# Discovery of TeV Gamma-Ray Emission from the Pulsar Wind Nebula 3C 58 by MAGIC

Rubén López-Coto on behalf of the MAGIC collaboration - IFAE, Barcelona
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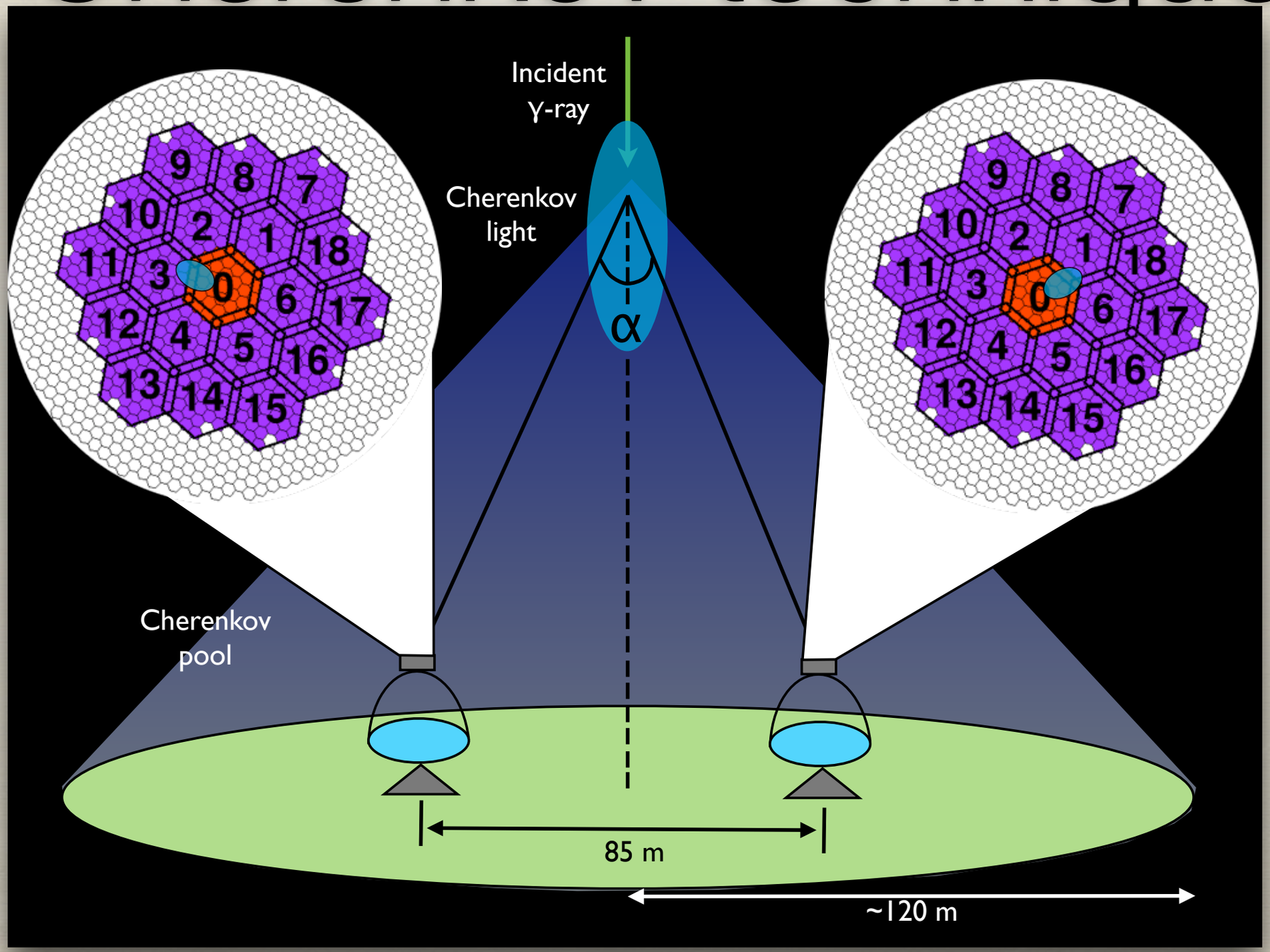
# Outline

- The IACT Technique. The MAGIC telescopes.
- Overview of the source.
- The previous VHE trials to detect it.
- MAGIC observations.
- Comparison with the existing models
- Conclusions

# The Imaging Atmospheric Cherenkov technique



# The MAGIC telescopes

The MAGIC Collaboration: 170 collaborators in 10 countries.
Stereo system of two Imaging Atmospheric Cherenkov telescopes (IACTs) (MAGIC-I 2004, MAGIC-II 2009).
17m diameter reflectors.
Light weight ➜ fast movement to catch GRBs (20s/180º).
The telescopes were recently upgraded to homogenize the system.

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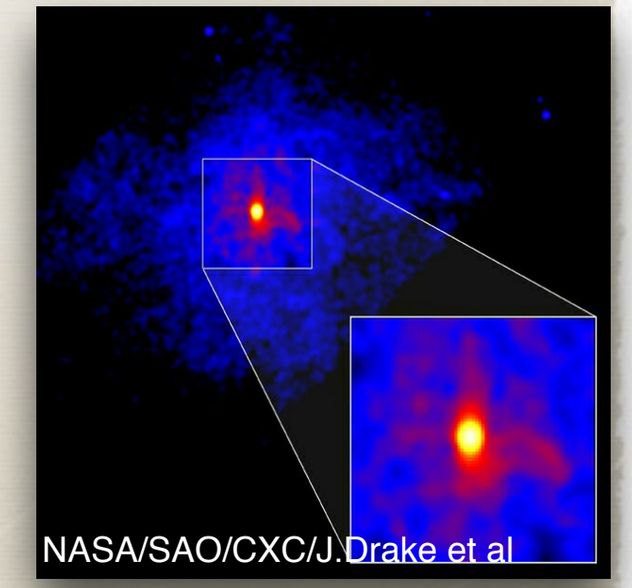
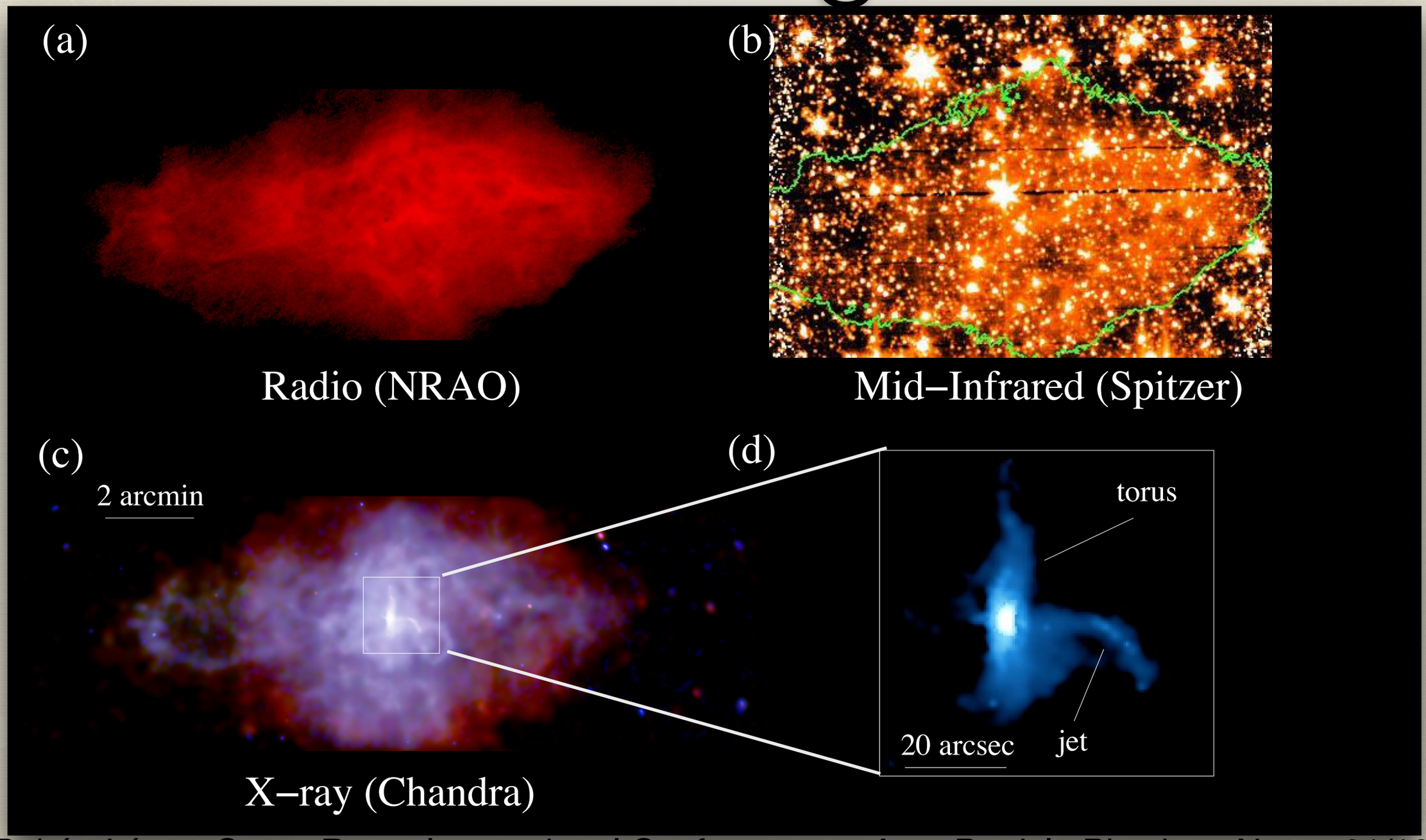
# Overview of 3C 58

- Centered in PSR J0205+6449 ➜ One of the highest spin-down power pulsars in the sky: E(dot)=2.7×$10^{37}$ erg $s^{-1}$ (5% Crab pulsar).
- Distance = 3.2 or 2 kpc (?)
- Age = 2.5 kyr (?) ➜ Spatially coincident with the supernova of 1181 CE and different estimations give it an age ranging from 0.8 to 7 kyr
- Size (Radio, IR, X-rays) = 9’ x 6’
- 3C 58 has been compared to Crab due to the jet-torus morphology ➜ One of the classical sources considered to emit gamma-rays.
- Pulsar detected by Fermi at E < 4 GeV
- Quark star? Neutron star is too cold for its age



# Morphology at different wavelengths



# Age and distance discrepancies

- Age estimated by different methods:
  - Historical association with SN 1181 ➡ 0.83 kyr
  - PWN evolution and energetics ➡ 2.5 kyr
  - Velocity measurements of optical knots ➡ 3-4 kyr
  - Neutron star cooling models ➡ >5 kyr
  - Pulsar characteristic age ➡ 5.4 kyr
  - Radio expansion of the nebula ➡ 7 kyr

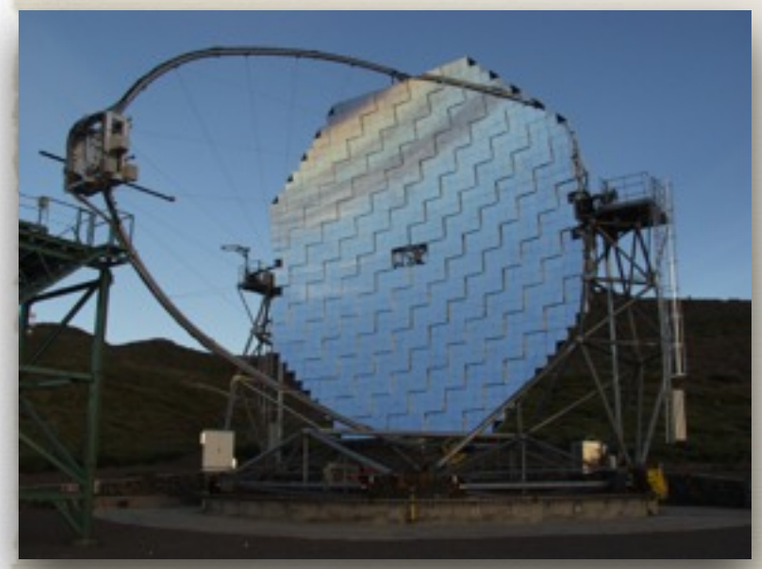
- All these methods took into consideration a distance of 3.2 kpc to the PWN. This distance was measured using HI absorption measurements of the Effelsberg telescope (Roberts et al. 1993)

- A recent measurement based on HI data of the Canadian Galactic Plane survey estimates the distance to be 2 kpc (Kothes 2013).

# Very High Energy history

Whipple observed 3C 58 in 2001 establishing upper limits at the level of 19 % of Crab above 500 GeV (Hall et al. 2001).

VERITAS in 2006 observed it for 12.8 hours. Point-like upper limit at 2.3% Crab above 300 GeV with a 1.1σ significance (Aliu 2008).

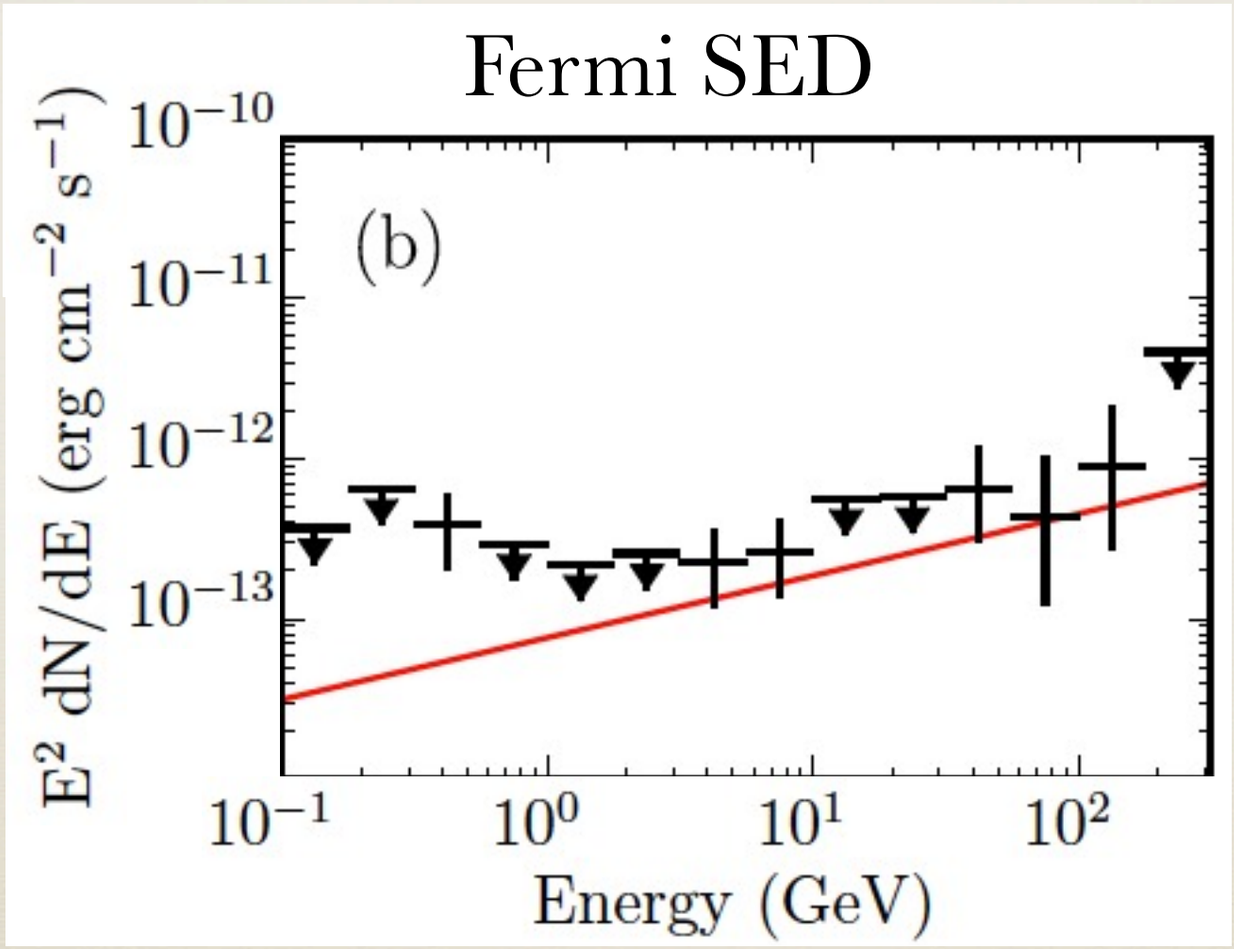


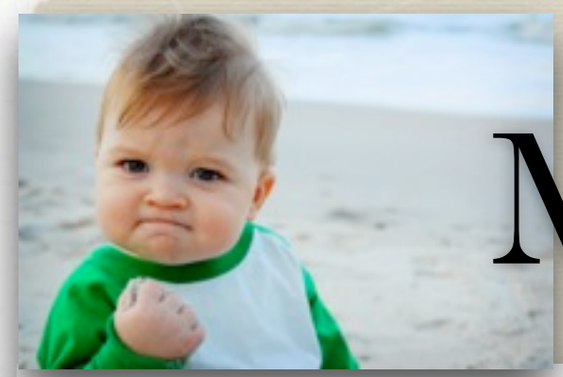
MAGIC I in 2005 observed it for 48 hours. Point-like upper limits were established above 320 GeV at the level of 4% Crab with a 1σ significance (Anderhub et al. 2010).

# Observations trigger

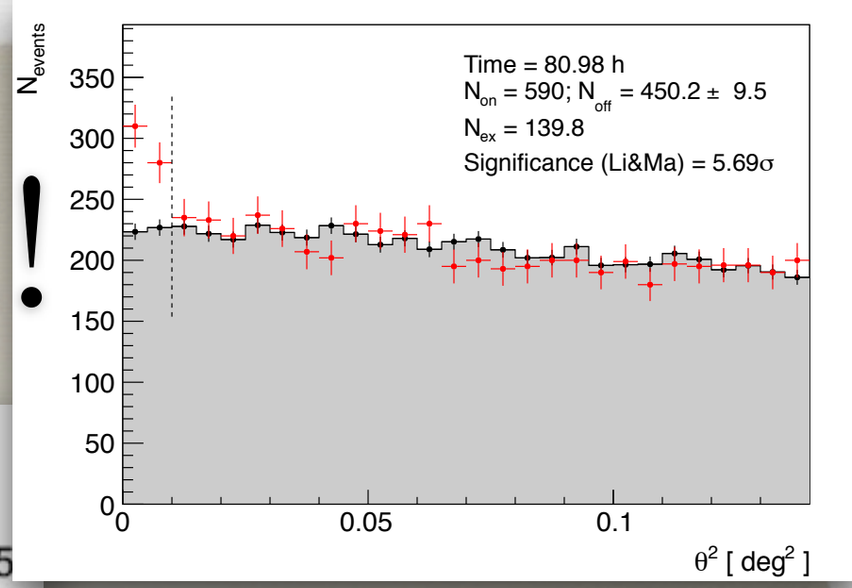
- Fermi publishes its 2nd pulsar catalog (19/05/13) ➜ They detected non-pulsed high energy gamma rays from 3C58

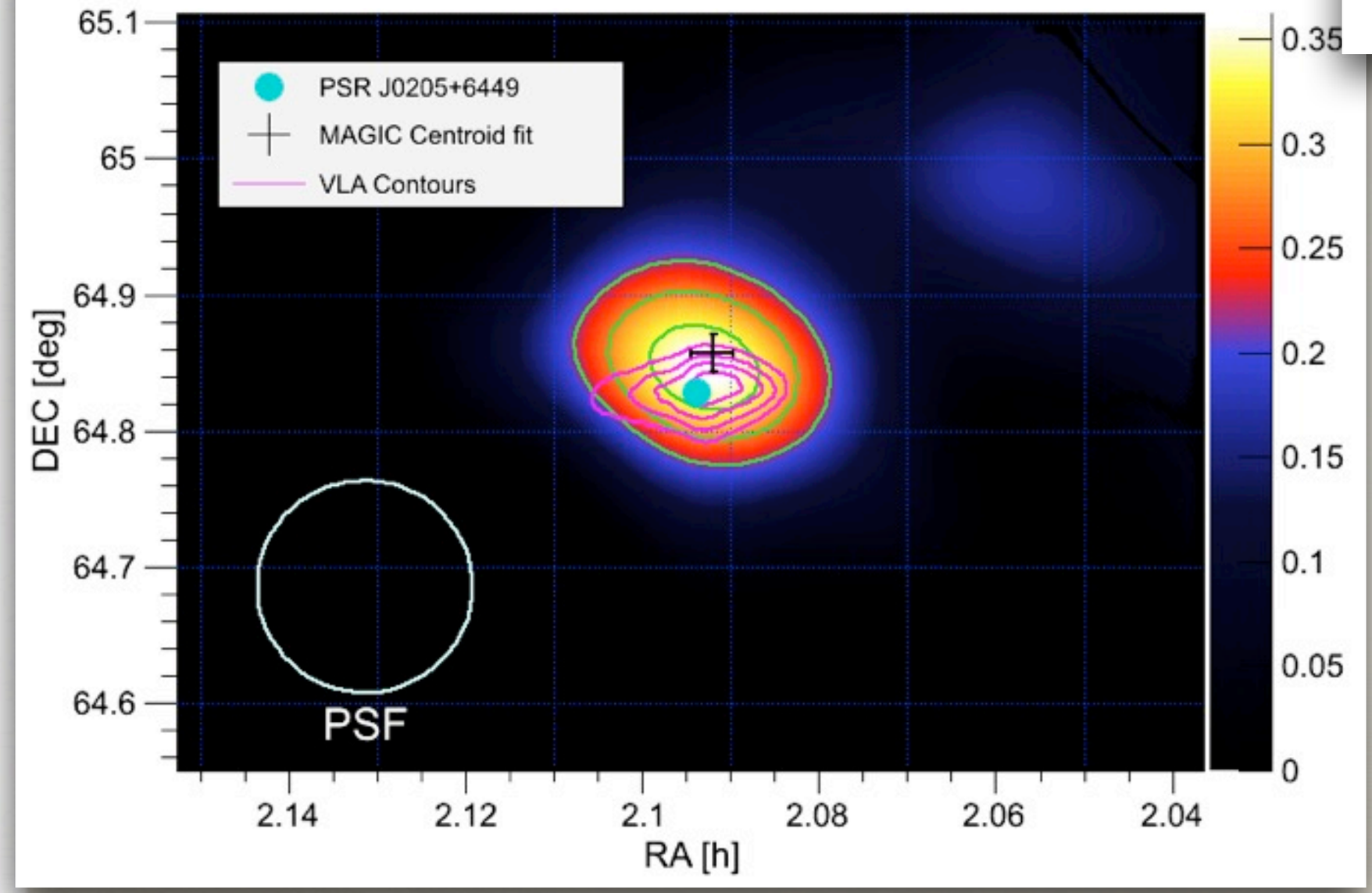
- The spectrum reported is a power-law with -1.6 slope that extends up to energies >100 GeV





# MAGIC got it!!!




MAGIC discovered a VHE gamma-ray source at the position of 3C 58 (MAGIC J0205+6451)

81 hours of observation

Fit to MAGIC excesses = 4.7'±1.4'
(MAGIC PSF = 4.8')

**Aleksić, J. et al., A&A 567 (2014) L8**

# SNR VHE association

- Following the model of Drury et al. (1994), we evaluated the possibility that the VHE gamma rays are produced by hadronic emission in the SNR.

- We assumed:
  - Distance of 2 kpc.
  - SN initial energy explosion of $10^{51}$ erg.
  - Density of the medium 0.38 $d^{-1/2}$ $cm^{-3}$

- According to the model, the efficiency necessary to accelerate cosmic ray nuclei is larger than 100 % to account for the flux observed ➜ VHE emission detected associated with the SNR is highly unexpected

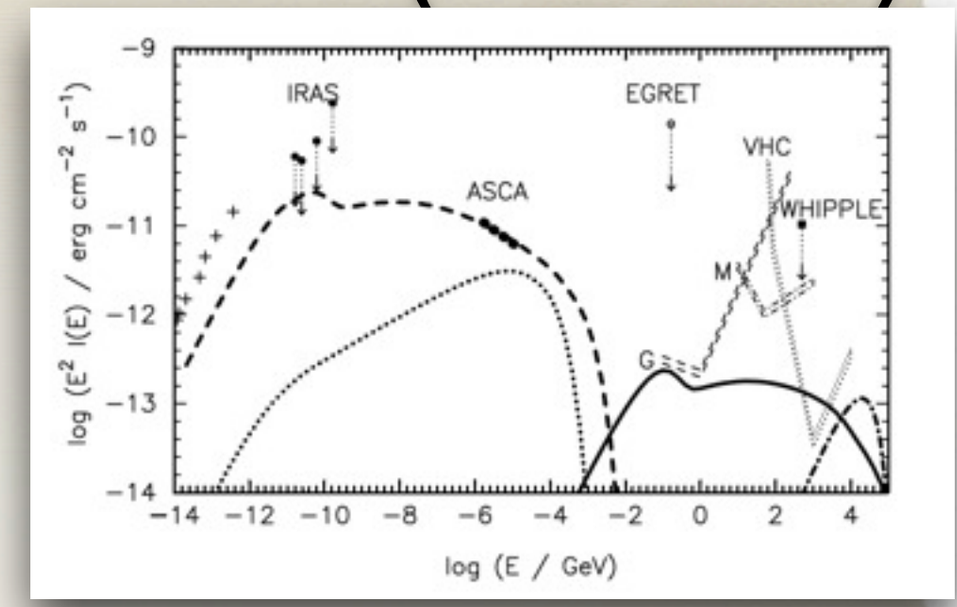
# PWN Models

- There are several models of the VHE gamma ray emission of PWNe, but only a handful predicting the emission from 3C 58, all of them being time-dependent:

  - **Bednarek & Bartosik (2003)** modeled the emission by considering a PWN where positrons gain energy by interacting with nuclei ➜ It fits VHE emission under some particular conditions, but it does not fit radio emission
  - **Tanaka & Takahara (2013)** computed the evolution of the PWN by solving the advective diffusion-loss equation➜ It fits the multiwavelength (MW) data considering a 2 kpc distance and 2.5 kyr age.
  - **Torres et al. (2013)** models the evolution of the PWN solving the complete diffusion-loss equation and computes the emission not making any radiative approximation ➜ It fits the MW data if assuming an unexpectedly high FIR energy density

**→ All of them derive a low magnetic field for the PWN**

# Bednarek & Bartosik (2003)



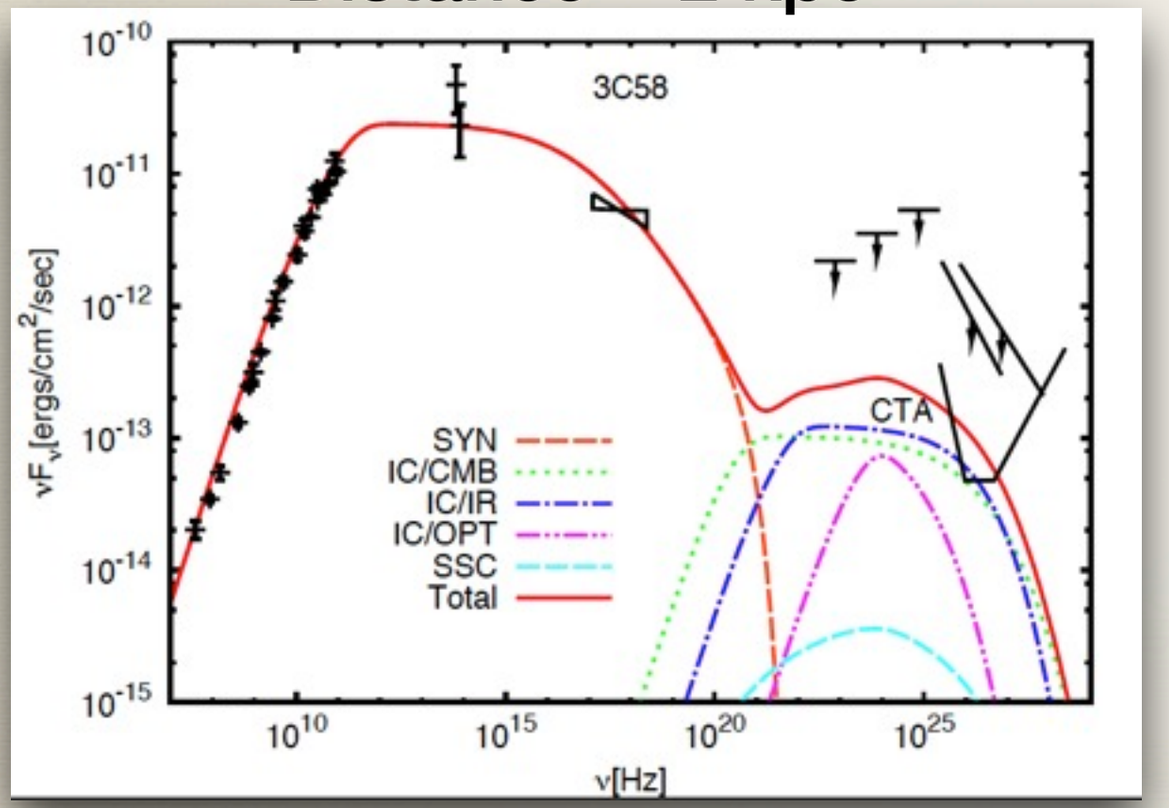

- Age considered for the nebula: 5 kyr;
- Distance: 3.2 kpc
- Gamma-rays in the PWN produced by:
  - Positrons up-scattering CMB, IR and synchrotron photons
  - Pion decay
- The predicted flux is 5 times smaller than the observed by MAGIC.
- A change in the initial expansion velocity estimates larger fluxes, more compatible with our observations (Bednarek and Bartosik, 2005).
- The magnetic field derived is 14 μG.
- However, this model underestimates the radio emission.

# Tanaka & Takahara (2013)

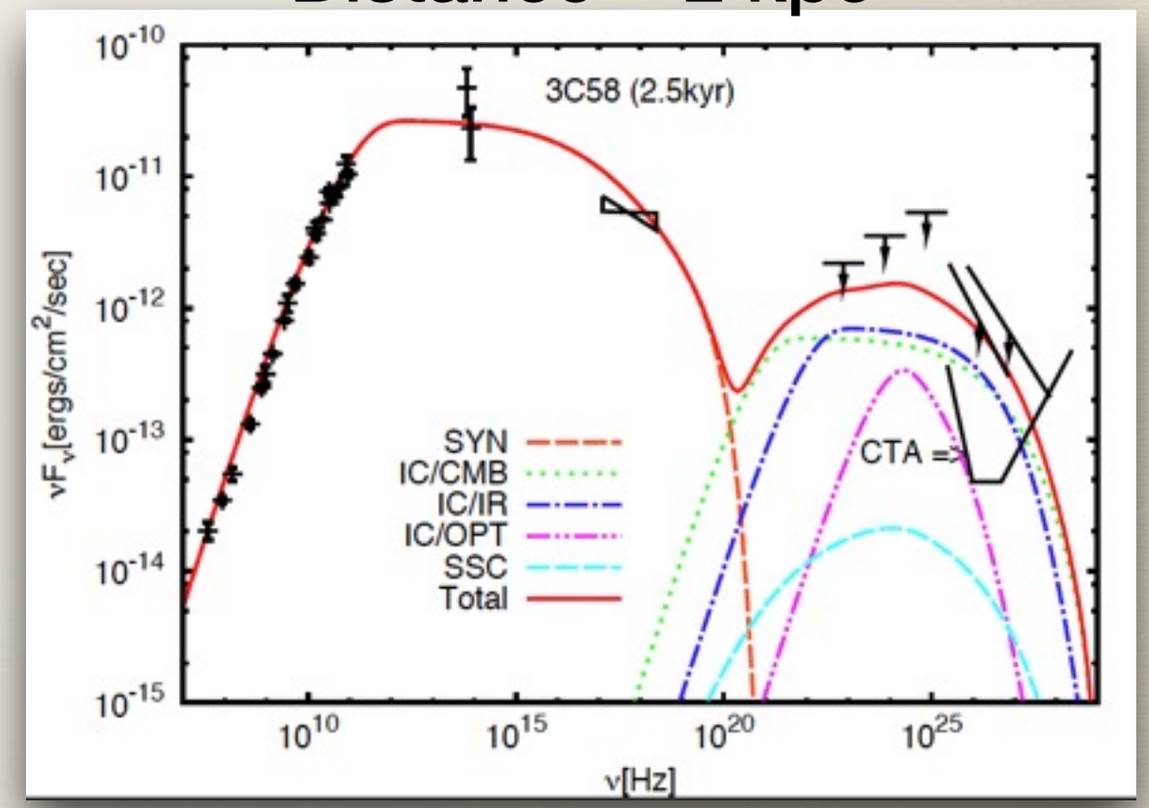
- To model the spectral evolution of the PWN, they solve the time-dependent diffusion-loss equation neglecting the escape term.
- Age considered for the nebula: 1 kyr and 2.5 kyr.
- Distance: 2 kpc
- Gamma-rays in the PWN produced by:
  - Synchroton; Inverse Compton of CMB, IR and optical photons; and synchroton-self Compton.
- Magnetic field derived is between 17-40 μG.

# Tanaka & Takahara (2013)

**Age = 1 kyr**
**Distance = 2 kpc**

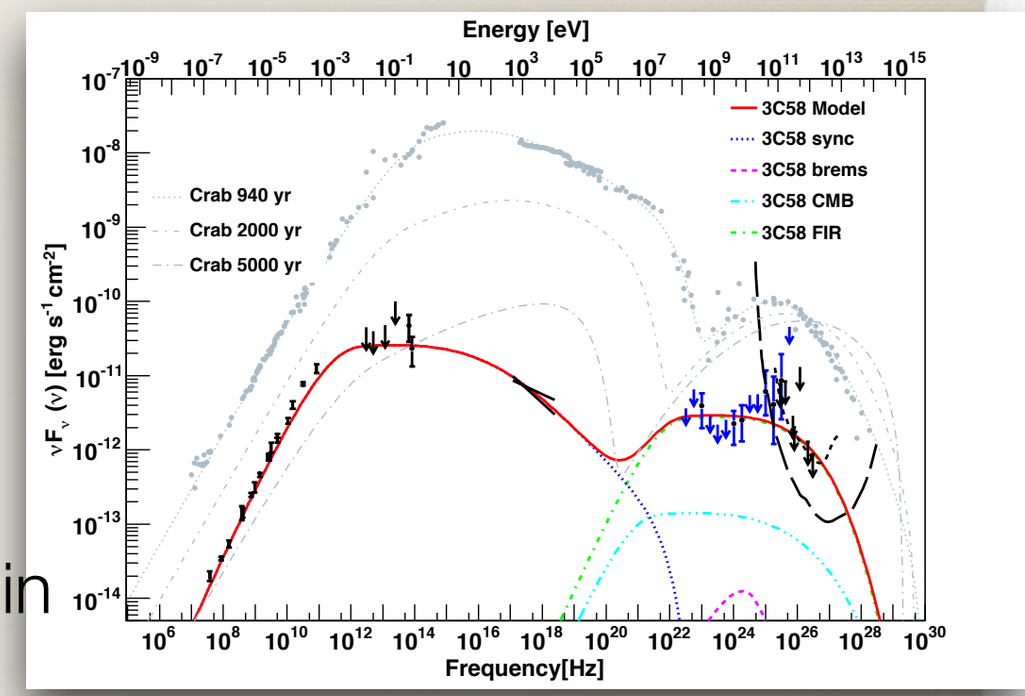



**Age = 2.5 kyr**
**Distance = 2 kpc**

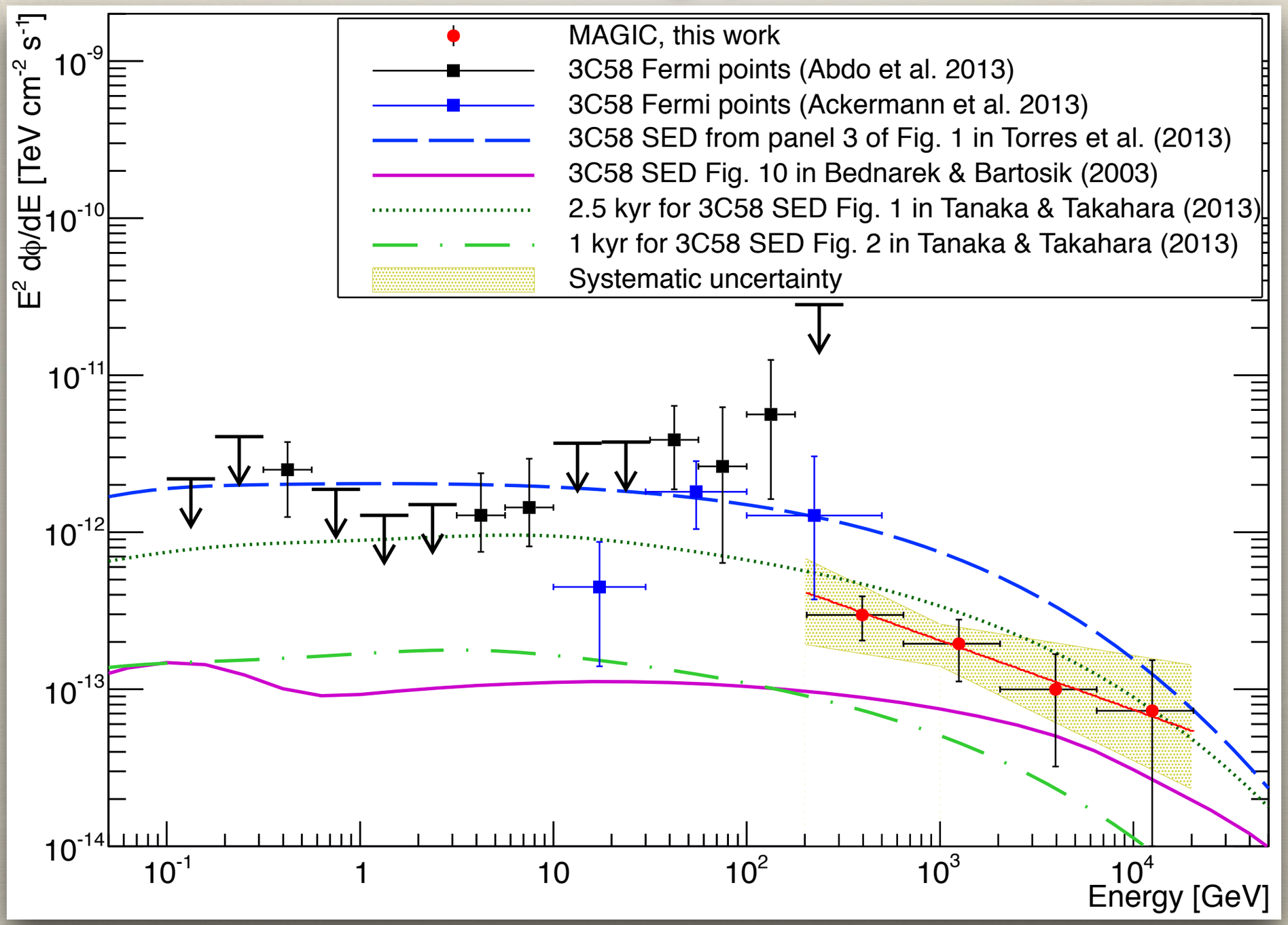


# Torres et al. (2013)

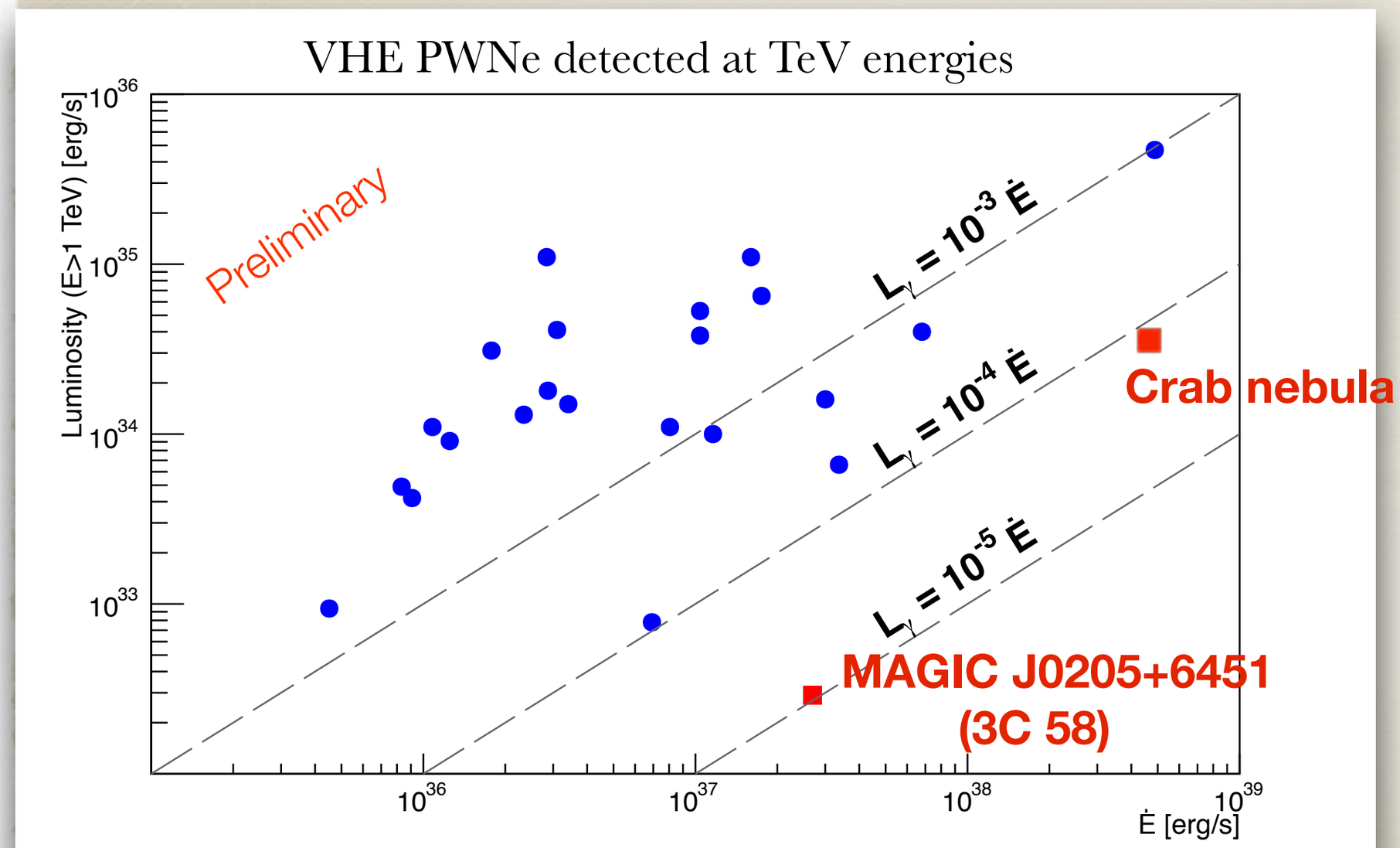
- They modeled the PWN evolution solving the time-dependent diffusion-loss equation without making any approximation.
- Age considered for the nebula: 2.5 kyr;
- Distance: 3.2 kpc
- Radiation in the PWN produced by:
  - Synchroton, Inverse Compton of CMB, IR and optical photons, synchroton-self Compton and Bremsstrahlung.
- It predicts emission detectable by MAGIC only in the case of an unexpectedly high FIR density.
- If the distance is reduced to 2 kpc, the photon target densities necessary to account for the VHE gamma-rays observed are reduced.
- The magnetic field derived by the model is 35 μG.



# Spectral Energy Distribution



# Gamma-ray luminosity




PWN with the lowest luminosity at VHE gamma rays ever detected

Also the one with the lowest flux (0.65% C.U.)

$L\gamma \simeq 10^{-5}$ Edot

# Conclusions

- MAGIC has discovered the least luminous PWN and the one with the lowest flux at VHE gamma rays to date.

- Following the assumptions made in Drury et al. (1994), we find that the association of the VHE emission with the SNR is highly unlikely.

- In the context of the existing models:
  - We favor an explanation of the multiwavelength SED measured by the models assuming a distance of 2 kpc to the source and comparable FIR to the average in the Galaxy.
  - The possibility that the VHE flux is explained with a distance of 3.2 kpc an unexpectedly high FIR component is not ruled out.
  - The rest of the models are not able to reproduce the multiwavelength data.

- The magnetic field drawn from all the models is far from equipartition and low for a young PWN.

# Thanks!!!

# Backup

# Bucciantini et al. (2011)

- One-zone time-dependent leptonic model for the evolution of PWNe
- Distance = 3.2 kyr
- Gamma-rays in the PWN produced by:
  - Positrons up-scattering CMB, IR and synchrotron photons
  - Pion decay
- The addition of the magnetic plus the electrical energy is larger than 1 ➡ It does not conserve the energy.
- Flux predicted at VHE far from the observed one.