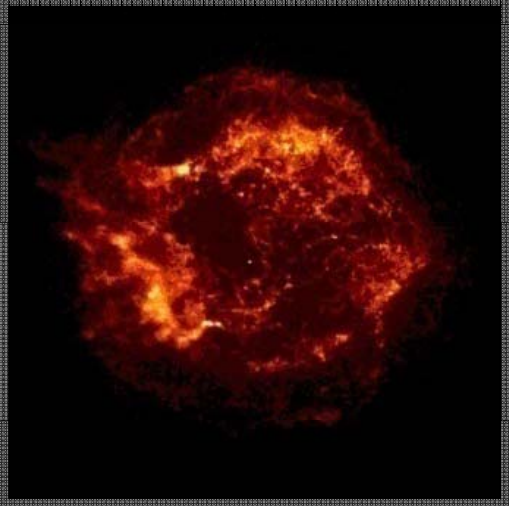
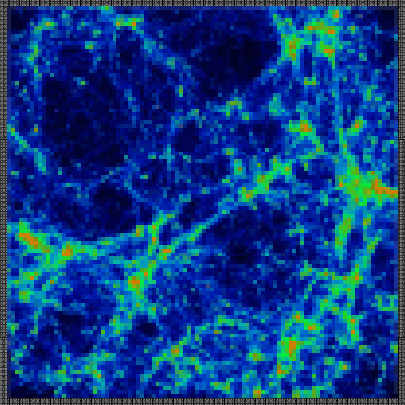
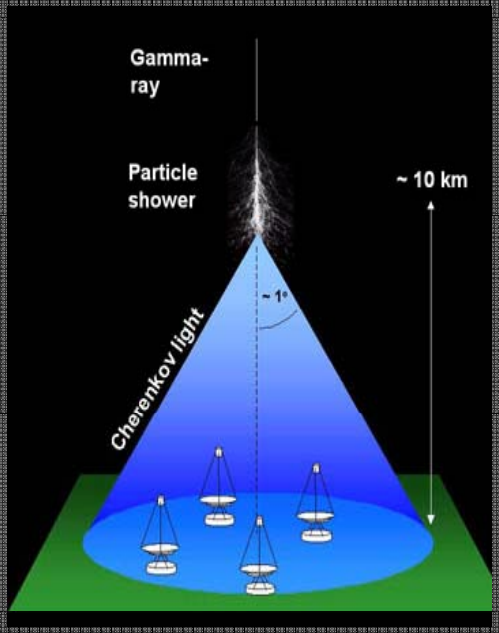
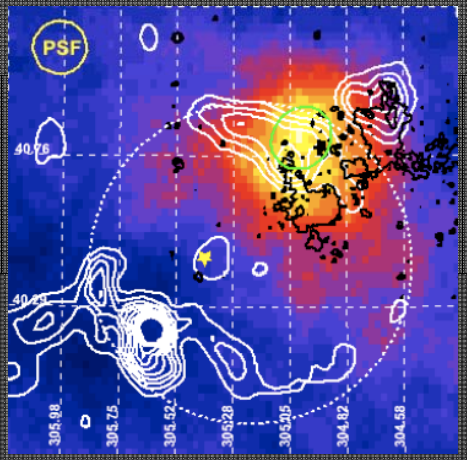
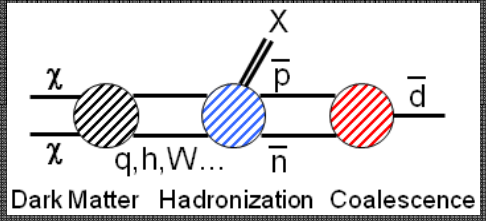
Particle Astrophysics at the TeV Scale

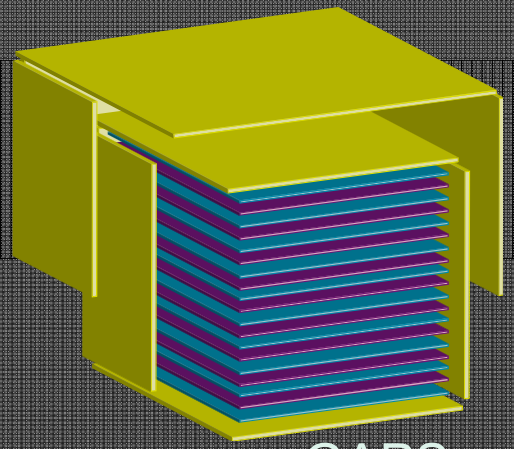












GAPS

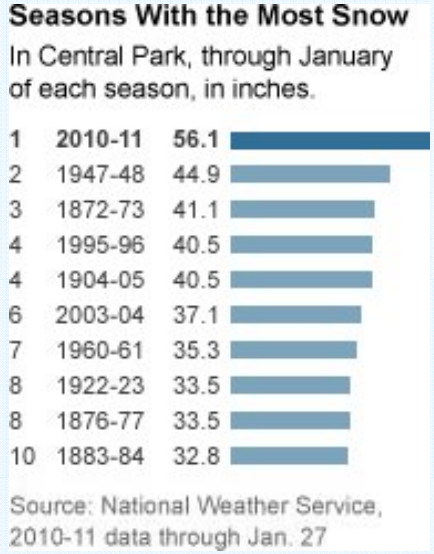
Sabbatical Trends ?

This is (only) my second sabbatical; first was U. Michigan in 2005.

Both were marked by:

- wonderful hospitality,
- very stimulating research environment, and
- being able to get a lot done !

YEAR	LOCATION	SNOWFALL Average	Actual
2005	Ann Arbor, MI	107 cm	187 cm
2010	New York, NY	68 cm	142 cm (to date!)



Outline

The (Non-Thermal) TeV Universe:

- Observed sources & relevant astrophysics

Two Key Scientific Questions:

- Astrophysical particle acceleration → origin of cosmic rays
- Physics beyond the standard model → dark matter

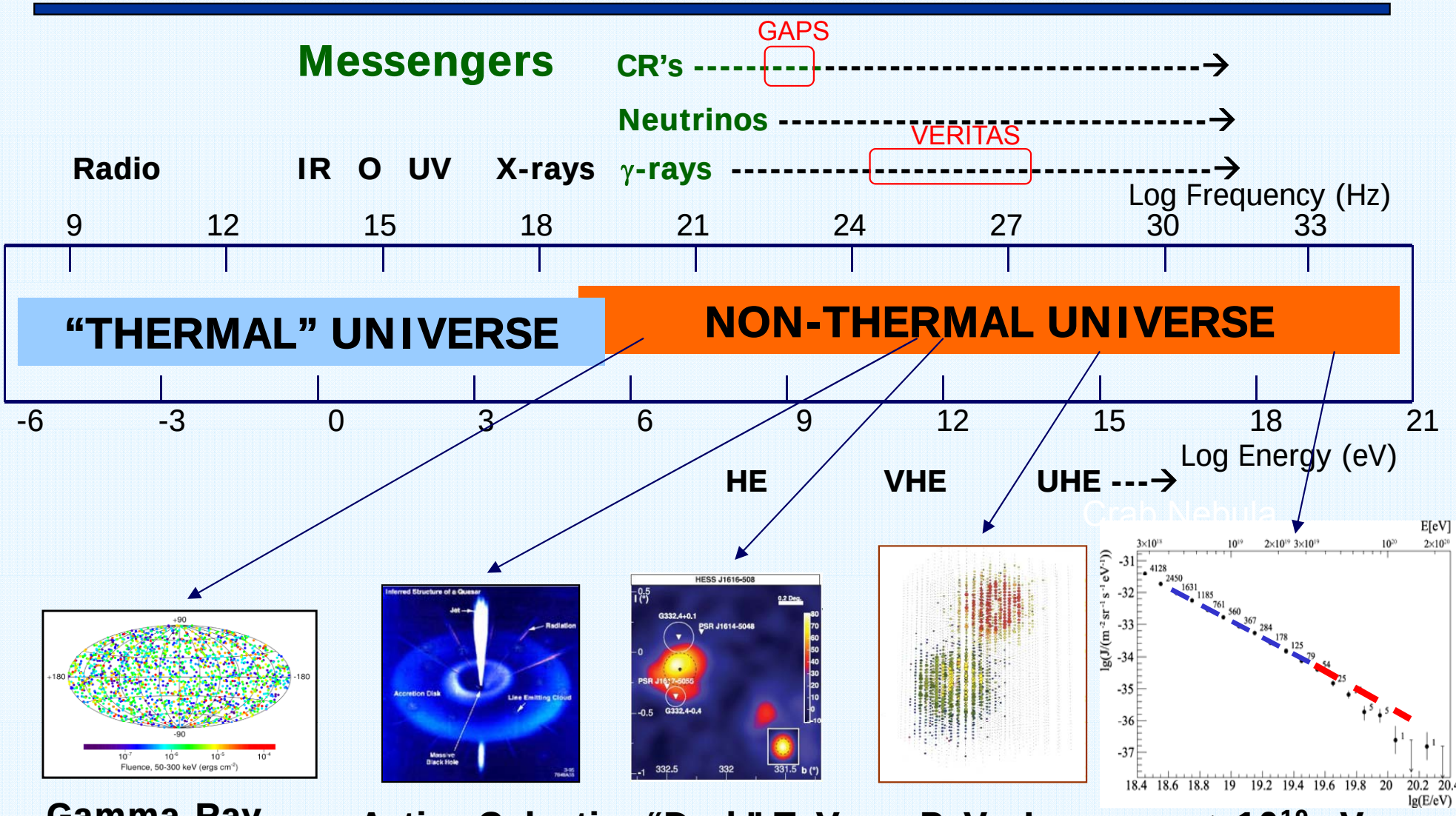
VERITAS γ-ray Telescope:

- Design & performance
- Latest results on these two questions

Future Experiments:

- GAPS Balloon Instrument to study dark matter
- (Cherenkov Telescope Array)

New Windows, New Messengers



Gamma-Ray Bursts (GRBs)

Active Galactic Nuclei (AGN)

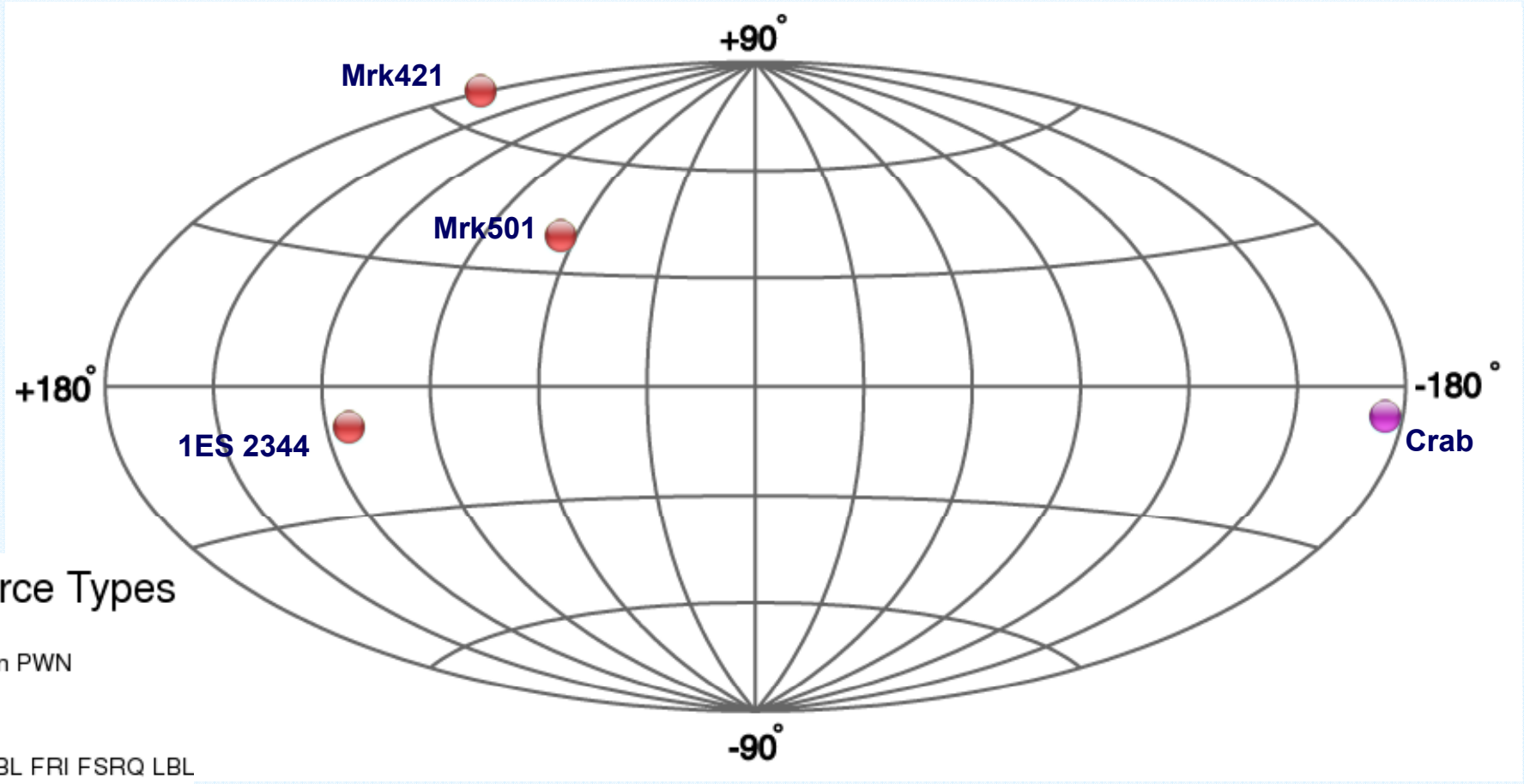
"Dark" TeV Accelerators

PeV ν's

>10^{19} eV Particles

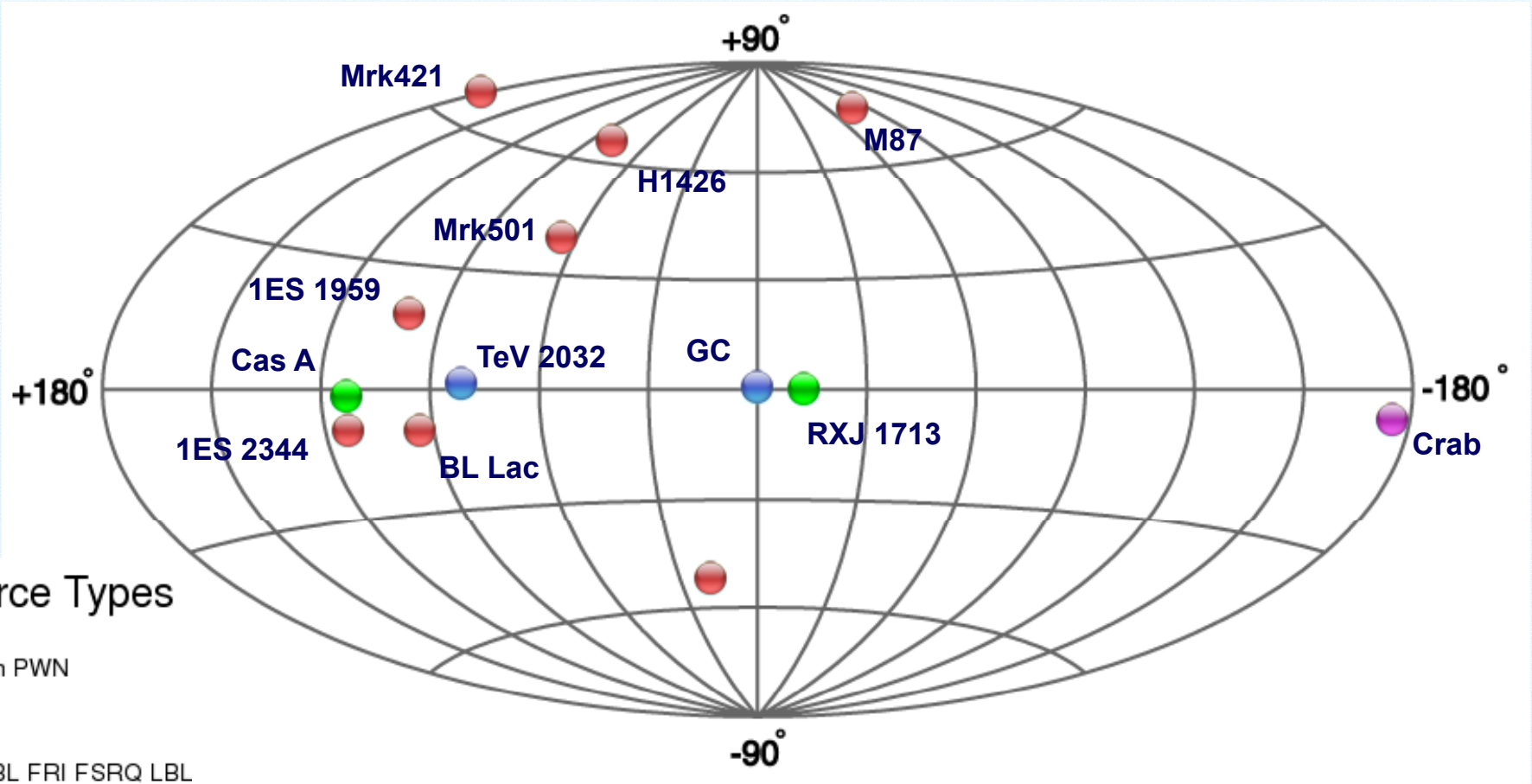
The TeV γ-ray Sky - 1999

4 sources



The TeV γ-ray Sky - 2010

13 sources

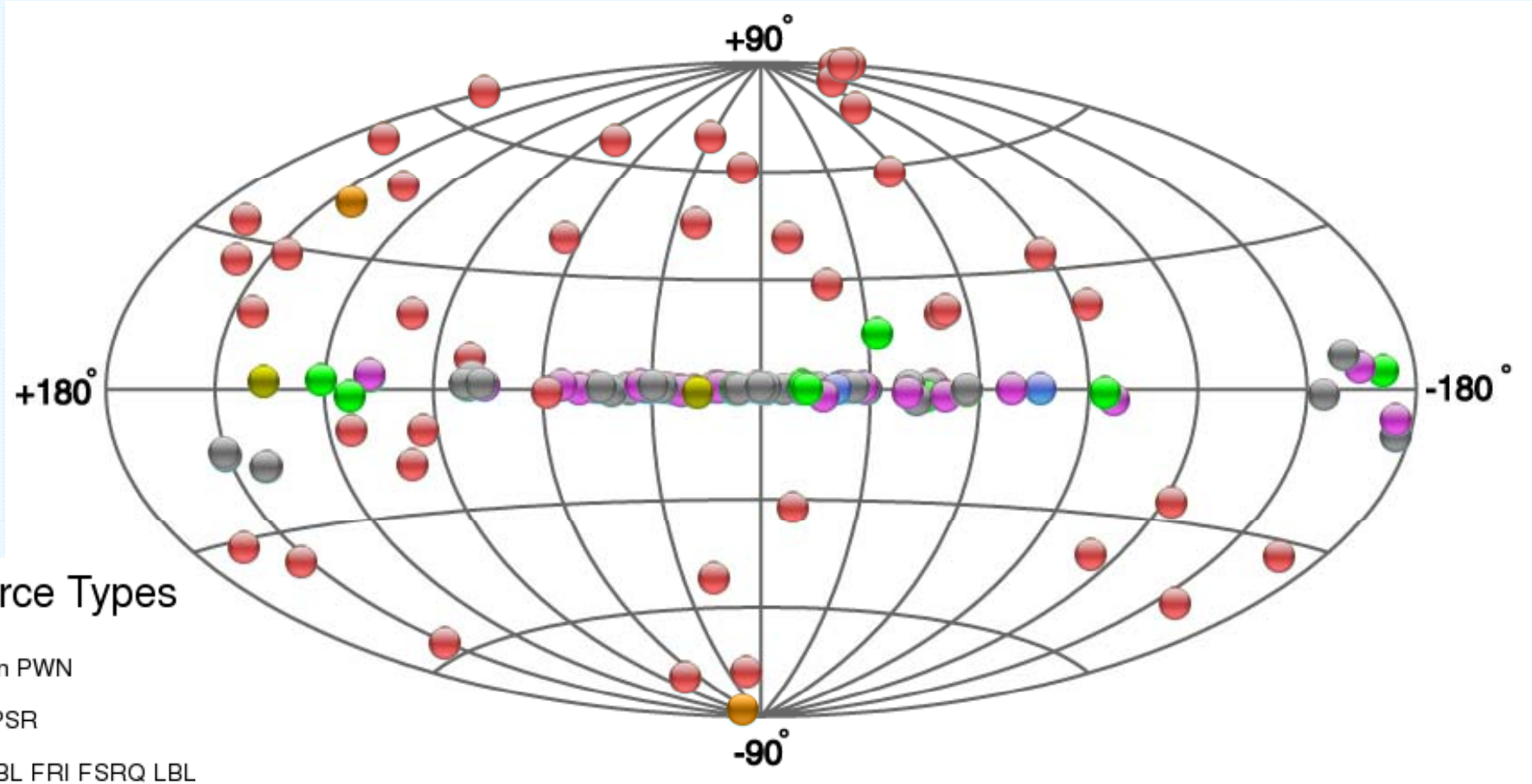


Source Types

- Plerion PWN
- HBL IBL FRI FSRQ LBL
- Shell
- MQS Cat. Var. UNID Other BIN WR

The TeV γ-ray Sky - 2011

~120 sources

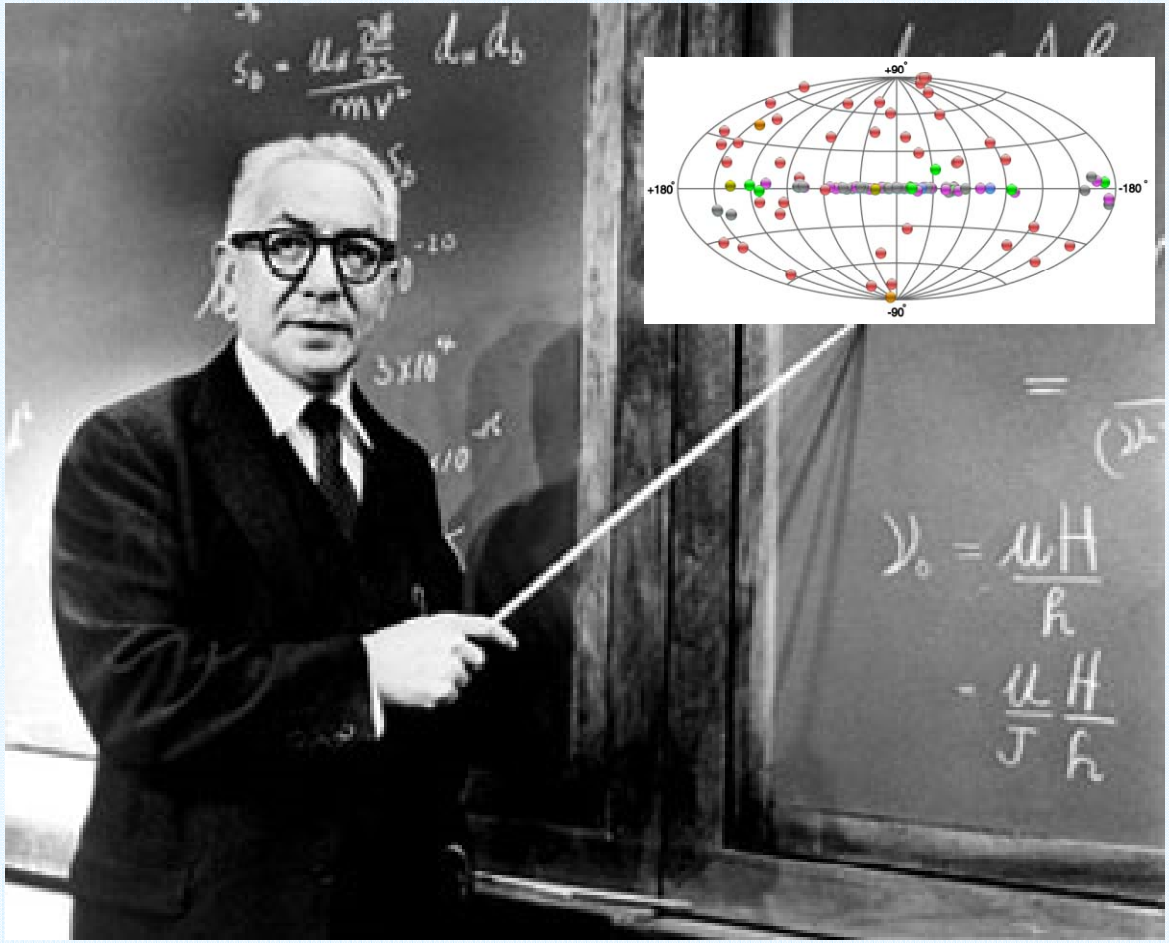


Source Types

- Plerion PWN
- XRB PSR
- HBL IBL FRI FSRQ LBL
- Shell
- Starburst
- DARK
- MQS Cat. Var. UNID Other BIN WR

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

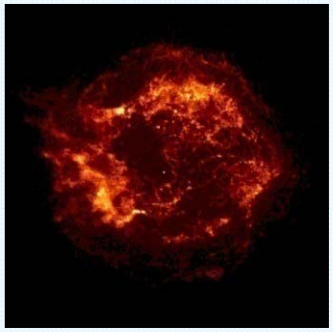
Most discoveries made by Atmospheric Cherenkov Telescopes



“Who Ordered Them ?”

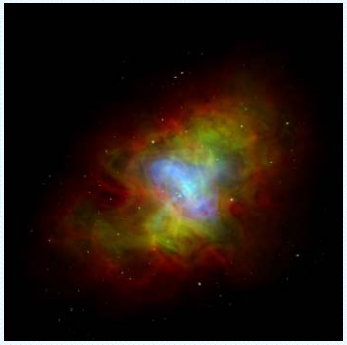
A Wide Variety of Sources …

Supernova Remnants



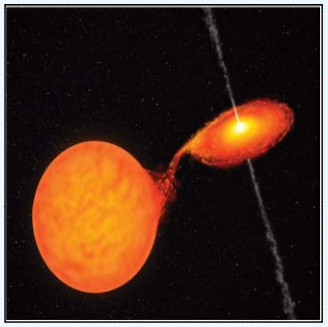
Shocks
Fermi mechanism

Pulsars/PWN



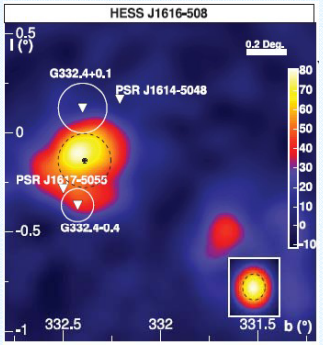
NS dynamo
Winds

HMXBs (microquasars)



Accretion-powered jets,
Colliding winds, or …?

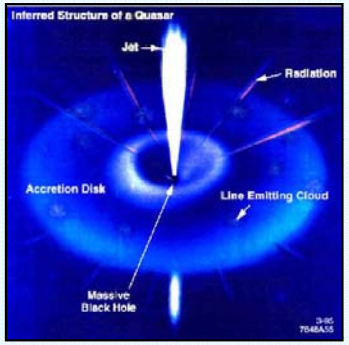
"Dark accelerators"



???

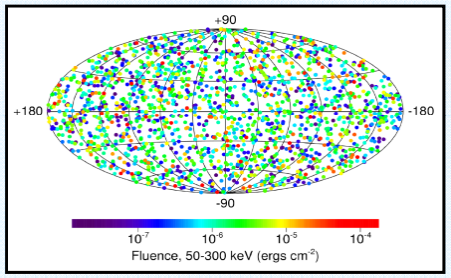
GALACTIC

Active Galactic Nuclei



Supermassive BH
Jets

Gamma-Ray Bursts



Massive star collapse
Relativistic shocks

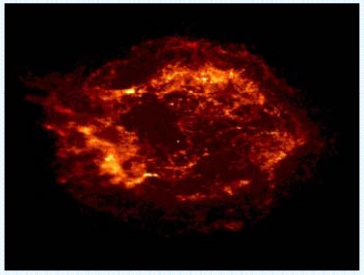
Starburst Galaxies

Star forming activity
HE Cosmic rays

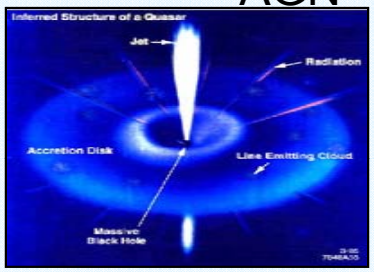
EXTRA-GALACTIC

Key Physics Issues

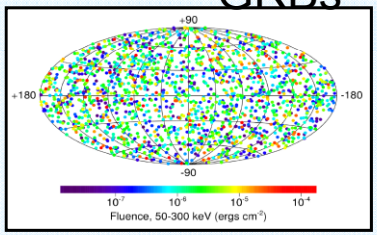
SNR

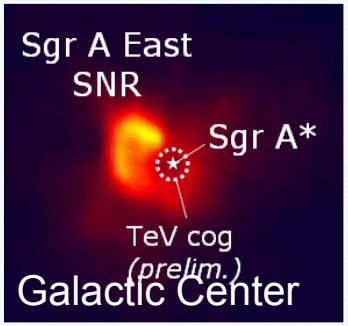


AGN

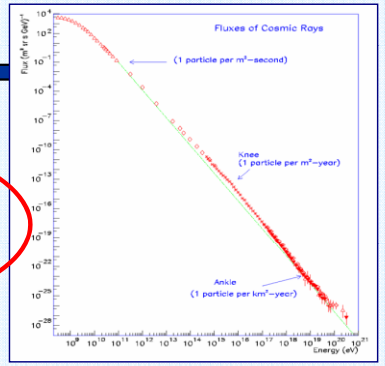


GRBs



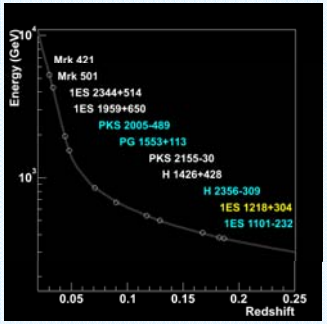


Origin of cosmic rays

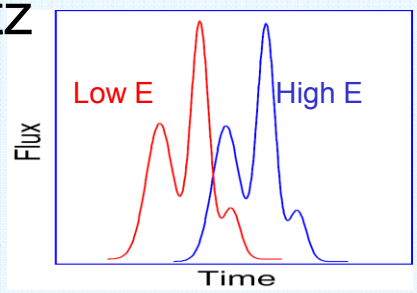


?

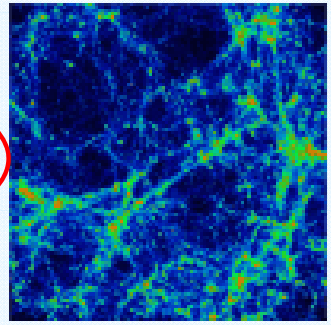
Cosmological γ-ray horizon



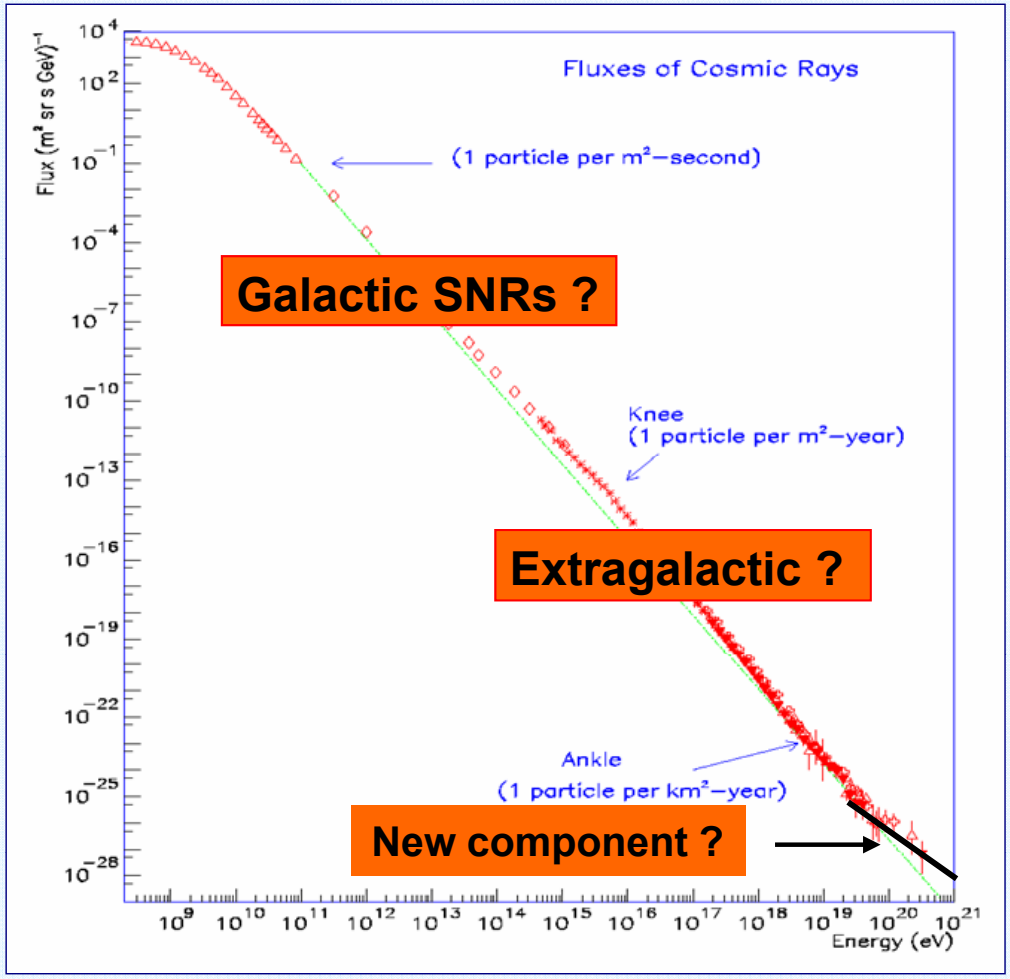
Tests of Lorentz invariance



Cold dark matter (WIMP) searches



Origin of Cosmic Rays



Diffuse, all particle spectrum

90 year old mystery !

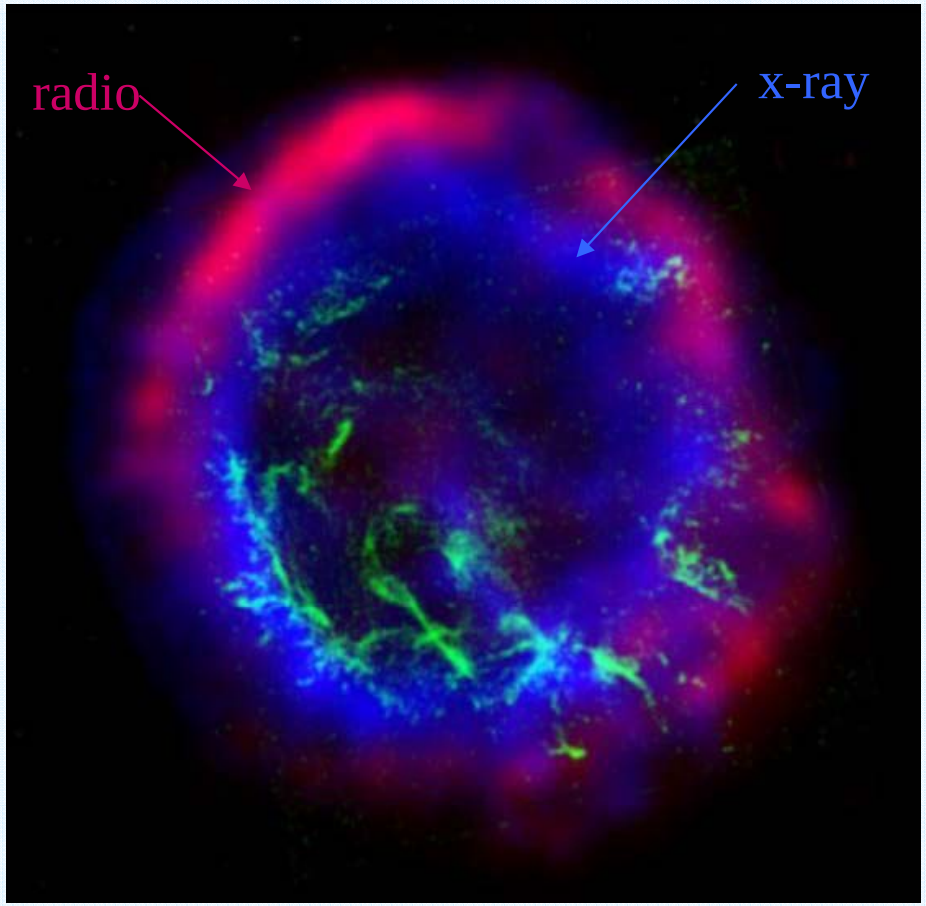
- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm^3

Neutral messengers:

γ, ν

are required to directly observe cosmic accelerators.

Supernova Remnants (SNR's)



SNR E102

- Collapse of massive star; 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.
- In ~ 10^4 yrs, blast wave deccelerates and dissipates.
- Can supply and replenish CR's if $\varepsilon \sim 5\%$.

Electrons or Protons ?

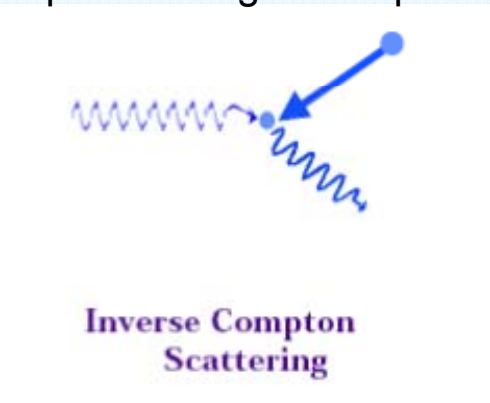
TeV γ-rays are:

- *Not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.

But both electrons and protons produce γ-rays.

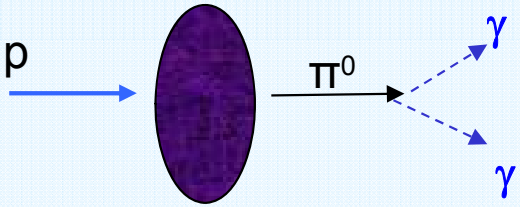
Accelerated electrons
→ TeV γ-rays

Up-scattering of soft photons



Accelerated protons
→ TeV γ-rays

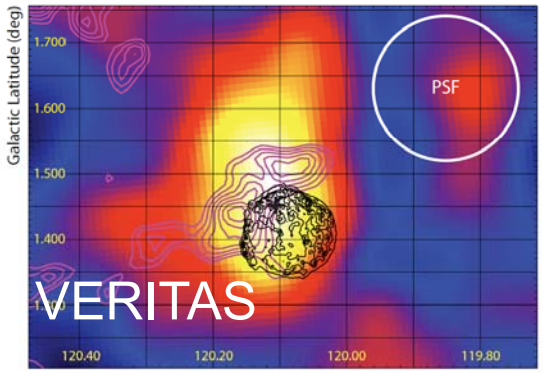
Target interaction, π^0 decay

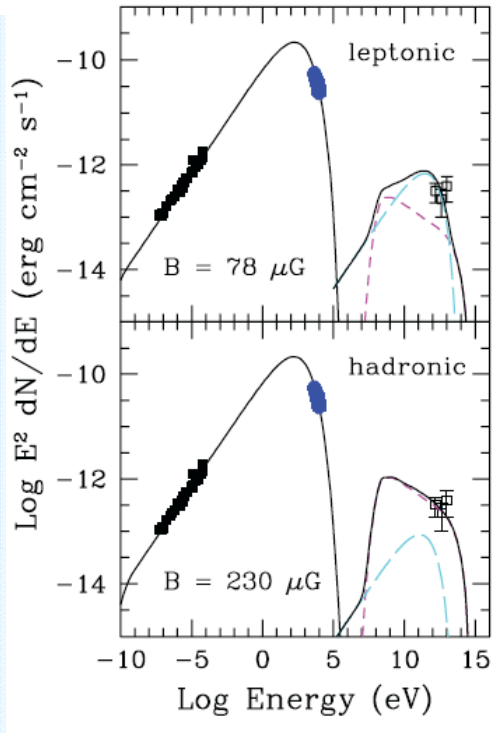


Target material

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

Tycho's SNR
VERITAS Discovery
in 2010 (Barnard mtg.)





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 know.
- Axions – motivated by particle physics; searches underway.
- Weakly interacting massive particles (**WIMPs**).

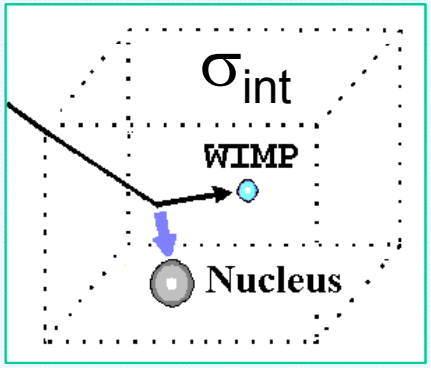
"WIMP miracle": present relic density is consistent with expected for a weakly interacting particle & new particle physics is required at the weak scale (EWSB).

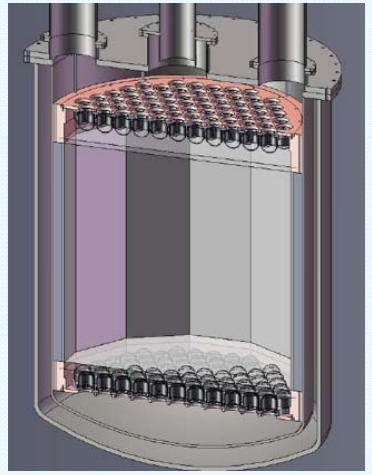
DM Detection: Complementary Approaches

Produce DM particle in accelerators

LHC at CERN

Direct Detection



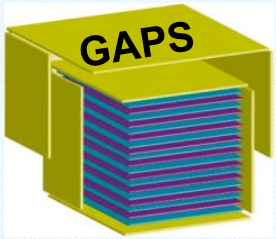


Xenon1T Detector

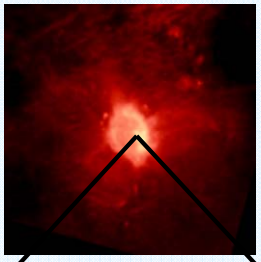
Astrophysical Indirect Detection

Sextens dwarf galaxy

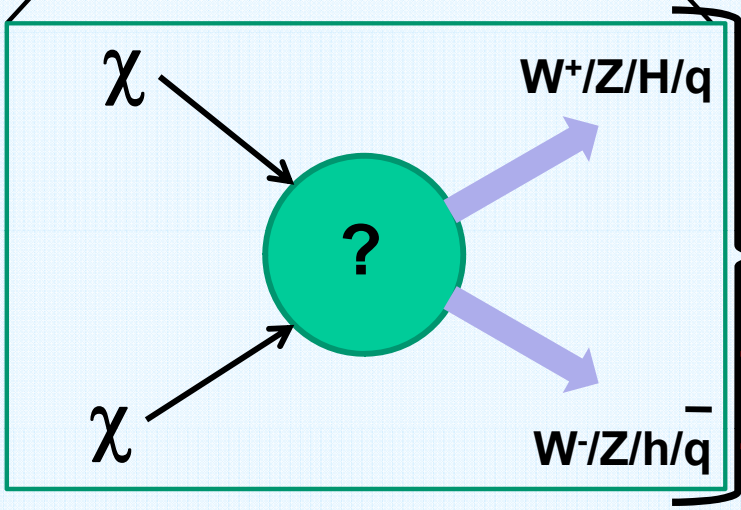
Annihilation (σ_A)
$\chi\chi$ →
γ's, ν's, anti-matter



Indirect Detection



WIMP
Annihilation
(e.g. GC)



Telescopes

- γ VERITAS, HESS, Fermi …
- ν IceCube

Cosmic Ray Expts

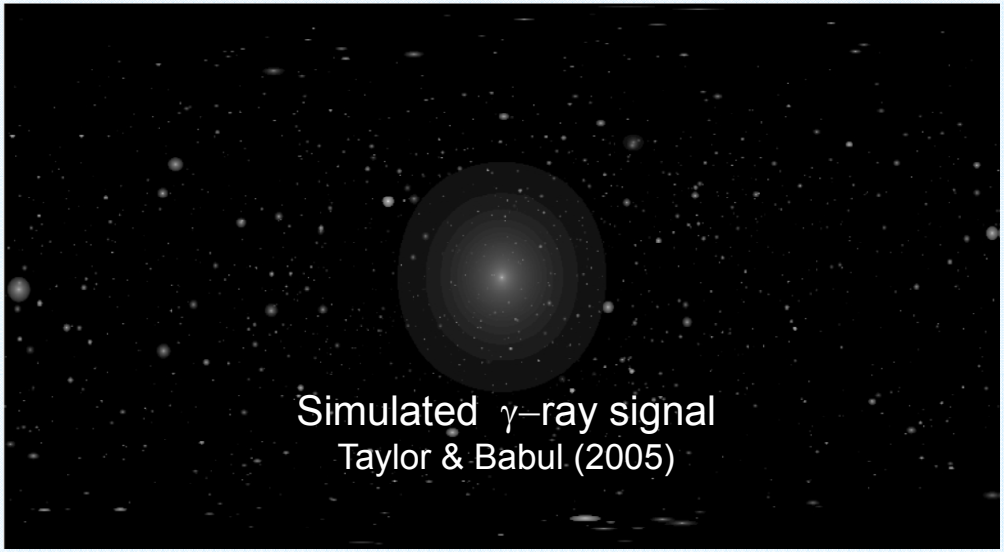
- e^- ATIC, Fermi …
- e^+ Pamela, AMS
- $\bar{p}$ HEAT, Pamela, AMS
- $\bar{d}$ GAPS

decreasing background

DM Detection via γ-rays

Target regions with:

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

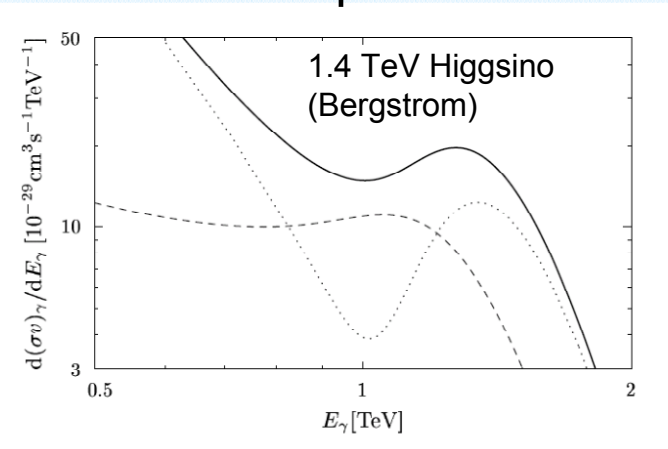


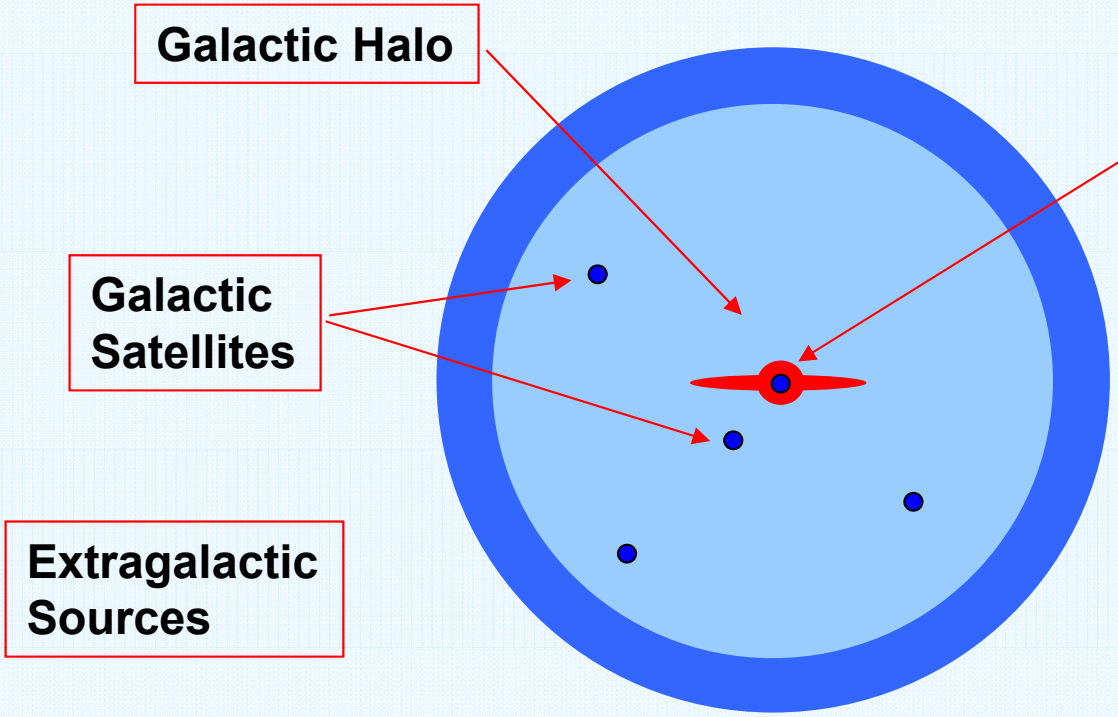
DM Detection via γ-rays

Target regions with:

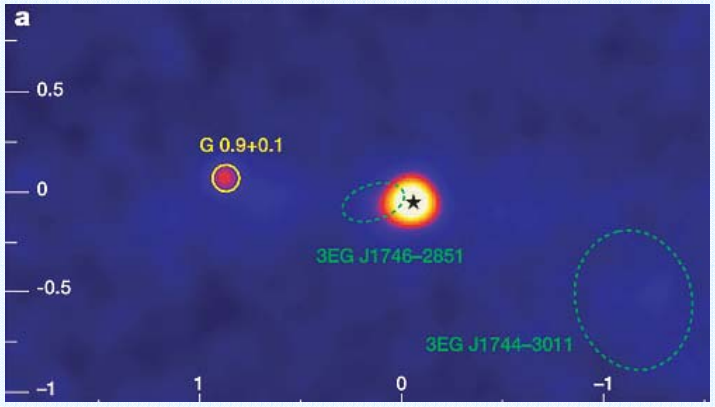
- Favorable DM distributions.
- Large mass/light ratio.

"Universal" Spectrum





HESS



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

→ Is it dark matter ?

DM Detection via anti-Deuterons

Unlike anti-protons,
anti-deuteron secondaries are
severely suppressed.

Primary Component (DM):

$\chi\,\chi \rightarrow \gamma, \bar{p}, \bar{d}$

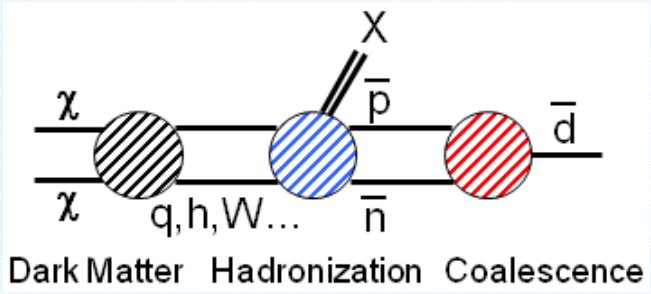
Secondary Component:

$p\,A \rightarrow \bar{d}\,X$ [via $p(\bar{p}n)n$]

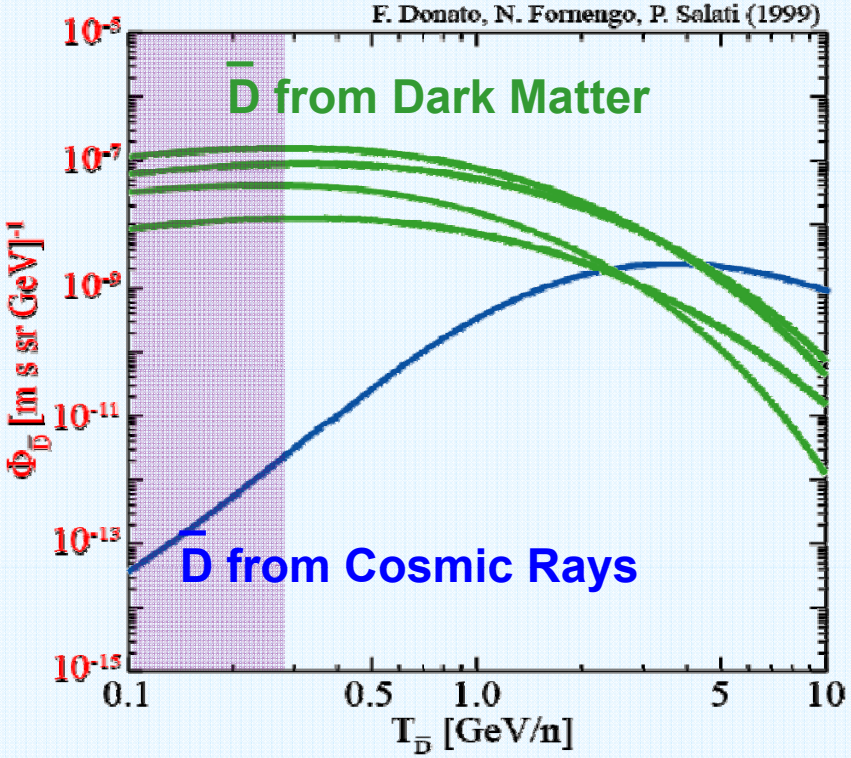
where A = p, He

Anti-deuterons provide extremely clean signature, but low fluxes result in a daunting experimental challenge !

DM production of $\bar{d}$

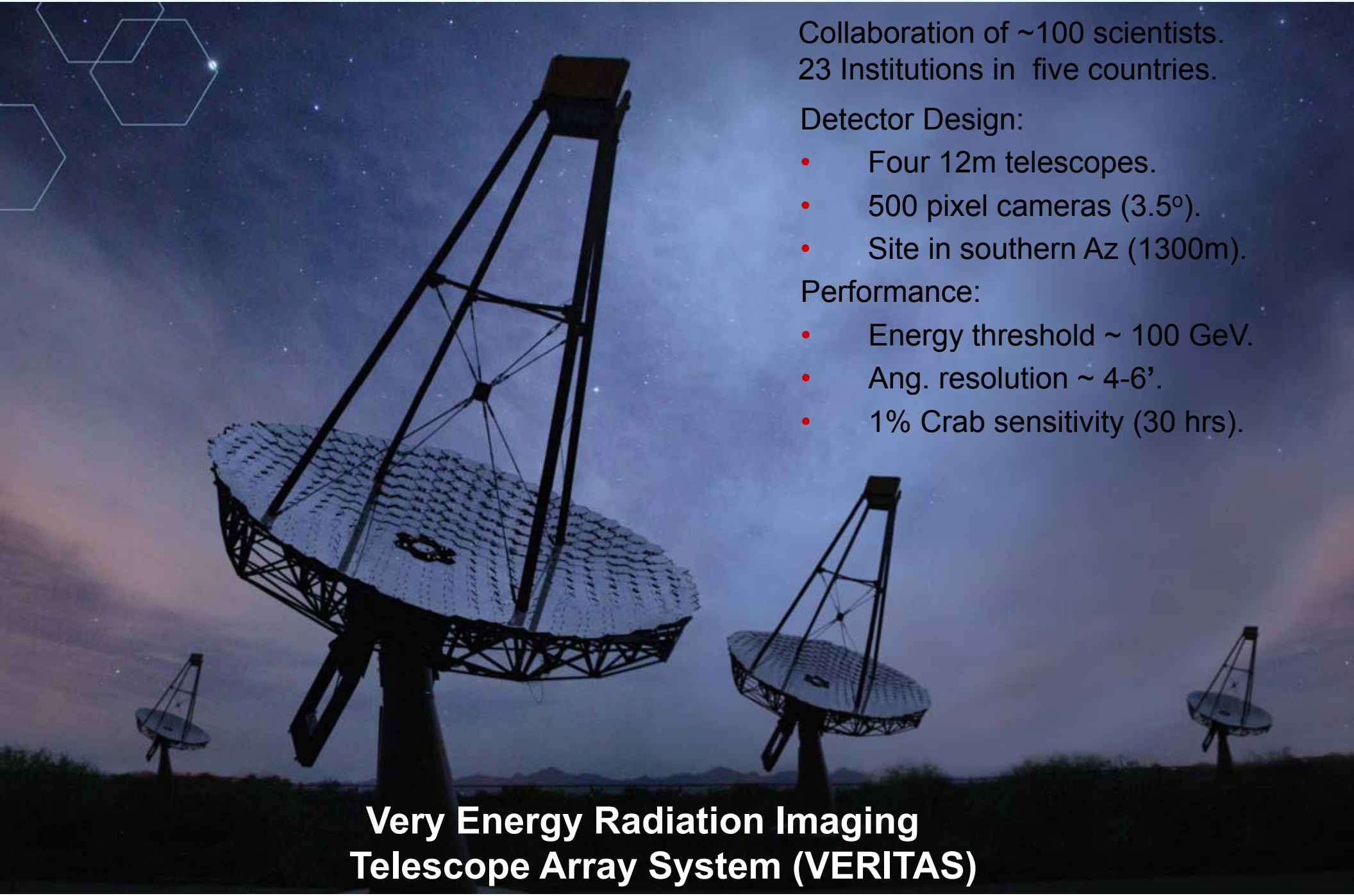


Anti-deuteron flux at the earth (w/propagation and solar modulation)



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 in southern Az (1300m).

Performance:

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

Very Energy Radiation Imaging Telescope Array System (VERITAS)

Major VHE Telescopes

Fermi

Multi-messenger Astronomy

MAGIC

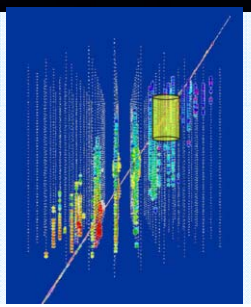
VERITAS

(Auger, CR's)

HESS

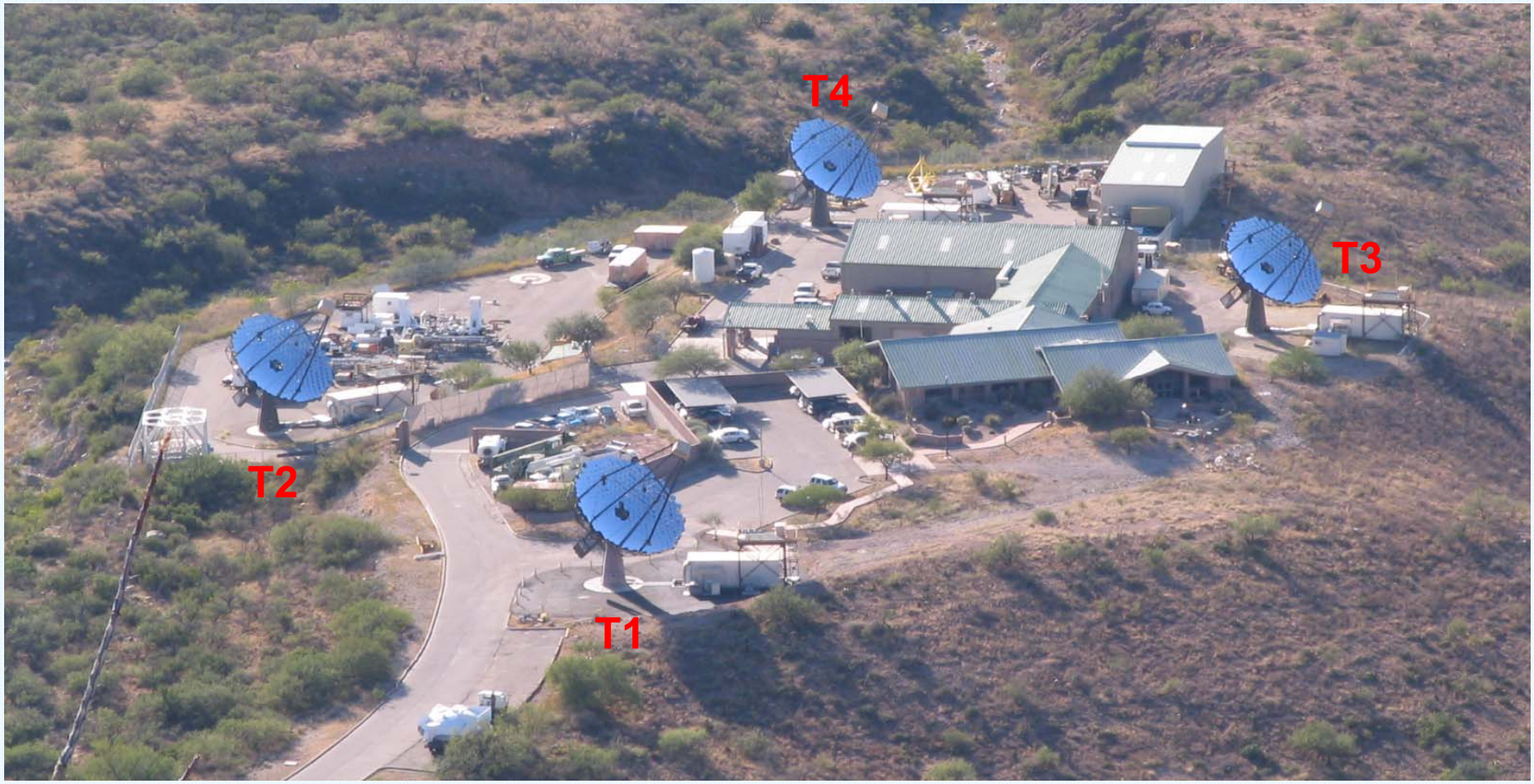
IceCube, ν's

CANGAROO III



IceCube

VERITAS @ Mt. Hopkins, AZ



St… et al. 2006

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.

Ireland

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

Non-Affiliated Members

DESY/Potsdam
Penn State U.

+ 35 Associate Members
Theorists, MWL partners, IceCube, Fermi, Swift, etc.

From my talk back in 2005 ...

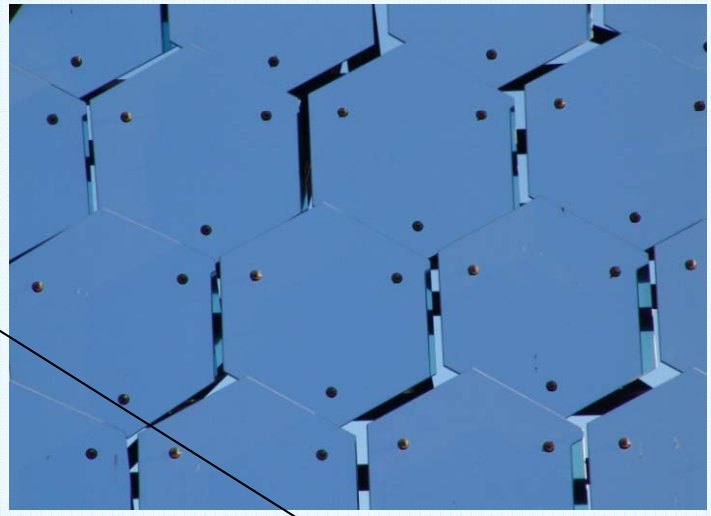
Whipple Base Camp
Mt. Hopkins, AZ

Telescope1

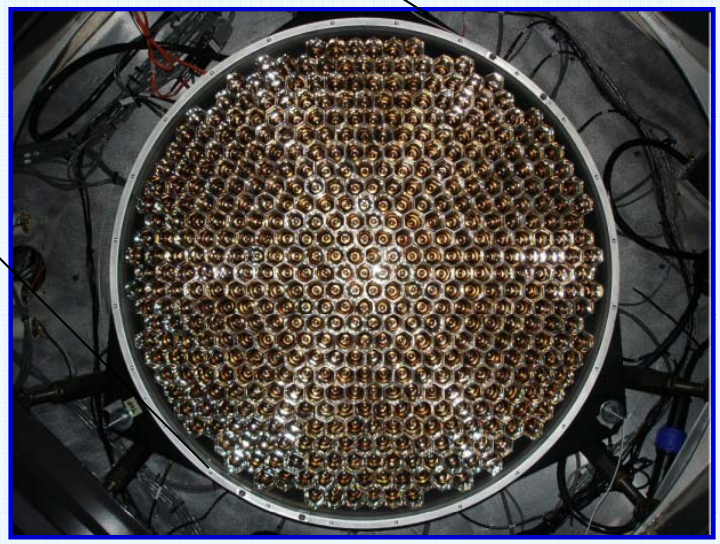
Electronics trailer

A VERITAS Telescope

12m reflector, f1.0 optics

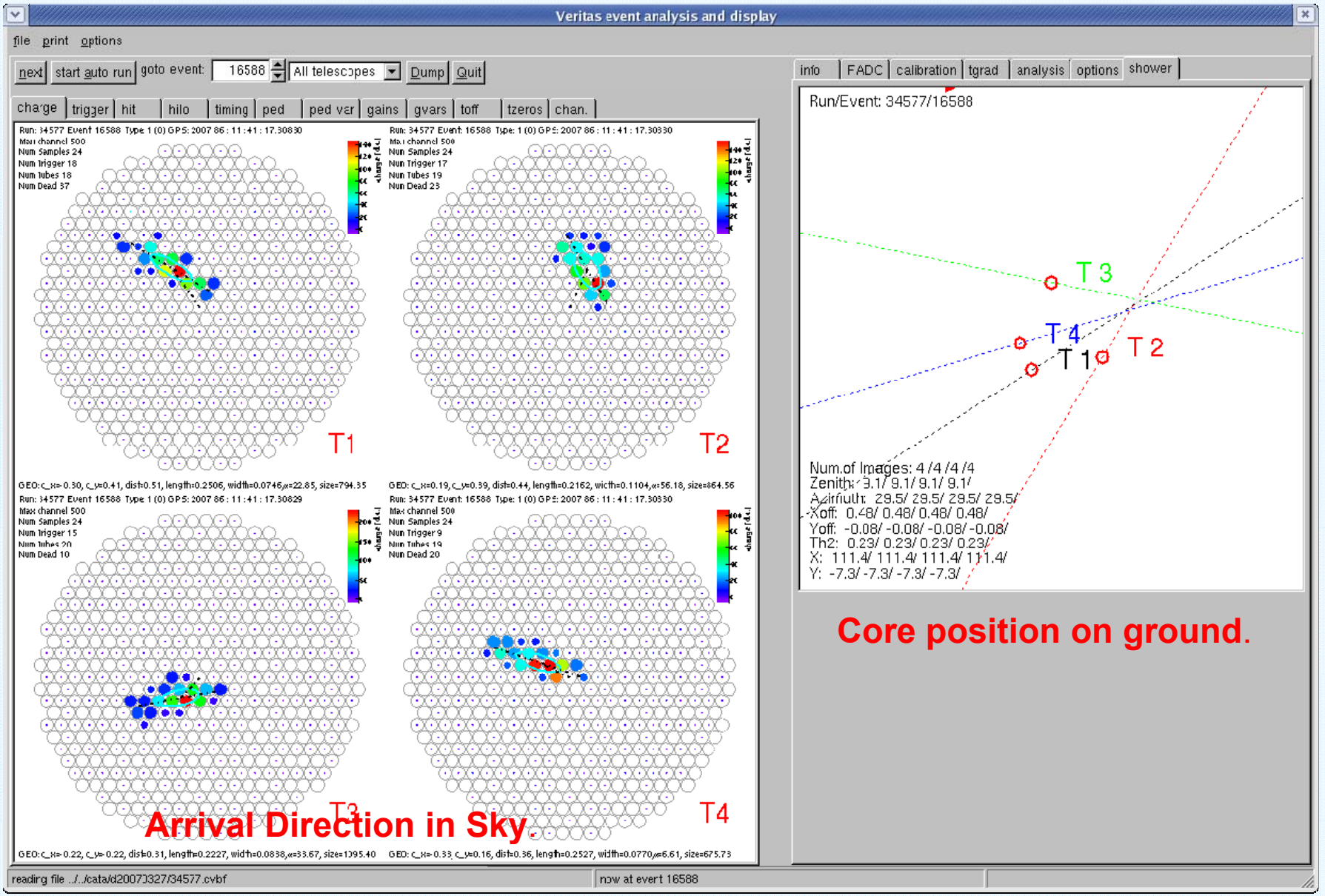


350 Mirror Facets



500 pixel Camera

Four-Telescope Event



Arrival Direction in Sky.

Core position on ground.

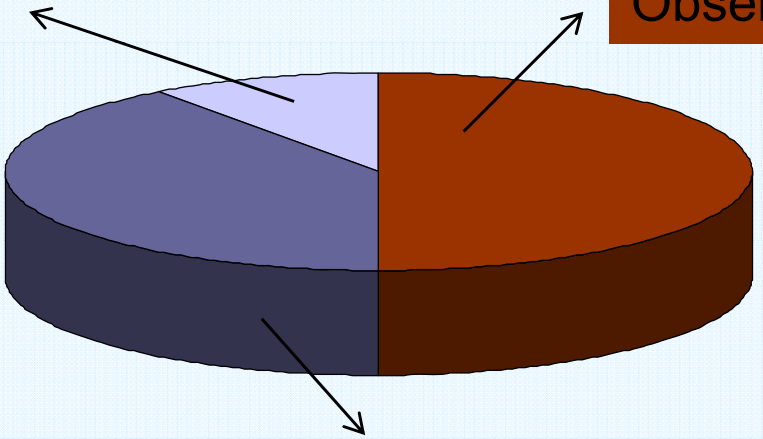
Observation Strategy

Discretionary (10%)

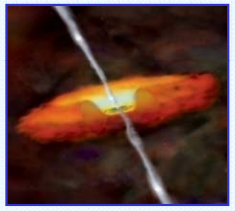
- ToO's, GRBs
- Higher risk sources

Observing Proposals (50%)

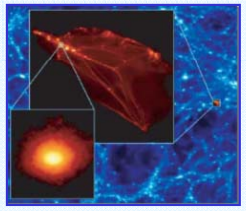
- Science WG's & TAC



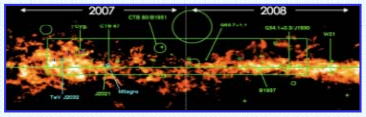
Key Science Projects (40%)



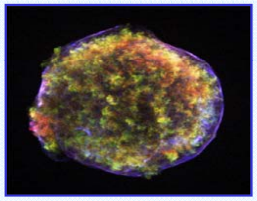
BLAZARS



Dark Matter



Cygnus Sky Survey (2007-9)

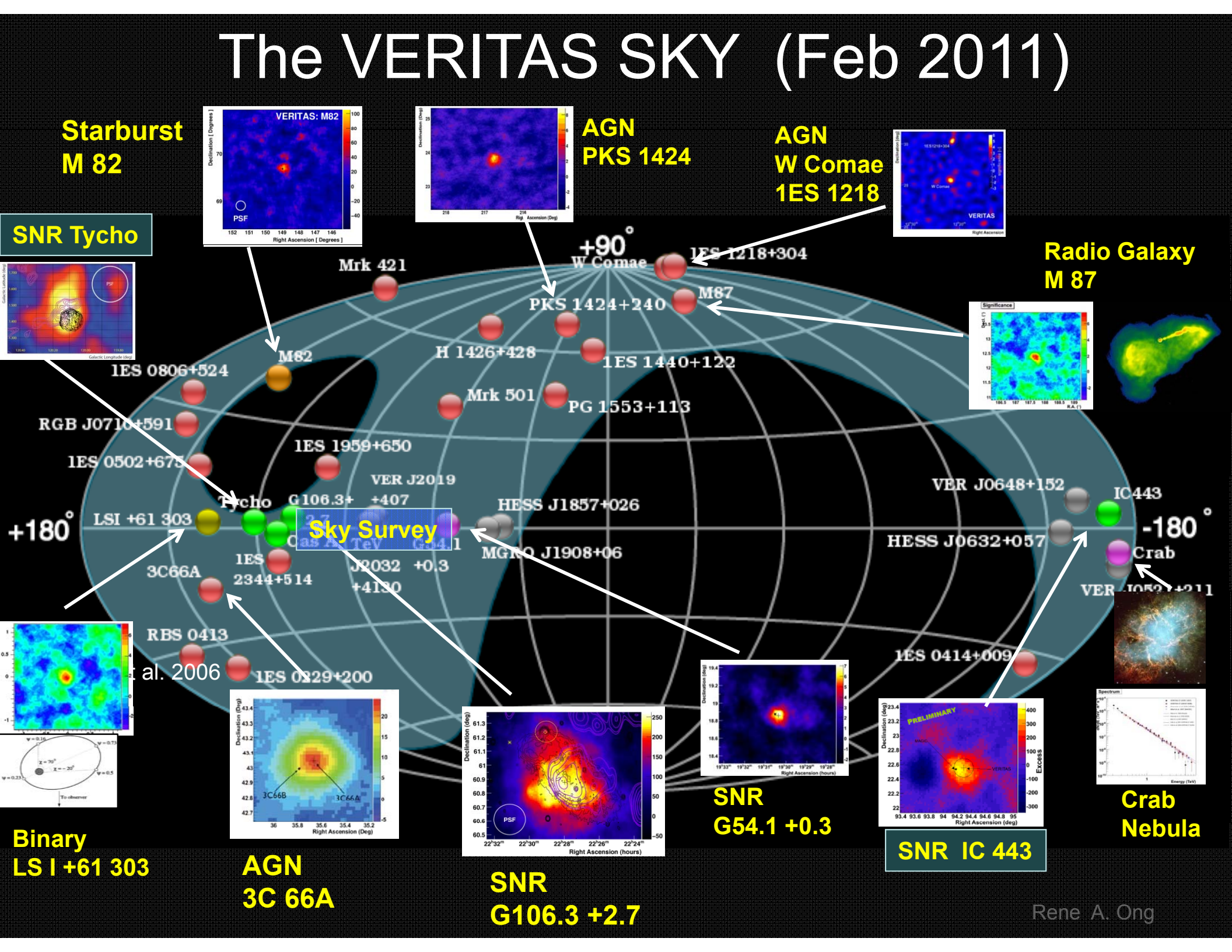


SNRs/PWN

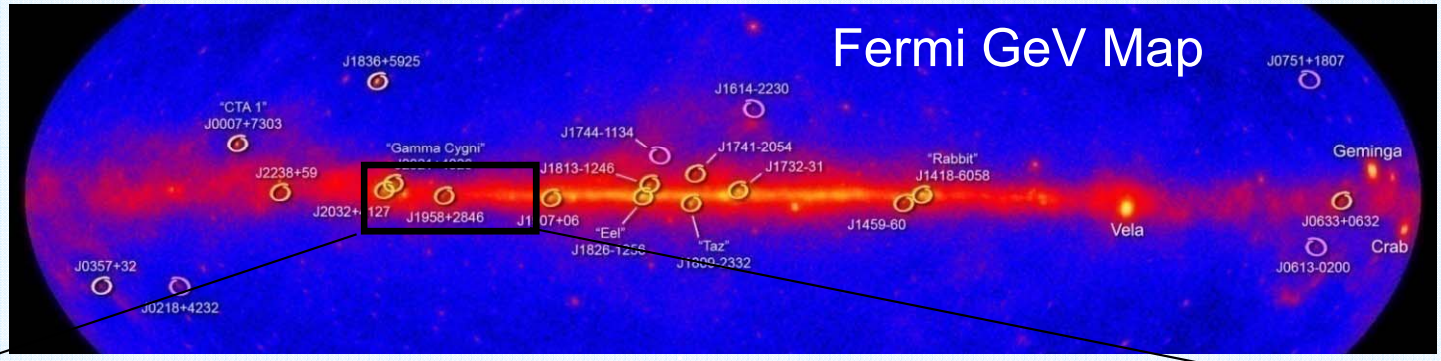
- 850 hours/year Dark Time + 20% Moonlight (= 1000 hours total).
- > 95% Data taken with all four telescopes operational.

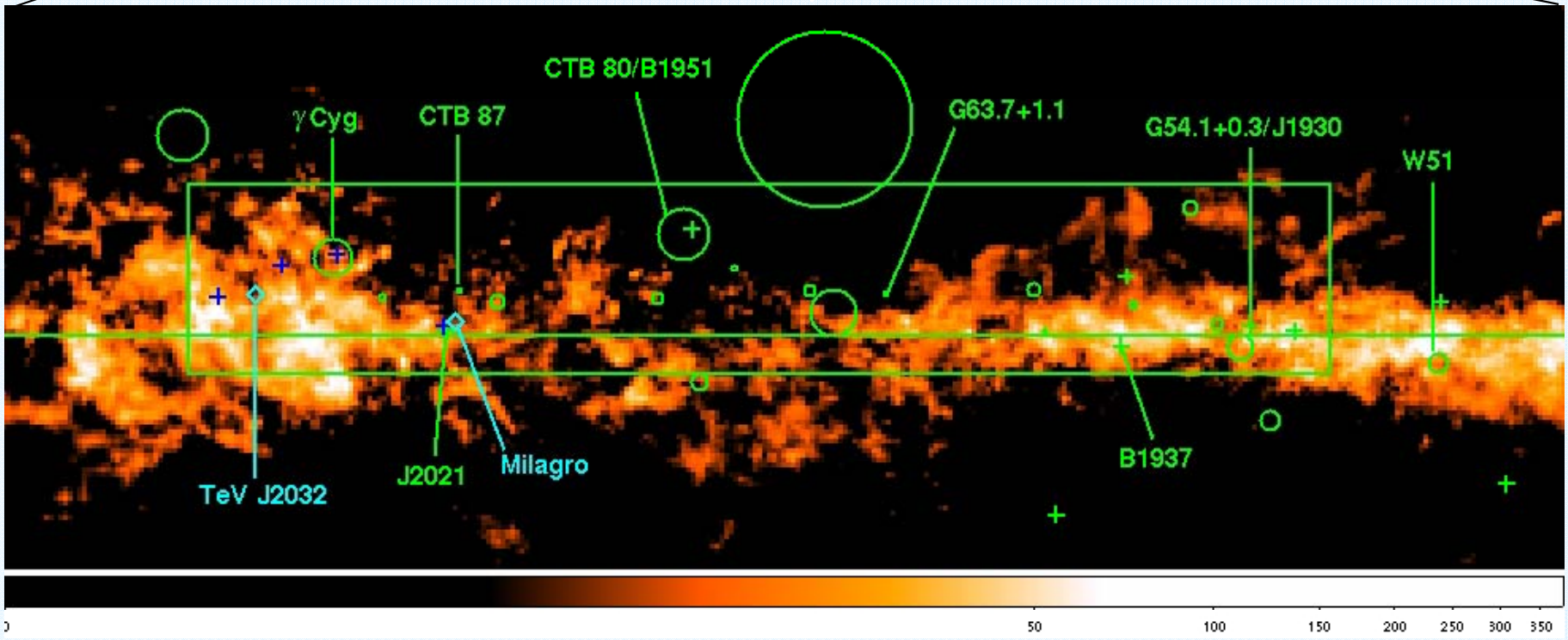
VERITAS Results

The VERITAS SKY (Feb 2011)



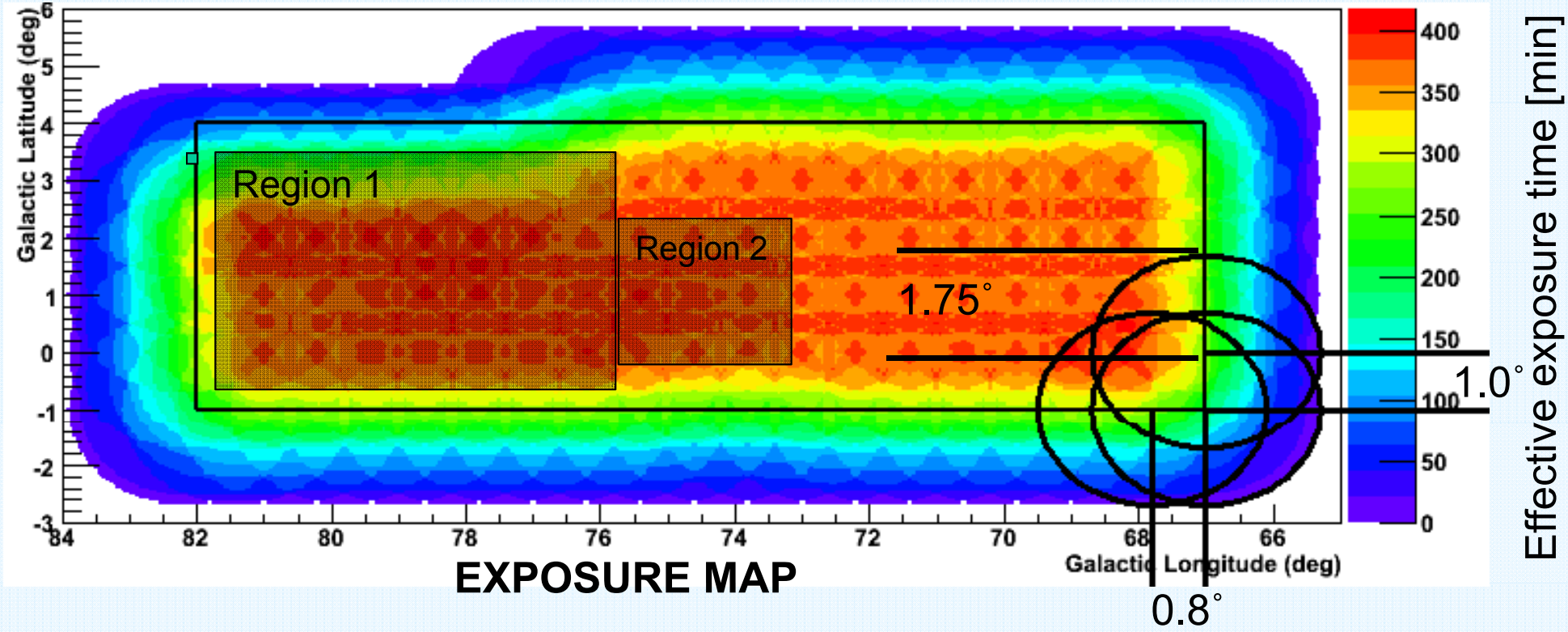
Cygnus Arm Sky Survey





Cygnus: rich region of SNR's, PWN, binaries, GeV sources

VERITAS Sky Survey: Strategy

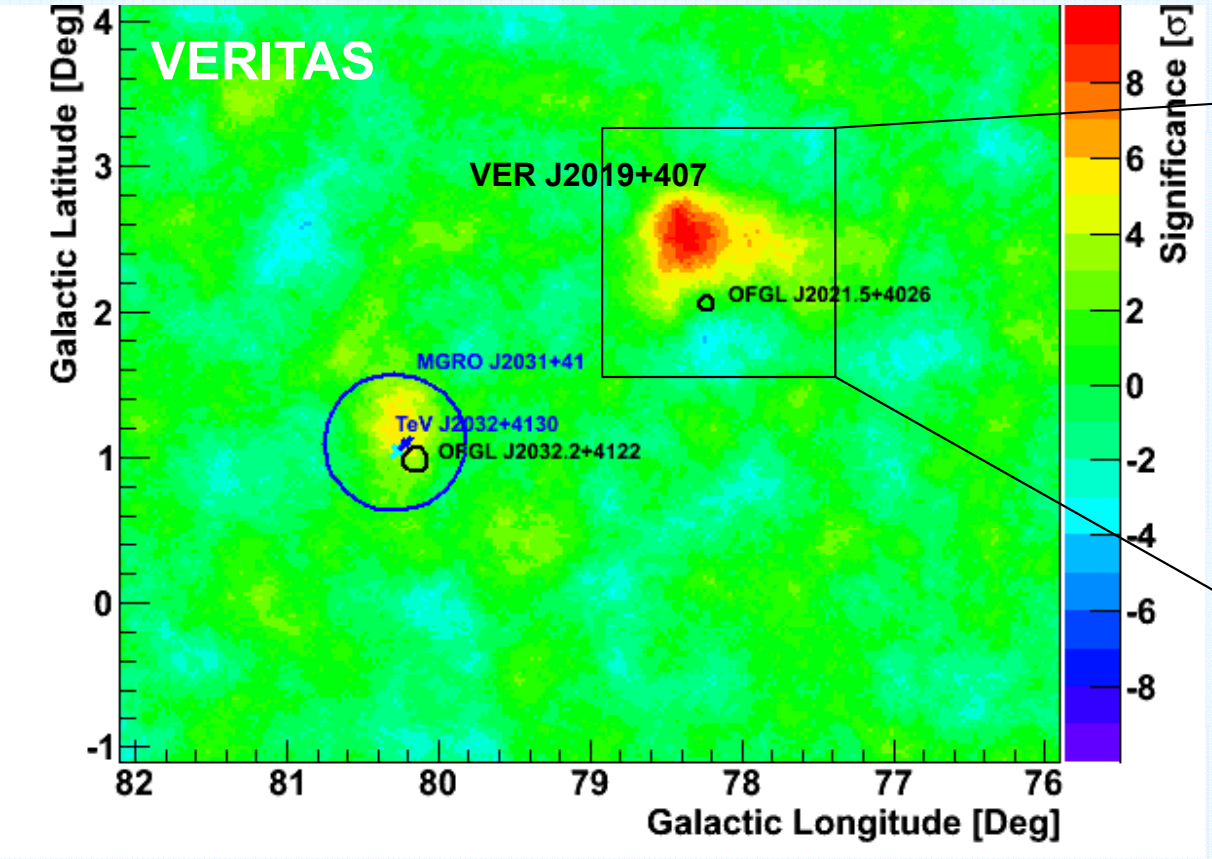


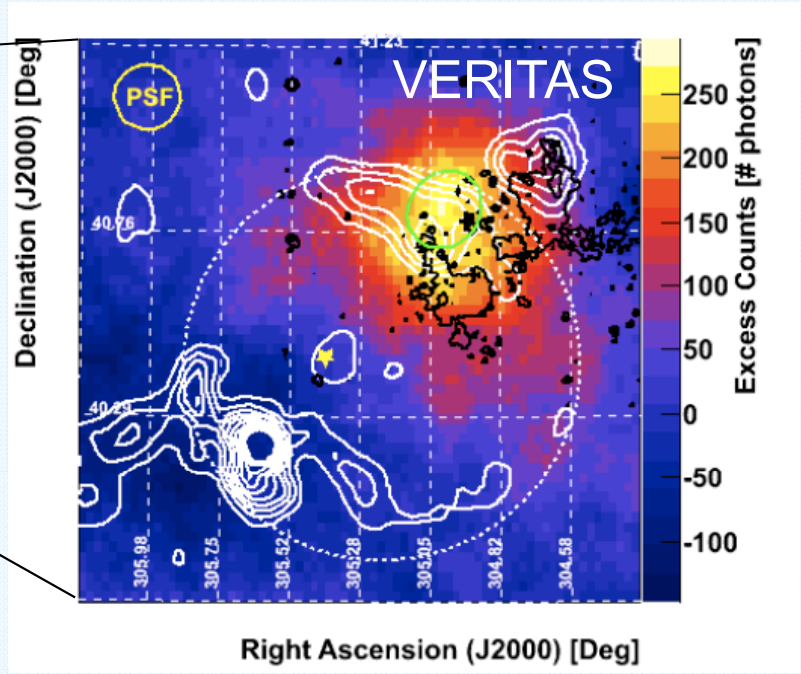
Made possible by good VERITAS off-axis sensitivity

- Survey covered region 67˚ < l < 82˚, -1˚ < b < 4˚
- Over 2 year period: ~112 hours in base survey, ~100 hours follow-up.
- ~6 hrs equivalent exposure at every location (before follow-up).

Most sensitive N. Hemisphere survey ever done at TeV energies.

Sky Survey: Region 1





- VER J2019+407
  - **New TeV source**
- TeV J2032+4130
  - known source, perhaps associated with pulsar.

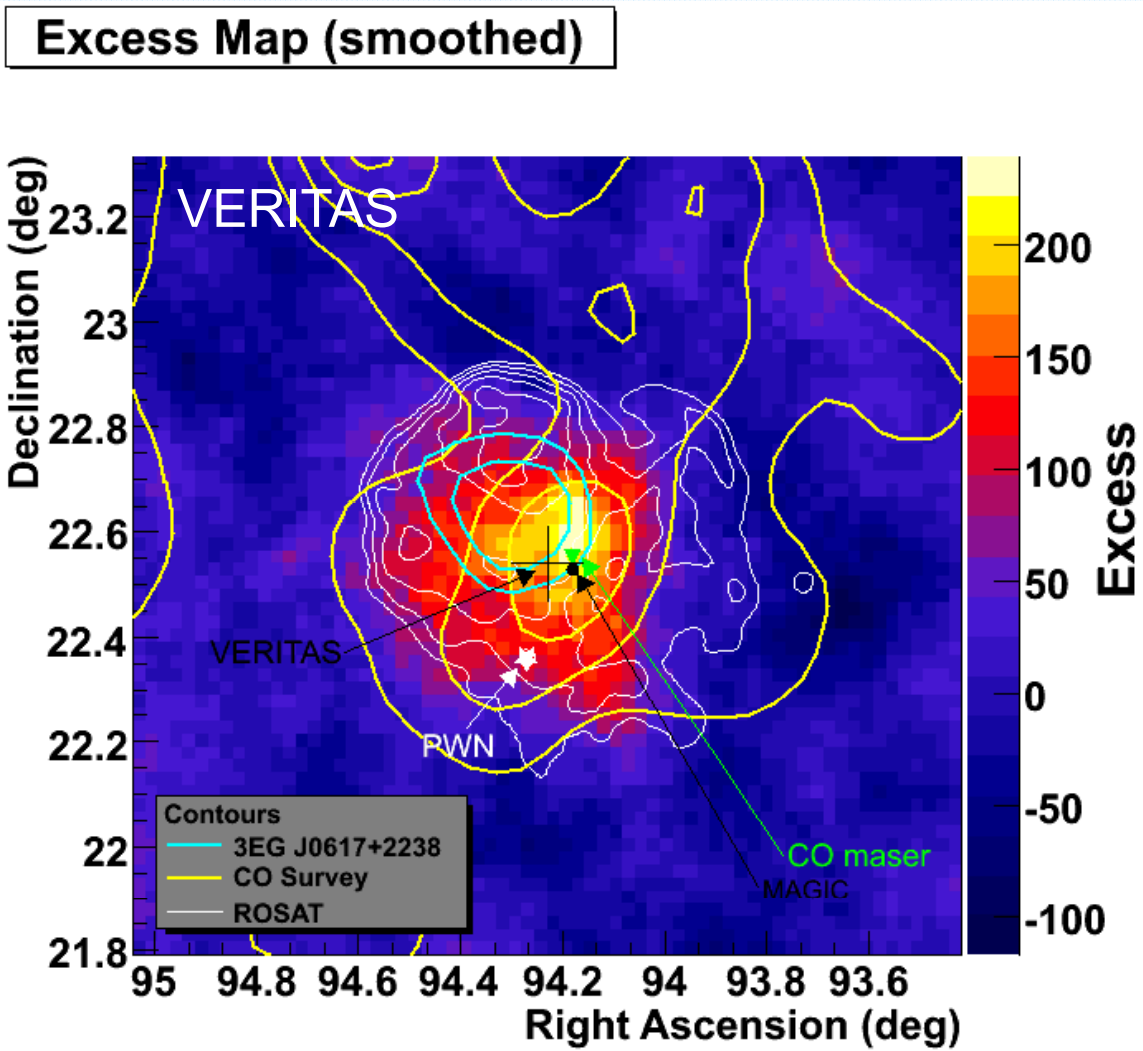
VER J2019+407 may indicate:

Interaction of SNR shell with HI shell → evidence for acceleration of protons. (Leptonic model possible too).

Region 2: “Cisne”

- Targeted observations followed survey data.
- Motivation and analysis done by Ester Aliu (Barnard postdoc).
- Results to be released soon.

Targeted Discovery: SNR IC443



V.A. Acciari et al., ApJ 698, L133 (2009)

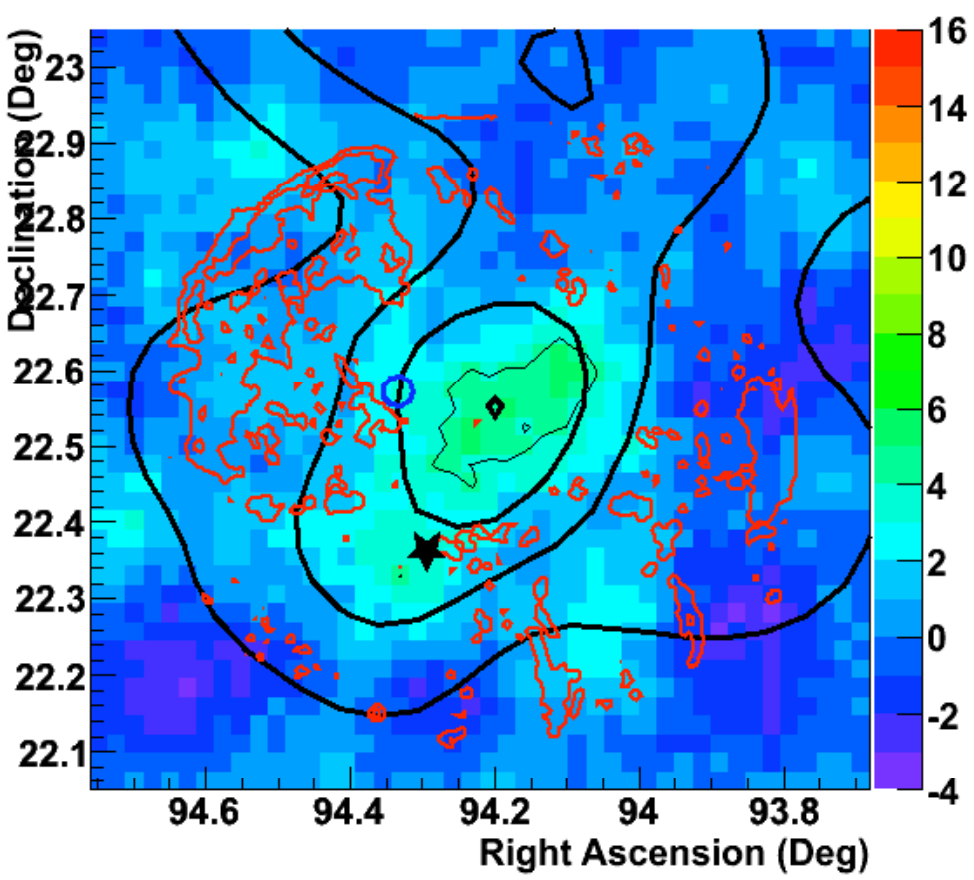
- Overlap with CO indicating molecular cloud along line of sight.
- Maser emission suggests SNR shock interacting with cloud.
- TeV emission could be from CR-induced pion-production.

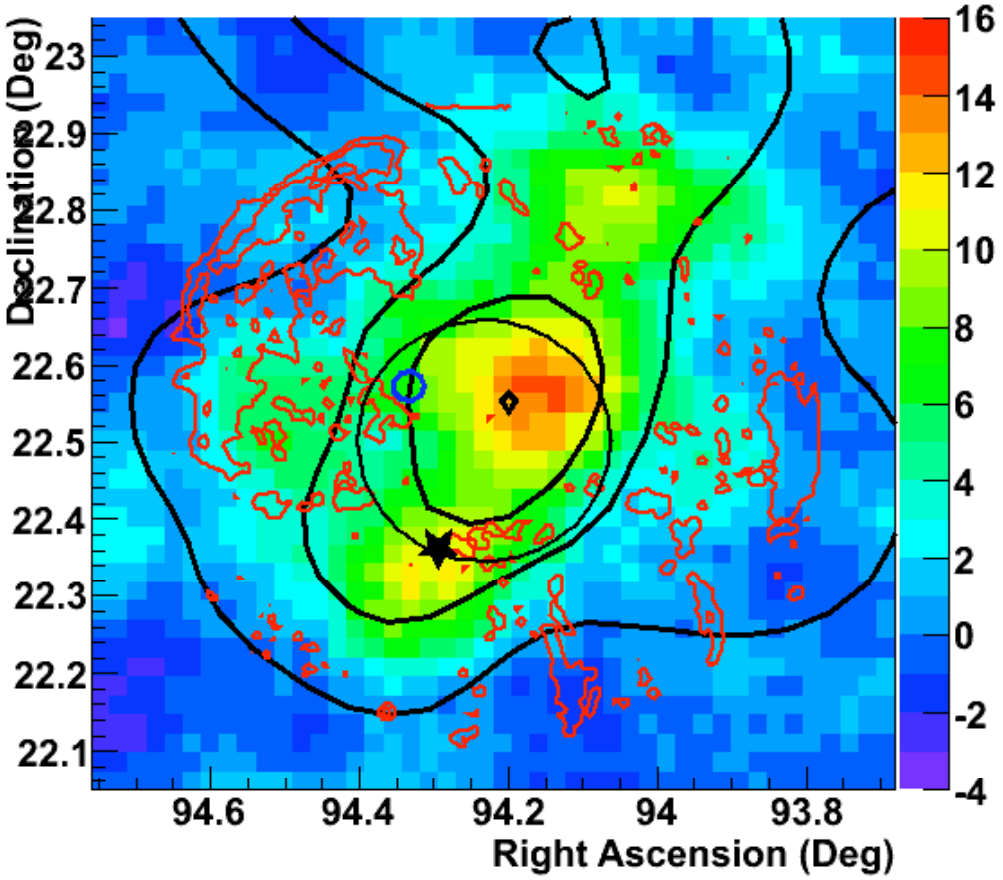
Future Deep Observations of IC 443

Upgraded VERITAS Detector

Existing data (20 hours)

Simulated – 100 hours, assuming the emission maps CO





Dark Matter

Results & Future Prospects

VERITAS Dark Matter Program

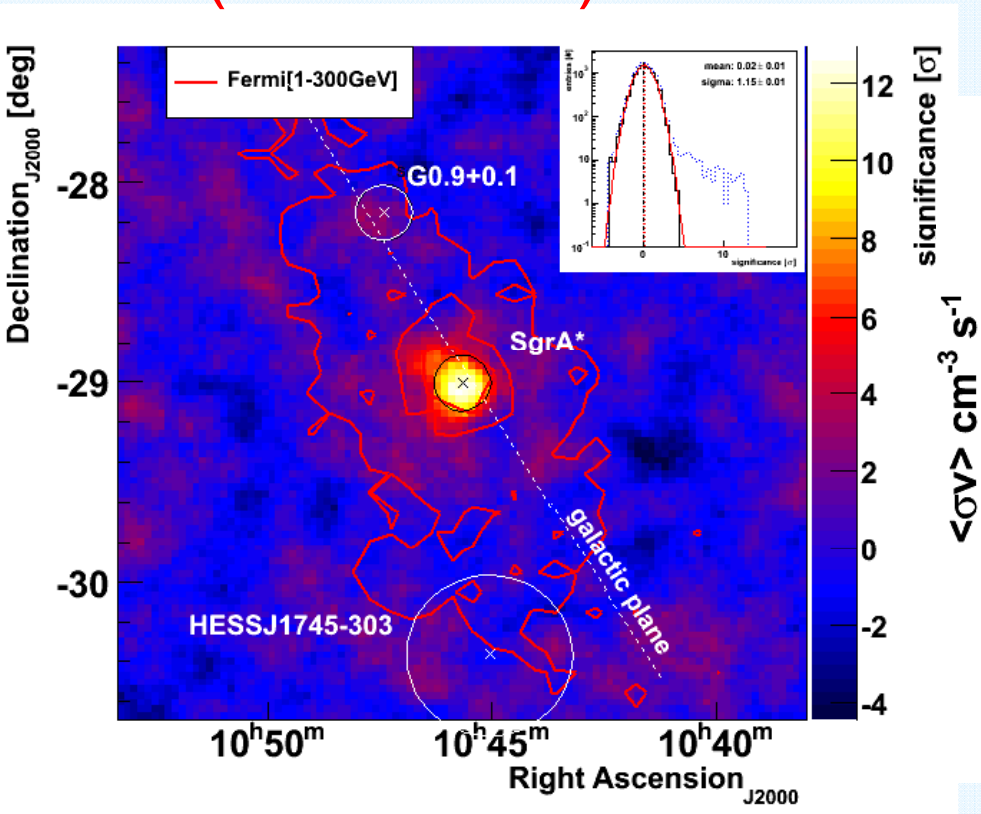
Because of large uncertainties (WIMP mass, σ, astrophysical flux), VERITAS observing strategy targets a variety of potential sources.

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

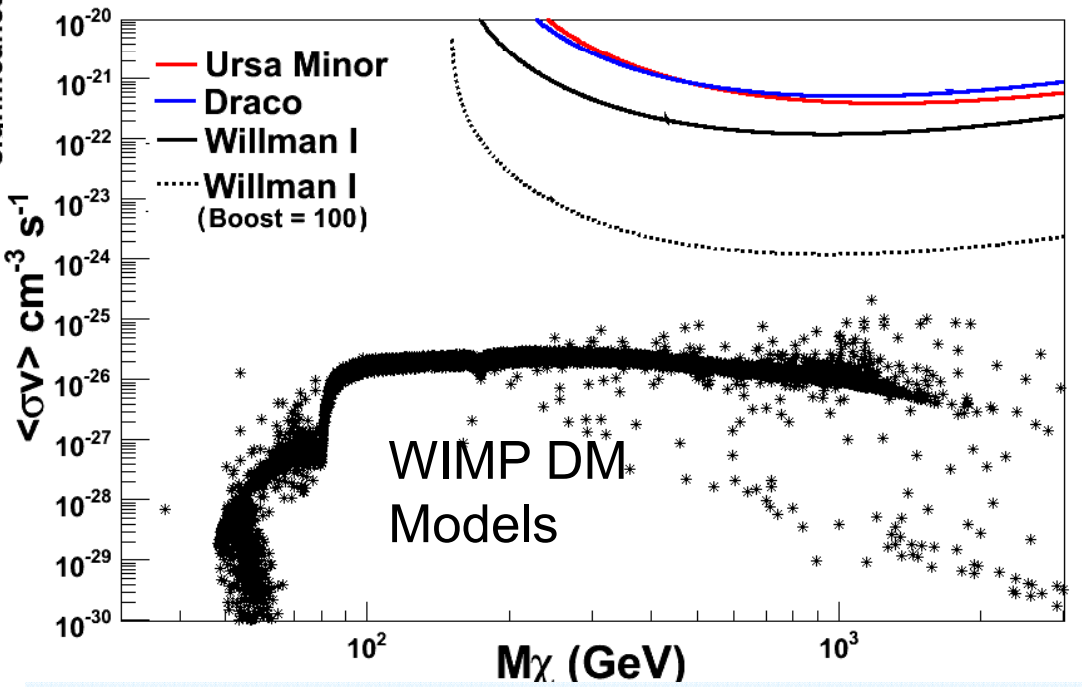
Galactic Center (brand new!)



Strong detection by VERITAS, but interpretation is still unclear.

Dwarf Spheroidal Galaxies

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



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

The GAPS Experiment

Columbia University in the City of New York

Berkeley University of California

UCLA

JAXA Japan Aerospace Exploration Agency

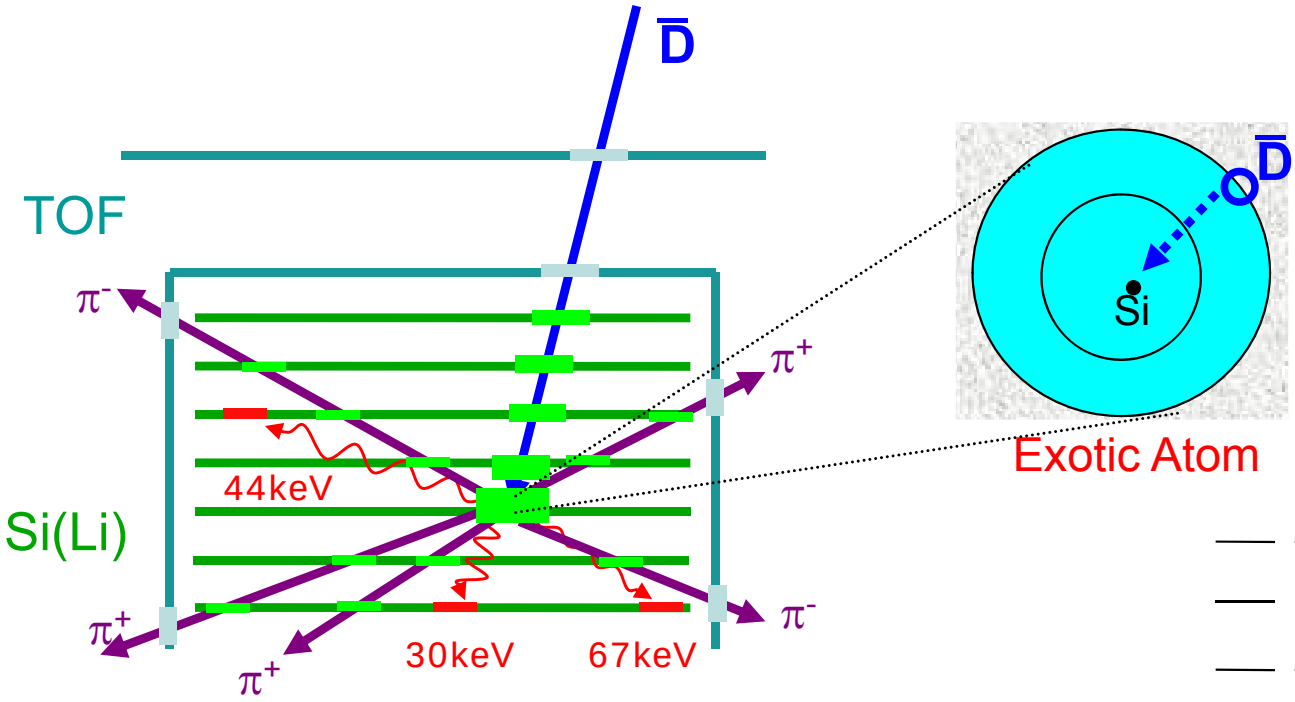
(+ LLNL, Univ. of Latvia)

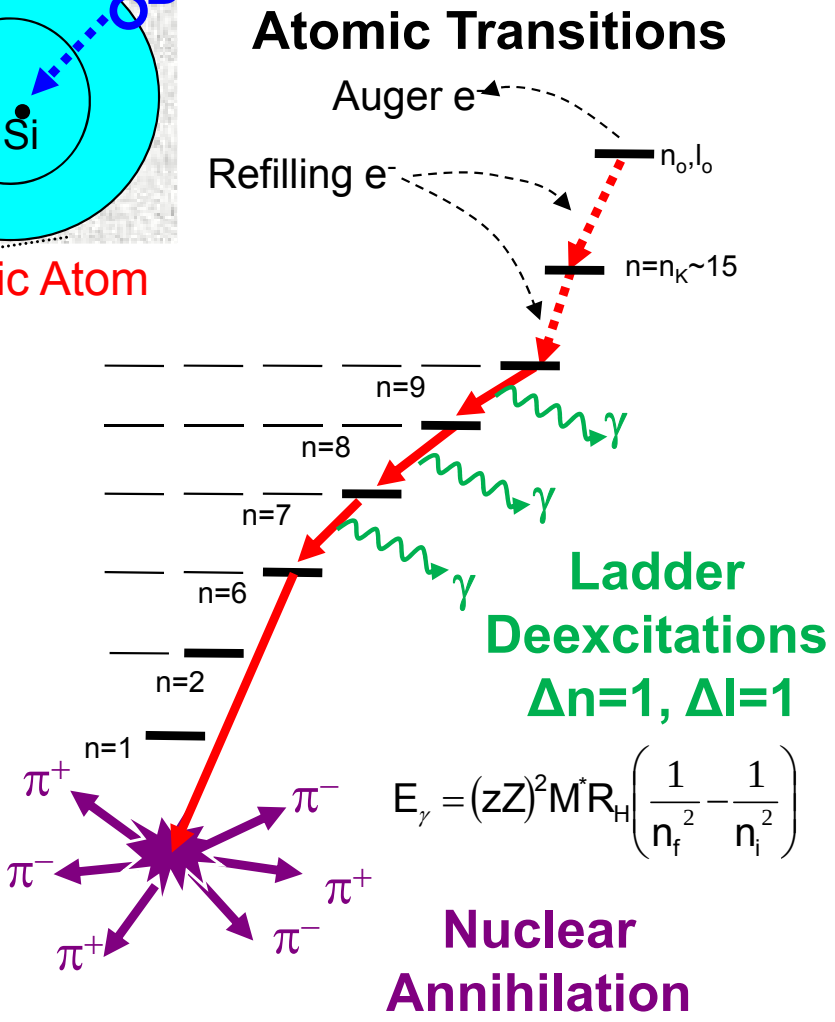
Collaboration meeting, UCB May 2010

T. Aramaki, N. Bando, S. Boggs, W. Craig, P. von Doetinchem, H. Fuke, F.H. Gahbauer, **C. Hailey (PI)**, J. Koglin, N. Madden, I. Mognet, K. Mori, R.A. Ong, A. Takada, T. Yoshida, T. Zhang, J.A. Zweerink

GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).

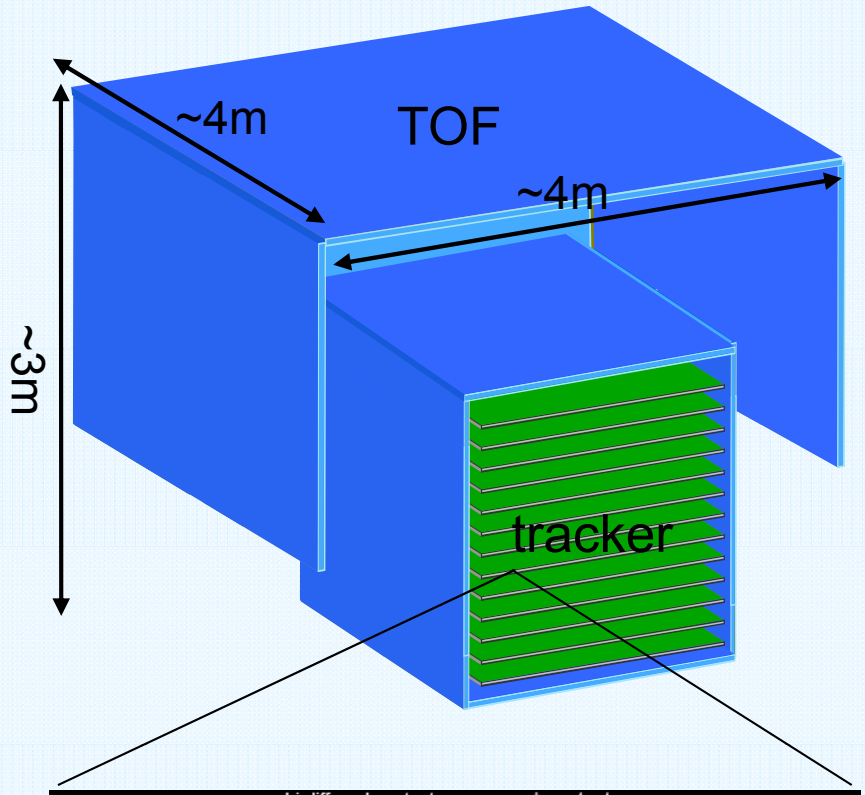


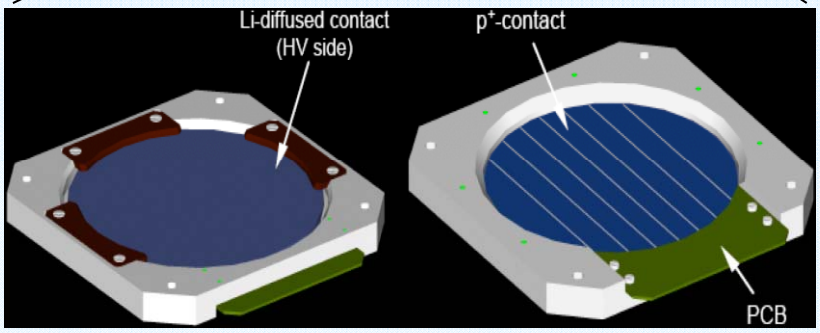


1. Once $\bar{D}$ is slowed down and stopped in the target,
2. an excited exotic atom is formed,
3. which de-excites with emitting X-rays,
4. and annihilates with producing a pion shower.

- Detection principle was verified and high X-ray yield was shown in accelerator tests (KEK antiproton beam, '04 - '05).

GAPS Concept





LD Balloon flight in 2015 ?

GAPS consists of two detectors (acceptance ~2.7 m^2sr):

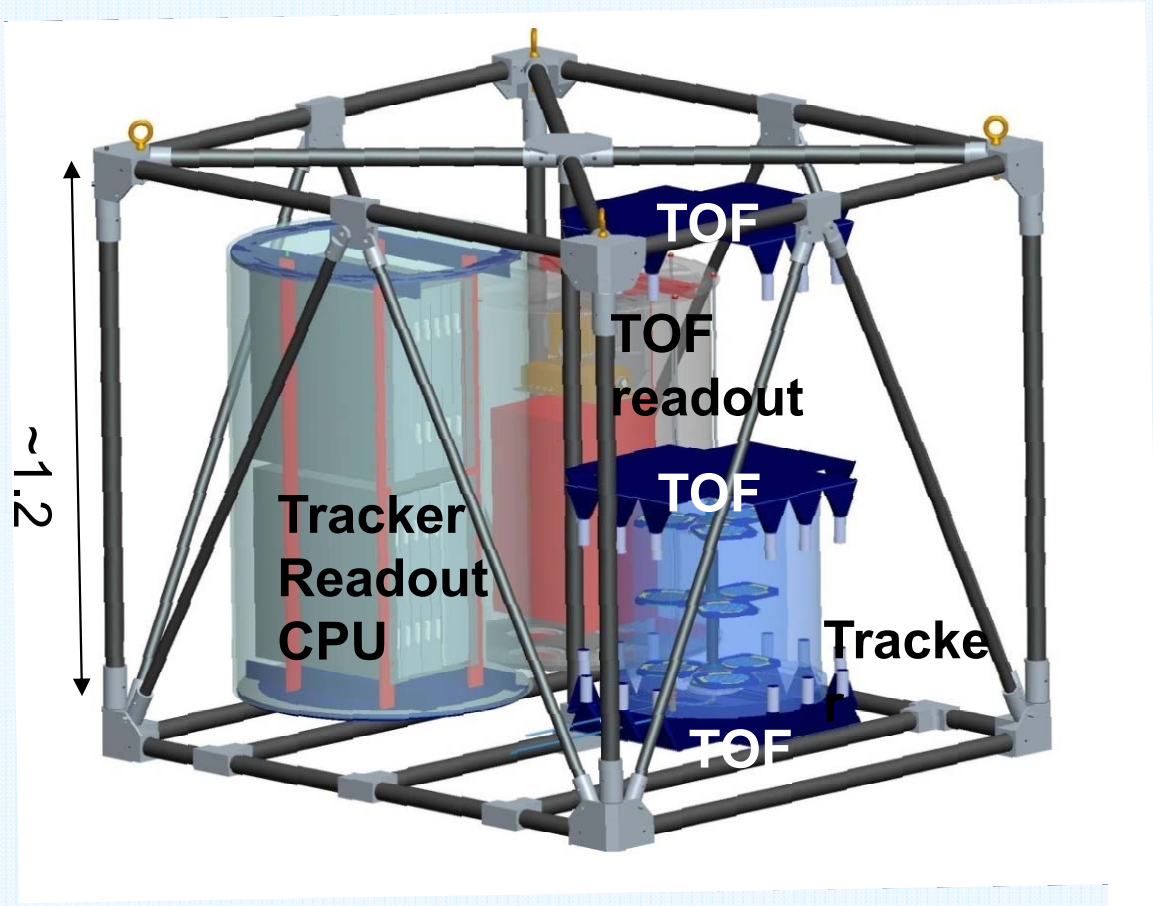
Si(Li) Detector (target and tracker):

- Si(Li) tracker:13 layers of Si(Li) wafers
- relatively low Z material
- good X-ray resolution
- circular modules segmented into 8 strips
  → 3D particle tracking
- 270 per layer (total: ~3500)
- timing: ~50 ns
- dual channel electronics
  5-200 keV: X-rays (resolution:~2 keV)
  0.1-200 MeV: charged particle

Time of flight and anticoincidence shield:

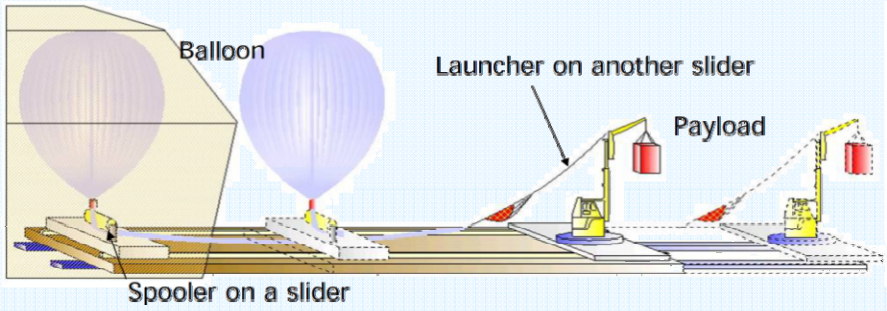
- plastic scintillator with PMTs surrounds tracker
- track charged particles, dE/dX
- velocity measurement
- anticoincidence for charged particles

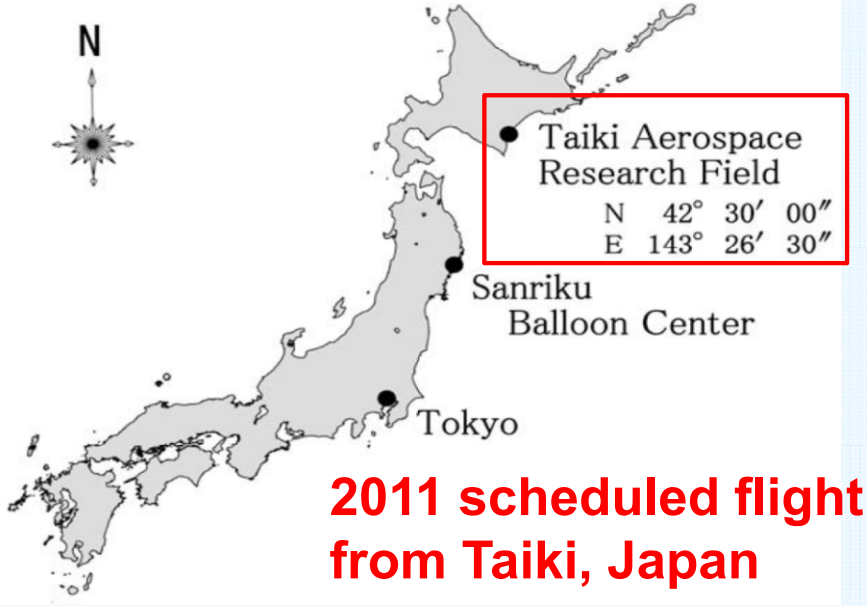
Prototype Experiment



Prototype GAPS (pGAPS) goals:

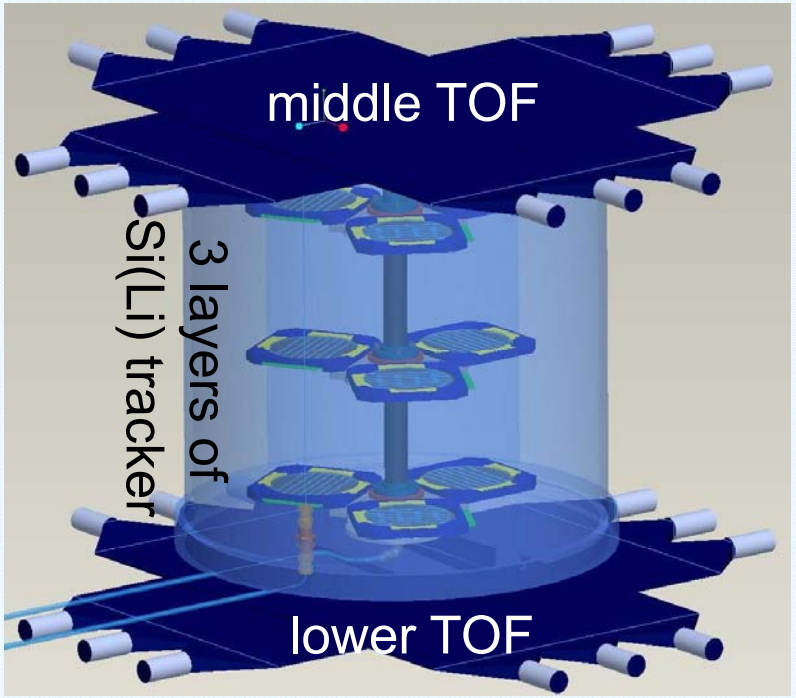
- demonstrate stable, low noise operation of components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model.
- measure incoherent background level in a flight-like configuration.

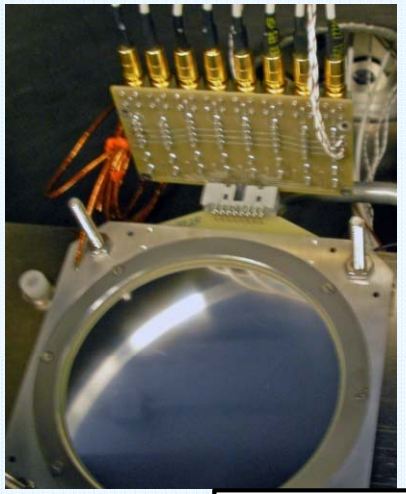


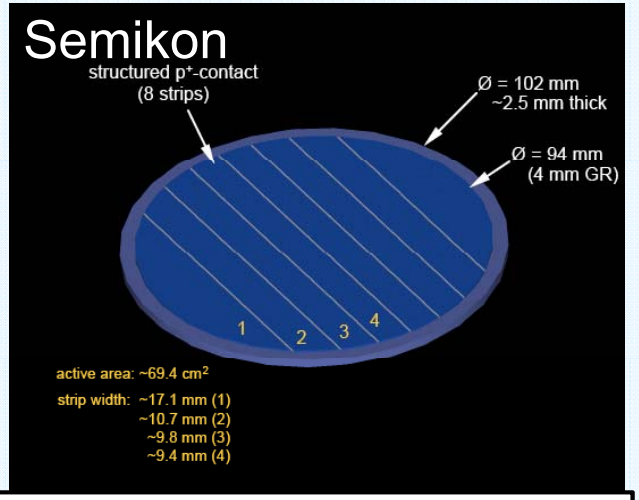


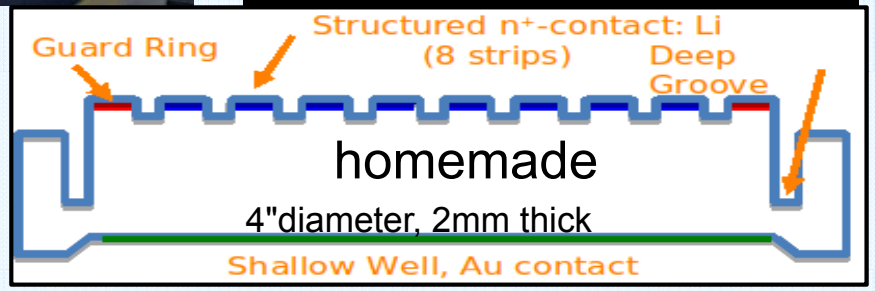
2011 scheduled flight from Taiki, Japan

Si(Li) Tracker



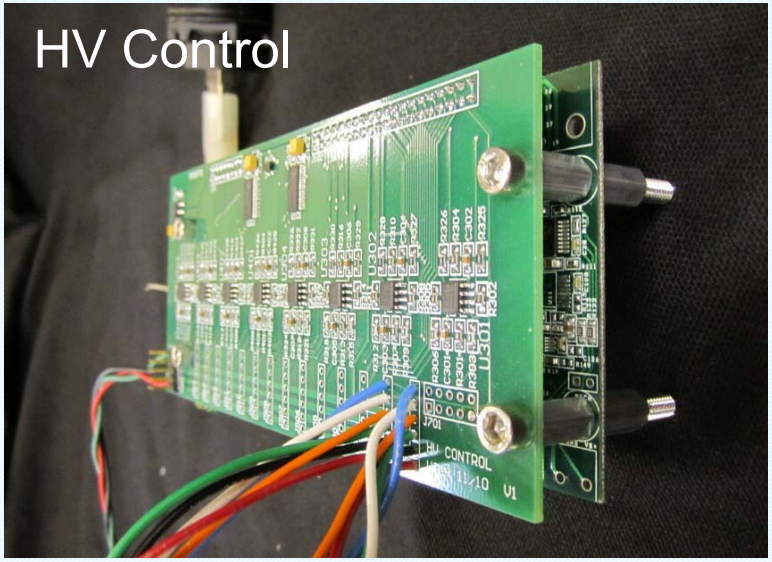


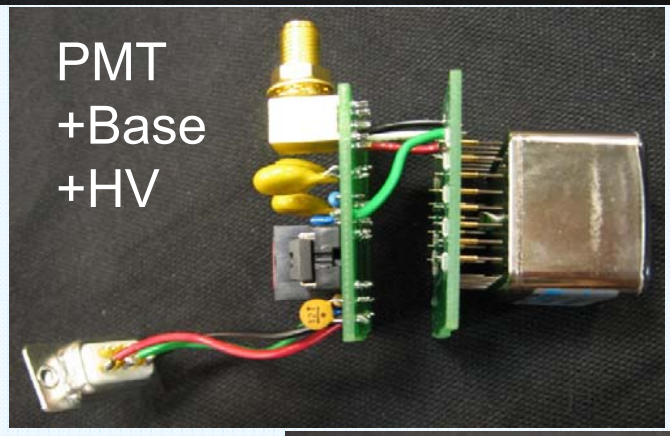


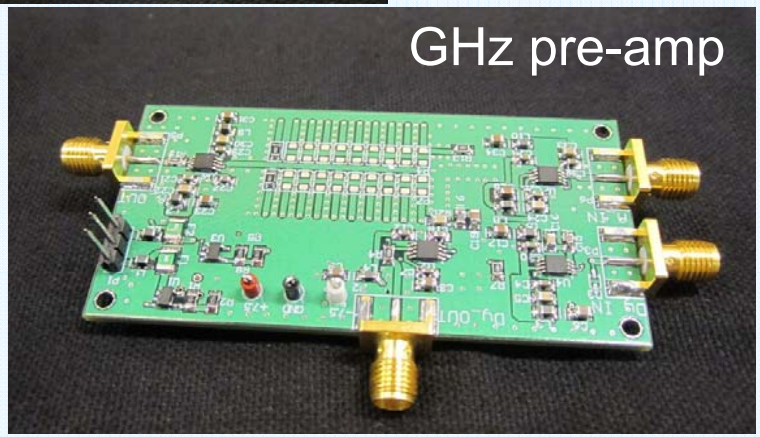


- 6 commercial Semikon detectors.
- homemade detectors
  (test for the bGAPS fabrication).
- Energy resolution < 3 keV @ 60keV.
- operation at ambient pressure.
  (8mbar).
- cooling system delivers: -35°C.

Time of Flight System





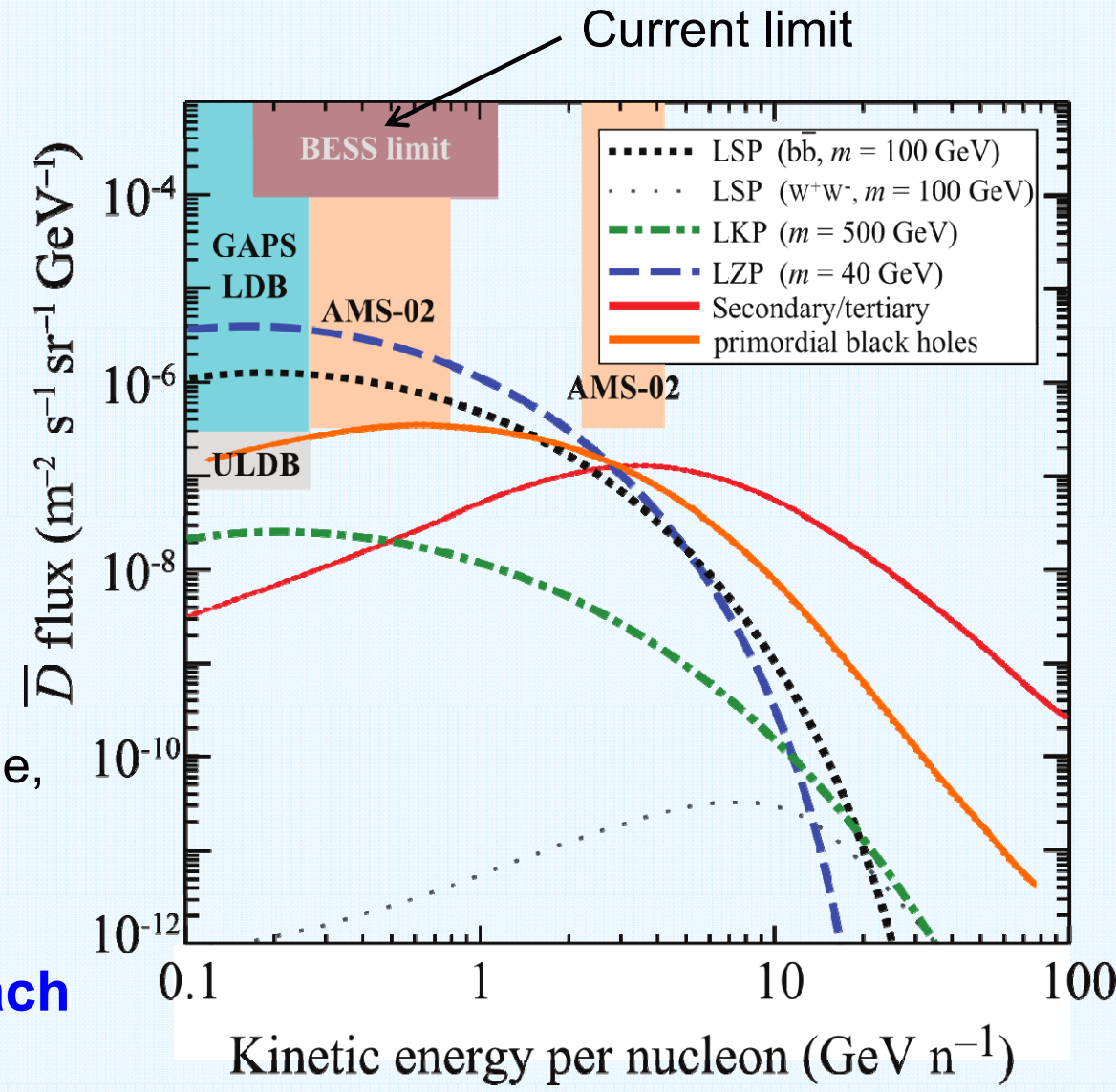


- 3 planes of TOF
  1 plane = 3×3 crossed paddles
  = **18 paddles and 36 PMTs**
- 3mm scintillator (EJ-200, BC-408)
- Hamamatsu R-7600 PMT (UBA)
- timing resolution: **< 400 ps**
- charge resolution: **< 0.30 e**
- angular resolution: **8°**

GAPS anti-D Sensitivity

- Cosmic anti-D have never been detected. Could be produced by new physics.
- Primary anti-D production:
  - Supersymmetry (LSP)
  - Kaluza-Klein UED (LKP)
  - Warped ED (LZP)
  - Primordial BH's !
- Sub-GeV region is background free – the detection of even a single, clean event would be important.

GAPS will extend sensitivity reach by 2-3 orders of magnitude.



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.
- **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.
- **GAPS** is a proposed balloon expt to search for signatures of dark matter in the cosmic rays. Prototype experiment is well underway.

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

Marcel Proust (1871-1922)

VERITAS & GAPS @ Columbia

VERITAS :

Reshmi Mukherjee

Brian Humensky

GAPS :

Chuck Hailey

Thanks !

Reshmi Mukherjee
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Chuck Hailey
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John Parsons
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Mike Shaevitz
Mike Tuts

Bill Zajc
Andy Millis
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Lydia A., Joey C., John C., Rasma M., Randy T., Yasmin Y.

And anyone else that I forgot !