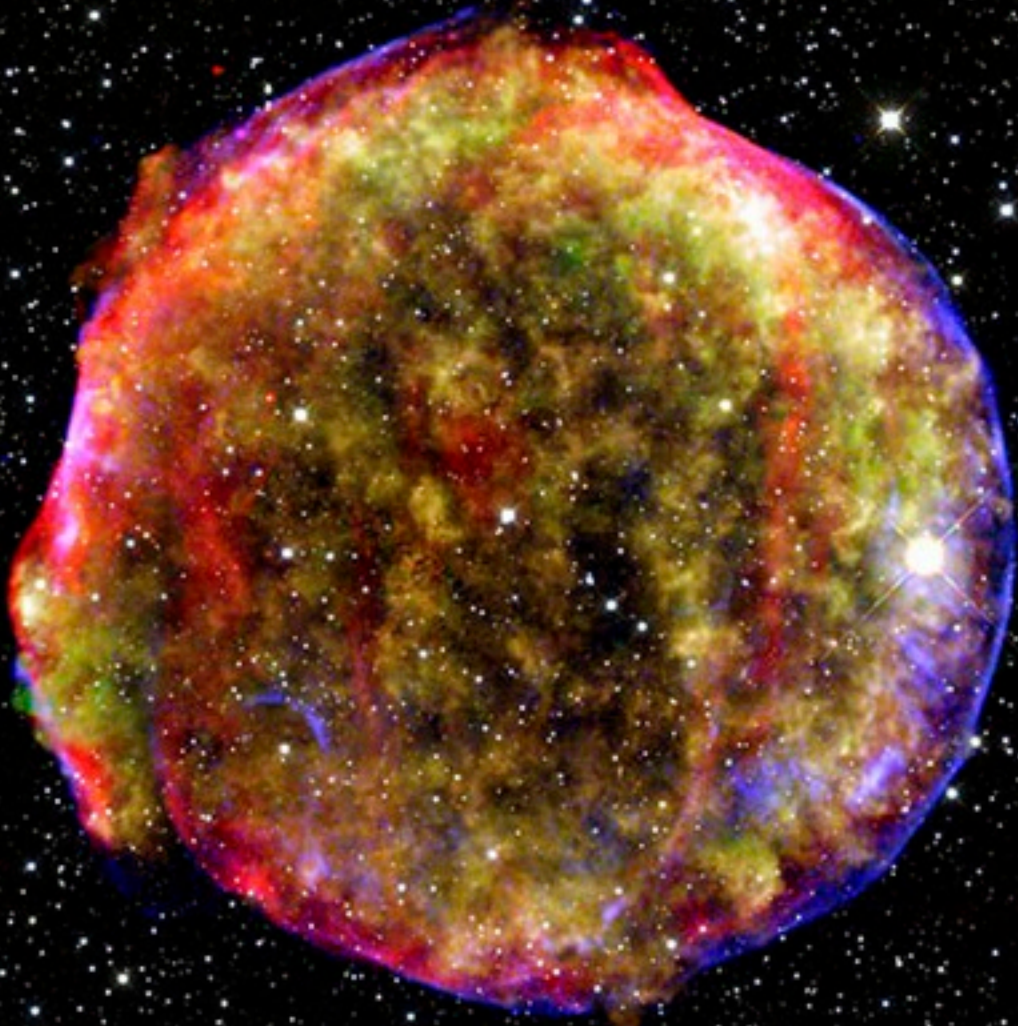
Supernova Remnants in the FERMI Era



Melitta Naumann-Godó

APC/Univ. Paris 7
AIM/IRFU/CEA Saclay

Irfu
cea
saclay

Credit: X-ray: NASA/CXC/SAO, Infrared: NASA/JPL-Caltech, Optical: MPIA, Calar Alto, O.Krause et al.

Travaux de recherche

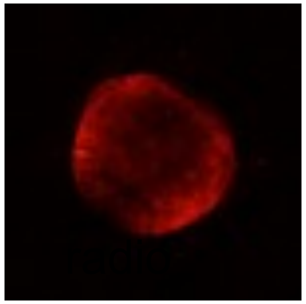
- „Diplomarbeit“ sur la physique hadronique
  - production des mesons η sur faisceau et cible polarisé
- Thèse sur ANTARES à l’Université d’Erlangen: 2007
  - développement d’une méthode de reconstruction
  - modélisation des sursauts gamma
- Post-doc sur HESS à l’École Polytechnique (LLR)
  - amélioration et vérification de l’analyse HESS (Model 3D) par comparaison MC/données
  - analyse du vestige de supernova SN 1006
- Post-doc sur FERMI au Sap à CEA/IRFU
  - travaux et analyses sur les catalogues de FERMI : 1FGL et 2FGL
  - analyse du vestige de supernova Tycho

Why do we study SNRs ?

The SNR paradigm:

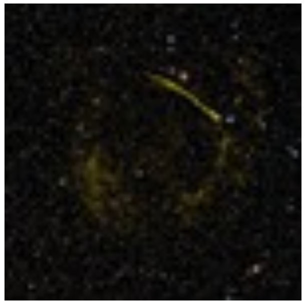
- Cosmic rays are accelerated in SNRs by diffusive shock acceleration: $Q(E) \sim E^{-\gamma}$
- They should reach energies up to the knee

Multiwavelength Observations necessary to understand the SNR emission:



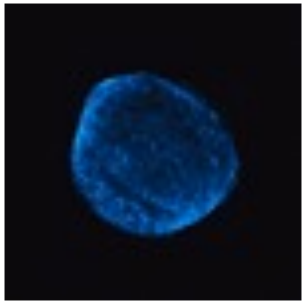
Radio (synchrotron)

+



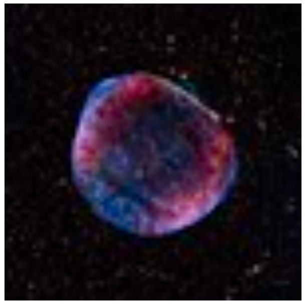
Optical

+



X-ray (synchrotron + thermal)

=



full picture ?

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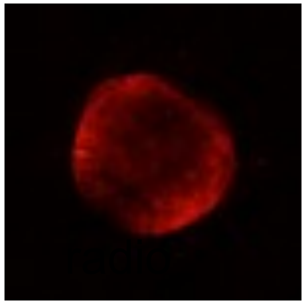

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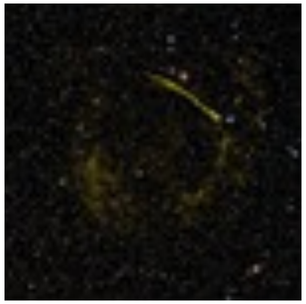

Optical

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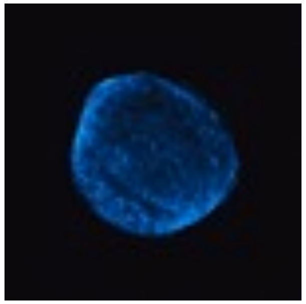

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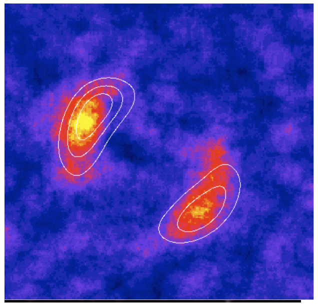


full picture ?
gamma-rays !!!
(IC / bremsstrahlung / π^0-decay)

What are the challenges in SNRs ?

Pending questions:

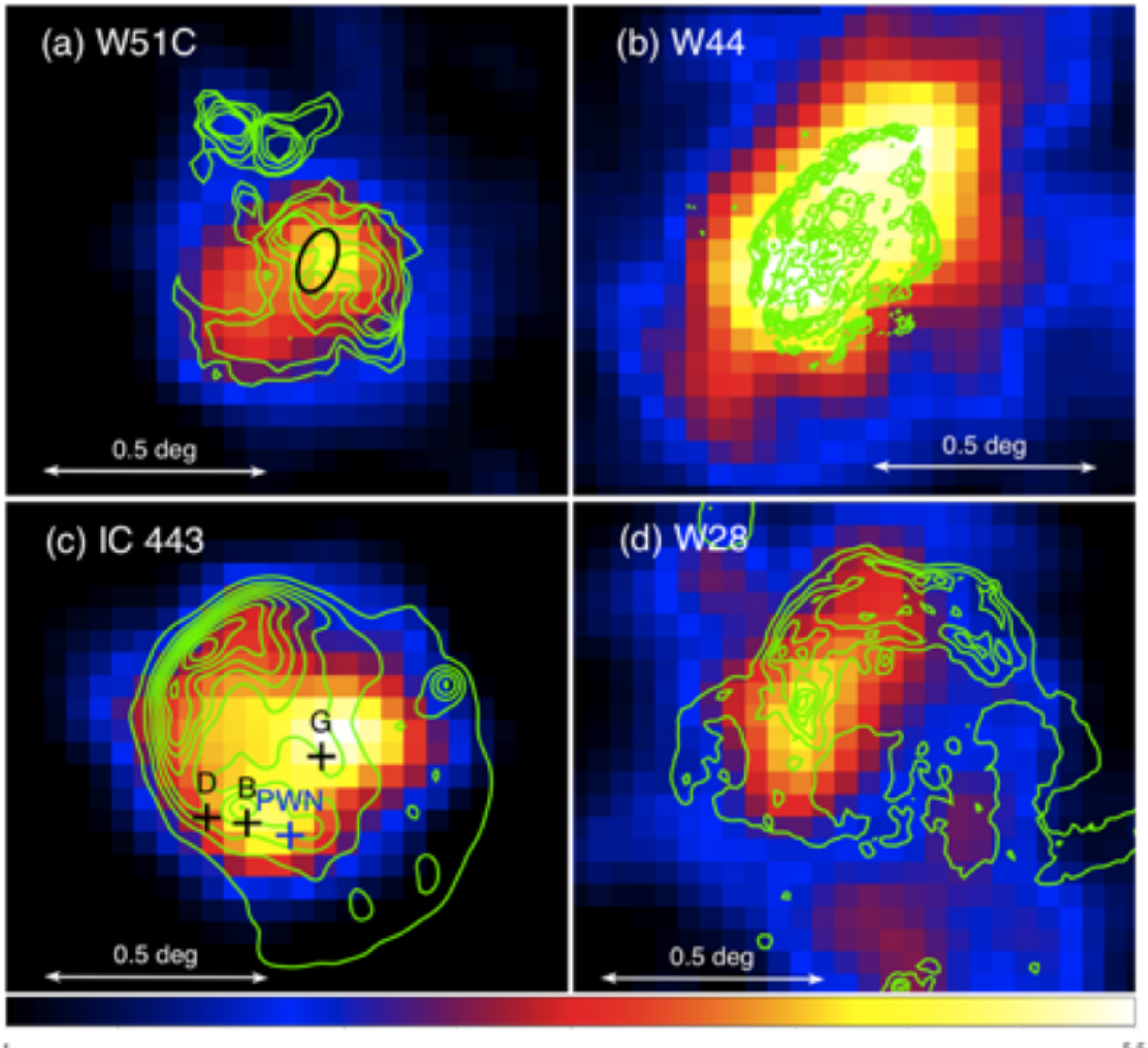
- How efficient is cosmic ray acceleration in SNRs ?
  - What is the energy density of the accelerated particles ?
- What is the maximum energy of the accelerated particles ?
- What is the nature of the accelerated particles (electrons/hadrons)?
- How large is the magnetic field ?
  - Has it been amplified ?

Let us see what we can learn from gamma-ray observations

SNRs seen in γ-rays

- SNRs interacting with molecular clouds:
  - W51C, W44, IC443, W28, W49B, W30(G8.7-0.1), CTB37A, ...
- Evolved SNR without molecular cloud interactions:
  - Cygnus loop, (Puppis A)
- TeV-bright SNRs:
  - RXJ 1713
  - Vela junior
- Historical SNRs:
  - Cassiopeia A
  - SN 1006 ☜
  - Tycho ☜

SNRs interacting with molecular clouds



2.5 yr count maps (>2 GeV, front-converted)

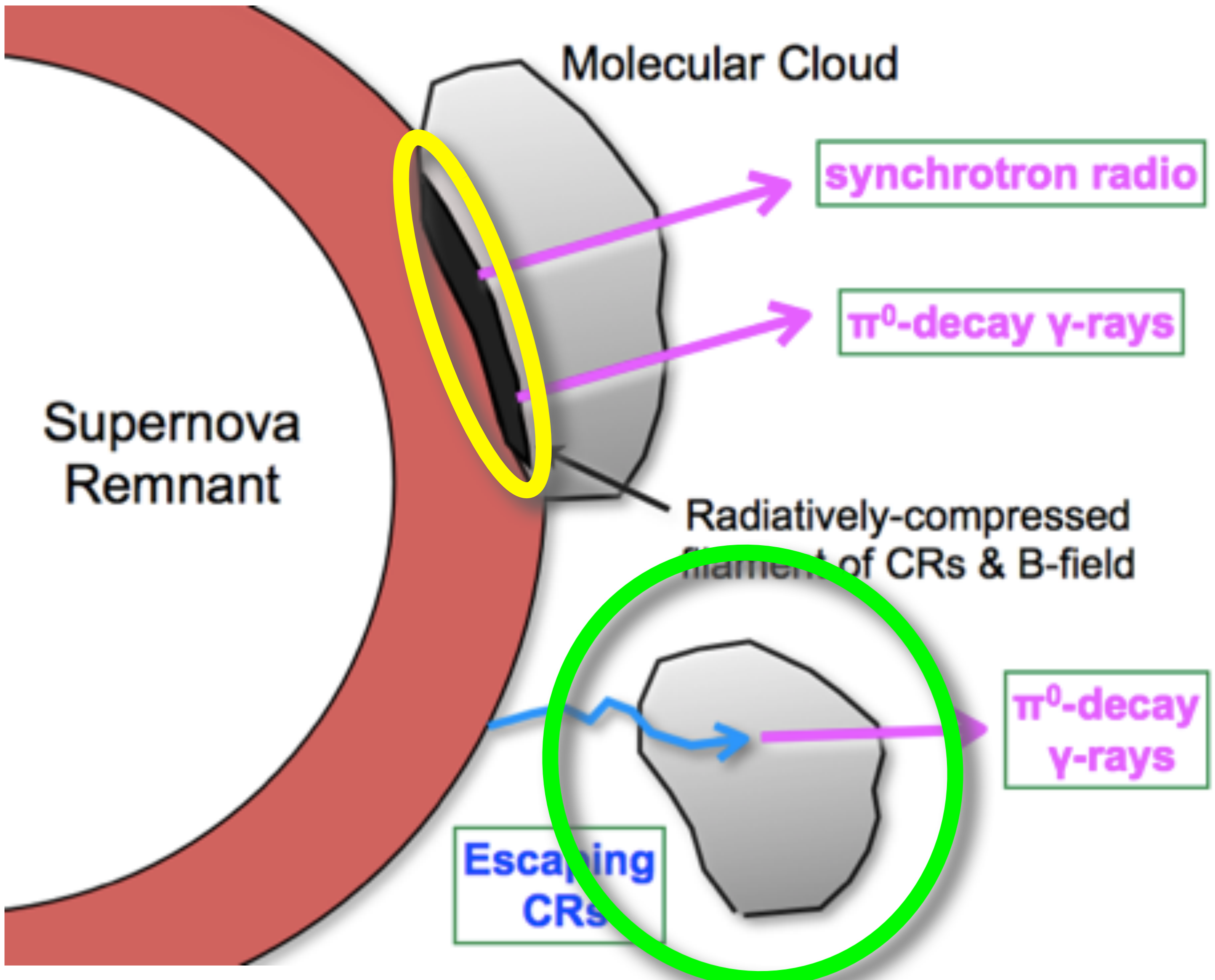
- Extended GeV emission has been discovered from several SNRs with molecular cloud (MC) interactions
- GeV extension is consistent with the size of the radio remnant

➠ SNRs interacting with MCs are GeV-bright + the dominant class of FERMI SNRs

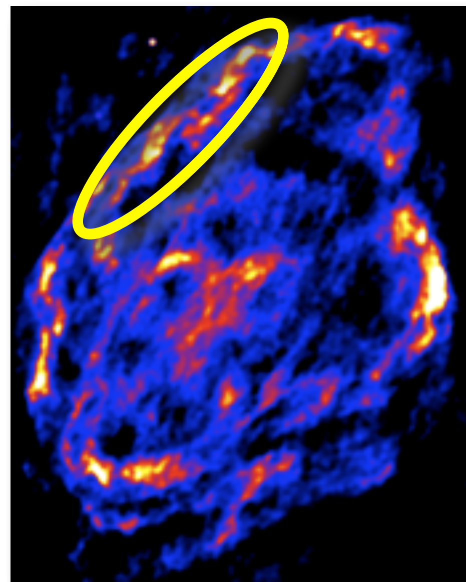
SNRs interacting with molecular clouds

☞ Uchiyama et al. 2010

Crushed cloud model: radio and gamma-ray emission comes from radiatively-compressed filaments

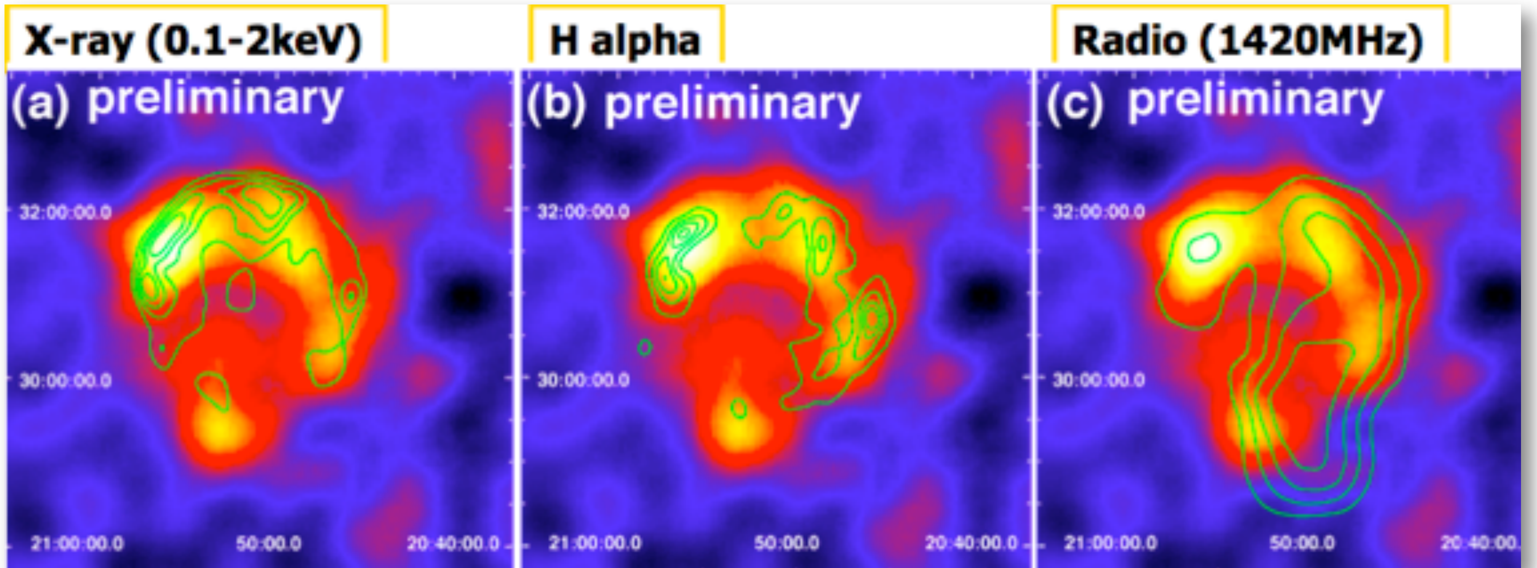


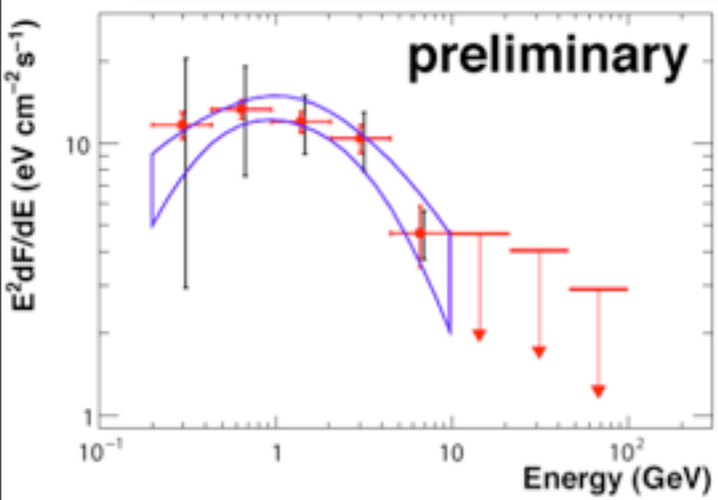
SNR W44



synchrotron radio emission correlated with shocked H_2 gas

The Cygnus loop





- Spectral break at 2-3 GeV
- γ-ray luminosity is ~10^{33} erg/s between 1-100 GeV (< other Fermi SNR)
- ringlike morphology with radii 0.7°±0.1° and 1.6°±0.1°
- strong correlation between X-ray rims, Hα filaments and γ-rays

➠ γ-rays originate in interactions between accelerated particles in the SNR and interstellar gas or radiation fields adjacent to the shock regions

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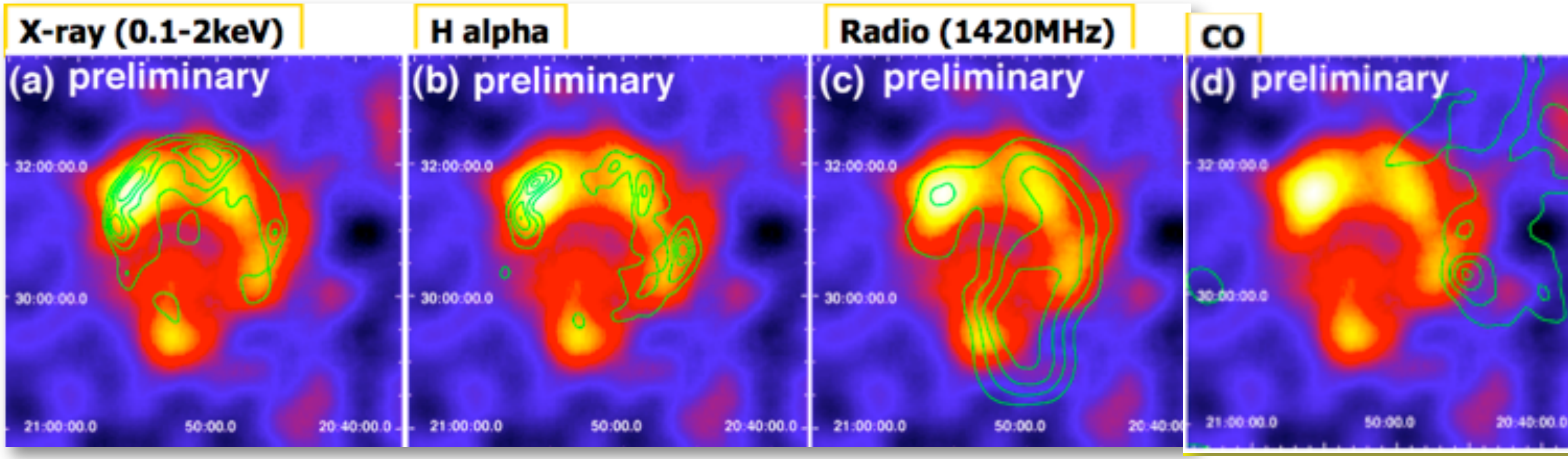

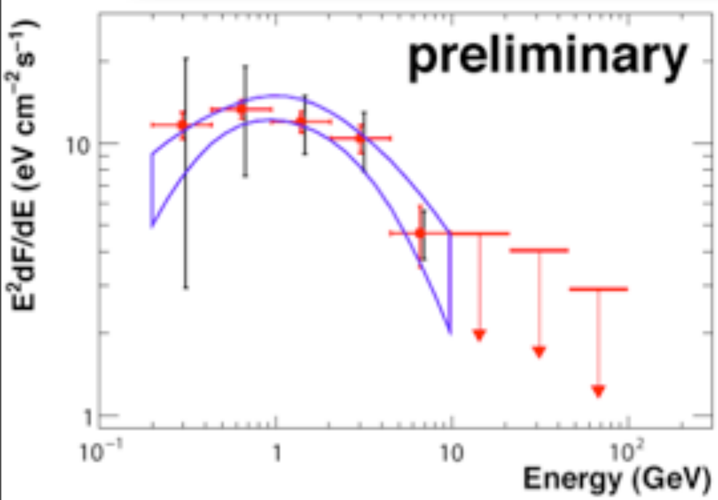

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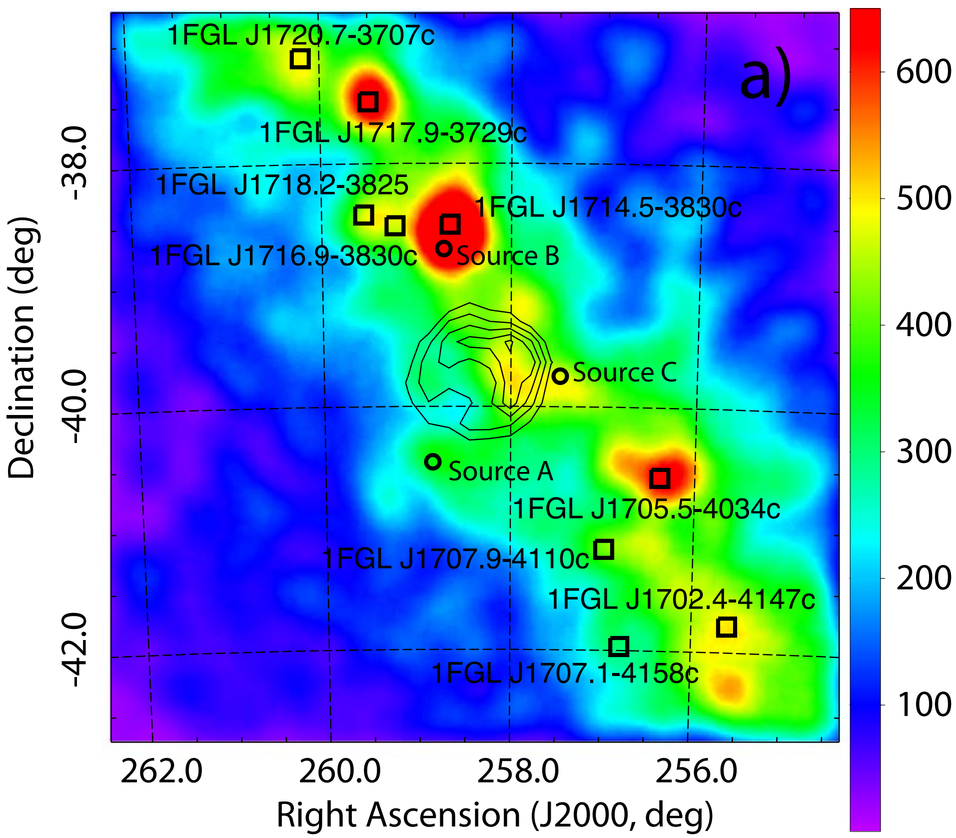
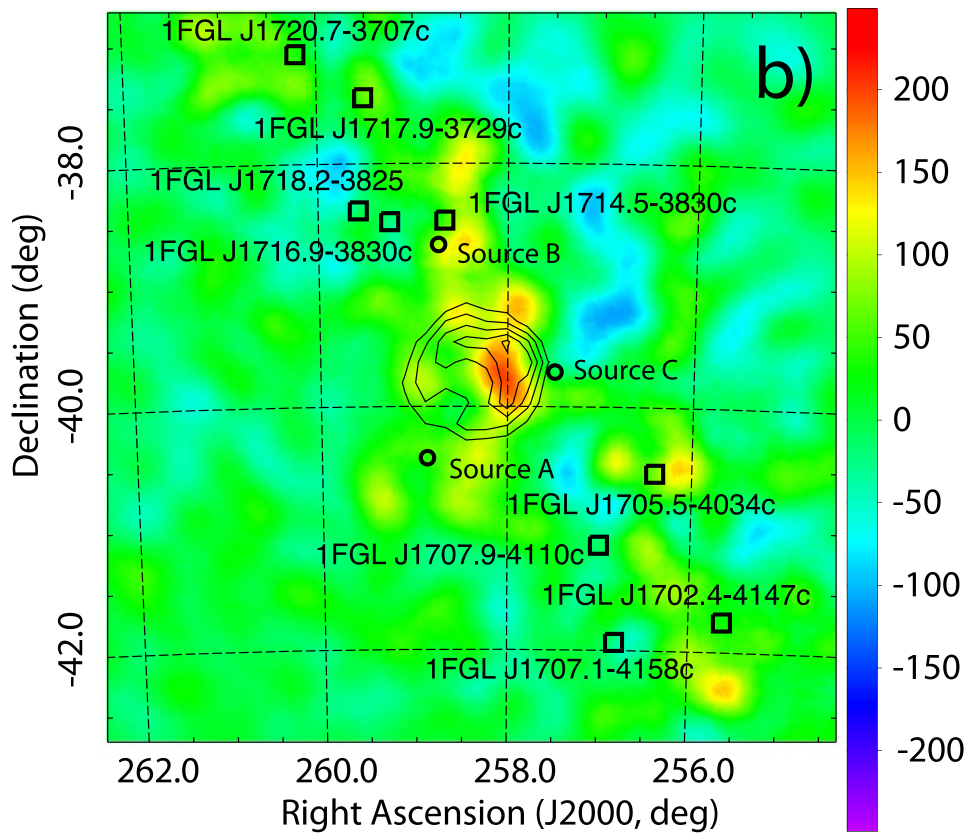
RXJ 1713.7-3946

Fermi LAT count maps (> 3 GeV)



Before background subtraction

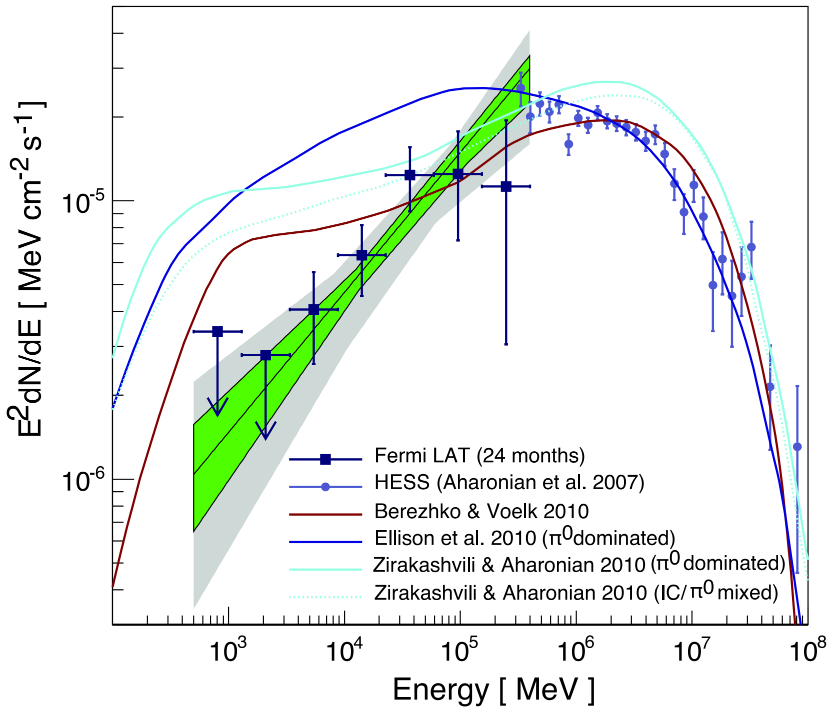


After background (contributions from diffuse backgrounds + other sources) subtraction

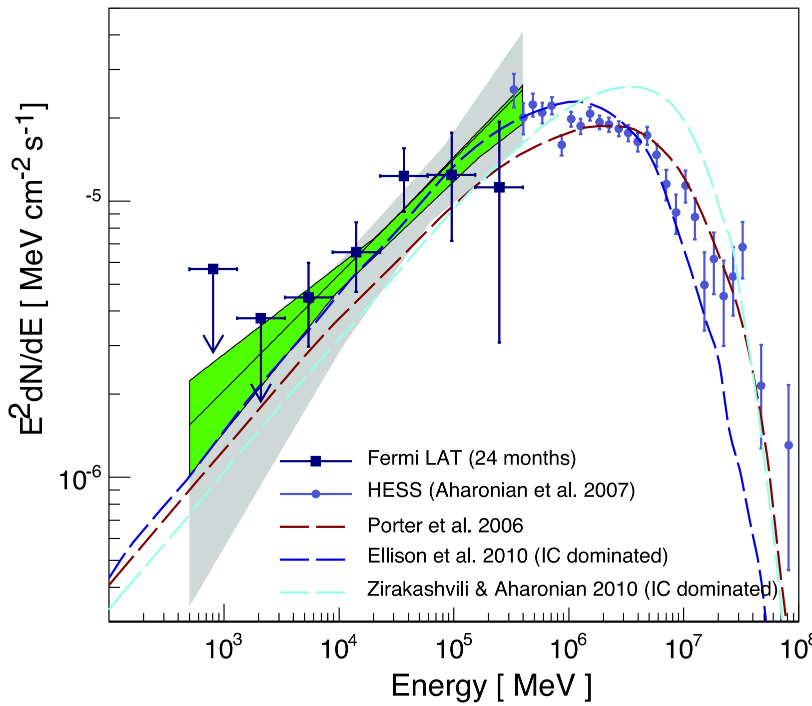
RXJ 1713.7-3946

Fermi LAT spectrum: Very hard with $\Gamma = 1.5 \pm 0.1$ (stat) $\pm$ 0.1 (sys)

Hadronic Models



Leptonic Models



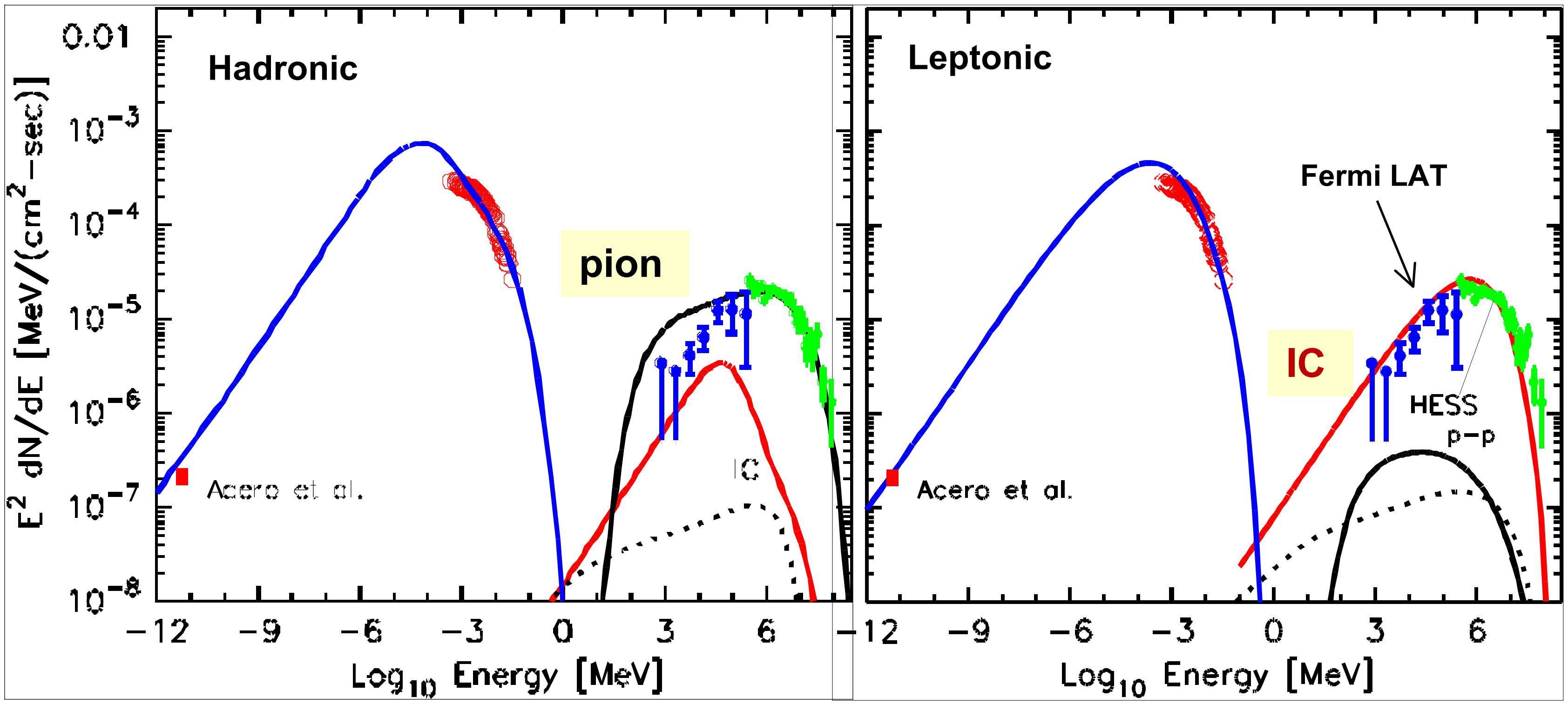
The Fermi LAT + H.E.S.S. spectrum can be fit well with leptonic models
If interpreted with hadronic models, extremely efficient particle acceleration is required to fit the data (proton index must be $s_p \sim 1.5$ to fit the Fermi LAT spectrum)

➠ Joint FERMI/HESS gamma-ray spectrum favoures the leptonic model

RXJ 1713.7-3946

☞ Ellison et al. 2010

For J1713, reasonable fits possible to continuum only with either pion-decay or inverse-Compton dominating GeV-TeV emission



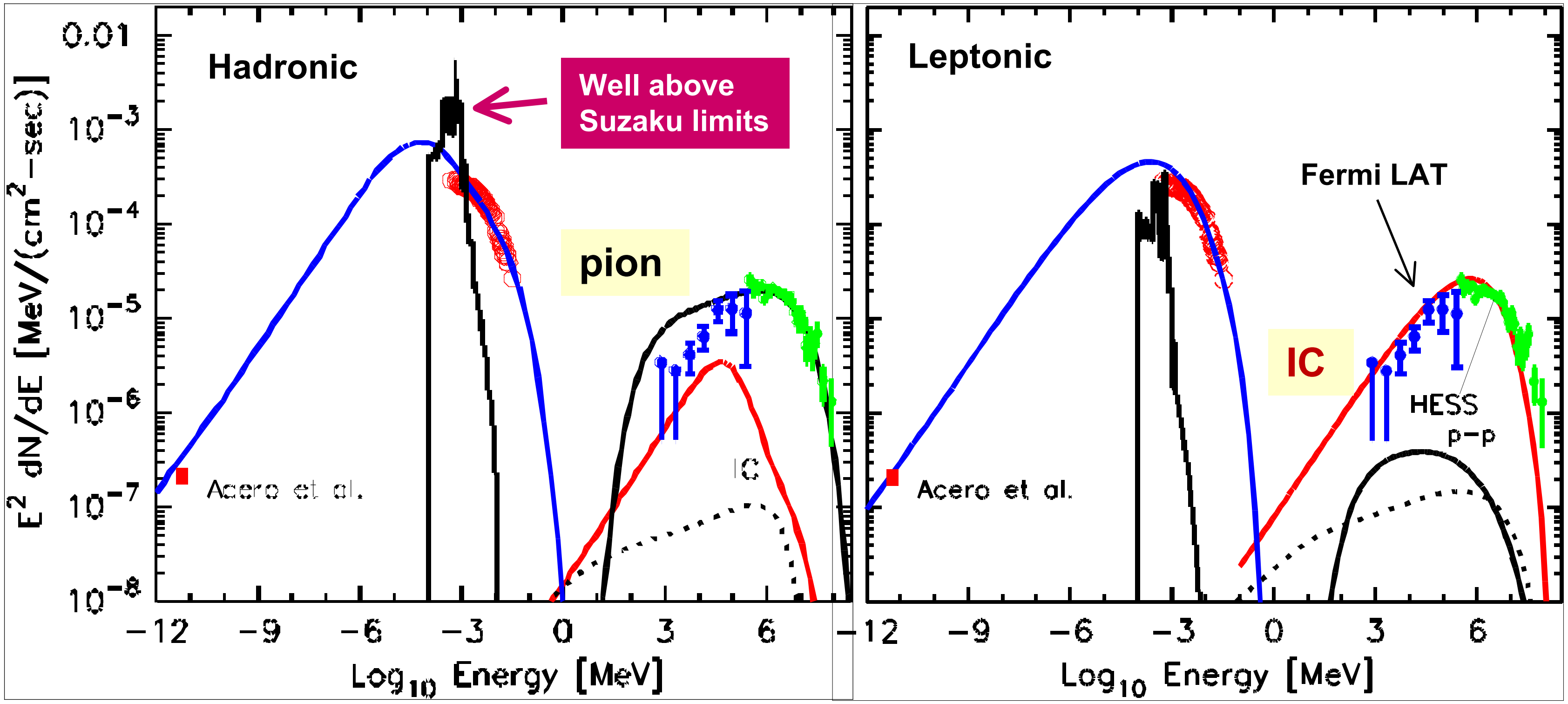
Hadron model parameters:
n_p = 0.2 cm^{-3}
e/p = K_{ep} = 5 10^{-4}
B_2 = 45 μG

Lepton model parameters:
n_p = 0.05 cm^{-3}
e/p = K_{ep} = 0.02
B_2 = 10 μG

RXJ 1713.7-3946

☞ Ellison et al. 2011

When X-rays are calculated self-consistently, force lower density and higher K_{ep} = 0.02, eliminates pion-decay fit



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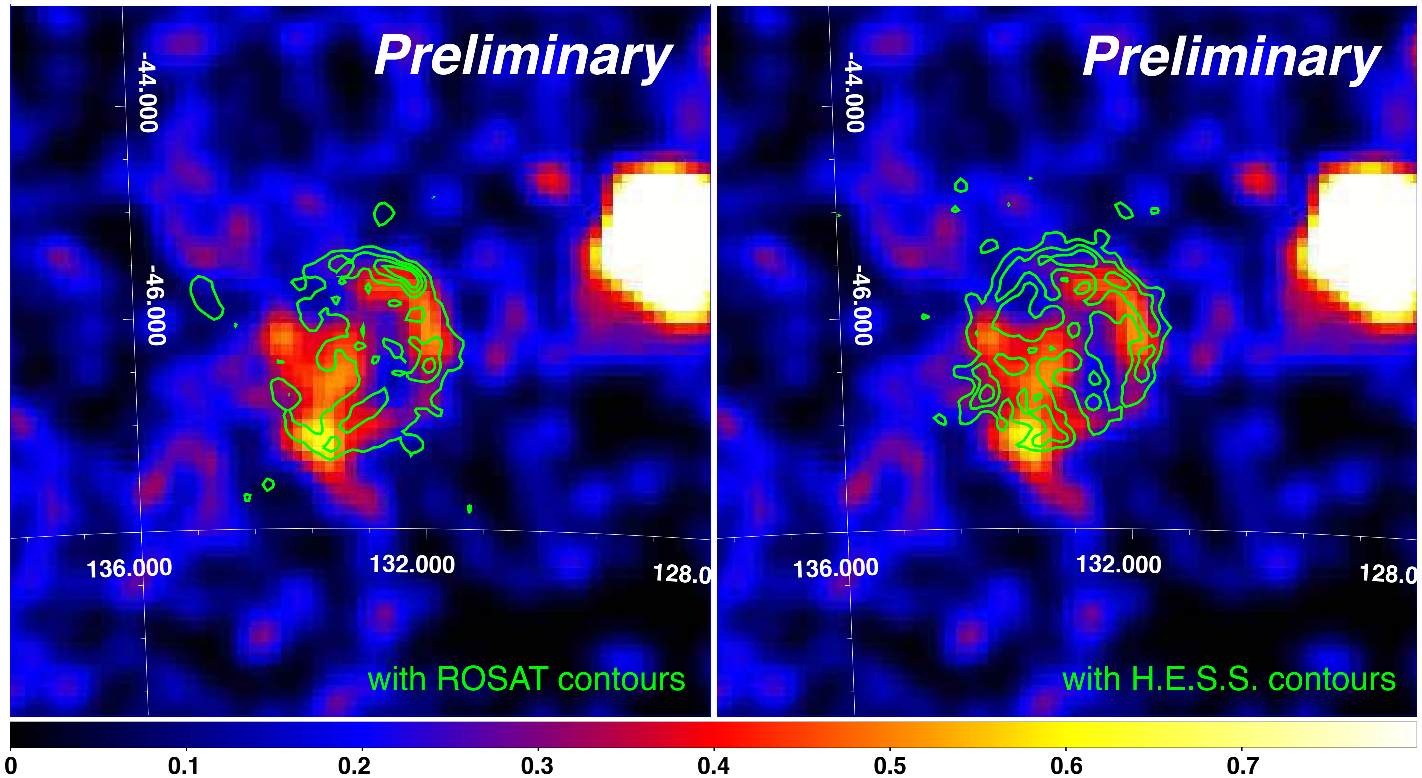
Vela junior

Fermi LAT count maps (> 10 GeV)



Spatially extended source at the location of the SNR RX J0852.0–4622

The emission clearly detected in the high energy region (Hereafter we show results with events > 5 GeV)

TS = 221 with the H.E.S.S. image used as a spatial template

Using a uniform disk as a spatial template, we obtain a radius of 1.12 (+0.07, –0.06) deg, which is consistent with the extent observed in radio, X-rays, and TeV gamma rays

Vela junior

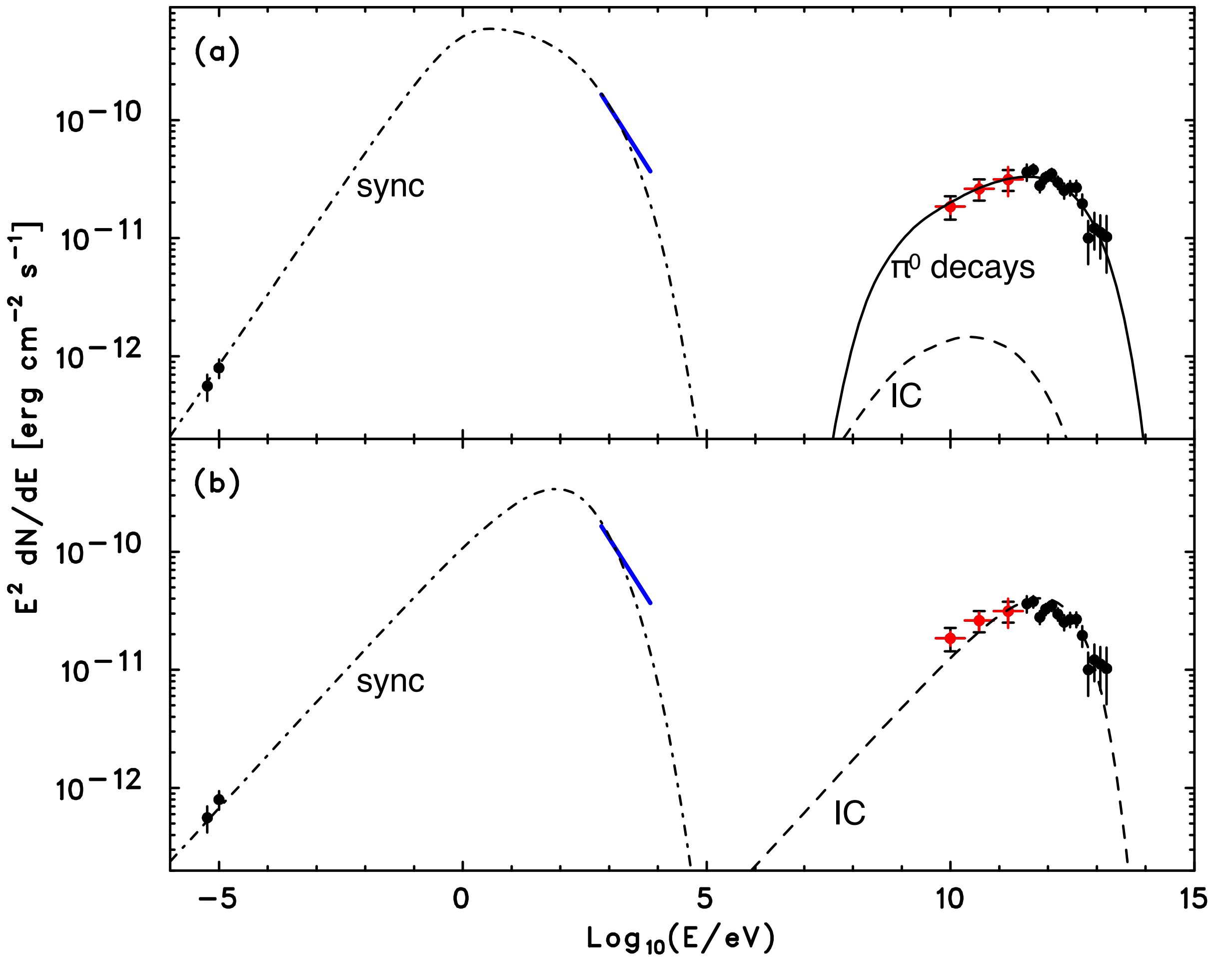
Calculated assuming
D = 750 pc
constant injection over 3000 yr

(a) Hadronic scenario

$s_p = 1.8, s_e = 1.8$
$B = 100\ \mu G$
$W_p = 5.2 \times 10^{50}\ (n/0.1\ cm^{-3})^{-1}$ erg
$W_e = 3.9 \times 10^{46}$ erg

(b) Leptonic scenario

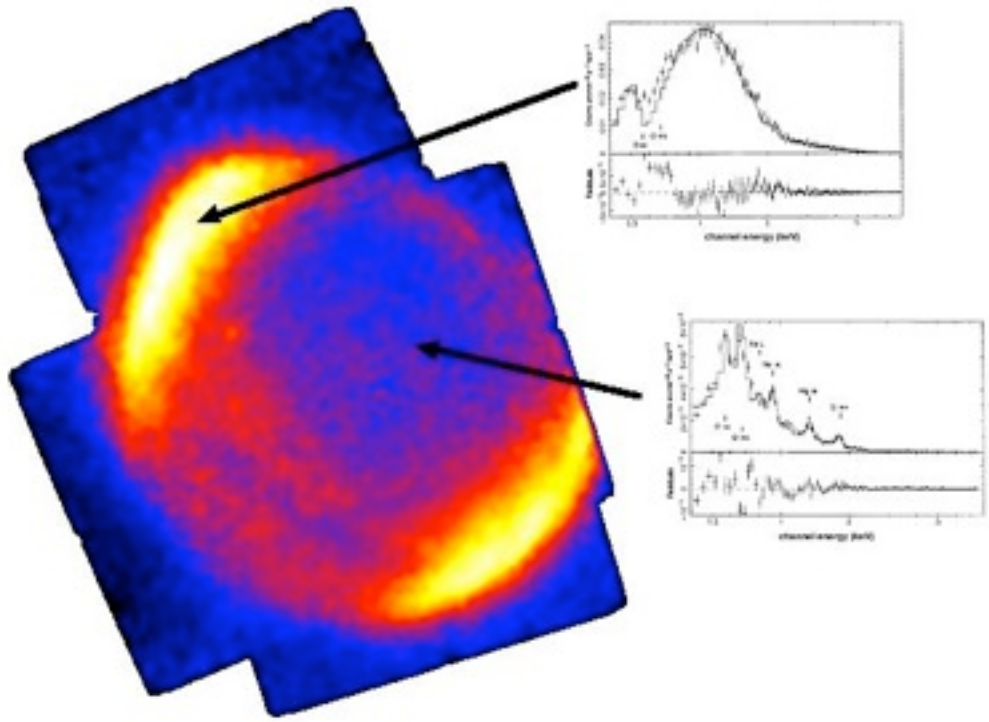
$s_e = 2.1$
$B = 12\ \mu G$
$W_e = 6.9 \times 10^{47}$ erg



The keys to disentangling the emission mechanisms:
Low energy data from Fermi LAT
Estimate of the gas density (n) from thermal X-rays (not yet detected)
How to reconcile the weak magnetic field with X-ray filaments in the case of the leptonic model

SN 1006

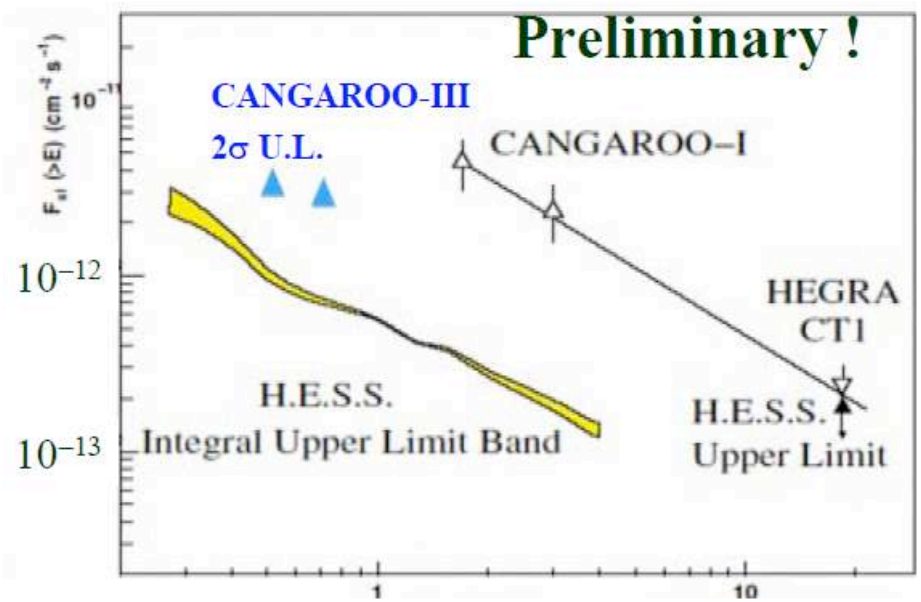
- SN Type Ia ☞ Schaefer et al., 1996
- distance: 2.2 kpc ☞ Winkler et al., 2003
- diameter: 30‘
- 500 pc above the galactic plane -> clean environment
- First detection of nonthermal component of hard X-rays (synchrotron radiation) in the rims of SN 1006 by ASCA ☞ Koyama et al., 1995 and ROSAT ☞ Willingale et al., 1996



➠ An (almost) sure SNR candidate for gamma-ray telescopes

SN 1006 observations in γ-rays

- CANGAROO-I observation → signal claim ☞ Tanimori et al., 1998
- CANGAROO-II observation → signal claim ☞ Tanimori et al., 2001
- HESS observation in 2003 (18h, 2 tel) and 2004 (6h, 4 tel) → upper limit: Flux(E>0.26 TeV) < 2.39 10^{-12} ph $cm^{-2}s^{-1}$ ☞ Aharonian et al., 2005
- CANGAROO-III observation → upper limit ☞ Tanimori et al., 2005



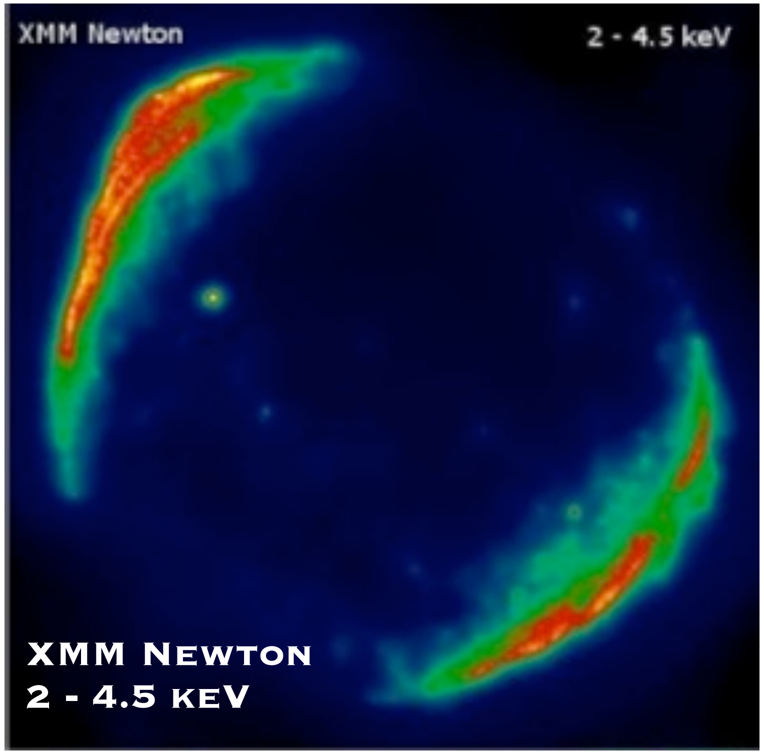
Gamma-ray energy (TeV)

- HESS continued observations in 2006, 2007 and 2008
- The source is both extended and very faint (~1% of Crab, 130 h of data)
- SN 1006 - a difficult field of view to analyse due to bright stars (2.7 mag)
-

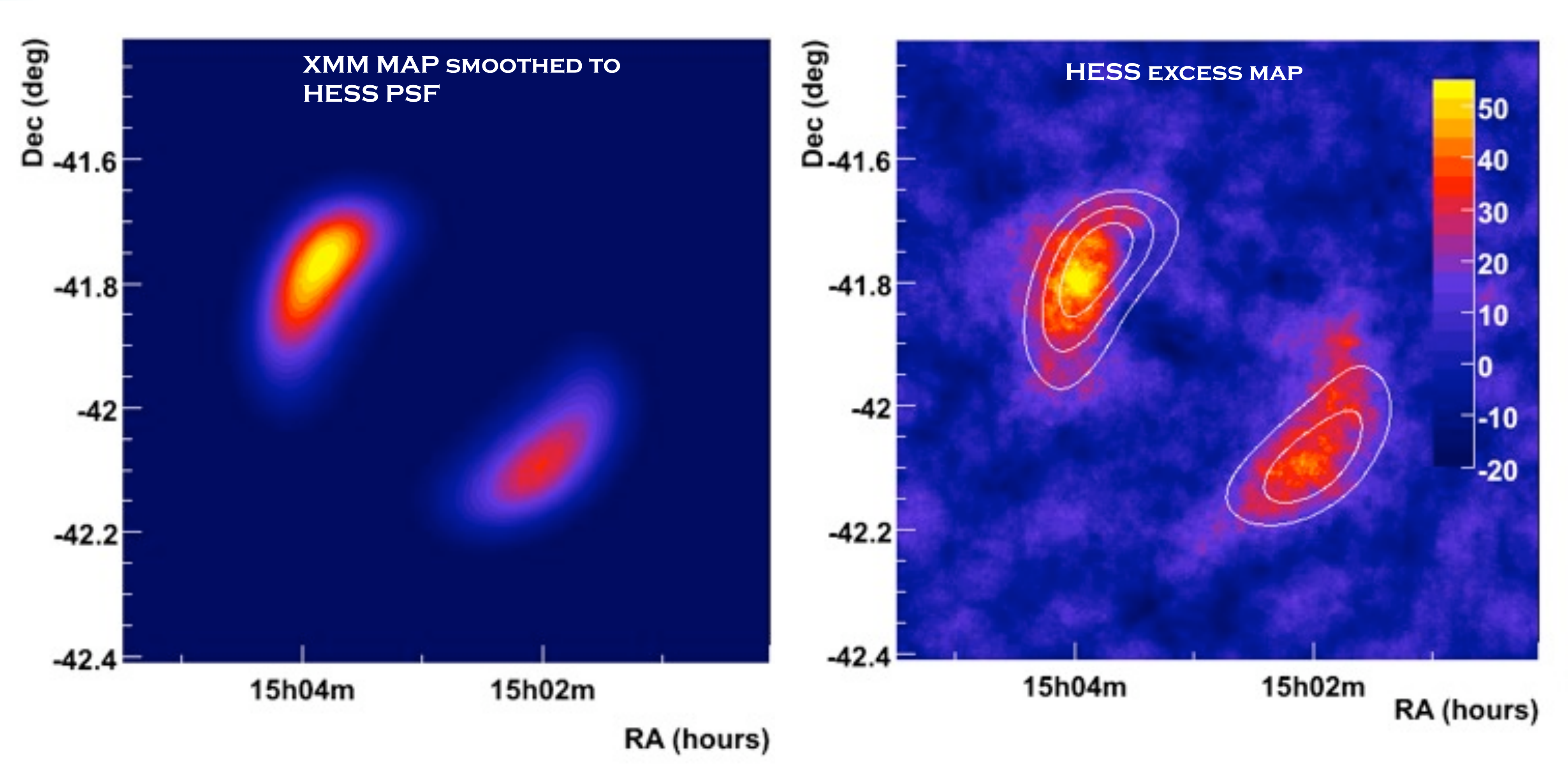
Donnerstag, 12. Januar 2012

X-ray morphology

- Comparison with XMM-Newton data in the 2 - 4.5 keV energy band
- synchrotron emission regions are located in the filaments
- shock-acceleration of particles

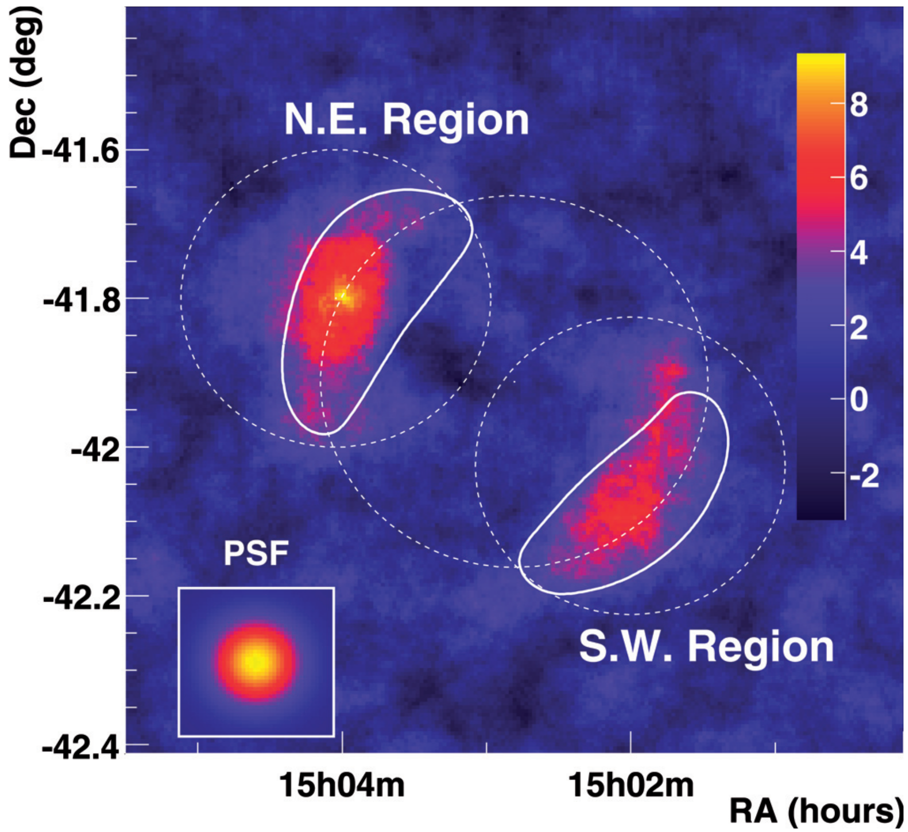


XMM-Newton vs H.E.S.S.



➠ TeV-morphology traces very well the non-thermal X-ray emission if PSF is accounted for

H.E.S.S. data analysis

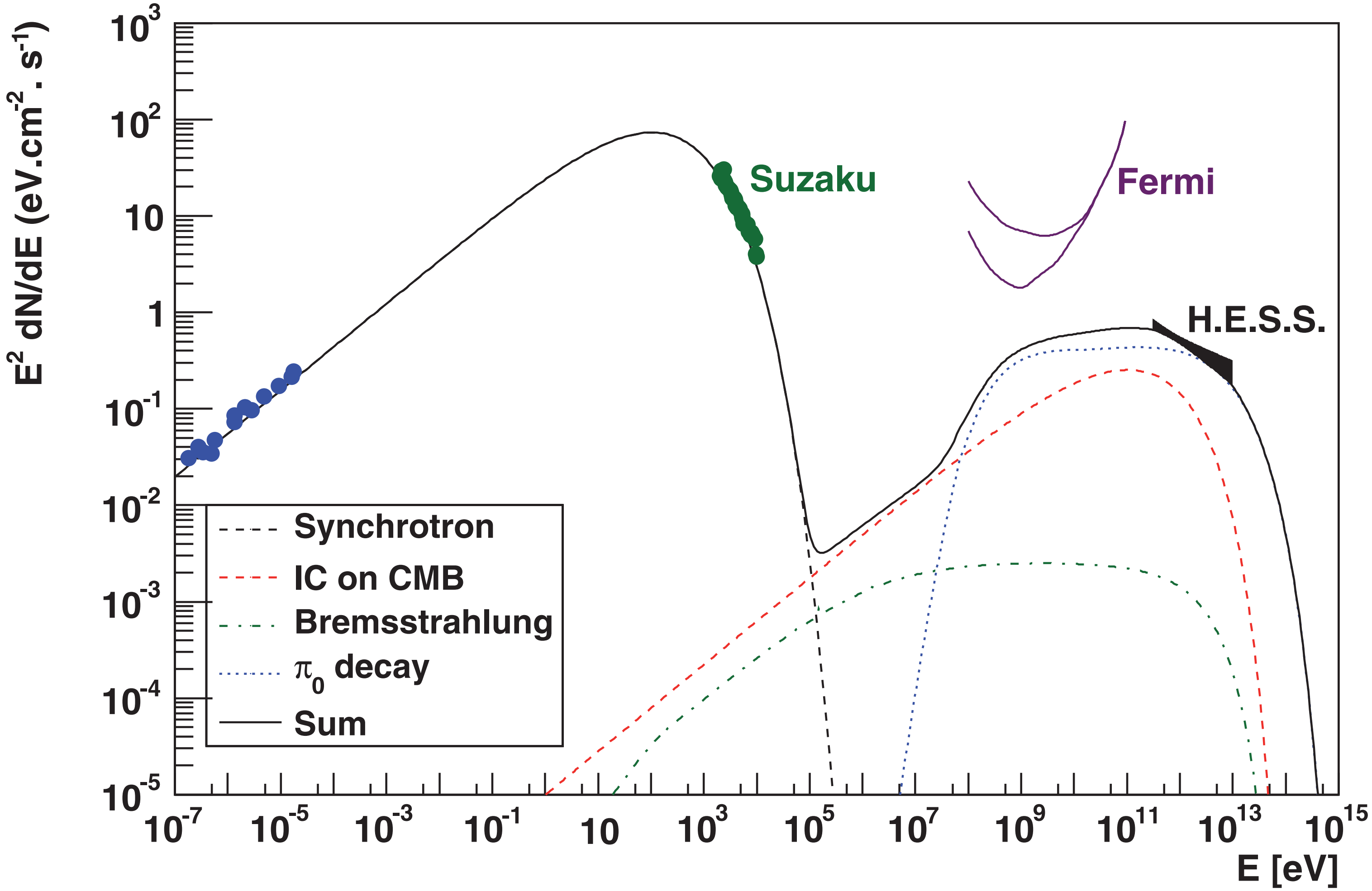


- 1°x1° significance map using hard cuts (>200 p.e.)
- PSF R_{68}=0.064°
- NE and SW region defined as regions which contain 80% of the non-thermal X-ray emission in the 2-4.5 keV energy range ☞

Rothenflug et al., 2004 after smearing with the HESS PSF

Region	ON	OFF	α	# γ	Significance
NE, Std Cuts	4306	25421	6.67	495	7.3
NE, Hard Cuts	619	2575	6.44	219	9.3
SW, Std Cuts	3798	26523	7.615	315	4.9
SW, Hard Cuts	548	2591	7.25	191	8.7

Mixed emission model



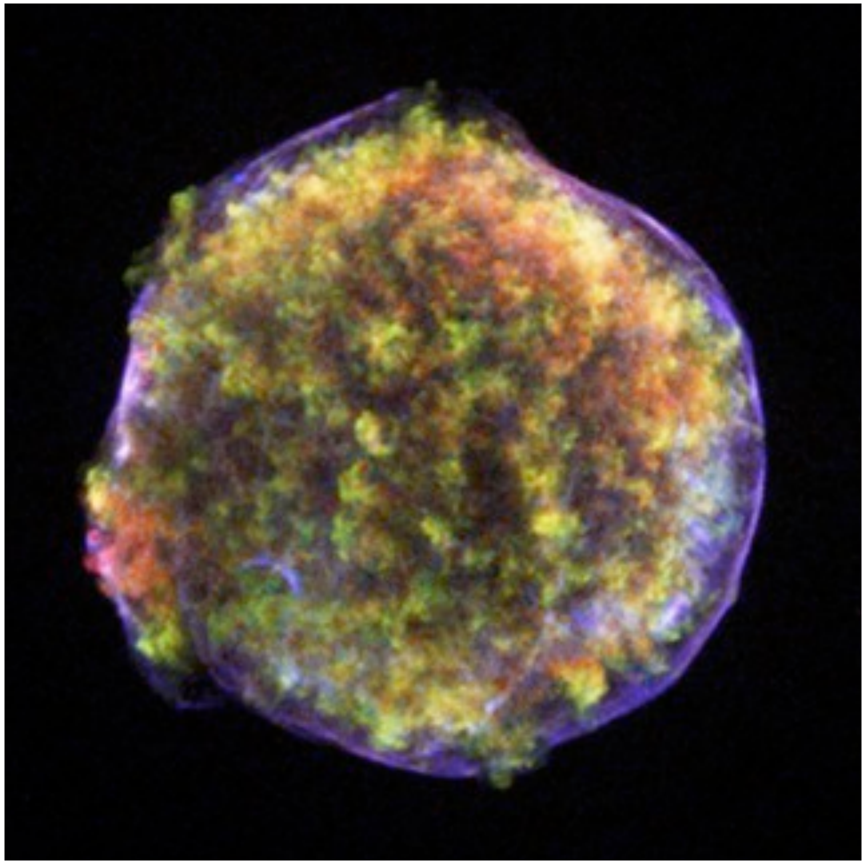
➠ A mixed model (hadronic + leptonic) fits all multi-wavelength data best

Tycho SNR: introduction

SNR parameters:

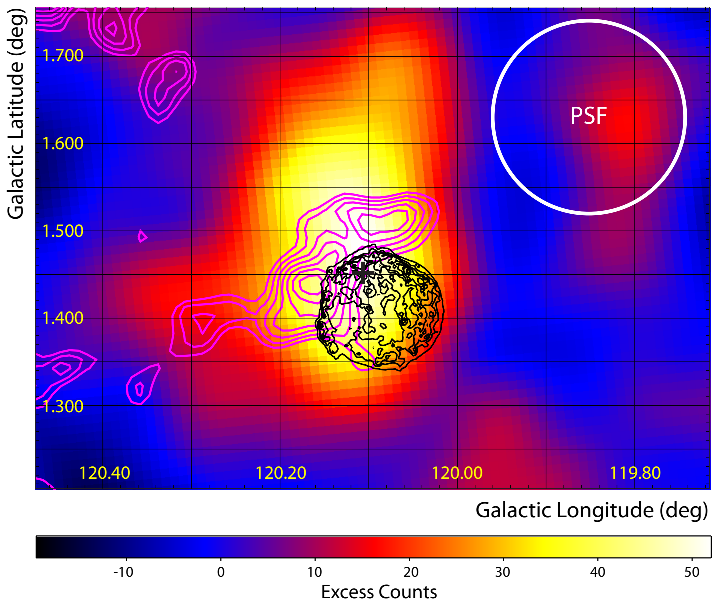
- Type Ia
- ejected Mass: 1.4 M_{sol}
- radius: 256''
- age: 439 yr
- distance measurements:

  ☛ Hayato et al. 2010: d=4 (3-5) kpc by combining the proper motion measurements and Doppler broadening of thermal X-ray lines of Si
  ☛ Krause et al. 2008: d=3.8 (2.7-5.3) kpc based on the optical echo

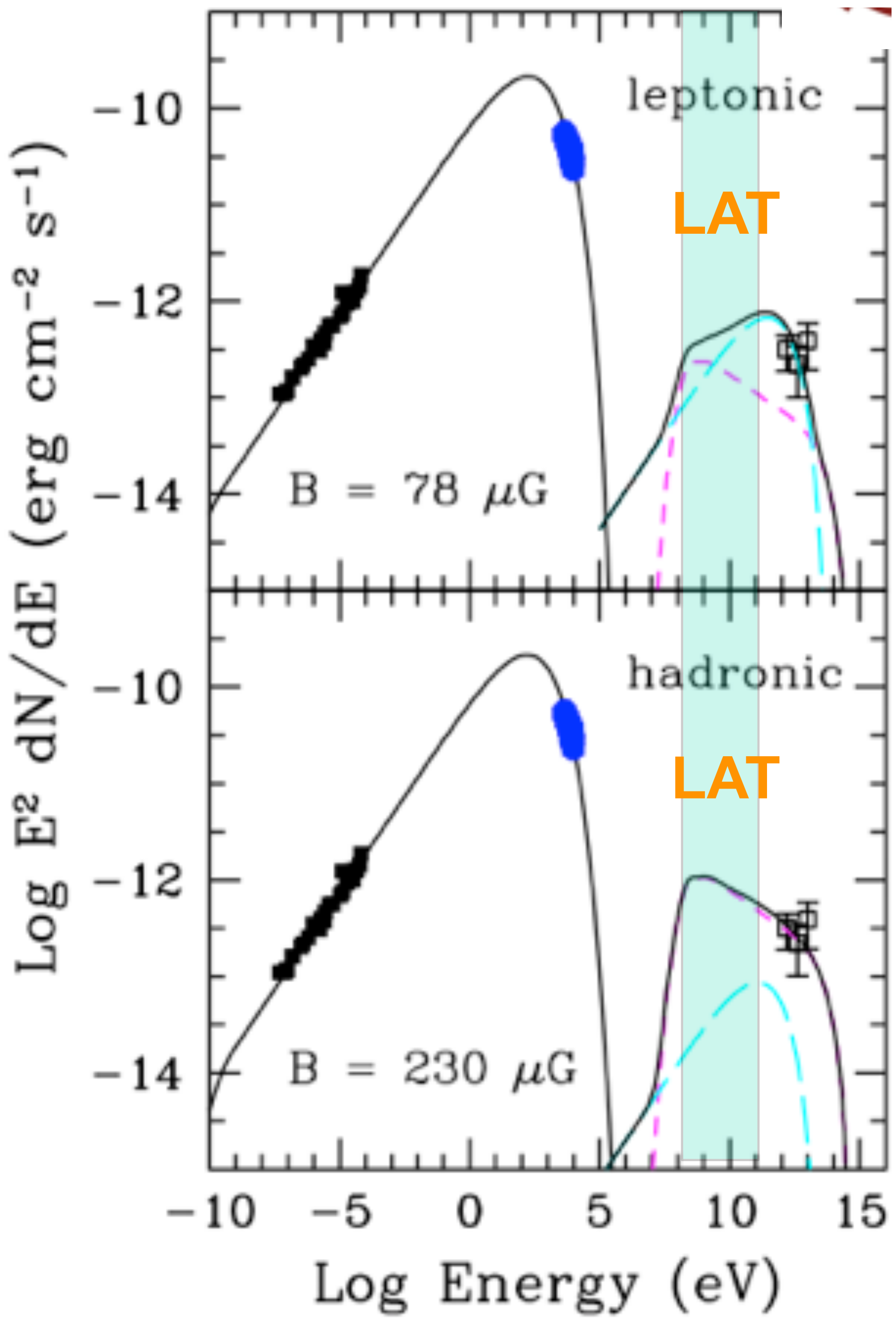


Multi-Wavelength Observations

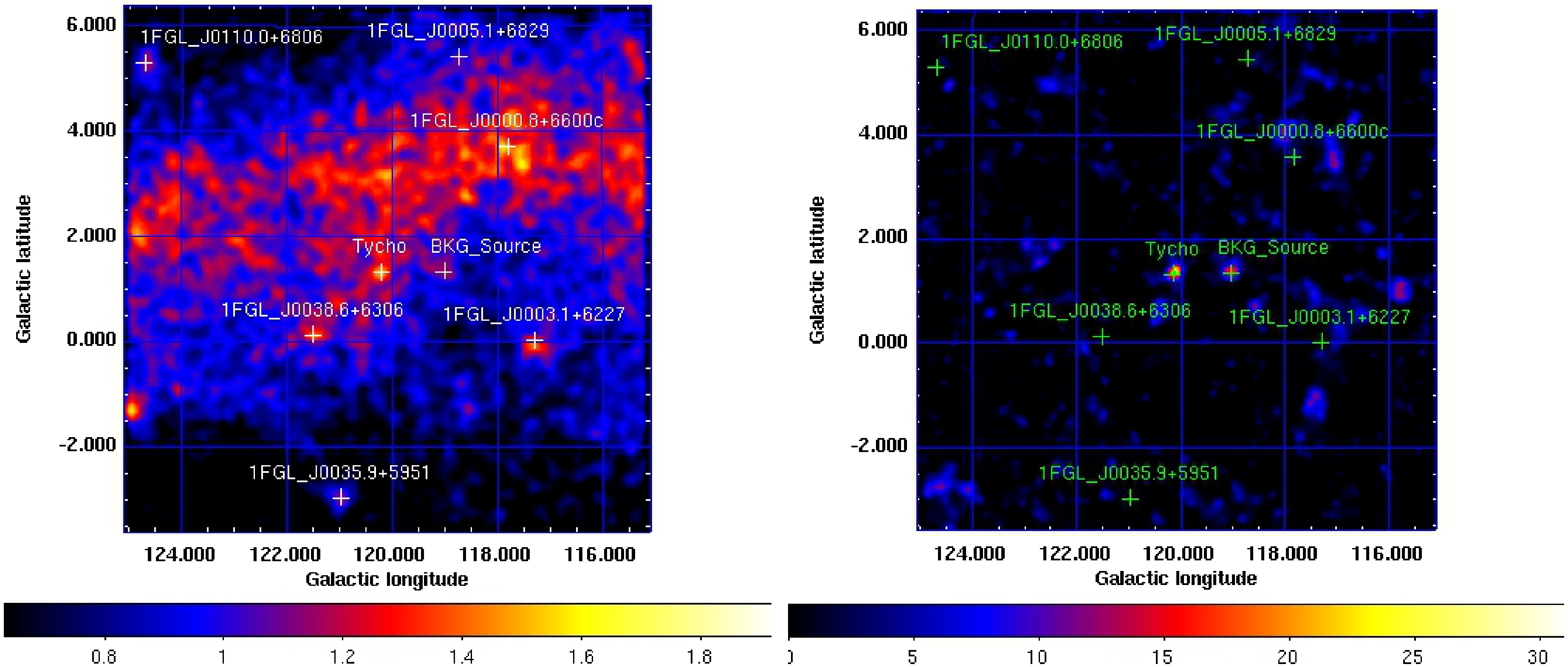
Recent VERITAS results:



- Flux(> 1TeV) = 0.9% Crab
- 5.0 sigma detection (post-trial)
- B-field constraint by X-ray measurements does not rule out IC origin
- Fermi-LAT can test : "leptonic versus hadronic"



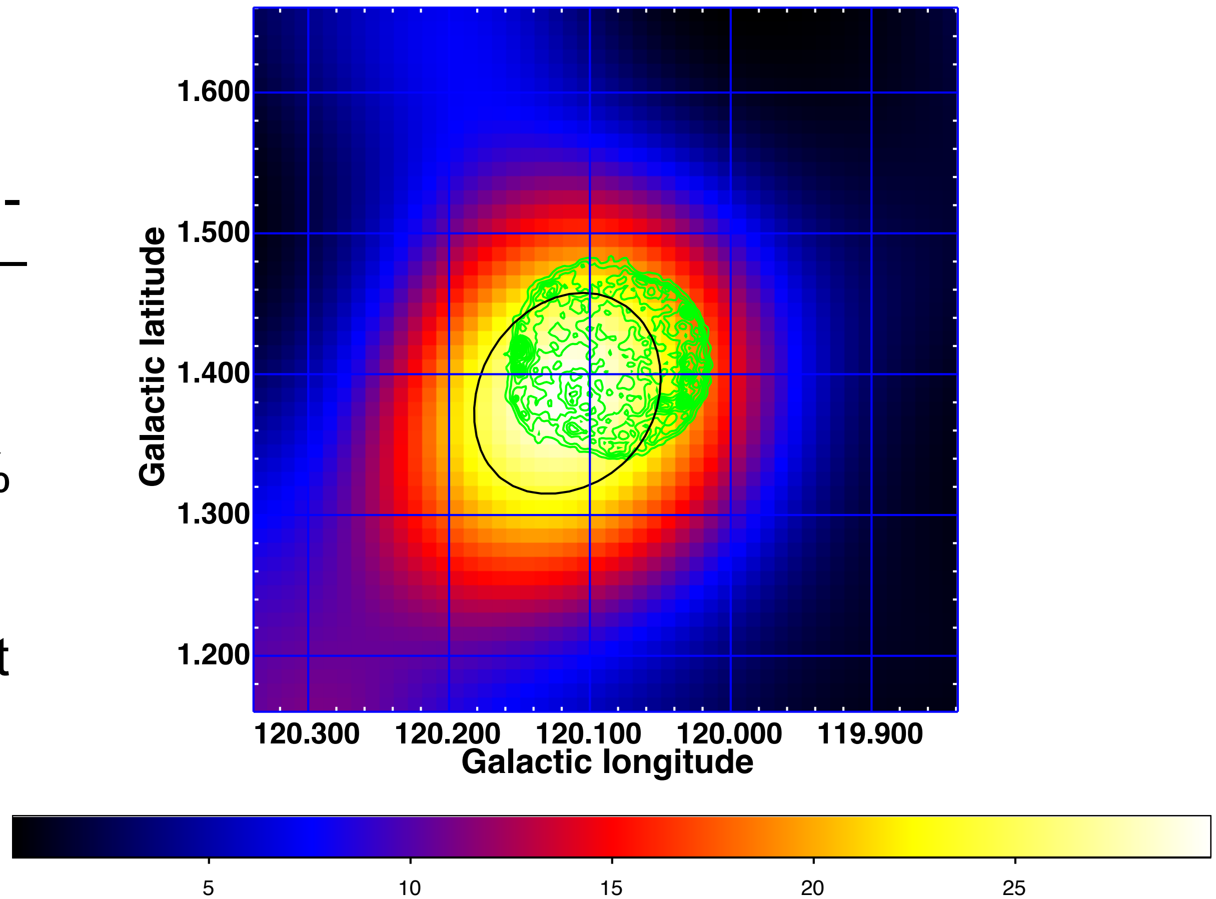
Fermi-LAT Observations of Tycho



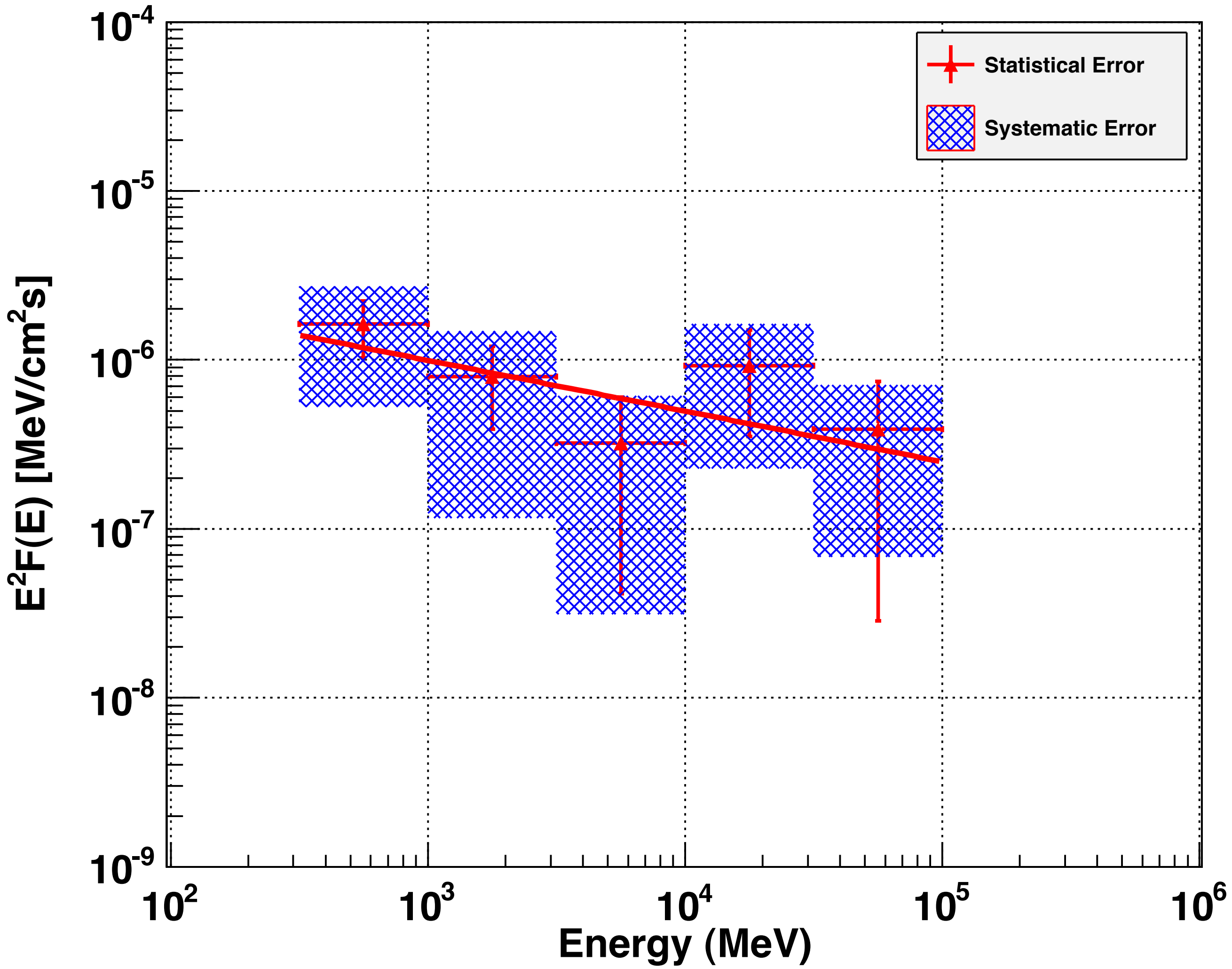
- Data-set: 34 months
- Zenith-angle cut: <100 deg
- Energy range: 0.4 - 100 GeV
- Binned analysis mode

Fermi-LAT Localisation

- TS-map in the energy range 1 – 100 GeV
- Green contours correspond to the XMM-Newton map in the 4.5 – 5.8 keV energy range
- The pointlike emission can be localised at 95% confidence level within the black line, thus implying that the best fit is compatible with Tycho's supernova position.



Fermi-LAT Spectrum

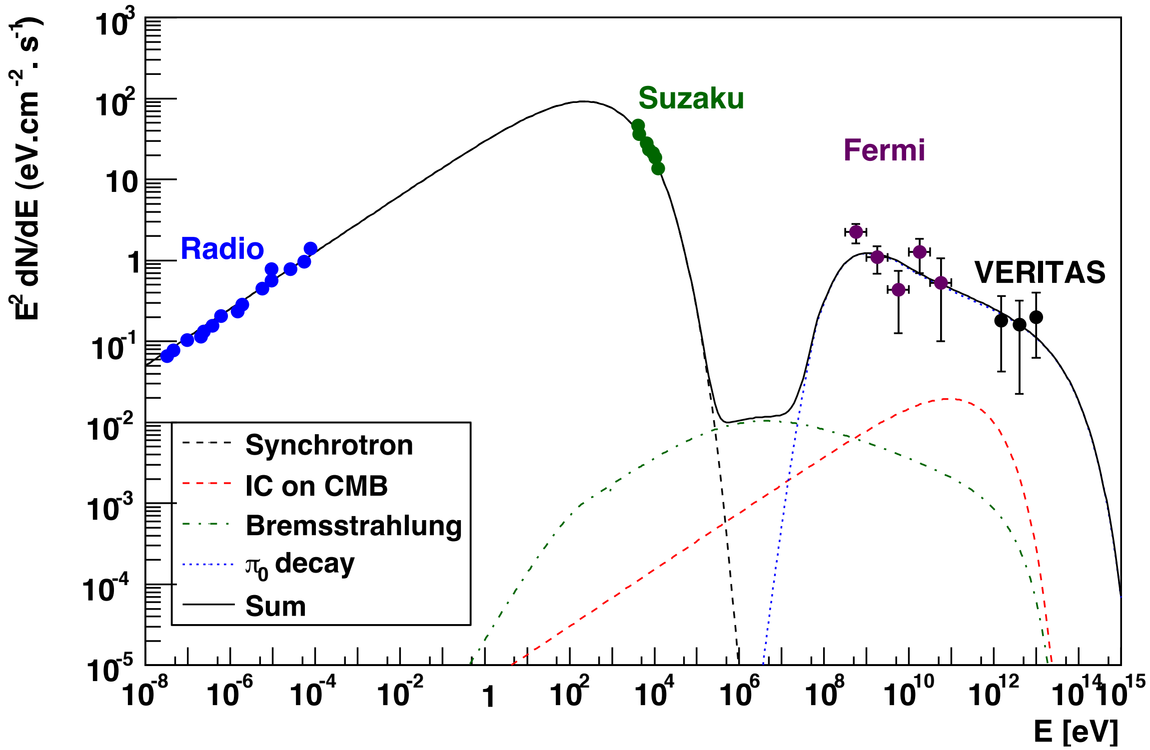


Integral flux 0.4 - 100 GeV of: $(3.5 \pm 1.1_{stat} \pm 0.7_{syst}) \times 10^{-9}$ cm^{-2} s^{-1}

Photon index: $2.3 \pm 0.2_{stat} \pm 0.2_{syst}$

Significance is 5 standard deviations.

Tycho: Origin of the emission



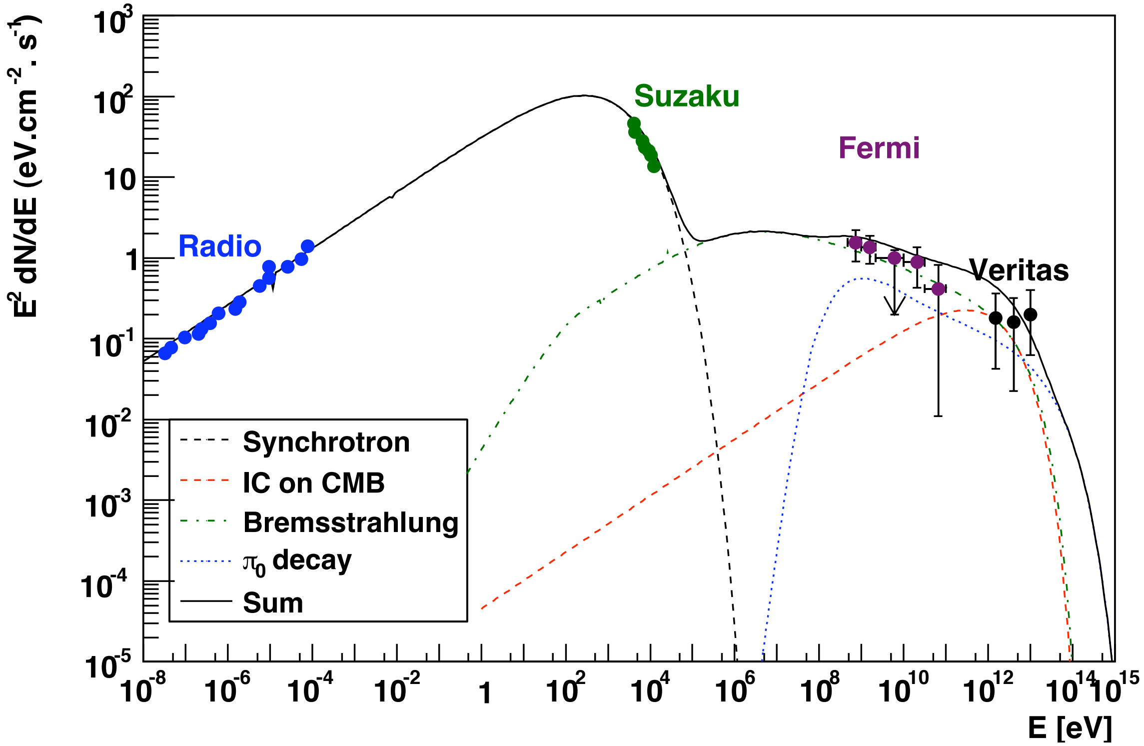
Results:

- $B = 215\ \mu G$
- $E_{e,max} = 6$ TeV
- $\Gamma_p = 2.2$

Case	D_{kpc} [kpc]	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{50}erg]	K_{ep}	$E_{p,max}$ TeV
Far	3.50	0.24	2.0	1.50	4.5×10^{-4}	540
Nearby	2.78	0.30	1.0	0.61	7.0×10^{-4}	340

➠ Hadronic model fits all multi-wavelength data very well

Tycho: Is a leptonic model possible ?



Results:

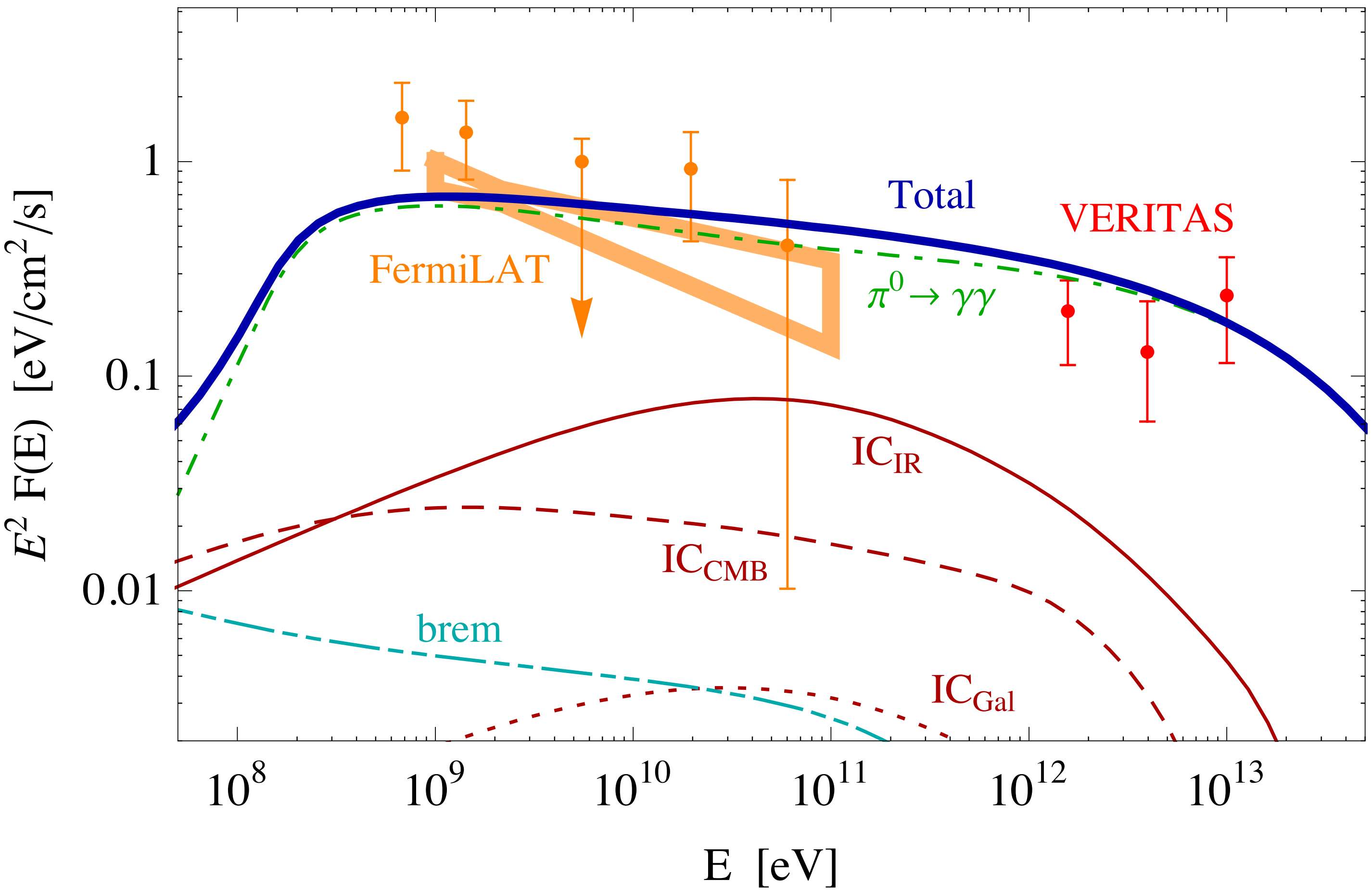
- B = 65 μG
- $E_{e,max}$ = 6 TeV
- Γ_p = 2.2
- n_H = 6.5 cm^{-3} : 20 times too high!
- K_{ep} = 0.2 : much too high!

➠ Leptonic model severely exceeds the measured density limit

Tycho: more about modelling

☞ Morlino & Caprioli 2011 arXiv: 1105.6342

The unequivocal evidence of hadron acceleration in Tycho's Supernova Remnant



$D = 3.3$ kpc
$\Gamma_p = 2.2$
$E_{cut} = 500$ TeV
E_{CR} ~12% of

$E_{SN} = 10^{51}$ erg
$B_2 = 300\ \mu G$
$n_0 = 0.3\ cm^{-3}$

Summary of SNRs

- SNRs interacting with molecular clouds:
  - W44, W51C, IC443, W28, W49B, W30, CTB37A, ...
  - Hadronic origin + reacceleration of ambient CRs in most cases
- Evolved SNRs without molecular cloud interactions
  - Cygnus loop
  - Blast wave region ? (X-ray) or radiative shock ? (Hα)
- Young TeV-bright SNRs:
  - RX J1713.7-3946, Vela junior
  - Leptonic origin ?
- Historical SNRs: B-field amplification, CR acceleration
  - Tycho: hadronic origin almost certain
  - SN 1006: hadronic + leptonic origin
  - Cassiopeia A: not conclusive
- Fermi-LAT SNR catalogue in the making

Conclusions

SNR physics

- Categorising SNRs is possible with respect to their
  - age (young, intermediate, evolved)
  - type (thermonuclear or core collapse)
  - environment (molecular cloud, dense or thin ISM, bubble)
- But SNRs are essentially individual objects
  - local environmental conditions dominate emission processes

Future of SNR Measurements

- Multiwavelength measurements are crucial for understanding SNRs
  - Radio + X-ray (electron population, density)
  - Infrared (target photons for IC)
  - GeV + TeV gamma-rays (IC, brems and CR acceleration)
- Fermi-LAT, HESS/CTA and HESS 2 to cover the whole gamma-range

Backup Transparencies

Tycho Discussion: general constraints

- starting point: X-ray paper ☞ Cassam-Chenai et al. 2007
- authorised maximal density by X-rays: $n_0 = 0.84\ cm^{-3} / D_{kpc}$
- $n_0 = 388 \times D_{kpc}^{-7} \times E_{51}^2$
- fix $E_{p,tot} = 0.1\ E_{amb}$
- consider 2 scenarios:
  - "Nearby" in order to fix $E_{SN} = 1.0 \times 10^{51}$ erg
  - "Far" D = 3.5 kpc in order to come close to Hayato's measurement

Emission models in comparison

Model	$E_{\rm cut,e}$ [TeV]	$E_{\rm cut,p}$ [TeV]	$W_{\rm e}$ [10^{47}erg]	$W_{\rm p}$ [10^{50}erg]	B [μG]
Leptonic	10	–	3.3	–	30
Hadronic	5	80	0.3	3.0	120
Mixed	8	100	1.4	2.0	45

- Leptonic case:
  - 30μG + Bohm diffusion → electrons of 1 TeV confined to a shell of 10 arcsec (compatible with radial profile)
  - Measured flux well reproduced but not the slope
- Hadronic case:
  - 120μG consistent with B field amplification at shock
  - 20% of E_{SN} needs to be converted in CR
- Mixed case:
  - 14% of E_{SN} in CR, $K_{ep}=3.9 \times 10^{-3}$

The FERMI Observatory

Large area telescope (LAT)

Large area, large field of view,
good angular and energy resolution
E: 20 MeV to 300 GeV

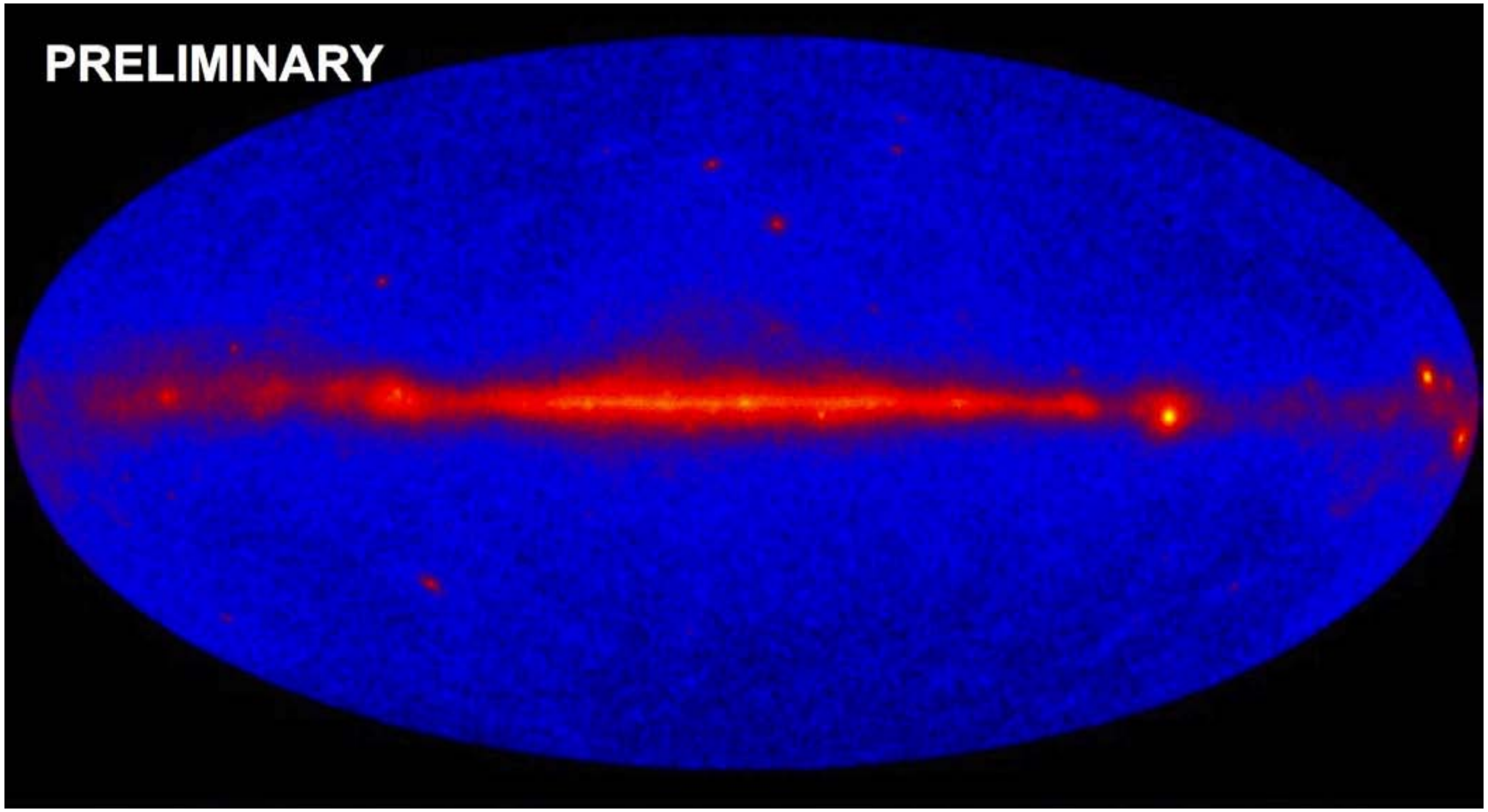
Gamma-ray burst monitor (GBM)

Full sky coverage, BGO, CsI detector
E: few keV to 30 MeV

The FERMI Observatory

• *Energy range:*	20 MeV to 300 GeV
• *Energy resolution:*	15% – 100 MeV to 10 GeV
• *Collecting area:*	9,500 cm^2
• *Field of view:*	2.4 sr (104° cone)
• *Angular resolution:*	0.6°@1GeV, 0.15°@10GeV
• *Observation mode:*	sky survey, rocking 35° N/S
• *Orbital period:*	95 minutes
• *Full sky view:*	3 hrs (~uniform in 55 days)

The 2FGL Catalogue

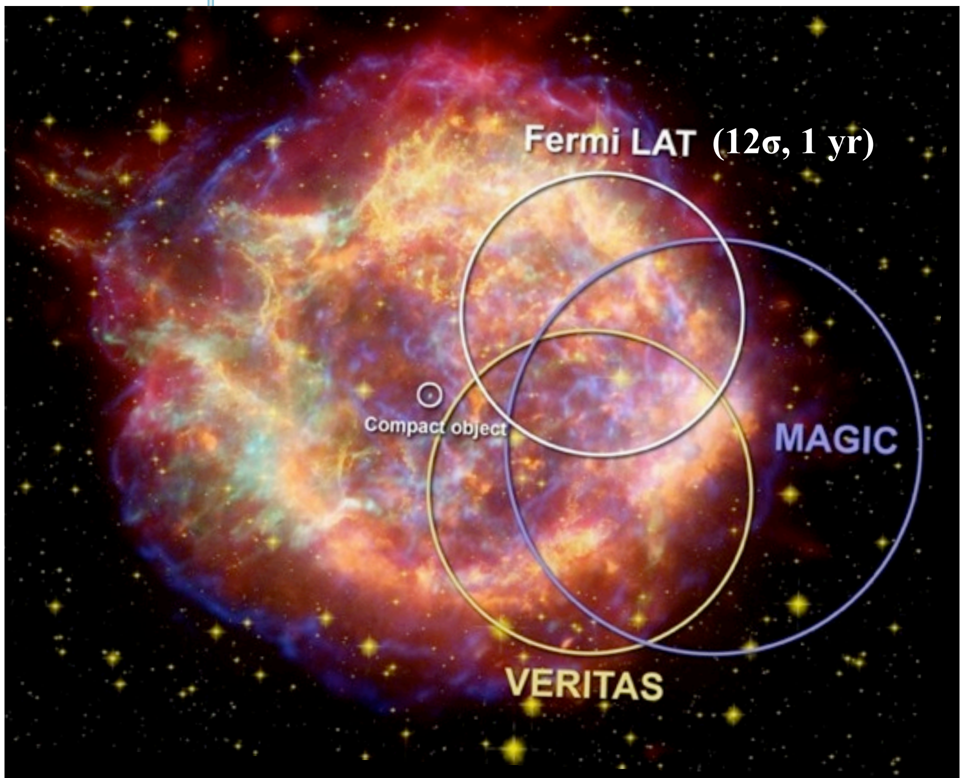


- Analysis of 24-month data from 100 MeV to 100 GeV with maximum-likelihood method based on "LAT Science Tools"
- 1888 sources in the 2FGL catalogue
- Separating sources from each other and from the background is challenging, especially in the Galactic ridge

FERMI statistics: 2FGL

Type	Number	Percentage of total
Active Galactic Nuclei	832	44%
Candidate Active Galactic Nuclei	268	14%
Unassociated	594	32%
Pulsars (pulsed emission)	86	5%
Pulsars (no pulsations yet)	26	1%
Supernova Remnants/Pulsar Wind Nebulae	60	3%
Globular Clusters	11	< 1%
Other Galaxies	7	< 1%
Binary systems	4	< 1%
TOTAL	1888	100%

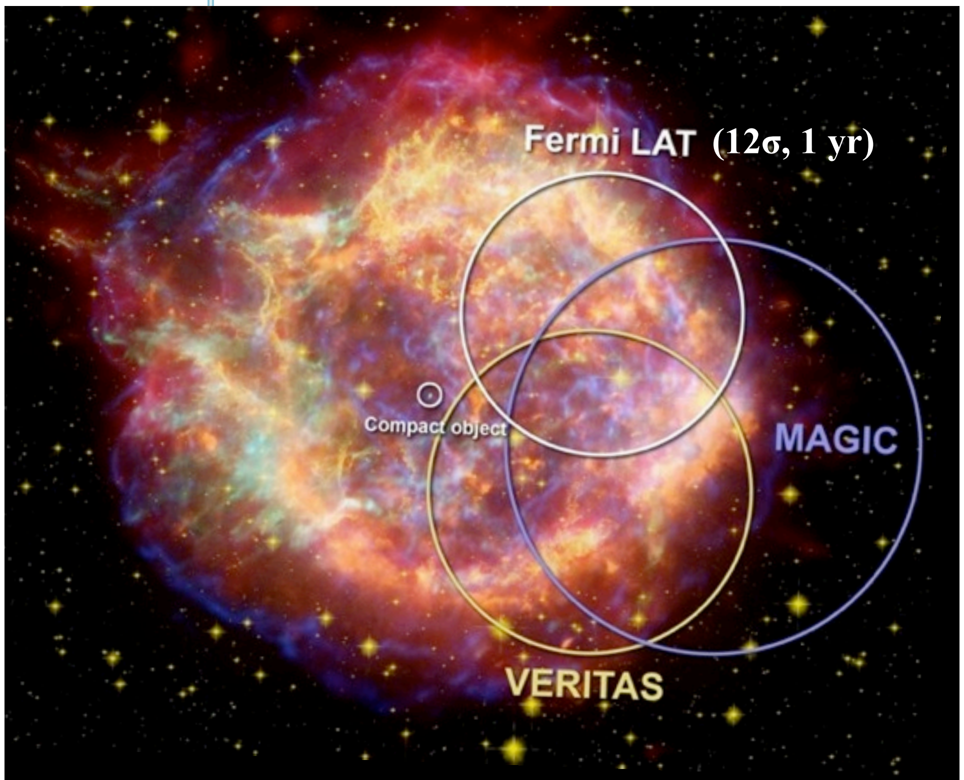
Historical SNR: Cassiopeia A

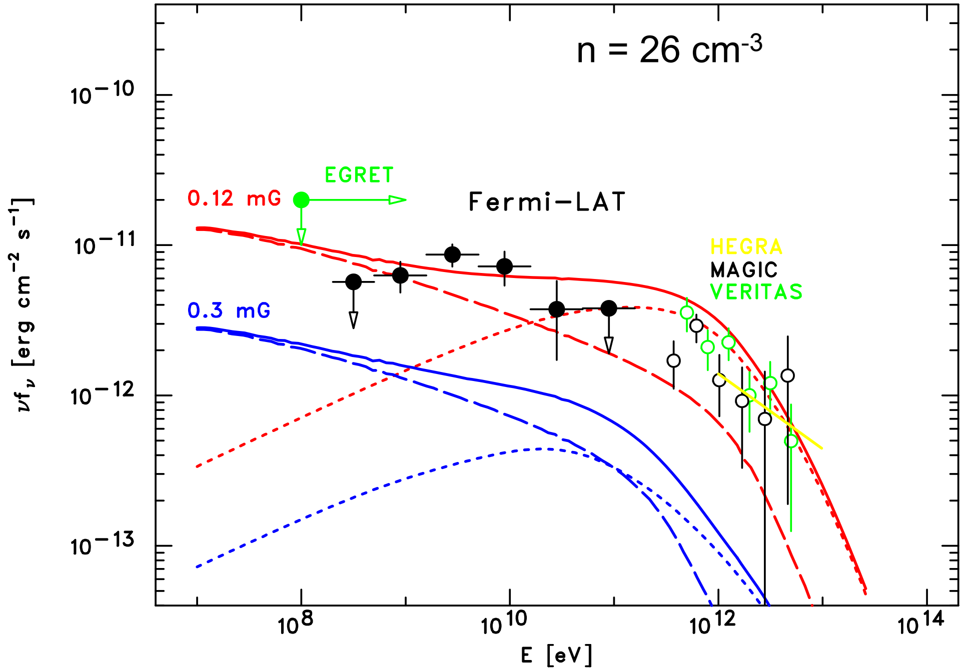


Fermi-LAT spectrum:
$\Gamma = 2.0 \pm 0.1$

in hadronic model:
CR: 0.4×10^{50} erg
E_{CR} ~2% of $E_{SN} = 2 \times 10^{51}$ erg

Historical SNR: Cassiopeia A





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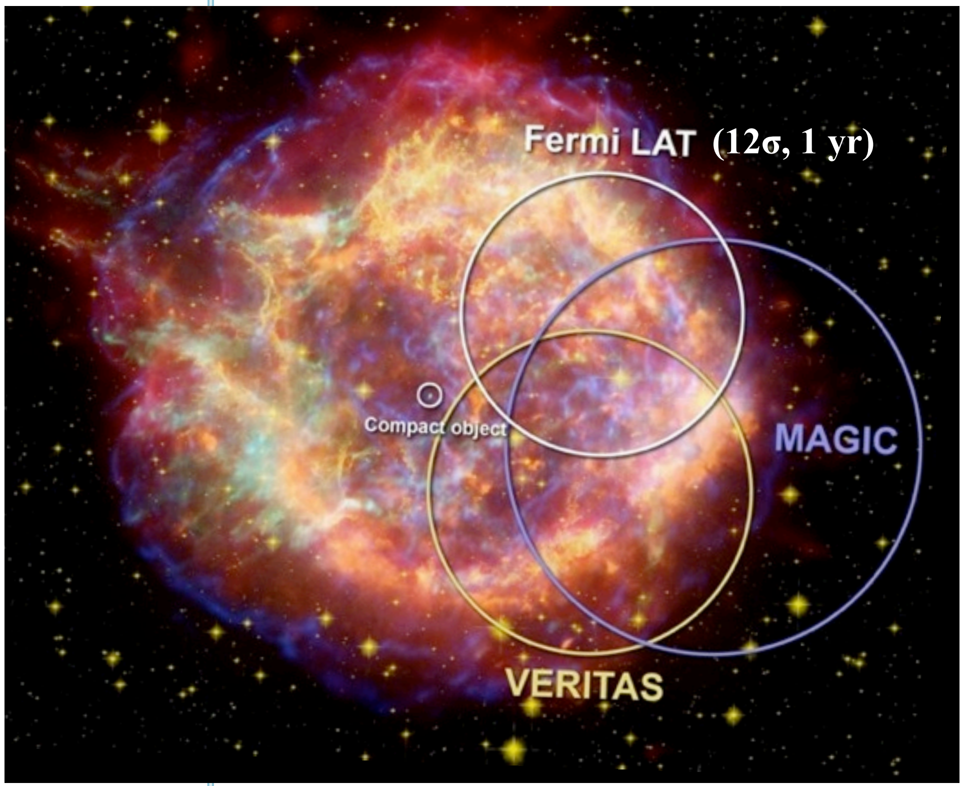

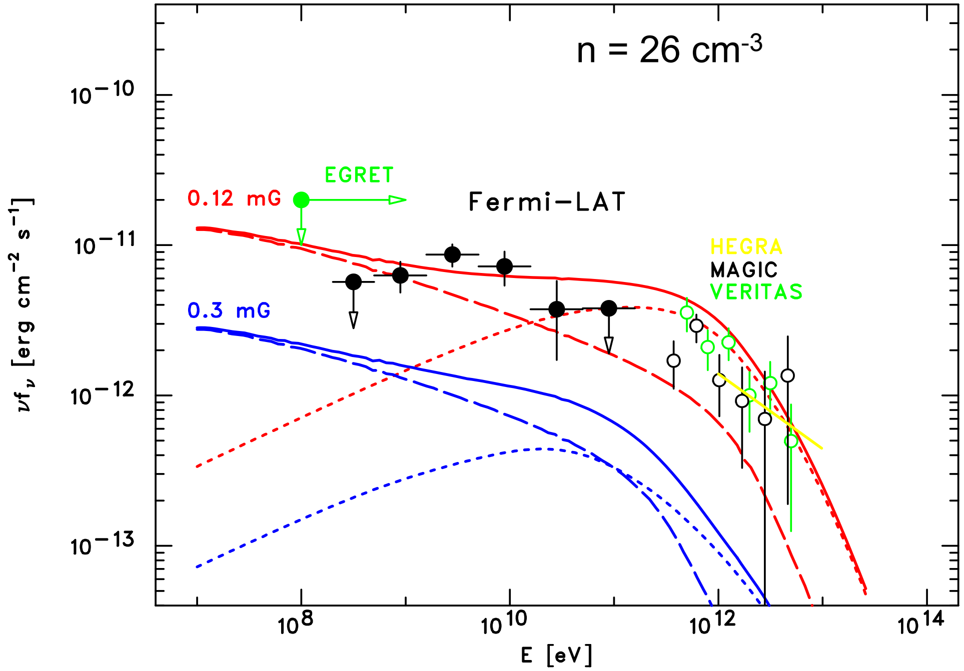

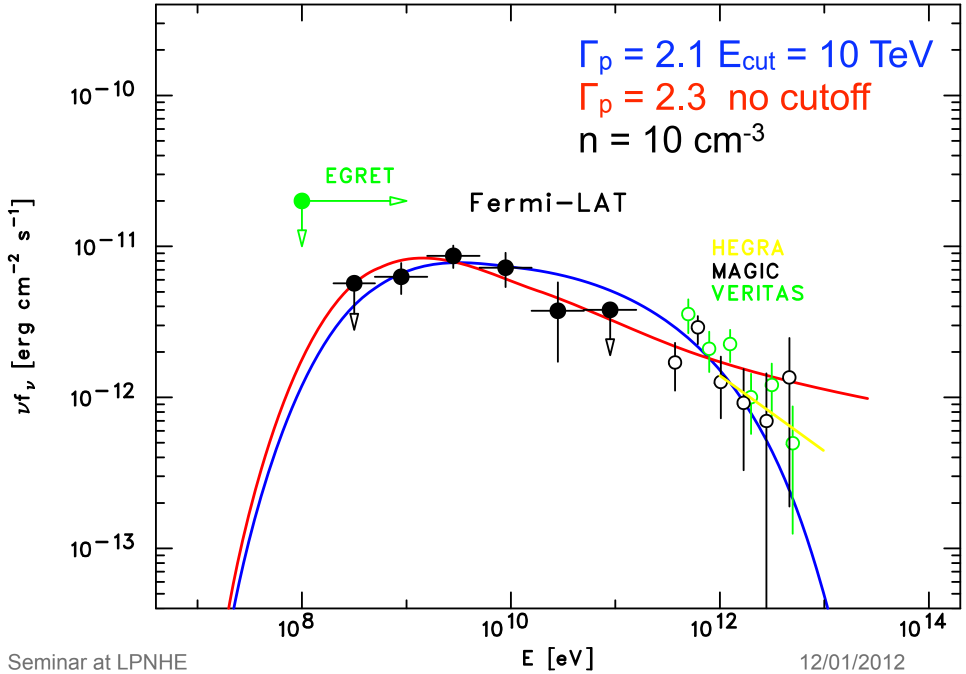

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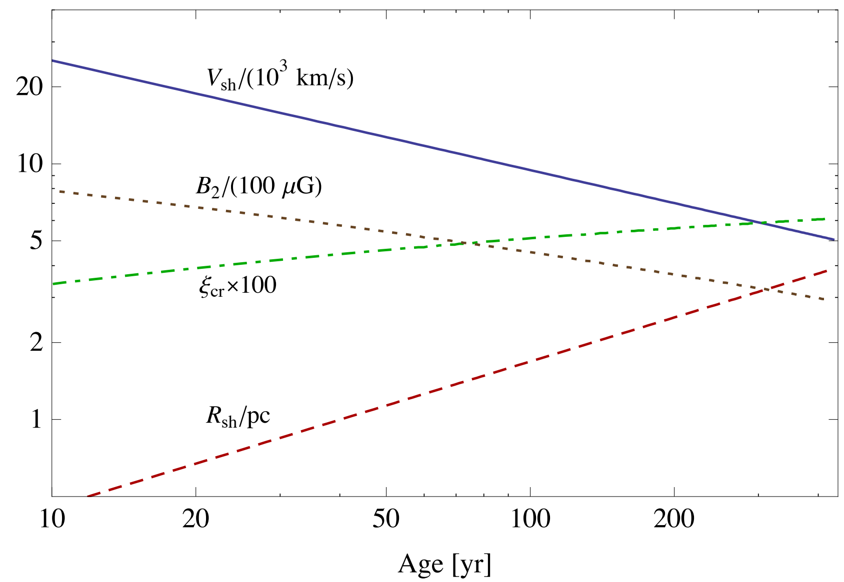
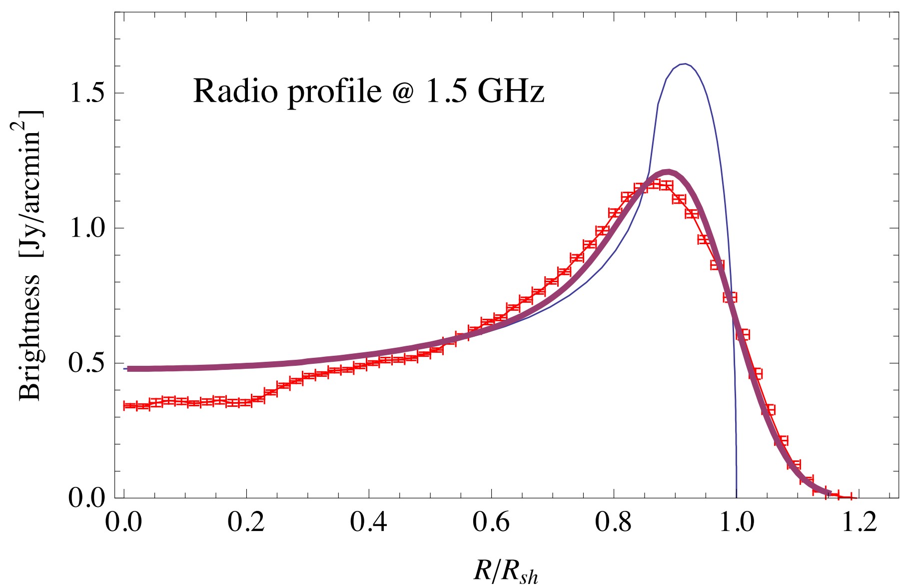
Tycho: more about modelisation

☞ Morlino & Caprioli 2011 arXiv: 1105.6342



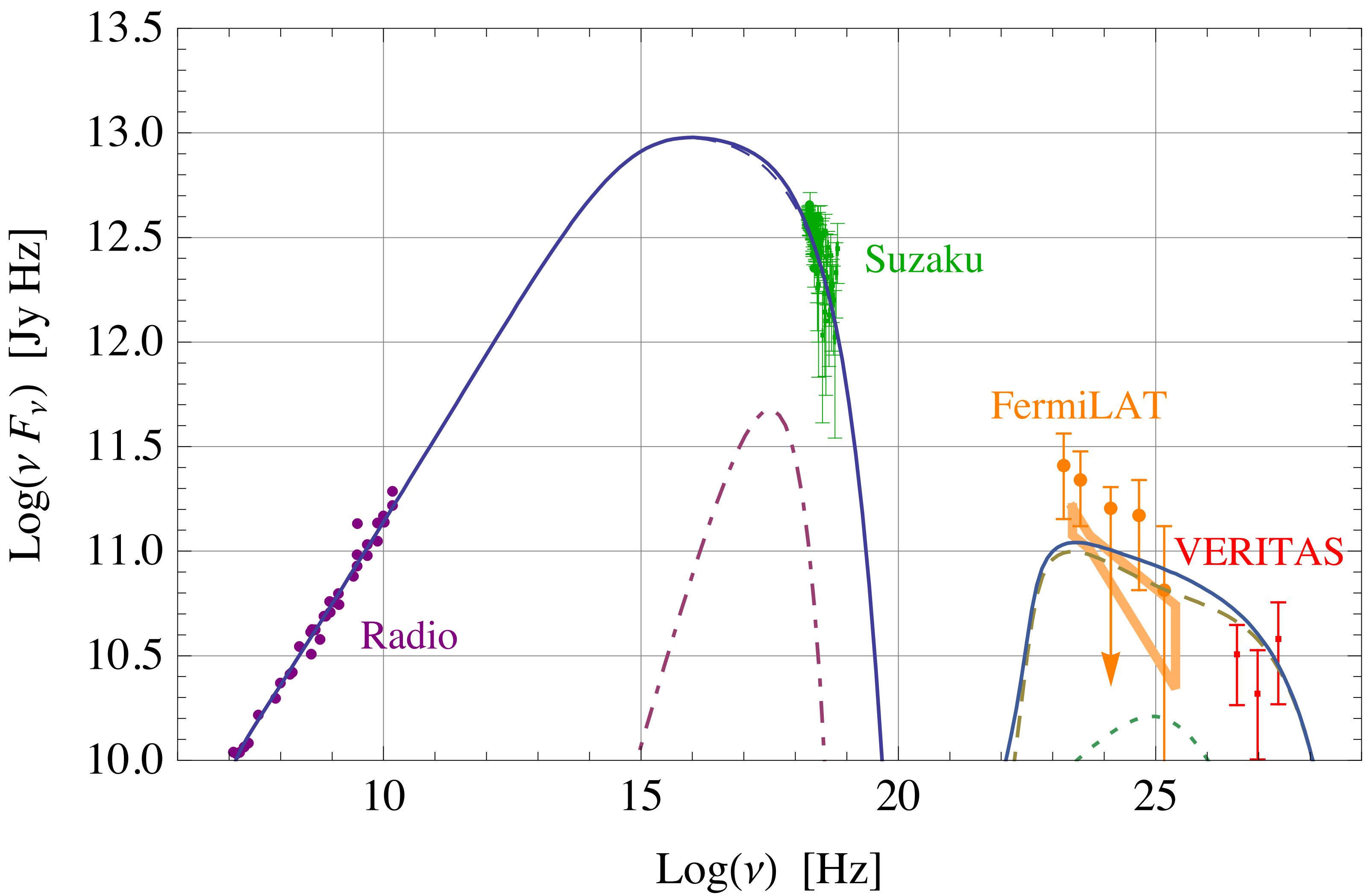


Hydrodynamic model for SNR evolution and non-linear DSA

Computed radio profile in good agreement with measured

Tycho: more about modelisation

☞ Morlino & Caprioli 2011 arXiv: 1105.6342



Towards a FERMI SNR catalogue

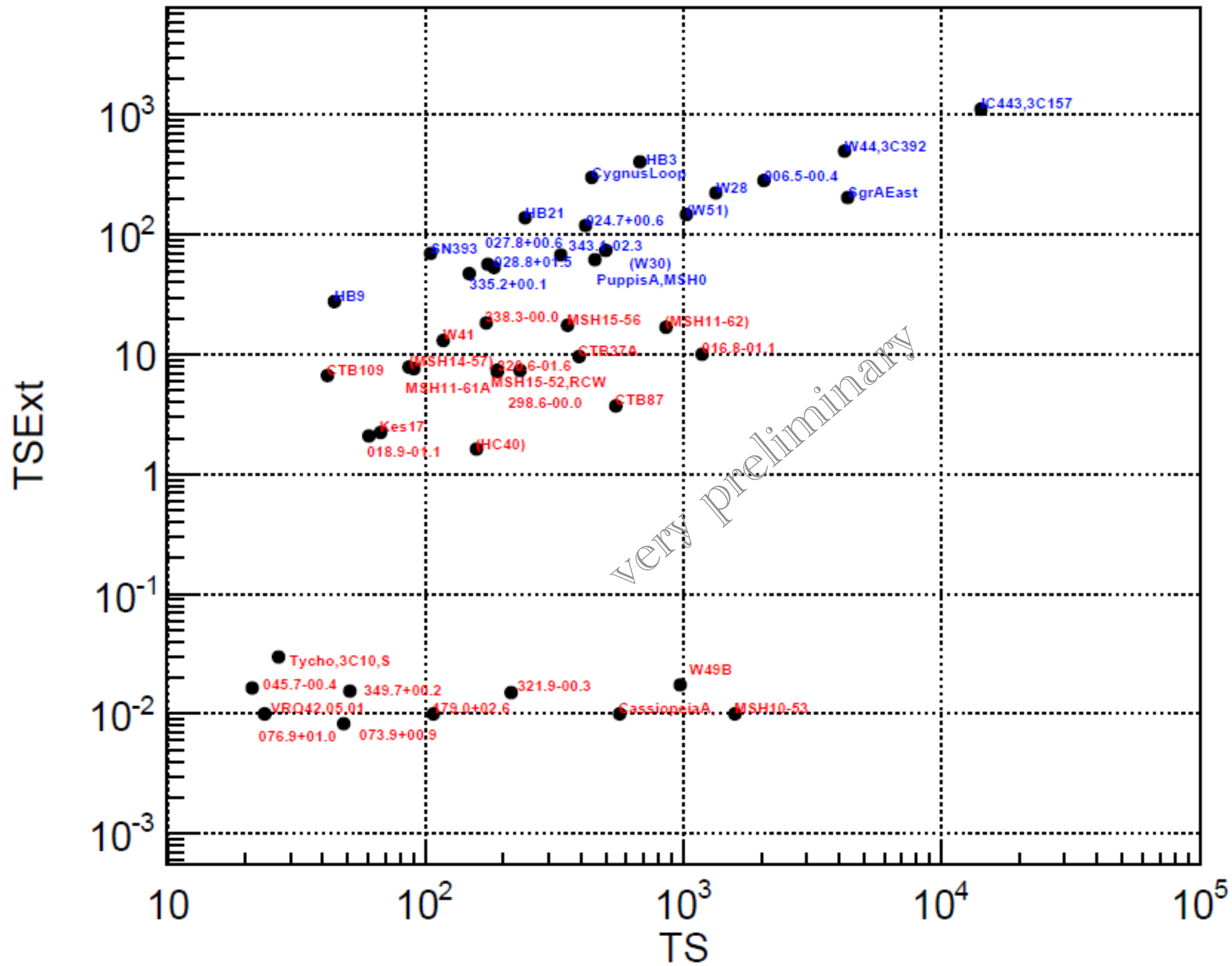
- After 3 years of data-taking FERMI sensitivity in the Galactic plane has improved sufficiently to allow the detection of SNRs
- Green catalogue of radio SNRs offers a good starting point to search for correlations in Fermi-LAT data
- Analysis pipeline for this analysis is currently set-up using:
  - 36 month data
  - 12 deg ROI
  - Pass7_V6 source
  - energy threshold: 1 GeV, 500 MeV, ...
  - catalogue containing TS>10 as input model for neighbouring sources
  - SNR modelled as extended disk (extension given by radio), 2D Gaussian and soon radio template fits-file

Towards a FERMI SNR catalogue

- Analysis results w.r.t. individual SNRs include:
  - smoothed counts map
  - integral flux, photon index
  - spectrum points
  - TS
  - TS map
  - residual TS map
  - localisation coordinates, error ellipse
  - extension TS
  - radial and azimuthal profile

Preliminary results on SNR extension

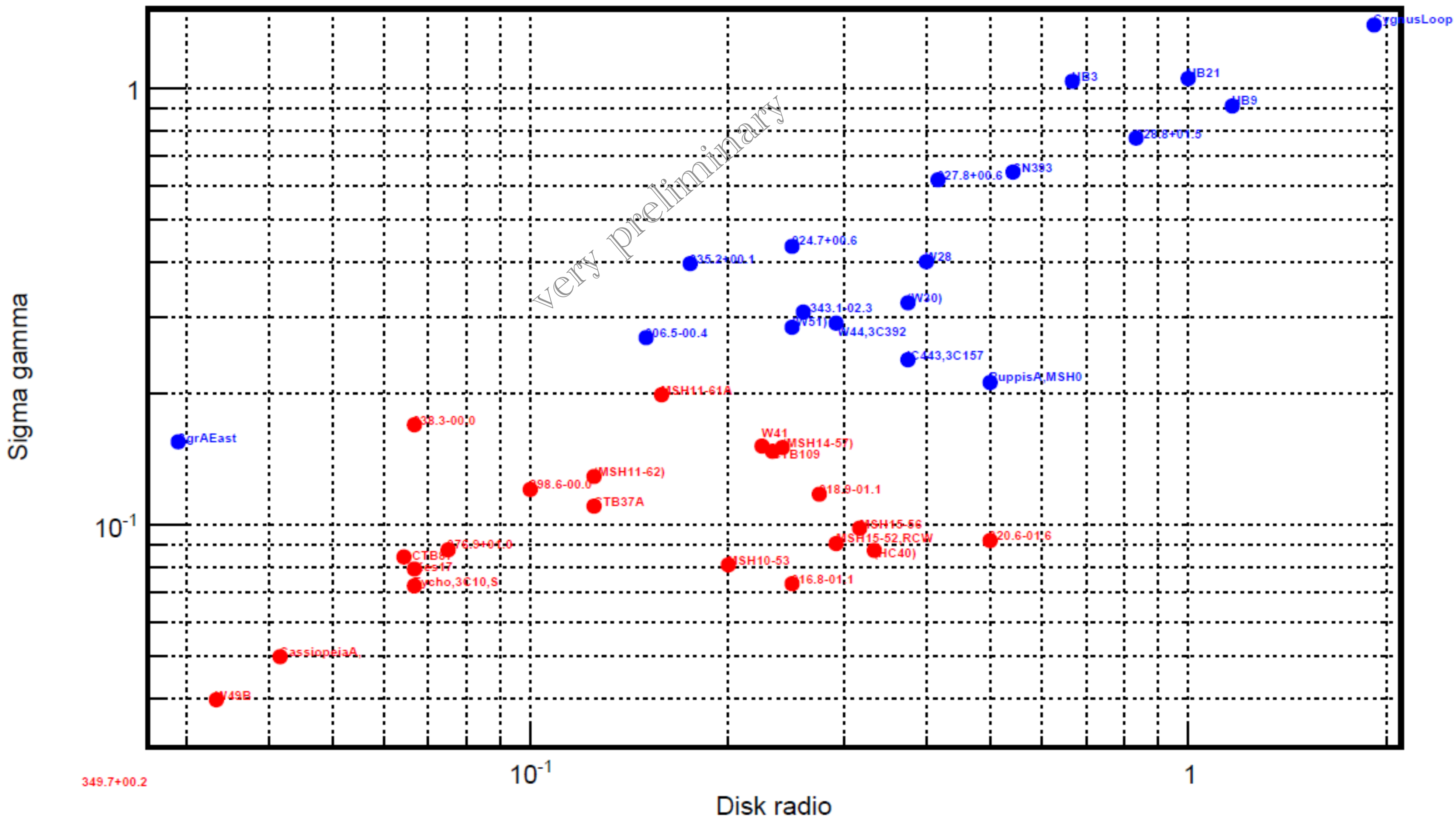
- Significance of the SNR extension vs. detection significance



Preliminary results on SNR extension

Graph

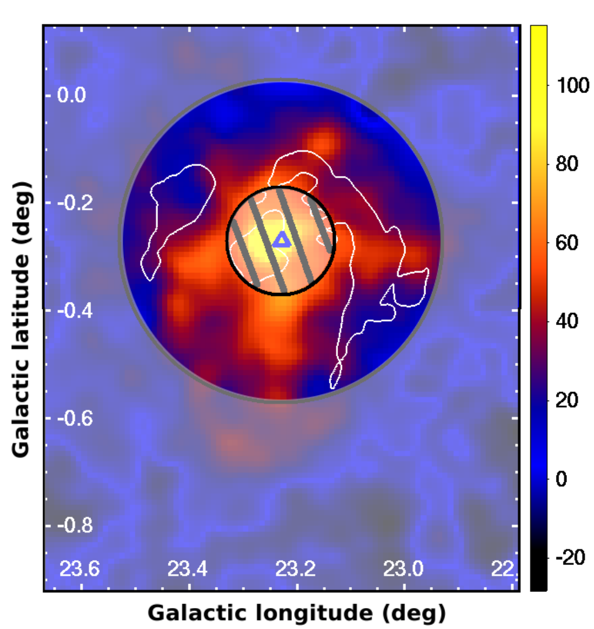
- SNR extension in gamma-rays vs. extension in radio

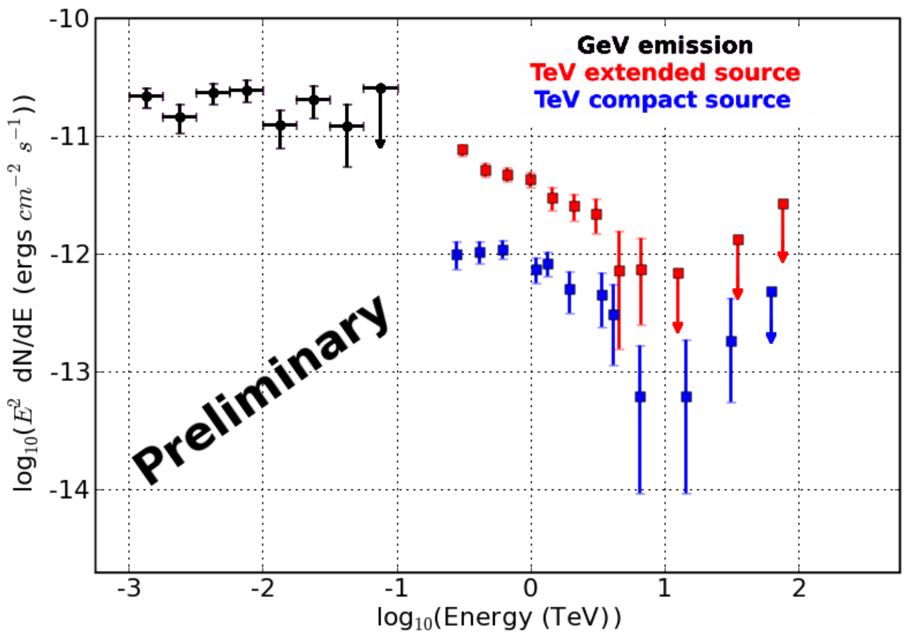


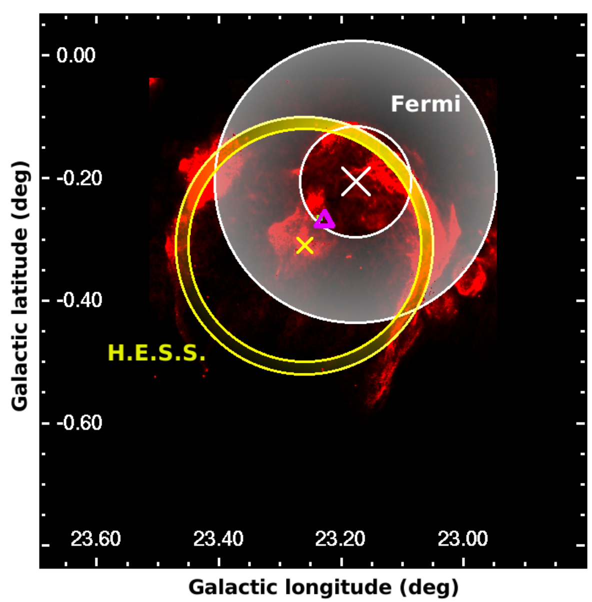
2FGL statistics: extended sources

Extended Source	Spatial Form	Spectral Form
SMC	2D Gaussian	Exp Cutoff PL
LMC	2D Gaussian[a]	Exp Cutoff PL
IC 443	2D Gaussian	Log Parabola
Vela X	Disk	Power Law
Centaurus A (lobes)	Contour Map	Power Law
MSH 15−52	Disk	Power Law
W28	Disk	Log Parabola
W30	Disk	Log Parabola
HESS J1825−137	2D Gaussian	Power Law
W44	Ring	Log Parabola
W51C	Disk	Log Parabola
Cygnus Loop	Ring	Exp Cutoff PL

SNRs interacting with MC: W41

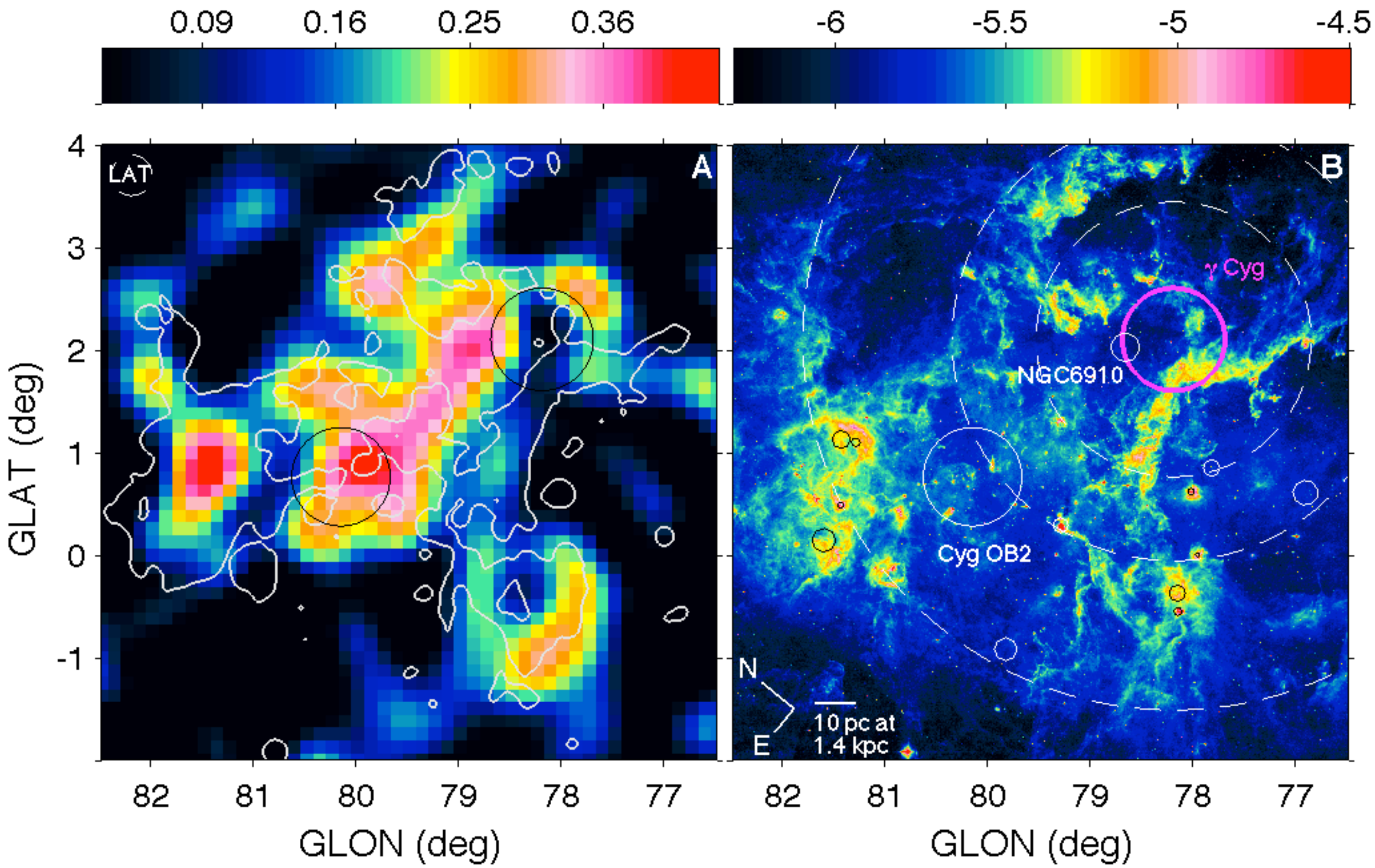






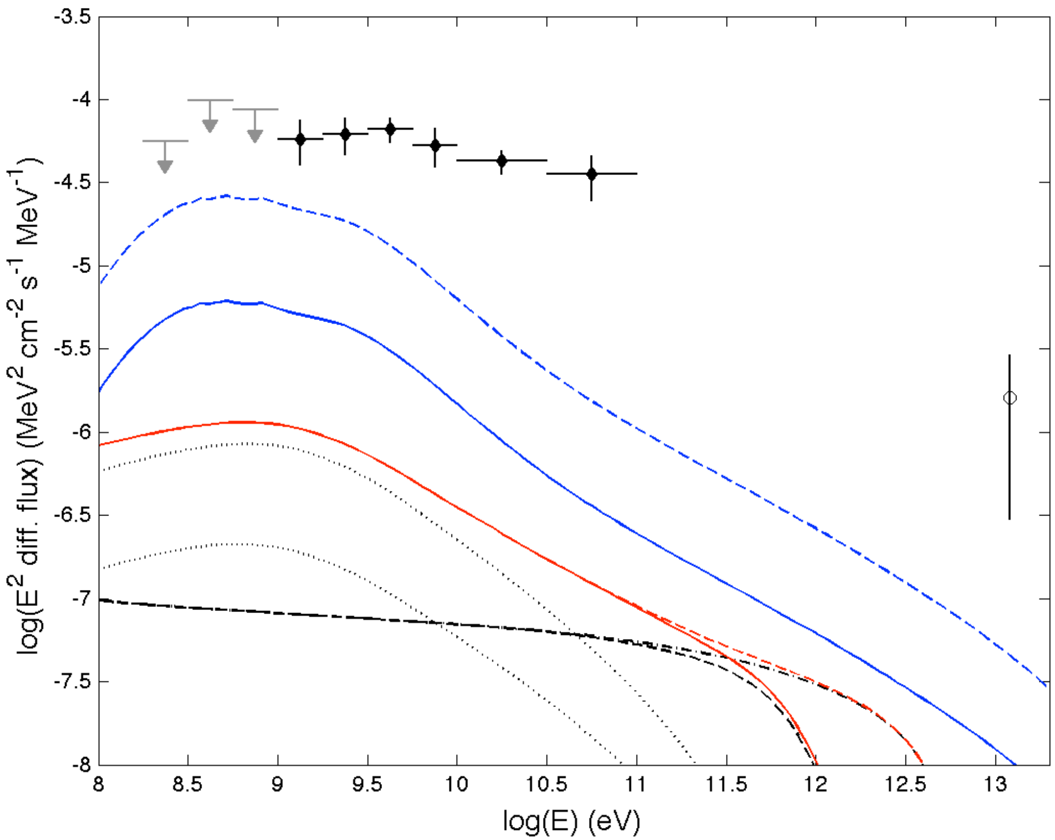
- **TeV Extended emission:**
  - Good matching with GeV emission
  - Compatible intrinsic sizes
  - γ-ray spectra like interacting SNRs
  - W41 possibly in interaction with a cloud
  - **Interacting SNR scenario ?**
    But TeV morphology does not match ^{13}CO density
  - **PWN scenario ?**
    But GeV spectrum not typical and PSR younger than SNR?
- **TeV Compact source:**
  - Not seen by *Fermi*-LAT
  - Coincident with *Chandra* compact nebula and pulsar candidate
  - No pulsations found in GeV, X-ray and radio data
  - **Young PWN scenario ?**
    But PSR younger than SNR?

Cygnus X and CR acceleration



Cocoon emission seems to be diffuse rather than a combination of individual point sources.
Lack of significant spectral variations supports this.

Cygnus X and CR acceleration



— ionised gas n=10 cm^{-3}

--- ionised gas n=2 cm^{-3}

— total IC

... IC from Cyg OB2 (upper)

... IC from NGC 6910 (lower)

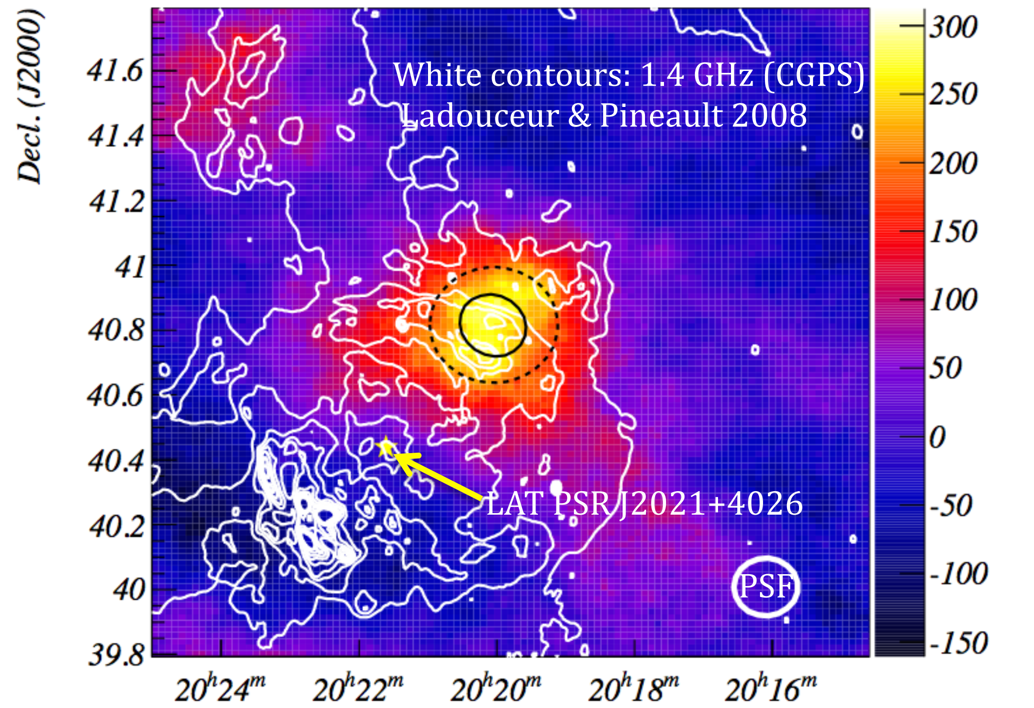
IC emission (upscattering of intense stellar light) too faint and too soft

CR acceleration by shockwave of Cyg X ?

CR acceleration by stellar winds in superbubble ?

γ-Cygni and VER J2019+407

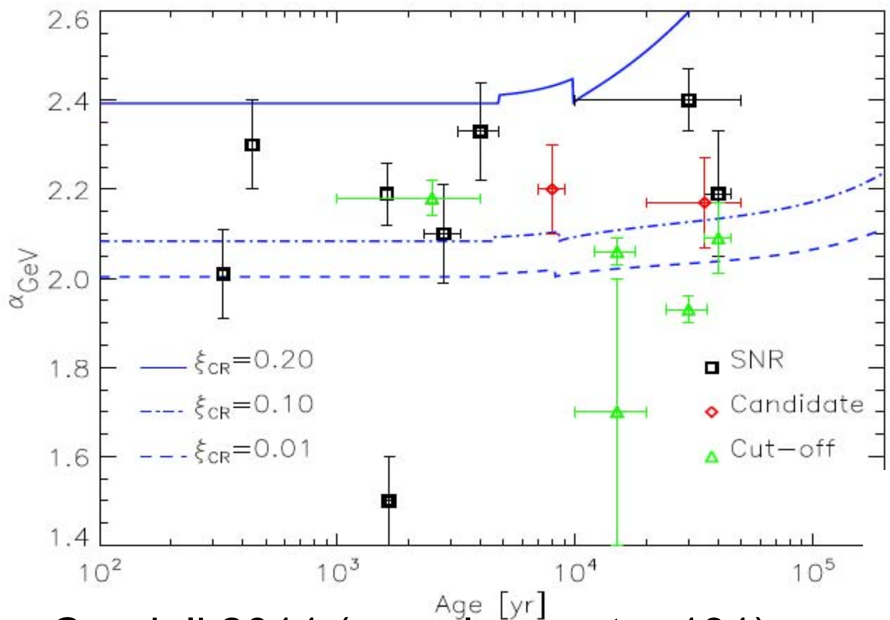
- G78.2+2.1 (γ-Cygni):
  - Distance ~ 1.5 – 1.8 kpc, Age ~ 5-10 kyr.
- VERITAS: 18.6 hrs live time Sep-Nov, 2009.
  - Detection: 9.6 (7.5) σ pre (post) trials.
  - Extended emission: σ ~ 0.18° ± 0.03°$_{stat}$ ± 0.02°$_{sys}$
- *What's driving the TeV emission?*
  - Likely SNR shock interacting with ambient material:
    - Partial HI shell encloses north, west (Gosachinskij 2001).
    - Suggests hadronic emission.
  - Lack of CO: differs from W28, W44, IC 443, W51C, ...



Acciari et al. 2011 in prep.

DSA of Cosmic Rays in SNRs

TROUBLE WITH SLOPES ?

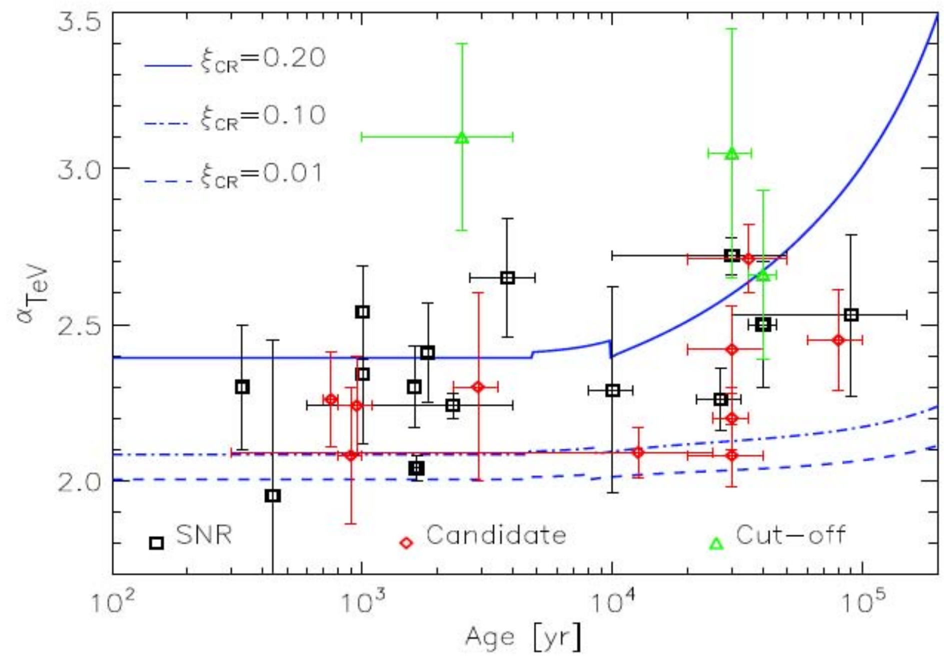


Caprioli 2011 (see also poster 131)

VERY SURPRISING TO SEE THAT THE REQUIRED ACCELERATION EFFIC ARE HIGH BUT THE SPECTRA ARE STEEP

POSSIBLE SIGNATURE OF FINITE SPEED OF THE SCATTERING CENTERS !!!???

$$\tilde{r} = \frac{u_1 + v_{A,1}}{u_2 + v_{A,2}} \qquad \alpha = \frac{\tilde{r} + 2}{\tilde{r} - 1}$$



DSA of Cosmic Rays in SNRs

- REQUIRED POWER → NON LINEAR THEORY OF ACCELERATION
- MAGNETIC FIELD AMPLIFICATION → MOST LIKELY CR INDUCED
- EFFICIENT ACCELERATION SEEN IN SIZE OF X-RAY FILAMENTS, ABSENCE OF X-RAYS FROM PRECURSOR, EMAX @ KNEE, ANOMALOUS BALMER LINE WIDTHS
- ANISOTROPY SUGGESTS $\delta \sim 1/3$ → INJECTION SLOPE 2.3-2.4
- GAMMA RAYS ALSO SUGGEST STEEP INJECTION → PROBABLY ACTION OF SCATTERING CENTERS SPEED, BUT ALSO NEUTRALS
- TYCHO PROBABLY THE FIRST UNAMBIGUOUS HADRONIC SOURCE
- IN GENERAL EFFICIENT ACCELERATION DOES NOT IMPLY GAMMA
- AS A BY-PRODUCT OF SNR PARADIGM → TRANSITION TO EXTRA GALACTIC CR AT 10^{18} eV, NOT @ ANKLE