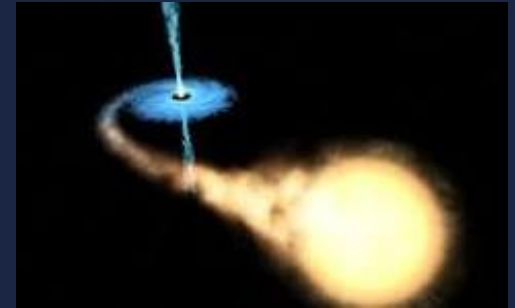
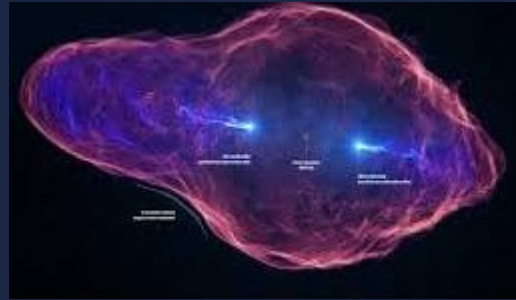


Very-high-energy gamma rays and compact objects: observations, constraints, and prospects



M. de Naurois, LLR, Ecole Polytechnique - IN2P3/CNRS

Compact Objects – Kesako

- Compactness Parameter: $\Xi = \frac{GM}{c^2 R} = \frac{R_s}{2R}$
- Describes how “close” to a black hole a celestial body is
- Some orders of magnitude:

Body	Mass (M_{\odot})	Radius (km)	Density (kg/m ³)	Ξ
Earth	3×10^{-6}	6×10^3	5×10^3	10^{-10}
Sun	1	7×10^5	10^3	10^{-6}
White Dwarf	0,1 – 1,4	$\sim 10^4$	$\sim 10^{10}$	$10^{-4} - 10^{-3}$
Neutron star	1 – 3	~ 10	$\sim 10^{18}$	$\sim 0,2$
Stellar Black Hole	~ 3	9	N.A.	0,5
Supermassive Black Hole	$\sim 10^9$	20 a.u.	N.A.	0,5

Compact



Energetic

- Fraction of mass energy that can be extracted from a system

- Electroweak (chemistry):

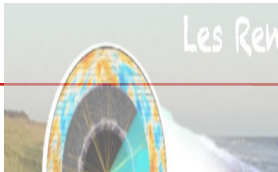
$$\epsilon \approx \frac{1 \text{ eV}}{1 \text{ GeV}} \sim 10^{-9}$$

- Strong (nuclear energy):

$$\epsilon \approx \frac{1 \text{ MeV}}{1 \text{ GeV}} \sim 10^{-3}$$

- Gravity (accretion):

$$\epsilon \approx \frac{E_p}{m c^2} = \Xi \quad (\text{Newtonian})$$



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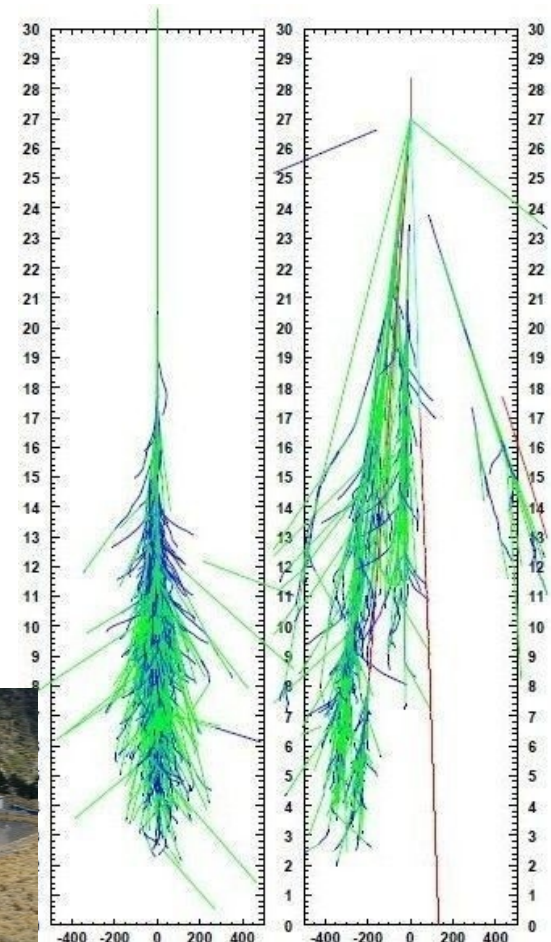
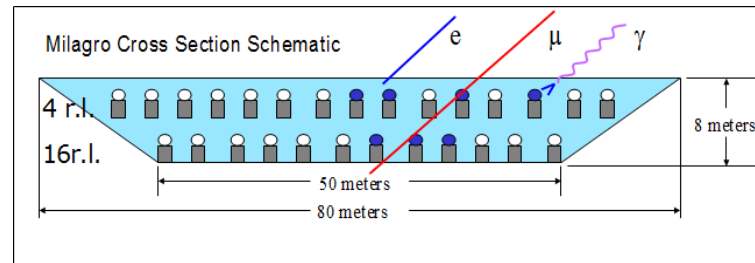
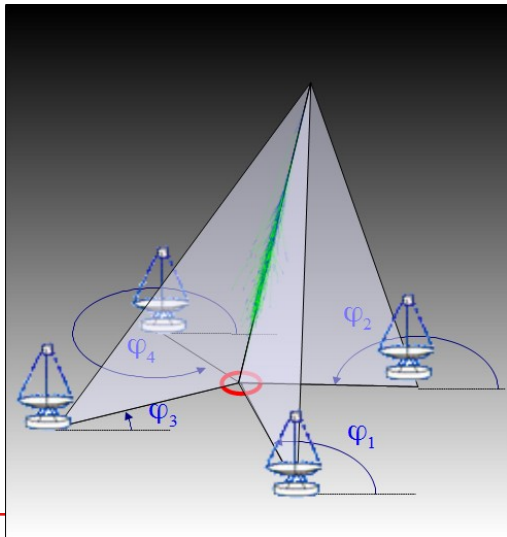
Compact objects are among the most energetic phenomena

Laboratories for General Relativity (in strong field)



VHE γ -ray Astronomy

- Ground-based instrument relies on the detection of atmospheric showers
- 2 complementary techniques
 - Imaging Atmospheric Cherenkov Telescopes
 - Wavefront sampling (Water Cherenkov, Particle Arrays)



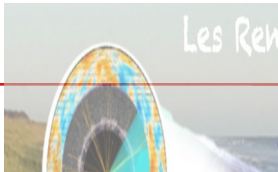
Techniques – Merits & drawbacks

Imaging Atmospheric Cherenkov Telescopes

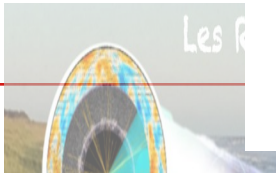
- Small F.O.V.
- Low duty cycle
- High rejection
- High resolution

Sampling experiments (Water Cherenkov, Particle Arrays,...)

- Large F.O.V.
- High duty cycle
- Poor rejection
- Poor resolution

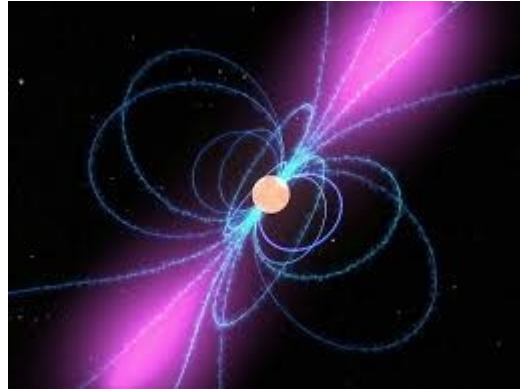
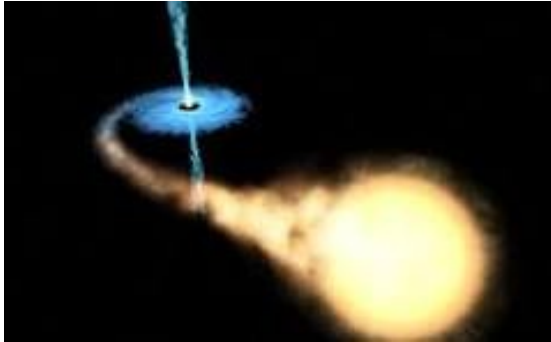


VHE γ -ray world



Compact Objects in Nature

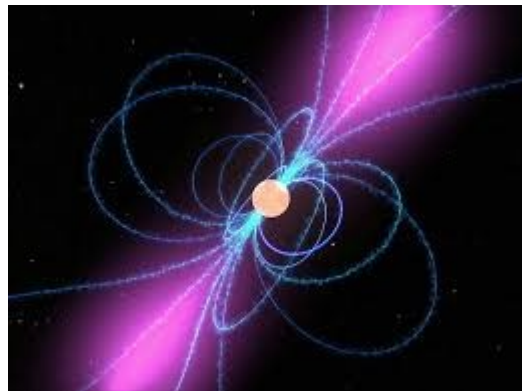
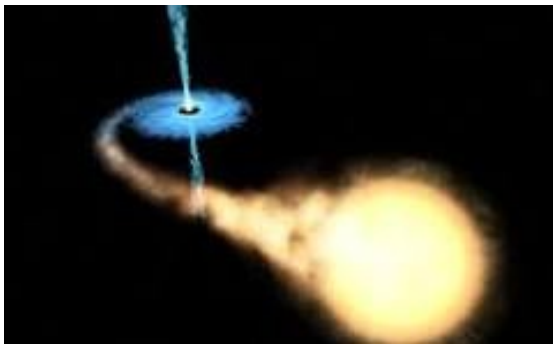
- Galactic:
 - Neutron stars, pulsars, magnetars (binary systems)
 - Accreting Stellar black holes aka “microquasars”
- Extragalactic
 - Accreting super-massive black holes, aka “Active Galactic Nuclei”
 - Associated with Gamma-ray bursts (NS coalescence, massive star collapse)



Compact Objects in Nature

Galactic:

- Neutron stars, pulsars, magnetars (binary systems)
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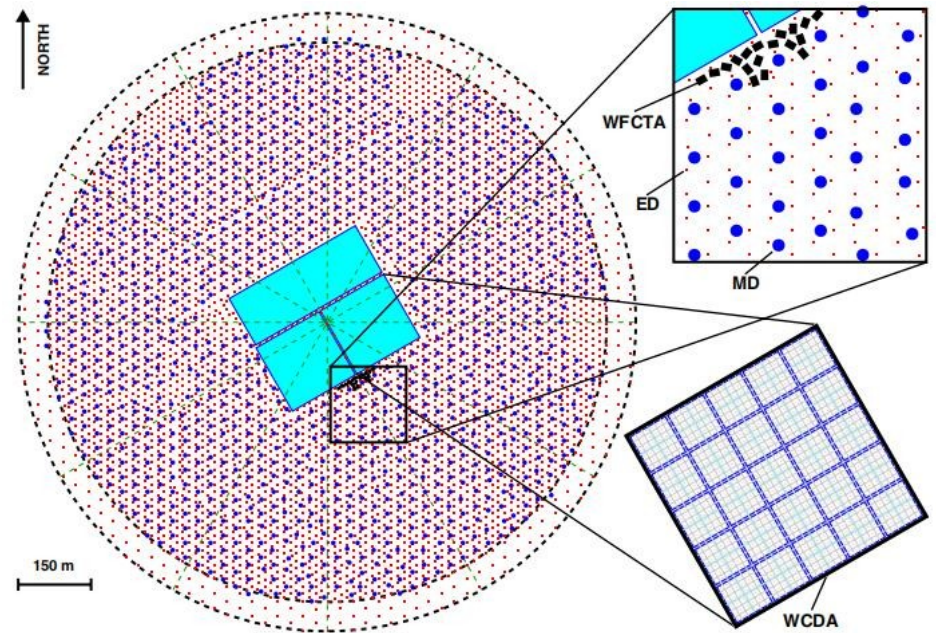
This Talk

rencontres de Noirmoutier 2026

Talks on Thursday 

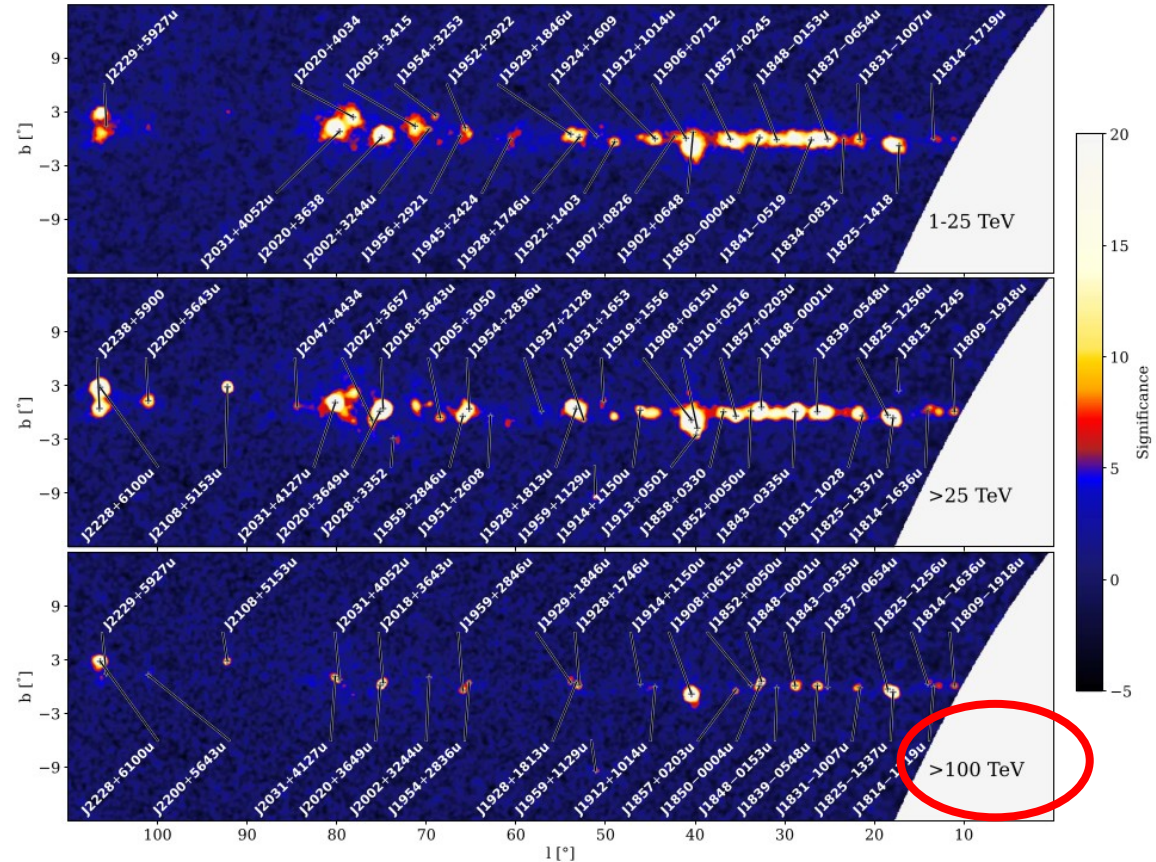
LHAASO – Large High Altitude Air Shower Observatory

- New player in the game
- Haizi mountain, Sichuan, China
- 4410 m above the sea level
- km² array (KM2A)
+ Water Cerenkov (WCDA)
- Upcoming LACT (Imaging Atmospheric Cherenkov Telescopes)



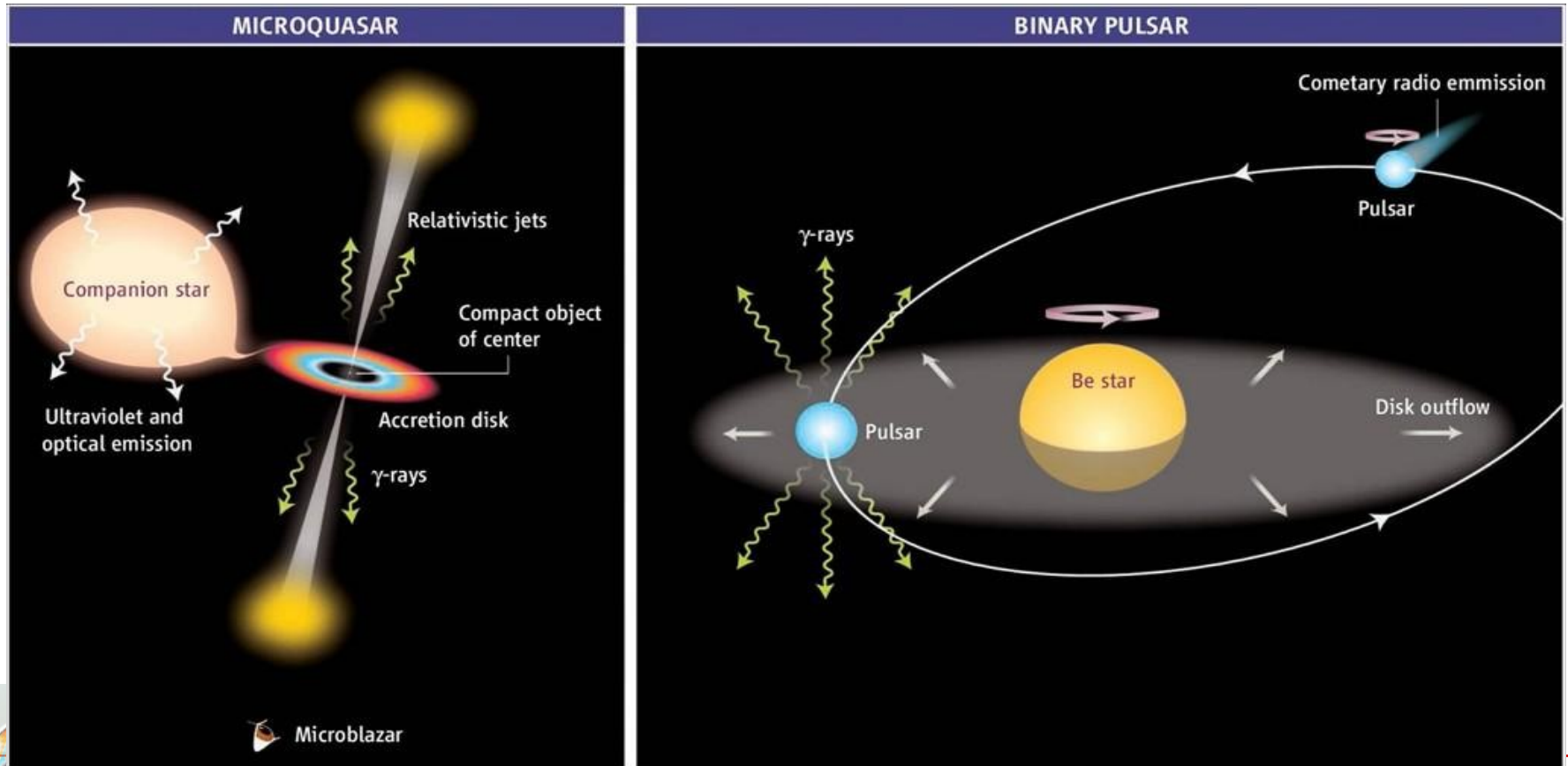
LHAASO – Large High Altitude Air Shower Observatory

- 90 sources detected by LHAASO (≥ 1 TeV)
- 43 UHE ($E \geq 100$ TeV) source
- 35 sources associated with young, energetic pulsars
- 10 UHE sources not detected in 1 – 25 TeV range: new source class?

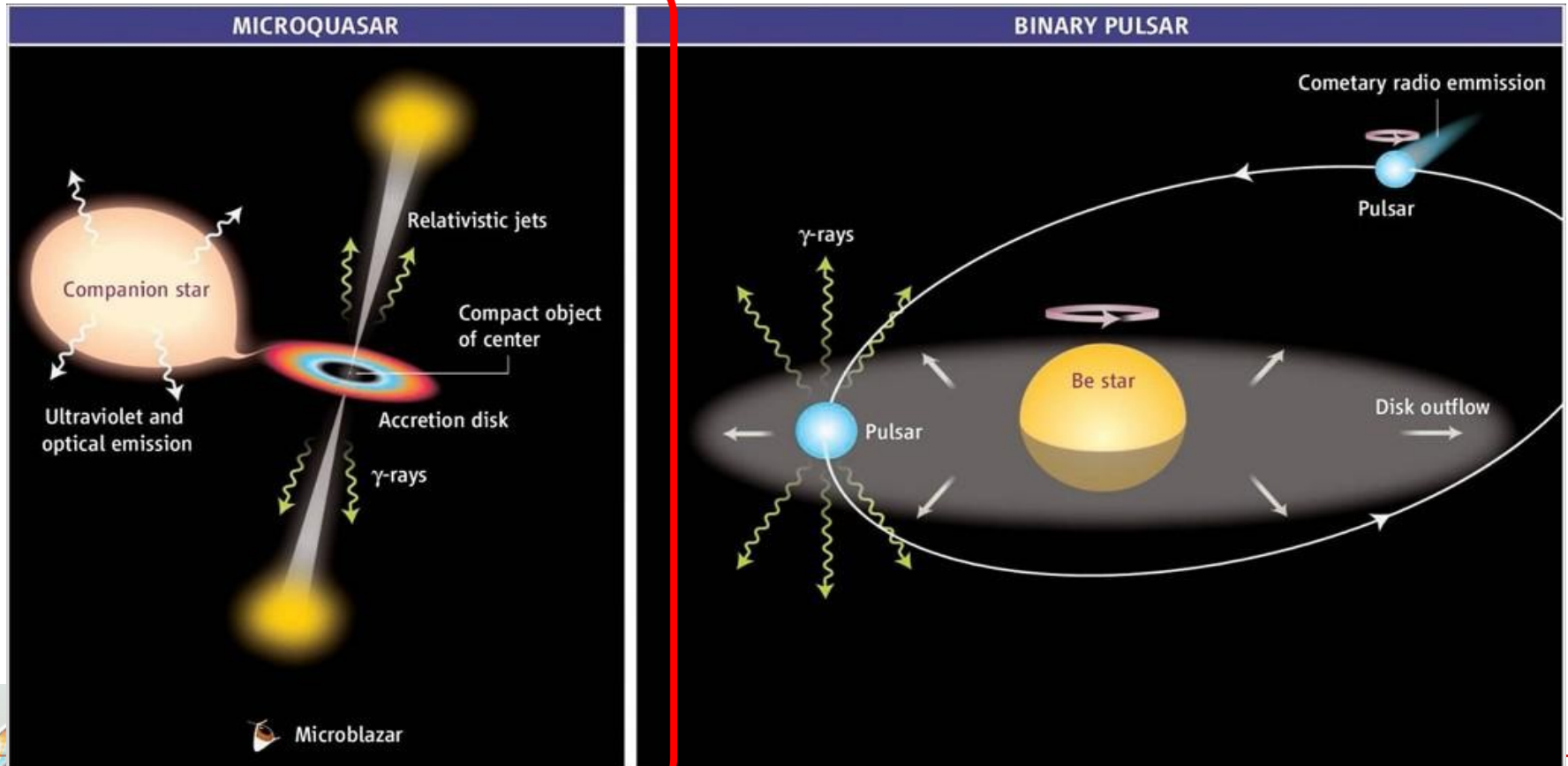


Les Rev

Gamma-ray binaries

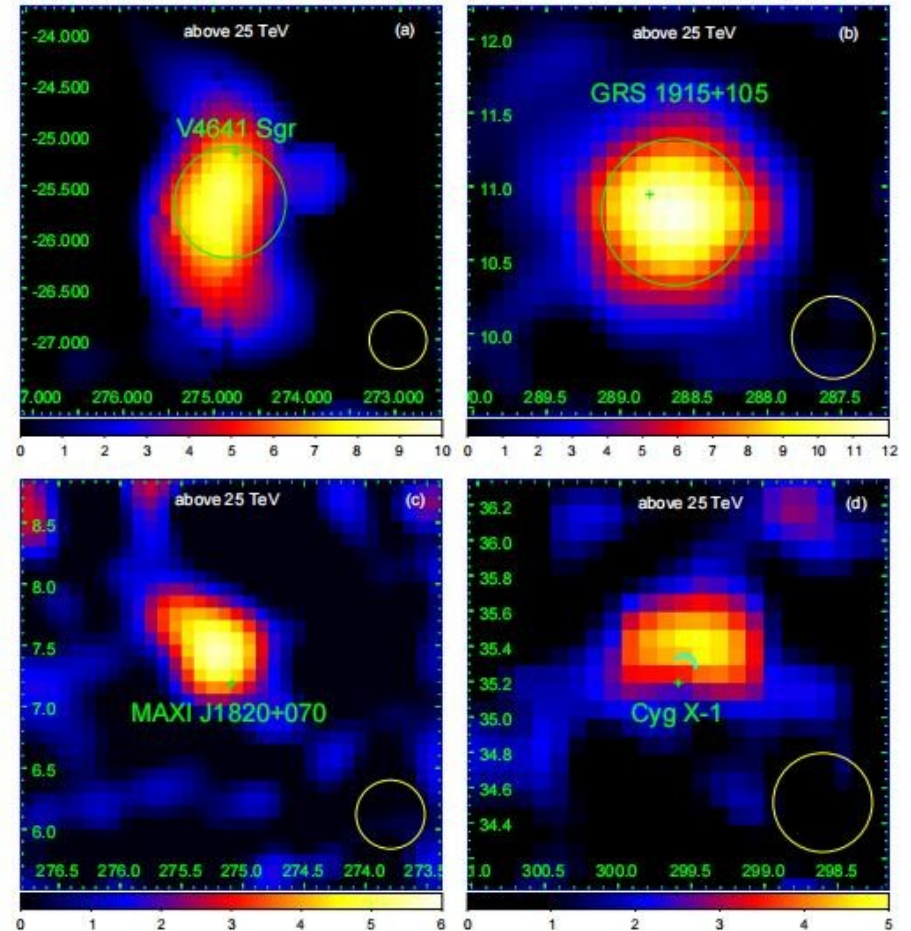
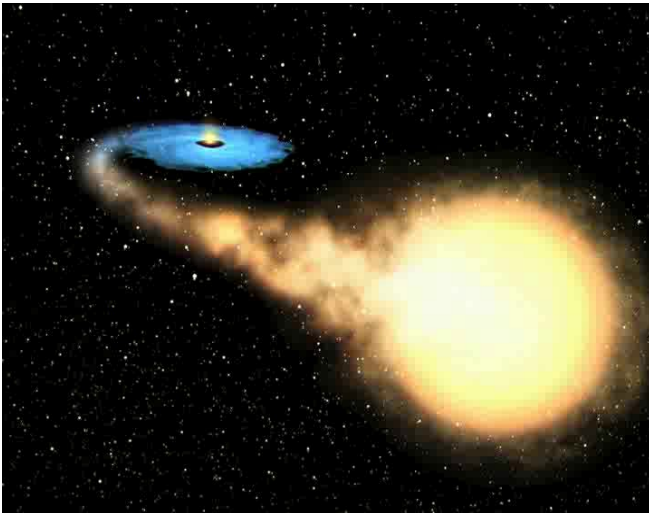


Gamma-ray binaries

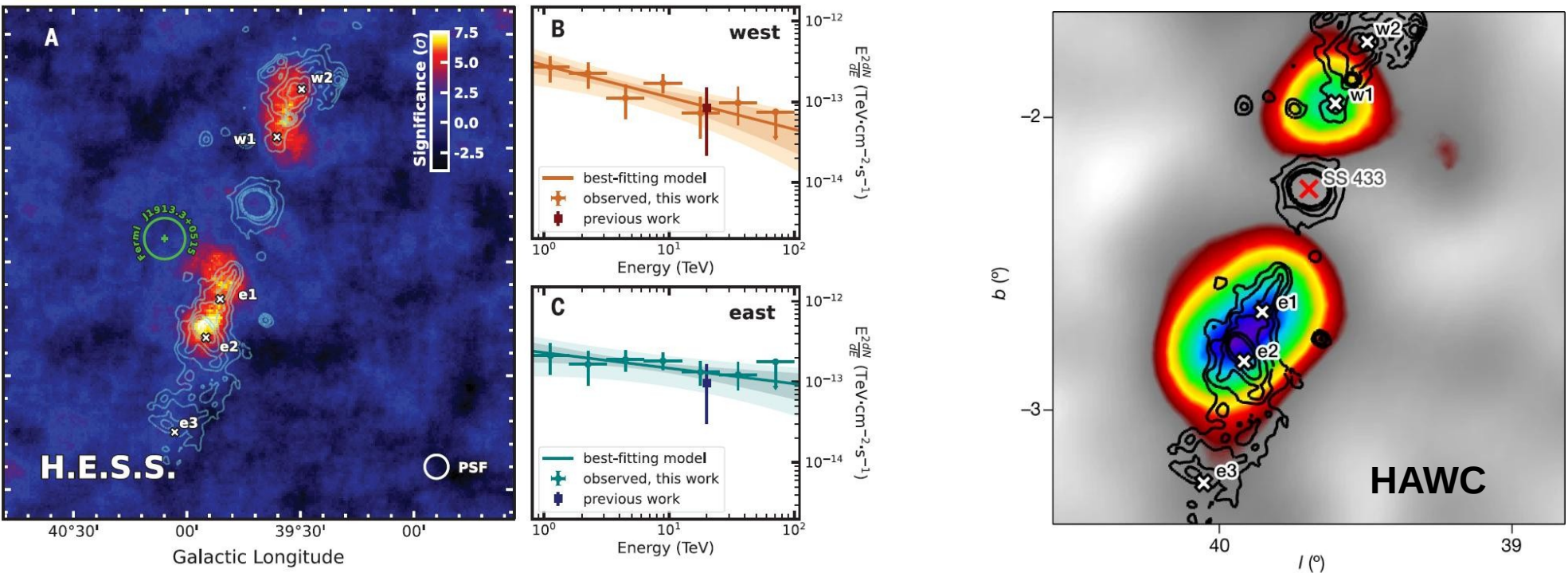


VHE Microquasars

- Accretion powered systems
- Five VHE microquasars: SS 433, V4641 Sgr, GRS 1915+105, MAXI J1820+070, Cygnus X-1



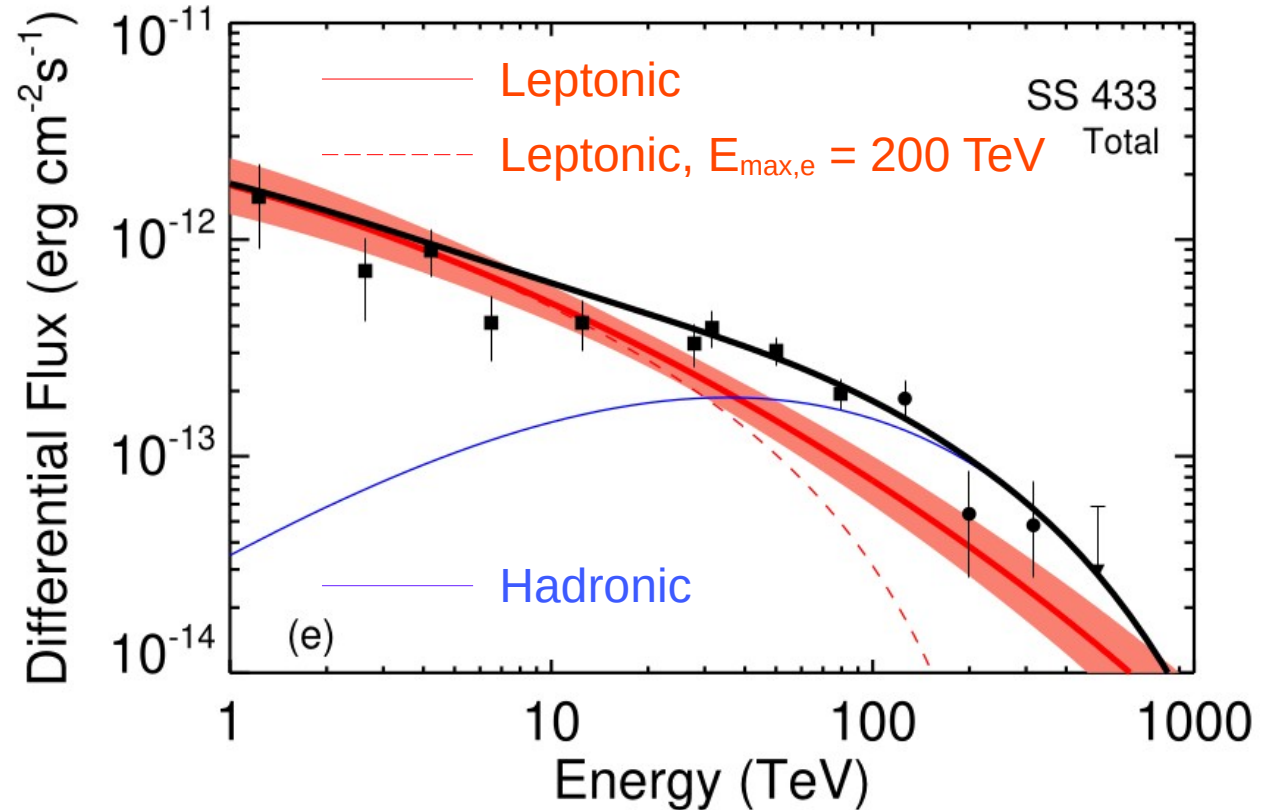
SS 433



- Extended emission detected by HAWC (2018), H.E.S.S. (2024) and LHAASO (2024)
- Far from central black hole: interaction of jet ($v \sim 0.26c$) with ISM

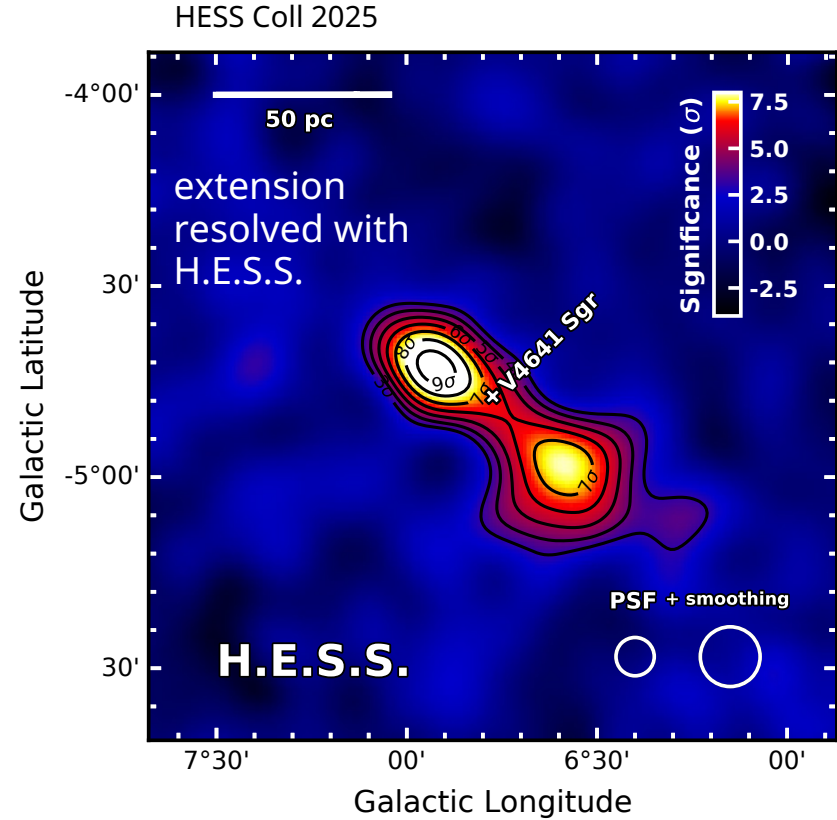
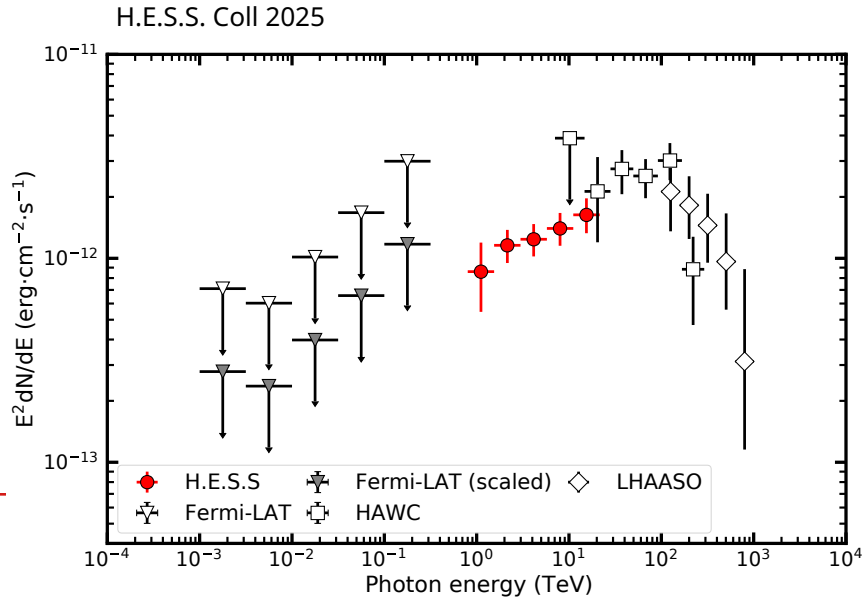
SS 433 – Emission

- TeV energy most likely of leptonic origin from energetic (relatively steep spectrum, energetics, variability)
- LHAASO UHE emission favours a second hadronic component



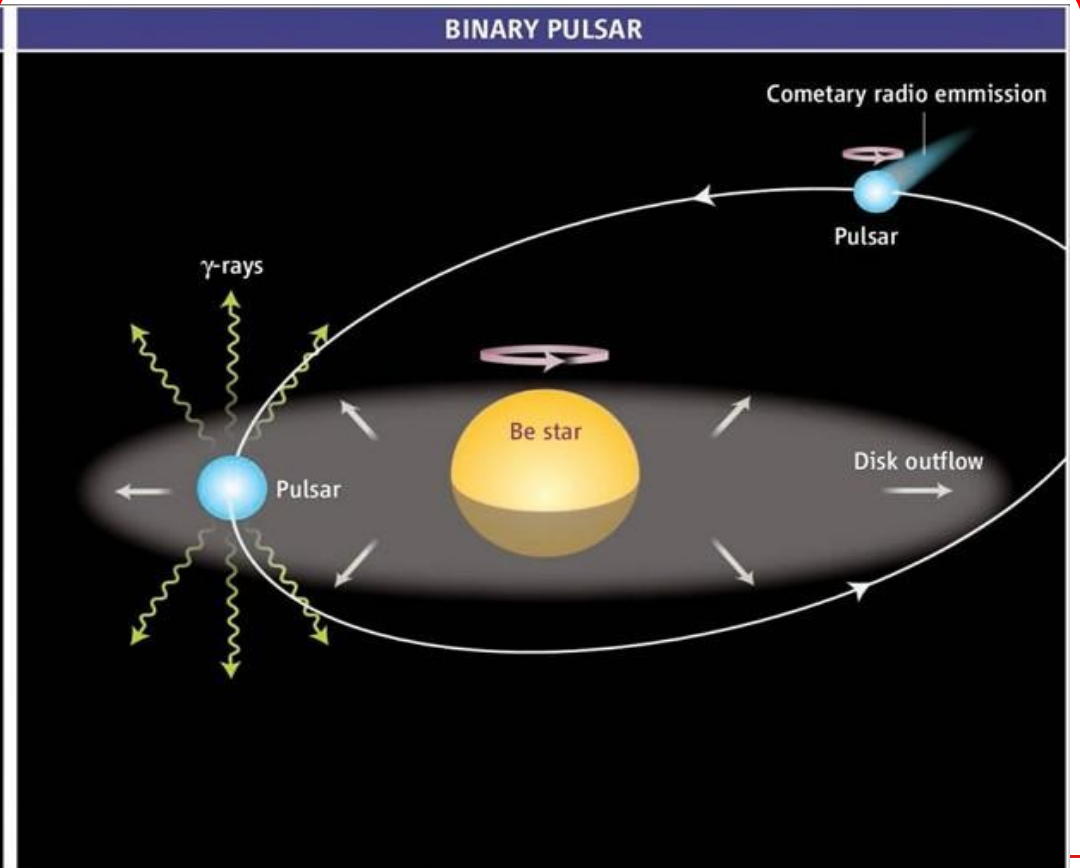
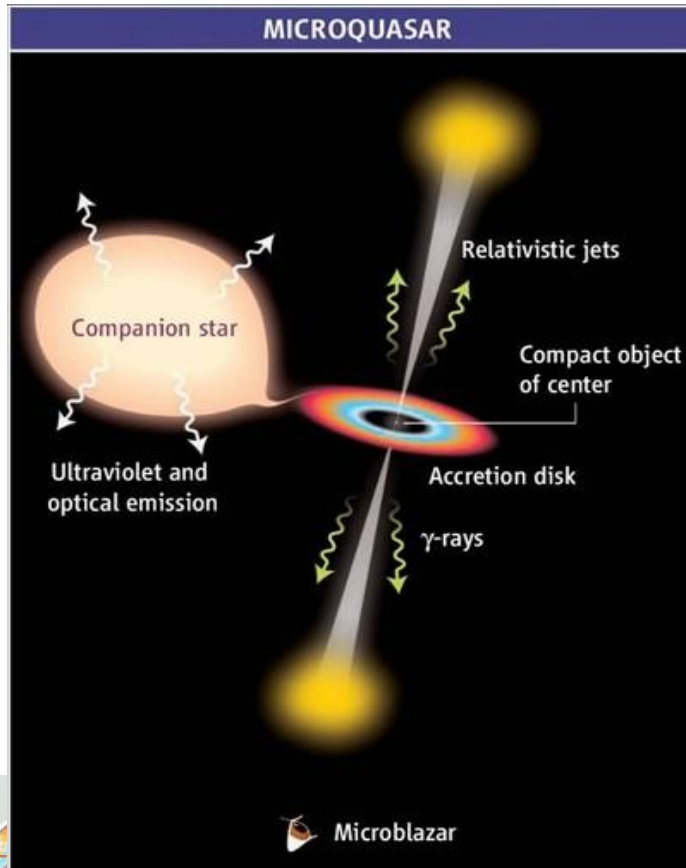
V4641 Sgr

- Brightest LHAASO source, detected up to 800 TeV
- 1-2 orders of magnitude brighter than SS 433
- Leptonic models favoured (low density)



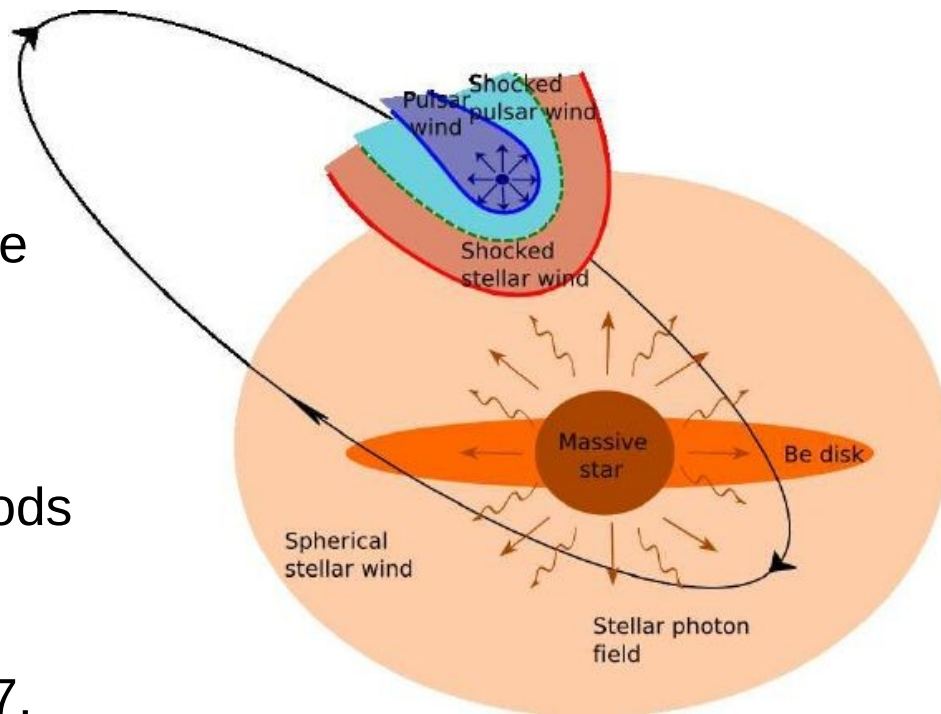
Laura Olivera-Nieto,
CTAO Science Meeting, 2026

Gamma-ray binaries



γ -ray binaries

- Rotation powered systems (neutron star)
- VHE emission arising from interaction between pulsar- and stellar winds
- Complex geometry (eccentric orbit, relative orientation of spins and winds)
- Complex physics (disk passages, clumpy wind, disruption of PWN, ...)
- Large varieties of (accessible) orbital periods (days to hundreds of years)
- Several objects known: PSR B1259-63, LS 5039, LS I +61+303, HESS J0632+057, 1FGL J1018.6-5856, HESS J1832-093, PSR J2032+4127, LMC P3

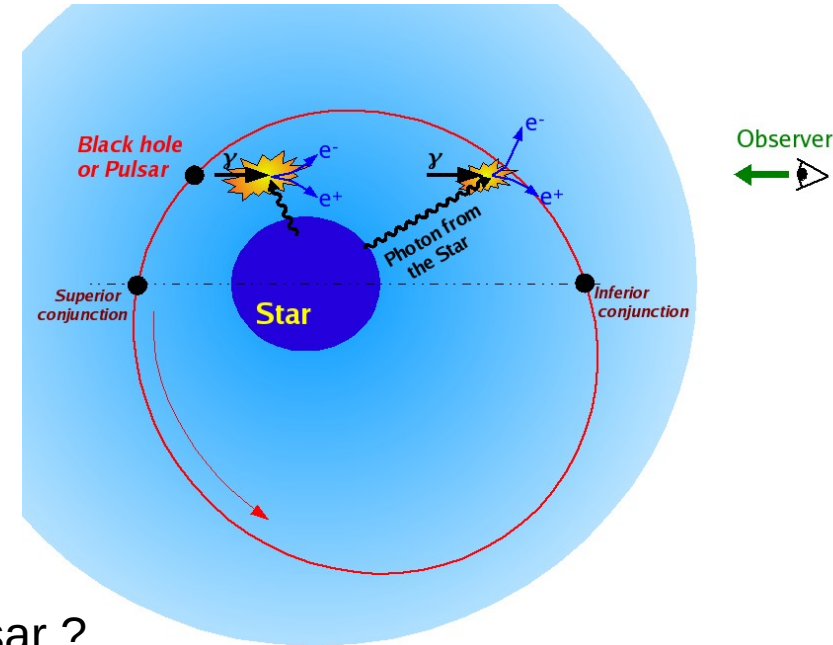


Credit: O. Porth



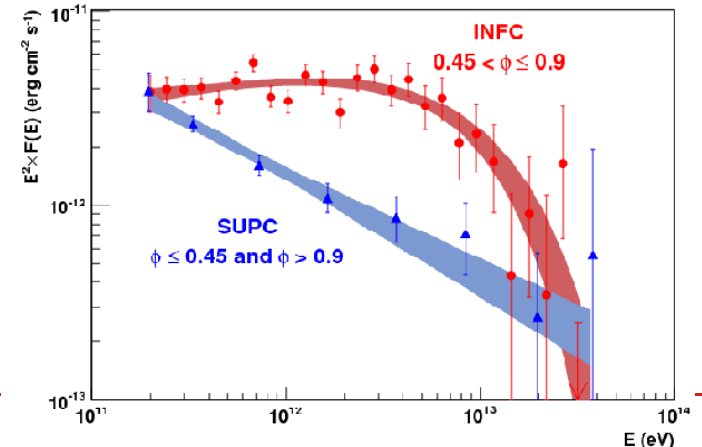
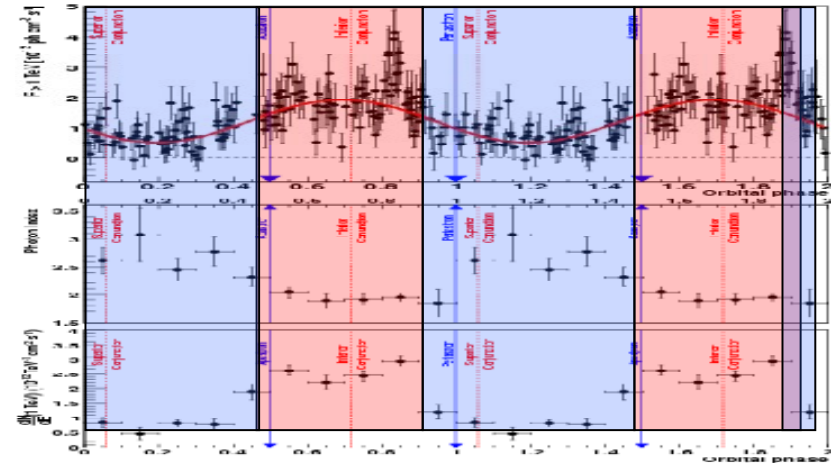
LS 5039 – A gamma-ray binary

- Binary system
 - Massive O6.5 star ($20 M_{\odot}$), UV (39 000 K)
 - Unidentified Compact Object, $M = [1.5 - 5] M_{\odot}$
 - Tight orbit ($d = [2 - 4.5] R_{\star}$) ~ 0.1 AU !
 - Orbital period ~ 3.9 days
 - Distance ~ 3 kpc (9 000 light yr)
 - High Non Thermal Luminosity ($\sim 10^{29}$ W)
- Nature of compact object still debated
 - Black hole (Jets in radio, mas scale) \Rightarrow Micro-quasar ?
 - Neutron star \Rightarrow PWN like in PSR B1259-63 ?
 - Magnetar ?



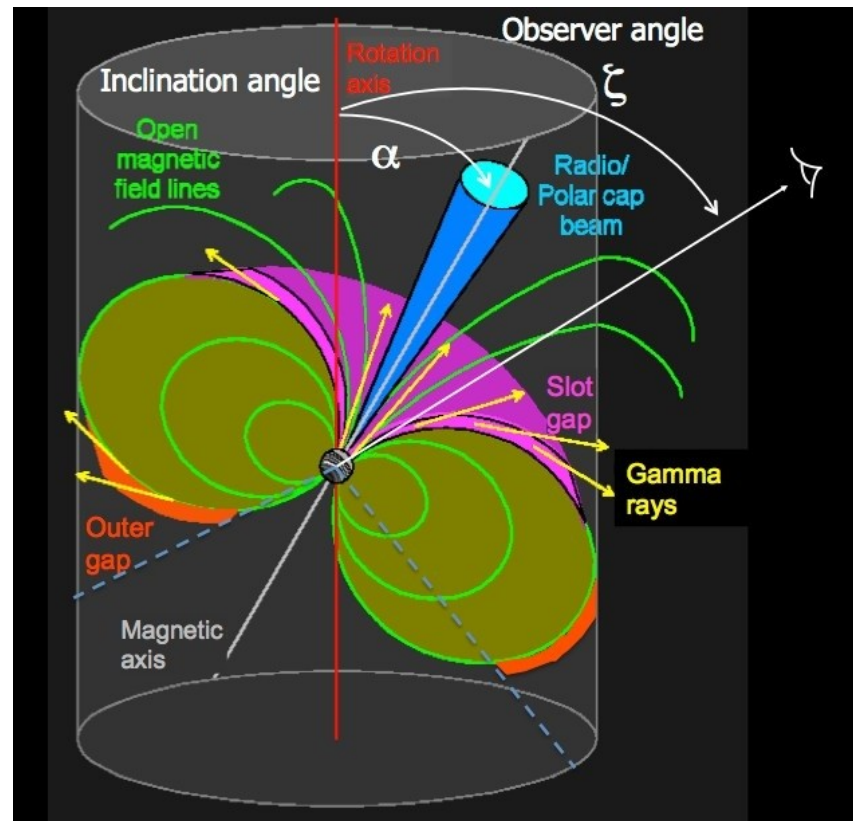
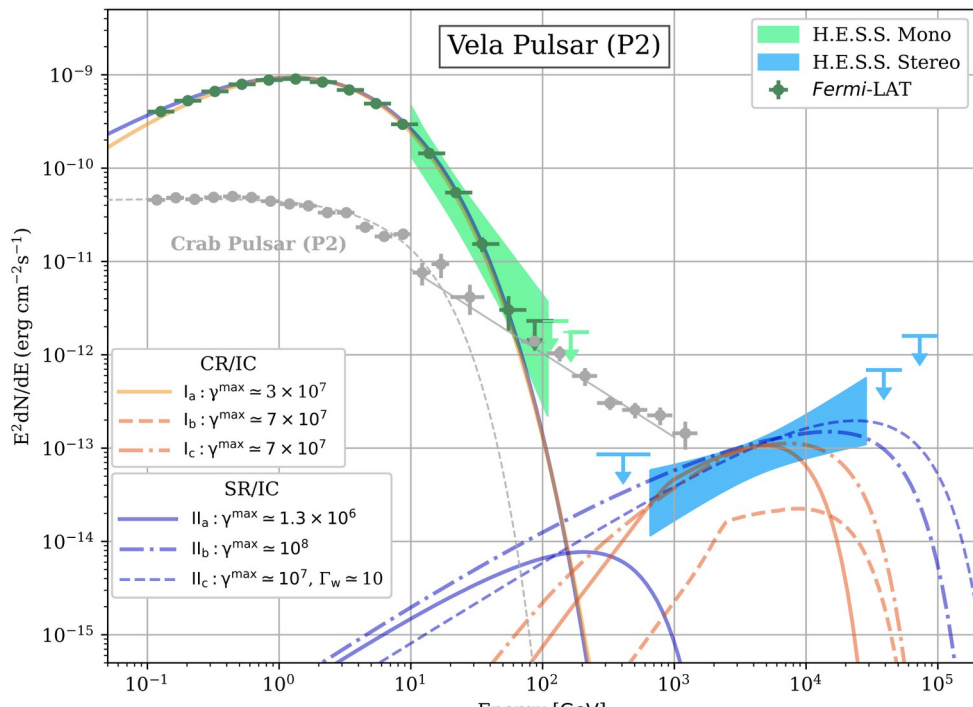
Orbital Modulation @ LS 5039

- γ -ray emission modulated @ 3.9 days
 - Maximum @ inferior conjunction (compact object in front of the star),
 - Minimum @ superior conjunction
 - Spectral modulation
- First periodic source in VHE
 - Period **3.9058785 days \pm 3.7 s**
- Modulation caused by anisotropic IC & absorption of VHE photons by pair creation on stellar photons
- Kind of swiss-clock over 20 years



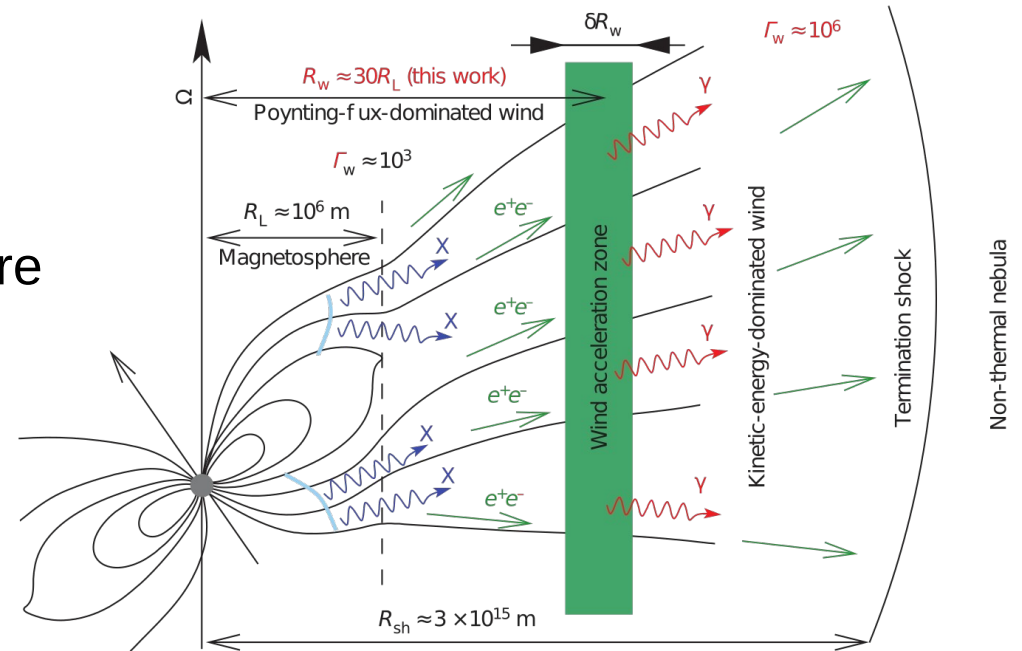
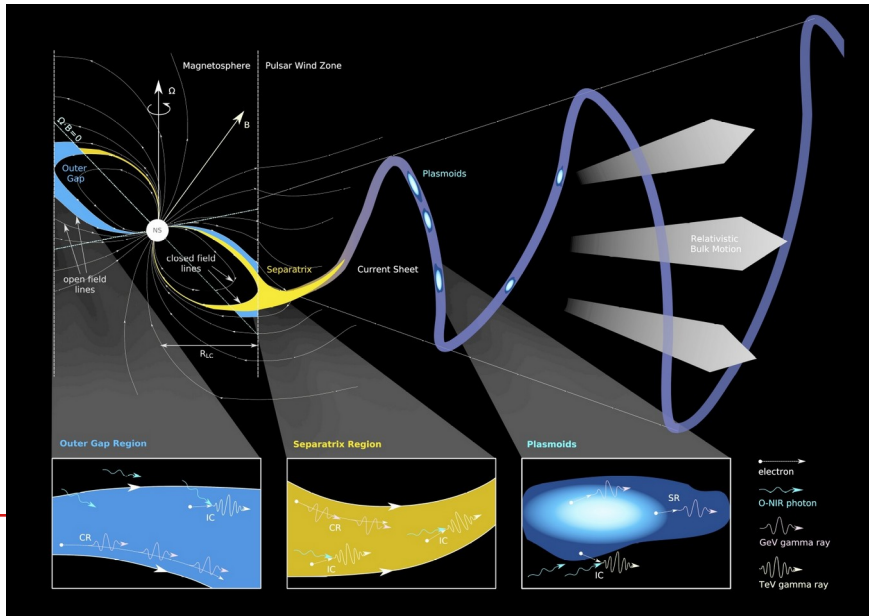
VHE Pulsars

- Rotation-powered Neutrons stars
- Several VHE pulsars now: Crab, Vela (20 TeV), Geminga, PSR B1706-44, PSR J1509-5850)



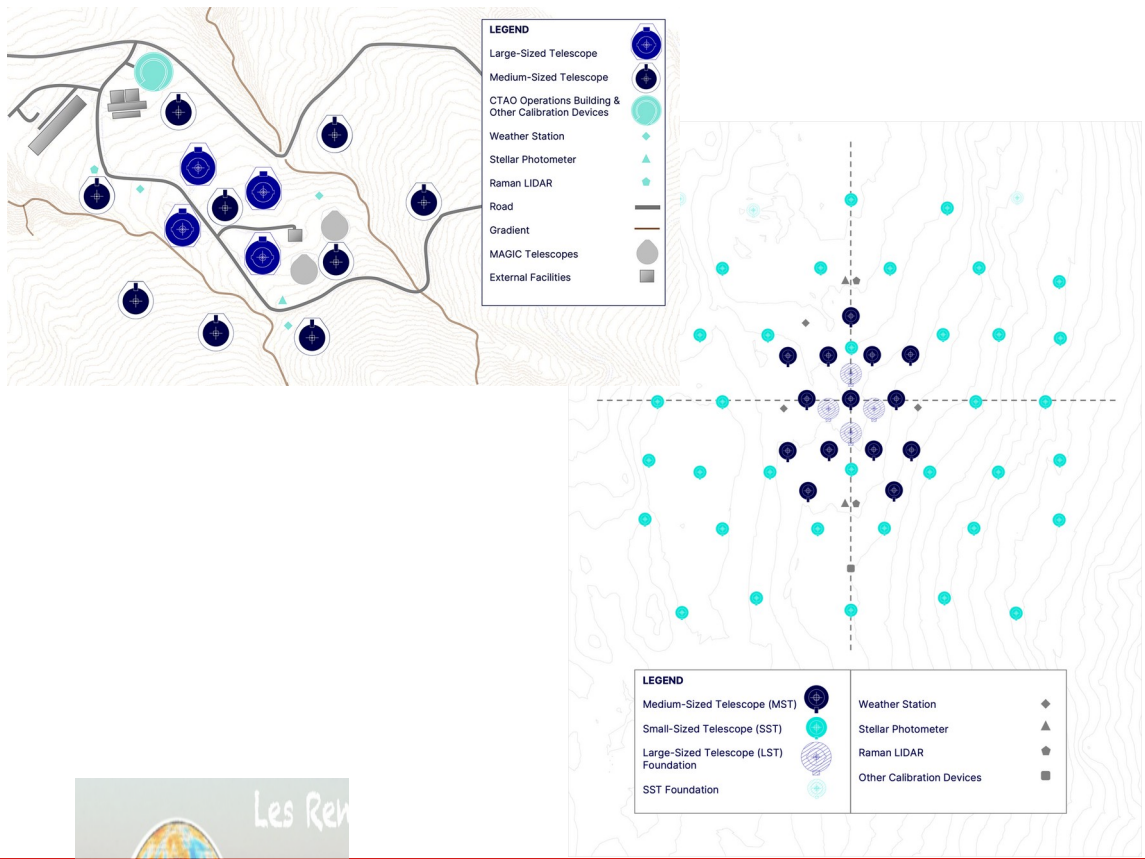
VHE Pulsar

- High B Field prevent emission close to neutron star (synchrotron cooling)
- Acceleration in (stripped) wind zone
- Mixture of Synchrotron (GeV), Curvature Radiation and Inverse Compton



Perspectives

CTAO – Cherenkov Telescope Array Observatory



- Explore the sky between 10 GeV and 100 TeV
- Sensibility x 10
- Improved angular resolution
- Large field of view
- Use proved technology in a 4th generation of instruments
- Construction 2025 – 2030



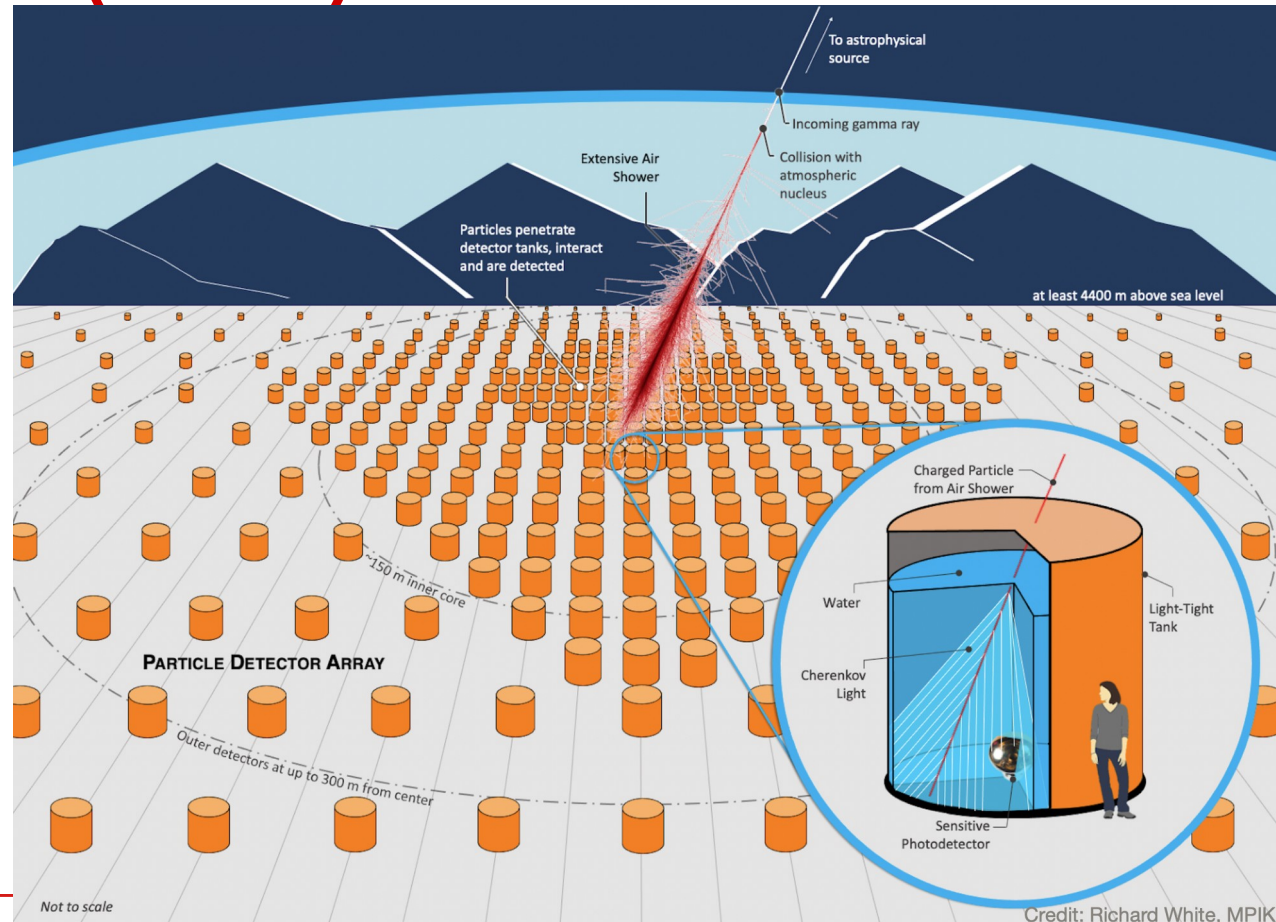
Timeline

- ERIC (“European Research Infrastructure Consortium”) signed January 5th, 2025
- 4 LST in construction, inauguration October 2026
- Development of southern site starting in 2026 (foundations ongoing)
- First science ~ 2028



The Southern Wide-field Gamma-ray Observatory (SWGGO)

- Proposed instrument (not founded yet)
 - Atacama Astronomical Park, Chile, 4770 m asl.
 - Energy range 100s of GeV up to the PeV scale.
 - Based primarily on water Cherenkov detector units.



Conclusions

- SNRs were considered prime candidates for Galactic CR based on rate and energetics
 - But unclear whether (all) SNRs can reach PeV energies.
 - Other Galactic sources (micro-quasars and/or pulsar wind nebula) seems now able reach PeV
 - Pevatrons might be much more numerous that expected
- New instruments coming soon (CTAO, LACT) or proposed (SWGGO)
- Not discussed here
 - Magnetars, colliding wind binaries (η -Car), Novae, ...
 - Extragalactic sources (mostly Active Galactic Nuclei and Gamma-Ray Burst: See talks on Thursday)

