# The Cherenkov Telescope Array

*Workshop on the Future of Dark Matter Astro-Particle Physics: Insights and Perspectives*
*Trieste, 8th-11th October 2013*

*Giovanna Pedaletti (IEEC-CSIC Barcelona)*

# Outline

- CTA characteristics:
  - large improvement wrt current IACTs
  - synergy with other instruments
- Which physics output is expected?
  - Focus on CR related studies
  - Focus on DM expectations

Most of the work presented here is published in the Special Issue of Astroparticle Physics (vol 43, March 2013): "*Seeing the High-Energy Universe with the Cherenkov Telescope Array --- The Science Explored with CTA*"

Energy threshold ~ 100 GeV. Thanks to the 17m dishes, MAGIC-II achieves 55GeV and 25 GeV for pulsar dedicated trigger. HESS II, with a dish of ~28m will have a threshold of ~50 GeV for normal observations

FoV: 5° (~3.5º for MAGIC)

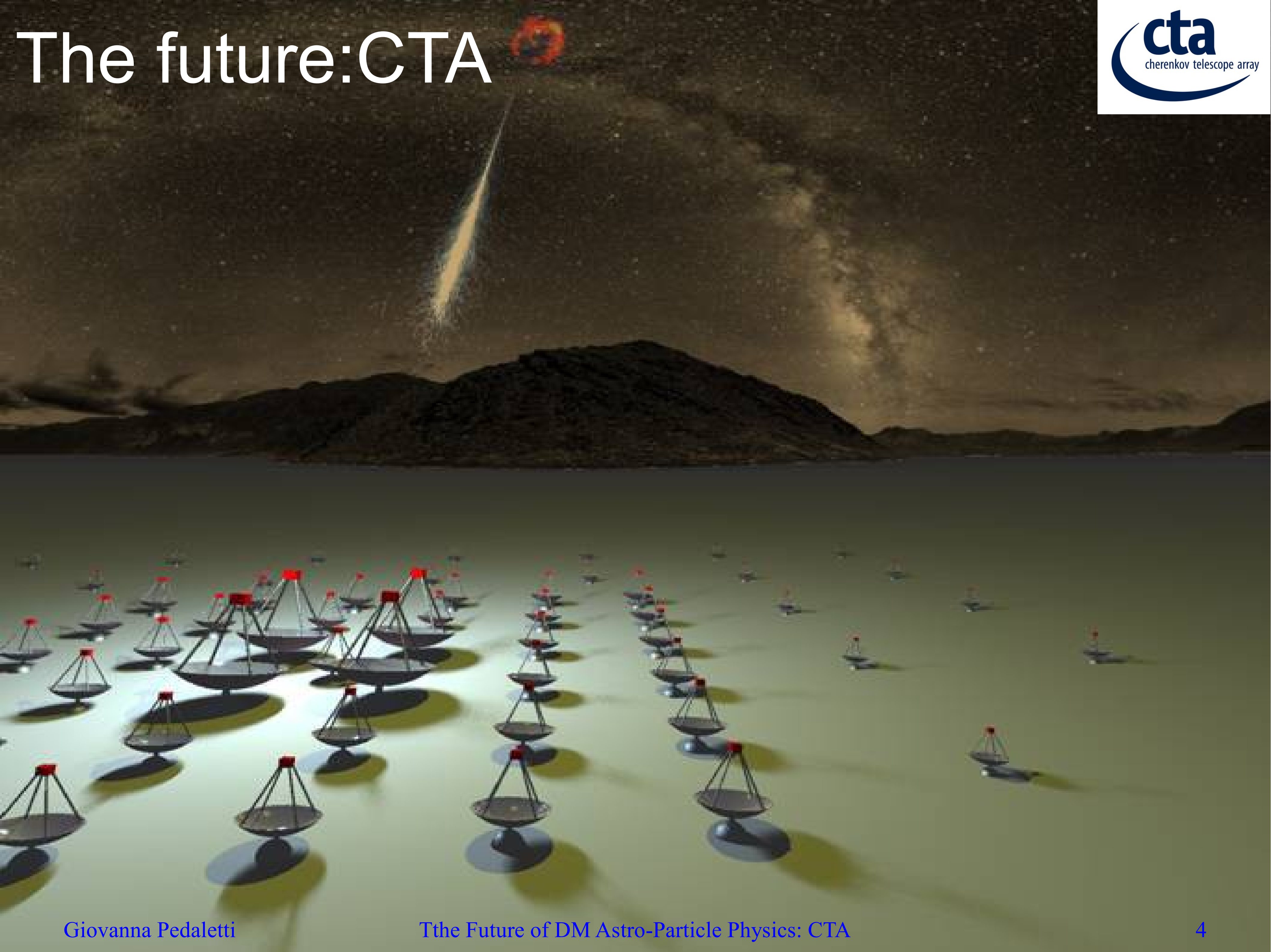
Angular resolution: 0.1°  Energy resolution ~15%

Flux sensitivity: 5σ for 1% Crab in <50hrs

Duty cycle: If observations possible only in moonless time => 1000 hs a year +30% in moonlight (higher energy threshold, lower sensitivity)



# The future:CTA



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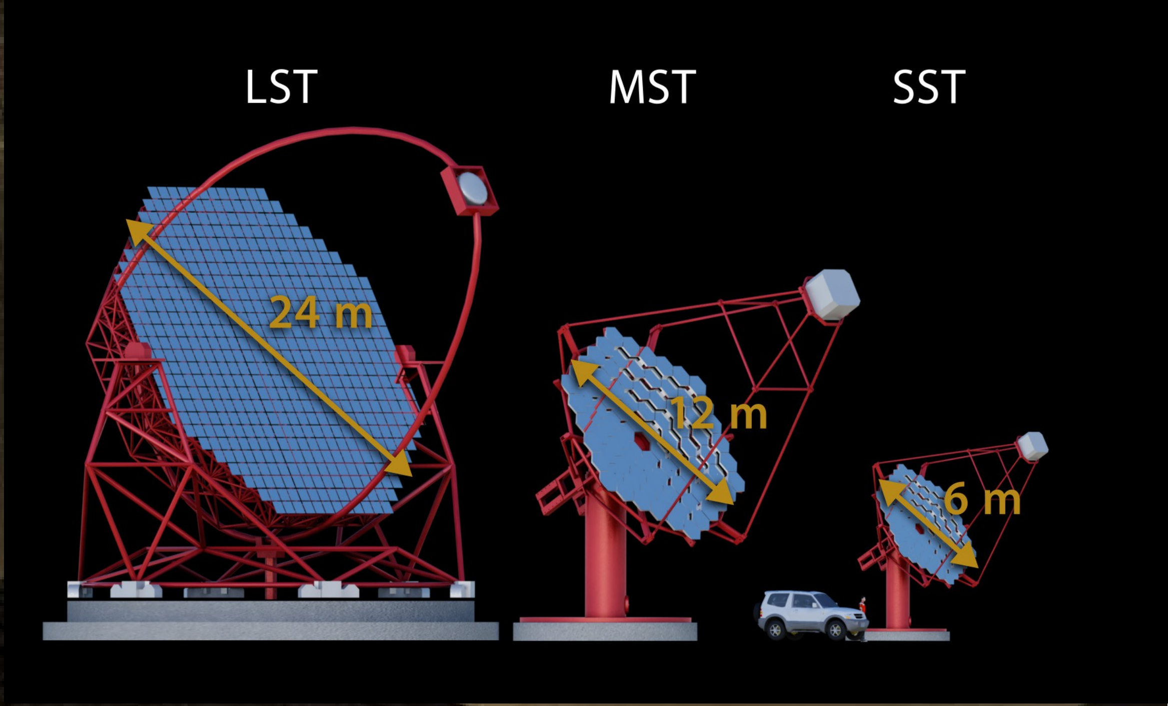



LST dishes ~23 m (3-4-5 at center of the array)

=> lowering the energy threshold to a few 10s of GeV

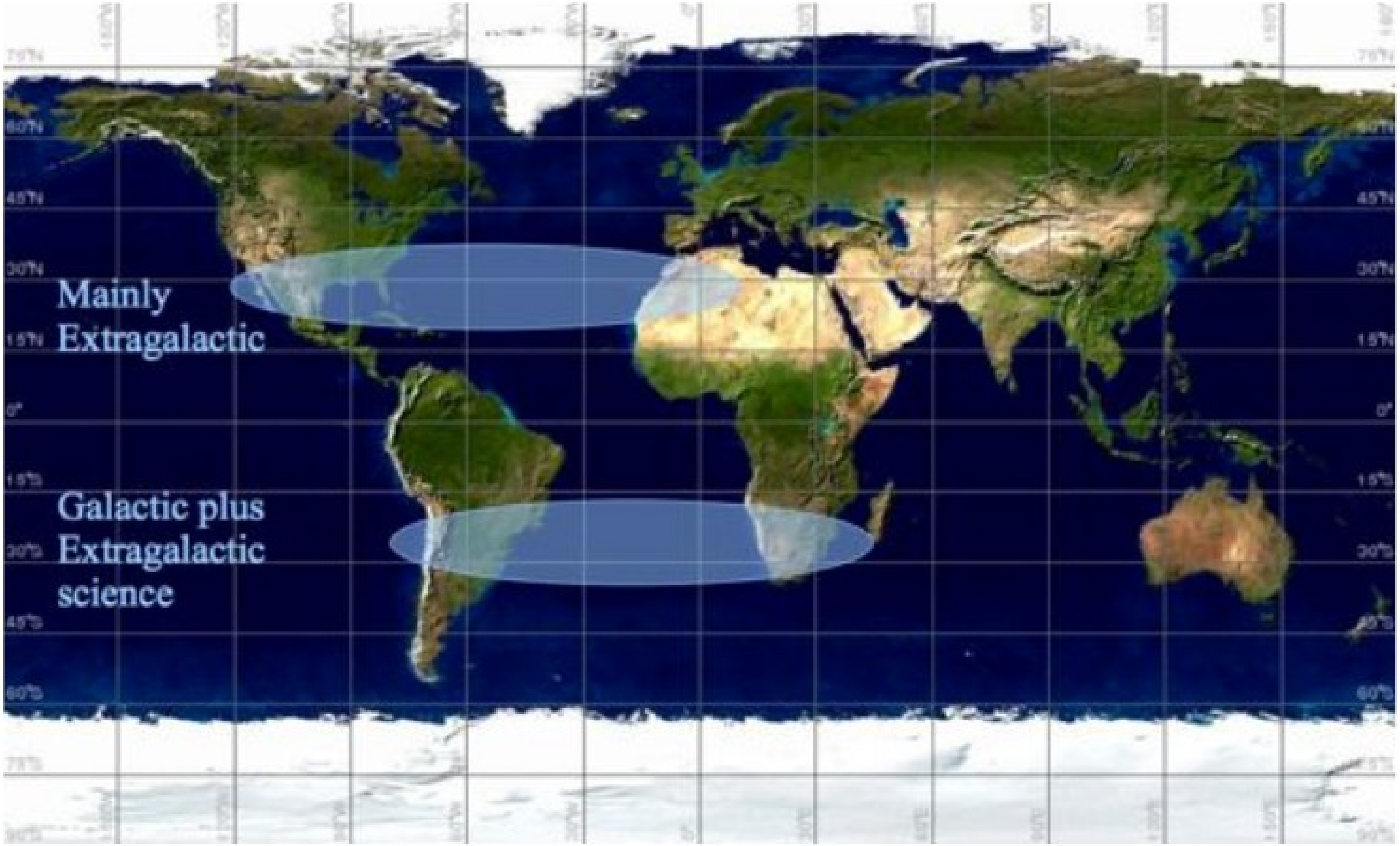
Tens of MSTs (dishes diameter ~11 m)

=> enhancing event reconstruction at 1TeV

An outer ring of SSTs (dishes ~4-7m)

=> enlarging the effective area for the bright but rare events at > 10 TeV

# The future: CTA



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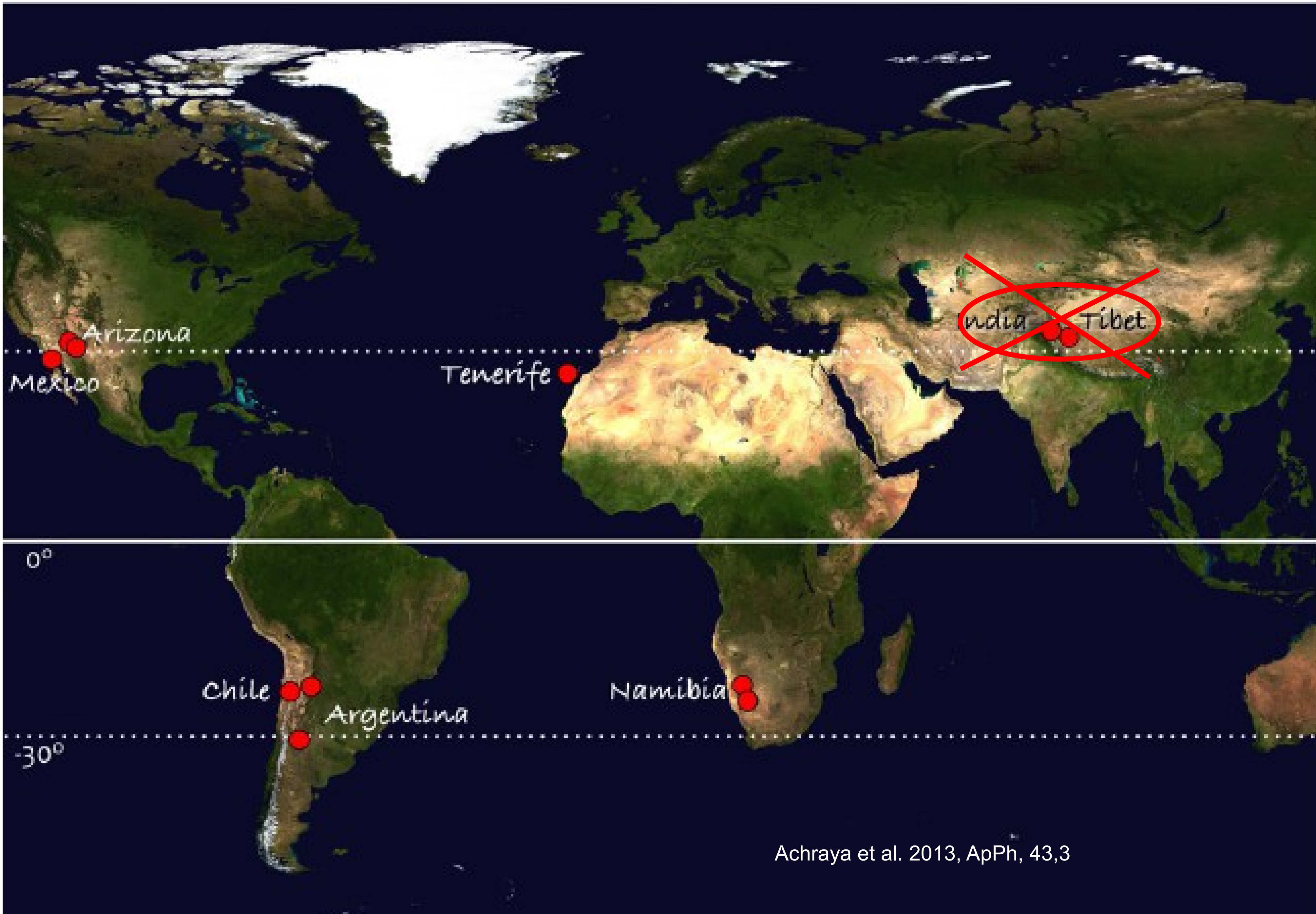
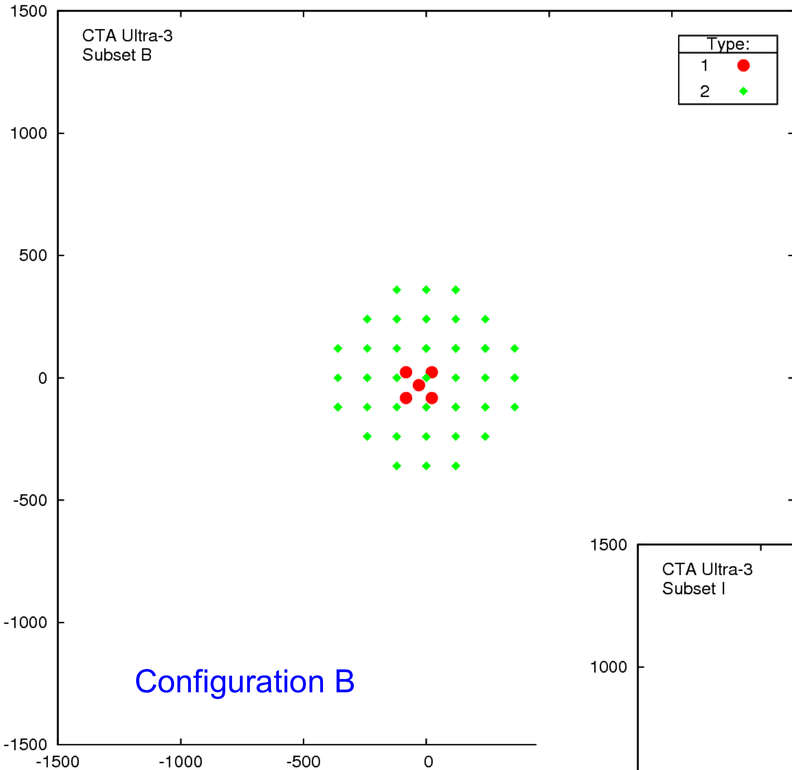
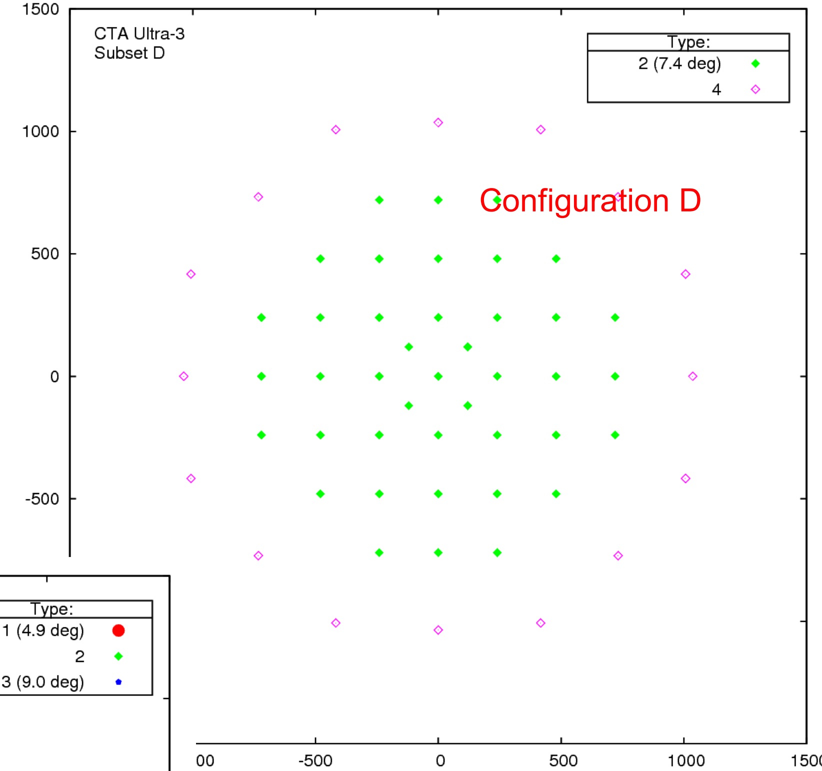
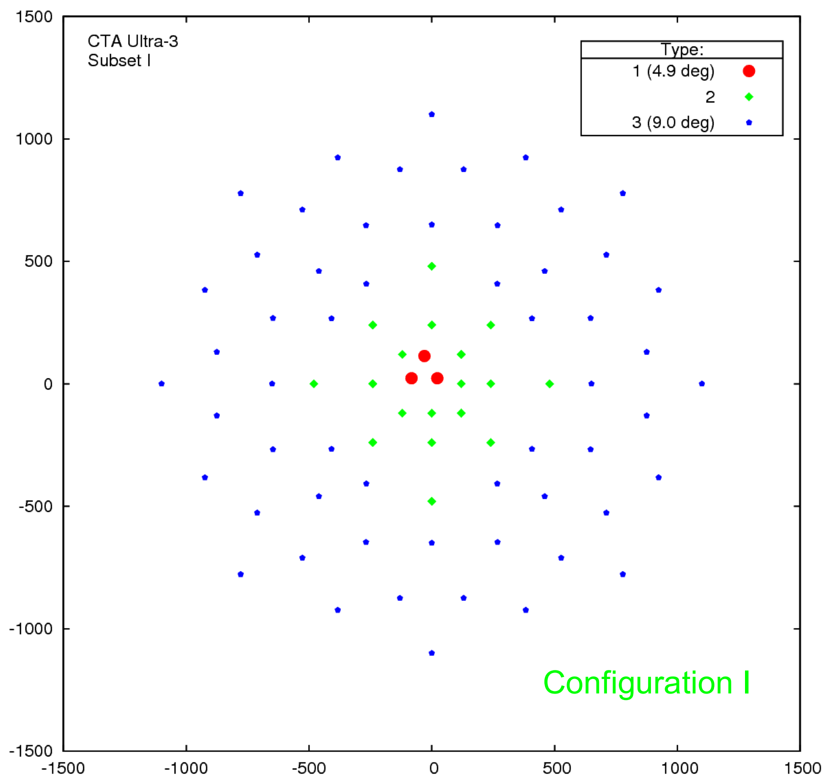


# CTA configurations

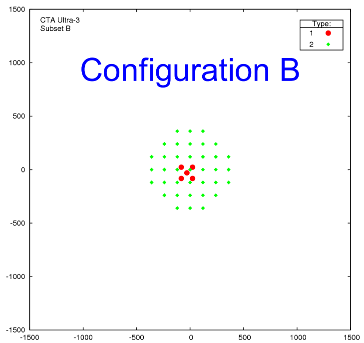


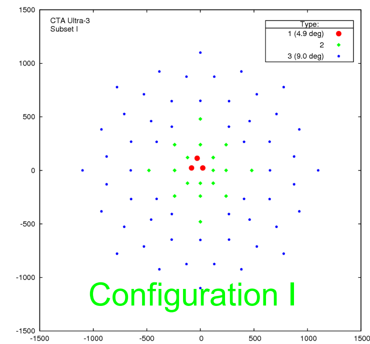



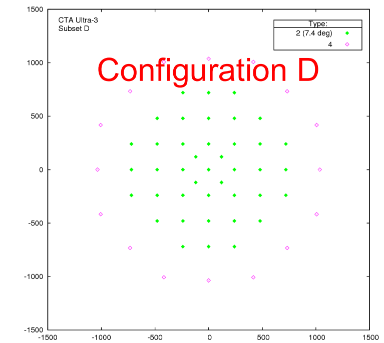



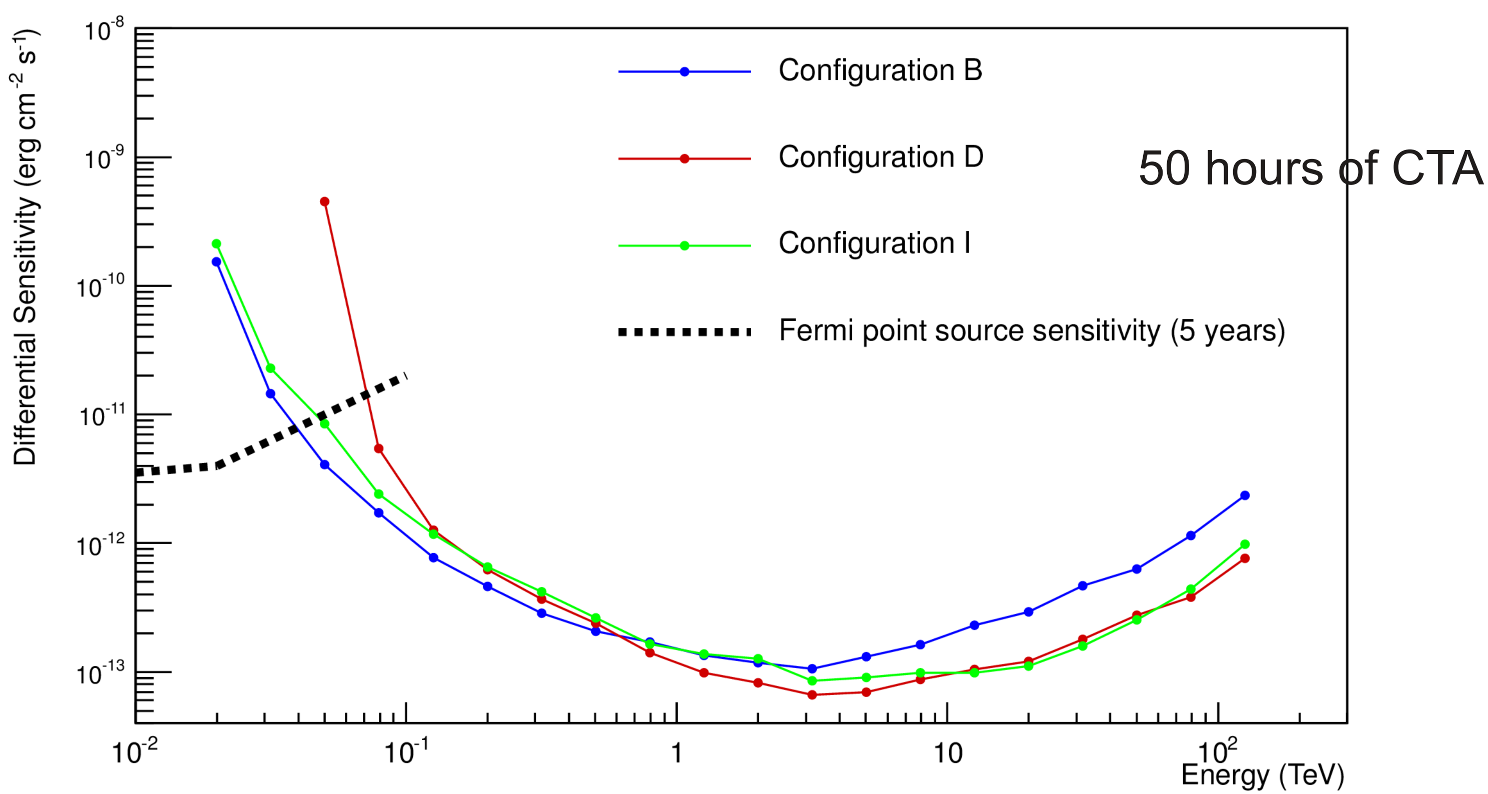

For all configuration details see
Bernlöhr et al. 2013, ApPh 43, 171

# CTA expected performance



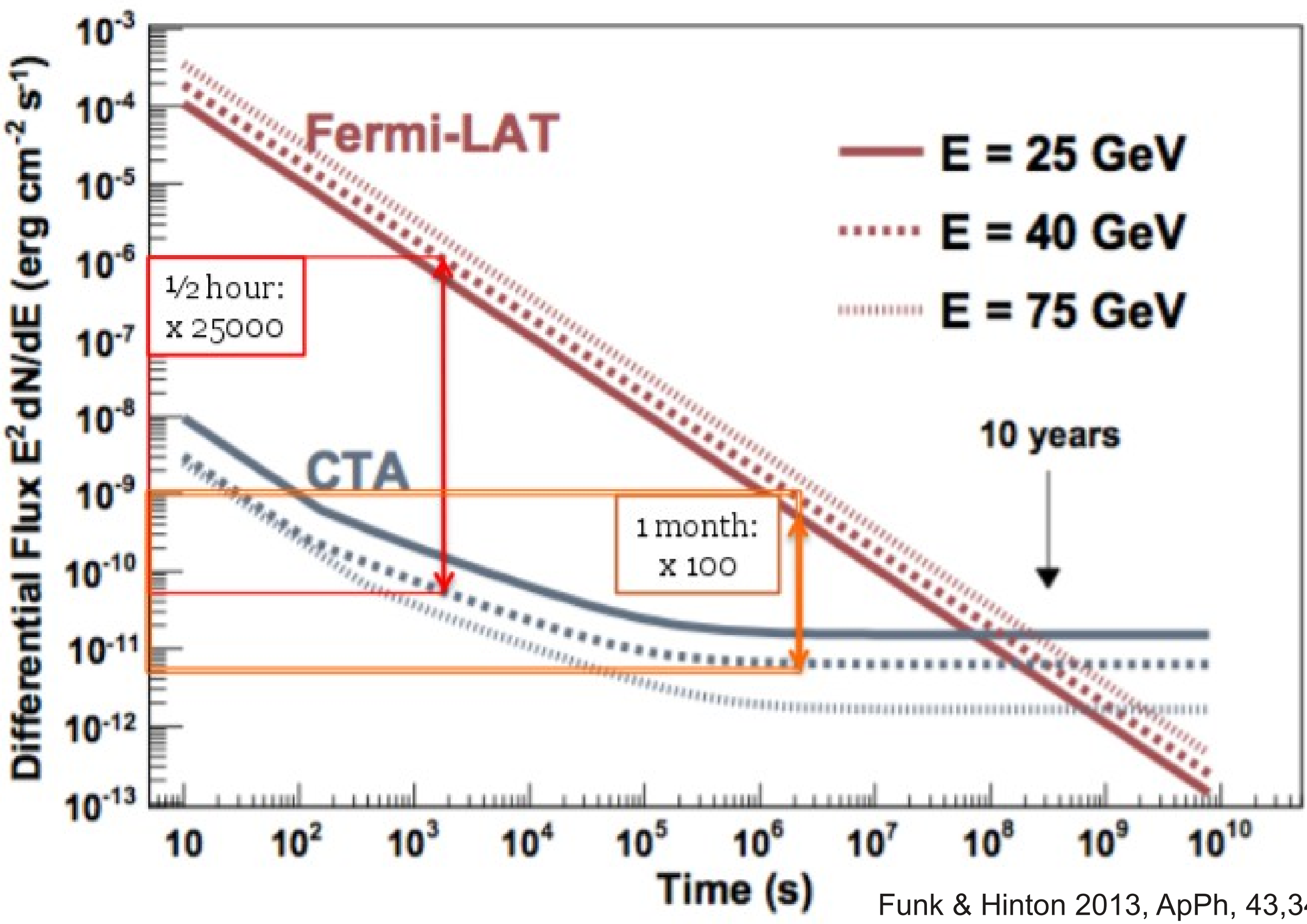



# Shorter timescales?

Fermi-LAT is signal limited above 10 GeV, and its sensitivity decreases rapidly with event duration.




Funk & Hinton 2013, ApPh, 43,348

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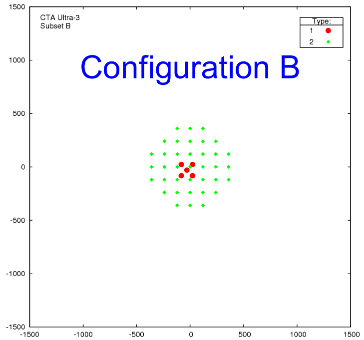
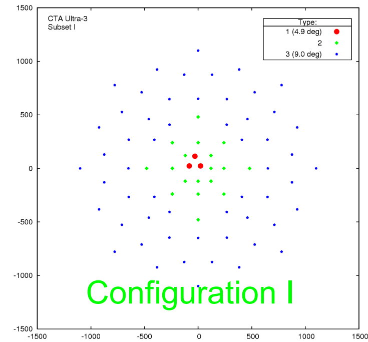
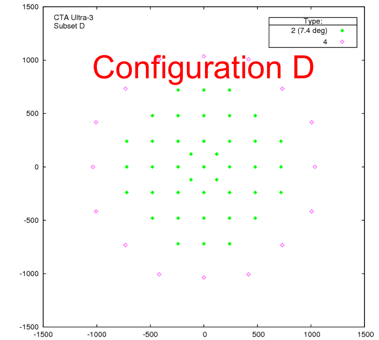
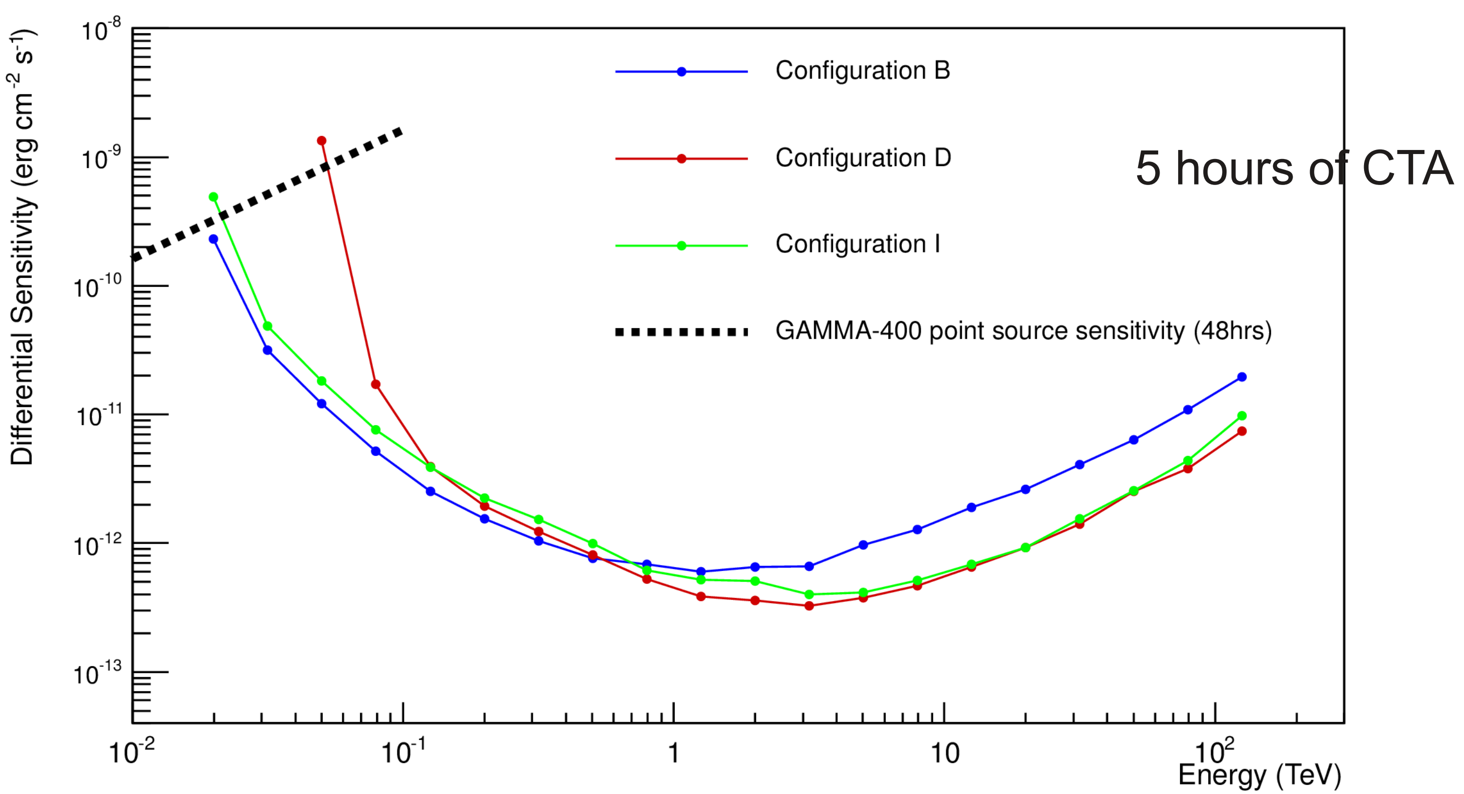
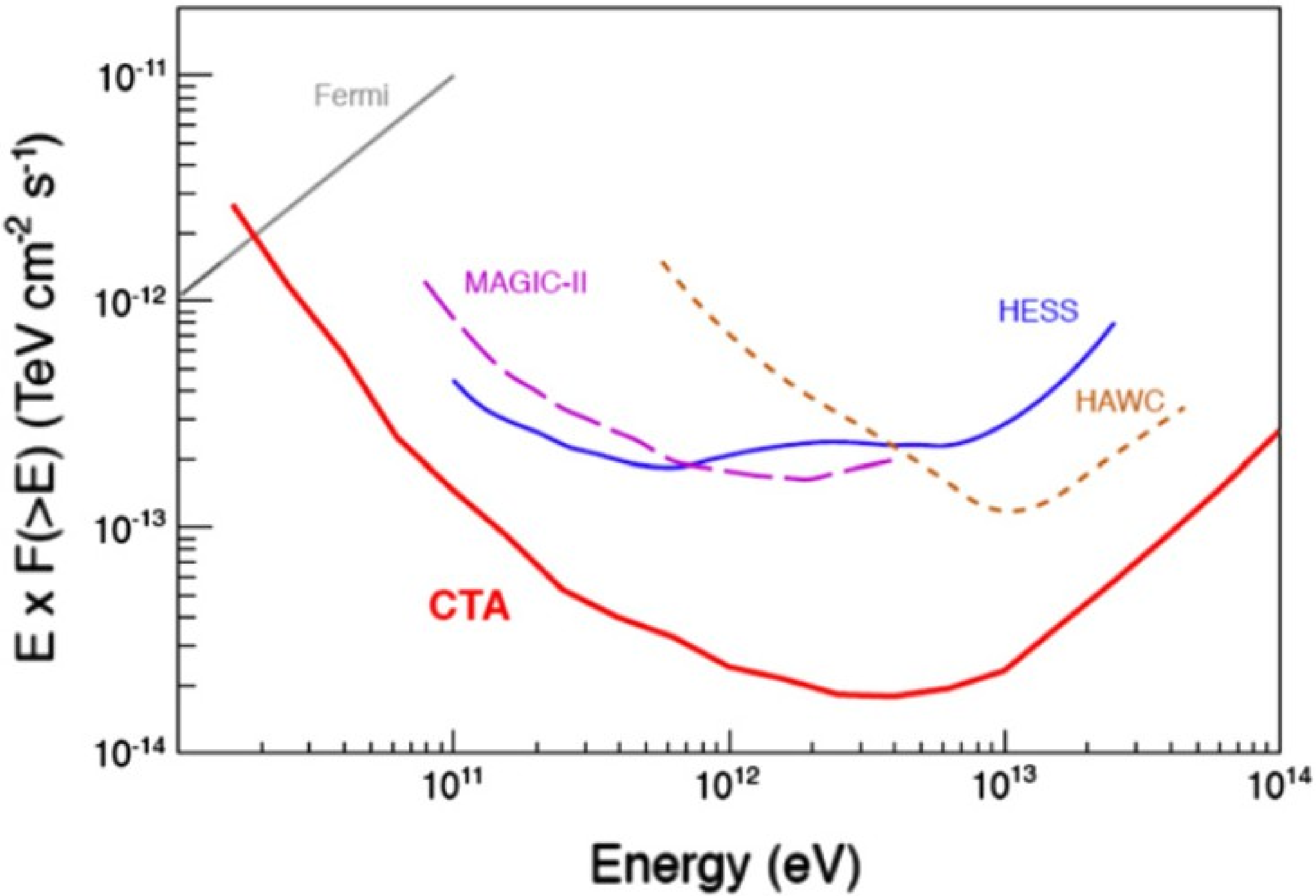


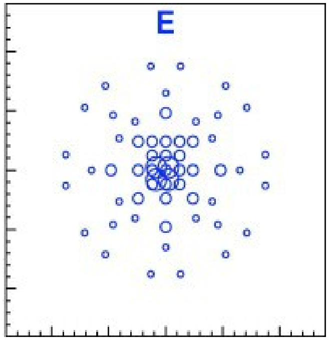



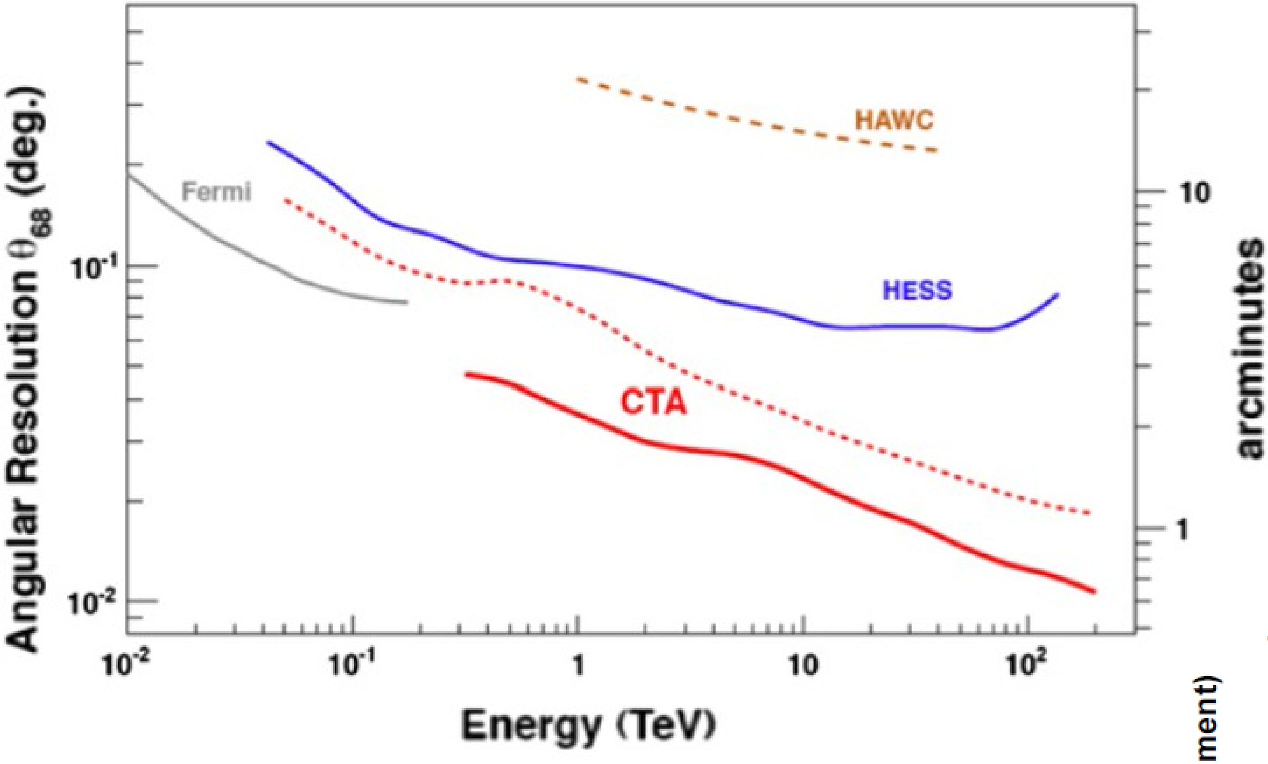




Preliminary performances of GAMMA 400, from A. Vacchi slides (July 2012). extrag 100x100




Achraya et al. 2013, ApPh, 43,3

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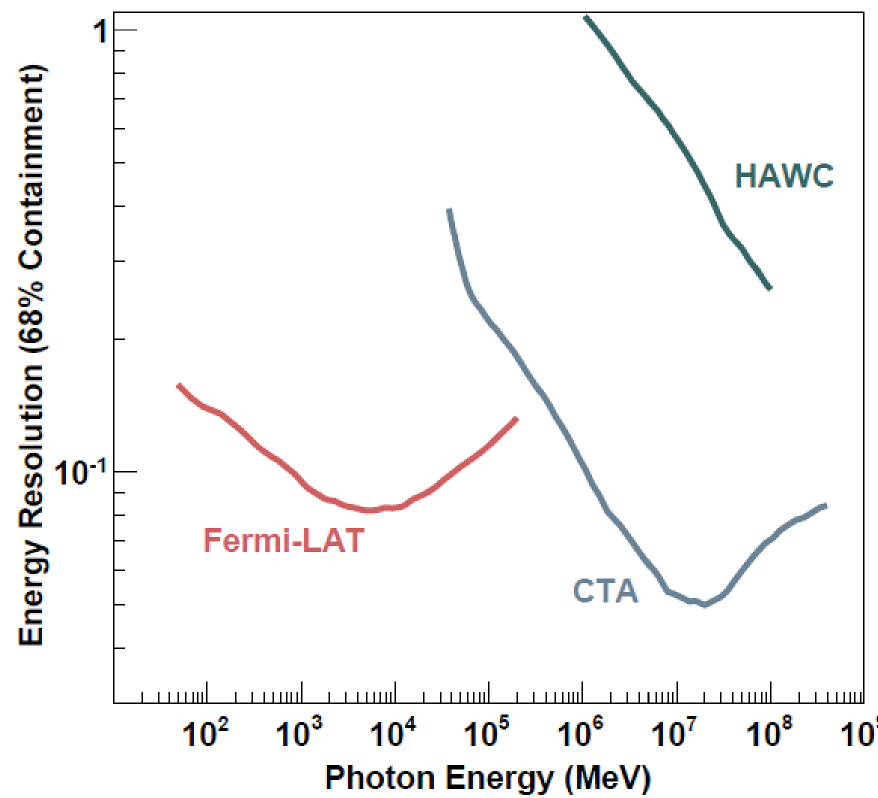


# 3 themes for science impact


- **Understanding the origin of cosmic rays and their impact on the constituents of the Universe**

The study of the physics of Galactic particle accelerators, such as pulsars and pulsar wind nebulae, supernova remnants, and gamma-ray binaries, the impact of the accelerated particles on their environment and the cumulative effects seen at various scales, reaching from massive star forming regions to starburst galaxies.

- **Understanding the nature and variety of black hole particle accelerators**

Concerns particle acceleration by supermassive and stellar black holes, comprising blazars but also radio galaxies and other classes of AGN that can potentially be studied in high-energy gamma rays. The fact that CTA will be able to detect a large number of these objects enables population studies that will be a major driver of this theme. EBL, Galaxy clusters and GRB studies are also connected to this field

- **Searching for the ultimate nature of matter and physics beyond the standard model**

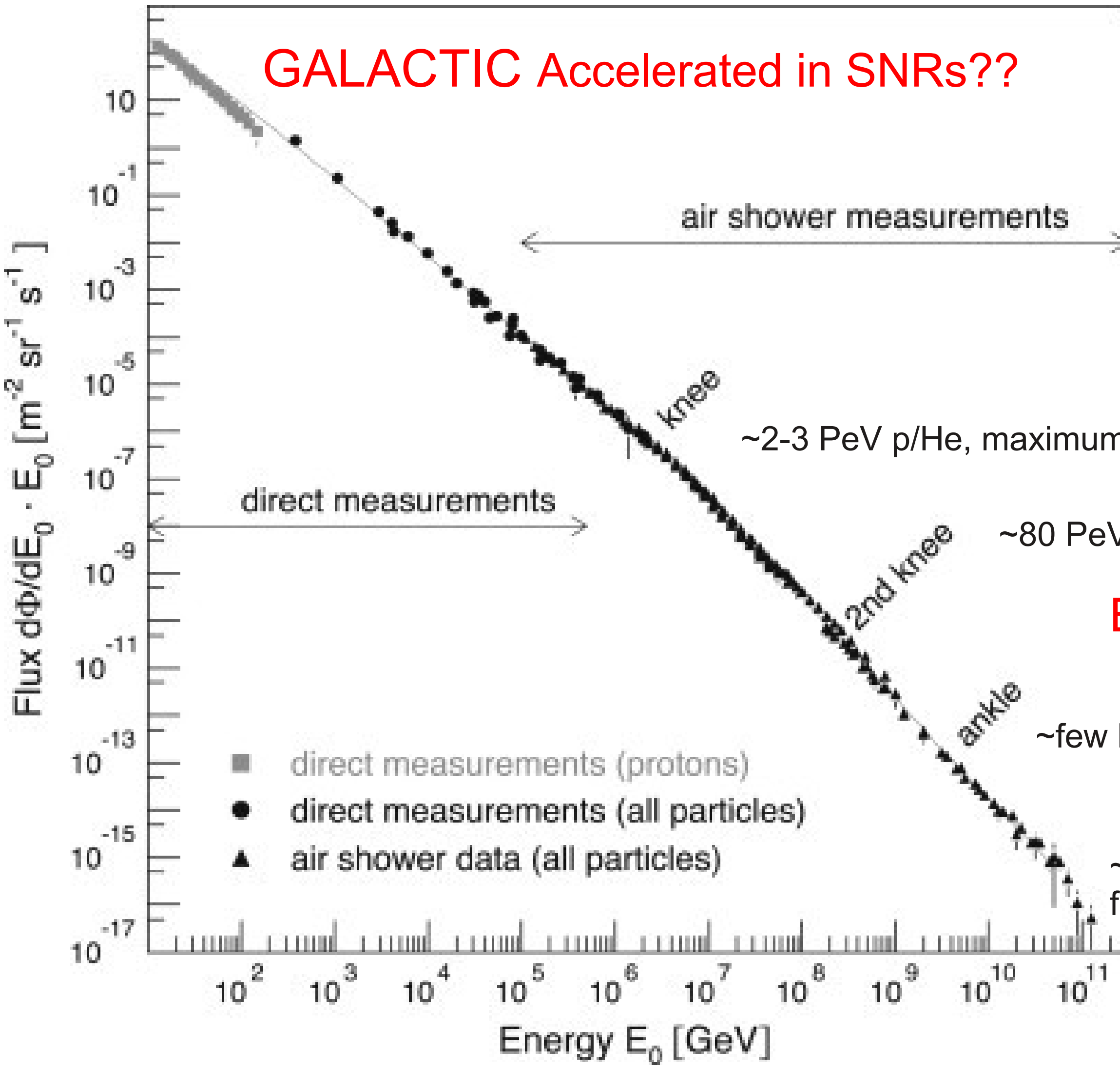
Concerns what can be called new physics and comprises the search for dark matter and its possible annihilation signatures, tests of Lorentz invariance, and any other observational signatures that may change our most basic description of the Universe.

# Key questions

- Where and how are the bulk of CR particles accelerated in our Galaxy and beyond? Understanding transitions in the CR spectra. (one of the oldest surviving questions of astrophysics)
- How cosmic-rays propagate, interact, and heat the environment? Which are the consequences from Galactic to cosmological scenarios?
- What makes black holes of all sizes such efficient particle accelerators?
- What do high-energy gamma-rays tell us about the star formation history of the Universe, the structure of spacetime, or the fundamental laws of physics?
- What is the nature of dark matter? Can it be discovered via indirect searches? Can we map dark matter halos?
- Are there short-timescale phenomena at very high energies? Are GRBs VHE gamma-ray emitter? Is there new Galactic phenomenology to uncover?

# A (by now) classic picture

Figure from Progress in Particle and Nuclear Physics, 2012, 67, 3, 651




GALACTIC Accelerated in SNRs??

Existence of features is a hint for passage to a different population

~2-3 PeV p/He, maximum energy for Galactic particles

~80 PeV might originate from heavy primaries

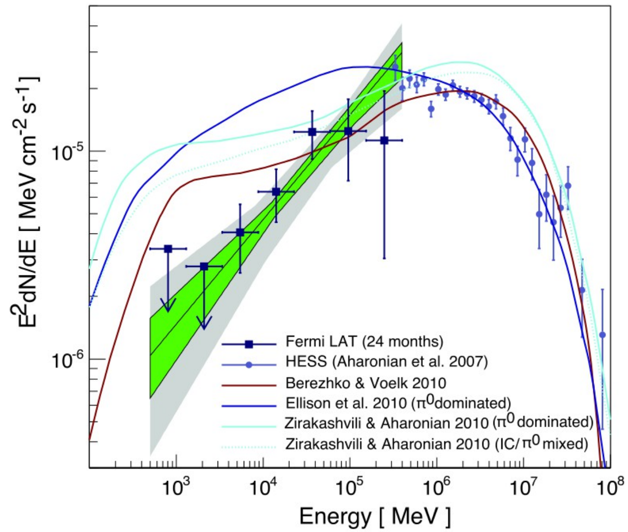
EXTRAGALACTIC Accelerated in … ??

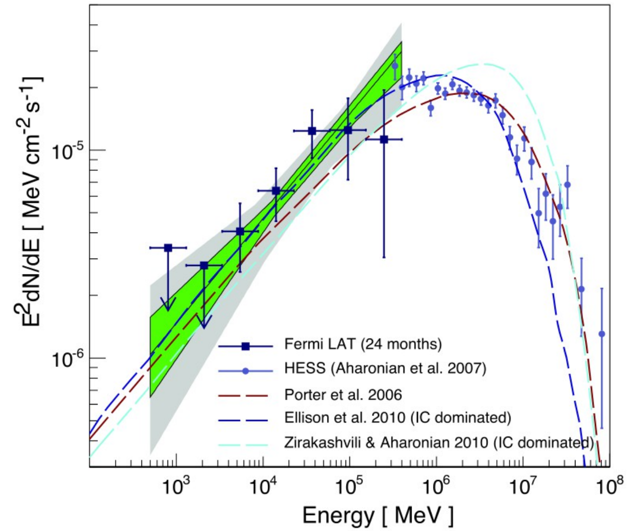
~few EeV surely extragalactic

~few 100 EeV: GZK cut-off or maximum energy from source

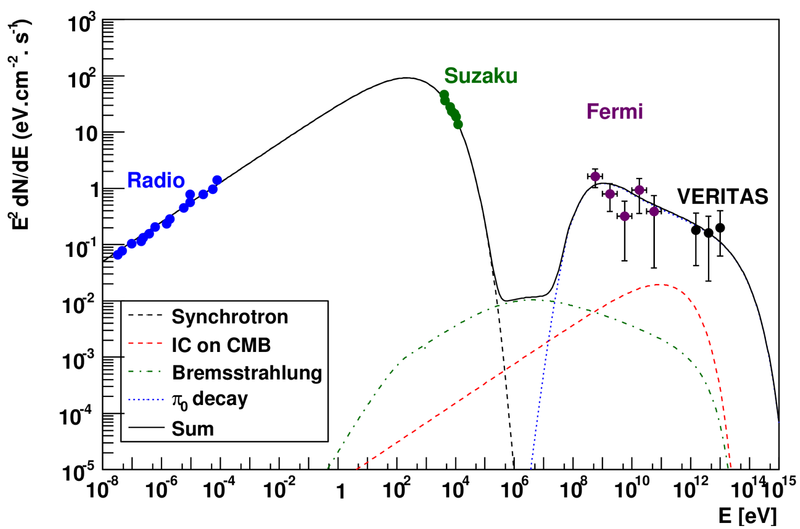
# Distinguish hadronic from leptonic origin

Dominant leptonic contribution from spectra in, e.g., RXJ 1713




Abdo et al. 2011



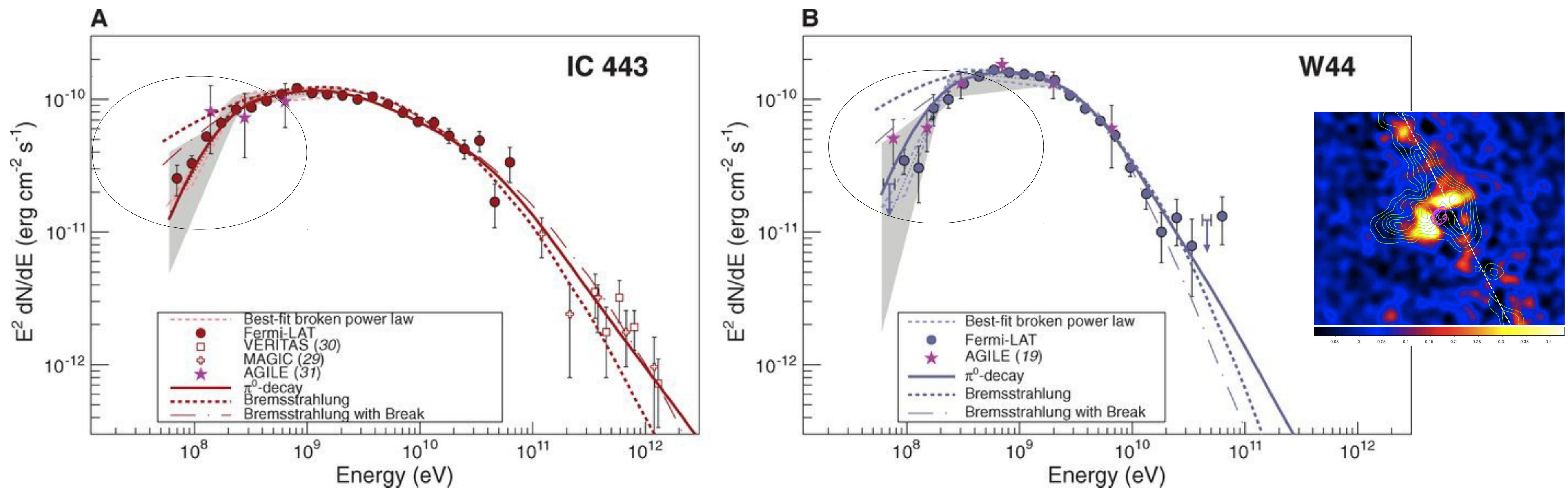

Dominant hadronic contribution from spectra in, e.g., Tycho

Giordano et al. 2010

# AGILE & FERMI results

•SNRs as sources of galactic CR?

YES! Concerning the bulk of cosmic rays ...



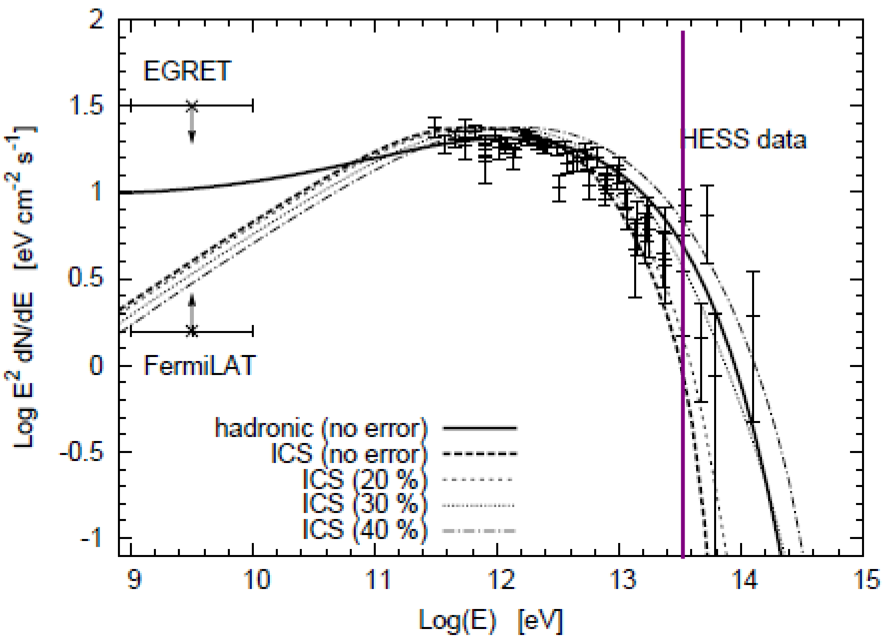

Ackermann et al. 2013, Science FERMI/LAT
Giuliani et al. 2011

Both sources are interacting with massive molecular clouds and hadronic models are the best-fitting.

# The cut-off in RX J1713-3946

M. Renaud et al.

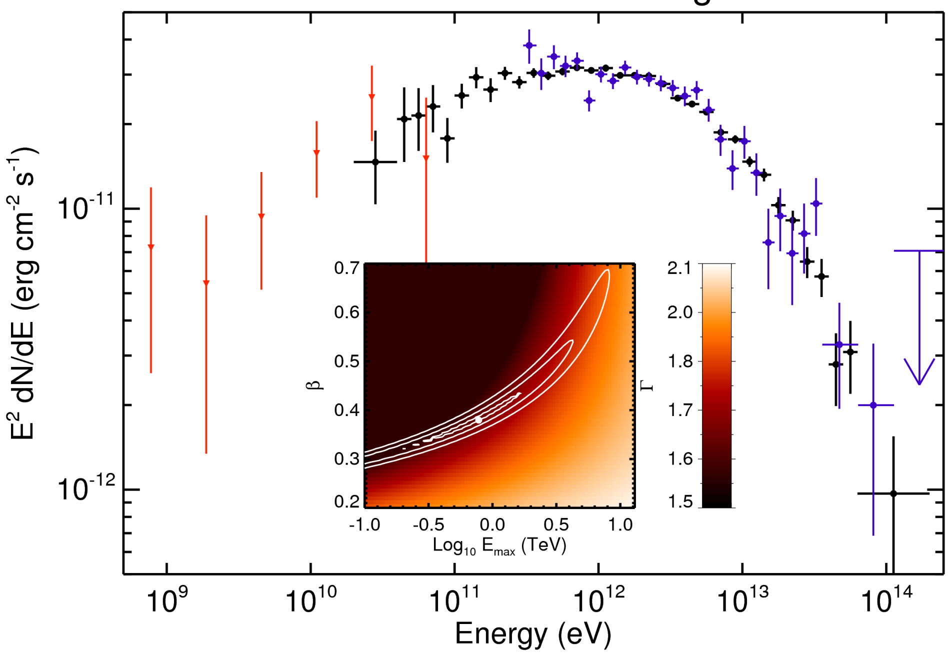
Need to get significant emission E>35 TeV




Morlino et al 2009

35 TeV

RXJ1713.7-3946 CTA config. I 50 h




The predominance of the leptonic contribution has been established at Fermi energies, what about VHE?
Will also constrain better the maximum particle energy

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

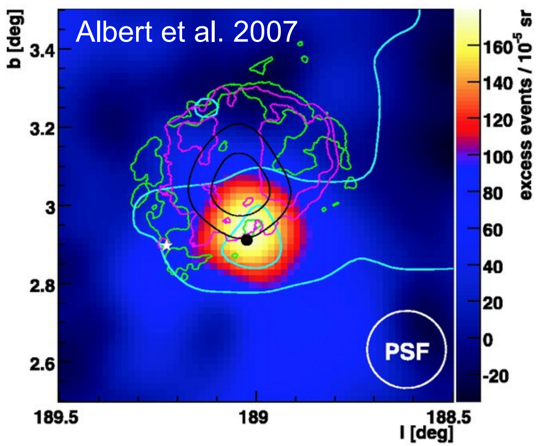
$\{\Gamma, \beta, E_{max}\}$ well constrained

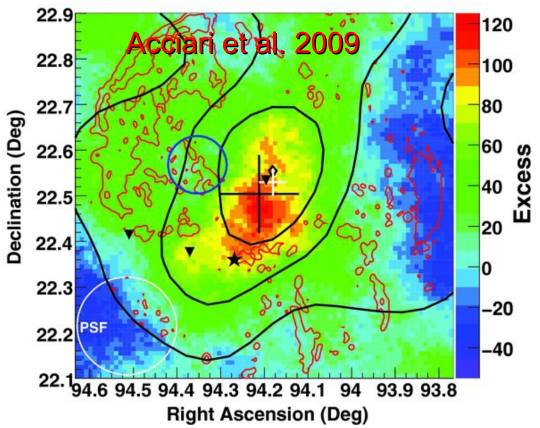
Config. I → $S/N_{\alpha=1}$ = 5.86 +/- 0.67

$S/N_{\alpha=0.1}$ = 7.33 +/- 0.88

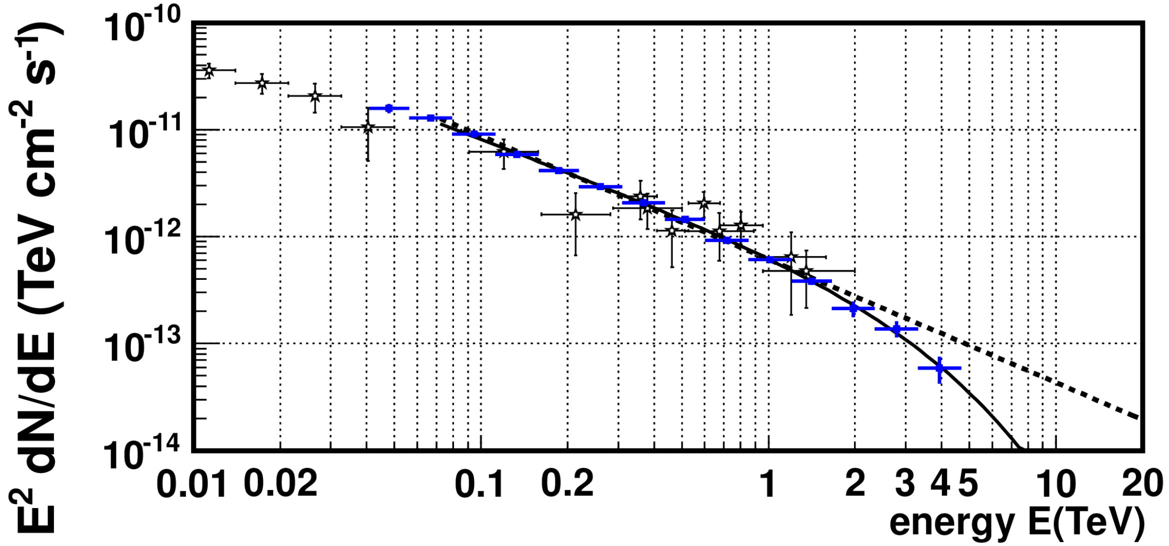
# IC443

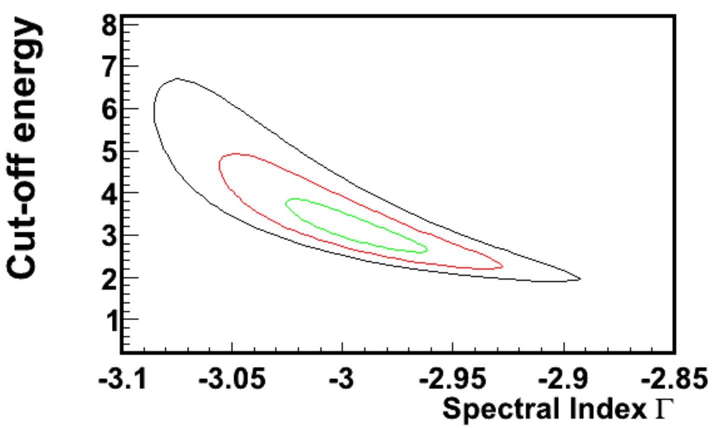
E. de Cea, D. Hadasch, GP, D. F. Torres




Maximum energies can be assessed also for steep sources, like IC443. Assuming that high energy cut-off in the spectrum is at 3-5 TeV, it will be reconstructed



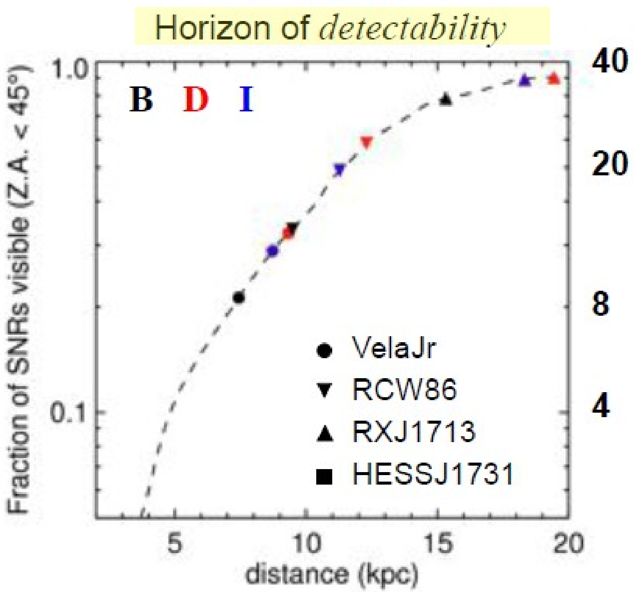




Acero et al. 2013, ApPh 43, 276

# Horizons

M. Renaud et al.

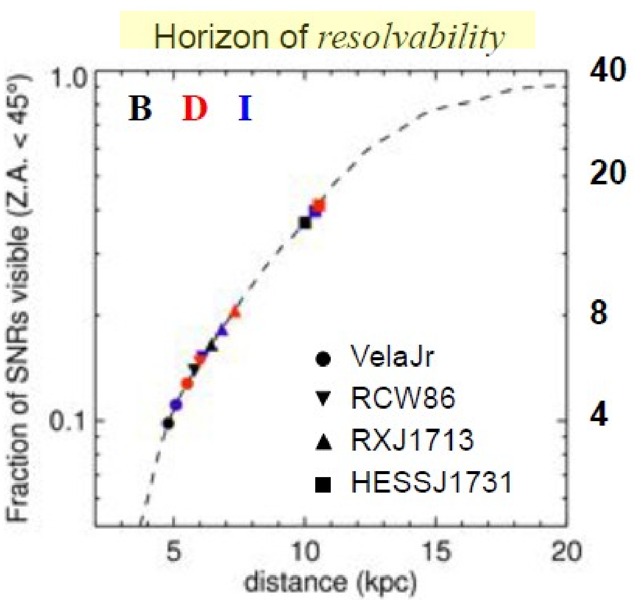
Acero et al. 2013, ApPh 43, 276




If the SNR detected so far are representative of the population, the maximum distance at which they can be detected can be estimated. It amounts in all cases to a significant fraction of the galaxy

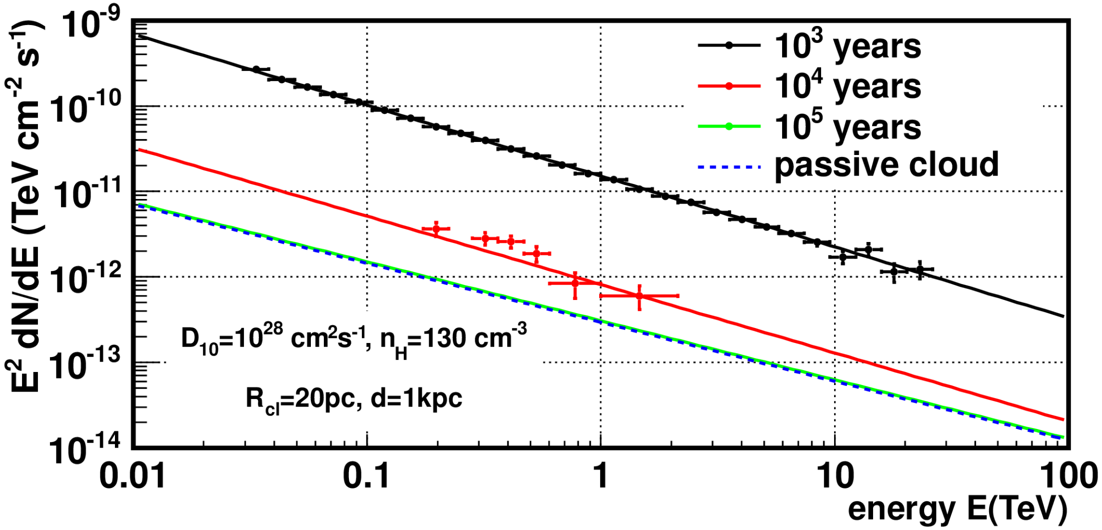
If all SNRs shine ~2000yrs at VHE -> total of 40 SNRs

For cases where the first id of the SNR shell comes from VHE (like in HESS J1731-347), it is useful to define an horizon of resolvability




Improvement in PSF by a x2 leads to 2x more resolvable SNRs

# Interactions with molecular clouds

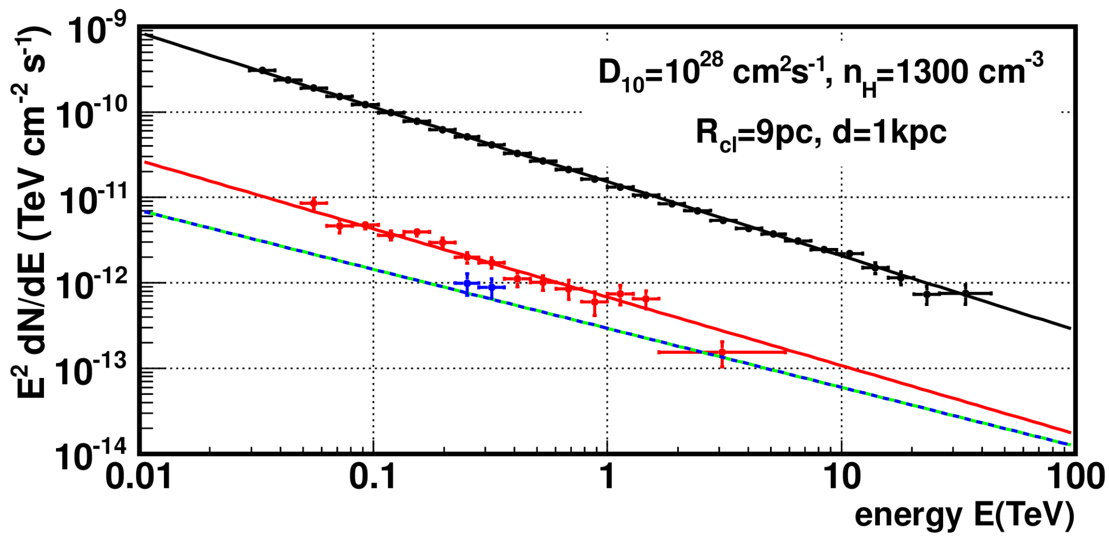



Association of accelerators with molecular clouds is essential to probe the universality of the intensity of cosmic rays in the galaxy and their diffusion properties.

GP, D. F. Torres

$$F(>E_\gamma) \sim 1.45 \times 10^{-13} \kappa \left(\frac{E}{\mathrm{TeV}}\right)^{-1.75} \times \left(\frac{M}{10^5 M_\odot}\right)\left(\frac{D}{1\mathrm{kpc}}\right)^{-2} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Depending on mass and extension of the cloud, it could be possible to detect passive clouds, i.e. with CR only from the CR background.

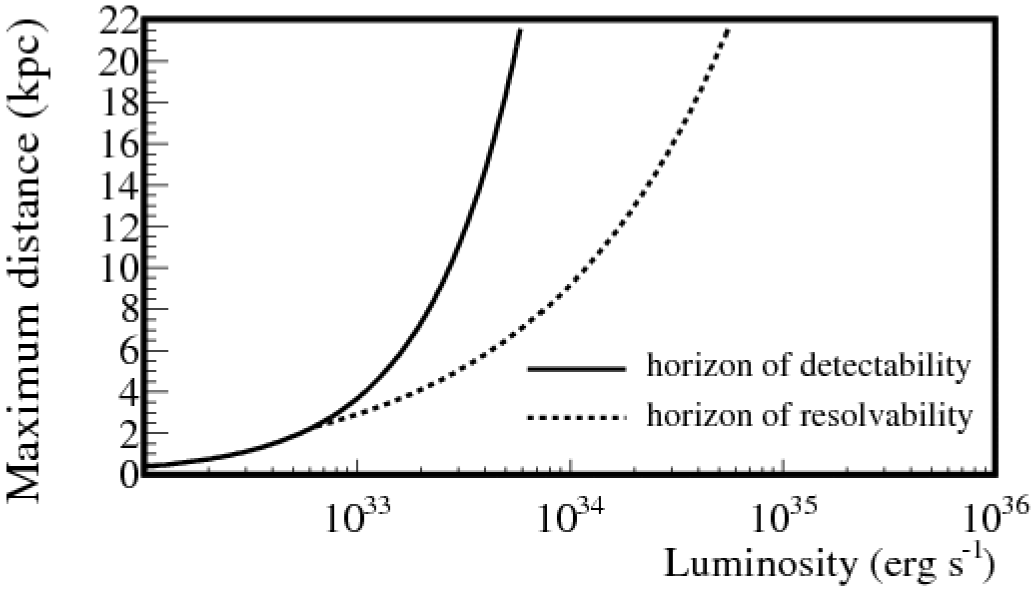



Acero et al. 2013, ApPh 43, 276

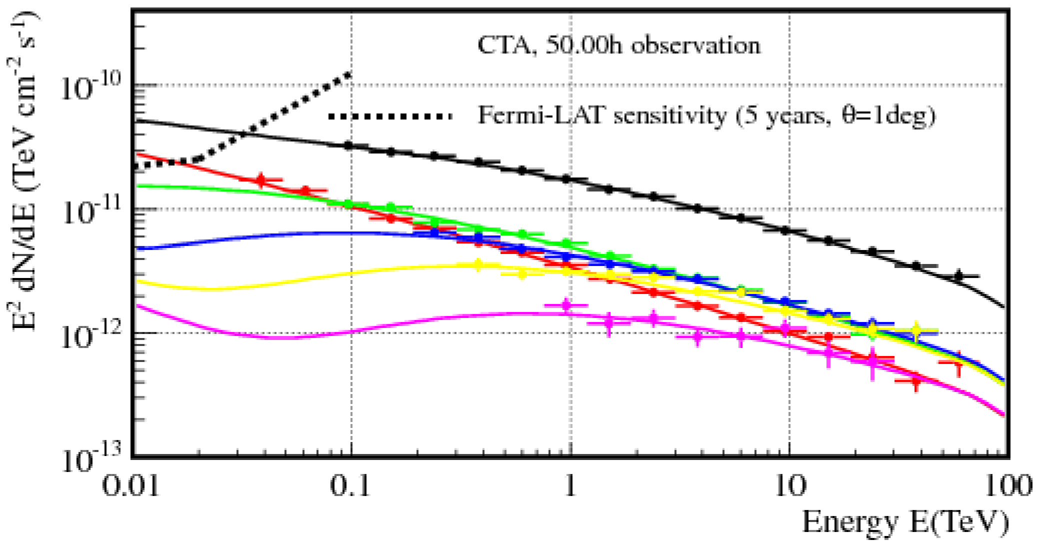
# CTA impact

Pedaletti et al. 2013

Capability of detect and resolve extended objects farther in the galaxy.

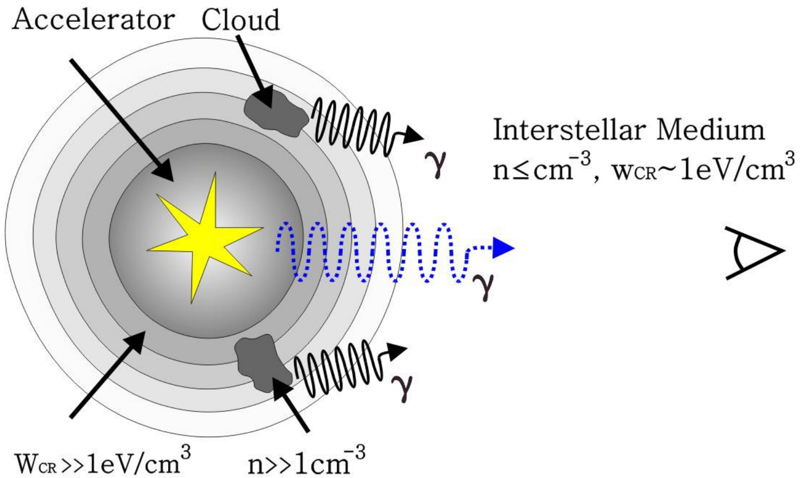



Better angular resolution will allow a spatially resolved spectral study and possibly the determination of the diffusion process thanks to spectral features

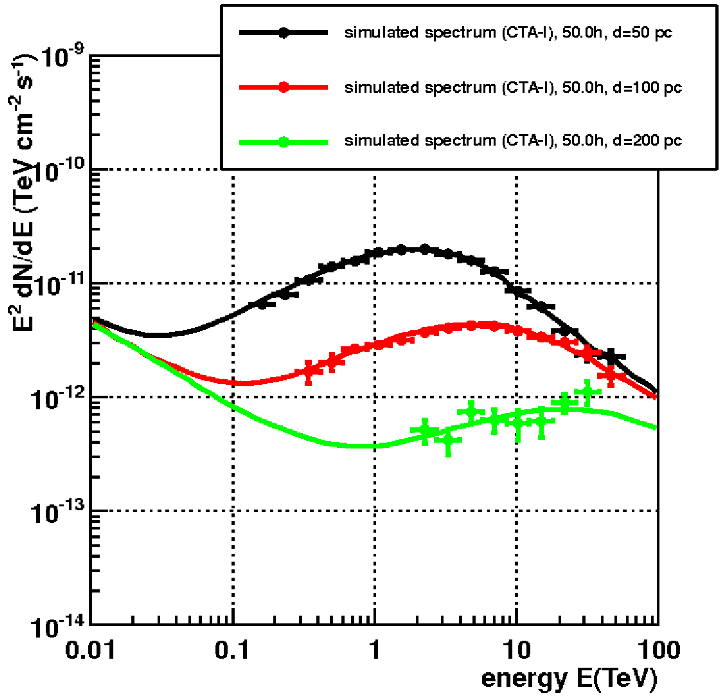


# Tracing CR diffusion

E. de Cea, D. Hadasch, GP, D. F. Torres




Acero et al. 2013, ApPh 43, 276



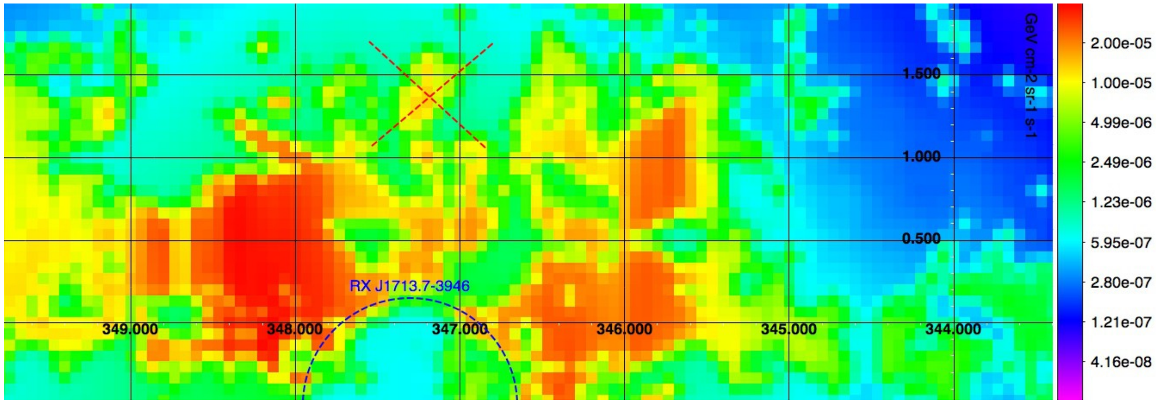

CRs contribution from:

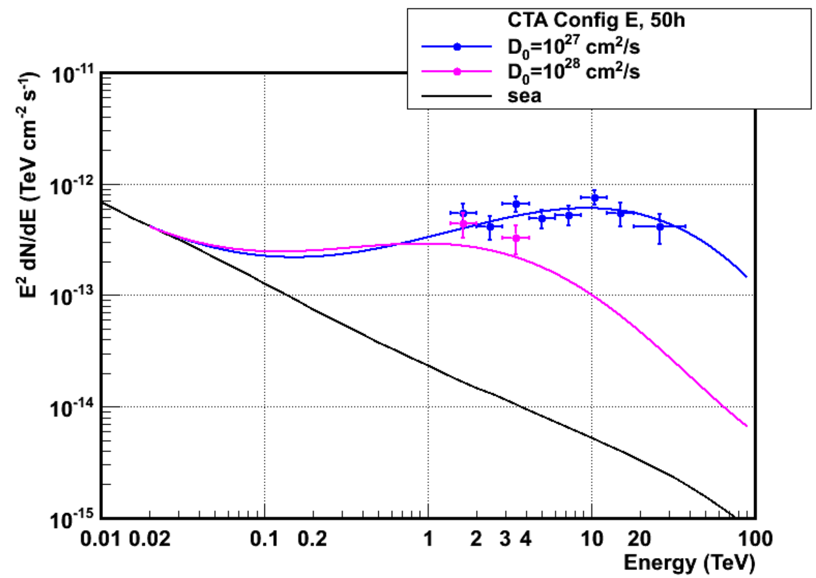
- Galactic background: steep spectrum, steady in time, peaks at GeV energy region;
- runaway from SNR: hard spectrum, variable in time, second peak at TeV energies moves to lower and lower energies (the highest the energy, the earlier and faster CRs diffuse away)

Gabici, Aharonian & Casanova 2009
Rodriguez Marrero, Torres, de Cea 2009

Peak moves at higher energies with increasing distance: CR with lower and lower energies progressively reach the cloud

# Tracing runaways




The highest energy particle can reach the surrounding overdensity first.
Emission can be expected even if the gas is not as dense as in a molecular cloud.

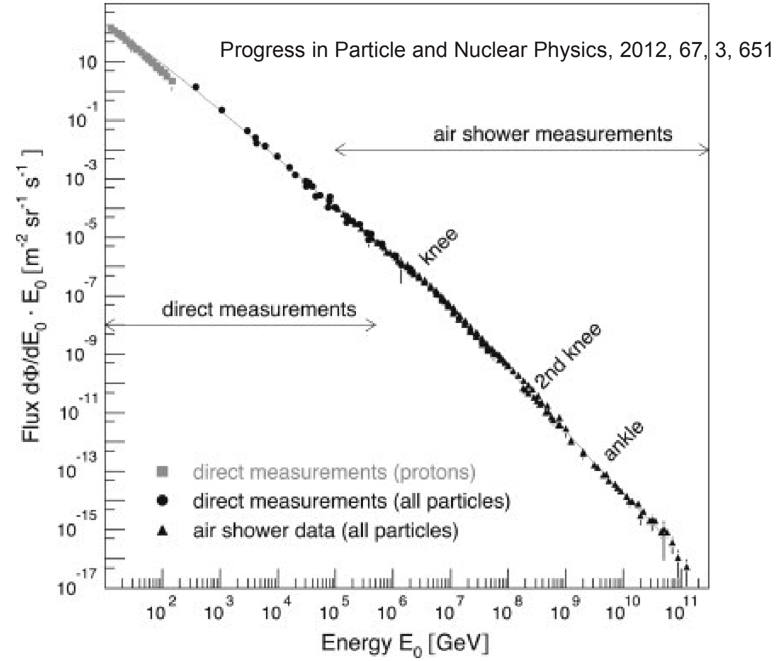
Emission only related to the CR background would not be detected in this case.

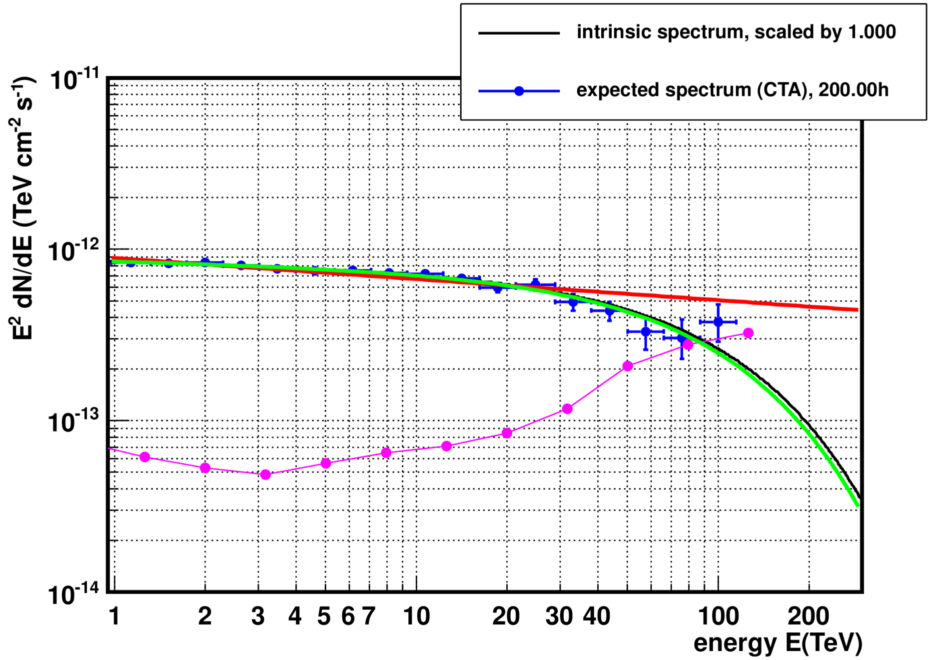
Acero et al. 2013, ApPh 43, 276

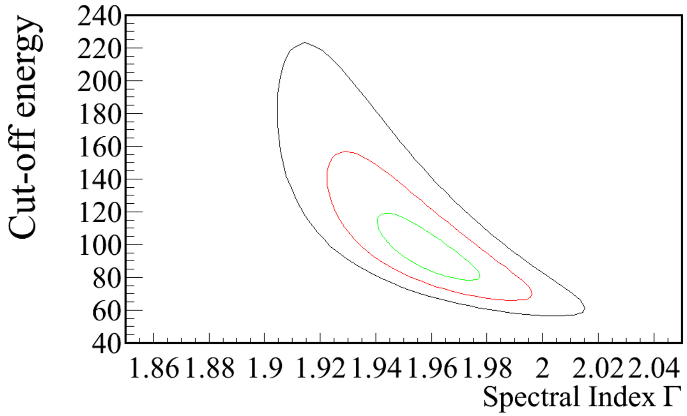
S. Casanova, E. De Oña, F. volpe, C. van Eldik

# What about pevatrons?

Very young SNRs (at the beginning of the Sedov phase) are strongly favoured for PeV particle acceleration. Acting as pevatrons for a short time → expecting few objects in the galaxy




GP, D. F. Torres, E. de Oña

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# VHE and CDM

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = B_F \cdot \underbrace{\frac{1}{4\pi}\frac{(\sigma_{\text{ann}} v)}{2m_\chi^2}\sum_i BR_i \frac{dN_\gamma^i}{dE_\gamma}}_{\text{Particle physics}} \cdot \underbrace{\tilde{J}(\Delta\Omega)}_{\text{Astrophysics}}$$

Density enhancement from, i.e., subhalos or enhancement of cross-section.
Could account for several orders of magnitude.

$$\tilde{J} = \int_{\Delta\Omega} d\Omega \int_{\text{los}} ds\, \rho^2(s, \Omega)$$

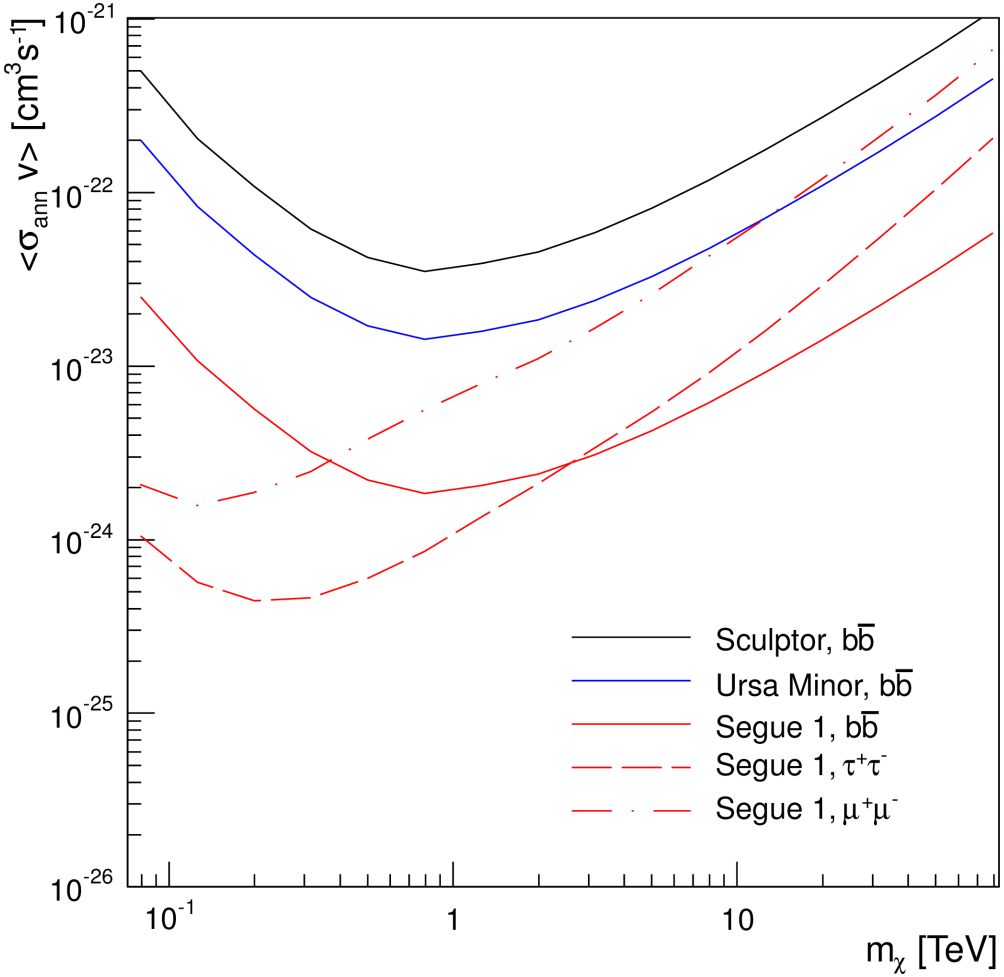
Look for dense regions

# CDM in DSGs

Dwarf spheroidal galaxies are the most DM dominated objects and basically free of astrophysical background.

Characterization of the DM particle through the determination of its mass and its velocity-weighted annihilation cross section, assuming a given annihilation spectrum and DM halo profile in dSph galaxies.

Assume 100% BR for each channel.




P. Brun, J.F. Glicenstein, E. Moulin, A. Viana
J.A. Barrio, J.L. Contreras, T. Hassan, N. Mirabal, D. Nieto

Doro et al. 2013, ApPh 43, 189

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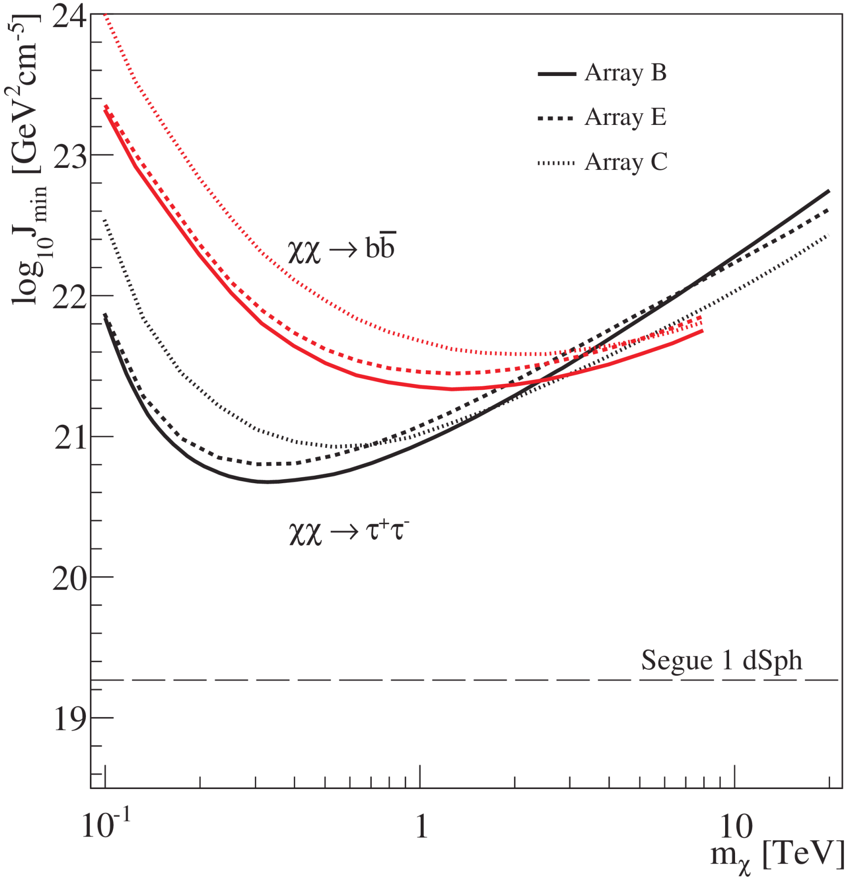


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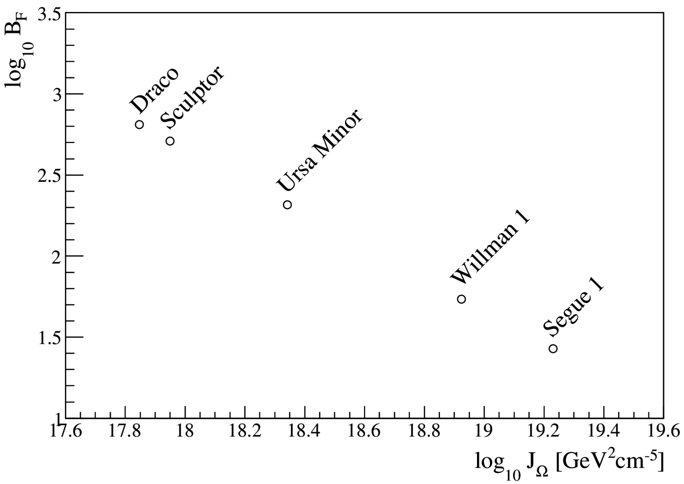



Doro et al. 2013, ApPh 43, 189

Best candidates are: Segue 1 in the northern sky; Sculptor in the southern sky. In the last years, new ultra-faint dSph are being discovered. New and possibly better targets are to come in the near future in both hemispheres. Data combination from different objects should also be considered.

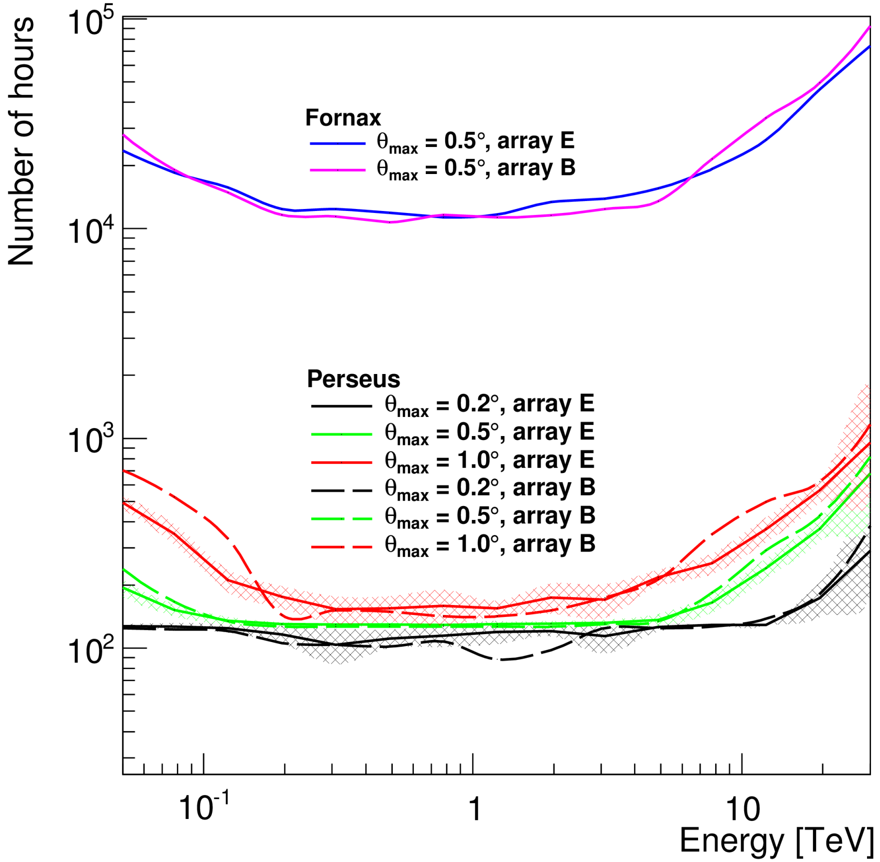
# CDM in galaxy clusters

The large FoV of CTA will be crucial to study the possible boost from subhalos in galaxy clusters away from the halo center.
Expected emission also at the degree level extension.

Perseus has the highest CR contribution (northern source)

Fornax (southern source) is the best candidate cluster for DM signal.

The possible detection of Perseus in ~100 hours would be an exceptional result per se, even decoupled from DM signal interpretation.




M. Doro & M. Fornasa

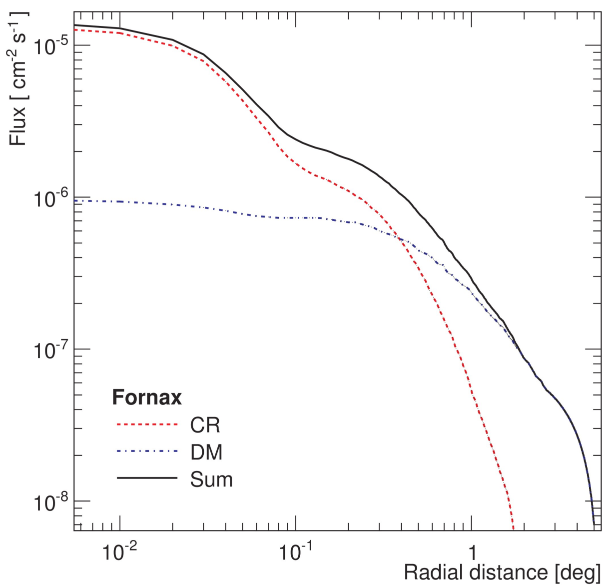
Doro et al. 2013, ApPh 43, 189

# CDM in galaxy clusters

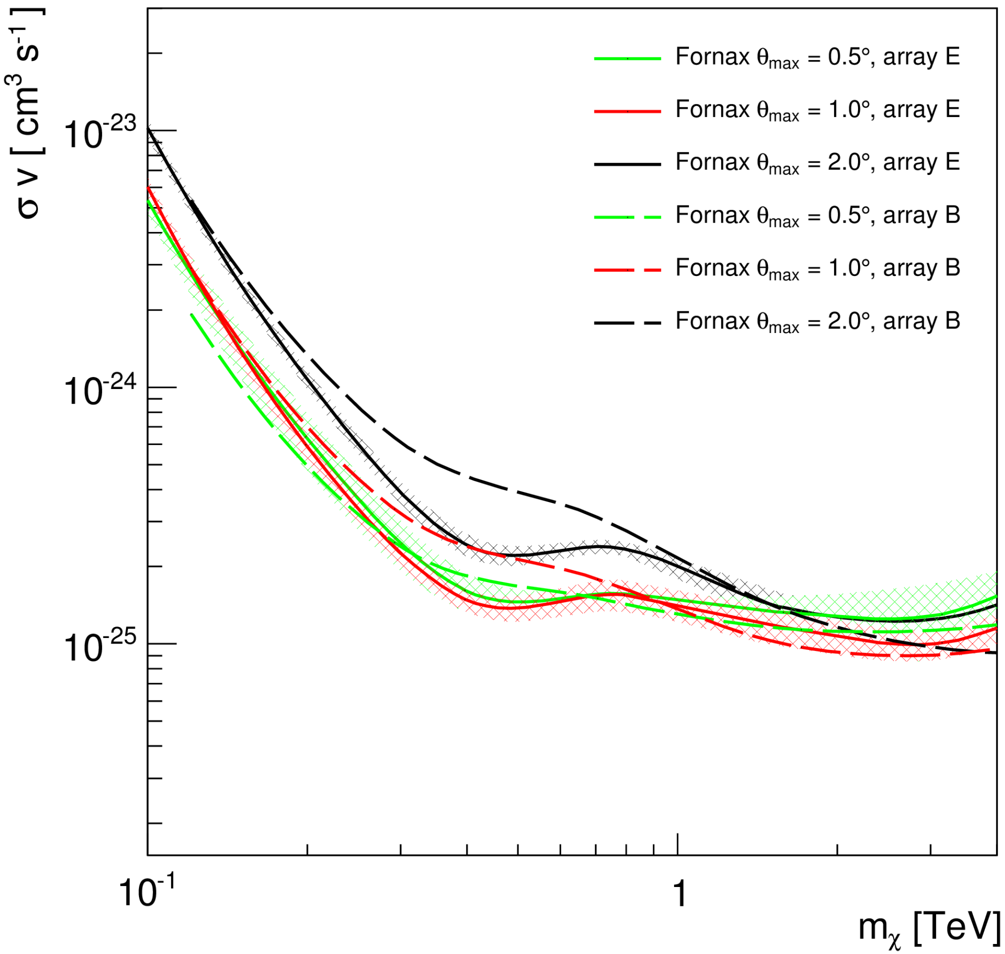
The large FoV of CTA will be crucial to study the possible boost from subhalos in galaxy clusters away from the halo center.

Boost factor would be paramount for more stringent limits

Different surface brighness profiles will help in disentangling the contributions (CR vs DM)




M. Doro & M. Fornasa




Doro et al. 2013, ApPh 43, 189

# Galactic halo and center

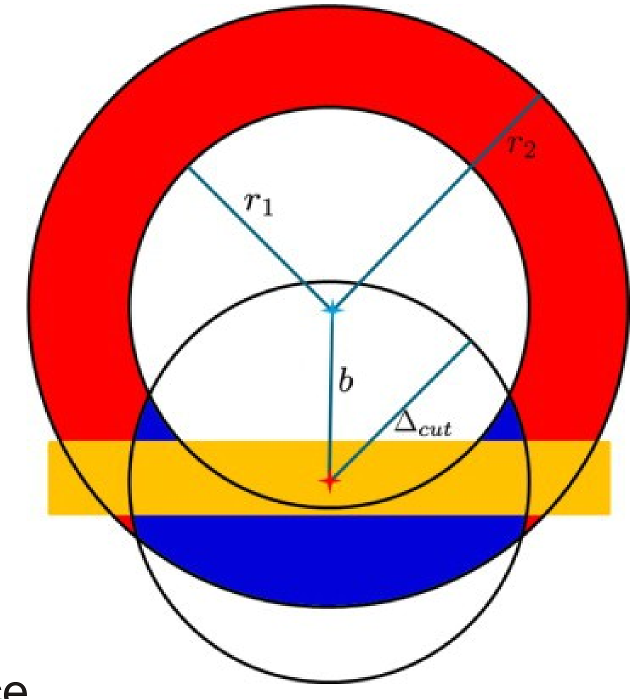
The annihilation signal is dominated by the diffuse DM in the main halo. However, the Galactic center is a region rich in astrophysical sources.

Avoid the galactic plane to avoid astrophysical sources, but remain in a region close enough to so that the expected flux is still detectable (HESS result gives a velocity-averaged annihilation cross-section of few x 10^-25 in 112hrs, most constraining UL)

Also search for features in the excess spectra.

Chose ON and OFF regions carefully

| Array | b | $r_1$ | $r_2$ | $\Delta_{cut}$ |
|---|---|---|---|---|
| E | 1.42º | 0.55º | 2.88º | 1.36º |
| B | 1.40º | 0.44º | 2.50º | 1.29º |




Still ~ inside the 50% acceptance

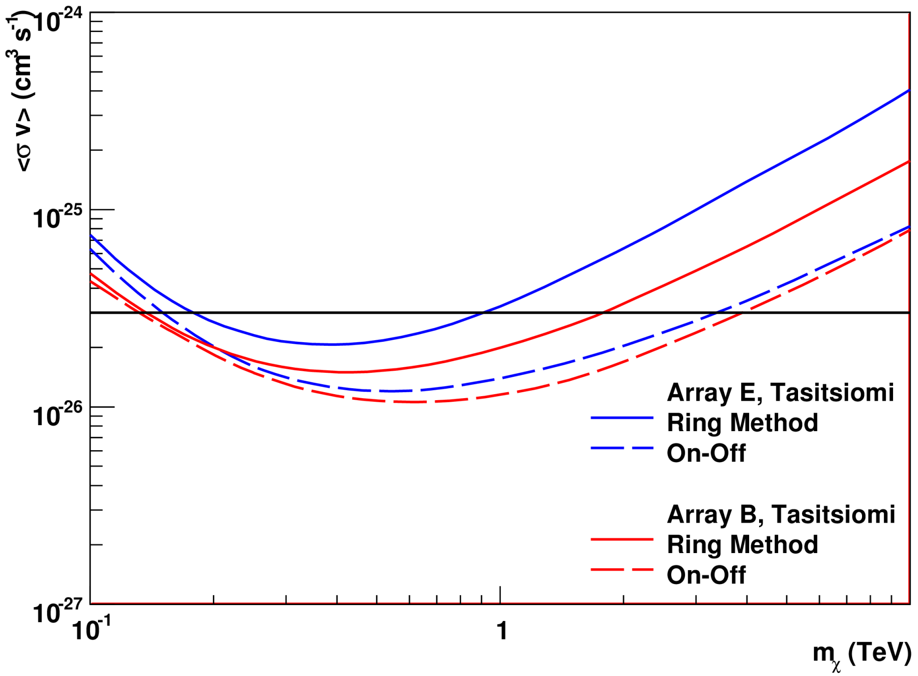
U. Schwanke & L. Oakes

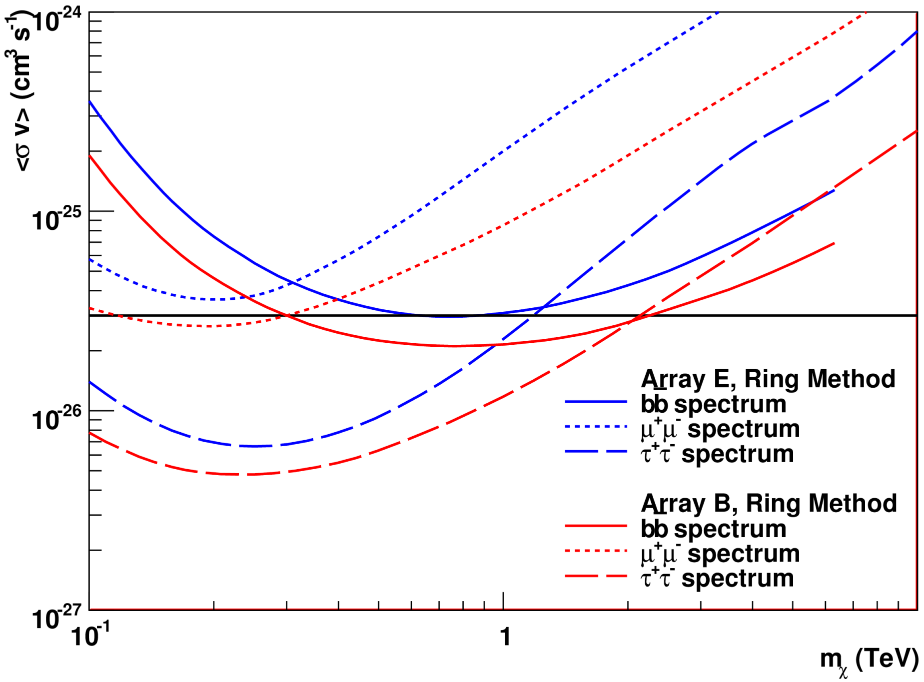
Doro et al. 2013, ApPh 43, 189

# Galactic halo and center

The most stringent limits are expected from this analysis

Array B is always favourite for any mass.




U. Schwanke & L. Oakes

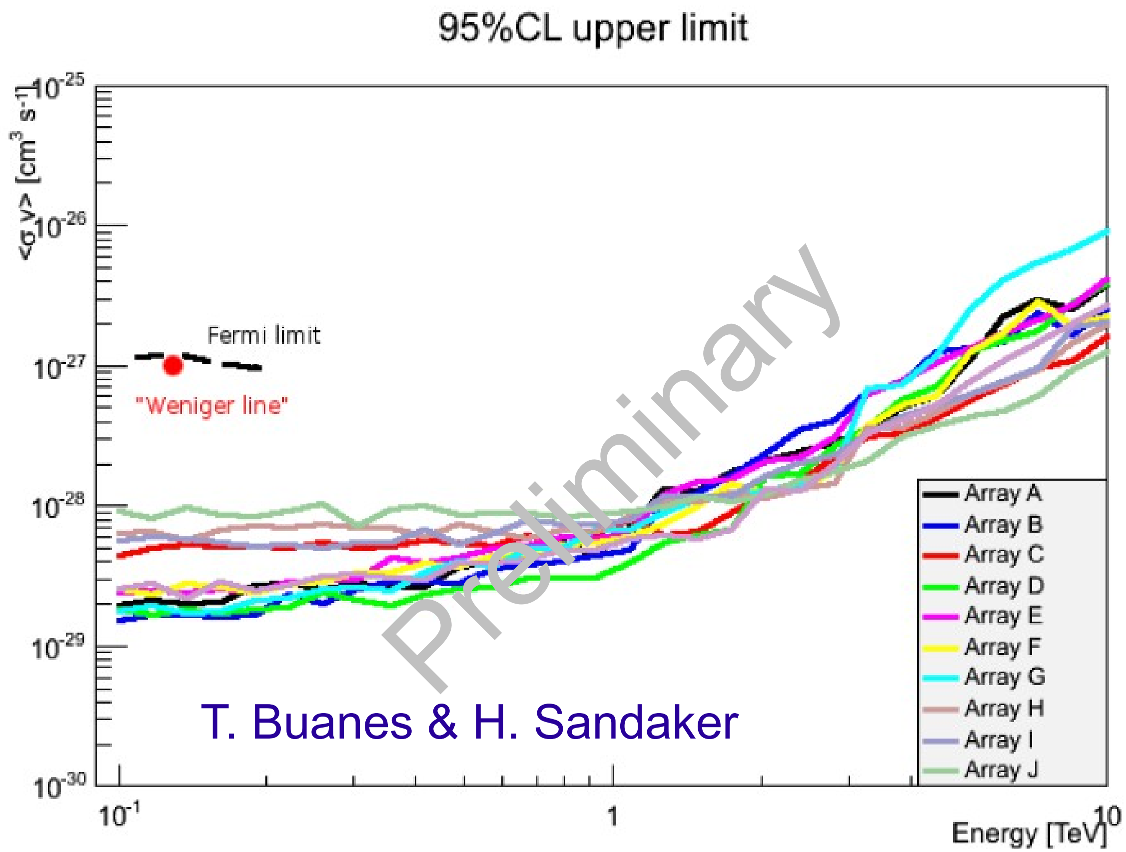
Doro et al. 2013, ApPh 43, 189

# Future perspectives

The study of line features with CTA is on his way, superimposing a feature on top of GC emission

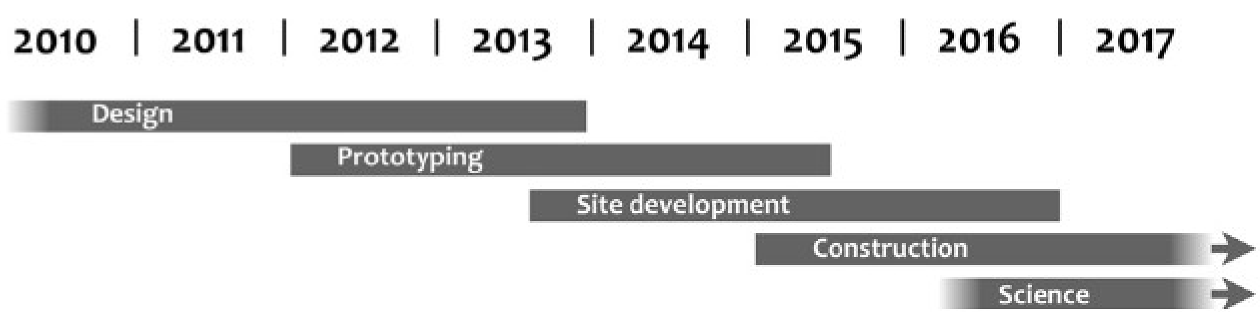
Very interesting thanks to the “safe” interpretation. No lines from astrophysical process are expected.

The largest difference among arrays is seen at low energies



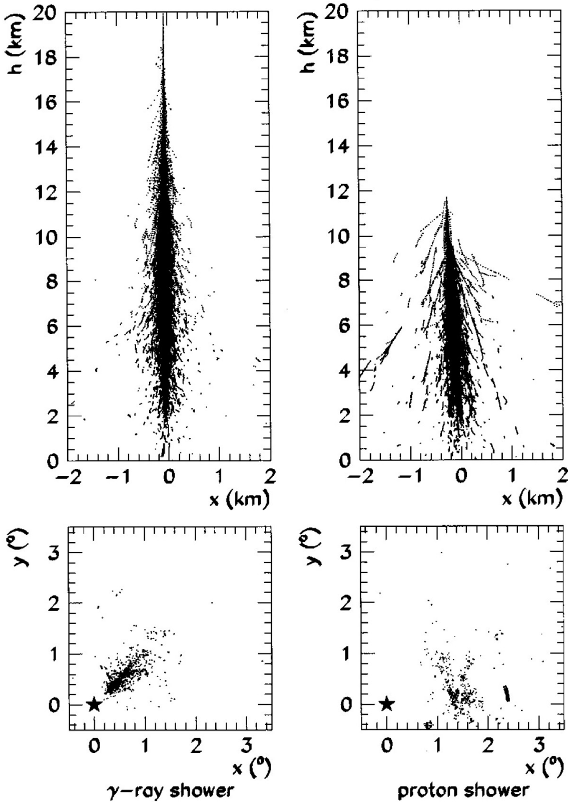
# In summary

- The Cherenkov Telescope Array is the future of the field:
  - much is already expected ("secure" physics output)
  - power of serendipity in order-of-magnitude improvements
- Remember that it will be an Observatory: after construction, the whole community can participate!

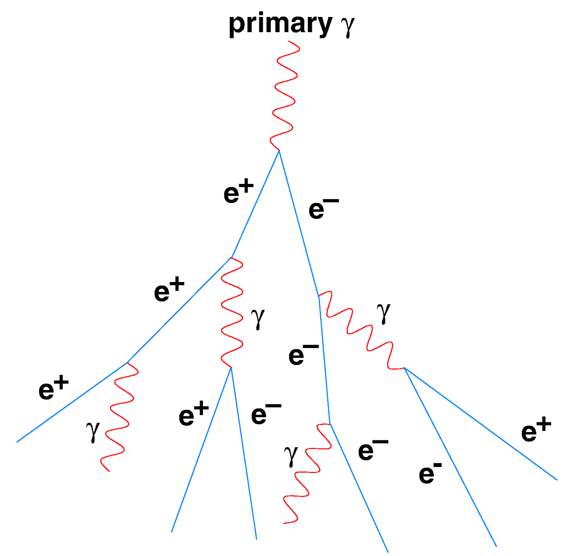


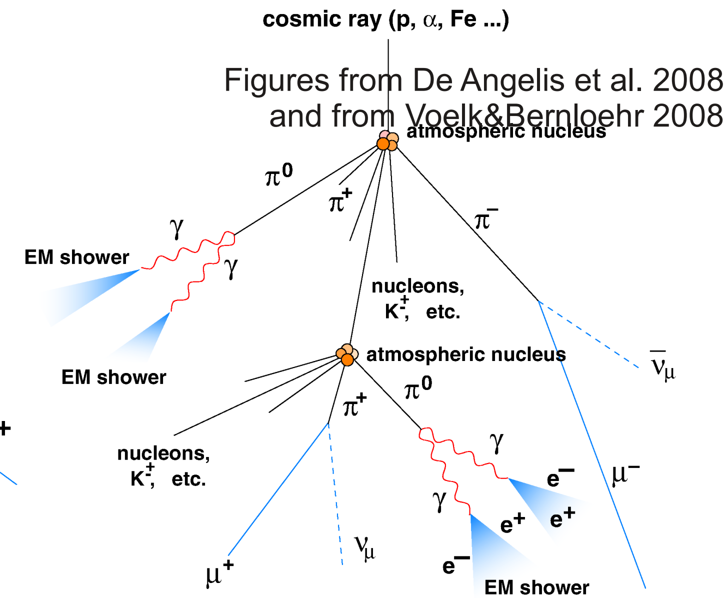
# Backups

# Cherenkov Technique




Low photon number, therefore use of the atmosphere as a detector




Figures from De Angelis et al. 2008
and from Voelk&Bernloehr 2008

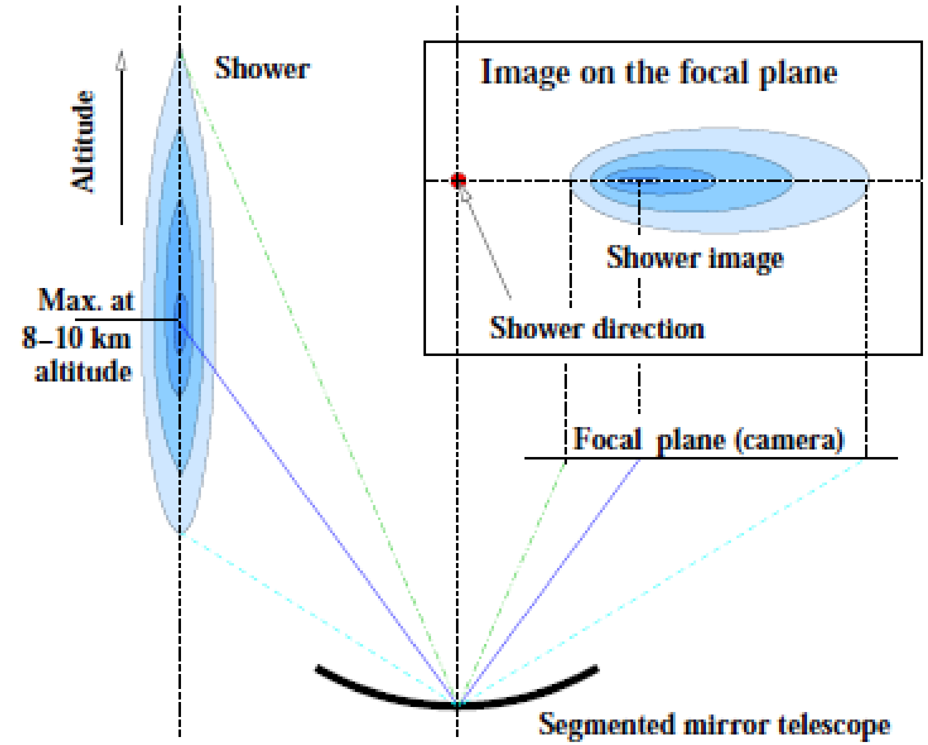
VHE gamma-rays interact with the atmosphere leading to a particle cascade.

Velocities in the cascades are larger than the speed of light in the medium and Cherenkov emission takes place.

Particle cascades can also be initiated by hadrons.

Gamma initiated showers can be distinguished by hadron initiated ones mainly from **shape** difference

# Cherenkov Technique

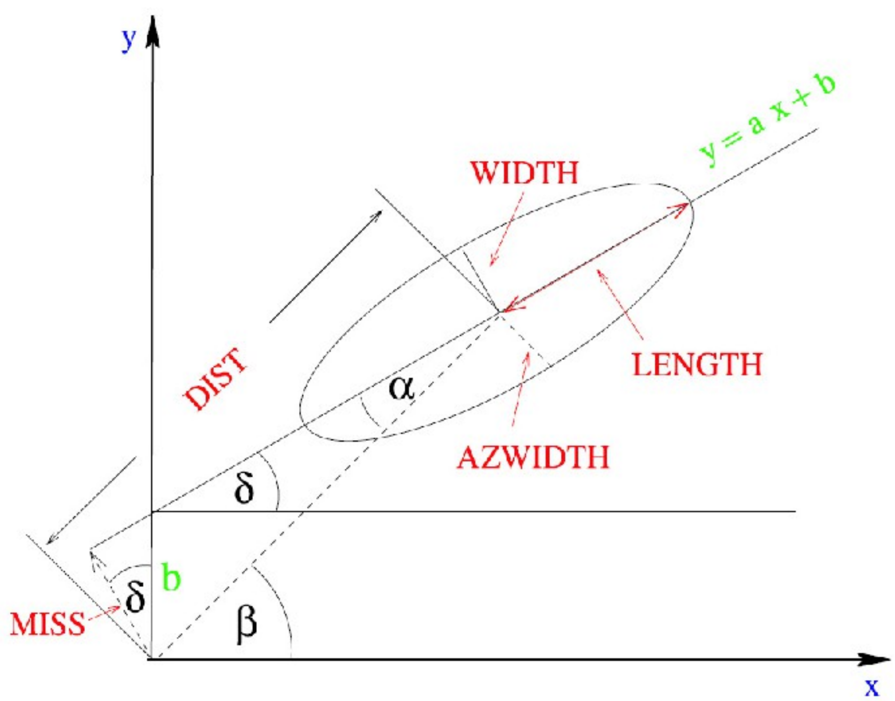



Figures from De Angelis et al. 2008
and from Voelk&Bernloehr 2008

The shower can be imaged as a nanosecond long flash of blueish (O/UV) light by PMT (photomultipliers).

The number of Cherenkov photons is basically proportional to the initial gamma-ray photon energy

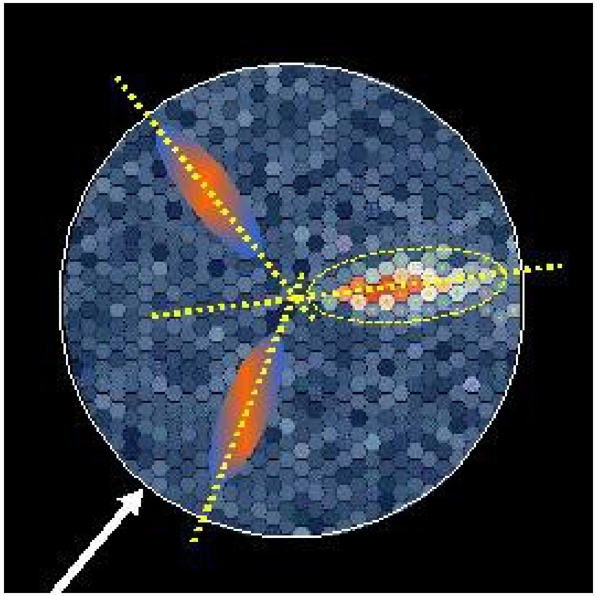
# Standard Hillas




Figures from De Angelis et al. 2008
and from Voelk&Bernloehr 2008

Arrival direction and energy of the photon can be reconstructed with the classical Hillas parametrization of the elliptical image:

- CoG (position in the camera)
- Length
- Width
- Size
- Orientation



The Cherenkov flashes illuminate a pool of ~120 m.
Precision of reconstruction and gamma-hadron separation increased by stereoscopic technique

# Observation basics

Moonlight is a huge source of background. Need to study the introduced systematics very well if the moon is up.
For example, HESS observes only in moonless nights => 1000 hours of observation every year.

Influence of offset and zenith angle on the energy threshold (via angular and energy resolution):
Higher offsets and higher zenith angles lead to higher energy thresholds

Wobble observation:
The source is alternately offset by a small distance within the field of view. This observation mode allows the other side of the field of view, which does not contain the source, to be used as a control region for estimation of the background level.

# Extensive Air Showers detectors

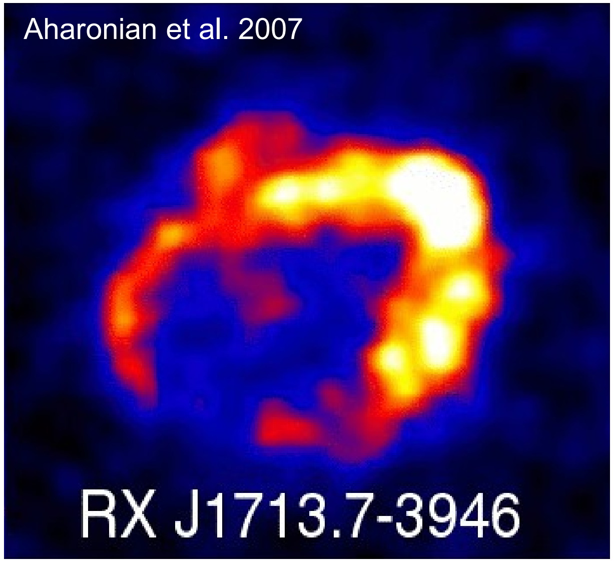
| Quantity | IACTs | EAS |
|---|---|---|
| Energy range | 100 GeV – 50 TeV | 400 GeV – 100 TeV |
| Energy resolution | 15-25% | $\sim$ 50% |
| Duty Cycle | 15% | $>$ 90% |
| FoV | 5 deg $\times$ 5 deg | $4\pi/6$ |
| Resolution(PSF) | 0.07 deg | 0.5 deg |
| Sensitivity | 1% Crab (0.5 TeV) | 0.5 Crab (5 TeV) |
| | 50 hours | 1 year |

Example:
Milagro (2000-2008)
Water Cherenkov detector

- Direct detection of particles of the air shower thanks to interaction with detector material.
- As the shower is probed at ground level, the energy threshold is incresead wrt IACTs.
- Gamma rates are very low -> detector surface $>10^3$ $m^2$.
- Arrival direction from shower front timing.
- Hadronic background rejection is made on the muon content of the shower and on the particle distribution at the ground.

Upcoming HAWC experiment:4100m a.s.l. With a 22500$m^2$ sensitive area, the sensitivity will increase by 1 order of magnitude

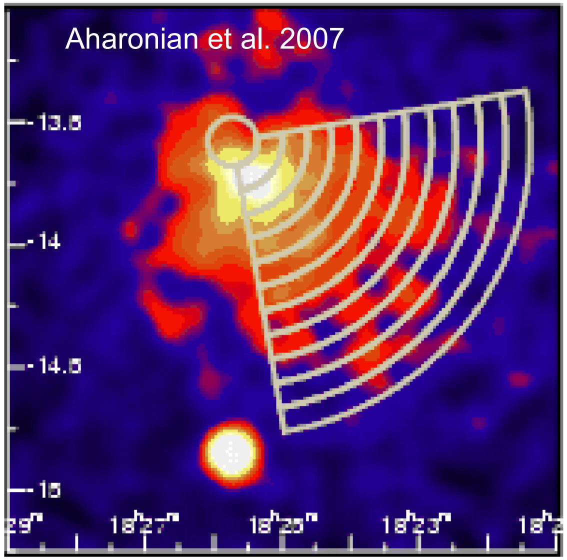
# Topics of interest




- SNRs as sources of galactic CR?
- Open questions on diffusive shock acceleration
- CR spectrum universality

- Maximum and minimum sizes in PWN
- Energy dependent morphology in PWN
- Composite systems

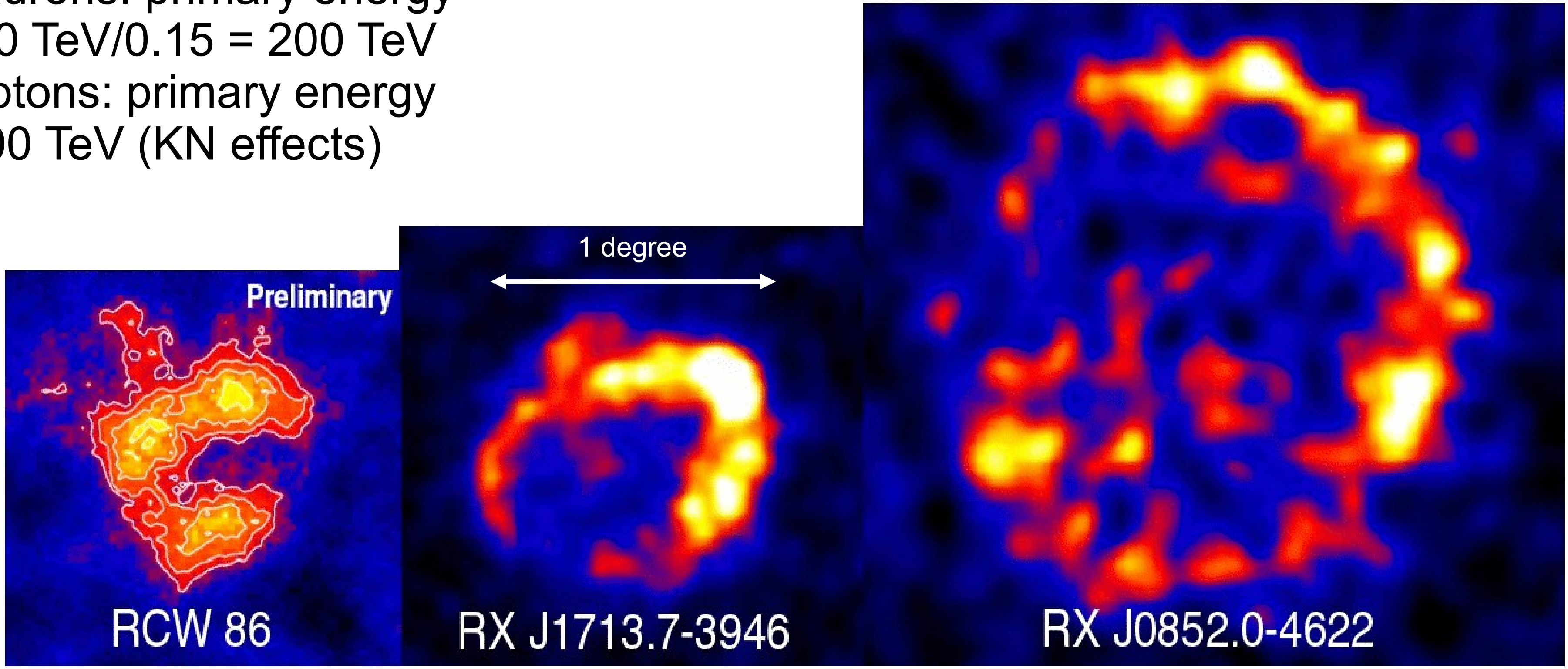
- Population studies



# Observations of SNRs: shells

Several shell-type supernova remnants have been already resolved as TeV gamma-ray shells: direct proof of shock acceleration of particles to hundreds of TeV energies at supernova remnant shocks

RX J1713 has E>40 TeV gammas: 1st model independent proof of particle acceleration to E>100 TeV
if hadrons: primary energy
~ 30 TeV/0.15 = 200 TeV
if leptons: primary energy
~100 TeV (KN effects)



# MWL scenario

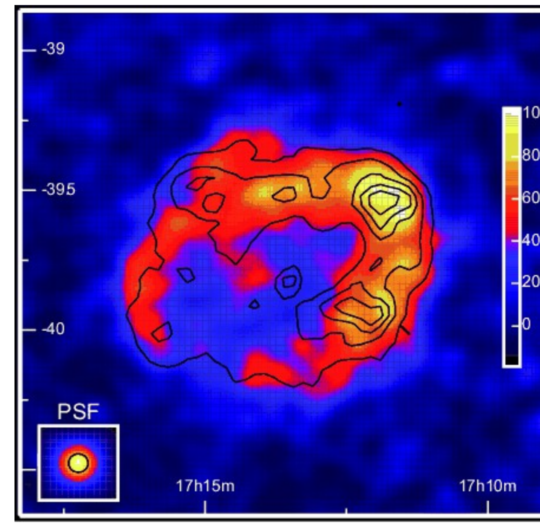
MWL information from lower energy bands is crucial to complete the VHE picture:

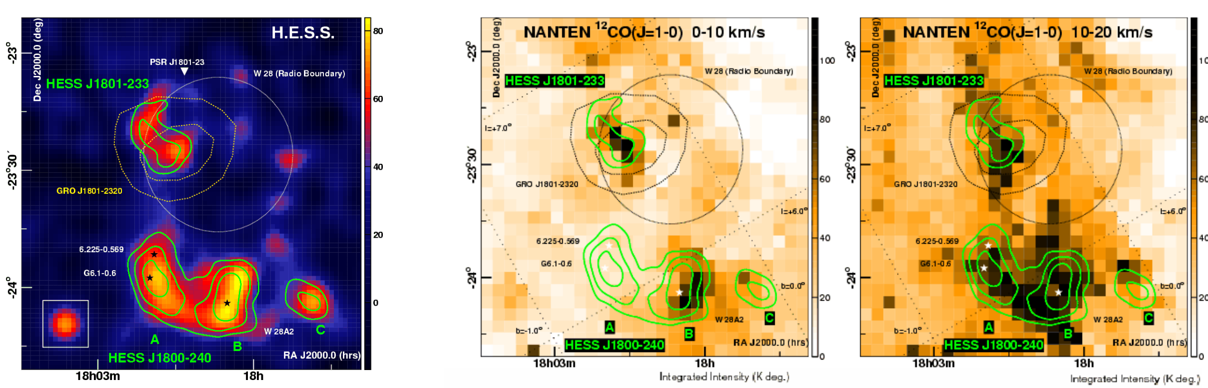
• Radio continuum representing the synchrotron emission from relativistic accelerated particles

• Determine hadronic and leptonic components:

- correlation with X-ray emission

- correlation with molecular material (and atomic gas). Many SNR in association with molecular clouds (W28, W 51C, IC 443, W44 ...)

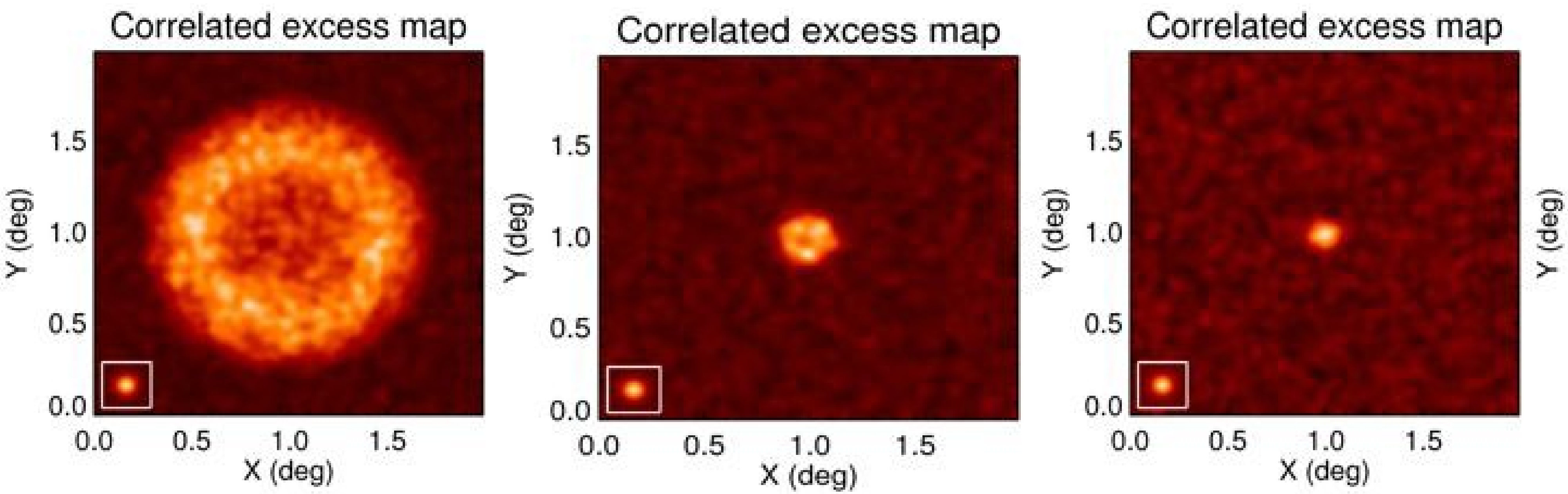


# Population studies of SNR

M. Renaud, Y. Gallant et al.

Many SNRs are extended (RX J 1713-3946, Vela Junior, RCW 86, HESS J1731-347) so that the maximum distance at which they will be detected or resolved depends on the angular extent.



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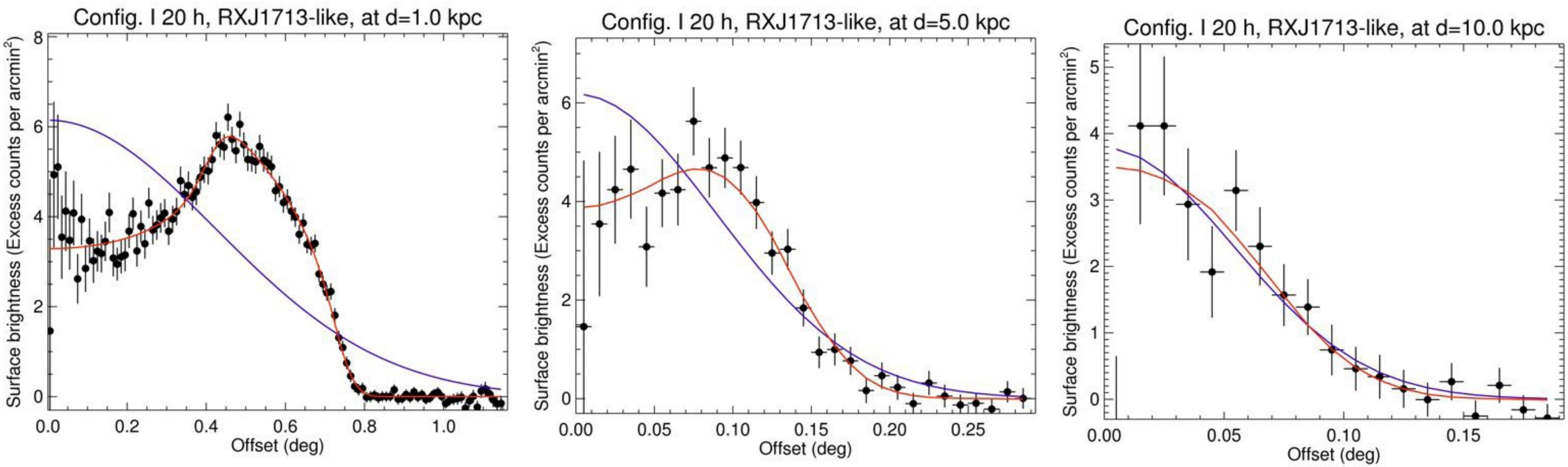
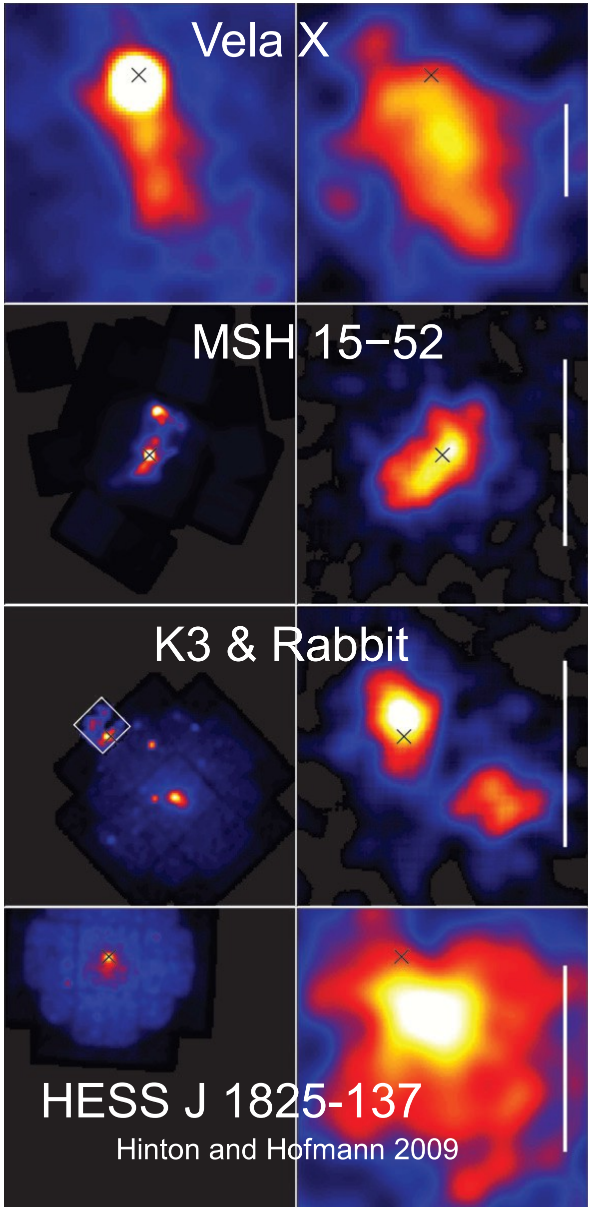


# PWN as VHE sources




PWN are the most numerous TeV galactic population

Some known facts:
- larger extension in TeV wrt X-ray nebula

- middle age objects detected so far (~10 kyrs)

- offset btw X-ray and VHE nebula

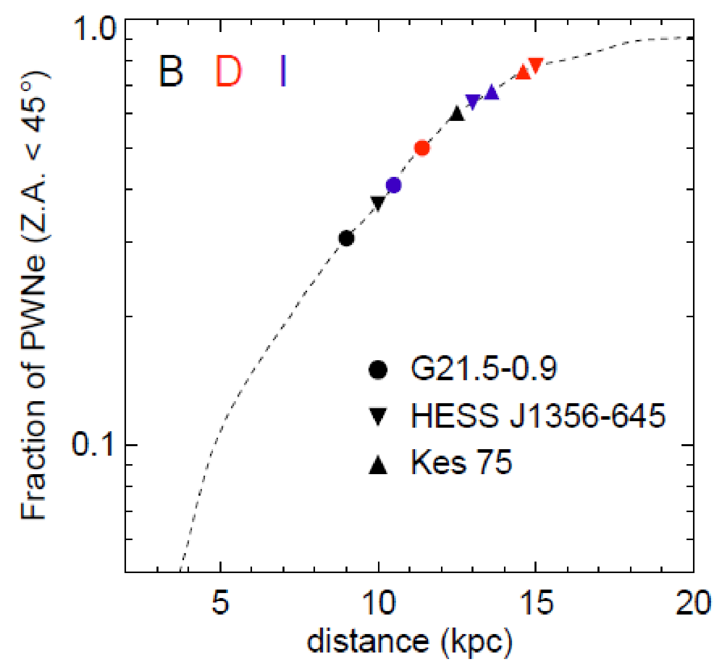
# Horizons of detectability

M. Renaud et al.

For a faint source, like Kes 75 (2% Crab nebula flux) observed for for 20 hours, resulting in a maximum distance of ~15 kpc.
Faint PWNe are expected to be detected in a large fraction of the Galaxy.

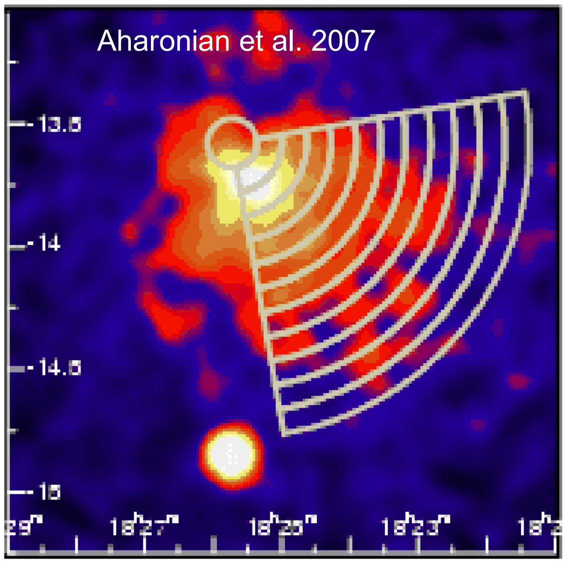
A PWN distribution in the Galaxy was simulated, and the horizon of detectability derived for 3 different types of VHE PWN, Kes 75, G21.5–0.9 and HESS J1356–654.

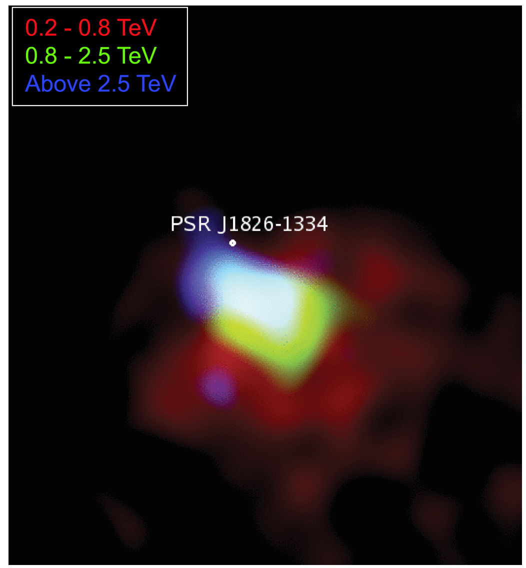
if all PWNe shine 10 000 yrs in TeV energies, a total of 200 PWNe will be detected in the Galaxy.




De Oña-Wilhelmi et al. 2013, ApPh 43, 287

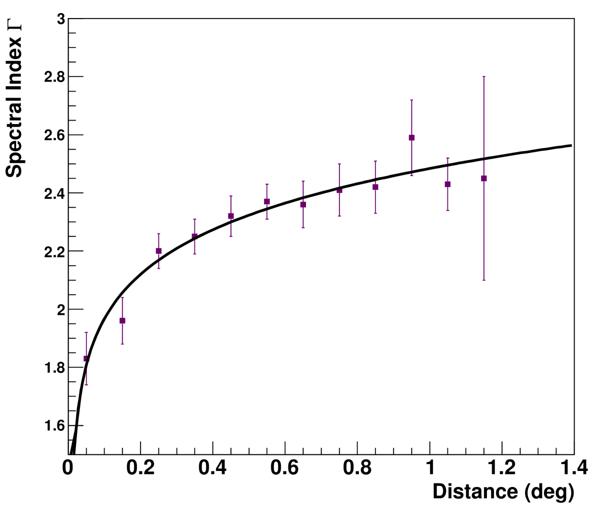
# Electron Cooling in PWN

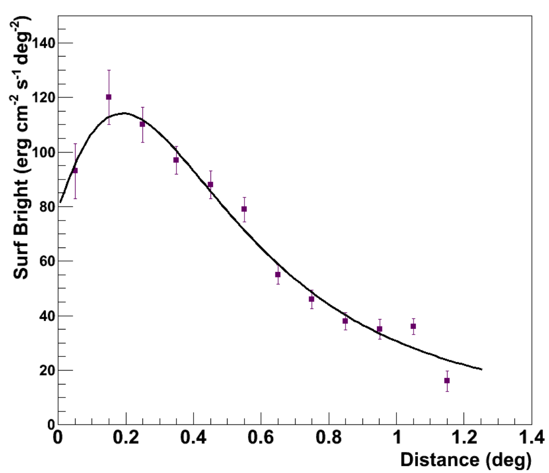



Softening of the spectral index in the observation of HESS J 1825-137

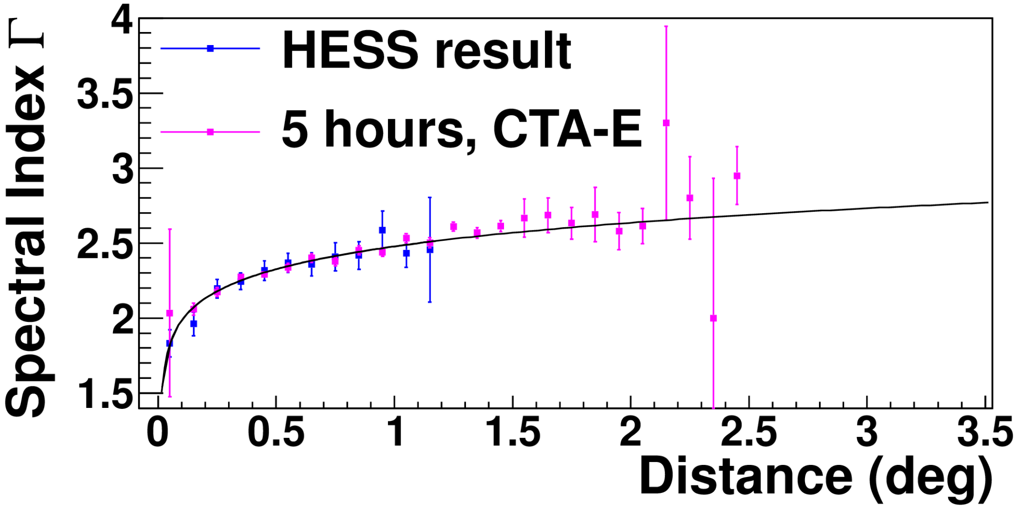
Consistent with synchrotron electron cooling



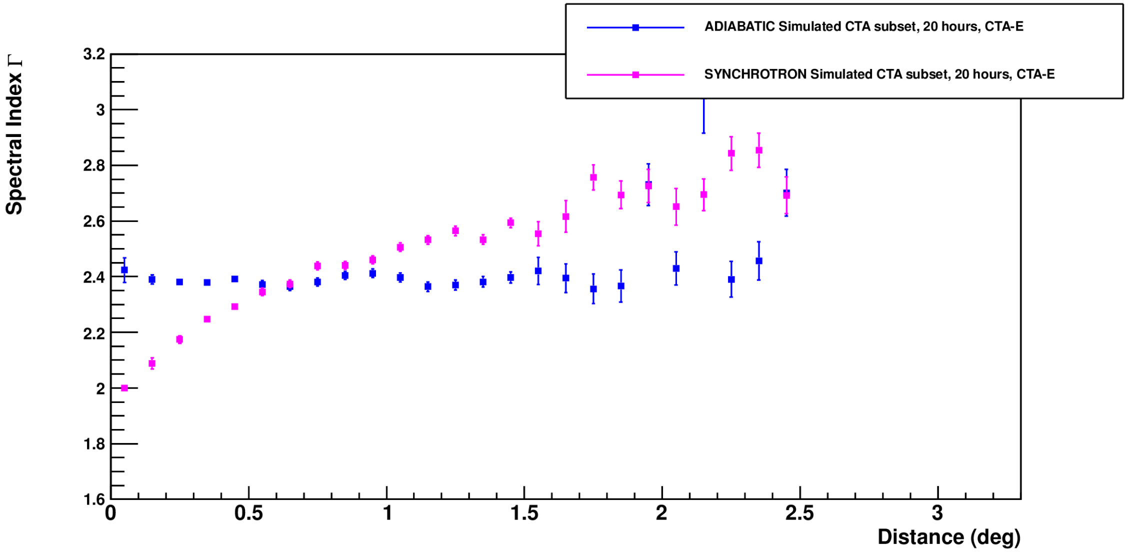




A&A 460, 365–374 (2006)

# Spatial spectral evolution



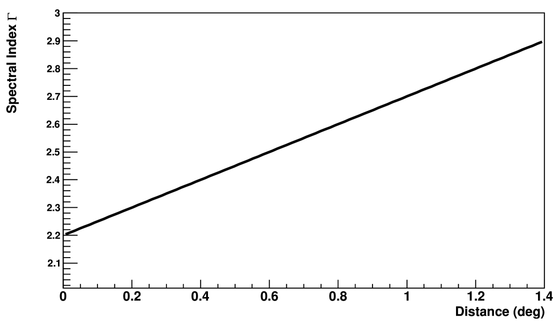

Reproduce results in 5 hours (vs >50 hrs in HESS) and to larger extension → probe maximum size




Clearly distinguish between adiabatic and synchrotron cooling with same surface brightness distribution

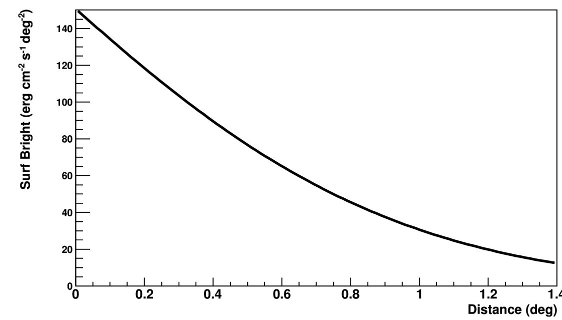
De Oña-Wilhelmi et al. 2013, ApPh 43, 287

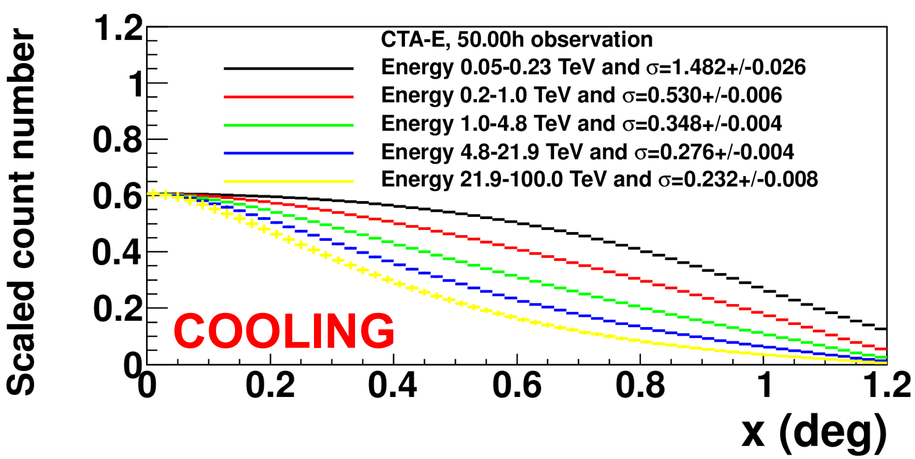
# Energy dependent extension

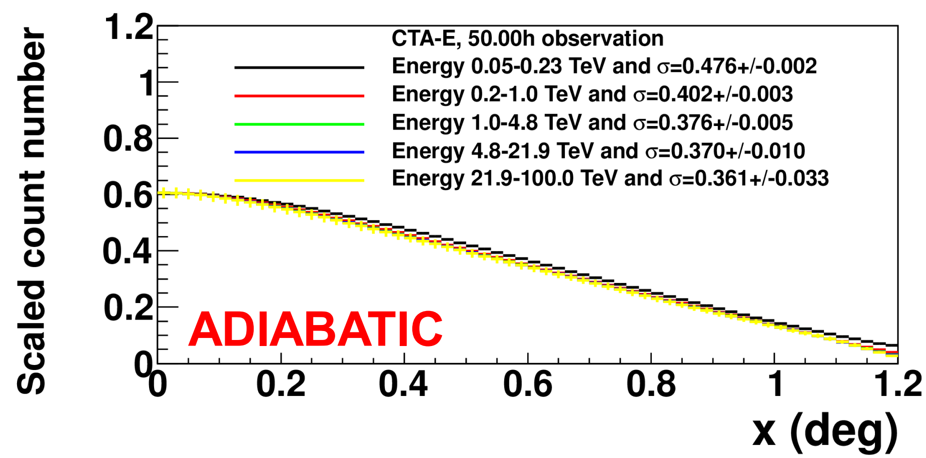



Softening of spectral index

Decreasing surface brightness




Energy dependent morphology will prove invaluable to study unidentified ("dark") source

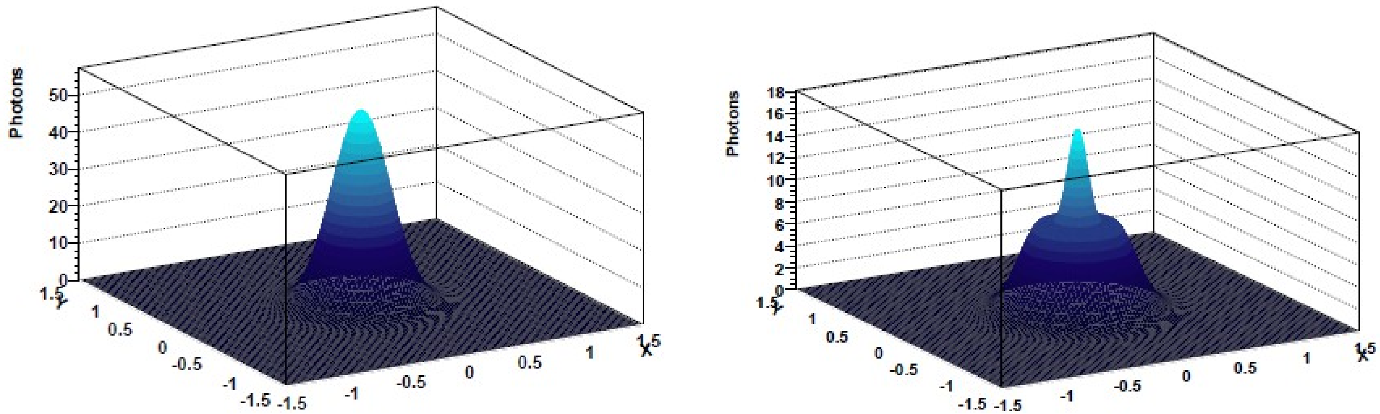
De Oña-Wilhelmi et al. 2013, ApPh 43, 287

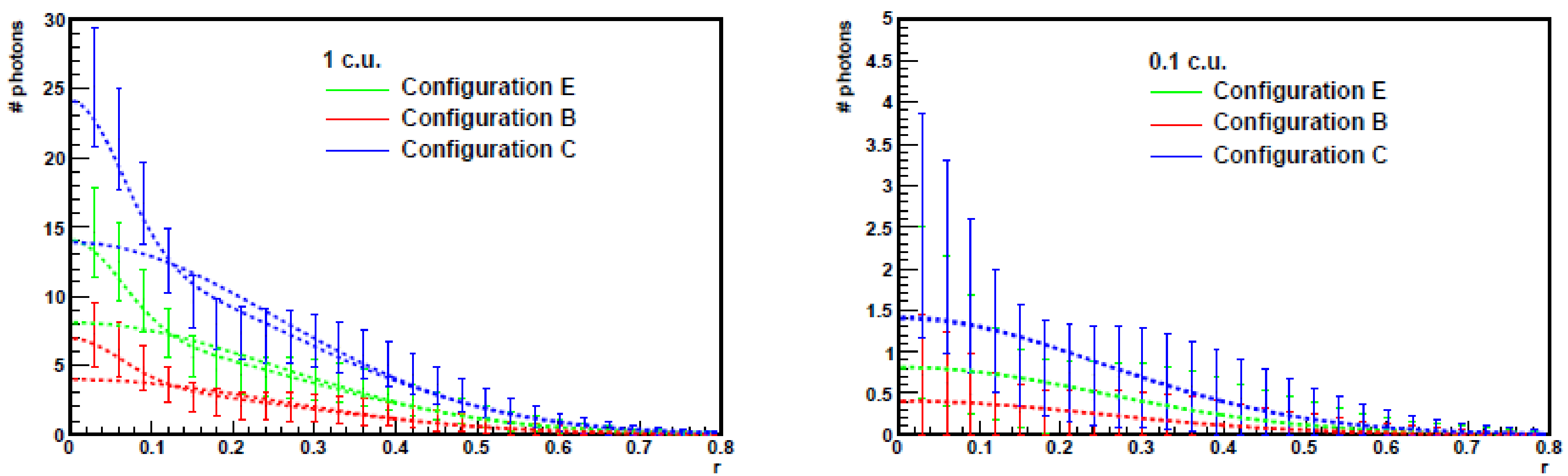
# Composite objects: SNR+PWN

E. de Oña Wilhelmi

De Oña-Wilhelmi et al. 2013, ApPh 43, 287

Thanks to unprecedented angular resolution, finally could disentangle SNR and PWN contribution from morphology

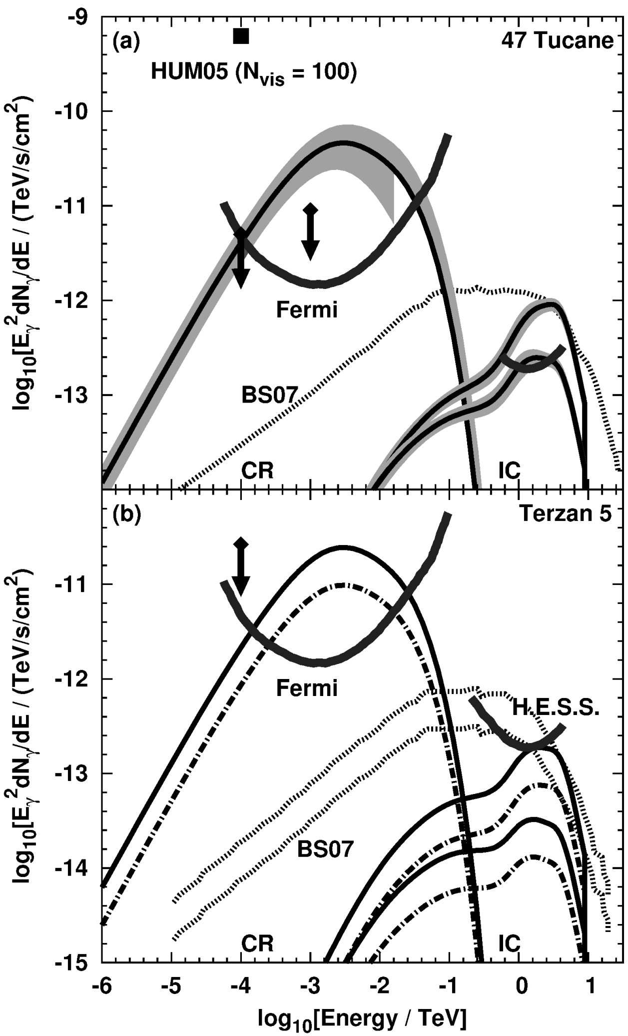


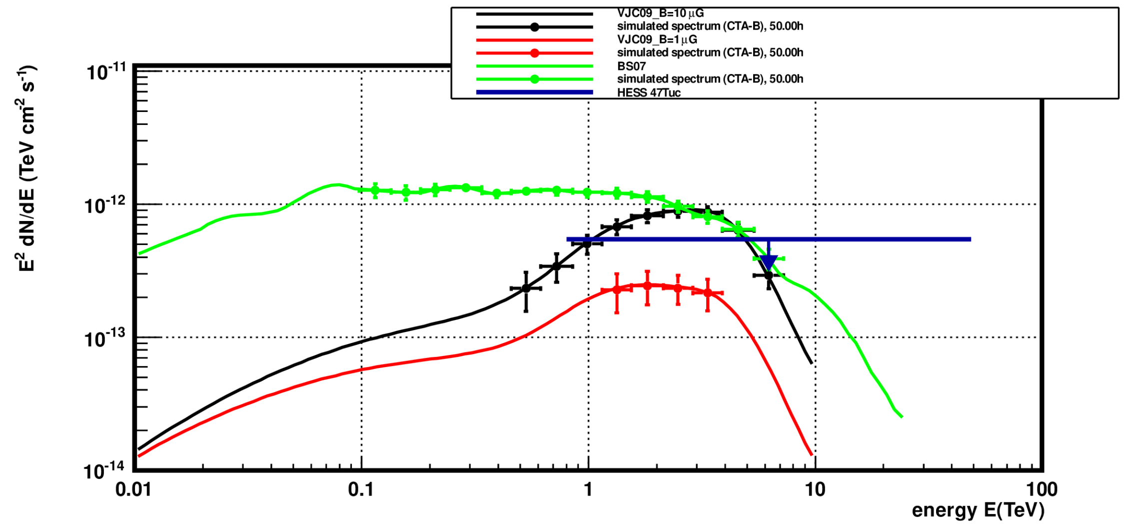



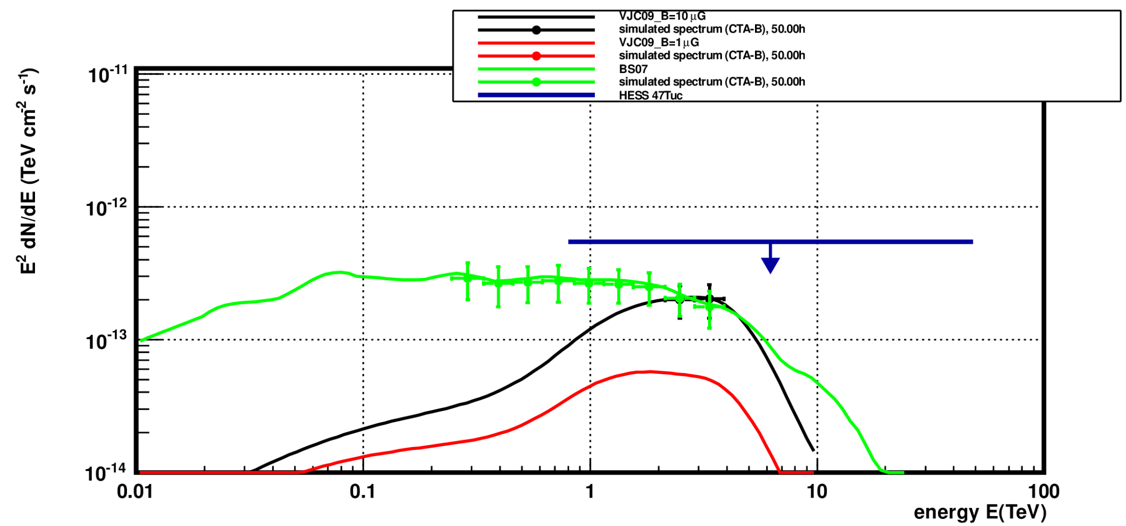
# Globular clusters

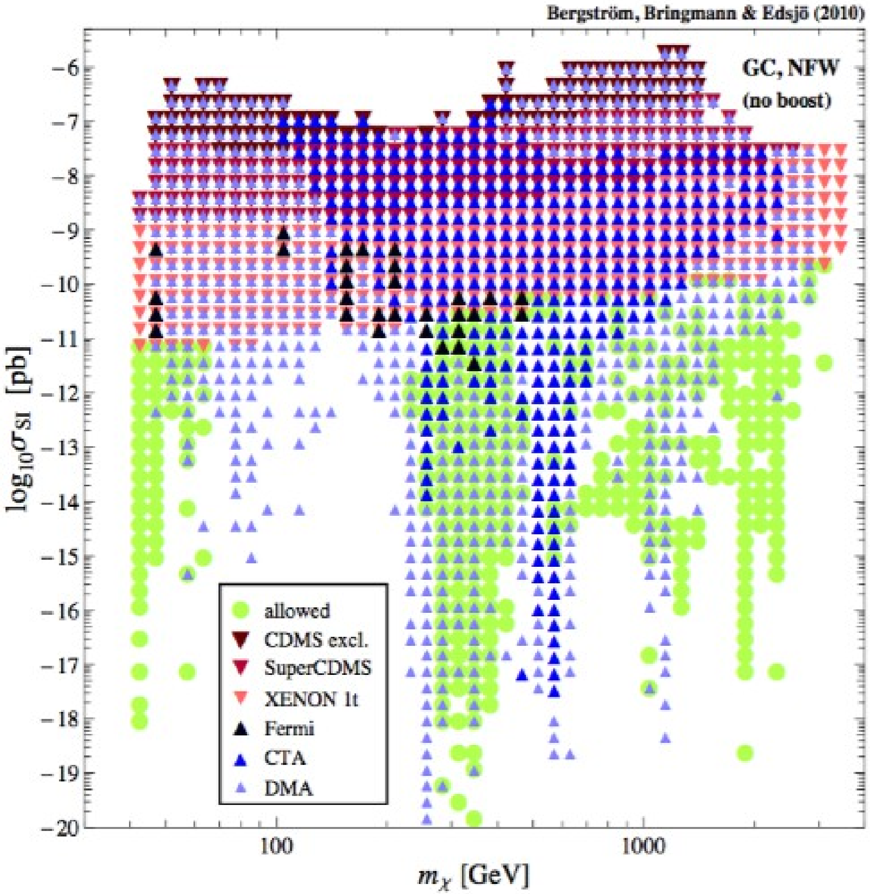
## Pre-Fermi model ApJ.696:L52-L55,2009

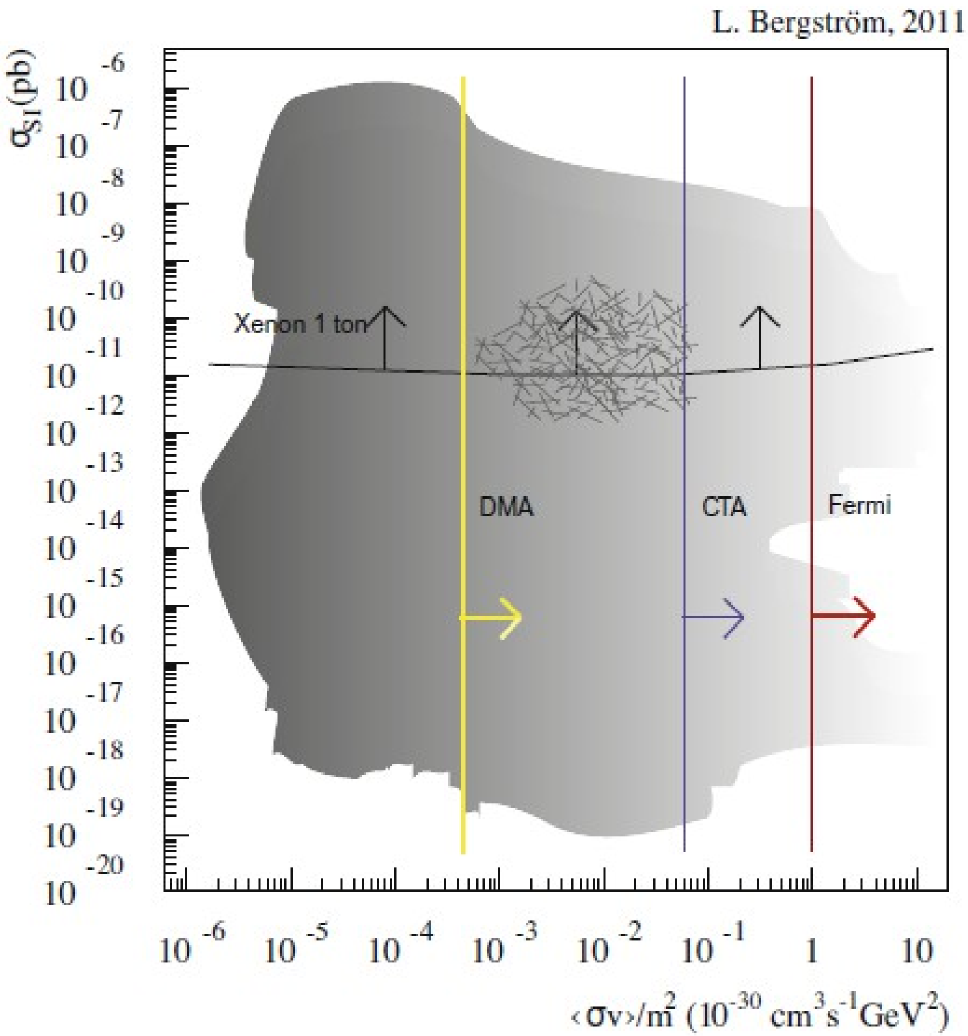
De Oña-Wilhelmi et al. 2013, ApPh 43, 287




Bergström, Bringmann & Edsjö (2010)
GC, NFW
(no boost)
allowed
CDMS excl.
SuperCDMS
XENON 1t
Fermi
CTA
DMA
$\log_{10}\sigma_{SI}$ [pb]
$m_\chi$ [GeV]


L. Bergström, 2011
$\sigma_{SI}$(pb)
Xenon 1 ton
DMA
CTA
Fermi
$\langle\sigma v\rangle/m^2$ ($10^{-30}$ cm$^3$s$^{-1}$GeV$^2$)

Doro et al. 2013, ApPh 43, 189