



Highlights from VERITAS



John Quinn

(University College Dublin)

on behalf of the VERITAS Collaboration



VERITAS Status



Facility and Collaboration:

- Located at the [Fred Lawrence Whipple Observatory](#) in southern Arizona @ 1,268 m a.s.l.
 - CTA prototype SCT telescope co-located
- VERITAS just [completed its 15th year of full-array operations.](#)
- International Collaboration:
 - 97 members incl. 32 graduate students and 16 Postdocs
 - +20 active Associate Members

Funding Sources:

- **USA:** National Science Foundation, Smithsonian Astrophysical Observatory
- **Canada:** Natural Sciences and Engineering Research Council
- **Germany:** Helmholtz Association

News:

- **Recommended** for next NSF operations funding cycle through 2025
- Two instrument upgrade grants awarded

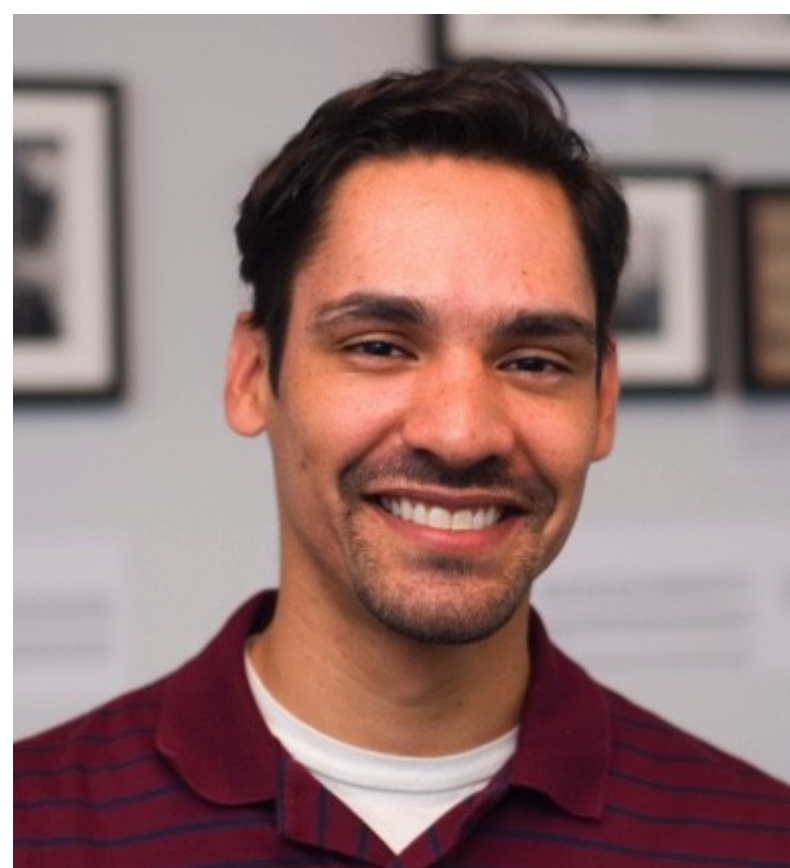
- Awards to "...formally recognize the significant contributions of more early-career members of the collaboration in the *critical service work that enables scientific publications of VERITAS and/or the pSCT, but do not result in any scientific publications directly*".

- Simon Swordy Award (graduate students)
- Trevor Weekes Award (postdocs)

+ VERITAS Code of Conduct

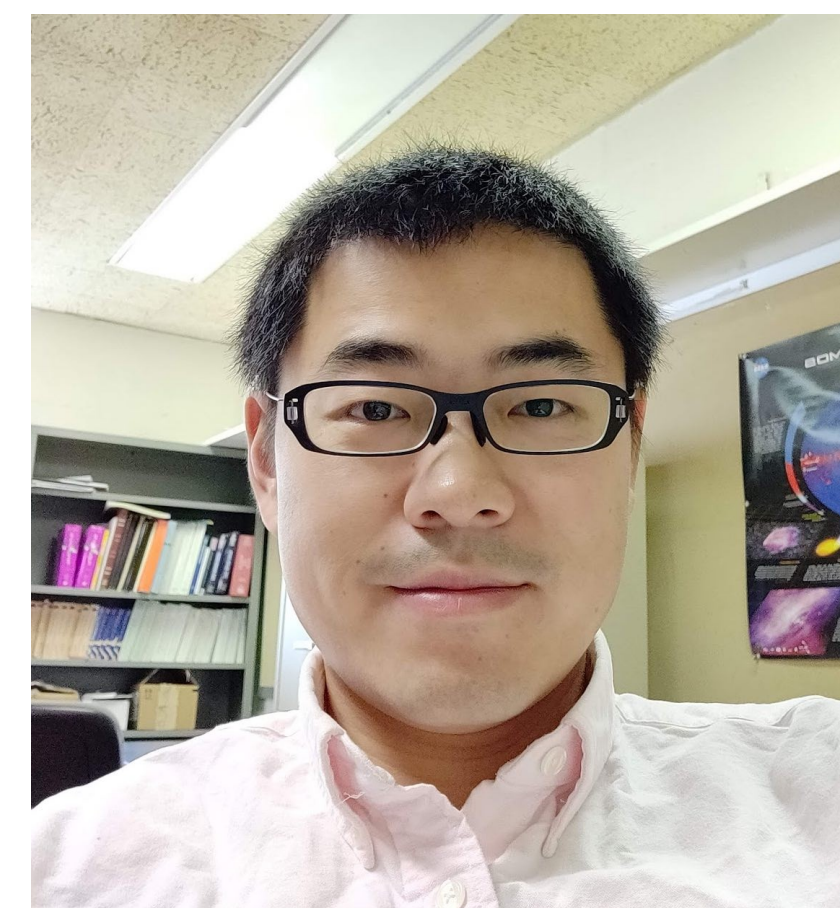
2021 Simon Swordy Award Winner: Deivid Ribiero (Columbia):

for wide-ranging contributions to VERITAS & the pSCT including ... data analysis software, remote observing capability, pSCT optics, mentoring and outreach



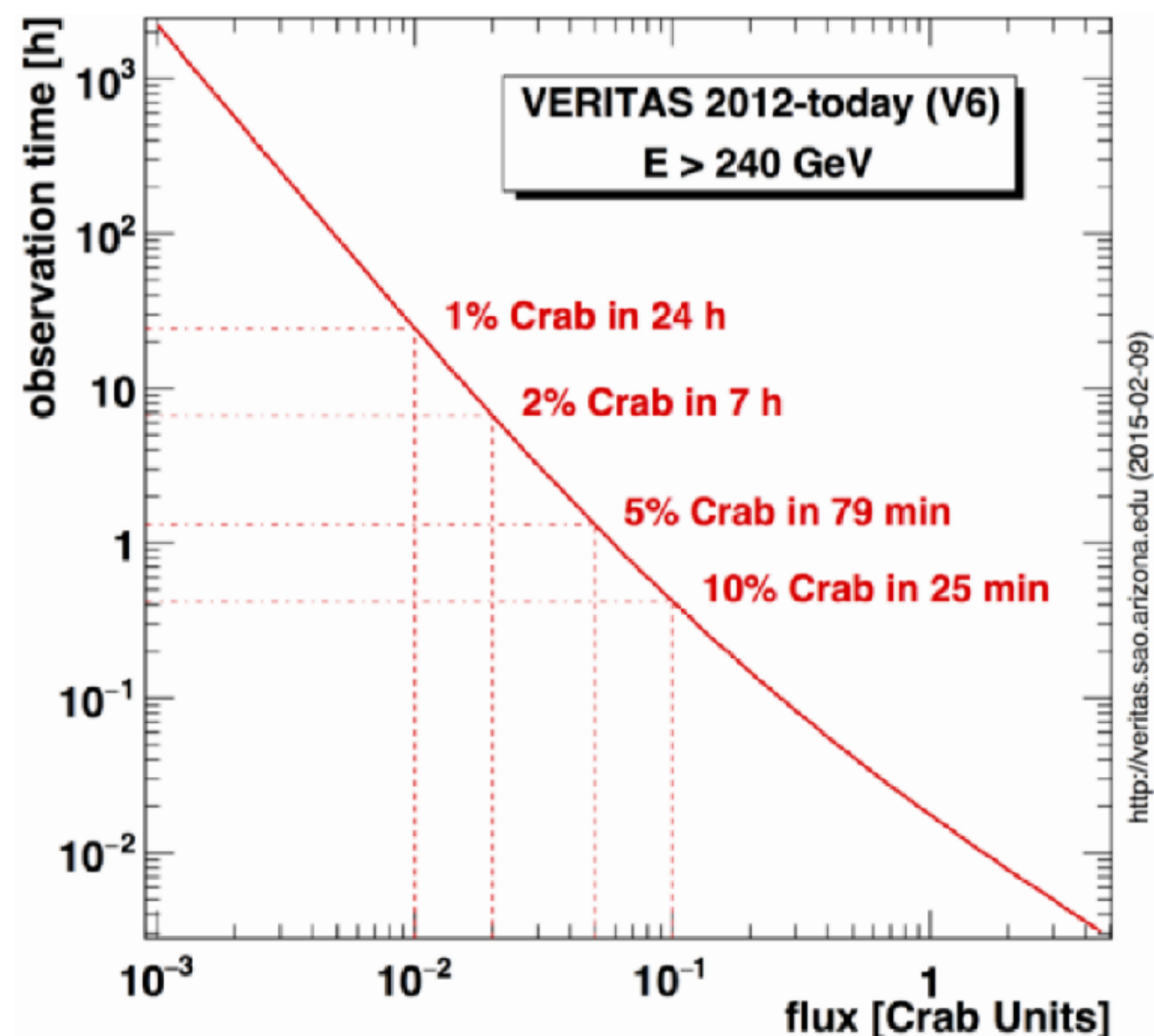
2021 Trevor Weekes Award Winner: Qi Feng (Columbia):

for numerous and ongoing contributions to the VERITAS Observatory and multiple innovations in the commissioning of the optics system for the prototype SCT Telescope, outreach - Muon Hunter Zooniverse project"

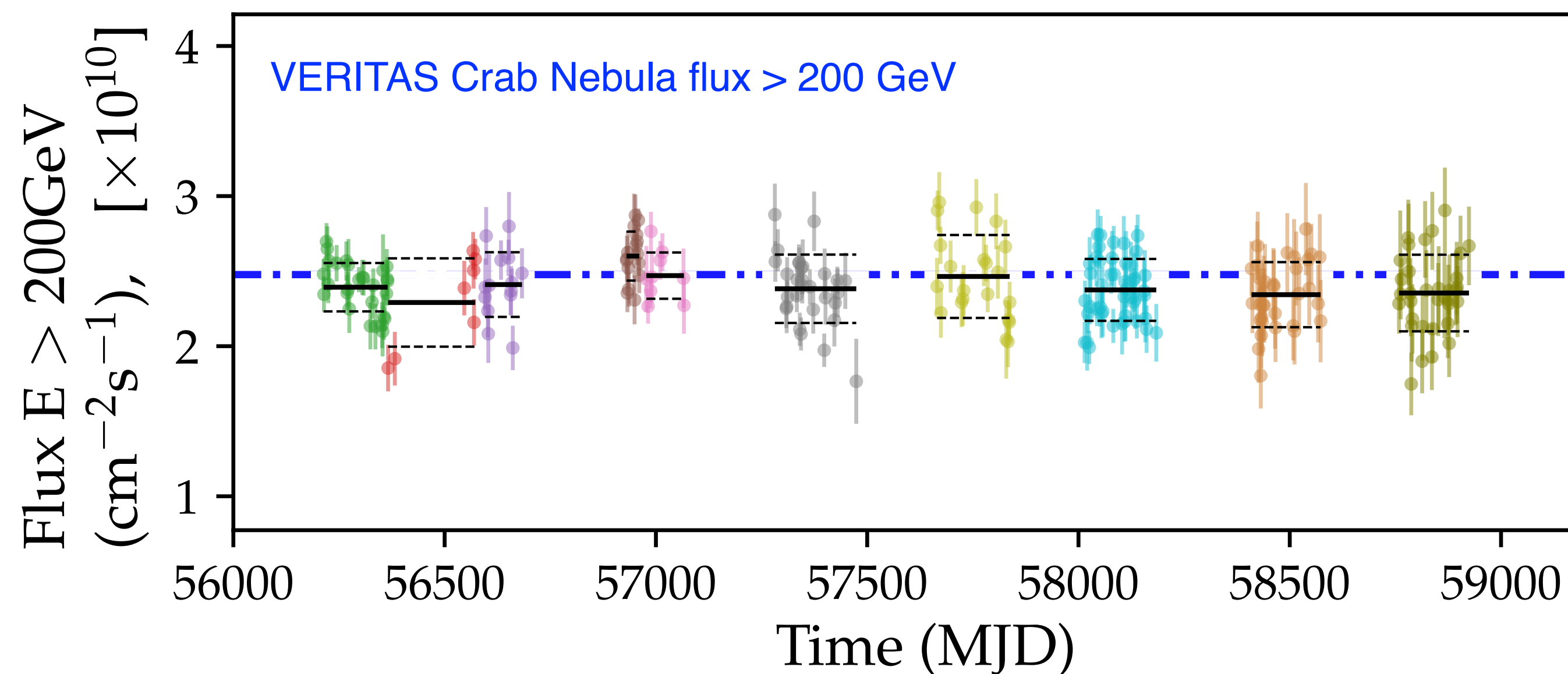


Field of view	3.5° diameter
Energy Range	~85 GeV to ~30 TeV
Effective Area	~10 ⁵ m ² at 1 TeV
Sensitivity	1% Crab in <25 h

Angular Resolution (r_{68})	~0.08° @ 1 TeV
Energy Resolution	~17%
Sys. Errors: Flux	~20%;
Sys. Errors: Spectral Index	~ 0.1



Long-term instrument response well understood:
(Adams et al., A&A 658, A83 (2022)):



VERITAS Observations

- **Season:** September to July each year.
- **Good-weather γ -ray data / yr:**
 - ~950 h in “dark time”
 - ~250 h in “bright moon” (illum. 30-65%)
- **4-Telescope efficiency:** ~ 97%
- **Stellar Intensity Interferometry Observations:**
 - Utilise very bright and full-moon time
 - 250 hrs+ / year

COVID impact :

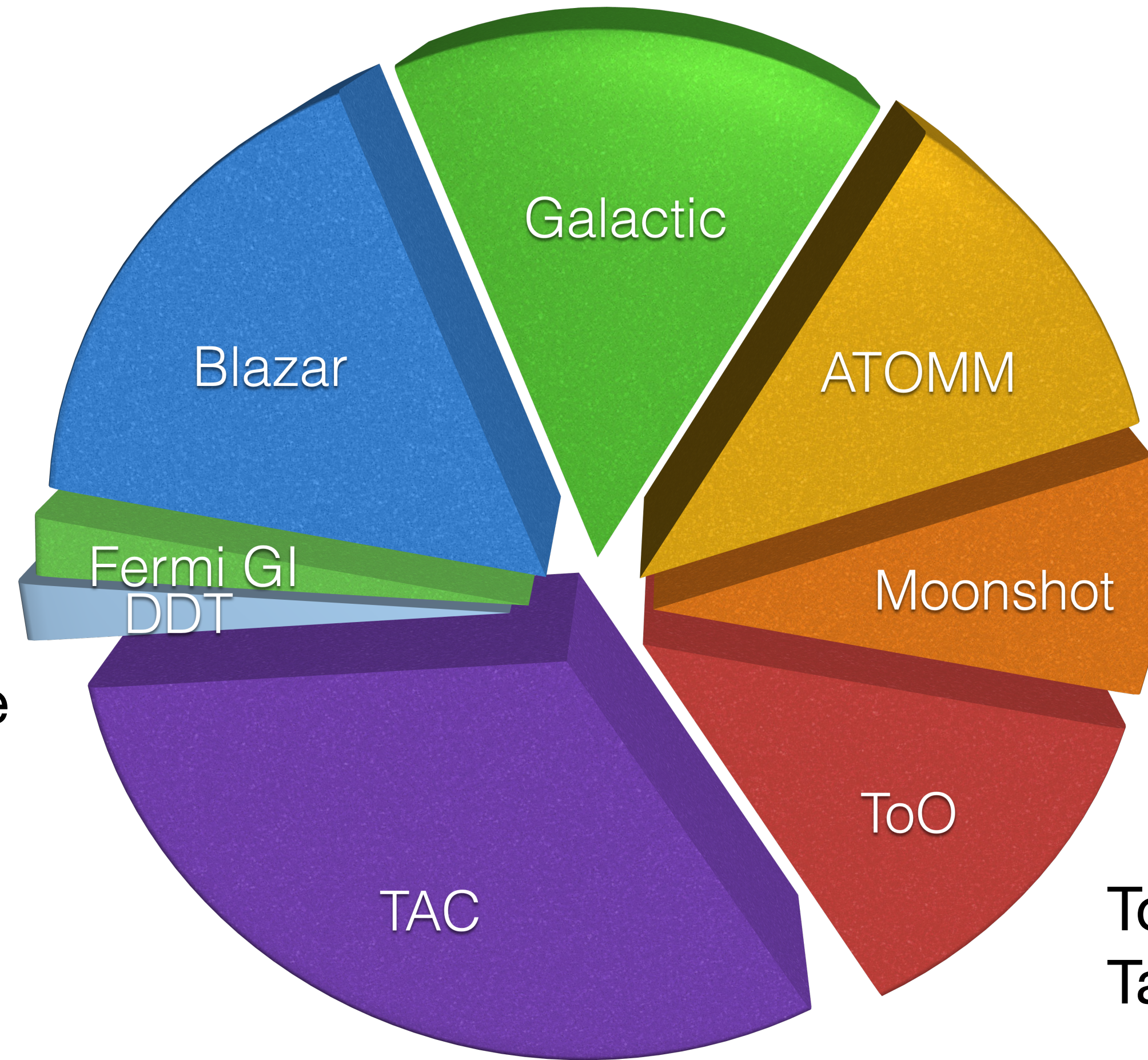
- **Shut down on 17 March 2020**
- **Resumed in early September 2020** with **remote observing capability** - long term option.



Fermi GI:
Fermi Guest
Investigator Program

DDT:
Director's Discretionary Time

TAC:
Time Allocation Committee



ATOMM:
Astroparticle, Transient,
Optical, Multi-Messenger

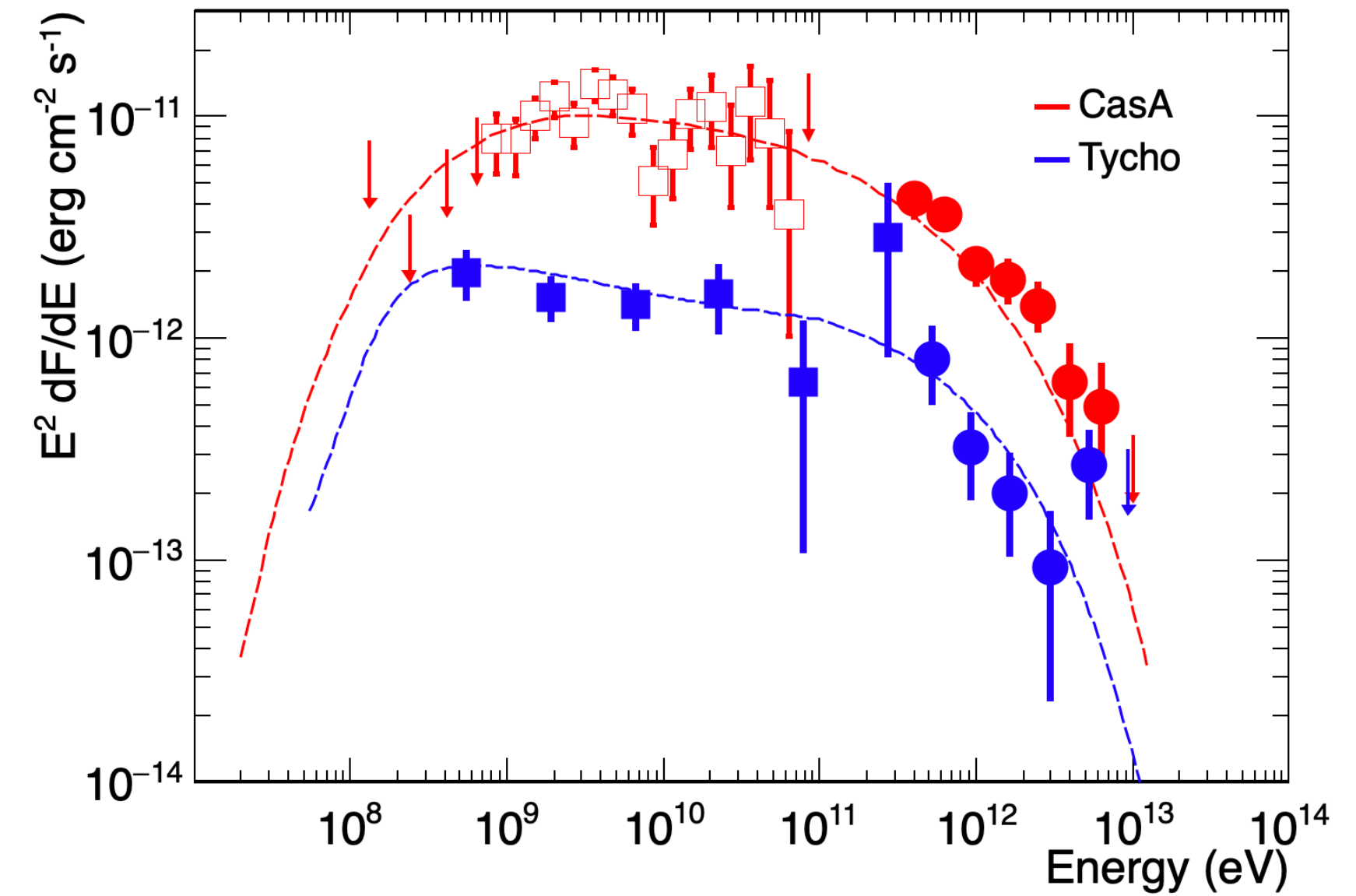
ToO:
Target of Opportunity

Deep observations of the young Supernova Remnants

- **Tycho's SNR** : 147 hrs: $E_{\text{cut}} \text{ (TeV)} = 1.70 \pm 1.23 \text{ (} 2\sigma \text{)}$ (*Archambault et al, 2017*)
- **Cassiopeia A** : 65 hrs: $E_{\text{cut}} \text{ (TeV)} = 2.31 \pm 0.51 \text{ (} 4\sigma \text{)}$ (*Abeysekara et al, 2020*)

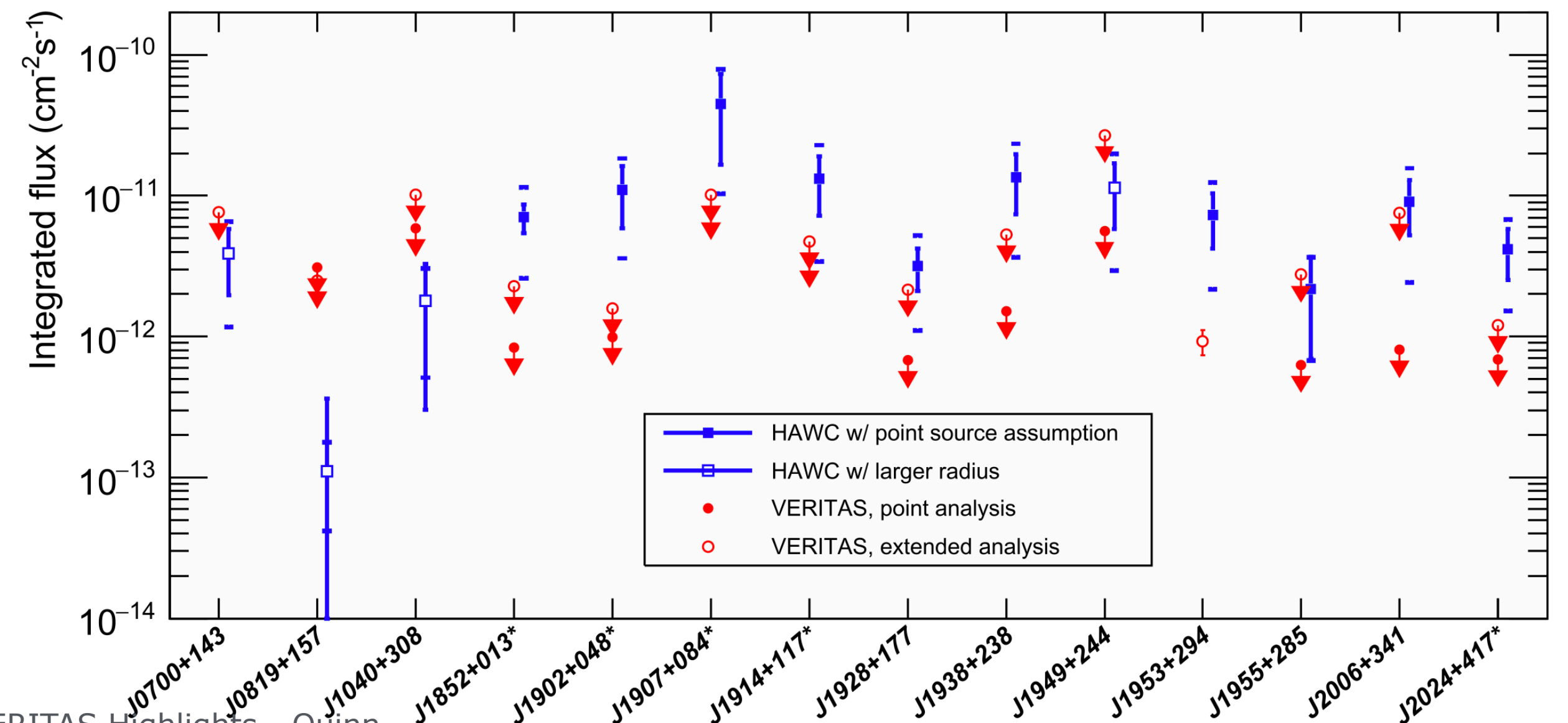
Studies of the origins of unidentified, hard-index sources

- MGRO J2019+37
- MGRO J1908+06
- **VER J2227+608 (SNR G106.4+2.7 region, "Boomerang")**



Studies of ultra-high-energy gamma-ray sources

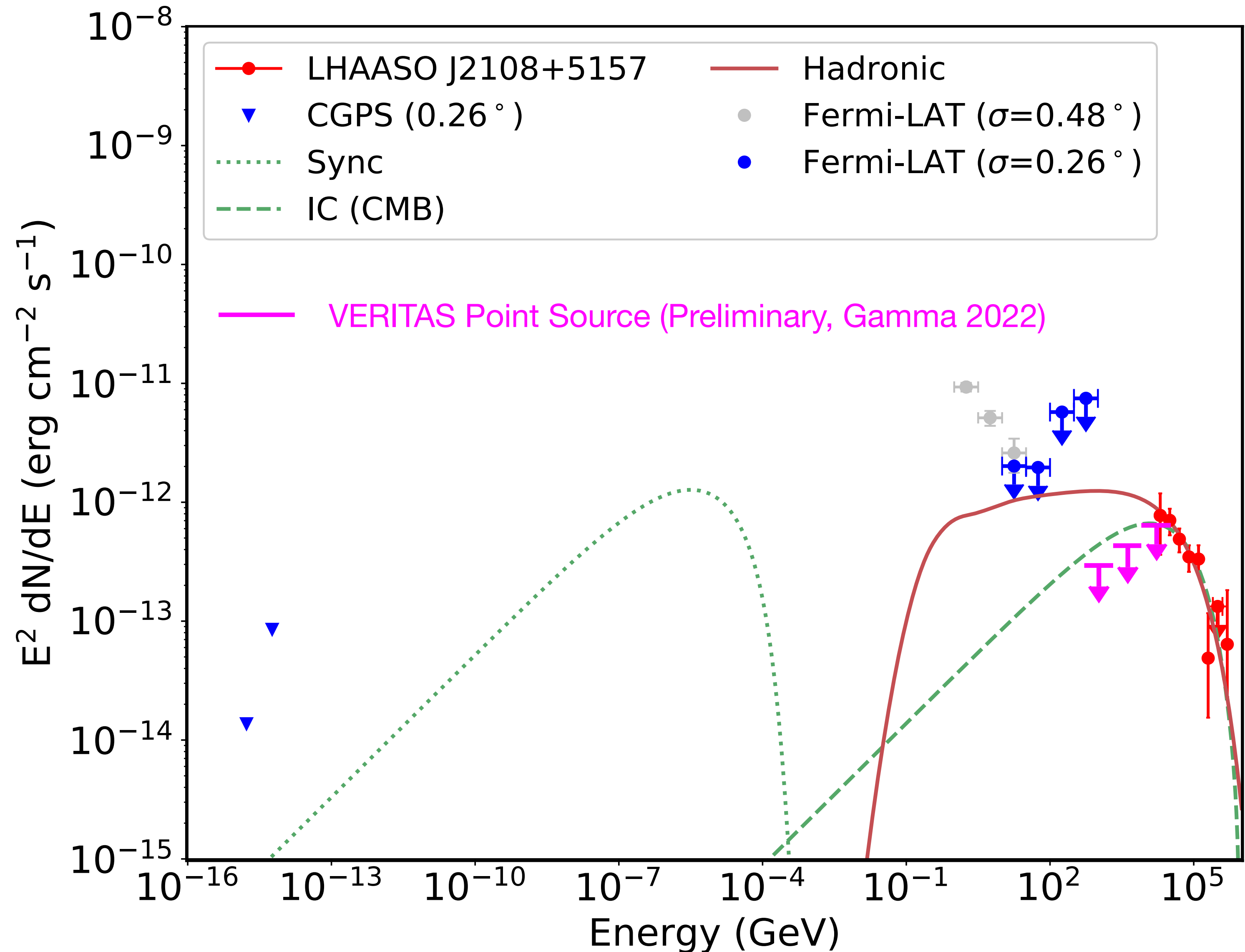
- Followup observation of HAWC sources (*2HWC follow-up: Abeysekara et al, 2018*)
- Followup observation of LHAASO sources: including **LHAASO J2108+5157** & LHAASO J0341+5258



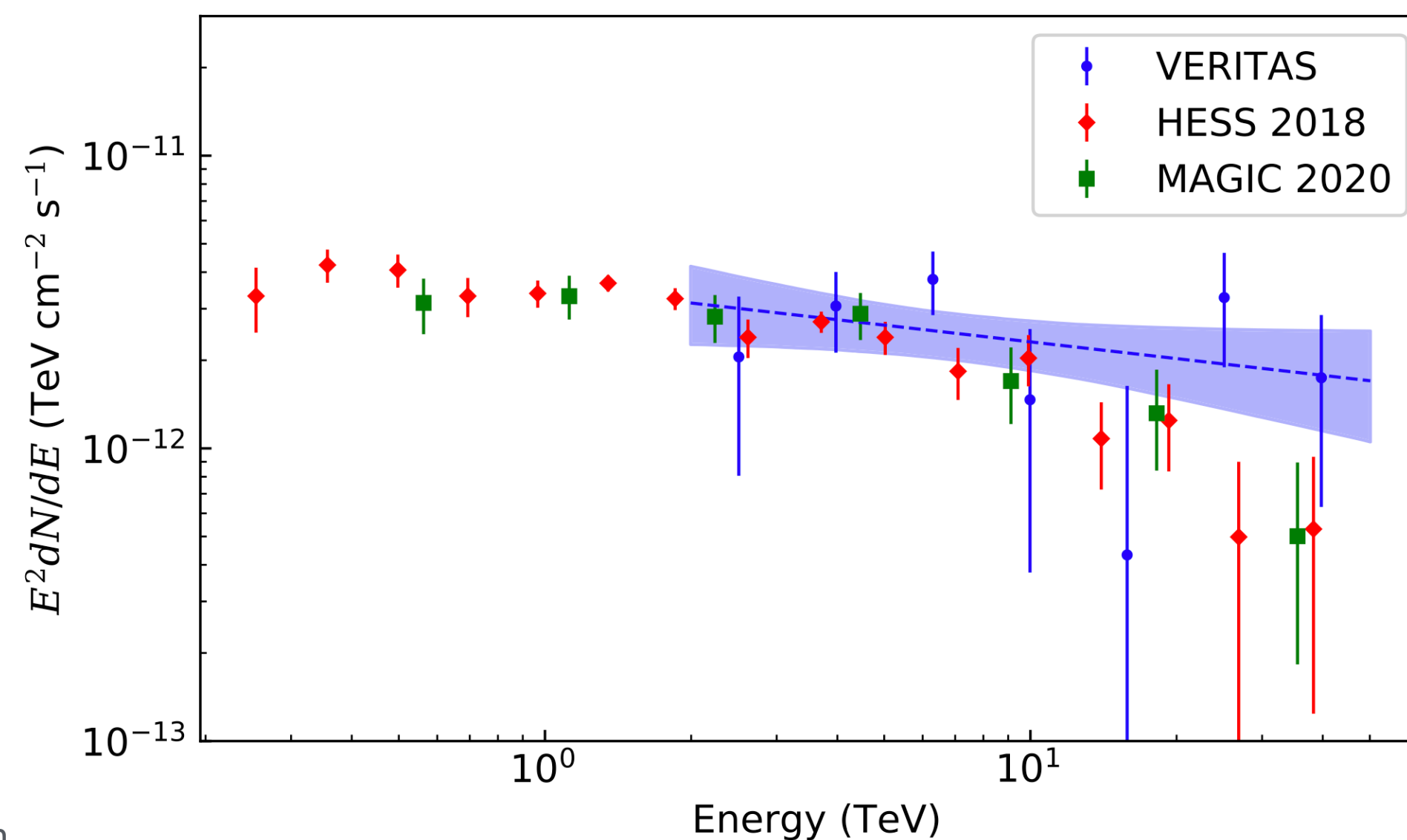
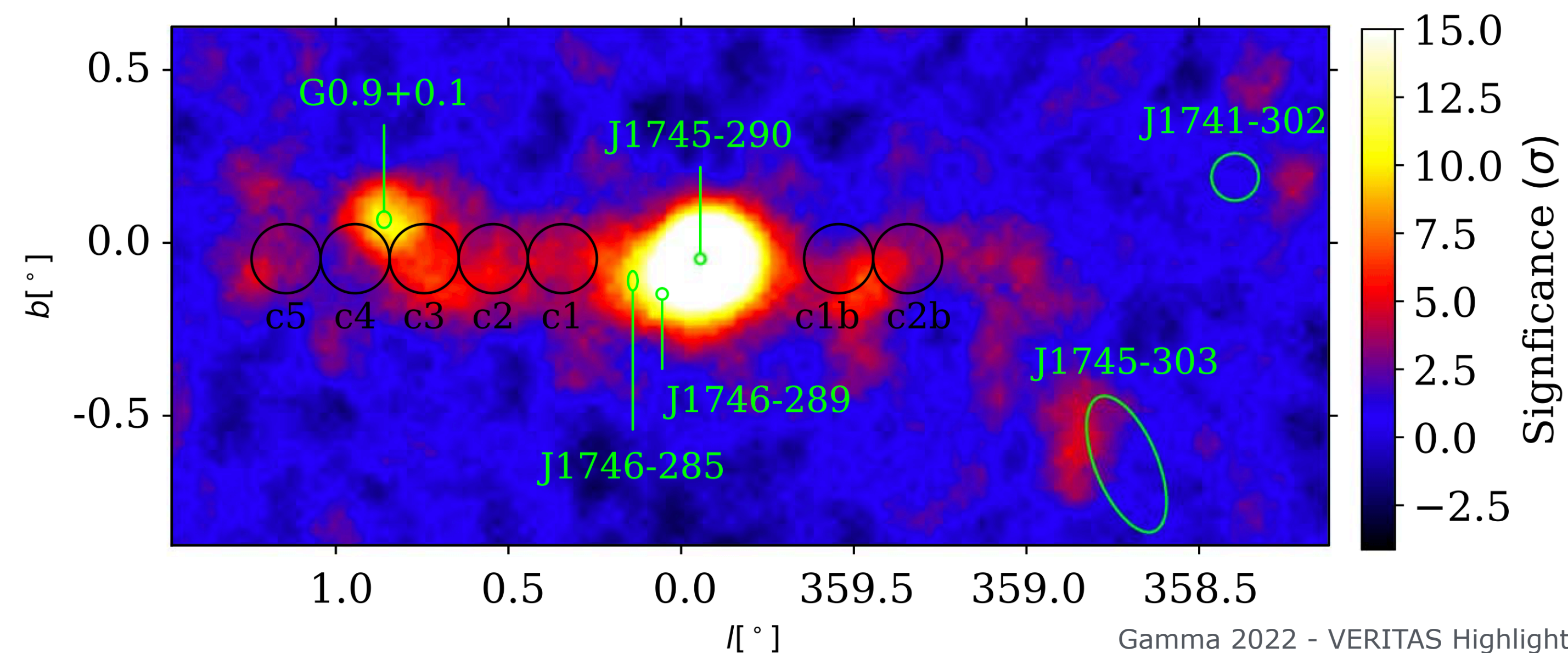
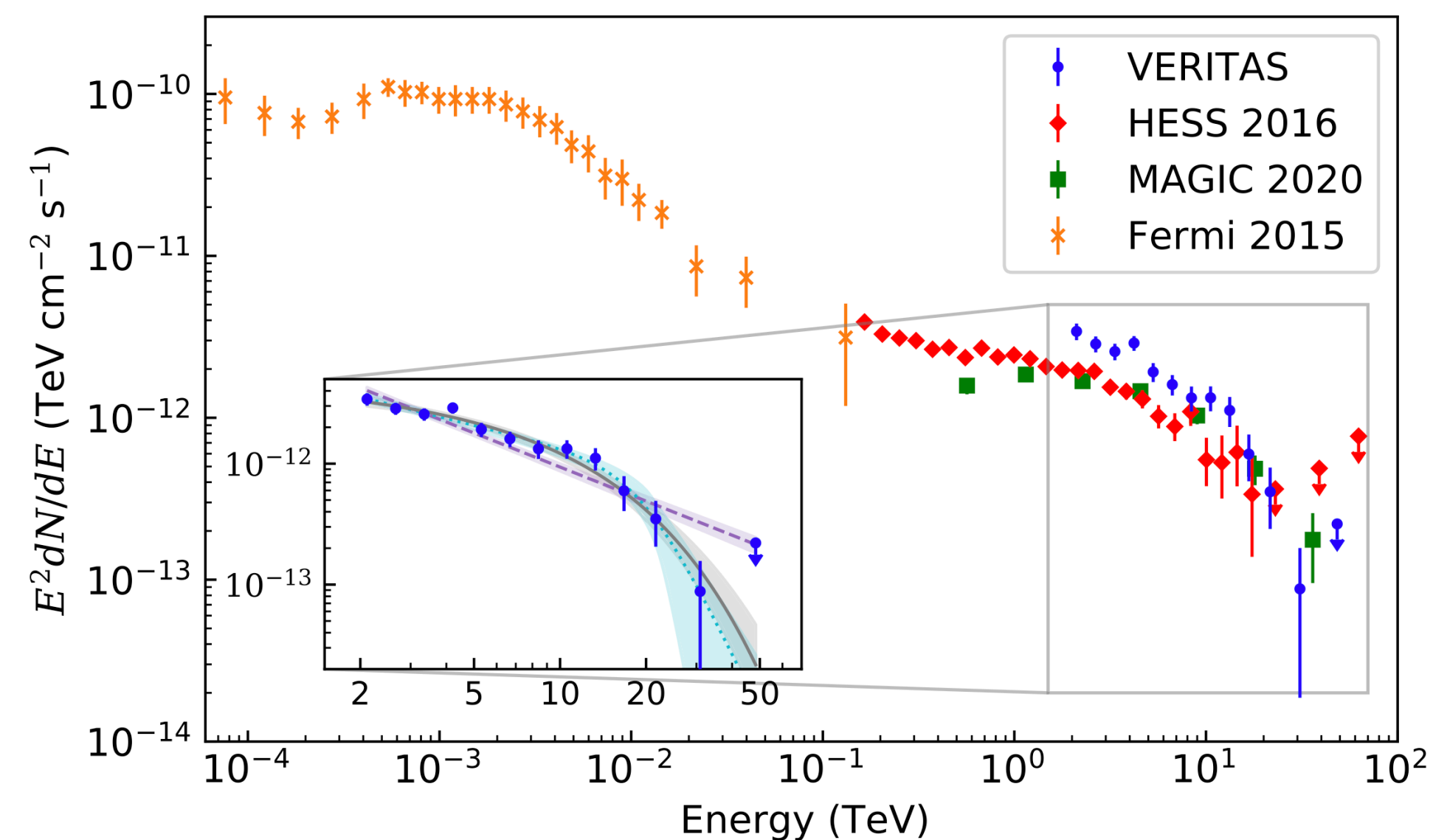
See talk by Nahee Park on LHAASO J2108+5157 & Boomerang MWL this afternoon

LHAASO J2108+5157

- A point-like source detected by LHAASO with no known counterparts in TeV gamma rays
- Non-detection after 35 hours of VERITAS observations in point and extended (0.25°) analyses
- VERITAS limits below IC CMB Model of Cao et al., 2021.
 - Point-source upper limits (95%) shown.

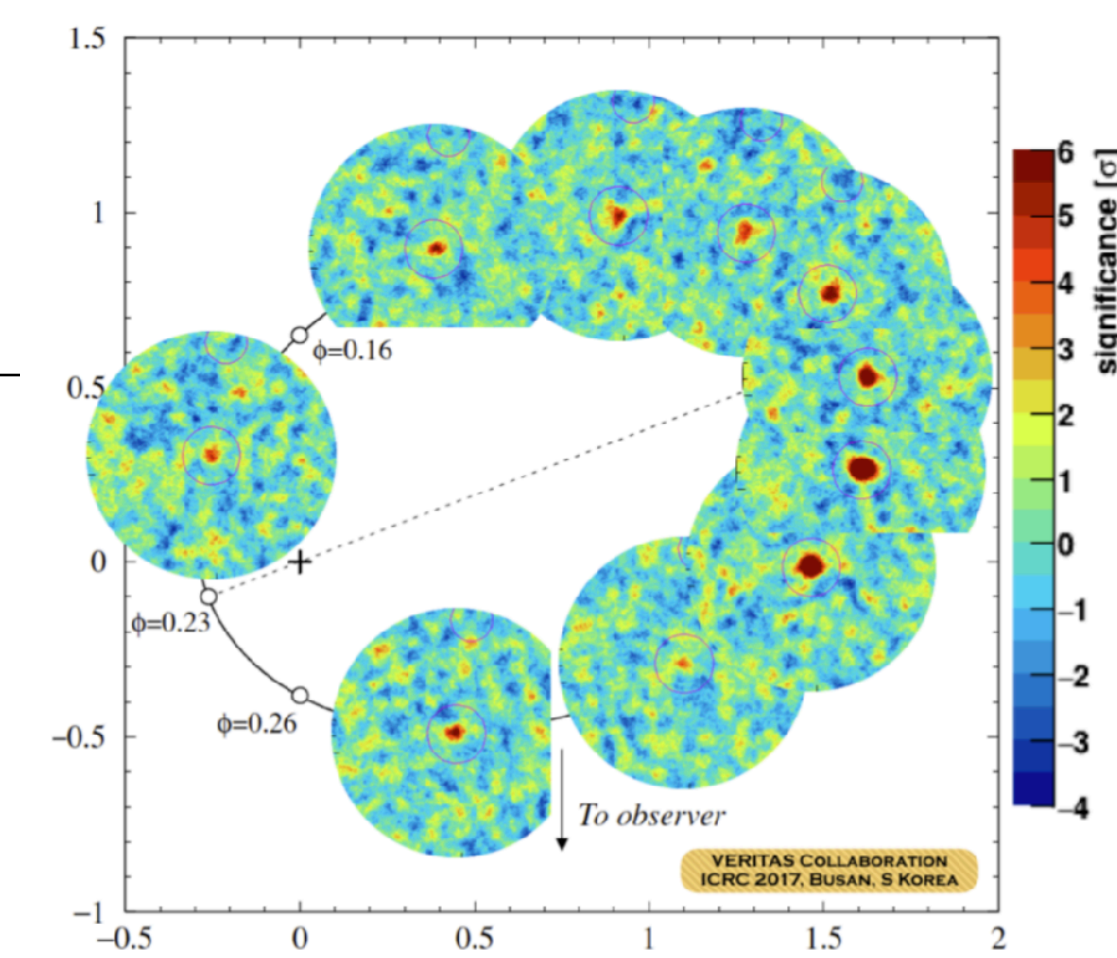


- VERITAS observations (*Adams et al., ApJ 913, 115 (2021)*):
 - 125 hours at zenith angle $\sim 60^\circ - 65^\circ$ yielding $E > 2$ TeV
 - **Sagittarius A***:
 - Detected at 38σ ,
 - Spectrum: PL Exp. Cutoff, $\Gamma = 2.12^{+0.22}_{-0.17}$, $E_c = 10$ TeV
 - Variability? no
 - **Diffuse Emission**:
 - Detected at 9.5σ
 - Spectrum: power law $\Gamma = 2.2 \pm 0.2$, no cutoff up to 40 TeV

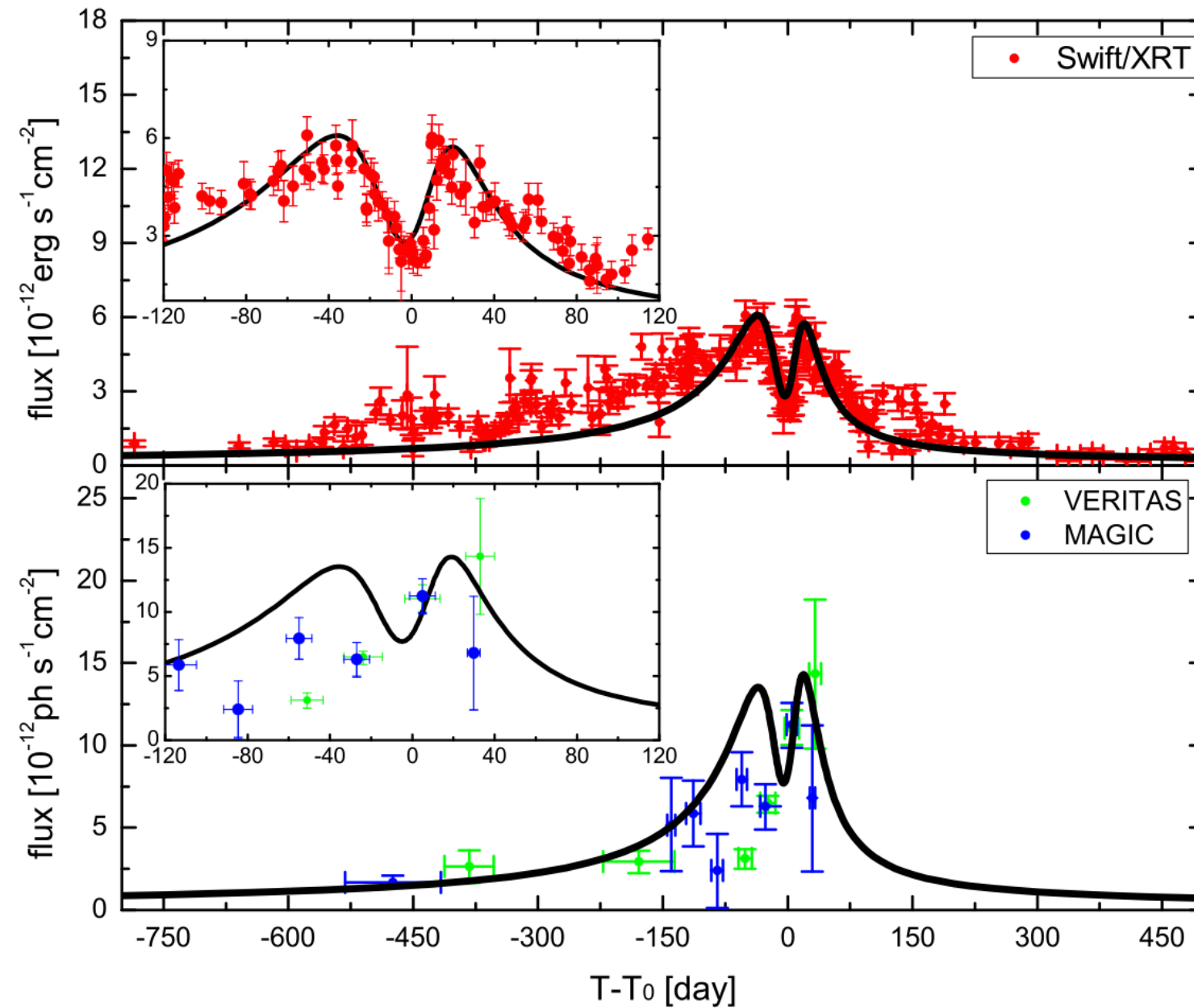


Galactic Science: Binaries

- VERITAS has detected **three binary systems** and conducts extensive monitoring
- See talk by Sonal Patel on Wednesday



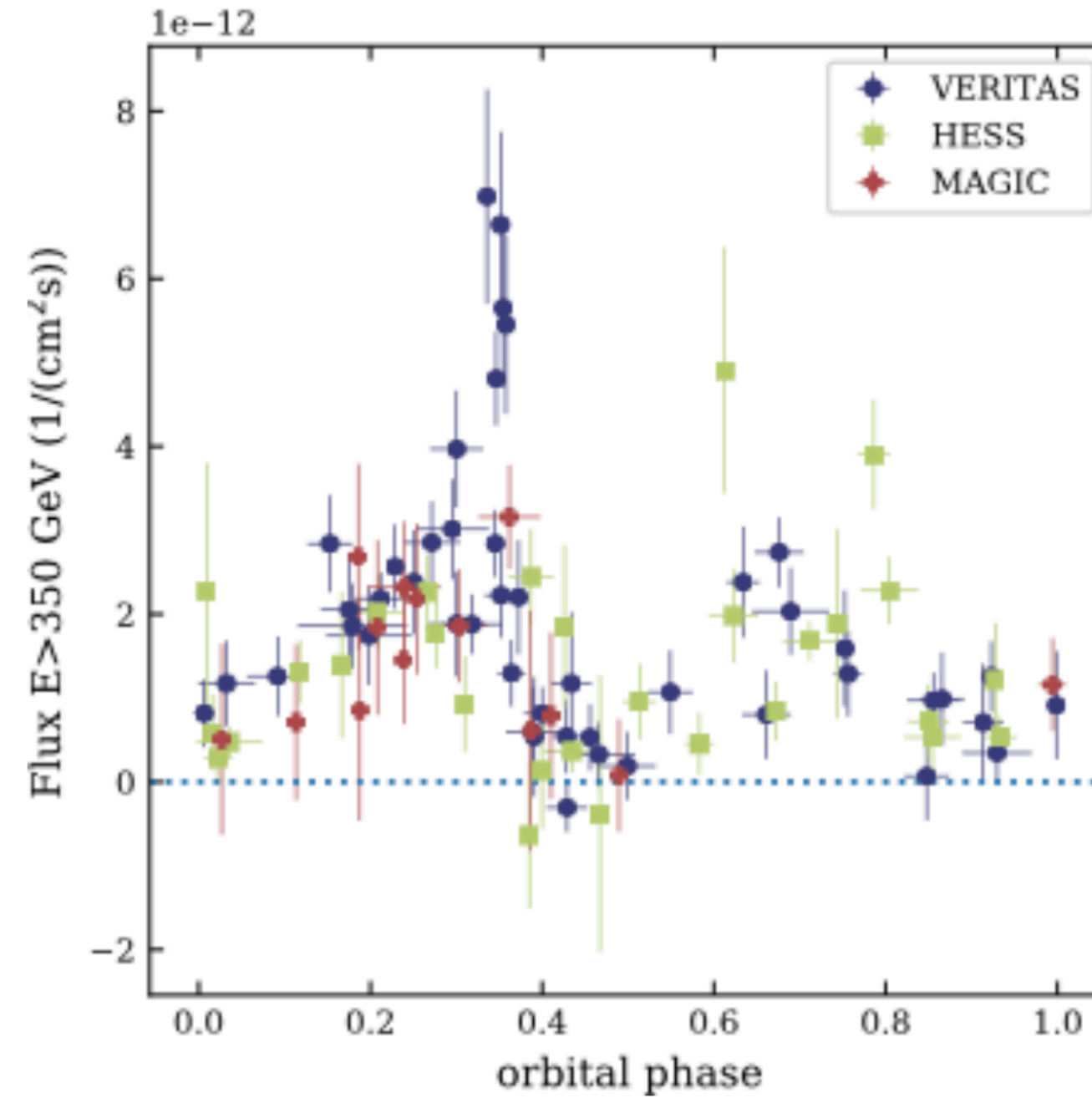
PSR J2032+4127/MT91 213



VERITAS & MAGIC data from: [Abeysekara et al., ApJ, 867 L19 \(2018\)](#)

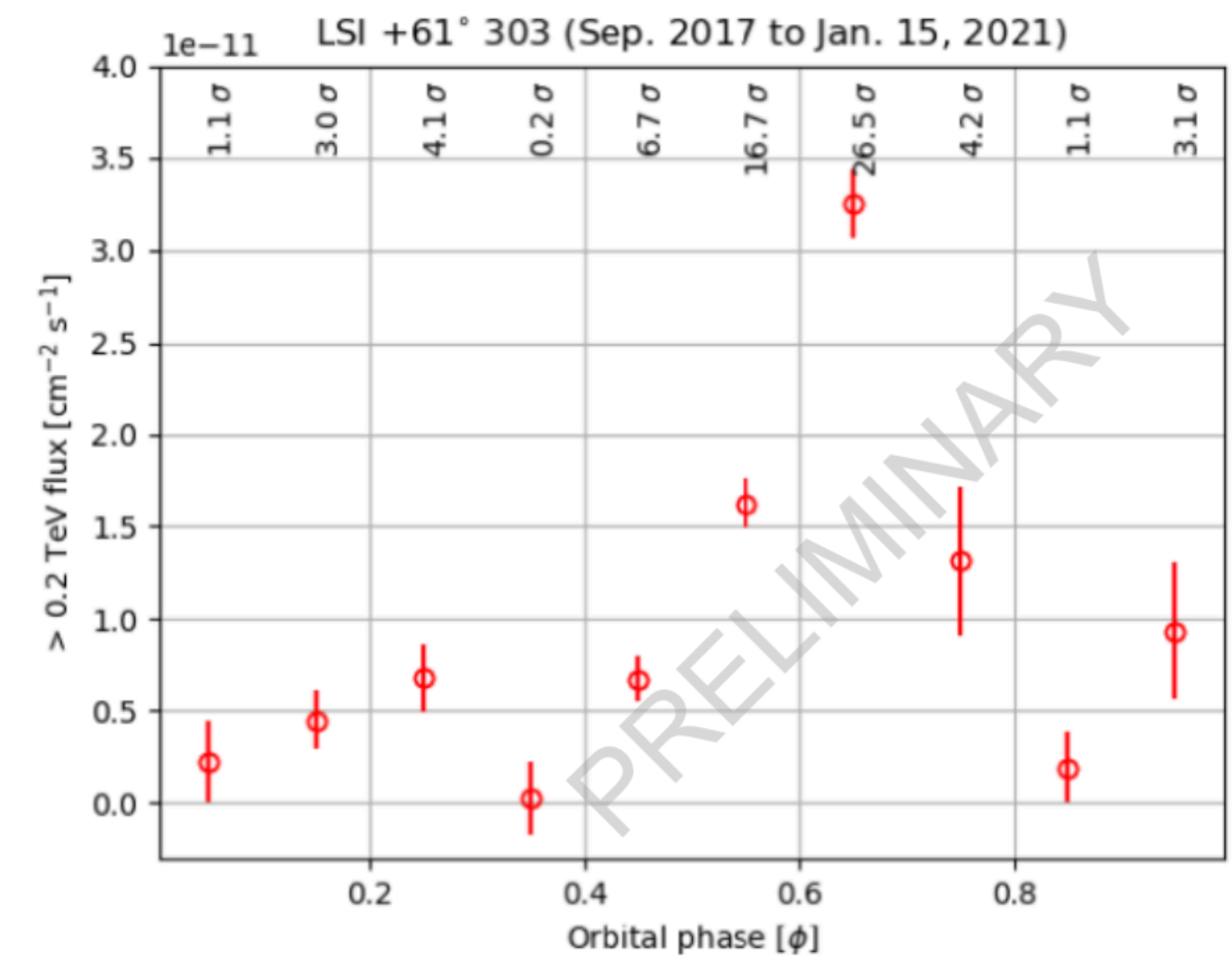
X-ray data and modelling: [Chen & Takata, A&A, 658, 153 \(2022\)](#)

HESS J0632



[Adams et al, ApJ , 923, 241 \(2021\)](#)

LS I +61 303



VERITAS:

- 180 hrs from Oct 2009 to November 2021
- Flux and spectra as function of orbital phase
- Correlation studies
- Superorbital modulation study

- **Science drivers:**

- particle location, content & acceleration mechanisms, magnetic fields in Blazar and Radio Galaxy jets
- Statistical properties of TeV emitting blazars as a population and contributions to cosmic ray and neutrino astrophysical fluxes

- **Observations:**

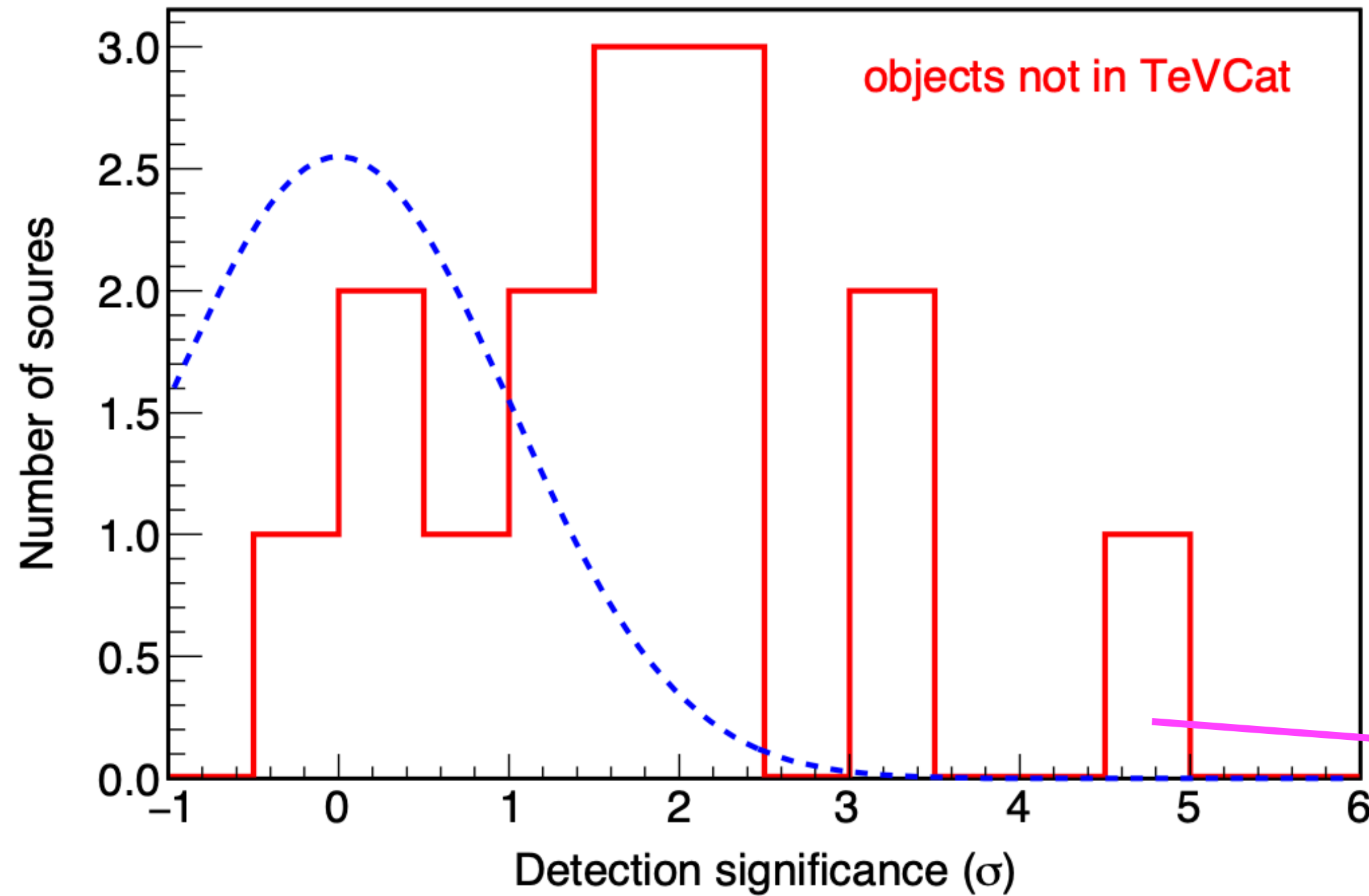
- ~200 hrs per year: monitoring & ToO
- MWL coverage: especially Swift XRT
 - 2022-2025 simultaneous with IXPE (Manel Errando - poster)
- **Flaring:**
 - OJ 287 (Oliver Hervet - talk this afternoon)
 - Mrk 421 giant flare (*Abeysekara et al., ApJ, 890, 97 (2020)*)
 - FSRQs (*Adams et al., ApJ, 924, 95 (2022)*)
 - Radio Galaxies (Lucy Fortson - talk this afternoon)
- **Multi-year deep exposures on many objects:**
 - Unbiased HBL Survey (Manel Errando talk yesterday)
 - HBL variability & spectra (Pedro Batista talk yesterday & Ste O'Brien poster)
 - Markarian 421 snapshots every night (Olivier Hervet poster)

Blazar	Type	z
1ES 0647+250	HBL	>0.29
3C 66A	IBL	0.33 < z < 0.41
RGB J2243+203	HBL	>0.39
PG 1553+113	HBL	0.43 < z < 0.58
1ES 0033+595	HBL	0.467?
HESS J1943+213	HBL	?
RGB J2056+496	Blazar	?

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
IC 310	FR I/HBL	0.019
3C 264	FR I	0.026

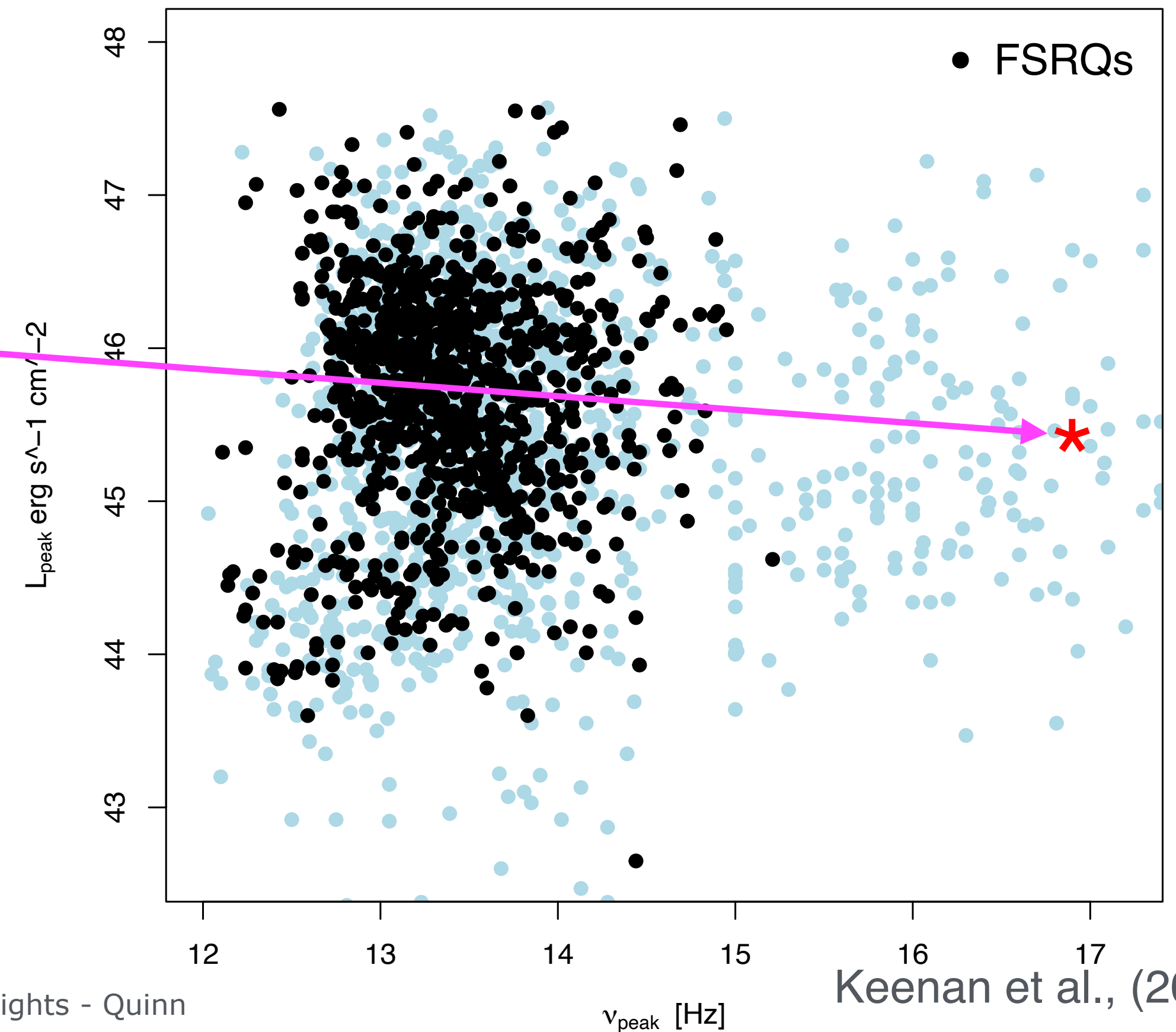
Blazar	Type	z
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	IBL	0.069
1ES 1741+196	HBL	0.084
W Comae	IBL	0.102
VER J0521+211	IBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
B2 1215+30	HBL	0.131
S3 1227+25	IBL	0.135
1ES 0806+524	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	0.190
1ES 1011+496	HBL	0.212
MS 1221.8+2452	HBL	0.218
RBS 1366	HBL	0.237
1ES 0414+009	HBL	0.287
OJ 287	LBL	0.306
TXS 0506+056	HBL	0.337
1ES 0502+675	HBL	0.341
PKS 1222+216	FSRQ	0.432
PKS 1424+240	IBL	0.601
Ton 599	FSRQ	0.720
PKS 1441+25	FSRQ	0.939

Unbiased HBL Survey



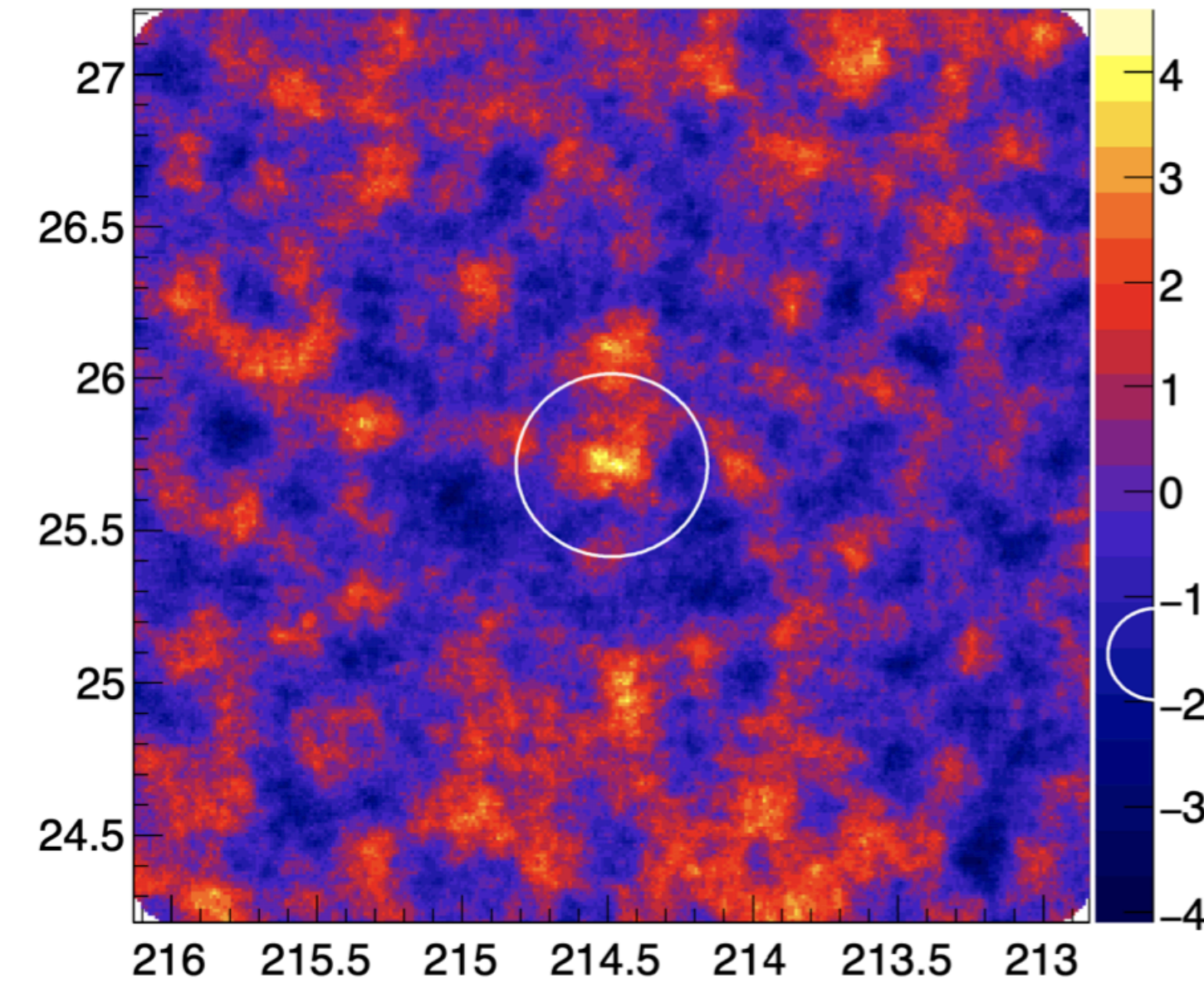
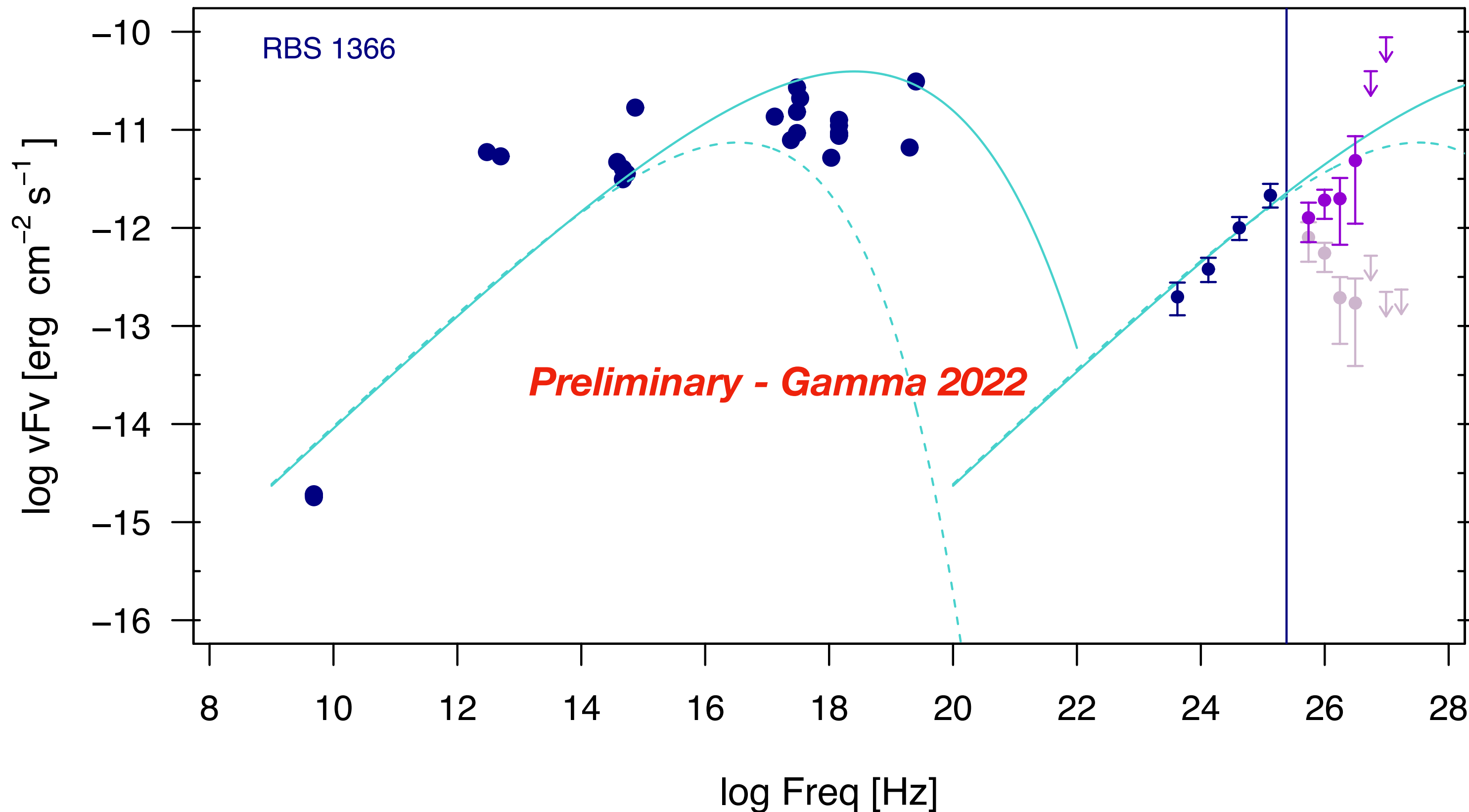
RBS 1366 (RGB J1417+257)

- $z = 0.237$
- Extreme HBL: $\log \nu_{peak}^{sync} [\text{Hz}] \approx 17.2$
- Proposed as TeV-peaked BL Lac (*Constamante (2020)*)
- Possible UHECR accelerator (*Twoomey et al., (2020)*)



- Talk by Manel Errando yesterday
- Unbiased study of 36 HBLs selected from 3HSP (Chan et al. 2019) based on synchrotron peak energy and luminosity.
- >2,000 hrs of archival data + new observations (all exposures > 8 hrs)

- Acquired additional data for unbiased Luminosity Function study \Rightarrow 60 hrs total.
- Analysis of complete data set $> 5\sigma \Rightarrow$ **New VHE Extreme HBL**
 - Flux $\sim 0.5\%$ Crab
 - Spectral index: -3.1 ± 0.5 (preliminary)



RBS 1366:

- $\log \nu_{peak}^{sync}$ [Hz] = 17.2 ± 0.2
- $z = 0.237$

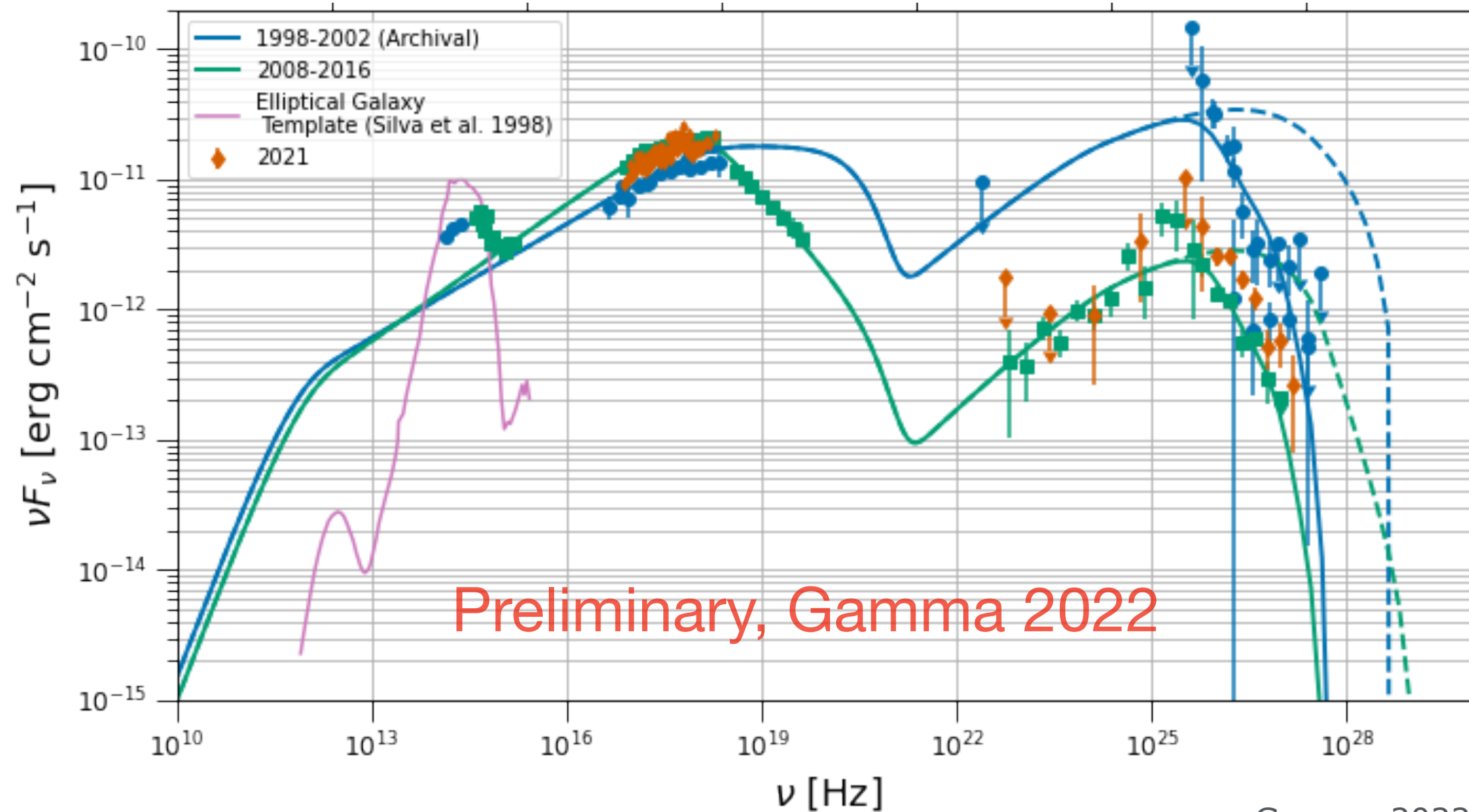
MWL data and SSC scaling courtesy of Eileen Meyer

Poster by Ste O'Brien+

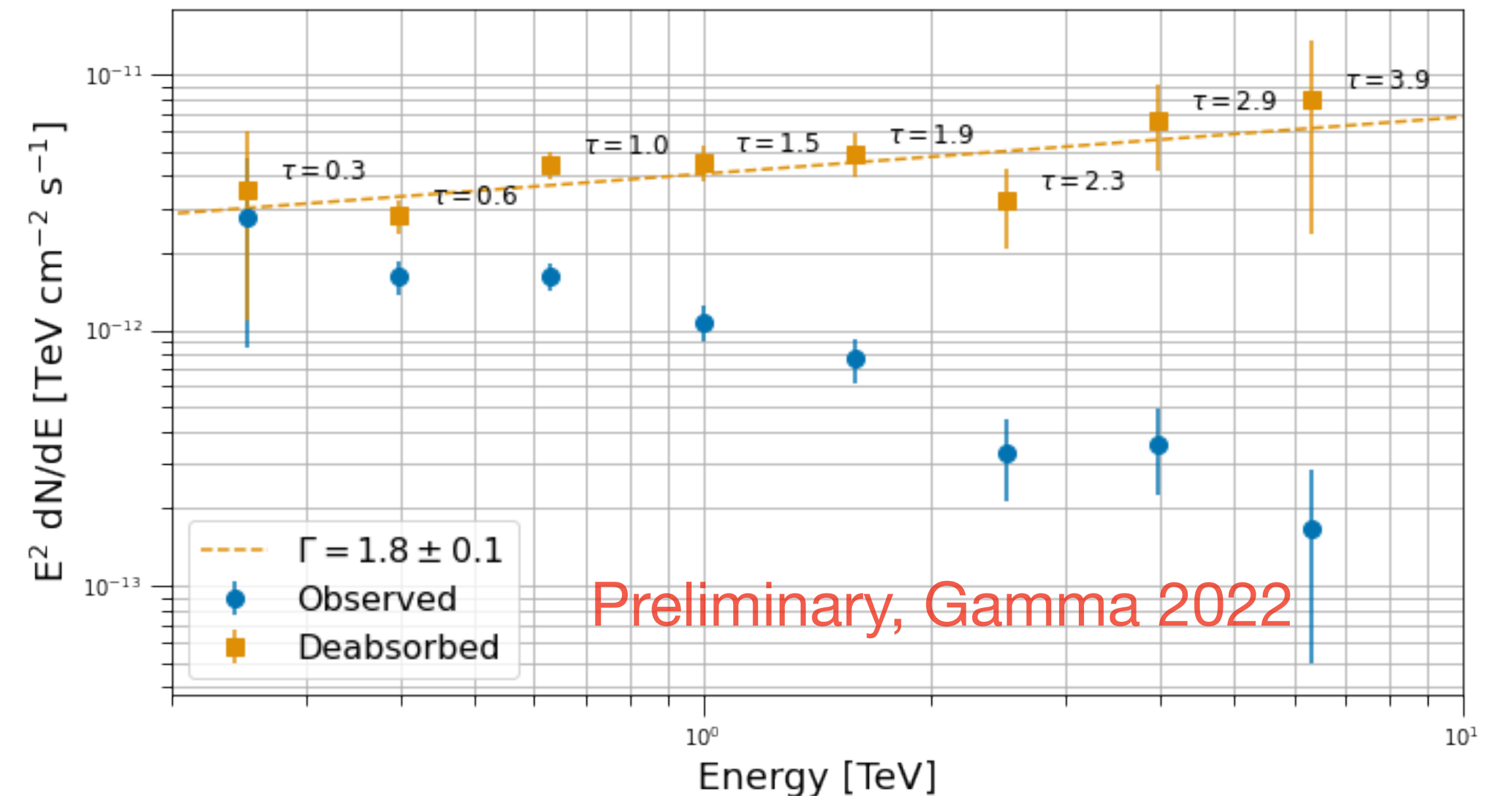
- 2008 - 2016 (86 hrs):
 - Detection: 13.7σ ,
 - mean flux: $(1.77 \pm 0.14) \% \text{ Crab}$, no evidence for VHE variability
 - spectrum: PL with $\Gamma = -2.79 \pm 0.12$ (up to 2.5 TeV)
 - MWL study with optical, Swift (UVOT, XRT, BAT), Fermi-LAT
 - Time-averaged SED modelled by Finke

- 2021 (42 hrs):
 - Detection: 16.8σ ,
 - mean flux; $(3.40 \pm 0.24)\% \text{ Crab}$
 - spectrum: PL with $\Gamma = -2.61 \pm 0.07$ (up to 6.3 TeV)
 - EBL-corrected (Finke et al., 2010) spectrum shows no evidence for a cutoff up to at least 6 TeV

Spectral Energy Distribution(s)

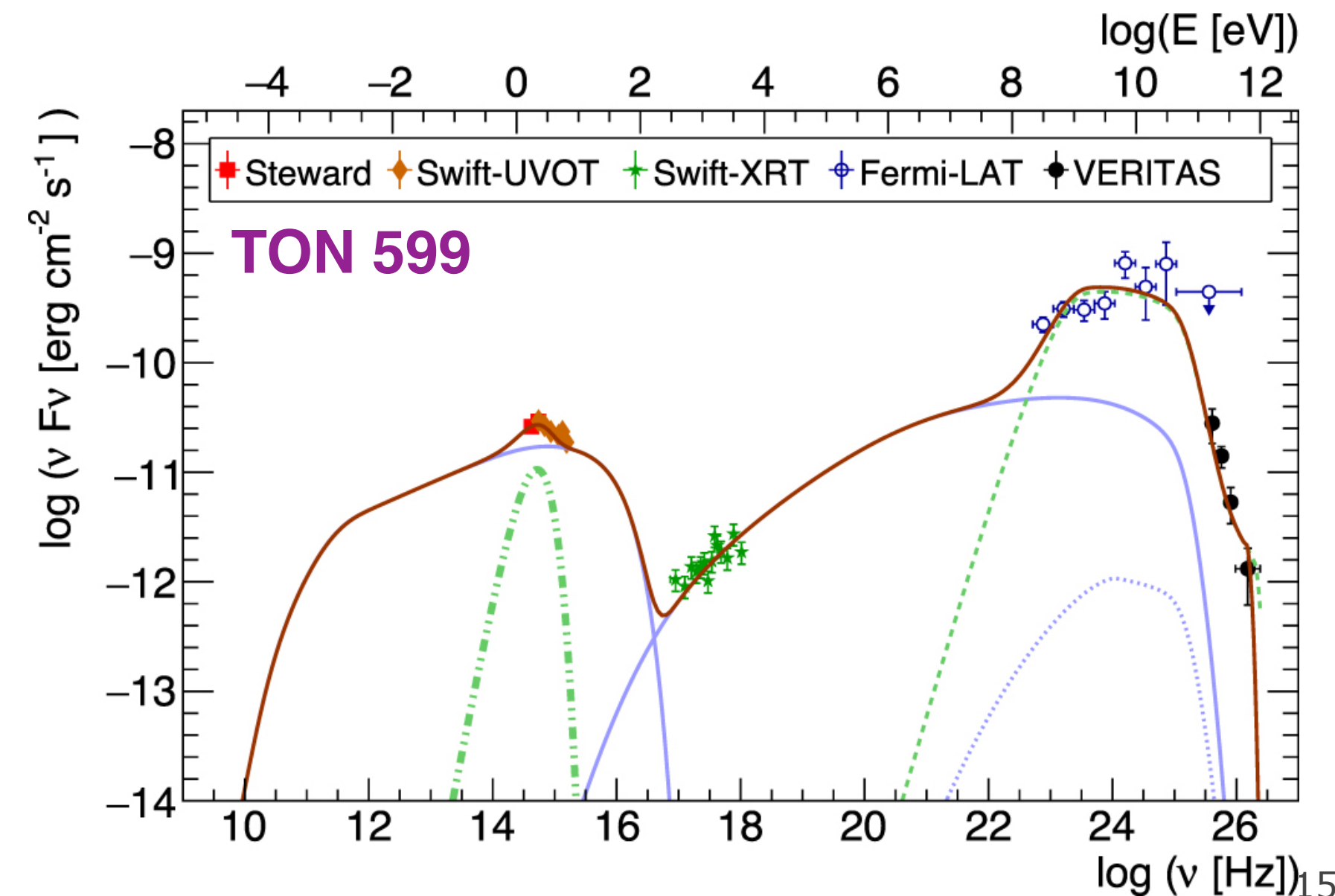
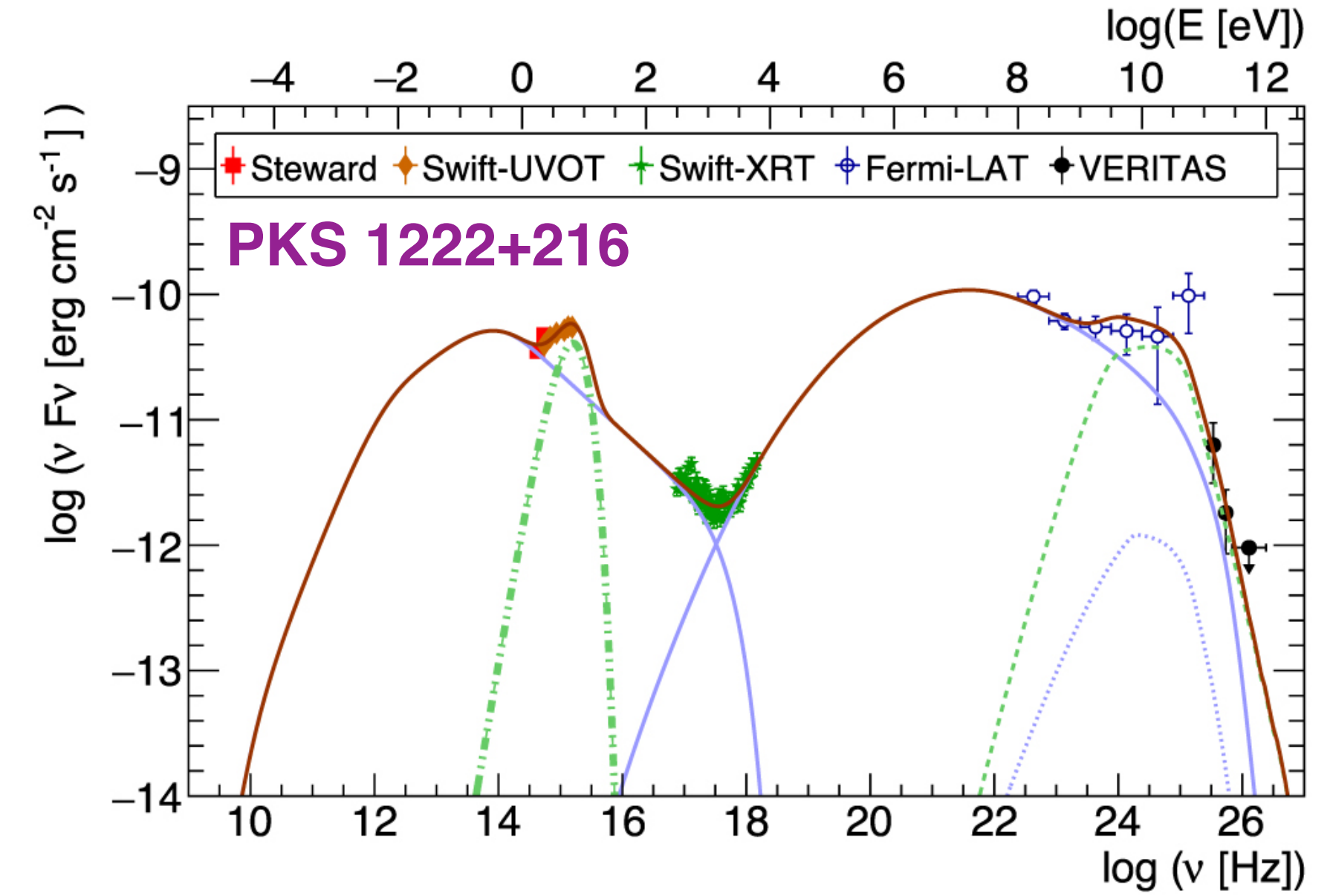
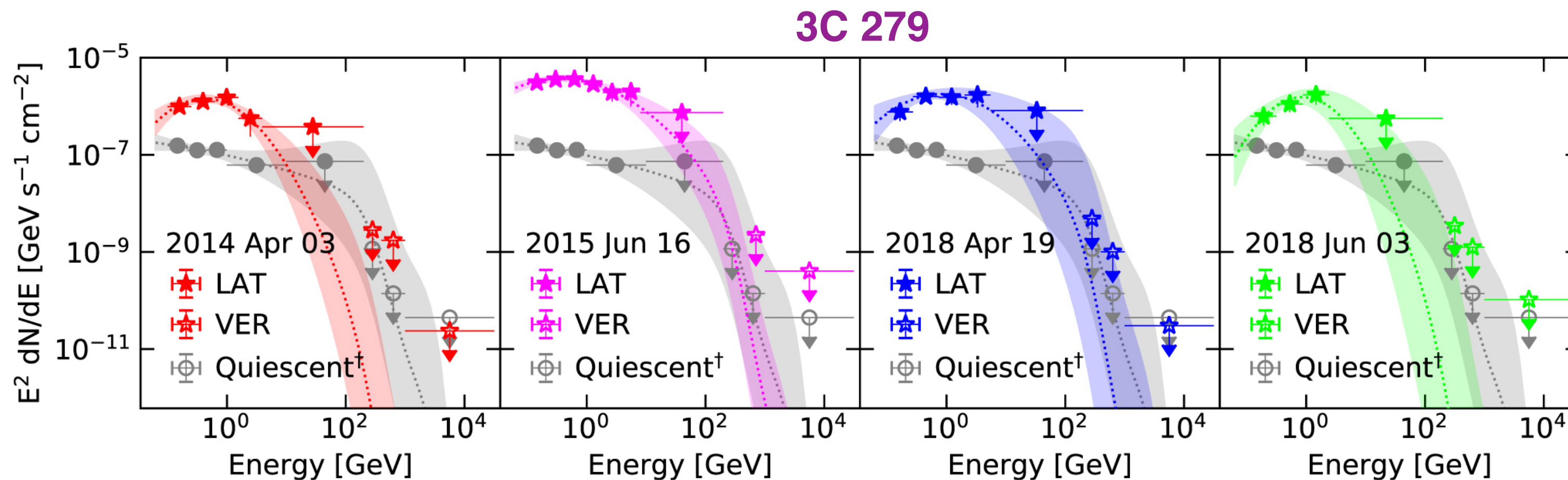


2021 VERITAS H 1426+428 spectrum



Variability and Spectral Characteristics of Three Flaring Gamma-Ray Quasars Observed by VERITAS and Fermi-LAT, (Adams et al., ApJ, 924, 95 (2022))

- 100 hrs of VERITAS observations spanning 10 years + Fermi LAT
- PKS 1222+216 and Ton 599 detected by VERITAS during flaring states
- Flux upper limits only on 3C 279
- Flare SEDs:
 - Modelled with purely leptonic model with external IC component:
 - TeV emission dominated by EIC of BLR photons
 - Doppler factor for PKS 1222+216 $\gtrsim 40$ and Ton 599 $\gtrsim 50$



Due to viewing angles larger than blazars, radio galaxies can aid understanding of jet physics

Catalog of VHE-detected radio galaxies

Name	Cross-ID	Type	Distance	BH mass [10 ⁸ M _⊙]
Cen A	NGC 5128	FR I	3.7 Mpc	(0.5-1)
M87	NGC 4486, Virgo A	FR I	16 Mpc	(20-60)
NGC 1275	3C84, Perseus A	FR I	70 Mpc	3-4
IC 310	B0313+411	FR I/ BL Lac	80 Mpc	3 [0.3?]
3C 264	NGC 3862	FR I	95 Mpc	4-5
PKS 0625-35	OH 342	FR I/ BL Lac	220 Mpc	~10

Rieger & Levinson 2018

VERITAS detected so far

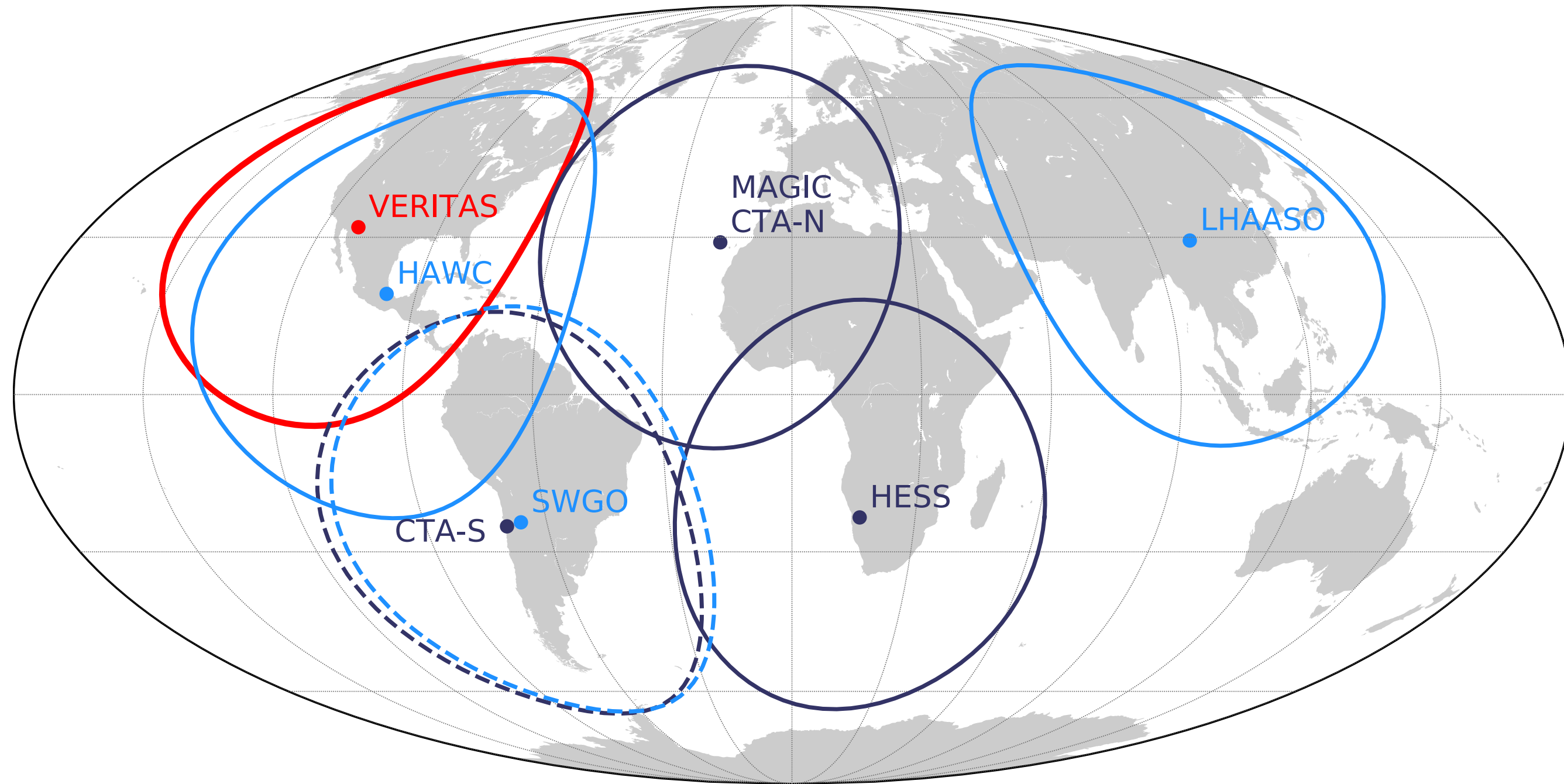
Long-term monitoring of all detected radio galaxies:

- M87 including and independent of EHT campaigns
- NGC 1275: 8 years of VERITAS and MWL data
 - See Lucy Fortson talk this afternoon

Discovery program ongoing.....

Non-detections to date:

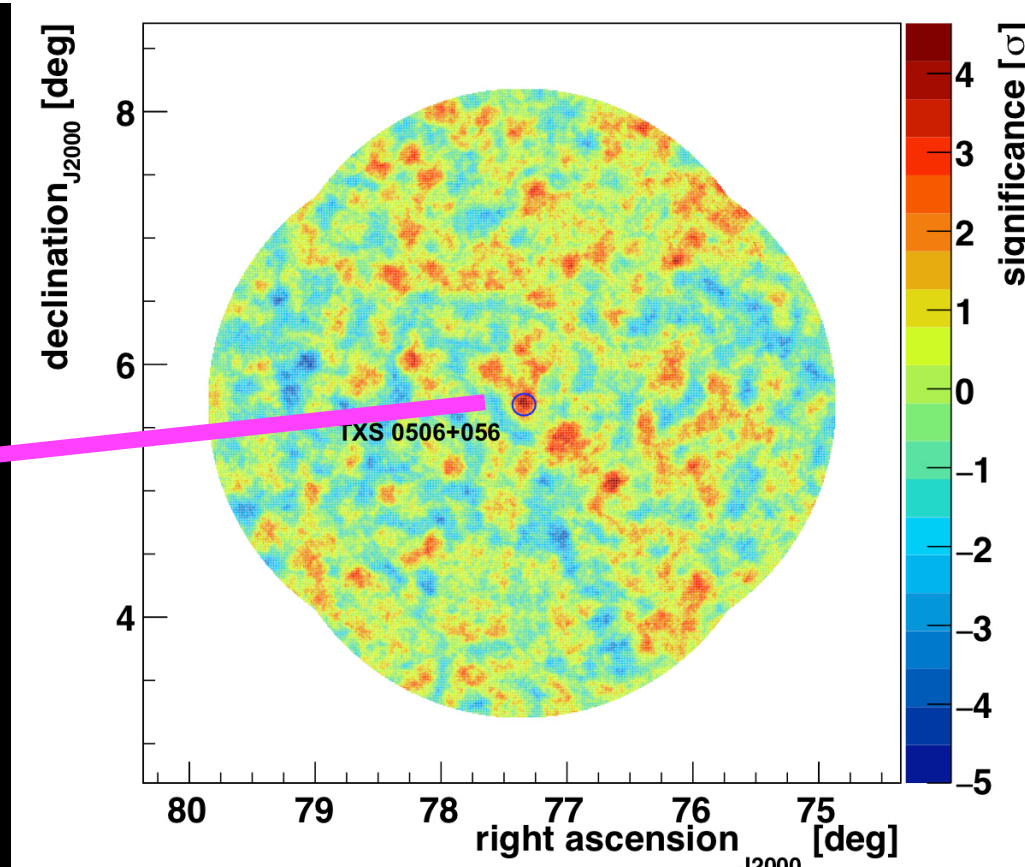
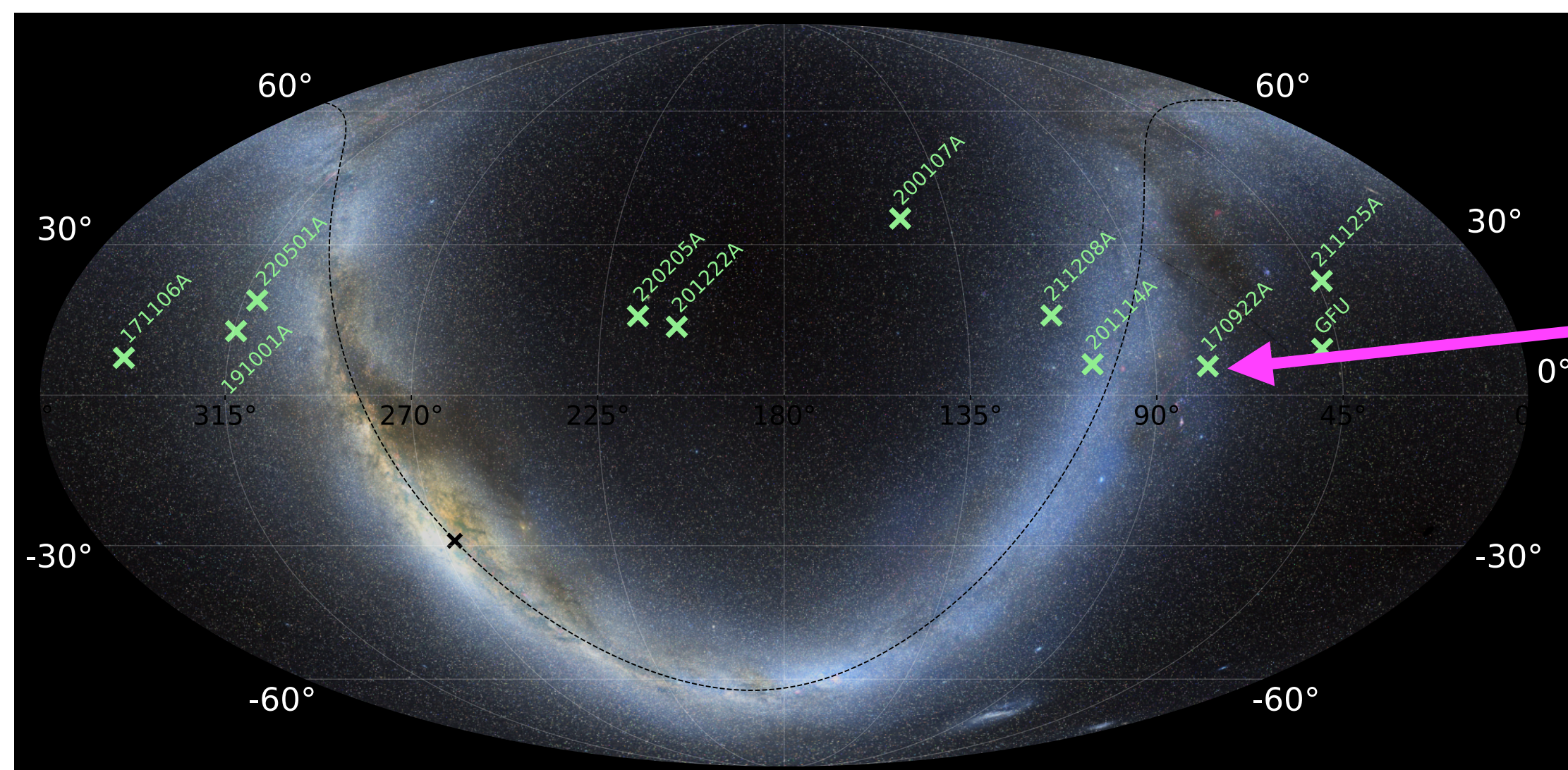
- 4C +39.12: 11 hrs → 0.17σ
possible neutrino source with hard Fermi-LAT spectrum
- 3C 303: 9.5 hrs → 1.23σ
- B2 1113+29: 9.5 hrs → 0.89σ



Extensive follow-up programs:

- Neutrinos
- Gravitational Waves
- Fast Radio Bursts
- Gamma-ray Bursts
- Tidal Disruptions
- Superluminous Supernovae

 Air-shower arrays
 IACTs



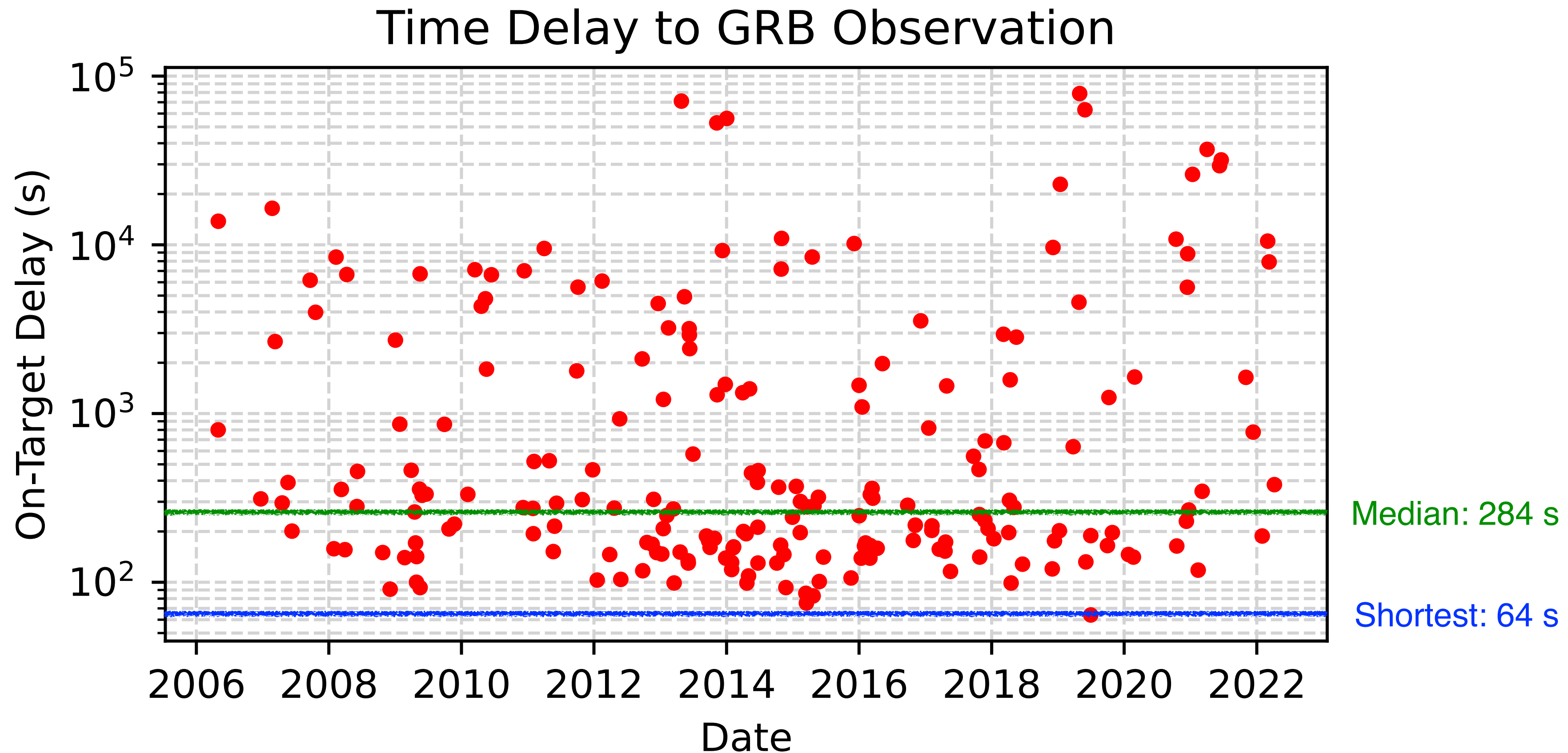
Name	Energy [TeV]	Signalness	FACT	H.E.S.S.	MAGIC	VERITAS
IceCube-171106A	230	0.75	19 h	—	4.5 h	2.5 h
IceCube-181023A	120	0.28	1 h	—	—	—
IceCube-190503A	100	0.36	—	—	0.5 h	—
IceCube-190730A	299	0.67	—	—	3.1 h	—
IceCube-190922B	187	0.50	5.4 h	—	2.2 h	—
IceCube-191001A	217	0.59	2.0	—	2.3 h	1.0 h
IceCube-200107A	—	—	—	—	2.7 h	9.5 h
IceCube-200926A	670	0.44	—	1.3 h	1.0 h	—
IceCube-201007A	683	0.88	—	3.25 h	0.5 h	—
IceCube-201114A	214	0.56	—	14.5 h	6 h	7 h
IceCube-201222A	186	0.53	—	—	—	1.0 h

MAGIC, IceCube, FACT, H.E.S.S. and VERITAS collaborations PoS ICRC2021 960

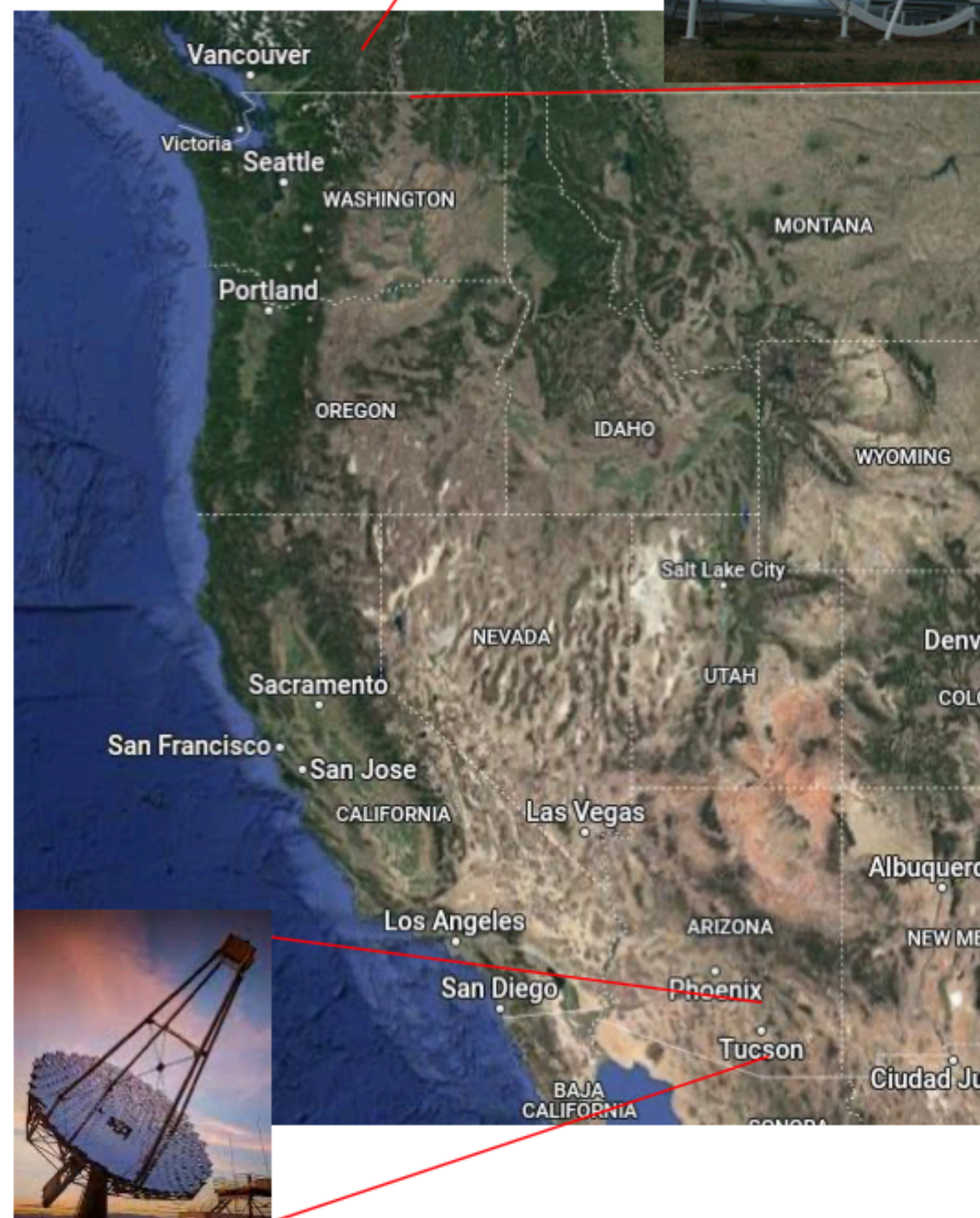
- **Automatic repointing** for alerts from IceCube through GCN (GOLD and BRONZE) or private email.
- **9 follow-up observations on real-time neutrino alerts since TXS 0506+056 + 1 from Gamma-ray Follow-Up (GFU) program.**
 - **No detections**
- **TXS 0506+056:**
 - collected **>100 hrs** so far.
 - **Low-flux state since 2018** (0.5% Crab in 61 hrs).
 - **MWL campaigns** including NuSTAR+Swift to characterise long-term behaviour.
 - Paper in preparation.
- Collaborative papers with MAGIC, FACT, H.E.S.S. and IceCube.

VERITAS Gamma-Ray Burst Program

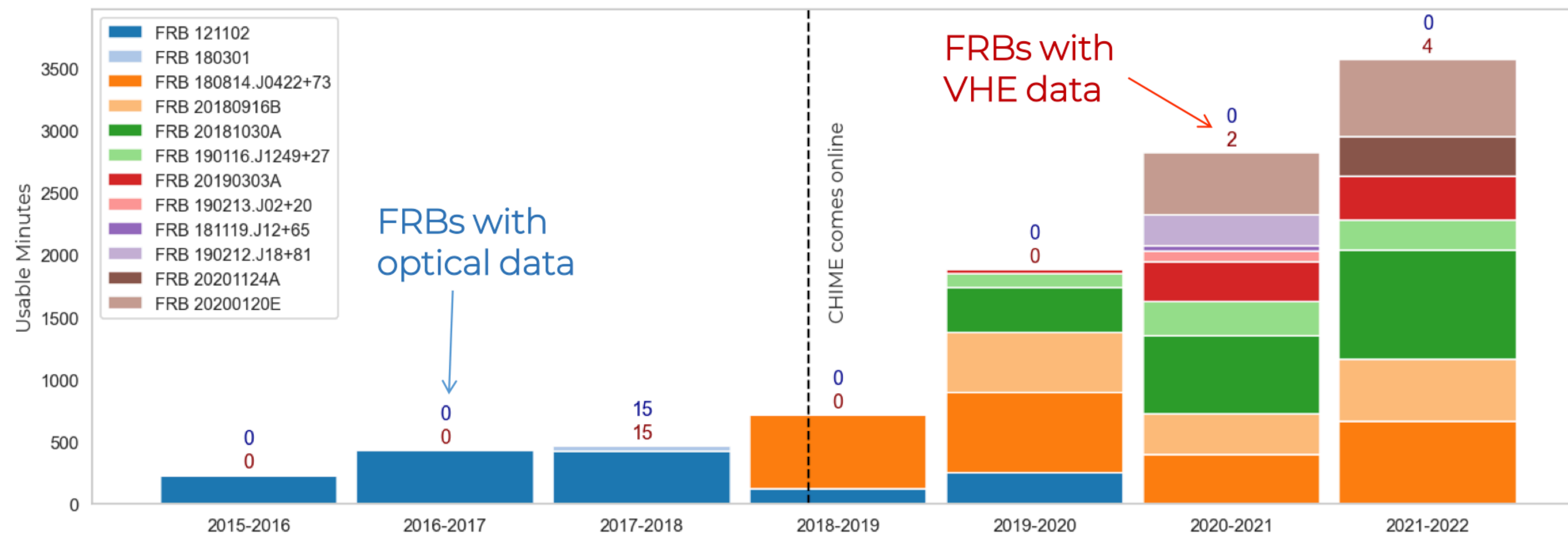
- Gamma-ray burst observations have high-priority - interrupt all other observations.
- 211 GRBs observed to date
- 127 bursts with a position < VERITAS PSF (Swift [122], INTEGRAL[4], MAXI[1])
- No detections, stacked analysis underway



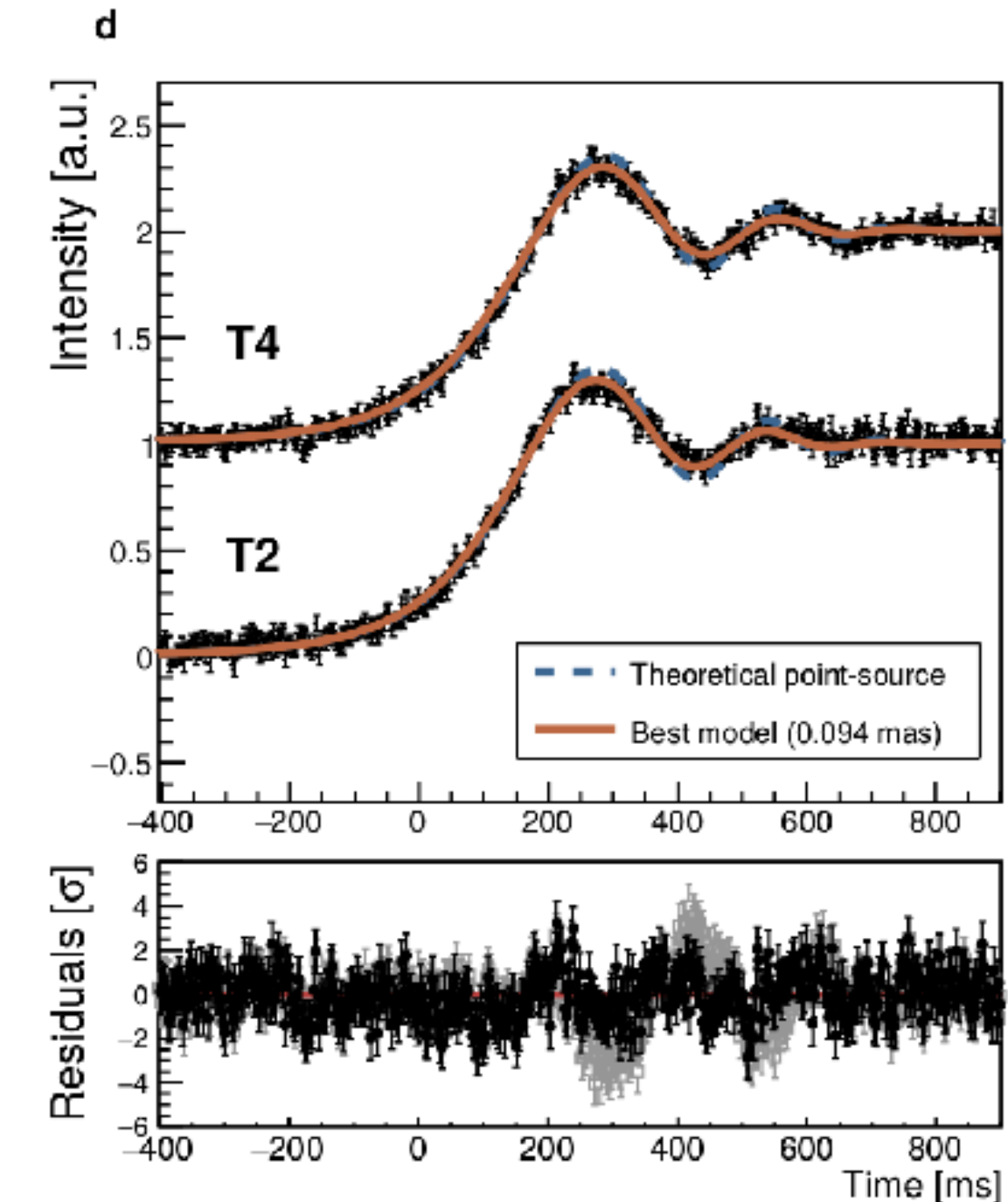
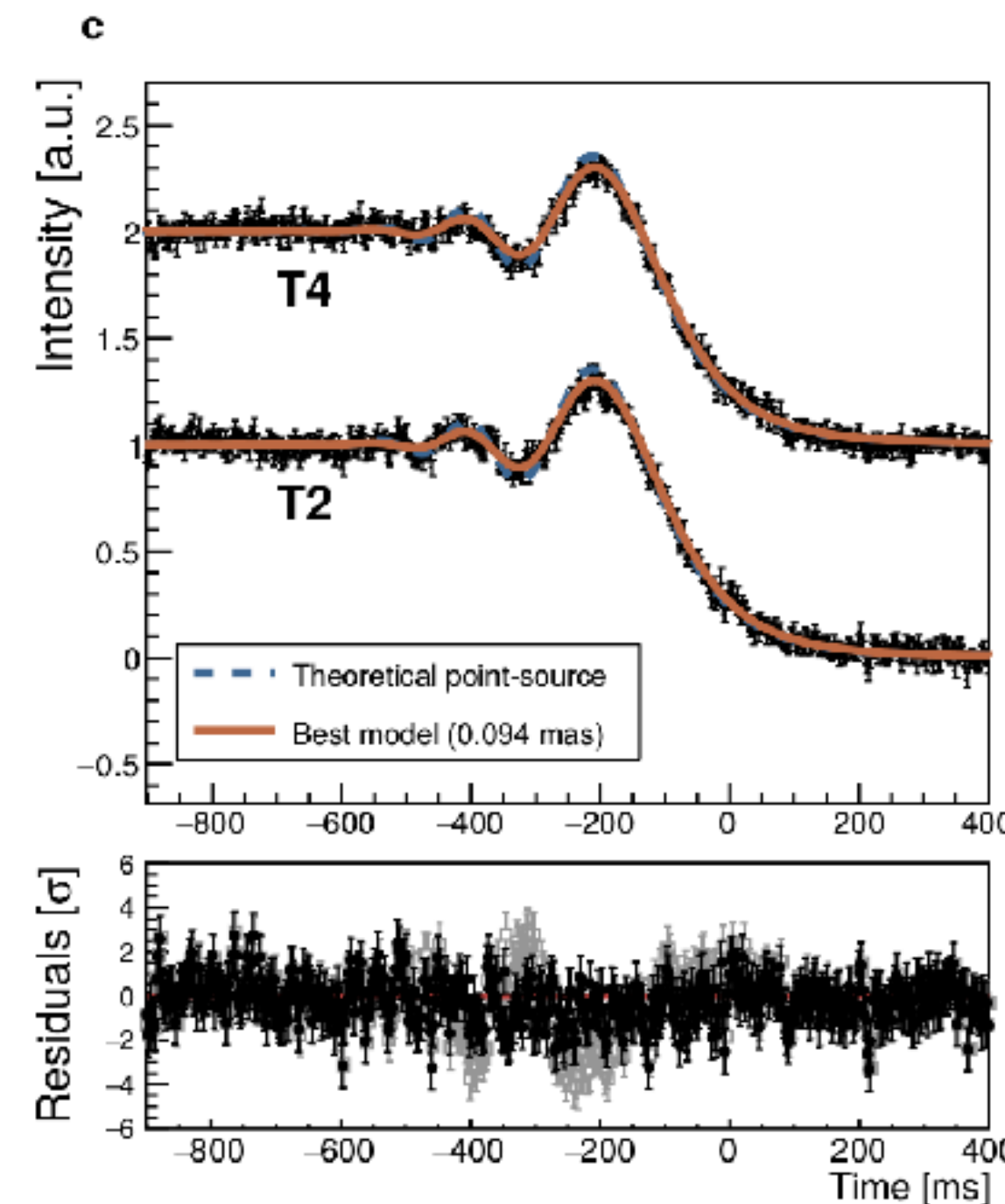
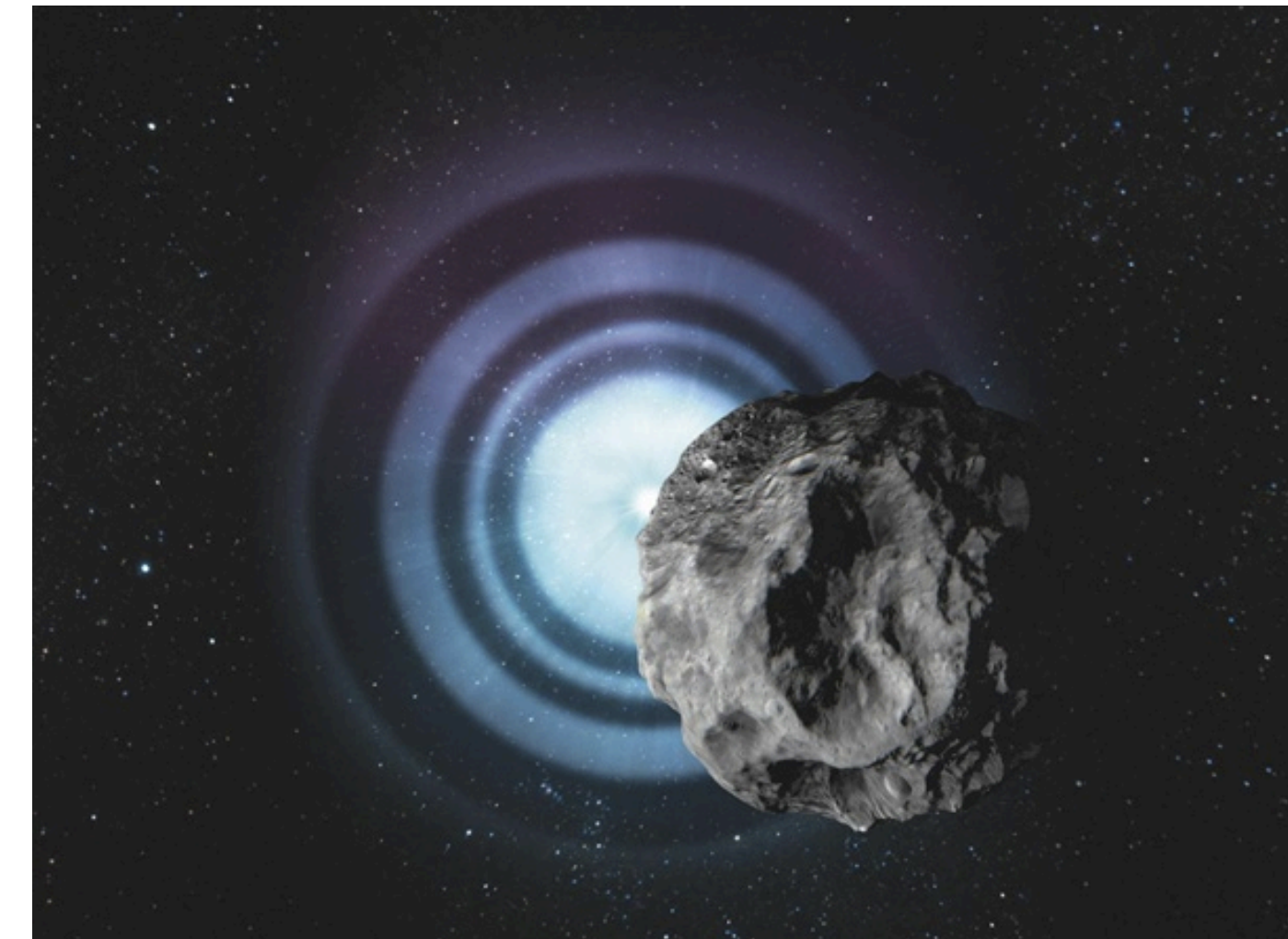
VERITAS - CHIME Synergy



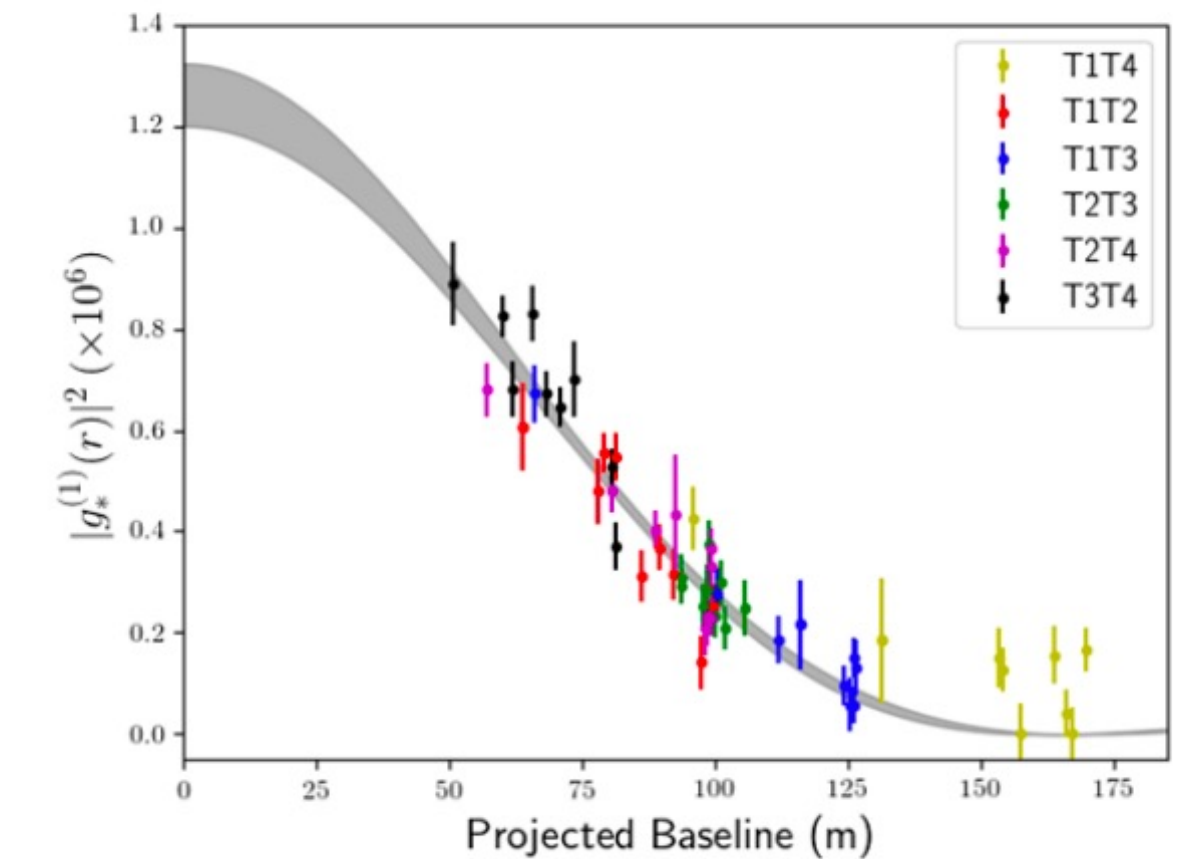
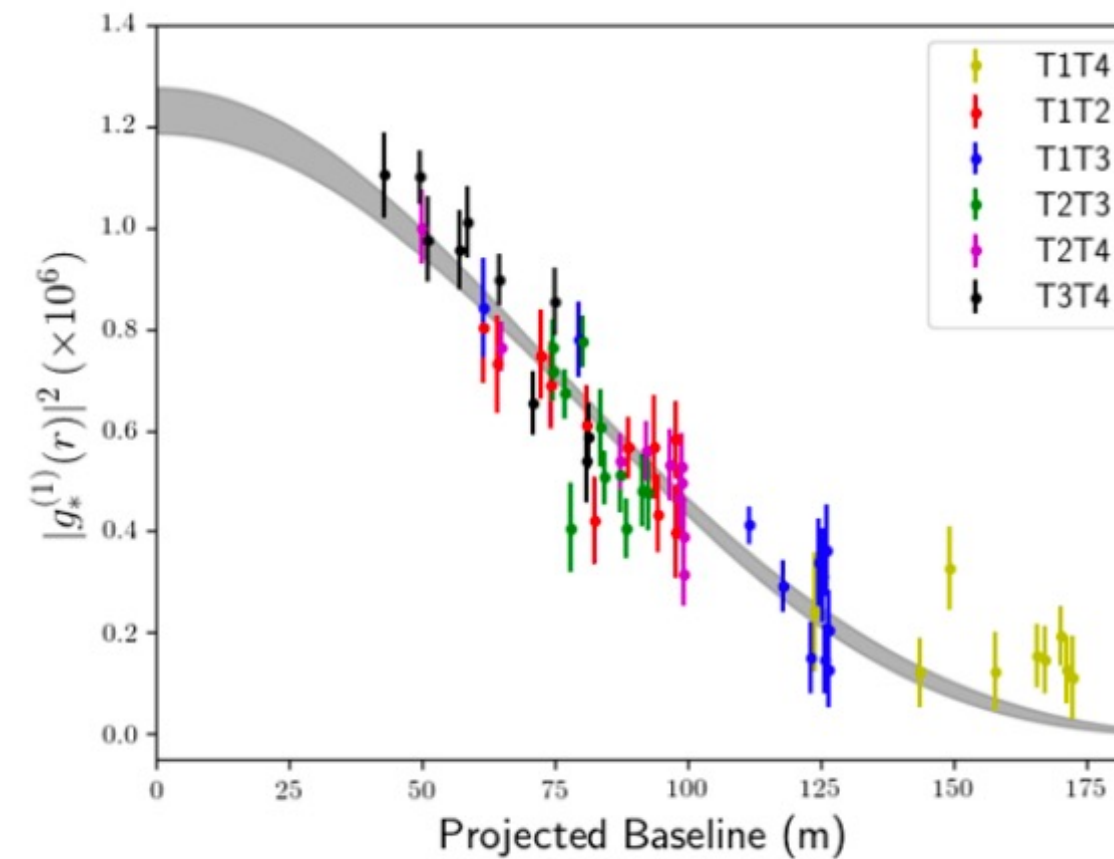
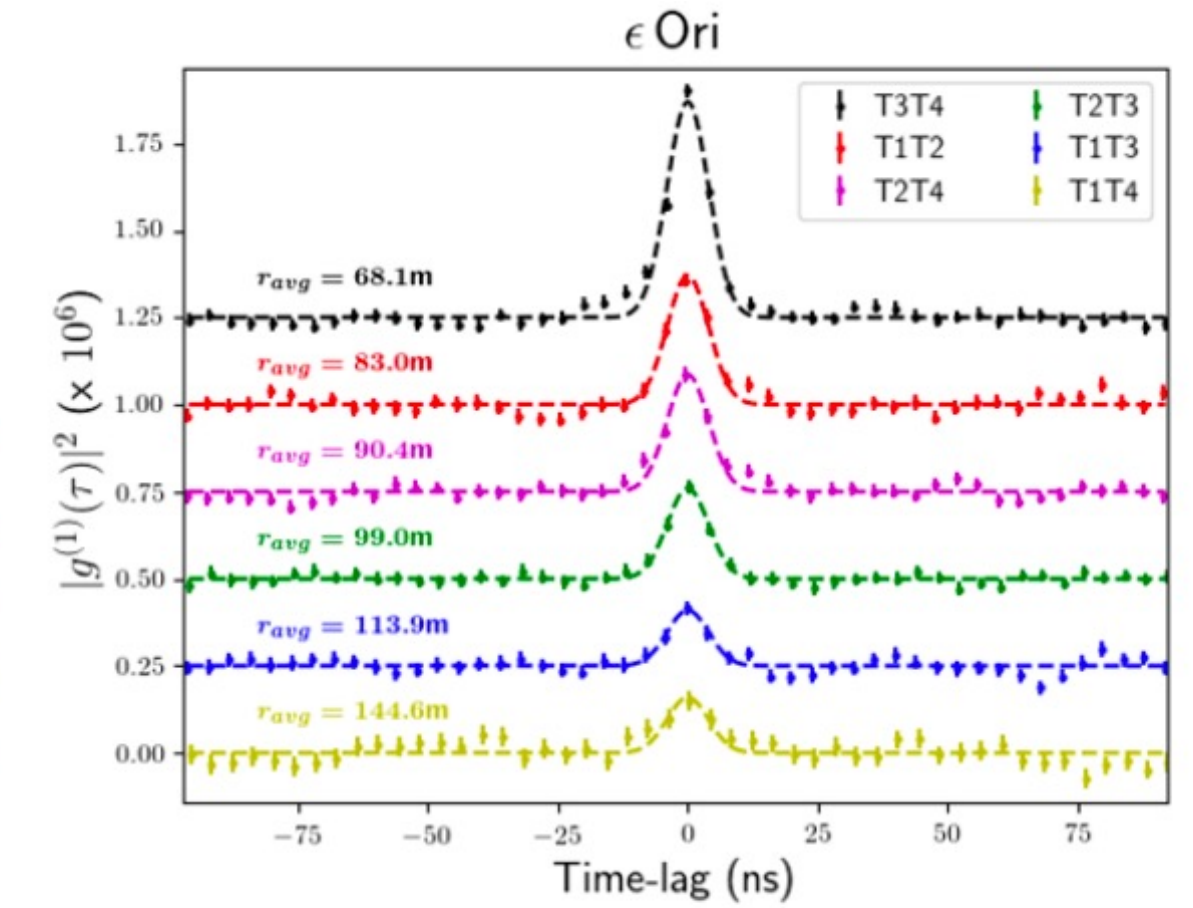
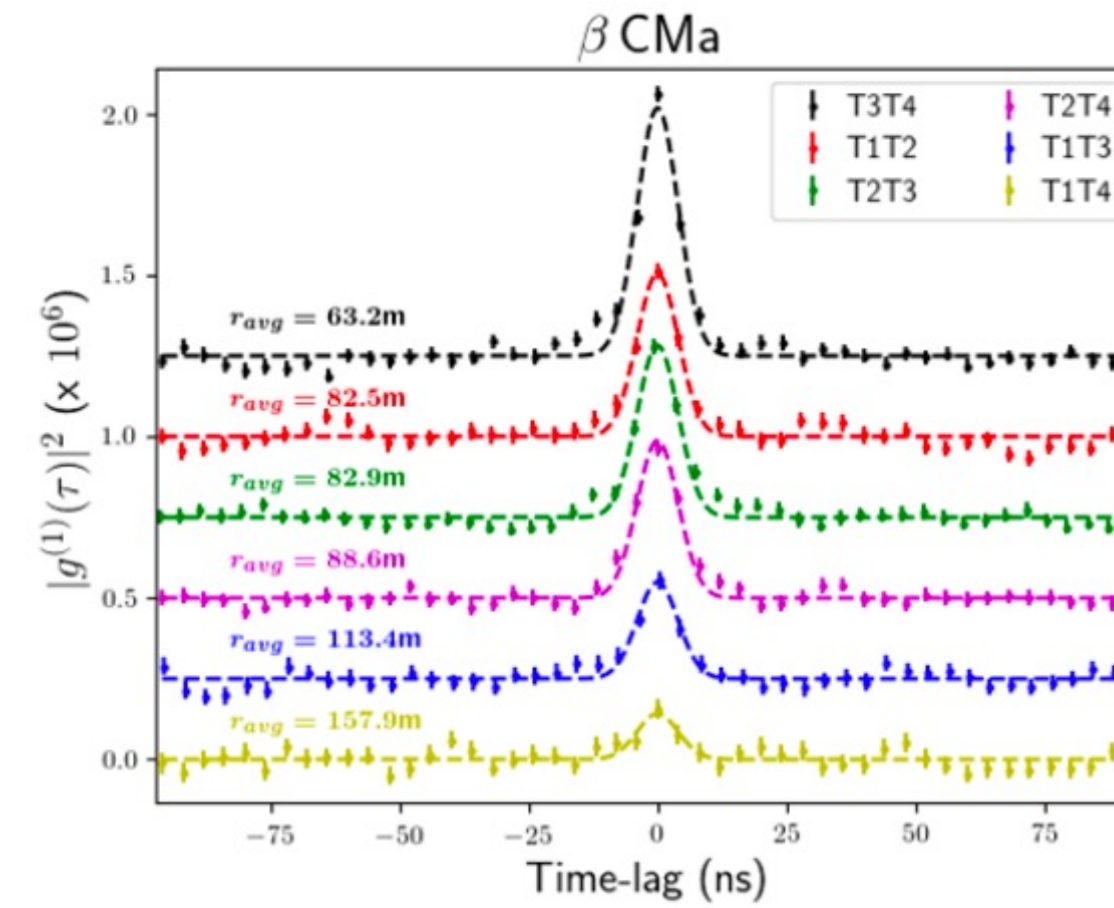
- Canadian Hydrogen Intensity Mapping Experiment (**CHIME**) is a radio (400-800 MHz) wide FoV instrument that has detected > 500 FRBs.
- **VERITAS** is able to observe **simultaneously** with **CHIME**.
- Contemporaneous CHIME data on all VERITAS observations of repeaters **if VERITAS observes ~35 minutes from culmination.**
- VERITAS performs **simultaneous gamma-ray and rapid optical** observations (2-4 pixels)
- Data taken on ~11 FRBs (mostly repeaters) with overlapping VHE data on 21 bursts.
- **See talk by Matthew Lundy tomorrow**



- VERITAS Enhanced Current Monitor: measures 2-4 pixels in the camera at a rate of 1,200 - 2,400 Hz down to a magnitude limit of ~12 mag
- Applications:
 - FRBs (talk by Matthew Lundy tomorrow)
 - Direct measurement of stellar angular diameters by the VERITAS Cherenkov Telescopes (Nature Astronomy, 3, 511 (2019))
- VERITAS NSF-funded FADC upgrade
 - Continuous NSB monitoring of all pixels.
 - Capability:
 - Full FoV optical transients on timescales from μs to 10s of seconds (mag. ~10 to ~19)



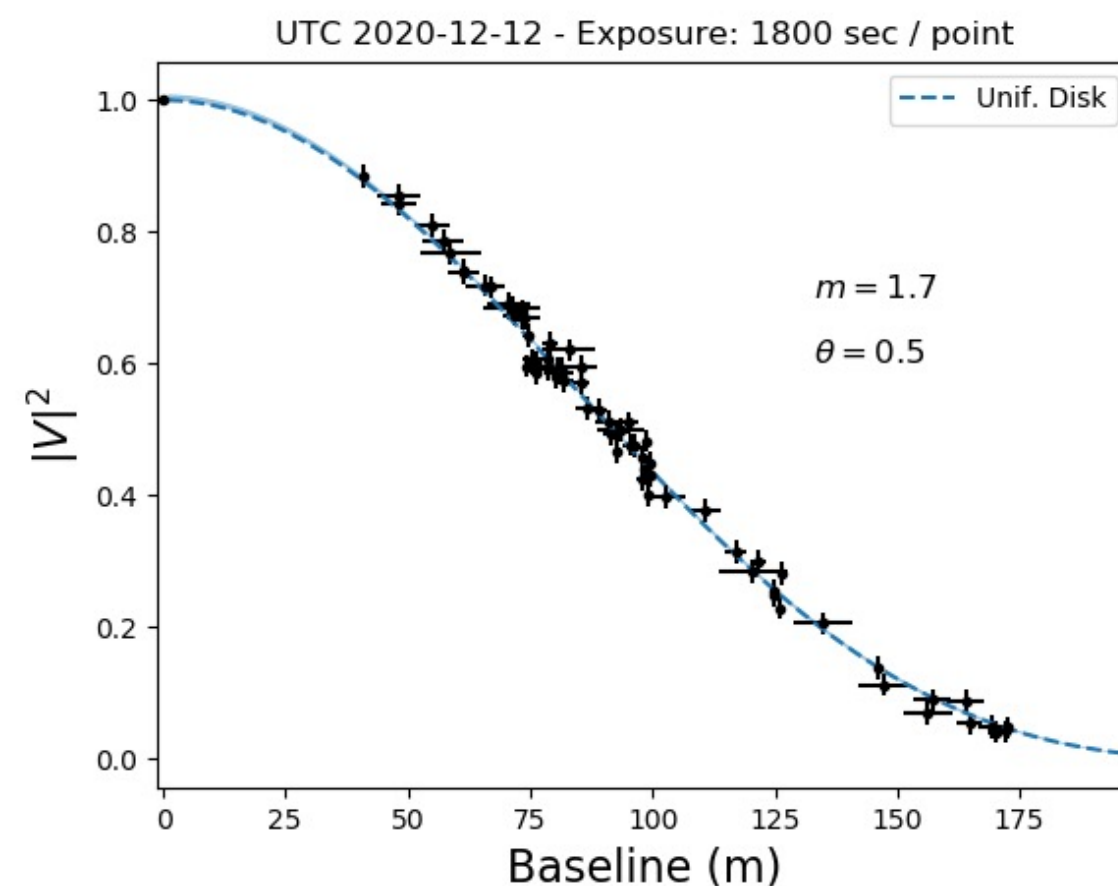
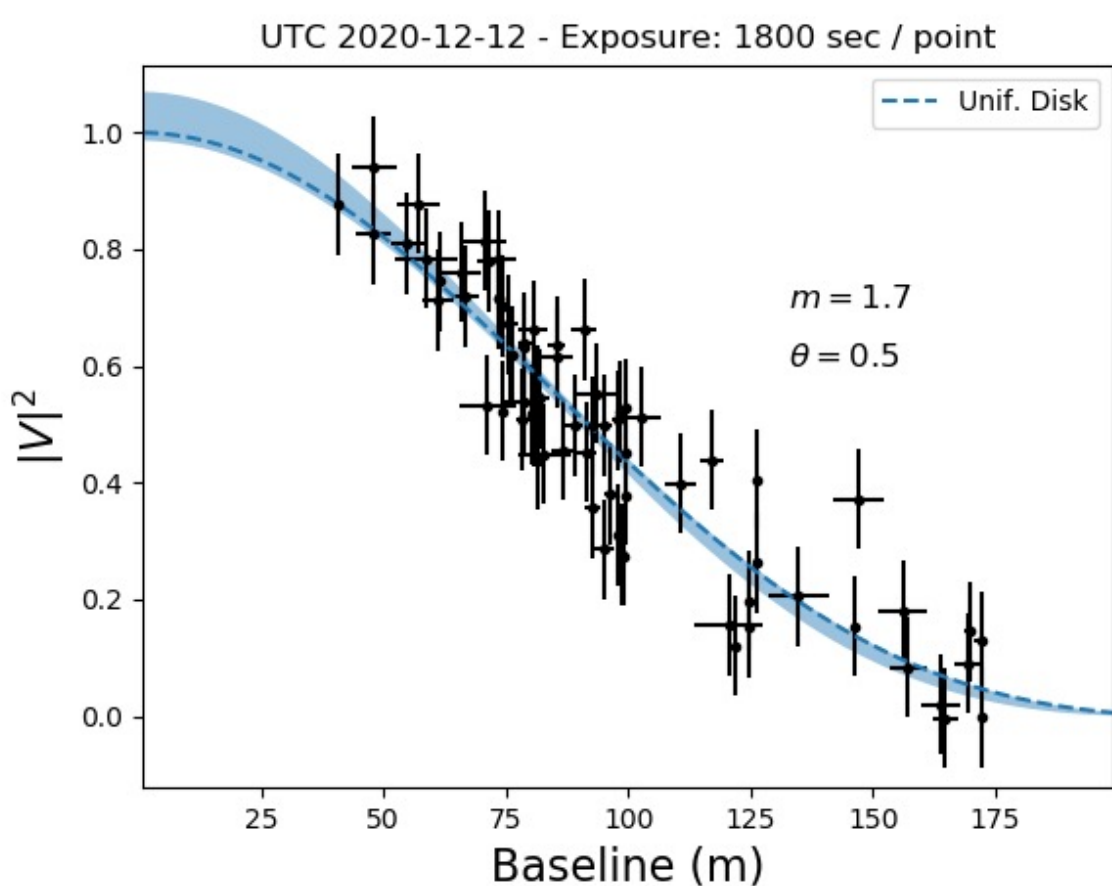
- Digital (offline) version of Michelson Stellar Interferometer
- *Demonstration of stellar intensity interferometry with the four VERITAS telescopes* (*Nature Astronomy* 4, 1164 (2020)):
 - Sub-milliarcsecond optical resolution @ 400 nm
- Extensive work done since on **expanding SII working group**, **improving hardware and analysis techniques**, **science targeting** + **lots of observations**.
- **Science:** **survey of stellar diameters**, **Cepheids & fast rotators**, **Limb darkening** (post upgrade)
- Awarded NSF grant to improve sensitivity:



Source	θ_{UD} (mas)	T (h)	θ_{UD} (mas)	T (h)	(T= Observation Time)
β CMa	0.50 ± 0.03	63.4	0.523 ± 0.017	5.5	
ϵ Ori	0.67 ± 0.04	56.0	0.631 ± 0.017	4.25	

Narrabri SII
Observations 1970

VERITAS-SII
Nature Astronomy 2020



- **Optical SETI:**

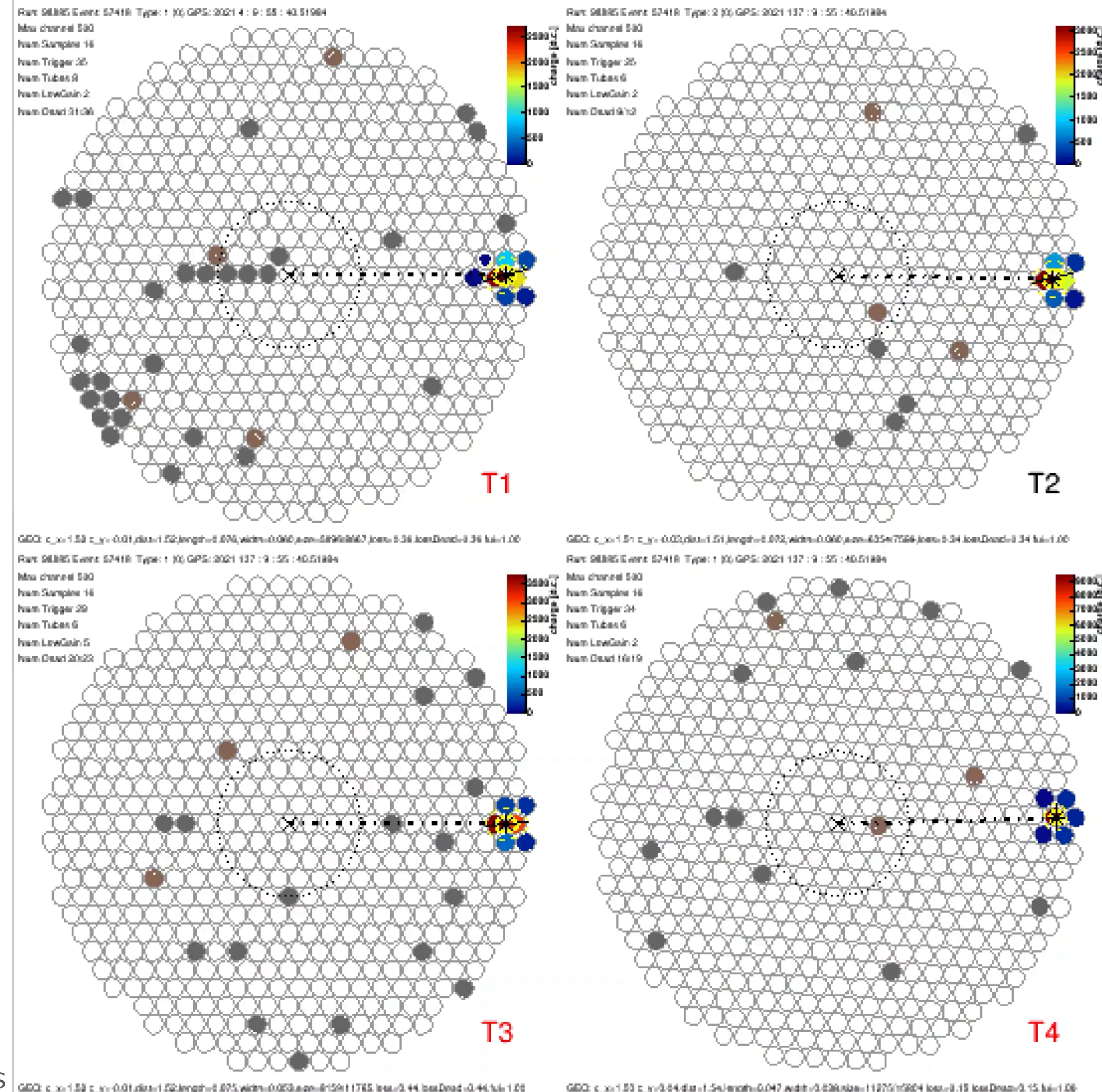
- *A Search for Brief Optical Flashes Associated with the SETI Target KIC 8462852 (Abeysekara et al., ApJ 818, 33 (2016))*
- Breakthrough Listen joint project

- **LIDAR Satellites**

- e.g. **CALIPSO:**
 - 20 ns pulses at 532 nm with pulse rate of 20 Hz (publicly available calibrations of pulse intensity to 0.4%)
 - 700 km altitude
 - Detectable down to at least ~50 degrees elevation
 - Observable a few times per month. 1 minute exposures.

- Applications:

- Proof-of-principle for OSETI
- Relative telescope efficiency
- Optical performance
- Time-dependent array efficiency
- Cross-calibration with other IACTs



- VERITAS is operating well and has been recommended for the next cycle of NSF operations funding through 2025
- VERITAS has a strong and varied science program in the gamma-ray and optical regimes.
- We are a relatively small consortium compared to others (with lots of data) and welcome collaboration...

VERITAS Poster Contributions at Gamma 2022:

Colin Adams	Search for Axion-like Particles with Observations of the Blazar Markarian 421 with VERITAS
Ste O'Brien	Multiwavelength observations of the TV Blazar H 1426+428
Olivier Hervet	Looking for a repeating flaring pattern in Mrk 421, from X-ray to gamma ray
Dongguan Tak	Indirect Dark Matter Searches in VHE Gamma Rays with Legacy VERITAS Dwarf Spheroidal Observations
Manel Errando	VERITAS observations of TV blazars in the IXPE first-year observing plan

VERITAS Oral Contributions at Gamma 2022:

Nahee Park	Multiwavelength studies of Galactic PeVatron candidates with VERITAS
Sonal R. Patel	VERITAS observations of gamma-ray binaries
Matthew Lundy	VERITAS Search for Gamma-ray and Optical Counterparts to Fast Radio Bursts
Olivier Hervet	A multiwavelength look on the 2017 flare of OJ 287
Manel Errando	An unbiased search for TV emission from high-frequency peaked BL Lacs
Pedro Batista	Characterizing the VHE emission of the extreme HBLs with VERITAS
Lucy Fortson	The Great January 2017 Flare of NGC 1275: VERITAS and Multiwavelength Results

Thank you!



VERITAS hybrid Summer Collaboration Meeting 2022 at DESY (Zeuthen)