Gamma-ray (and Neutrino) Observations of the Sources of Galactic Cosmic Rays

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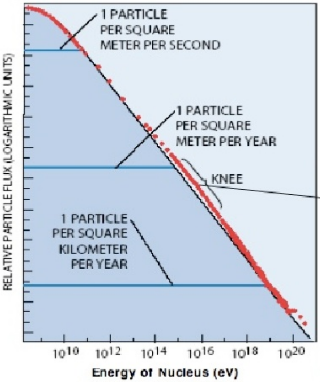
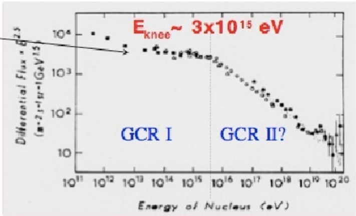
Galactic Cosmic Rays (GCRs)

- (piecewise) **power law** energy spectrum, $\frac{dN}{dE} \propto E^{-\Gamma}$
- confined by Galactic magnetic field: $r_L \approx 0.3 \frac{E_{\rm PeV}}{Z}$ pc



- E< a few hundred MeV :Solar cosmic rays
- E> 3 X 10^18 eV (not confined by *B*) : extragalactic (UHE)CRs
- in between: Galactic CRs



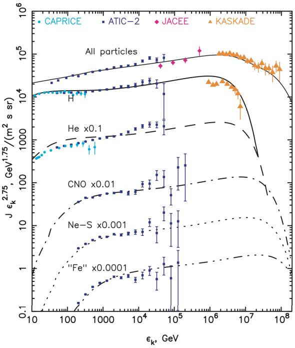
- diffusion in turbulent field (below “ankle”, $E \ll 3 \times 10^{18}$ eV)
  $\Rightarrow$ nearly isotropic, arrival directions cannot pinpoint sources
- indirect detection through γ-ray observations

"PeVatrons" as the sources of Galactic CRs

"knee" likely injection spectrum feature

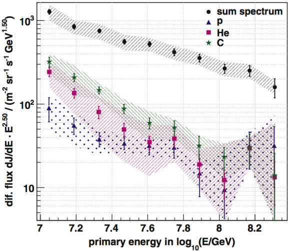
electromagnetic acceleration mechanism: energy cutoff $\propto Z$ (Peters 1961)

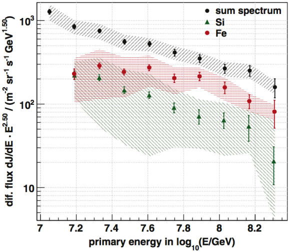
e.g. prediction (Berezhko & Völk 2007) $\rightarrow$



recent data (KASCADE-Grande 2013) $\downarrow$

$\Rightarrow$ GCR sources must accelerate *protons* at least to $E \sim 3\,\text{PeV}$ (hence **PeVatrons**)





Hadronic vs. leptonic γ-ray emission

Hadronic (proton and ion) emission

- CR p + ISM $p \to +\pi$'s, $\quad \pi^0 \to 2\gamma \quad$ (similarly for nuclei)
- also $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e \quad$ (similarly π^-)
- cross-section $\sim E$-independent $\Rightarrow$ γ-ray spectral index Γ $\approx$ proton spectral index p (at $E_\gamma \sim 0.1 E_p$)

$$\text{luminosity} \propto \int n_{\rm CR}\, n_{\rm ISM}\, dV \quad \propto \quad E_{\rm CR}\, n_{\rm ISM} \quad (\text{if } n_{\rm ISM} \text{ uniform})$$

$$\propto \quad n_{\rm CR} M_{\rm cloud} \quad (\text{if CRs uniform})$$

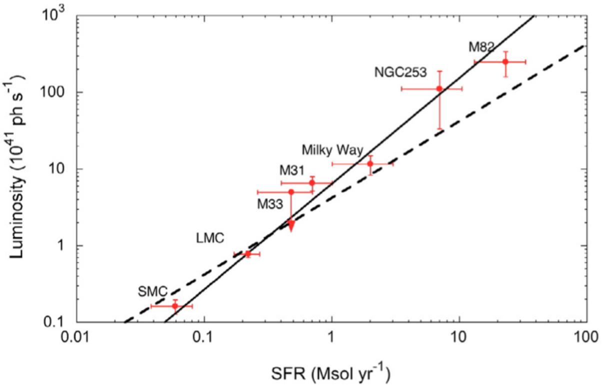
- γ-ray morphology correlates with CR and ISM density

Leptonic (electron and positron) emission

- inverse Compton: low-energy γ + CR $e^- \to$ high-energy $\gamma + e^-$
- low-energy γ from CMB (+ Galactic IR) $\Rightarrow$ IC correlates only with $n_{\rm e}$ (unless local source of photons, e.g. IR-emitting dust cloud)
- (need also include *Bremsstrahlung*, but not generally dominant)
- synchotron + IC $\Rightarrow$ infer B (in one-zone approximation)
- *Caveat*: synchrotron $\propto n_e B^2$, B not generally uniform

Cosmic Rays and Star Formation Rate

- cosmic rays known to fill Galaxy from diffuse γ-ray emission
- inferred CR density comparable in Andromeda Galaxy (M31), but lower in Large and (especially) Small Magellanic Clouds
- high γ-ray luminosity of NGC 253 and M82



(Abdo et al. 2010)

- consistent with cosmic-ray production $\propto$ massive star formation
- to go further, need to examine individual sources

Supernova Remnants as Galactic PeVatrons?

- shock waves and debris from explosions of massive stars
- birth events of neutron stars, and sources of the Galactic cosmic rays? (Baade & Zwicky 1934)

- widely considered likely sources of GCRs up to the "knee":
  - energetics require $\sim$10% of total SN energy of 10^{51} erg;
  - Galactic CR composition enriched in heavy elements (high "metallicity"), compatible with an SNR origin (?);
  - well-studied shock acceleration mechanism, variation of a stochastic mechanism proposed by Fermi (1949)

- general expectations of modern, non-linear diffusive shock acceleration (NLDSA) theory (e.g. Blasi 2013 review):
  - concave, hard proton spectrum ($\Gamma \sim 2$)
  - at some point in SNR evolution, $E_{\rm max} \sim$ few $\times\, 10^{15}$ eV ("PeVatrons")

High-energy observations of (shell-type) SNRs and the origin of Galactic Cosmic Rays

X-ray observations of SNRs

- Observational evidence for accelerated e^- (synchrotron)
- indirect evidence for accelerated protons/ions (magnetic field amplification, modified hydrodynamics)

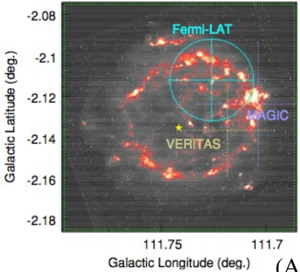
GeV/TeV γ-ray observations

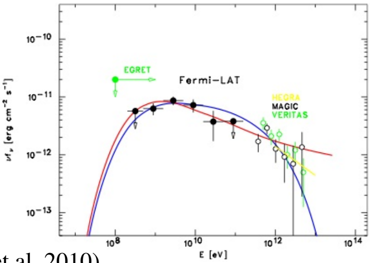
- For accelerated p (and ions), **hadronic** interactions with ambient matter produce π^0, decaying into two γ-rays which we observe
- Major historical aim of TeV astronomy (e.g. Drury et al. 1994)
- But how to discriminate from **leptonic** (IC) emission?

- In principle, detecting corresponding high-energy **neutrinos** would be clear signature of hadronic emission. . .

GeV / TeV γ-ray spectra of (isolated) SNRs

- e.g. **Cassiopeia A** (*Fermi*-LAT detection, Abdo et al. 2010)
- sharp X-ray rims, etc. $\Rightarrow$ high $B \sim$ mG $\Rightarrow$ leptonic disfavoured
- improved *Fermi*-LAT statistics: clear detection of π^0 spectral signature "break" (Yuan et al. 2013) $\Rightarrow$ hadronic preferred



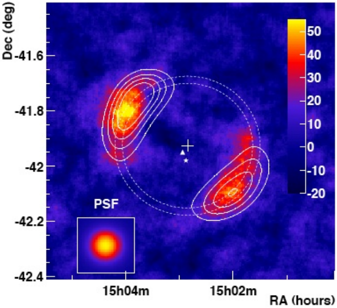


(Abdo et al. 2010)

- GeV / TeV hadronic spectral fits imply either :
  - energy cutoff at 10 TeV (and $\Gamma = 2.1$)
  - steeper spectral index $\Gamma = 2.3$ (and no cutoff)

Angularly resolved historical SNR : **SN 1006**

- H.E.S.S. detection of the remnant of **SN 1006**:



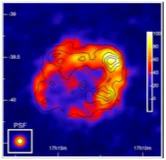
(*HESS* 2010, *A&A* **516**, A62)

- morphology correlated with non-thermal X-rays (contours)
- reveals spatial distribution of high-energy particles
- ambiguity between hadronic and leptonic (IC) emission scenarii

- VHE γ-ray map unambiguously shows that accelerated particles (protons or electrons) are more numerous to the NE and SW (unlike synchrotron, which could also be due to enhanced B)
- regions of quasi-parallel magnetic geometry (Reynoso et al. 2013)
- leptonic scenario suggests relatively low B-field $\approx 30\,\mu$G
- hadronic scenario requires hard spectrum, $E_{\text{cutoff}} \sim 10\,$TeV

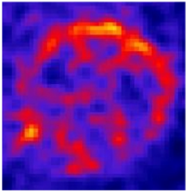
TeV shell SNRs : other examples

RX J1713



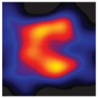
HESS (2006)

Vela Junior



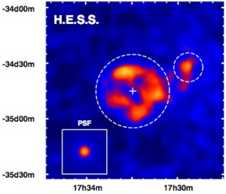
HESS (2007)

RCW 86



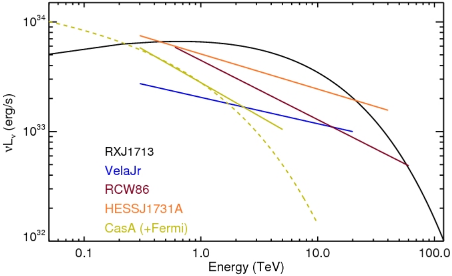
HESS (2009)

HESS J1731–347



HESS (2011)

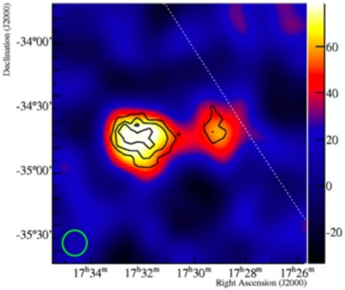
(M. Renaud)

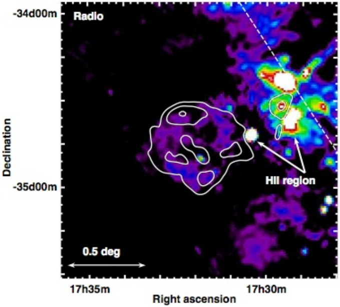


Median luminosity : $L_{1-10\,\mathrm{TeV}} \approx 9 \times 10^{33}$ erg/s

A new non-thermal shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell found by Tian et al. (2008): G 353.6-0.7





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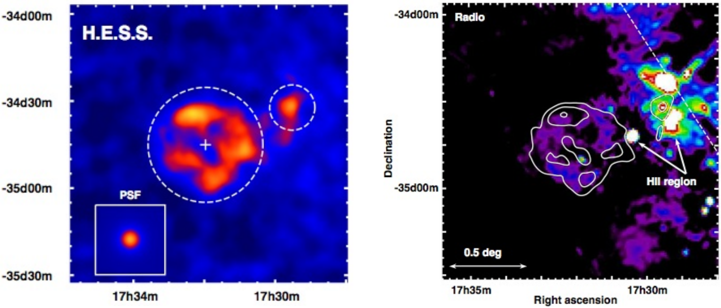

- further *HESS* observations : significant (3.9 σ) limb-brightening

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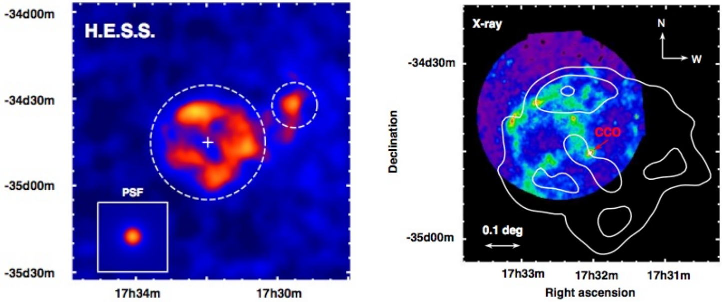


- further *HESS* observations : significant (3.9 σ) limb-brightening
- *XMM* observations of (part of) shell show rims of emission with non-thermal spectra (no evidence for thermal emission)
- next generation TeV γ-ray observatory (**CTA**) should discover many more non-thermal shell SNRs

Young and γ-ray shell SNRs: general properties

Leptonic emission scenario

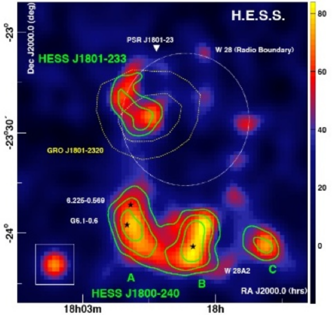
- might explain spatial correlation with synchrotron X-rays
- implies fairly low $B \sim 10\,\mu$G (in one-zone model), in apparent contradiction with evidence for turbulent B-field amplification
- difficult to reproduce γ-ray spectral shapes in one-zone model

Hadronic emission scenario

- no obvious explanation for high correlation with X-rays, and poor correlation with medium density (in resolved SNRs)
- relatively high surrounding medium density ($n \sim 1\,\mathrm{cm}^{-3}$) required to explain RX J1713, Vela Jr and HESS J1731
- **all** (V)HE-detected shell SNRs have $\Gamma > 2.0$ or cutoff at $E_\gamma \sim 10\,\mathrm{TeV} \;\Rightarrow\; E_p \sim 10^{14}\,\mathrm{eV}$ — well short of “knee”

SNR / Molecular Cloud interactions : **W 28**

(*HESS* 2008, *A&A* **481**, 401)



TeV $\Gamma = 2.7 \pm 0.3_{\text{stat}}$,
$L_{1-10\,\text{TeV}} \approx 5 \times 10^{32}$ erg/s

HESS J1800–240B matches CO cloud at same velocity

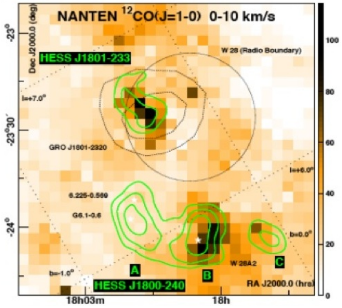
"passive" MC "illuminated" by *escaping* CRs from W 28?

HESS J1801–233 on E rim of SNR W 28, radio hot spot

coincident with GeV source

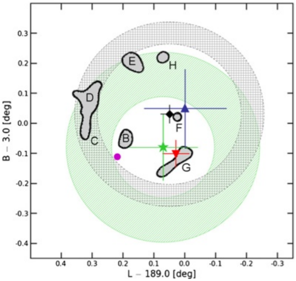
morphology matches CO cloud

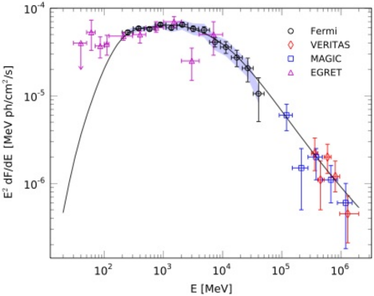
coincident with 1720 MHz OH maser ⇒ shock/MC interaction



SNR / Molecular Cloud interactions : **IC 443**

- *MAGIC* discovery of compact γ-ray source (Albert et al. 2007)
- *VERITAS* confirmation of TeV emission (Acciari et al. 2009)
- *Fermi* LAT confirmation of GeV emission (Abdo et al. 2010)
- **extended** source, compatible with shocked molecular clouds





- best-fit LAT spectrum broken power law (single PL poor fit)
- hard spectrum $\Gamma_1 = 1.93$ up to $E_{\rm break} = 3.3 \pm 0.6\,$GeV
- steep spectrum $\Gamma_2 = 2.6 \pm 0.1$ at higher energies, compatible with *MAGIC* and *VERITAS* data

Summary on γ-ray SNRs and GCRs

SNRs interacting with molecular clouds

- often clear correlation with dense matter $\Rightarrow$ **hadronic** interpretation natural; probes of CR acceleration?
- steep spectra (flattening in GeV range?), low TeV luminosities
- important theoretical issues: changes in shock acceleration, evolution and modification due to interaction with dense cloud
- key observational issue : angular resolution in γ-rays

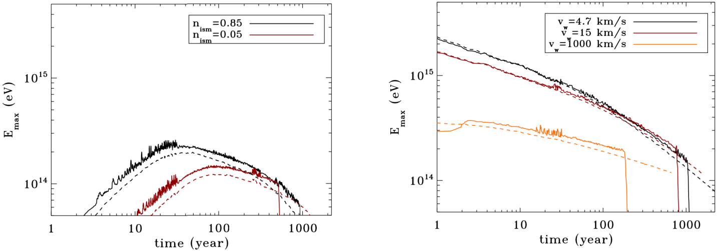
Implications of γ-ray SNRs for GCR origin

- no clear evidence that $E_{\mathrm{max}} \sim 3 \times 10^{15}$ eV can be attained by protons in **any** SNR detected in γ-rays (at least not with $p \sim 2$)
- observational proof that SNRs can accelerate Galactic cosmic rays to the “knee” energy is currently lacking

Where are the PeVatrons ? (Lemoine-Goumard 2012)

Theoretical solution: short-lived PeVatrons?

- if SNRs are the main sources of Galactic cosmic rays, they must at some stage of their evolution be "PeVatrons"
- challenging theoretically to reach $E_{\rm max}\sim 3$ PeV for protons (need high enough δB to confine them near the shock)
- **Schure & Bell (2013a)** consider Bell's non-resonant hybrid instability for SNRs evolving in pre-supernova stellar winds

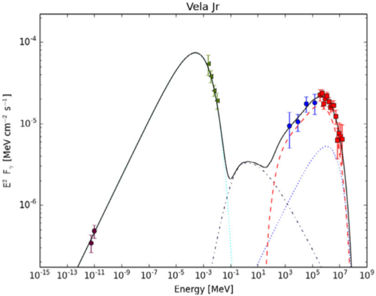


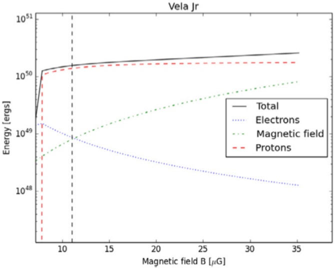
- "[...] we get to about a PeV but not too much beyond, and only for SNRs younger than a few decades."
- related suggestions (some on faster scales) by Völk & Biermann (1988), Tatischeff (2009), Marcowith et al. (2014)

(Prospects for) VHE ν observations of SNRs

- detecting neutrinos would provide unambiguous discrimination between hadronic and leptonic γ-rays
- for a given **assumed hadronic** γ-ray spectrum, can directly predict the corresponding neutrino spectrum

- **Mandelartz & Becker Tjus (2015)** model 24 γ-ray SNRs

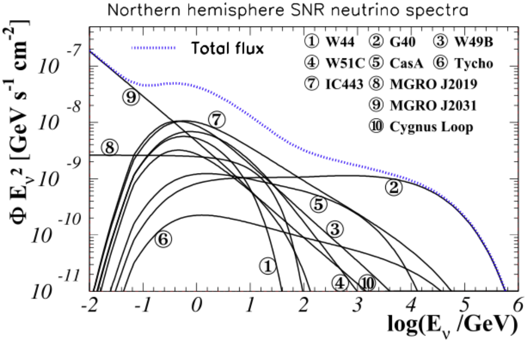




- fit multiwavelength spectrum with synchrotron, π^0 decay, inverse Compton and *Bremsstrahlung* emission
- choose magnetic field sufficiently high for γ-ray spectrum to be dominantly hadronic

Predicted SNR ν_μ spectra for IceCube

- follow from modeling of hadronic γ-ray component
- in IceCube range for source search ($\sim$1–100 TeV), brightest predictions are for **MGRO J1908** ("G40"), **Cas A** and **IC 443**

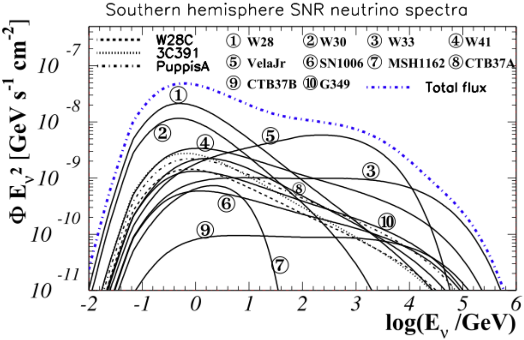


(Mandelartz & Becker Tjus 2015)

- predicted fluxes are still factors $\sim$3 (J1908), $\sim$15 (IC 443) and $\sim$ **30** (Cas A) below current upper limits…
- *Caveat:* for MGRO J1908 and IC 443, took $E_{p,\max} = 1\,\mathrm{PeV}$ (!), likely overestimating the fluxes (**Cas A** spectrum is more robust)

SNR ν_μ predictions for ANTARES, KM3NeT

- brightest prediction is for **Vela Jr** (a.k.a. RX J0852.0–4622, G 266.2–1.2), followed by **HESS J1813–178** ("W33") and **W41**
- Vela Jr prediction is still a factor >6 below ANTARES sensitivity. . . but could be in reach of KM3NeT



(Mandelartz & Becker Tjus 2015)

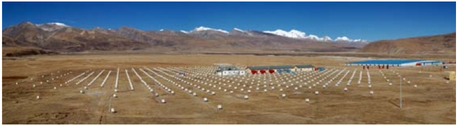
- *Caveats:* HESS J1813 and W41 models assume $E_{p,\max} = 1\,\mathrm{PeV}$
- a significant or dominant leptonic component is likely in Vela Jr

Direct γ-ray shower detector experiments

Milagro

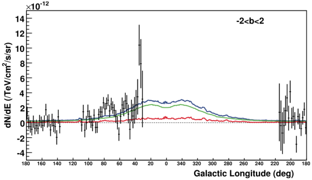
water Cherenkov

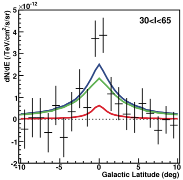
Tibet ASγ (and ARGO-YBJ)



scintillation array (and RPC carpet)

- large field of view ("all-sky"), high duty cycle ($\sim$100%)
- limited angular resolution, low background rejection
- poor sensitivity relative to IACTs, but better for flare monitoring or diffuse emission: **Milagro** measurements of Galactic diffuse γ-ray emission around 15 TeV (Abdo et al. 2008)

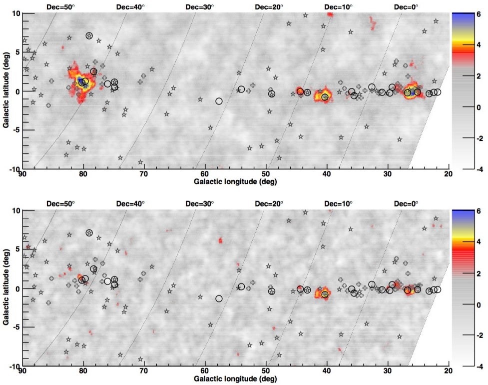




Galactic TeV γ-ray sources

- good sensitivity of current-generation Imaging Atmospheric Cherenkov Telescopes, starting with HESS > one decade ago
- currently >80 Galactic TeV sources known
- ~40% identified as pulsar wind nebulae (PWNe) or candidates

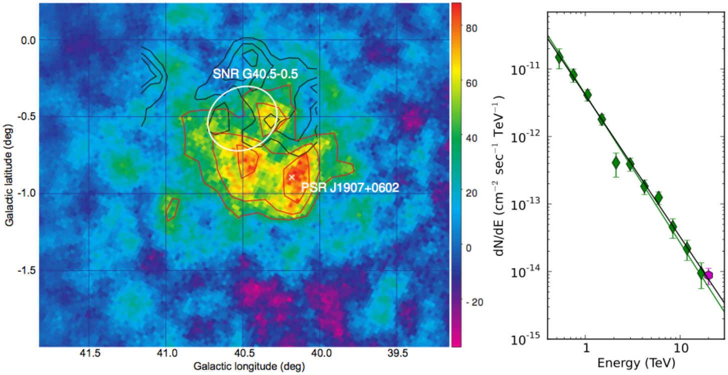
- also important Galactic source class at higher energy: Crab, MGRO J1908+06, HESS J1912+101, HESS J1841–055, …



(ARGO, Bartoli et al. 2013)

Unveiling the nature of MGRO J1908+06

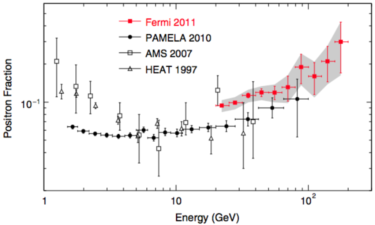
- discovered by Milagro (Abdo et al. 2007), median energy 20 TeV
- observed by HESS (Aharonian et al. 2009), hard $\Gamma = 2.10 \pm 0.07$
- partial overlap with SNR G 40.5–0.5
- PSR J1907 discovered by *Fermi*-LAT (Abdo et al. 2009, 2010)



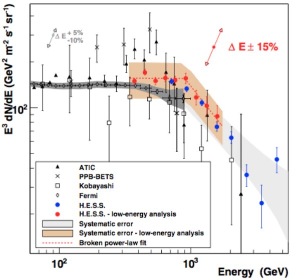
- **VERITAS** observations (Aliu et al. 2014) confirm hard spectrum
- morphology suggests bulk of the source is the TeV nebula of PSR J1907, with only part possibly associated with G 40.5–0.5

Pulsar (Wind Nebulae) and Cosmic-ray e^+

- *PAMELA* measured positron fraction $e^+/(e^+ + e^-)$ increase with E, inconsistent with secondary origin in propagation
- confirmed up to higher E by *Fermi*-LAT, ∼30% at ∼200 GeV
- measured with high precision by *AMS*



(Ackermann et al. 2012)



(Aharonian et al. 2009)

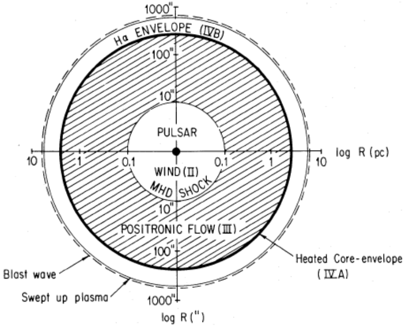
- tending towards 50% up to $(e^+ + e^-)$ steepening at $E \sim 1$ TeV?
- spectrum and positron fraction require **primary** $e^{\pm}$ source
- signature of DM annihilation? But another “natural” scenario…

Pulsar wind (termination shock and) nebula

- relativistic pulsar wind meets ambient medium (remnant of the supernova which gave birth to the pulsar) ⇒ **shocks**

(Kennel & Coroniti 1984)

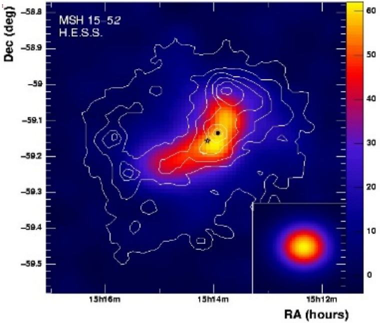
1. pulsar wind termination shock (quasi-stationary)
2. nebula expansion shock into ejecta (in young PWNe; non-relativistic)
3. reverse (if young) and
4. forward shock of SNR



- synchrotron nebula (radio, optical, X-rays, . . .) downstream of wind termination shock (nebula ≡ shocked pulsar wind)
- ⇒ electrons/positrons accelerated at wind termination shock

Young PWNe (in composite SNRs)

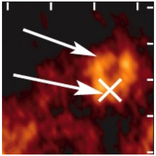
- in addition to the **Crab**, HESS discovered TeV emission from **G 0.9+0.1** (A&A, **432**, L25, 2005), **G 21.5–0.9** and **Kes 75** (Djannati-Ataï et al. 2007, ICRC, `arXiv:0710.2247`)
- *VERITAS* discovered TeV emission from plerions **G 54.1+0.3** (*ApJ* **719**, L69, 2010) and **G 74.9+1.2** (*ApJ* **788**, 78, 2013)
- **MSH 15–52** : first PWN angularly resolved in TeV γ-rays
- A&A **435**, L17 (2005)
- contours: ROSAT
- X-ray thermal shell and non-thermal "jet-like" nebula (IC discriminates)
- other composites similar in X-rays



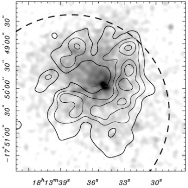
- IC emission $\propto$ (approximately uniform) target photon density $\Rightarrow$ direct inference of spatial distribution of electrons

Subsequently identified young PWNe in SNRs

The progressive identification of **HESS J1813–178**

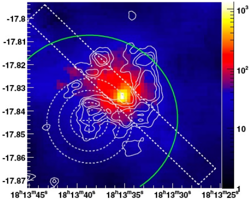


- *XMM* revealed an extended non-thermal nebula inside the shell (Funk et al. 2007a)

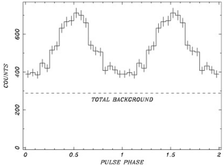


- *XMM* found pulsed emission, $\dot{E} = (6.8 \pm 2.7) \times 10^{37}$ erg/s (Gotthelf & Halpern 2009)

- Brogan et al. (2005) revealed its coincidence with a shell-type radio SNR (and *ASCA* source)

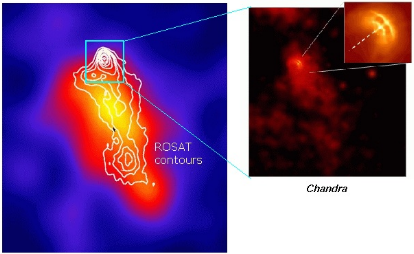


- *Chandra* revealed a pulsar candidate (Helfand et al. 2007)



Older, "offset" PWNe

- TeV emission from the **Vela X** nebula (A&A **448**, L43, 2006)



- coincident with one-sided "jet" (Markwardt & Ögelman 1995)
- compact X-ray nebula not conspicuous in TeV γ-rays $\Rightarrow$ torii and jets bright in X-rays because of higher magnetic field
- offset morphology explained by passage of anisotropic reverse shock, "crushing" the PWN (Blondin et al. 2001)?
- two TeV PWNe in **Kookaburra** appear to fall in same category
- radio / X-ray nonthermal emission matching **HESS J1356–645** places it in same category (*HESS* 2011, *A&A* **533**, A103)

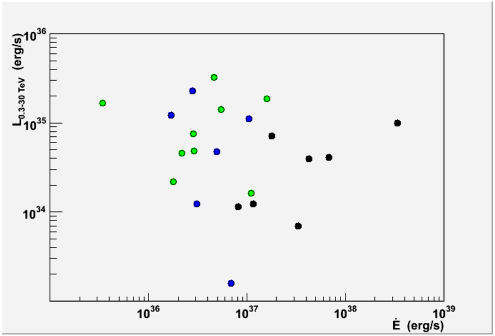
TeV γ-ray luminosity distribution of PWNe

- PWN TeV luminosities $L_{0.3-30\,\mathrm{TeV}} = 4\pi D^2 F_{0.3-30\,\mathrm{TeV}}$, plotted against (current) pulsar spin-down energy loss $\dot{E}$

young PWNe

offset PWNe

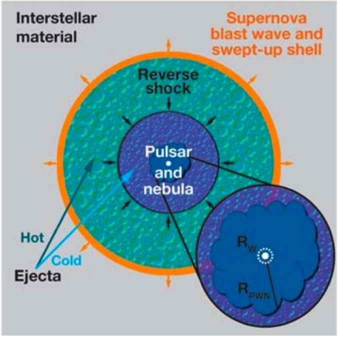
candidate PWNe



- relatively narrow range of L_γ ($\sim$2 decades); median luminosity for established PWNe is $L_{0.3-30\,\mathrm{TeV}} \approx 4.5 \times 10^{34}$ erg/s
- no correlation with $\dot{E}$, unlike L_X (Grenier 2009, Mattana et al. 2009)
- $\Rightarrow$ use TeV γ-ray observations to infer high-energy $e^\pm$ content of PWNe... and their $e^\pm$ CR contribution?

Issue : confinement and energy losses

- $e^{\pm}$ accelerated in inner part of PWN (wind termination shock)
- no immediate escape into interstellar medium (ISM) possible (unlike SNR forward shock acceleration); accelerated $e^{\pm}$ then suffer:



(Gaensler & Slane 2006)

Young composite phase

- confinement by PWN B
- radiative energy losses

Offset PWN phase

- reverse shock "crushing" $\Rightarrow$ enhanced losses
- further expansion $\Rightarrow$ adiabatic energy losses

- only after SNR dissipates into ISM ($\sim 10^4$–10^5 yr?) can these particles escape and propagate in the Galaxy
- accurate description much more complicated than simple "escape time" from magnetosphere

Summary

Supernova Remnants and Galactic Cosmic Rays

- clear evidence for particle acceleration to high energies in young SNRs, but often hadronic/leptonic ambiguity
- in several cases, esp. molecular cloud interactions, hadronic favoured; but steeper spectra than predicted or cutoffs
- no evidence that any observed SNR is currently a "PeVatron"

Prospects for VHE Neutrinos from SNRs

- optimistic predicted fluxes are below current upper limits
- next-generation detectors may meaningfully constrain hadronic components of brightest hard-spectrum Galactic γ-ray sources

Pulsars and their Wind Nebulae

- young PWNe in composite SNRs vs older, "offset" PWNe
- γ-ray observations of inverse Compton emission reveal spatial and spectral distributions of high-energy $e^{\pm}$
- radiative and expansion losses important for cosmic-ray $e^{\pm}$

Supplementary slides

UHE (>30 TeV) γ-rays and the cosmic-ray knee

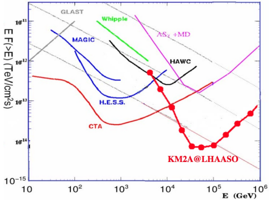
Where are the PeVatrons?

- no clear evidence that $E_{\max} \sim 3 \times 10^{15}$ eV can be attained by protons in **any** SNR detected in γ-rays (at least not with $p \sim 2$)
- a sufficiently sensitive UHE γ-ray detector should reveal any currently active PeVatrons in the Galaxy

Is the knee "universal" in the Galaxy?

- spectral knee only known from direct measurements at Earth
- indirect inferences from diffuse Galactic emission

- cosmic-ray protons at the "knee" energy ($\sim 3 \times 10^{15}$ eV) should radiate $\sim$100–300 TeV γ-rays when interacting with ambient matter
- science for LHAASO project (Sichuan province, China)



(S. Cui / LHAASO)