Recent Results from VERITAS

Season 2009/2010

Gernot Maier for the VERITAS Collaboration

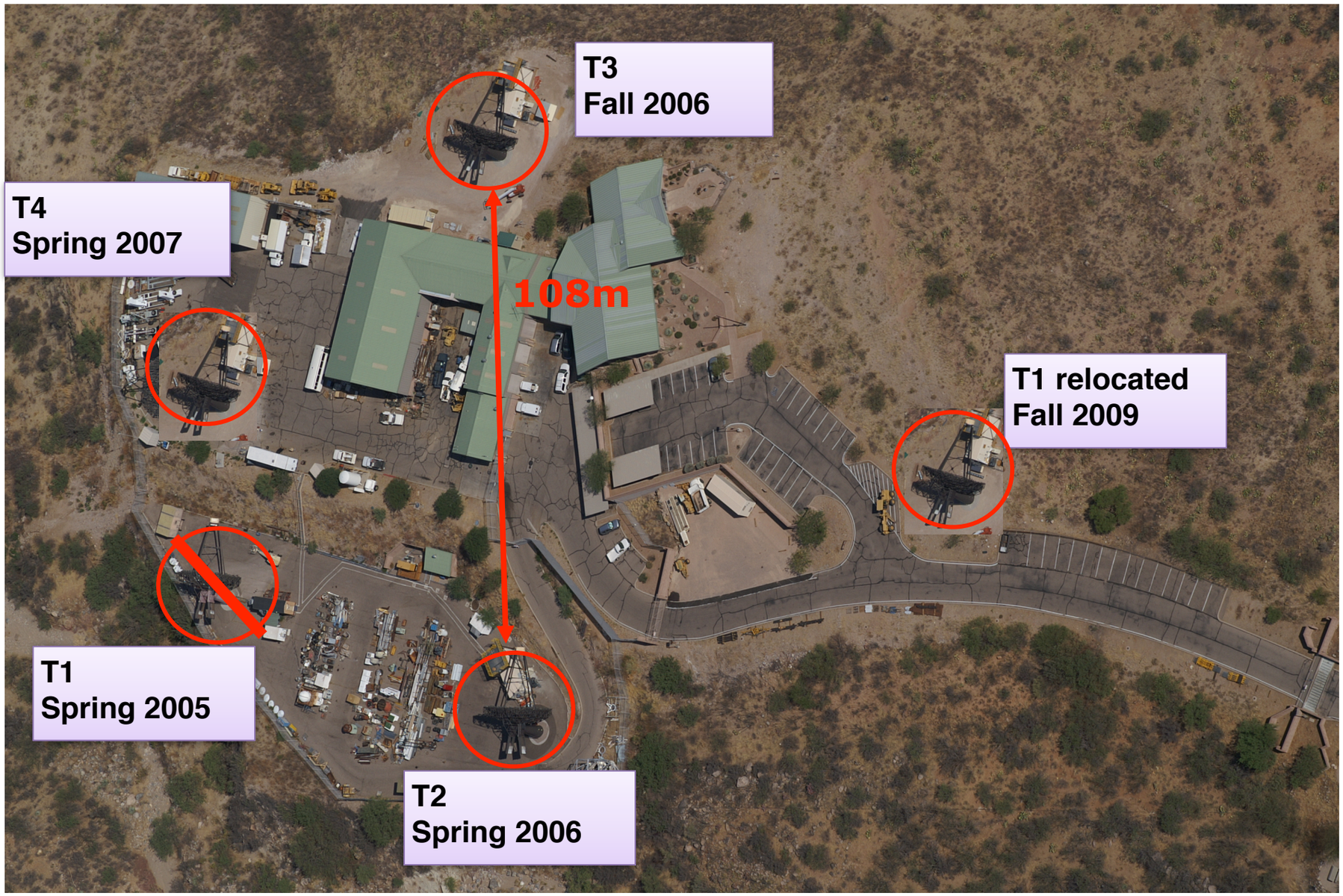
DESY

HELMHOLTZ ASSOCIATION

Very Energetic Radiation Imaging Telescope Array System

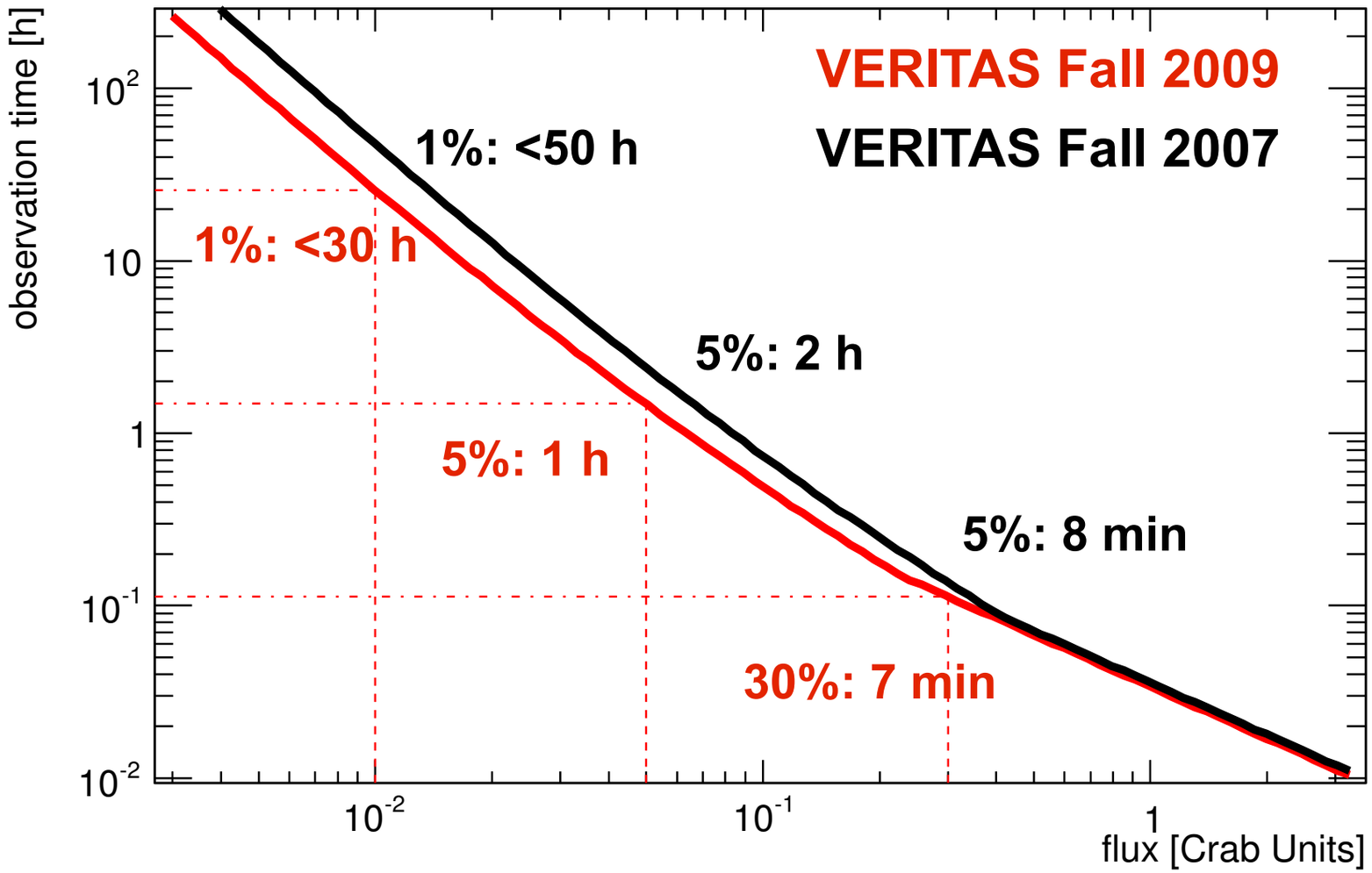
- array of four 12 m Imaging Atmospheric Cherenkov Telescopes
- located at the Fred Lawrence Whipple Observatory in southern Arizona
- US-led collaboration of ~85 scientists, 22 institutions in five countries

VERITAS Fall 2009 - Array Layout Optimization



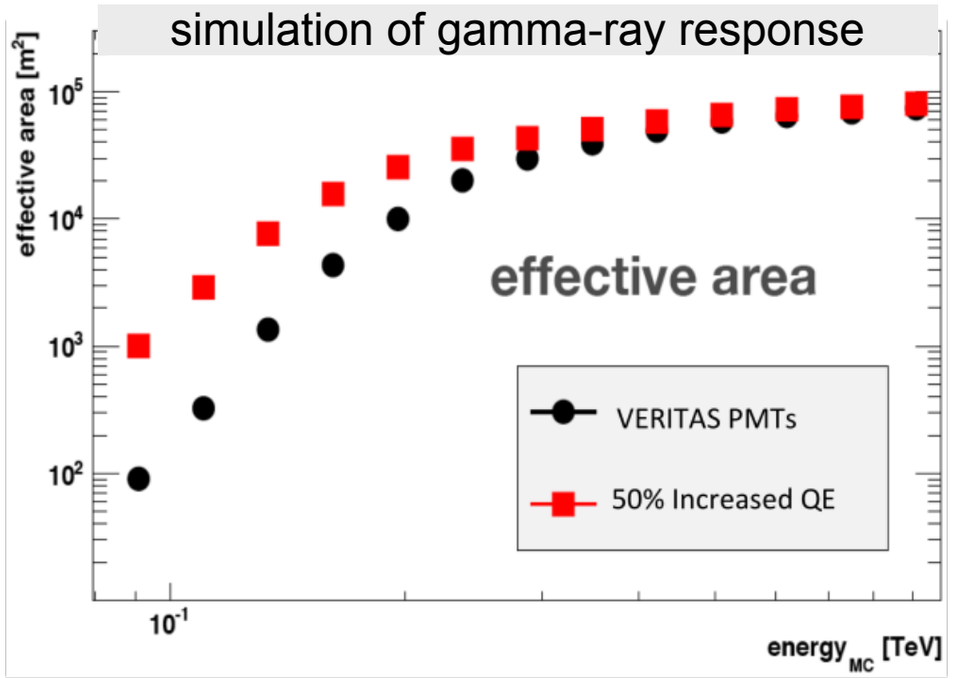
August 2009: telescope relocation and improved mirror alignment

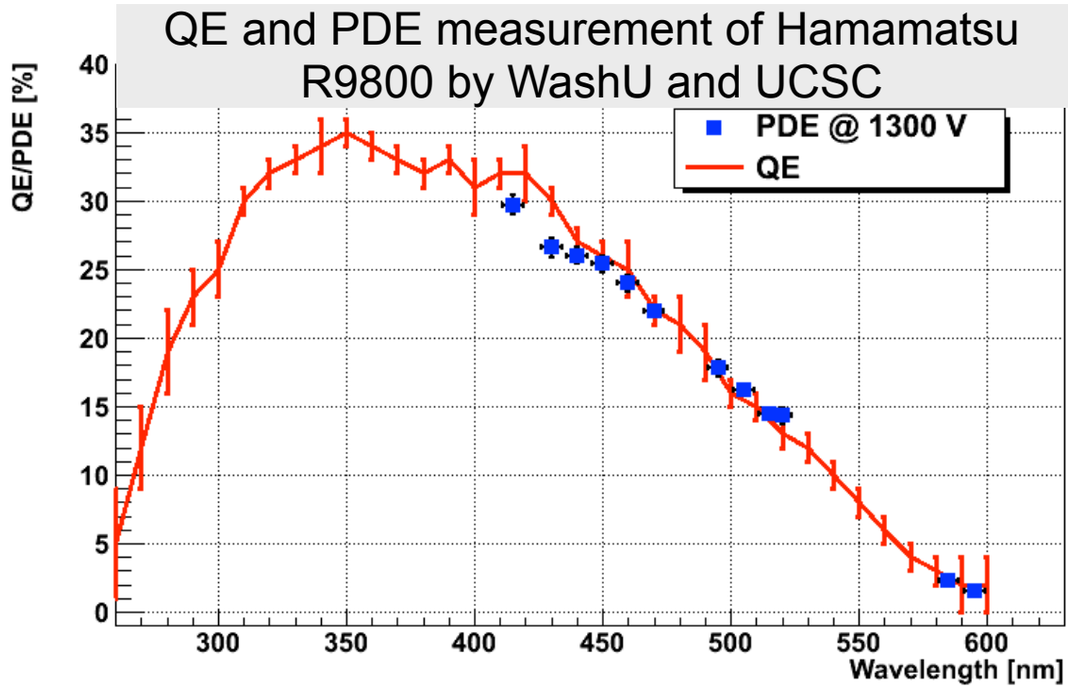
VERITAS Sensitivity



- Data:
  - 2009/2010: ~1180 h of observing (~15% in moonlight; 94% with 4 telescopes)
- Characteristics:
  - angular resolution: $r_{68\%}$<0.1°
  - energy range 100 GeV to 30 TeV
  - energy resolution: ~15%

VERITAS Upgrades (2010-2012)

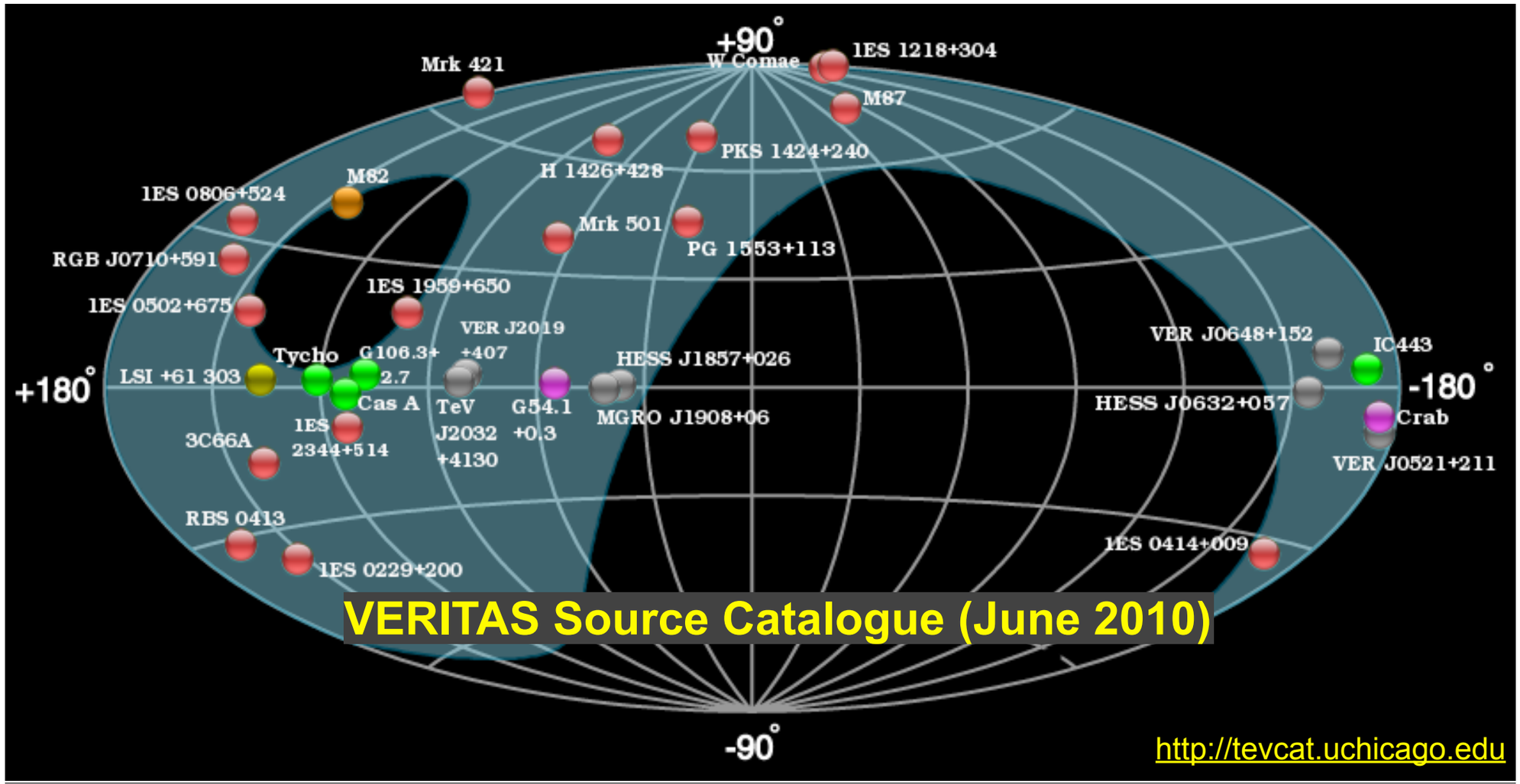




- PMT replacement with high efficiency PMTs (Summer 2012, funded)
  - lower energy threshold (trigger threshold from 120 GeV → 80 GeV)
  - improved sensitivity
- trigger upgrade (installation/commissioning Summer/Fall 2010, funded)
  - lower energy threshold and improved CR event rejection
- drive update (study phase) shorter response time to GRBs, etc.

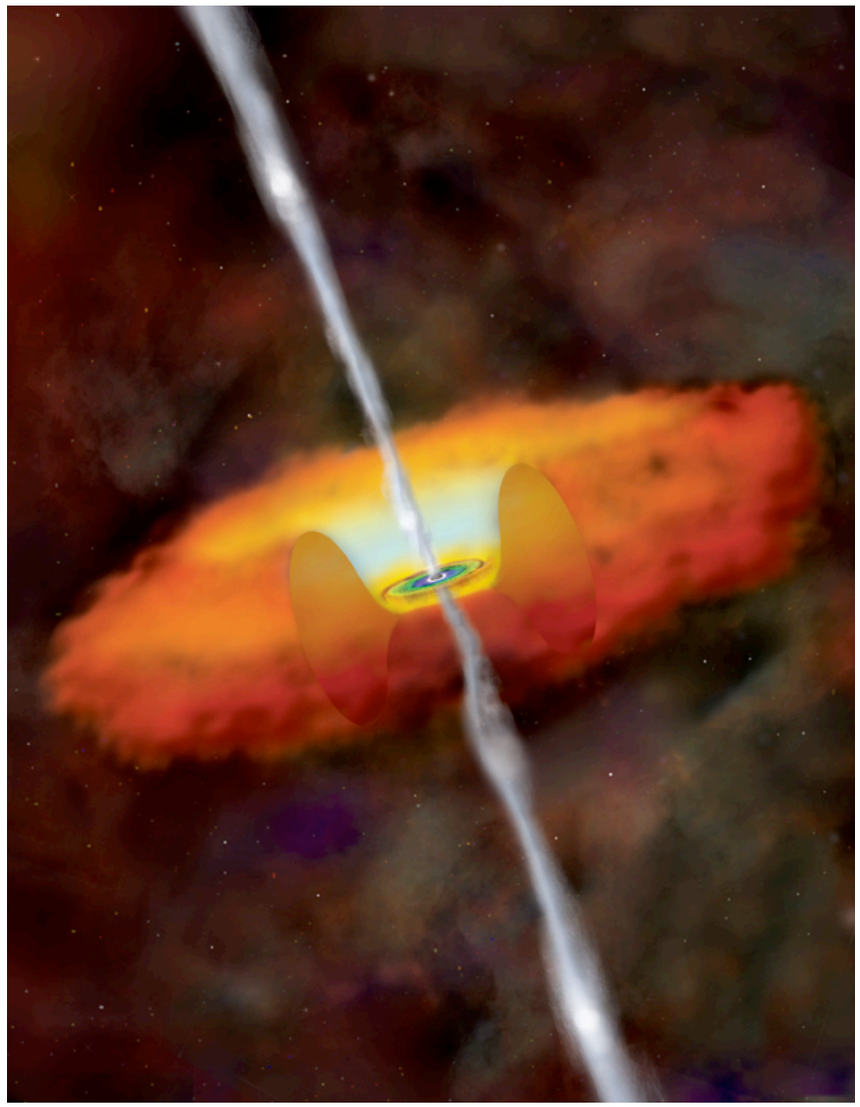
VERITAS: Astrophysics, Cosmology, Fundamental Physics

- Extragalactic Science (GRBs, AGNs, Starburst Galaxies)
- Galactic Science (SNRs, PWNs, Binaries)
- Search for Dark Matter



VERITAS Science with Extragalactic Objects

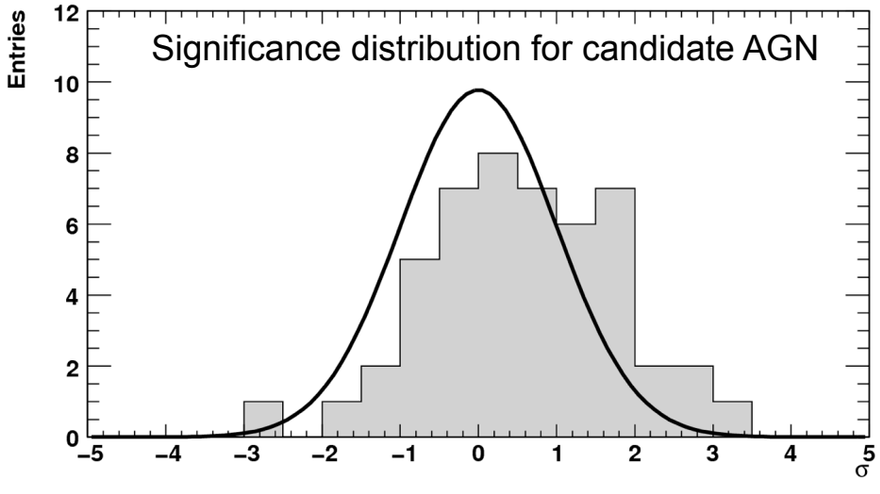
- Gamma-ray Bursts
  - Search for afterglow emission
  - highest priority in observing procedure
- Starburst Galaxies (M82)
  - Are SNRs the sources of charged cosmic rays?
  - Nature 462, 770 (2009)
- Radio Galaxies (M87, NGC 275)
  - Search for emission region of VHE photons
  - Science 325, 444 (2009)
- Blazars
  - AGN population studies; Blazar sequence
  - AGN emission mechanism and region; AGN states
  - Constrain optical/IR extragalactic background light
  - Fundamental physics (e.g. quantum gravity)



NASA/CXC/M.Weiss

Observations of AGNs with VERITAS

- ~700 h (incl. moonlight data) in 2009/2010
  - discovery; deep exposures of known sources (multiwavelength); ToO
- 20 detections **(10 discoveries);** all with MW data
- 4 VHE intermediate BL Lac
- Target selection:
  - Fermi LAT / EGRET;
  - X-ray bright HBL & IBL
- 2007-2009
  - Exposures on 49 X-ray selected AGN (~6 h each)
  - ~5σ 'stacked' excess

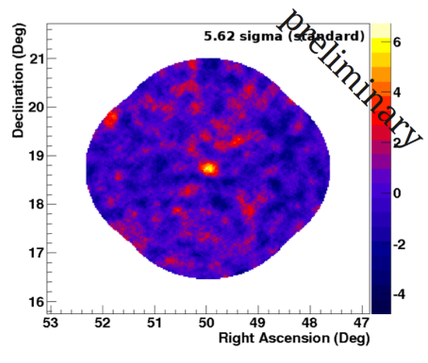


AGN	Type	z
M87	FR I	0.004
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
W Comae	IBL	0.102
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 0229+200	HBL	0.139
1ES 0806+524	HBL	0.138
1ES 1440+122	IBL	0.162
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 0414+009	HBL	0.287
PG 1553+113	HBL	0.34 < z < 0.47
1ES 0502+675	HBL	~~0.341~~ ?
3C 66A	IBL	0.444 ?
PKS 1424+240	IBL	?
VER J0521+211	Blazar	?
RX J0648.7+1516	Blazar	?

New Blazar Detections - the impact of Fermi/LAT

New Blazar Detections - the impact of Fermi/LAT

RBS 0413



- ~5.5σ in 25 h
- 1.6% Crab
- X-ray bright HBL @ z=0.19
- brightest LAT extrapolation

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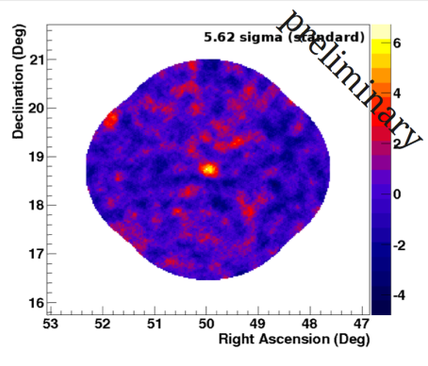

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VER J0521+211

- ~18σ in 15 h
- 4% Crab
- z=? (unsuccessful MMT, MDM, & IR efforts)
- bright flare (>20% Crab)

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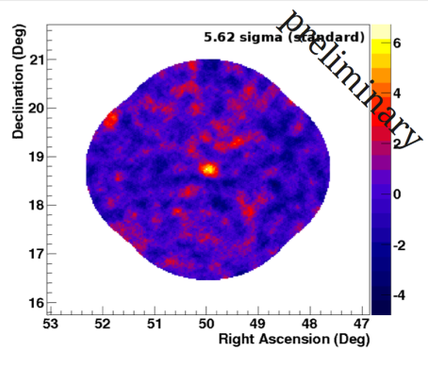

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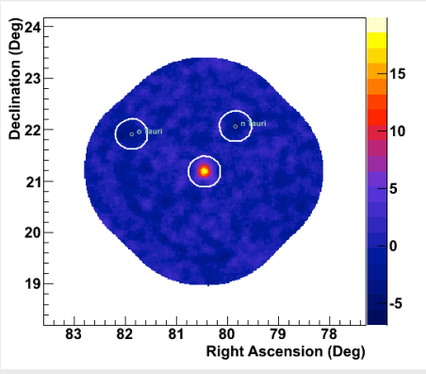

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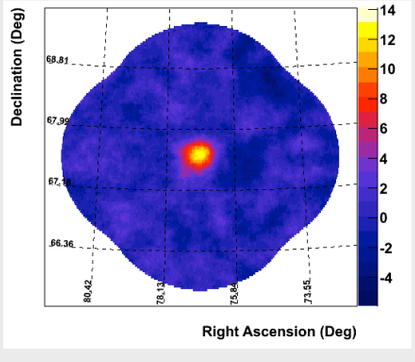
1ES 0502+675



- ~12σ in 30 h
- 5% Crab
- z≠0.341 (1h MMT exposure (10x sensitivity)

New Blazar Detections - the impact of Fermi/LAT

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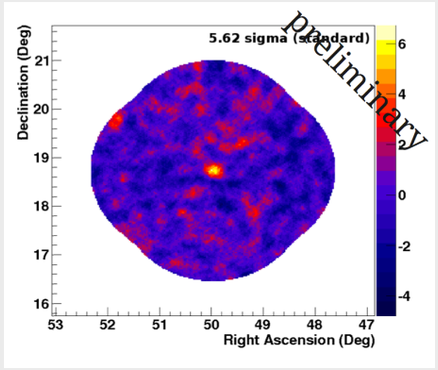

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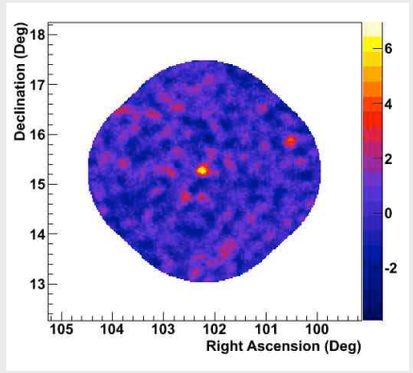

- ~5.2σ in 18 h
- 2% Crab
- Keck: Blazar
- z≠?

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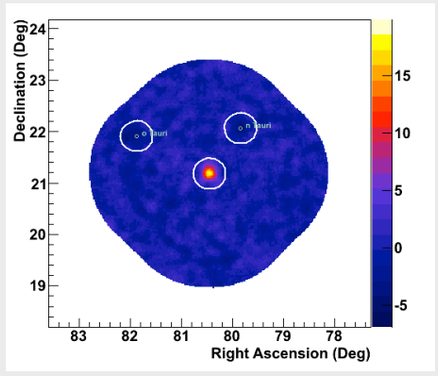

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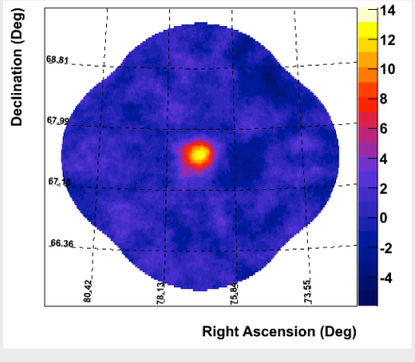

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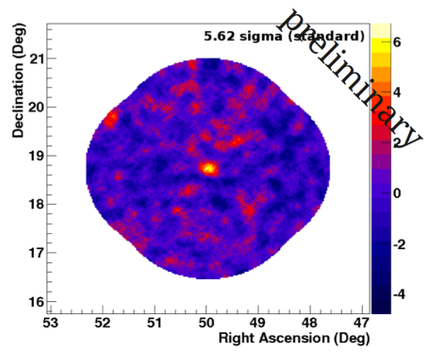

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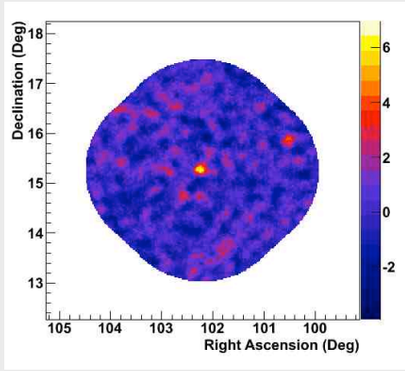

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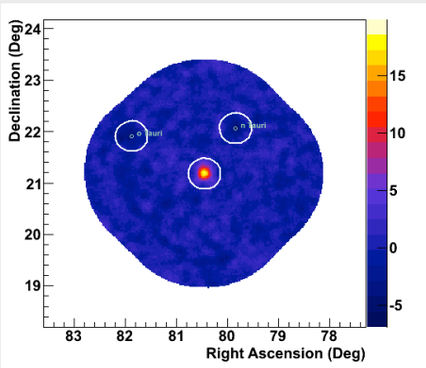

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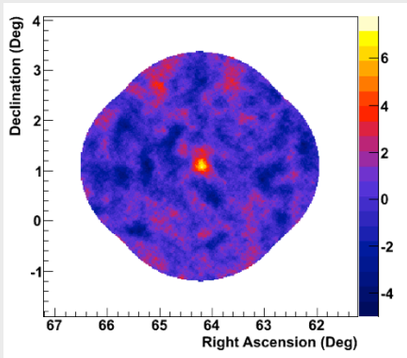

- ~7σ in 45 h; 2% Crab
- among X-ray brightest HBL
- z=0.287
- EBL! high-z Mkn 421
- H.E.S.S. detection

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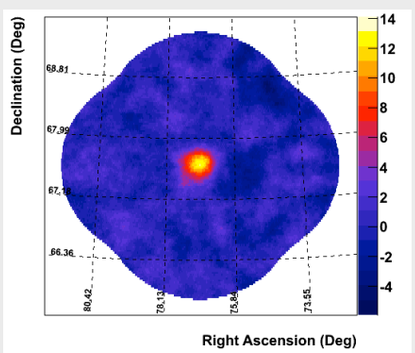

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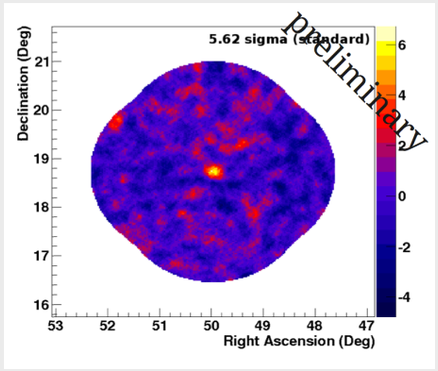

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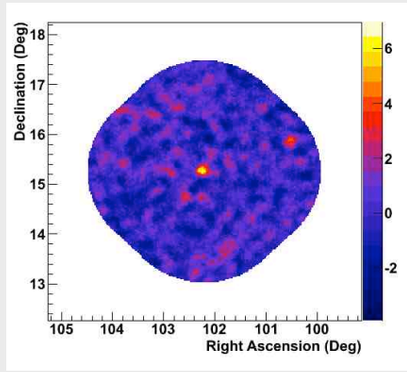

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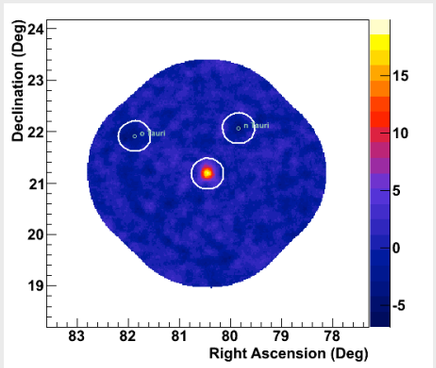

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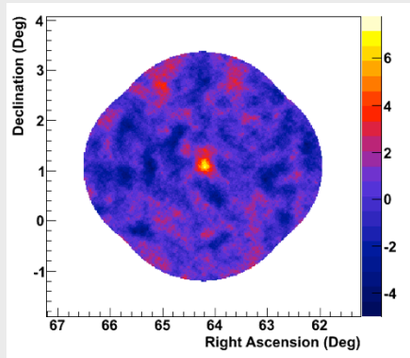

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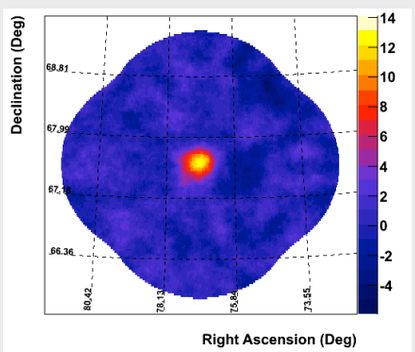

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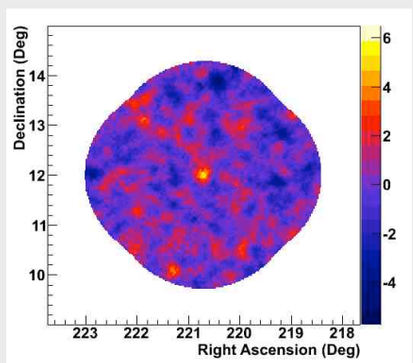
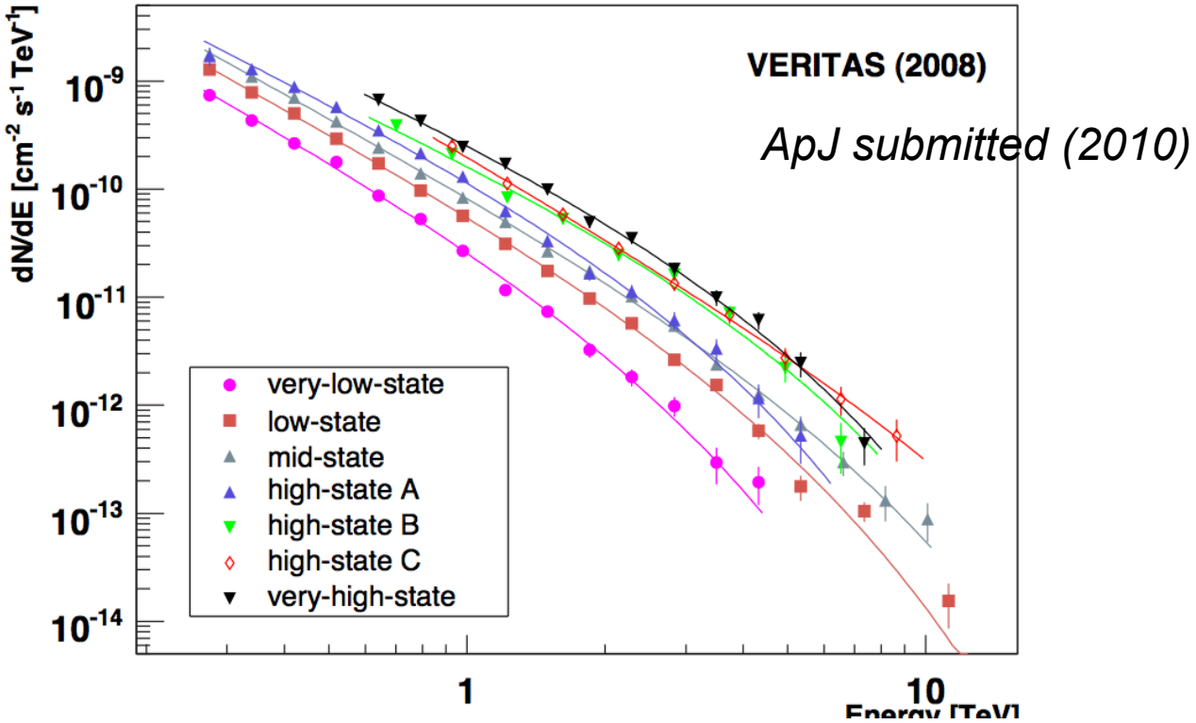
1ES 1440+122

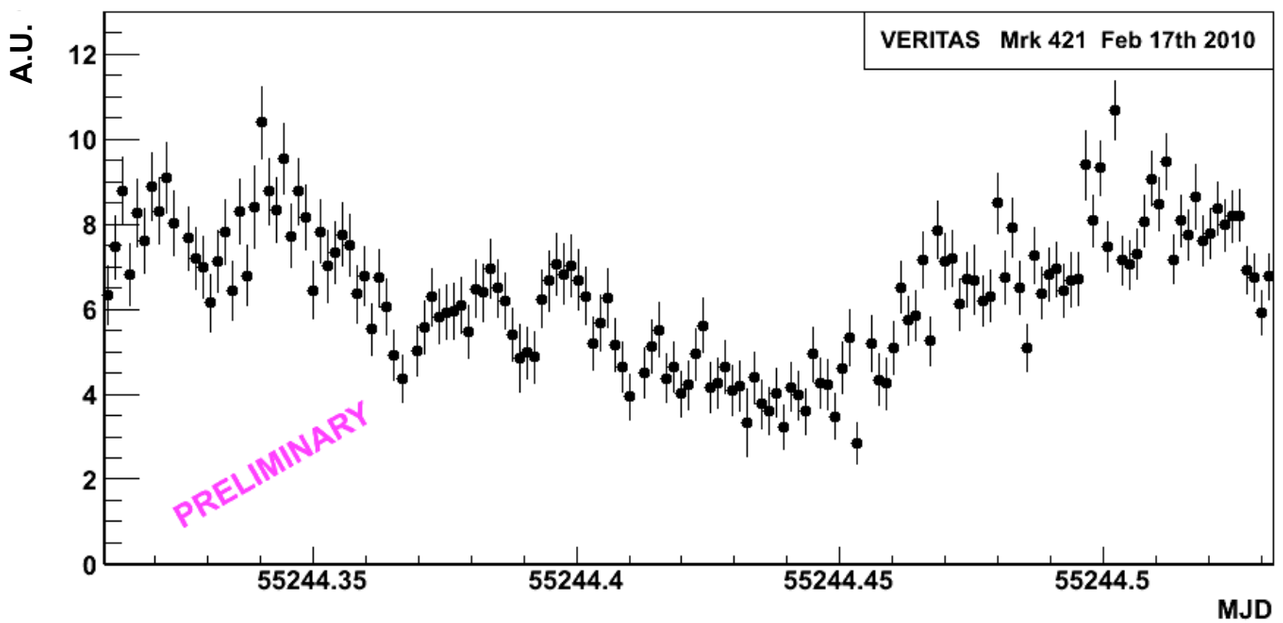


- ~5.2σ in 50 h
- <1% Crab
- hard-spectrum IBL (LAT)
- z=0.162

Mkn 421 monitoring

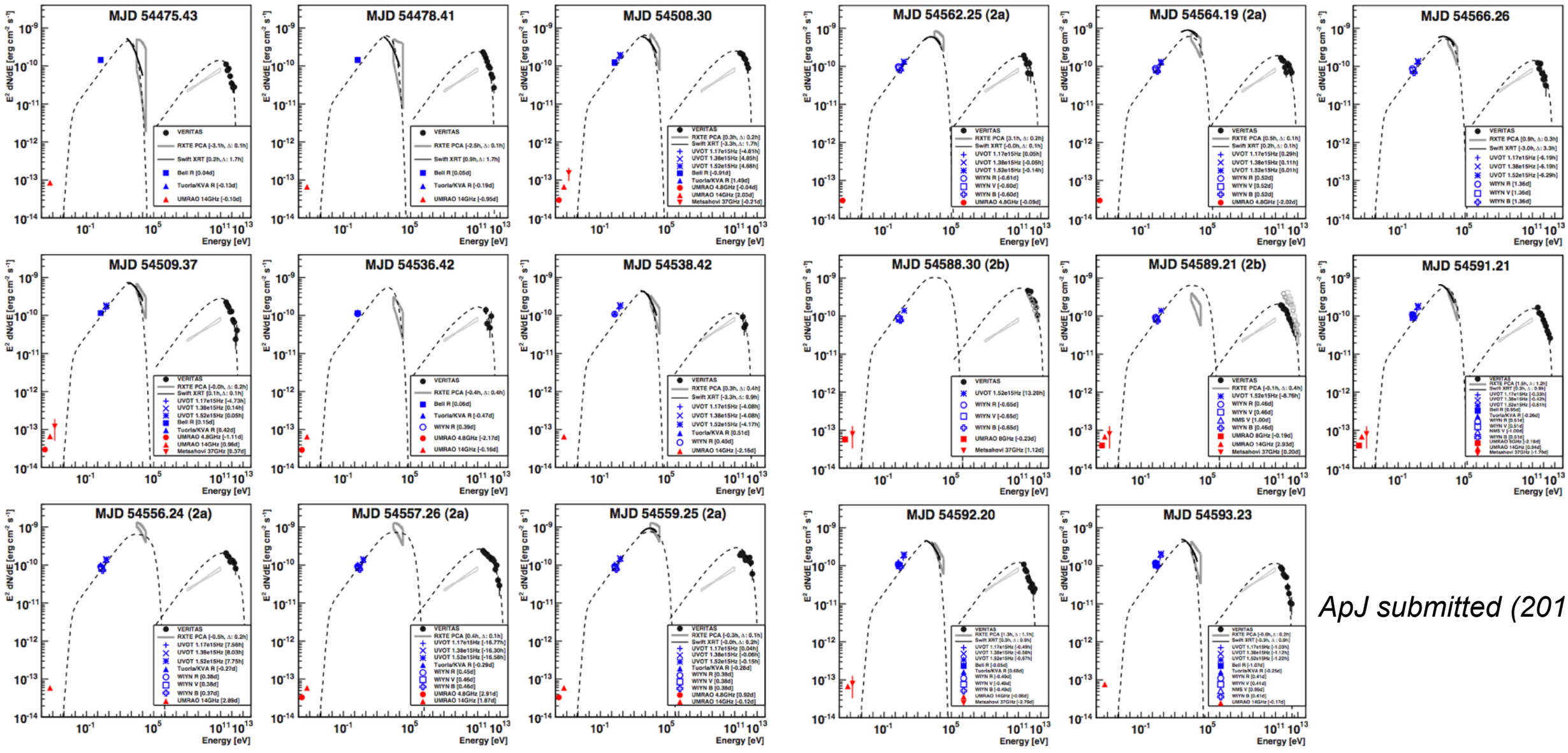
- long-term monitoring program
  - Whipple 10 m / VERITAS
- major flares in 2008 & 2010
  - initiated large MWL efforts
  - spectral hardening with increasing flux
- high in VHE & X-ray since 11/09
  - VHE & X-ray monitoring
  - 35 h of data; ~400σ
- huge flare on Feb 17th 2010
  - variability on 5-10 min time scales
  - >10σ per 2 minute bin





Mkn 421: SED Evolution

2006-2008: ~50 h VERITAS, 100 h Whipple



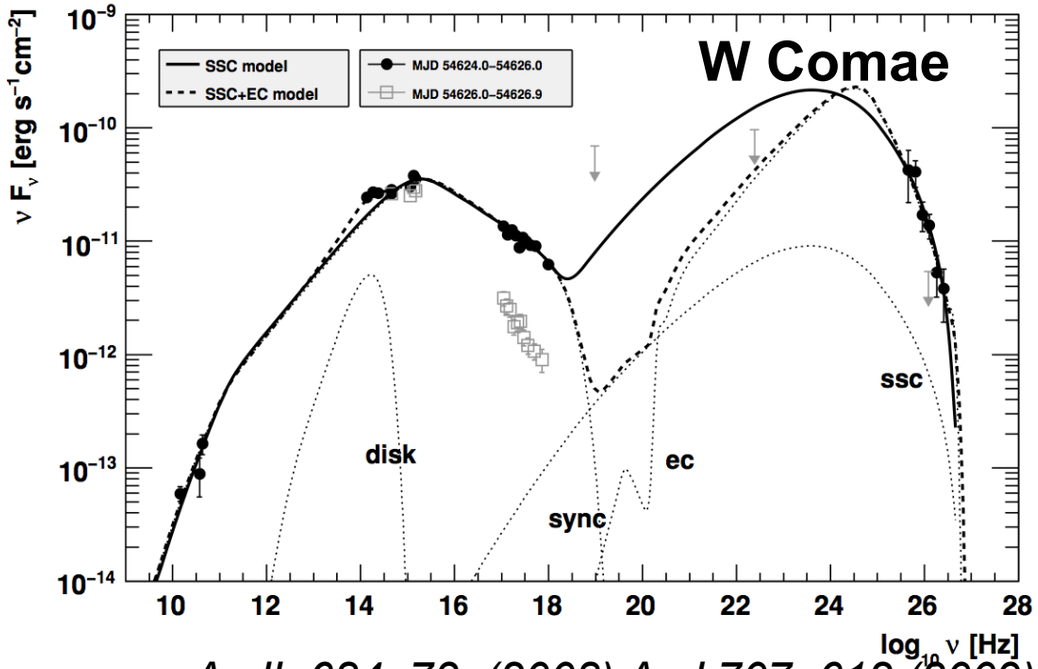
ApJ submitted (2010)

Quasi-simultaneous SEDs for 17 days ($\Delta_{X\text{-ray}}$<0.15d; Δ_{opt}<1.5d, Δ_{radio}<3d)

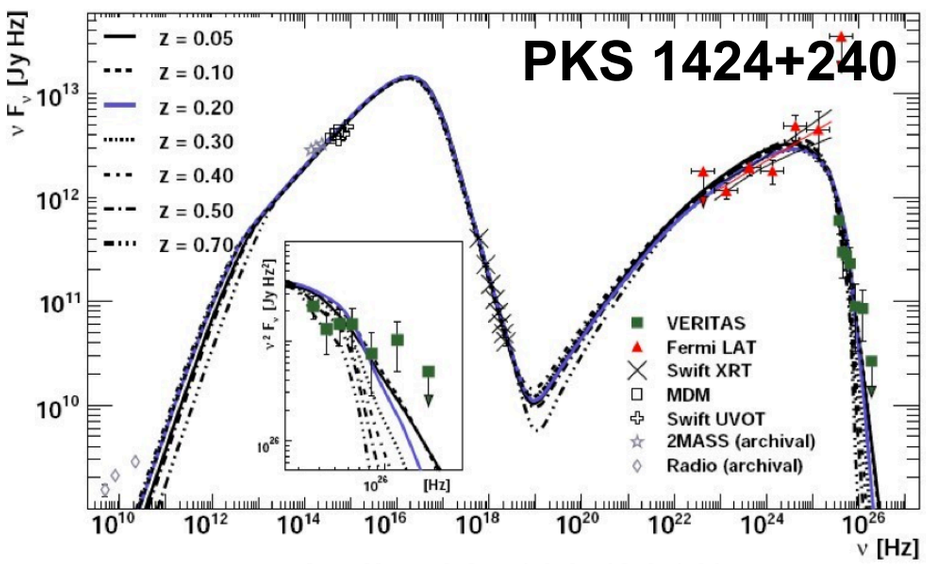
SSC works in all flare states for Mkn 421

Intermediate BL Lac Modeling: SSC or SSC+EC

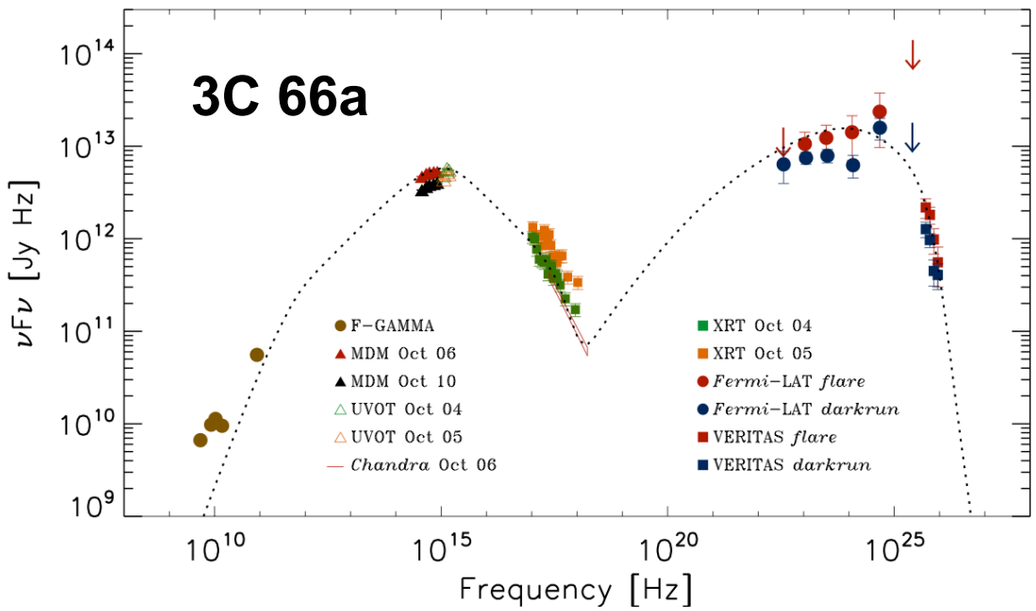
- 3C 66A & W Comae - flare states
  - SSC needs large unnatural emission region and very low magnetic fields
- PKS 1424+240 - steady flux state
  - SED: SSC works; no EC needed
  - borderline HBL?
- PKS 1440+122 (analysis ongoing)
  - IBL: SSC+EC preferred
  - HBL: SSC works in all states



ApJL 684, 73, (2008) ApJ 707, 612 (2009)



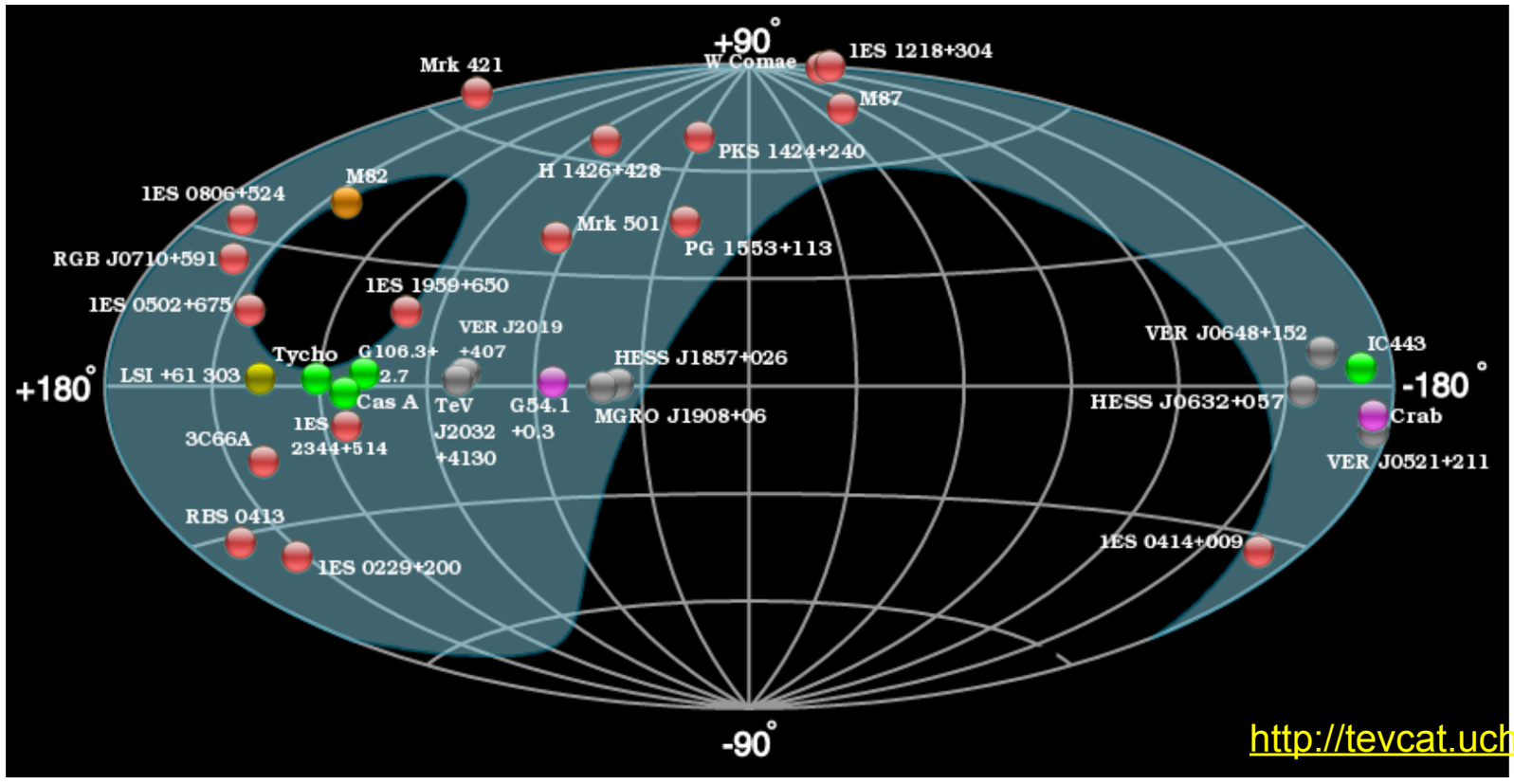
ApJL 708, 100 (2010)



ApJL 693, 104, (2009) ApJ submitted (2010)

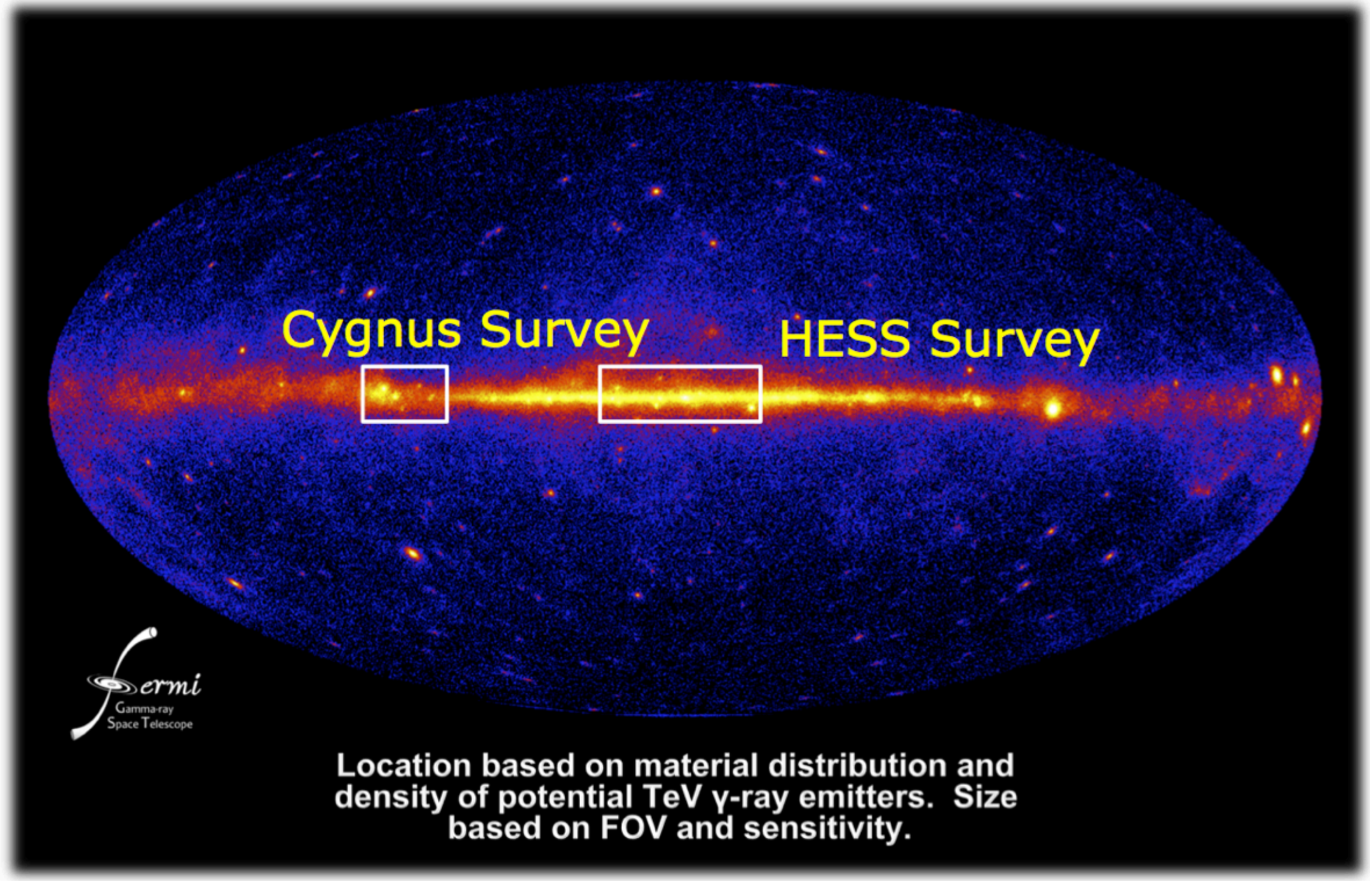
VERITAS Galactic Observations

- Survey of the Cygnus region
- Supernova Remnants and Pulsar Wind Nebula
  - Cas A, IC 443, SNR G106.3+2.7/PSR J2229+61114, G54.1+0.3, VER J2019+407, Tycho
- Binaries
  - LS I +61 303, 1A0535+262
- Unidentified
  - HESS J0632+057



http://tevcat.uchica

Survey of the Cygnus Region



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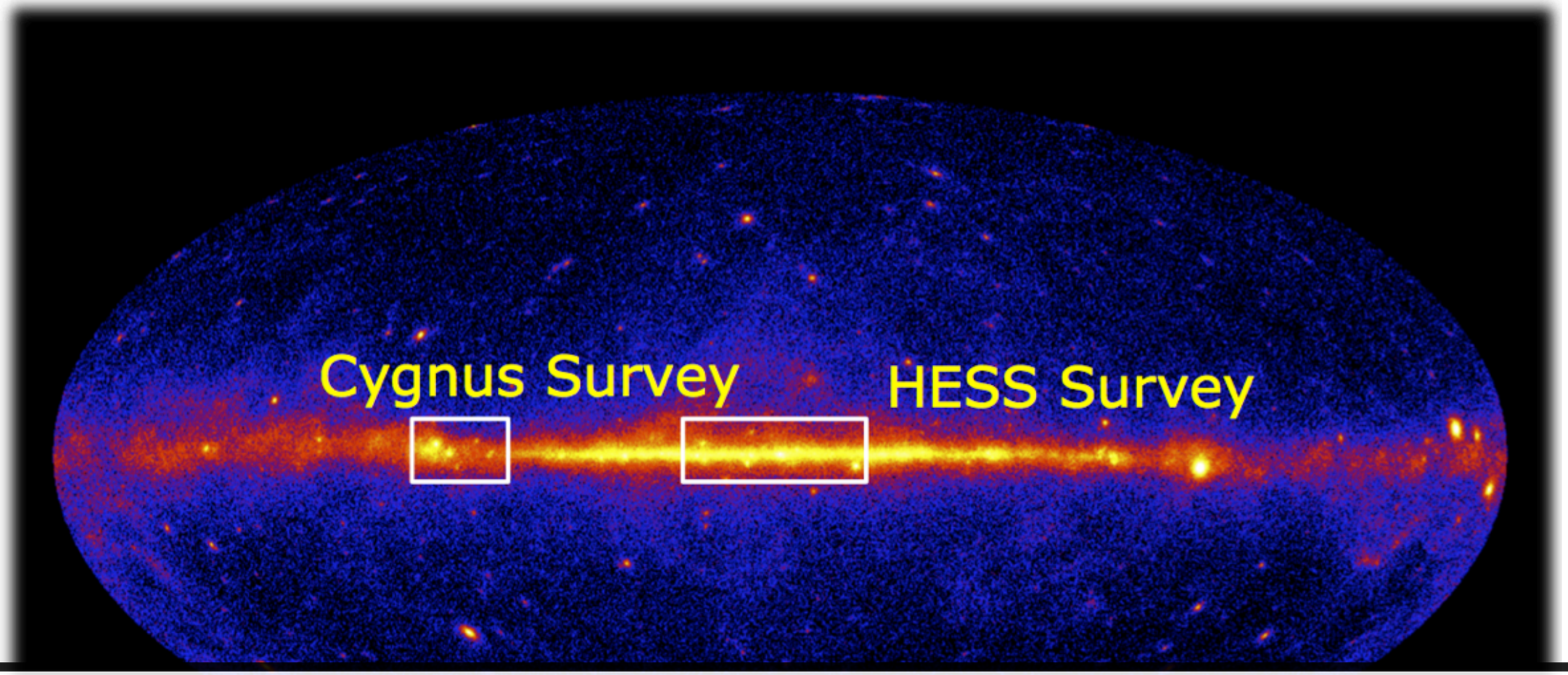
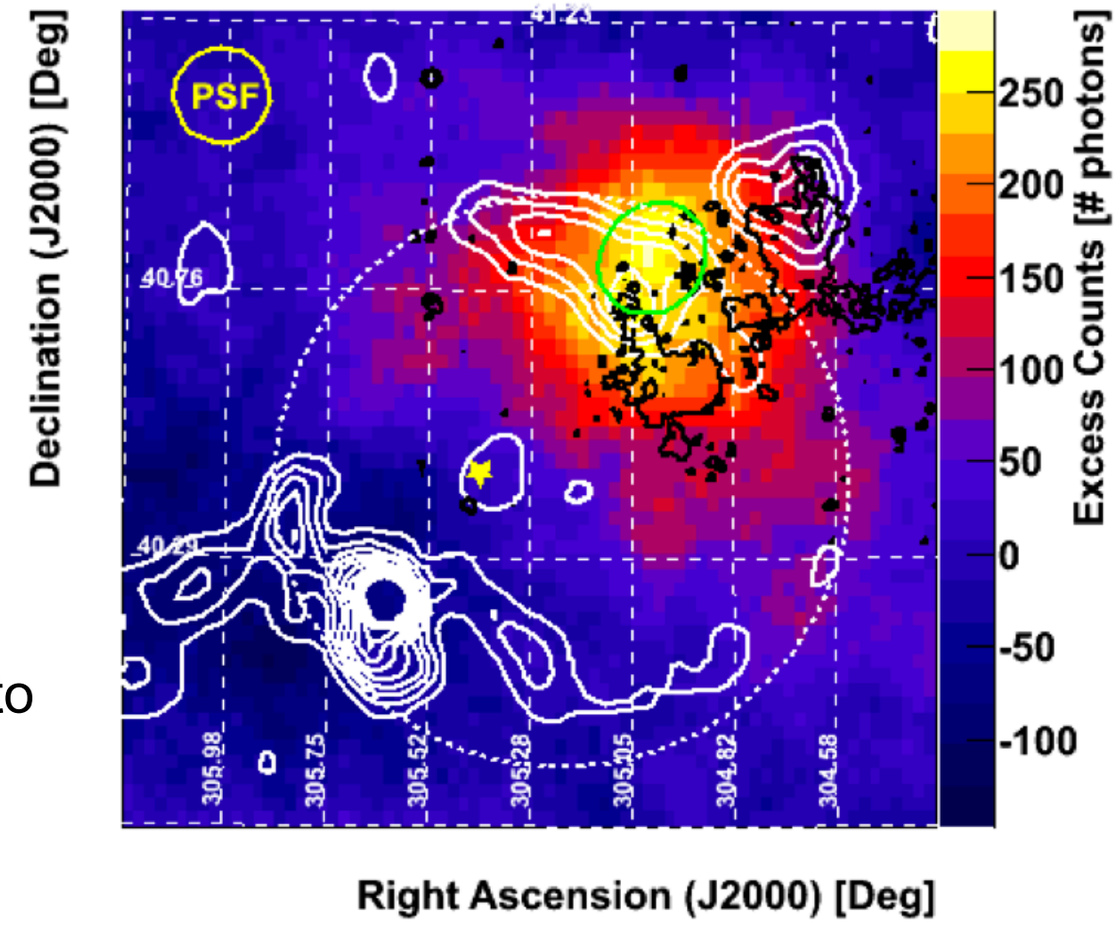


- 2007-2009, 112 base hrs with 56 hrs of follow-up studies
- Cygnus region coverage:
  $67^o < l < 82^o$, $-1^o < b < 4^o$
- 4 pre-defined cut-sets
- depth: <3% Crab E>200 GeV [99% CL] for point-like sources

VER J2019+407 (coinc. with γ Cygni)

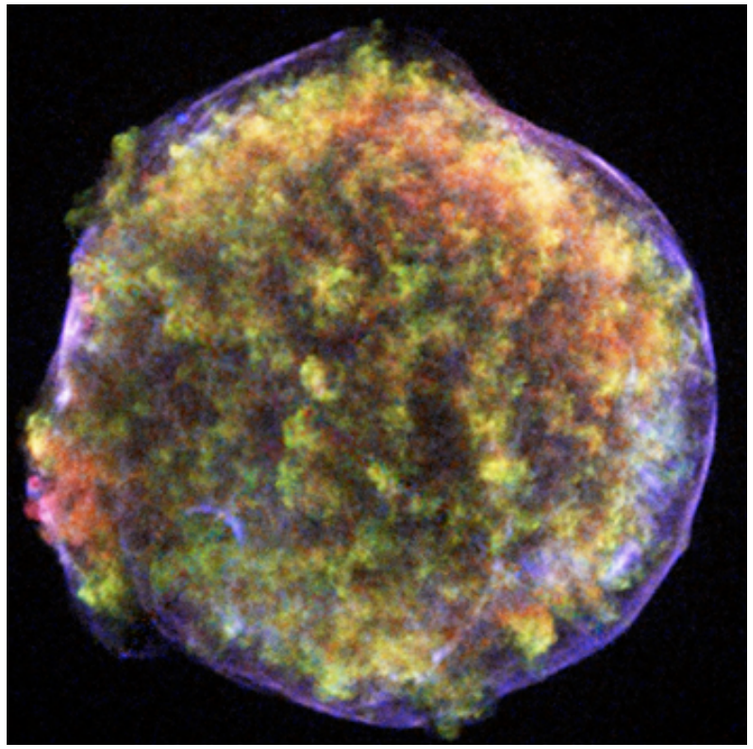
- early survey follow-up candidate
  - independent data set from Fall 2009 confirms new source with ~7.5σ
- Preliminary flux level >1 TeV: ~2-5% Crab
- Preliminary Extension: ~0.2º (Symmetric Gaussian Fit)
- Peak in NW of γ-Cygni
  - distance 1.5-1.8 kpc
  - Age 5-10 kyr
- VHE mechanism?
  - PWN of PSR J2021+4026
  - shock-matter interaction (but most matter to the SE)
  - ...

- Multiwavelength picture
  - white: Radio (4.865 GHz)
  - black: optical (red-band)
  - yellow star: Fermi pulsar (PSR J2021+4026)
  - white dashed: SNR extend



Tycho (G120.1+1.4)

- remnant of a Type Ia Supernova event of 1572
  - size: ~8 arcminutes
  - distance: 1.5-3 (5) kpc
  - bright x-ray rims and filaments interpreted as evidence for electrons up to 10 TeV
  - MWL expansion studies suggest entry into Sedov phase (slower expansion to the east might indicate interaction with a molecular cloud)
  - detailed x-ray morphology studies suggest efficient hadronic particle acceleration (Warren et al 2005)
- HE/VHE observations
  - no detection by EGRET, no 1FGL sources nearby
  - limits from Whipple, HEGRA, MAGIC (point source limit: J(>1TEV) <1.7% Crab [3σ])

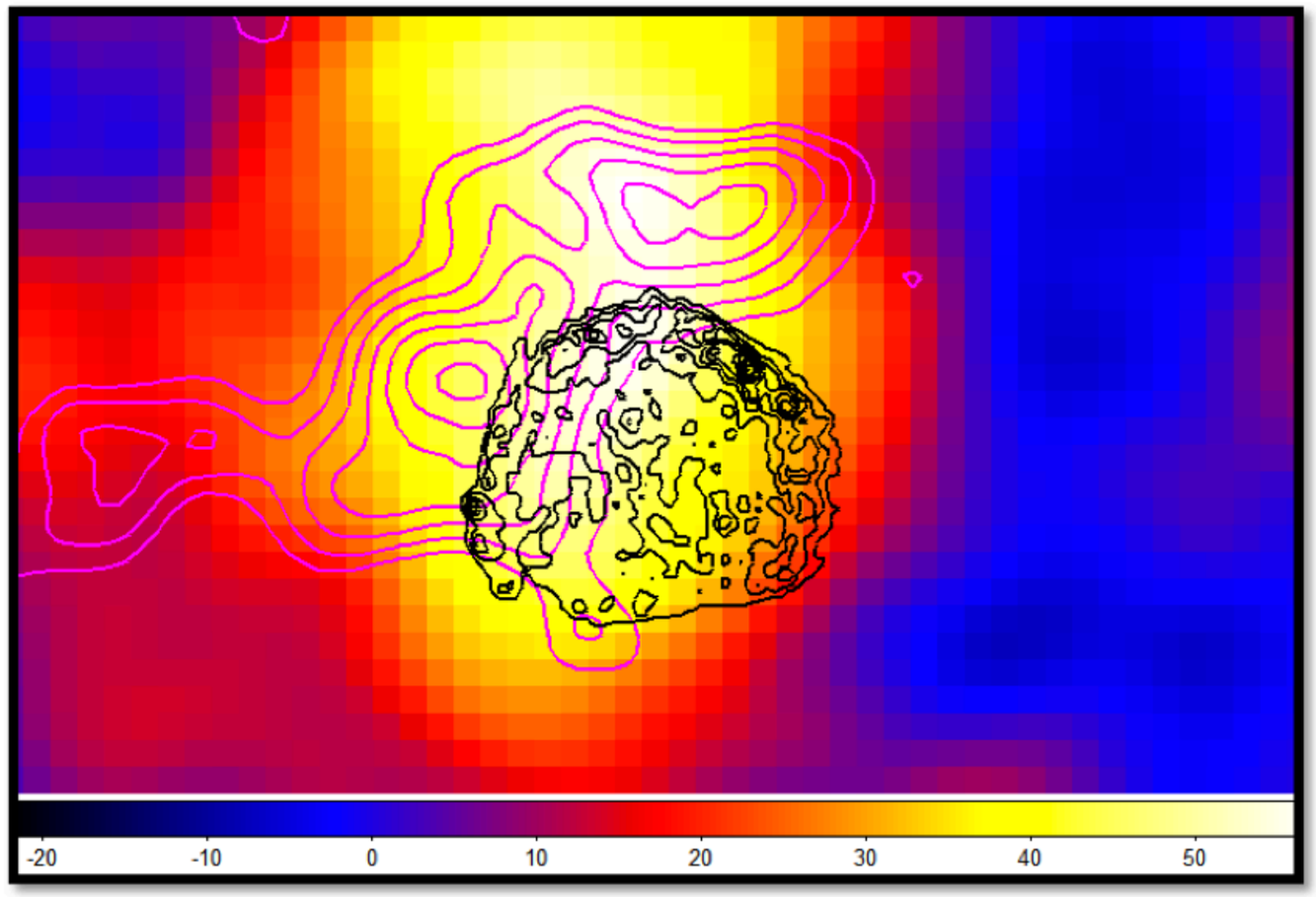


Tycho - VERITAS results

- 67 hrs of observations
  - 2007 and 2010
  - mean zenith - 38 deg
- 5σ post-trials
  (scan over area x2 area of remnant + 2 cut sets)
- peak significance located close to molecular cloud
- no strong statistical evidence for angular extension
- flux level above 1 TeV: 1% Crab

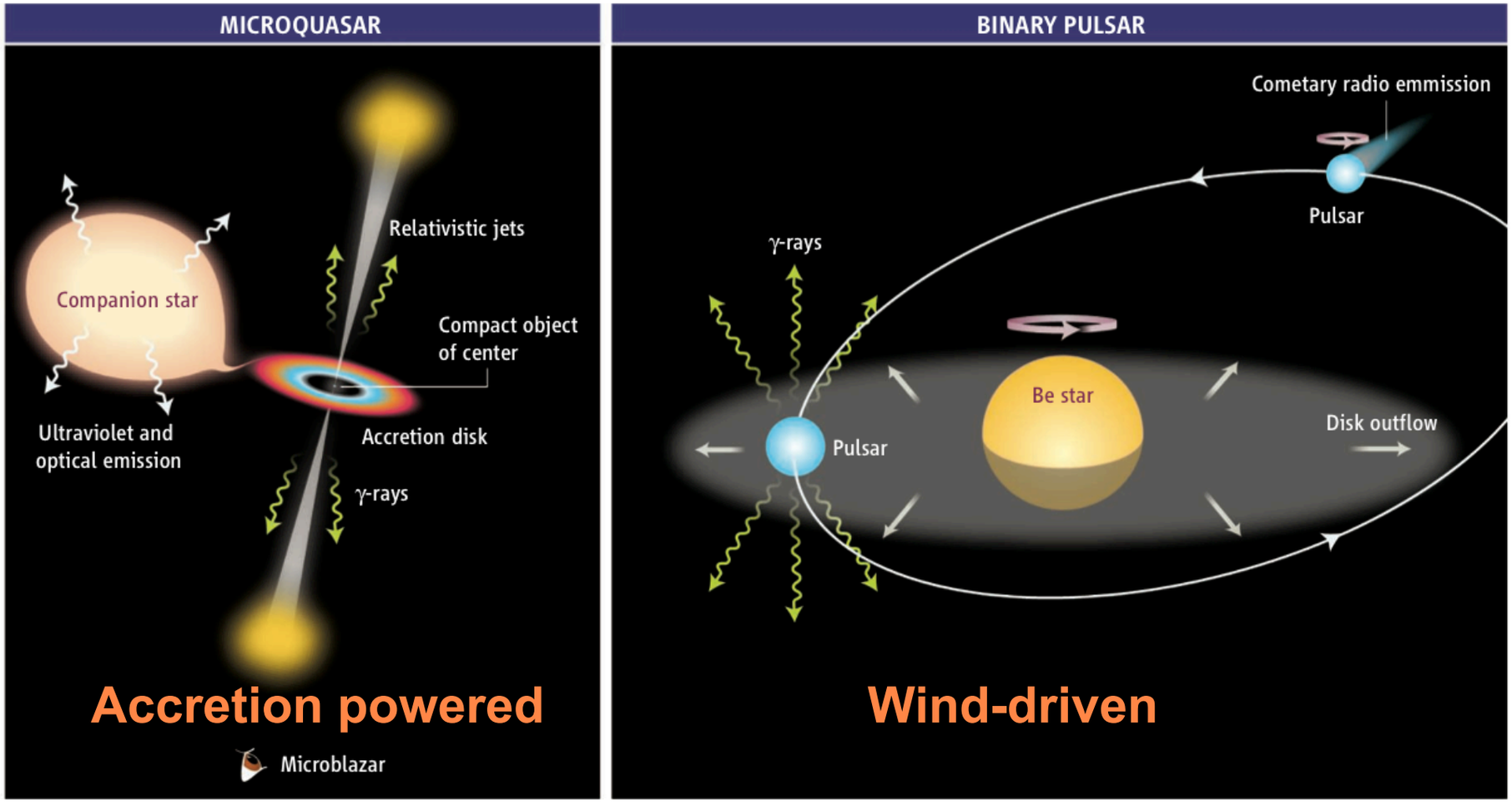
smoothed VHE excess map

PRELIMINARY



black: X-ray (Chandra)
purple: ^{12}CO emission (FCRAO)

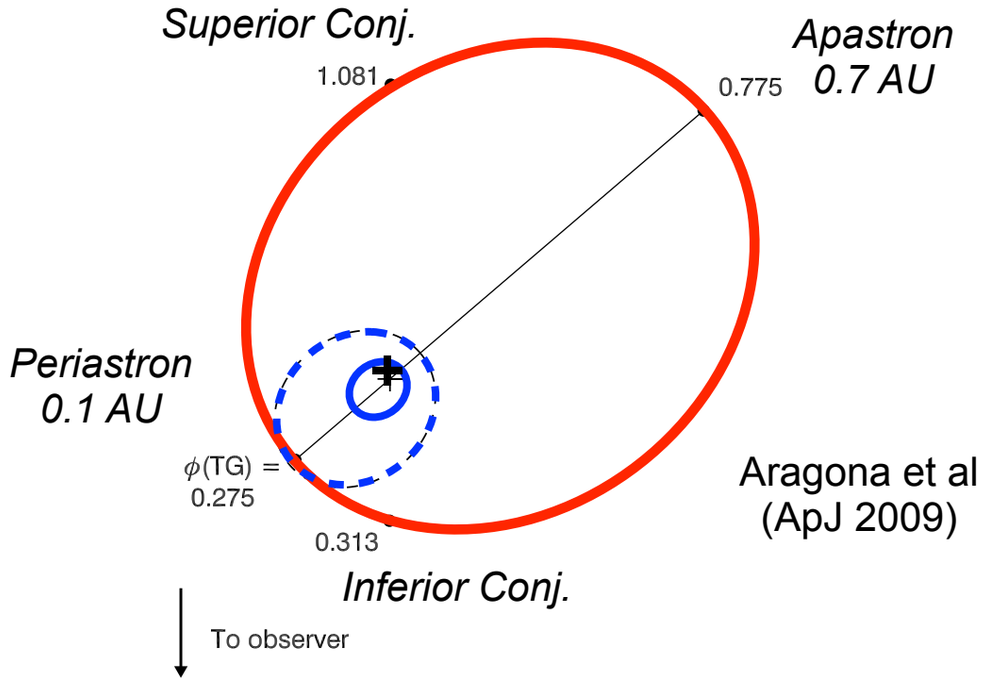
VHE Binaries



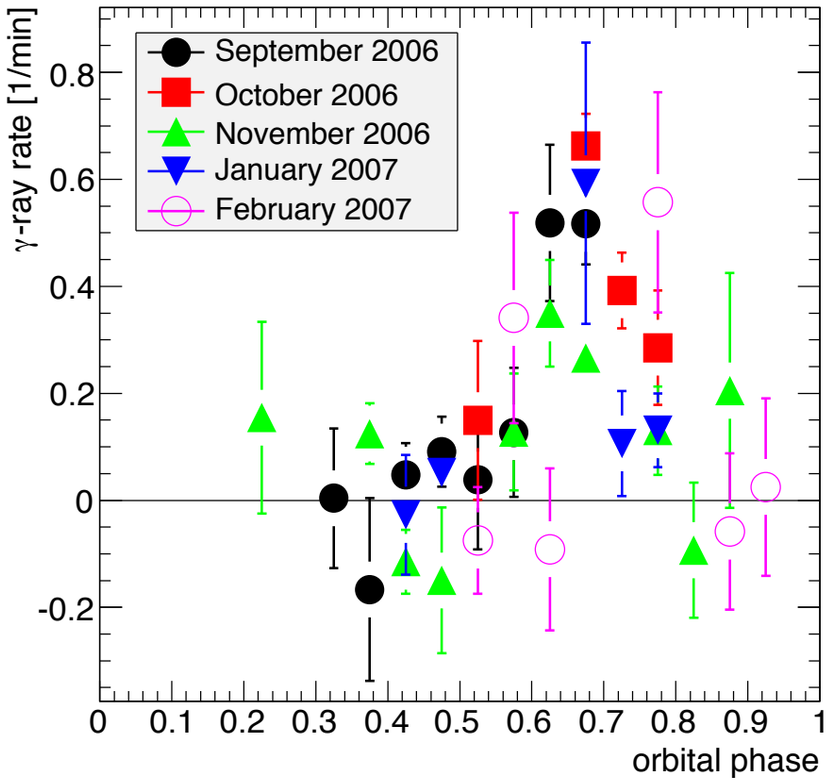
- only variable galactic VHE sources known
- particle accelerators operating under varying, but regularly repeating, environmental conditions; some have jets
- each system is unique - and the population is increasing
  (Cyg X-1, Cyg X-3, LS 5039, LS I +61 303, PSR B1259-63, HESS J0632+057 (?))

LS I +61 303

- compact object orbiting a BOVe companion
  (12.5 M_θ), 26.5 day, inclined orbit, e=0.54, circumstellar disk
- extended radio structure; microquasar?
  (but radio images shows morphology change with orbital position)
- VHE emission **near apastron**
  (10-15% Crab, ϕ=0.5-0.8) (MAGIC/VERITAS)

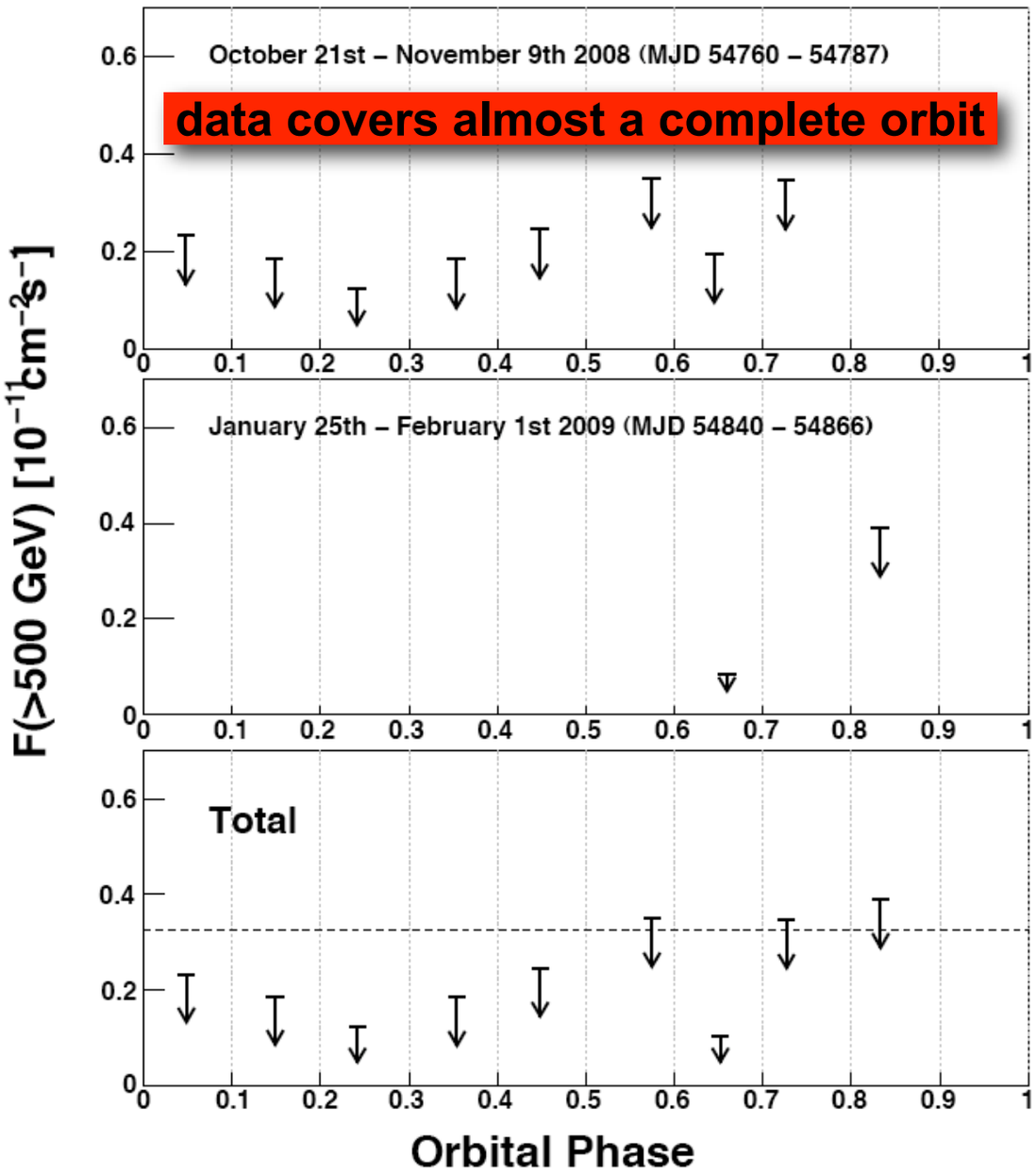


- Fermi/LAT: GeV emission peaks **near periastron**; 6 GeV cut-off; orbital modulation (**but:** not seen since 40% flux increase in 03/2009)
- GeV spectrum looks like a pulsar.
  But why modulated? Where are the pulses at other wavelengths?

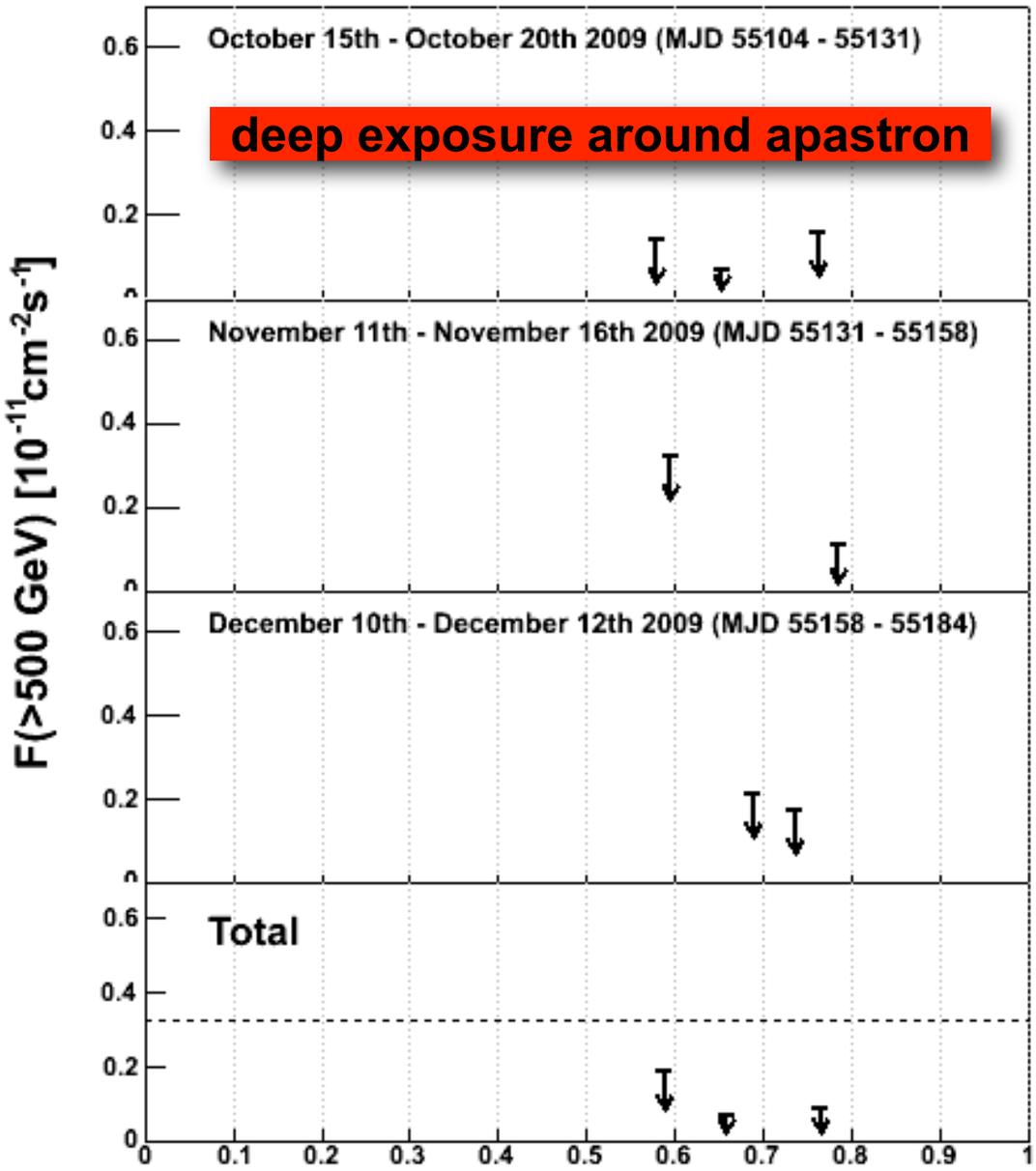


LS I +61 303 in 2008-2010 - VERITAS results

2008/2009: 37 h of data, 3.4σ overall



2009/2010: 18 h of data, 0.8σ overall



ApJ in preparation (2010)

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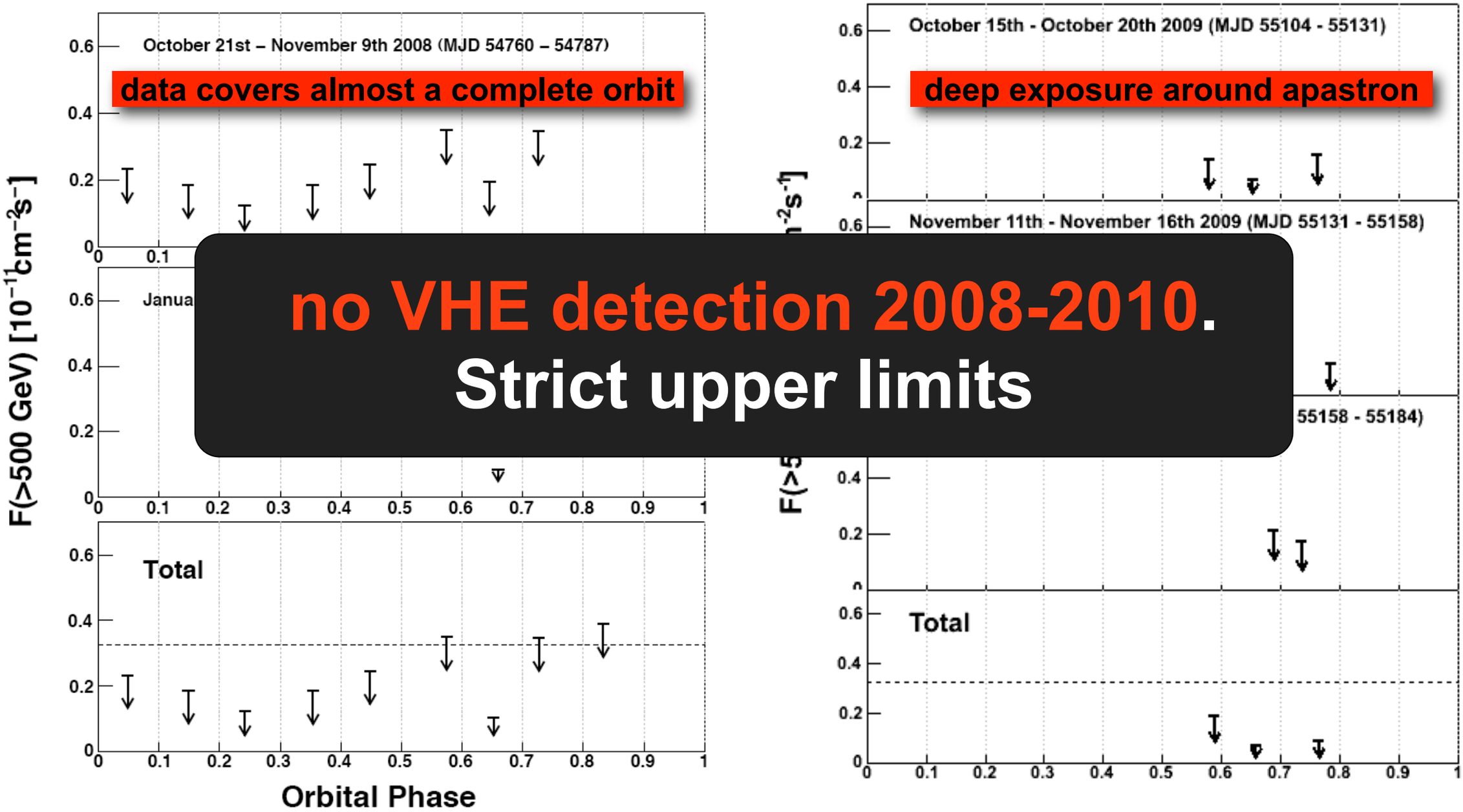
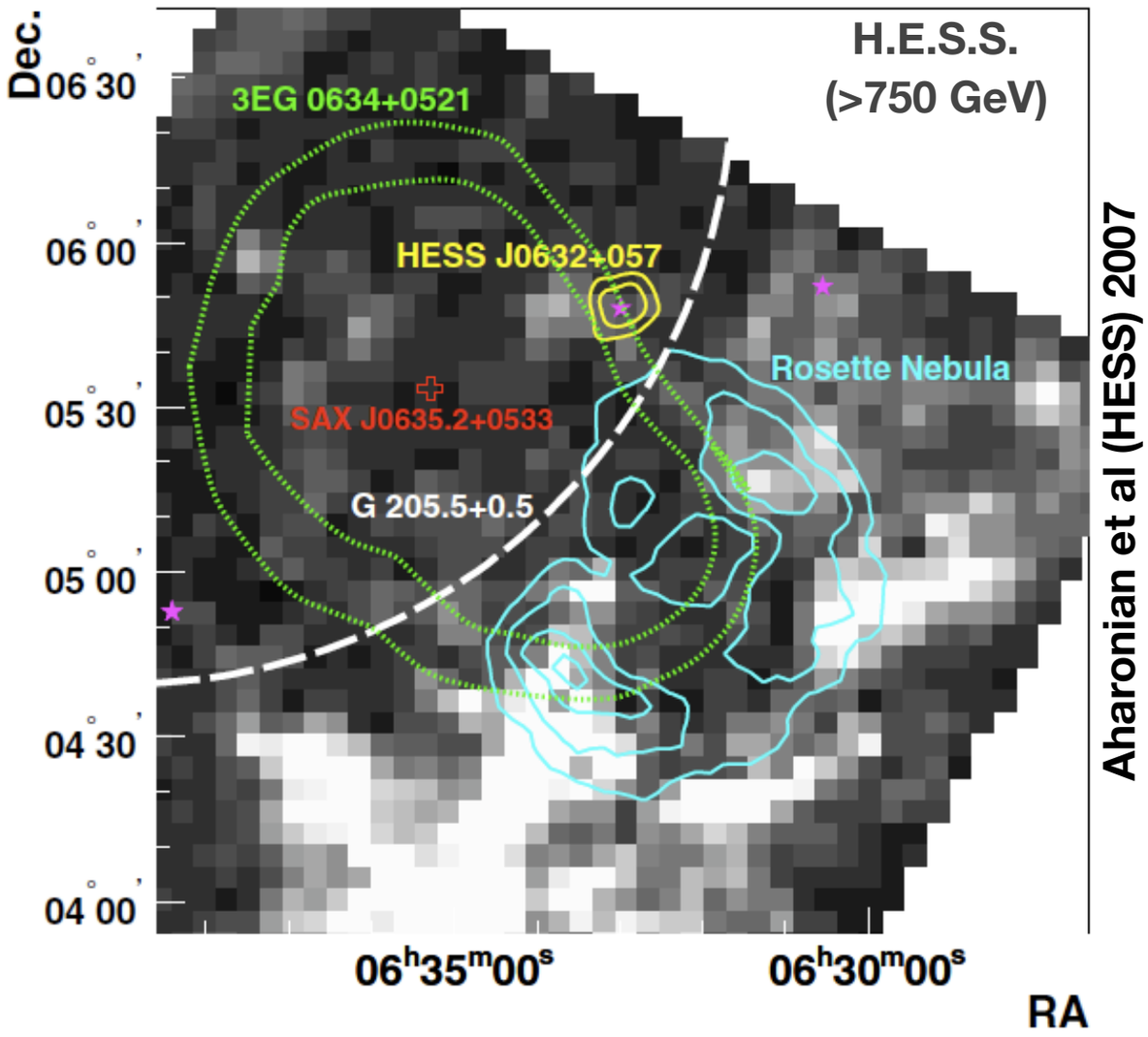


no VHE detection 2008-2010.
Strict upper limits

ApJ in preparation (2010)

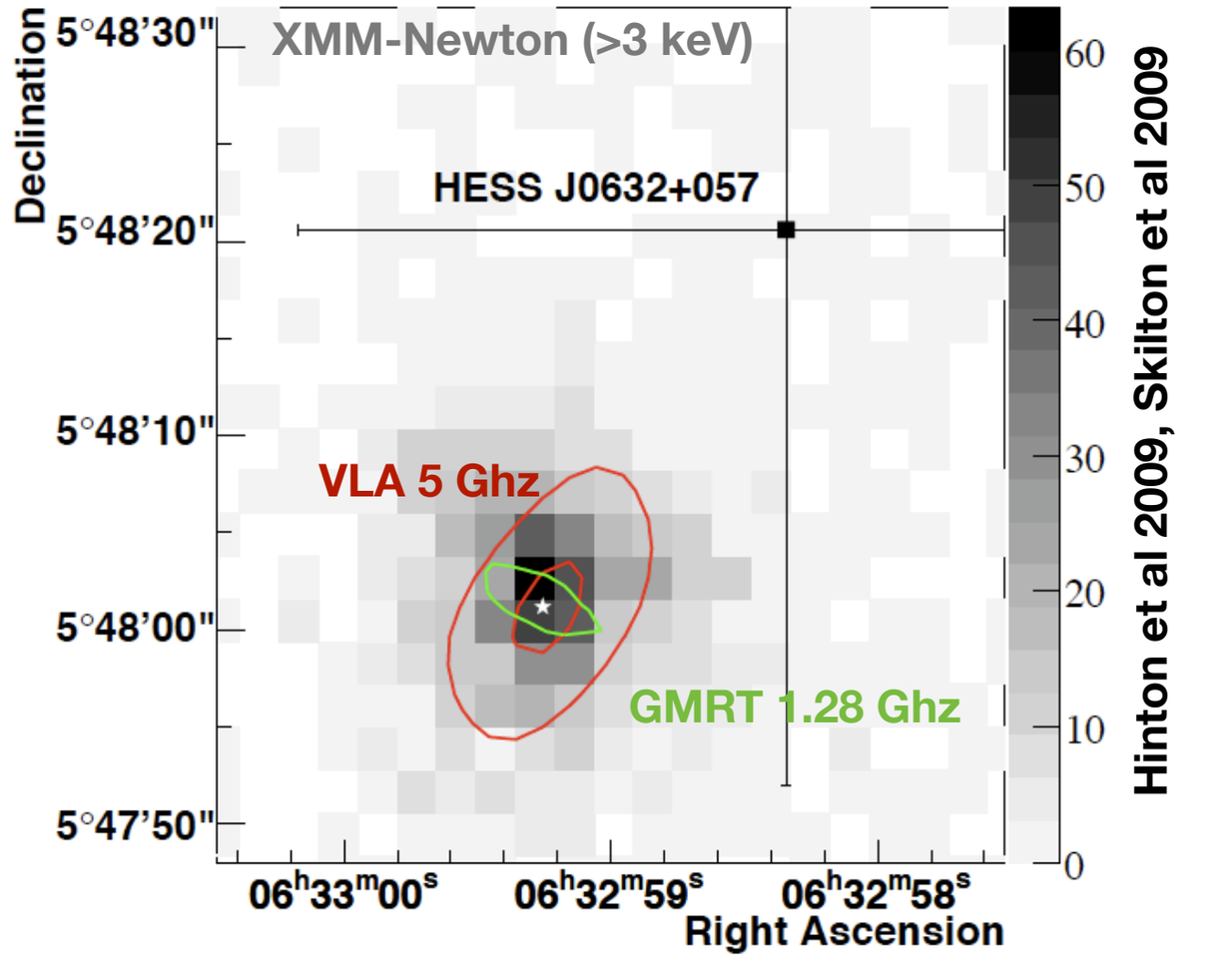
HESS J0632+057 - a new VHE binary?

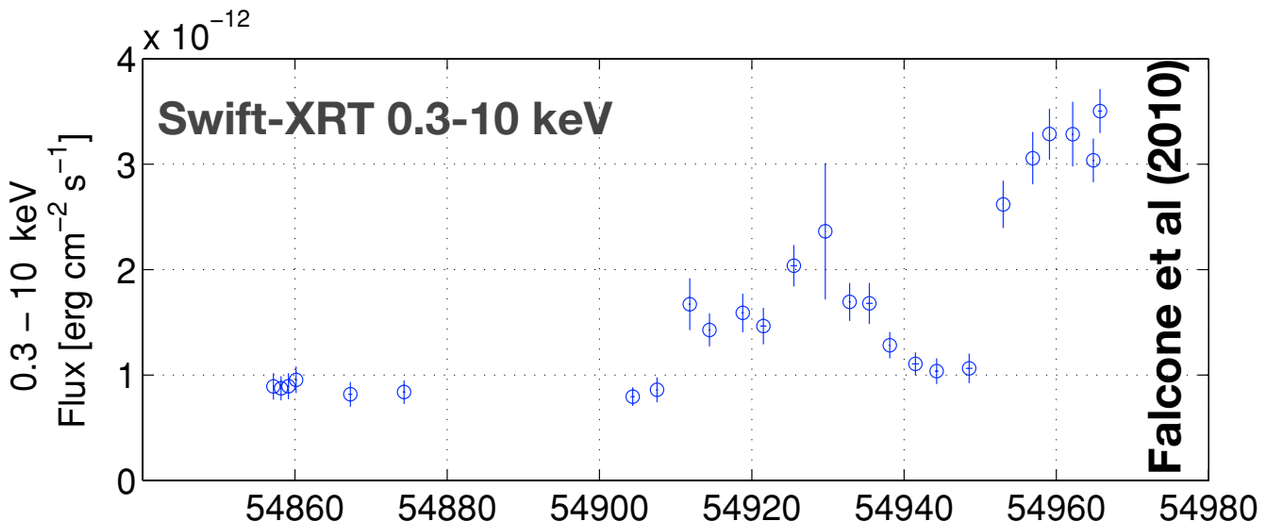
- discovered by H.E.S.S. in 2004/2006
  (Γ=2.53, F(>1 TeV) ~3% CU)
- only unidentified VHE point source
  (<2' extension)
- located in Rosette Nebula and Monoceros loop
  (young stellar cluster/molecular cloud, complex and SNR, distance 1.4-1.6 kpc)
- coincident with massive star MWC 148
  (spectral type B0pe (strong surface magnetic fields, fast stellar winds, large mass loss rates))
- optical data inconclusive
  (no binary system identified)



HESS J0632+057 - radio and X-ray data

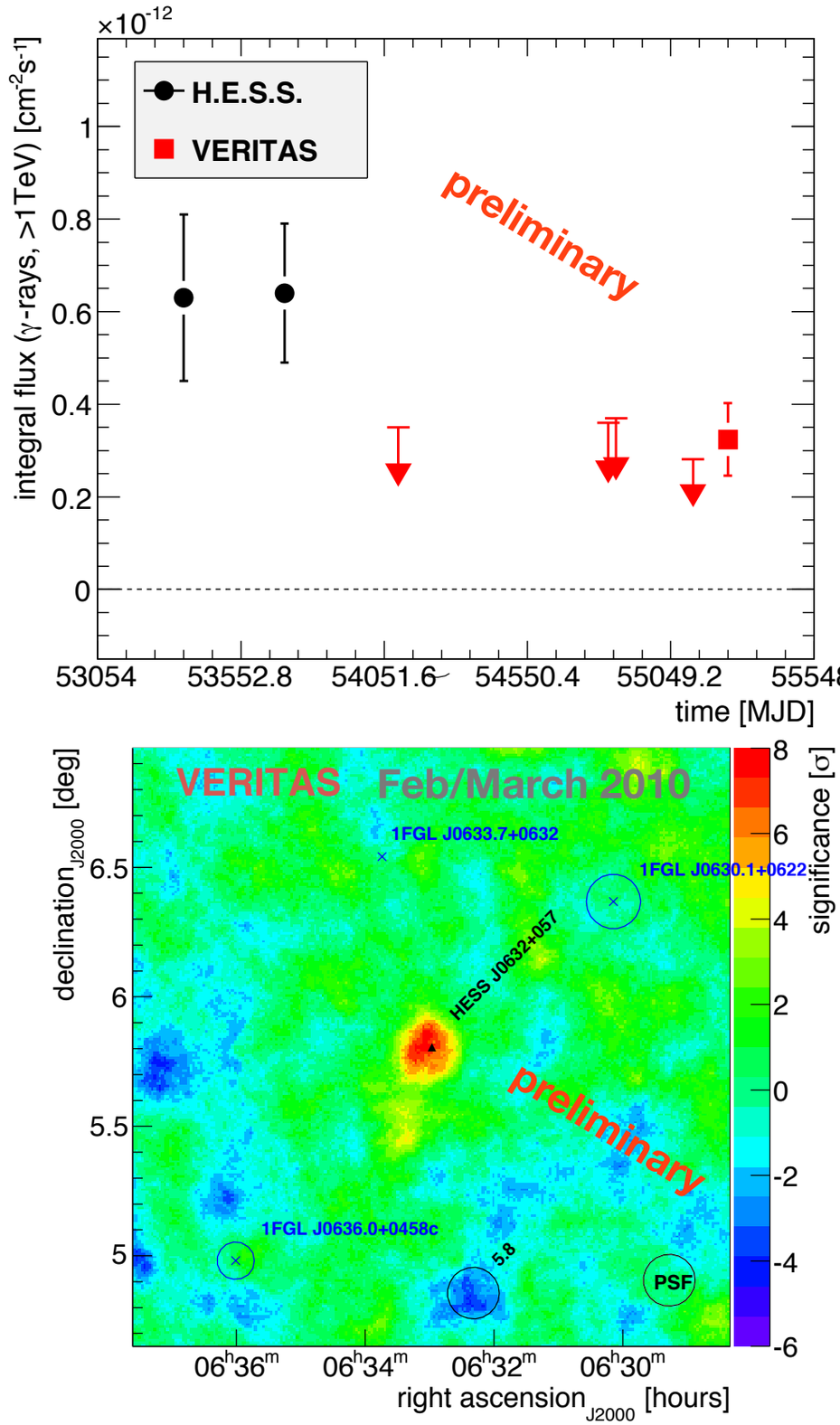
- faint point-like, variable radio source
  (<2” extension, 0.19-0.4 mJy, Skilton et al 2009)
- optical data inconclusive
  (no binary system identified)
- hard spectrum X-ray source
  (Γ~1.2-1.9)
- variable X-ray source
  (hours: *XMM-Newton*, weeks: *Swift-XRT*)
- not detected by Fermi/LAT
- **What is it?**
  - **a new VHE binary?**
    (see Hinton et al 2009)
  - **an unusual isolated massive star**
    (confined stellar wind model, Townsend et al 2007)





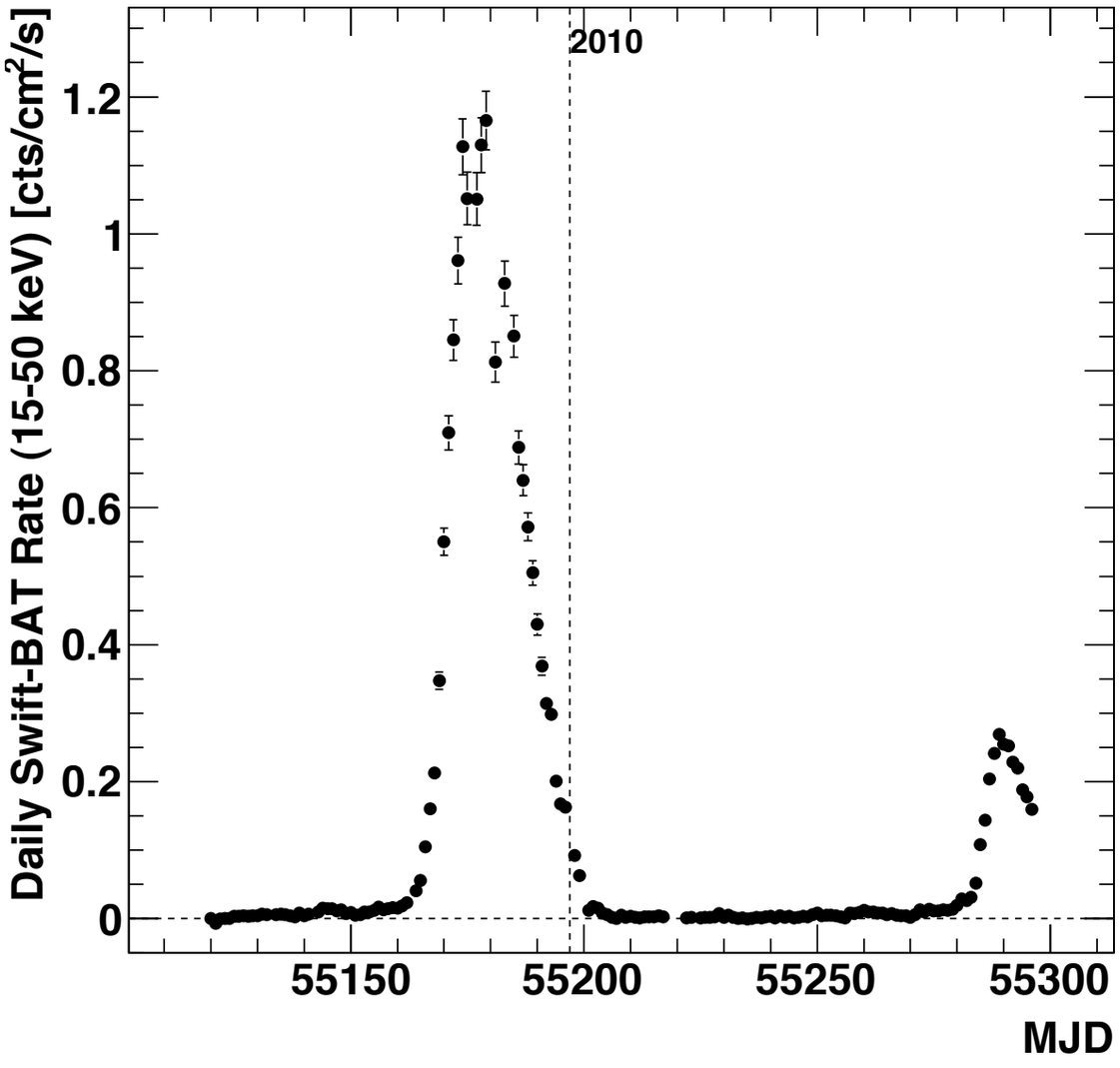
HESS J0632+057 - VERITAS results

- 30 h in Dec 2006 - Jan 2009: **not detected** by VERITAS *(ApJ 687 L94 (2009))*
- excluded with ~4σ confidence that HESS J0632+057 is a steady gamma-ray emitter
- H.E.S.S./VERITAS campaign in 2009/2010
- 8h in Oct 2009: **no detection**
- 20 h in Feb/March 2010: **clear detection** (7.5 σ)
- position in agreement with HESS J0632+057 and MWC 148
- clearly variable in VHE gamma rays



1A0535+262 - Observations during a giant X-ray flare

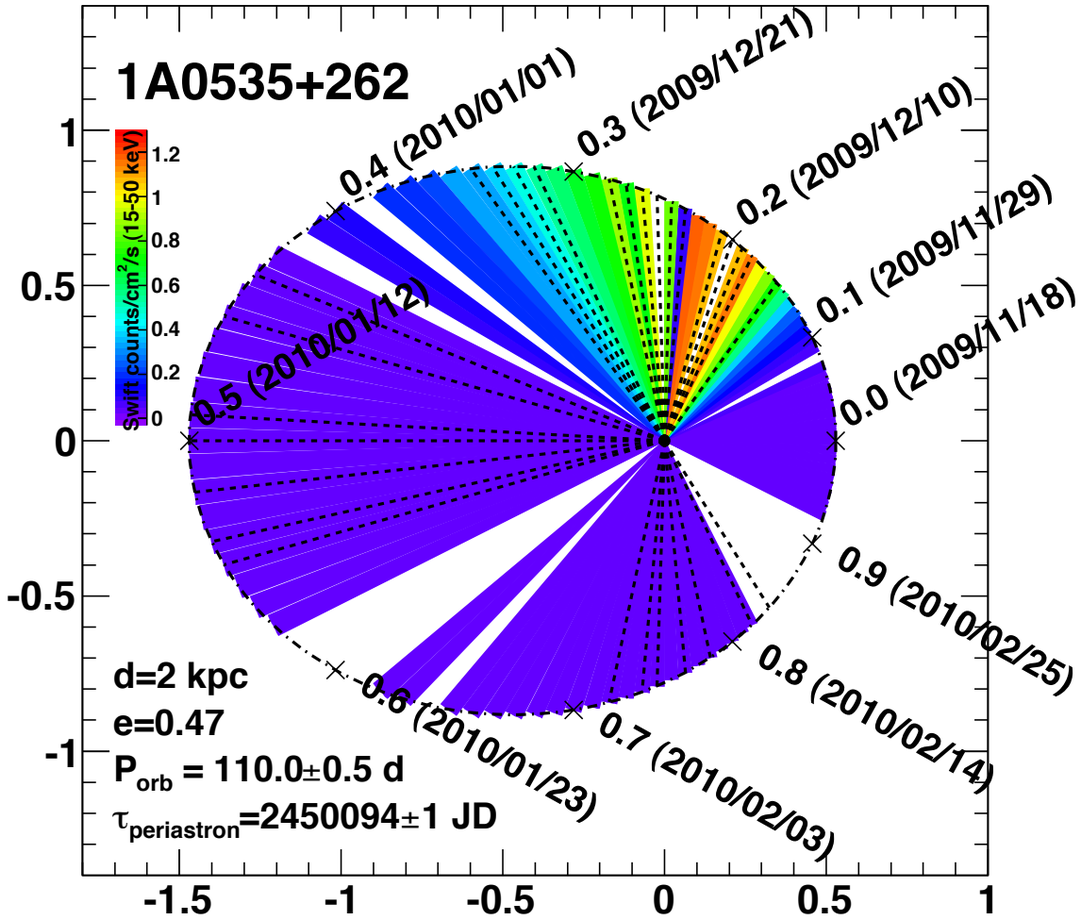
- HMXB, Be-star and X-ray pulsar (P_{Spin}=104s)
- orbital period 110 d, eccentric orbit (e= 0.47)
- distance 2.4±0.4 kpc
- large magnetic field (~10^{13} G)
- giant outbursts about every 5 years (October 1980, June 1983, March/April 1989, February 1994, May/June 2005)
- VHE emission: Cheng & Ruderman mechanism; VHE maximum expected about 10-20 days after X-ray flare (Orellana & Romero 2004)



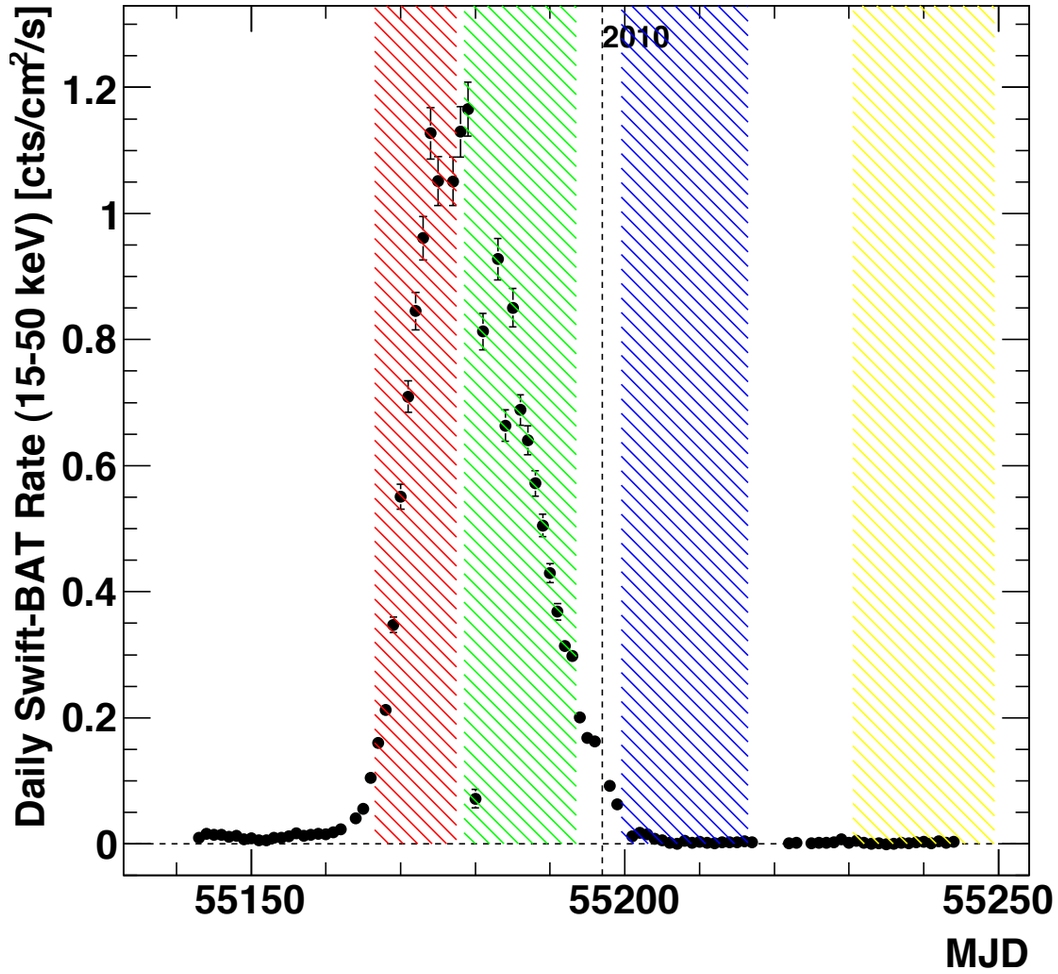
But: no detailed modeling for VHE emission, no flux prediction, SED, etc.

1A0535+262 - VERITAS observations

- Dec 2009: ToO triggered on flaring Be/ X-ray binaries
- 23 hours of data with VERITAS
- high elevations: mean ~70^{o}

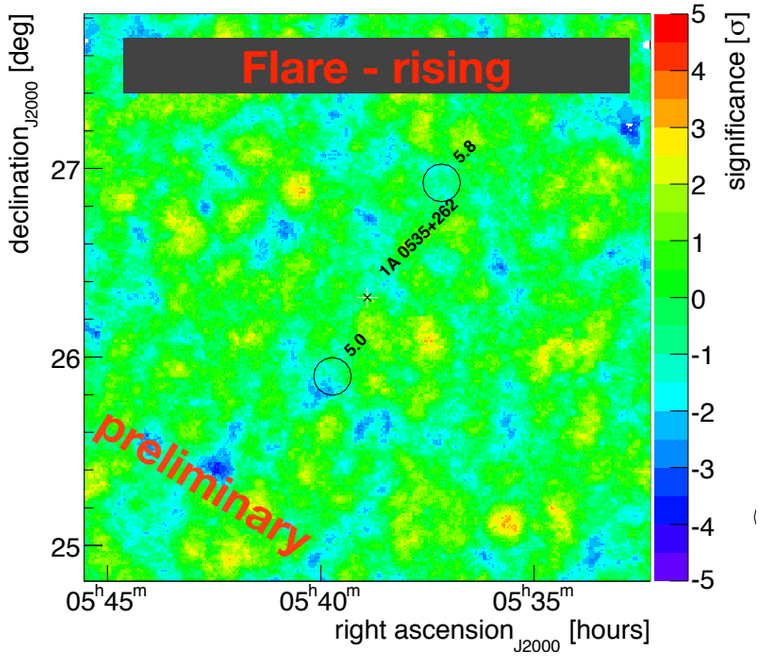


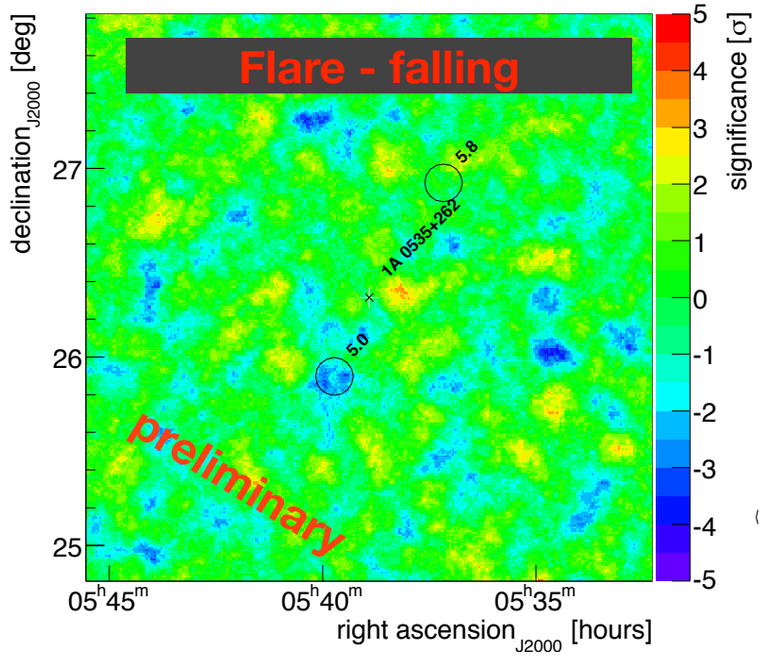
- good coverage of flare phase (rising/falling edge), apastron and periastron approach
- flare occurred at best time for VERITAS

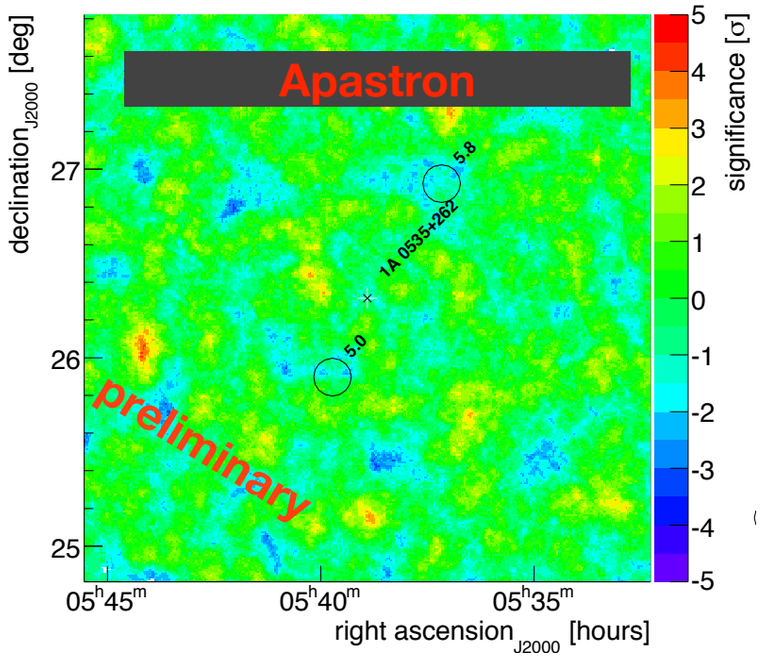


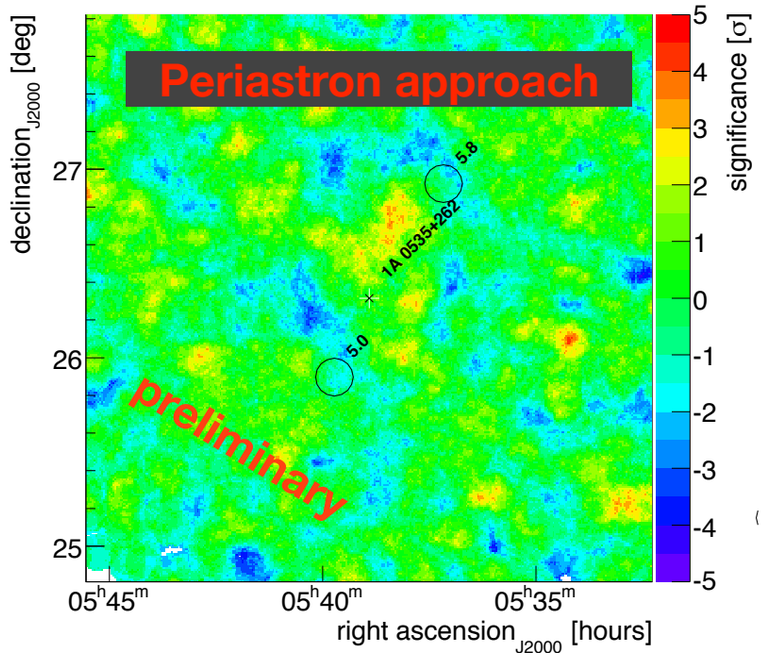
1A0535+262 - VERITAS results

- early results; campaign just concluded
- 5-8 hours of VERITAS observations in each bin
- no VHE emission detected
- 99% flux upper limits above 300 GeV: 0.5-2% Crab Nebula flux
- lots of data at other wavelengths available - publication in preparation
- definite measurement from current VHE instruments



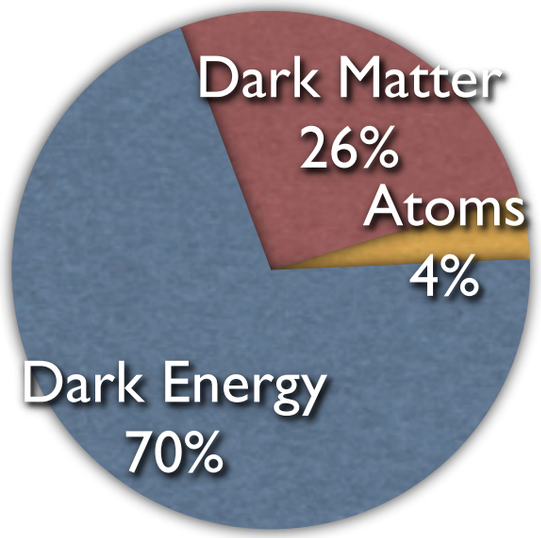






Search for Dark Matter

- DM: ~25% of the energy budget of the Universe
- mainly observed through its gravitational interaction
- well-described by Weakly Interacting Massive Particles
  (SuSY, models with extra dimensions, etc):
  50 GeV ≤ m_{WIMP} ≤ 10 TeV



- search for γ-rays from annihilation and decay of WIMPS
- expected γ-ray flux proportional to squared DM density:

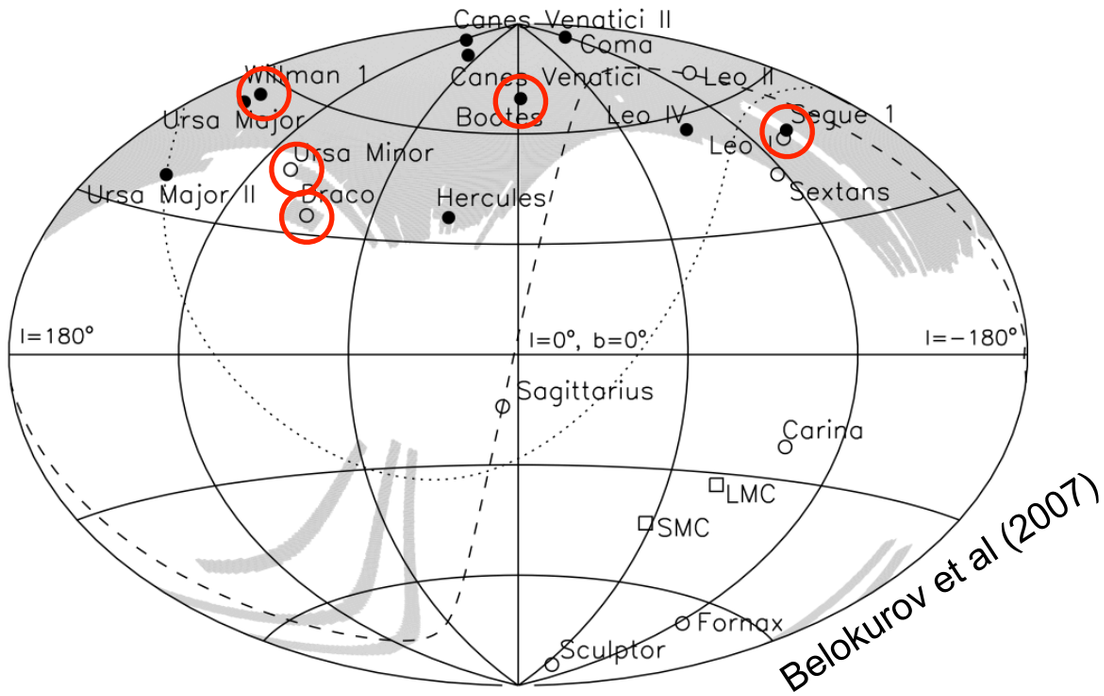
$$\frac{d\phi}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \left[\frac{dN(E, m_\chi)}{dE} \right]_{DM} \boxed{\langle J \rangle}$$

$$\langle J \rangle = \int_{\Delta\Omega} d\Omega \int dl \, \rho^2(r(l))$$

- observe astrophysical targets with high DM content
- challenge: distinguish dark-matter / astrophysical γ-rays

Search for Dark Matter from Dwarf Galaxies with VERITAS

- Dwarf Galaxies are DM dominated (as revealed by star kinematics)
- close (tens of kpc)
- high latitude objects and low gas content (low γ-ray background)
- tidal disruptions can make DM content estimation difficult



Belokurov et al (2007)

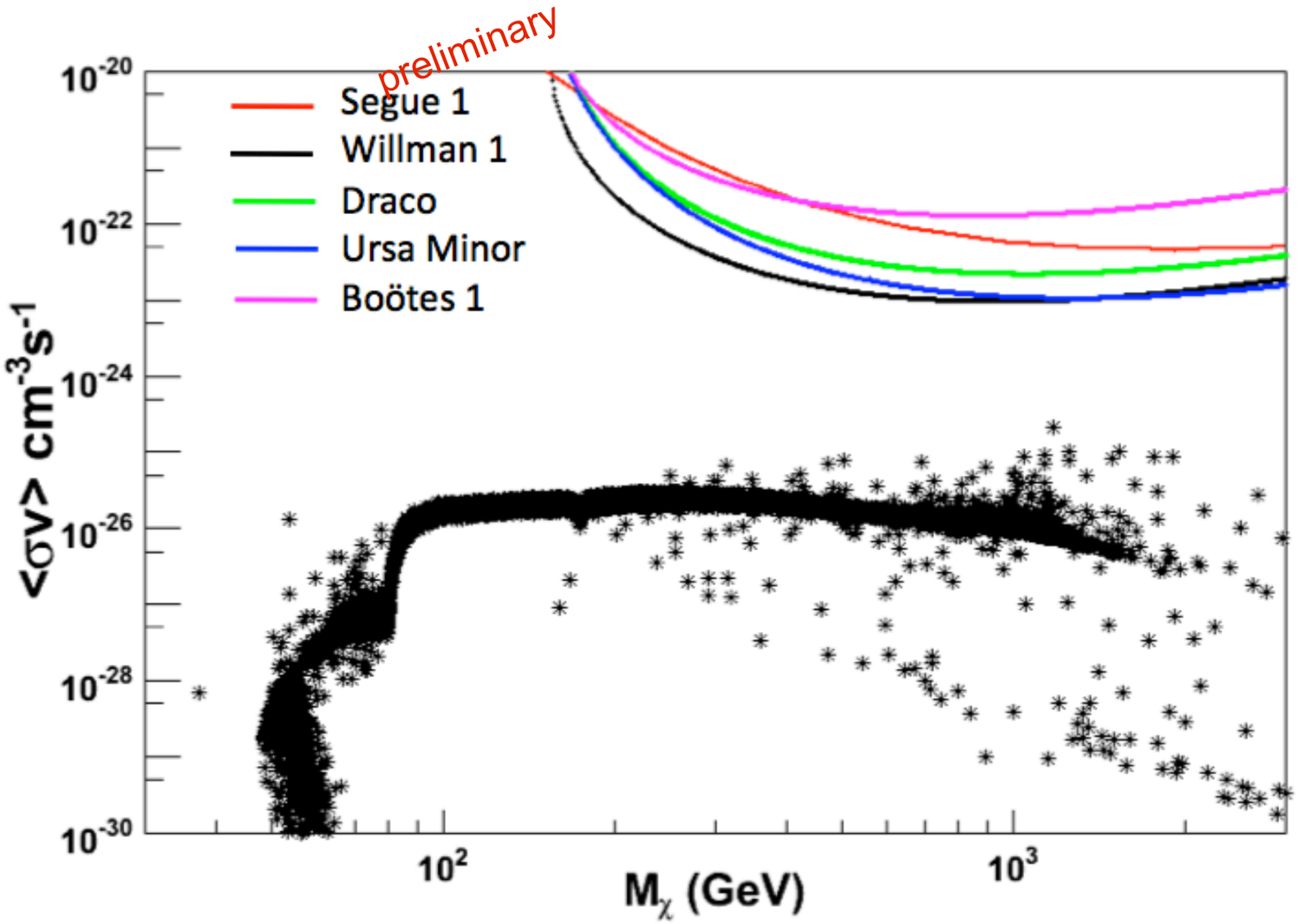
dSph	distance [kpc]	Exposure [hrs]	Zenith angle [^{0}]	Energy threshold [GeV]	Signi-ficance [σ]	Flux limits (95%) [$cm^{-2}s^{-1}$]	Astrophysical factor <J> [GeV^2cm^{-5}]
Draco	80	18.4	26-51	340	-1.5	$0.5x10^{-12}$	NFW: $1.53x10^{18}$
Ursa Minor	66	18.9	34-46	380	-1.8	$0.4x10^{-12}$	NFW: $2.68x10^{18}$
Boötes 1	62	14.3	14-29	300	1.3	$2.2x10^{-12}$	Model by Martinez: $1.15x10^{18}$
Willman 1	38	13.7	19-28	320	0.0	$1.2x10^{-12}$	NFW: $8.43x10^{18}$
Segue 1	23	27.7	16-33	300	-1.1	$0.3x10^{-12}$	Einasto: $1.16x10^{18}$

preliminary

ApJ 720, 1174 (2010)

Search for Dark Matter from Dwarf Galaxies with VERITAS

- particle physics model need for computation of γ-ray fluxes
- choice of composite DM annihilation spectrum that represent the average yield of γ-rays for neutralino annihilation in pMSSM models: BR (XX→bbbar) = 0.9 and BR(XX→ττ)=0.1:



ApJ 720, 1174 (2010)

Uncertainty: ±1 order of magnitude due to systematics in halo modeling

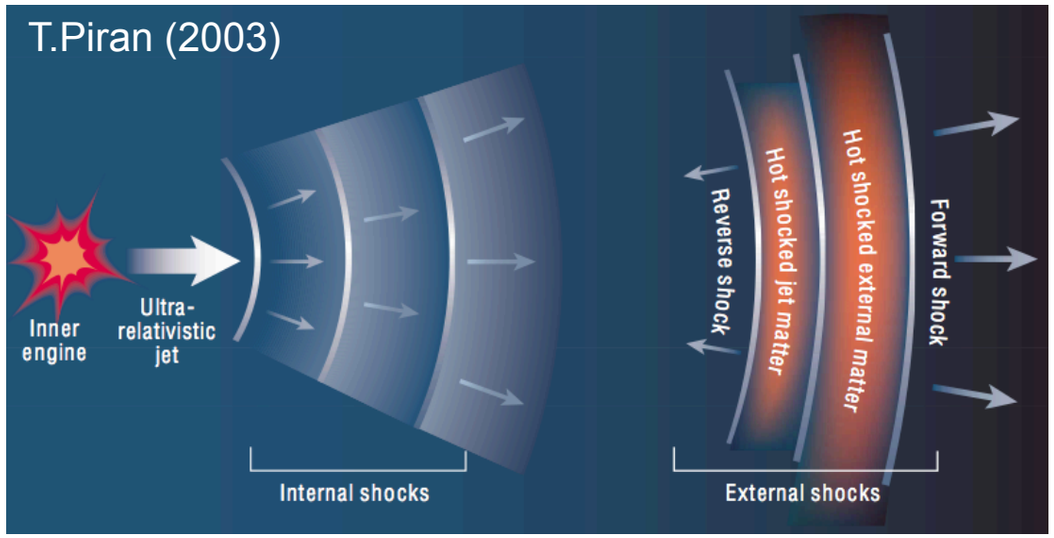
Limits from VERITAS on annihilation cross-sections: ~10^{-23} cm^{-3}s^{-1}

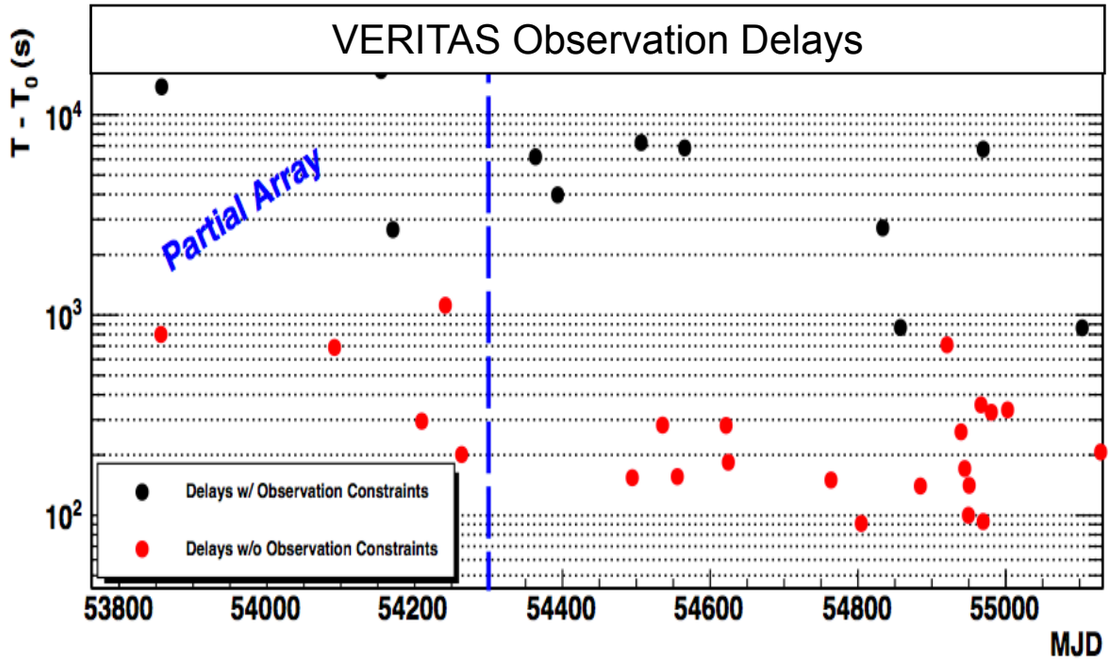
Summary

- array layout optimization highly successful (1% of Crab in <30h)
- upgrade of cameras and trigger ongoing (low energies)
- VERITAS has made most-sensitive measurements of ~20 AGN
  - all AGN studies have simultaneous MWL data for SED modeling
- detections of several galactic objects:
  - Tycho: historical Type 1a SNR
  - γ-Cygni: new VHE-emitting SNR in sky survey
  - Cas A, IC 443, G106.3+2.7, G54.1+0.3, ...
  - HESS J0632+057: a variable point-source in the Galaxy
- non-detections:
  - LS I +61 303 (2008-2010): together with Fermi/LAT measurements a bit puzzling
  - 1A 0535+262: definite measurements at VHE of a X-ray binary during a giant outburst

Gamma-ray Bursts Observations with VERITAS

- most luminous events in the Universe
- >100 GeV γ-rays expected:
  - long-lived afterglows models: blazar-like SEDs
  - Fermi/LAT: GeV photons after powerful GRBs
  - delayed X-ray flares detected by Swift
- VERITAS: GRBs have highest priority
  - socket connection to GCN network
  - Fermi (GBM/LAT)/AGILE/Swift/Integral trigger
  - observe if <3h old and zenith <70°
  - ~30 h / year of GRB observations
- >40 GRBs observed; no detection
  - best ΔT ~ 90s
  - study of drive upgrade to improve slew speed





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