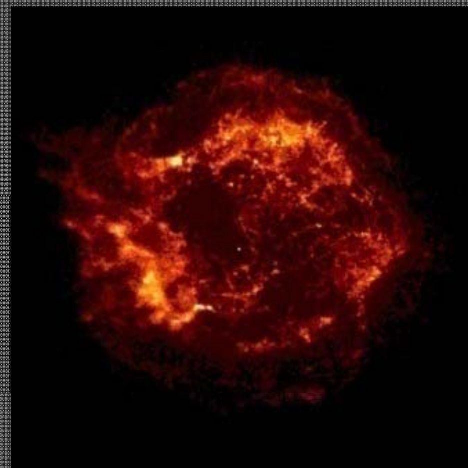
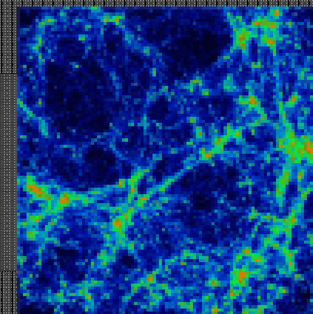
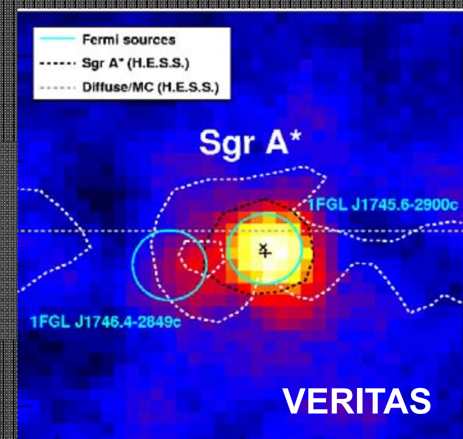
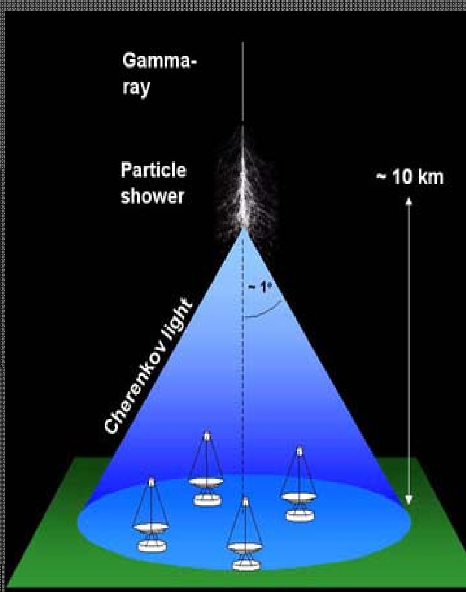
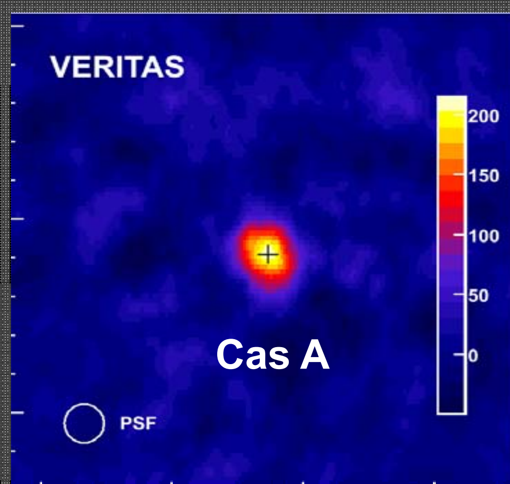
Viewing the Universe in High-Energy γ-rays with VERITAS

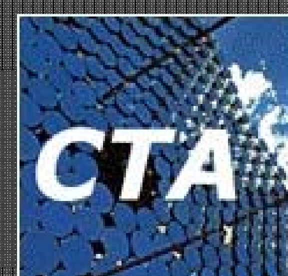












Rene A. Ong **Colloquium @ IAFE, Buenos Aires** **20 Sept 2011**

Outline

The (Non-Thermal) GeV/TeV Universe:

- A new astronomical window
- Relevant Physics issues

  Particle acceleration → Origin of cosmic rays
  Physics beyond SM → dark matter ?

Atmospheric Cherenkov Technique

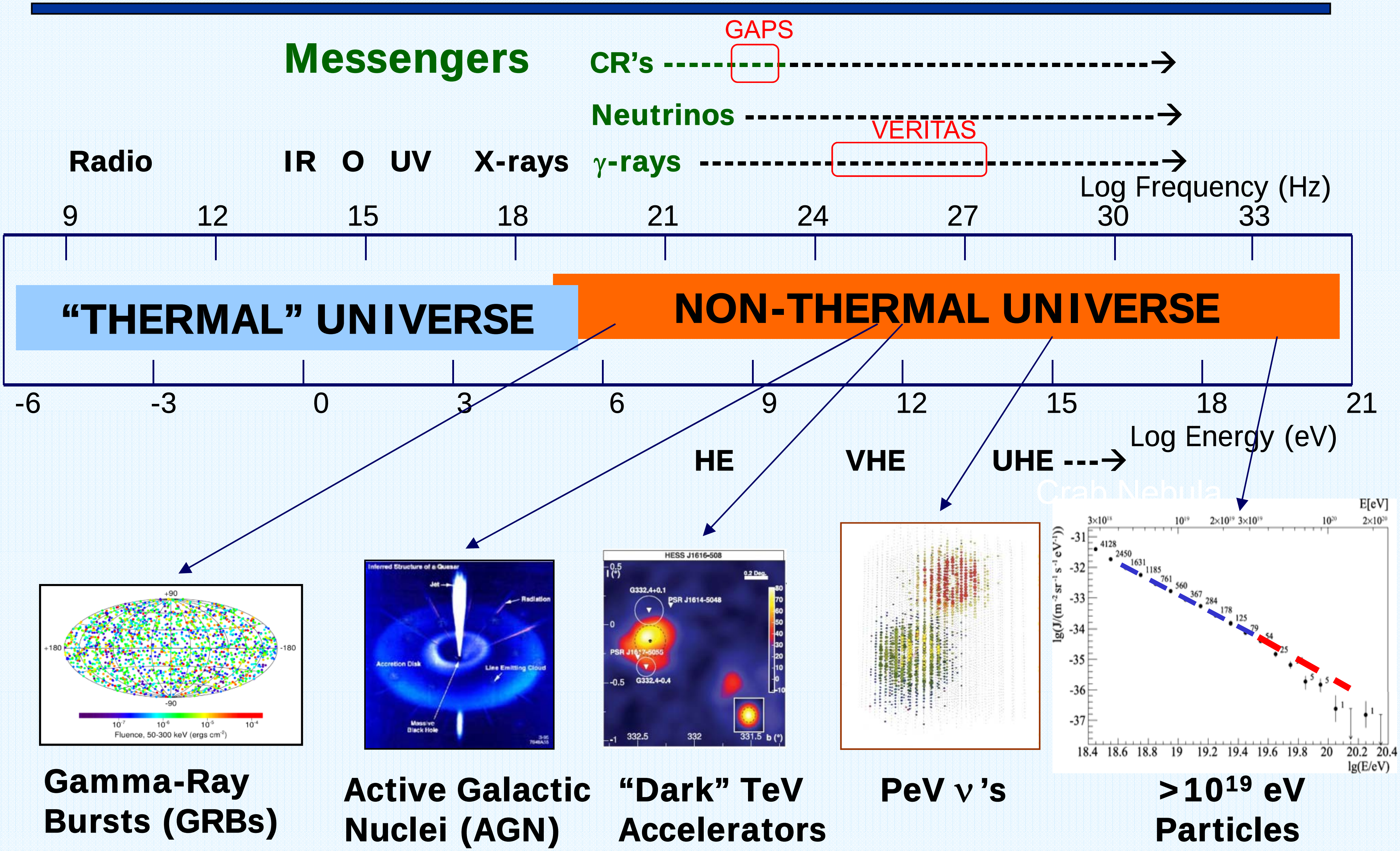
VERITAS γ-ray Telescope:

- Design & performance
- Latest results on Galactic sources, DM

The Future:

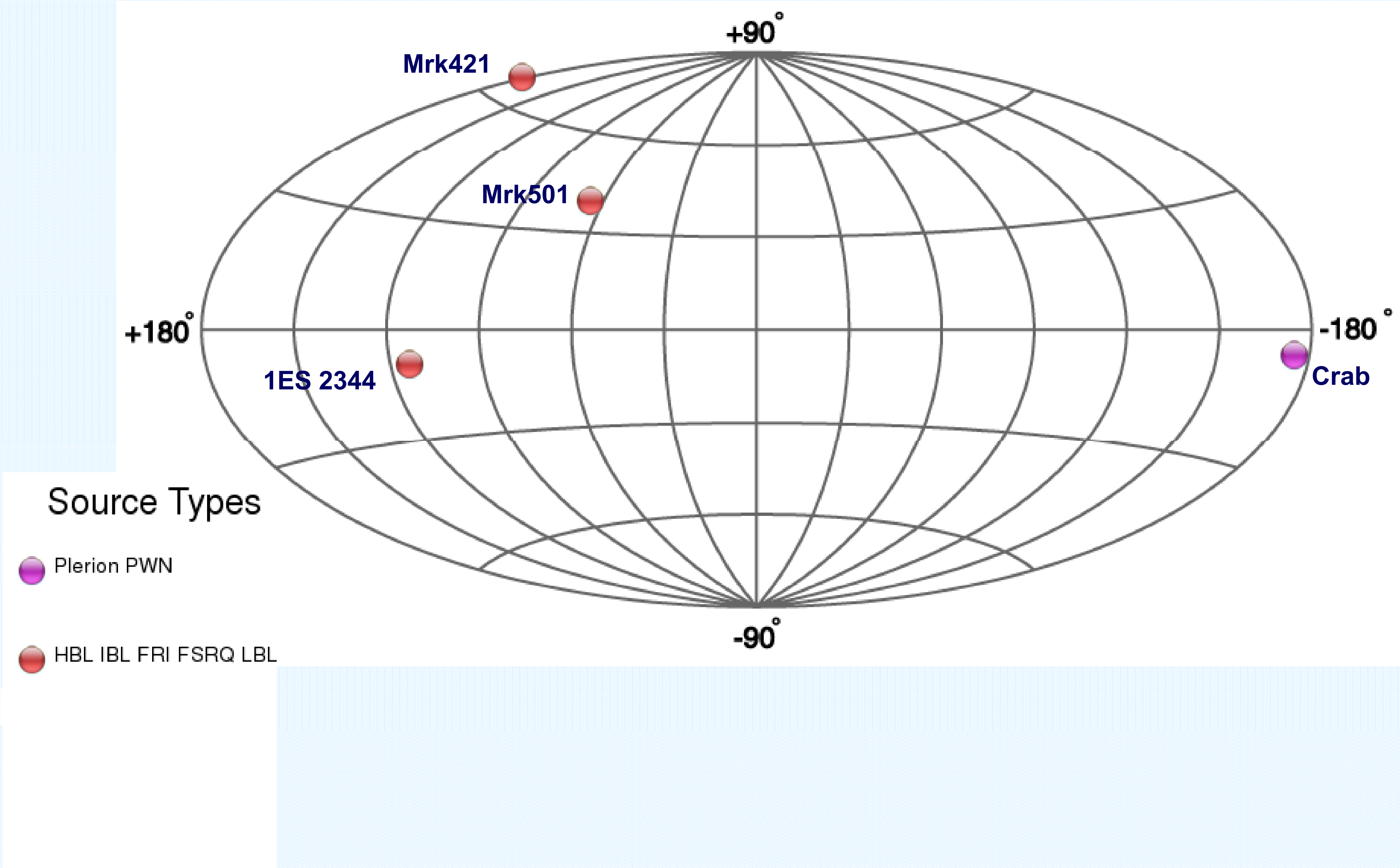
- Cherenkov Telescope Array (CTA)
- (GAPS balloon instrument for DM)

New Windows, New Messengers



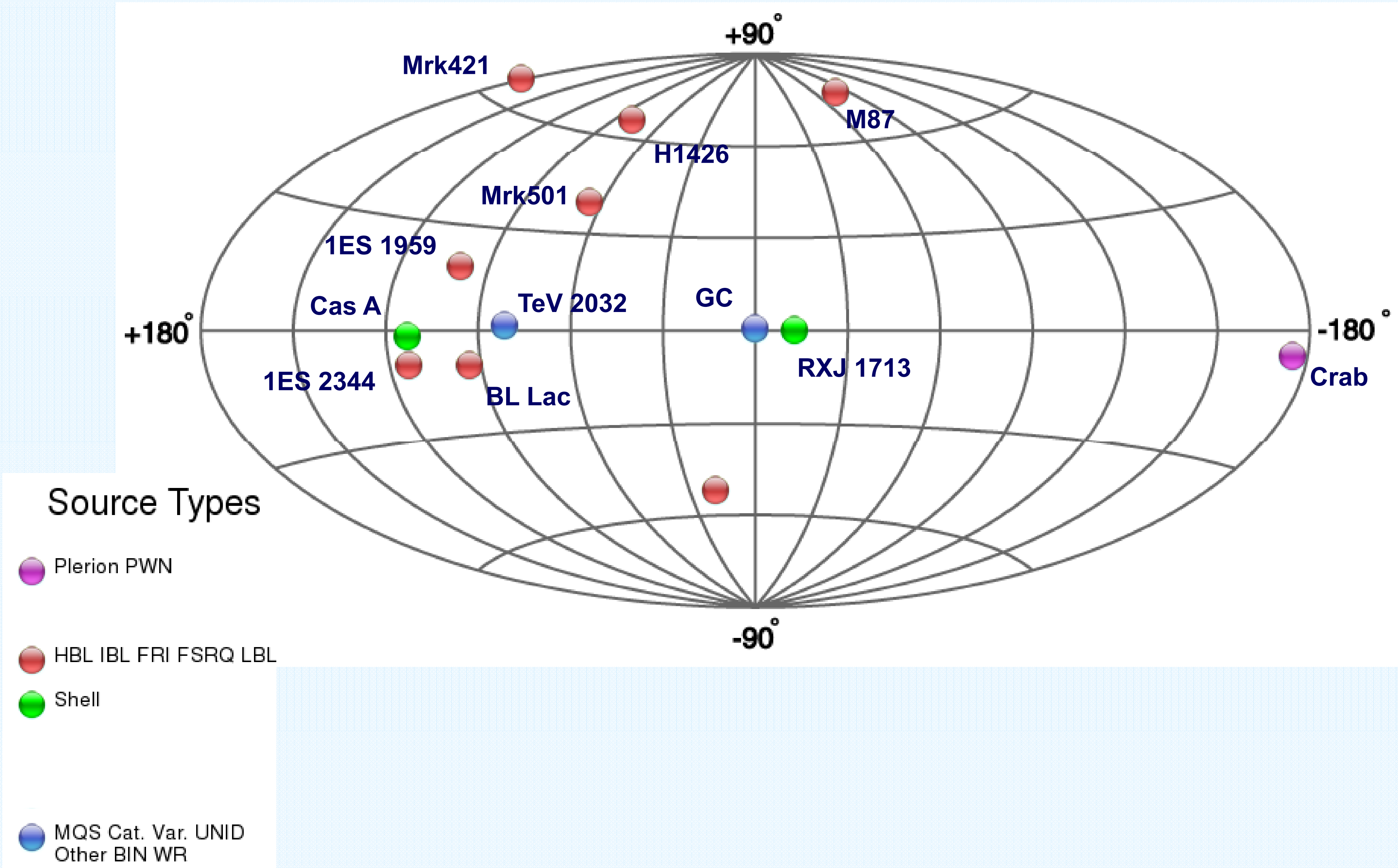
The TeV γ-ray Sky - 1999

4 sources



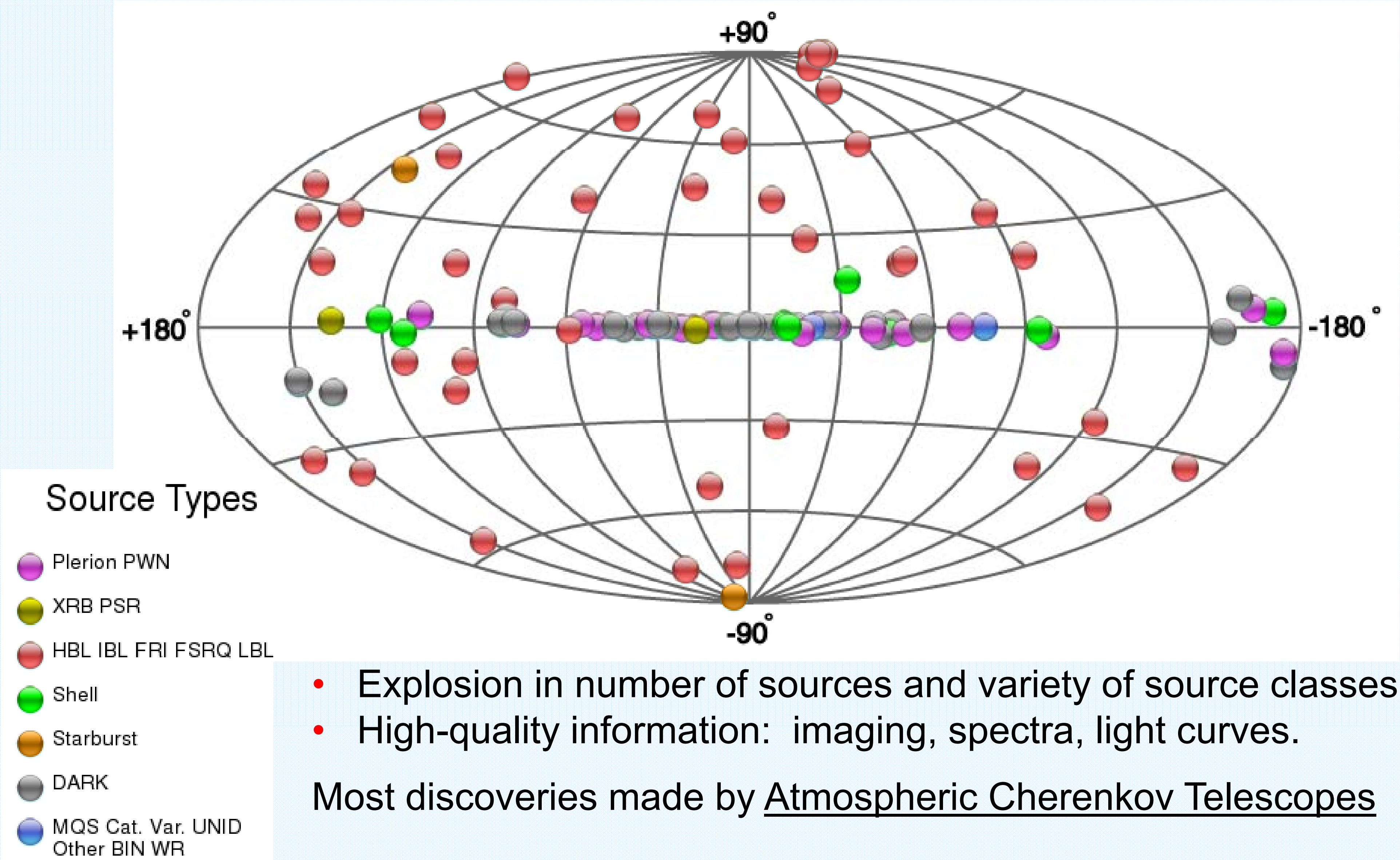
The TeV γ-ray Sky - 2010

13 sources



The TeV γ-ray Sky - 2011

~120 sources



- Explosion in number of sources and variety of source classes.
- High-quality information: imaging, spectra, light curves.

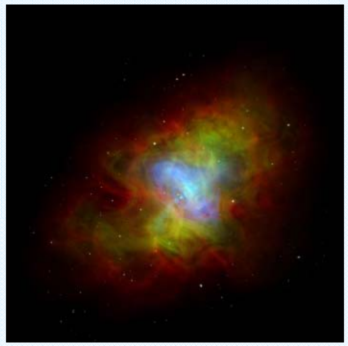
Most discoveries made by <u>Atmospheric Cherenkov Telescopes</u>

A Wide Variety of Sources …

Supernova Remnants

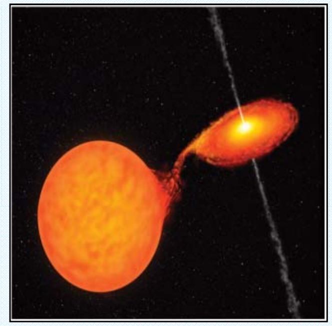
Shocks
Fermi mechanism

Pulsars/PWN



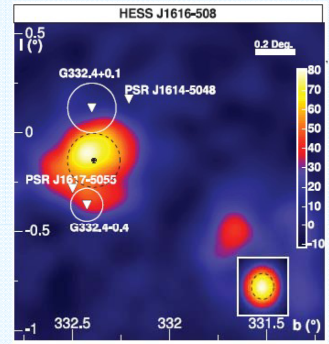
NS dynamo
Winds

HMXBs (microquasars)



Accretion-powered jets,
Colliding winds, or …?

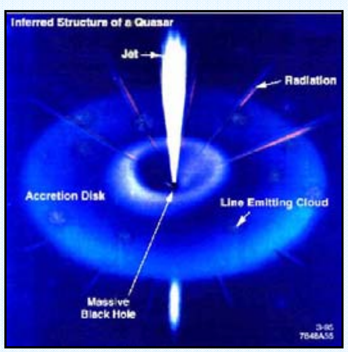
"Dark accelerators"



???

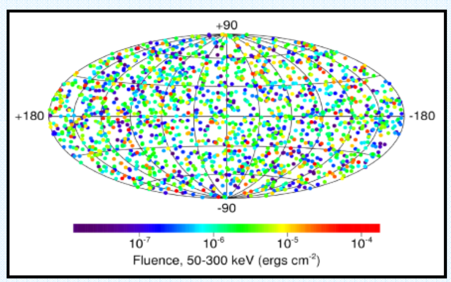
GALACTIC

Active Galactic Nuclei



Supermassive BH
Jets

Gamma-Ray Bursts



Massive star collapse
Relativistic shocks

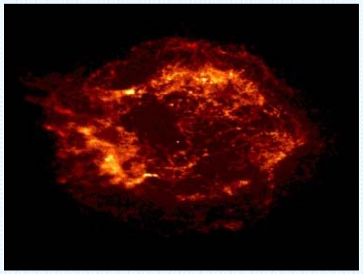
Starburst Galaxies

Star forming activity
HE Cosmic rays

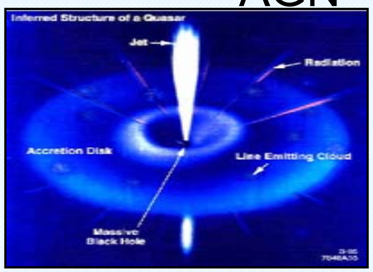
EXTRA-GALACTIC

Key Physics Issues

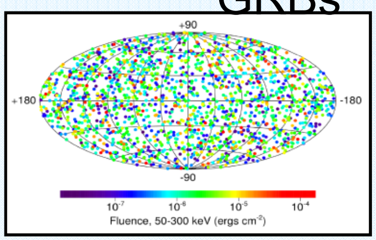
SNR

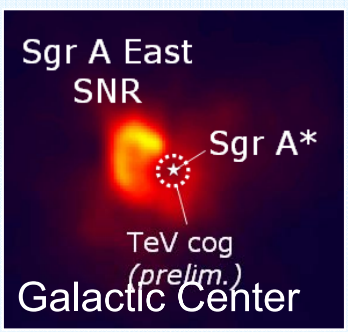


AGN

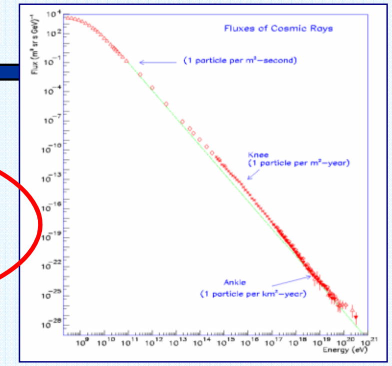


GRBs



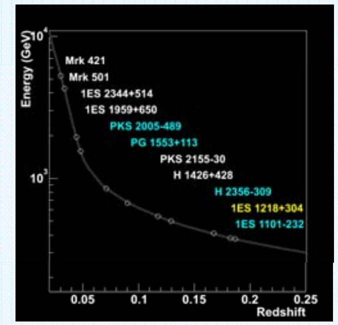


Origin of cosmic rays

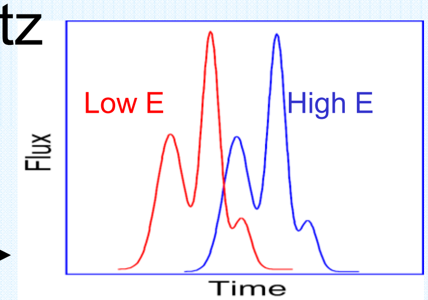


?

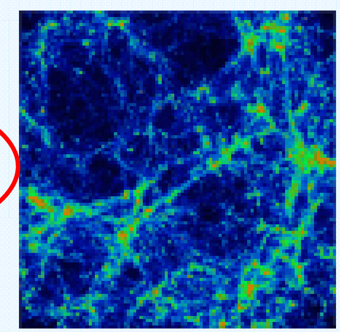
Cosmological γ-ray horizon



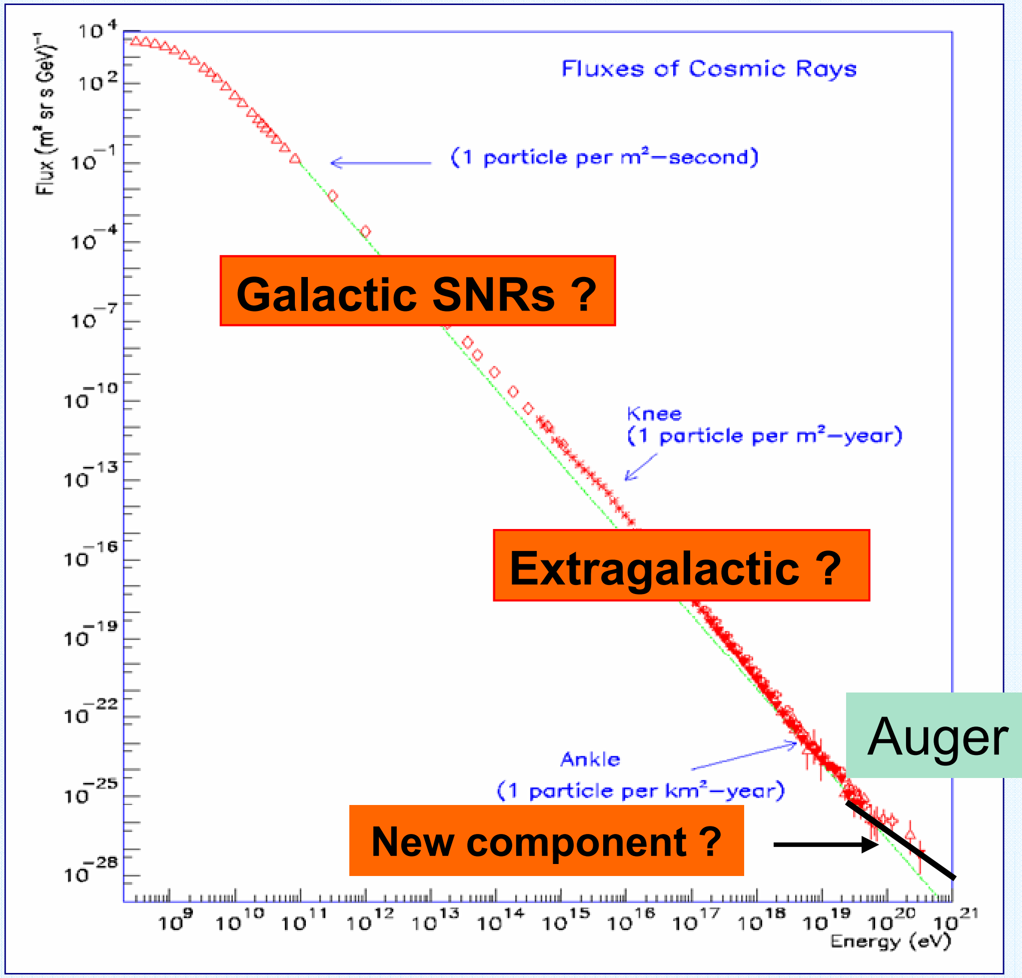
Tests of Lorentz invariance



Cold dark matter (WIMP) searches



Origin of Cosmic Rays



Diffuse, all particle spectrum

90 year old mystery !

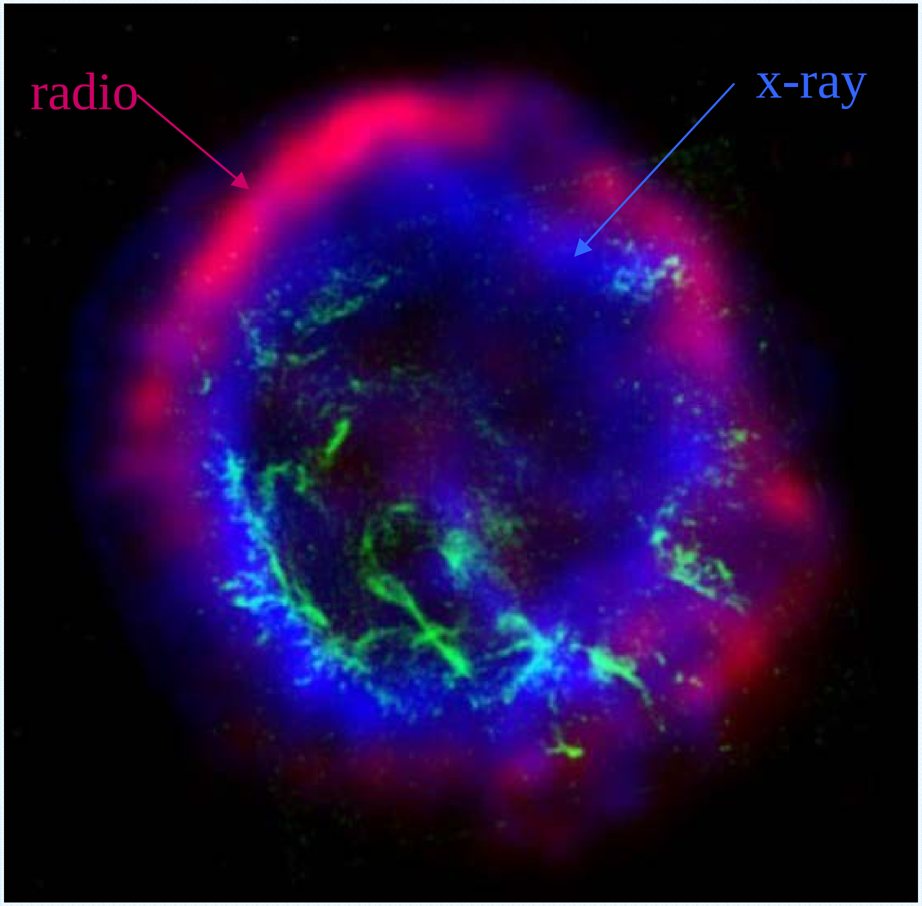
- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm^3

Neutral messengers:

γ, ν

are required to directly observe cosmic accelerators.

Supernova Remnants (SNR's)



SNR E102

- Collapse of massive star or detonation of white dwarf.
- Outer layers ejected with
  $v \sim 3 \times 10^3$ km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via "canonical" Fermi process – or diffusive shock acceleration.
- In ~ 10^4 yrs, blast wave deccelerates and dissipates.
- Can supply and replenish CR's if $\varepsilon \sim 5$-10%.

Electrons or Protons ?

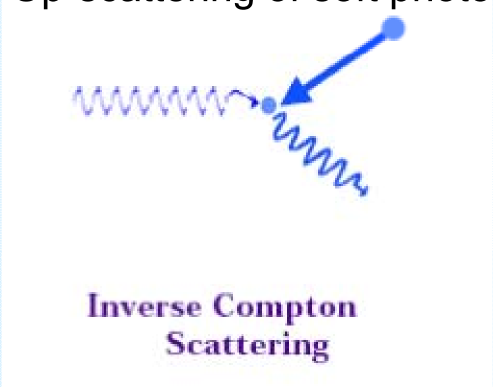
VHE γ-rays are:

- ***Not deflected*** **by interstellar magnetic fields.**
- ***Tracers*** **of parent particle populations – those particles accelerated by shocks, combined with possible target material.**

But both electrons and protons produce γ-rays.

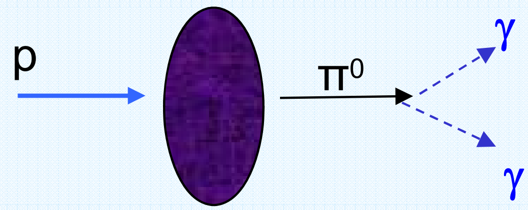
Accelerated electrons
→ TeV γ-rays

Up-scattering of soft photons



Accelerated protons
→ TeV γ-rays

Target interaction, π^0 decay



π^o and target material

There is now good evidence for SNR acceleration of CRs, but the case is not yet ironclad.

Cold Dark Matter

There is overwhelming astrophysical evidence for dark matter, from e.g.:

- rotation curves of spiral galaxies,
- velocity distributions in galaxy clusters,
- colliding clusters & gravitational lensing, &
- cosmological measurements.

Cosmology, in particular, points towards DM being:

- non-baryonic
- non-relativistic

→ **Cold dark matter (CDM)**

Numerous CDM candidates exist:

- Primordial BH's – possible, but production mech. not known.
- Axions – motivated by particle physics; searches underway.
- Weakly interacting massive particles (**WIMPs**).

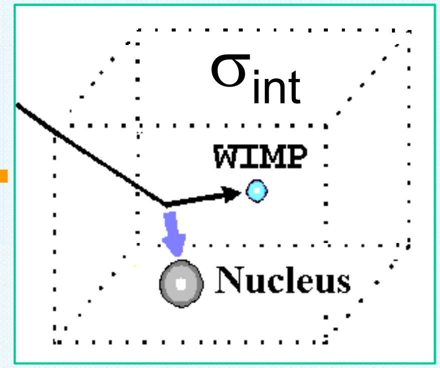
"**WIMP miracle**": present relic density is consistent with expected for a weakly interacting particle & new particle physics is required at the weak scale (EWSB).

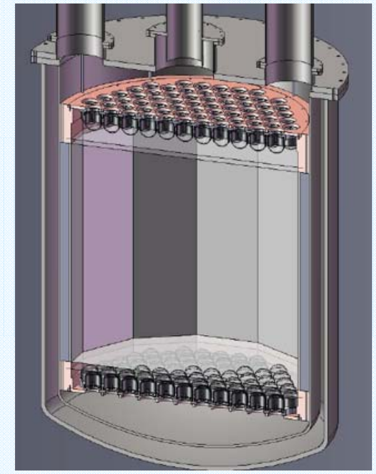
DM Detection: Complementary Approaches

Produce DM particle in accelerators

LHC at CERN

Direct Detection



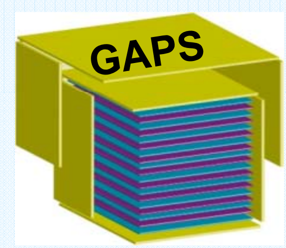


Xenon1T Detector

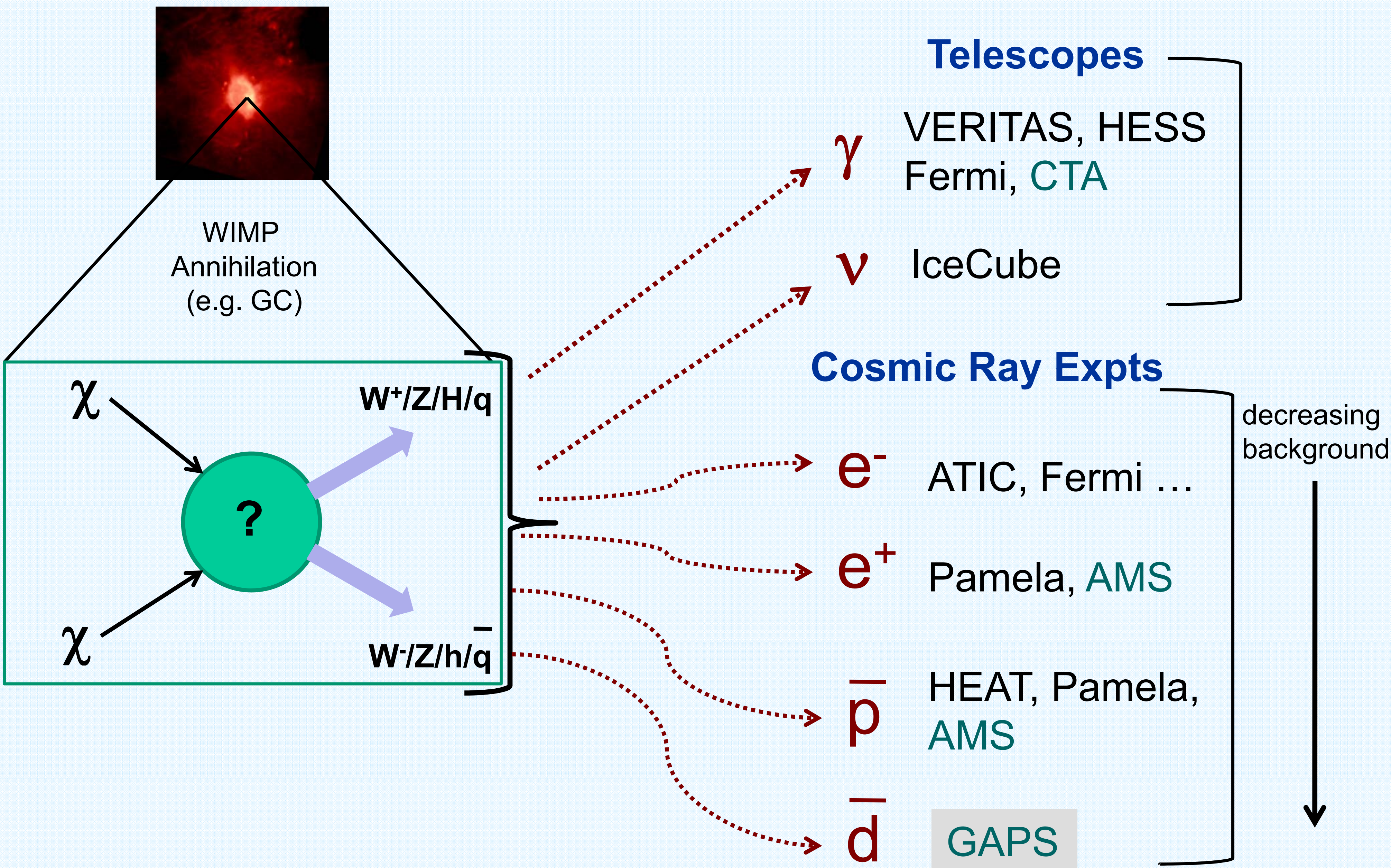
Astrophysical Indirect Detection

Sextens dwarf galaxy

Annihilation (σ_A)
$\chi\chi \rightarrow$ γ's, ν's, anti-matter



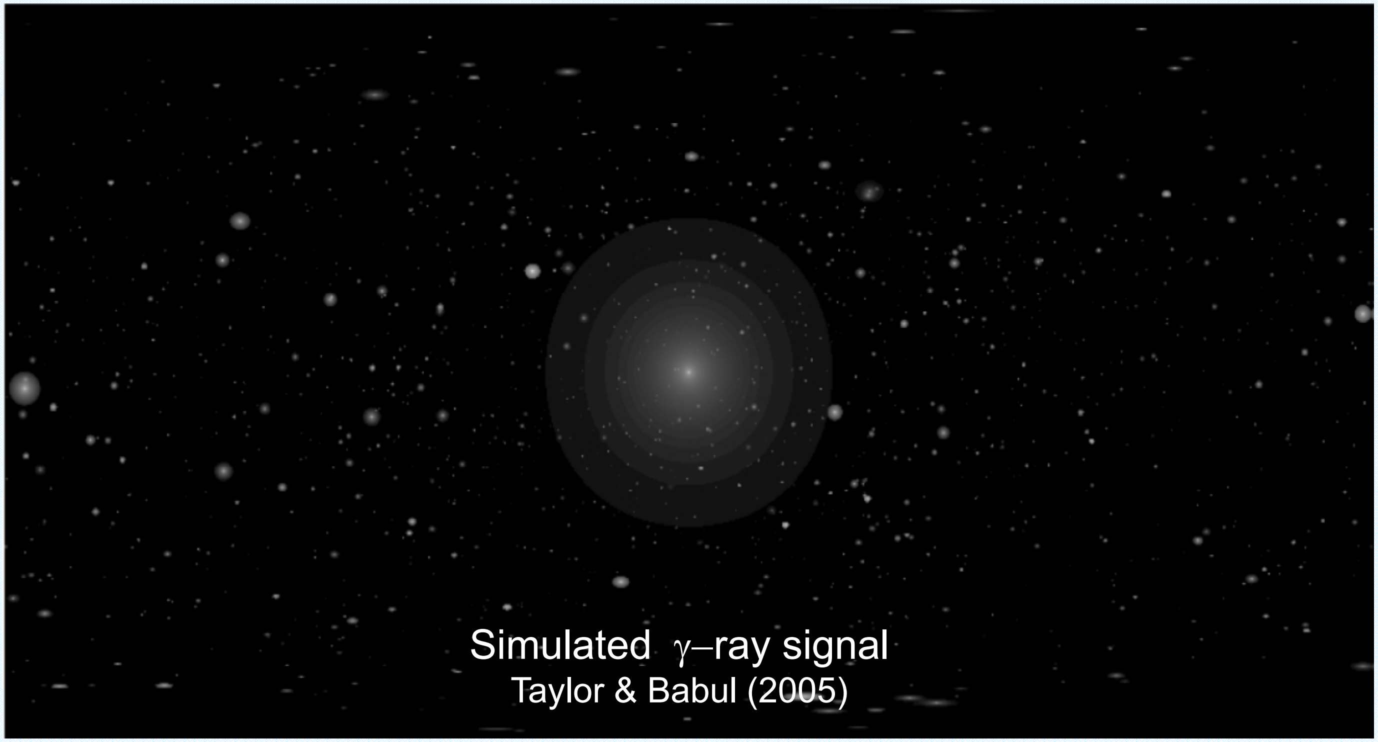
Indirect Detection



DM Detection via γ-rays

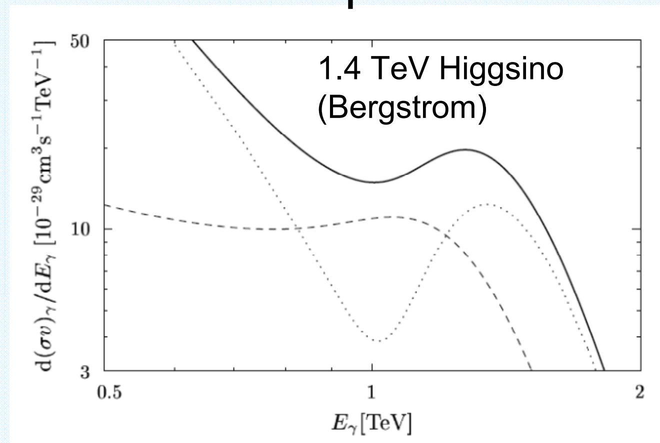
Target regions with:

- Favorable DM distributions.
- Large mass/light ratio.



DM Detection via γ-rays

"Universal" Spectrum



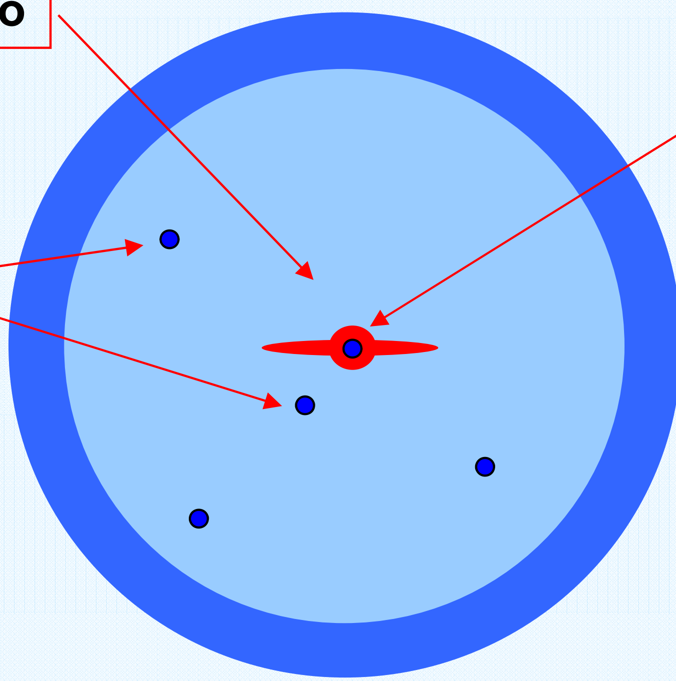
Target regions with:

- Favorable DM distributions.
- Large mass/light ratio.

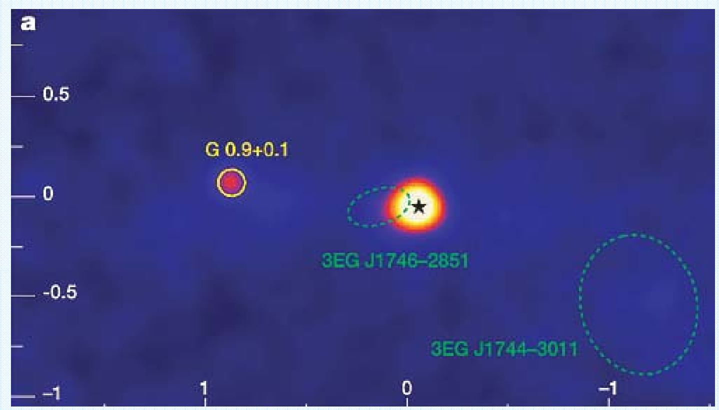
Galactic Halo

Galactic Satellites

Extragalactic Sources



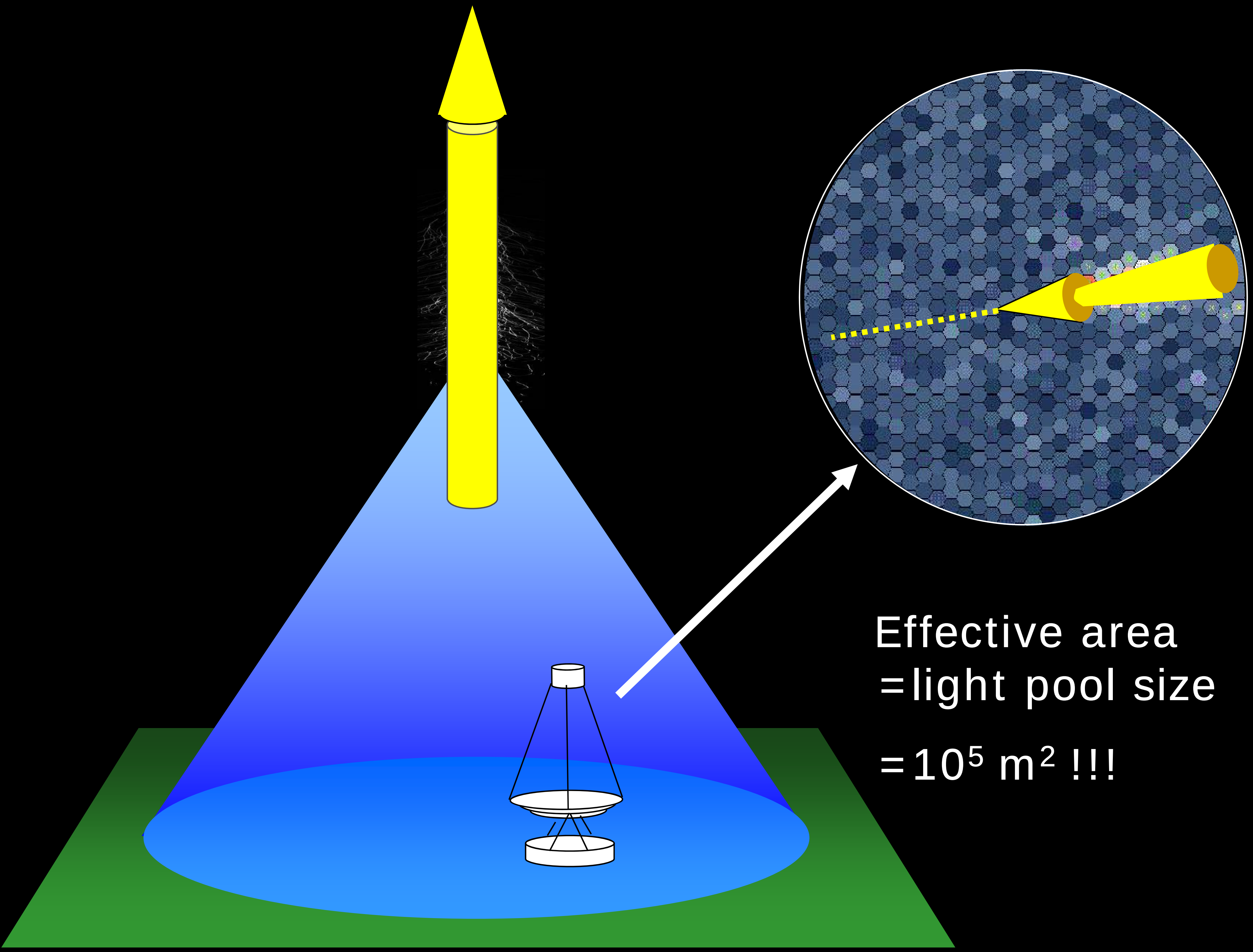
Galactic Center



HESS, Whipple, & Cangaroo detected a strong source at Gal. Center

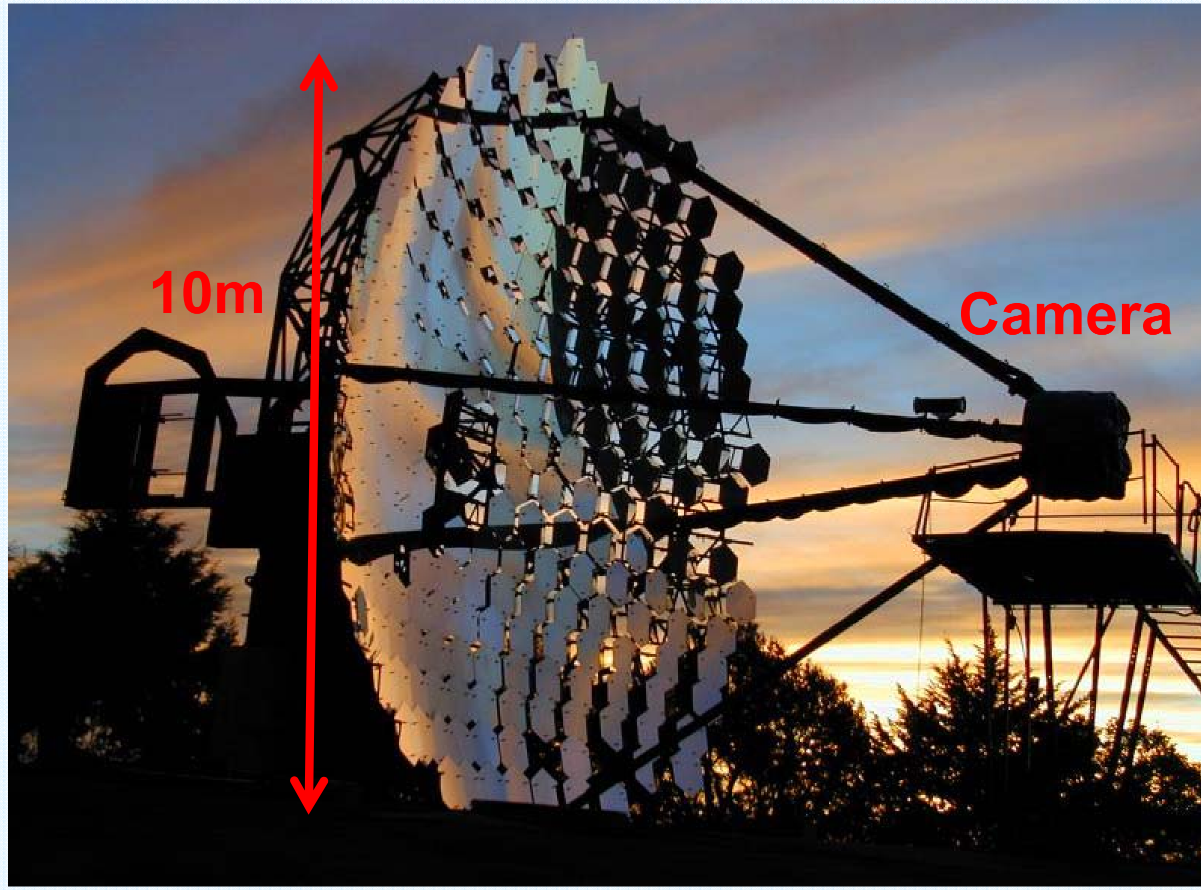
→ Is it dark matter ?

Atmospheric Cherenkov Technique



Effective area
=light pool size
$=10^5\ m^2$!!!

Whipple 10m
γ-ray Telescope



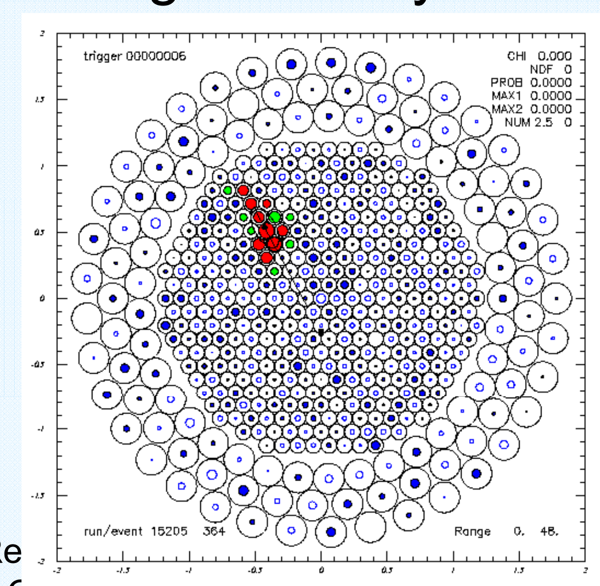
- The Whipple 10m (1968-2011)

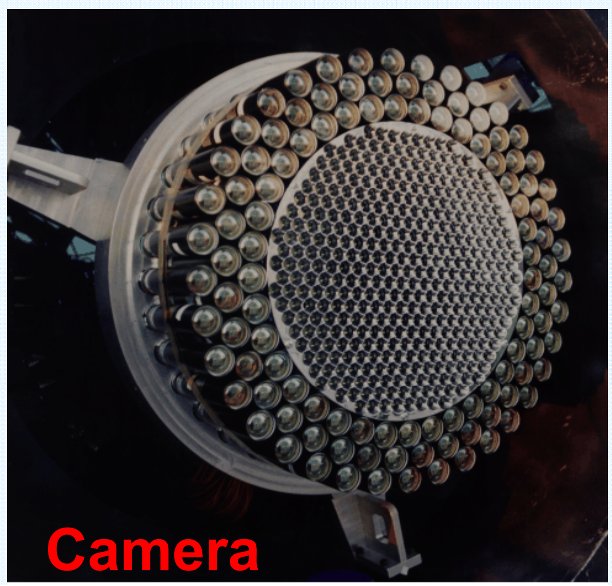
.

- Pioneered use of Imaging.
  (T. Weekes et al.)

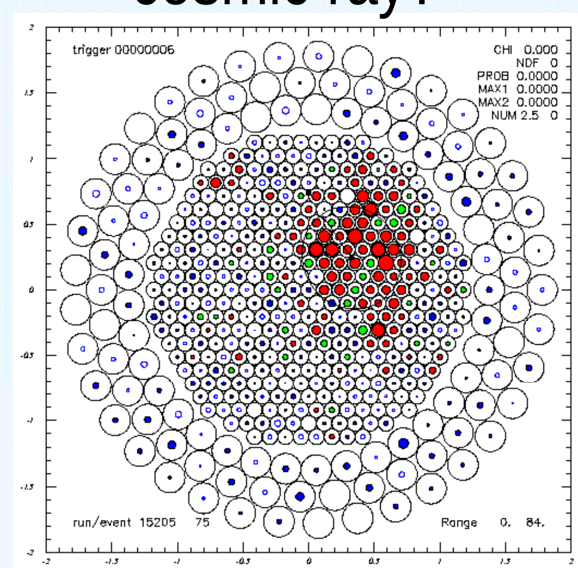
- Made first source detections.
  (Crab Nebula in ~90 hours)

gamma ray?



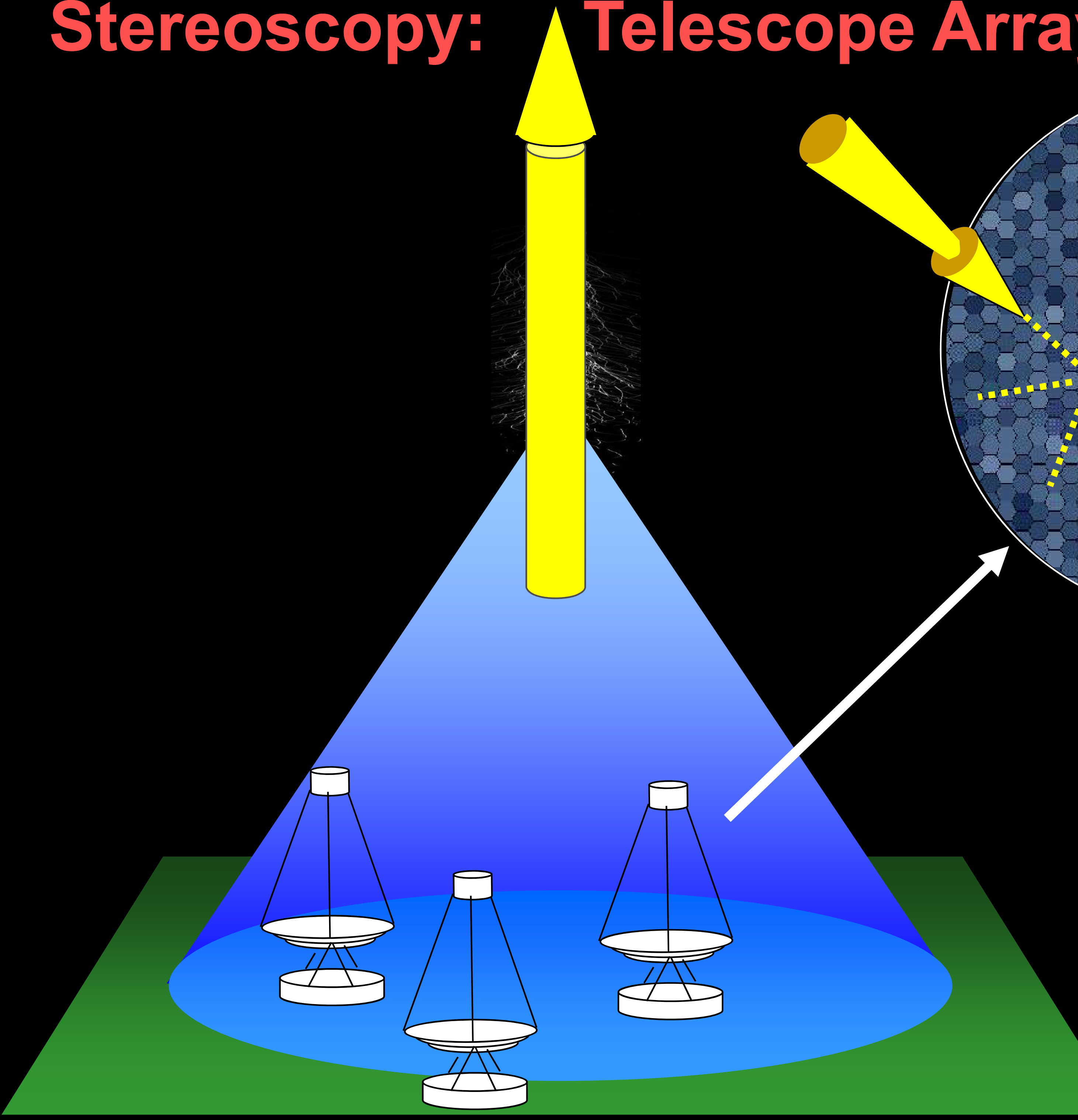


cosmic ray?



Re

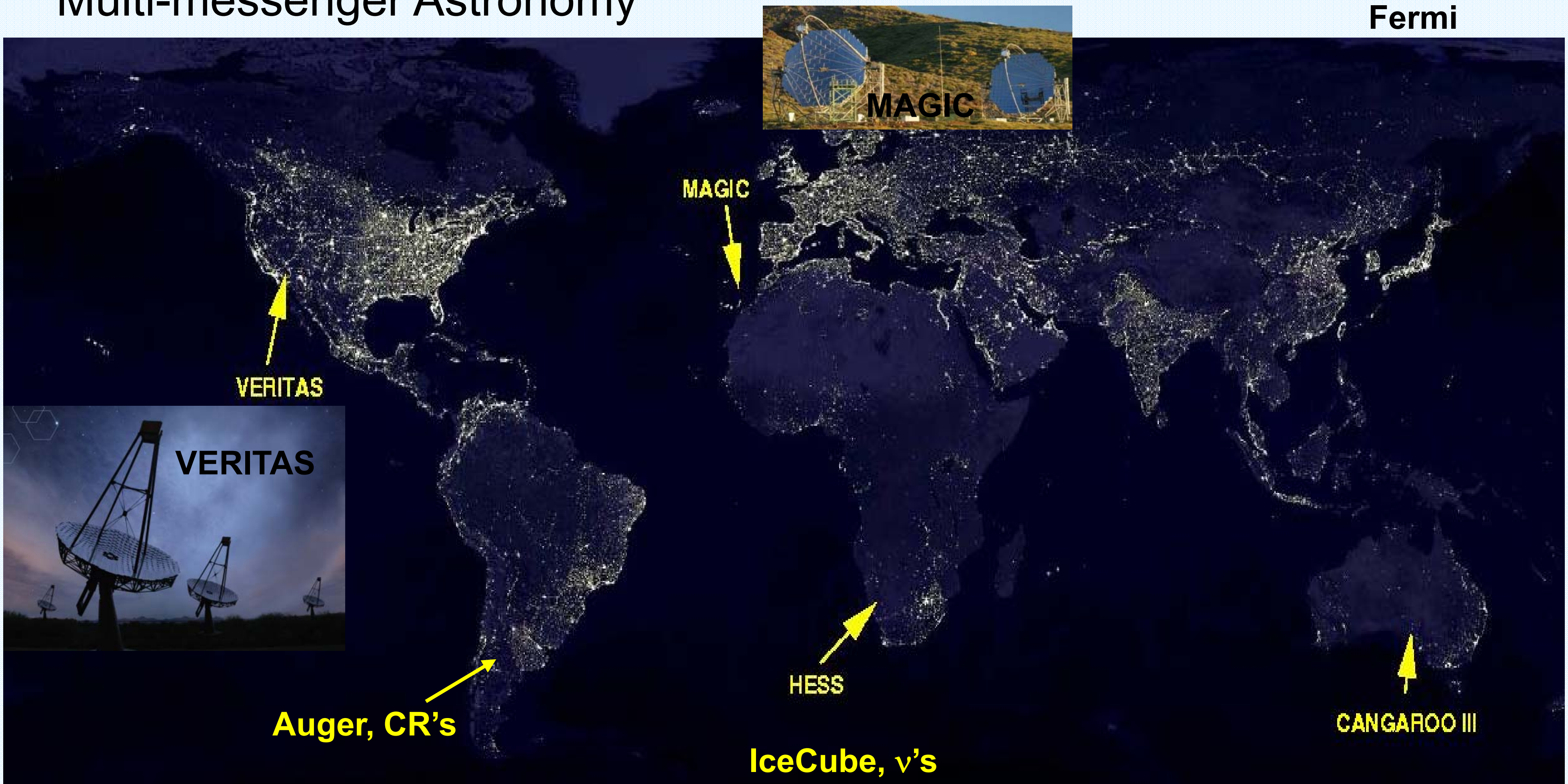
Stereoscopy: Telescope Arrays



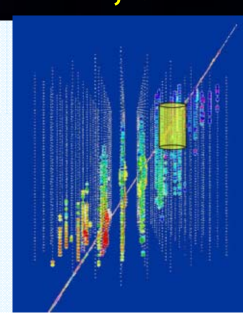
Major VHE Telescopes

Fermi

Multi-messenger Astronomy



IceCube



VERITAS
γ-ray Telescope

VERITAS

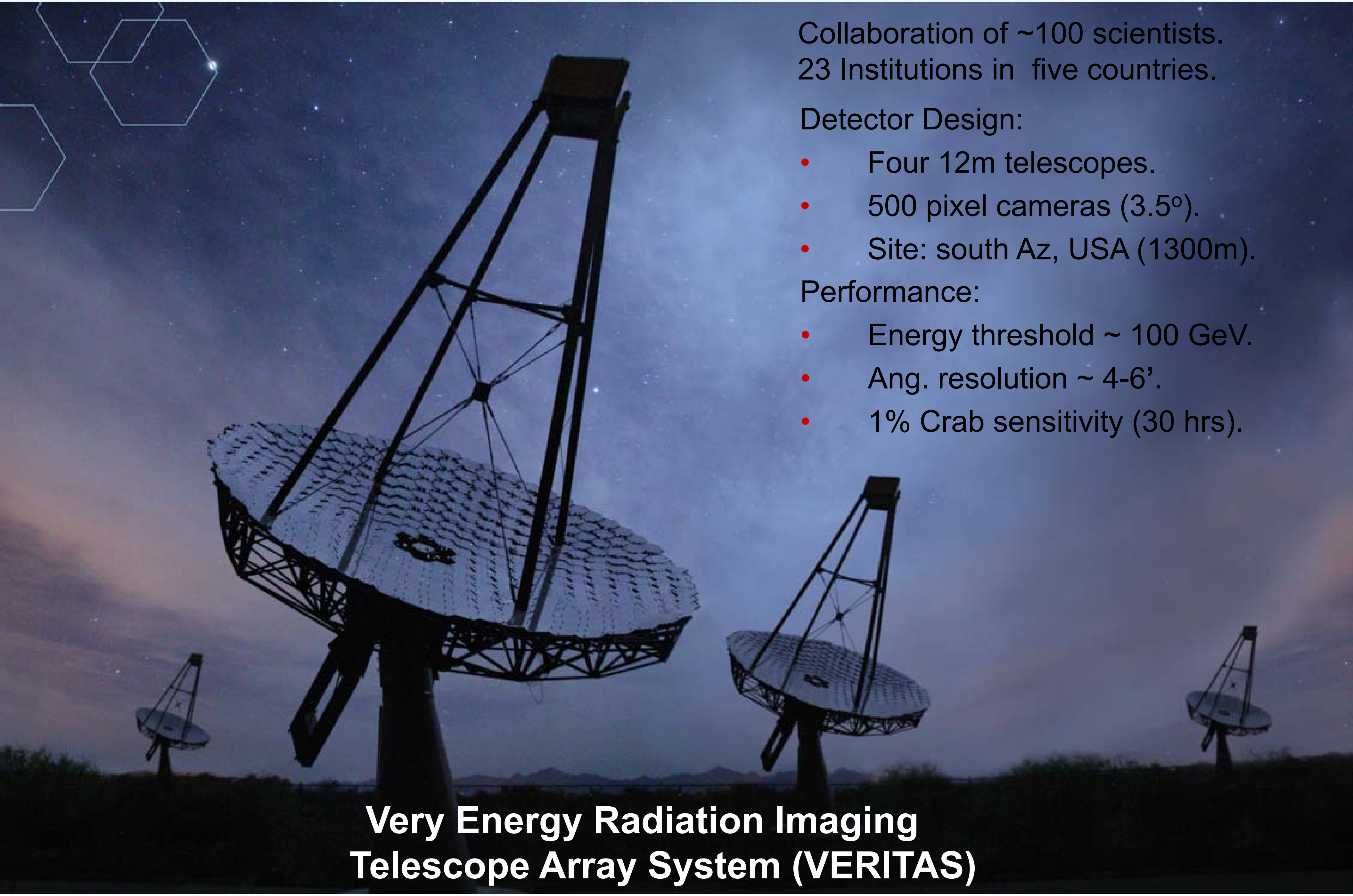
Collaboration of ~100 scientists.
23 Institutions in five countries.

Detector Design:

- Four 12m telescopes.
- 500 pixel cameras (3.5^o).
- Site: south Az, USA (1300m).

Performance:

- Energy threshold ~ 100 GeV.
- Ang. resolution ~ 4-6'.
- 1% Crab sensitivity (30 hrs).



Very Energy Radiation Imaging Telescope Array System (VERITAS)

VERITAS @ Mt. Hopkins, AZ

U.S.

Adler Planetarium
Argonne Nat. Lab
Barnard College
DePauw Univ.
Grinnell College
Iowa St. Univ.
Purdue Univ.
SAO
UCLA
UCSC
U. of Chicago
U. of Delaware
U. of Iowa
U, of Minnesota
U. of Utah
Washington U.

Canada

McGill Univ.

U.K.

Leeds Univ.

Non-Affiliated Members

DESY/Potsdam
Penn State U.

Ireland

Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

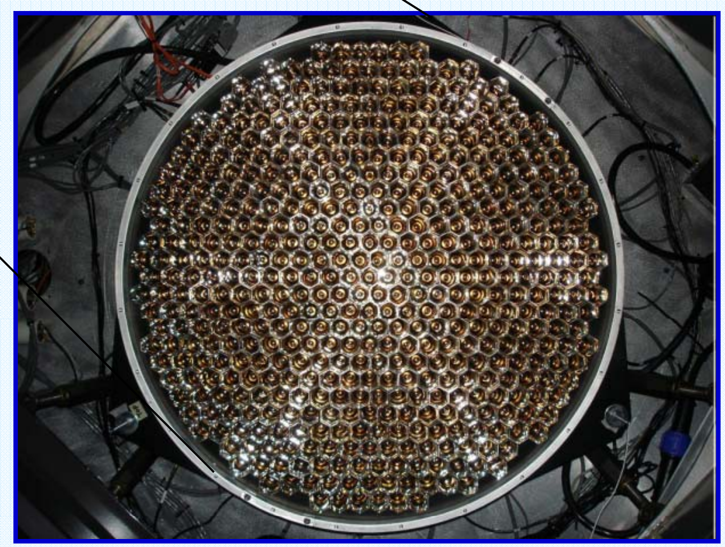
Collaboration Mtg.
July 2011, McGill University

+ Associate Members (e.g. A. Rovero, A. Pichel)

A VERITAS Telescope

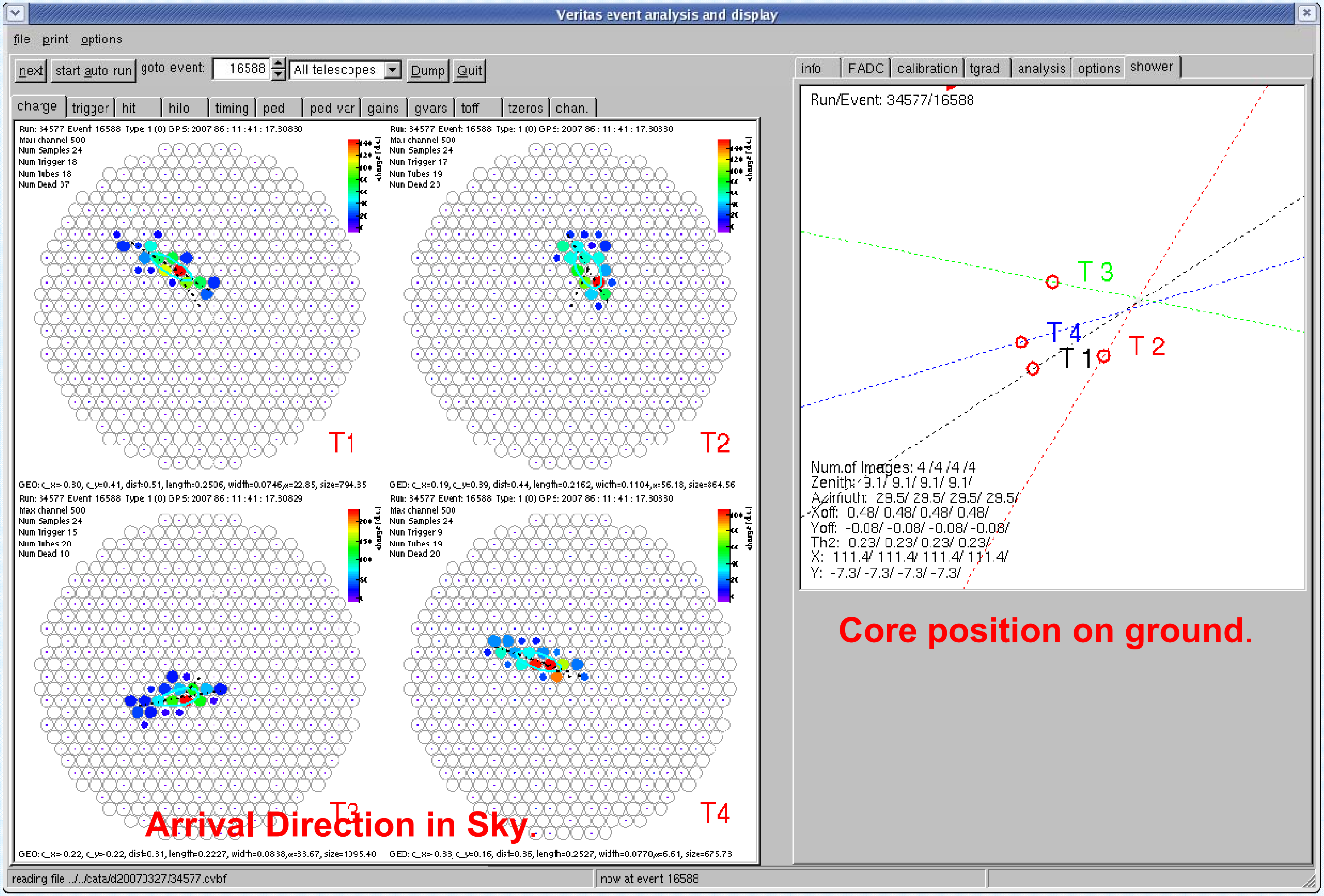
12m reflector, f1.0 optics

350 Mirror Facets



500 pixel Camera

Four-Telescope Event



Latest VERITAS Results

Dark Matter

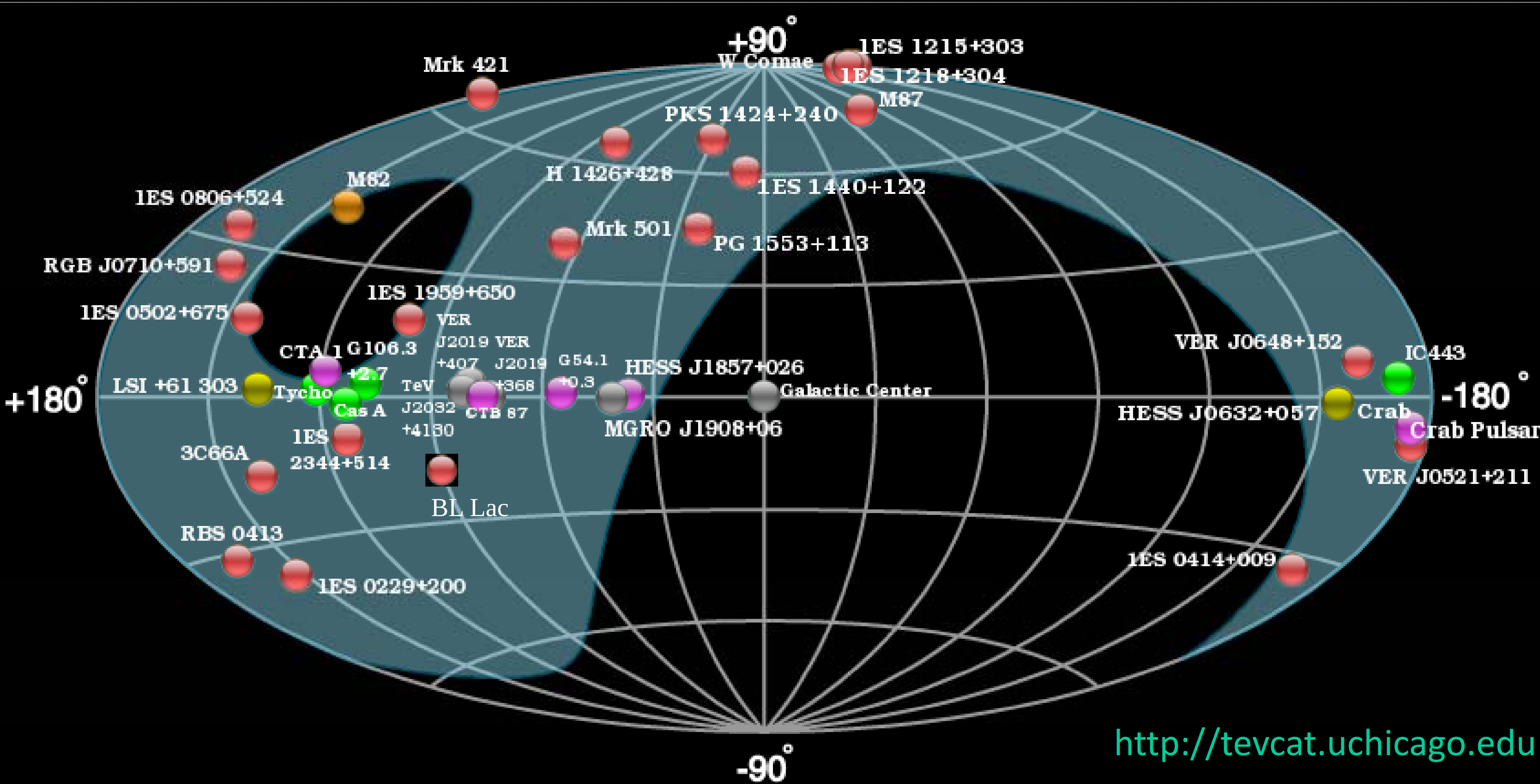
Galactic Sources:

- Supernova Remnants: Tycho
- Crab Pulsar

VERITAS Sky Map (2011)

40+ sources covering 8 source classes

At least 17 sources are likely Galactic (SNRs, PWNe, Binaries, UnIds, Pulsars)



http://tevcat.uchicago.edu

VERITAS Sky Map (2011)

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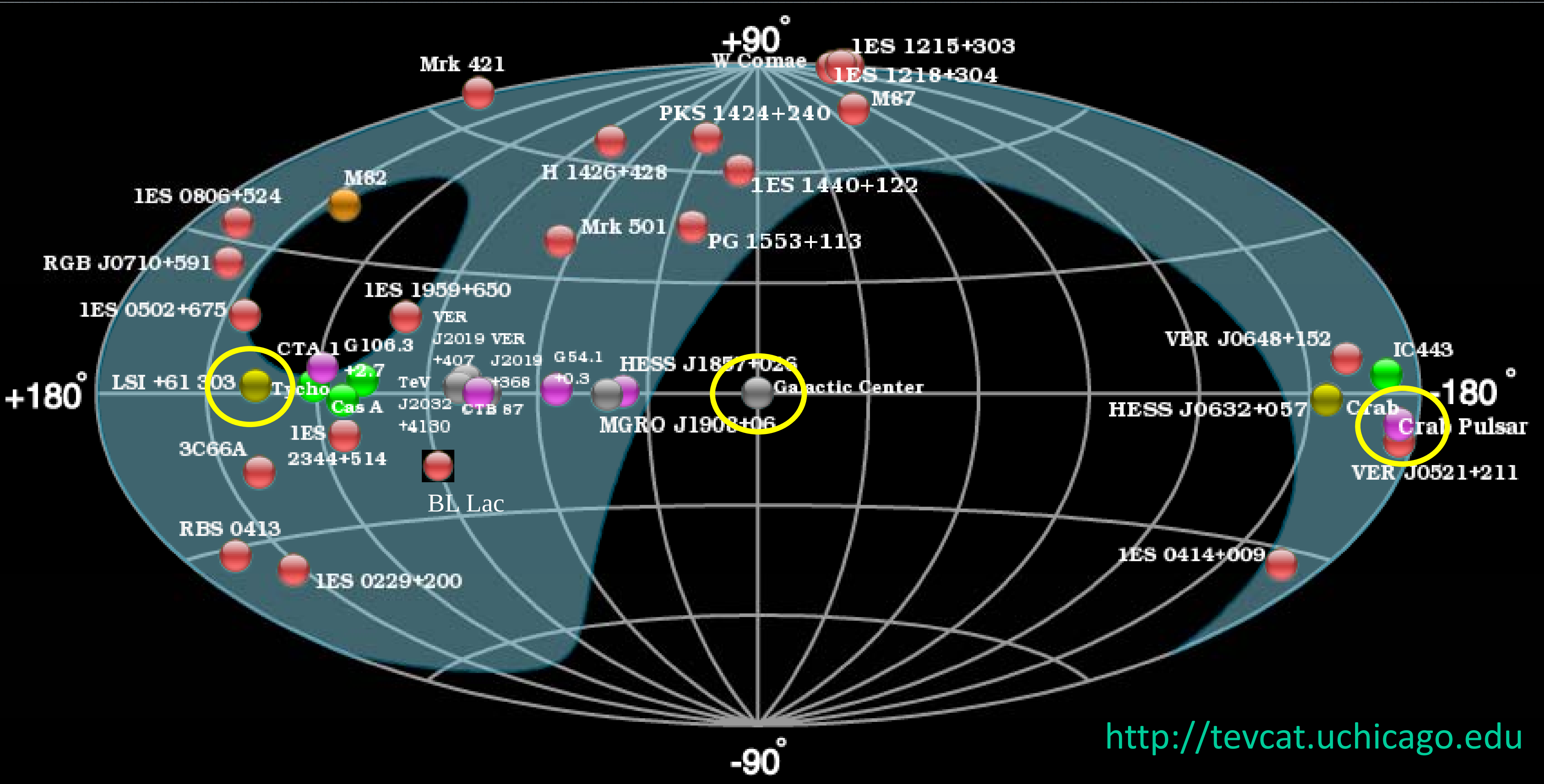
At least 17 sources are likely Galactic (SNRs, PWNe, Binaries, UnIds, Pulsars)



http://tevcat.uchicago.edu

VERITAS Dark Matter Program

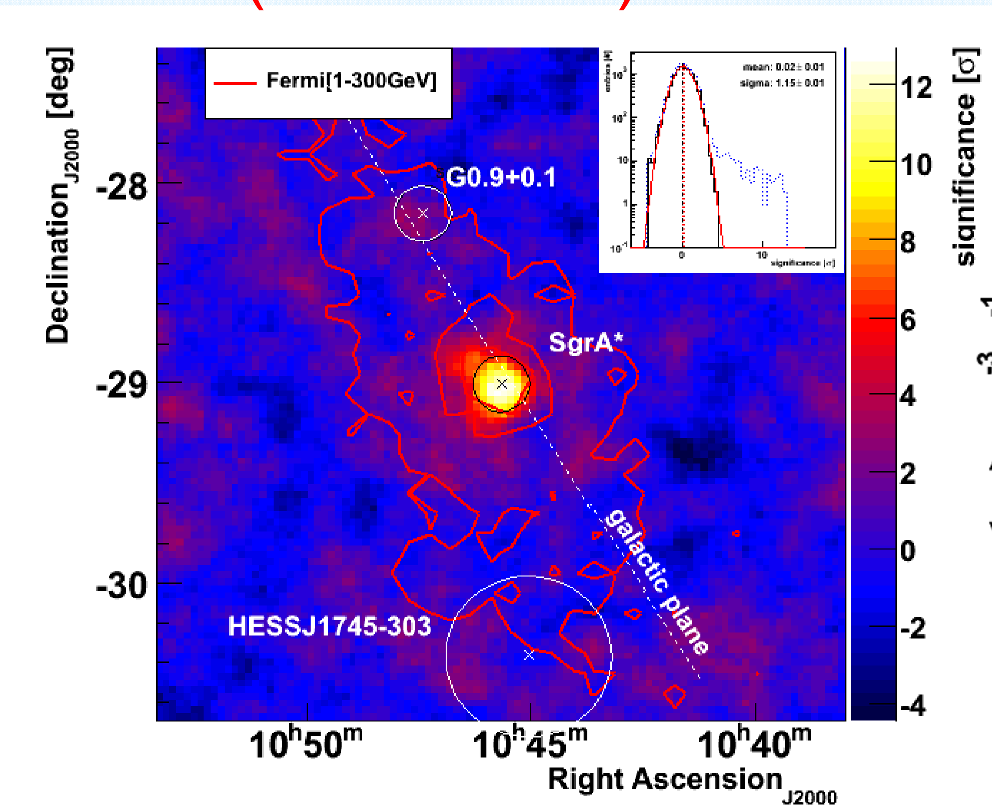
Because of large uncertainties (WIMP mass, σ, astrophysical flux), VERITAS observing strategy targets a variety of potential sources.

Target	Advantages	Disadvantages
→ **Galactic Center**	**- Close by** **- Huge amount of DM**	**- Many astrophysical backgrounds** **- Big uncertainty in the DM distribution**
→ **Dwarf spheroidal galaxies**	**- DM dominated** **- Clear of astrophysical backgrounds**	**- May be beyond reach of current instrument sensitivity** **- Can be tidally disrupted: uncertainty in the DM distribution.**
Globular clusters	**- Very close**	**- Not DM dominated** **- Astrophysical backgrounds** **- Interplay of baryons with DM not well known**
Clusters of galaxies	**- Huge amount of DM**	**- Very far** **- Astrophysical backgrounds**

There have been no detections to date.

VERITAS DM Searches

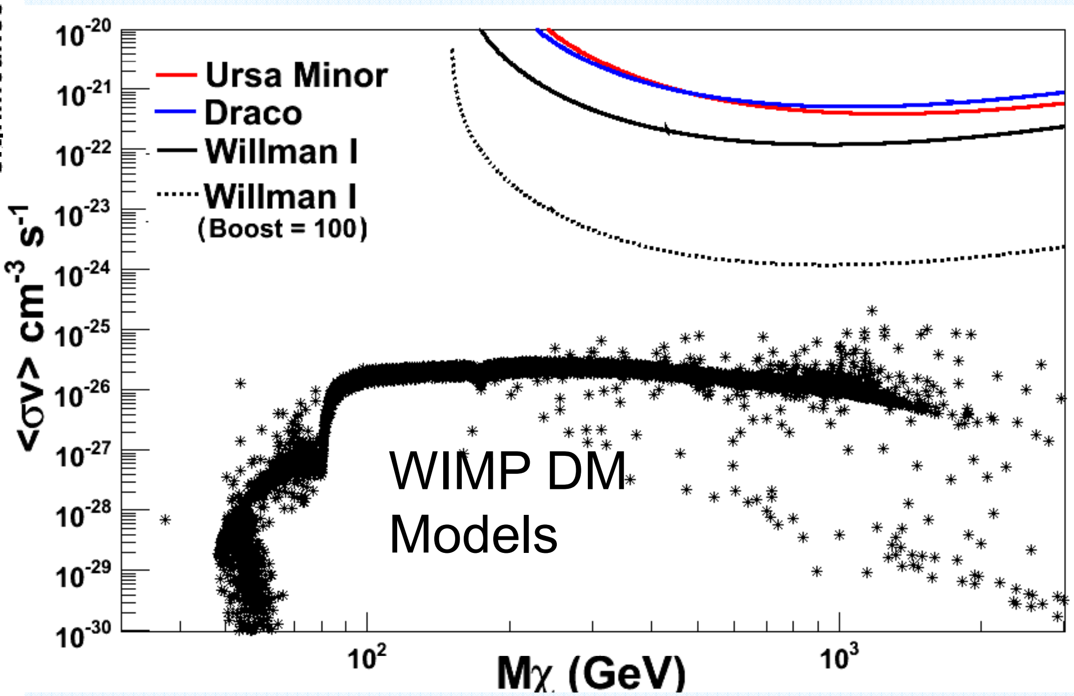
Galactic Center (brand new!)



Strong detection by VERITAS, but interpretation is still unclear; strong astrophysical source present.

Dwarf Spheroidal Galaxies

V.A. Acciari et al., ApJ 720, 1174 (2010)



Limits, based on moderate observations, do not yet rule out any models.

New Result on Dwarf Segue 1

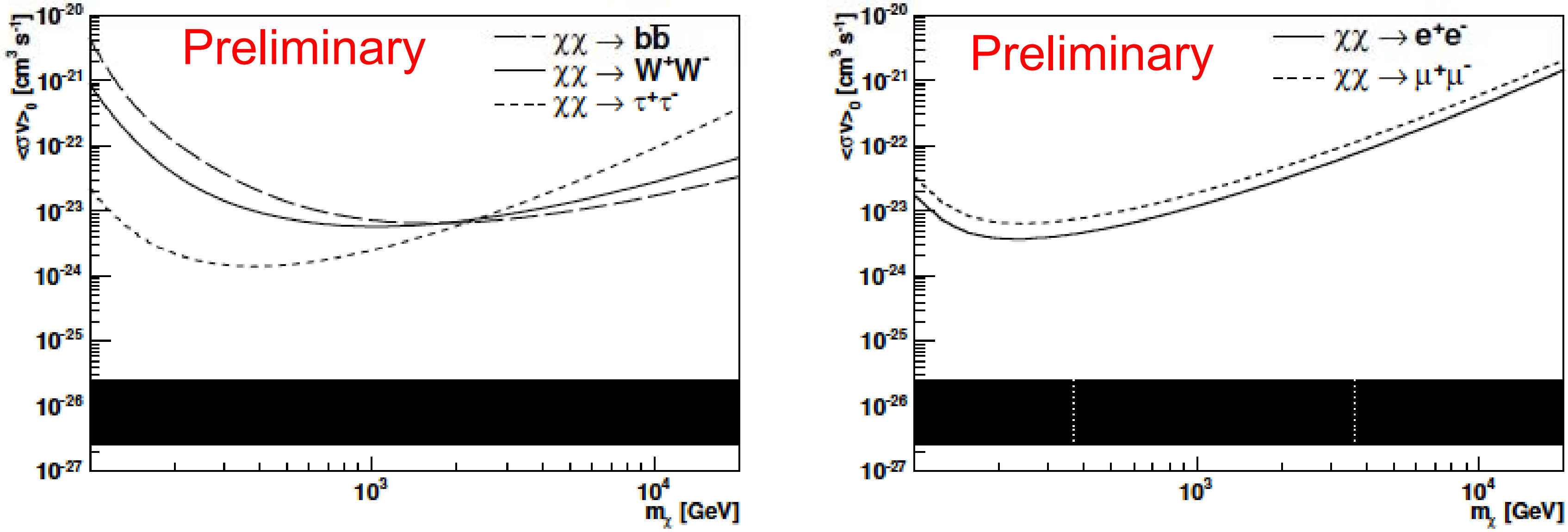


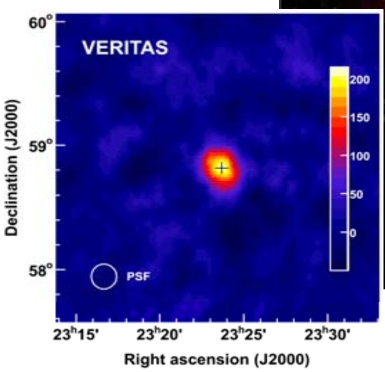
FIG. 3. 95% CL ULs on the WIMP velocity-weighted annihilation cross-section $\langle\sigma v\rangle_0$ as a function of the WIMP mass, considering different final state particles. The grey band area represents a range of generic values for the annihilation cross-section in the case of thermally produced DM. Left: hadronic channels W^+W^-, $b\bar{b}$ and $\tau^+\tau^-$. Right: leptonic channels e^+e^- and $\mu^+\mu^-$.

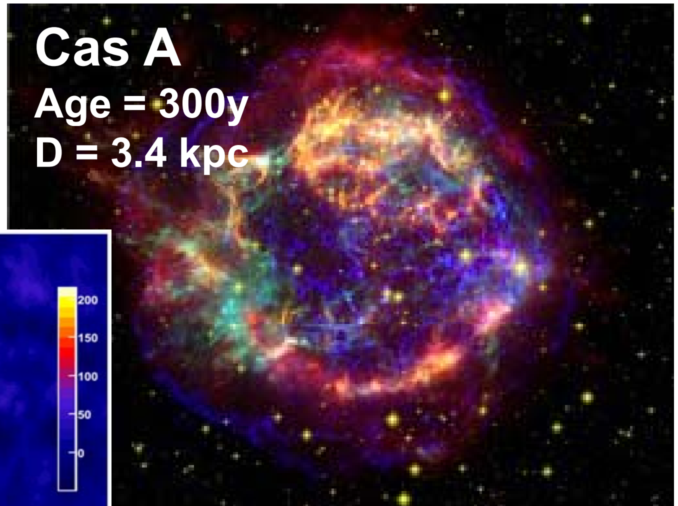
$\langle\sigma v\rangle_{min} \leq 1\text{-}8 \times 10^{-24}$ cm^3 s^{-1}

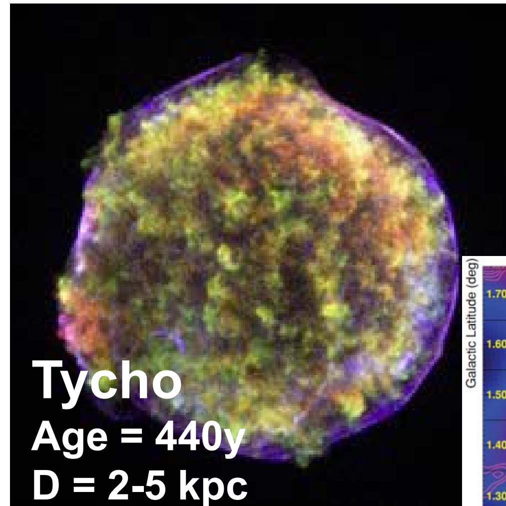
Limits are factor of 4-5x better than our previous dSph results and best on dSph reported so far.

VERITAS Supernova Remnants

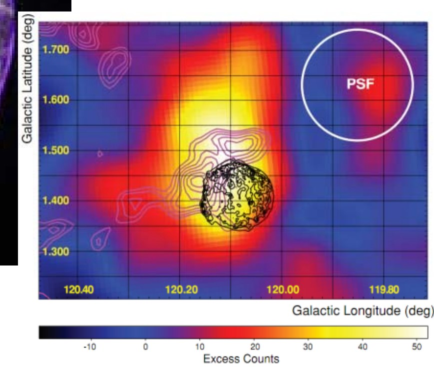
Cas A
~3% Crab

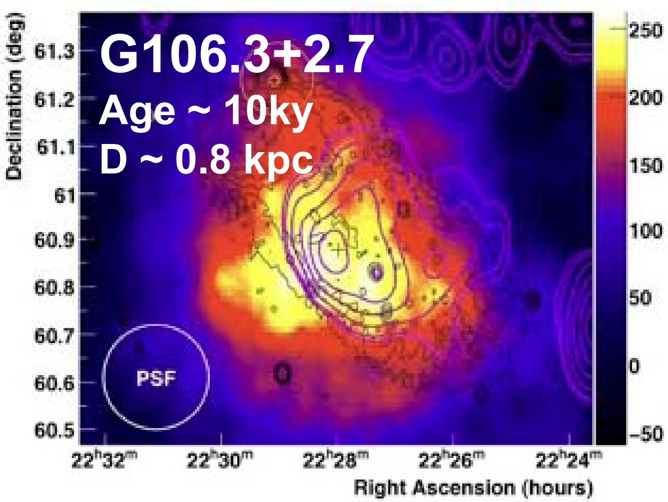






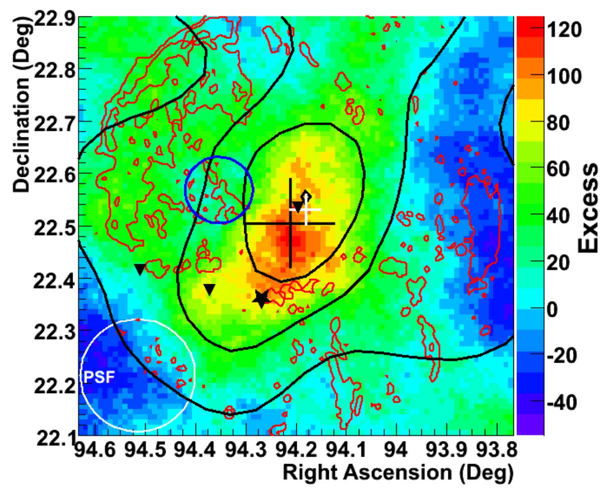
Tycho
~1% Crab

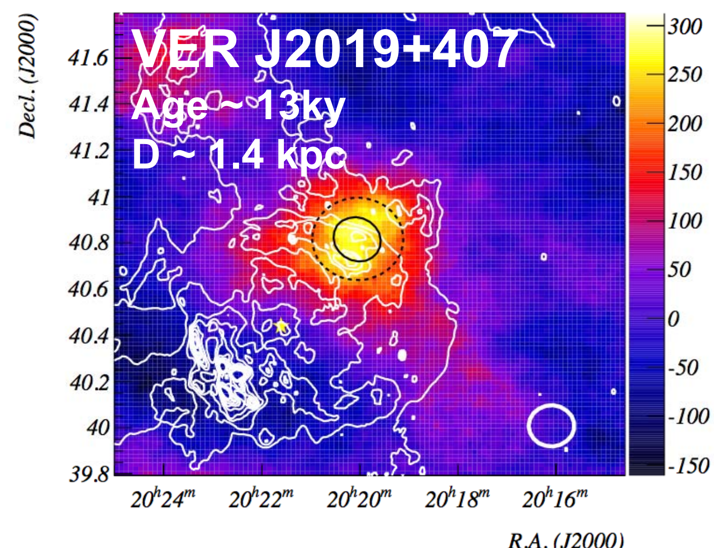




Boomerang

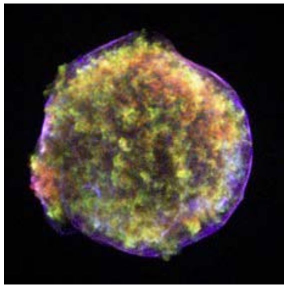
IC 443
Age ~ 30ky
D ~ 0.8kpc

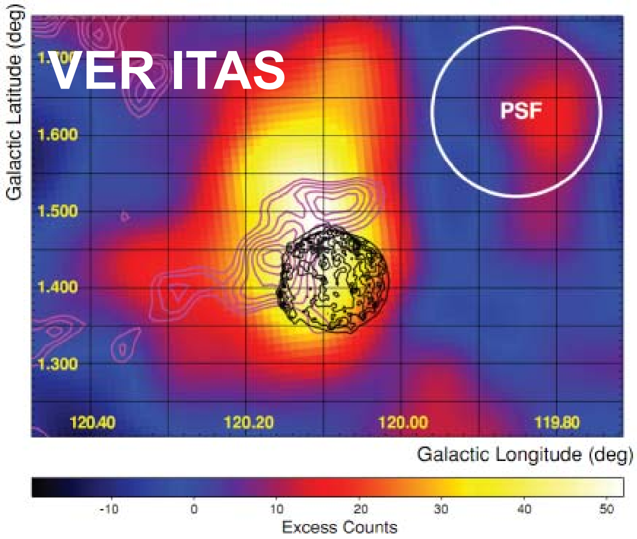




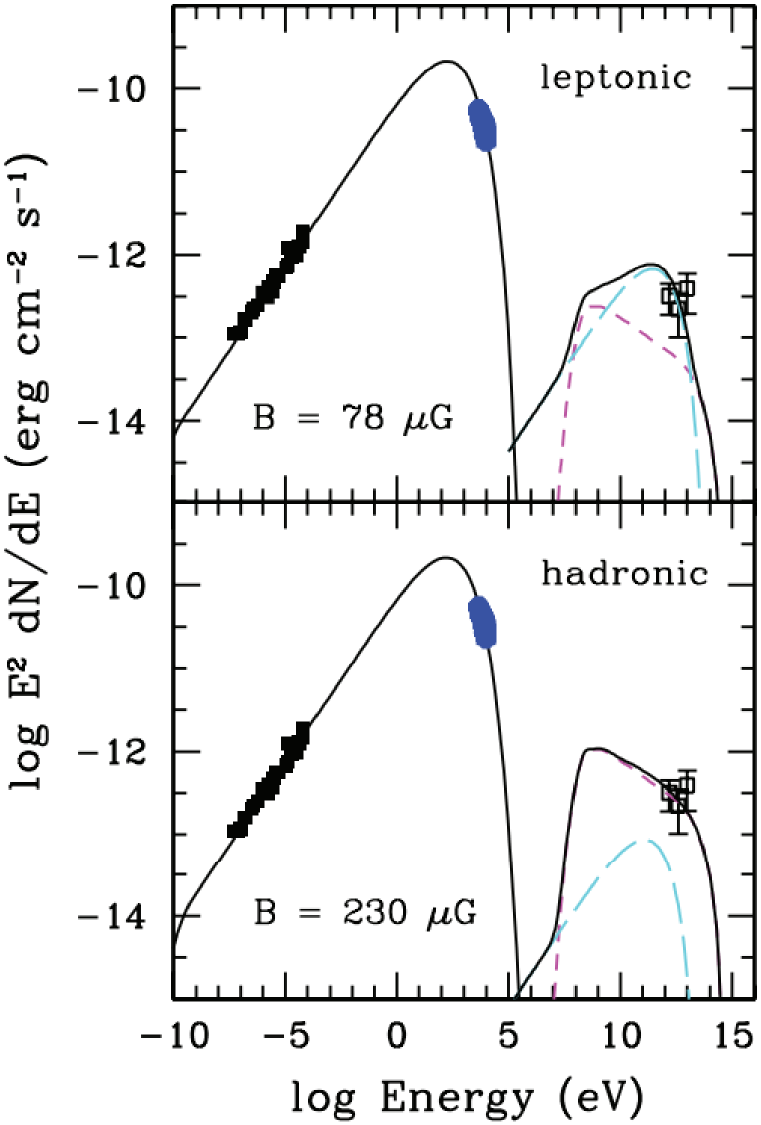
γ-Cygni

Tycho's SNR: VERITAS Discovery





V.A. Acciari et al., ApJ 720, L20 (2011)



Tycho's SNR:

- Historical Type 1a SN of 1572.
- X-ray morphology argued for hadronic acceleration (Warren et al. 2005).
- VERITAS discovery in 2010 with 68 hrs.
- Weak source (0.9% Crab) with hard power-law spectrum $\Gamma = 1.95 \pm 0.51 \pm 0.30$.
- Consistent with leptonic or hadronic models.

Tycho with Fermi-LAT & VERITAS

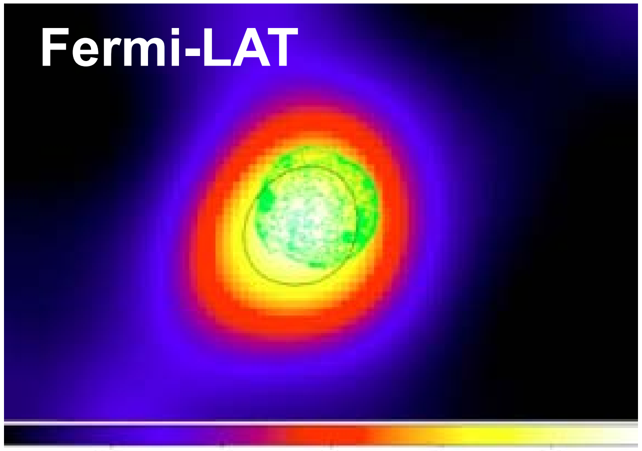
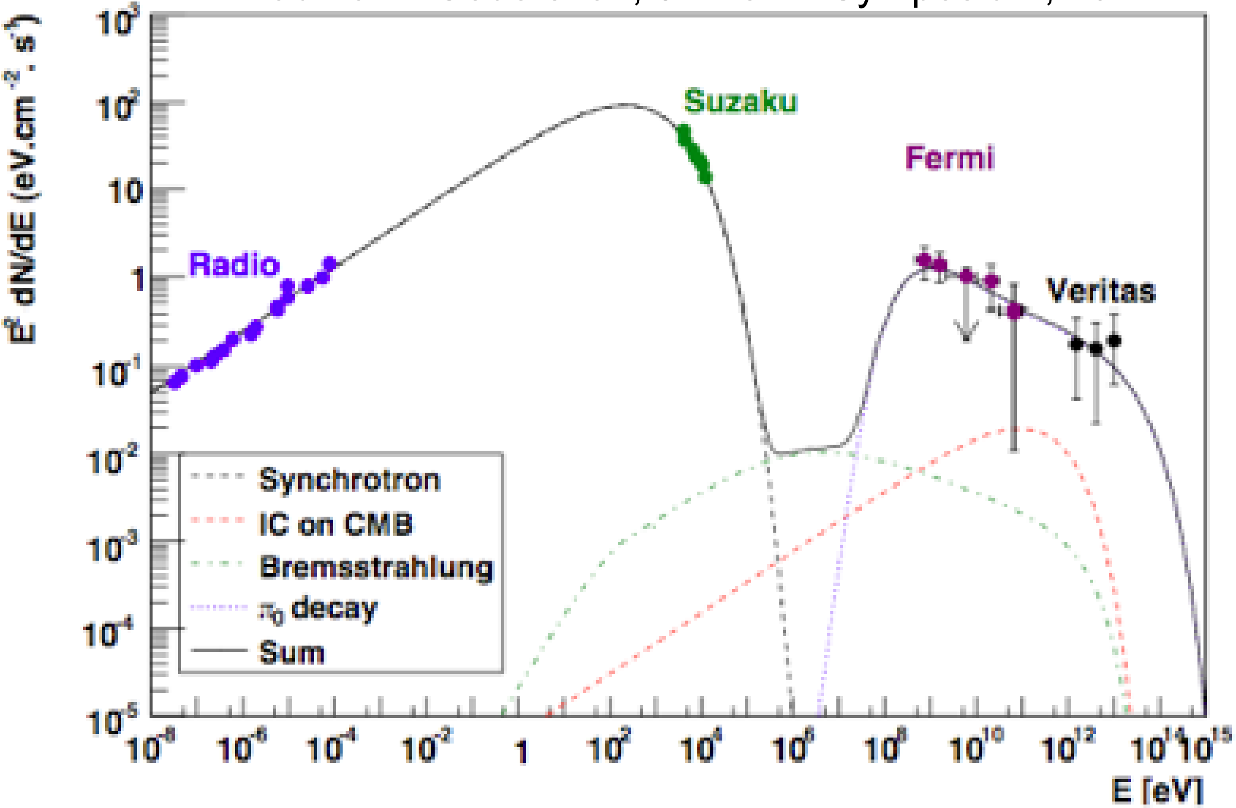


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

M. Naumann-Godo et al., 3rd Fermi Symposium, 2011



Fermi-LAT & VERITAS:

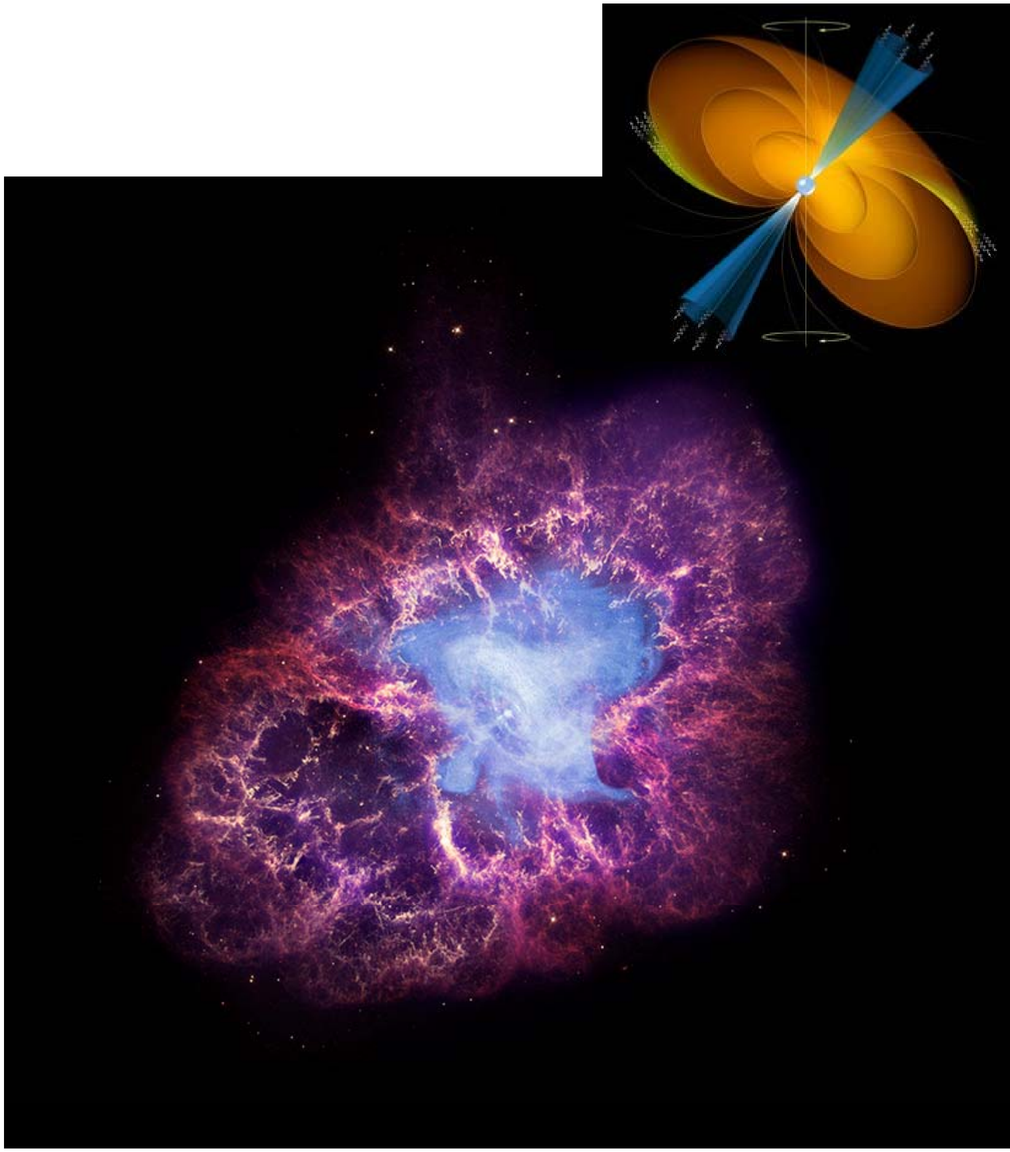
- New Fermi-LAT detection.
- Hard photon index of 2.3 ± 0.1 favors hadronic origin.
- 6-8% of E_{sn} transferred to CR acceleration (D~2.8kpc).

Good evidence for hadron accelerator; similar for Cas A

Crab

Crab Nebula and Pulsar

- Remnant from historical SN in 1054.
- One of the most energetic pulsars and brightest γ–ray pulsars.
- Nebula is the brightest, steady VHE source.



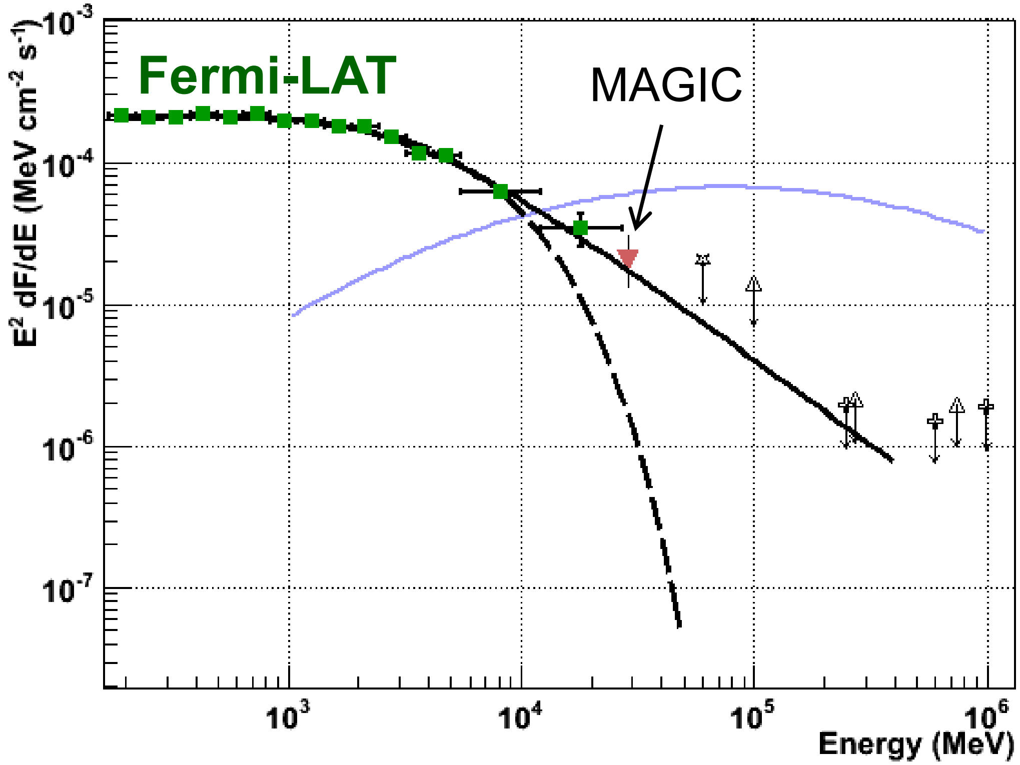
γ-ray observations of Pulsar

- **Fermi-LAT (first EGRET):** exquisite measurements around spectral break near few GeV.
- **MAGIC:** detection at 25 GeV and hint at 60 GeV.
- Numerous, constraining limits from **many VHE experiments**.
- 30-year effort to detect at VHE.

Crab Pulsar at HE and VHE

MAGIC Result at 25 GeV
(Aliu et al., 2008)

- Special trigger to lower E_{th}.
- Similar pulse profile to EGRET.
- Exponential E_{cutoff} ~ 18 GeV.
- Rule out polar cap model.



Conventional view:

- Spectral break is described by exponential cut off; i.e. there is a single component.
- Most-favored γ-ray production mechanism is curvature radiation.
- Emission come from outer regions >6 stellar radii. Outer-gap or slot-gap models favored.

VERITAS Observations & Analysis

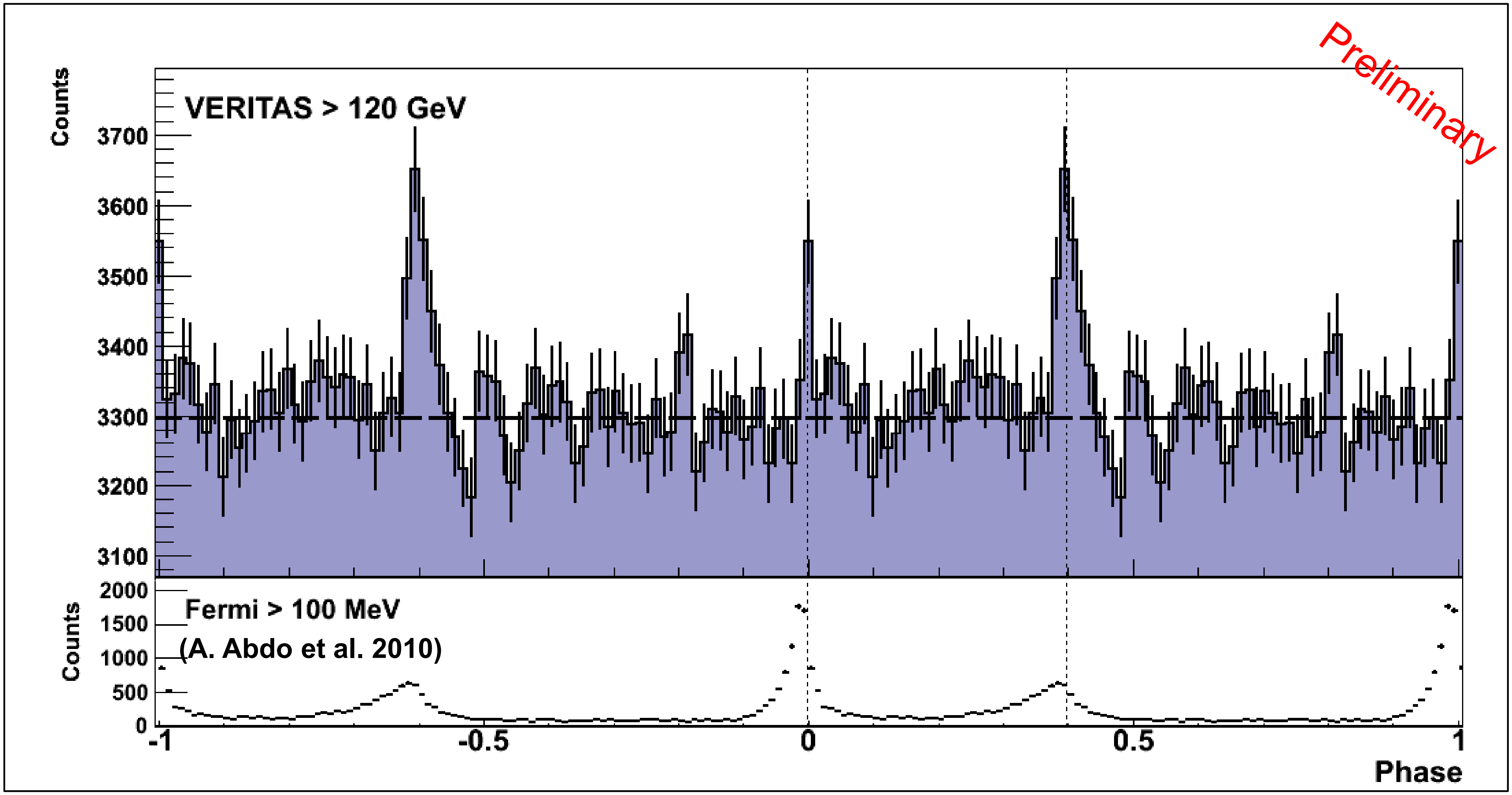
VERITAS Observations:

- Total of 107h of data (2007-09: 45h, 2010: 62 h), taken with 4 telescopes.
- Zenith angle < 25^{o}.
- Event times from four independent GPS receivers.

Analysis:

- Standard trigger, standard analysis tools (two ind. packages).
- Analysis selection set *a priori* for weak (few % Crab Nebula) source with soft spectrum, $\Gamma = 4$.
- Event time barycentering with two custom codes and tempo2.
- Phase folding of data using Jodrell Bank empherides.

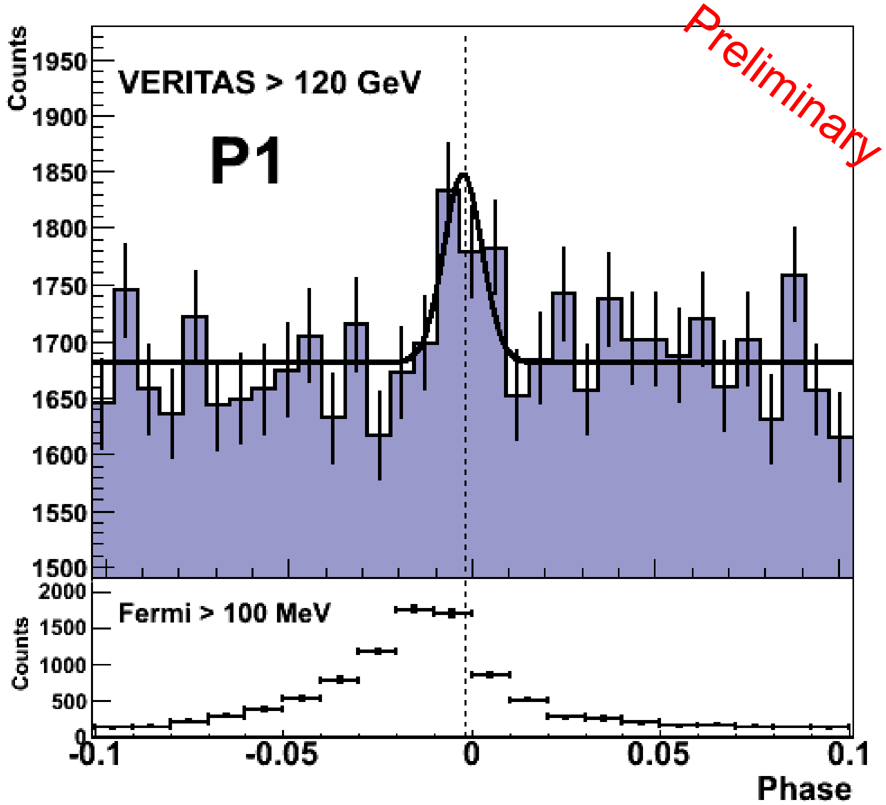
VERITAS Pulsed Signal



Statistical significance of pulsed signal:
H-Test value of 50, i.e. 6.0σ.

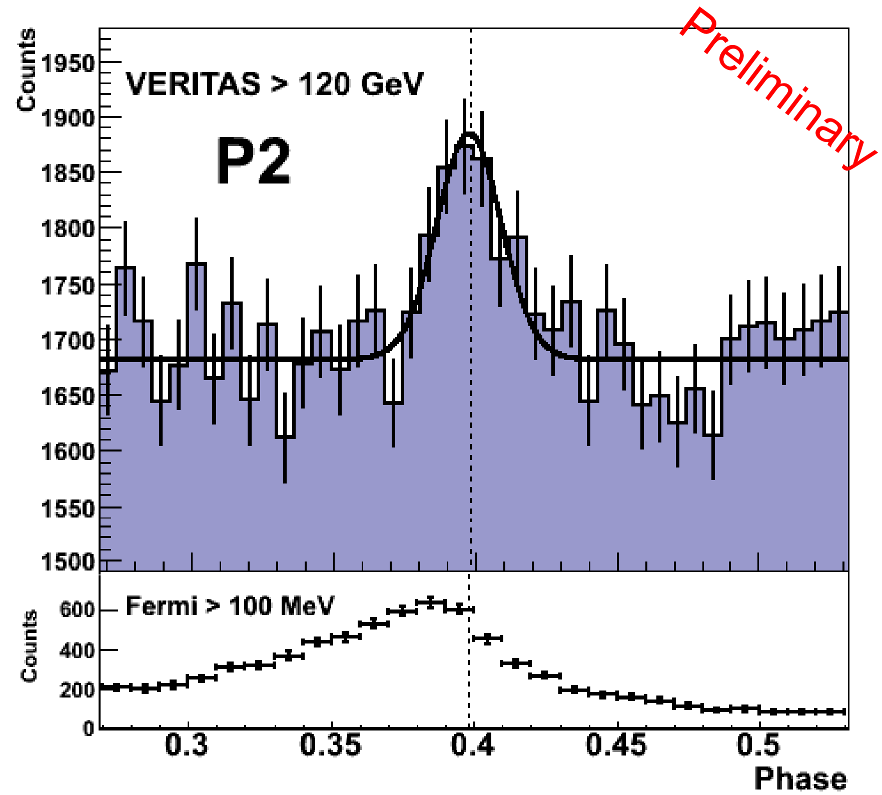
E. Aliu et al.,
to be published in Science (2011)

A Closer Look at the Peaks



Position: -0.0023 ± 0.0020

Width: 0.0132 ± 0.0035 FWHM



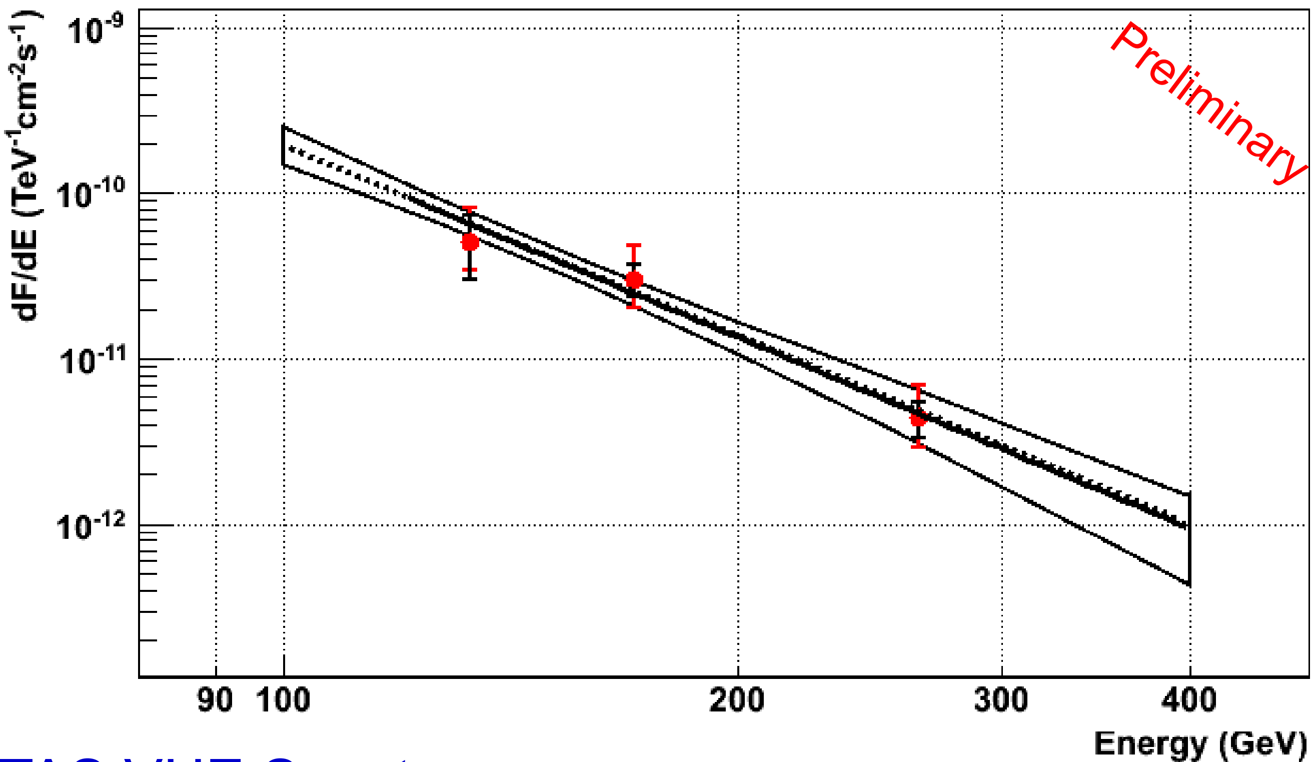
Position: 0.3975 ± 0.0020

Width: 0.0268 ± 0.0052 FWHM

Peak positions **aligned with peak positions in radio.** The shift with respect to Fermi-LAT data is an analysis effect

Pulses above 120 GeV **2-3 times narrower than in Fermi-LAT data**
→ possible interpretation: the acceleration zone tapers

VHE Spectrum of Crab Pulsar



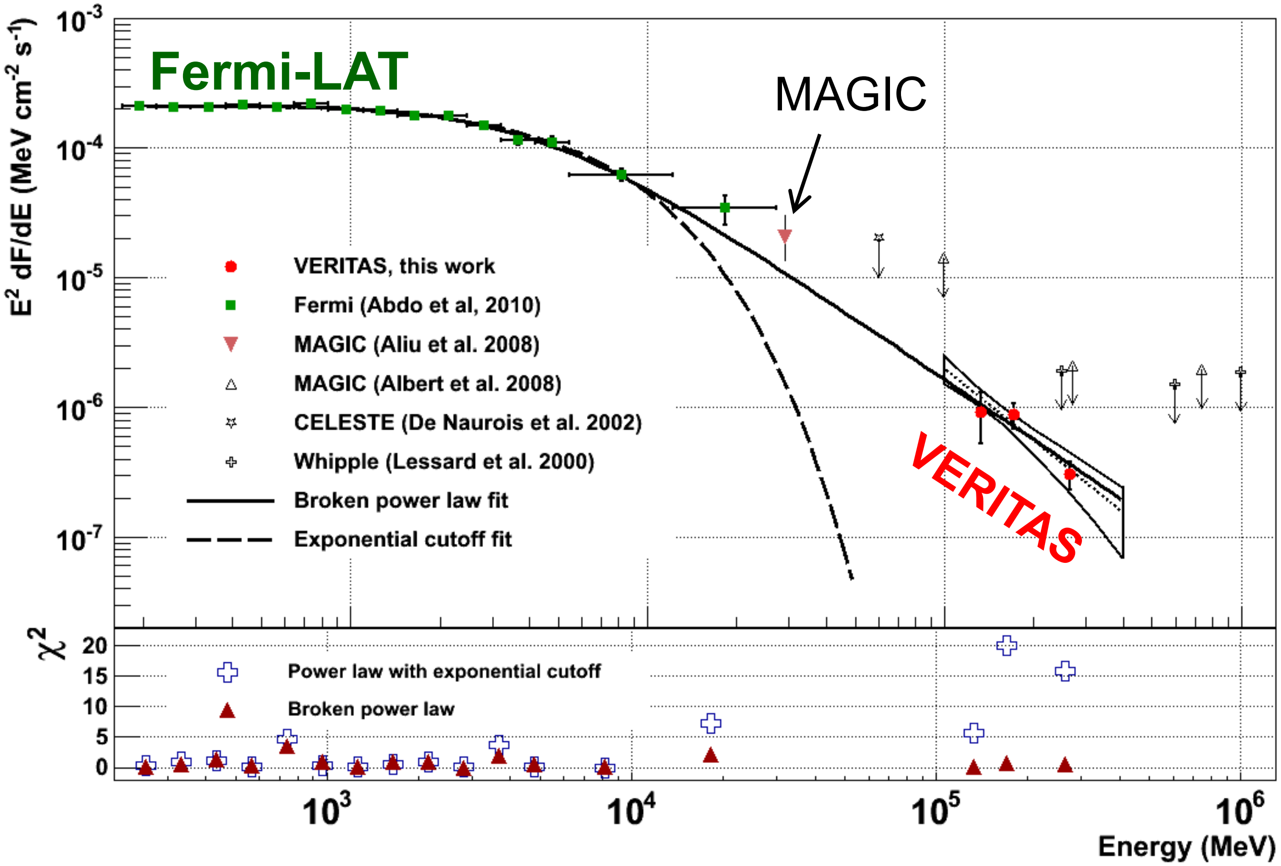
E. Aliu et al., to be published Science (2011)

VERITAS VHE Spectrum:

- Combine P1 and P2 regions – good approx.of phase-averaged spectrum.
- Highest energy point at 280 GeV.
- Crab Pulsar ~ 1% Nebula flux at 150 GeV.
- **Power-law form !**

$$dN/dE = A(E/150\text{ GeV})^{\alpha} \quad \text{for } \alpha = -3.8 \pm 0.5_{stat} \pm 0.2_{syst}$$

The New Picture of the Crab Pulsar

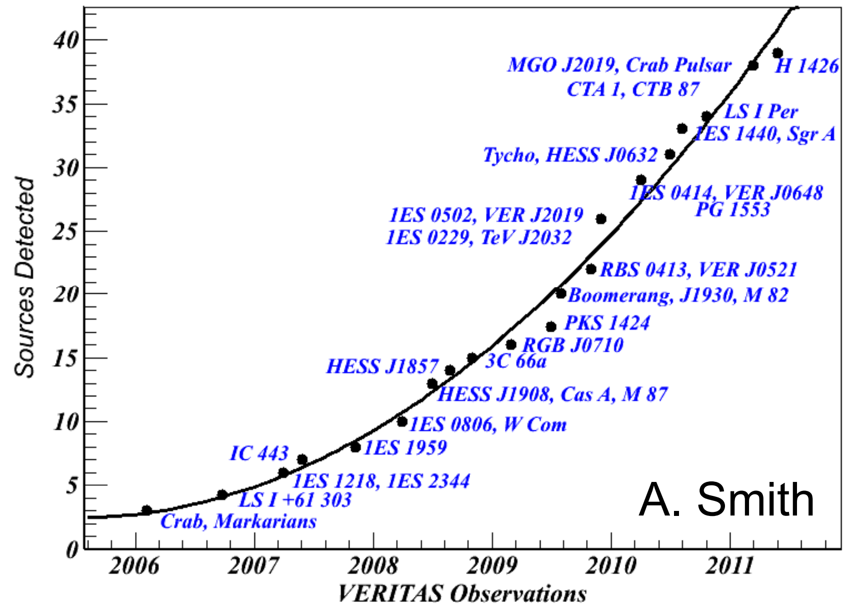


- **First detection of a pulsar above 100 GeV.**
- VERITAS detection @ 280 GeV → emission region > 10 stellar radii.
- Detection above 100 GeV → curvature radiation unlikely to be dominant mech.
- Narrowing of pulses → tapered acceleration region ?
- Competitive limits on LIV – stay tuned.

The Future

Future Prospects: VERITAS Upgrade

VERITAS detections vs time



VERITAS in 2011:

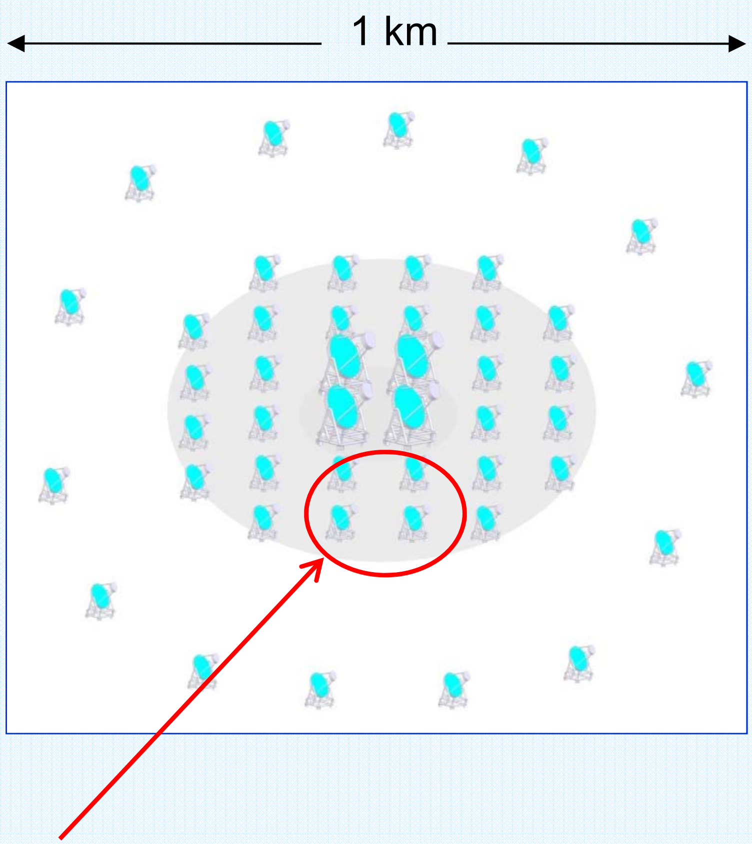
- Operating smoothly with excellent sensitivity and science output.
- With excitement of field (and power of Fermi), we want to improve the sensitivity – especially at ~100 GeV.

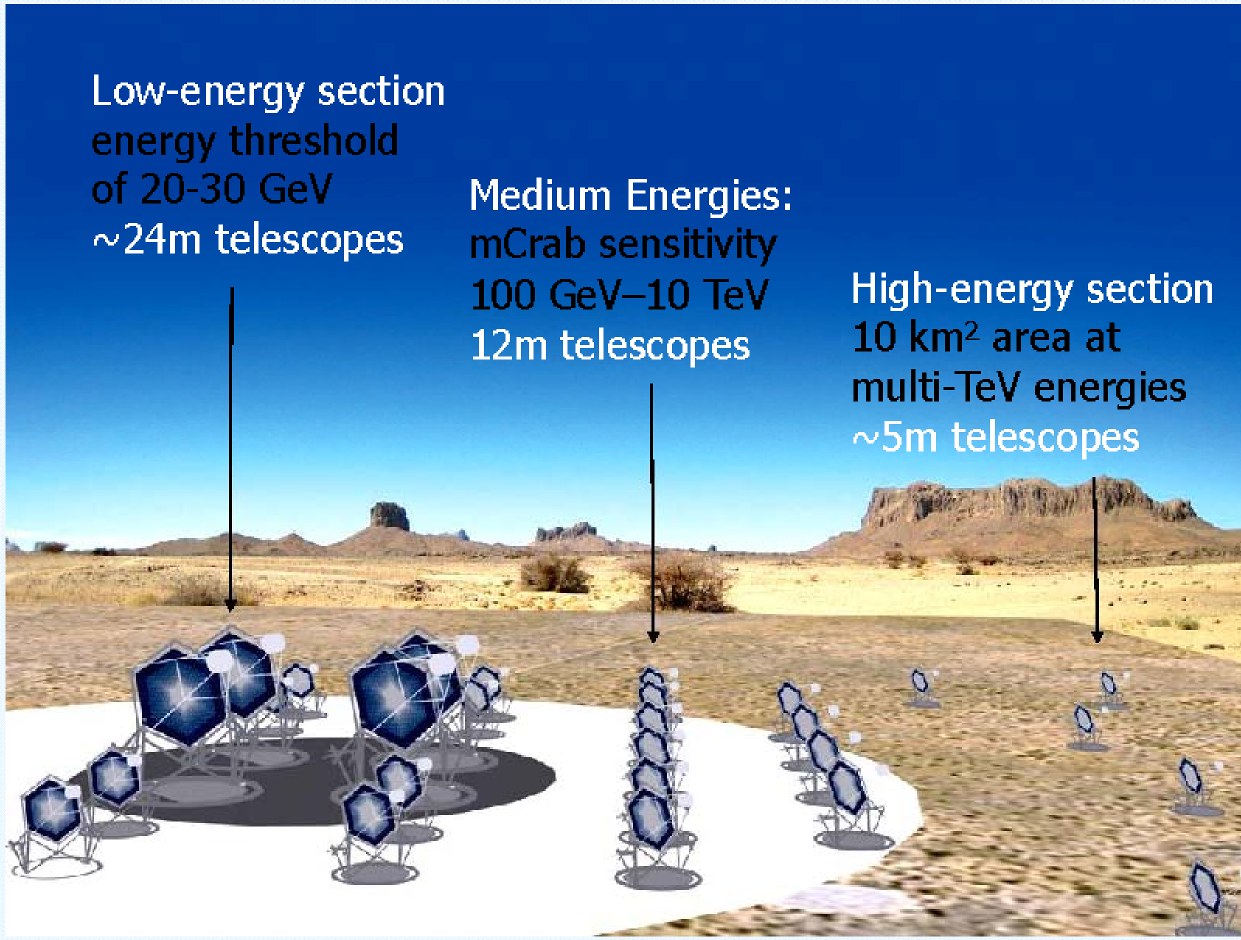
VERITAS UPGRADE (2009-2012):

1. Improved optical point spread function ← completed
2. Relocating telescope T1 ← completed
3. Upgrading cameras with high efficiency PMTs ← 2012
4. New trigger system ← 2011-12
5. An additional telescope T5 ← possible in the future

Cherenkov Telescope Array

- > 10 times more sensitive than VERITAS
- two sites (S and N hemispheres)
- array of many atm. Cherenkov telescopes (~ 10 km^2 in S, ~1 km^2 in N)
- construction complete towards end of decade.

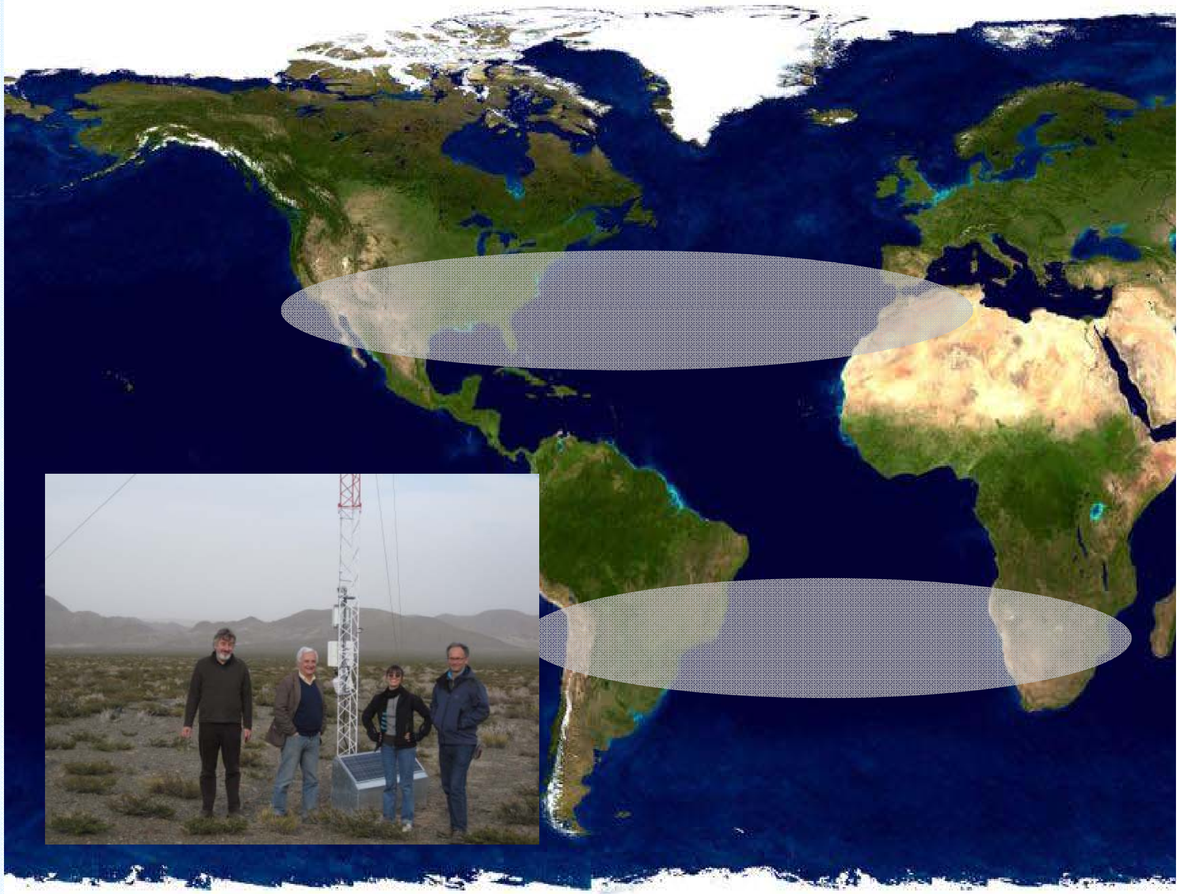




Medium-sized telescopes
are the core of CTA

Cherenkov Telescope Array

One observatory with two sites for all-sky coverage operated by one consortium



Two candidate sites in Argentina
El Leoncito (San Juan)
S. Antonio de los Cobres (Salta)

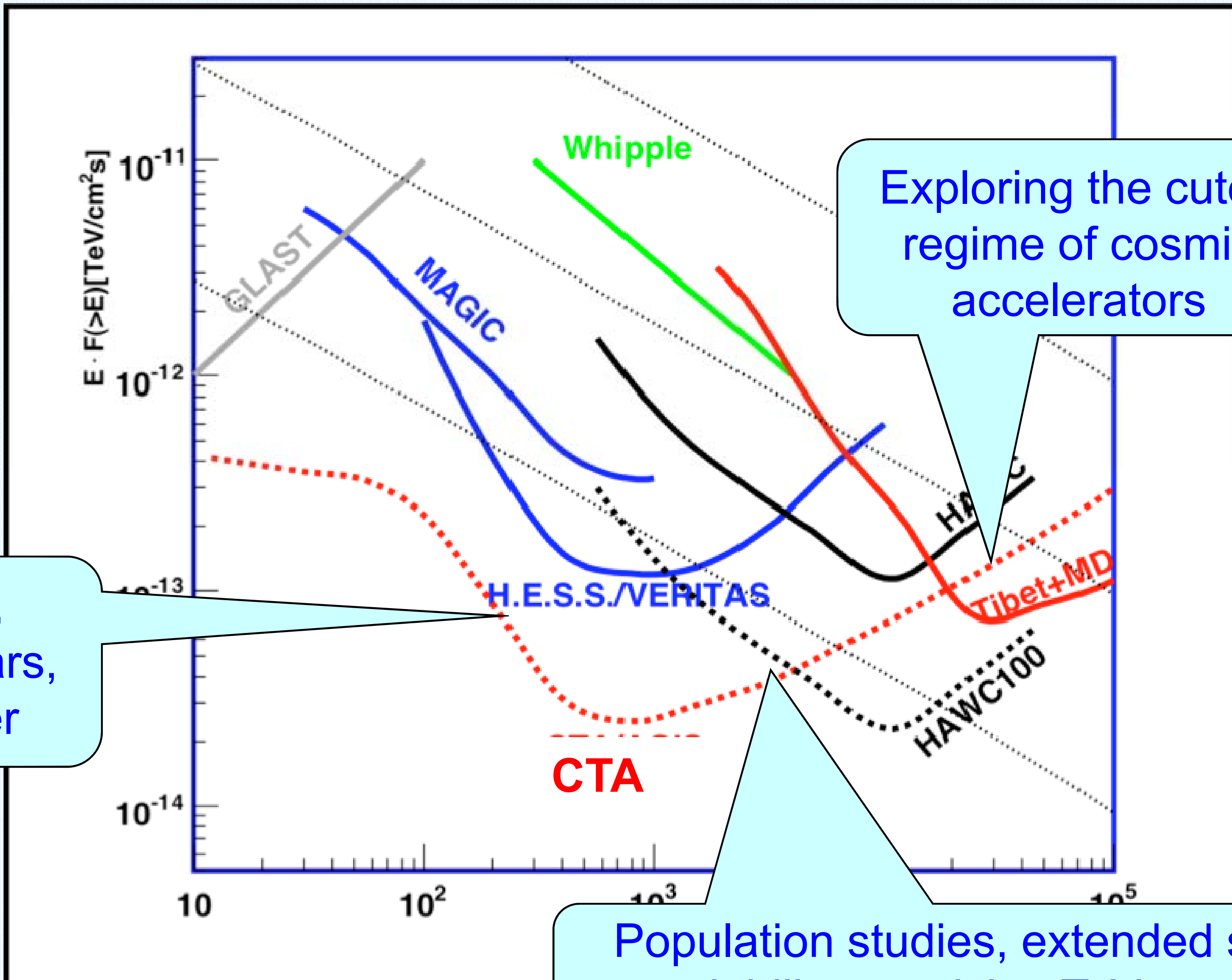
Northern Array

→ complementary to SA for full sky coverage
→ Energy range some 10 GeV .... ~1 TeV
→ Small field of view Mainly extragal. Sources

Southern Array

→ Full energy and sensitivity coverage some 10 GeV .... 100 TeV
→ Angular resolution: 0.02 ... 0.2 deg
→ Large field of view Galactic + Extragal. Sources

Cherenkov Telescope Array



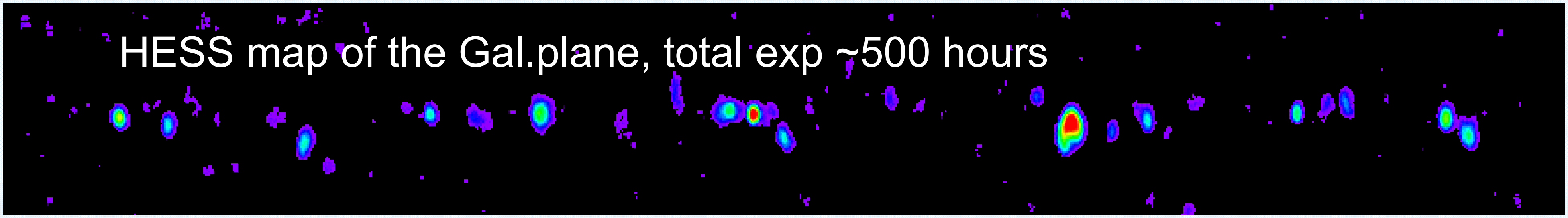
Exploring the cutoff regime of cosmic accelerators

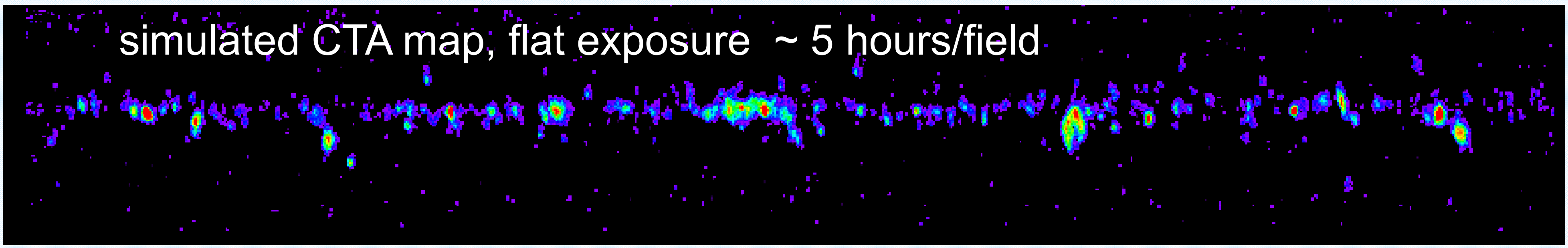
Hi-z AGN, GRBs, pulsars, dark matter

Population studies, extended sources, variability, precision TeV astronomy

CTA Galactic Plane Survey

Funk,Hinton,Hermann,Digel, arXiV0901.1885





Assumes:

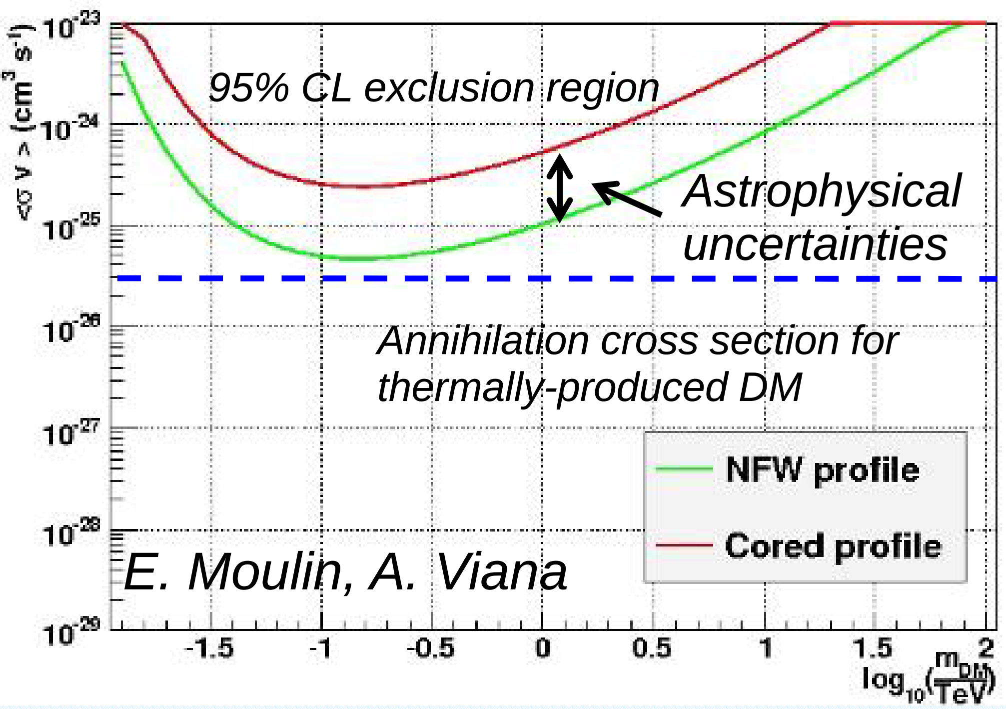
- **x 2 improvement in hadron rejection**
- **x 2 gain in angular resolution**
- **x 10 gain in effective area**

⇒ overall increase in sensitivity of ~ **9**

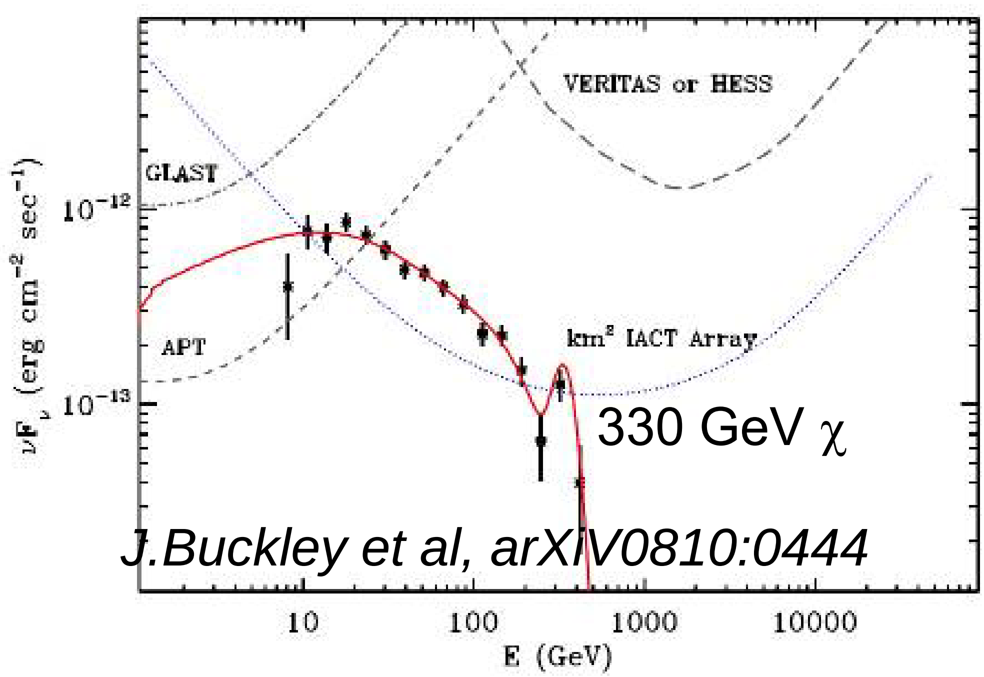
- expect ~ **300 sources** in -30 deg≤ l ≤ 30 deg.

CTA: Dark Matter

Draco dwarf galaxy, 20 hours



Ursa Minor dwarf galaxy



Sensitivity Estimate for CTA

Detection Scenario

Summary

- VHE γ-rays probe astrophysics of TeV particle acceleration in the cosmos, as well as probing for new physics beyond the standard model.
- Among the key scientific questions being attacked are the origin of cosmic rays and the nature of dark matter.
- The imaging **atmospheric Cherenkov technique** allows for sensitive telescopes with good angular & energy resolution.
- **VERITAS** is fully operational and producing numerous exciting results; the on-going upgrade will further improve sensitivity. A future experiment, **CTA**, would achieve an order of magnitude further improvement.

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes."

Marcel Proust (1871-1922)