Hadronic TeV emission of the supernova remnant W51C observed wit the MAGIC Telescopes?!

(Aleksic et al. 2012, A&A, Volume 541, id.A13)

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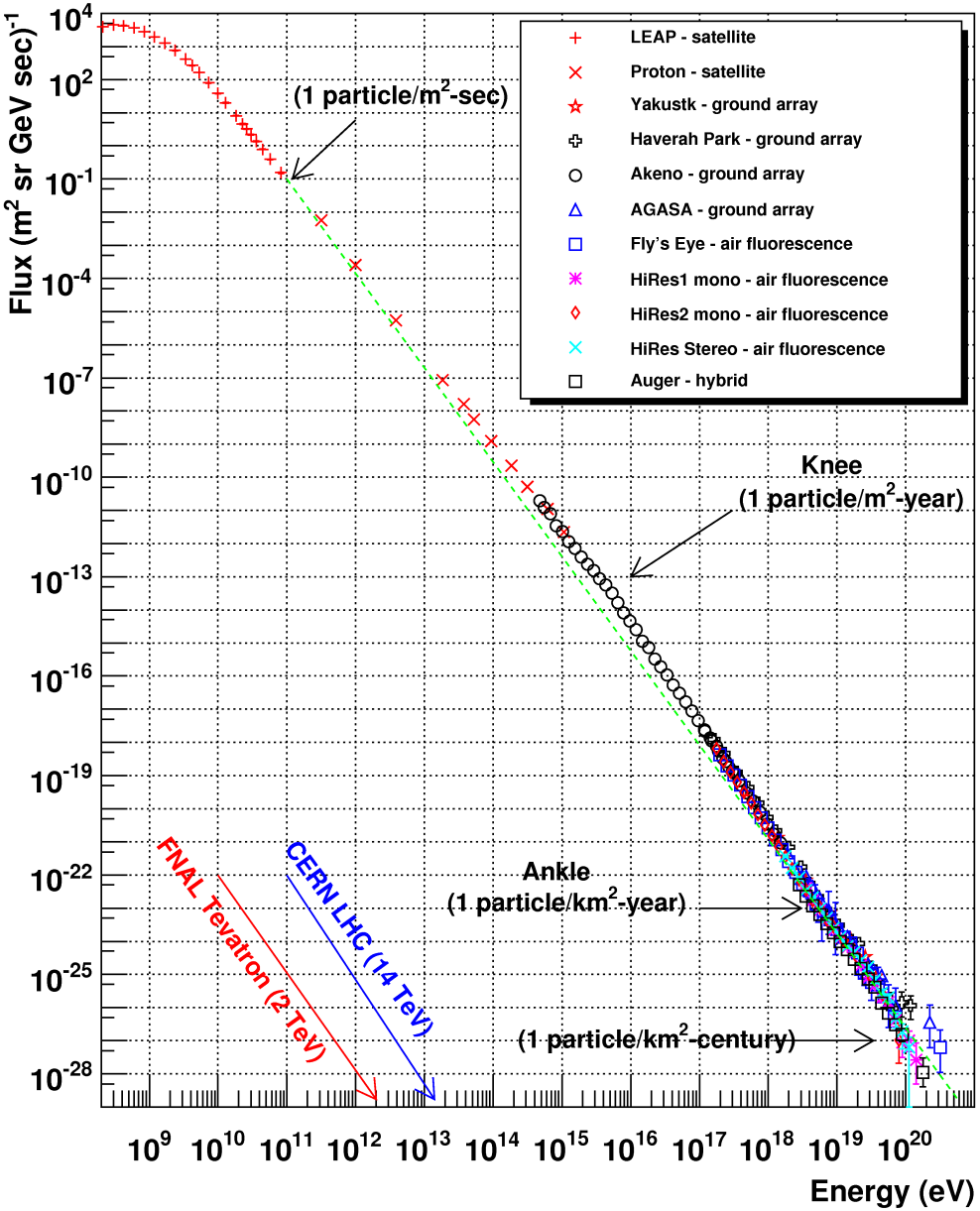
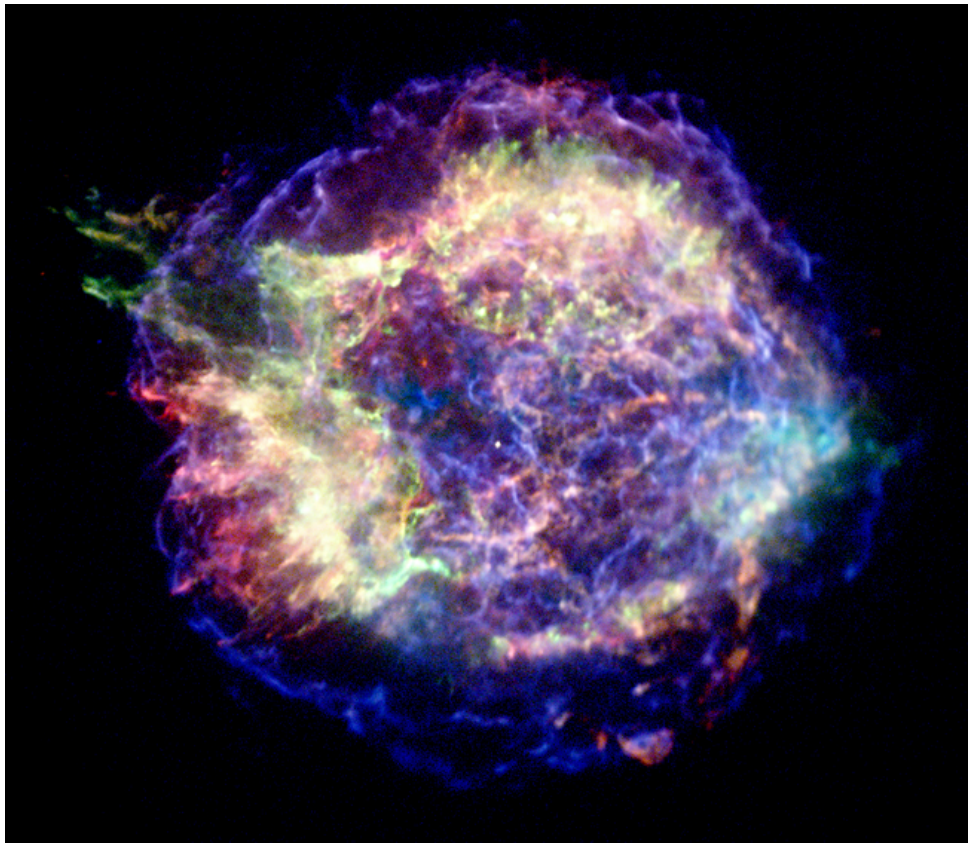
Cosmic rays & their interstellar medium, June 24 – 27, 2014

Relativistic particles in the universe: Cosmic Rays



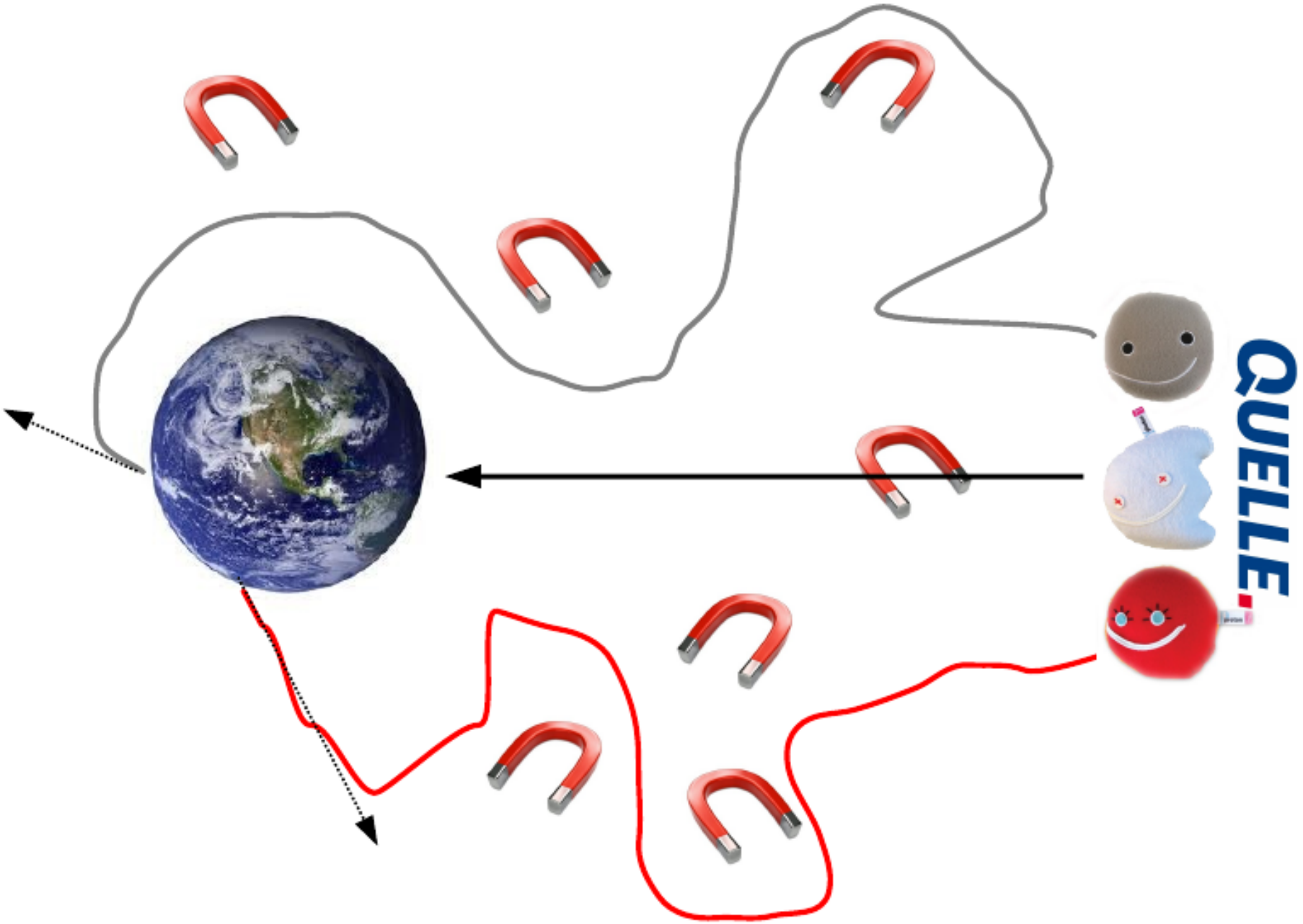
- isotropic flux
- power-law spectrum $E^{-2.7}$ (below the knee)
- $\sim$89% protons
- $\sim$10% helium
- $\sim$ 1% electrons
- below the knee ($\sim 10^{15}$) galactic origin
- above the ankle ($\sim 10^{18}$) extragalactic origin
- CR energy density $\sim$1 eV/cm^3

The origin of galactic CRs: Supernova remnants



- provide enough energy $\Rightarrow$ kinetic energy of a SN $\approx 10^{51}$ erg (5-20% needed for CR)
- reproduce observed power-law spectrum $\Rightarrow$ shock acceleration
- accelerate CR up to the knee $\rightarrow$ theoretically possible in SNR

The *problem* with CRs



Relativistic particles do produce gamma-rays

1. Leptonic processes (electrons, positrons)
   - Inverse Compton scattering

     up-scattering of a soft photon (e.g. CMB) by an relativistic electron

     $L_\gamma \propto n_e \times n_{photons}$
   - Bremstrahlung

     Radiation of a soft photon in the electric field of an nuclei (ISM)

     $L_\gamma \propto n_e \times n_{ISM}$

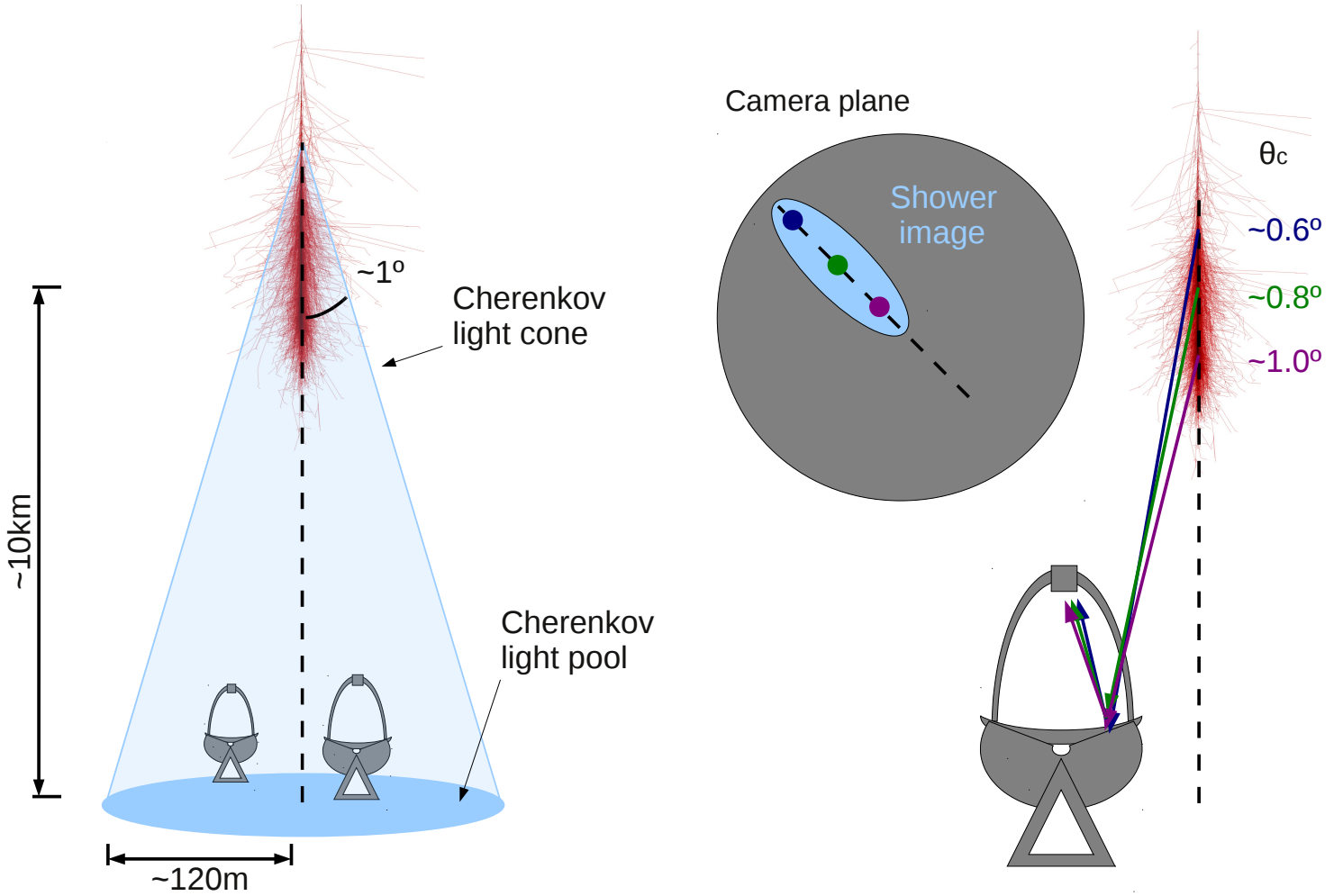
2. Hadronic processes (protons, nuclei)
   - Proton-proton interactions

     Inelastic scattering of a relativistic proton and an ambient proton (ISM)
     Among other particles, π^0's are produced
     $\pi^0 \Rightarrow 2\gamma's$ (99%)

     $L_\gamma \propto n_p \times n_{ISM}$ $(L_\gamma \sim L_\nu)$

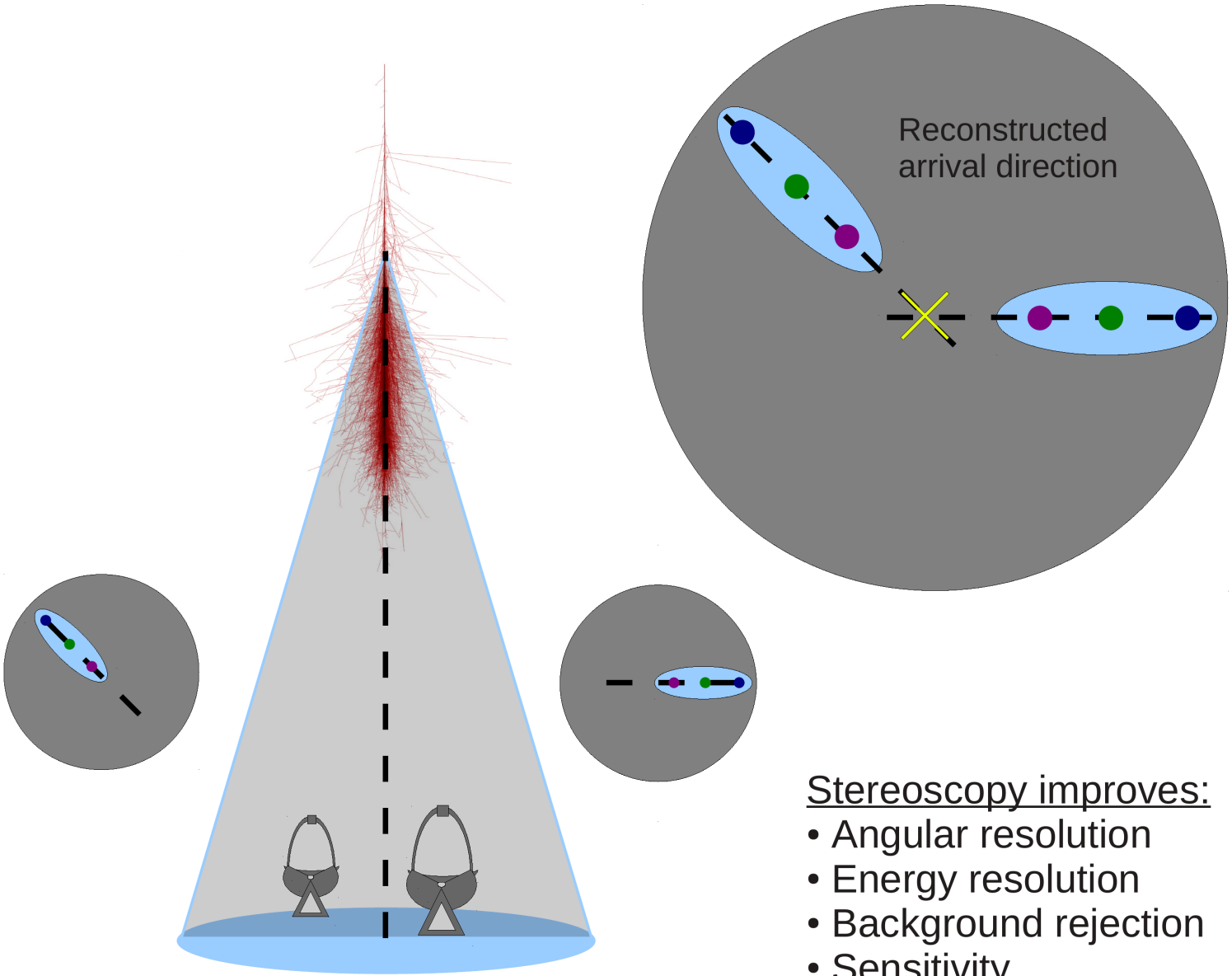
     Gamma ray astronomy offers the unique possibility
     to measure relativistic protons

The imaging air Cherenkov technique



- Light in the Cherenkov image $\propto$ energy of the primary
- Shape of the Cherenkov image $\Leftrightarrow$ nature of the primary

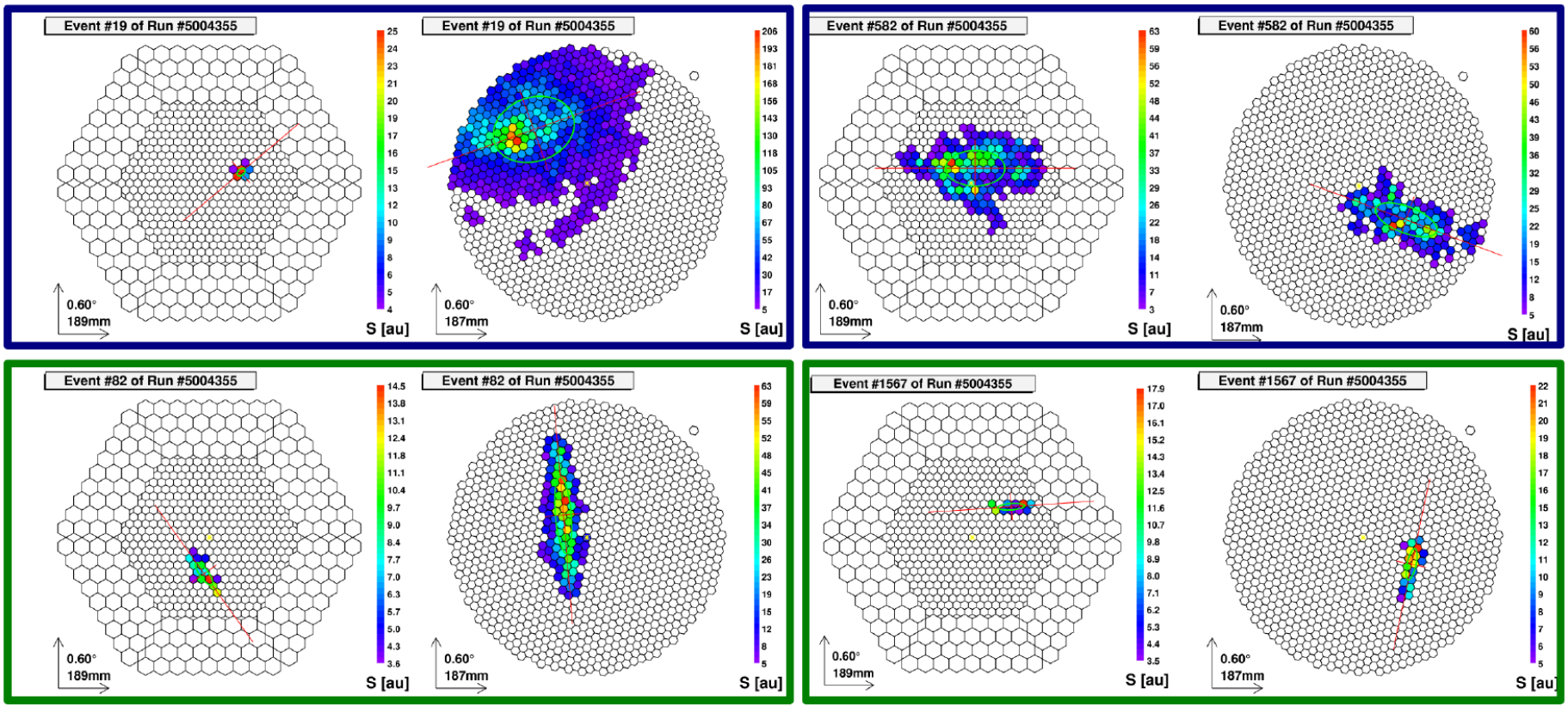
Stereoscopic observations



Stereoscopy improves:

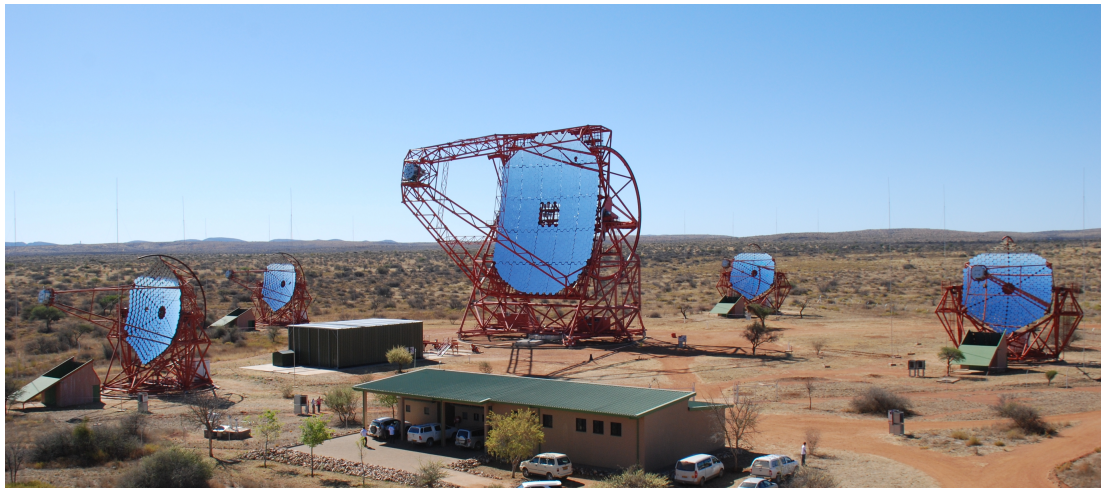
- Angular resolution
- Energy resolution
- Background rejection
- Sensitivity

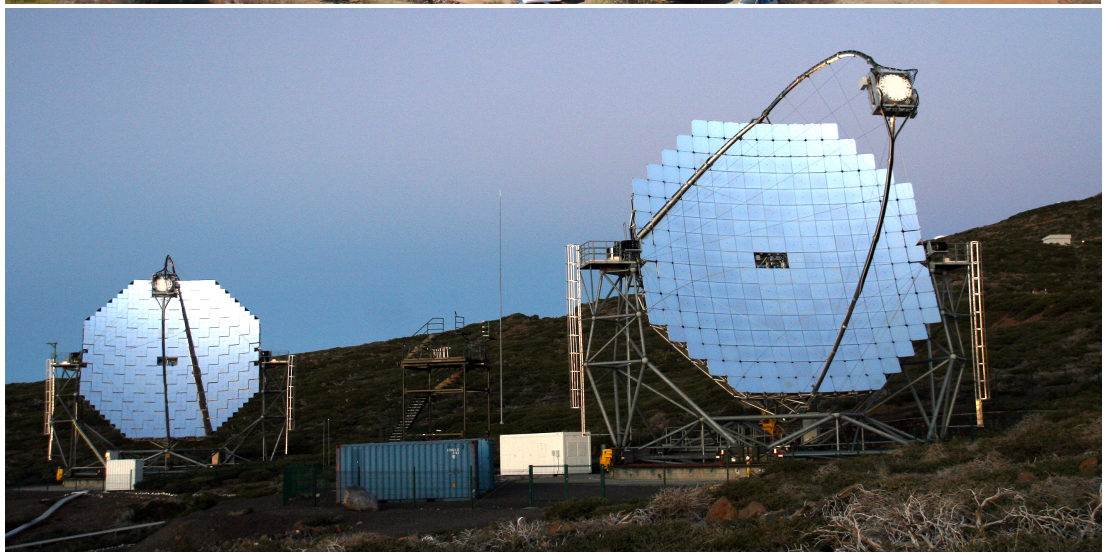
Detecting a VHE gamma-ray source



- Determine the primary of each event: gamma (green) or hadron (blue)
- Remove hadron-like events (event-wise selection)

- **VERITAS**
  - Telescopes: 4
  - Diameter: 12 m
  - Threshold: 100 GeV
  - Location: Mount Hopkins (USA)
- **H.E.S.S.**
  - Telescopes: $4(+1)$
  - Diameter: $12(28)$ m
  - Threshold: 160 GeV
  - Location: Gamsberg mountain (Namibia)
- **MAGIC**
  - Telescopes: 2
  - Diameter: 17 m
  - Threshold: 50 GeV
  - Location: Roque de las Muchachos, La Palma (Canaries)





The MAGIC Telescopes

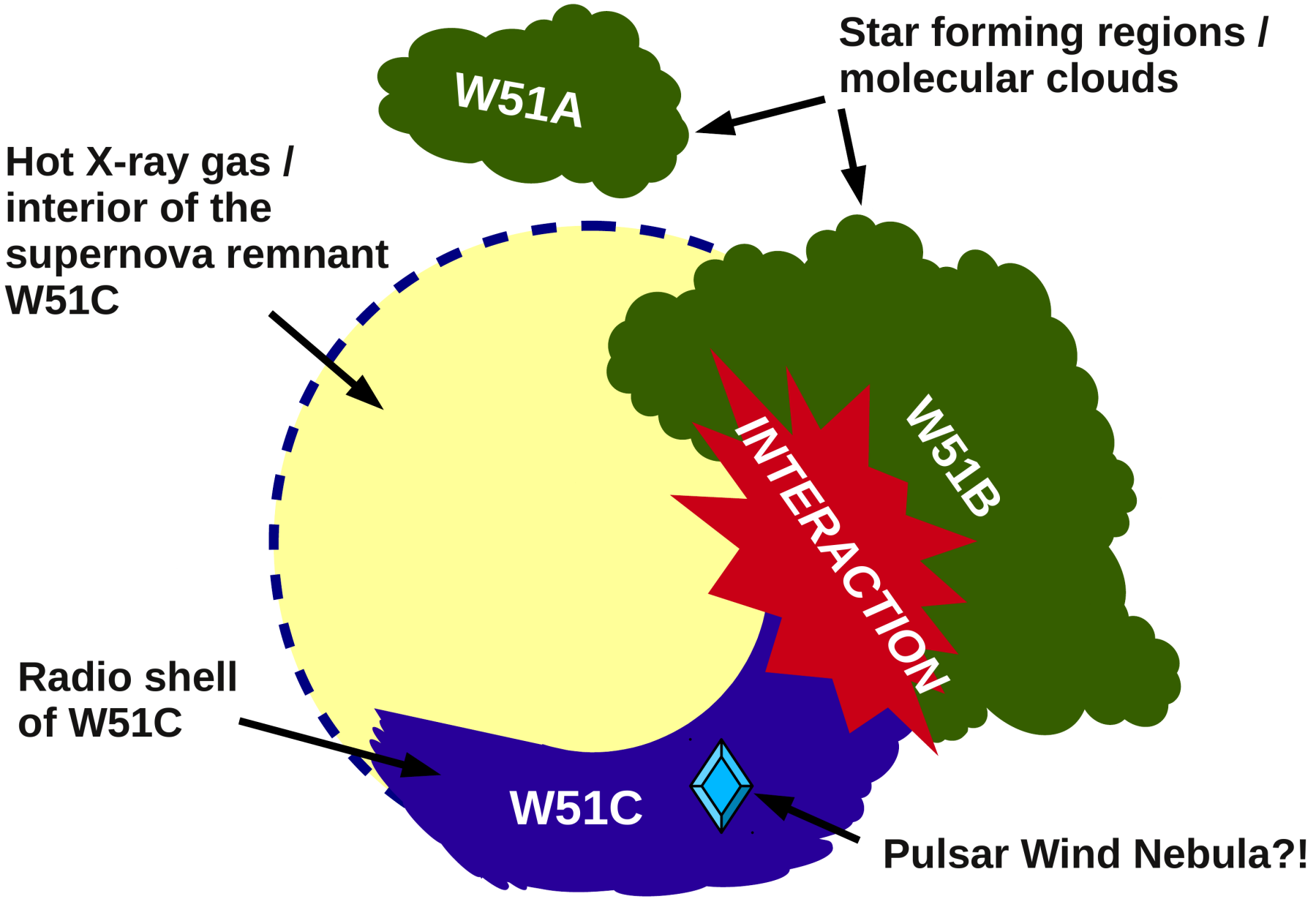
Located on La Palma (Canaries)
Roque de los Muchachos
2200 meter a.s.l.

Stereoscopic system of two imaging air Cherenkov telescopes

- Reflector diameter 17 m
- Energy threshold $\sim$ 50 GeV

Performance	> 0.3 TeV	> 1 TeV
Sensitivity$_{50h}$ [crab]	$\sim 0.8\%$	$\sim 0.9\%$
Angular resolution	$\sim 0.07^\circ$	$\sim 0.05^\circ$
Energy resolution	$\sim 17\%$	$\sim 17\%$

An illustration of the W51 complex

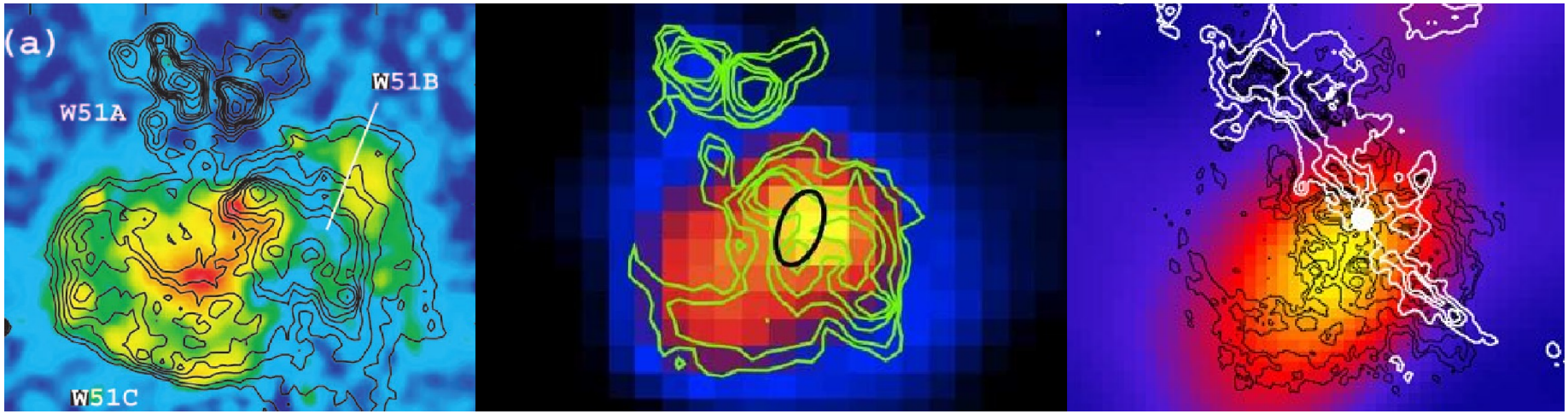


Details about the W51 complex

ROSAT 0.7-2.5 keV
Koo et al. 2002

Fermi / LAT 2-10 GeV
Uchiyama et al. 2011

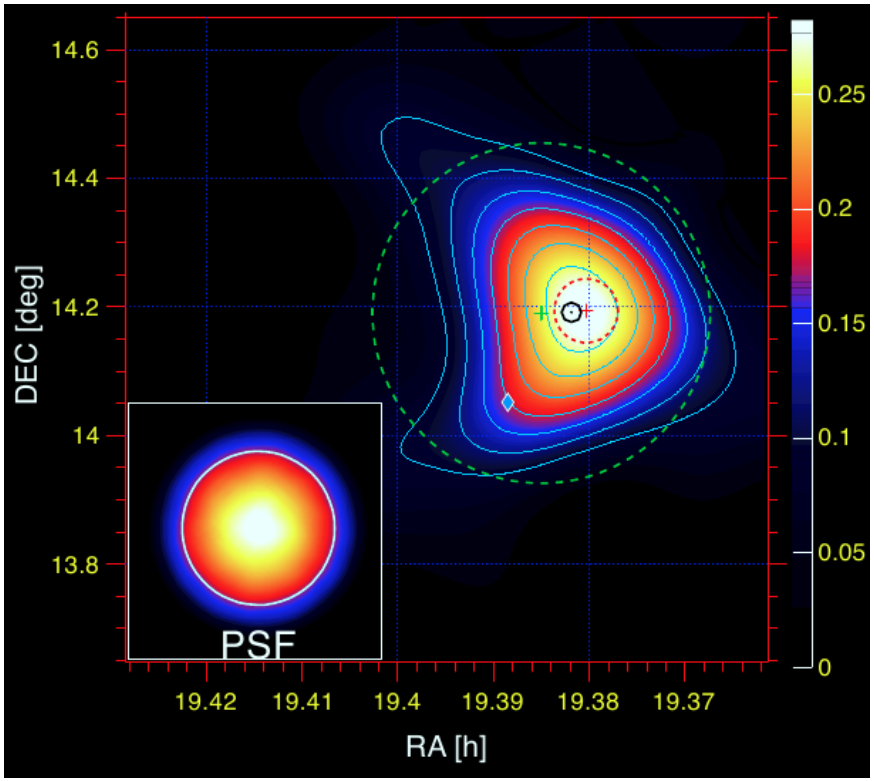
H.E.S.S. $>$1 TeV
Fiasson et al. ICRC 2009

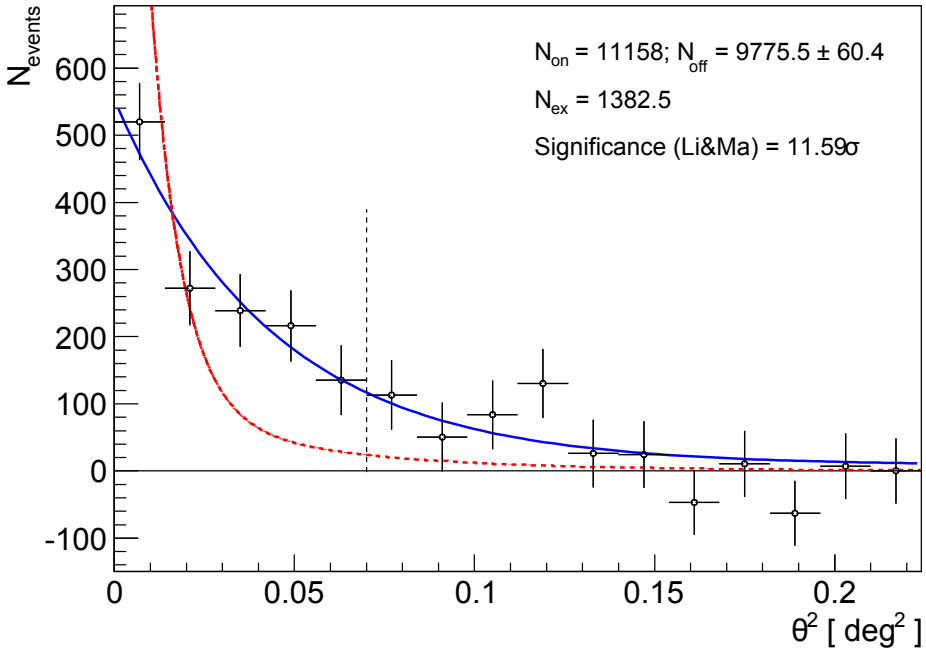


- W51C (d $\sim$ 5.5kpc) is a medium age ($\sim$ 30kyr) supernova remnant [SNR]
- Possible Pulsar Wind Nebula associated to W51C (Koo et al. 2005)
- The SNR interacts with W51B (Koo et al. 1997a&b, Green et al. 1997)
- Discovered by *Fermi* / LAT ($\sim$ GeV) and H.E.S.S. (4.4σ, flux > 1 TeV)
- High CR ionization, $\sim 100 \times$ ISM value (Ceccarelli et al. 2011)

Promising candidate to test and study cosmic ray acceleration in SNR's

Detection of W51 with MAGIC (>150 GeV)

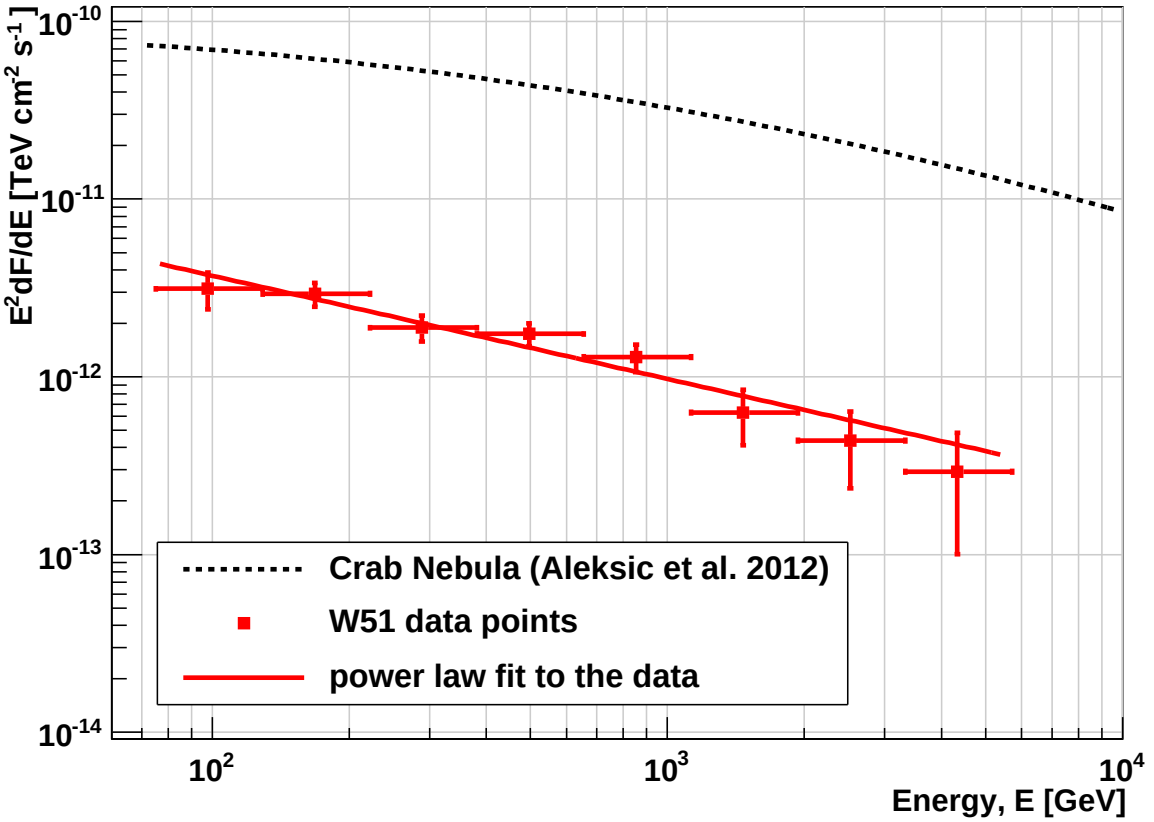




- data taken in 2010 & 2011
- 53 h effective time
- stereoscopic wobble data
- zenith range: 14-35°

- 11 σ detection $>$ 150 GeV
- centroid:
  $\mathrm{RA} = 19.382 \pm 0.001\mathrm{h}$
  $\mathrm{DEC} = 14.191 \pm 0.015\,^{\circ}$
- extension:
  $0.12 \pm 0.02_{\mathrm{stat}} \pm 0.02^{\circ}_{\mathrm{syst}}$

MAGIC high energy γ-ray spectrum of W51



- integration radius 0.26 deg
- from 75 up to 5500 GeV
- well fitted by power law $\chi^2/\mathrm{d.o.f.} = 5.26/6$
- flux $\sim 3\%$ crab compatible with H.E.S.S.
- spectral index compatible with *Fermi*/LAT $>$10 GeV

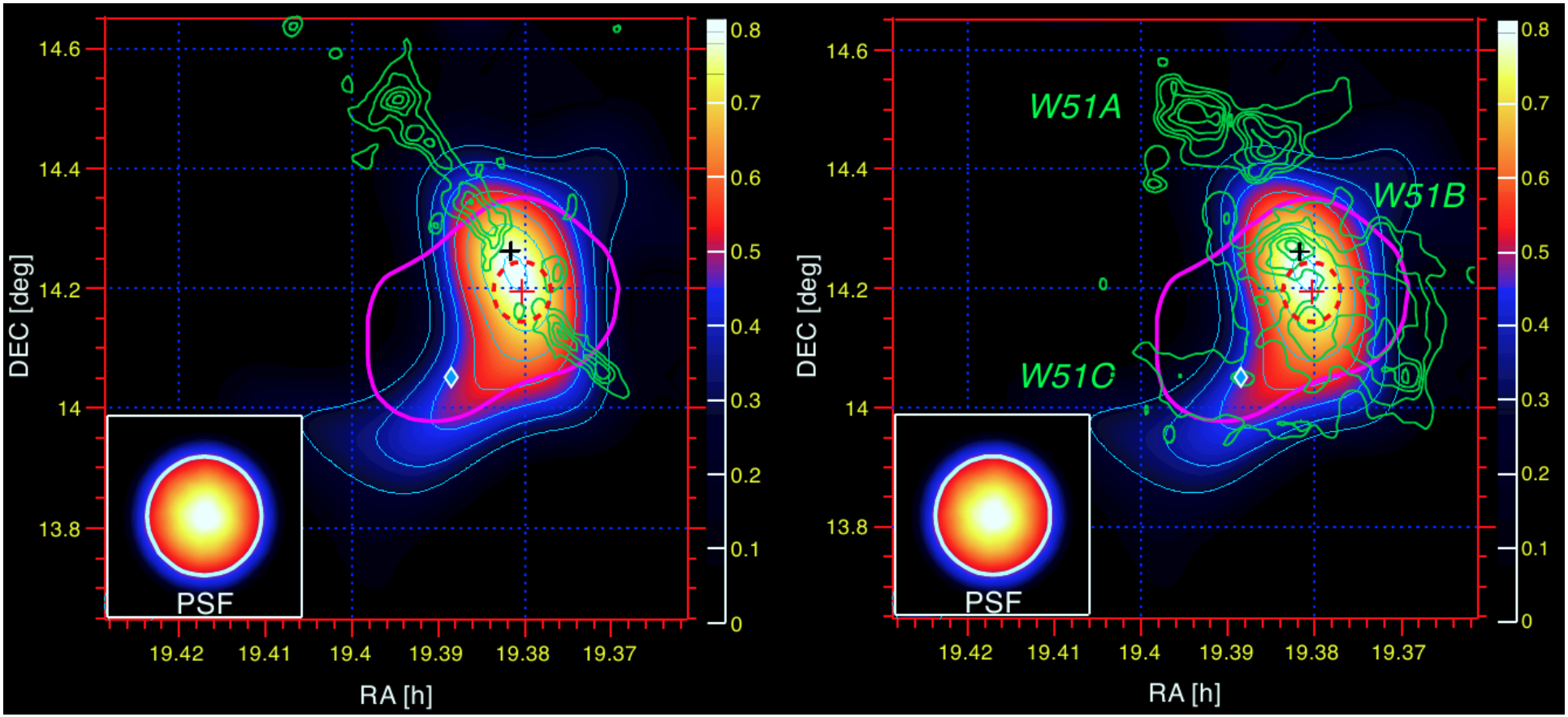
Differential energy spectrum:

$$\frac{\mathrm{dF}}{\mathrm{dE}} = (9.7 \pm 1.0_{\mathrm{stat}}) \times 10^{-13} \left(\frac{\mathrm{E}}{\mathrm{TeV}}\right)^{(-2.58 \pm 0.07_{\mathrm{stat}})} [\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

Morphology (300 – 1000 GeV)

– ^{13}CO J=1-0 emission

– 21 cm continuum emission



+ OH Maser

♦ CXO J192318.5+140305 (possible PWN)

⊕ Shock cloud interaction region

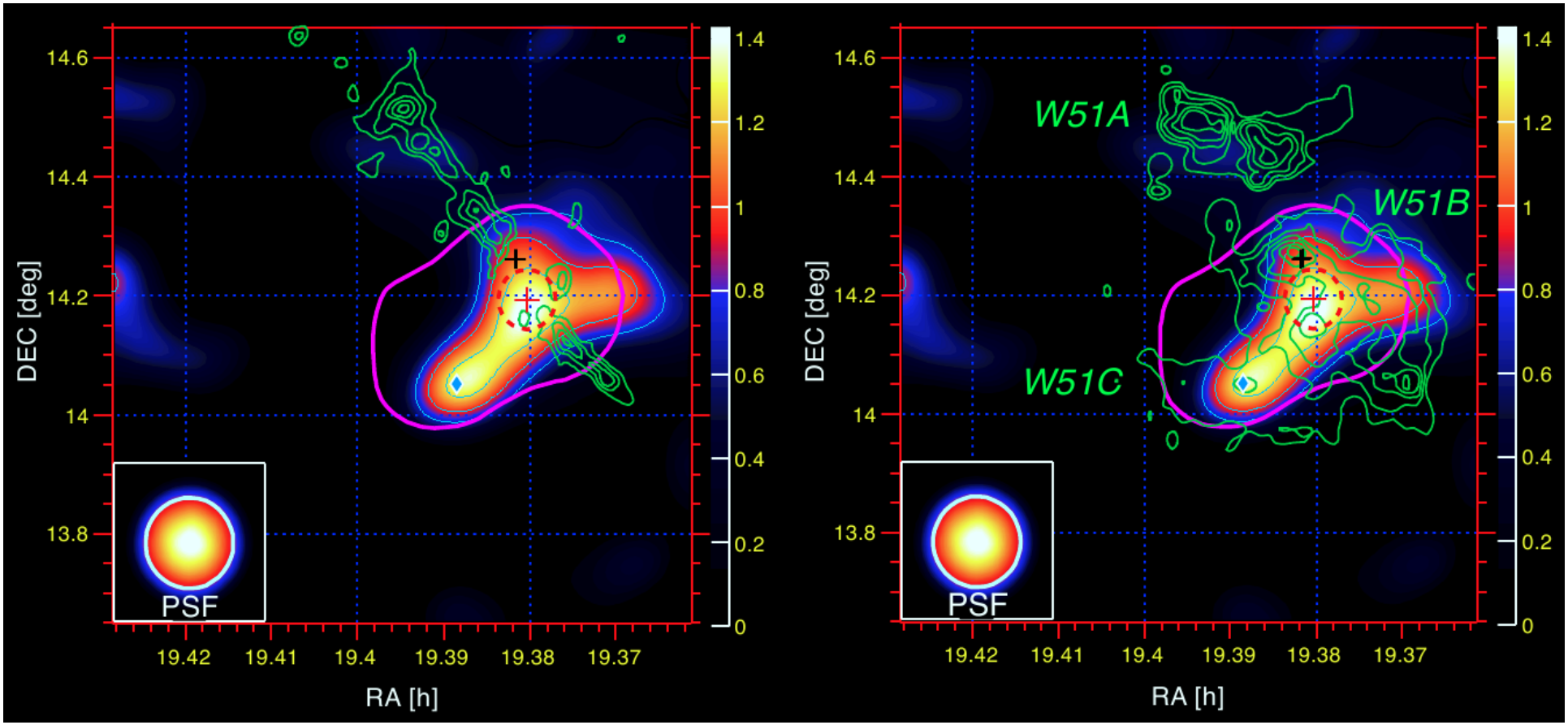
— *Fermi*/LAT 3 counts contour >1 GeV

— MAGIC test statistics starting at 3 (+1 per contour)

Morphology ($>$ 1000 GeV)

– ^{13}CO J=1-0 emission

– 21 cm continuum emission



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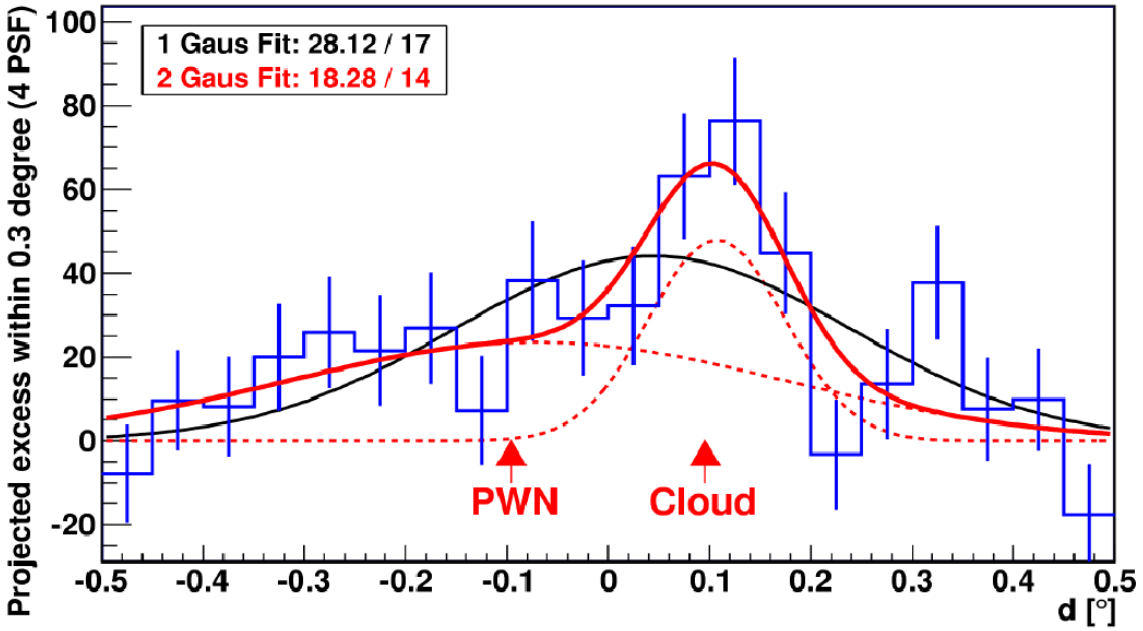
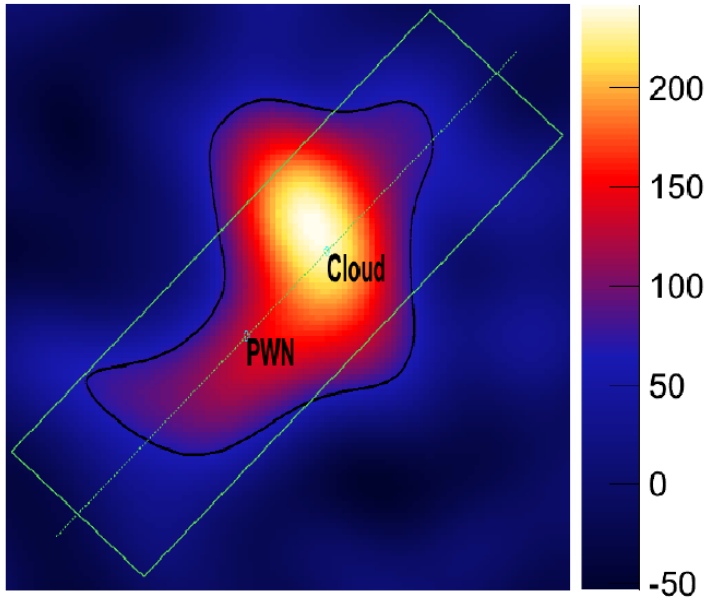
— *Fermi*/LAT 3 counts contour $>$1 GeV

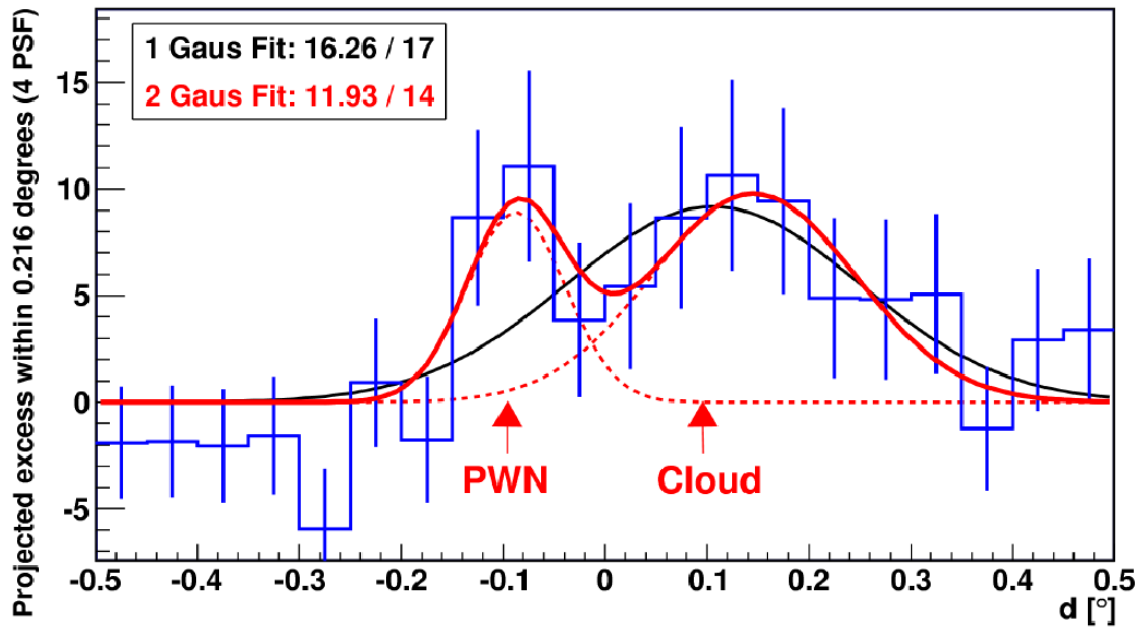
— MAGIC test statistics starting at 3 (+1 per contour)

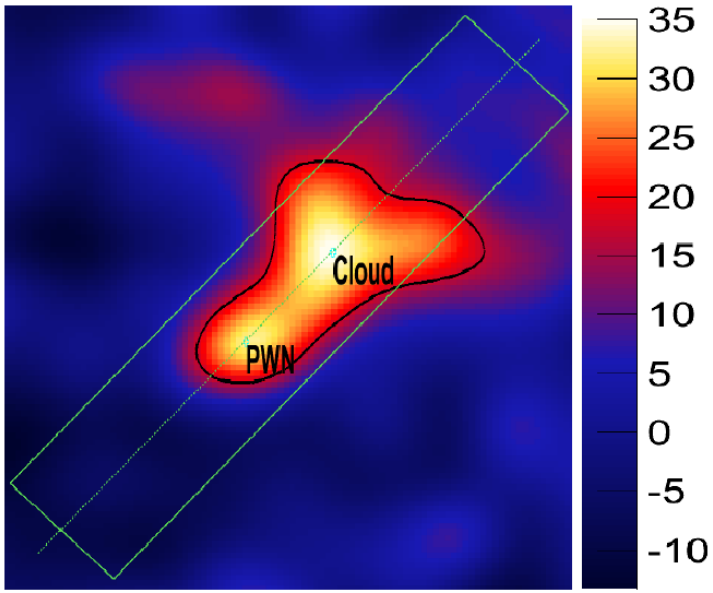
Underlying structures?

(top: 300 – 1000 GeV, bottom: >1000 GeV)



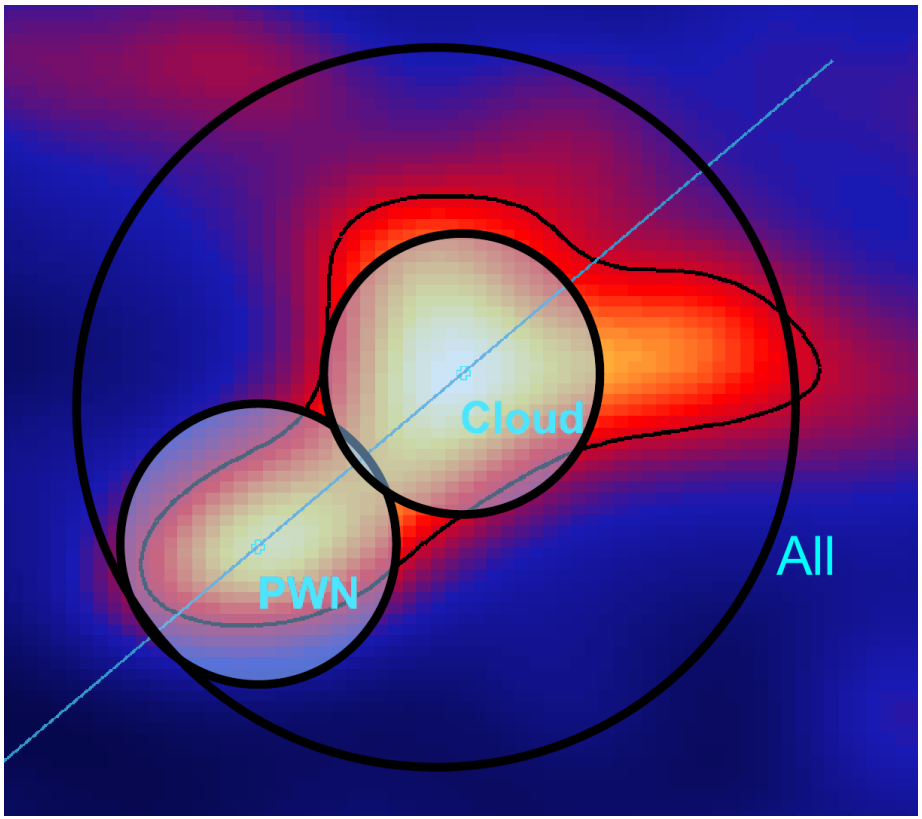






Excess contributions

$E\,[\mathrm{GeV}]$	*cloud*	*PWN*	*cloud*/all [%]	*PWN*/all [%]
> 300	200 ± 30	132 ± 25	30 ± 5	19 ± 4
> 500	116 ± 17	79 ± 17	32 ± 6	22 ± 5
> 1000	48 ± 10	27 ± 10	43 ± 12	24 ± 10



- Integration radius: $0.1°$
- Significance for the individual regions > 300 GeV :
  $10\,\sigma$ (All)
  $7\,\sigma$ (*Cloud*)
  $5\,\sigma$ (*PWN*)

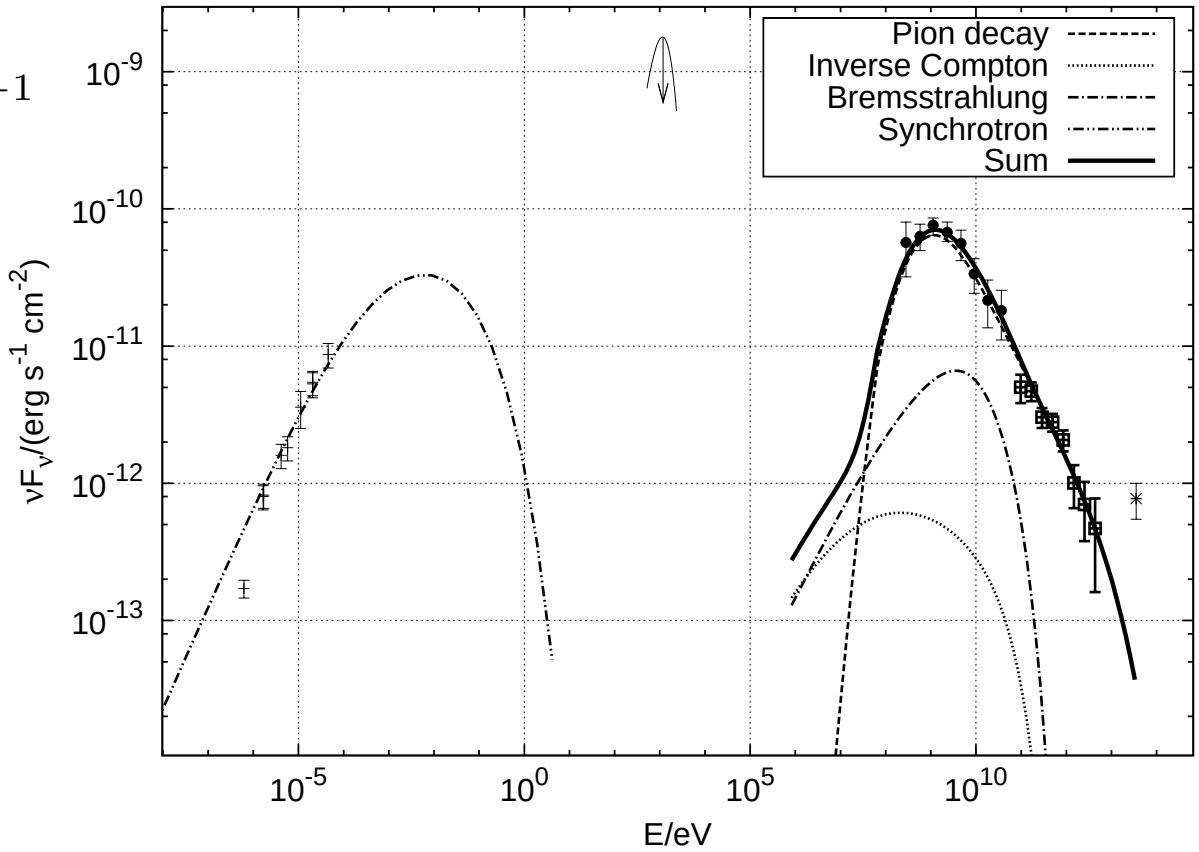
- **No** energy dependence
- Flux (point-source):
  PWN $\sim 0.7\%$ crab nebula
  Cloud $\sim 1.2\%$ crab nebula

Leptonic or Hadronic ?!

Cosmic ray spectrum

$$\propto \left(\frac{E_{e,p}}{E_0}\right)^{-s} \left[1 + \left(\frac{E_{e,p}}{E_{\mathrm{br}}}\right)^{\Delta s}\right]^{-1}$$

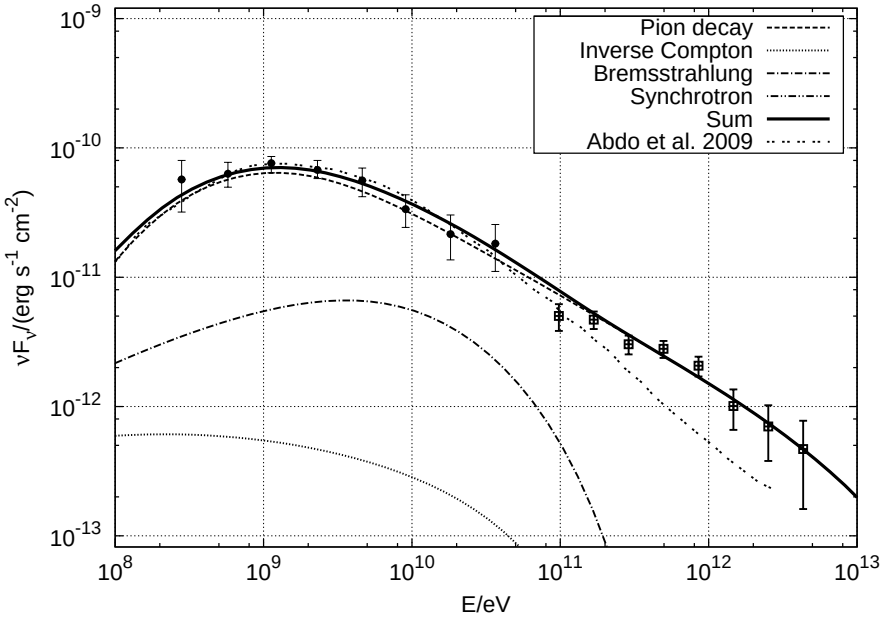
- Best fit results:
  - $s = 1.5$
  - $E_{\mathrm{br}} = 10$ GeV
  - $\Delta s = 1.2$
  - $n = 10$ cm^{-3}
  - $B = 53\ \mu$G
  - $K_e/K_p = 1/80$
  - $W_p = 5.8 \times 10^{50}$ erg

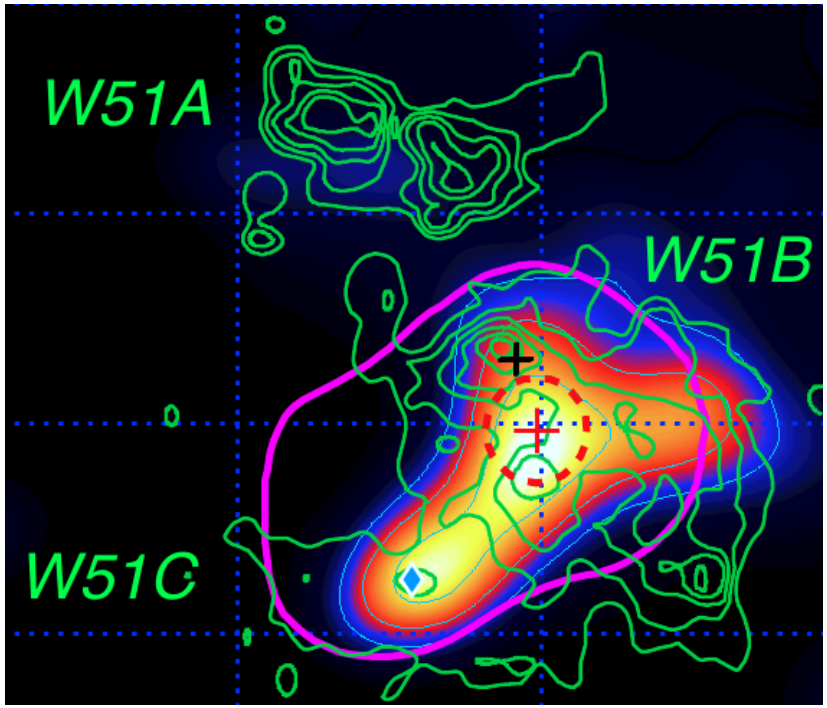


- Simple 1-zone hadronic model explains the data
  $\sim 16\%$ conversion of kinetic SNR energy to CR's
- No (1-zone) leptonic description matching the data could be found
  in agreement with the results of Abdo et al. 2009

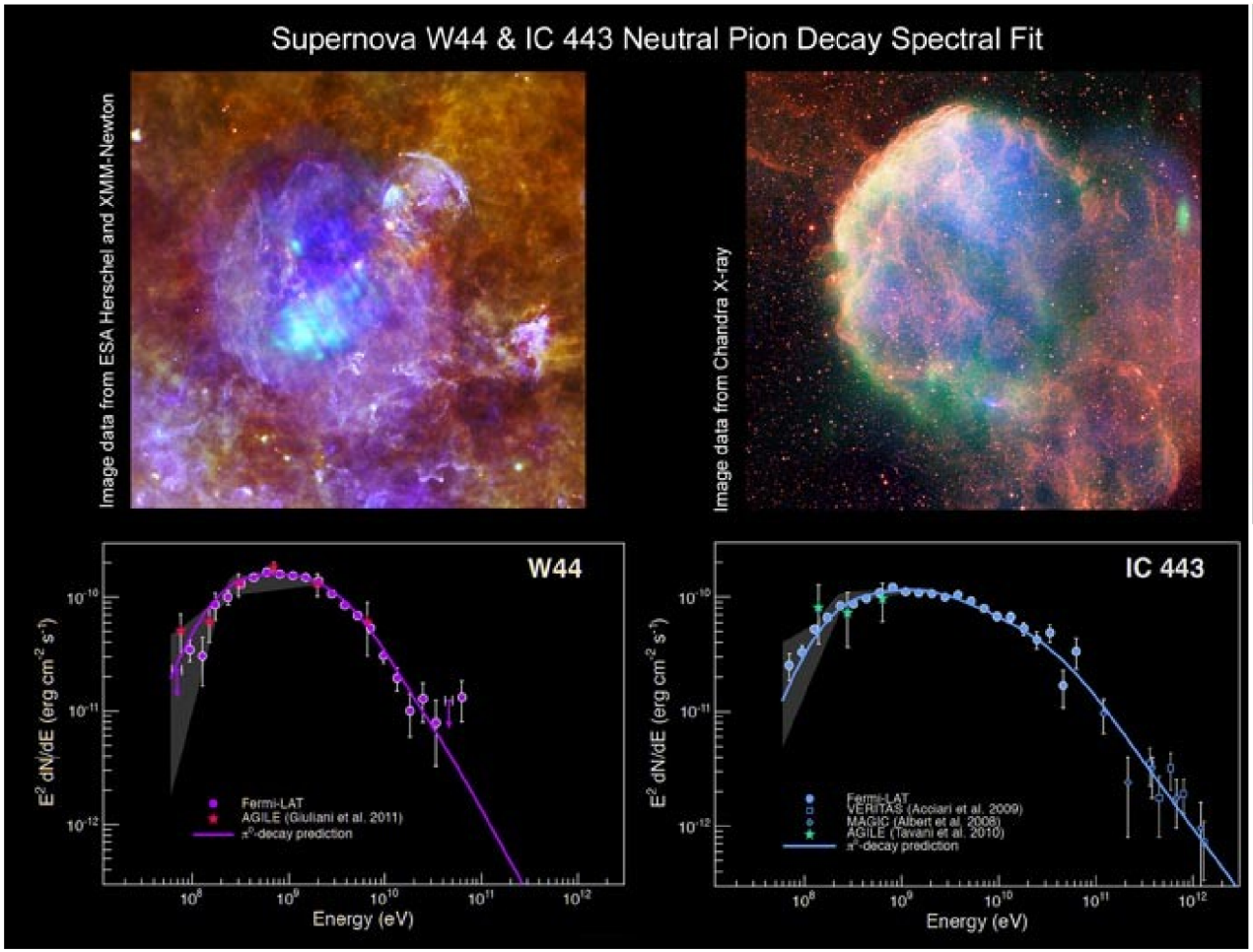
Summary & Conclusions

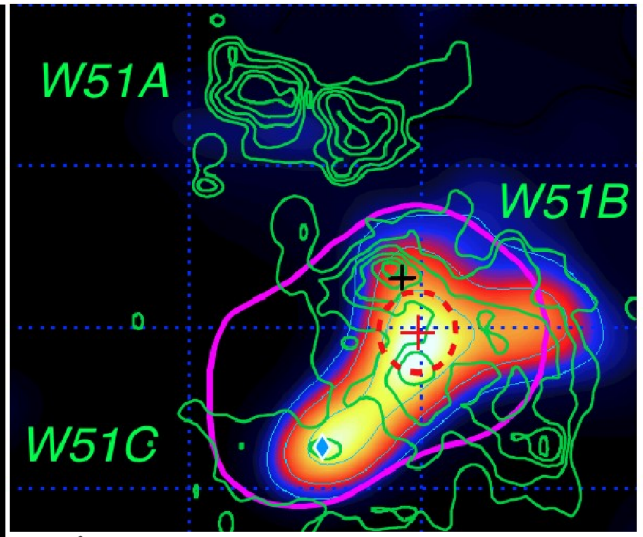
- **Spectral and morphological properties of W51**
  - Flux $\sim 3\%$ crab nebula
  - Simple power law from ~ 10 GeV to ~ 5 TeV
  - Centroid at shock cloud interaction
  - Feature towards possible PWN ($\sim$0.7% crab nebula)
  - Edges of W51B *dark* in VHE γ rays
- **Physical interpretation**
  - Emission most probably hadronic
  - VHE γ rays from (re-)acceleration zone
  - Ongoing CR acceleration at least up to ~ 50 TeV

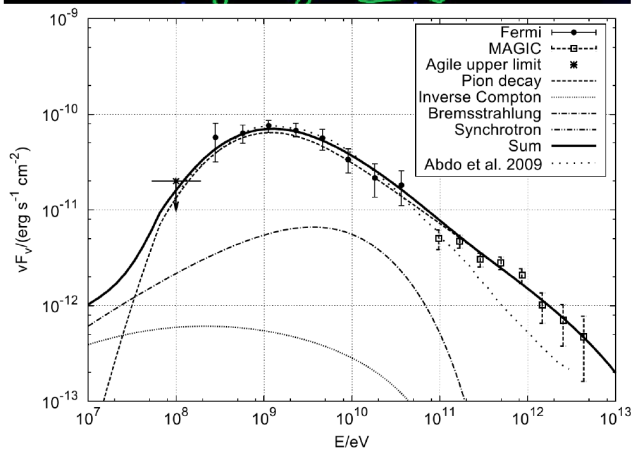




Supernova remnants are sources of CRs







Other highly probable hadronic accelerators are W28, Tycho, and potentially SN 1006, Cas A, among others

Properties of (*hadronic*) SNRs

Object	slope1	break	slope2	Maximum observed gamma ray energy
W51C	-1.5	10	-2.7	$\sim$ 5 TeV (Aleksić et al. 2012b)
IC443	-1.9	3	-2.6	$\sim$ 2 TeV (Albert et al. 2007b; Acciari et al. 2009)
W28	-1.7	2	-2.7	$\sim$ 3 TeV (Aharonian et al. 2008b)
W44	-1.7	6	-3.0	$\sim$ 100 GeV (Abdo et al. 2010c)

- There is proof that SNRs can accelerate protons
- SNRs interacting with MCs tend to show spectral brakes at GeV
- Spectral indices much steeper than 2
  $\Rightarrow$ effects of particle escape?!