



cherenkov
telescope
array

the observatory for
ground-based
gamma-ray astronomy



UNIVERSITÉ
DE GENÈVE



University of
Zurich^{UZH}

Galactic Science with CTA et al.

CTA Swiss day 24th Nov

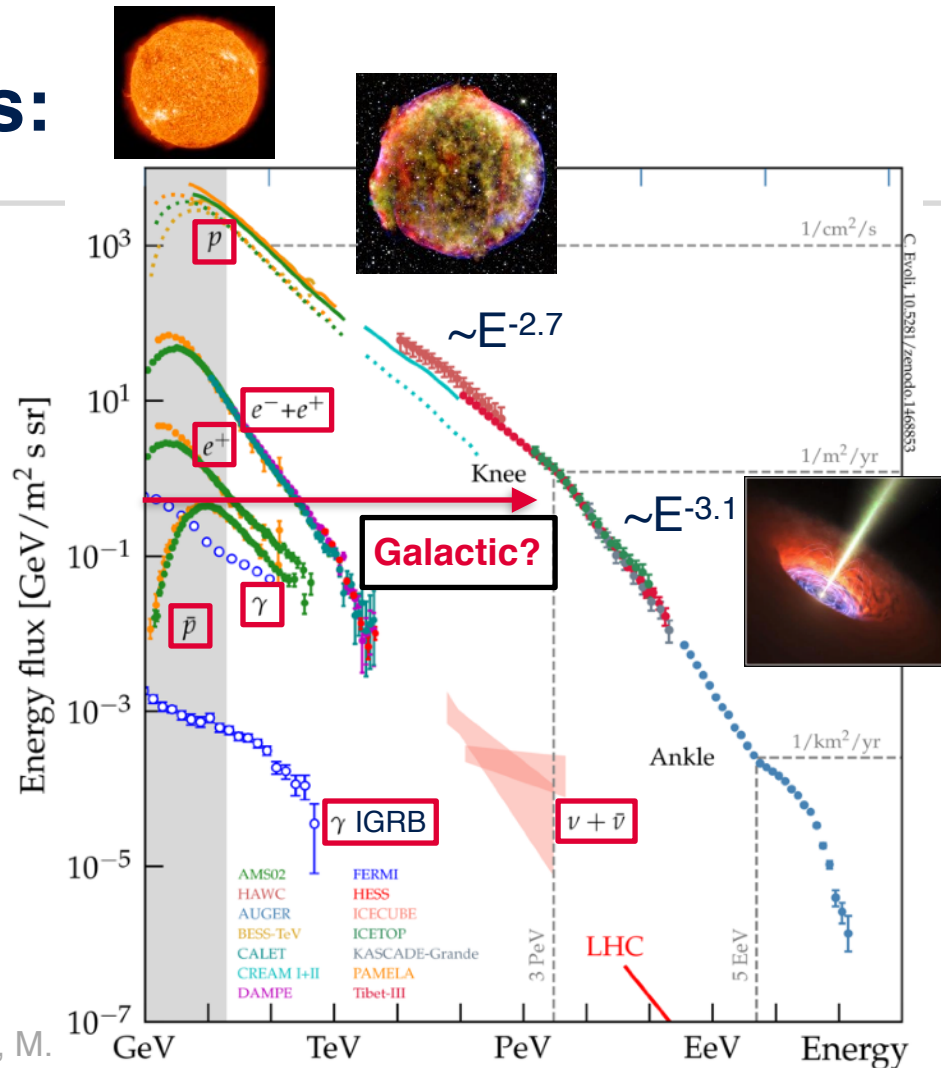
Sources, particle acceleration, shocks and feedback

Matteo Balbo & Alison Mitchell

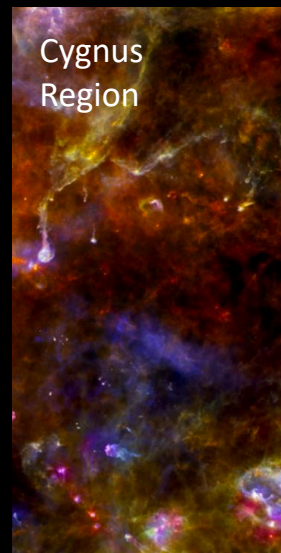


Still unresolved questions:

- The origin of relativistic cosmic particles?
- Where are they accelerated?
- Through which physical mechanisms?
- How do they propagate in the Galaxy?
- How do they influence the environment/evolution? (Galactic feedback, SFR)
- How can we probe them: through direct & indirect measurements?



A zoo of Galactic particle accelerators



Cygnus Region



Novae



SNR



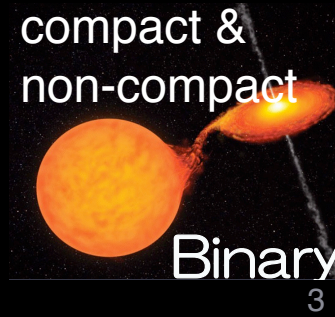
$G\dot{E}$

Pulsar



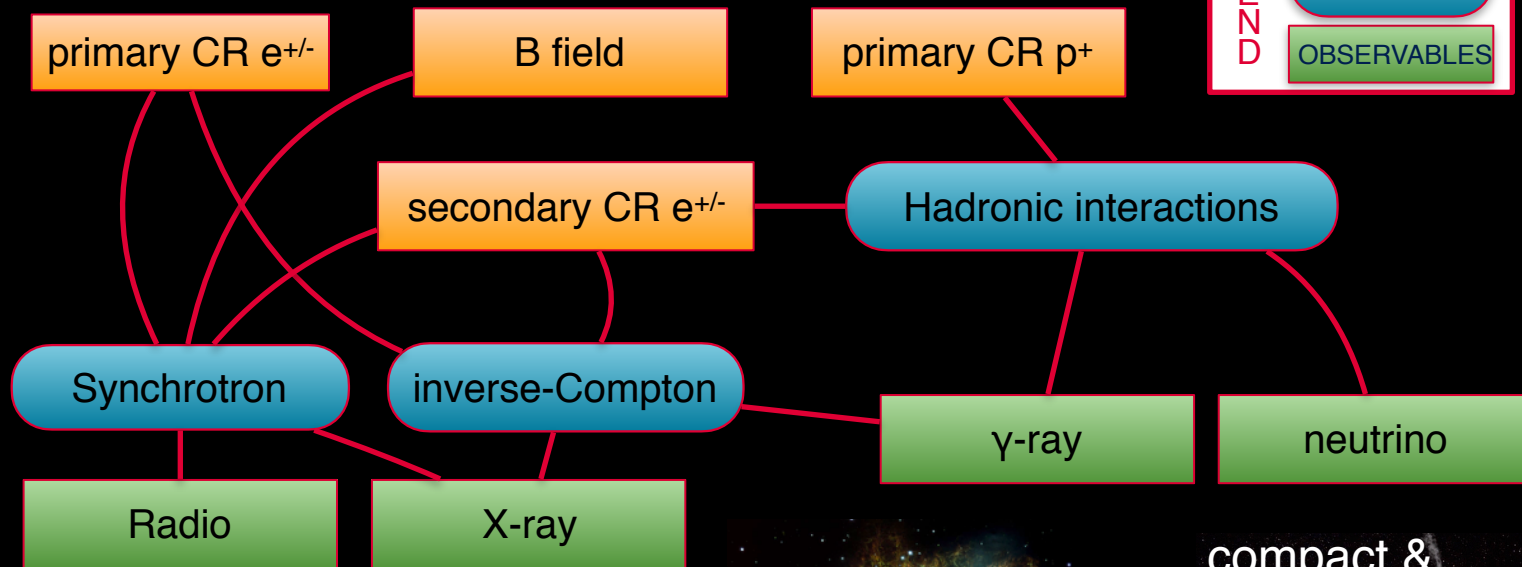
Ball

PWN



compact & non-compact

Binary



LEGEND

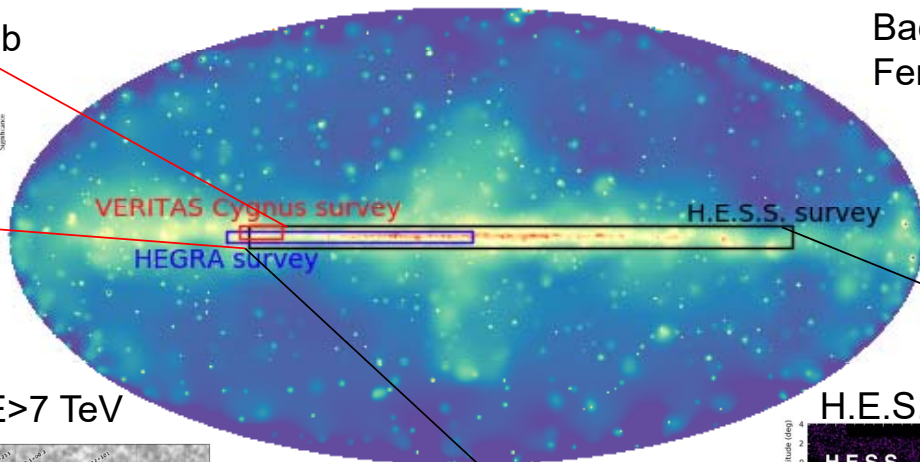
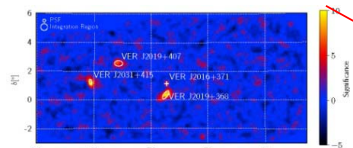
INPUTS

PHYSICAL PROCESSES

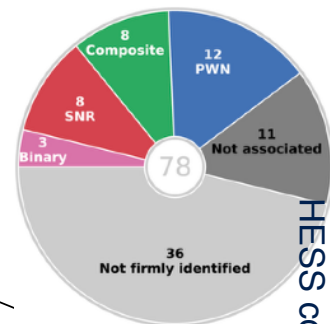
OBSERVABLES

Galactic Plane Survey

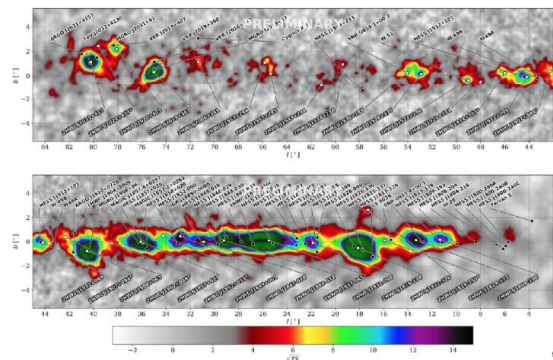
VERITAS ~2% Crab



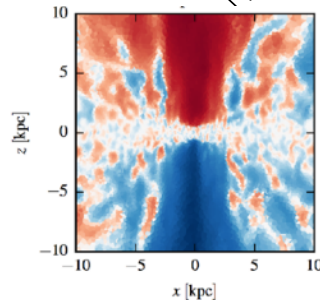
Background:
Fermi-LAT > 50GeV map



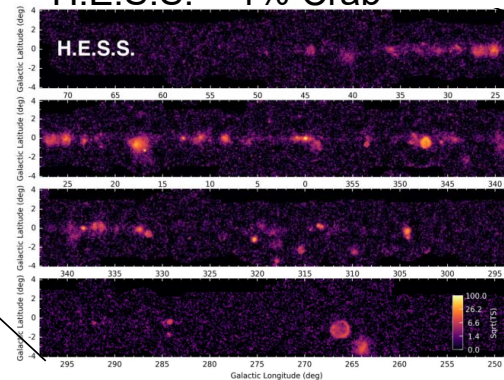
HAWC
Overhead sky, E>7 TeV



(Pfrommer et al., 2016)

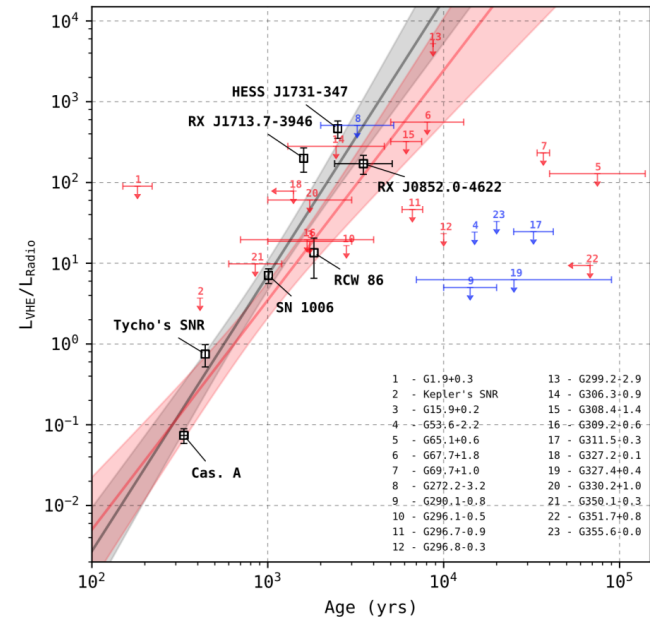
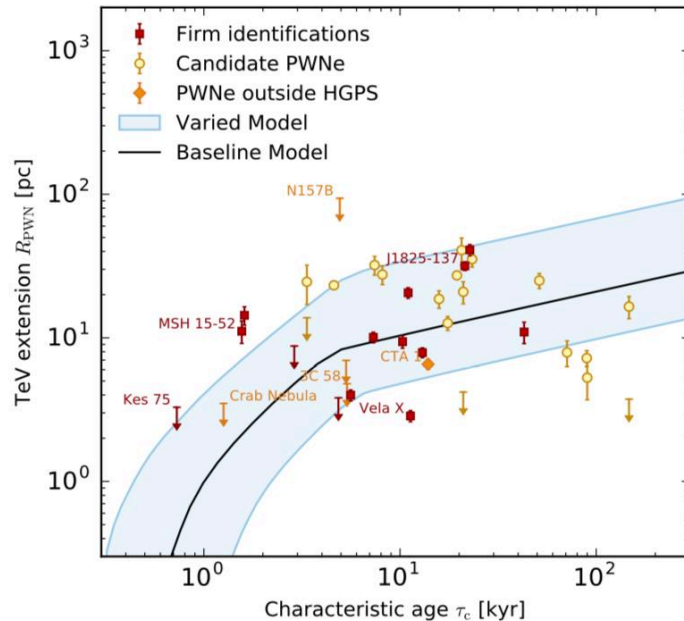


H.E.S.S. ~1% Crab



Galactic population studies

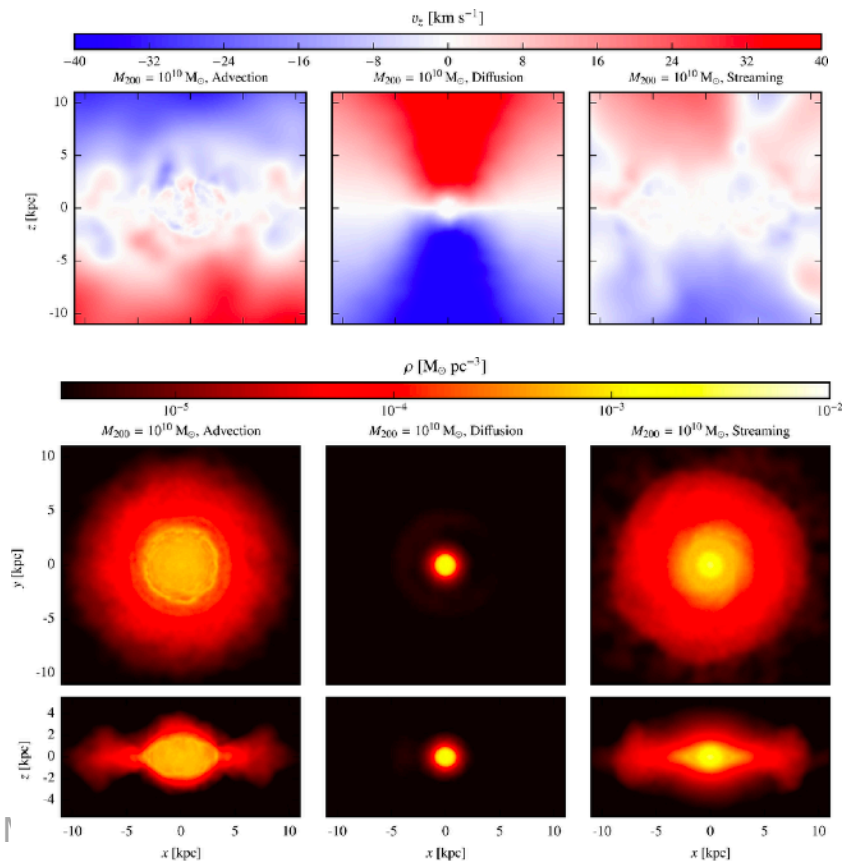
- The growing catalogue of Galactic TeV sources allows the first population studies of the properties and evolution of VHE emission from PWNe and SNRs



HESS collaboration, A&A 612 (2018)

Galaxy Evolution and CR Feedback

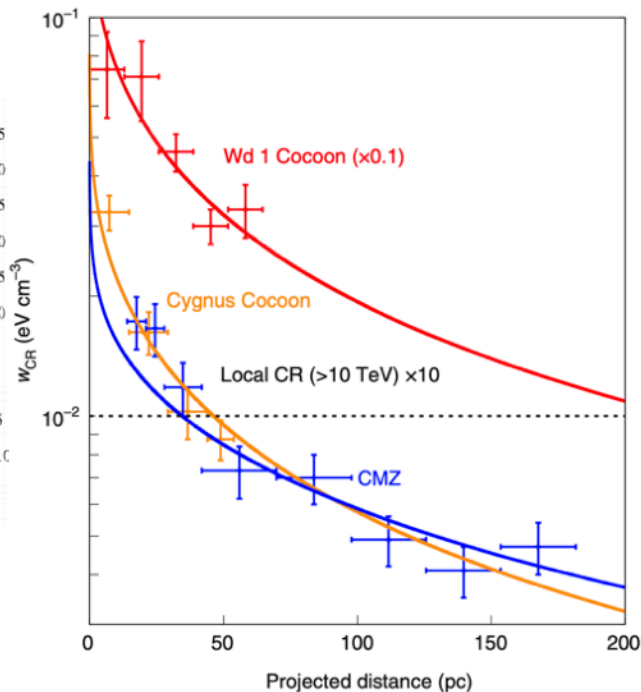
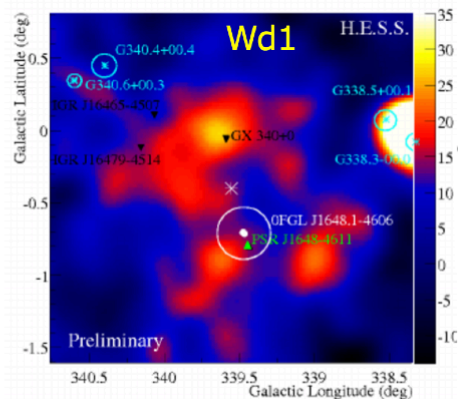
- Fermi Bubbles - prominent outflows seen in GeV gamma-rays
- Galaxy is dominated by low energy Cosmic Ray pressure
- CR pressure sufficient to launch Galactic wind and can drive gas away, limiting further star formation
- Mass loss of \sim few solar masses / yr comparable to star formation rate
- CR driven outflow can alter Galaxy morphology substantially



Star Forming Regions (SFR)

Investigating the relationship between:

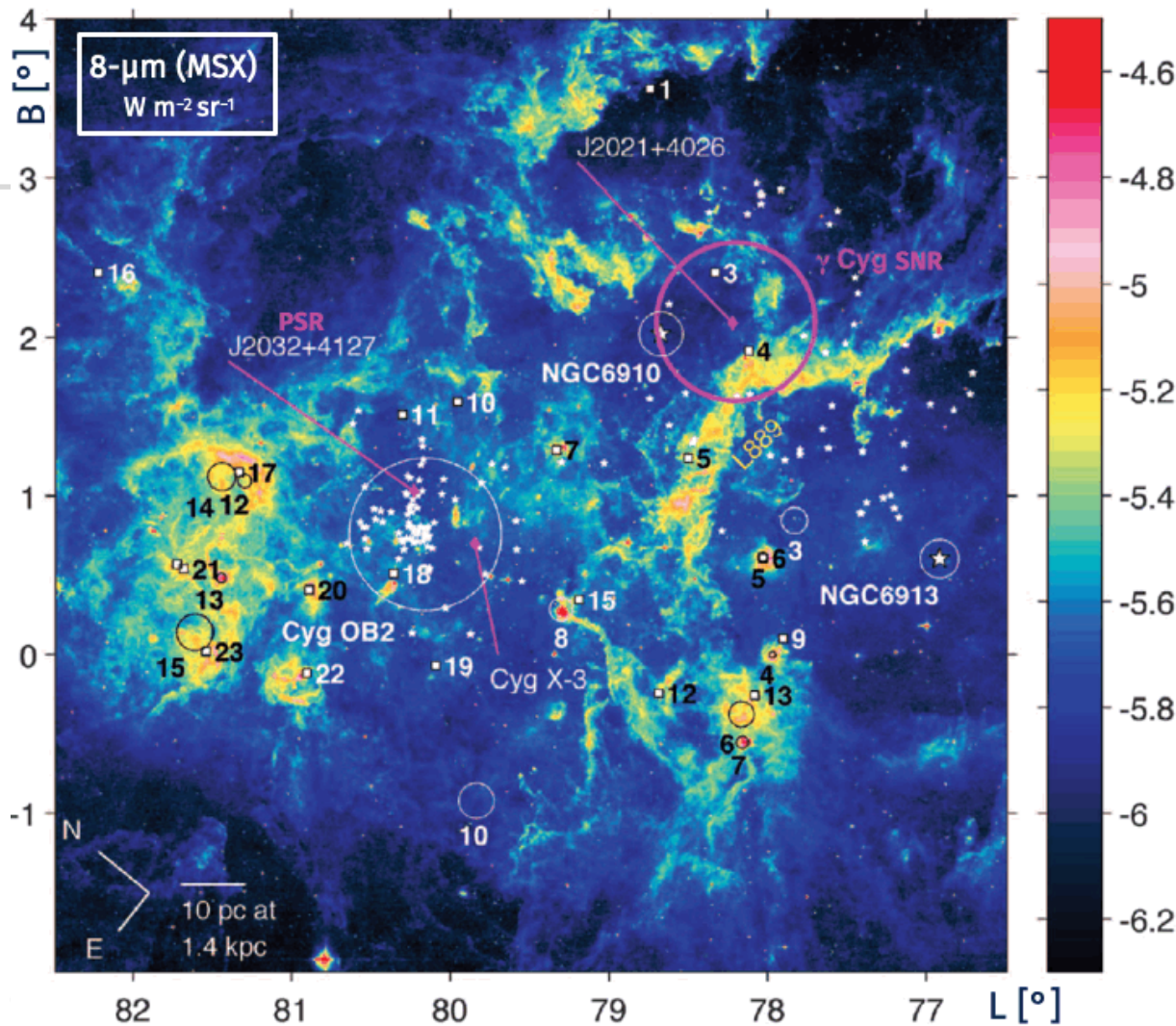
- star formation and γ -ray emission
- impact of CRs on their environment



Target	Exposure (hrs)	Array	Year	Zenith
Carina [†]	100	S	1 – 3	< 45°
Cygnus (OB1/OB2) [†]	130	N	1 – 2	< 50°
Wd 1 [†]	40	S	0 – 1	< 50°

Cygnus Region

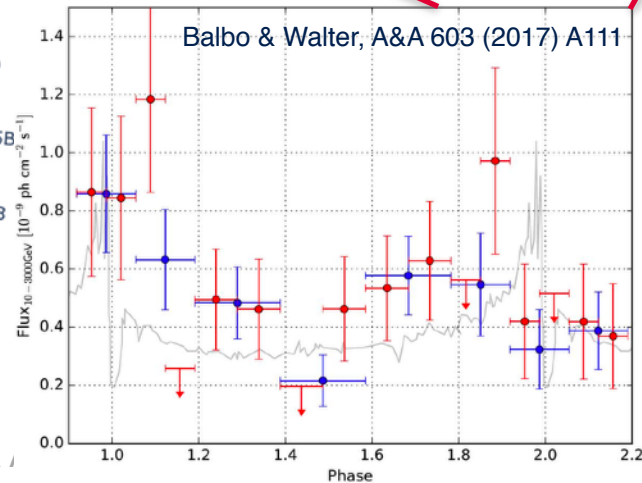
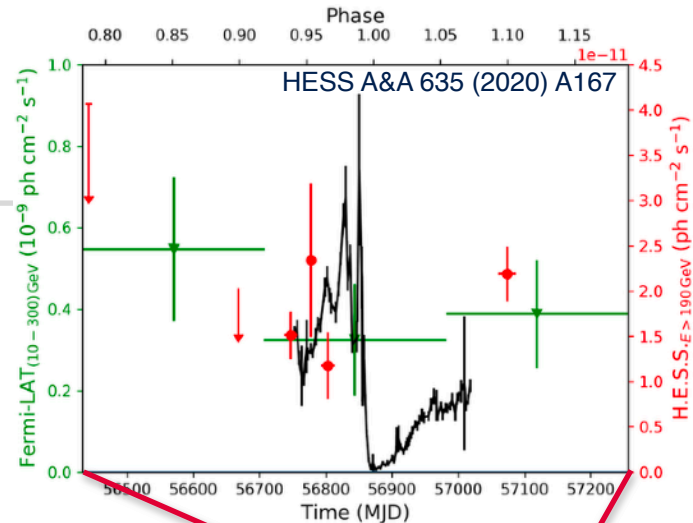
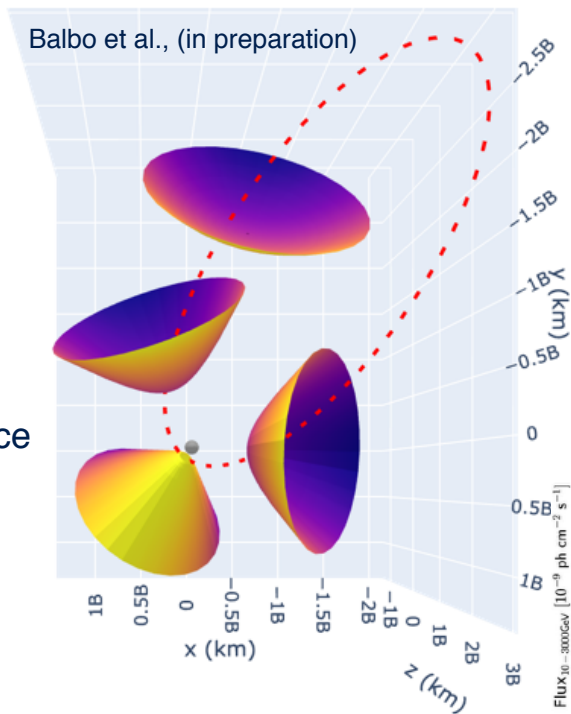
- Letter to Nature: 1972! First HE γ -ray from Cygnus & Cassiopeia (Browning et al.), OSO III satellite and balloon γ -ray experiment
- TeV J2032+4130 discovered by HEGRA: first extended TeV source without LE counterpart (Aharonian et al. 2002)
- Fermi-LAT detection of hard and extended GeV γ -ray emission in Cygnus
- “Cocoon” of freshly accelerated cosmic rays?
- Extent ~ 50 pc between OB2 and SNR Gamma Cygni
- Origin possibly attributed to Gamma Cygni or/and OB2?



γ -ray binaries ?

- accretion-powered jet
- pulsar wind
- colliding wind binary

- Eta Carinae: colliding wind binary
- Periastron passage (closest approach) every ~ 2023 days
- Spectrum:
 - X-ray thermal shocked gas
 - MeV-GeV: e^- IC
 - GeV-TeV: photo- π^0
- γ - γ absorption and its dependence on orbital phase:
 - ➔ crucial for understanding GeV/TeV emission
- CTA will confirm hadronic acceleration and pair creation

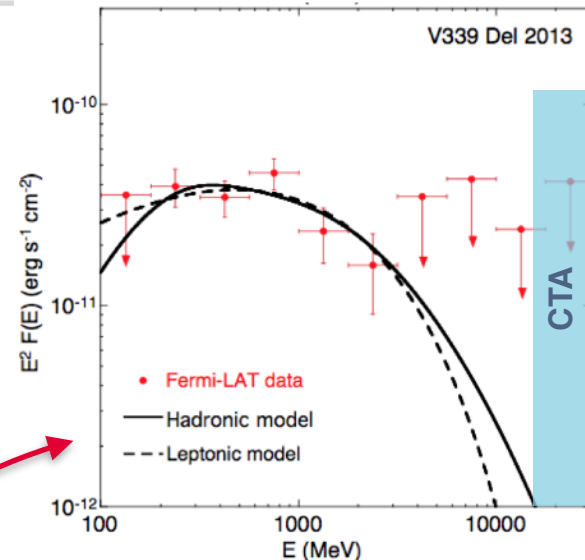
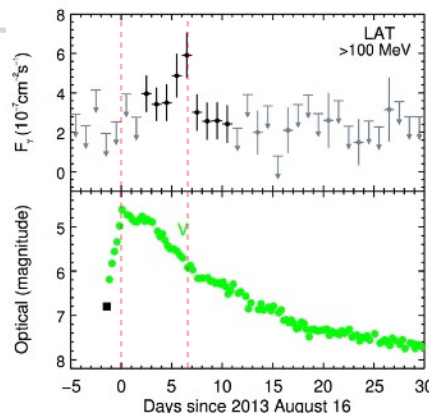
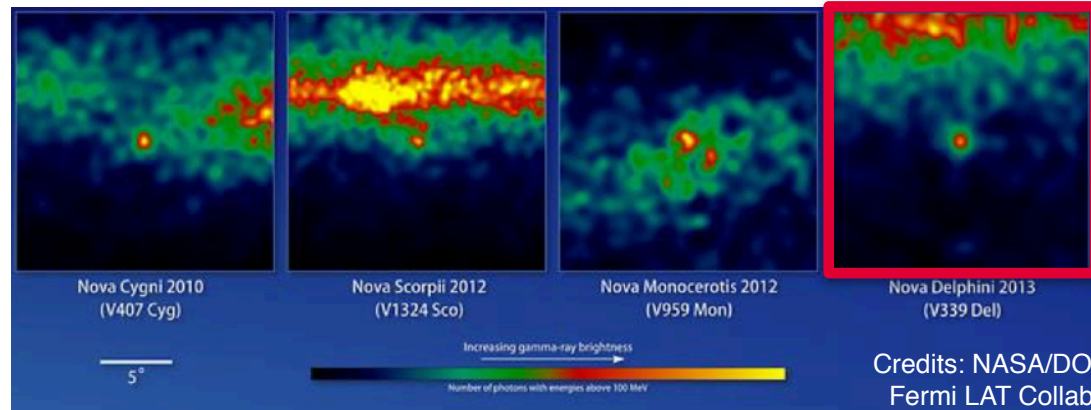


Other CWB candidates: γ^2 Velorum, WR147, WR125,...

Other binary γ -ray sources: Stellar Novae

Particles accelerated in multiple shock wave in the rapidly expanding debris shell

- VHE γ -ray upper limits from MAGIC
 - constraint on total luminosity of protons to $\leq 15\%$ of electrons



currently > 10 detected Novae in GeV by Fermi-LAT
—> not yet IACTs, CTA target?

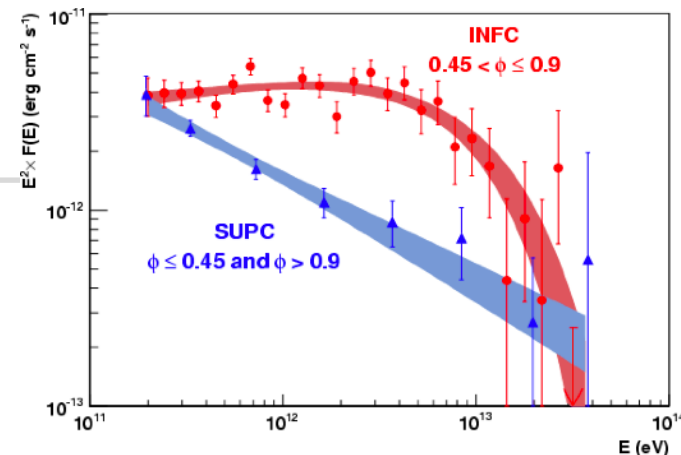
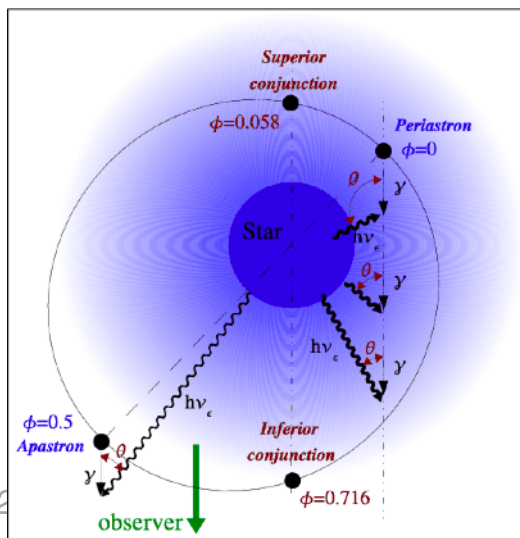
Credits: NASA/DOE
Fermi LAT Collab

Other binary γ -ray sources

X-ray binaries:

- compact neutron star or black hole
- Often with mass transfer from a donor companion
- Wide variety in system properties
- SS433 microquasar (eclipsing binary)

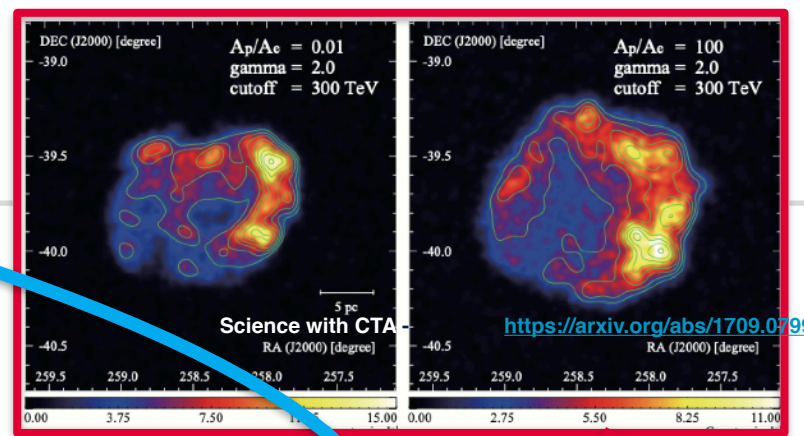
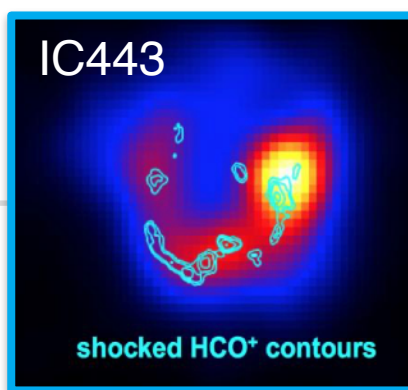
Aharonian et al., A&A 460, 743-9 (2006)



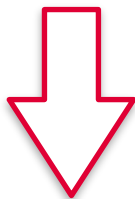
	PSR B1259-63 (*)	LS 5039 (†)	LS I 61° 303 (•)	HESS J0632+057 (◊)
P_{orb} (days)	1236.724526(6)	3.90603(8)	26.496(3)	315(5)
e	0.86987970(6)	0.24(8)	0.54(3)	0.83(8)
ω (°)	138.665013(11) (#)	212(5)	41(6)	129(17)
i (°)	$153.3^{+3.2}_{-3.0}$	13-64	10-60	47-80
d (kpc) ⁽¹⁾	2.39 ± 0.18	2.07 ± 0.22	2.63 ± 0.26	2.76 ± 0.34
Spectral type	O9.5Ve	O6.5V(f)	B0Ve	B0Vpe
M_* (M_{\odot})	14.2-29.8	23	12	16
R_* (R_{\odot})	9.2	9.3	10	8
T_* (K)	33 500	39 000	22 500	30 000
$d_{\text{periastron}}$ (AU)	0.94	0.09	0.19	0.40
d_{apastron} (AU)	13.4	0.19	0.64	4.35
$\phi_{\text{periastron}}$	0	0	0.23	0.967
$\phi_{\text{sup. conj.}}$	0.995	0.080	0.036	0.063
$\phi_{\text{inf. conj.}}$	0.048	0.769	0.267	0.961

Detectable SNRs

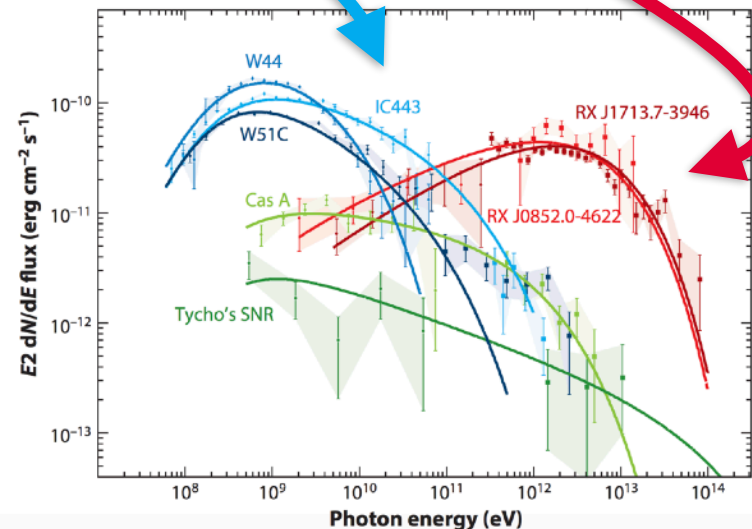
- CTA morphological studies:
 - extract gas target distribution
 - infer the production mechanism



γ -ray spectra cut-off at few 10s TeV



too low to explain the *knee* of the CR spectrum



Detectable SNRs

- CTA morphological studies:
 - extract gas target distribution
 - infer the production mechanism

...BUT...

HAWC J2227+610 (G106.3+2.7) :

- No cut-off up to 35 TeV (120 TeV if combined with VERITAS)
- if hadronic:
 - proton cutoff $E_c > 800$ TeV !

Galactic Pevatron!

- IceCube no detection so far

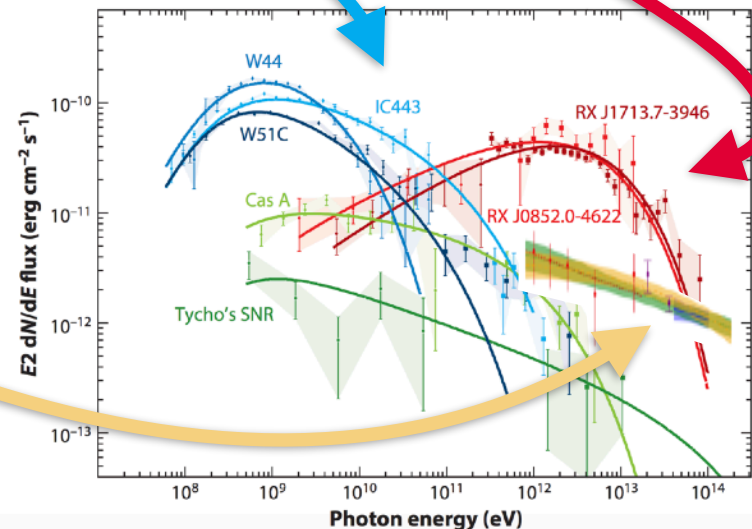
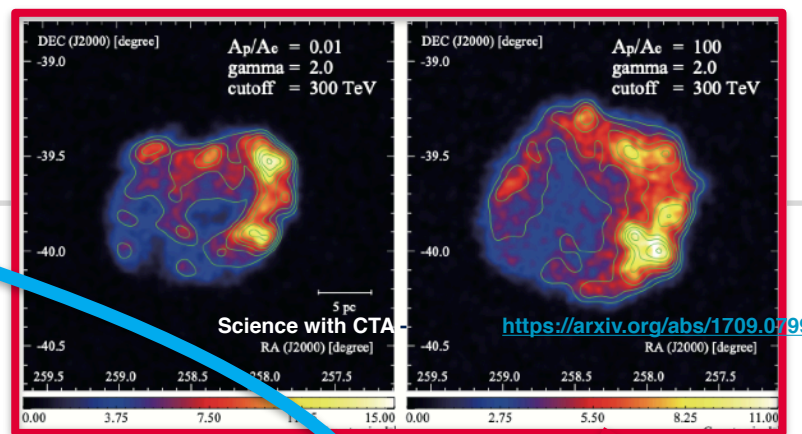
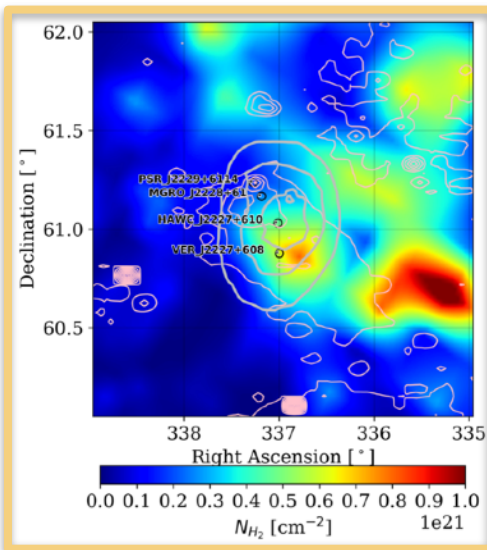
$$\frac{dN_{\nu\mu}}{dE_{\nu\mu}} = \frac{E_\gamma}{E_{\nu\mu}} \frac{dN_\gamma}{dE_\gamma}, \quad E_\gamma \approx 2 E_{\nu\mu}$$

- Observable by CTA North & LHAASO

IC443

shocked HCO^+ contours

[arXiv:2005.13699](https://arxiv.org/abs/2005.13699)

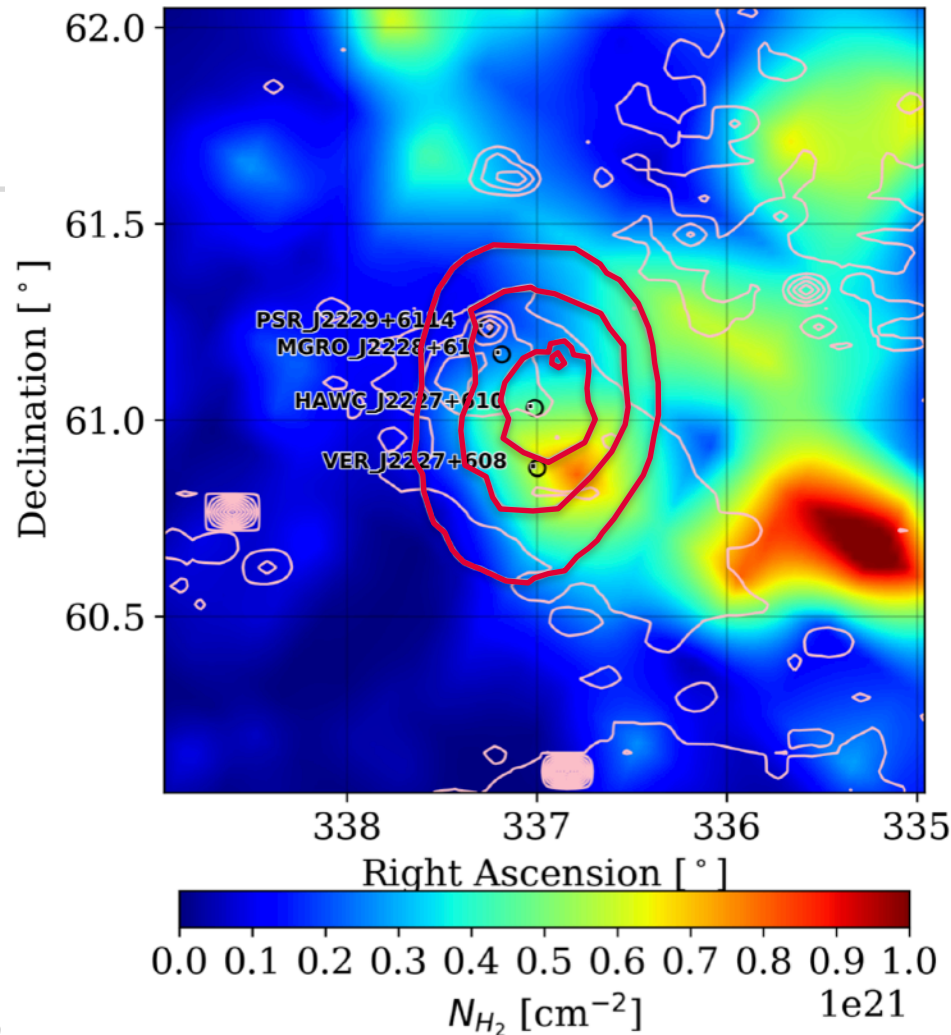


PeVatrons and mol. Clouds

HAWC J2227+610 (G106.3+2.7) :

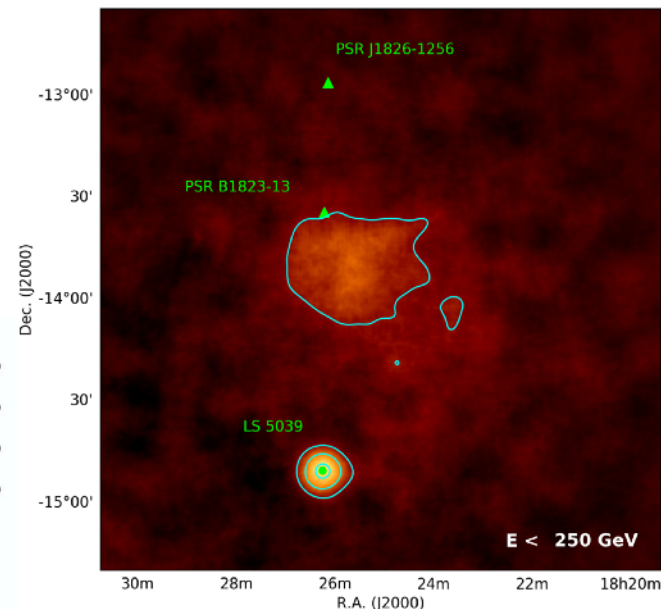
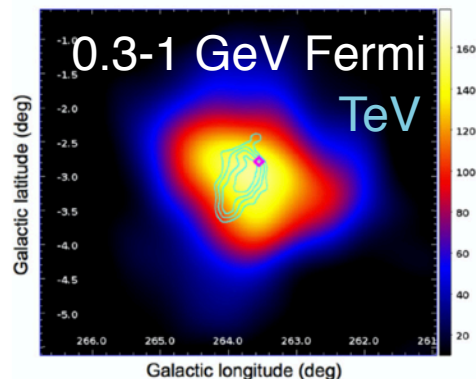
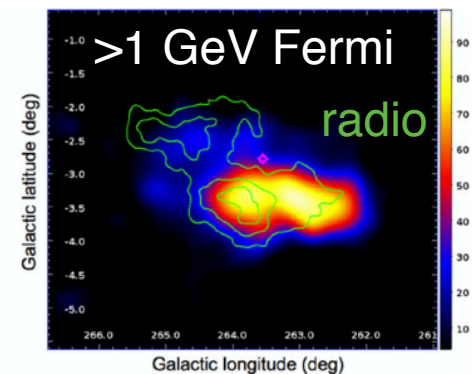
- molecular hydrogen column density (coloured-map)
- HAWC confidence region source position 1-2-3 σ (red contours)
- 1.4 GHz continuum brightness temperature CGPS from 1-100 K (pink contours)
- PSR + MGRO + HAWC + VERITAS centroids (black)
- Also detected in GeV Fermi-LAT data

- The highest energy particles **escape** the source region at early times.
- Hadronic gamma-ray emission will correlate with target material
- Look for mol. clouds near PeVatrons



Pulsar Wind Nebulae: Vela X, HESS J1825-137

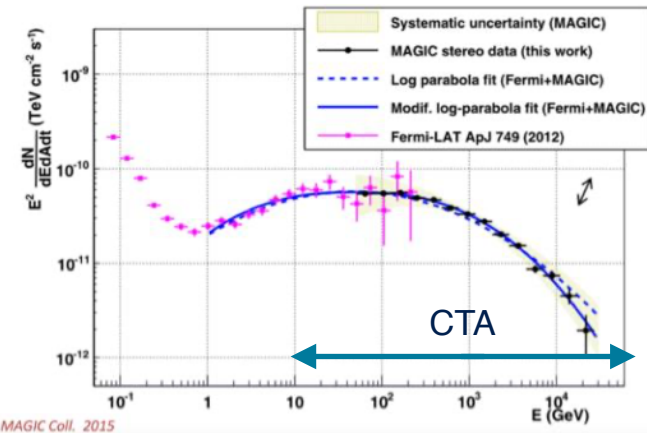
- **Vela X** morphology
 - ★ Radio & HE γ -rays: Halo (old population)
 - ★ X-rays & VHE: Cocoon (young population)
- Favours a 2-component model (de Jager et al. 2008)
- **HESS J1825-137** morphology
 - Strong energy dependence
 - Determine particle transport
 - Emission $> 100\text{TeV}$ seen by HAWC from region
 - Complex - nearby sources



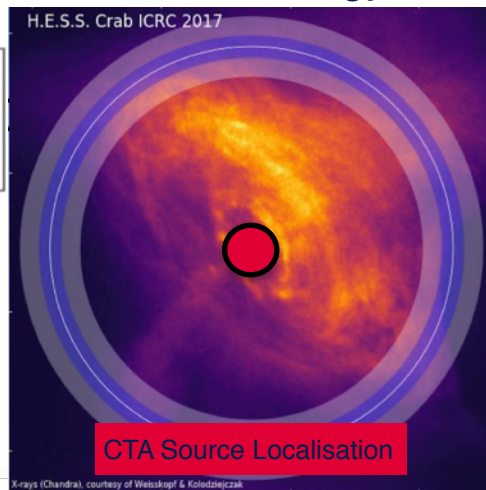
HESS collaboration A&A 621 (2019) A116

TeV γ -ray emission from the Crab Nebula

- First astrophysical TeV γ -ray source detected (Whipple Collaboration in '89)
- Emission is SSC of leptons accelerated near the termination shock of the pulsar wind
- Precision measurements by current generation IACTs:
 - The Crab emission is spatially resolved at TeV energies
 - The IC spectrum flattens in the low energy band of IACTs

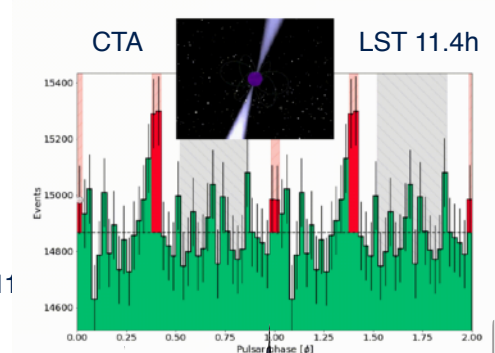
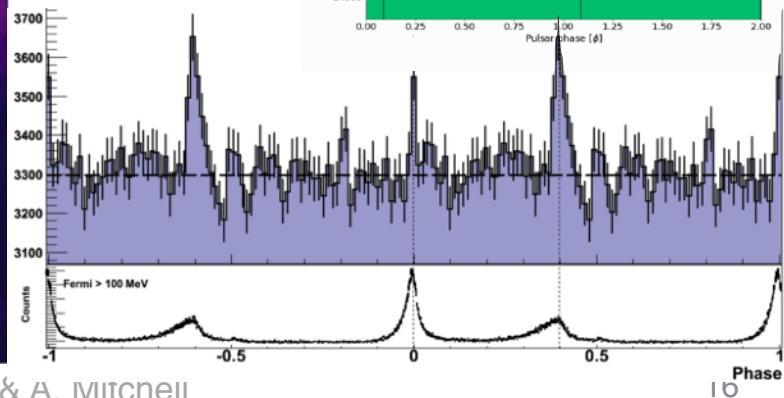


MAGIC Coll. 2015



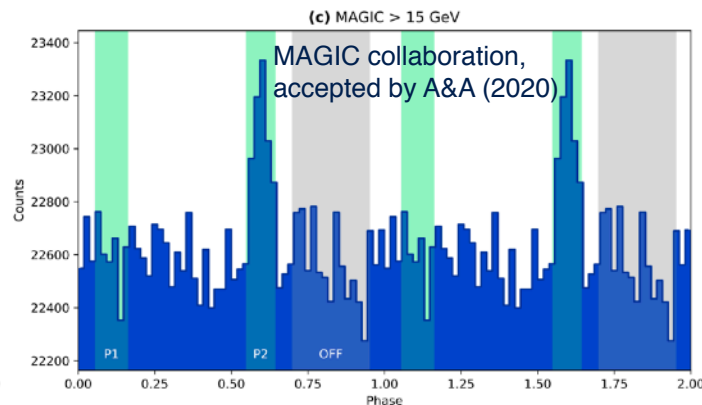
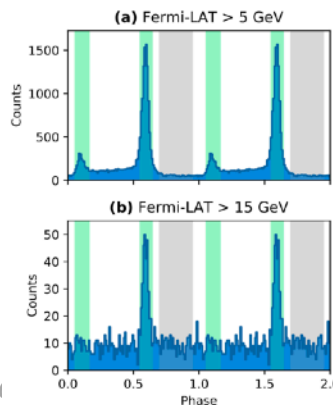
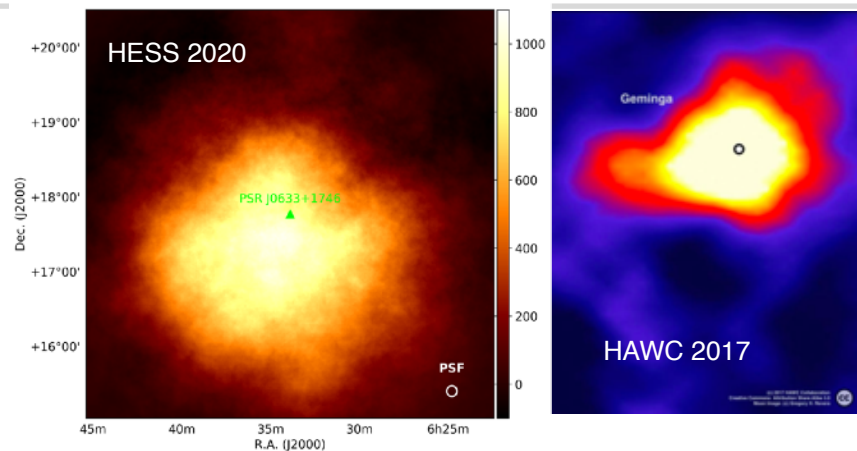
X-rays (Chandra), courtesy of Weisskopf & Kalodziejczak

VERITAS Collab,
Science, 334, 69, 2011



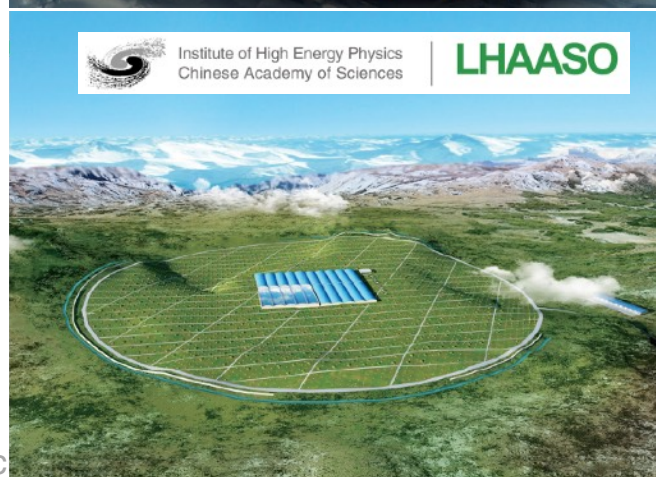
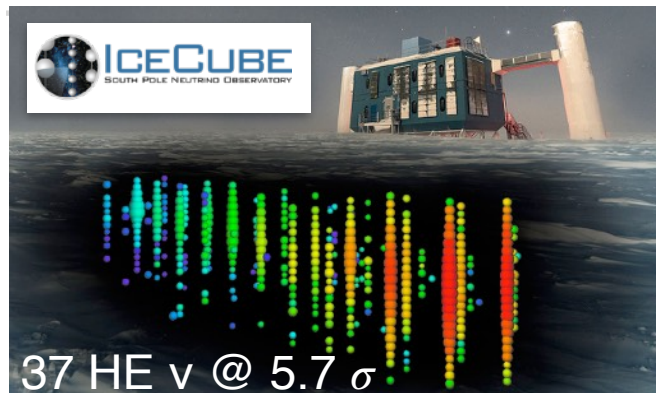
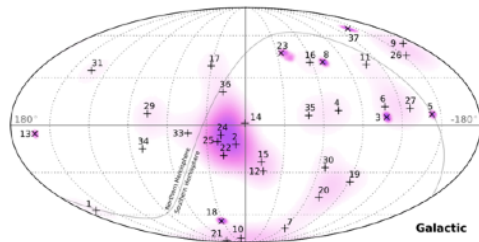
Geminga: an enigma

- Vela pulsar detected by HESS, Geminga pulsar detected by MAGIC
- Both pulsar and extended emission evaded detection for a long time
- Very nearby ~ 250 pc
- Escaping electrons and positrons form an extended halo of GeV and TeV gamma-rays
- Halos - a new source class?
- Recently detected by HESS, HAWC and Fermi-LAT
- Highly extended emission is now detectable by IACTs



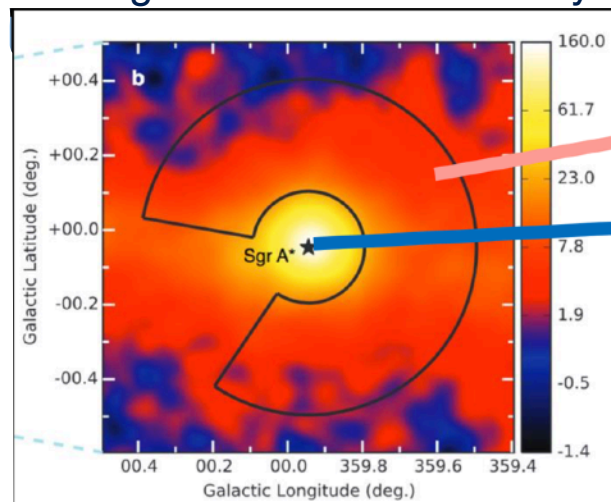
Synergies & multi-messenger observations

- Icecube
 - the presence/absence of neutrino could unambiguously claim/exclude hadronic particle acceleration
- LHAASO:
 - The most sensitive γ -ray instrument for energies > 100 TeV (big discovery potential)
 - ➔ Identify possible targets for deep observations
 - same latitude as CTA-North
 - ➔ Derive much better background and diffuse emission estimation (fundamental for morphological studies, SNR & SFR)
 - perfect complement to CTA:
 - LHAASO high sensitivity (CTA low sensitivity) for diffuse sources
 - LHAASO poor angular resolution (CTA high angular resolution) for morphology studies
 - Began scientific observations in 2019; construction works supposed to finish in 2021 (probably prolonged due to pandemic)

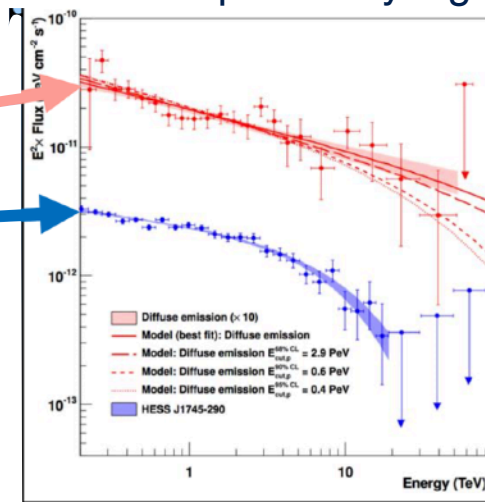


The Galactic Centre Region

- HESS detected a bright, steady TeV source, spatially coincident with SgrA*
- Diffuse emission is observed along the plane, within a few degrees of the GC
- The diffuse spectrum extends to 40 TeV with no cut-off
- Indicates presence of PeV particles, but not sufficient to explain Galactic CR flux
- Large zenith observation by northern instruments help to study highest energies



HESS Collab,
Nature 531,
476, 2016



- If emission is produced by hadronic interactions with molecular clouds: expect a neutrino counter-part

Summary / take home message

- The scope of Galactic science with CTA is rich and diverse
- Cosmic Rays are an important contribution to Galactic energetics: $1\text{eV}/\text{cm}^3$, comparable to CMB, starlight & radiation fields
- Multi-wavelength and multi-messenger astrophysics further enhances the discovery potential for PeVatrons and enables insights into unidentified sources
- Switzerland is involved in several current and future experimental facilities working towards a better understanding of the high energy universe (incl. HERD, AMS, DAMPE, MAGIC, IceCube, LHAASSO, CTA...)

