Highlights from Extragalactic Observations by VERITAS

Jon Dumm

for the VERITAS Collaboration

IceCube Particle Astrophysics Symposium

May 14, 2013





The VERITAS Collaboration



~100 Scientists at 22 institutions in 5 countries

Supported by:
U.S. DoE
U.S. NSF
Smithsonian
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

U.S.

Adler Planetarium
Argonne Nat. Lab
Barnard College
Columbia University
Grinnell College
Iowa State Univ.
Purdue Univ.
SAO
UCLA
UCSC
Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Minnesota
Univ. of Utah
Washington Univ.

Germany

DESY Zeuth.

Ireland

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

U.K.

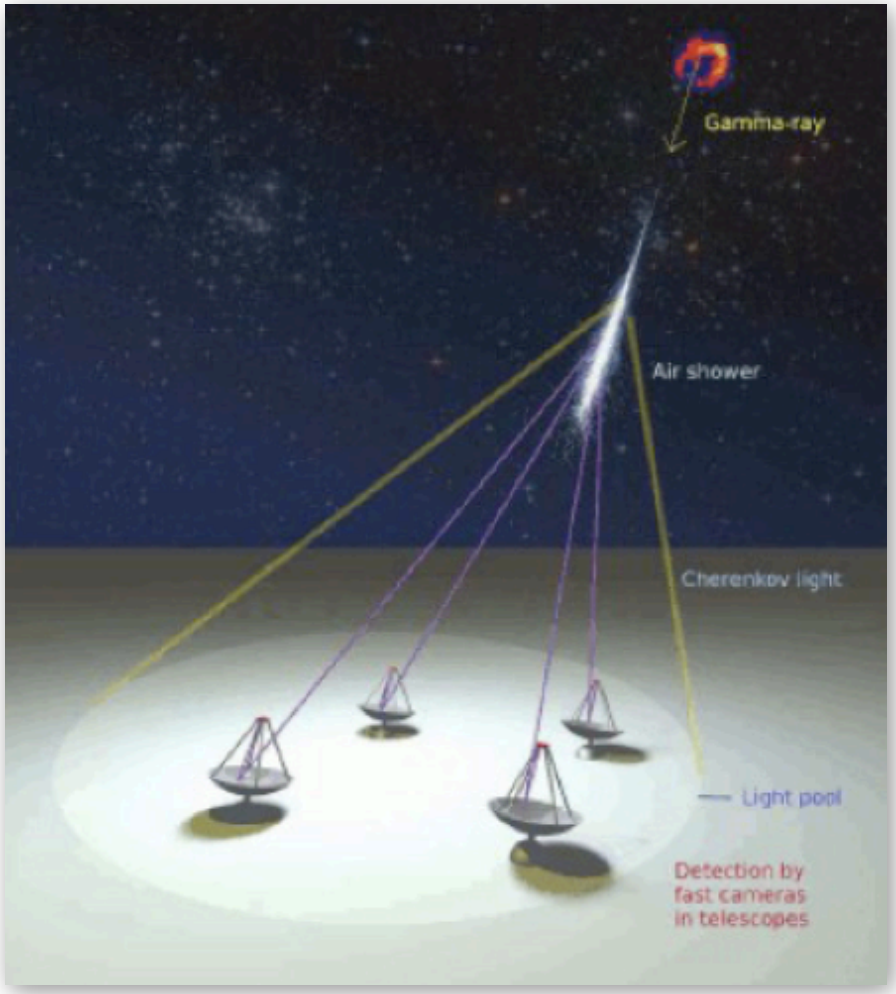
Leeds Univ.

Canada

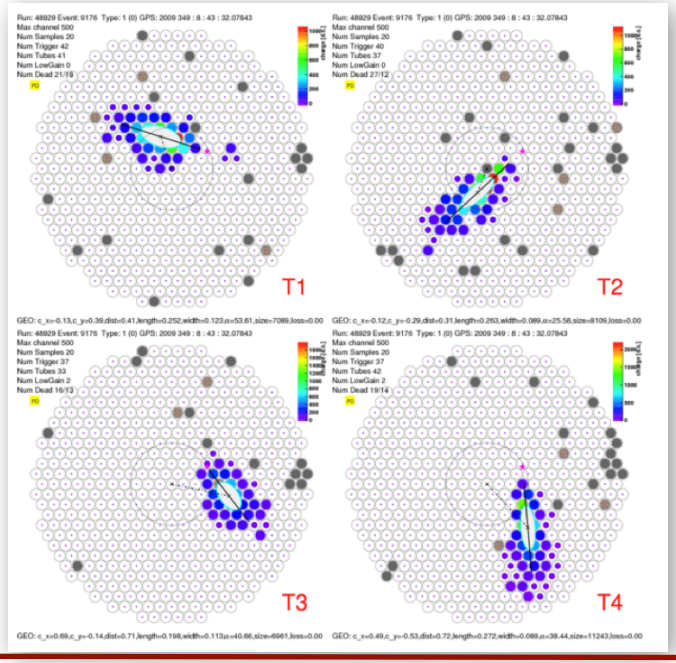
McGill Univ.

+ 35 Associate Members incl. theorists and MWL partners (IceCube, Fermi, Swift...)

The IACT Technique



- VHE γ-rays interact with nuclei in the atmosphere, initiating EM showers
- IACTs image the Cherenkov light from the shower using large reflectors and fast cameras and electronics
  - → Discrimination between cosmic rays and gamma ray
  - → Direction and energy of primary gamma ray

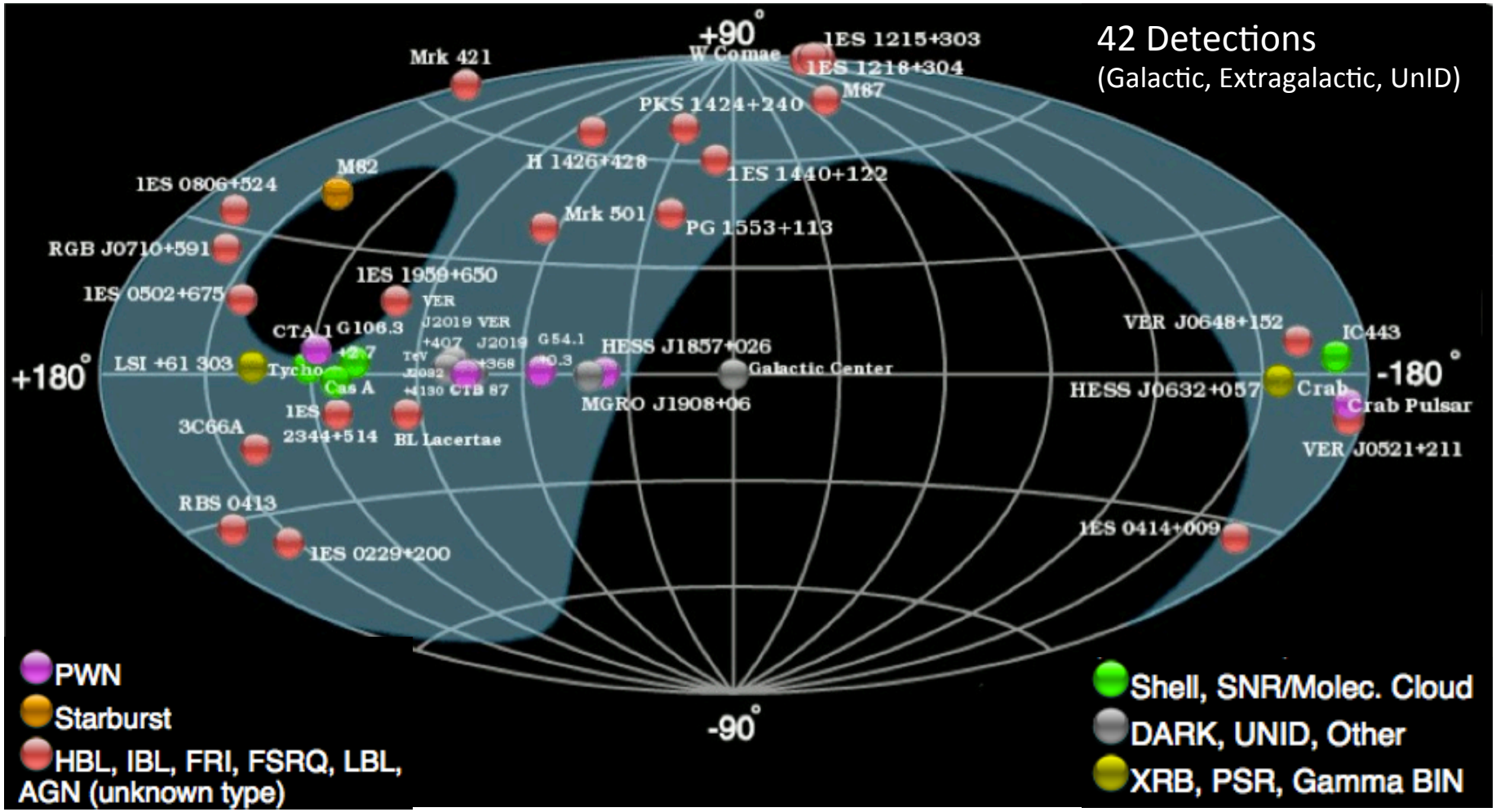


VERITAS



- **100 GeV – ~30 TeV**
- **15 – 20% energy resolution**
- **0.1° angular resolution**
- **1% Crab detection in < 30 hrs (pre-upgrade)**
- **Recent Upgrades: Trigger (2011) and Camera (2012)**

The VERITAS Sky



Extragalactic Sources

Key extragalactic science goals:

- Supermassive black holes
  - Jet physics
    - Origins of ultra high energy cosmic rays
  - Environment
  - Evolution
- Fundamental physics
  - Search for new particles/processes
    - Dark matter
    - Axion-like particles
    - Lorentz invariance violation
- Cosmology
  - Extragalactic background light
  - Magnitude of intergalactic B field

Source	Type	z
M 82	Starburst	-
M 87	FR I	0.004
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
BL Lac	LBL	0.069
W Comae	IBL	0.102
VER J0521+211	IBL/HBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1440+122	IBL/HBL	0.162
RX J0648.7+1516	Blazar	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
1ES 0414+009	HBL	0.287
1ES 0502+675	HBL	0.341 ?
3C 66A	IBL	0.3347 < z < 0.41
PG 1553+113	HBL	0.43 < z < 0.62
1ES 0647+250	HBL	~0.45
PKS 1424+240	IBL/HBL	>0.6035
B2 1215+30	IBL/HBL	?

Indirect Dark Matter Targets

Point IACT: Regions with high dark matter densities
Regions where the astrophysical background is small

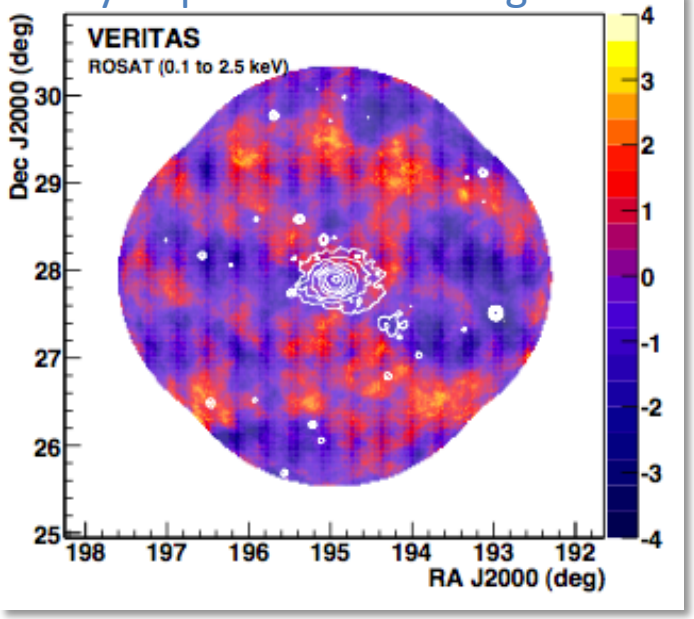
Target	Advantages	Drawbacks
Galactic Center	• Close by • Huge amount of DM	• Many astrophysical backgrounds • Huge uncertainties in the DM distribution ($O(10^3)$)
Dwarf spheroidal galaxies	• DM dominated • Clear of any astrophysical background	• Can be too distant for the current instrument sensitivity • Can be tidally disrupted: uncertainties in the DM distribution ($O(10)$).
Globular clusters	• Very close	• Not DM dominated • Astrophysical background • Interplay of baryons with DM not well known
Clusters of galaxies	• Huge amount of DM	• Very distant • Astrophysical background • Very extended

Coma Cluster

RA (J2000) 12 59 49 Dec +27 58 50 z=0.0232



Skymap of smoothed significance

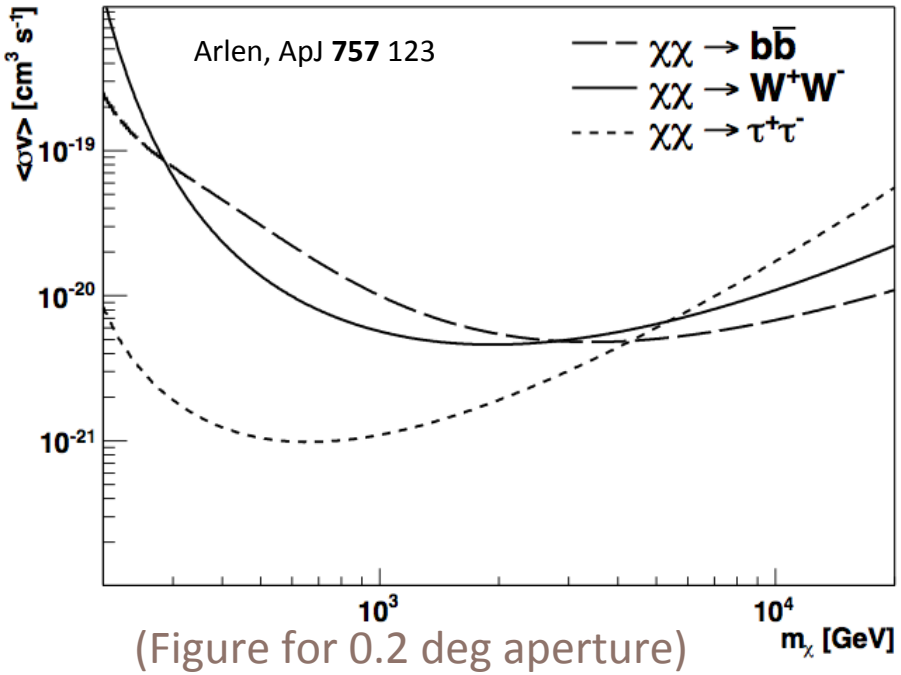


- Nearby (about 100 Mpc), massive and rich cluster
- DM profile (NFW) extension within VERITAS field of view
  - Simpler background considerations
- Other nearby massive clusters (Virgo, Perseus) have known gamma emitters – difficult analysis to separate potential DM component

Arlen, ApJ **757** 123

Coma: DM Limits

- No statistically significant excess observed in 18.6 hours
- Place constraints on WIMP parameter space (m_χ,<σv>) with upper limits on observed gamma-ray rate:

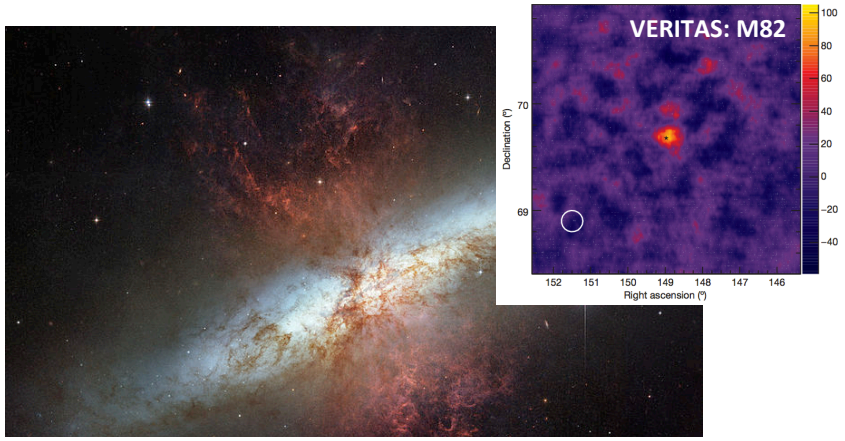


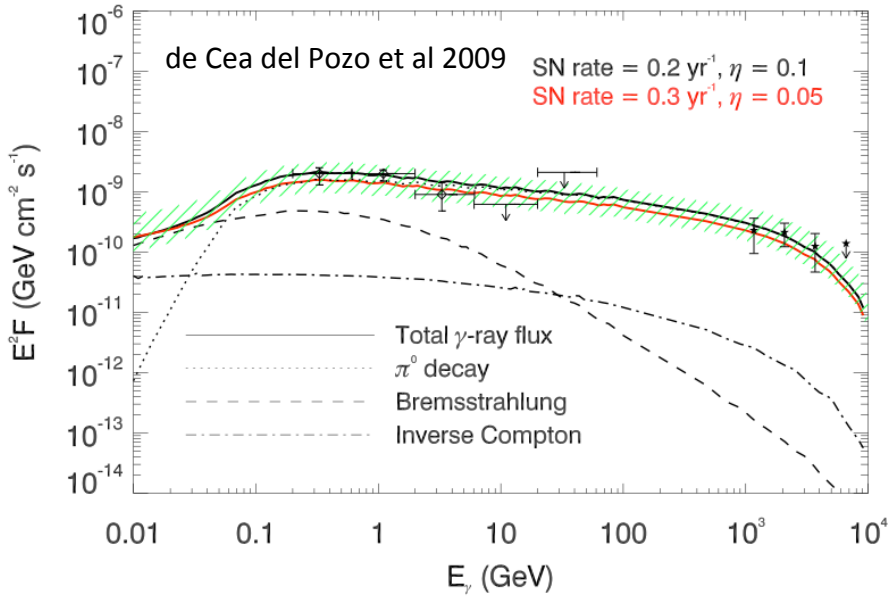
(Figure for 0.2 deg aperture)

Channel	R [deg]	m_χ [GeV]	$\langle\sigma v\rangle$ [cm^3 s^{-1}]
W^+W^-	0	2000	1.1×10^{-20}
	0.2	1900	4.3×10^{-21}
	0.4	1900	8.4×10^{-21}
$b\bar{b}$	0	3500	1.2×10^{-20}
	0.2	3400	4.4×10^{-21}
	0.4	3500	8.7×10^{-21}
$\tau^+\tau^-$	0	670	2.4×10^{-21}
	0.2	650	9.1×10^{-22}
	0.4	660	1.8×10^{-21}

Lack of gamma-ray signature can also be translated into limits on **CR-to-thermal pressure ratio < 1.7%**

M82: Nearby Starburst Galaxy





- M82 is a prototypical starburst galaxy
  - Close: distance ~ 3.9 Mpc
  - Diameter ~ 1'
  - Central SMBH: < 3 x 10^7 M_{sun}
    - No evidence for AGN
- Tidal forces with nearby M81 => active starburst region
  - Star formation rate: ~10x Milky Way
  - High supernova rate: 0.1 – 0.3 / year

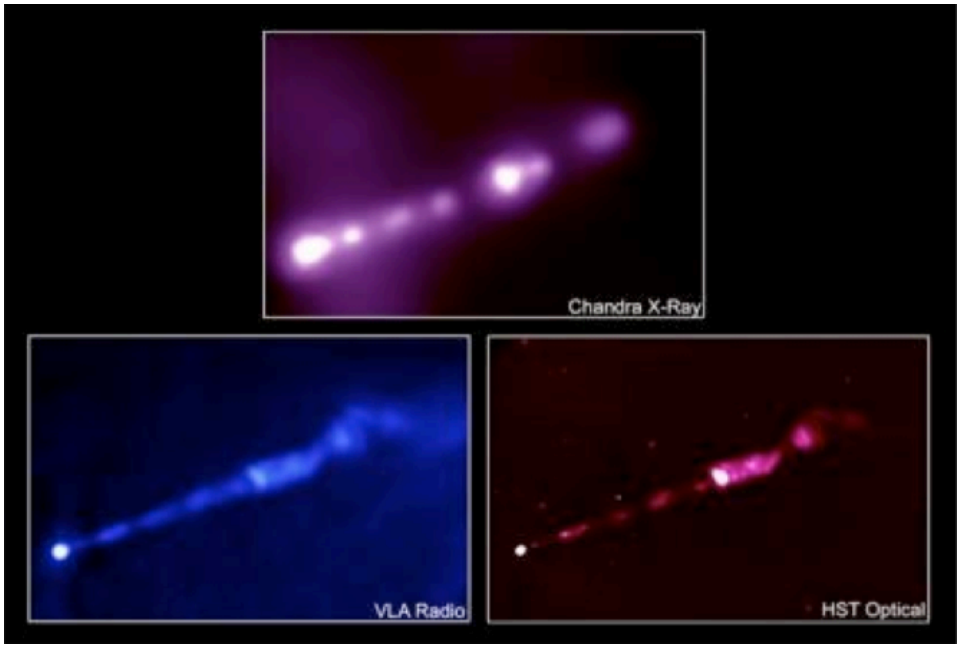
CR hadrons + gas → pions → **γ-rays**
CR e^- + ambient photons → **γ-rays**

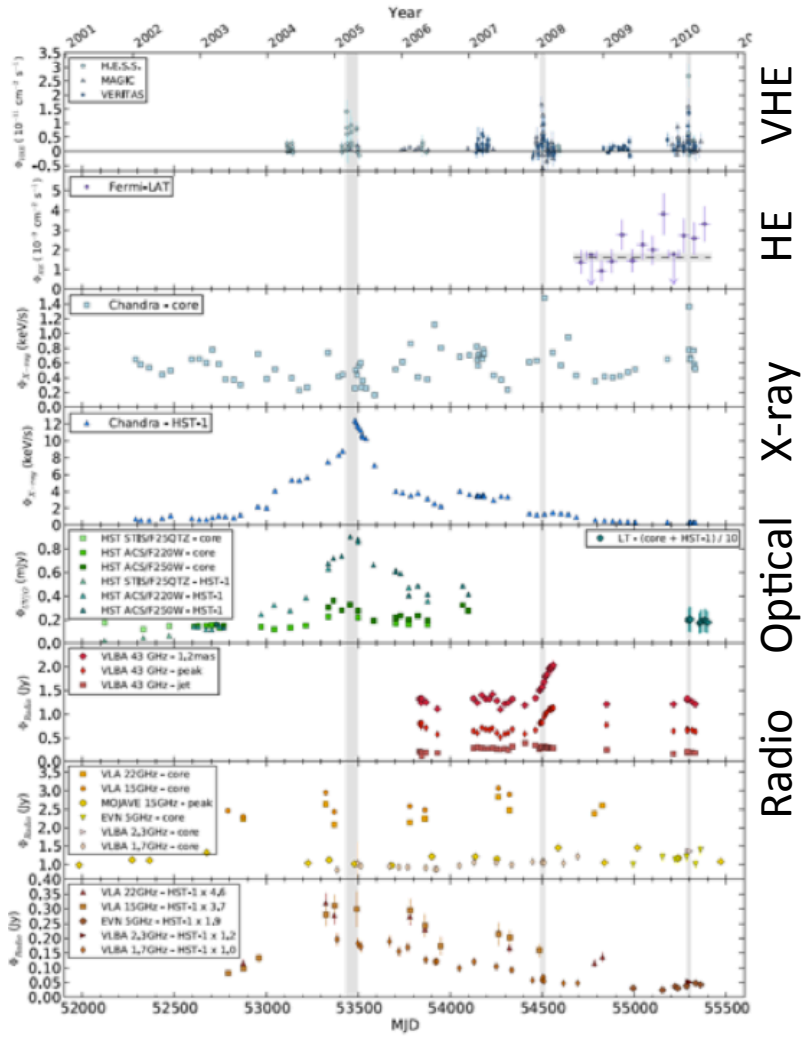
- VERITAS 2007 – 2009: 137 hours of data
  - higher than normal 700 GeV threshold at elevation ~ 39°

Nice model agreement with **$E^{-2.5}$** power-law connecting Fermi-LAT and VERITAS detection

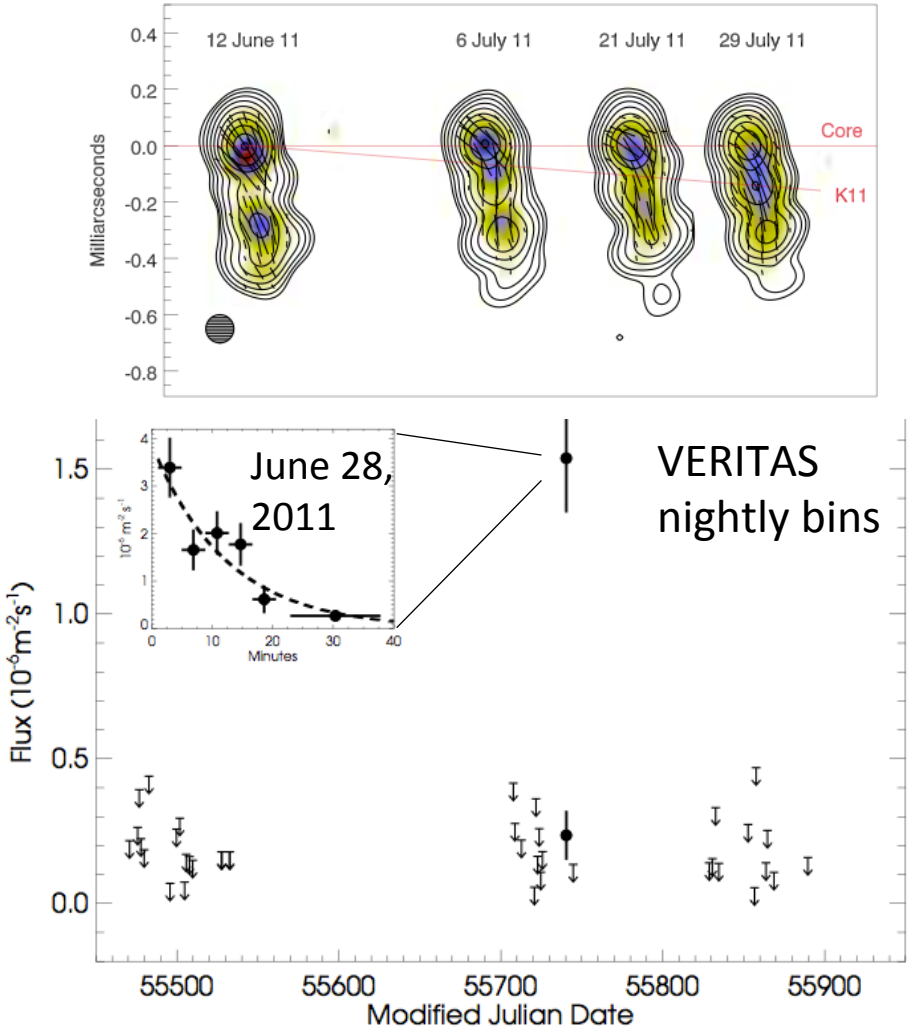
M87: Nearby Radio Galaxy

- Jet substructure evident in MWL imaging
- Coordinated MWL γ-ray, X-ray and Radio campaign
  - VERITAS/MAGIC/HESS/VLBA/Chandra, 2008 – 2011
- Multiple flares detected in 2005, 2008, 2010
  - 1% – 20% Crab units > 250 GeV

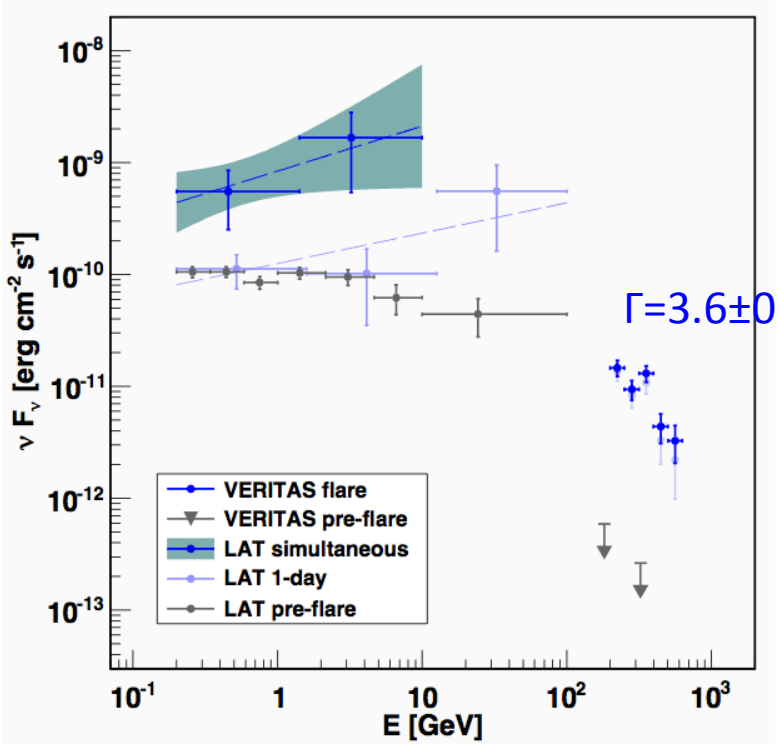




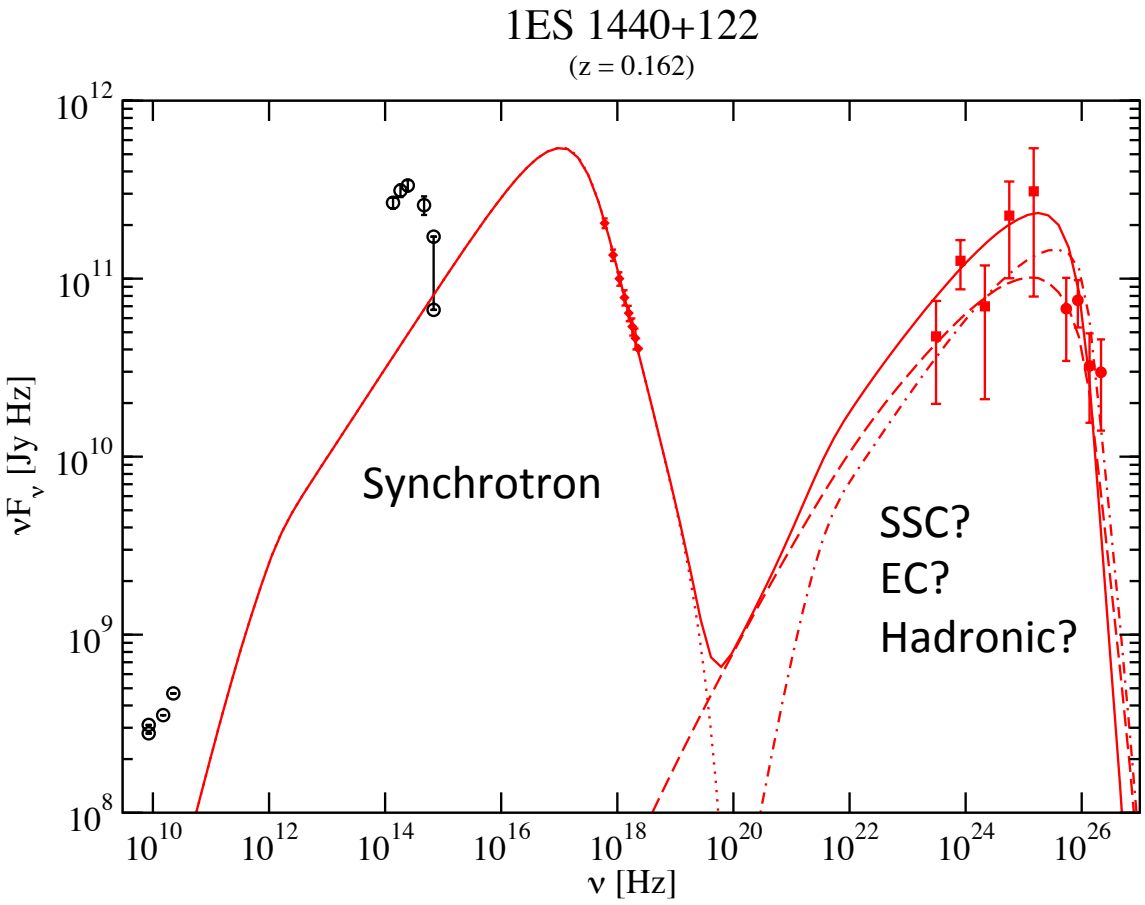
BL Lac: Rapid Variability



- MWL activity → increased VERITAS monitoring
  - 125% Crab units > 200 GeV
  - 13 ± 4 min flare decay time
  - Soft spectrum: Γ=3.6 ± 0.4
- Emergence of radio knot linked to gamma ray flare



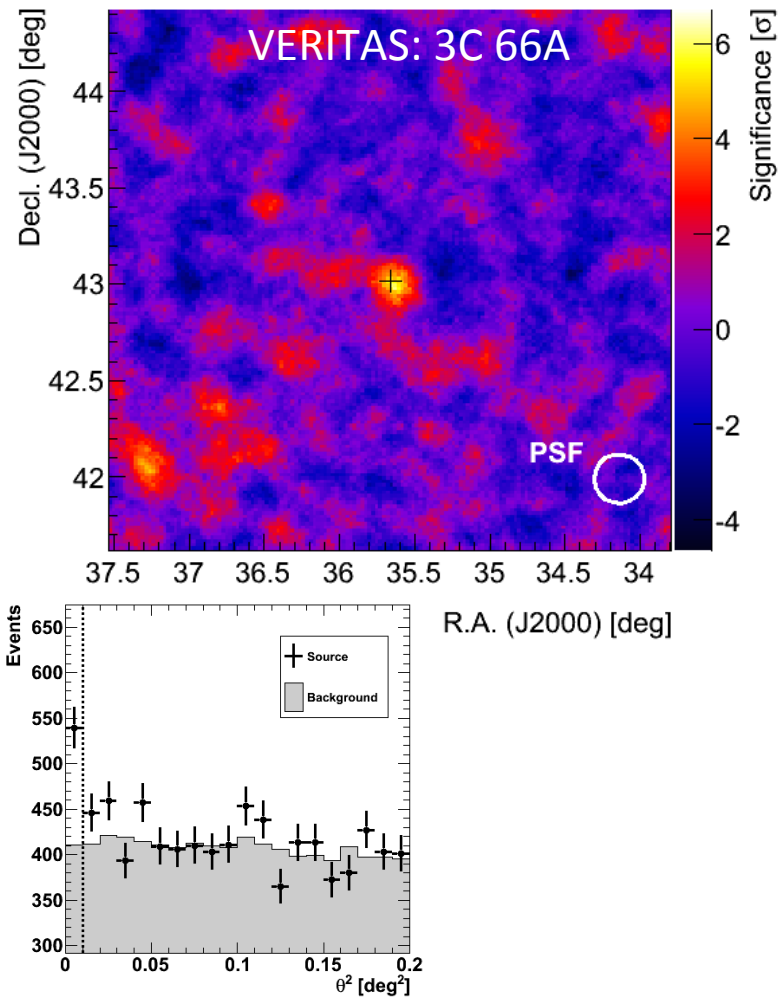
1ES 1440+122 Classification



External Compton model shown, fitting jet parameters to SED

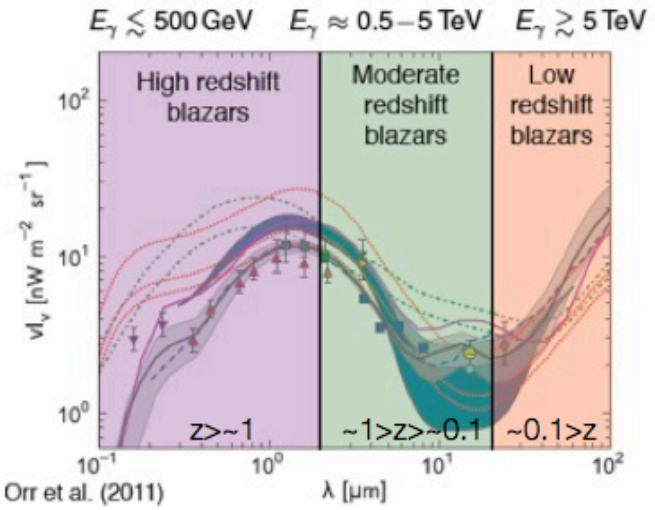
- Using Swift, Fermi-LAT, and VERITAS to build SEDs:
  - Synch. self-Compton (SSC)
  - External Compton (EC)
  - Hadronic
- All models fit data well
  - EC closest to equipartition
  - $\nu_{peak} = \sim 10^{17}$ Hz
- $\nu_{peak} = 10^{16.4}$ Hz from model fit in Nieppola et al. (2006)
  → borderline case between IBL and HBL

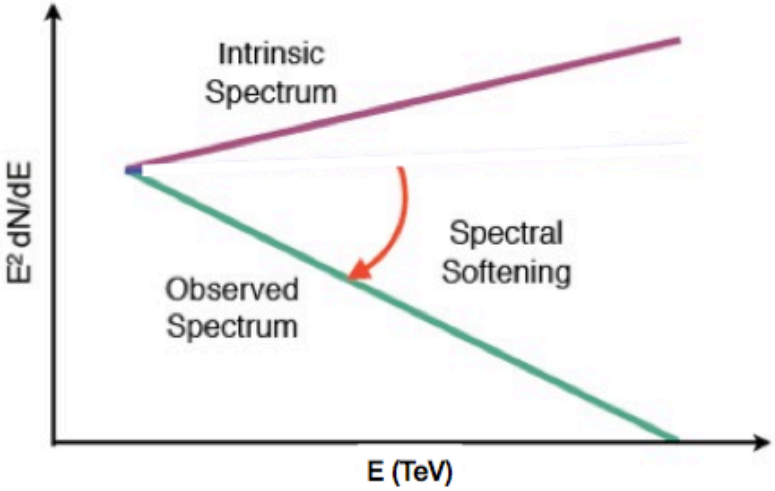
3C 66A: Low-state Detection



- VERITAS detections of IBLs and LBLs have been in flaring states
  - Flaring HBLs can have different SED properties
- Little is known about quiescent flux states of lower-frequency peaked BL Lacs
- Deeper observations have lead to quiescent detections of 3C 66A (17 hrs) and W Comae (30 hrs)
- 3C 66A flux ~5x lower than flaring state
- Analysis of optical, UV, X-ray, and GeV gammas rays also underway

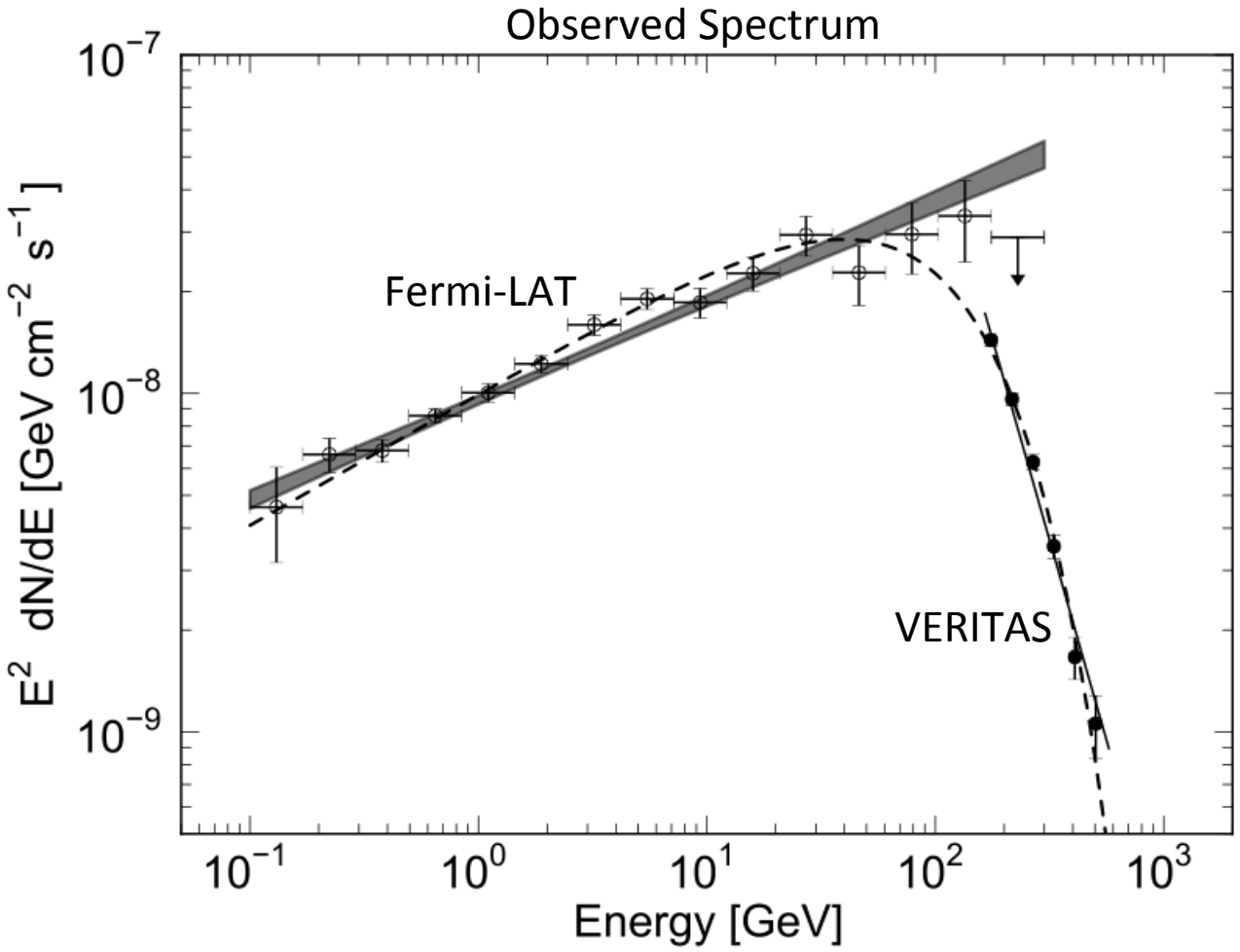
Extragalactic Background Light





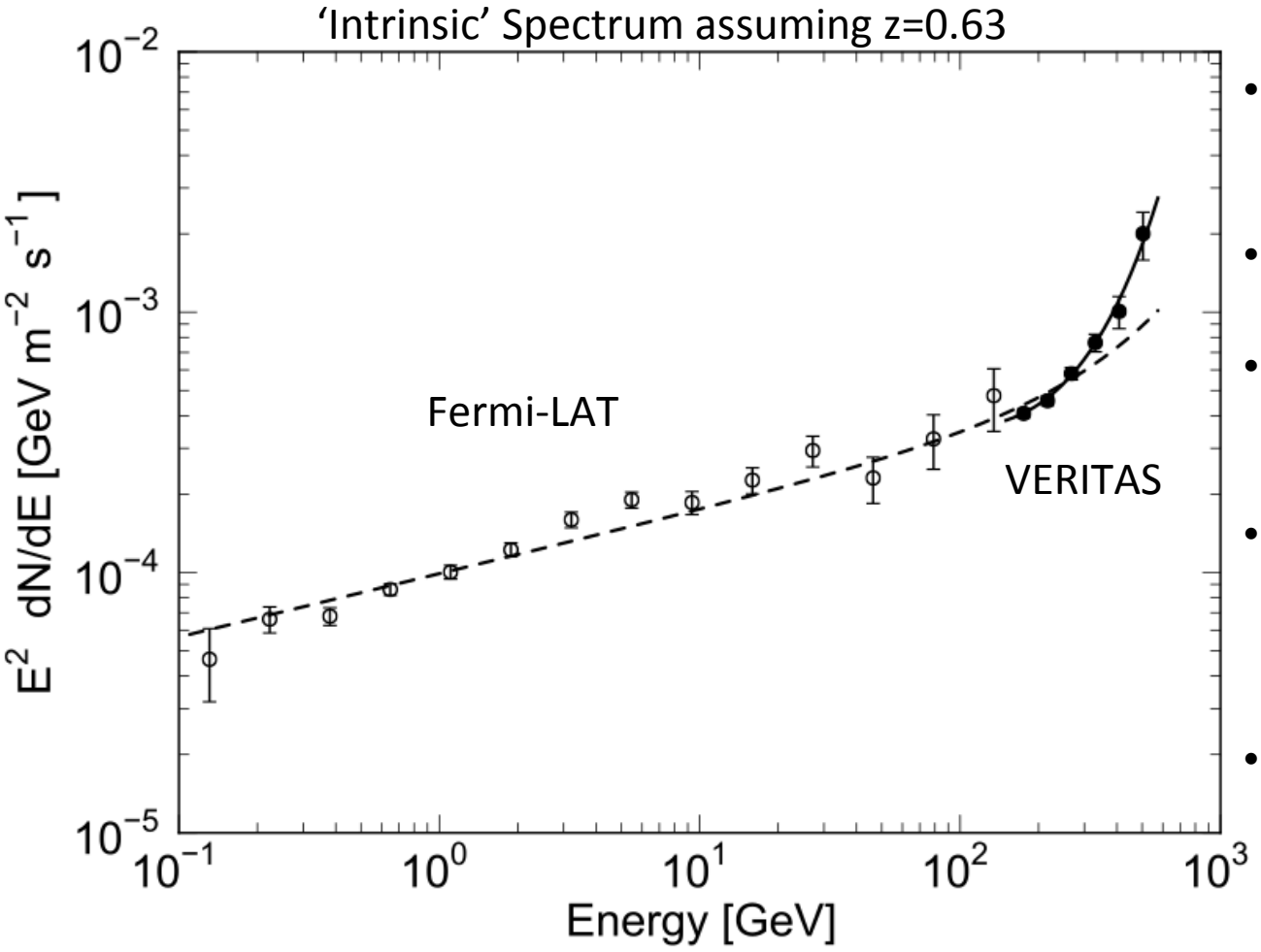
- The Extragalactic Background Light (EBL) originates from radiative energy releases throughout cosmic history
- Spans ultraviolet to infrared
- Encodes information about stellar evolution throughout cosmic history
- Direct measurement difficult
- Pair production attenuates gamma ray flux from distant sources and high energy
  - Modifies spectra in specific ways

PG 1553+113: New Redshift Constraints



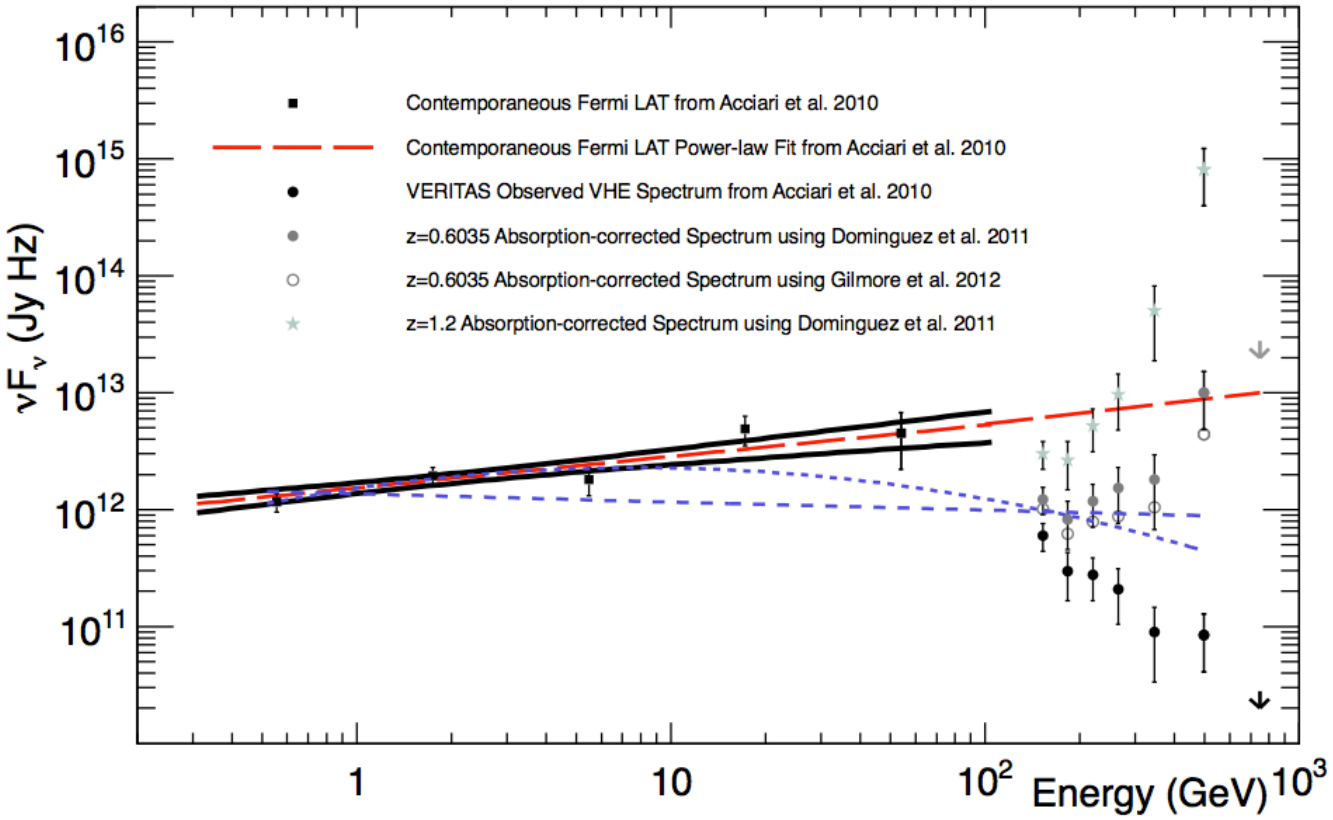
- Fermi and VERITAS spectra shown
- Clear cutoff ~100 GeV
- Unknown redshift
  - $z > 0.4$

PG 1553+113: New Redshift Constraints



- Fermi and VERITAS spectra shown
- Clear cutoff ~100 GeV
- Unknown redshift
  - $z > 0.4$
- Assuming minimal EBL, de-absorb to obtain intrinsic spectrum
- At **z>0.63**, the spectrum becomes unphysical for a standard blazar

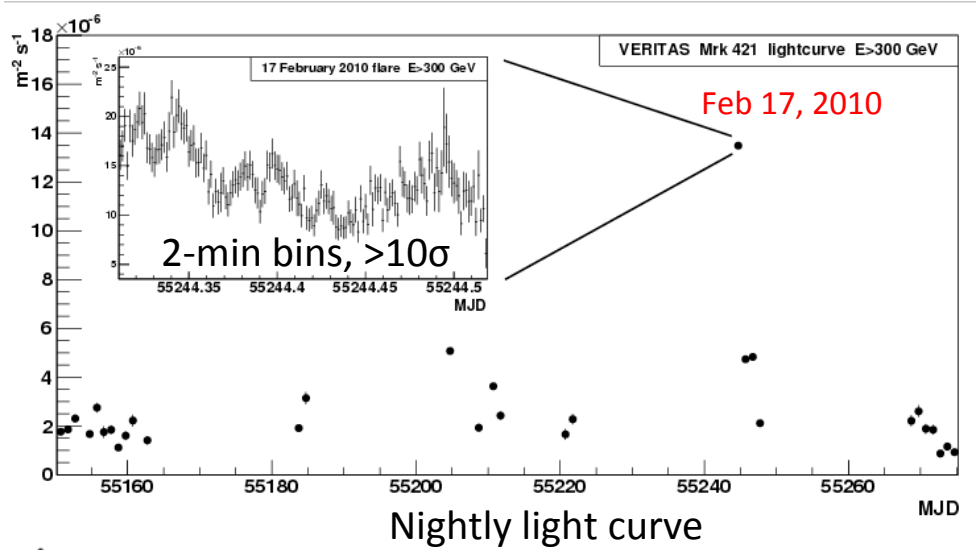
PKS 1424+240: Farthest VHE Source



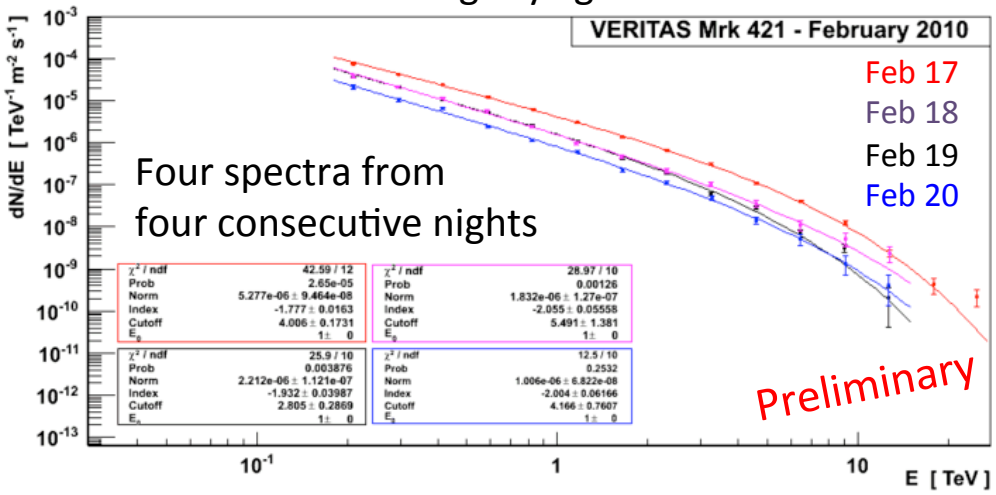
- New strict lower limit from absorption features: $z > 0.6035$
- Interesting discontinuity between Fermi-LAT and VERITAS
- Correcting for EBL leads to very hard intrinsic spectrum
  - Finke EBL model: $\Gamma = 0.6 \pm 0.8$
- ~80 hrs of additional data collected so far this season

Furniss et al 2013

Mrk 421: 2010 Extreme VHE Flare

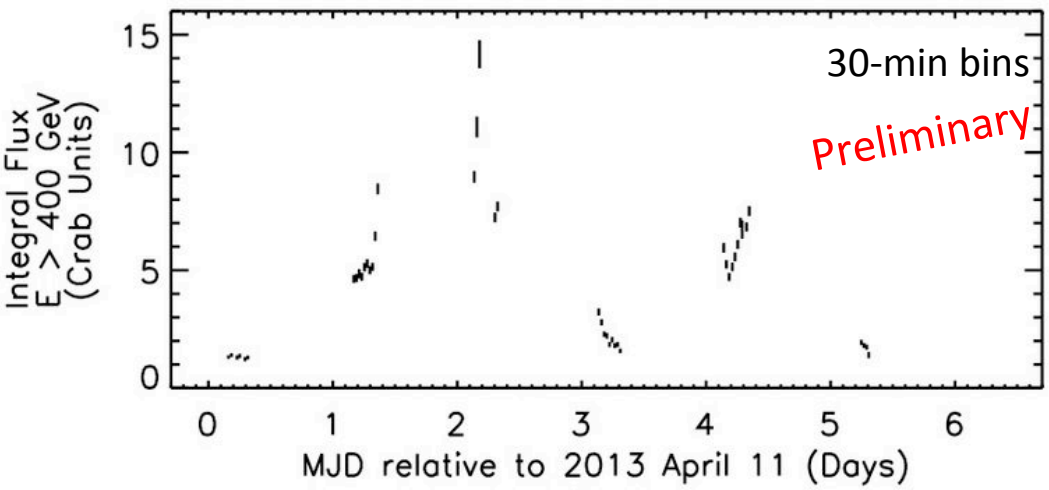


Nightly light curve



- Multiwavelength campaign, 2009 – 2010
- ~8 Crab flare observed in Feb 2010
- Minute-scale variability detected
- > 20 TeV spectral point at high optical depth
- Work underway on SED modeling, EBL, and LIV – publications underway

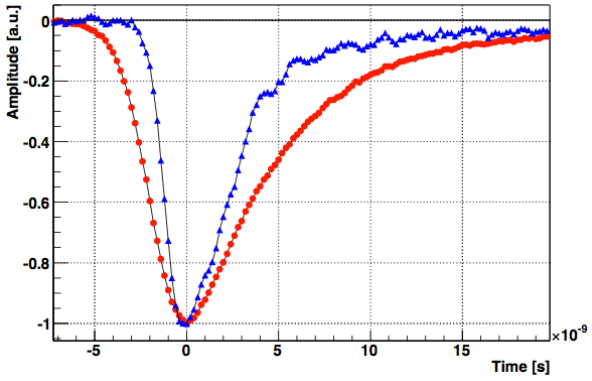
Mrk 421: Recent VHE Flare

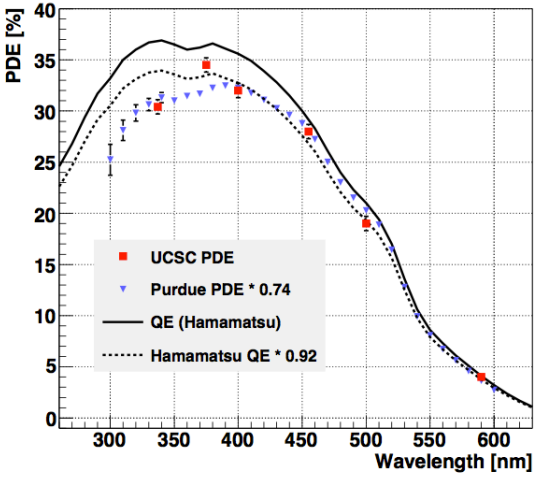


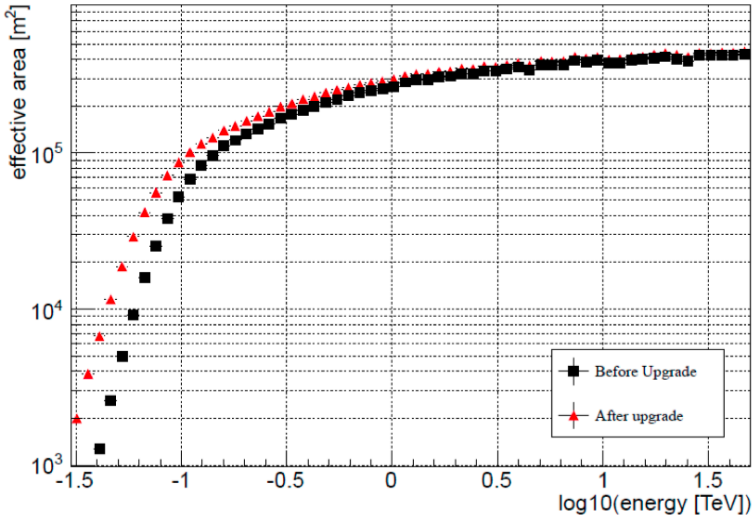
- Monitoring as part of a multiwavelength campaign with NuSTAR revealed another extreme flaring event just recently in April
  - Elevated flux observed over ~6 nights
- ~14 Crab units at max
- 11 hrs of truly simultaneous coverage with NuSTAR just during April
  - Swift and optical coverage as well
- MAGIC took data during gaps in the VERITAS data
- An extraordinary dataset that we are just beginning to explore in detail!
- Similar campaign with Mrk 501 just starting

Camera Upgrade



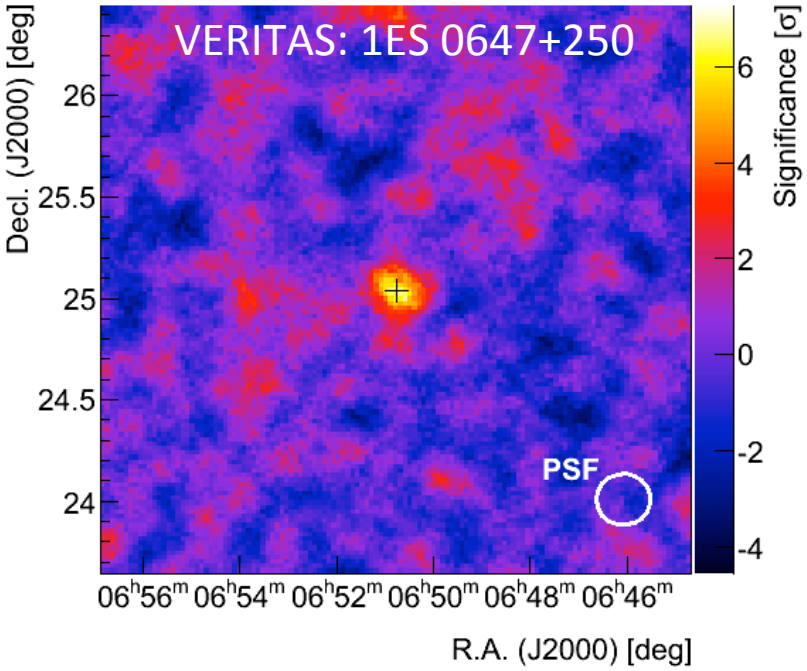




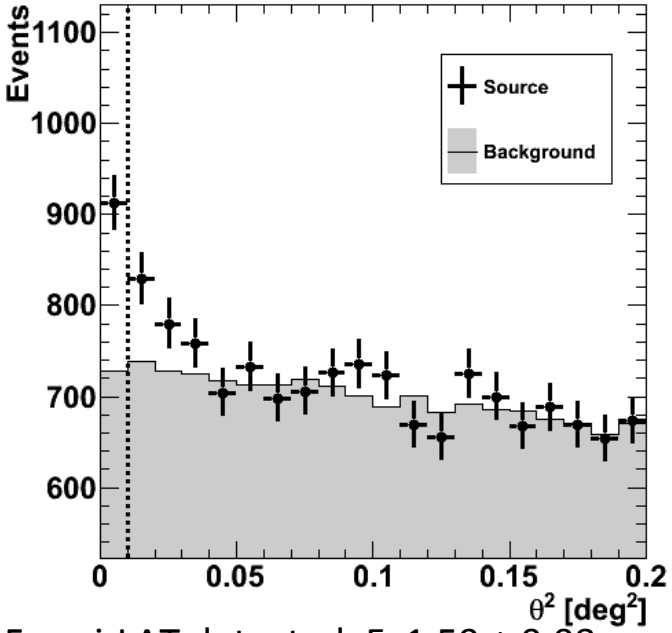


- During Summer 2012, all PMTs replaced
  - Faster pulse shape
  - QE increased 35% (for Cherenkov signal)
- Biggest increase in effective area at low energy
- Currently finalizing calibrations, simulations, and analysis chain

1ES 0647+250: A New VERITAS Detection

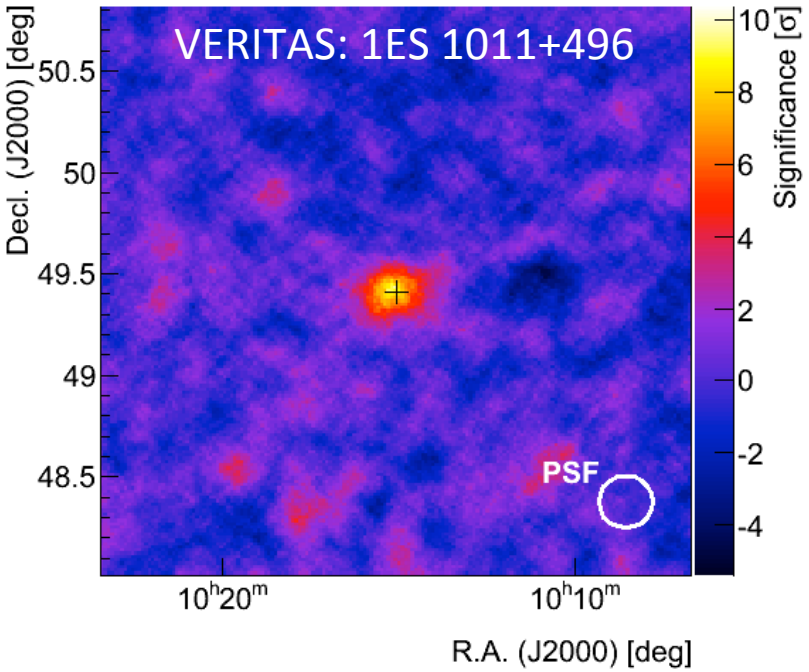


- Redshift uncertain (no spectral features)
  - z = 0.45 ± 0.08 Meisner & Romani 2010
  - z = 0.41 ± 0.06 Kotilainen et al. 2011
  - z > 0.49 Shaw et al. 2013

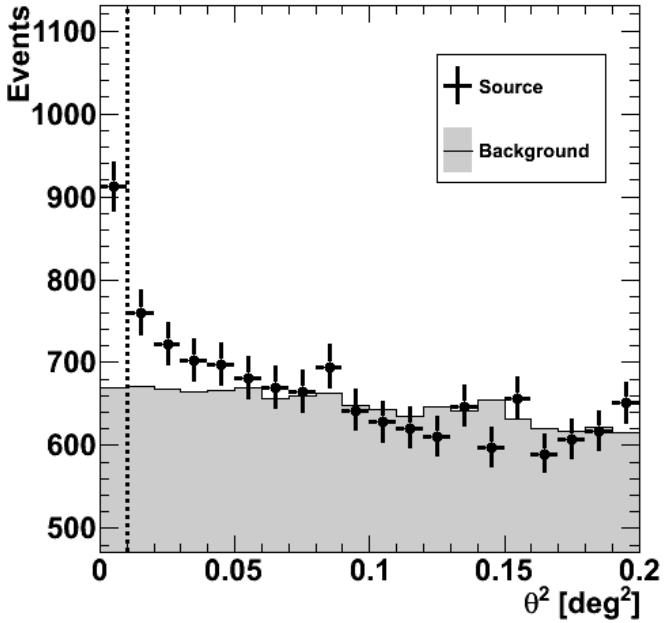


- Fermi-LAT detected, Γ=1.59 ± 0.08
- VHE discovery by MAGIC in 2011, 3% Crab units
- VERITAS monitoring during partial moonlight lead to ToO and 10.9 hours of observing
  - **6.2σ** detection
  - **2.9% Crab** units > 140 GeV
  - more details coming

1ES 1011+496: A New VERITAS Detection



- VHE discovery by MAGIC in 2007
  - 7% Crab units > 200 GeV
  - Γ=4.0 ± 0.5 stat ± 0.2 sys
- z = 0.212
- Optical and VHE variability reported



- VERITAS monitored during partial moonlight, triggered ToO
- Detected at **8.5σ** in 10.4 hours
- ~**6.3% Crab** units > 150 GeV
- Obtained simultaneous x-ray observations
- Again, more details underway

Conclusions

- Very active extragalactic science program addressing a range of questions
  - Supermassive black holes
  - Fundamental physics
  - Cosmology

- Camera upgraded with new higher QE PMTs
  - Two new VERITAS blazar detections

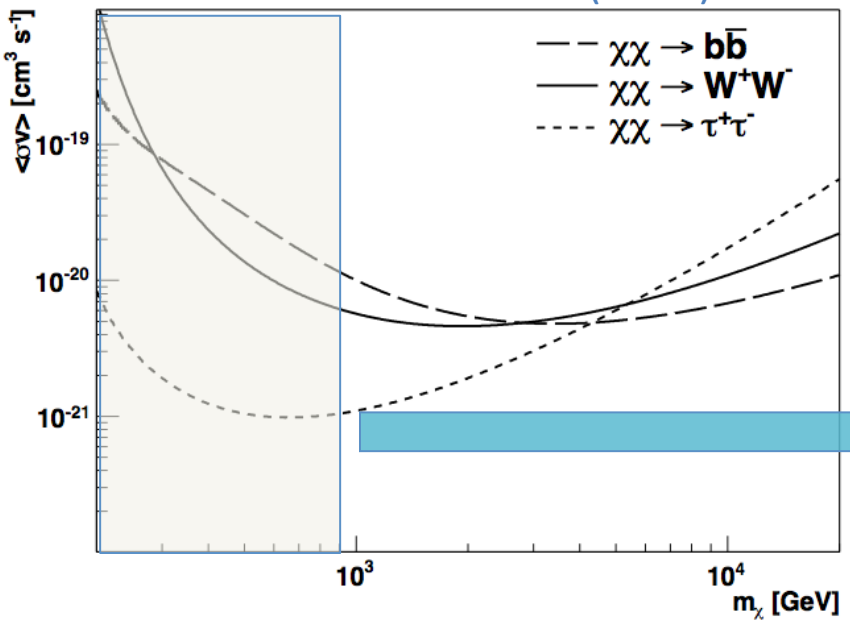
Backup Slides



Comparisons with Fermi LAT results

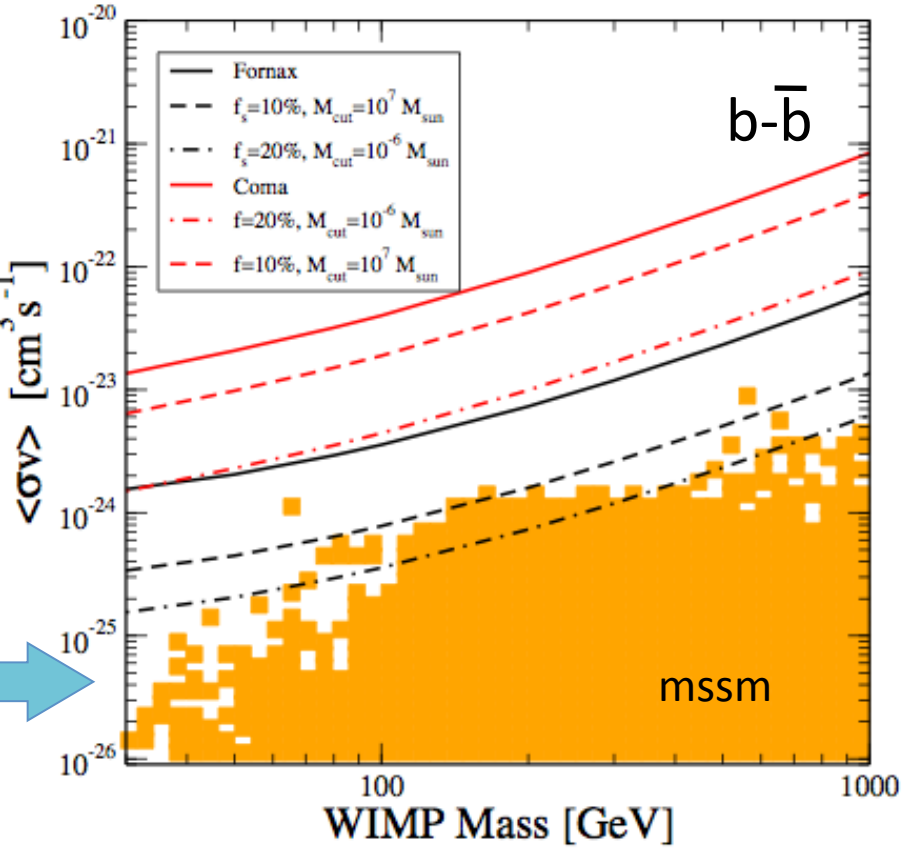
- Fermi LAT probes lower WIMP mass

Coma Cluster – VERITAS (2012)



T. Arlen et al submitted 2012

Coma Cluster (red line) – Fermi(2012)



T. Porter et al 1104.2836