

# VERITAS

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on behalf of the VERITAS Collaboration

<https://veritas.sao.arizona.edu/>



**NSERC  
CRSNG**

Smithsonian Astrophysical Observatory

TAUP 2017



# Very Energetic Radiation Imaging Telescope Array System

4x 12m IACT

85GeV < Energy Range < 30 TeV

Energy Resolution 17% @1TeV

3.5° field of view

Angular Resolution 0.08° @1TeV

1% Crab in <25h, 10% Crab in 25m



**VERITAS**  
Ten-Year Celebration

>12,000h observations

<http://veritasj.sao.arizona.edu/10Years/>

A celebration and conference to mark ten years of VERITAS operations.

**JUNE 28-29, 2017**  
Tucson, AZ

**BARNARD**  
Smithsonian

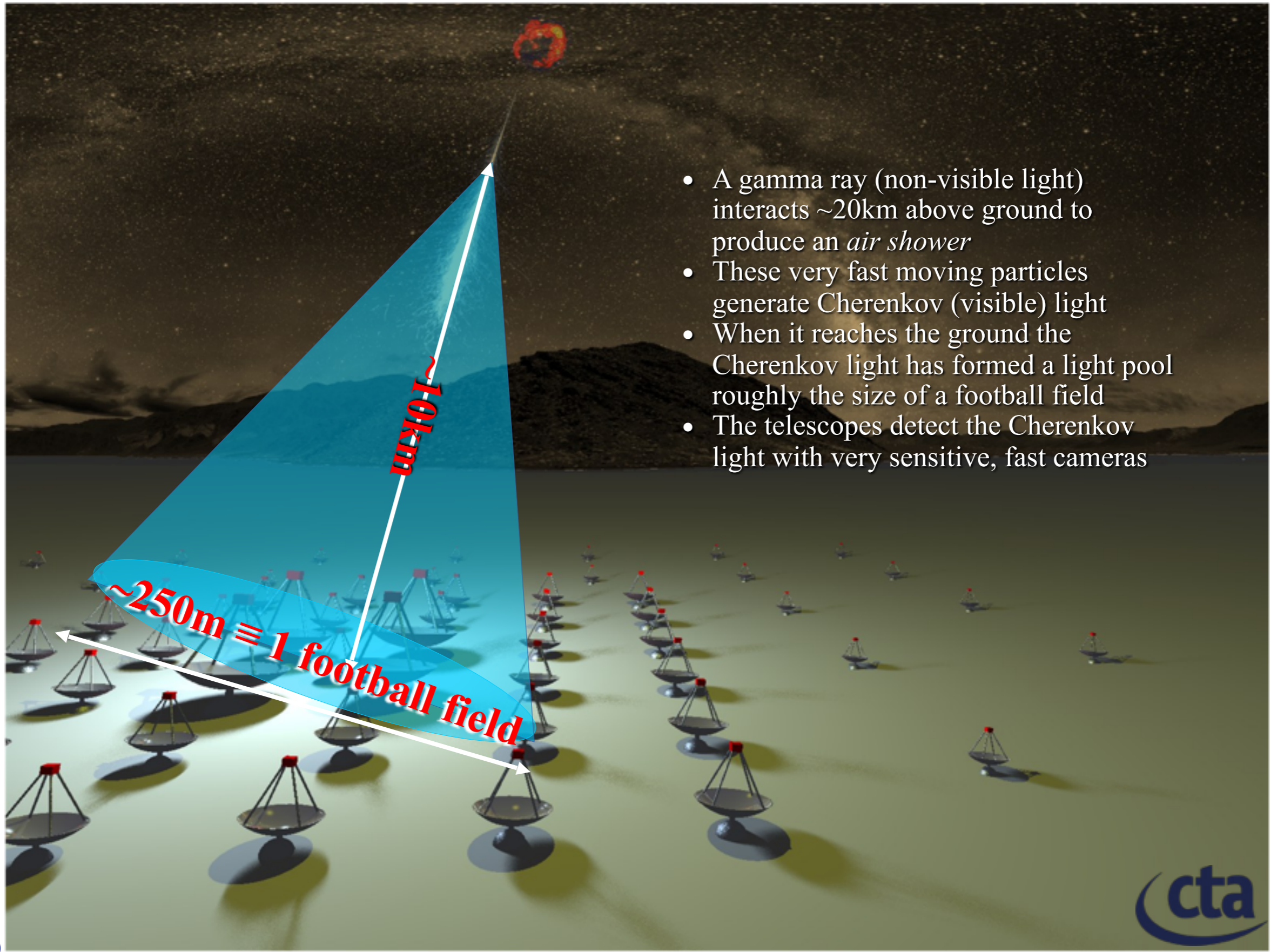
CALIFORNIA STATE UNIVERSITY EAST BAY  
UCLA

IOWA STATE UNIVERSITY  
UNIVERSITY OF DELAWARE

PURDUE UNIVERSITY  
UNIVERSITY OF UTAH

McGill  
Washington University in St. Louis





- A gamma ray (non-visible light) interacts ~20km above ground to produce an *air shower*
- These very fast moving particles generate Cherenkov (visible) light
- When it reaches the ground the Cherenkov light has formed a light pool roughly the size of a football field
- The telescopes detect the Cherenkov light with very sensitive, fast cameras

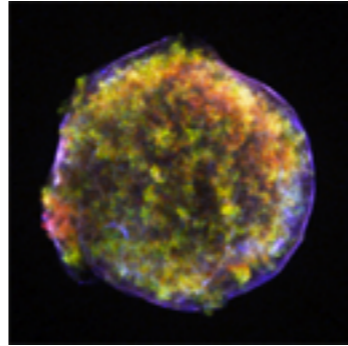




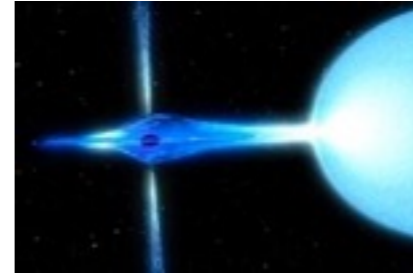
Probes:  
Active Galaxies,  
Supermassive Black Holes,  
Relativistic Jets



Probes:  
Supernova  
Remnants



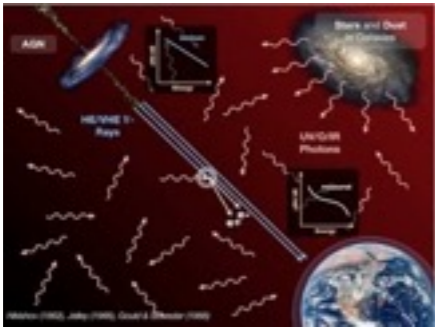
Probes:  
Binary Star  
Interactions



Probes:  
Pulsars  
Pulsar Wind  
Nebulae



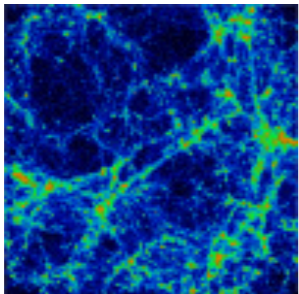
Probes:  
Star  
Formation



## Science Themes

- Understanding the origin of cosmic rays and their role in the Universe.
- Understanding the nature and variety of particle acceleration around black holes.
- Searching for the ultimate nature of matter and physics beyond the Standard Model.

Probes:  
Dark  
Matter



Search for  
Gamma Ray  
Bursts



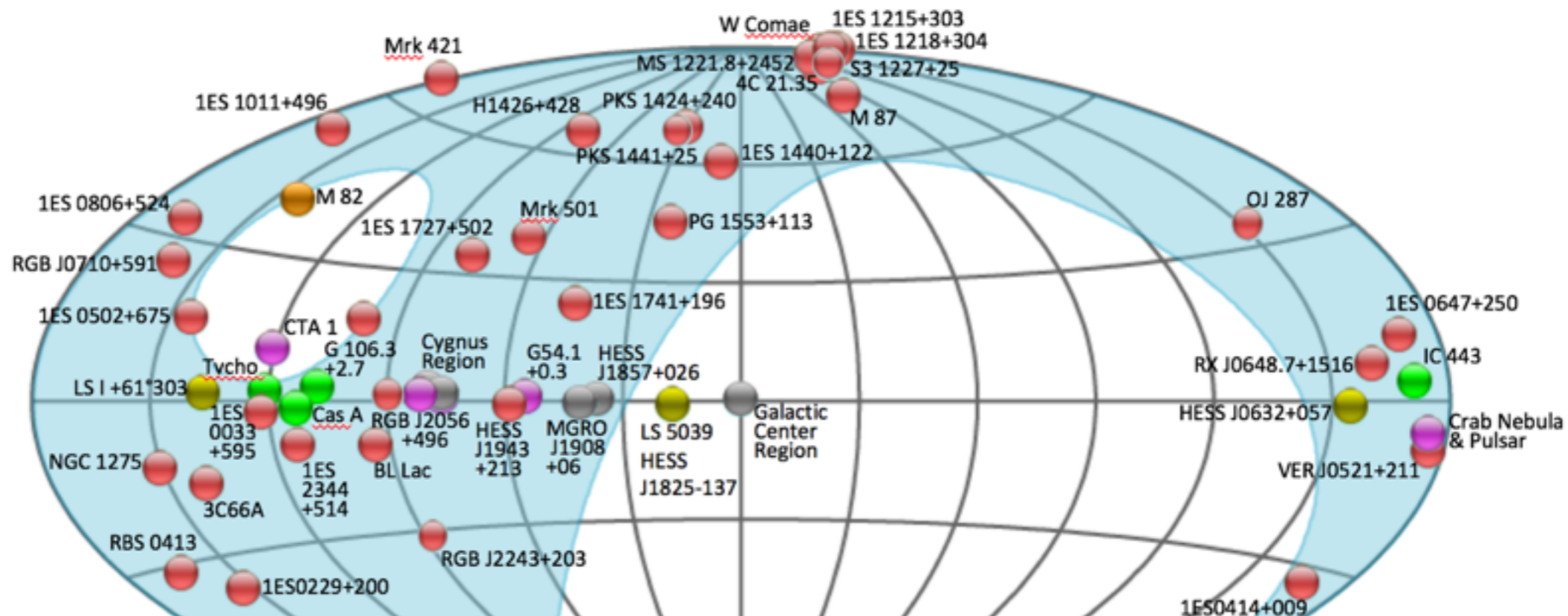
Probes:  
Quantum  
Gravity



# VERITAS source catalogue

## Source Types

- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRQ  
Blazar LBL AGN  
(unknown type)
- Shell SNR/Molec. Cloud  
Composite SNR  
Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming  
Region Globular Cluster  
Cat. Var. Massive Star  
Cluster BIN BL Lac  
(class unclear) WR



**Cygnus Region**  
TeV J2032+4130  
 VER J2019+407  
 VER J2019+368  
 VER J2016+372

**Galactic Center Region**  
 Galactic Center  
 Galactic Center Ridge  
 VER J1746-289  
 G 0.9+0.1

J. Holder & [tevcat.uchicago.edu](http://tevcat.uchicago.edu)

58 sources





# Some science highlights from the past season

**ATel #9599** (Oct. 2016): BL Lac flare

**ATel #9690** (Oct. 2016): NGC 1275 flare

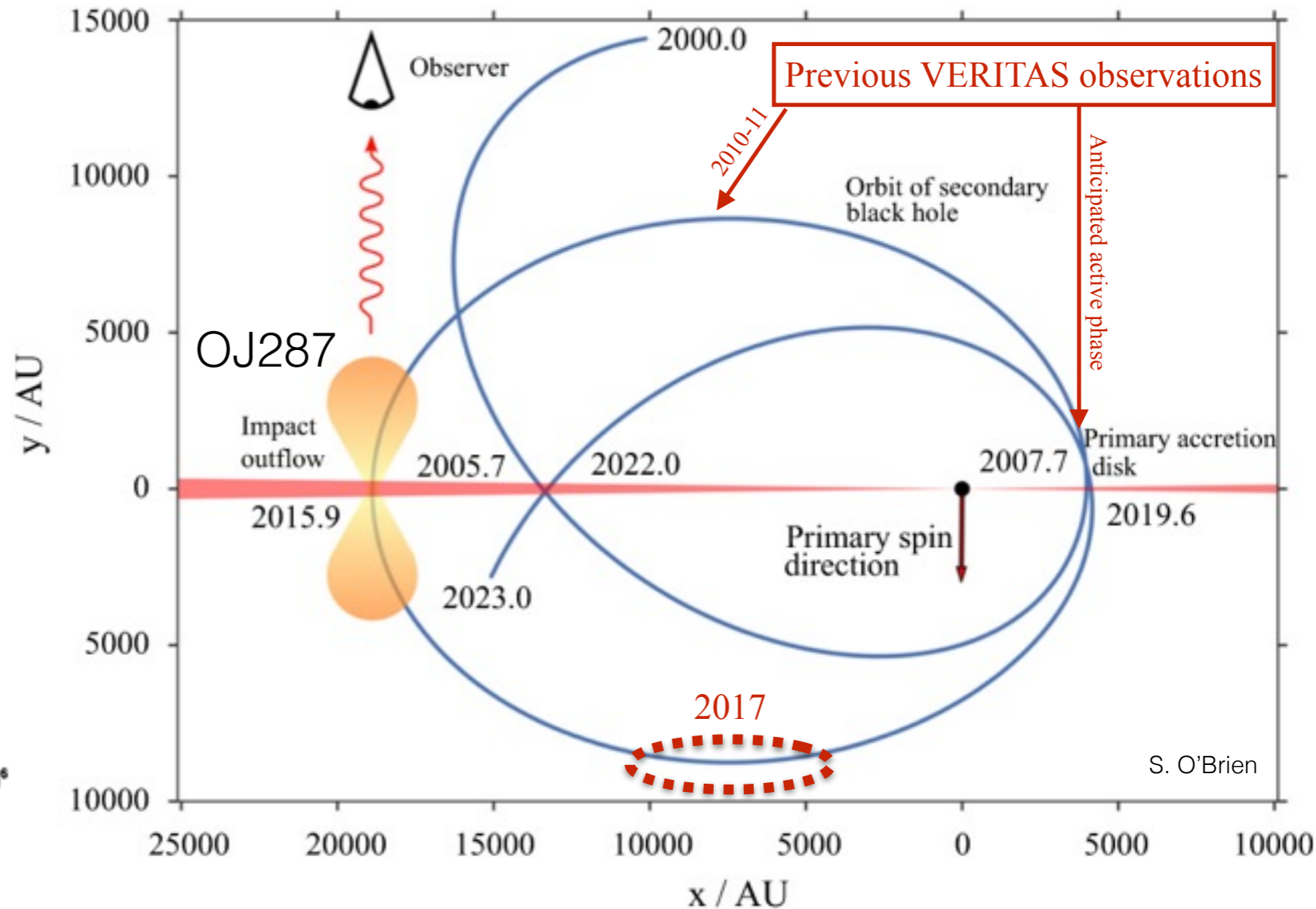
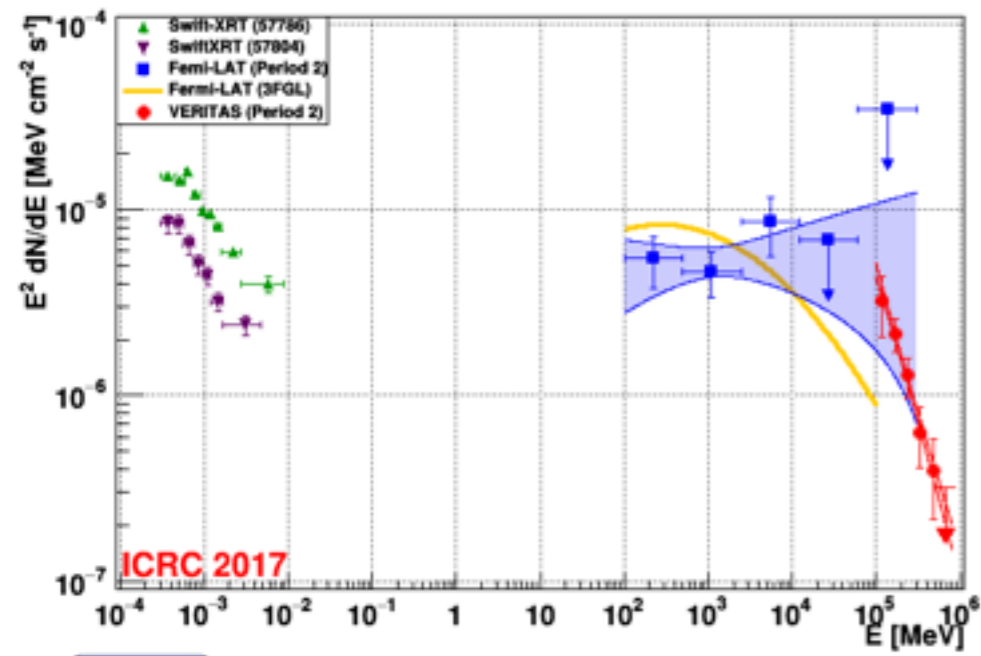
**ATel #9721** (Nov. 2016): VERITAS detection of RGB J2056+496

**ATel #9931** (Jan. 2017): VERITAS observations of NGC 1275

**ATel 10051** (Feb. 2017): VERITAS detection of VHE Emission from OJ 287

**ATel 10252** (Apr. 2017): VERITAS [upper limits] of Cygnus X-3 during a major radio flare

OJ287 obs coincident with record Swift high state



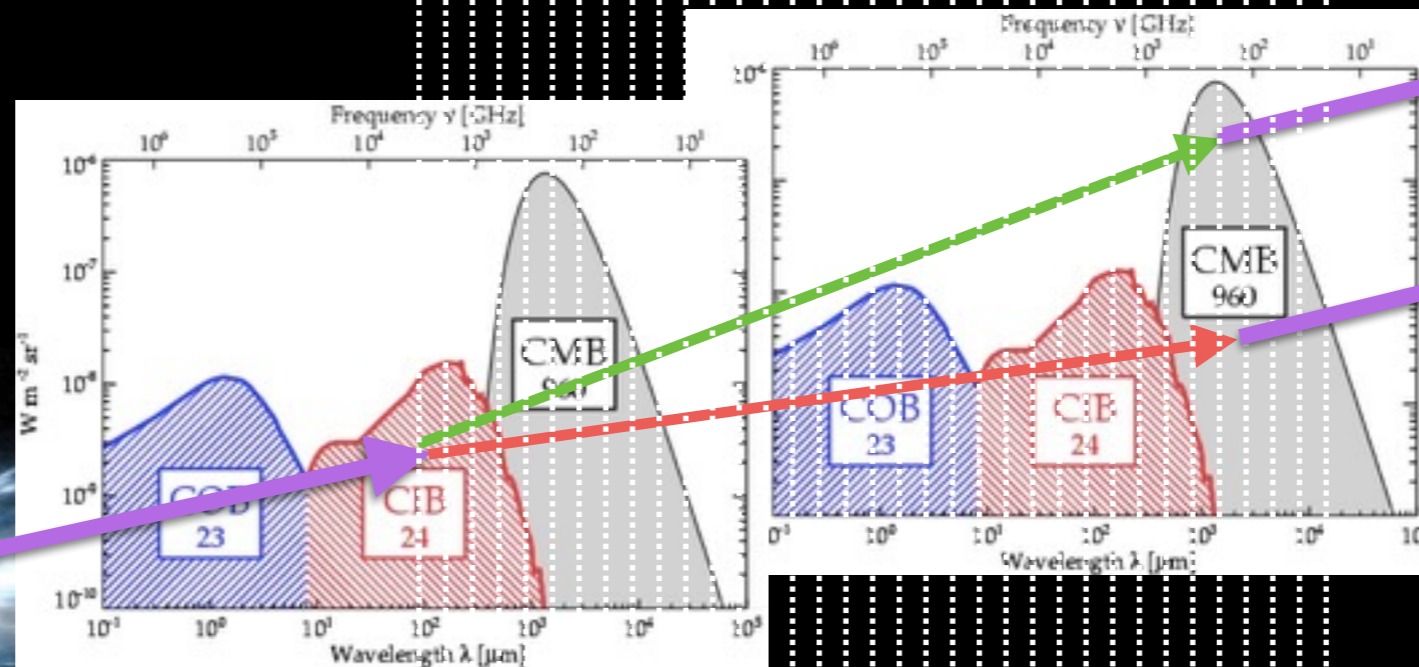
S. O'Brien



# AGN as probes: IGMF

- VHE photon pair produces on EBL
- $e^+e^-$  cascade paths diverge due to B-field
- $e^+e^-$  IC upscatter EBL photons
- ➔ point source appears broadened due to IGMF

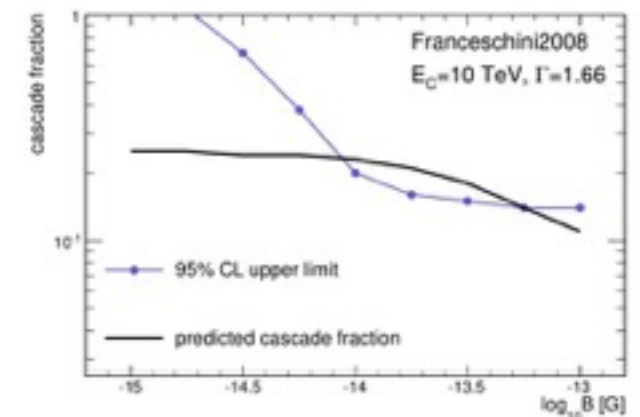
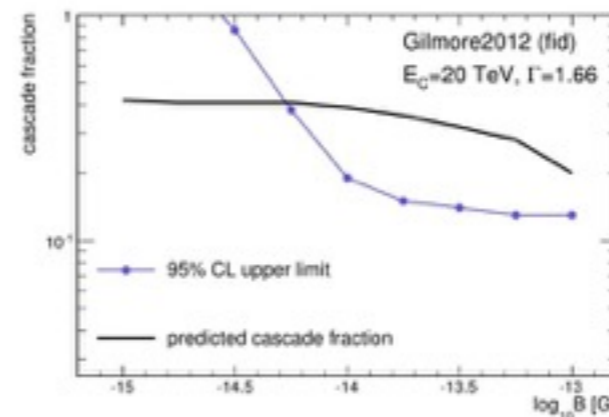
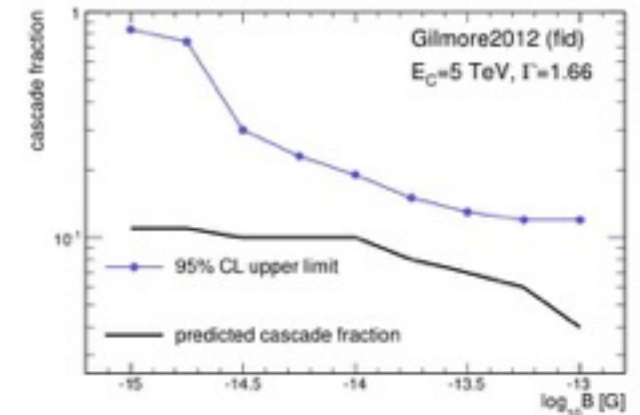
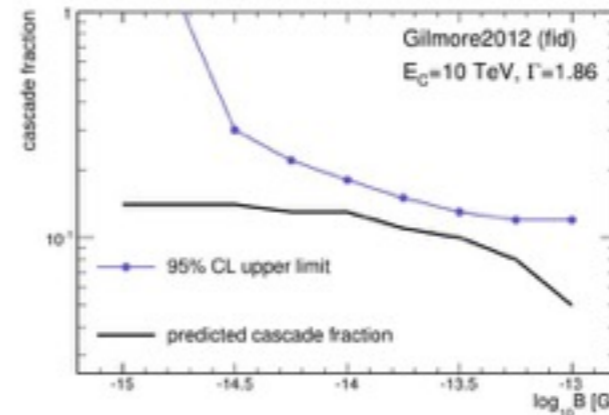
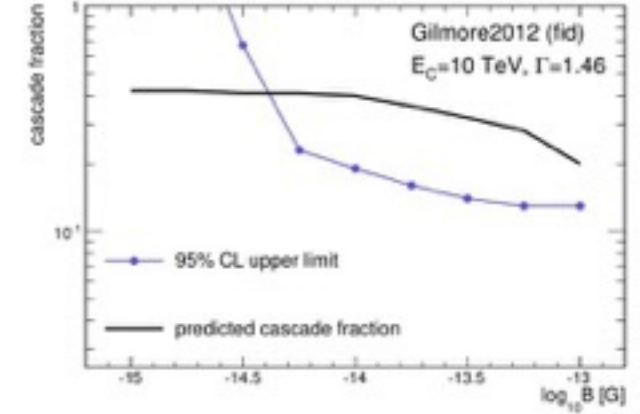
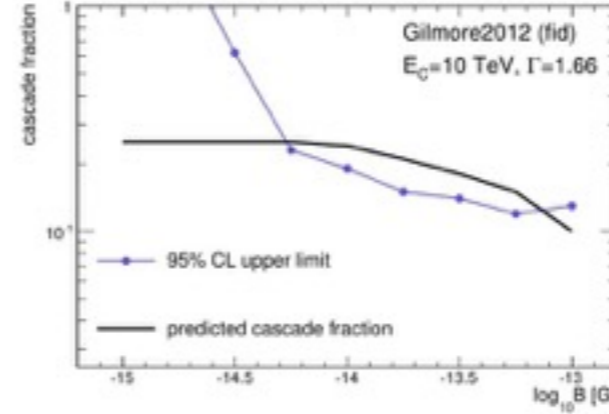
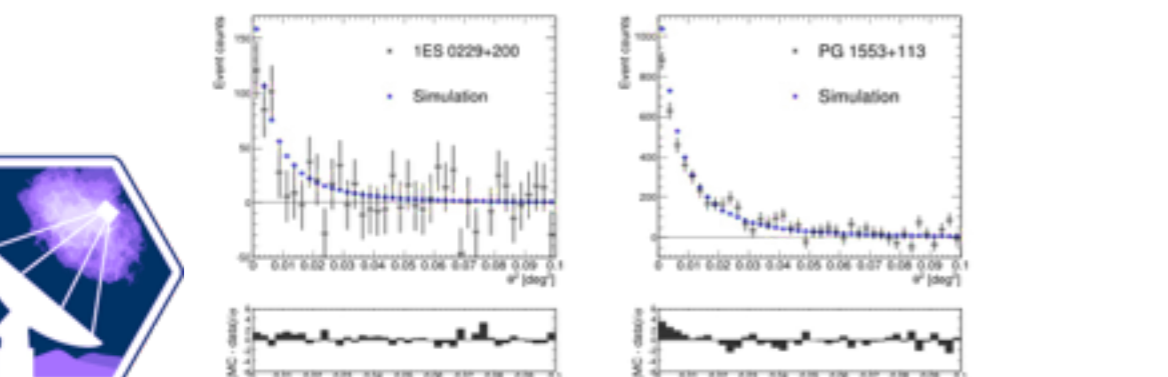
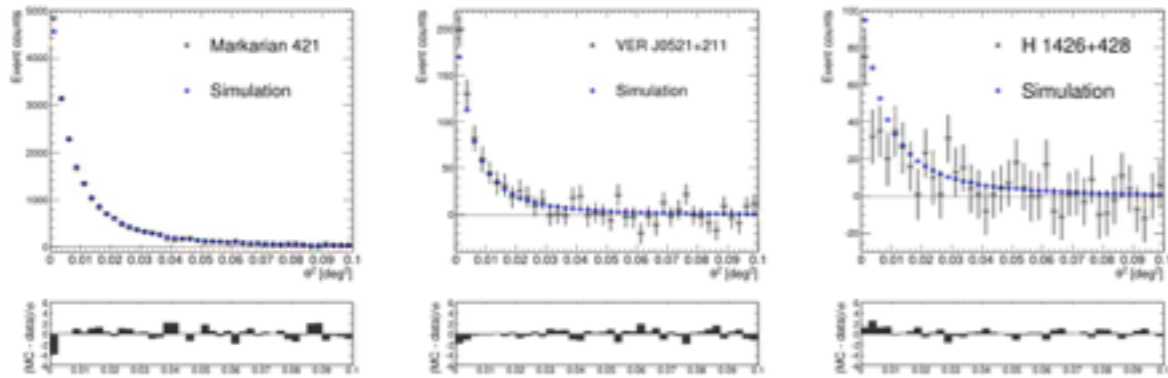
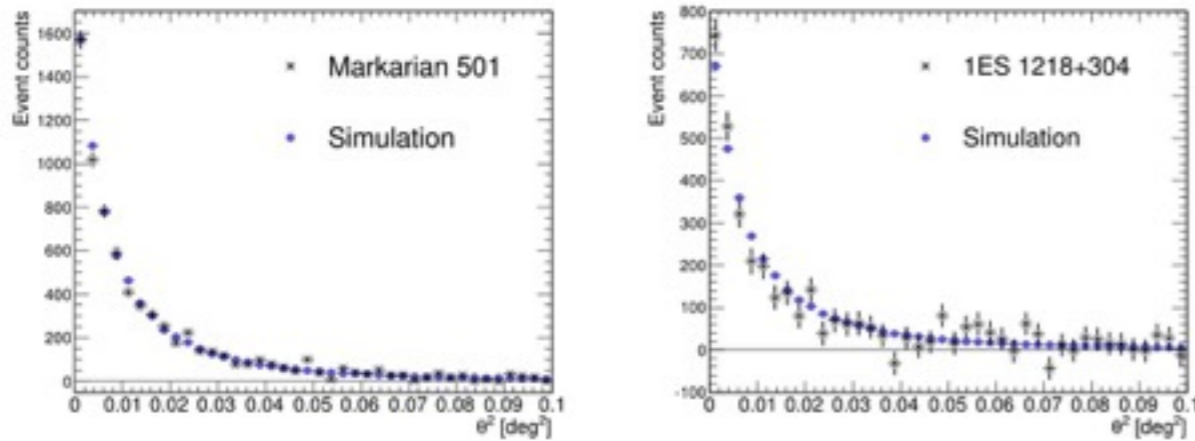
**B**



# AGN as probes: IGMF

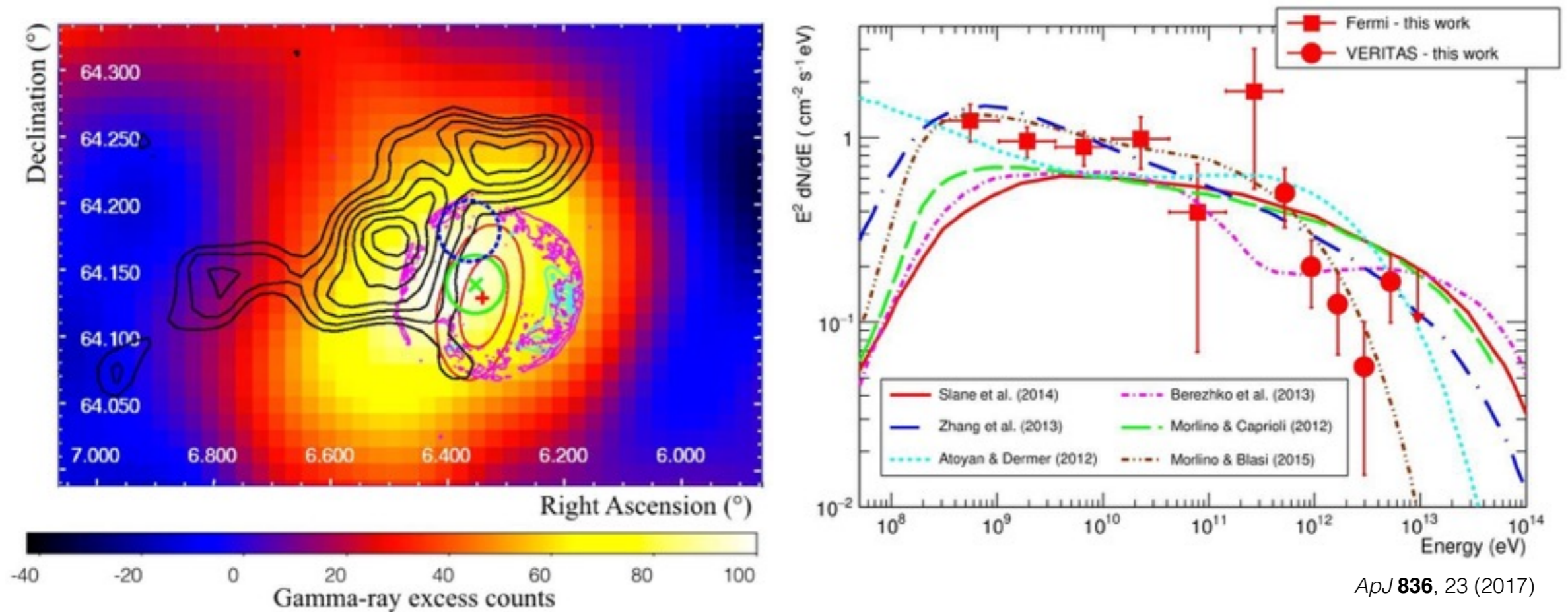
- Seven blazars studied for evidence of angular extension due to cascade emission

- No evidence of cascade found  
 → IGMF strength of  $\sim 10^{-14}$ G excluded at 95% confidence.





# Galactic: Tycho SNR



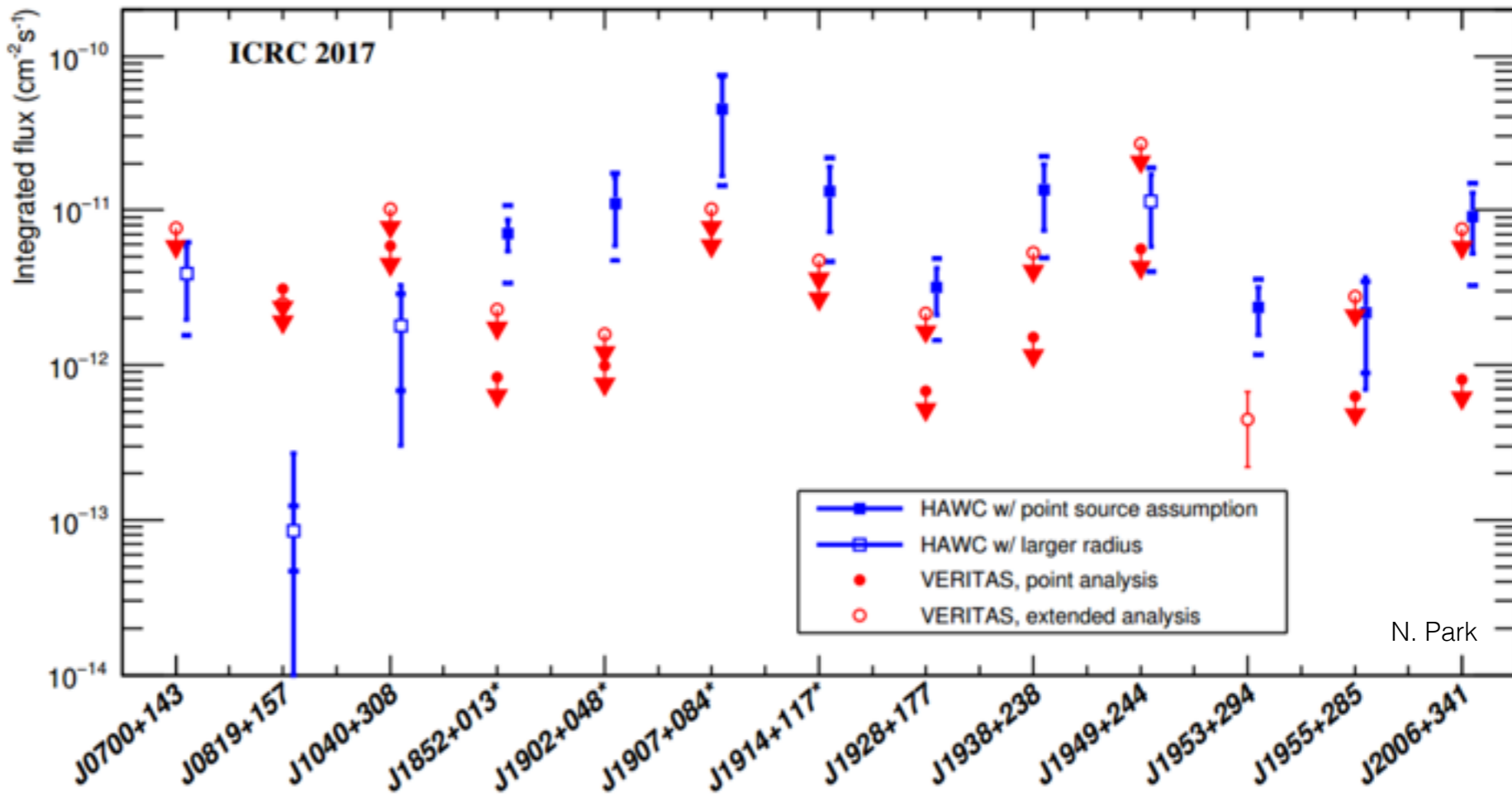
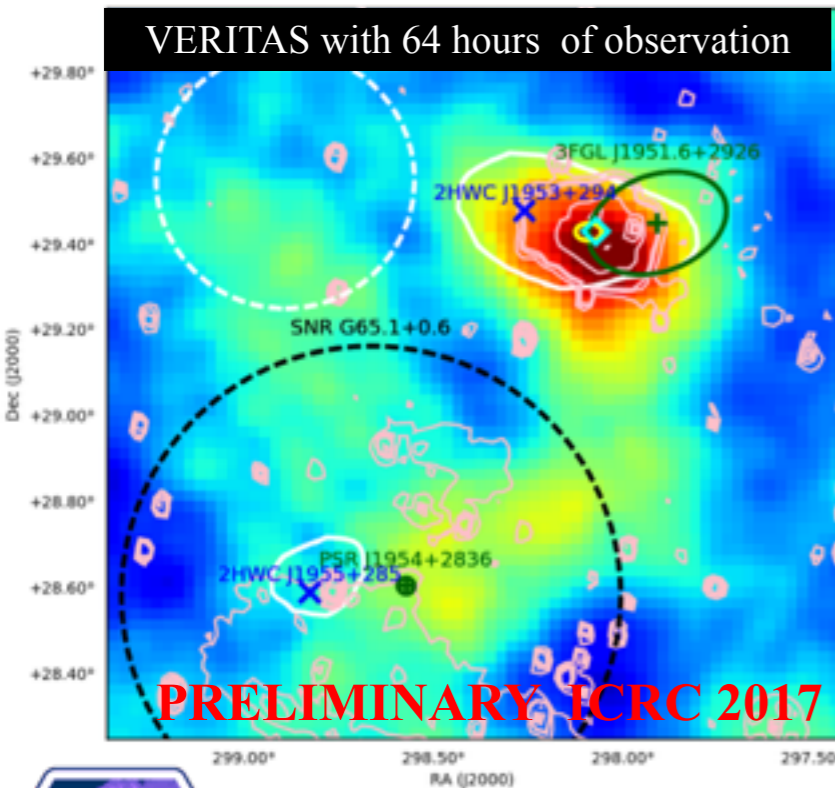
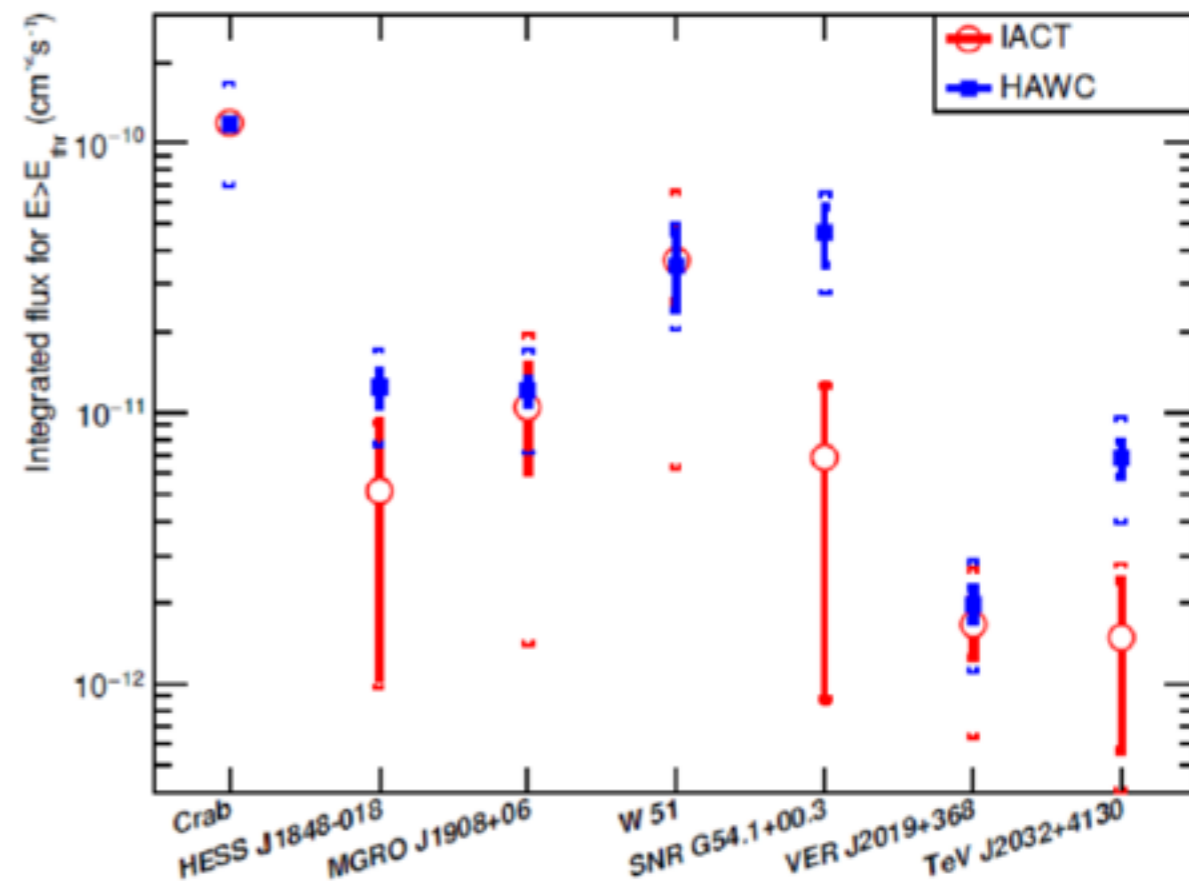
147h VERITAS, 84 months Fermi

The results are consistent with a SNR shell origin of the emission, as many models assume. The updated spectrum points to a lower maximum particle energy than has been suggested previously.



# HAWC 2<sup>nd</sup> catalogue follow up

- 2HWC contains 39 sources
- 16 are ~1degree from known TeV sources
- VERITAS accumulated 187h exposure for 13 of these
  - ➔ 1 detection - 2HWC J1953+294



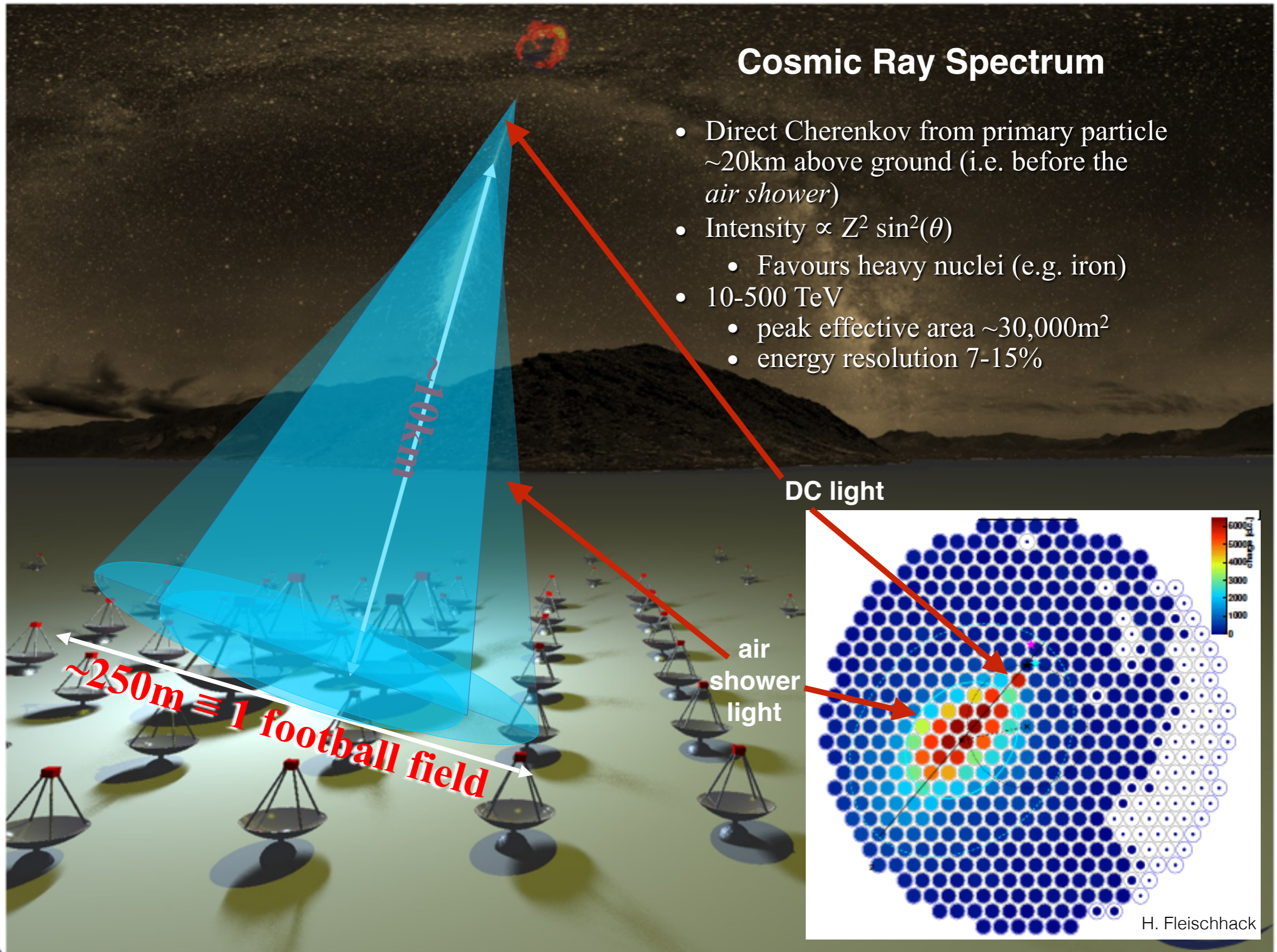
N. Park





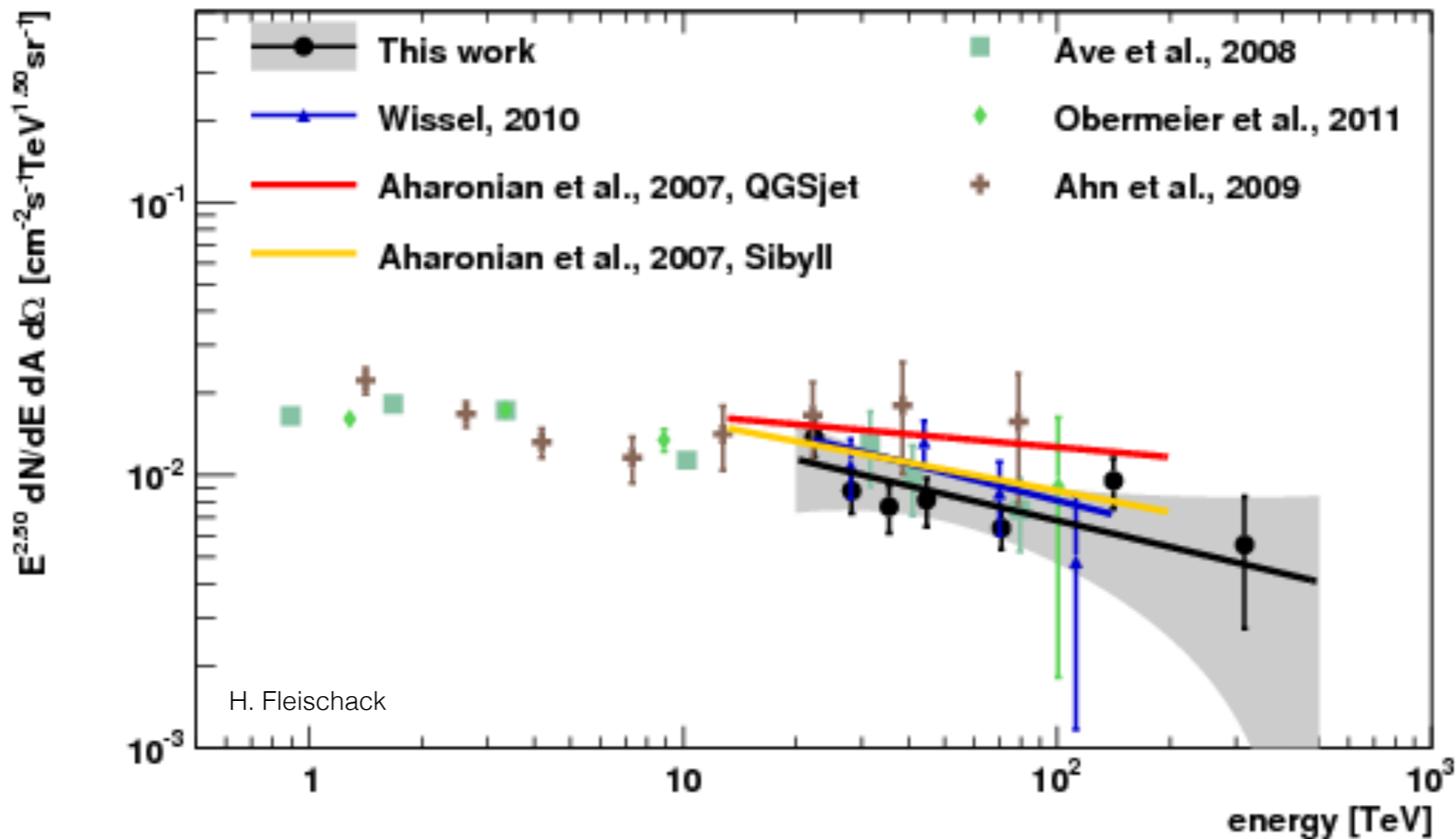
# Cosmic Ray Spectrum

- Direct Cherenkov from primary particle  
~20km above ground (i.e. before the *air shower*)
- Intensity  $\propto Z^2 \sin^2(\theta)$ 
  - Favours heavy nuclei (e.g. iron)
- 10-500 TeV
  - peak effective area ~30,000m<sup>2</sup>
  - energy resolution 7-15%



# Iron Spectrum

Analysed 71 hours of data taken on various targets from 2009 - 2012 (winter months only), >80 degrees elevation, clear moonless nights with all four telescopes operating.



Power Law Fit (E/50 TeV)

$$(4.82 \pm 0.98_{\text{stat}} \text{ } ^{+2.12}_{-2.65} \text{ syst}) \times 10^{-7} \text{ /cm}^2\text{/s/sr/TeV}$$

$$\text{slope} = -(2.82 \pm 0.30_{\text{stat}} \text{ } ^{+0.23}_{-0.25} \text{ syst})$$

Require DC pixels in  $\geq 2$  cameras





# DM limits from dSph observations

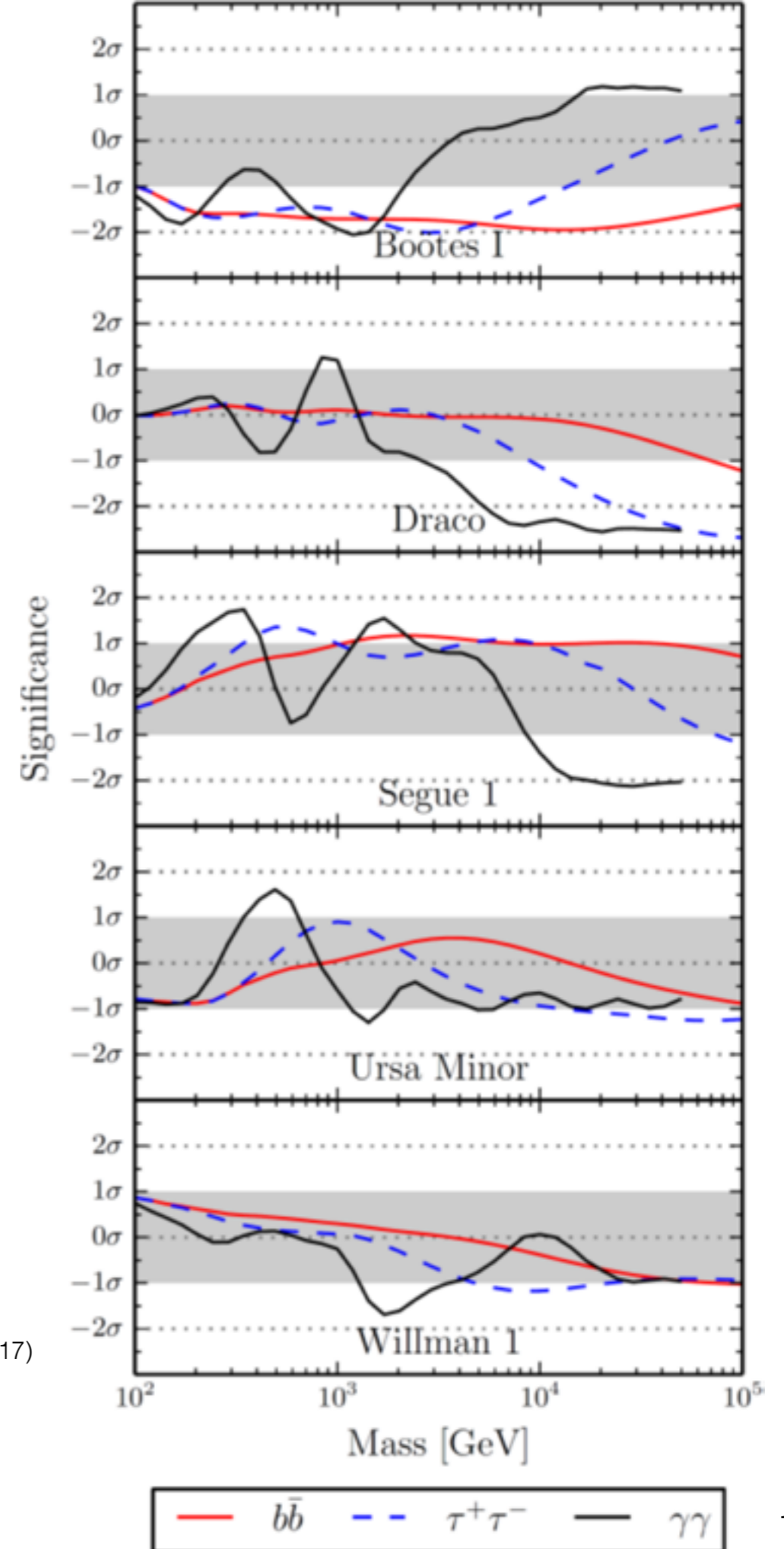
230h observations of 5  
dSph galaxies

Segue 1,  
Draco,  
Ursa Minor,  
Bootes 1,  
Willman 1

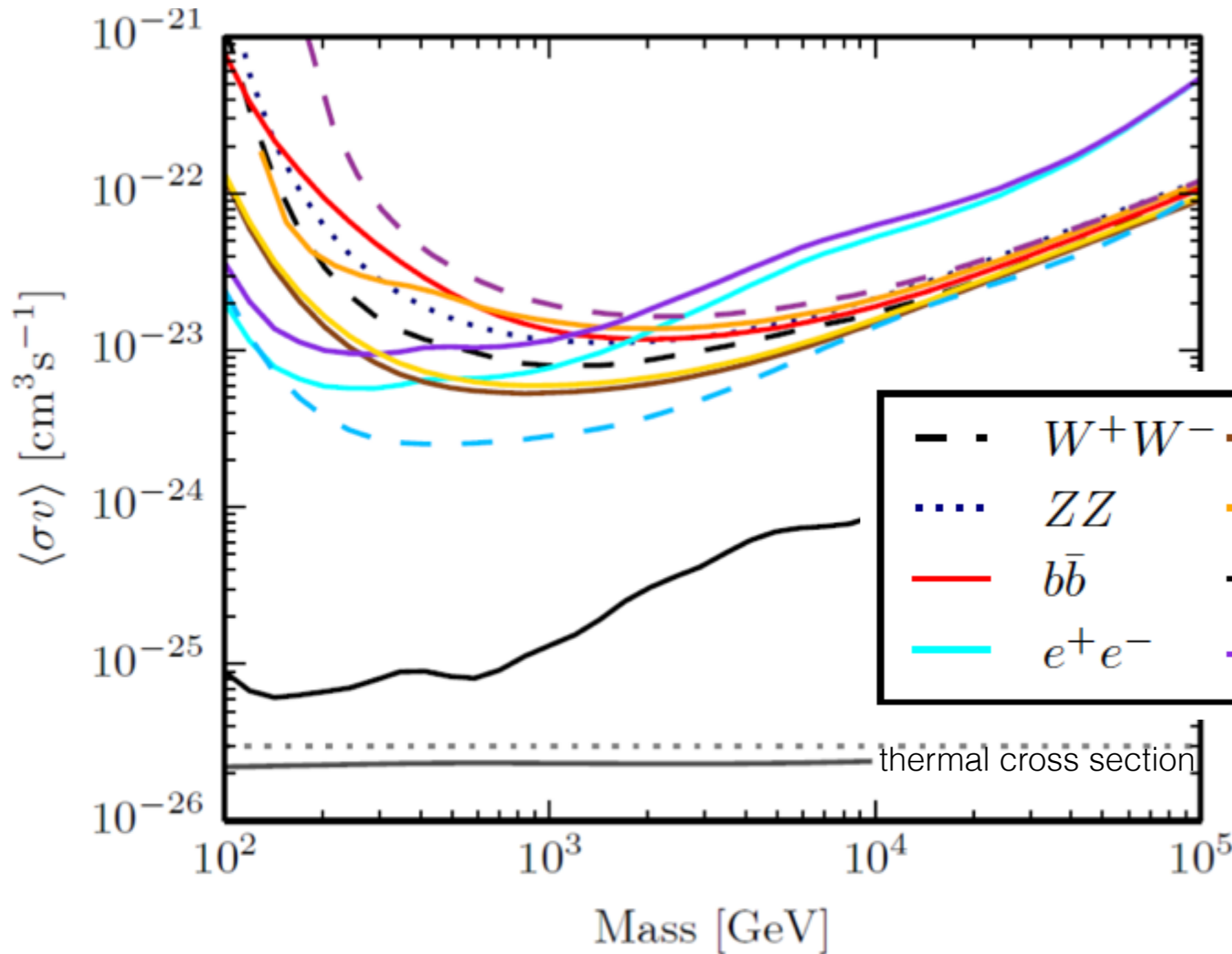
no significant detection

For each dark matter mass (x-axis), the y-axis gives the significance of detection, defined as the quantile of the probability distribution of the background-only model. This probability is converted into a “sigma value” using the inverse CDF of a standard Gaussian.

*Phys. Rev. D* **95**, 082001 (2017)



# DM limits from dSph observations



216h observations of stacked observations

*Phys. Rev. D* **95**, 082001 (2017)

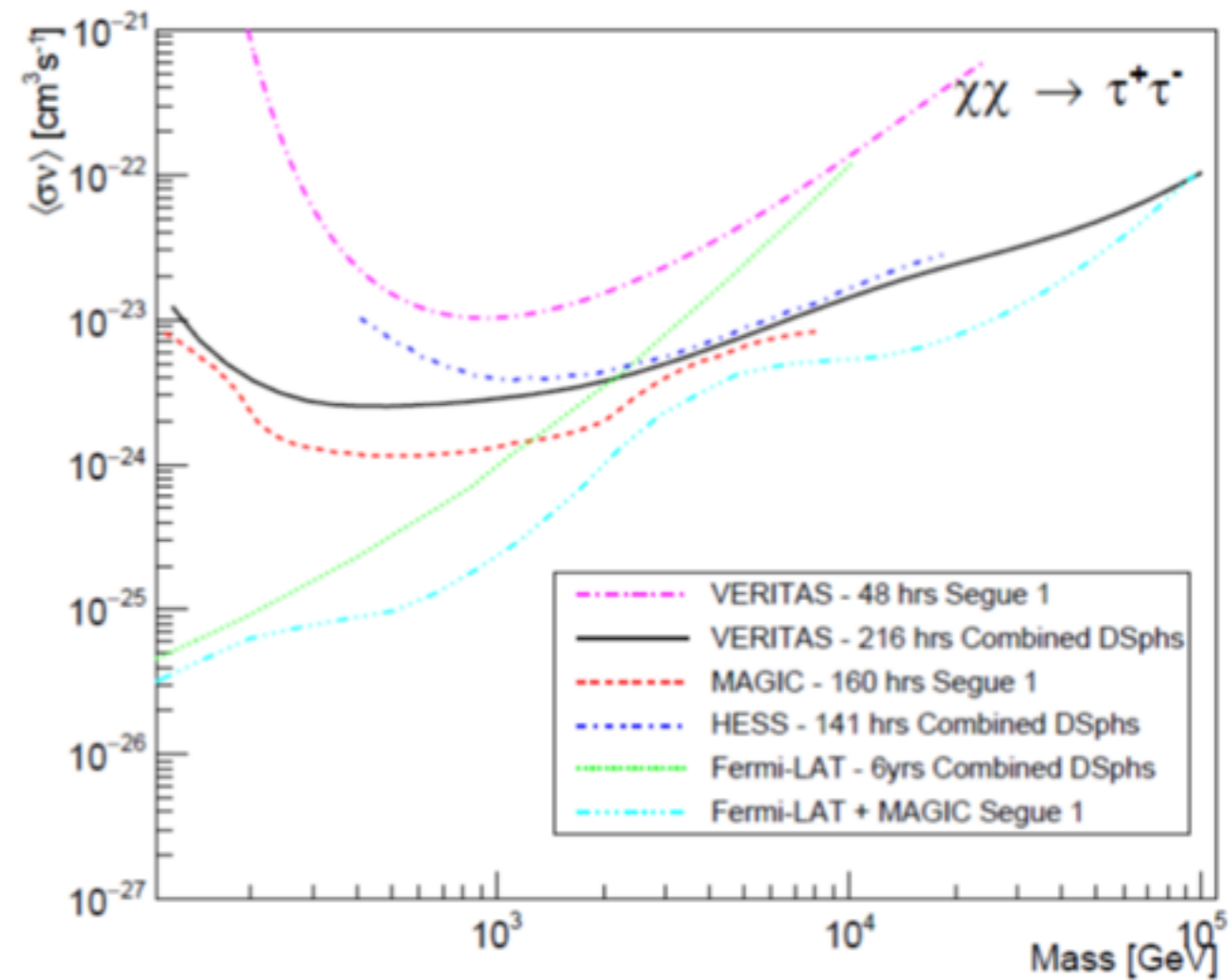
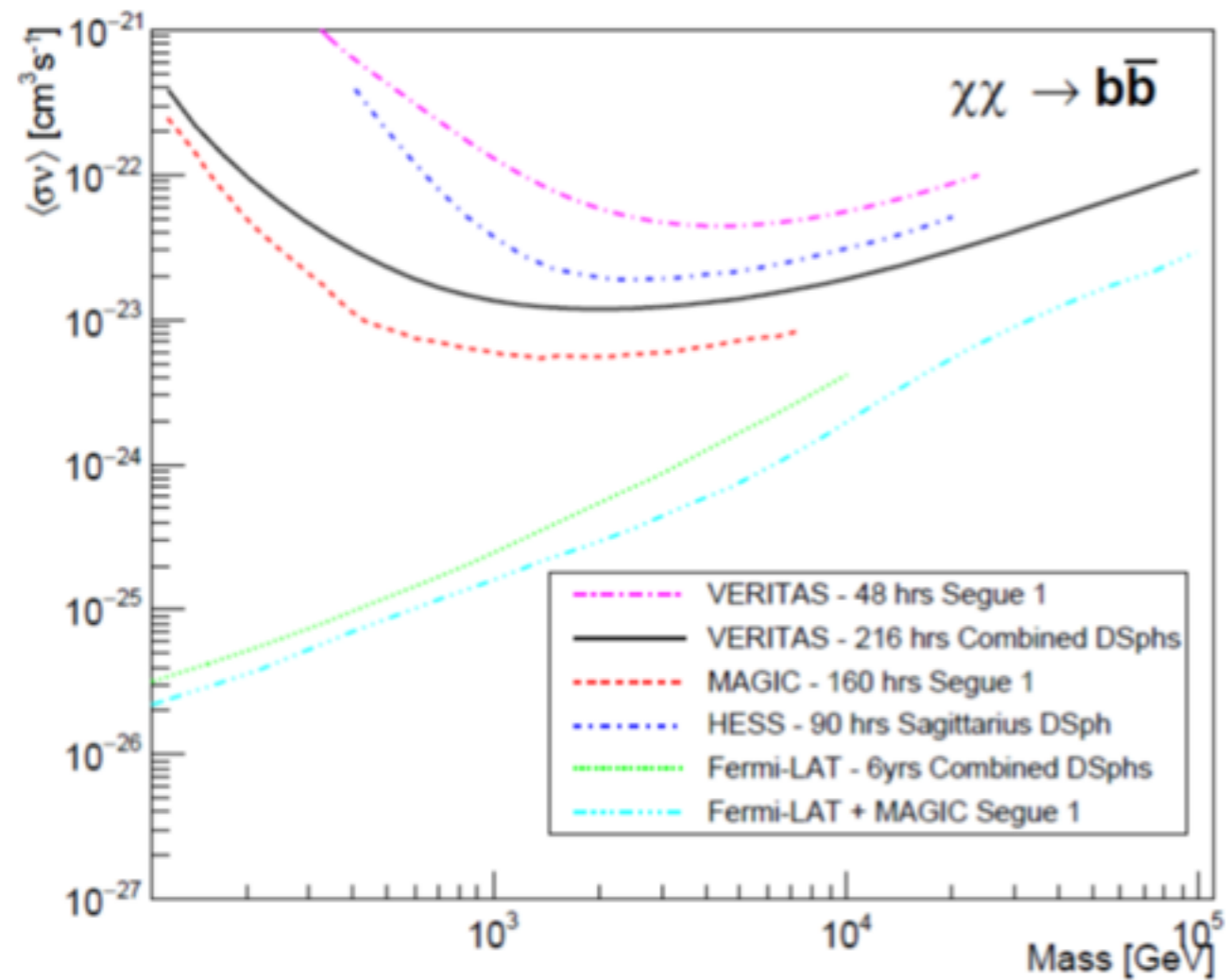
**Segue 1, Draco, Ursa Minor, Bootes 1, *Willman 1***

those in **bold** included in stacking analysis





# DM limits from dSph observations



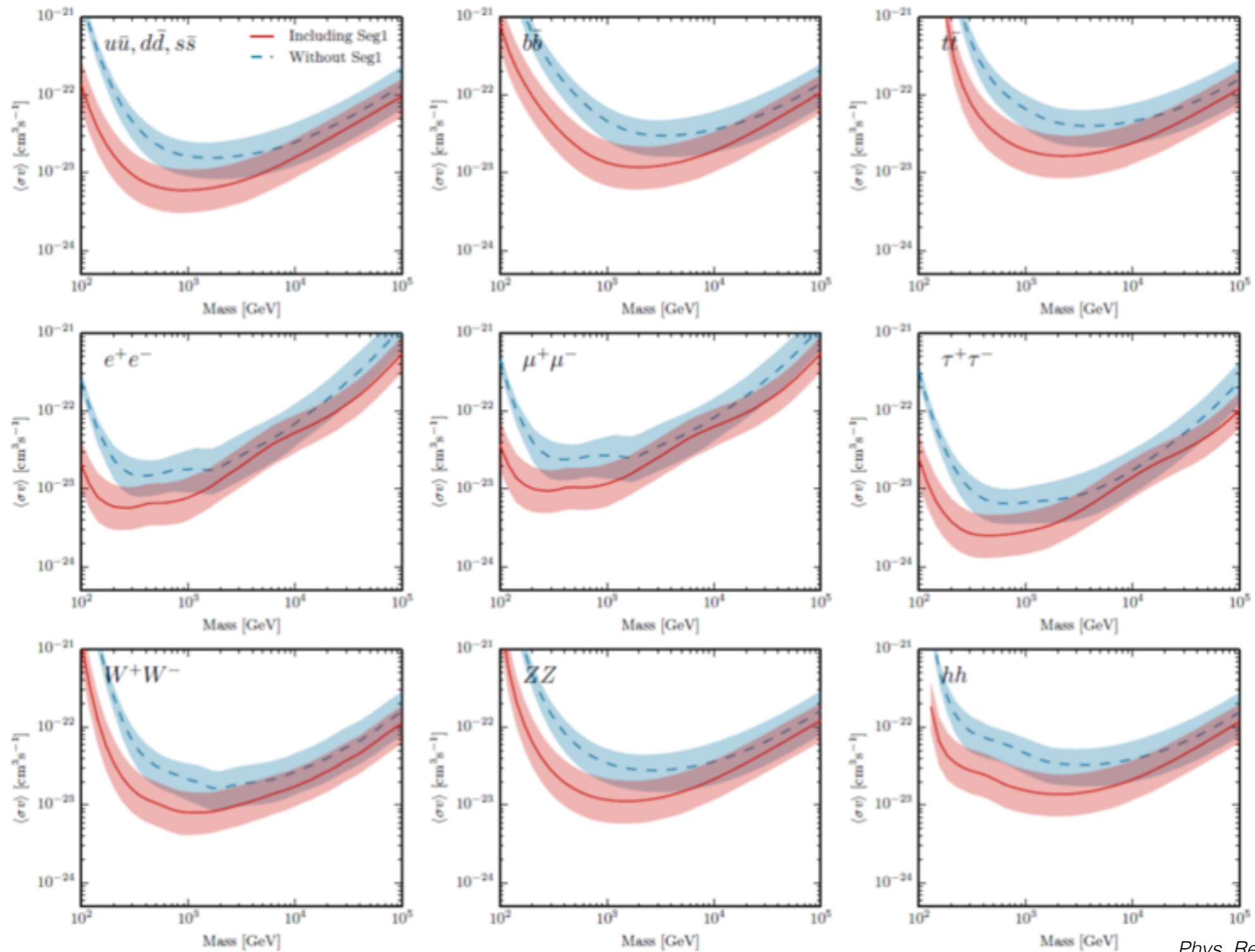
*Phys. Rev. D* **95**, 082001 (2017)

from 216h observations of stacked data

**Segue 1, Draco, Ursa Minor, Bootes 1, *Willman 1***



# DM limits from dSph observations



Phys. Rev. D **95**, 082001 (2017)

**Segue-1**, **Draco**, **Ursa Minor**, **Bootes 1**, *Willman-1*  
 those in **bold** included in stacking analysis





# VERITAS Multi-Messenger Program: Neutrino Follow Up

**Goal:** search for potential hadronic VHE emission signatures at the location of high-energy muon neutrino events (single or cluster)

Variety of follow-up approaches:

minutes-days-weeks-months-years

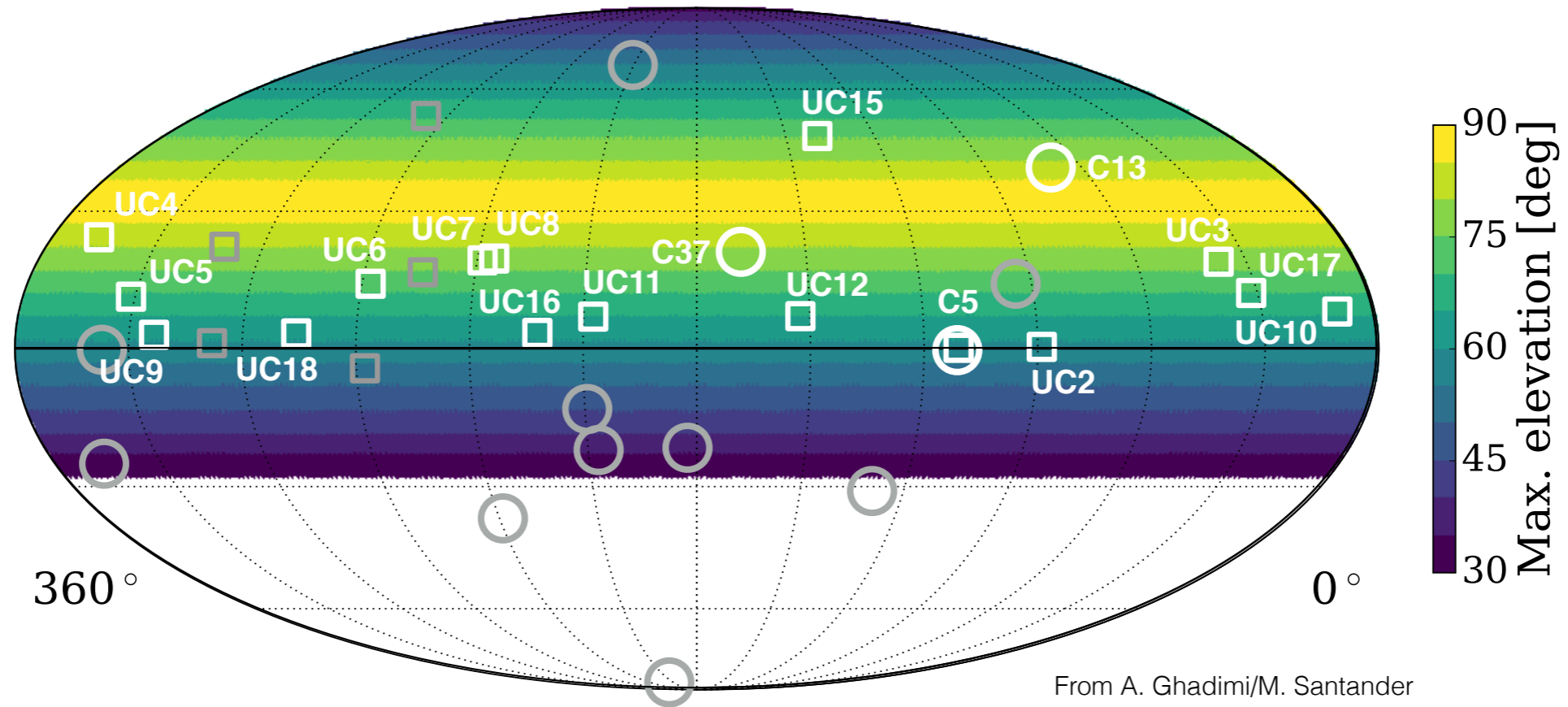


- \* Correlation studies of neutrino and gamma-ray emission from known VHE sources (e.g. 1ES1959+650).
- \* Searches for VHE emission at “archival” likely astrophysical neutrino positions
  - \*  $E_\nu \gtrsim 100$  TeV.
  - \* Observation of neutrino multiplets.
- \* Observation of neutrino “flares” from known VHE sources.
- \* Observation of prompt online alerts (e.g. HESE, EHE)



# VERITAS Follow-up Observations of Muon Neutrino Positions

Track-like muon events from charged current muon neutrino interactions with  $\sim 1^\circ$  ang. res.  
64 hours of observations on 28 high energy muon event locations in good weather

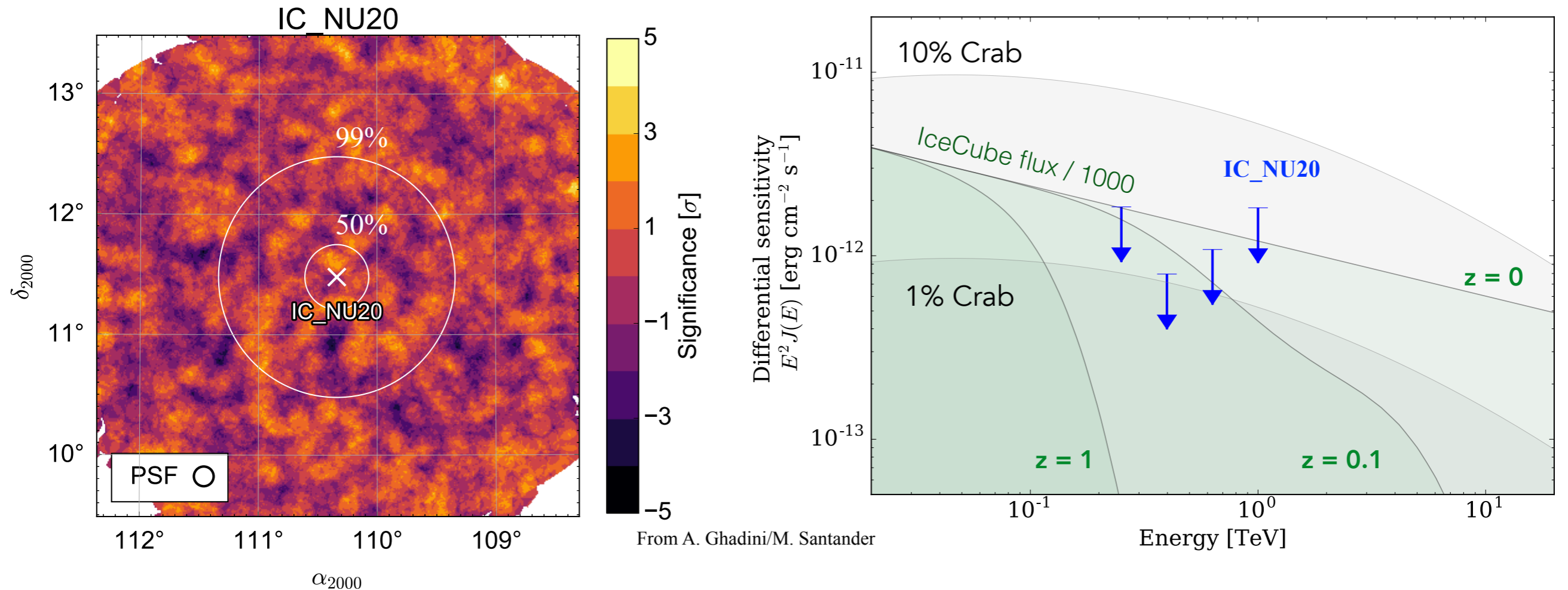


- Most 99% CL upper limits for through-going muons are at the 1-5% Crab nebula flux above 100 GeV.





# VERITAS Follow-up Observations of Muon Neutrino Positions



From A. Ghadini/M. Santander

- 4 runs (1.83 hr of live-time) taken on 03/27/2016 under dark conditions. Analysis optimized for soft-spectrum sources.
- **No gamma emission detected** within the neutrino error circle. ULs at the level of a few percent of the Crab.
- **Upper limits at the level of 0.1% of the all-sky astrophysical neutrino flux** (depends on spectral extrapolation and source redshift).

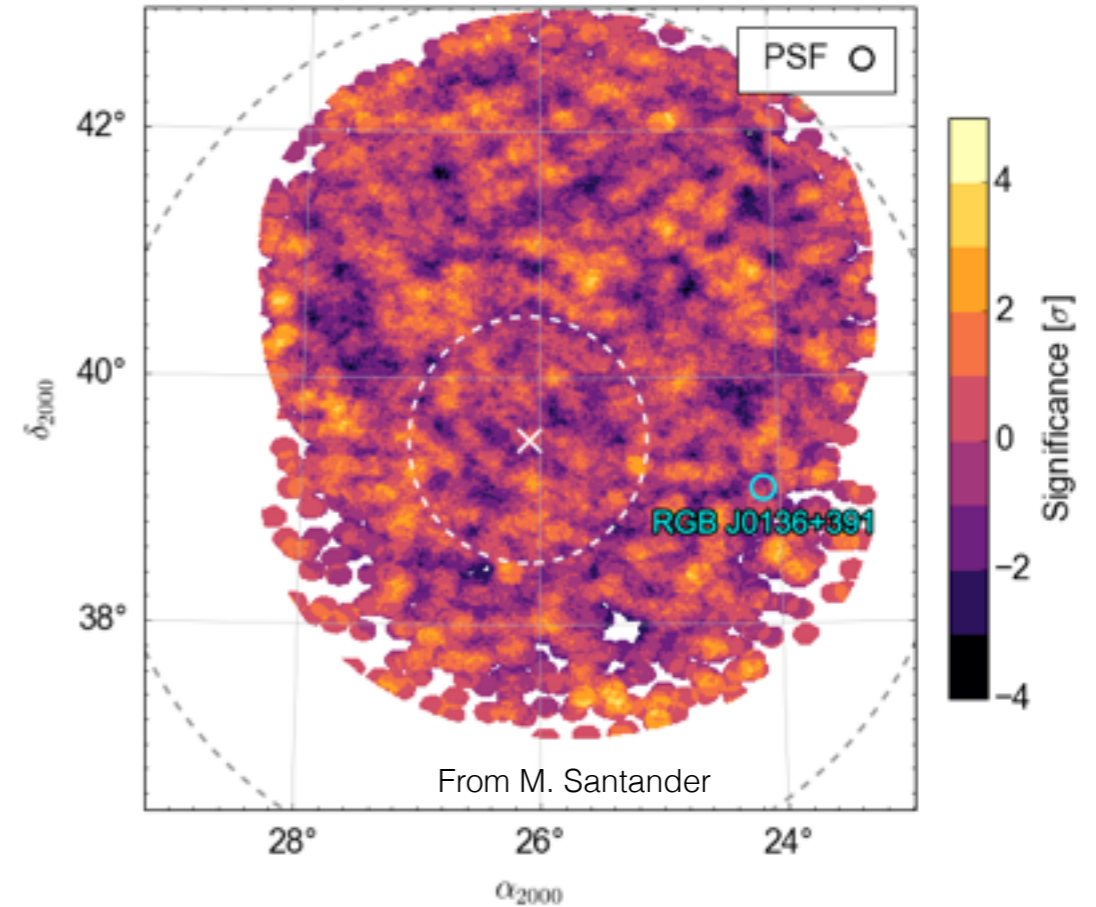


# “Triplet” follow-up campaign

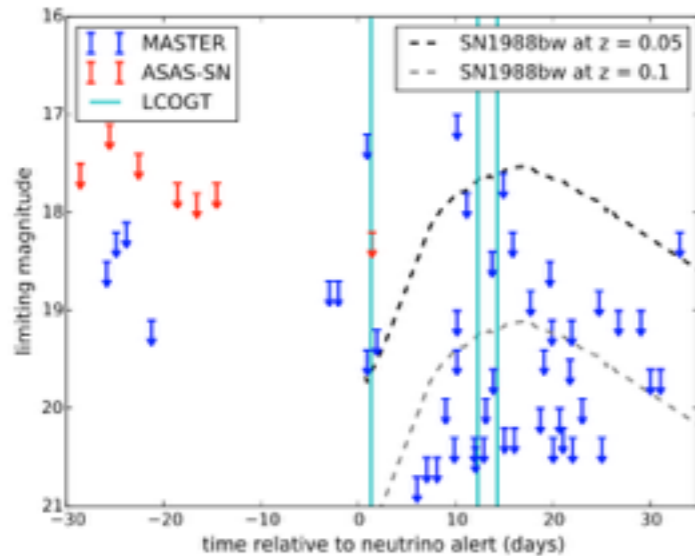
“**Neutrino triplet**”: Two doublets (with one event in common) detected within 100s on 2016-02-17. False alert rate once per  $\sim 14$  years.

- **Optical**: ASAS-SN, LCOGT, MASTER
- **X-ray**: Swift-XRT and BAT
- **Gamma-ray**: Fermi-LAT, *VERITAS*, HAWC
- No likely counterparts. Constraints on GRB or SN emission. No blazar correlation.

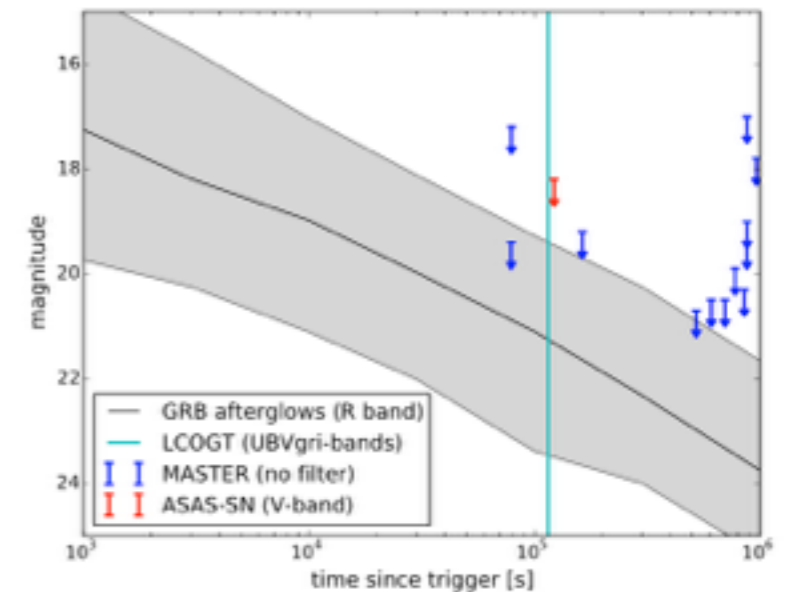
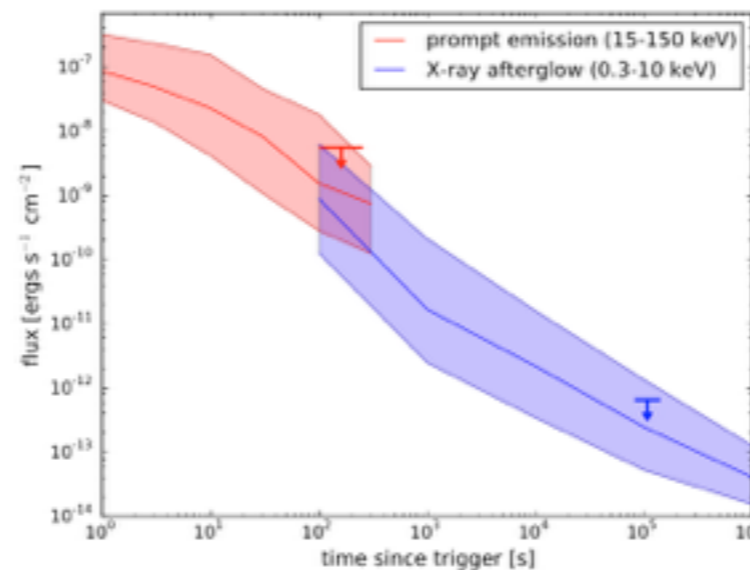
VERITAS observations (start 8 days after)



Optical limits vs hypernova



Optical/X-ray limits vs GRB afterglow

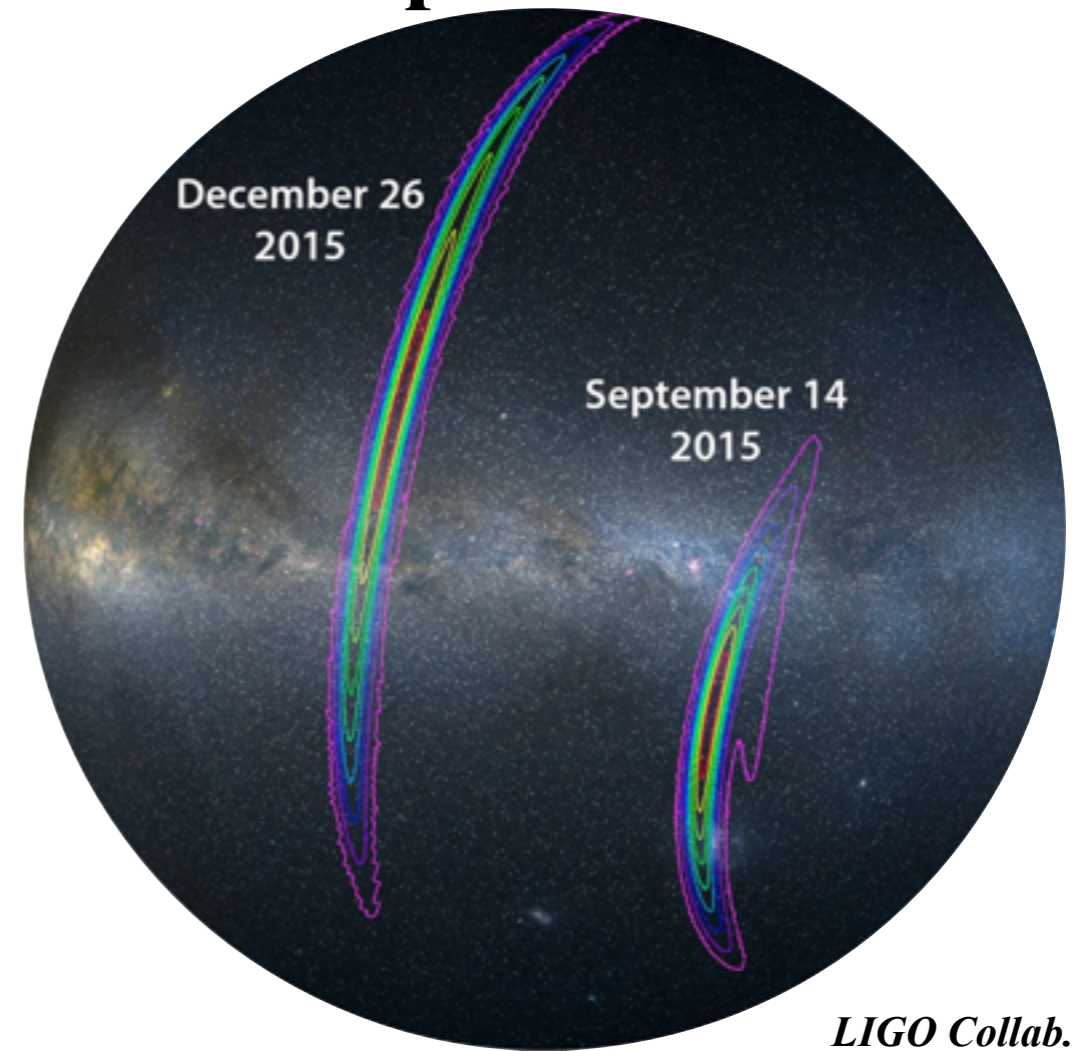
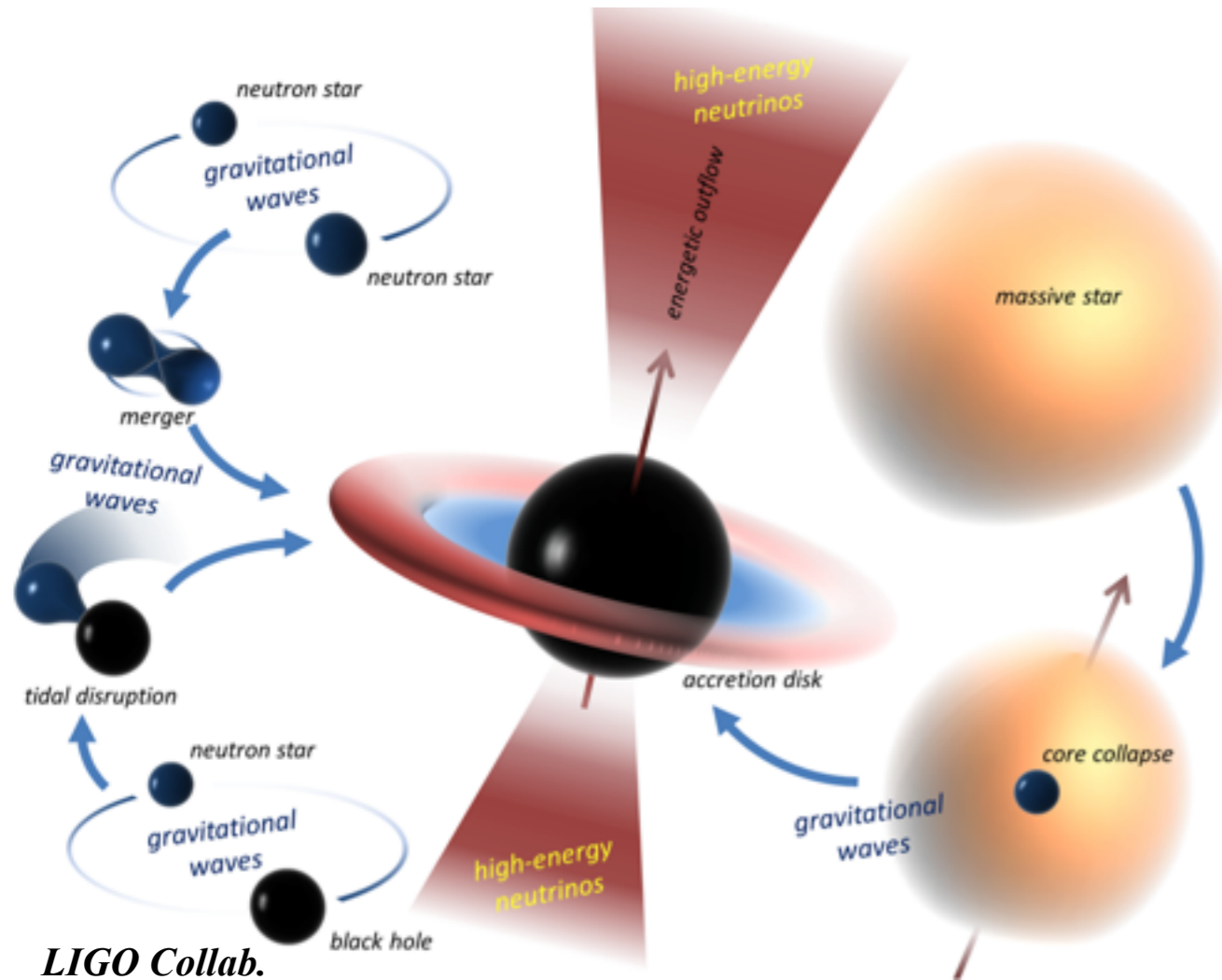


IceCube + MWL partners arXiv:1702.06131





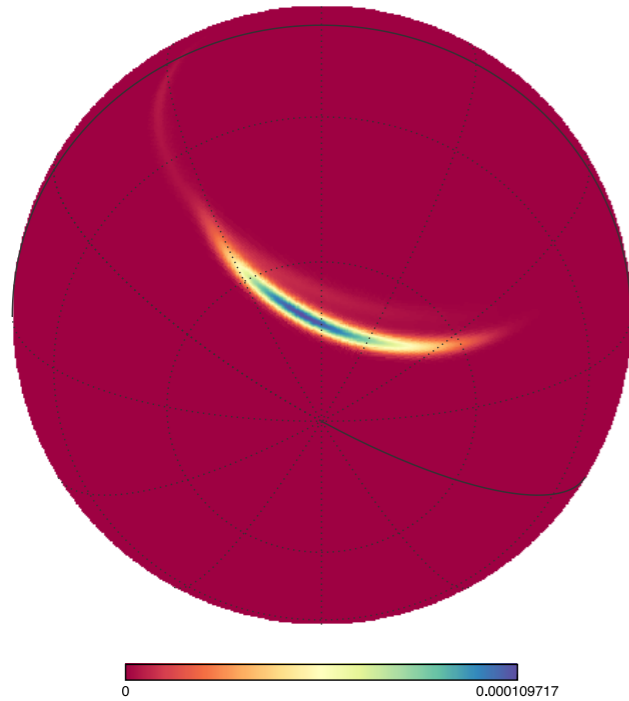
# Gravitational Wave Follow up



- **LIGO detection:** 2 events associated with BH-BH mergers (not expected to be EM bright). Associated keV emission detected by Fermi-GBM? (GBM Collab. [arXiv/1602.03920](https://arxiv.org/abs/1602.03920)).
- NS-NS merger may be associated with short GRBs. A NS-NS merger within the LIGO horizon ( $\sim 100$  Mpc) may be detected by TeV instruments (Bartos et al. [arXiv/1403.6119](https://arxiv.org/abs/1403.6119))
- VERITAS is part of the LIGO GW follow-up community. It can use its  $\sim 10$  deg<sup>2</sup> FoV to cover the  $O(100$  deg<sup>2</sup>) error region.

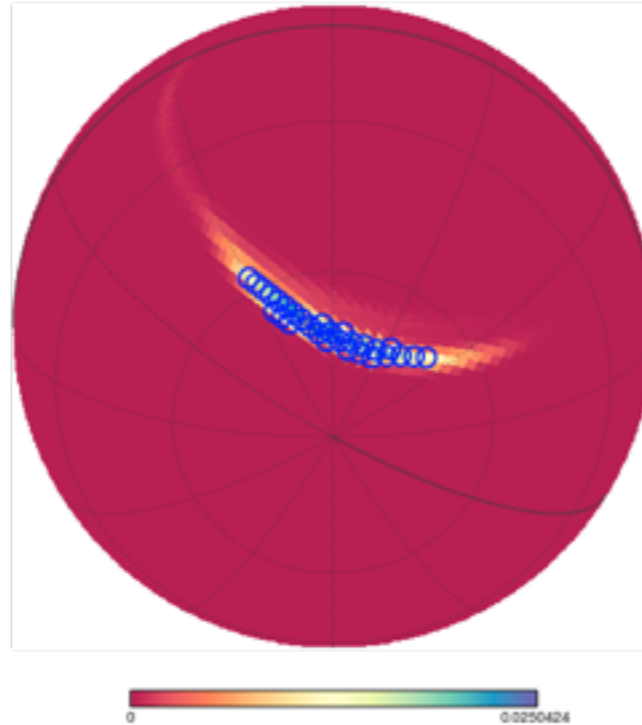


*Basic map*

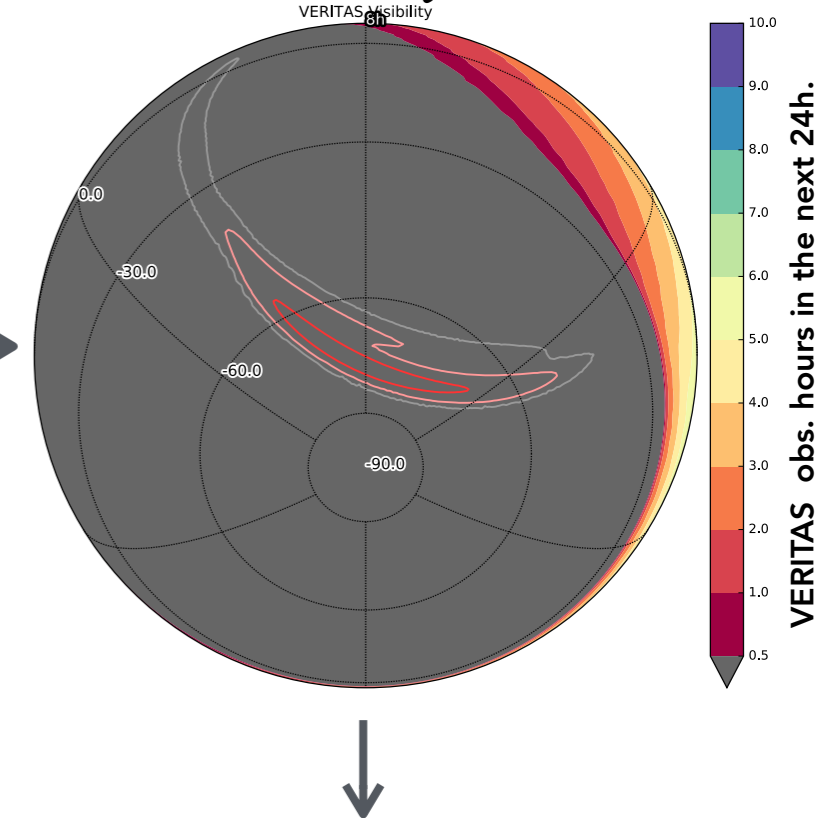


From M. Santander

*50% CL, 1.83° avg spacing*



*Visibility*



*Pointing list*

ra:	112.5	dec:	-72.39	prob:	0.073
ra:	135.0	dec:	-69.42	prob:	0.067
ra:	140.6	dec:	-66.44	prob:	0.067
ra:	145.0	dec:	-63.45	prob:	0.059
...					

- Parse alert and download map.
- Tile with 5 minutes on-target per pointing (Westward pointings are observed first).
- (under ideal conditions) sensitive to 0.5 Crab source ( $E > 100$  GeV).

GCN circular 21153: VERITAS obs. of LIGO/Virgo G268556





# Summary

VERITAS is going strong

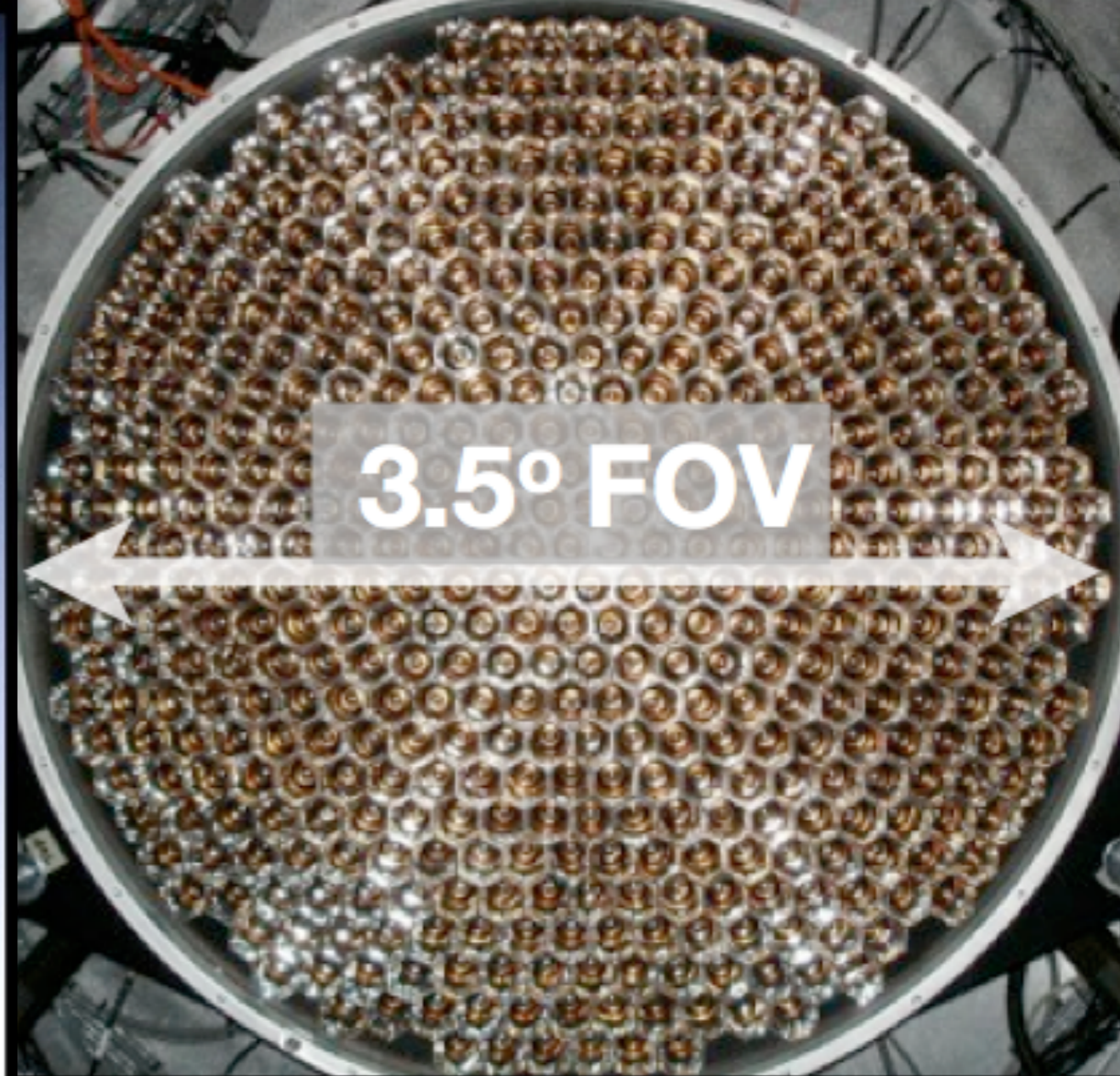
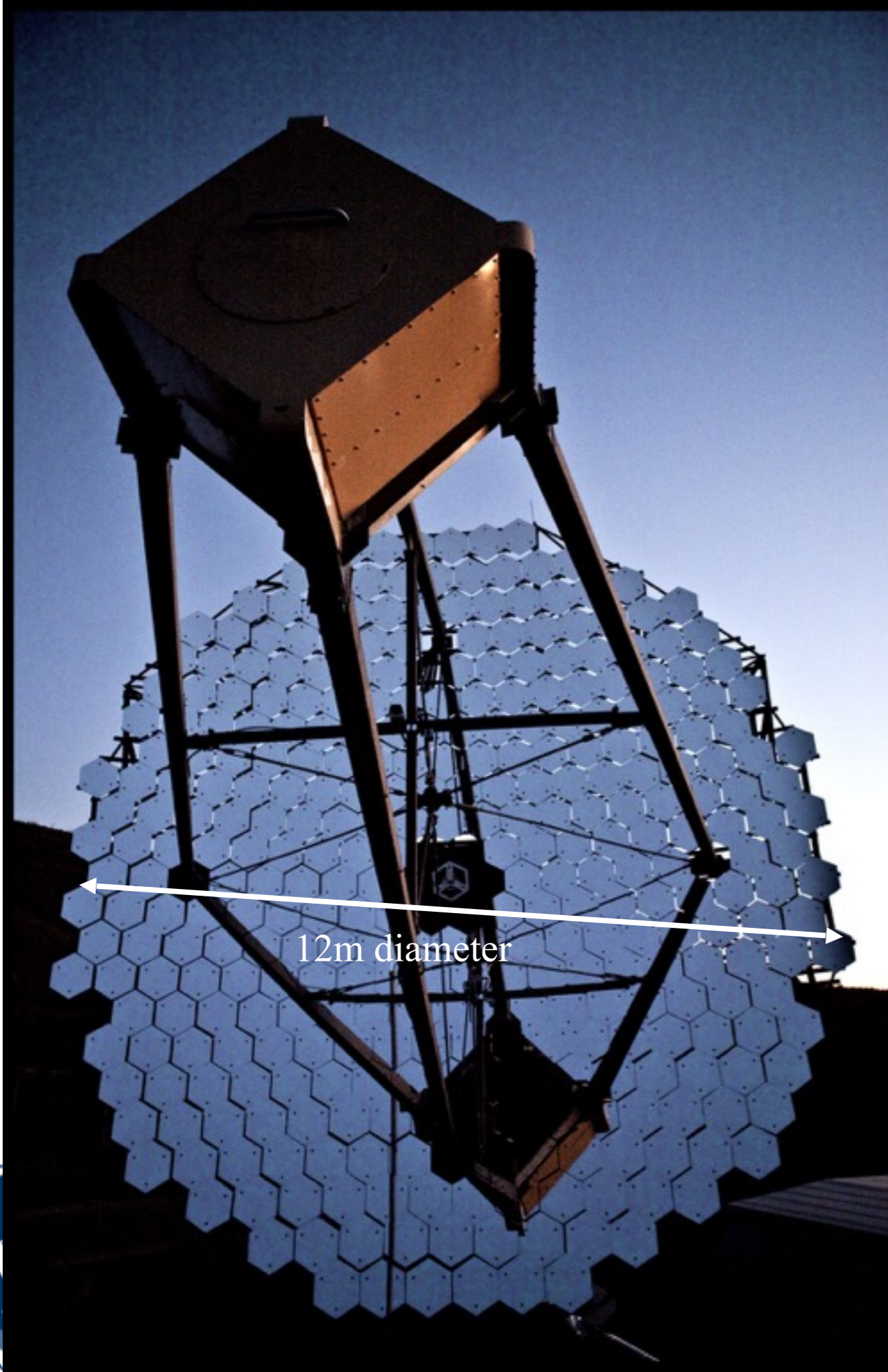
- Galactic, Extragalactic & Astroparticle programs
- Active multiwavelength & multimessenger programs
- Large archive of data



# Extras



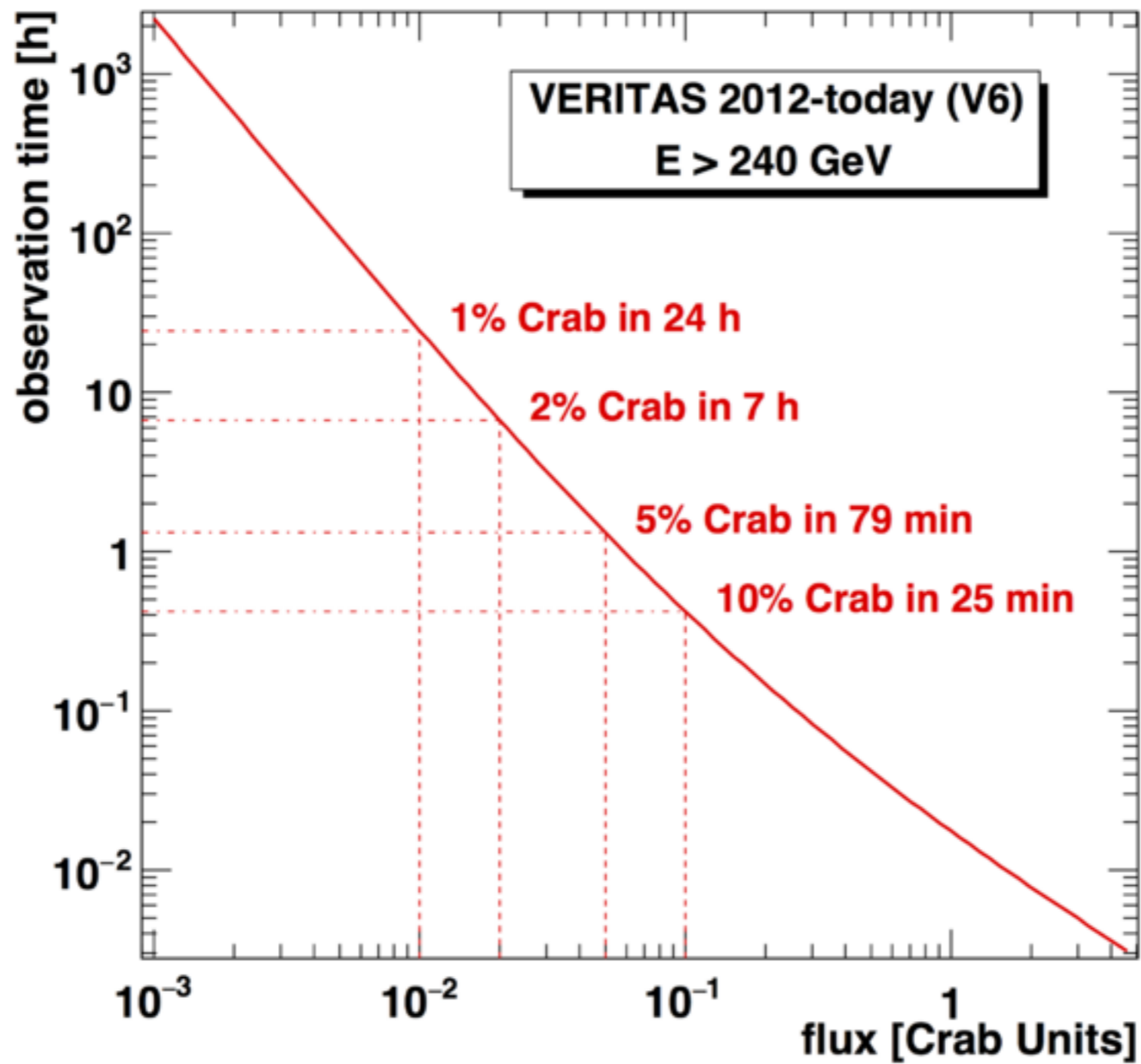




499 pixel camera  
each image exposure is few nanoseconds

~100m<sup>2</sup> mirror area  
from 345 individual adjustable glass facets

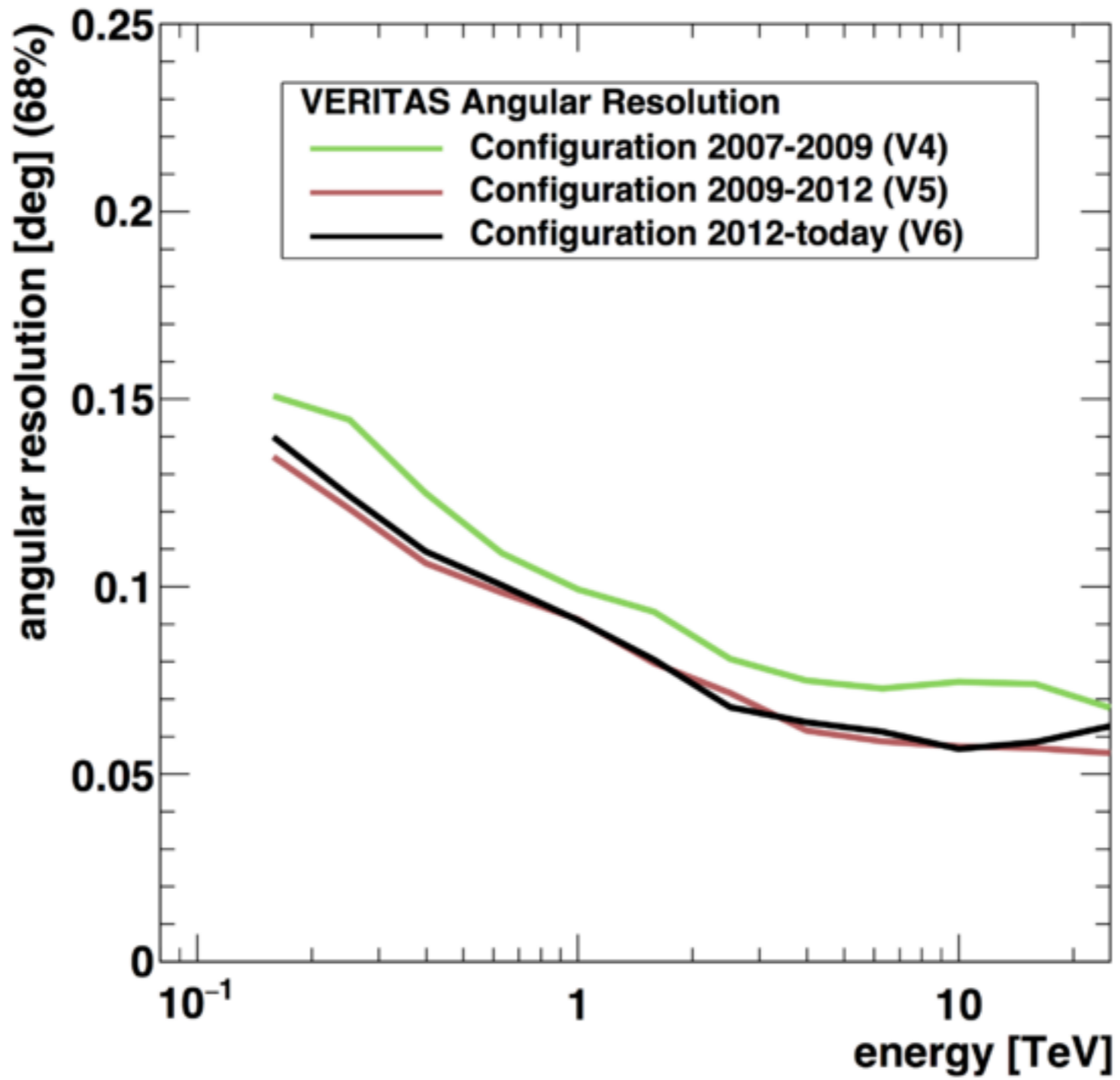




After 2012 PMT upgrade

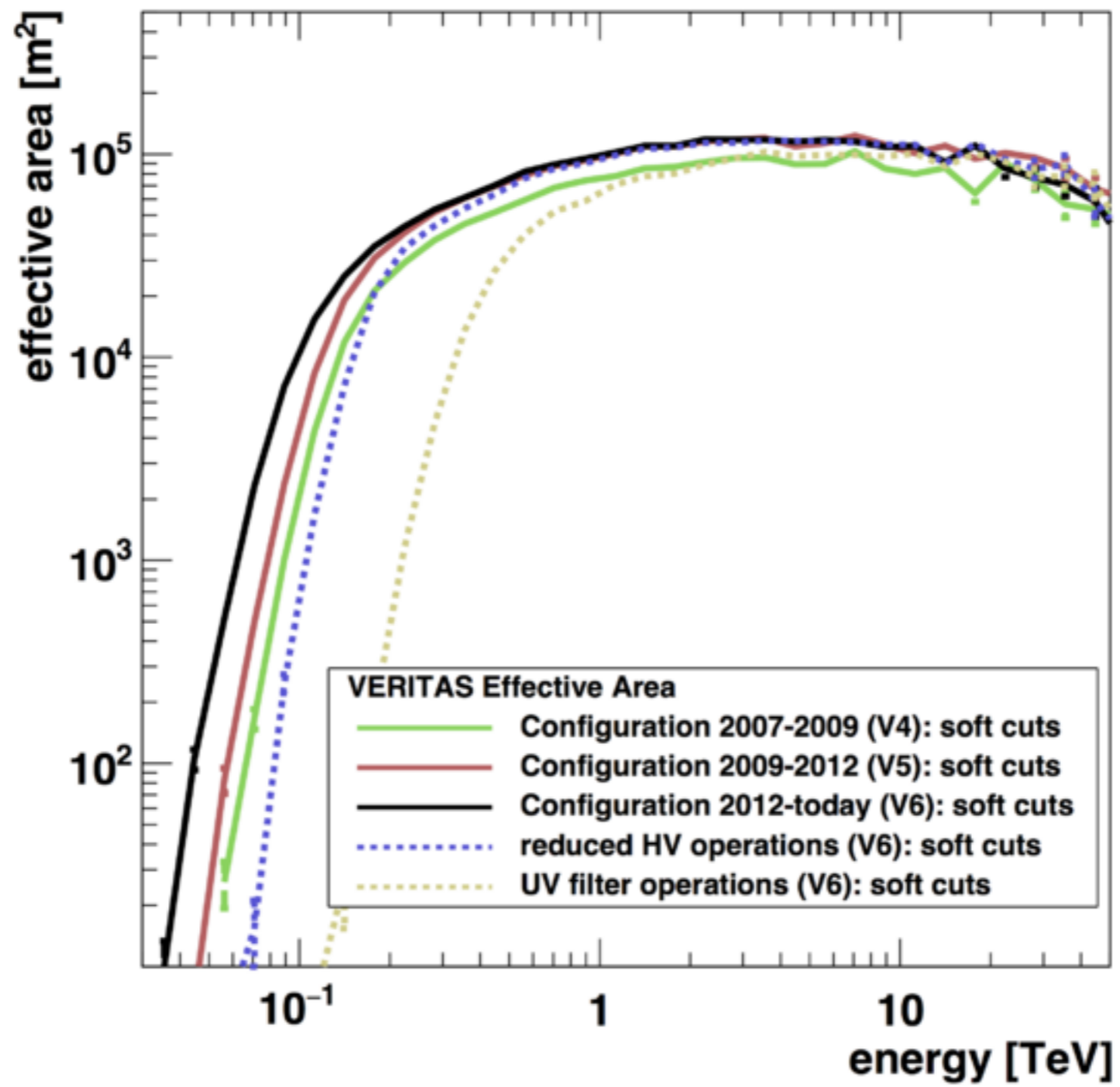






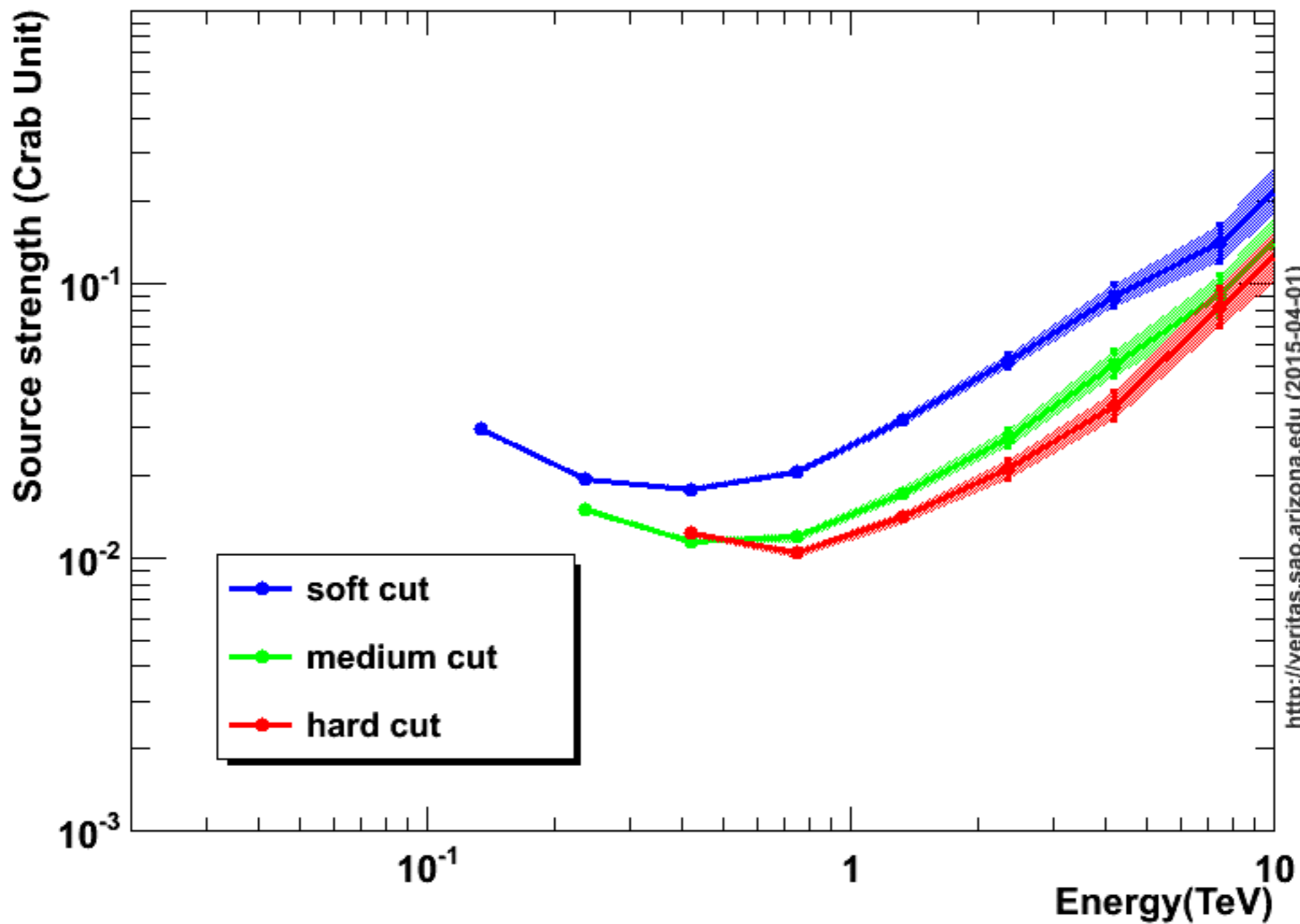
<http://veritas.sao.arizona.edu> (2015-02-09)







50 hours of exposure time with VERITAS 2012-today (V6)



<http://veritas.sao.arizona.edu> (2015-04-01)

