Recent discoveries from TeV and X-ray non-thermal emission from SNRs

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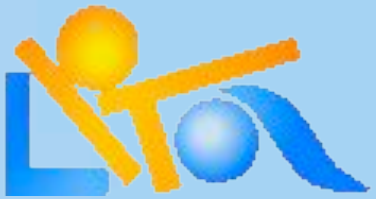


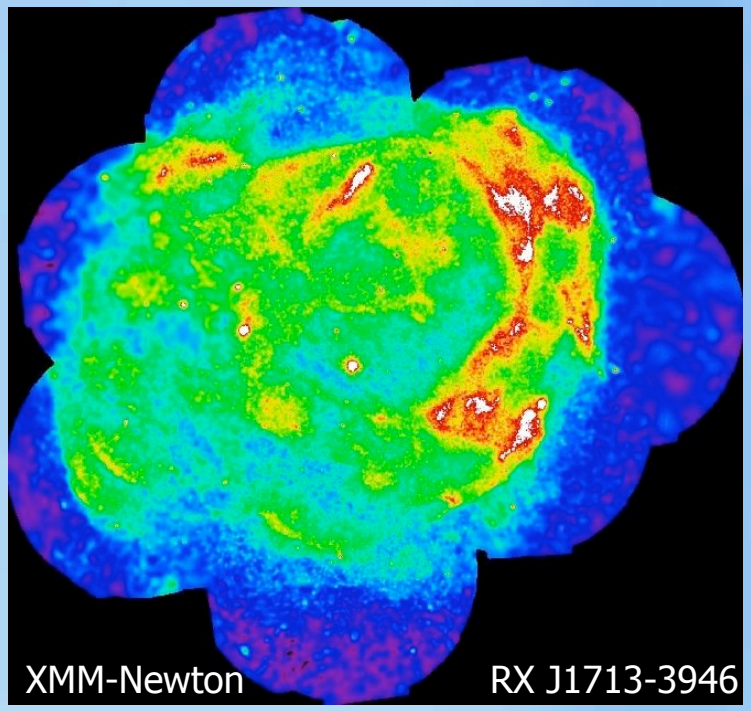
Outline

- Evidence of acceleration in SNRs using X-ray synchrotron
- Brief presentation of Cherenkov astronomy
- TeV emission from shell SNRs
- Comparison of X/γ-ray thickness of the shell
- TeV emission from SNRs in interaction with molecular clouds

Shell SNRs in non thermal X-rays

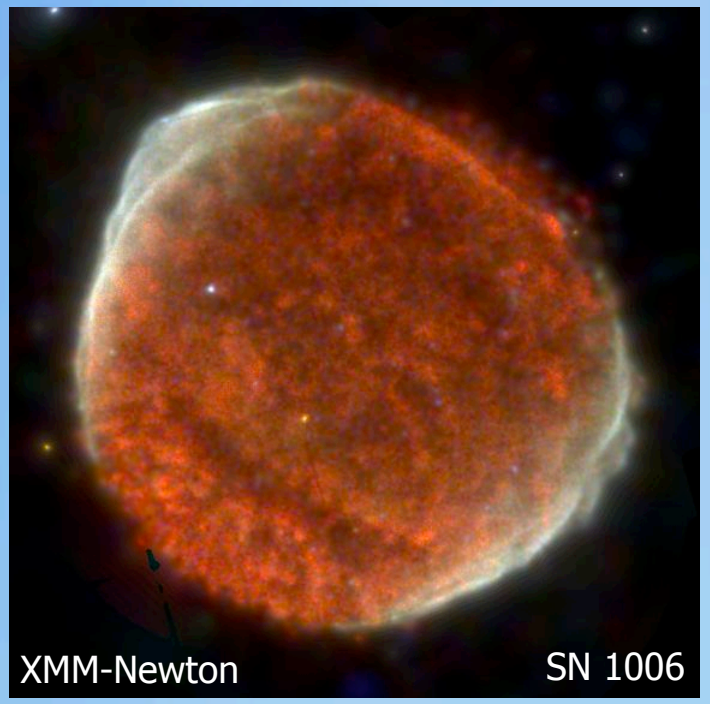
Non-thermal dominated

Vela Jr, RX J1713-3946

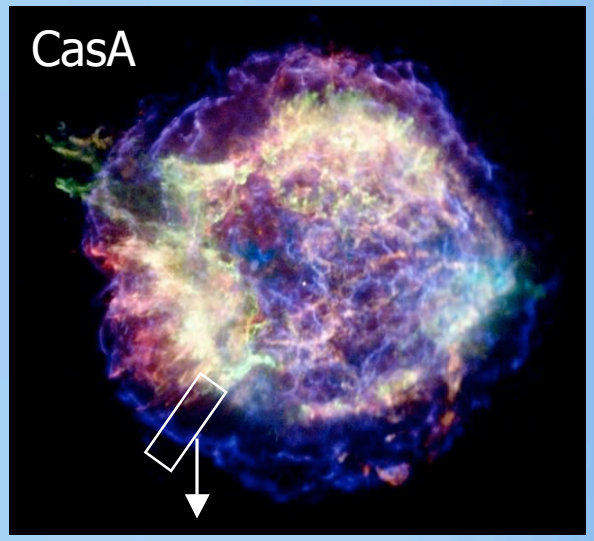


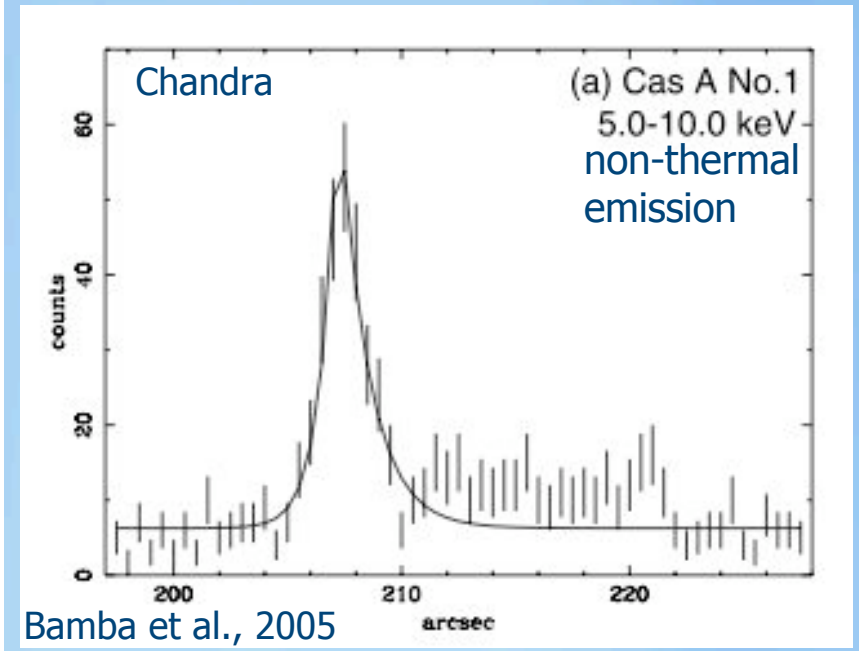
Thermal+Non-thermal

SN 1006, Tycho, Kepler, RCW 86, CasA, …



Highly amplified B





Bamba et al., 2005

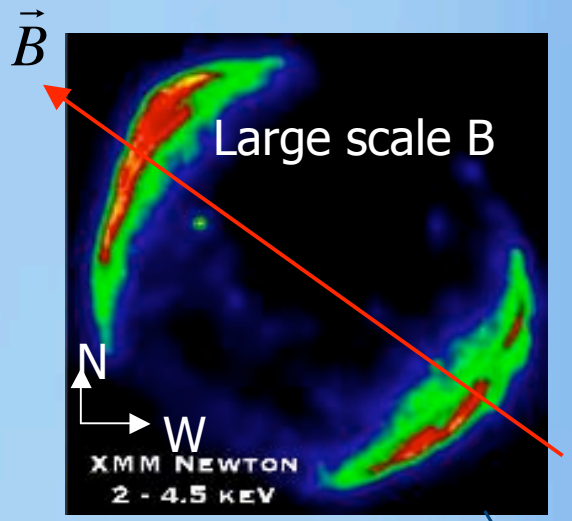
- X-ray emission confined in very thin filaments (arcsecs)
- Most likely due to synchrotron losses of high energy radiating electrons
- The derived magnetic field is highly amplified Vink & Laming, 2003, Berezhko & Voelk 2004, Parizot et al., 2006

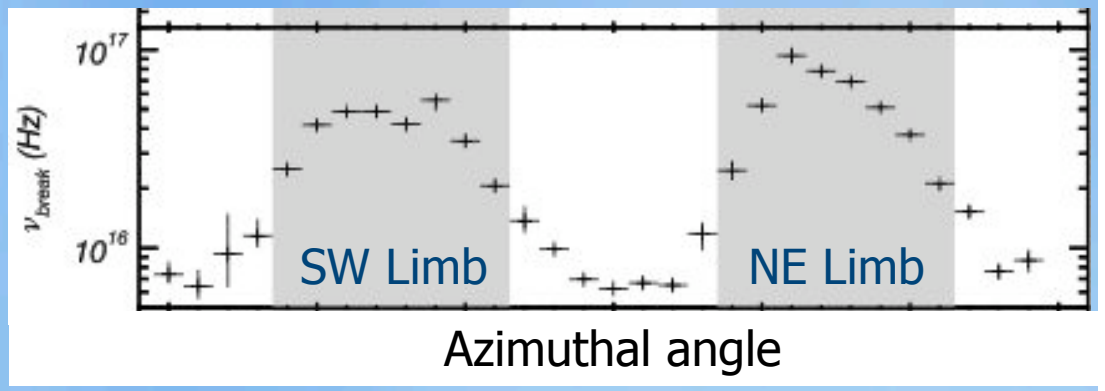
CasA -> B~500 μG (B_{ISM} ~ 5 μG)

- Could also be damping of B (Pohl et al., 2005)
  -> Not consistent with radio morphology in Tycho (Cassam-Chenaï et al., 2007)

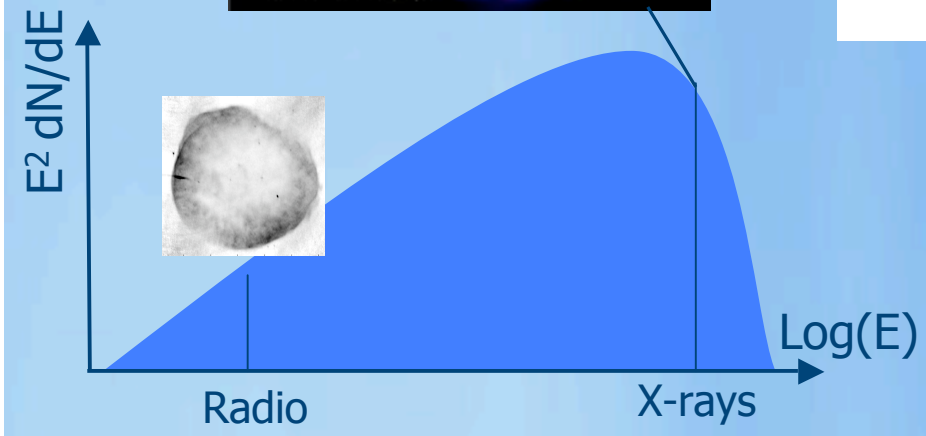
Cutoff frequency azimuthal variation

SN 1006





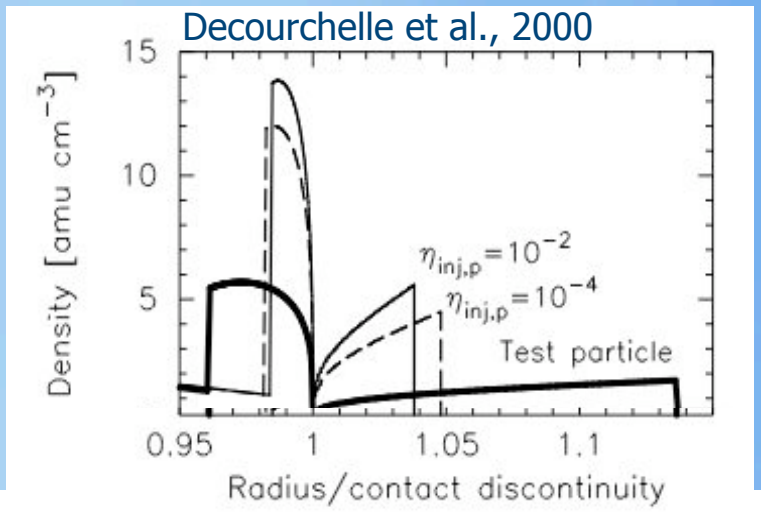
Miceli et al., 2009
See also Rothenflug et al., 2005

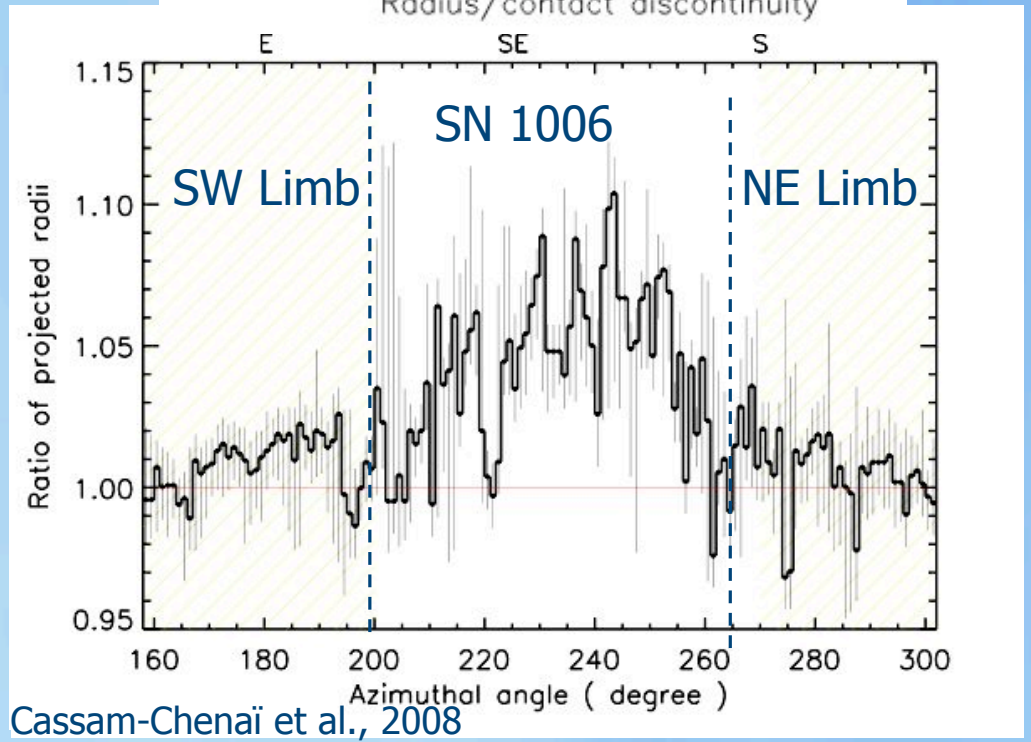


- Acceleration seems faster for parallel shocks than for perpendicular ones

Efficient acceleration

Decourchelle et al., 2000





Cassam-Chenaï et al., 2008

Ratio of :

- Forward shock ->Halpha
- Contact discontinuity ->X-ray 0.5-0.8 keV (tracing shocked ejecta)
- Efficient acceleration has modified the shock structure

Indirect evidence of proton acceleration

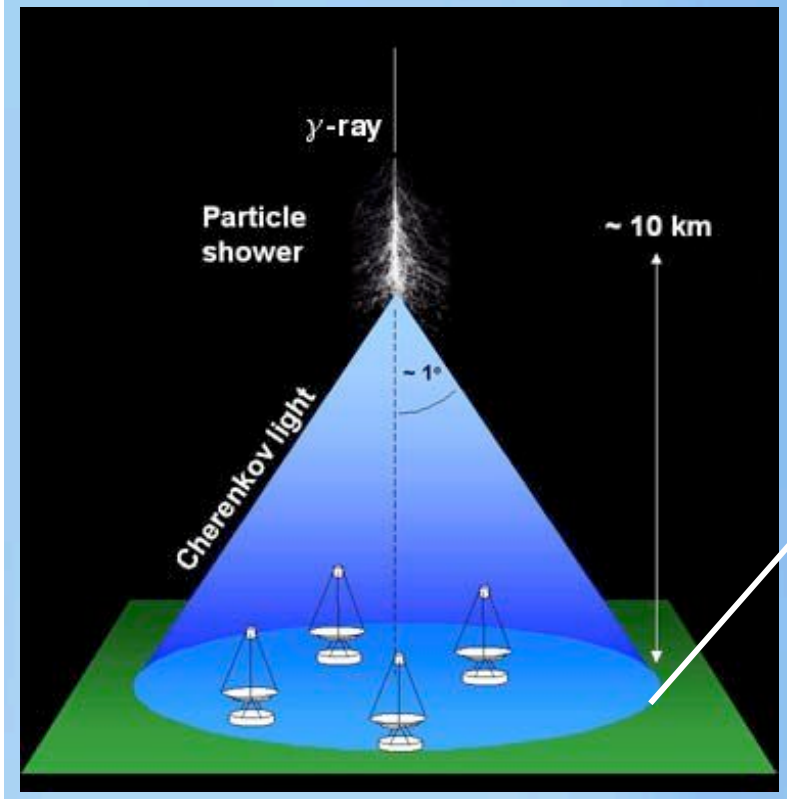
Cherenkov astronomy

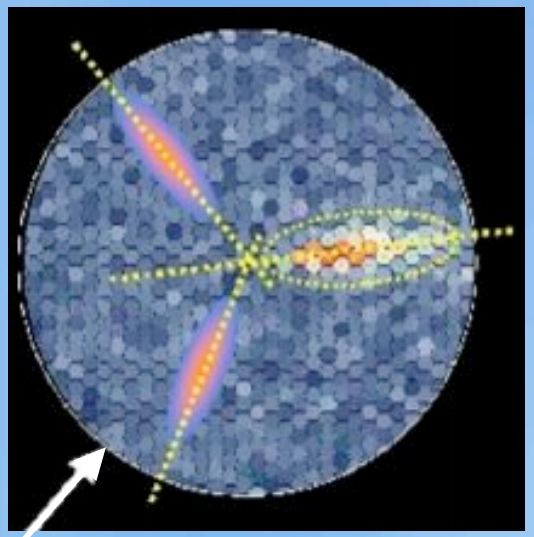
- At TeV energies satellite observations no longer possible
  collecting area and calorimeter depth

- Earth's atmosphere as part of the detector
  -> Imaging atmospheric Cherenkov telescopes (IACT)

- Cherenkov flash : faint and short ~ 3ns
  -> Fast cameras and large mirrors (10m-17m)

Cherenkov telescopes technique

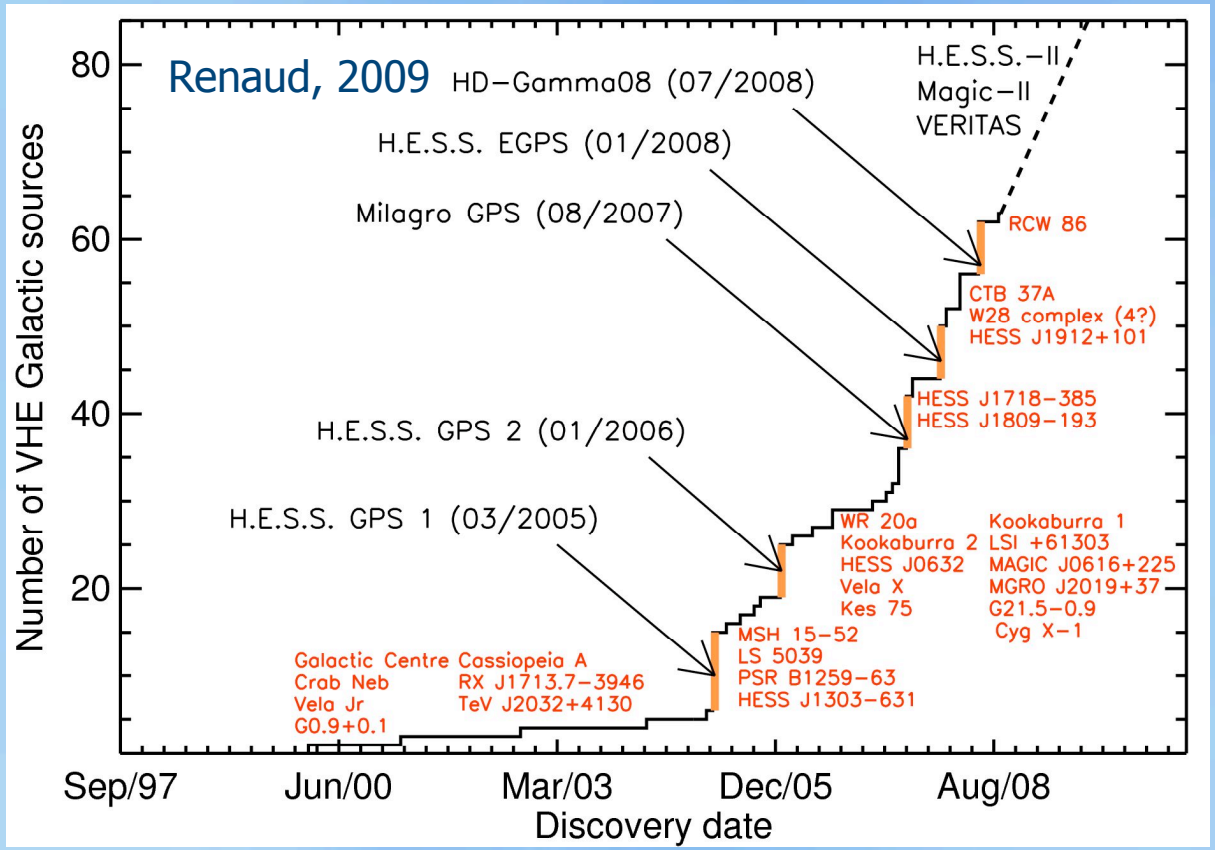




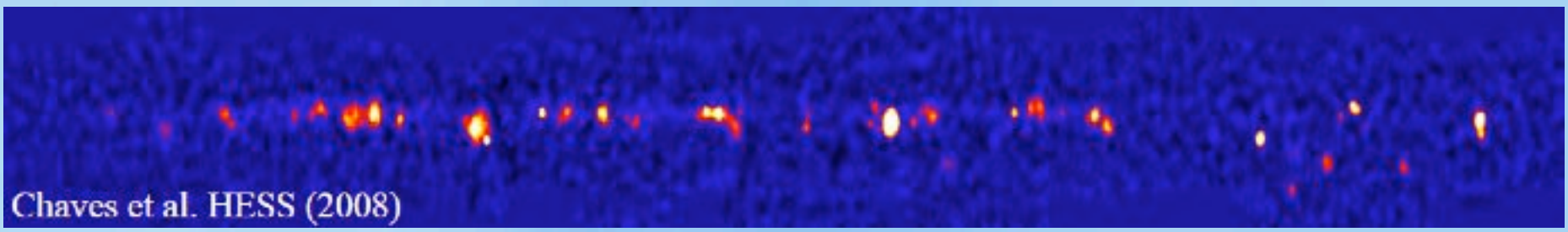
- Cherenkov flash from particle shower observed in telescopes
- Stereoscopy allows to reconstruct original γ-ray with a better :

  - angular/energy resolution
  - background (hadrons) rejection
  - sensitivity

Cherenkov astronomy



We have entered in the TeV astronomy era



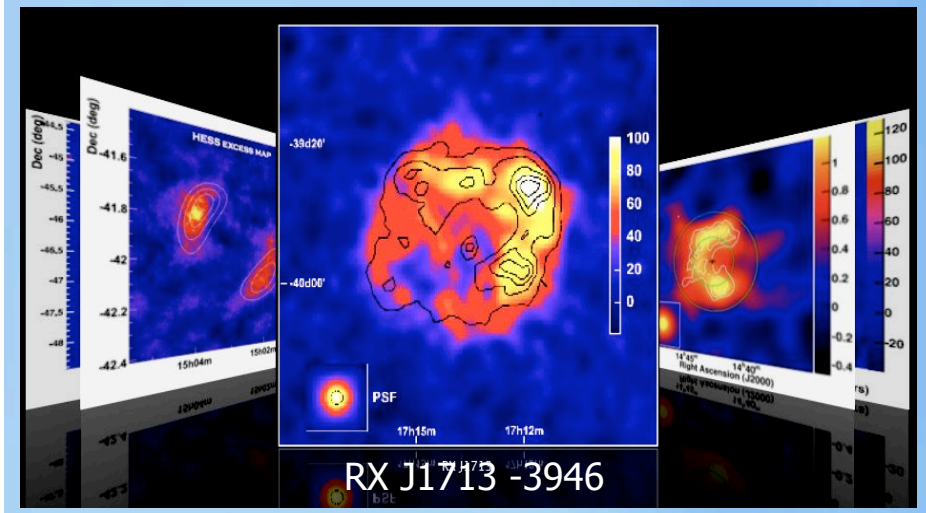
TeV emitting SNRs

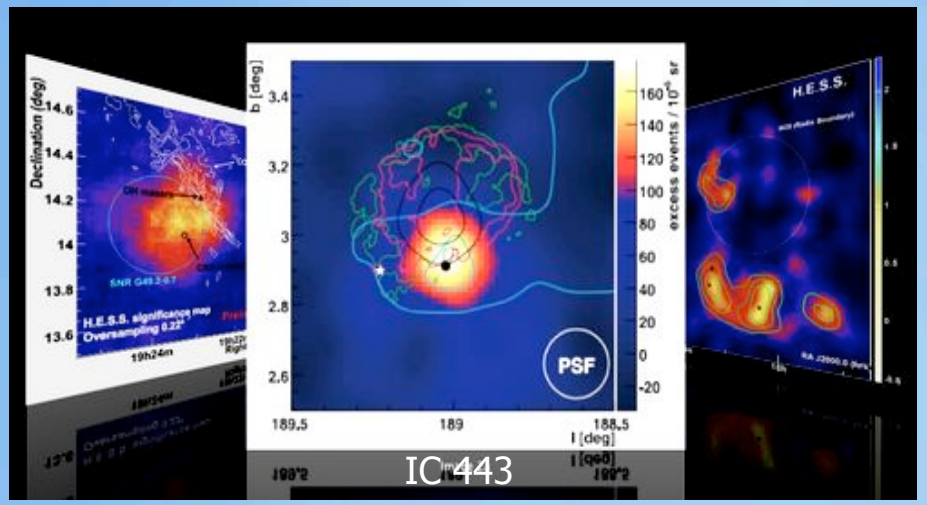
Shell-morphology

Vela Jr, RX J1713-3946,
RCW 86 (?), SN 1006

Interacting with molecular clouds

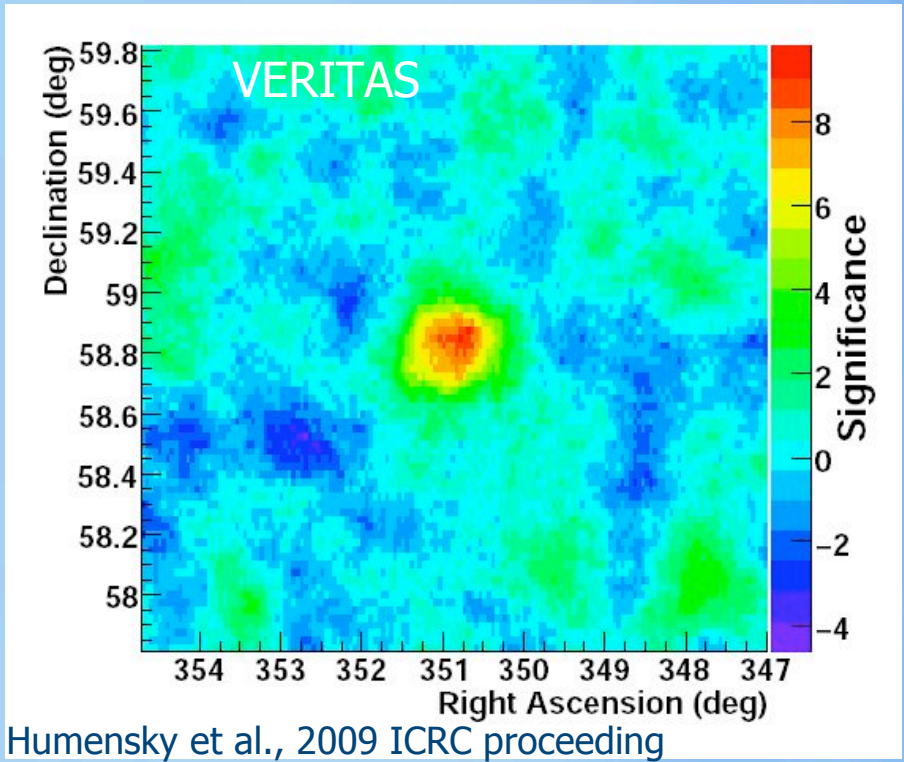
IC 443, W28, W51





- Possibility to directly investigate proton acceleration through hadronic process

Cassiopeia A



Humensky et al., 2009 ICRC proceeding

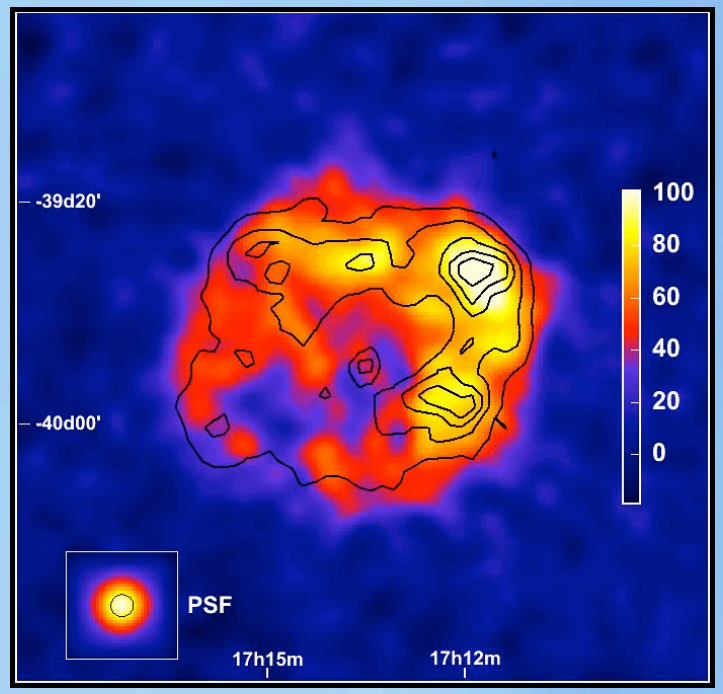
- First SNR discovered in TeV by HEGRA : 5 σ in 232 hrs (!!)
  Aharonian et al., 2001
- Assuming all TeV emission is leptonic : X/γ flux ratio -> B~100 μG
- Very thin X-ray filament -> B~500 μG
- Assuming all TeV emission is hadronic : -> n ~ 1 cm-3
- MAGIC :TeV spectral index $\Gamma = 2.3 \pm 0.2_{stat}$
  Albert et al., 2007

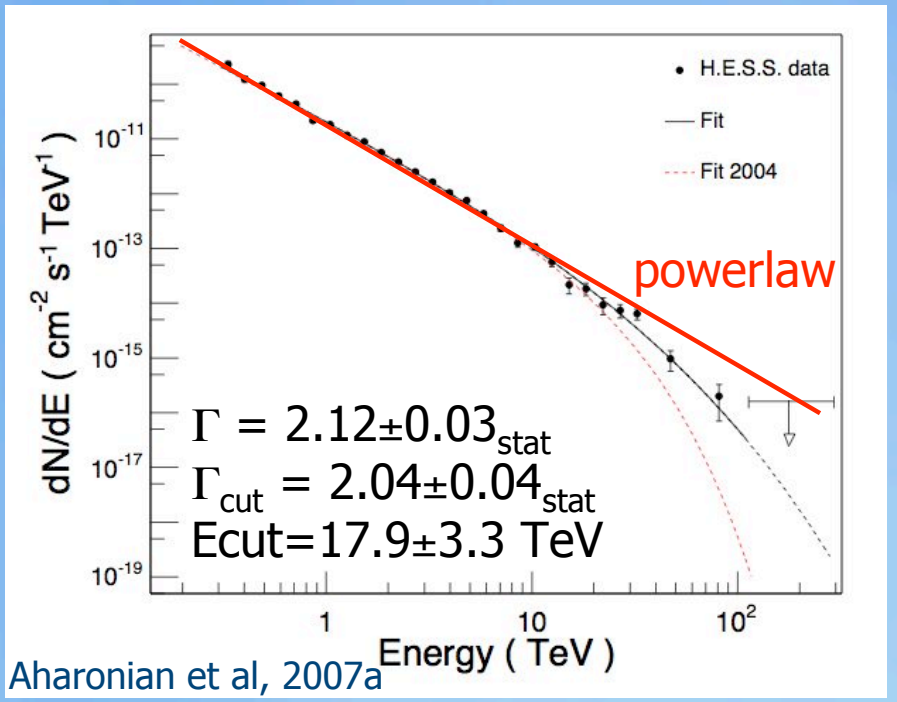
ID CARD

T = 330 yrs

d = 3.4 kpc

RXJ 1713-3946





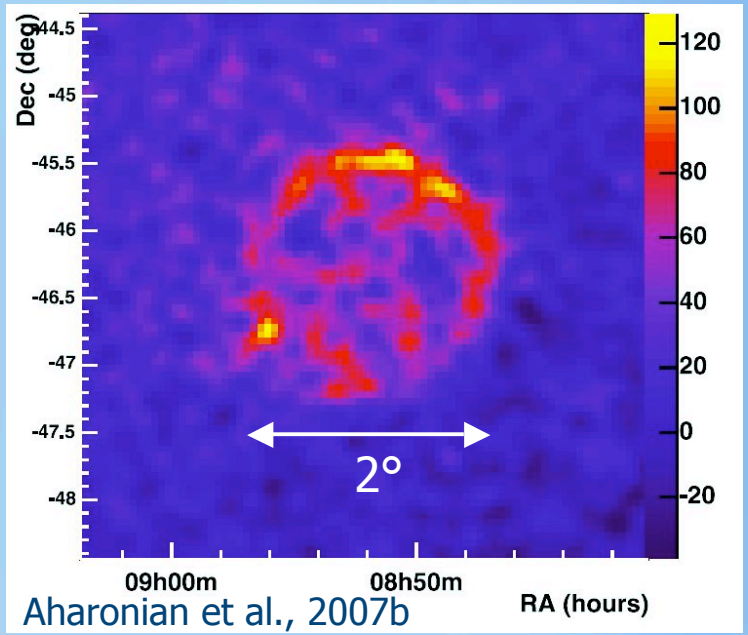
Aharonian et al, 2007a

- Unique example of cutoff in SNR
  -> Maximum energy below the knee
  γ : 18 TeV -> p : ~200 TeV
- Thick shell in γ-ray : 48%*R_{SNR}
  Deprojected and deconvoluted from the PSF

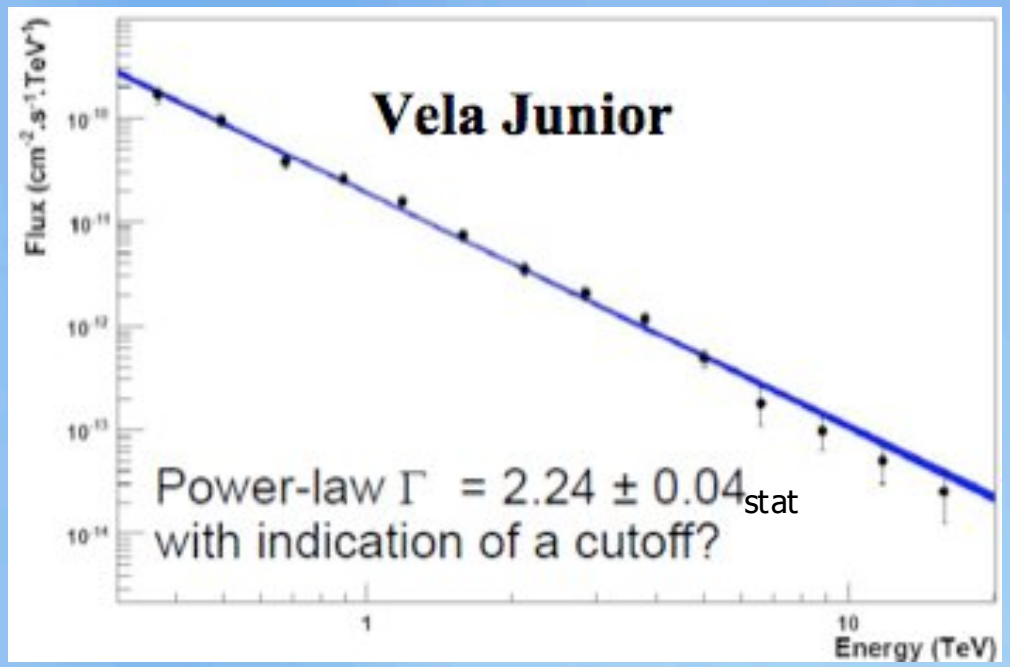
Magnetic field
Filament:~70 μG
X/ γ:14 μG

ID CARD
T = 1600 yrs
d ~ 1 kpc

Vela Jr



Aharonian et al., 2007b

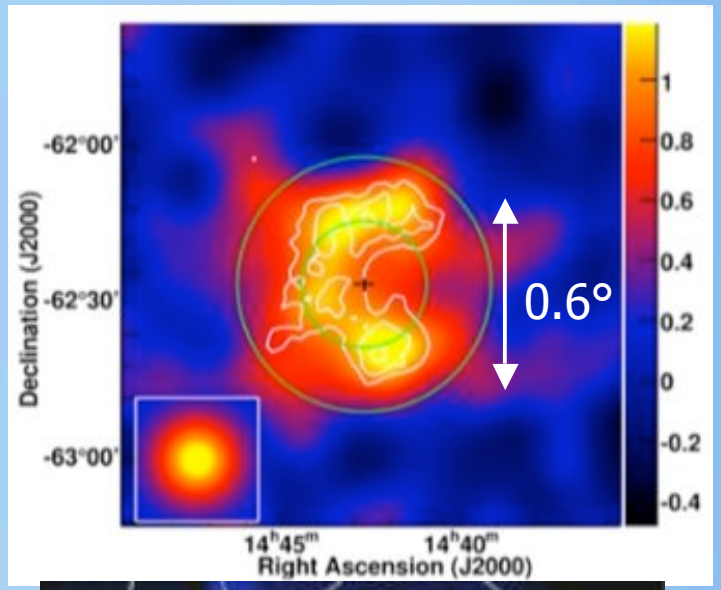


- Largest SNR in TeV
- Thick shell in γ-ray : 18%*R_{SNR}
  Deprojected and deconvoluted from the PSF

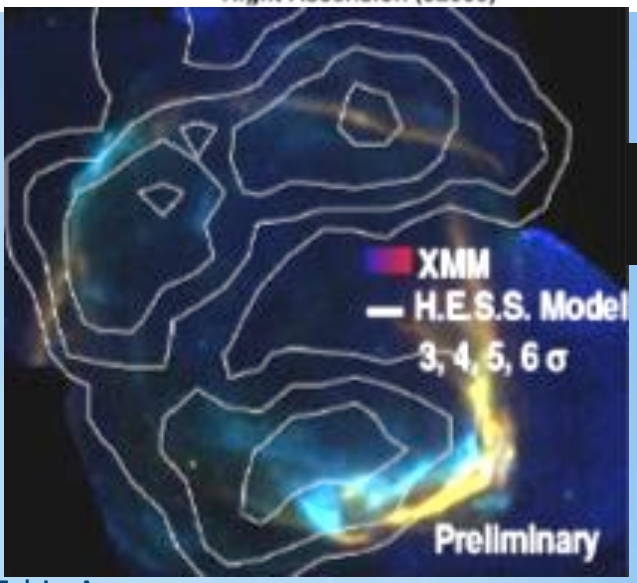
Magnetic field	ID CARD
Filament: 200 μG	T = 600-4000 yrs
X/ γ:14 μG	d ~ 200-800 pc

RCW 86

Aharonian et al., 2009



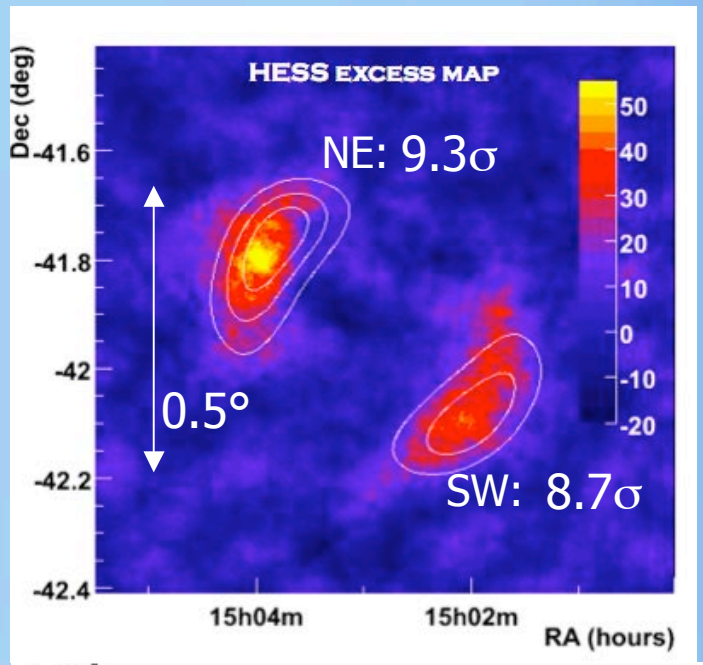
- Indication of a shell morphology in gamma-rays (Not statistically significant)
- No strong enhancement in γ in the SW interaction region (dense material)
- $\Gamma = 2.54 \pm 0.12_{stat}$

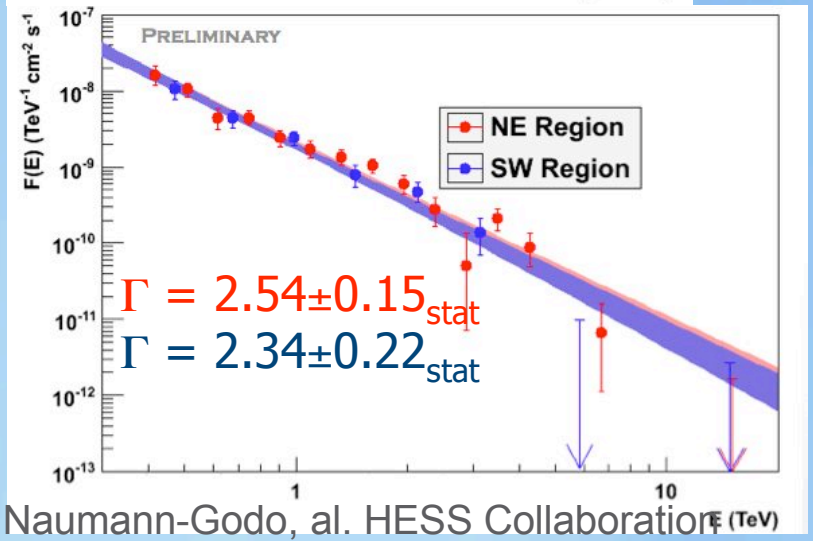


Synchrotron
Thermal

Magnetic field	ID CARD
Filament:~100 μG	T = 1800 yrs
X/ γ:~30 μG	d ~ 2.5 kpc

SN 1006





Naumann-Godo, al. HESS Collaboration

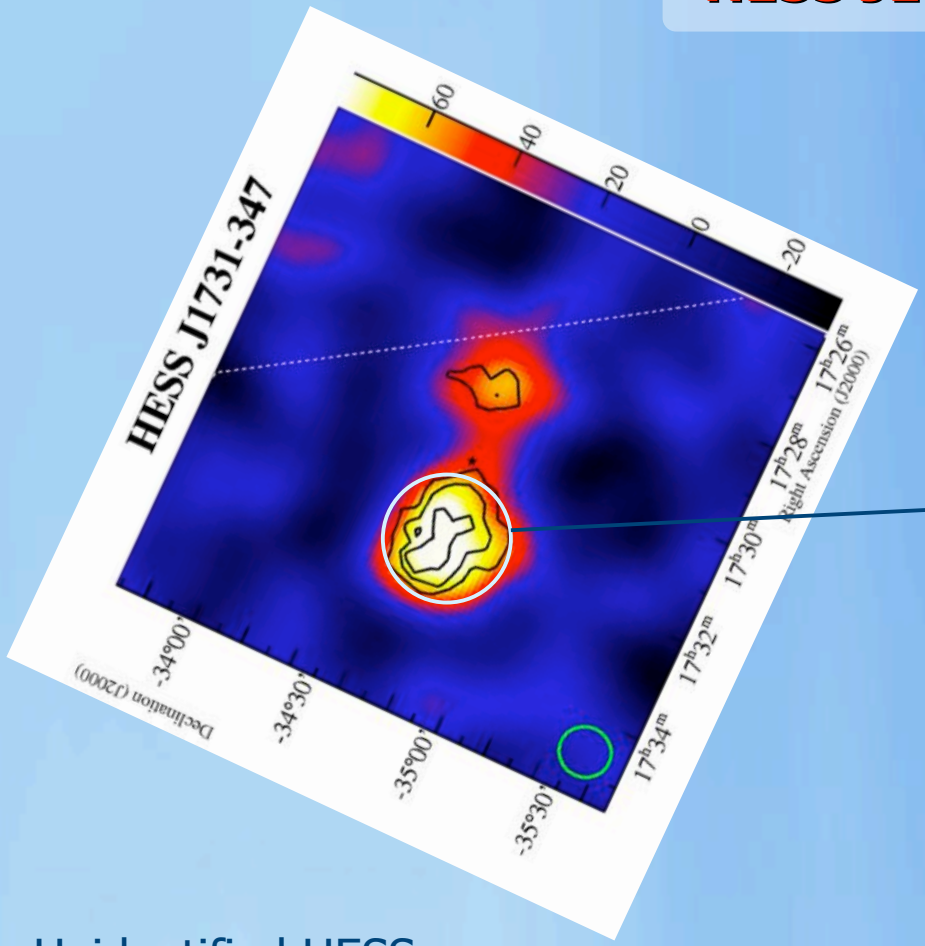
- 130h live time observation
  -> SN 1006 detected !
- Flux ~1% Crab
  -> one of the faintest VHE source detected
- Similar X-ray/γ-ray bi-polar morphology

Leptonic scenario : e^- acceleration is more efficient in the bright limbs

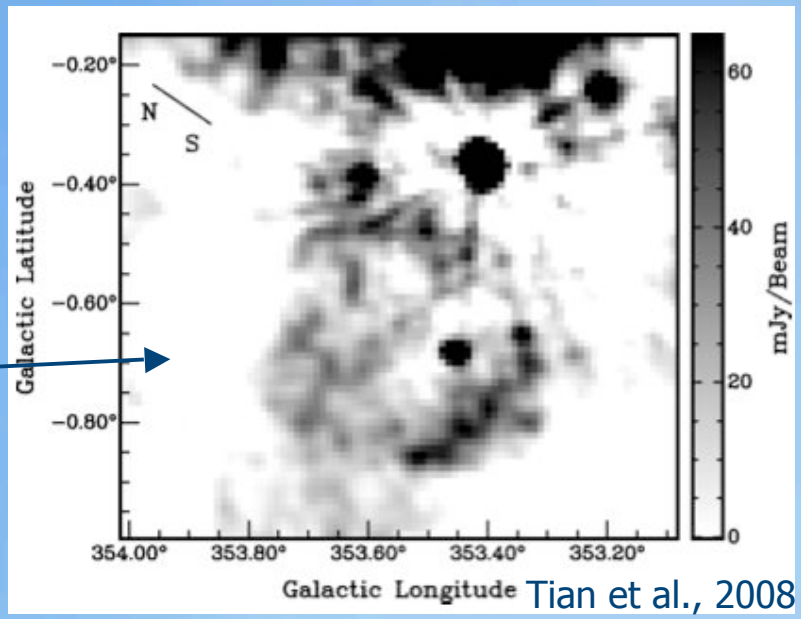
Magnetic field	ID CARD
Filament:~70 μG	T = 1003 yrs
X/ γ:~30 μG	d = 2.2 kpc

Previously unidentified sources

HESS J1731-347



Radio, ATCA telescope



Tian et al., 2008

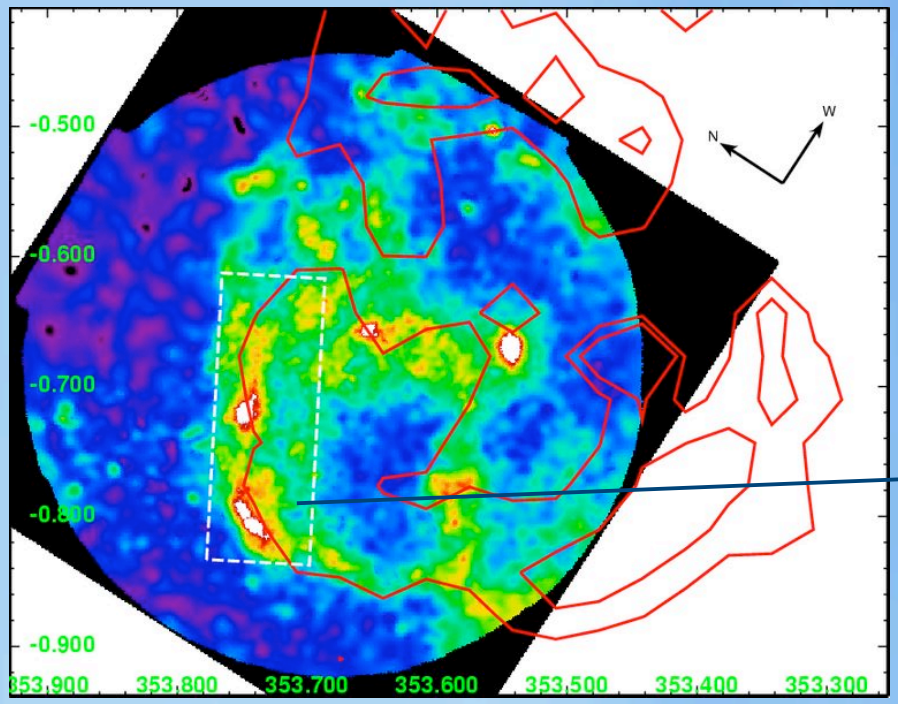
Unidentified HESS source
Aharonian et al., 2008

→ Shell of SNR in spatial coincidence

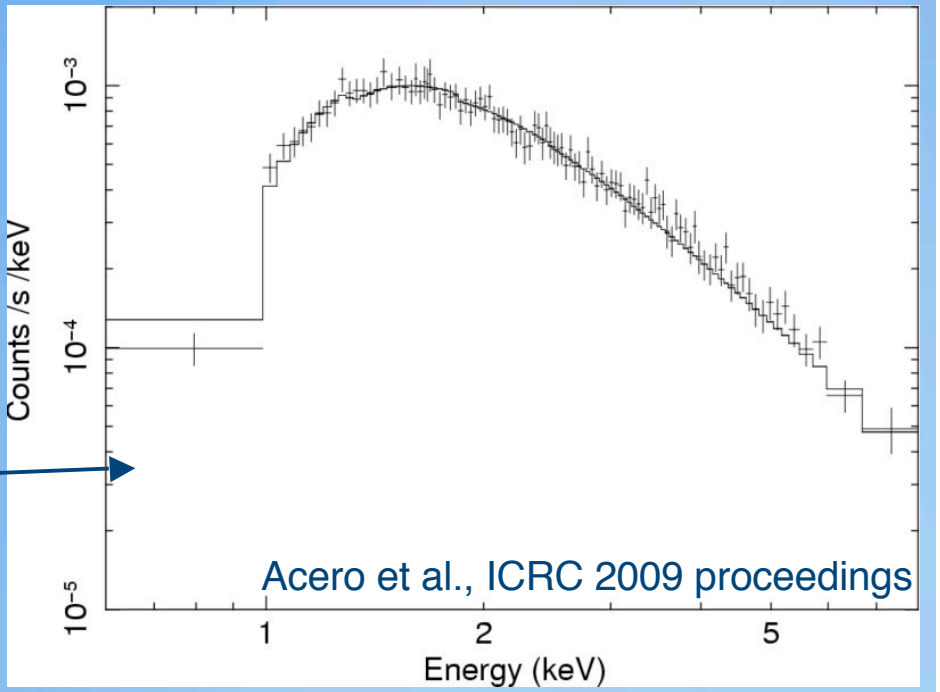
HESS J1731-347

Non thermal shell !

XMM + ATCA radio contours



MOS instrument spectrum

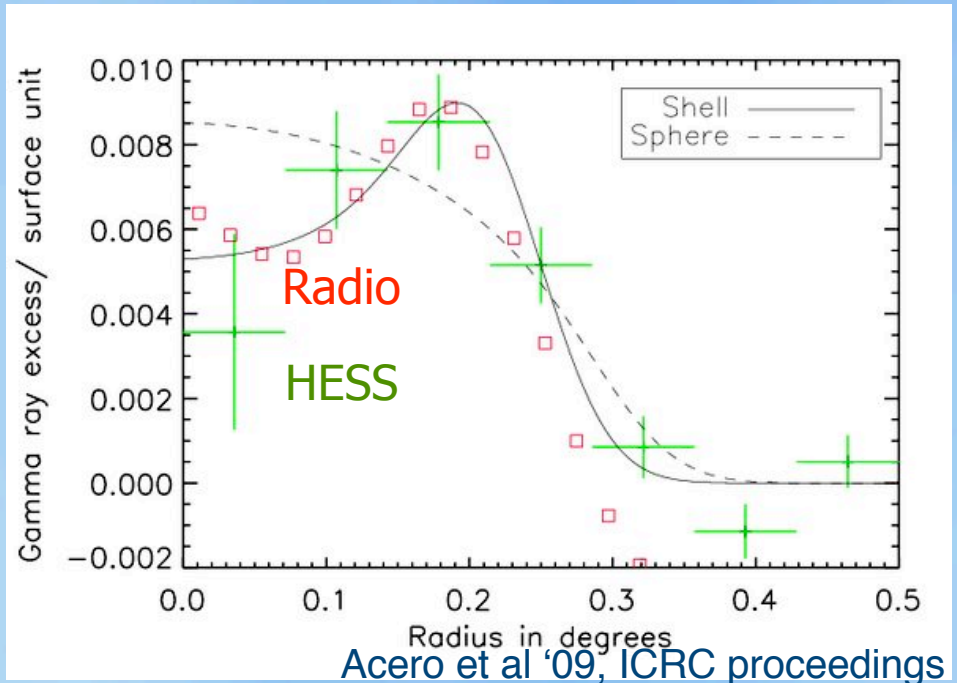


- SNR's filament well fitted by an absorbed powerlaw
- X-ray synchrotron emission -> e^- accelerated to ~10 TeV

HESS J1731-347

HESS

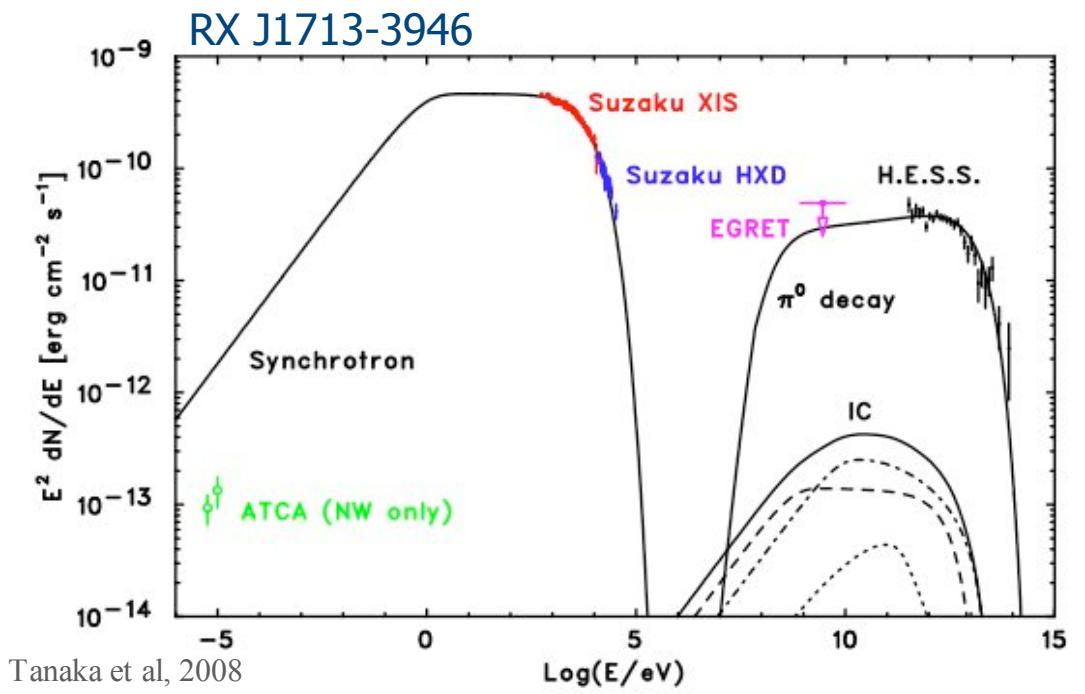
Radial profiles



Acero et al '09, ICRC proceedings

*Spatially coincident with radio shell
*Indication of shell like morphology
Not statistically significant (yet)

Spectral Energy Distribution : Hadronic scenario

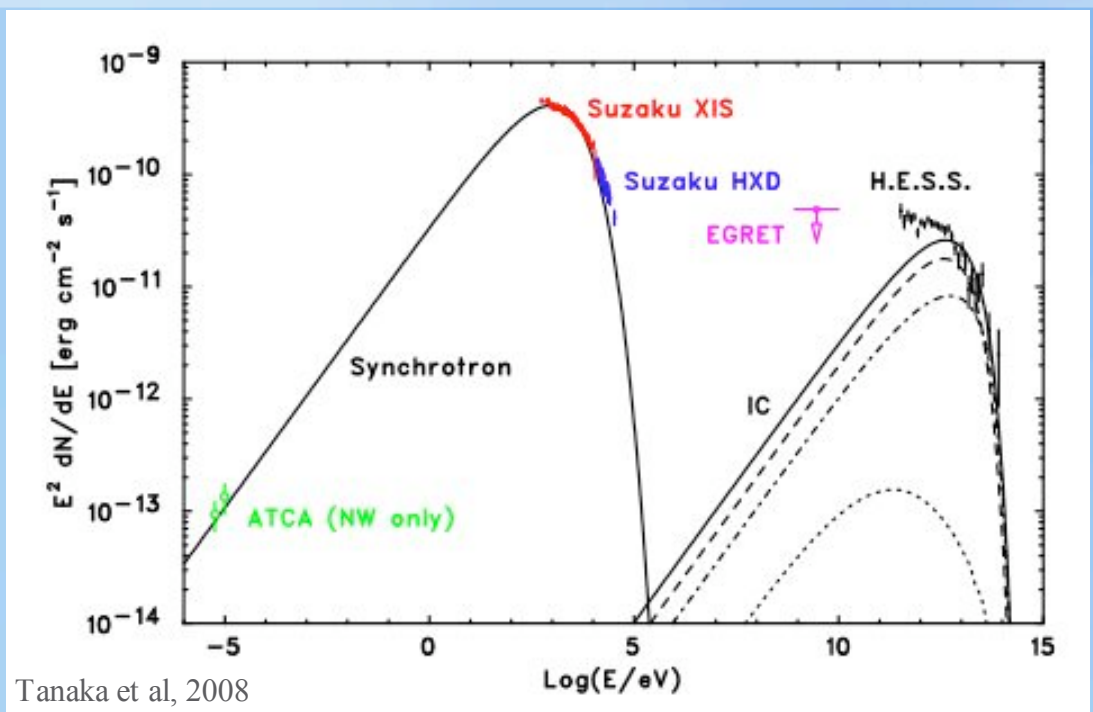


- Magnetic field = 200 μG
  -> in agreement with X-ray filament

- High density required : n~1 cm^{-3}
  -> Not in agreement with density measurement : n < 0.02 cm^{-3}

- Caveat : efficient acceleration can decrease thermal emission behind the shock (Drury et al., 2009, Helder et al., 2009)

Spectral Energy Distribution : Leptonic scenario



Tanaka et al, 2008

One zone model :

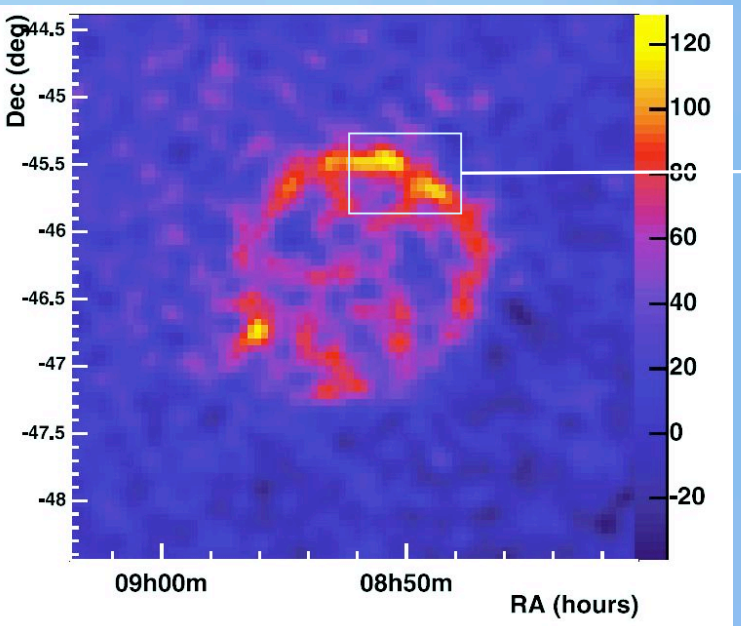
-One population of e-
-Uniform magnetic field

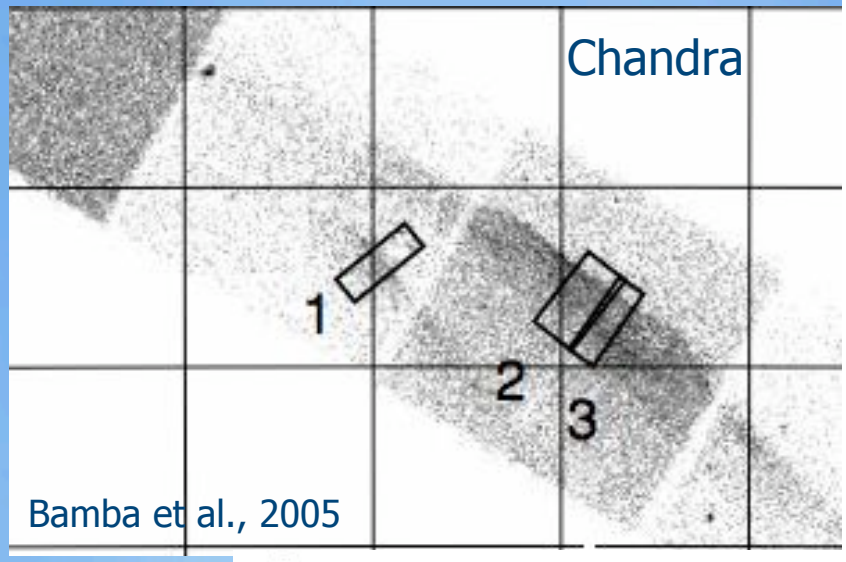
- Difficult to fit TeV spectral shape in one zone model with only CMB

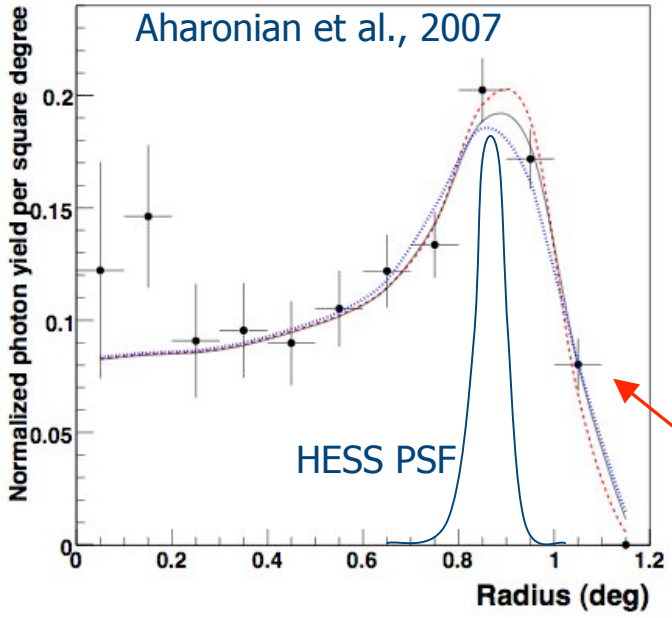
- Magnetic field = 14 μG
  -> NOT in agreement with filament

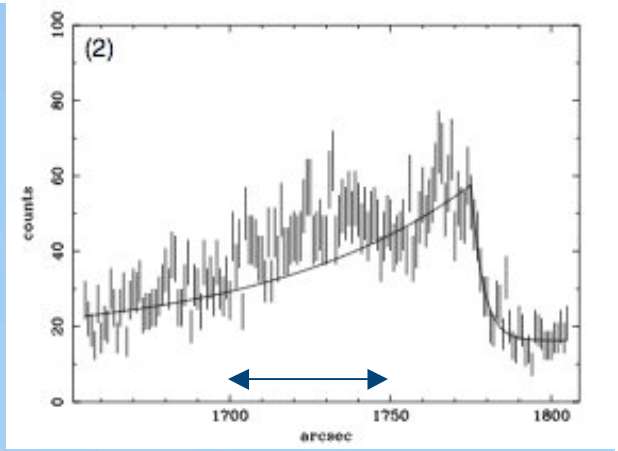
BUT ...

Gamma spatially resolved shell







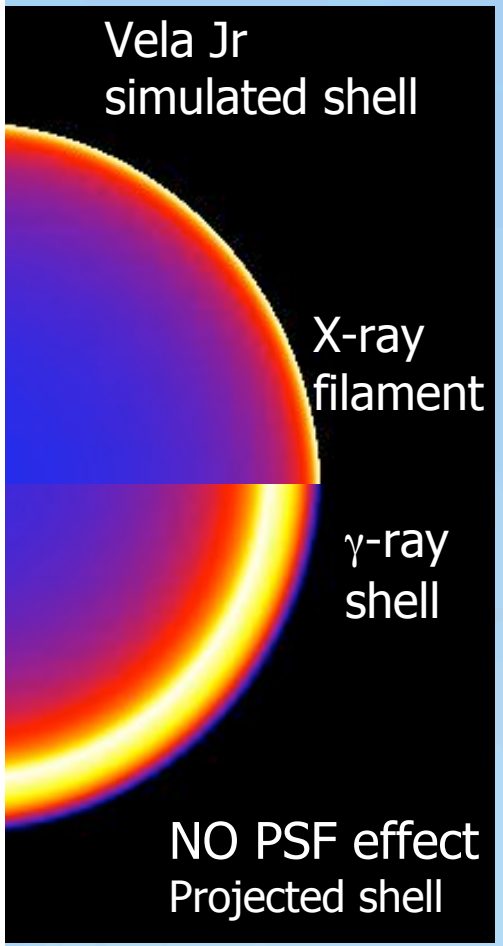


50 arcsecs

- X/gamma-ray emission do NOT stem from the same regions

Real thickness=0.18±0.03°

Magnetic field estimate

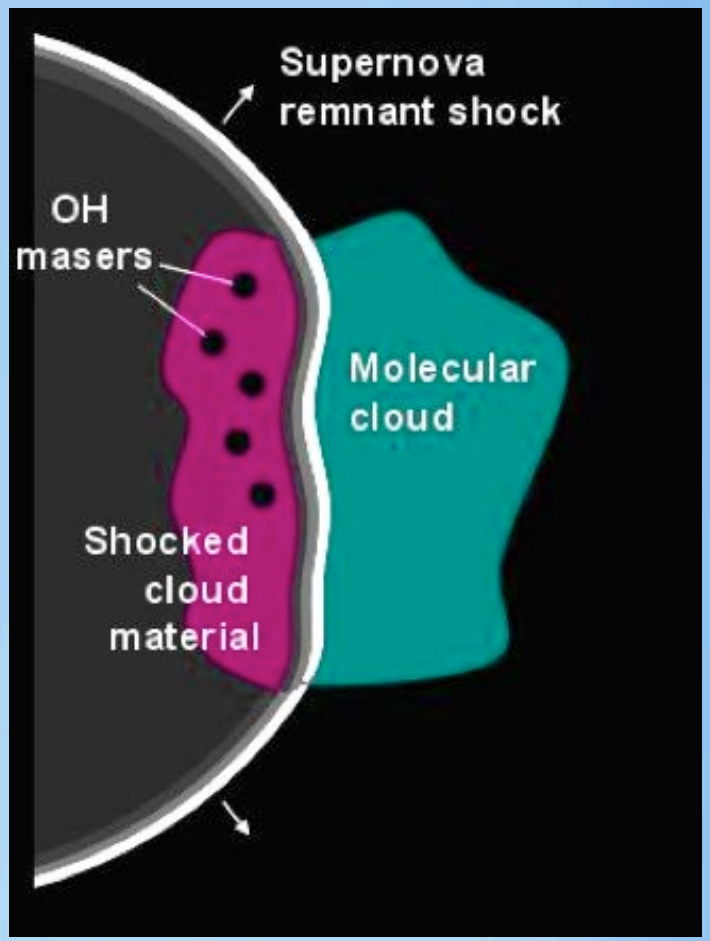


- X-ray filament width ⟶ B ~ 200 μG
  Probed region 2%*R_{SNR}
- X/γ-ray flux ratio ⟶ B ~ 14 μG
  Probed region 18%*R_{SNR}
- **Different emitting X/γ-ray volume**

*** Decay of the magnetic field on a large scale ?**
*** Hadronic : expect wider shell but not as large ?**
(See H. Voelk talk)

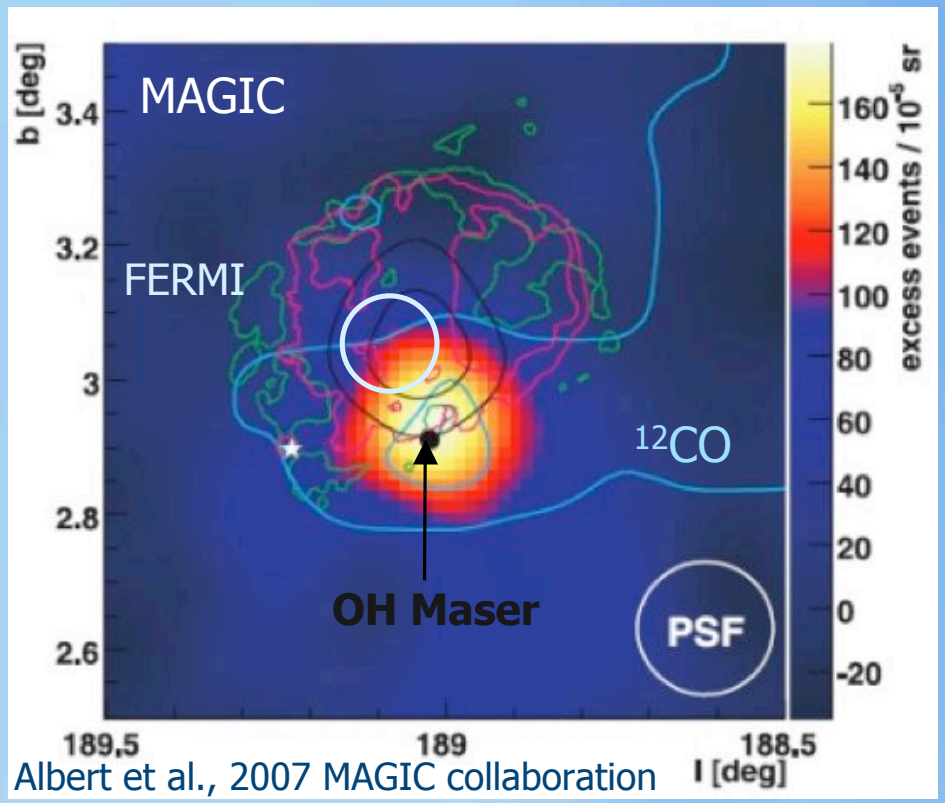
Interacting SNRs with molecular clouds

Interacting SNRs can probe the hadronic process



- Provide high density targets
  -> n = 10-100 cm^{-3}
- OH maser can trace this interaction
  -> Radio observation at 1720 MHz
- For old SNRs, TeV electrons have vanished
  -> Less confusion leptonic/hadronic process

IC 443



Albert et al., 2007 MAGIC collaboration

Detection confirmed by VERITAS
Γ=2.99±0.38 (Acciari et al., 2009)

- Direct coincidence between :

  SNR shell + ^{12}CO + OH Maser

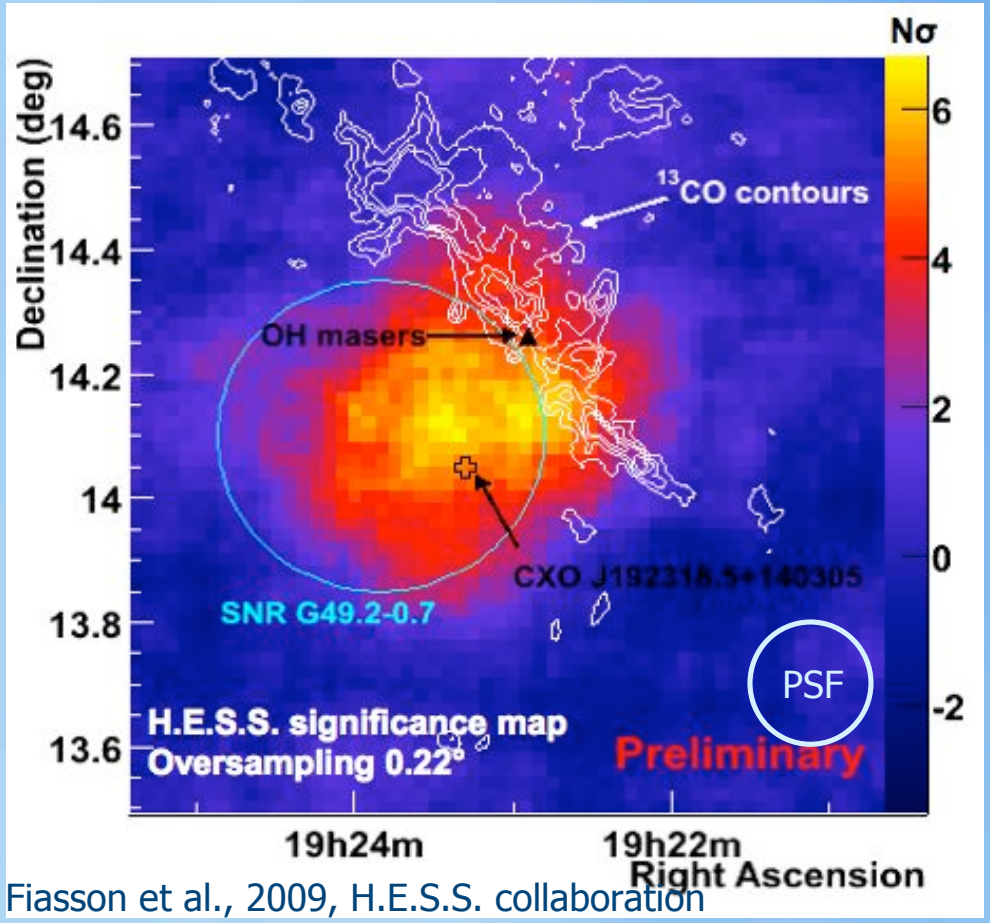
- Not coincident with the pulsar (white star)

- Flattening in the FERMI range
  Γ =1.9 -> 2.5 ; break at few GeV
  Rodriguez et al., ICRC 2009 proceeding

- Steeper TeV spectrum Γ=3.1±0.3

- MeV - > GeV -> TeV
  Γ =1.9 -> 2.5 -> 3.1

W51 / HESS J1923+141



Fiasson et al., 2009, H.E.S.S. collaboration

- Extended TeV emission in comparison to the PSF
- FERMI extended emission recently detected
- Other possible counterpart : PWN
- An interesting new candidate

Conclusion

- We have entered the TeV-astronomy era
- X-ray (+GeV) + TeV provide a unique tool to constrain acceleration in SNRs
- All TeV SNRs have Γ>2 ; Are we in the cutoff of those SNRs
  - -> Difficulties to reach the knee (3000 TeV) in SNRs
  - -> Cutoff seen in RX J1713-3946 at 200 TeV
- TeV SNR shells are thicker than X-ray shells -> Decay of B in leptonic scenario ?
- New candidates in TeV :

  Shell : HESS J1731
  Interacting SNR : W51