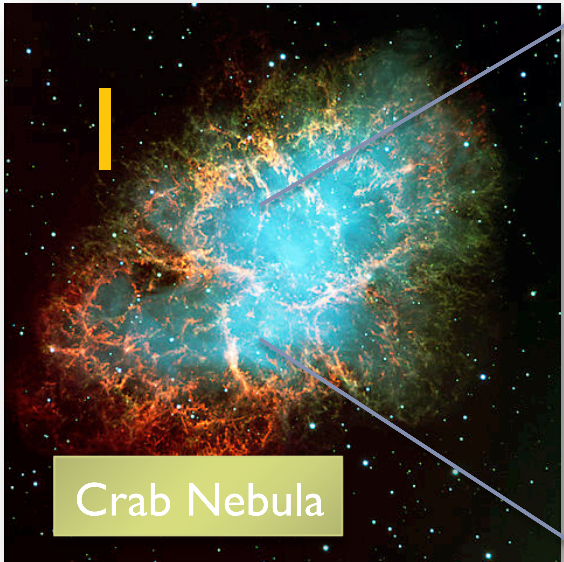
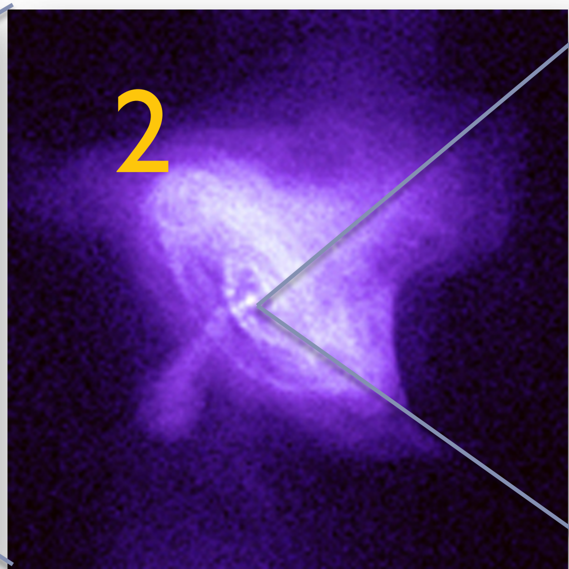
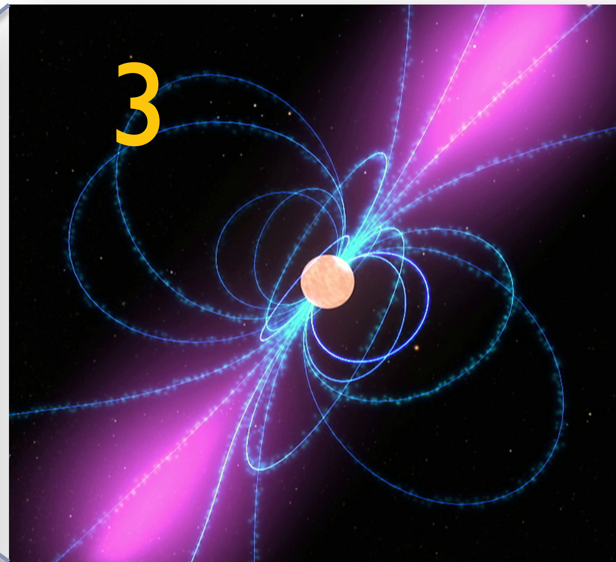


Optical+X-ray images



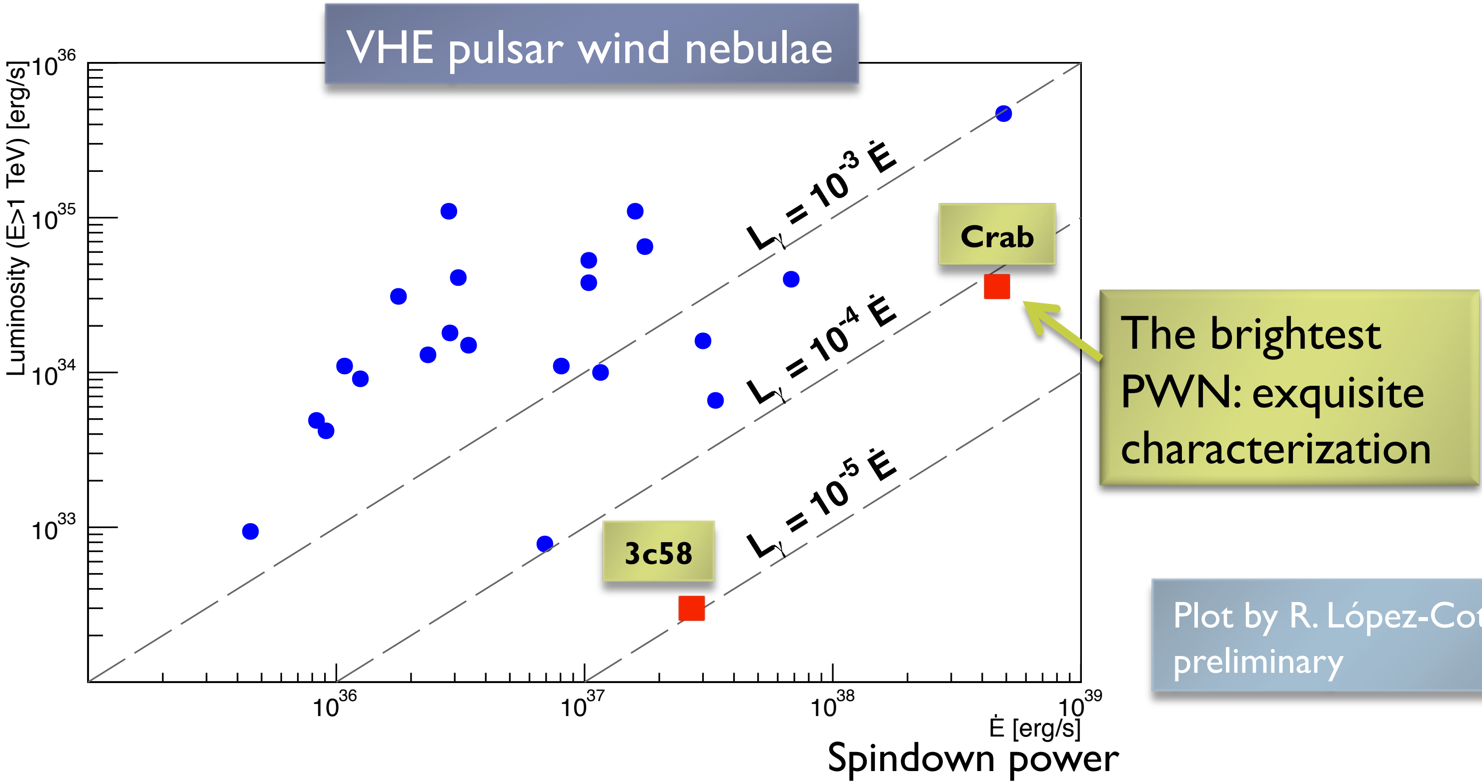
X-ray: Chandra



Artist's view

Monsters haunt MAGIC

- HESS made a survey of the inner galaxy and discovered tens of VHE-bright PWN.
- Instead MAGIC has only studied two PWN. Why should people care about MAGIC's results?
- Because MAGIC has studied two "**Monster PWN**".



Plot by R. López-Coto preliminary

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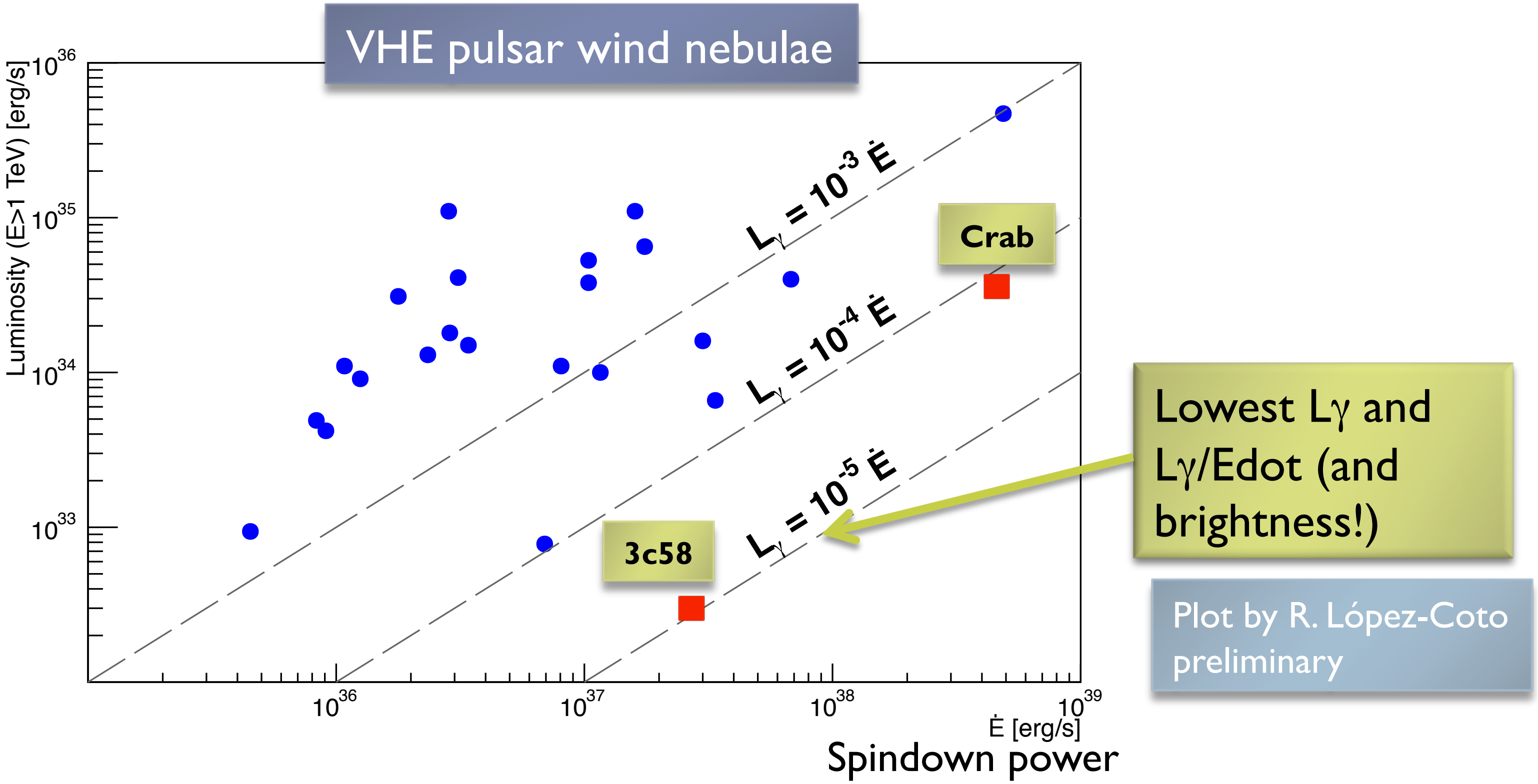
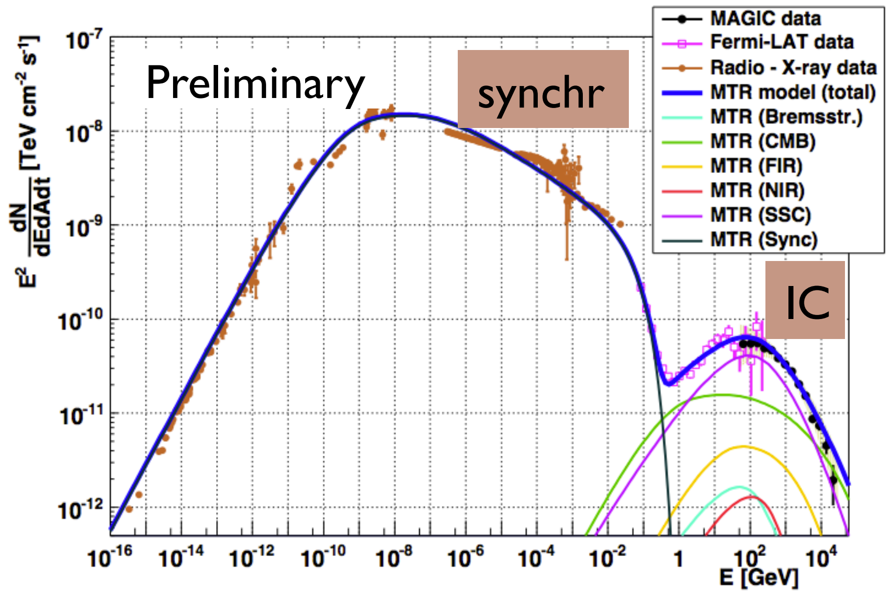
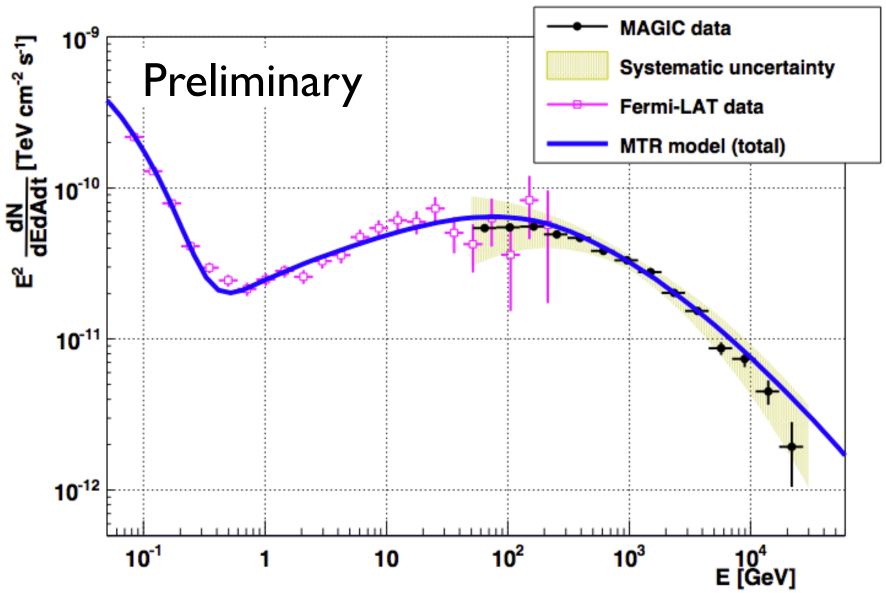


Plot by R. López-Coto preliminary

Monster 1: the brightest PWN, **Crab**

- Latest result, based on 70h stereo observation 2009-2011, about to be submitted for publication:
  - Differential spectrum with a single instrument from 50 GeV up to ~30 TeV and a statistical precision as low as 5% at E<100 GeV
  - Combined with the Fermi-LAT data, yields the most precise measurement of the IC peak so far, at (52.5±2.6) GeV
- Fitted to two different models, but not really satisfactory:
  - Model 1 (Meyer, Horns et al): IC peak is too broad.
  - Model 2 (Martin, Torres et al): hard to fit if one assumes real dependence of PWN morphology on energy.

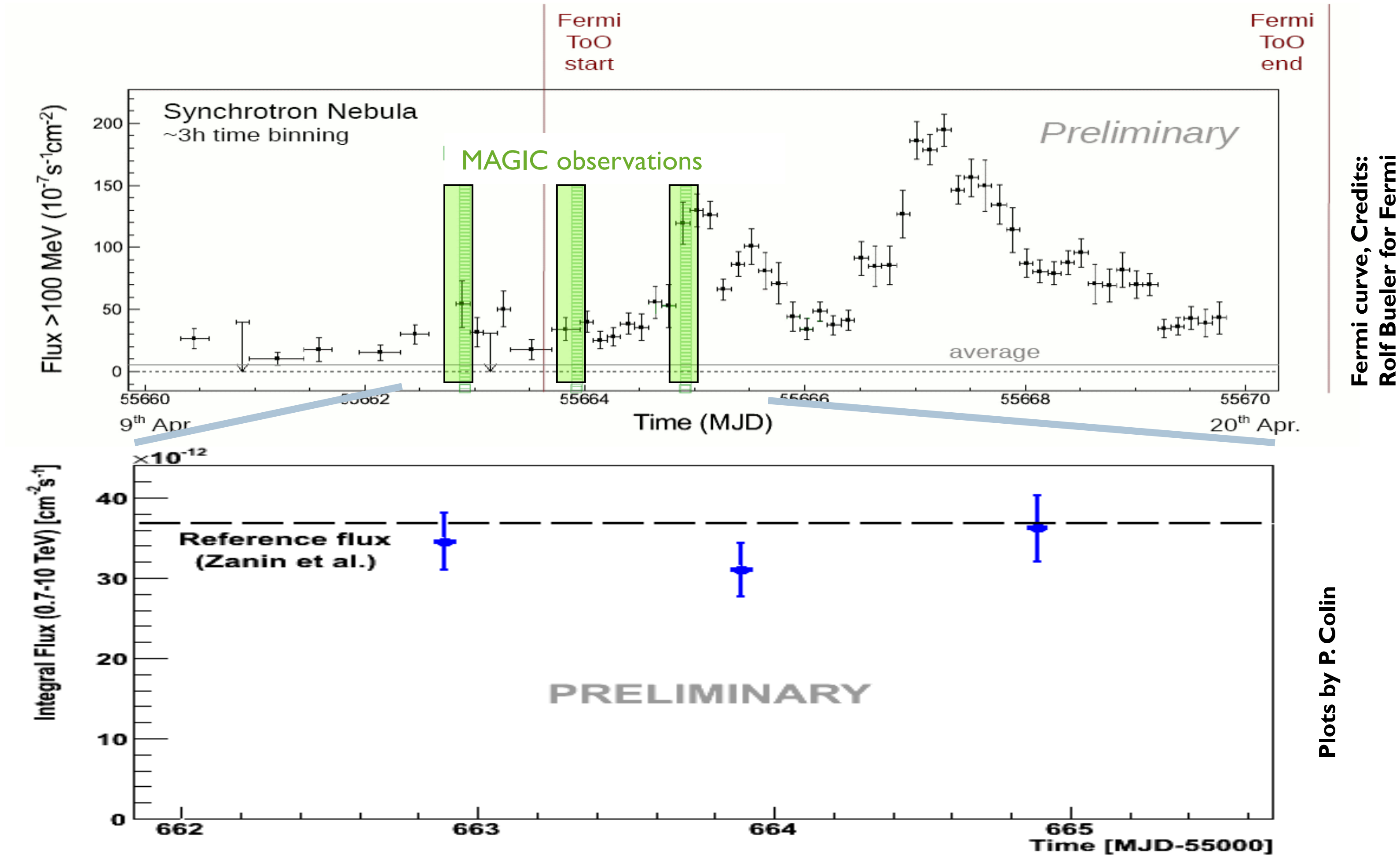




Crab April 2011 GeV flare

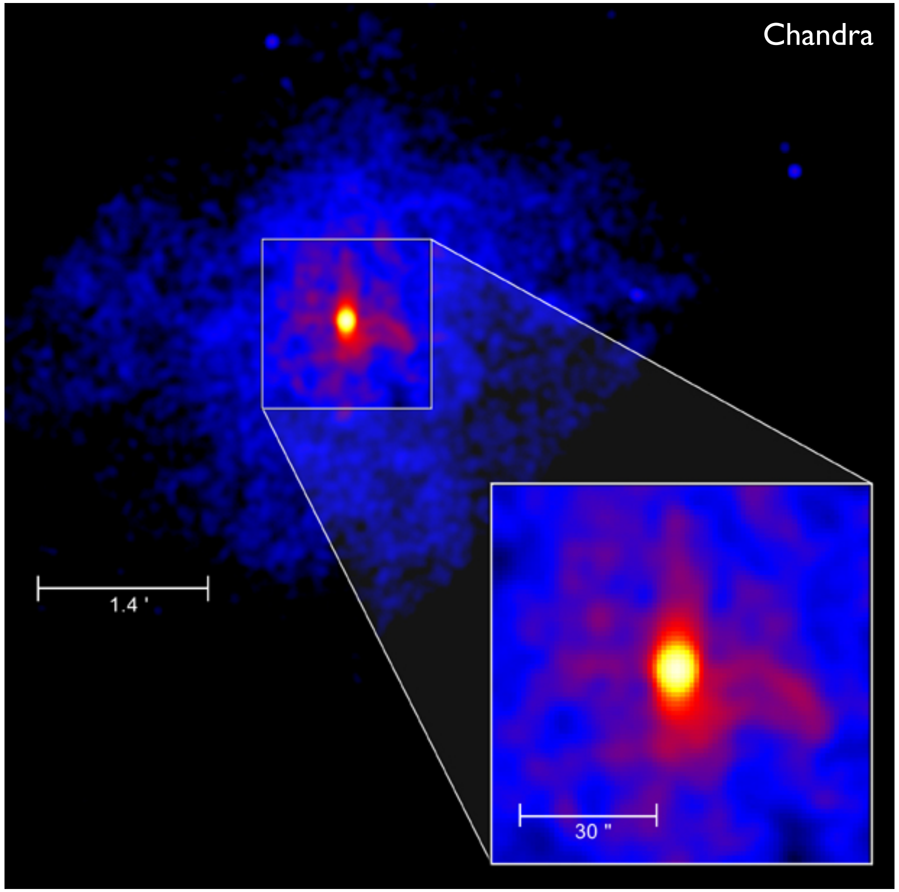
FERMI

MAGIC

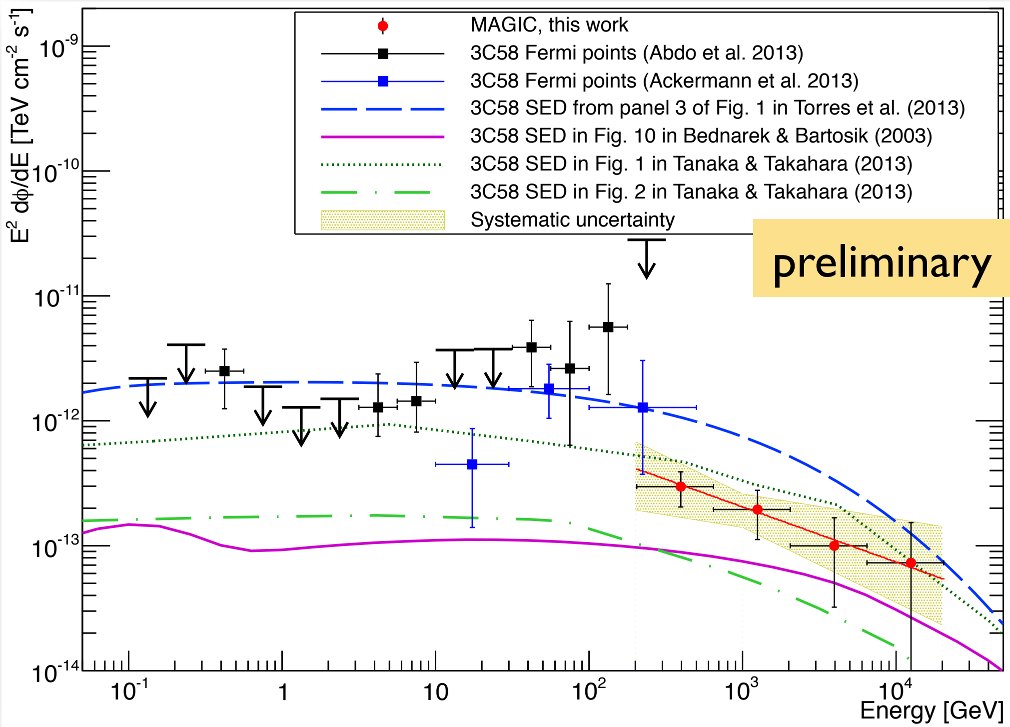


Monster 2: the least luminous PWN, **3c58**

- Centered in PSR J0205+6449 One of the highest spin-down pulsars in the sky: Edot=2.7×10^{37} erg s^{-1} (2% Crab pulsar).
- Distance = 3.2 kpc or 2 kpc?
- Age = 2.5 kyr (?) ➡ Spatially coincident with the supernova in 1181 CE but estimates range from 0.8 to 7 kyr
- X-ray morphology similar to Crab: torus and jet.
- Fermi: pulsar detected at E < 4 GeV, PWN detected up to ~100 GeV.
- Quark star? Neutron star is too cold for its age (Slane et al, ApJ, 571 (2002) L45)



Monster 2: the least luminous PWN, **3c58**



- MAGIC: **discovery** after a 85h observation. Flux is 0.65% crab, the weakest PWN detected at VHE.
- For existing models, only a closer distance of 2 kpc or a high IR density can reproduce the data from radio to VHE. The IR density is probably unrealistically high, so a closer distance of 2 kpc is favored.
- The derived magnetic field by all the models fitting the γ-ray data is in any case smaller than 35 μG, very far from equipartition.

Dark matter

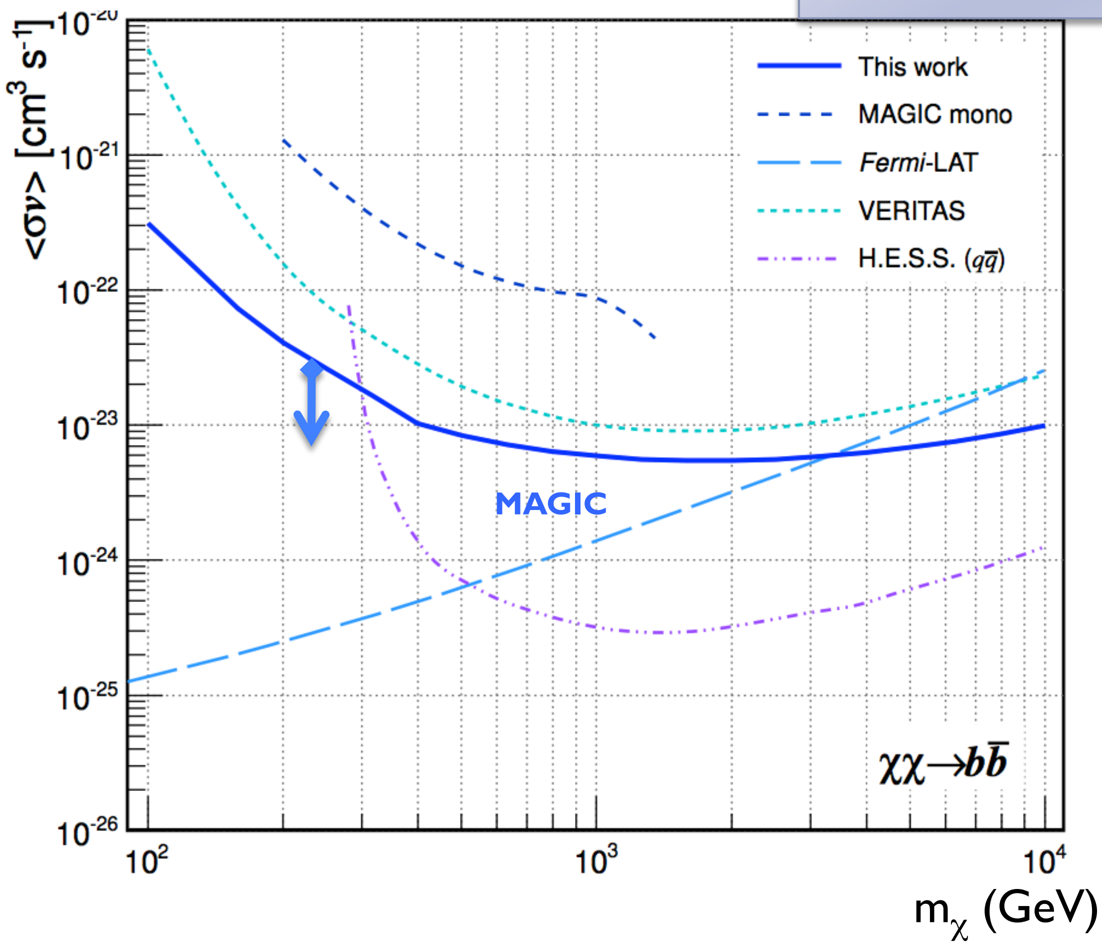
Deep observations of dwarf galaxy Segue1

- Since we don't know exactly how the DM is distributed in different astronomical objects, studying different targets is essential. Not enough to study the Galactic Center!
- 160h stereo observation of Segue 1 (JCAP 02(2014)008): deepest survey of any dSph by any IACT so far.
- Data analysed with full likelihood method: optimized for the recognition of spectral features, like the ones expected from DM annihilation or decay.
- Extracted limits for the spectral shapes expected for secondary γ-rays from annihilation and decay into the SM pairs (bb, tt, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^- and ZZ), for monochromatic gamma-ray lines…

Deep observations of dwarf galaxy Segue1

- Some of the ULs:

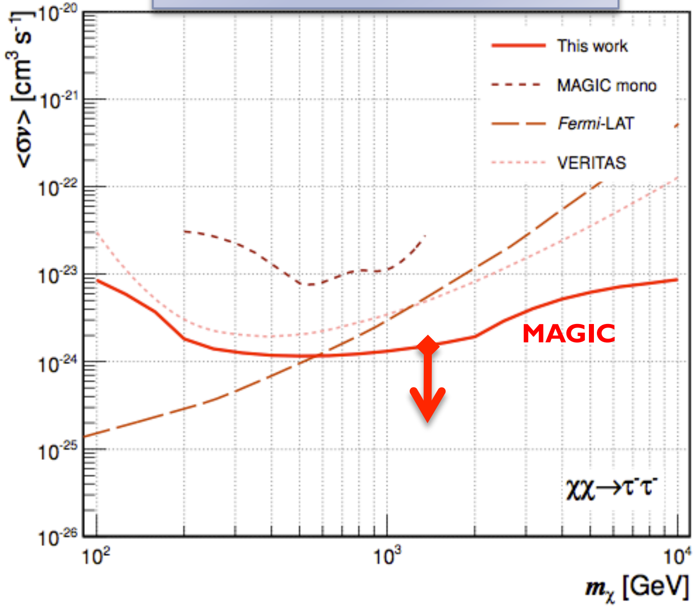
Annihilation into b-bbar



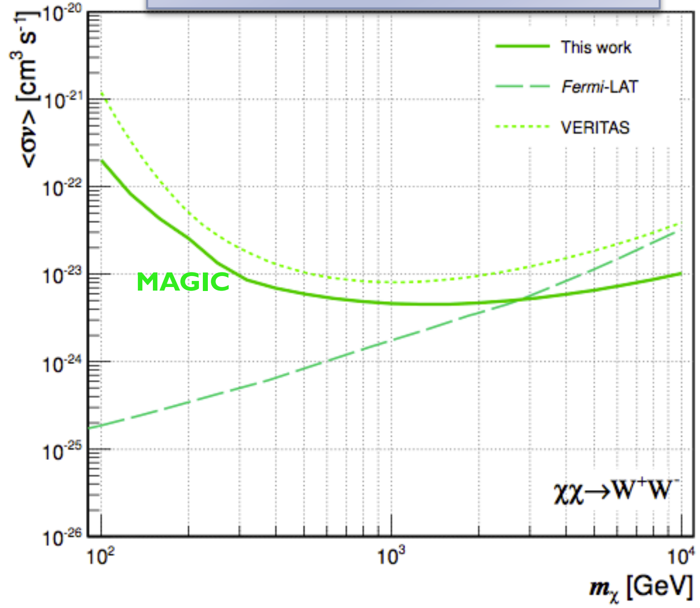
Deep observations of dwarf galaxy Segue1

- Some of the ULs:

Annihilation into $\tau^{-}\tau^{+}$

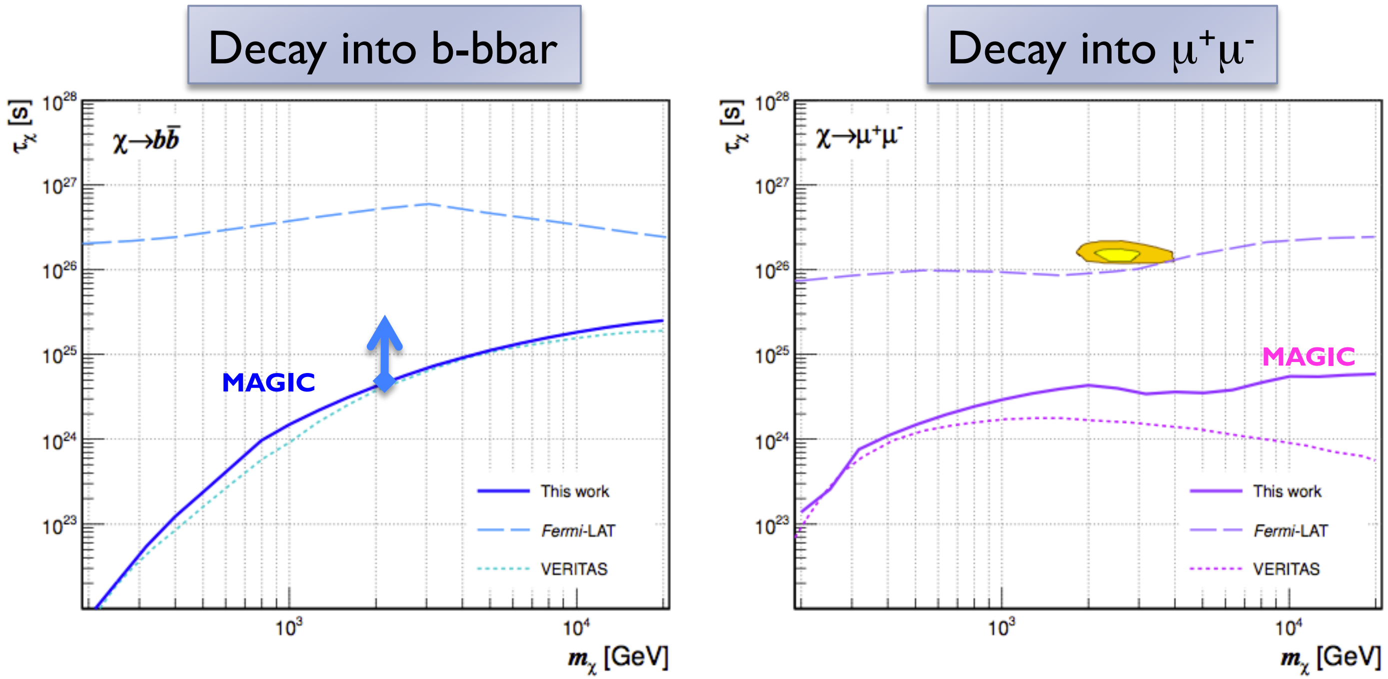


Annihilation into $W^{+}W^{-}$



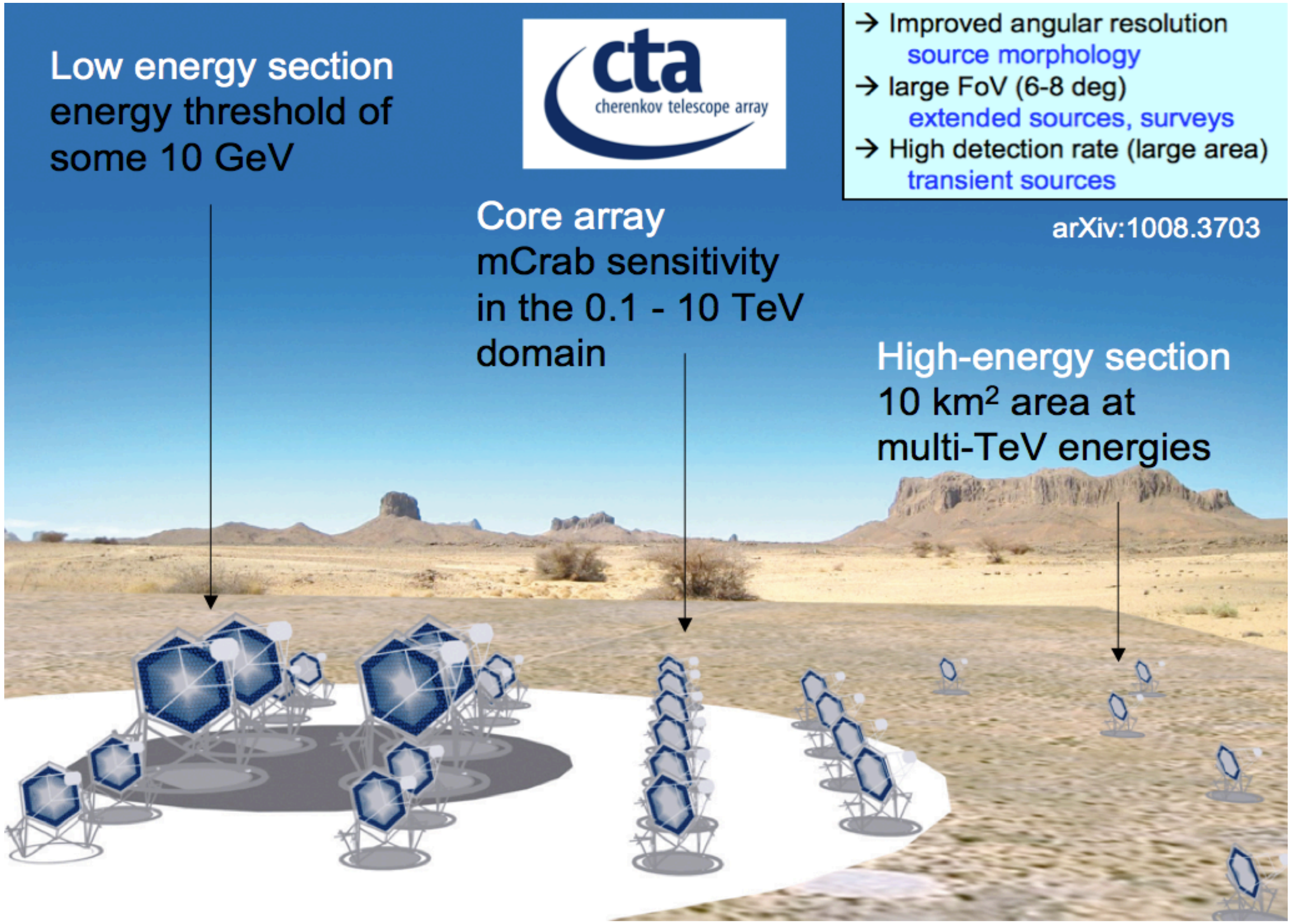
Deep observations of dwarf galaxy Segue1

- Some of the lower limits:



Looking ahead: CTA

- Most of these studies are hitting the limit of sensitivity of MAGIC and other IACTs.



MAGIC: the next years

- Our key physics goals when we designed MAGIC with an energy threshold <100 GeV were:

✓ 1. Discovery of VHE emission from pulsars.

✓ 2. Detection of AGNs up to cosmological redshifts to set limits on EBL.

✗ 3. Detection of GRB at VHE.

- <u>So we need to detect a GRB with MAGIC!</u> A matter of luck?
- During the next years we'll concentrate on a few selected goals: last year we set up 5 Key Observations Programs.