



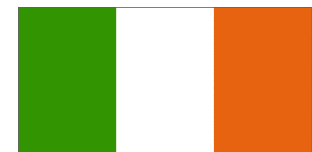
Recent Science Highlights from VERITAS



John Quinn
University College Dublin
& on behalf of the VERITAS Collaboration



The VERITAS Collaboration



- | | | |
|--|---|--|
| <ul style="list-style-type: none"> • ~100 members, 20 institutions <ul style="list-style-type: none"> • 24 non-affiliated members • +35 associate members • Managing Organization: Smithsonian Astrophysical Observatory • Adler Planetarium • Argonne National Lab • Barnard College / Columbia University | <ul style="list-style-type: none"> • Bartol Research Institute / University of Delaware • Georgia Institute of Technology • Iowa State University • Purdue University • University of California, Los Angeles • University of California, Santa Cruz • University of Chicago • University of Iowa | <ul style="list-style-type: none"> • University of Minnesota • University of Utah • Washington University in St. Louis • McGill University, Montreal • University College Dublin • Cork Institute of Technology • Galway-Mayo Institute of Technology • National University of Ireland, Galway |
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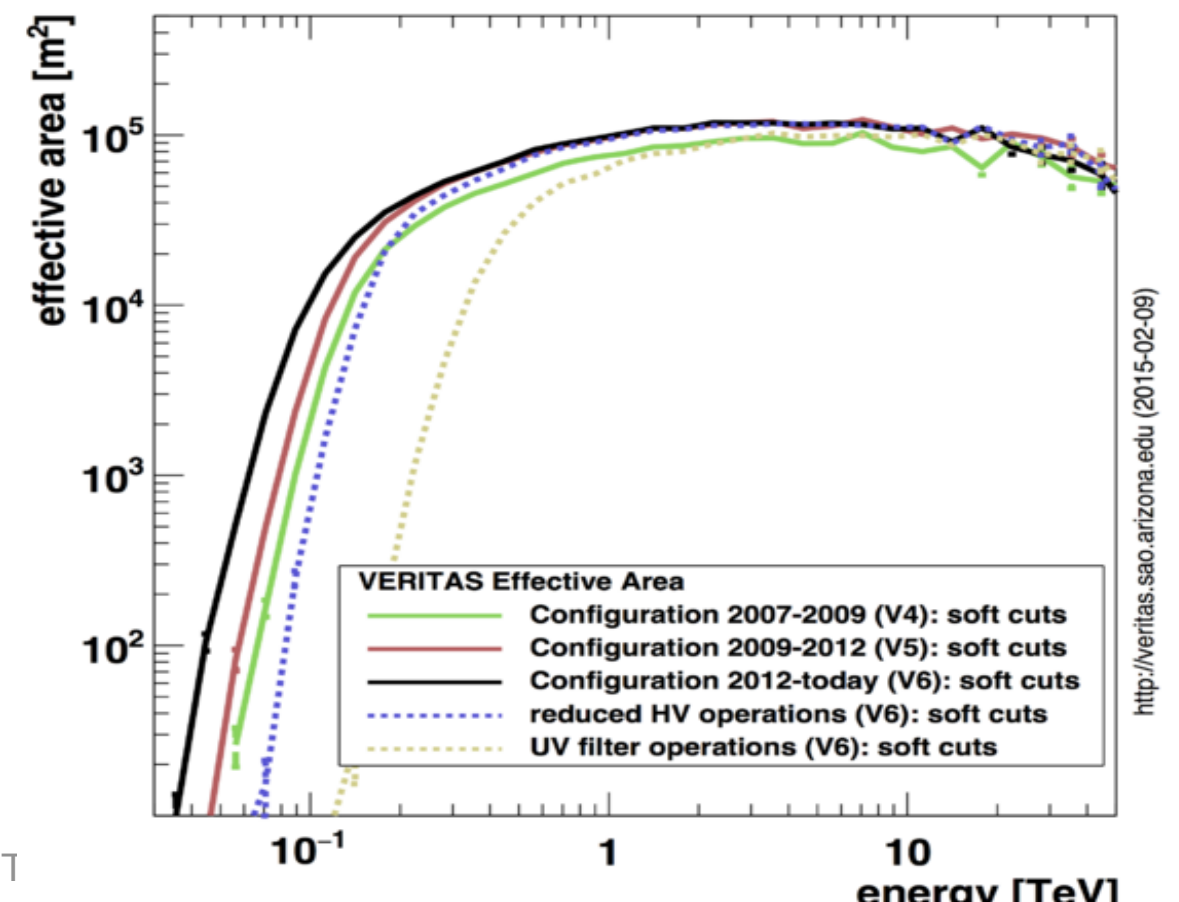
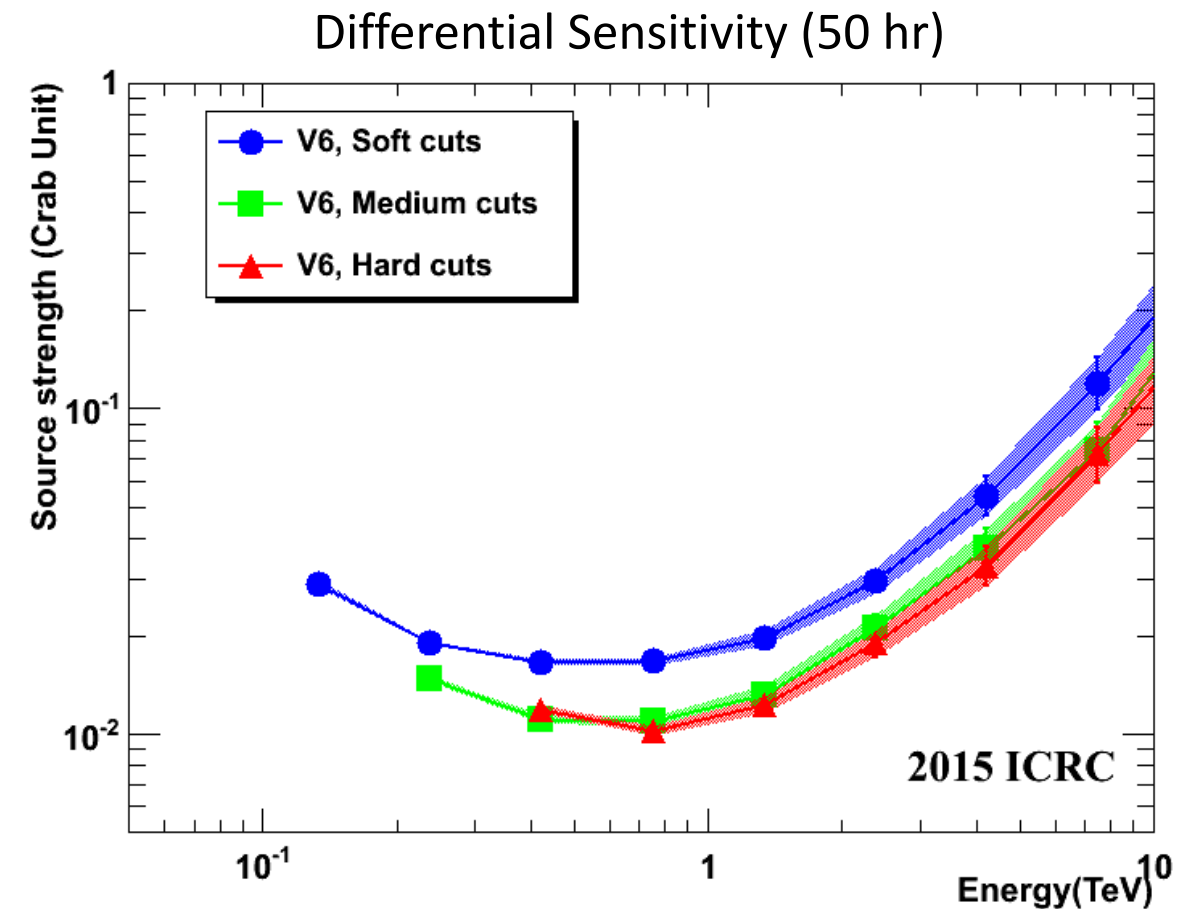
Acknowledgments: This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, and by NSERC in Canada. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument. The VERITAS Collaboration is grateful to Trevor Weekes for his seminal contributions and leadership in the field of VHE gamma-ray astrophysics, which made this study possible.

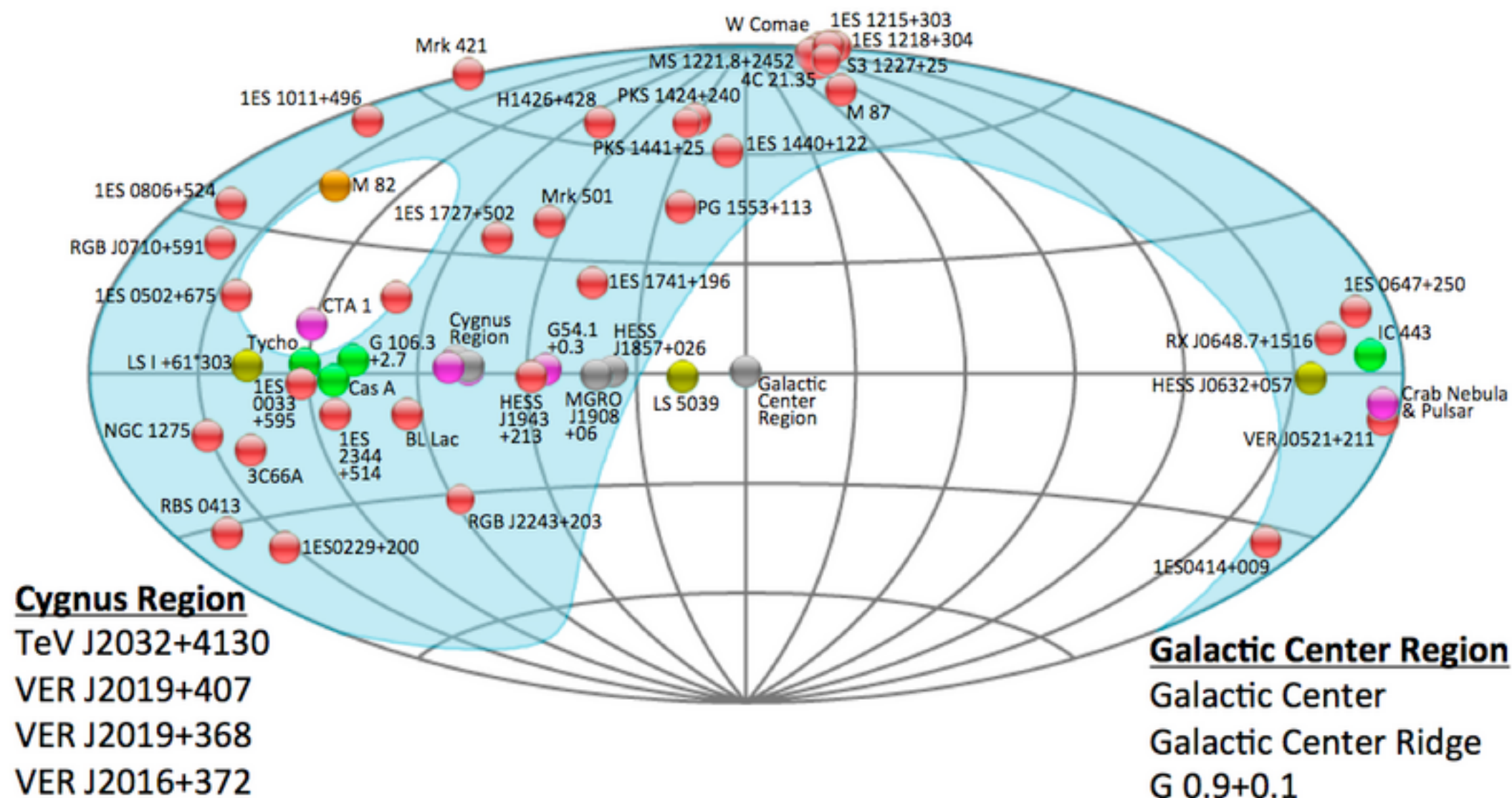
- Entered full scientific operation in 2007 with four-telescope array.
- Funding is in place to operate through 2017, with an application to support operations through 2019 submitted.
- Two major upgrades in 2009 and 2012
- Bright Moonlight: reduced-HV and UV filter operations: ~ 1000 dark + ~ 300 bright moon hours of observation per year.

VERITAS Current Performance

Energy Range:	85 GeV - 30 TeV
Energy Resolution	15 - 25%
Angular Resolution	$< 0.1^\circ$ at 1 TeV
Pointing Accuracy	$< 50''$
Effective Area	$\sim 10^5 \text{ m}^2$ at 1 TeV

Can detect 1% Crab source in 25 hrs





55 sources from 8 astrophysical classes

Extragalactic: 35

- 32 blazars, 2 radio galaxies
- 1 starburst galaxy

Galactic: 20

- 7 PWN, Crab Pulsar
- 3 SNRs
- 3 binaries
- 6 Unid.

Scientific Objectives:

- Supermassive black holes, jet structure and dynamics
- Cosmology: EBL & IGMF studies
- Fundamental Physics: Lorentz Invariance

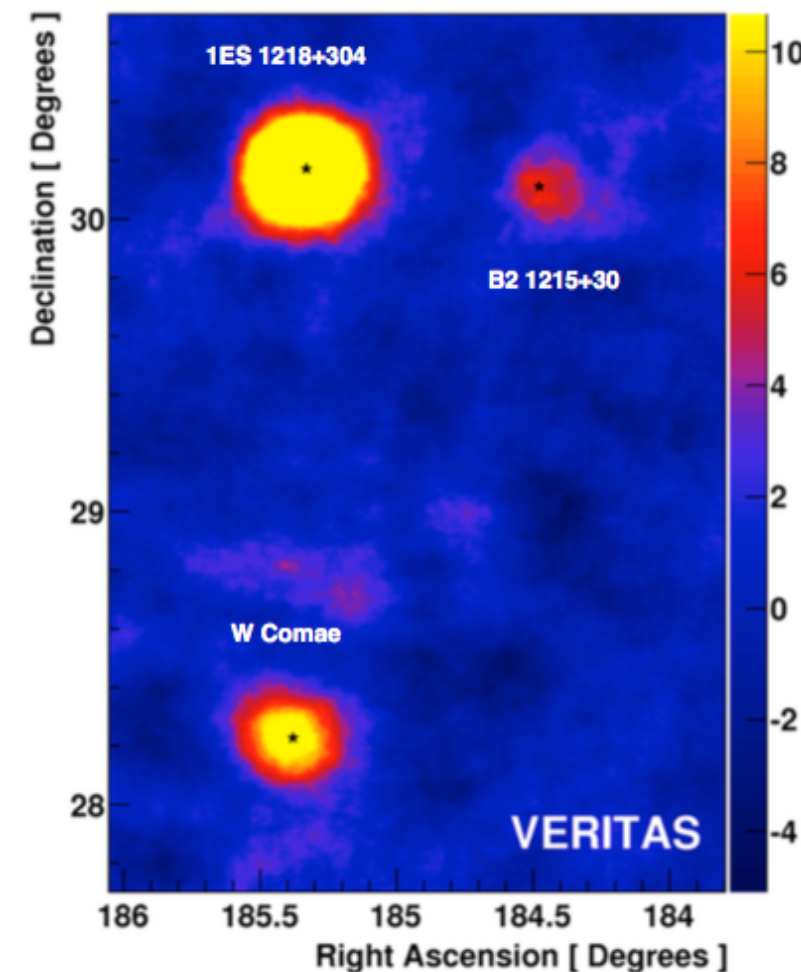
Strategy:

- Discovery
- ToO
- Monitoring & Deep Exposures
- Simultaneous MWL observations.

Catalogue: 34 VHE AGN:

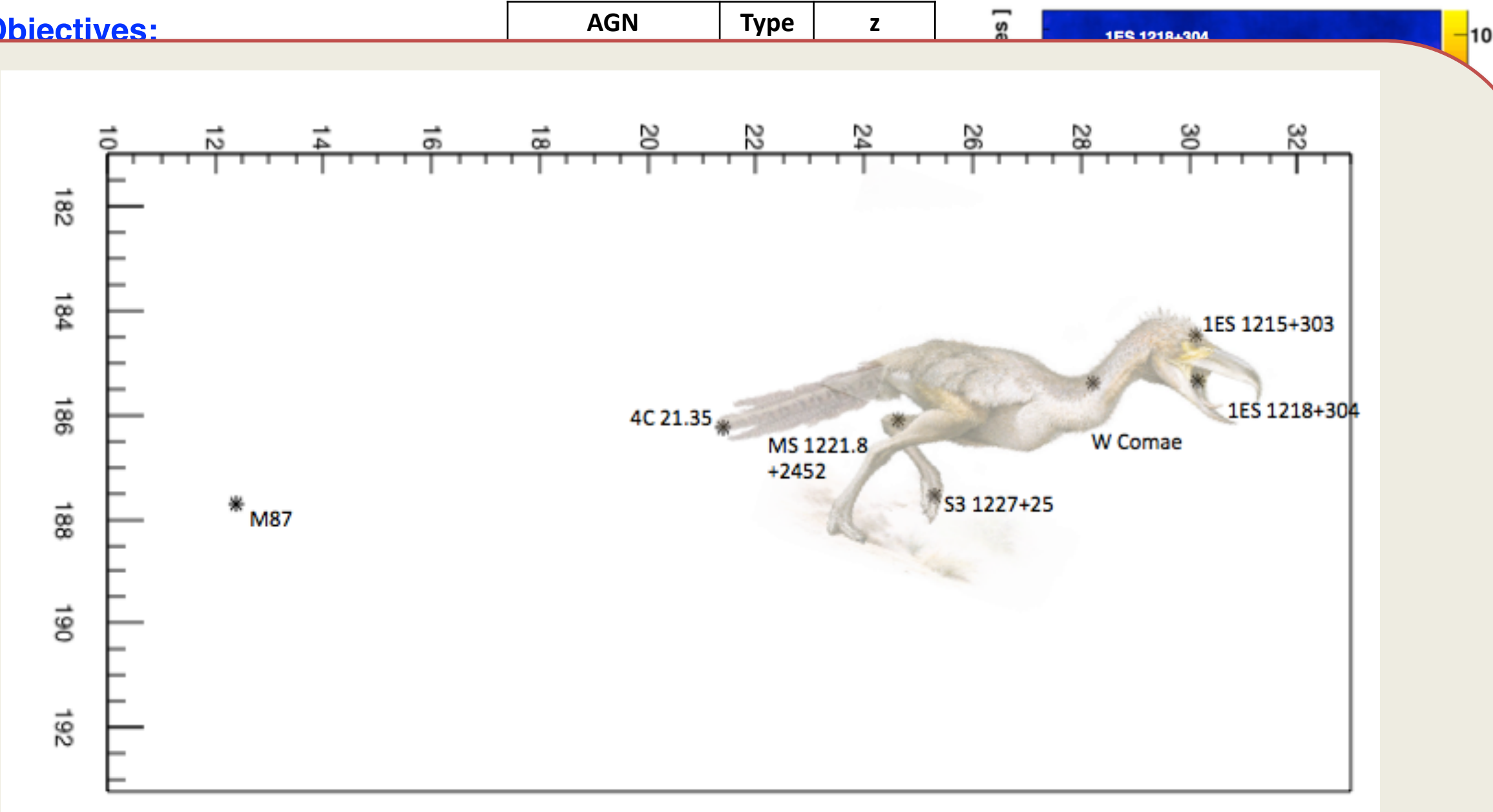
- 23 HBL, 7 IBL, 2 FSRQ, 2 FR I
- **2013-2014:** 1ES 0033+595, MS 1228.8+2452, PKS 1222+216, HESS J1943+213
- **2014-2015:** S3 1227+25, PKS 1441+25, RBG J2243+203

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
Mkn 421	HBL	0.03
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	IBL	0.069
1ES 1741+196	HBL	0.084
W Comae	IBL	0.102
VER J0521+211	HBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
S3 1227+25	IBL	0.135
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.19
1ES 1011+496	HBL	0.212
MS 1221.8+2452	HBL	0.218
1ES 0414+009	HBL	0.287
PKS 1222+216	FSRQ	0.432
PKS 1441+25	FSRQ	0.939



AGN	Type	z
3C 66A	IBL	$0.33 < z < 0.41$
PKS 1424+240	IBL	>0.604
PG 1553+113	HBL	$0.43 < z < 0.58$
1ES 0033+595	HBL	?
1ES 0502+675	HBL	?
1ES 0647+250	HBL	?
B2 1215+30	IBL	?
HESS J1943+213	HBL	?
RGB J2243+203	IBL	?

Scientific Objectives:



The first VHE constellation?! Introducing Tera-bird (credit Jamie Holder)

1ES 0414+009	HL	0.287	B2 1215+30	IBL	?
PKS 1222+216	FSRQ	0.432	HESS J1943+213	HL	?
PKS 1441+25	FSRQ	0.939	RGB J2243+203	IBL	?

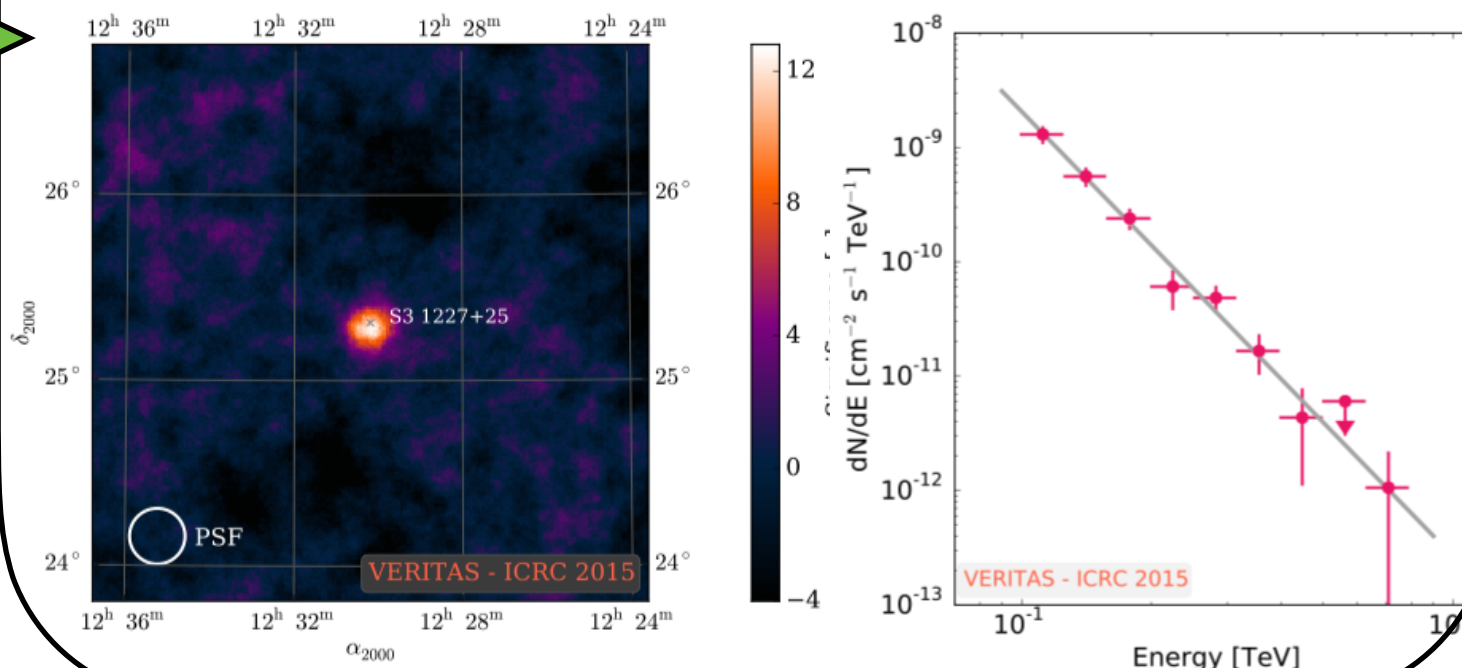
The Astronomer's Telegram

Recent VERITAS Blazar ATELS

8148	VERITAS observation of a bright very-high-energy gamma-ray flare from 1ES 1959+650	Reshmi Mukherjee for the VERITAS Collaboration 10 Oct 2015; 01:21 UT
7516	VERITAS Detection of Very High-Energy Gamma-Ray Emission from S3 1227+25	Reshmi Mukherjee 16 May 2015; 21:46 UT
7433	Very-high-energy gamma-ray emission from PKS 1441+25 detected with VERITAS	Reshmi Mukherjee 23 Apr 2015; 03:37 UT
6849	VERITAS Discovery of Very High-Energy Gamma-Ray Emission from RGB J2243+203	Jamie Holder 24 Dec 2014; 23:09 UT
5981	Detection of Persistent VHE emission from PKS 1222+216 (4C +21.35) with VERITAS	J. Holder for the VERITAS Collaboration 14 Mar 2014; 18:34 UT

Discovery of VHE Emission from S3 1227+25

- *Fermi*-LAT-detected LBL/IBL @ $z=0.135$
- Unlikely VHE source: $\Gamma_{3\text{FGL}} \sim 2.2$ $\Gamma_{1\text{FHL}} \sim 3.3$; $F(>10 \text{ GeV}) \sim 1\% \text{ Crab!}$
- May 2015: LAT 40x flare, $\Gamma_{\text{LAT}} \sim 1.9$
- VERITAS: 13σ in 6 h (3 nights) $\Gamma_{\text{VERITAS}} \sim 3.89 \pm 0.24$



Discovery of VHE Emission from RGB J2243+203

- *Fermi*-LAT-detected LBL/IBL @ $z>0.39$
- $\Gamma_{2\text{FGL}} \sim 1.75$ $\Gamma_{1\text{FHL}} \sim 2.4$;
- VERITAS LAT-monitor trigger: 20 Dec. 2014 (Sub-LAT-Team threshold)
- VERITAS: 6σ in 6 h (3 nights) $\Gamma_{\text{VERITAS}} \sim 4.64 \pm 0.55$

Yesterday: [Joint Fermi / VERITAS / MAGIC press release.....](#)

<http://www.nasa.gov/feature/goddard/nasas-fermi-satellite-kicks-off-a-blazar-detecting-bonanza>

Fermi Space Telescope

Dec. 15, 2015

NASA's Fermi Satellite Kicks Off a Blazar-detecting Bonanza



A long time ago in a galaxy half the universe away, a flood of high-energy gamma rays began its journey to Earth. When they arrived in April, NASA's Fermi Gamma-ray Space Telescope caught the outburst, which helped two ground-based gamma-ray observatories detect some of the highest-energy light ever seen from a galaxy so distant. The observations provide a surprising look into the environment near a supermassive black hole at the galaxy's center and offer a glimpse into the state of the cosmos 7 billion years ago.



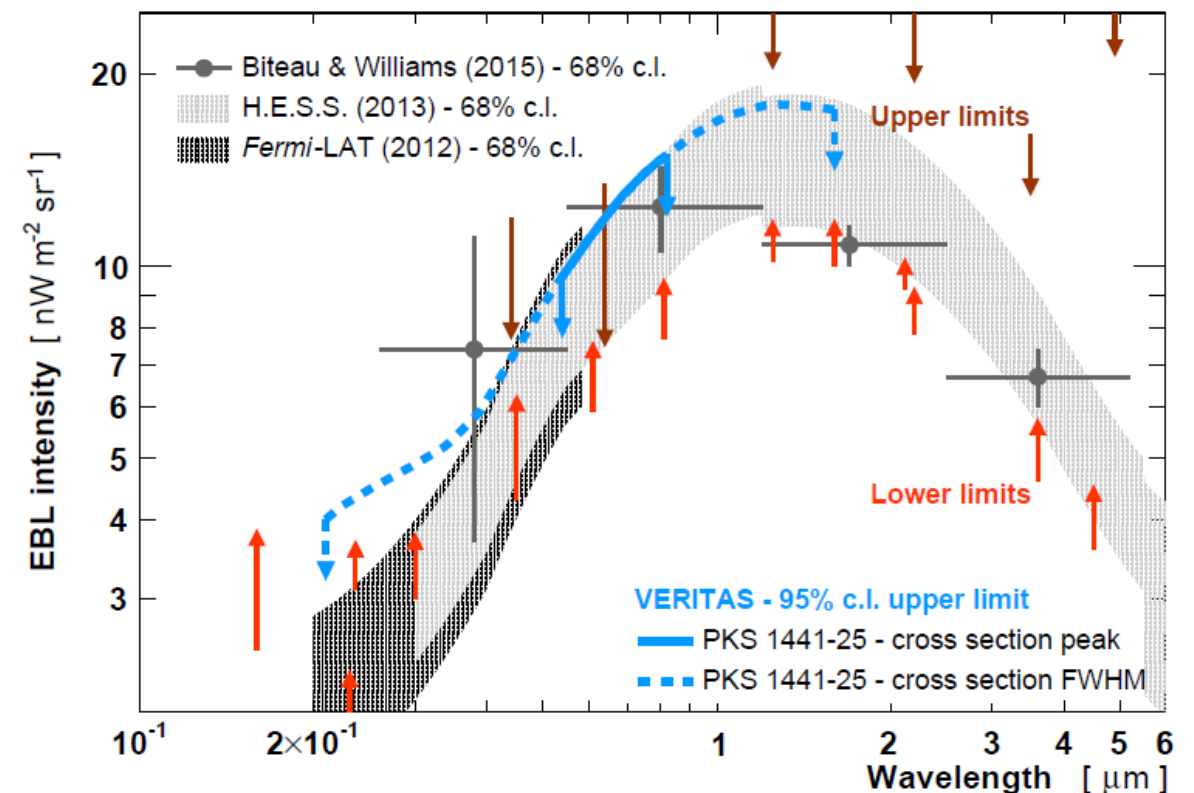
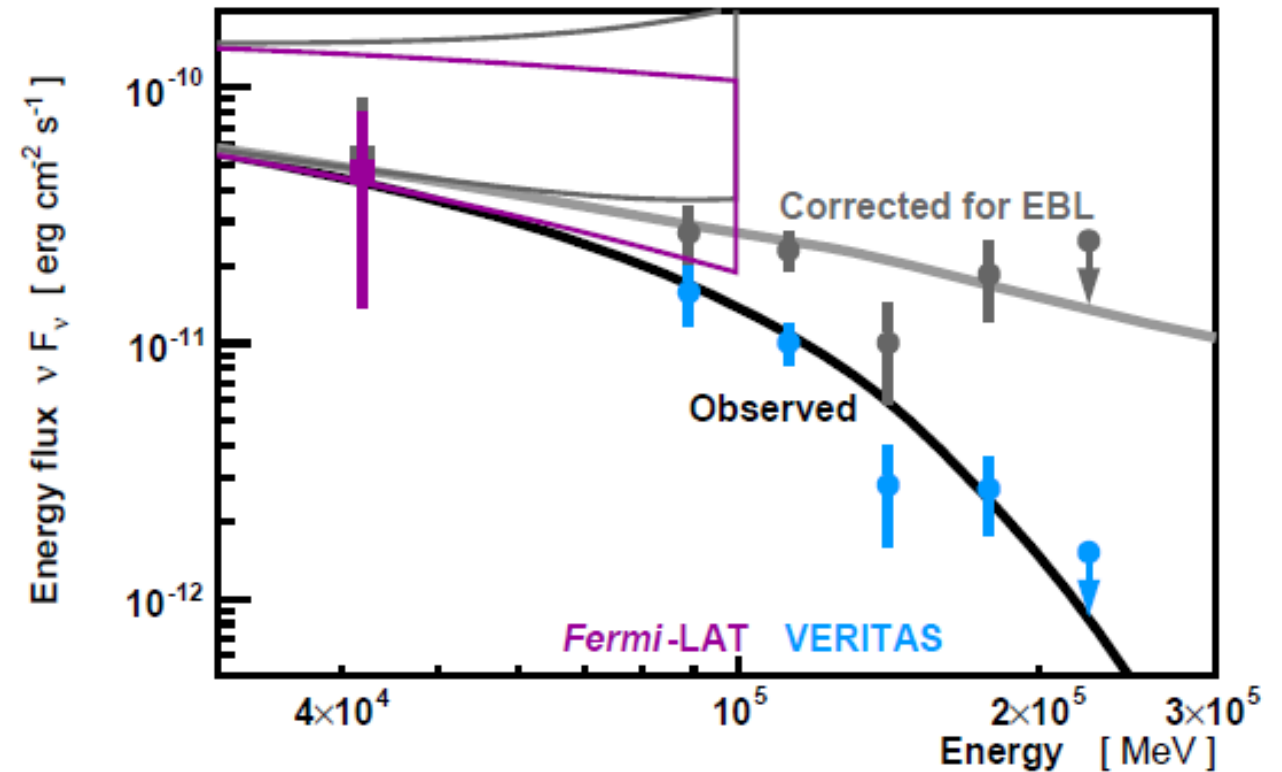
Published yesterday in ApJ: <http://iopscience.iop.org/article/10.1088/2041-8205/815/2/L22> arXiv:1512.04434

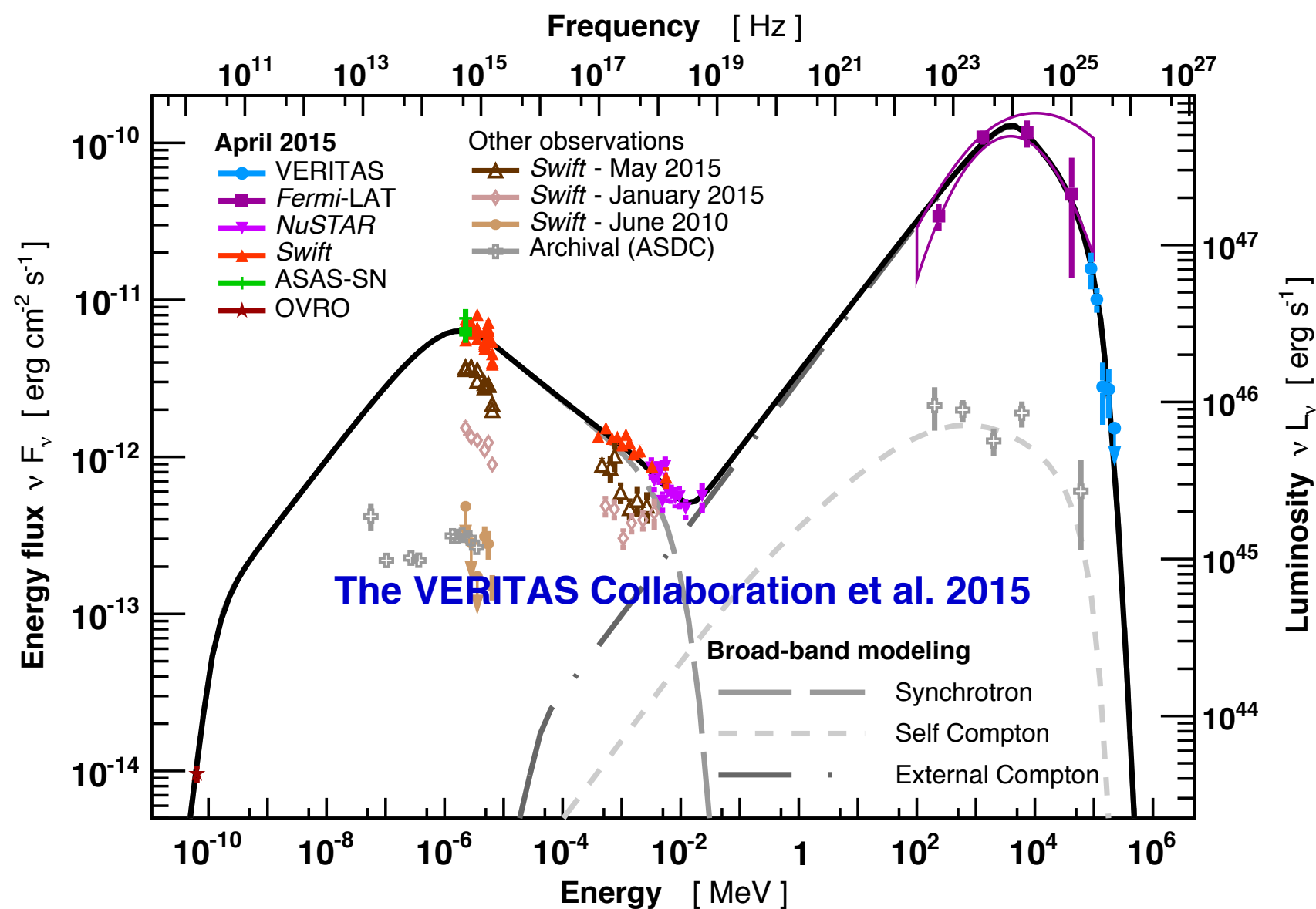
- (Joint) most-distant VHE FSRQ at $z=0.94$
- 2nd VERITAS FSRQ
- **ToO in April 2015**

- Triggered by *Fermi*-LAT and MAGIC
- VERITAS:
 - observed for ~ 1 week, ~ 15 hrs
 - 400 γ rays, 8σ
 - Steady flux (>85 GeV) $\sim 5\%$ Crab
 - $\Gamma_{\text{VHE}} \sim 5.4 \pm 0.5$
 - 4 hrs obs. in May 2015 \rightarrow no signal

• Implications for EBL:

- De-absorbed VERITAS points (Gilmore et al., 2012 'fixed') connect smoothly to *Fermi*-LAT spectrum
- Constrain significant region of EBL SED from just one source - suggesting galaxy surveys have resolved most if not all of EBL at probed wavelengths.
- Despite $z \sim 1$ it is not impossible to detect sources with E up to 200 GeV with IACTs.





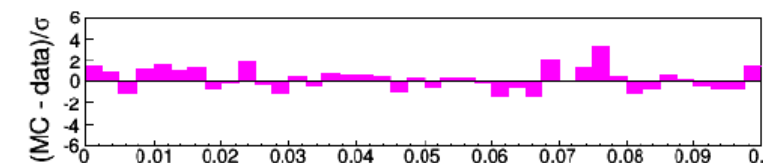
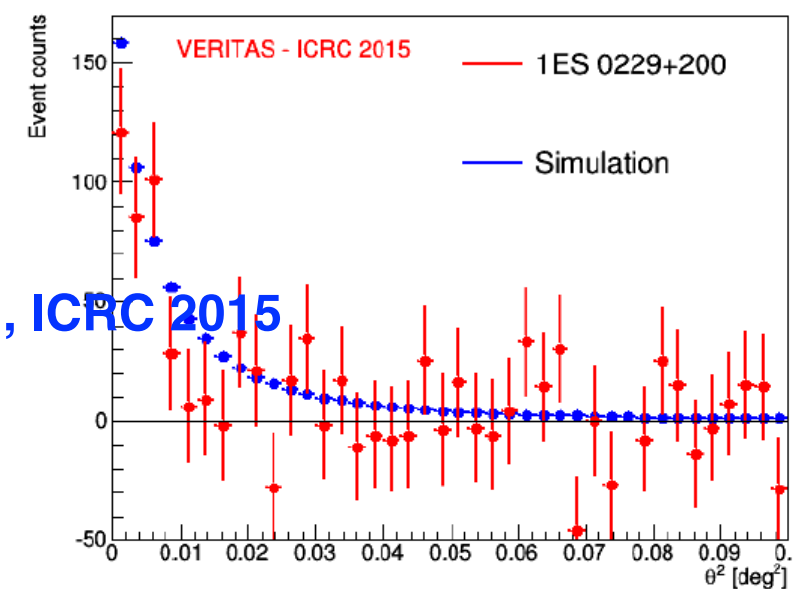
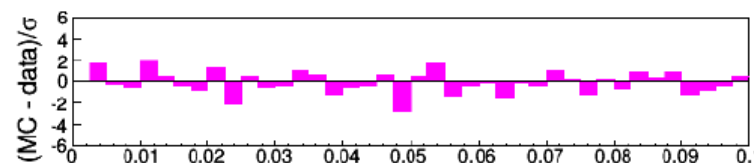
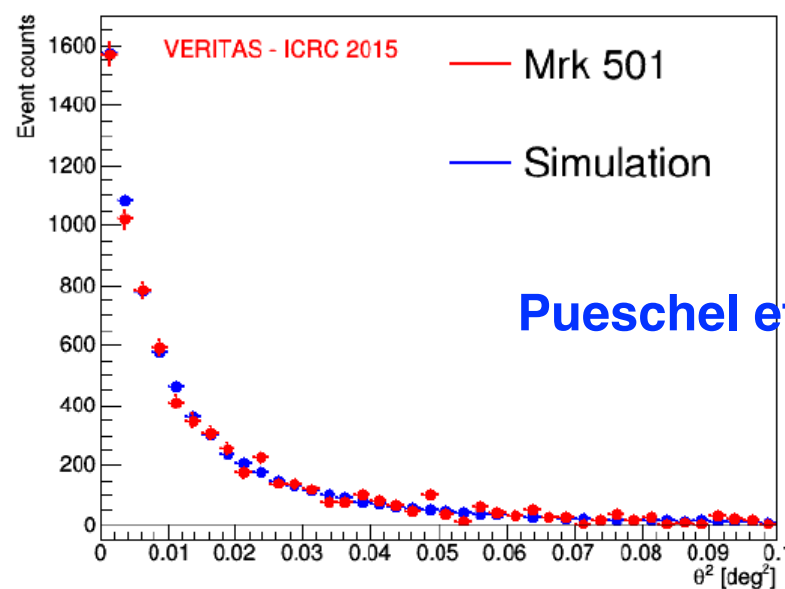
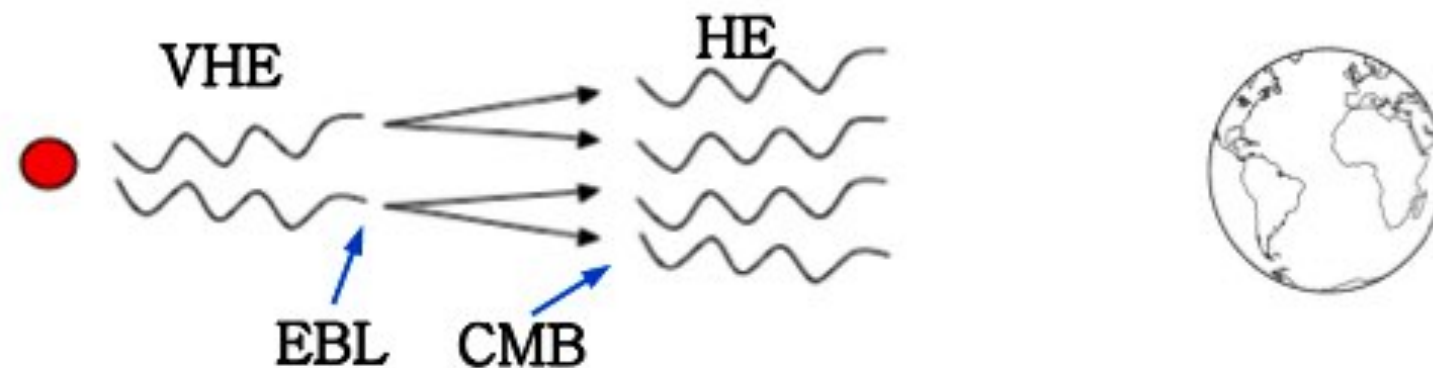
Extensive Multiwavelength Observations & Modeling:

- Radio, Optical, *Fermi*-LAT, **correlated enhanced emission with no delay.**
- VERITAS detection coincident with period of enhanced MWL emission and high polarisation
- X-ray: **Variability timescale < 2 weeks, Synchrotron emission to ~30 keV**
- Gamma-ray **emission** must be **from outside BLR** ($\tau \sim 9$ @ 100 GeV)
- EIC Model: Low doppler factor ($\delta \sim 18$) & close to equipartition → **Large-scale emission far from R_s**

- **Extragalactic Background Light (EBL):** Pueschel talk yesterday.
- **InterGalactic Magnetic Field (IGMF):** search for spatially-extended emission around blazars

- IGMF extremely weak, possibly of primordial origin.
- EBL produces e^+e^- pair which up-scatter CMB photons to high energies
- These secondary particles have their paths deflected by IGMF.
- Search for IGMF-broadened cascade emission

- **7 blazars studied** - profiles compared to simulated instrumental broadening for a point source - **no evidence for extended emission found.**
- Limits set for model-dependent extended emission (model: semi-analytic 3D cascade simulation: Weisgarber, 2012)



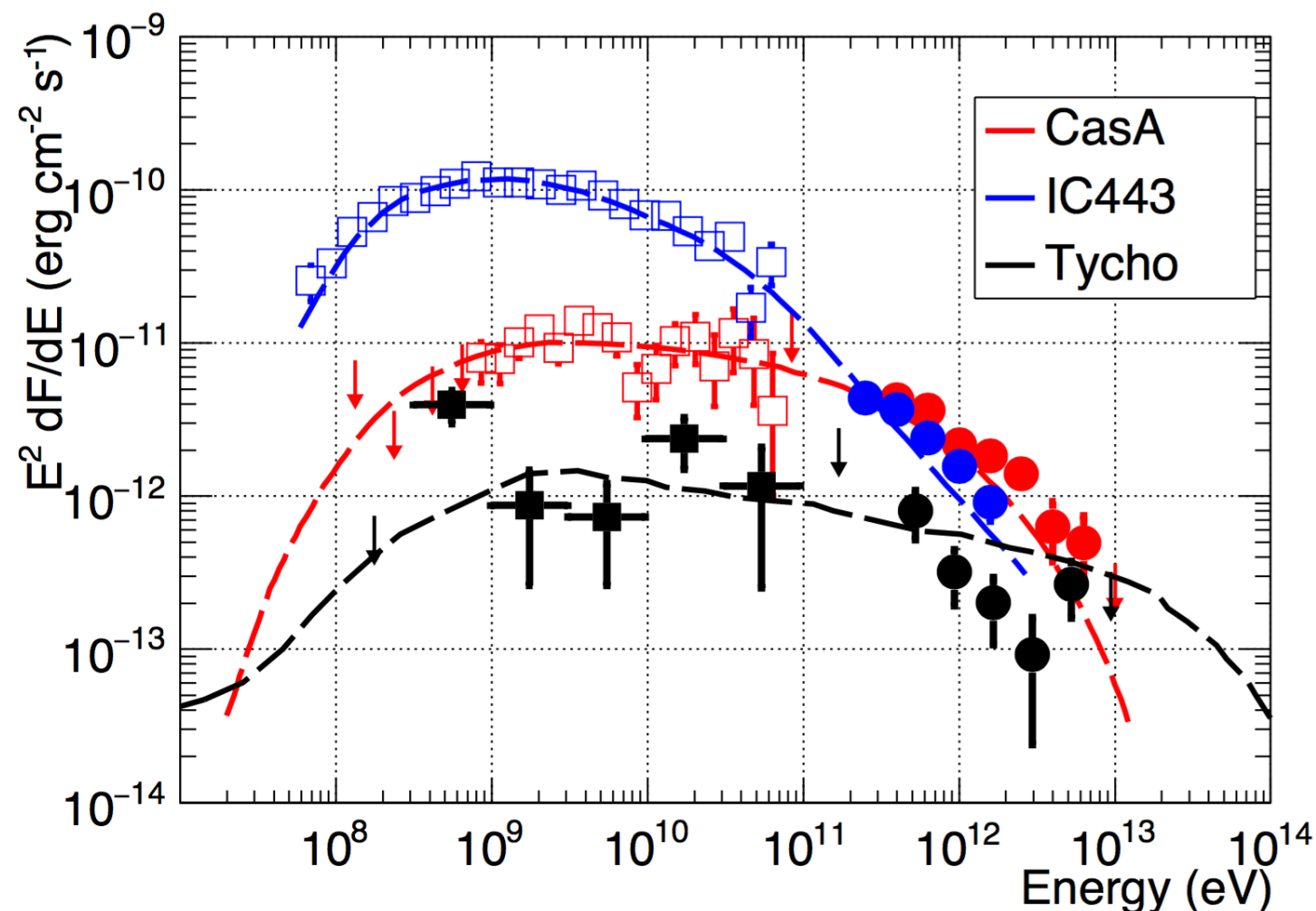
Pueschel et al., ICRC 2015

Model-dependent limits set: exclude IGMF strengths $(5.0-10.0) \times 10^{-15}$ G at 95% CL

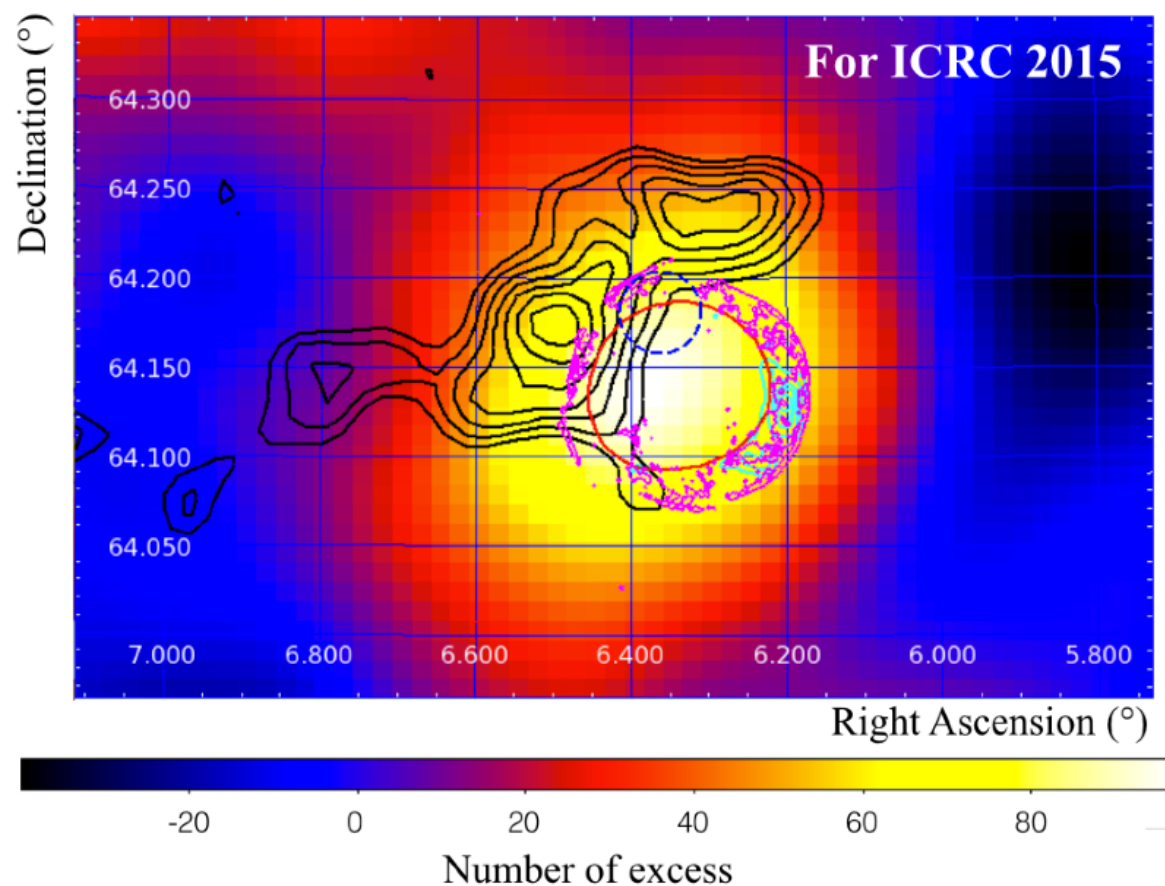
• Deep Exposures of three northern SNRs:

- Investigate the mechanisms of cosmic-ray acceleration
- Probe the distribution of energetic particles in the acceleration region
- Study the importance of SNR type, age, target material, magnetic fields, progenitor

> 150 hours of exposure for IC443 and Tycho

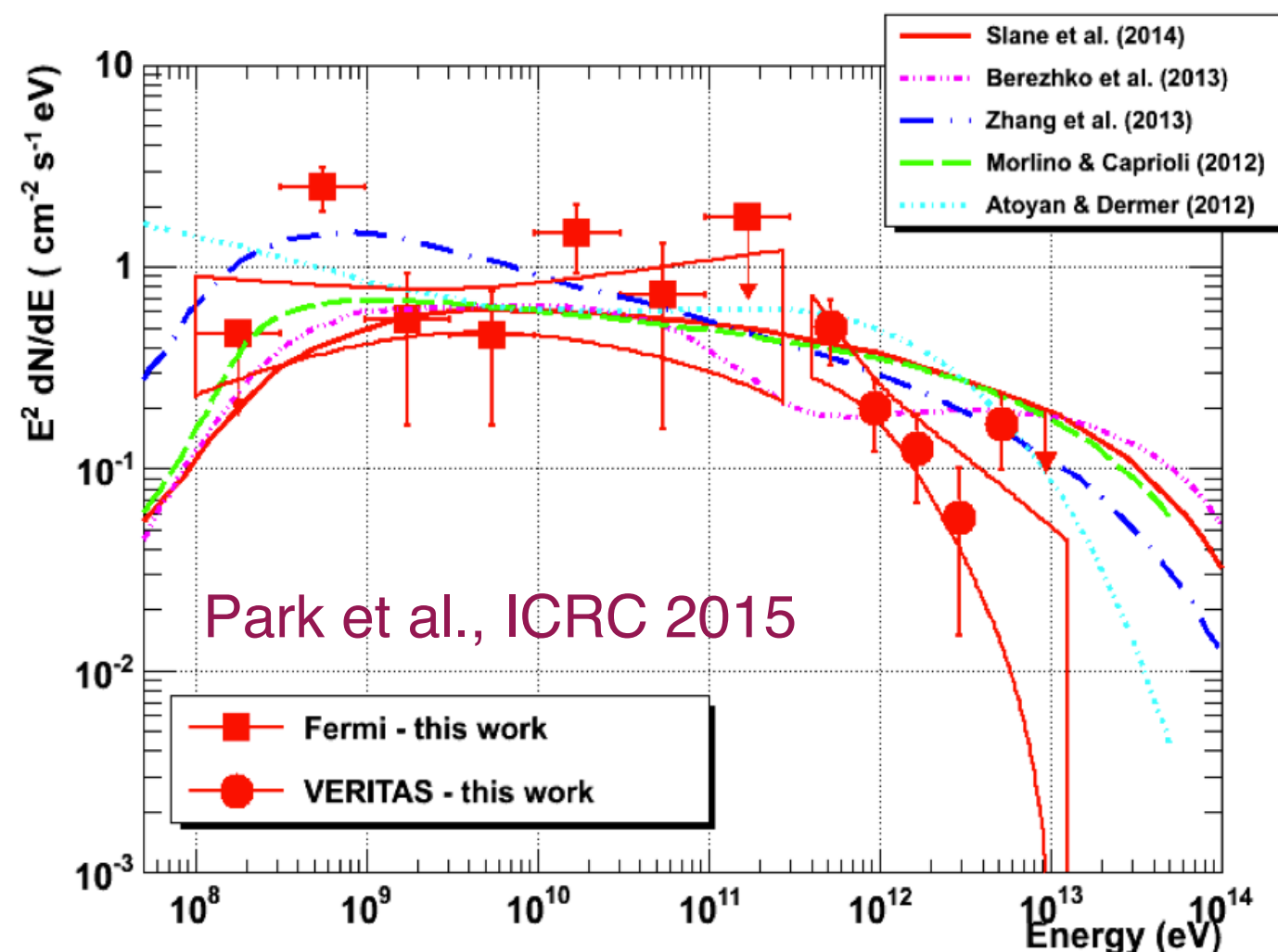


CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)
Tycho model (Slane et al., 2014), Fermi (ICRC 2015), VERITAS (ICRC 2015)



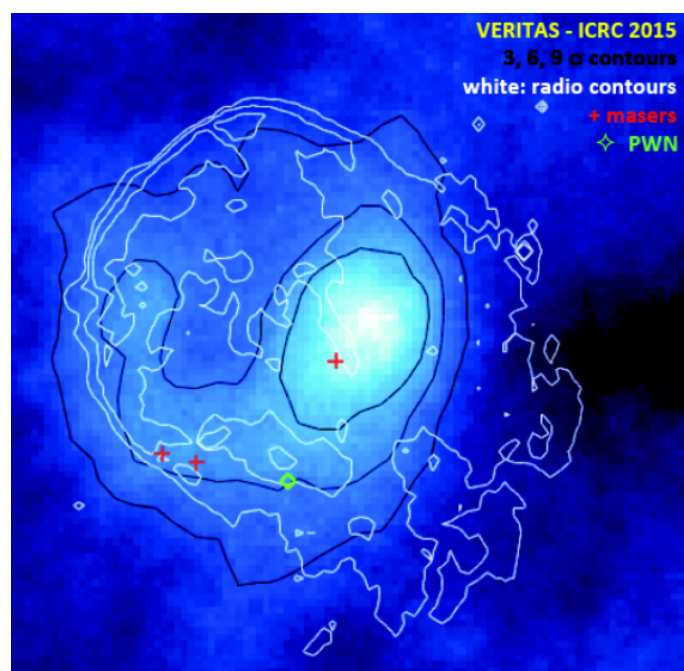
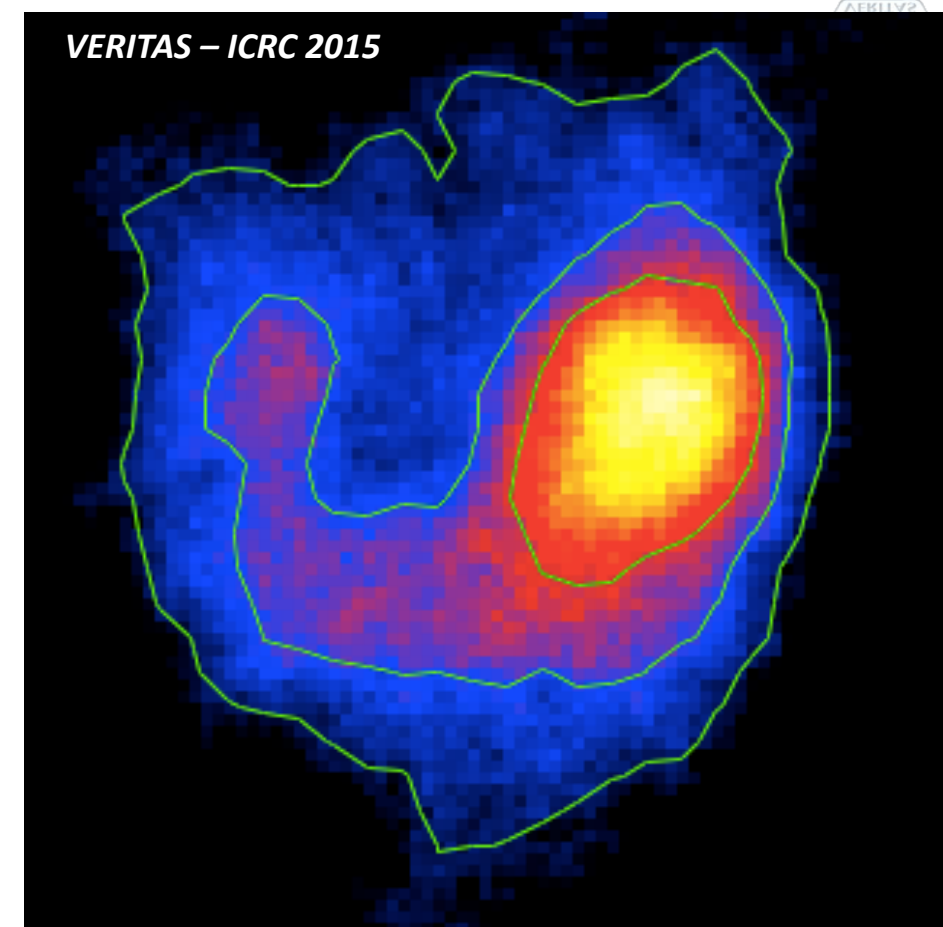
- Good candidate for testing hadronic emission scenarios:
 - exploded in a clean environment
 - young type Ia (1572)
 - well studied at other wavelengths
- Discovered in VHE by VERITAS in 2010 with 67 hrs of data, **we now have ~150 hours**

- Updated VHE spectrum extends to lower energies
- +77 months of *Fermi*-LAT data.
- Latest spectrum constrains and challenges existing particle acceleration models
 - these models mainly of hadronic particles with some multi-zone leptonic

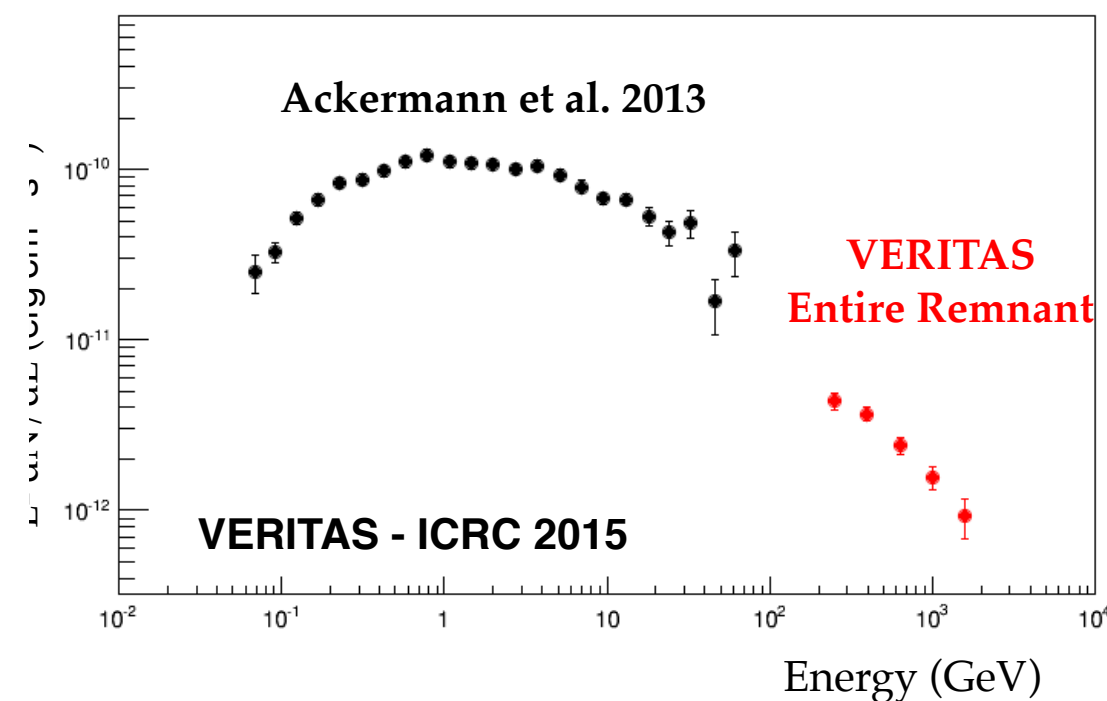
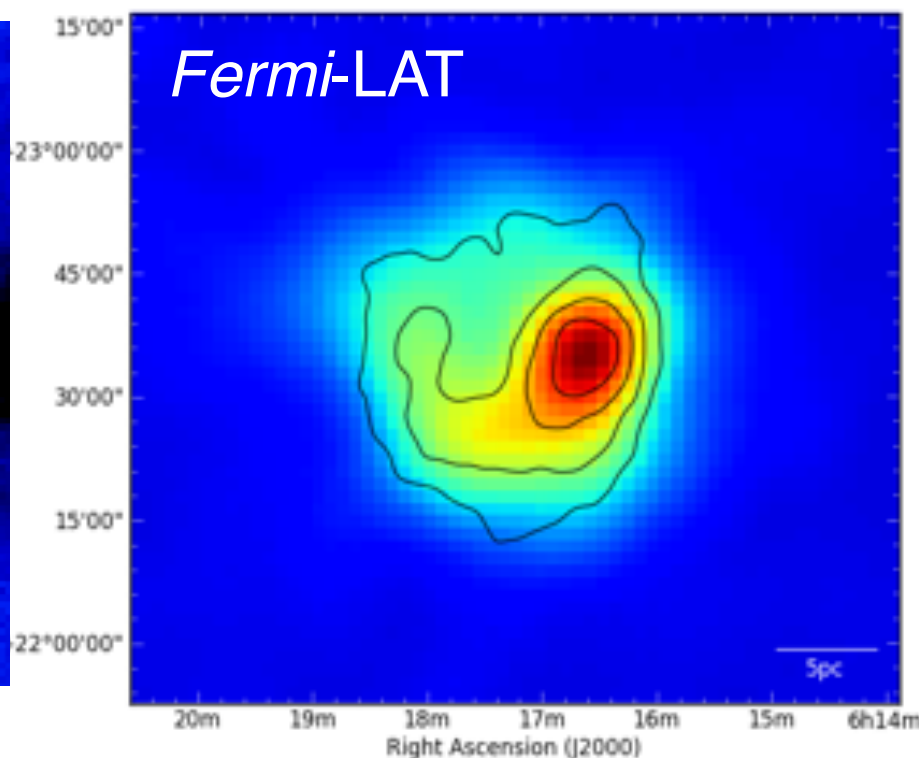


- Core-collapse SNR with Molecular Cloud interaction
- 156 hrs → spatially resolve nebula (0.75° (20 pc) diameter)
- GeV/TeV emission show remarkable spatial correlation
- Strong spatial correlation of γ -ray emission with masers and molecular gas
- Anti-correlation with thermal X-rays
- Can extract spectra from different regions to probe the environmental dependence of cosmic-ray diffusion

A single population of Cosmic Rays interacting with swept-up / shocked gas?

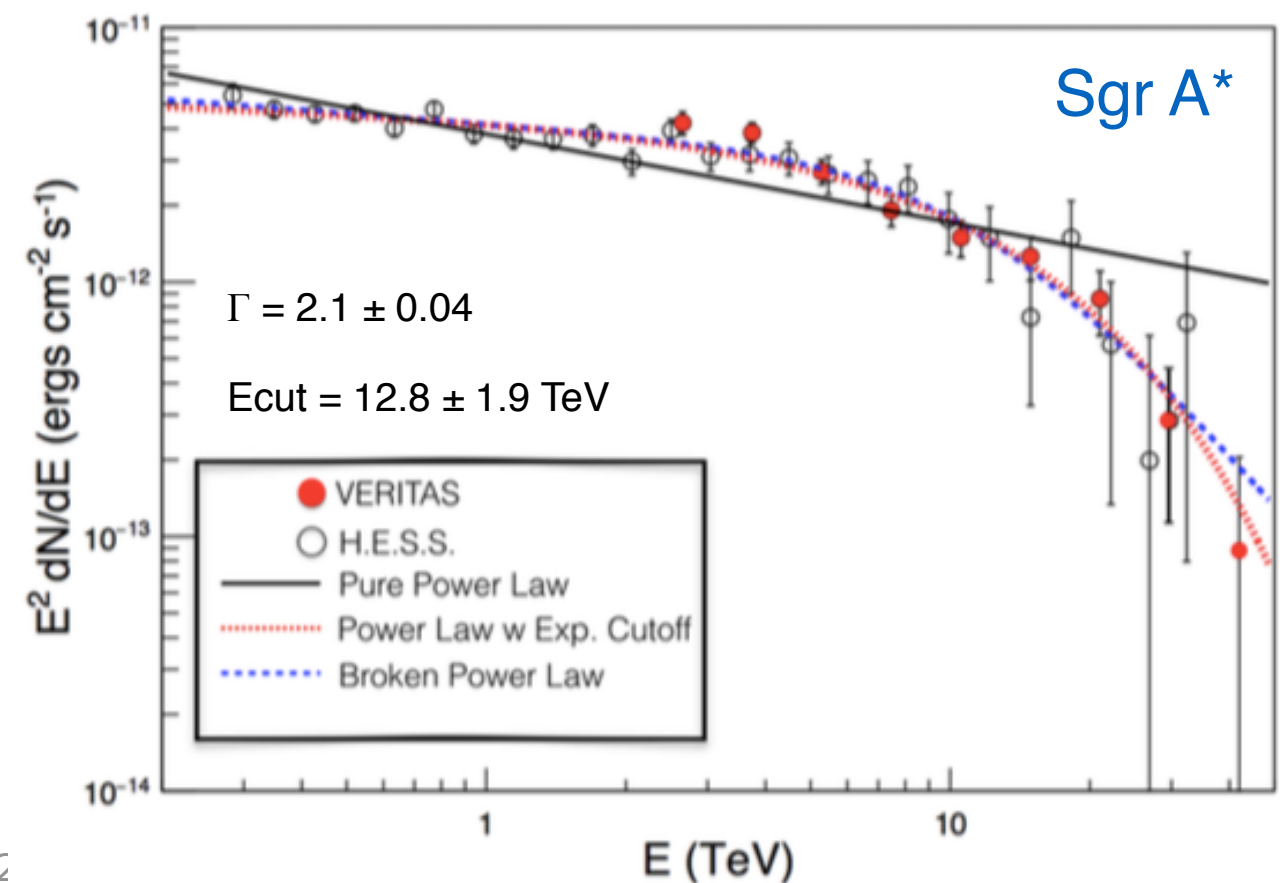
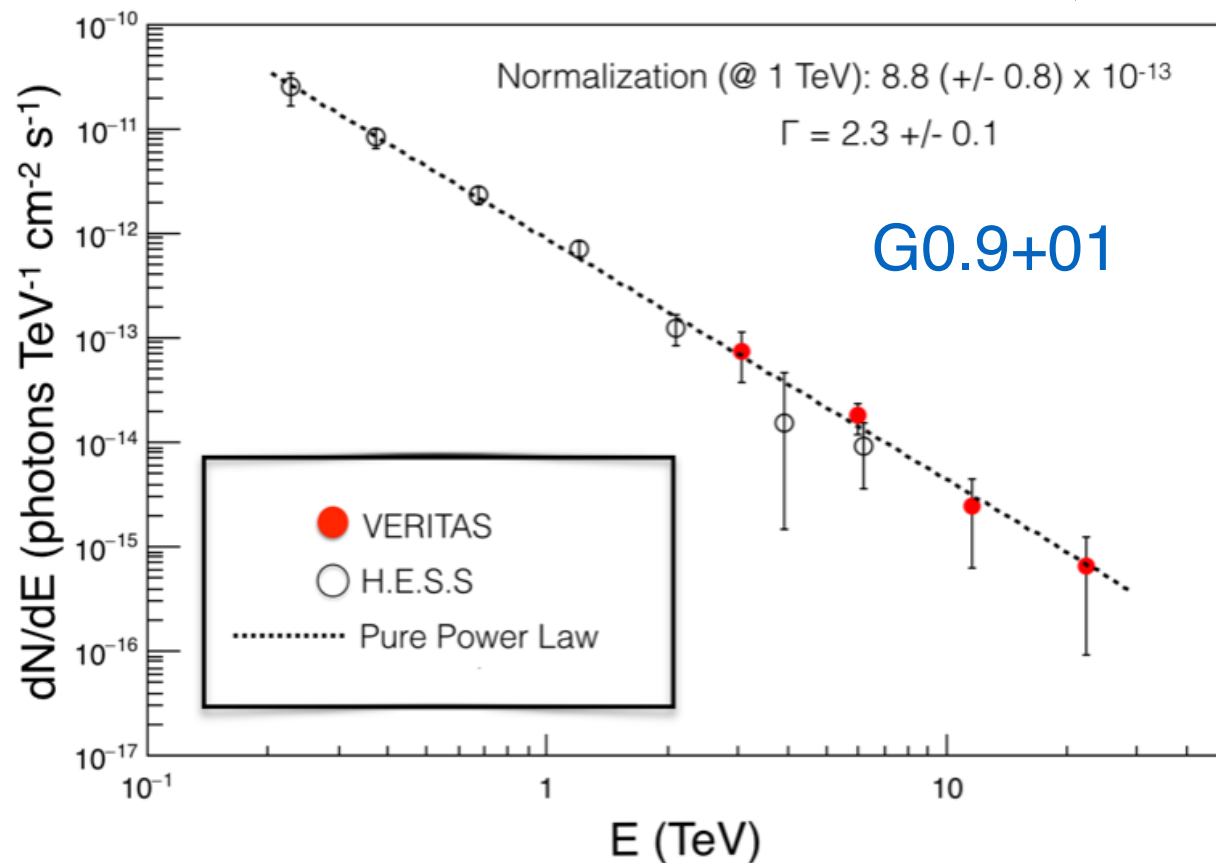
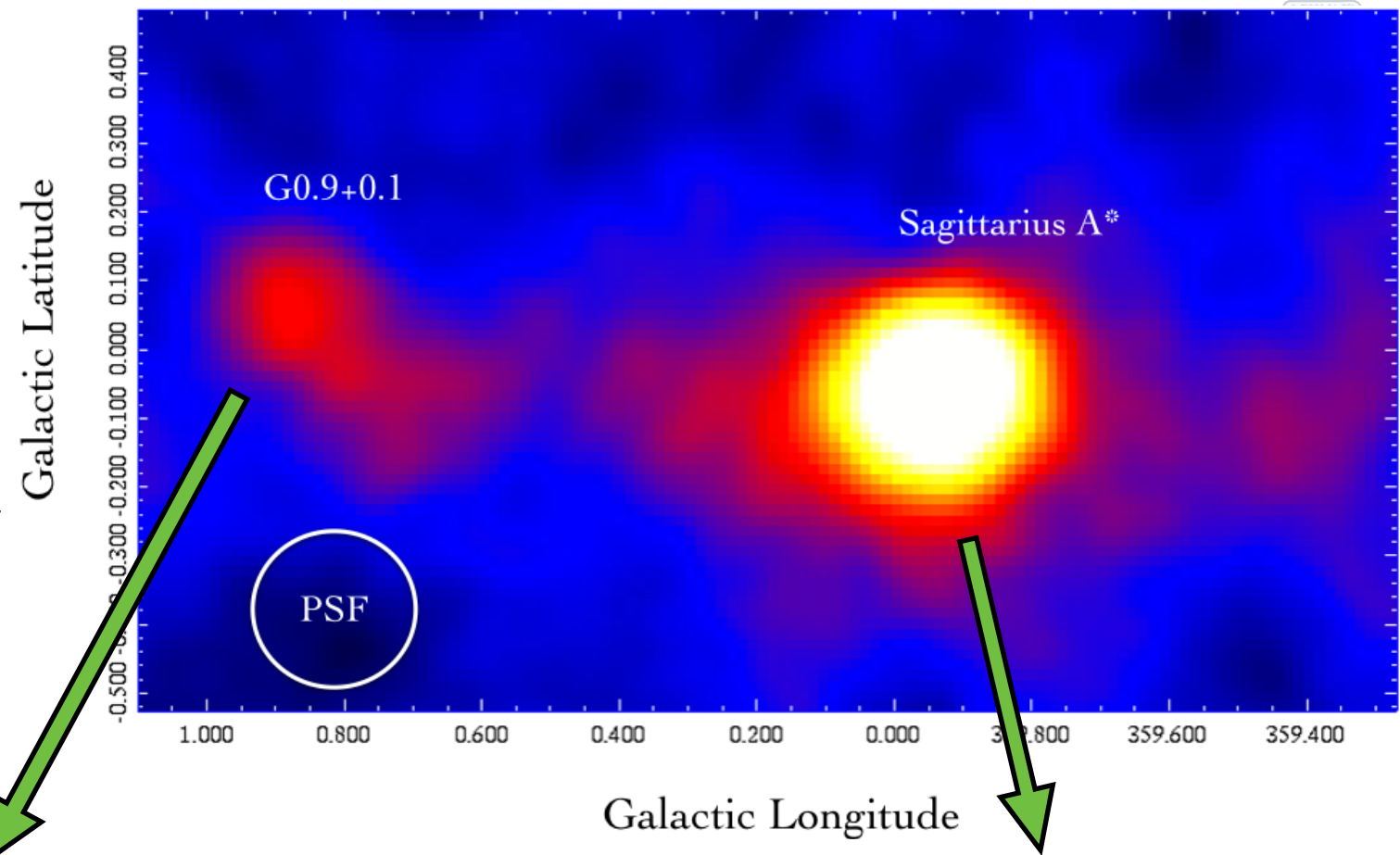


J. Quinn, *Re*

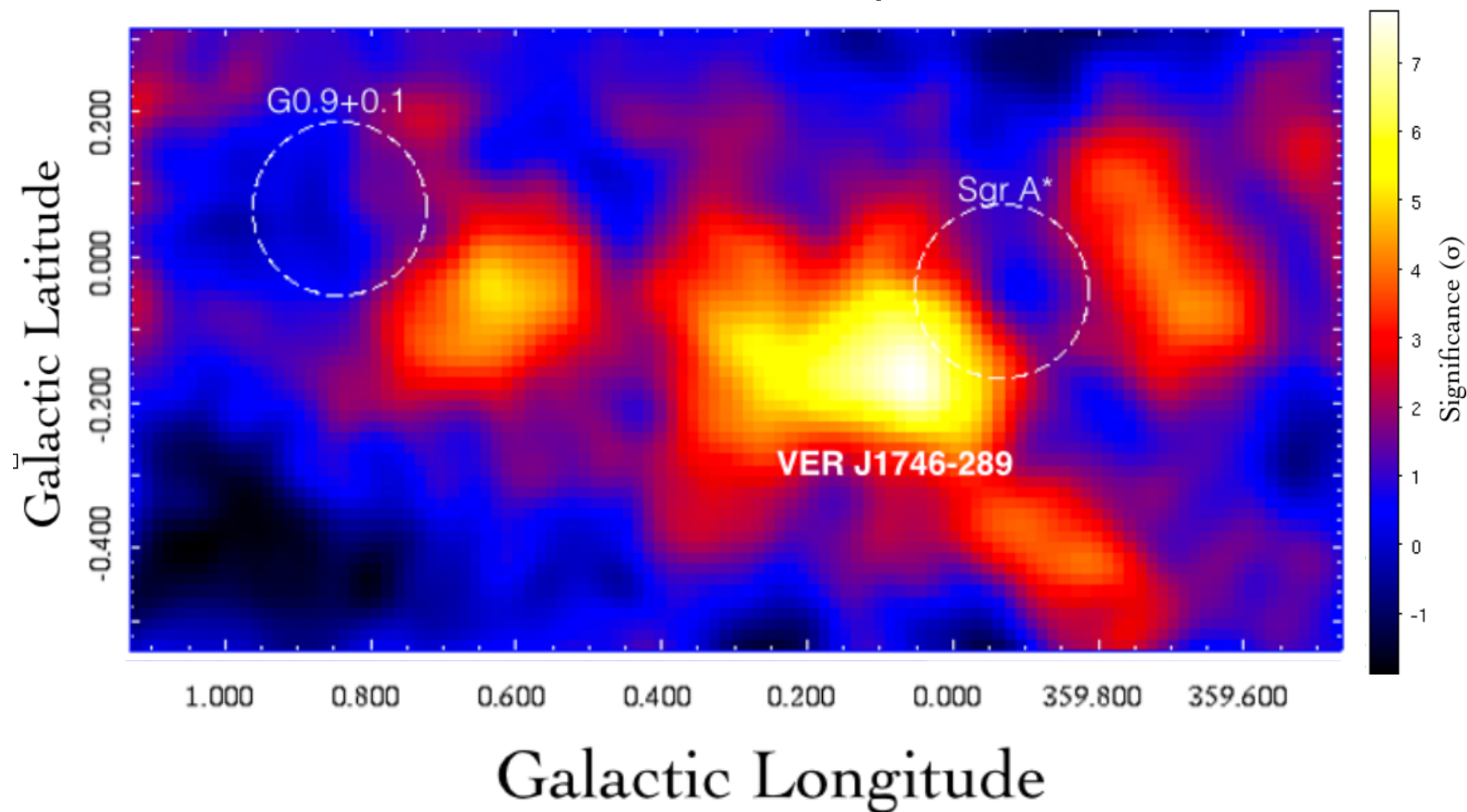


The Galactic Centre & Ridge

- 85 hrs
- Large Zenith Angle:
 - increased energy threshold
 - increased A_{eff}
- Two sources:
 - G0.9+01: $>7\sigma$, PL, no cutoff to 25 TeV
 - Sgr A*: $>25\sigma$, steady, PL+Exp cutoff
- Diffuse TeV band....



Residual Map



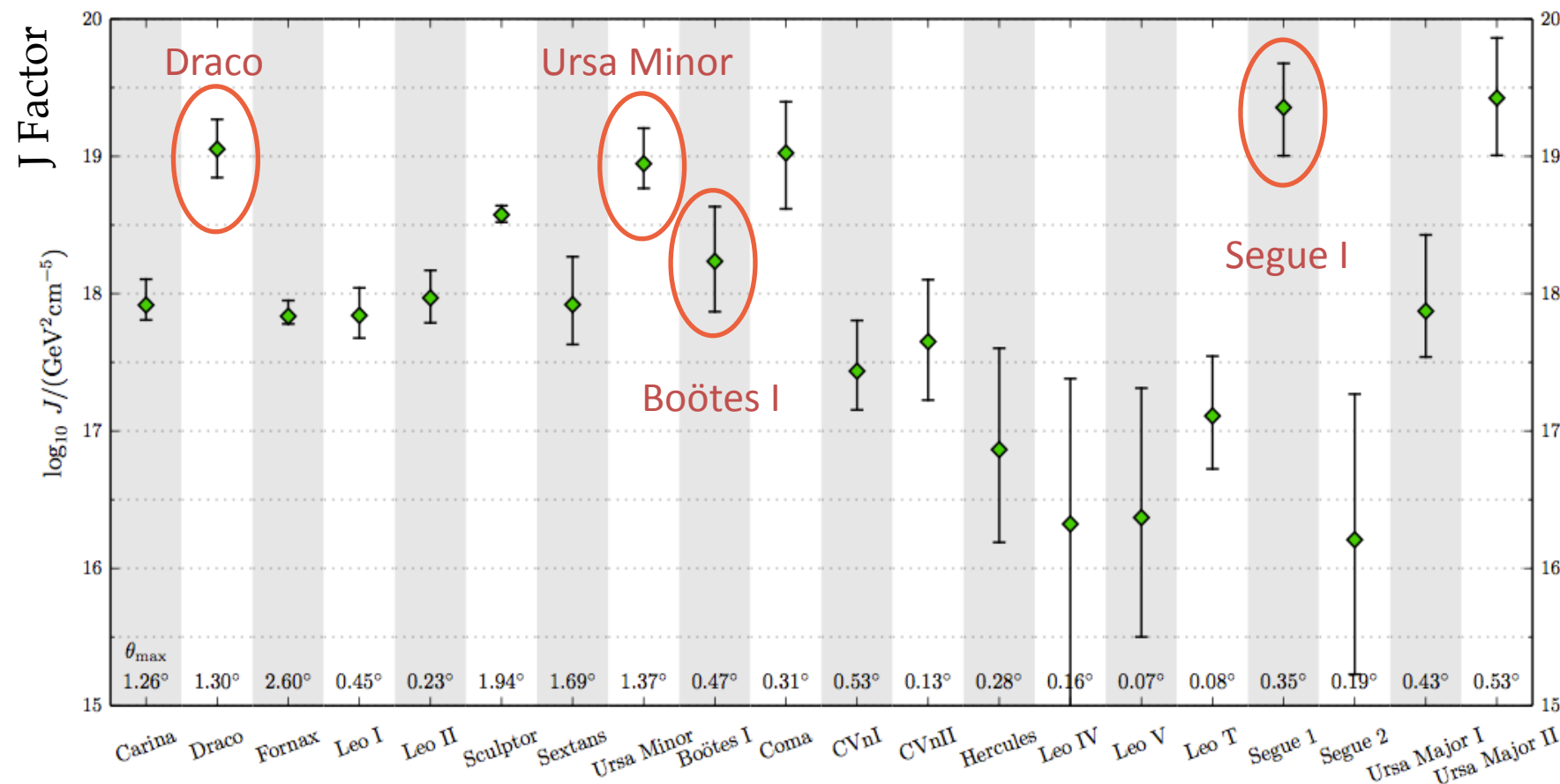
- Remove point-source excesses from Sgr A*, G0.9+0.1 to study residual diffuse emission > 2 TeV
- New VERITAS source VER J1746-289 revealed adjacent to Sgr A*, detected at 7.8σ
 - Located near radio arc, but not clearly correlated
- Additional 5.3σ (4.1σ post trials) enhancement correlated with Sgr B2 Molecular Cloud
- VERITAS > 2 -TeV residual emission overlaps reasonably well with H.E.S.S. > 300 GeV

- Search for gamma-ray flux of particle DM annihilation or decay from 100 GeV to the multi-TeV scale:

$$\frac{d\phi}{dE} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi m_x^2} \left[\frac{dN(E, m_x)}{dE} \right]_{DM}}_{\text{Particle Physics}} \underbrace{\langle J \rangle}_{\text{Astrophysics}}$$

Search for signals in DM-dominated regions: Dwarf Spheroidal Galaxies (dSphs), the Galactic Centre, Galaxy Clusters, and Fermi Unassociated Sources

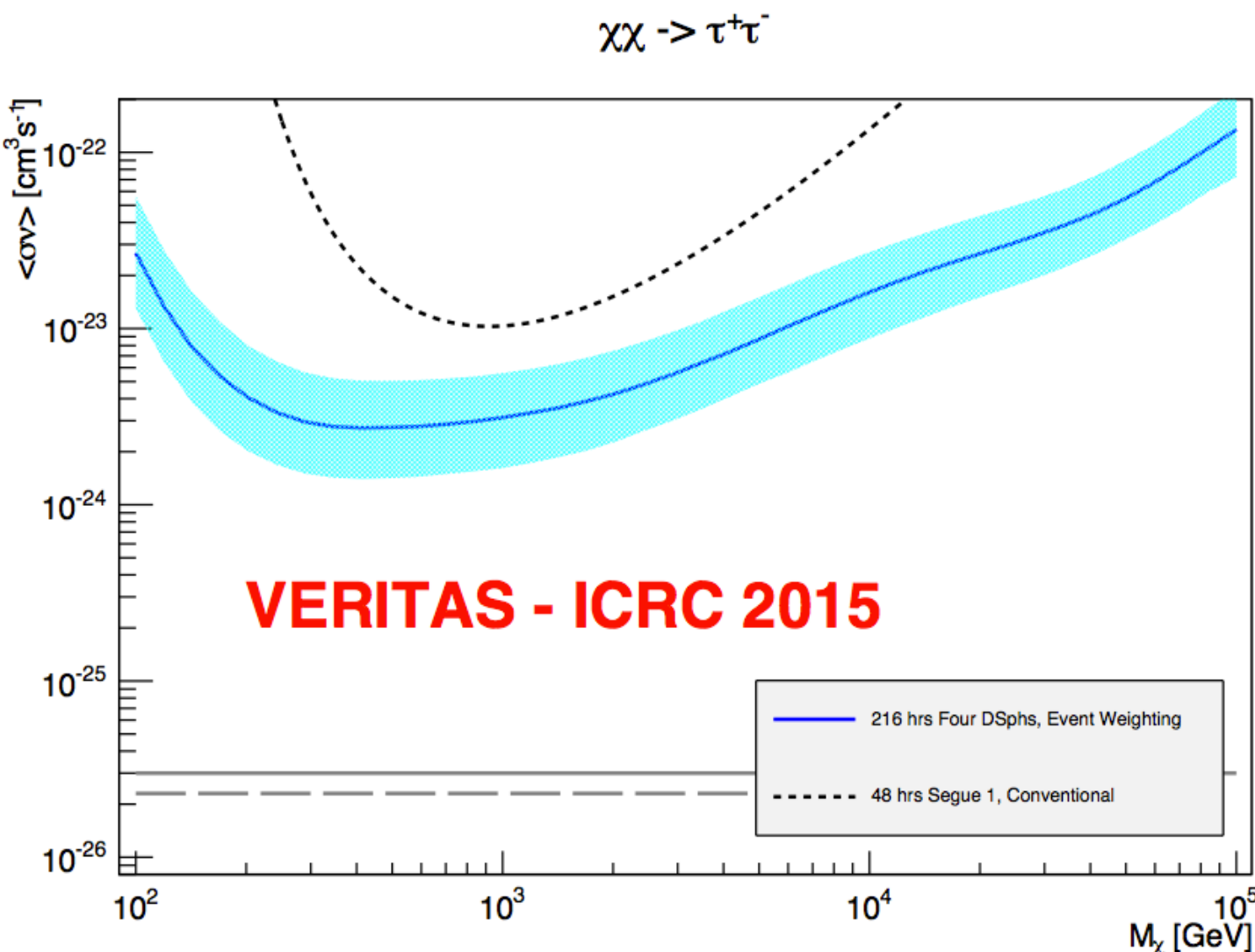
*Ideal DM targets: **dSph galaxies** are nearby, with $O(10^3)$ times more DM mass than visible matter, and little expected astrophysical background*



Long-term Plan:
150 hours annually on dSphs, including deep exposures on several high J-factor objects + survey of ~all known northern dSph

- New combined result with data from 4 dSphs

Dark Matter Search/Limits using 216 hours of Dwarf Spheroidal data from 2007-13.



- Methodology (Geringer-Sameth et al. 2015) utilizes individual event energy, dwarf field and direction information
 - Limits presented as a band to represent systematic uncertainty in J-Factors
- Previous single-source results published by VERITAS: the most constraining from 48-hours on Segue 1

- *Phys. Rev. D.* 85, 062001 (2012)
 (Erratum) *Phys. Rev. D.* 91, 129903 (2015)

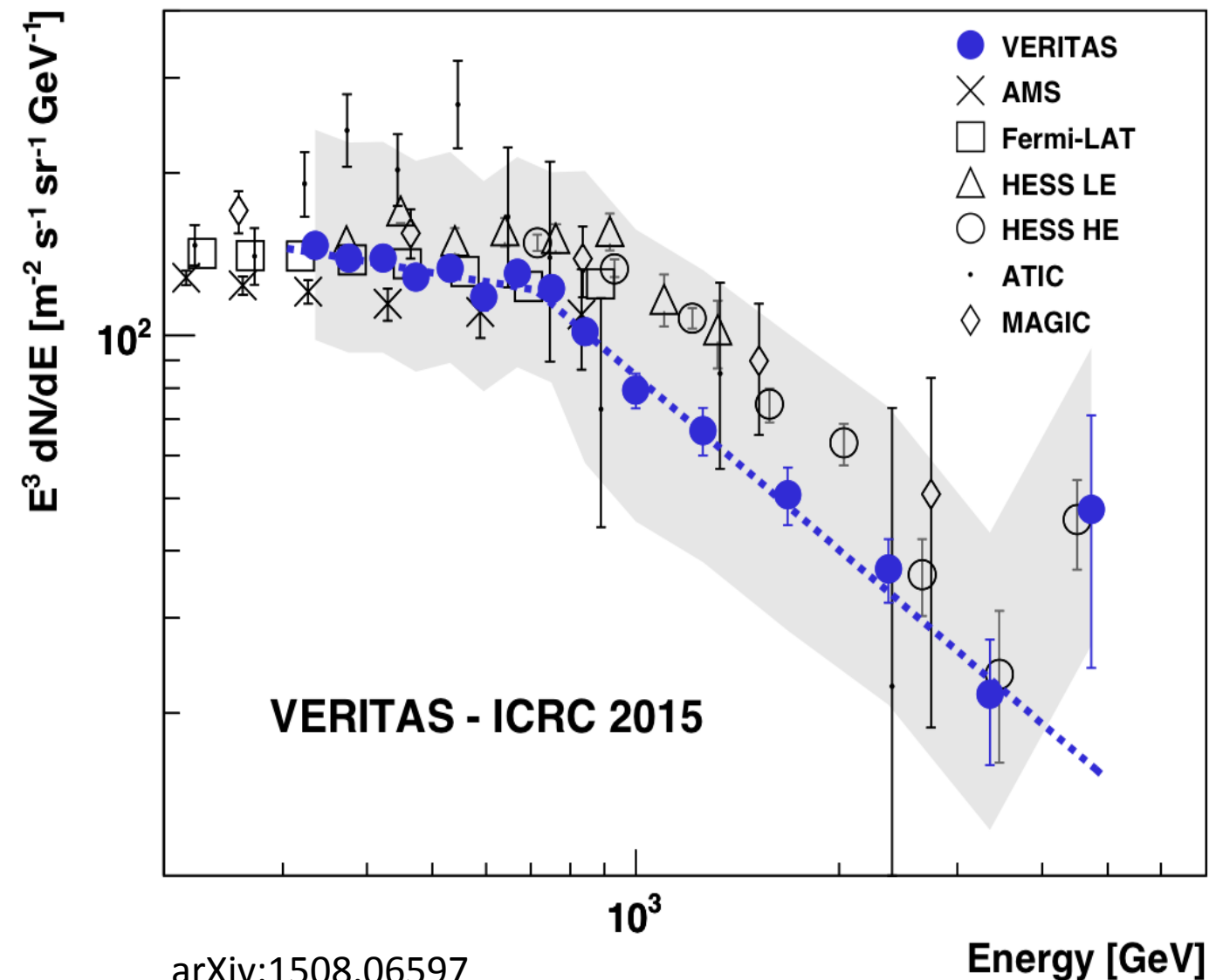
arXiv:1509.01105

Cosmic Ray Electrons with VERITAS

Cosmic-ray electrons at TeV energies are a direct probe of nearby ($\sim 1\text{kpc}$) accelerators

296 hours of data between 2009 and 2012

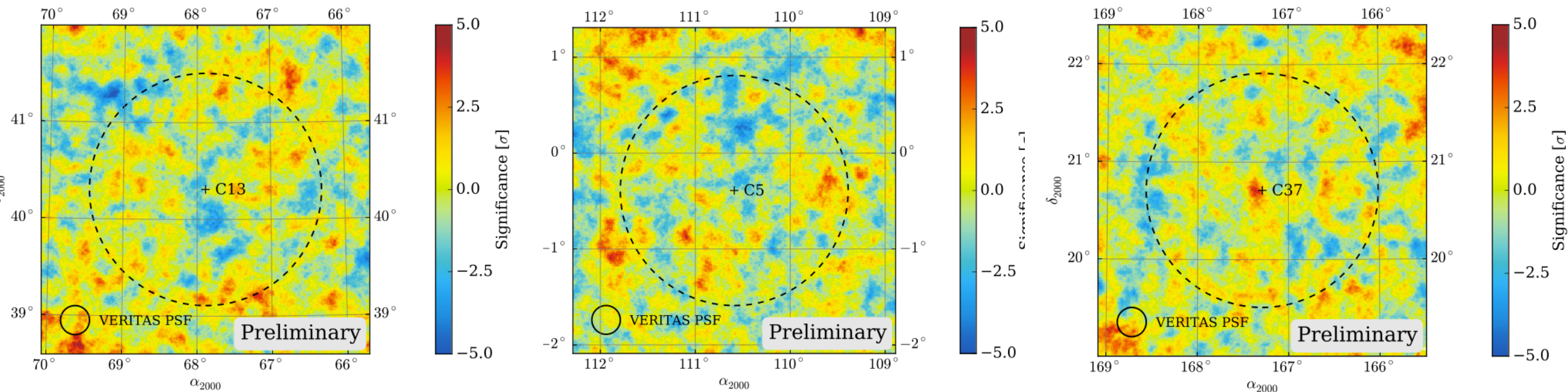
- Electron-like events selected by Boosted Decision Trees and extended likelihood fitting
- Spectrum agrees qualitatively with other experiments within systematic uncertainty
 - Break at $710 \pm 40 \text{ GeV}$
 - Index below/above break of $-3.2 \pm 0.1_{\text{STAT}}$ / $-4.1 \pm 0.1_{\text{STAT}}$



- Confirms evidence of at least one nearby CR electron emitter
- Second high-statistics measurement of a break below $\sim 1 \text{ TeV}$

IceCube discovery of astrophysical flux of high-energy neutrinos provides evidence of sites of cosmic ray generation... however, no significant neutrino point sources seen yet (isotropic)

arXiv:1509.00517



- Observations of 22 IceCube ν_μ -induced muon-track events for a total of 40 hours
 - muon-track events have good localization, ~ 1 degree angular uncertainty
 - 3 positions publicly released, 19 shared by a mutual agreement

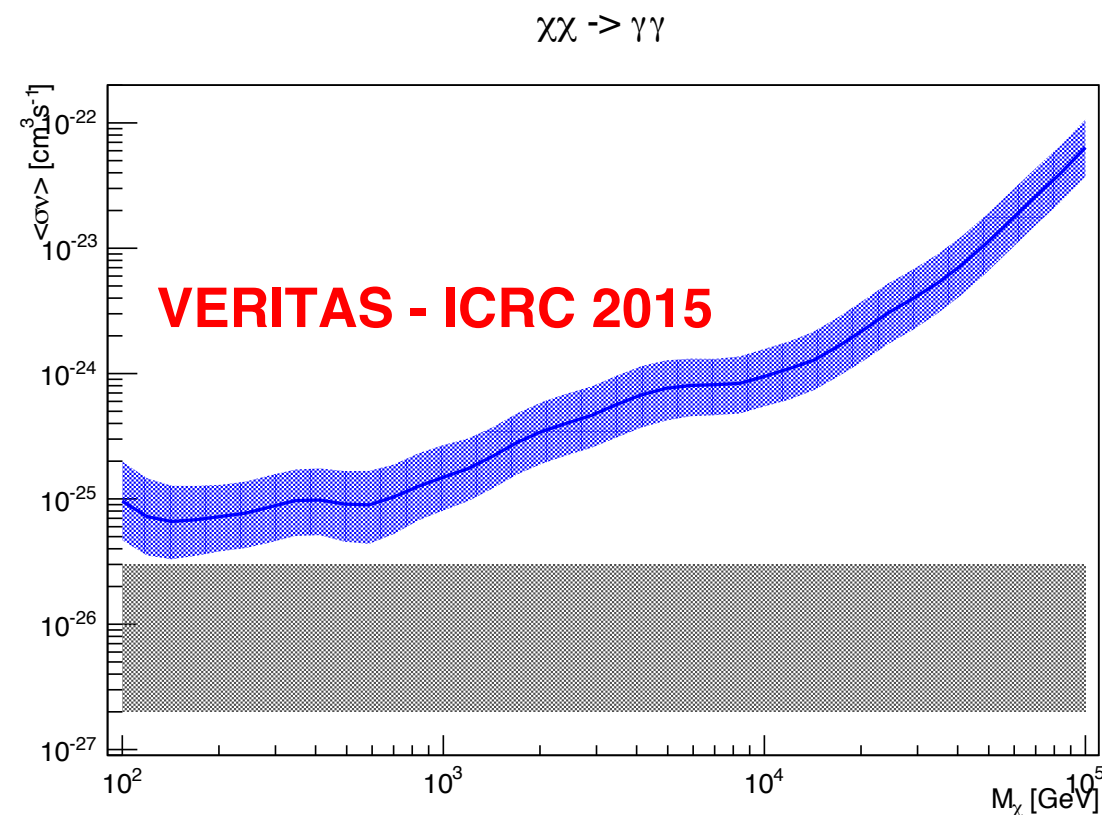
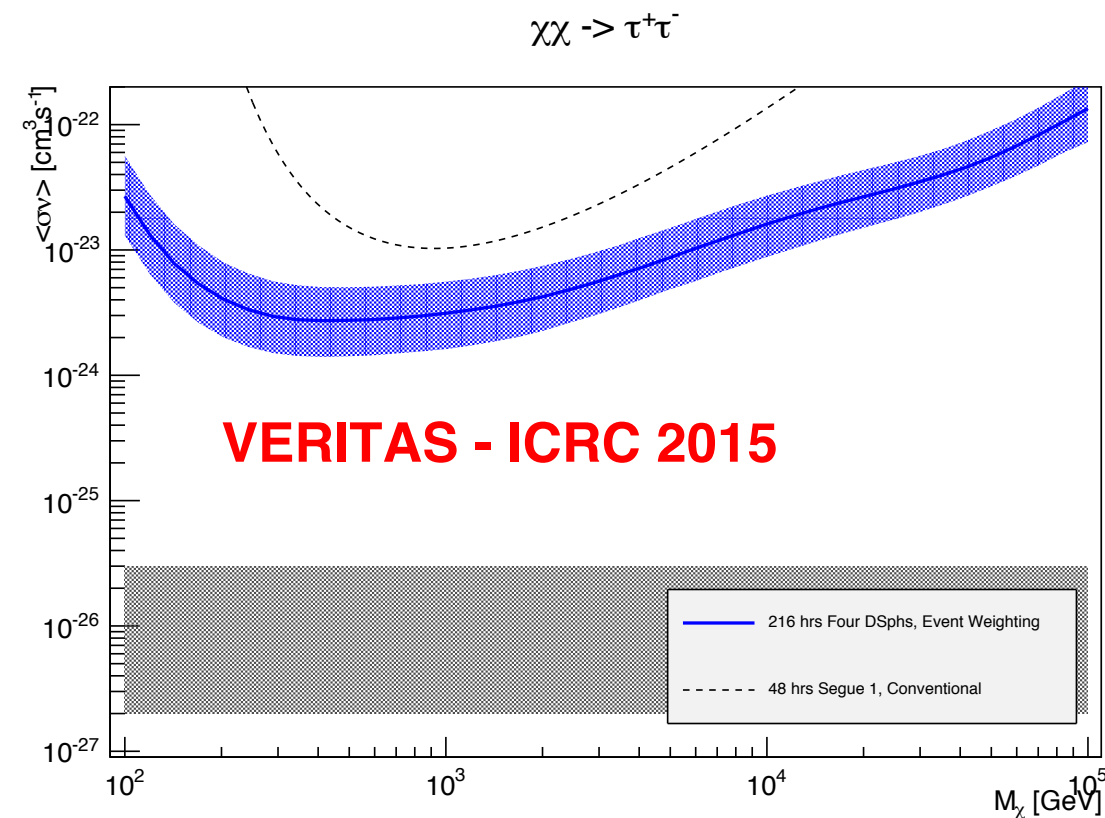
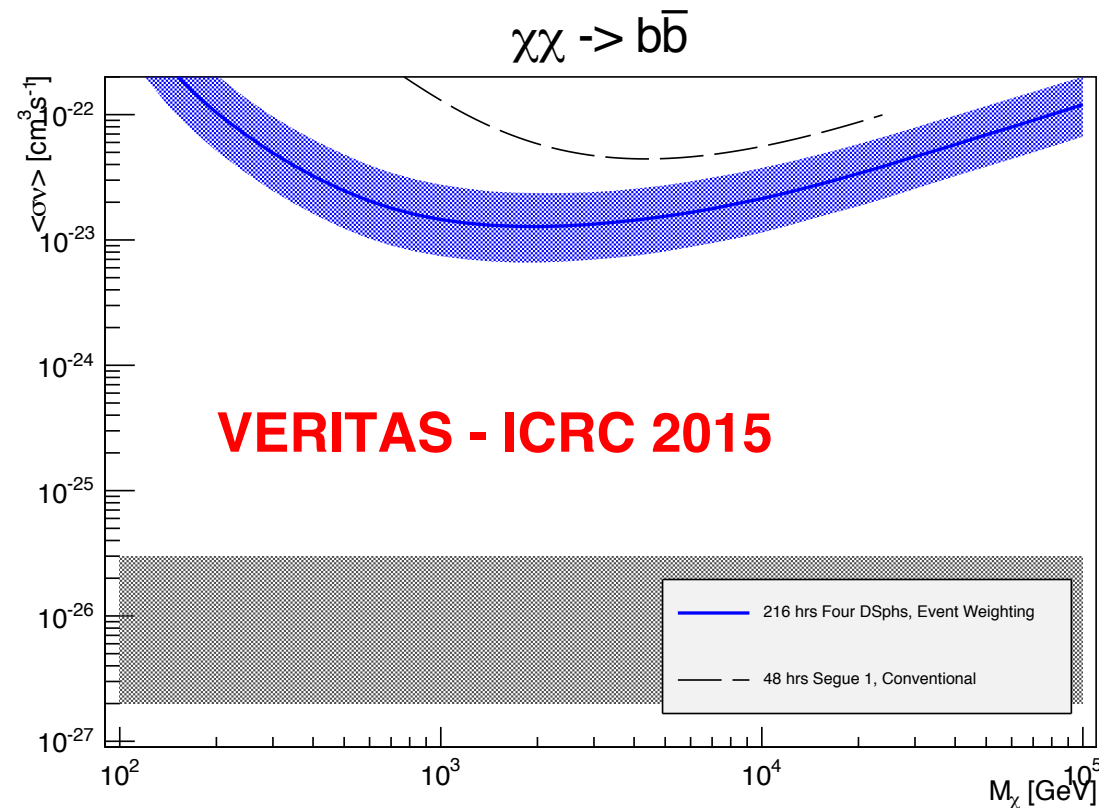
No significant signals seen: flux upper limits for each of the positions found in the range of ~ 2 -10% Crab Nebula flux

- VERITAS is operating with excellent sensitivity and an expanded observing program including observations under bright moonlight.
- VERITAS has as strong multifaceted science program with recent highlights from the extragalactic, galactic, cosmic ray and dark matter programs presented here.
- Additional science topics not mentioned here include:
 - Galactic: Pulsars, PWN, Binary Systems, Cygnus region survey
 - Extragalactic: Radio Galaxies, Starburst Galaxies, M31
 - Gamma-ray burst follow-up program
- We are optimistic for many more exciting results over the coming years.

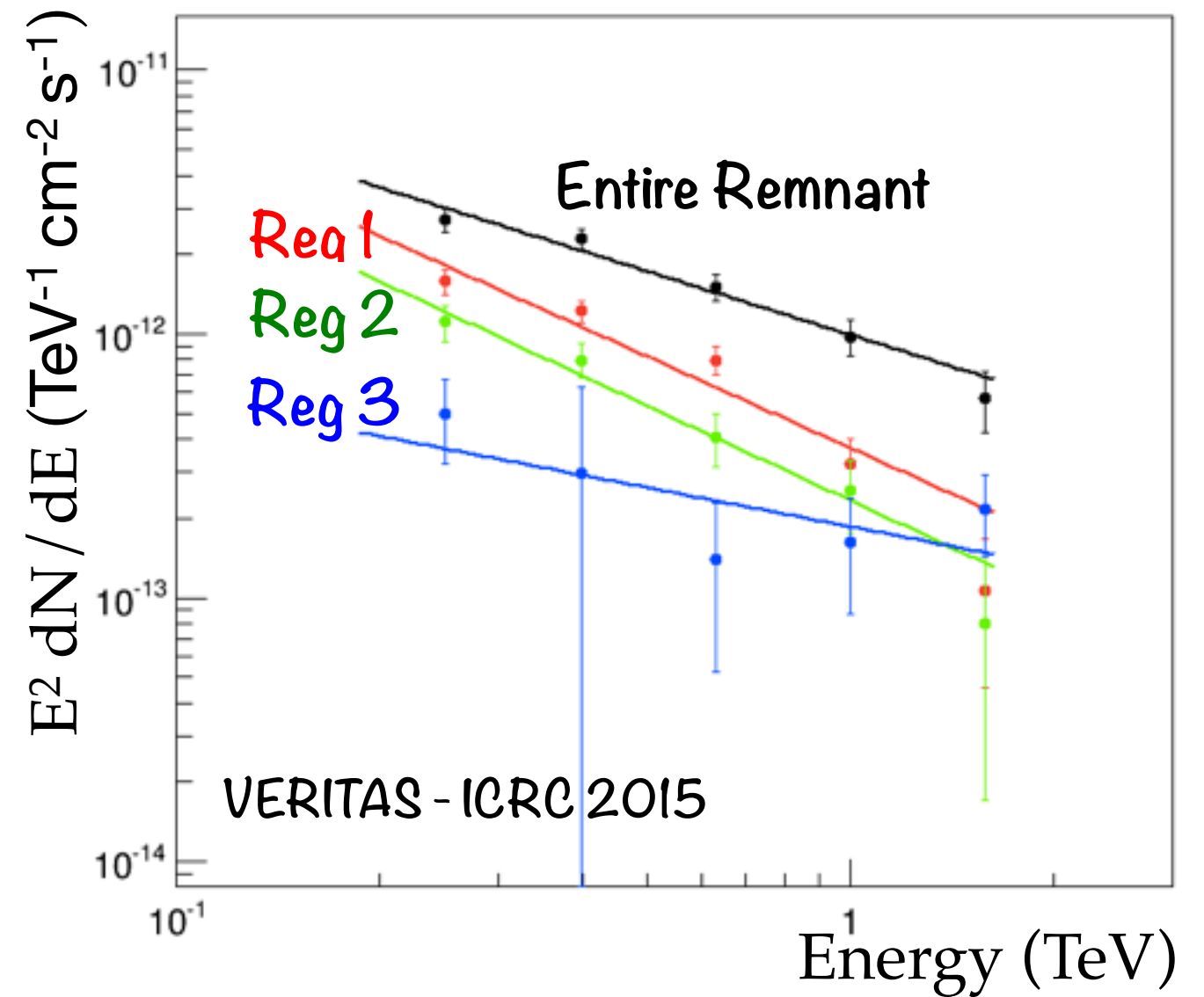
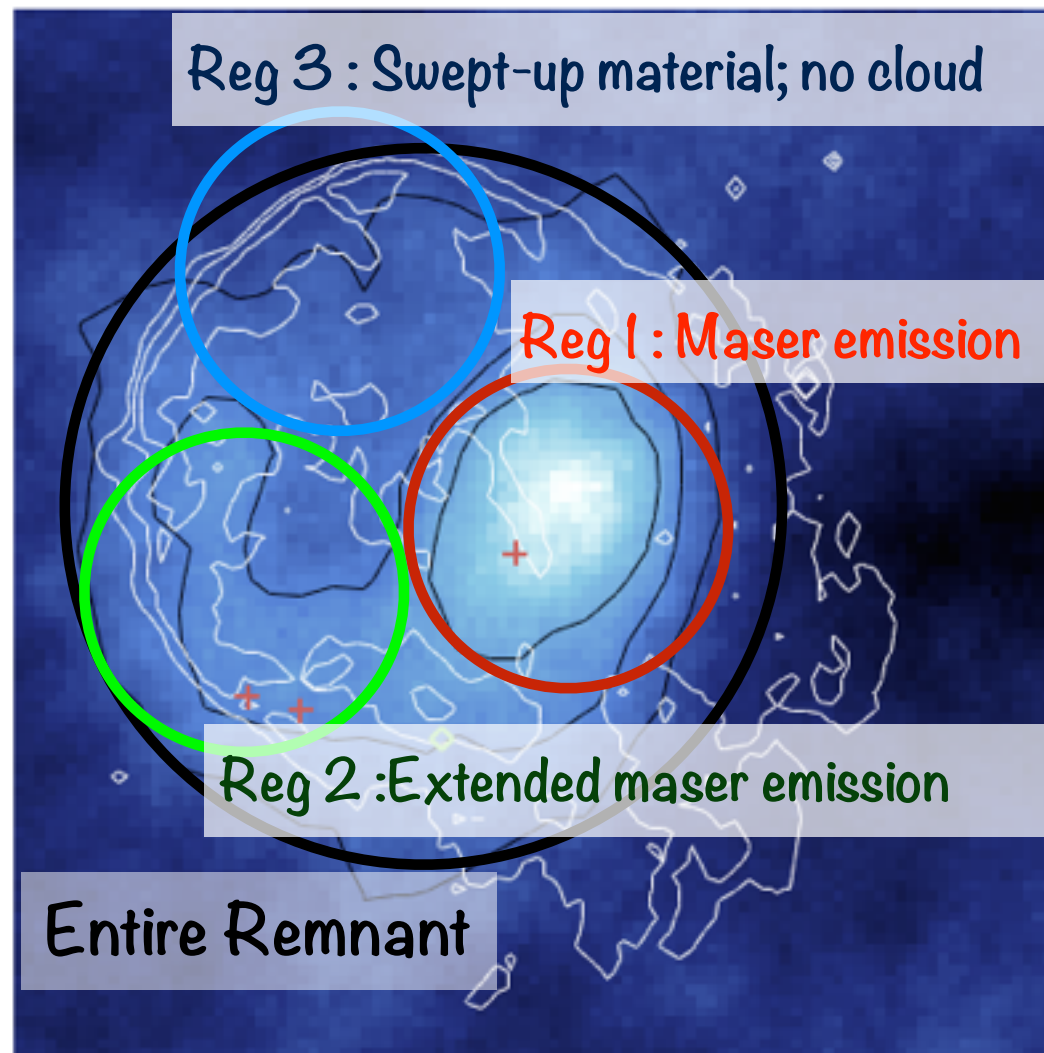


Background





Flux & spectra measurement in IC 443



Power-law fit results:

Region	Norm (/550 GeV) * 10 ⁻¹³ TeV ⁻¹ cm ⁻² s ⁻¹	Index	χ^2 / ndf
Entire Remnant	9.92 ± 0.90	-2.80 ± 0.09	2.76 / 3
Region 1	3.69 ± 0.42	-3.15 ± 0.11	9.98 / 3
Region 2	2.33 ± 0.42	-3.19 ± 0.17	1.85 / 3
Region 3	1.86 ± 0.49	-2.49 ± 0.42	2.64 / 3