7th Heidelberg International Symposium on
High-Energy Gamma-Ray Astronomy (γ-2022)

Barcelona, 8 July 2022

Rapporteur: Galactic Science

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EXCELENCIA MARÍA DE MAEZTU

IEEC

OUTLINE

1. Disclaimer
2. Facilities
3. Binaries: RS Ophiuci, SS 433, gamma-ray binaries, CWBs
4. PeVatrons
5. Star Clusters
6. TeV Halos
7. SNR
8. Conclusions and outlook

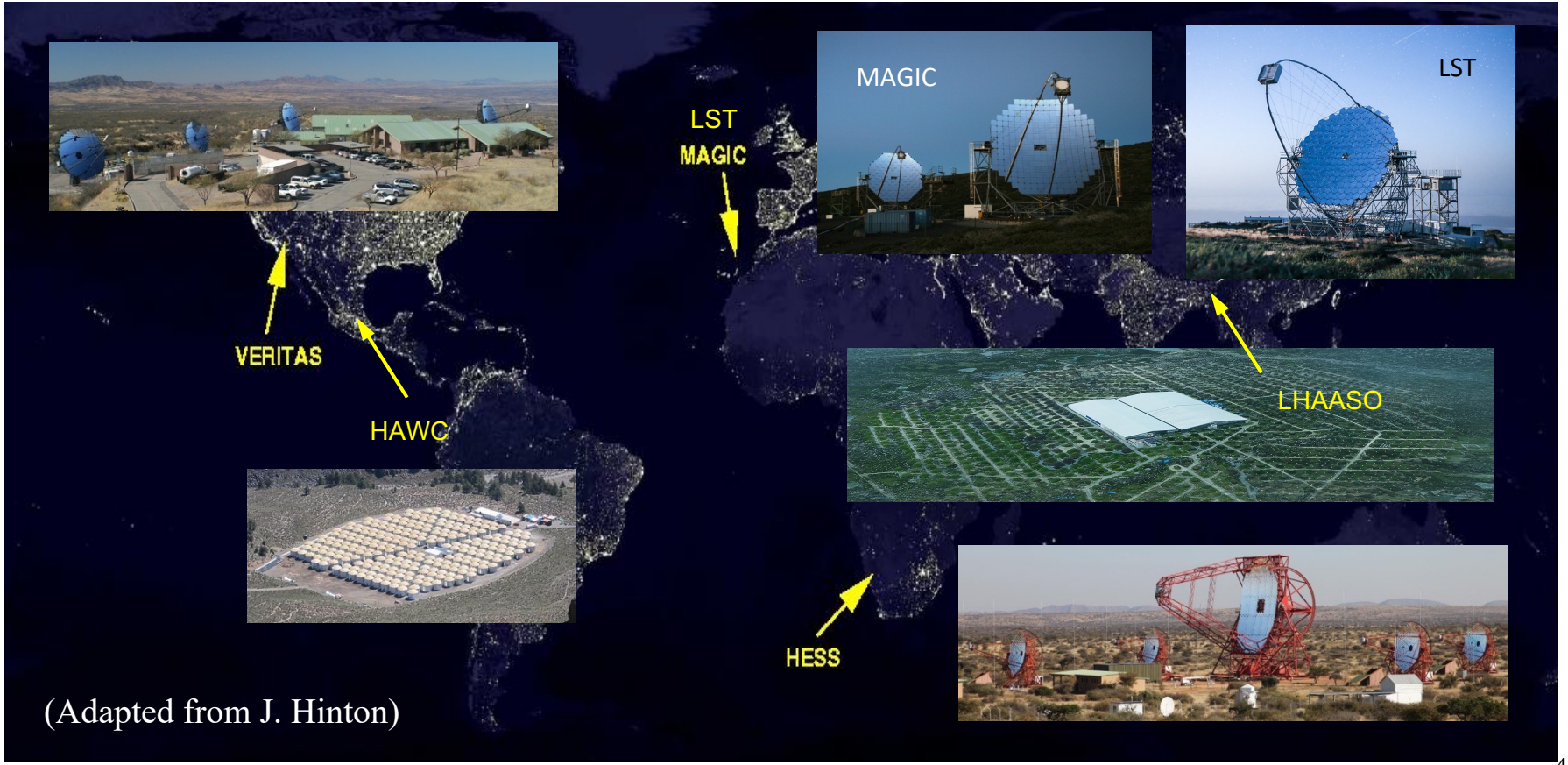
Disclaimer

Several items to be mentioned:

- Around **64 talks** contained Galactic science.
- This amounts to more than **18 h of talks**… to be summarized in **30 minutes**.
- Big **mistake**: accept being rapporteur while being organizer at the same time…
- … and getting convinced to play sports by PhD students…
- All days busy! Welcome reception on Monday, sports on Tuesday, dinner on Wednesday… everything to be done on Thursday night!
- Anyway, this is my **personal choice**, so don't feel bad if your work is not highlighted.
- **Excellent Galactic scientific results** were presented during the meeting !!

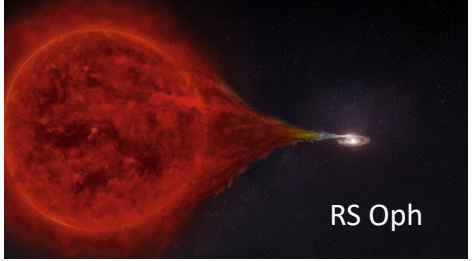
Facilities

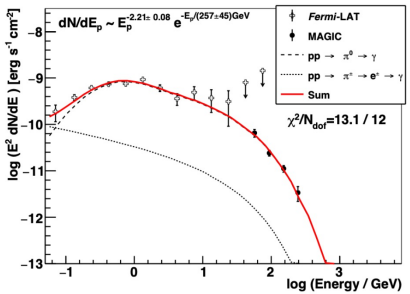
TeV energies: usual players and new players (LHAASO, LST, etc.).

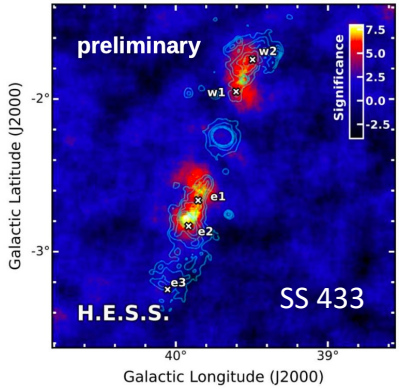


Facilities

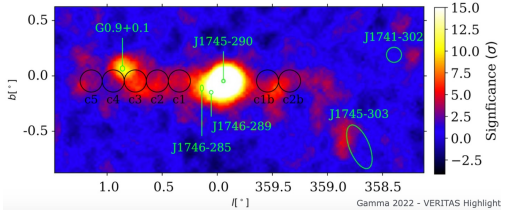
Reports by Collaborations.



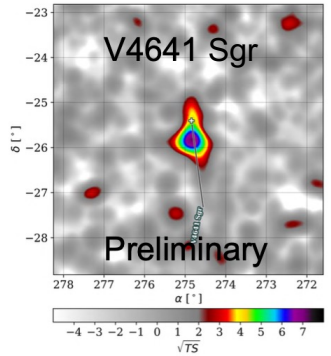




- **MAGIC**: **Oscar Blanch Bigas** (RS Oph, Geminga, Binaries, etc.).
- **HESS**: **Stefan Wagner** (RS Oph, SS433, PeVatrons, etc.).
- **VERITAS**: **John Quinn** (PeVatrons, Galactic Center, Binaries, etc.).



- **HAWC**: **Jordan Goodman** (PeVatrons, Binaries, V4641 Sgr, etc.).
- **LHAASO**: **Zhen Cao** (PeVatrons candidates everywhere!).
- **LST**: **Juan Cortina** (Crab Nebula & pulsar, RS Oph, PeVatrons, etc.).



Facilities

Plus all the multi-wavelength ground-based and space-borne facilities.

- **Radio**: single dish or interferometers up to VLBI, spectral lines and continuum, total flux and polarization, timing mode (JVLA, VLBA, EVN, Mopra, Nanten, CHIME, etc.).
- **Infrared**: near, medium and far (ground telescopes, *Spitzer*, *WISE*, etc.).
- **Optical**: photometry, spectroscopy, polarization (many different telescopes).
- **X rays**: soft, hard (*Chandra*, *XMM-Newton*, *NuSTAR*, *INTEGRAL*, etc.). Soon polarization (*IXPE*).
- **The MeV gap**… (put here any of your favorite names and delete it 2 years later: Astrogam, etc…).
- **HE gamma rays** (*Fermi*/LAT, *AGILE*, etc.).

Facilities

Plus multi-messenger facilities:

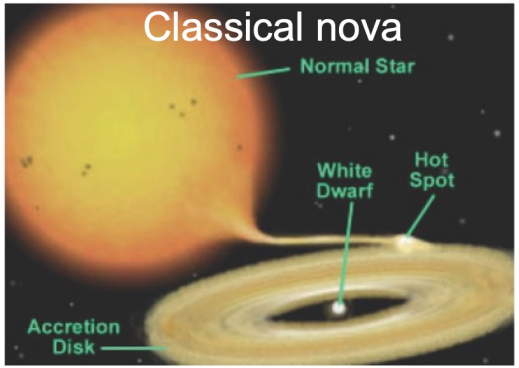
- **Neutrinos**: to test hadronic models (IceCube, ANTARES, etc). **Teresa Montaruli**, **Elisa Resconi**.
- **Gravitational Waves**: to search for space-time ripples (LIGO, Virgo, KAGRA). Run O4 approaching (and receding…). **Marica Branchesi**.
- **CR detectors**: to learn more Galactic physics (AMS, etc.). **Eun-Suk Seo**.

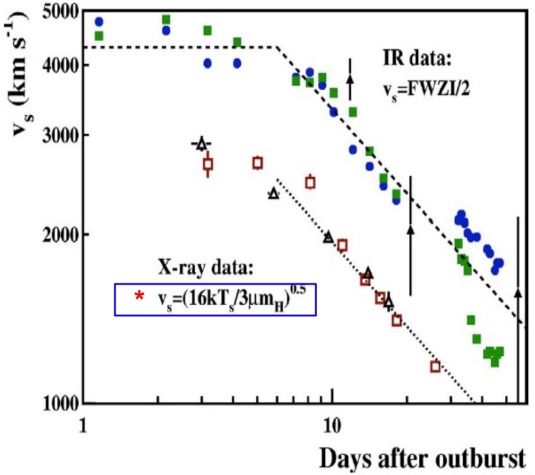
To understand Galactic TeV sources we need at least the whole multi-wavelength picture to test possible models.

Multi-messenger facilities to complement the information.

Binaries: RS Ophiuci

Good introductory talk on **Novae** by **Margarita Hernanz**.

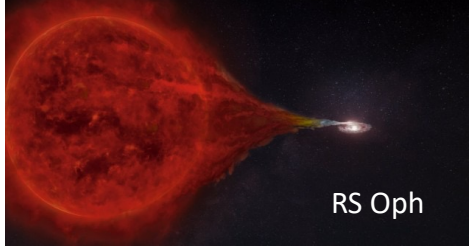




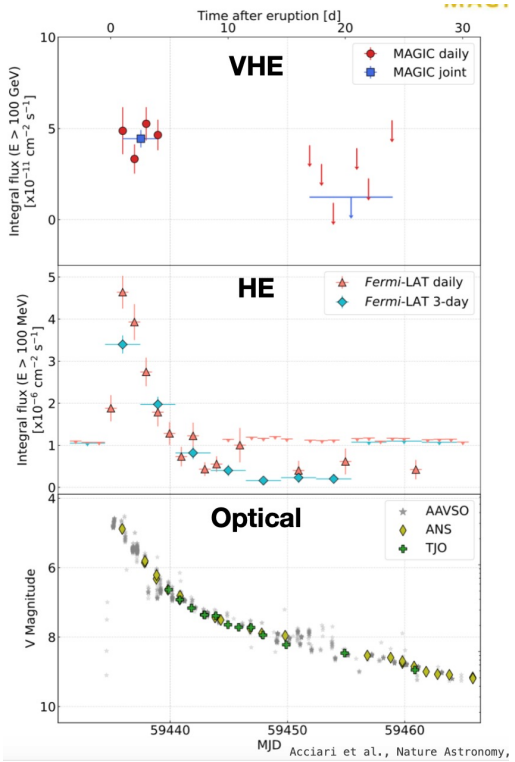
- Particle acceleration in strong external shocks between ejecta and circumstellar material (or internal shocks within the ejecta):
  - red giant wind in symbiotic recurrent nova
  - "dense circumstellar matter"
  - IC (leptonic) or π^0 decay (hadronic) ➔ photons with ***E>100 MeV***
  - detected with *Fermi/LAT* (now in several novae) - and also in VHE γ-rays in **RS Oph in 2021 (MAGIC, HESS, ...)**

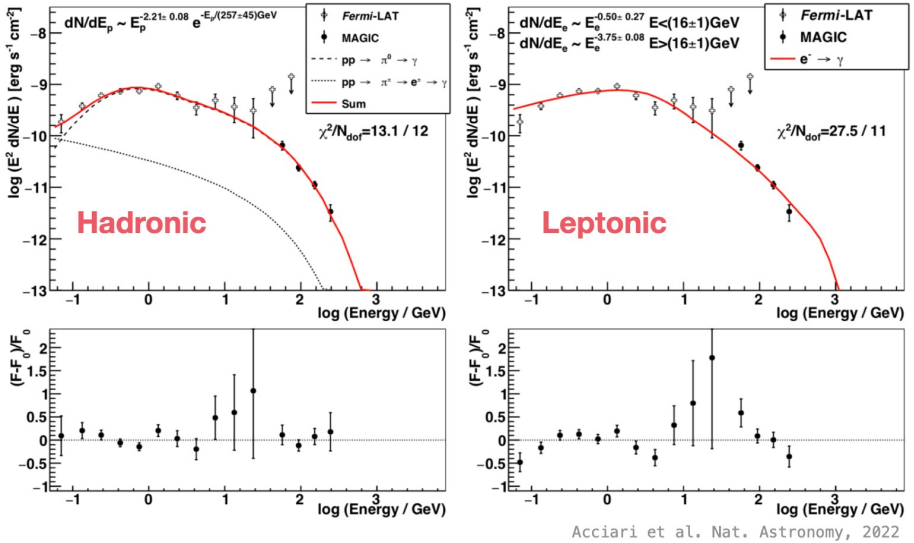
The different velocities & decay times indicated **efficient particle acceleration**: prediction of HE gamma rays (Tatischeff & Hernanz 2007).

Binaries: RS Ophiuci



MAGIC (+*Fermi*) view by **Alicia López-Oramas**.





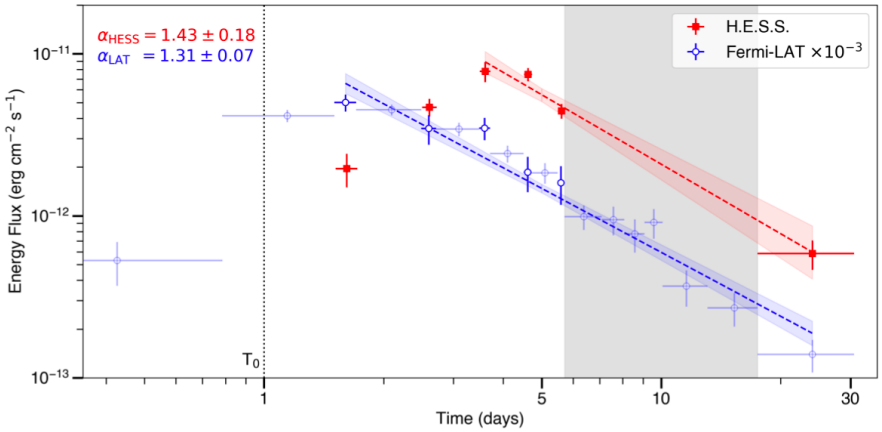
Different arguments favor **proton acceleration**:

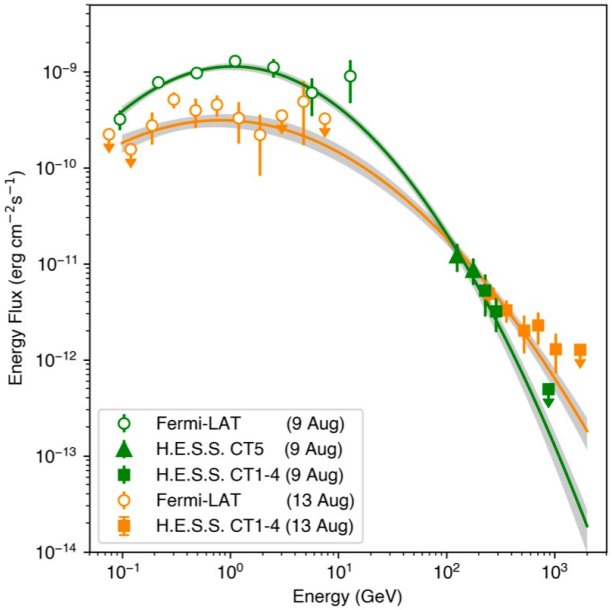
- Flux evolution at different wavelengths.
- Spectral fitting at different epochs.
- Acceleration and cooling timescales.

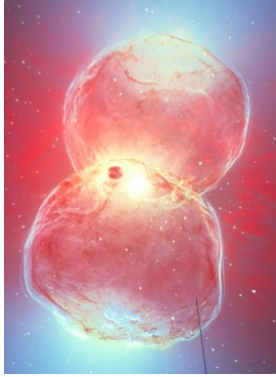
Bubbles of increased CR density.

Binaries: RS Ophiuci

H.E.S.S. (+*Fermi*) view by **Simon Steinmassl**.



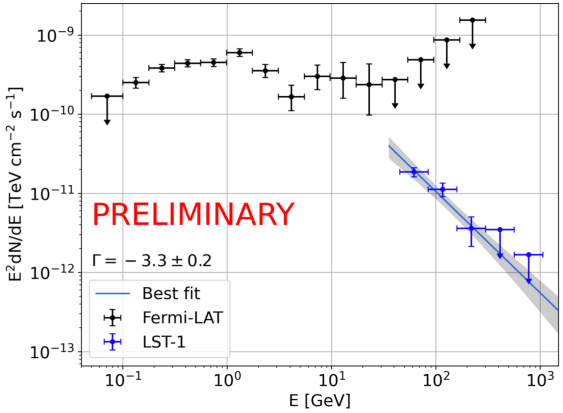


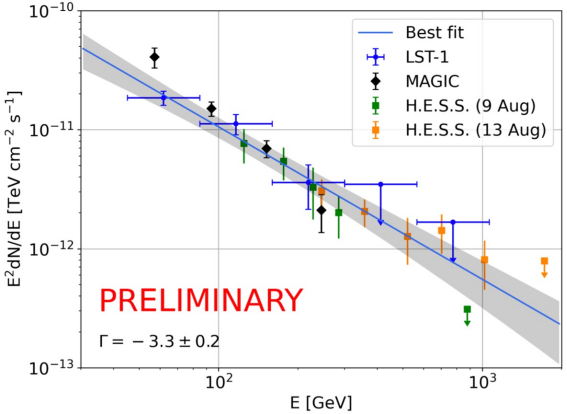


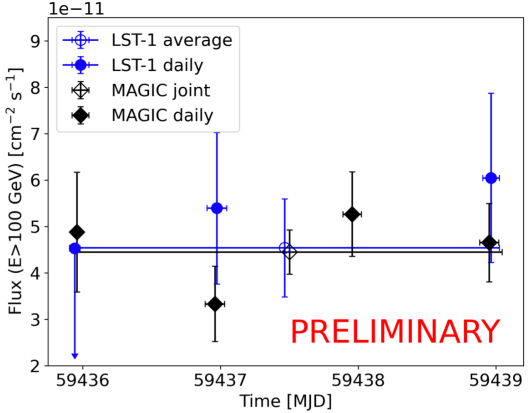
- First nova seen in the VHE regime - hopefully more to come!
- Strong signal allows time resolved analysis
- Combined Fermi & H.E.S.S. analysis suggests single component for gamma rays
- Gamma ray emission with
  - Most likely hadronic origin
  - Extremely efficient acceleration to $E_{max} \approx 1 - 10$ TeV

Binaries: RS Ophiuci

LST (+*Fermi*) view by **Arnau Aguasca-Cabot**.



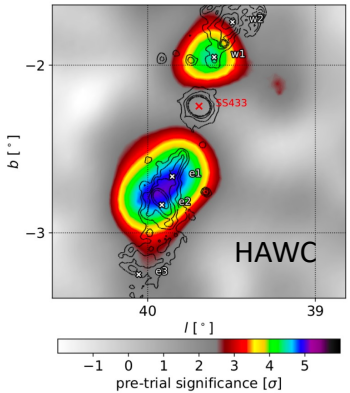


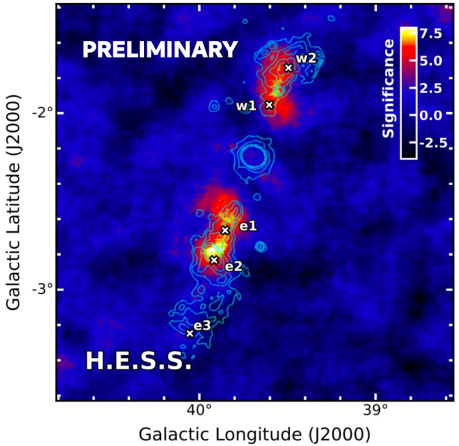


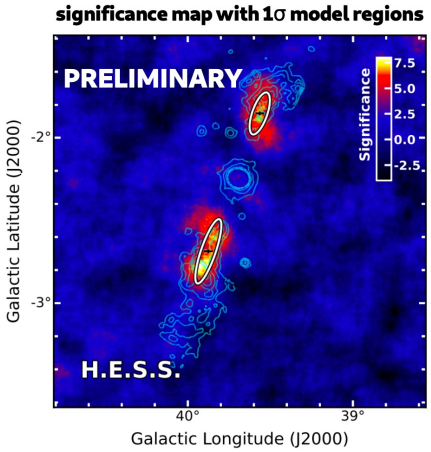
- Clear detection of RS Ophiuchi by LST-1 after 6.4 h of observations. Significance of ~ 7.5 sigma
- LST-1 allows us to study RS Ophiuchi down to ~45 GeV
- Preliminary results compatible with MAGIC/H.E.S.S. results
- LST-1 has exceptional capabilities for transient source studies below 100 GeV

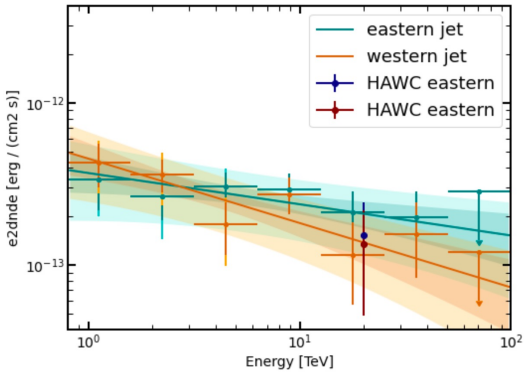
Binaries: SS 433

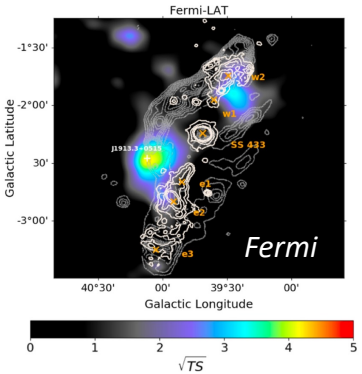
H.E.S.S view by **Laura Olivera-Nieto**.







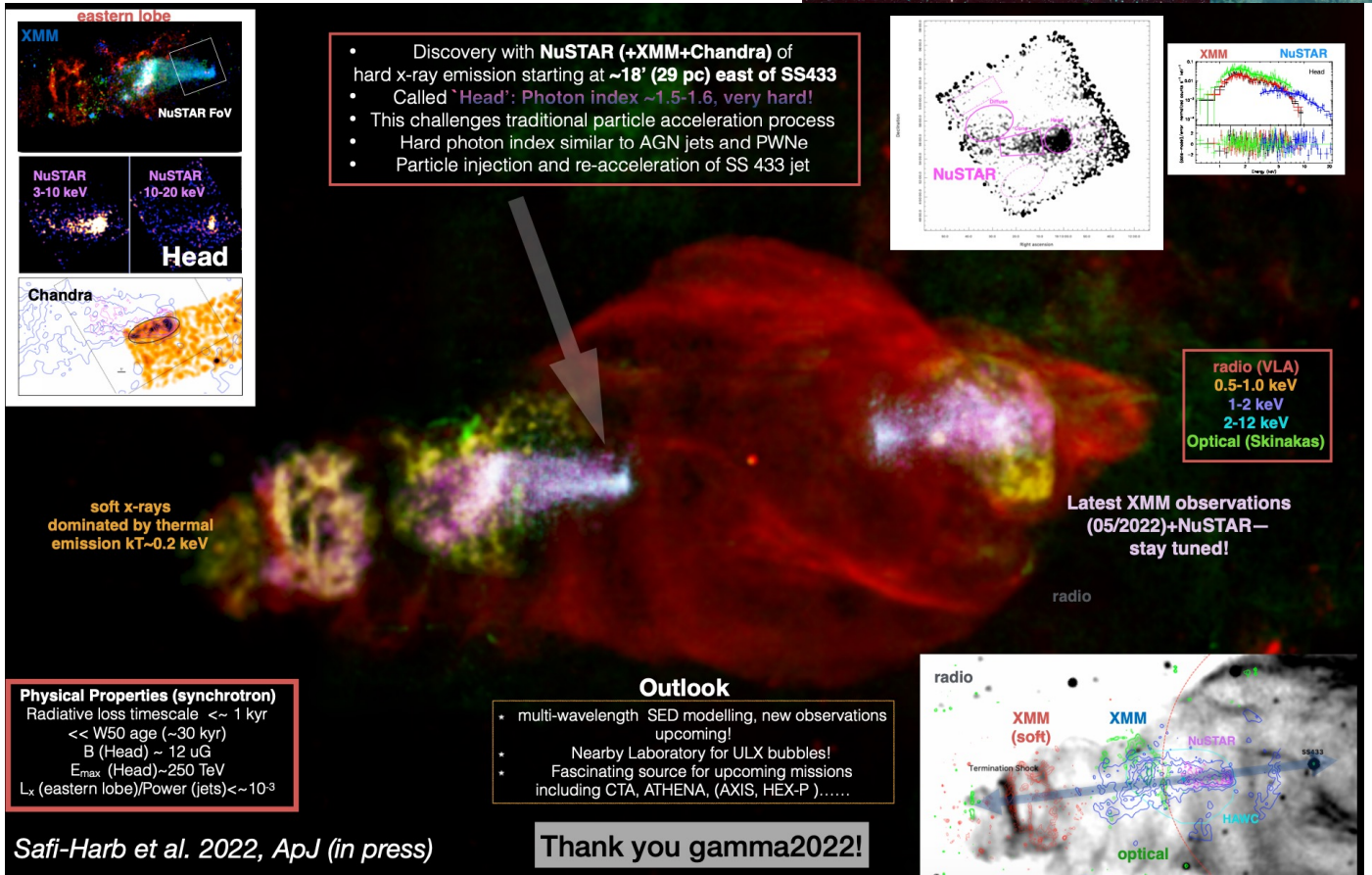




- Confirmation of TeV emission from the jets of SS 433 following HAWC discovery. First detection by an IACT array.
- Better energy and spatial resolution → more detailed characterization!
- Measured spectra between 0.8 TeV and 50 TeV, UL in 50-100 TeV range.
- TeV spectra from both jets remarkably consistent.
- Spatial properties consistent with the extended x-ray jets.

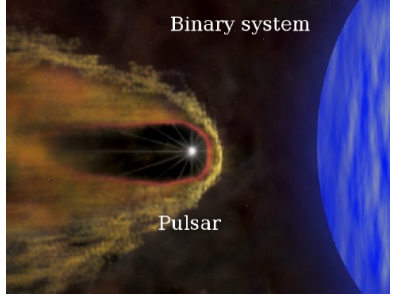
Binaries: SS 433

X-ray view by **Samar Safi-Harb**.



Binaries: gamma-ray binaries

LS I +61 303 pulsations by **Diego F. Torres**.

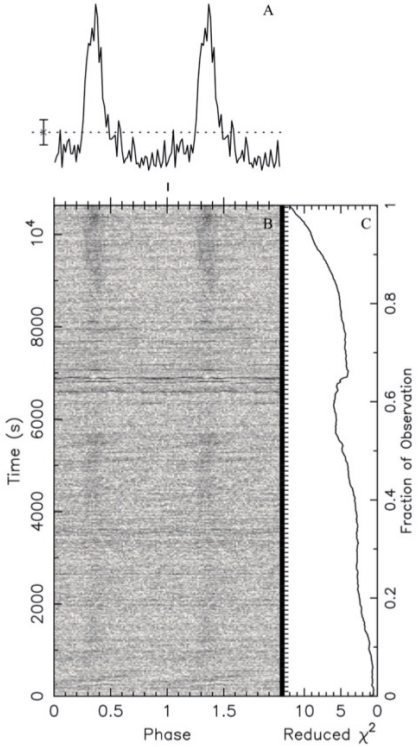


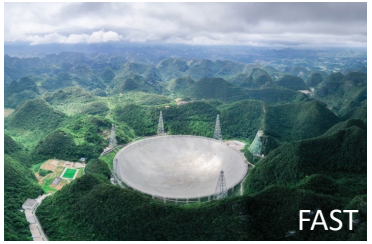
PSR B1259-63
PSR J2032+4127

?
LS 5039
LS I + 61 303
HESS J0632+057
1FGL J1018.6-5856
4FGL J1405.1-6119
HESS J1832-093
LMC P3

Check careful update on gamma-ray emitting binaries by **Pol Bordas**.

Also, **theoretical talk** by **Valentí Bosch-Ramon**.





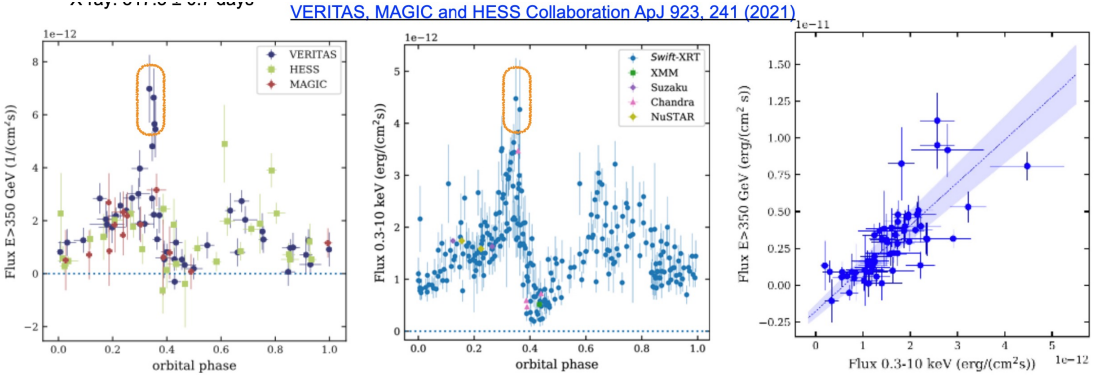
- 269 ms pulsations, same DM of 240 pc cm^{-3}.
- The pulsation appears to be non-steady in nature.

	Mid of observation time	Orbital phase	Exposure Time/h	Sampling Time/μs	Pulse detected	$S_{mean}/S_{UL}/\mu$Jy
11-01-2019	58,788.7257	0.07	2.2	98.304	No	–/1.61
01-07-2020	58,855.5278	0.59	3.0	98.304	Yes	4.40/1.37
09-01-2020	59,093.8646	0.58	3.0	196.608	No	–/1.37
09-02-2020	59,094.8681	0.62	2.0	196.608	No	–/1.68

- LS I +61 303 is the first system containing a pulsar behaving as a magnetar.
- The period found is consistent with the flip-flopping system.
- New observations ongoing.
- Aim to understand better the cause of the turning off of the pulsar and characterize its behavior.

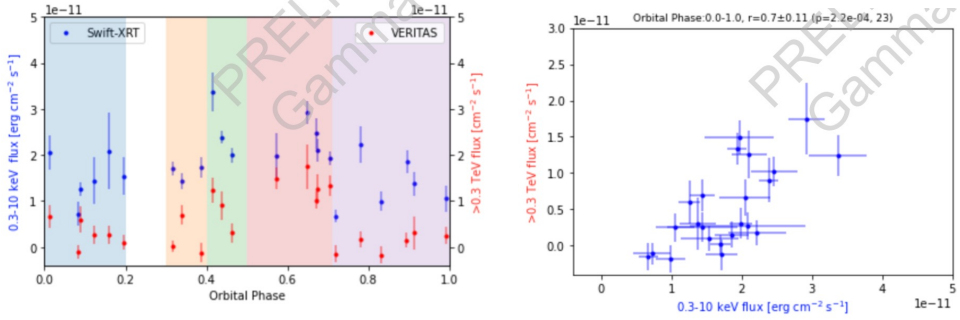
Binaries: gamma-ray binaries

VERITAS, MAGIC, H.E.S.S view of HESS J0632+057 by **Sonal Ramesh Patel**.



X-ray/TeV correlation indicates common population of particles (synchrotron and IC).

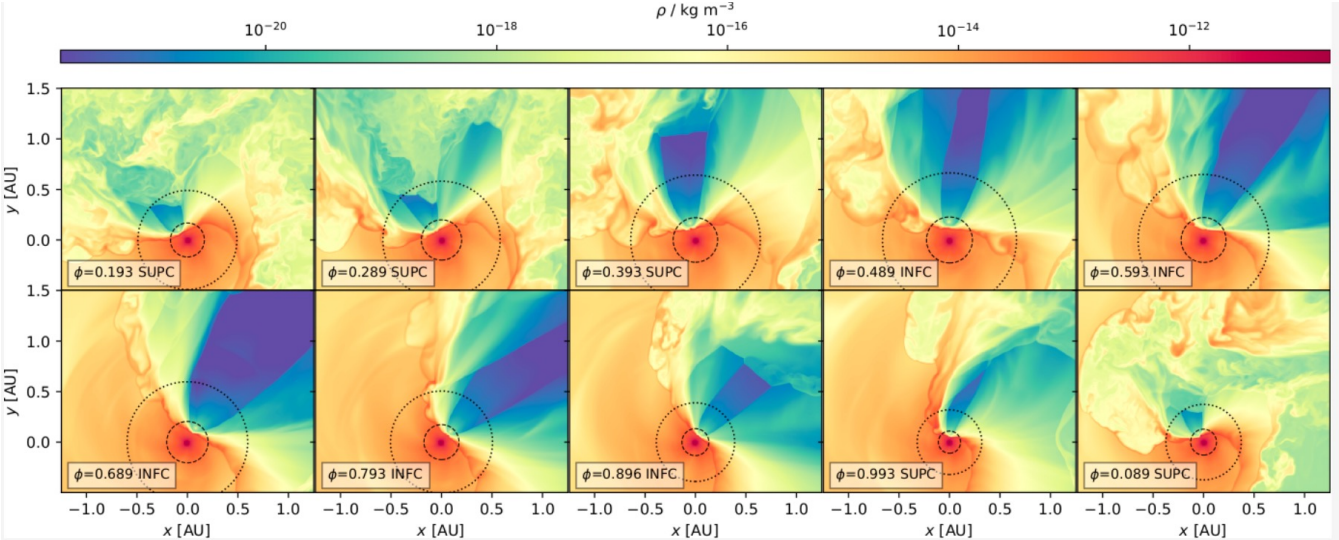
VERITAS view of LS I +61 303 by **Sonal Ramesh Patel**.



X-ray/TeV correlation found only with data within 0.5 h (not within 24 h). Again, could be common population of particles (see Anderhub et al. 2009 for earlier MAGIC results).

Binaries: gamma-ray binaries

Simulations of LS 5039 HE/VHE emission by **Ralf Kissmann**. 3D relativistic hydrodynamics.



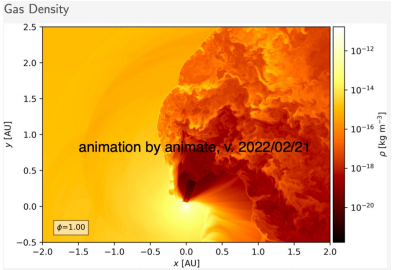
(Huber et al. (2021))

Issues

- Need hard spectral index (1.5)
- Wrong phase dependence at low energies → magnetic field?
- Magnetospheric emission?
- Partly missing Coriolis shock

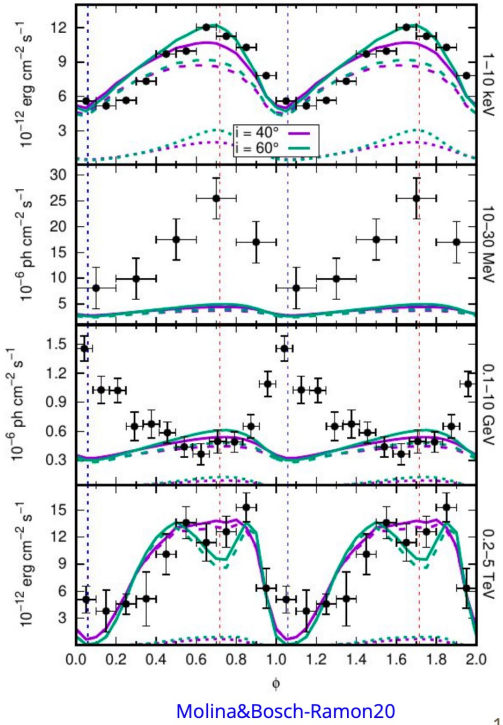
Current Status

- Coupled RHD plus transport
- Pulsar-wind scenario
- Currently: higher-resolution model
  - Post processing
  - Analysis of RHD winds
- Future: Magnetic field!

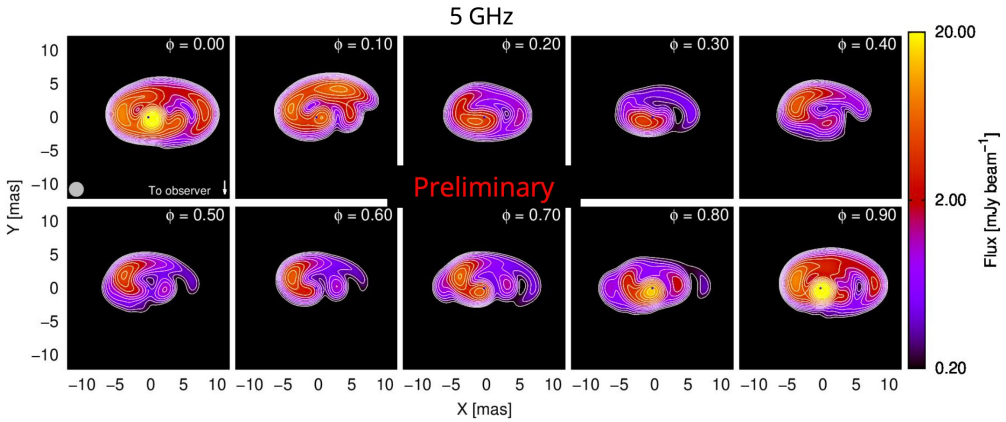


Binaries: gamma-ray binaries

Simulations of LS 5039 MW emission and radio images by **Edgar Molina**.
Analytical modelling.



Molina&Bosch-Ramon20



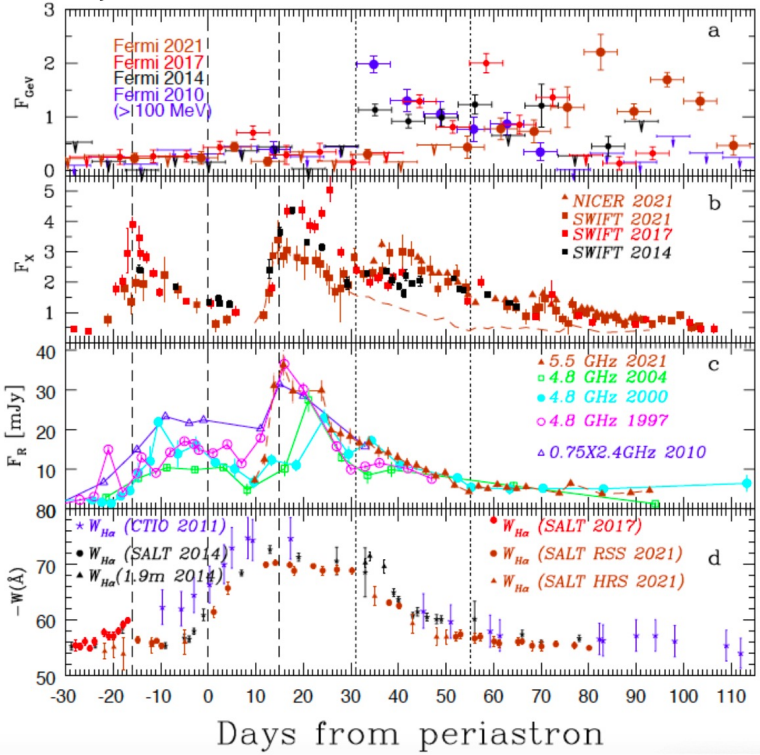
- Overall spectral shape from X-rays to VHE gamma rays well reproduced, except for the 10 MeV range.
- X-ray and VHE modulation also reproduced by the model.
- A modified model accounting for reacceleration is needed for a comparison with radio data.

- Include mass-loading into the outflow.
- Produce radio maps for many parameter combinations and compare with observations.
- Implement the microquasar scenario.
  - Favor one scenario over the other?

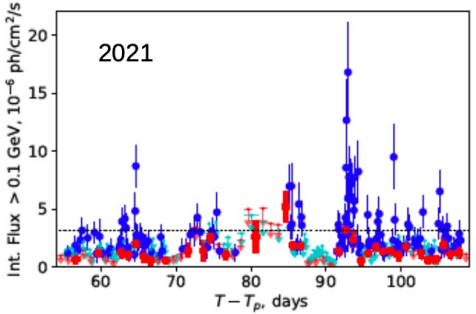
Binaries: gamma-ray binaries

PSRB1259-63 2021 periastron passage from radio to GeV by **Masha Chernyakova**.

Chernyakova et al. 2021



- GeV flare is delayed and weaker on short time scales
- Very different X-ray LC:
  - dim 1st and 2nd flares
  - presence of 3rd peak!
- Radio - X-ray correlation during the 2nd peak
- Correlation breaks at the beginning of the 3rd peak.
- No major change in optical behaviour around GeV peak.
- IR studies are crucial to study the disk closer to the edge.

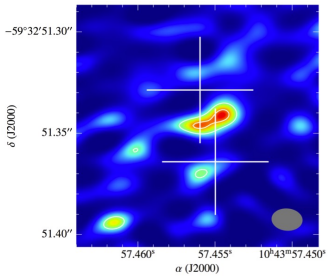


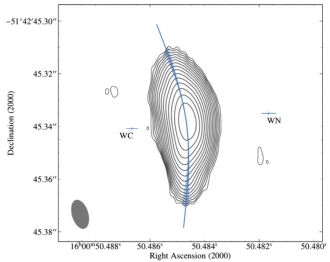
Modeling:

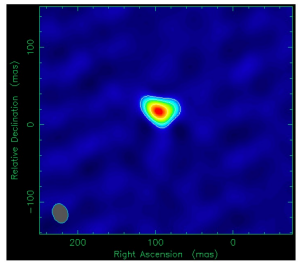
- Indication that radio emission is coming from accelerated stellar wind

PSRB1259-63 2021 periastron passage by HESS still preliminary by **Charles Thorpe-Morgan**.

Binaries: Colliding Wind Binaries





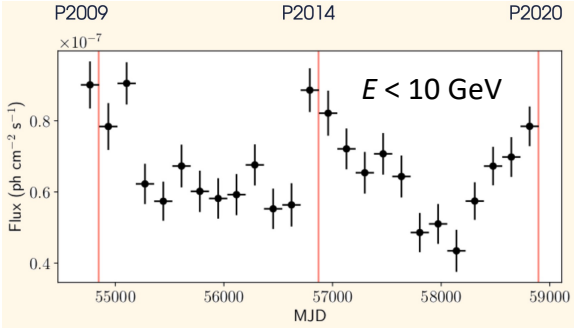


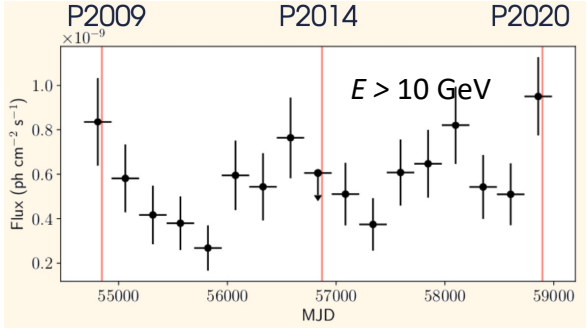
Search for new CWBs by **Benito Marcote**.
HD 93129A, Apep, HD 168112.

Modelling non-thermal emission from CWBs by **Santiago del Palacio**.

- Radio observations are insufficient to characterize the non-thermal emission from CWBs. Great synergy with observations at high-energies (X-rays and γ-rays).
- Multi-wavelength observations combined with detailed theoretical modelling can shed light on the properties of CWBs (magnetic fields, particle-acceleration efficiency...).

2020 periastron passage of Eta Carinae at HE by **Guillem Martí-Devesa**.





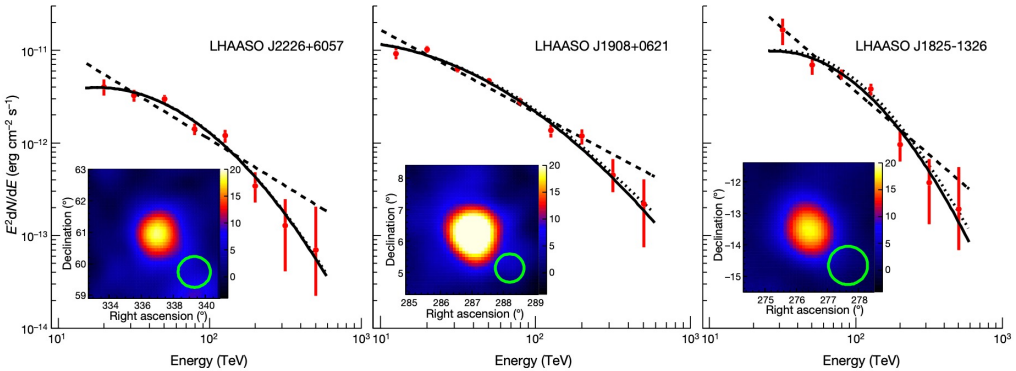
Clear variability between orbits: evidence of different spatial distribution of 2 particle populations?

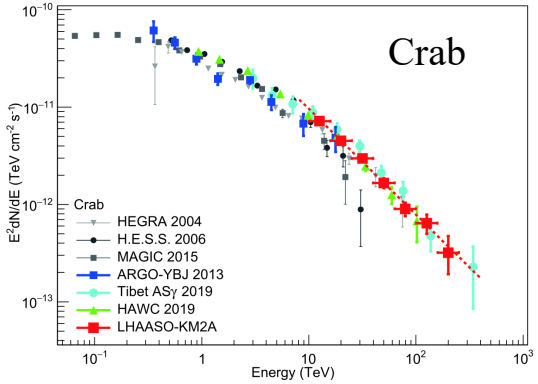
PeVatrons

LHAASO PeVatrons by Zhen Cao.

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)



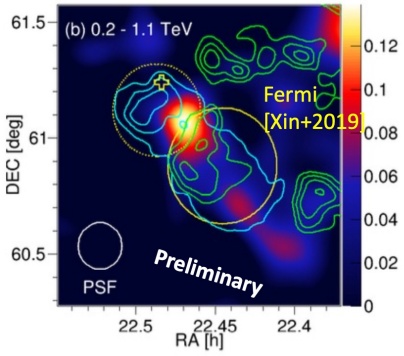


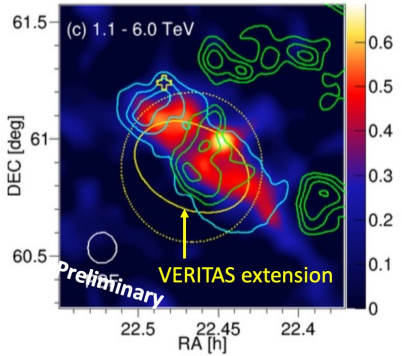
- LHAASO Completed in July 2021.
- Opened UHE (>0.1 PeV) Astronomy.
- Many new sources are discovered (stay tuned).
- Prospects:
- Cygnus region: CR origin.
- Extragalactic sources.
- Diffuse gamma-ray emission.
- Spectra of individual CR species at “knees”.

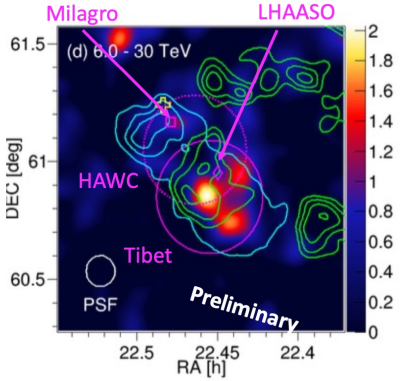
PeVatrons

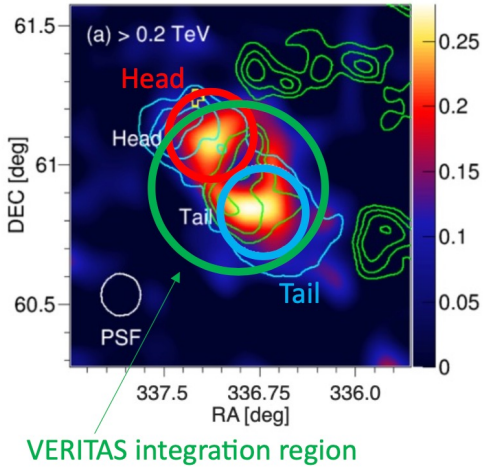
Assuming emission > 10 TeV measured by Air Shower experiments are all from tail,
head: electrons escaped from PWN?
tail: protons accelerated in the past up to PeV and colliding with cloud later?

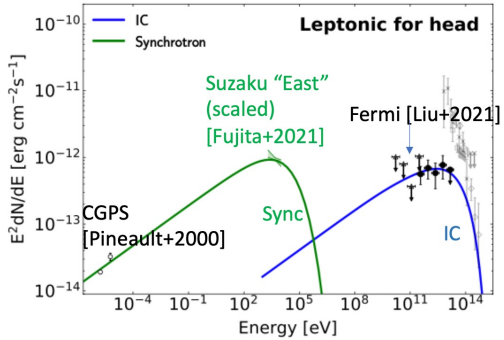
SNR G106.3+2.7/Boomerang/LHAASO J2226+6057 by Takayuki Saito.

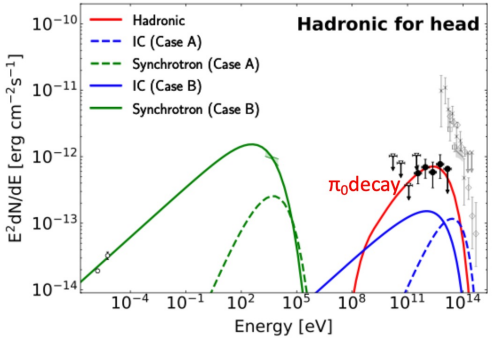


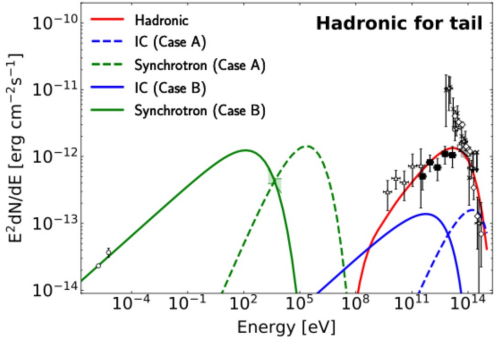






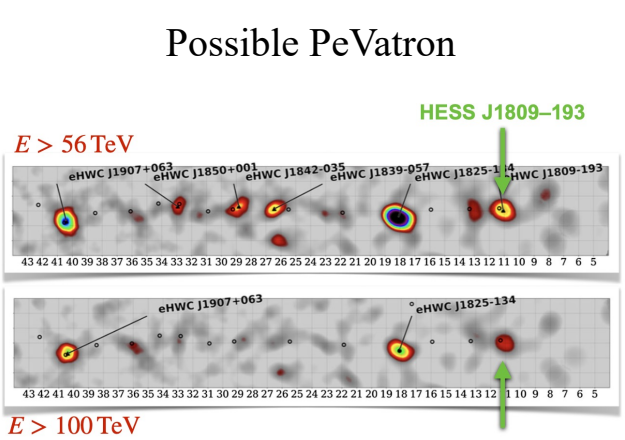


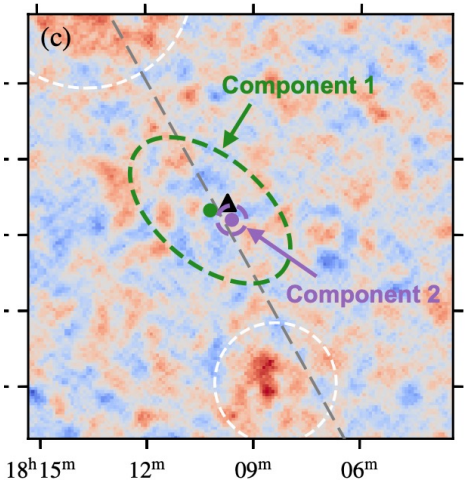


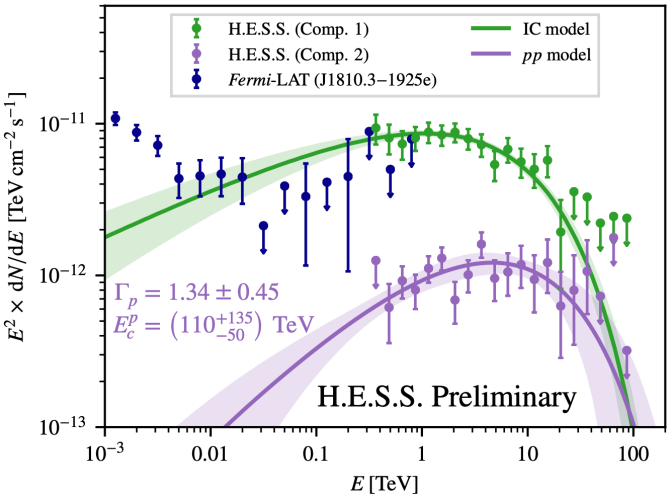


PeVatrons

HESS J1809-193 by **Lars Mohrmann**.



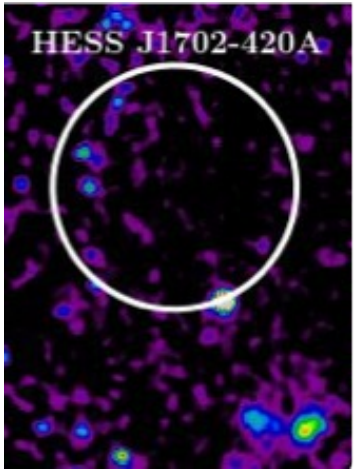




Complex environment → interpretation challenging! PWN or PWN+SNR

- Extended H.E.S.S. component 1 compatible with a halo of "relic" electrons (cf. Vela X)
- Origin of compact H.E.S.S. component 2 & relation to Fermi-LAT emission unclear (overlaps with molecular clouds / shell of SNR → hadronic origin?)

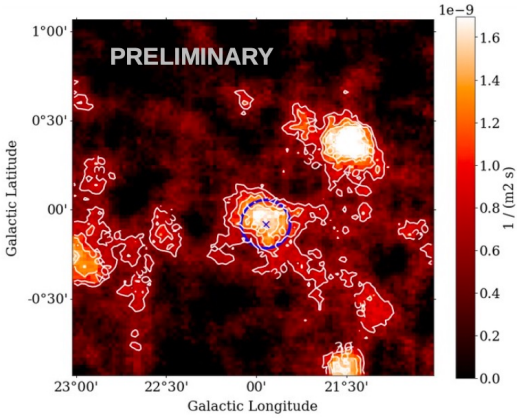
PeVatrons

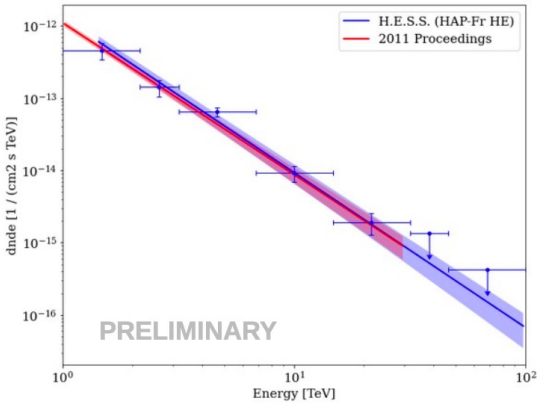


PeVatron candidate HESS J1702-420 with XMM-Newton by **Luca Giunti**.
The absence of an X-ray counterpart and the tight magnetic field upper limits strengthen the classification of HESS J1702-420A as a PeVatron candidate.
A new diffuse X-ray source with hard spectral index was discovered:

- no counterparts for this object were found
- a runaway PWN associated with HESS J1702-420A? Not excluded

PeVatron candidate HESS J1831-098 by **Iryna Lypova**.



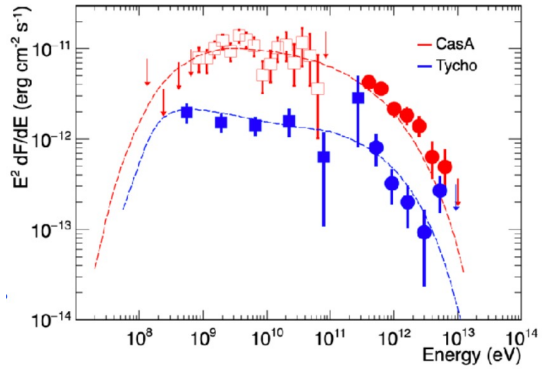


Hard spectrum up to 30-40 TeV. PeVatron?
Possible associations:

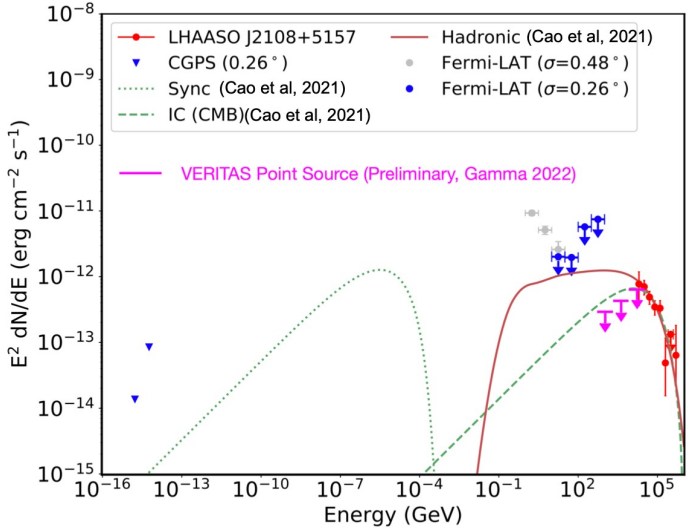
- 3HWC J1831-095. Position proximity and good spectral similarity.
- PSR J1831-0952. Possibly extended X-ray counterpart (PWN?) Suggests PWN nature.
- Molecular cloud (21.97, -0.29) illuminated by nearby SNR. SNR G21.6-0.8 ? SNR candidate G21.8+0.2 ?

PeVatrons

MW studies of PeVatron candidates with VERITAS by **Nahee Park**.
Tycho and Cas A show cutoffs.



LHAASO J2108+5157
VERITAS's measurements indicate the cut-off energy to be in the multi-TeV range, ruling out the hadronic model of Cao et al. (2021).

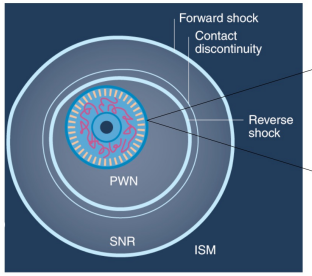


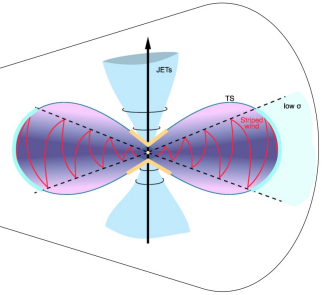
See also poster by **Jakub Jurysek** with **LST** data.

Also, **VERITAS** studies of the SNR G106.4+2.7/Boomerang region (not commented here).

Multi-wavelength investigation of LHAASO J1908+0621 by **Silvia Crestan**. Several possible counterparts → CTA is needed.

PeVatrons



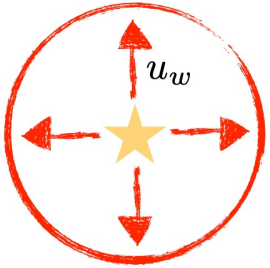


Lopez-Coto, dOW et al, 2022

Brigth young pulsars to power UH gamma-ray sources by **Emma de Oña Wilhelmi**.

- Bright pulsars can in theory accelerate particles (electrons and protons) to the observed PeV energies => Two of the LHAASO sources cannot be explained by pulsars in the FoV
- For young pulsars with magnetic field of ~100 μG, the maximum energy is constraint by the synchrotron losses, whereas for older ones (~few μG) by the potential drop
- We constrain the maximum photon energy in Geminga to less than 200 TeV, whereas the Crab twin (N157B) in the LMC could also be an efficient accelerator.
- The synchrotron counterpart of the 100 TeV IC nebula should be bright in the X-ray domain => eROSITA
- More constraints should come from the size of the gamma-ray emission (in preparation)

Star Clusters



Wind Term. Shock

Supperbubles…

Star clusters as cosmic ray accelerators by **Stefano Gabici**.

- star clusters do accelerate CRs (**WTS** or in **superbubbles**)
- Source of energy: WTSs ~10%, SNae ~90%
- the acceleration proceeds in a different way in young and old clusters
- PeVatrons? Extreme WTS might do, doable for SBs (see next talk by Thibault)
- mixed scenarios (acceleration at SNR+WTS) fit both CR spectra and abundances

Star clusters as sources of UHE CRs and gamma-rays? by **Thibault Vieu**.

- Can massive star clusters produce PeV photons?

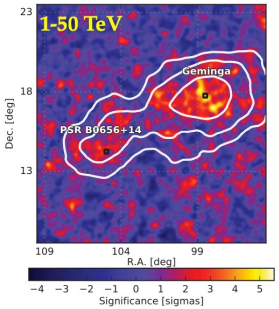
Fast SN exploding within young compact massive star clusters can account for UHE GCR up to 100 PeV. Very few of these events are required (~ 1/10 000 yr) and UHE particles escape within 1kyr => O(1), or possibly O(0) gamma-ray counterpart!

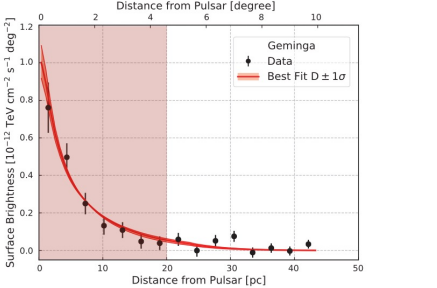
- Can massive star clusters produce ɣ-rays up to 100 TeV?

Young compact clusters can accelerate particles at the WTS up to 1 PeV and produce detectable photons up to 100s TeV.

See also talk by **Stefano Menchiari** on **Cygnus OB2**.

TeV Halos





HAWC Collaboration, Science, 358, 911 (2017)

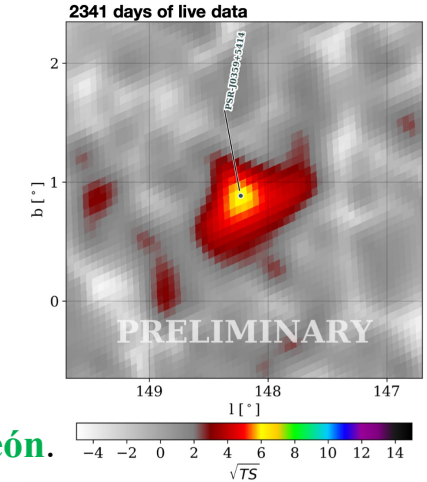
Probing pulsar halos with *Fermi*-LAT by **Soheila Abdollahi**.
TeV extended emission around young/middle-aged pulsars.
2 detections at GeV energies (M. Di Mauro+ 2019, 2021).
Right diffusion coefficient to produce such structures.

- A catalog of 61 extended components above 10 GeV
- Spatial coincidence of extended components with bright PSRs and TeV sources
- Extended components with high flux and hard spectrum
- The mock population study of halos suggests a minority of the extended components could be halos
- Correlation of extended components with 12 4FGL extended sources
- Improvement in the γ-ray morphology of 4FGL extended sources
- Detection of new extended sources candidates

TeV Halos

Are pulsar halos rare? by **Pierrick Martin**.

- The commonness of pulsar halos is still unclear
  - Rare scenario suggested by local positron flux constraint+ATNF
  - Widespread scenario consistent with Galactic TeV observations
- The occurrence rate could be as low as 5-10%
- Going beyond static phenomenological diffusion model
  - Dynamical effects *(Evoli et al. 2018, Mukhopadhyay et al. 2021)*
  - Early stages: PWN-halo transition (after reverse-shock crushing ?)
  - Late stages: Halo dissolution into ISM ?

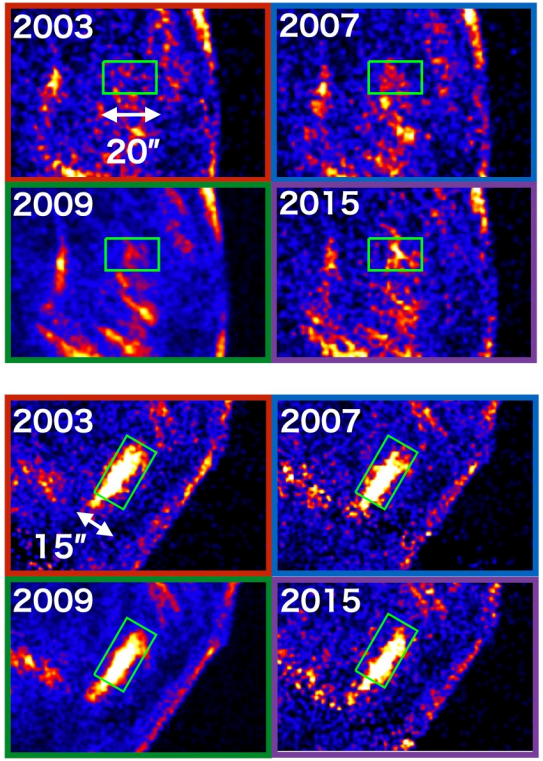


TeV halo candidate around PSR J0359+5414 with HAWC by **Sara Coutiño de León**.

- TeV halo candidate near the Galactic plane in a non-crowded region.
- Likely associated to the radio-quiet pulsar PSR J0359+5414.
- This TeV halo candidate shares similar characteristics to others, suggesting that TeV halos could be a general feature of middle-age pulsars.
- It is important to perform multi-wavelength observations to confirm the finding.

SNRs

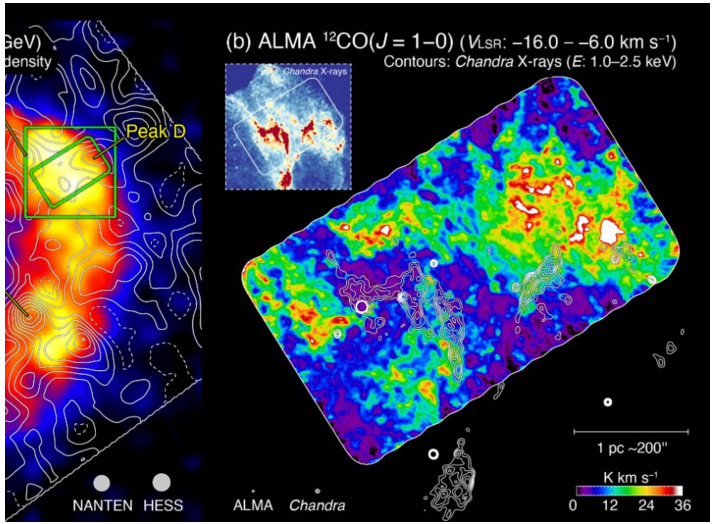
Recent Results in Supernova Remnants at Highest Energies by **Takaaki Tanaka**.

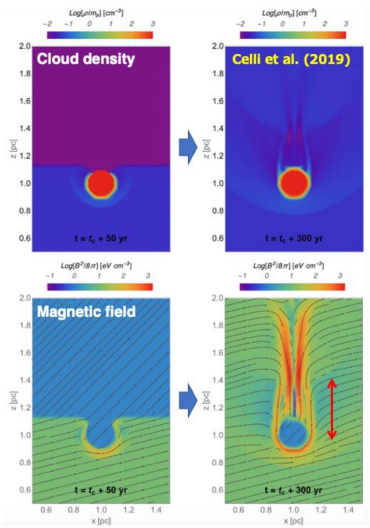


- Particle acceleration in SNRs extensively studied through observations in X-rays and gamma rays.
- Although gamma-ray emissions from some SNRs are firmly identified as π0 decay, none of them extends up to ~ 100 TeV.
- PeVatrons search is currently one of the hottest topics in the field.
- Observations of interacting SNRs would be important for this purpose since highest-energy particles may have escaped in the past.
- LHAASO J1908 and G106.3 may be such examples.
- Multi-wavelength studies are important to reveal the nature of those sources.
- Synchrotron X-ray variability can provide indirect evidence that SNRs has ability to accelerate particles up to ~ PeV.
- Shock-cloud interactions seem to work as another mechanism to amplify magnetic fields.

SNRs

ALMA CO observations of SNR RX J1713.7-3946 by **Hidetoshi Sano**.





Cloudlets within a wind bubble, which are physically associated with both the X-ray filaments and the hotspots.

Spatial separation consistent with numerical results of shock-cloud interactions (Celli et al. 2019).

Particle escape from SNR shocks: gamma-ray and CR signatures by **Silvia Celli**.

- Modelling is needed for interpreting the steep spectra and low maximum energy observed in the HE and VHE emission of many middle-aged SNRs (e.g. IC443, W28, W51C, Cygnus Loop).
- Results obtained can be used as a strategy to search for PeV CR- proton accelerators.

Conclusions and outlook (1/2)

Gamma 2022 has been a very exciting meeting with excellent results on Galactic sources:

- **Facilities continue to improve** and provide new and better results.
- We have detected a **Nova** at VHE for the first time and discovered proton acceleration there.
- The microquasar **SS 433** has revealed VHE emission in the interaction regions, together with hard X-ray emission. New results soon.
- Gamma-ray binaries. **LS I +61 303 shows pulsations**. New X-ray/TeV correlations in some systems. The understanding of these systems is complicated from a theoretical/simulation point of view.
- We know more than a dozen sources emitting above 100 TeV, several **PeVatron** candidates, but their nature appears diverse and most of times scenarios are not yet clear.
- **Star clusters** can accelerate CR and in particular cases behave as PeVatrons.

Conclusions and outlook (2/2)

- **TeV Halos** are being searched for at GeV and TeV energies, but their abundances are not yet clear.
- **SNR** reveal cloudlets able to produce B amplification.
- I did not have time to focus on the **Galactic Center**, **diffuse emission**, **DM** or **Theoretical aspects**, among others. Check the talks by: **Pedro De la Torre Luque, Justine Devin, Naomi Tsuji, Martin Pohl, Giada Peron, Kaya Mori, Javier Rico, Marianne Lemoine-Goumard, Riccardo Di Tria, Denys Malyshev, Andrey Timokhin, Nanda Rea, Barbara Olmi, Lorenzo Sironi, Benoît Cerutti, Michelle Tsirou, Anabella Araudo, Jonatan Martin, Carmelo Evoli, Tomohiro Inada, Sami Caroff**.
- Hopefully in the next Gamma meeting new and exciting results will follow !