Theory and field amplification for SN 1006

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- \`Simple´ object (historical SN, Type Ia, uniform environment: B-Field, density)
- Very good synchrotron data (radio, X-rays), **plus** recent gamma observations *(H.E.S.S.)*
- Theoretical model: acc\`n & gas dynamics, magnetic field amplification

Santa Barbara Conference, 2009

XMM X-rays

suggest dipolar structure of non-thermal synchrotron emission

B-field structure dipolar ?
Amplification ?

VHE particle acceleration only over part of shock surface ?

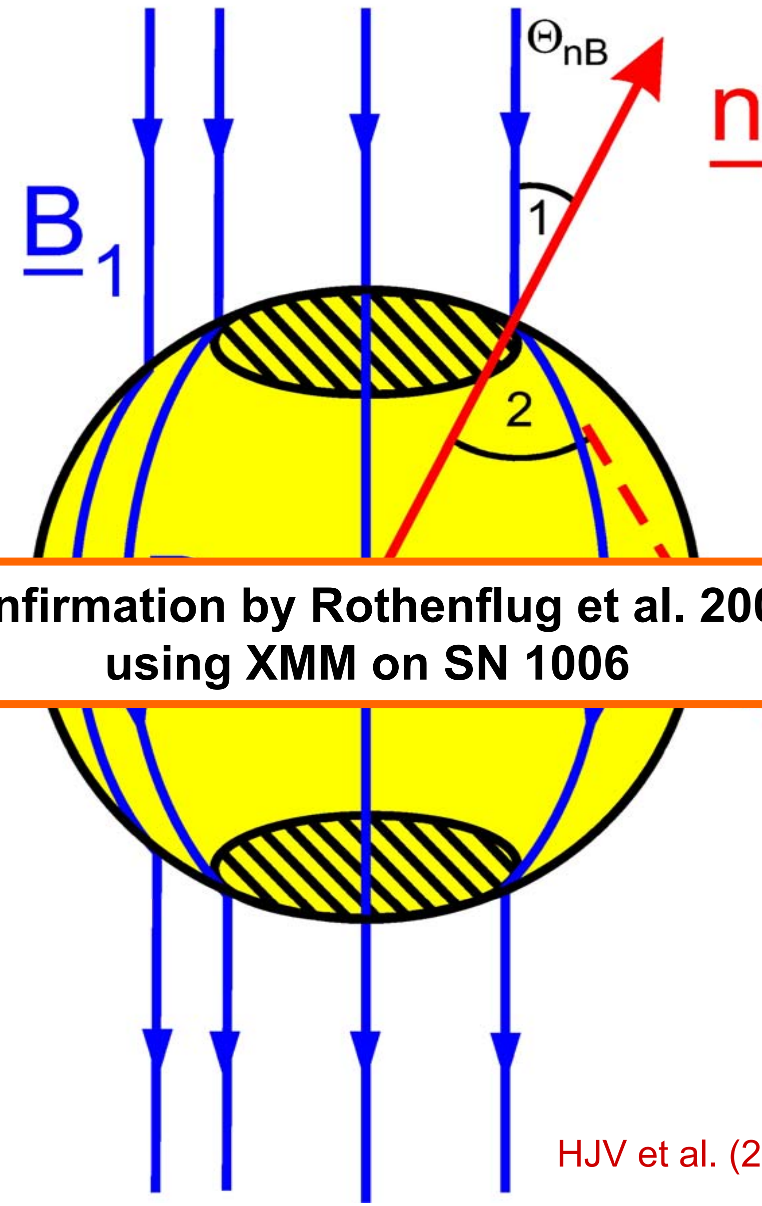
SN 1006

Non-spherical aspects of SNRs

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

(Ellison et al. 1965; Malkov & HJV 1965)

- Stochastic self-limitation of injection rate through nonlinear wave pro – duction: from $\eta_{||} \approx 10^{-2}$ 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 (from quasi-|| shock)
- X-ray synchrotron emission also overall dipolar for uniform external $\underline{B}_1$

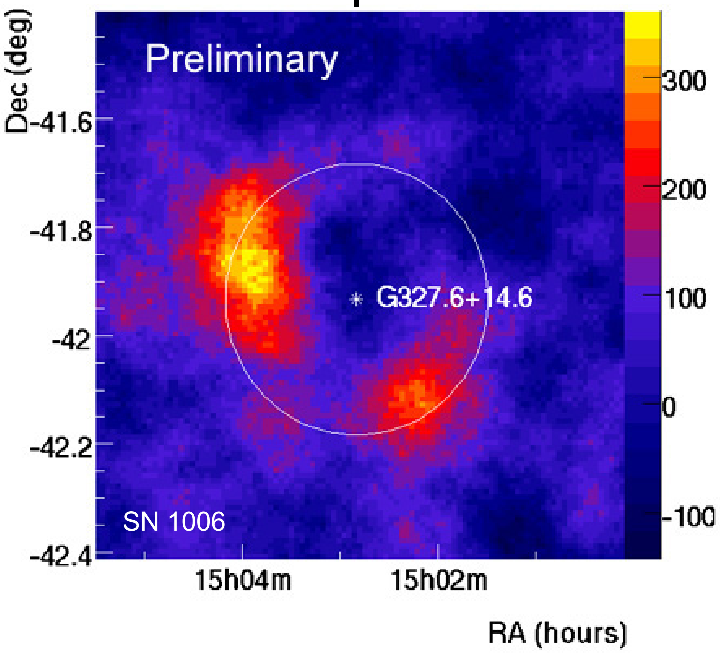


Confirmation by Rothenflug et al. 2004 using XMM on SN 1006

HJV et al. (2003)

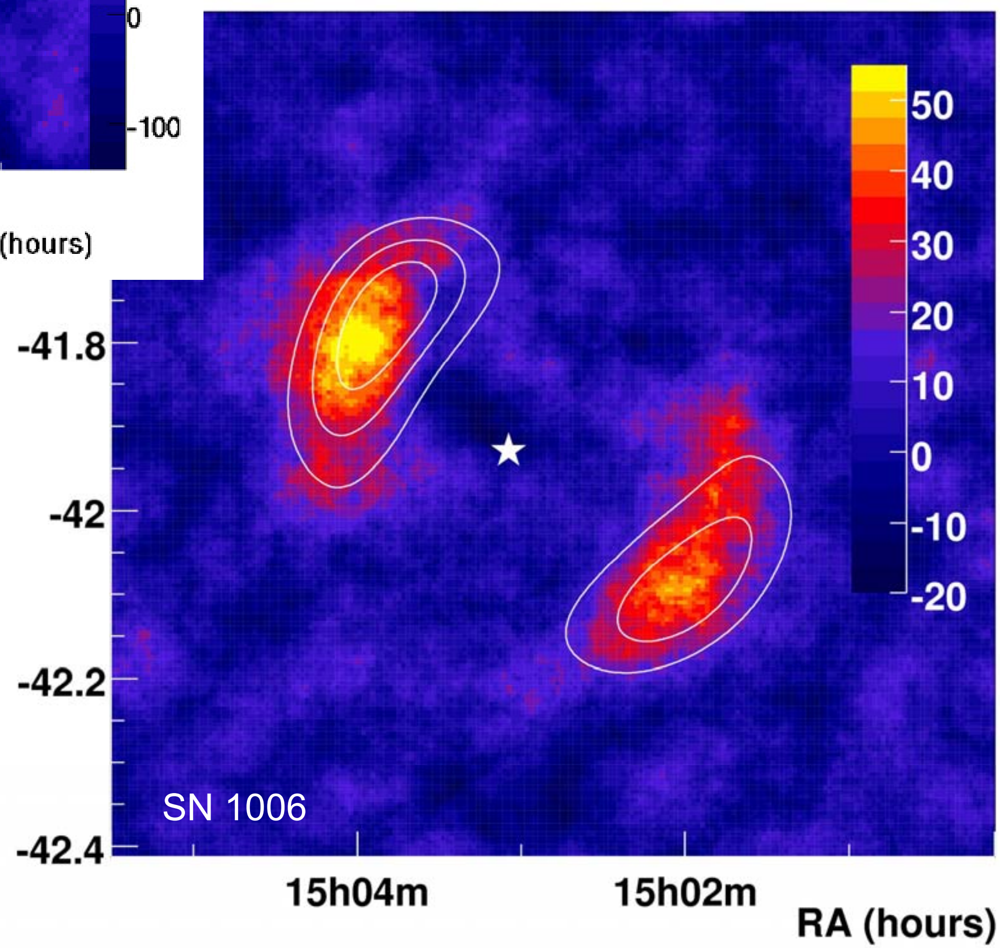
_H.E.S.S._ detection consistent with this morphology

= Primary argument for hadronic part of gamma-ray emission



Naumann-Godo et al. (H.E.S.S. Coll'n), Proc. ICRC (Lodz), 2009

_H.E.S.S._ excess counts/(angle)²

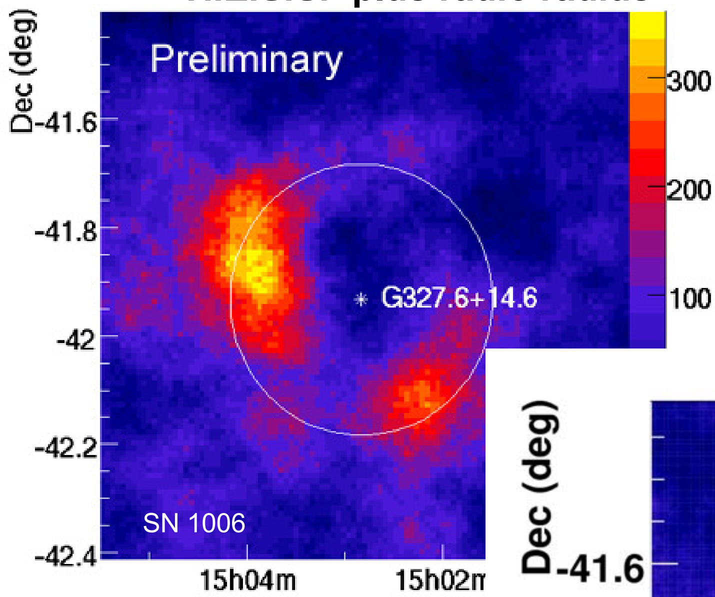


But very low gas density !

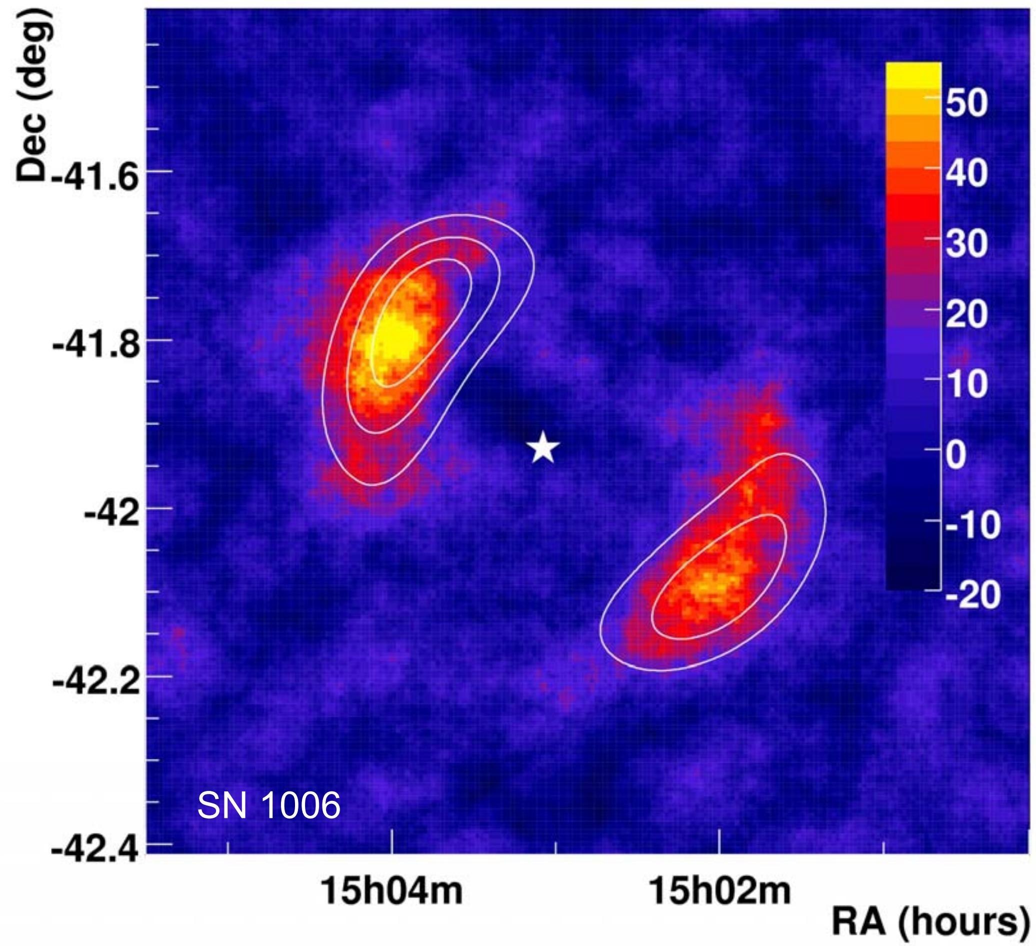
H.E.S.S. **detection consistent with this morphology**

= Primary argument for hadronic part of gamma-ray emission

***H.E.S.S.* plus radio radius**



***H.E.S.S.* excess plus smoothed *XMM* contours, 2 – 4.5 keV energy range**



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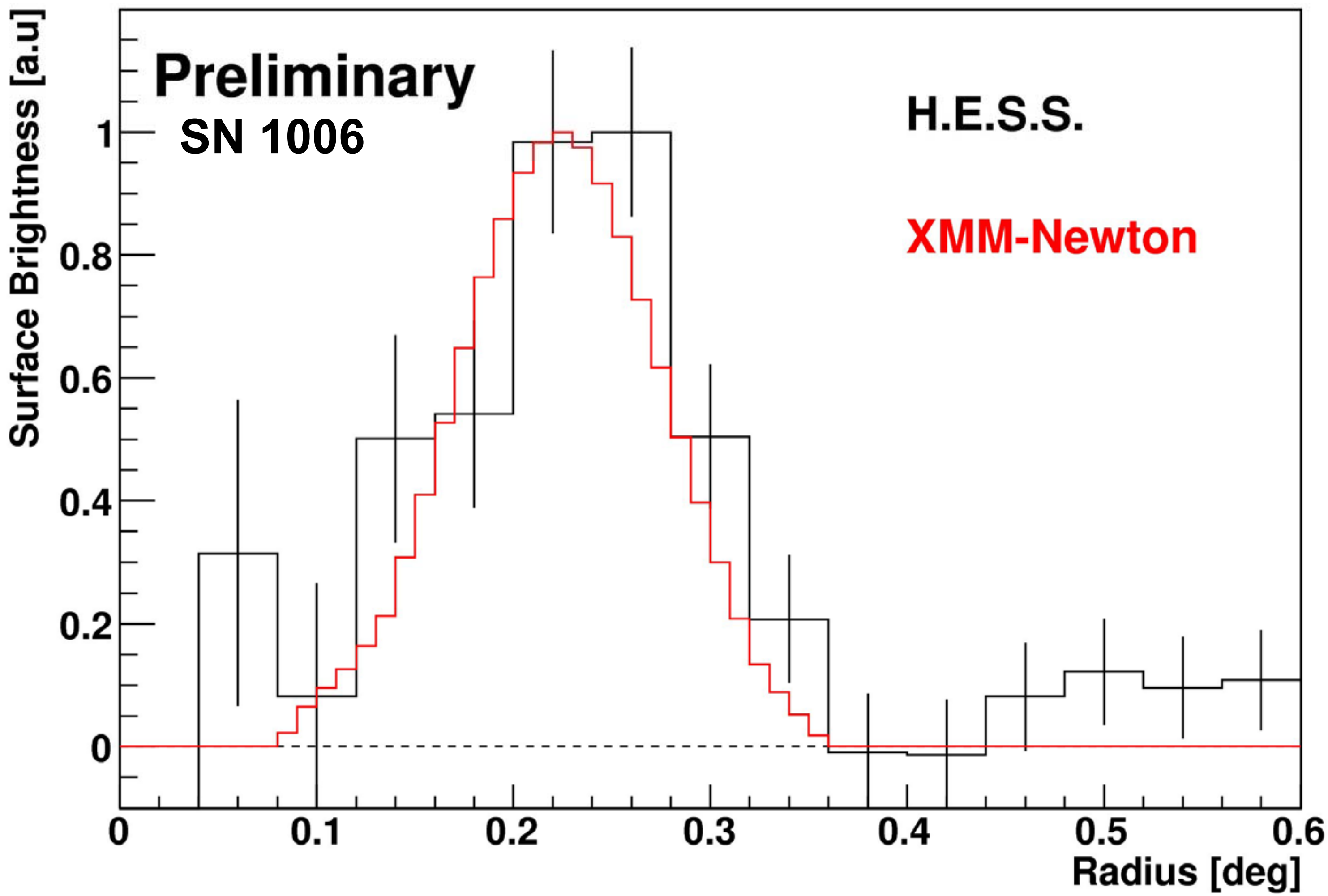
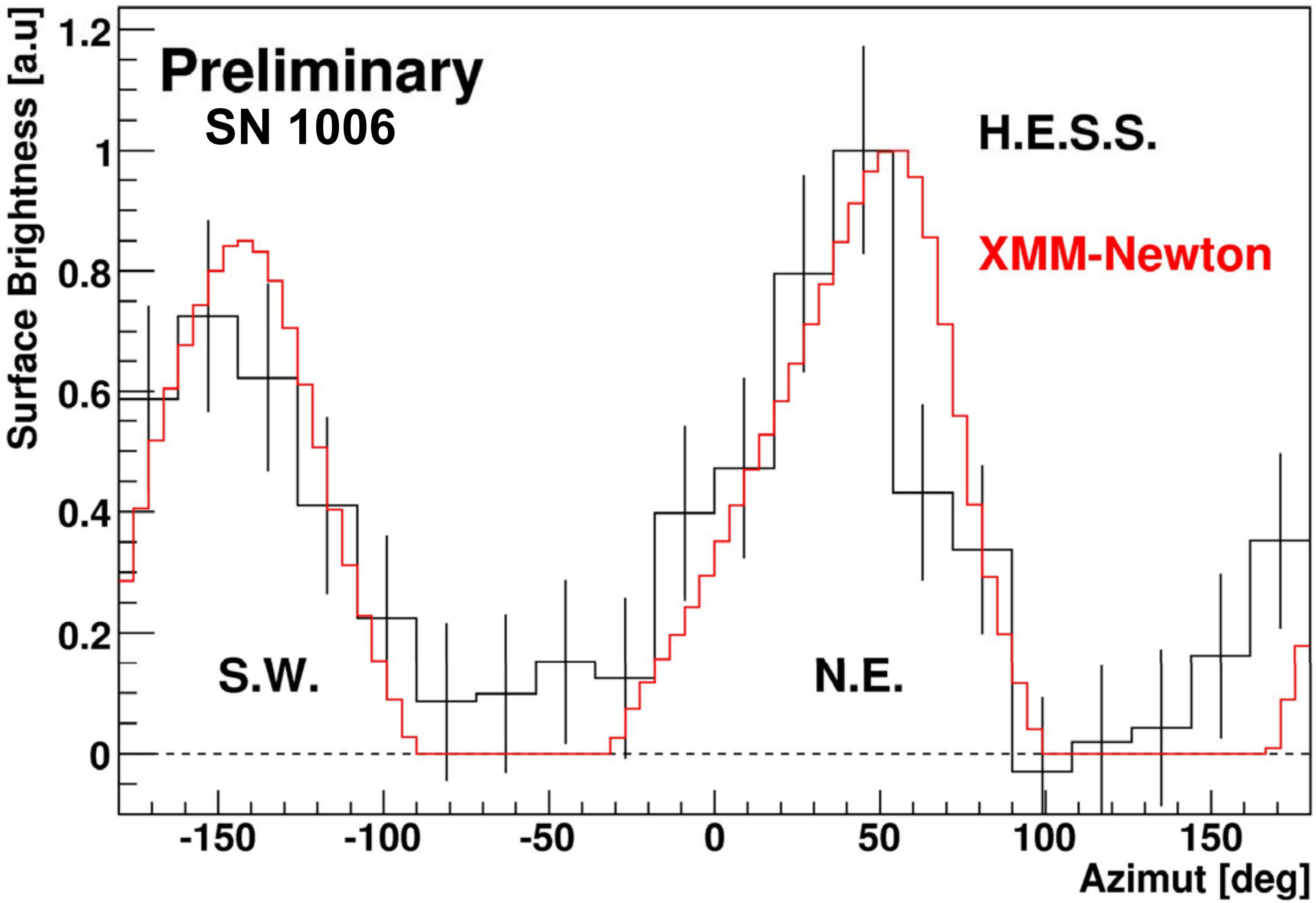
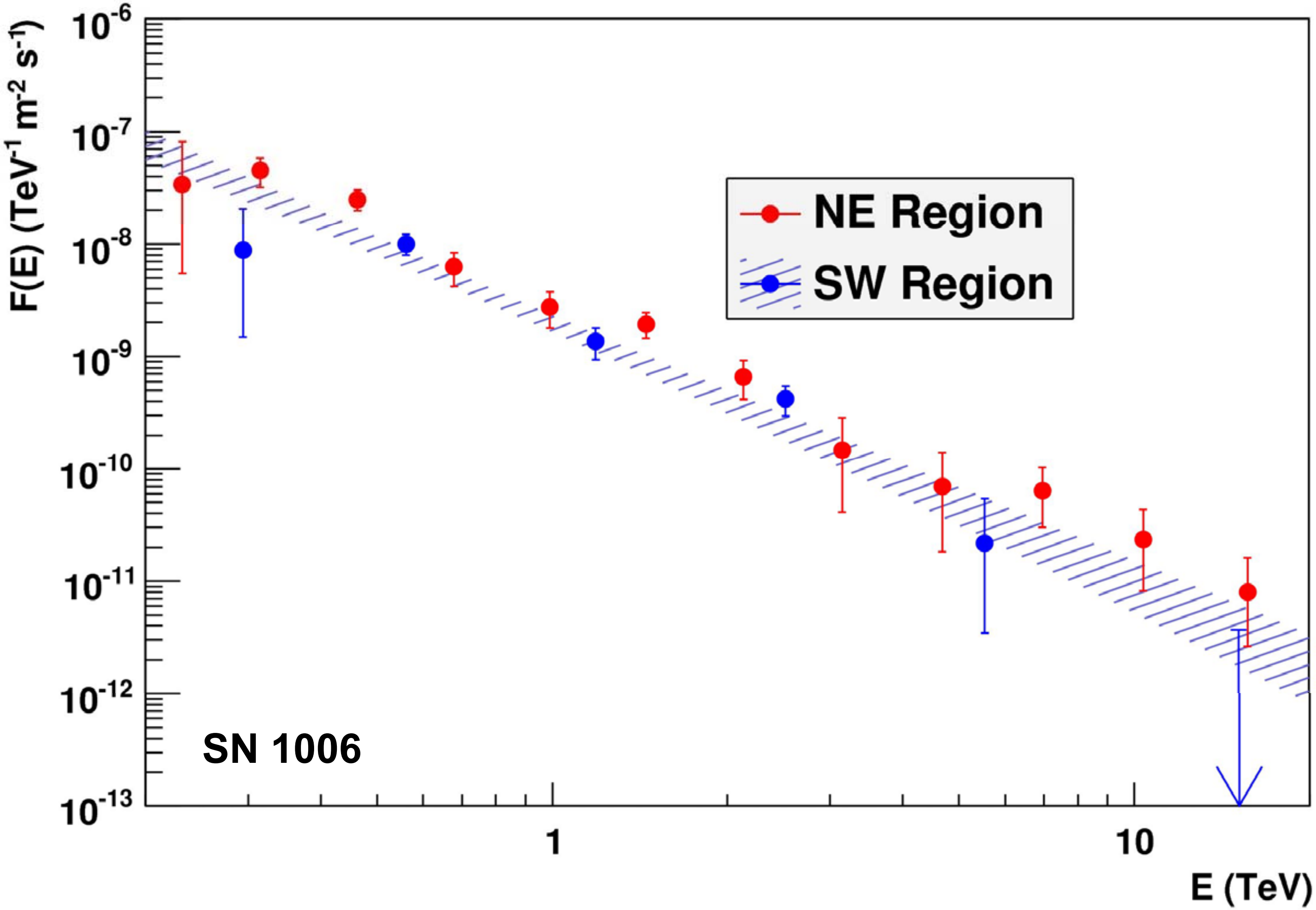


Radial profiles has width 0.076º ± 0.014º, consistent with *H.E.S.S.* point spread function ➡ compatible with a thin rim also in gamma rays. Expected hadronic gamma-ray profile narrower by a factor ~ 2 (Berezhko et al. 2002).



Also factor > 10 variation in synchrotron cut-off frequency in azimuth
(Rothenflug et al. 2004) ➡ Consistent with low, only MHD – compressed B - field and diffusion coefficient $\kappa > \kappa_{Bohm}$ in equatorial regions.
[See Petruk et al. (2008) and Miceli et al. (2009) for a different view.]

H.E.S.S. differential photon spectrum:



Compatible with power law of coefficient $\Gamma = 2.36 \pm 0.1_{stat} \pm 0.2_{syst}$ in NE

VLA radio

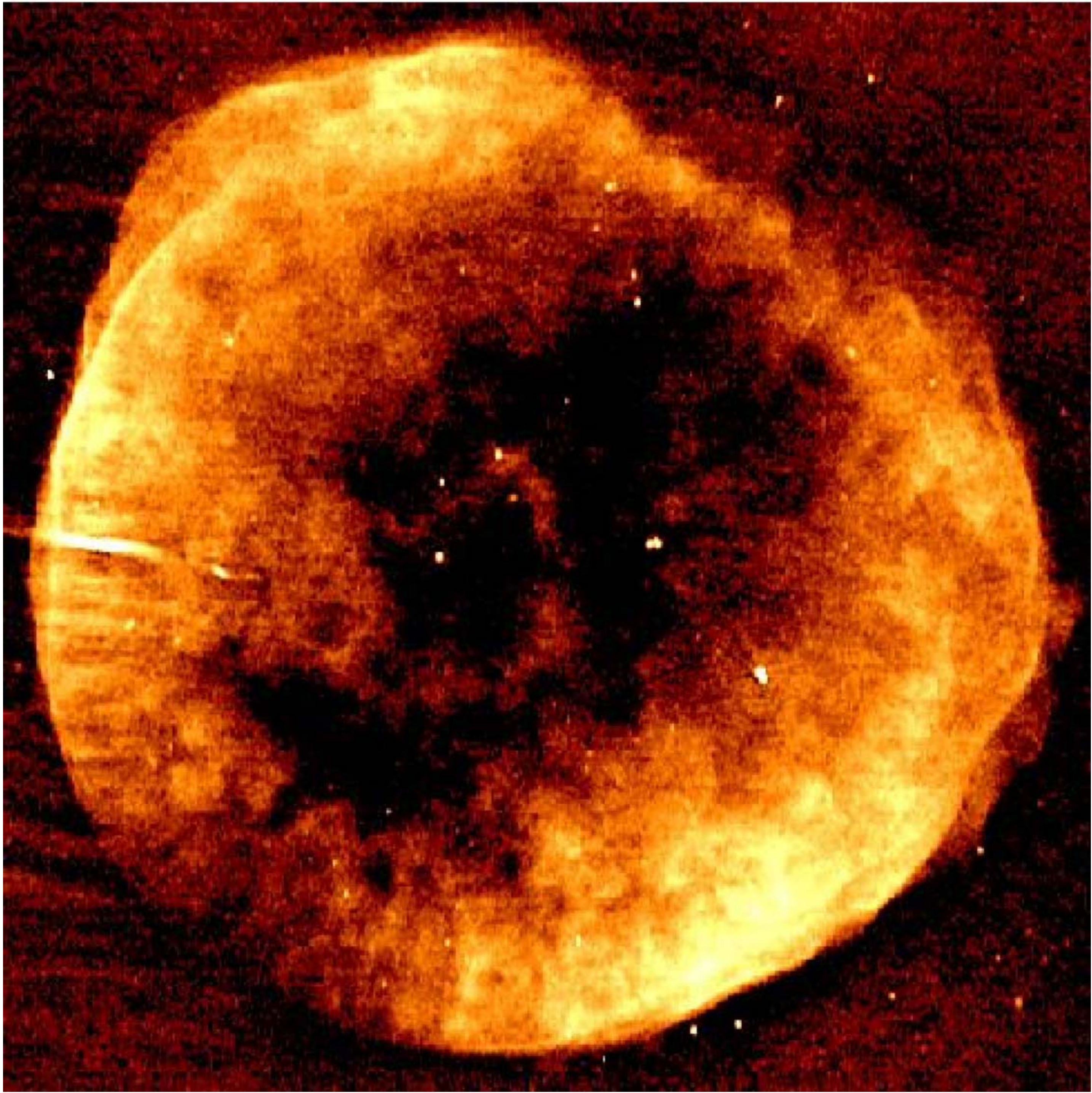
More or less everywhere around circumference.

Smoother spatial structures than in X-rays
(Cassam-Chenaï et al. 2008)

Probably:

Electron injection evervywhere

SN 1006



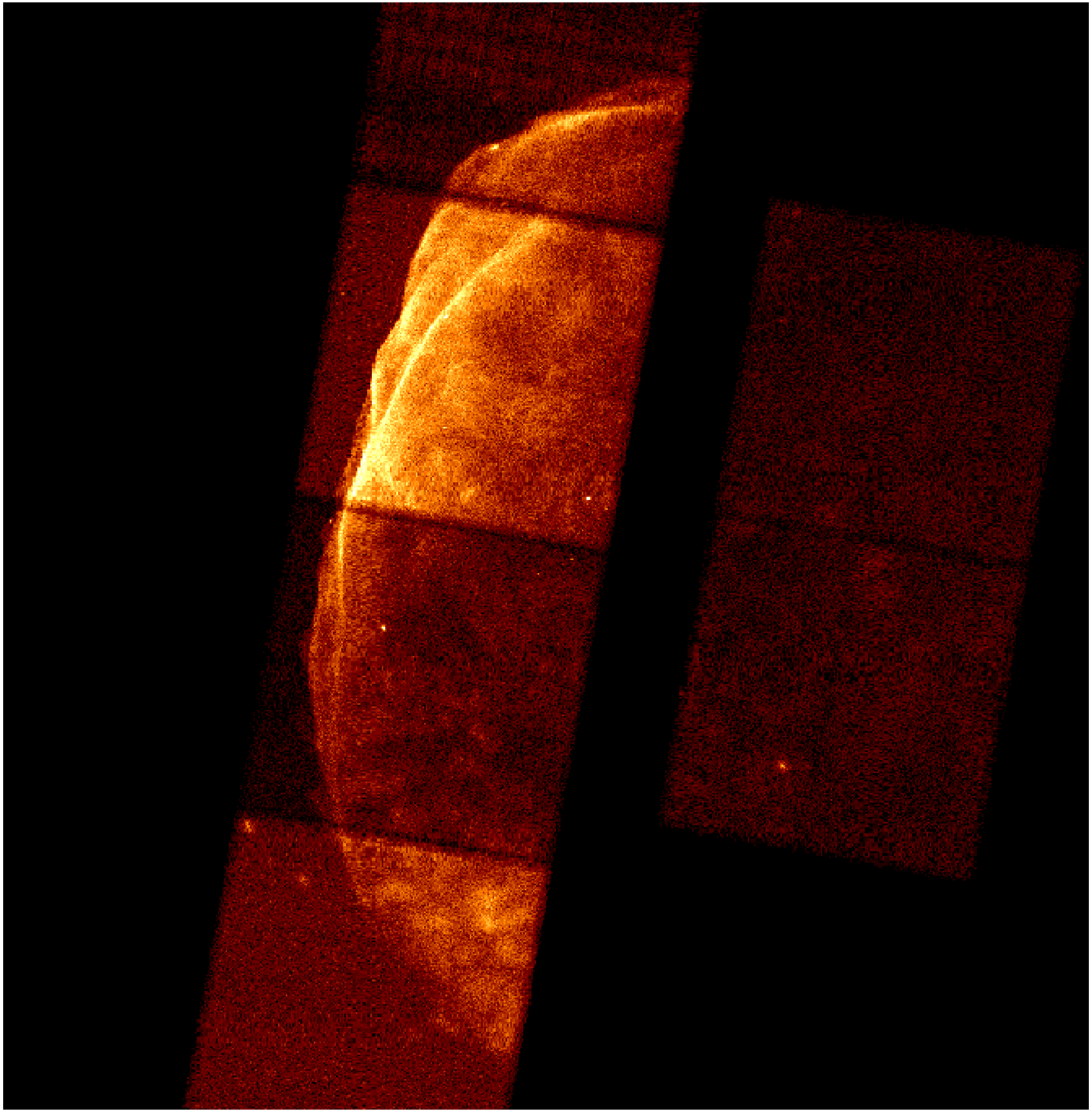
Chandra
X-rays:

Spatial scale of filaments $\sim 10^{-2} R_{shock}$

= synchrotron loss length downstream of shock
➡ B_d (locally)

Amplified by factor up to 10.

Only possible through nuclear component.



SN 1006

Comparison with nonlinear theoretical model:

(i) Kinetic equation for CR distribution functions $f_i(p,r,t)$ and $f_e(p,r,t)$ in spherical symmetry + quasi-parallel shock, coupled with gas dynamics of thermal plasma through CR pressure and wave dissipation (gas heating). Requires full time-dependence (Berezhko et al. 1994, 1996; Berezhko & HJV 1997).

(ii) Still $\kappa \approx \kappa_{Bohm}$ due to excessive wave excitation (McKenzie & HJV, 1982).

(iii) B-field amplified to $B_0(t) = B_0(t_{sn}) \left(P_c(t) / P_c(t_{sn})\right)^{1/2}$ in shock precursor by nonresonant CR instability (Bell 2004) plus resonant Alfvén wave instability (Lucek & Bell 2000; Pelletier et al. 2006). Assume strong wave dissipation $\approx c_A (B) \cdot \mathrm{grad}\, P_c$ (e.g. Berezhko & Ellison 1999) due to internal shock formation (Bell 2004; Zirakashvili et al. 2008), for non-resonant / resonant modes.

(iv) Simplifying assumption: $B(r,t) = B_0(t) \times \rho(r,t)/\rho_\infty$, uniform downstream $\equiv B_d(t)$.

(v) \`Renormalization' of nuclear particle distribution to exclude quasi-perpendicular shock regions by factor $f_{re} < 1$ (HJV et al. 2003).

(vi) Theoretically poorly known/unknown: B_0, proton injection rate η, electron:proton ratio K_{ep}

➡ Need observational input to determine these \`theory parameters'.

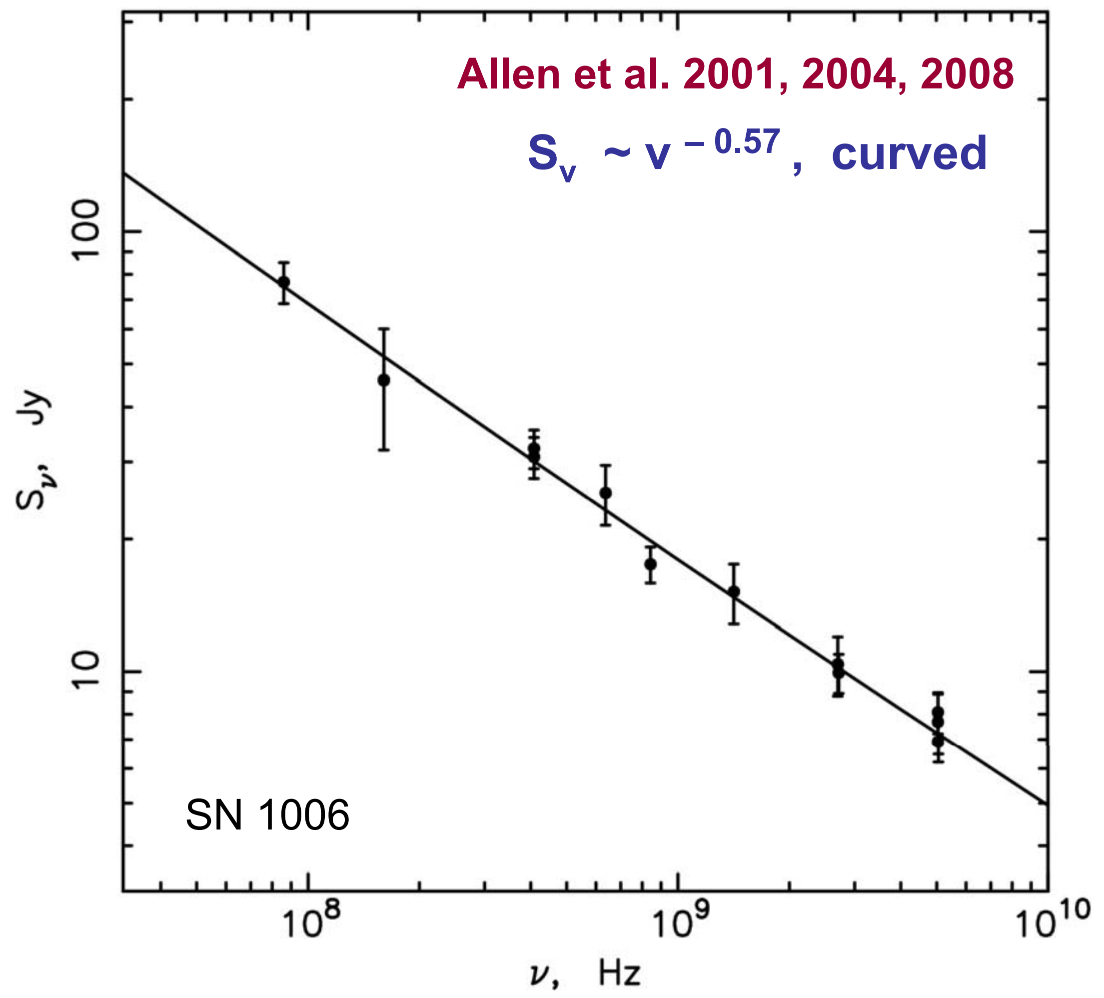
In a nonlinear theory everything is connected to everything else !

Nevertheless, start description with `theory parameters' here:

Nuclear particle nonthermal pressure P_c modifies shock to precursor and subshock.

Subshock compression ratio determines spectral index $\alpha > 0.5$ of low-energy radio electrons.

➡ Value of α and hardening of spectrum (Allen et al. 2008) determines ion injection rate.



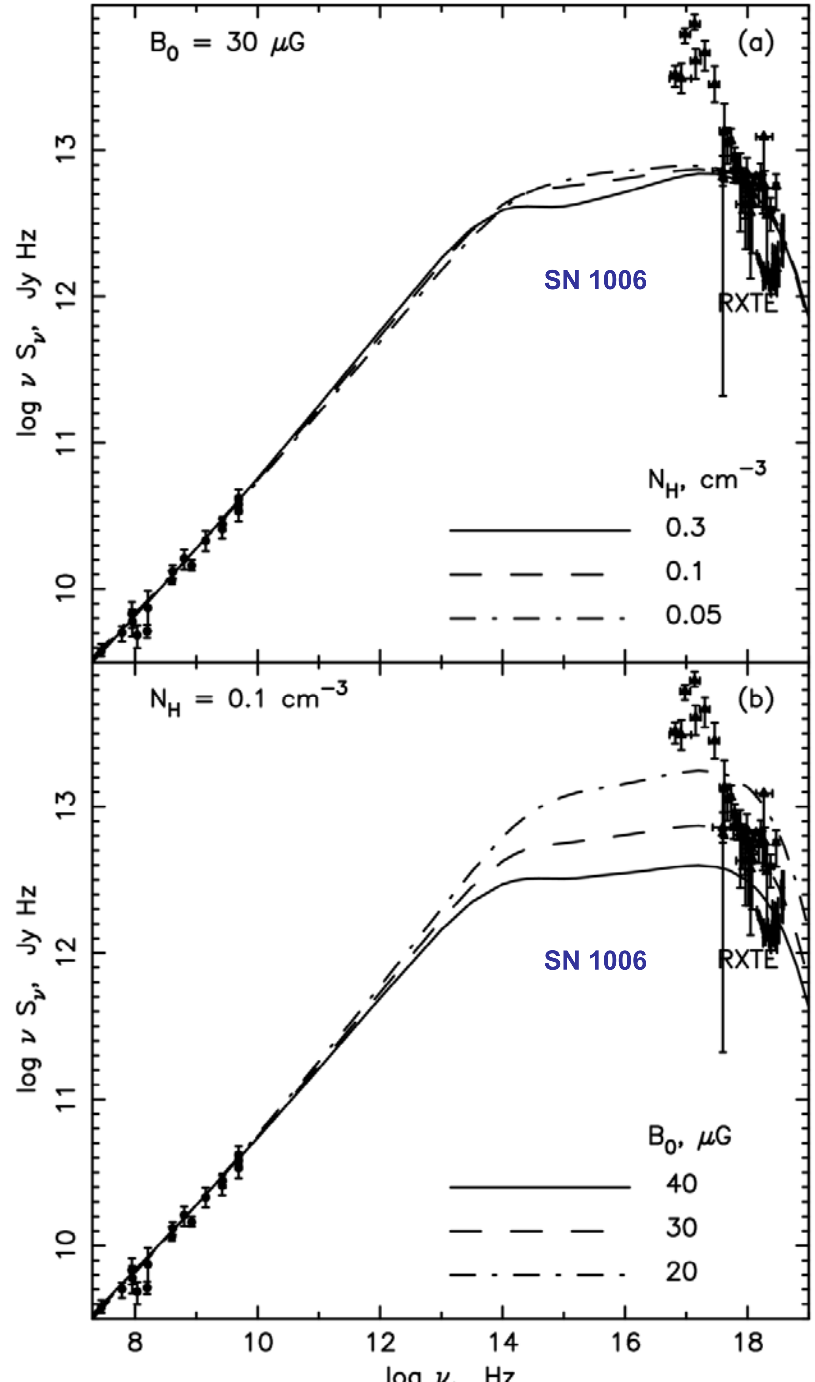
Volume-integrated synchrotron spectrum:

(i) Influenced at high frequencies $\nu > \nu_{loss}$ by synchrotron cooling ➡ flat-topped spectrum with cutoff at hard X-rays, quite sensitive to internal field B_d:

$$\nu_{loss} S_\nu (\nu_{loss}) \propto B_d^{-3/2}$$

(ii) Use latest Suzaku/Chandra measurements to optimize value of $B_d (t_{sn})$

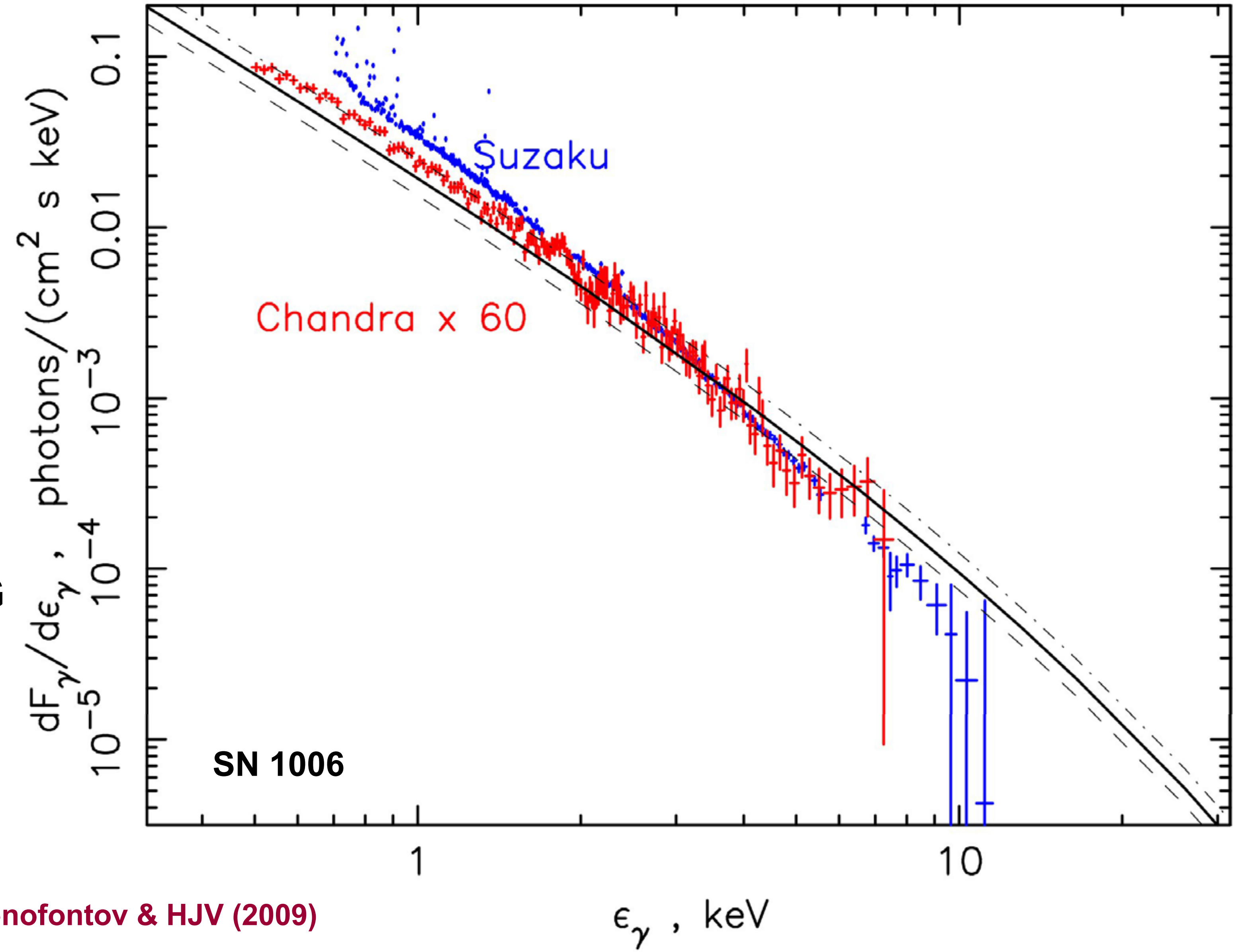
(iii) Finally, determination of electron: proton ratio K_{ep} from radio amplitude



Ksenofontov et al. (2005), using *RXTE data*

New determination of B_d with *Chandra* and *Suzaku*:

B_d (t_{sn}) = 150 ± 15 μG

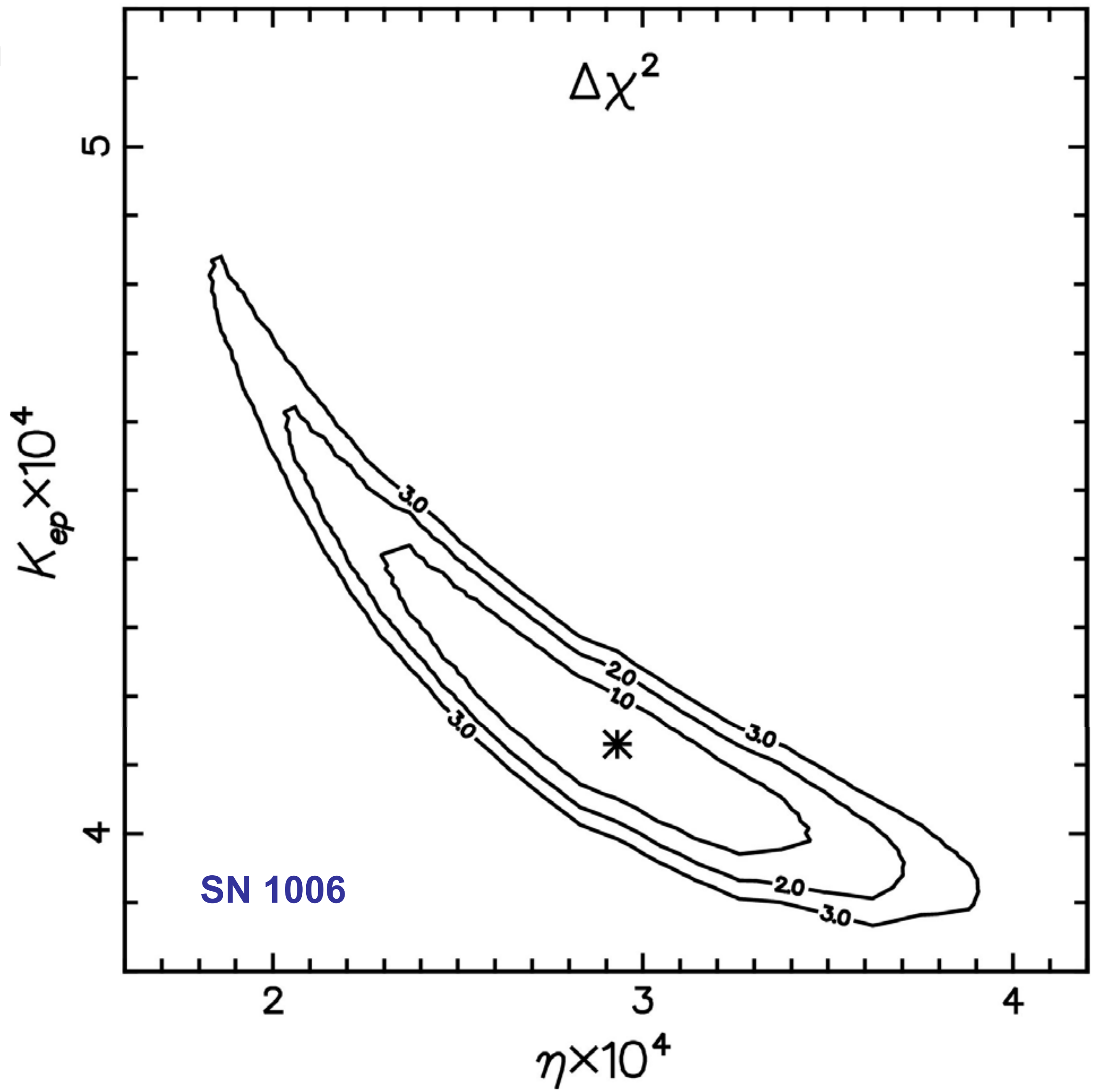


(Agrees with value $B_d \approx 150$ μG from filament thickness)

Berezhko, Ksenofontov & HJV (2009)

X^2 - minimization

of fit of radio and X-ray spectrum for $\varepsilon_\gamma < 2$ keV, for different values of η and K_{ep}



Result:

For B_0 = 30 μG one obtains

X^2 / dof = 1.3

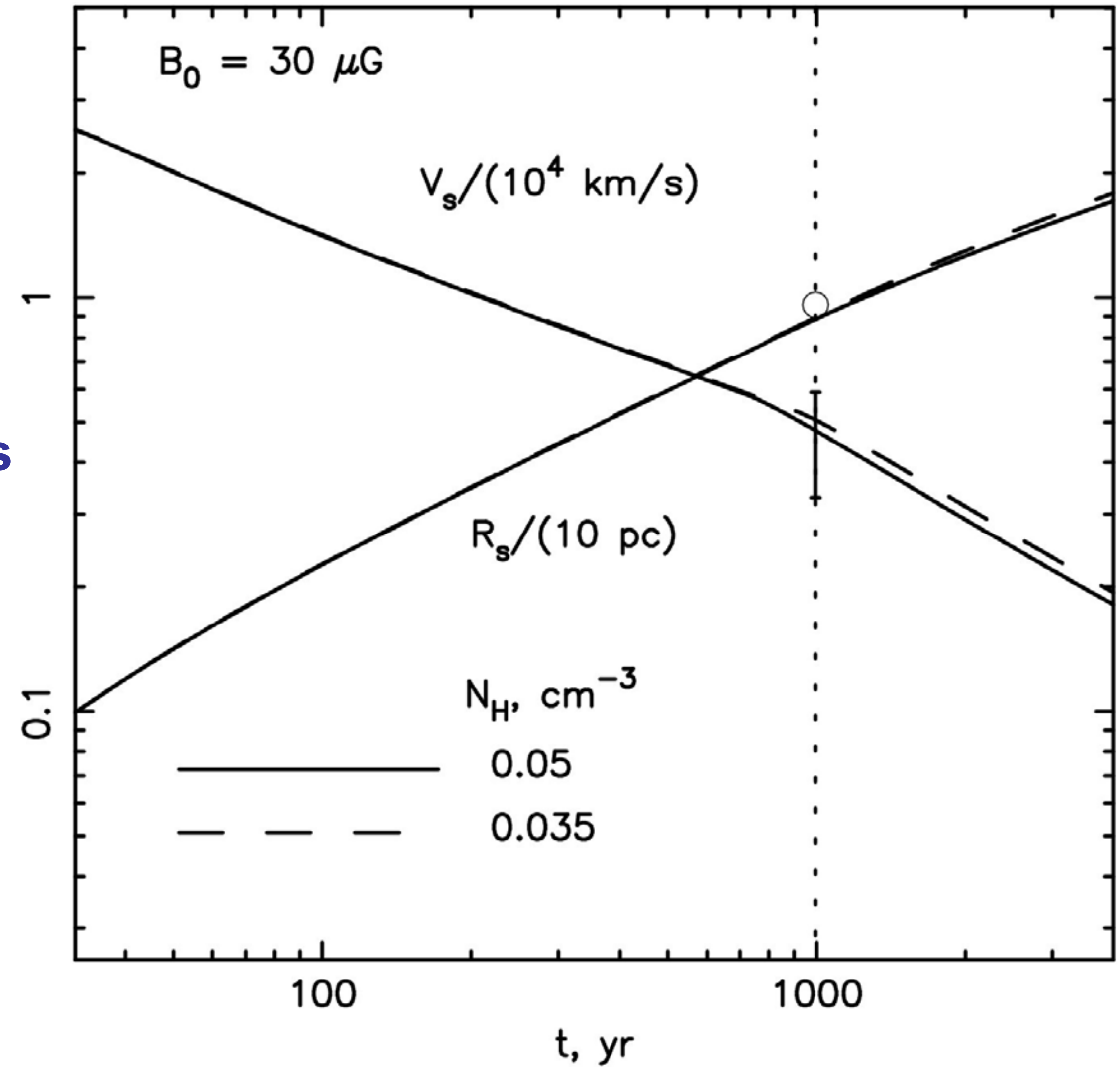
An increase $\Delta X^2 \approx 1$ of X^2 implies change of field strength by **10%**

Gas dynamical evolution (for two values of explosion energy E_{sn} and therefore hydrogen number density N_H):

(i) $E_{sn} = 1.8 \times 10^{51}$ erg
$N_H = 0.05\ cm^{-3}$

(ii) $E_{sn} = 1.5 \times 10^{51}$ erg
$N_H = 0.035\ cm^{-3}$

$E_{sn} \lesssim 1.6 \times 10^{51}$ erg from SN explosion theory limits gas density from above



Fitted at $t = t_{sn}$ to observed values of R_s and V_s

Expected Gamma-ray spectrum

H.E.S.S. **flux** **requires very low gas density**

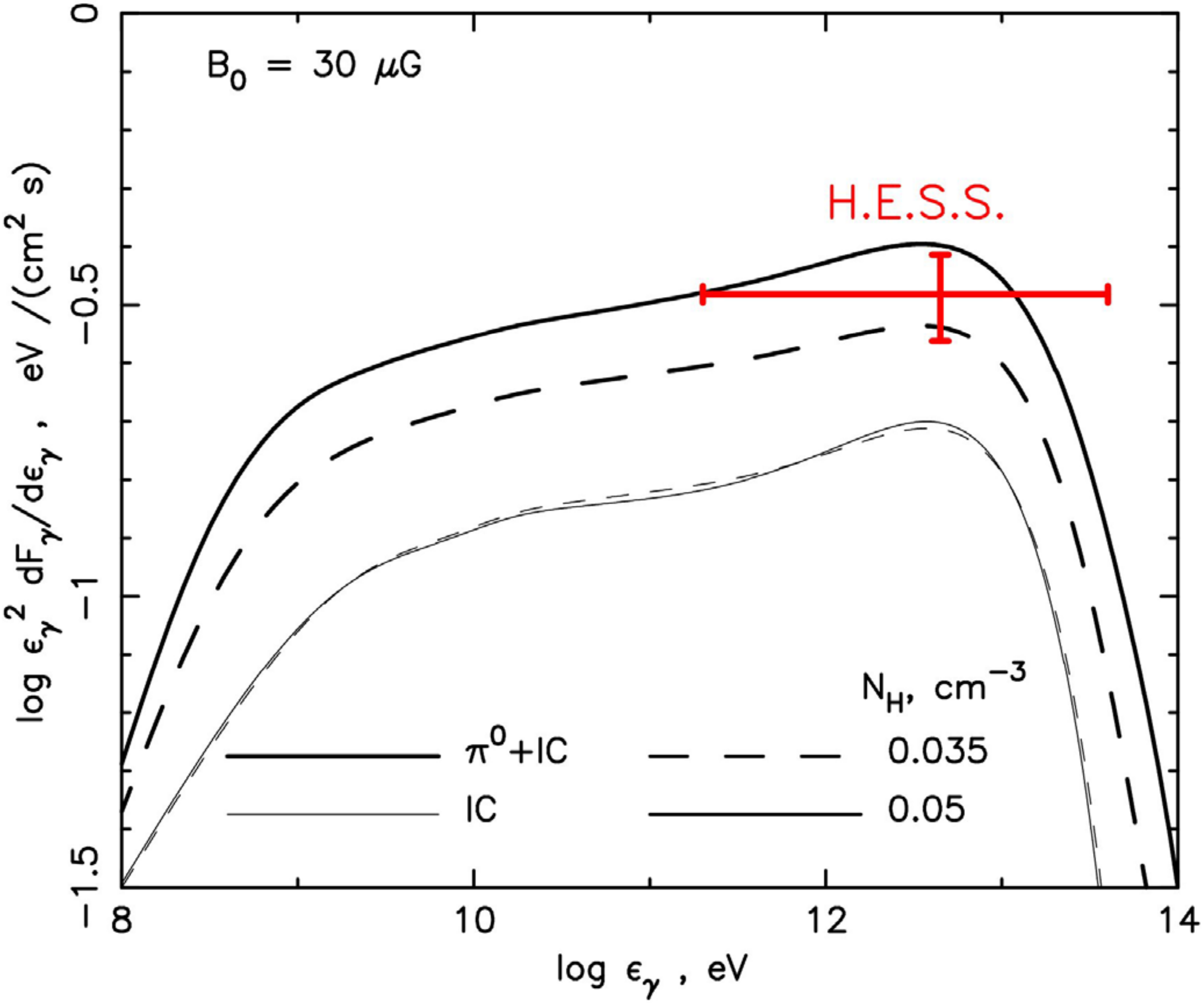
Hadronic and IC flux about equal

„Pile-up" of IC spectrum due to synchrotron losses ?
(e.g. Drury et al. 1999)

Energy density dominated entirely by nuclear component, nonlinear modification

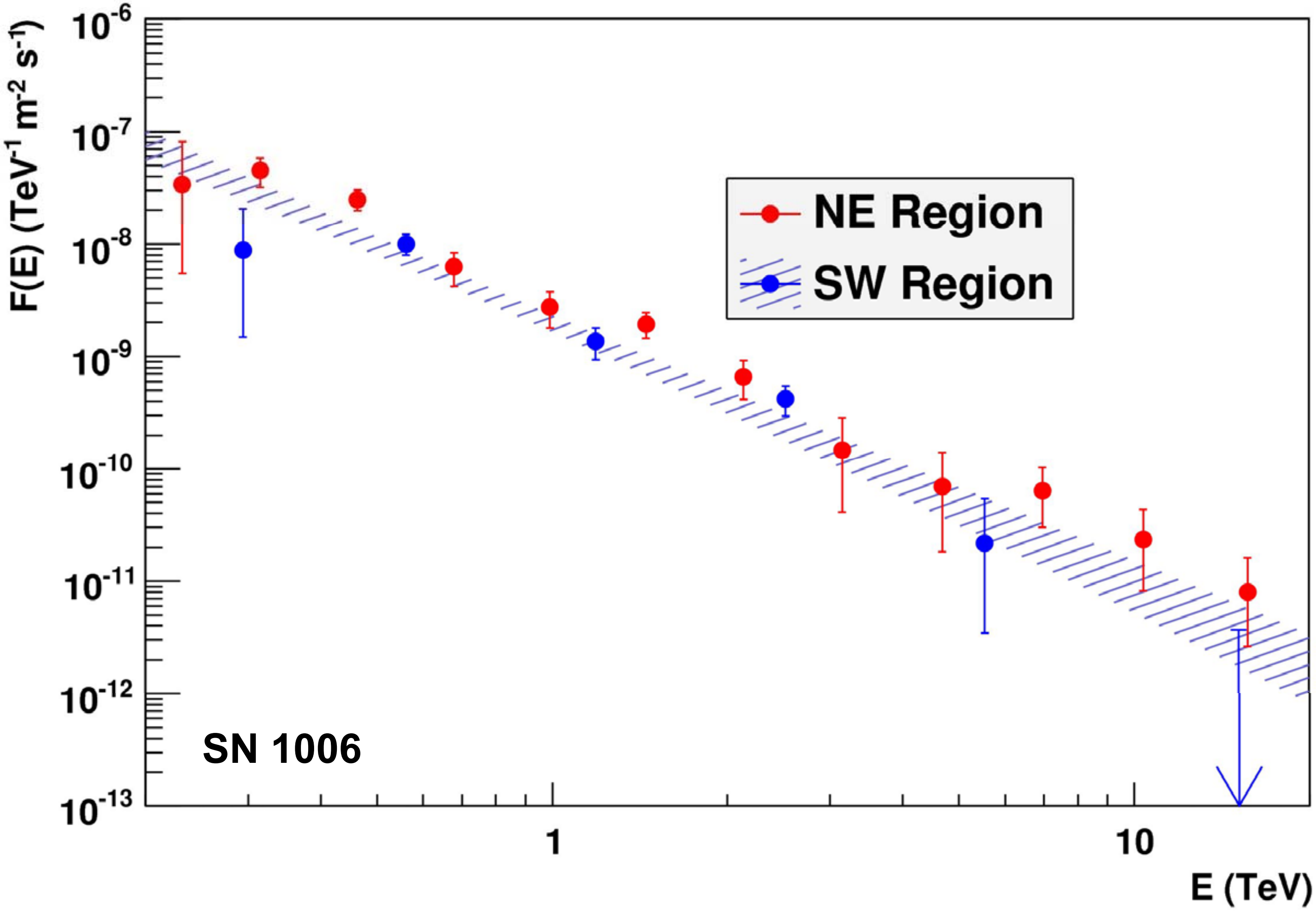
Problem: **rather soft** ***H.E.S.S.*** **spectrum**

Field amplification weaker at early times?
Escape at early times?
$\kappa \approx \kappa_{Bohm}$ ➡ **upper limit**



Need to be investigated

H.E.S.S. differential photon spectrum:



Compatible with power law of coefficient $\Gamma = 2.36 \pm 0.1_{stat} \pm 0.2_{syst}$ in NE

Conclusions:

Except for form of VHE gamma-ray spectrum excellent agreement with observations in SN 1006. In other cases, like RX J1713.7-3946, also spectral form consistent

Nonthermal energy density entirely dominated by nuclear particles. Gamma-ray flux can be mixed leptonic/hadronic in case of very low gas density, even for strong field amplification

Azimuthal X-ray / gamma-ray correlations in SN 1006 naturally explained by ion injection and magnetic field amplification only in quasi-paralell shock regions.

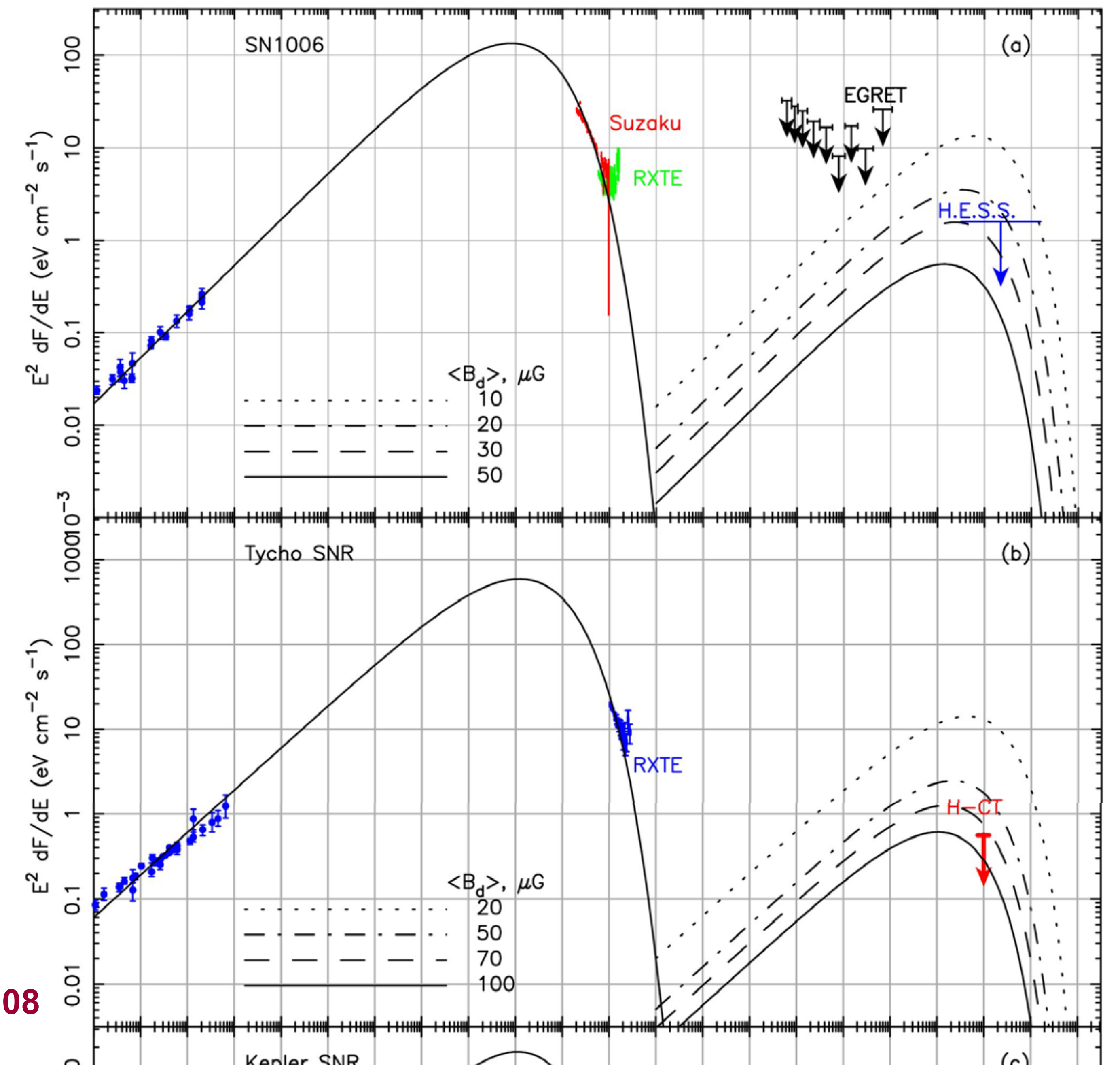
Theses and questions:

Time-dependent theory indispensible for explosion-type phenomena. Steady state models realistic ? Are they physical ?

B-field amplification and wave-particle interactions best described in a consistent semi-empirical theory, to be checked by future fully 3-dimensional particle-in-cell simulations (strong kinetic/MHD turbulence, local shock formation and dissipation).

END

Simple IC models for type Ia Supernovae



HJV et al. 2008