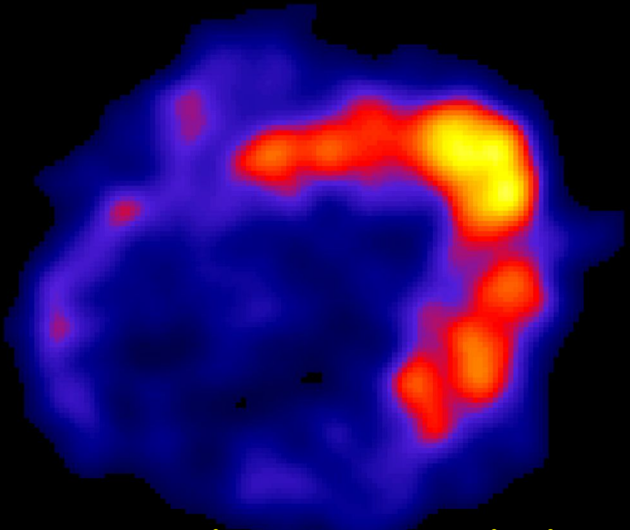
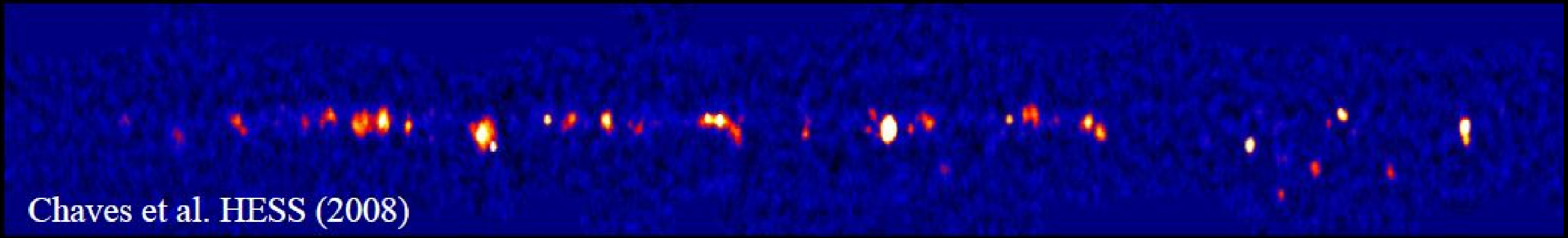


Constraints on cosmic-ray origin from gamma-ray observations of supernova remnants



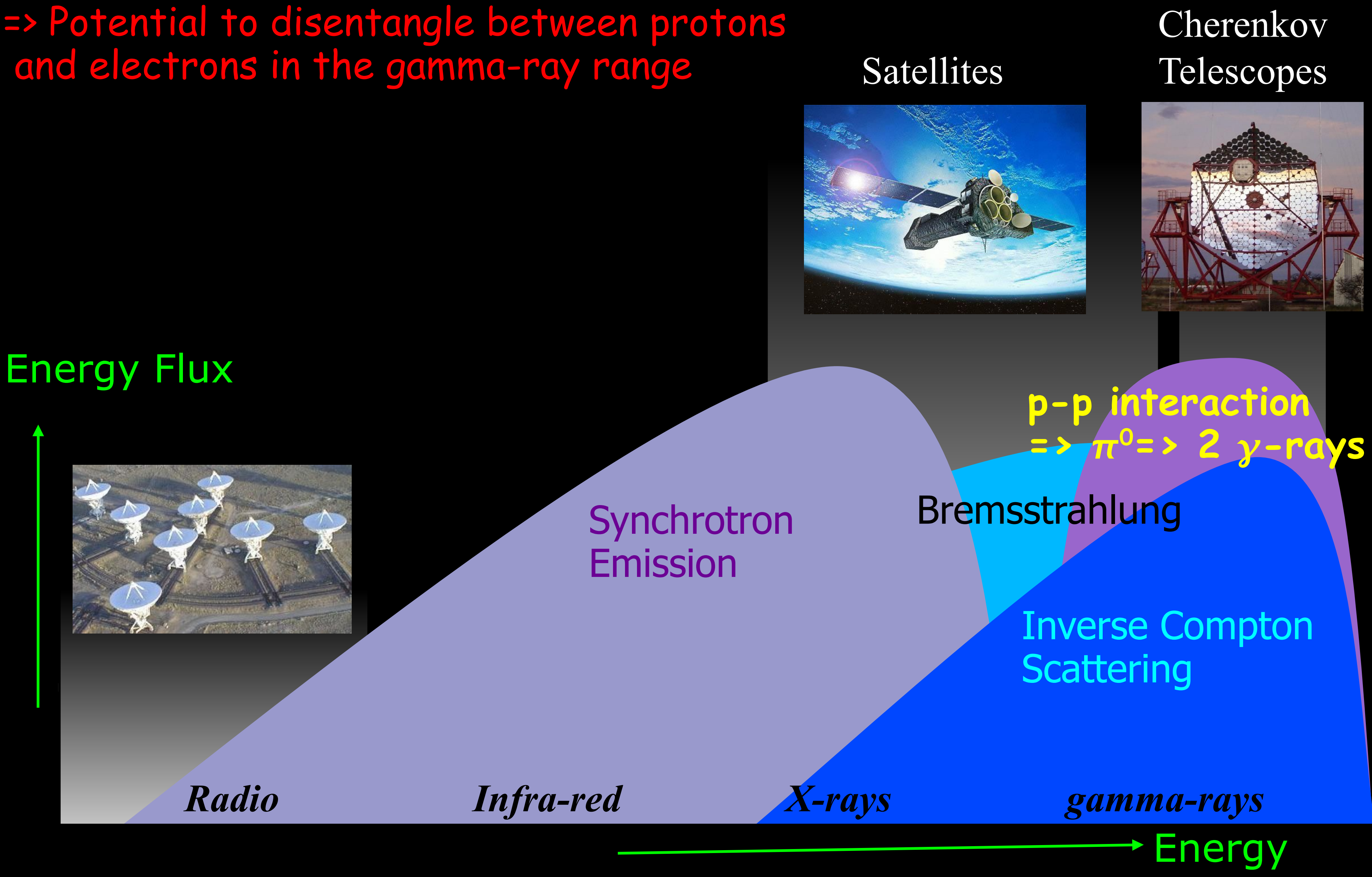
Marianne Lemoine-Goumard

(CENBG, Université Bordeaux, CNRS-IN2P3, France)

On behalf of the Fermi-LAT and HESS Collaborations

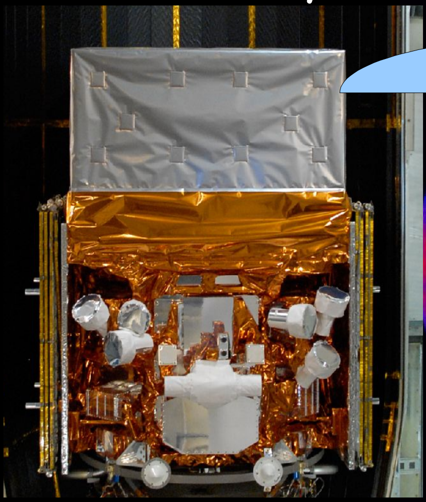
Radiative processes in SNRs

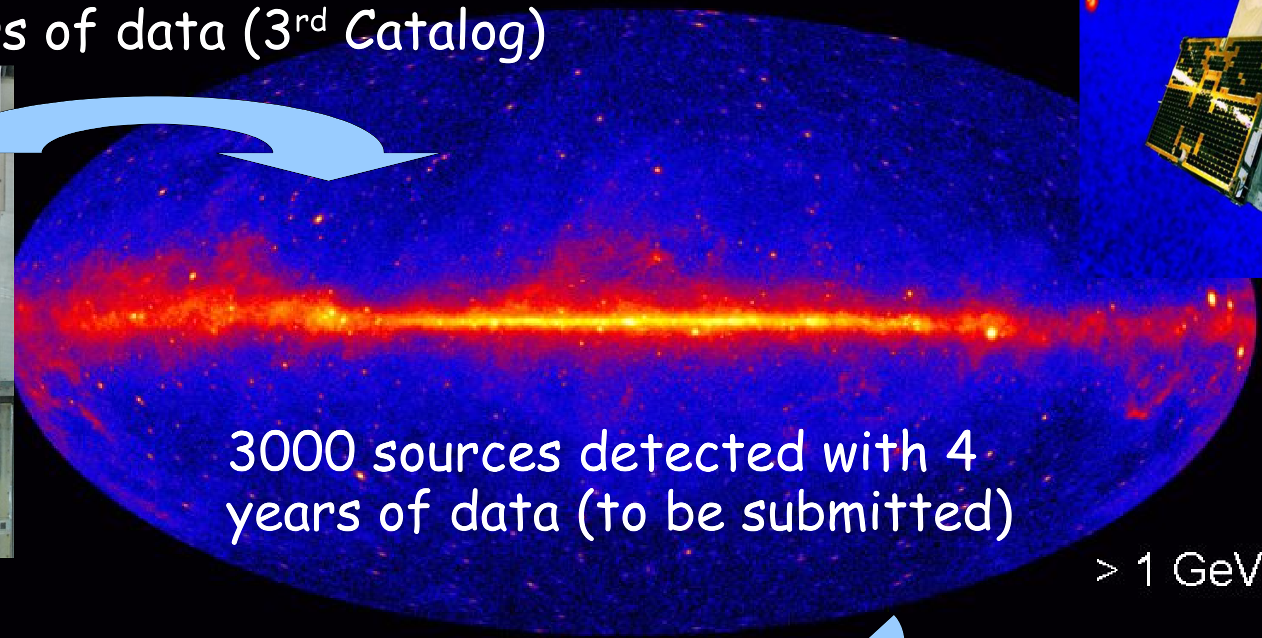
=> Potential to disentangle between protons and electrons in the gamma-ray range



The gamma-ray sky viewed by satellites

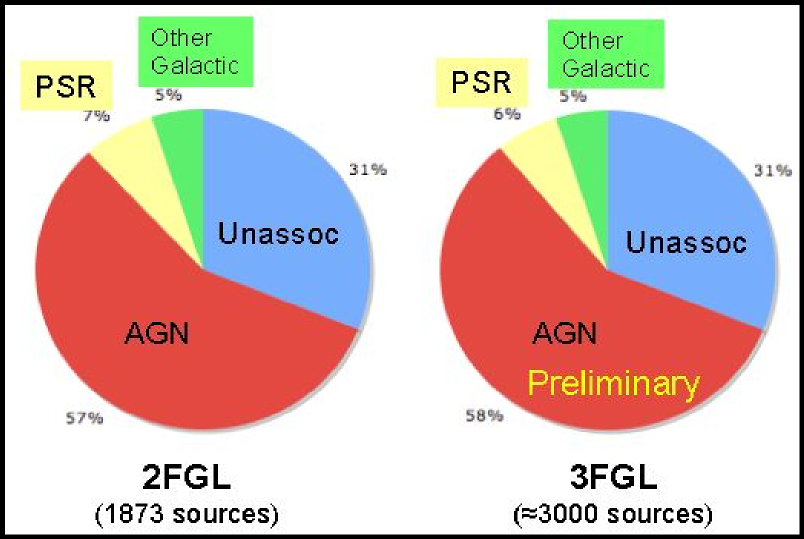
4 years of data (3rd Catalog)





3000 sources detected with 4 years of data (to be submitted)

> 1 GeV



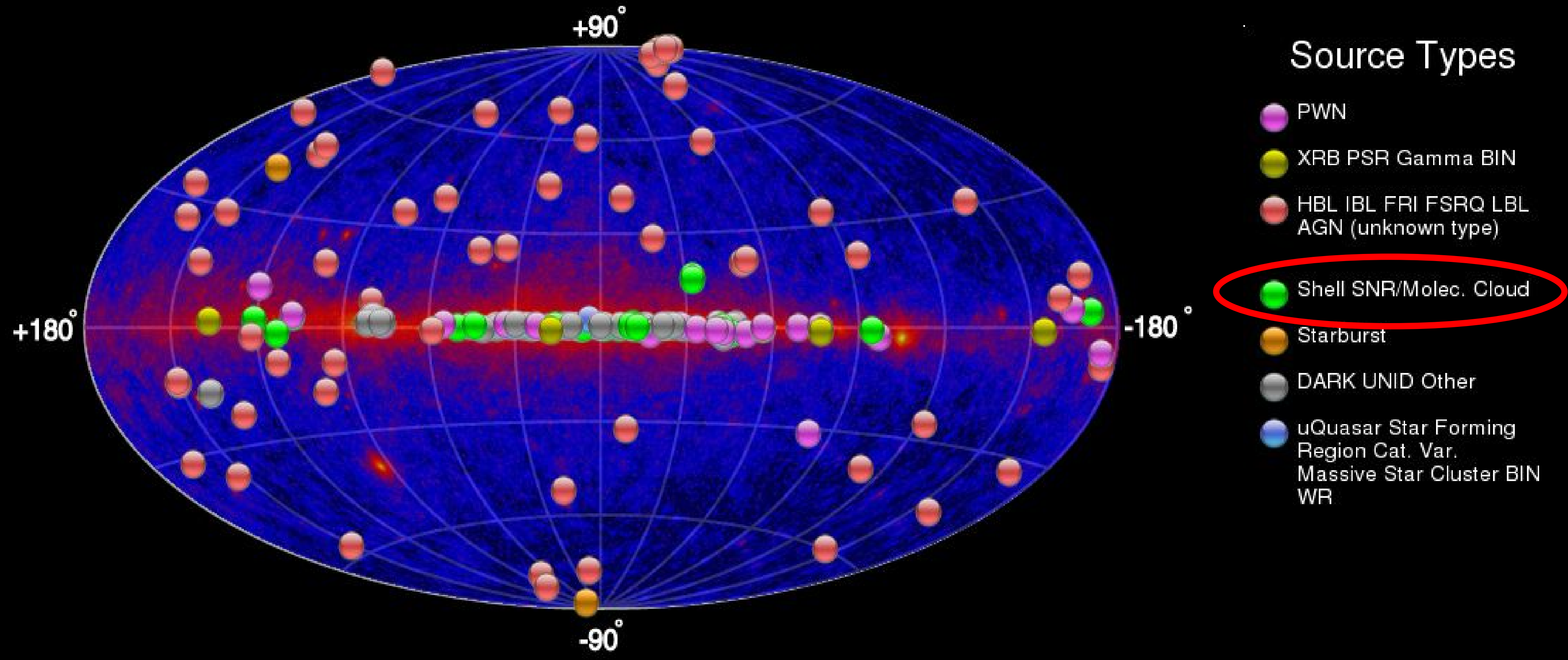
Similar percentage of unassociated sources (thanks to on-going effort on deepening counterpart catalogs)

VHE gamma-ray experiments

Higher energy coverage (E > 20 GeV)
Smaller field of view: 3.5° (MAGIC) – 5° (HESS)
Better angular resolution (in comparison to Fermi !): <0.1°

~150 VHE gamma-ray sources (2/3 are Galactic)

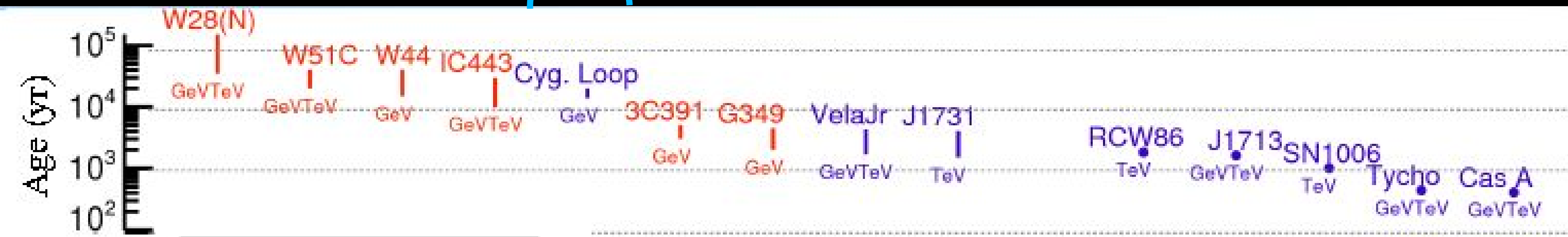
20 being associated to SNRs/molecular cloud



A large sample of SNRs detected in gamma-rays

Evolved SNR without MC interaction

Credit: M. Renaud, SF2A, 2011



Evolved SNRs Interacting with Molecular Clouds

Young SNRs interacting with Molecular Clouds

Young shell-type SNRs

Historical SNRs

interaction/association with MC

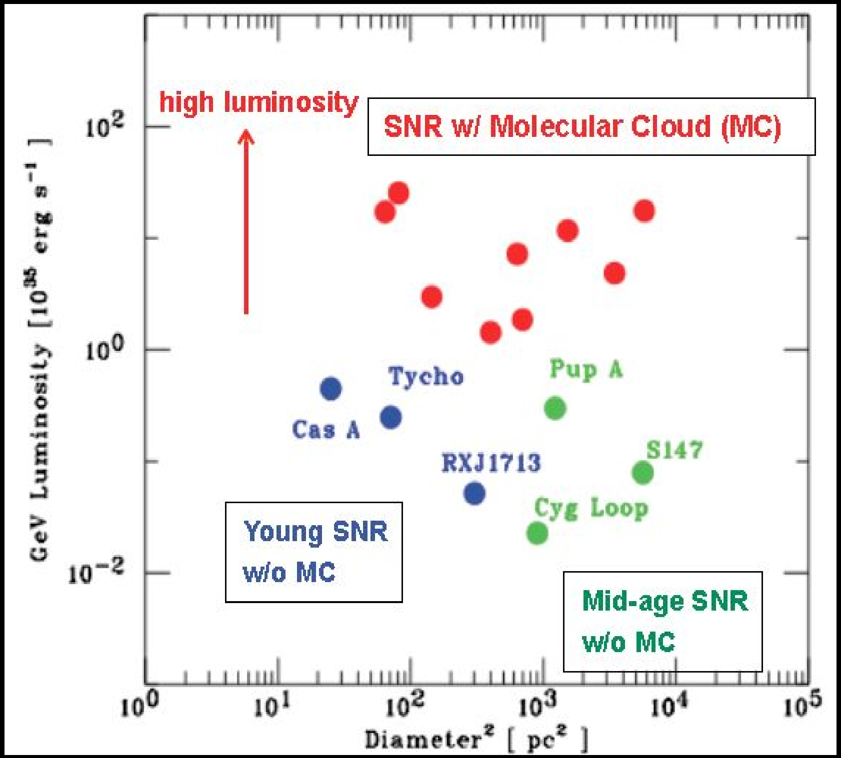
isolated

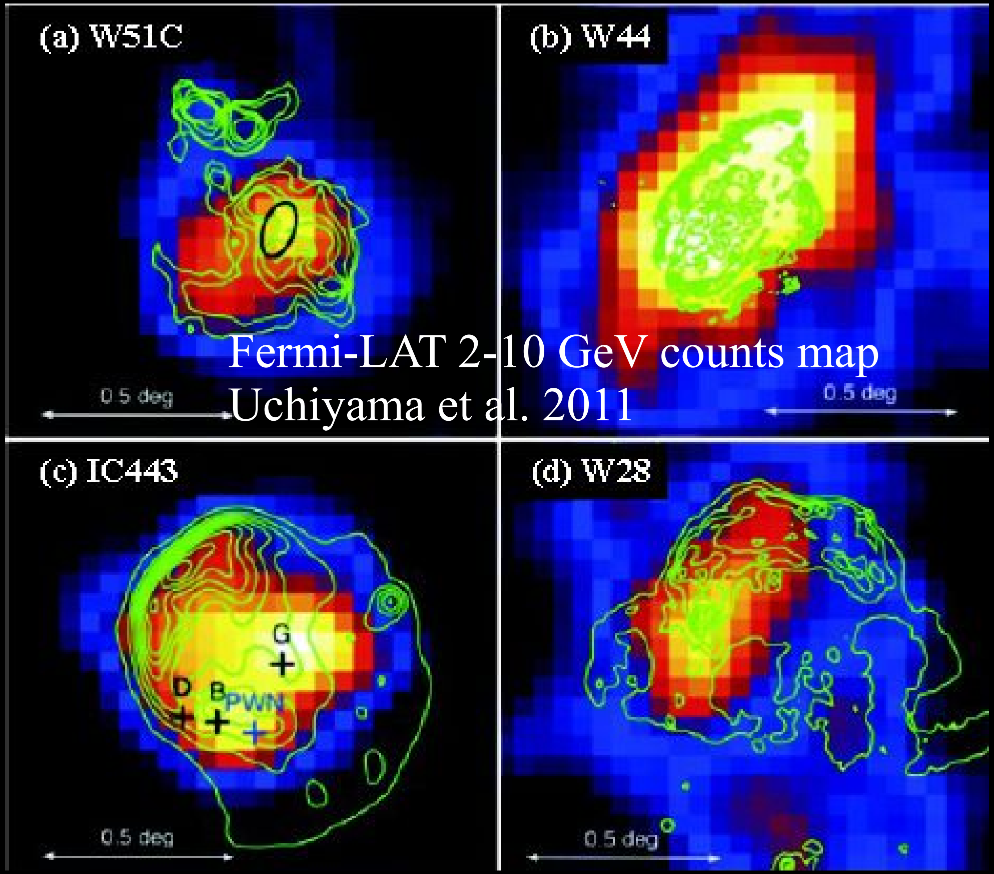
N.B: ~50% SNRs are detected at GeV (Fermi) and TeV

See Talk by
Emma de Oña tomorrow

SNRs interacting with Molecular Clouds at GeV

- Ages between 10 000 to 100 000 years
- Interaction with MCs can act as target material for pion production
- Bright in Fermi-LAT energy range (very high luminosity up to 10^{36} erg/s)
  - Usually extended with a size consistent with the radio emission

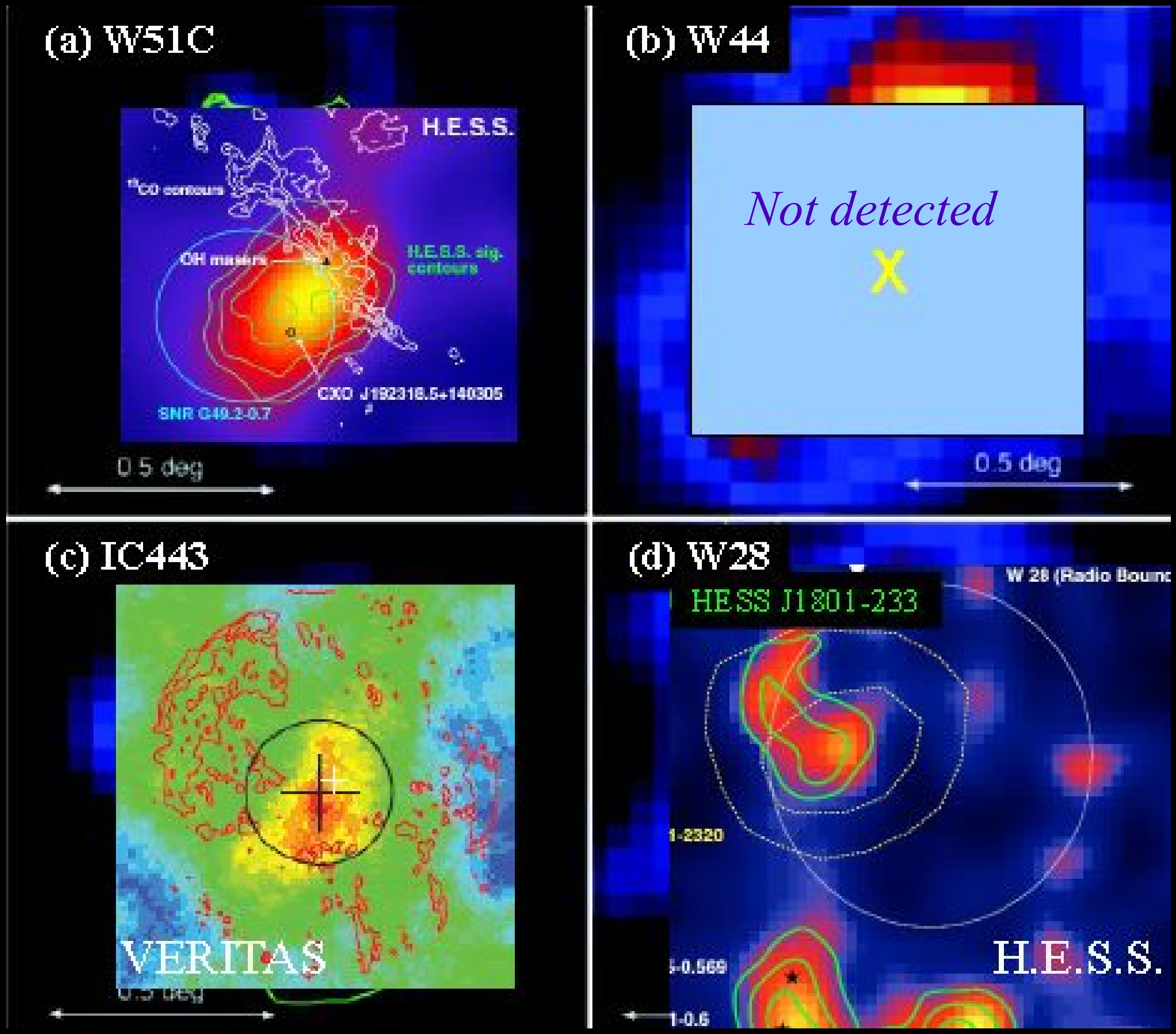




Fermi-LAT 2-10 GeV counts map
Uchiyama et al. 2011

SNRs interacting with Molecular Clouds at TeV

Typically faint TeV sources (if detected)



A good example: the SNR W51C

D ~6 kpc; Age ~20 kyrs

Clear sign of molecular cloud interaction (OH maser)

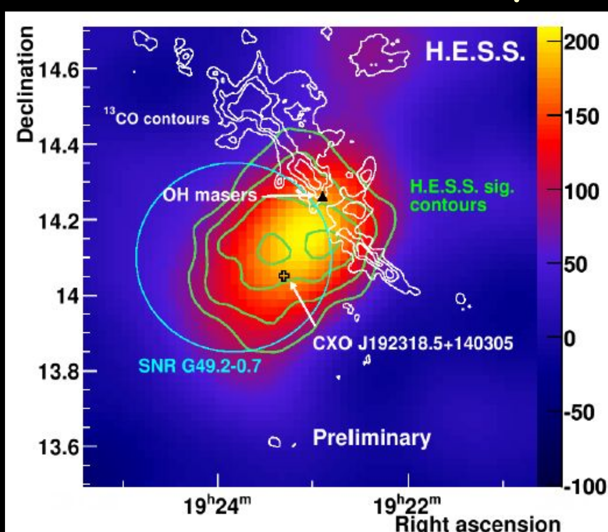
SNR diameter: 30 arcmin

Detected by HESS at TeV energies: 3% Crab (above 1 TeV)

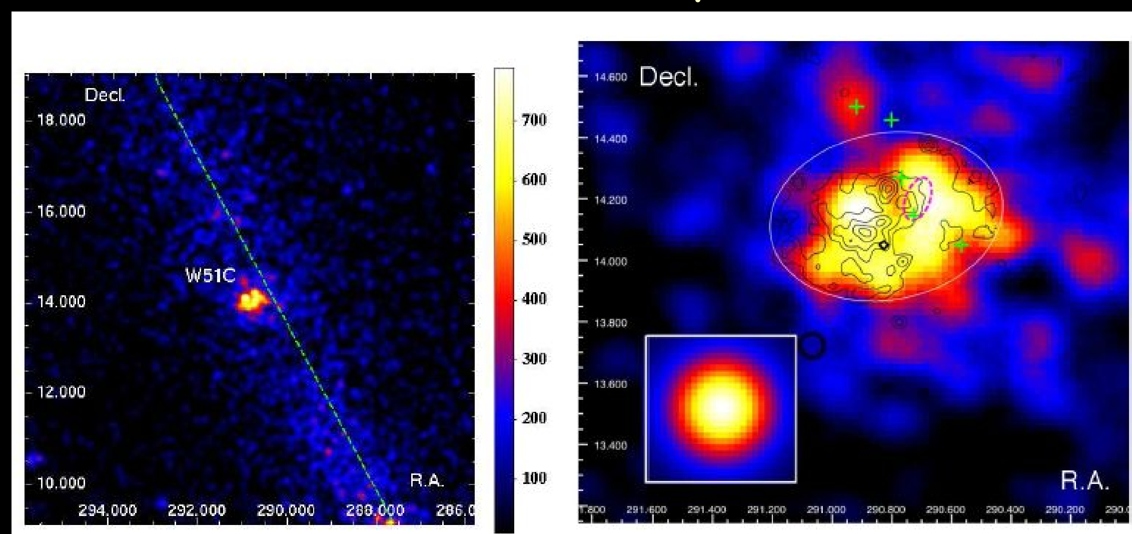
- Several possible associations: PWN, star forming region, molecular cloud interaction

Detected by Fermi-LAT above 200 MeV; clearly extended

HESS excess map



Fermi-LAT counts map (2 - 10 GeV)



Broad-band modeling of W51C

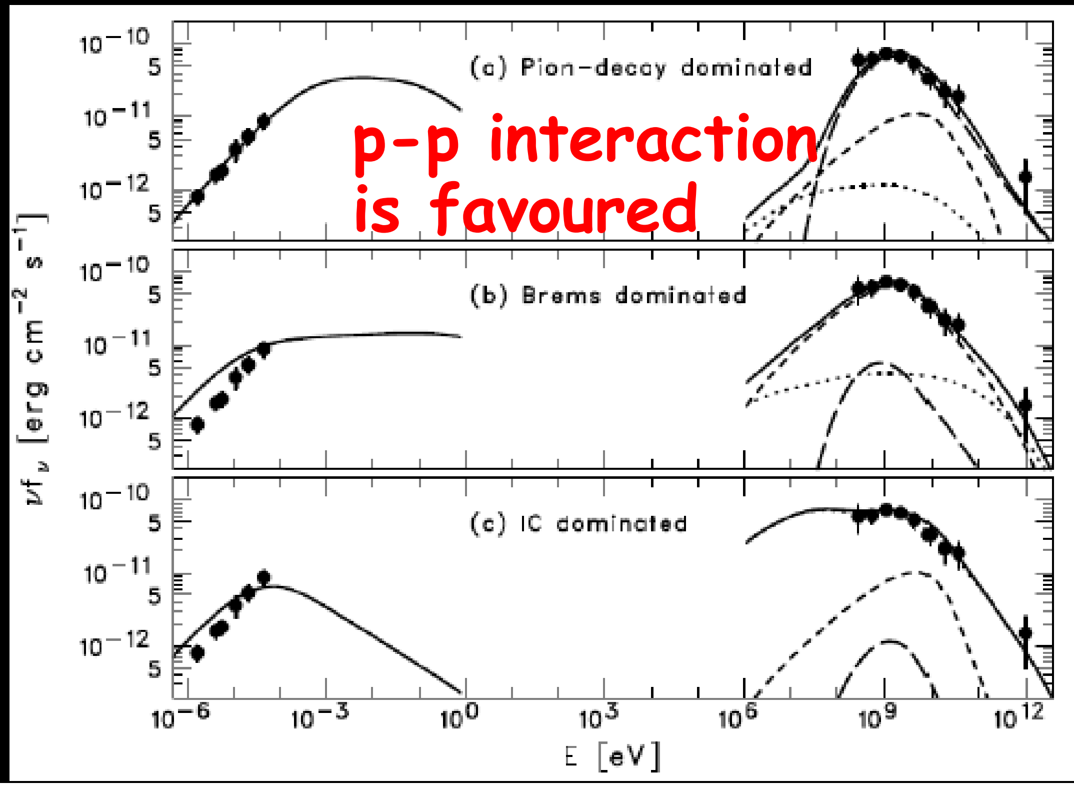
Abdo, A. A. et al. 2009, ApJL, 706, L1

Broken PL spectrum

Leptonic models need large electron/proton ratios; pion-decay is favoured

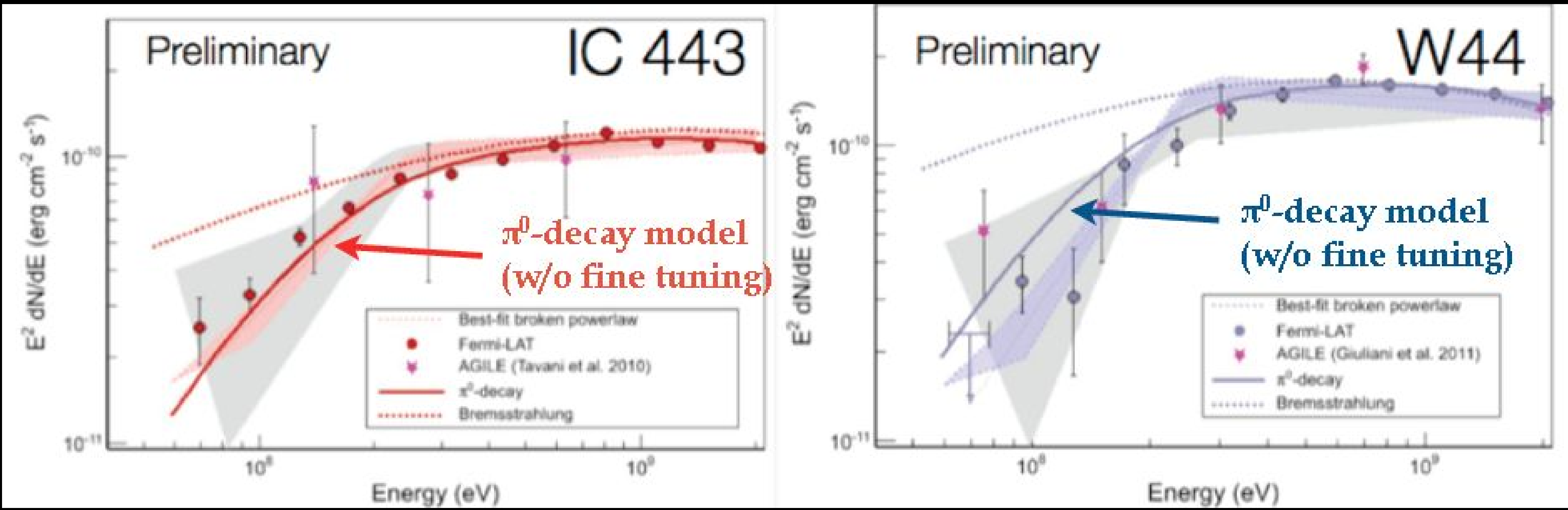
Brems: hard to reproduce the radio synchrotron spectrum => less likely but not fully excluded

IC: very large energy content in electrons and very low density => very unlikely



	Parameters					Energetics	
Model	a_e/a_p	Δs	p_{br} (GeV c^{-1})	B (μG)	$\bar{n}_H$ (cm^{-3})	W_p (10^{50} erg)	W_e (10^{50} erg)
(a) π^0-decay	0.02	1.4	15	40	10	5.2	0.13
(b) Bremsstrahlung	1.0	1.4	5	15	10	0.54	0.87
(c) Inverse Compton	1.0	2.3	20	2	0.1	8.4	11

Fermi LAT Spectra of SNRs W44 & IC443: Signature of π^0-decay gamma-rays



Our previous papers reported spectra only >200 MeV

Here we report spectra down to 60 MeV thanks to:

Recent update ("Pass-7") of event reconstruction, which largely improved effective area at low energies

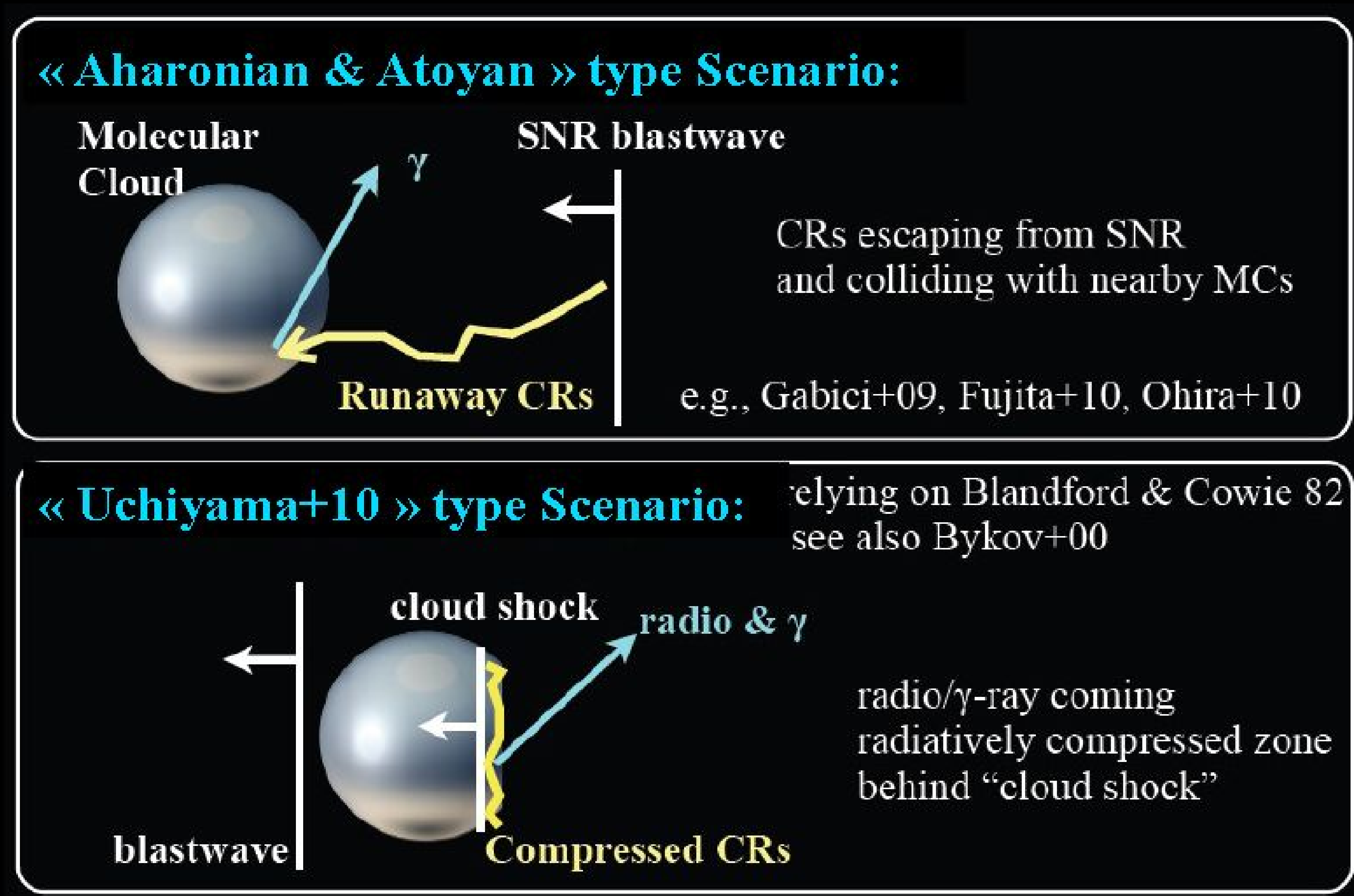
Increased exposure time: 1 yr ➔ 4 yr

Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra

Ackermann, M. et al. 2013, Science, 339, 807

Two main scenarii proposed

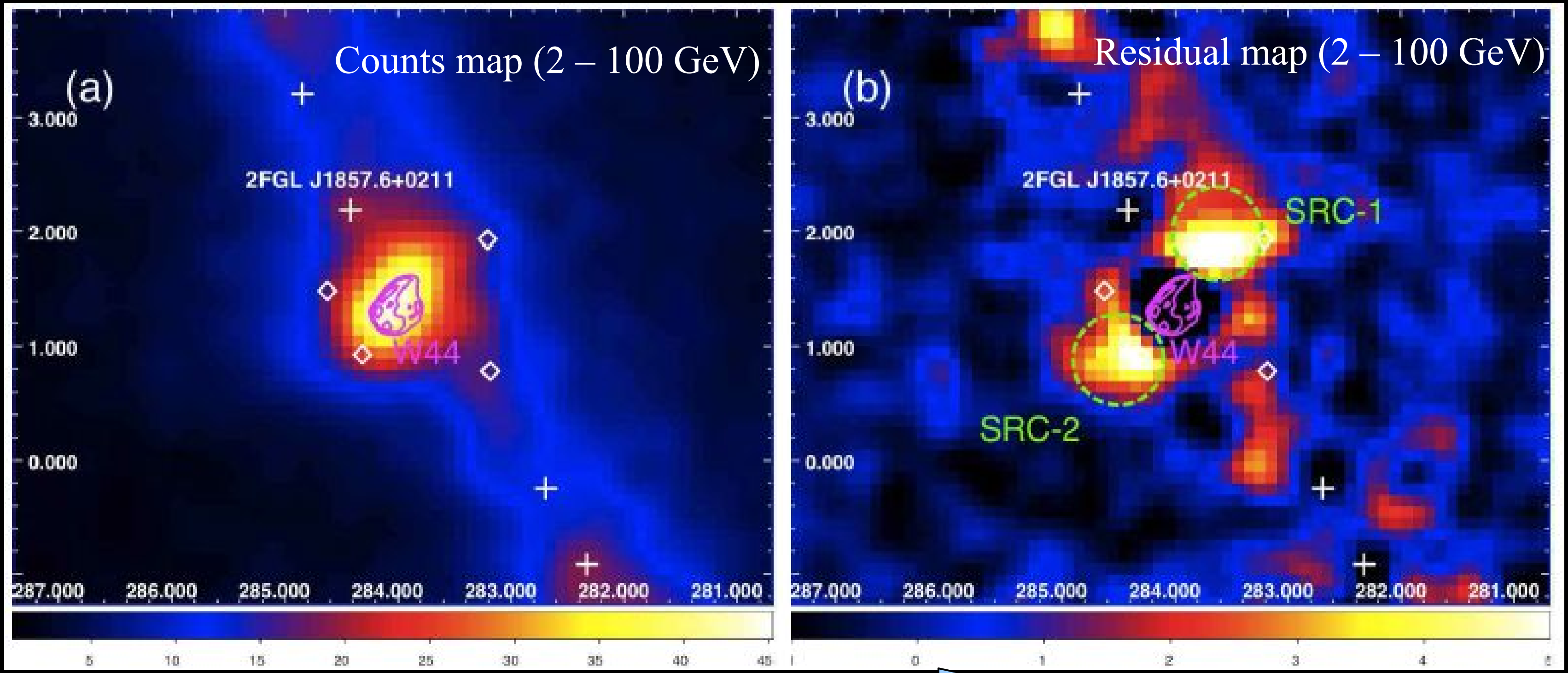
See Talk by S. Gabici



Escaping cosmic-rays: the case of W44

Presence of large-scale GeV emission found in the vicinity of W44

Uchiyama et al. 2012, ApJL, 749, 35

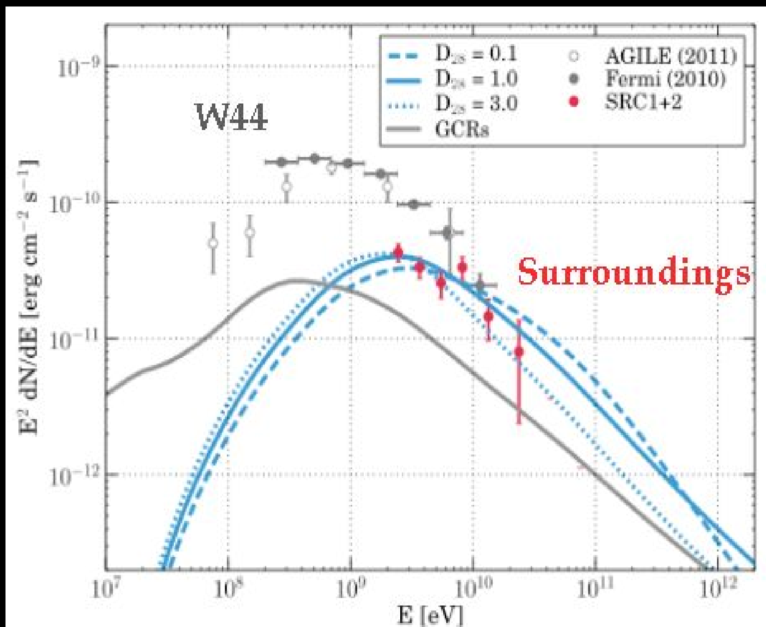


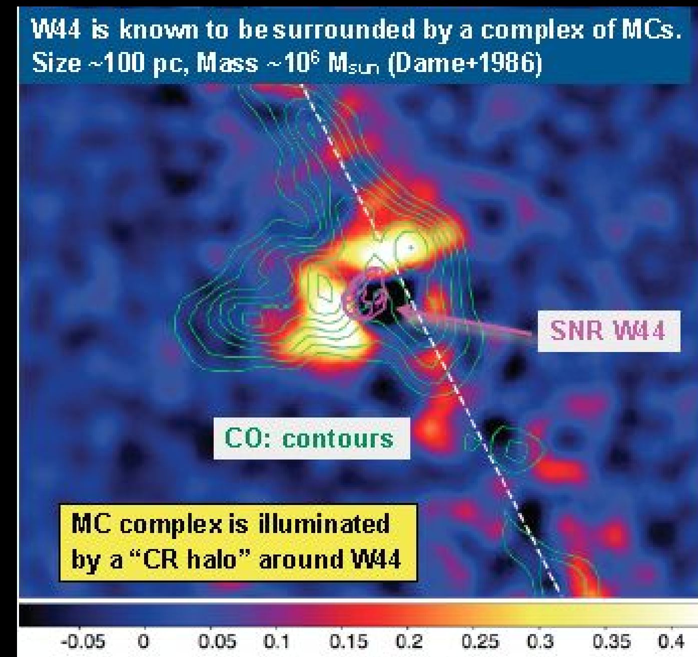
Subtraction of W44 assuming radio map = gamma-ray map

- Excess gamma-ray emission coincident with surrounding dense clouds
- Cosmic-rays that escaped from the SNR ?

Amount of escaping cosmic-rays

Energetics in broad agreement with the conjecture that SNRs are the main sources of Galactic CRs



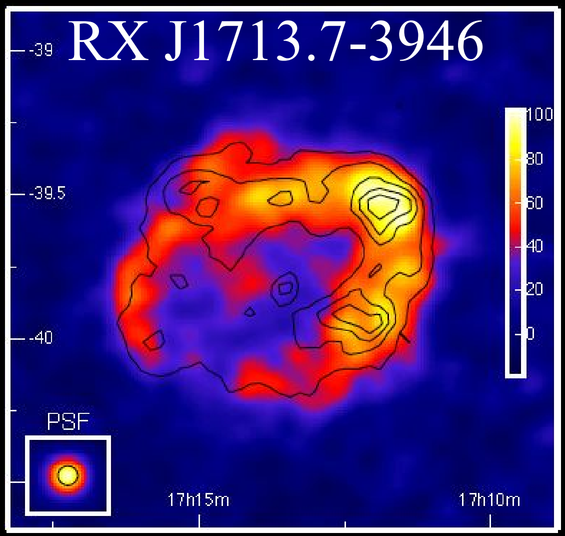


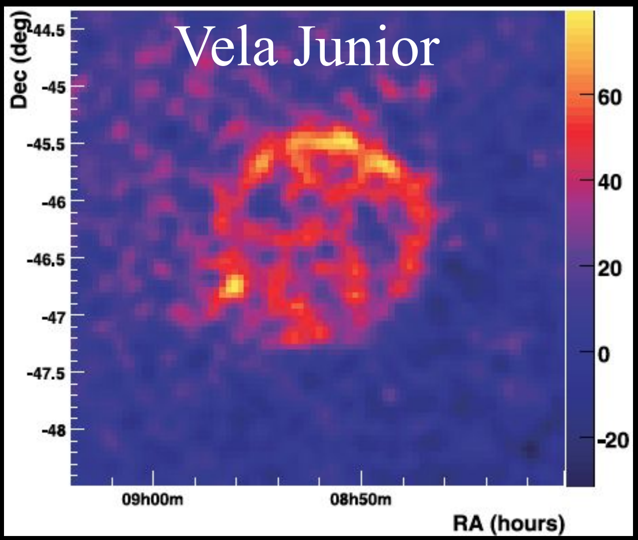
- ☑ Molecular clouds illuminated by escaping CRs (assumed to be uniform within r<L)
  - L ~100 pc, Mass = 0.5×10^5 $M_\odot$
- ☑ Diffusion coefficient of the ISM (isotropic)
  - $D(p) = D_{28}\,(cp/10\ \mathrm{GeV})^{0.6}\,10^{28}\ \mathrm{cm^2/s}$

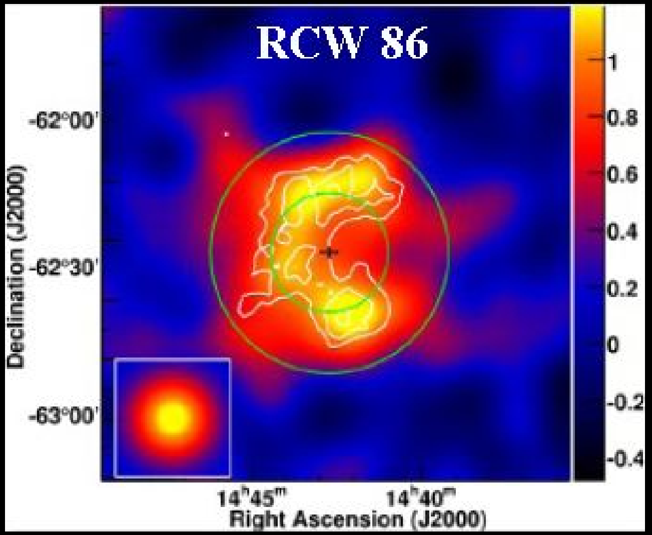
→ Solving the diffusion equation, we estimate the total kinetic energy channeled in CRs to $(0.3\text{-}3)\times10^{50}$ erg

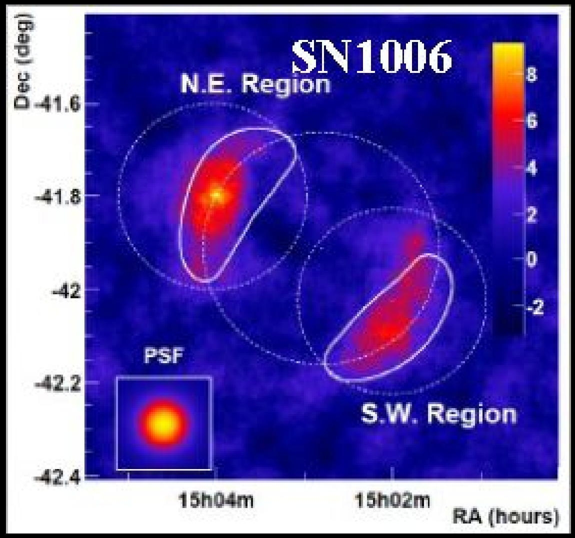
Young shell-type SNRs in the TeV range

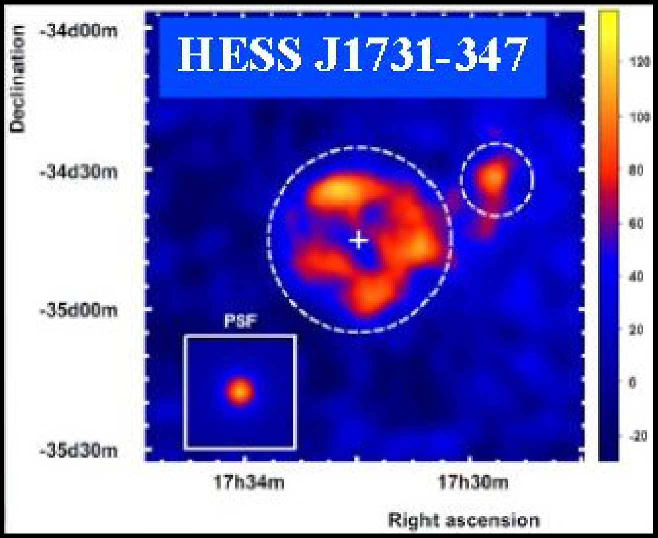
5 shell-type SNRs detected by HESS









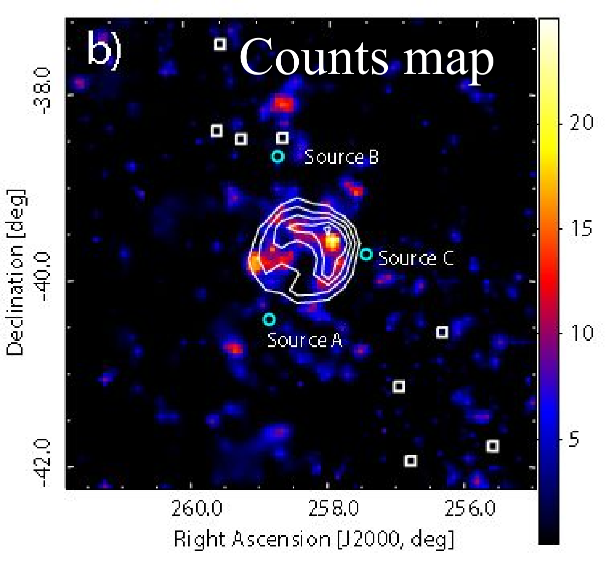


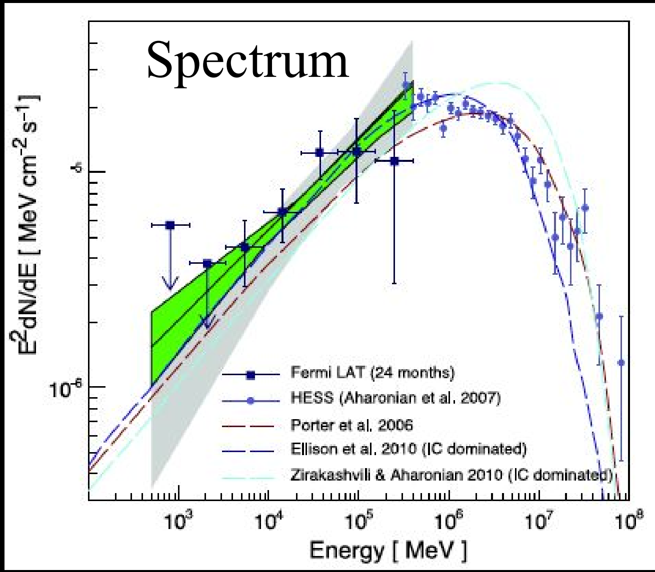
Marianne Lemoine-Goumard, TeVPA-IDM, Amsterdam, June 2014

Young shell-type SNRs in the GeV range

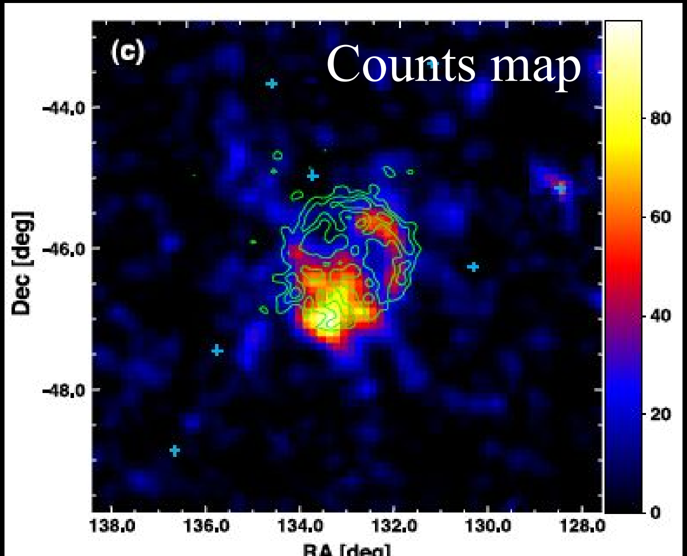
The 2 brightest are detected by Fermi-LAT

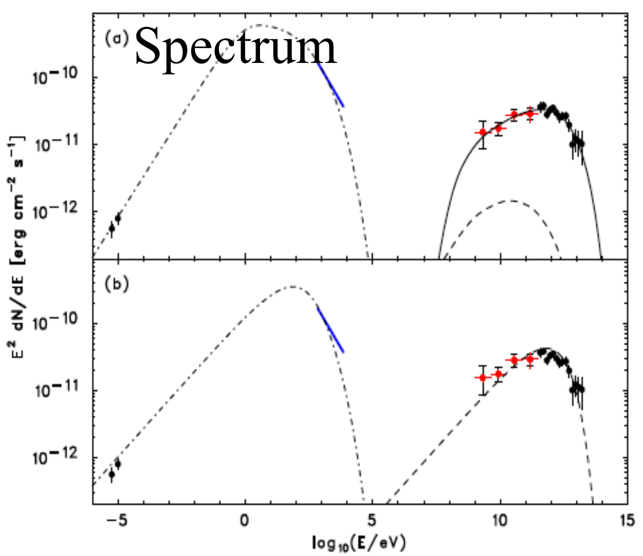
RX J1713.7-3946





Vela Junior





The case of RCW 86

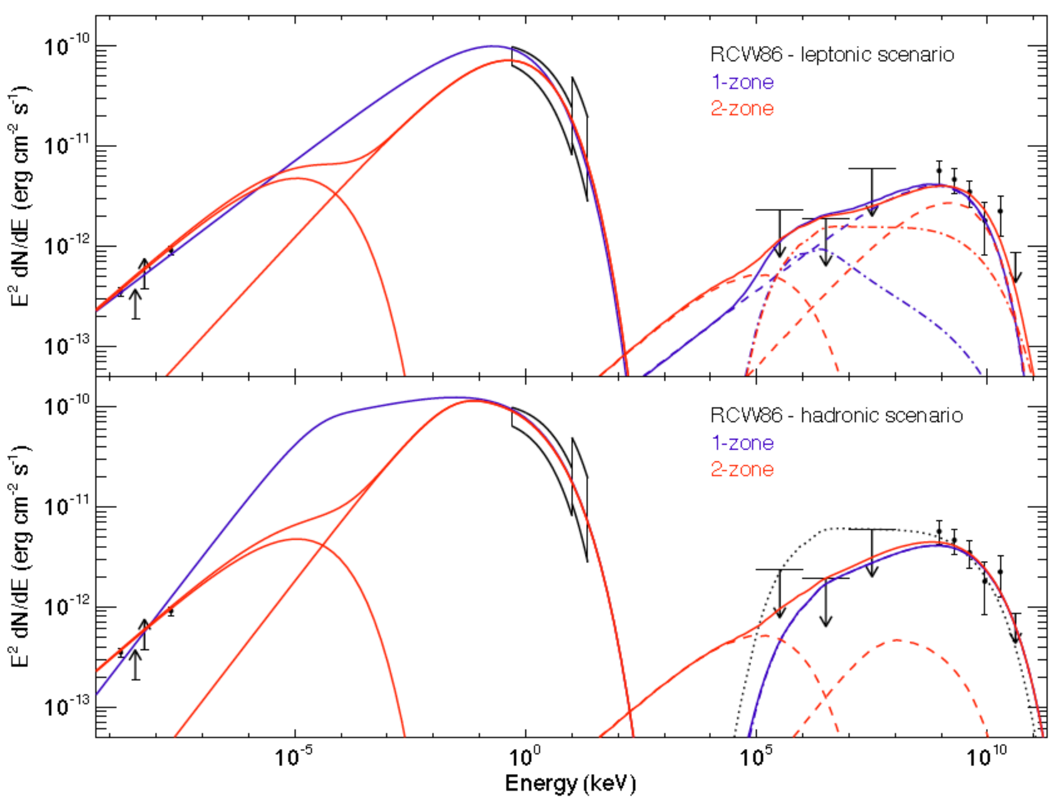
Lemoine-Goumard, M. et al. 2012, A&A, 545, A28

No significant detection using 40 months of Fermi observations

Upper limits derived

$\Gamma < 1.8$

Whatever the origin of the gamma-ray signal: $E < 8\% \, E_{SN}$



	Leptonic model			Hadronic model		
	One-zone	Two-zone		One-zone	Two-zone	
		radio	X-ray		radio	X-ray
B (μG)	15 (25)	> 10 (> 25)	15 (25)	400	> 10 (> 25)	> 50
Γ	2.3	2.2	2.0	1.8	2.2	1.8
$E_{break,e}$ (TeV)	–	–	–	0.04	–	3.0
$E_{max,e}$ (TeV)	25 (20)	0.2 (0.15)	25 (20)	7	0.2 (0.15)	20
$E_{max,p}$ (TeV)	100	–	100	80	–	80
η_e ($\times 10^{-2}$ $d_{2.5}^2$)	2 (0.9)	< 2.5 (< 0.5)	0.04 (0.02)	0.004	< 2.5 (< 0.5)	0.006
η_p ($\times 10^{-2}$ $d_{2.5}^2/\bar{n}_{cm^{-3}}$)	< 2	–	< 4	7	–	7
K_{ep}	> 0.1 (> 0.05)	–	> 0.006 (> 0.003)	0.002	–	0.001

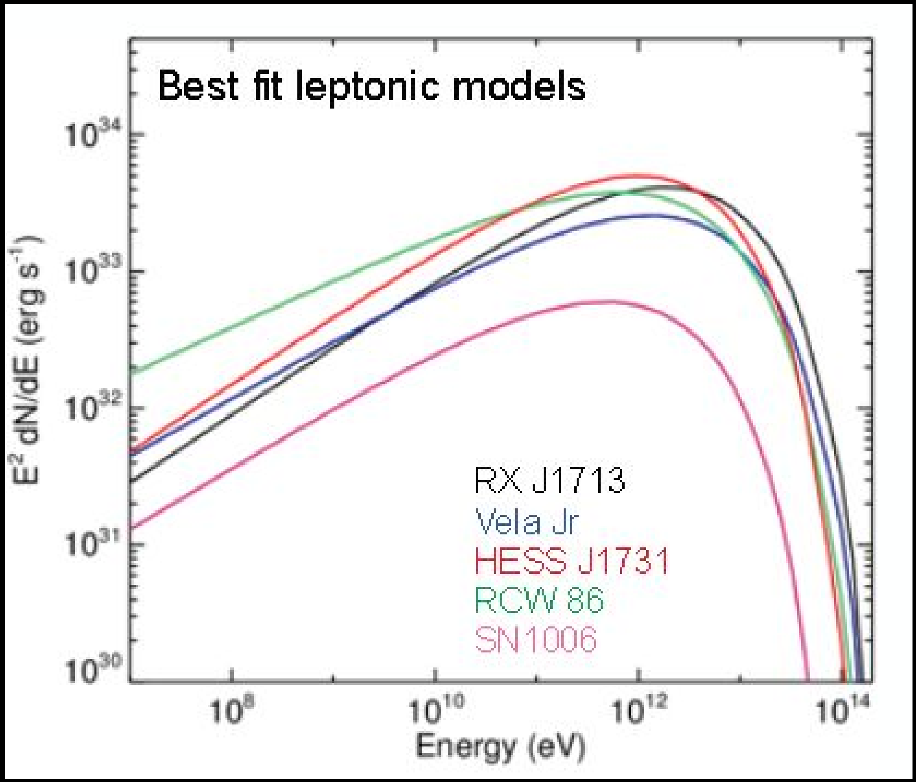
Young shell-type SNRs in leptonic-dominated model

Using parameters from literature

- Similar γ-ray luminosity for different SN type
- Similar physical scenario ?

Leptonic dominated scenario ?

Similar seed photons for IC



Credit: F. Acero

- Except SN 1006. Why ?

- high latitude
- Bipolar morphology, lower V_{accel}

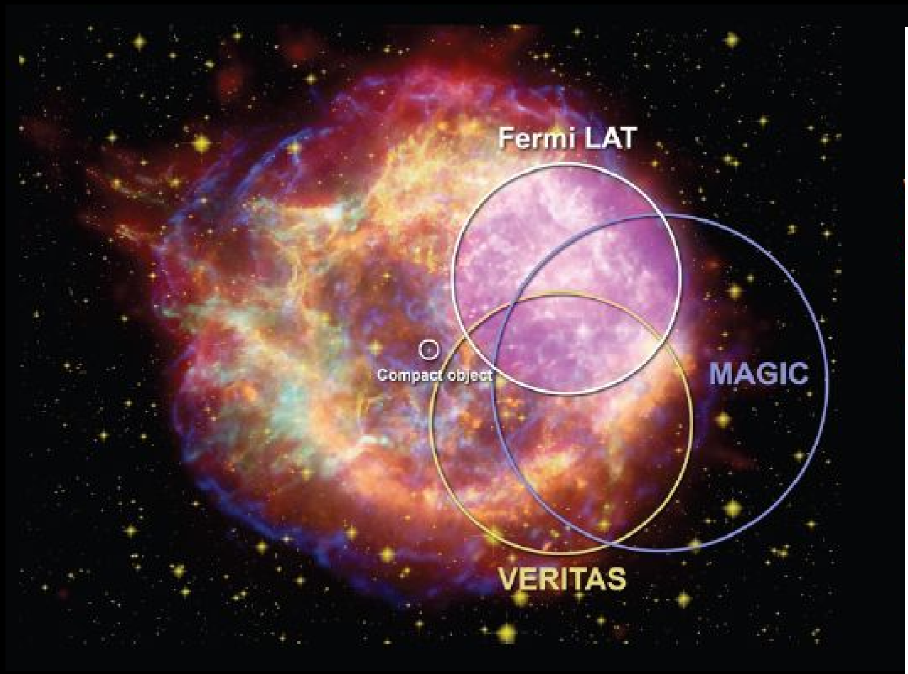
- Caveat:

Distance uncertainties can be large

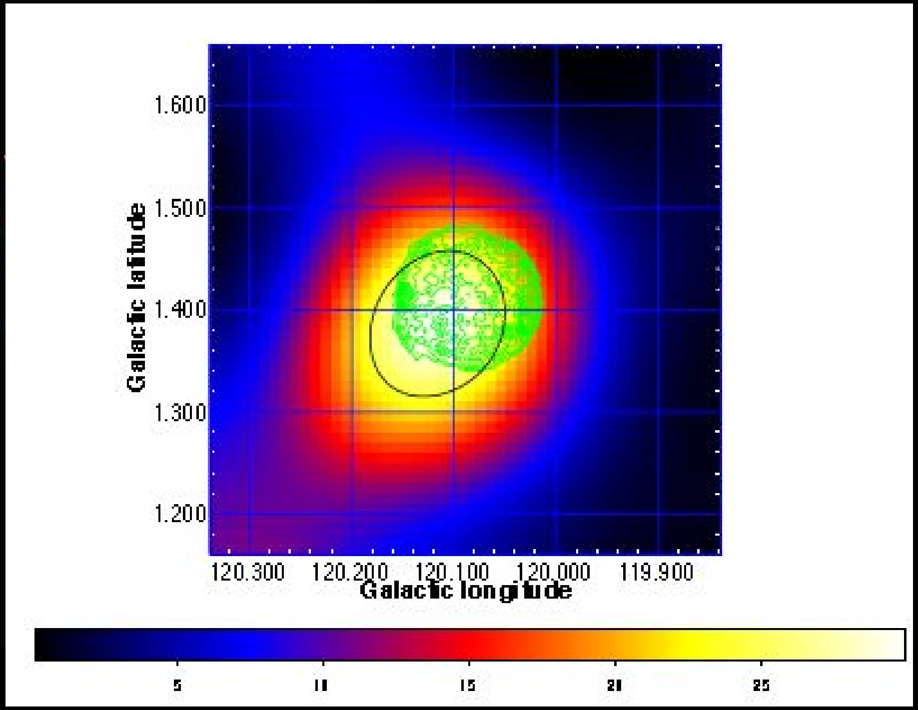
The Historical SNRs Cas A & Tycho

Cas A: Type II, ~AD1680
Detected by MAGIC, VERITAS & Fermi

Tycho: Type Ia, SN1572
Detected by VERITAS & Fermi



Abdo at al., 2010, ApJL, 710, 92



Fermi-LAT TS map with X-ray contours

Good cases for proton acceleration

For Tycho, hadronic scenario implies:

Steep spectrum (Γ=2.2)

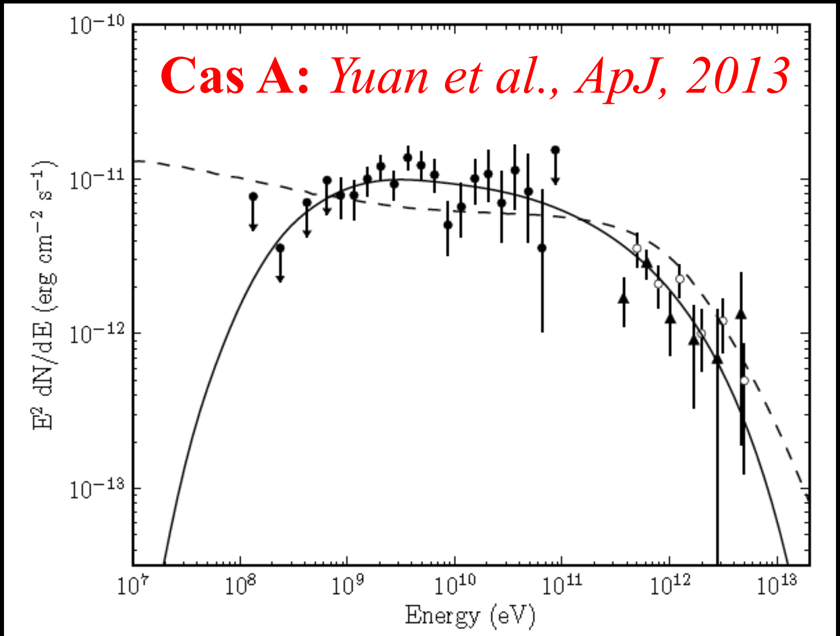
Maximal energy ~ 500 TeV

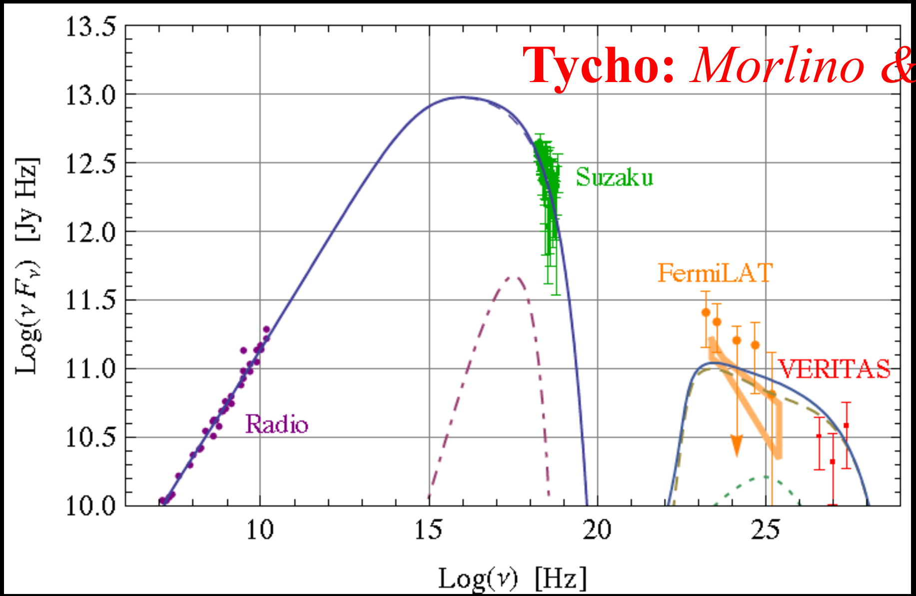
B field > 200 μG

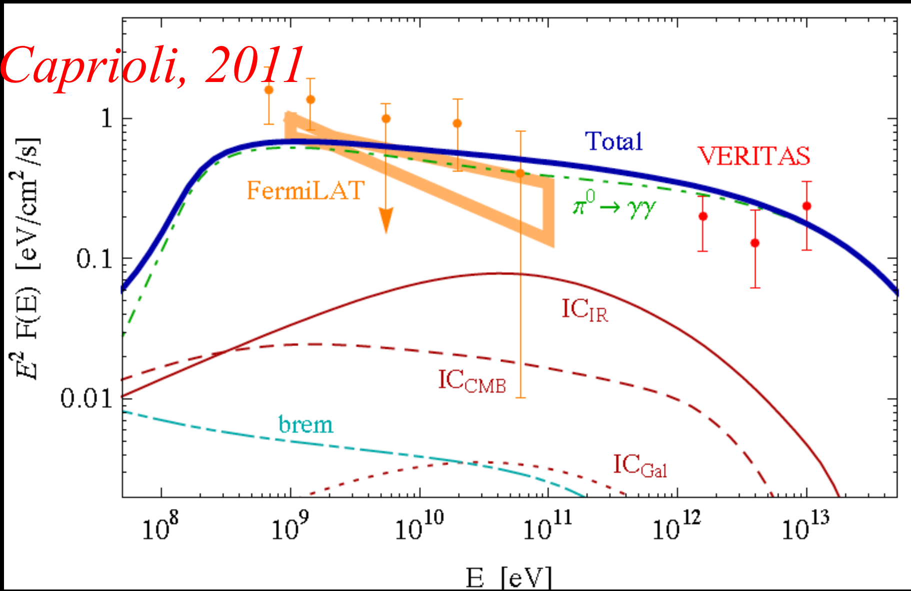
Energy content in CR ~ 6% E_{SN}

(~ 2% for Cas A)

Proton acceleration favoured for 2 different SN types







Some first thoughts

Finally: proof of proton acceleration in SNRs

....but we're far from smoking gun for PeV Galactic CRs

And the acceleration efficiency in young SNRs is much lower than the 10% generally used to maintain the CR flux in our Galaxy

Some ideas.....

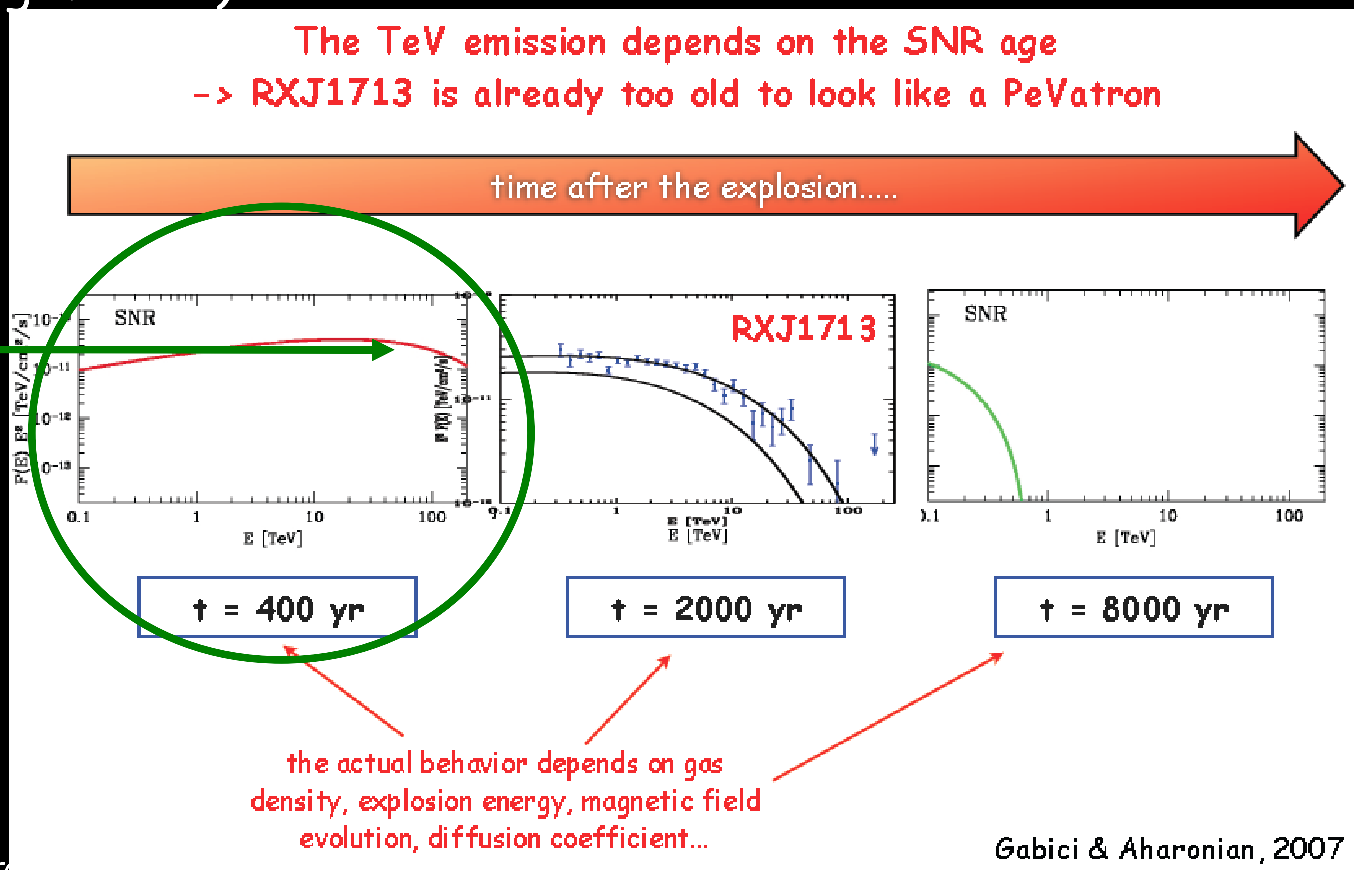
1- Very rare PeVatrons ?

If 3SN/century and SNRs are PeVatrons for few 100yrs => only ~10 PeVatrons in whole Galaxy

Distant sources => hard to detect with current instruments sensitivity

...However, if SNRs accelerate up to PeV energies, they should still be surrounded by an over density of escaped PeV cosmic-rays (see Gallant et al., Cosmic-ray Origin 2014)

No IC emission at this energy due to Klein Nishina effect



2- Extreme Accelerators ? The case of HESS J1640-465

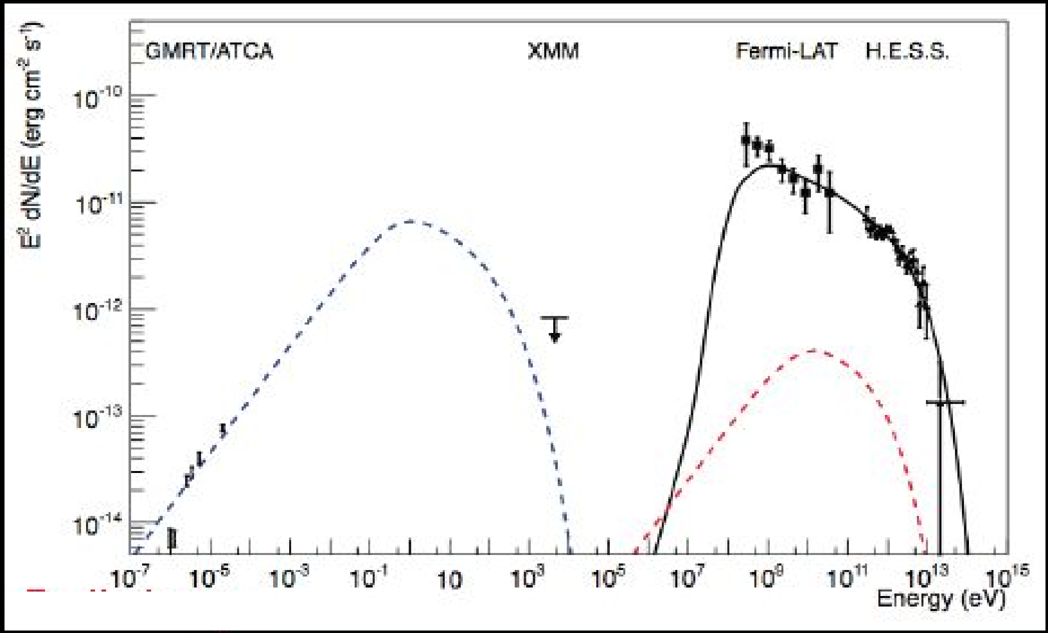
HESS Collaboration, Abramowski et al. 2014, MNRAS

See talk by S. Ohm (tomorrow)

Previously associated as a PWN
New HESS data suggest an asymmetry along northern SN shell
GeV-TeV spectra connect and looks like other SNR detected at GeV/TeV

Implication of SNR scenario:
Product of energy in protons and target density of 4 x 10^{52} erg cm^{-3} is required to explain observed luminosity
=> need high densities (up to 350 cm^{-3}) such dense gas has not been found

for density of ~100 cm^{-3} and canonical 10% in CRs:
→ E_{SN} could be ~4 x 10^{51} erg
→ Acceleration efficiency could be up to 40%



Still so much to learn ! An exciting field