On The Origin of γ-ray Emission Toward SNR CTB 37A with *FERMI* LAT

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HIROSHIMA UNIVERSITY

Outline

- Mid-aged SNRs Interacting with Molecular Clouds (MCs)
- Scientific Goals
- SNR CTB 37A in Various Wavebands
- CTB 37A Analysis with Pass 8 of *Fermi* LAT
  - Source Localisation & Extension Fit
  - Spectral Analysis
- Broadband SED Modeling
- Discussion & Conclusion

Mid-aged SNRs Interacting with MCs

- Evidence of hadronic origin of the γ-ray emission in IC 443, W44, and W51C
- Expanding in dense medium as evidenced by 1720 MHz OH maser emission
- Usually as Mixed-morphology SNRs
- In most SNR/MCs, GeV γ-ray spectrum is best describes by a broken power law
  - Spectral breaks at an energy of several GeV
  - Less luminous at TeV energies

CTB 37A

- A member of this category with age of $\sim$ 10 kyr
- Distance of $\sim$ 7.9 kpc
- Interacting with several dense MCs
- Observed non-thermal X-ray emission: signature of a PWN?

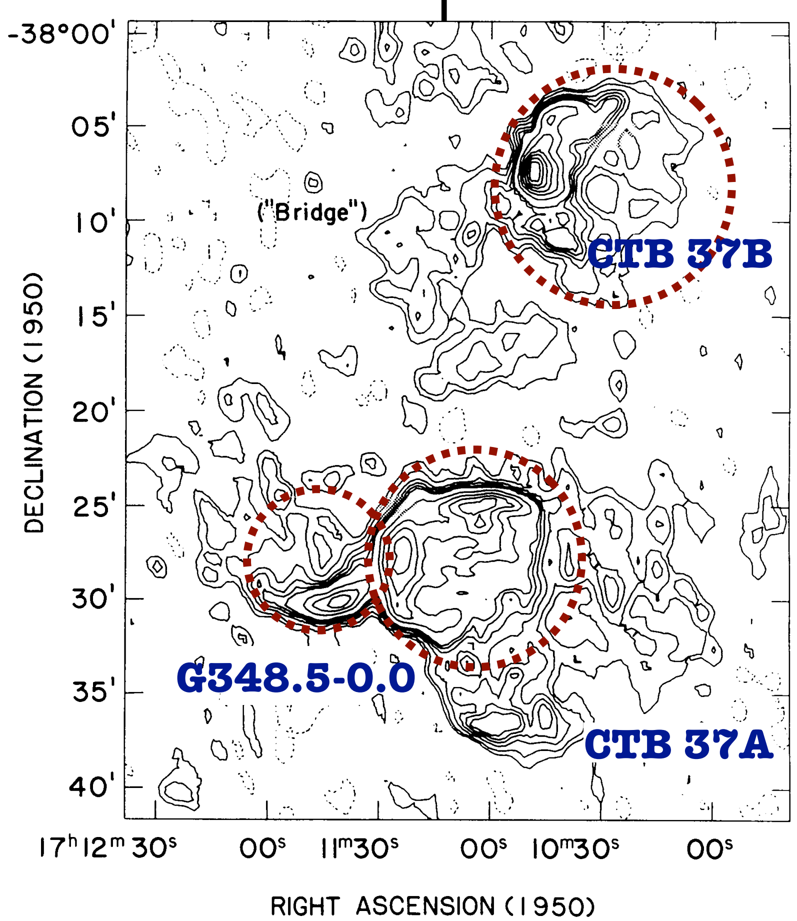
Motivations

- Origin of Galactic CRs from γ-ray observation of SNR/MCs
  - Morphological study of SNR CTB 37A
  - Study of Wideband spectrum

Broadband Observation of CTB 37A

VLA radio image of complex CTB 37
(Kassim et al., 1991)

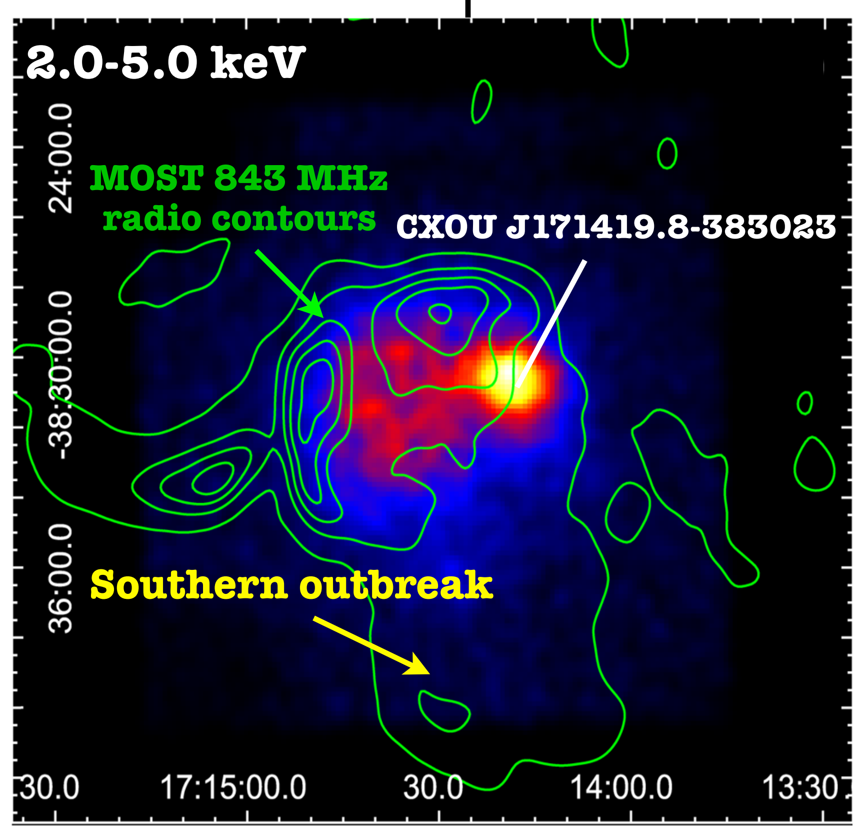
Discovered in radio (Clark et al., 1975)
Break-out radio morphology



Radio

Suzaku XIS image
(Yamauchi et al., 2014)

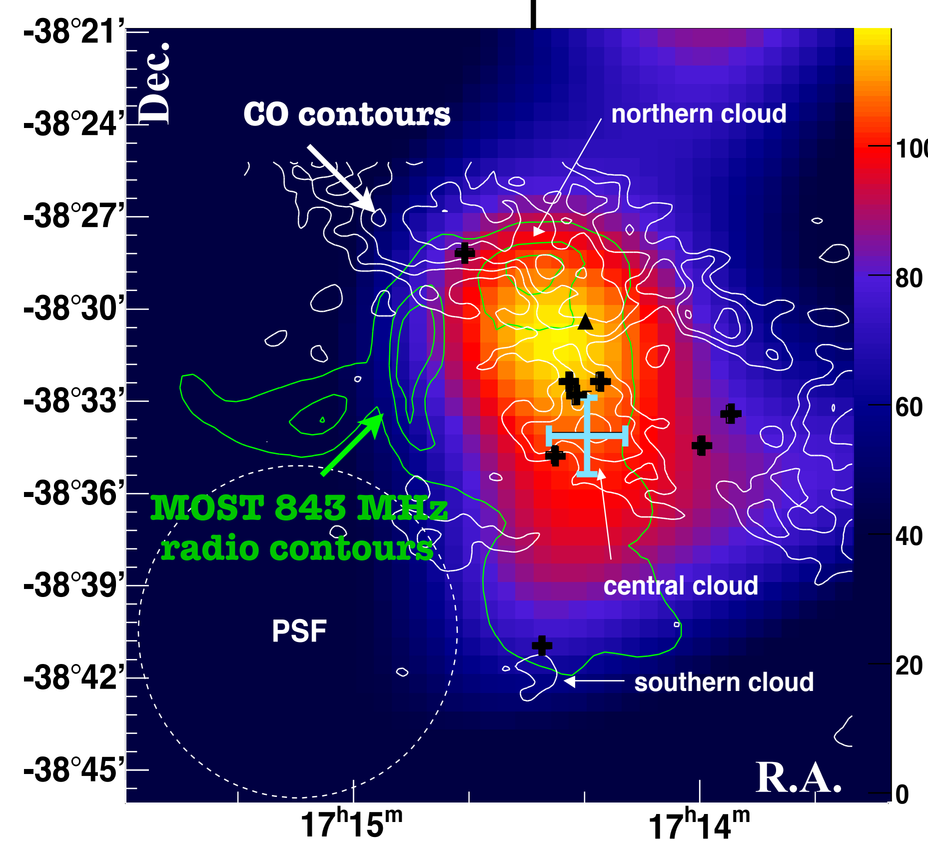
Two X-ray components:
a soft diffuse at the NE & a hard X-ray source in the NW



X-ray

H.E.S.S. excess map
(Aharonian et al., 2008)

Extended TeV emission



Blue cross: best-fit position of HESS J1714-385
▲: X-ray source CXOU J171419.8-383023
✚: OH masers at 1720 MHz

VHE γ-ray

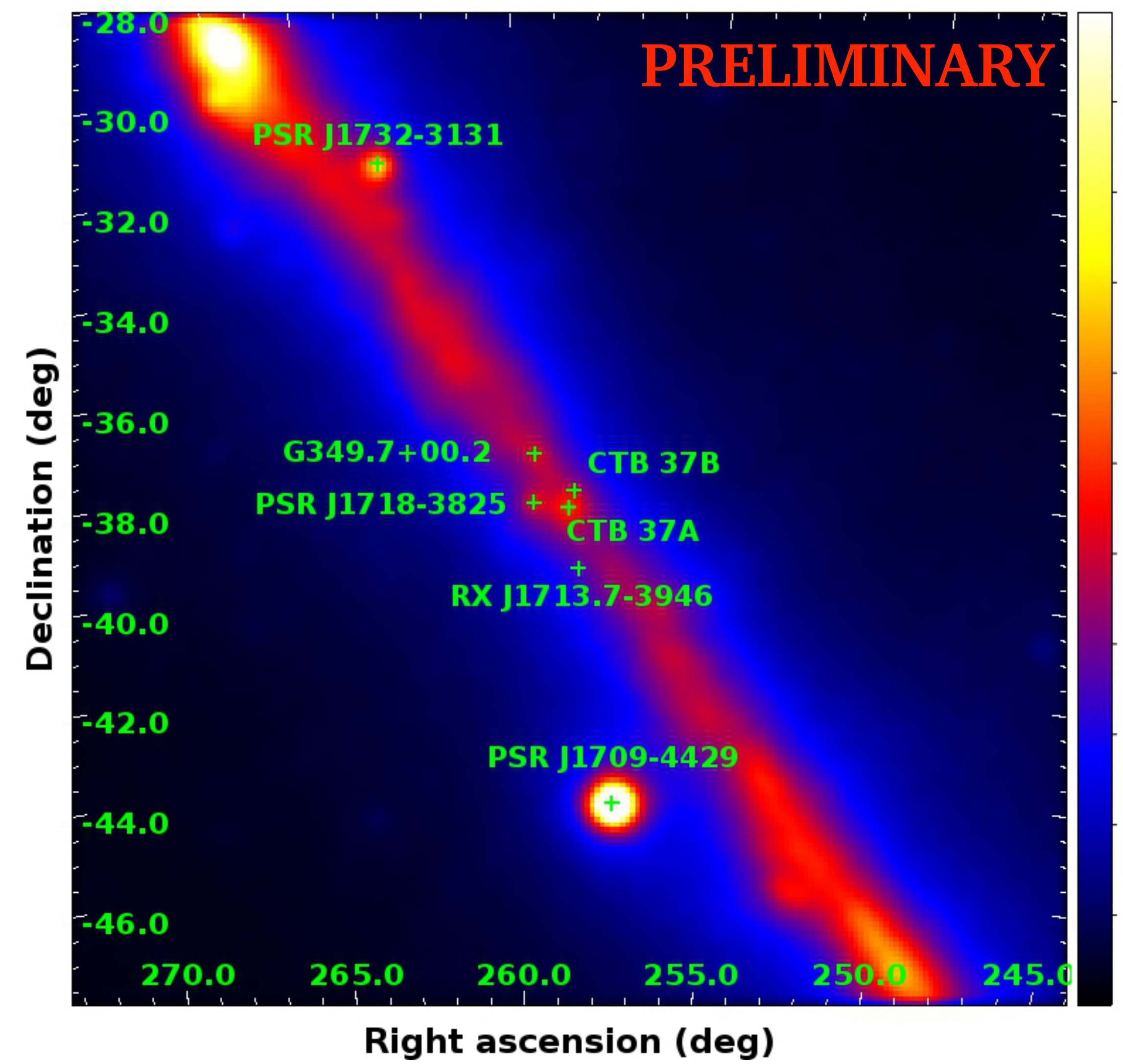
S. Abdollahi

Look around CTB 37A

DATA SET

- 8 years of Pass 8 data
- Energy: 200 MeV- 200 GeV
- Zmax: 105° (>1 GeV) and 90° (<1 GeV)
- ROI: 15° in radius
- Standard diffuse Galactic and isotropic models
- 3FGL catalog for background sources + CTB 37B
  - an angular distance of < 0.35° from CTB 37A
  - resolved above 10 GeV in 3FHL catalog

Counts map (with gtlike) with a pixel size of 0.1° smoothed with σ = 0.15°



Previous studies:

D. Castro & P. Slane, 2010

T. J. Brandt, 2013

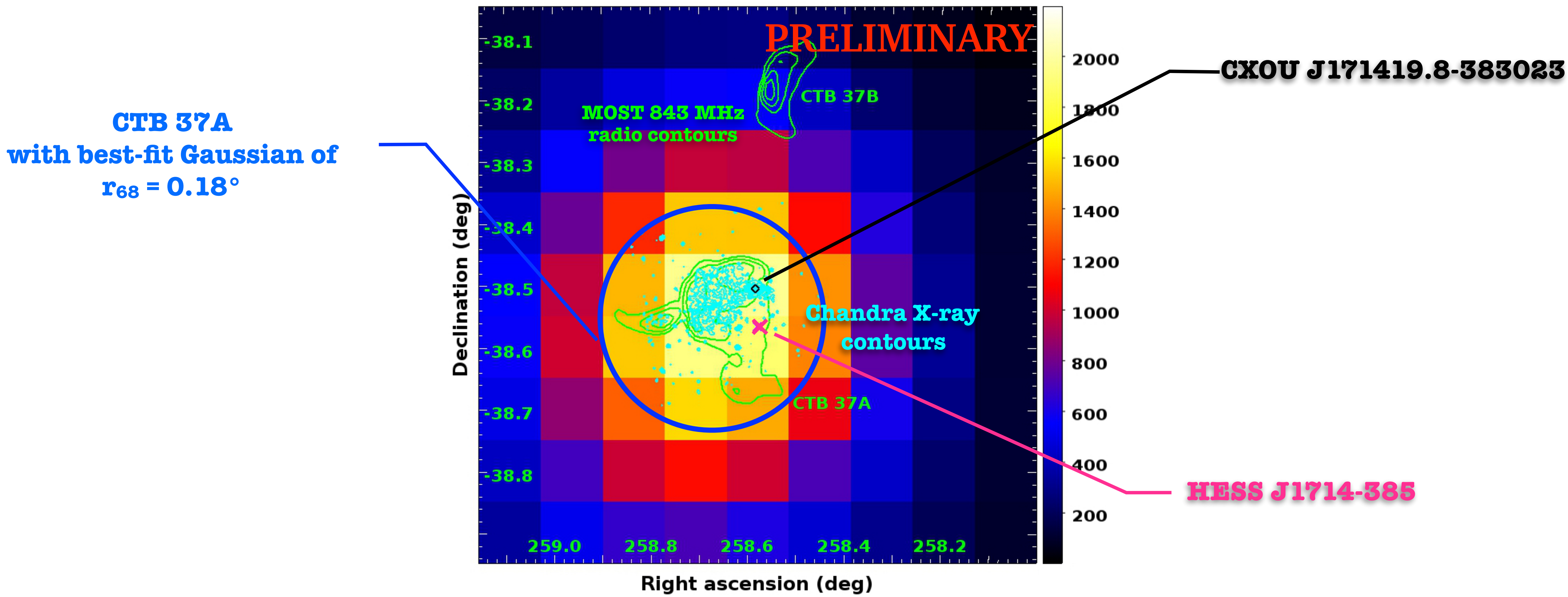
Highlights

- More detailed morphological and spectral studies of CTB 37A, using improved performance in Pass 8 and more accurate treatment of the nearby source CTB 37B.

Morphological Analysis

- Best-fit Gaussian spatial model of r_{68}=0.18° ± 0.02° above 0.2 GeV with LogParabola spectral shape
- A good agreement with the radio extension

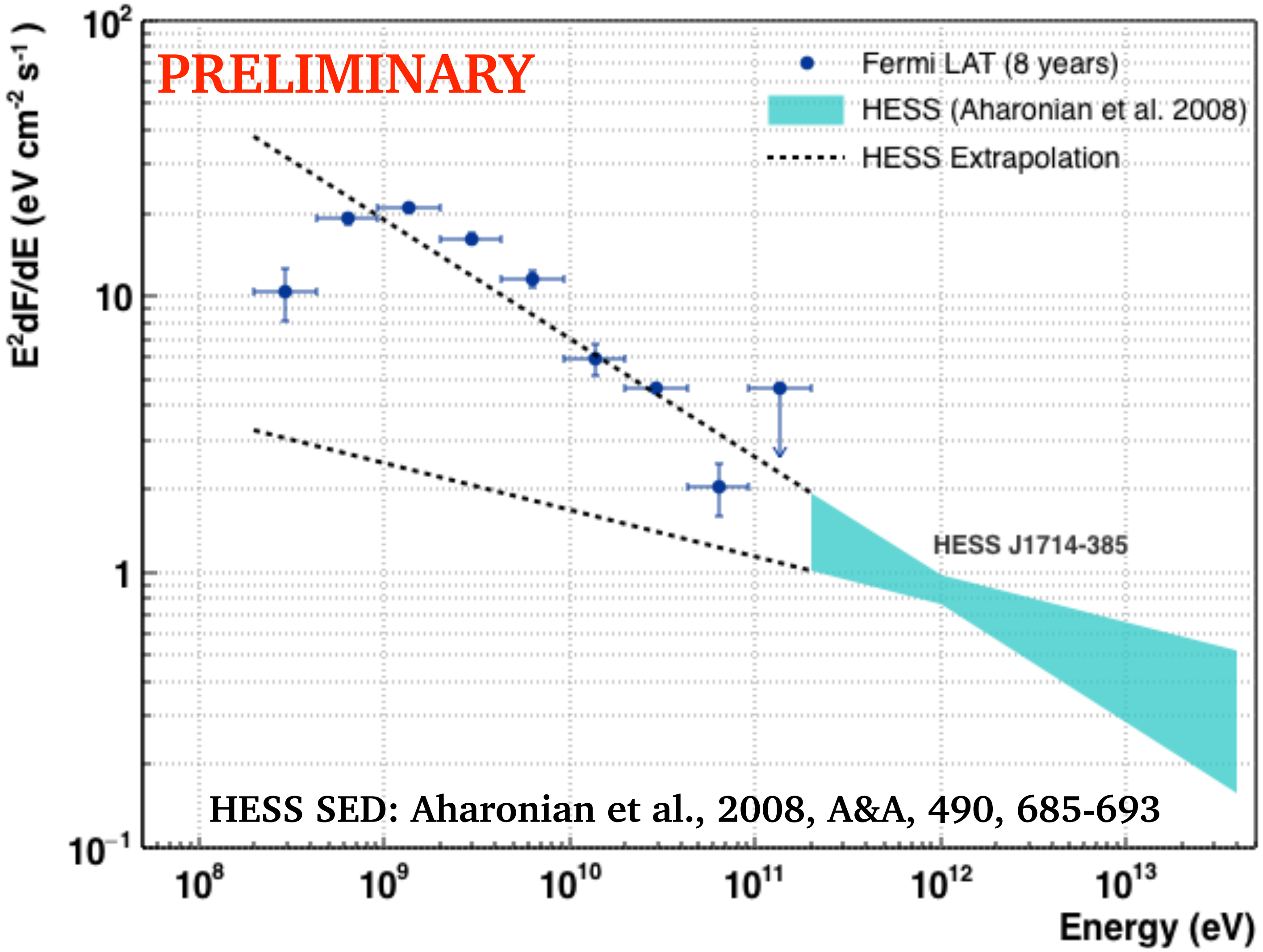
TS excess map in the energy range 0.2-200 GeV in 0.9°×0.9°



Spatial model	RA	Dec.	r_{68} (°)	TS_{ext}	Spectral Index (α)
Point Source	258.65 ± 0.01	-38.54 ± 0.01	—	—	2.13 ± 0.01
Disk	258.68 ± 0.01	-38.56 ± 0.01	0.17	138	2.057 ± 0.003
Gaussian	258.67 ± 0.01	-38.55 ± 0.01	0.18	145	2.04 ± 0.01

- Reference energy (E_b): 1.11 GeV
- LogParabola curvature (β): 0.12
- Statistical error only is included

Spectral Energy Distribution



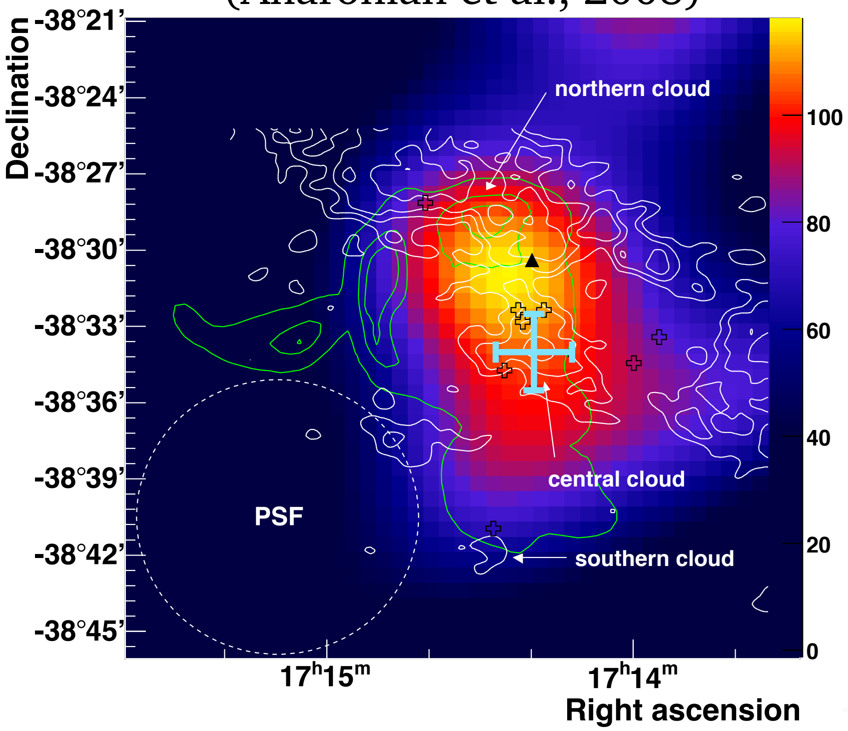
- Spatial model: best-fit Gaussian of $\sigma = 0.12° \pm 0.01°$
- Systematic error is not included yet
- Total energy flux in the energy range 0.2-100 GeV:

  $(90.54 \pm 2.83_{stat.})$ eV cm^{-2} s^{-1}

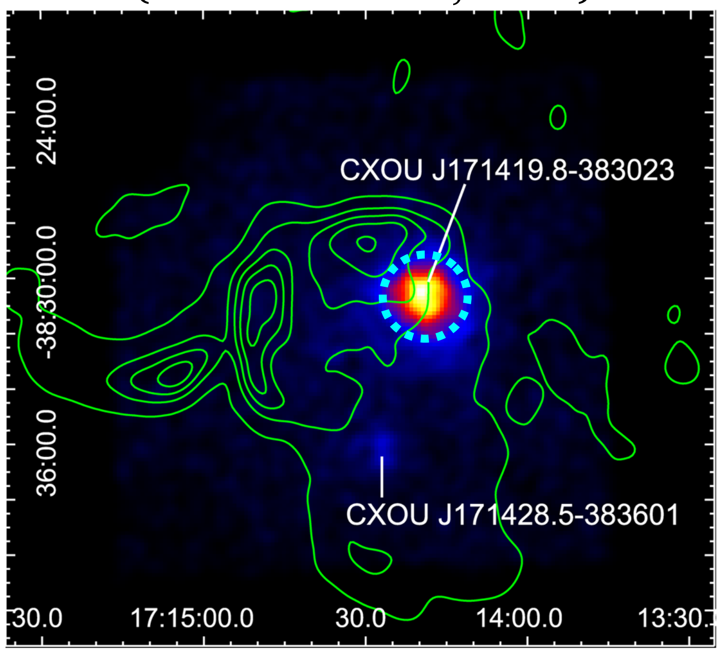
Extrapolation of HESS data toward the LAT range slightly underpredicts the LAT measurements

Discussion: CTB 37A as a Composite SNR?

(Aharonian et al., 2008)



(Yamauchi et al., 2014)



Morphological Point of View:

- The TeV & X-ray offset of $\sim 3.6'$ can be explained by breakout morphology of the remnant due to a strong density gradients
- TeV emission size of $4' \pm 1'$ in radius
- Non-thermal X-ray emission size is consistent with the mid-aged PWNe

A possible composite SNR

Spectral Point of View:

- Spectral analysis of NW hard spot:
  - Suzaku Index: 1.94 (+0.15 -0.14) typical index value of PWNe, source extraction radius: 2'
  - Chandra & XMM-Newton Index: 1.32 (+0.39 -0.35), source extraction radius: 50"
- VHE γ-ray source: spectral index of $2.30 \pm 0.13_{stat.} \pm 0.20_{sys.}$

Nature of the γ-ray emission: SNR Contribution

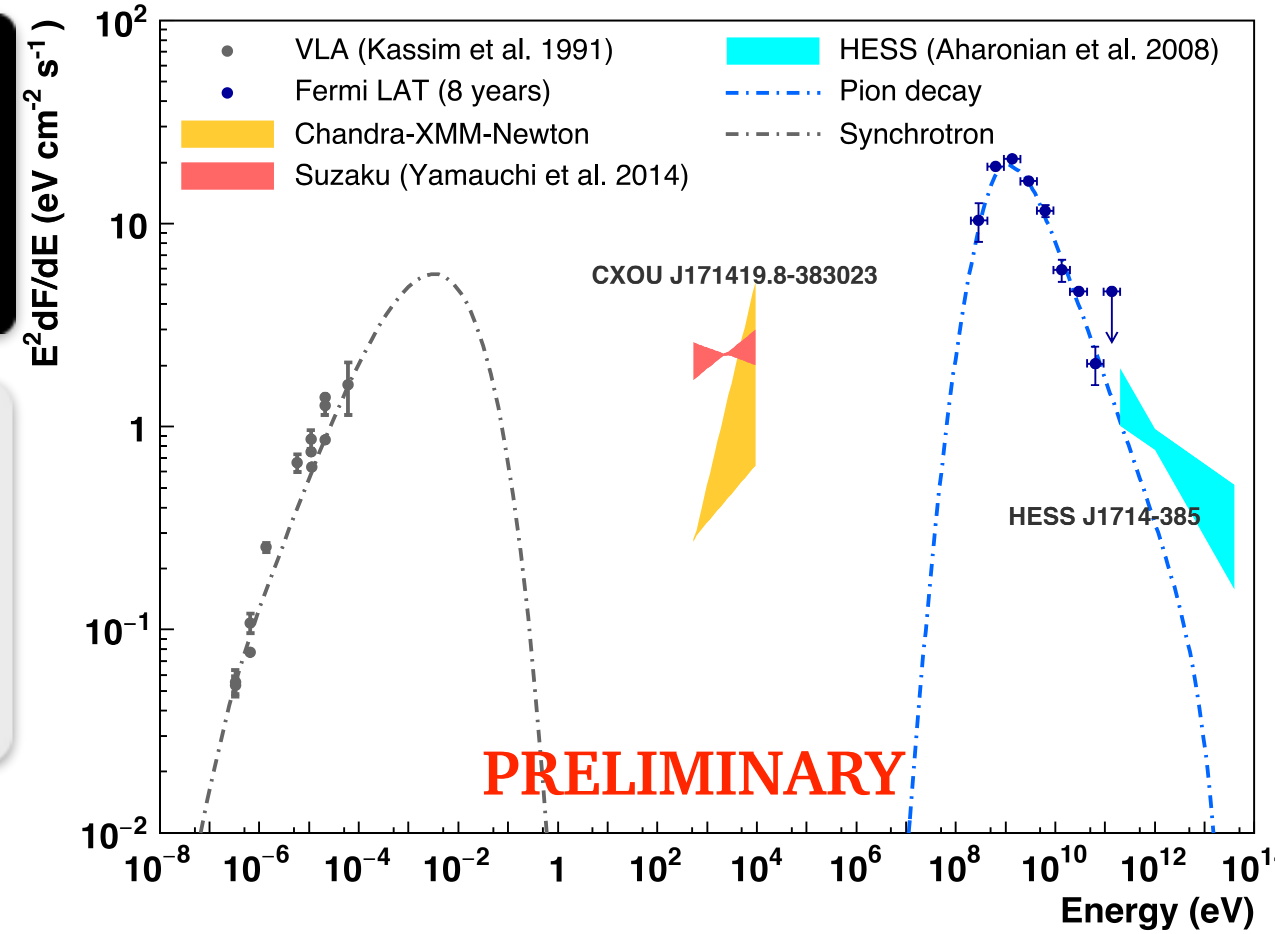
Baseline Model (SNR part)

Two independent sources: an SNR and a plausible PWN

- The radio and GeV emission with a hadronic one

Model Characteristics:

- Broken Power Law with a break at 10 GeV/c
- Amplified magnetic field
- Dense environment
- $W_p = 1.50 \times 10^{49}$ erg



Similar to SNR W44

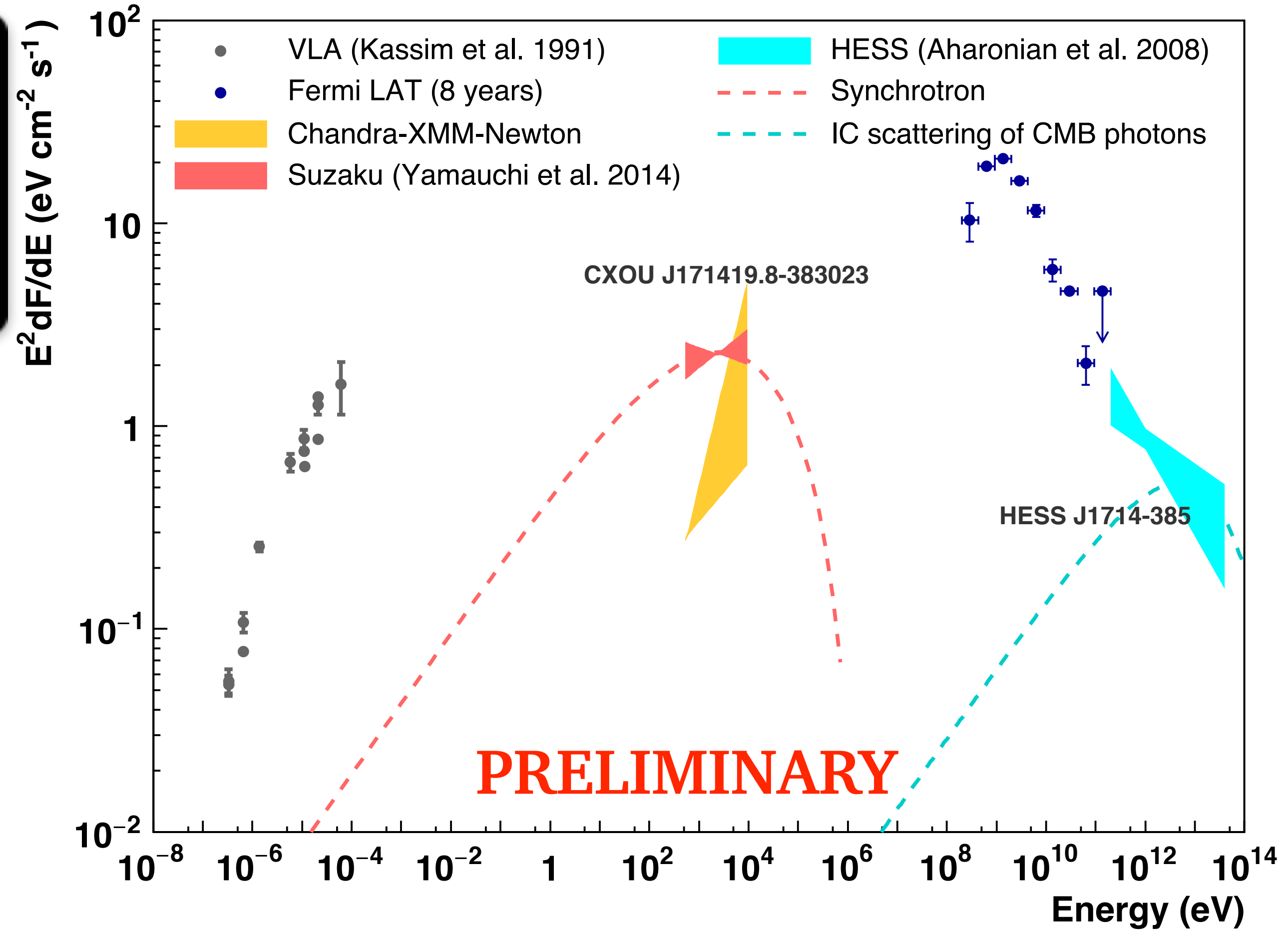
Hadronic Model					K_{ep}	E_{max}	B	n_H	W_p	W_e
Protons: Broken Power Law			Electrons: PL with Exp. Cut-off							
α_L	α_H	P_{br} (GeV/c)	α	E_c (GeV)		(GeV)	(μG)	(cm^{-3})	(10^{49} erg)	(10^{49} erg)
2.1	2.7	10	1.6	10	0.01	6.0E+03	350.0	350	1.50	2.38E-02

Nature of the γ-ray emission: PWN Contribution

Baseline Model (PWN part)

Two independent sources: an SNR and a plausible PWN

- The X-ray and TeV emission with energetic leptons

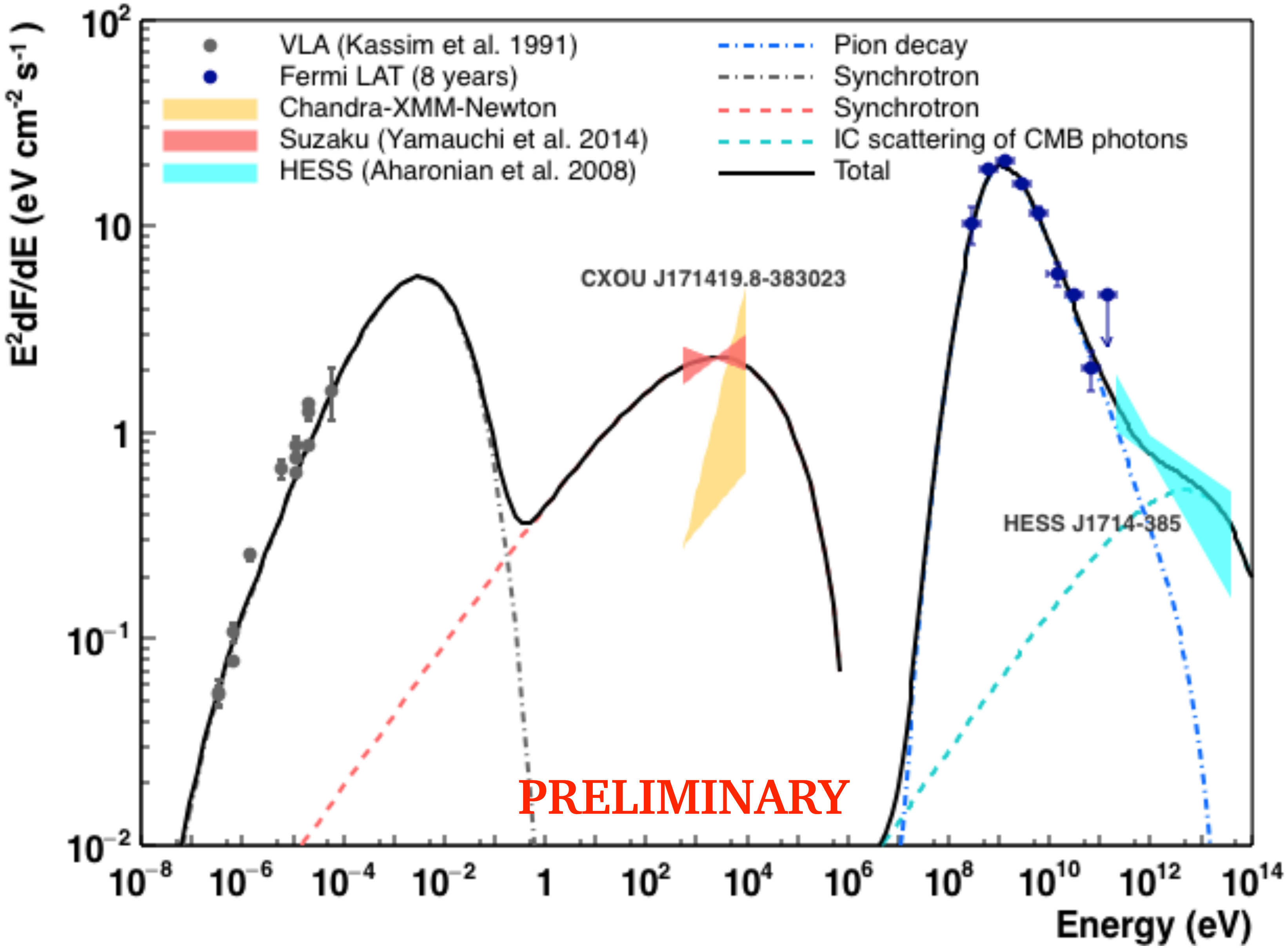


Suzaku by looking at a relatively large region can sample both young and old population of electrons

- 1st hump in X-ray via synchrotron radiation of younger and high energetic electrons
- 2nd hump in TeV via ICS of CMB photons by older and less energetic electrons

Leptonic Model			K_{ep}	B	W_e
Electrons: PL with Super Exp. Cut-off					
α	E_c (GeV)	β		(μG)	(10^{48} erg)
2.30	9.5E+04	0.65	1	5.1	5.17

Broadband SED Modeling of CTB 37A: Summation of SNR & PWN models



Summary & Conclusion

- CTB 37A extension:
  - Best-fit Gaussian model of $r_{68} = 0.18° \pm 0.02°$ is favored over a point-like source with $TS_{ext} = 145$.

- Nature of γ-ray emission:
  - GeV emission can not connect to the TeV emission, smoothly.

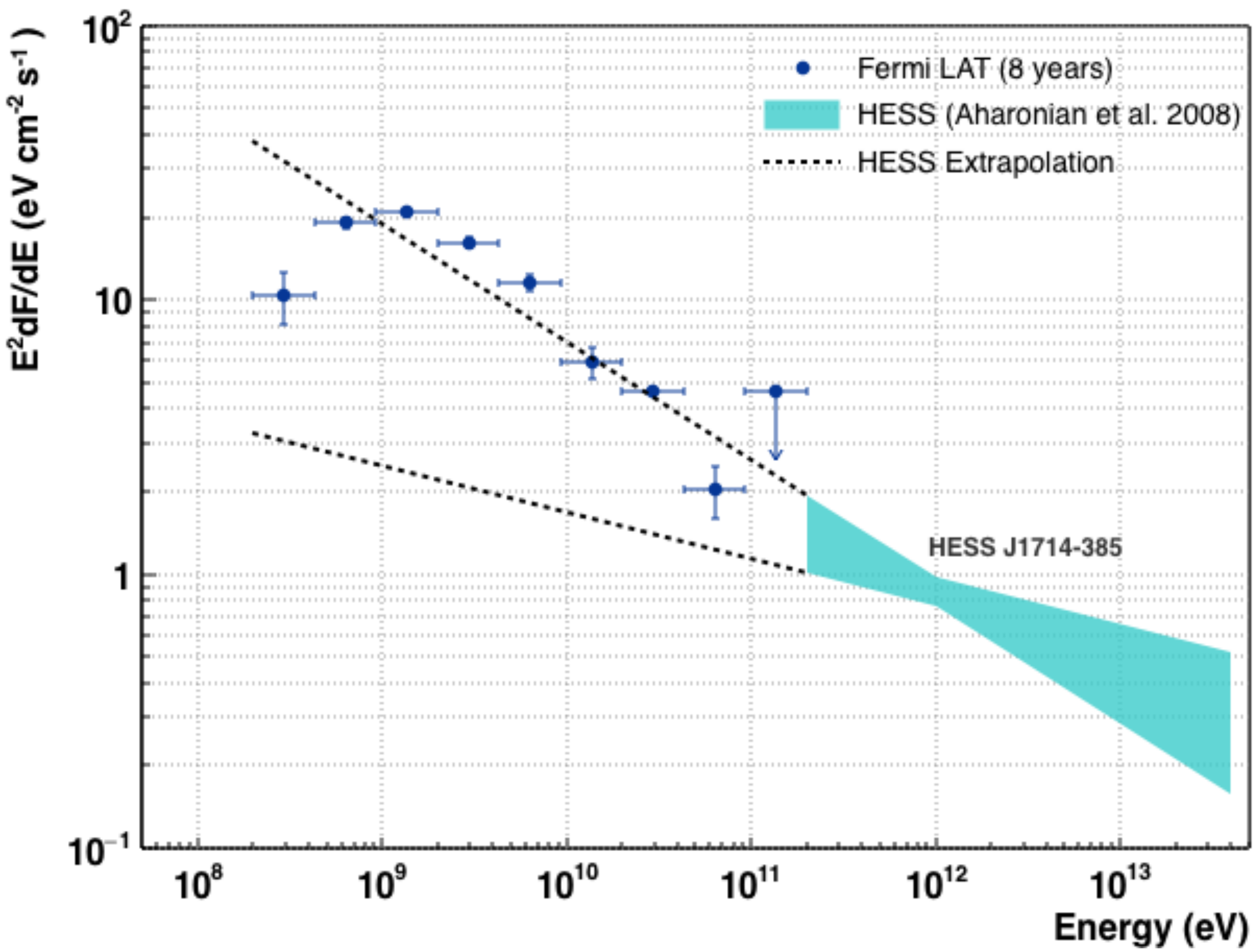
    ➜ Suggests two different origins for GeV and TeV emission

- Implication of the multi-wavelength spectrum: an SNR + a PWN
  - Non-thermal X-ray and TeV emission can be explain by a plausible PWN
  - Radio and GeV emission from the SNR

- SNR model Characteristics:
  - Broken power law spectrum of proton with a break at 10 GeV/c and index of 2.1 before break and 2.7 after break.
  - Amplified magnetic field of 350 μG
  - $W_p = 1.50 \times 10^{49}$ erg

BACK-UP

Spectral Energy Distribution



E_{min} (GeV)	E_{max} (GeV)	SED (MeV cm^{-2} s^{-1})	TS	N_{pred}
0.200	0.430	1.03E-05	136.76	5843
0.430	0.930	1.91E-05	670.65	6630
0.930	2.0	2.08E-05	1158.68	4325
2.0	4.31	1.62E-05	836.10	1666
4.31	9.28	1.16E-05	404.95	542
9.28	20.0	5.91E-06	101.24	129
20.0	43.090	4.63E-06	40.34	47
43.090	92.830	2.04E-06	5.22	9
92.830	200.0	0< 4.62E-06	0.65	2

*** Upper limits for TS < 4**

Model Parameters of Several SNR/MC

Model Parameter (Hadronic)	W51C[1]	W44[2]	W28[3] Source N	W28[3] Source S
Age (10^4 yr)	3.0	2.0	4.0	
d (kpc)	6	3.1	2.0	
B (μG)	40	210	160	1.2×10^3
n_H (cm^{-3})	10	300	100	1000
K_{ep}	0.02	0.01†	0.01	
α_L	1.5	2.2±0.1	1.7	
α_H	- - -	3.2±0.1	2.7	2.4
$\Delta\alpha$	1.4			
Radio Spectral Index	-0.26	-0.37	-0.35±0.18	
E_b (GeV)	15	20±1	2	
W_p (10^{49} erg)	52	5	1.3	1.5×10^{-2}
W_e (10^{49} erg)	1.3	5.6×10^{-2}	1.9×10^{-2}	6.5×10^{-5}

[1]W51C: A. A. Abdo et al., 2009, ApJL, 706, L1

[2]W44: M. Cardillo et al., 2014, A&A, 565, A74
†at 10 GeV
Note: For the leptonic contribution: a simple PL with cut-off for electrons with α = 1.74 and E_c = 12±1 GeV

[3]W28: A. A. Abdo et al., 2010, ApJL, 718, 348