TeV γ-ray and Lower-Energy Observations of Particle Acceleration in Supernova Remnants

Yves Gallant

(LPTA, CNRS / U. Montpellier II, France)

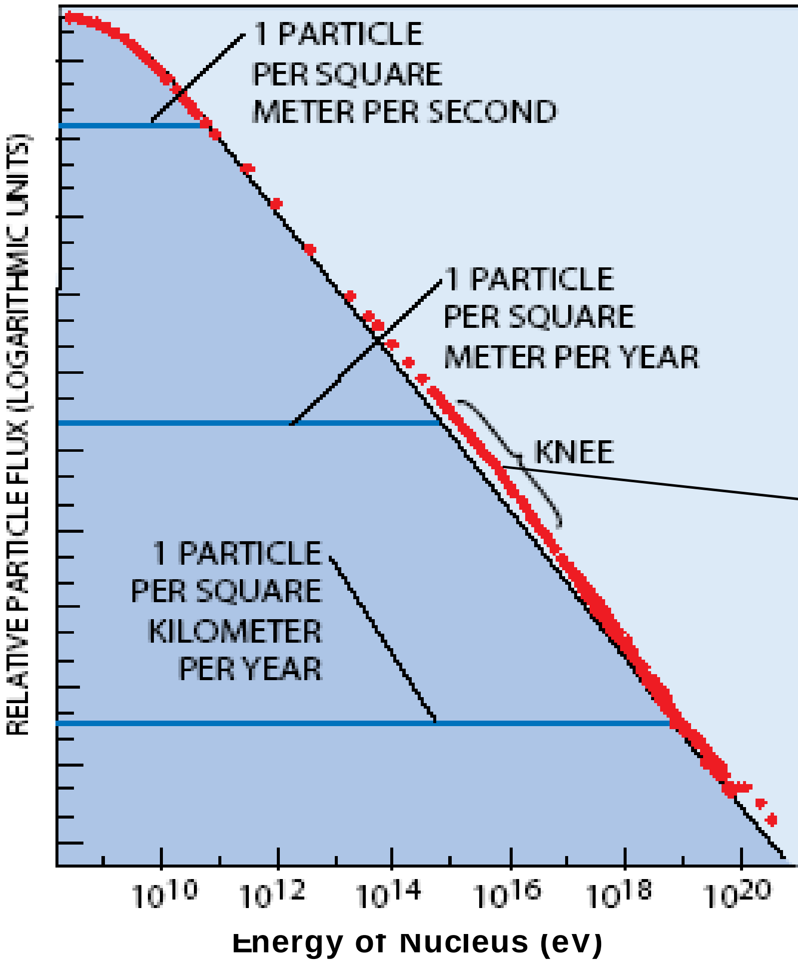
(with contributions from A. Marcowith, M. Lemoine-Goumard...)

"Kinetic Modeling of Astrophysical Plasmas",

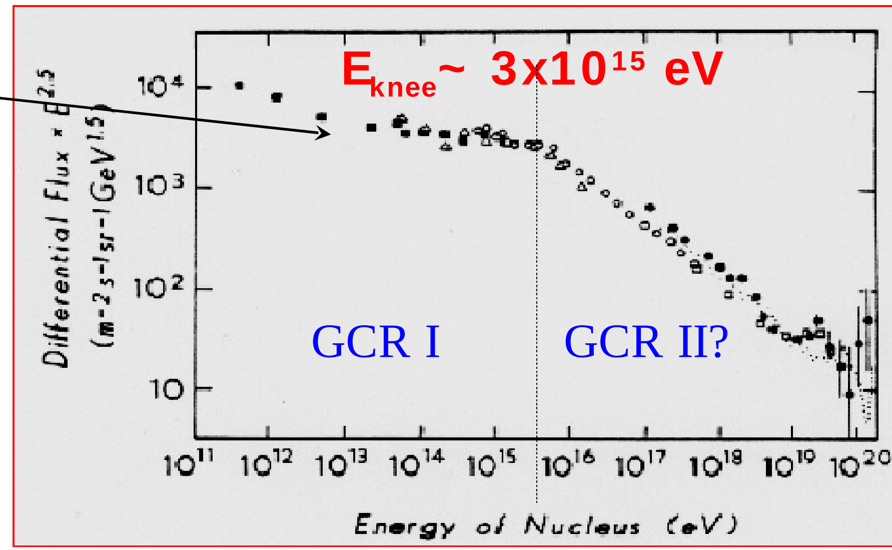
Krakow, October 8, 2008

- Introduction and motivation
  - SNRs and the origin of Galactic cosmic rays
  - Basics of VHE γ-ray astronomy
- Supernova Remnants in VHE γ-rays
  - VHE shells : RX J1713.7-3943, ...
  - Young (historical) SNRs : Cas A, ..., SN 1006
  - Interacting Molecular Clouds: W28, ...
- Other relevant observations of SNRs
  - Non-thermal X-ray rims
  - Modified hydrodynamics
- Discussion and summary

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)**

VHE γ-rays from (shell-type) supernova remnants and the origin of Galactic cosmic rays

- Supernova remnant are widely considered likely sources of Galactic cosmic rays up to the “knee”, $E \sim 3\times10^{15}$ eV :
  - Well-studied shock acceleration mechanism;
  - GCR composition compatible with an SNR origin;
  - Energetics require ~ 10% of total SN energy of 10^{51} erg
- Observational evidence for accelerated e^- (synchrotron)
- For accelerated protons (and ions), hadronic interactions with ambient matter produce π^0, decaying into two γ-rays which can be observed.
- One of aims of VHE γ-ray astronomy (e.g. Drury et al. 1994)

“TeV” or Very High Energy (VHE, 100 GeV < E_γ < 100 TeV) Gamma-Ray Astronomical Detectors

- “GeV” γ-rays detected in space experiments (*EGRET*, *Fermi*)
- at high E, limited by calorimeter depth and collecting area

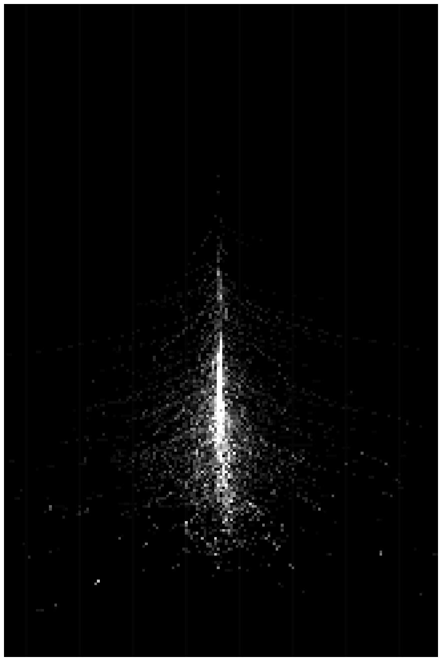
⇒ for higher energies, use Earth's atmosphere as detector

- *imaging atmospheric Cherenkov telescope* (IACT) experiments
- highest-energy photons yet observed (~100 TeV)

Current generation of VHE γ-ray experiments

- large mirrors, fine pixels, stereo technique ⇒ high sensitivity
- *MAGIC* (Canary Isl.); *VERITAS* (U.S.); *CANGAROO-III* (Australia)
- *H.E.S.S.* (Namibia) : 4 mirrors of 12 m diameter, fast cameras (~ns), observing in stereo on dark, moonless nights

Imaging Telescopes

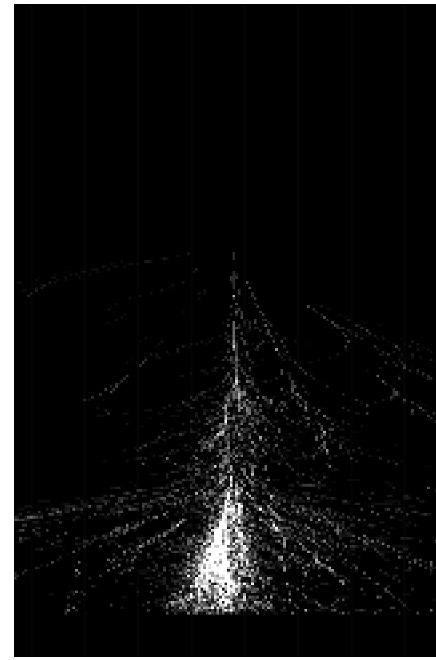


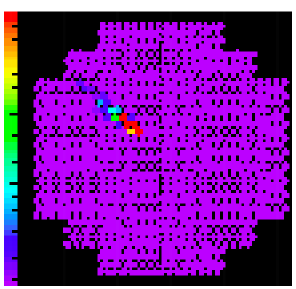
Gamma-ray showers develop quite smoothly in the atmosphere.

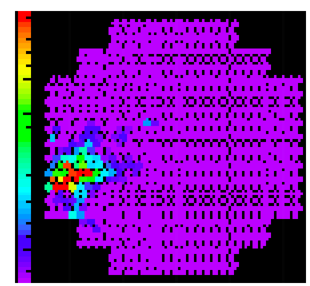
Their camera images are lean and compact

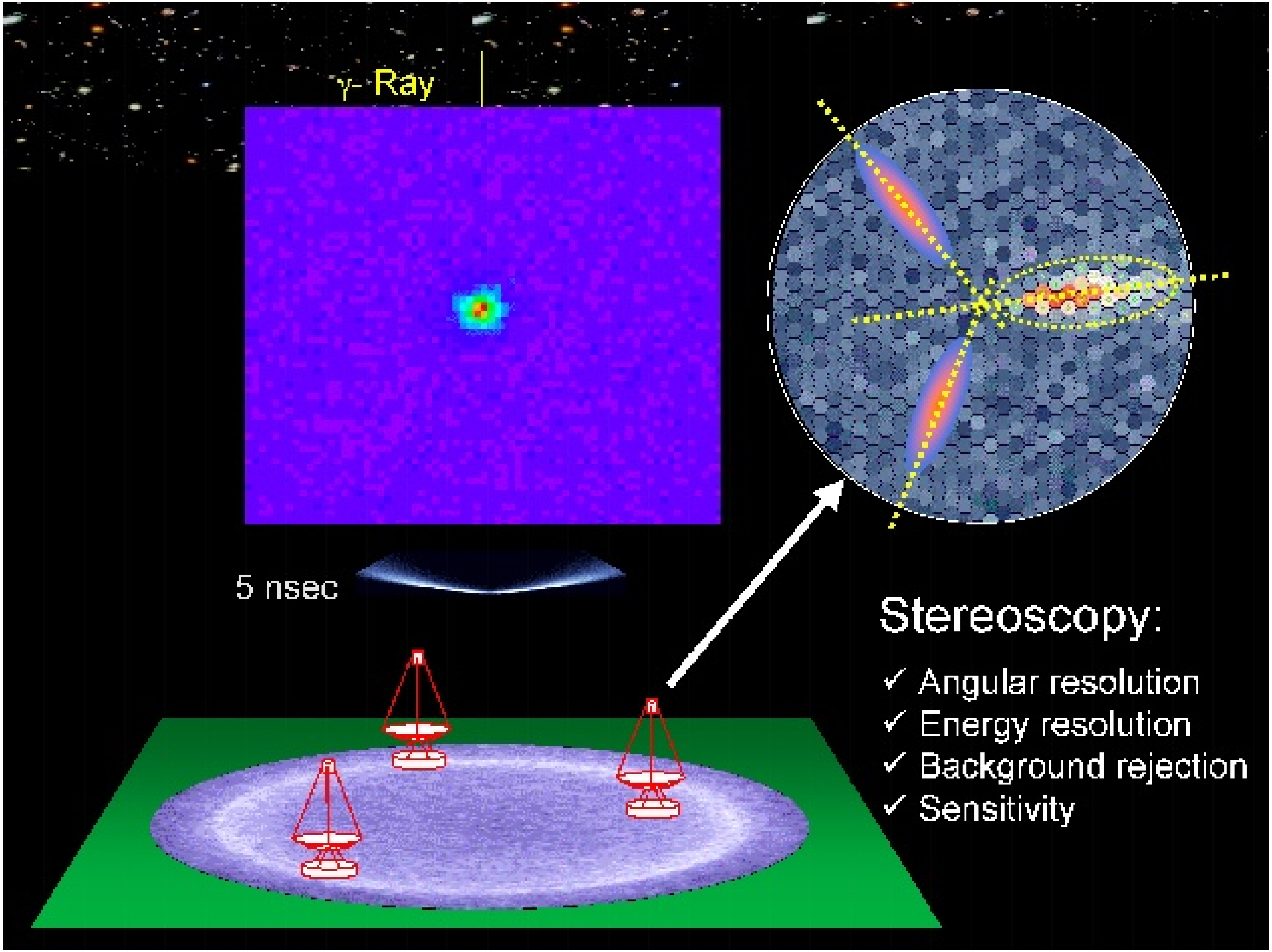
Showers from charged cosmic rays develop in an irregular way.

Their camera images are broader and less compact.





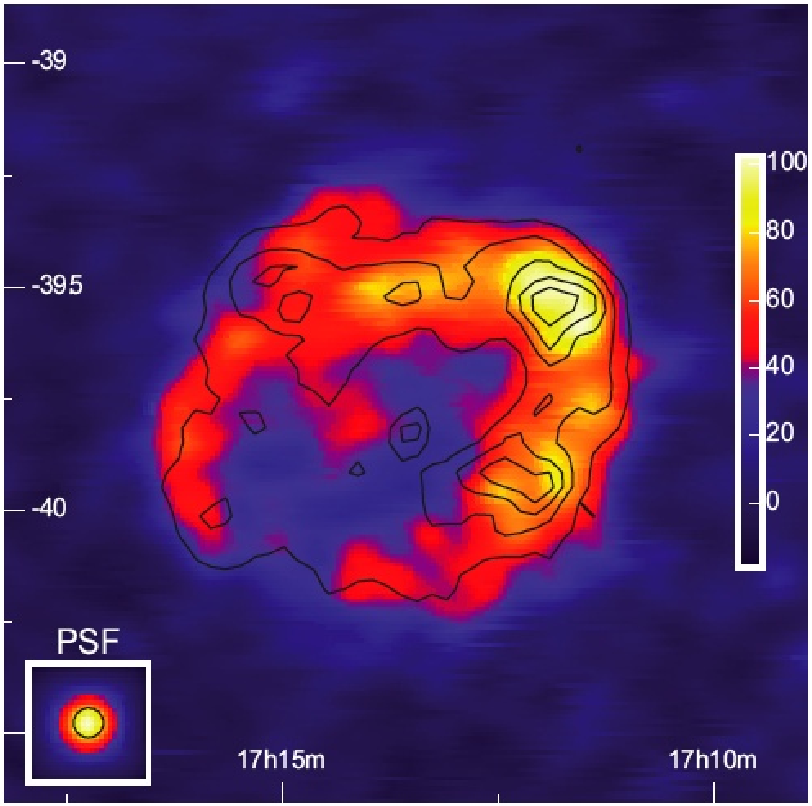




γ- Ray
5 nsec
Stereoscopy:
✓ Angular resolution
✓ Energy resolution
✓ Background rejection
✓ Sensitivity

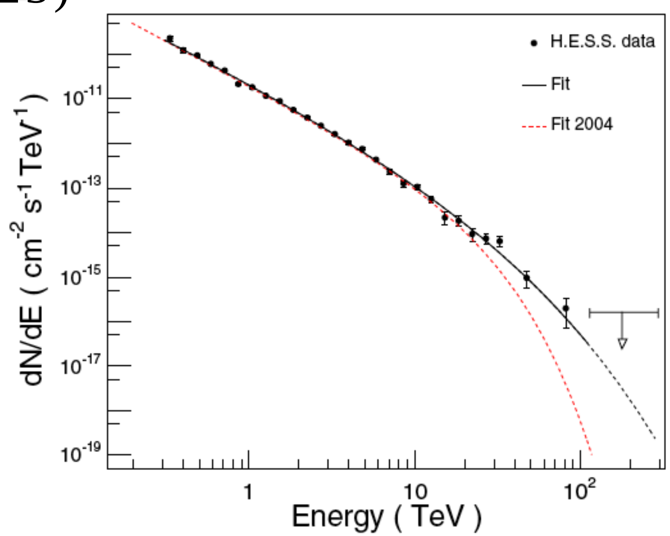
SNRs with shell morphology in VHE γ-rays

RX J1713.7-3947 (or **G347.3-0.5**)



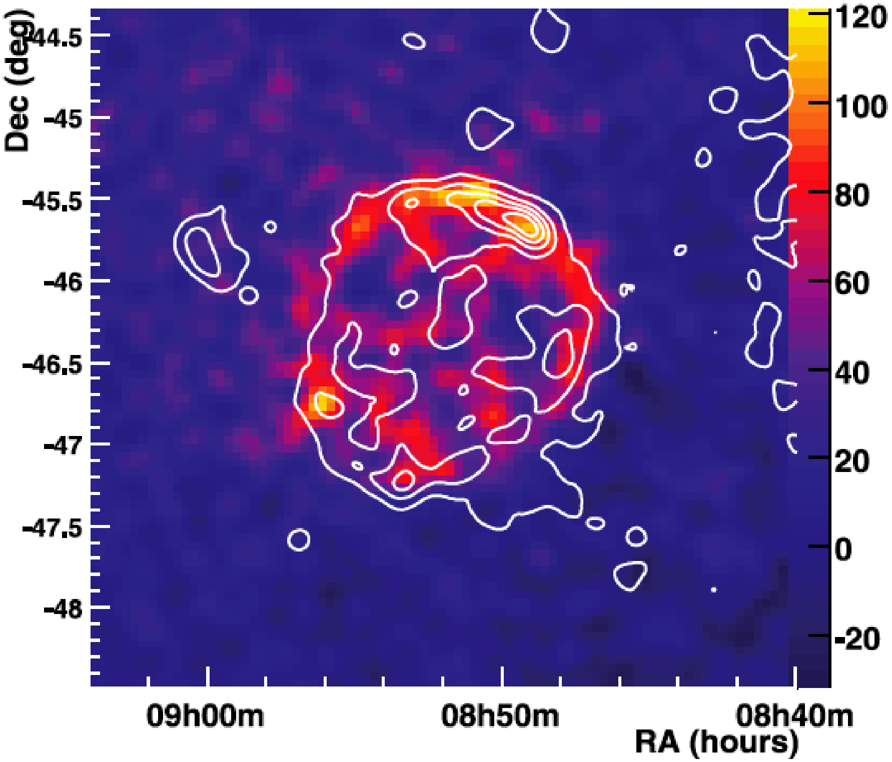
- VHE γ-ray emission discovered by *CANGAROO* (Muraishi et al. 2000)
- first resolved SNR shell in VHE γ-rays (*H.E.S.S.* 2004, *Nature* **432**, 75)
- very good spatial correlation with (non-thermal) X-rays (ASCA 1-3 keV) (*H.E.S.S.* 2006, *A&A* **449**, 223)
- large zenith angle observations ⇒ spectrum 0.3–100 TeV (*H.E.S.S.* 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 ⇒ $B \sim 9\ \mu$G

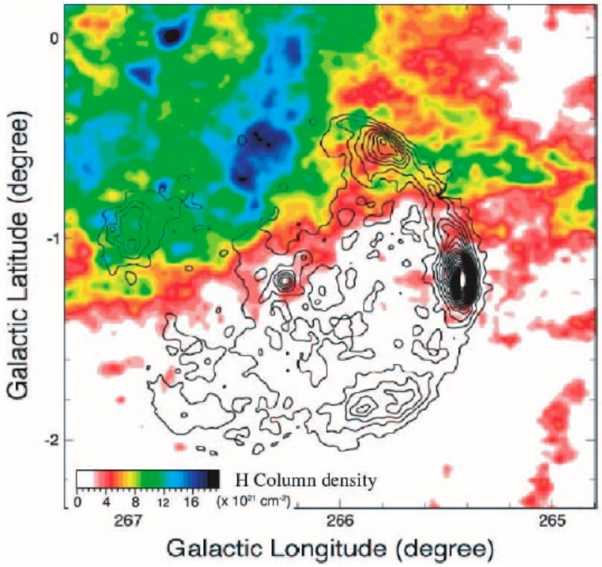


VHE γ-ray shells

RX J0852.0-4622 (or **G266.2-1.2, “Vela Junior”**)



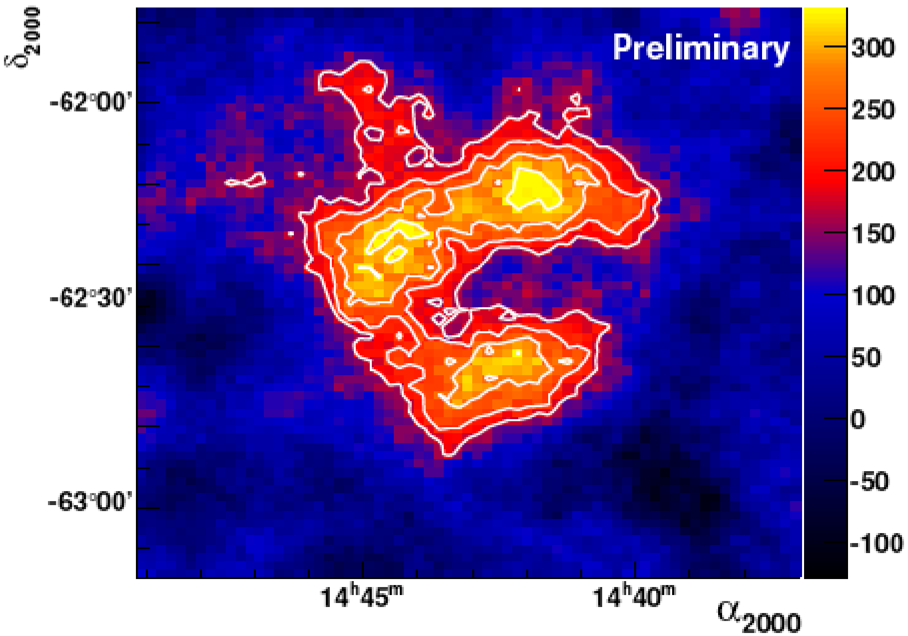
- Detection of a thin, 2° diameter shell (*H.E.S.S.* 2005, *A&A* **437**, L7)
- *CANGAROO-II* detected NW rim (Katagiri et al. 2005), -*III* confirmed the shell (Enomoto et al. 2006)
- High spatial correlation with X-rays (ROSAT, ASCA); no clear correlation with CO (*H.E.S.S.* 2007, *ApJ* **661**, 236)



- power law $\Gamma=2.24\pm0.04_{stat}\pm0.15_{sys}$ (indication of steepening at high energies)
- $L_{1-10\ TeV} \sim 6\times10^{33}$ erg/s at “far” $D \approx 1$ kpc
- leptonic emission scenario $\Rightarrow B \sim 7\ \mu$G

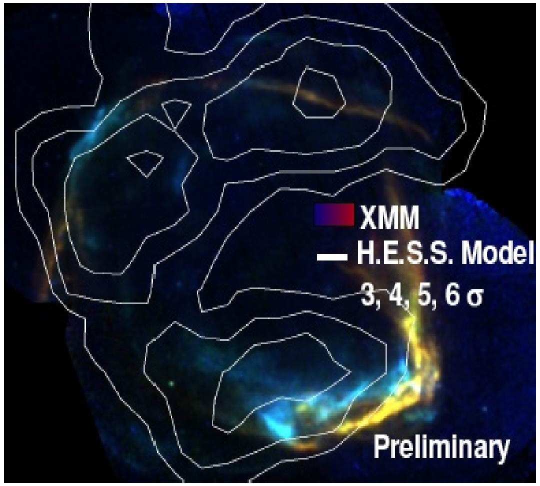
Latest VHE γ-ray shell? **RCW 86**

Hoppe & Lemoine-Goumard (for *H.E.S.S.*), 30th ICRC, July 2007



- ~ 4σ excess earlier reported by *CANGAROO* (Watanabe et al. 2003)
- ~ 9σ in ~ 30h : clear detection
- hint of shell morphology (more data needed), like synchrotron X-ray and radio shell
- no hint of strong enhancement at SW dense interaction region

- fairly steep power law, Γ=2.5±0.1$_{stat}$
- $L_{1\text{-}10\ \mathrm{TeV}}$ ~ 4×10^{33} erg/s assuming $D\approx2.5$ kpc
- leptonic emission scenario $\Rightarrow B \sim 22\ \mu$G (compatible with X-ray rims, Vink et al. 2007)
- hadronic scenario : extrapolated proton spectrum too high, need $\Gamma\approx2$ and cutoff (also compatible with spectral data)



VHE γ-ray shells : general properties

- dominantly non-thermal X-ray emission
- weak radio synchrotron emission
- similar VHE luminosities, $L_{1\text{-}10\ \mathrm{TeV}} \sim$ several$\times 10^{33}$ erg/s

Leptonic emission scenario

- disfavoured by spectrum; implies fairly low $B \sim 10\ \mu$G, in apparent contradiction with turbulent B-field amplification

Hadronic emission scenario

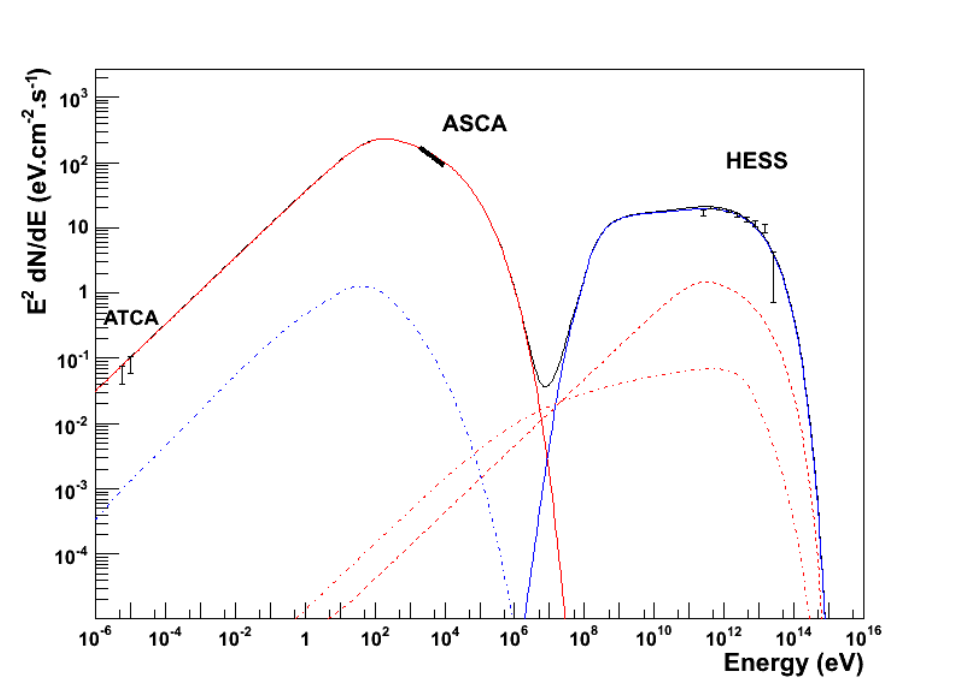
- no obvious explanation for high correlation with X-rays, and poor correlation with surrounding medium density

- Steep spectrum or cutoff at $E_\gamma \sim 10$ TeV $\Rightarrow$ $E_p \sim 10^{14}$ eV
  $\Rightarrow$ spectrum steepens well short of "knee" at $E_p \sim 3\times 10^{15}$ eV
  (also the case for Cas A)

Spectral modeling of G347.3-0.5

Primary population: protons ?

- Spectral shape at injection : power-law w/ exponentional cut-off
  E_{cut} = 120 TeV and index = 2.0
- Energy injected = 10^{50} ergs
- Electron/proton ratio = 5 x 10^{-4}
- Magnetic field = 35 µG & Density = 1.5 cm^{-3}

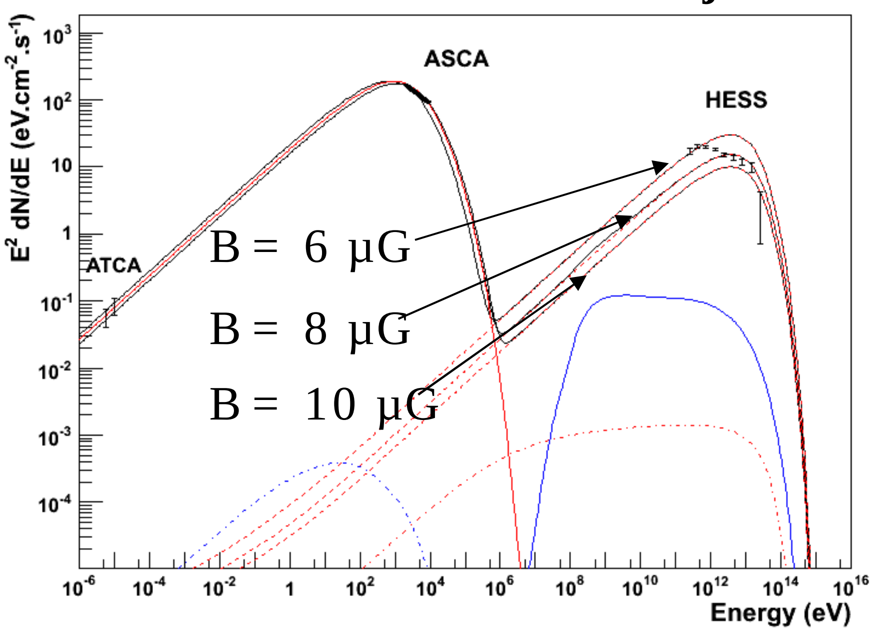


Primary population: electrons ?

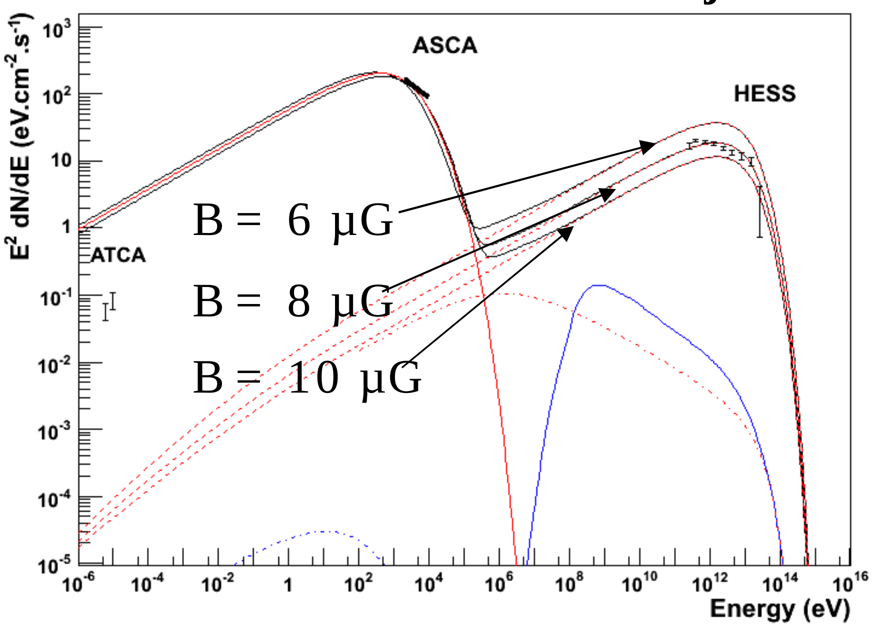
- Need about 8 μG B field to match flux ratios
- Simplest electronic models don't work well

- Simple one-zone model
- Electrons & protons injected with the same spectral shape
- Energy losses + escape of particles out of the shell taken into account

Power-law index = 2.2 at injection

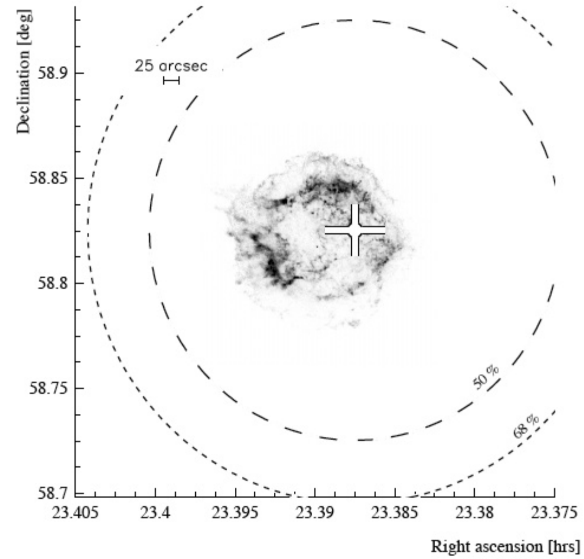


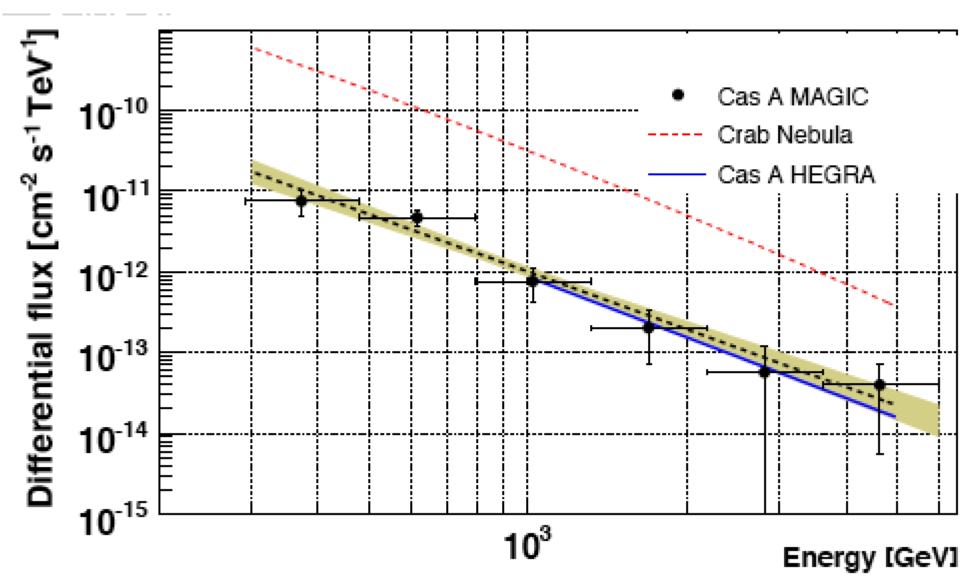
Power-law index = 2.4 at injection



The youngest Galactic SNR : Cassiopeia A

- age~ 330 yr (no clear SN observation)
- VHE emission discovered by *HEGRA* (Aharonian et al. 2001, *A&A* **370**, 112)
- 232 hours (!), significance 5 σ
- unresolved, centroid in Cas A
- Confirmed by *MAGIC* : 5.2 σ in 47 h (Albert et al. 2007, *A&A* **474**, 937)





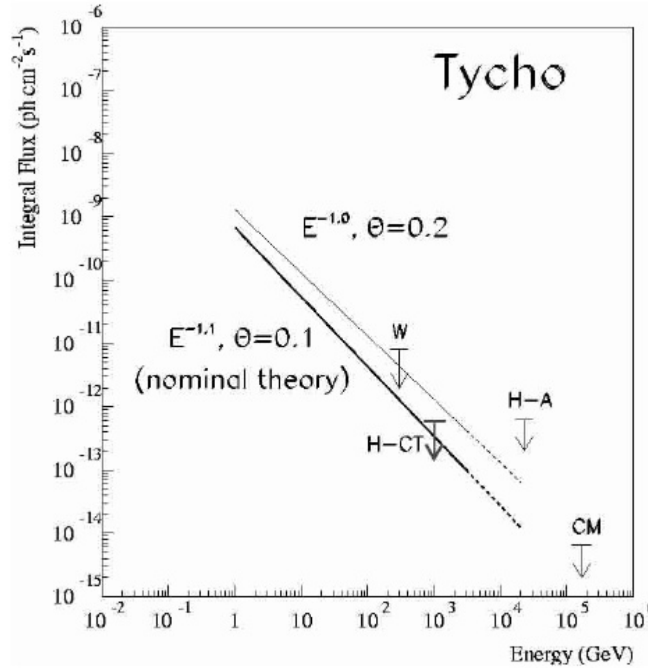
- spectra compatible
- steep spectrum : $\Gamma = 2.4 \pm 0.2$
- $L_{1\text{-}10\ \mathrm{TeV}} \sim 3 \times 10^{33}$ erg/s ($D \approx 3.4$ kpc)
- sharp synchrotron X-ray rims, etc. $\Rightarrow$ high $B \sim$ mG
- hadronic emission favoured

Other young (historical) shell-type SNRs

Tycho (SN 1572)

- deepest upper limit: *HEGRA* 2001 (*A&A* **373**, 292) with 65 hours
- $L_{1\text{-}10\ \mathrm{TeV}} < 10^{33}$ erg/s

  (assuming $D \approx 2.3$ kpc and $\Gamma = 2$)
- synchrotron X-rays $\Rightarrow B > 22\ \mu$G



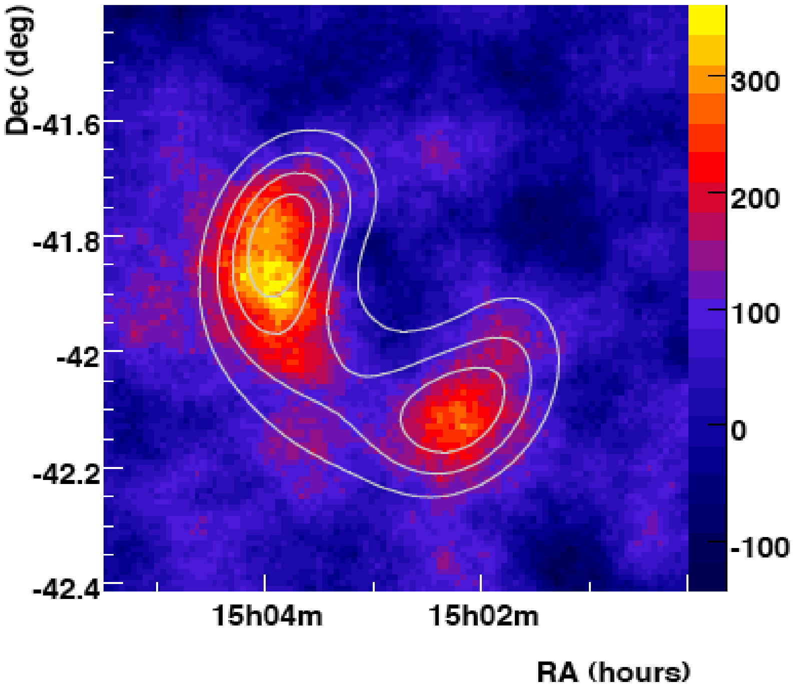
Kepler (SN 1604)

- recent H.E.S.S. upper limit (*H.E.S.S.* 2008, *A&A* **488**, 219)
- $L_{1\text{-}10\ \mathrm{TeV}} < 10^{33}$ erg/s (assuming $D \approx 4.8$ kpc and $\Gamma = 2$)

  (distance uncertain by ± 1.5 kpc $\Rightarrow$ factor ~ 2 in $L_{1\text{-}10\ \mathrm{TeV}}$)

Other historical shell-type SNR : **SN 1006**

- ~30' diameter shell
- *CANGAROO-I* claimed bright NE hotspot (Tanimori et al. 1998), not confirmed by *H.E.S.S.* (2005, *A&A* **437**, 135) nor *CANGAROO-III*



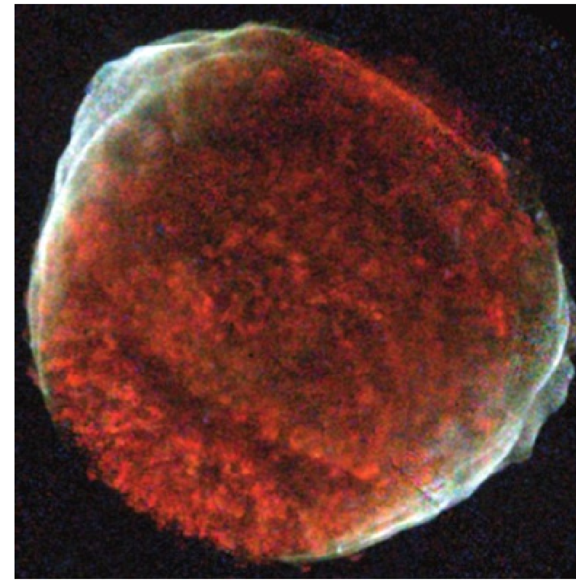
- after 103 h, *H.E.S.S.* detection!
  (Naumann-Godo et al., Gamma 2008)
- flux ⇒ $L_{1\text{-}10\ \mathrm{TeV}} \sim 10^{33}$ erg/s
  (assuming $D \approx 2.2$ kpc)

- Morphology seems to match X-ray synchrotron
  (contours: Chandra map smoothed to match H.E.S.S. PSF)
- Leptonic scenario ⇒ $B \sim 30\ \mu$G (lower than inferred from rims)
- Hadronic scenario : given low ($n \sim 0.05$ cm^{-3}) medium density, requires flat ($p \approx 2$) spectrum for reasonable energetics

- whether protons or electrons, shows distribution of accelerated particles in SN 1006

Bipolar morphology of particle acceleration in SN 1006

- SN 1006 : explosion in nearly uniform, undisturbed medium?
  - Type Ia : no stellar progenitor wind
  - High above the Galactic plane



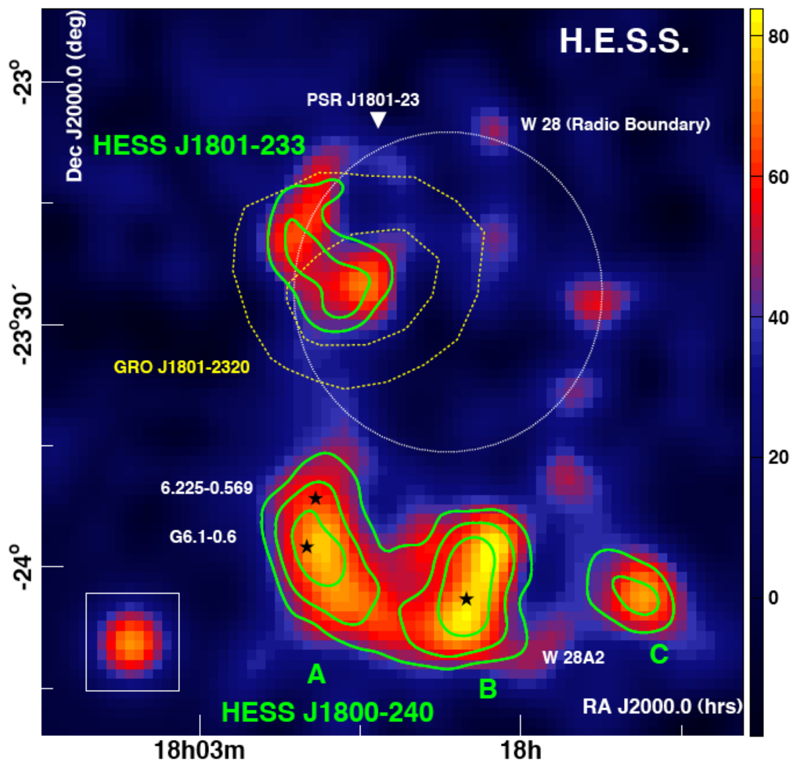
- Rothenflug et al. (2004) : X-ray image compatible with synchrotron "polar caps", not with "equatorial band"
- Suggests that **parallel** shocks, and not **perpendicular**, are where particle acceleration is most efficient

Young SNRs in TeV gamma-rays

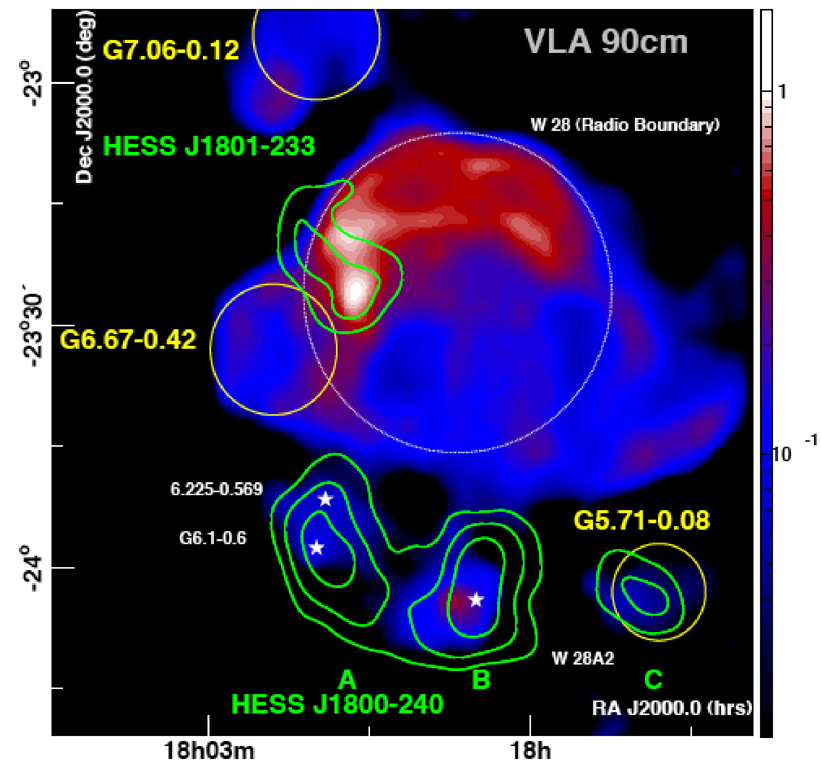
- Other historical shell-type SNRs a factor > 3 less luminous in VHE γ-rays than Cas A
- Lower surrounding medium density(?), or less efficient particle acceleration

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

(*H.E.S.S.* 2008, *A&A* **481**, 401)

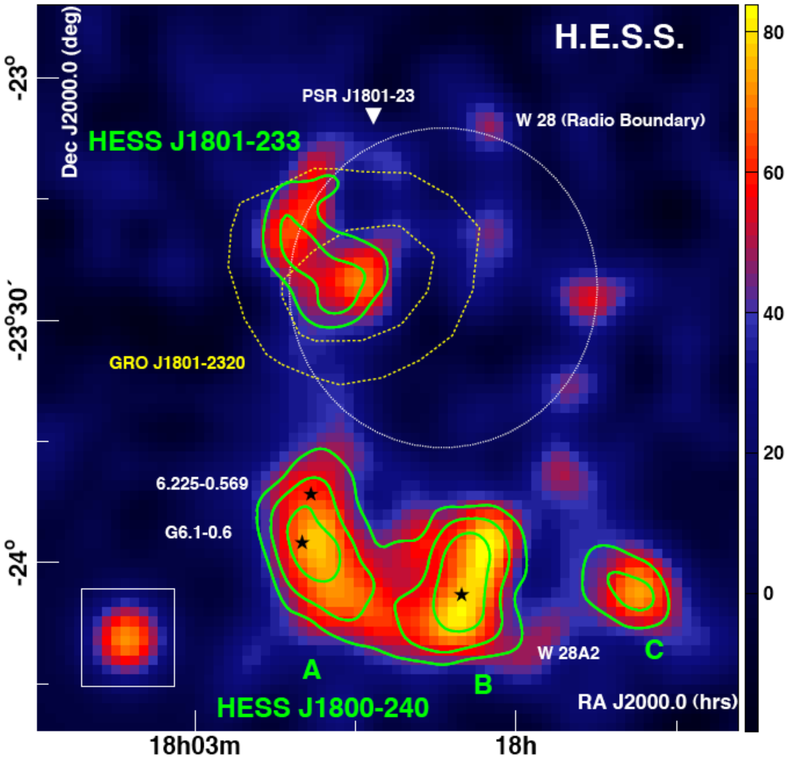


- new source HESS J1801-233 on E rim of SNR W 28, radio hot spot
- coincident with EGRET source

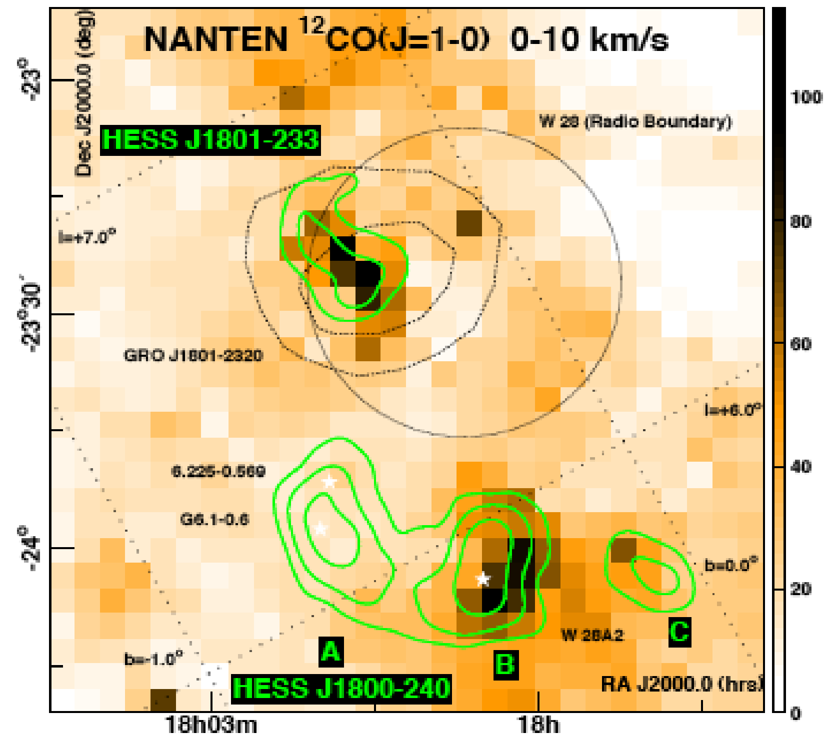


SNR / Molecular Cloud interactions : **W 28**

(*H.E.S.S.* 2008, *A&A* **481**, 401)

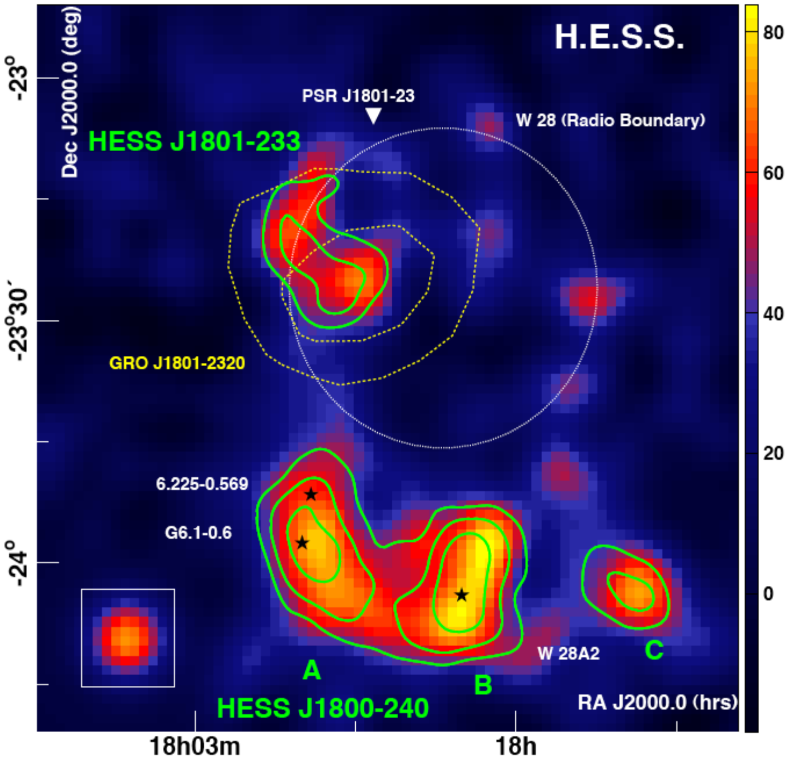


- new source HESS J1801-233 on E rim of SNR W 28, radio hot spot
- coincident with EGRET source
- morphological match to CO cloud
- 1720 MHz OH masers : signature of shock / MC interaction



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

(*H.E.S.S.* 2008, *A&A* **481**, 401)



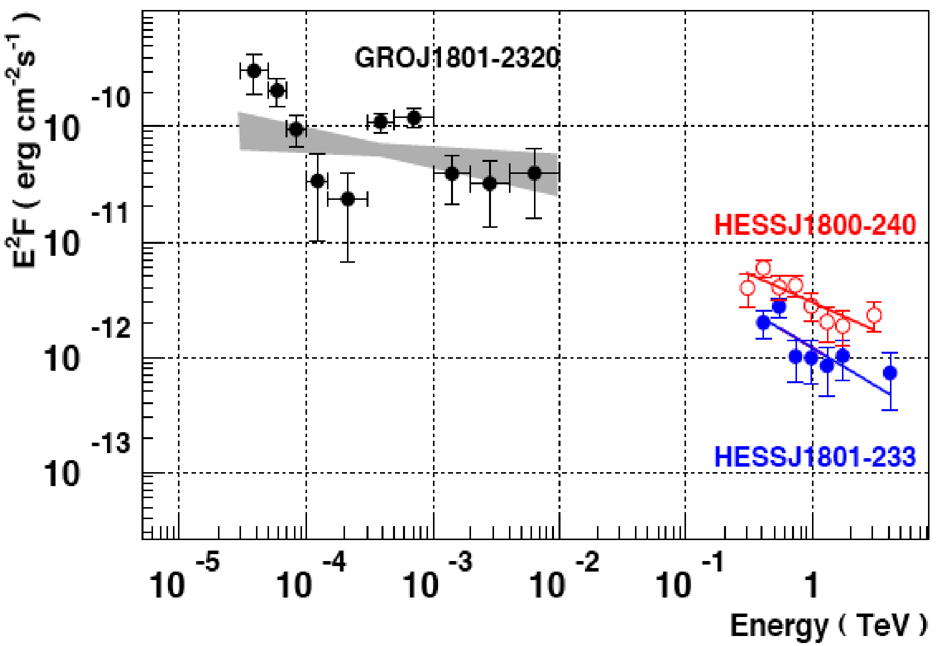
- new source HESS J1801-233 on E rim of SNR W 28, radio hot spot
- coincident with EGRET source
- morphological match to CO cloud
- 1720 MHz OH masers : signature of shock / MC interaction

steep spectrum, $\Gamma = 2.7 \pm 0.3_{stat}$

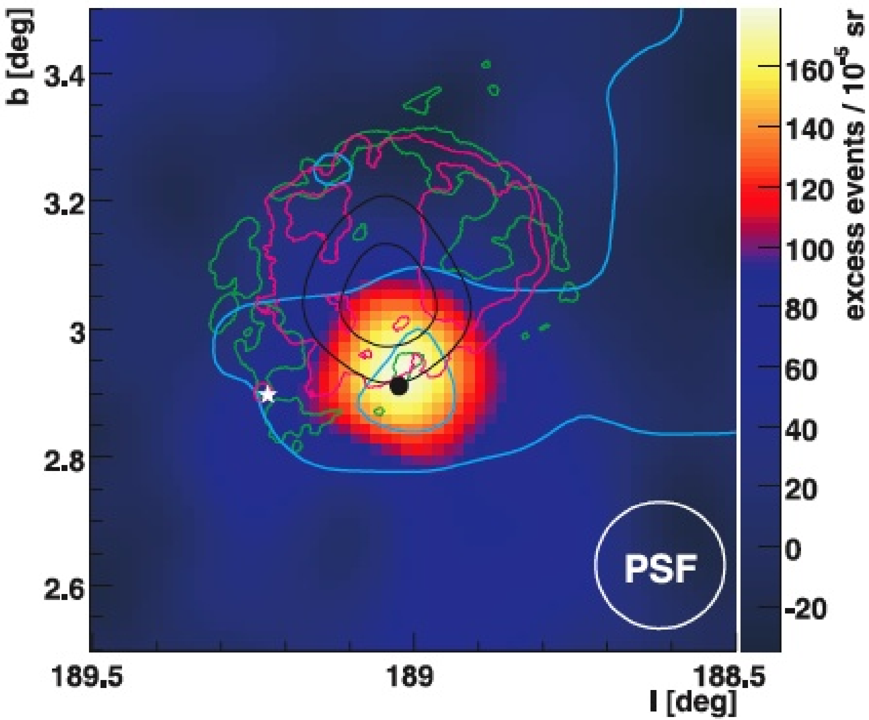
(flattening in EGRET range)

$L_{1\text{-}10\ TeV} \sim 5 \times 10^{32}$ erg/s, assuming

$D \sim 2$ kpc



VHE γ-rays from SNR / MC interactions : **IC 443**



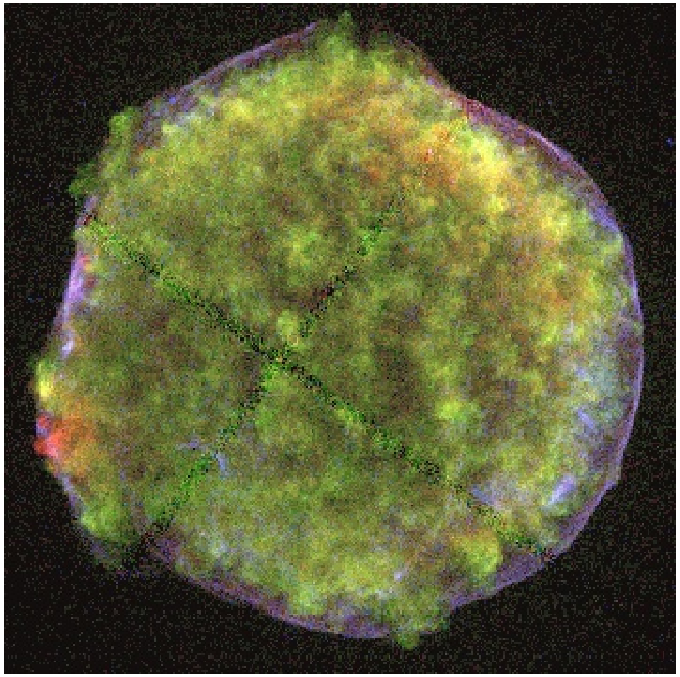
- discovery of an unresolved source in IC 443 (*MAGIC* 2007, *ApJ* **664**, L87)
- not coincident with PWN (white star)
- direct coincidence with peak CO density (blue contours), 1720 MHz OH maser (black dot)
- compatible with 3EG J0617+2238
- very steep spectrum, $\Gamma = 3.1 \pm 0.3_{stat}$
- $L_{1\text{-}10\ \mathrm{TeV}} \sim 2\times10^{32}$ erg/s with $D \approx 1.5$ kpc

General properties

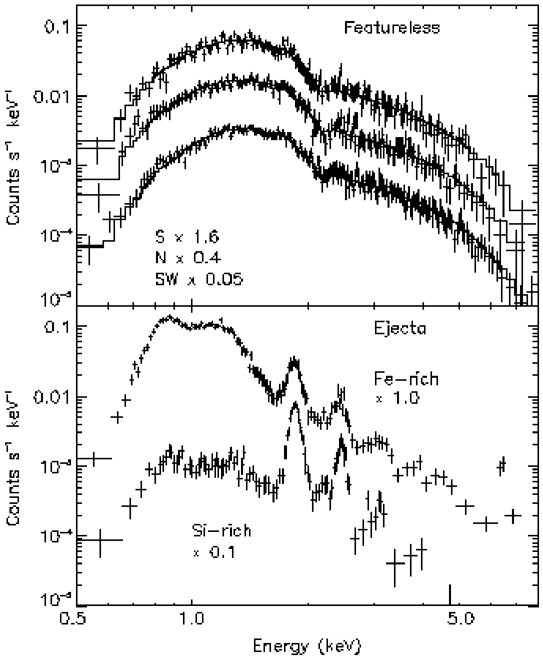
- correlation with high density ⇒ strongly suggests hadronic emission
- steep spectra, flattening in EGRET range, low 1-10 TeV luminosities
- Probe of accelerated proton spectra in SNRs?
- Caveat : passage in MC may alter shock acceleration properties

X-ray evidence for acceleration: the case of Tycho's SNR

(1) Non-thermal spectra (Warren et al. 2005)



X-ray colors: S,Si and Fe line Emission (thermal from ejecta), 4-6 keV continuum



Continuum rim (blast wave) shows featureless power-law spectra (no detectable thermal line emission)

- most young shell SNRs (Cas A, *Kepler*, SN 1006, **G347.3-0.5**, **G266.2-1.2**, RCW 86...) display (dominant) non-thermal spectra
- if synchrotron radiation, $\Rightarrow E_e \sim$ 10-100 TeV (for typical B)

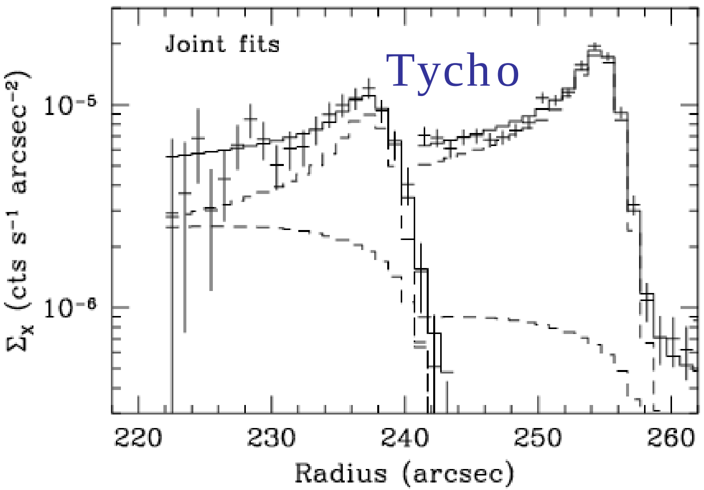
(2) Morphology : Thin non-thermal rims

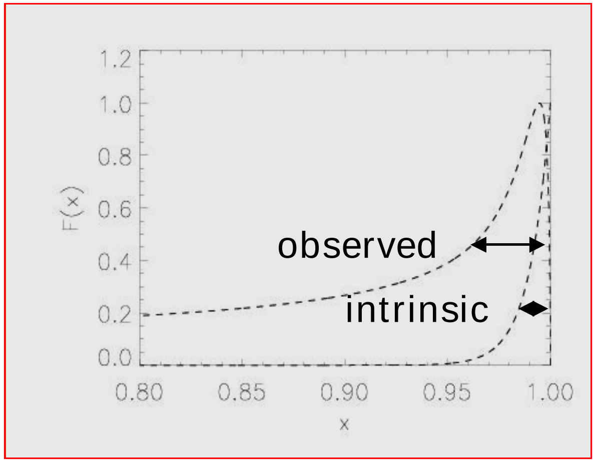
- Thin, non-thermal filaments at SNR edge: not expected morphology for thermal or adiabatic synchrotron emission
  - Most likely due to synchrotron losses of the high-energy emitting electrons (Vink & Laming 2003, Berezhko & Völk 2004…); implies large magnetic fields
  - Magnetic field amplification driven by CRs (Bell & Lucek 2001, Bell 2004) can help accelerate ions towards $E \sim 3 \times 10^{15}$ eV
- Filament geometry: projection effect

Δ For an exponential profile the de-projected width is P/4.6 (Ballet 2005)

Typical filament width = 0.05 - 0.2 pc

- Alternate explanation: sharp rim due to decay of magnetic turbulence (Pohl, Yan & Lazarian 2005); but consistent with radio morphology?





Methodology: Self-consistent magnetic field

- *Isotropic* turbulence + diffusion laws up/downstream
  - Radiatively limited rims:

$$t_{acc}(E_{emax}) = t_{sync}(E_{emax})$$

  - Compare $\Delta R_{obs}/P$ with size of the rim:

$$\Delta R_{rim}(D,B) = f(\Delta R_{adv},\Delta R_{diff})$$ Berezhko & Voelk 2004

$\Rightarrow \Delta R_{rim}$, $E_{emax} \Rightarrow B(\alpha, r, V_{sh}, E_{ph\text{-}cut\text{-}off}, \Delta R_{obs})$

Parizot, Marcowith, Ballet & Gallant 2006

SNR	(r=4)	B(α=1, r=4) μG	B(1,10)	B(1/3,4)
Cas A	3.2	390	280	350
Kepler	4.5	340	250	300
Tycho	10	530	400	400
SN 1006	1	110	95	100
G347.5-0.5	1	96	84	92

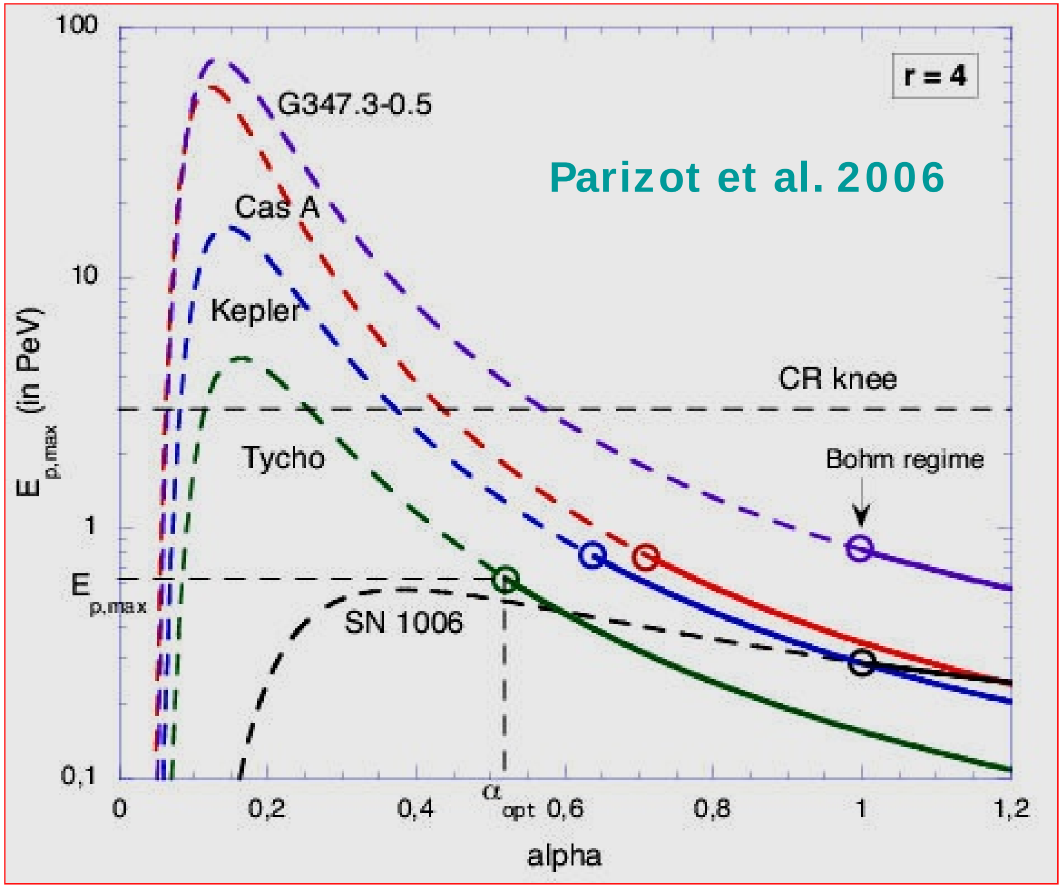
The magnetic field is highly amplified in SNR displaying X-ray filaments

Maximum particle energies and constraints on turbulence

- $B \Rightarrow E_{pmax}(\alpha)$ for protons
  $t_{acc}(E_{pmax}) = t_{SNR}$

- <u>Constraints on α:</u>
  Dashed lines are the rejected values of α: $D(E_{pmax}) < D_{Bohm}$

- $E_{pmax} < E_{knee}$ (3 PeV)
- "Worse" for r = 10

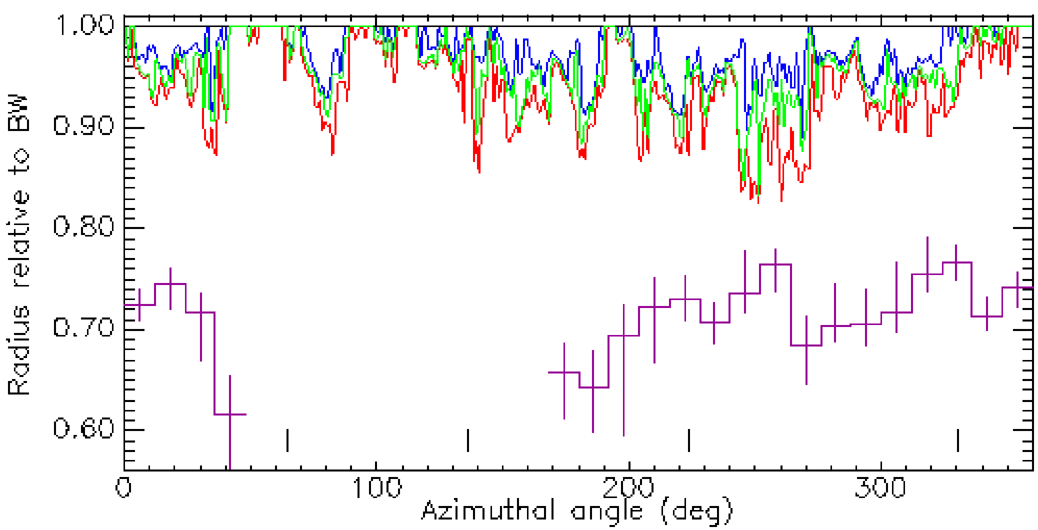


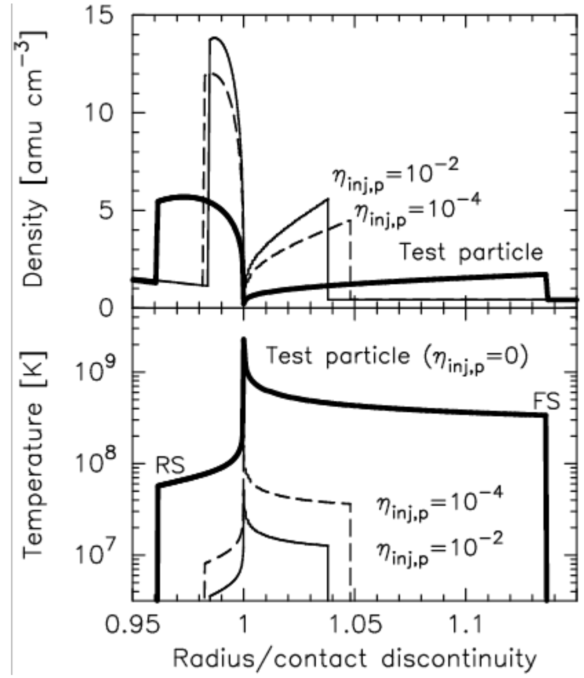
It is difficult to reach/ go beyond the knee
even with B-field amplification

Caveat: Turbulence assumed *isotropic*: $\kappa_{perp} = \kappa_{parallel}$

(3) Indirect evidence for ion acceleration: hydrodynamics

- Warren et al. (2005) measured ratio between blast wave (BW) and contact discontinuity (CD) radii : mean 0.96
  - ejecta / shocked ambient medium CD subject to Rayleigh-Taylor instability => protruding fingers; correcting for this bias, still get ~ 0.93
  - pure gas dynamics: expect 0.86 or less

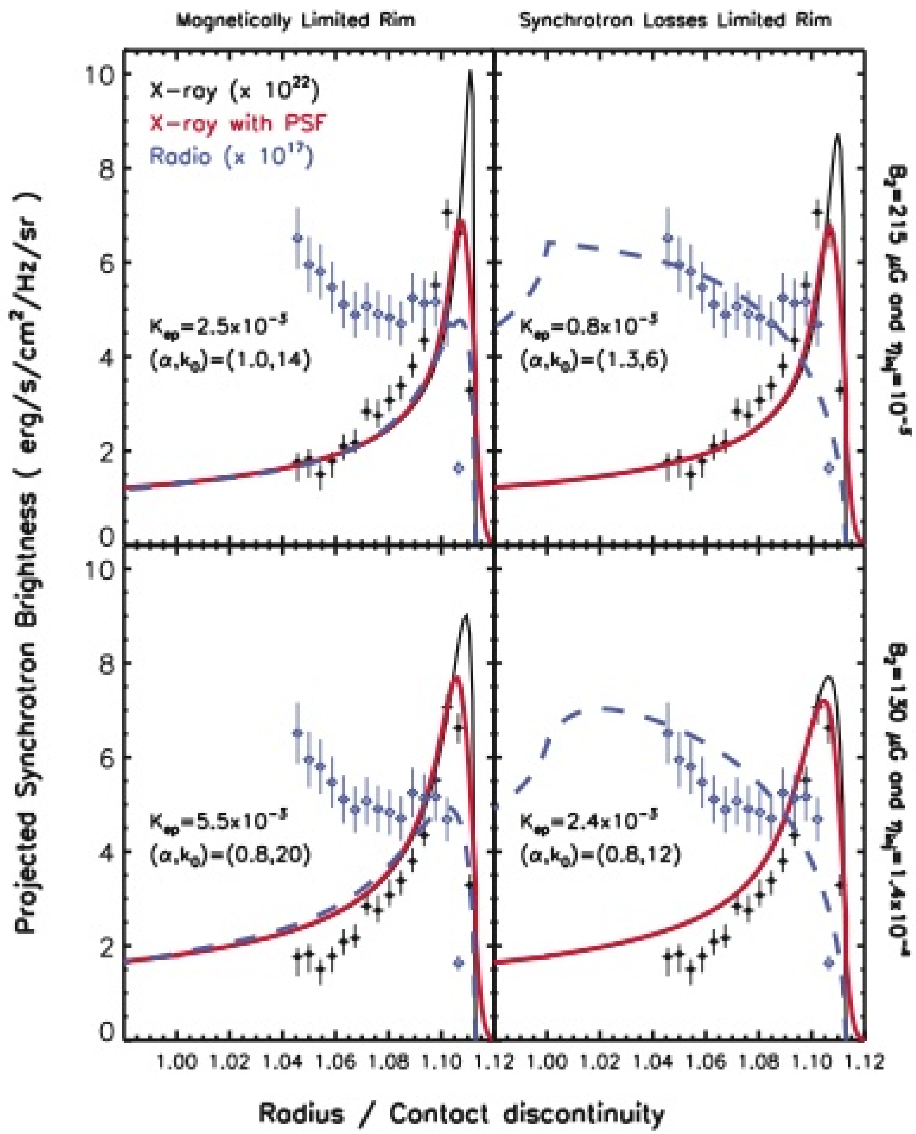




- Decourchelle, Ellison & Ballet (2000) showed this can be explained by significant accelerated ion pressure
  - **Caveat**: turbulent *B*-field pressure not taken into account

More detailed studies in Tycho (Cassam-Chenaï et al. 2007)

- Observe X-ray spectral steepening behind shock (synchrotron losses)
- Lack of thermal emission from rim: $n_0 < 0.6\ \mathrm{cm}^{-3}$
- Use cosmic-ray-modified hydrodynamics to reproduce distance between blast wave and contact discontinuity
- Consider synchrotron-loss vs magnetic damping-limited rims, radio and X-ray profiles
- Magnetic damping scenario fails to explain radio profile



Summary : shell-type SNRs in TeV γ-rays

VHE shells : RX J1713.7, RX J0852.0, RCW 86

- Leptonic scenario disfavoured due to low implied *B*-fields
- Hadronic scenario fails to explain high correlation with X-rays, poor correlation with surrounding medium density
- High-energy cutoff or break ⇒ difficult to reach the "knee"?

Young (historical) SNRs

- **Cas A** confirmed, with somewhat steep spectrum : hadronic scenario favoured; high *B*-field
- **Tycho, Kepler** a factor > 3 less luminous
- **SN 1006** detected : bipolar morphology for acceleration

SNR / MC interactions : W 28, IC 443, CTB 37A...

- Correlation with CO density strongly suggests hadronic
- Relatively steep spectra, low luminosity in 1-10 TeV band
- Passage through MC may alter shock acceleration properties