Recent Results from VERITAS

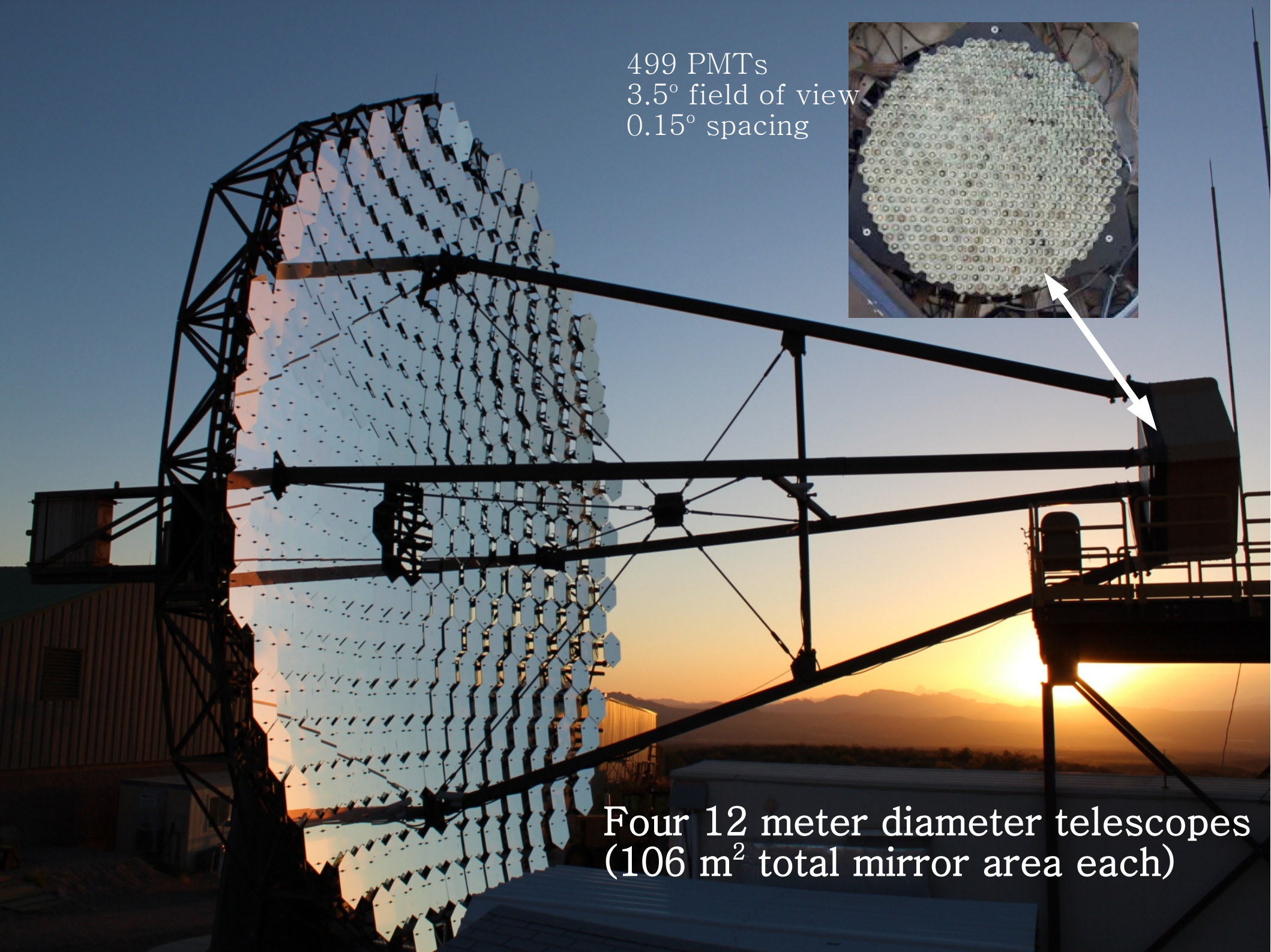
David Staszak, McGill University

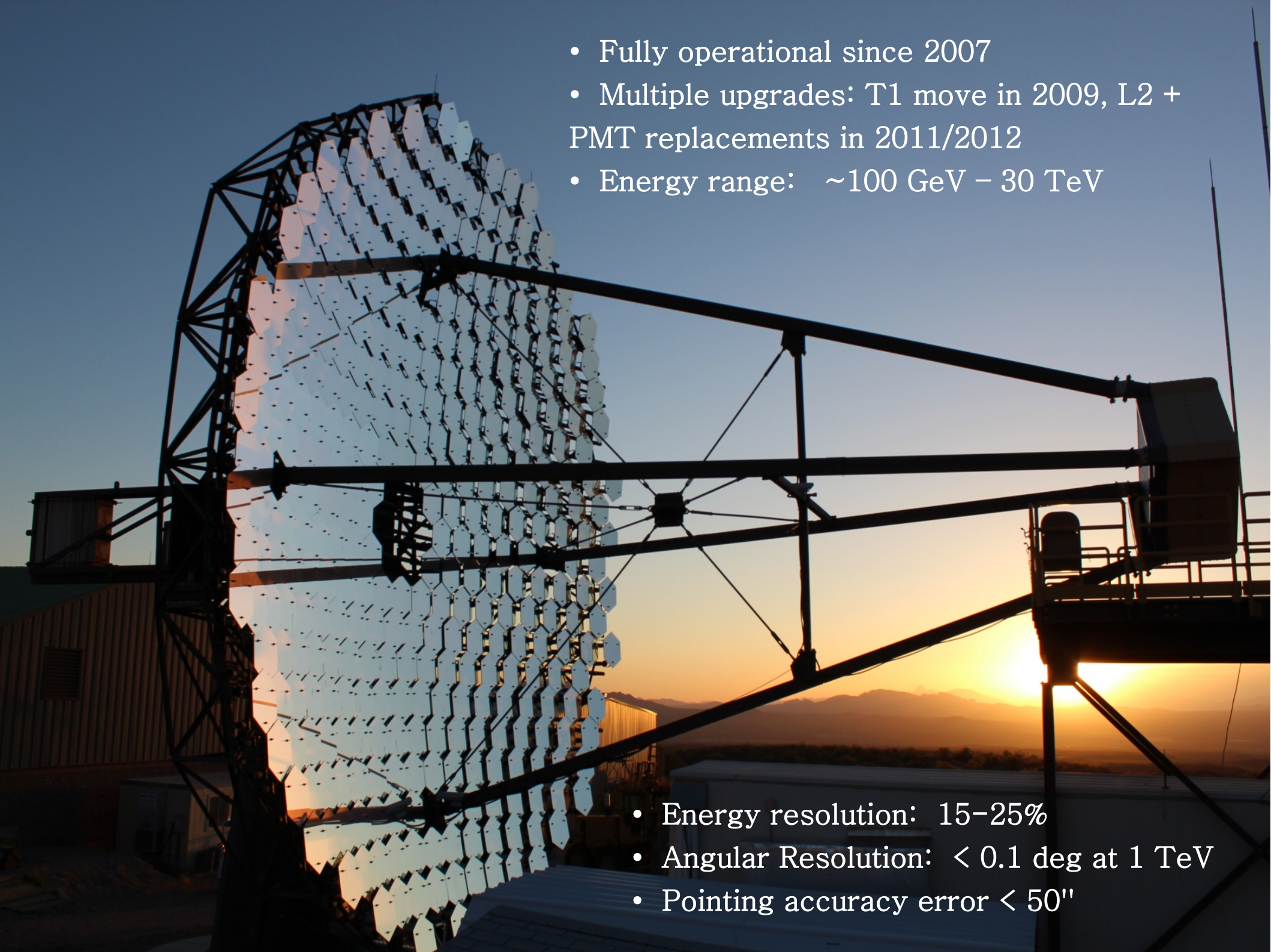
2013 RICAP Conference

Roma, May 2013

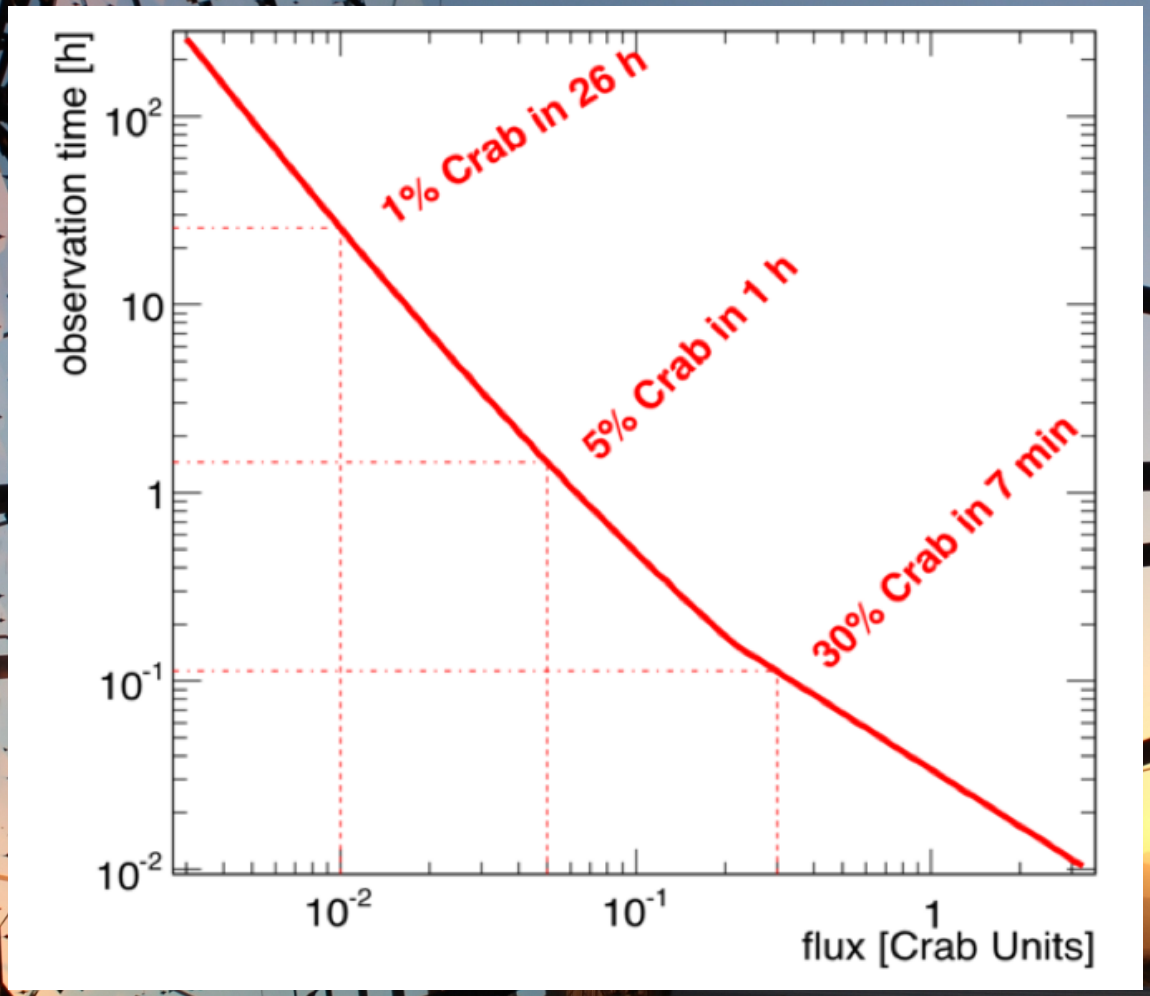
The VERITAS Collaboration

~95 scientists from 5 countries, with ~35 associate members (including theorists, MWL partners, IceCube, Fermi, Swift, etc)


499 PMTs
3.5° field of view
0.15° spacing
Four 12 meter diameter telescopes
(106 m^2 total mirror area each)

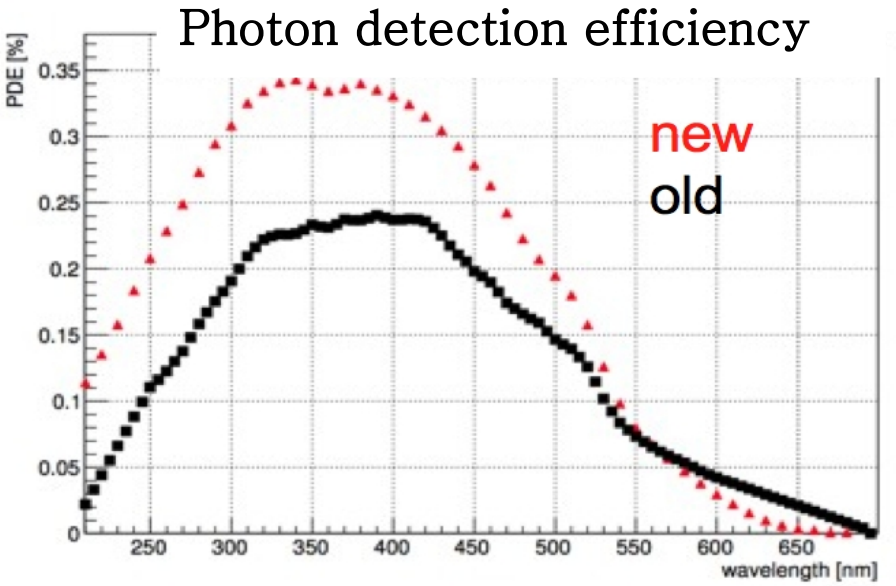

• Fully operational since 2007
• Multiple upgrades: T1 move in 2009, L2 + PMT replacements in 2011/2012
• Energy range: ~100 GeV – 30 TeV
• Energy resolution: 15-25%
• Angular Resolution: < 0.1 deg at 1 TeV
• Pointing accuracy error < 50"

Crab Sensitivity: 1% Crab in ~25 hours (5σ in ~70 seconds!)



Upgrade and new observation modes

• New high-Q.E. PMTs in all VERITAS cameras
  - Installed during the summer 2012 shutdown, resulting in no observing downtime
  - PDE now reaches up to 35%
  - Lower energy threshold



• Observations now cover a larger fraction of the moon cycle
  ~800 hours of dark sky data collected
  ~200 hours of normal moonlight data collected (with both standard-HV and reduced-HV configurations)
  ~250 hours of bright moonlight data collected with UV-filters installed over the cameras

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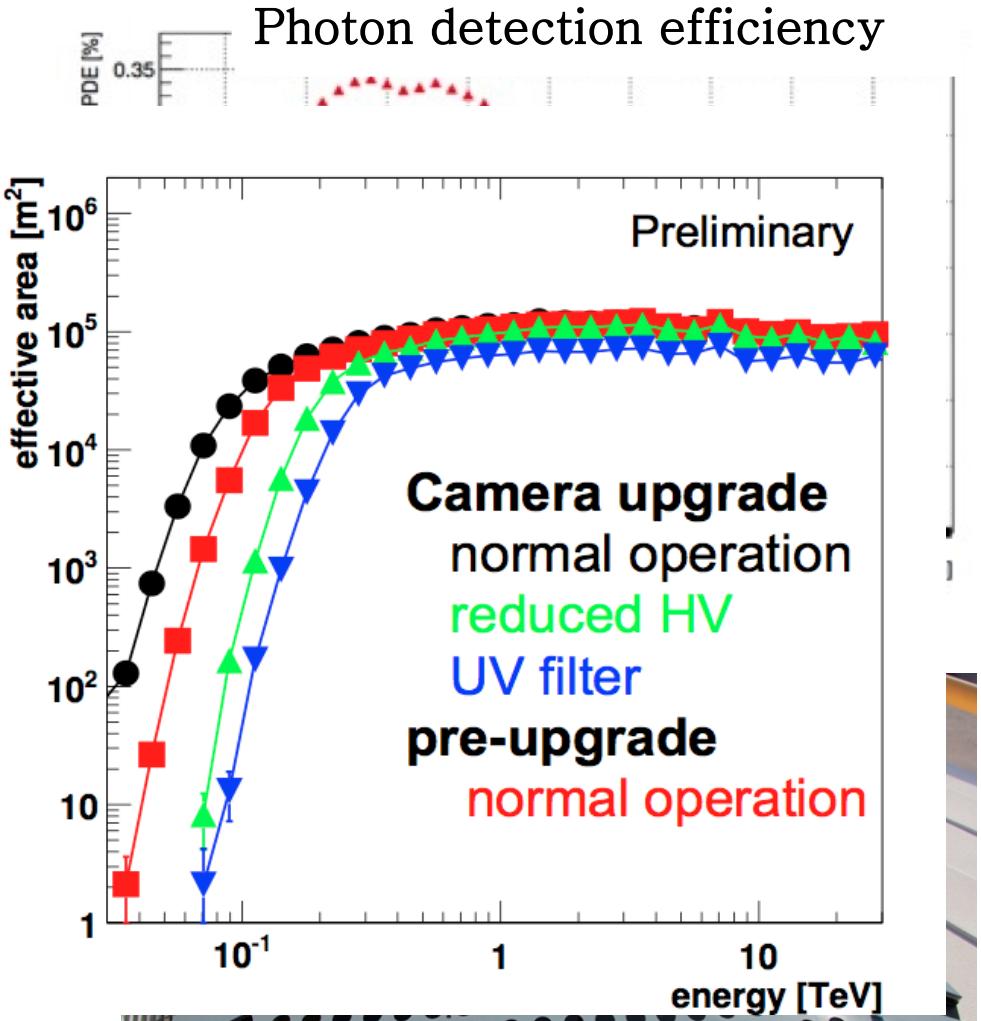
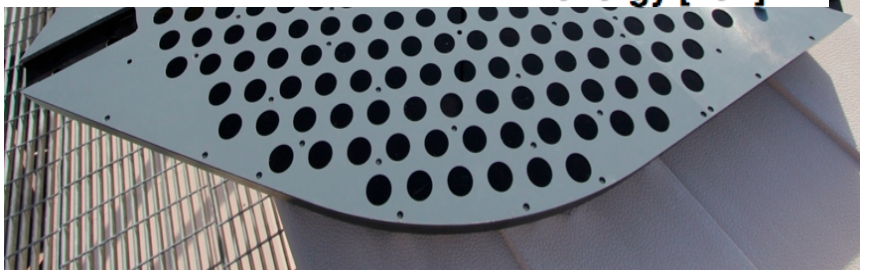
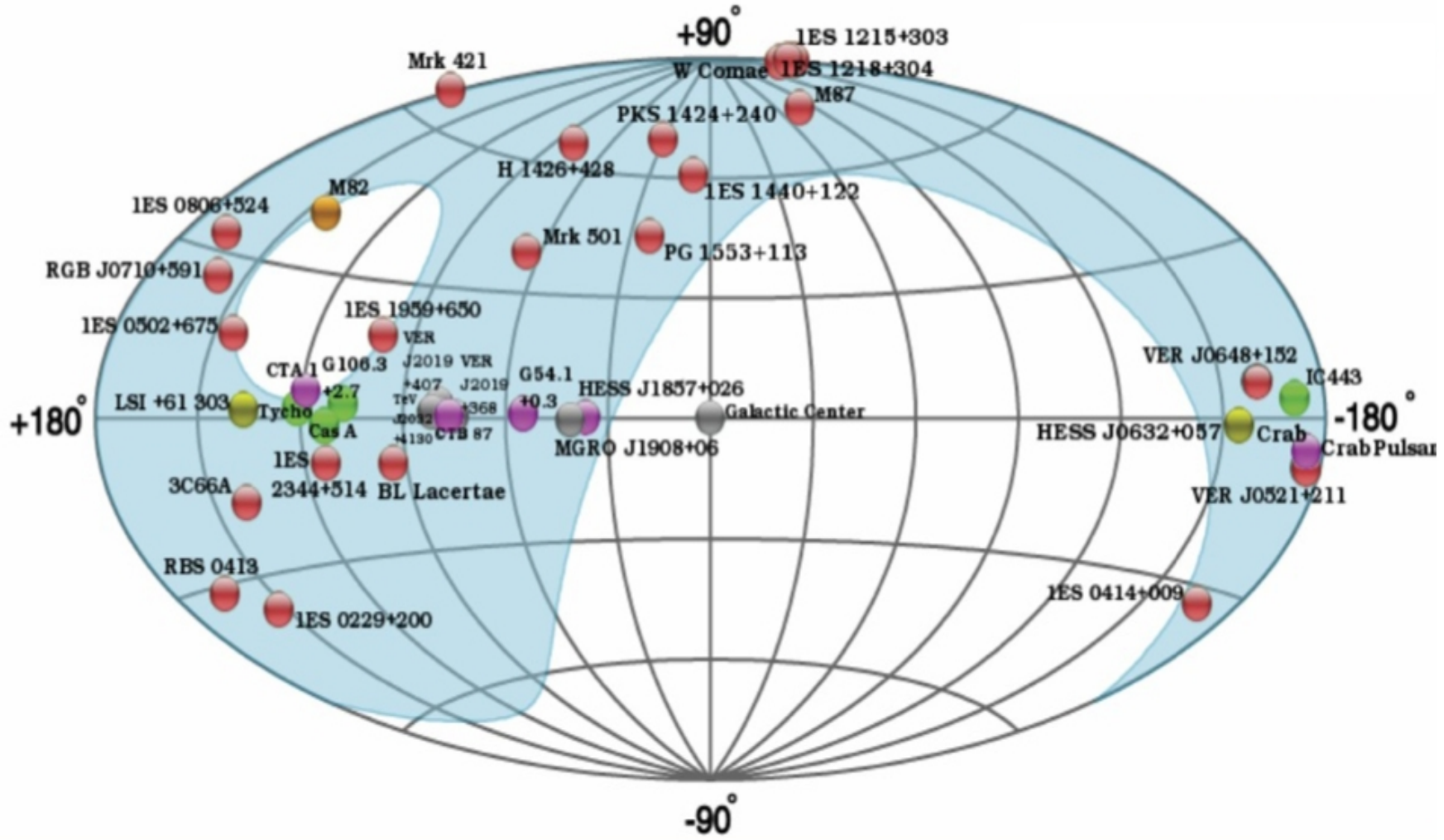




The VERITAS Catalog



- 40+ sources detected from 8 source classes:
  Active Galactic Nuclei, *Binary Systems*, *Pulsar Wind Nebulae*, *Supernovae Remnants*, one *Starburst Galaxy*, one *Pulsar*, and several *Unidentified Sources*

Extragalactic Observations Overview

- Scientific objectives:
  - Understand supermassive black holes – the origin of the jet emission, the dynamics of the black hole environment
  - Cosmology: EBL/IGB studies
  - Fundamental Physics: Lorenz Invariance studies, search for new particles and/or Dark Matter

- VERITAS detections in the extragalactic sky are mostly blazars with two exceptions
  - M82: starburst galaxy
  - M87: radio galaxy

- AGN strategy:

⇒ Monitoring programs key to *finding interesting events (flares)*

⇒ MWL observations key to *understanding those events*

Source	Type	Red-shift
Mrk 421	HBL	0.030
Mrk 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
BL Lac	LBL	0.069
1ES 1741+196	HBL	0.083
W Comae	IBL	0.102
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 0229+200	HBL	0.139
1ES 0806+524	HBL	0.138
1ES 1440+122	IBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 0414+009	HBL	0.287
PG 1553+113	HBL	0.43<z<0.58
1ES 0502+675	HBL	?
3C 66A	IBL	?
PKS 1424+240	IBL	?
RGB J0521.8+2112	HBL	?
B2 1215+30	IBL	?
M87	FR I	0.004
M82	Starburst	–

Extragalactic Observations

- PKS 1424+240 is now the farthest VHE-detected blazar

  Furniss, et al ApJ (2013)

- VHE emission discovered by VERITAS (*Acciari et al ApJ 2010*), the highest energy spectral point reported at 500 GeV

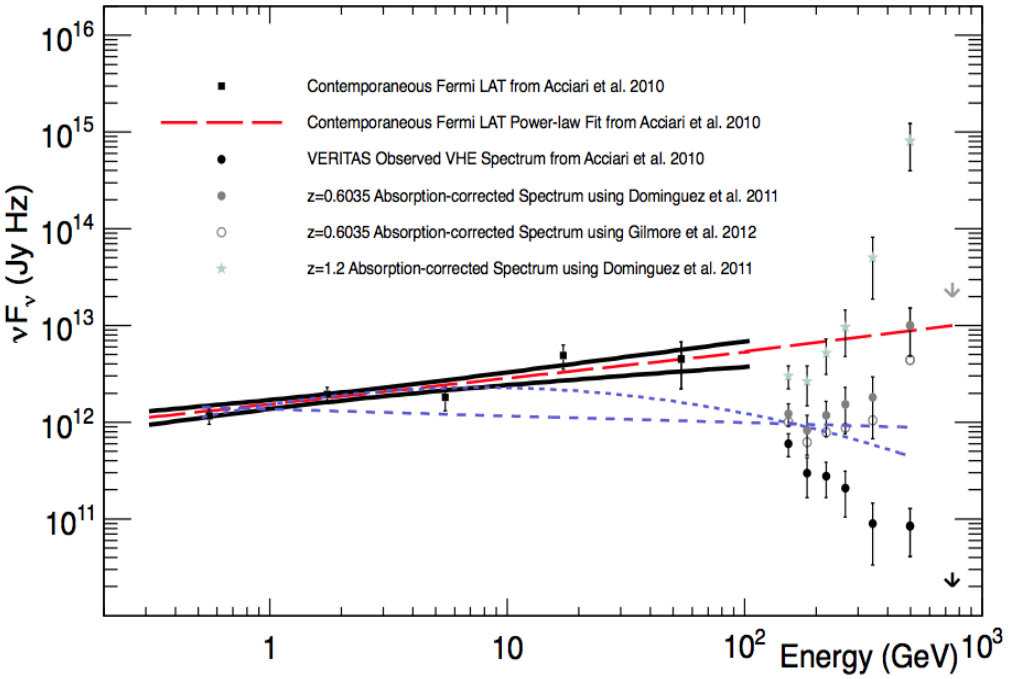
- Important piece of information for understanding the opacity of the Universe

$$\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^-$$

- Spectral break at ~100 GeV:

  $\Gamma_{LAT} = 1.73 \pm 0.07 \pm 0.05$

  $\Gamma_{VTS} = 3.8 \pm 0.5 \pm 0.3$



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PKS 1424+240	IBL	$z \geq 0.6035$
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B2 1215+30	IBL	?
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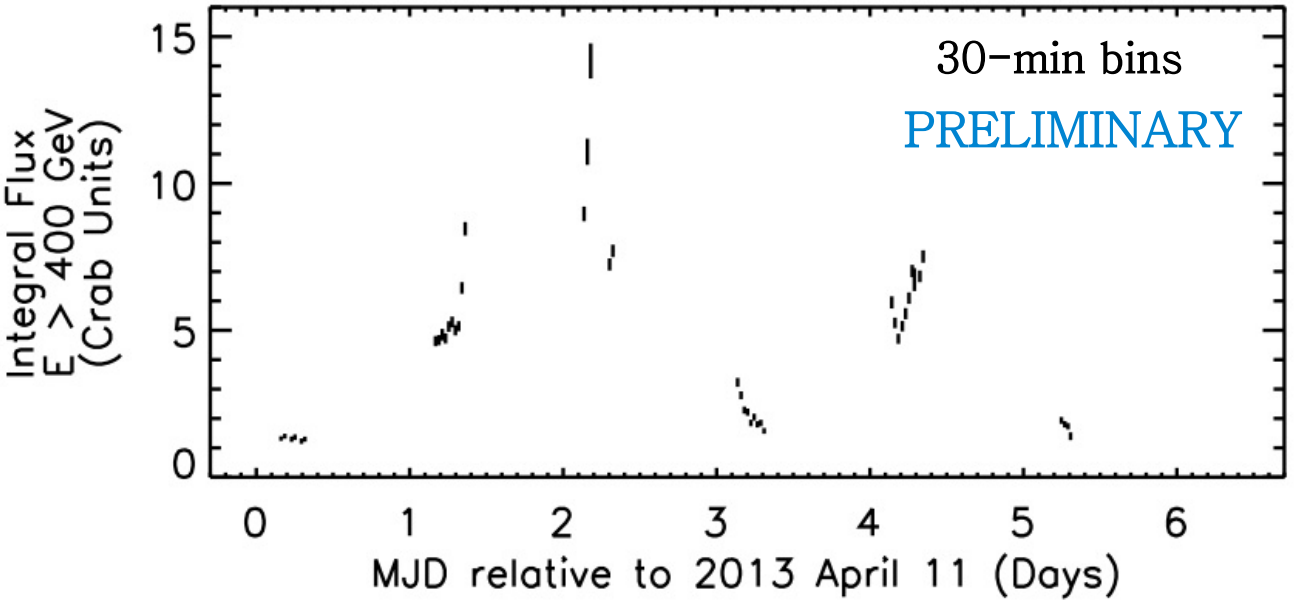
M82	Starburst	-

Extragalactic Observations: 2013 Mrk 421 Flare



- MWL campaign (MAGIC, VERITAS, NuSTAR) began just prior to the onset of a giant flare – great timing!

- Preliminary VERITAS results show Mrk 421 with fluxes ~14 Crab

- Holes in VERITAS coverage filled by MAGIC (not shown here)

- Rich dataset including ~11 hours of VHE/x-ray overlap (NuSTAR, Swift) that we've only begun to explore... stay tuned

NuSTAR detects extreme X-ray flaring of Mrk 421

ATel #4974; *Mislav Balokovic (Caltech), Amy Furniss (UCSC), Grzegorz Madejski (KIPAC/Stanford), Fiona Harrison (Caltech)*
on 13 Apr 2013; 00:00 UT
Credential Certification: Amy Furniss (afurniss@ucsc.edu)

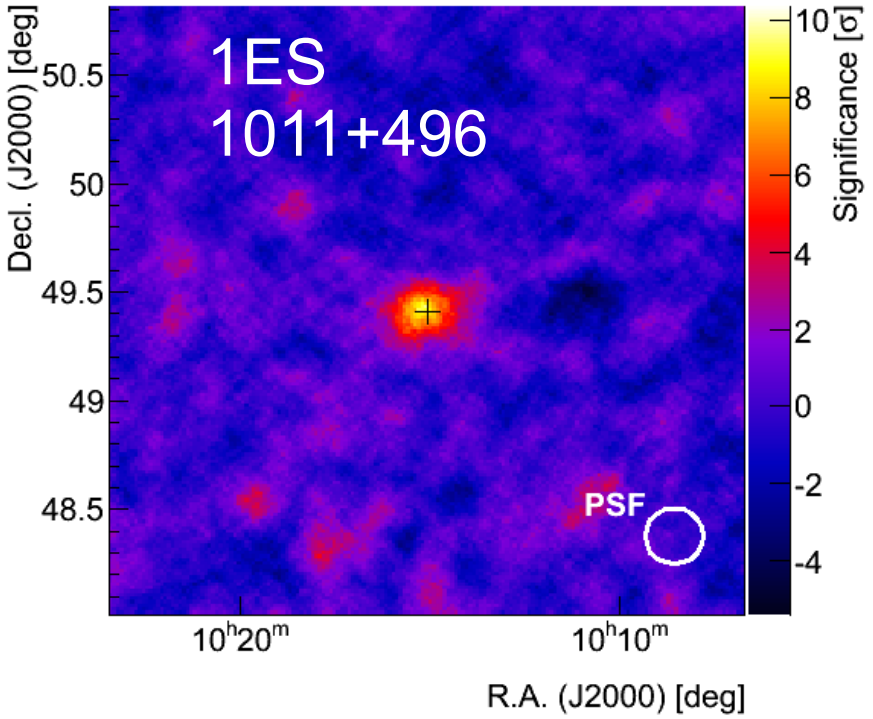
MAGIC and VERITAS detect an unprecedented flaring activity from Mrk 421 in very high energy gamma-rays

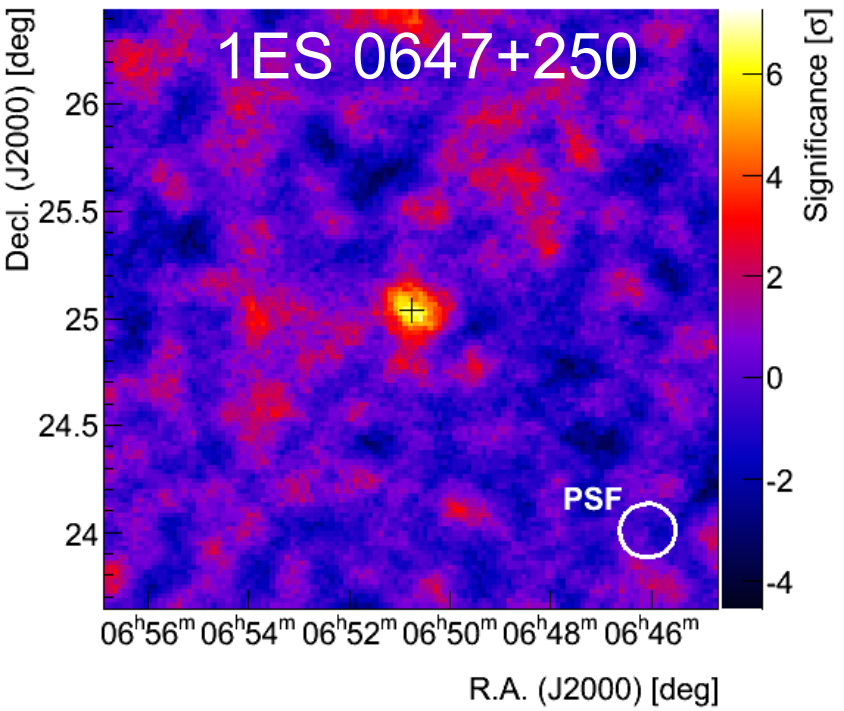
ATel #4976; *Juan Cortina (IFAE Barcelona) and Jamie Holder (University of Delaware) for the MAGIC and VERITAS collaborations*
on 13 Apr 2013; 20:22 UT
Credential Certification: Juan Cortina (cortina@ifae.es)

Fermi-LAT and Swift-XRT observe exceptionally high activity from the nearby TeV blazar Mrk421

ATel #4977; *D. Paneque (MPI for Physics, Munich), F. D'Ammando (INAF-IRA Bologna), M. Orienti (INAF-IRA Bologna) on behalf of the Fermi LAT Collaboration, and A. Falcone (PSU) on behalf of the Swift team*
on 13 Apr 2013; 20:30 UT
Credential Certification: David Paneque (dpaneque@slac.stanford.edu)

New Blazar Detections in 2012/2013





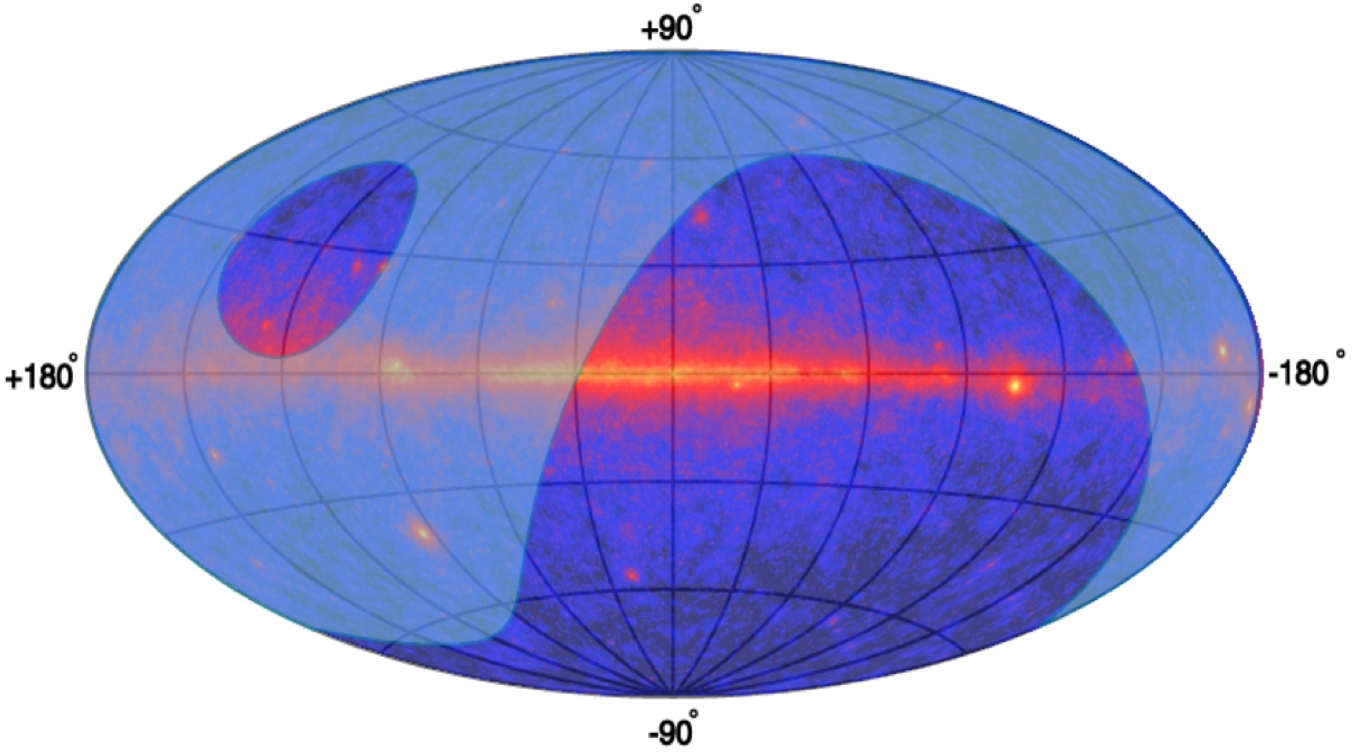
- Monitoring during partial moonlight led to ToO:
  - 8.5σ in 10 hours of data
  - 6.3% Crab > 151 GeV
- Discovered in VHE by MAGIC (7% Crab)
- Simultaneous x-ray data obtained

- Monitoring during partial moonlight led to ToO:
  - 6.2σ in 11 hours of data
  - 2.9% Crab > 138 GeV
- Discovered in VHE by MAGIC (3% Crab), detected also by Fermi-LAT

First new source detections with our upgraded cameras (both soft-spectrum)

Galactic Observations Overview

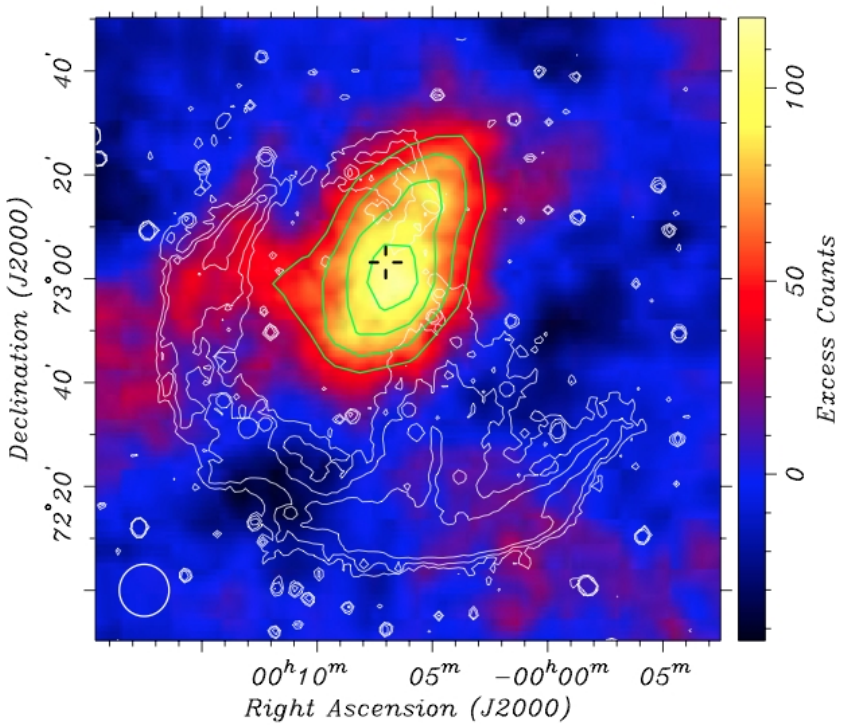
Source Name	Class (likely)
Crab Nebula	PWN
Crab Pulsar	Pulsar
LS I +61°303	Binary
IC 443	SNR
Cas A	SNR
G106.3+2.7	SNR/PWN
G54.1+0.3	PWN
HESS J0632+057	Binary
CTA 1	PWN
Tycho's SNR	SNR
HESS J1857+026	PWN?
CTB 87	PWN
MGRO J1908+06	PWN?
TeV J2032+4130	PWN?
Galactic Centre	UID
VER J2019+407	UID
Cyg OB1 TeV complex	UID



- VERITAS is a northern hemisphere observatory, so primarily observes the outer galaxy

- Galactic observations account for ~35% of VERITAS observation time

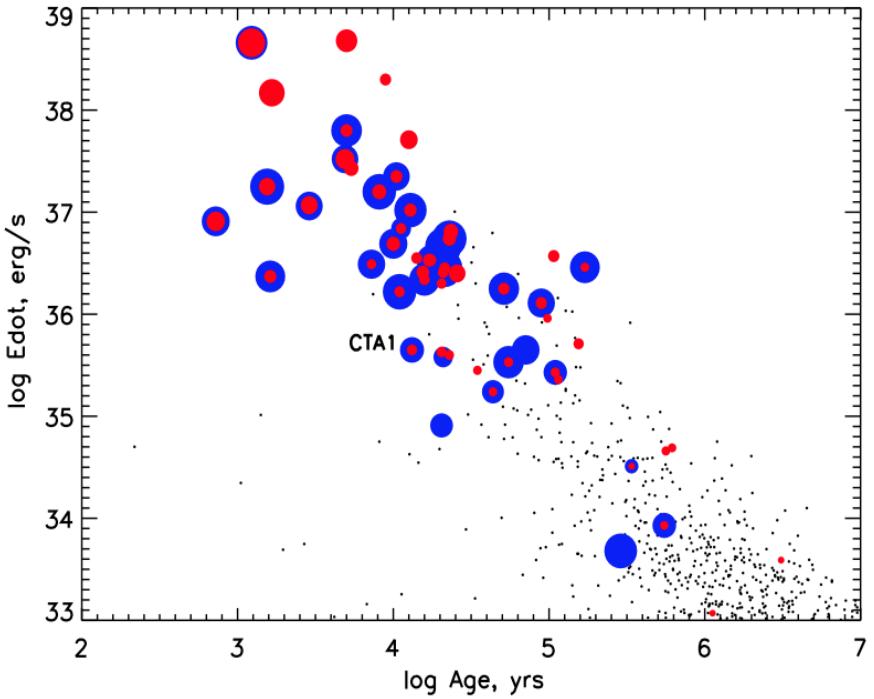
Galactic Observations: CTA 1



Aliu, et al. ApJ 764 (2013)

- Composite SNR, radio shell, X-ray filled
  - Diameter ~1.8°
  - Age ~14 kyrs
  - Distance 1.4 kpc
- Fermi discovered ɣ-ray pulsar (p=315 ms)
  - blind search discovery (Abdo, et al. 2008)
  - supports PWN interpretation
- VERITAS discovery in 41 hours of data
  - 6.3σ detection
  - Flux ~4% Crab > 1 TeV
  - 5 arcmin from Fermi pulsar

- TeV detected PWN (blue) and X-ray detected PWN (red), circle size represents luminosity

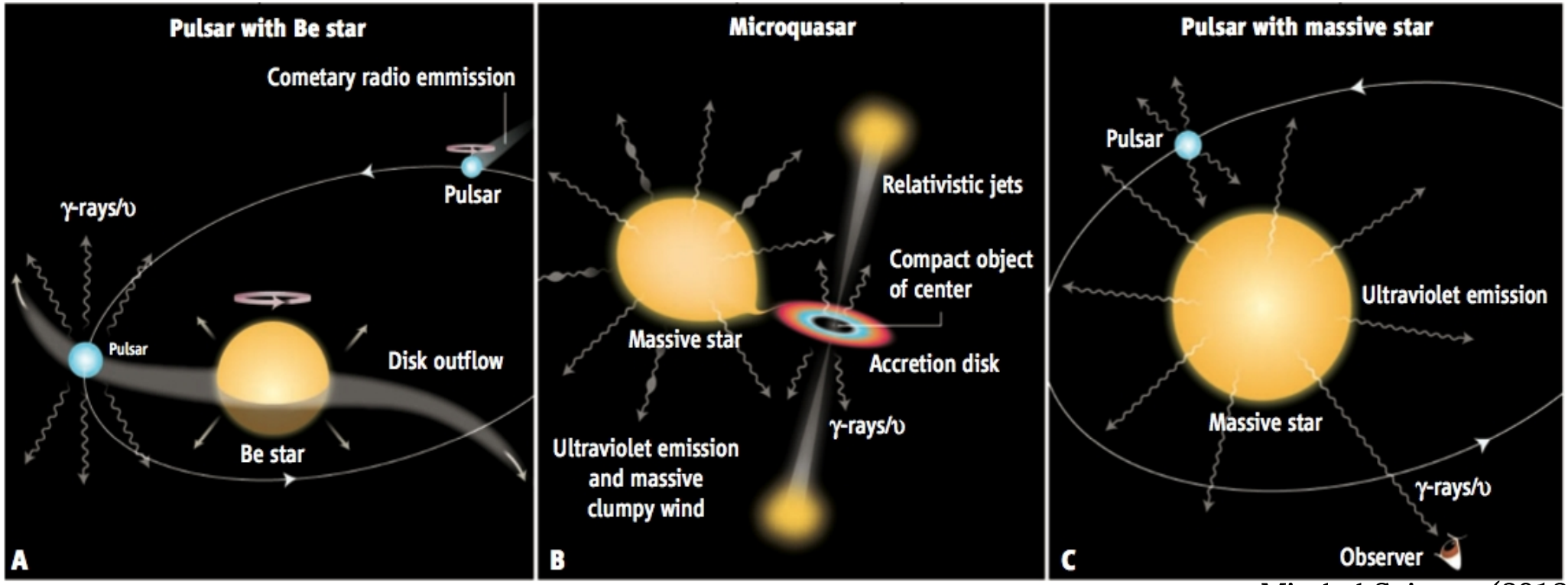


- CTA 1 fits well with the picture of relatively young, high-Edot pulsars being good candidates for TeV PWN emission

Kargaltsev & Pavlov (2010)

Galactic Observations: Binaries

VHE emission may arise from colliding winds or be powered by accretion:



Mirabel Science (2012)

4 γ-ray binary systems detected at VHE energies (6 seen by the LAT):

- PSR B1259-63
- LS 5039
- LS I +61 303
- HESS J0632+057 (VHE-only)
- Cygnus X-1 (HE-only)
- Cygnus X-3 (HE-only)
- 1FGL J1018.8-5856 (HE-only)

Galactic Observations: LSI +61 303

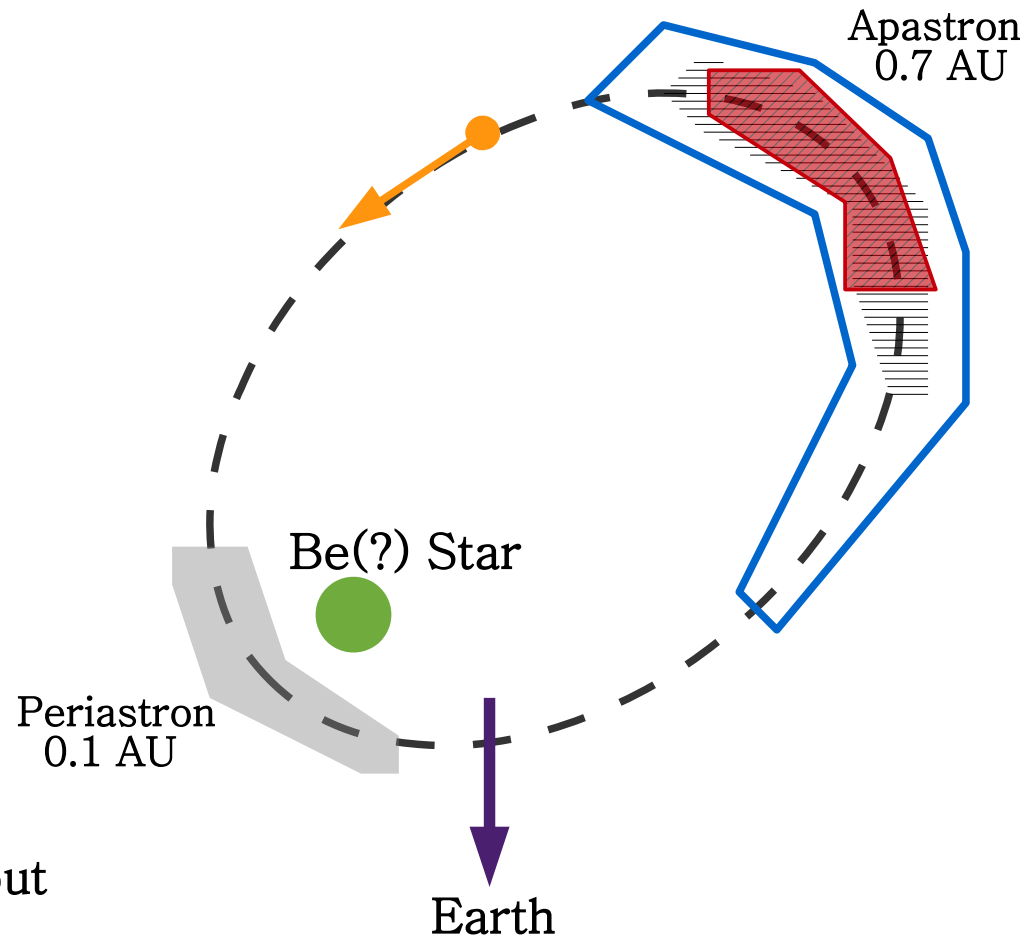
- High mass x-ray binary system
  - 2 kpc distance
  - Pairing of a Be(?) star and a compact object (unknown, BH? NS?)
  - 26.5 day elliptical orbit

- X-ray activity throughout the orbit, variable, strongest at apastron/periastron

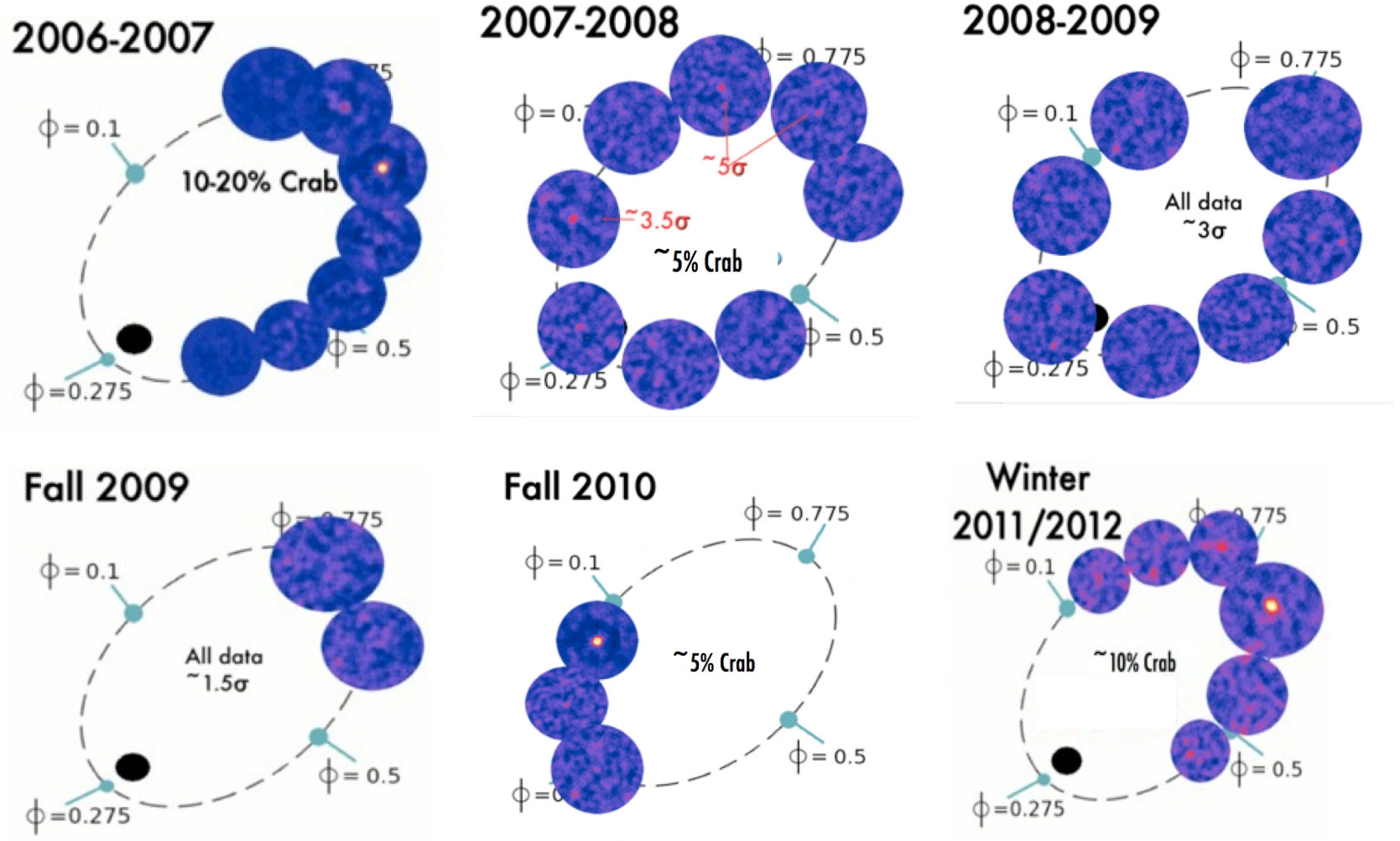
- extended radio emission peaks at periastron/apastron, ~4 year modulation (Gregory 2002)

- Fermi LAT MeV/GeV emission throughout orbit

- TeV activity (MAGIC/VERITAS) detected around apastron (typically, not always)

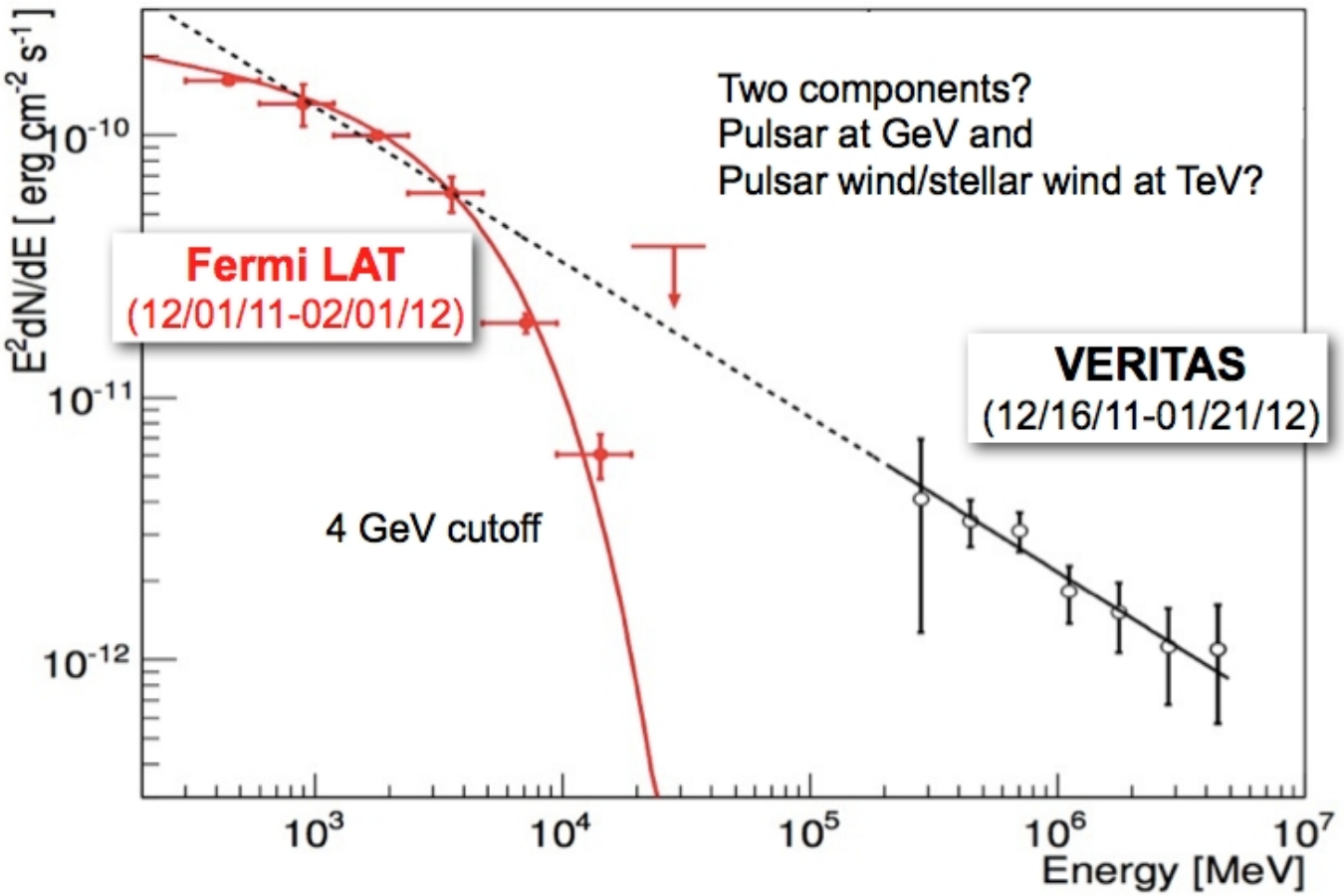


Galactic Observations: LSI + 61 303



- VERITAS can't rule out that we 'missed' emission in intervening years, but LSI may go through multiyear TeV modulation
- Detection in 2012/2013 (not shown here)

Galactic Observations: LSI + 61 303



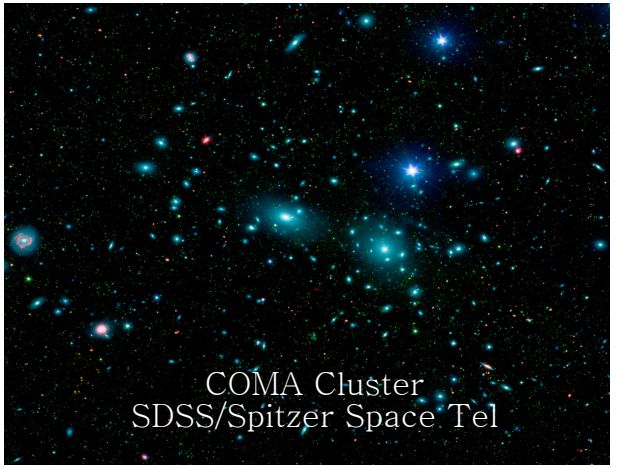
- Contemporaneous data with LAT MeV/GeV and X-ray collected during 2011-2012 VERITAS campaign
- MWL data may be the key to distinguishing between pulsar/microquasar scenarios – particularly GeV/TeV connection...

DM Source Targets

- Choose targets weighing background levels, distance, M/L ratio, ρ_{DM}
- Observe a variety of targets, a DM signature will be independent

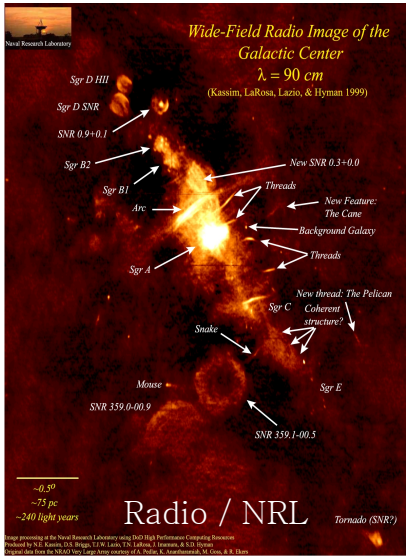
Galaxy Clusters

+ Lot of DM content
− Far away
− Possible Astrophysical Background



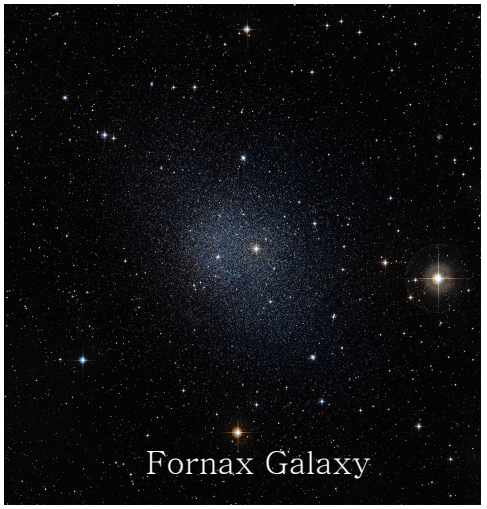
Galaxy Center

+ High Flux
+ Nearby
− High Astrophysical Background



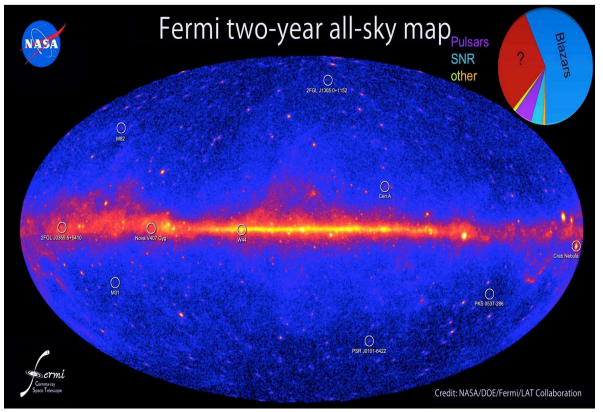
Dwarf Galaxies

+ DM Dominated ($O(10^3)$ times more DM mass than visible matter)
+ Little astrophysical background
+ Nearby
− Low Flux



Unidentified HE Sources

+ High statistics from Fermi-LAT in the HE regime
+ DM clumps or substructure not seen at other wavelengths



Measuring DM: putting the pieces together

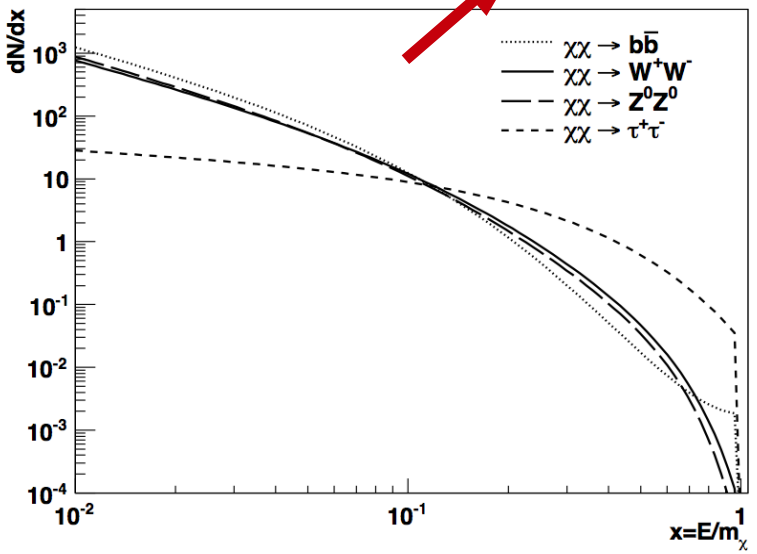
Velocity weighted cross-section. With a non-detection, we can constrain this.

$$\frac{d\phi}{dE}(\Delta\Omega, E) = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \left(\frac{dN_\gamma}{dE} \right)_{DM} \langle J(\Delta\Omega) \rangle$$

γ-ray flux: do you see any?

Particle physics piece: depends on M_{DM} and your particle physics model

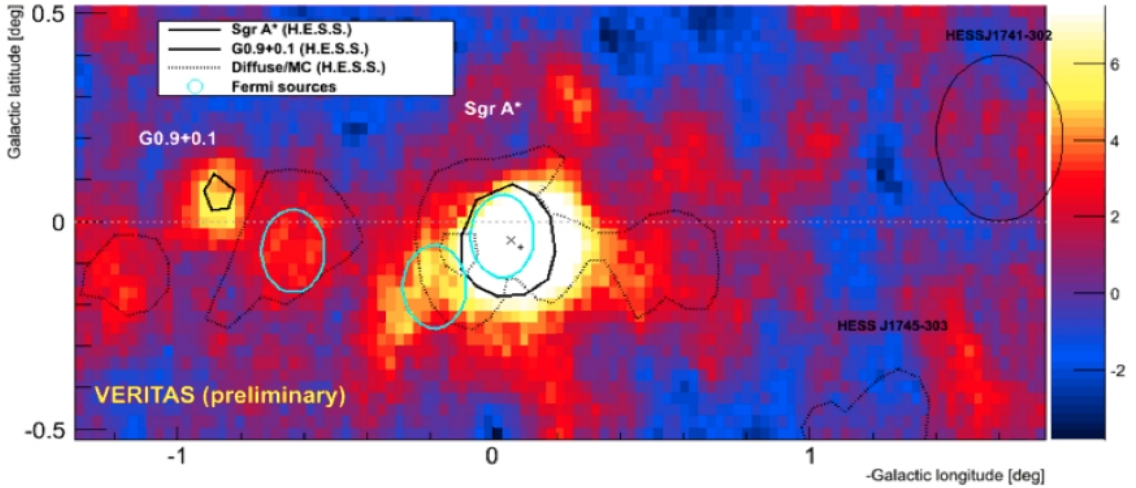
Astrophysical piece: integral along the line of sight and instrumental solid angle



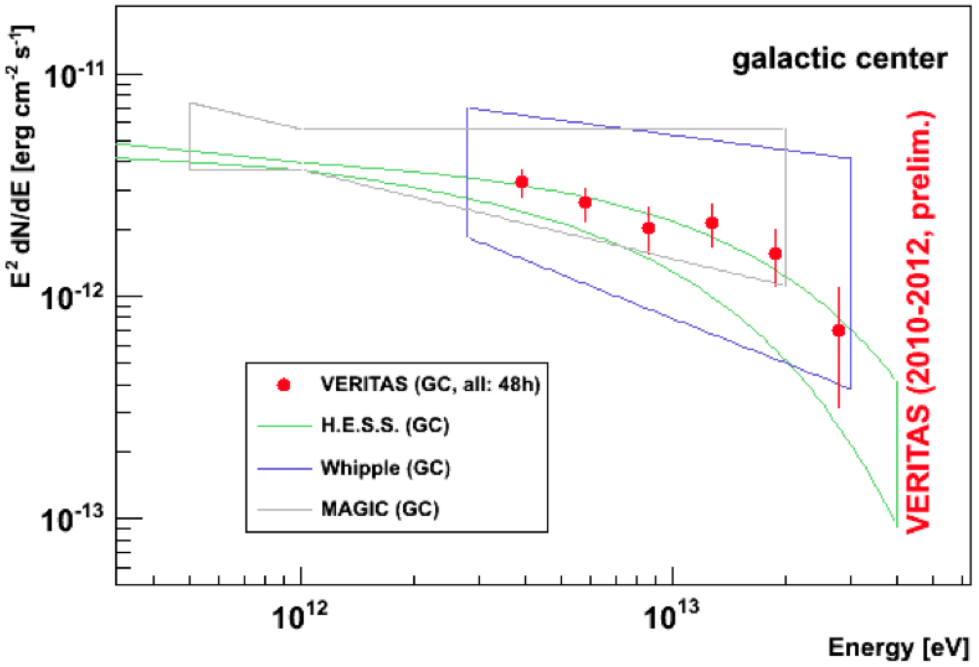
$$\langle J(\Delta\Omega) \rangle = \int d\Omega \int \rho_{DM}^2(r[s])ds$$

Get this from astronomical models of the object

DM/Galactic Observations: Galactic Center Detection

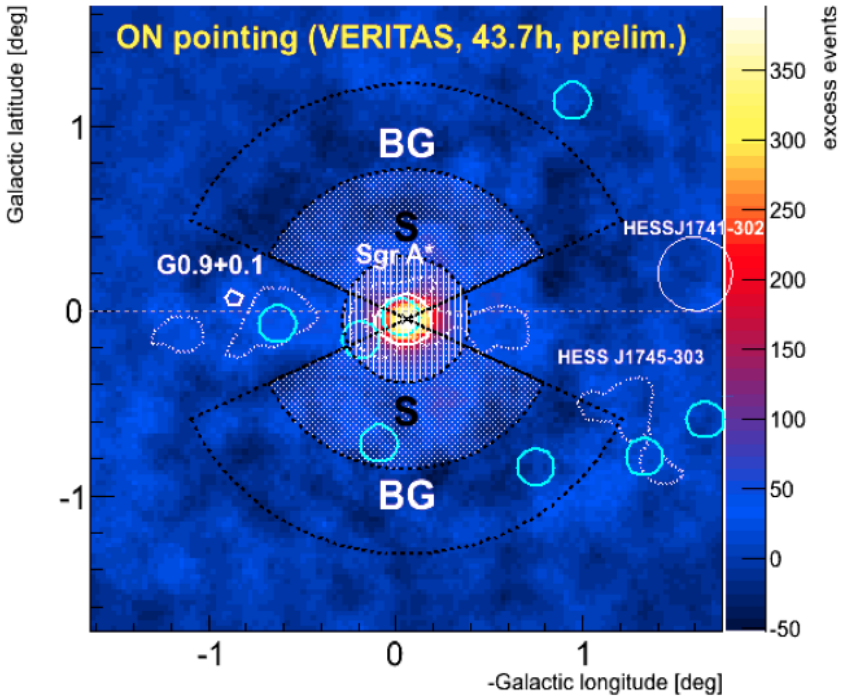


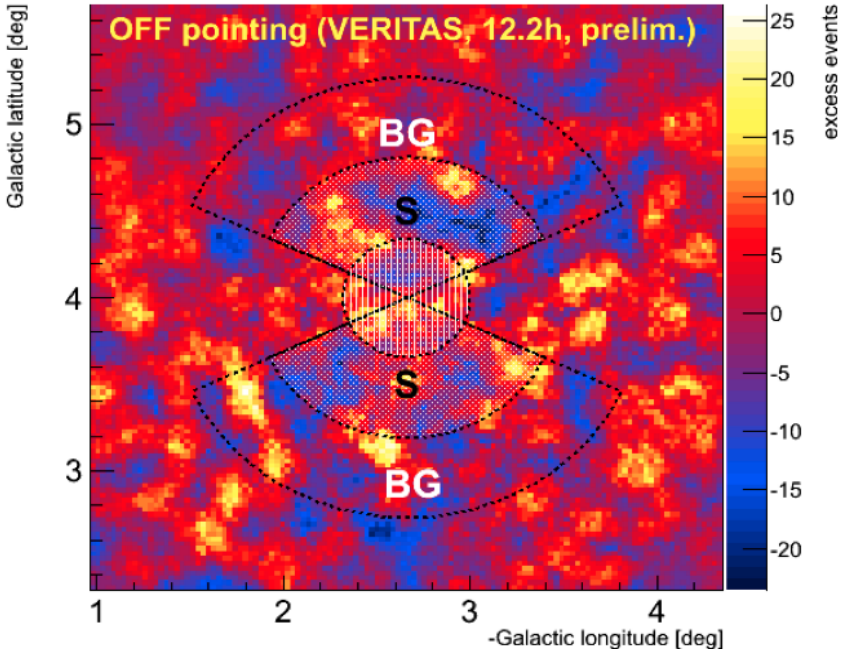
- VERITAS observes the galactic center at large zenith angles:
  - zenith 60–66 degrees
  - energy threshold ~2 TeV
  - ~46 hours of good data
  - Galactic Center is detected at 18σ

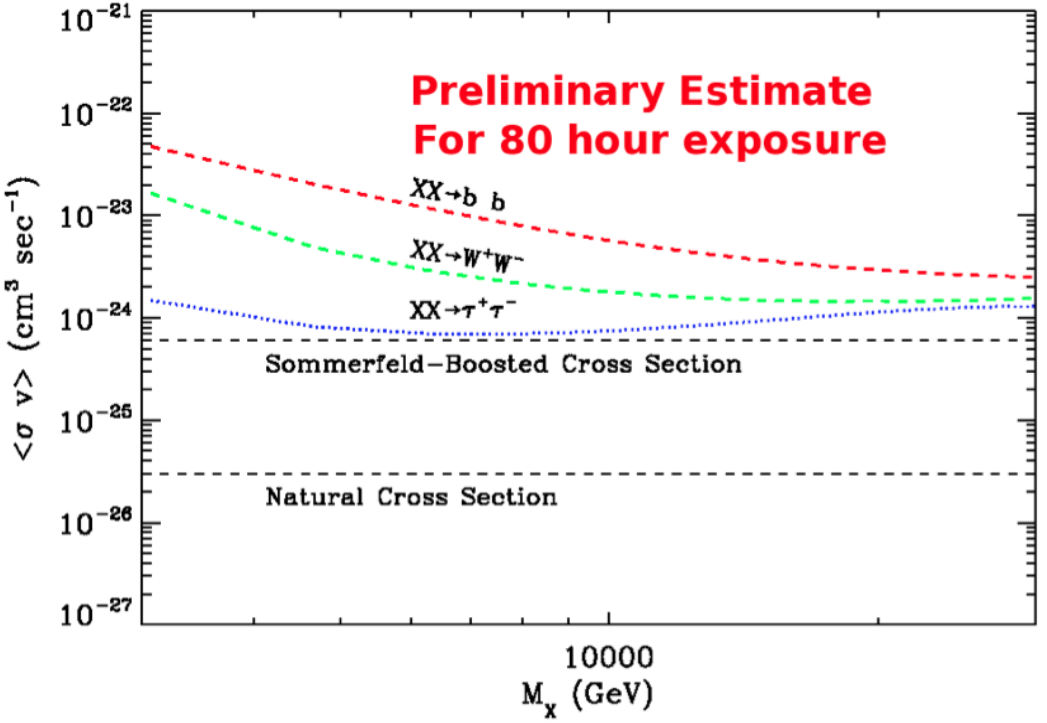


- VERITAS detected spectrum and localization agree with results from HESS/MAGIC/Whipple
  - No evidence of variability

DM Observations: Galactic Center



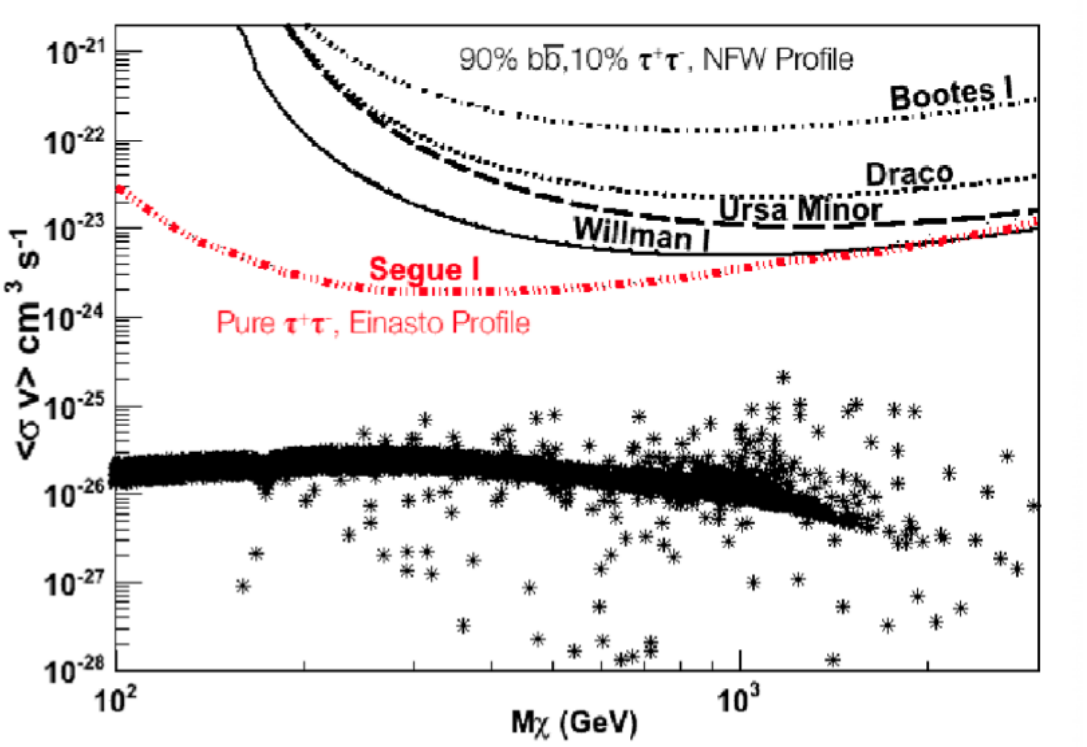




- Larger energy threshold makes us sensitive to higher WIMP masses (and that may be good… 130 GeV mass Higgs may point to higher mass neutralinos)

- Estimates shown are for data collected through the 2013 observing season

DM Observations: Dwarf Galaxies



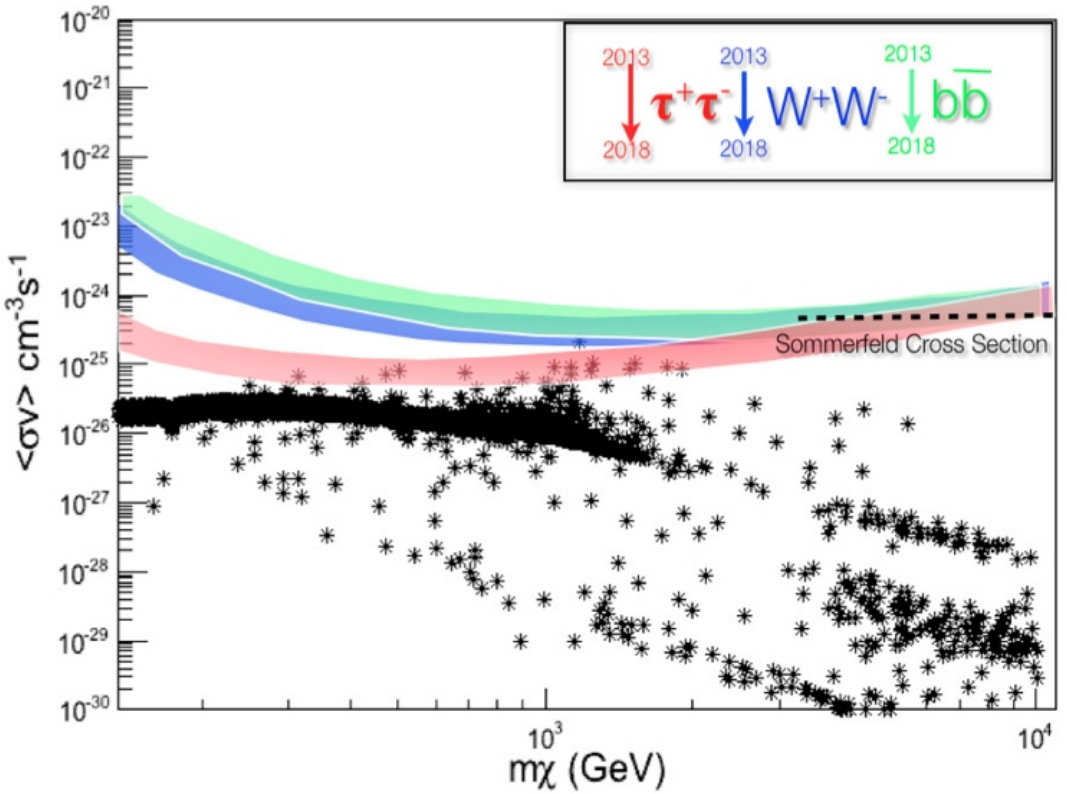
Segue I:
- 48 hour exposure
- Phys Rev D85, 062001 (2012)

Draco, Ursa Minor, Willman 1, Bootes 1:
- 15–20 hour exposures
- ApJ 720: 1174 (2010)

• Measured Dwarf DM limits ~2 order of magnitude away from canonical cross section

• Results do constrain some models which predict large boosts, both astrophysical in nature or from particle physics processes (i.e. Sommerfeld enhancements)

DM Observations: Dwarf Galaxies



Stacked Dwarf Projection:

→ 2013 Estimate using 250 hours

→ 2018 Estimate using 1000 hours

A. Smith et al, Snowmass DM white paper (arxiv:1304.6367)

Updated exposure time totals:

Draco:	18 hours	→	48 hours
Ursa Minor:	19 hours	→	47 hours
Segue I:	48 hours	→	123 hours

218 hours now on disk

A dwarf stacking analysis underway which has been shown to significantly improve constraints

A. Garinger-Sameth and S. Koushiappas, PRL 2011.

Conclusions

• VERITAS is yielding results in a range of areas: astronomy, particle physics, and cosmology

- Lots of data and plenty of sources, both galactic and extragalactic
- Two orders of magnitude off constraining the canonical models of DM
- Improved analysis (stacking) is on the way + DM is a high priority in the coming years
- Two new blazars detected this year (so far), first new source detections with the upgraded cameras
- Giant Mrk 421 flare detected during MWL campaign with NuSTAR, MAGIC… analysis underway
- Binaries continue to surprise us, MWL may be the key to distinguishing between scenarios

• Final note… VERITAS/Fermi-GI pilot program initiated for Fermi GI Cycle-6 (2013-2014)

- Open up a fraction of VERITAS observing time to the larger community
- First of its kind for IACT experiments, moving towards the CTA model
- ~4% of accepted GI proposals were joint Fermi/VERITAS