The Fermi-LAT and H.E.S.S. Views of the Supernova Remnant W49B

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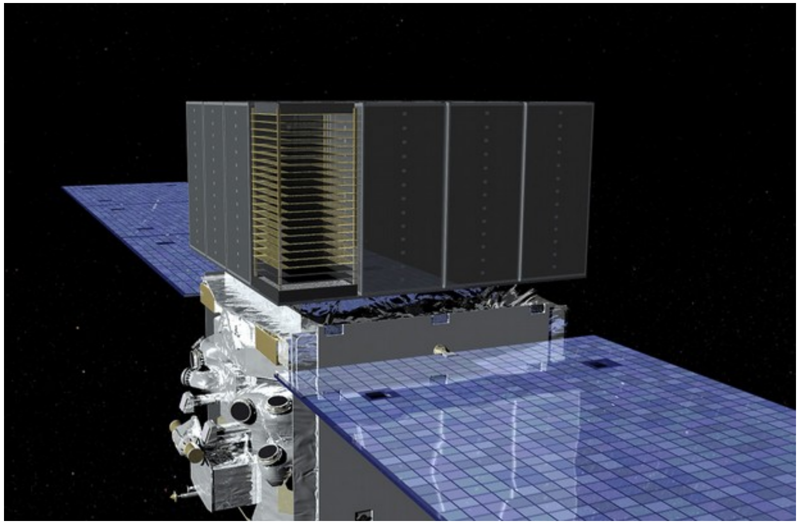
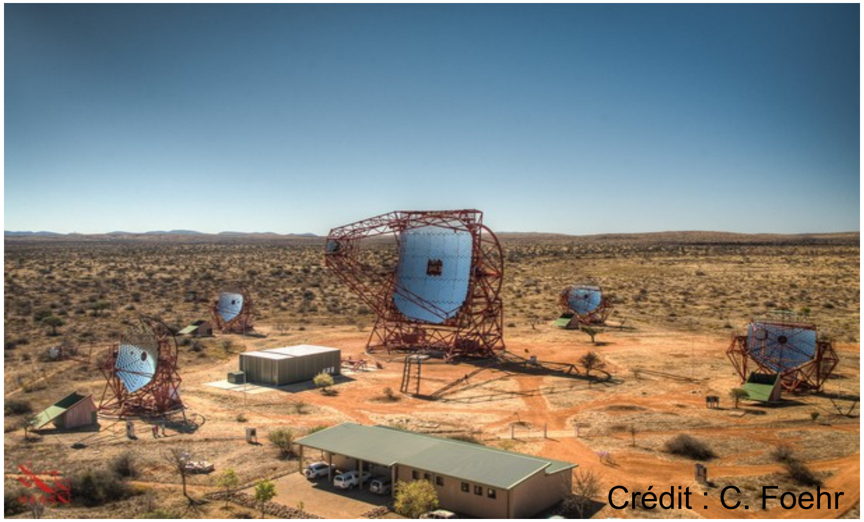
For the H.E.S.S. and Fermi-LAT Collaborations

The Fermi Large Area Telescope (LAT) and the High Energy Stereoscopic System (H.E.S.S.)

- Fermi-LAT
  - Satellite based instrument
  - Pair-conversion telescope
  - Detects gamma rays in the range **~20 MeV – ~300 GeV**
  - Angular resolution ~ 0.1°



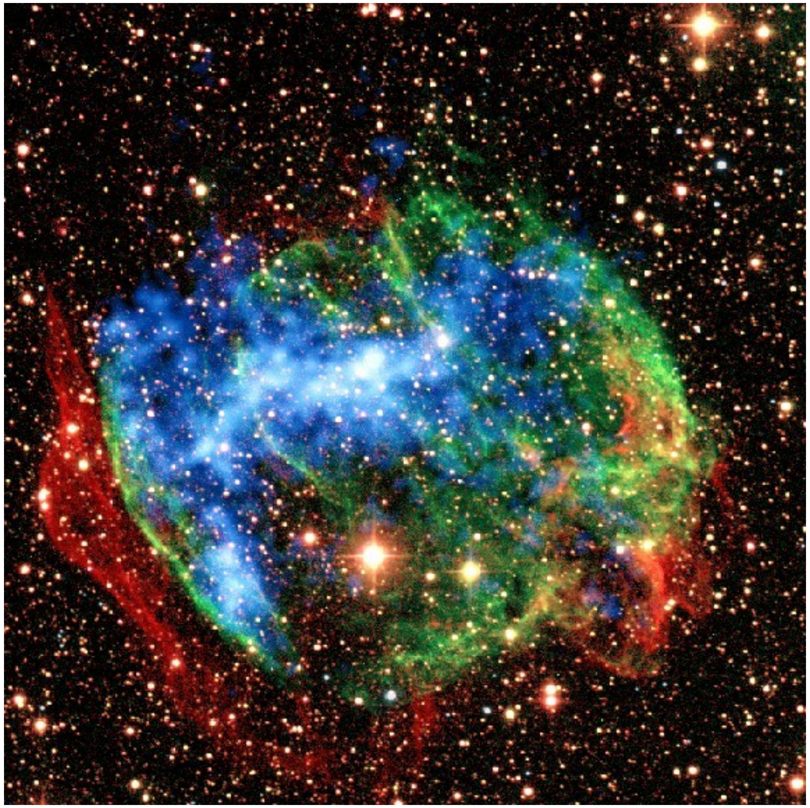
- H.E.S.S.
  - 5 Imaging Cherenkov Telescopes
  - Khomas highland, Namibia
  - 5° field-of-view
  - Detects gamma rays in the range (CT1-4) : **~100 GeV – Tens of TeV**
  - Angular resolution ~ 0.07°



The Supernova Remnant W49B

- SNR G43.3-0.2 (3C 398)
- Mixed-morphology SNR :
  - radio shell (3' x 4')
  - centrally filled with thermal X rays
- Age ~ 1 – 4 kyr (Moffett & Reynolds 1994)
- D ~ 10 kpc (Zhu et al. 2014)
- Interacting with molecular cloud (Keohane et al. 2007)
  - Expected enhanced gamma-ray emission from p-p interaction
  - Could point at hadronic nature of accelerated particles at the SNR shock

Composite image : 2.12 µm mid-IR from shocked molecular hydrogen & 1.64µm [FeII] (Palomar), X-ray image (Chandra)



Credits Xrays : NASA/CXC/SSC/J. Keohane et al.; Infrared : Caltech/SSC/J. Rho and T. Jarrett

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Gas density : ~ 0.1 – 3 x 10^3 cm^{-3}

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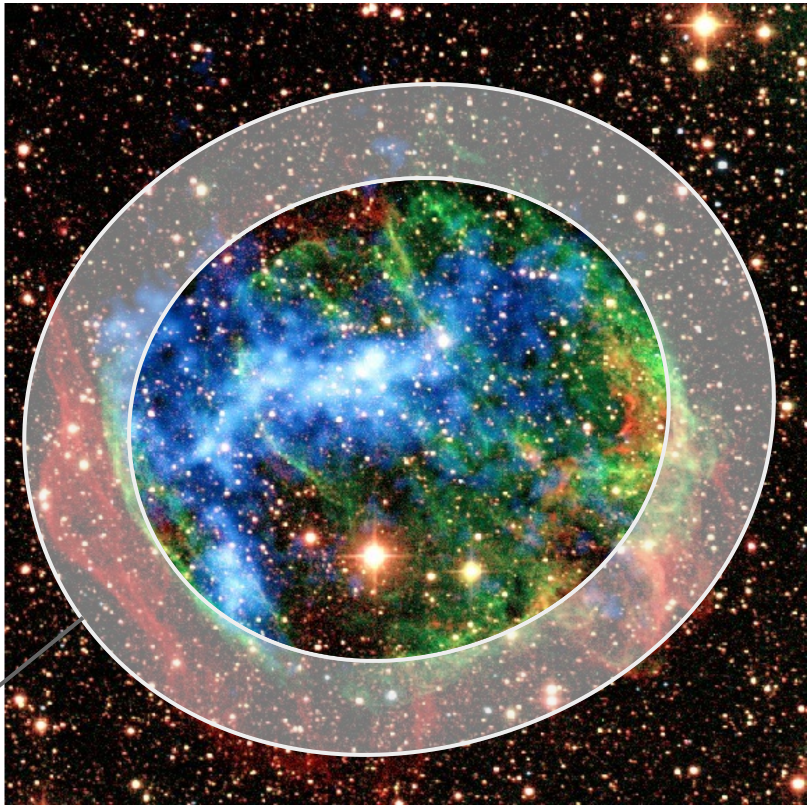

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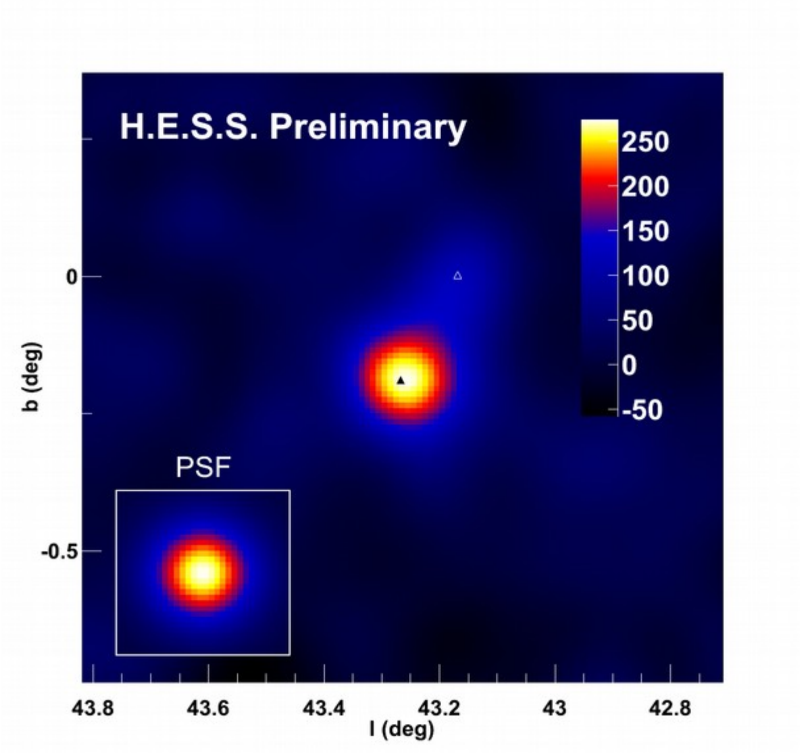
W49B : H.E.S.S. and Fermi-LAT Analysis Results

- H.E.S.S. :
  - 75 hours (live-time) of data taken between 2004 and 2013 (no CT5)
    - Model Analysis using *Standard cuts* (E_{th} ~ 290 GeV)
  - W49B detected at 12.9σ
  - Morphology : point-like source
    - PSF ~ shell size → emission from the center or from the shell itself



H.E.S.S. Gaussian-Smoothed excess map (0.06°).
Black marker : W49B position

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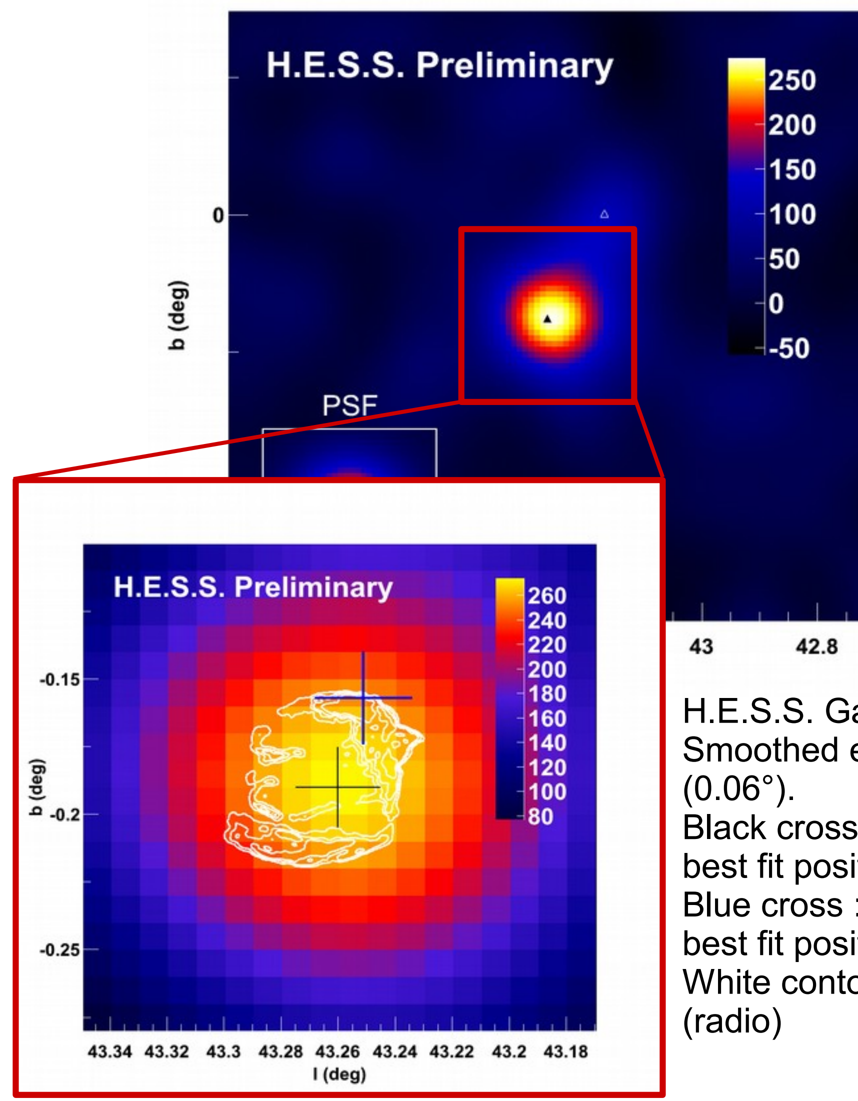
- Fermi-LAT : 5 years of data
  - Morphology : point-like source
    - Coincident with the shell
    - Slightly offset from H.E.S.S position (but TeV emission could come from the shell)

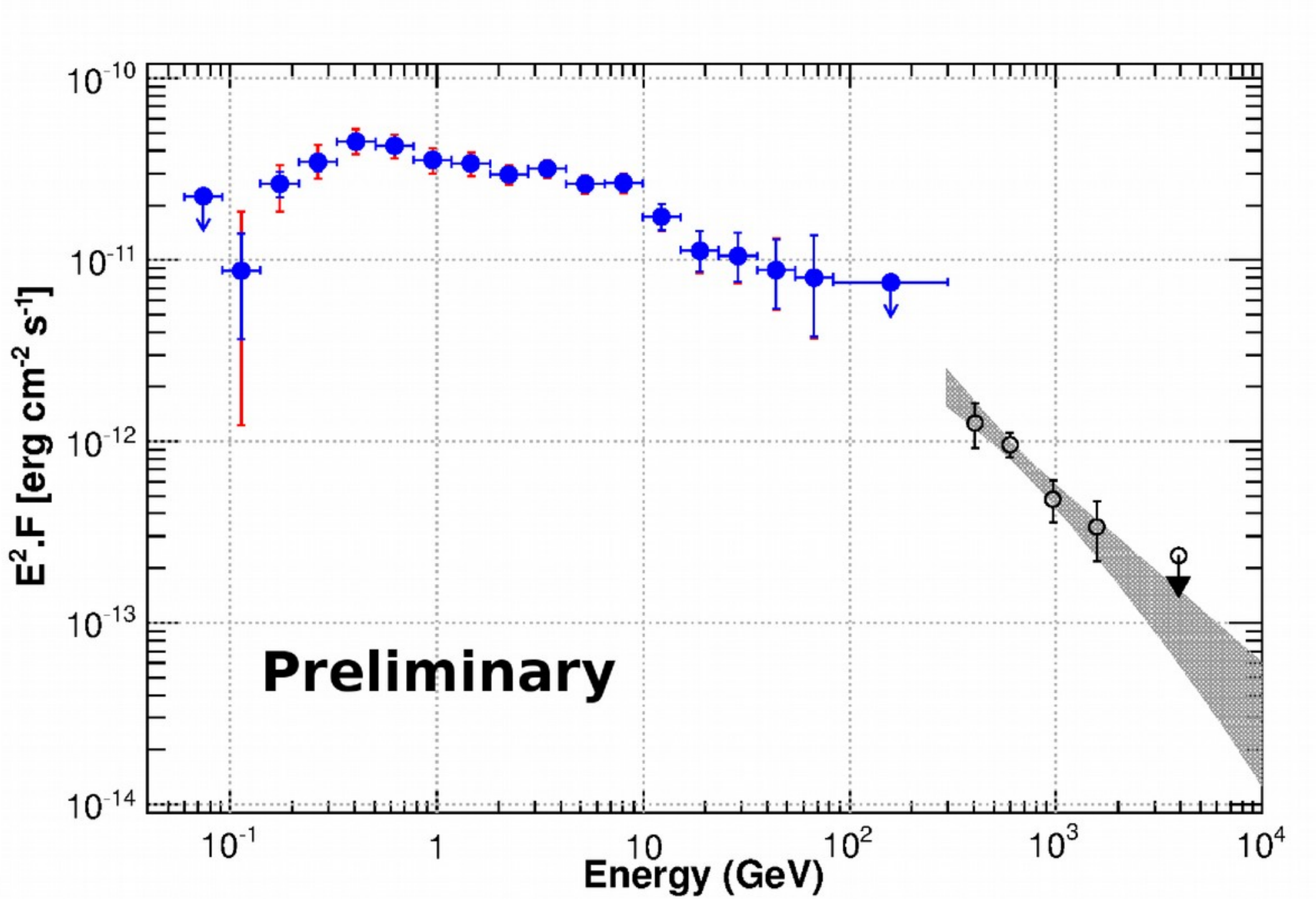


H.E.S.S. Gaussian-Smoothed excess map (0.06°).
Black cross : H.E.S.S. best fit position
Blue cross : Fermi-LAT best fit position
White contours : NVSS (radio)

H.E.S.S.

W49B : H.E.S.S. and Fermi-LAT Spectra

Fermi-LAT and H.E.S.S. spectra connect very smoothly!



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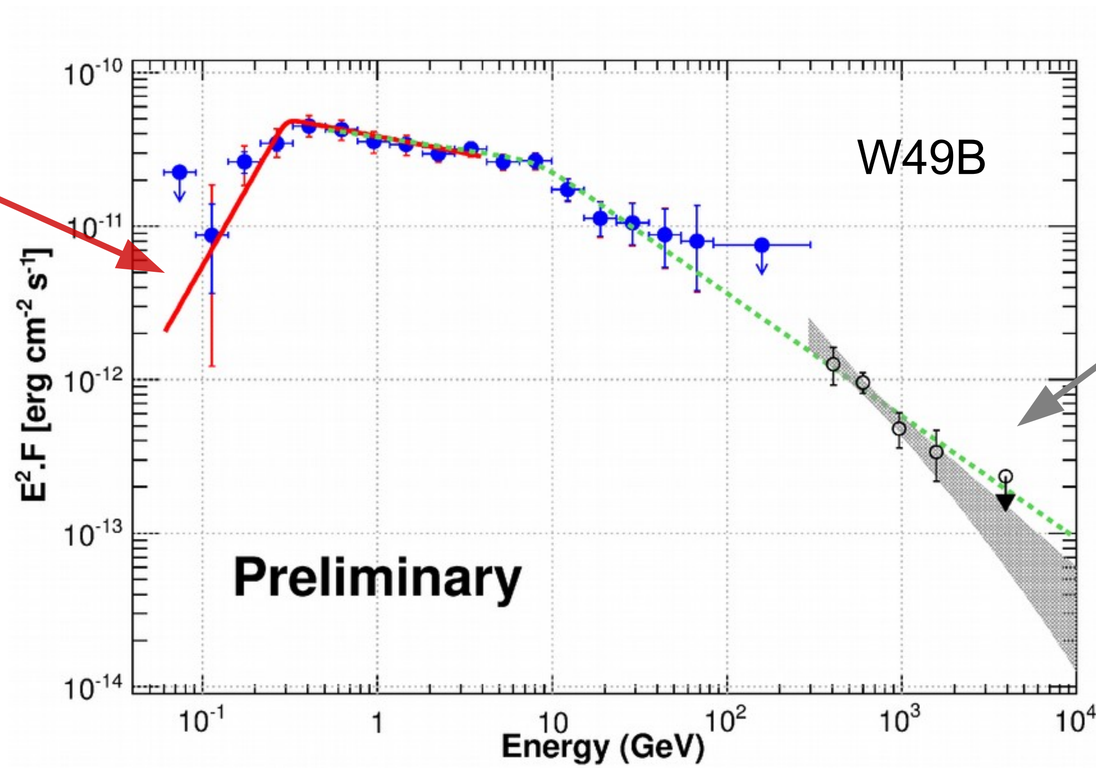
Fermi-LAT : **Broken Power-Law** (60 MeV – 4 GeV)
- **Preferred by 8σ w.r.t. Power-Law**
- ϕ_0(200 MeV) = (3.3±0.5) x 10^{-10} $cm^{-2}s^{-1}MeV^{-1}$
- Γ_1 = 0.10±0.30 , Γ_2 = 2.21±0.05 , E_{br} = 304±20 MeV

H.E.S.S. : **Power-Law** (> 290 GeV)
- $\phi_{\_0}$(1TeV) = (3.15±0.46) x 10^{-13} $cm^{-2}s^{-1}TeV^{-1}$
- Γ = 3.14±0.23



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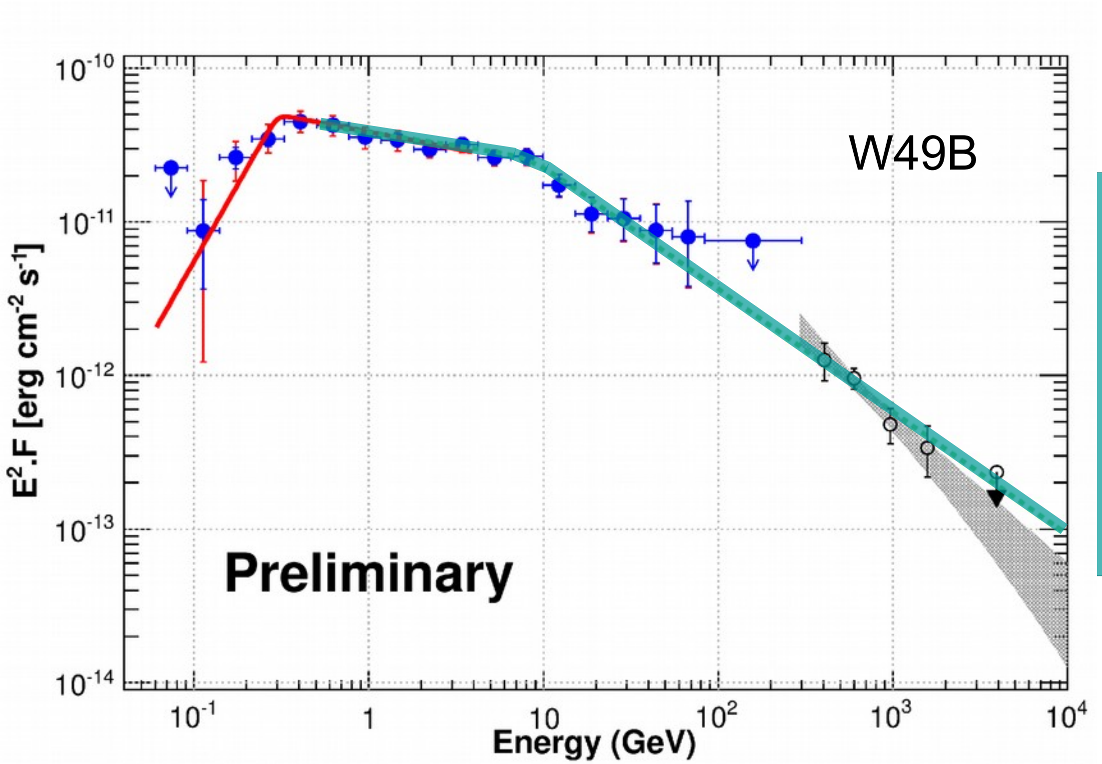
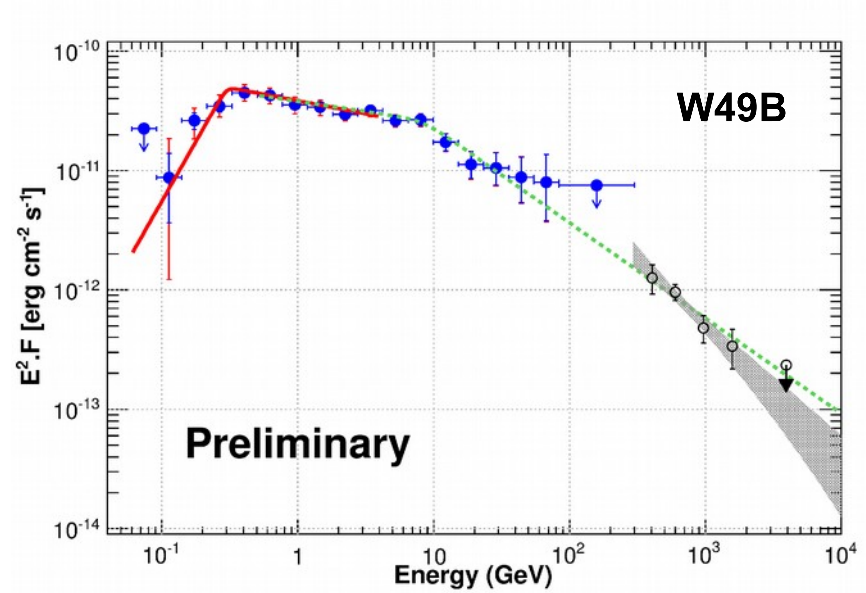
Fermi-LAT + H.E.S.S. joint fit :
Broken Power-Law
(500 MeV – 10 TeV)

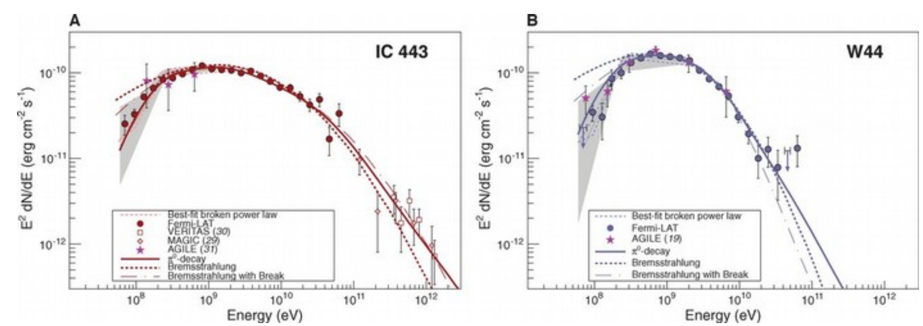


- Preferred by 6.5σ w.r.t. Power-Law
- Γ_1 = 2.17$\pm$0.06
- Γ_2 = 2.80$\pm$0.04
- E_{br} = 8.4$\pm$2.5 GeV

Interpretation

- Low-energy break feature detected by the Fermi-LAT, as in IC443 and W44
  (Ackermann et al. 2013)





Ackermann et al. 2013

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- Low-energy break feature detected by the Fermi-LAT, as in IC443 and W44
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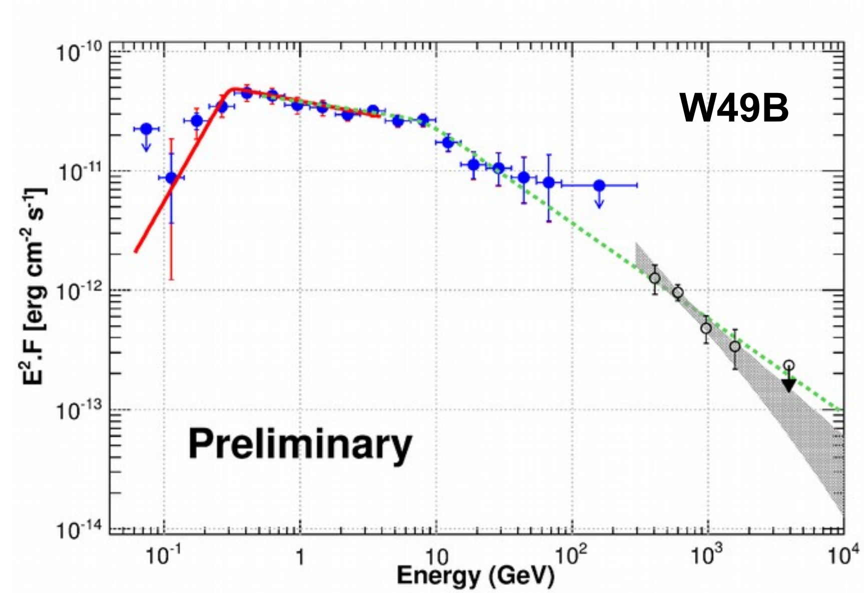
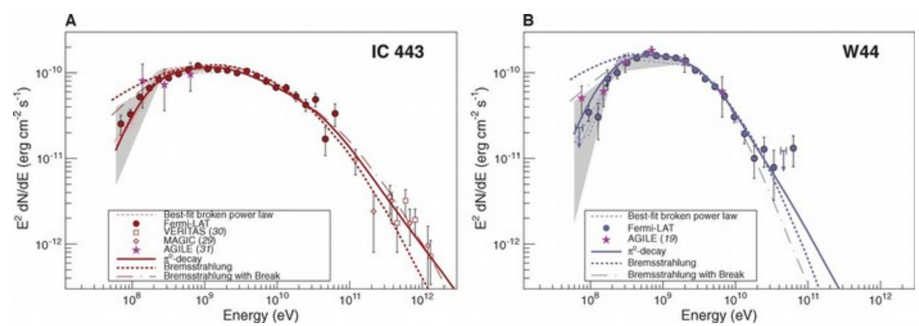
- 2^{nd} spectral break as in several other SNR/MC objects (W51C, IC443, W28...)
- Lot of theoretical works to explain the 2^{nd} break (in a hadronic context) :
  - Diffusion (Ohira et al. 2011, Li & Chen 2012)
  - Acceleration (Inoue et al. 2010, Malkov et al. 2012)
  - Re-Acceleration of ambiant CRs (Uchiyama et al. 2010, Cardillo et al. 2016)





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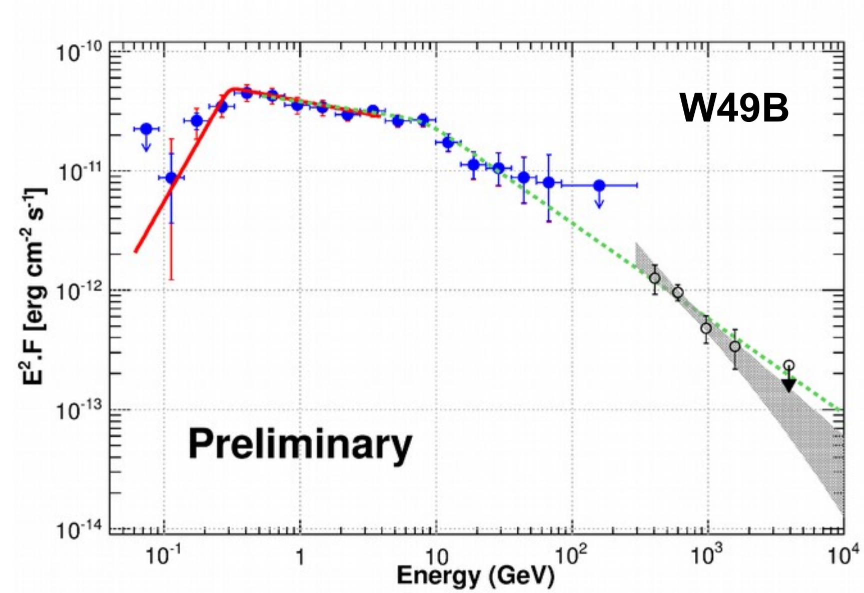
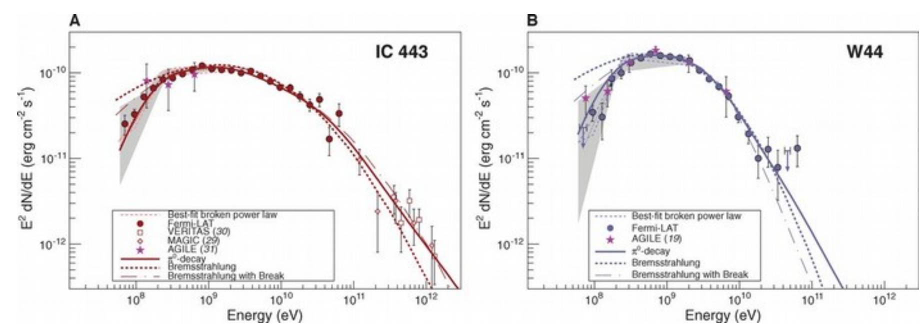
  (Ackermann et al. 2013)
- 2nd spectral break as in several other SNR/MC objects (W51C, IC443, W28...)
- Lot of theoretical works to explain the 2nd break (in a hadronic context) :
- E_{br} (W49B) : ~ same energy range as the others (~ 1 – 20 GeV)
  - W49B is 1 – 4 kyr vs ~ a few 10 kyr
  - Another object with a similar feature/age : G349.7+0.2, but E_{br} ~ 5 times higher
    (H.E.S.S. Collaboration, 2015)





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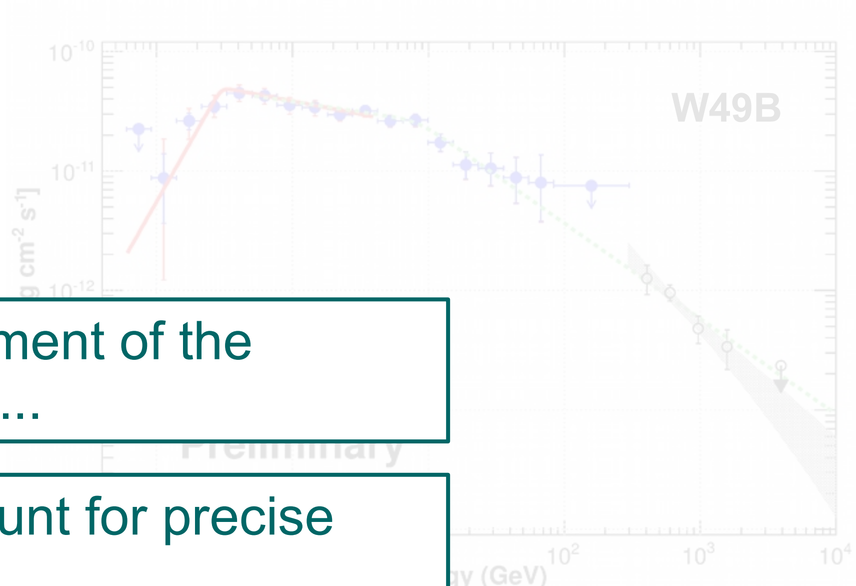
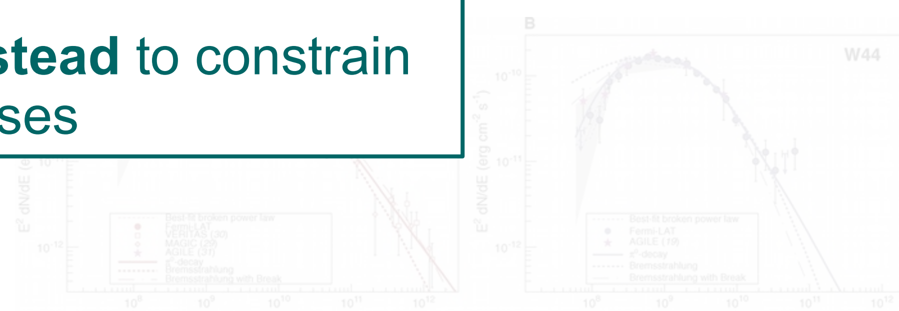
- Low-energy break feature detected by the Fermi-LAT, as in IC443 and W44 (Ackermann et al. 2013)
- 2[nd] spectral break as in several other SNR/MC objects (W51C, IC443, W28, ...)
- Lot of theor… break (in a h… context) ?
- E_{br} (W49B) … others (~ 1 …
  - W49B is …
  - Another … G349.7+0.2, but E_{br} ~ 5 times higher (H.E.S.S. Collaboration, 2015)





Ackermann et al. 2013

The whole history and environment of the remnant play an important role...

This should be taken into account for precise modeling

→ Simple one-zone model **instead** to constrain energetics & dominant processes

Modeling

- Same model as in Fermi 1st paper on W49B (Abdo et al. 2010)
- Assumptions
  - Age = 2000 years, d = 10 kpc
  - Gamma-rays come from the same shell region with
    - Constant density n_H and B field
  - Empirical injection distributions for protons and electrons (Broken Power-Law)

$$Q_{e,p}(p) = a_{e,p} \left(\frac{p}{p_0}\right)^{-s} \left(1 + \left(\frac{p}{p_{\mathrm{br}}}\right)^2\right)^{-\Delta s/2}$$

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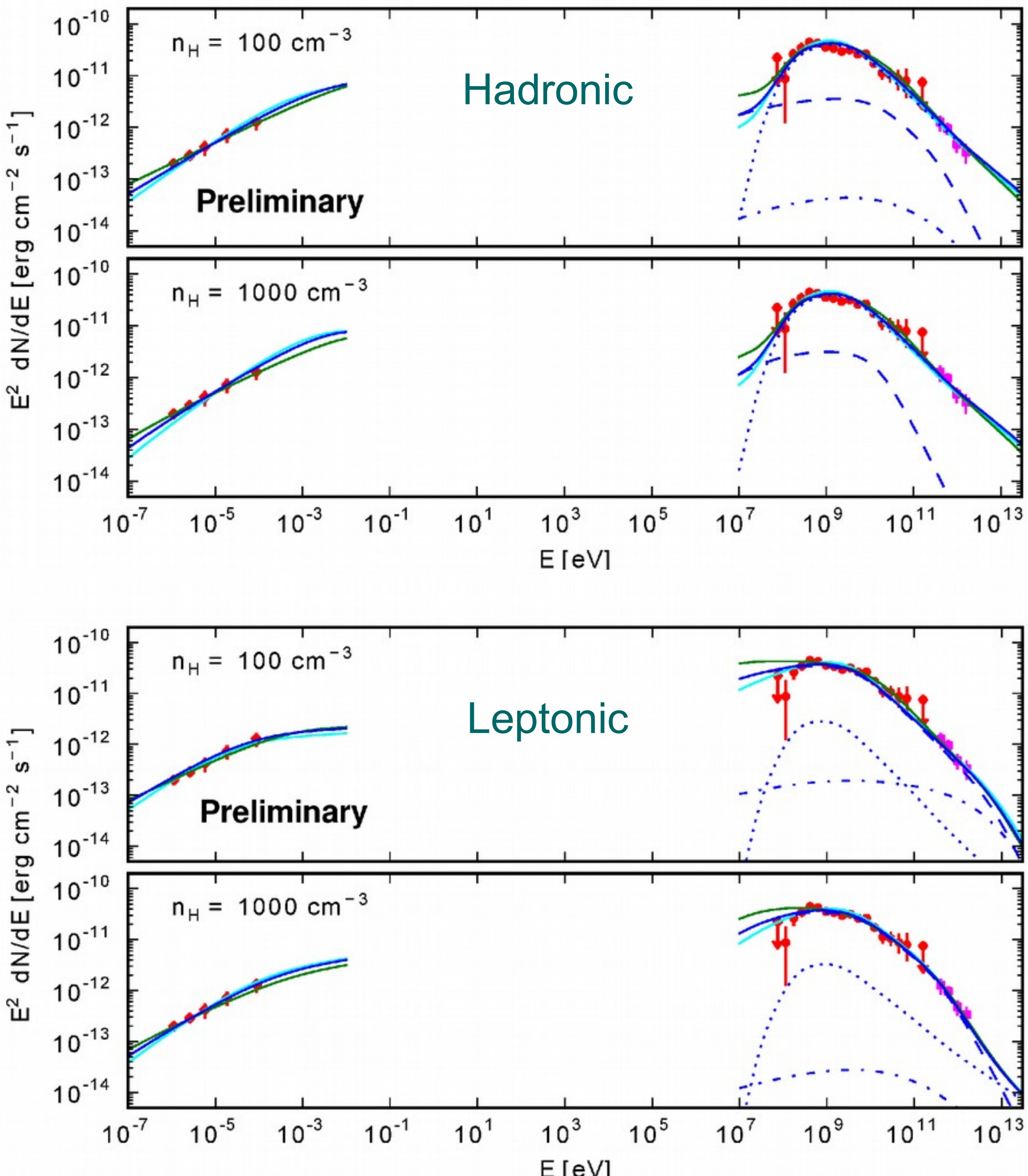
- Parameters tested
  - electron to proton ratio
    K_{ep} = 0.01 (hadronic), 1 (leptonic)
  - n_H = 100, 1000 cm^{-3}
  - Radio synchrotron index s = -0.48
    → e^- index ~ 2.0

    → s = 1.8, 2.0, 2.2
- Emission processes :
  - Inverse Compton
  - Synchrotron
  - Bremsstrahlung
  - pion decay



- Hadronic- or leptonic-dominant models could explain the data
- Hadronic model preferred : better agreement with Fermi-LAT spectrum point at lowest energies
- To explain data, leptonic models need a rather hard electron spectrum (s ≤ ~1.8) when radio data indicate s ~ 2.0

Summary

- Detection of W49B with H.E.S.S. and joint analysis with 5 years of Fermi-LAT data
- Spectrum derived from 60 MeV to a few TeV
- Two spectral breaks :
  - At 8.4 GeV : as in other SNR/MC

    → further supports other MWL evidence of interaction
  - At 304 MeV

    → Similar to IC443 and W44
- Broad band spectrum and modeling :

  → seems to favor hadronic-dominant models

  → Leptonic need hard electron spectrum, hard to reconcile with the radio observations

Thanks for your attention !

Additional content

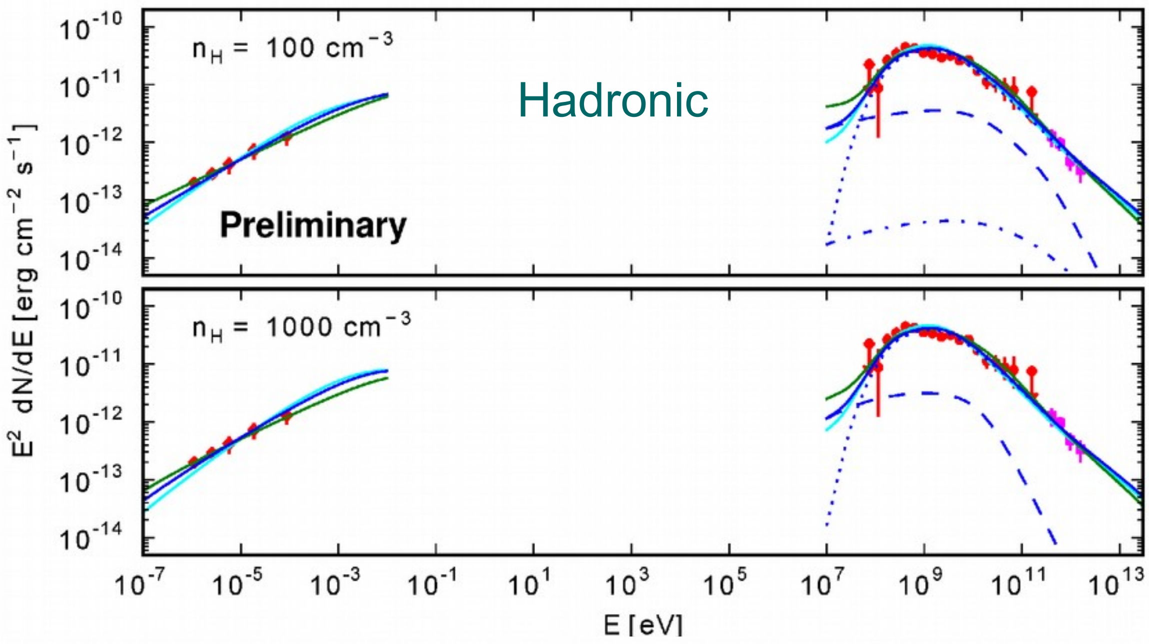


Table 2. Parameters for the hadronic scenario

Model	$n_{\rm H}$ (cm^{-3})	s	Δs	$p_{\rm br}$ (GeV c^{-1})	B (μG)	W_p (10^{49} erg)
(a1)	100	1.8	1.0	15	100	12
(a2)	100	2.0	0.8	30	100	11
(a3)	100	2.2	0.7	100	90	12
(a4)	1000	1.8	1.0	15	500	1.1
(a5)	1000	2.0	0.8	30	500	1.1
(a6)	1000	2.2	0.7	100	400	1.1

Note. — K_{ep} is set at 0.01. The seed photons for IC include infrared ($kT_{\rm IR} = 3 \times 10^{-3}$ eV, $U_{\rm IR} = 0.7$ eV cm^{-3}), optical ($kT_{\rm opt} = 0.3$ eV, $U_{\rm opt} = 0.8$ eV cm^{-3}), and the CMB. The total kinetic energies ($E_{\rm kin}$) of the radiating particles ($W_{e,p}$) are calculated for $E_{\rm kin} > 100$ MeV at assumed distance of 10 kpc.

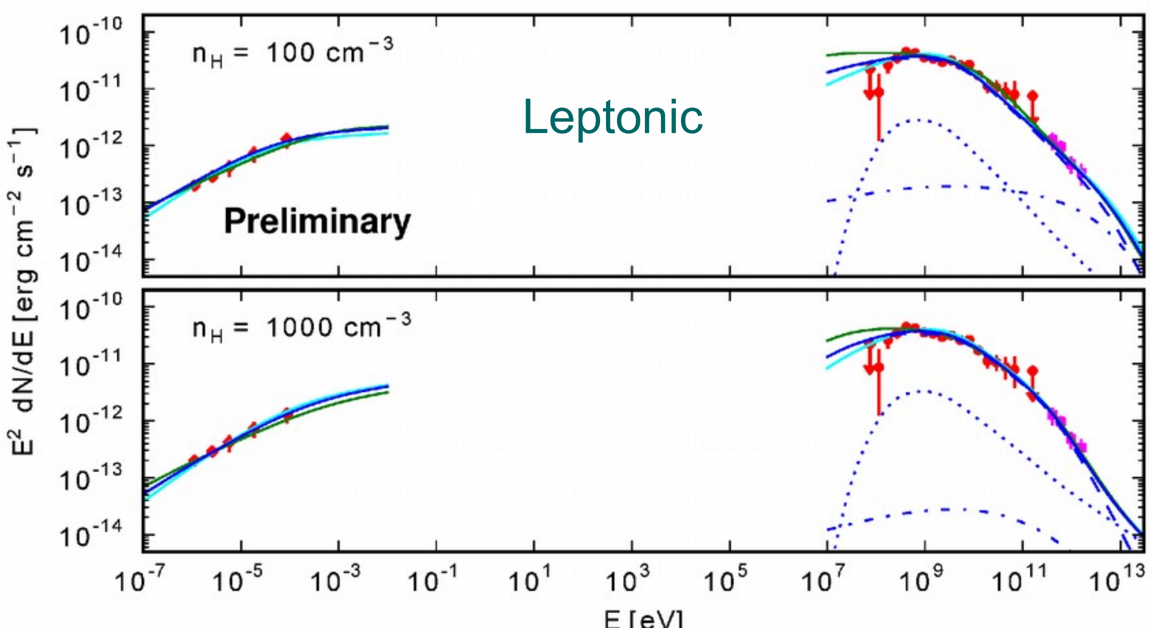


Table 3. Parameters for the leptonic scenario

Model	$n_{\rm H}$ (cm^{-3})	s	Δs	$p_{\rm br}$ (GeV c^{-1})	B (μG)	W_e (10^{49} erg)
(b1)	100	1.8	1.1	7	22	1.6
(b2)	100	2.0	0.9	10	25	1.6
(b3)	100	2.2	0.8	30	22	2.0
(b4)	1000	1.8	0.9	7	100	0.16
(b5)	1000	2.0	0.7	10	100	0.16
(b6)	1000	2.2	0.5	15	90	0.19

Note. — Same as Table 2 except for K_{ep}, which is set at 1.