Optical and VHE pulsar observations with VERITAS

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McGill TSI CRAQ Comprendre l'Univers NERSC VERITAS

VERITAS

VERITAS is an array of four 12m IACTs located in Arizona, USA (31° N)

→ On-sky since 2007

→ Sensitive to VHE gamma-rays from ~100 GeV to ~30 TeV

Many impactful pulsar-related publications

→ A Search for Pulsed Very High-Energy Gamma Rays from Thirteen Young Pulsars in Archival VERITAS data (2019)

→ A Search for Very High-Energy Gamma Rays from Missing Link Binary Pulsar PSR J1023+0038 With VERITAS (2016)

→ A Search for Pulsations from Geminga Above 100 GeV with VERITAS (2014)

→ Search for correlation between VHE gamma rays and giant radio pulses in Crab pulsar (2012)

→ Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar (2011)

+ many more on PWNe, TeV halos, microquasars, etc.

Current status of pulsar studies with VERITAS

- VHE
  - Crab pulsar →
    - Confirm MAGIC >400 GeV spectral point
    - Search for a TeV spectral component
  - TeV (Vela-like?) pulsars → Analysis of archival data on Vela-like (Fermi-bright) pulsars
- Optical
  - Crab pulsar →
    - Instrument calibration and commissioning
    - Search for flux enhancement coincident with CHIME GRPs
  - Discovery pulsars → Discovery of optical pulses from known pulsars

I. Optical pulsars

Non-Cherenkov optical observations with IACTs

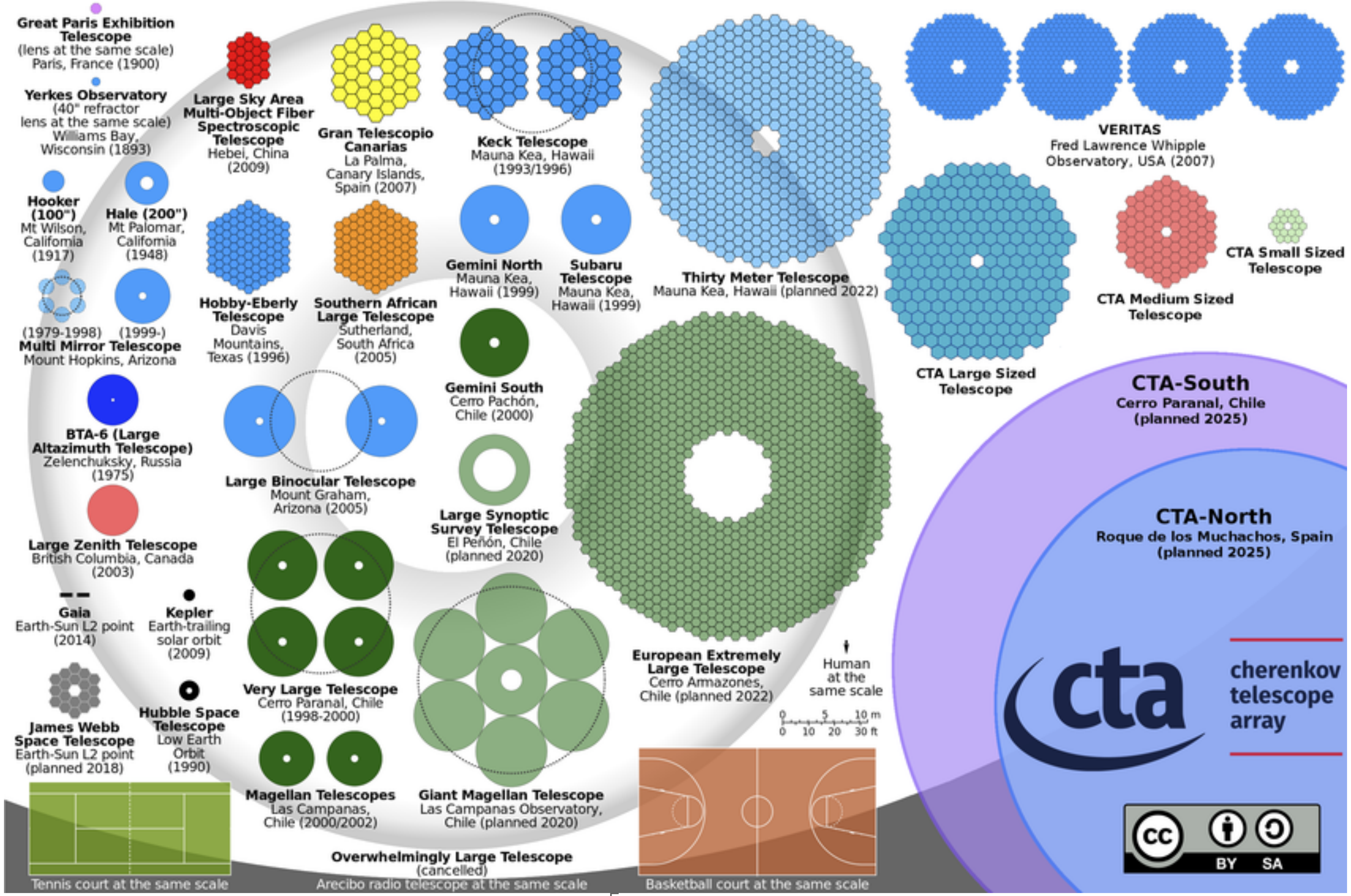
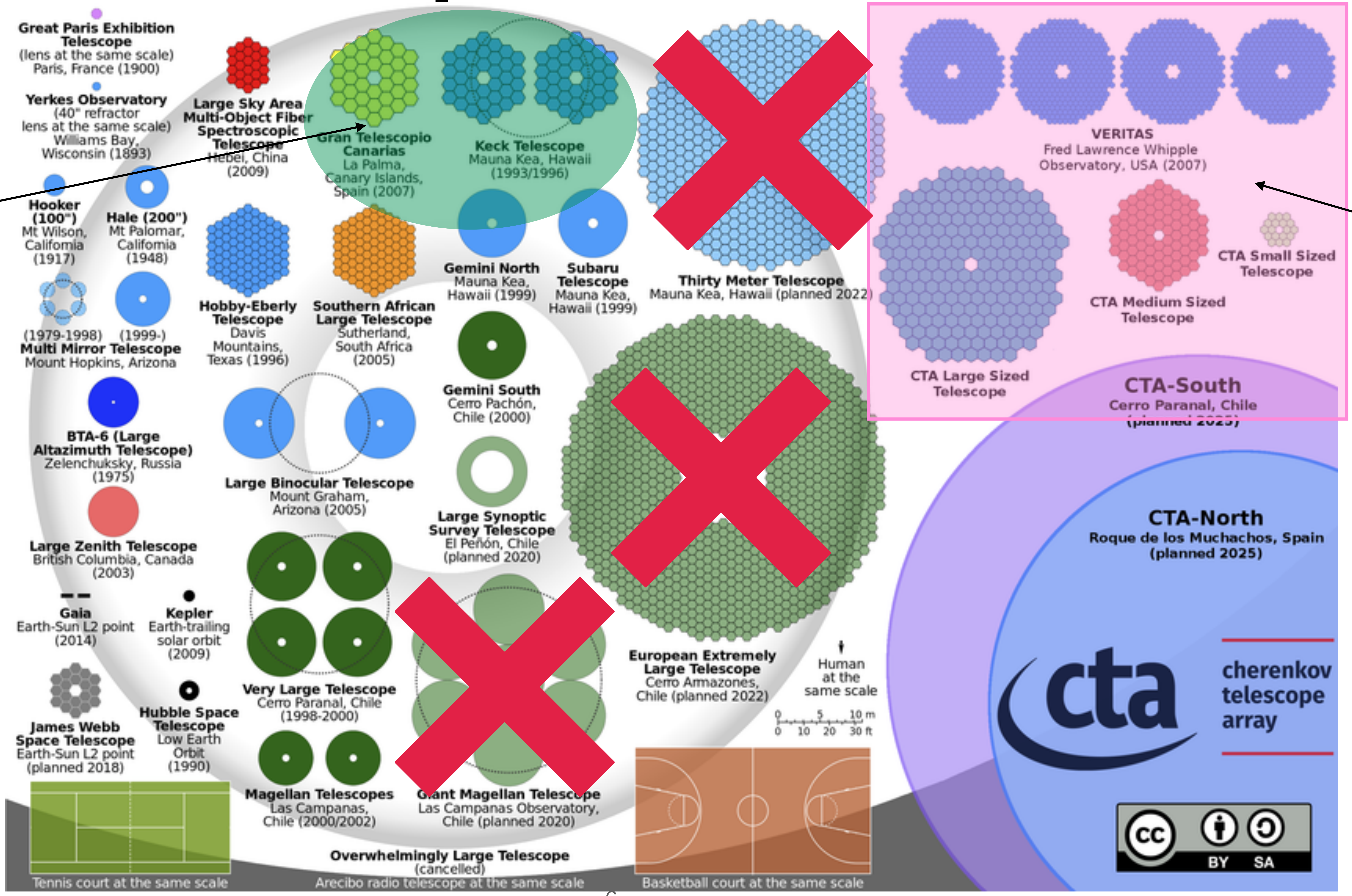


Image credit: T. Hassan

Non-Cherenkov optical observations with IACTs

Largest (currently operating) optical telescopes



Largest telescopes with optical capabilities

Image credit: T. Hassan

VERITAS optical backend

PMTs have a quantum efficiency that peaks in the **optical ~B band** (nUV)

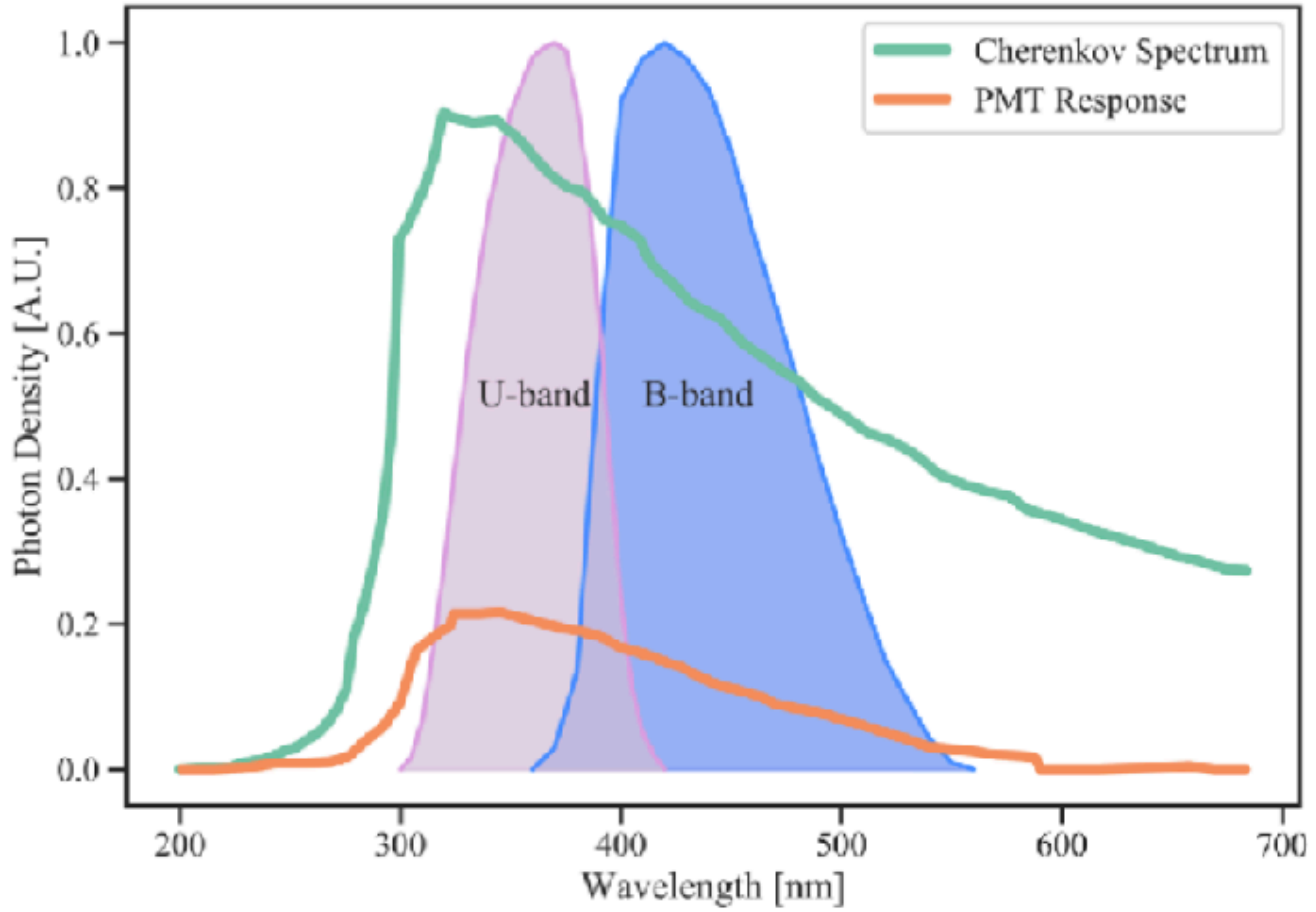
Enhanced Current Monitor = non-triggered optical readout working parasitically off of a pre-existing system that monitors PMT current ⇒ **rapid optical photometry**

Currently an off-the-shelf data acquisition device connected to individual **0.15°** PMTs

→ Samples at a frequency of 4800 Hz / # pixels (though instrumental effects limit sampling to ~**1200 Hz** in a single pixel)

→ Digitization bins at +/- 100 mV (roughly 18th mag)

→ NSB limits magnitude for one-off transients to 13th mag, but Fourier/folding analysis of pulsed signals can push this limit much lower



Why observe pulsars in optical wavelengths?

Huge potential discovery space:

- Only ~6 optical pulsars discovered to pulse in optical wavelengths

- This may be limited by instrumentation! We expect optical pulsars to be dim — need good time resolution and large light collecting area

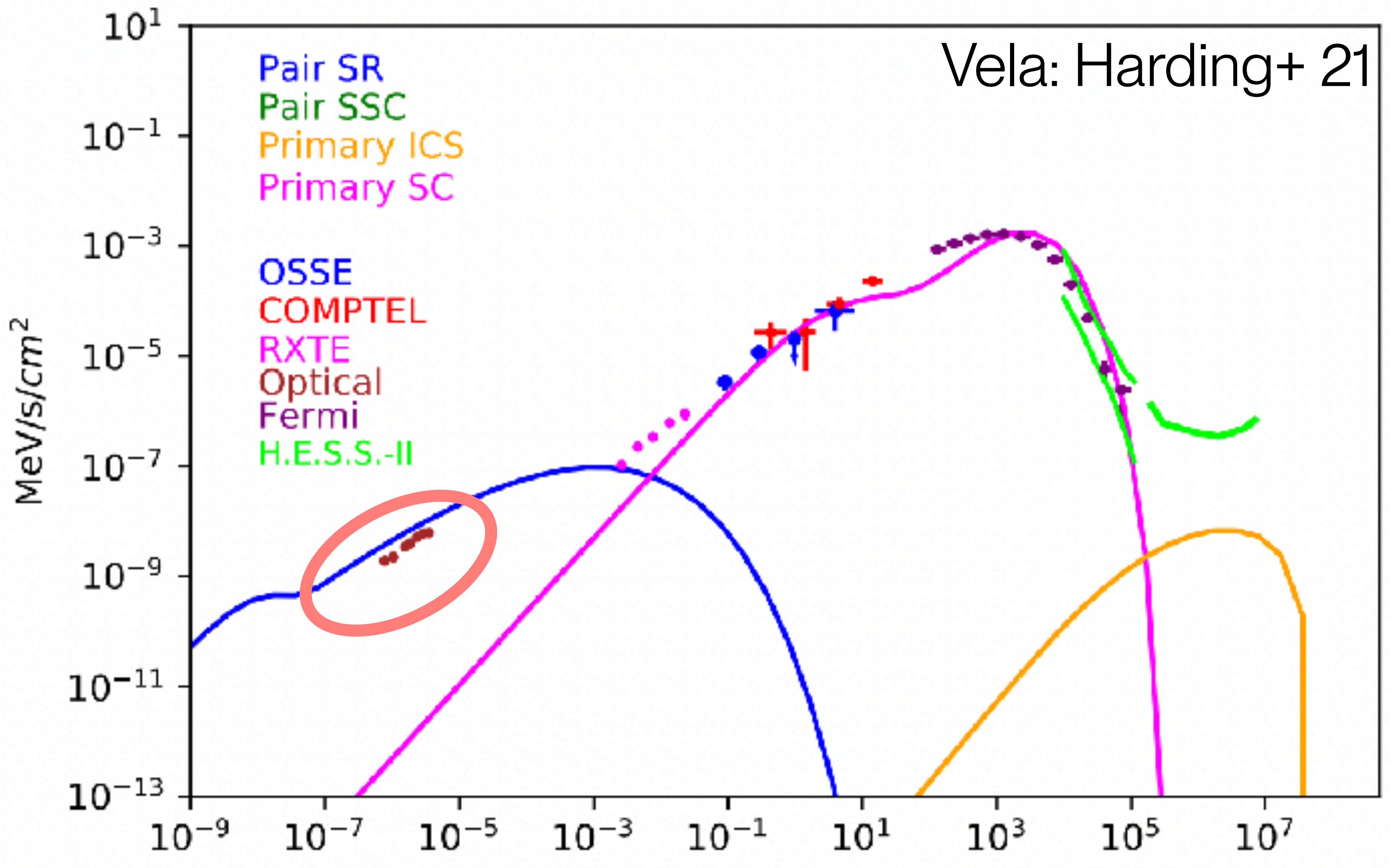
- Could detect the first optical MSP

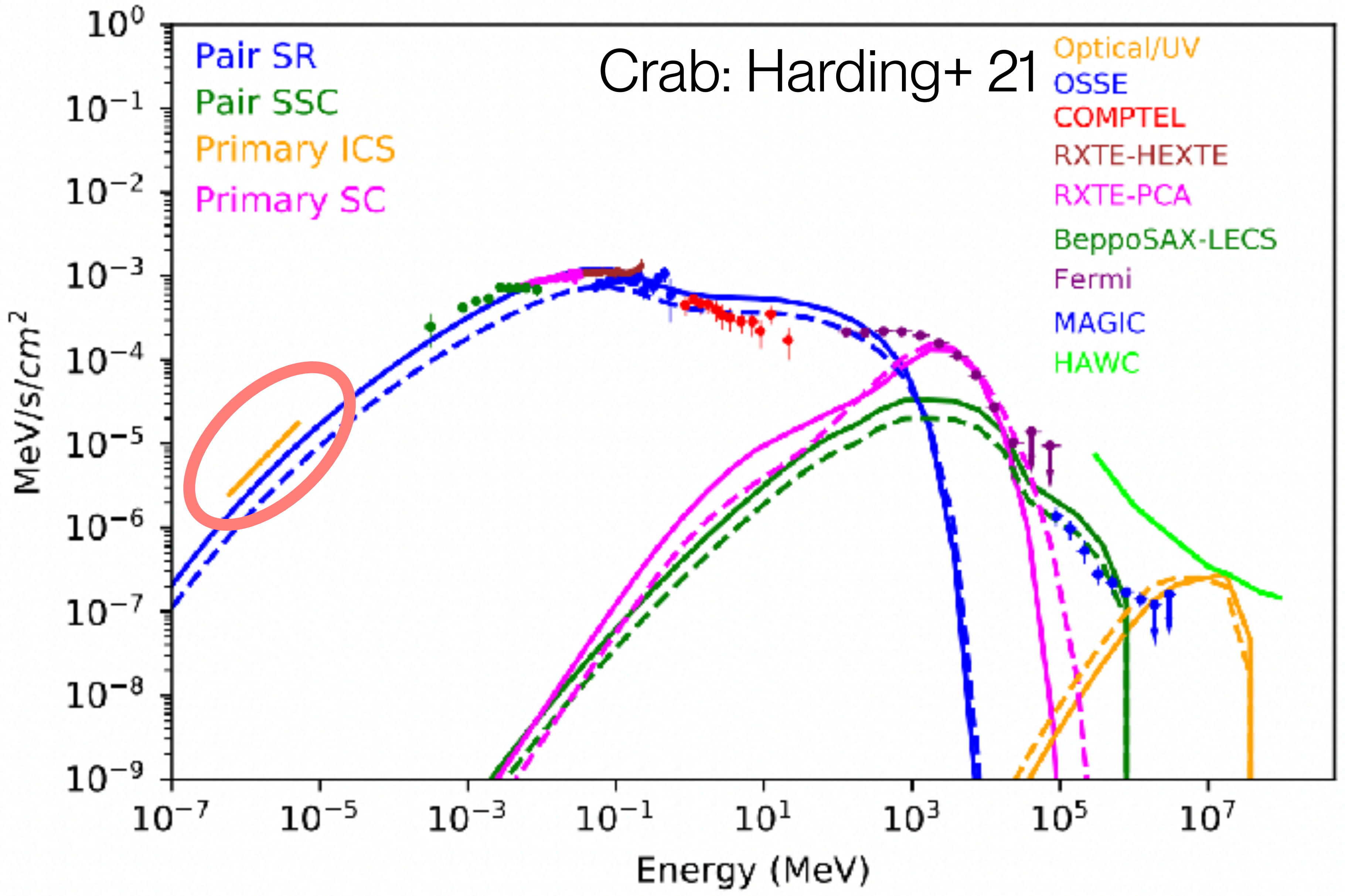
(Non-thermal) optical detections would help constrain pulsar high energy emission models:

- Few discoveries = few pulsars with SED points between radio and X-ray

- How do optical pulse phases align with the rest of the high energy spectrum?

- Do we see enhancement of optical emission during radio giant pulses?





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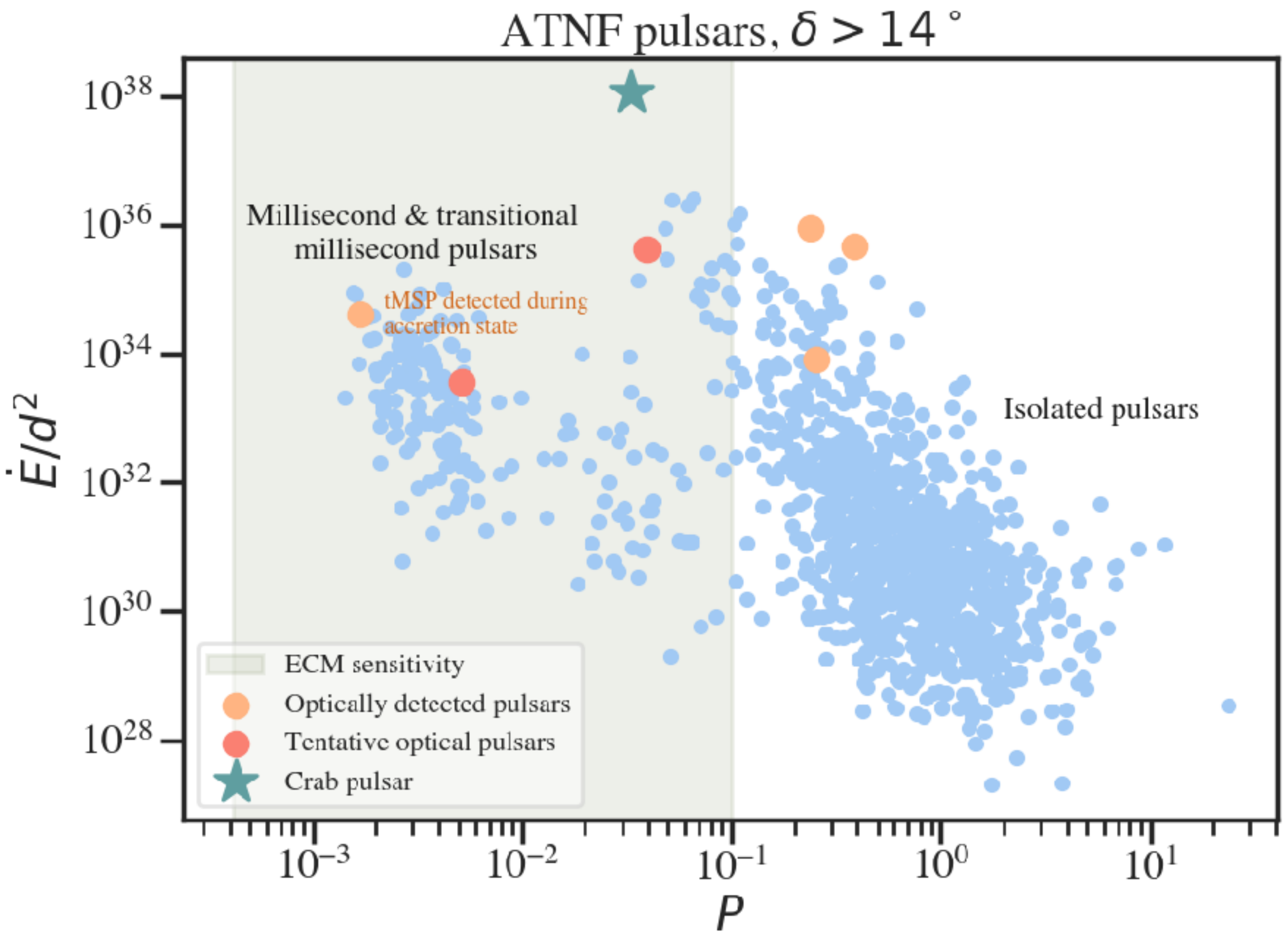


Optical target selection

Base criteria:

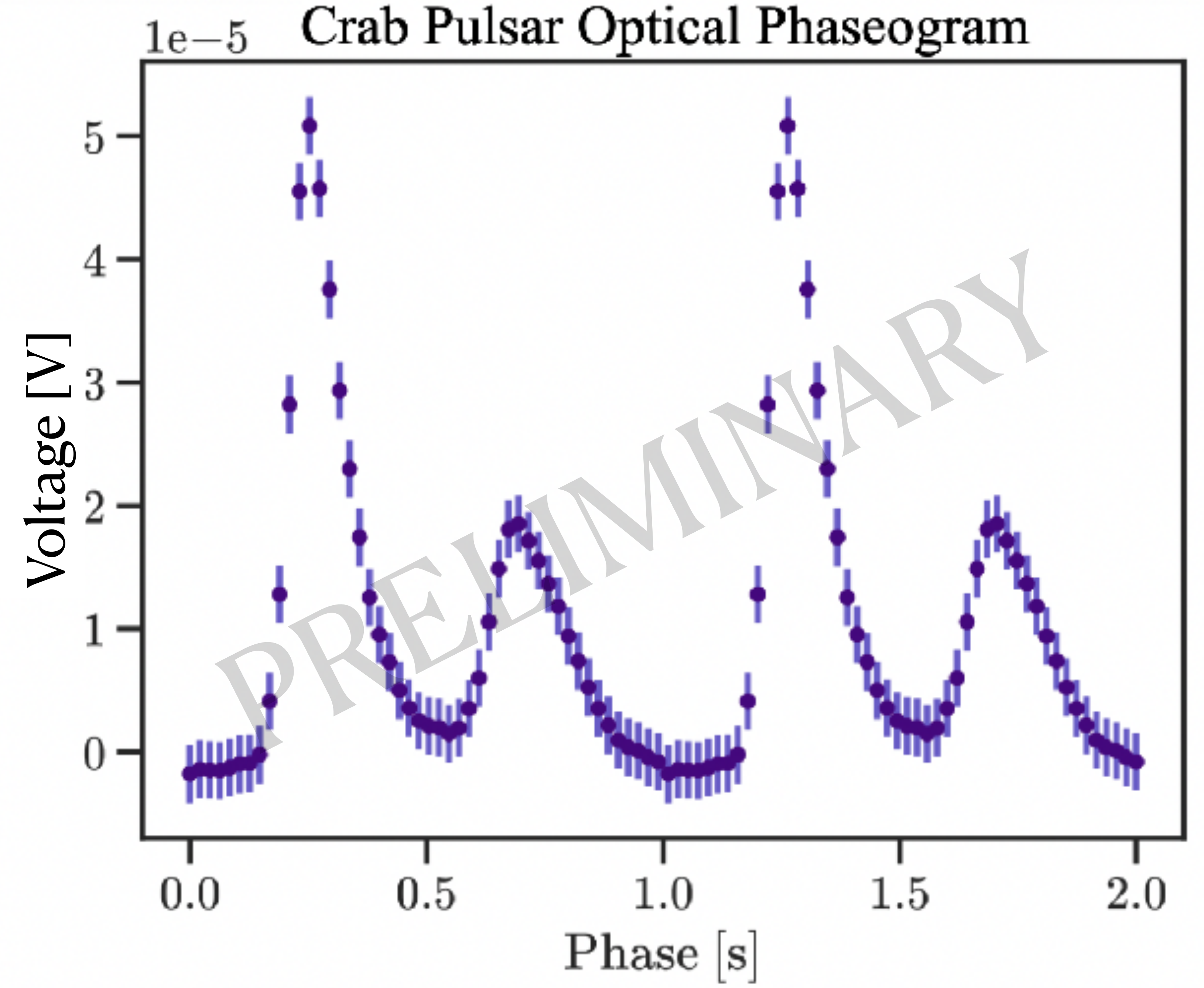
- Visible to VERITAS (> -15 deg declination)
- < 1s pulse period (instrumental limitation)
- Non-thermal X-ray emission

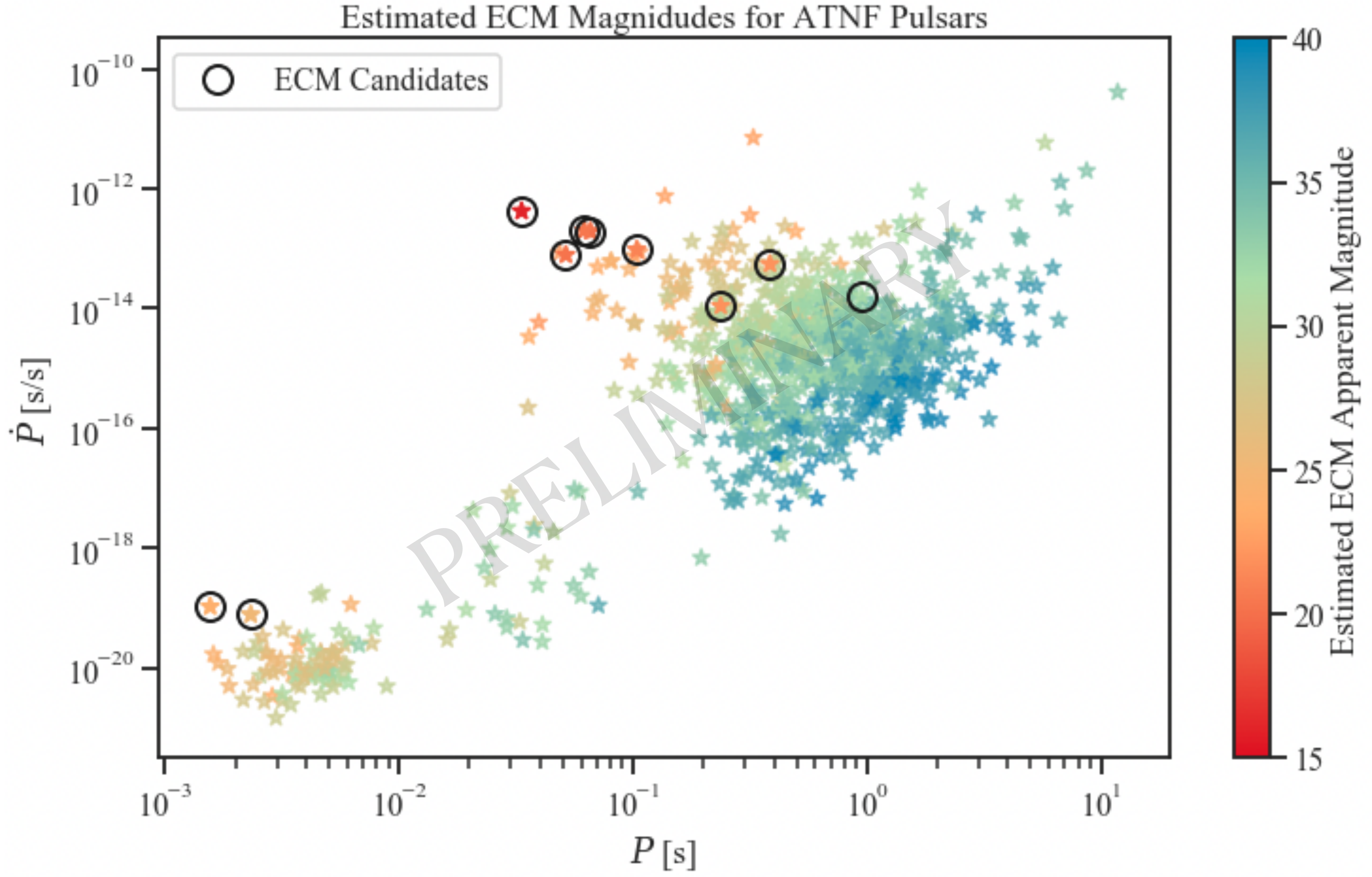
Optical magnitude is predicted by scaling with X-ray flux (adapted from Zharikov+ 2006) and using Crab pulsar as instrument calibration.

There are problems with this method:

→ X-ray and optical shouldn't be expected to come from the same spectral component

→ **Are there better ways to predict optical flux?**





Current optical limitations & future prospects

Current limitations:

- Coarse digitization creates a poisson-like counting of pulses that are rounded up to a higher bin than baseline noise

- Timing precision is limited to +/- 1s (not ideal for ~ms pulsar signals!)

- Limited sampling rate and signal smearing

(Near) future upgraded system:

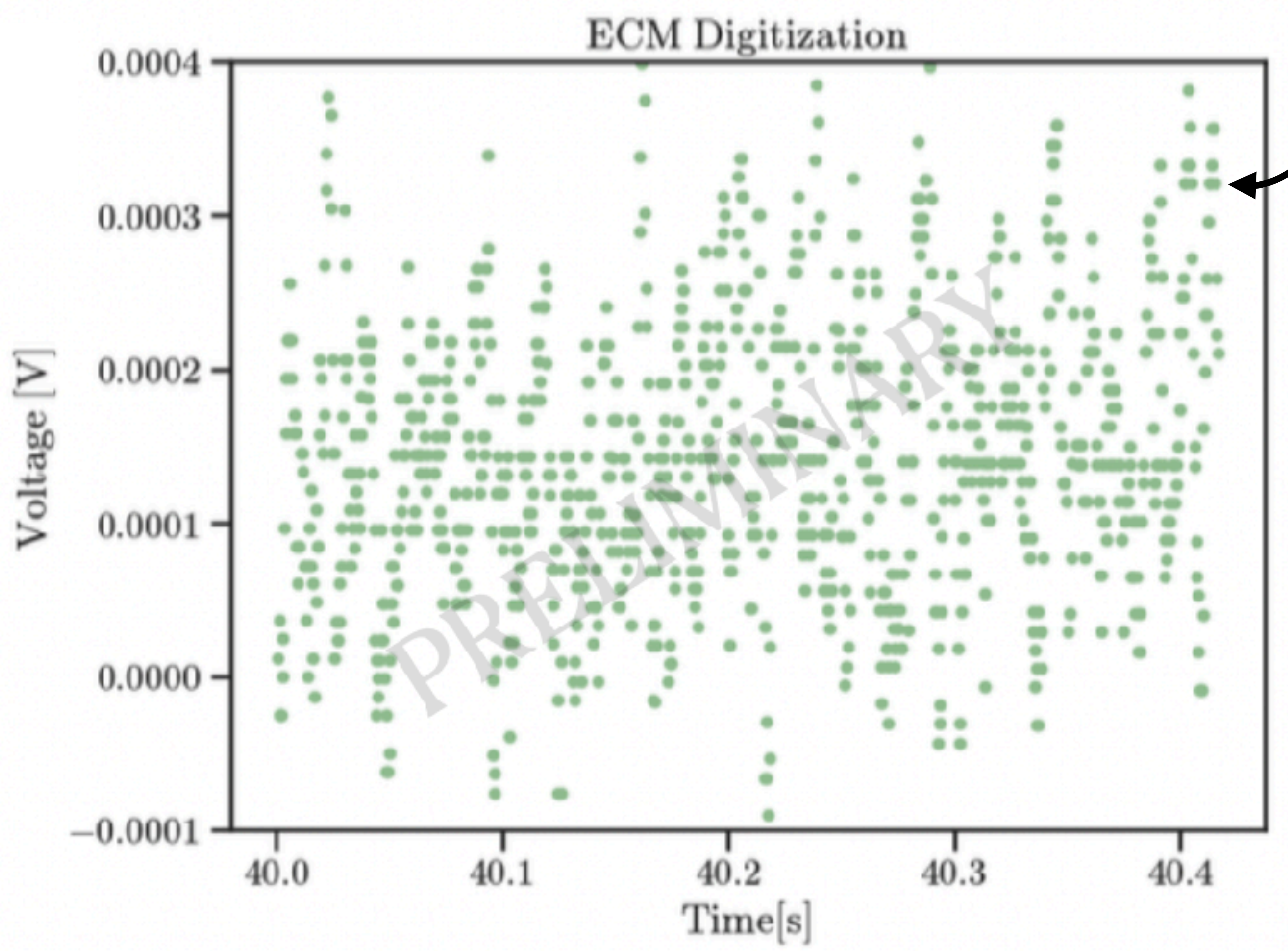
- AC optical readout integrated into FADC boards

- **Full 3.5 deg FoV equipped with continuous optical monitoring**

- **> 10 kHz sampling**

- Tests conducted at VERITAS last week and initial boards to be installed ~Jan. 2025

Bin size ~18th mag — we don't expect any undiscovered optical pulsars to be brighter than this limit



II. VHE pulsars

Rethinking VHE pulsar analysis

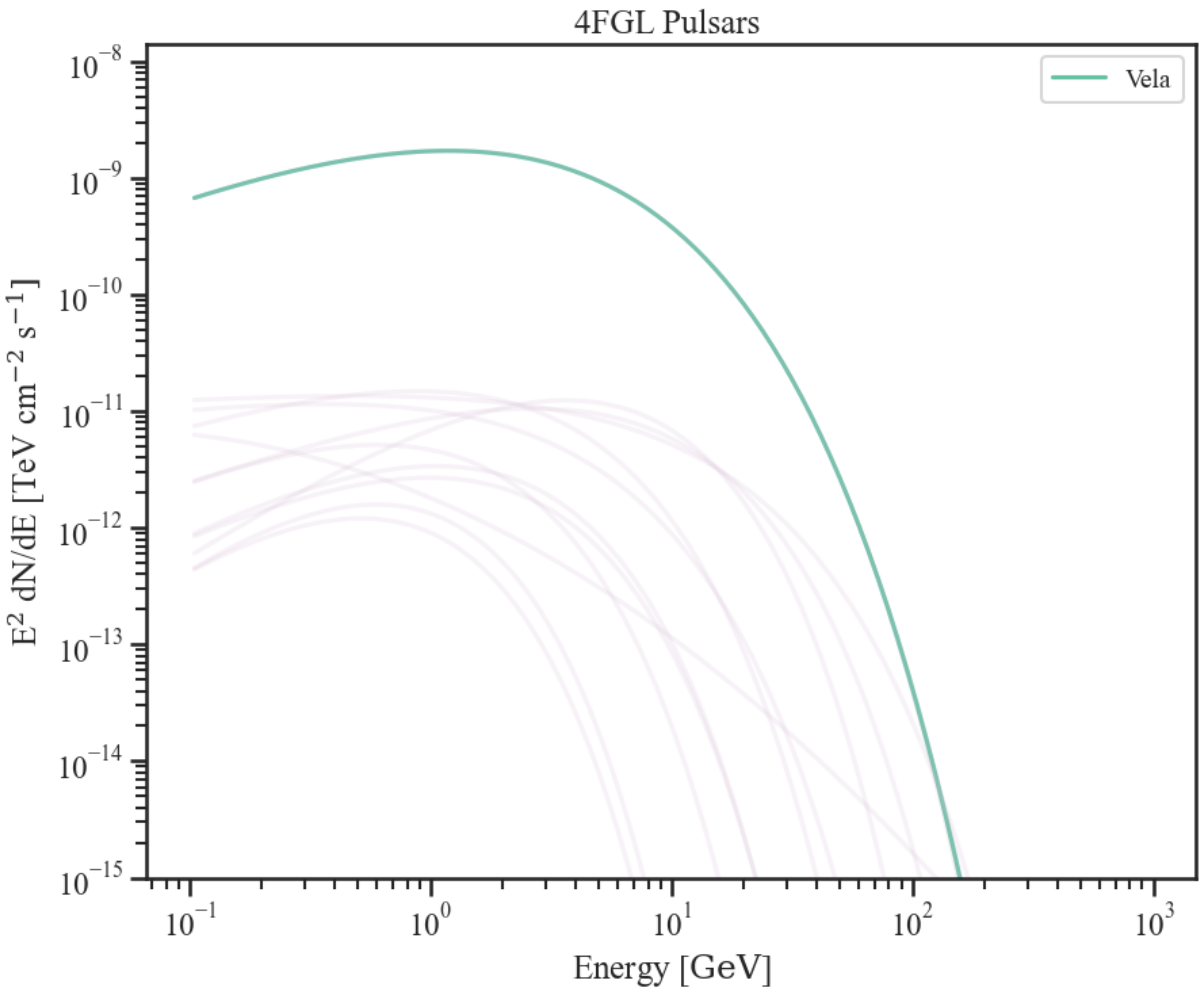
Previously, analysis has focused on detecting the GeV “tail” of pulsar spectra

→ H.E.S.S.'s Vela detection reveals a potential new class of pulsars VHE-peaking spectral components

→ What about the Northern Hemisphere?

VERITAS Cygnus survey (300h during 2007-2008) + deep exposures on Galactic sources over 17 years of operations provide large datasets coincident with known pulsars

We should have sufficient exposures on several Vela-like (Fermi-bright) pulsars to detect or place constraining limits on TeV-peaking spectral components



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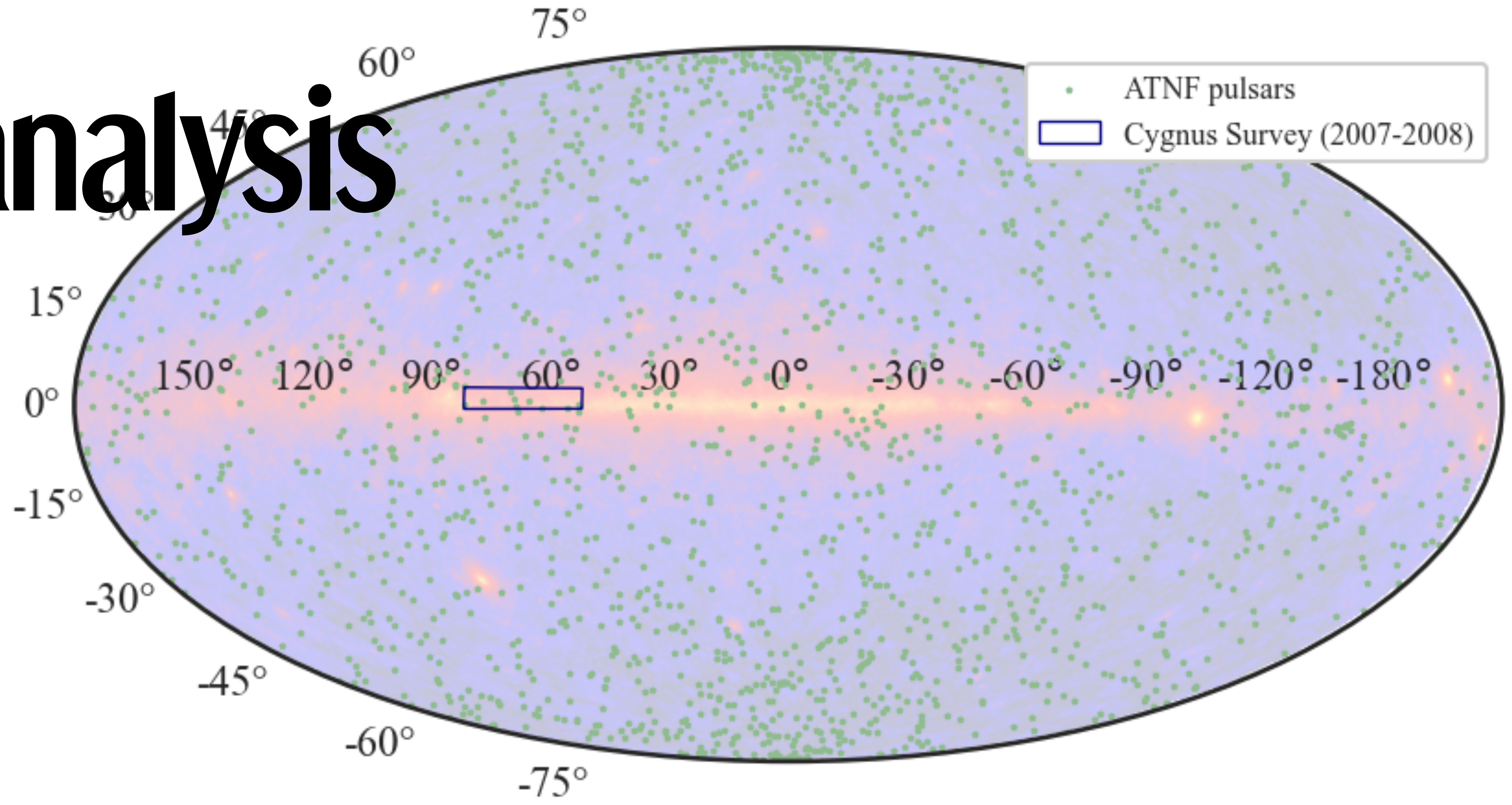


Brightest 4FGL integral flux (0.1 - 100 GeV) pulsars

4FGL flux [cm-2 s-1]	ATNF distance [kpc]	% Vela flux	% Vela flux (scaled w/ distance)	VTS exposure (h)
2.77e-08	3	2.08	239.14	210
3.01e-08	2.37	2.26	162.03	146
4.11e-08	1.4	3.09	77.16	115
6.64e-08	1.8	4.99	206.05	98
7.21e-08	2.15	5.42	319.44	78
1.10e-07	0.286	8.25	8.61	9
1.89e-08	0.835	1.42	12.64	6.5
2.30e-08	0.1365	1.73	0.41	0.5
1.03e-07	0.3	7.75	8.89	0.5
5.44e-08	2.635	4.09	362.04	0

Rethinking VHE pulsar analysis

VERITAS 2013 paper: *A Search for Pulsed Very High-energy Gamma-Rays from 13 Young Pulsars in Archival VERITAS Data* → no detections or hint of a signal - why?

Table 3
Results for the 13 Pulsars Appearing in Archival VERITAS Data

Pulsar	Exposure Time (hr)	Cut Type	Significance	*H* Statistic	Spectral Analysis Threshold (GeV)	*H*-Test Flux UL (10^{-9} m^{-2} s^{-1})	Rolke Flux UL (10^{-9} m^{-2} s^{-1})
J0007+7303	32.4	soft	−1.74	4.32	320	16.7	1.24
		moderate	−0.95	2.37	460	6.20	2.48
		hard	−0.51	3.15	1100	1.38	0.767
J0205+6449	22.2	soft	−1.29	1.28	240	13.7	2.77
		moderate	−1.11	3.29	350	7.63	1.63
		hard	−1.40	3.94	500	4.12	0.575
J0248+6021	45.9	soft	0.00	3.26	220	19.4	11.0
		moderate	0.85	3.69	290	10.7	8.65
		hard	0.44	1.34	600	1.9	1.72
J0357+3205	7.92	soft	−0.47	0.74	140	33.6	20.9
		moderate	−0.17	0.32	200	10.7	10.1
		hard	0.12	2.36	380	5.26	4.01
J0631+1036	2.79	soft	−1.27	3.61	150	79.4	13.9
		moderate	0.81	0.56	220	18.2	22.2
		hard	−1.07	1.44	460	7.44	2.44
J0633+0632	108	soft	−1.37	3.66	180	8.92	1.00
		moderate	0.41	0.32	260	1.95	1.59
		hard	0.70	4.80	500	1.01	0.523
J1907+0602	39.1	soft	−1.49	1.60	180	11.7	1.72
		moderate	0.36	10.4	260	7.72	3.72
		hard	−0.15	2.60	550	1.73	0.953
J1954+2836	5.18	soft	1.07	7.01	130	68.4	40.3
		moderate	0.58	2.46	200	19.3	14.0
		hard	−1.50	0.60	290	8.24	1.48
J1958+2846	13.9	soft	−0.70	1.62	130	24.9	8.62
		moderate	−1.24	0.82	180	9.49	2.24
		hard	−1.54	3.00	260	6.81	0.658
J2021+3651	58.2	soft	−0.56	9.46	150	25.4	4.53
		moderate	0.25	2.28	220	7.23	2.96
		hard	0.95	6.46	420	2.48	1.06
J2021+4026	20.6	soft	0.18	0.73	170	24.1	32.1
		moderate	0.15	3.28	240	15.0	13.8
		hard	−1.93	2.42	460	4.68	0.0615
J2032+4127	47.9	soft	−0.37	0.34	170	10.9	4.07
		moderate	0.58	4.29	220	10.4	3.56
		hard	0.42	2.00	460	2.22	0.974
J2229+6114	47.2	soft	0.72	0.30	240	8.75	9.41
		moderate	0.19	0.58	320	5.28	4.07
		hard	−0.75	2.35	660	1.97	0.648

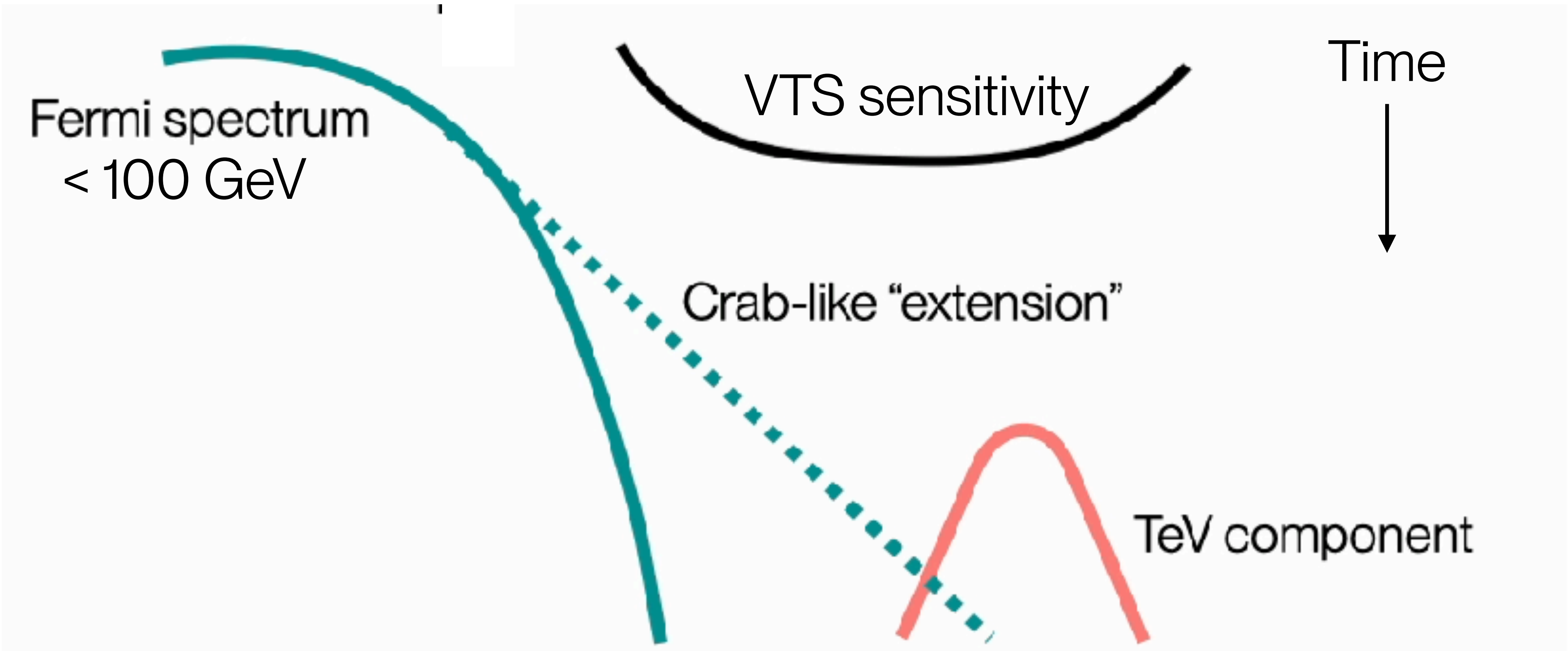
Note. Each pulsar has three sets of results, one for each set of cuts applied to the data. Column 2 lists the exposure time for each pulsar, copied here from Table 1 for convenience. Column 3 specifies the set of cuts used in the analysis. Columns 4 and 5 give the phase-gate test pre-trials significance and *H* statistic, respectively. Column 6 gives the spectral analysis energy threshold in GeV. Integral flux upper limits at the 95% CL above the spectral analysis threshold in column 6 from the *H* test and Rolke methods are given in columns 7 and 8, respectively.

Rethinking VHE pulsar analysis

VERITAS 2013 paper: *A Search for Pulsed Very High-energy Gamma-Rays from 13 Young Pulsars in Archival VERITAS Data* → no detections or hint of a signal - *why?*

- Very short exposures (2-50 h, excl. Geminga)

- Standard cuts/cuts optimized on very soft emission spectrum



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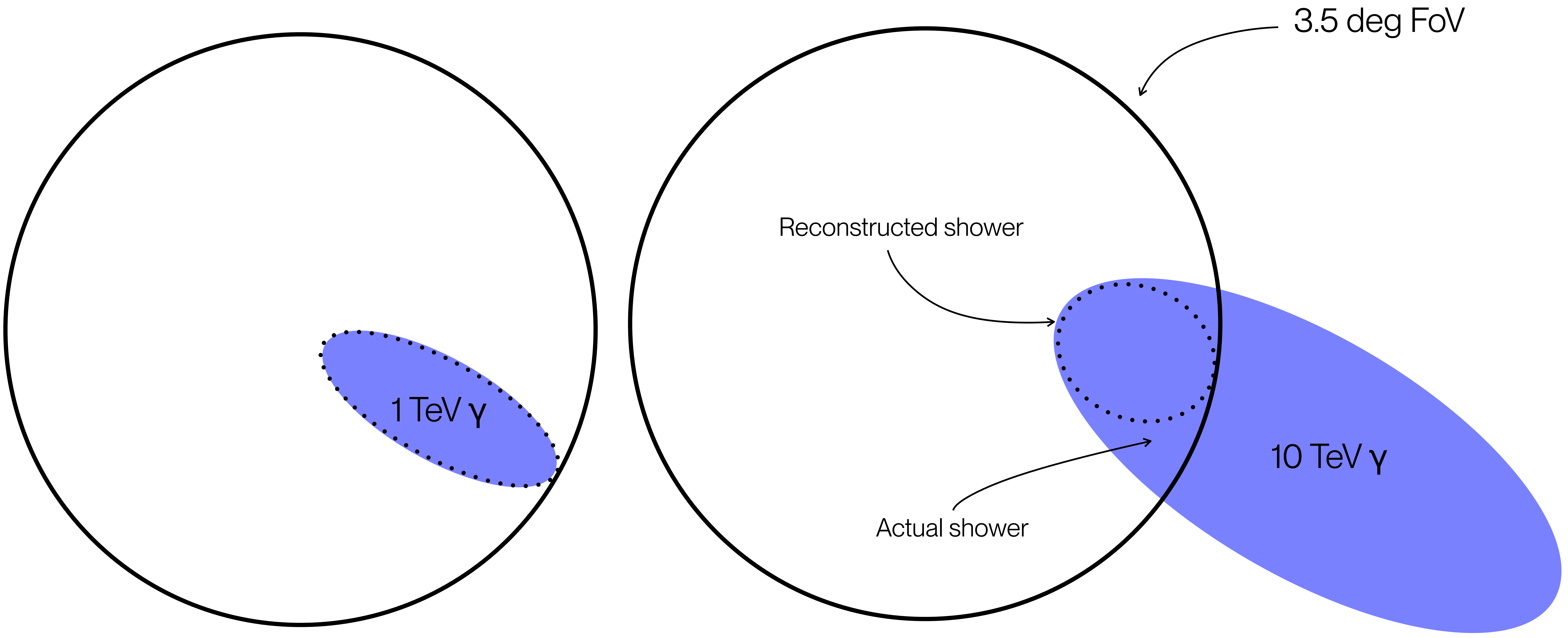
High energy analysis for VHE pulsars



*Not to scale!

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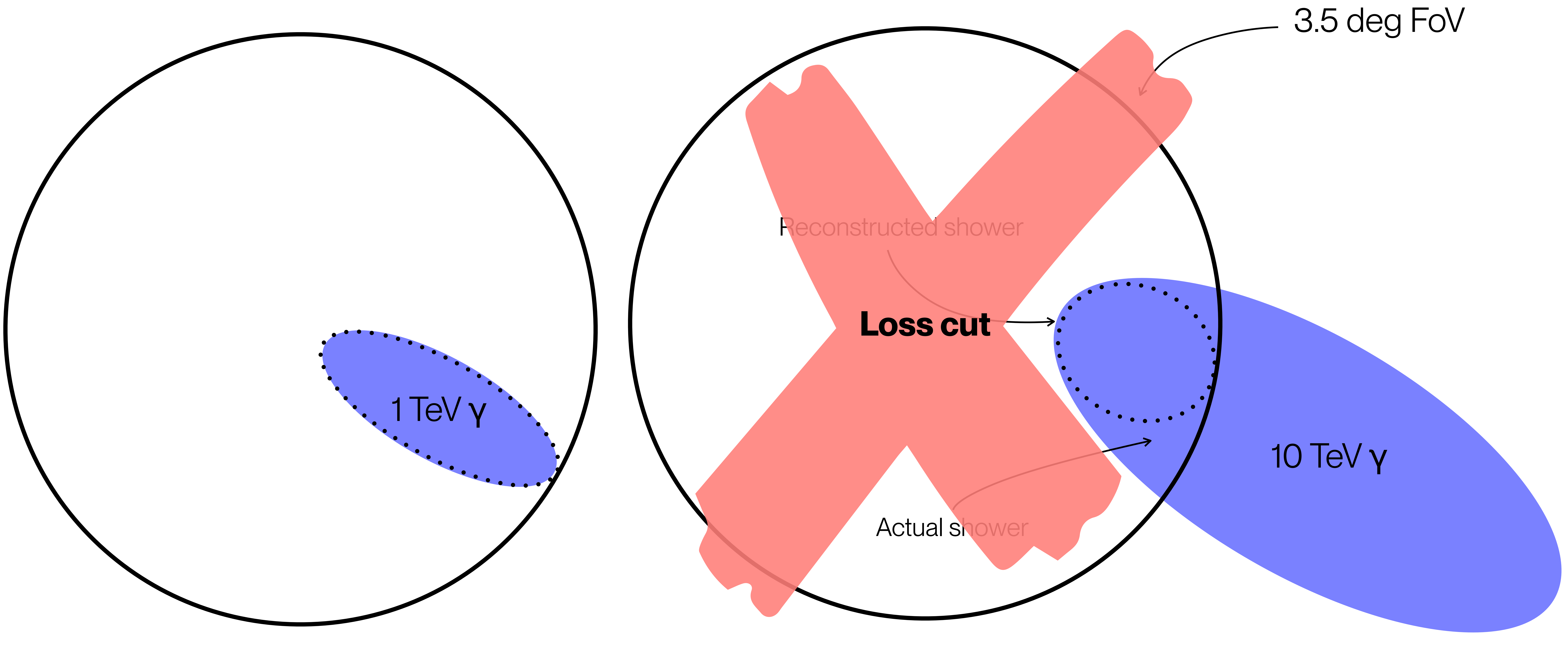

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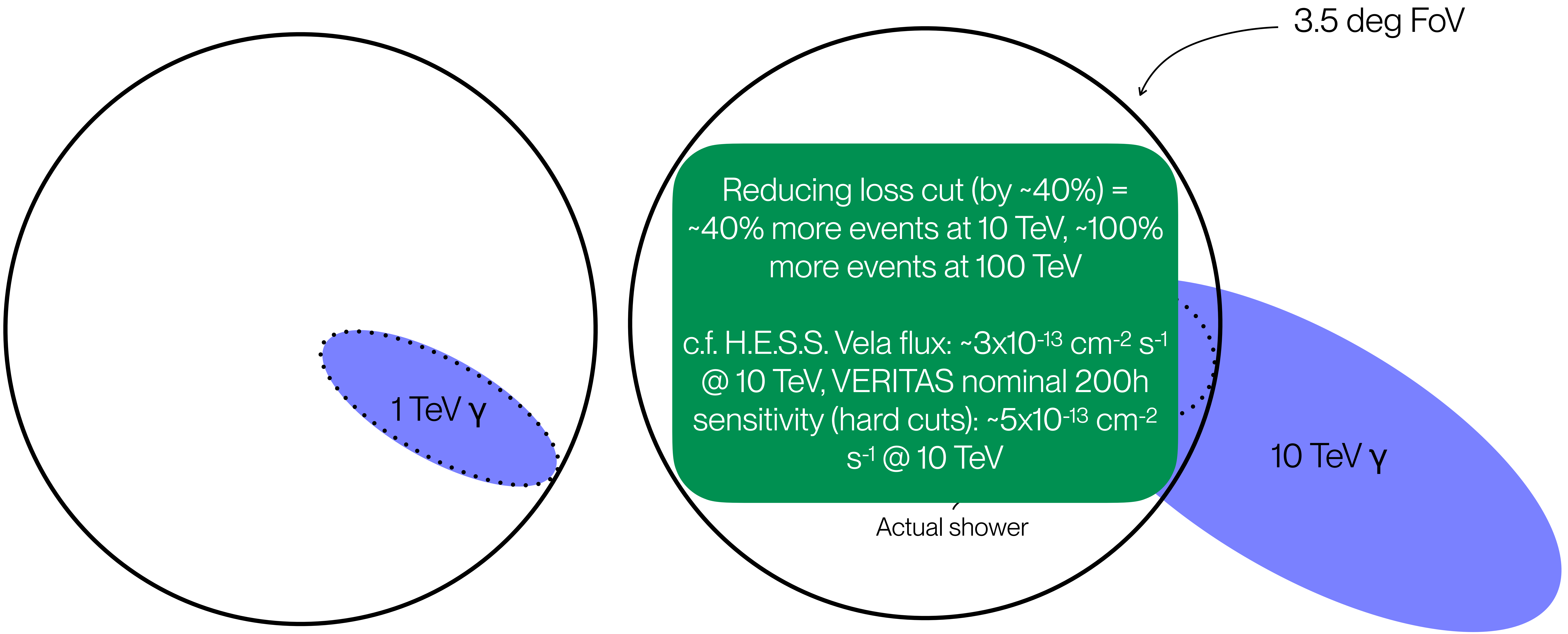


Reducing loss cut (by ~40%) = ~40% more events at 10 TeV, ~100% more events at 100 TeV

c.f. H.E.S.S. Vela flux: ~3x10^{-13} cm^{-2} s^{-1} @ 10 TeV, VERITAS nominal 200h sensitivity (hard cuts): ~5x10^{-13} cm^{-2} s^{-1} @ 10 TeV

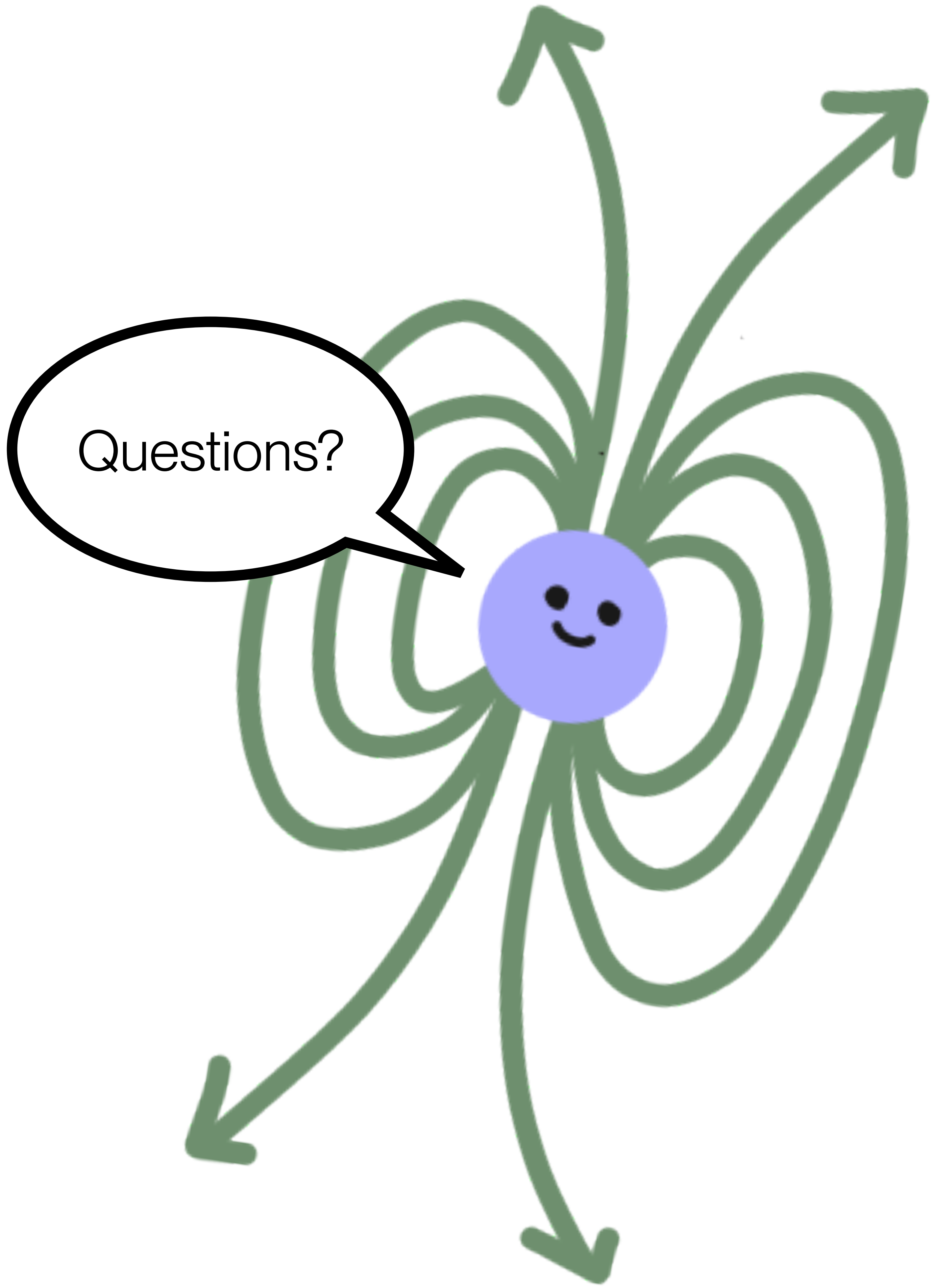
*Not to scale!

Summary & conclusions

VERITAS has **large archival Galactic datasets** and a new optical instrument that can continue to contribute new pulsar science over the next few years.

Predicting optical pulsar flux is hard! We don't have populations to study and it's difficult to predict which pulsars may be discovered to pulse optically.

It would be great to find a **Northern Hemisphere "Vela"** — discovery of other H.E.S.S. TeV pulsars makes us optimistic that bright Fermi pulsars might be detectable at TeV energies with large datasets.



Thank you!

contact: samantha.wong2@mail.mcgill.ca