TeV Galactic Source Physics with CTA

Yves Gallant, Matthieu Renaud
LPTA, CNRS/IN2P3, U. Montpellier 2, France

for the CTA consortium

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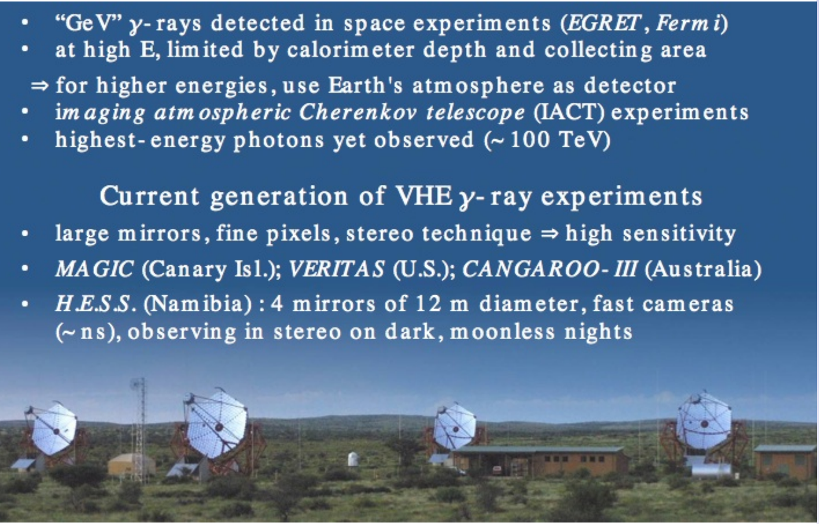
Very High Energy (VHE, $30\,\mathrm{GeV} < E_\gamma < 100\,\mathrm{TeV}$) or “TeV” γ-Ray astronomical detectors



- “GeV” γ-rays detected in space experiments (*EGRET*, *Fermi*)
- at high E, limited by calorimeter depth and collecting area

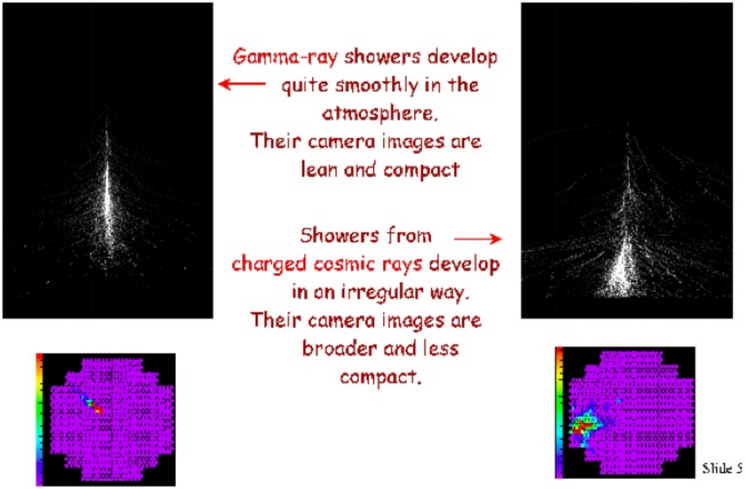
⇒ for higher energies, use Earth's atmosphere as detector

- *imaging atmospheric Cherenkov telescope* (IACT) experiments
- highest-energy photons yet observed (~ 100 TeV)

Current generation of VHE γ-ray experiments

- large mirrors, fine pixels, stereo technique ⇒ high sensitivity
- *MAGIC* (Canary Isl.); *VERITAS* (U.S.); *CANGAROO-III* (Australia)
- *H.E.S.S.* (Namibia) : 4 mirrors of 12 m diameter, fast cameras (~ ns), observing in stereo on dark, moonless nights

Imaging high-energy atmospheric showers

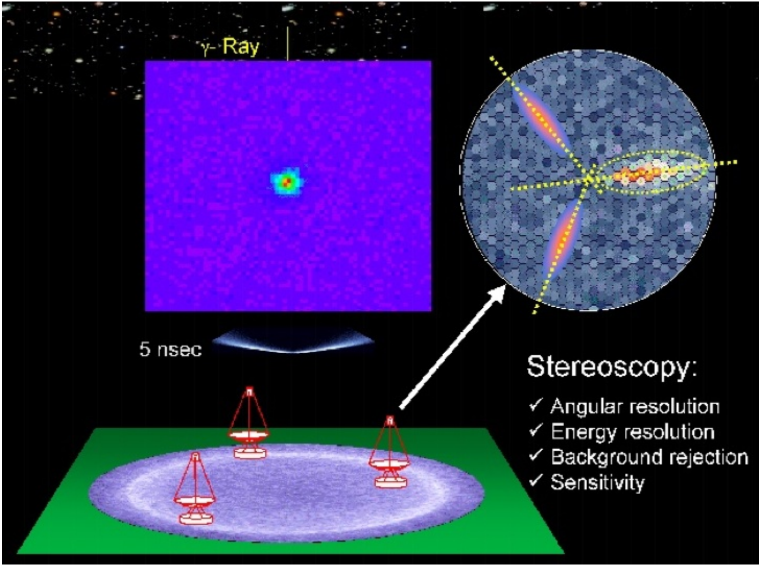


← Gamma-ray showers develop quite smoothly in the atmosphere. Their camera images are lean and compact

Showers from → charged cosmic rays develop in an irregular way. Their camera images are broader and less compact.

Slide 5

Stereo imaging and event reconstruction

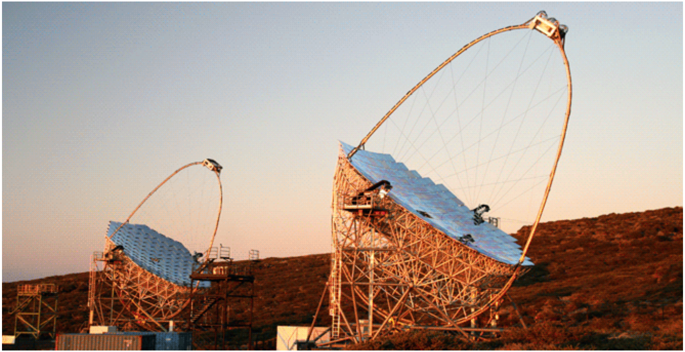


Stereoscopy:

- ✓ Angular resolution
- ✓ Energy resolution
- ✓ Background rejection
- ✓ Sensitivity

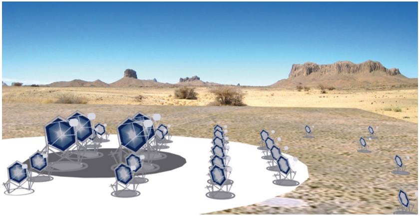
Energy threshold and large telescopes

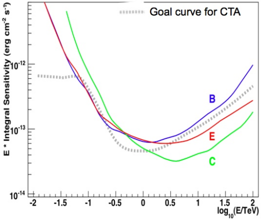
- energy threshold limited by Cherenkov photon collecting area



- **MAGIC** telescopes : 17-meter diameter telescopes
- energy threshold can reach as low as 25 GeV

CTA (Cherenkov Telescope Array) project

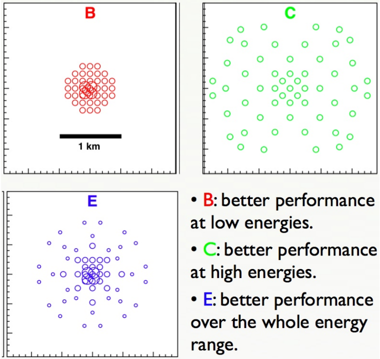




- Next generation of imaging atmospheric Cherenkov telescopes
- One order of magnitude sensitivity improvement over current generation of IACT instruments (e.g. H.E.S.S. or MAGIC)
- Energy range from ~10 GeV to 100 TeV
- Two sites foreseen : Northern and **Southern** Hemisphere (better for Galactic physics)

Sample CTA configurations under study

- Many telescopes spread over large area for sensitivity
- Combination of different size telescopes for energy coverage



- B: better performance at low energies.
- C: better performance at high energies.
- E: better performance over the whole energy range.

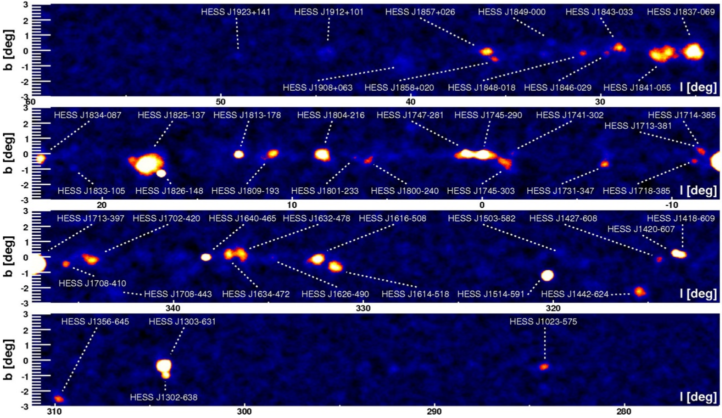
- B: compact distribution with large telescopes
- C: extended distribution with medium telescopes
- E: combination of both

- In what follows, compare performance of three configurations optimised for different energy ranges
- More details on CTA project in poster by **I. Puerto et al.** and review talk by **J. Hinton**

The Galactic TeV γ-ray sky (I)

- much improved sensitivity of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), inaugurated by HESS (initial 4-telescope array completed >6 years ago)
- HESS Galactic plane survey : longitudes $\ell \approx -80^\circ$ to 60°

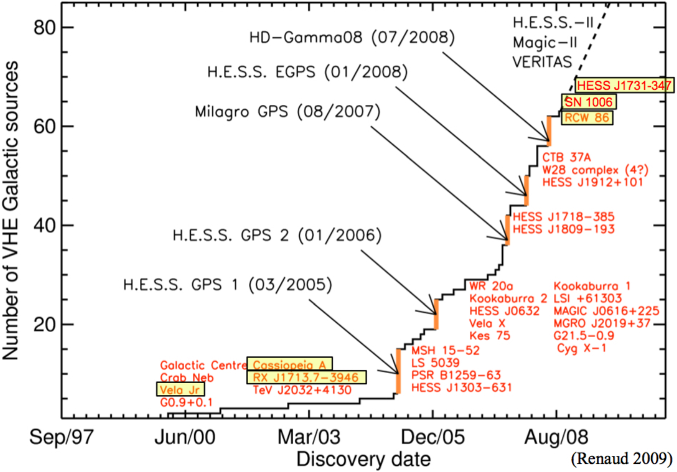
(Chaves, H.E.S.S., 2009 ICRC)



- currently about 70 Galactic TeV sources known

The Galactic TeV γ-ray sky (II)

- Of particular interest are shell-type **supernova remants (SNRs)**



(Renaud 2009)

- latest discovery : **Tycho**'s SNR (*VERITAS*, 2010)

High-energy observations of (shell-type) SNRs and the origin of Galactic Cosmic Rays

- Supernova remnants are widely considered likely sources of Galactic cosmic rays up to the "knee", $E \sim 3 \times 10^{15}$ eV :
  - well-studied shock acceleration mechanism;
  - GCR composition compatible with an SNR origin;
  - energetics require $\sim$10% of total SN energy of 10^{51} erg

X-ray observations of SNRs

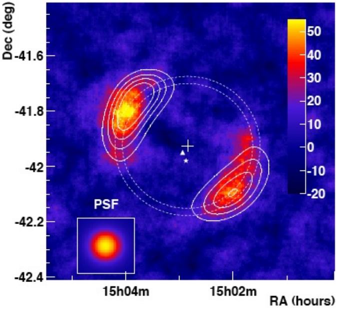
- Observational evidence for accelerated e^- (synchrotron)
- indirect evidence for accelerated protons/ions (magnetic field amplification, modified hydrodynamics)

TeV γ-ray observations

- For accelerated p (and ions), **hadronic** interactions with ambient matter produce π^0, decaying into two γ-rays which we observe
- On of aims of TeV γ-ray astronomy (e.g. Drury et al. 1994)
- But how to discriminate from **leptonic** (IC) emission?

A historical TeV shell SNR : **SN 1006**

- H.E.S.S. detection of the remnant of **SN 1006**:



(Naumann-Godo et al., H.E.S.S., 2009 ICRC ; *A&A*, in press)

- 130 hours of good-quality data
- morphology correlated with non-thermal X-rays (contours)
- reveals spatial distribution of high-energy particles
- ambiguity between **hadronic** and **leptonic** (IC) emission scenarii

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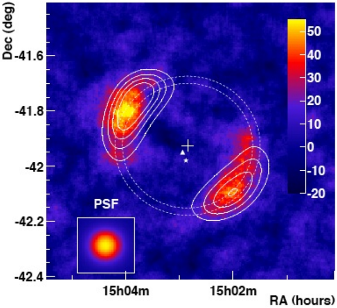

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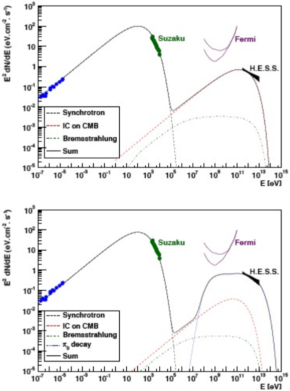
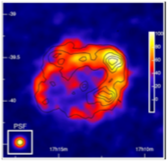


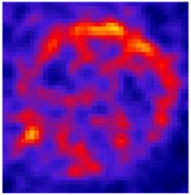
- leptonic scenario suggests relatively low B-field $\approx 30\,\mu$G
- hadronic scenario require hard spectrum, $E_{\text{cutoff}} \sim 10\,$TeV

TeV shell SNRs : examples



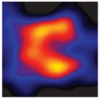
RX J1713

HESS (2006)



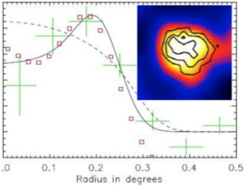
Vela Junior

HESS (2007)



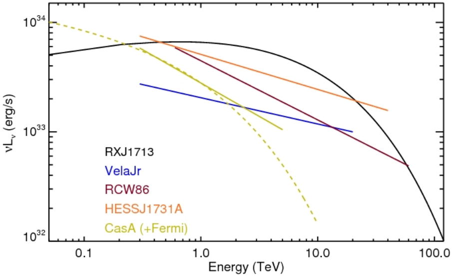
RCW 86

HESS (2009)



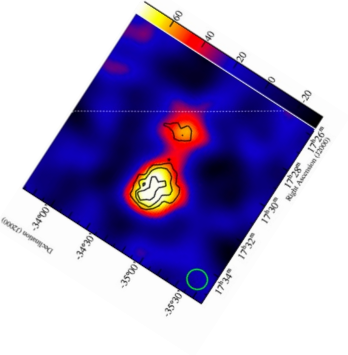
HESS J1731-347

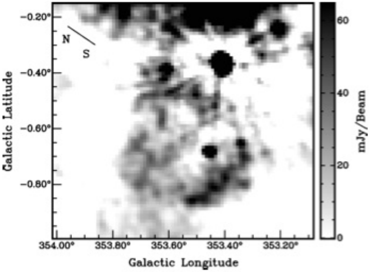
HESS (2008)
Acero et al. (2009)



Identifying a new TeV shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell discovered with ATCA data: G 353.6–0.7




(Tian et al. 2008)

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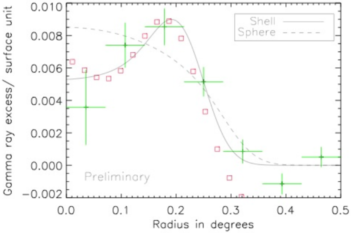

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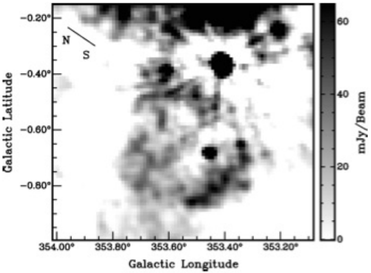
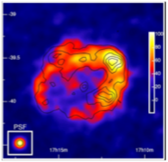


- deeper *HESS* observations: evidence for limb-brightening
- X-ray observations of (part of) shell reveal rims of emission with non-thermal spectra! (no evidence for thermal emission)
- X-ray absorption gradient suggest SNR lies behind a CO cloud
- $D > 3.5\,\mathrm{kpc} \quad \Rightarrow \quad L_{1-10\,\mathrm{TeV}} > 2 \times 10^{34}\,\mathrm{erg/s}, \quad R > 15\,\mathrm{pc}$

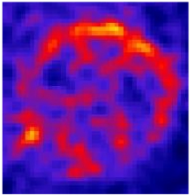
TeV shell SNRs : simulations

RX J1713



HESS (2006)

Vela Junior



HESS (2007)

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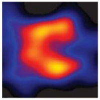

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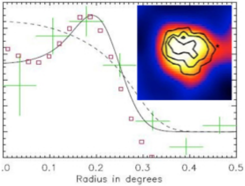

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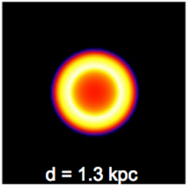
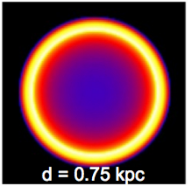


HESS (2006)

Vela Junior



HESS (2007)

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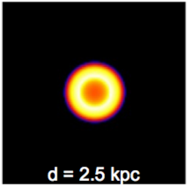

HESS (2009)

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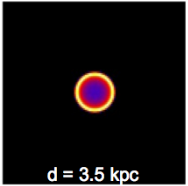
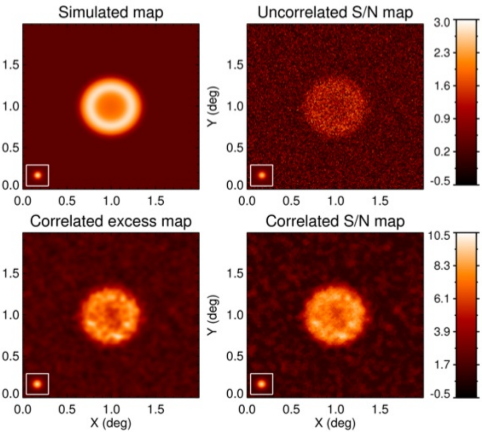


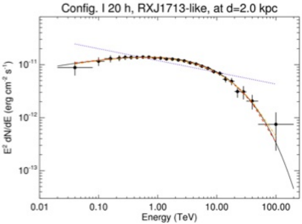
HESS (2008)

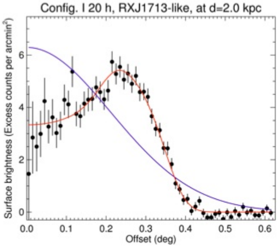
images simulated with $E_{\rm min}$ threshold that optimises S/N ratio :
0.5–0.7 TeV depending on object spectrum

Simulated CTA observations : $D = 2\,\text{kpc}$

RX J1713.7-like SNR, 20 hour exposure (Galactic plane survey)

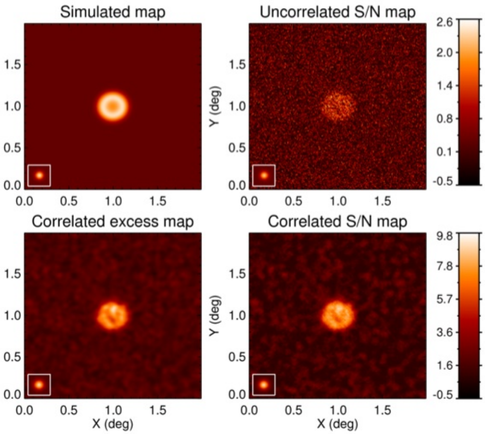


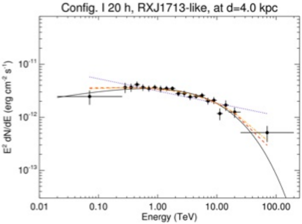


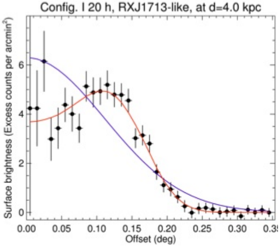


Simulated CTA observations : $D = 4\,\mathrm{kpc}$

RX J1713.7-like SNR, 20 hour exposure (Galactic plane survey)

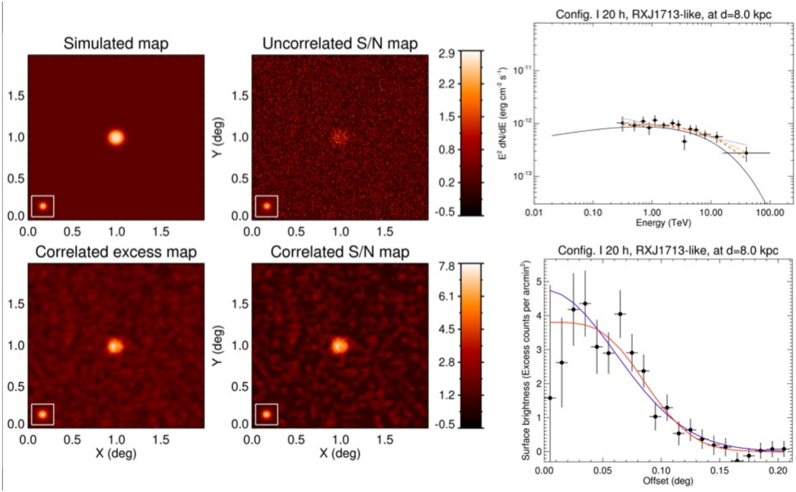






Simulated CTA observations : $D = 8\,\mathrm{kpc}$

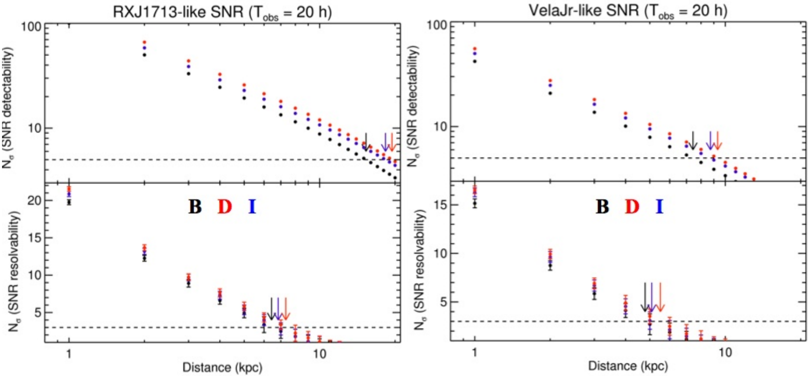
RX J1713.7-like SNR, 20 hour exposure (Galactic plane survey)



Detectability and resolvability with CTA

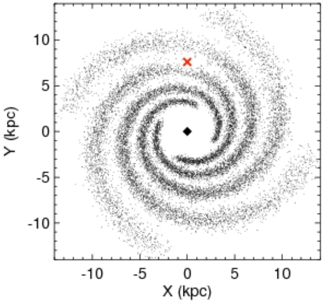
Horizon of *detectability* → distance / S/N = 5σ

Horizon of *resolvability* → distance / shell fit favored at 3σ over a sphere fit (100 simulated images per distance bin [1-20 kpc])

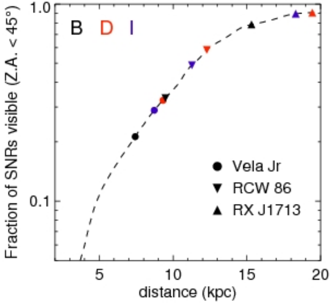


Galactic SNR shell population seen by CTA

- 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 model of Drimmel & Spergel (2001)



Horizon of **detectability**



- If all SNRs shine ~2000 yr in TeV, total of ~40 SNRs!

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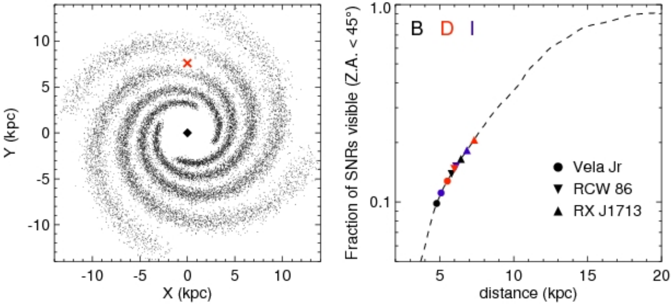
Horizon of **resolvability**



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Conclusions on SNR shells

- CTA will dramatically expand the population of known Galactic TeV γ-ray sources

Supernova Remnant Shells

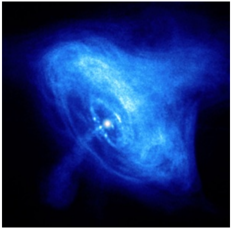
- in a CTA Galactic plane survey, currently known shell SNRs detectable to 10–15 kpc (i.e. throughout most of the Galaxy)
- if shells shine 2000 yr in TeV, $\sim$40 TeV shells in Galaxy; $\sim$25 detectable (vs 6 currently known)
- gamma-ray shell directly resolvable by CTA to 5–7 kpc
- more distant SNR shells identifiable through follow-up multi-wavelength (e.g. radio) observations

- but another source category major for Galactic TeV sky…

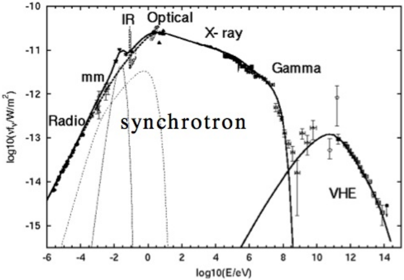
TeV γ-ray emitting Pulsar Wind Nebulae

In the beginning, there was the Crab Nebula...

- "standard candle" of TeV γ-ray astronomy since its discovery



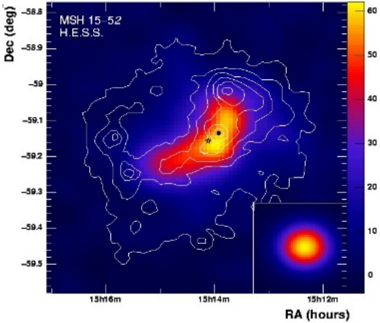
Chandra



- *synchrotron* emission in most of the electromagnetic spectrum, from $e^{\pm}$ accelerated in the pulsar, wind, termination shock
- TeV γ-ray emission results from *Inverse Compton* scattering of lower-energy photons (synchrotron, CMB, IR, starlight...)
- (hadronic contributions also proposed, e.g. **Horns et al. 2007**)
- important sources of high-energy cosmic-ray e^+ (and e^-)
- for most other such *plerions*, non-thermal radiation detected only in radio and X-rays — until recently...

I – Young PWNe (and composite SNRs)

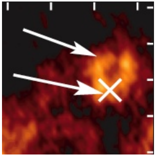
- Beyond the **Crab**, HESS discovered TeV emission from **G 0.9+0.1** (A&A, **432**, L25, 2005), **G 21.5–0.9** and **Kes 75** (Djannati-Ataï et al. 2007, ICRC, `arXiv:0710.2247`)
- *VERITAS* discovery of TeV emission from plerion **G 54.1+0.3** (Acciari et al. 2010, `arXiv:1005.0032`)
- **MSH 15–52** : first PWN angularly resolved in TeV γ-rays
  - H.E.S.S., A&A **435**, L17 (2005)
  - contours: ROSAT
  - X-ray thermal shell and non-thermal “jet-like” nebula
  - other composites similar in X-rays



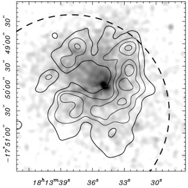
- IC emission $\propto$ (approximately uniform) target photon density $\Rightarrow$ direct inference of spatial distribution of electrons

Newly identified young PWNe in SNRs

The progressive identification of **HESS J1813–178**

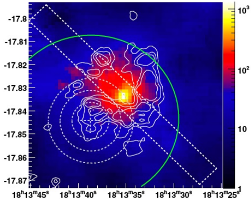


- *XMM* revealed an extended non-thermal nebula inside the shell (Funk et al. 2007a)

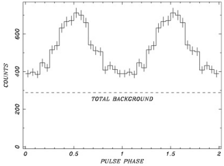


- *XMM* found pulsed emission, $\dot{E} = (6.8 \pm 2.7) \times 10^{37}$ erg/s (Gotthelf & Halpern 2009)

- Brogan et al. (2005) revealed its coincidence with a shell-type radio SNR (and *ASCA* source)

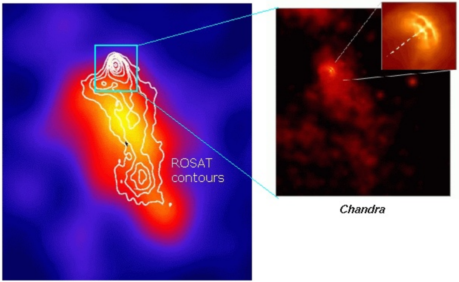


- *Chandra* revealed a pulsar candidate (Helfand et al. 2007)



II – Older, “offset” PWNe

- TeV γ-rays from the **Vela X** nebula (HESS, A&A **448**, L43, 2006)



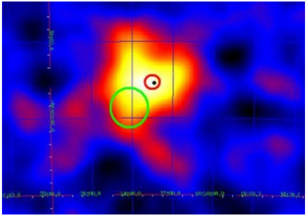
- coincident with one-sided “jet” (Markwardt & Ögelman 1995)
- compact X-ray nebula not conspicuous in TeV γ-rays $\Rightarrow$ torii and jets bright in X-rays because of higher magnetic field
- offset morphology explained by passage of anisotropic reverse shock, “crushing” the PWN (Blondin et al. 2001)?
- two TeV PWNe in **Kookaburra** appear to fall in same category

New pulsars coincident with TeV sources

- Discovery with Arecibo of **PSR J1856+0245**, possibly powering **HESS J1857+026**, $L_\gamma/\dot{E} \sim 3\%$ (Hessels et al. 2008)
- coincident with unresolved *ASCA* source AX J185651+0245

Fermi-LAT discovered pulsars in TeV sources

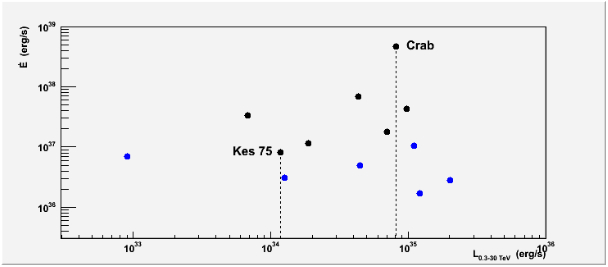
- PSR J1418–6058 discovered in **"Rabbit"**, second HESS source in Kookaburra (Abdo et al. 2009, Science **325**, 840)
- PSR **J1907+0602** ($\dot{E} = 2.8 \times 10^{36}$ erg/s) discovered in MGRO J1908+06 / HESS J1908+063 (Abdo et al. 2010, ApJ **711**, 64)
- PSR **J1022–5746** discovered in HESS J1023–575 ($\dot{E} = 1.1 \times 10^{37}$ erg/s): alternative scenario to emission from Westerlund 2 (Dormody et al. 2009)



- About **half** of Galactic TeV sources are PWNe or candidates

TeV luminosities of established PWNe

- Distances: when pulsar detected (in radio), use DM (dispersion measure) and Galactic electron distribution (Cordes & Lazio 2002)

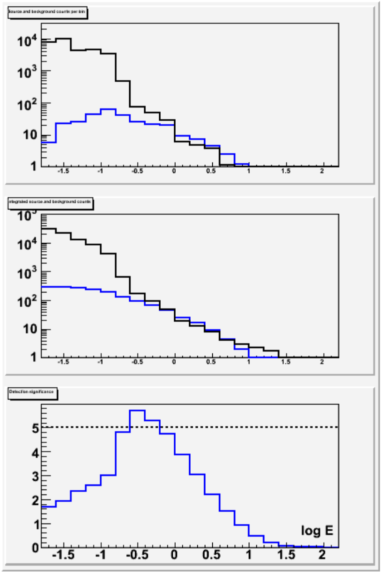


- relatively narrow range of L_{TeV} (Grenier 2009, Mattana et al. 2009)
- no correlation with spin-down power $\dot{E}$, unlike L_X
- X-rays trace recently injected particles, whereas TeV γ-rays reflect history of injection since pulsar birth

- bright TeV PWNe have **Crab**-like luminosities; **Kes 75** representative of a population of fainter TeV PWNe

CTA detectability of a Crab-like PWN

Assume HESS Crab spectrum (*A&A* **457**, 899), $T = \mathbf{50\,h}$, subarray B



$$N_{src}(E_i) = A_{eff,i} \times T \times F(E_i) \times \Delta E$$

$$N_{bkg}(E_i) = R_{bkg,i} \times T$$

$$I_{src}(>E_i) = \textstyle\sum_{j>i} N_{src}(E_j)$$

$$I_{bkg}(>E_i) = \textstyle\sum_{j>i} N_{bkg}(E_j)$$

$$S(>E_i) = I_{src,i} / \sqrt{I_{bkg,i} + I_{src,i}}$$

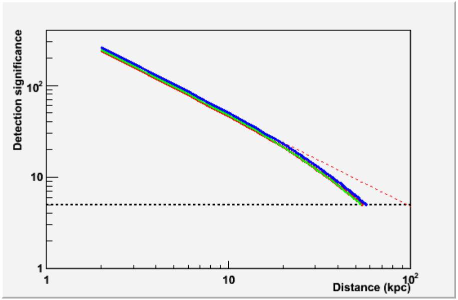
⇒ can define **optimal energy cut** for faint source detection, a priori for a given spectral shape

for subarray B, $E > \mathbf{250\,GeV}$

How far away could CTA detect the Crab?

$$F(E) = F_{Crab}(E) \times \left(\frac{2\,\mathrm{kpc}}{D}\right)^2 \qquad \text{(above was for } D = 50\,\mathrm{kpc}\text{)}$$

$$I_{src} \propto 1/D^2 \qquad \Rightarrow \qquad S = \frac{I_{src}}{\sqrt{I_{bkg} + I_{src}}} \propto 1/D \quad \text{if} \quad I_{src} \gg I_{bkg}$$



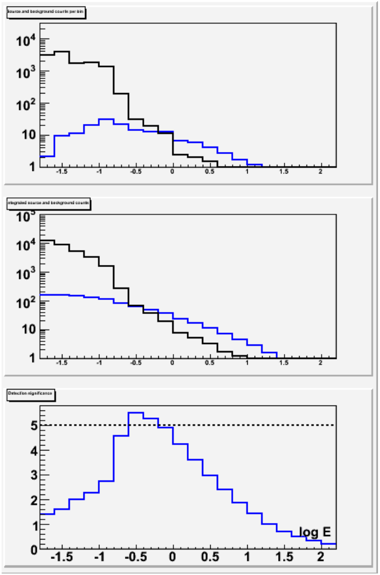
Subarrays
B $(E > 250\,\mathrm{GeV})$
D $(E > 600\,\mathrm{GeV})$
I $(E > 250\,\mathrm{GeV})$

Maximum distance :
53 kpc 54 kpc 57 kpc

- CTA could detect all Crab-like luminosity sources in the **Large Magellanic Cloud**, in a moderately deep (50 hours) exposure
- LMC survey for Crab-like PWNe : well-determined distance, in contrast to large uncertainties on PWN distances in the Galaxy

CTA detectability of a Kes 75-like PWN

Spectrum from Djannati-Ataï et al. (2007), $T = \mathbf{20\,h}$, subarray B



$N_{src}(E_i)$
$N_{bkg}(E_i)$

$I_{src}(> E_i)$
$I_{bkg}(> E_i)$

$S(> E_i)$

Subarrays

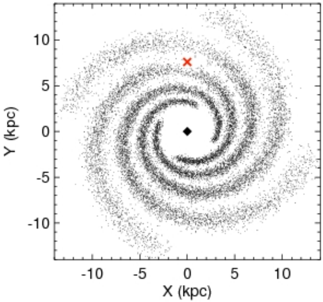
B ($E > 250\,\mathrm{GeV}$)
D ($E > 600\,\mathrm{GeV}$)
I ($E > 250\,\mathrm{GeV}$)

Maximum distance :

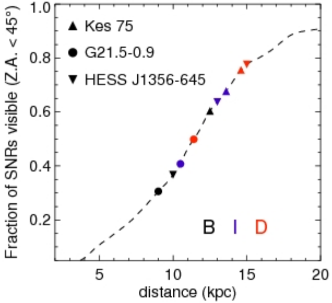
13 kpc 14 kpc 15 kpc

Galactic PWN population seen by CTA

- 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 model of Drimmel & Spergel (2001)
- Ignore displacement from pulsar birth place due to velocity kick



Horizon of **detectability**



- If all PWNe shine ∼10 000 yr in TeV, total of ∼200 PWNe!

Conclusions (II)

Pulsar Wind Nebulae

- CTA will detect luminous PWNe like the Crab to the distance of the Large Magellanic Cloud ⇒ luminosity-limited survey
- if PWNe shine 10 000 yr in TeV, ∼200 TeV PWNe in Galaxy
- in a CTA Galactic plane survey, weaker PWNe like Kes 75 detectable to ∼13–15 kpc (i.e. in large fraction of Galaxy)
- identifiable through follow-up MWL observations (non-thermal X-ray nebulae, pulsar search)

General considerations

- similarly for other Galactic TeV γ-ray sources : binaries, SNRs interacting with molecular clouds, star forming regions. . .
- CTA will find large number of previously unknown high-energy particle sources in the Galaxy; multi-wavelength follow-up observations essential for identification

- increased sensitivity and resolution of CTA will yield improved spectral and morphological data on currently known sources