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# Cosmic-ray world with gamma-ray astronomy: a wealth of information, an ever more open issue

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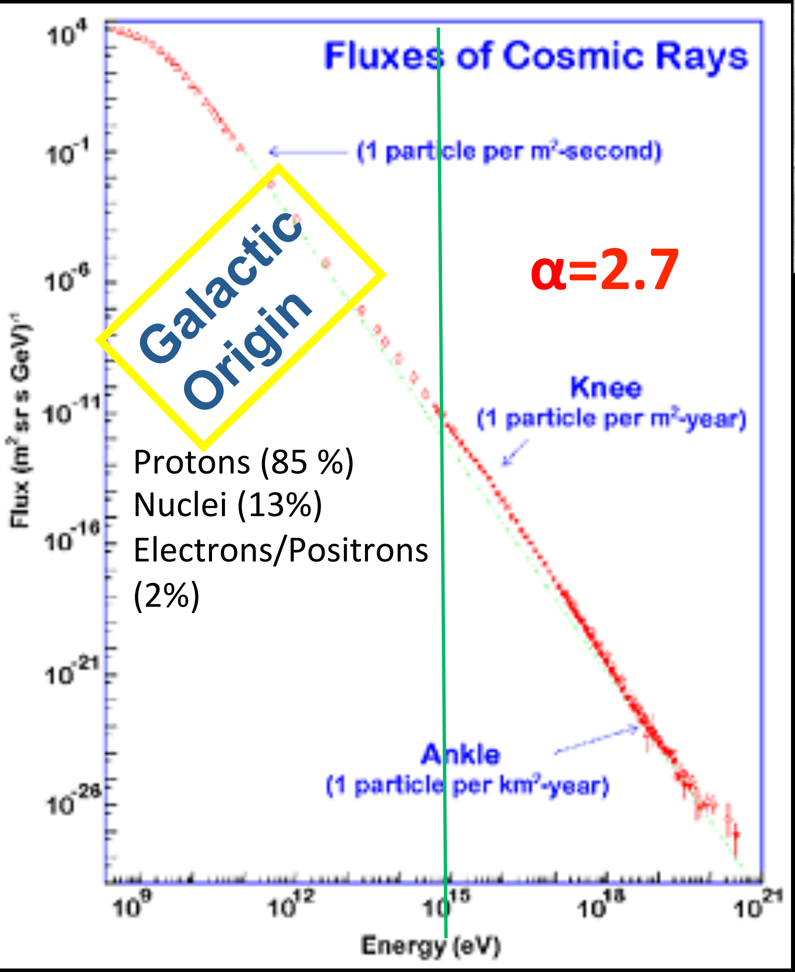
September 9, 2014

# Index

- ✧ SNR/CR context and gamma-rays
- ✧ Main Issue: can we resolve the problem of the origin of hadronic cosmic-rays?
- ✧ The breakthrough:
  - The SNR W44 and the first direct proof
- ✧ Challenges:
  - data vs theory
- ✧ Prospects for the future

# Context




1949 E. Fermi
(Fermi acceleration)

1959. V.Ginzburg
(SNRs hypothesis)

## Supernova Remnants

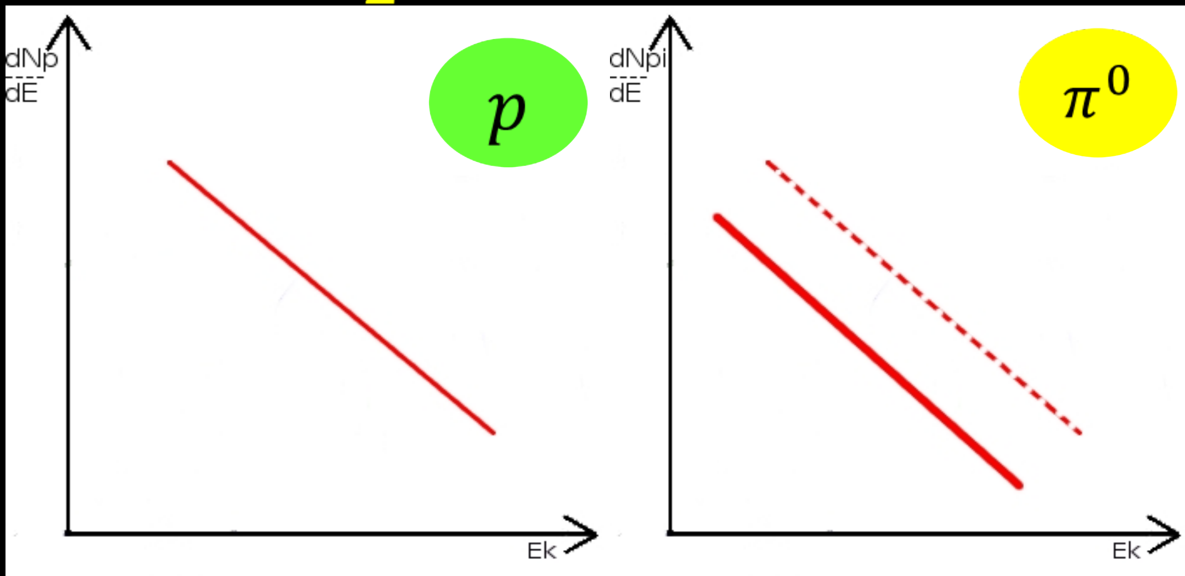
- Energetic shock waves
- Possibility of energy gains by repeated shock crossing

# DIFFUSIVE FERMI ACCELERATION

## (MAGNETIC TURBULENCE)

# Context

$$E_{th,\gamma} = \frac{m_{\pi^0}}{2} \sim 67\ MeV$$




$p$

$$\frac{dN_p}{dE} \propto E^{-p}$$

$$p + p_{target} \rightarrow \cdots + \pi^0 \rightarrow 2\gamma$$

$$\frac{dN_{\pi^0}}{dE} \propto E^{-p}$$

$$E_{\pi^0} \sim 10\%\ E_p$$

$$p = \frac{r+2}{r-1}$$

$$r = \frac{V_{up}}{V_{down}}$$

**Linear DSA**

Injection → p~ 2

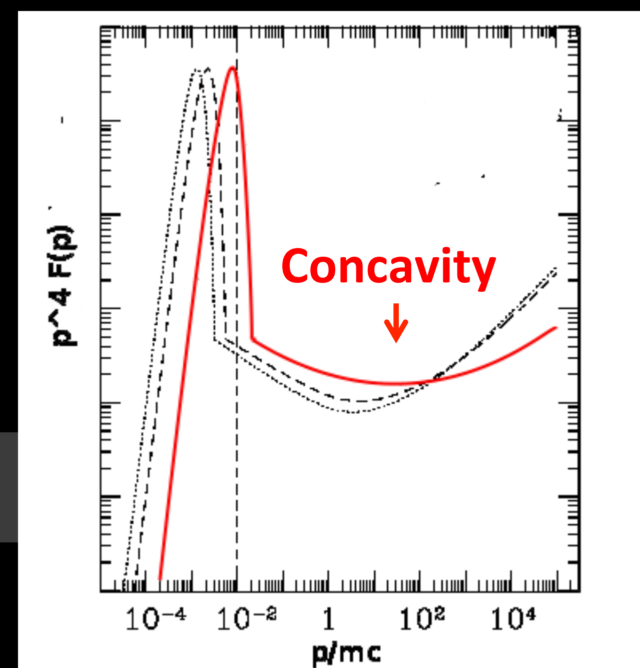
Inject.+ diffusion

→ α~ 2,7

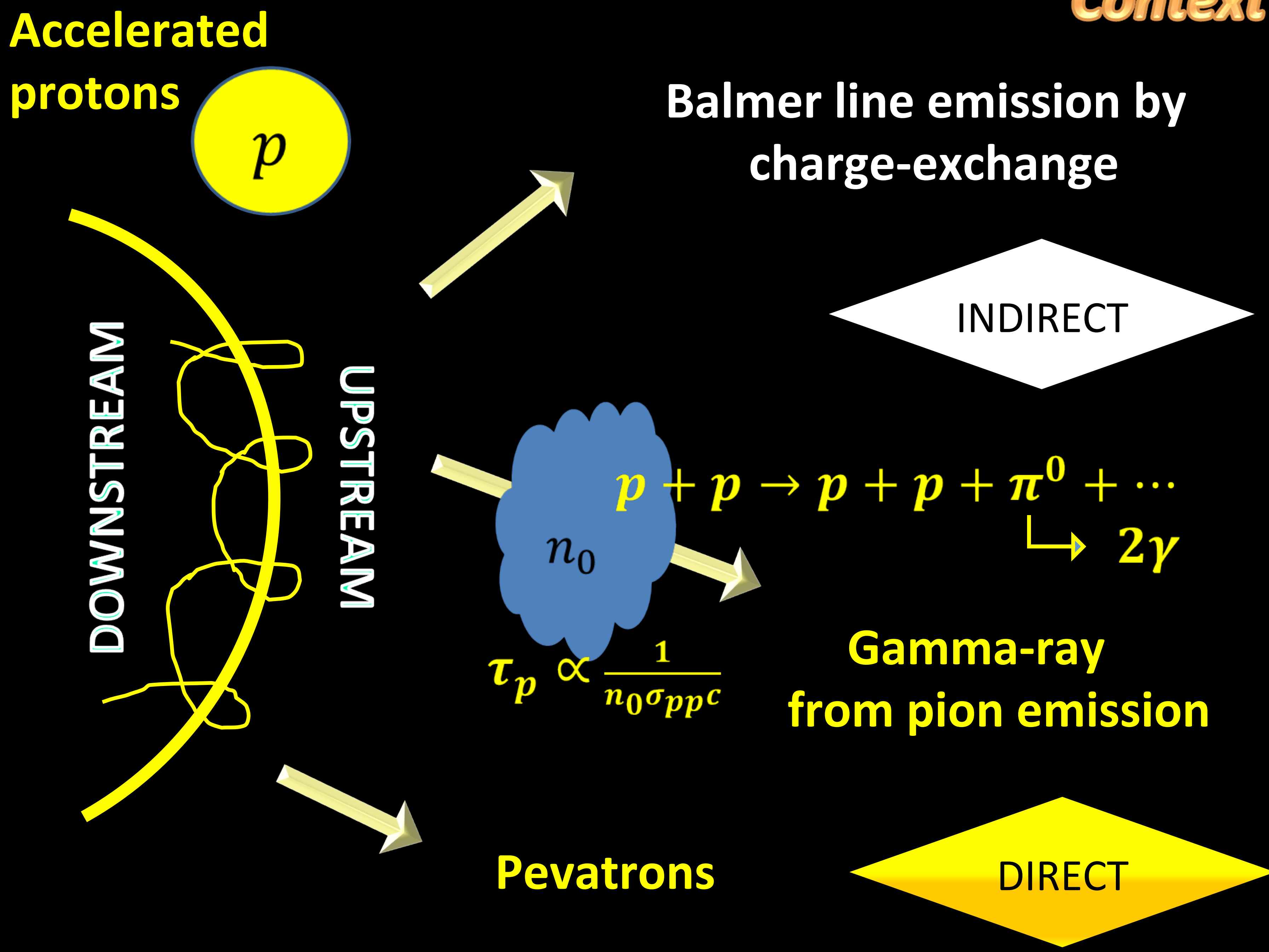
STRONG SHOCK → r=4

**Non Linear DSA**

Injection → p < 2



## Context

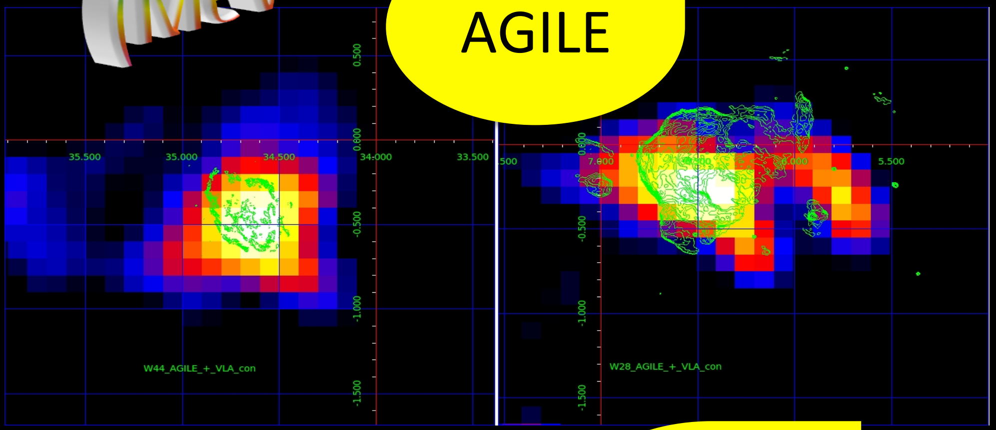


Accelerated protons
$p$
Balmer line emission by charge-exchange
INDIRECT
DOWNSTREAM
UPSTREAM
$n_0$
$p + p \rightarrow p + p + \pi^0 + \cdots$
$2\gamma$
$\tau_p \propto \frac{1}{n_0 \sigma_{pp} c}$
Gamma-ray from pion emission
Pevatrons
DIRECT

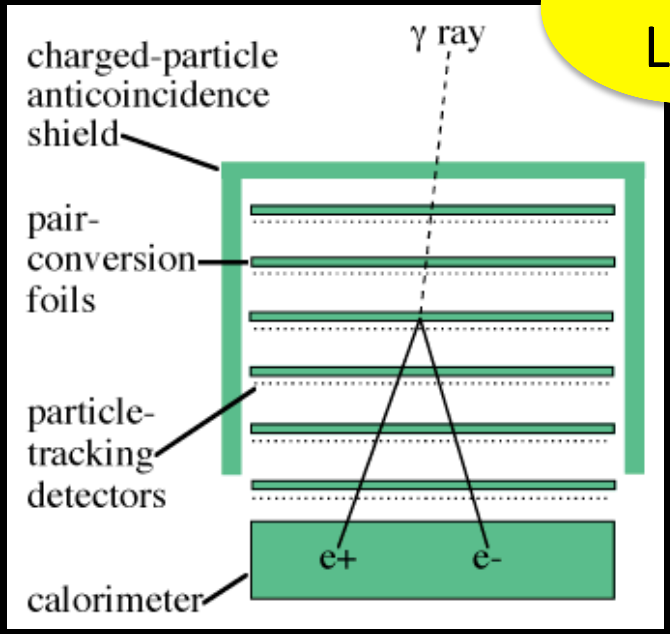
# Gamma-rays

## Space (MeV-GeV)

AGILE




Fermi-LAT



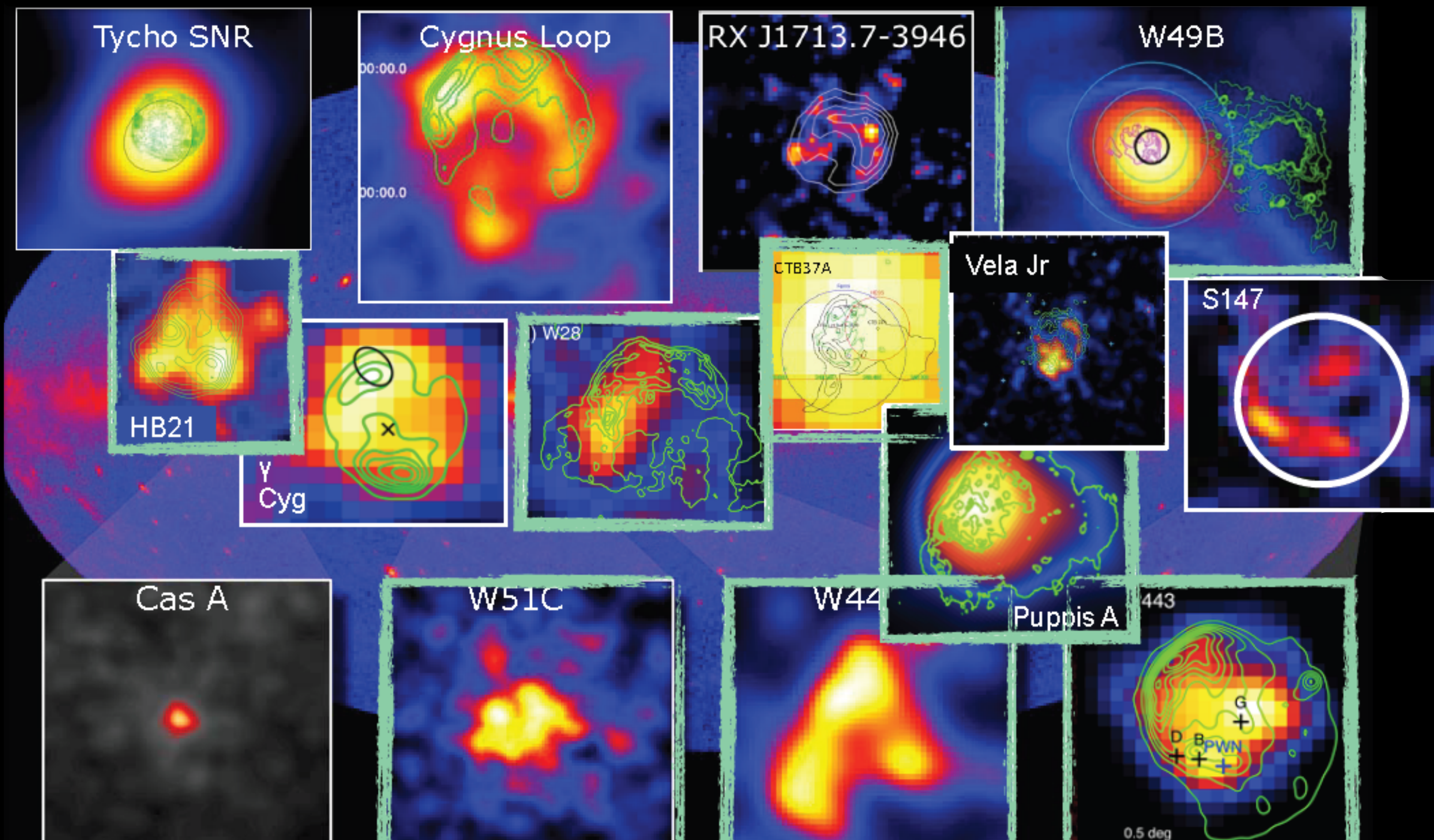

## Earth (GeV-TeV)


MAGIC

VERITAS


HESS

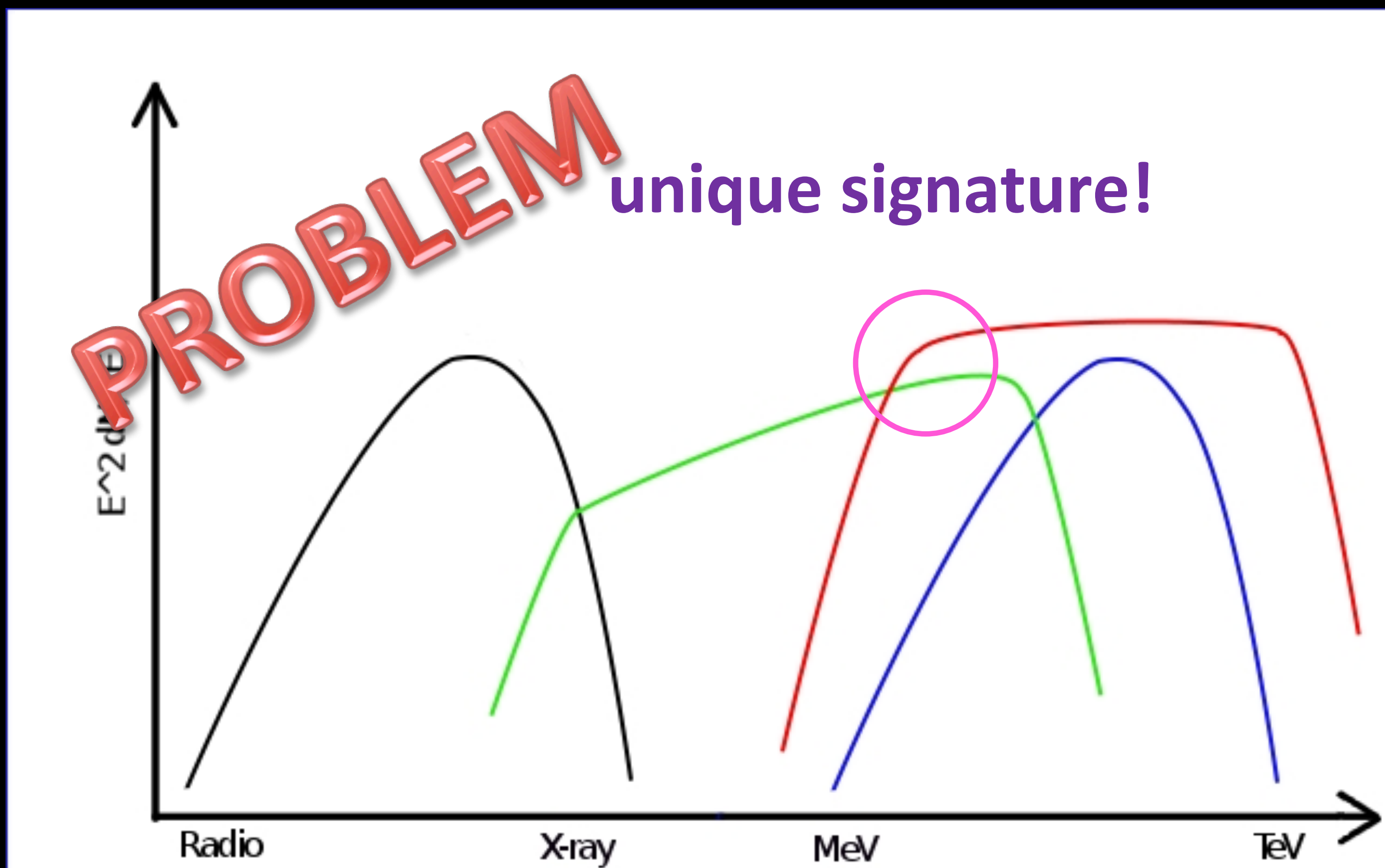
# Gamma-ray SNRs




**Several SNRs detected in gamma-rays, but finding a clear proof is very difficult!**

# Gamma-ray detection: problem

$e^-$



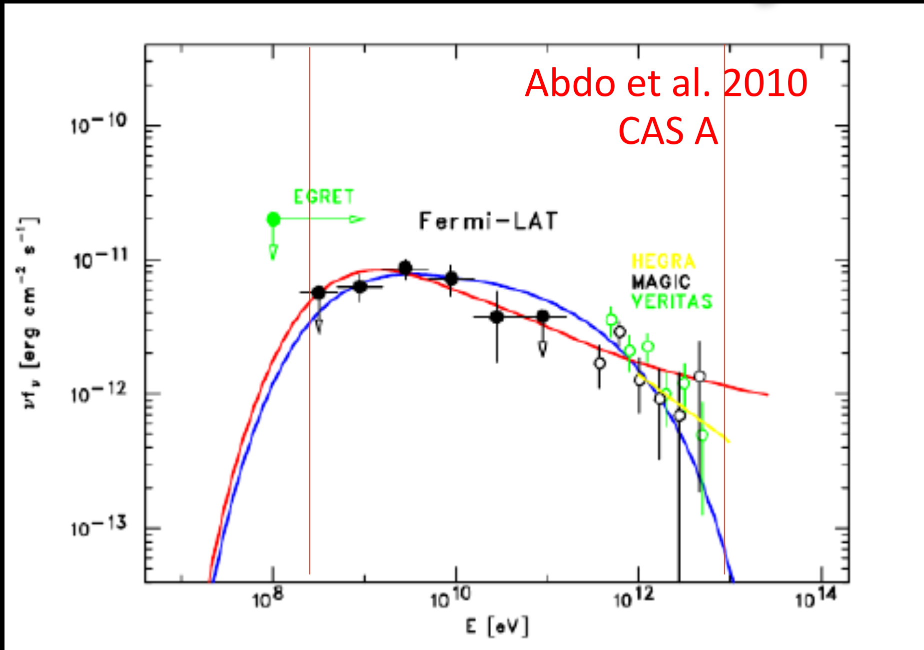

$p$

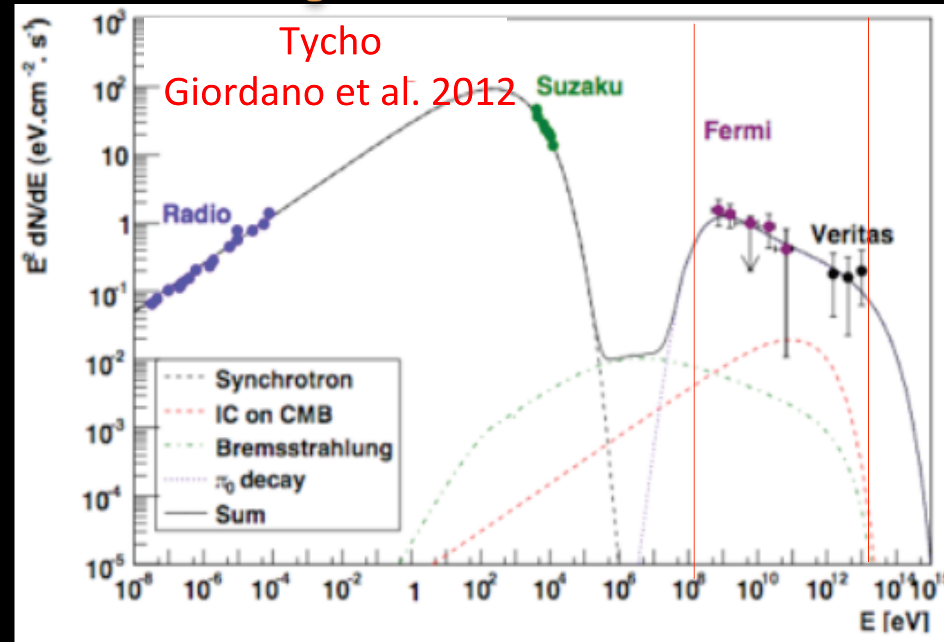
**Synchrotron →** $\propto B^2$

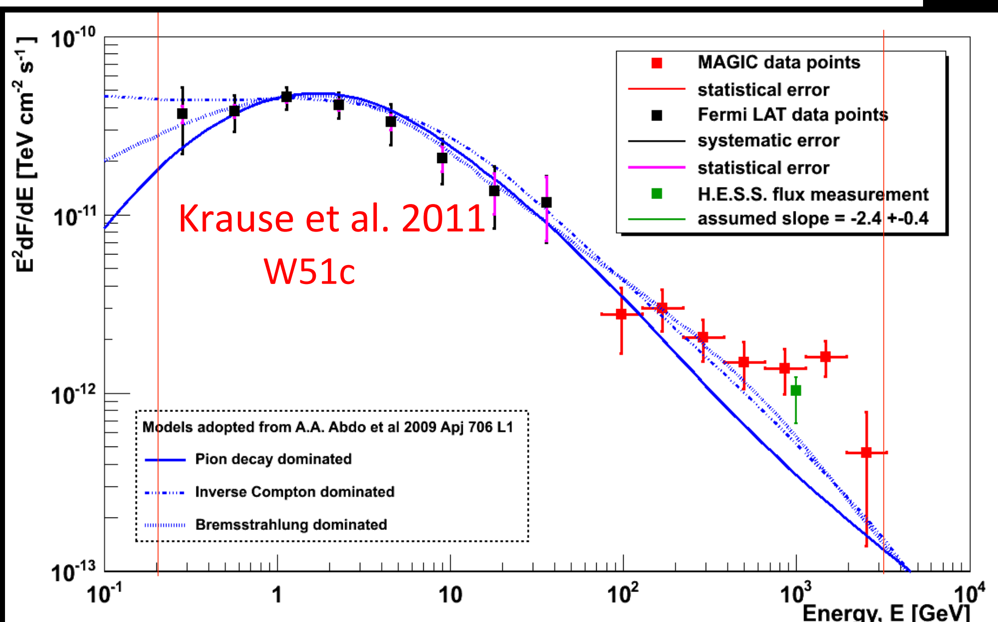
**Inverse Compton →** $\propto \gamma^2 w_{soft-ph}$

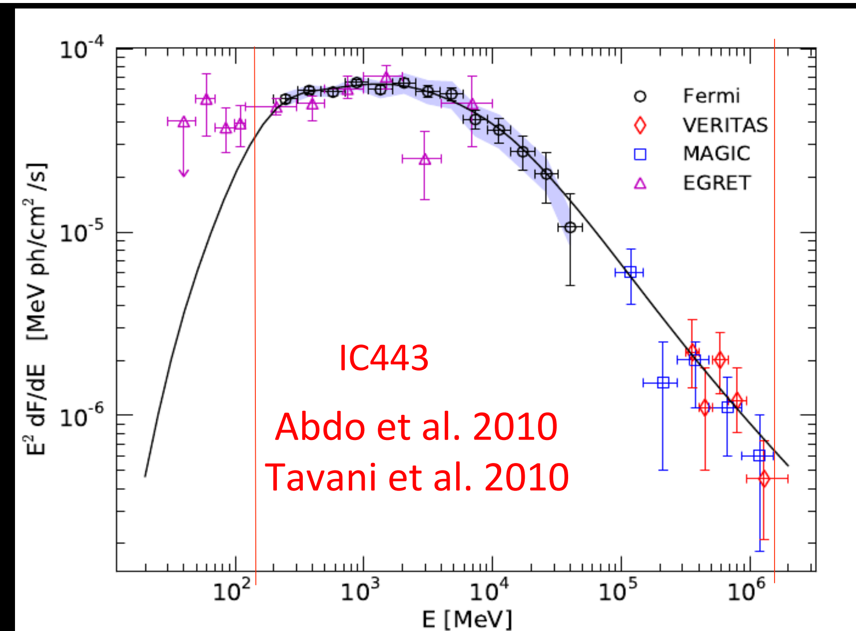
**Relativ. Bremsstrahlung →** $\propto n_H$

# Gamma-ray detection: problem

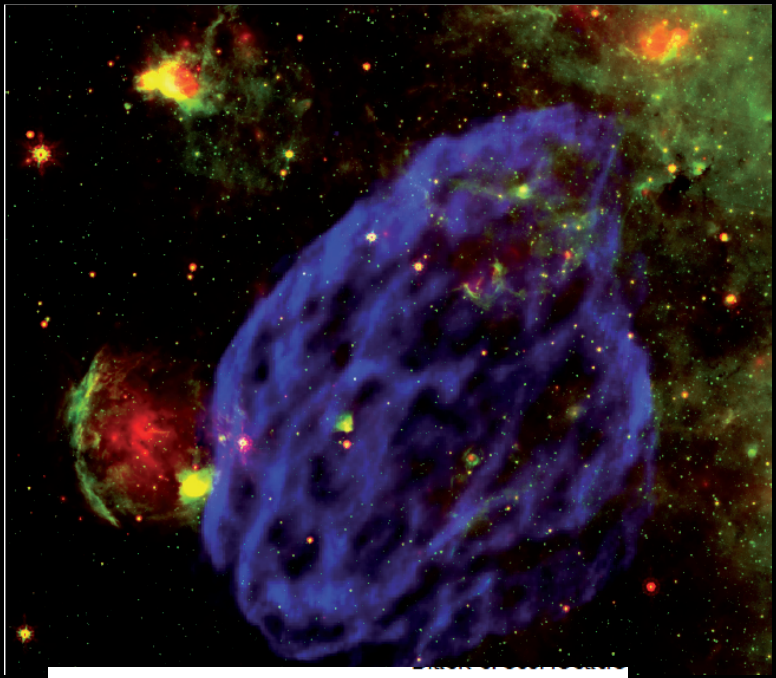


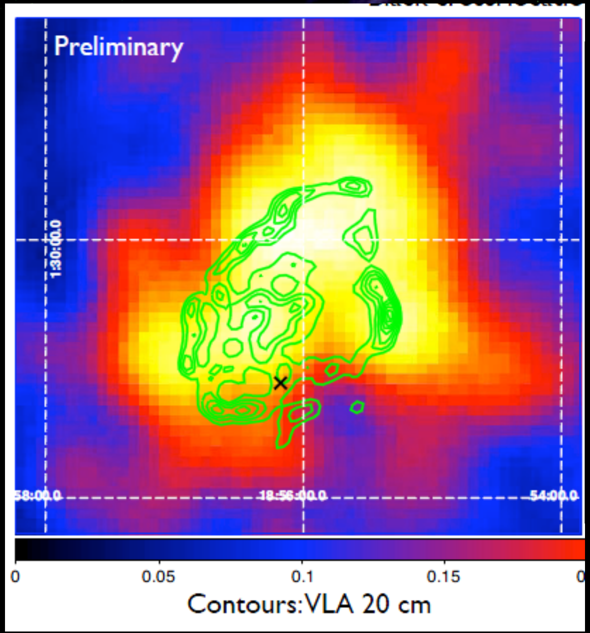



# The breakthrough: the SNR W44



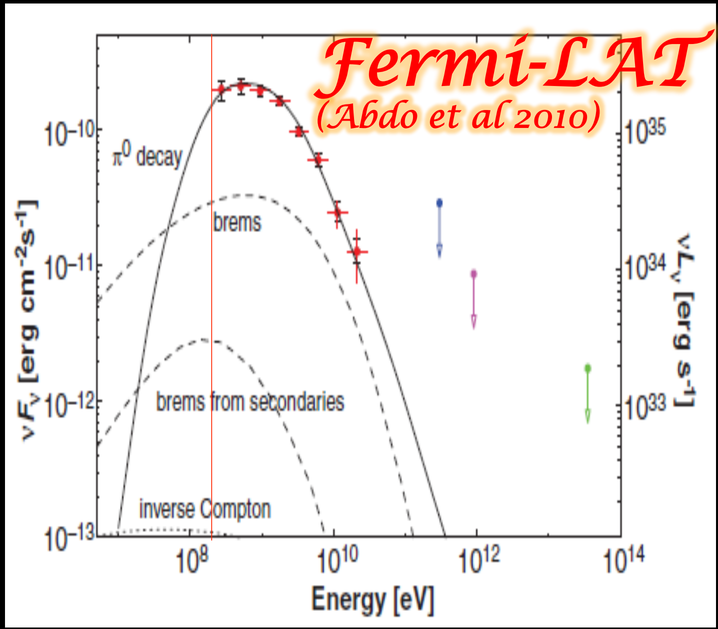
Galactic Plane: (34.7, -0.4)
d~3.1 kpc
t~2 × $10^4$ yrs
Mixed morphology
Molecular cloud on SE side
Very bright

W44: radio 324 MHz(VLA) + IR 8 and 24 $\mu m$ (Spitzer)
(Castelletti et al., 2007)



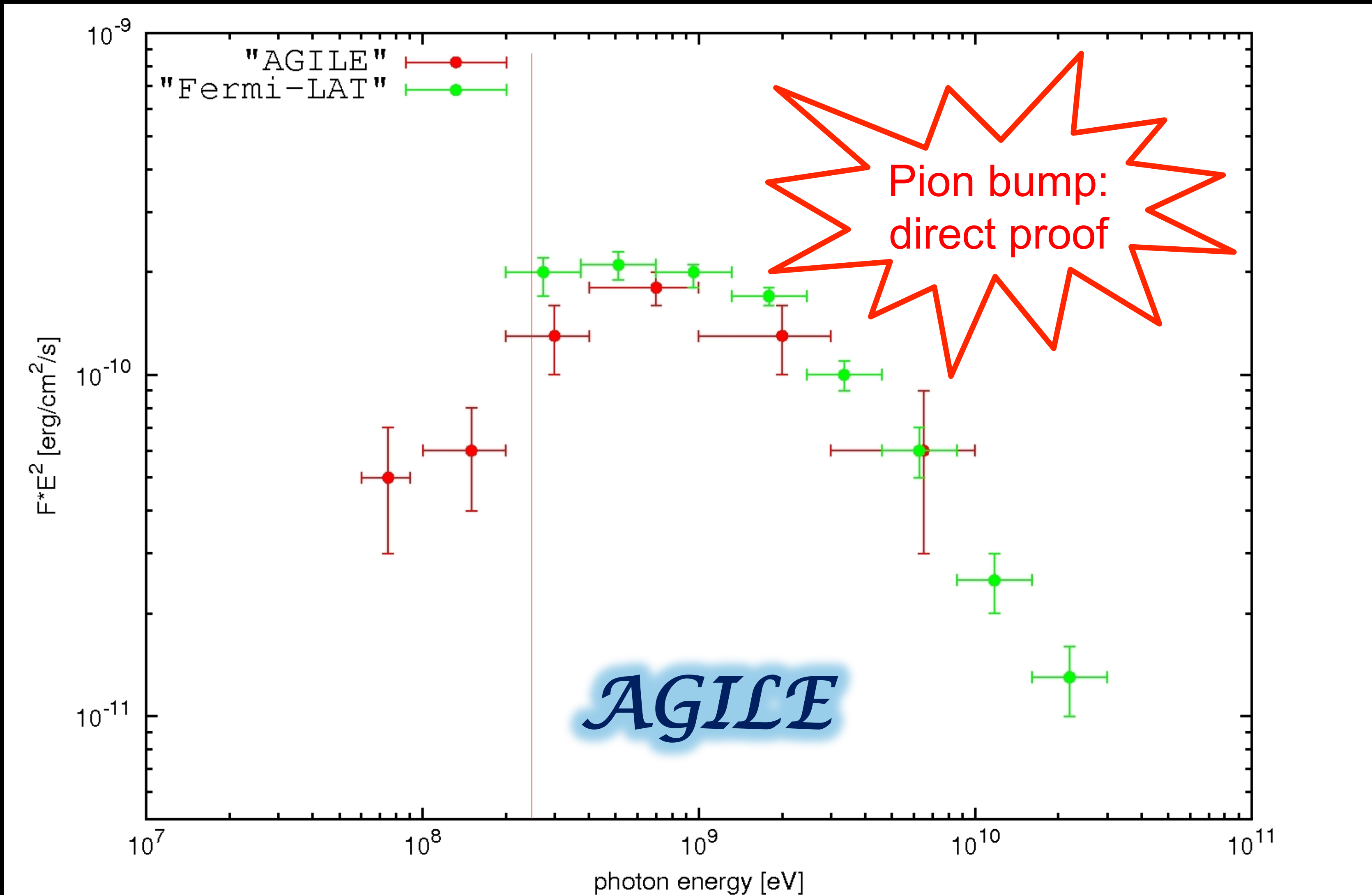

Bremsstrahlung is excluded as dominant contribution assuming n= $10^2$ and $K_{ep}$~$10^{-2}$→ B~70$\mu G$

W44: gamma-ray emission (Fermi)
(Abdo et al. 2010)

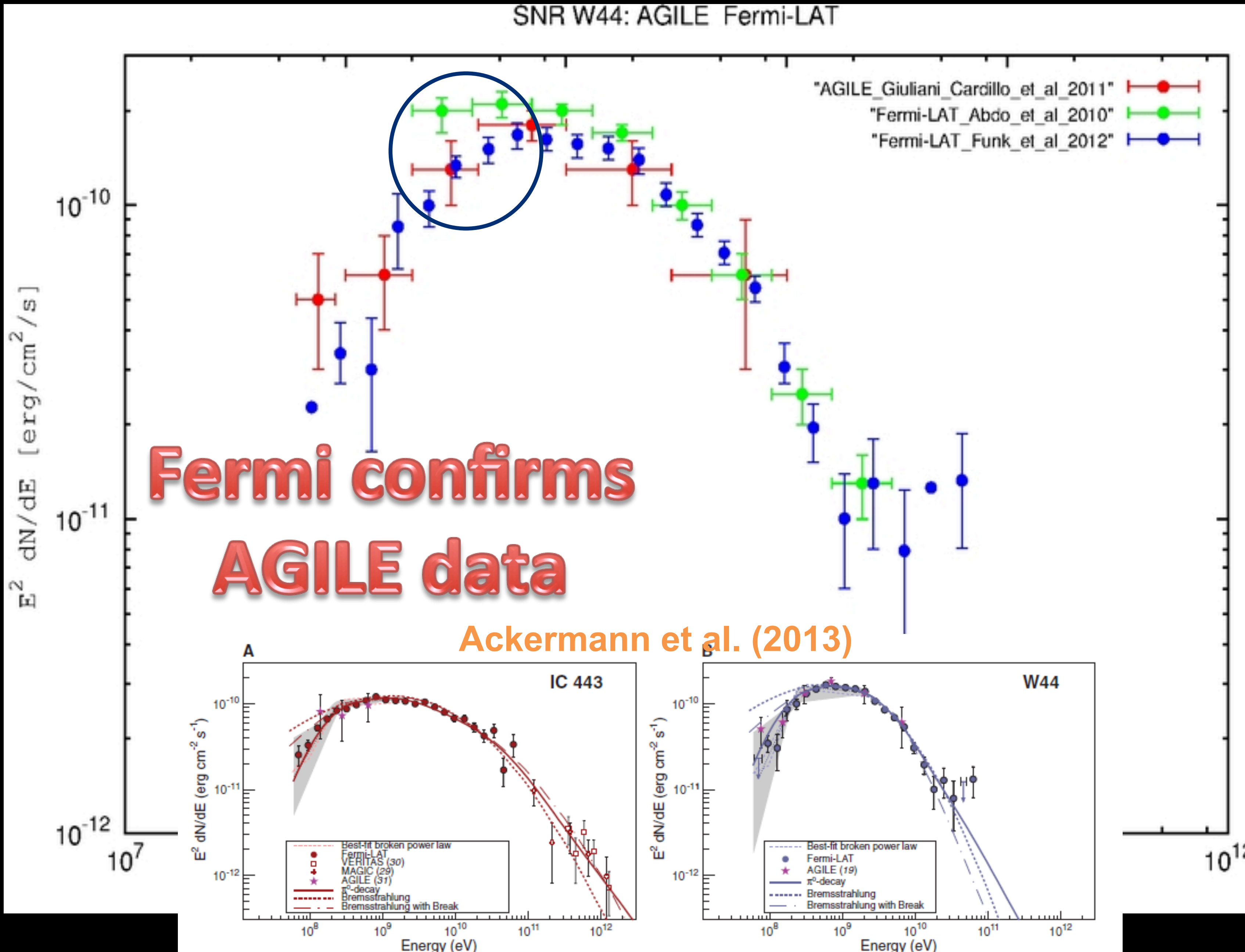


# The breakthrough: the SNR W44

Giuliani, Cardillo, Tavani et al .(2011)



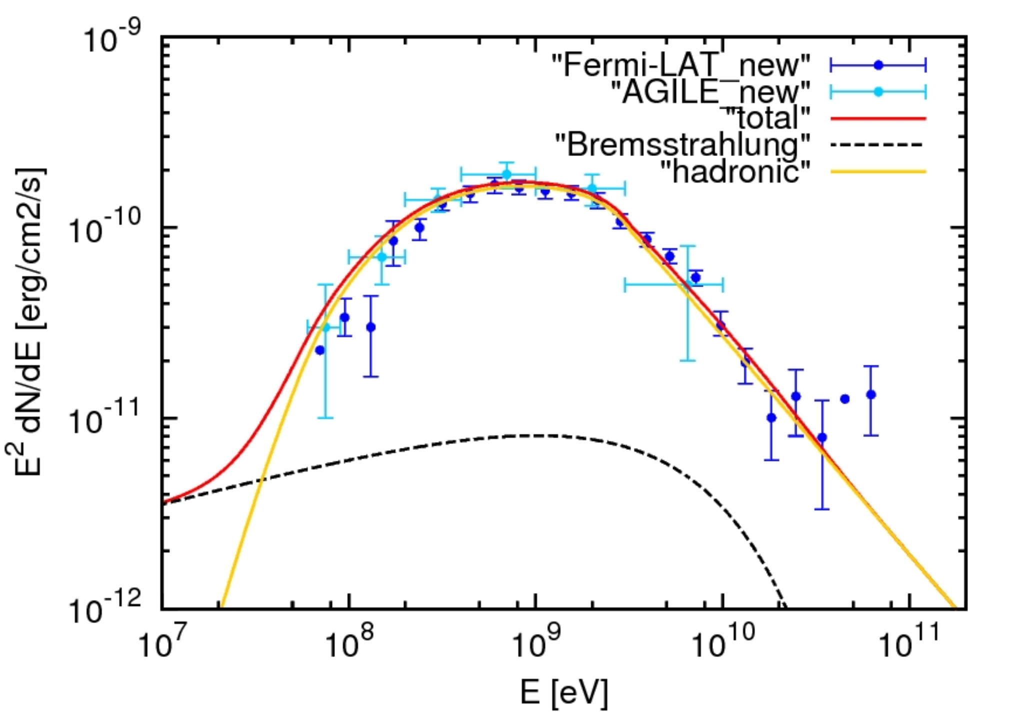
# The breakthrough: the SNR W44

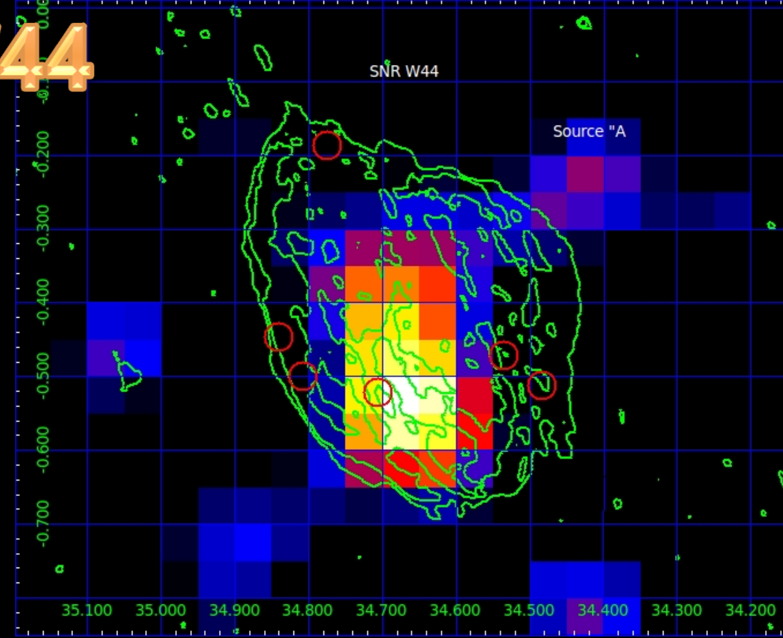



Fermi confirms AGILE data

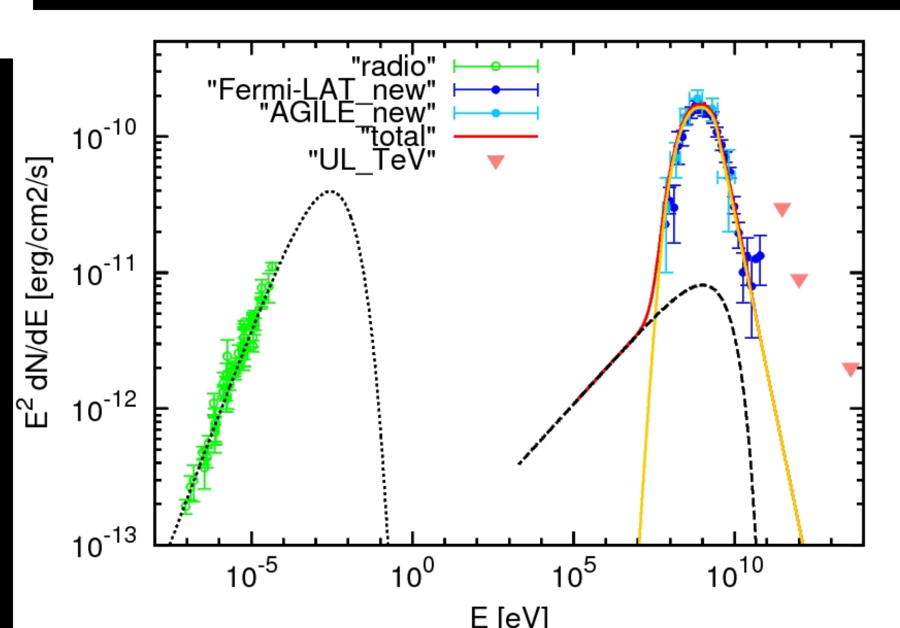
Ackermann et al. (2013)

# The challenge: the SNR W44




Cardillo et al. 2014



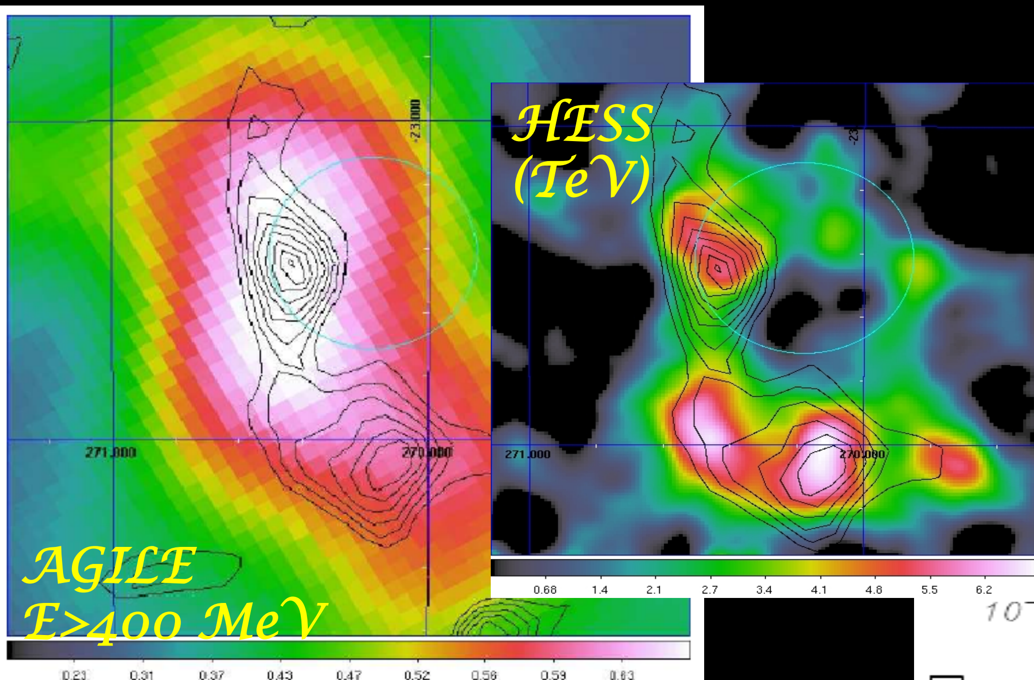

- E = total energy
- n = 300 cm^-3
- B = 210$\mu G$
- $E_{br}$= 20 GeV
- $p_1$= 2,2
- $p_2$= 3,2

# The challenge: from W44 to all the others

- First pion bump signature:
  - * low-E index $p_1$ ~ 2.2 → as like as the young SNRs
- High density: $n \approx 300\ cm^{-3}$
  - * In all the middle-aged SNRs → related to high magnetic field
- High magnetic field: B ≈ 200 μG
  - * in the most of the SNRs → amplification
  - * differences between young and old
- Steepness:
  - * $p_2 \geq 3$ → Why?

Cardillo et al., 2014

# The SNR W28

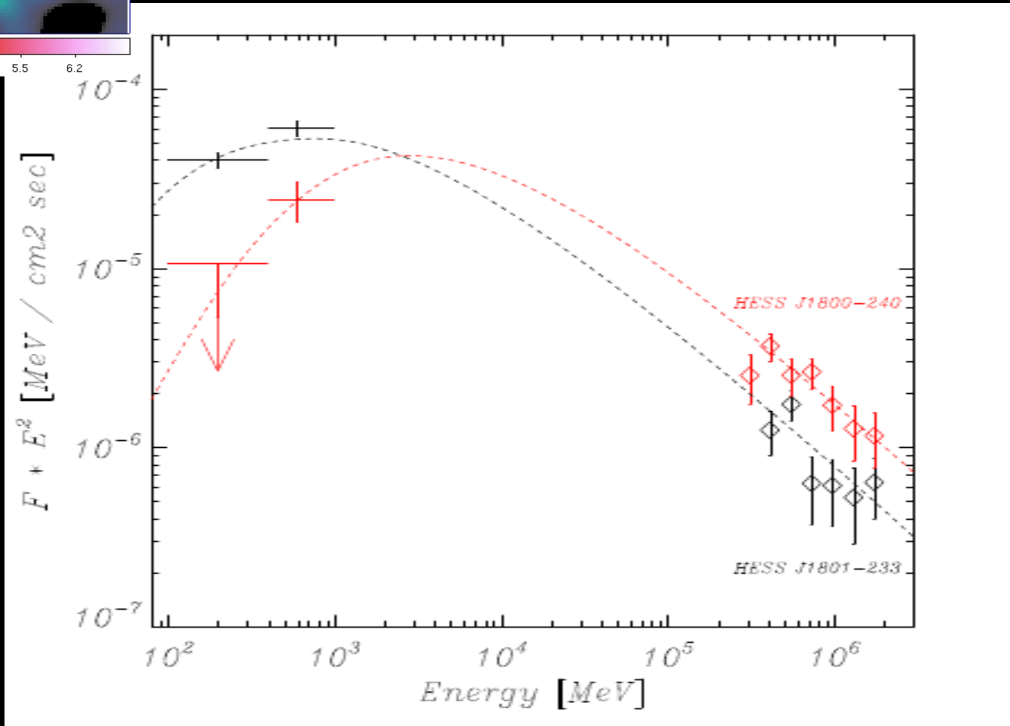



- Galactic Plane
- d~1.8-3.3 kpc
- t~3.5 × $10^4$ yrs
- Mixed morphology

Giuliani et al., 2010

- Spectral index for E>1 GeV → α=2.7
- Linear DSA model

$$D(E) = D_0 \left( \frac{E}{E_0} \right)^{\delta}$$



# W28 and W44

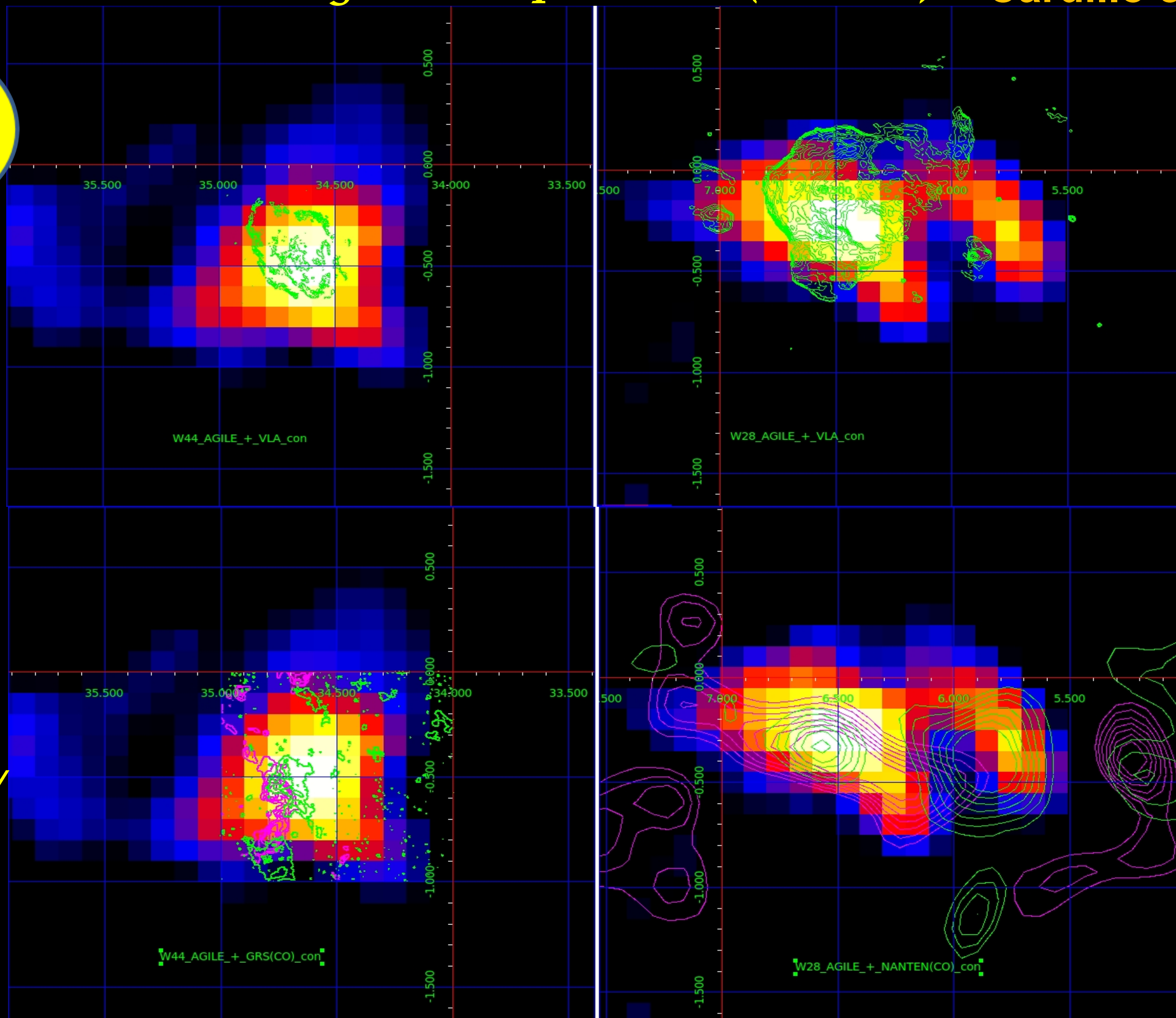
*AGILE E>400 MeV (bin=0.1)*

Cardillo et al. 2014b

*W44*

*VLA radio contours (324 MHz)*

*GRS CO contours (40-43 Km/s)*




*W28*

*VLA radio contours (30 cm)*

*NANTEN CO contours 0-17/18-27 km/s*



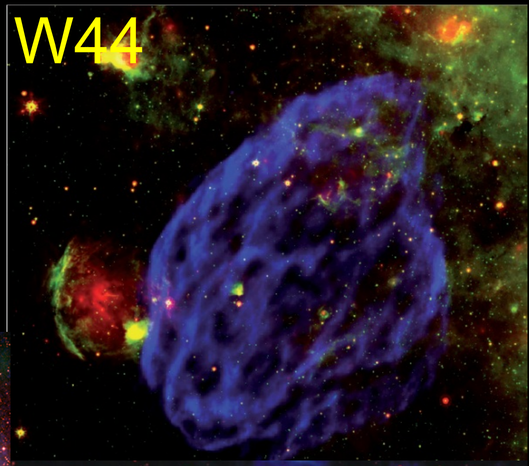

# Young SNRs

t < 1000-2000 yrs

Primary spectrum

<u>Environment</u>

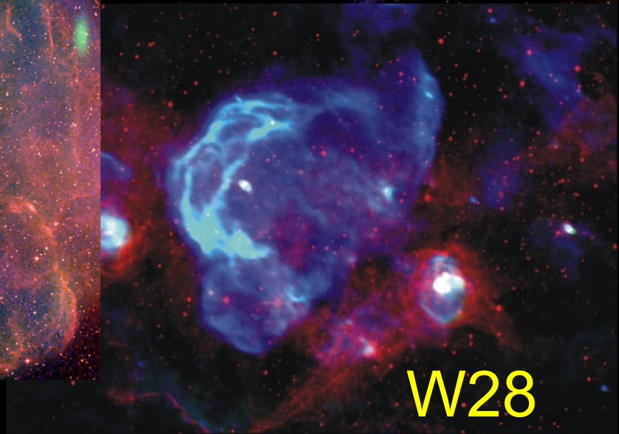
<u>(ISM, molecular clouds)</u>



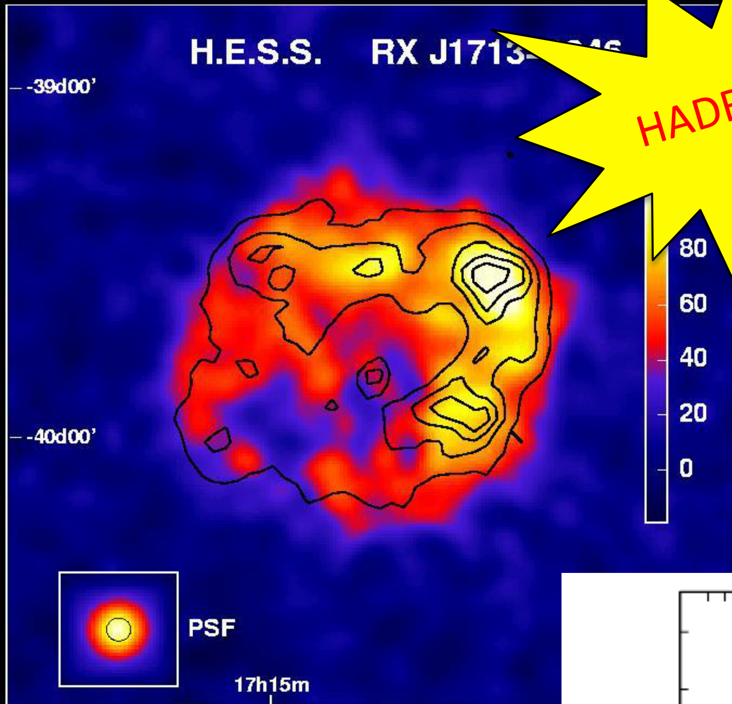

# Middle-aged SNRs

t > 1000-2000 yrs

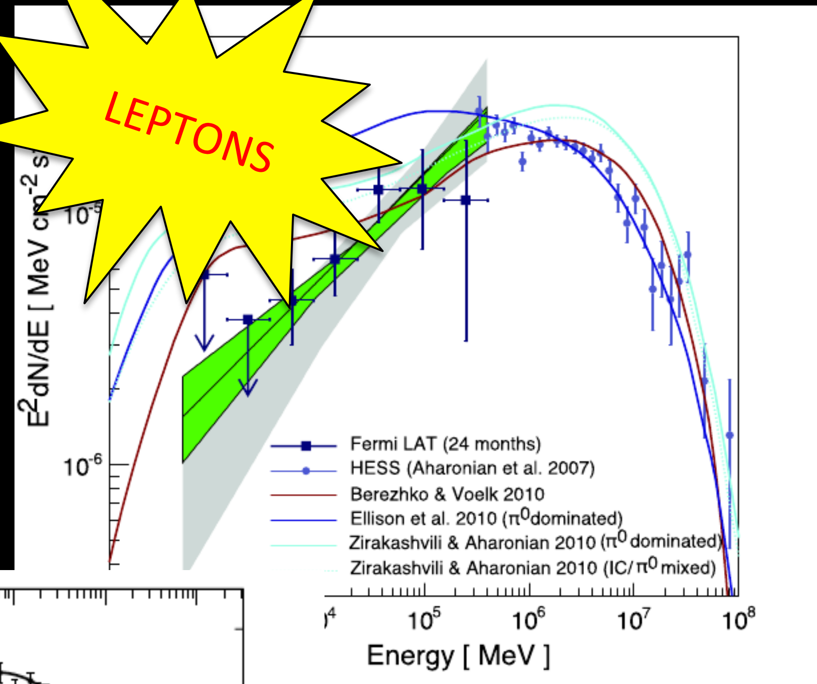
Secondary spectrum

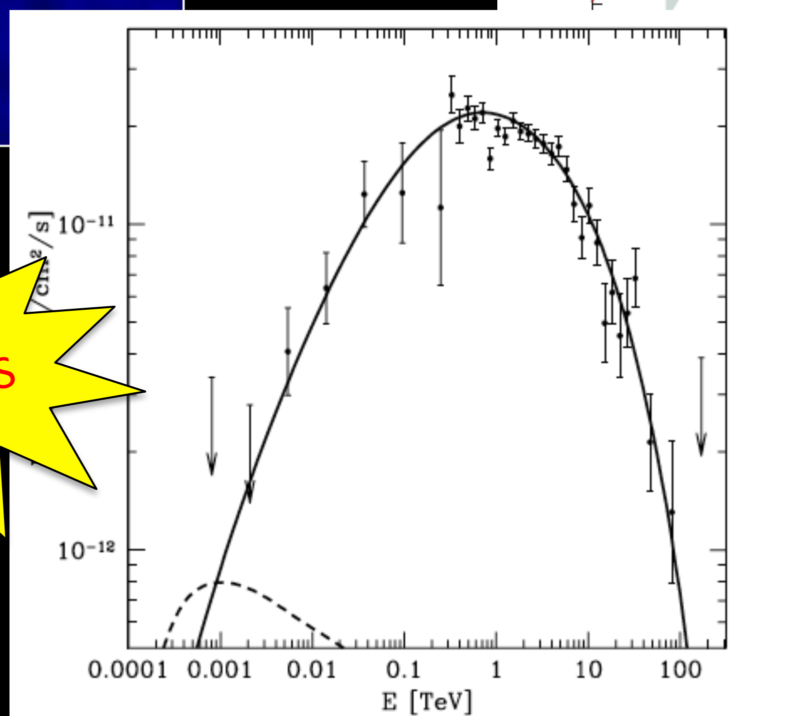
# Environment importance: the SNR RX J1713-3946




Aharonian et al. 2007




Abdo et al. 2011

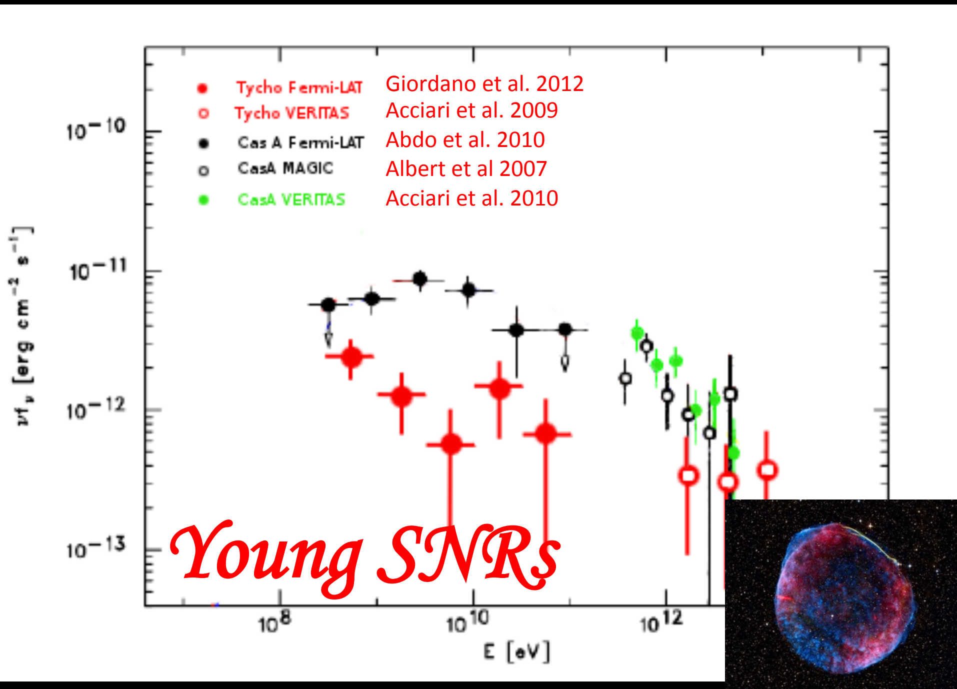


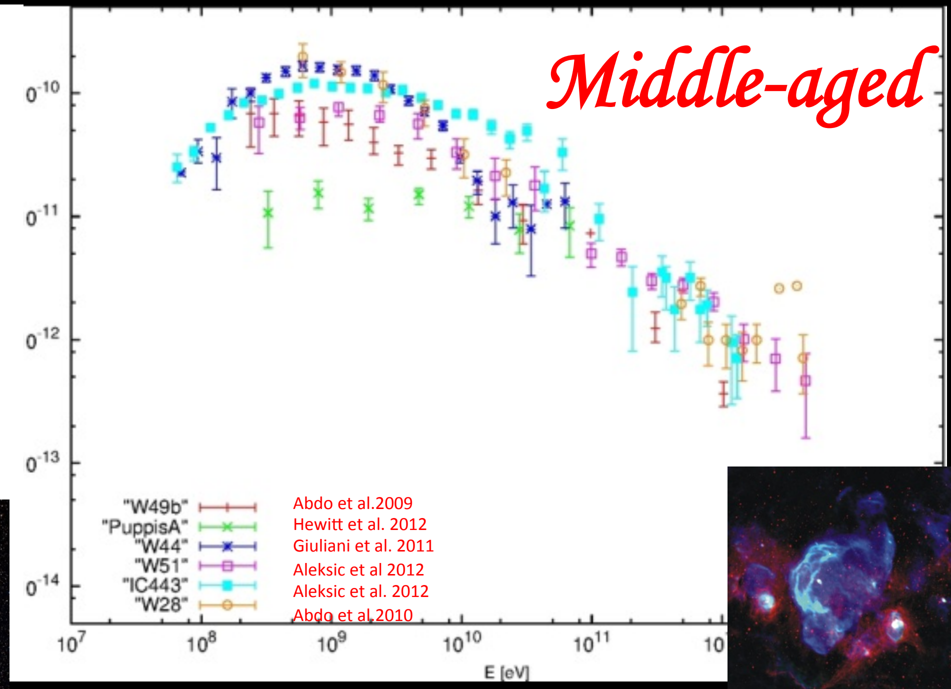

Fukui et al.2013
Gabici & Aharonian 2014

...even if the leptons maybe could...

# Summary: a great confusion

Cardillo et al. 2014b



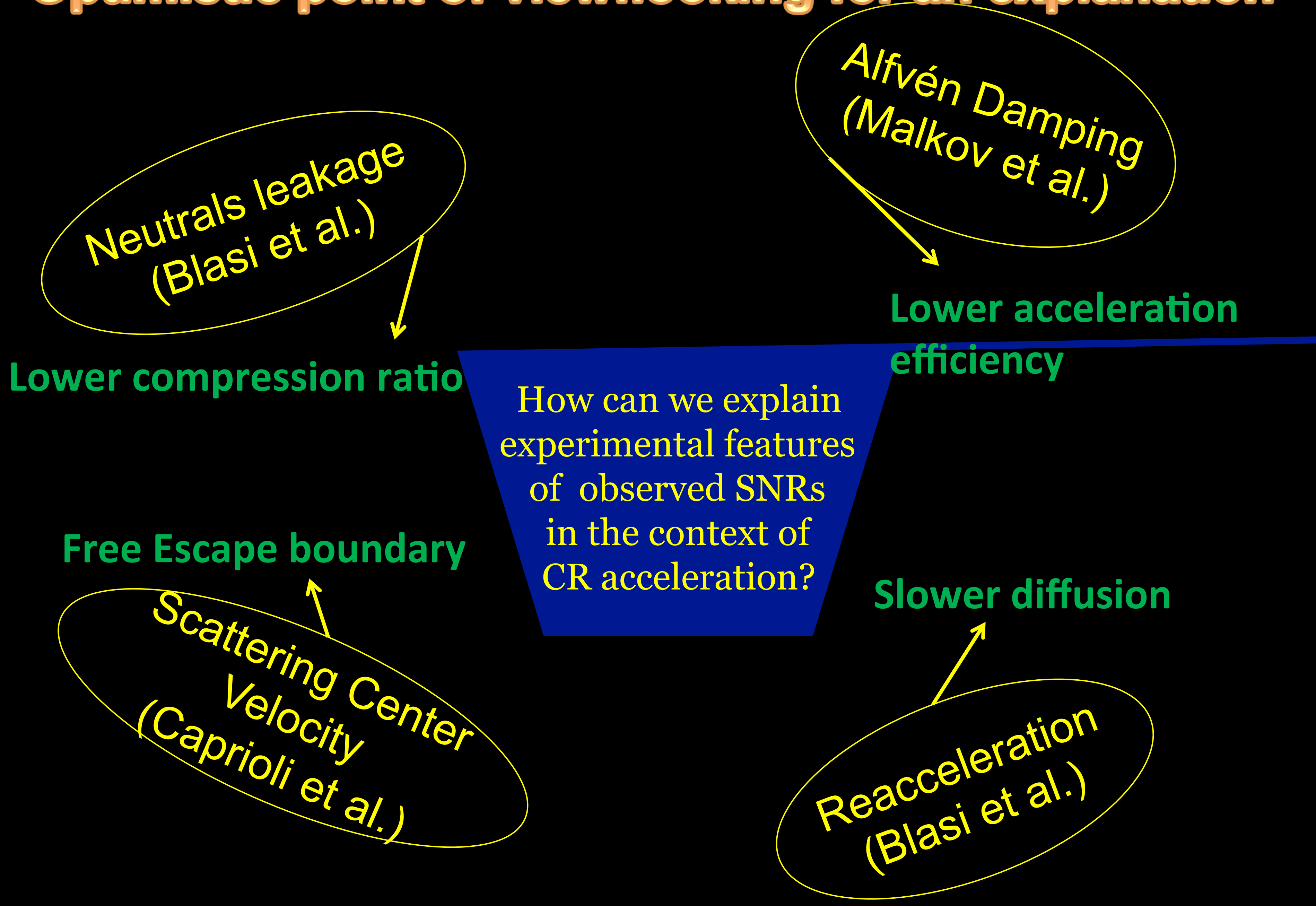

## Young:

- Low-density medium
- p= 2,2-2,4 → No concavity!!
- No obvious Pevatrons

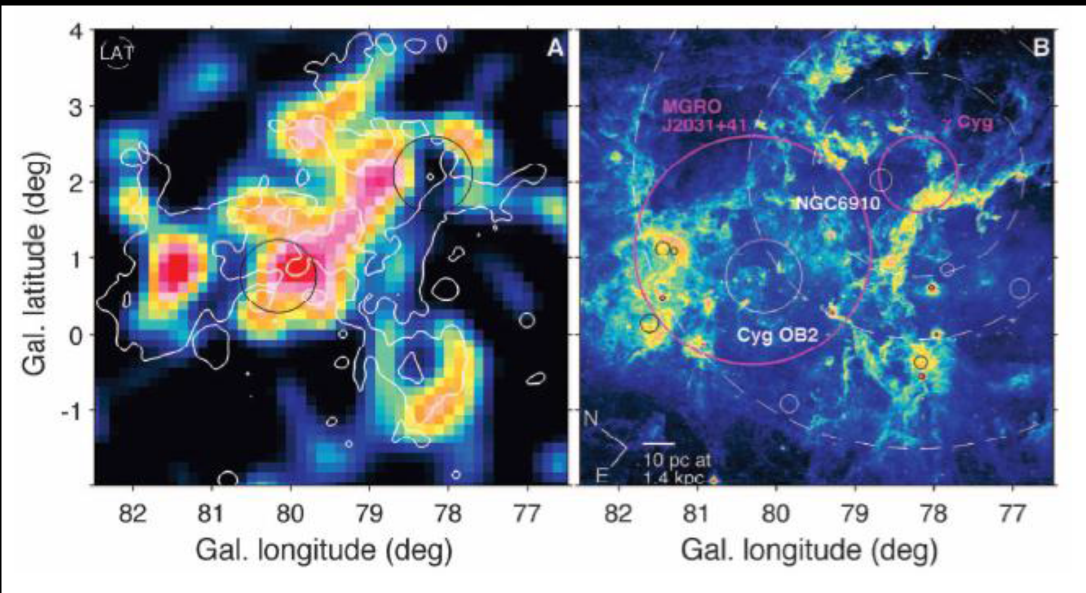
## Middle-aged:

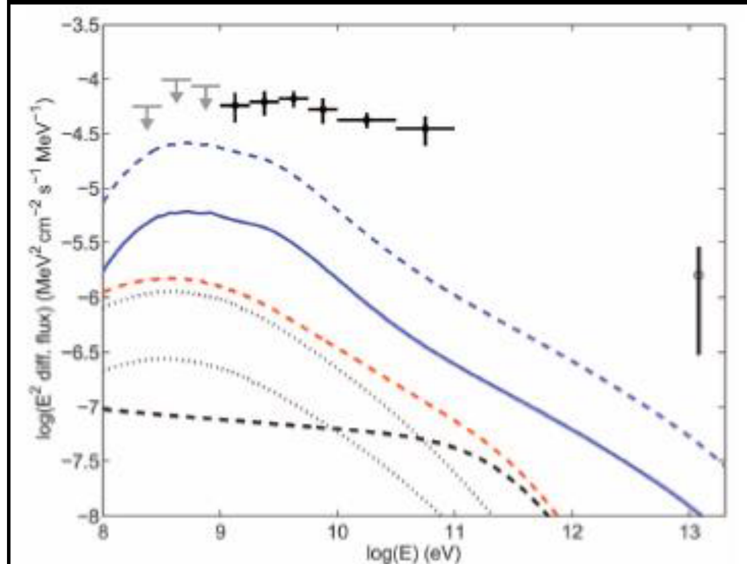
- High-density medium
- 2,6 < p < 3
- No hope for Pevatrons !

# Optimistic point of view:looking for an explanation



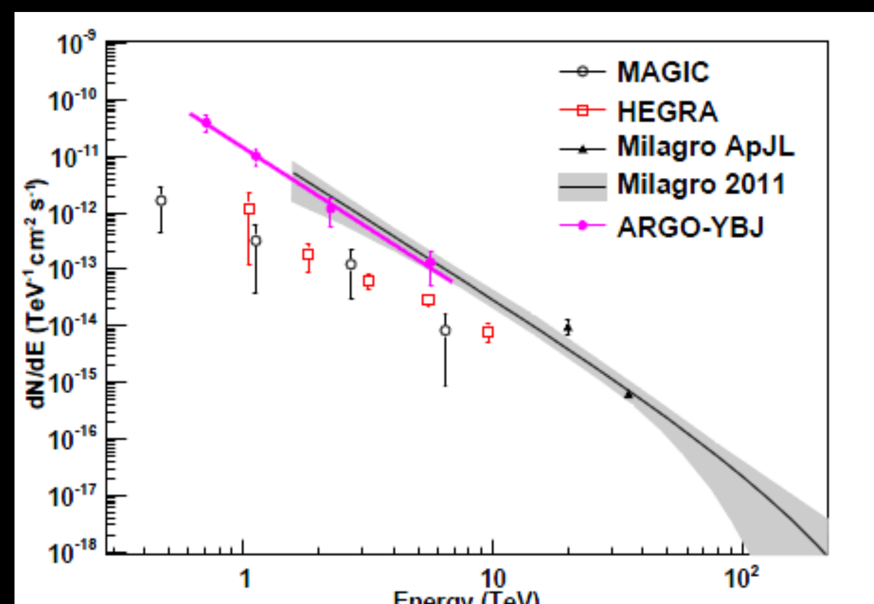
# Pessimistic point of view: no SNRs, other sources




Cygnus region: GeV emission
from Fermi-LAT (Ackermann et al.2011)

**Superbubbles**

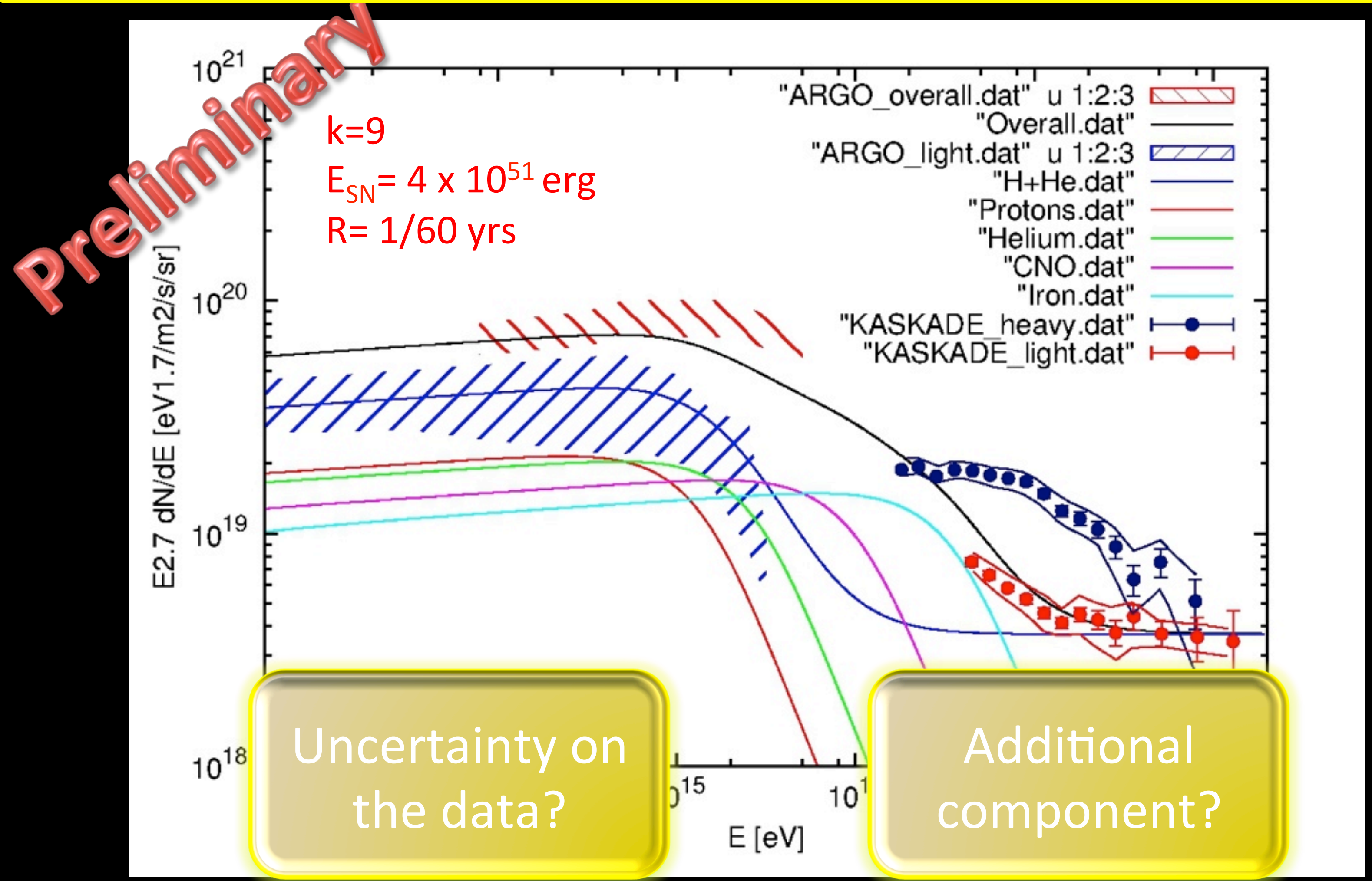



MGRO2031+41: TeV emission
from ARGO (Bartoli et al. 2012)

# And particle spectrum?

Cardillo, Amato, Blasi, in preparation

## Non resonant instability and CR current (Bell 2004)



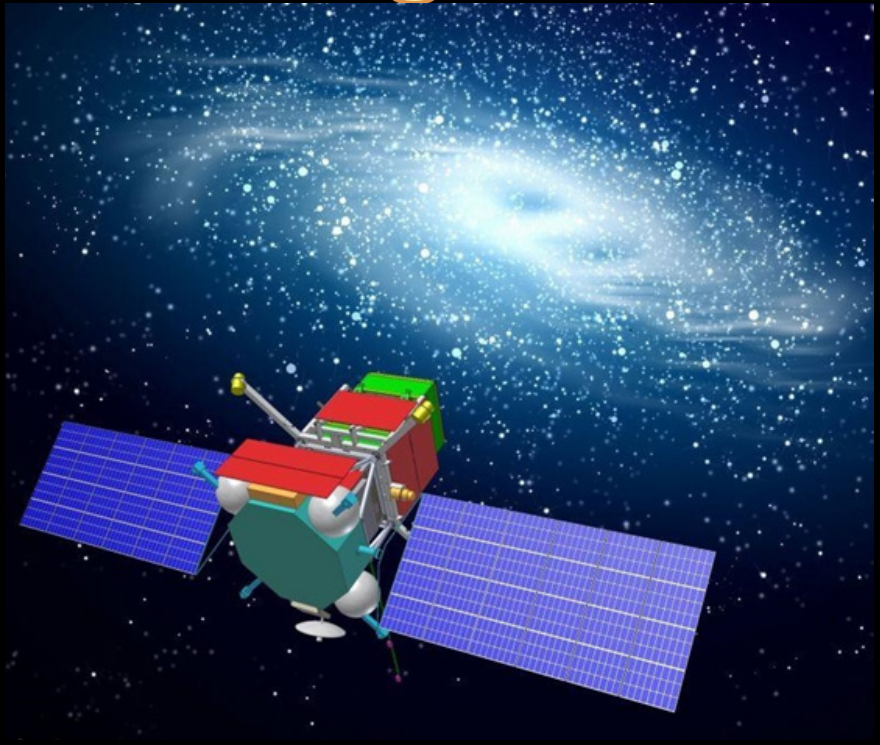

$E_M \cong$ 1.2 x $10^{15}$ eV

$\xi_{CR} \cong$ 4.5 %

$t_0 \cong$ 42 yrs

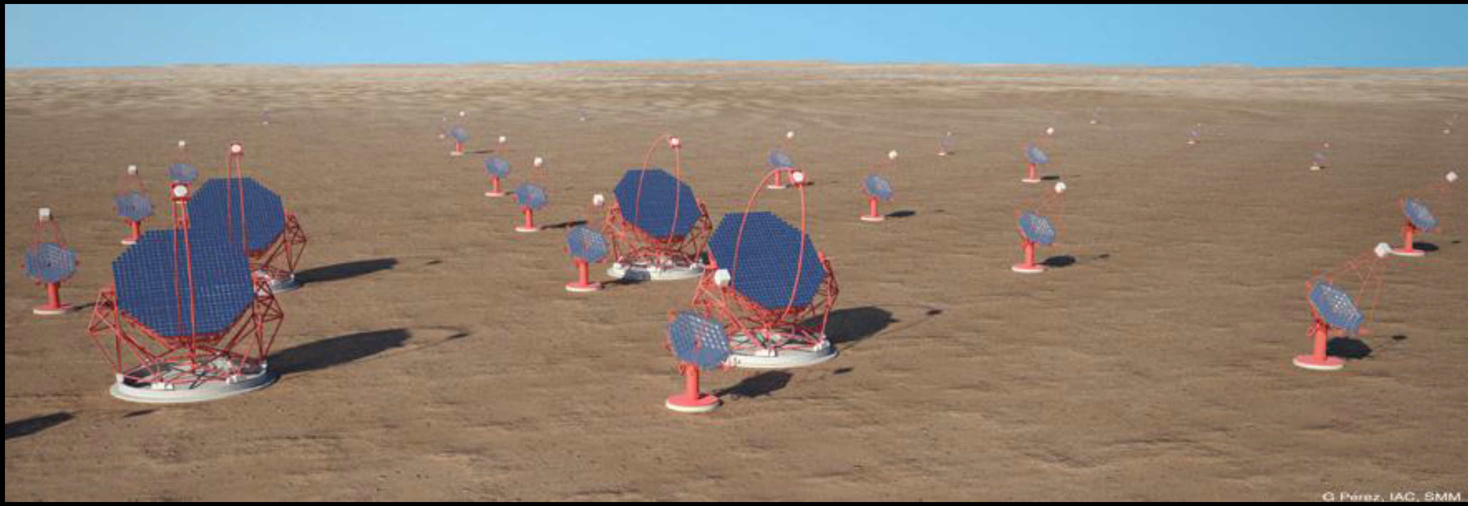
$v_0 \cong$23.700 km/s

# Future for gamma-ray astronomy



Gamma 400
(Galper et al.)

CTA

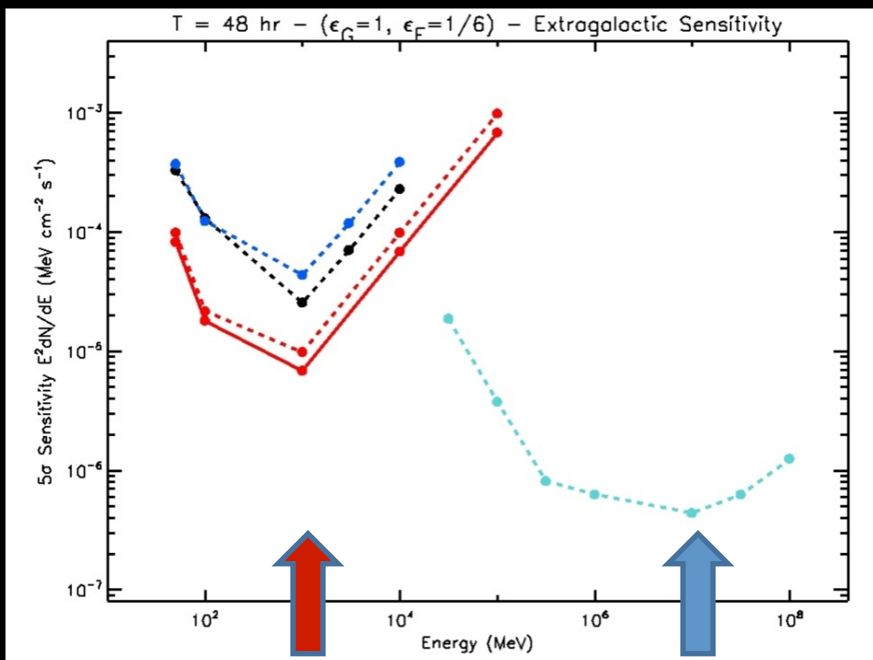


# Future for gamma-ray astronomy

## G-400 and CTA sensitivity (extragal. pointing)

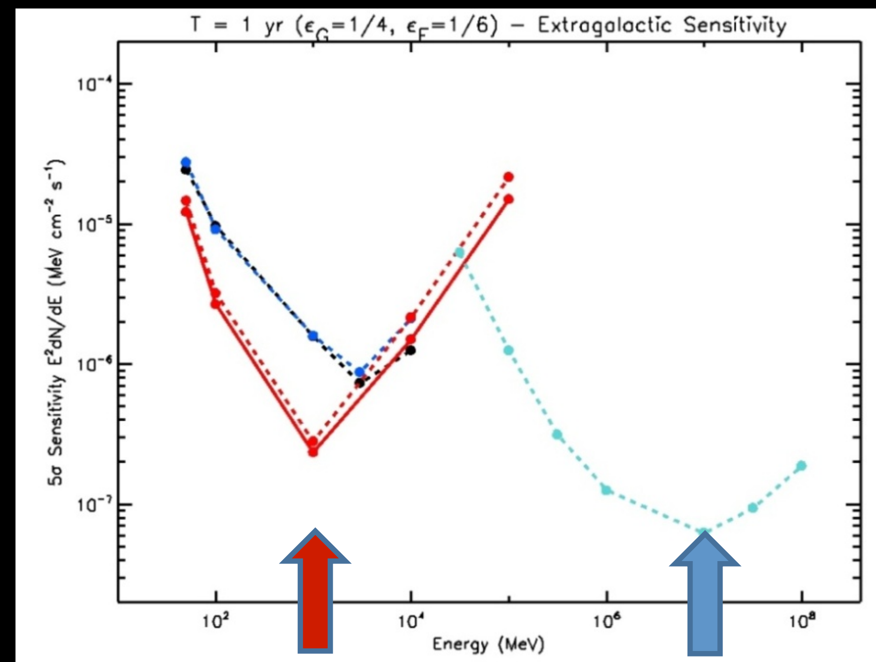
### Fermi-LAT (blue) G-400 (red), CTA (cyan)

**G-400 48 hr, CTA 5 hr**




G-400 CTA

**G-400 1 yr, CTA 50 hr**




G-400 CTA

We need to improve detection at energy below 100 MeV → several proposals, never materialized yet (Gamma-Light ?)

# Conclusions

- ✧ Gamma-ray astronomy is fundamental for the understanding of Galactic CR origin

→ we need to enhance the number of SNRs detected in the critical energy range, after the breakthrough of W44 and IC443

- ✧ Evidence a power-law index steeper than the one provided by theoretical models in the most of gamma-ray detected SNRs

→ inconsistency between data and theories

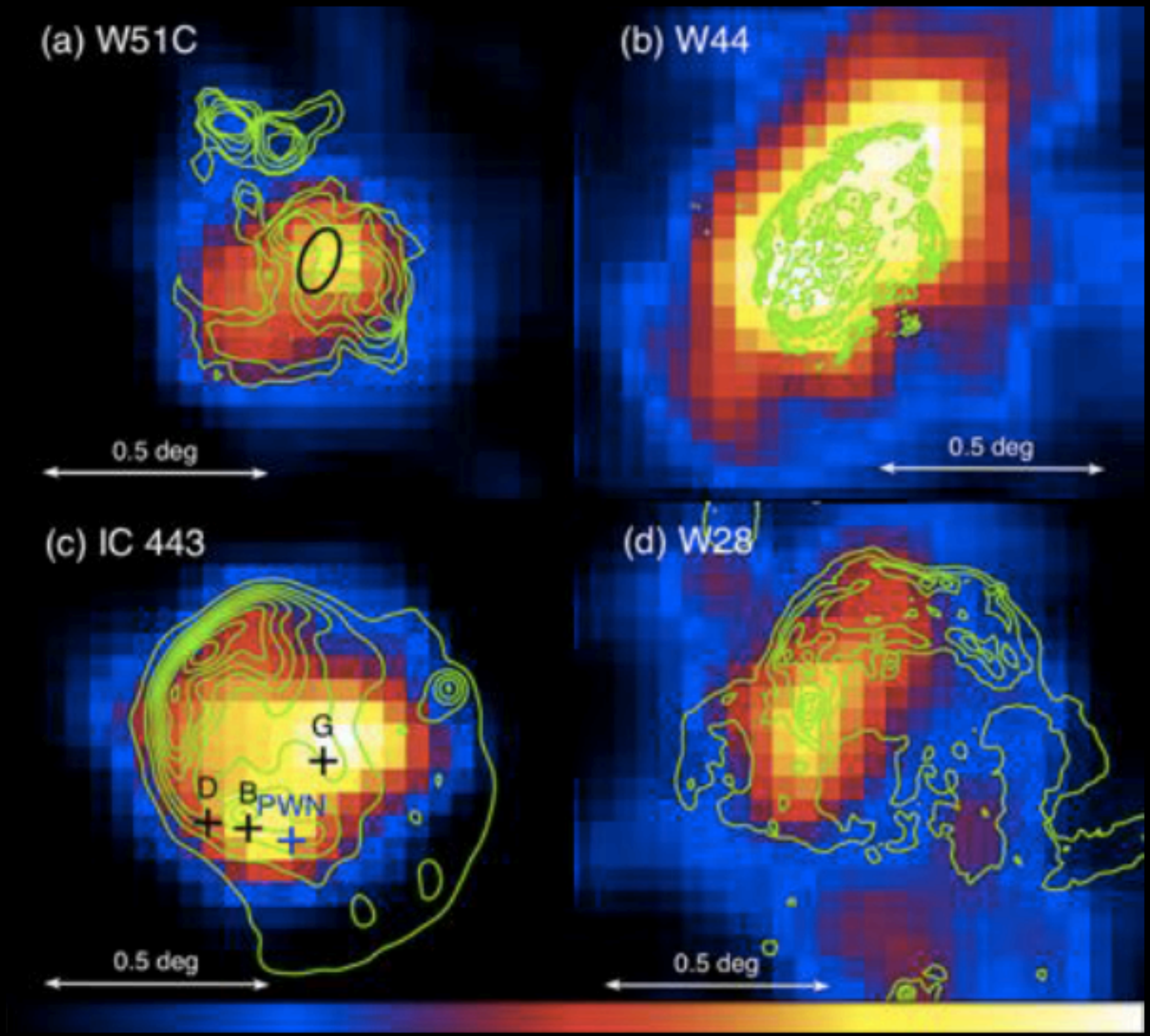
- ✧ In spite of the amount of data, CR origin is still an opening issue

→ new generation of gamma-ray instruments
→ multiwavelength analysis
→ deeper understanding of acceleration and transport mechanisms


Thank you
very much!

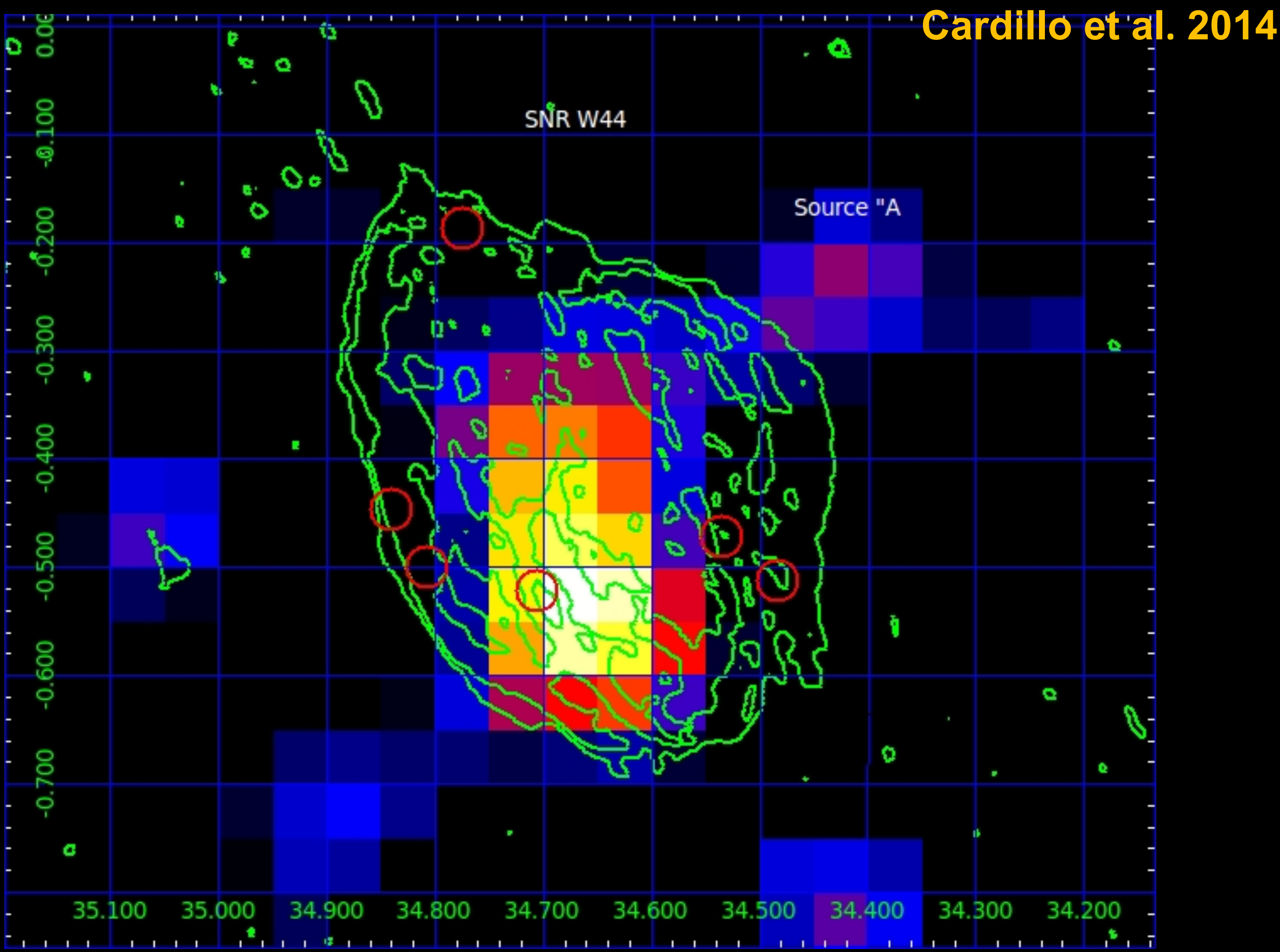
# Uchiyama et al. 2011

Context



- Young SNRs without dense nearby clouds: ‘‘shell’’ emission
- It needs improvements of the GeV and TeV spectra
- Pion bump is needed !
- Are young SNRs accelerating up to the knee ?
- With the right numbers/energetics ?

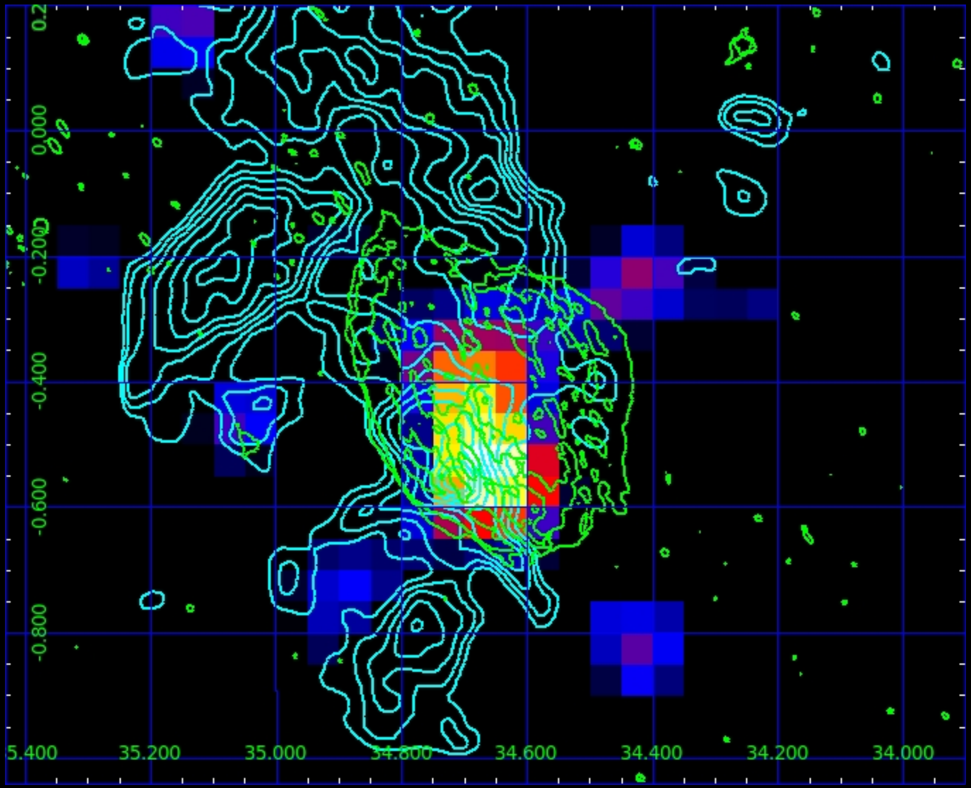
# New data analysis



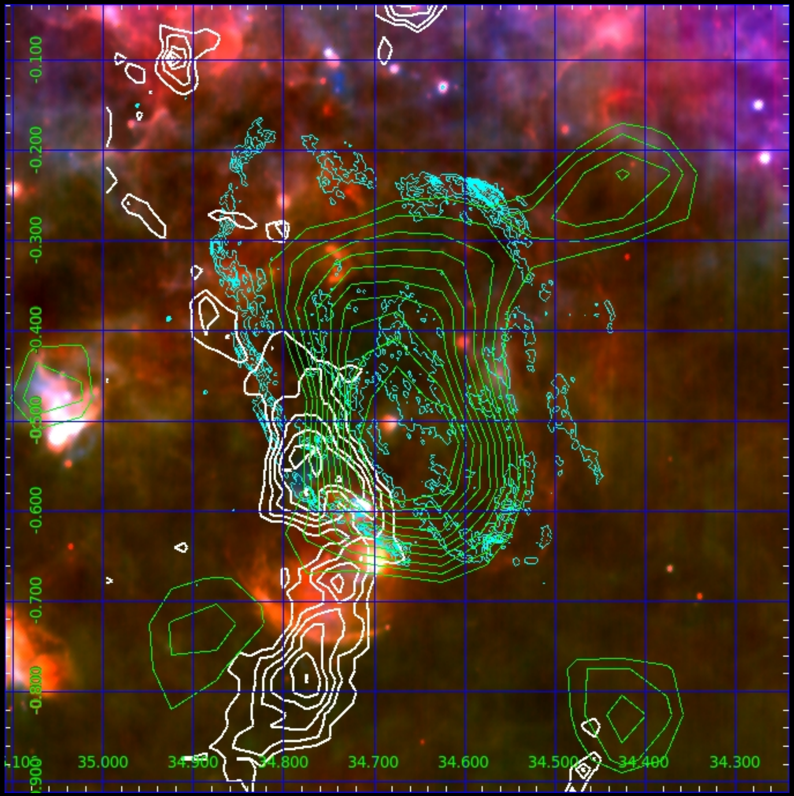

AGILE 400-10000 MeV
Radio(VLA), Masers

# New data analysis

Cardillo et al. 2014




AGILE 400-10000 MeV
Radio(VLA), CO(NANTEN2)



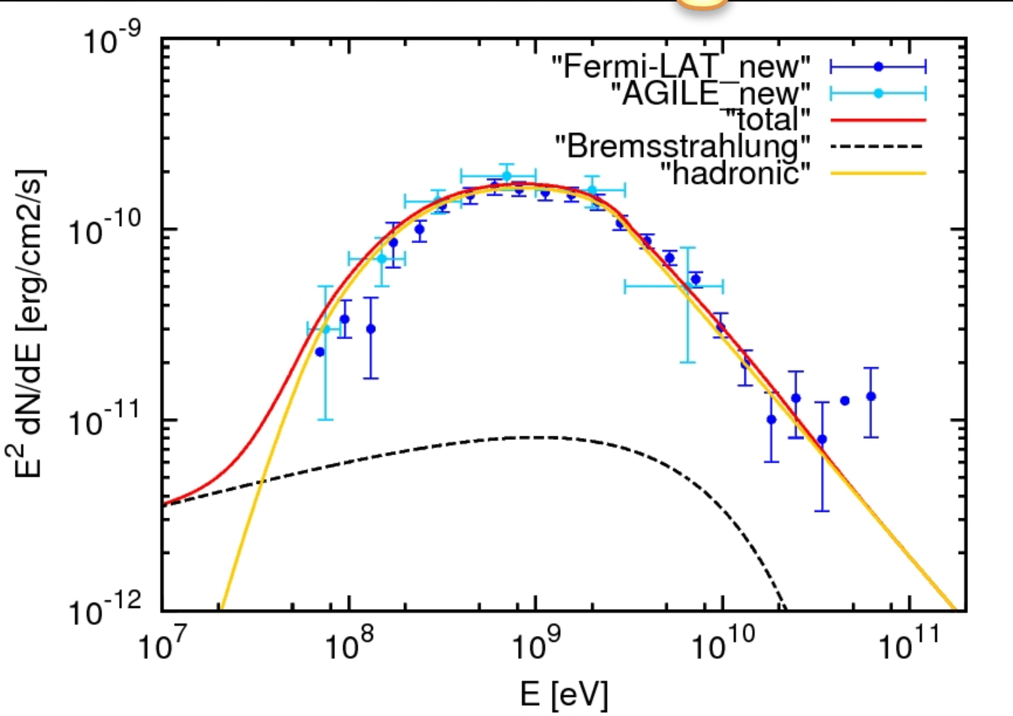

Infrared (HERSCHEL)
Gamma-ray(AGILE),CO(GRS)

$$\mathcal{M} = 2 \times 10^4 \, Ms$$

$$n_p \sim 1000 \, cm^{-3}$$

$$n_{av} \sim 200 \, cm^{-3}$$

# New modeling: hadrons

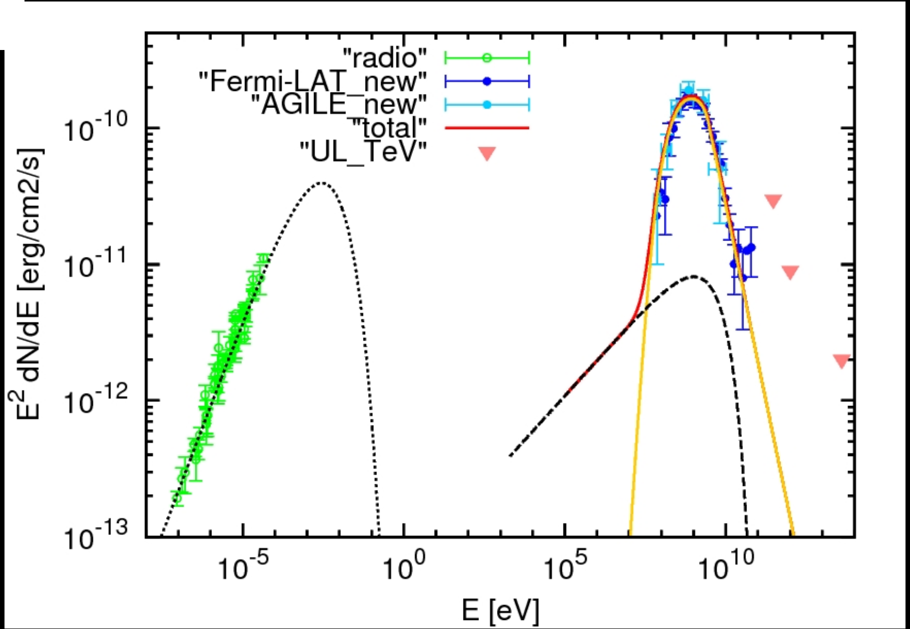



Cardillo et al. 2014

$$\frac{dN_p}{dE}(E) = \begin{cases} K_{p_1}E^{-p_1} & E < E_{br} \\ K_{p_2}E^{-p_2} & E > E_{br} \end{cases}$$

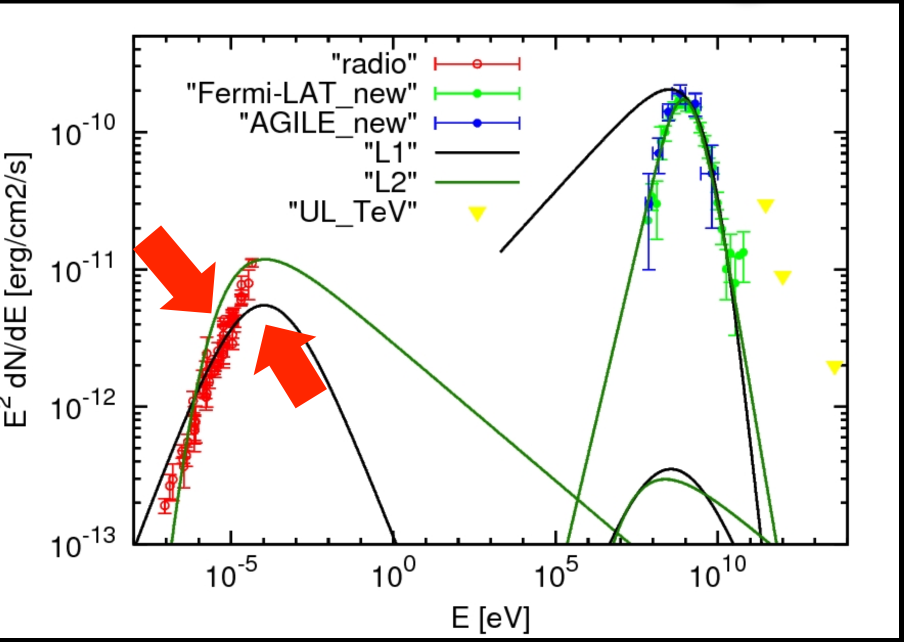
H3

- E = total energy
- n = 300 cm^-3
- B = 210$\mu G$
- $E_{br}$= 20 GeV
- $p_1$= 2,2
- $p_2$= 3,2

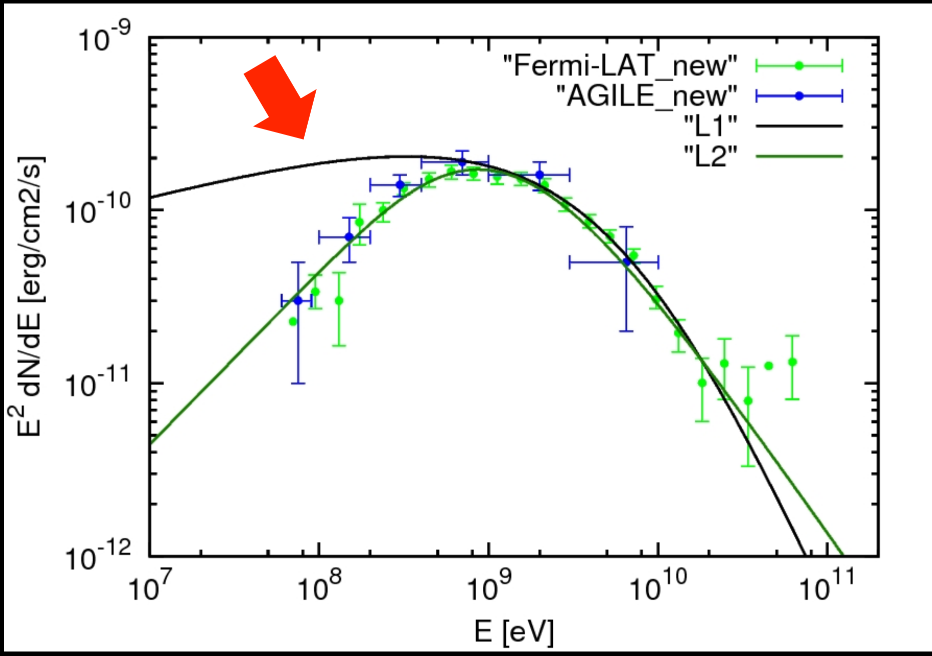


# New modeling: leptonic-only

Cardillo et al. 2014, accepted by A&A




$$\frac{dN_e}{dE}(E) = K_e \left(\frac{E}{E^e_{br}}\right)^{p'_1} \left(\frac{1}{2}\left(1 + \frac{E}{E^e_{br}}\right)\right)^{p'_1 - p'_2}$$




**L1**

- n = 300 cm^-3
- B = 25$\mu G$
- $E_{br}$= 8 GeV
- $p_1$= 1,74
- $p_2$= 4,2

**L2**

- n = 300 cm^-3
- B =40 $\mu G$
- $E_{br}$= 0,5 GeV
- $p_1$= -2,5
- $p_2$= 3,4

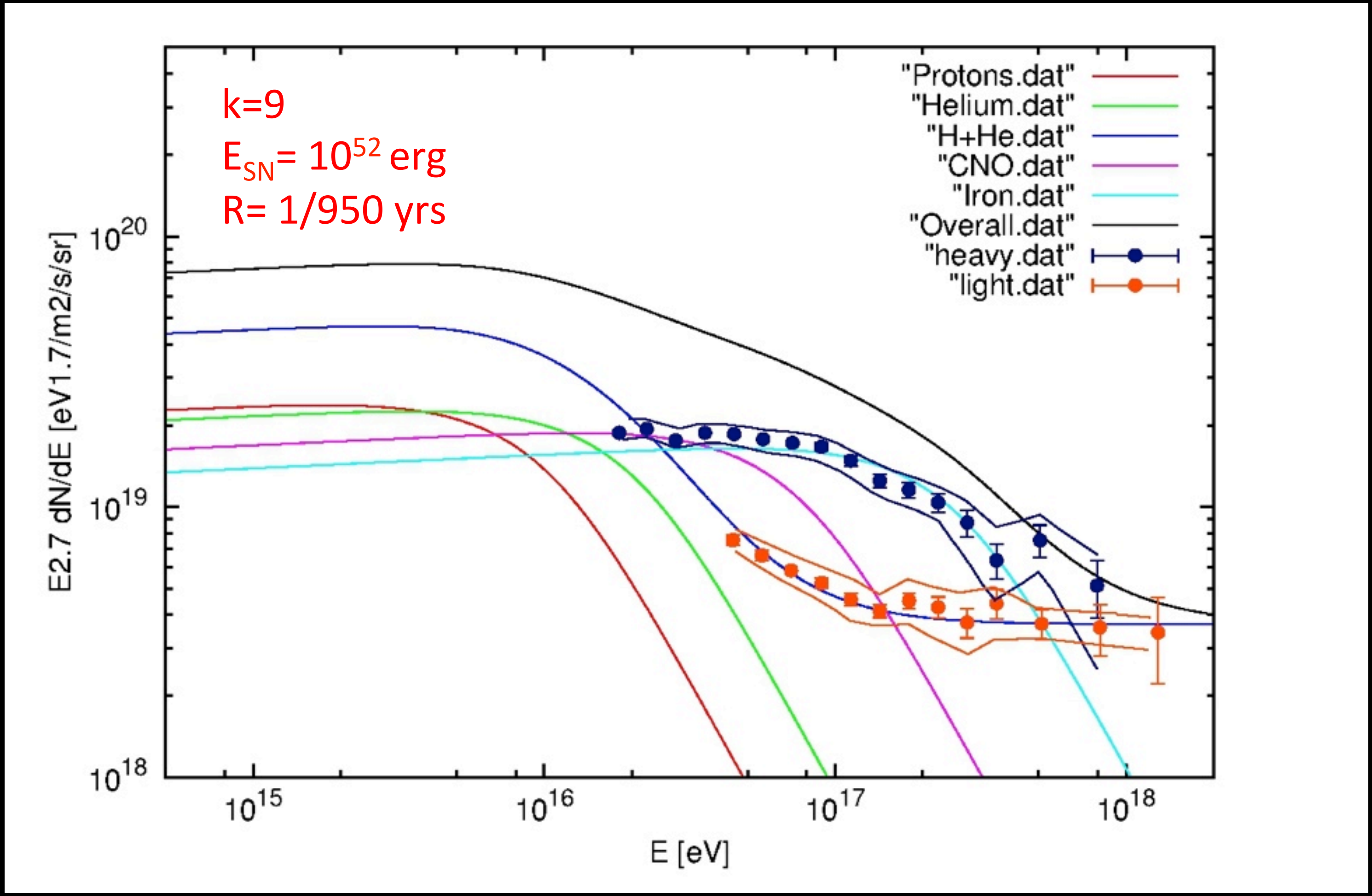
# Discussions

Cardillo PhD thesis

| SNR (l,b) | AGILE | Fermi-LAT | MC detect. | TeV |
|---|---|---|---|---|
| CAS A (G111.7-2.1) | no | yes | yes | Veritas, MAGIC |
| Tycho (G120.1+1.4) | no | yes | yes | Veritas |
| SN 1006 (G327.6+14.6) | no | no | - | HESS |
| RXJ1713 (G347.3-0.5) | no | yes | yes | HESS |
| W49B (G43.3-0.2) | no | yes | yes | HESS |
| Puppis A (G260-3.4) | no | yes | no | - |
| $\gamma$-Cygni (G78.2+2.1) | yes | no | yes(?) | Veritas |
| W44 (G34.7-0.4) | yes | yes | yes | - |
| W51 (G49.2-0.7) | no | yes | yes | MAGIC |
| IC443 (G189.1+3) | yes | yes | yes | Veritas, MAGIC |
| W28 (G6.71-0.05) | yes | yes | yes | HESS |

| SNR (l,b) | radio density flux | radio index | GeV index | TeV index | n $cm^{-3}$ | B $\mu G$ |
|---|---|---|---|---|---|---|
| **CAS A**(G111.7-2.1) | 2720 [1GHz] | 0.77 | $\sim 2.2 - 2.3$ | ~2.6 | 1-10 | 120 |
| **Tycho**(G120.1+1.4) | 40.4 [1.4GHz] | 0.65 | $\sim 2.3$ | ~2.0 | ¡1 | 200-300 |
| **SN 1006**(G327.6+14.6) | 15.2 [1.4GHz] | 0.6 | - | $\sim 2.3$ | $\leq 1$ | 150 |
| **RXJ1713**(G347.3-0.5) | 3.5 [1GHz] | 0.5 | $\sim 1.5$ | $\sim 2.0$ | $\sim 0.1$ | 15 |
| **W49B**(G43.3-0.2) | 38 [1GHz] | 0.48 | $\sim 2.2$ to 2.9 | - | 5-8 | $> 15$ |
| **Puppis A**(G260-3.4) | 263 [327MHz] | 0.5 | $\sim 2.1$ | - | order of 1 | order of 1- 10 |
| **$\gamma$-Cygni**(G78.2+2.1) | 340 [1 GHz] | 0.51 | $\sim 2.4$ | $\sim 2.37$ | 10-100 | ? |
| **W44**(G34.7-0.4) | 634 [74 MHz] | 0.37 | $\sim 3.0$ | - | 250-300 | $\geq 100$ |
| **W51c**(G49.2-0.7) | 130 [11 cm= 3 GHz] | 0.3(?) | $\sim 2.5$ | $\sim 2.6$ | 400 | $\leq 150$ (koo10) |
| **IC443**(G189.1+3) | 470 [74 MHz] | 0.36 | $\sim 2.4$to3.1 | $\sim 3$ | 400 | $\leq 150$ (tavani10) |
| **W28**(G6.71-0.05) | 246 [1.4 GHz] | 0.35 | $\sim 2.6 - 2.7$ | | 5 | $10^2 - 10^3$ |

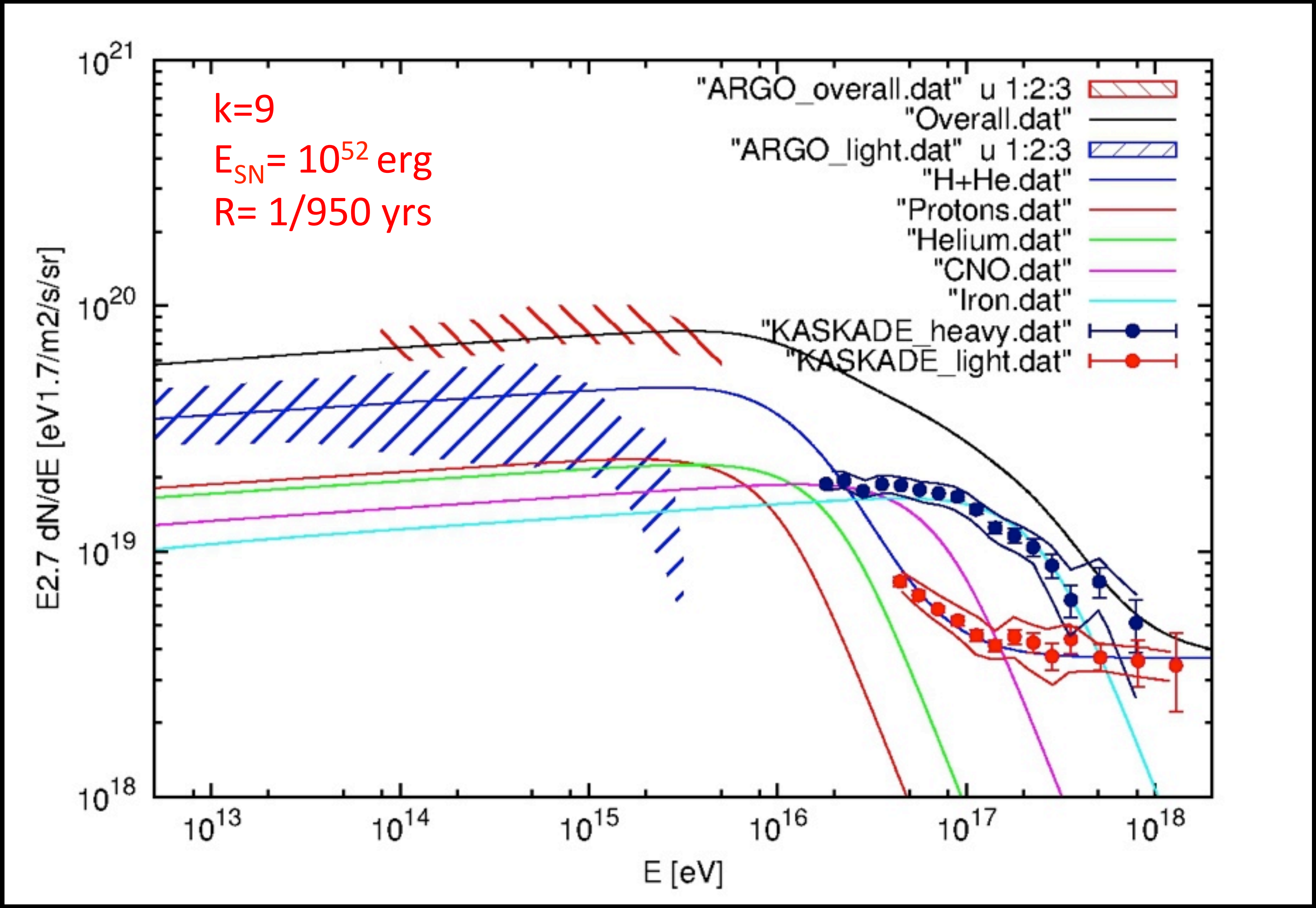
# KASKADE Grande (Apel,2013)




$E_M \cong 9.4 \times 10^{15}$ eV $\quad$ $t_0 \cong 27$ yrs

$\xi_{CR} \cong 13$ % $\quad$ $v_0 \cong 37.500$ km/s

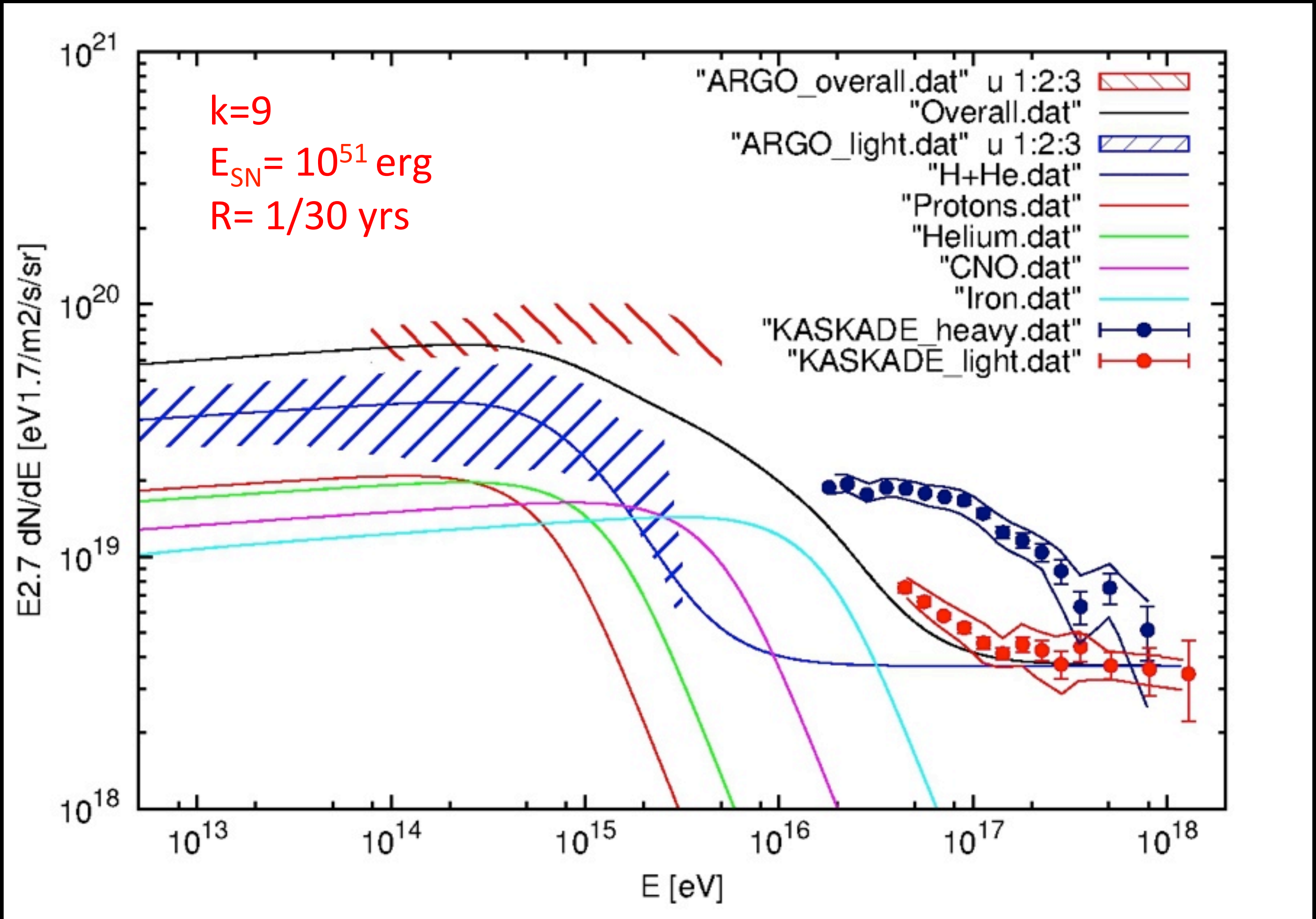
# KASKADE Grande + ARGO (Di Sciascio, 2014)




$E_M \cong 9.4 \times 10^{15}$ eV $\quad t_0 \cong 27$ yrs

$\xi_{CR} \cong 13$ % $\quad v_0 \cong 37.500$ km/s

# ARGO




$E_M \cong$ 6.3 x $10^{14}$ eV $t_0 \cong$ 84 yrs

$\xi_{CR} \cong$ 8.5 % $v_0 \cong$11.800 km/s

# a future after Fermi and AGILE for MeV-GeV astrophysics ?

- Silicon technology can be pushed to the limits.
- **Substantial PSF improvement expected by a combination of thin converter + analog readout.**
- **GAMMA-400, a new space mission concept (at the moment under study by groups in Russia, Italy, …).**
- Much improved Gamma-Ray Tracker, very deep calorimeter; a new gamma-ray and charged CR exploration.

- **0.5 – 100 MeV range !**
- several proposals, never materialized yet.
- maybe we should improve the Compton telescope concept (e.g., GRIPS, other being considered now) and reach larger energies (e.g., GAMMA-LIGHT).
- a very important window, sensitivity needs to be good to compete and do better than Fermi-LAT

# a future after Fermi and AGILE for MeV-GeV astrophysics ?

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# Conclusions

- ✧ Direct proofs: the first direct proof of hadronic acceleration in SNRs (the pion bump in W44)

→ we need to enhance the number of SNRs detected in the critical energy range

- ✧ Evidence in W44 of a power-law index steeper than the one provided by theoretical models

→ as like as in the most of other gamma-ray detected SNRs

- ✧ Data and theorie inconsistencies

- ✧ In spite of the amount of data, CR origin is still an opening issue

→ new generation of gamma-ray and particle instruments