Joint optical/VHE observations of pulsars with VERITAS

Samantha Wong | McGill University | CTAO School 2024 | samantha.wong2@mail.mcgill.ca

A brief introduction to VERITAS

VERITAS is an array of **four 12m IACTs** located near Tucson, AZ (**Northern hemisphere**) that has been taking data since 2007

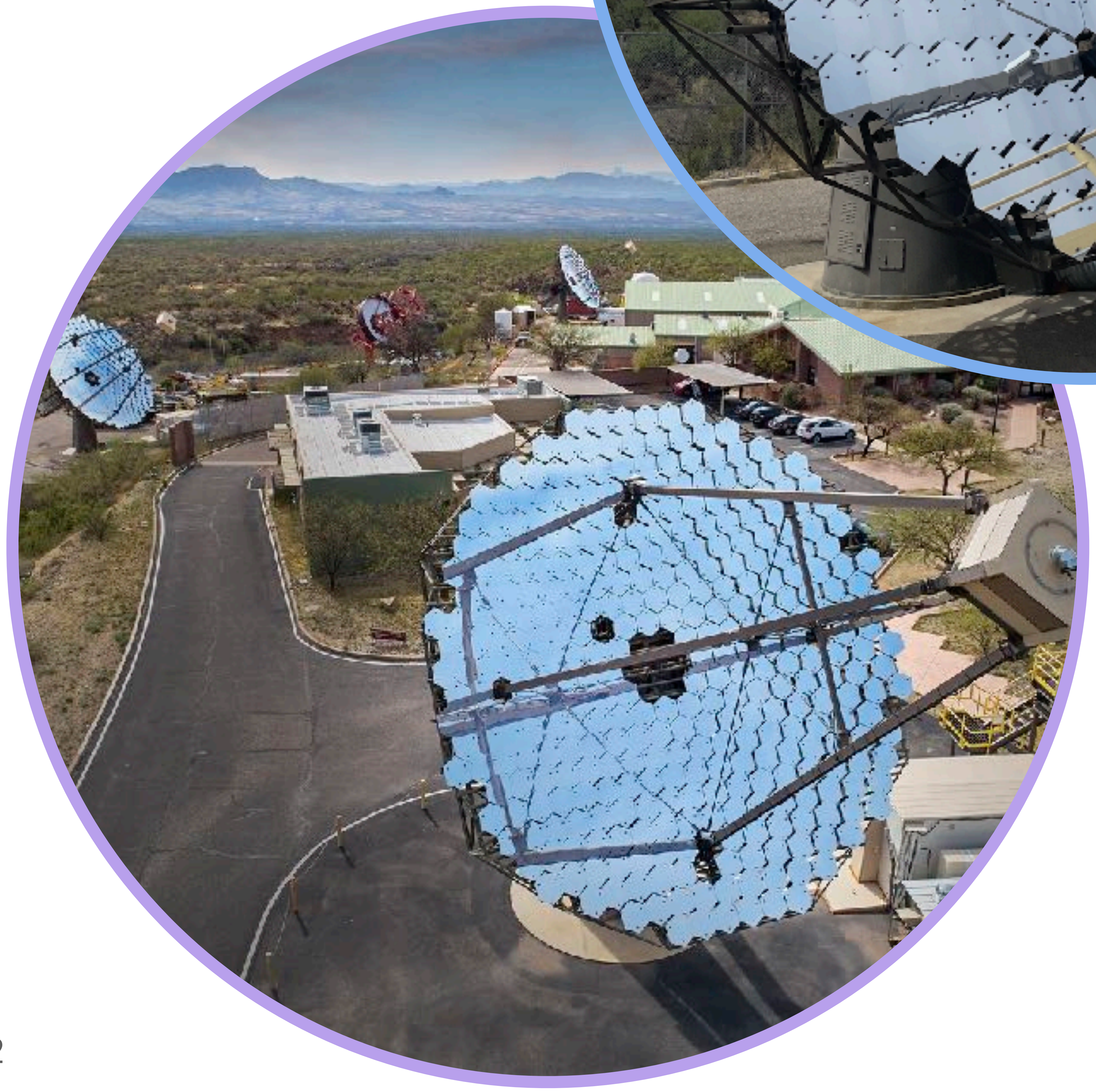
Sensitive to VHE γ-rays from ~100 GeV to > 30 TeV

Our cameras each consist of 499 PMTs

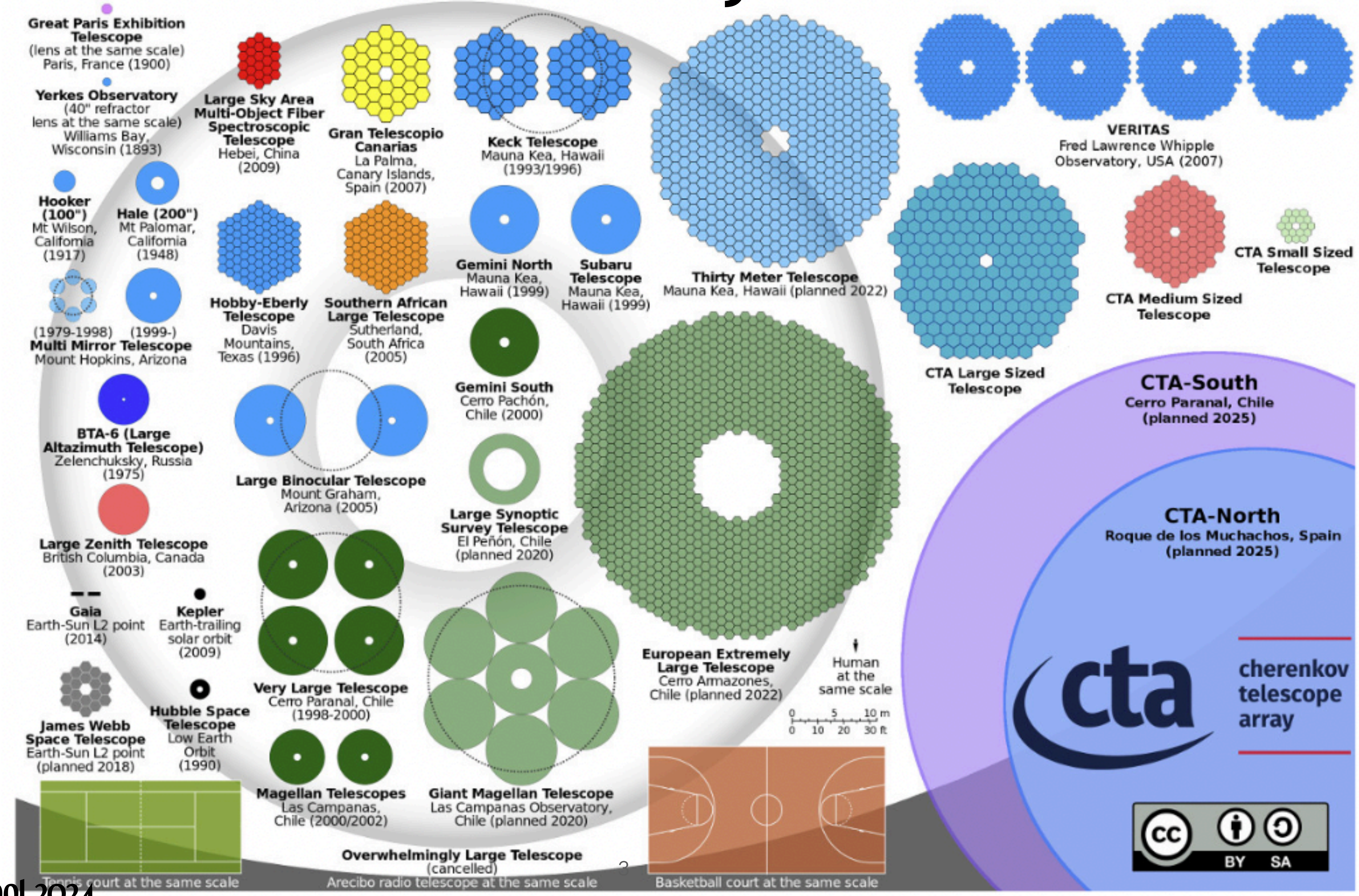
The VERITAS Collaboration has ~80 members and ~50 associate members

→ Members from institutions in USA, Canada, Ireland, Germany, Japan, Spain, and Denmark

VERITAS is located at similar longitude to the **CHIME** radio survey telescope in Penticton, Canada ⇒ we can easily monitor radio transients simultaneously

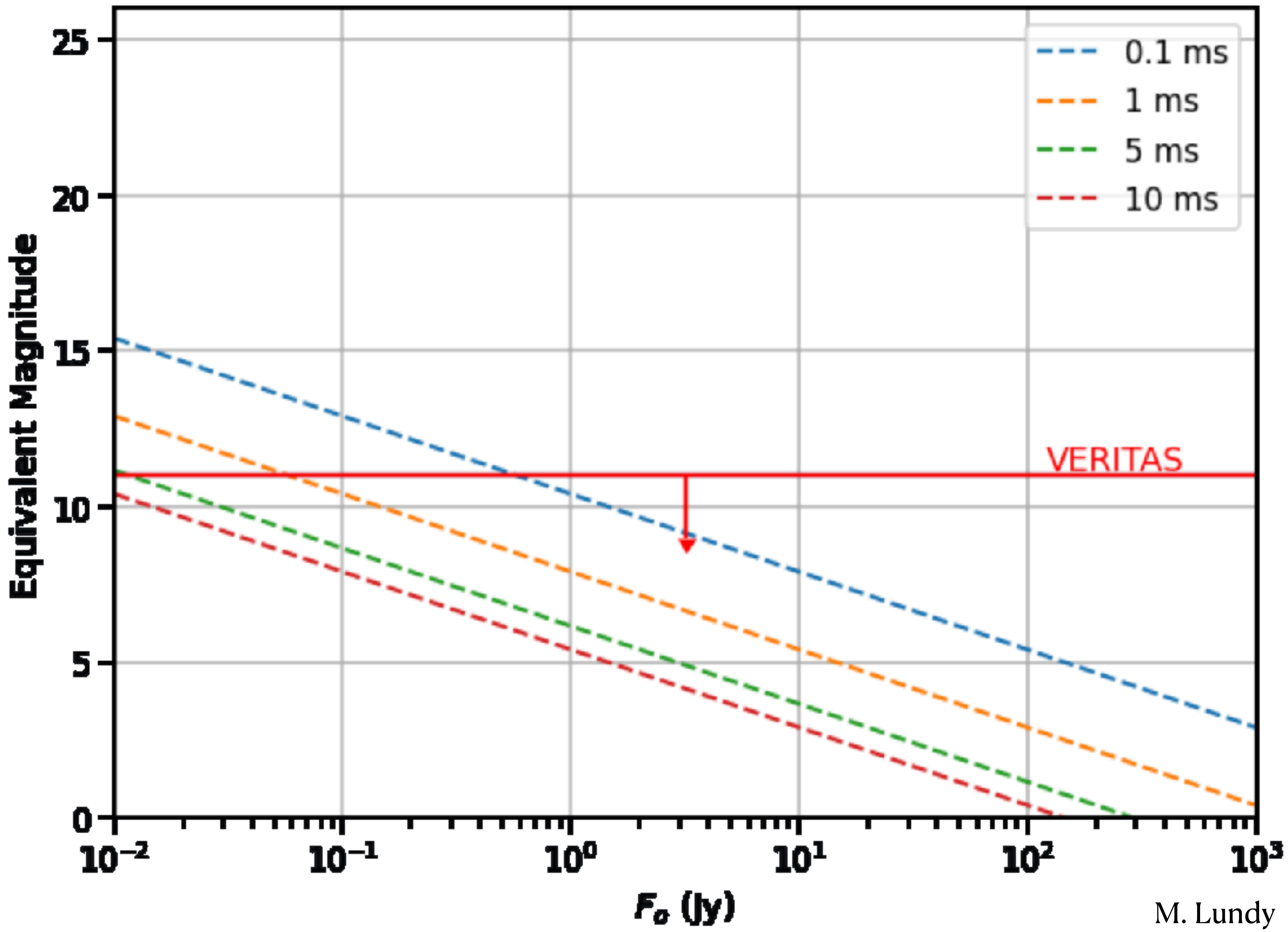


Non-Cherenkov astronomy with IACTs



CMG Lee / T. Hassan

Non-Cherenkov astronomy with IACTs



M. Lundy

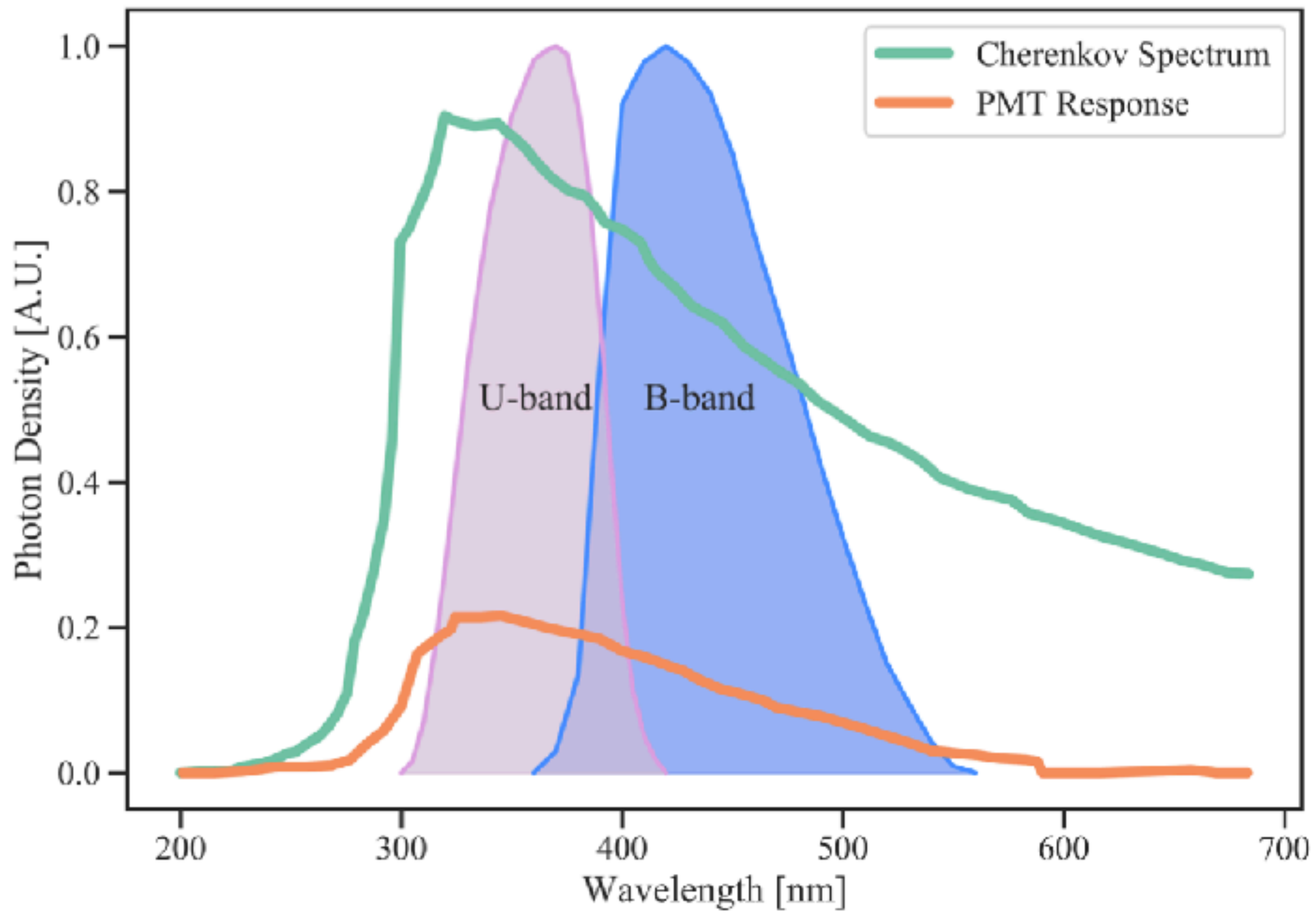
The VERITAS optical backend

VERITAS has a parasitic photometric optical backend that uses our current readout (traditionally used to monitor PMT currents) to monitor optical voltage in a pixel ⇒ **optical photometry!**

→ PMTs are used for detecting Cherenkov light (**~B-band**)

Our optical sampling rate is **~1 kHz** ⇒ VERITAS is one of the most sensitive optical telescopes in the world for fast (<0.1 s) transients!

We can use this backend to look for time-varying & transient optical sources: fast radio bursts, asteroid occultations, pulsars, X-ray binaries, M dwarf flares, etc.



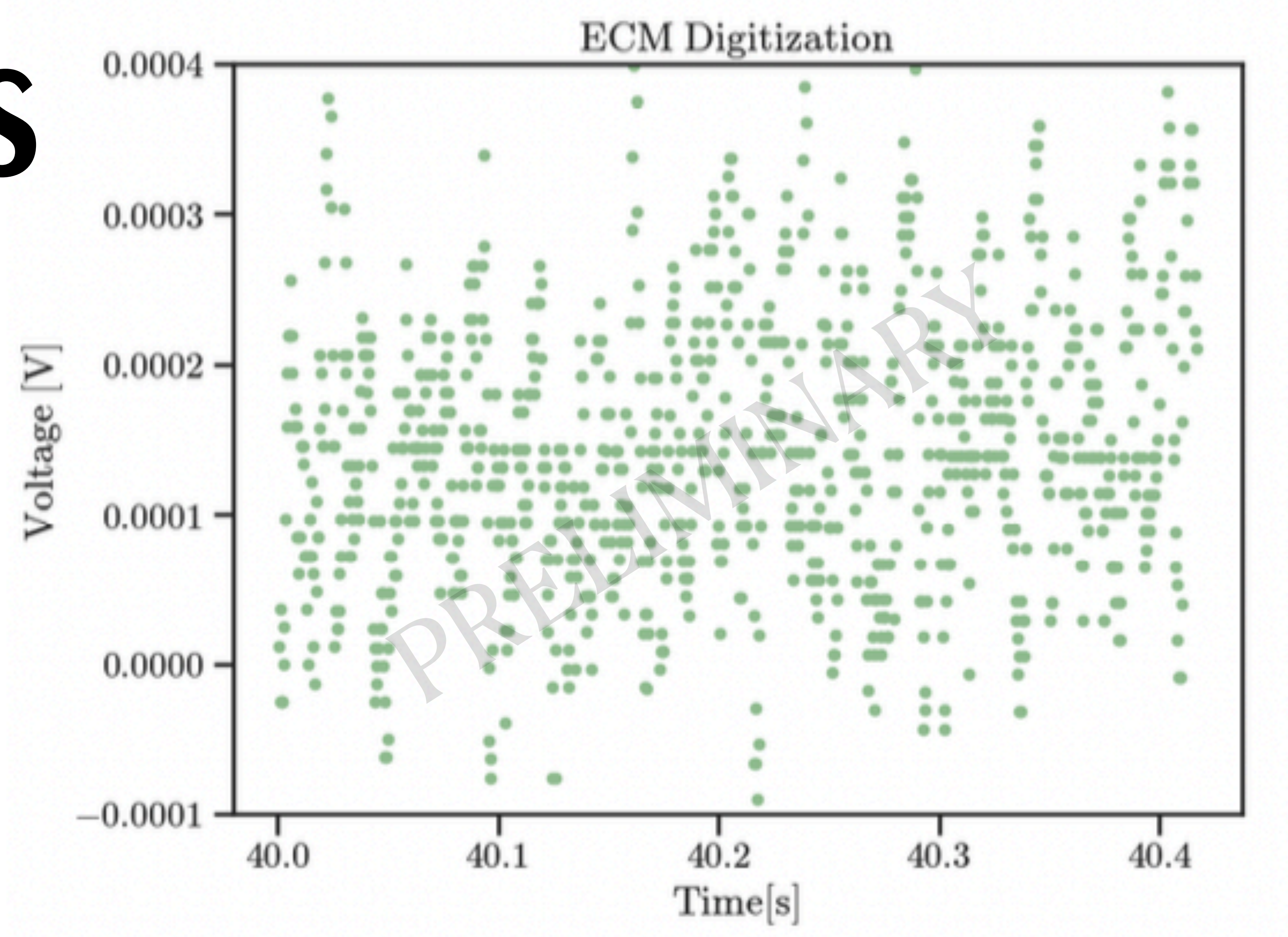
ECM: Instrumental limitations

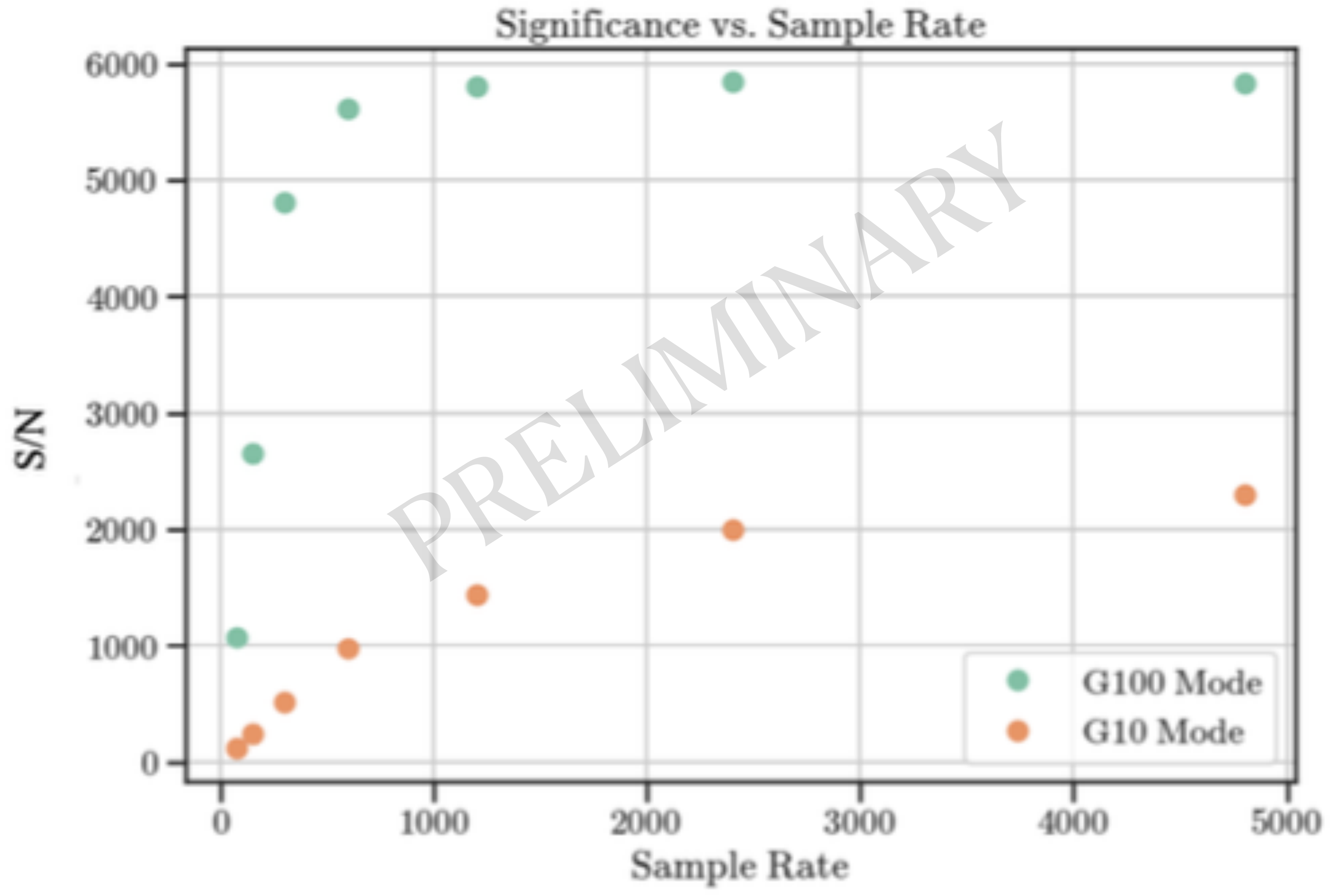
ECM data are digitized fairly coarsely (122 mV), which erases dim signals

Sampling rate does not seem to be able to reach the quoted maximum of 4800 Hz

→ Our **maximum sampling rate sits at ~ 1200 Hz**, as derived from observations, but we do see small improvement for higher sampling rates

→ This creates a smearing of rapid pulsed signals





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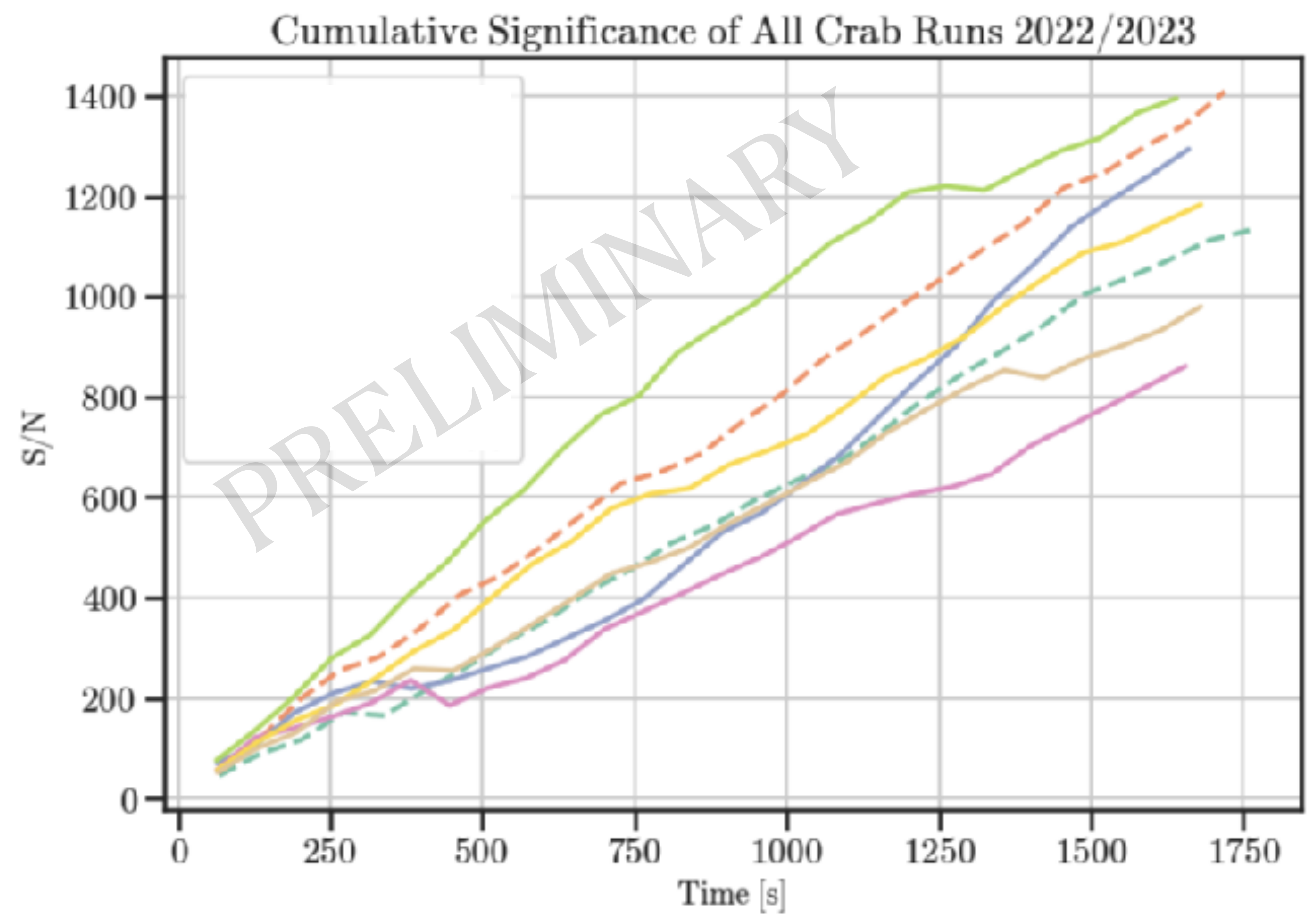
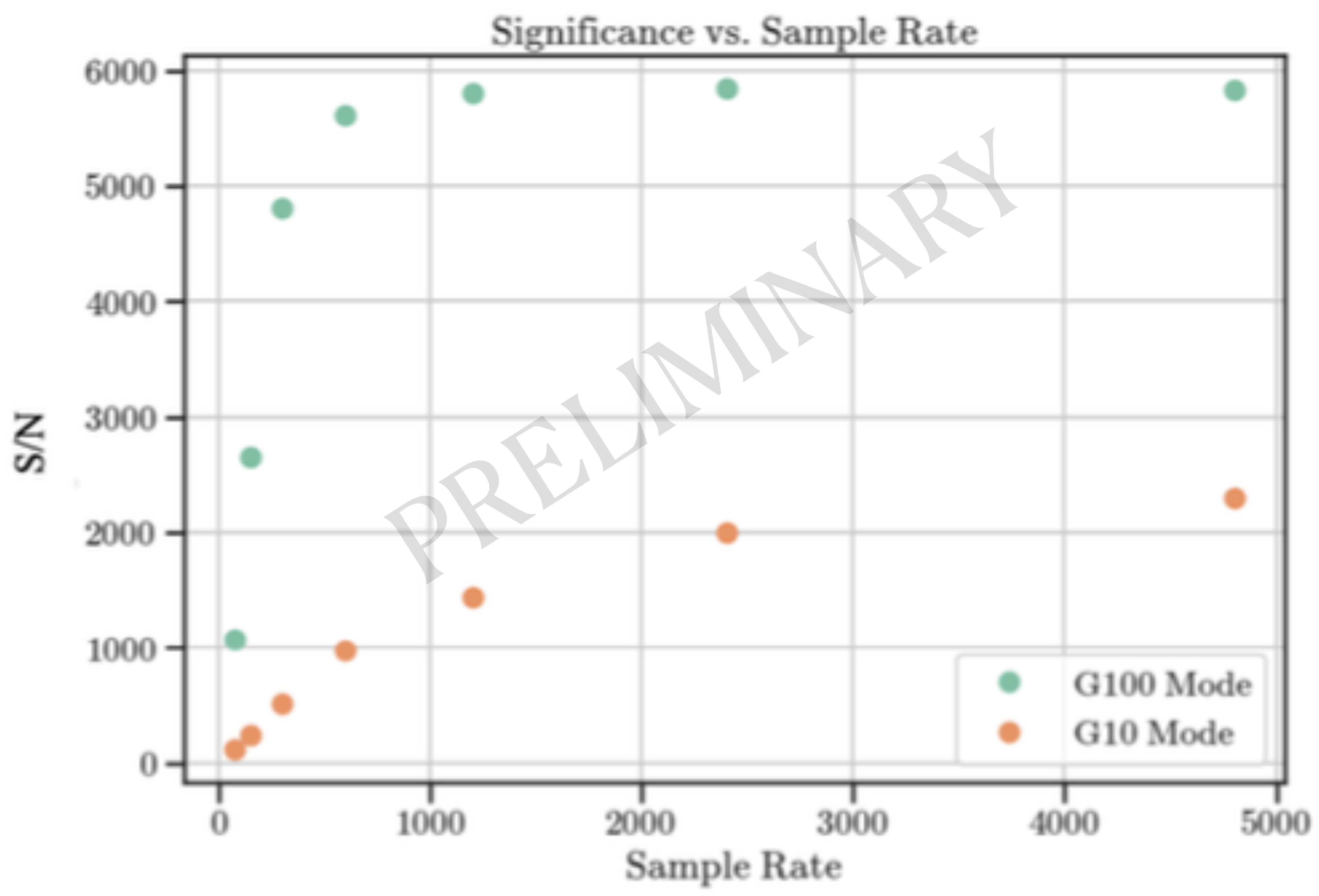




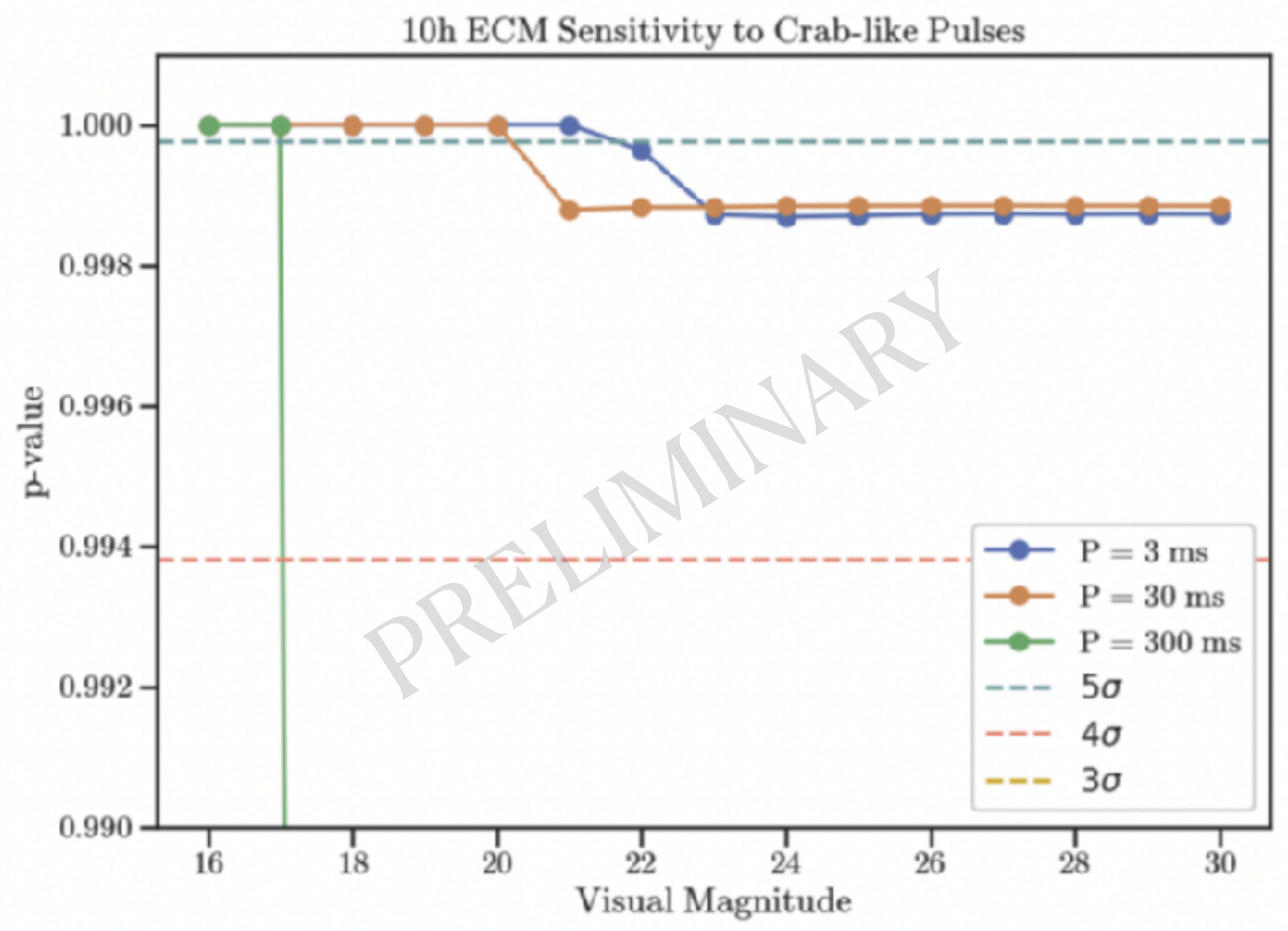
ECM — Limiting factors

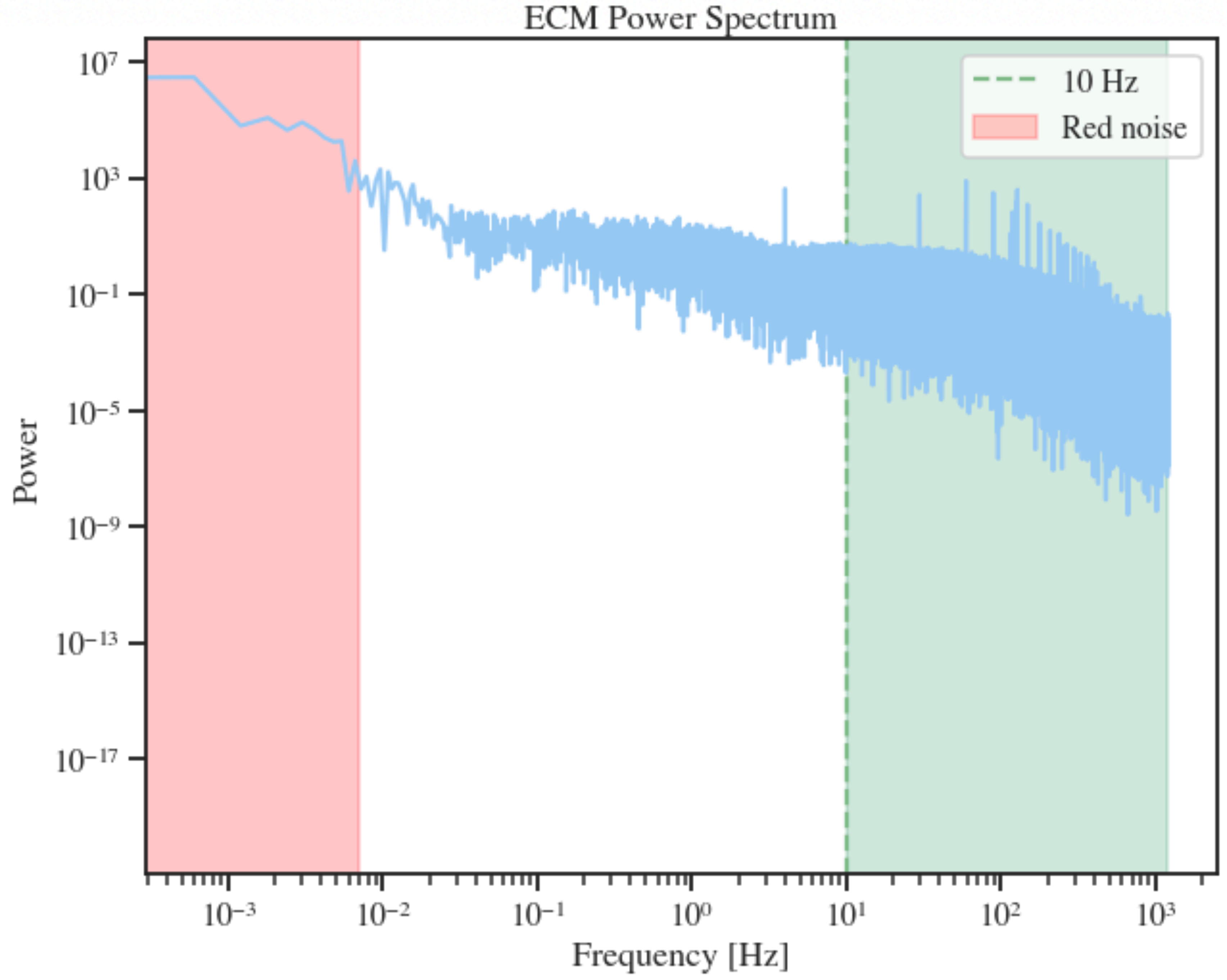
We're really most sensitive to very fast periodic signals (< **0.1 s/10 Hz**)

→ Atmospheric scintillation, electronic noise, etc. become dominant below 10 Hz

→ > 10 Hz ECM noise is Gaussian distributed & peaks in a L-S periodogram are distributed as a χ^2 distribution

We can detect bright sources (pulsed & single transients) at low magnitudes, but most of the new science we can do with the ECM involves dim sources 😢





I. VHE & optical pulsars

Why study pulsars with VERITAS?

1) Discovery of optical emission from known pulsars

→ VERITAS can detect pulsed optical emission from the Crab pulsar

→ Very few (< 10) pulsars have been detected to pulse at optical wavelengths — largely due to lack of instrumentation

2) Discovery of second γ-ray emission component from known pulsars

→ In 2023, H.E.S.S. discovered a new component of high energy emission from the Vela pulsar

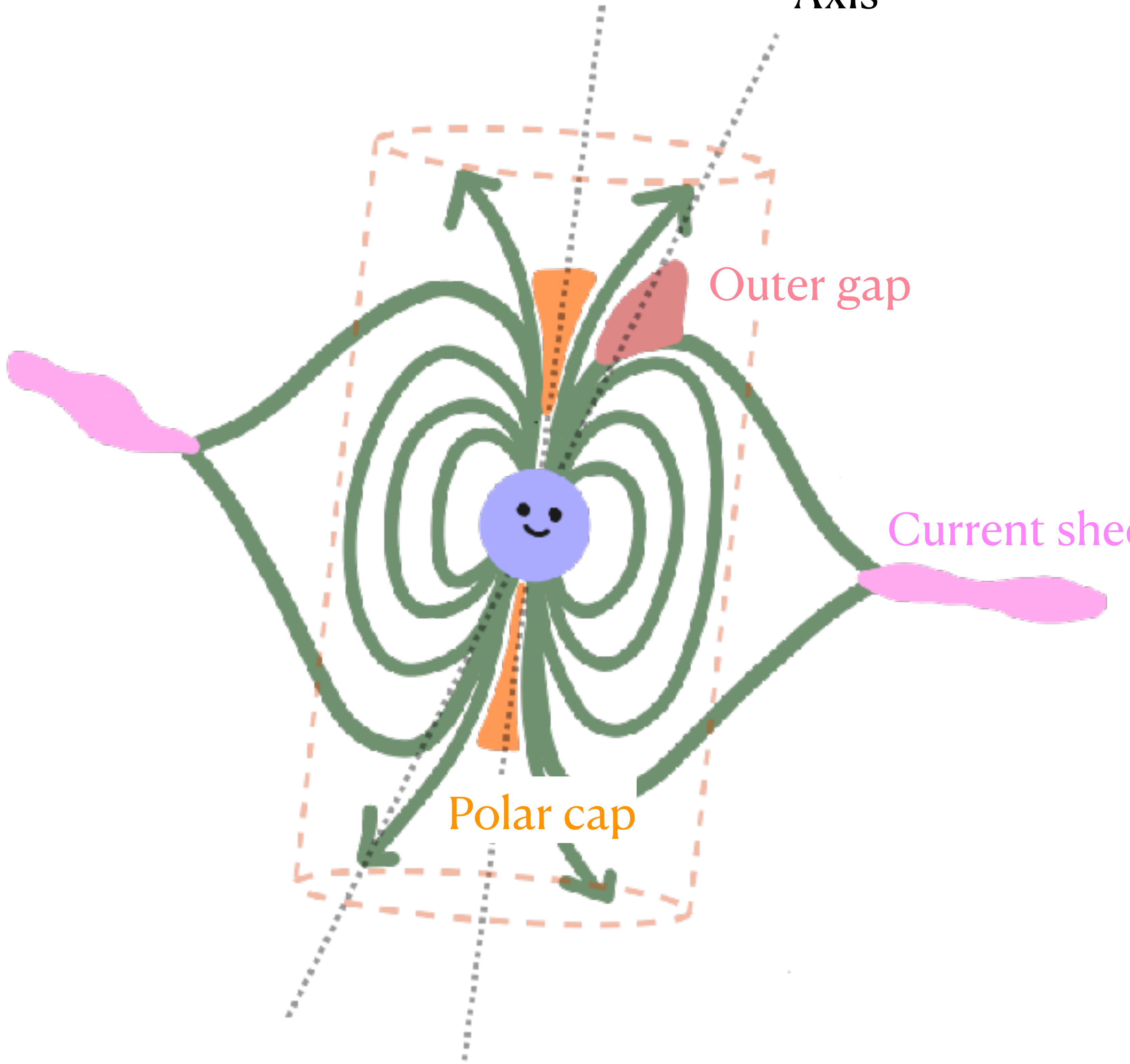
→ VERITAS and H.E.S.S. sensitivity are comparable but operate in different hemispheres ⇒ VERITAS may be capable of detecting this emission component from similar pulsars

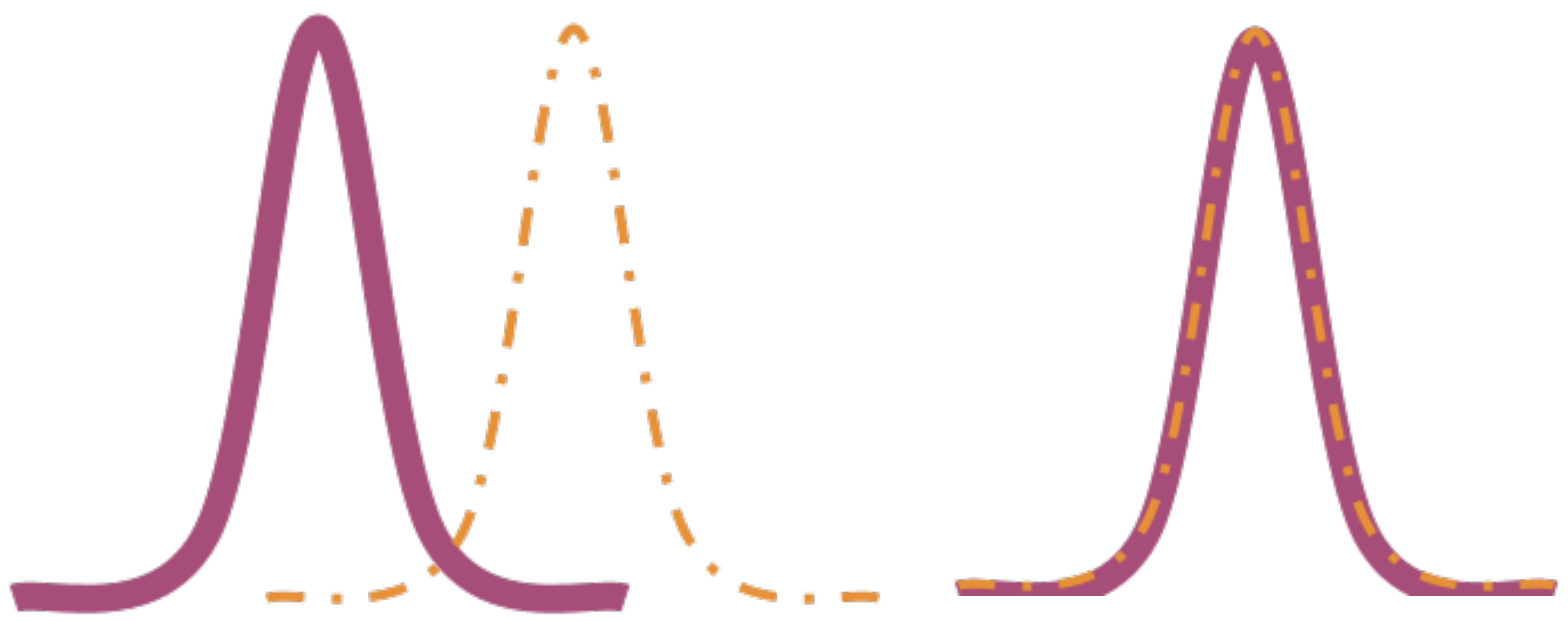
3) Characterization of extended Galactic VHE γ-ray sources

→ Recently, extended TeV emission has been detected around several middle-aged pulsars without any associated multiwavelength component

→ New instruments are revealing more candidates for such sources, but don't have the angular resolution to confirm the nature of these sources or to confirm association with known pulsars

Why optical/VHE pulsars?

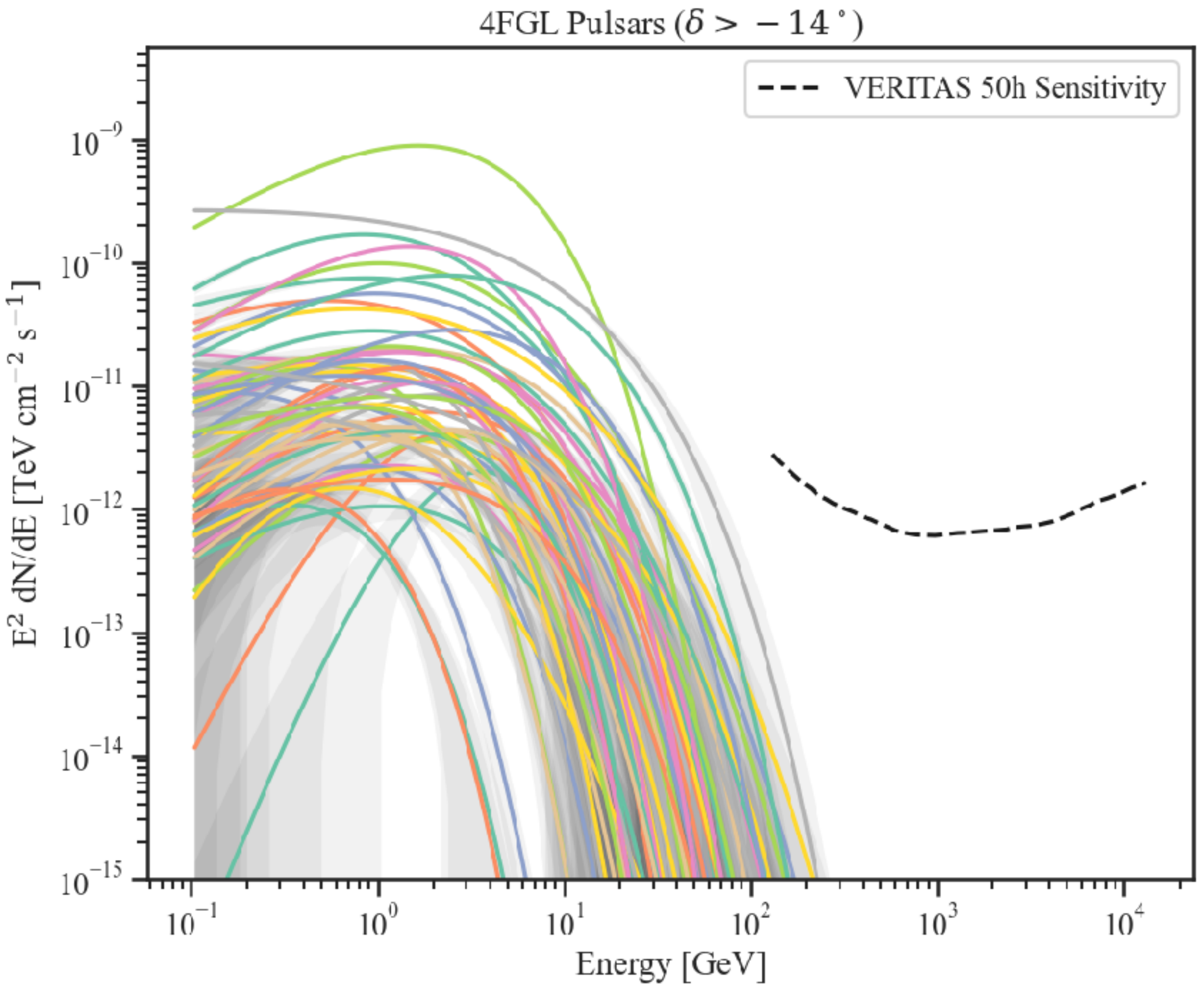


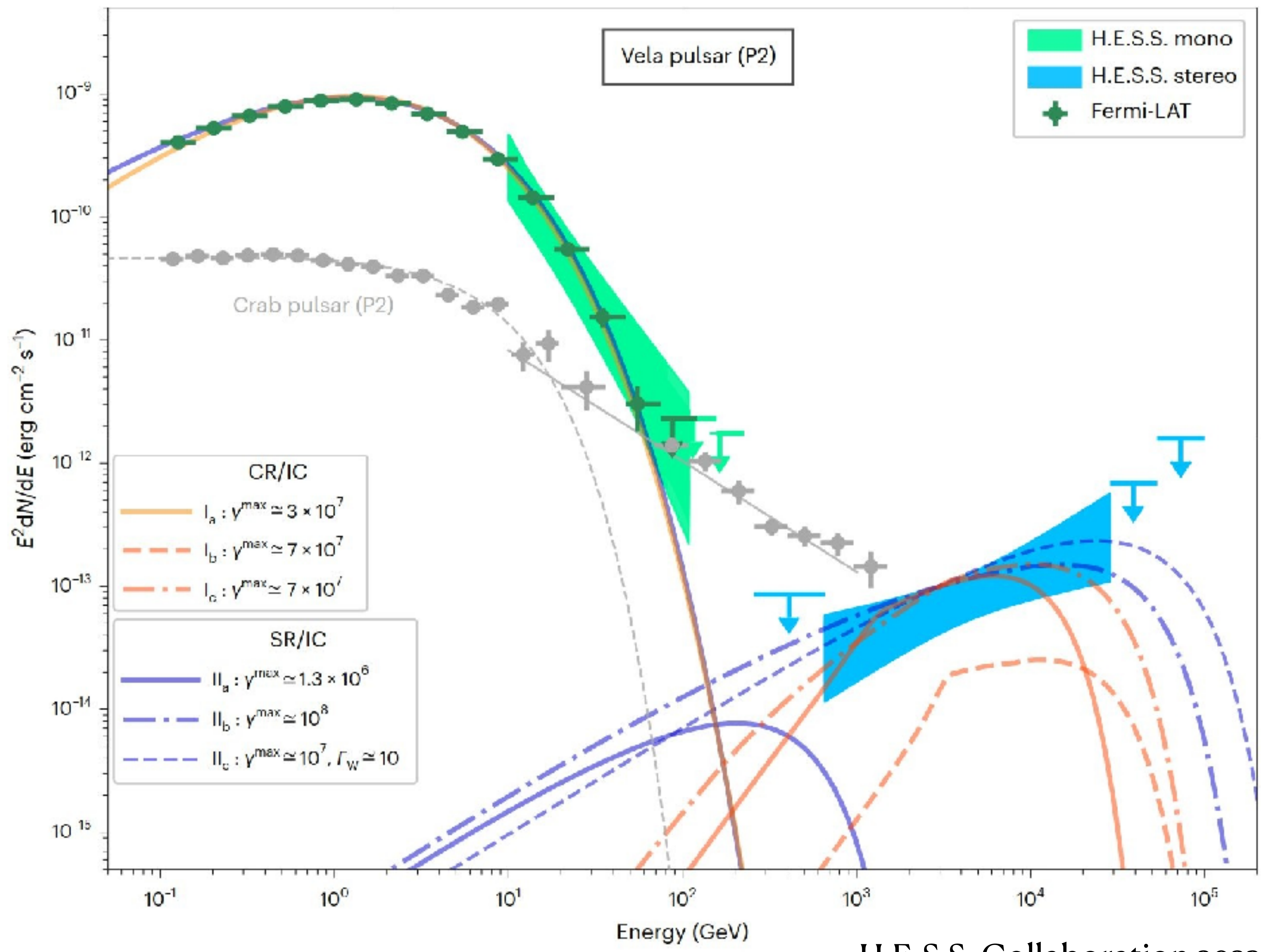


Radio/HE pulses misaligned
(most pulsars)

Radio/HE pulses aligned
(very few pulsars)

Why VHE pulsars?





H.E.S.S. Collaboration 2023

Optical pulsar selection

Criteria:

→ Visible to VERITAS (> -14 deg declination)

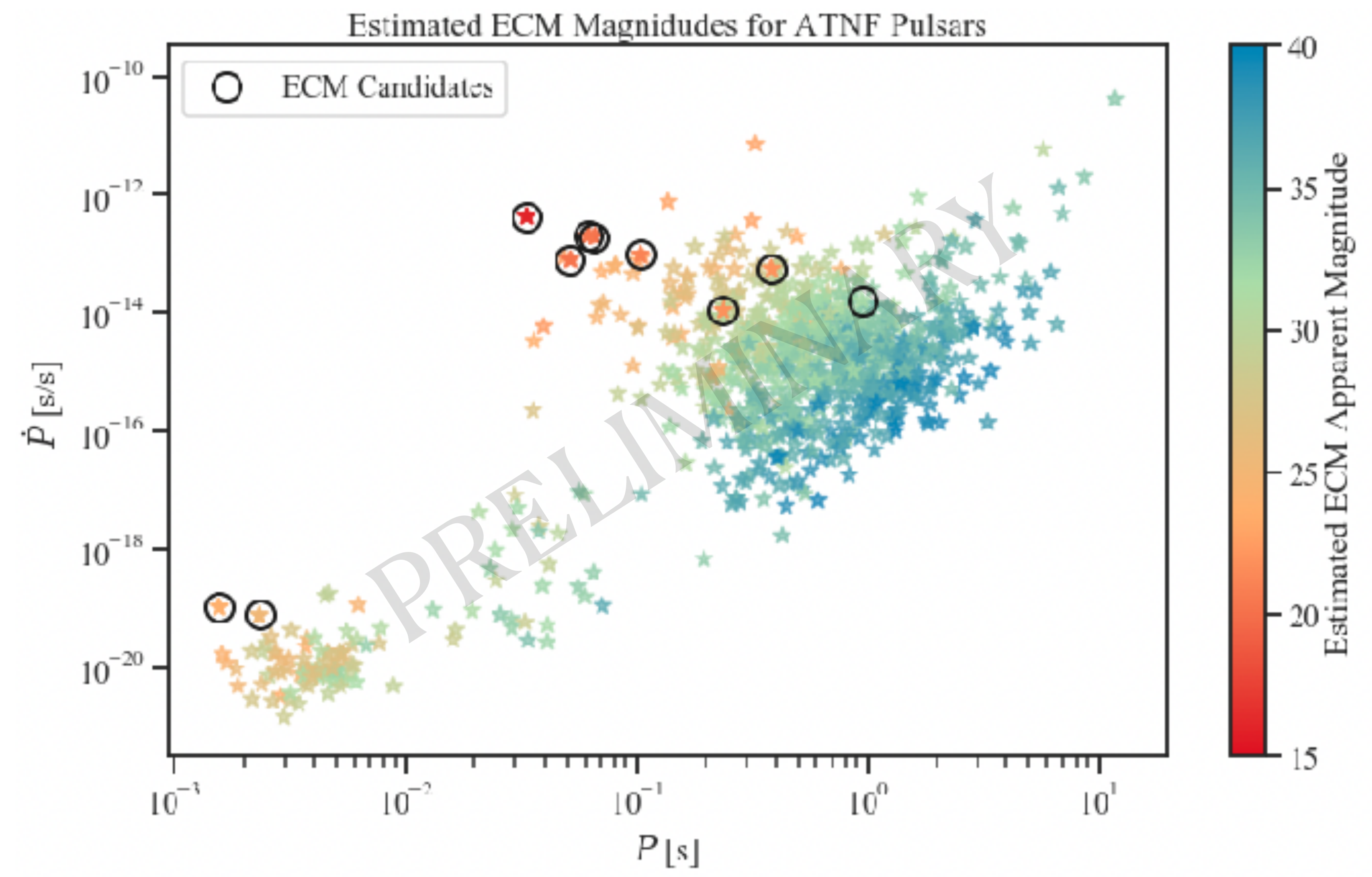
→ Rotation powered pulsar

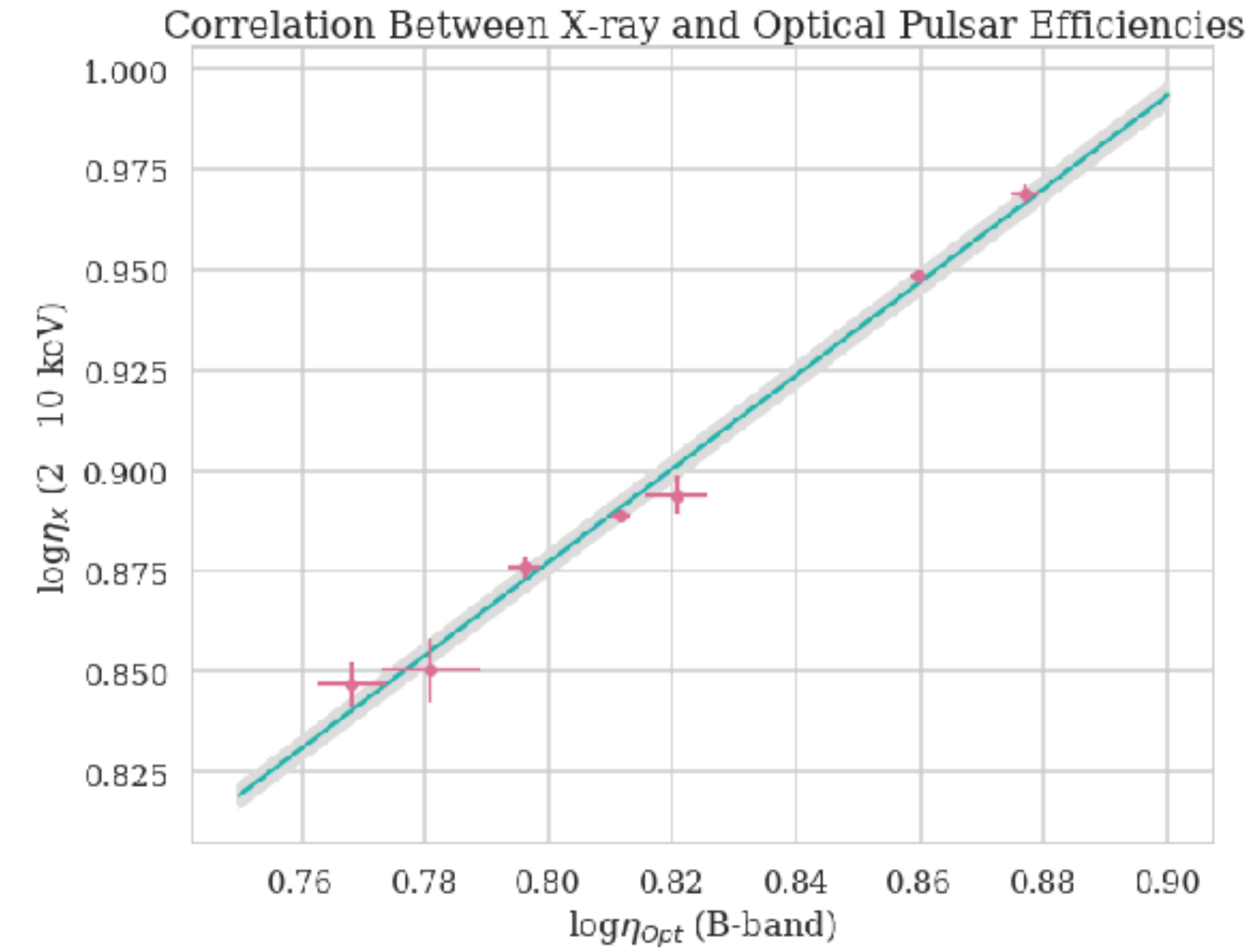
→ Non-thermal X-ray or *Fermi*-LAT pulses detected

→ < 0.1 s period

Magnitude estimates are from an **assumed linear correlation of optical/X-ray flux**

These are converted into simulated pulse trains using the X-ray pulse width and the Crab magnitude as seen by the ECM





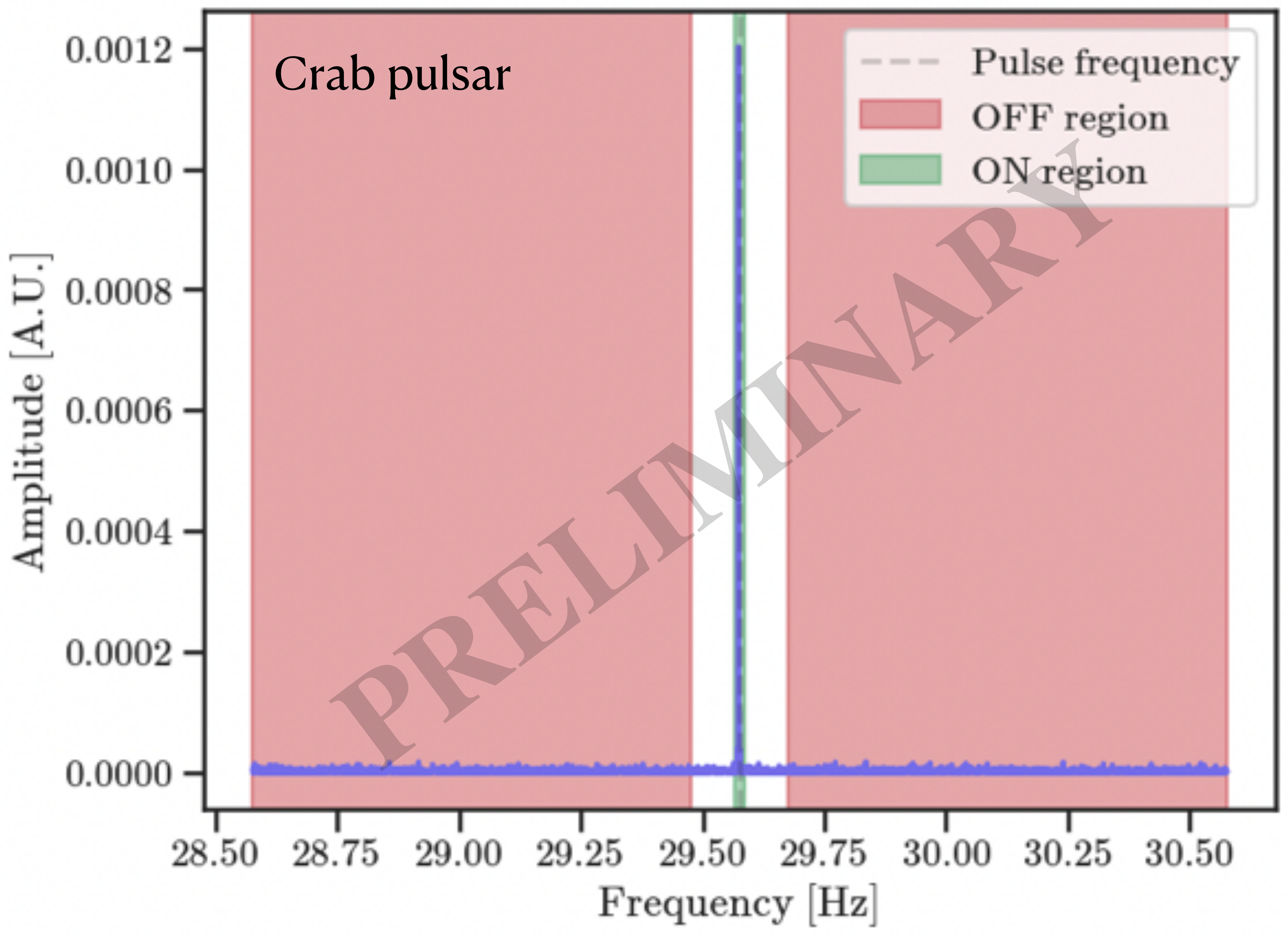
Optical data analysis

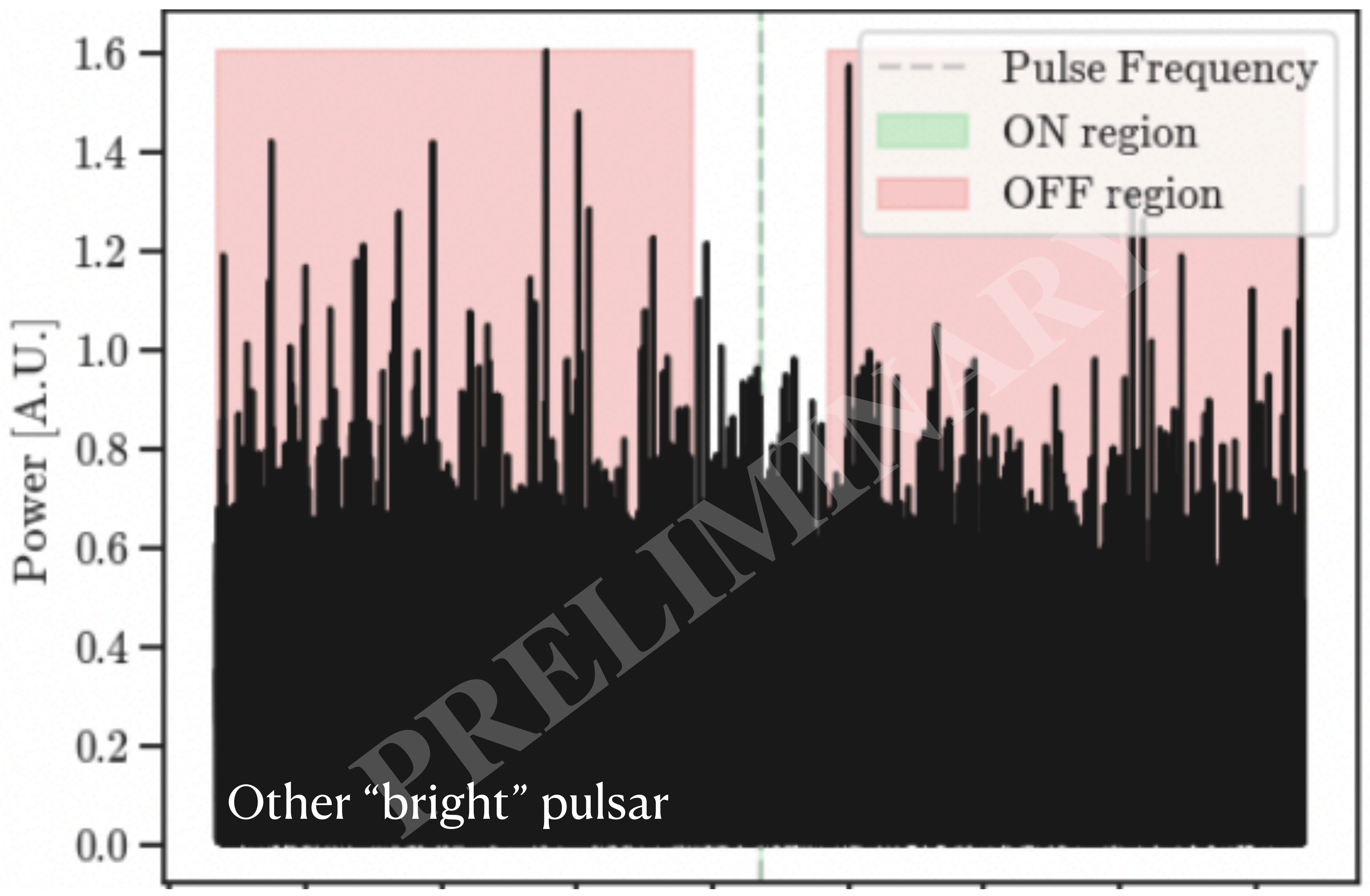
Preliminary analysis: just concerned with detection

Frequency space analysis using a Lomb-Scargle periodogram (as implemented in astropy)

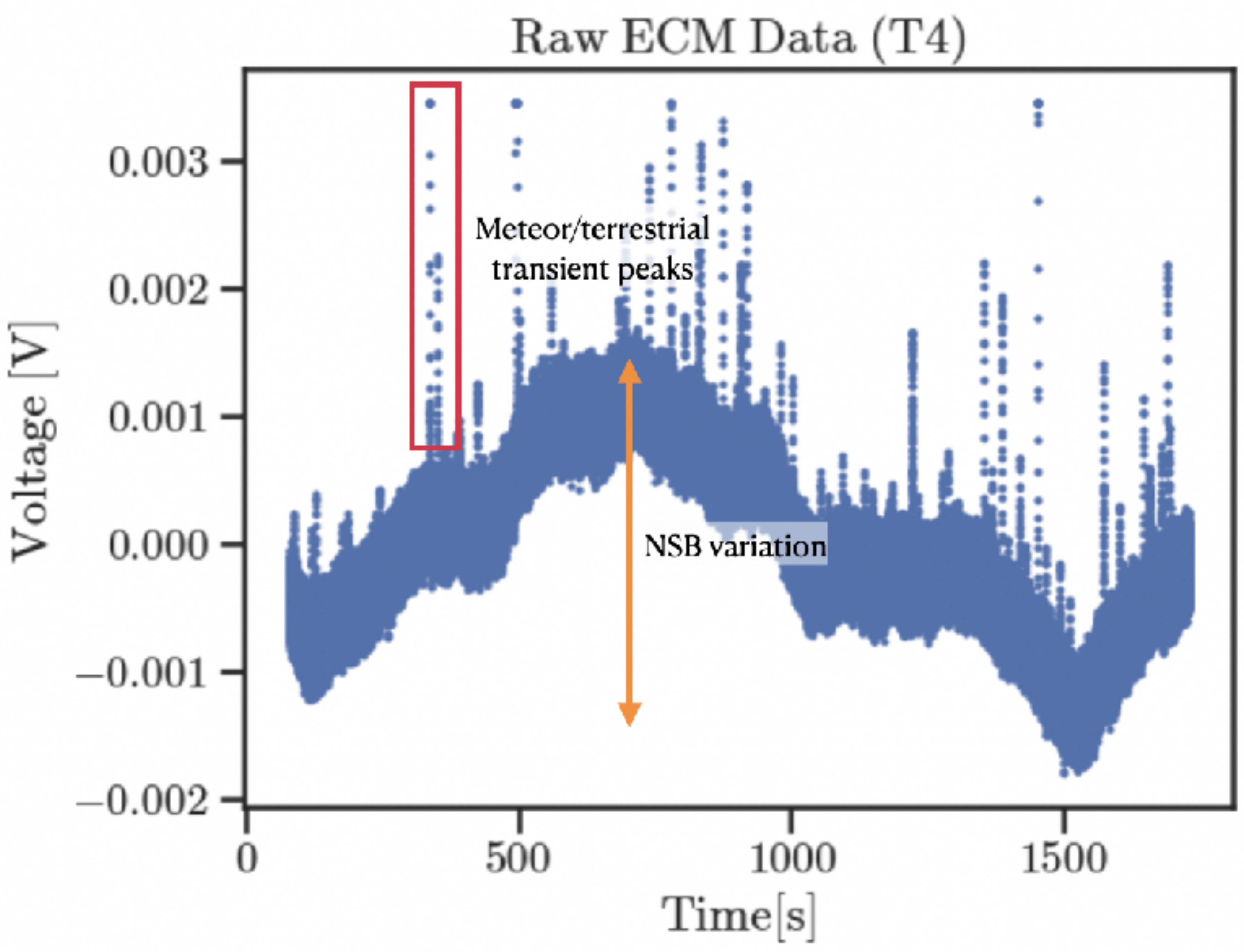
Significance calculated as the level at which we reject the null hypothesis that a frequency peak originates from just background/instrumental noise

With this method, **we detect the Crab pulsar in < 2s!!**

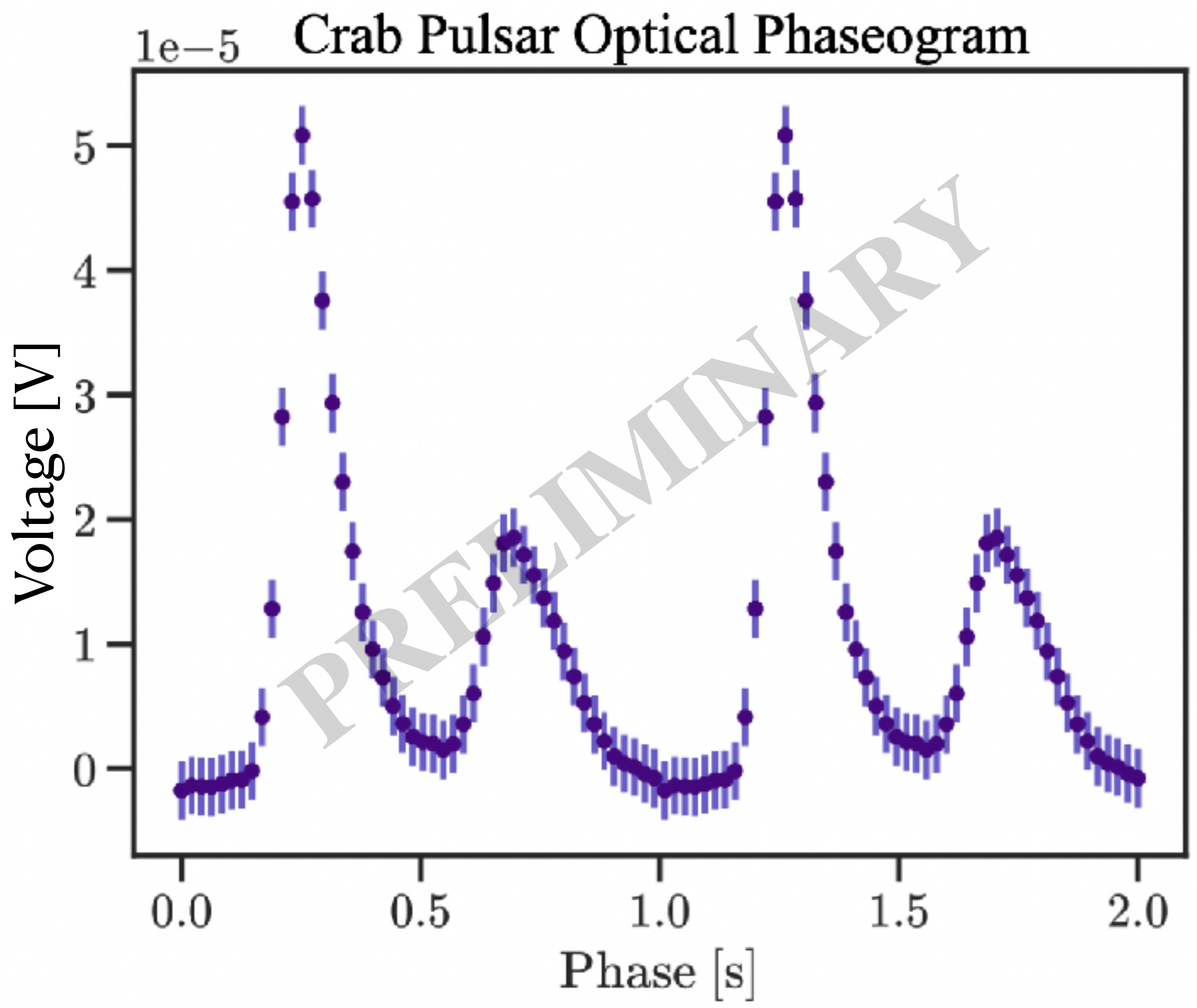




Crab pulsar

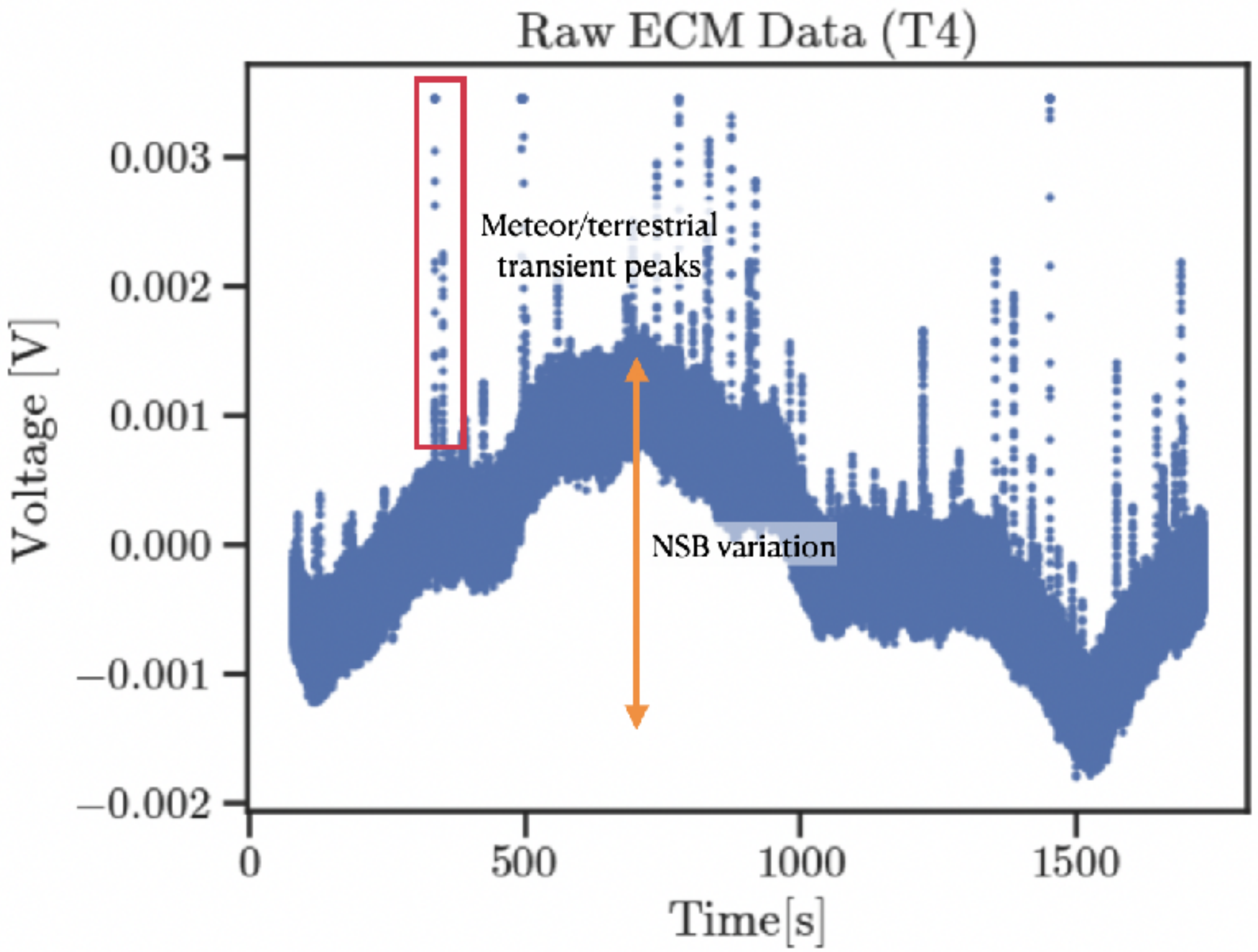


Raw ECM Data (T4)
Meteor/terrestrial transient peaks
NSB variation
Voltage [V]
0.003
0.002
0.001
0.000
−0.001
−0.002
0
500
1000
1500
Time[s]



Crab Pulsar Optical Phaseogram
1e−5
PRELIMINARY
Voltage [V]
5
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
Phase [s]

Crab pulsar


Raw ECM Data (T4)
Voltage [V]
0.003
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−0.001
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0
500
1000
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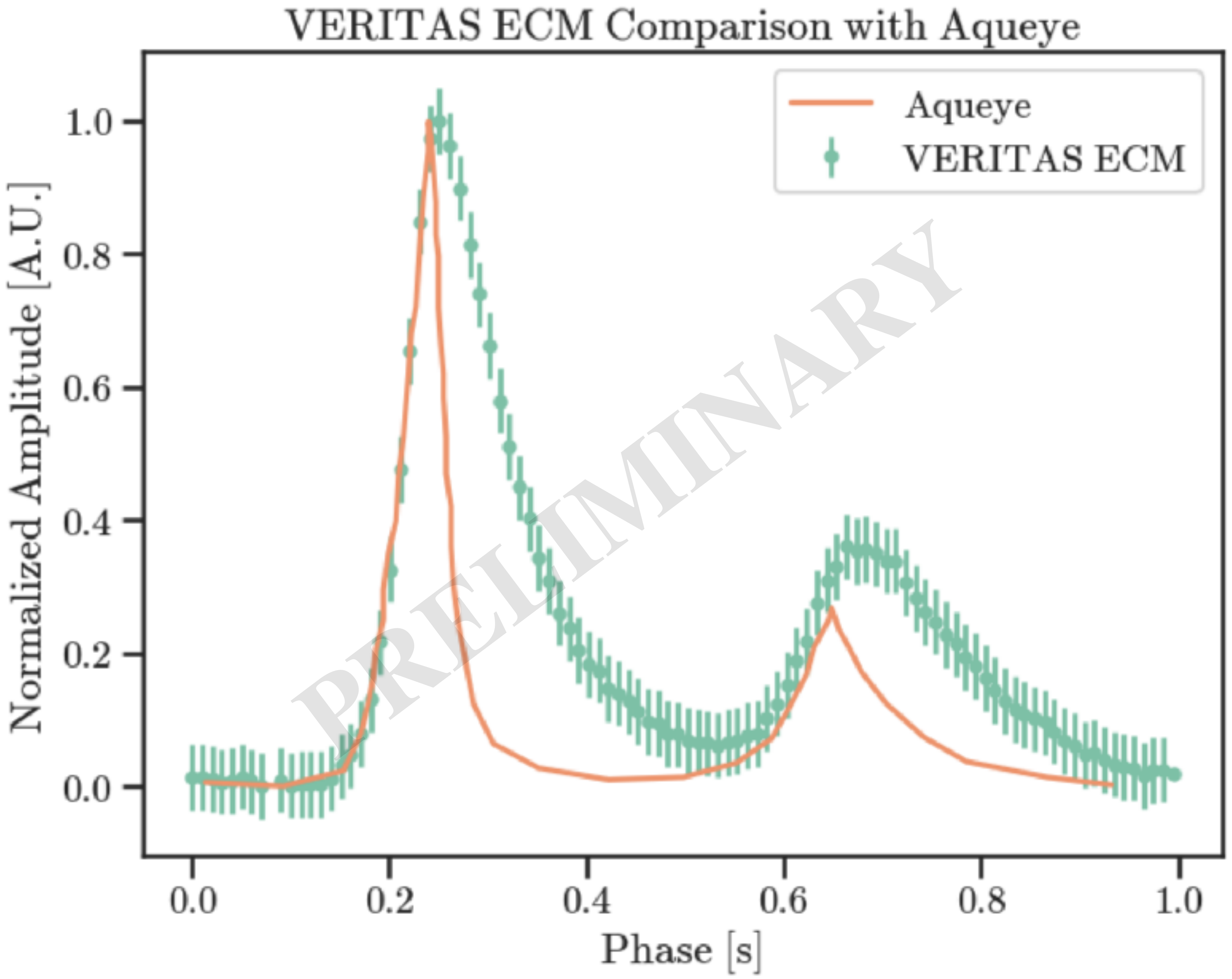
Time[s]
Meteor/terrestrial transient peaks
NSB variation


VERITAS ECM Comparison with Aqueye
Normalized Amplitude [A.U.]
Aqueye
VERITAS ECM
PRELIMINARY
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Phase [s]

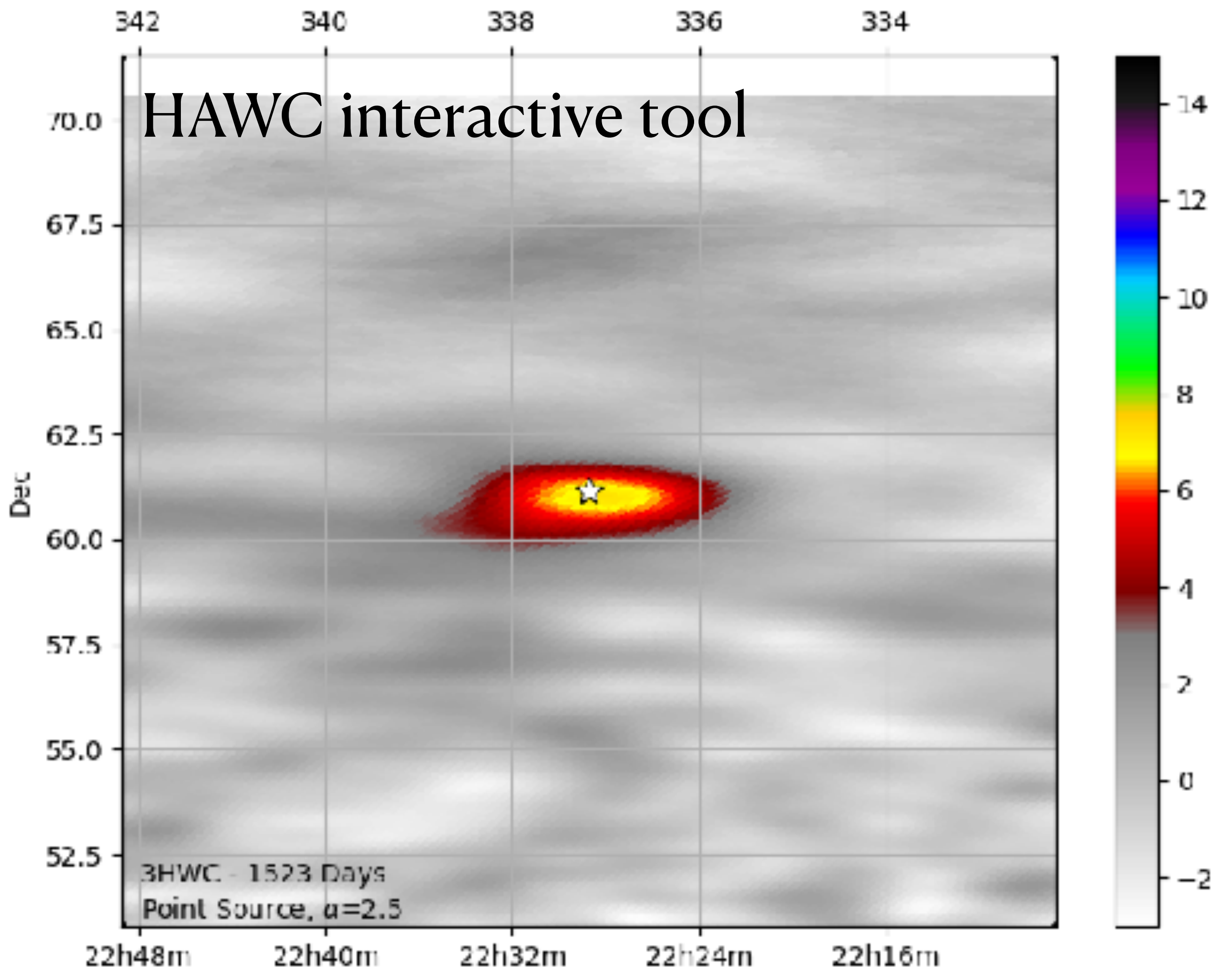
II. Pulsar environments: PWNe & TeV halos

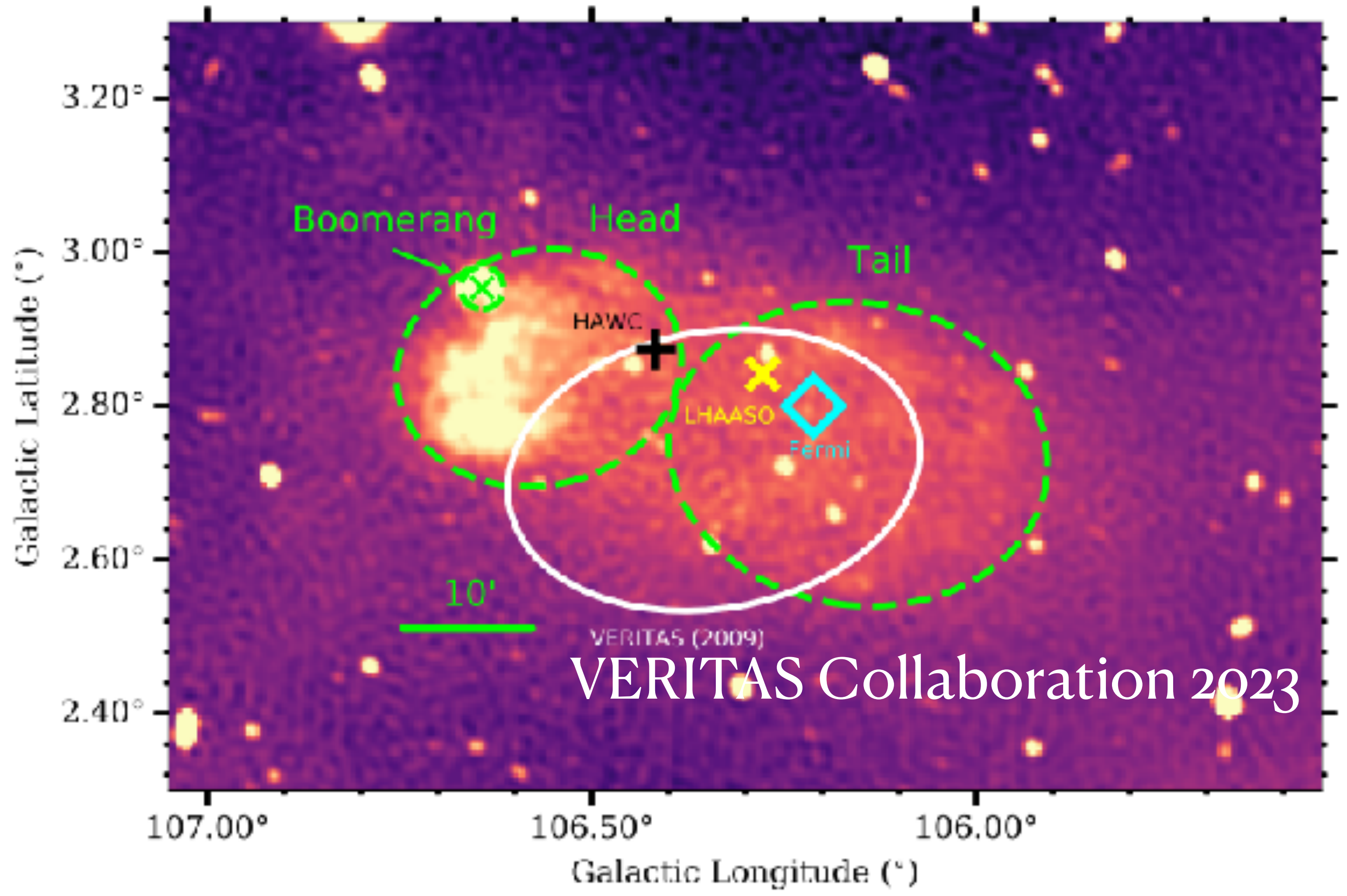
Pulsar wind nebulae/TeV halos

With ECM data we get simultaneous VHE γ-ray data

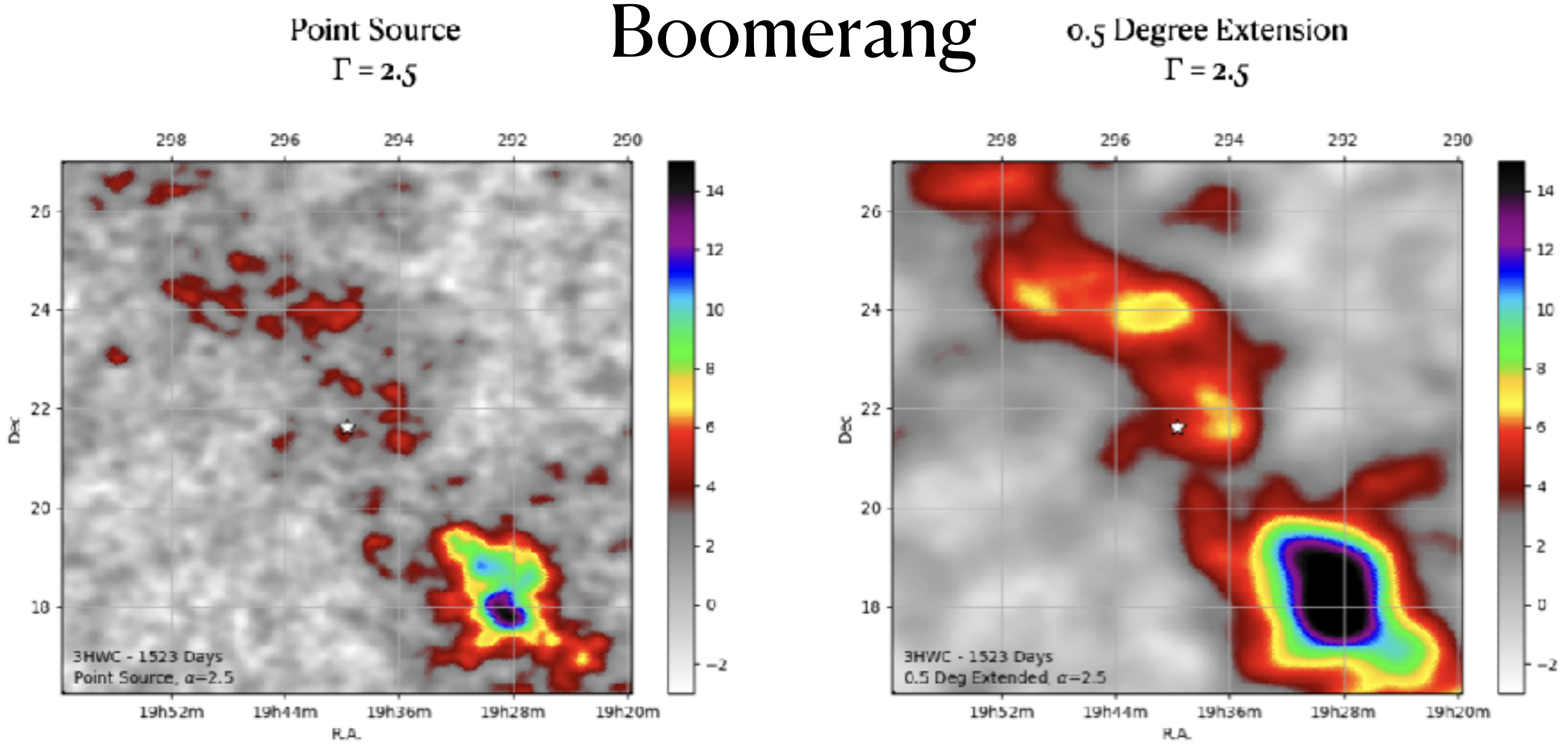
Many pulsars have associated pulsar wind nebulae (PWNe) or TeV halos

IACTs are particularly well-suited to associating and characterizing PWNe/TeV halo emission due to **improved angular & spectral resolution** compared to EAS detectors that operate at similar to higher energies





Boomerang



PSR B1937+21

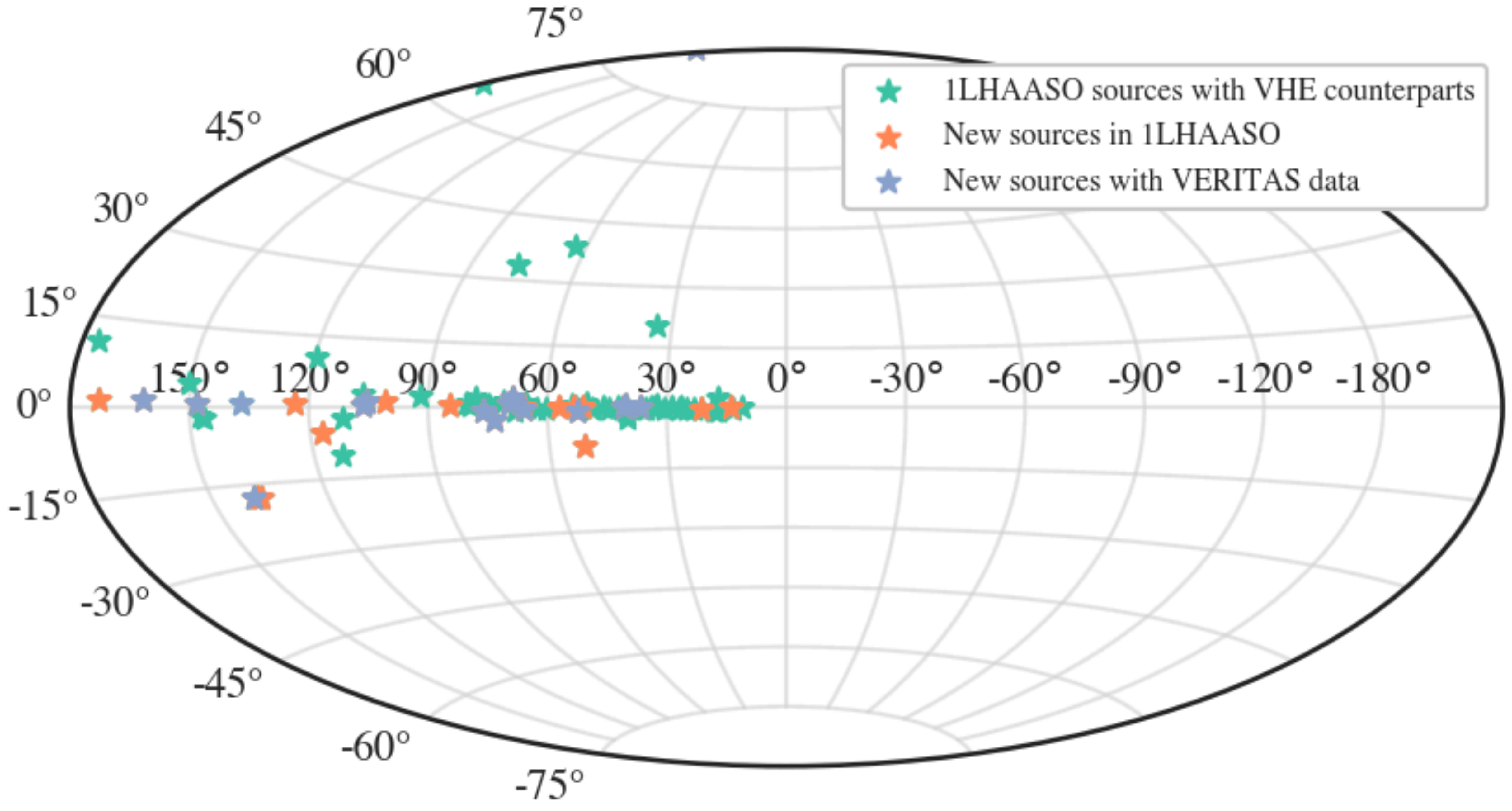
LHAASO source follow up

The first LHAASO catalog has revealed **32 new VHE/UHE sources** in the Northern sky

→ 16 of these sources have (tentative) **pulsar or PWN/SNR** associations

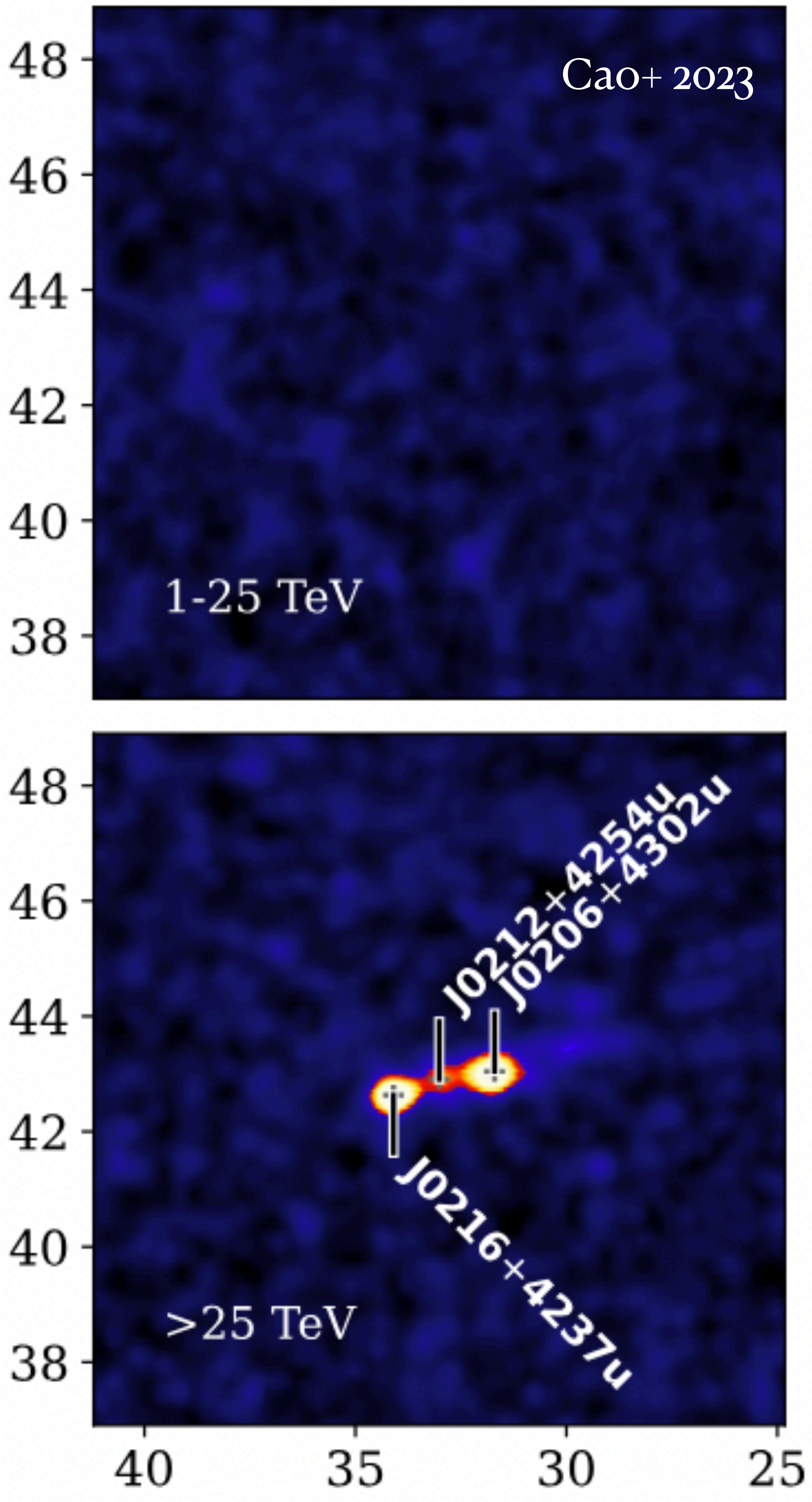
19 of these new sources overlap with archival VERITAS data!

→ However, the location of these sources in our observations and large extensions of some sources make it difficult for a traditional reflected regions analysis

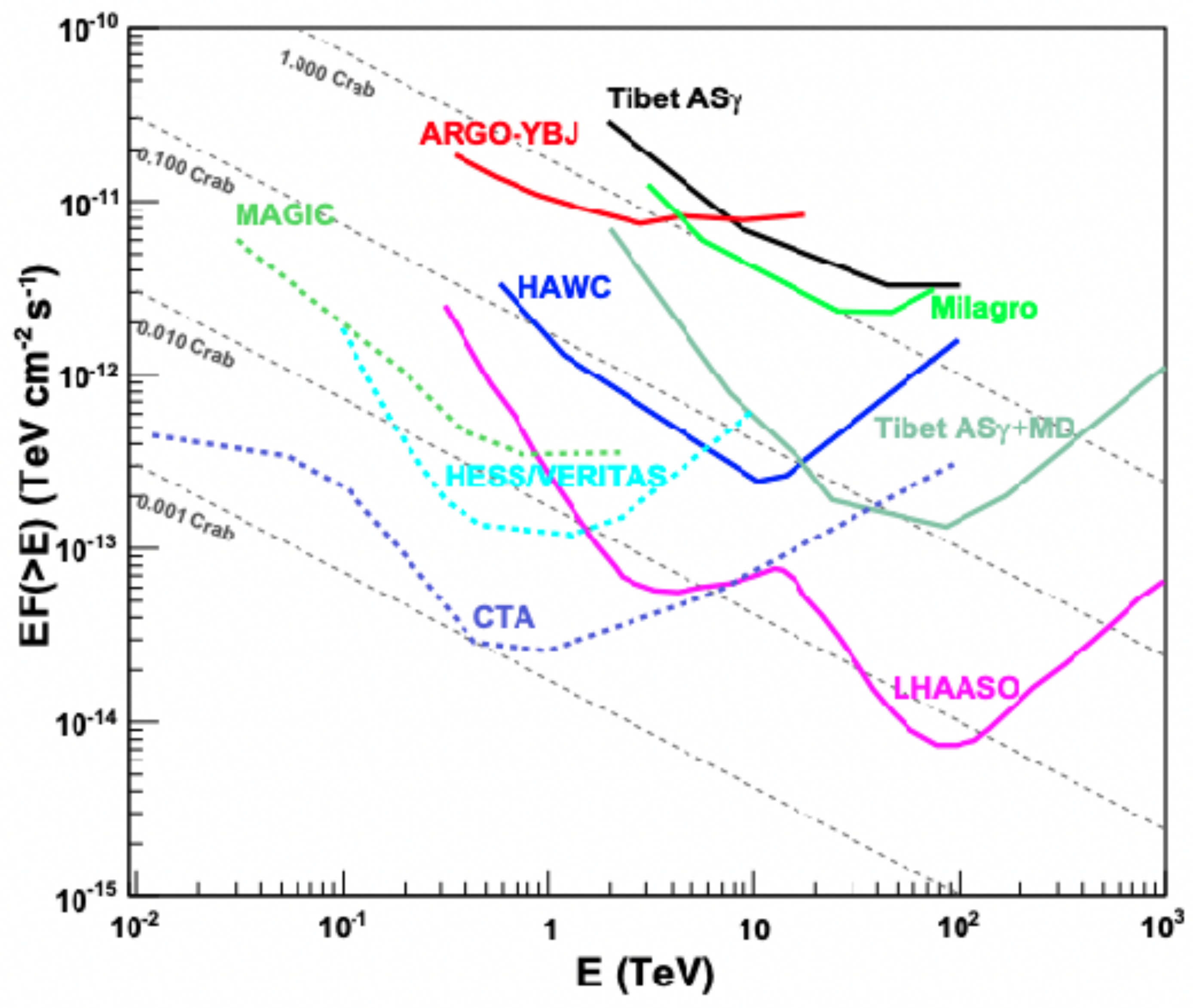


LHAASO source follow up — strategy

1. Find archival data overlapping with 1LHAASO sources
2. Validate ring background method in gammapy for extended source analyses
3. Validate FoV method for 3D spectra of extended sources
4. Characterize biases in steps 2 & 3 using mimic data
5. Optimize gamma/hadron cuts for very hard sources, if necessary
6. Analysis of real data 🎉 (hopefully detections)
7. Perform spectro-morphological studies and try to confirm associations with MWL sources



The future of pulsar astronomy with VERITAS & CTA



Optical:

→ VERITAS is getting an **optical upgrade ~late 2024** to directly read out voltage values from the FADCs ⇒ ~ns time resolution, GPS timing & improved digitization

→ The larger mirror area of LSTs with a similar backend to the proposed VERITAS upgrade will

γ-ray:

→ Inclusion of the **pSCT** in VERITAS observations gives us a larger FoV for very extended sources

→ The much **larger FoV** of CTA (> 8 deg for SSTs), increased sensitivity, and broader energy range will allow for much more detailed spectra-morphological studies of LHAASO sources

→ The **lower energy threshold** of CTA will help bridge the gap between Fermi-LAT and IACTs for better understanding the transition between GeV and TeV pulsar spectra

Instrument	Instantaneous FoV (deg)	Angular resolution (deg)	Energy Range (TeV)
VERITAS	3.5	0.08 @ 1 TeV	0.1 - 30
CTA	4 deg (LST), 7 deg (MST), 8 deg (SST)	0.06 @ 1 TeV	0.02 - 300
LHAASO WCDA	~180	0.45	0.2 - 10
LHAASO KM2A	~180	0.2	10 - 1.6 PeV

Thank you!

Questions?

Calibrations