Nonthermal emission of supernova remnant SN 1006 revisited: theoretical model and the H.E.S.S. results

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We have already studied the case of SN 1006 before (Berezhko et al. 2002, 2003, 2009; Ksenofontov et al. 2005; Völk et al. 2008).

SN 1006 in synchrotron X-rays (blue colors)

Up to now SN 1006 is the only example, for which many astronomical parameters are quite well known

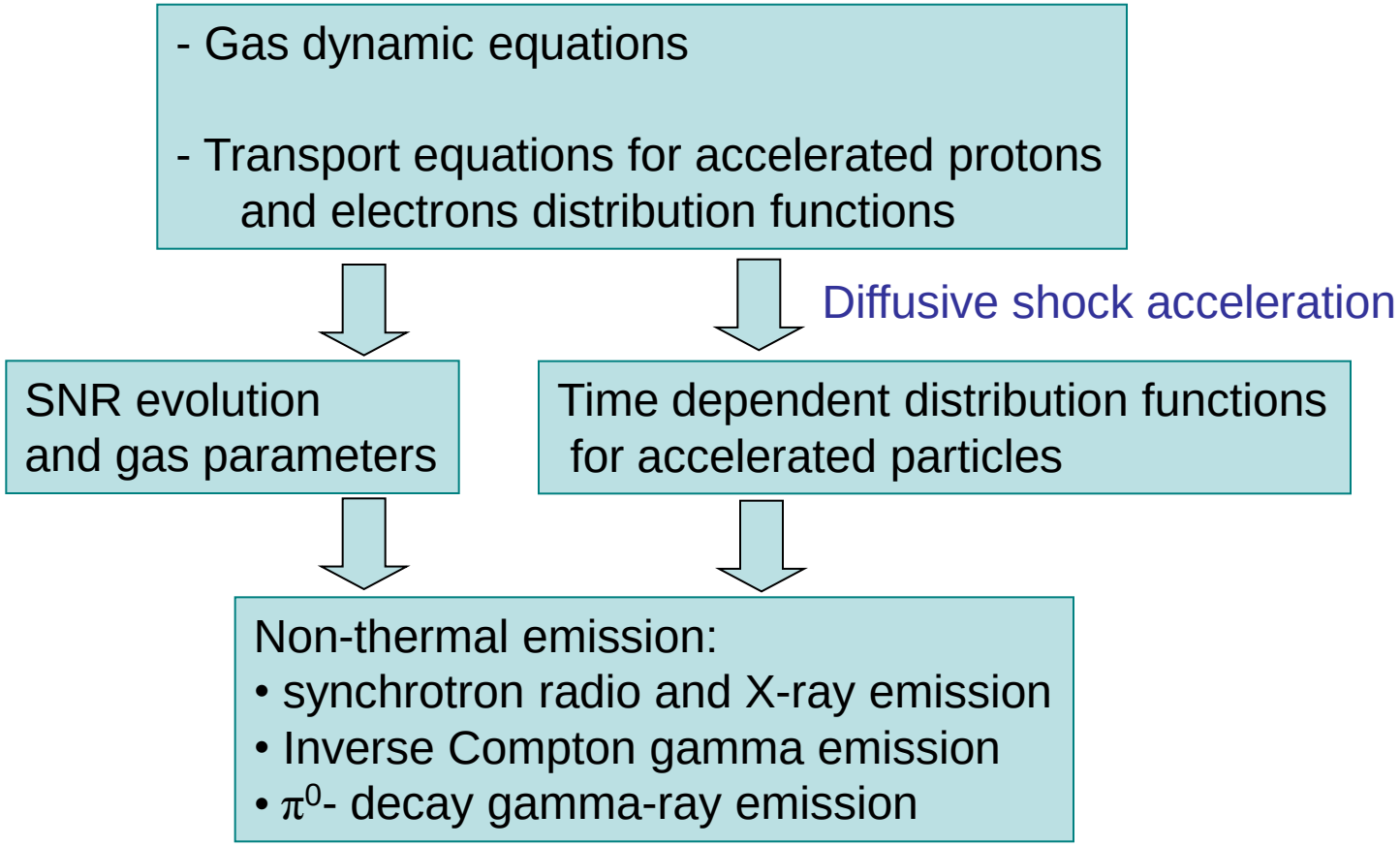
- type of explosion
- SNR age
- distance
- circumstellar medium
- nonthermal emission

The TeV gamma emission of SN 1006 has been recently detected with H.E.S.S., both regarding its flux and its morphology (Acero et al.2010).

This makes SN 1006 uniquely suitable for theoretical study and for a detailed comparison with the experimental data.

Nonlinear kinetic model of CR acceleration in SNRs

Berezhko, E.G., Yelshin, V.K., Ksenofontov, L.T. (1994)
Berezhko, E.G., Völk, H.J. (1997)



It has been applied SN1006, Tycho, Kepler, SN1987A, Cas A, RXJ1713, Vela Jr. …
(see Berezhko, E.G. 2008, *Advances in Space Research* 41, 429 for a review)

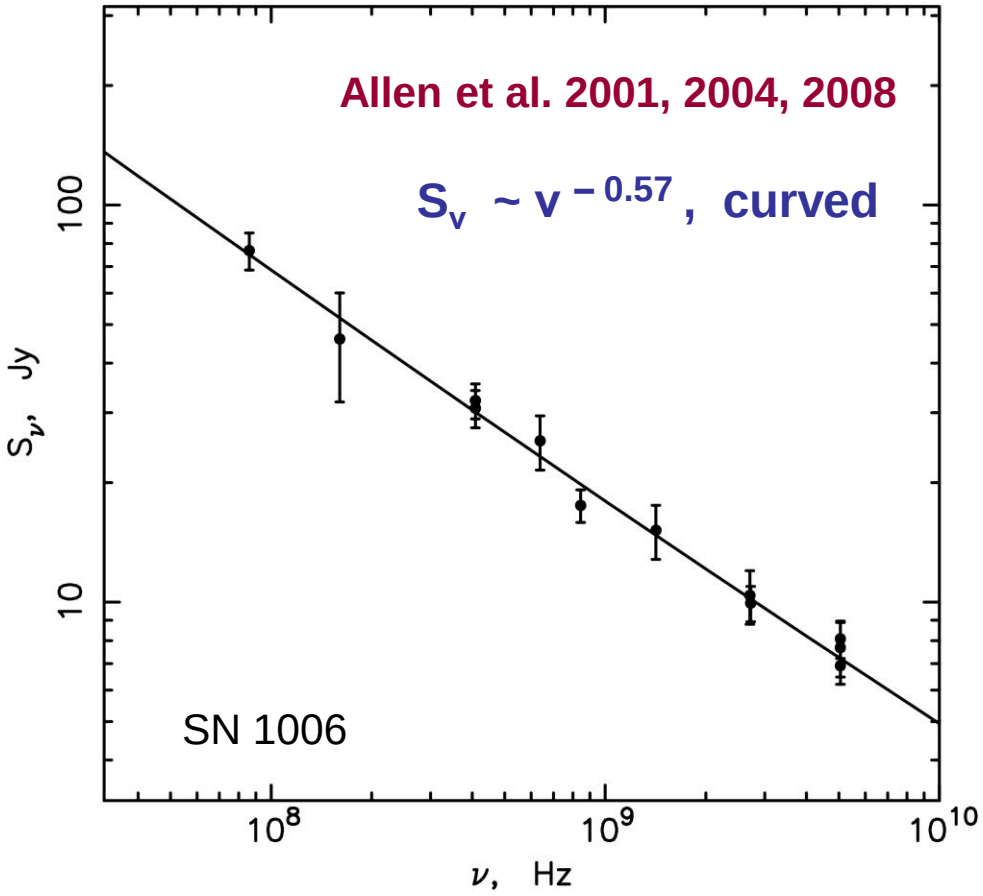
Summary of assumptions and earlier results

Type Ia, $M_{ej} = 1.4\ M_{SUN}$, Uniform ISM

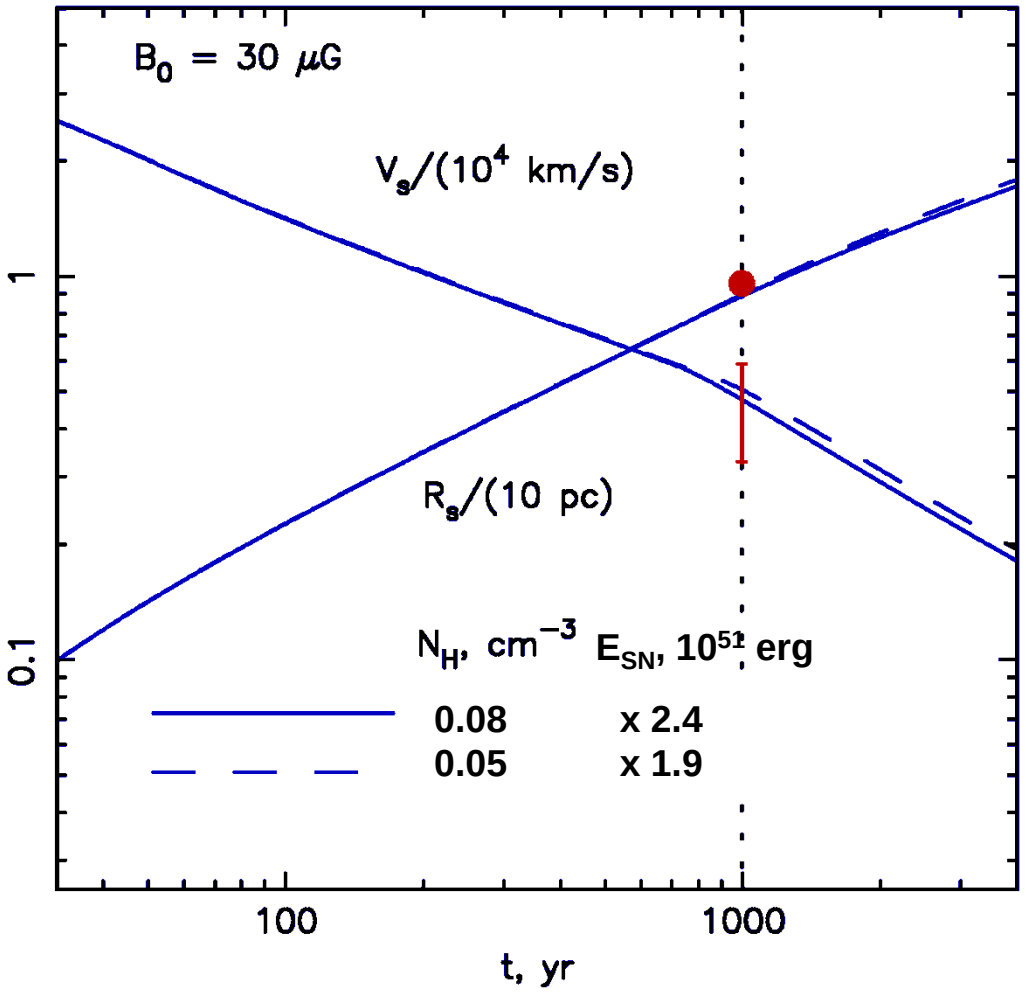
➡ Value of α and hardening of spectrum (Allen et al. 2008) predicts nuclear particle injection rate = 3×10^{-4} .

[$B_{eff} = r_{tot} \times B_o \approx 150\ \mu G$, $r_{tot} \approx 5$, e:p-ratio $\approx 4 \times 10^{-4}$ from fit to synchrotron X-ray spectrum, and from radio amplitude. Consistent with filaments]

$$B_0(t) = B_0(t_{sn}) \sqrt{P_c(t)/P_c(t_{sn})}$$



Overall SNR dynamics

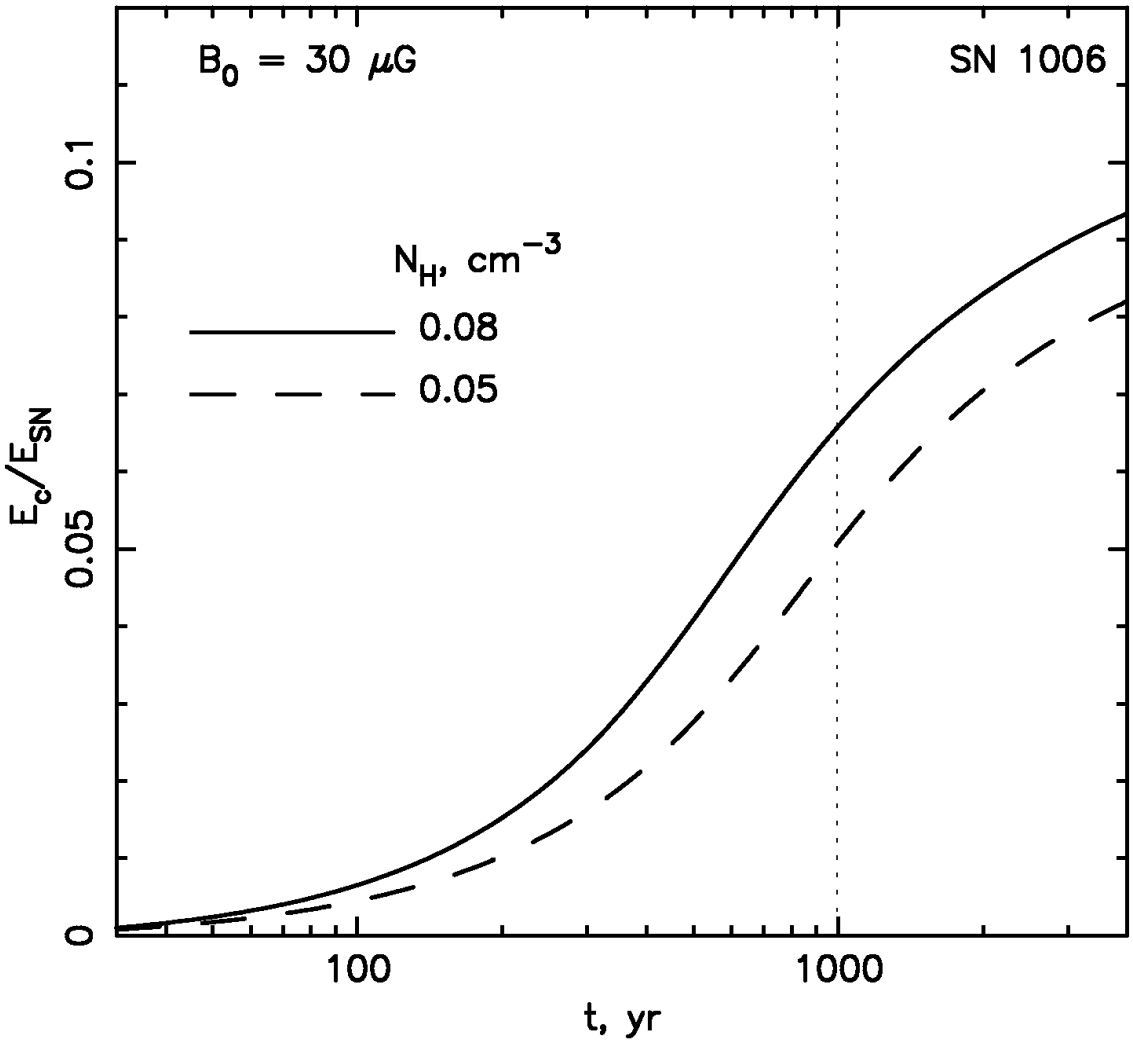


Observations (Moffet et al.1993):
$R_S = 9.5 \pm 0.35$ *pc*
$V_S = 4500 \pm 1300$ *km/s*
Distance (Winkler et al. 2003)
$d = 2.18 \pm 0.08$ *kpc*
Circumstellar density very low:
$N_H < 0.1$ *cm*$^{-3}$

The remnant is at the end of the free expansion phase

SN explosion energy is close to the upper end $E_{sn} = 1.6 \times 10^{51}$ erg of the typical range of type Ia SN

Acceleration efficiency



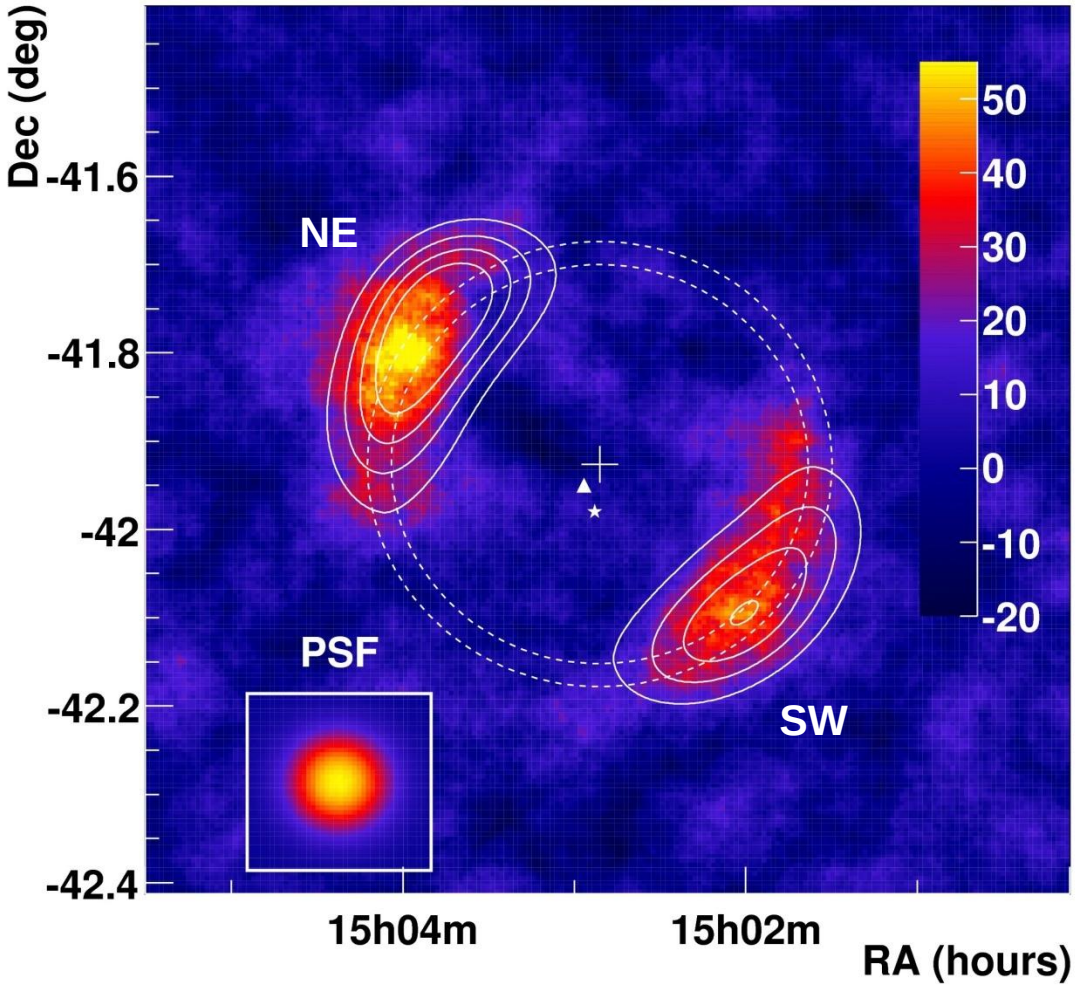
Efficiency $E_c/E_{SN} \approx 0.06$ at present epoch. Expected to grow to about 10 percent in the further evolution

Gamma-ray morphology

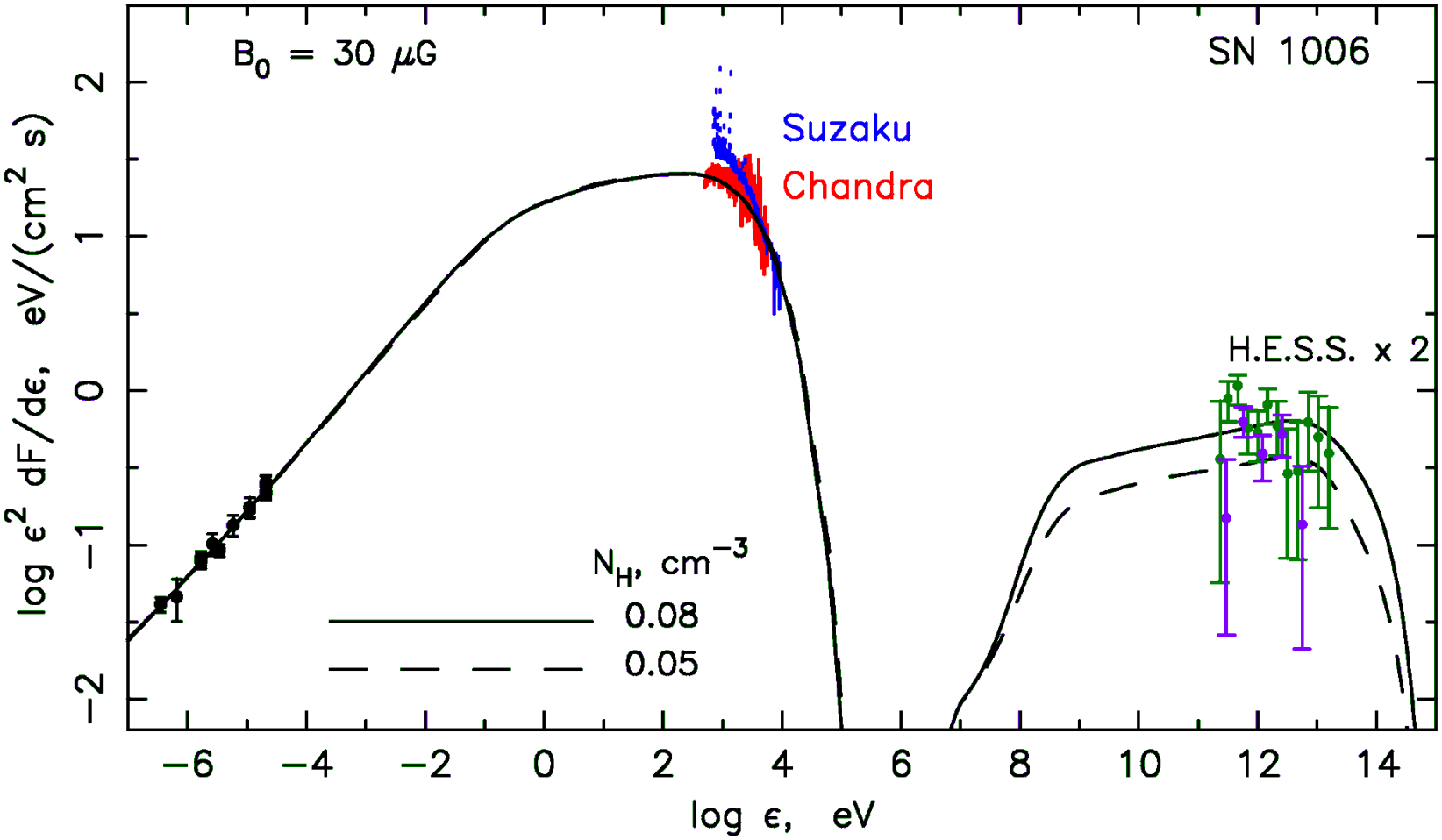
Polar caps also in Very High-Energy gamma rays. Similar to polar caps in hard X-rays and radio

(Solid contours from XMM X-ray image, smeared to H.E.S.S. resolution)

Acero et al. (H.E.S.S. Collaboration) 2010



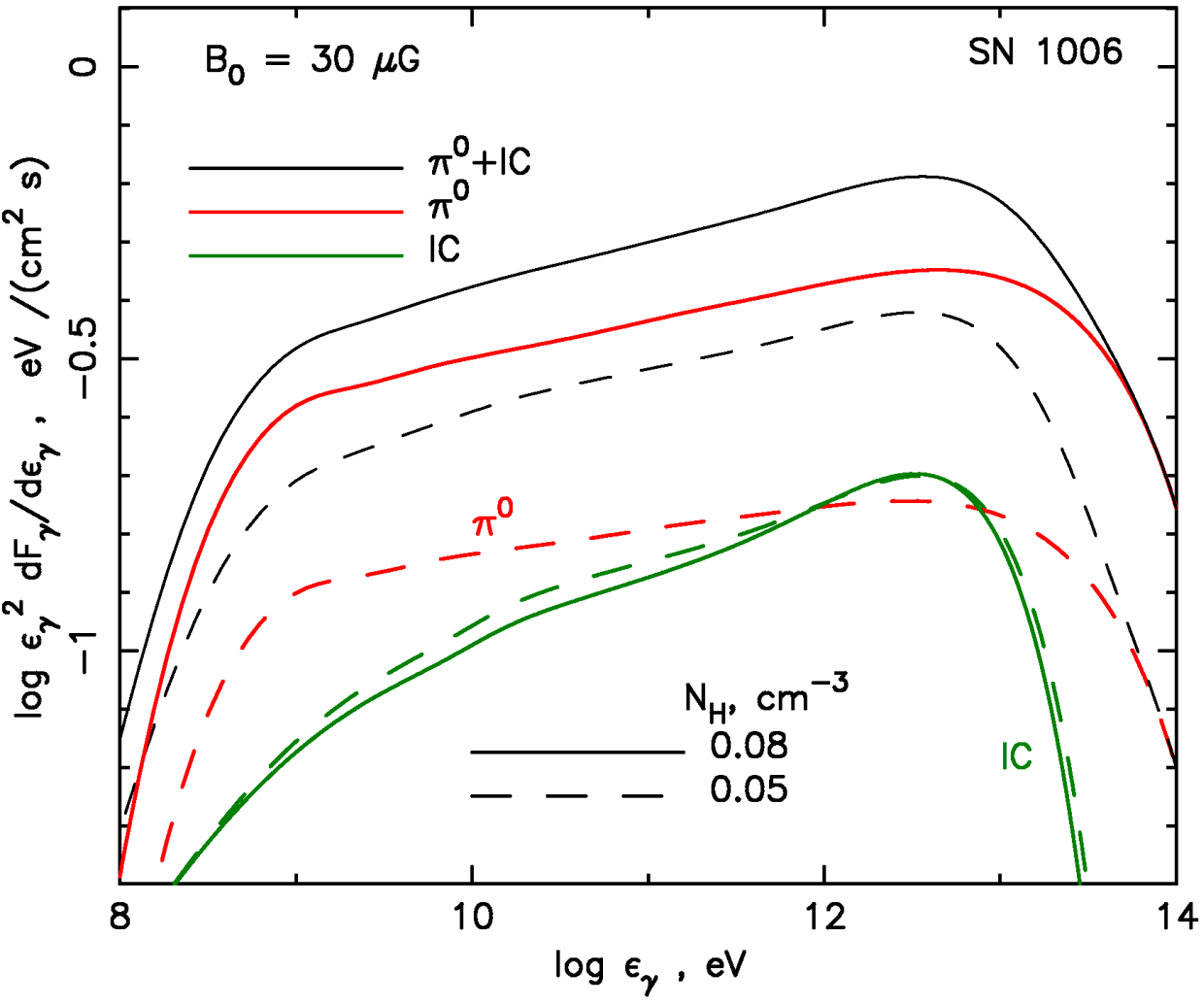
Overall nonthermal spectra



NE polar cap and SW polar cap
may have somewhat different densities. Agree with H.E.S.S. overall.

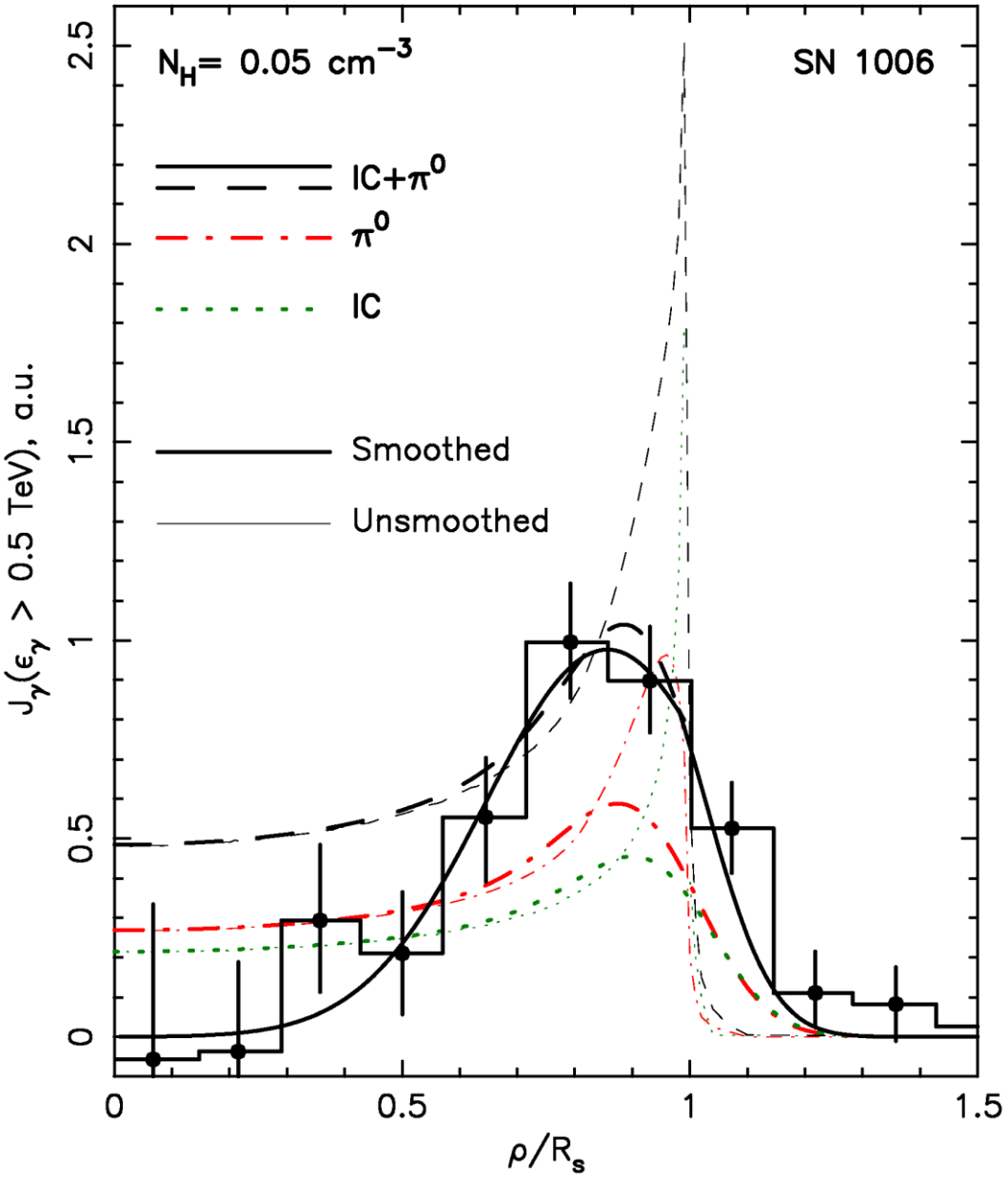
$N_H \approx 0.05$ /cc from thermal X-rays (Acero et al. 2007)

Relative contributions to the gamma-ray flux



Hadronic contribution larger / comparable to inverse Compton emission despite low ambient gas density

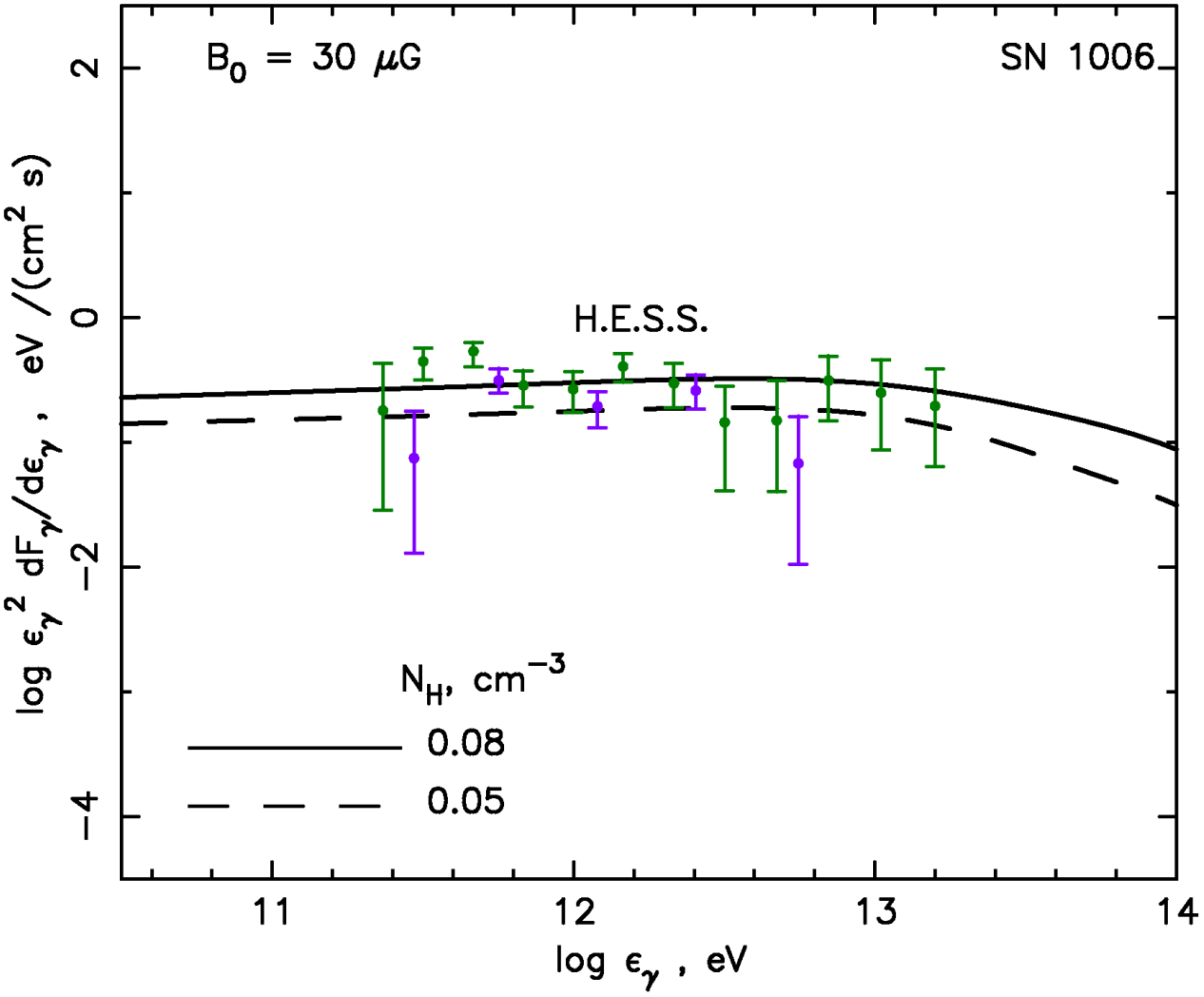
Radial profile of gamma-ray brightness



The radial profile of the TeV emission measured by H.E.S.S. is evidence that the nuclear CR component is indeed efficiently produced.

In the opposite case of inefficient nuclear CR production the magnetic field would not be expected to be amplified and the radial profile of the IC-dominated -ray emission would be expected to be significantly smoother than observed.

External density



$$\frac{\chi^2}{Dof} = 1.05 \text{ and } 2.2$$

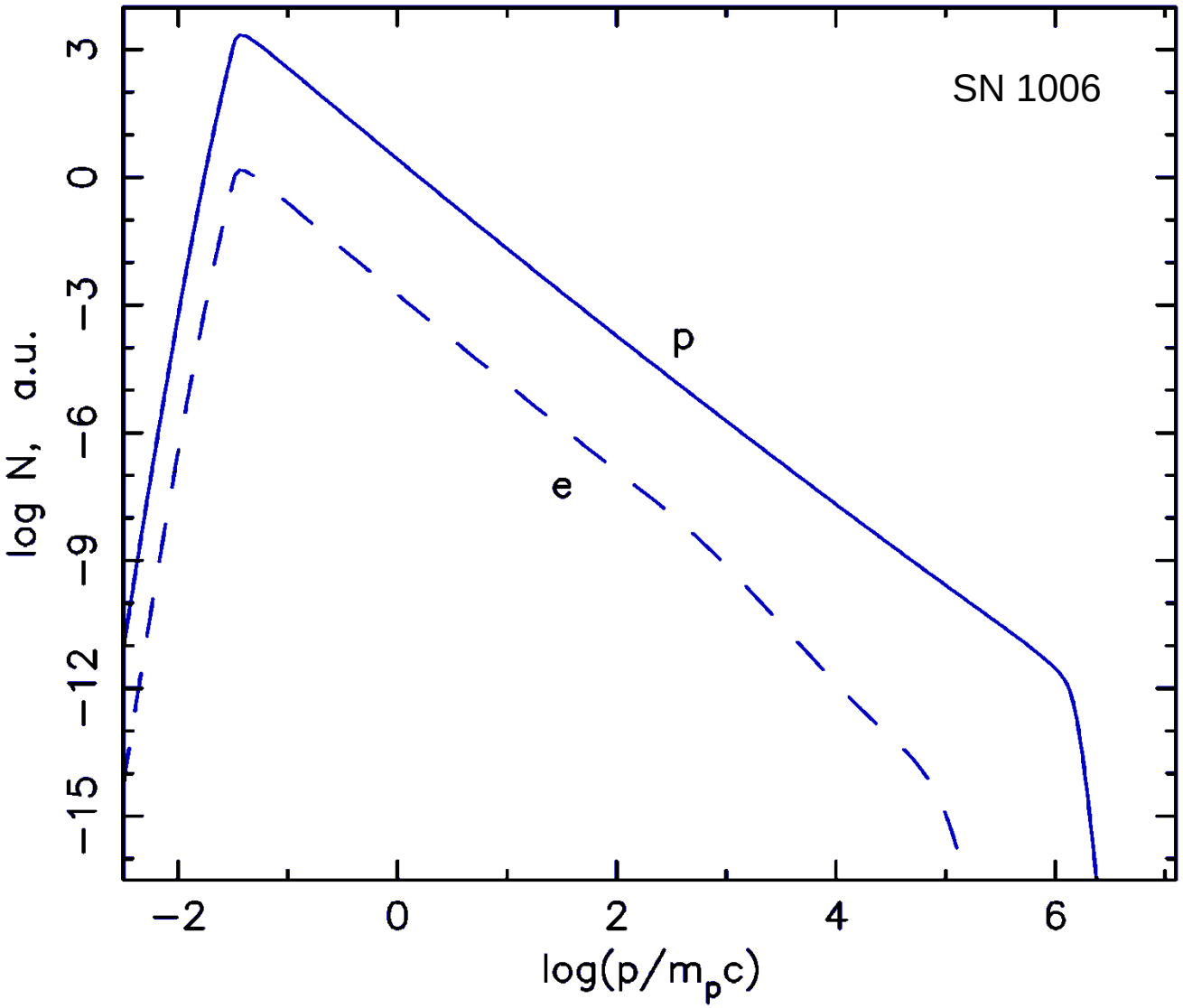
for the NE and SW

For pure power law fit:

$$\frac{\chi^2}{Dof} = 1.3 \text{ and } 2.5$$

for the NE and SW

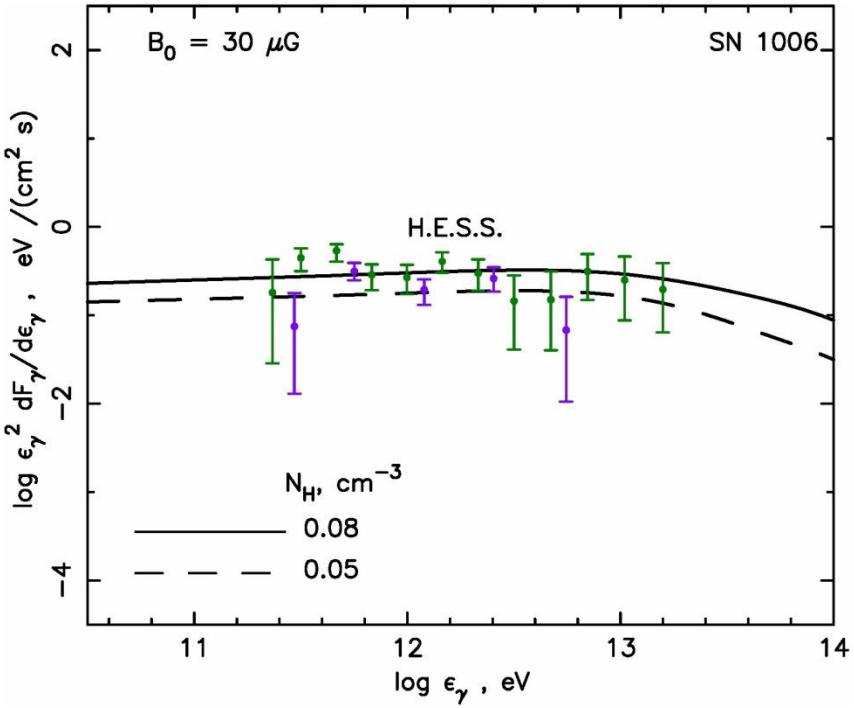
Volume-integrated CR spectrum:



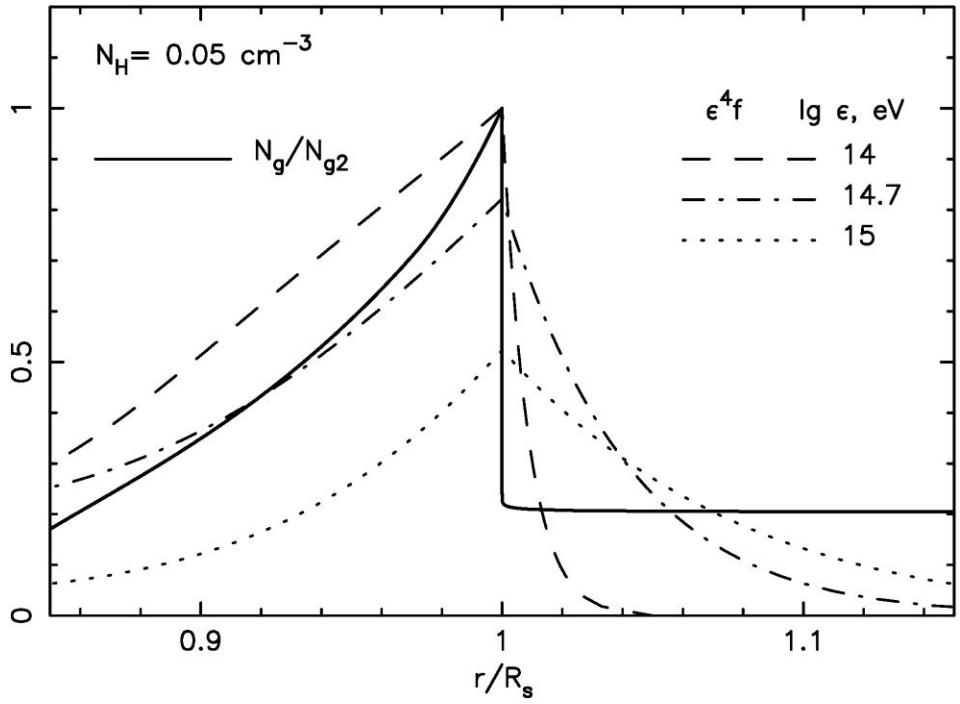
$p_{max} \approx 2 \times 10^6 \, m_p c$, for protons, $\approx 2 \times 10^{15}$ eV

≈ Consistent with CR source requirement ("knee")

“Escape” of accelerated nuclei from acceleration region:



Theoretical (and observed?) gamma-ray spectrum shows cutoff already for gamma energies ≈ 10^{13} eV in contrast to calculated nuclear particle spectrum which reaches “knee” !



Reason: lack of spatial overlap of highest-energy particles with gas density profile (“escape”) diminishes production rate of highest- energy gamma-rays.

Conclusion

High-energy tail of gamma-ray spectrum is affected by CR escape from the SNR interior

The flux of TeV emission detected by H.E.S.S. is consistent with the ISM number density 0.05-0.08 cc

The radial profile of the TeV gamma-ray emission measured by H.E.S.S. is evidence that the nuclear CR component is indeed efficiently produced.

Sum of multi-wavelength evidence suggests the conclusion that SN 1006 is indeed a source with high efficiency of nuclear CR production, required for the Galactic Cosmic Ray sources, both in flux as well as in cutoff energy !