

SUPERNOVA REMNANTS interacting with MOLECULAR CLOUDS

A NEW COSMIC-RAY REVELATOR

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Supernova remnants and cosmic rays

- **Blast waves passing through the interstellar medium**
 - ⇒ the plausible particle accelerators at work in the Galaxy
- **First-order Fermi acceleration mechanism**
 - gain energy by multiple passage through the supersonic shock
 - expect $\sim 10\%$ of the explosion energy accelerates hadrons
 - enough power to compensate cosmic-ray escape from the Galaxy
- **We miss an undisputable experimental evidence**
 - ⇒ very high energy γ rays are good tracers for such mechanism

The High Energy Stereoscopic System

- Four Imaging Atmospheric Cherenkov Telescopes
- Khomas Highlands of Namibia at **1800 m above sea level**
Southern hemisphere => inner Galactic plane => most emitters

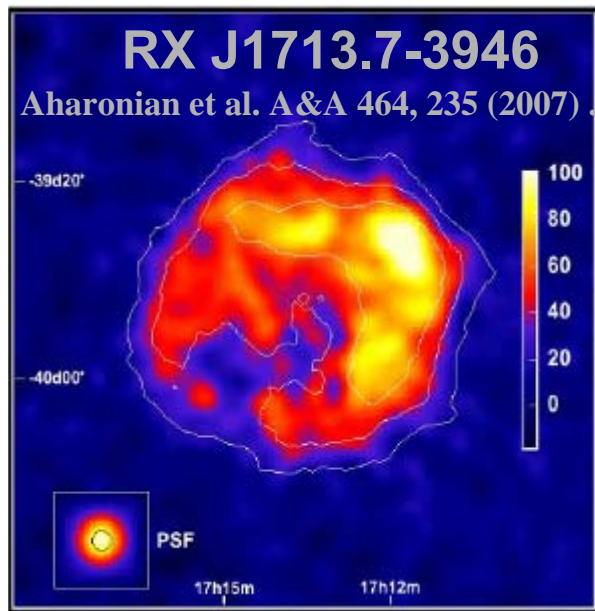
- **Completed in December 2003**
=> more than 6 years of observation in full configuration mode

The H.E.S.S. telescope

- 5° field of view, fine grain, fast readout cameras
- Detects Cherenkov light from atmospheric showers in stereoscopic mode

- Resolution: $\Delta\theta \sim 0.15^\circ$
- Energy range: 0.2 - 50 TeV; $\Delta E/E \sim 15\%$

Particle acceleration in shell-type SNRs

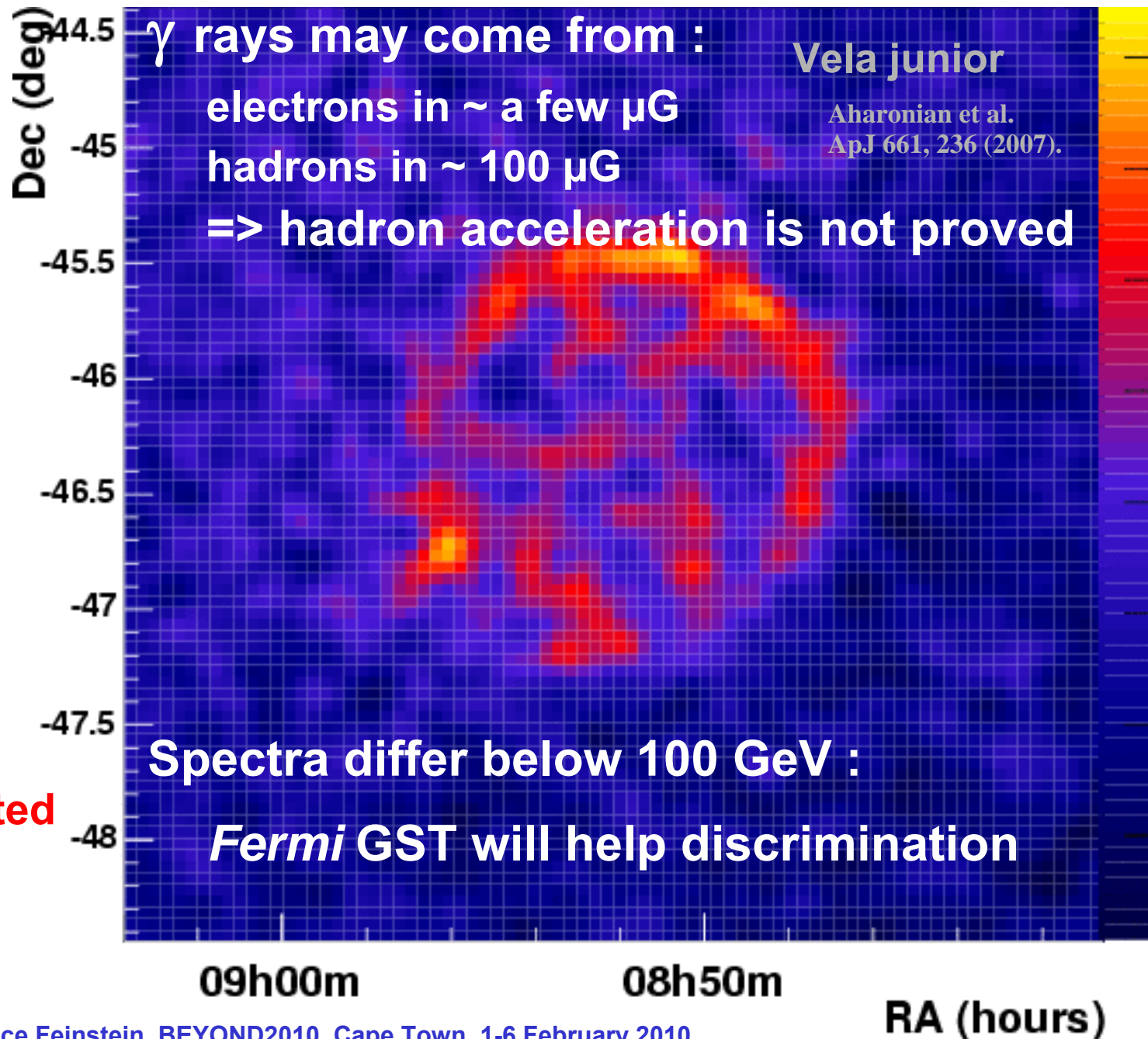


**First shell resolved
in VHE γ rays**

– Spectral index ~ 2 ,
up to 30 TeV

**=> particles accelerated
beyond 100 TeV**

– Correlation with
non-thermal X rays



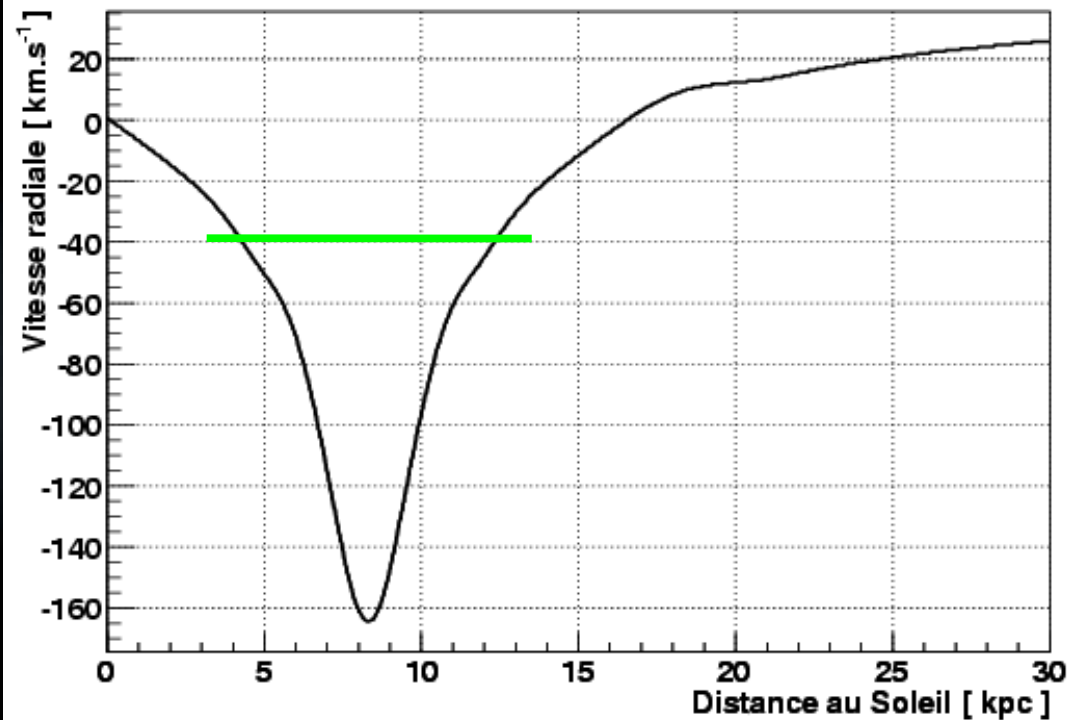
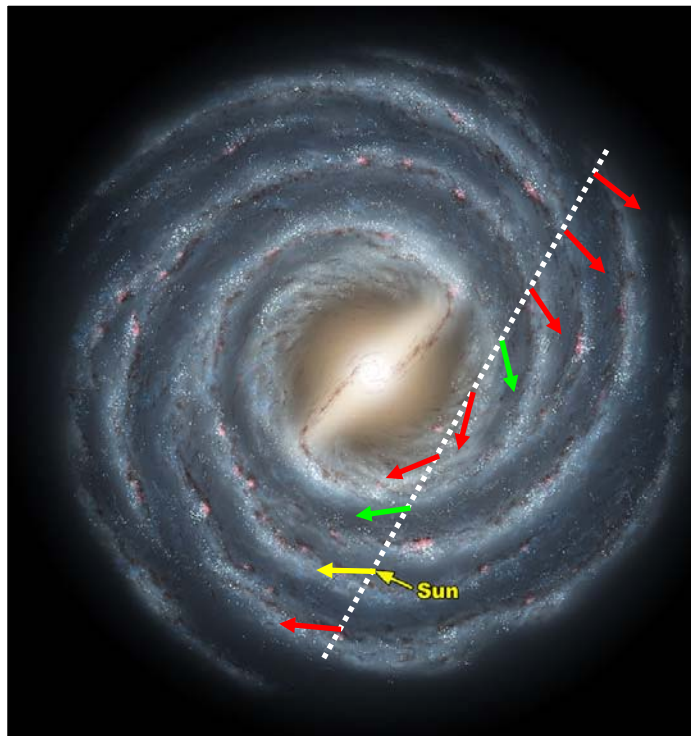
Molecular clouds probe cosmic rays

- Molecular clouds host supernova remnants
 - **Natural association:** birth place of massive stars ending as SNe
- Matter provides a target for accelerated hadrons $\rightarrow \pi^0 \rightarrow \gamma \gamma$
 - We expect a correlation between matter density and γ -ray emission

=> CRs accelerators associated with dense clouds should help to discriminate them from electrons accelerators

Molecular cloud detection

- Rotational lines of CO, CS in radio (H_2 has no rotational lines)
 - ⇒ line intensity proportional to H_2 column density (main component)
- Ambiguity in distance determination
 - ⇒ rotation of the Galaxy gives Doppler effect
 - ⇒ same radial velocity : two possible distances



1720 MHz OH maser (10^{-17} TeV !)

- OH population inversion **only** via **collisionnal** pumping with H_2

Elitzur M. ApJ, 203, 124 (1976)

- Specific conditions: $10^3 - 10^5 \text{ cm}^{-3}$, $T \sim 25 \text{ K} - 200 \text{ K}$
=> A **blast wave** passing through a **molecular cloud**
- **maser** effect if line of sight tangent to blast wave
- Strong suppression outside these temperature and density ranges
=> No detection does not mean no shocked cloud

- **BUT ! Detection means true interaction of SNR with MC**

- No fake associations due to imprecise distance determination
- Several surveys towards SNRs in the 1720 MHz line

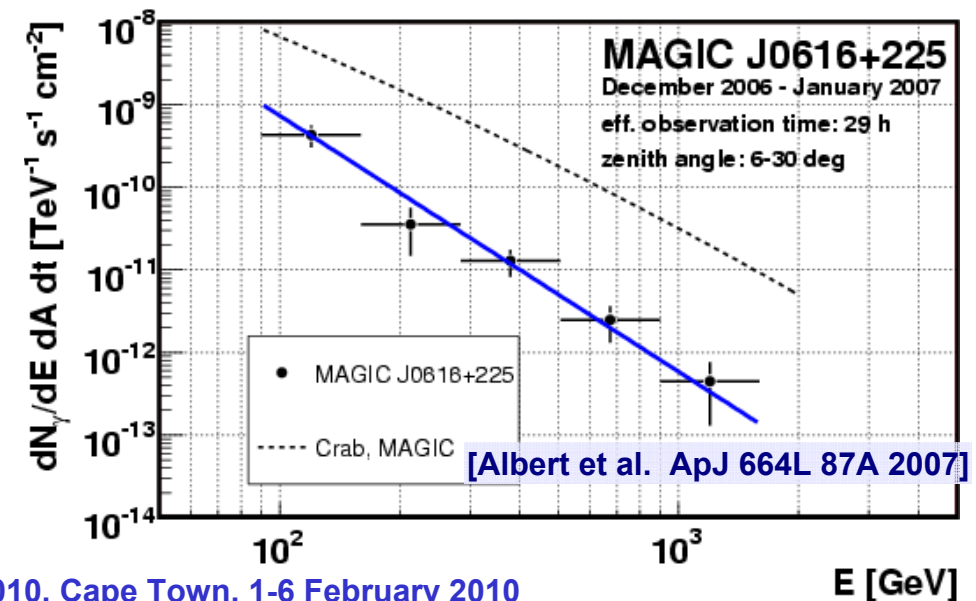
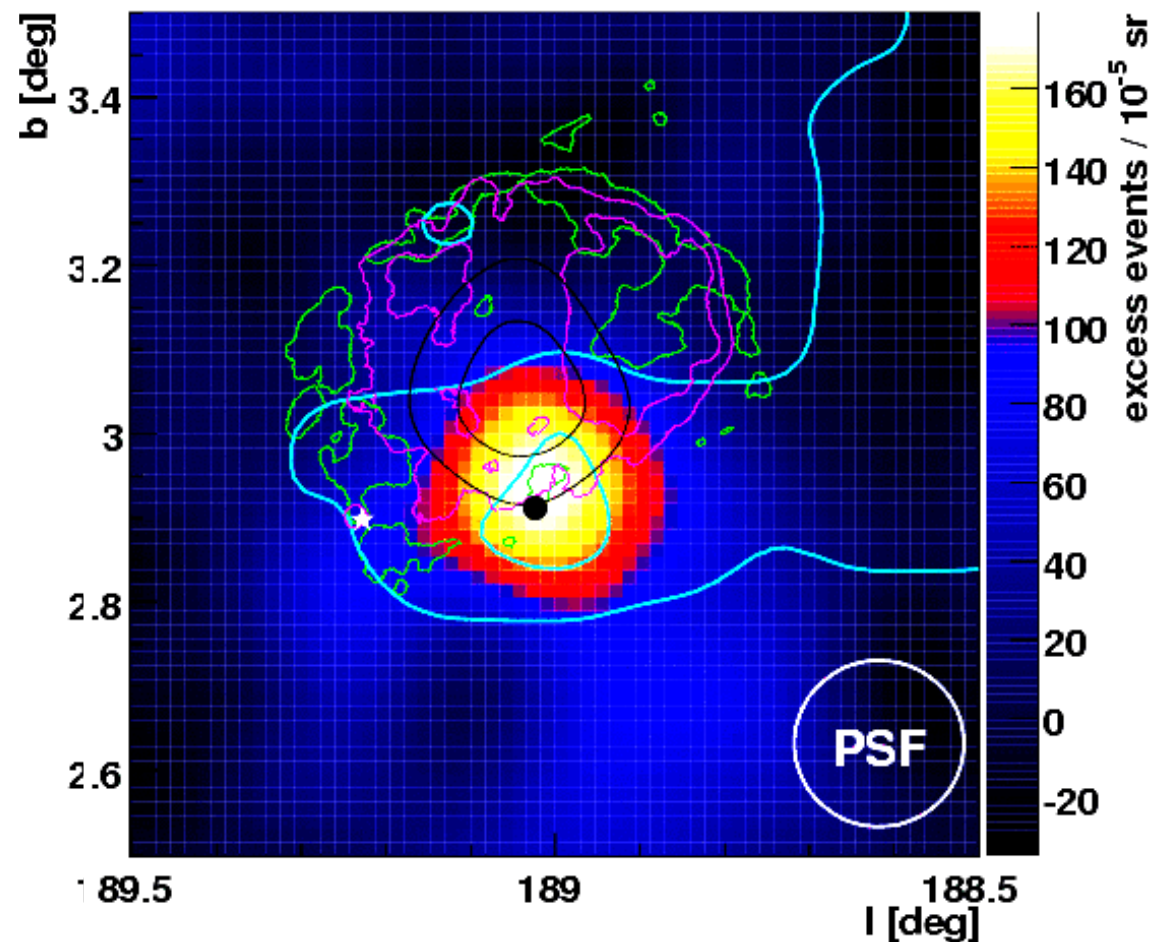
Frail et al. 1996, Green et al. 1997, Claussen et al. 1997, Koralesky et al. 1998, Yusef-Zadeh et al. 1999

- **18 SNRs showed 1720 MHz OH maser emission line**

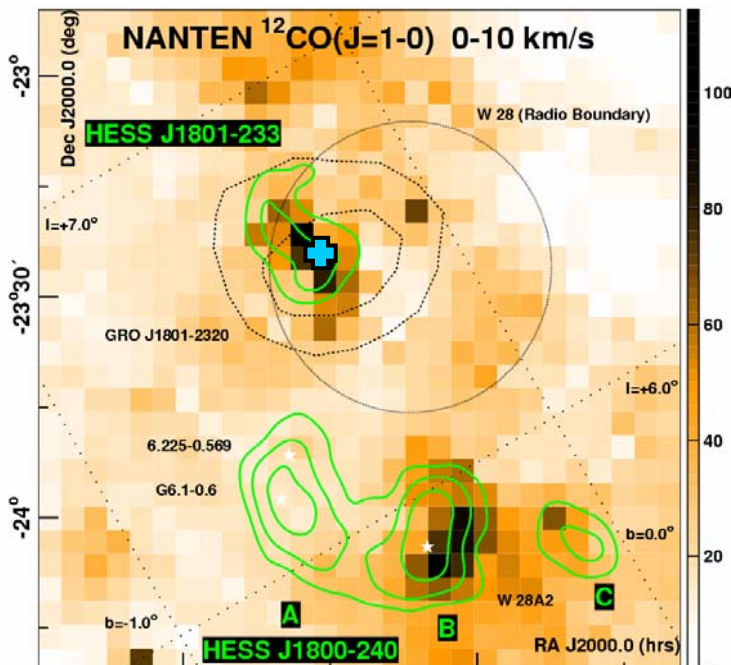
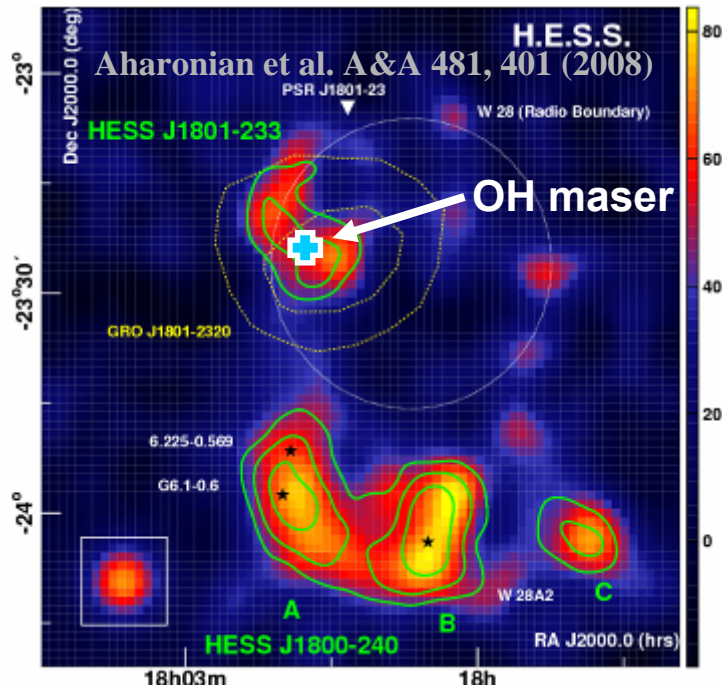
- Not exhaustive ... More surveys needed

IC 443

- SNR interaction with molecular cloud
 - OH masers ensuring true association
 - Correlation with matter density
- seen by MAGIC & VERITAS
 - gamma-ray excess coincides with cloud and masers
 - soft spectrum: $\Gamma = 3.1 \pm 0.3$
- no X-ray sources
 - => hadronic origin likely
 - 3% Crab

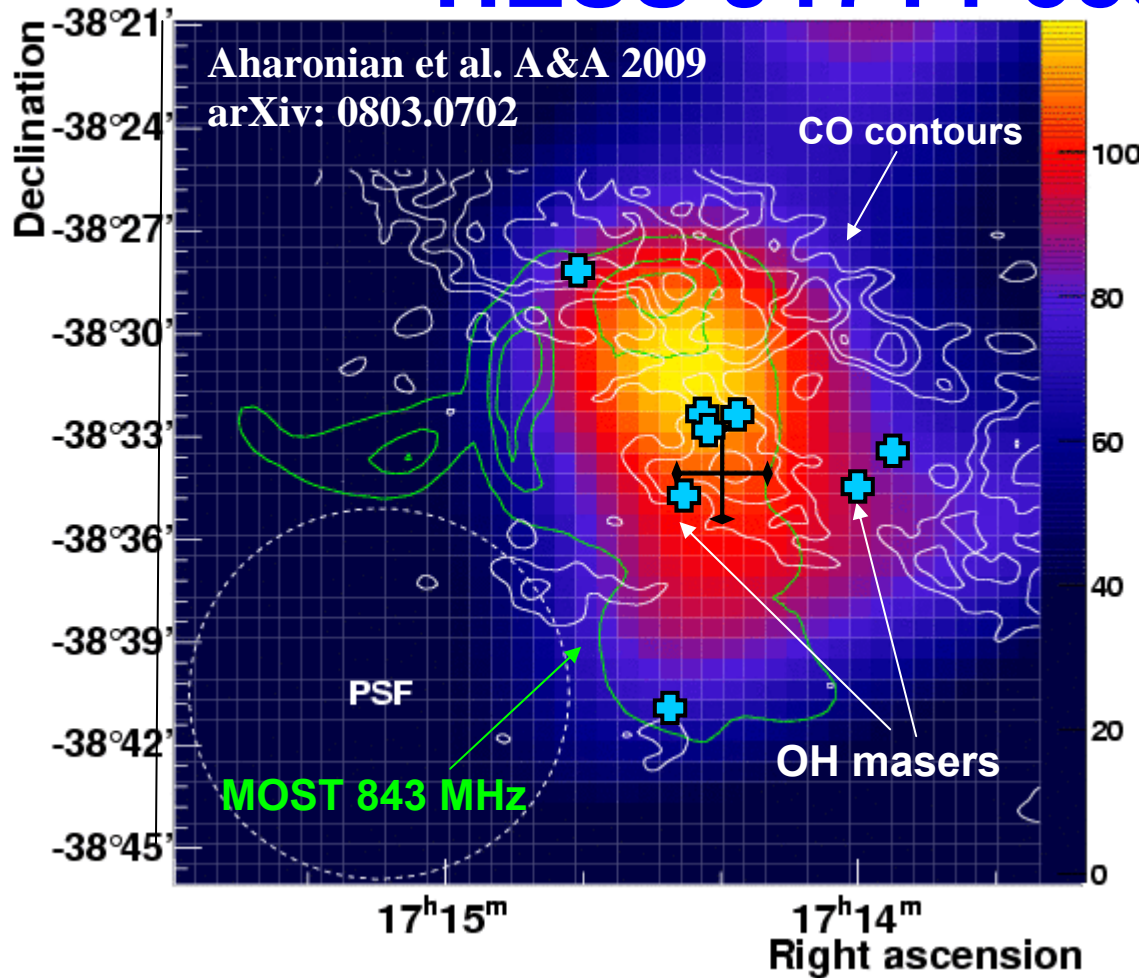


The W28 (SNR G6.4-0.1) field



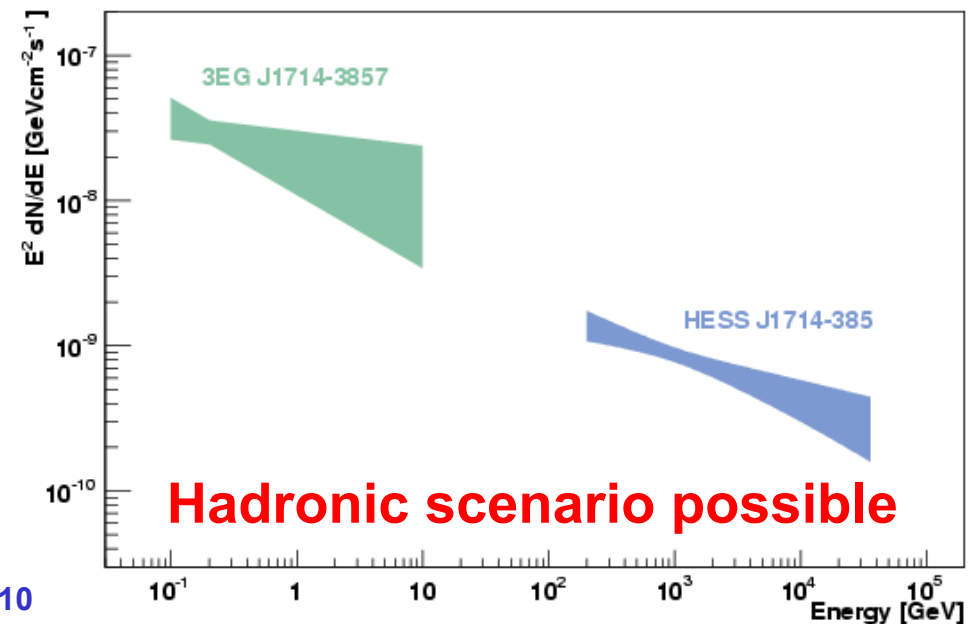
- Complex region in MWL
 - Several SNRs
 - Star formation regions
 - H_{II} regions
 - Northern excess coincident with EGRET source
 - Interaction of the remnant with a dense molecular cloud seen in NANTEN CO observations
 - Northern gamma-ray emission coincident
- => Energy compatible with CRs accelerated by the SNR and interacting with the cloud
- => hadronic scenario likely
- **2% Crab flux**

HESS J1714-385 & CTB 37A



- Coincident with SNR G348.5+0.3 (CTB 37A)
 - spectral index : $\Gamma = 2.30 \pm 0.13$
 - Extended source: $\sigma \sim 4'$
 - **3% Crab flux**
- 3EG J1714-3857 counterpart ?

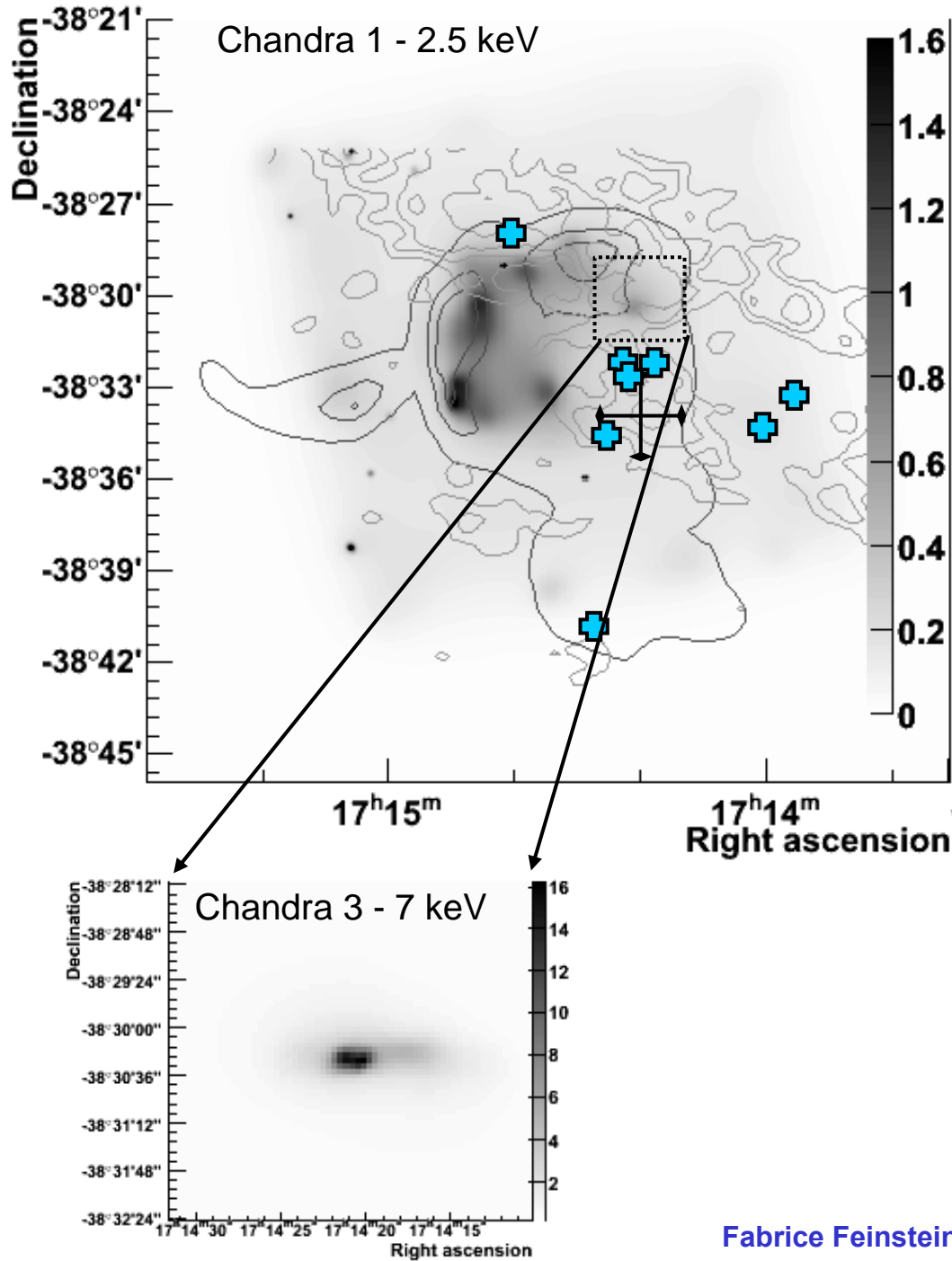
Spectral compatibility



Gamma-ray energetics compatible with CRs accelerated by CTB 37A

=> [4% - 30%] of the SN explosion energy into CRs

Or a PWN ?

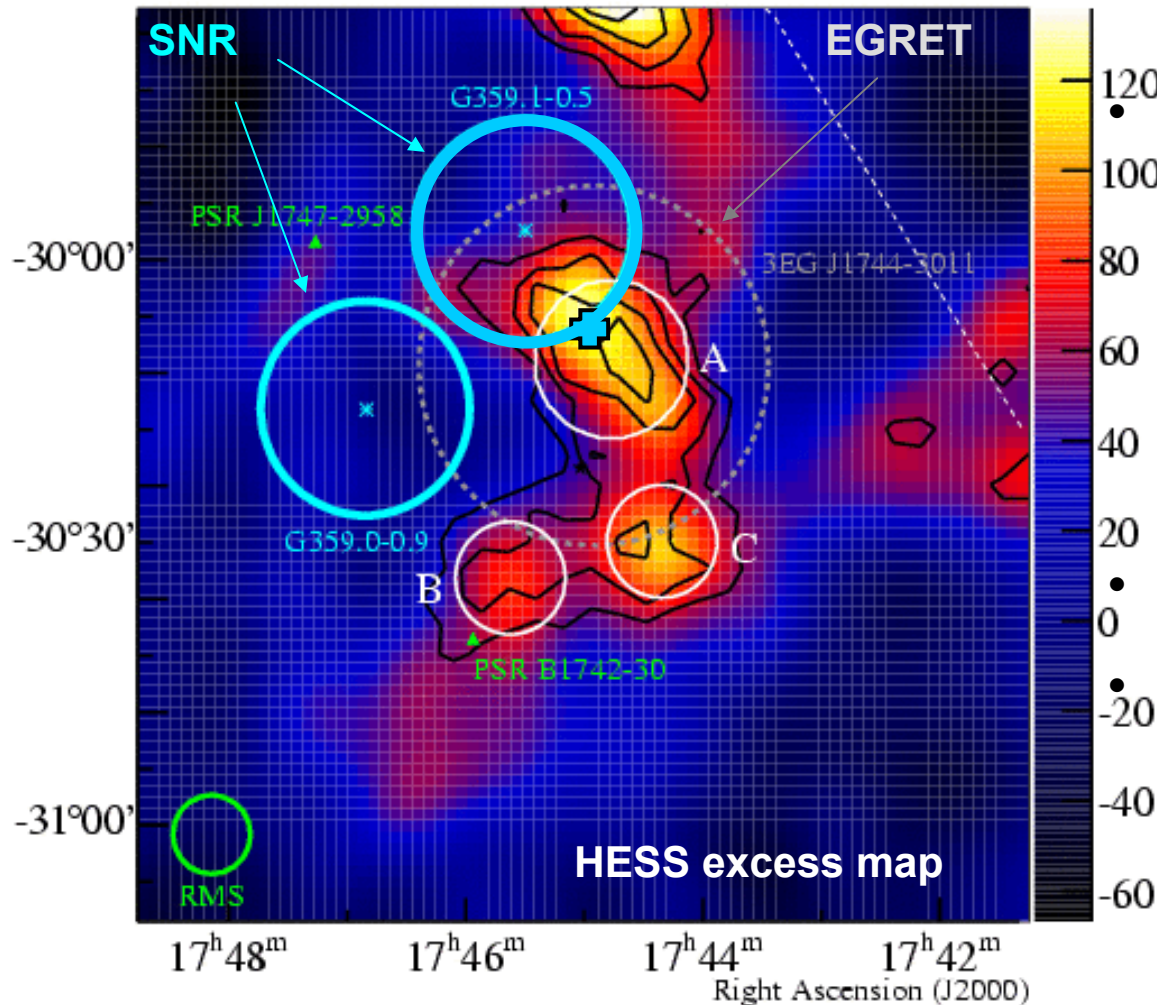


- Recent X-ray observations
 - Chandra & XMM-Newton
- Thermal emission from the interior of the remnant
- PWN candidate discovered coincident with the remnant
- Possibly associated with CTB 37A
- X-ray luminosity implies a spin-down luminosity around 10^{37} erg/s, rather powerful

=> ~0.1% conversion in γ rays

Leptonic scenario possible

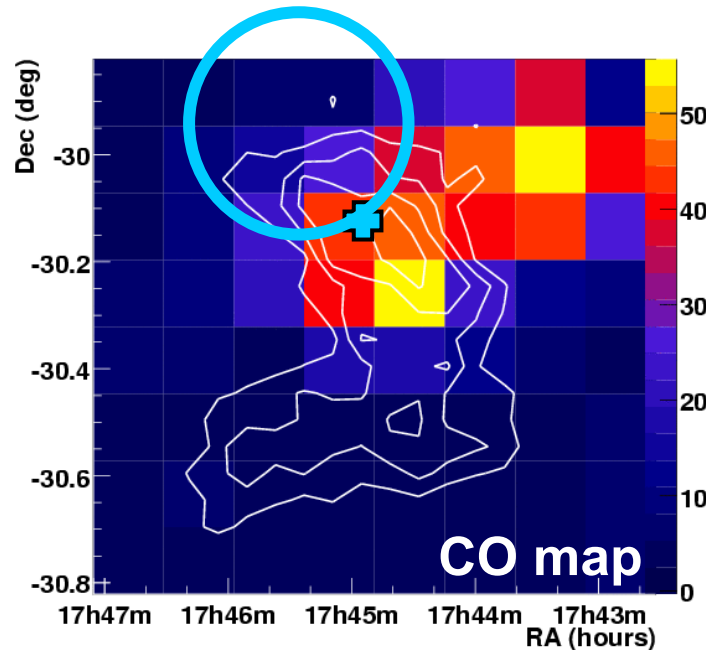
HESS J1745-303



- Discovered in 2004 : Galactic scan
 - 2005 – 2007 : statistics increase
 - ⇒ complex morphology, possibly multiple
 - ⇒ unidentified
- Power law of index $\Gamma = 2.71 \pm 0.1$
- Candidate for **part A** ?
 - Unidentified EGRET source (95% CL)
 - **EGRET** flux compatible
 - **no** XMM counterpart
 - **1.5% Crab flux**

CR hadrons accelerated by G359.1-0.5?

- SNR G359.1-0.5



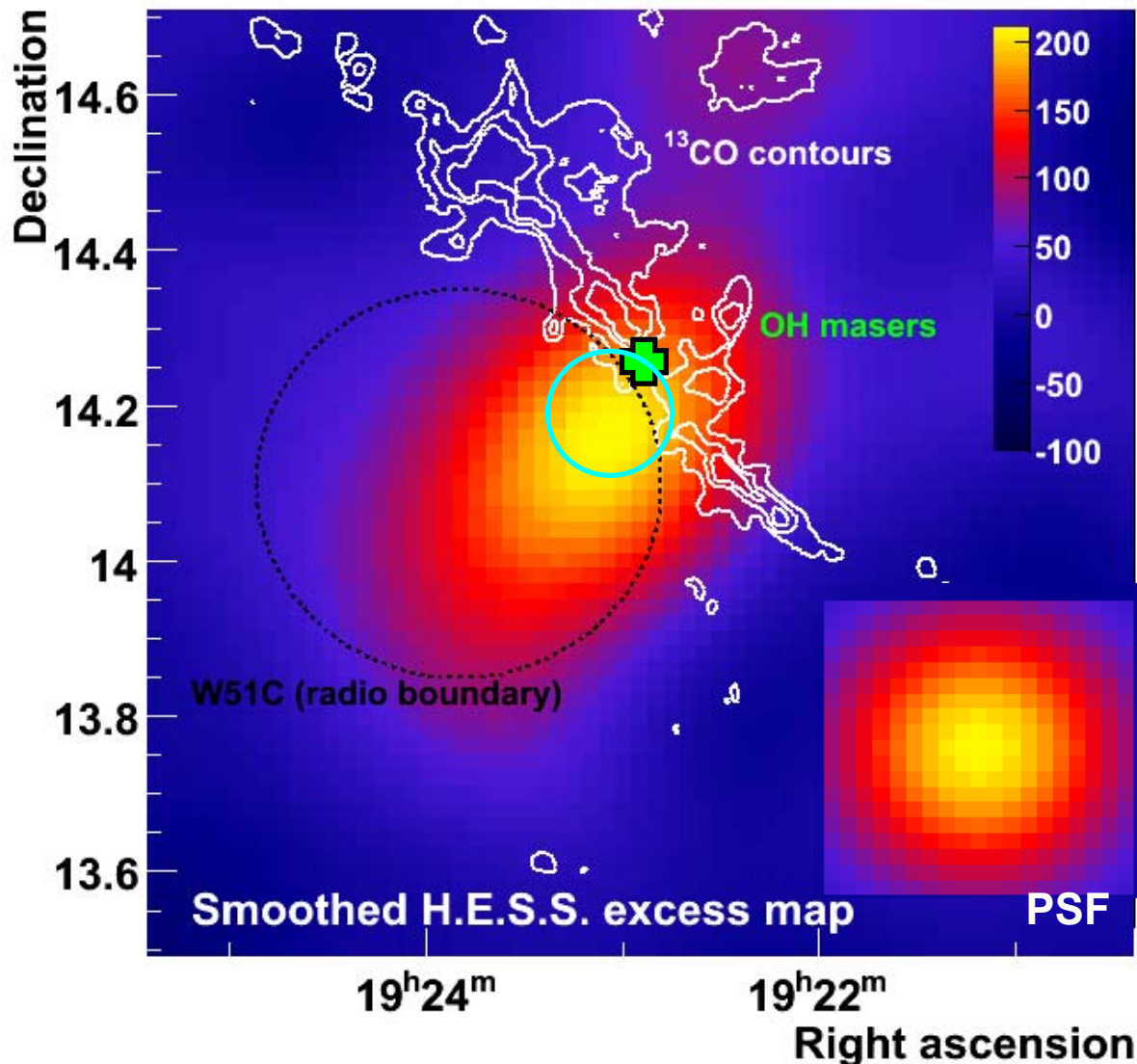
H1 abs. \Rightarrow near GC : $7,6 \pm 0,4$ kpc

- Blast wave interacts with a ring of matter
 - OH masers at 1720 MHz towards the rim of the SNR
 - CO observations [-100 km/s, -60 km/s], comp. with GC, reveal a coincidence with γ - ray source

Aharonian et al. A&A 483, 509A (2008)

- Hadrons interact with the cloud ?
 - \Rightarrow 15% to 60% of the SN explosion energy into cosmic rays

A new OH / γ -ray SNR: HESS J1923+141



3 % Crab

flux

- **Shell-type SNR W51C/G49.2-0.7**

- Radio partial shell
- Thermal X-rays

- **Shocked molecular cloud**

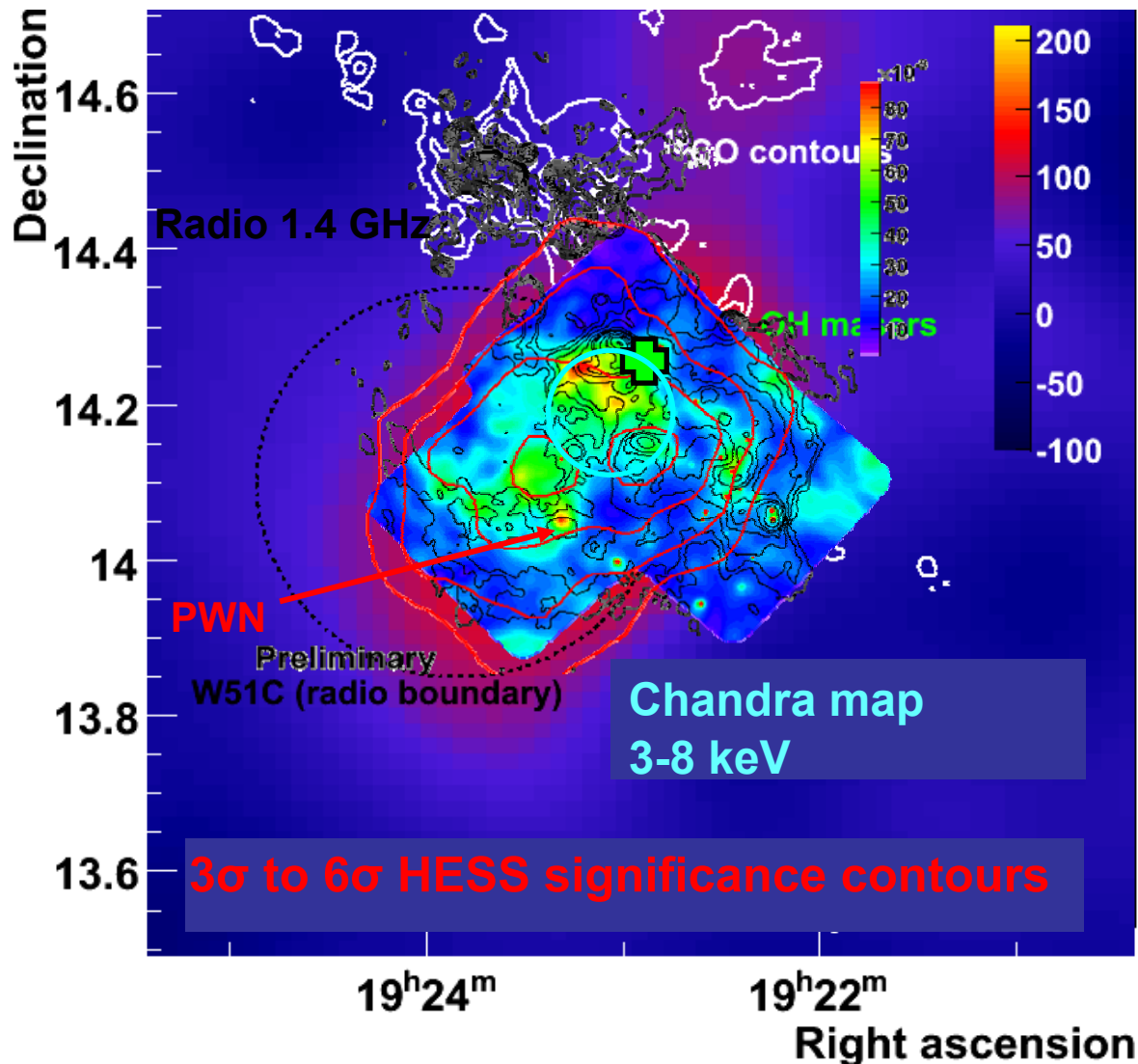
- $M_{\text{cloud}} = 1.9 \times 10^5 M_{\odot}$
- $1500 M_{\odot}$ of shocked gas

=> **potential target for cosmic rays accelerated by W51C**

- ~ 10% of the cloud contained in the shocked region

=> **~ 30x the local cosmic-ray density above 1 TeV**

Accelerated **hadrons** or **electrons** ?



- Complex region in X rays
- Thermal SNR shell
- Hard X rays from star forming regions
- Non-thermal emission coincident with the remnant

CXO J192318.5+140305

\Rightarrow a likely PWN

- According to Li, Lu & Li (2008) the pin-down luminosity L_{sd} can be estimated from X rays

- $L_{sd} = 4.5 \cdot 10^{36} \text{ erg/s}$

\rightarrow the γ -ray luminosity is less than 0.1% of this L_{sd}

Summary, conclusions, prospects

Several SNR/MC associations observed by HESS + 1 MAGIC/VERITAS
more in store...

- Physical associations revealed by OH masers at 1720 MHz
- EGRET + *Fermi* counterpart possible to lower energy for all of them
- **A hadronic scenario is plausible for each case**

=> Gamma-ray flux compatible with CRs accelerated by the SNR

An alternative leptonic scenario for some of them

A VAST FUTURE !

New (young...) SNRs
to discover

New multi- λ [ν ?]
observations

developments
in MHD

New chemical tracers
of non-thermal eq.

More accurate
GMC surveys