(V)HE γ-Ray Emission from Supernova Remnants

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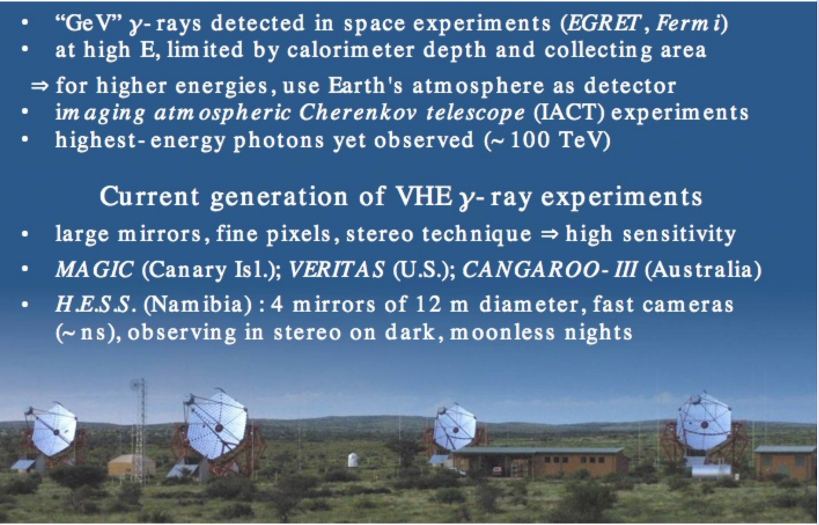
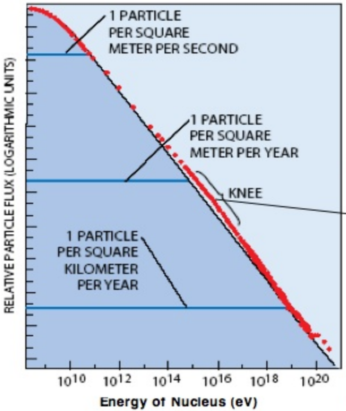
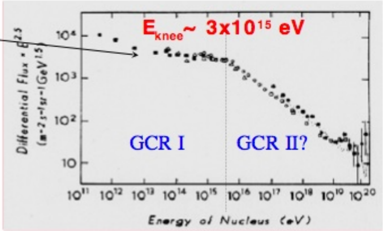
High Energy (HE, or “GeV”, 0.1–100 GeV) and Very High Energy (VHE, or “TeV”, 0.1–100 TeV) γ-Ray Detectors



Galactic Cosmic Rays (GCRs)



- 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



- Direct measurements only at Earth (satellites and atmosphere)
- Known to fill the Galaxy from diffuse gamma- ray emission (*EGRET*)
- Known *not* to fill intergalactic space from non- detection of SMC (and lower inferred CR density in LMC)

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

- Supernova remnants are widely considered likely sources of Galactic cosmic rays up to the "knee", $E \sim 3 \times 10^{15}$ eV :
  - well-studied shock acceleration mechanism;
  - GCR composition compatible with an SNR origin;
  - energetics require $\sim$10% of total SN energy of 10^{51} erg

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
- On of aims of TeV γ-ray astronomy (e.g. Drury et al. 1994)
- But how to discriminate from **leptonic** (IC) emission?

Hadronic vs. leptonic γ-ray emission

Hadronic (proton and ion) emission

- CR p + ISM/CSM $p \to +\pi$'s, $\pi_0 \to 2\gamma$ (similarly for nuclei)
- cross-section $\sim$ E-independent $\Rightarrow$ γ-ray spectral index Γ $\approx$ proton spectral index p (at $E_\gamma \sim 0.1 E_p$)

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

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

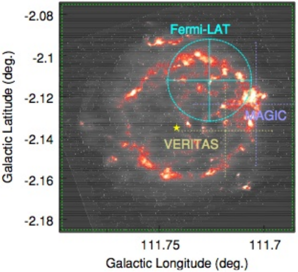
- γ-ray morphology correlates with CR and ISM density

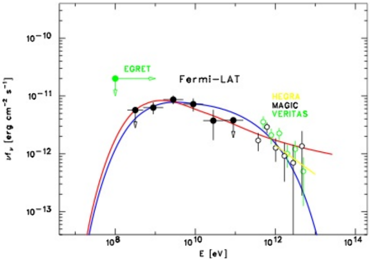
Leptonic (electron) emission

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

GeV / TeV spectrum of **Cassiopeia A**

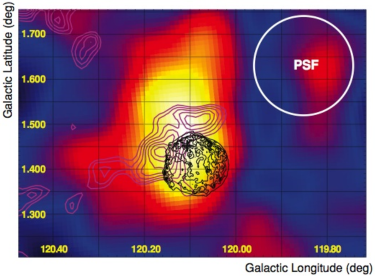
- general expectations of modern, non-linear diffusive shock acceleration (NLDSA) theory :
  - concave, hard proton spectrum ($\Gamma \sim 2$)
  - at some point in SNR evolution, $E_{\max} \sim$ few $\times\, 10^{15}$ eV ("PeVatrons")
- sharp X-ray rims, etc. $\Rightarrow$ high $B \sim$ mG $\Rightarrow$ hadronic favoured
- *Fermi*-LAT detection of Cas A (Abdo et al., ApJL 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)

TeV detection of **Tycho**'s SNR (SN 1572)



(VERITAS 2011, *ApJ* **730**, L20)

- $\Gamma = 2.0 \pm 0.5_{\rm stat} \pm 0.3_{\rm sys}$ (low statistics; 5σ detection)
- $L_{1-10} \approx 1.3 \times 10^{33}$ erg/s (assuming $D = 4$ kpc)

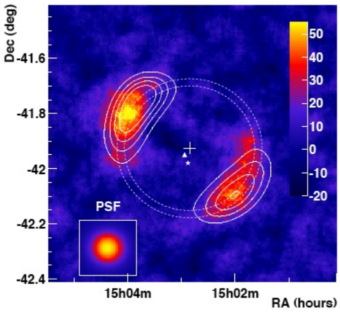
- γ-ray centroid shifted NE of center (by $2.4' \pm 1.4'_{\rm stat} \pm 0.8'_{\rm sys}$), towards interacting(?) CO cloud (and brighter synchrotron region)
- leptonic emission $\Rightarrow B \geq 80\,\mu$G ; hadronic requires large particle energy ($\sim 8 \times 10^{50}$ erg), unless $n \gg 0.2\,{\rm cm}^{-3}$

TeV observations of **Kepler**'s SNR (SN 1604)

- *HESS* 2008 upper limit (*A&A* **488**, 219)
- $L_{1-10\,{\rm TeV}} < 2 \times 10^{33}$ erg/s (assuming $D \approx 4.8$ kpc and $\Gamma = 2$; distance uncertain by ± 1.5 kpc $\Rightarrow$ factor ~ 2 in $L_{1-10\,{\rm TeV}}$)

Angularly resolved historical SNR : **SN 1006**

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



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

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

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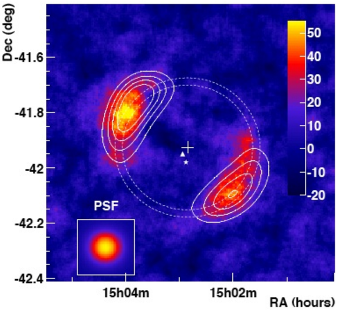

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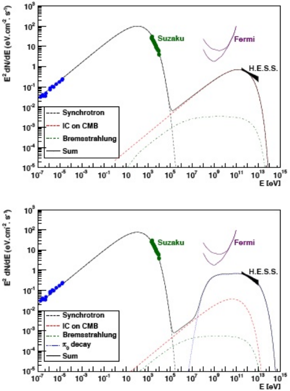
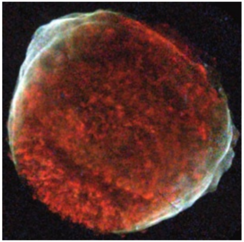


- leptonic scenario suggests relatively low B-field $\approx 30\,\mu$G
- hadronic scenario require hard spectrum, $E_{\rm cutoff} \sim 10\,$TeV

Bipolar morphology of particle acceleration

- 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)

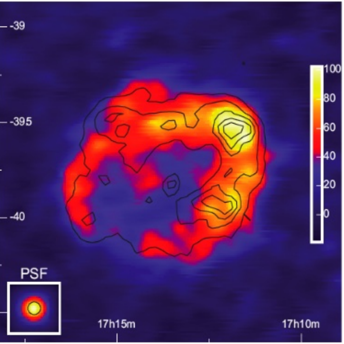
- SN 1006 : explosion in nearly uniform, undisturbed medium?
  - Type Ia : no stellar progenitor wind
  - High above the Galactic plane
- Rothenflug et al. (2004) : X–ray image compatible with synchrotron "polar caps", not with "equatorial band"
- Suggests that **parallel** shocks, and not **perpendicular**, are where particle acceleration is most efficient



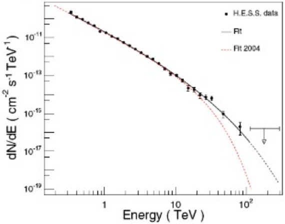
- *post-shock* magnetic geometry influenced by instabilities ⇒
- confirmation of this scenario would require measurement of ***B*** direction in the *unshocked* medium upstream: impossible(?)

SNRs with shell morphology in TeV γ-rays

RX J1713.7−3947 (or G347.3−0.5)



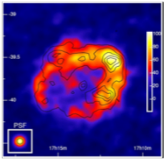
- VHE γ−ray emission discovered by *CANGAROO* (Muraishi et al. 2000)
- first resolved SNR shell in VHE γ−rays (*HESS* 2004, *Nature* **432**, 75)
- very good spatial correlation with (non−thermal) X−rays (ASCA 1−3 keV) (*HESS* 2006, *A&A* **449**, 223)
- large zenith angle observations ⇒ spectrum 0.3−100 TeV (*HESS* 2007, *A&A* **449**, 223)



- power law $\Gamma \approx 2.0$ with cutoff or break at $E_\gamma \sim 10$ TeV (depending on model)
- $L_{1-10\ \mathrm{TeV}} \sim 10^{34}$ erg/s (assuming $D \approx 1.3$ kpc)
- leptonic emission scenario $\Rightarrow B \sim 9\ \mu$G

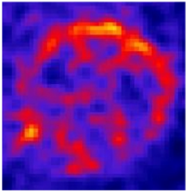
TeV shell SNRs : other examples

RX J1713



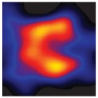
HESS (2006)

Vela Junior



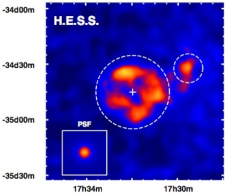
HESS (2007)

RCW 86



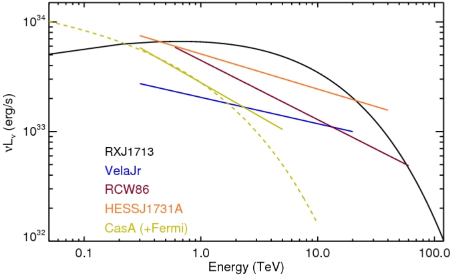
HESS (2009)

HESS J1731–347



HESS (2011)

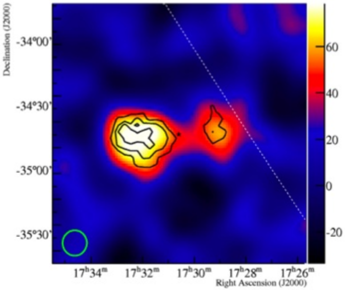
(M. Renaud)

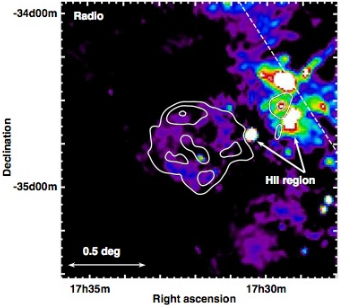


Median luminosity : $L_{1-10\,\mathrm{TeV}} \approx 9 \times 10^{33}$ erg/s

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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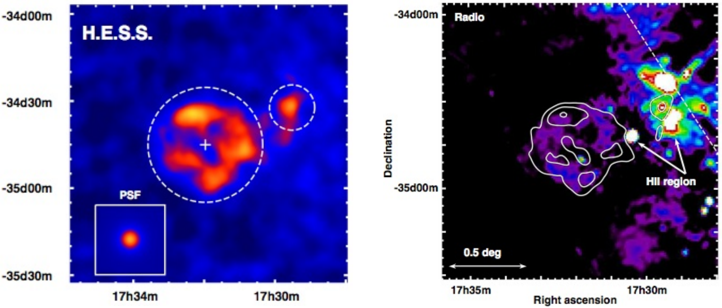

- further *HESS* observations : significant (3.9 σ) limb-brightening

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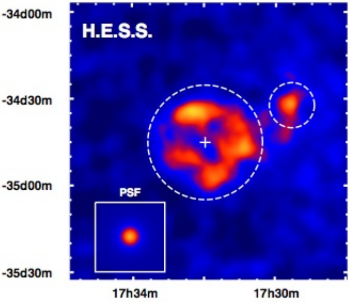
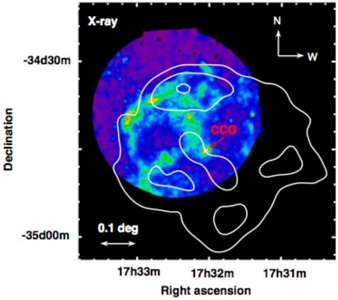




- further *HESS* observations : significant (3.9 σ) limb-brightening
- *XMM* observations of (part of) shell show rims of emission with non-thermal spectra (no evidence for thermal emission)
- next generation TeV γ-ray observatory (**CTA**) should discover many more non-thermal shell SNRs (see talk by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

Young and γ-ray shell SNRs: general properties

- dominantly non-thermal X-ray emission (thermal seen only in RCW 86, and historical SNRs)
- weak radio synchrotron emission (except younger SNRs)
- TeV luminosities $L_{1-10\,\mathrm{TeV}} \sim$ a few $\times\ 10^{34}$ erg/s (historical SNRs lower, TeV shells higher)

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
- TeV shell widths larger than X-ray filaments (e.g. Renaud 2009): if rapid B-field damping behind the shock, may be compatible with weak *spatially-averaged* B value
- difficult to reproduce γ-ray spectral shapes in one-zone model

Young and γ-ray shell SNRs: general properties

Hadronic emission scenario

- no obvious explanation for high correlation with X-rays, and poor correlation with medium density (in resolved SNRs)

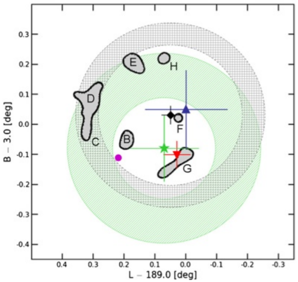
- **all** (V)HE-detected shell SNRs have $\Gamma > 2.0$ or cutoff at $E_\gamma \sim 10\,\mathrm{TeV} \Rightarrow E_p \sim 10^{14}\,\mathrm{TeV}$ — well short of "knee"
- spectrum must flatten to $\Gamma \sim 2$ at lower energies (seen in Cas A, RX J1713 and hinted in others), else CR energetics prohibitive

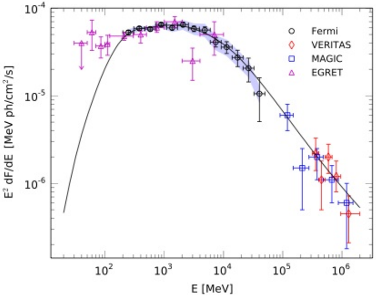
- relatively high surrounding medium density ($n \sim 1\,\mathrm{cm}^{-3}$) required to explain RX J1713, Vela Jr and HESS J1731
- but upper limits on n from lack of thermal X-ray emission are a few$\times 0.01\,\mathrm{cm}^{-3}$ (assuming $k_B T \sim \mathrm{keV}$)

- **Caveat:** distances to these SNRs uncertain; most precise estimates often rely on unmodified shock jump conditions

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

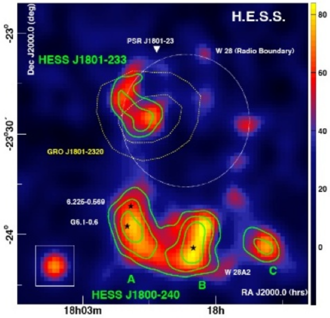




- best-fit LAT spectrum broken power law (single PL poor fit)
- hard spectrum $\Gamma_1 = 1.93$ up to $E_{\rm break} = 3.3 \pm 0.6\,$GeV
- steep spectrum $\Gamma_2 = 2.6 \pm 0.1$ at higher energies, compatible with *MAGIC* and *VERITAS* data

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

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



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

coincident with GeV source

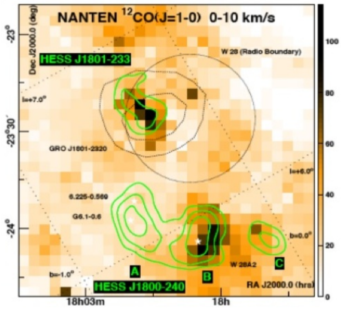
morphology matches CO cloud

coincident w/methanol maser!
(D. Frail) shock/MC interaction

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

HESS J1800–240B matches CO cloud at same velocity

"passive" MC "illuminated" by *escaping* CRs from W 28?
(see talk by S. Gabici)



SNRs interacting with Molecular Clouds

- coincidence with dense cloud suggests hadronic VHE emission
- signature of shock interaction with cloud : 1720 MHz OH maser
- several other TeV γ-ray sources coincident with SNR/MC interactions, including CTB 37A and W51C (G49.2–0.7)... (see talks by R. Chaves, J. Méhault, I. Reichardt)
- generally coincide with *Fermi*-LAT sources (Castro & Slane 2010) (see talk by T. Brandt)
- flux and cloud mass imply CR density enhanced by large factor
- but steep VHE spectra / low-E cutoffs : accelerated hadrons reach maximum energy well below cosmic-ray "knee"?

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 $E_{\rm max} \sim 3 \times 10^{15}$ 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
- no current "PeVatron": is SNR PeVatron phase extremely short?
- is knee a "local" feature of Galactic cosmic ray distribution?

Superbubbles as the Main GCR Accelerators?

- core-collapse supernova progenitors (massive stars) are typically formed not in isolation but in giant molecular clouds (**GMCs**), becoming **OB associations** (open star clusters)
- combined energy input of powerful **stellar winds** and/or successive **supernovae** blow a bubble of hot gas in the medium
- $\sim$***75%*** of all SNe may occur in such "superbubbles"; explains lack of other radio SNRs like Cas A? (Higdon & Lingenfelter 2005)

Particle acceleration in superbubbles

- SNRs in superbubble gas $\approx$ "hot" phase of interstellar medium ($n \sim 0.003\mathrm{cm}^{-3}$, $T \sim 10^6$ K)?
- (colliding) winds of massive stars (e.g. Cassé & Paul 1980)?
- turbulent and multiple shock acceleration (e.g. Parizot et al. 2004)?

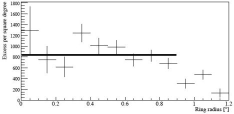
(see talk by Th. Montmerle)

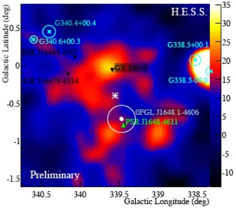
- relative paucity of observational evidence for acceleration to very high energies in these objects — until recently…

Discovery of TeV γ-rays from Westerlund 1

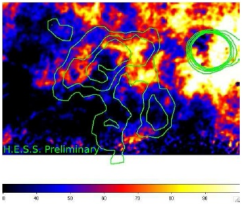
- extremely massive star cluster: 24(!) Wolf-Rayet stars (versus 2 in Westerlund 2), 80 blue supergiants…

(Ohm et al., H.E.S.S., ICRC 2009)





HI (SGPS)



- very extended TeV γ-ray emission, up to 0.9° from Westerlund 1
- hint of shell morphology, but limb-brightening not significant

- at $D = 4\,\mathrm{kpc}$, fills region of $R \sim 60\,\mathrm{pc}$ (!)
- matches HI shell around Westerlund 1 (Kothes & Dougherty 2007)
- more than enough power in stellar winds ($L \sim 10^{39}$ erg/s, + SNe, Muno et al. 2006) to explain a superbubble of this size

- spectral analysis in progress…

Discussion : TeV γ-rays from superbubbles

Observations

- Westerlund 1 and 2 supported by match to MWL blister or shell
- HESS J1848–0145 / W43? (see talk by M. Lemoine-Goumard)
- unidentified source TeV J2032+4130 (confirmed by *MAGIC* 2008, *ApJ* **675**, L25) proposed association with Cygnus OB2
- HESS J1614–518 may be associated with Pismis 22

Interpretation

- direct evidence for $\sim 10^{14}$ eV particles overlaps superbubbles
- **hadronic** emission? Mass in surrounding (HI) shell, interacting molecular cloud ($7 \times 10^4 M_\odot$ in Wd 2); but limb-brightening?
- **leptonic** emission? Intense photon fields for IC scattering: stellar photons, HII region, cloud IR emission...

Open questions

- in principle, most of Galactic SN energy deposited inside SBs
- what is the efficiency of SNR shock acceleration in hot medium?
- can other mechanisms (stellar winds, turbulence) be more efficient?