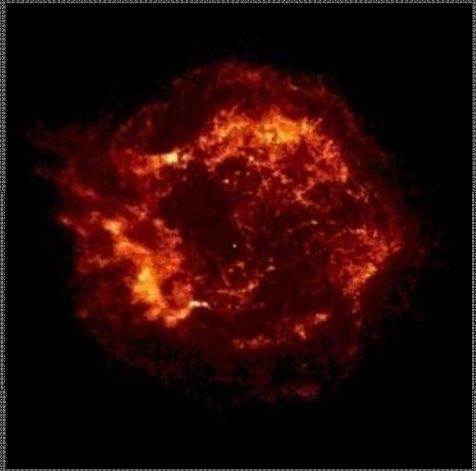
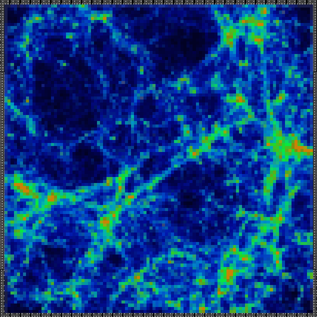
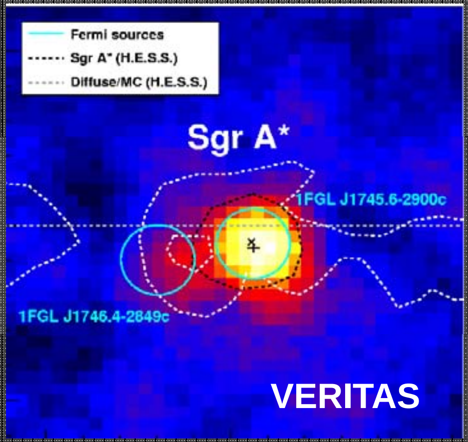
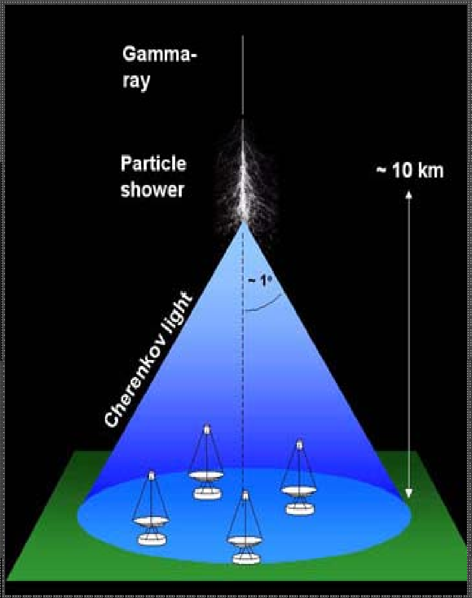
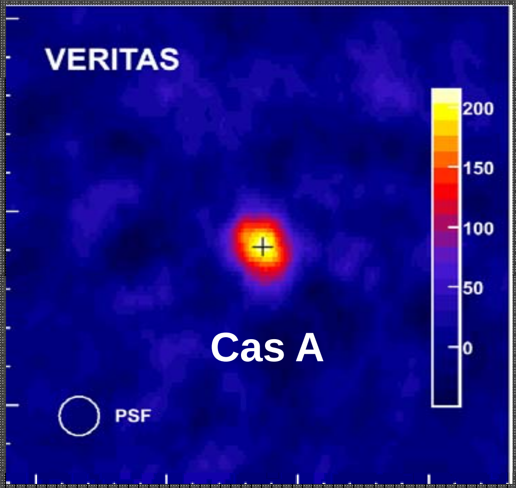
The Mysterious Gamma-Ray Universe











Rene A. Ong **Talk @ Moreno Valley College** **19 April 2012**

Outline

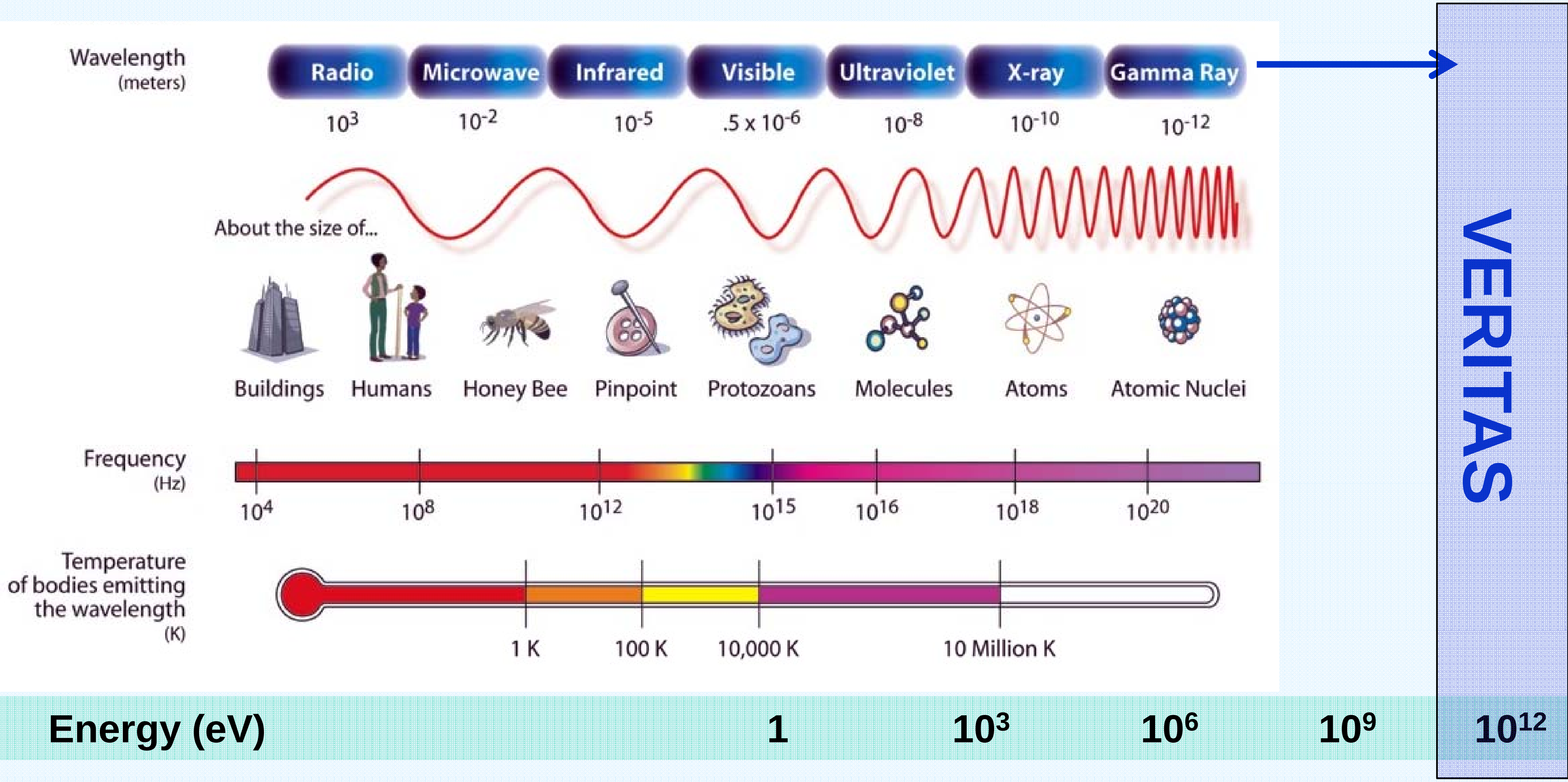
1. The Gamma-Ray Universe:
   - A new Astronomical window
   - Relevant Physics issues

2. Atmospheric Cherenkov Technique

3. VERITAS γ-ray Telescope:
   - Design & performance
   - Some recent results

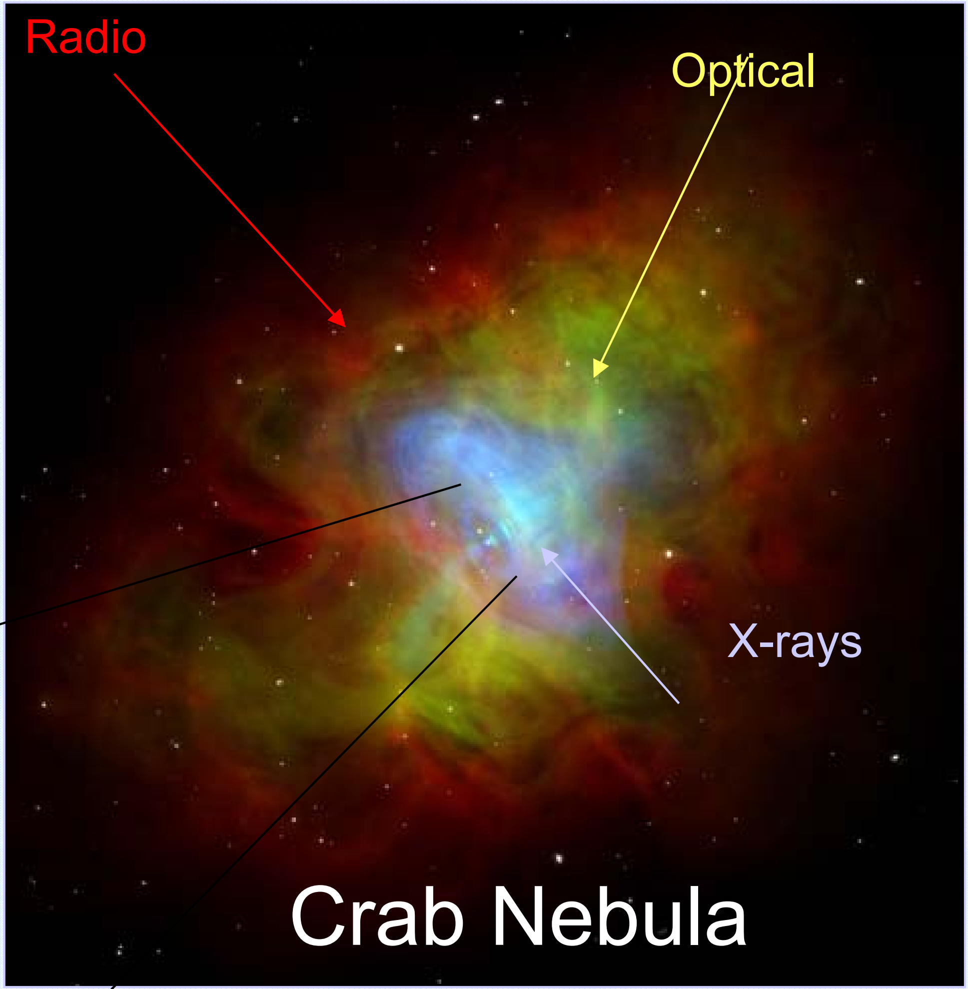
4. The Future:
   - Cherenkov Telescope Array (CTA)

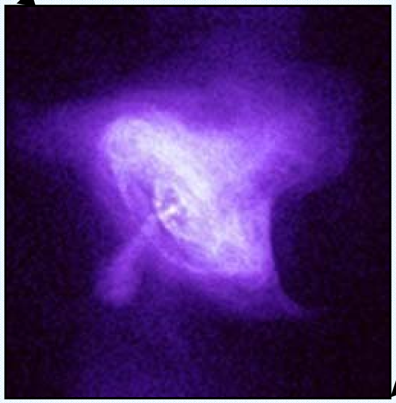
Spectrum of Light



A New Astronomy

- Before 1940's – Astronomy only used visible light.
- New wavebands (radio, IR, X-ray, γ-ray) change our picture of the universe.
- Other messengers too: neutrinos & grav. waves.





Crab Pulsar (X-rays)

Gamma Rays

With gamma rays, we:

- Study extreme processes in the cosmos not visible to the naked eye.
- Probe distance scales much smaller than the size of the atom.
- Study fundamental physics at a much earlier time in the Universe.

Energy Scale

1 GeV = 10^9 eV

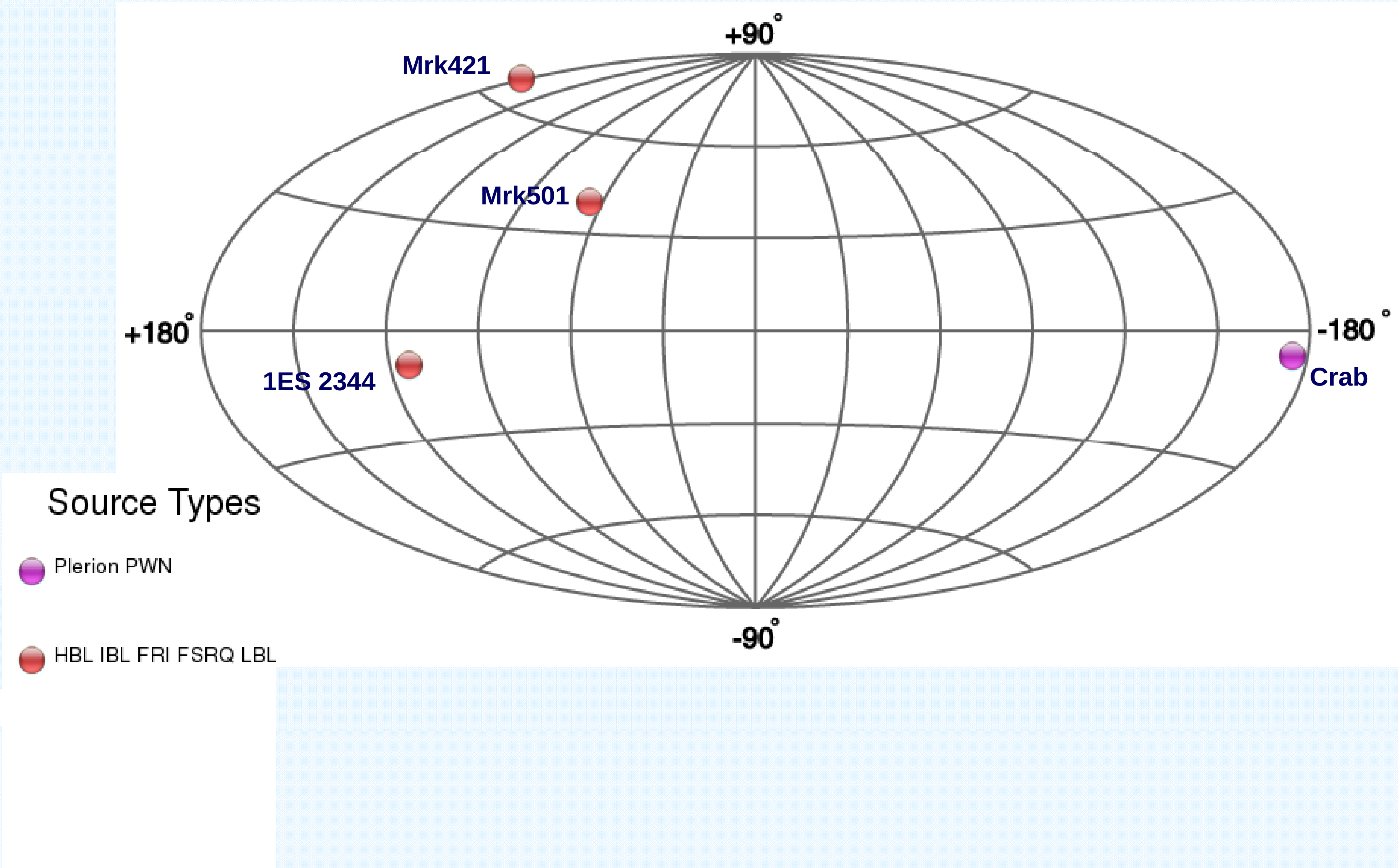
1 TeV = 10^{12} eV

(Optical light ~ 1 eV)

Q: Do astrophysical sources of GeV/TeV γ-rays even exist ?

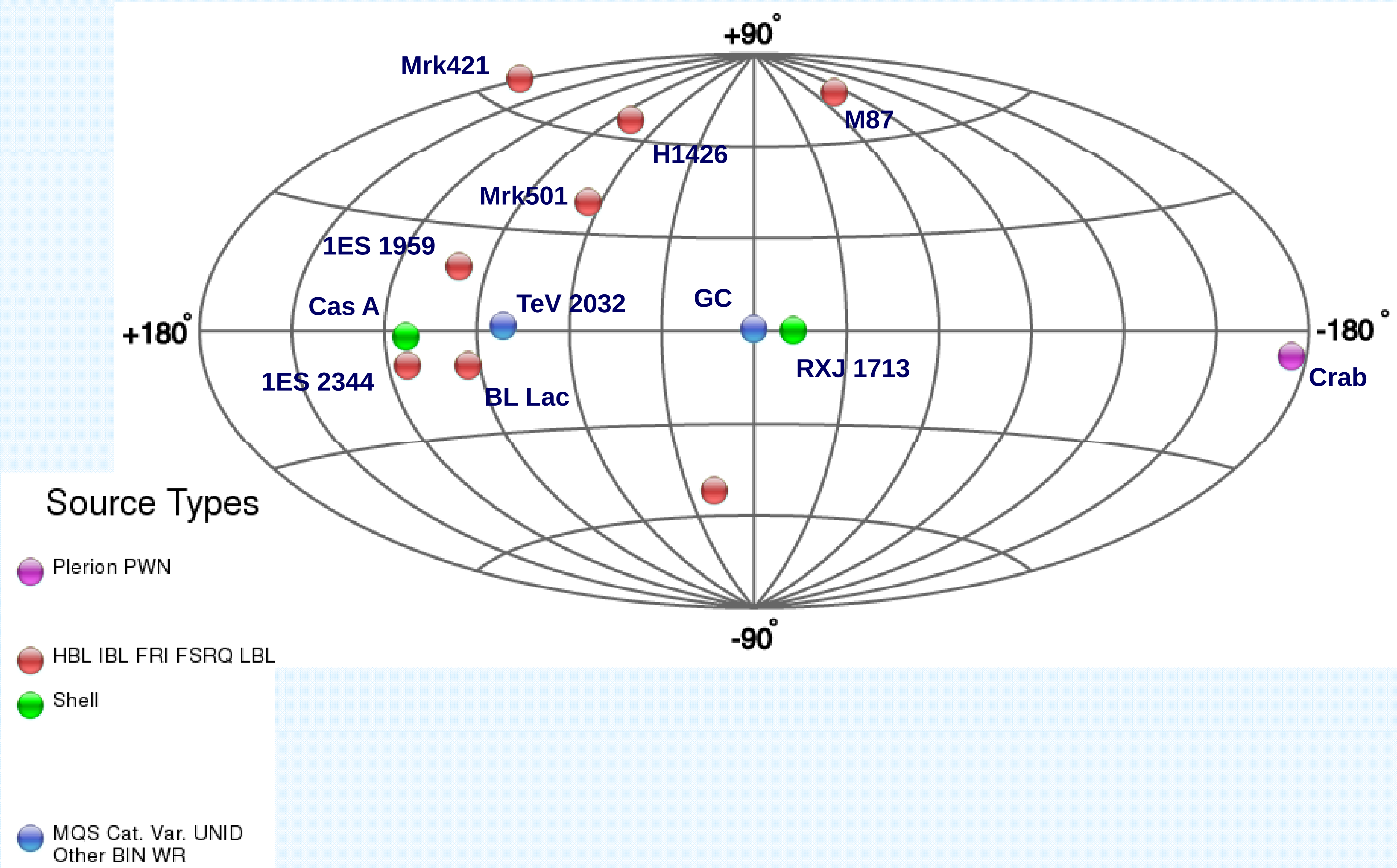
The TeV γ-ray Sky - 1999

4 sources



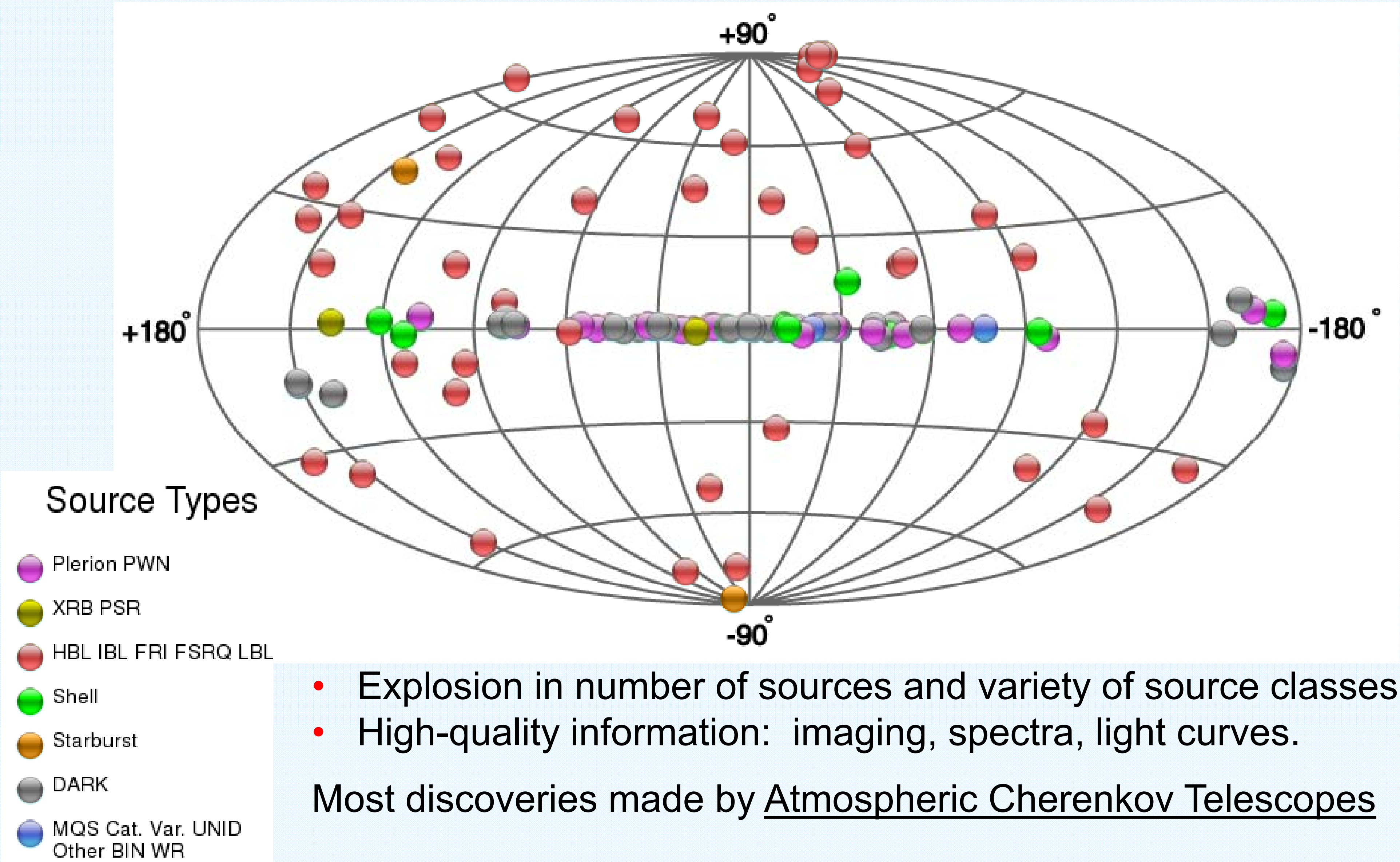
The TeV γ-ray Sky - 2010

13 sources



The TeV γ-ray Sky - 2012

~120 sources

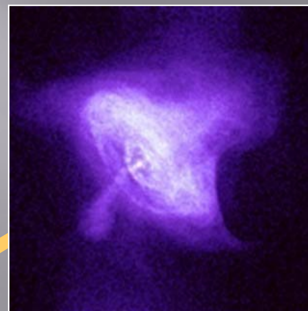


- Explosion in number of sources and variety of source classes.
- High-quality information: imaging, spectra, light curves.

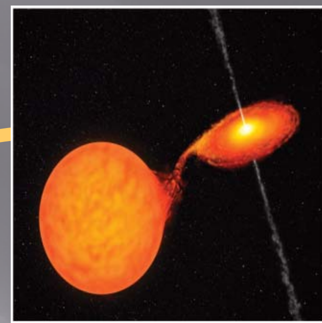
Most discoveries made by Atmospheric Cherenkov Telescopes

Science of VHE γ-ray Astrophysics

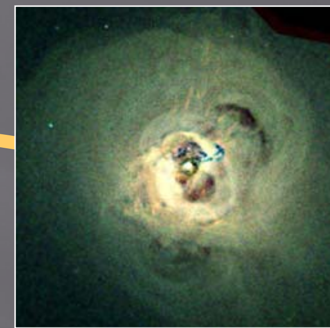
Pulsars



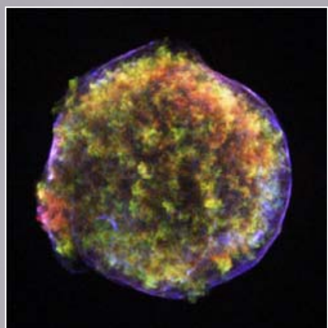
μQuasars



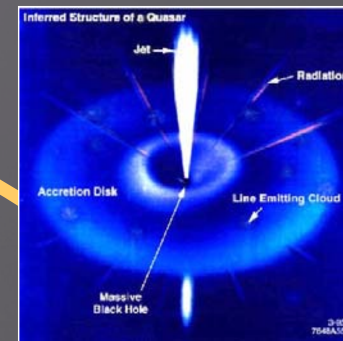
Starbursts



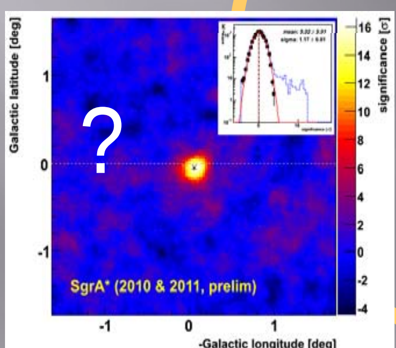
SNRs/CRs

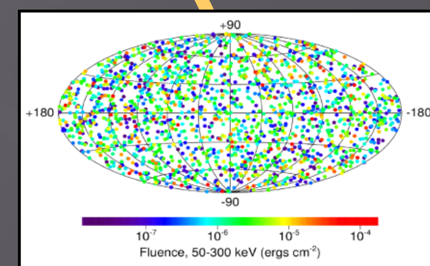


AGN



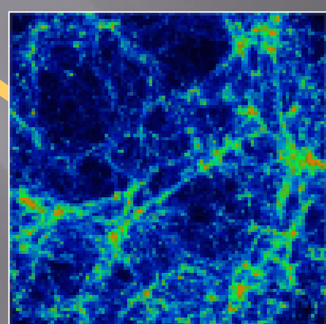
Exploring the non-thermal Universe

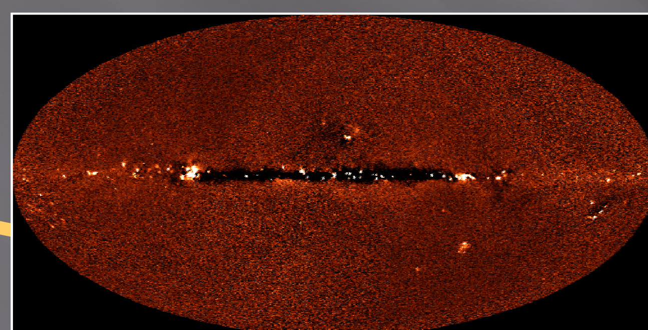


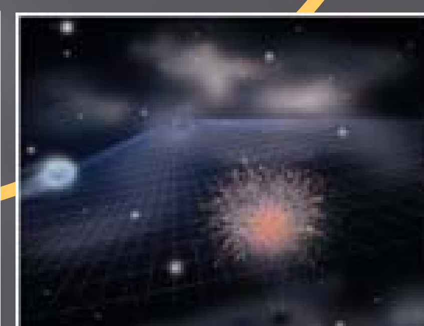


GRBs

UnIDs
Dark Accel.





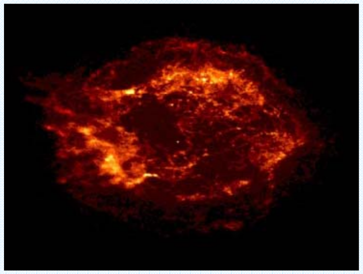


Dark Matter Cosmological Fields PBHs, QGr

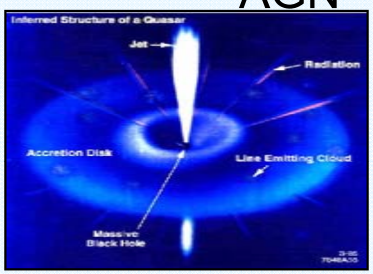
Probing new Physics at GeV/TeV scale

Key Physics Issues

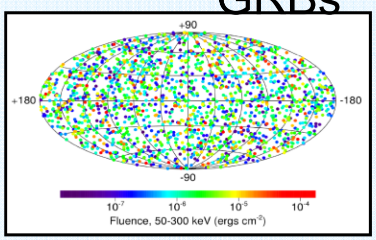
SNR

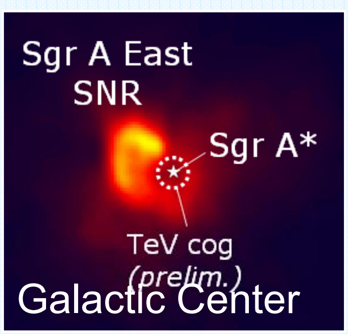


AGN



GRBs





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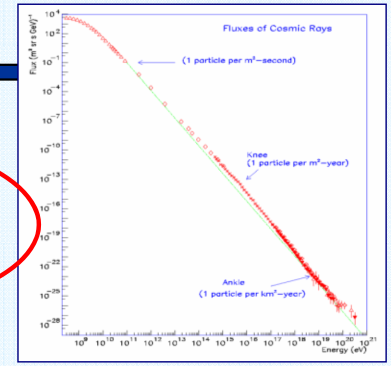
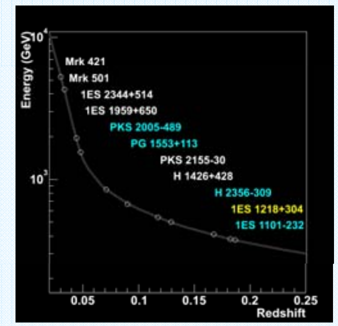
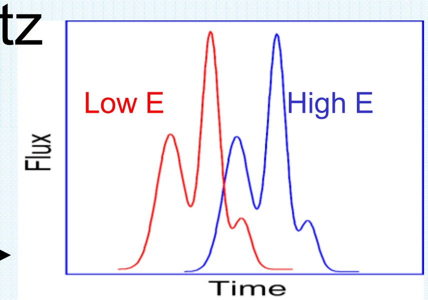
Origin of
cosmic rays



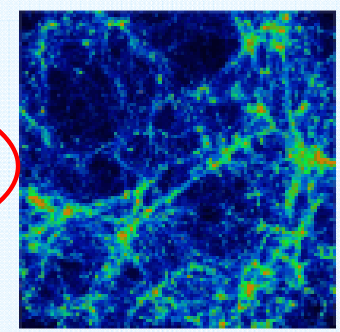
Cosmological
γ-ray horizon



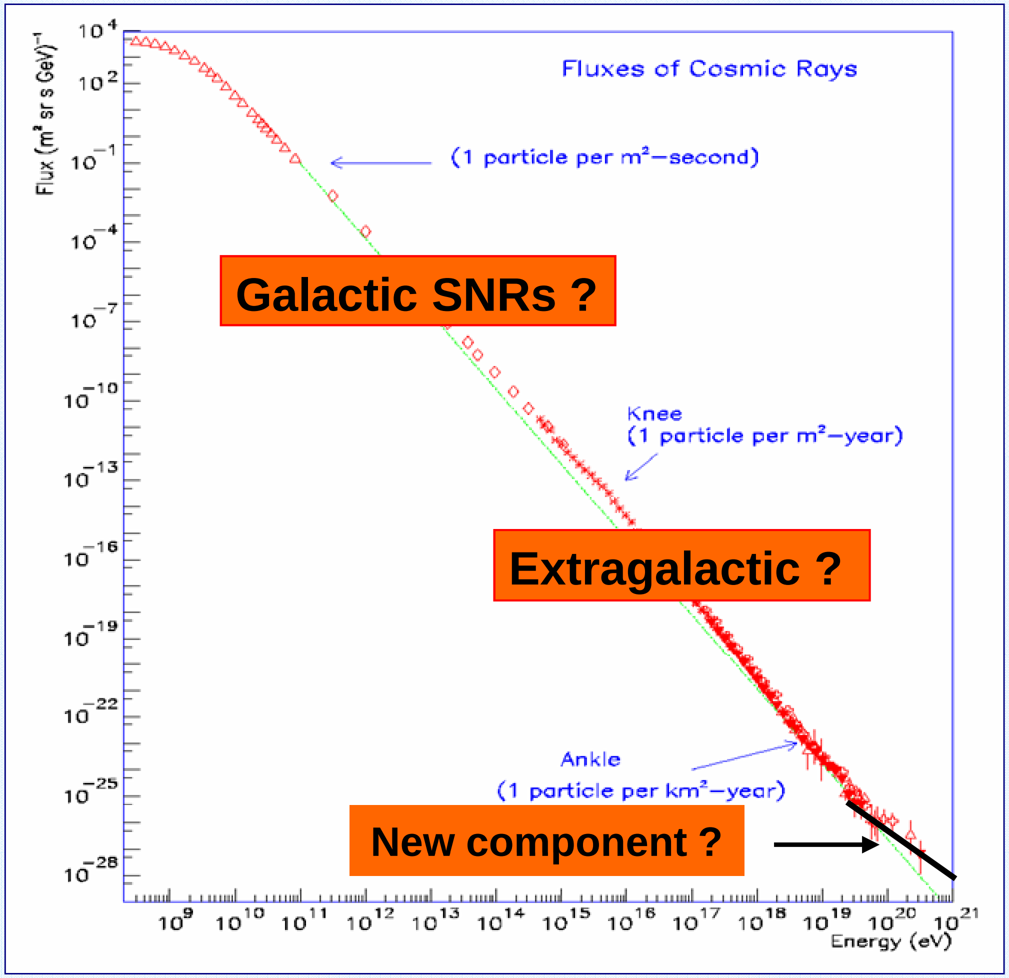
Tests of Lorentz
invariance



Cold dark matter
(WIMP) searches



Origin of Cosmic Rays



Diffuse, all particle spectrum

90 year old mystery !

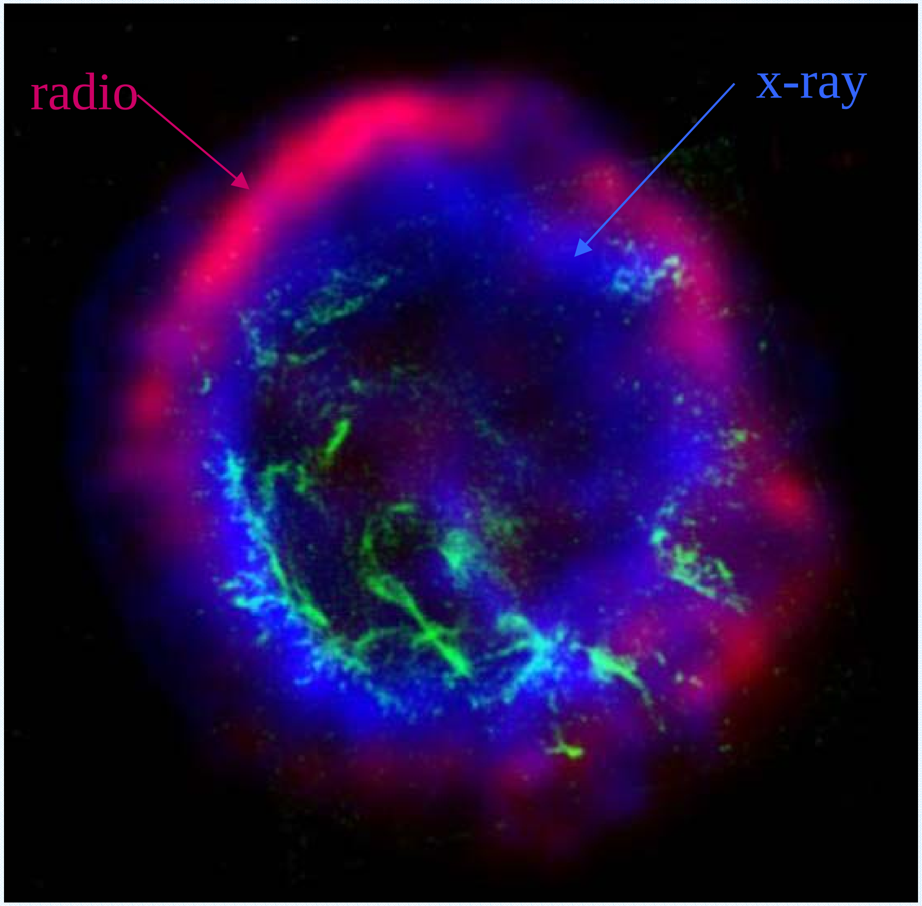
- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm^3

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.
- Acceleration of particles via "canonical" Fermi process – or diffusive shock acceleration.
- In ~ 10^4 yrs, blast wave deccelerates and dissipates.
- SNRs can supply and replenish CR's if $\varepsilon \sim$ 5-10%.
- **Electrons or Protons ?**

Cold Dark Matter

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

- rotation curves of spiral galaxies,
- 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
- Axions
- Weakly interacting massive particles (**WIMPs**).

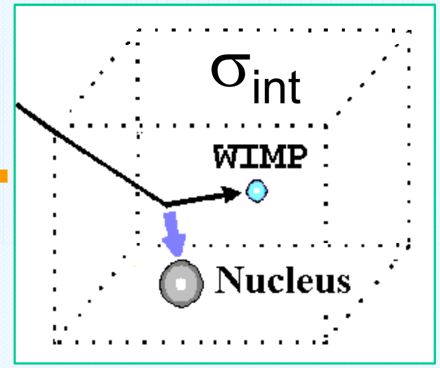
"**WIMP miracle**": present relic density is consistent with expected for a weakly interacting particle & new particle physics is required at the weak scale (EWSB).

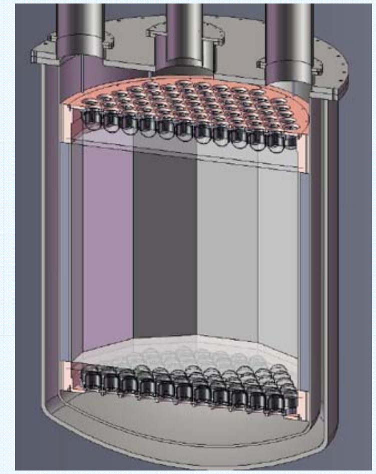
DM Detection: Complementary Approaches

Produce DM particle
in accelerators

LHC at CERN

Direct Detection



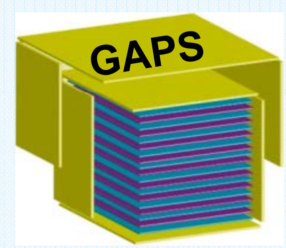


Xenon1T Detector

Astrophysical
Indirect
Detection

Sextens dwarf galaxy

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

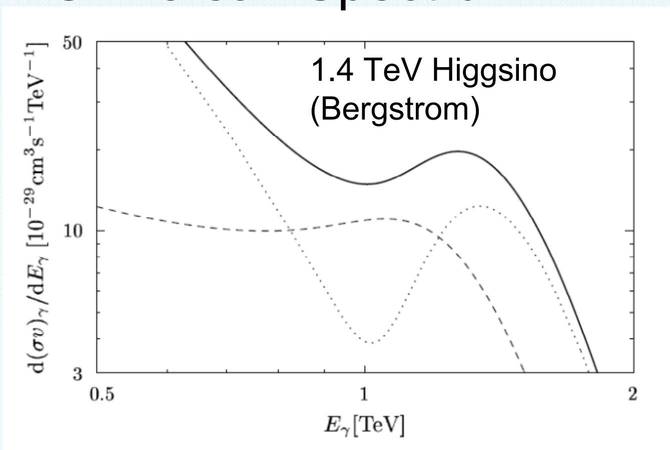


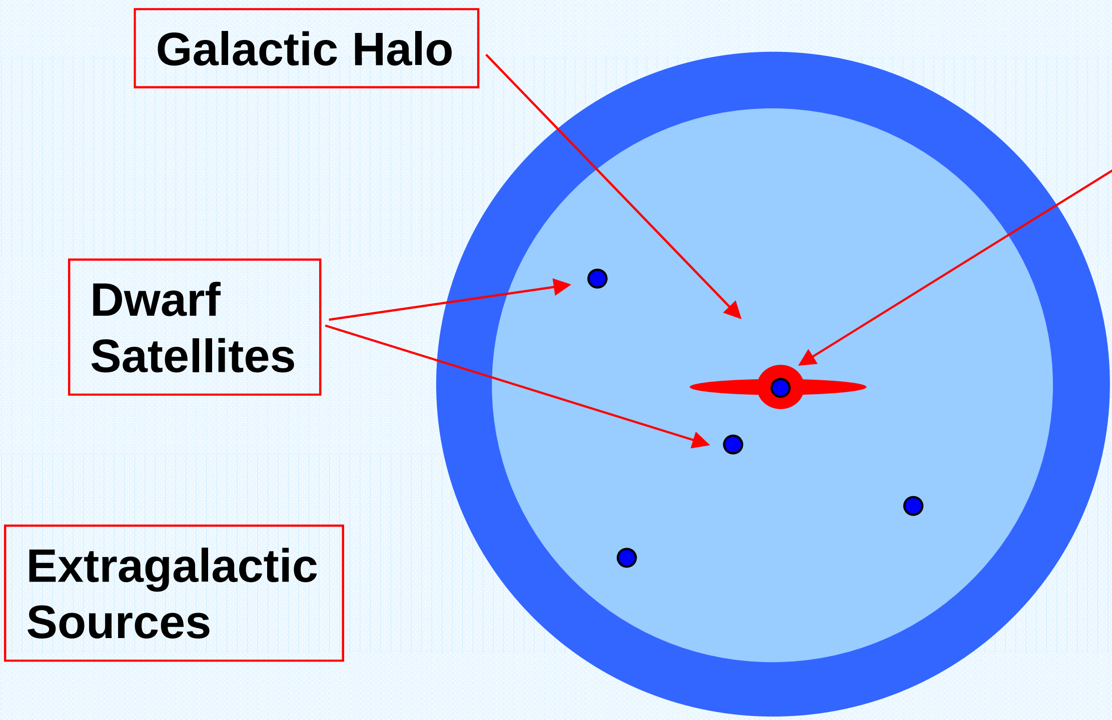
DM Detection via γ-rays

Target regions with:

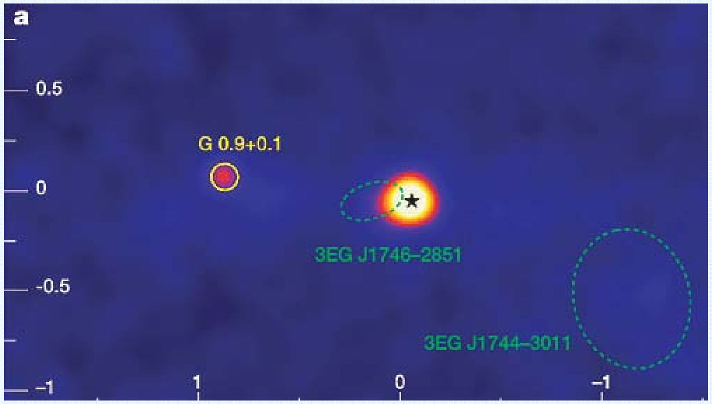
- Favorable DM distributions.
- Large mass/light ratio.

“Universal” Spectrum





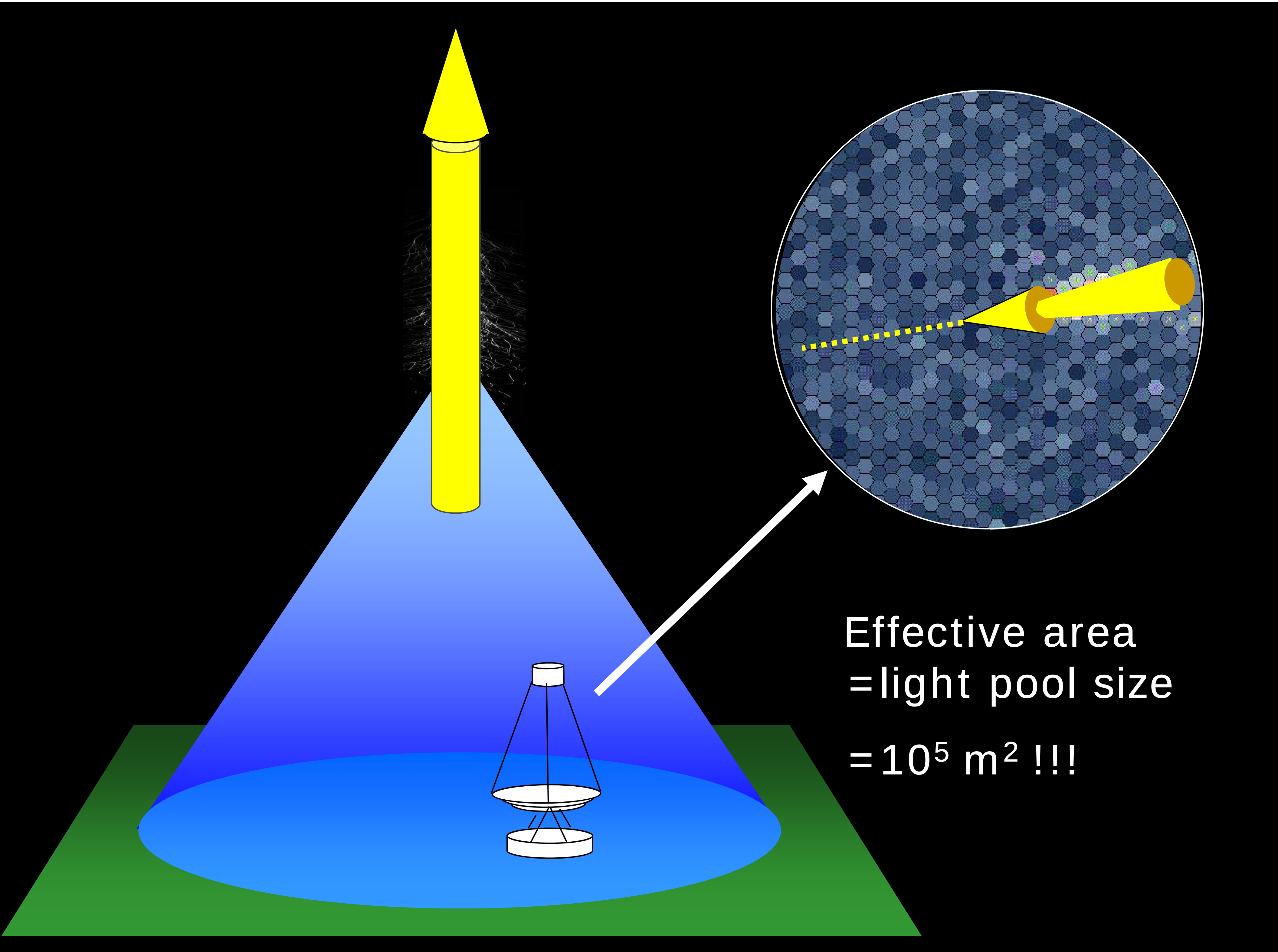
HESS



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 !!!

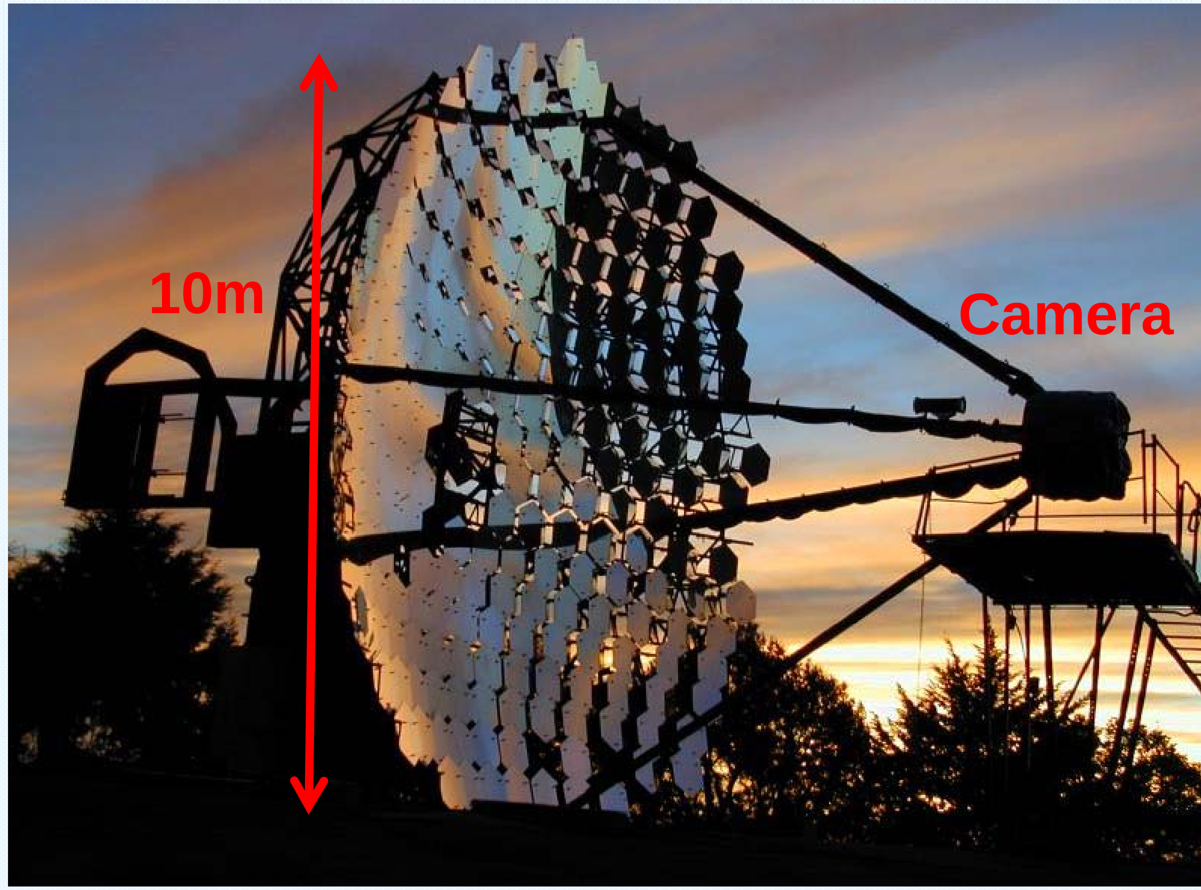
Whipple 10m γ-ray Telescope

- Pioneering telescope (1969-2011).

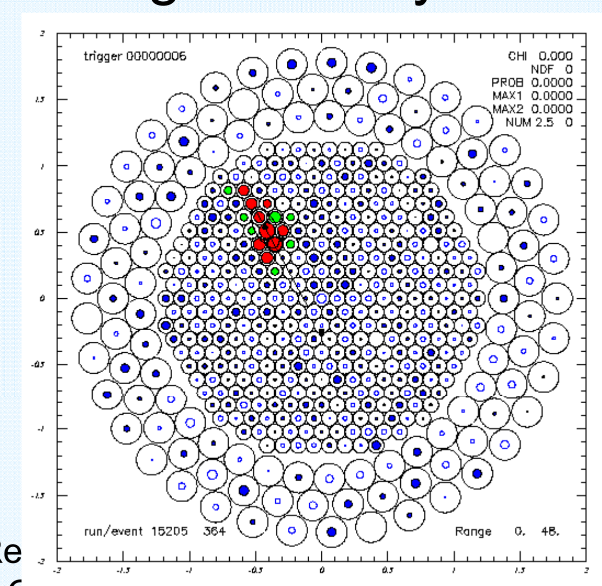
.

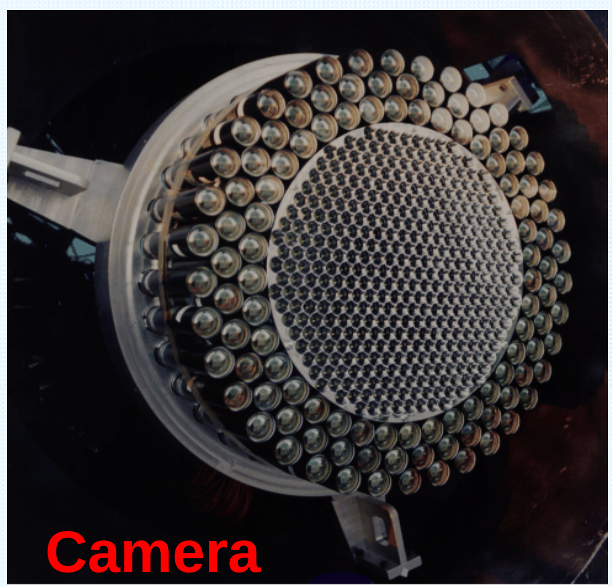
- Used Imaging Technique.

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

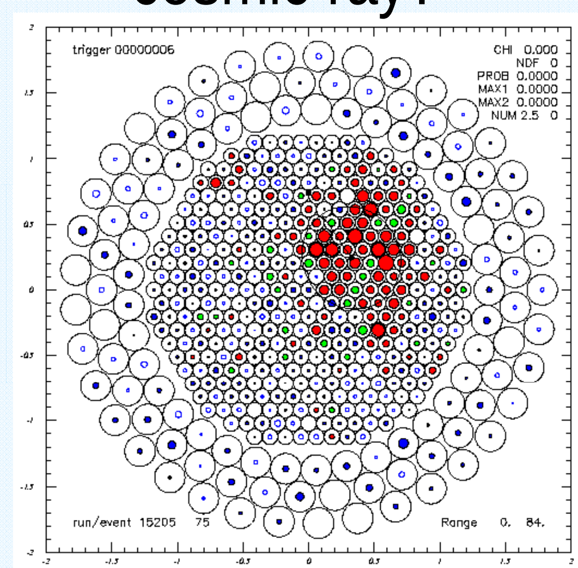


gamma ray?





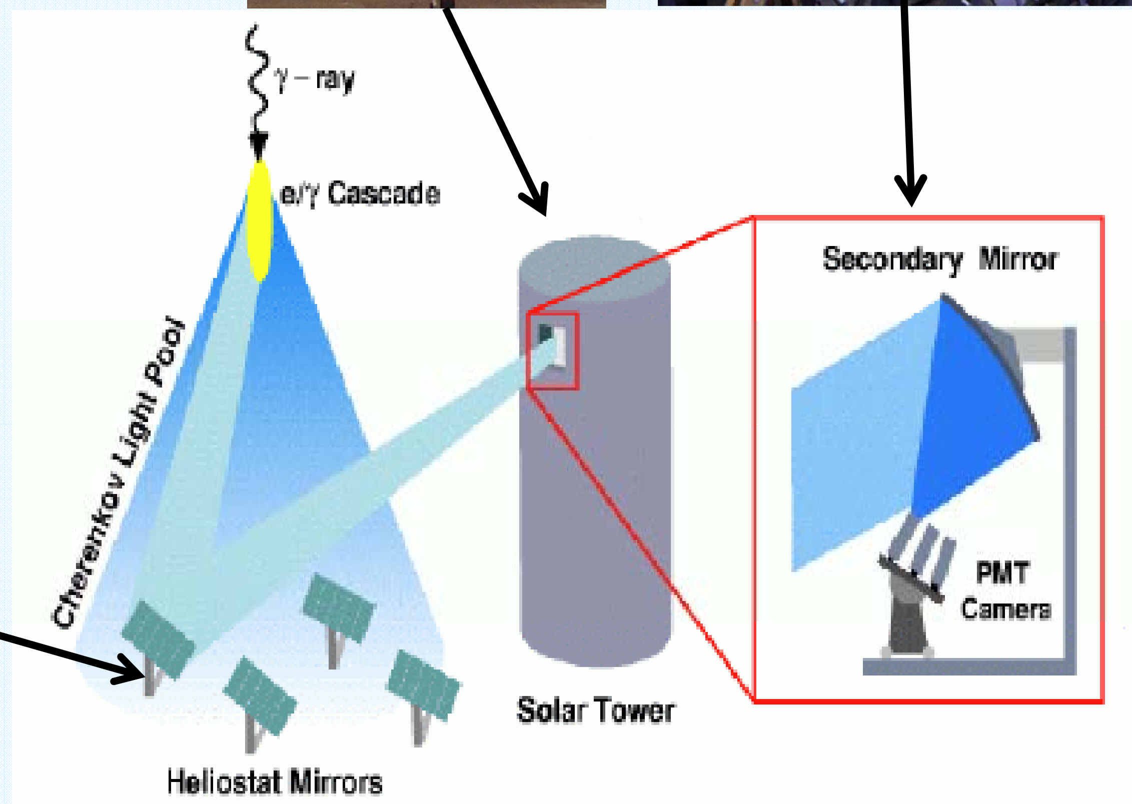
cosmic ray?



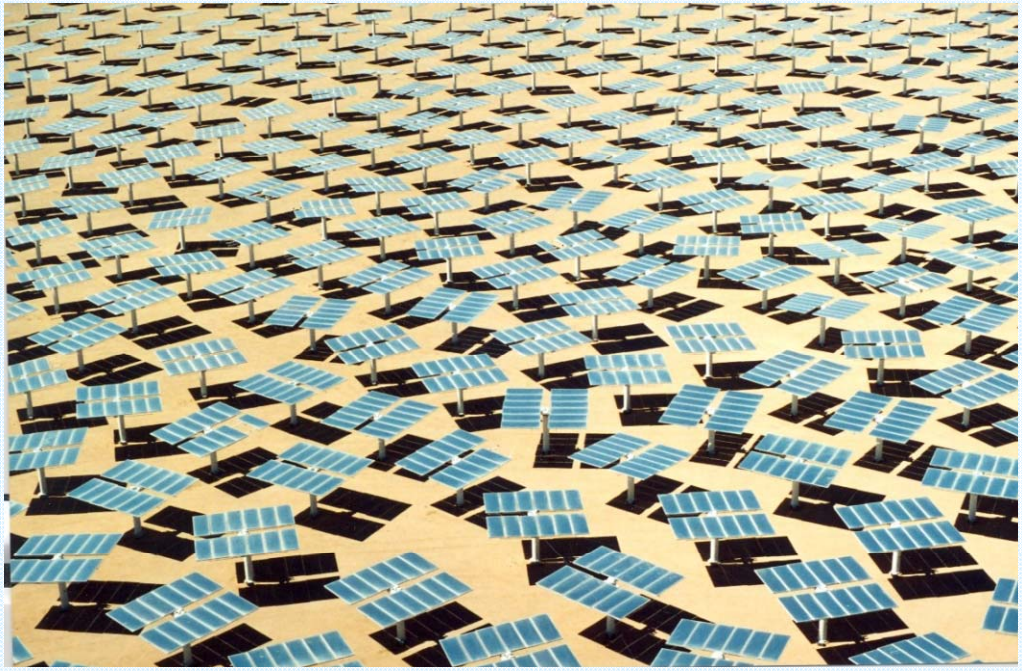
Re

Large Area Cherenkov Telescopes

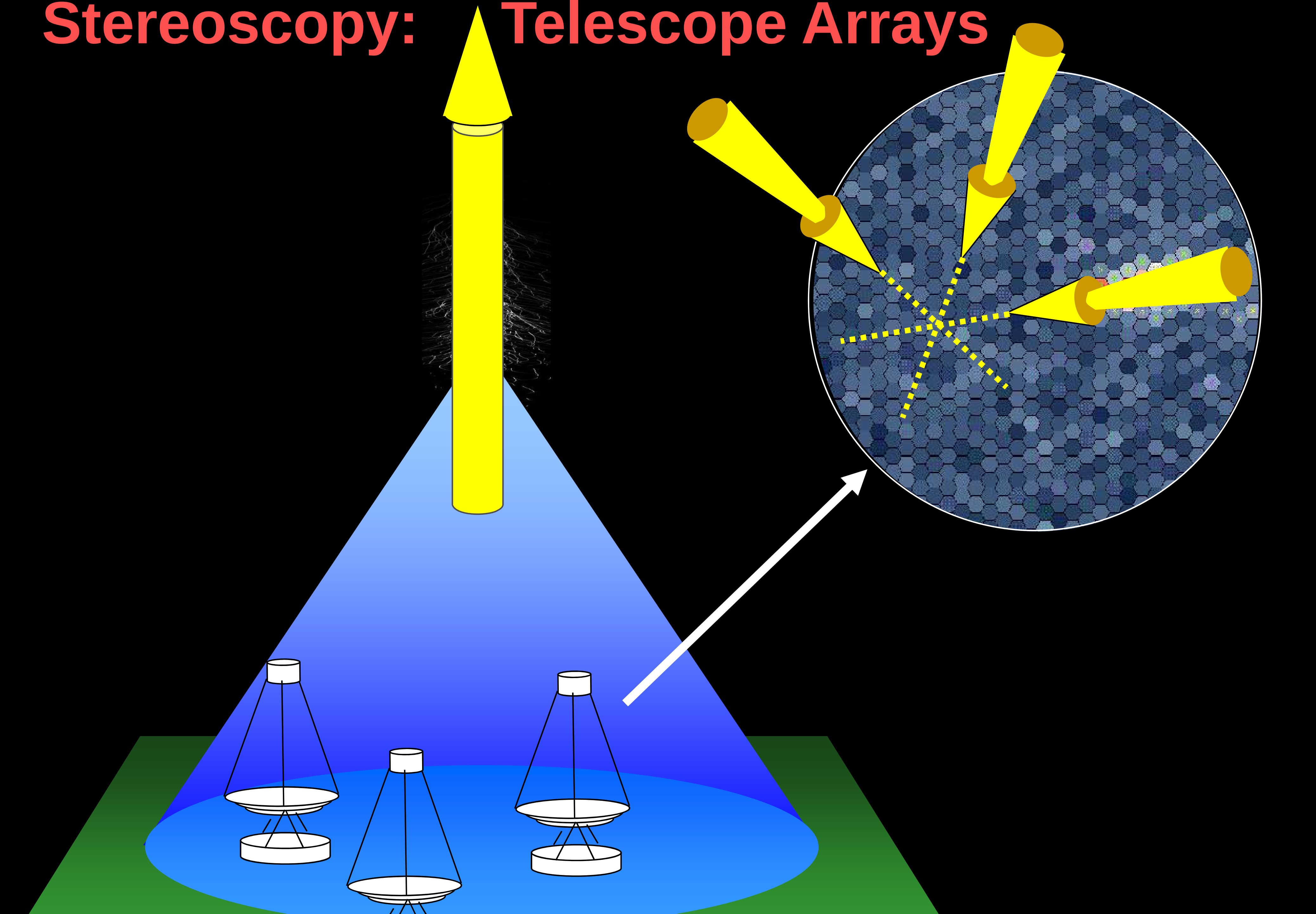
- 1990's: Developed telescopes to sample entire light pool.
- Large array of heliostat mirrors.
- STACEE (NM), Solar 2 (CA), CELESTE (France)



Solar-2 Cherenkov Telescope

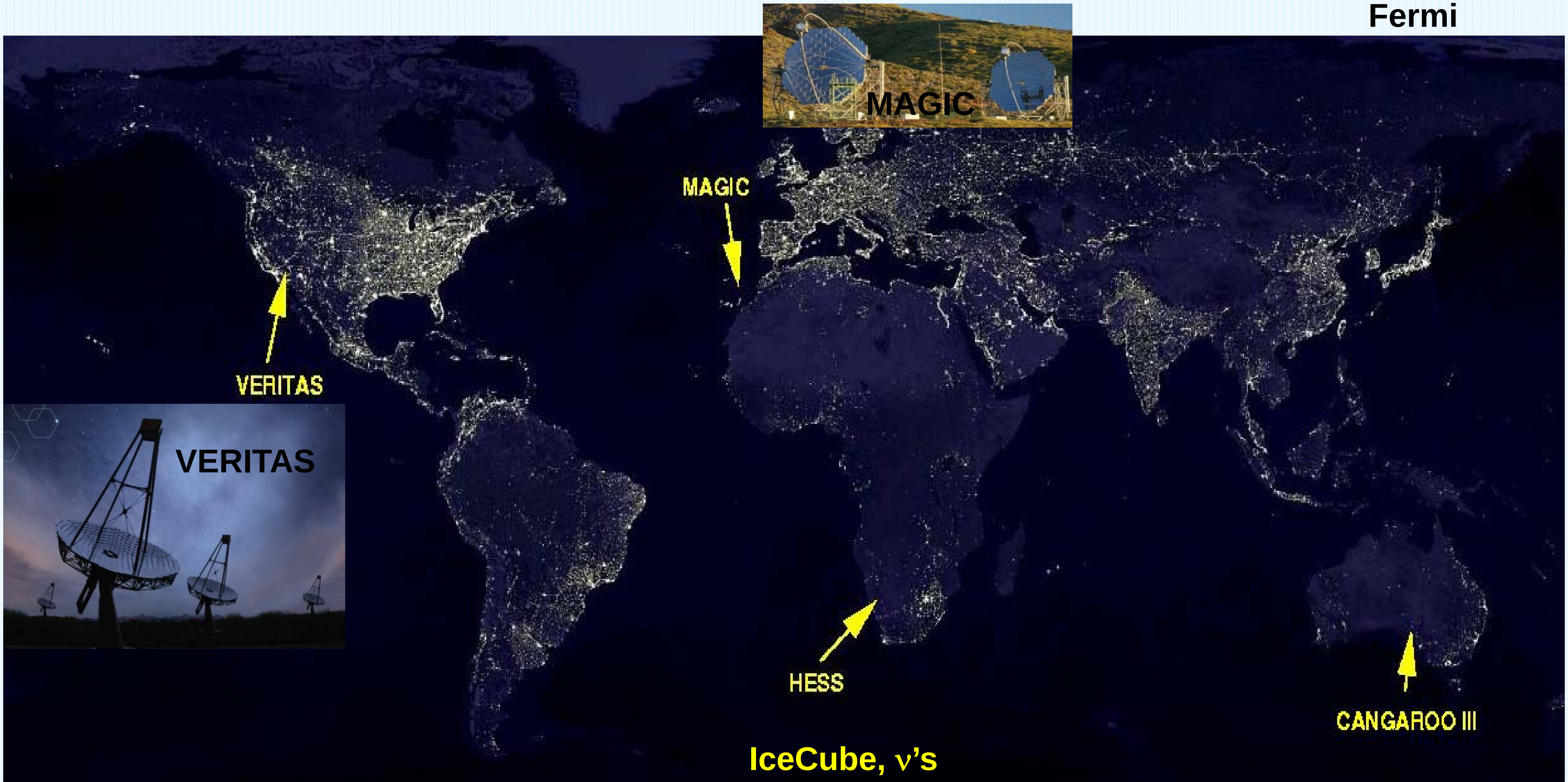


Stereoscopy: Telescope Arrays

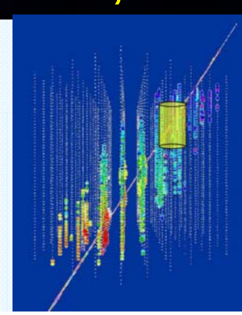


Major VHE Telescopes

Fermi

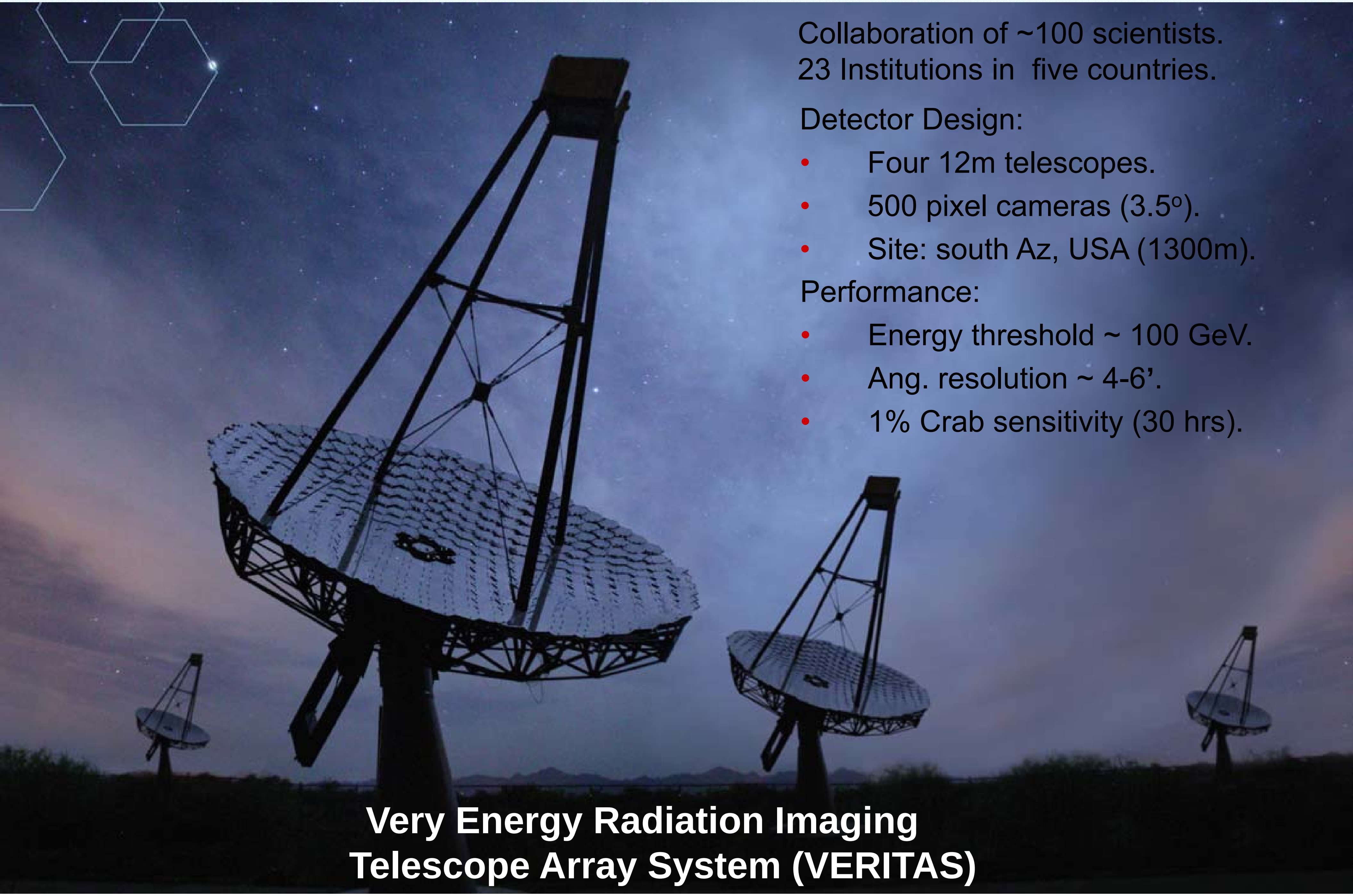


IceCube



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

Collaboration Mtg.
July 2011, McGill University

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

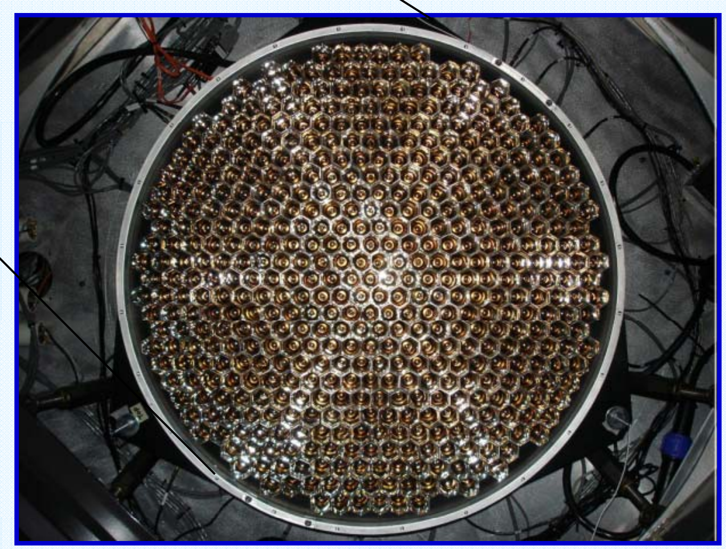
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

+ 25 Associate Members

A VERITAS Telescope

12m reflector, f1.0 optics

350 Mirror Facets



500 pixel Camera

Working @ VERITAS

- VERITAS is a collaboration of ~100 scientists, evenly distributed between faculty, postdocs, grad. students.
- Typical grad. student time is ~4 yrs of research work on VERI
- All m / own group cellent hand
- We b and all of ou
- A lot iki page

Latest VERITAS Results

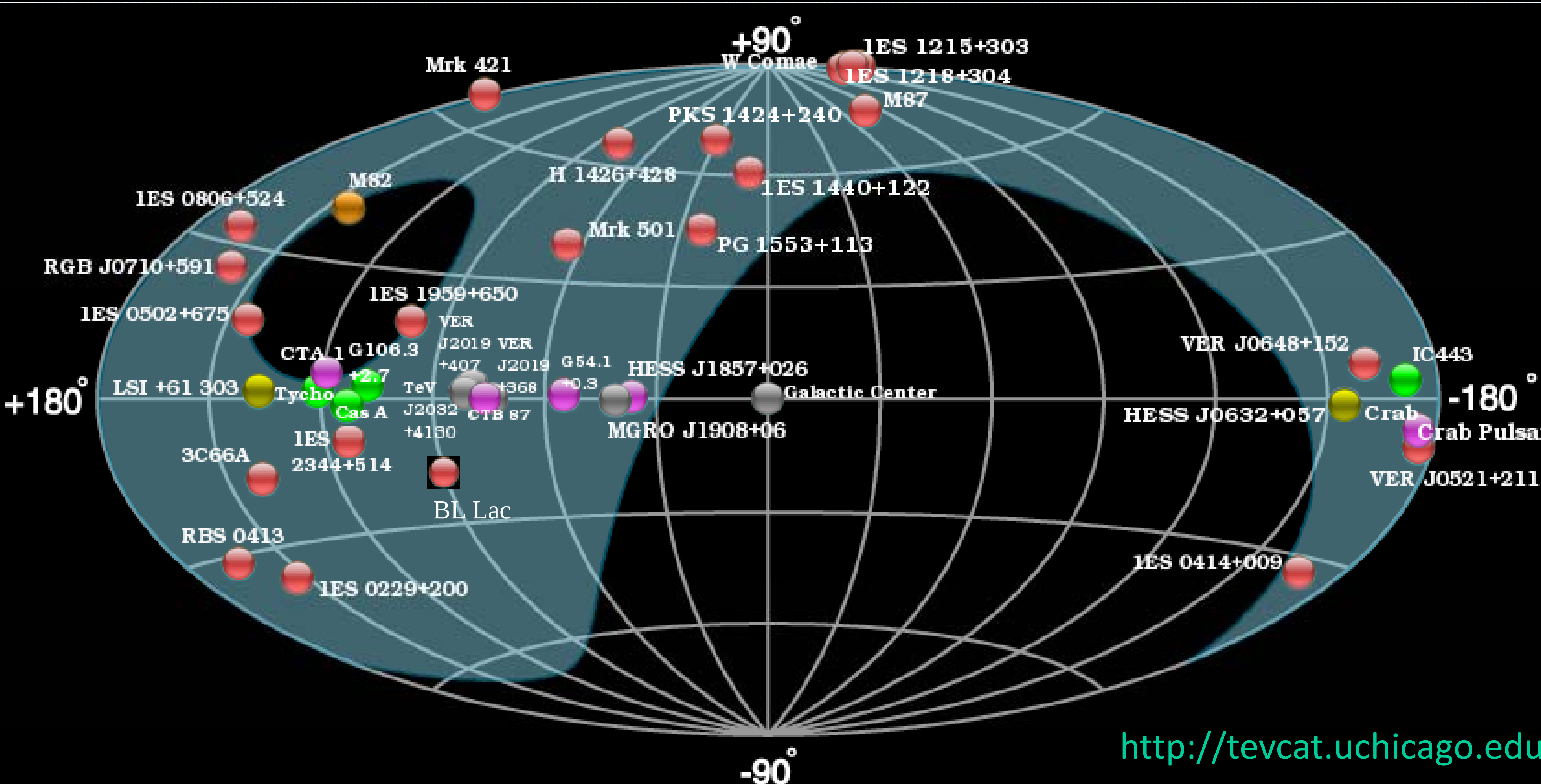
Dark Matter

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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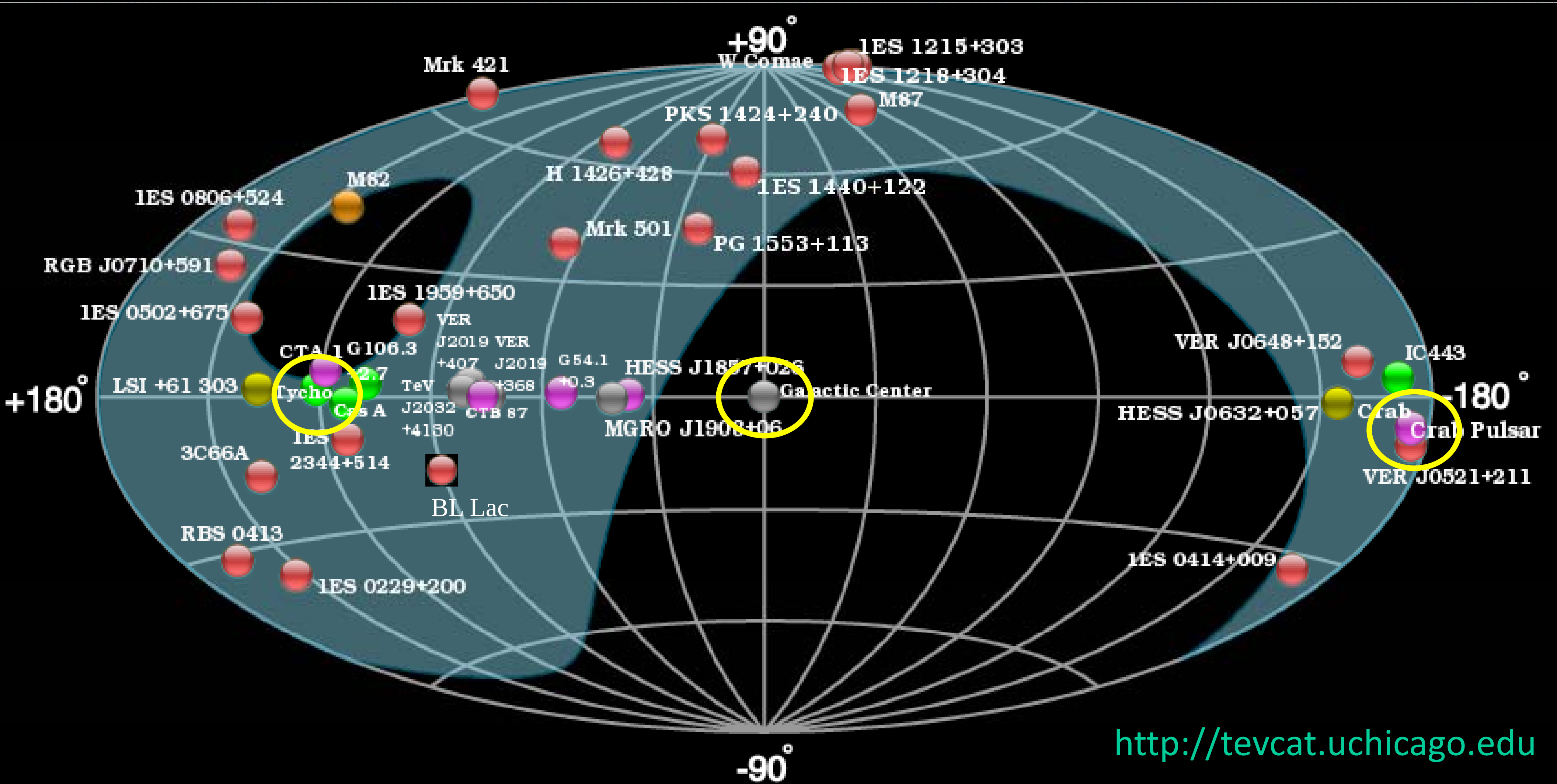
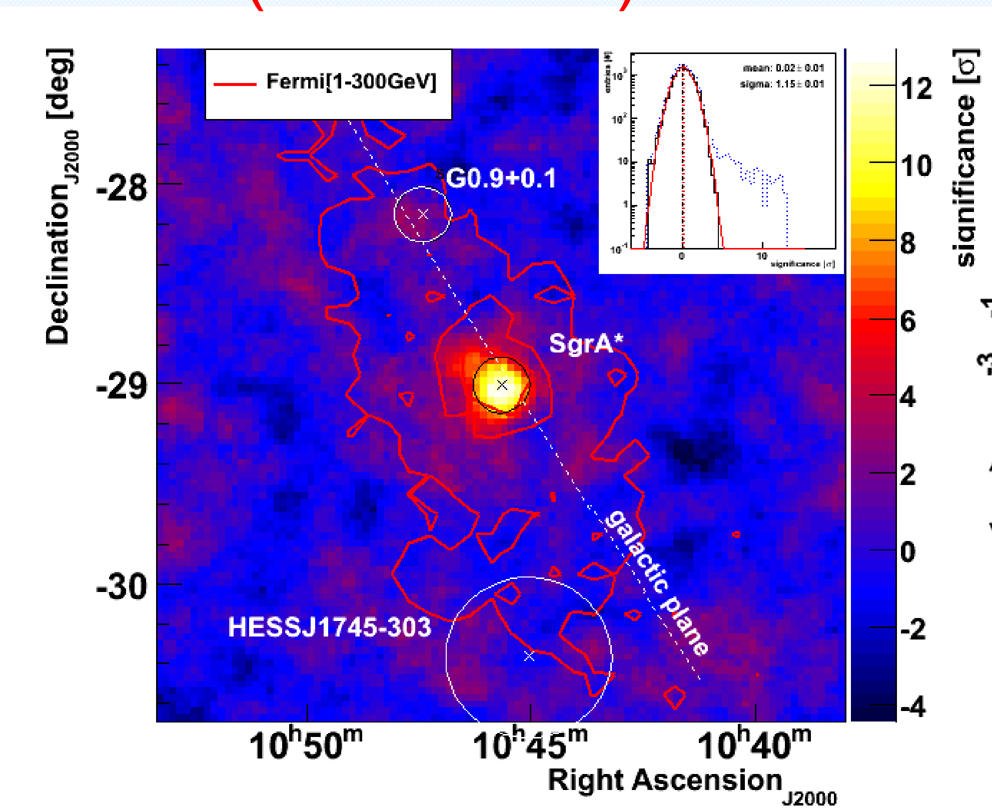


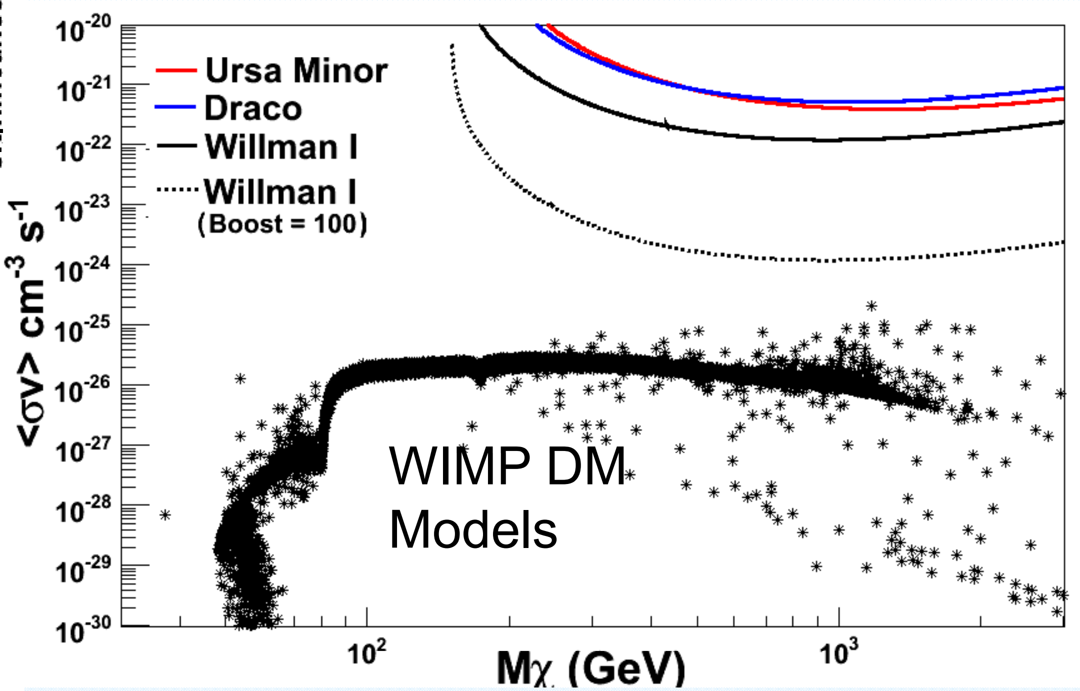
VERITAS DM Searches

Galactic Center
(brand new!)



Dwarf Spheroidal Galaxies

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

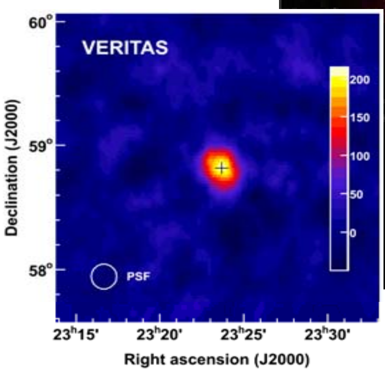


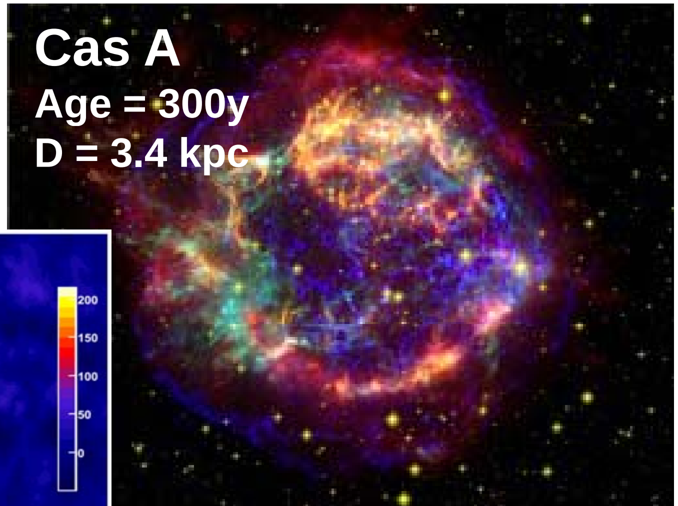
Strong detection by VERITAS, but interpretation is still unclear; strong astrophysical source present.

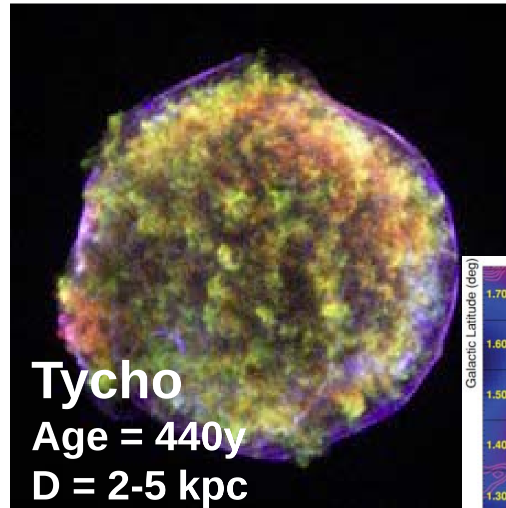
Limits, based on moderate observations, do not yet rule out any models.

VERITAS Supernova Remnants

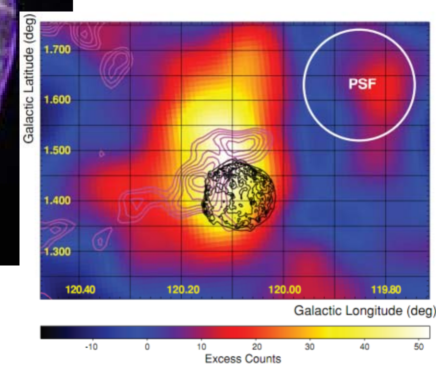
Cas A
~3% Crab



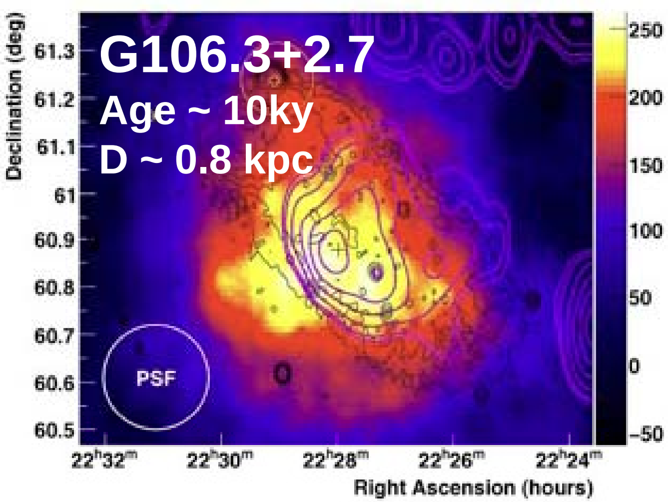




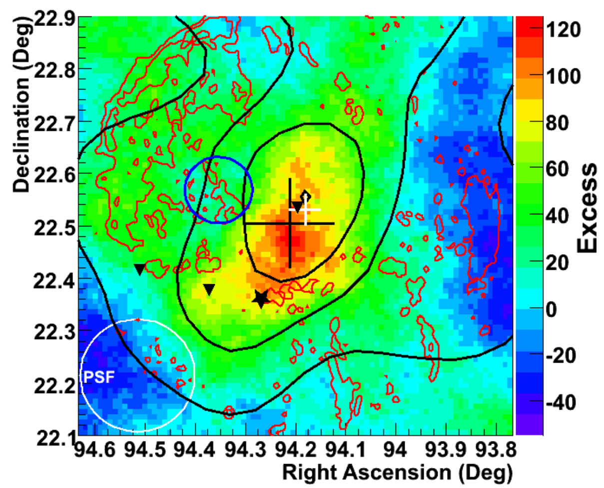
Tycho
~1% Crab

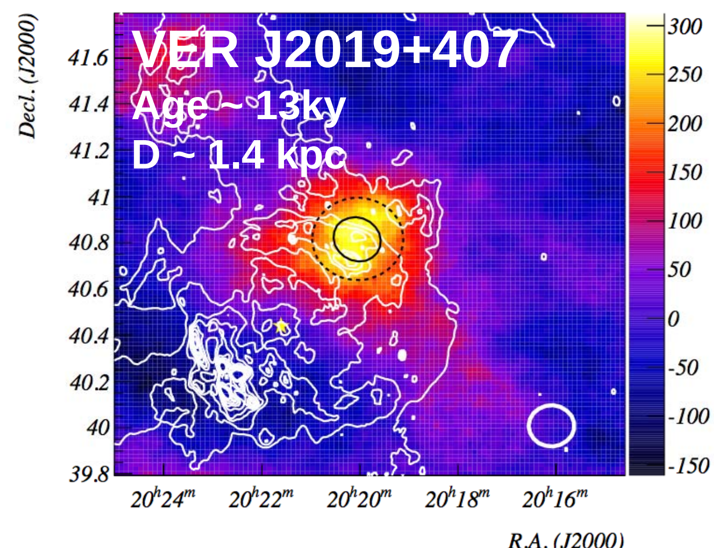


IC 443
Age ~ 30ky
D ~ 0.8kpc



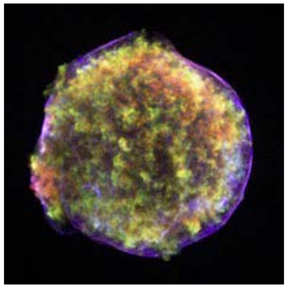
Boomerang

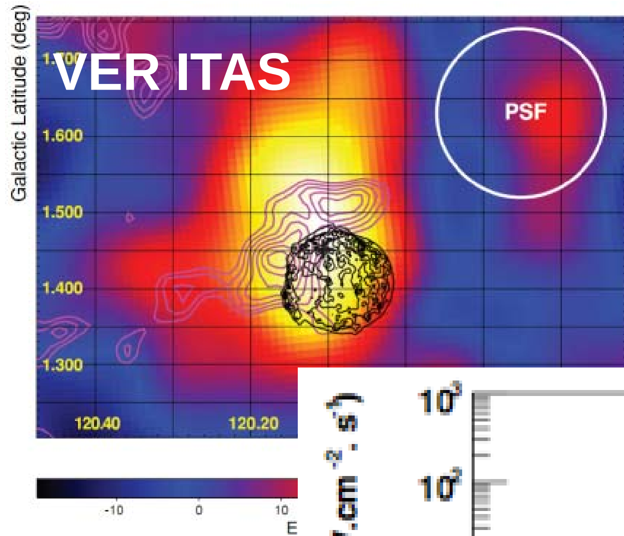




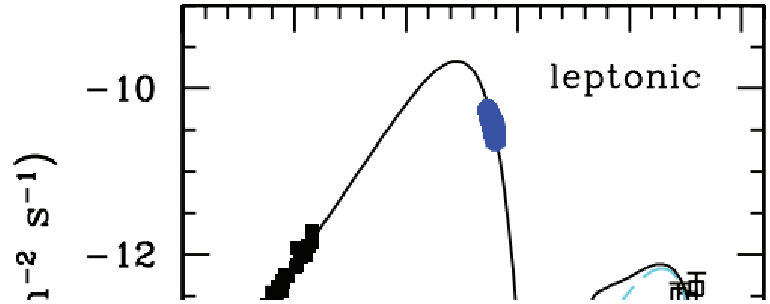
γ-Cygni

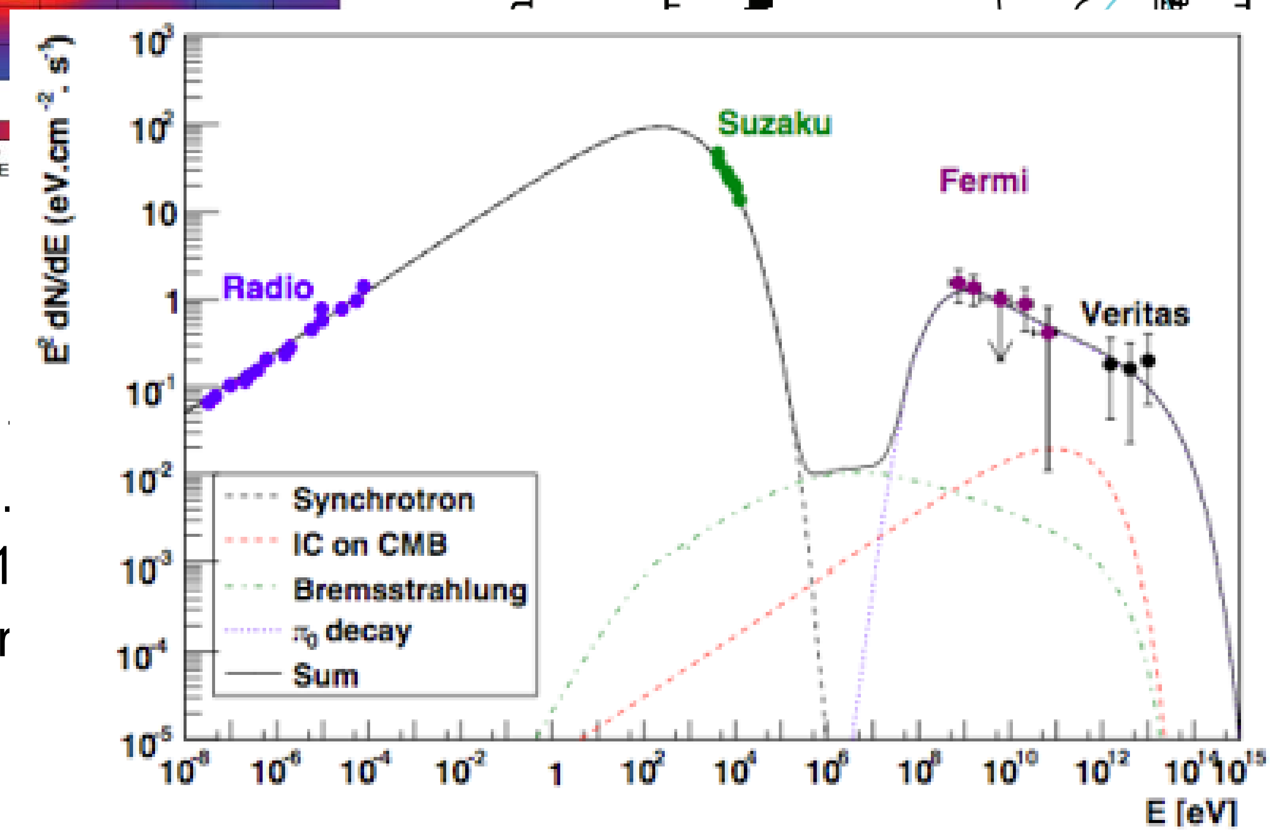
Tycho's SNR: VERITAS Discovery





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





Tycho's SNR:

- Historical Type 1a SN of 1
- X-ray morphology argued acceleration (Warren et al.
- VERITAS discovery in 201
- Consistent with leptonic or
- Combination of VERITAS for hadronic acceleration.

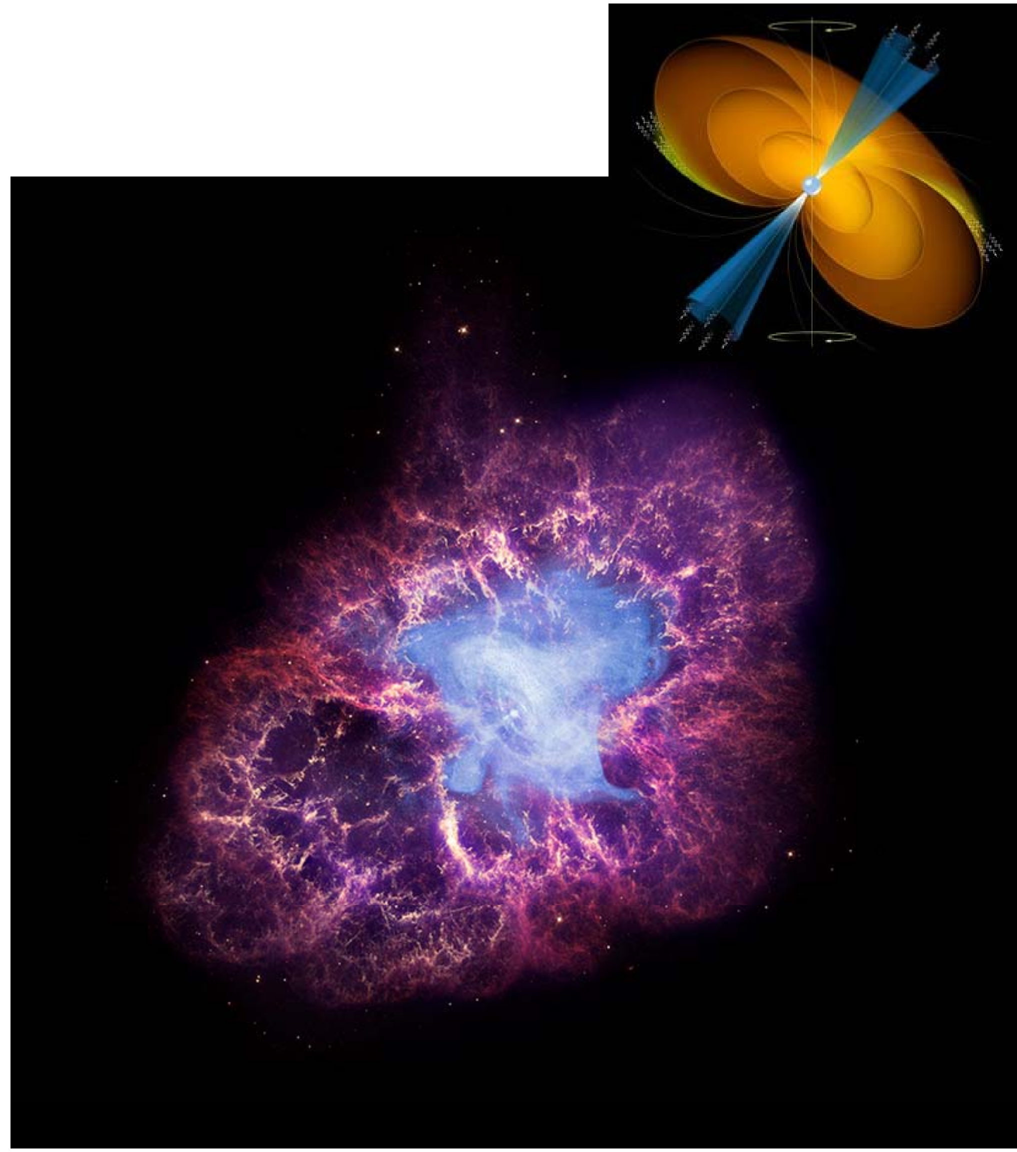
Crab

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

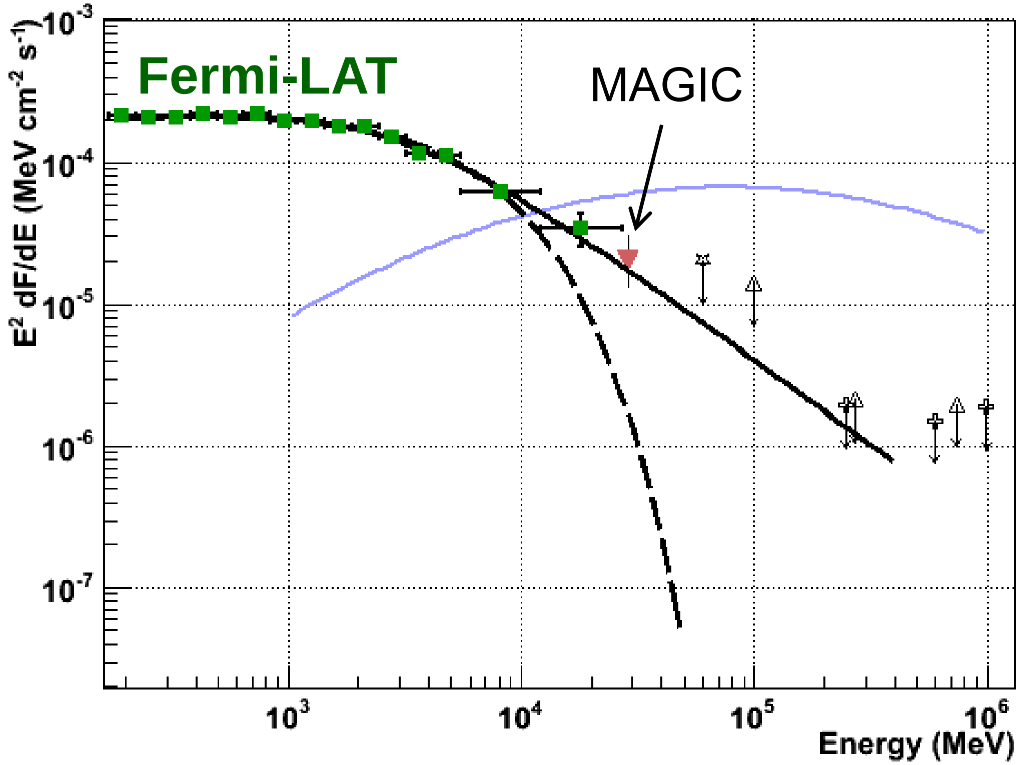
- **Fermi-LAT (first EGRET):** exquisite measurements around spectral break near few GeV.
- **MAGIC:** detection at 25 GeV and hint at 60 GeV.
- Numerous, constraining limits from **many VHE experiments**.
- 30-year effort to detect at VHE.



Crab Pulsar at HE and VHE

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

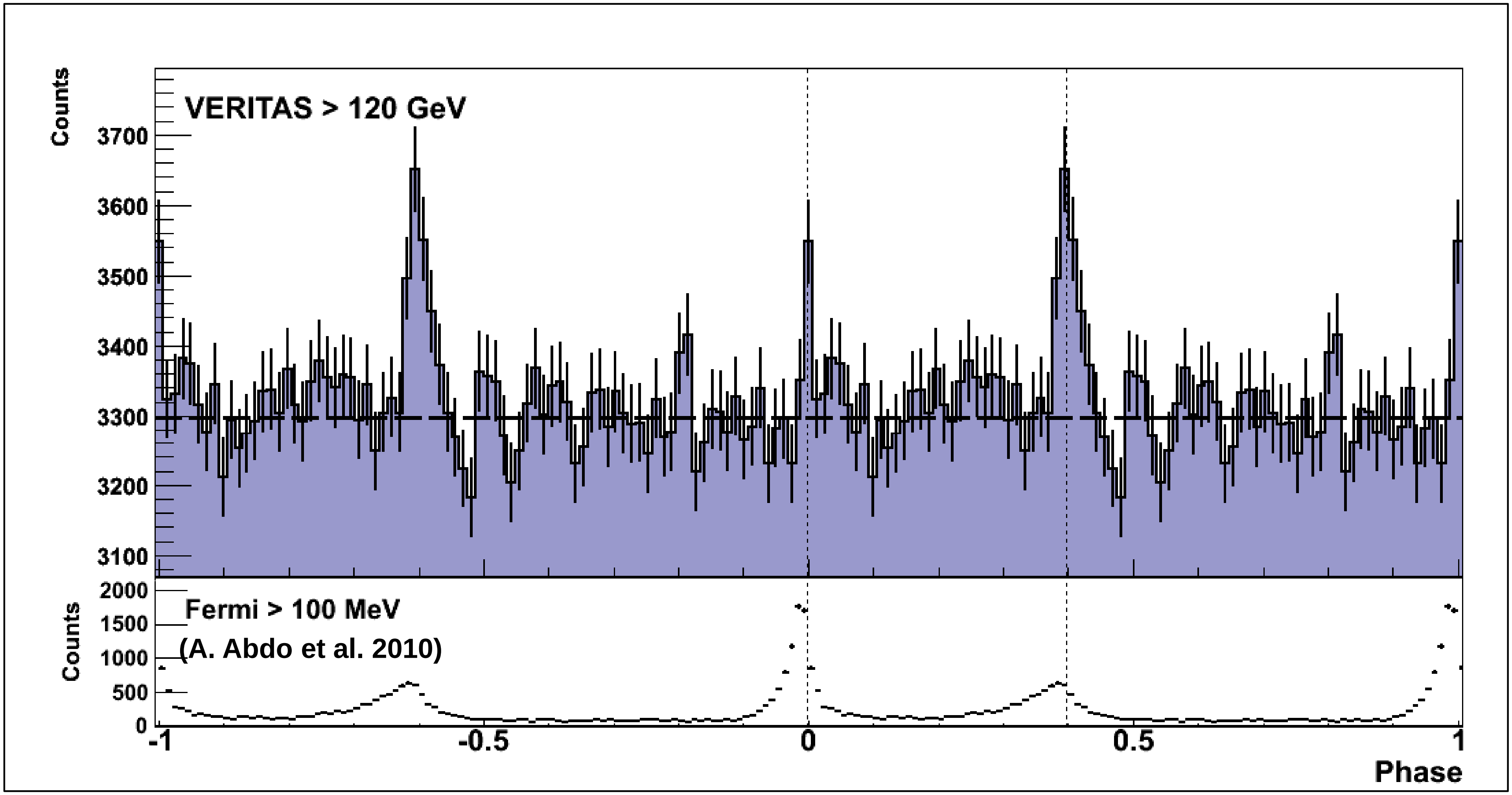
- Special trigger to lower E_{th}.
- Similar pulse profile to EGRET.
- Exponential E_{cutoff} ~ 18 GeV.
- Rule out polar cap model.



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.

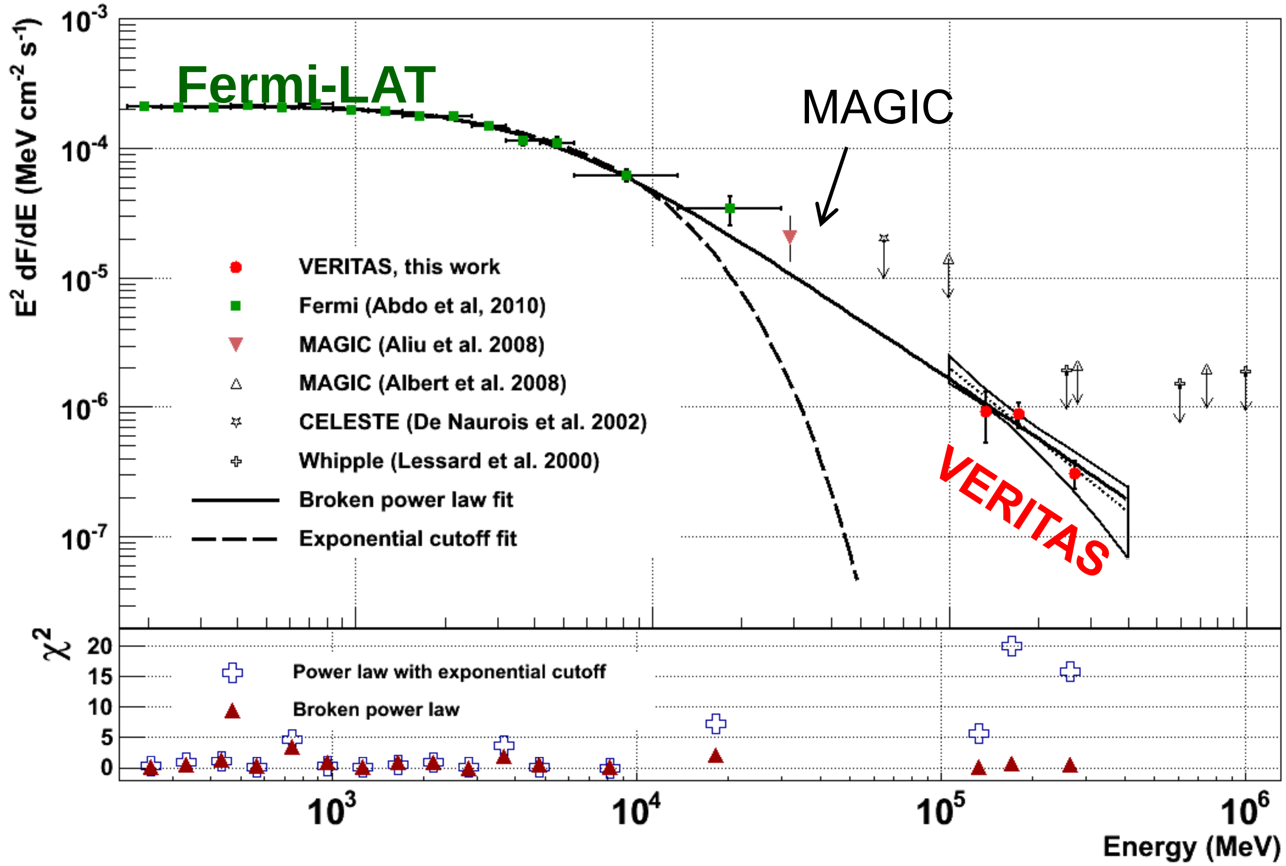
VERITAS Result: Detection !



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

E. Aliu et al.,
Published in Science (2011)

The New Picture of the Crab Pulsar



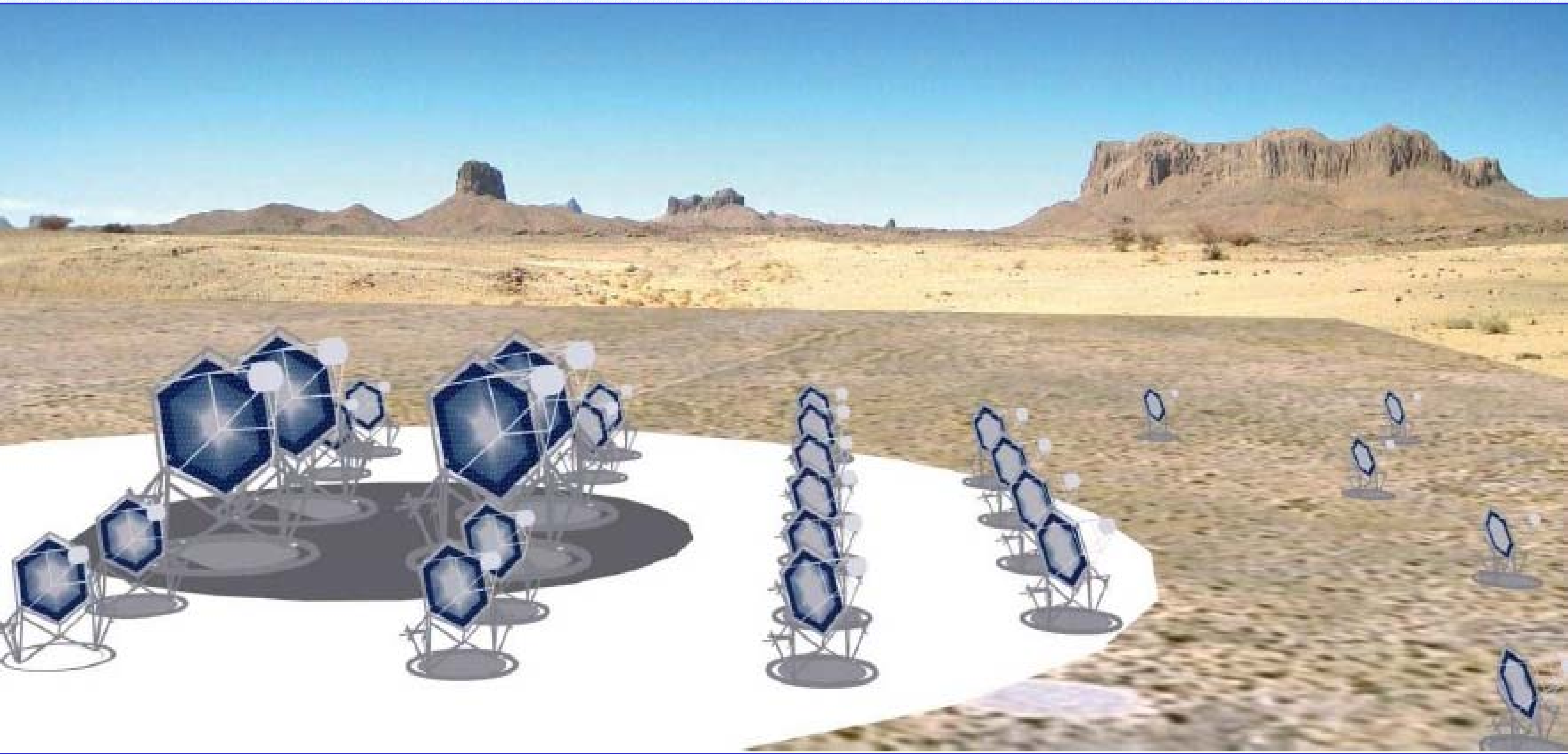
- **First detection of a pulsar above 100 GeV – new astrophysics**
- VERITAS detection → emission region > 10 stellar radii.
- Narrowing of pulses → tapered acceleration region ?
- Competitive limits on LIV – stay tuned.

NSF Press release:

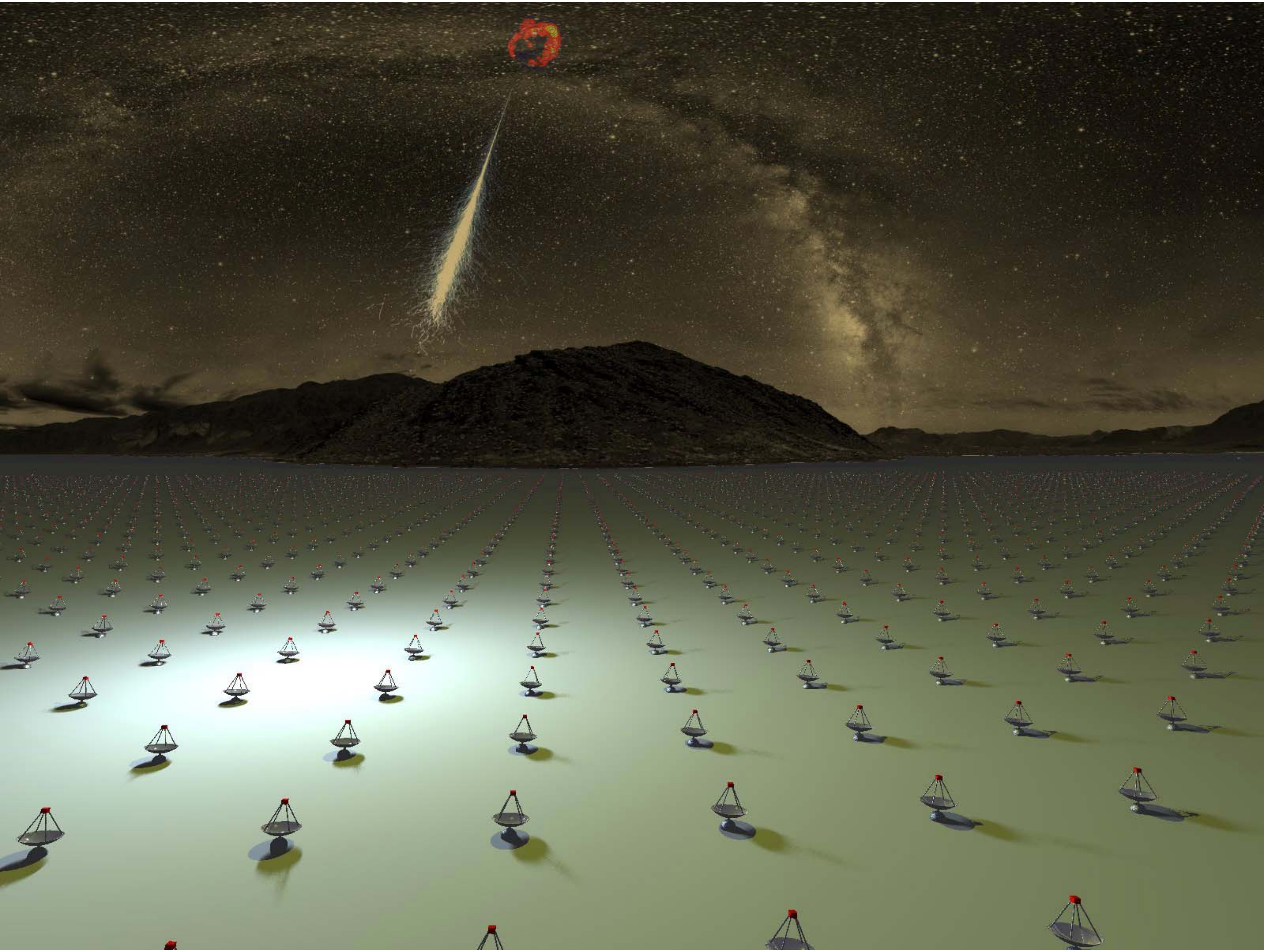
http://www.nsf.gov/news/news_summ.jsp?cntn_id=121926&org=MPS&from=news

The Future

Cherenkov Telescope Array

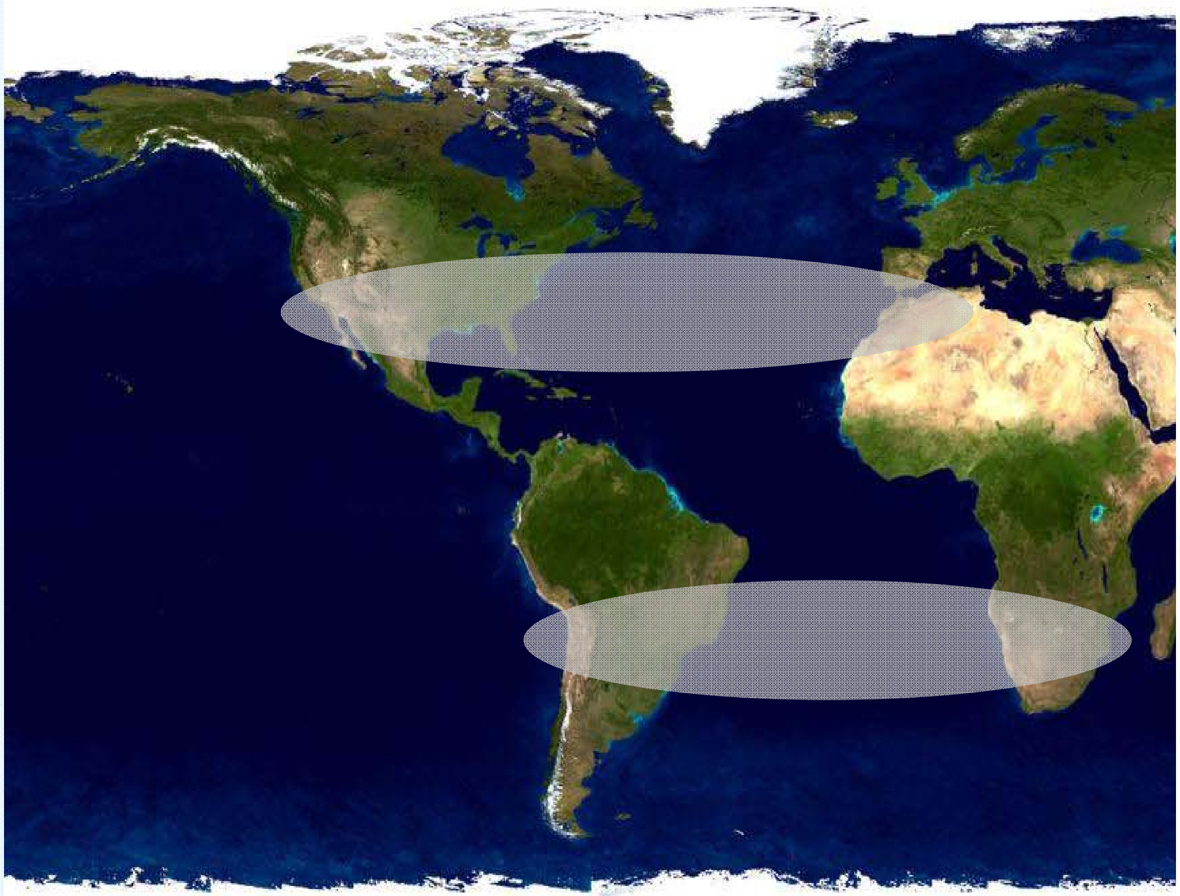


- Factor of ten more sensitive than VERITAS.
- Two sites: South (3km x 3km), North (1km x 1km).
- 40-80 Telescopes per site.



Cherenkov Telescope Array

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



Two candidate sites in N. Arizona
Coconino, Yavapai Counties

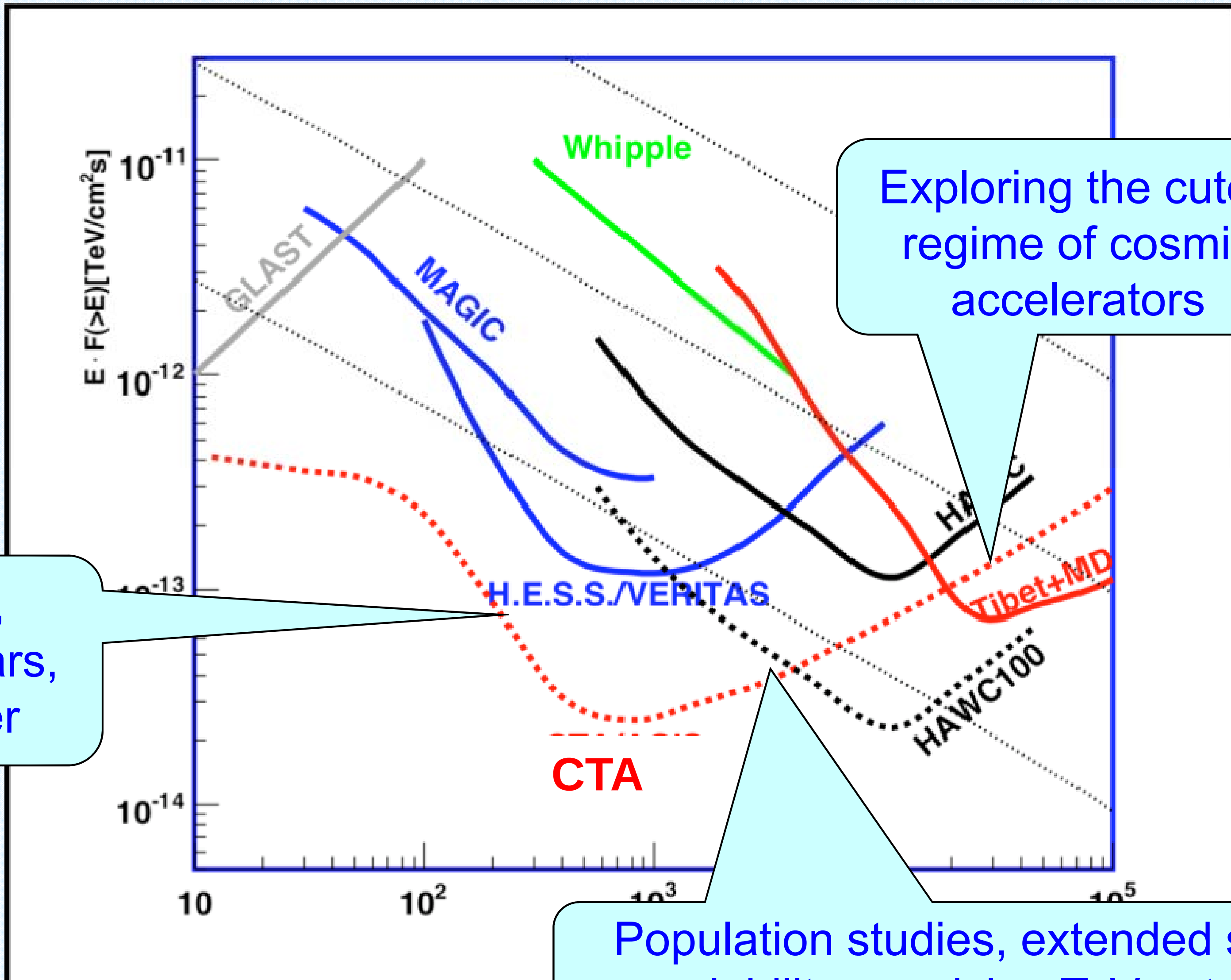
Northern Array

- → 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

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 the world's best VHE telescope 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)**