Proton acceleration in SN 1006 traced by the Fermi-LAT

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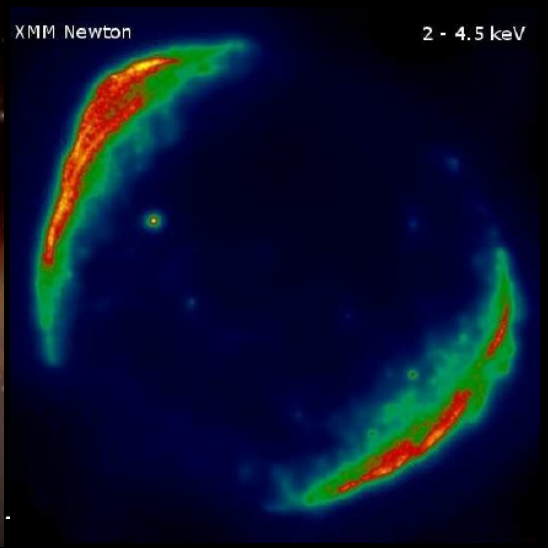
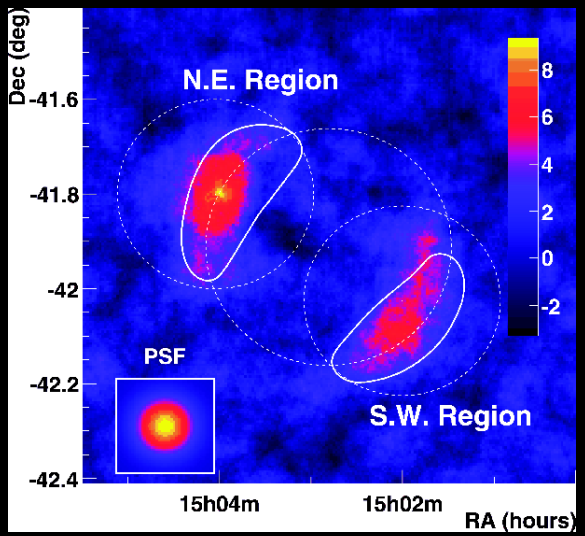


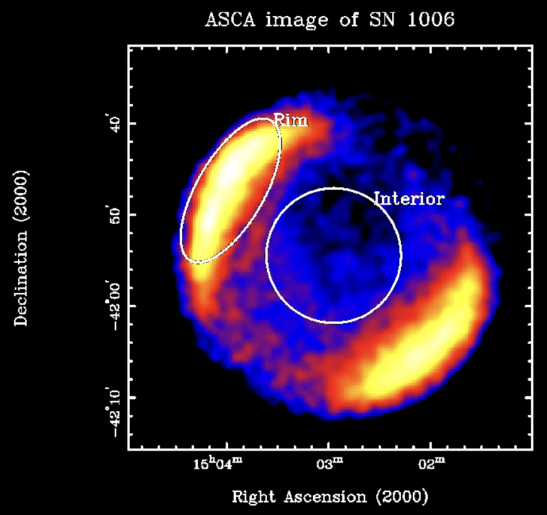


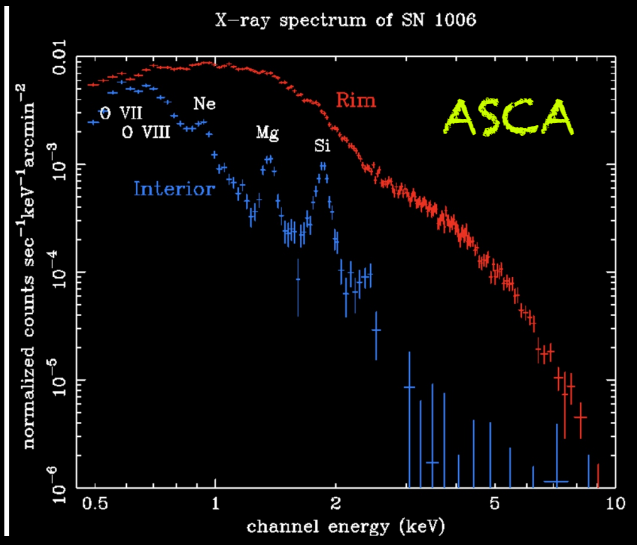
First evidence of electrons accelerated up to TeV energies

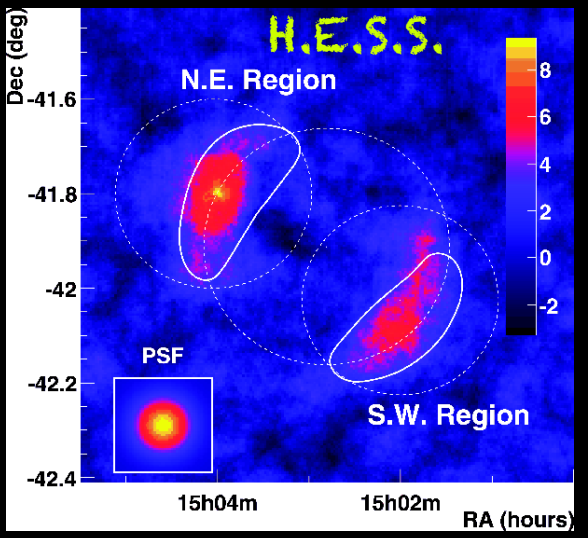
- Discovery of X-ray synchrotron emission in the bright rims of SN 1006 with *ASCA* (Koyama et al. 1995) => very high energy electrons

- Chandra revealed small-scale structure in the non-thermal X-ray filaments of the NE rim of SN 1006 (Long et al. 2003) => High B fields

- Discovery of TeV emission with H.E.S.S. ; correlation with X-rays (Acero et al. 2010)







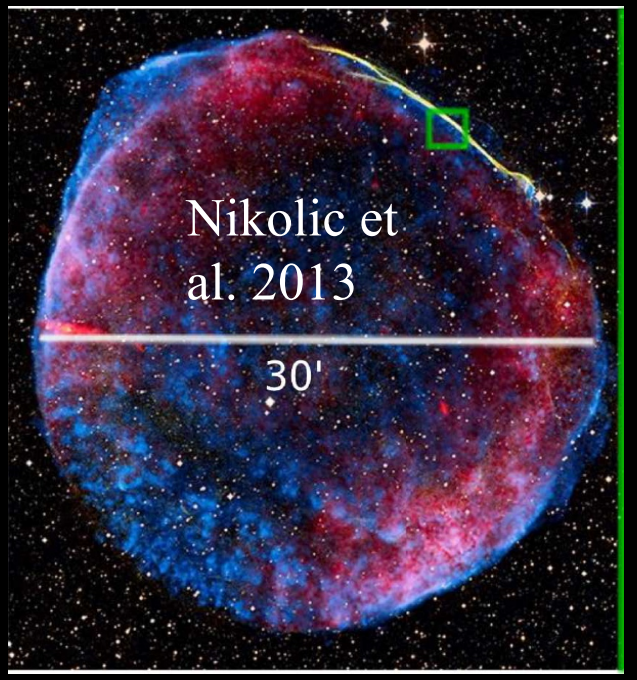
Atomic clouds

Overall tenuous environment : 0.035 cm^{-3} (Miceli et al. 2014)

Dense material in the NW : bright and sharp Hα filament but particle acceleration not efficient

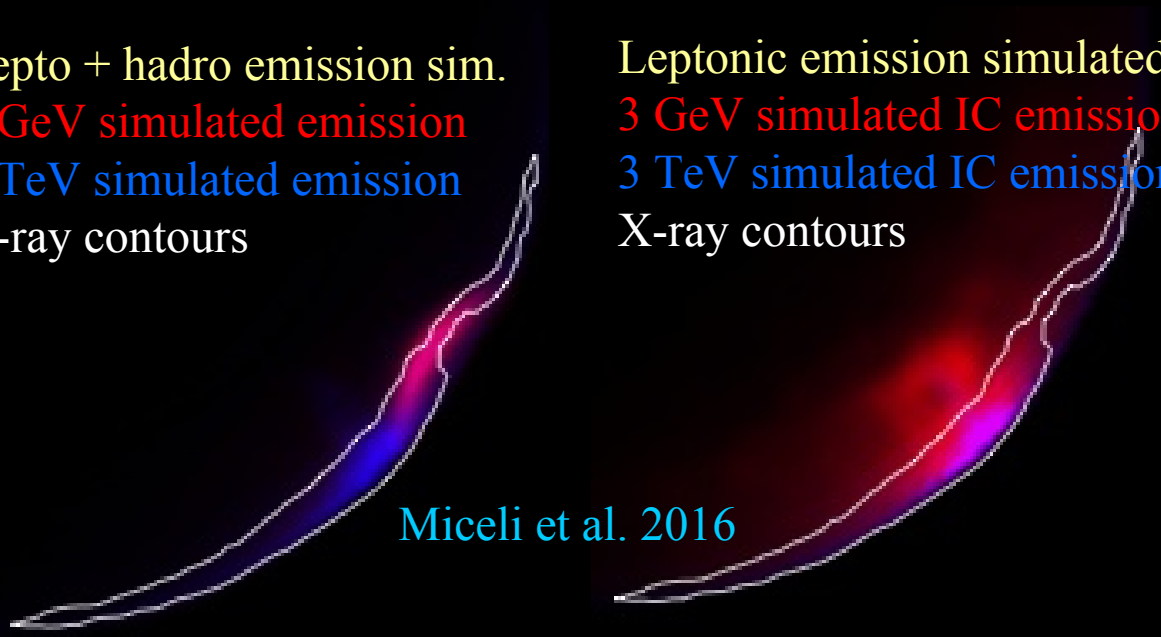
Efficient acceleration in SW + atomic cloud

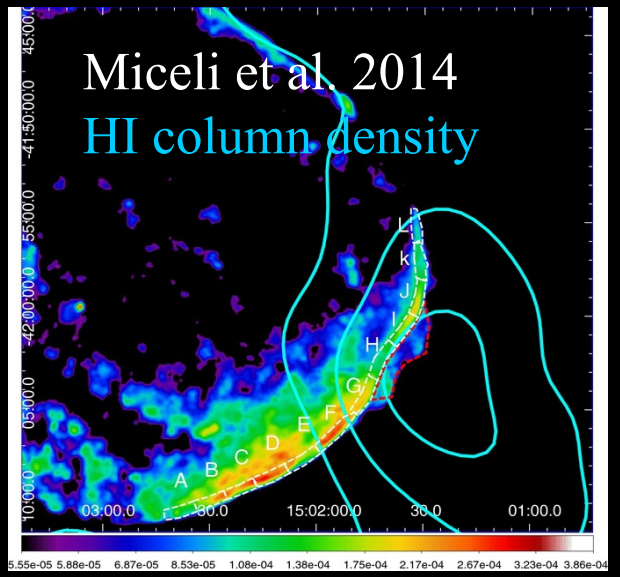
=> in SW, we expect contribution from IC + pp interaction with cloud material + pp with tenuous environment



Lepto + hadro emission sim.
3 GeV simulated emission
3 TeV simulated emission
X-ray contours

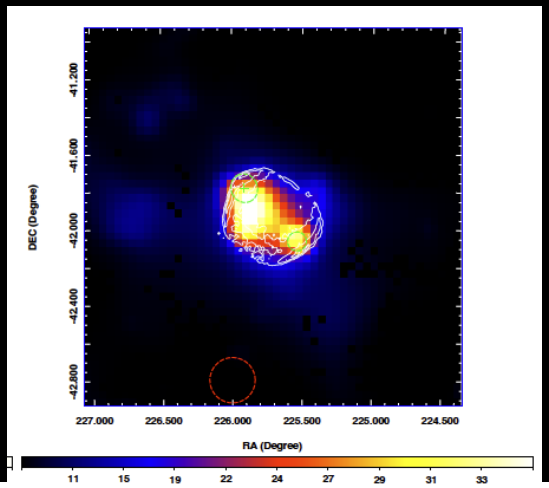
Leptonic emission simulated
3 GeV simulated IC emission
3 TeV simulated IC emission
X-ray contours

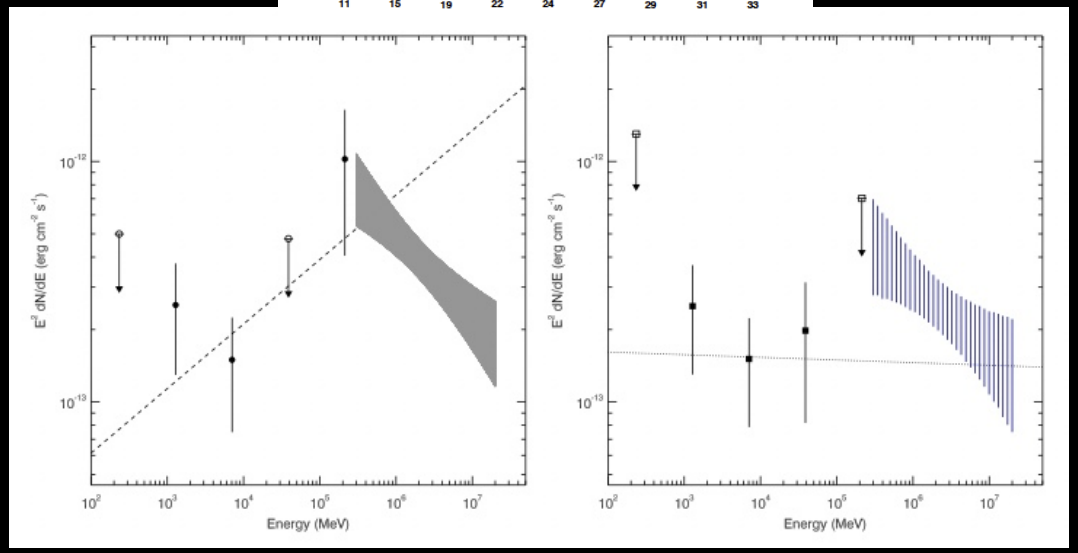




A brief recap of previous studies with Fermi

Xing et al. 2016 : (7 years of Fermi data)
Detection of the SNR at 4 sigma level
Spectra differ but not significantly





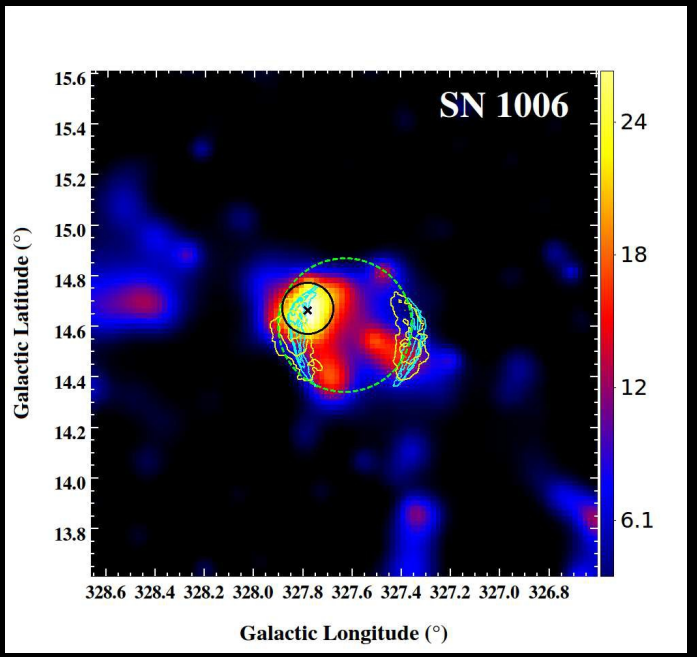
Condon et al. 2017 :

First detection of the NE limb with Fermi (8 years of data)

Hard spectrum (1.5 +/- 0.3)

Indication of asymmetry in the γ-ray emission announced at 3.6 sigma

(SW limb fit with an index 2.6 +/- 0.8)



Data analysis

Data selection:

- Pass 8 data
- Time interval : 15 years (2008 August 04 – 2023 August 03)
- IRF : P8R3_SOURCE_V3 with associated galactic and isotropic diffuses

Morphology:

- 1 GeV – 1 TeV
- zmax : 105°
- edisp_bins = - 1
- Binned likelihood analysis with 0.03° bin size with fermipy over a 15° width region

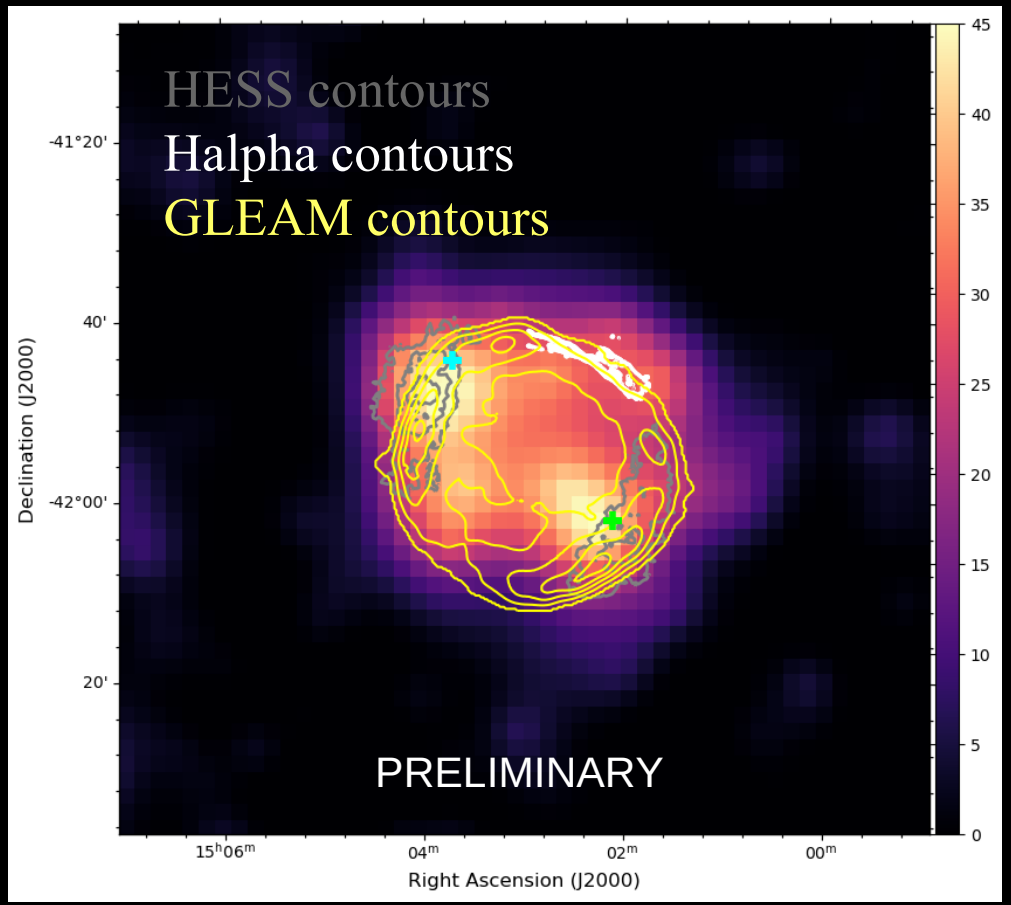
Spectra:

- 4 components : PSF3, PSF2, PSF1 (100 MeV – 1 GeV ; zmax=90° ; 0.1° bin size), ALL (1 GeV – 1 TeV, zmax = 105° ; 0.03° bin size)
- edisp_bins = -2
- Summed likelihood analysis over a 15° width region with fermipy

The region as seen by Fermi above 1 GeV

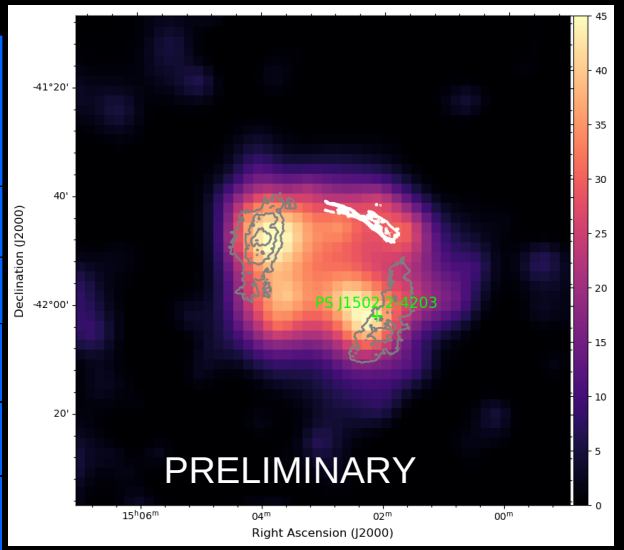
An additional source PS J1502.2-4203 is detected with TS=40
in addition to Point source 4FGL J1503.6-4146 (TS=35)=> significant detection of SW !

Excess TS map removing
4FGL J1503.6-4146 & PS
J1502.2-4203 in the Model



Best spatial model above 1 GeV

Excess TS map with contours from H.E.S.S. & Halpha template



Spatial Model	Log-like	NDoF	$\Delta AIC = AIC_{2Pt} - AIC_i$
2 Pt srcs	-678288.4	8	0
Disk	-678289.2	5	4.4
HESS (NE) + HESS (SW)	-678288.5	4	7.8
HESS (NE) + Pt src	-678286.0	6	8.8
HESS (NE) + 2 Pt srcs	-678279.5	10	13.8
HESS (NE) + HESS (SW) + Hα	-678283.1	6	14.6
HESS (NE) + Miceli sim. + Hα	-678284.2	6	12.4
HESS (NE) + Pt src + Hα	-678280.2	8	16.4
Radio	-678289.7	2	9.4
Radio (2 halves)	-678285.9	4	13.0
Radio (mid) + HESS (NE) + HESS (SW)	-678282.3	6	16.2

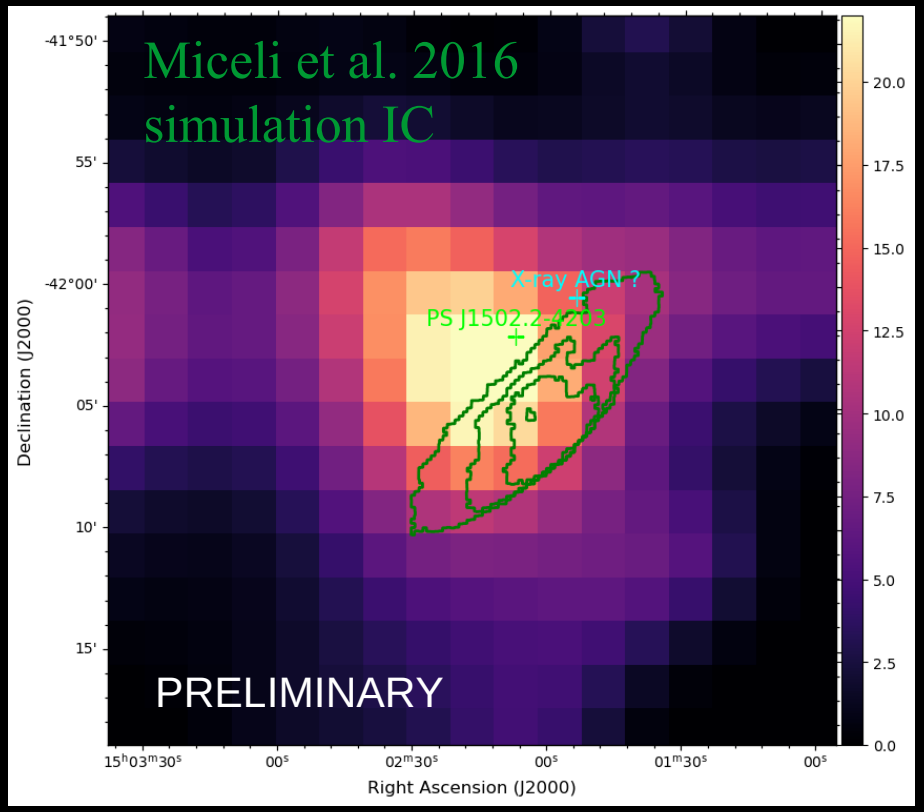
Best spatial model

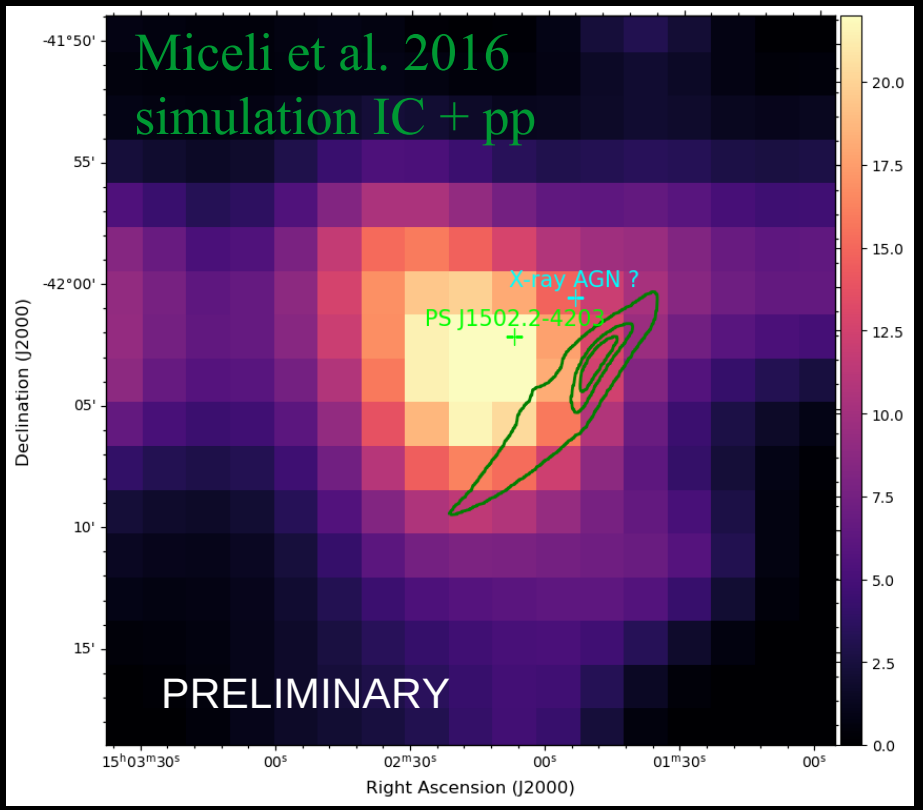
Best with only 2 components

A closer view at the SW limb

AGN candidate detected in X-ray with *NuSTAR* (Li et al. 2018)
=> 0.06° away from PS J1502.2-4203

Fixing these coordinates for our Pt source degrades the likelihood by 3.7
=> not favoured (despite two fewer degrees of freedom)





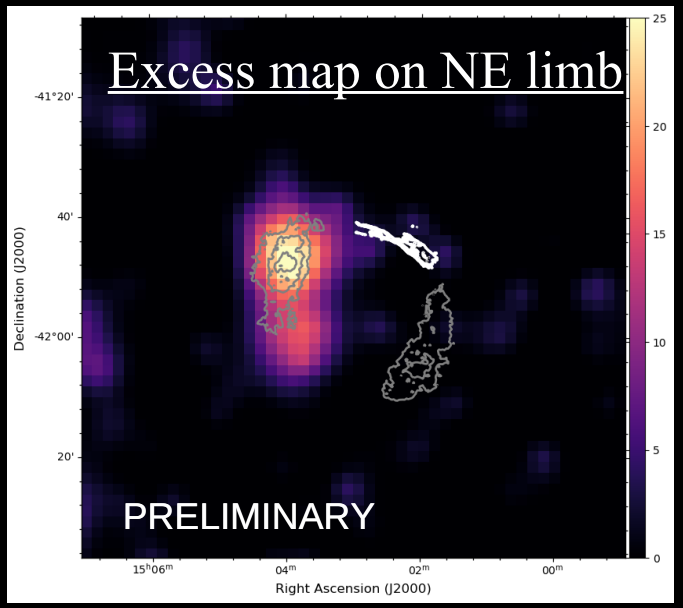
The different components at 1 GeV (I)

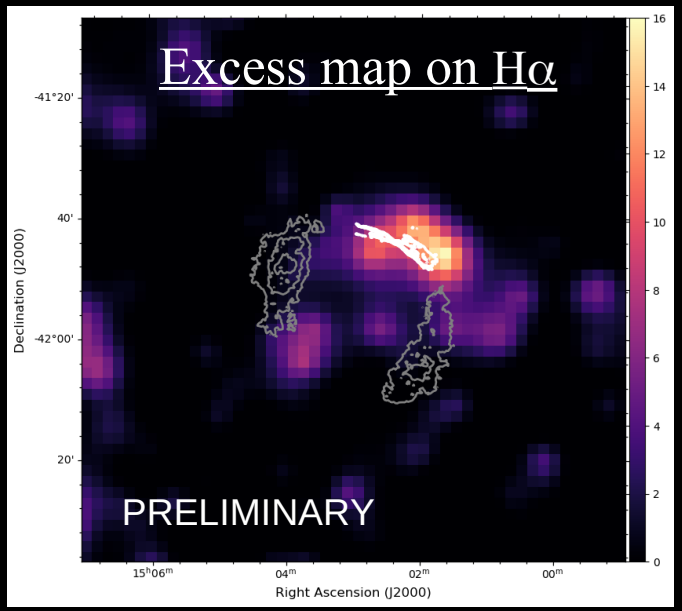
Using the HESS (NE) + Pt src + Hα spatial model :

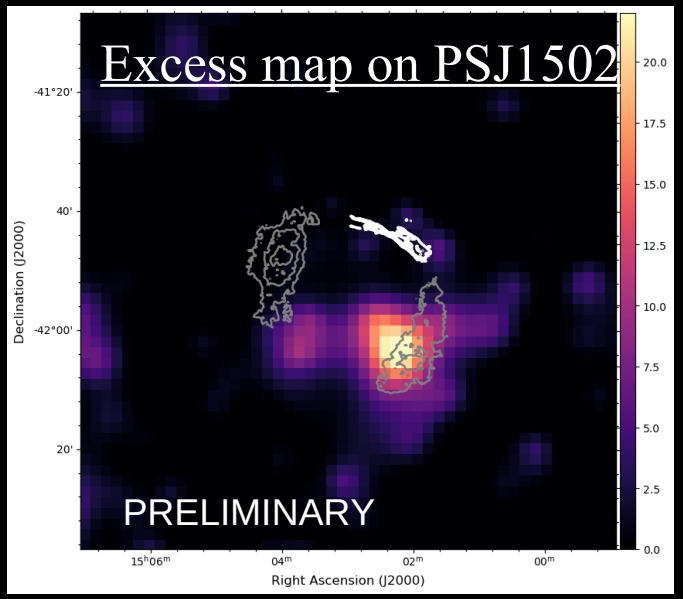
NE limb : TS=36
PL of ~1.6

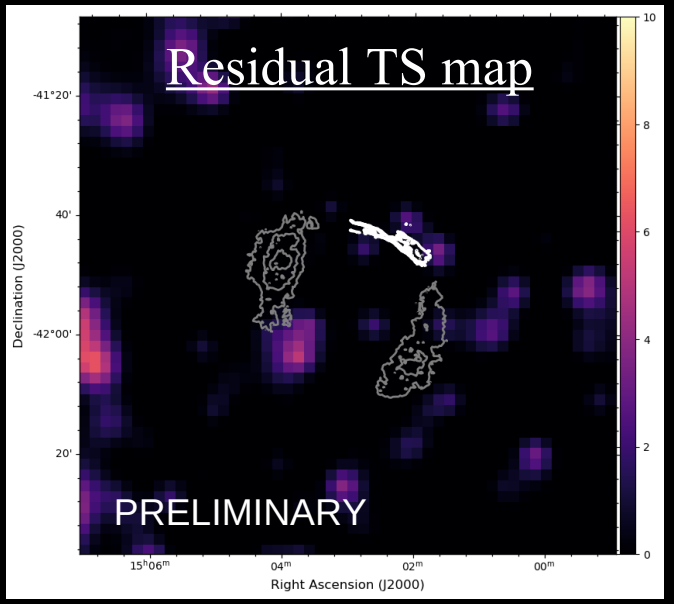
PS J1502 : TS=26
PL of ~2.3

Hα: TS=14
PL of ~2.2





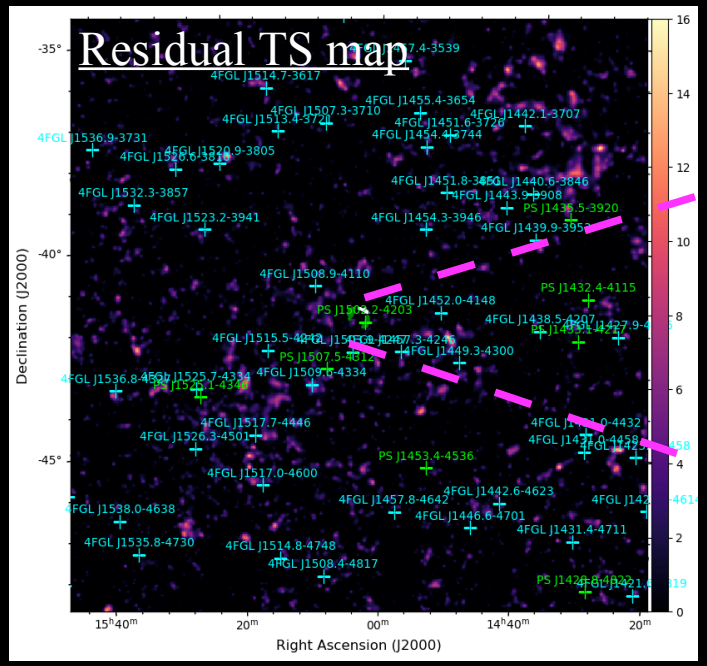


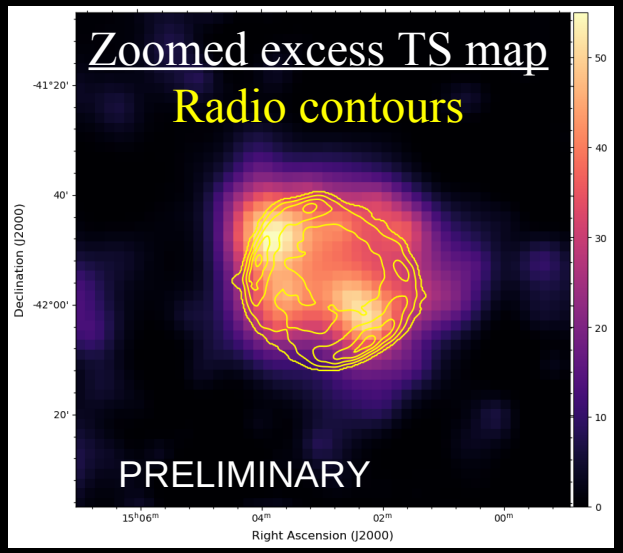


Spectral analysis above 100 MeV

- Add a Point source if TS map excess above 25 : 3 additional Point sources

- gtlike summed analysis over a 15° width region with fermipy (4 components)
- Spectral points derived in 10 logarithmically-spaced energy bins
- Systematics include uncertainties on the Galactic diffuse emission model, on the effective area and on the spatial shape of the source

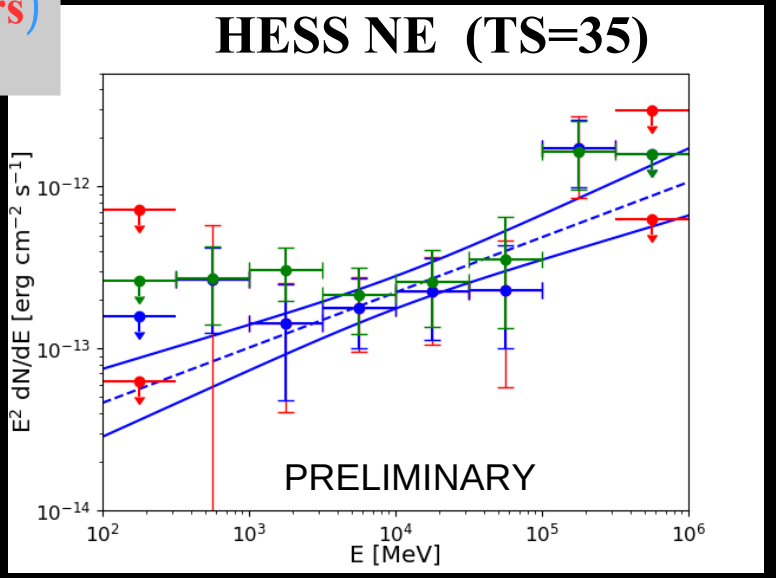


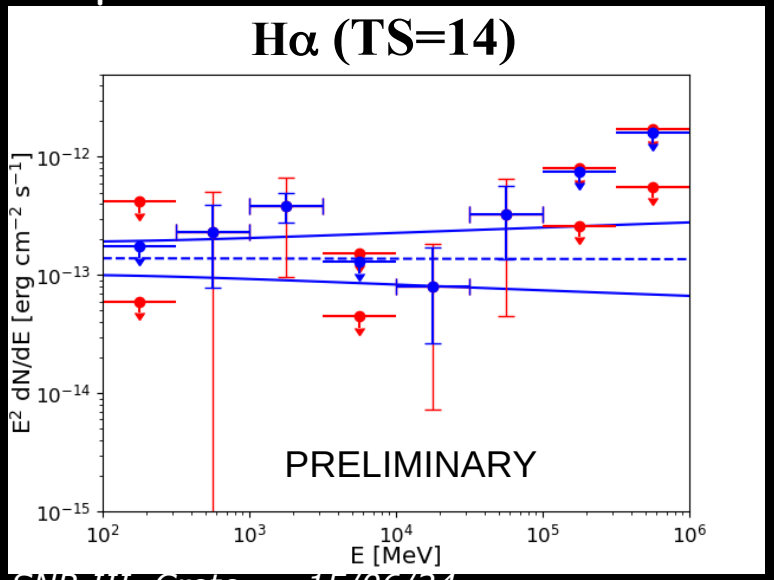


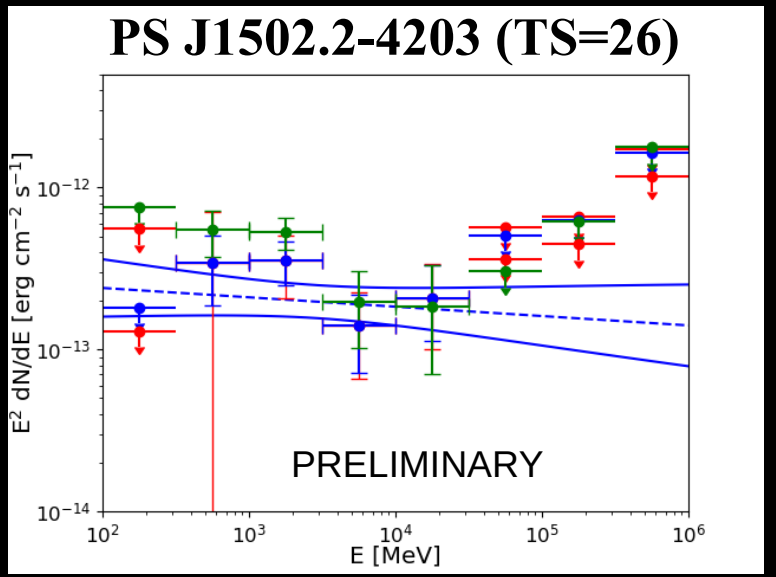
2 components with different spectral shape

2 spatial models tested :
HESS (NE) + Pt src + Hα (**stat.** / **stat + syst errors**)
Radio (NE) + Radio (SW) (stat errors)

- Confirmation of the hard spectrum for NE limb :
  $\Gamma = 1.7 \pm 0.1 \pm 0.1$
- Confirmation of the « softer » SW spectrum :
  $\Gamma = 2.1 \pm 0.1 \pm 0.1$
- Marginal detection (3.3σ) of emission coincident with the Hα filament
- Spectra robust against spatial model assumed





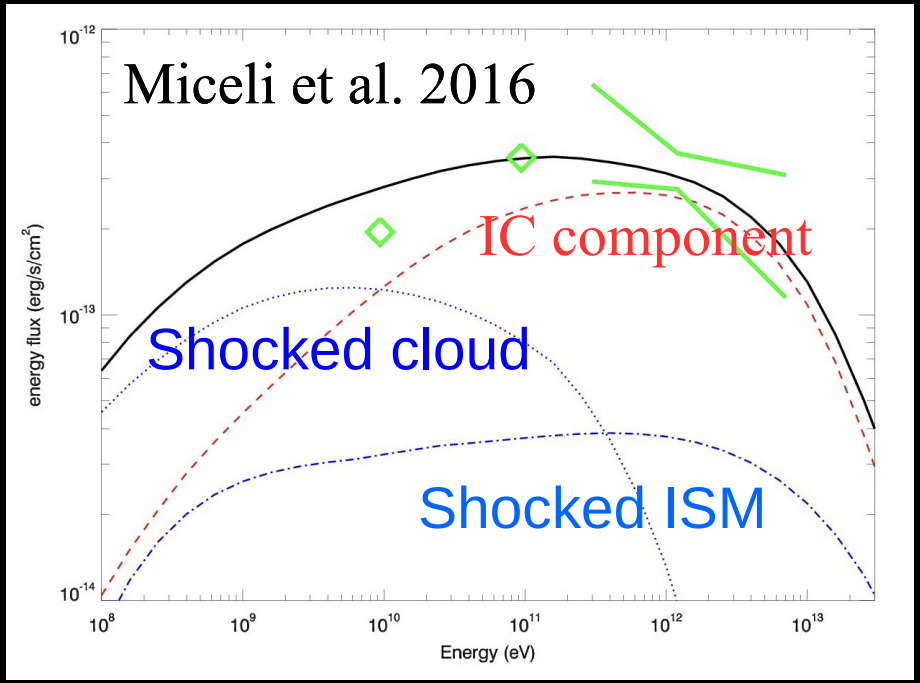


Assumptions for the modeling

- Softer SW emission in line with prediction from Miceli 2016 : hadrons ?

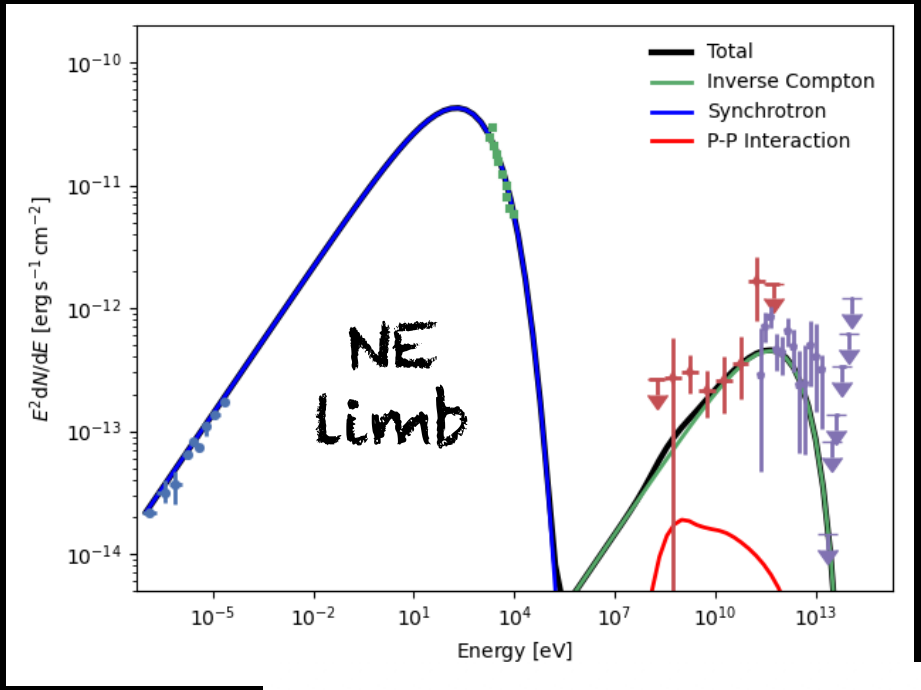
Model each limb separately using identical parameters except the density of the medium :

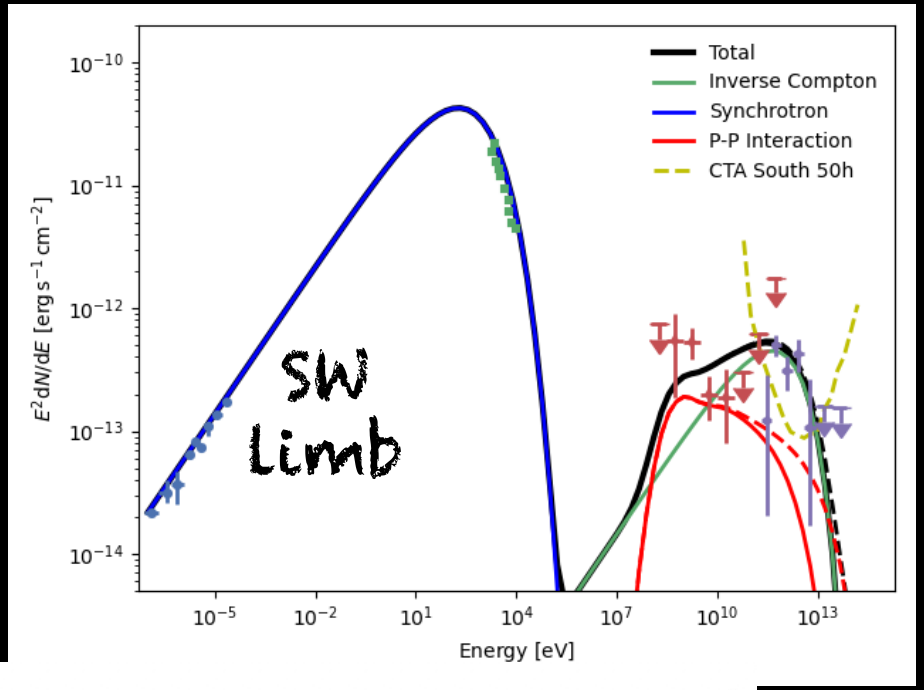
- Simple fit using naima assuming gamma-ray emission is dominated by:
  - IC scattering for NE
  - pp interaction for SW (due to enhanced density)
- Assume same spectral index of injection for electrons and protons : 2.2 (Allen et al. 2001)



Modeling of the MWL data

- Use the 2 radio halves for Fermi and scaling the radio & X-ray spectra of the whole SNR
- A density of 0.035 cm^{-3} in NE and 0.35 cm^{-3} in SW reproduces the data
- Total energy injected in protons is 2.6×10^{49} erg (concentrated on the limbs)
- No constraints on Emax for protons : more than 50hrs needed for CTA

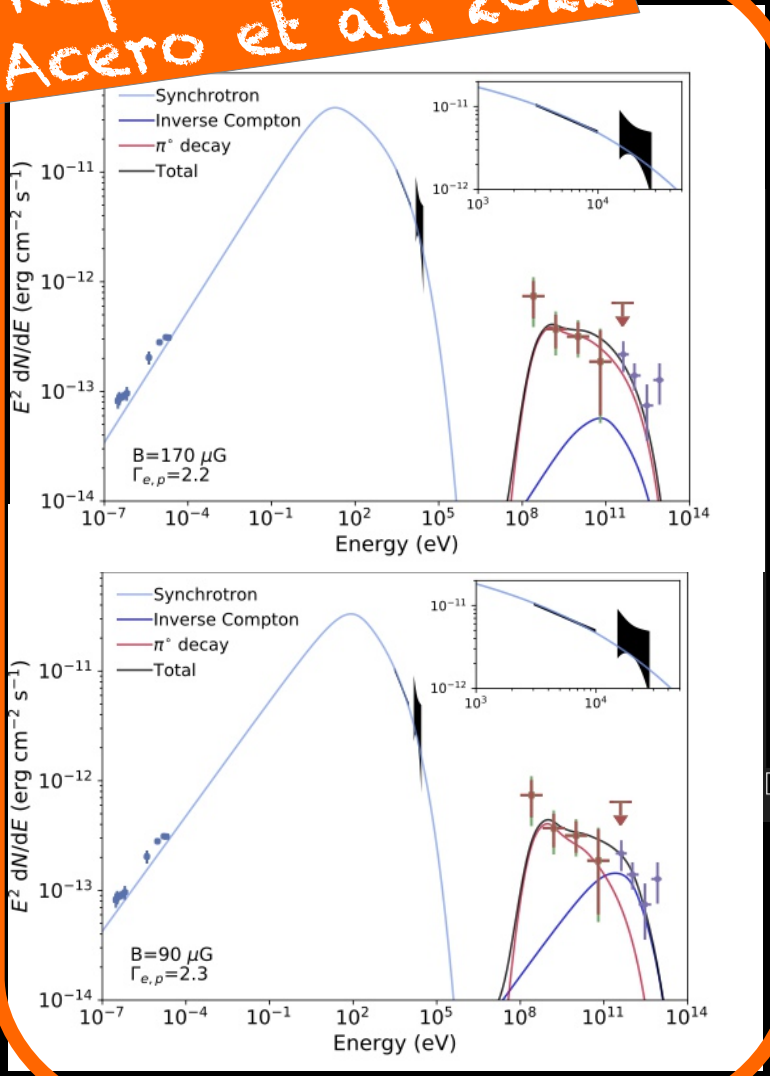




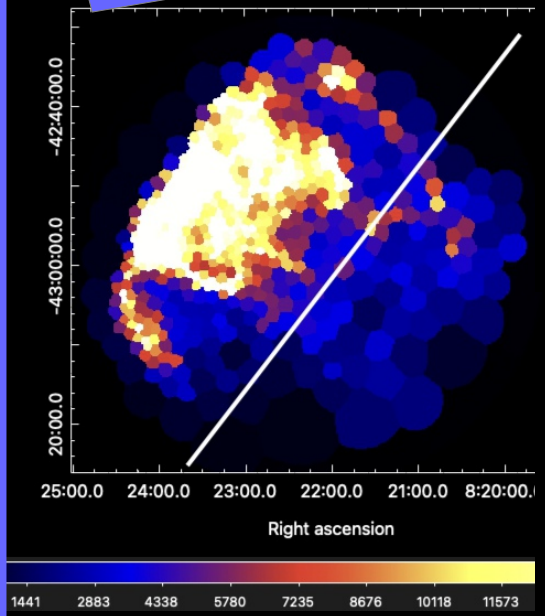
Limb	B μG	n_0 cm^{-3}	Γ	$E_{\rm max,e}$ TeV	$E_{\rm max,p}$ TeV	W_p erg	Kep
NE	30	0.035	[2.2]	15	20 / (200)	1.3×10^{49}	0.01
SW	30	0.35	[2.2]	15	20 / (200)	1.3×10^{49}	0.01

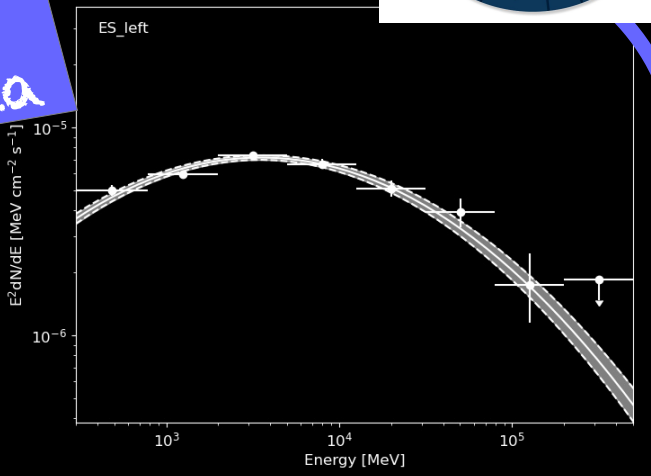
CSM/ISM interaction traced by Fermi

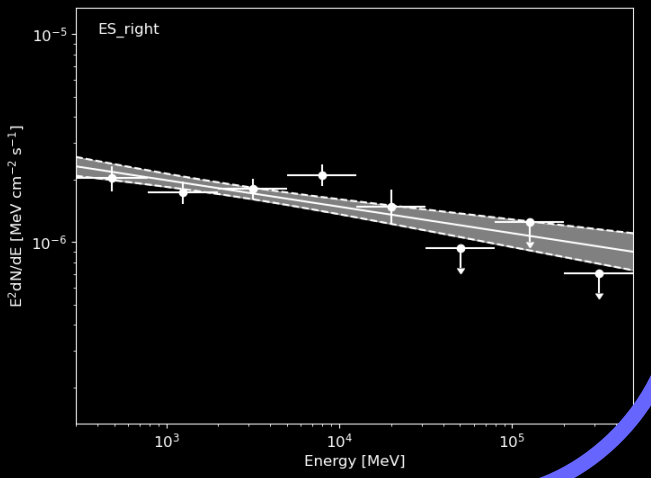
Kepler SNR
Acero et al. 2022



Poster S5.6
R. Giuffrida







Conclusions

Significant detection of the NE and SW limb with Fermi

Best spatial model requires 3 components : NE limb, SW (Point source) + Hα

- Hard spectrum for NE limb
- Softer spectrum for SW limb
- Marginal detection of emission coincident with the Hα component

- A density of 0.035 cm^{-3} in NE and 0.35 cm^{-3} in SW reproduces the MWL data
- No constraints on Emax for protons ; would require more than 50 hours for CTA
- Total energy injected required = 2.6 x 10^{49} erg (concentrated on the limbs)
- Agreement with acceleration efficiency traced by X-rays (Giuffrida et al. 2022)

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