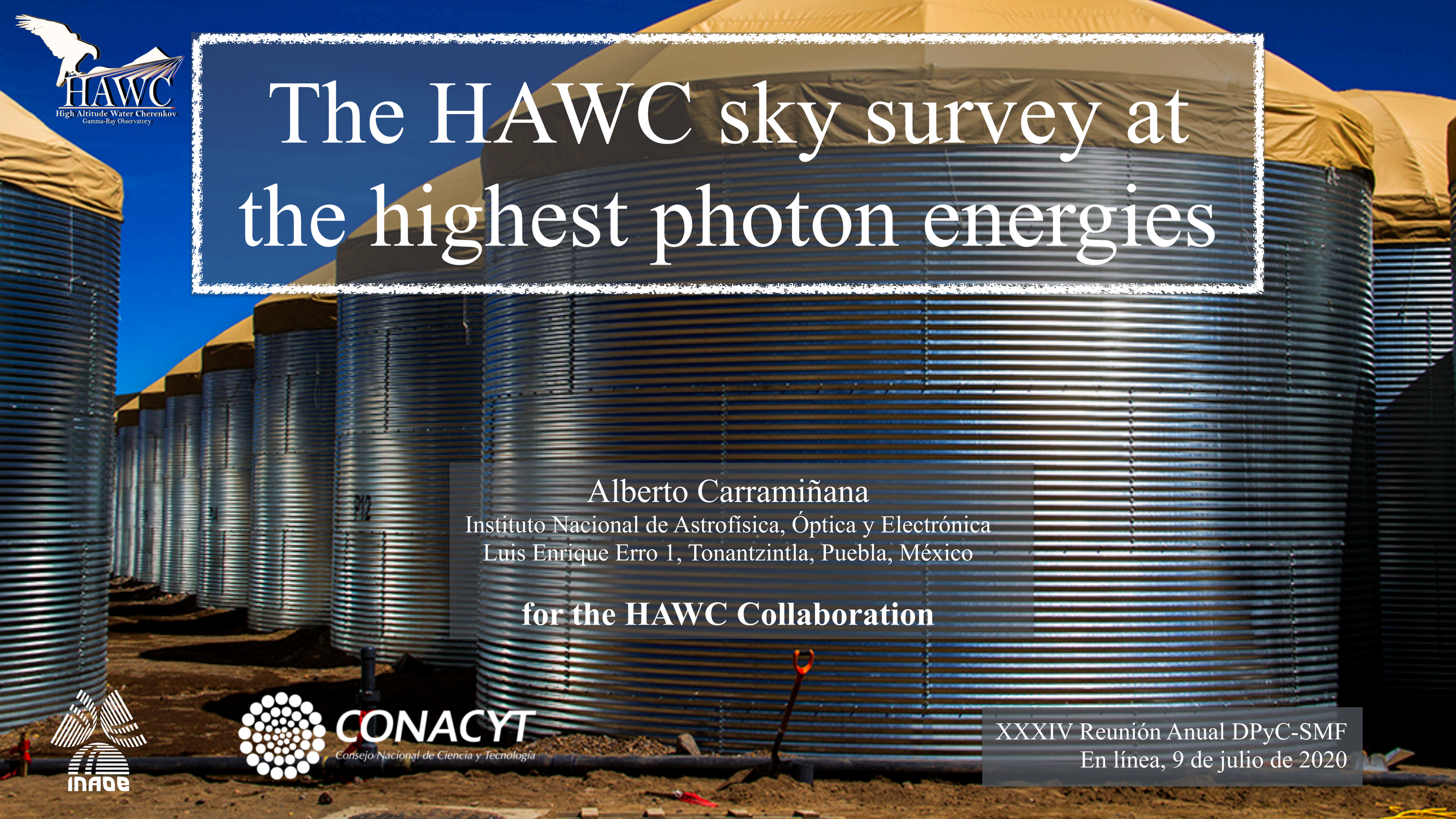

The HAWC sky survey at the highest photon energies

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HAWC

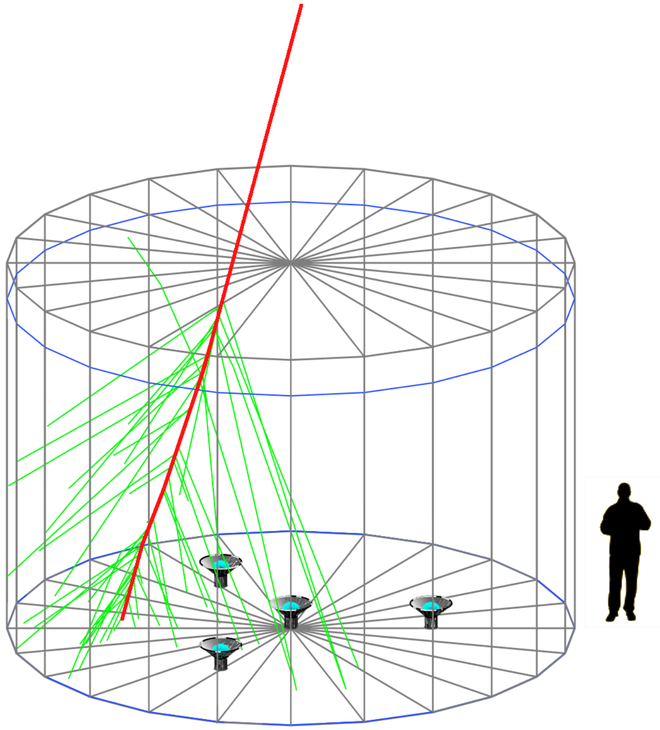
- HAWC is for High Altitude Water Cherenkov (GRO).
- HAWC is a multi-national collaboration.
- HAWC is a high altitude Extended Air Shower array located at Sierra Negra, Puebla (19ºN; 4100m altitude).
- HAWC is a wide field-of-view γ-ray detector (almost) continuously observing the sky as it transits over its zenith:
  - energy range ~ 0.1 - 100 TeV : optimal around 7 TeV.
  - field of view ~ 1.8 sr (15% of the sky)
    → surveys ~ 8.4 sr / s.day (2/3 of the sky).

HAWC Collaboration

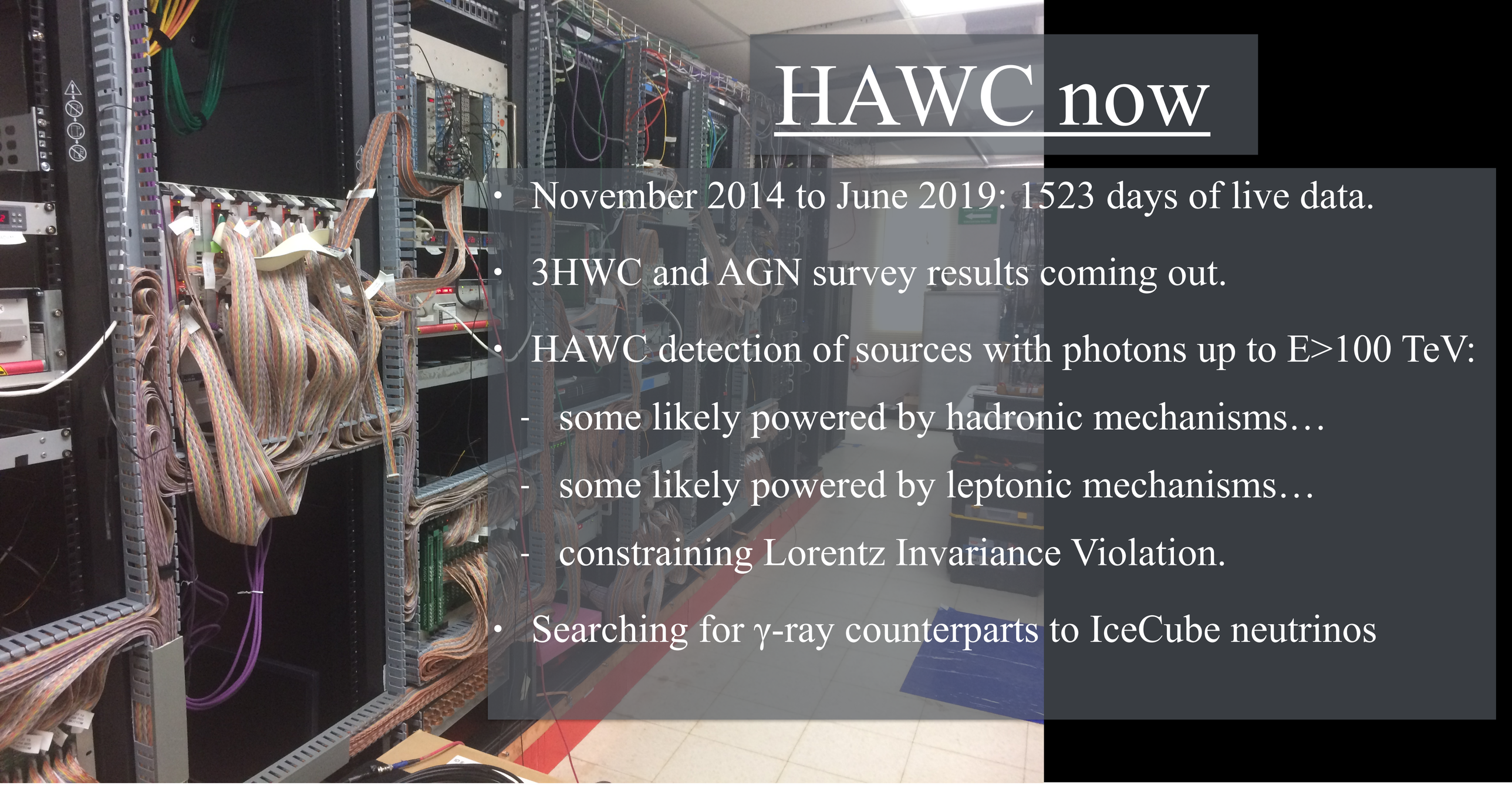
Originally México, United States; now with participation of Europe, Latin America and Asia..

HAWC Observatory

EAS array of 300 water Cherenkov detectors covering 24,000 m^2



WCDs: 5 m × 7.2 m
180 m^3 of transparent water
4 PMTs in darkness



HAWC now

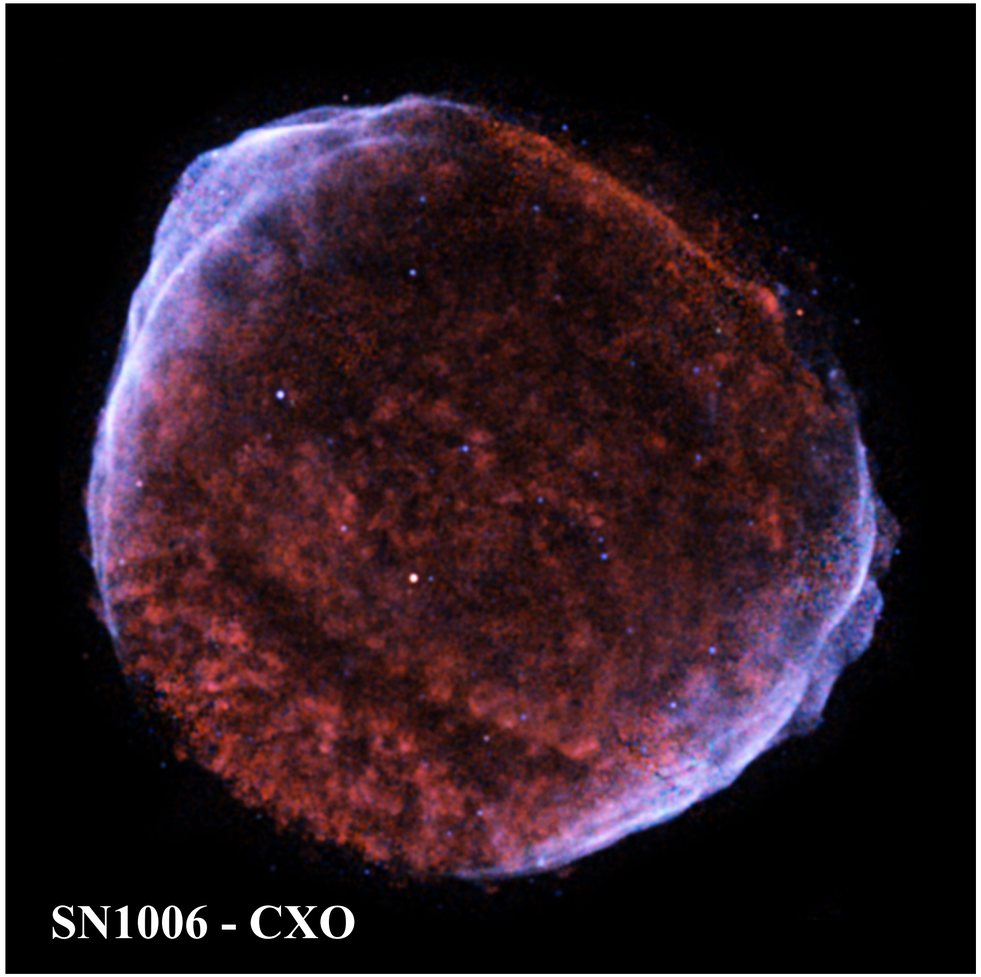
- November 2014 to June 2019: 1523 days of live data.
- 3HWC and AGN survey results coming out.
- HAWC detection of sources with photons up to E>100 TeV:
  - some likely powered by hadronic mechanisms…
  - some likely powered by leptonic mechanisms…
  - constraining Lorentz Invariance Violation.
- Searching for γ-ray counterparts to IceCube neutrinos

Supernova: the sources of cosmic rays?

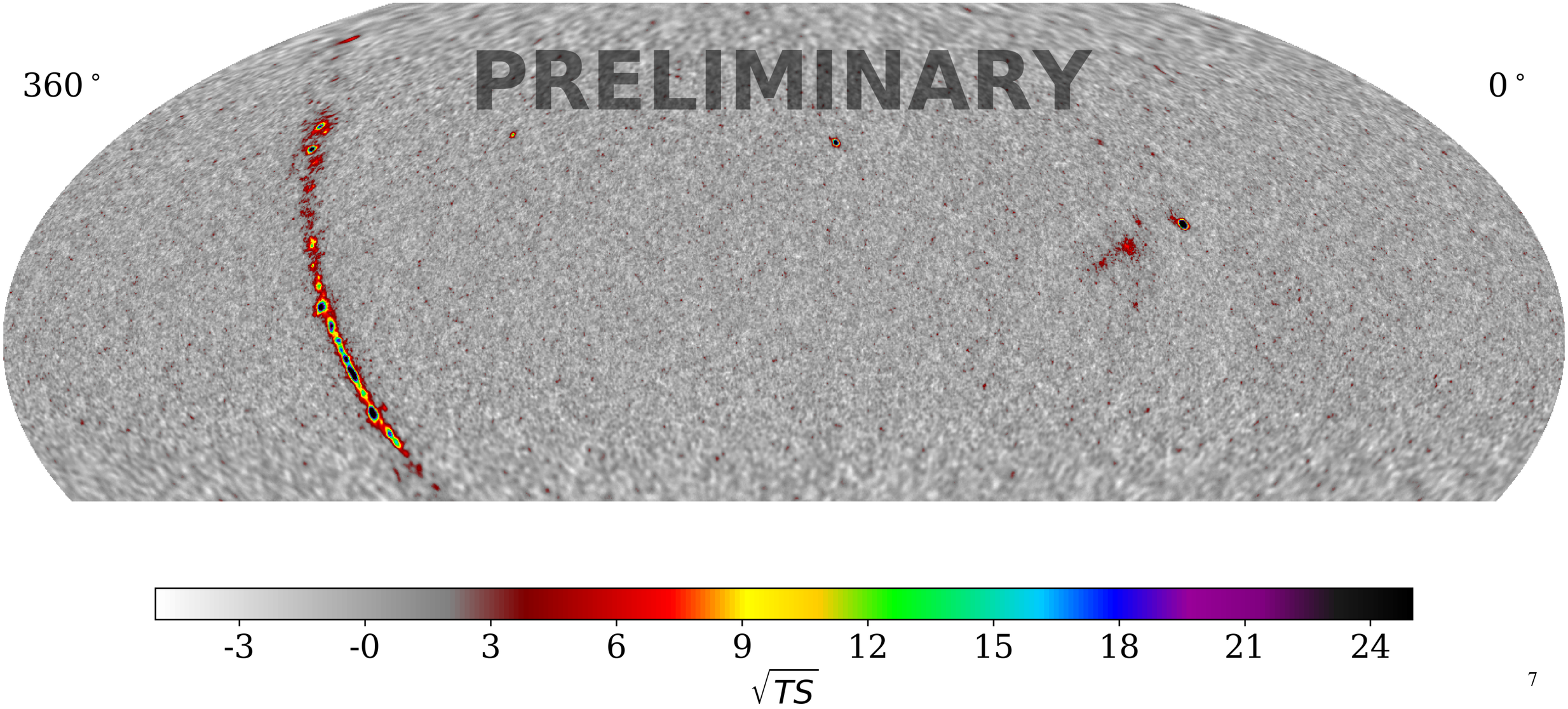
- Energy output needed to supply cosmic rays energy density:

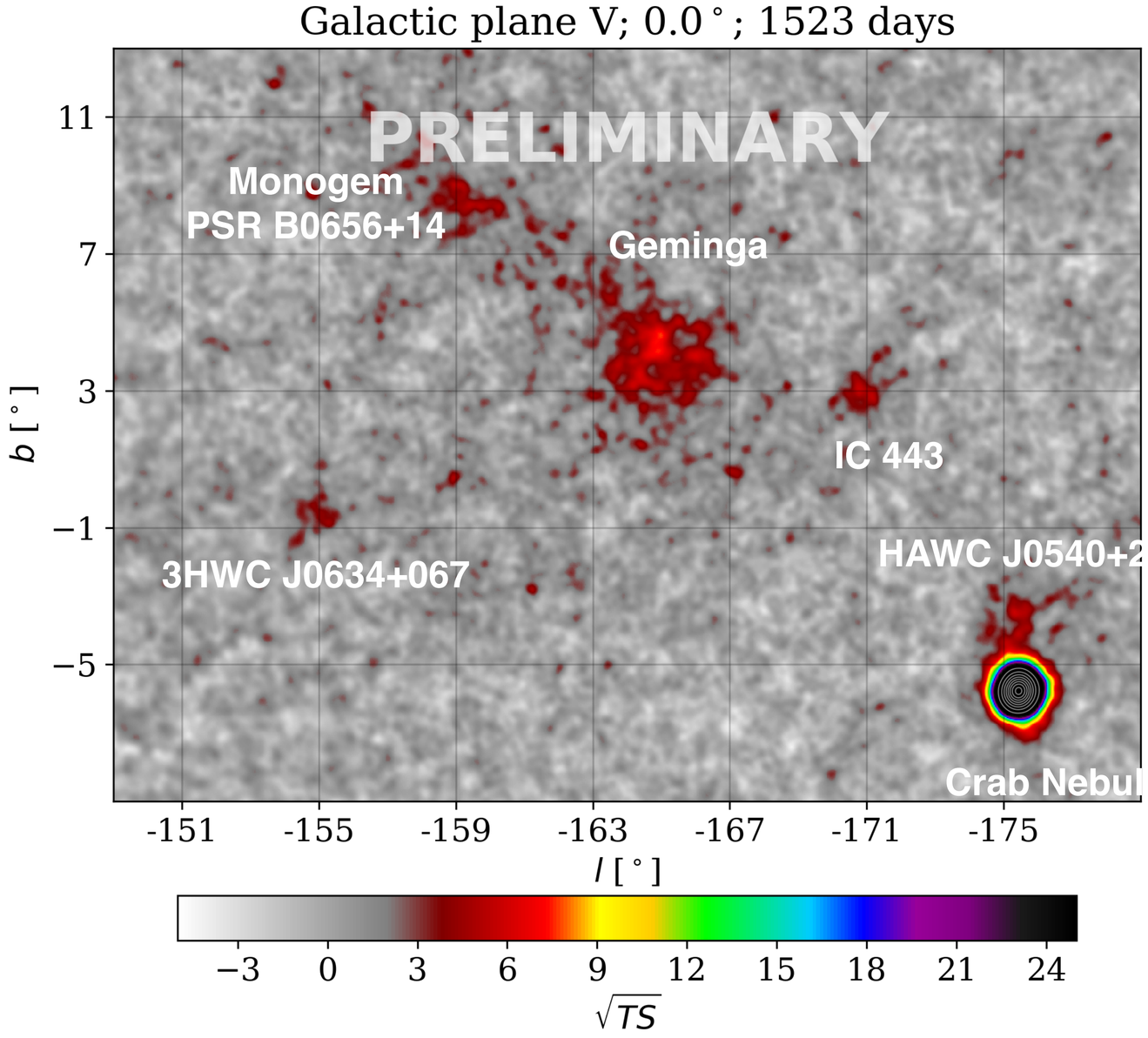
$$L_{\rm CR} \approx \frac{u_{\rm CR} V_{\rm gal}}{t_{\rm esc}} \simeq 10^{40}\,{\rm erg/s}\,.$$

- Energy output in Galactic supernovae ≃ 10^{51} erg / 10^{9} s ≃ 10^{42} erg/s, for 1 SN / 30 years.
- Fermi first showed that shocks in expanding supernova fronts can produce power-law spectra of particles.



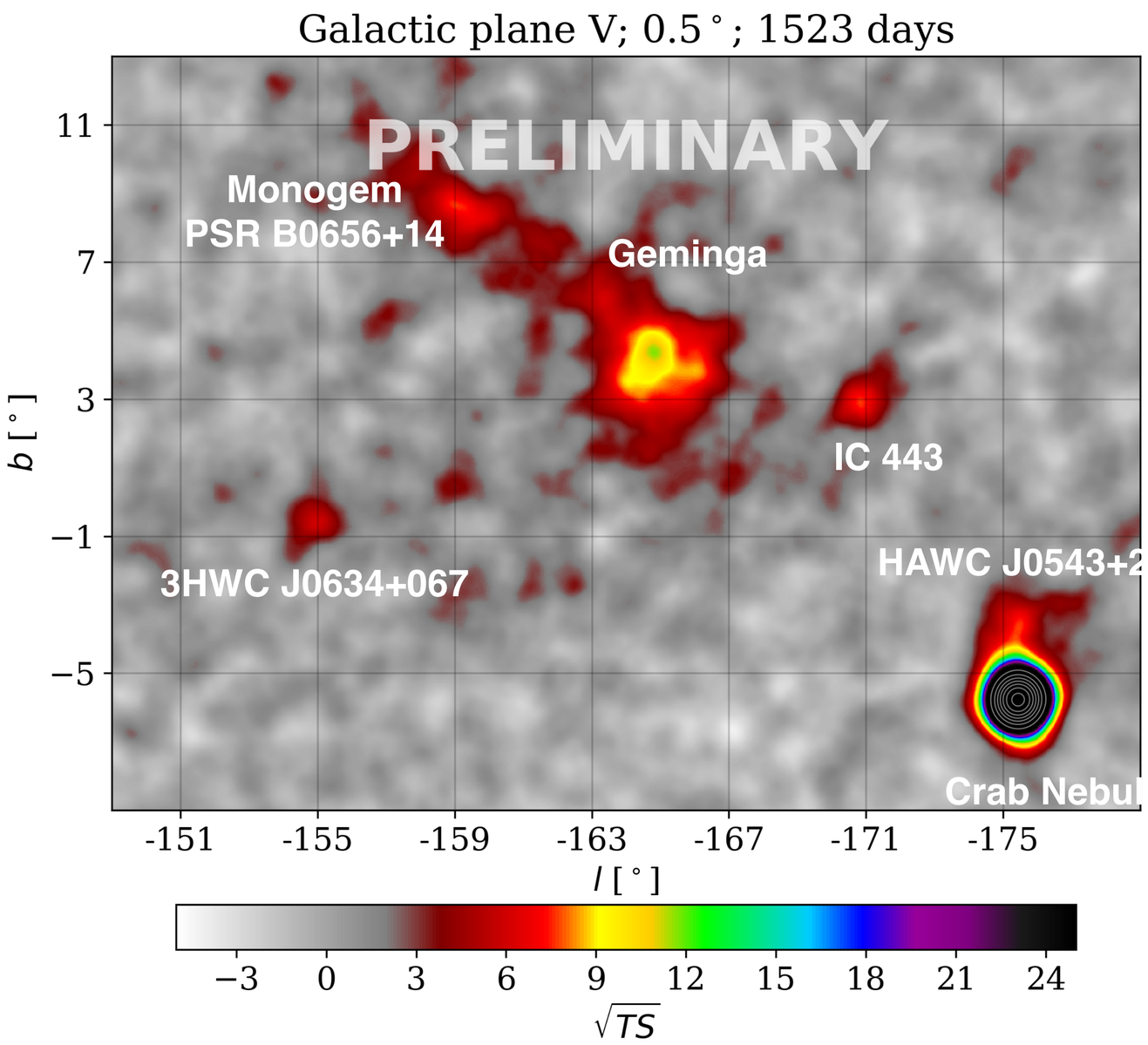
3HWC skymap

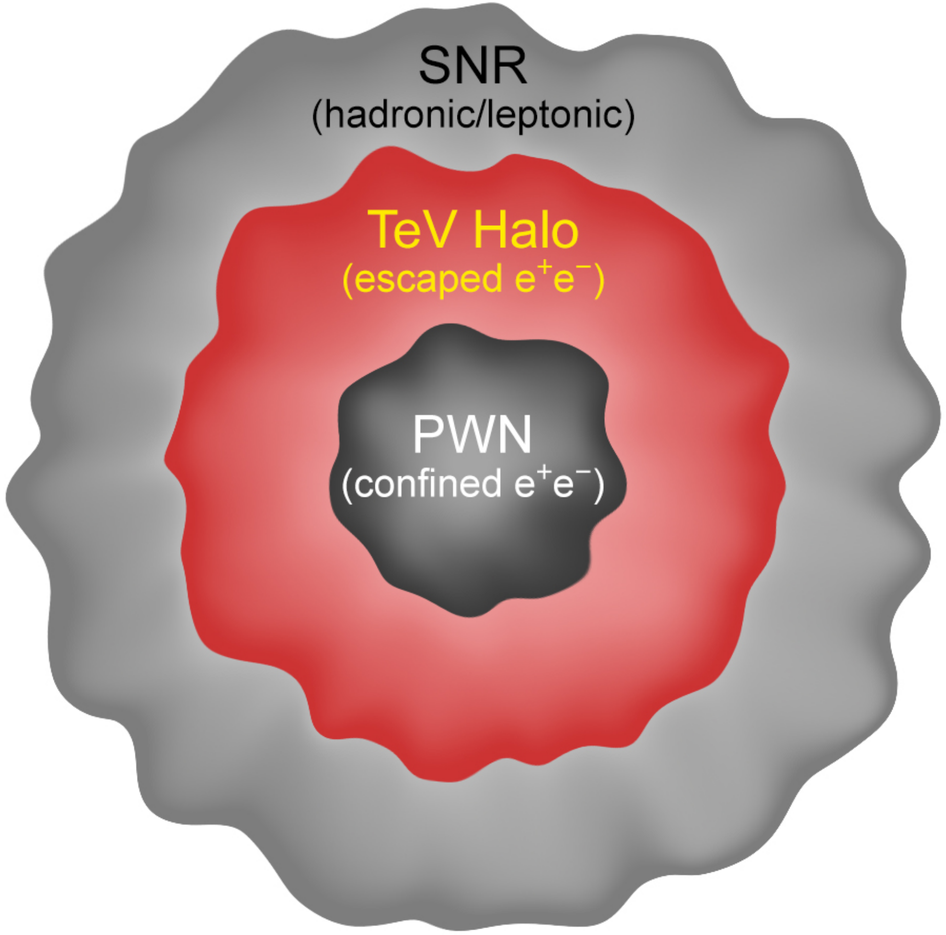




Galactic AntiCenter

- Pulsar powered sources:
  - The Crab Nebula (Pulsar Wind Nebula - PWN);
  - Geminga and Mongem (PSR B0656+14) - TeV haloes;
  - HAWC J0540+233 (PSR B0540+23) a TeV halo (?);
  - 3HWC J0634+067 (PSR J0633+0632) a TeV halo (?).
- The SNR IC 443





Electrons can produce γ rays with energies of 100 TeV only through inverse Compton scattering of CMB photons.

Pulsar power

- High rotational power:

$$\frac{dE_{\rm rot}}{dt} = -4\pi^2 I \frac{\dot{P}}{P^3} = 2.6 \times 10^{38}\,{\rm erg/s} \left(\frac{\dot{P}}{4.2\times10^{-13}}\right)\left(\frac{P}{33\,{\rm ms}}\right)^{-3}$$

- Large magnetic field:

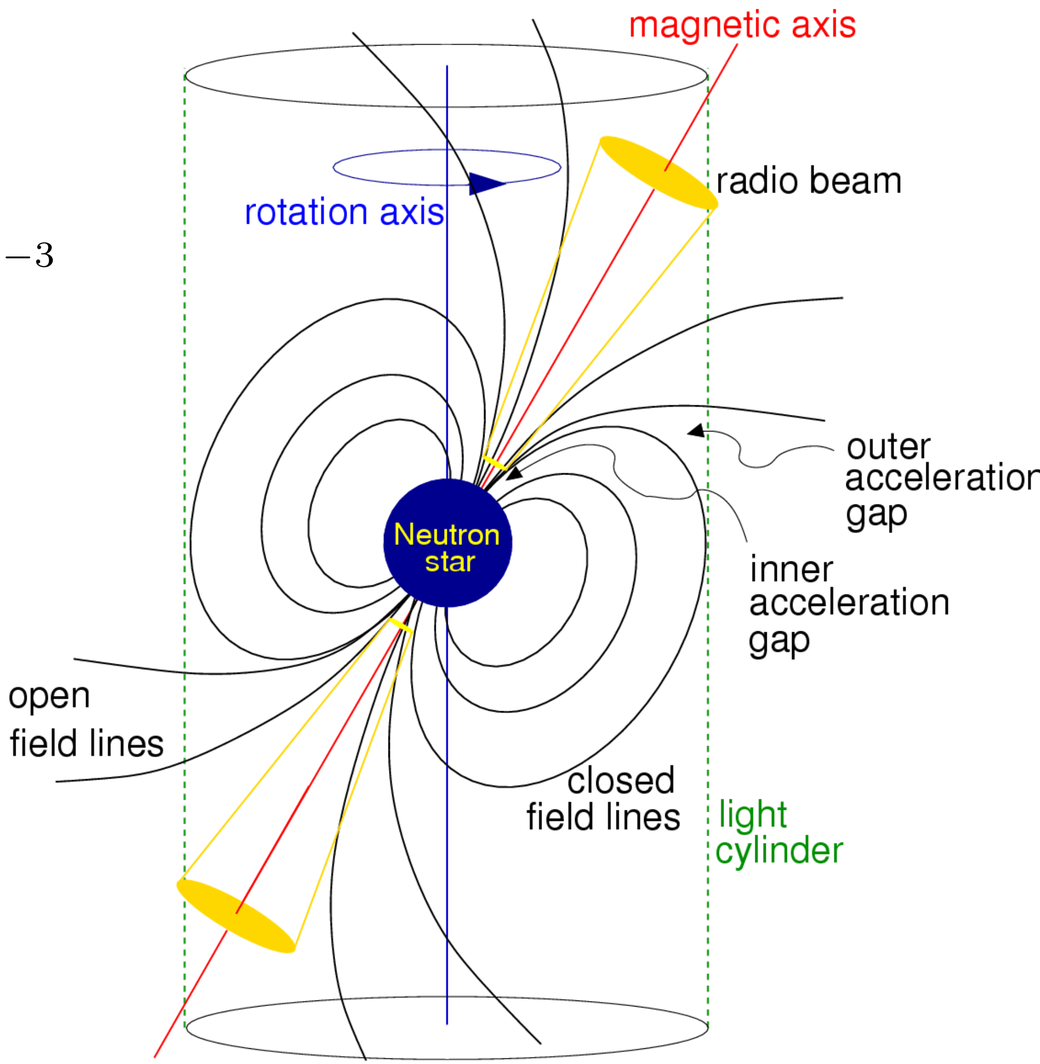
$$B_\star = 2.8 \times 10^{12}\,{\rm G} \left(\frac{P\,\dot{P}}{33\,{\rm ms}\cdot 4.2\times10^{-13}}\right)^{1/2}$$

- Particle acceleration potential:

$$\Delta\Phi \approx \frac{B_\star \Omega^2 R_\star^3}{2c^2} \simeq 1.1\times10^{16}\,{\rm V}\left(\frac{P}{33\,{\rm ms}}\right)^{-3/2}\left(\frac{\dot{P}}{4.2\times10^{-13}}\right)^{1/2}$$

- Lifetimes of thousands of years:

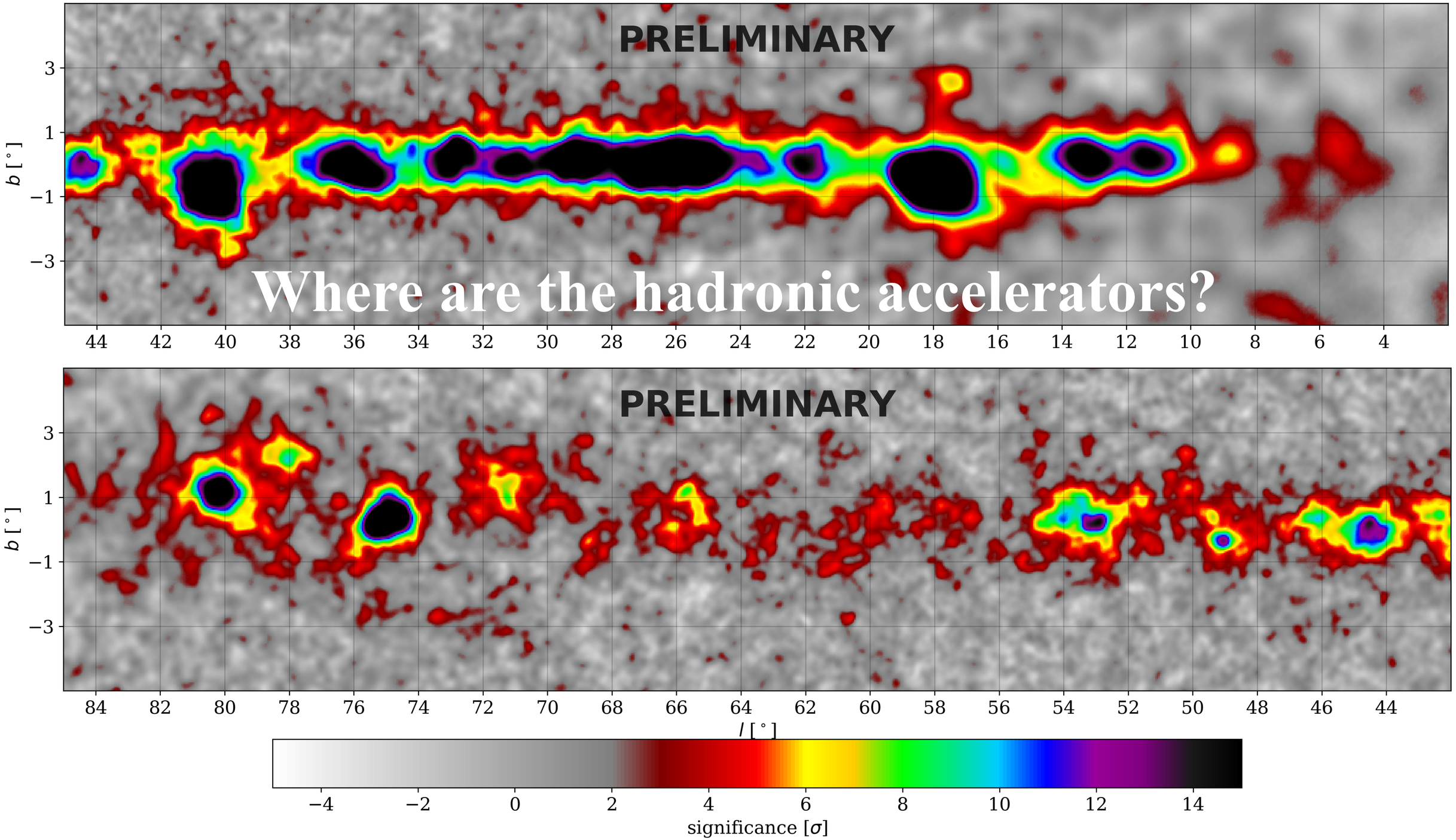
$$\tau = P/2\dot{P} = 1273\,{\rm years}\left(\frac{P/33\,{\rm ms}}{\dot{P}/4.2\times10^{-13}}\right)$$



No hadrons needed

Hadronic cosmic rays?

- Pulsars produce and accelerate $e^{\pm}$, likely up to PeV energies.
- Leptons can produce high-energy γ-rays through inverse Compton scattering; but ICS is limited by the Klein Nishina cross section (dependent on γω):
  - photons of energies close to 100 TeV can only be produced with the CMB;
  - electrons above 100 TeV loose energy rapidly in magnetized environments.
- High energy hadrons must be produced in shocks, like SN fronts or potentially in winds from massive stars.
- Neutrinos are produced together with hadrons.


PRELIMINARY
Where are the hadronic accelerators?
PRELIMINARY
b [°]
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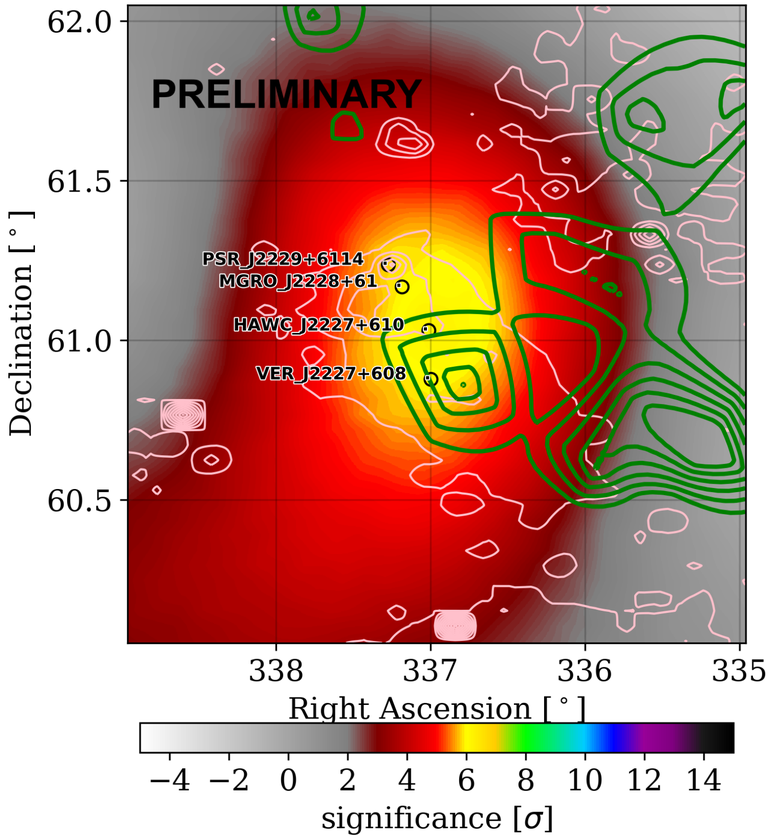
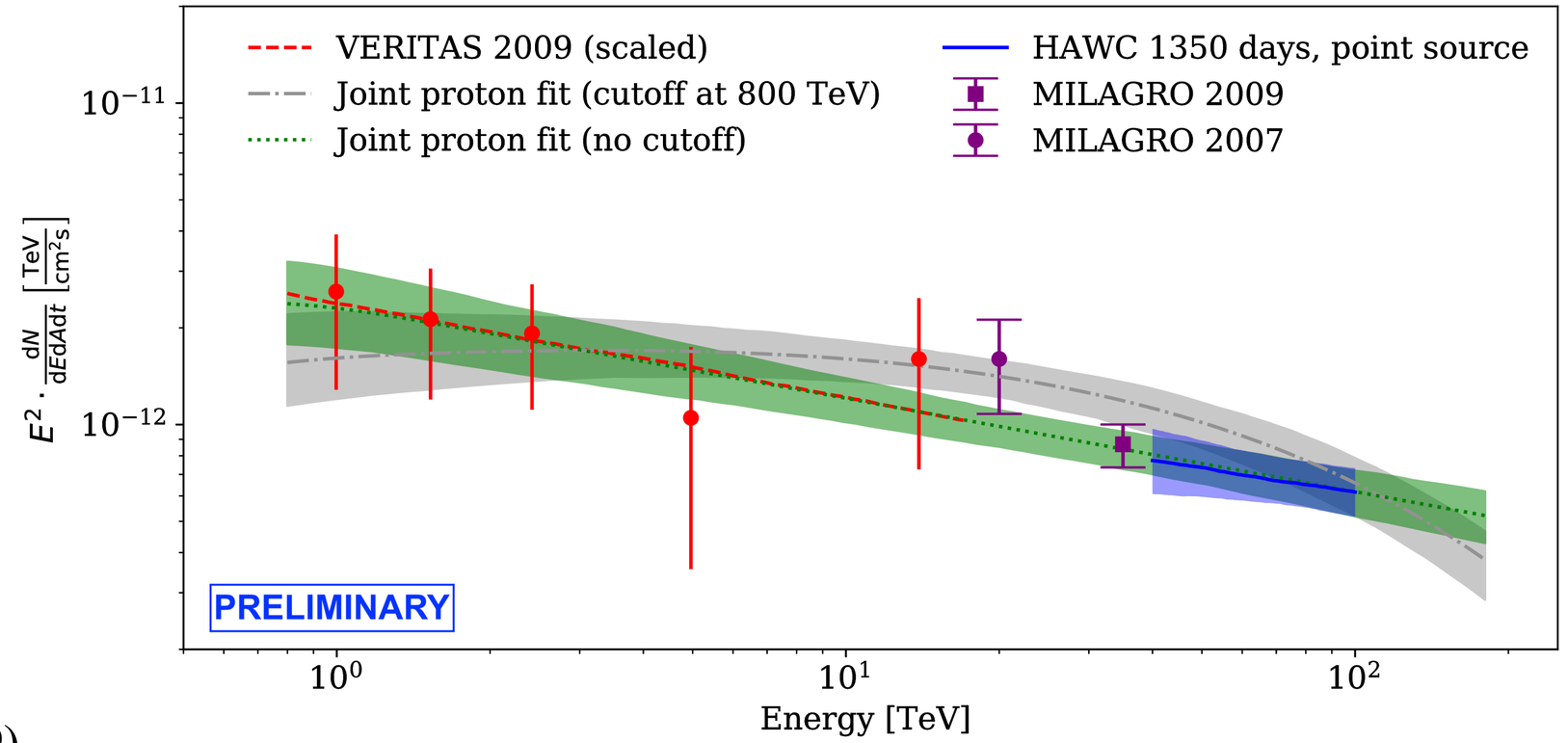
significance [σ]

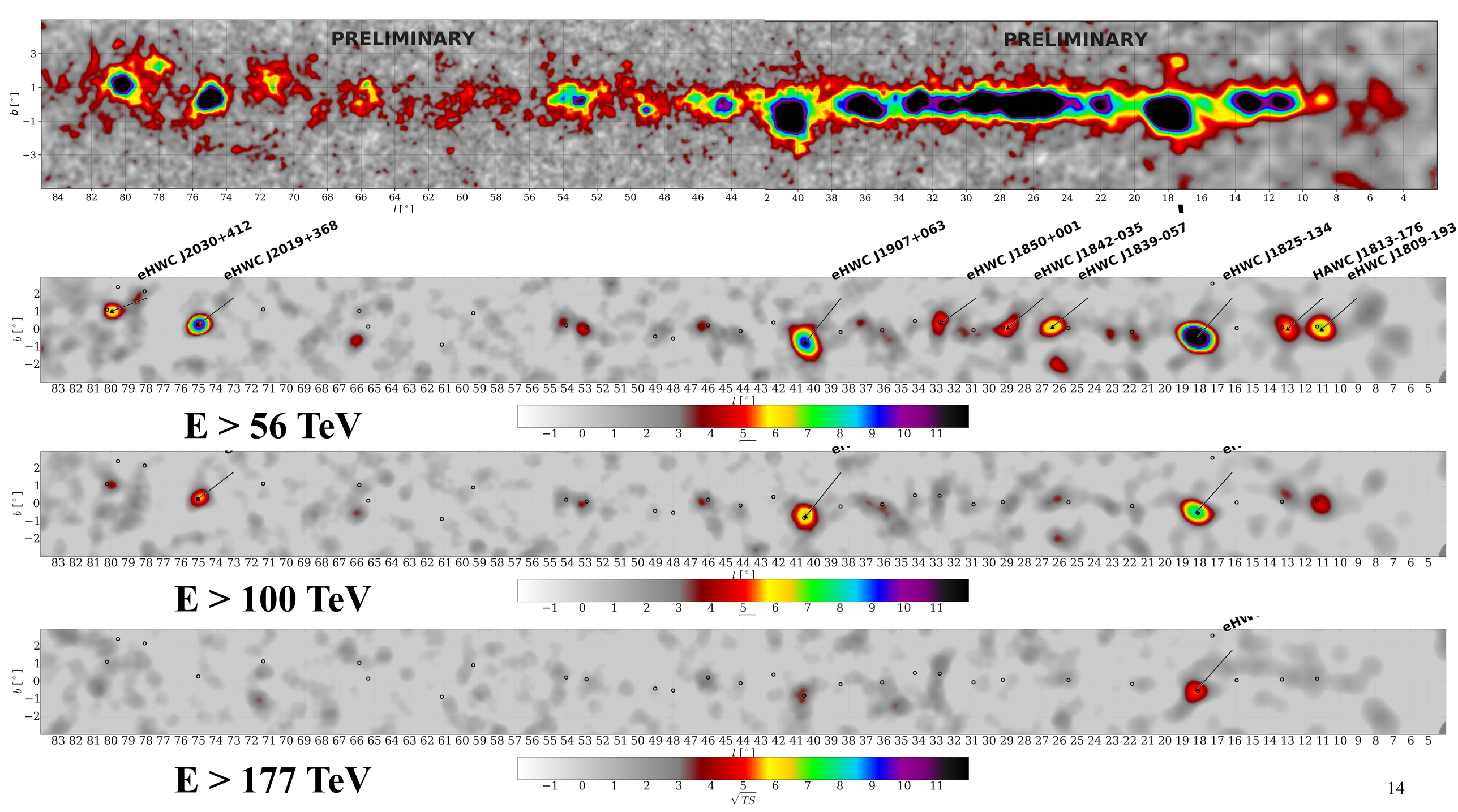
HAWC J2227+610

Associated to SNR G106.3+2.7





Accepted at ApJ Letters (arXiv 2005.13699)


PRELIMINARY
PRELIMINARY
eHWC J2030+412
eHWC J2019+368
eHWC J1907+063
eHWC J1850+001
eHWC J1842-035
eHWC J1839-057
eHWC J1825-134
HAWC J1813-176
eHWC J1809-193
E > 56 TeV
E > 100 TeV
E > 177 TeV
b [°]
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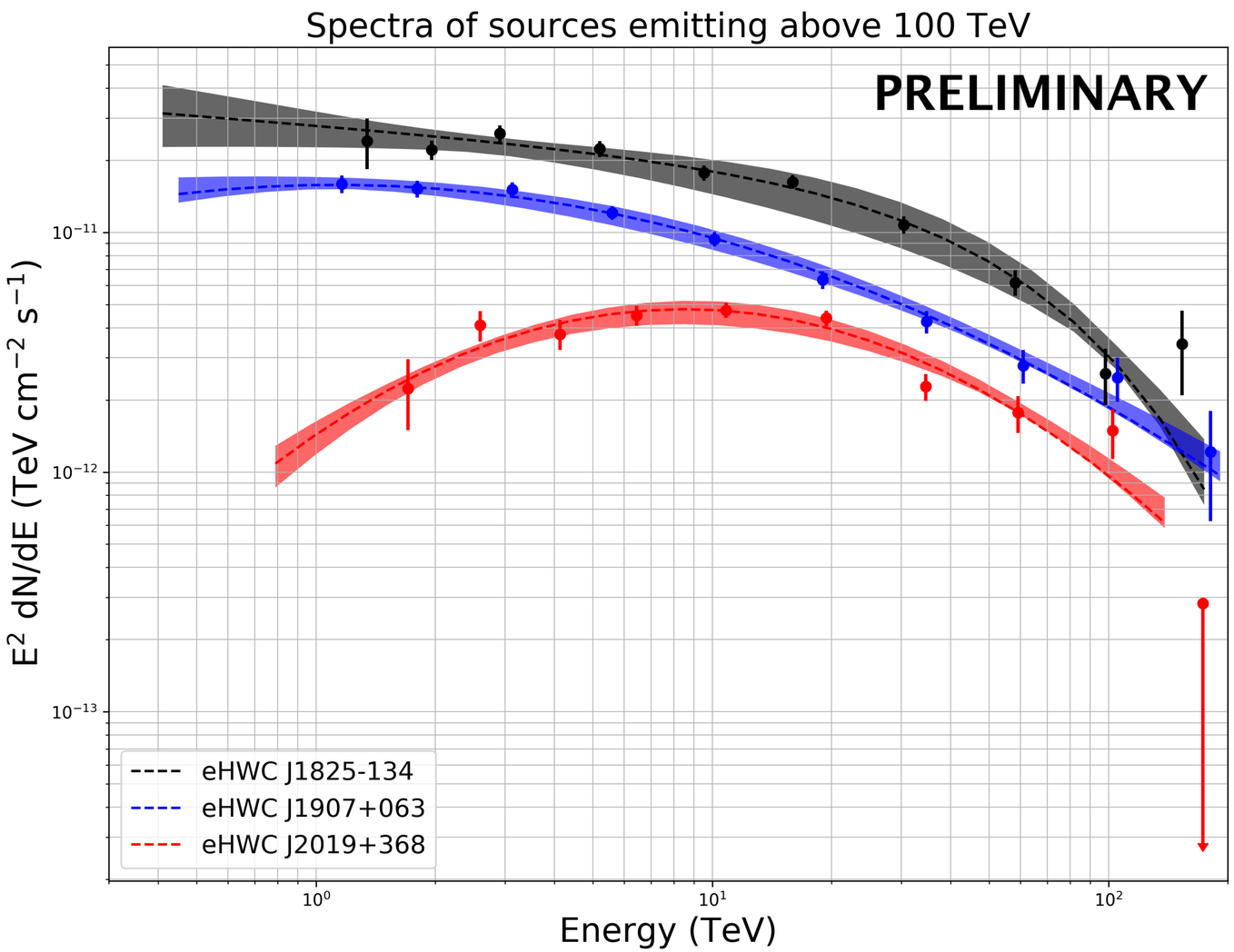
Hardest sources

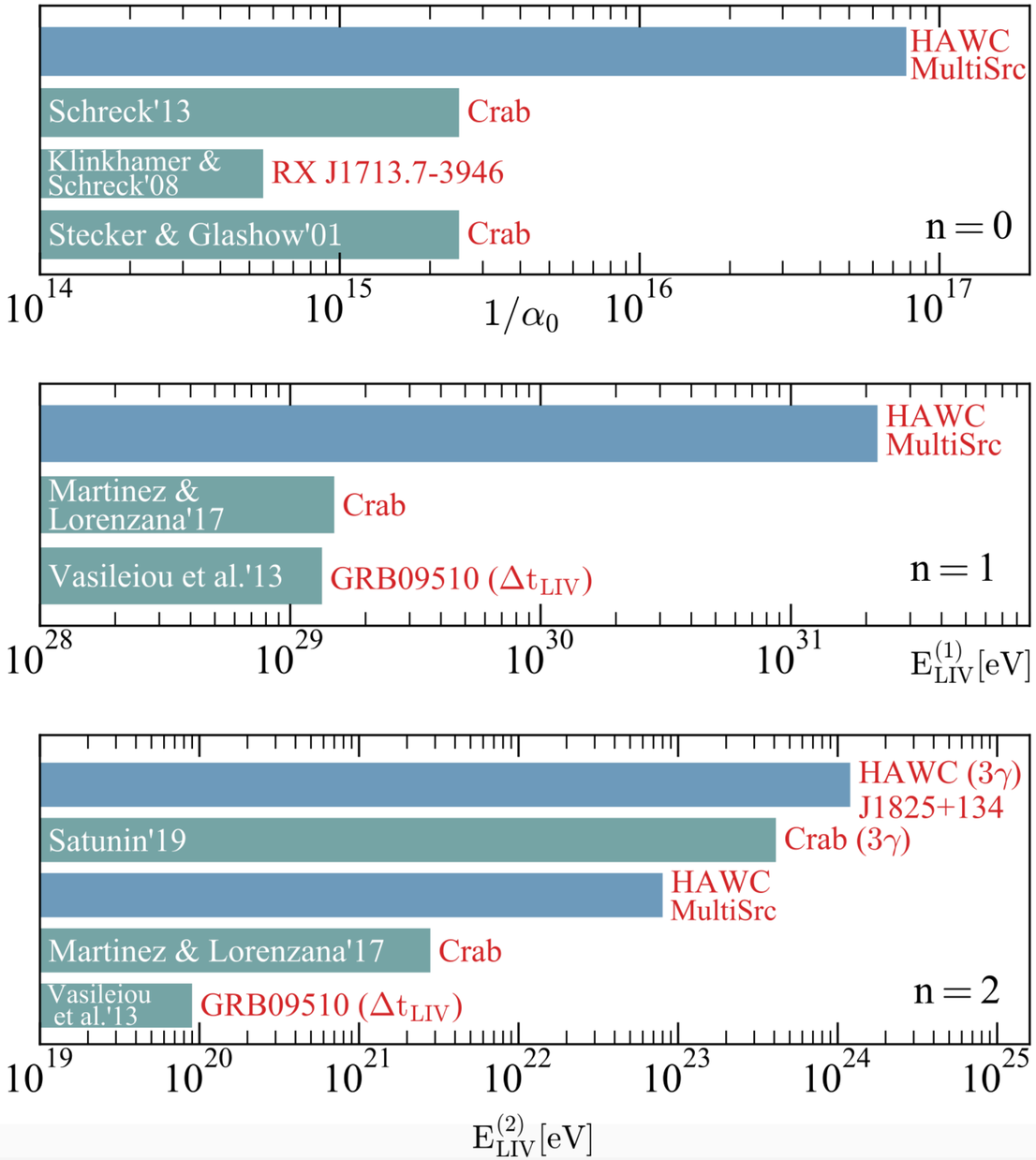


Source	p-Value	E_c (95%)	E_c (3σ)
eHWC J1825-134	1.000	244 TeV	158 TeV
eHWC J1907+063	0.990	218 TeV	162 TeV
eHWC J0534+220 (Crab Nebula)	1.000	152 TeV	104 TeV
eHWC J2019+368	0.828	120 TeV	88 TeV

- Hadronic scenarios are preferred to leptonic, bounded to inverse Compton scattering of CMB radiation.

PRL 124, 021102 (2020)

Limits on Lorentz Invariance Violation



Limits on ELIV for a modified dispersion relation,

$$E_\gamma^2 - p_\gamma^2 = - \pm |\alpha_n| \, p_\gamma^{n+2} \, ,$$

with

$$E_{\rm LIV}^{(n)} = \alpha_n^{-1/n} \, ,$$

for n > 0.

PRL 124, 131101 (2020)

Summary (and more)

- HAWC has operated successfully for more than five years, gathering 1523 days of data in its most recent dataset.
- HAWC has detected tens of sources, mostly along the Galactic plane, mostly PWNe, TeV haloes and SNRs.
  - The Cygnus OB2 star formation region is also a HAWC source
- HAWC has detected sources above 100 TeV, pointing to likely hadronic accelerators;
  - these sources provide the best current limits on potential Lorentz Invariance Violation.
- The search for coincidences with IceCube along the Galactic Plane is ongoing.