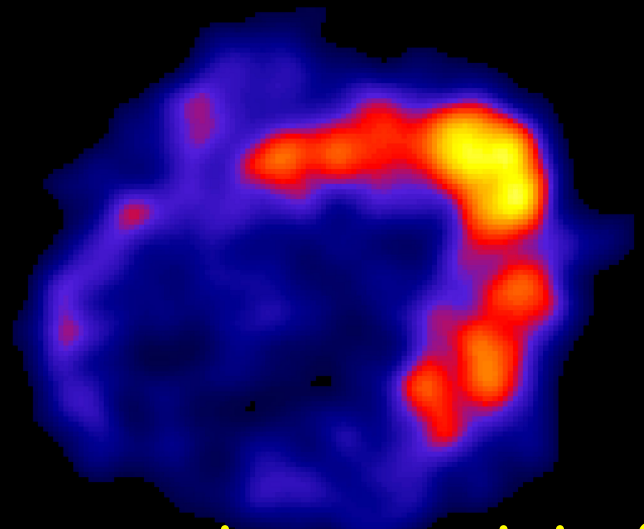
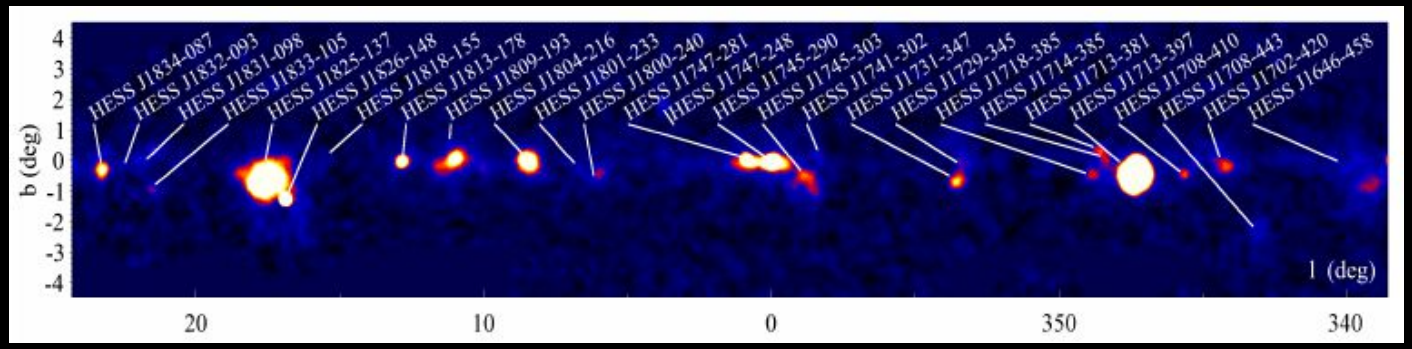


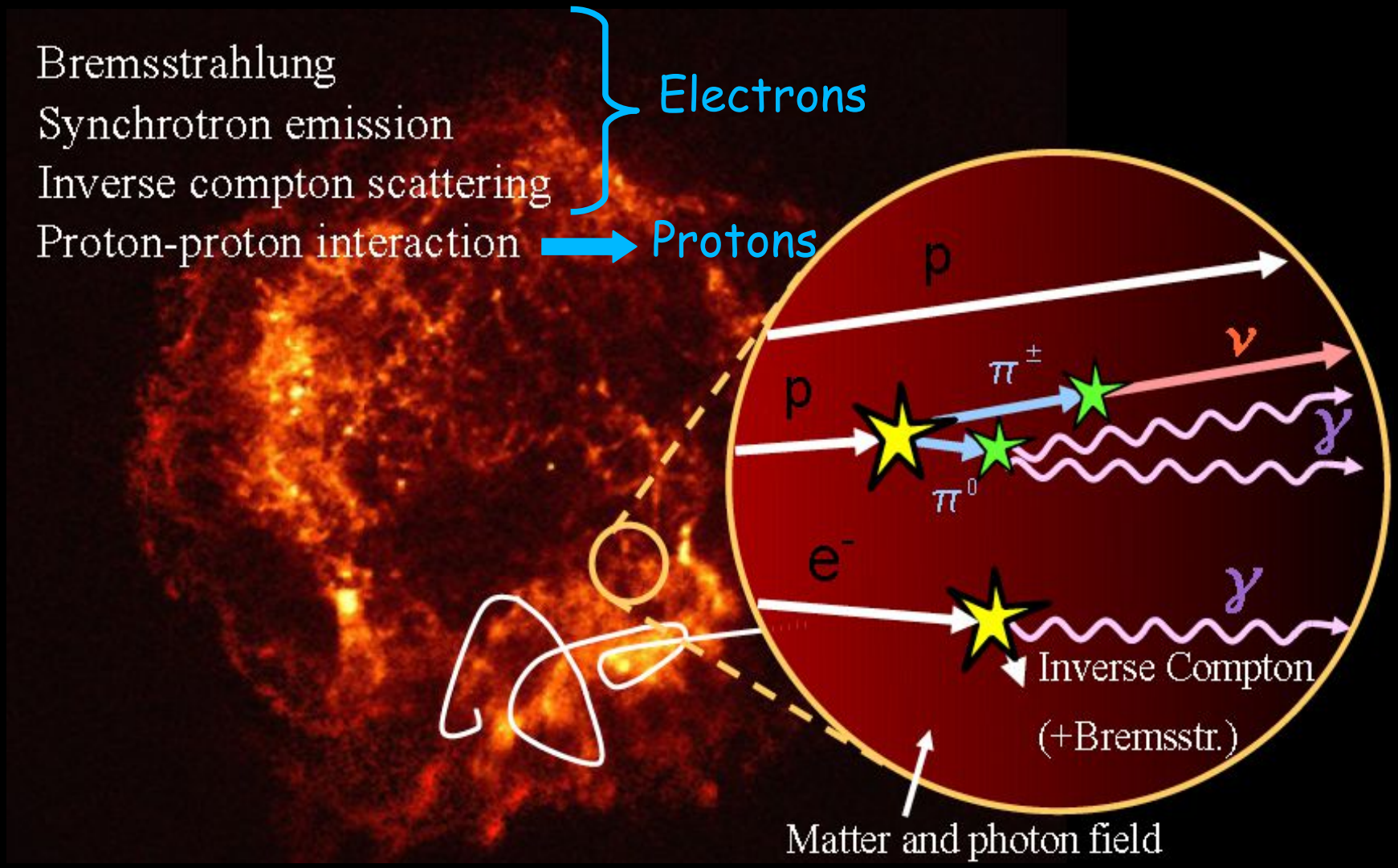
Constraints on cosmic-ray origin from gamma-ray observations of supernova remnants



Marianne Lemoine-Goumard

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

Accelerated particles in SNRs



Radiative processes in SNRs

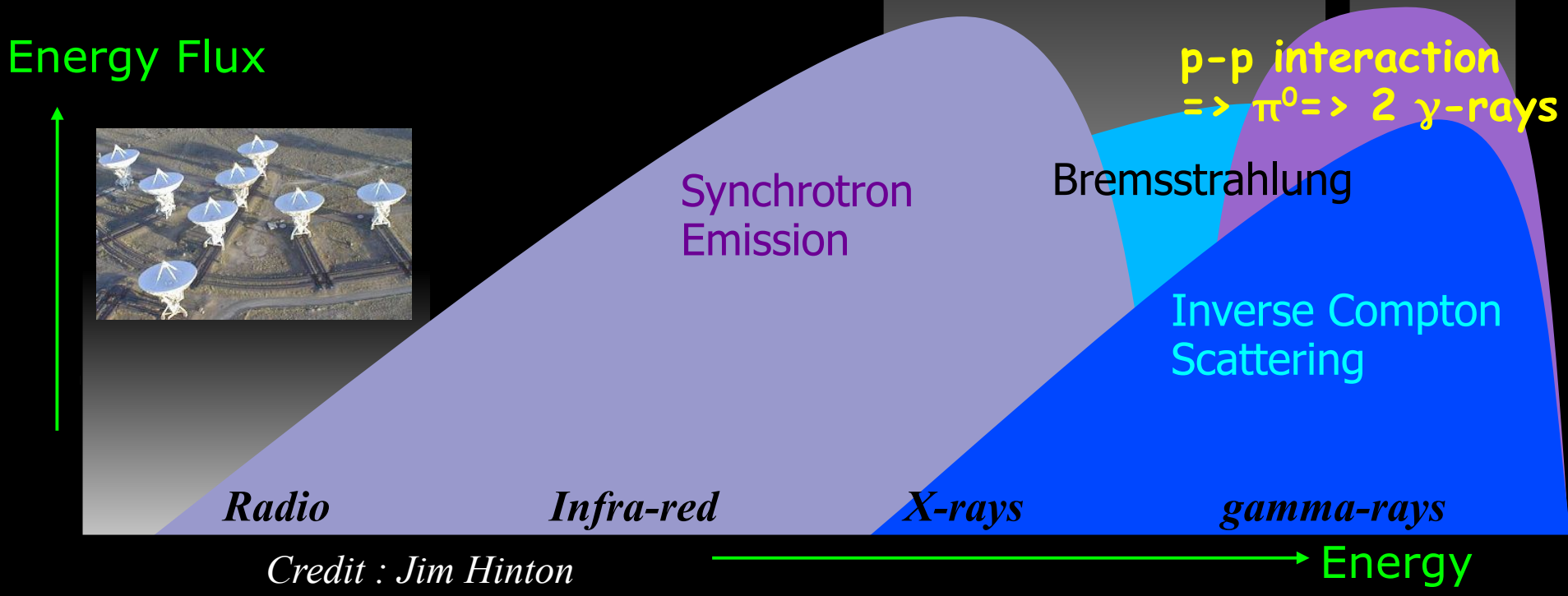
=> Potential to disentangle between protons and electrons in the gamma-ray range :

- TeV-observations:
shape of the high-energy IC component
cutoff in KN-regime (ambiguous)

- GeV-observations:
intensity & hardness of π_0 decay component

Satellites

Cherenkov Telescopes



Credit : Jim Hinton

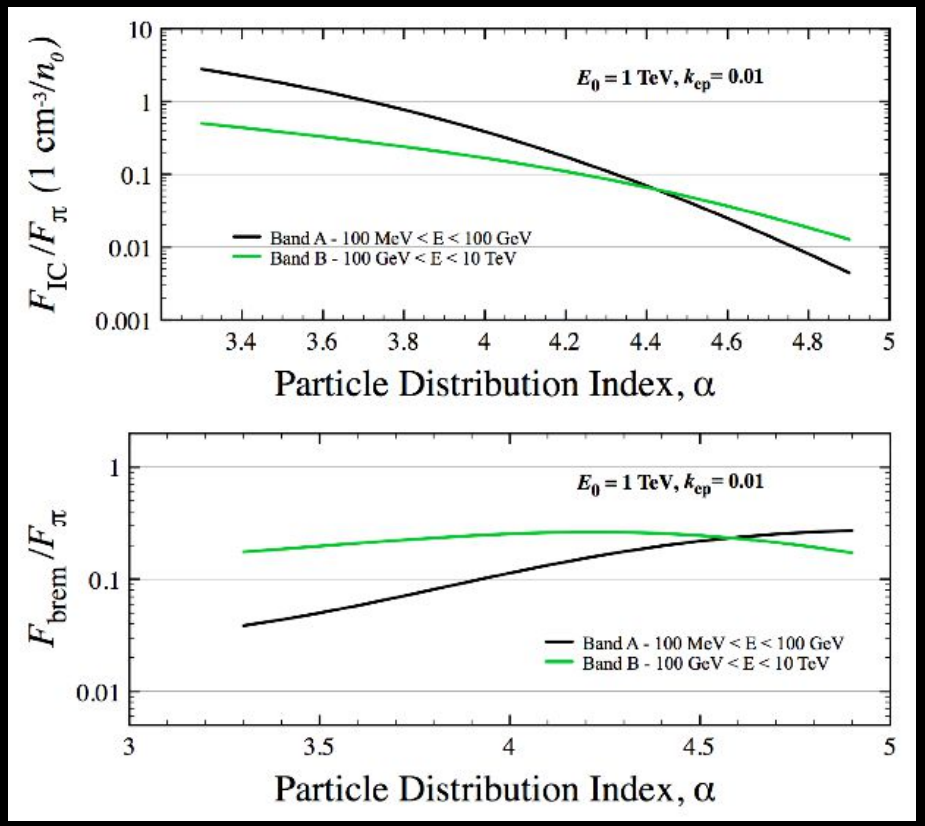
Ratios between the different radiative processes

Castro et al., 2013, ApJ, 774, 36

Assume Kep = 0.01
Photon field = CMB

Proton-proton dominates over IC for n > 1 cm^{-3}

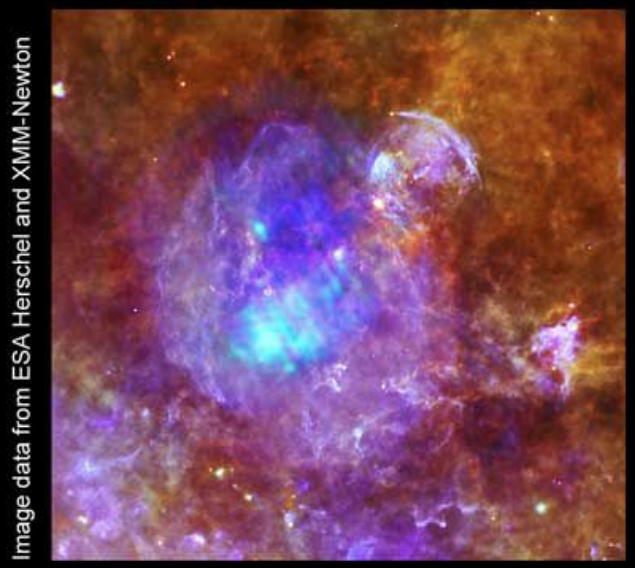
Bremsstrahlung needs Kep > 0.1 to dominate over pp interaction

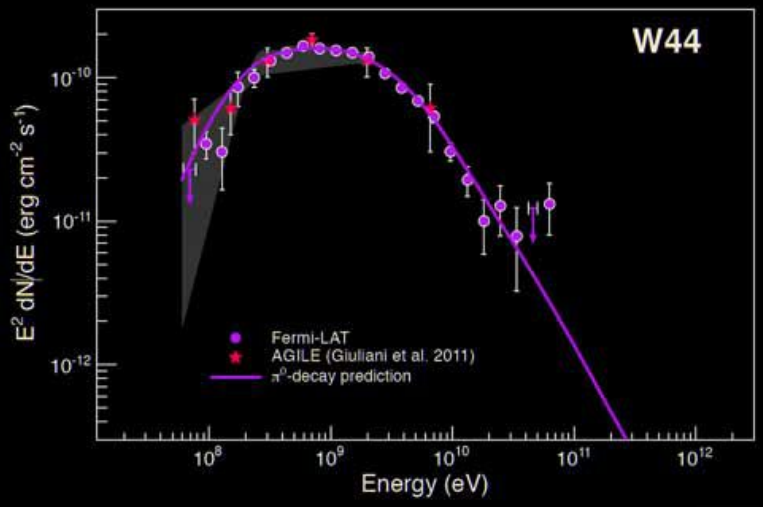


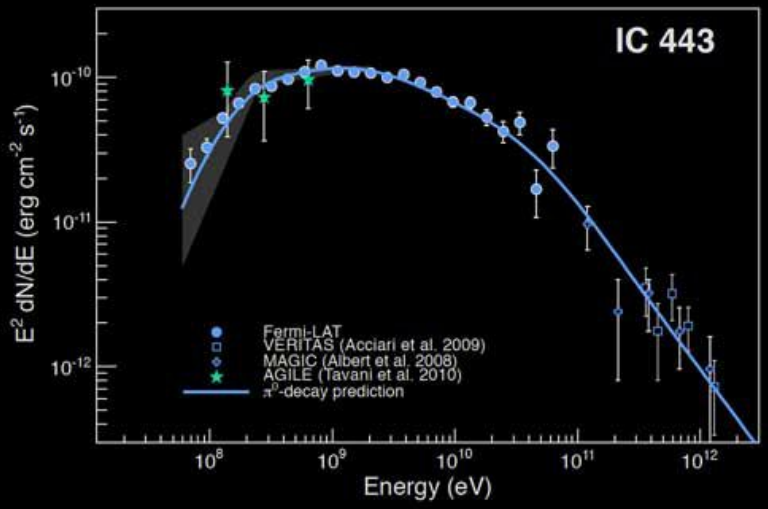
NASA press release (Feb 2013) : CR protons in SNRs

« NASA's Fermi Proves Supernova Remnants Produce Cosmic Rays »

Supernova W44 & IC 443 Neutral Pion Decay Spectral Fit

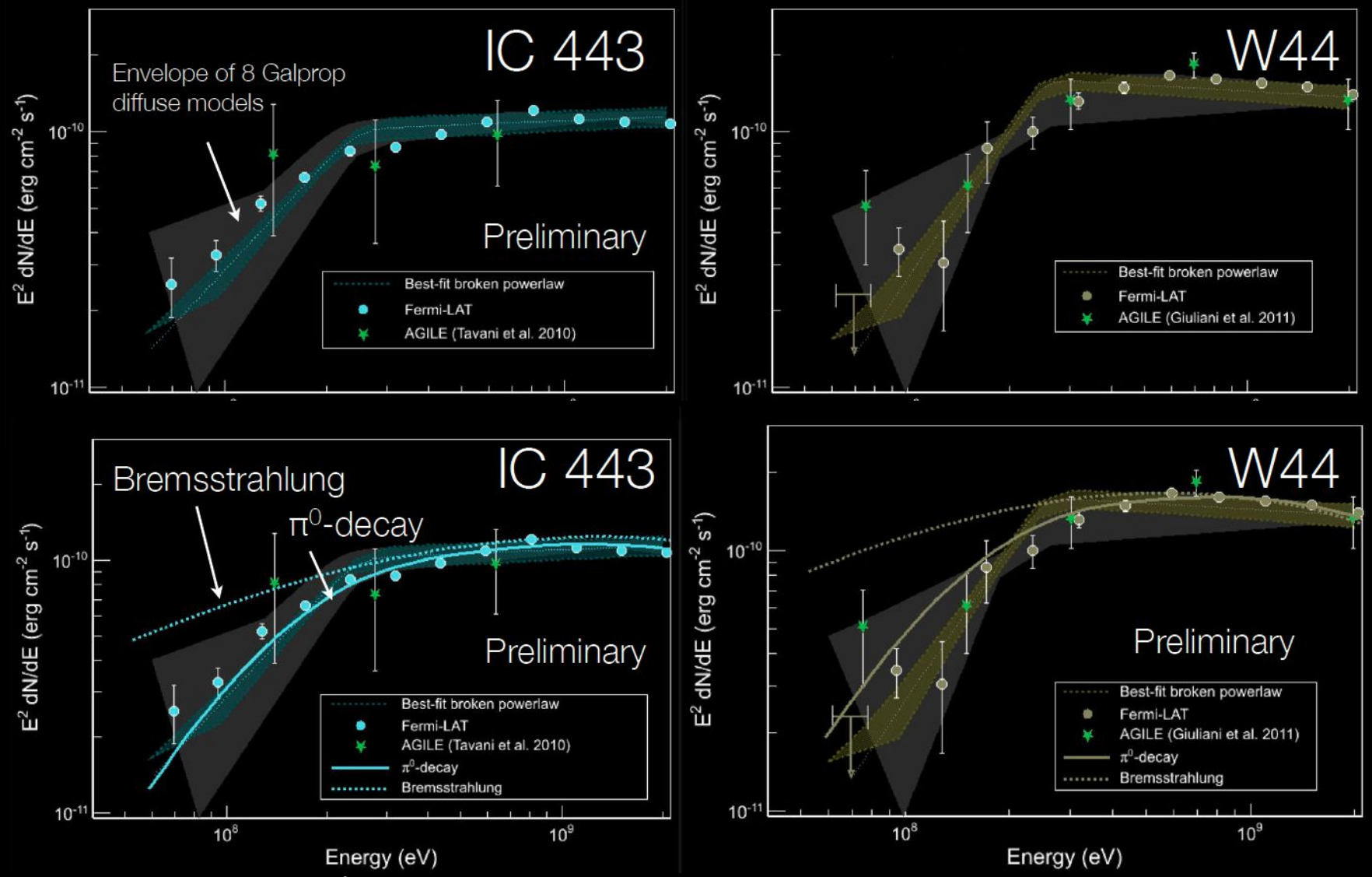






The pion bump at low energy

Hadronic scenario directly produces a break at low energy
Leptonic scenario would need artifical breaks



Marianne Lemoine-Goumard, IAU Symposium 2016, Crete

Going deeper with the case of IC 443

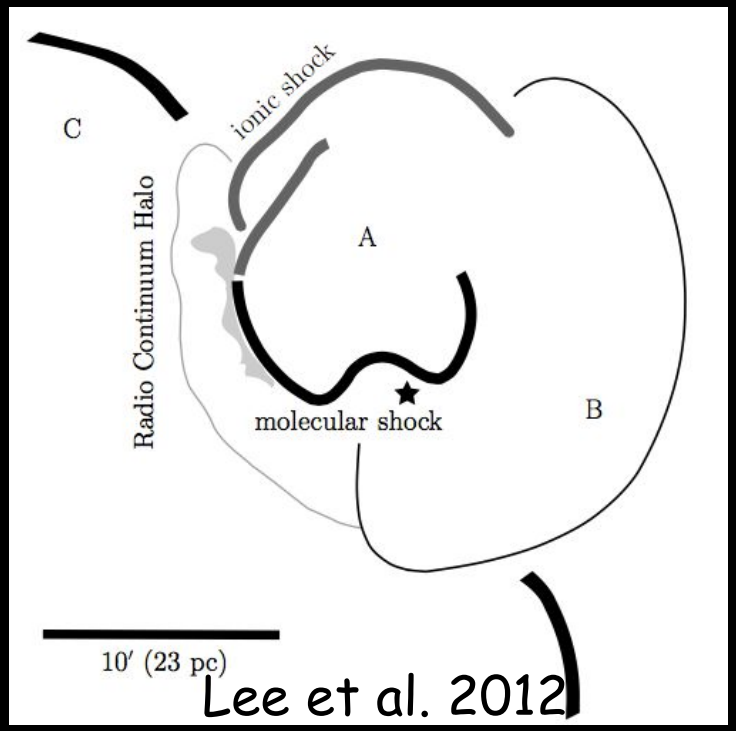
Remnant of core-collapse SN evolving in inhomogeneous environment

=> varying amount of target material

Distance of 1.5 kpc ; 0.75° diameter

Age uncertain : 3 – 30 kyr

PWN at southern edge of shell



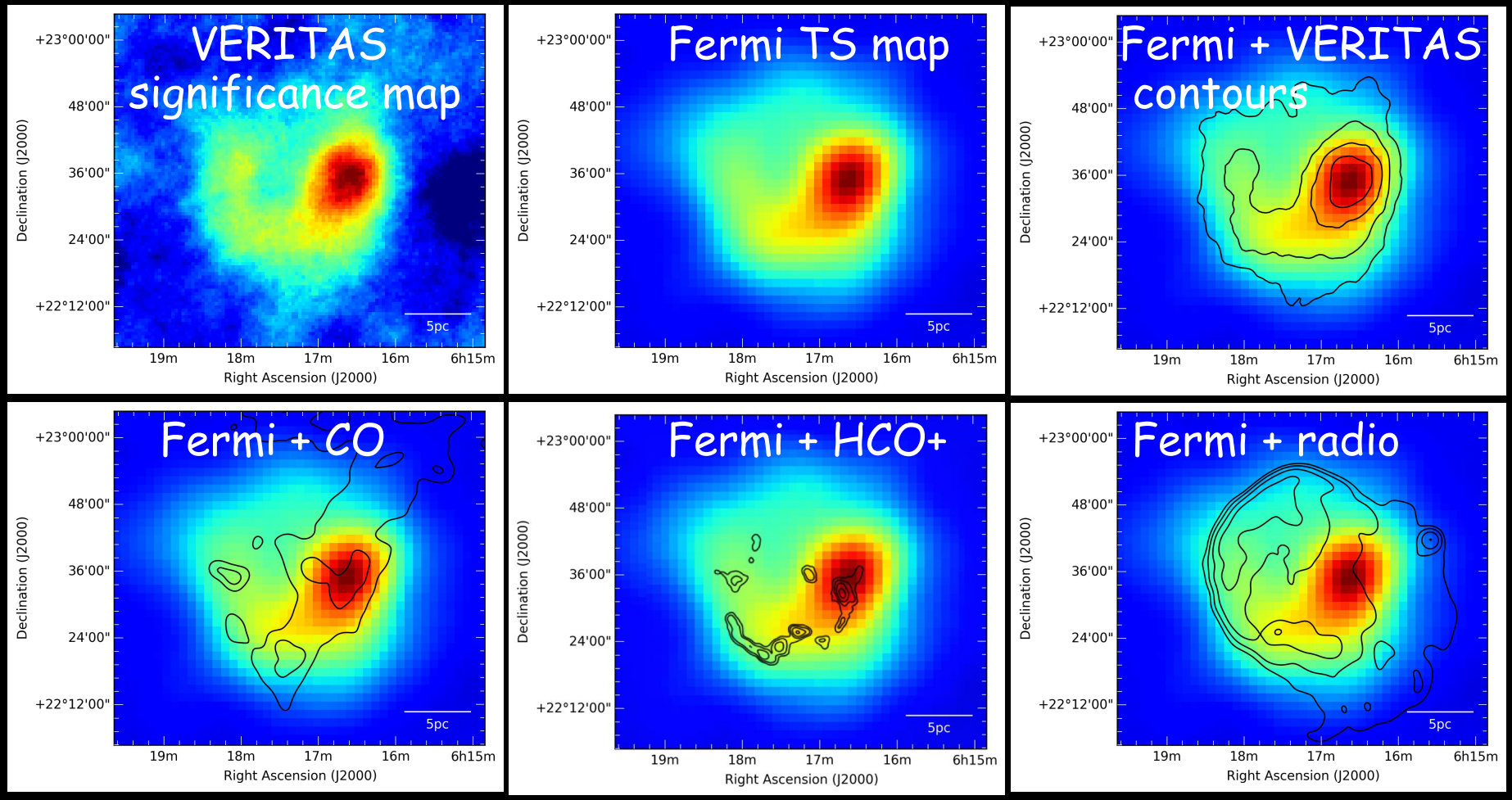
Lee et al. 2012

Resolving IC 443 (the Jellyfish nebula) in gamma-rays !

Fermi LAT 2010: 13 months P6V3 data → 2015: 83 months Pass 8 data

VERITAS 2007: 38hrs → 2015: 178hrs + PMT upgrade, T1 move

GeV/TeV correspondence with shock interaction gas density



Marianne Lemoine-Goumard, IAU Symposium 2016, Crete

Spectrally-resolved morphological analysis of IC 443

Able to resolve γ-ray emission zones on ~5 pc scales

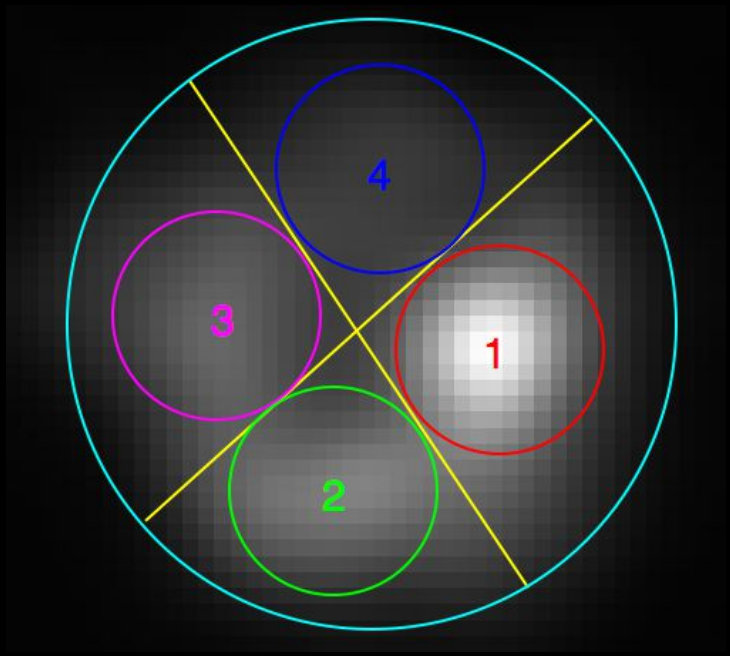
No clear differences in spectral shape for distinct emission regions :

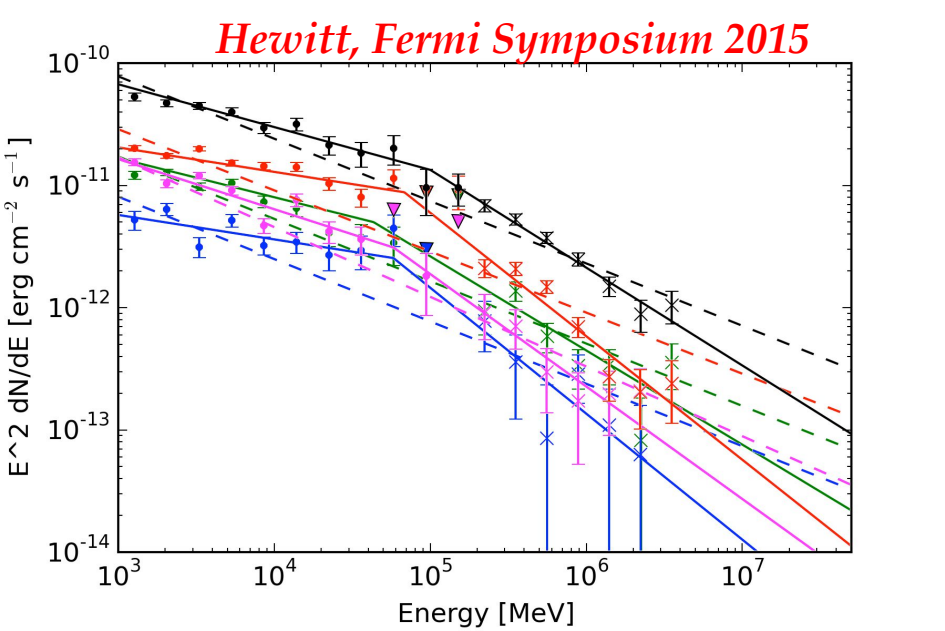
(e.g. dense cloud in region 1 vs. fast atomic shock in region 4)

Broken PL fits for all 4 regions: Γ1 ~ 2.3, Γ2 ~ 2.9, Eb ~ 60 GeV

=> unprecedented study of the environmental dependence of cosmic-ray diffusion in and around a hadronic accelerator

Poster S1.9 by Brian Humensky





W49B : a young SNR in interaction with Molecular Cloud

Pink: radio
Blue/Green : X-rays
Yellow : IR

SNR/MC W49B

1 - 4 kyr

8 kpc < D < 12 kpc

Radio shell (4') + Filled with X-rays

IR, X-ray studies indicate Type Ic

~25 Msol progenitor

Detected in IR (150 GHz mapping, IRAM)

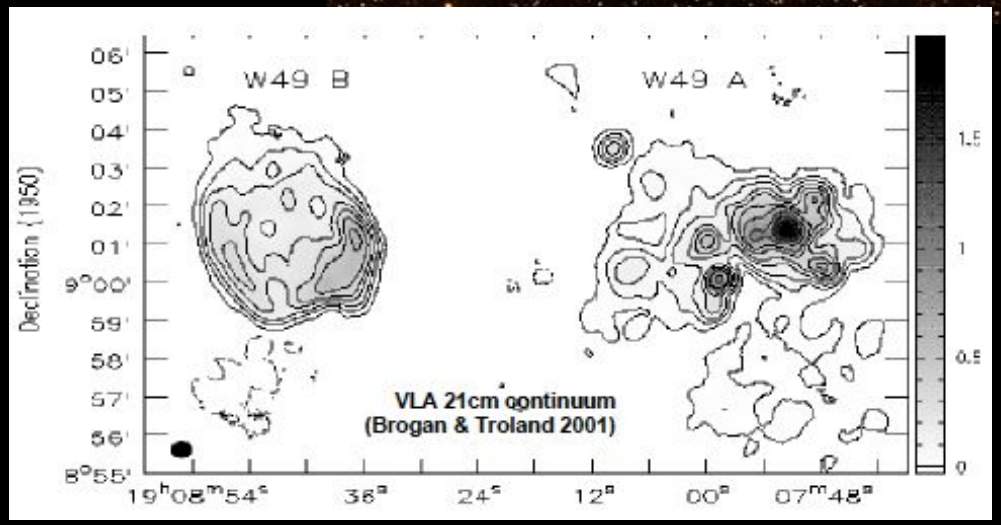
=> no spectral break (Hewitt et al., 2014)

Detected at TeV and GeV energies

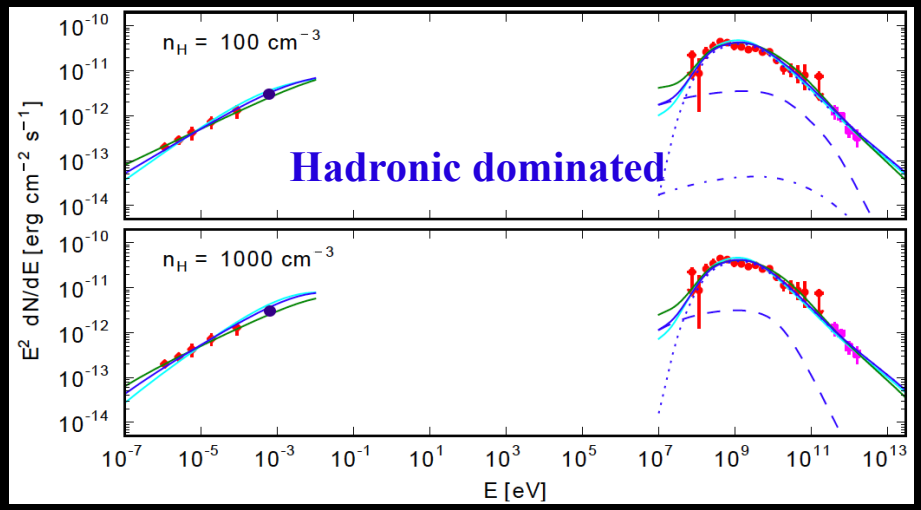
Star Forming Region W49A

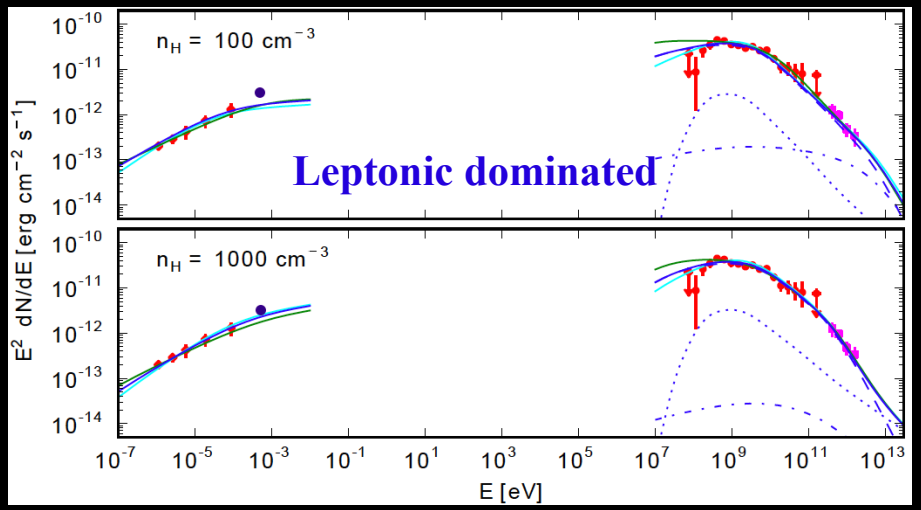
Densest part of a 10^6 $M_\odot$ MC

No detection in gamma-rays



Broad-band modeling of W49B





Abdalla et al., 2016, A&A submitted

Pion bump feature

Hadronic scenarii :
Kep = 0.01
B field of 100 - 500 μG
Spectral shape independent of n_H
(if set between 100 and 1000 cm^{-3})

Leptonic scenarii :
Kep = 1
B field of 20 – 100 μG

No spectral break in radio and IR => favours the hadronic scenario with dense medium

Acceleration or Re-acceleration ?

2 possible ways to produce the gamma-ray signal :

- Re-acceleration and compression of Galactic CRs
- Fresh acceleration and compression of particles at the shock

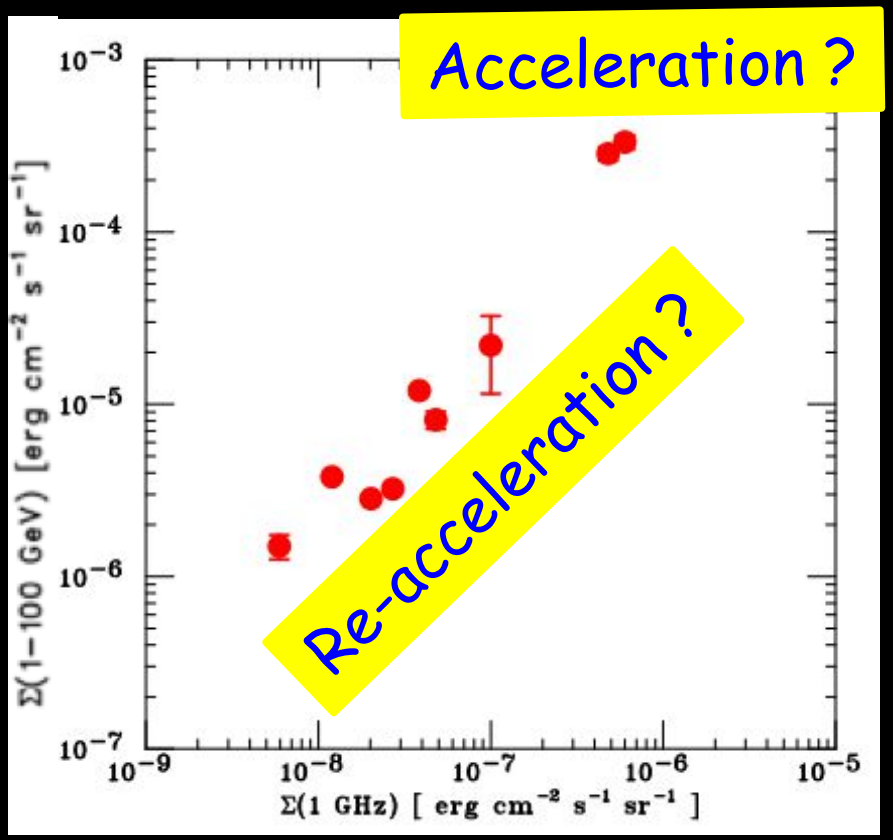
2 outliers : W49B & G349.7+0.2

LAT flux implies $u_{CR} \sim 10^5$ eV/cm^3

=> re-acceleration may not be enough

=> Freshly accelerated Crs ?

More details on re-acceleration in M. Cardillo's presentation



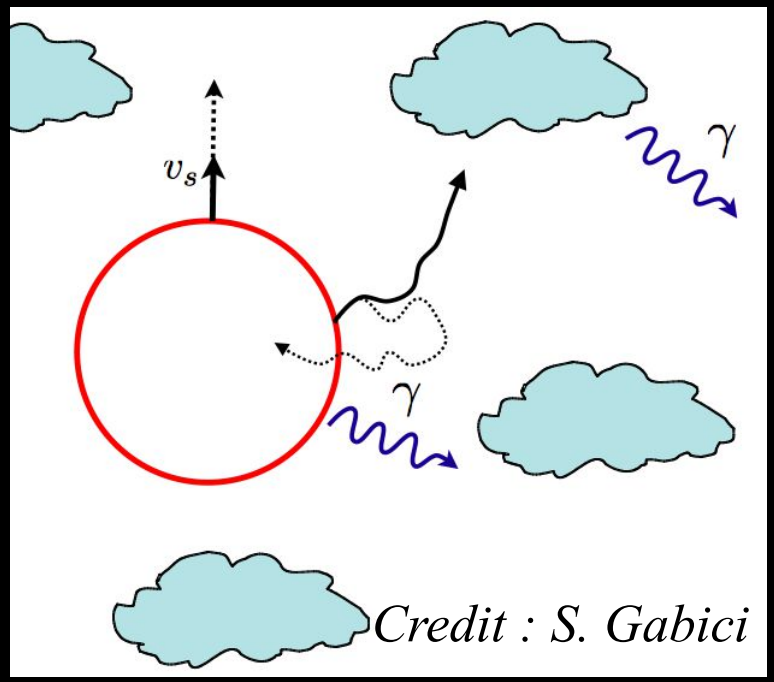
Uchiyama et al. 2011

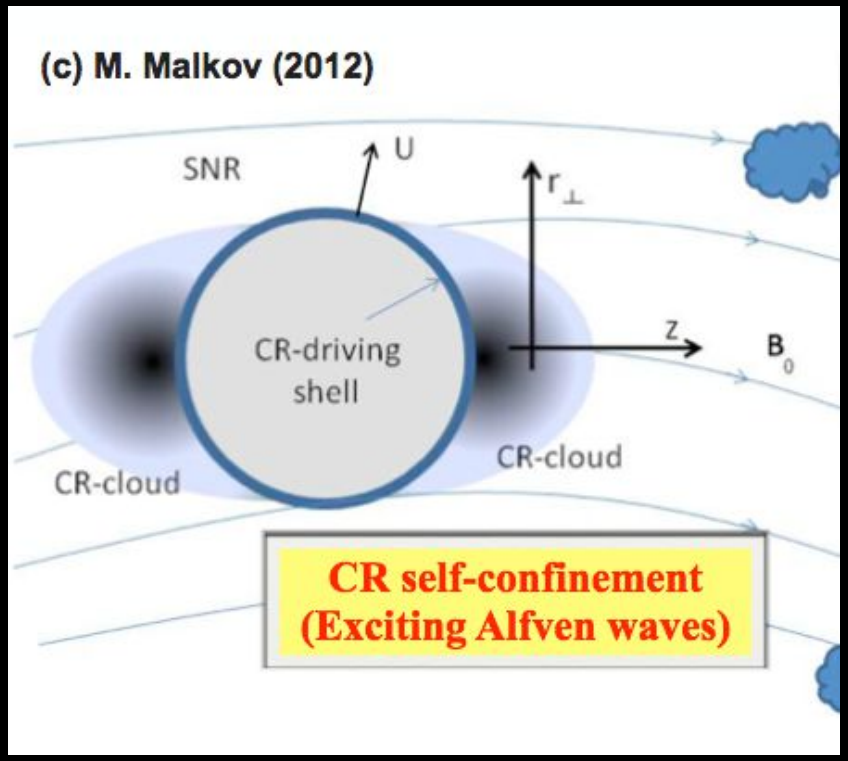
Particle escape from SNRs interacting with MCs

Both SNR and surrounding MC emit gamma-rays

After leaving the SNR, CRs diffuse along the external B-field direction

➔ bipolar morphology

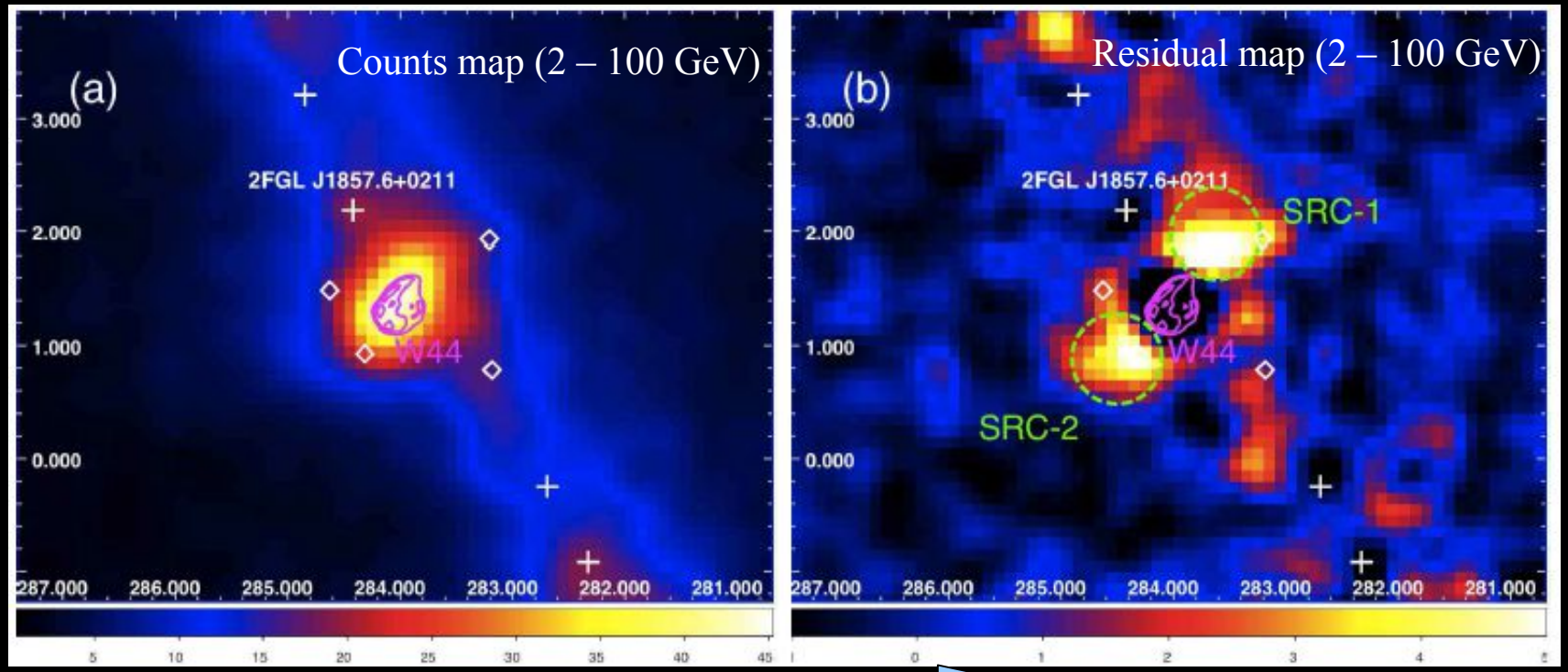




Escaping cosmic-rays: the case of W44

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

Uchiyama et al. 2012, ApJL, 749, 35

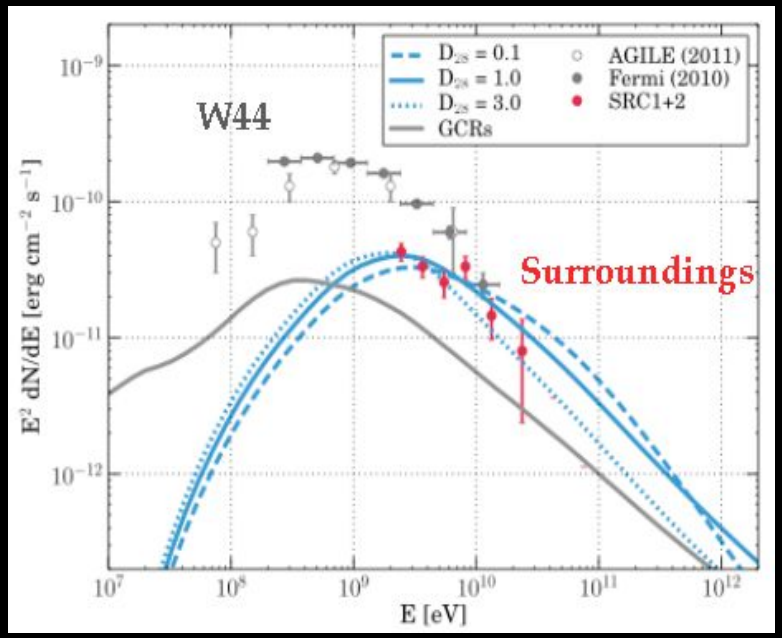


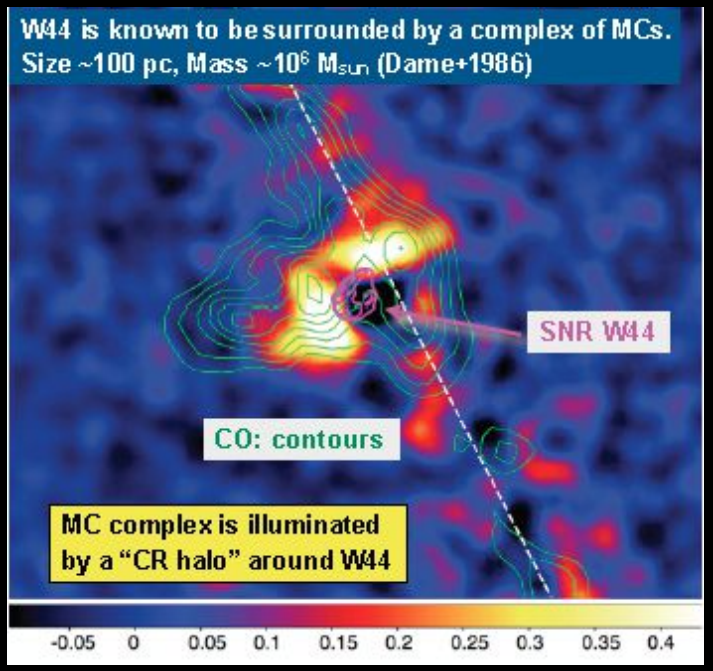
Subtraction of W44 assuming radio map = gamma-ray map

- 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



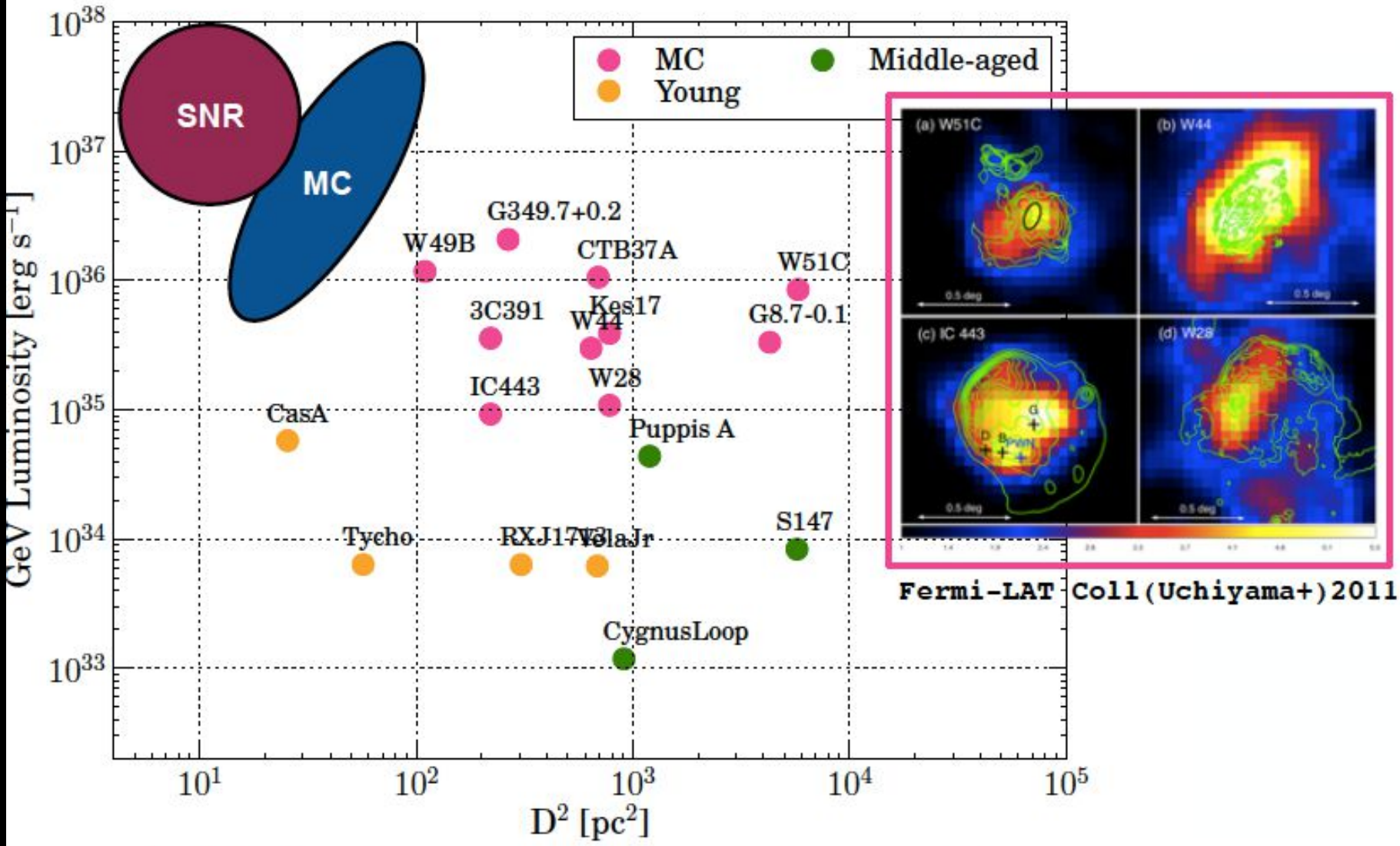


- ☑ Molecular clouds illuminated by escaping CRs (assumed to be uniform within r<L)
  - ✱ L ~100 pc, Mass = 0.5×10^5 $M_\odot$
- ☑ Diffusion coefficient of the ISM (isotropic)
  - ✱ $D(p) = D_{28}\,(cp/10\ GeV)^{0.6}\ 10^{28}\ cm^2/s$

Solving the diffusion equation, we estimate the total kinetic energy channeled in CRs to $(0.3\text{-}3)\times10^{50}$ erg
=> SNRs are the main CR sources

Marianne Lemoine-Goumard, IAU Symposium 2016, Crete

SNRs detections with Fermi

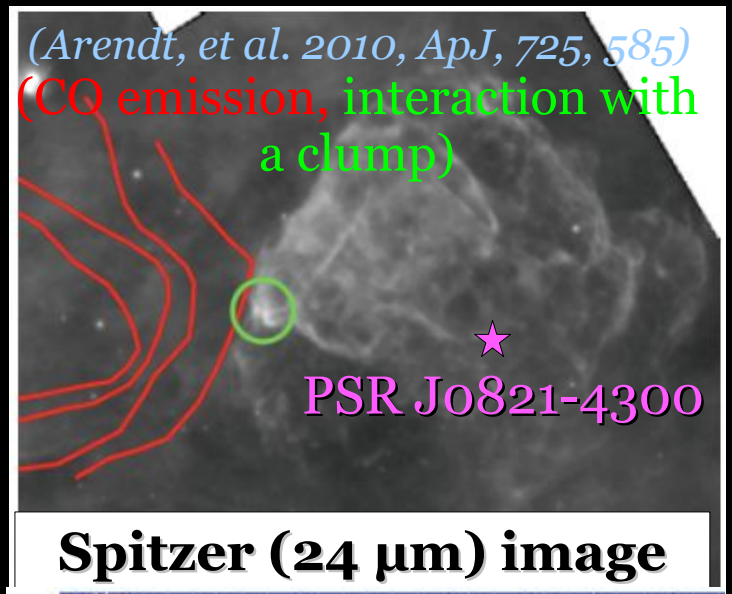


Marianne Lemoine-Goumard, IAU Symposium 2016, Crete

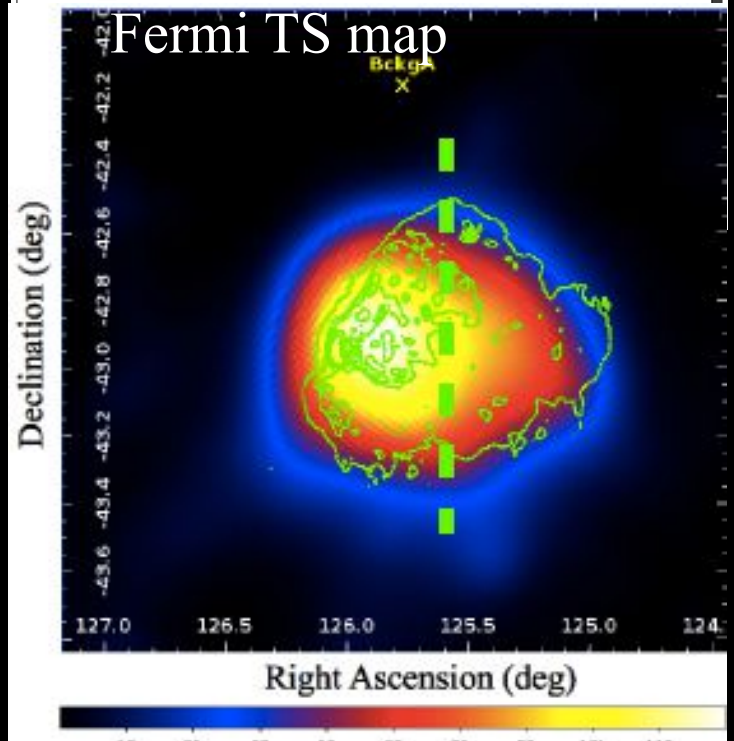
Puppis A : a transition case

- A well-defined SNR…
  - Distance of 2.2 ± 0.3 kpc
  - Physical diameter of 30 pc (0.8°)
  - Age : 3700 ± 400 yr
  - Sedov-Taylor phase
  - CCO identified as PSR J0821-4300 (X-ray pulsar, *Gotthelf & Halpern, 2009)*

- … in a well-known environment :
  - Evolving into the ISM in the vicinity of a mol. cloud
  - Non radiative shocks (except at certain knots where small clumps are shocked)
  - X-ray/IR correlation indicates n ~ 4 cm^{-3}

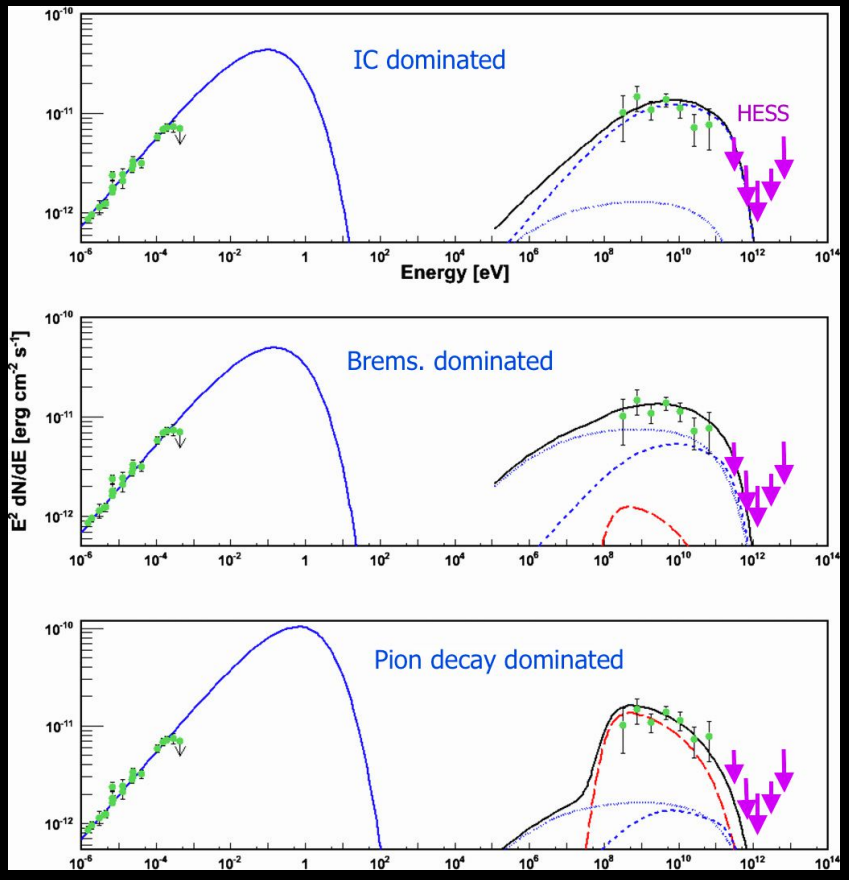


Spitzer (24 μm) image



Non-thermal modeling of Puppis A

- All mechanisms are viable requiring W_{CR}~(1-5) x 10^{49} erg but pion-decay is most reasonable:
  - IC dominates for n < 0.3 cm^{-3}
  - Brems dominates over pion-decay for e/p > 0.1
- One-zone models have a great difficulty explaining radio break if confirmed (would need very high B field)
- All models need a low energy max to account for the non-detection by HESS



Model	Index	E_{max} [TeV]	n_H [cm^{-3}]	B_{tot} [μG]	η_e/η_p	W_p [erg]	W_e [erg]
IC	2.1	0.5	0.3	8	1	8.0×10^{48}	2.9×10^{49}
Brems.	2.1	0.5	4	13	1	3.5×10^{48}	1.3×10^{49}
π^0-decay	2.1	0.8	4	35	0.02	4.0×10^{49}	2.8×10^{48}

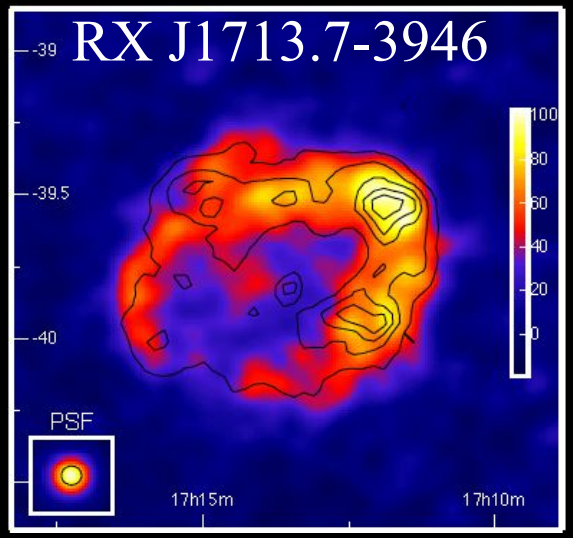
Hewitt et al. 2012, ApJ, 759, 89 + HESS Uls from Abramowski et al., 2015, A&A, 575, A81

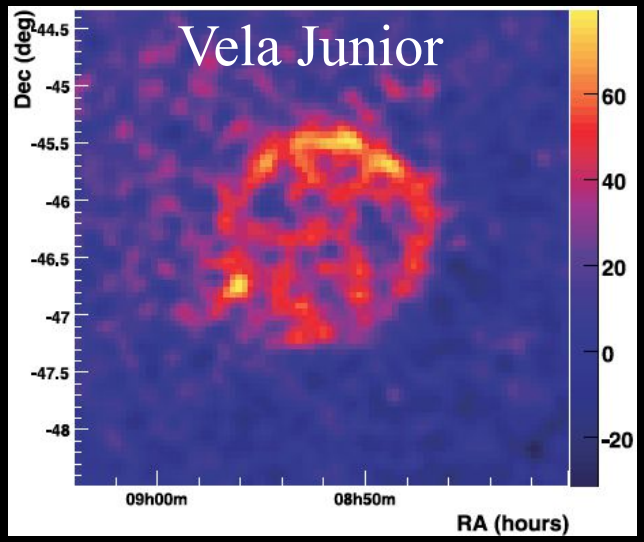
Location : the most important ingredient at gamma-ray energies

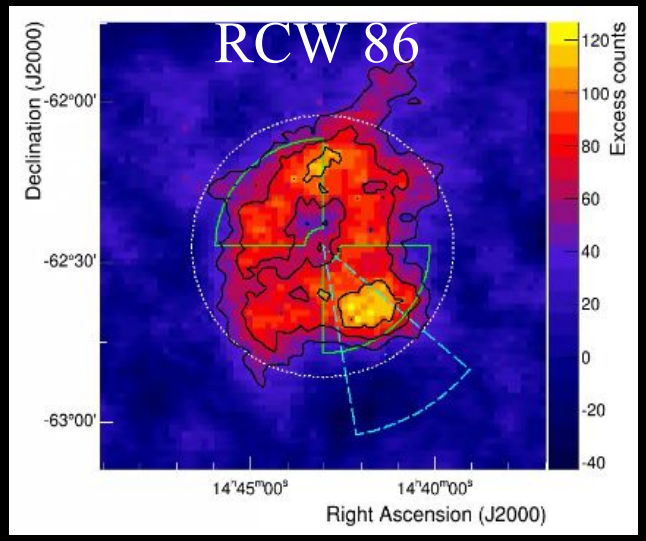
Credit : D. Caprioli, ICRC 2015

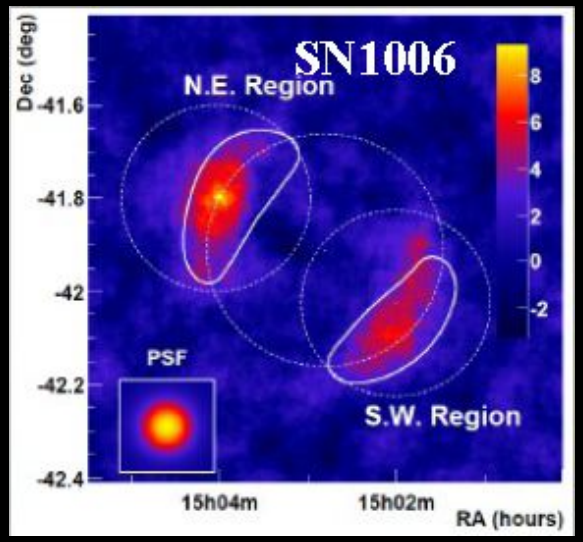
Young shell-type SNRs

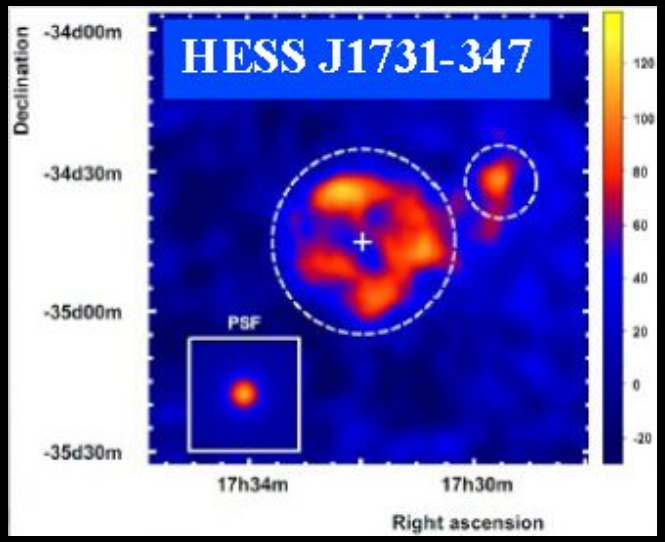
5 shell-type SNRs detected by HESS ; top 3 detected by Fermi











Poster S1.21 by Iurii Sushch on Vela Junior

The case of RCW 86

Ajello et al. 2016, ApJ, 819, 98

Remnant of a Type Ia SN

Associated to the historical SN 185

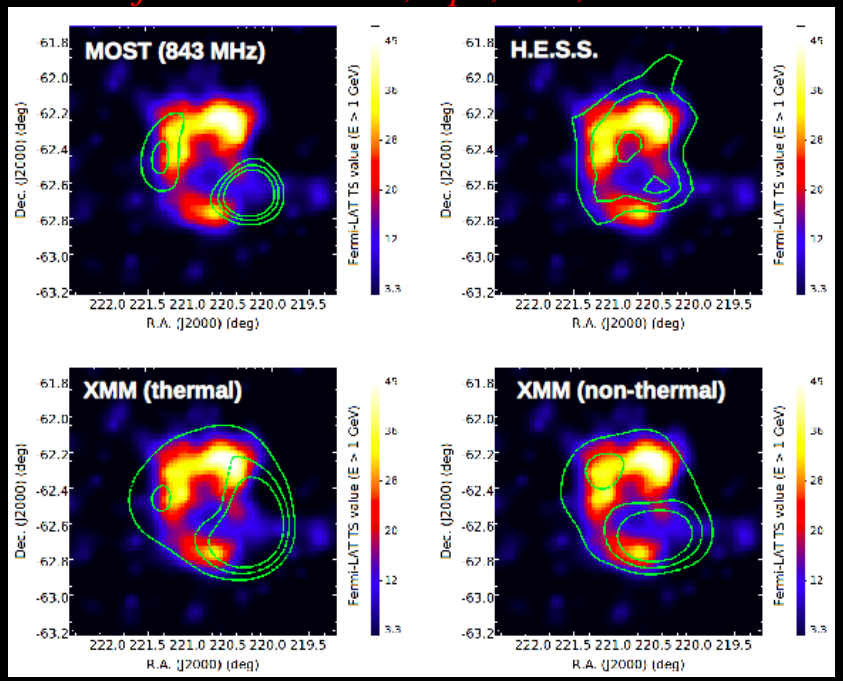
Age ~ 1850 years

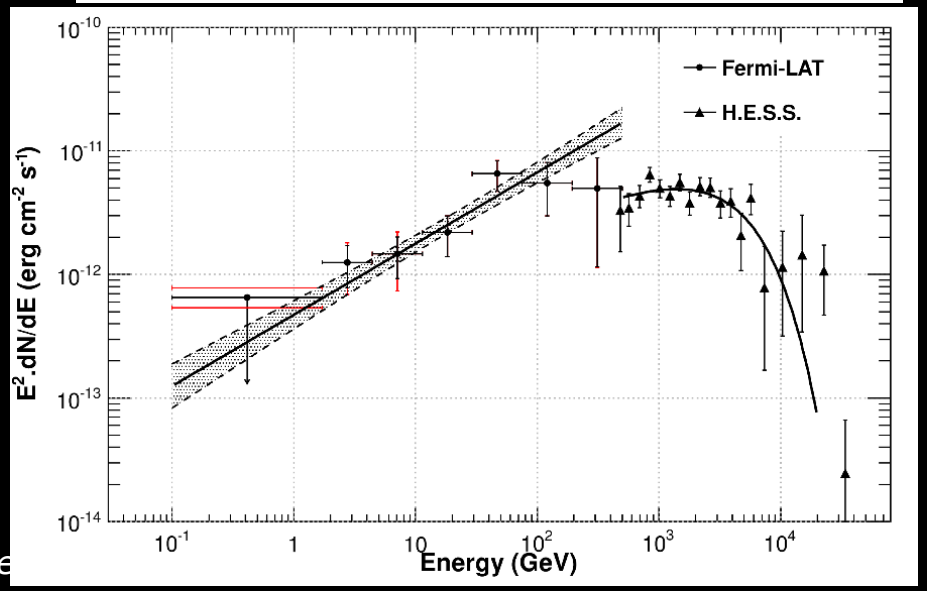
Distance ~ 2.5 kpc

Detected at TeV and GeV energies as an extended source

Correlation between both energy range is not perfect

Very good spectral consistency





Constraints on CR efficiency within RCW 86

One-zone model (obviously too simple !) :

Low density & soft particle spectrum

Two-zone model :

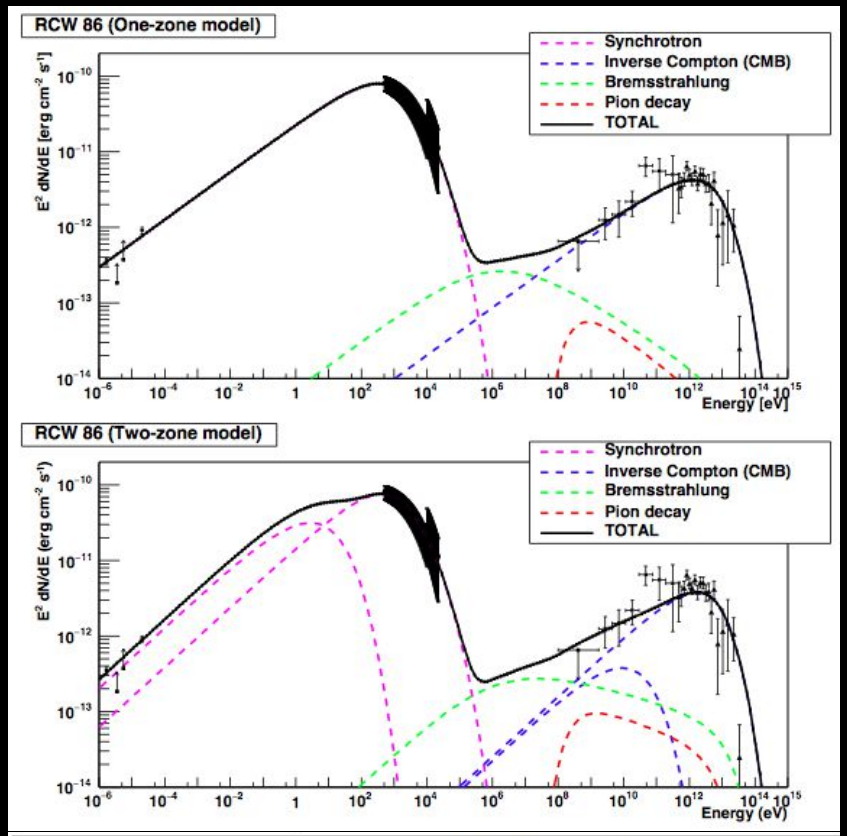
Relax constraints on density & particle spectrum

But, whatever the origin of the signal :

$\eta_p \sim 2\%\ E_{SN}$

Emax ~70 TeV

Very far from an efficient accelerator !



Parameters	Whole remnant		
	One-zone	Two-zone	
		Radio	X-ray
Density (cm^{-3})	0.1	1.0	1.0
B (μG)	10.2 ± 0.5	24	10.5 ± 0.7
$\Gamma_{e,p}$	2.37 ± 0.03	2.2	2.21 ± 0.1
E_{max} (TeV)	75 ± 5	2	67 ± 4
η_e (% of E_{SN})	3.84 ± 0.5	0.03	0.37 ± 0.02
η_p (% of E_{SN})	2	-	2
K_{ep} ($\times 10^{-2}$)	11.1 ± 1.5	-	13.6 ± 0.5

Young shell-type SNRs in leptonic-dominated model

Using parameters from literature

- Caveat: Distance uncertainties can be large

=> Similar γ-ray luminosity for different SN type

=> Similar physical scenario ?

Leptonic dominated scenario ?

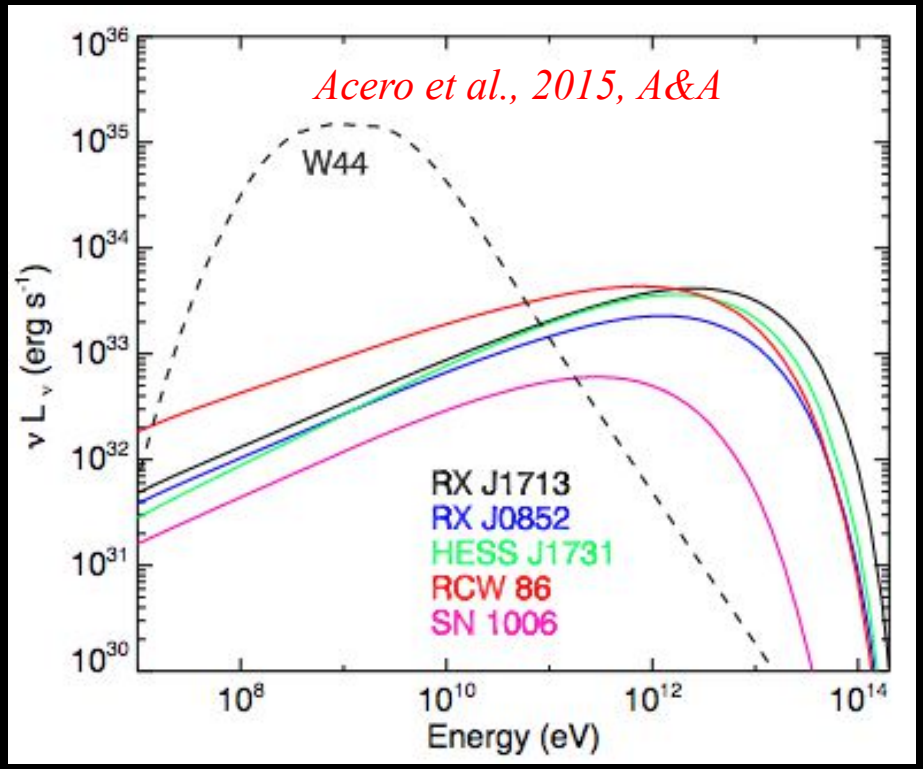
Similar seed photons for IC

- Except SN 1006. Why ?

- high latitude

- Bipolar morphology, lower Vaccel

But protons might play an important role



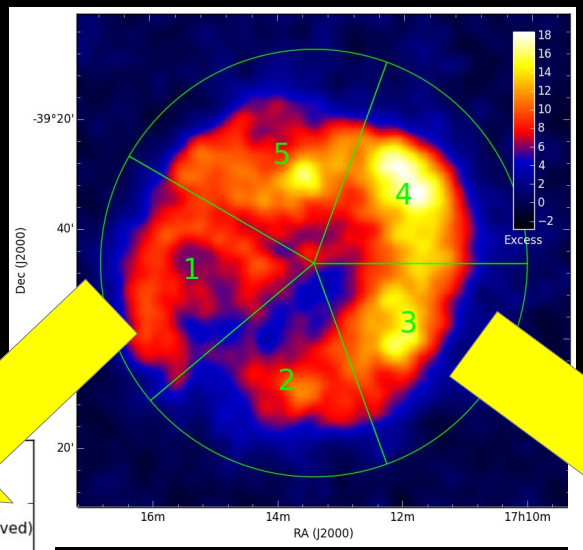
Protons leaking from RX J1713.7-3946 ?

TeV shell extended beyond X-ray shell in the Western part (region 3) :

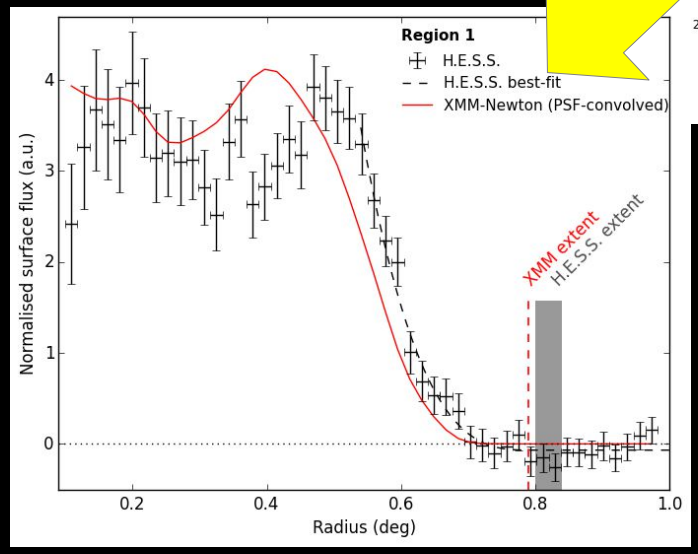
—> detection of particle escape ? (protons)

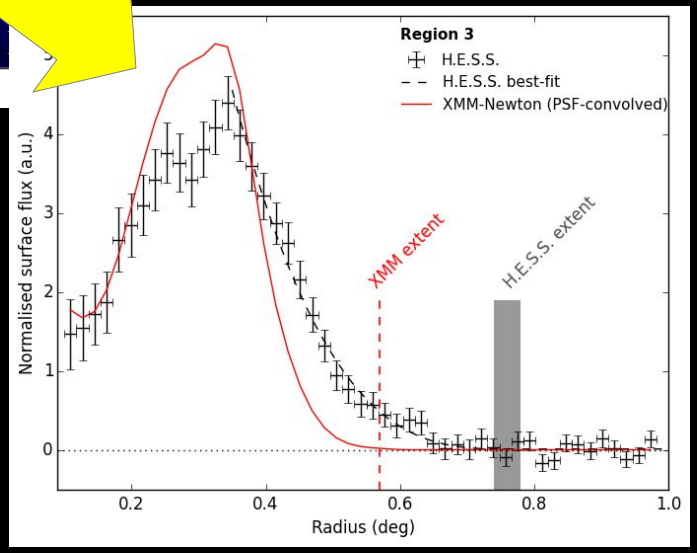
—> B-field evolution explaining faster X-ray emission drop ? (electrons)

Poster S1.24 by X. Zhang



P. Eger et al., ICRC 2015





Protons escaping HESS J1731-347 ?

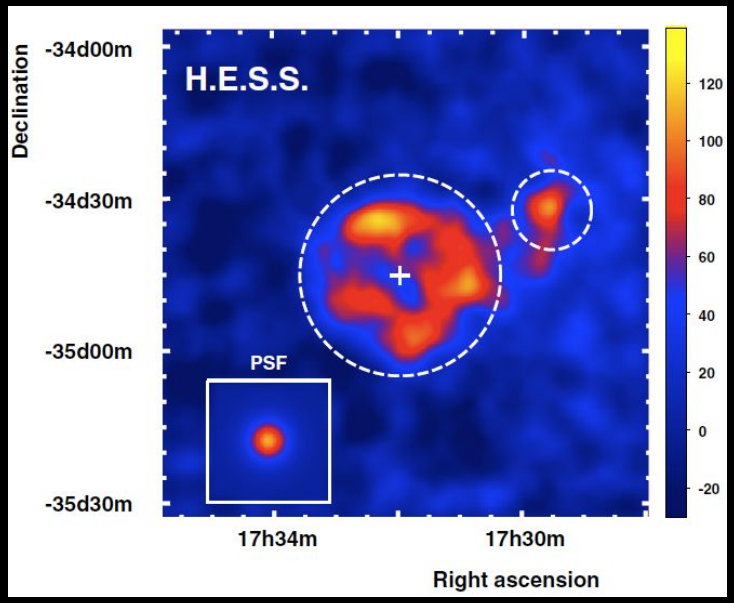
Similar case as RX J1713.7-3946:
Pure non-thermal X-ray spectrum from XMM-Newton (H.E.S.S. coll. 2011), Suzaku (Bamba, 2012)

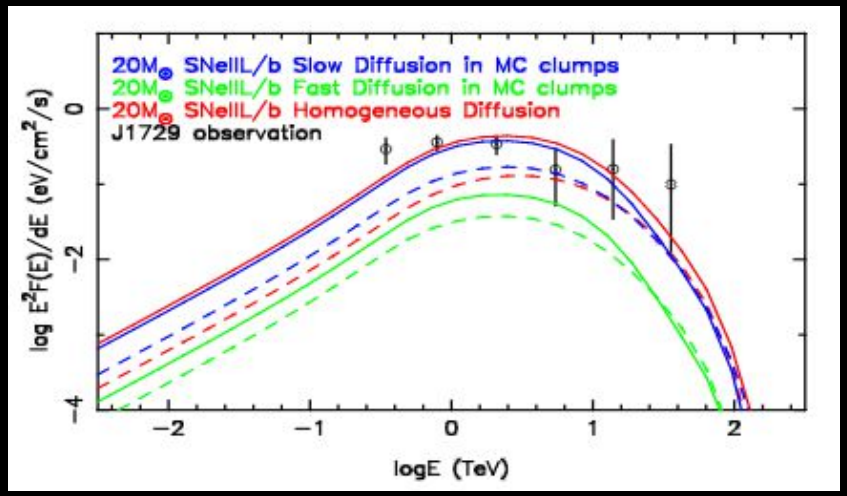
But adjacent TeV source (HESS J1729-345) may permit to better trace CR proton escape ?

Energetically plausible SNR evolution / CR escape scenario possible that explains J1729-345 through CRs illuminating a cloud

Important note : in contrast to W28, diffusion coefficient does not need to be suppressed

More details in Cui et al. 2016, A&A





Poster S1.17 by G. Puehlhofer

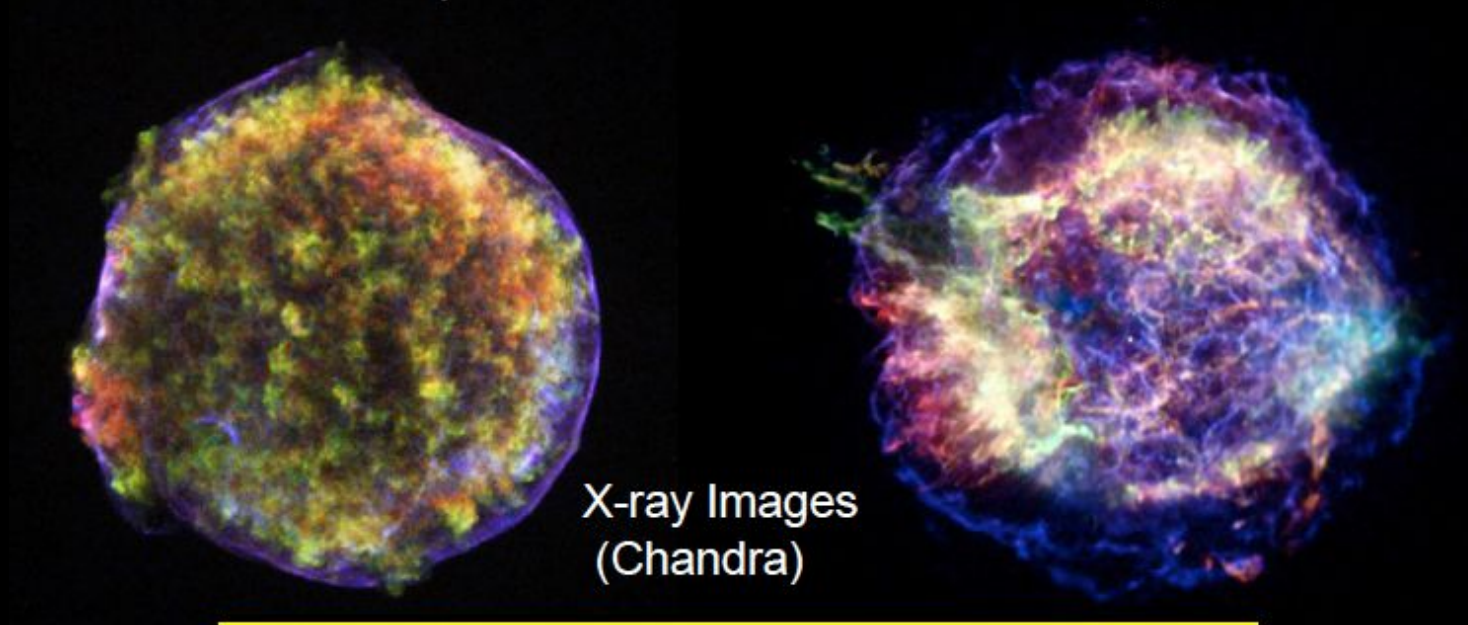
The Historical SNRs Cas A & Tycho

★ Tycho's SNR

- SN 1572
- SN type: Ia
- distance: ~3 kpc
- radius: ~3.7 pc

★ Cassiopeia A

- SN ~1680
- SN type: IIb
- distance: ~3.4 kpc
- radius: ~2.5 pc



X-ray Images
(Chandra)

Most parameters are reasonably well known.
→ largely help us interpret gamma-ray results.

The young SNR Cas A

Detected at GeV & TeV energies

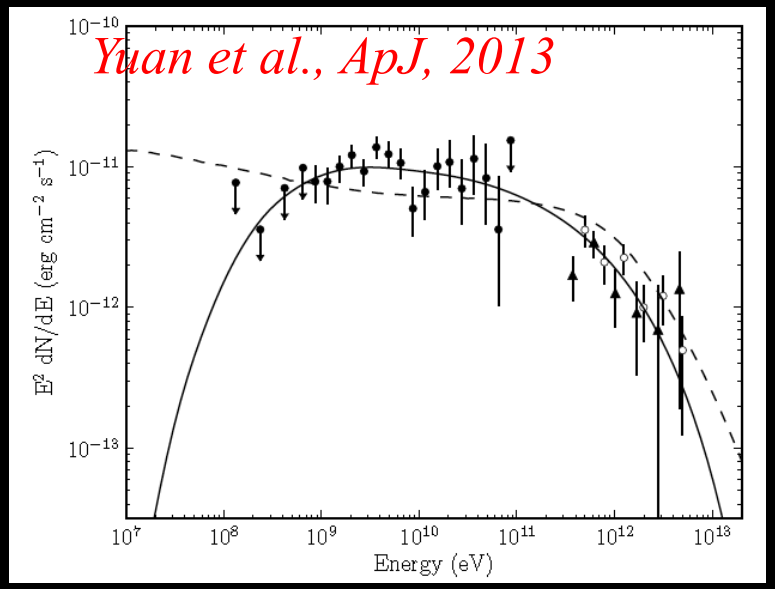
Pion bump feature at low energy =>

Leptonic scenario is ruled out

$W_{CR} = 4 \times 10^{49}$ erg ($n = 10$ cm^{-3})

$E_{max} = 10$ TeV

$B > 0.1$ mG

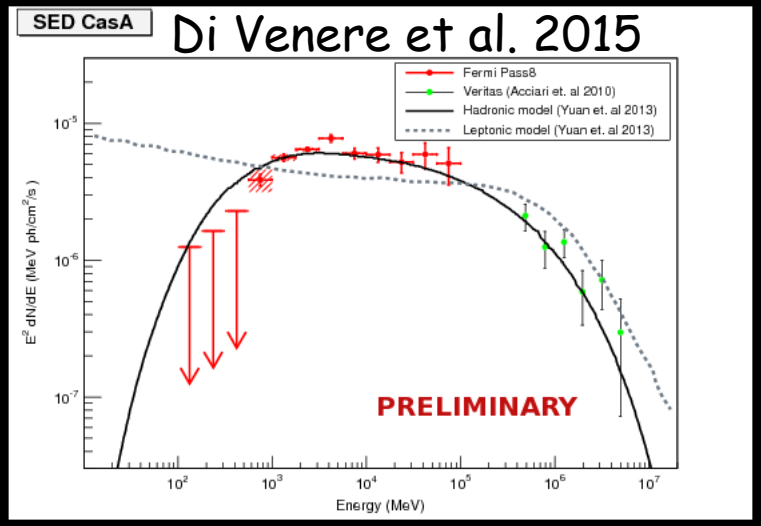


New Fermi data confirm the pion bump feature
=> Bremsstrahlung ruled out

But low CR efficiency and low Emax !

Plasma density overestimated ?

$W_{CR} = 2 \times 10^{50}$ erg (see Zirakashvili et al., 2013)

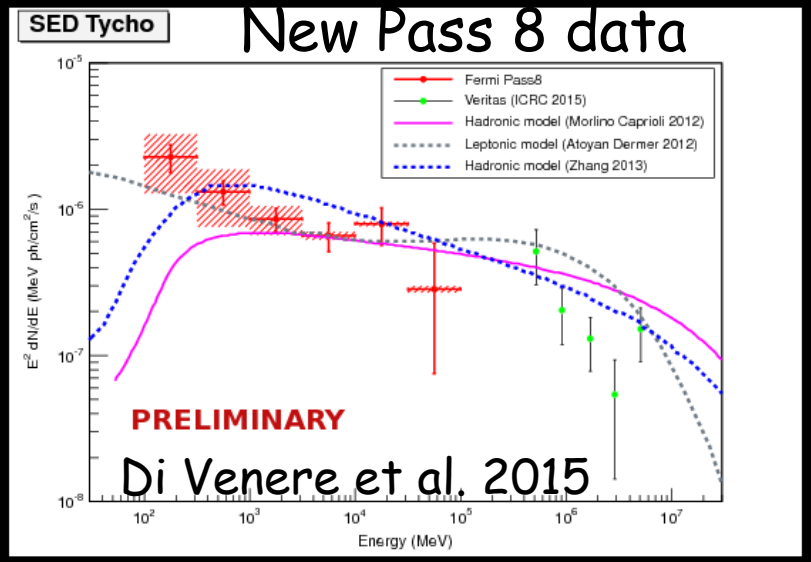


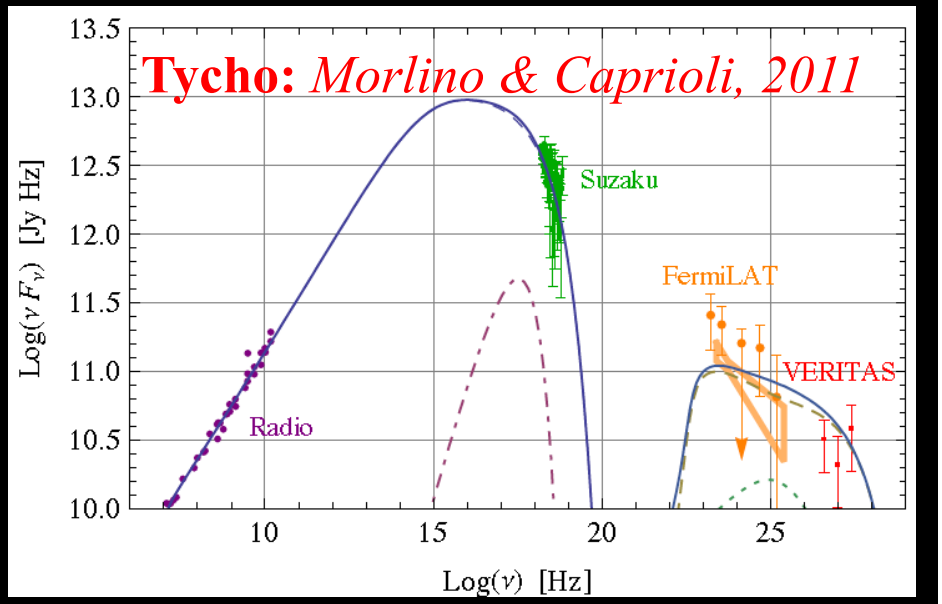
The young SNR Tycho

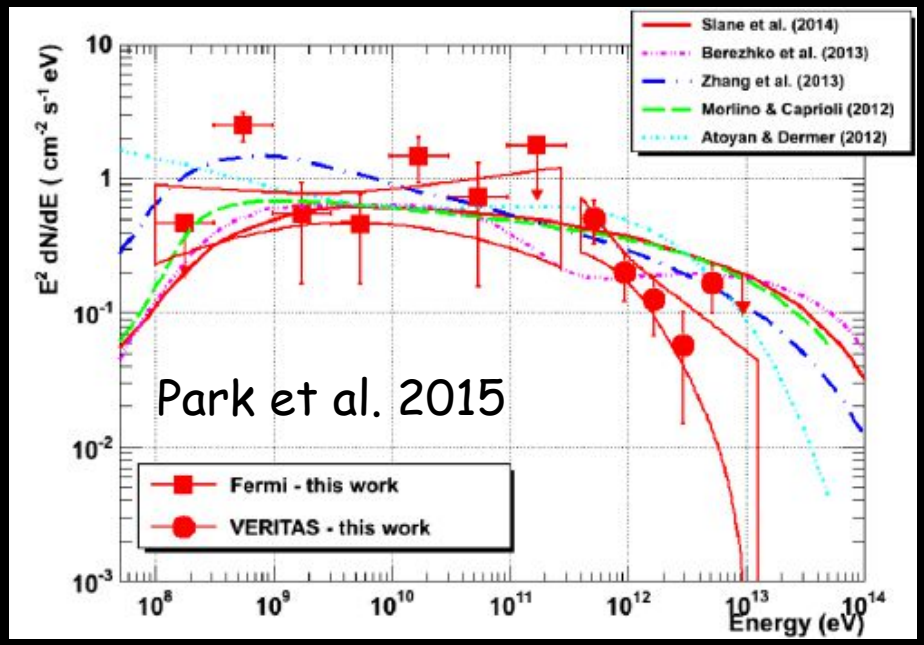
First Hadronic scenario suggested:
Steep spectrum (Γ=2.3)
Maximal energy > 500 TeV
B field > 200 μG
Energy content in CR ~ 6% E_{SN}

Lower Energy threshold for Fermi
+ modification of spectrum by VERITAS

Leptonic scenario is not completely ruled out







Some first thoughts

Finally: proof of proton acceleration in SNRs

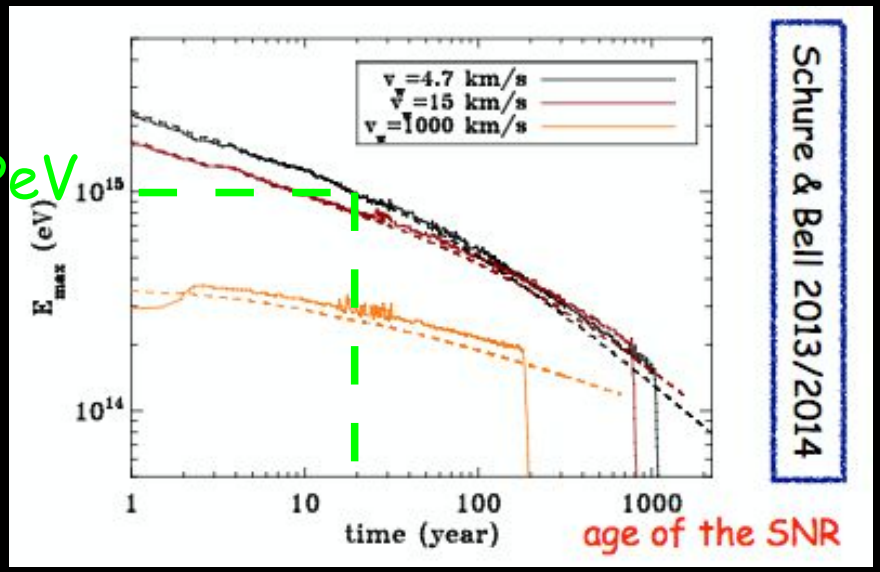
Clear in SNRs interacting with MCs
Plausible in young non-thermal SNRs
Clear in the historical SN Cas A

....but :
1- The acceleration efficiency in young SNRs is generally much lower than the 10% used to maintain the CR flux in our Galaxy

2- We're far from smoking gun for PeV Galactic CRs

Very rare PeVatrons ?

If 3SN/century and SNRs are PeVatrons for 10 - 100 yrs



=> only ~3 PeVatrons in whole Galaxy !

Distant sources => hard to detect

...However, if SNRs accelerate up to PeV energies, they should still be surrounded by an over density of escaped PeV cosmic-rays (eg. Gabici & Aharonian, ApJ, 2007):

$t^{diff}_{PeV} \sim 5000\ (d/100\ pc)^2\ (D_{PeV}/10^{29}\ cm^2/s)^{-1}$ years

The emission from the clouds is weaker than the one from the SNR but lasts longer => enhanced probability of detection !

Need better angular resolution (correlation with gas) & increased sensitivity

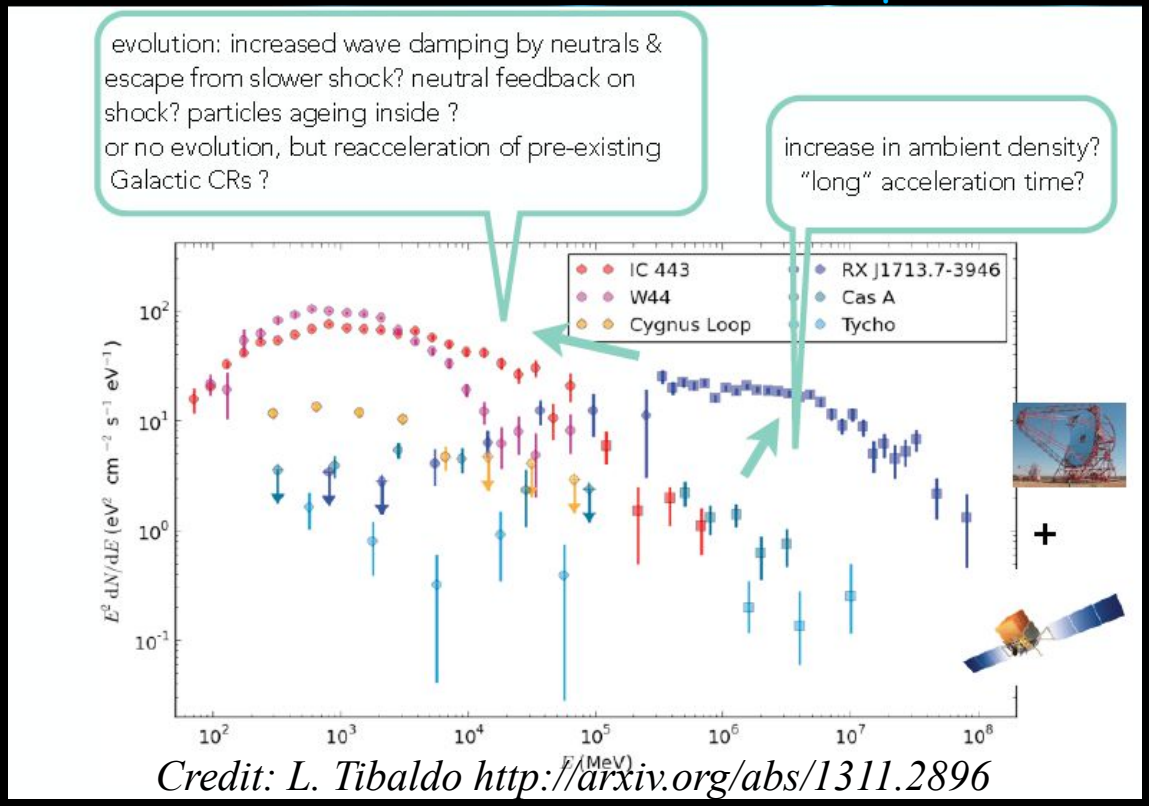
=> CTA is well suited

Still so much to learn ! An exciting field

Future GeV/TeV studies will constrain the fraction of SN energy injected into protons/electrons & look for indirect detections of PeVatrons (with MCs)

Future > 10 TeV studies will look for PeVatrons

Future MeV-GeV studies will look for proton accelerators



Credit: L. Tibaldo http://arxiv.org/abs/1311.2896

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