The VERITAS Science Program

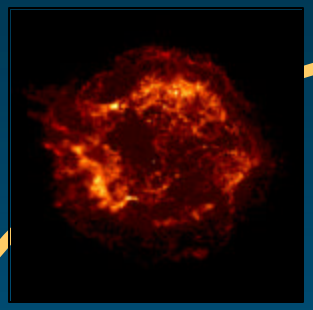
1. **VHE γ-ray Science and VERITAS**
   - Big picture, groups, plans
2. **Four Key Science Projects**
   - Motivation and early results.
3. **Other important science**

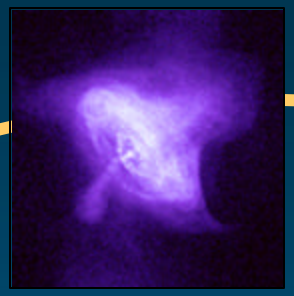
Note: spectra, MWL studies, more results coming.

VHE γ-ray Science

Origin of Cosmic Rays

SNRs

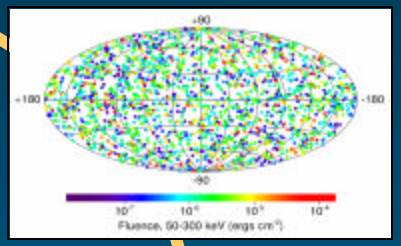


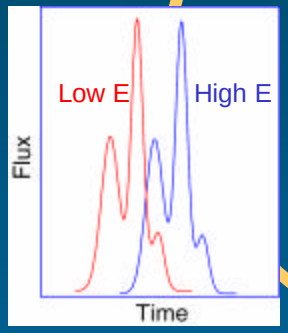


Pulsars

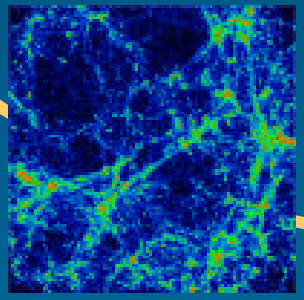
Microquasars

GRBs

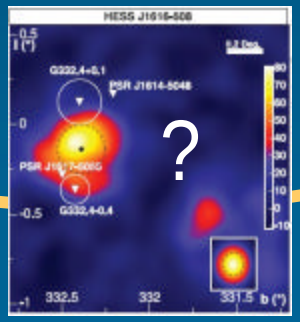




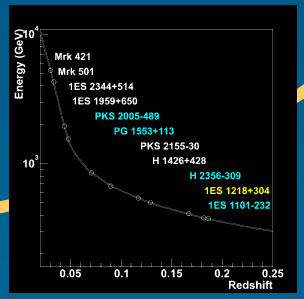
Testing Lorentz Invariance



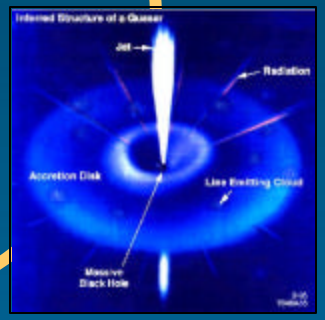
Cold Dark Matter



Something New !



cosmological γ-Ray Horizon



AGN

Credit: M. Martinez

Science Working Groups

Astroparticle	S. Wakely (U.Chicago)
Blazars	H. Krawczynski (Wash U.) / P. Moriarty (GMIT)
Dark Matter	J. Buckley (Wash U.) / K. Byrum (ANL)
Extragalactic	V. Vassiliev (UCLA) / R. Mukherjee (Barnard)
Gal. Compact	W. Cui (Purdue) / J. Kildea (SAO)
Gal. Diffuse	D. Carter-Lewis (ISU) / S. LeBohec (U.Utah)
GRB's	T. Weekes (SAO) / D. Williams (UCSC)
Sky Survey	R. Ong (UCLA) / P. Kaaret (U.Iowa)
SNRs/PWN	S. Swordy (U.Chicago) / J. Holder (Bartol)
UnID's	R. Mukherjee (Barnard)

Other Important Input

External Science Advisory Committee

M Baring, C. Dermer, E. Dwek, T. Gaisser, N. Gehrels,
S. Kahn, M. Kamionkowski, A. Marscher, R. Romani (Chair)

Other HE/VHE Telescopes

AGILE, GLAST
CANGAROO, HESS, MAGIC, Milagro
AMANDA/IceCube

Associate Members and Multiwavelength Partners

Observers in other wavebands, theorists.

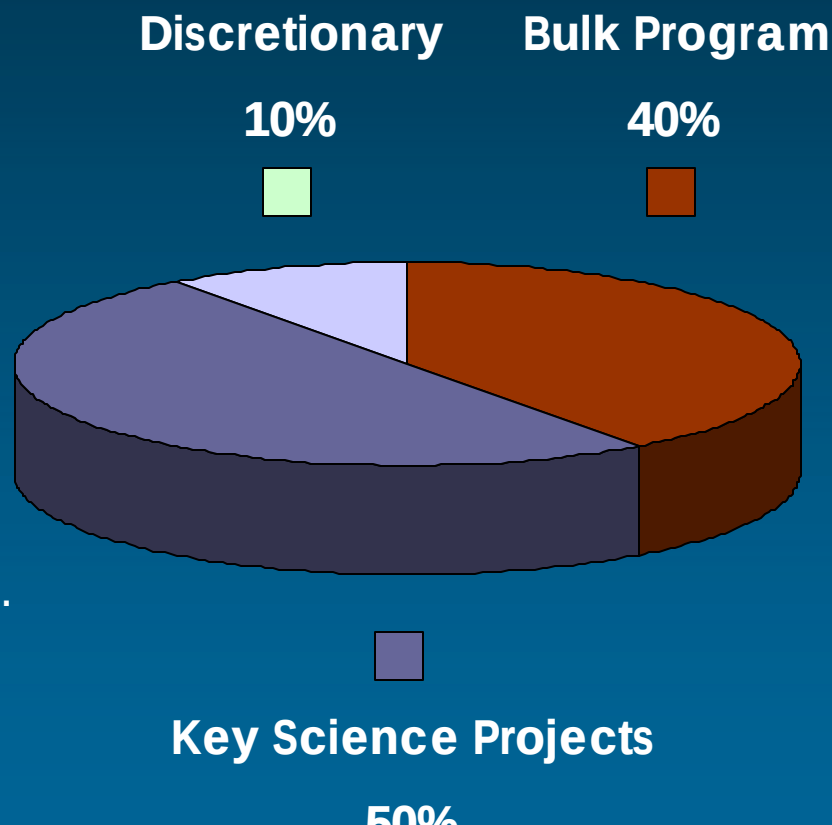
Apologies for any omissions !

General Science Plan

- Key Science Projects:
  - Four highlight science topics.
- Bulk Science Program
  - All possible topics.
  - Determined by TAC selection.
- Discretionary Time
  - ToO's, unique topics, engineering.
  - Determined by Spokesperson.

NEW !

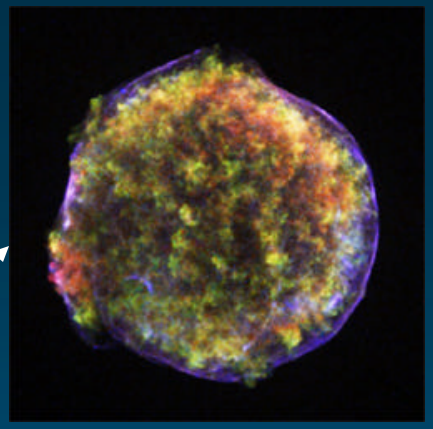
24Apr 2007: ToO observations of a HMXB with Swift



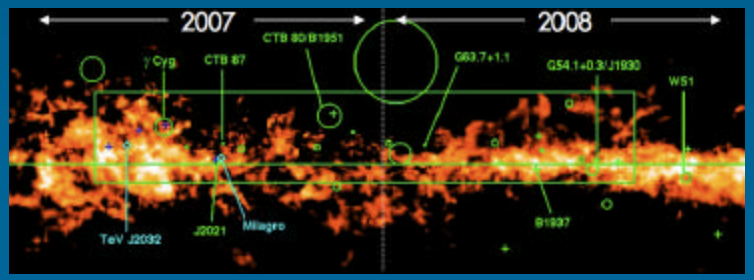
Key Science Projects

BLAZARS

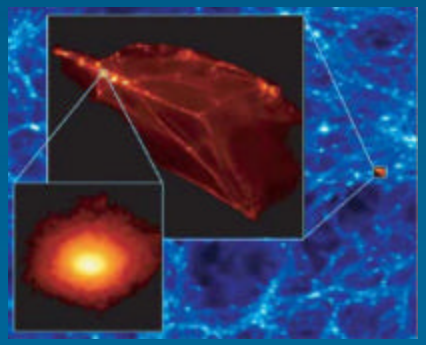
VERITAS



SNRs/PWN



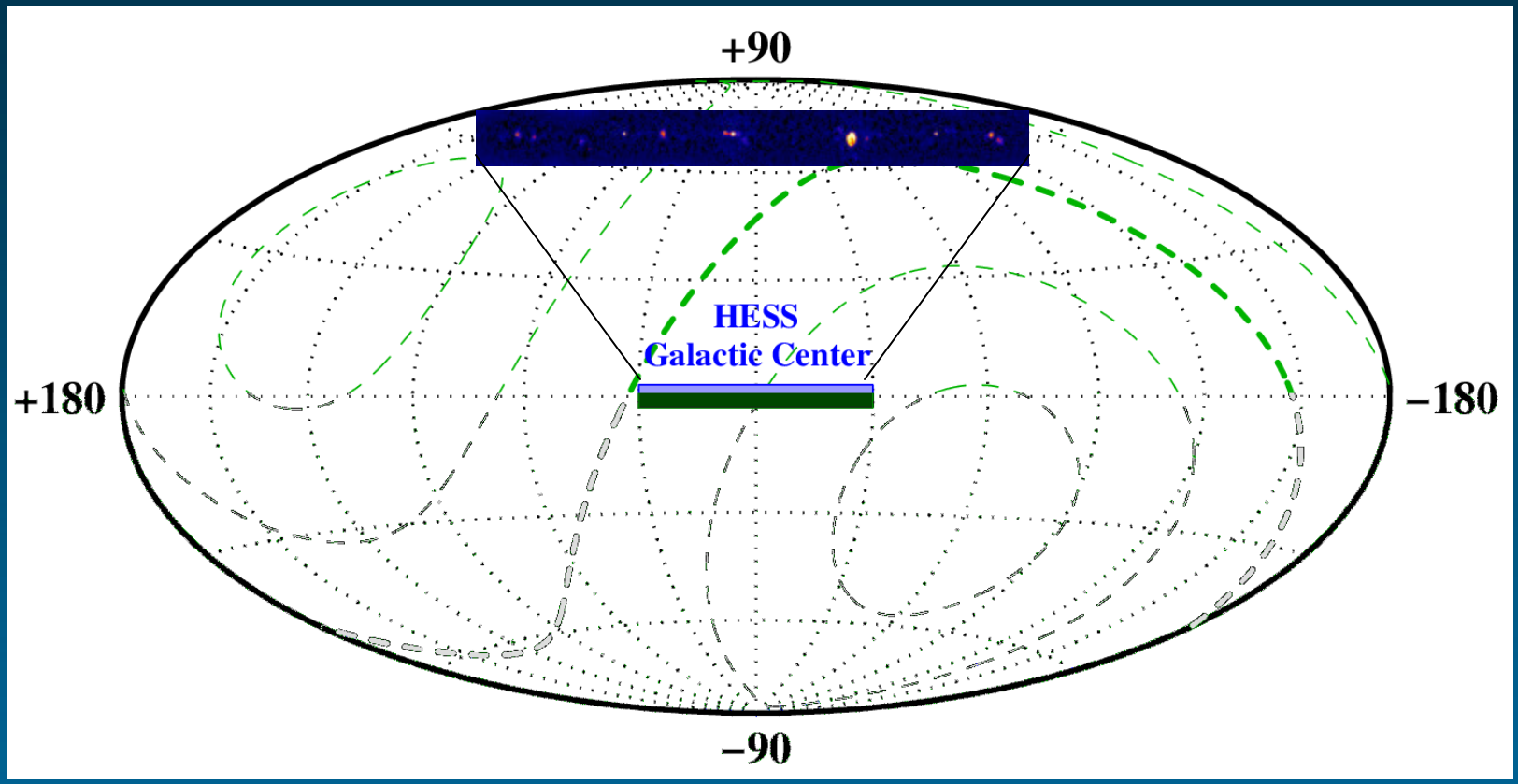
SKY SURVEY



DARK MATTER

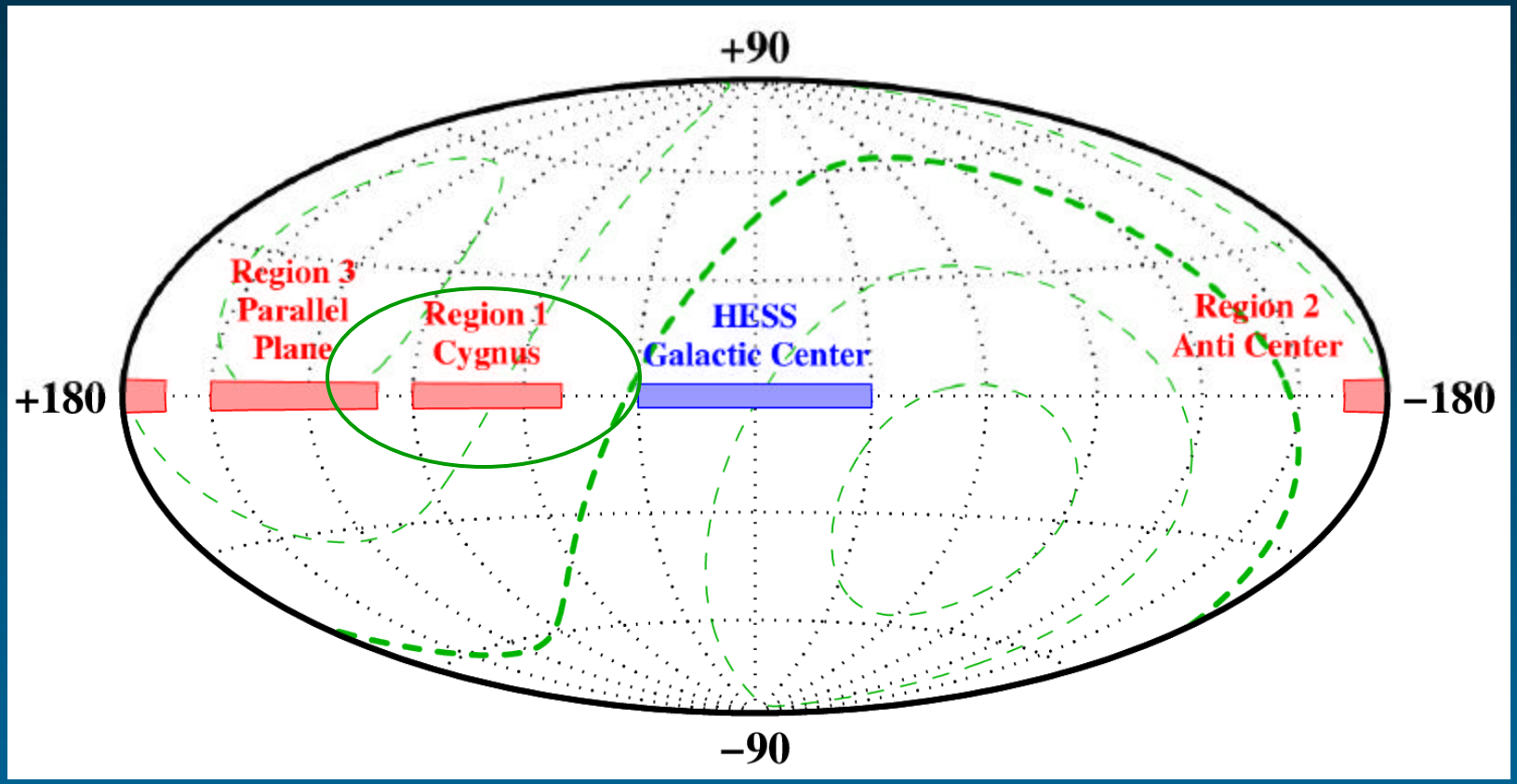
Sky Survey

HESS Survey



- 360 deg² centered on Galactic Center.
- Sensitivity 3% of Crab between b=±2 º.
- > 25 sources detected !

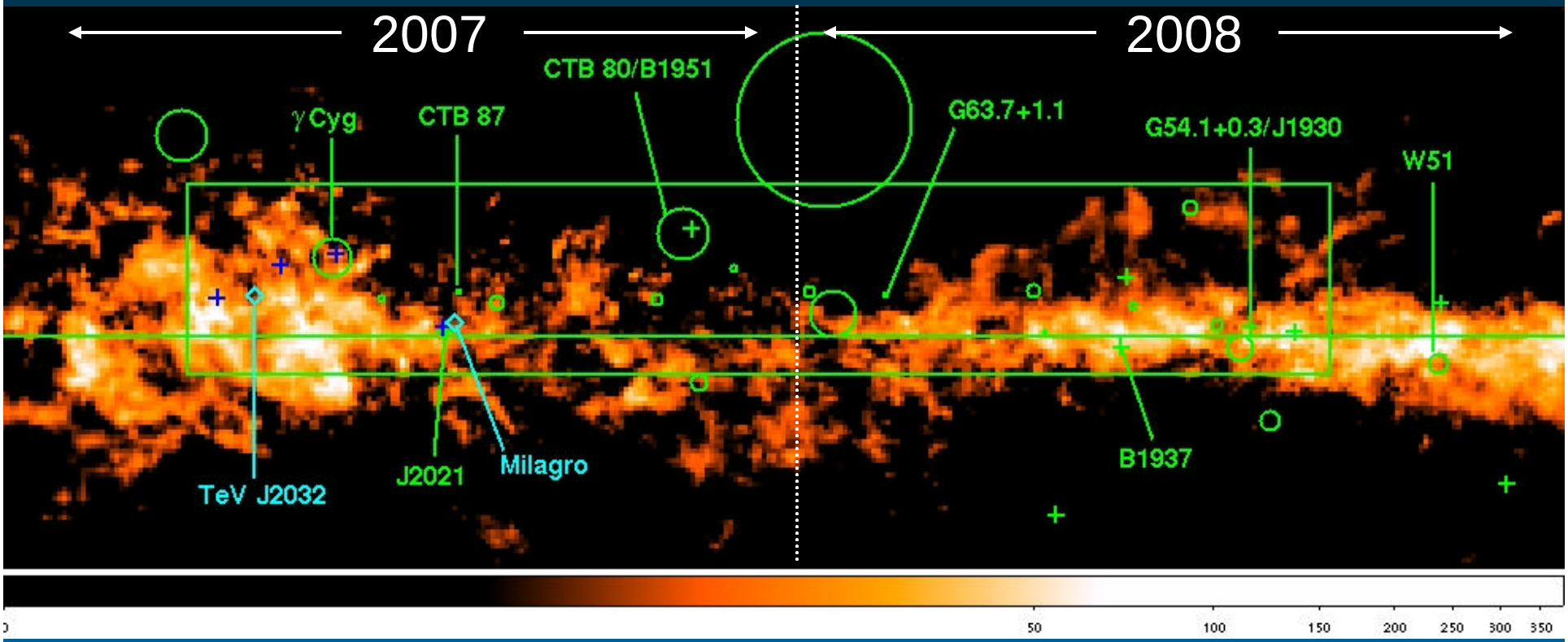
VERITAS Survey Regions



- 3 regions of Galactic Plane, start with Region 1.
- Sensitivity of ~5% of Crab.
- Surveyed earlier by HEGRA and Milagro.

Cygnus Arm

P. Kaaret



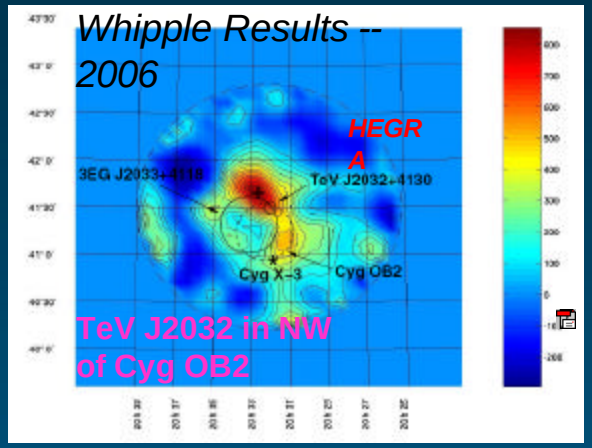
CO map, with circles=SNRs, blue pluses=EGRET GeV, green pluses=pulsars.

Most obvious targets:

SNRs, PWN, EGRET sources, X-ray binaries, VHE sources.

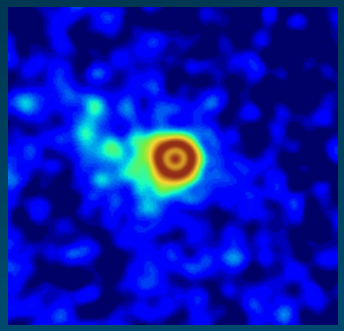
Many Targets

UNID TeV



TeV 2032 (HEGRA, Whipple, etc.)

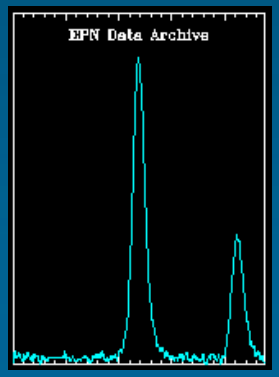
SNRs/PWN



CTB 80 (Einstein)

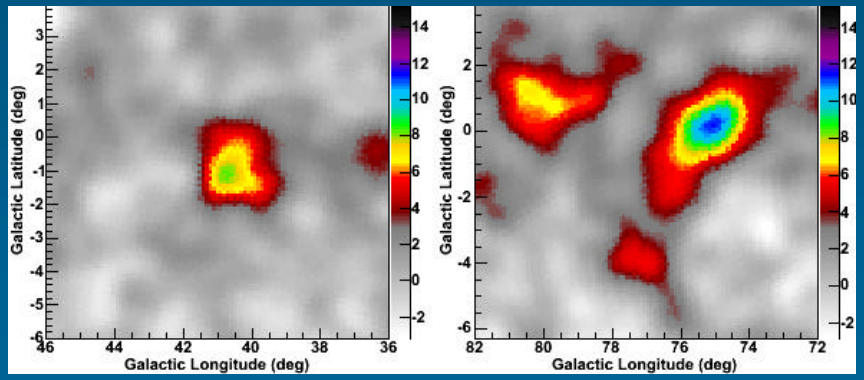
IC 1318 (γ-Cygni) (Palomar-DSS)

Pulsars



PSR 1937+21 (1.6 ms) (Jodrell Bank)

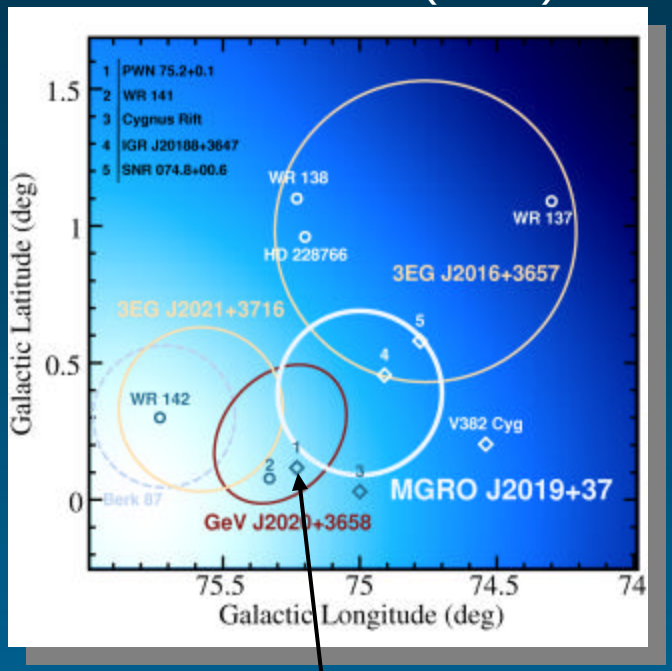
UNID TeV

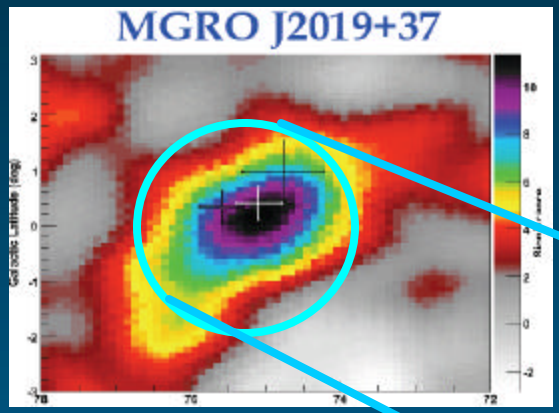


MGRO J1909+06	~1 Crab
MGRO J2019+37	~500 mCrab
MGRO J2033+42	~ 300 mCrab

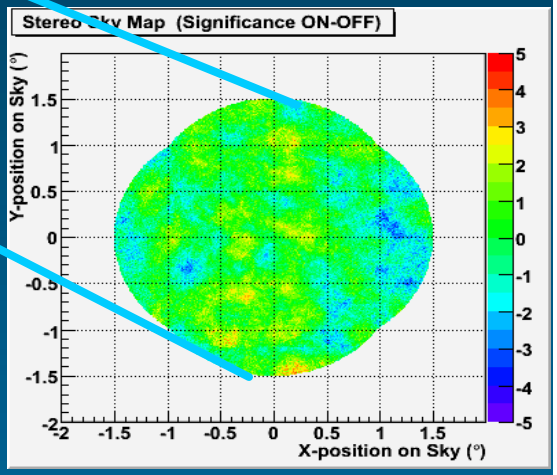
MGRO J2019+37 Region

Beacom & Kistler (2007)





VERITAS



Upper limit from VERITAS at PSR J2021 (PWN 75.2 +0.1).

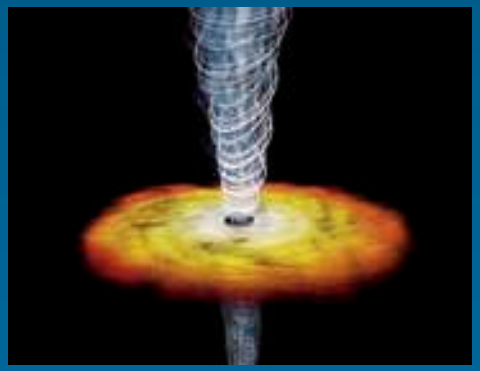
10 hr of data (T1-T2)
< 5 % Crab flux (pt. source)

Clearly an interesting region that requires more observation.

BLAZARS

BLAZAR KSP

- VERITAS observations will be carried out with the array of four 12-m telescopes.
- Observing plan includes new blazars as well as monitoring of well-known TeV blazars.
- Whipple 10m telescope will be used to monitor blazars. In case of strong flares, the VERITAS array would be used for follow-up observations.
- VERITAS follow-up observations will yield superior sensitivity data, with highly reliable energy spectra.



MWL Observations

Broadband data of VERITAS blazars will be key to understand the g-ray emission from TeV blazars.

VERITAS has set up collaborations with numerous observatories to assure excellent multiwavelength coverage:

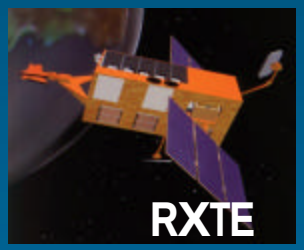
Radio: University of Michigan Radio Astronomical Observatory, Metsähovi Radio Observatory, and the Owens Valley Radio Observatory (OVRO), RATAN.

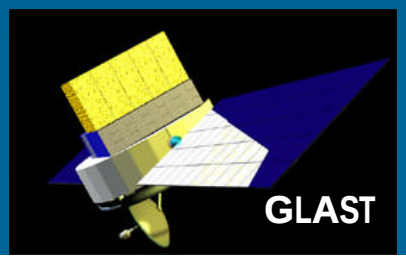
Infrared/Optical: PARITEL, Boltwood Observatory, Antipodal Observatory, Bordeaux Observatory, Bell Observatory, Abastumani Observatory, Coyote Hill Observatory, New Mexico Skies Observatories, Tuorla, Perugia, FLWO 48-inch, Bradford Robotic, Tenagra, WIYN.

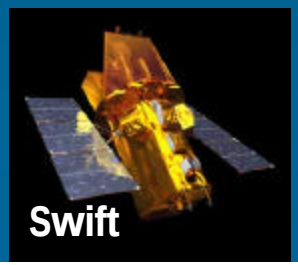
X-Rays: Guest observer time with Rossi X-Ray Timing Explorer (RXTE), INTEGRAL, Swift, XMM, Suzaku.

Gamma-Rays: H.E.S.S. and MAGIC (joint campaigns and mutual flare alerts), Whipple 10m, AGILE and GLAST (guest observer time and collaborative research).

OVRA







VERITAS/MAGIC/HESS Joint Observations

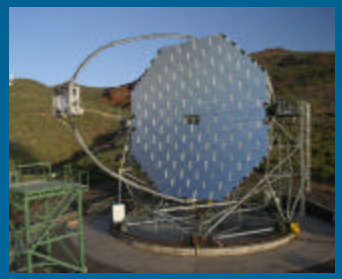
Maximize scientific output by cooperating as much as possible.

- Agreement with MAGIC & HESS on list of sources to send out alerts in case of a strong blazar flare.
- Alerts to be sent to the VERITAS collaboration: blazar@veritas.sao.arizona.edu. Emails sent to this address will be forwarded to the observers on shift.
- Cooperate on joint satellite observations (X-ray).
- Bi-monthly telecons with HESS/MAGIC and VERITAS Blazar SWG.
- Agreements expected to evolve a little over time. Eventually, expect to have similar, if not identical agreements between all the collaborations.

VERITAS/HESS/MAGIC Alert Sources

Object	Alert Threshold (Crab)
Mrk 421	2.0
Mrk 501	2.0
PKS 2155-304	1.0
H 2356-309	0.5
1ES 1218+304	0.5
1ES 1101-232	0.5
PG 1553+113	0.5
1ES 2344+514	0.5
1ES 1959+650	0.5
H 1426+428	0.5
BL Lac	0.5
Mrk 180	0.5

MAGIC



Catalog of TeV Blazars (2007)

Blazars:

Object	z
Mrk 421	0.031
Mrk 501	0.034
1ES2344+514	0.044
Mrk 180	0.046
1ES 1959+650	0.047
PKS 0548-322	0.069
1ES 2200+420	0.069
PKS 2005-489	0.071
PG 1553+113	>0.09
PKS 2155-304	0.116
H 1426+428	0.129
1ES 0229+200	0.139
H 2356-309	0.165
1ES 1218+304	0.182
1ES 1101-232	0.186
1ES 0347121	0.188

Blazars (?) with off-axis emission:

Object	z
M87	0.004

= Whipple/VERITAS

VERITAS is able to access the northern-sky TeV blazars.

Recent VERITAS results:

- Detection of Mrk 421, Mrk 501 with 2-Tels.
- Mrk 421: Strong detection, ~25σ in < 6hrs.
- M87: a first light curve has been produced.
- 1ES 1218+30.4 is strong emitter of TeV γ-rays.
- Other BL Lacs observed – stay tuned !

VERITAS Observations of M87

M87: Only radio galaxy with TeV emission (Aharonian et al. 2003, 2006).

Nearest giant radio galaxy. Distance ~ 16 Mpc.

R.A., Dec: 12 30 49.4 Dec. +12 23 28.04

Redshift: 0.004

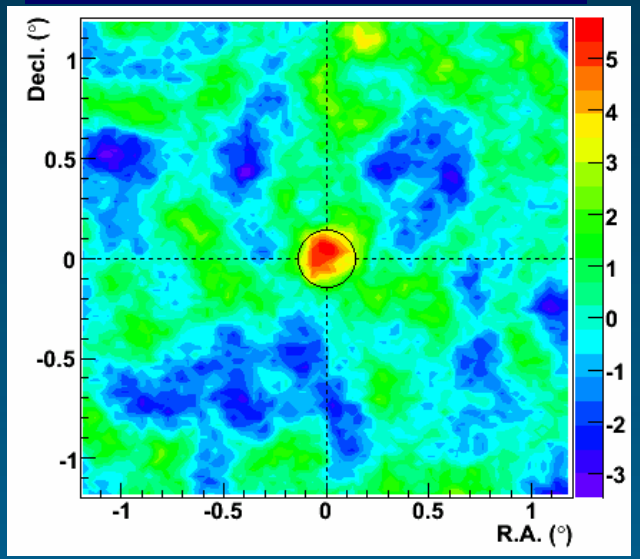
VERITAS Observations:

February-April, 2007 (~ 32 hrs)

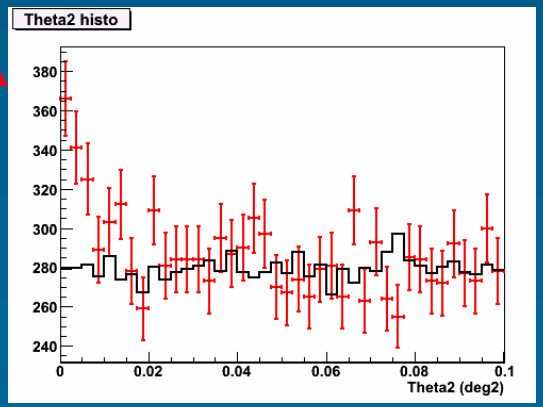
Excess: 5.1σ

Flux: 1.5%-2% Crab.

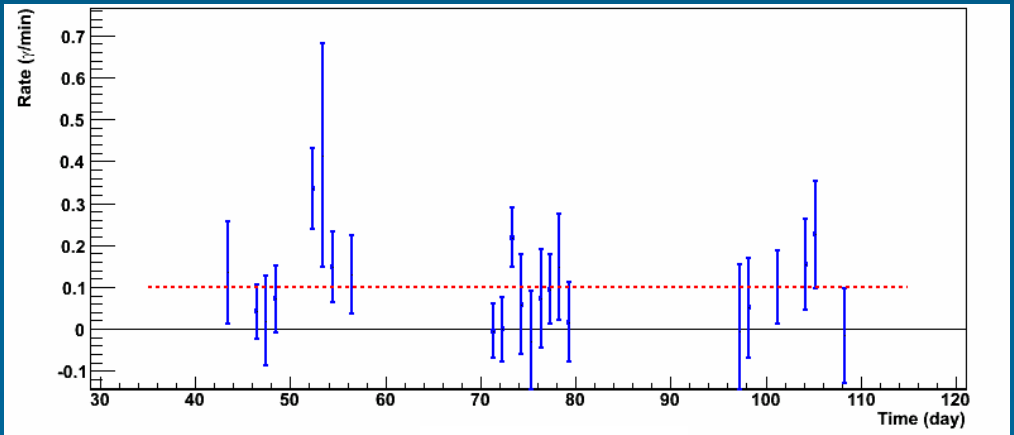
Map of excess significance in the surrounding of M87.



Theta-sq distribution is consistent with pt. source.



M87 Light Curve



Day of Year

VERITAS Observations of 1ES 1218+30.4

1ES1218+30.4:

One of most distant BL Lac objects discovered at TeV γ-rays (MAGIC, Albert el al. 2006)

R.A., Dec: 12 21 21.9, +30 10 37.1

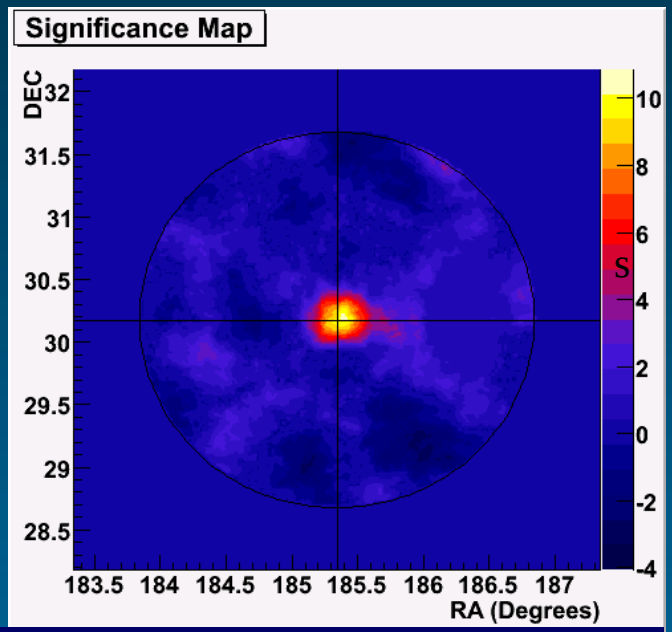
Redshift: 0.182

VERITAS Observations:

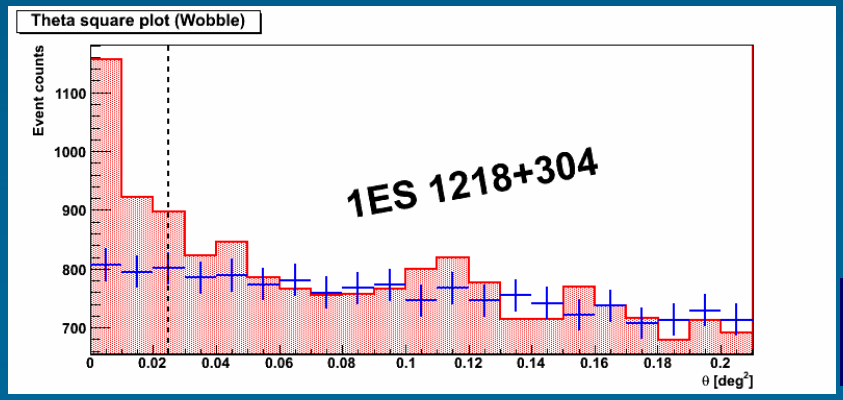
Dec. 2006 - March 2007 (~ 29 hrs)

Excess: 13 s

Flux: ~5% Crab.



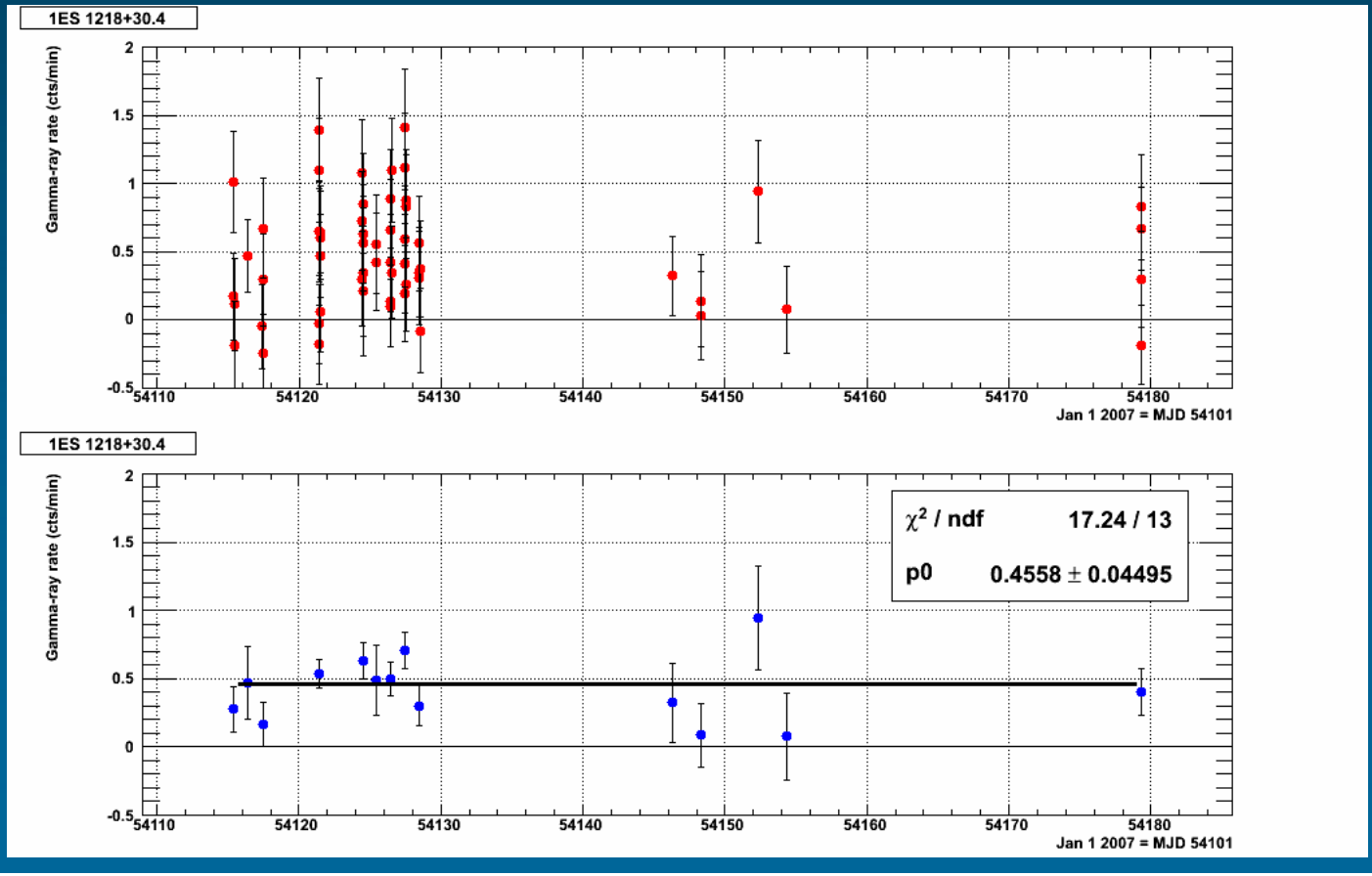
Map of excess significance in the surrounding of 1ES 1218+30.4



Theta-sq distribution of 1ES 1218+30.4

VERITAS Observations of 1ES 1218+30.4

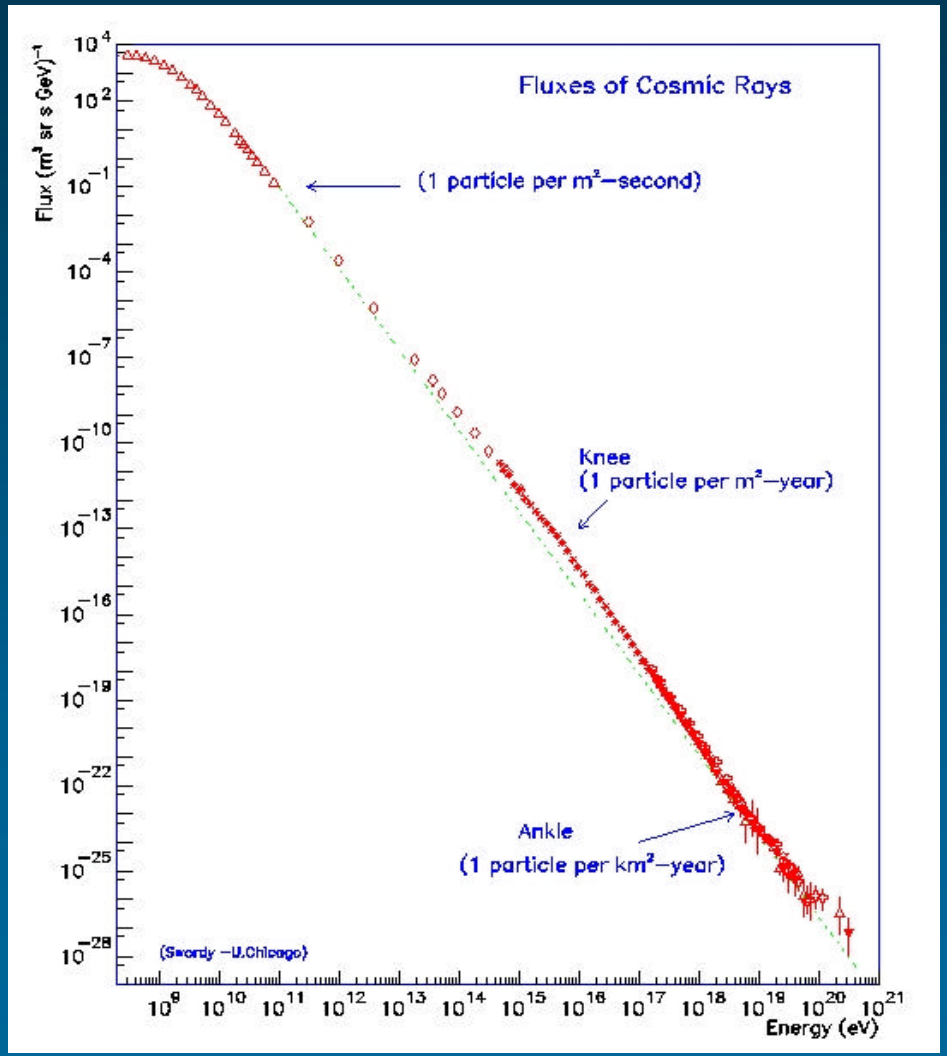
1ES 1218+304 Lightcurves:
Top: run-by-run averages
Bottom: daily average



SNRs / PWN

Targets: Supernova Remnants

- Galactic cosmic rays are believed to be accelerated by shock acceleration in the expanding shells of supernova remnants.
- But there is no direct evidence of this - the charged particles lose their orientation in magnetic fields.
- The original motivation for high energy gamma-ray astronomy was to find this evidence.
- Gamma-rays from π^0 decay can provide direct evidence for diffusive shock acceleration of cosmic rays.

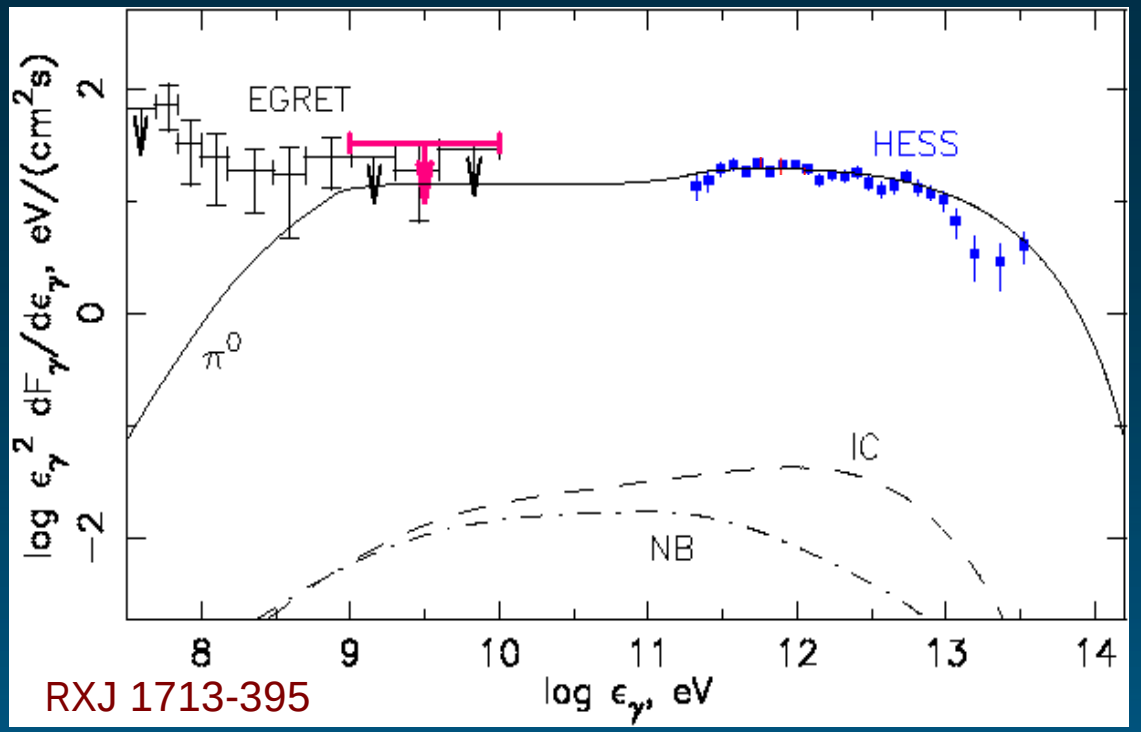


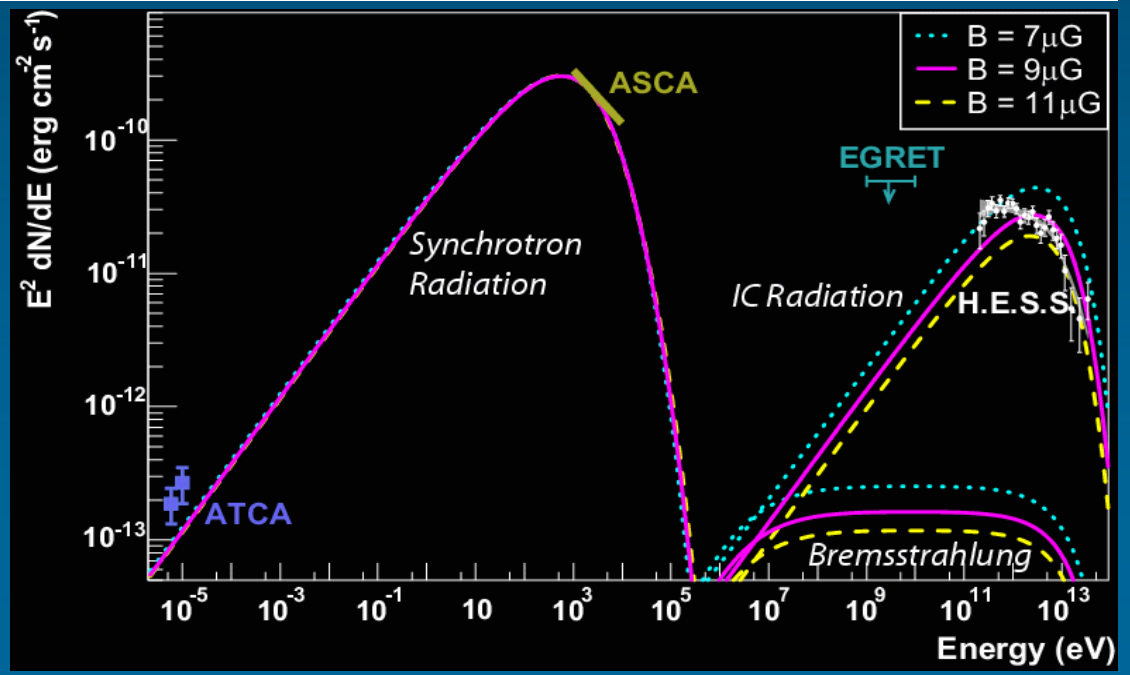
Supernova Remnants

BUT Emission depends on

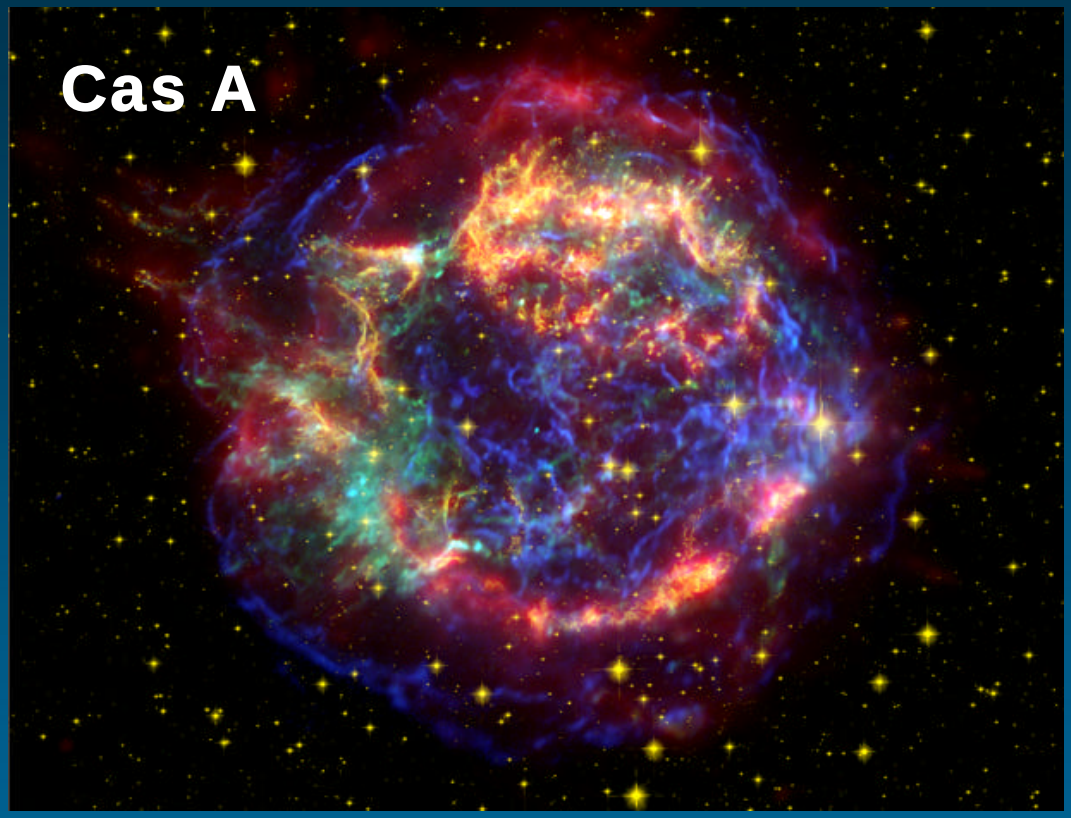
- Age
- Distance
- Expansion velocity
- Radiation environment
- Matter environment
- Magnetic field
- Morphology
- Progenitor
- etc.

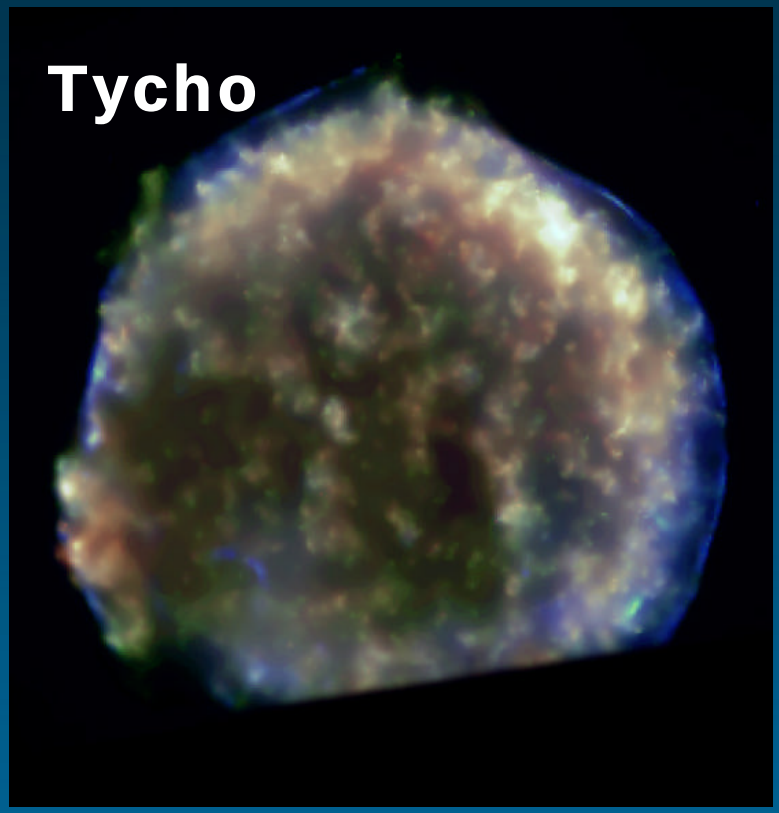
- Can model the emission as due to pion decay or inverse compton emission by relativistic electrons.
- Need population studies.
- Need better data.





Northern Hemisphere SNRs



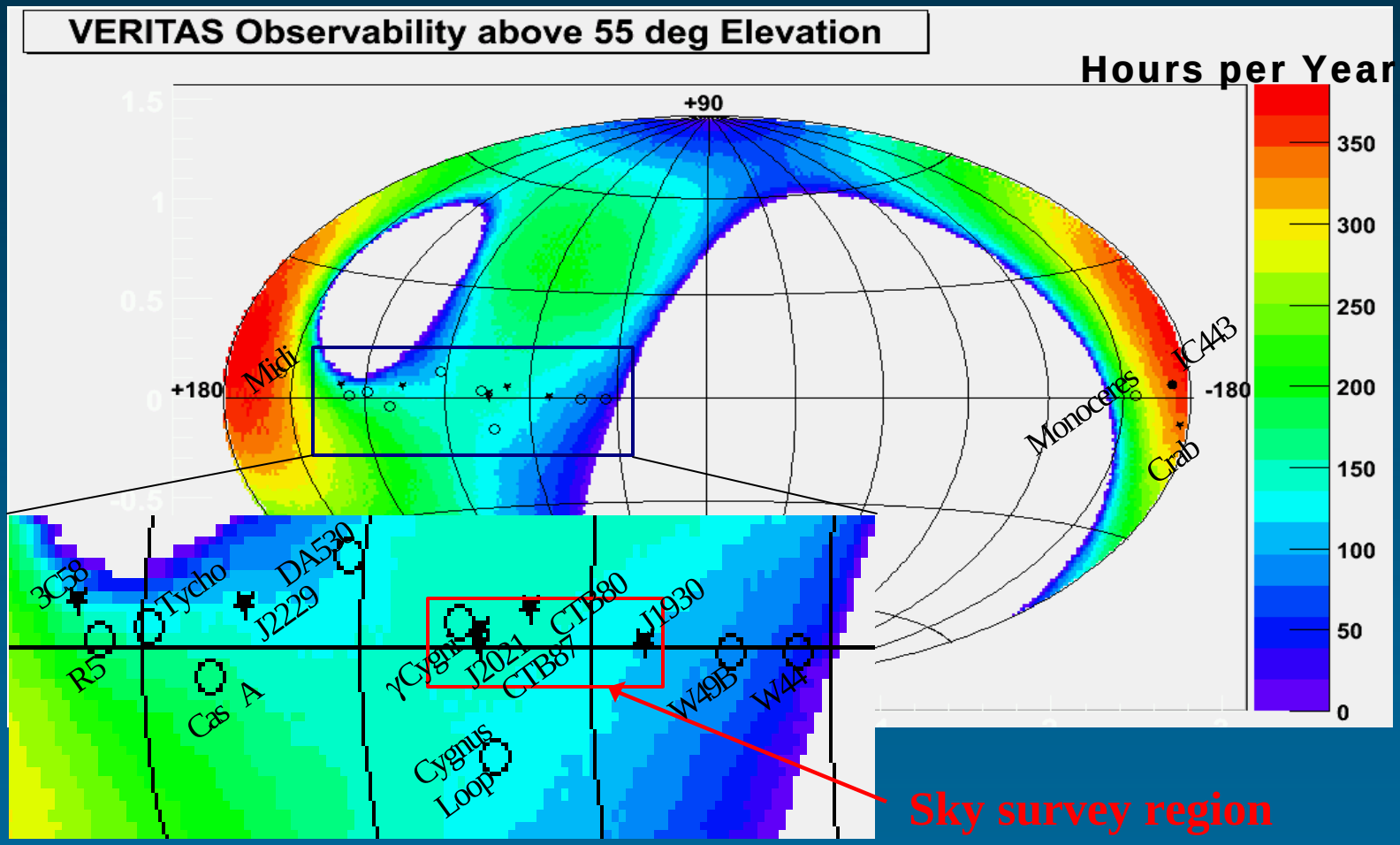


- Cassiopia A; 300 years old; Type II; HEGRA detection 0.03 Crab.
- Tycho; 430 years old; Type Ia; HEGRA upper limit 0.03 Crab.
- Also IC443, g-Cygni etc. etc.

SNR Key Science Project

- **Understand the role of SNRs in cosmic-ray acceleration.**
- **Increase the population of known TeV emitters**
  - Determine the factors which lead to cosmic-ray acceleration.
- **Study particle acceleration (hadronic and leptonic)**
  - What is the maximum energy achievable in shock acceleration?
  - Where does particle acceleration occur?
- **Use the spectral shape, morphology, and MWL information to discriminate between acceleration models.**
  - Even upper limits can place important constraints on models.
  - What are the conditions that lead to efficient cosmic-ray acceleration?
- **Study shell/nebula structure and evolution.**
  - **Constrain shell, nebula magnetic fields.**
  - Study reverse shock compression/asymmetries in surrounding medium.
  - Expansion rate and age of nebula.
- **Probe interstellar medium.**
  - Indirect measure of local photon densities.

SNR / PWN Observability



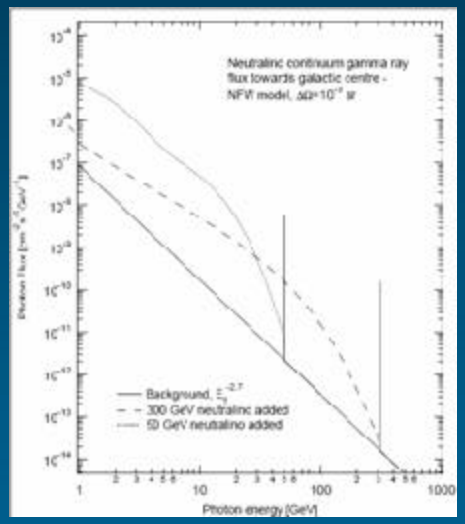
VERITAS has observed several SNR/PWN – results at ICRC 2007.

DARK MATTER

DM Key Science Program

Plan for first two years:
Observe a variety of targets that may harbor Dark Matter.

Favored" mechanism for gamma-ray production by Dark Matter is pair annihilation of neutralinos producing a mono-energetic line plus a continuum of gamma rays.

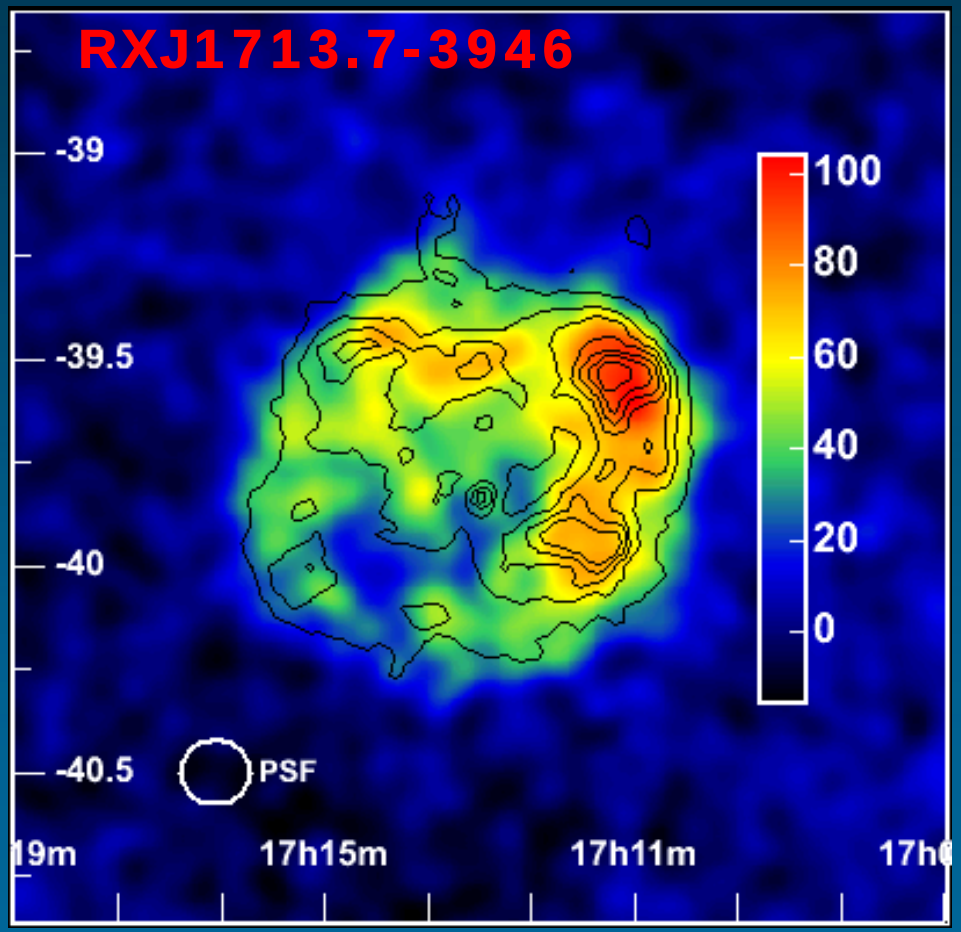


Since mechanism, mass, cross sections, astrophysical dynamics are poorly known, it's wise to survey a variety of sources:

- **Dwarf Galaxies –** large mass to light ratio.
- **Globular Clusters –** dense core could give rise to DM cusp?
- **Galaxy Clusters –** DM dominated with known density profile.
- **Nearby Galactic Nuclei –** possible cusp of DM near center.

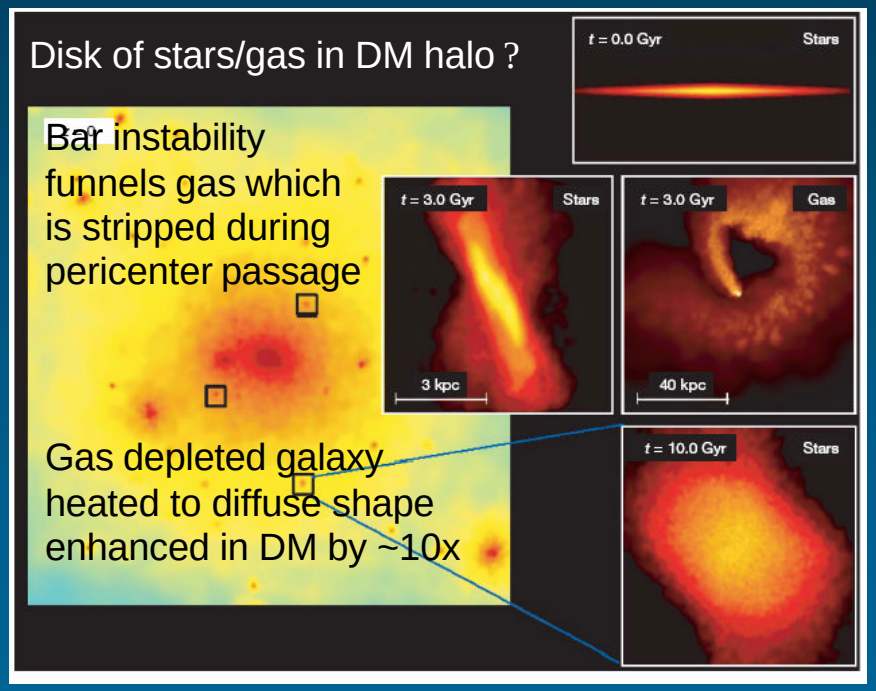
Targets: Supernova Remnants

- HESS and CANGAROO detections
  - RXJ1713.7
  - Vela Junior
  - others...
- Problem solved?



Recent Observations: Dwarf Galaxies

Mayer, Kazantzidis, Mastropietro, and Wadsley, *Nature,* **445,** 738 (2007).



- Recent simulation work on evolution of dSph Galaxies gives credible mechanism for high Mass/Light ratio.
- VERITAS will make observations of a number of spheroidal dwarfs.
- Data taken with VERITAS on several dwarf galaxies. Work is in progress!

Other Recent Observations

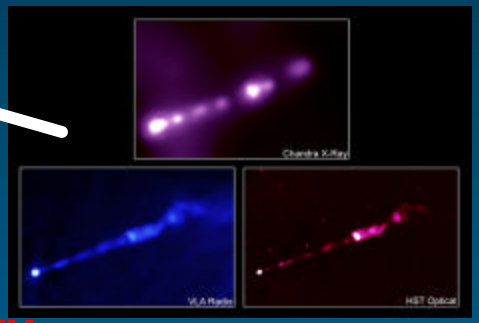
M15 – Globular Cluster

One of densest known concentrations of stars at center.

Central black hole? → *Central DM cusp?*

- *Observed in Fall, 2006, 2 telescopes.*
- *Expect more data in 2007.*

Energetic jet emanates from core



M87 – Giant elliptical galaxy

- *Also part of AGN program.*
- *Data taken in Feb-Apr reveal VHE emission consistent with pt. Source.*

Have to deal with known astrophysical bkgds. for DM analysis.

Recent Results from Whipple 10m

Six candidate DM sources

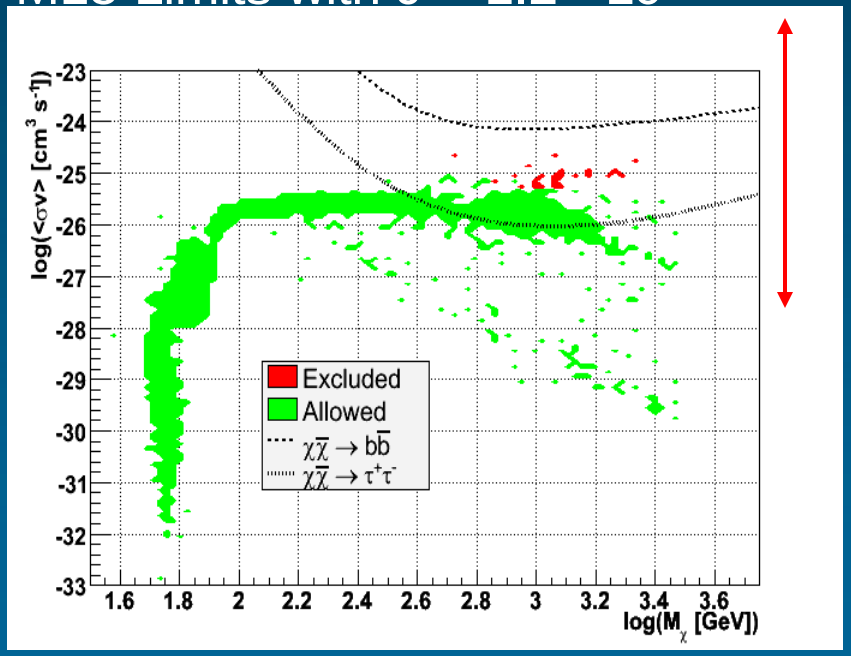
Significances obtained with standard point-source analysis

Source	σ
Draco	0.02
Ursa Minor	1.07
M32	-1.44
M33	-0.14
M87	0.28
M15	0.21

No Surprises…

Presented at SUSY06 June 2006

M15 Limits with J = 1.2 $\times 10^6$

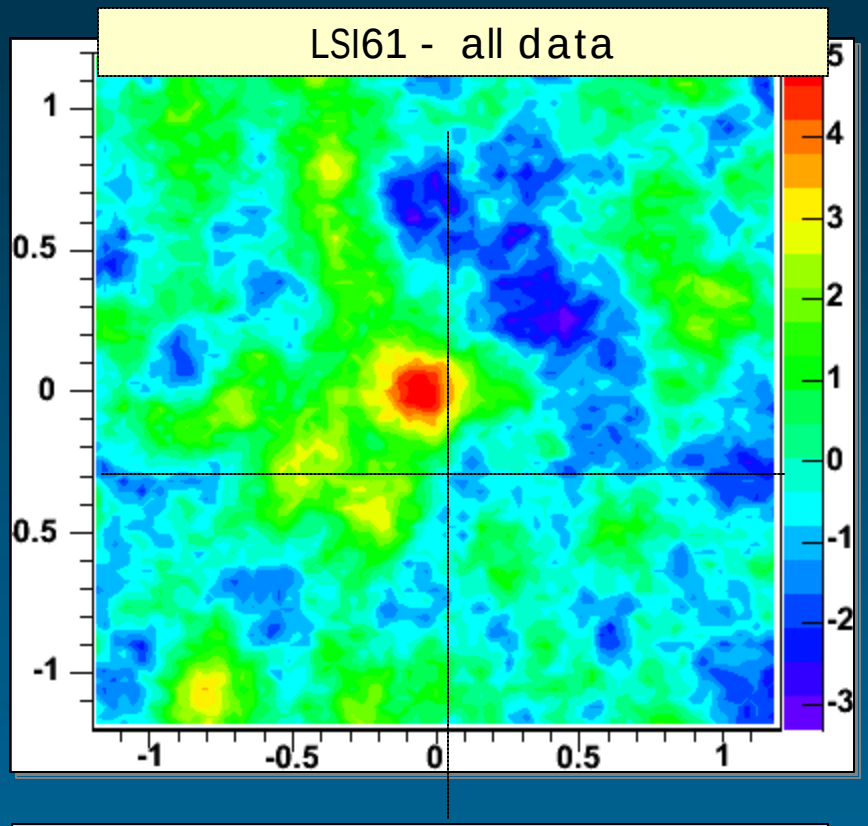


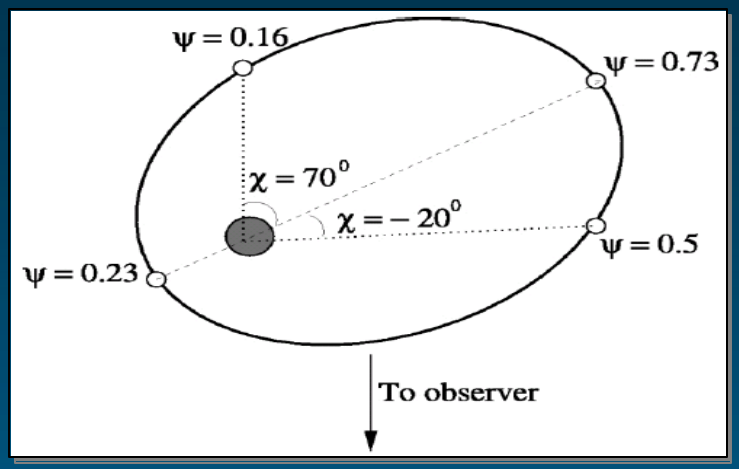
Astrophysical Uncertainty (J factor)

Scan of 10^6 MSSM Models with DarkSUSY (Gondolo et al. 2004)

MORE SCIENCE TOPICS

LS1+61 303





40.8 hr of data:
Oct. '06 – Jan. '07
Two/three telescopes
Significance = +8.6 s
Mean rate = 0.24 +/- 0.03 ?/min

- **HMXB located at 2 kpc distance**
- **Be Star coupled with NS**
- **X-ray/radio campaigns show**

Outbursts/26.5 day orbital cycle

VERITAS GRB Observations

GRB	VERITAS		Whipple	
	T_{obs}-T_0	Exposure	T_{obs}-T_0	Exposure
060501	13	101	6	140
061222a	11	120	68	112
070311	44	110	45	196
	5761	40	-	-
070419a	5	40	11	28

All times are in minutes

- VERITAS took 411 minutes of data on 4 GRBs.
  - Also got data on GRB070418 (not shown above) but it turned out to be a CR trigger from Swift - VERITAS got data on it after 5 minutes.

GRB Observations take priority over other observations.

VERITAS GRB Observations

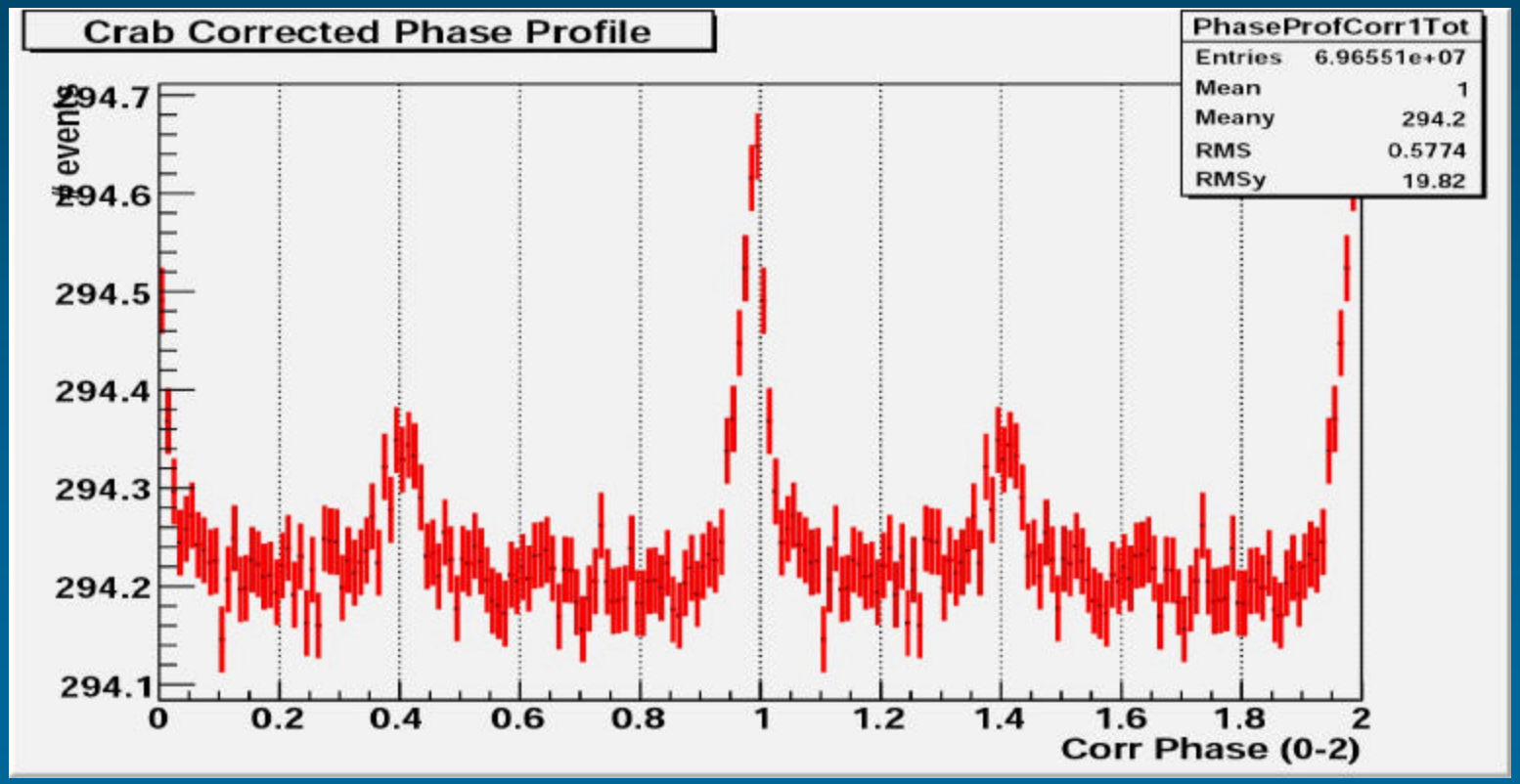
- **GRB 060501 (Swift)**
  - Swift Burst.
  - No Optical Afterglow.
  - Redshift unknown.
  - No X-ray flaring reported.

- **GRB 070419a (Swift)**
  - VERITAS took data 5 minutes after prompt emission.
  - Short exposure because burst occurred just before sunrise.
  - Redshift: 0.97 (Keck).
  - No X-ray flaring reported.

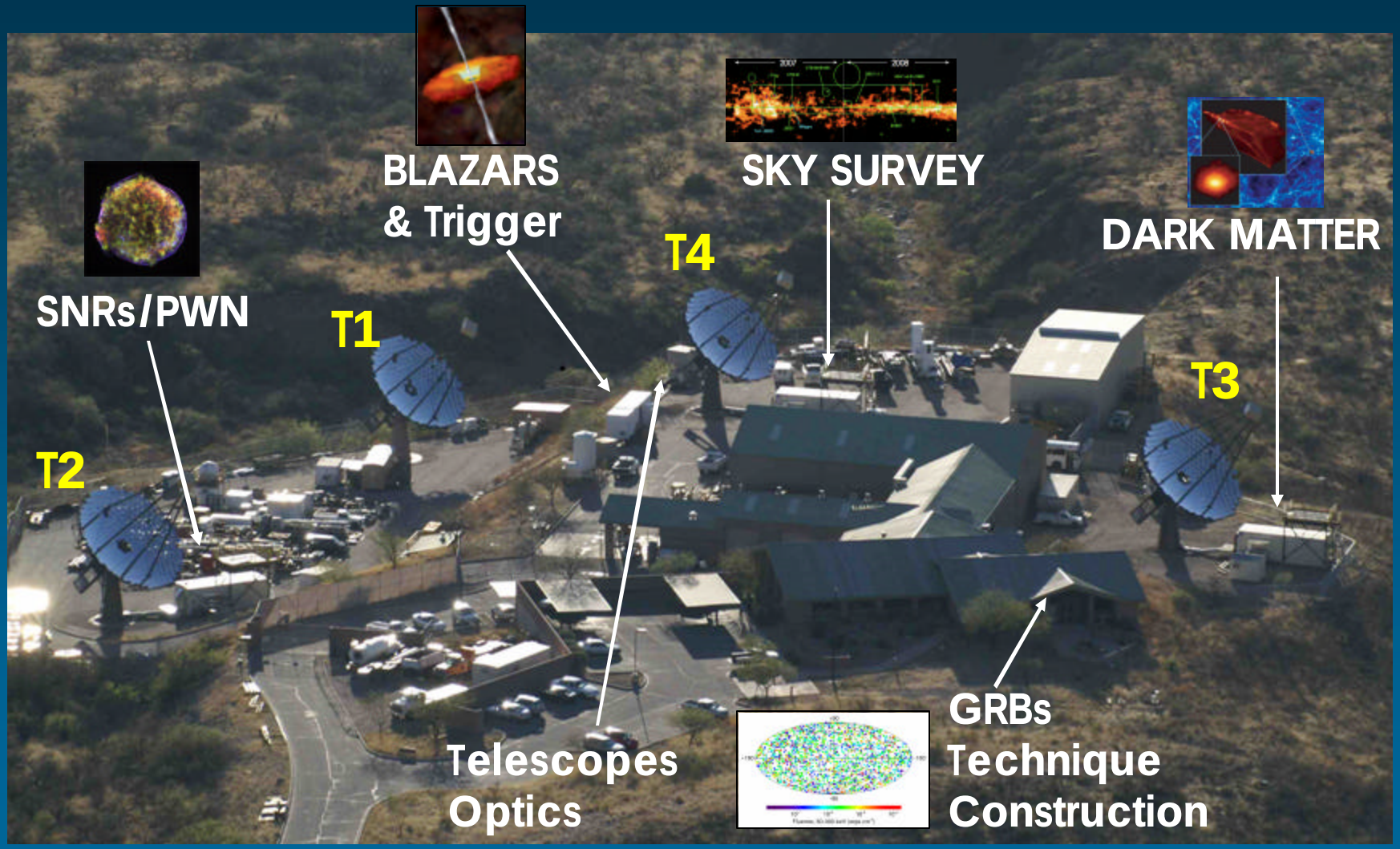
- **GRB 070311 (INTEGRAL)**
  - Delay in VERITAS data-taking because burst occurred ~44 mins before sunset (VERITAS got data as soon as sun set).
  - Optical afterglow detected at many telescopes.
  - Redshift: unknown but Halpern et al. say that "it is possible that this burst is at low redshift".
  - Optical REBRIGHTENING reported on 070313 - it peaked on Day 2 after the burst. Postulated to be due to late reactivation of the central engine (Kann et al.).

Crab Optical Pulsar from VERITAS

Four runs over the span of 3 days combined.
Total time: 33 mins.



Tomorrow's Displays



Summary

- VERITAS is now taking high-quality science data.
- VERITAS has a similar science plan to other telescopes. An important component of this is collaboration with other instruments.
- Key science projects are a critical component of the science to be done.
- Some early results presented here –
  expect to see more at ICRC 2007 !

Thank you for coming

We hope that you enjoy your visit .

END

MGRO J2019+37 Region

Upper limit from VERITAS At PWN 75.2+0.1

10 hr of data (T1-T2)
< 5 % Crab flux
(point source)

Clearly an interesting region that requires more observation.