(Selected) Science prospects for Galactic γ-ray astronomy at high altitude

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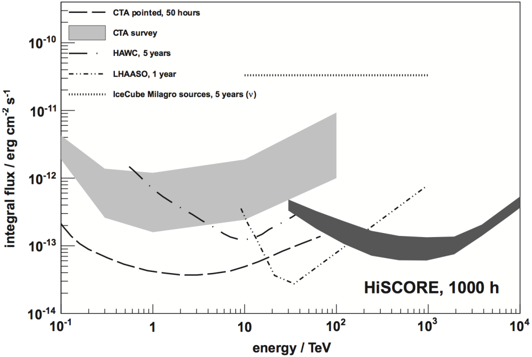
Context and Motivation
Supernova Remnants and Galactic Cosmic Rays
Gamma-ray "Halos" of Past PeVatrons
Pulsar Wind Nebulae (PWNe)

Next-generation experiments

- imaging atmospheric Cherenkov telescope system (CTA), high-altitude direct detection experiments (HAWC, LHAASO), non-imaging Cherenkov detectors (HiSCORE)…



(Tluczykont et al. 2014)

- *Caveat:* for a given zenith angle or source declination; estimation of zenith-angle dependence also important
- prospects "at high altitude" → with CTA and at higher energies

Galactic γ-ray science prospects
Yves Gallant
Paris, 27/5/2014
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Context contents of this talk and caveats

- science prospects discussed in lesser or greater detail in talks yesterday by J. Goodman, Zh. Cao, M. Tluczykont, S. Vernetto on HAWC, HiSCORE, LHAASO …

In this talk:

1. Supernova Remnants and the origin of Galactic Cosmic Rays; (e.g. Acero et al., CTA 2012)
2. search for possible gamma-ray "halos" of short-lived PeVatrons; (Gallant, Amato & Lavalle, in preparation)
3. Pulsar Wind Nebulae and the origin of cosmic-ray $e^{\pm}$. (e.g. de Oña-Wilheli et al., CTA 2012)

- current observational context, and theoretical issues
- will not discuss pulsars (pulsed emission), γ-ray binaries, nor **Galactic diffuse emission**…

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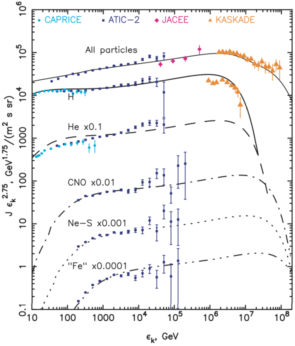
“PeVatrons” as the sources of Galactic CRs

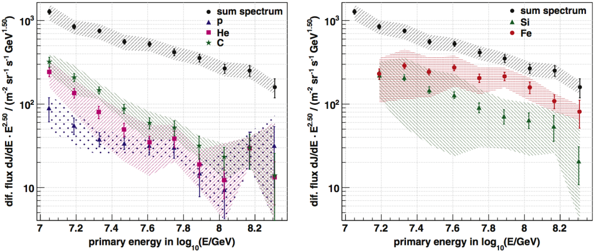
“knee” likely injection spectrum feature
electromagnetic acceleration mechanism:
energy cutoff $\propto Z$ (Peters 1961)

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

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

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





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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, $E_{\max} \sim$ few $\times\ 10^{15}$ eV (“PeVatrons”)

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

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X-ray observations of SNRs

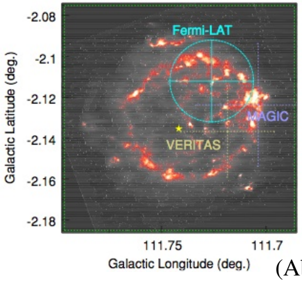
- Observational evidence for accelerated e^- (synchrotron)
- Indirect evidence for accelerated protons/ions (magnetic field amplification, modified hydrodynamics)

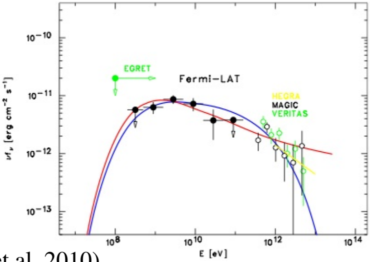
GeV/TeV γ-ray observations

- 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 often difficult to discriminate from **leptonic** (IC) 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)

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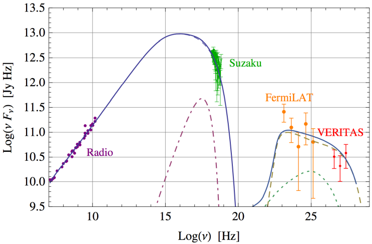
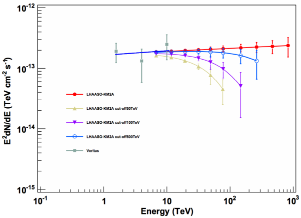
Could young SNRs be the Galactic PeVatrons?

- only if spectral index steeper than predictions of non-linear diffusive shock acceleration theory…
- possible improved theory including magnetic field amplification (Caprioli 2012) yields such steeper spectra
- Morlino & Caprioli (2012) model **Tycho** γ-ray emission as hadronic, with p energy cutoff at $\sim$500 TeV ("quasi-PeVatron")



(Morlino & Caprioli 2012)



(Cui et al. for LHAASO 2014)

- no purely observational constraint on high-energy γ-ray cutoff
- LHAASO simulations (Cui et al. 2014) of Tycho spectra with various cutoffs $\Rightarrow$ determine maximum proton energy

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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"

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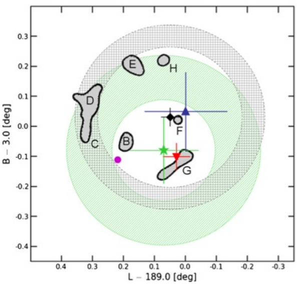
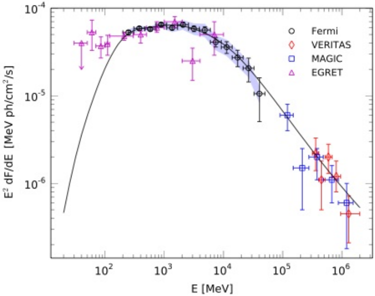
SNR / Molecular Cloud interactions : **IC 443**

- *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

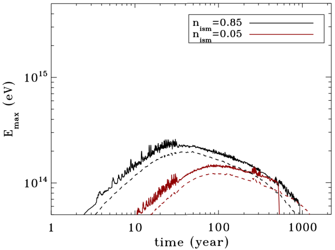
Implications of γ-ray SNRs for GCR origin

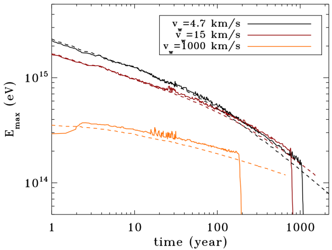
- no clear evidence that $E_{\max} \sim 3 \times 10^{15}$ eV can be attained by protons in **any** SNR detected in γ-rays (at least not with $p \sim 2$)
- observational proof that SNRs can accelerate Galactic cosmic rays to the "knee" energy is currently lacking

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 $E_{max} \sim 3$ 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), Renaud et al. (2014)

Implications of short-lived PeVatron scenarios

Hypothesis

- the sources of GCRs ("PeVatrons") reach $E_{p,\mathrm{max}} \sim$ few PeV for only a brief ($\Delta t \leq 10\,\mathrm{yr}$) period (e.g. the early SNR phase)

Consequences

- the current *confined* accelerated particle spectrum deduced from γ-ray observations of SNRs will cut off at $E_{\mathrm{esc}}(t) \ll 3\,\mathrm{PeV}$
  (would need to be very lucky to catch one "in the act")
- recent PeVatrons injected the *escaped* PeV cosmic rays with $E > E_{\mathrm{esc}}(t)$ into the surrounding medium, during a short time
  $\rightarrow$ could such PeV CRs be detectable through their interaction with the ISM, yielding **PeVatron halos** in γ-rays?

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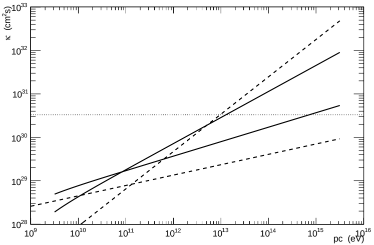
Required cosmic-ray yield per PeVatron

- must replenish Galactic CR density against (diffusive) escape:

$$n(E) = n_0 E^{-2.68}, \qquad t_{\rm res}(E) \approx H^2/[2\kappa(E)]$$

- Galactic diffusion coefficient $\kappa(E)$ at PeV energies? Extrapolate from lower-energy constraints (main uncertainty is in δ):



$$\kappa(E) \approx \kappa_0 E^{\delta}$$

Trotta et al. 2011 *(solid)*:
$\delta = \frac{1}{3}$ and 0.6

Putze et al. 2010 *(dashed)*:
$\delta = 0.24$ and 0.86

- assume PeVatrons at Galactic supernova rate: $1/\tau \approx 3/(100\,\mathrm{yr})$
- (time-integrated) PeVatron *escaping* particle spectrum:

$$Q(E) = \frac{V_{\rm Gal}\, n(E)\, \tau}{t_{\rm res}} = \frac{4\pi R_{\rm Gal}^2\, n_0\, \tau\, \kappa_0}{H} \times E^{-2.68+\delta}$$

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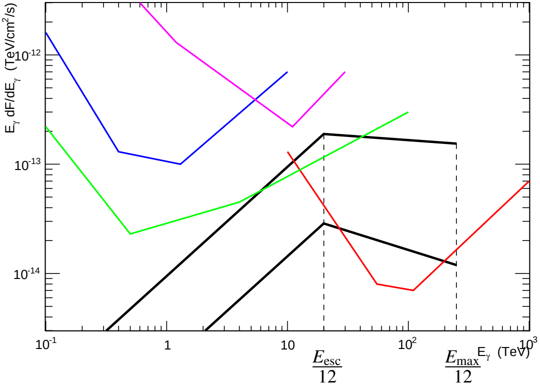
PeVatron halo γ-ray luminosity

- for $E > E_{\rm esc}(t)$, CRs already propagating in interstellar medium
- CR p + ISM $p \to p + p + \pi$'s, and $\pi^0 \to 2\gamma$:

  total $L(E_\gamma) \propto n_{\rm ISM}\, Q(12\, E_\gamma)$, for $E_\gamma \geq E_{\rm esc}(t)/12$



(point-source) sensitivities:

HESS/VERITAS

HAWC

CTA

LHAASO-KM2A

- predicted fluxes for the halo of e.g. **Cas A** (and $n_{\rm ISM}$=1 cm^{-3}) could be **detectable** by LHAASO-KM2A, if less extended than a few square degrees

Halo extent: diffusive regime

- at sufficiently large times, propagation will be diffusive:

$$R_h(E,t) \approx \sqrt{2\kappa(E)t}$$

- but this requires isotropisation of initial direction angle α:

$$\langle \Delta\alpha^2 \rangle \equiv \nu_\alpha t \approx \frac{c^2 t}{3\kappa(E)} \geq 1 \quad \Leftrightarrow \quad t \geq t_{\rm iso}(E) \equiv \frac{3\kappa(E)}{c^2}$$

$$t_{\rm iso}(E) = 4.2 \left(\frac{E_{\rm GeV}}{3}\right)^{1/3} \, {\rm yr} \approx 300\,{\rm yr} \quad \text{for } E = 1\,{\rm PeV},\ \delta = 1/3$$

- for cases of interest, isotropisation borderline for $\delta = 1/3$, not yet effective for $\delta = 1/2$ or larger: closer to free streaming at the speed of light ($\times \cos\alpha$)

- *Caveat:* generation of self-excited waves by streaming CRs might make isotropisation faster, and diffusive regime start earlier (with smaller $\kappa(E)$ $\Rightarrow$ more effective confinement)

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Halo extent: free-streaming regime

- with typical ISM scattering wave amplitudes, transition between free-streaming and diffusive regimes can be described as:

$$R_h(E,t) \leq \min\left\{ct, \sqrt{2\kappa(E)t}\right\}$$

- the free-streaming limit implies

$$R_h(t) \leq 30.7\,\mathrm{pc}\left(\frac{t}{100\,\mathrm{yr}}\right) \quad = \quad 107\,\mathrm{pc} \text{ for } \textbf{Cas A}\ (t \approx 350\,\mathrm{yr})$$

- if this were the apparent size of the halo, at $D = 3.4\,\mathrm{kpc}$, would have angular size $\theta_h \leq 1.8°$

- **N.B.**: this extent is along the regular magnetic field direction; *perpendicular* extent due to field-line wandering, much smaller

- but (at least in free-streaming regime) PeVatron halo appearance affected by beaming and light-travel-time effects

PeVatron "halo" appearance

Beaming

- π's from $p - p$ collisions beamed (with typical angle $1/\gamma_p$) in direction of CR proton
- γ-rays from π^0 decay beamed with typical angle $1/\gamma_\pi$

$\Rightarrow$ γ-ray emission from CRs travelling nearly along line of sight

Light travel time

- consider ISM magnetic field making angle ϕ with line of sight
- $r_\mathrm{L} \sim 1$ pc at 1 PeV $\Rightarrow$ escaping CRs are "gyrotropised"
- see emission from CRs with pitch angle $\alpha \approx \phi$; $v_{\parallel} \approx c \cos\phi$
- in free-streaming regime (neglecting pitch-angle scattering): (one-sided) distance in plane of sky $x_h(t) \approx ct \cos\phi \sin\phi$
- light travel time: $t_\mathrm{obs} \approx t\left(1 - \cos^2\phi\right) = t \sin^2\phi$

$\Rightarrow$ apparent sky velocity $v_\mathrm{app} \approx c/\tan\phi$ (can be superluminal!)

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

Where are the PeVatrons?

- no evidence that $E_{\rm max} \sim 3 \times 10^{15}$ eV can be attained by protons in **any** SNR detected in γ-rays (at least not with expected spectrum)

Observational prospects

- more sensitive instruments such as CTA will greatly expand the object populations, including younger, more distant objects
- higher-energy detectors can better constrain high-energy cutoffs, and find whether any SNR is currently a PeVatron

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Prospects for PeVatron "halo" detection

- if Galactic PeVatrons are short-lived, they are still surrounded by an over-density of *escaped* PeV cosmic rays
- the *ultra-high-energy* (UHE, $E_\gamma > 30\,\mathrm{TeV}$) γ-ray flux of such PeVatron halos may be detectable with planned experiments such as LHAASO-KM2A
- observed "halos" would extend along the local ISM magnetic field direction, with centroid displaced from the source
- the detection of such halos would provide **direct observational proof** of the acceleration of cosmic-rays up to the "knee" energy
- if detected, the energy-dependent size and shape of such halos could provide unique observational constraints on the transport properties of very-high-energy cosmic rays in the Galaxy

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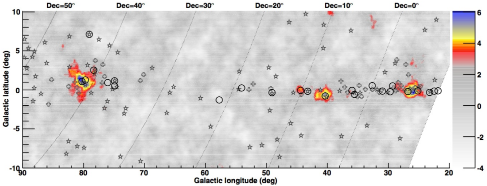
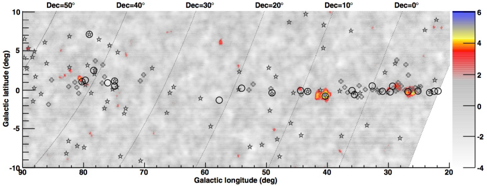
Galactic TeV γ-ray sources

- good sensitivity of current-generation Imaging Atmospheric Cherenkov Telescopes, starting with HESS > one decade ago
- currently >80 Galactic TeV sources known
- $\sim$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)

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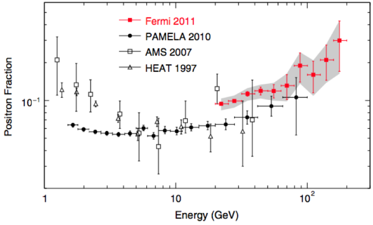
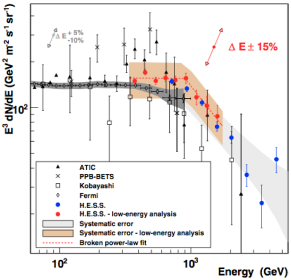
Pulsar (Wind Nebulae) and Cosmic-ray e^+

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



(Ackermann et al. 2012)



(Aharonian et al. 2009)

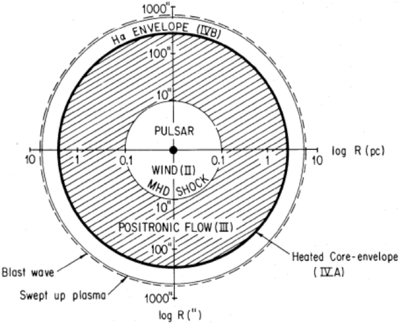
- tending towards 50% up to $(e^+ + e^-)$ steepening at $E \sim 1$ TeV?
- spectrum and positron fraction require **primary** $e^\pm$ source
- signature of DM annihilation? PWNe a "natural" scenario…

Pulsar wind (termination shock and) nebula

- relativistic pulsar wind meets ambient medium (remnant of the supernova which gave birth to the pulsar) $\Rightarrow$ **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 $\equiv$ shocked pulsar wind)
- $\Rightarrow$ electrons/positrons accelerated at wind termination shock

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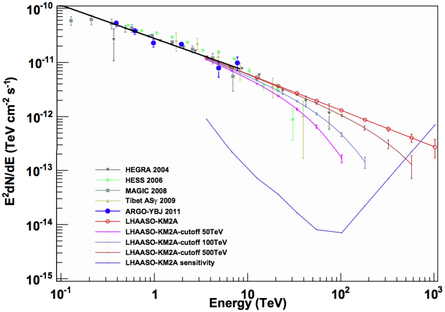
High-energy spectral observations

- gamma-ray emission thought to be Inverse Compton
  $\Rightarrow$ expect cutoff due to Klein-Nishina effects

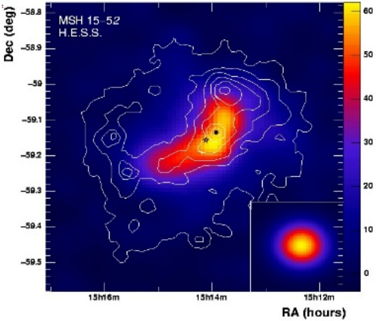


(Cui et al., LHAASO 2014)

- high-energy observations can help confirm nature of emission
- nucleonic γ-ray component in PWNe also proposed (e.g. Horns et al. 2006)
- any IC variability correlated with AGILE and *Fermi* flares would likely be seen at these high energies

Young PWNe (in composite SNRs)

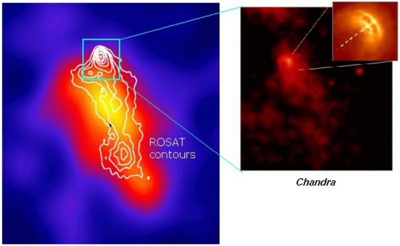
- in addition to the **Crab**, HESS discovered TeV emission from **G 0.9+0.1** (A&A, **432**, L25, 2005), **G 21.5–0.9** and **Kes 75** (Djannati-Ataï et al. 2007, ICRC, `arXiv:0710.2247`)
- *VERITAS* discovered TeV emission from plerions **G 54.1+0.3** (*ApJ* **719**, L69, 2010) and **G 74.9+1.2** (Aliu 2011, `arXiv:1110.4656`)
- **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

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)

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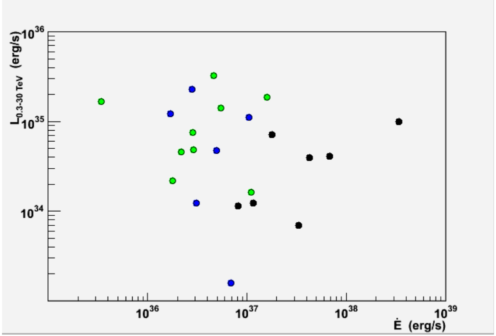
TeV γ-ray luminosity distribution of PWNe

- 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

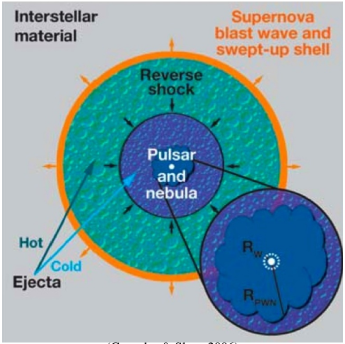
candidate PWNe



- 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

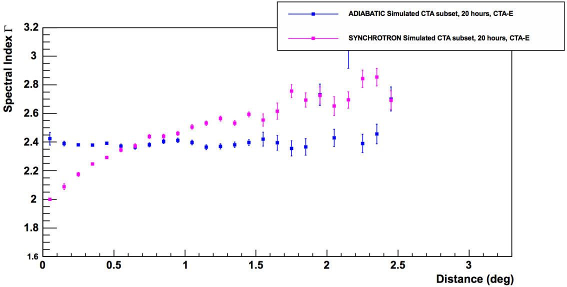
Offset PWN phase

- 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

Energy-dependent morphological studies

- spectral steepening with radius (or not) can constrain the nature of $e^{\pm}$ energy losses: radiative (synchotron) or adiabatic



(de Oña-Wilhelmi et al., CTA 2013)

- can also help constrain nature of emission in unidentified sources: hadronic emission would not show steepening
- diffusion away from a PeVatron (as in "halos") may in fact show spectral *hardening* with radius
- survey instruments: well-adapted for very extended sources

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”

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 $e^{\pm}$

Future observational prospects

- more sensitive and high-energy instruments will greatly expand the object populations, including very young, distant objects
- seeing Galactic “PeVatrons” with sensitivity at $E \sim 100$ TeV

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