SNRs in Wind bubbles and their Emission

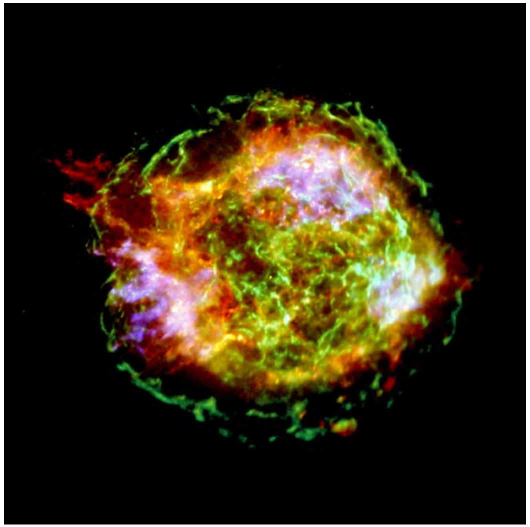
Heinz Völk, MPI Kernphysik, Heidelberg, Germany

- Time-dependent acceleration models for core collapse supernovae of massive stars: Vela Jr. (RX J0852.0-4622) and RX J1713.7-3946
- Calculation of particle populations and nonthermal emission: Comparison with *H.E.S.S.* and recent multi-wavelength data
- Theoretical model → Estimate of thermal emission
- Not a theory talk as such

5th Korean Astrophysics Workshop, Pohang, 18. – 21. Nov. 2009

SNRs from massive progenitor stars with stellar winds, wind bubbles and dense swept-up shells around them extremely complicated:

- Density structure not describable by simple power laws
- Self-similar gas dynamic solutions only at very early epoch, where shock crosses wind and bubble, usually not very relevant observationally, e.g. for γ-ray astronomy
- No analytical solutions/approximations possible
- Spherical symmetry nevertheless reasonable 1st order approximation in “shell epoch” (crossing the radiatively cooling swept-up shell), where all the action is (Injection of nuclear ions on chaotically directed magnetic field lines also ~ spherically symmetric)
- Intermediate case: Cas A, not consided here

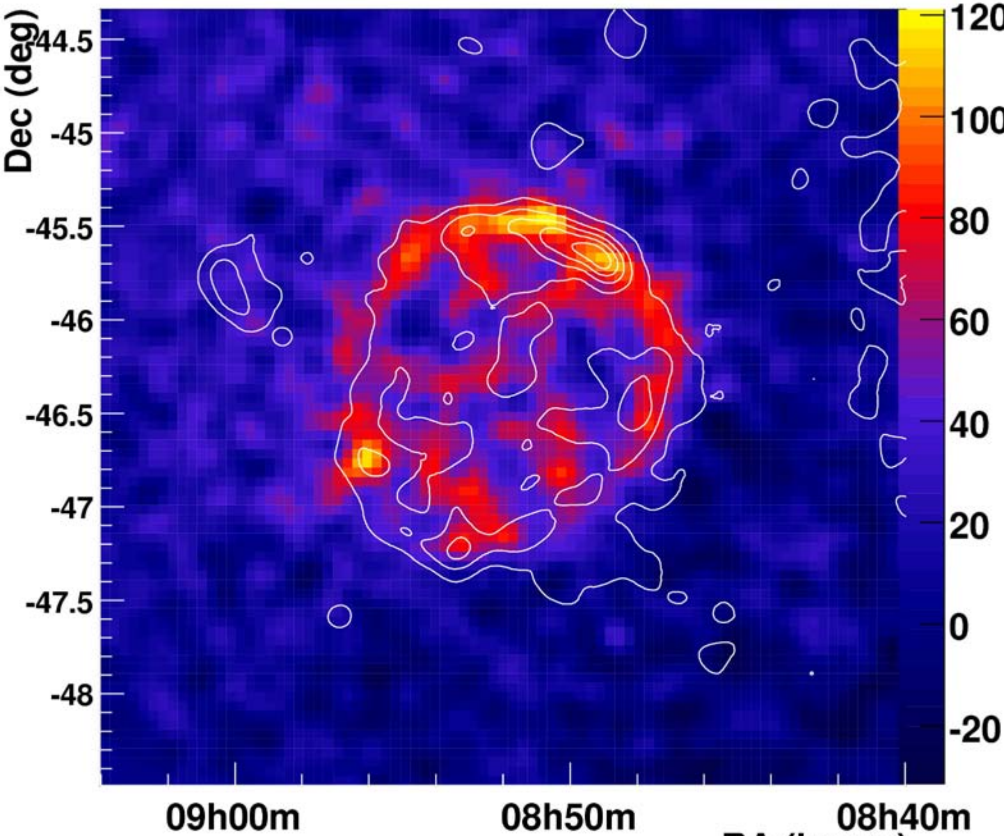


Cas A

Examples described here (*H.E.S.S.* morphologies):

Vela Jr.

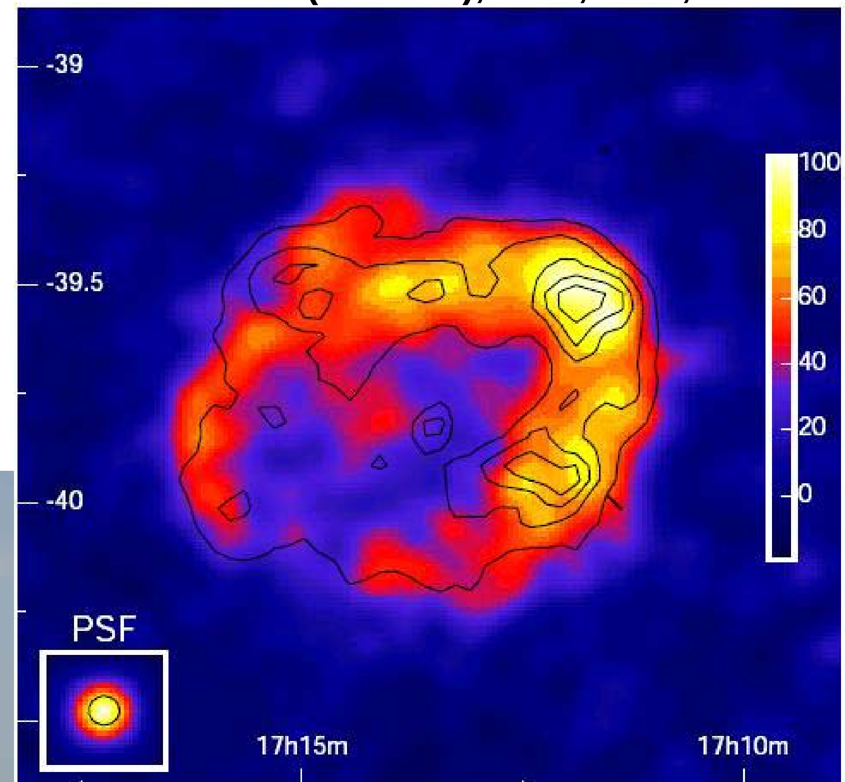
Katagiri et al. (*CANGAROO*), 2005
Aharonian et al. (*H.E.S.S.),* 2005, 2007



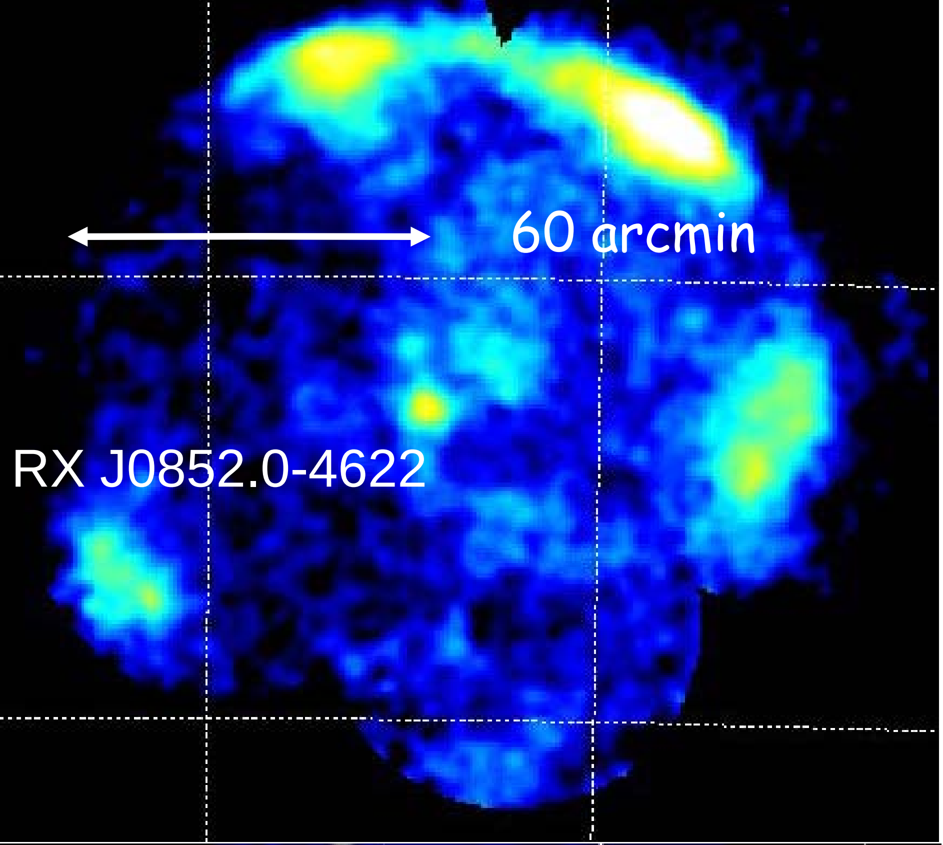
***H.E.S.S.* with *ROSAT* contours**

RX J1713.7-3946

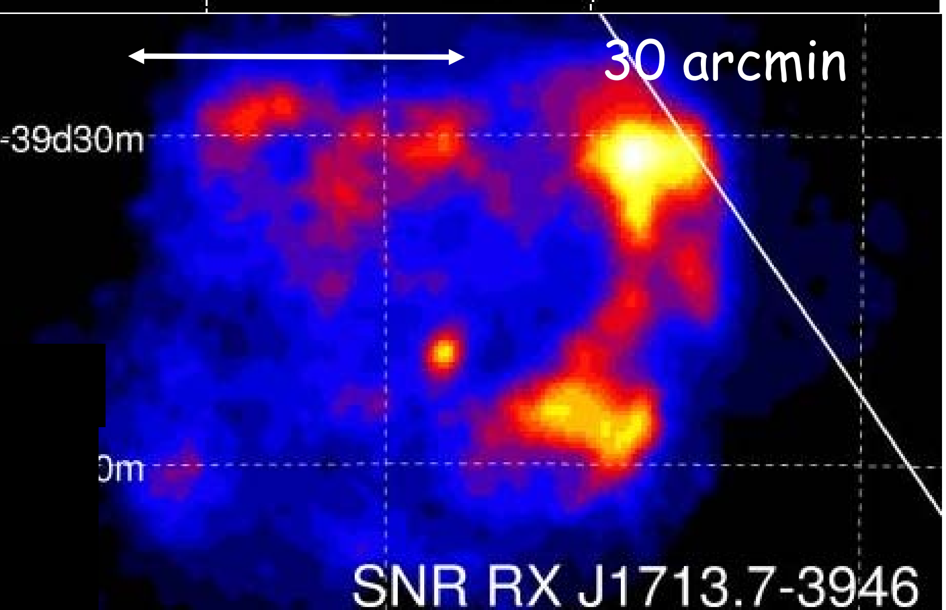
Enomoto et al. (*CANGAROO*), 2000, 2002
Aharonian et al. (*H.E.S.S*.), 2004, 2006, 2007

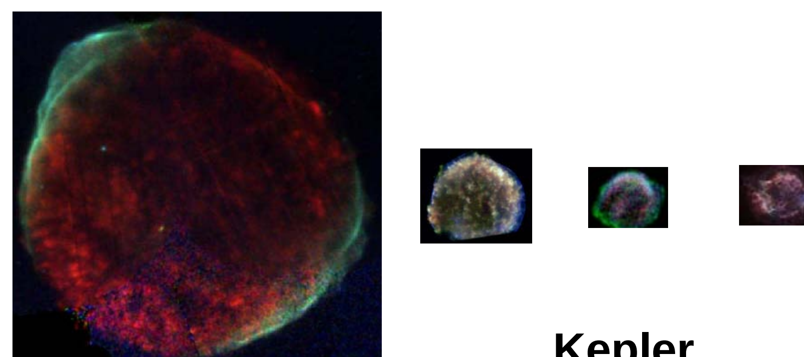


***H.E.S.S.* with *ASCA* contours**



Sizes of young SNRs in hard X-rays very different (with *ASCA, Chandra, XMM-Newton, Suzaku*). Only the large ones spatially resolvable in γ-rays





SN1006 **Tycho** **Kepler** **Cas A**

Model considers spherically symmetric transport equations for both nuclear particles and electrons

- They couple nonlinearly to gas dynamics of thermal plasma (i) through force of nonthermal particle pressure gradient and (ii) through turbulent gas heating from dissipation of particle-excited fluctuations
- Gas dynamics couples in turn to particle kinetics (i) through energetic particle convection by plasma velocity and (ii) through particle diffusion in plasma turbulence
- Fully time-dependent solution allows description of point explosion. Includes particle escape in decelerating shock (Escaping particles have zero pressure gradient)

(Berezhko et al. 1996; Berezhko & V. 1997, 2000; Kang & Jones 2006; Zirakashvili & Ptuskin 2009, …)

In the absence of a complete theory of field fluctuations:

→ Semi-empirical model for amplified B-field, particle scattering, and turbulent heating (1):

1) Invoke an upstream amplified mean field strength B_0, with $B_0 > B_{ISM}$, to be determined from observed electron synchrotron spectrum (radio → hard X- rays) and/or from filament-morphology in hard X- rays.

2) Approximate $B(r) = (\rho(r) / \rho_{ISM}) \times B_0$, for all $r > 0$

3) Disregard dissipation of amplified field in SNR interior

4) Assume $\kappa(r,p) = 1/3\ v\ r_g$, where $r_g = cp/eB$, i.e. Bohm diffusion in amplified field δB that is major part of B, for all p (→ upper limit for p_{max} of loss-free nuclear particles !) → *Bootstrap:*
~ ok with simulations (e.g. Reville et al. 2008), if $B \leq 10\ B_0$ (e.g. Bell 2004, Zirakashvili et al. 2008, Riquelme & Spitkovsky 2009, Ohira et al. 2009) as observed (e.g. V. et al. 2005, Vink 2005, Ballet 2006, Uchiyama et al. 2007)

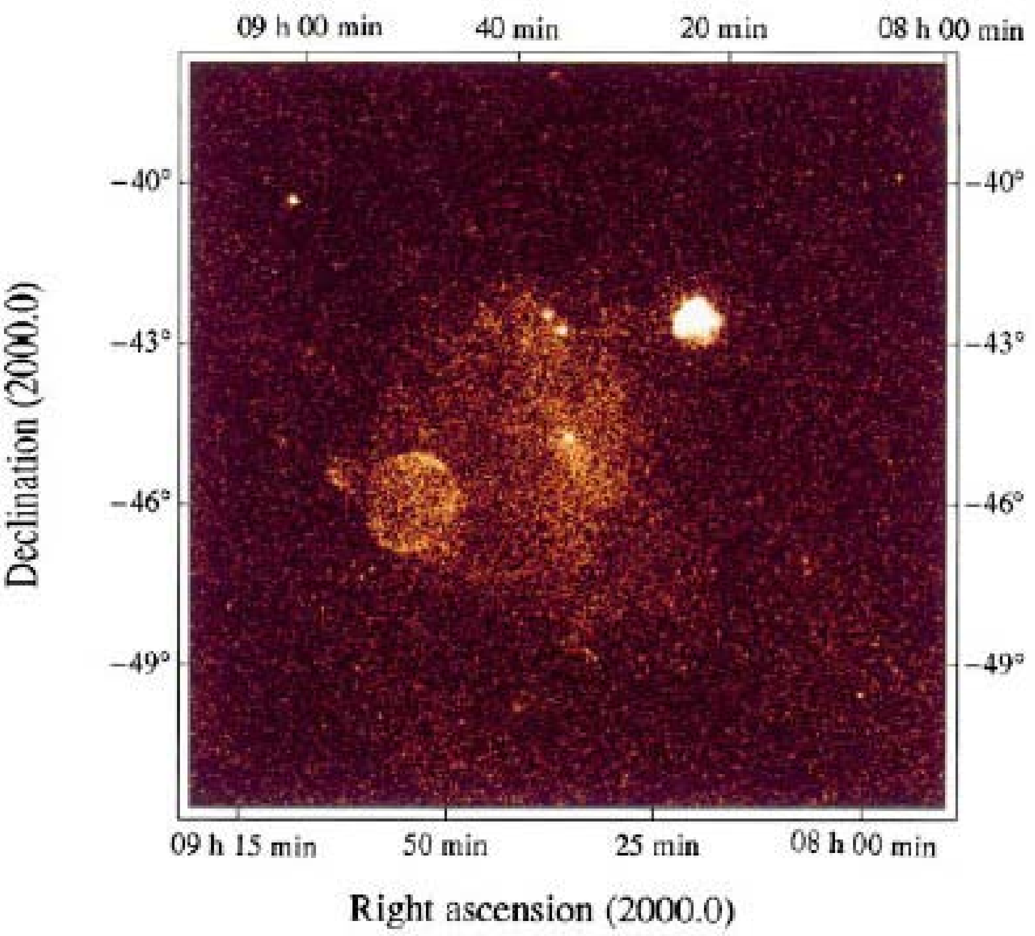
→ Semi-empirical model for amplified B-field, particle scattering, and turbulent heating (2):

5) Assume wave dissipation in precursor to avoid resonant over-amplification of B, i.e. a plasma heating rate $(de_g/dt)_{diss} = c_A \times dP_c/dr$, where c_a = Alfven velocity in amplified field:
~ ok if non – dissipative resonant amplification already >> B_0 (Pelletier et al. 2006, Berezhko 2008) → $4 < \sigma \leq 10$ (see also Hyesung Kang et al. yesterday).
Heating through nonlinear wave-particle interactions ("nonlinear Landau damping", e.g. Lee & V. 1973) in amplified B-field (Vladimirov et al. 2008) and internal shocks from CR-induced instabilities (Bell 2004, Zirakashvili et al. 2008) plus acoustic mode effects (so-called Drury instability). Fast enough !?

6) Treat plasma subshock as pure gas dynamical shock (For inclusion of "waves", see Caprioli et al. 2009)

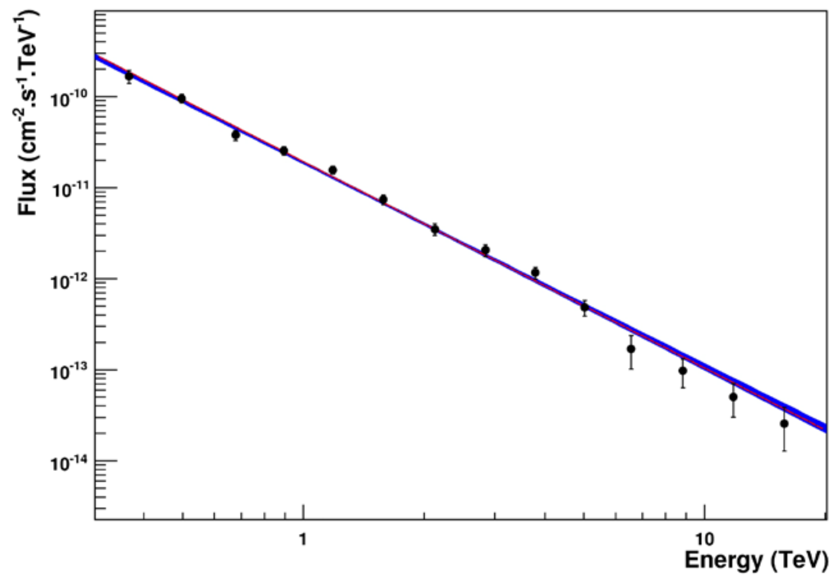
SNR RX J0852.0-4622 (Vela Jr.)

E.G. Berezhko (IKFIA,Yakutsk), G. Pühlhofer (Univ.Tübingen) & H.J.V.



Discovered by B. Aschenbach, 1998 (*ROSAT*)

H.E.S.S. differential spectrum **hard**



Power - law spectral index = $2.1 \pm 0.1_{stat} \pm 0.2_{sys}$

X-ray Observations: strong nonthermal X-ray emission, in Galactic Plane.

1) Thermal emission hardly seen, if at all (Uchiyama, 2008): within the much larger Vela SNR and distinguishable only in hard X-rays. Located probably behind the Vela SNR at about 1 kpc distance, because of rather high extinction

2) Sharp X-ray filaments (Bamba et al., 2005, using Chandra). These require amplified magnetic field > 100 µG. Can only result from a strongly accelerated nuclear particle component

3) Combination of large size and requirement of high shock velocity for a large non-thermal X-ray flux requires very low gas density. But in homogeneous medium then no efficient hadronic gamma-ray emission possible

4) Assumption: SN explosion into wind bubble of massive progenitor star (M ~ 20 solar masses), enclosed by a dense shell of swept-up ISM, similar to SNR RX J1713.7-3946, as proposed earlier by Slane et al., 2001

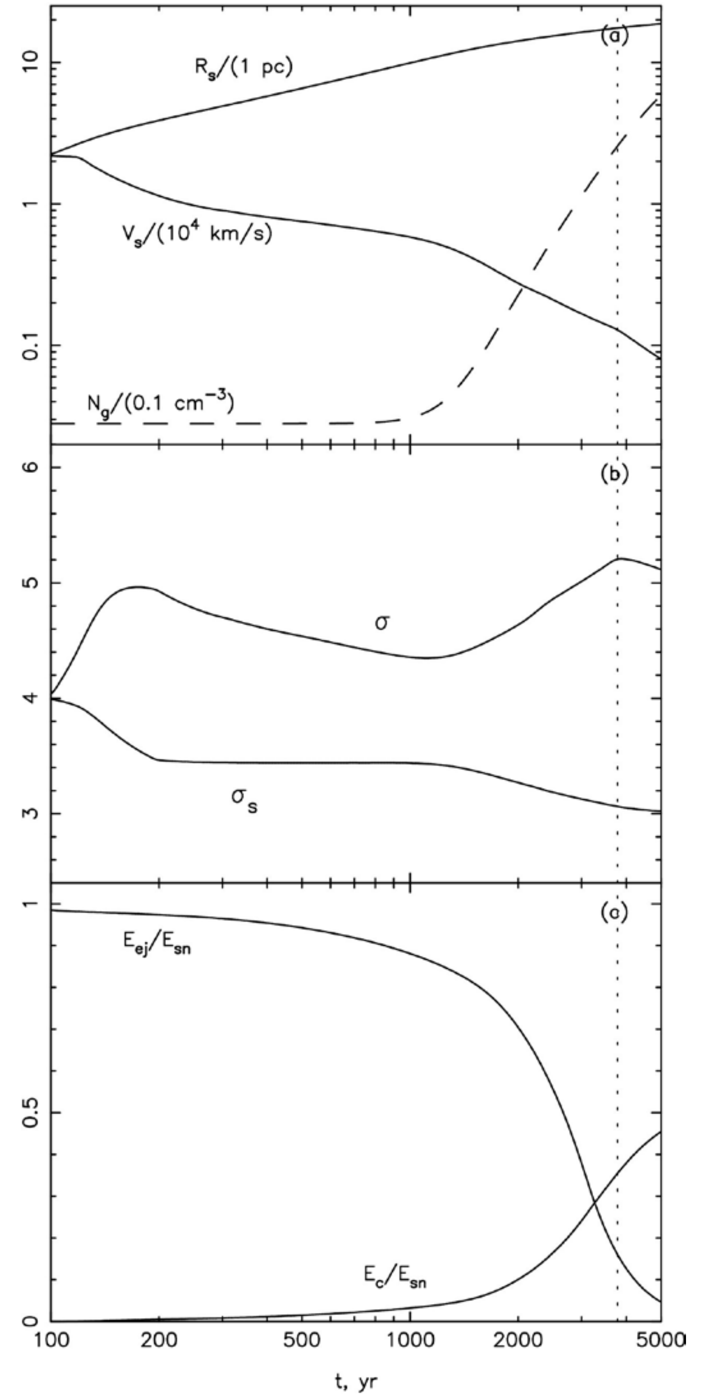
$\Rightarrow$ Calculation of SNR expansion in wind bubble plus particle acceleration and nonthermal emission

Dynamical evolution of SNR:

SNR has already reached shell of wind bubble ($N_g \approx 0.24$ cm^{-3})

Shock modification by accelerated particles: compression ratios $\sigma > 4$ and $\sigma_s < 4$

Relative CR energy E_c / E_{sn} quite high (35%) at present age ~ 4000 yrs

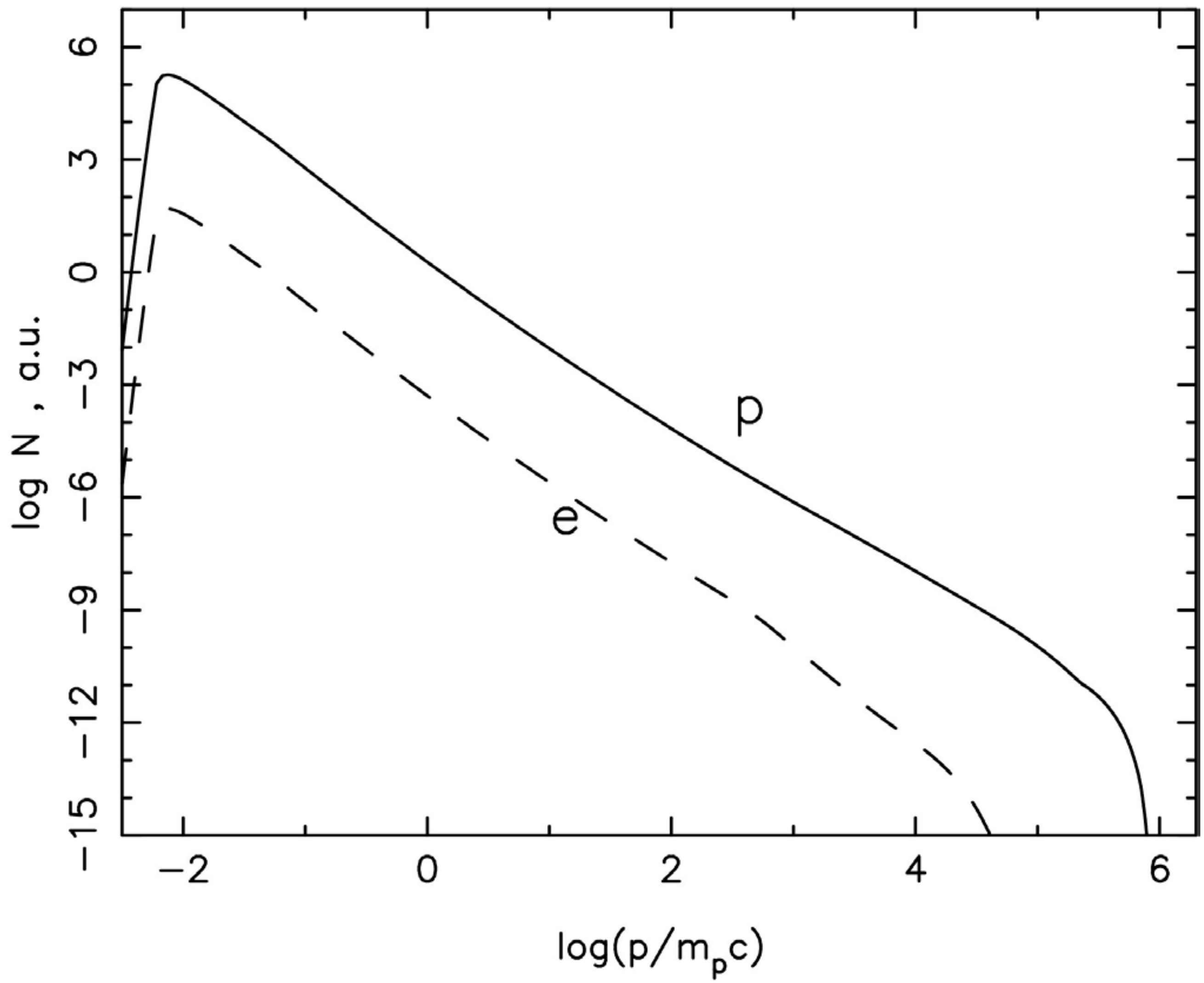


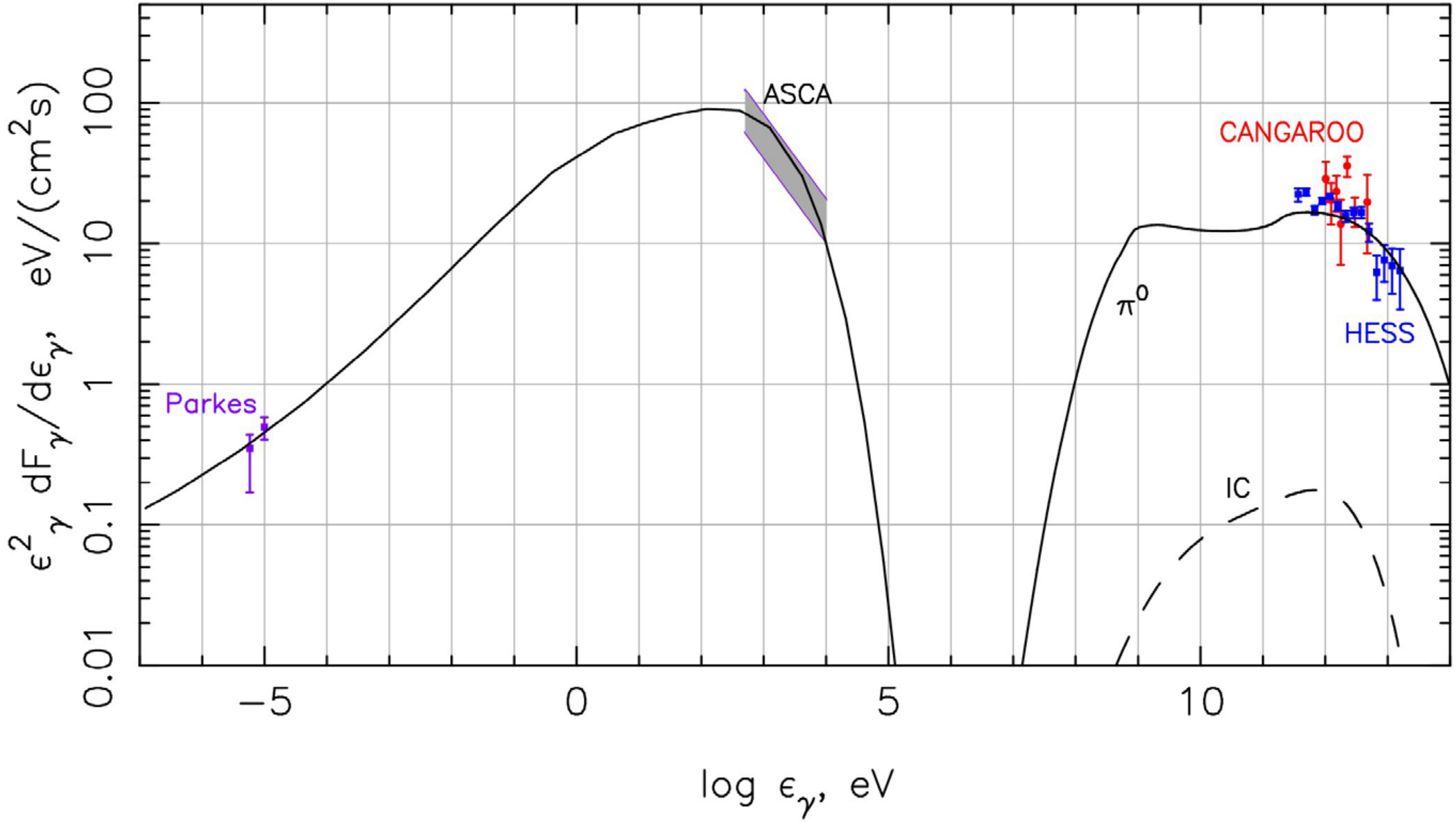
Charged particle spectra:

Spectrum hardening nonlinearly with increasing momentum

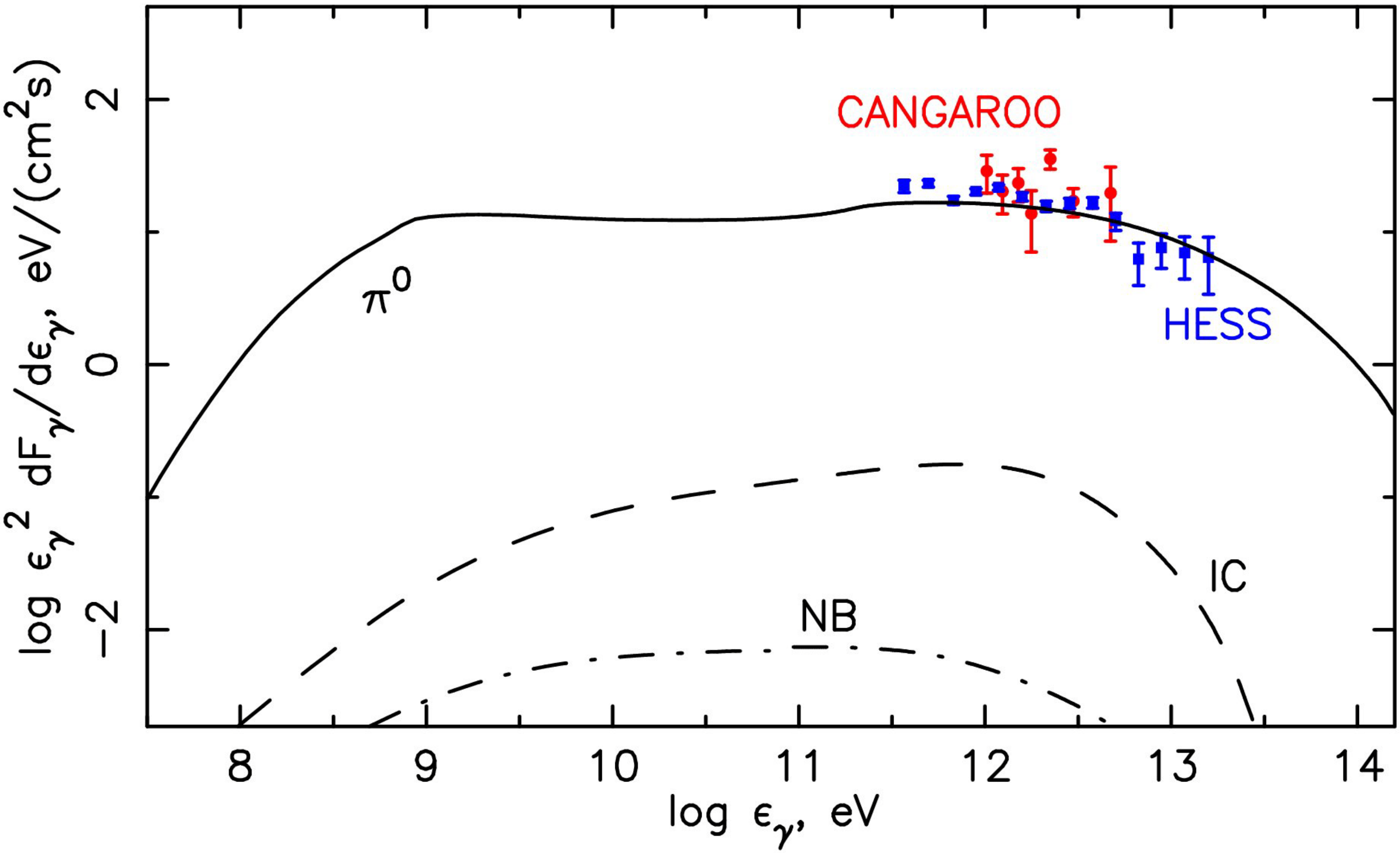
Synchrotron cooling for $p_{loss} > 350\ m_p\ c$

$B_d = \sigma B_0 = 104\ \mu G$
($B_0 = 20\ \mu G$)



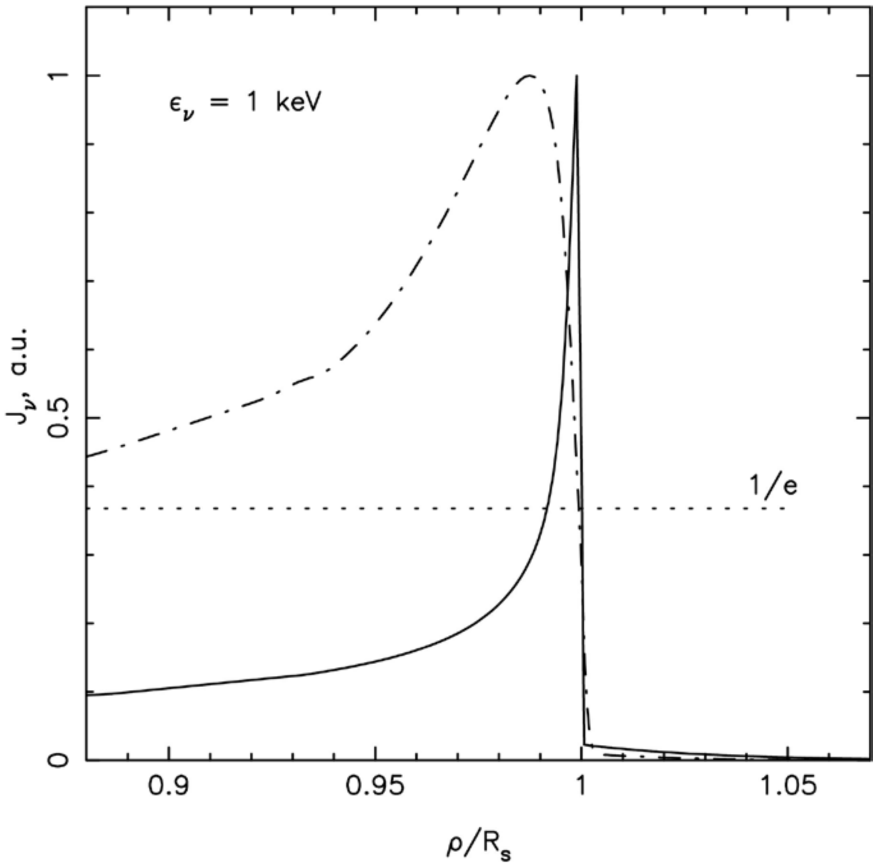


Spatially-integrated overall nonthermal
Spectral Energy Density (with fit of amplitude):
→ Gamma-ray emission hadronically dominated

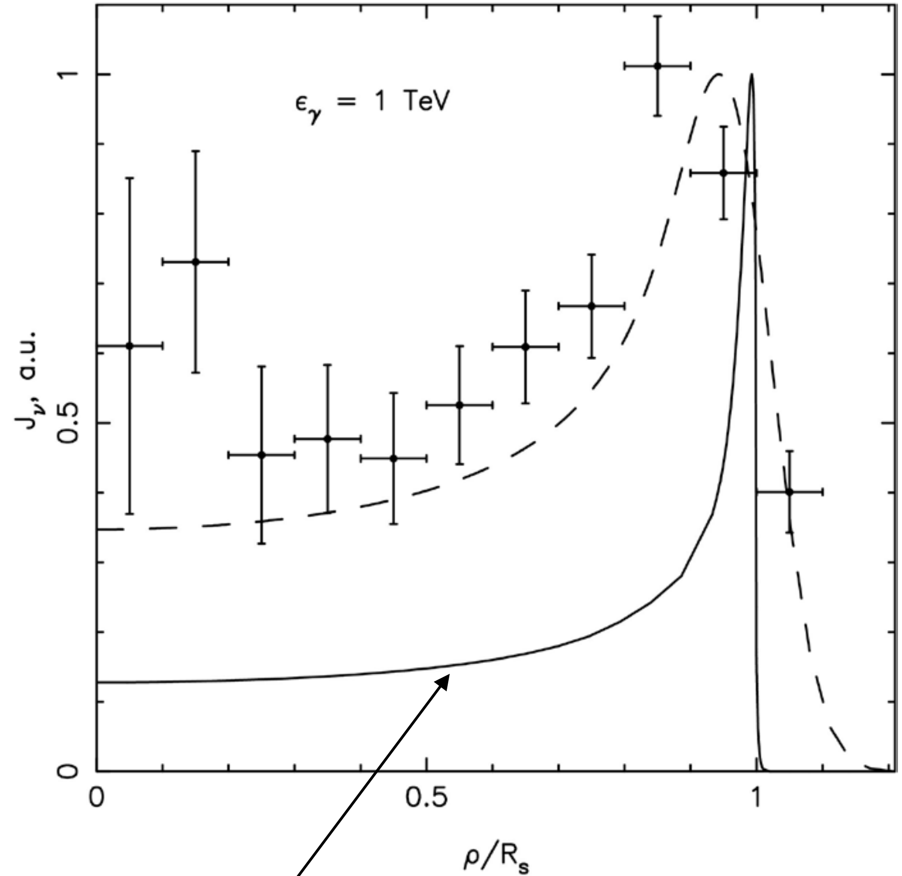


Detailed gamma-ray Spectral Energy Density

Radial emission profiles:



H.E.S.S. data (2007)



Hypothetical test particle X-ray profile –·–·–·– much too broad

Gamma-ray profile broadened to – – – – – – – – by finite PSF of H.E.S.S. instrument

“Problem”: thermal emission ?

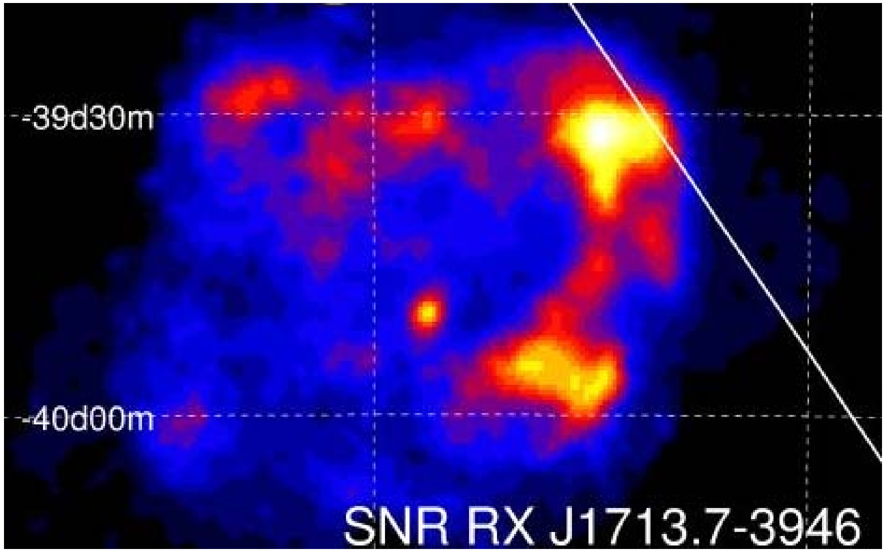
Thermal emission difficult to estimate. Only Sedov solutions in uniform environment available (Hamilton et al. 1983)

Not very appropriate for wind bubble configuration.

Compare nevertheless with (i) same E_{sn} (ii) same unmodified gas temperature (iii) same upstream gas density (iv) same distance. Correct by ratio of emission measures, and by reduction of downstream gas temperature due to shock modification

Estimate on this basis gives thermal flux at 1 keV ~ 8 x observed nonthermal flux.

Uncertainty remains to be resolved !



***ASCA* (1 - 3 keV)**

X-ray filaments ➡ $65 < B_{eff} < 230$ μG
from *XMM-Newton* (Hiraga et al. 2005)

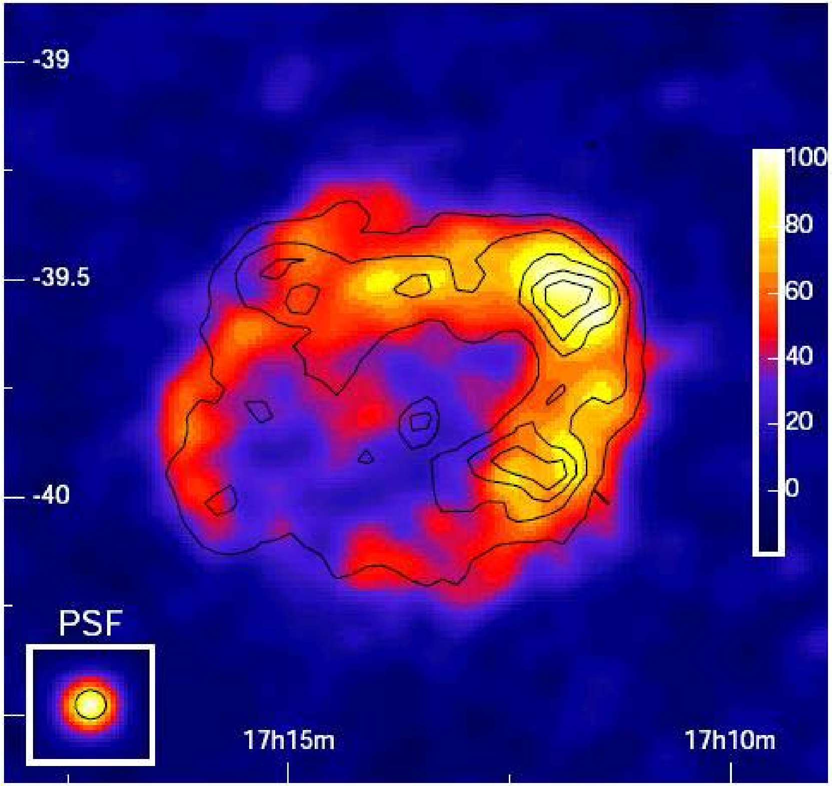
➡ Strong field amplification (also Uchiyama et al. 2007)

Central X-ray point source (neutron-star).

SNR RX J1713.7-3946

Berezhko & V. 2006, 2008, 2009

***H.E.S.S. 2007* image, plus 1 – 3 keV *ASCA* contours (Uchiyama et al. 2002)**



Overall shell structure coinciding closely in X-rays and γ-rays.

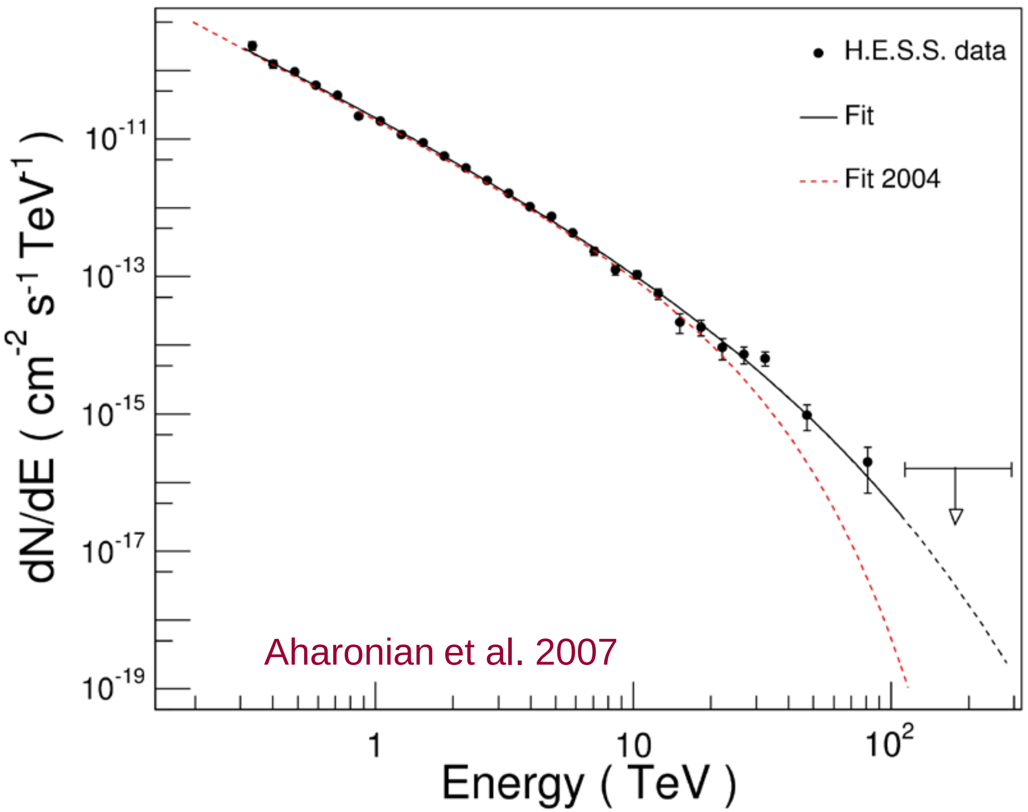
Rim : Center contrast ≈ 2

RX J1713-3946: VHE Energy - Spectrum

Hard Spectrum from whole SNR as expected from acc'd nuclei.
Phenomenological fit:

$dN/dE = I_0\, E^{-\Gamma} \exp\{(E/E_c)^{0.5}\}$
$\Gamma = 1.8 \pm 0.04$; $E_{cutoff} = 3.7$ TeV
Flux (1-10TeV) ~ Crab Nebula

Extends to > 30 TeV
➞ > 100 TeV particles
> 200 TeV (hadrons)



Total energy in energetic particles ***~ 10^{50}/<n> erg,***
if integrated over entire expected spectral range
Spectral imaging, energy-resolved morphology achieved ***➨ Model***

RX J1713.7- 3946, computed gas dynamical characteristics:

Assuming wind bubble with hot gas density:

$N_b = 0.008\ cm^{-3}$ from

$15 < M_* < 20\ M_{sun}$ star in

$110 < N < 500\ cm^{-3}$ ISM

➨ $M_{bubble} \approx 0.3\ M_{sun}$

$N_g \approx 0.25\ cm^{-3}$ at 10 pc

$R_s \approx 10$ pc

$V_s \approx 2200$ km/s

Age ≈ 1612 yrs

$\sigma \approx 5.7$ (total)

$\sigma_s \approx 3.3$ (sub-shock)

SN properties:

$E_{sn} = 1.3 \times 10^{51}$ erg

$M_{ej} = 3\ M_{sun}$

d = 1 kpc

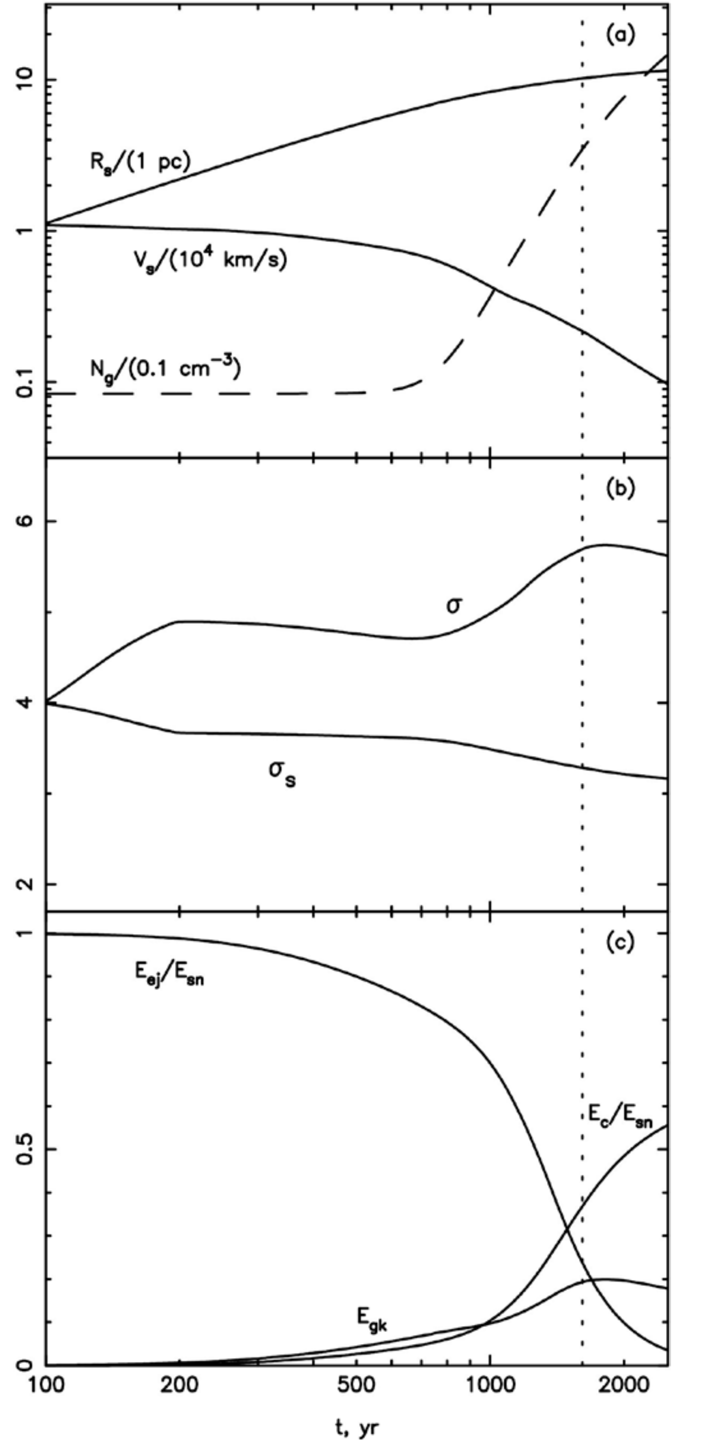
Assumed proton injection rate to fit gamma-ray amplitude:

$\eta = 5 \times 10^{-4}$

$E_c / E_{sn} \approx 0.35$

$B_d \approx 140\ \mu G$ (cf. obs's)

$(B_0 = 25\ \mu G)$



RX J1713: Energy Spectra (whole SNR)

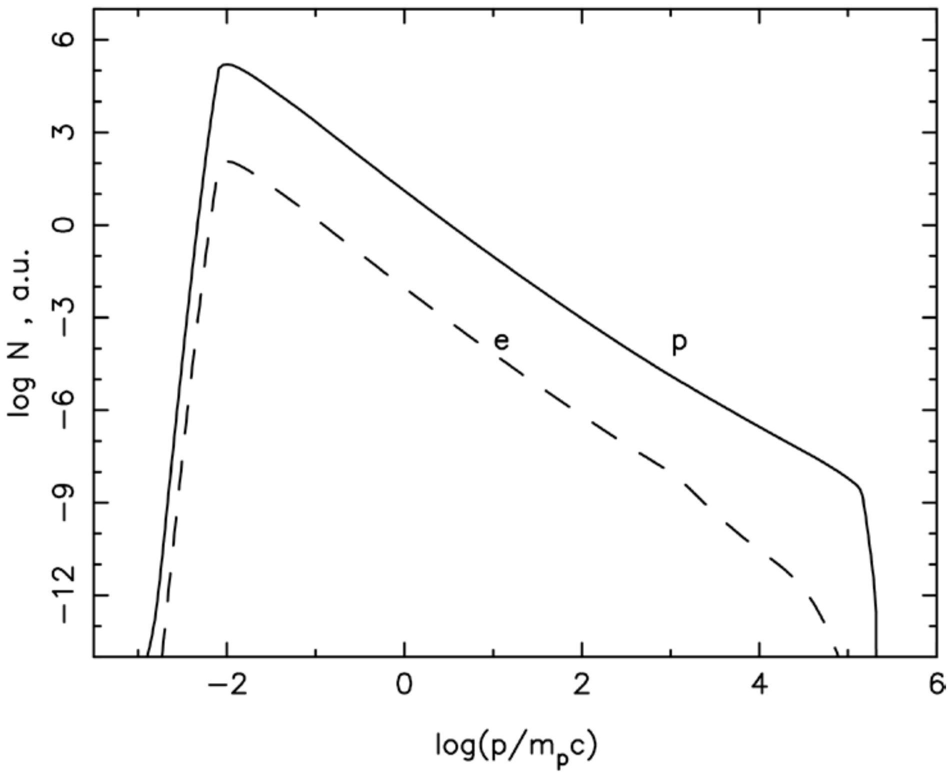
Theoretical particle spectra:

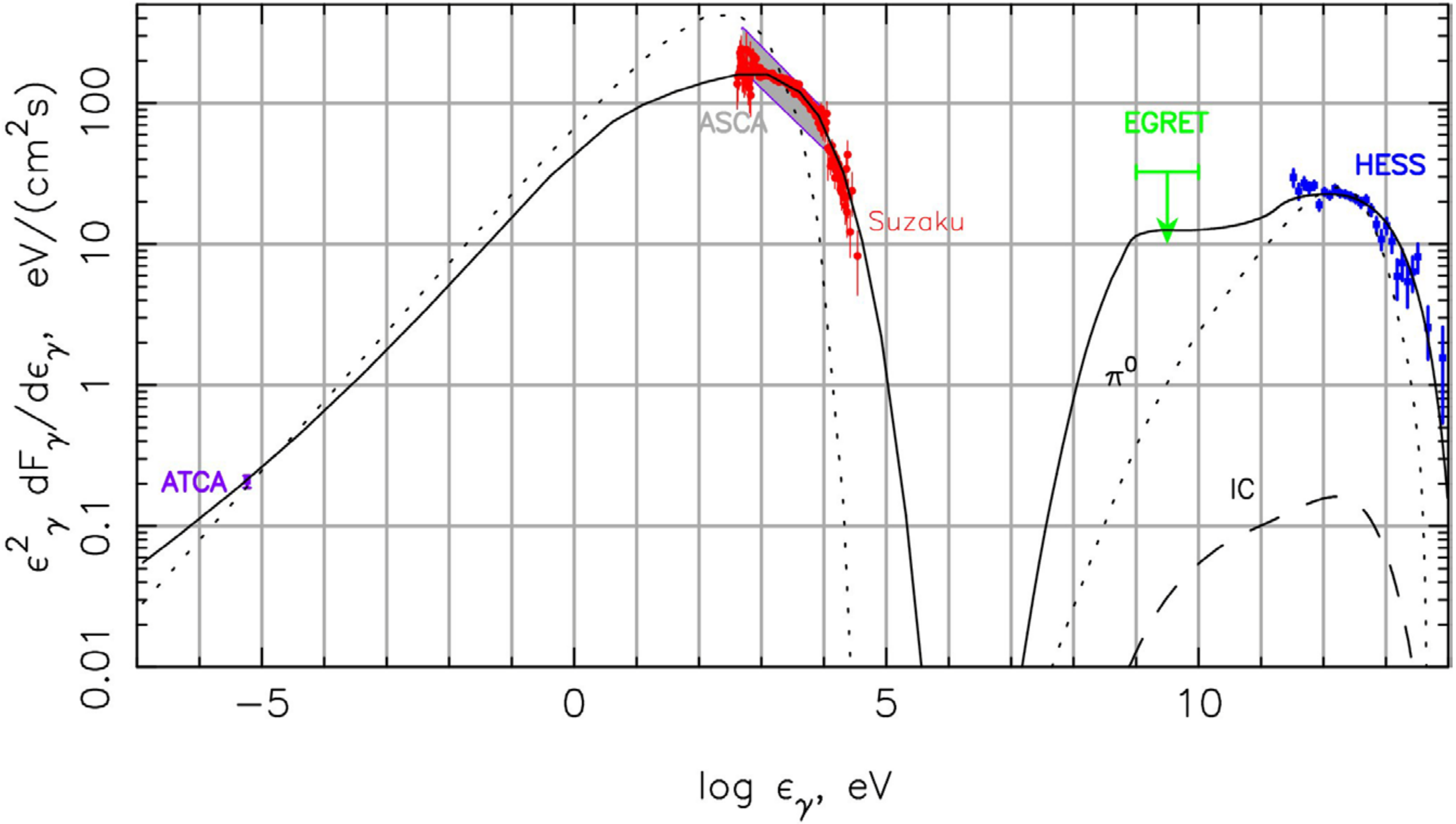
Nonlinear hardening to high momenta:

$\Gamma = 1.8$ *at* $p \geq 10^3\ m_pc$

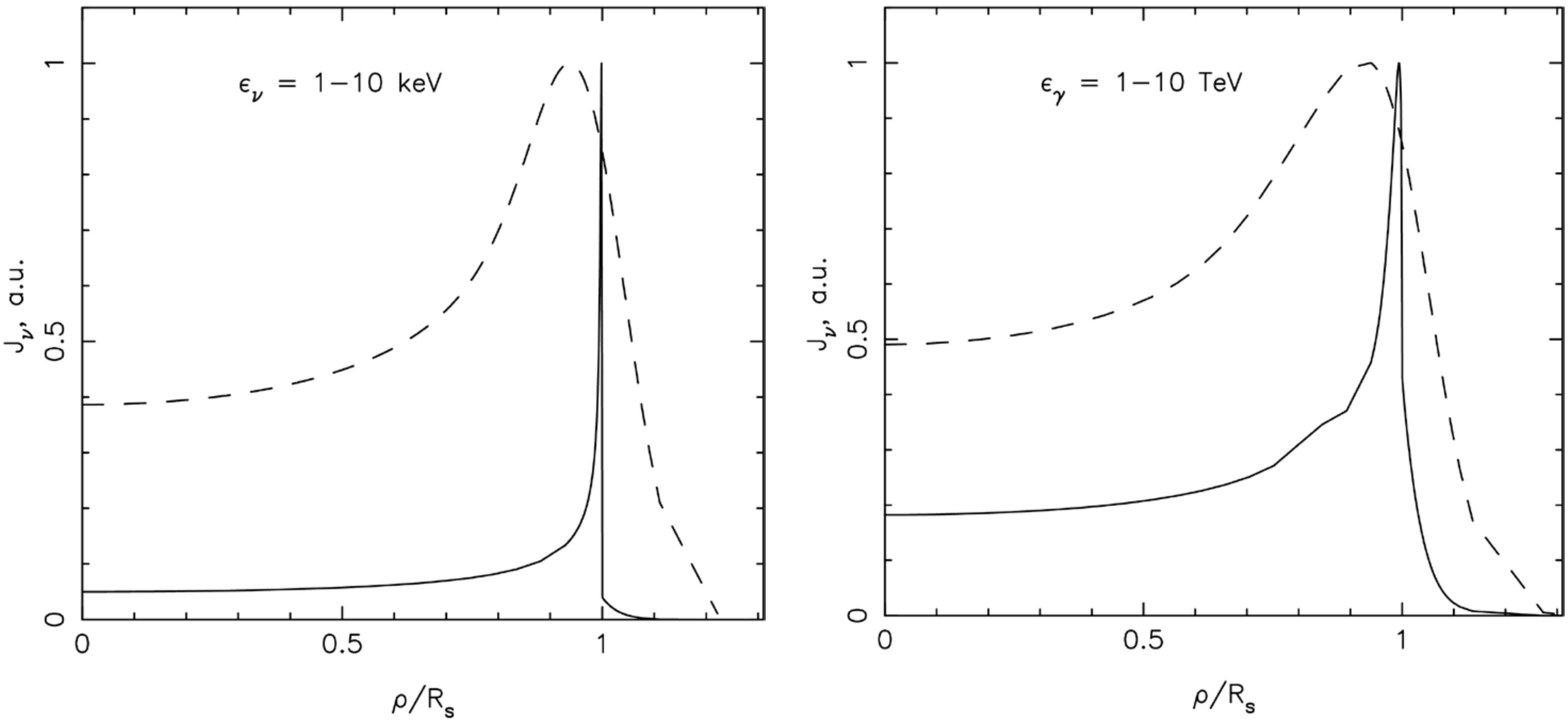
towards cutoff

Electron synchrotron cooling above $p \sim 10^3\ m_pc$



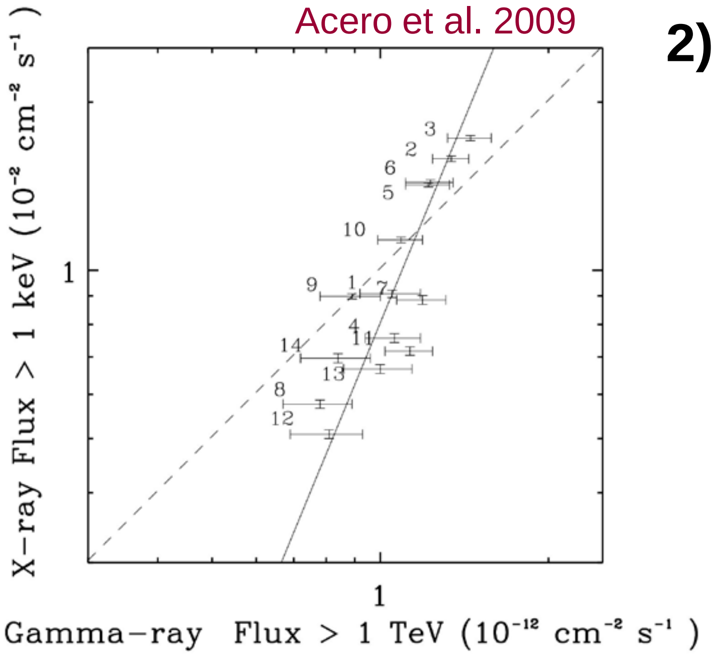


Resulting **form** of overall Spectral Energy Distribution with amplified field B = 142 μG dominantly hadronic. Phenomenological, purely leptonic test particle model · · · · · · gives poor fit. Preliminary results from *Fermi* consistent with hadronic spectrum (St. Funk, Fermi Symposium, 2 weeks ago). *Will be important to see how these results evolve as Fermi data base grows*



1) RX J1713.7-3946 radial emission profiles sharply peaked:
Nonthermal X-rays still ~ 3 x narrower than γ-rays in projected radius.

Dashed curves: Calculated profiles convolved with H.E.S.S. PSF of Gaussian width 0.05°obviously very similar, except for $\rho/R_s > 1$, where J_X/J_γ decreases with increasing ρ due to higher mobility of protons, consistent with Acero et al. 2009



2) Azimuthal correlation of measured X-ray and γ-ray fluxes: (cannot be described by a spherically symmetric model)

- **Qualitatively visible comparing *H.E.S.S.* and *ASCA* images**
- **Quantitative comparison by Acero et al. 2009, using *XMM:* $F_X \propto F_\gamma^\alpha$, with α =2.41 for E_X = 1 – 10 keV and E_γ = 1-10 TeV.**

SNR intermediate between sweep-up and a quasi-Sedov phase. Since ejecta kinetic energy together with kinetic energy of swept-up gas contain about 50% of explosion energy, the SN shock can be treated very approximately as piston-driven shock, with speed V_s only weakly depending on upstream gas density.

Local hadronic γ-ray flux is $F_\gamma \propto \rho\, E_c \propto \rho$, with E_c ~ uniform, roughly at saturation from highly mobile protons. Since X-ray emitting electrons in energy loss range, flux $F_X \propto K_{ep}\, \rho V_s^3$ not strongly dependent on B-field, if B is high, B_d > 140 μG, and in addition $F_X \propto F_\gamma$. Thus expect $F_X \propto F_\gamma$ in brighter parts of remnant.

Phenomenologically $B_d^2 \propto \rho V_s^{\beta}$; with $2 < \beta < 3$ roughly $B_d^2 \propto \rho$. Where ρ is lower than average, there B_d is lower and losses become smaller. Then $F_X \propto \rho\, K_{ep}\, B_d^{3/2} \propto \rho^{7/4}$. In dim part of SNR then $F_X \propto F_\gamma^{7/4}$, approximately consistent with observational inference.

Thermal Emission:

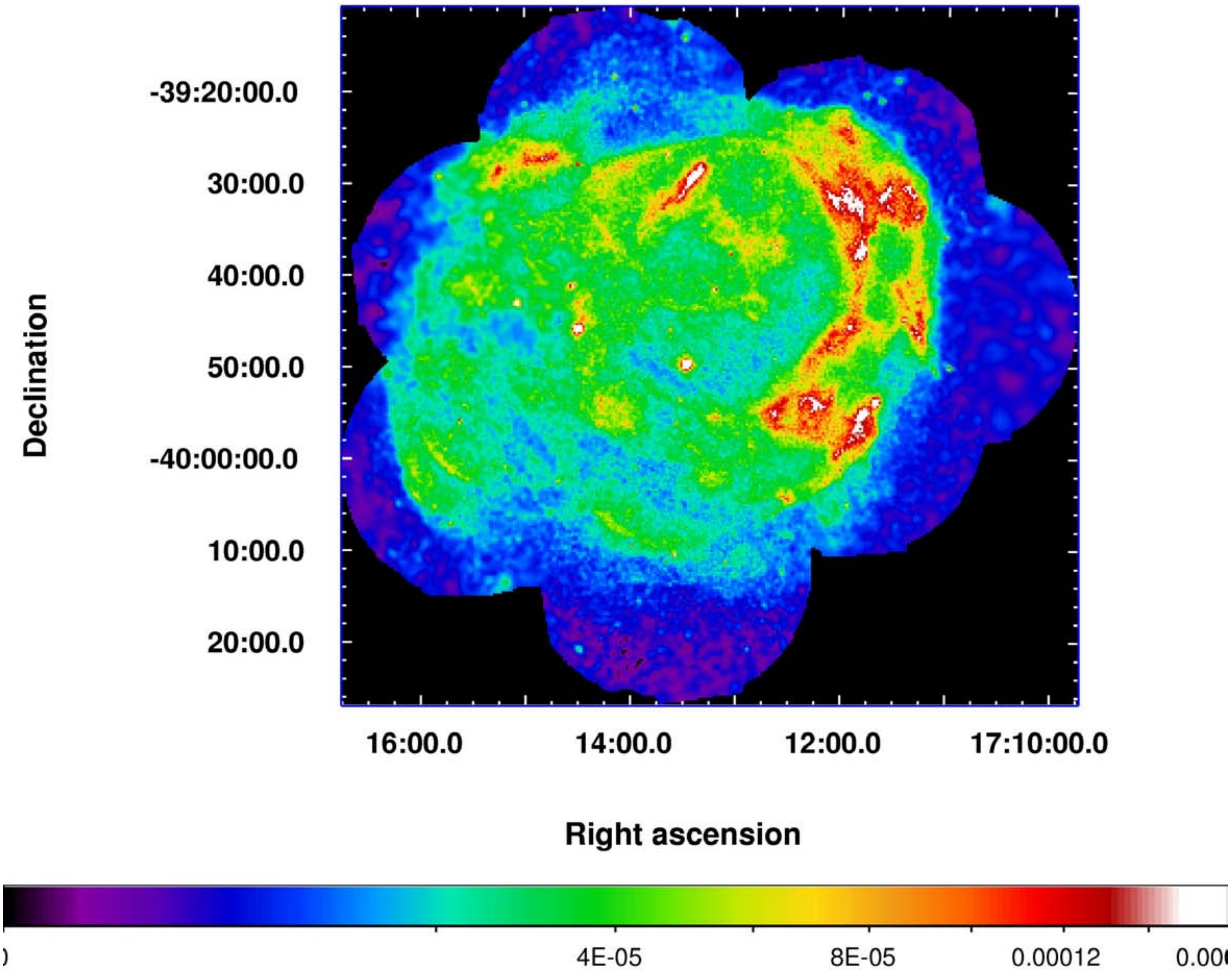
With analogous estimate, like for Vela Jr., resulting model thermal X-ray energy flux at 1 keV for RX J1713.7-3946 ≈ 118 eV cm^{-2} sec^{-1} ~ 50% of observed nonthermal energy flux (≈ 200 eV cm^{-2} sec^{-1}).

(See also Zirakashvili 2009, Zirakashvili & Aharonian 2009)

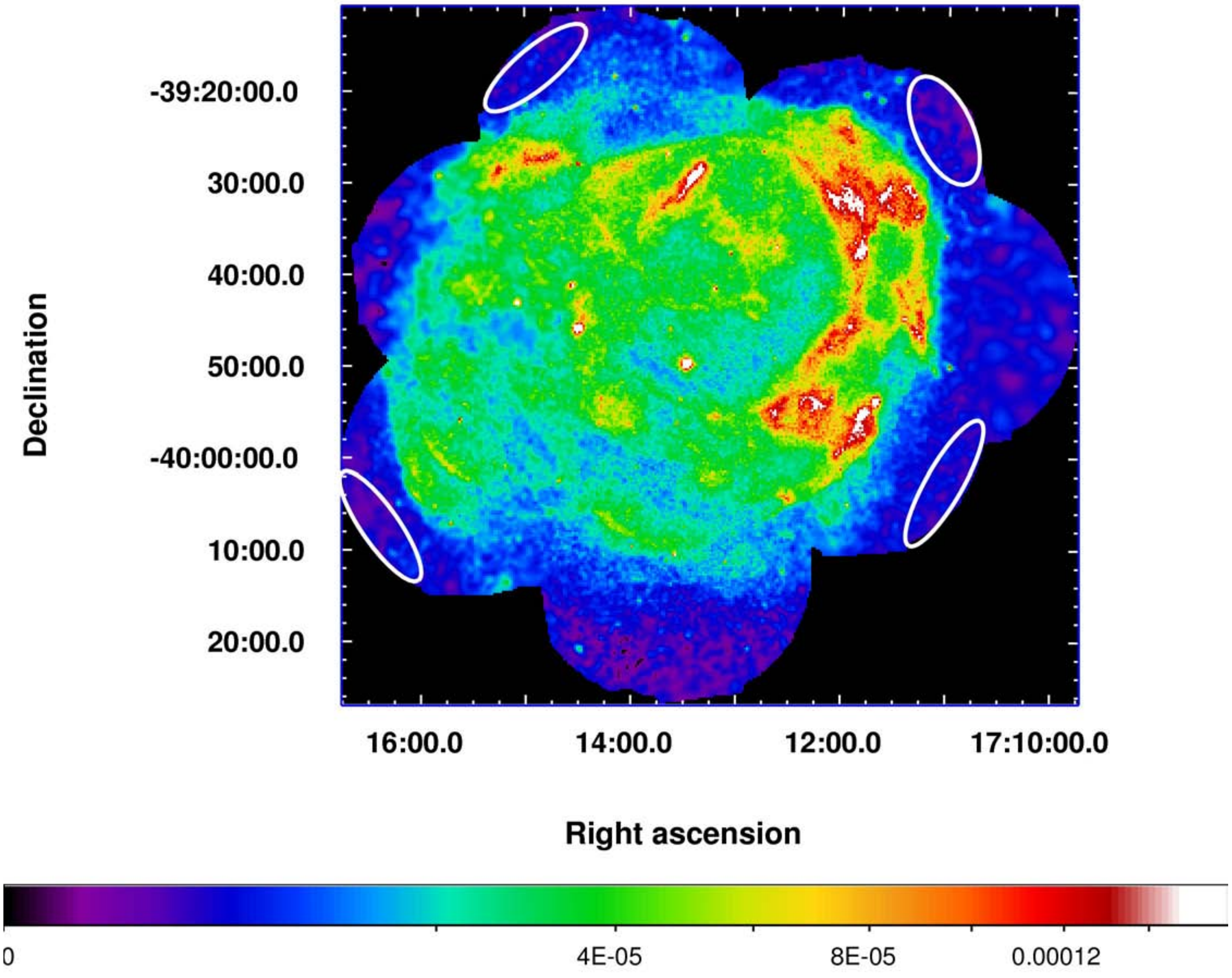
Not inconsistent with non-detection of thermal X-rays.

End

XMM-Newton (Acero et al. 2009)



XMM-Newton (Acero et al. 2009, with BG regions)



Examples described here (suggested by *H.E.S.S.* detections)

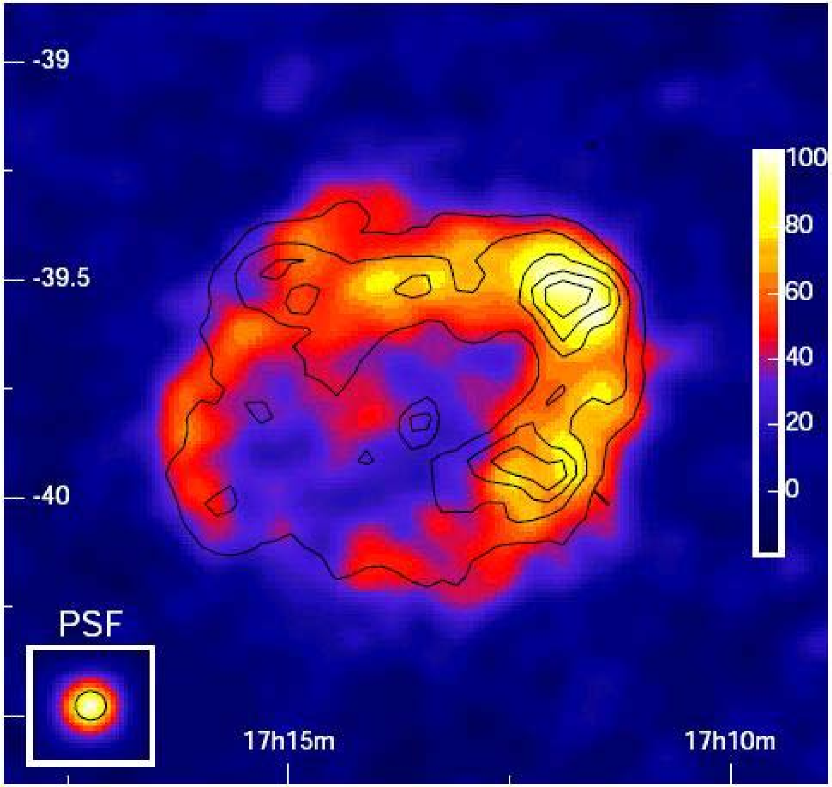
RX J1713.7-3946

Vela Jr.

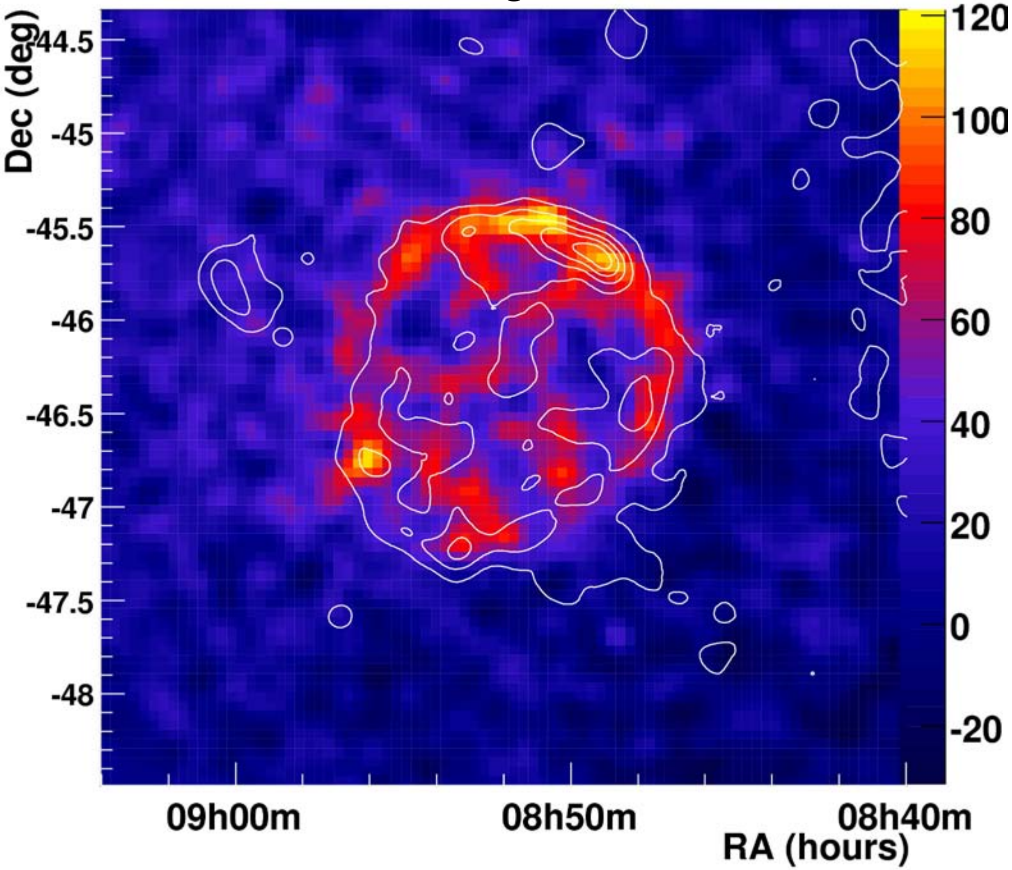
Katagiri et al. (*CANGAROO*), 2005
Aharonian et al. (*H.E.S.S.)* (2005, 2007)

Size ~ 2 degrees; Crab-like flux

RX J1713 (*H.E.S.S.* 2006)

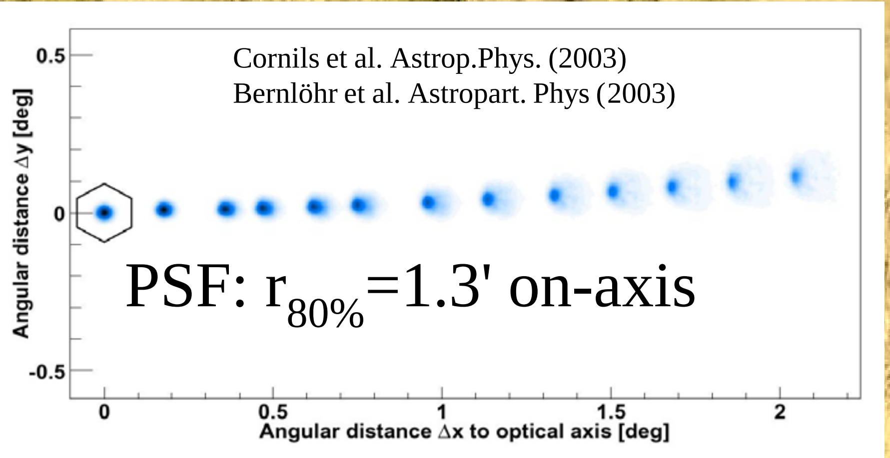


***H.E.S.S.* image with *ROSAT* contours**



Characteristics of the H.E.S.S.telescopes (fully operational since December 2003):

4 Telescopes each 107 m² Mirror surface
4 „smart“ cameras with 960 PMT (0.16°)
➞ 5° Field of View ➞ Surveys !
Digitization with ARS, 2 gains
Multi-Telescope trigger
Stereoscopic reconstruction



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