Supernova Remnants in the Cherenkov Telescope Array era

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for the CTA consortium
http://www.cta-observatory.org

with contributions from F. Acero, A. Bamba, E. de Cea, G. Dubus, S. Gabici, Y. Gallant, D. Hadasch, A. Marcowith, P. Martin, E. de Ona Wilhelmi, G. Pedaletti, D. Torres

Outline

<u>HE/VHE gamma-ray astronomy</u>

TeV sky : current status
SNRs at HE/VHE gamma-rays

<u>The CTA project</u>

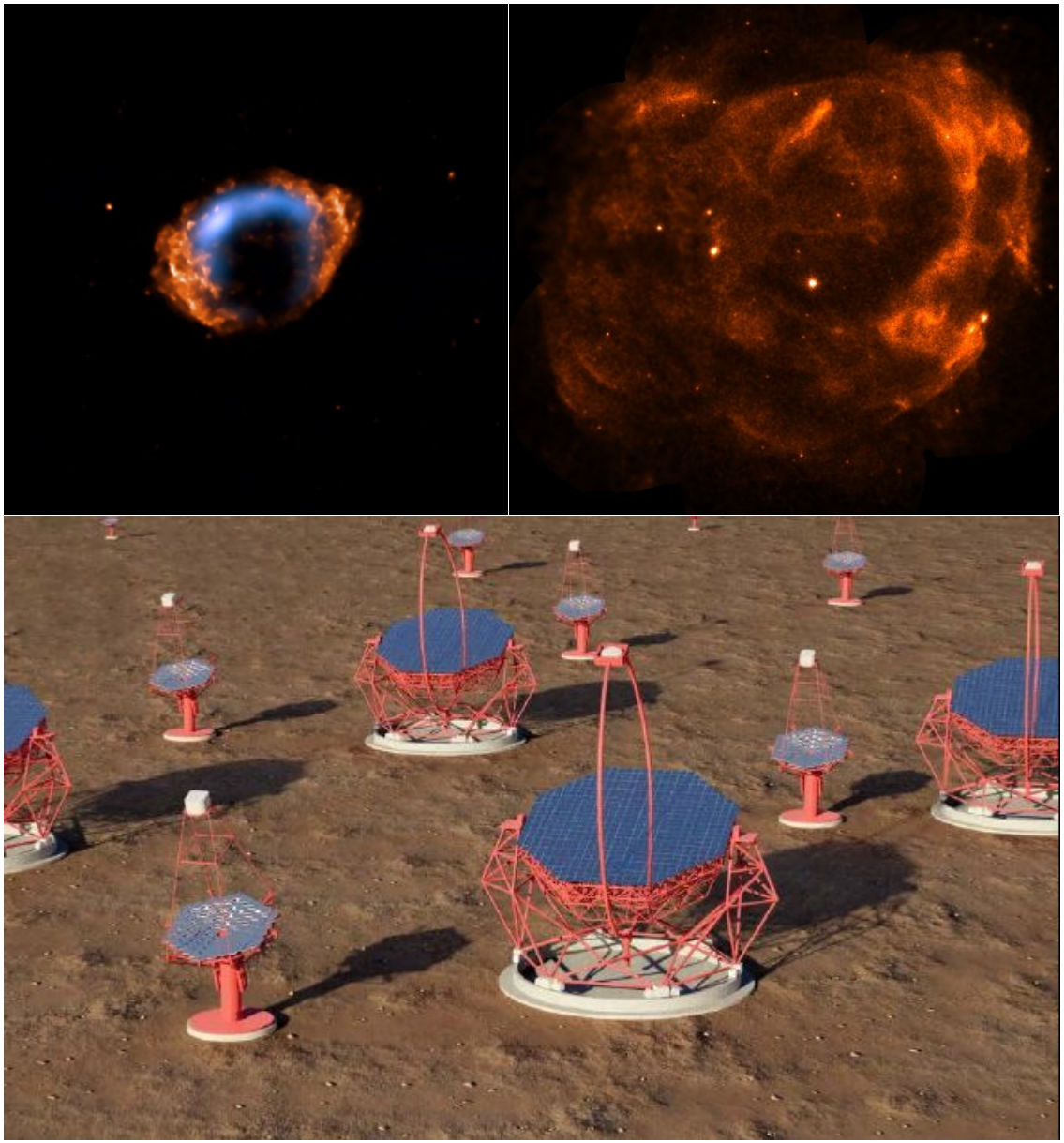
<u>Prospects on SNRs with CTA</u>

Isolated shell-type SNRs

TeV spectra (cutoff region)
Spectro-imaging analysis
Population studies

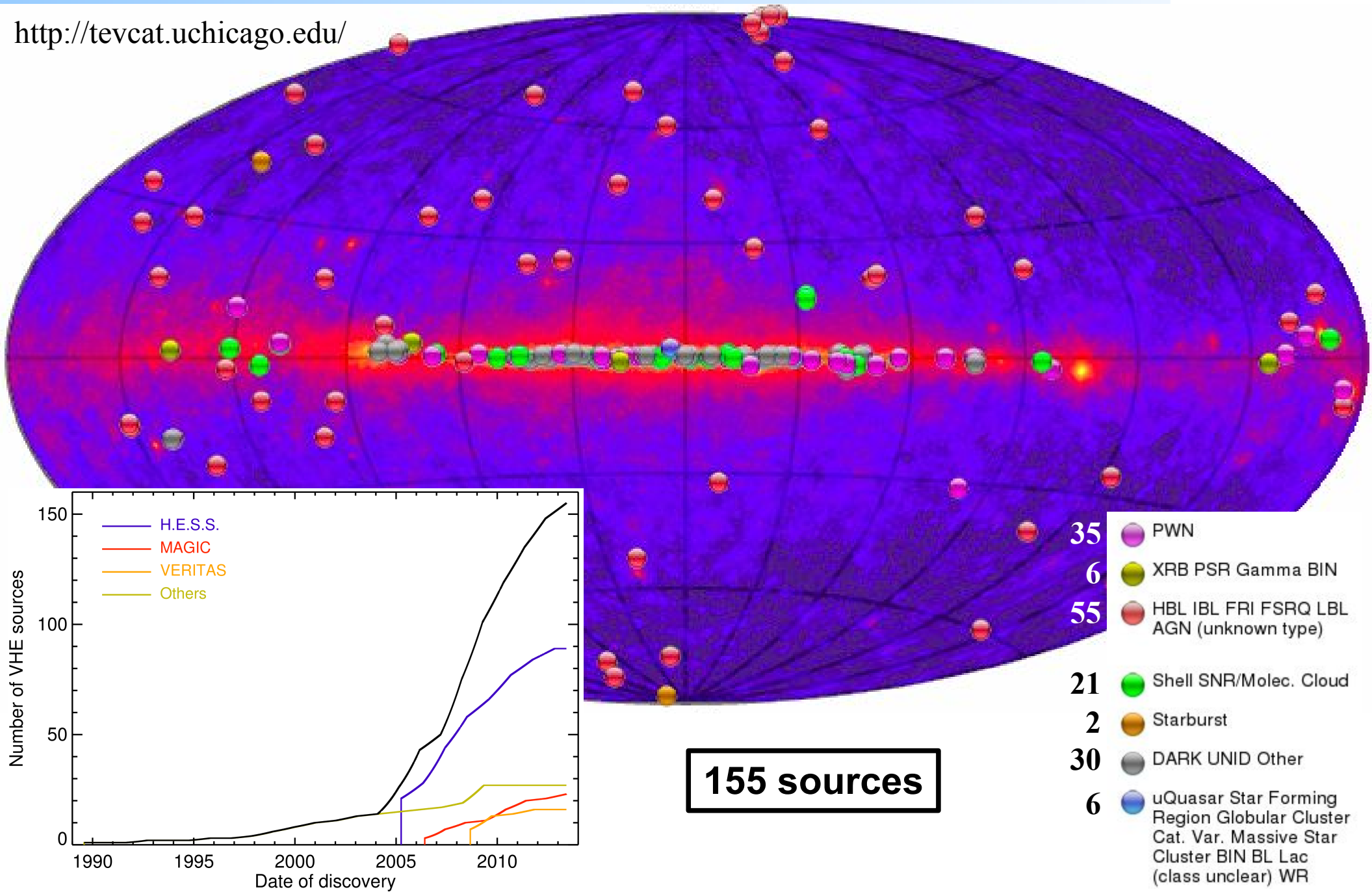
SNR/MC associations

<u>Conclusion & Perspectives</u>



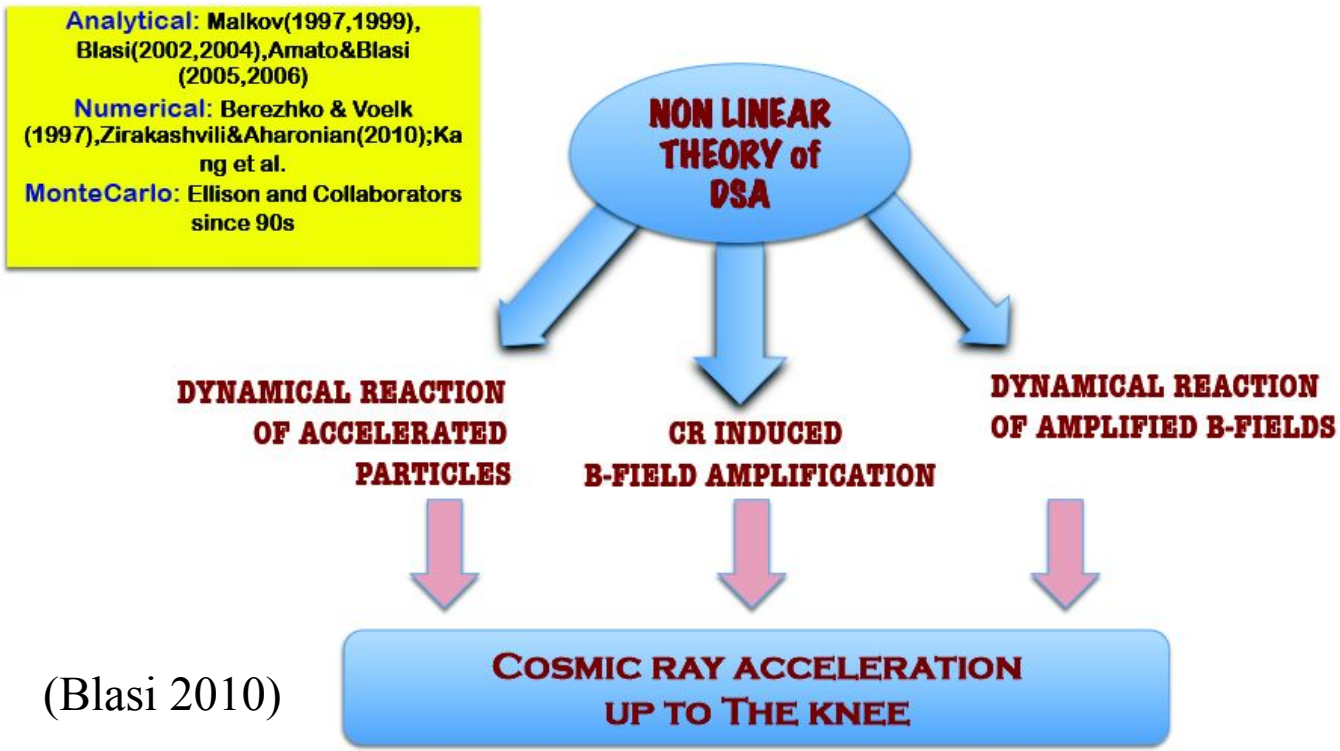
TeV sky as of June 2013

http://tevcat.uchicago.edu/

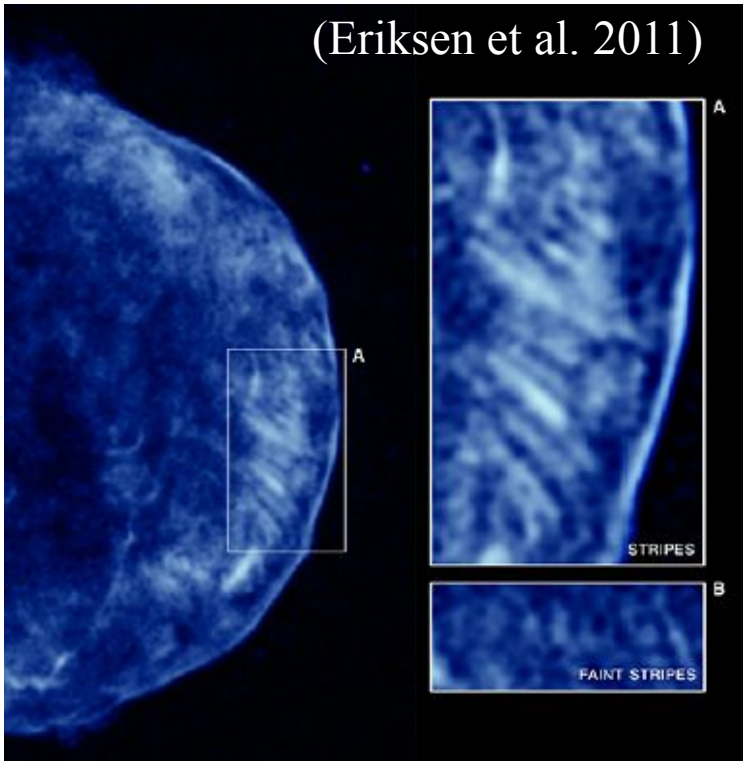


SNRs in HE/VHE gamma-rays

Galactic CR luminosity = $L_{CR} \sim 10^{41}$ erg/s → $\eta_{CR} \sim 0.1 \times (R_{SN}/0.03\ yr^{-1}) \times (10^{51}\ erg/E_{SN})$



(Blasi 2010)

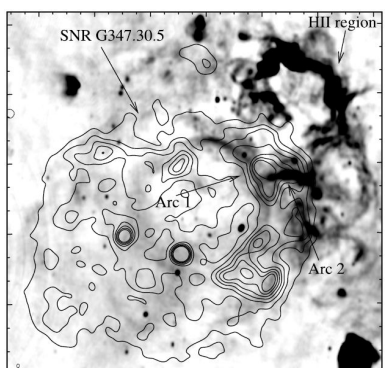


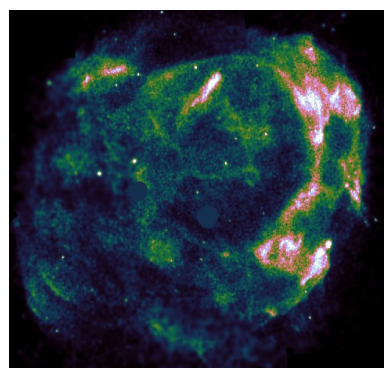
(Eriksen et al. 2011)

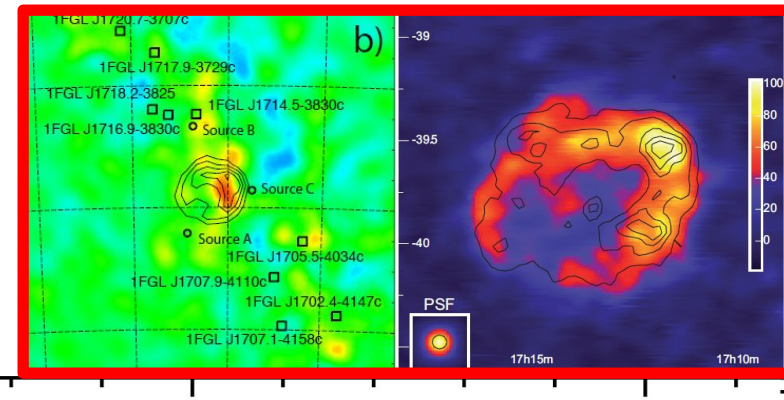
Successes of the NLDSA theory towards the CR origin in SNRs (Helder et al. 2012)

- Reduced heating (larger r, lower T_{down}) & Shock modification (precursor, r_{BW}/r_{CD}, concavity)
- X-ray filaments & knots → B > 100 μG (e.g. Völk et al. 2005, Bamba et al. 2005)
- Maximum energy → $E_{max} \sim E_{knee}$ (Blasi et al. 2007, Eriksen et al. 2012, Bell et al. 2013)
- Balmer-dominated shocks → high P_{CR} (e.g. RCW 86, Helder et al. 2009, 2013)

SNRs in HE/VHE gamma-rays







RX J1713.7-3946

Leptons (SC+IC)
Hadrons (p-p→π^0→2γ)

100 MeV – 100 TeV gamma-rays
Direct evidence for **GeV – PeV (e,p)**
being accelerated at the shock fronts

E^2 dN/dE (erg cm^{-2} s^{-1})

10^{-10}
10^{-11}
10^{-12}
10^{-13}

Very simple 1-zone modeling meant for illustration only!

(Lazendic et al. 2004; Aharonian et al. 2007, 2011; Tanaka et al. 2008; Acero et al. 2009; Abdo et al. 2011)

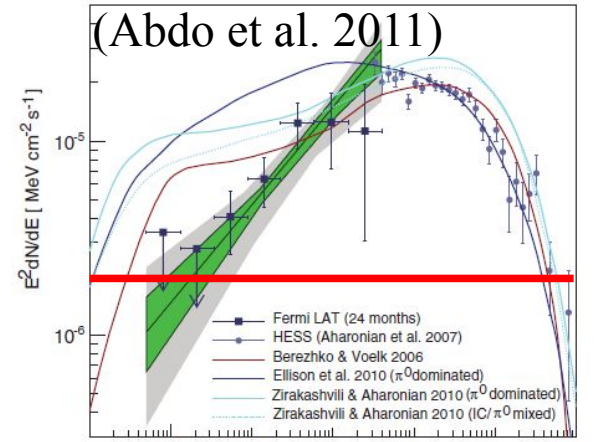
Energy (keV)

10^{-5} 10^{0} 10^{5} 10^{10}

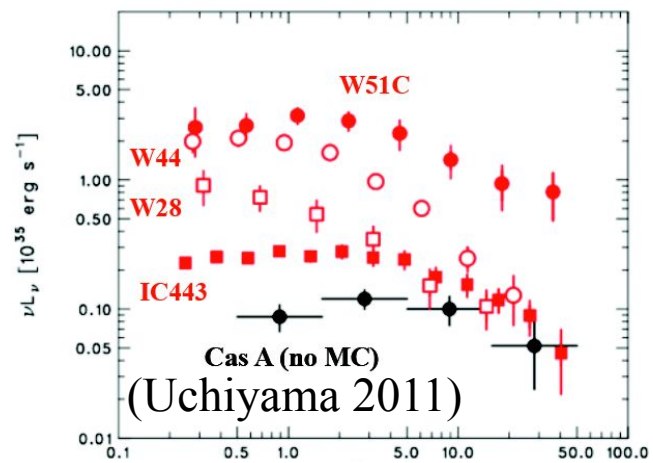
SNRs in HE/VHE gamma-rays

- GeV-hard TeV-bright SNRs
(RX J1713, Vela Jr, RCW 86, HESS J1731?) :
Leptonic-like shape ⇏ not an efficient CR source

η_{CR} ~ 0.3, n = 0.1cm^{-3} still compatible...
→ efficient CR source ≠ hadronic γ-rays

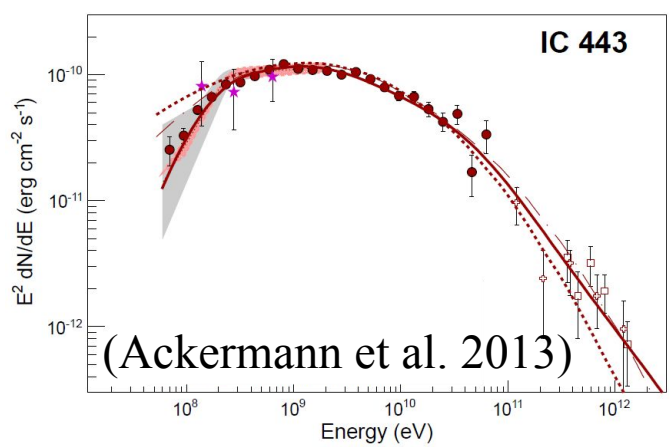


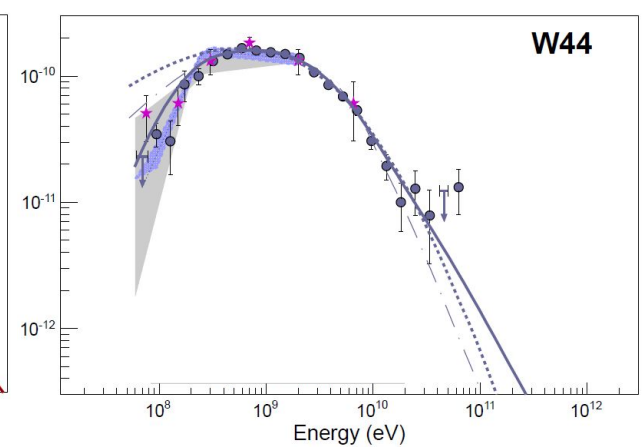
- GeV/TeV-faint SNRs
(Cas A, Tycho, SN 1006?) :
Hadronic-like shape ⇏ efficient CR source



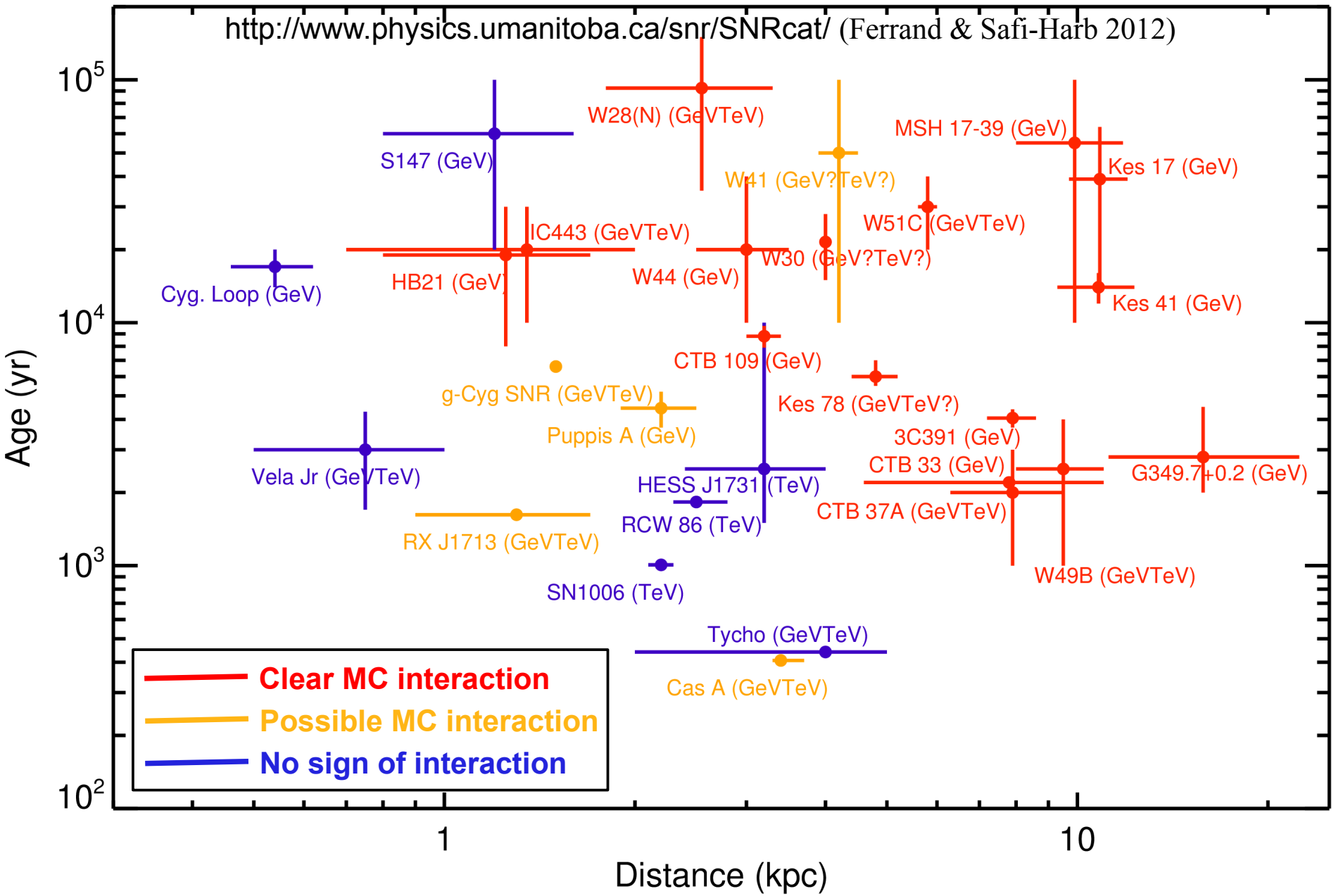
- GeV-bright TeV-soft SNRs, interacting with MCs
(W44, W51C, IC443, W49B...) :
Hadronic-like shape ⇏ efficient CR source...

...But recent detection of the « π^0 bump » → smoking-gun of the hadronic signal!
(Giuliani et al. 2011,
Ackermann et al. 2013)

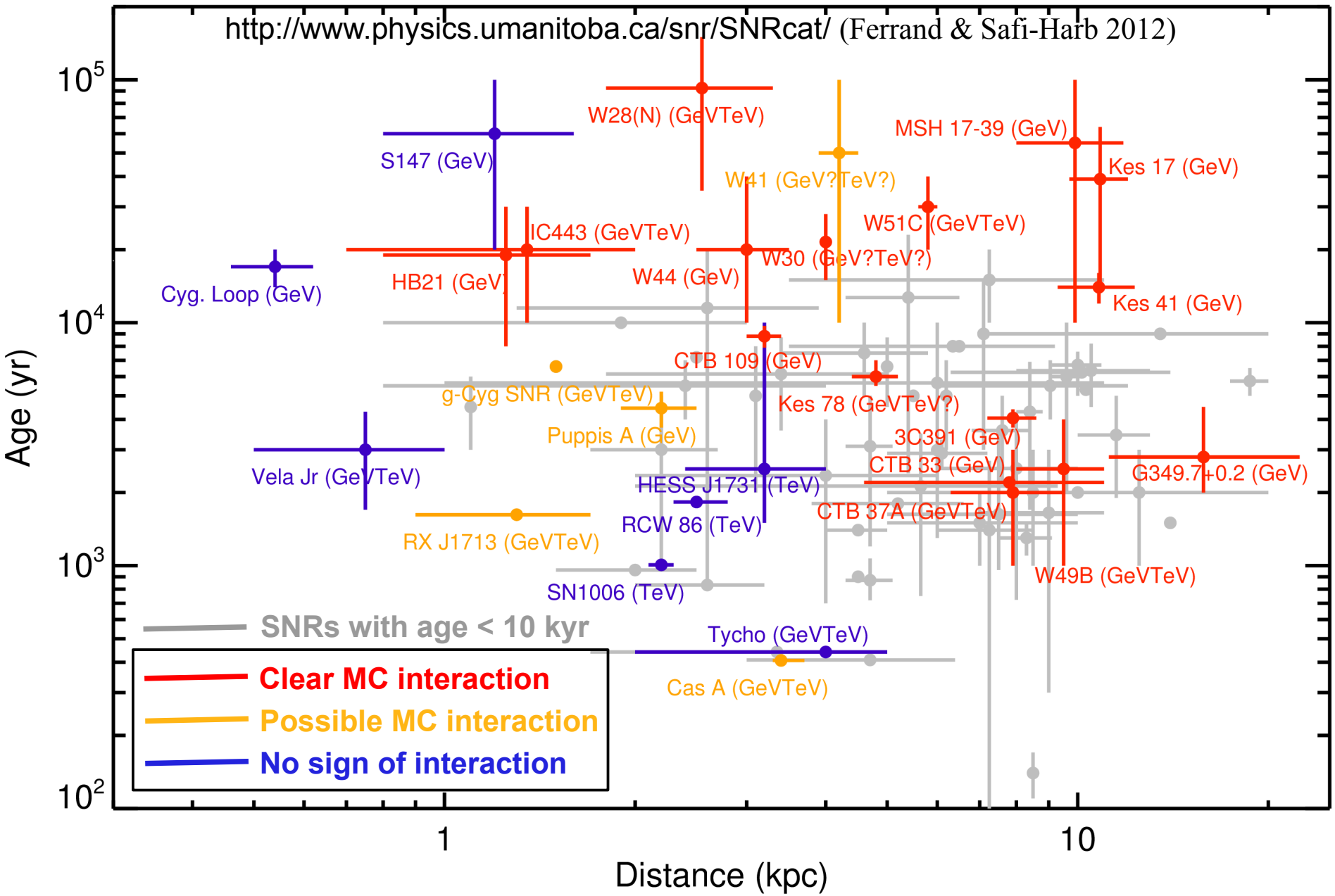




SNRs in HE/VHE gamma-rays

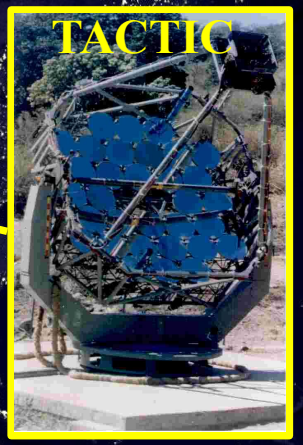


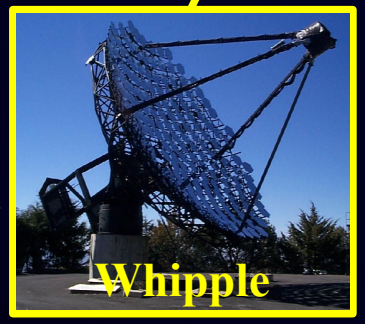
SNRs in HE/VHE gamma-rays

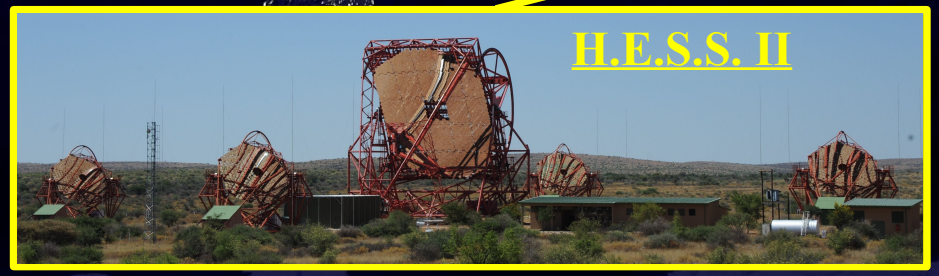


The CTA project

Adapted from J. Hinton





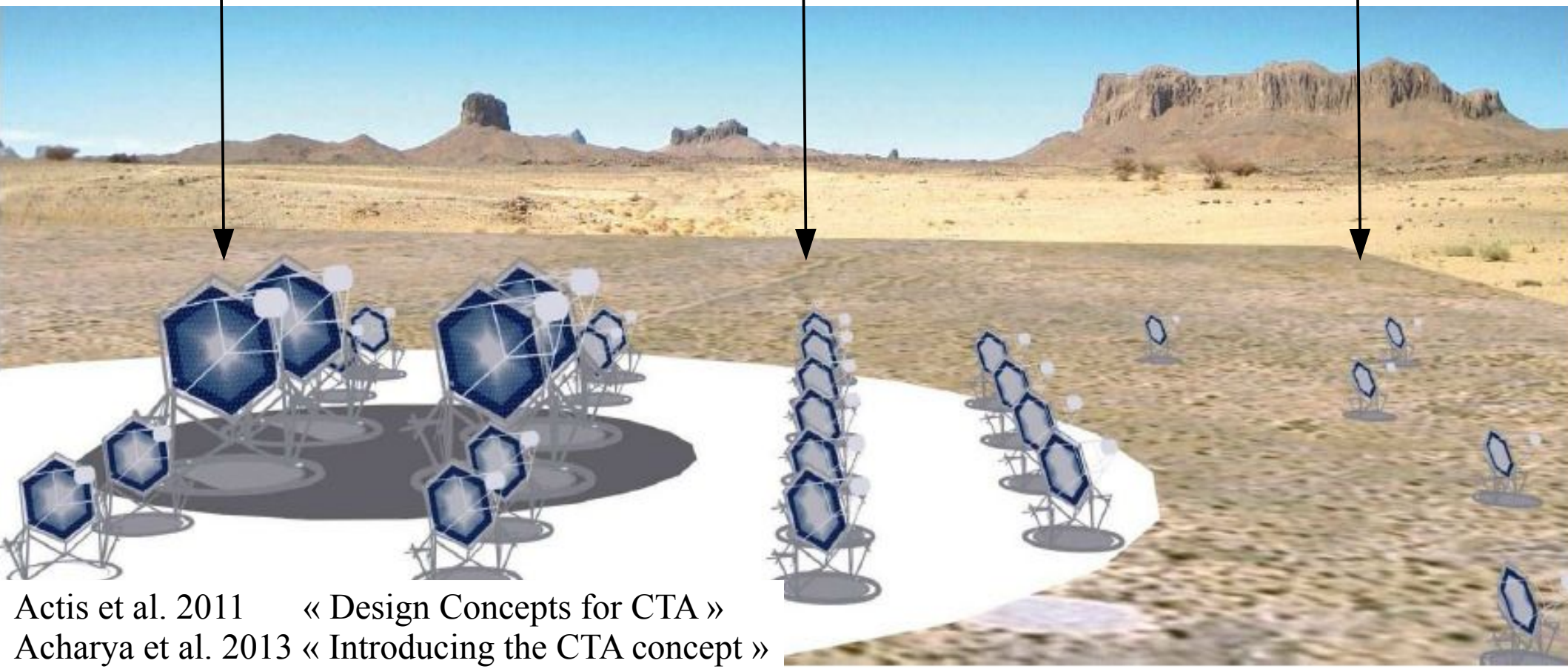


The CTA project

LSTs (a few)
Low-energy section
energy threshold
of ~ 20–30 GeV
20-30 m telescopes

MSTs (~25)
Medium energies
mcrab sensitivity
~100 GeV–10 TeV
10-15 m telescopes

SSTs (~70)
High-energy section
~10 km^2 area at
multi-TeV energies
5-8 m telescopes

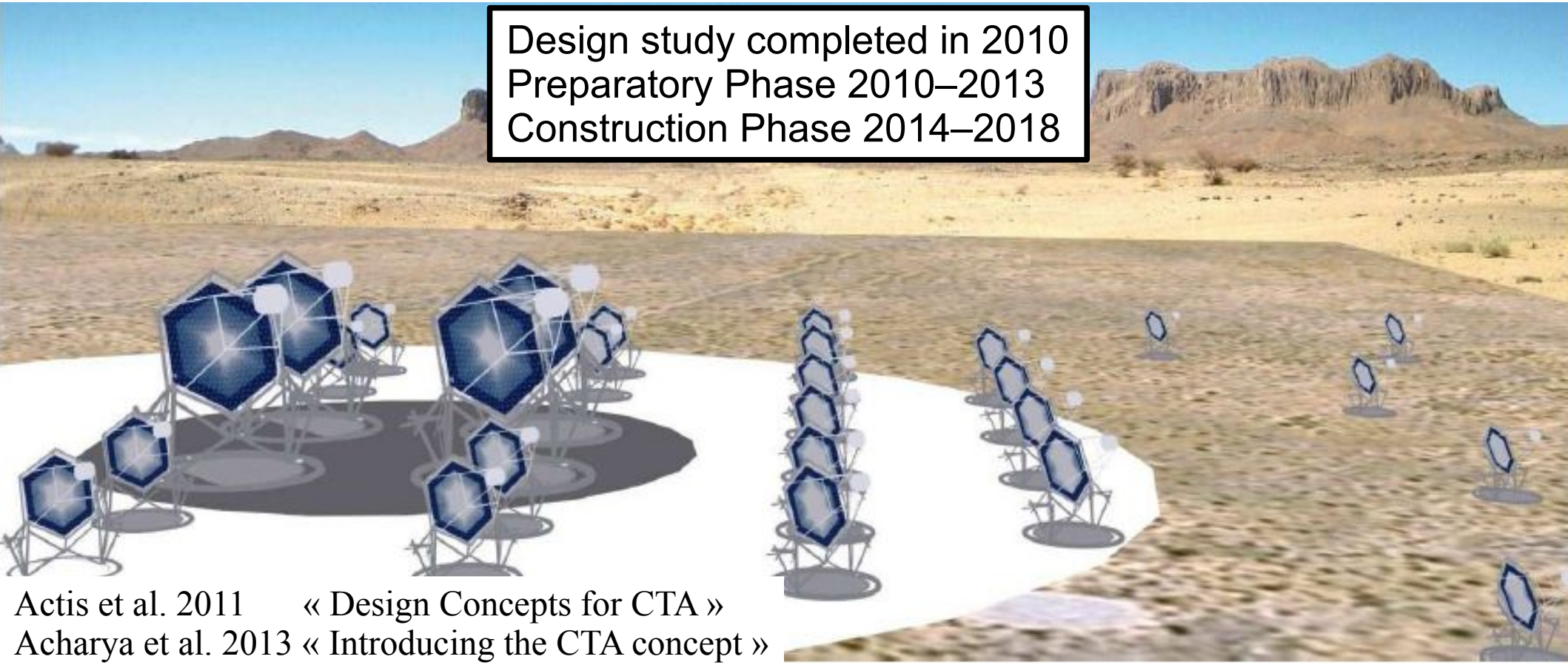


Actis et al. 2011 « Design Concepts for CTA »
Acharya et al. 2013 « Introducing the CTA concept »

The CTA project

Higher sensitivity	→ 1000 sources? Pop. studies	mCrab, 5σ, 50h @TeV
Wider energy coverage	Spectro(-imaging) capabilities	30 GeV – 300 TeV
Better angular resolution	Source identification, morphology	~3 arcmin @TeV
Better energy resolution	Cutoffs & spectral features	rms < 10% @TeV
Wider field-of-view	Extended sources & survey	6 – 8 degrees

Design study completed in 2010
Preparatory Phase 2010–2013
Construction Phase 2014–2018



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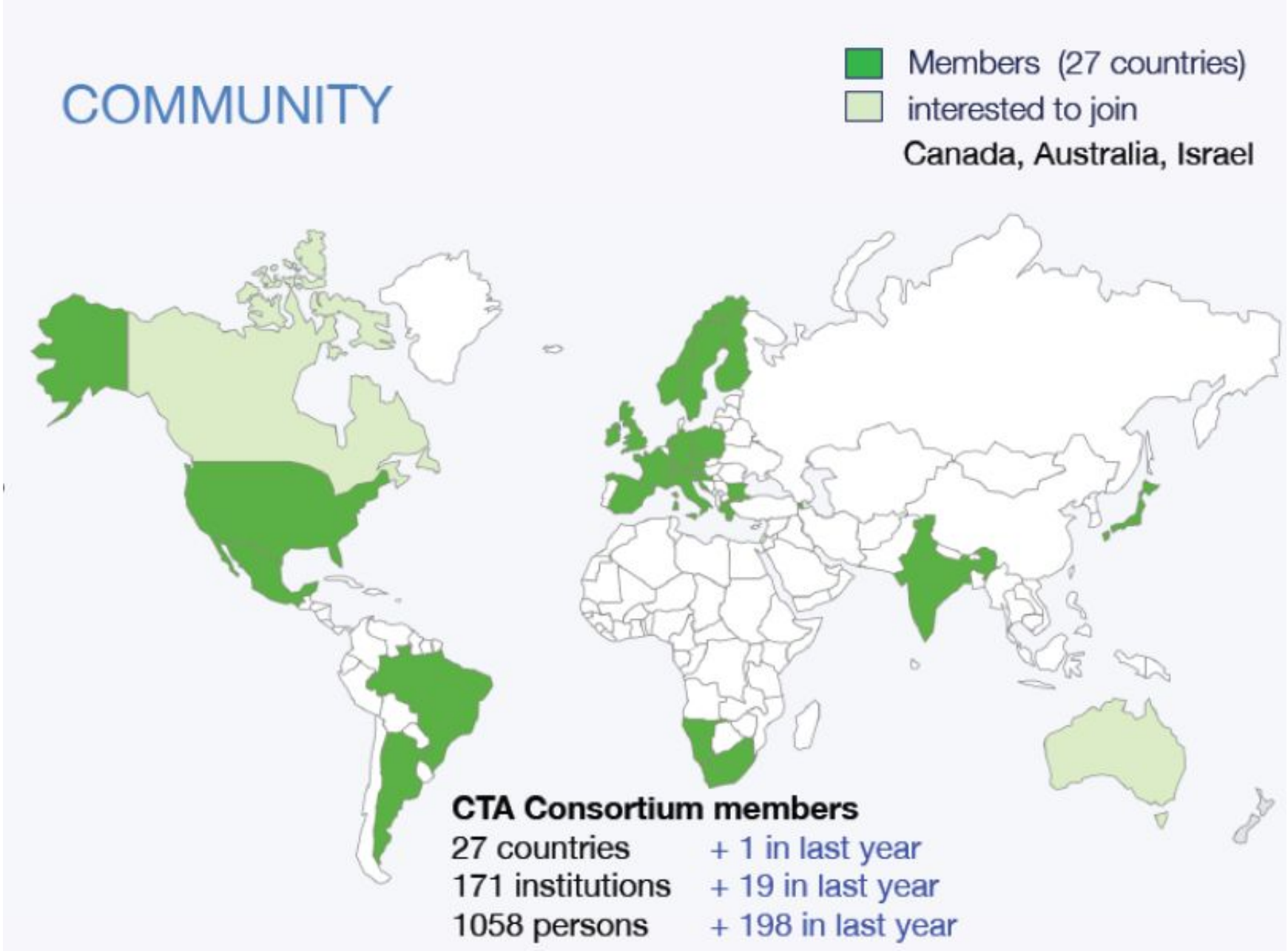
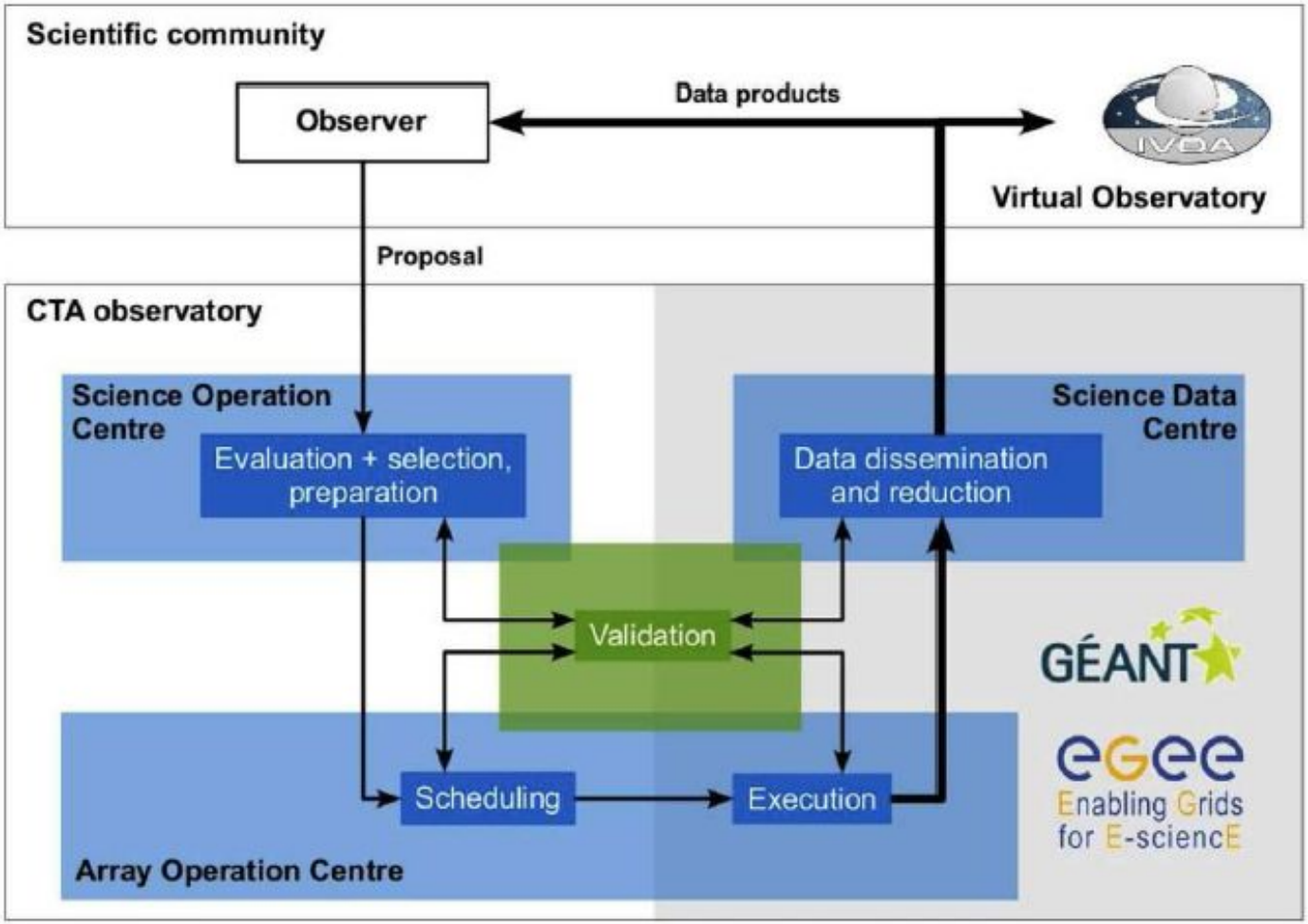
The CTA project



The CTA project

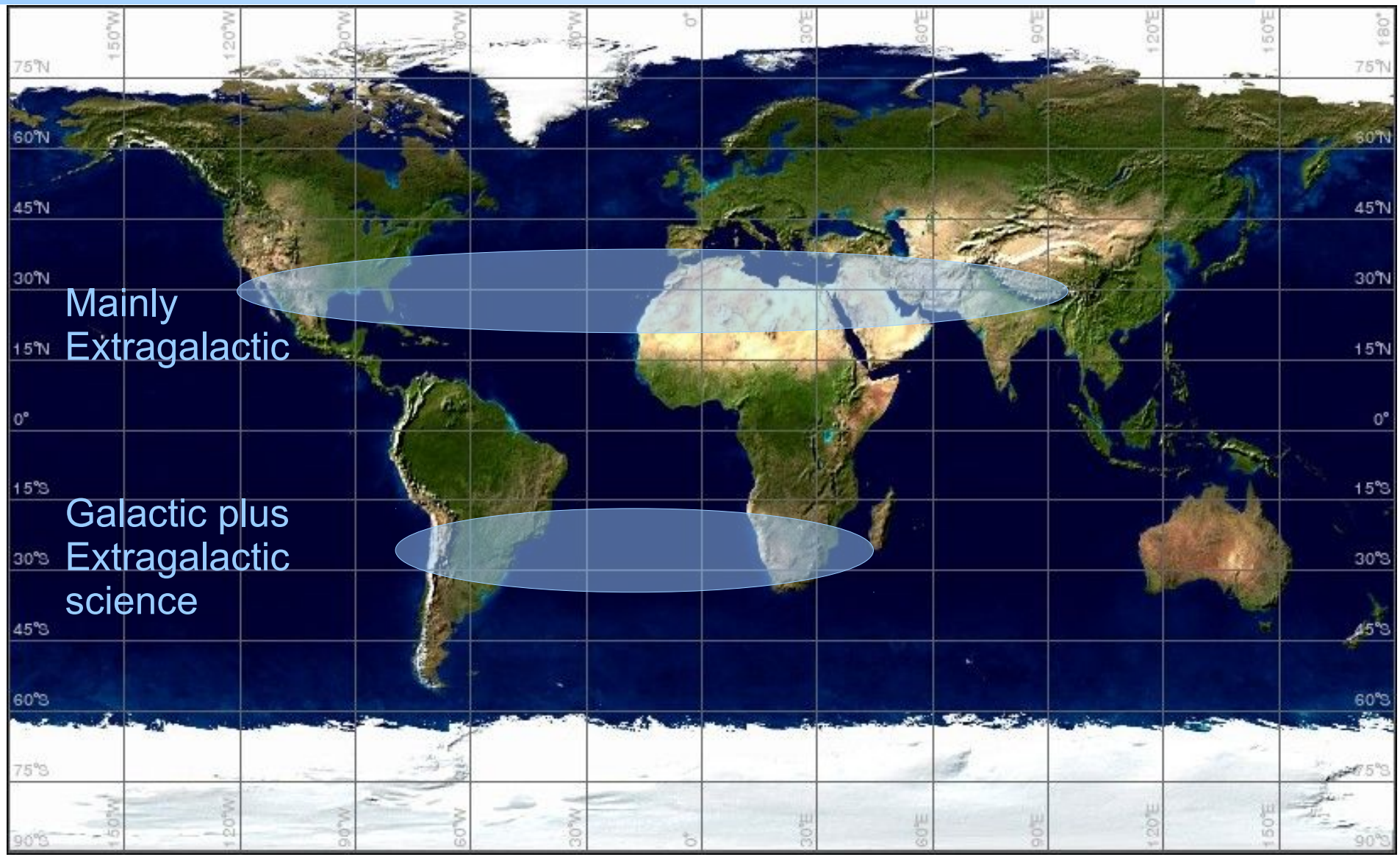
CTA as an Open Observatory



– Open formats and tools following astronomy standards (e.g. FITS) to represent and analyze data and instrument response functions (IRFs)

– User-oriented data center & Virtual Observatory interfaces

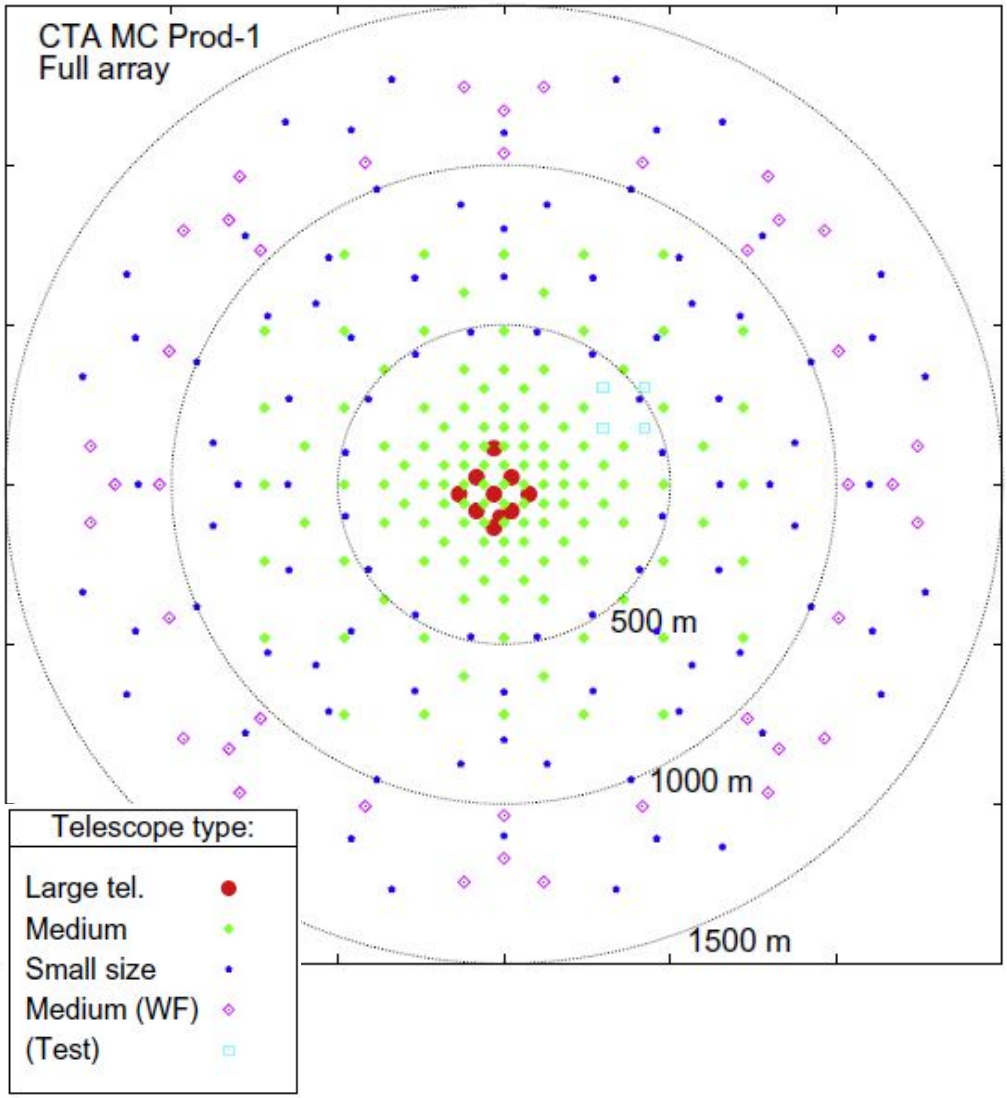
The CTA project



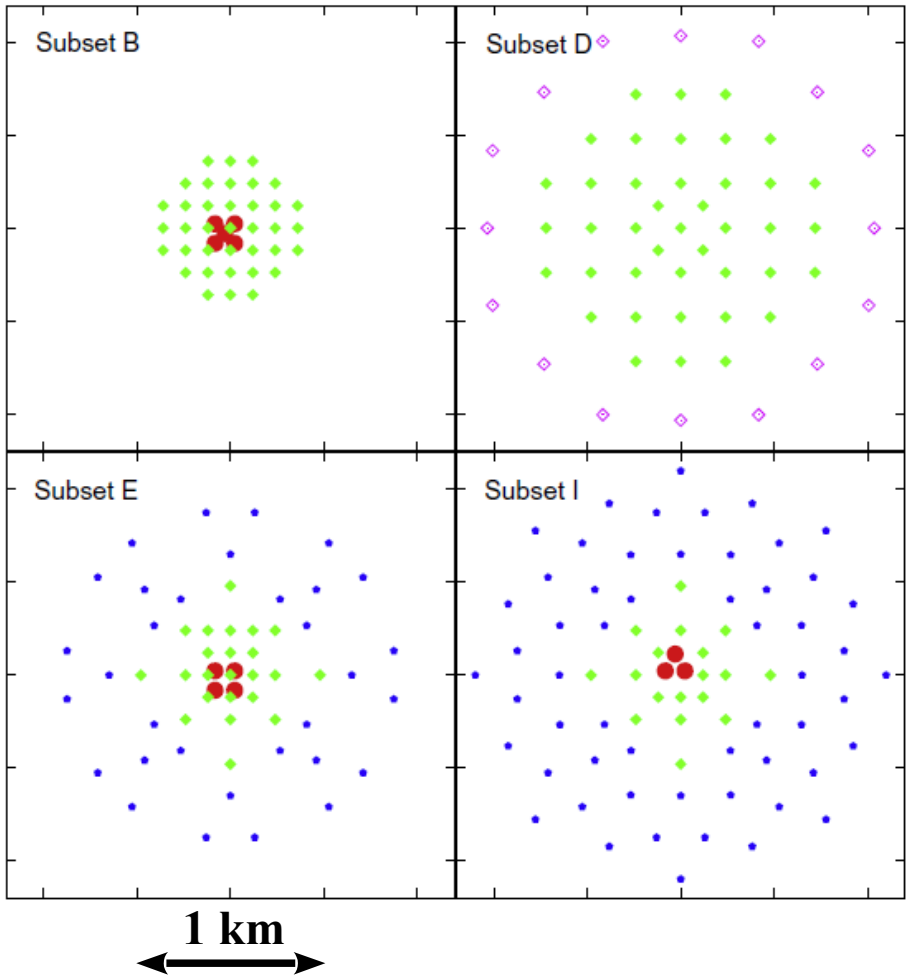
Selection of sites by 2013-2014

10 km^2 flat area, 1.5-4.0 km altitude, minimum cloud cover, easiest access, ...

The CTA project

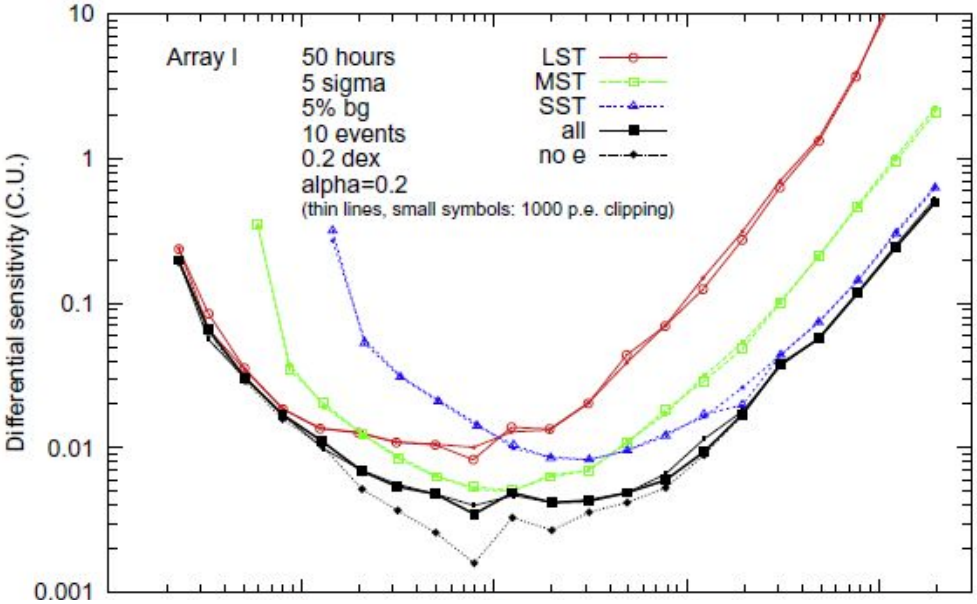


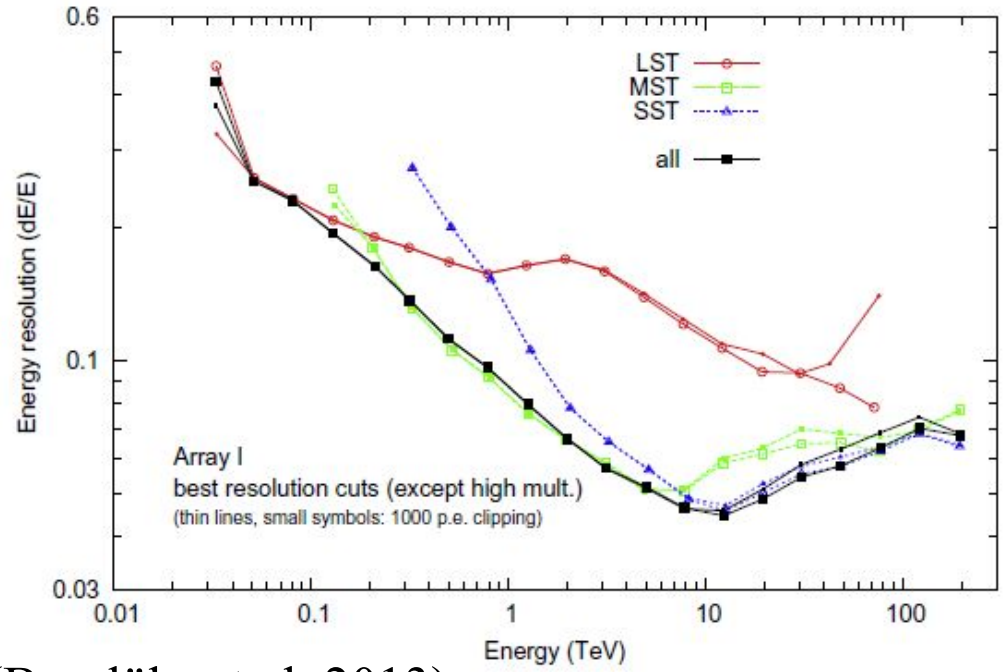
(Bernlöhr et al. 2013)



275-telescope configuration used in the MC simulations &
4 representative layouts considered for the science cases

The CTA project





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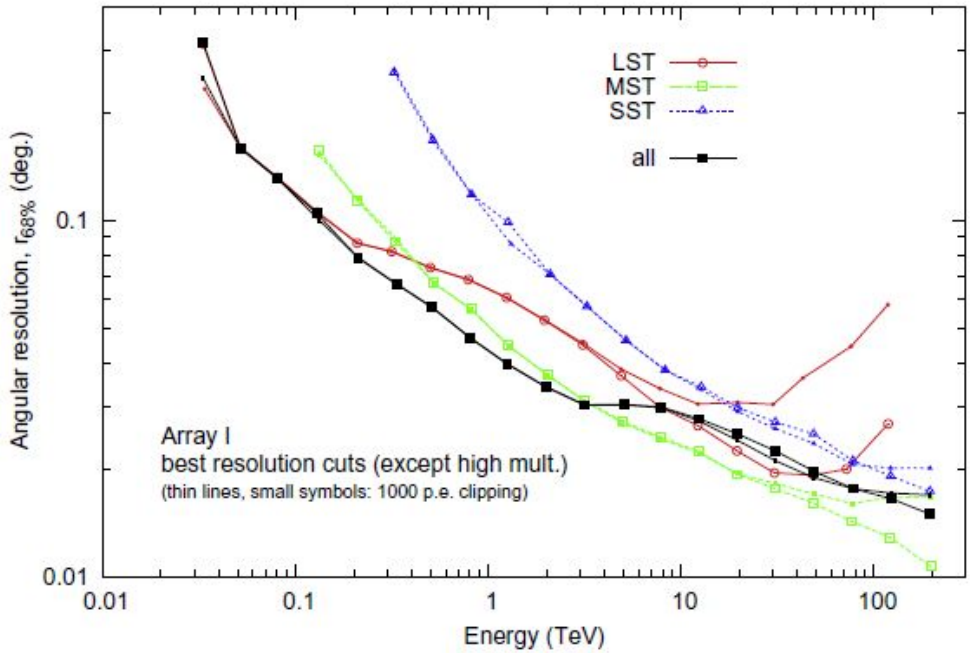
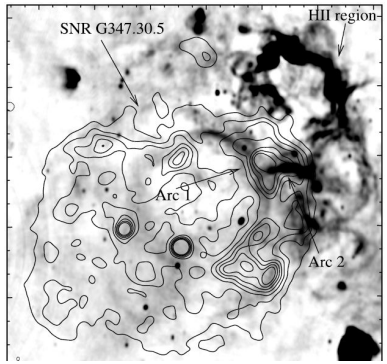
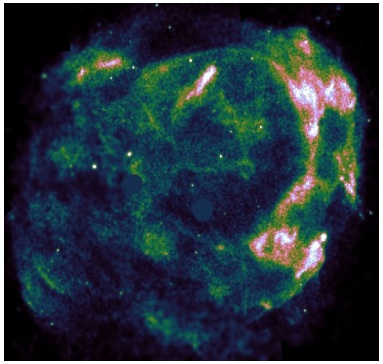


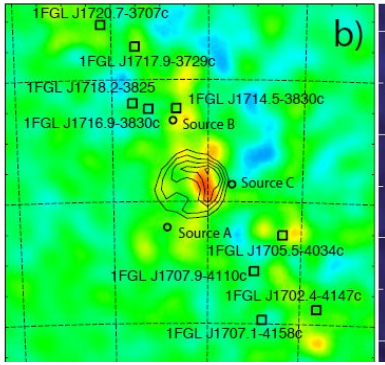
Performances of CTA configurations have been assessed for each scientific topic

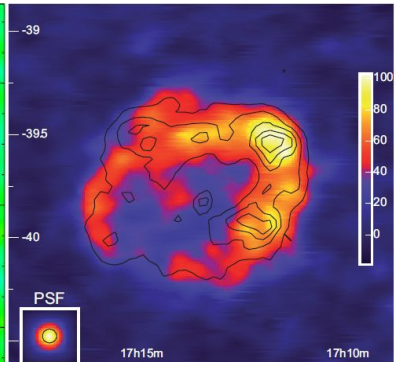
«Seeing the High-Energy Universe with the Cherenkov Telescope Array» 2013, APh, Vol. 43

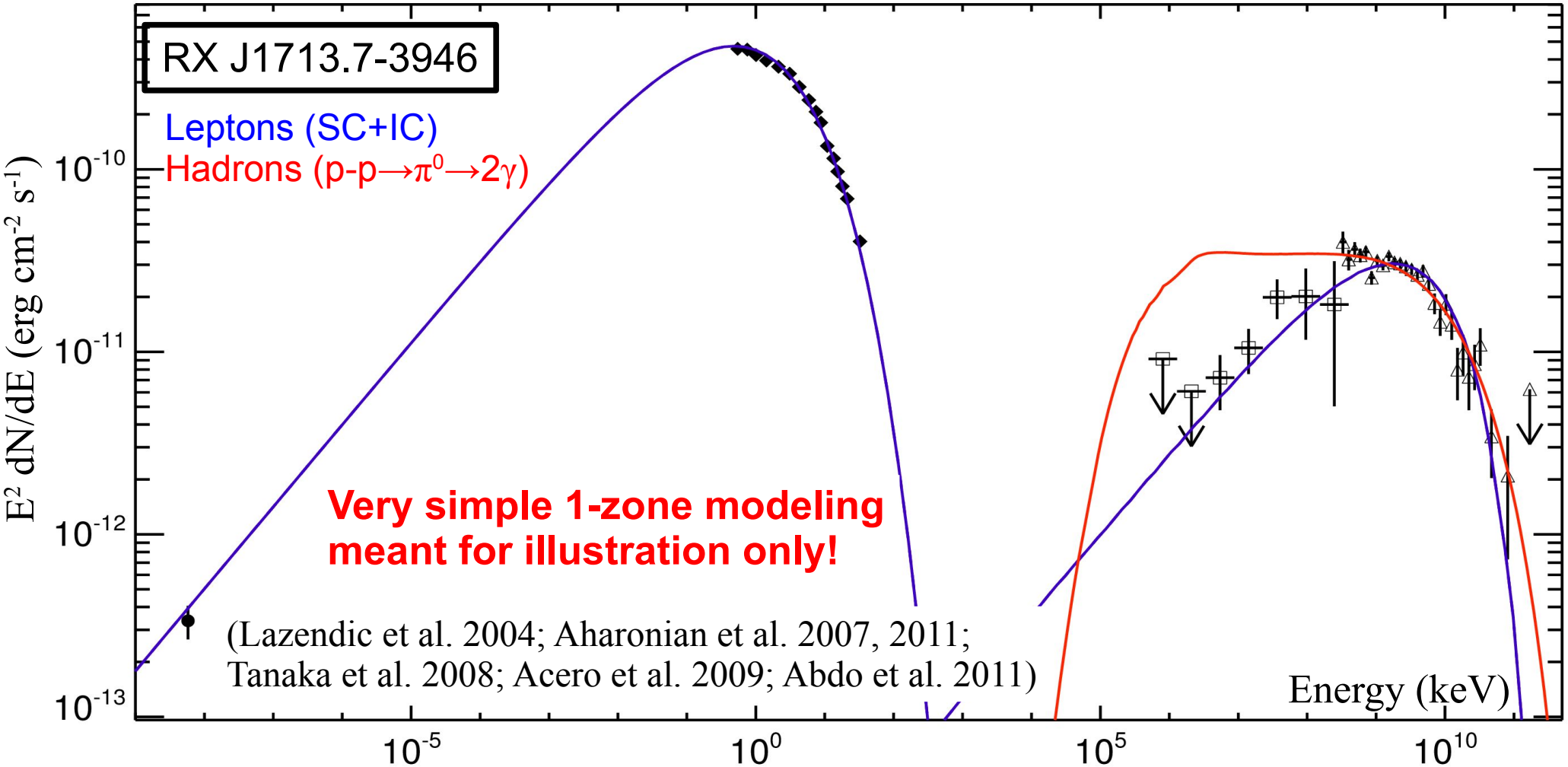
Prospects on SNRs with CTA











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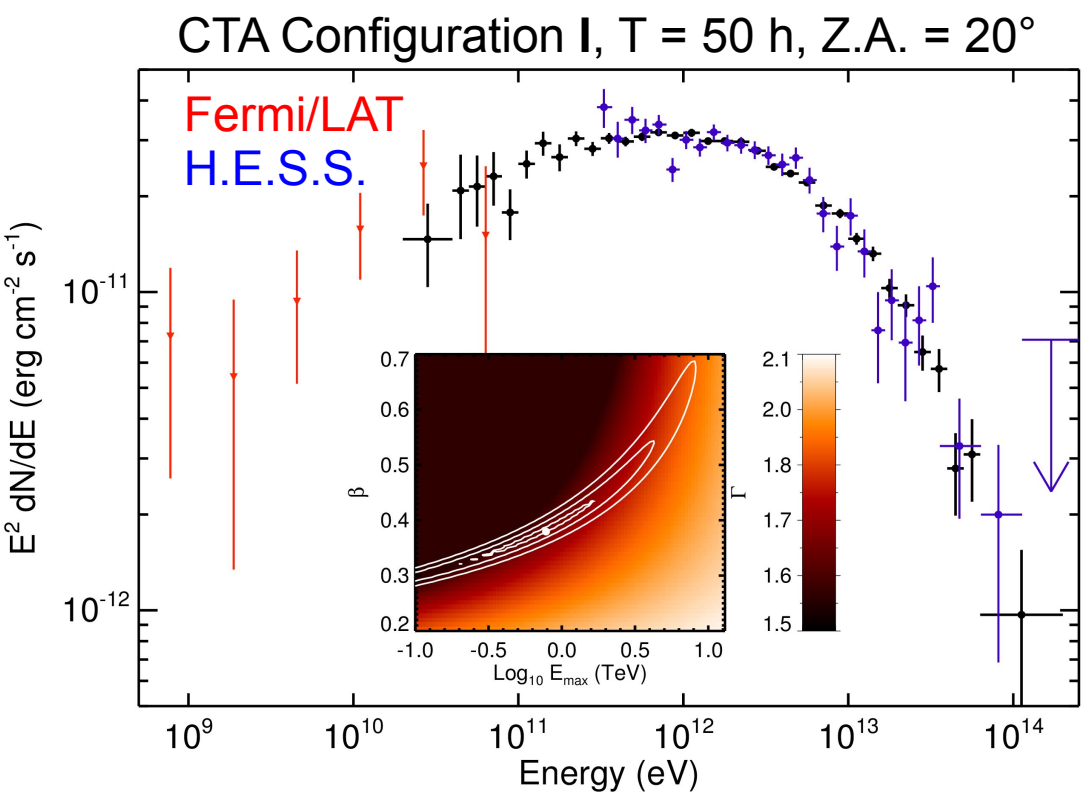
(Lazendic et al. 2004; Aharonian et al. 2007, 2011; Tanaka et al. 2008; Acero et al. 2009; Abdo et al. 2011)

Prospects on SNRs with CTA

RX J1713 TeV spectrum



RX J1713.7-3946 spectral parameters

Best-fit on the *Fermi*/LAT-H.E.S.S. data

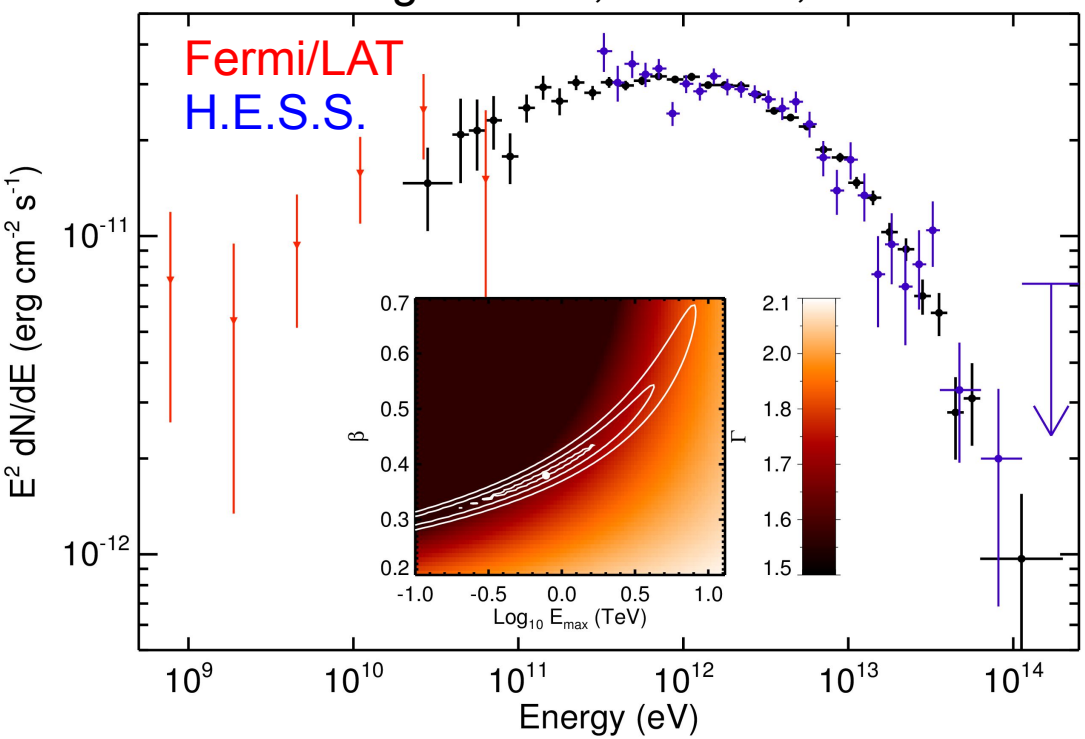
$dN/dE = N_0 E^{-\Gamma} \exp(-(E/E_{max})^{\beta})$

$\rightarrow \{\Gamma, \beta, E_{max}\}$ well constrained

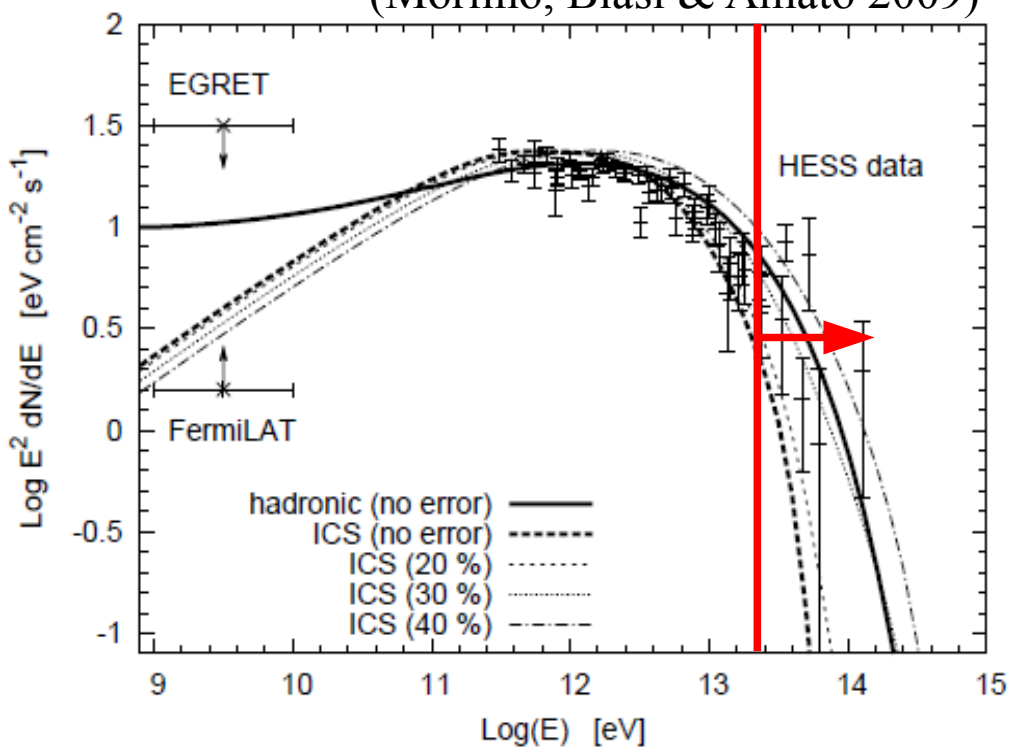
Prospects on SNRs with CTA

RX J1713 TeV spectrum

CTA Configuration **I**, T = 50 h, Z.A. = 20°



(Morlino, Blasi & Amato 2009)



RX J1713.7-3946 spectral parameters

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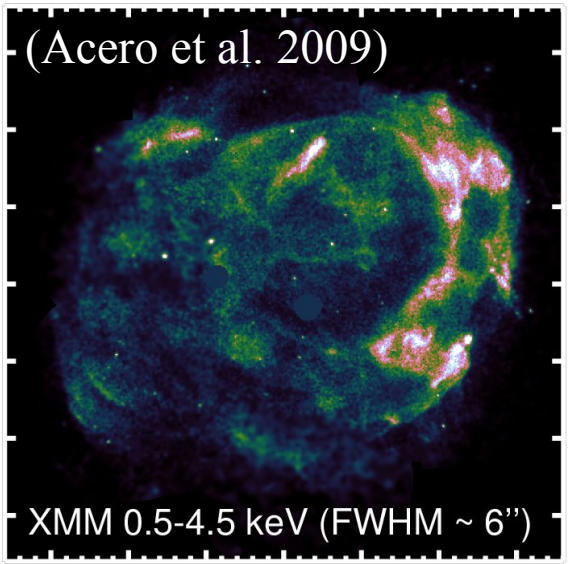
$dN/dE = N_0 E^{-\Gamma} \exp(-(E/E_{max})^{\beta})$
$\rightarrow \{\Gamma, \beta, E_{max}\}$ well constrained

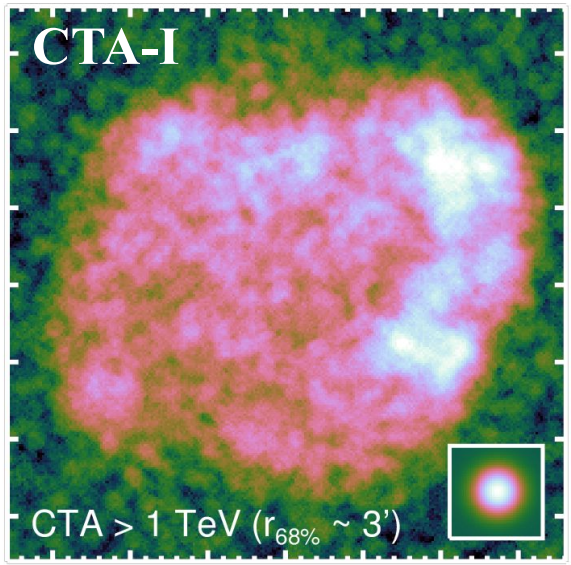
Nature of the VHE emission > 35 TeV ?

H.E.S.S. data > 35 TeV : 2.5, 1.5 & 0.6σ
CTA Config. **I** → **$S/N_{>35TeV} \sim 7\sigma$ in 50 h**

Prospects on SNRs with CTA

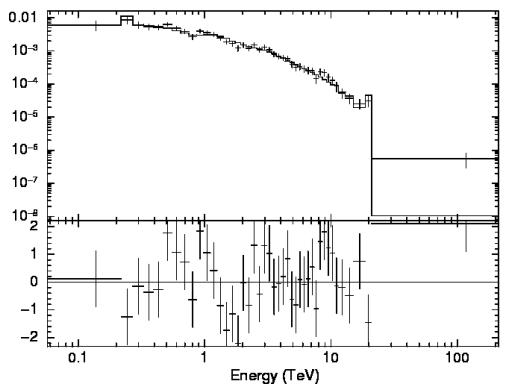
RX J1713 Spectro-imaging analysis

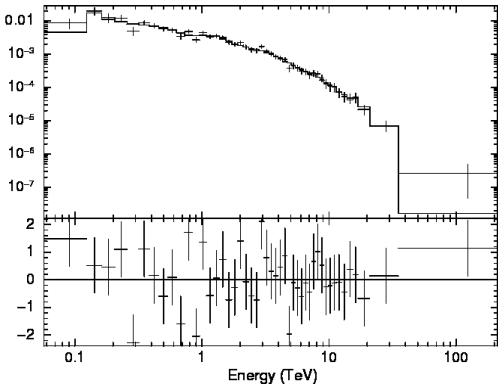


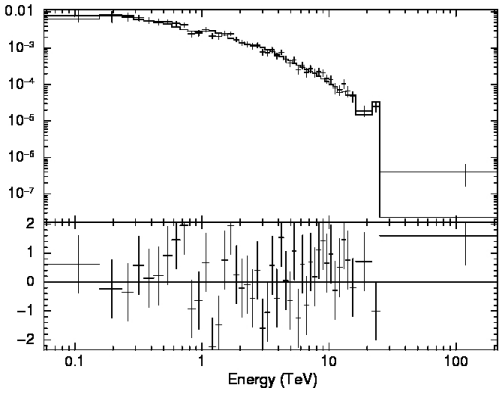


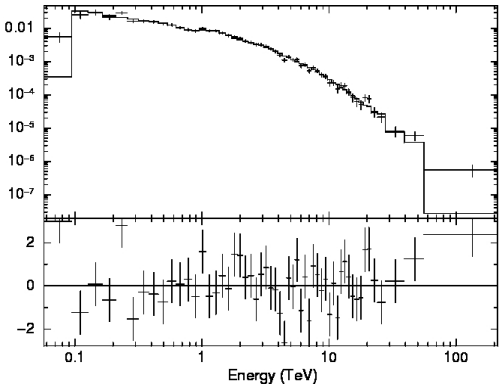
CTA simulation (T = 50 h, Z.A. = 20°) of RX J1713.7-3946 as seen by XMM with *Fermi*/LAT & H.E.S.S. spectrum: $dN/dE = N_0 E^{-\Gamma} \exp(-(E/E_{max})^{\beta})$

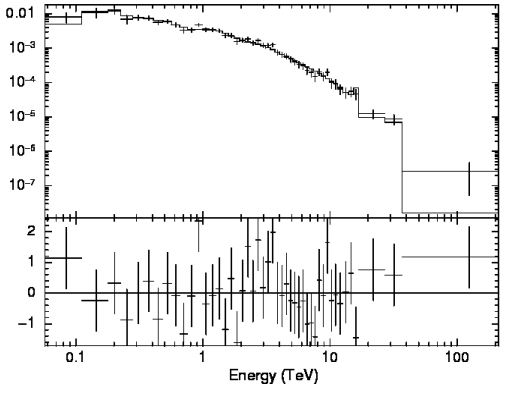
Prospects on SNRs with CTA

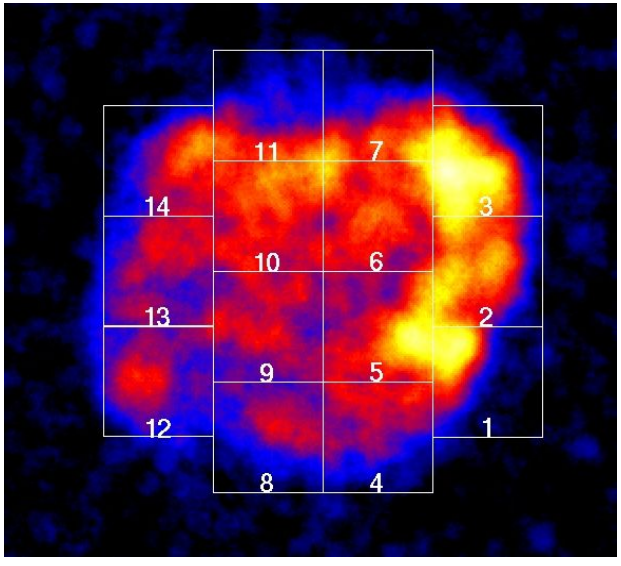










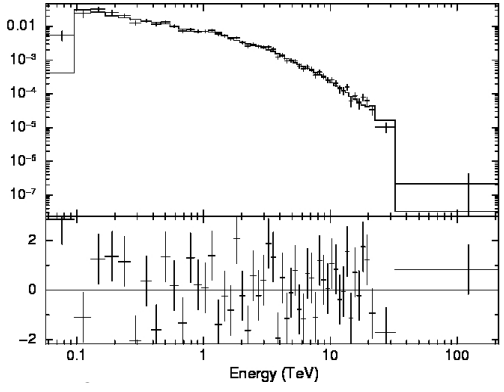


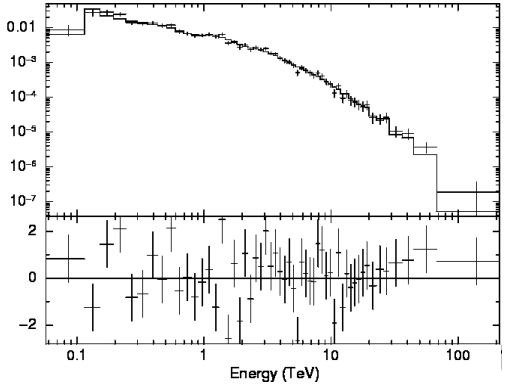
σ_{Γ} = 0.08

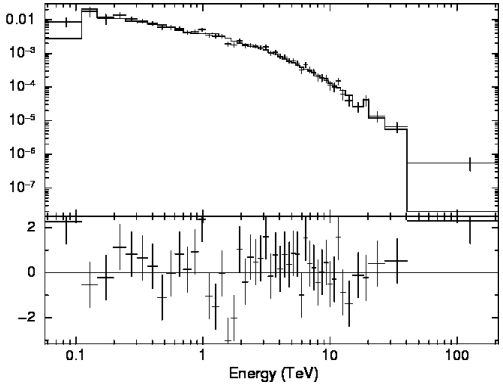
σ_{Emax} = 0.3 TeV

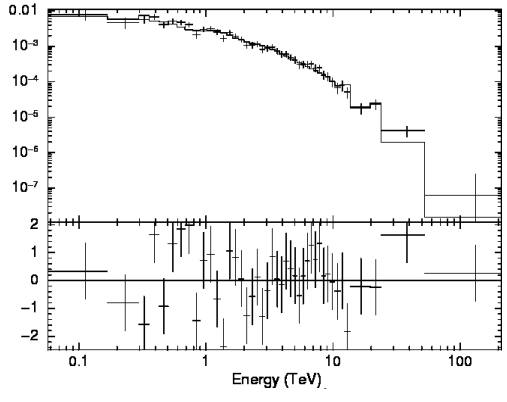
σ_{N1TeV} = 25 %

→ Possibility to explore azimuthal variations of E_{max}!

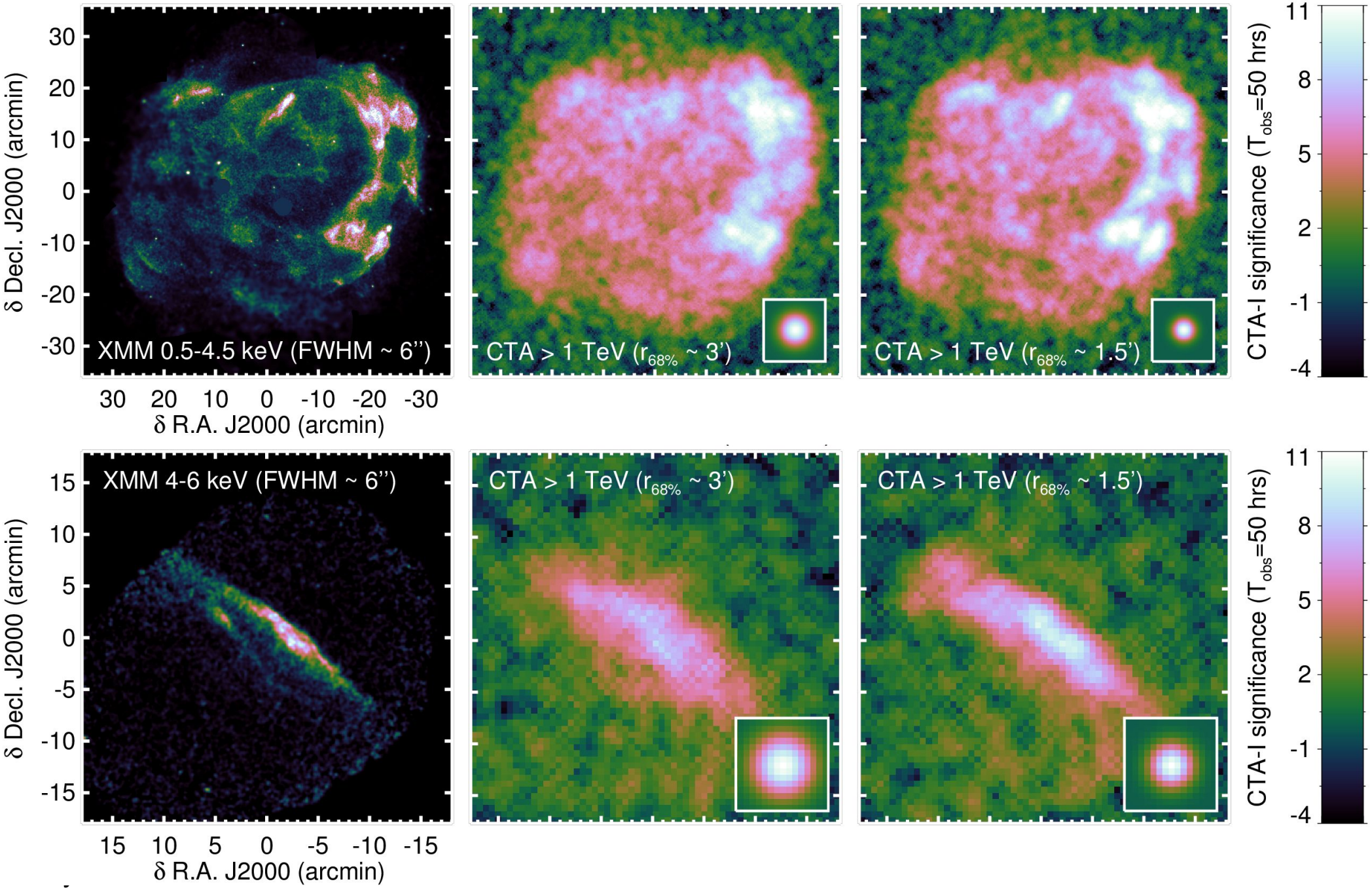








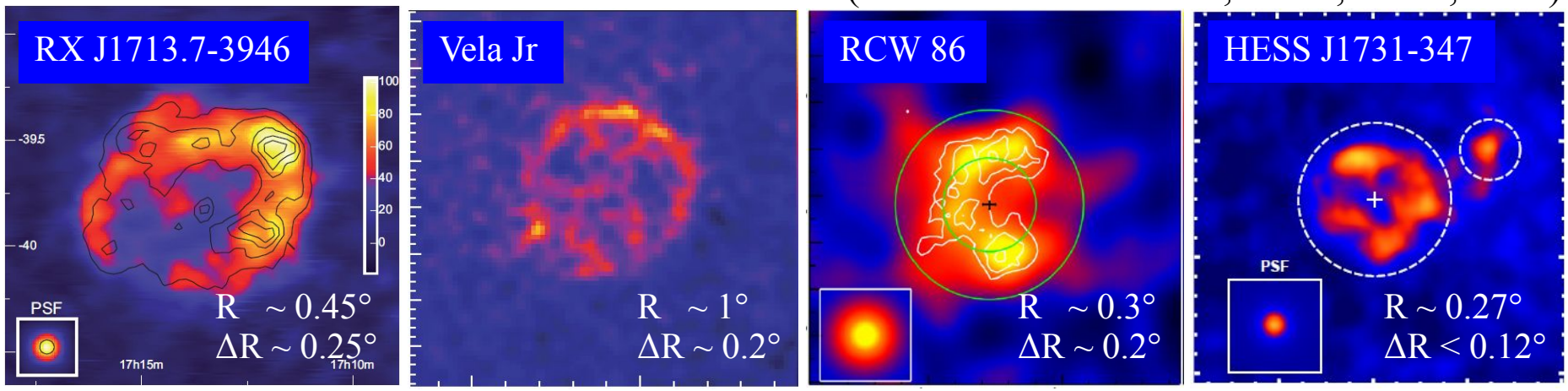
Prospects on SNRs with CTA

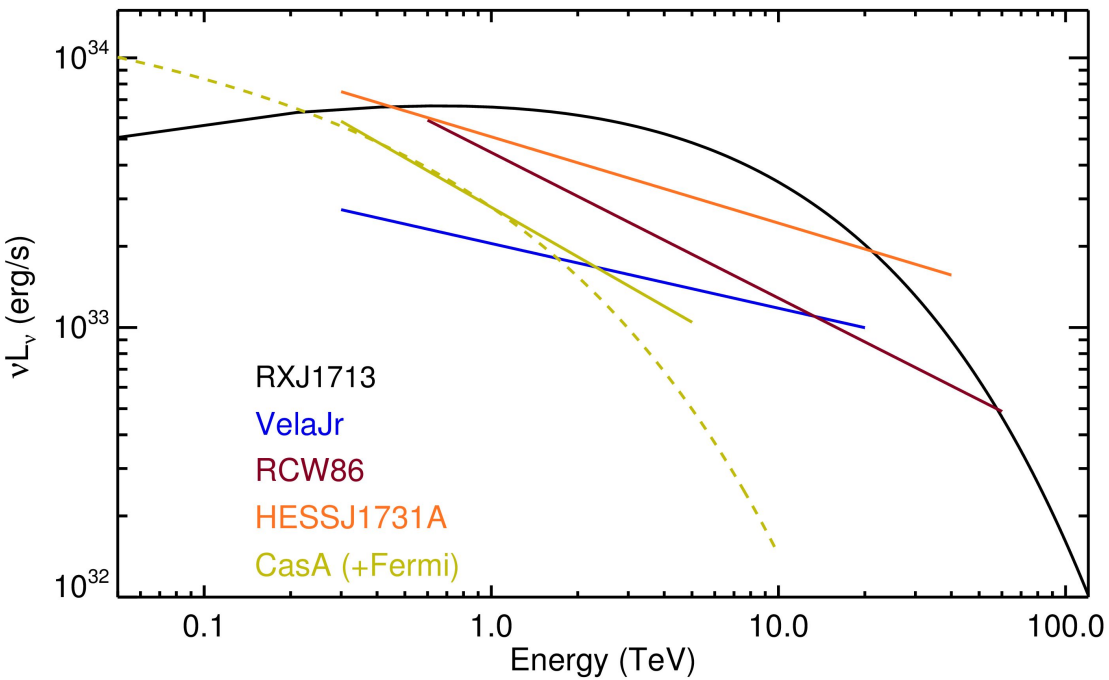


Prospects on SNRs with CTA

Population studies

(Aharonian et al. 2006 ; 2007 ; 2009 ; 2011)





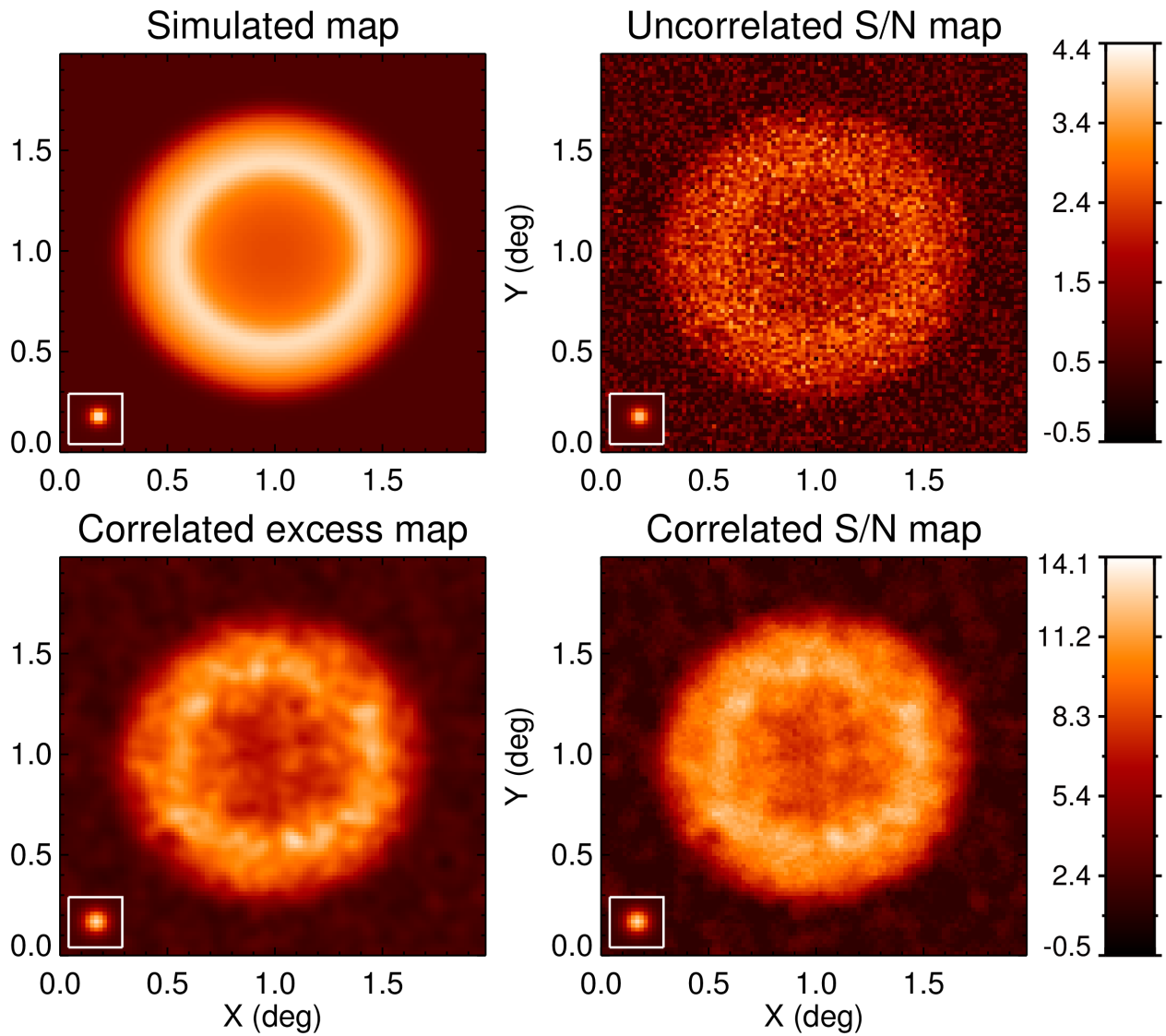
CTA simulations of RX J1713-, Vela Jr-, RCW86-, HESS J1731-like SNRs with their spectral and morphological properties as measured with H.E.S.S.

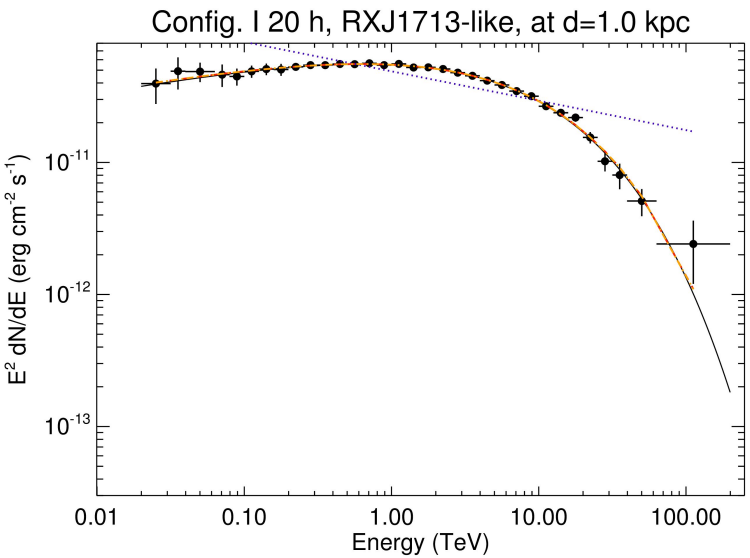
Horizons of :

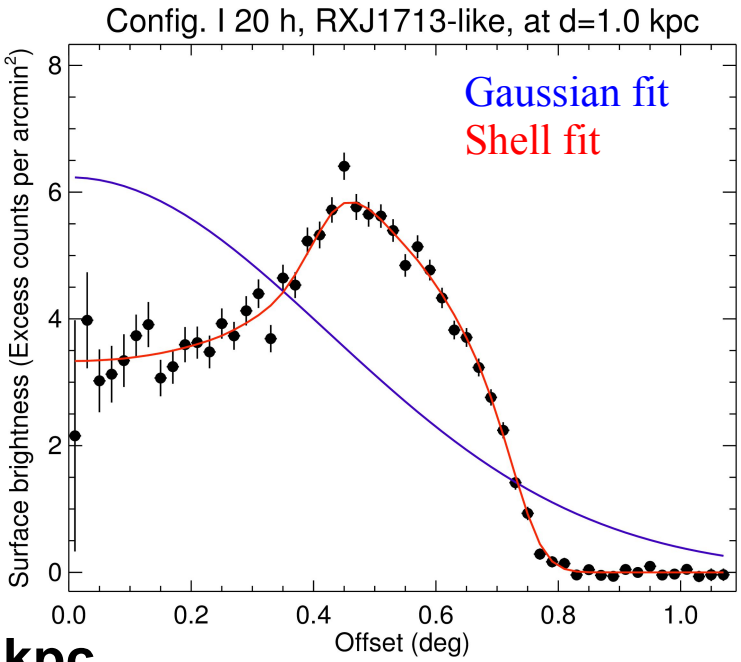
Detectability → d / S/N = 5σ
Resolvability → d / Shell favored over Gaussian fit

Prospects on SNRs with CTA

Population studies



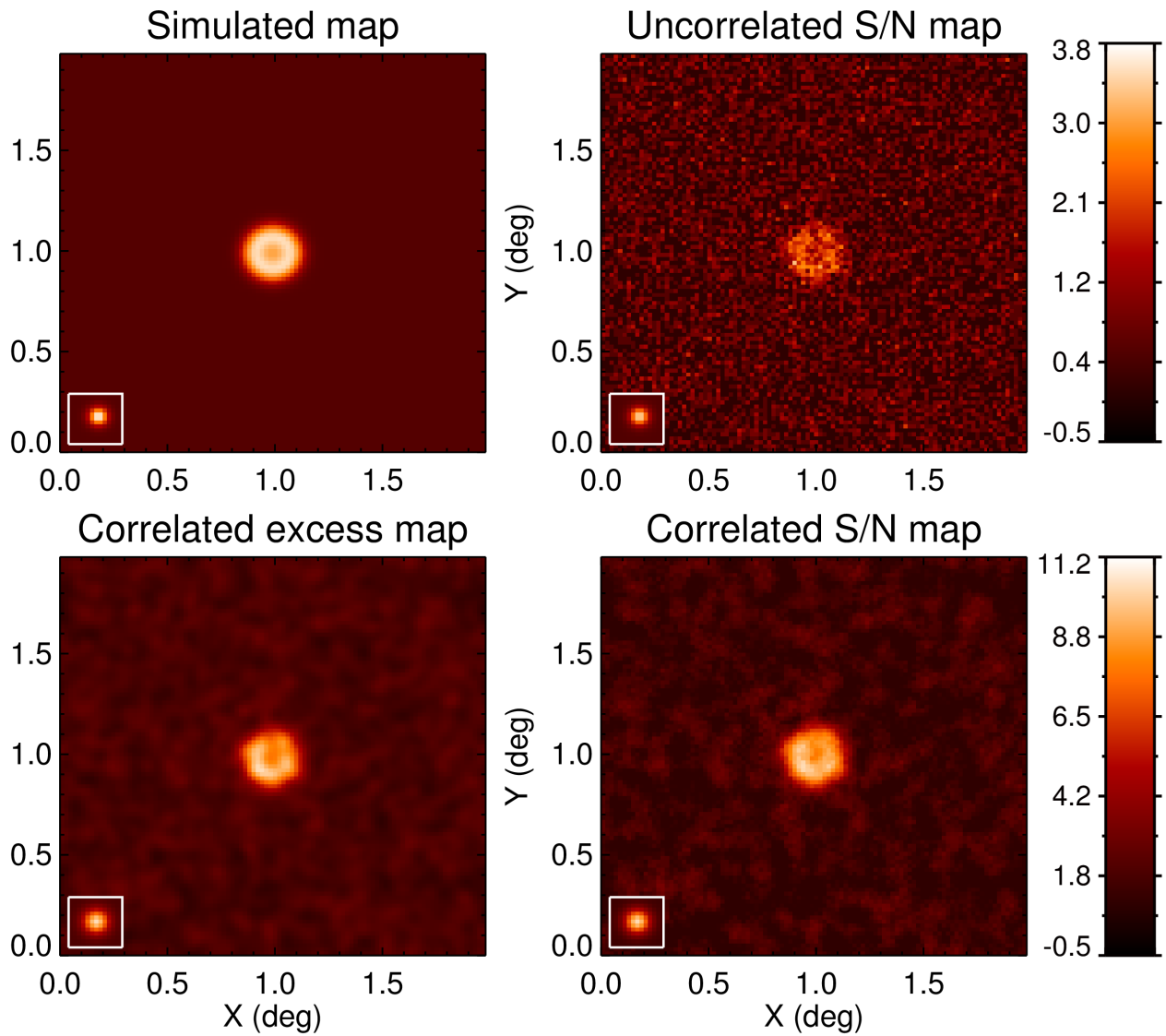


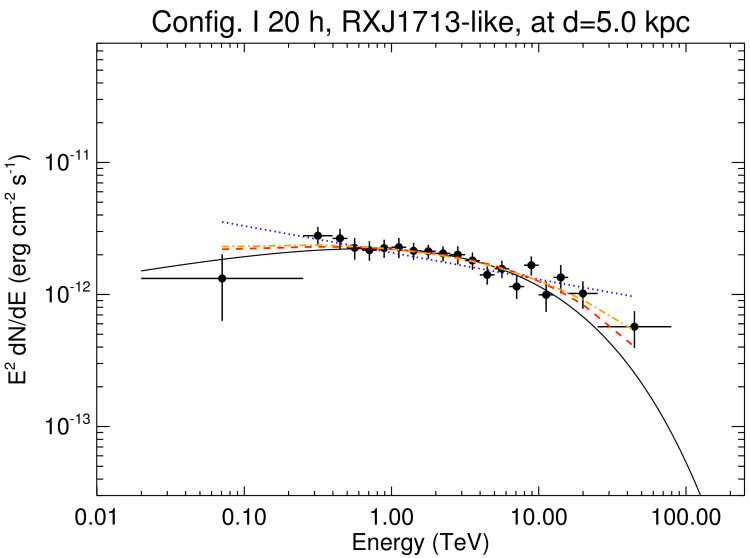


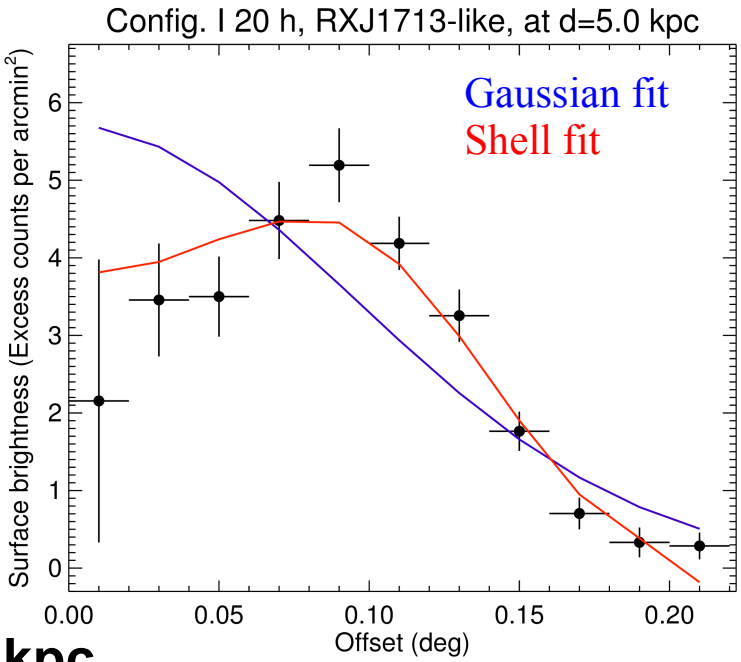
RX J1713-like SNR at 1 kpc

Prospects on SNRs with CTA

Population studies



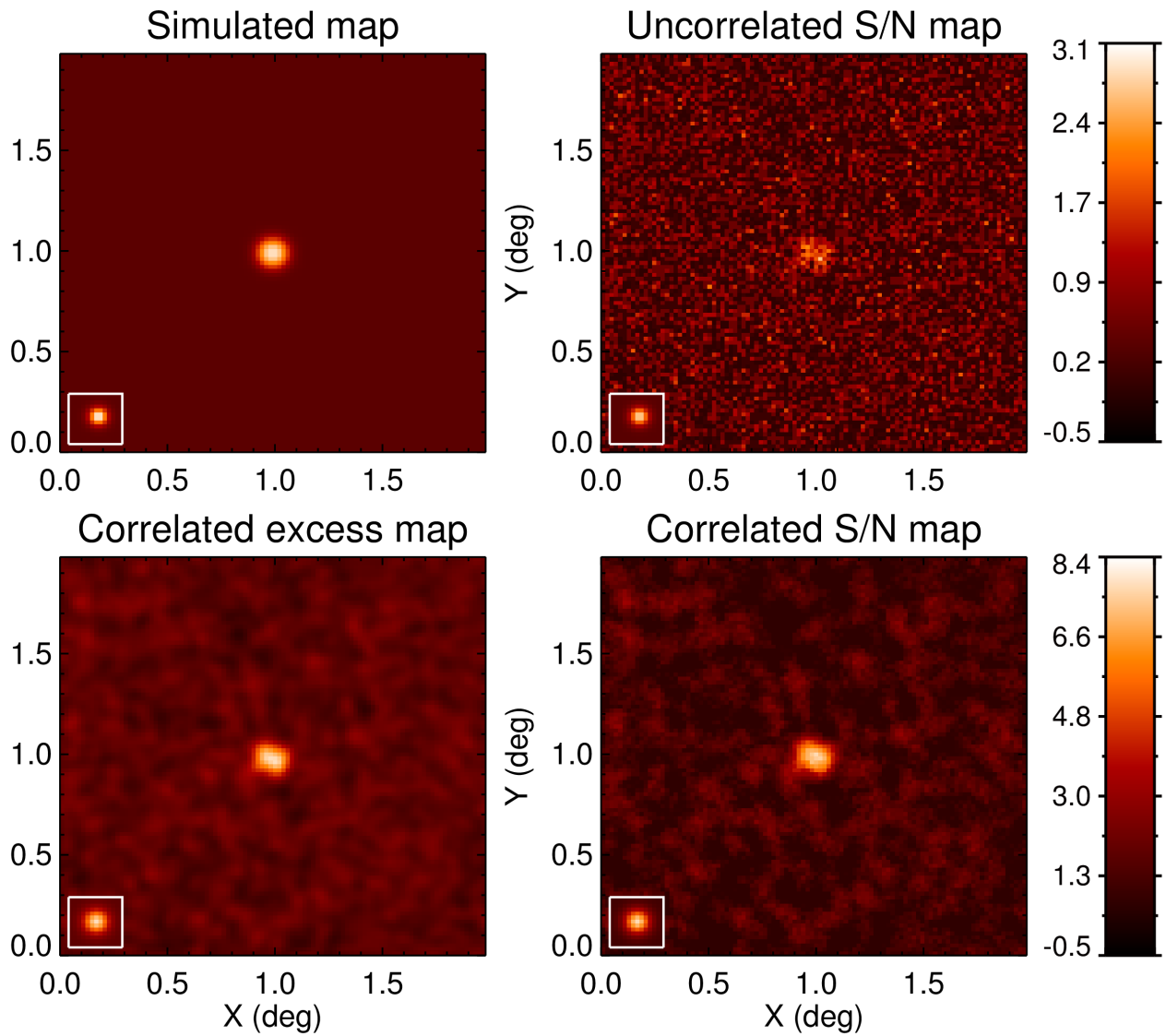


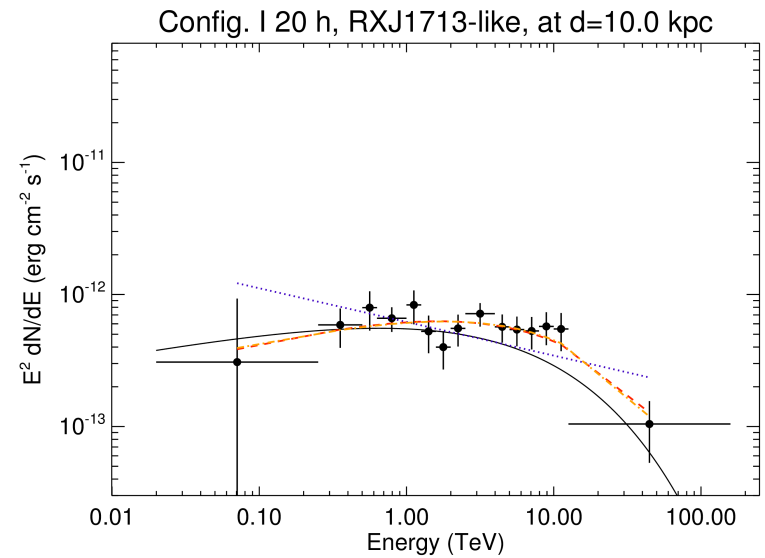


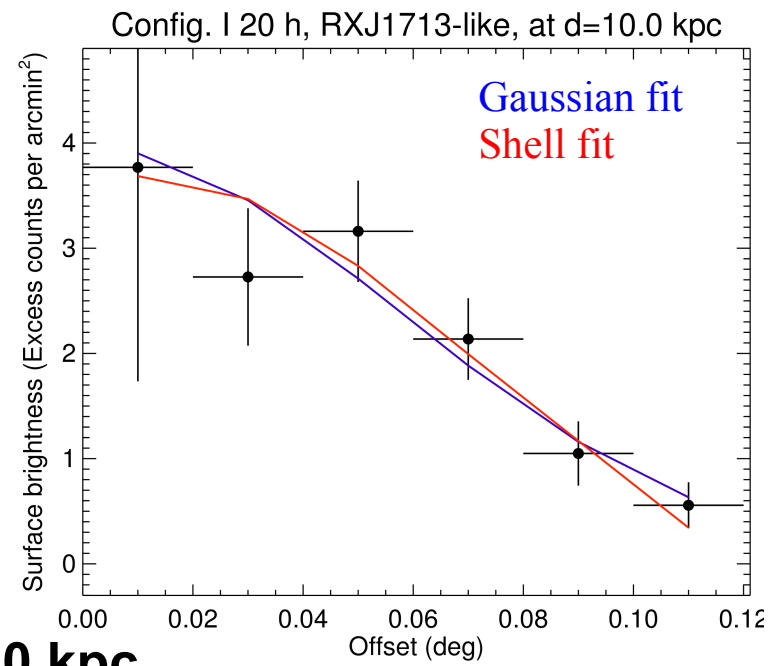
RX J1713-like SNR at 5 kpc

Prospects on SNRs with CTA

Population studies







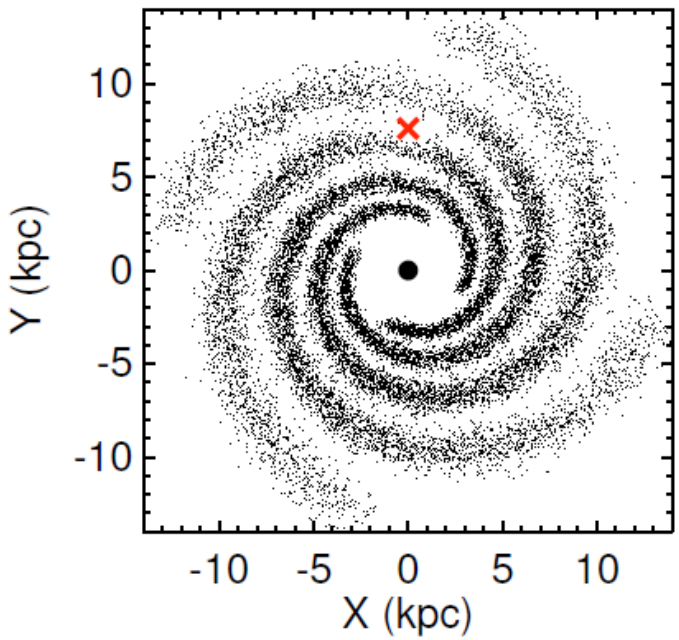
RX J1713-like SNR at 10 kpc

Prospects on SNRs with CTA

Population studies (Acero et al. 2013)

Simulate Galactic (core-collapse) SNR distribution :

Assume R_{gal} distribution of Case & Bhattacharya (1998)
Concentrated around spiral arms as given by Vallée (2008)
With arm dispersion as in dust model of Drimmel & Spergel (2001)



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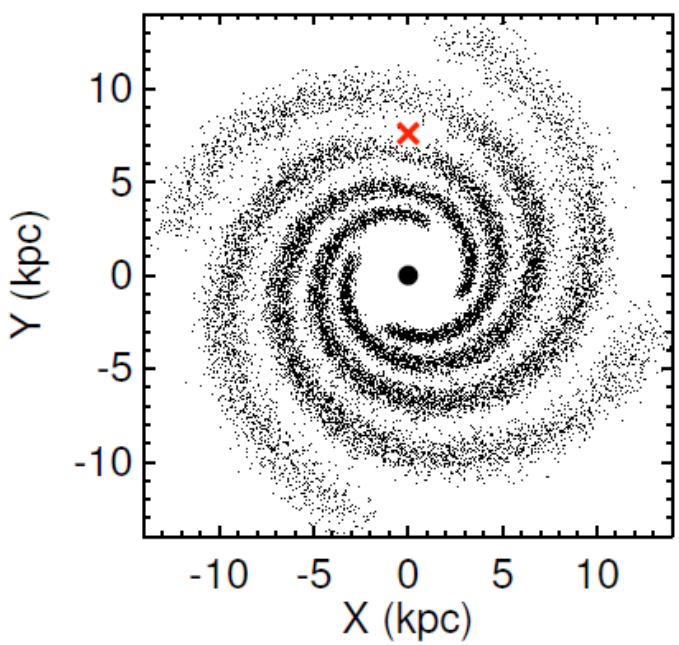

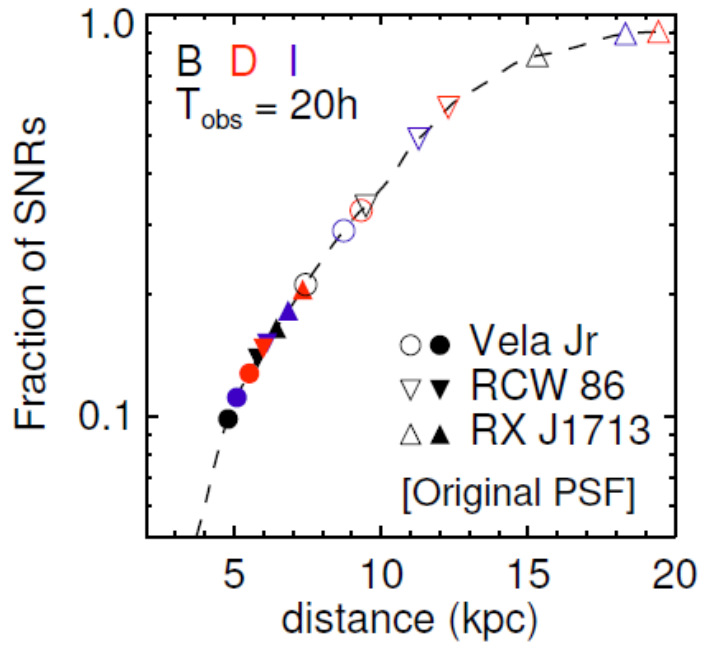

If all SNRs shine ~3000 yr in TeV → ~ 60 TeV-emitting SNRs
~ 20–55 would be **detectable** but only **~ 6–12** would be **resolvable** with CTA

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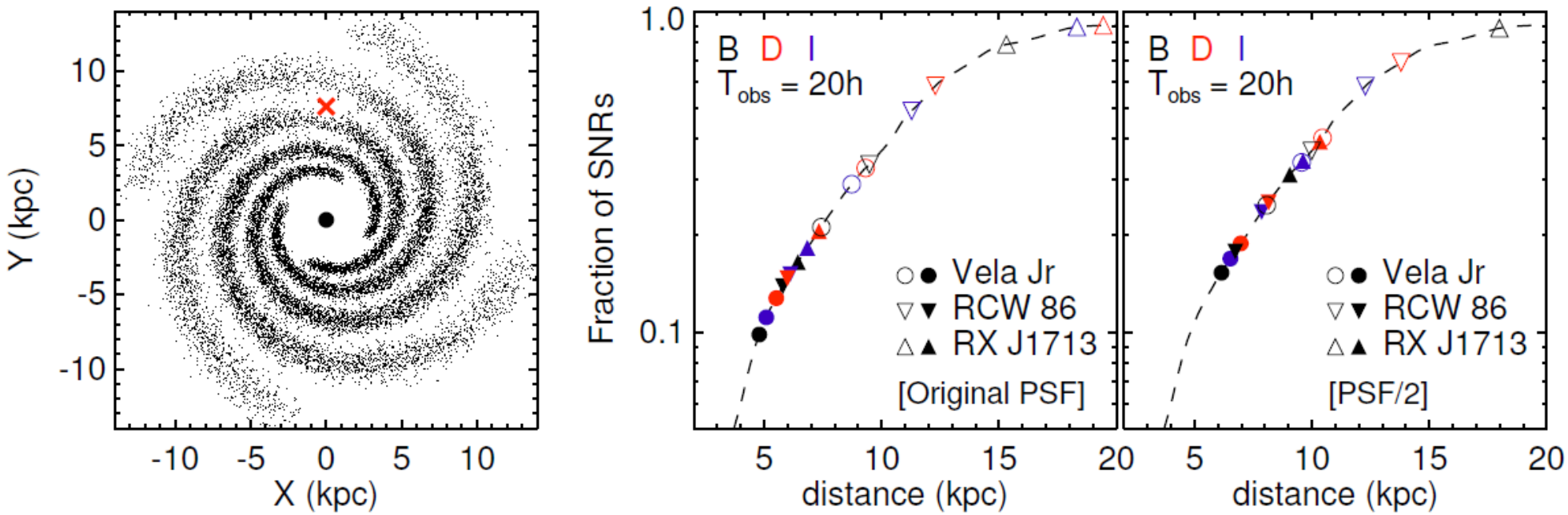

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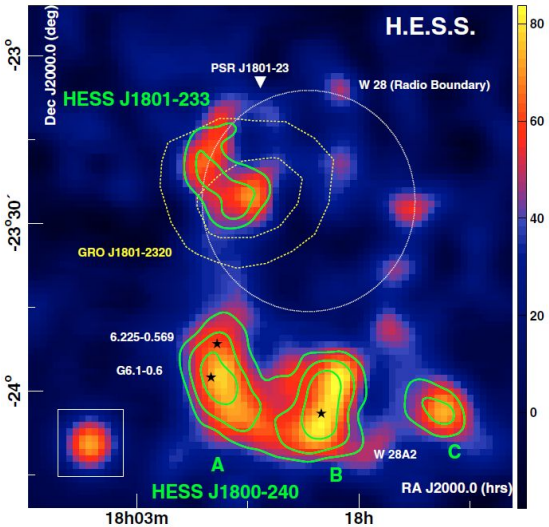
If CTA PSF improved by a factor of 2 → almost 2× more resolvable SNRs!

Prospects on SNRs with CTA

SNR/MC association



(Aharonian et al. 2008)

Prospects on SNRs with CTA

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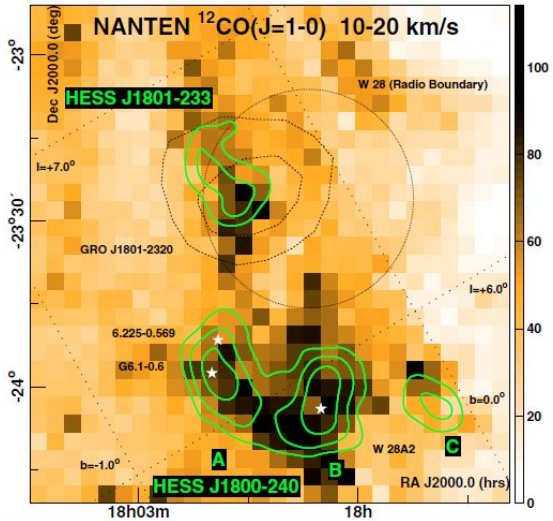

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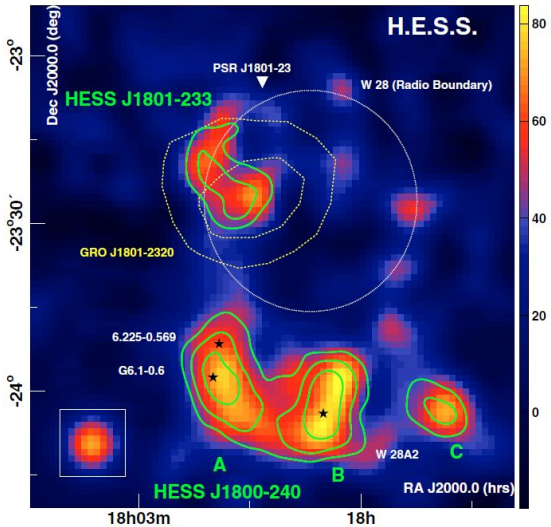

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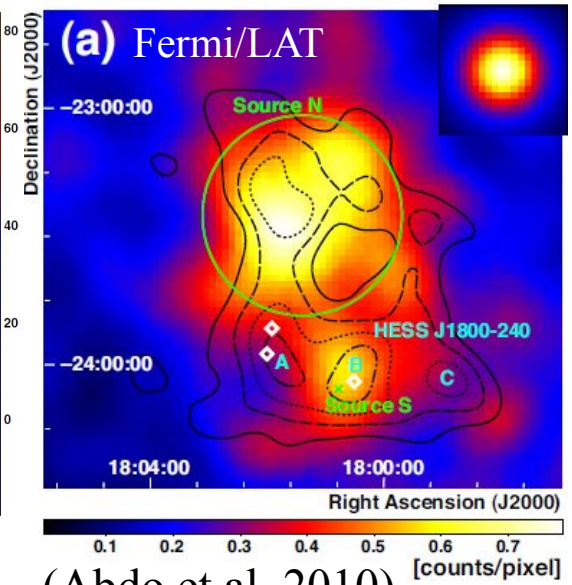
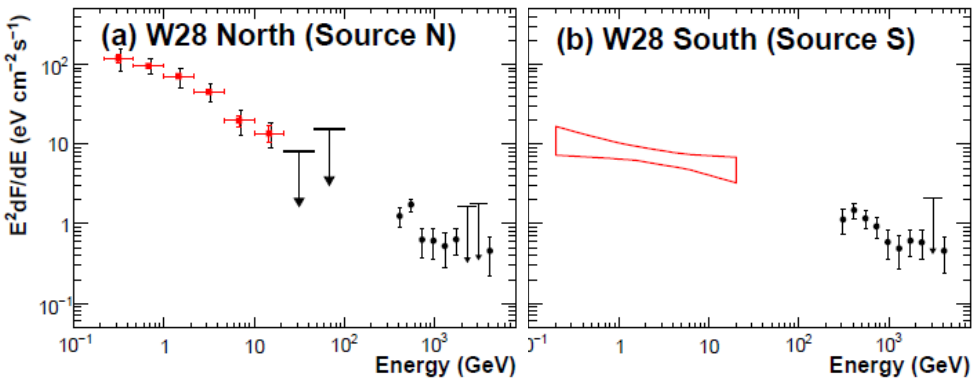


(Abdo et al. 2010)

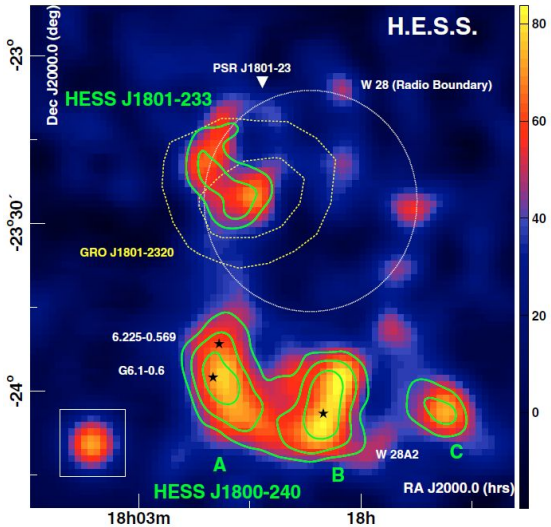


HESS J1801-233 **(Source N)** on E rim of W28
Coincident with GeV source
Coincident with CO cloud
1720 MHz OH maser : shock/MC interaction

HESS J1800-240B **(Source S)** outside W28
Coincident with GeV source
Coincident with CO cloud & HII region W28A2
MC illuminated by CRs escaping W28...?

Prospects on SNRs with CTA

SNR/MC association



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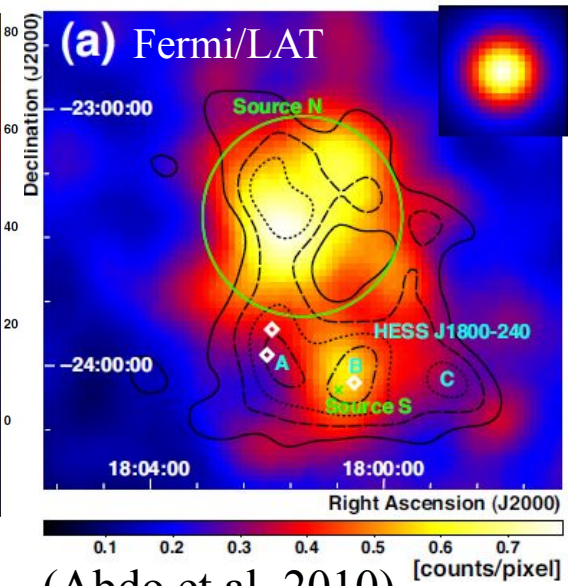

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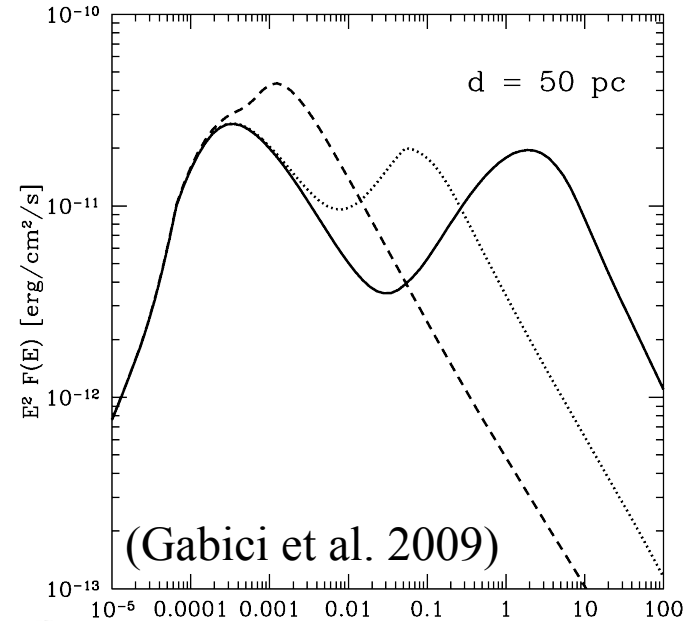

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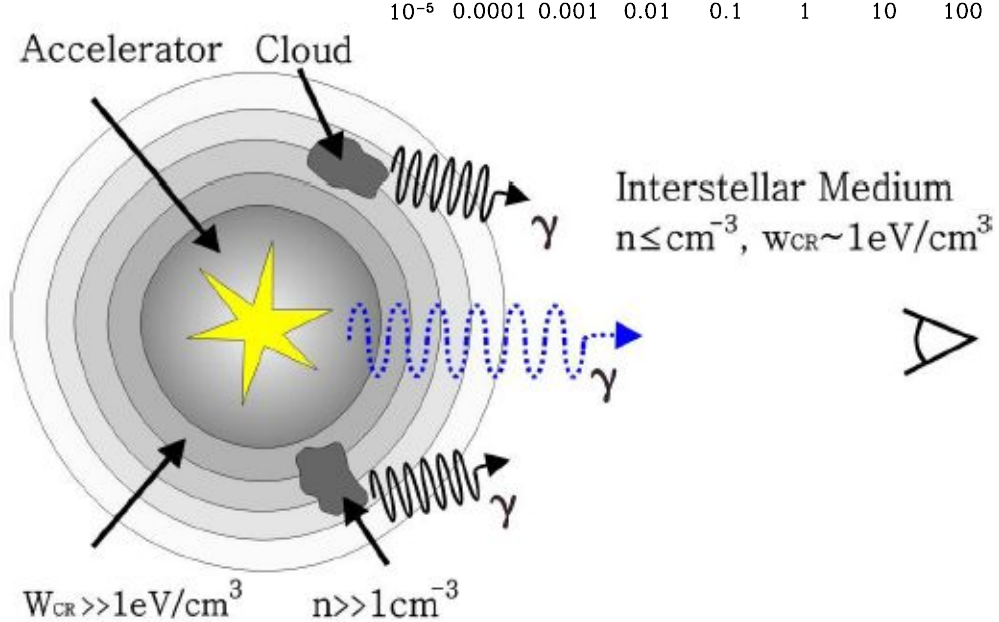

Prospects on SNRs with CTA

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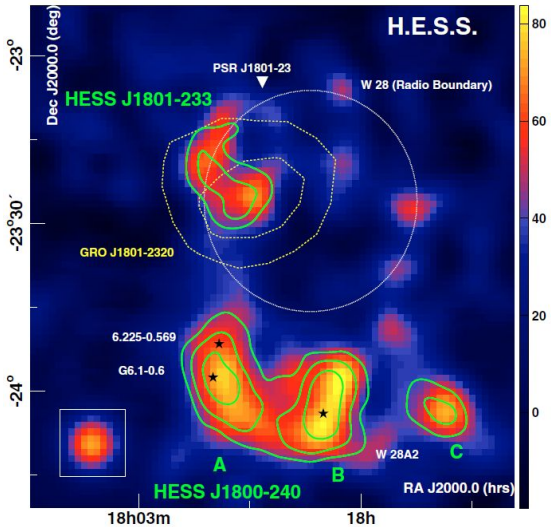

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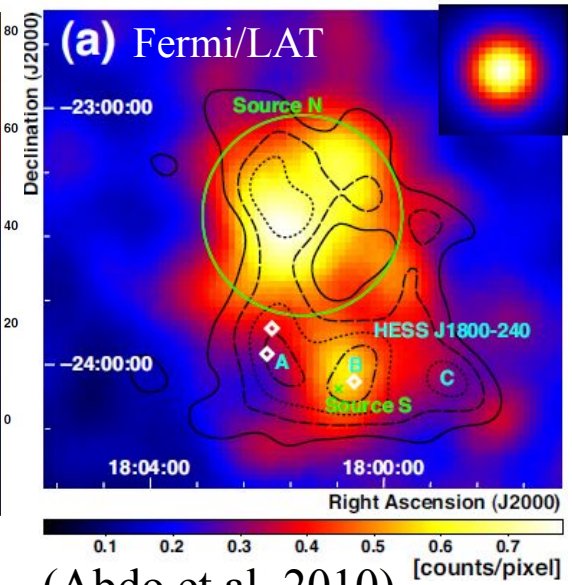
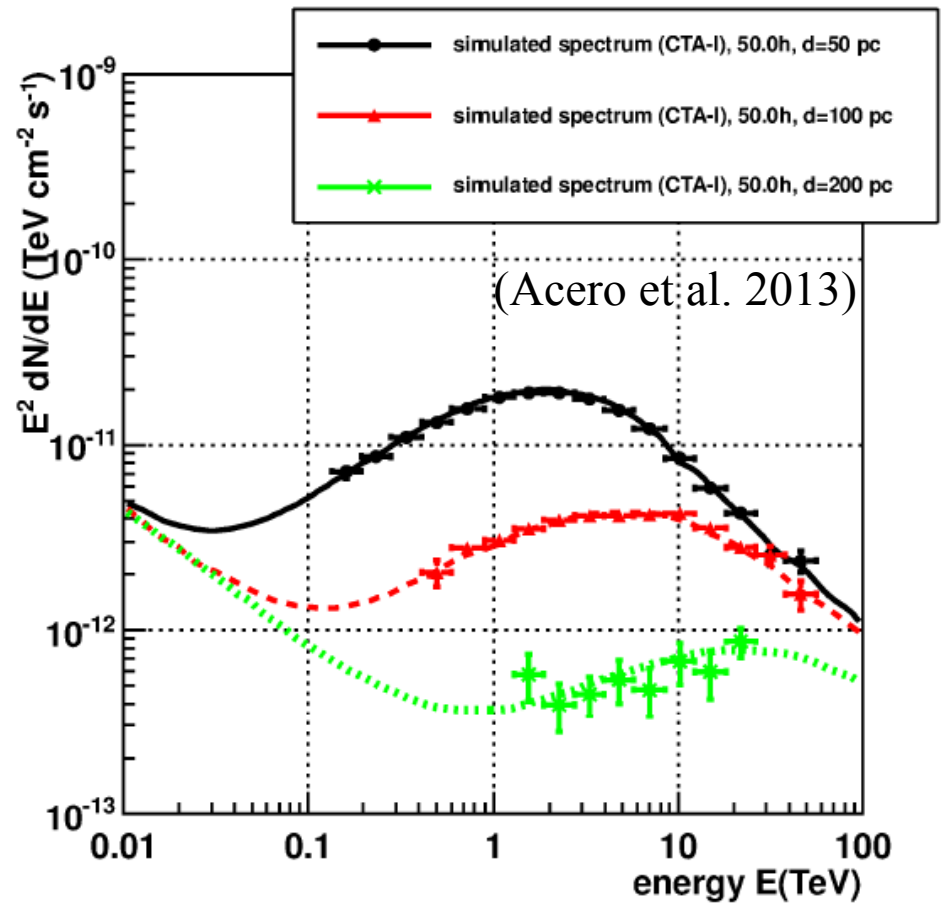


(Abdo et al. 2010)

Escaped CRs from a 2×10^3 yr-old SNR with E_{CR}/E_{SN} = 0.3, lying at **50**, **100**, **200** pc from a 10^5 M_0 Molecular Cloud (d = 1 kpc)



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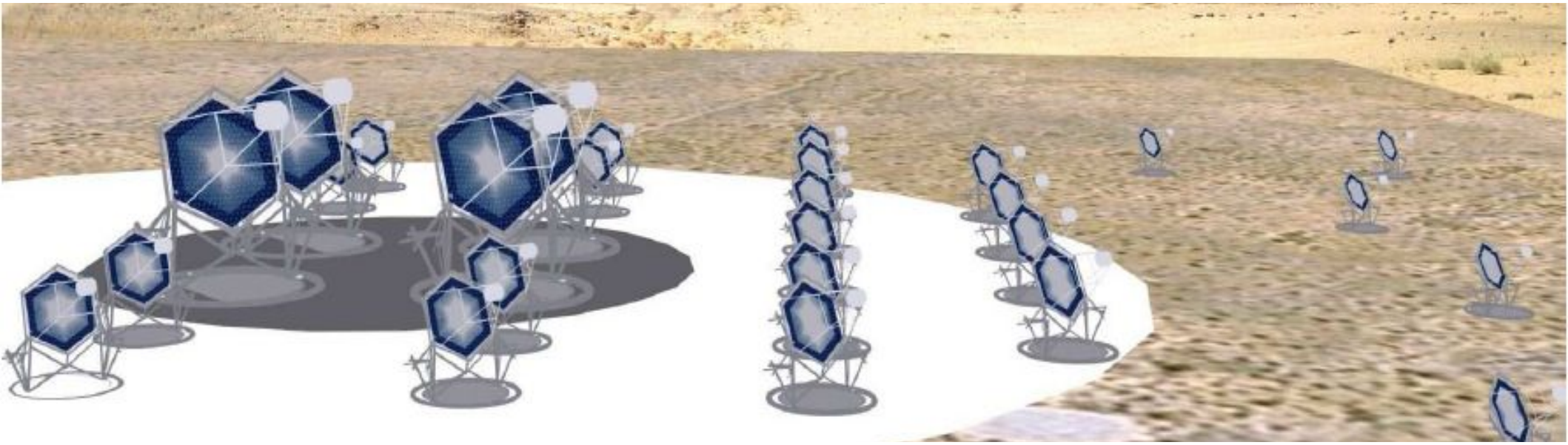
Conclusion & Perspectives

Precise TeV spectra of shell-type SNRs in order to discriminate between hadronic and leptonic emission, especially in the ***cutoff region*** (PeVatrons ?)

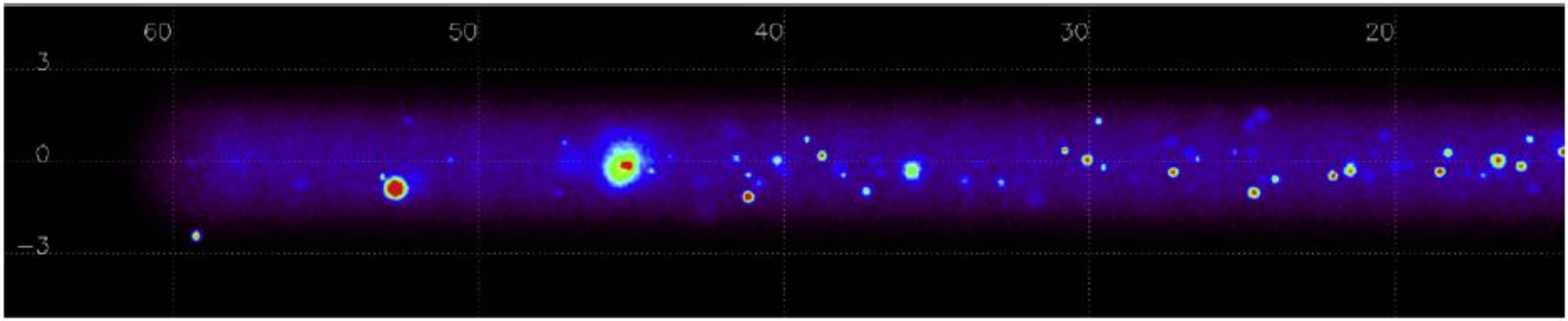
Spectro-imaging analysis (X-ray/TeV correlation studies & spatially-resolved TeV spectra) of the brightest SNRs (e.g. RX J1713.7-3946, Vela Jr)

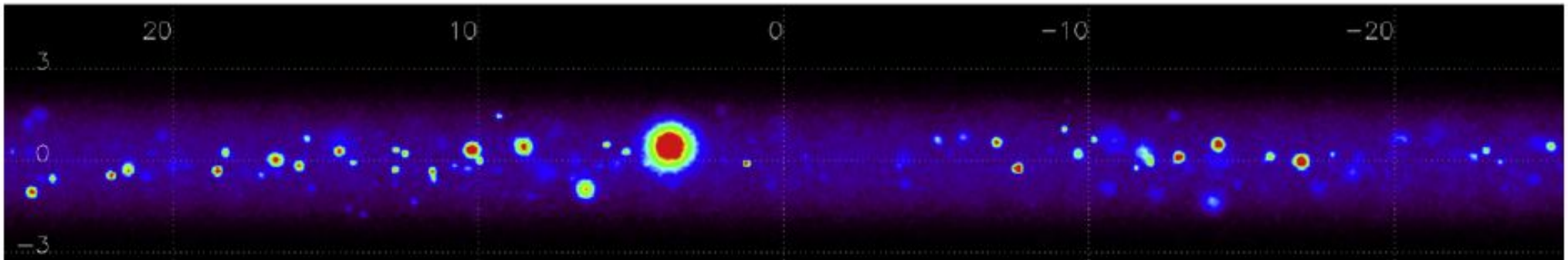
SNR/MC associations to constrain the ***CR propagation*** in the vicinity of sources (Pedaletti et al. 2013) & «passive» MCs as CR barometers → CR distribution

SNRs = CR *hadronic* sources? → ***Population studies.*** *Importance of the PSF* to measure shell morphology & to mitigate source confusion along the Galactic Plane

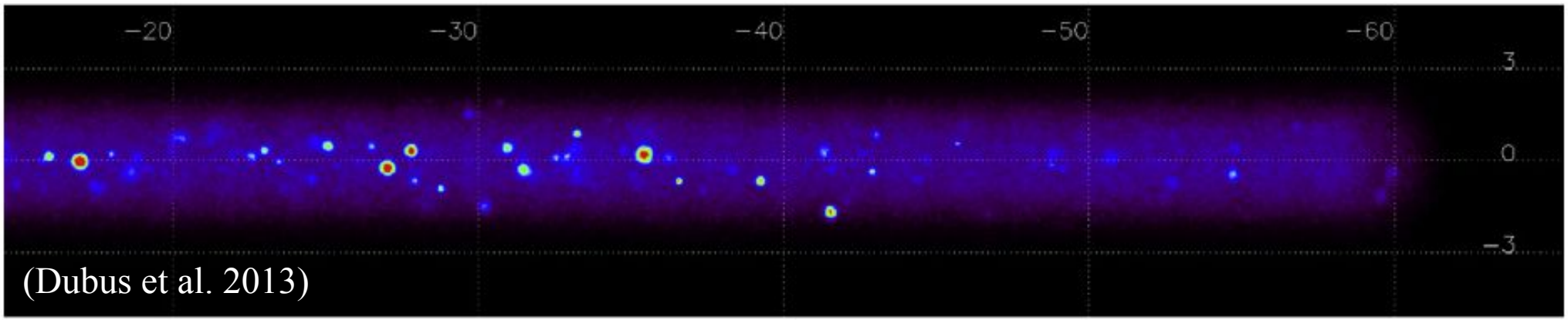


Conclusion & Perspectives





240 h CTA Galactic Plane Survey → ~ 500 PWNe expected ! (de Ona-Wilhelmi et al. 2013)

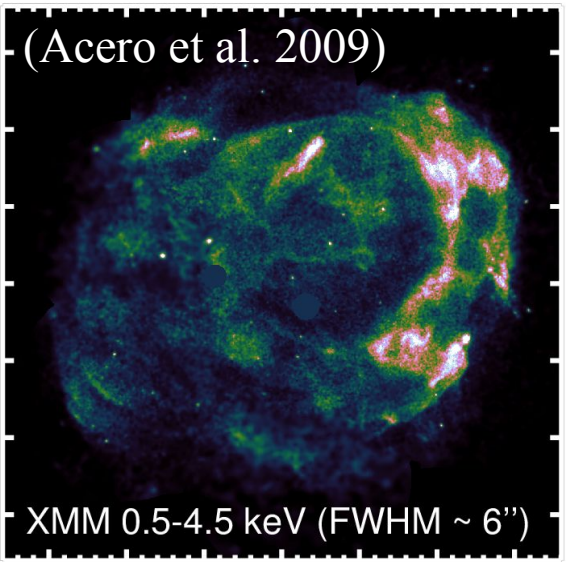


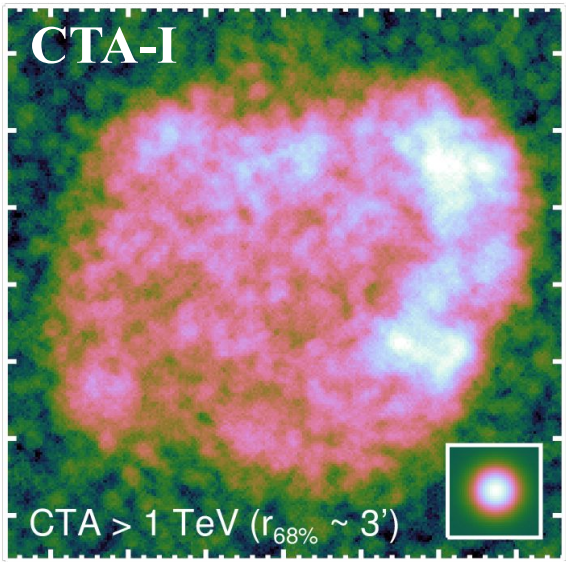
(Dubus et al. 2013)

BACK-UP SLIDES

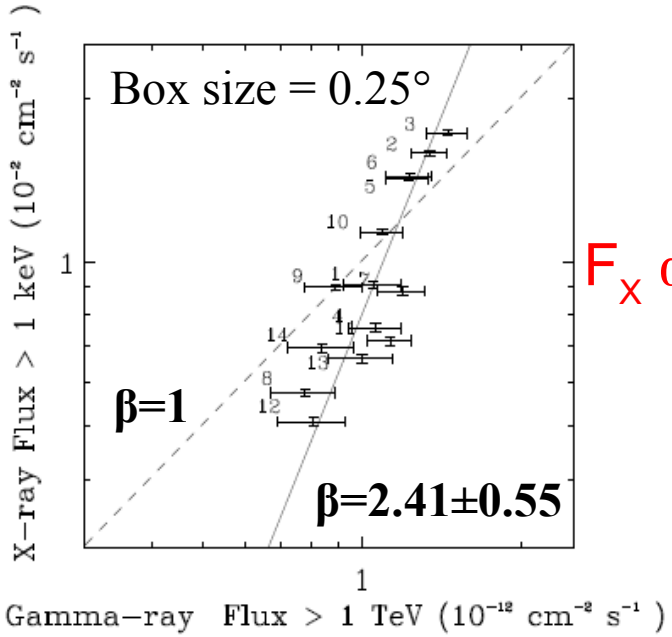
Prospects on SNRs with CTA

RX J1713 Spectro-imaging analysis

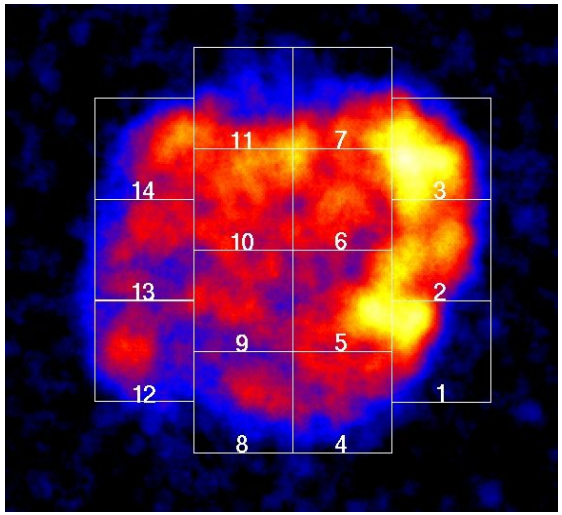




CTA simulation (T = 50 h, Z.A. = 20°) of RX J1713.7-3946 as seen by XMM with *Fermi*/LAT & H.E.S.S. spectrum: $dN/dE = N_0 E^{-\Gamma} \exp(-(E/E_{max})^{\beta})$

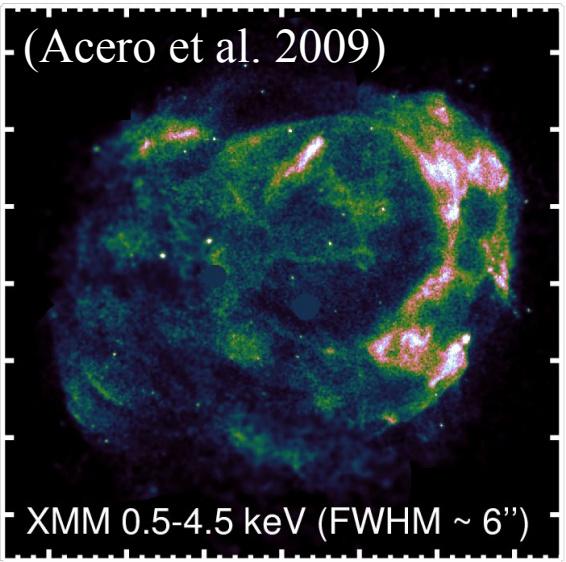


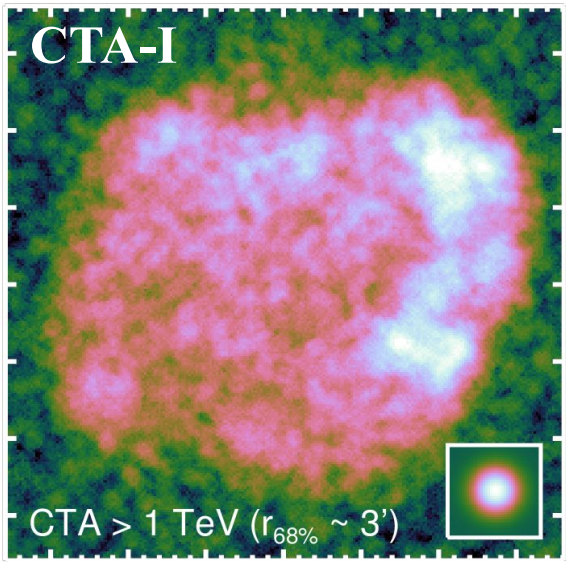
$F_X \alpha F_\gamma^{\beta}$



Prospects on SNRs with CTA

RX J1713 Spectro-imaging analysis





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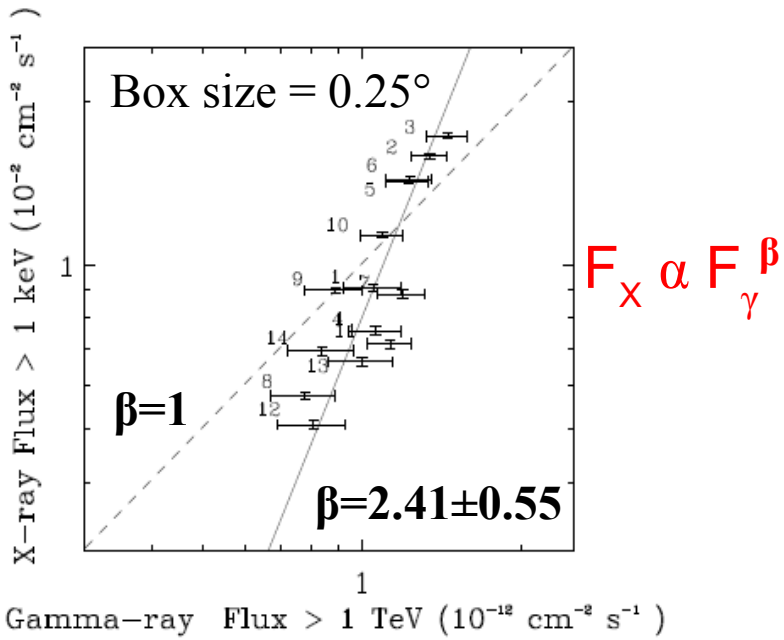

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