Galactic PeVatron candidates in the LHAASO J1956+2845 sky region

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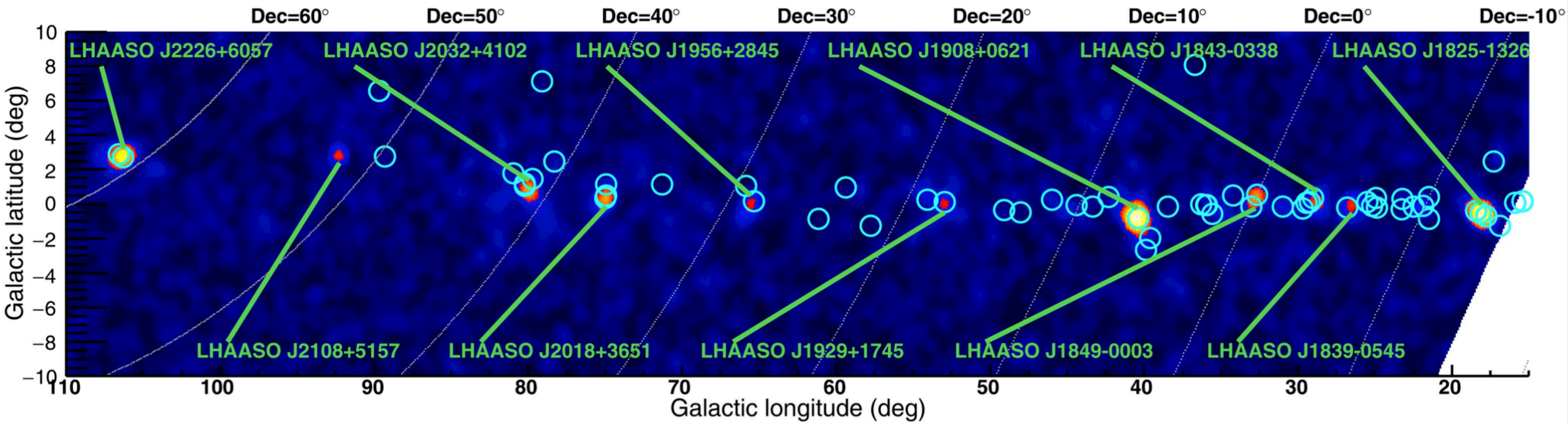
29/05/2023 — Roma

LHAASO SOURCES (E>100 TeV)



Science with the Cherenkov Telescope Array, 2017
Cao+ 2021, Nature 594, 33

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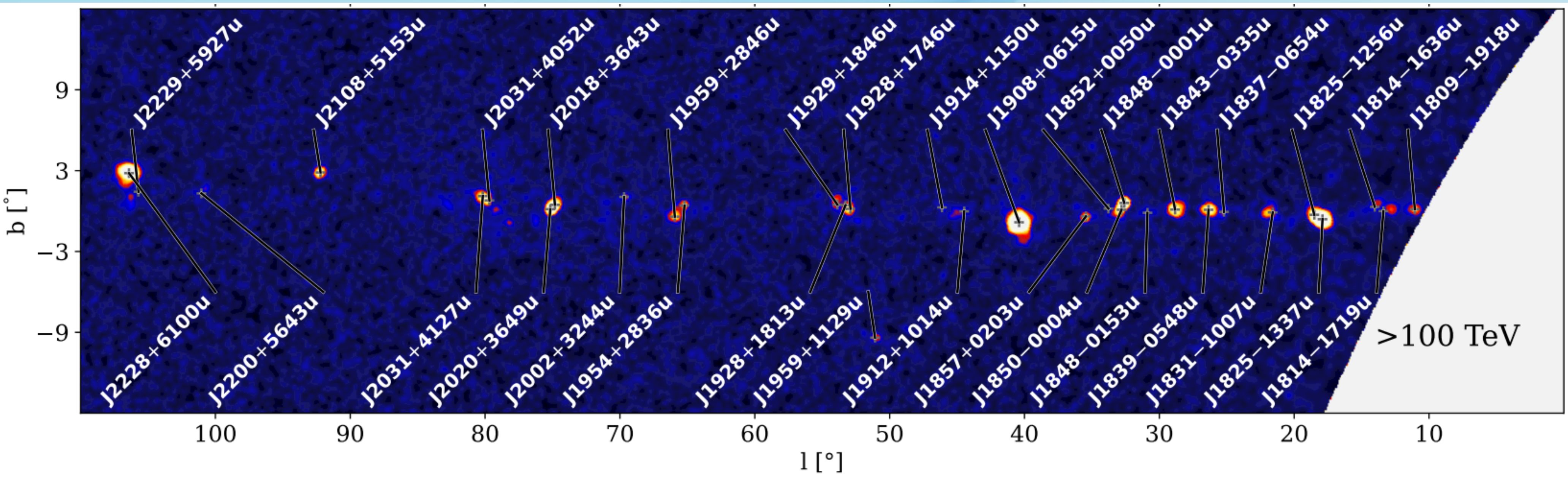

Science with the Cherenkov Telescope Array, 2017
Cao+ 2023, TODAY

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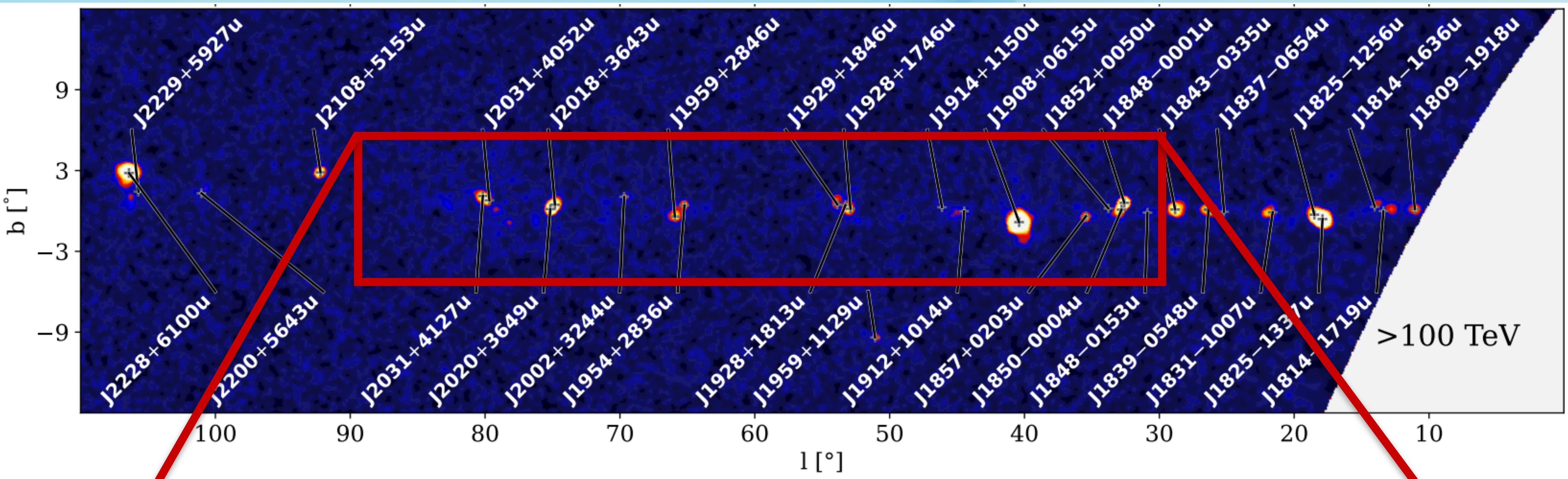
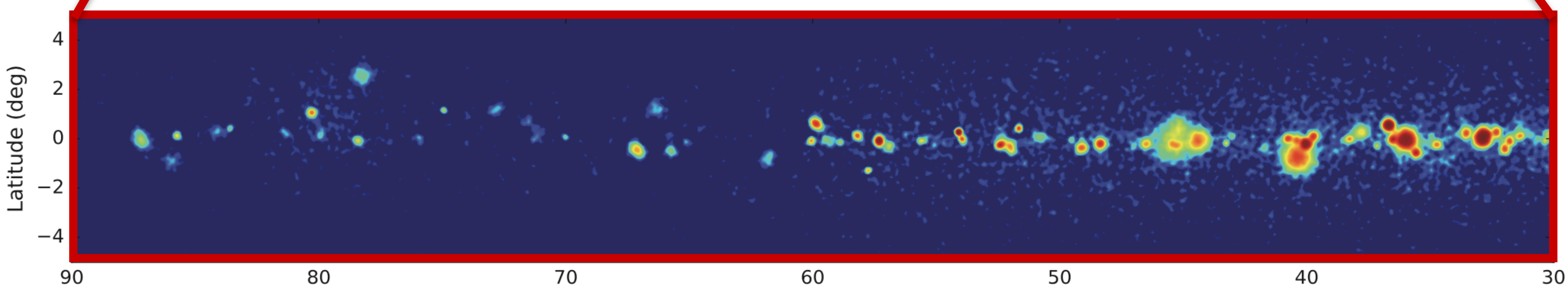


CTA Galactic Plane Survey (GPS) (0.1 TeV<E<10 TeV)



Science with the Cherenkov Telescope Array, 2017
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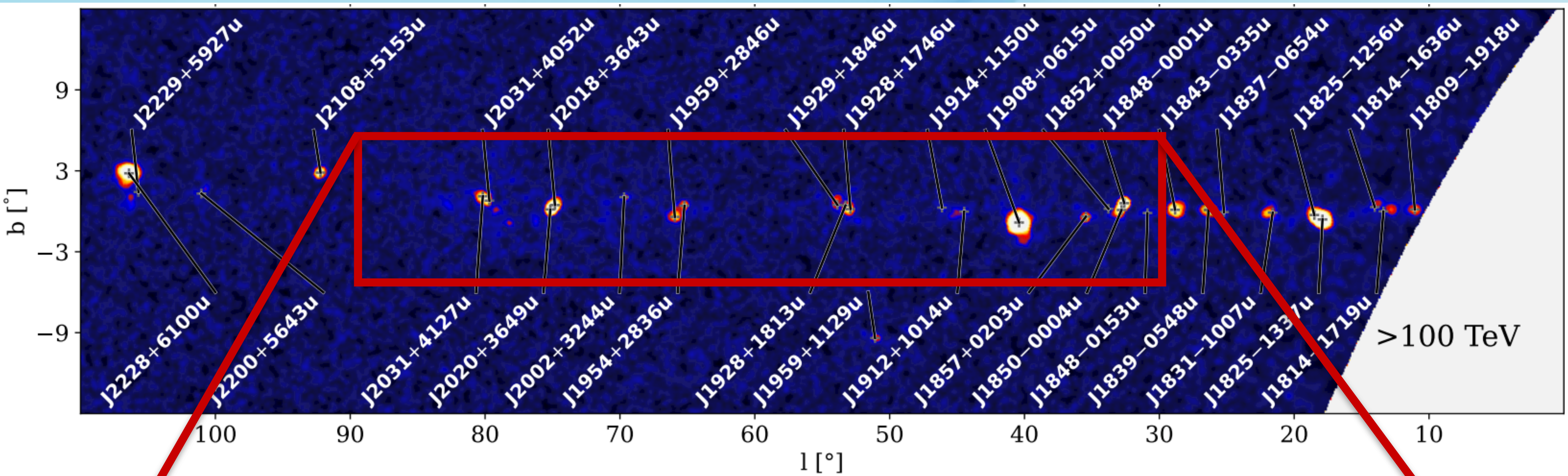
LHAASO SOURCES (E>100 TeV)



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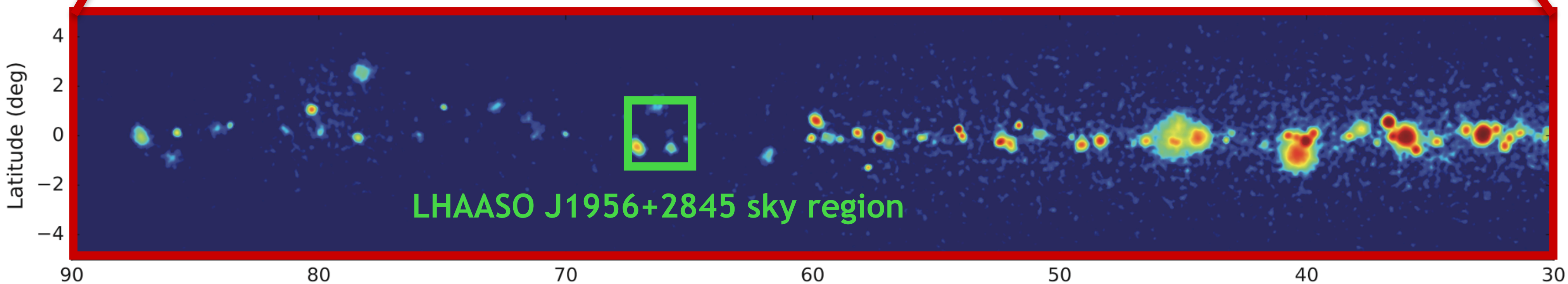
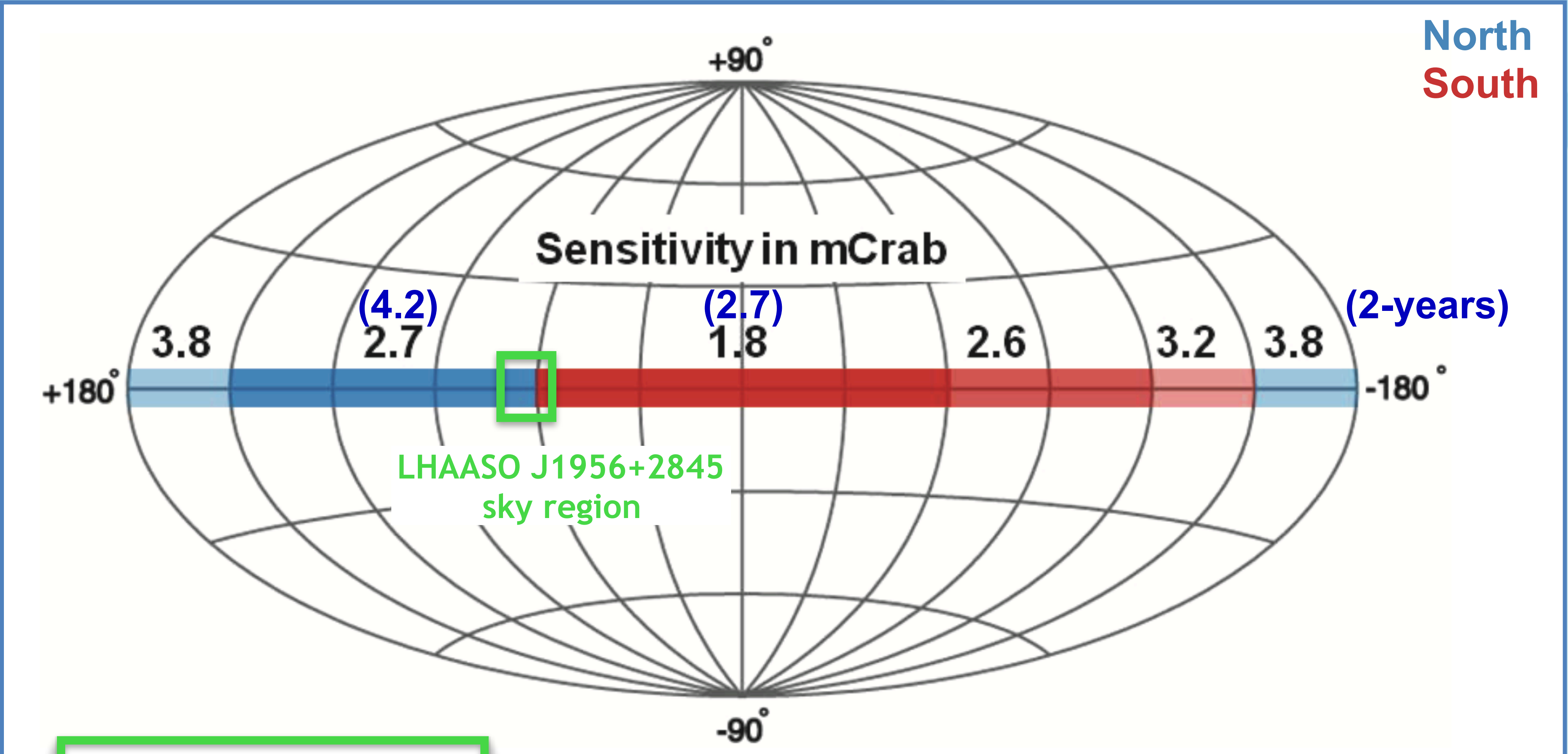


Science with the Cherenkov Telescope Array, 2017
Cao+ 2023, TODAY

10-year GPS sensitivity



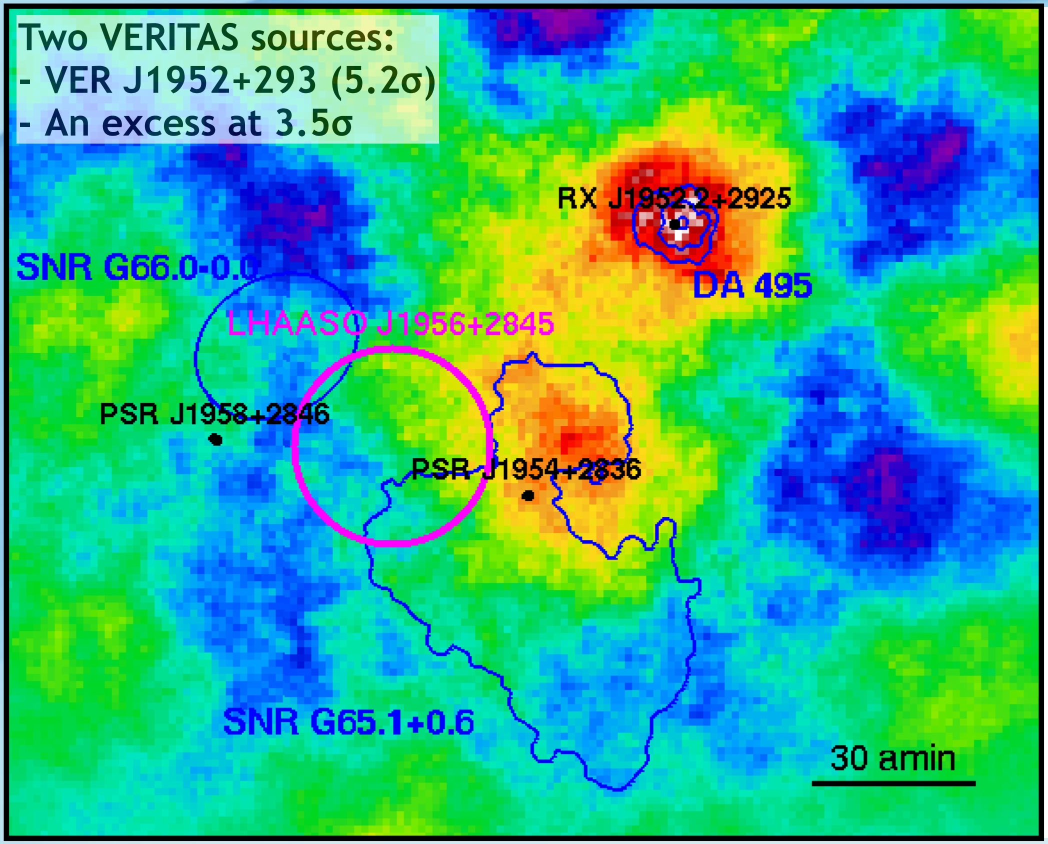
NB: a factor ~3 worse for sources of 0.25 deg

Our sources are about
5 — 8 mCrab
and < 0.15 deg

Science with the Cherenkov Telescope Array, 2017

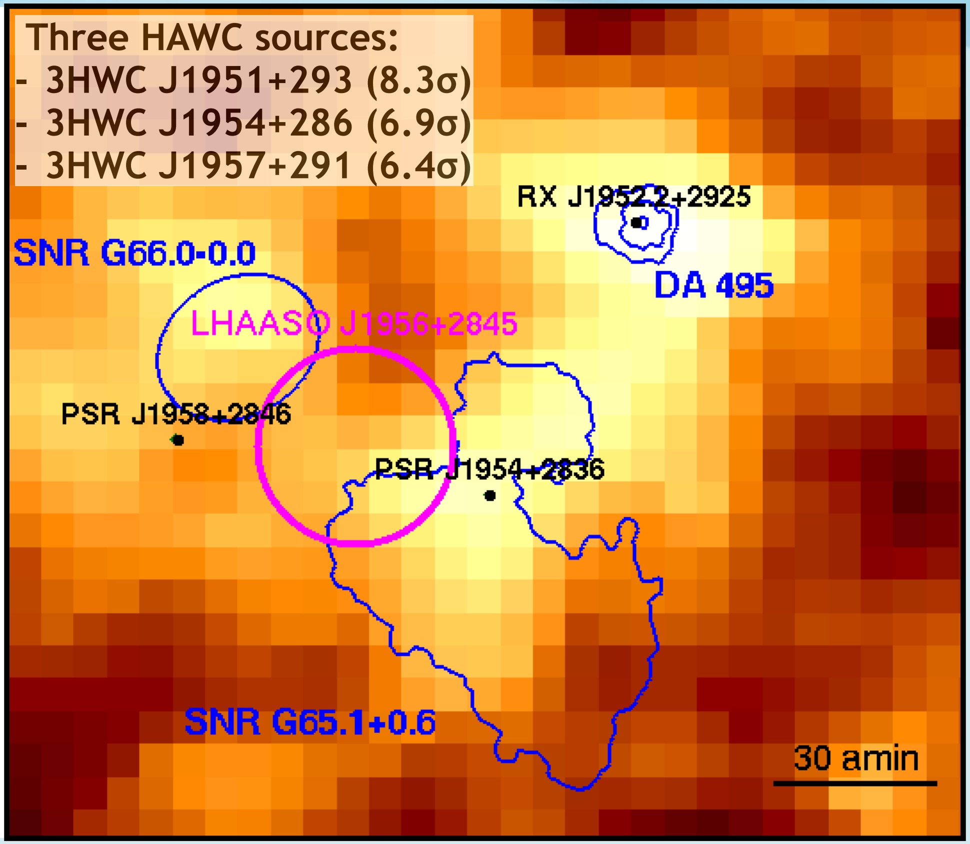
LHAASO J1956+2845 sky region

VERITAS



0.3 — 3 TeV
1 px = 0.02 deg

HAWC



1 — 100 TeV
1 px = 0.10 deg

Abeysekara+ 2018, ApJ 866, 24
Albert+ 2020, ApJ 905, 76
Cao+ 2021, Nature 594, 33

3HWC J1954+286

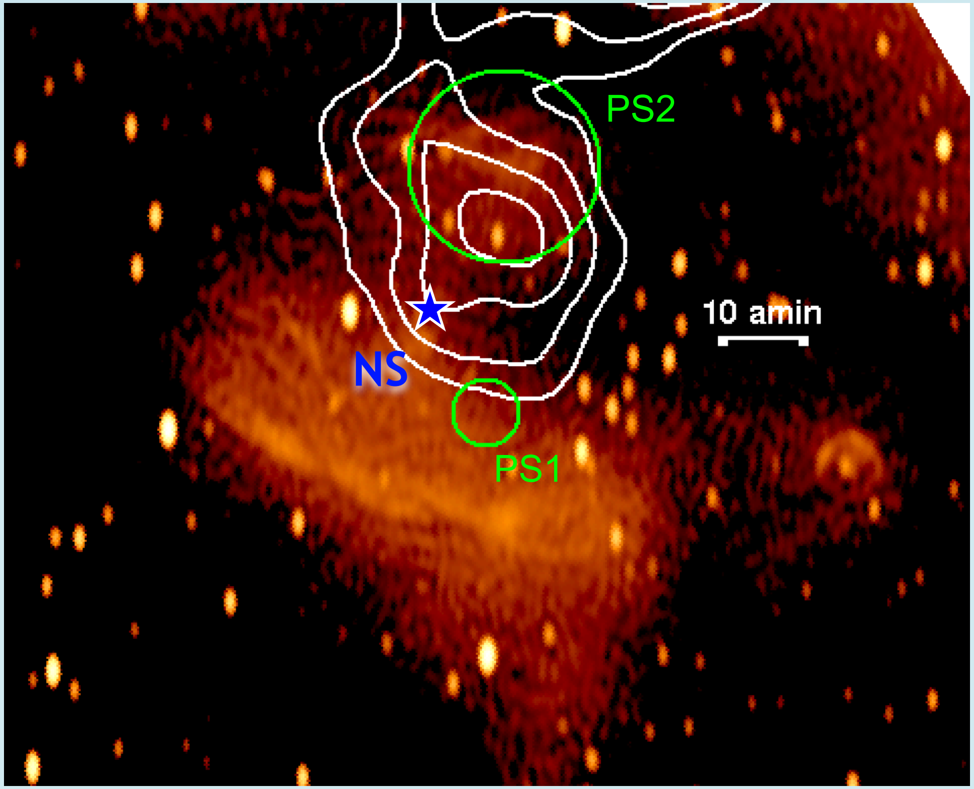
PSR J1954+2836:

- $\dot{E} = 1.0 \times 10^{36}$ erg/s, $\tau = 70$ kyr, $d \approx 2$ kpc (pseudo-distance)
- γ-ray pulsar ($F_{0.1-100\ \mathrm{GeV}}$ = 1.07(3)×10^{-10} erg/cm^2/s), no PWN
- X-ray yet to be observed

SNR G65.1+0.6:

- $\tau \approx 40 - 150$ kyr
- $d \approx 4 - 9$ kpc (opt. extinction or HI abs.)
- Radio shell-structure
- γ-ray emission in PS1 and PS2 (green), coincident with VERITAS (white contours)

Radio image, TeV contours



Tian+ 2006, A&A 455, 1053
Gao+ 2011, A&A 529, A159
Xing+ 2022, ApJ 930, 164
4FGL-DR3

3HWC J1957+291

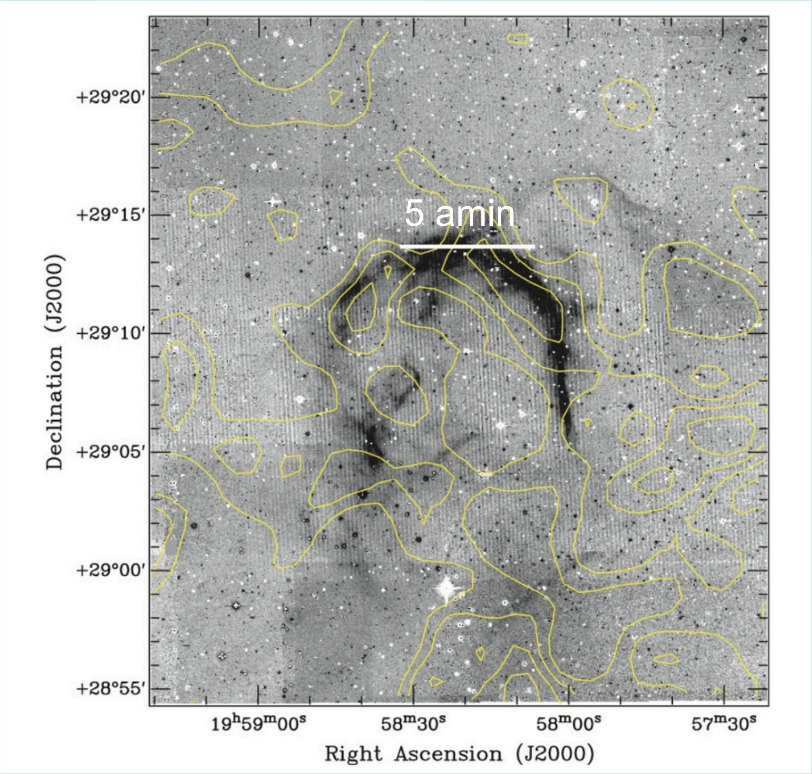
PSR J1958+2846:

- $\dot{E} = 3.4 \times 10^{35}$ erg/s, $\tau = 22$ kyr, $d \approx 2$ kpc (pseudo-distance)
- γ-ray pulsar ($F_{0.1-100\ \mathrm{GeV}}$ = 1.06(3)×10^{-10} erg/cm^2/s), no PWN
- X-ray ($F_{1-10\ \mathrm{keV}}$ = 1.7(5)×10^{-14} erg/cm^2/s)

SNR G66.0-0.0:

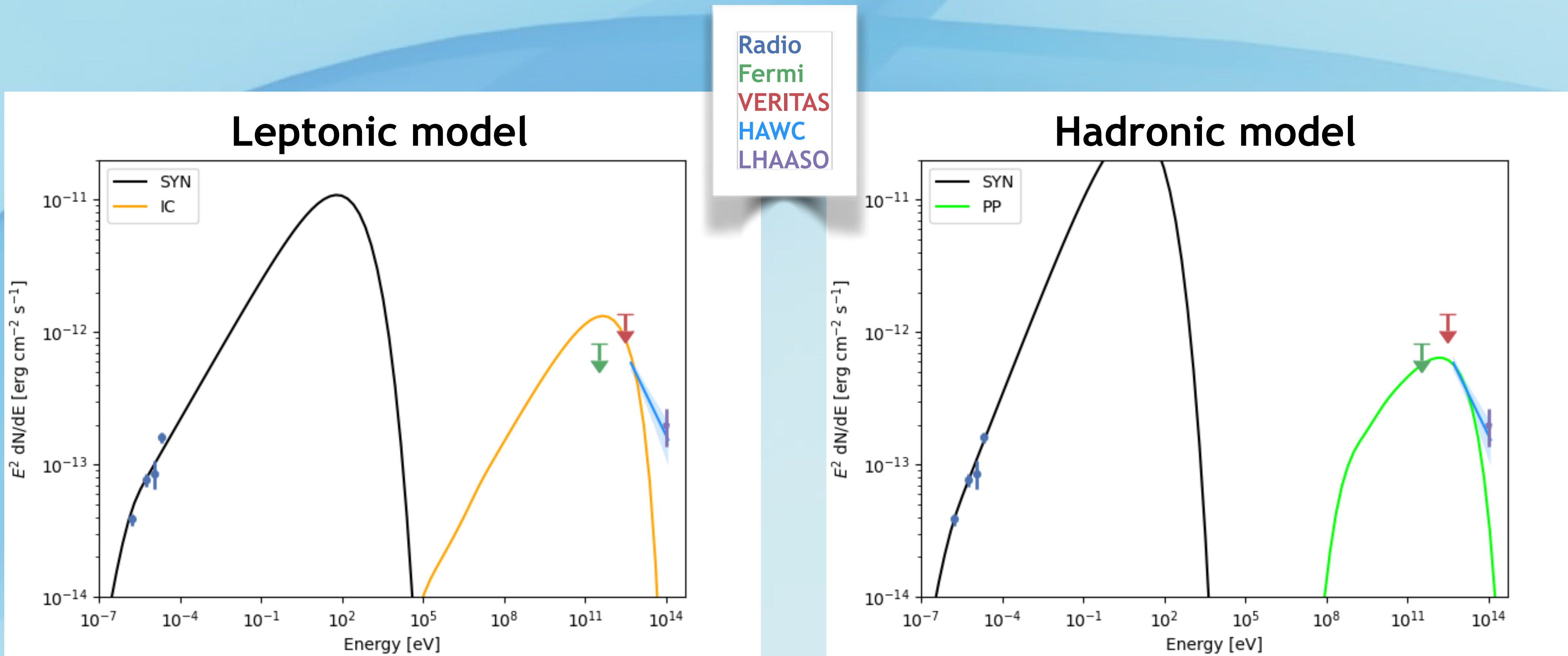
- $\tau = ?$, $d \approx 2-4$ kpc (optical extinction)
- Optical filaments (black), Hα survey
- Radio only at 6 cm (yellow contours)

Hα image, radio contours



Gregory+ 1996, ApJS 103, 427
Sabin+ 2013, MNRAS 413, 279
4FGL-DR3

3HWC J1954+286

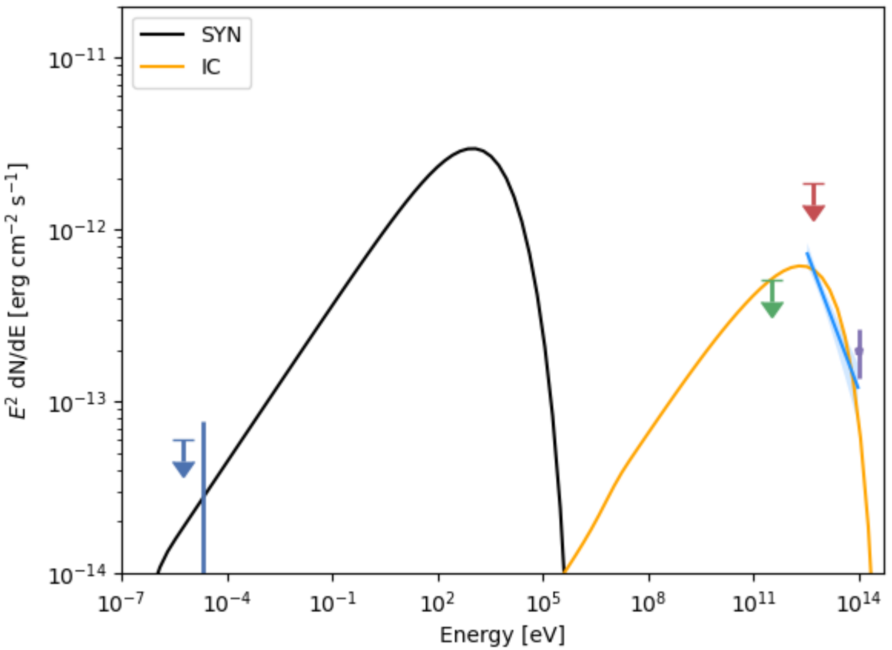


- B = 13 μG
- W_e = 2×10^{46} erg
- ECPL with Γ = 2.3 and E_c = 15 TeV

- B = 11 μG
- W_p = 2×10^{48} erg
- ECPL with Γ = 1.8 and E_c = 150 TeV

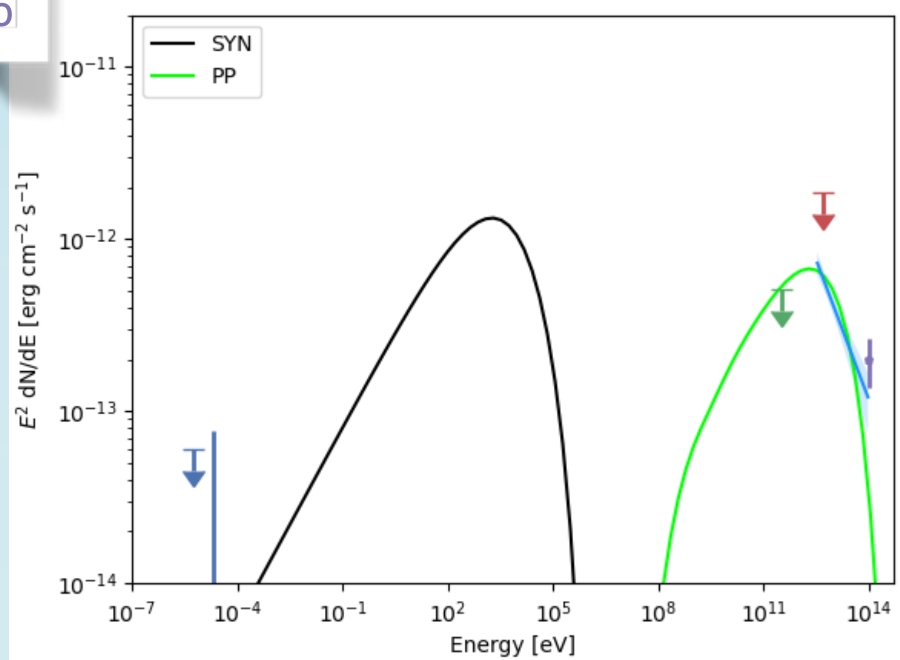
3HWC J1957+291

Leptonic model



- B = 8 μG
- W_e = 6×10^{45} erg
- ECPL with Γ = 2.4 and E_c = 90 TeV

Hadronic model



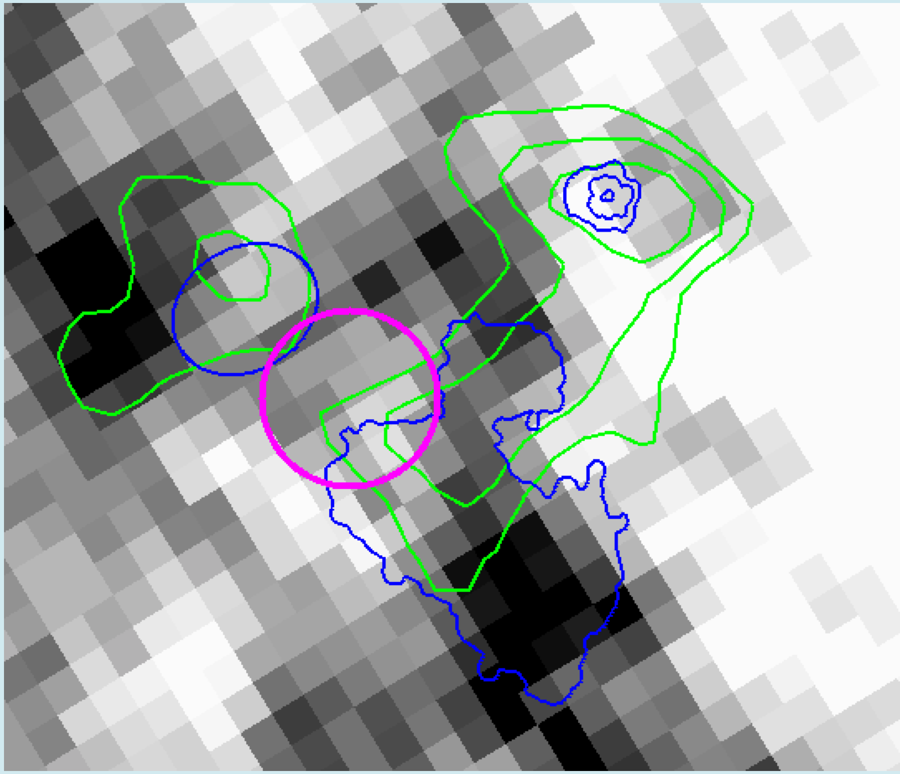
- B = 8 μG
- W_p = 10^{48} erg
- ECPL with Γ = 1.7 and E_c = 117 TeV

3HWC J1954+286 / J1957+291

What CTA can do:

- Confirm the HAWC/MILAGRO detections
- Detect the sources below 1 TeV
- Identify the source(s) of LHAASO J1956+2845:

CO Survey image, TeV/PeV contours



1) SNR

Both SNRs are middle-aged, interaction with molecular clouds is needed. No compelling evidence of MC in the position of LHAASO (magenta) HAWC (green) sources

Still missing: G66.0-0.0 needs to be better constrained at radio wavelenght, while G65.1+0.6 should be better investigate at ~1 GeV

Dame+ 2001, ApJ 547, 792

3HWC J1954+286 / J1957+291

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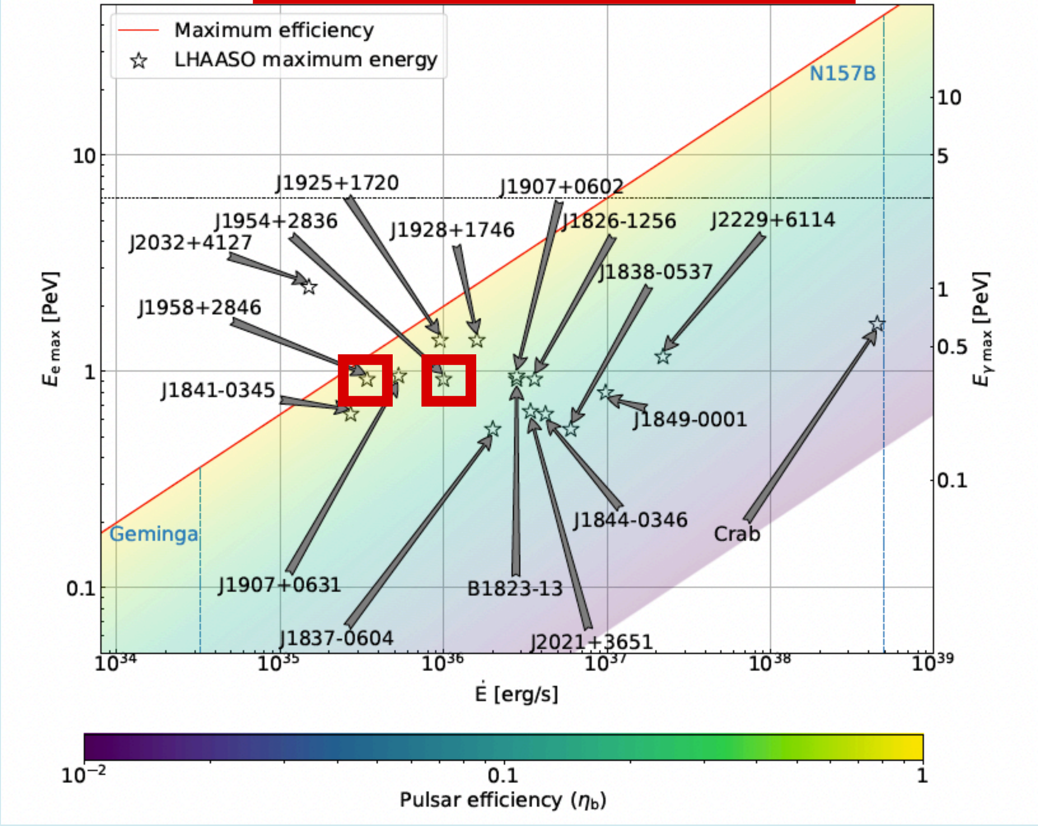
$$E_{e\,\max} \approx 2\eta_e \eta_B^{1/2} \dot{E}_{36}^{1/2}\ \text{PeV}$$



2) PWN

$$R \leq 5\,\text{pc}\ d_{2\,\text{kpc}}$$

According to this relation, both pulsars must be really efficient to accelerate electrons up to ~1 PeV

<u>Still missing:</u> Uncostraining upper limits on 0.1—10 keV and 0.1—100 GeV PWNe

de Oña Wilhelmi+ 2022, ApJL 930, L2

3HWC J1954+286 / J1957+291

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3) TEV HALO [assuming Geminga scale relations]

J1954+286

- $\theta = 0.25\,\mathrm{deg}\ d_{2\,\mathrm{kpc}}^{-1}$

  $\theta_{\mathrm{obs}} \leq 0.14\,\mathrm{deg}$
- $\phi_7 = 24 \times 10^{-15}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}\ d_{2\,\mathrm{kpc}}^{-2}$

  $\phi_{\mathrm{obs}} = (6.4 \pm 0.8) \times 10^{-15}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$

J1957+291

- $\theta = 0.25\,\mathrm{deg}\ d_{2\,\mathrm{kpc}}^{-1}$

  $\theta_{\mathrm{obs}} \leq 0.14\,\mathrm{deg}$
- $\phi_7 = 8 \times 10^{-15}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}\ d_{2\,\mathrm{kpc}}^{-2}$

  $\phi_{\mathrm{obs}} = (6.2 \pm 0.7) \times 10^{-15}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$

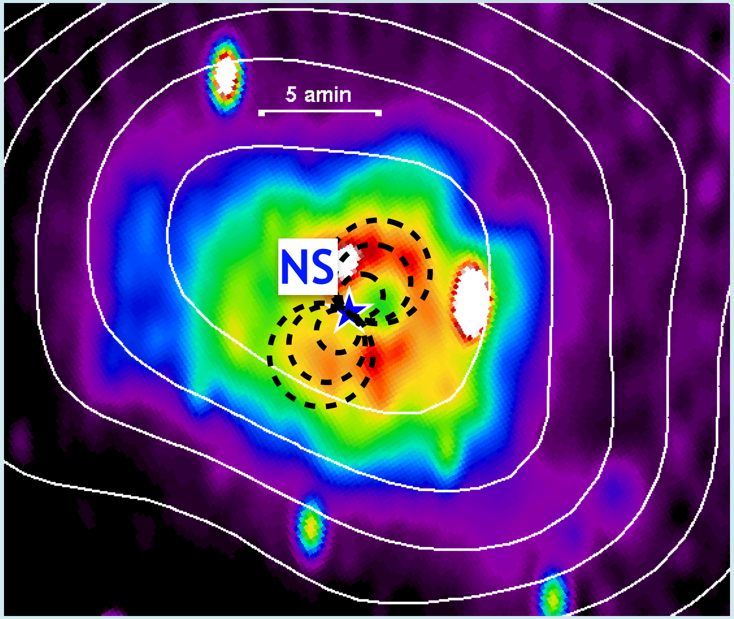
Linden+ 2017, PhRvD 96, 103016

3HWC J1951+293

RX J1952.2+2925:

- pulsations undetected yet
- $\tau = 10 - 100$ kyr (thermal spectrum), $d \approx 1 - 5$ kpc (X-ray absorption)
- X-ray point thermal source ($F_{0.2-2\ \mathrm{keV}}$ = 5.4(7)×10^{-13} erg/cm^2/s) + extended non-thermal source of r~20” ($F_{2-20\ \mathrm{keV}}$ = 2.4(1)×10^{-13} erg/cm^2/s)
- γ-ray pulsar ($F_{0.1-100\ \mathrm{GeV}}$ = 1.0(2)×10^{-11} erg/cm^2/s)

Radio image, TeV contours



DA 495 (or SNR G65.7+1.2):

- $\tau \approx 20 - 100$ kyr, $d \approx 1 - 5$ kpc (HI absorption)
- PWN or SNR? Shell like structure but polarization (black dashed lines) centered in NS position; torus of material ejected by the progenitor star
- Radio (image) and TeV (white contours) r~0.12 deg

Kothes+ 2008, ApJ 687, 516
Karpova+ 2015, MNRAS 453, 2241
Coerver+ 2019, ApJ 878, 126
4FGL-DR3

3HWC J1951+293

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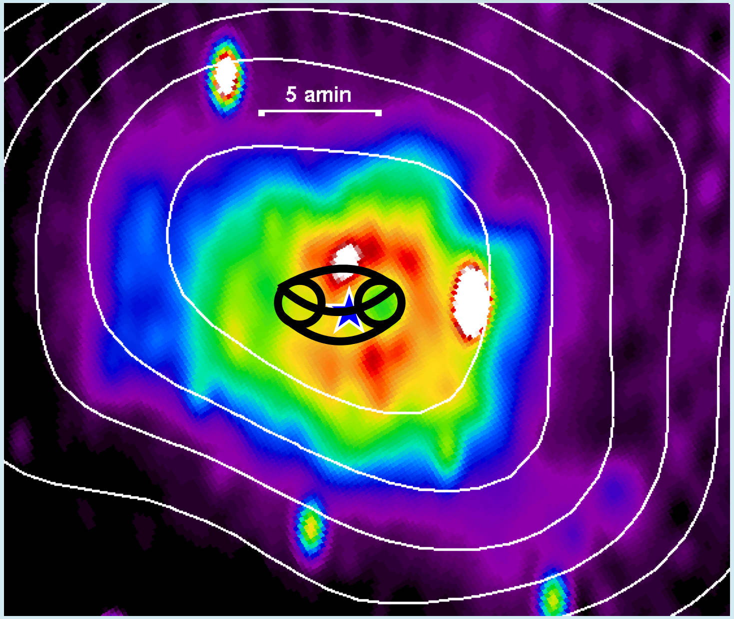
- pulsations undetected yet
- $\tau = 10 - 100$ kyr (thermal spectrum), $d \approx 1 - 5$ kpc (X-ray absorption)
- X-ray point thermal source ($F_{0.2-2\ \mathrm{keV}}$ = 5.4(7)×10^{-13} erg/cm^2/s) + extended non-thermal source of r~20" ($F_{2-20\ \mathrm{keV}}$ = 2.4(1)×10^{-13} erg/cm^2/s)
- γ-ray pulsar ($F_{0.1-100\ \mathrm{GeV}}$ = 1.0(2)×10^{-11} erg/cm^2/s)

Radio image, TeV contours



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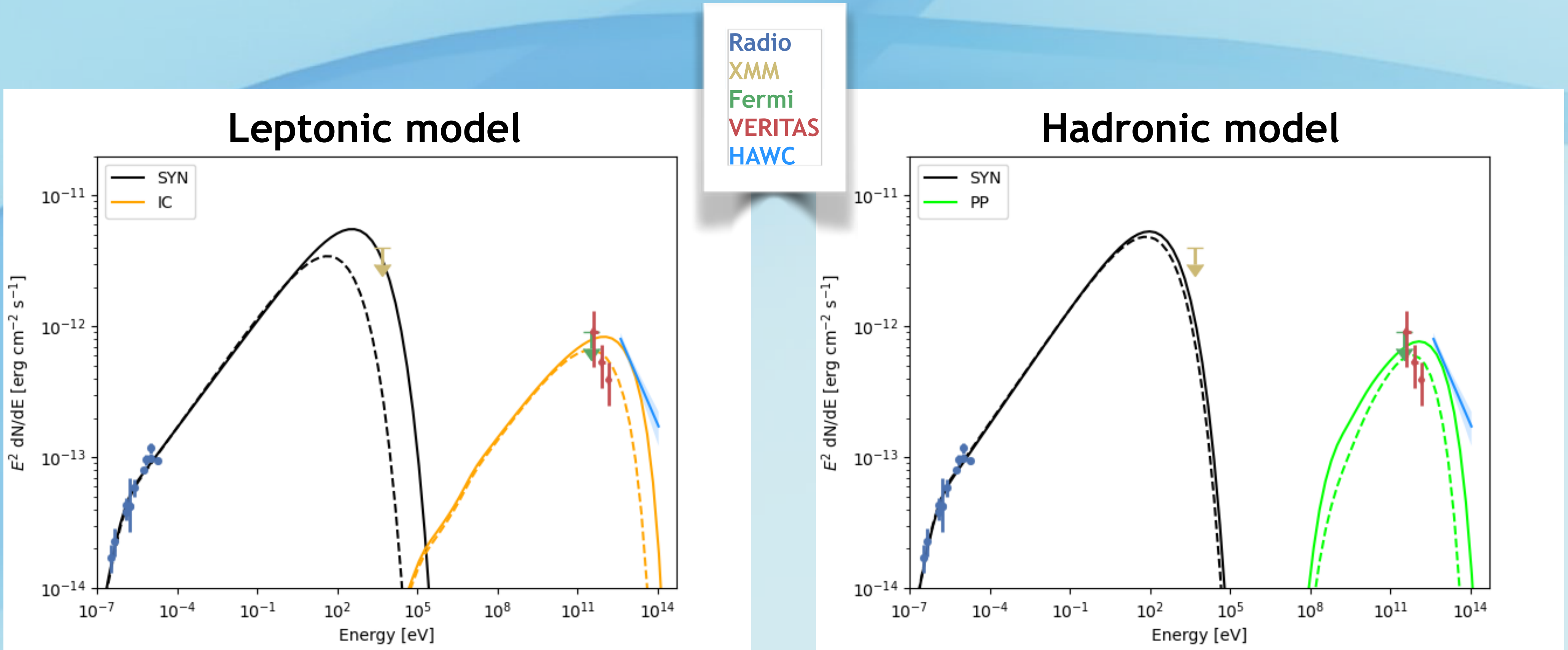
3HWC J1951+293



- B = 10 μG
- $W_e = 10^{46}$ erg
- ECPL with Γ = 2.45 and E_c = 50 TeV (or 17 TeV)

- B = 10 μG
- $W_p = 10^{48}$ erg
- ECPL with Γ = 1.6 and E_c = 90 TeV (or 30 TeV)

3HWC J1951+293

What CTA can do:

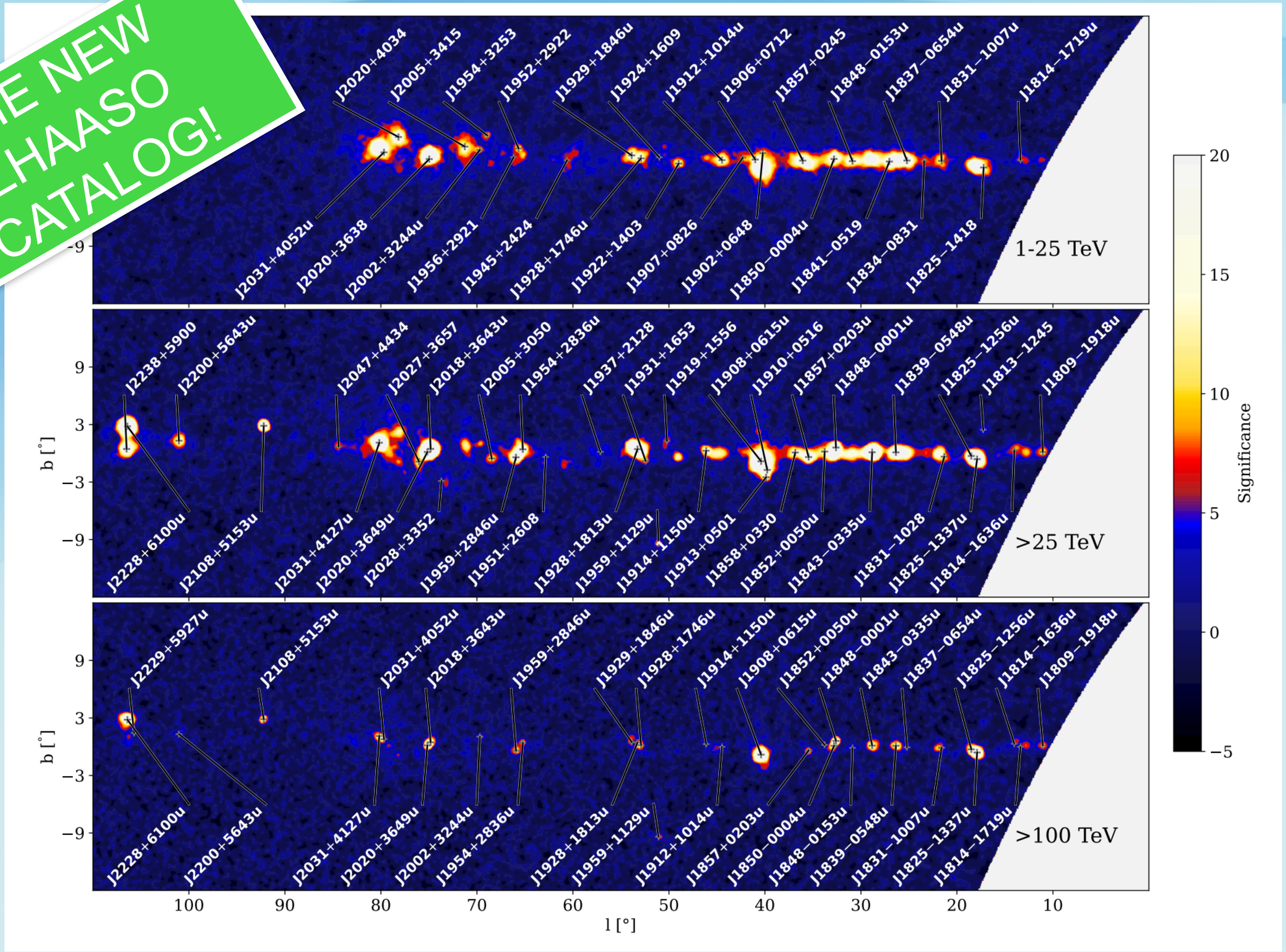
- $R \approx 2.2\,\mathrm{pc}\ d_{1\,\mathrm{kpc}}$
- Spatially-resolved analysis can help to discriminate between PWN and SNR (confirm or discard the hole at TeV energies)
- Solve the tension between VERITAS and HAWC and properly fit the SED (leptonic vs hadronic scenario)

Still missing: Measure the timing parameters (through FERMI or X-ray data) to infer the age and the energetics of the pulsar

Thanks for the attention!

Breaking news!!!

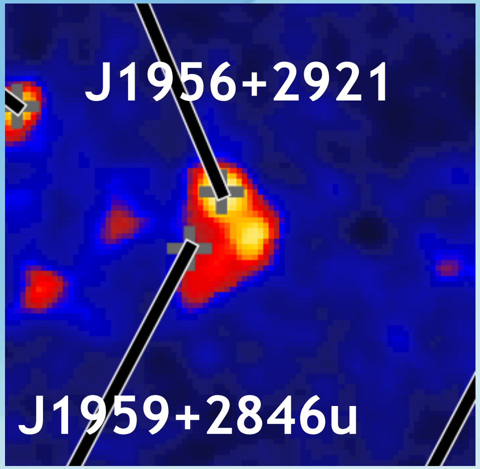
THE NEW LHAASO CATALOG!



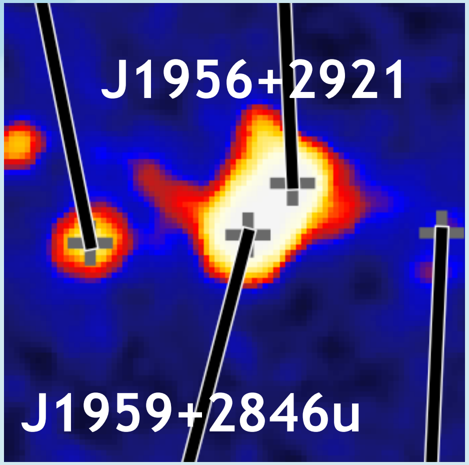
Cao+ 2023, TODAY

Breaking news!!!

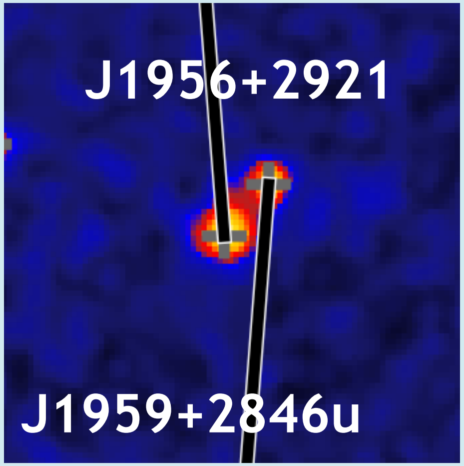
1 — 25 TeV



25 — 100 TeV



> 100 TeV

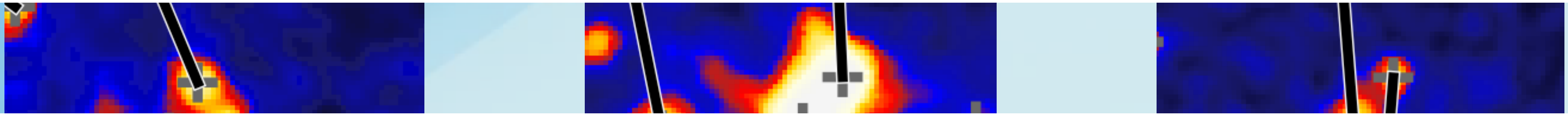


Cao+ 2023, TODAY

Breaking news!!!

$N_0/10^{-13}$ at 3 TeV, range 1—25 TeV [WCDA]
$N_0/10^{-16}$ at 50 TeV, range >25 TeV [KM2A]

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
1LHAASO J1956+2921	WCDA	299.24	29.35	0.38	0.99±0.07	161.3	1.47±0.16	2.03±0.06		LHAASO J1956+2845 (0.63)
	KM2A	298.84	28.92	0.23	0.78±0.05	151.3	1.62±0.14	3.42±0.12		
1LHAASO J1959+2846u	KM2A	299.78	28.78	0.09	0.29±0.03	213.2	0.84±0.07	2.90±0.10	74.0	
	WCDA						<0.38			

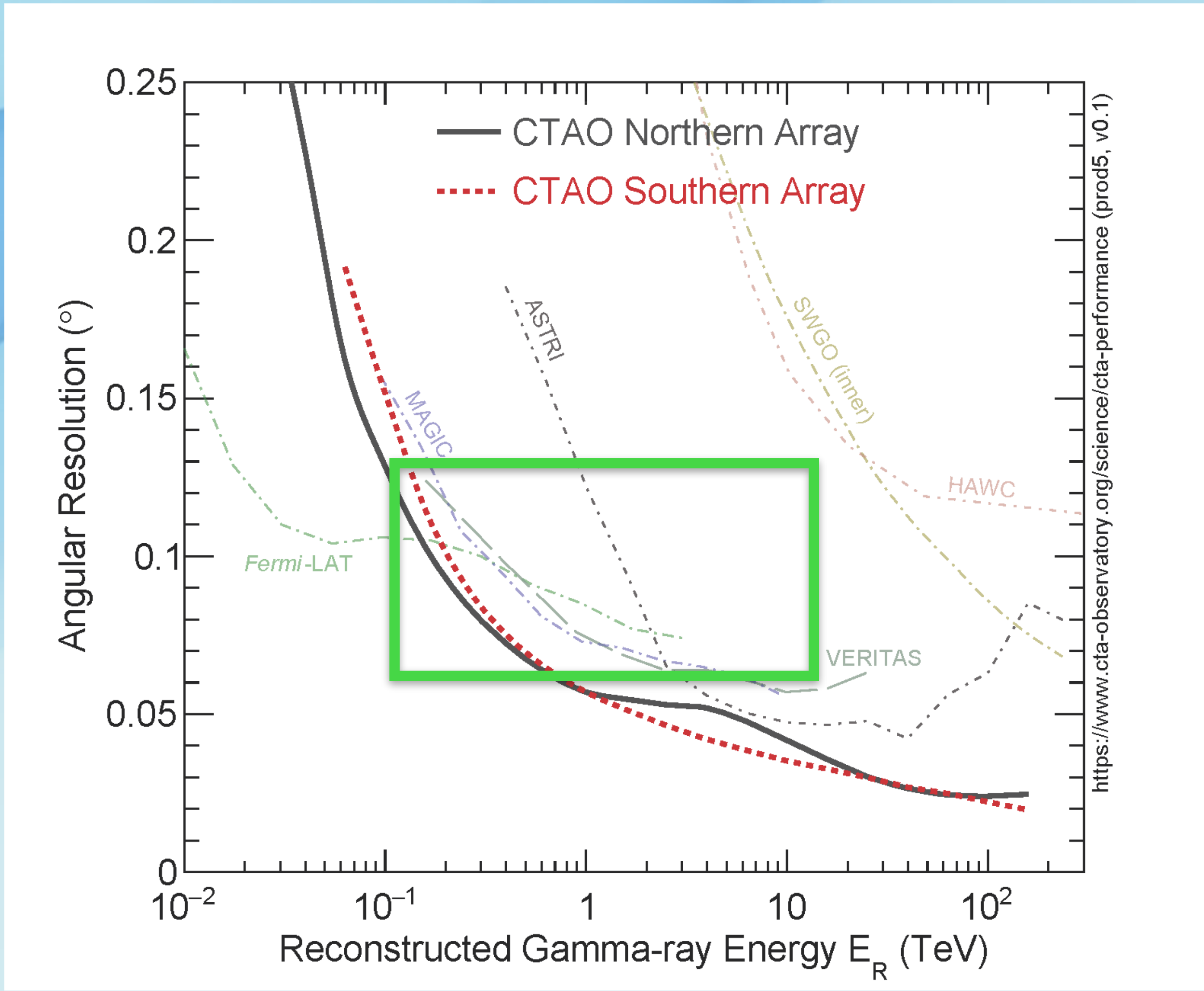


- 1LHAASO J1956+2921 is a large extended source with the $r_{39} \sim 0.99°$ WCDA component and the $r_{39} \sim 0.78°$ KM2A component. It is resolved from the public LHAASO source LHAASO J1956+2845. At 0.36° away from the position of WCDA component, the shell type SNR with radio size of $31' \times 25'$ is found.

- 1LHAASO J1959+2846u is an UHE TeV source with the extension size of $r_{39} \sim 0.3°$ only detected by KM2A, which is also resolved from previous public source LHAASO J1956+2845. The pulsar PSR J1958+2846 (0.1° away, $\dot{E} = 3.42 \times 10^{35}$ erg s^{-1}, $d = 1.95$ kpc, $\tau_c = 21.7$ kyr) is the only pulsar counterpart in our searching radius. SNR G065.8-00.5. and SNR G066.0-00.0 are found at 0.16° and 0.39° away from the position of 1LHAASO J1959+2846u, with a radio size of $\sim 10' \times 6'$ and $\sim 30' \times 25'$, respectively.

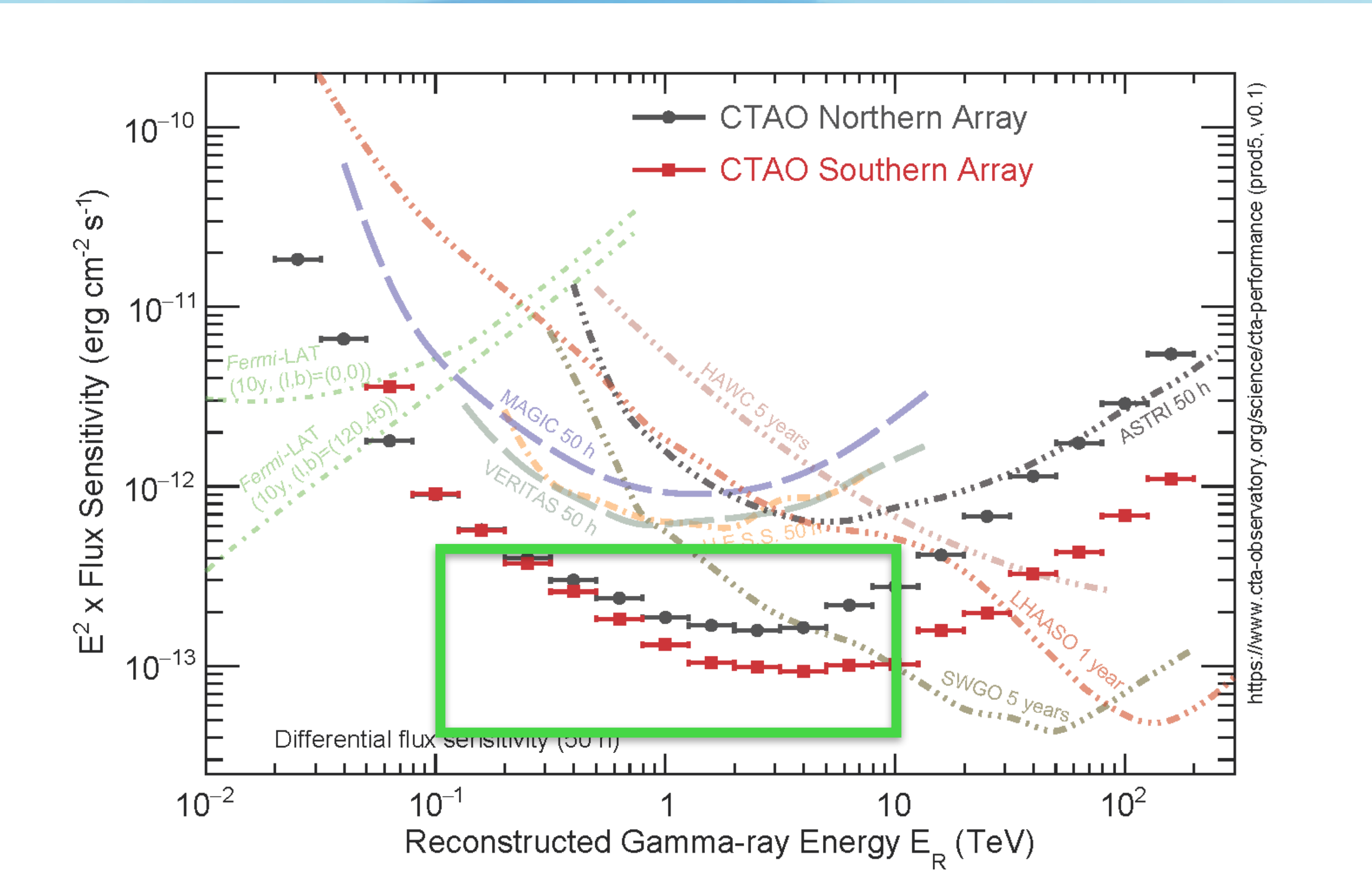
Cao+ 2023, TODAY

CTAO angular resolution



https://www.cta-observatory.org/science/ctao-performance

CTAO sensitivity



NB: a factor ~3 worse for sources of 0.25 deg

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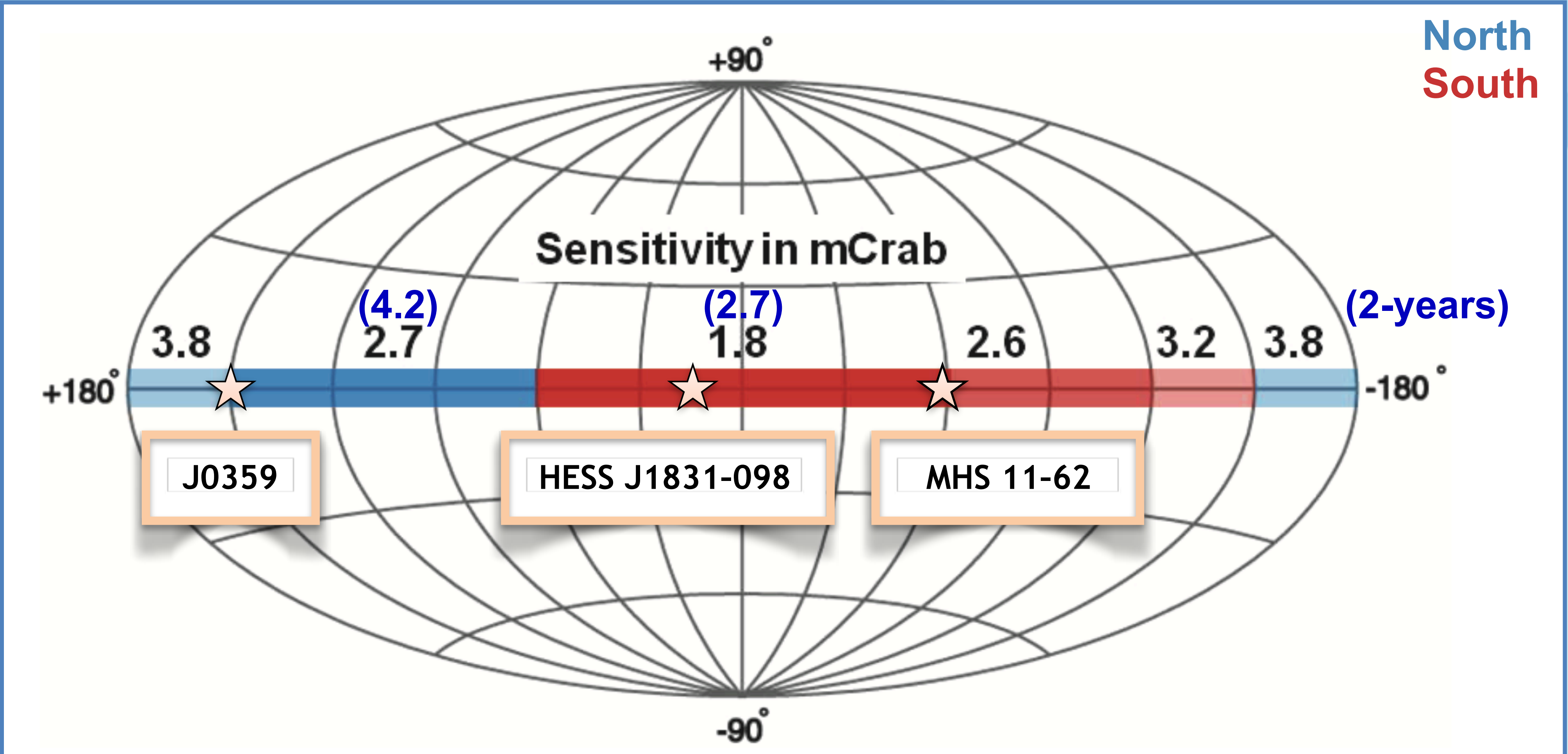
10-year GPS sensitivity



NB: a factor ~3 worse for sources of 0.25 deg

Science with the Cherenkov Telescope Array, 2017