Report (Part II) on the Aspen Workshop: "Physics At The End Of the Galactic Cosmic Ray Spectrum", (4/25-4/30)

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AspenWS concentrated largely on sources in the Galaxy and its Halo:

1) Reviews on experiments, old and future (Balloons, High mountain calorimeter, Tibet, KASCADE, KASCADE-(Grande), Akeno, HiRes, TA, TALE, ...), and on theory of shower physics (Tom Gaisser's part I)

2) New gamma-ray results (H.E.S.S., VERITAS), theory (Heinz Völk, Part II, here)

3) Requirements on theoretical source models and energetics, especially the continuity across the knee (HJV, TG)

4) Connection to the expected extragalactic component (TG)

- New γ-ray results and corresponding theory (here CR origin below knee; General H.E.S.S. results ⇨ Felix Aharonian [week 3])
- Cas A, SN 1006, RX J1713.7-3946, Vela Jr.
- Contribution of Galactic Plane Scan
- Field amplification for all (?) young SNRs
- Across the knee: Special SNRs, GRBs, Re-acc'n in extended Halo

Below knee: New γ-ray results, theory

Consensus: Energy production for Cosmic Rays must involve Supernova explosions, with energy efficiency of ~ 15%. Spectrum $\propto E^{-2.7}$ up to knee at $3\text{-}4 \times 10^{15}$ eV

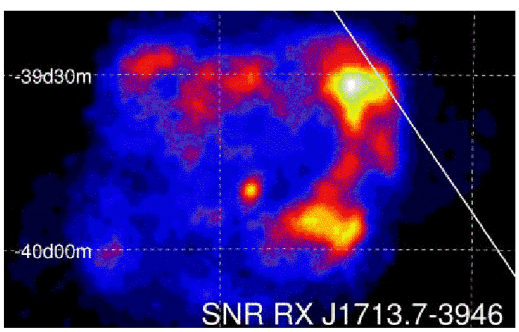
H.E.S.S. experiment in Namibia sees typically hard γ-ray spectra $dN/dE \propto E^{-\Gamma}$, with $\Gamma \approx 2$ up to ≥ 10 TeV.
Hadronic γ-rays would then require $E_{max} \geq 100$TeV !
Comment: Instrumental sensitivity decreasing $E \geq 10$ TeV. Rather cutoffs in several cases ("old" sources with loss of highest-energy particles ?)
$\Gamma \approx 2$ at the sources may require strong increase of CR escape with energy (re-acceleration, anisotropy ?)

Santa Barbara, May 6, 2005

H.E.S.S. results:

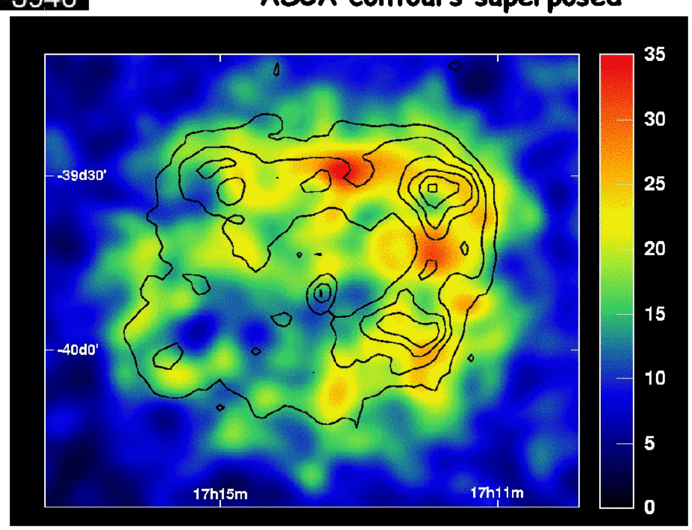
First spatially resolved SNRs with shell morphology, in addition to Cas A (HEGRA). Galactic Plane Scan.

No detection of SN 1006: Celebrated source in nonthermal X-rays (Koyama et al. 1995), claimed TeV-emission by CANGAROO until last week.



ASCA (1 - 3 keV)

H.E.S.S. > 800 GeV; >20σ overall.
ASCA contours superposed



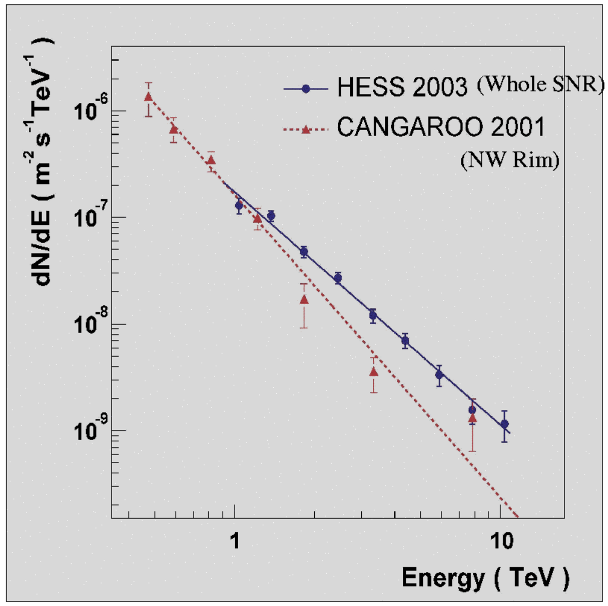
Overall shell structure coinciding closely in X-rays and γ-rays.

Despite complex structure unambiguous proof of acc'n of charged particles to energies beyond 100 TeV.

Results not inconsistent with ideas of shock acceleration.

RX J1713-3946: Spectrum

Hard Spectrum from whole SNR (H.E.S.S.)
(compare CANGAROO Spectrum for NW rim):
$dN/dE \sim E^{-2.19+/-0.1+/-0.15}$
(May be even a bit harder, also to lower energies)
F(1-10TeV) ~ 3×10^{-11} erg/cm^2/s
(~1 Crab)



Extends to 10 TeV
→ 100 TeV particles

Clouds (n ~ 100 cm^{-3}) NW region
→ **$E_p \sim 10^{50}$/n erg over entire expected spectral range**
→ 2004 data (> 50h) ....spectral imaging, energy resolved morphology
(Watch this space)

SNR RX J0852.0 - 4622 ("Vela Junior")

B. Aschenbach (ROSAT, 1998)

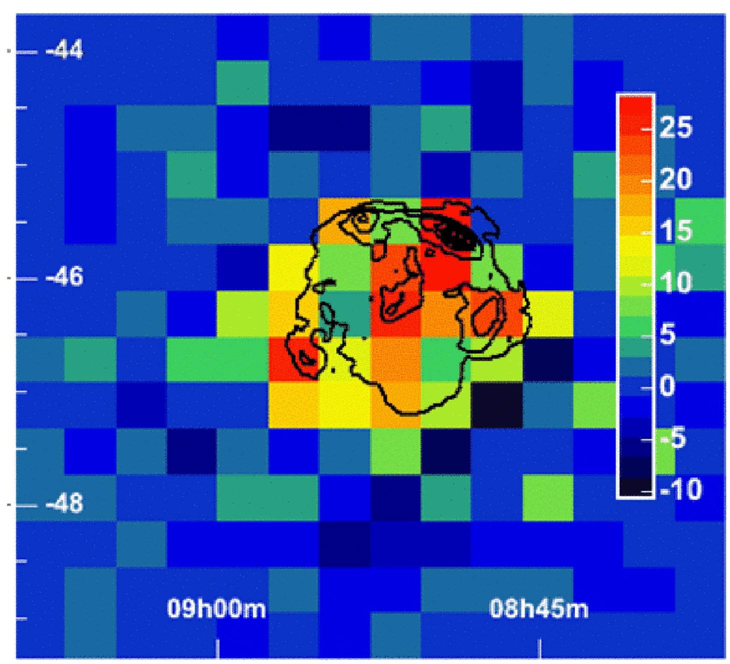
H.E.S.S. results:

Structure resolved: consistent with ASCA: 2° × 2°

Livetime = 3.2 hr
Significance 12 σ

Hard spectrum:
Γ = 2.1 ± 0.1 ± 0.1

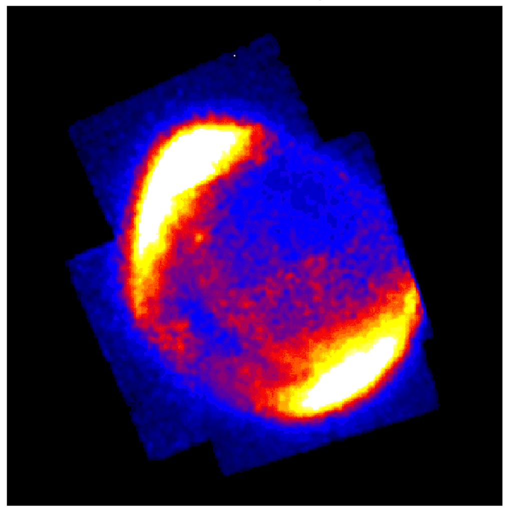
Flux (> 1 TeV)
> RX J1713.7-3946
~ Crab Nebula



SN 1006

- Accreting White Dwarf (Type Ia): $M_{ej} \approx 1.4\,M_\odot$
- Age = 999 yr
- Angular diameter ≈ 0.5 degrees

ASCA Koyama et al. (1995)



Extended source for γ-ray instruments:

H.E.S.S. upper limit < 0.02 Crab

From other measurements:

N_H = 0.3 - 0.05 cm^{-3} (!)
Distance = 1.8 - 2.2 kpc

Winkler et al. (2003)

Non-spherical aspects of SNRs

Ion injection only for instantaneously quasi-parallel shocks $\Theta_{nB} \ll \pi/2$

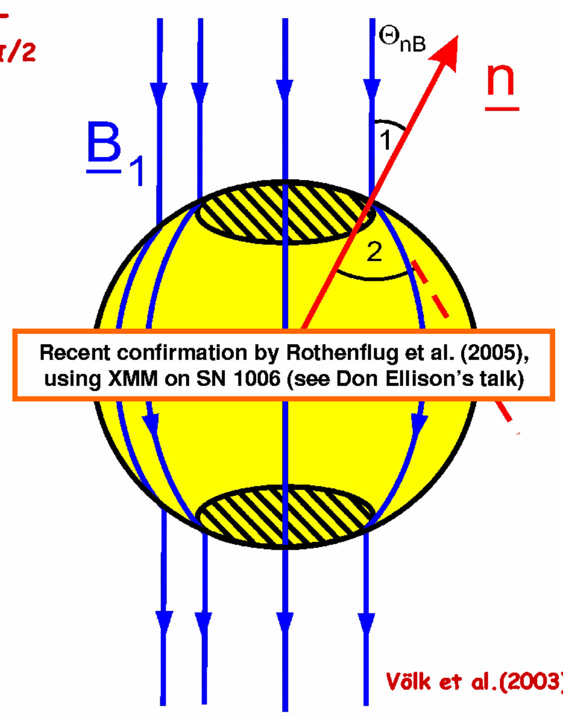
➡ Stochastic self-limitation of injection rate through nonlinear wave pro – duction: from $\eta_{\parallel} \approx 10^{-2}$ to $\eta_{eff} \approx 10^{-4}$

➡ Plus systematic reduction of ion injection. Strong wave production only locally in "polar" regions

➡ Hadronic γ-ray emission dipolar for uniform external $\underline{B}_1$

Renormalization of spherically symmetric flux

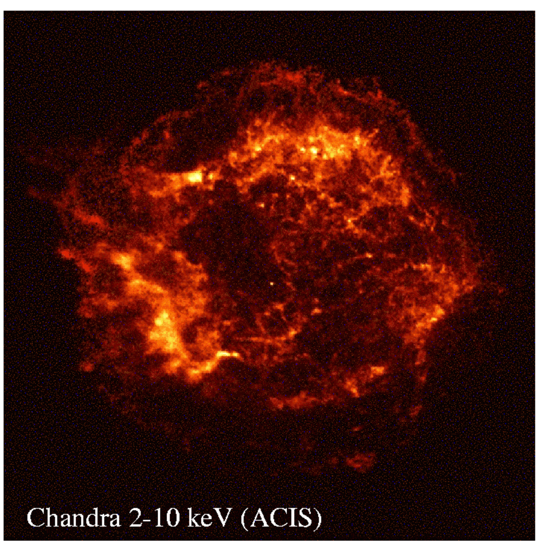
➡ Synchrotron emission also overall dipolar for uniform external $\underline{B}_1$

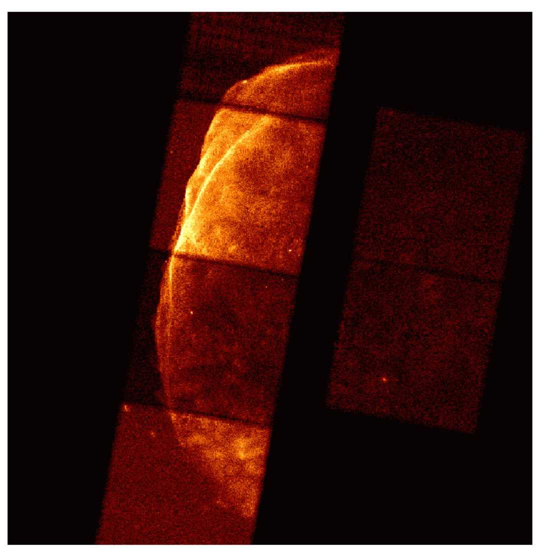


In Aspen:

Controversy with advocates of acceleration in strictly perpendicular shocks (i.e. when shock surface ⊥ external B-field (J.R. Jokipii))

X-ray imaging of young SNRs with Chandra



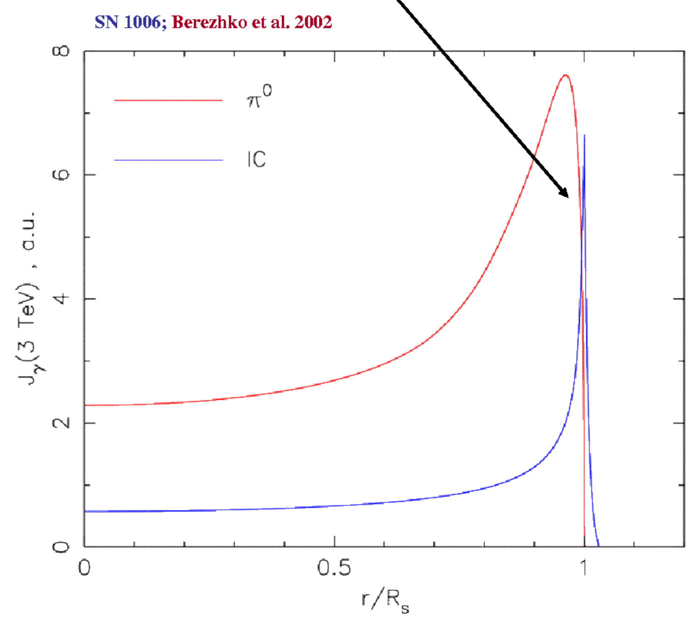


- small spatial scales detected in X-rays with Chandra = Synchrotron loss length !
- need to extract the non-thermal part
- used to determine / verify B-field-amplification

Predicted radial gamma-ray brightness (3 TeV)

Extremely small scale (l_e~10^{-2} R_s) of HE (ε_e~100 TeV) electrons !
Result of strong synchrotron losses.

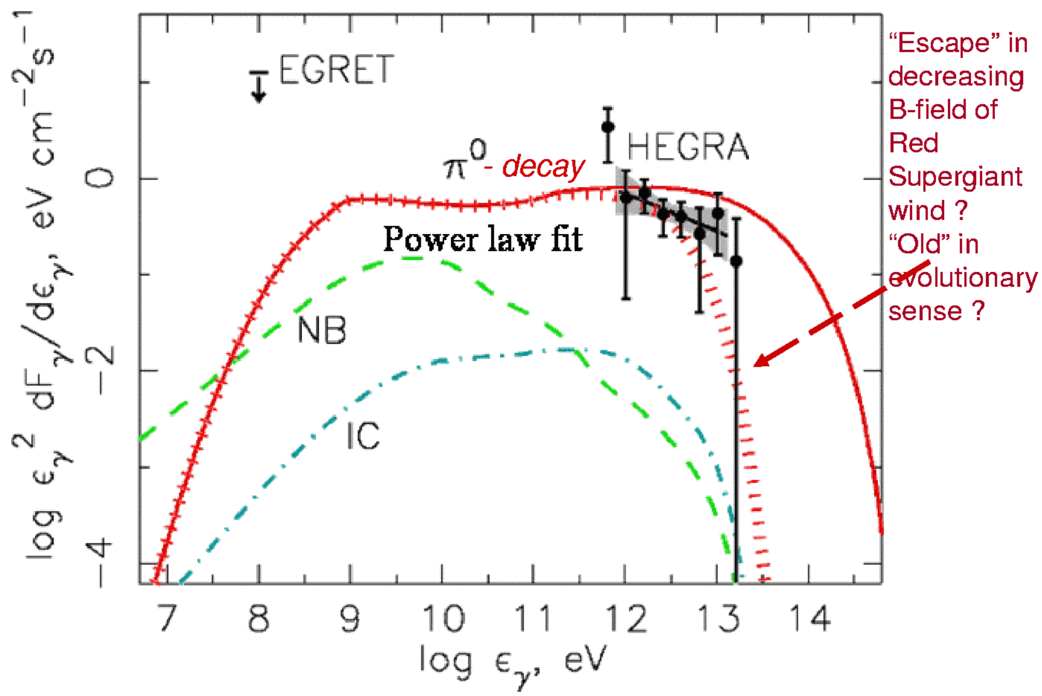
Confirmed through
Chandra observations



Magnetic field amplification by accelerating particles in shocks

- Accelerated particles tend to stream
  ahead upstream ⇨ Instability (Bell 1978)
- Nonlinear evolution ⇨ Bohm limit of scattering
  ⇨ Mean field amplification
  (Bell & Lucek 2001; Bell 2004, 2005)
- High field B_{eff} ⇨ Depression of IC emission
  ⇨ Faster scattering and
  ⇨ Increase of p_{max} for nuclei
- Instabilities driven by dominant nuclear component

Cas A (Berezhko et al. 2003): Completely hadron-dominated



Present state of SN 1006

Hydrodynamically in Sedov Phase: $R_{shock} \propto t^{2/5}$

$\Rightarrow$ Hydrodynamic explosion energy: $E_{sn} \propto N_H$,

for fixed R_{shock} and dR_{shock}/dt from observations

Hadronic gamma-ray flux $F_\gamma \propto N_H E_c$

However: $E_c \propto N_H$ also for strong shocks,

since $E_c/E_{sn} \sim 10\ \%$

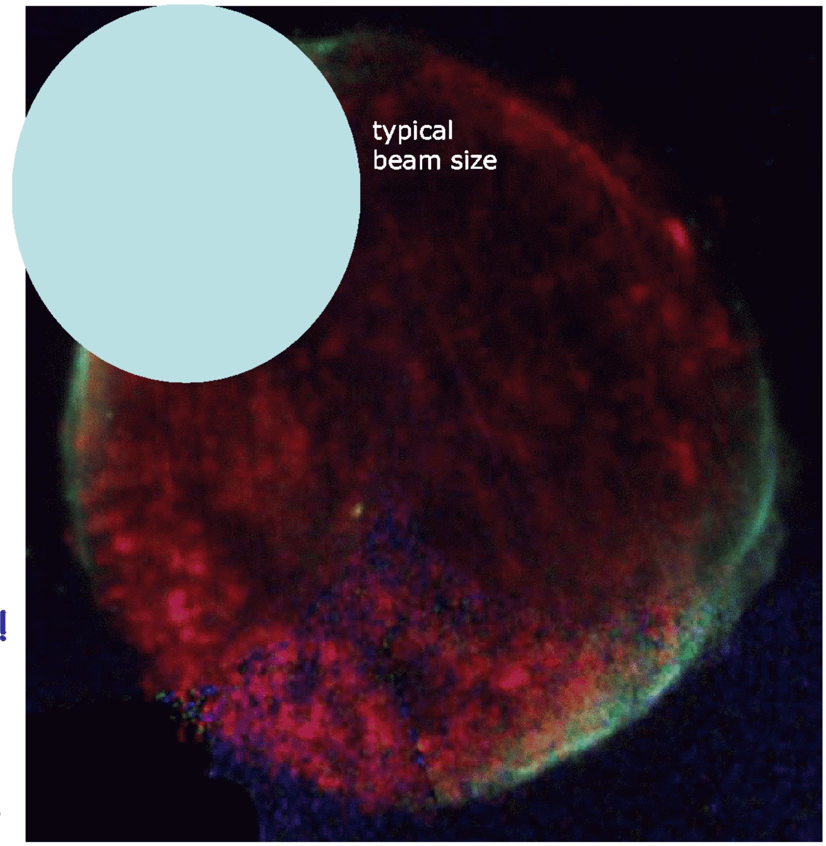
$\Rightarrow$ $F_\gamma \propto N_H^2$

in first approximation

SN1006:

CANGAROO (and H.E.S.S. "CANGAROO hotspot") include only ~ 1 polar cap

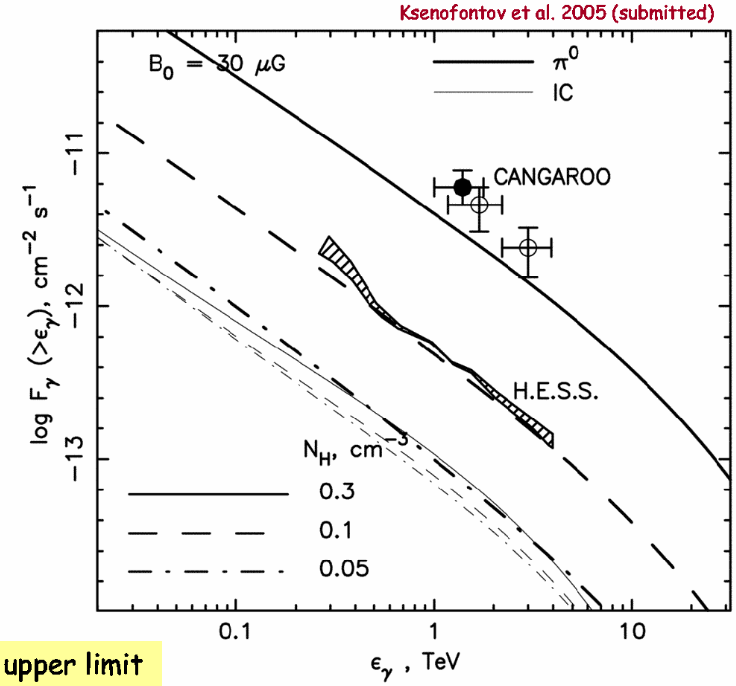
B_{eff} = 150 μG !



XMM

High energy emission from the NW rim of SN 1006

H.E.S.S. upper limit is still about three times larger than the total γ-ray flux (Hadronic + Inverse Compton) expected for N_H = 0.05 cm^{-3} (which is at the lower end of the expected range of ambient densities)



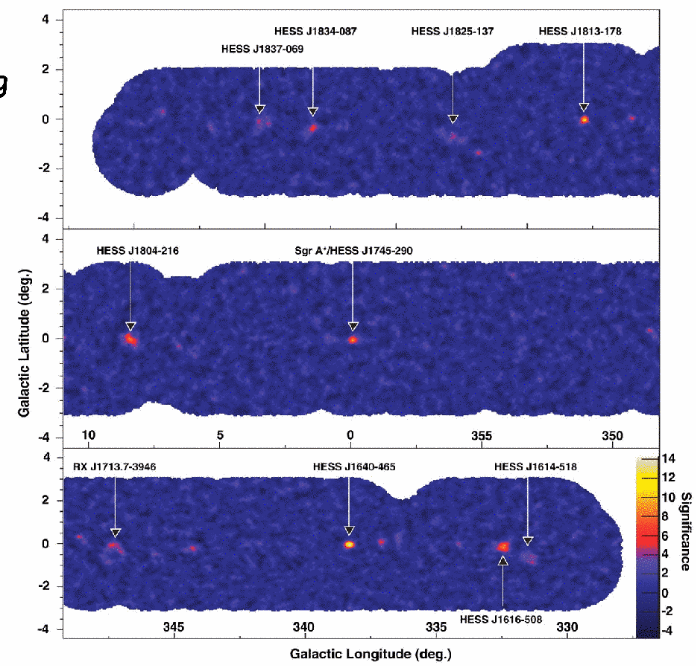
Consistent with H.E.S.S. upper limit

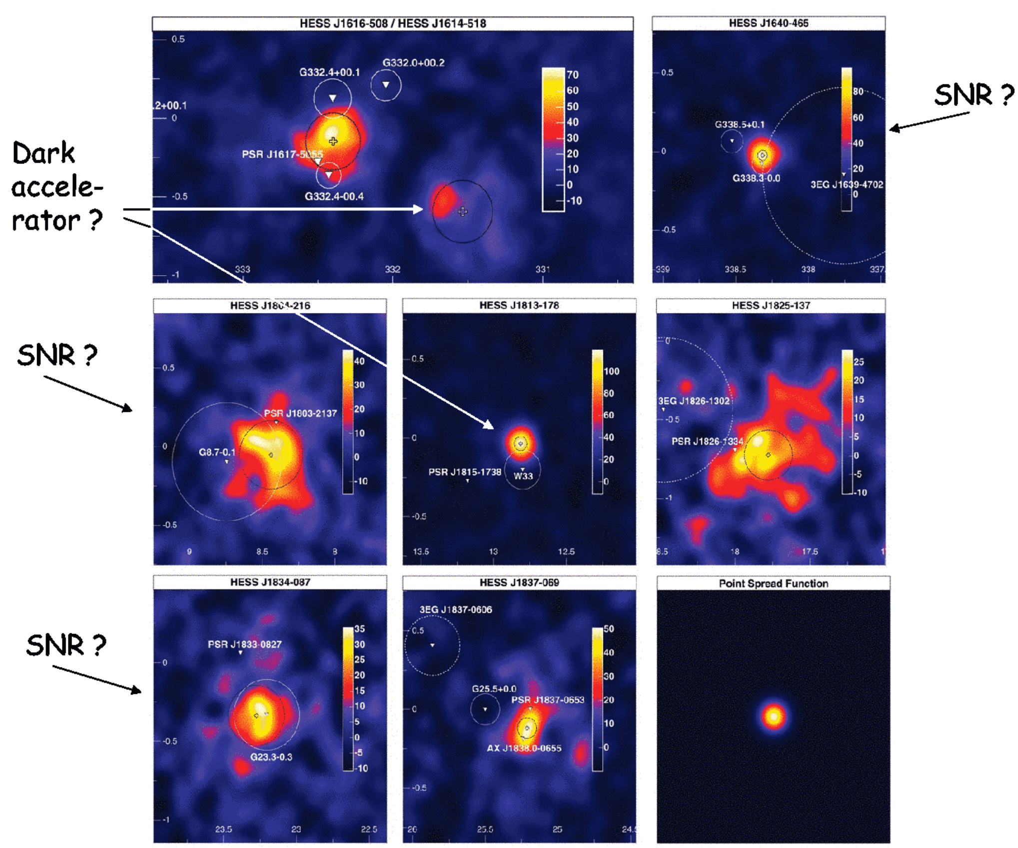
Are there more SNRs visible in VHE ?

- Counterpart search ongoing
- Many Pulsars !
- Evolved ("older") SNRs ?
- Wind-SN into Bubbles ?
- Superbubbles ?
- Confusion ?

My expectation:
"Dark accelerators"
= evolved objects
in or behind dense
molecular regions.
Or: poorly studied in
radio/X-rays until now.

Aharonian et al. 2005 (H.E.S.S. Collaboration)

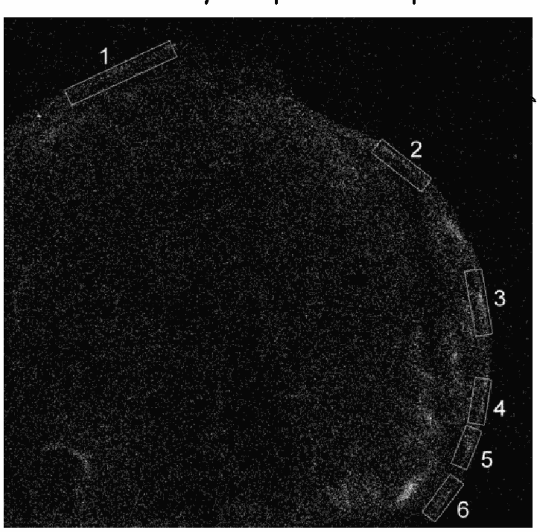




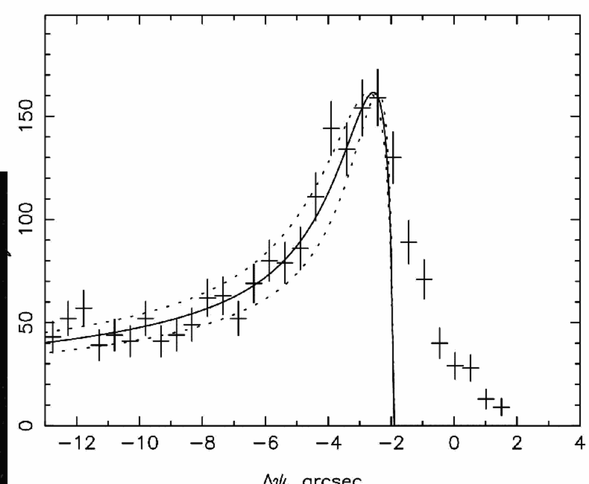
Continue with field amplification

Tycho's Supernova Remnant

Outer shock very sharp ⇨ sum of profiles



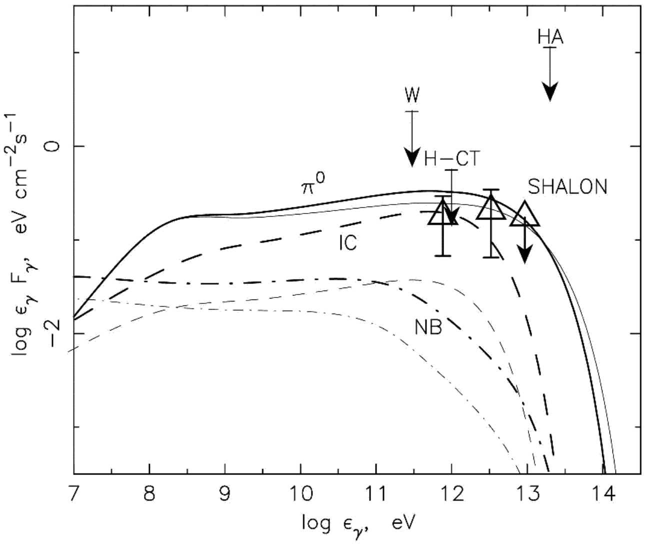
Chandra; Völk et al. 2005



B_{eff} = 273 (+ 49 - 37) μG

Consistent with acceleration theory (overall synchrotron spectrum)

Tycho in TeV gammas



Predicted gamma-ray emission primarily hadronic for $B_0 \geq 50\ \mu G$

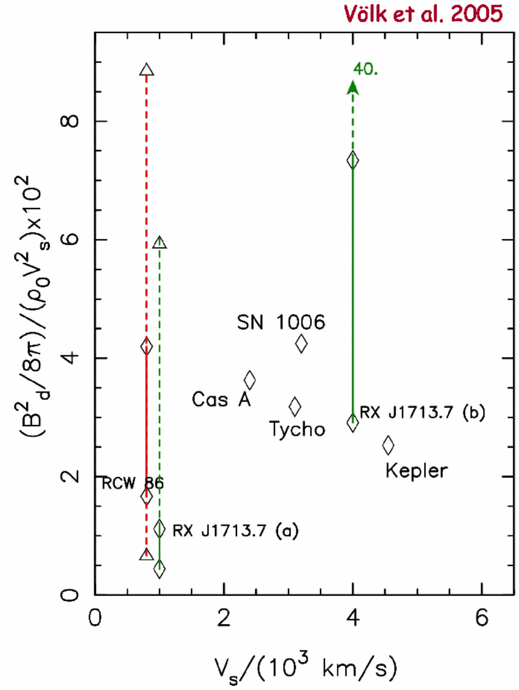
$B_0 = 40\ \mu G$ ————

$B_0 = 60\ \mu G$ ————

Field amplification shown by all young SNRs measured:

Cas A, SN 1006,
Tycho, RCW 86,
Kepler, RX J1713.7-3946

Völk et al. 2005



Magnetic energy density
~ few percent of
kinetic energy density

Need only measure
all the young objects
to conclude on whole
population ?

If already done so,
then conclusion:
Galactic SNRs source
population of Galactic CRs

Result for generic Supernova Remnant

[Using $B^2_d / 8\pi$

$\sim 10^{-2}\ \rho_O V^2_{shock}$]

Assumptions:

$\lambda_{mfp} = r_g(B_{eff})$

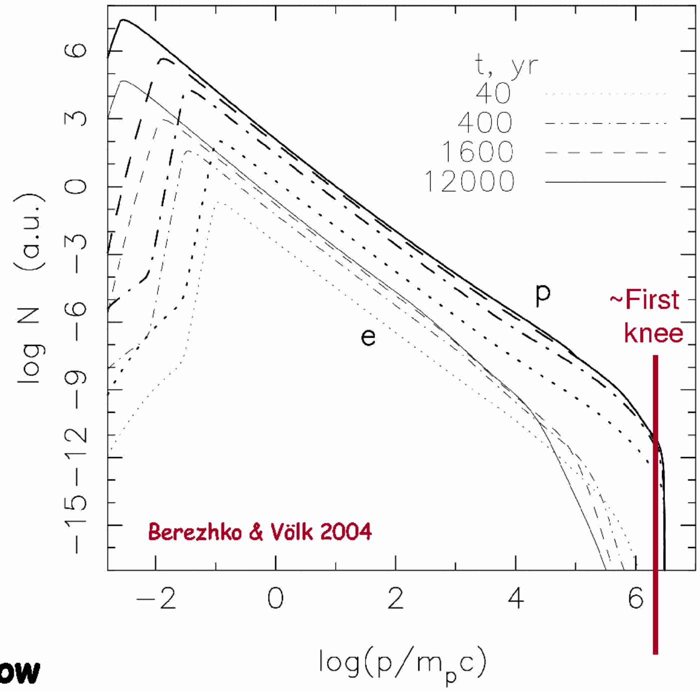
$\eta = 10^{-4}$

$N_H = 0.3\ cm^{-3}$

$E_{SN} = 10^{51}$ erg

$M_{ej} = 1.4\ M_{Sun}$

$B_0 = 10^{-3}\ (8\pi\ P_c)^{1/2}$
$\geq 5\mu G$, if P_c too low



Across the knee: Spectral Continuity

1) Special SNRs (massive stars in high-density environment) have very high B_{eff} very early on, and might produce very high E_{max} even up to second knee (Bell)

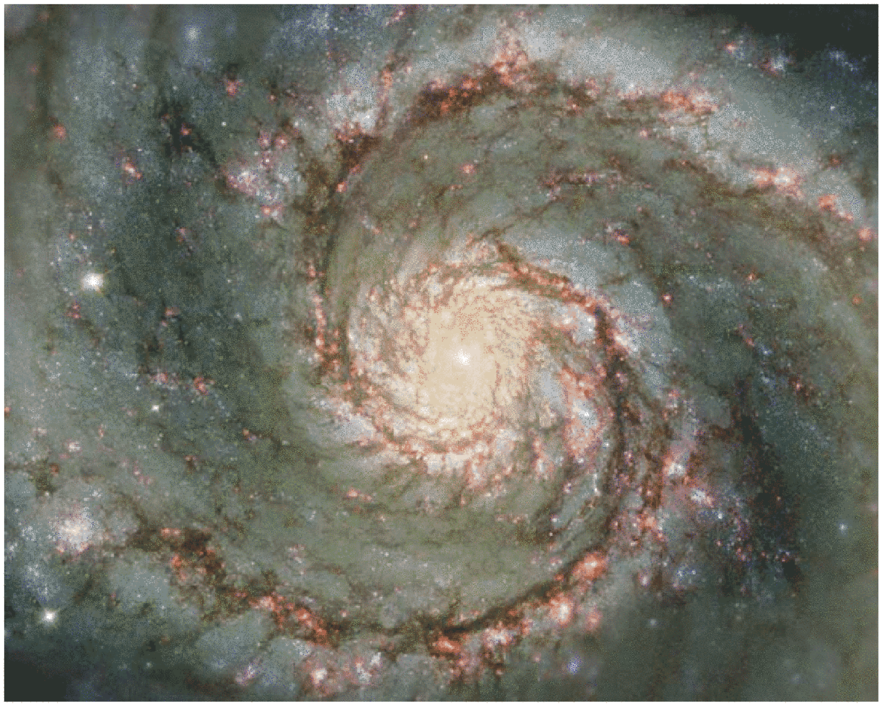
2) Galactic GRB (Atoyan)

3) Re-acceleration of highest-energy disk particles in Galactic Wind Halo by CR-dominated, smooth shocks, emanating from spiral arms ⇨ Composition heavy; negligible anisotropy (Zirakashvili)

M51

Spiral

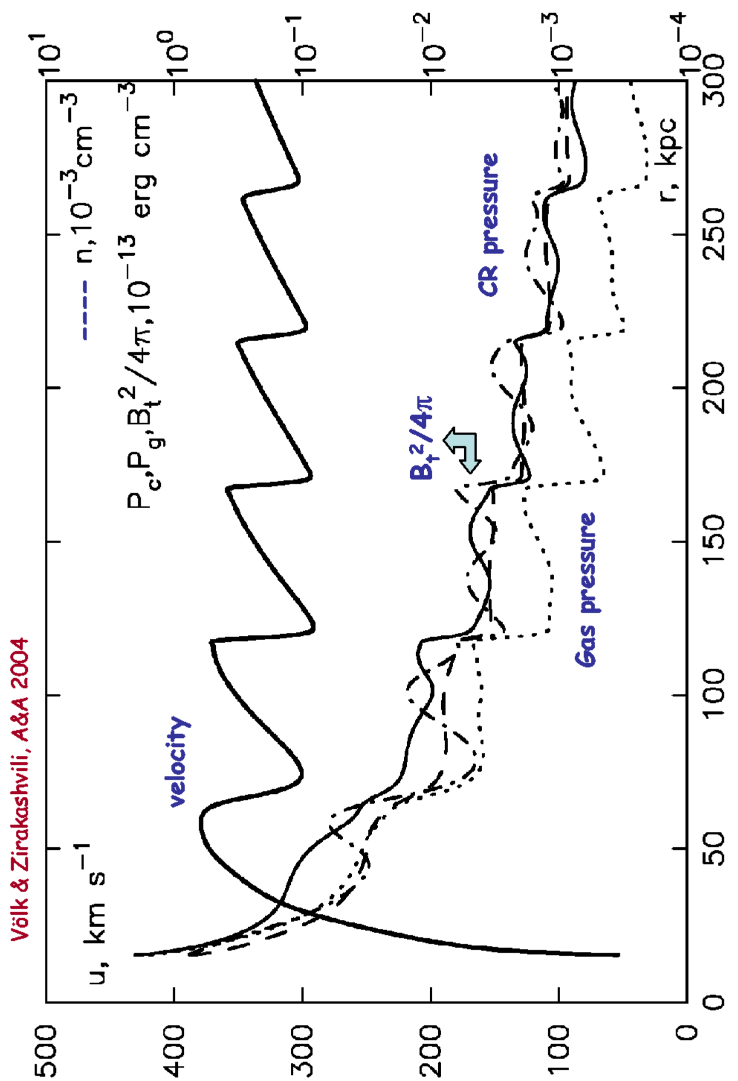
Arms

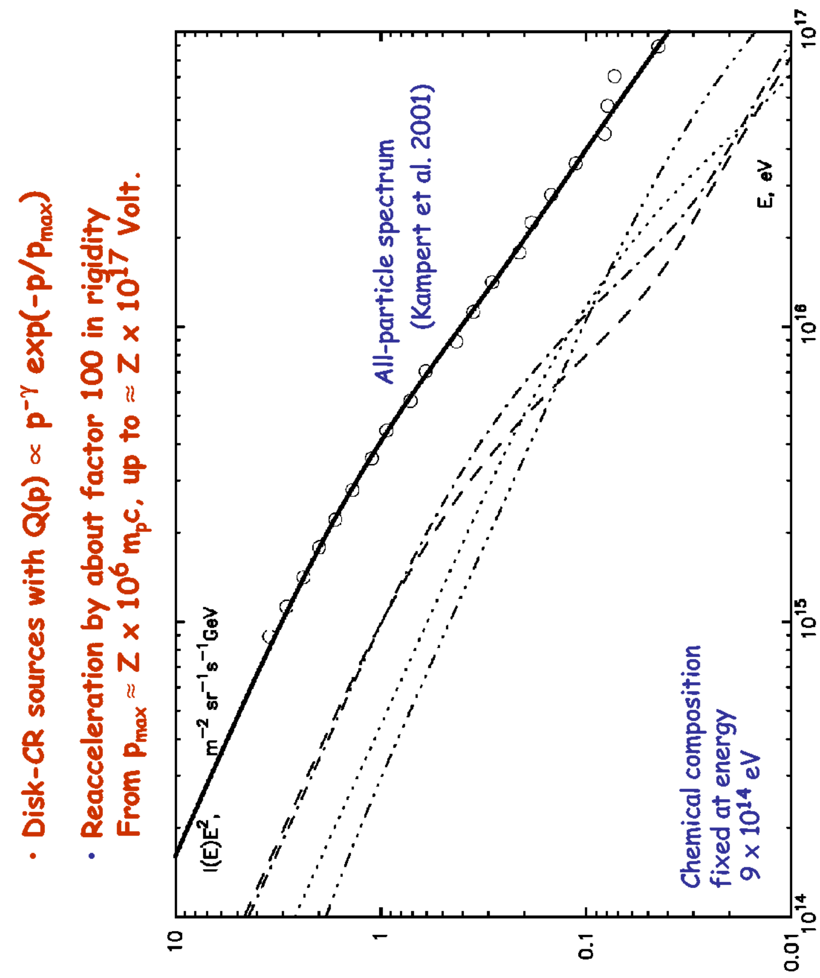


HST

Zirakashvili:

- Enhanced CR-production in spiral arms ⇨ fast streams ⊥ disk
- Rotation of spiral pattern ⇨ interaction of fast and slow streams ⇨
- Giant saw-tooth wave in wind out to termination shock at ~ few 100 kpc
- Wind internal energy dominated by CRs and B-field ⇨
- Shocks in wind smoothed on CR scale ⇨
- No injection of (supra-)thermal ions
- Only re-acceleration of disk-particles close to cutoff at knee
- Composition therefore dominantly “heavy”
- Huge acceleration volume enshrouding Galactic disk ⇨
- Negligible anisotropy
- Natural source of particles beyond knee out to extragalactic component


Völk & Zirakashvili, A&A 2004
u, km s^{-1}
velocity
---- n, 10^{-3}cm^{-3}
$P_c, P_g, B_t^2/4\pi, 10^{-13}$ erg cm^{-3}
CR pressure
$B_t^2/4\pi$
Gas pressure
r, kpc


• Disk-CR sources with $Q(p) \propto p^{-\gamma} \exp(-p/p_{max})$
• Reacceleration by about factor 100 in rigidity
From $p_{max} \approx Z \times 10^6 m_p c$, up to $\approx Z \times 10^{17}$ Volt.
All-particle spectrum
(Kampert et al. 2001)
Chemical composition
fixed at energy
9×10^{14} eV
$I(E)E^2$, m^{-2} sr^{-1} s^{-1} GeV
E, eV

Higher energy side of Aspen Workshop from Tom Gaisser, together with latest KASCADE results [Part I]