13th Cosmic-Ray International Studies and Multi-messenger Astroparticle Conference

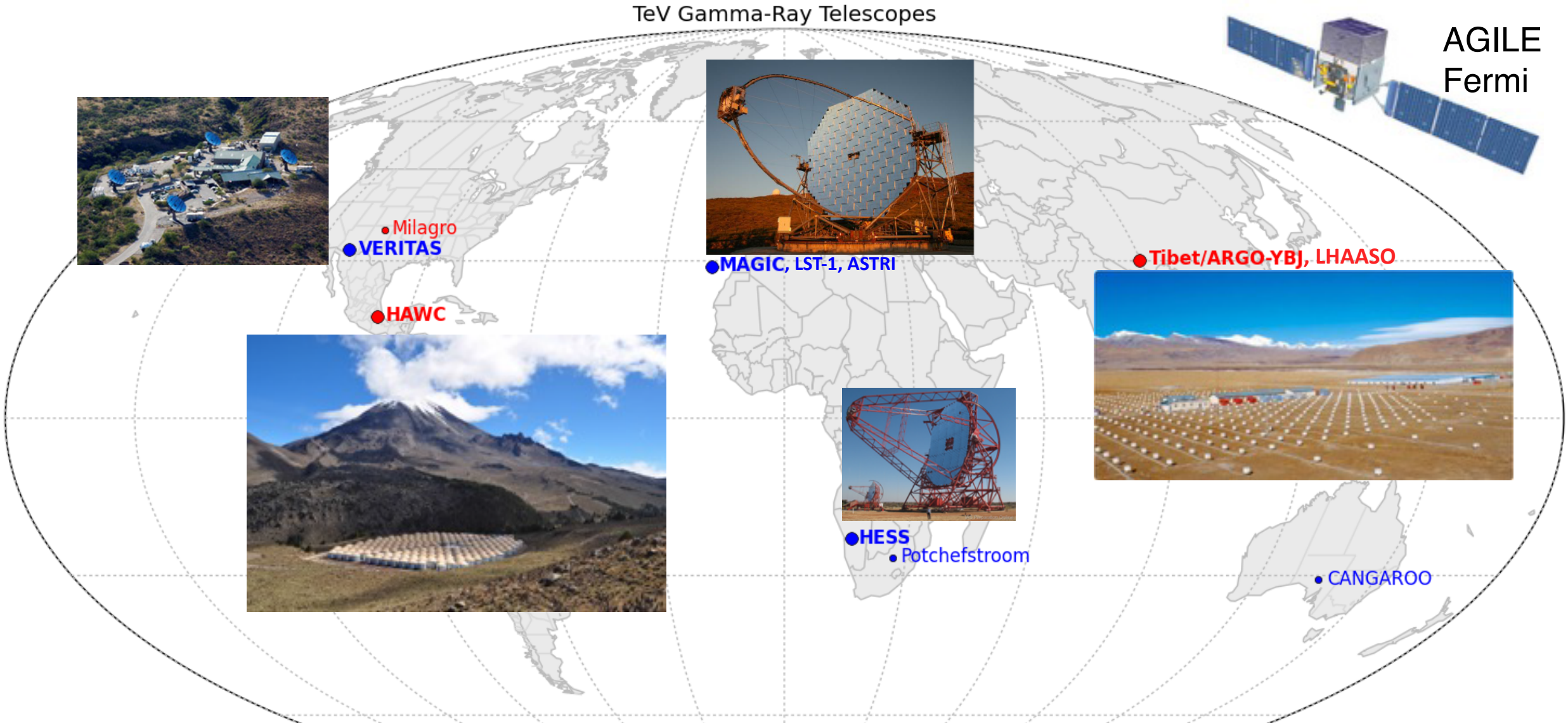
CRIS-MAC 2024

Aftermath of the current generation of IACTs

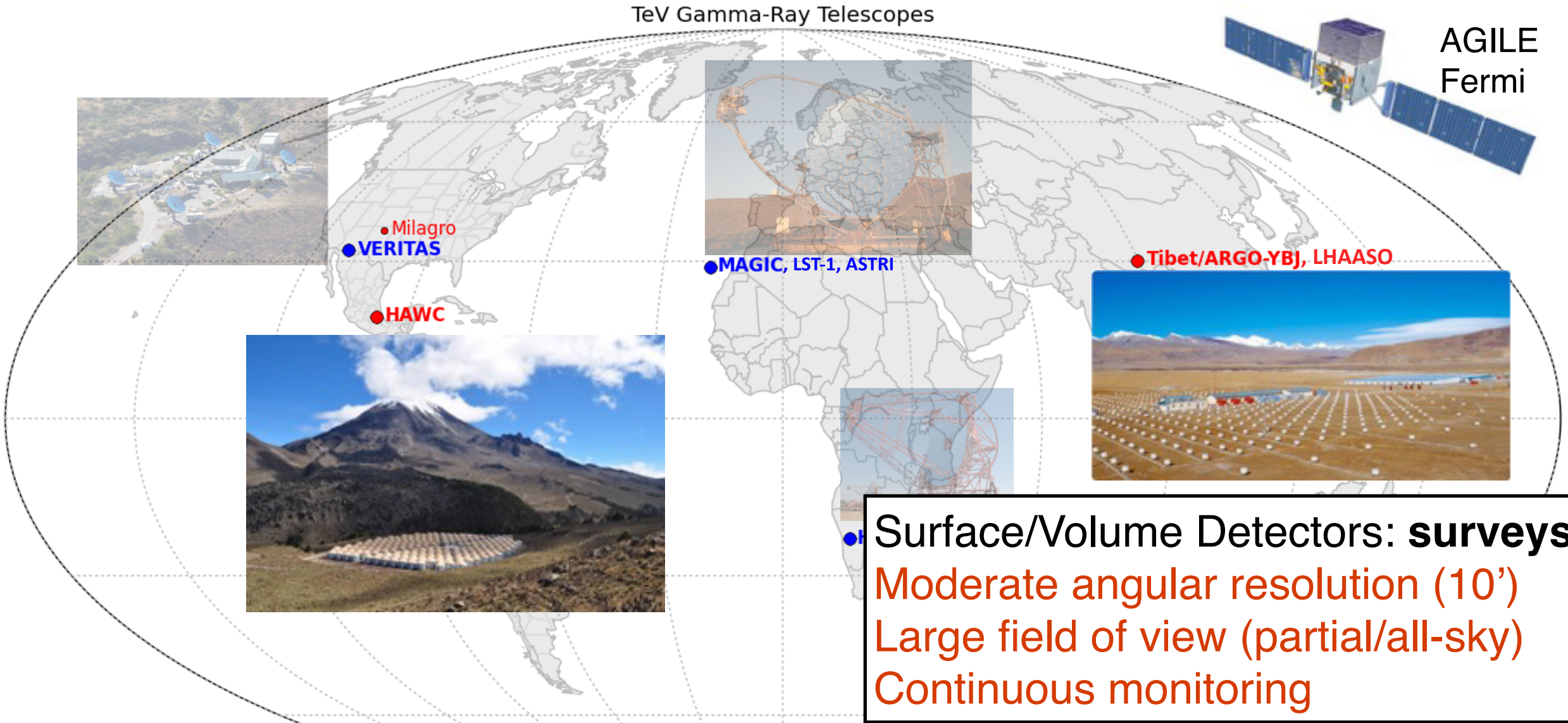
Glance to the latest results and peep into the future

Rubén López-Coto
Instituto de Astrofísica de Andalucía, Granada, Spain
13th CRIS-MAC, Trapani, 17/06/24

Gamma-ray astronomy

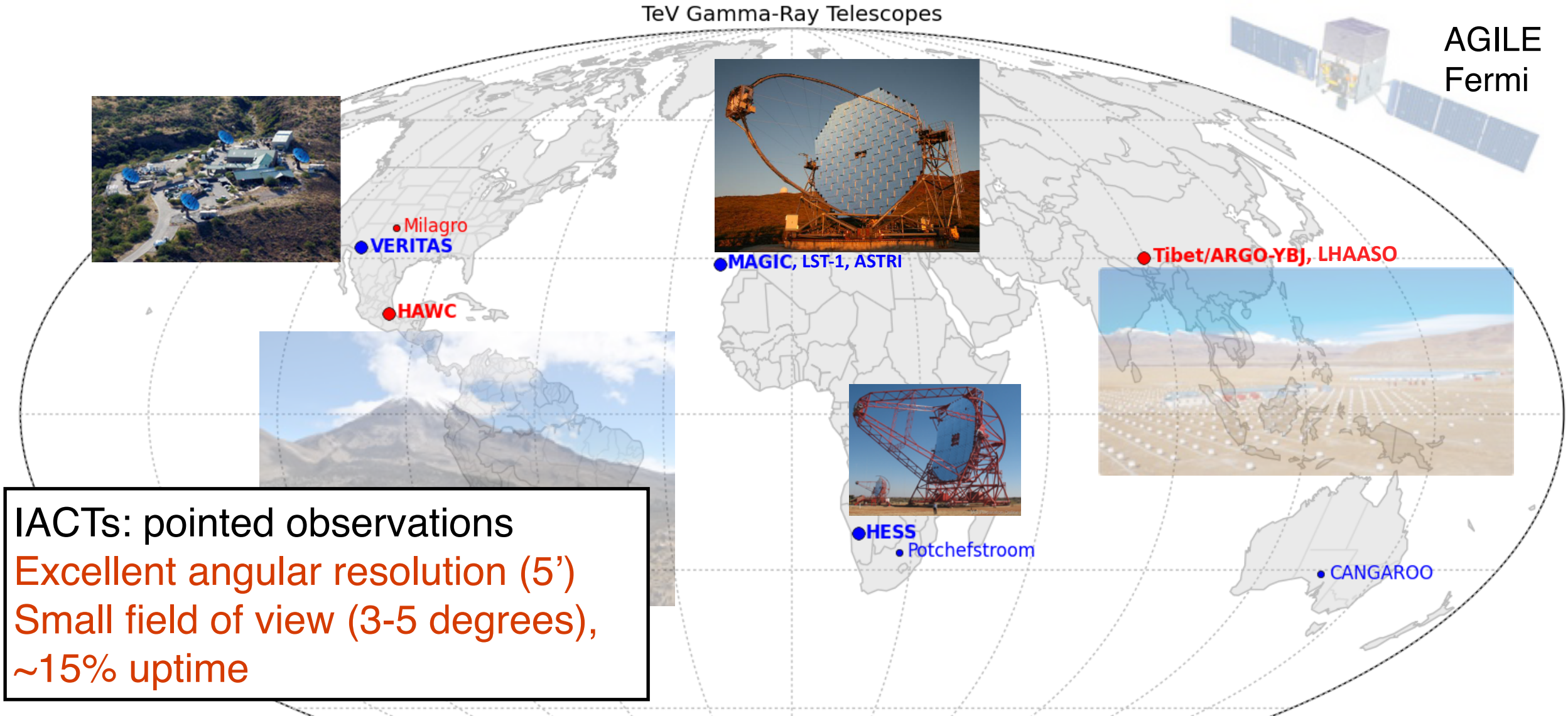


Gamma-ray astronomy



Surface/Volume Detectors: **surveys**
Moderate angular resolution (10')
Large field of view (partial/all-sky)
Continuous monitoring

Gamma-ray astronomy



IACTs: pointed observations
Excellent angular resolution (5')
Small field of view (3-5 degrees),
~15% uptime

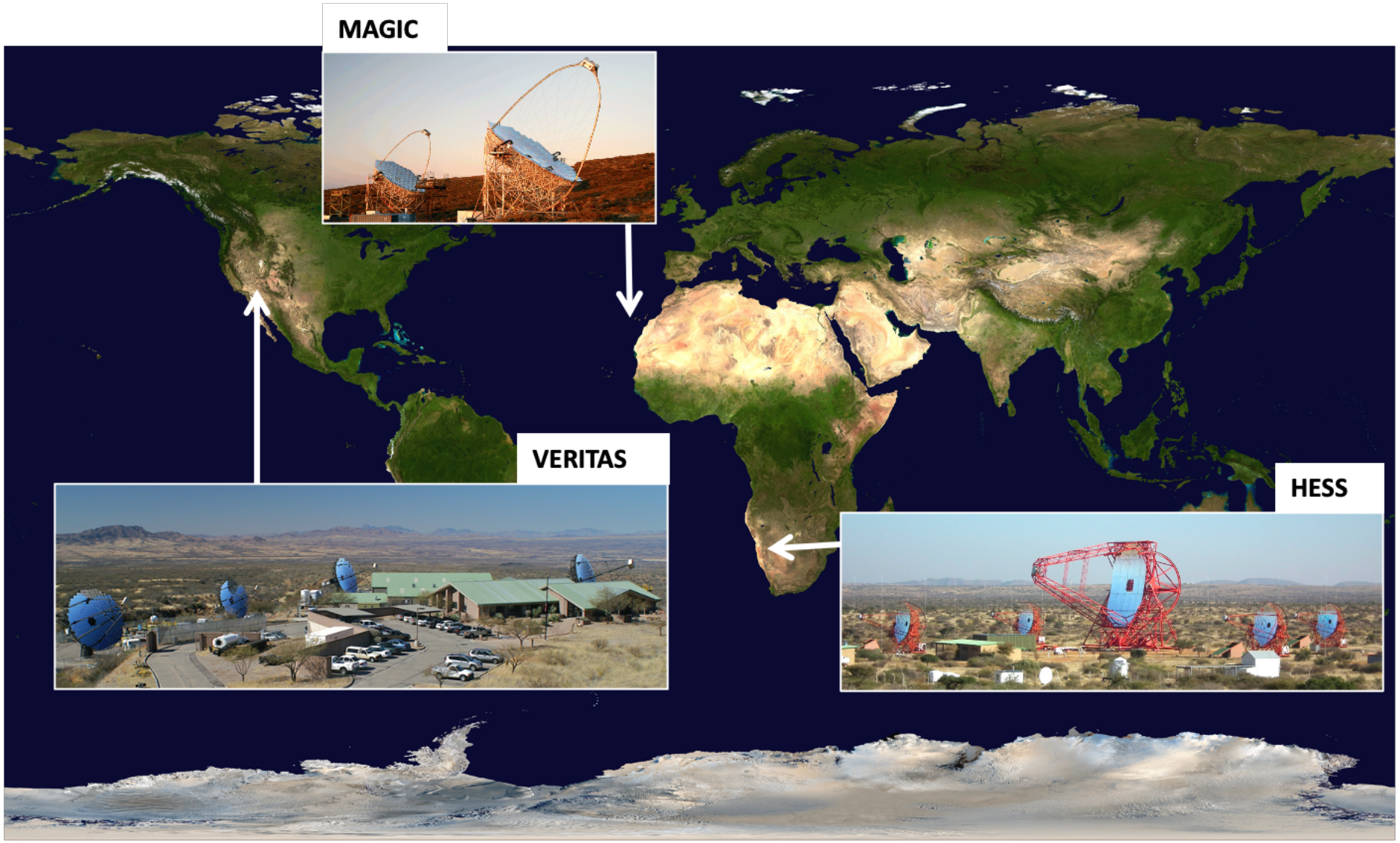
The IACT technique

The IACT technique

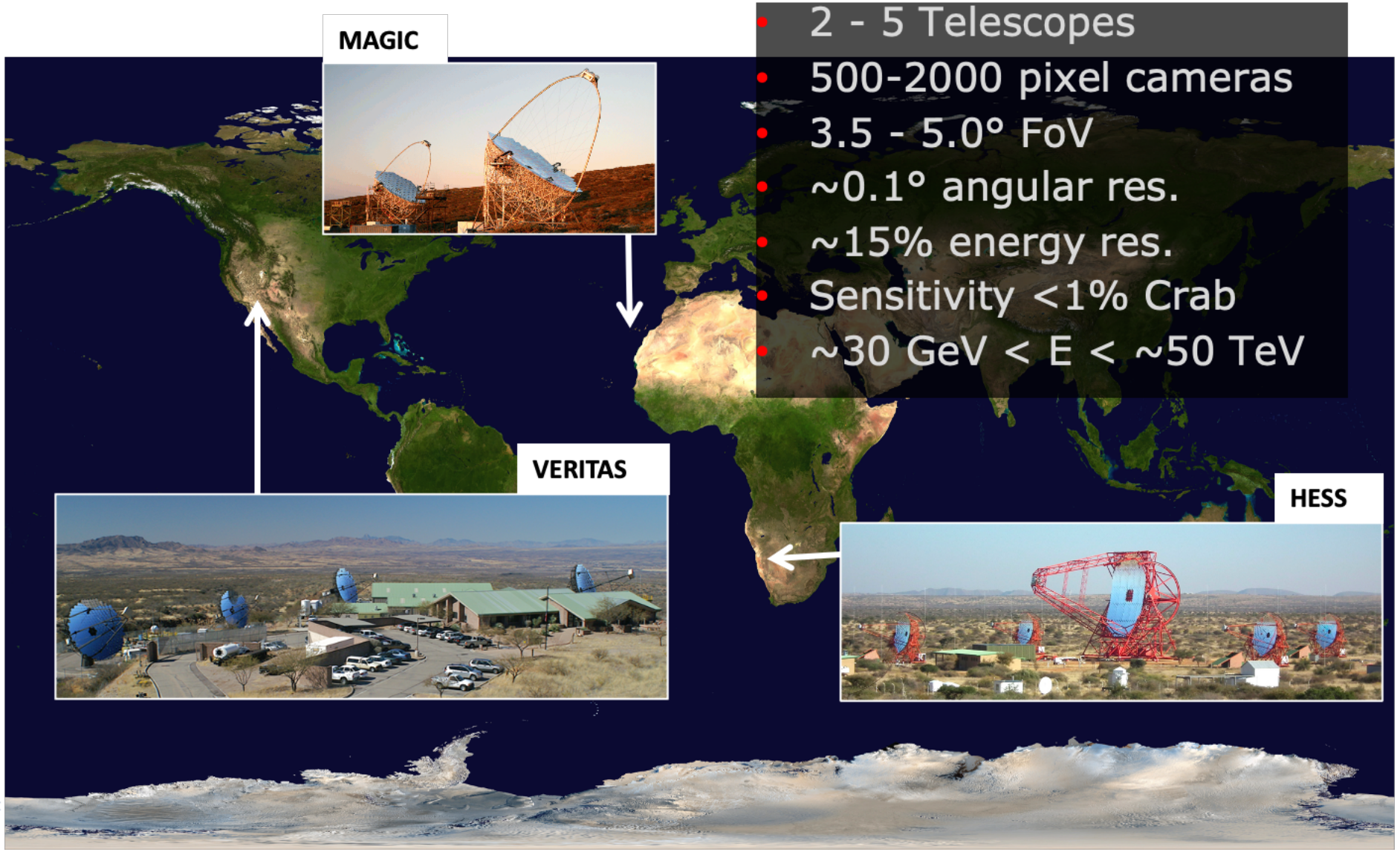
The IACT technique

The IACT technique

Current IACTs



Current IACTs



INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

Current IACT track record

- **AGN**: Science 314 (2006), Science 325 (2009), Science 346 (2014)
- **Cosmic Ray Electrons**: PRL 101, 261104 (2009)]
- **Dark Matter**: PRL 96, 221102 (2006), PRL 106, 161301 (2011)
- **EBL**: Nature 440 (2006), Science 320 (2008)
- **Galactic Centre**: Nature 439, 695 (2006)
- **GRBs**: Nature 575 (2019), Science 372 (2019)
- **Microquasars**: Science 383, 6681 (2024)
- **Neutrino-Blazar**: Science 361 (2018)
- **Novae**: Science 376 (2022), Nat. Astronomy 6 (2022)
- **Lorentz Invariance Violation**: PRL 101(2008)
- **Pulsars**: Science 322, 1221 (2008), Science 334, 69 (2011), Nat. Astronomy 7 (2023)
- **Pulsar Wind Nebulae**: Nat. Astronomy 4 (2020)
- **Pevatrons**: Nature 531 (2016)
- **Supernova Remnants**: Nature 432, 75 (2004)
- **Surveys**: Science 307, 1839 (2005), PRL 95, 251103 (2005)
- **Starburst Galaxies**: Nature 462, 770 (2009), Science 326,1080 (2009)

Current IACT track record

- **AGN**: Science 314 (2006), Science 325 (2009), Science 346 (2014)
- **Cosmic Ray Electrons**: PRL 101, 261104 (2009)]
- **Dark Matter**: PRL 96, 221102 (2006), PRL 106, 161301 (2011)
- **EBL**: Nature 440 (2006), Science 320 (2008)
- **Galactic Centre**: Nature 439, 695 (2006)
- **GRBs**: Nature 575 (2019), Science 372 (2019)
- **Microquasars**: Science 383, 6681 (2024)
- **Neutrino-Blazar**: Science 361 (201
- **Novae**: Science 376 (2022), Na
- **Lorentz Invariance Violation**:
- **Pulsars**: Science 322, 1221 (20 (2011), Nat. Astronomy 7 (2023)
- **Pulsar Wind Nebulae**: Nat. Astro 020)
- **Pevatrons**: Nature 531 (2016)
- **Supernova Remnants**: Nature 432, 75 (2004)
- **Surveys**: Science 307, 1839 (2005), PRL 95, 251103 (2005)
- **Starburst Galaxies**: Nature 462, 770 (2009), Science 326,1080 (2009)

I'm sorry, I cannot possibly make justice...

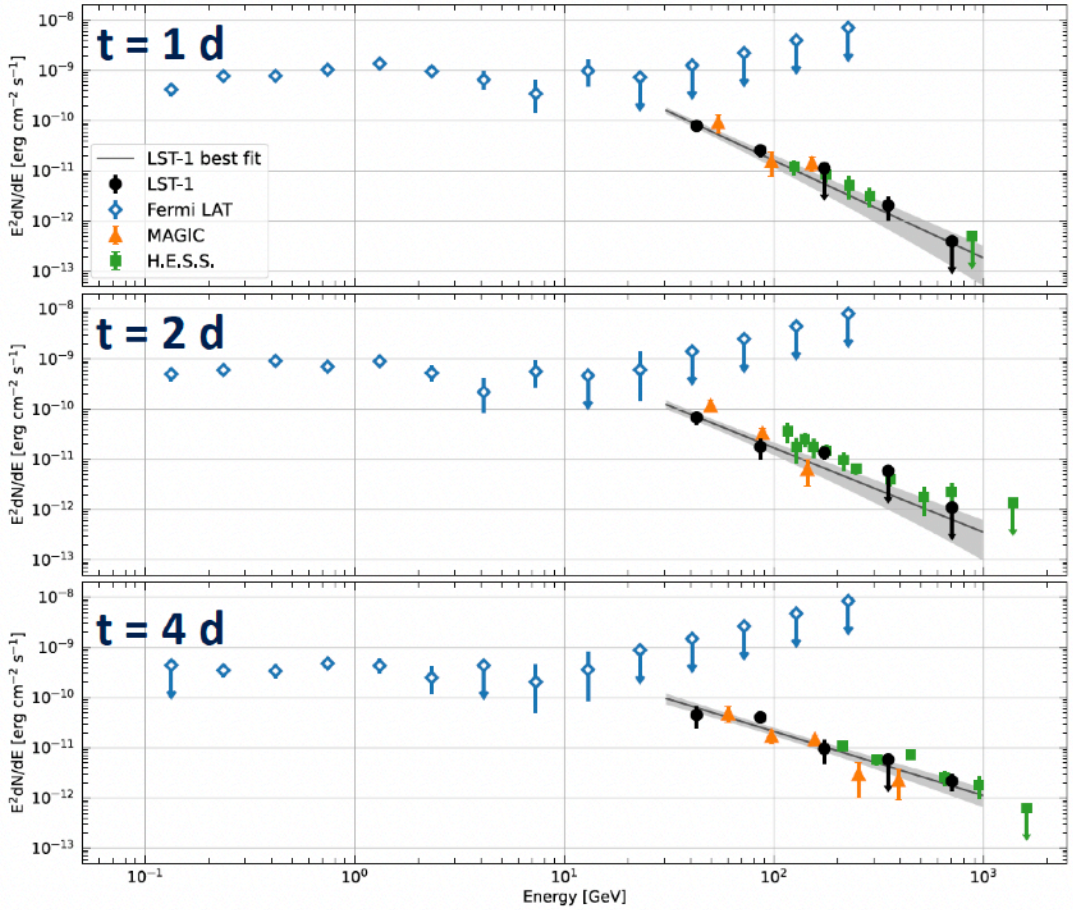
A few selected highlights: novae

- Novae: Thermonuclear explosions caused by accumulation of material from a donor star on the surface of a white dwarf.
  - Emission from radio up to GeV
- RS Oph: Recurrent nova in a symbiotic binary
  - Outbursts every 15-20 years

- Previous to last outburst in 2006 => no sensitive gamma-ray satellites available

Credit: https://superbossa.com / MPP

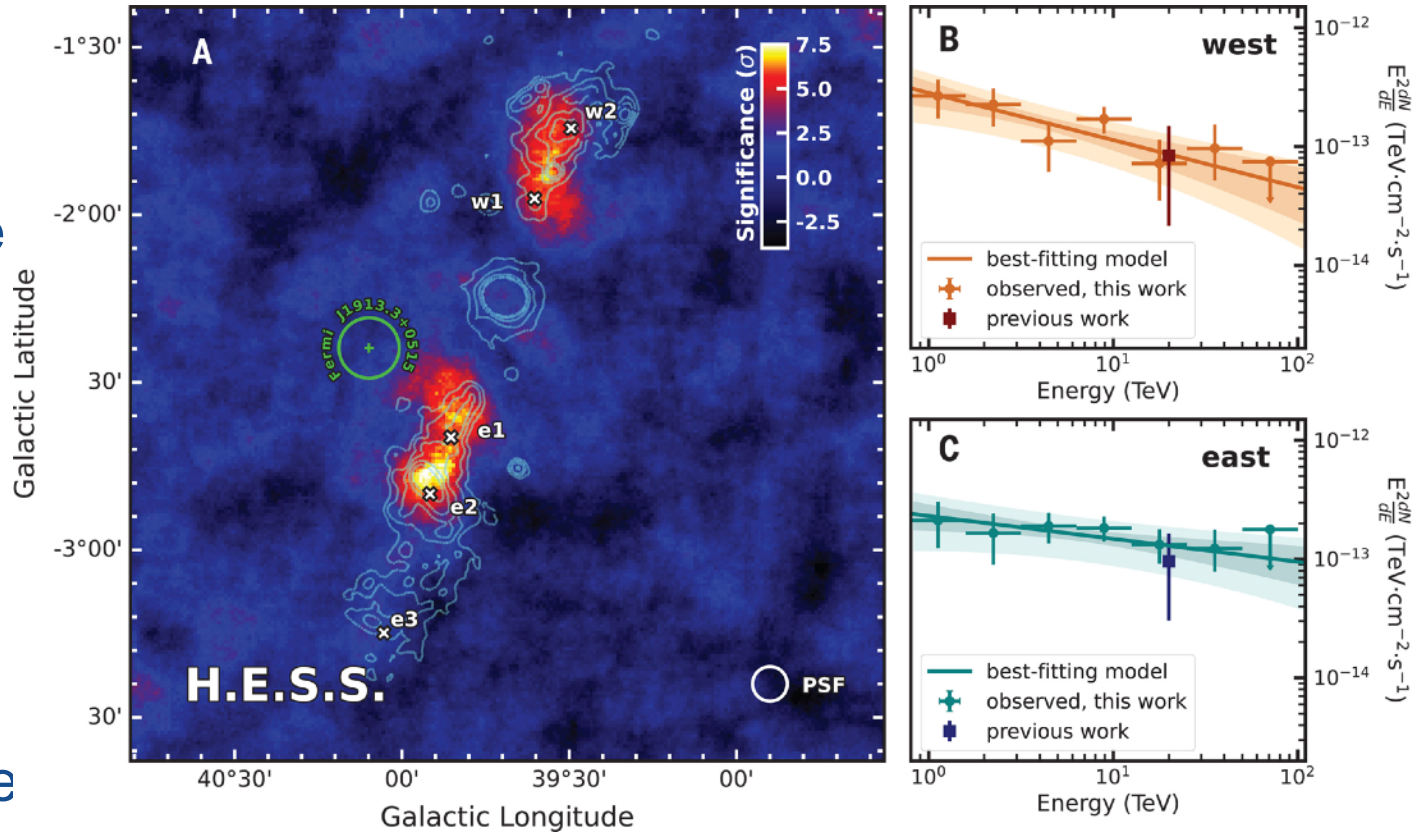
RS Ophiuchi in gamma rays



- RS Oph erupted again Aug. 8th 2021
- Detected by HESS, MAGIC and LST-1
- RS Oph opened new class of VHE gamma-ray sources – **novae.**
- **Proton** acceleration strongly favored:
  - Accelerated protons will eventually escape nova shock and contribute to the sea of CRs.
- Single-shock scenario disfavored to explain GeV and TeV emission.

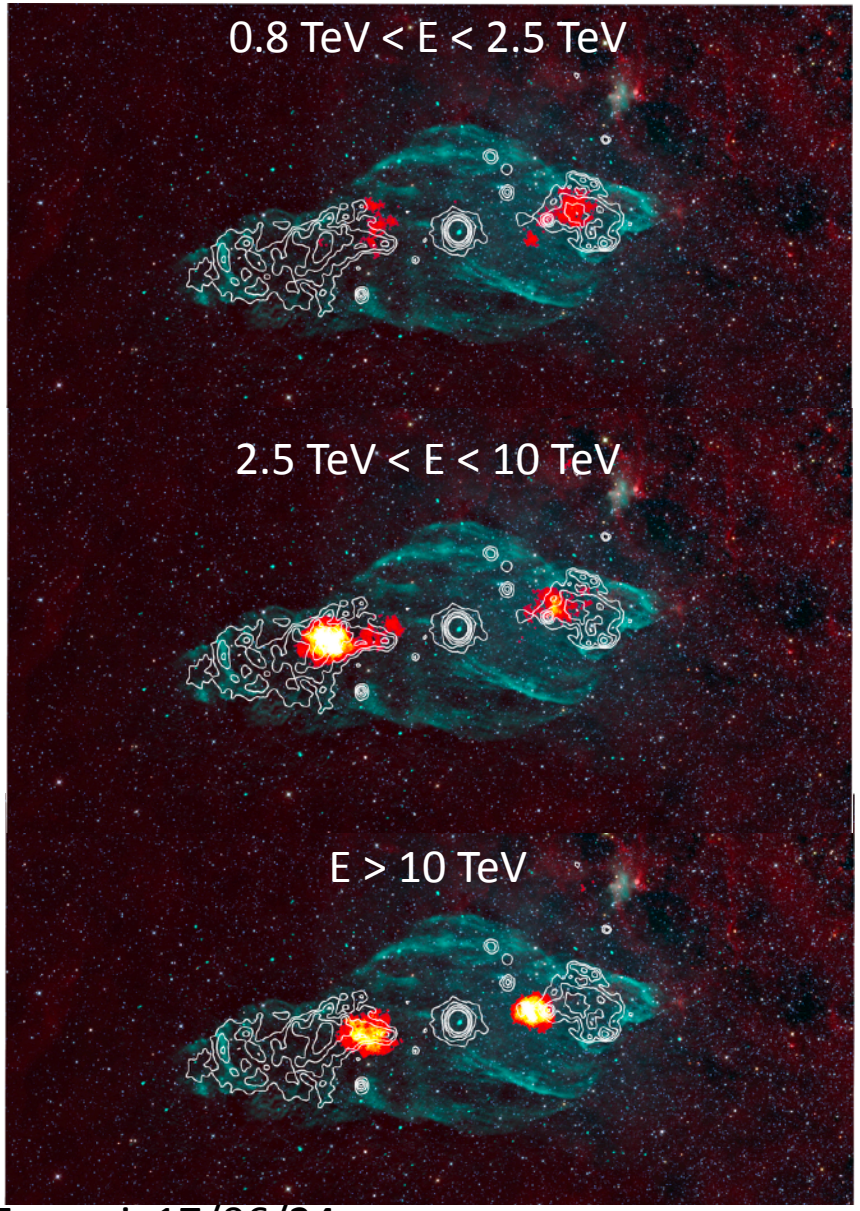
The microquasar SS 433

- **SS433**
  - Compact object + type A supergiant star
  - Ultrarelativistic jets caused by the accretion onto the black holes
- VHE gamma-ray emission
  - Discovered by HAWC in gamma rays
  - Both jets detected by HESS after 200+ hours of observations.
  - Observed and undetected by othe IACTs



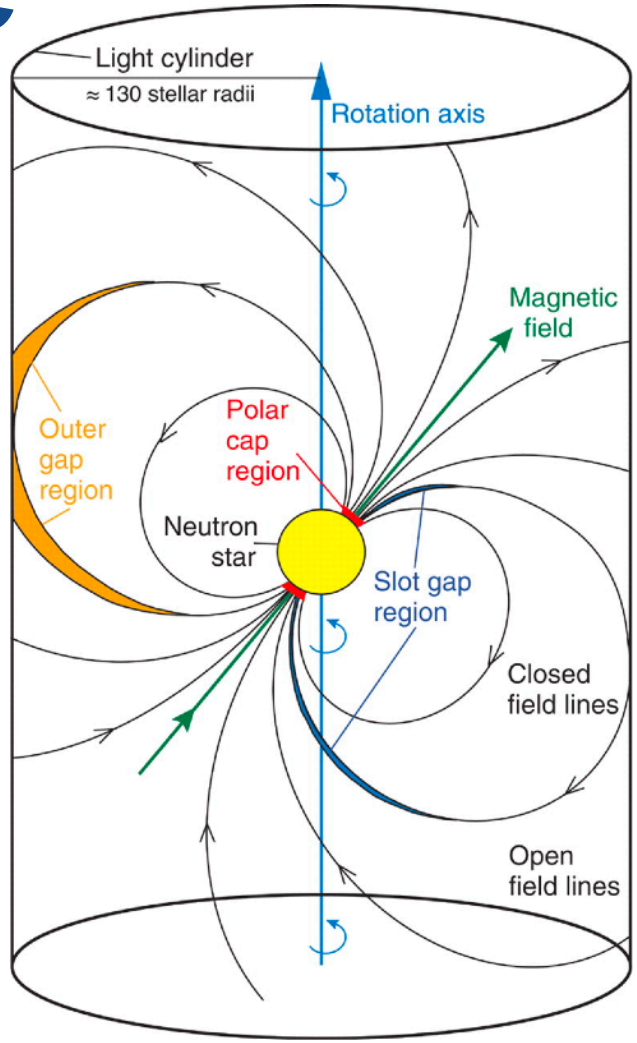
The microquasar SS 433

- HESS observations favor a leptonic origin of the emission
  - Energy-dependent morphology shows a mild dependence of the distance to the central engine of the VHE emission
- No emission from the central object
  - Shocks are produced at ~25 pc distances from the binary system
  - Electron acceleration is produced in these shocks that are later inverse Compton scattering of ambient photon fields



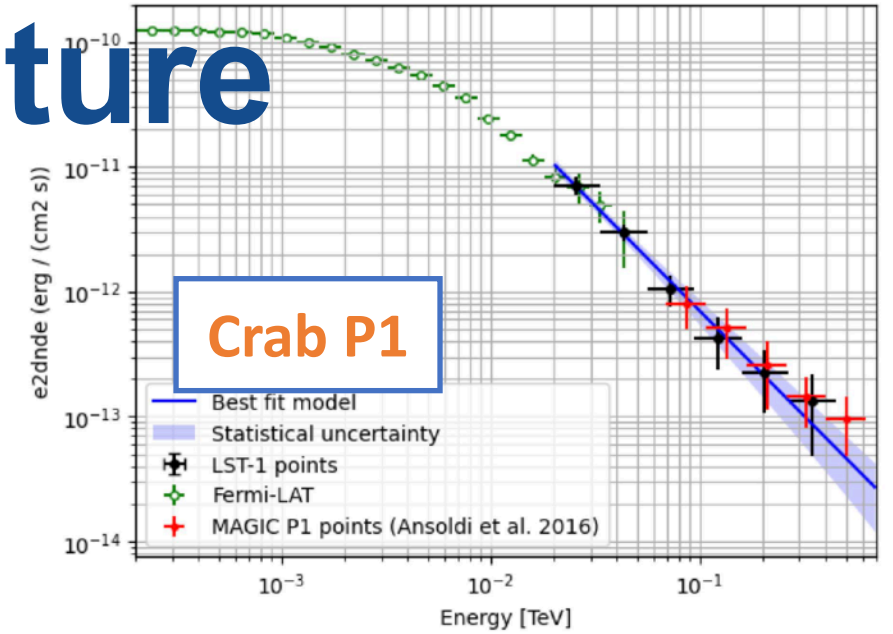
Pulsars: Present and future

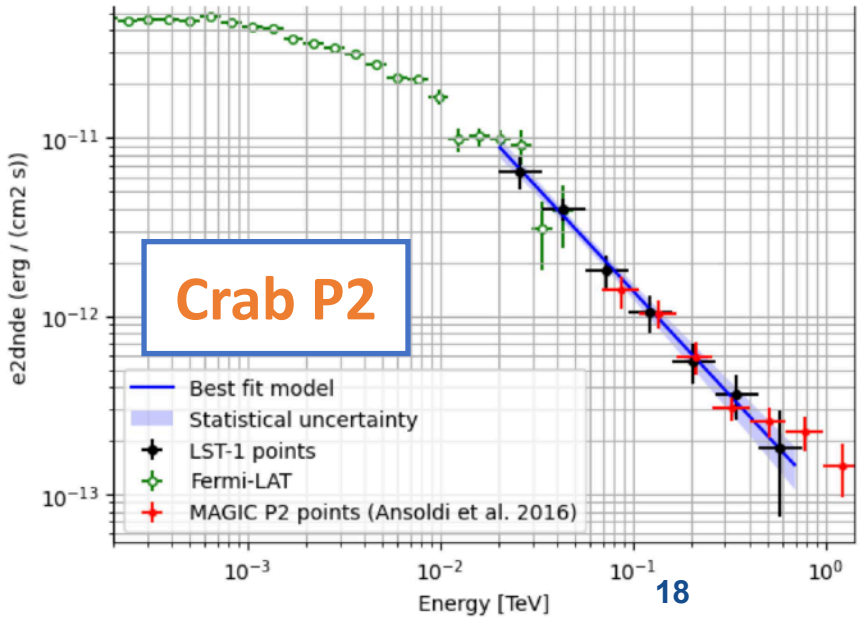
- Rapidly rotating highly magnetized neutron stars
  - $e^{\pm}$ plasma fills the magnetosphere and co-rotates with the pulsar.
- Up to early 2000'
  - No VHE gamma-ray emission detected
  - Models where emission close to the neutron star were favored
- Crab pulsar discovered by MAGIC in 2008
  - Subsequent measurements by VERITAS and also MAGIC extended the emission up to TeV energies
  - Rules out VHE gamma-ray production close to the neutron star



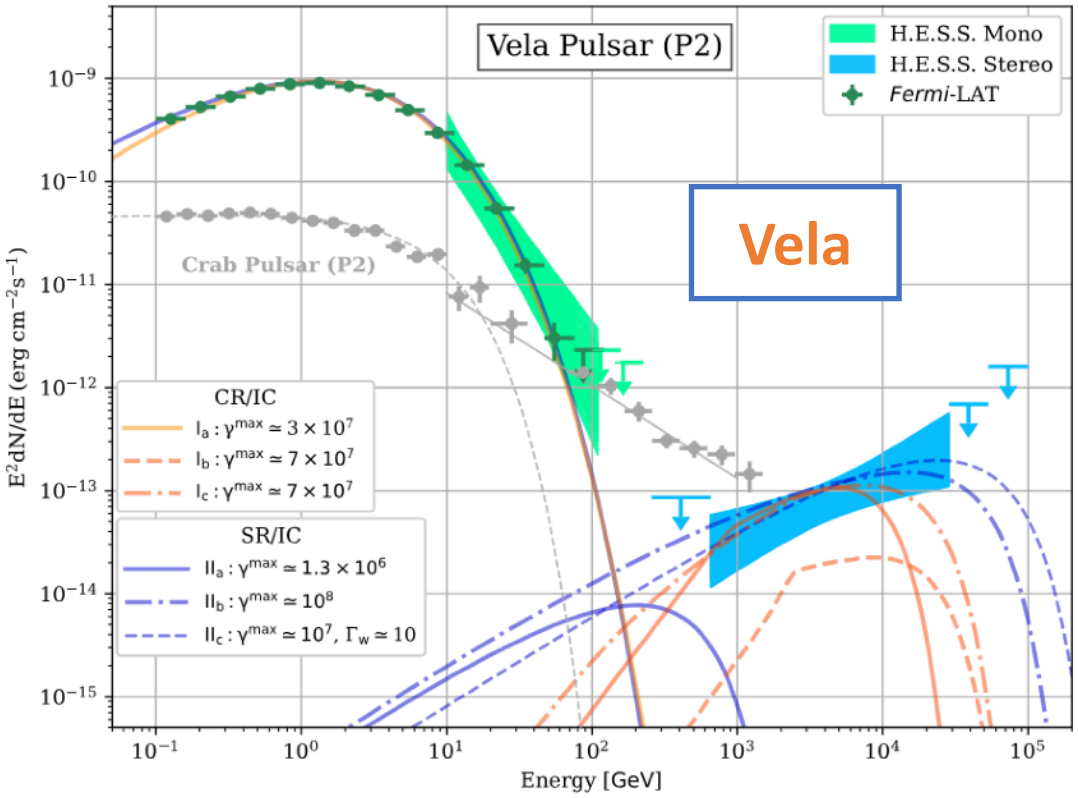
Pulsars: Present and future

- Rapidly rotating highly magnetized neutron stars
  - $e^{\pm}$ plasma fills the magnetosphere and co-rotates with the pulsar.
- Up to early 2000'
  - No VHE gamma-ray emission detected
  - Models where emission close to the neutron star were favored
- Crab pulsar discovered by MAGIC in 2008
  - Subsequent measurements by VERITAS and also MAGIC extended the emission up to TeV energies
  - Rules out VHE gamma-ray production close to the neutron star

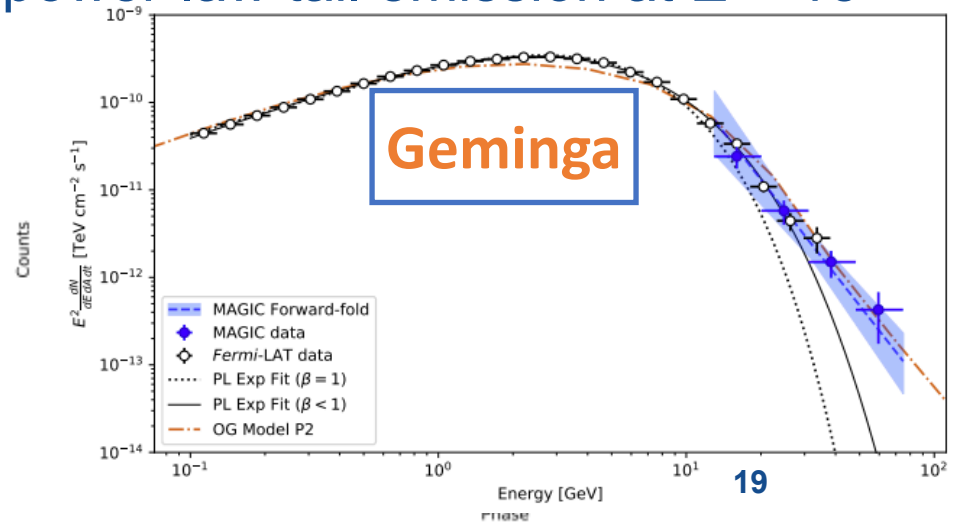




Pulsars: Present and future

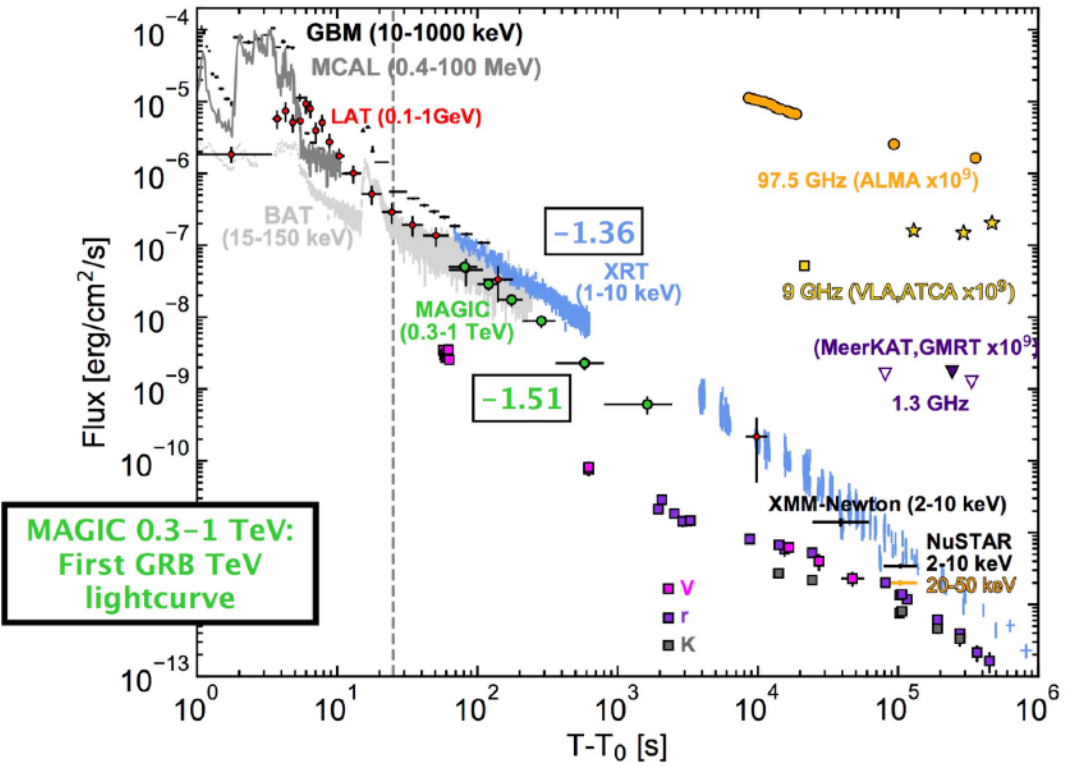


- Vela pulsar detected by HESS up to tens of GeV
  - And then up to 7 TeV!
  - Difficult to confine the origin of the emission to the pulsar magnetor
- Geminga discovered by MAGIC and detected by LST-1
  - Hinting a power-law tail emission at E > 15 GeV



Gamma Ray Bursts

- A lot of interesting results in the past from the sub-GeV band
  - We didn't have any at TeV energies until a few years ago

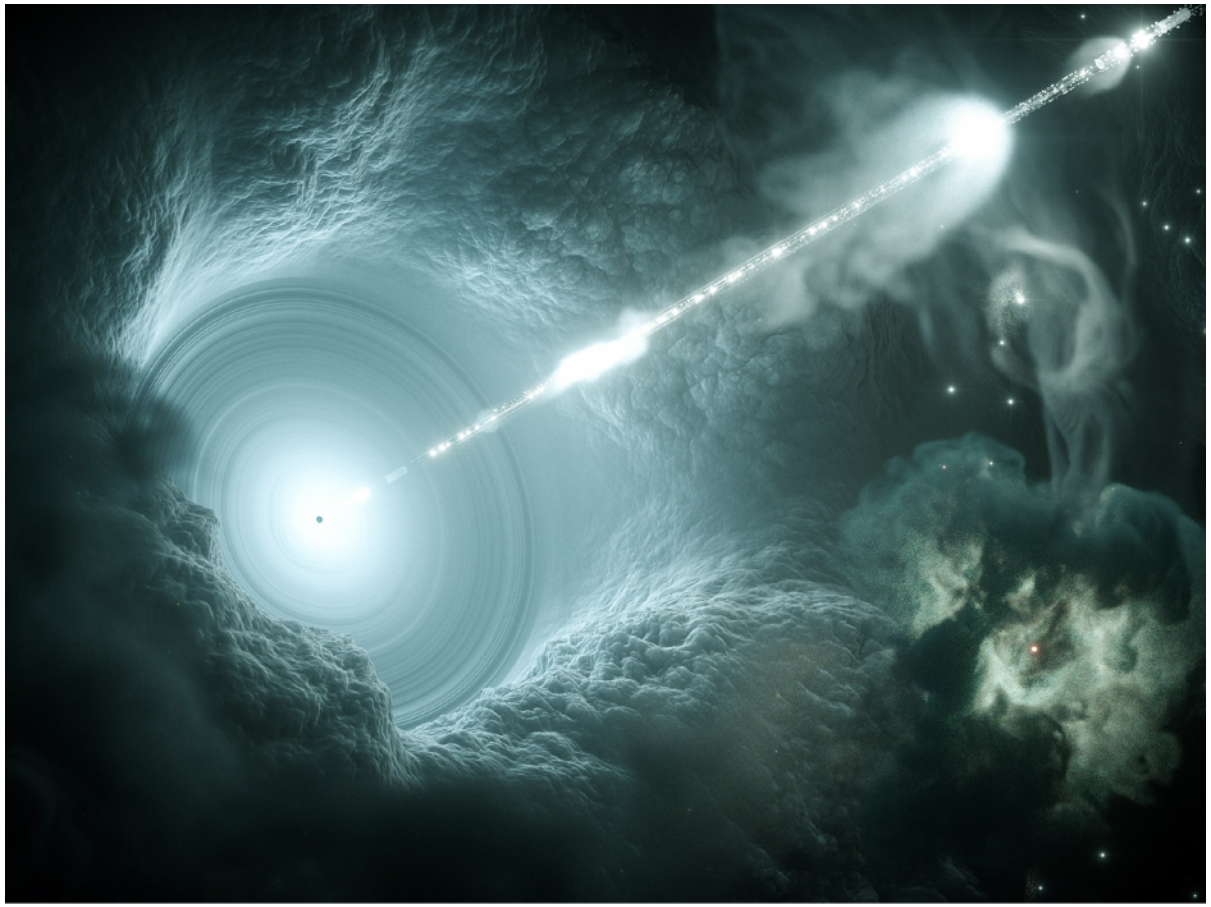


- So far 5 GRBs have been detected at very high energy (VHE, > 50 GeV) gamma rays.
  - GRB 180720B (H.E.S.S.), GRB 190114C (MAGIC), GRB 190829A (H.E.S.S.), GRB 201216C (MAGIC), GRB 221009A (LHAASO)
  - All long GRBs (duration T90 > 2 sec)
    - detection of the afterglow emission
  - SSC by relativistic electrons in the forward shock as an explanation for the VHE emission

The beginning of multimessenger astronomy

- Neutrino emission detected from IceCube coincident with the location of the **TXS 0656+056** blazar.

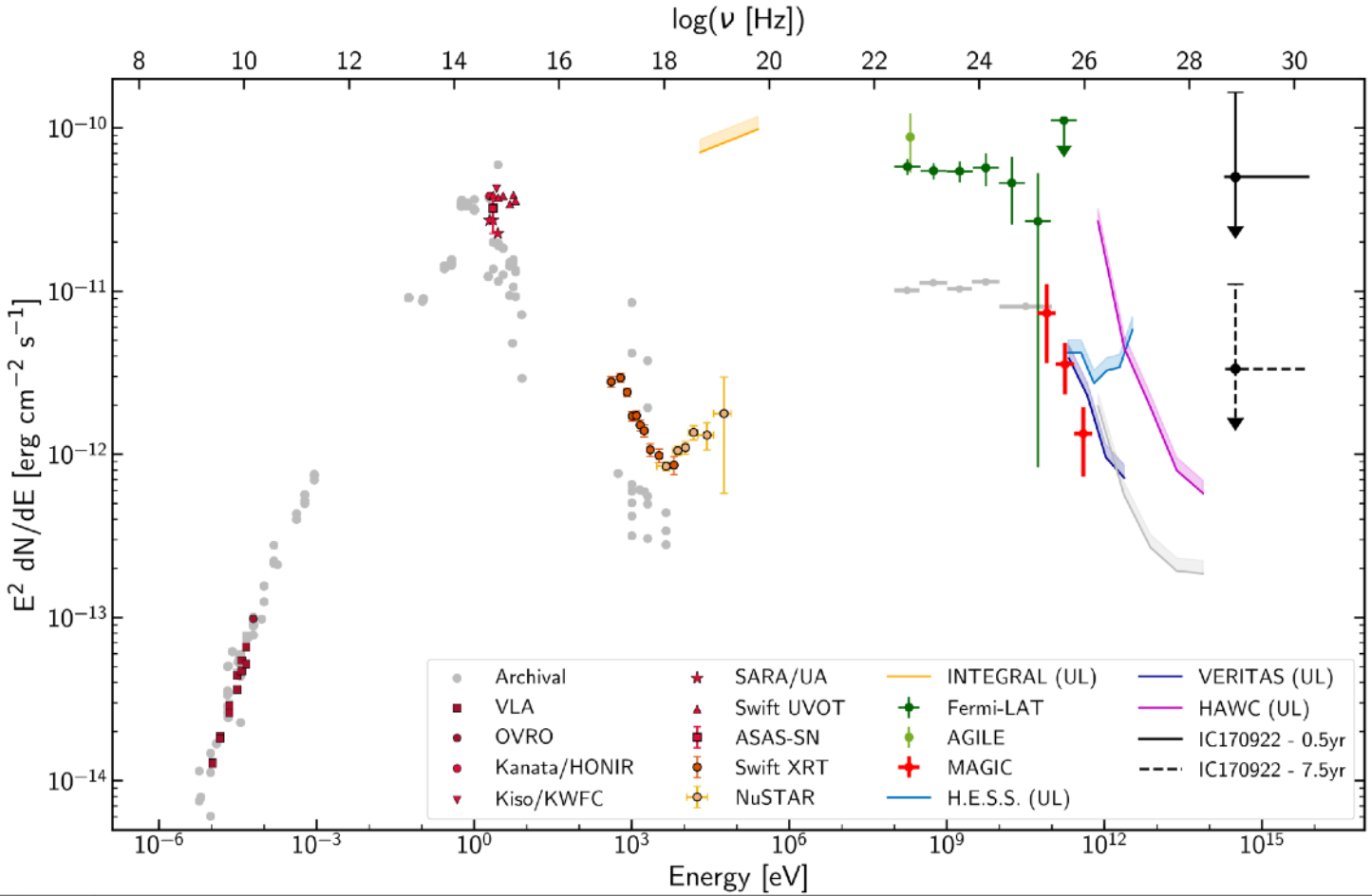
- *Fermi*-LAT detected enhanced emission from the blazar and IACTs also followed it up



The beginning of multimessenger astronomy

- Neutrino emission detected from IceCube coincident with the location of the **TXS 0656+056** blazar.

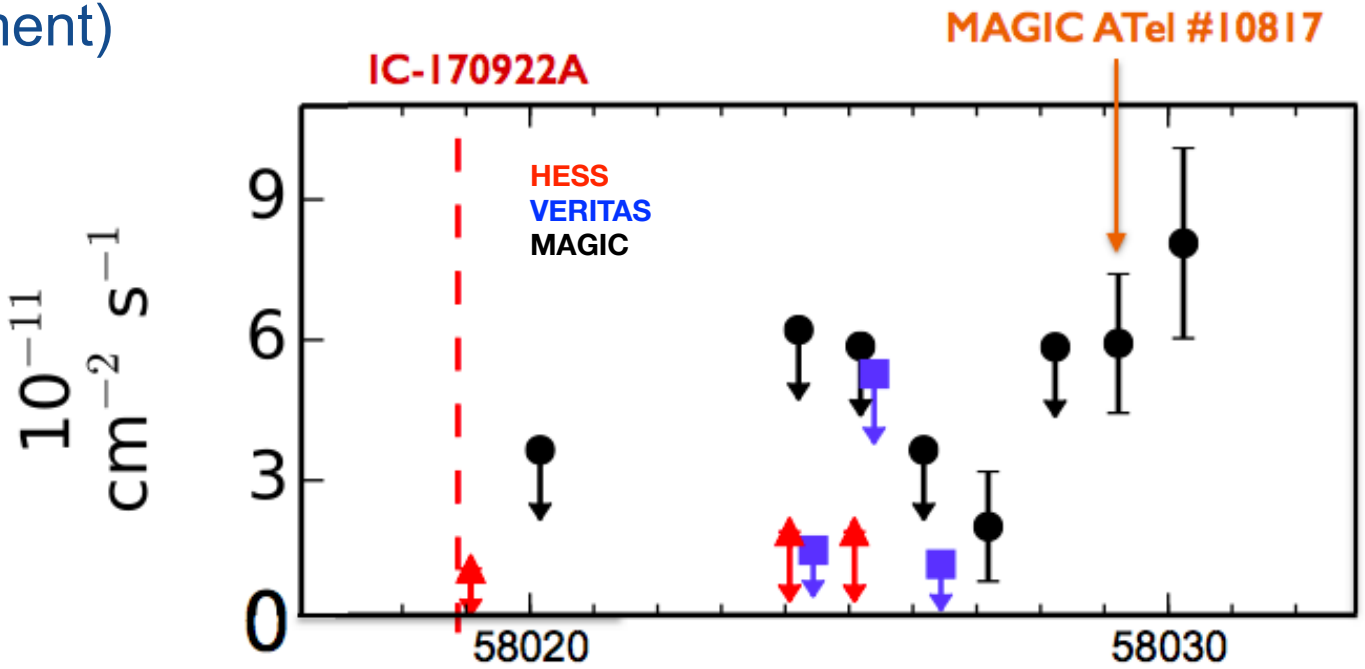
- *Fermi*-LAT detected enhanced emission from the blazar and IACTs also followed it up



IC+Fermi+MAGIC++., Science 361, 146 (2018)

TXS 0656+056

- **MAGIC:** First observation with ~32 h delay (Sep 24th 2017).
  - Sep 28th - Oct 4th -> Detection above 90 GeV.
  - Coincidence chance probability: ~3σ (space + flux enhancement)



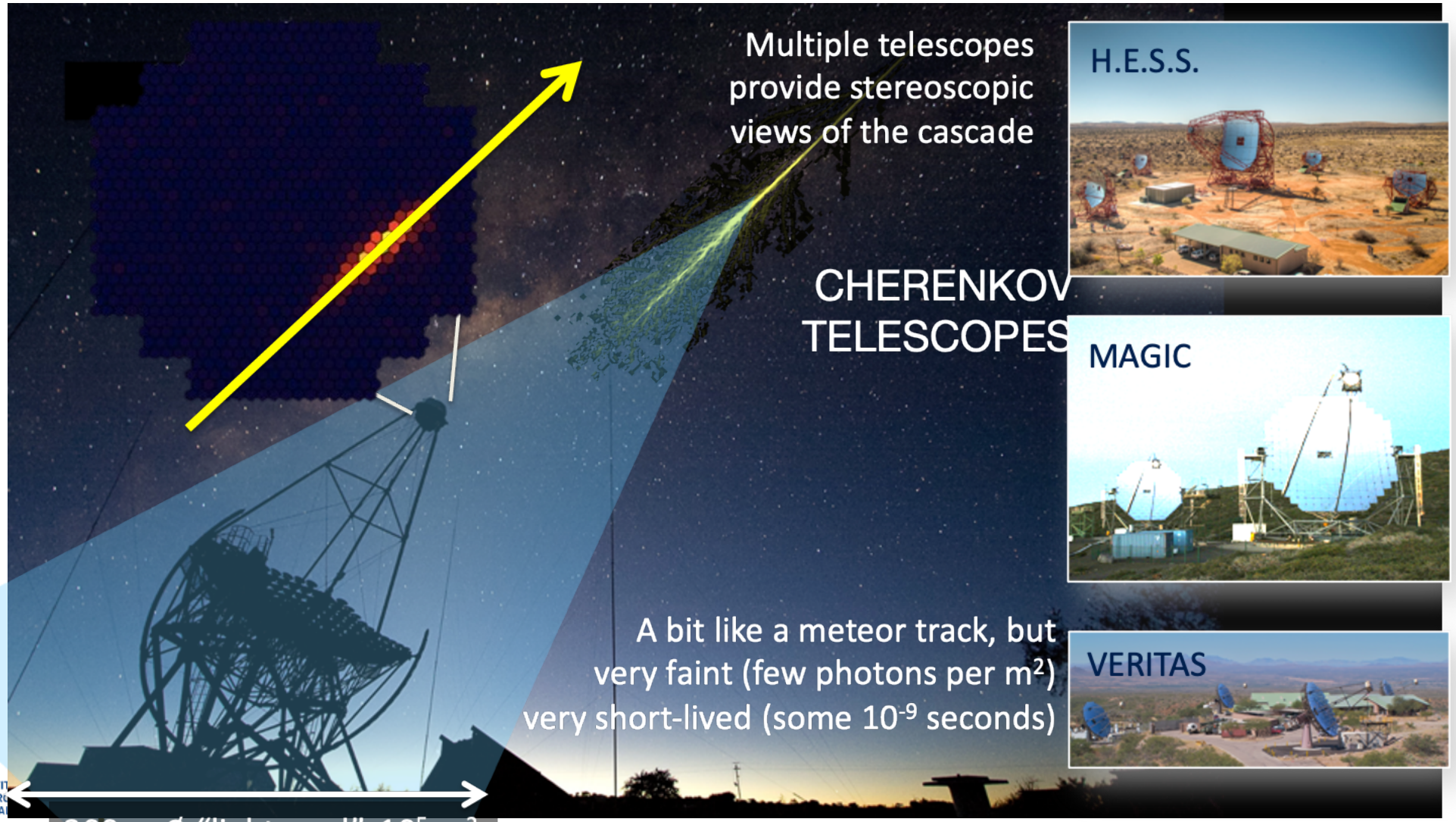
Summary

- The sky in very high energy gamma rays keeps giving us results of very high scientific value
  - Great Science produced for more than two decades.
  - Exploitation of current observatories is still worth it!
- IACT's future is already here
  - First LST of CTAO already producing scientific results
  - The rest are coming very soon (see F. di Pierro's presentation)

6/24

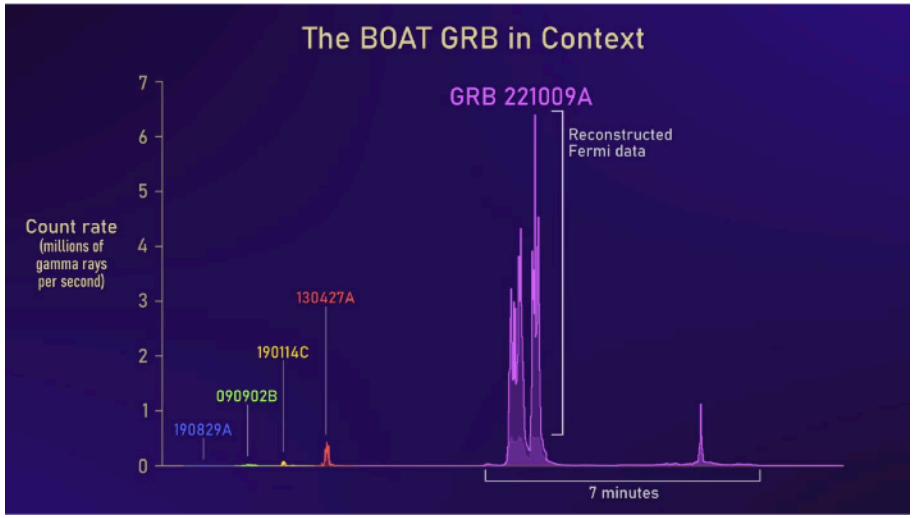
THANKS

The IACT technique



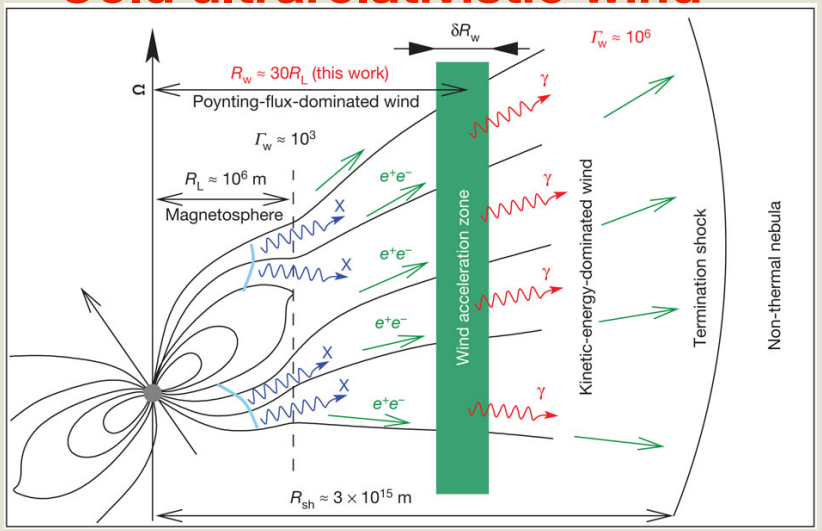
The BOAT: GRB 221009A

- Brightest of all times GRB located at z = 0.151
  - Detections in all wavelengths, even saturating some detectors
- Undetected by IACTs, but measured by LHAASO up to 13 TeV from the afterglow
  - Most stringent limits on the prompt TeV emission (emission detected only 230 s after the alert)
    - no SSC or too high absorption?
  - Data above 3 TeV hints to an additional component
  - Difficult to explain ≳ 10 TeV leptonic emission due to SSC [Das]



(A couple of) VHE pulsar models

Cold ultrarelativistic wind

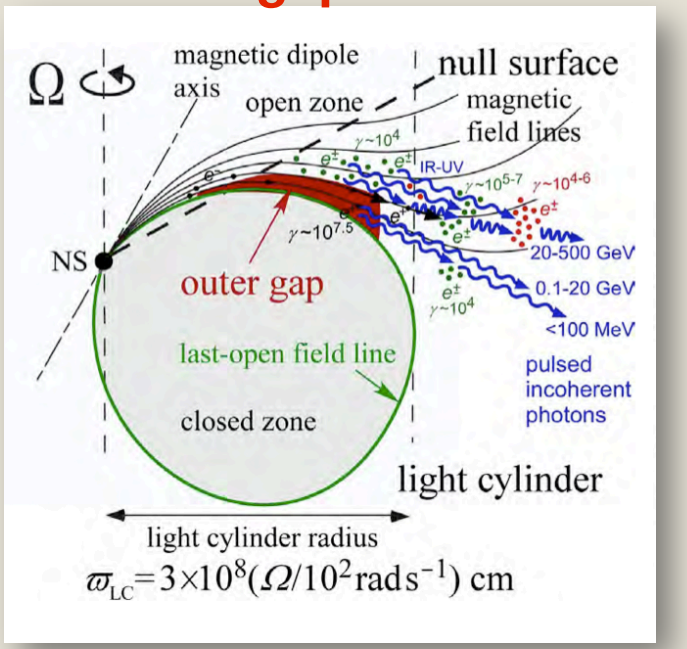


Aharonian, F. et al., Nature 482 (2012) 507

It proposes that VHE gamma-rays are produced in the wind region.

Predicts bridge emission but broader peaks than observed.

Outer gap

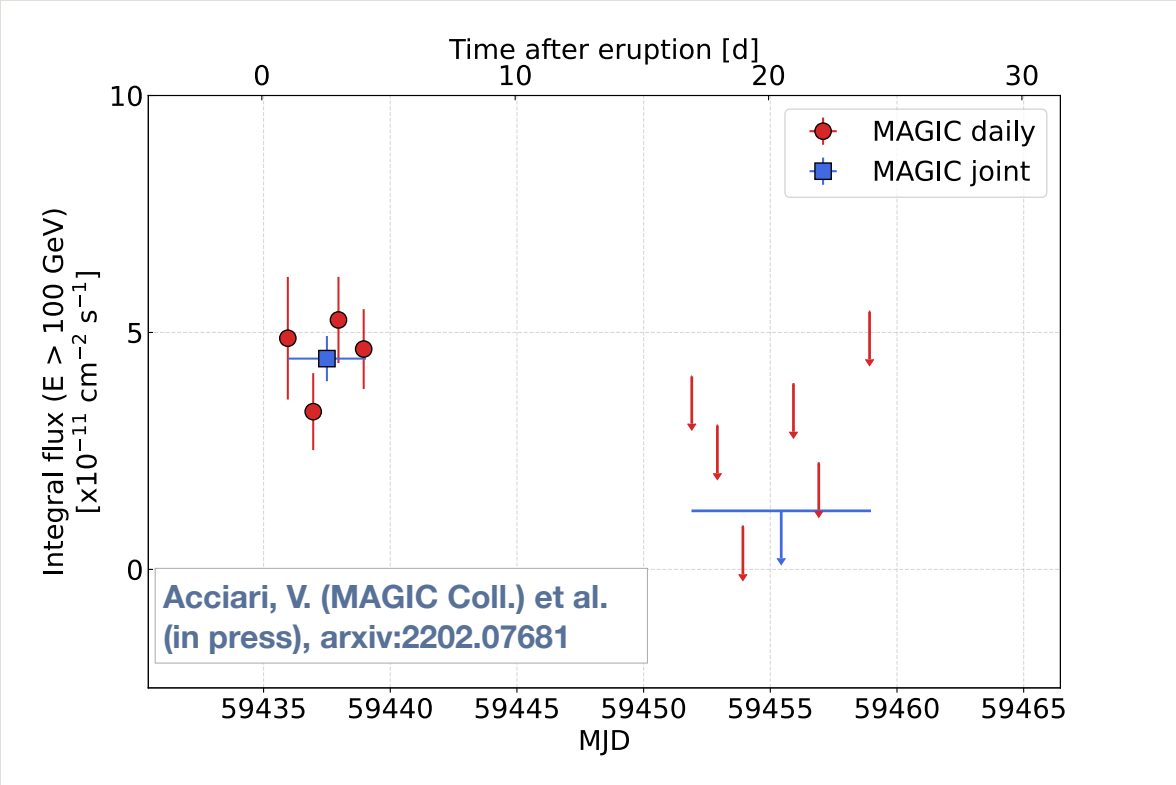


Hirotani, K., ApJ, 733 (2011) L49
Hirotani, K., ApJ, 766 (2013) 98

VHE gamma rays are produced inside the magnetosphere in an “outer gap”

It can explain the spectrum extending up to 400 GeV and also the bridge emission if the magnetic field also has a toroidal component.

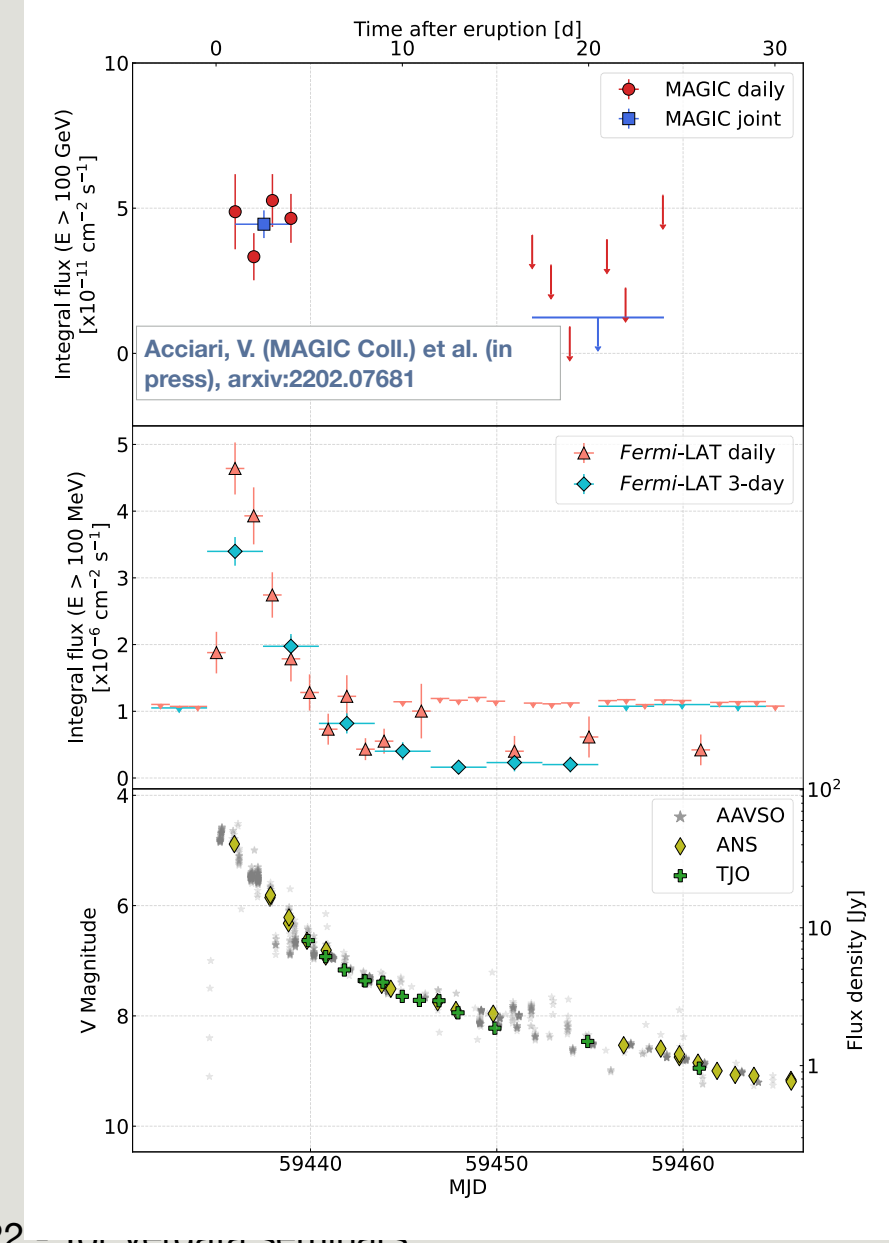
MAGIC Lightcurve



- MAGIC flux is compatible with a constant
- Bad weather prevented us to continue observations after 4 days
- After the moon break, no detection is achieved, either on individual nights or jointly

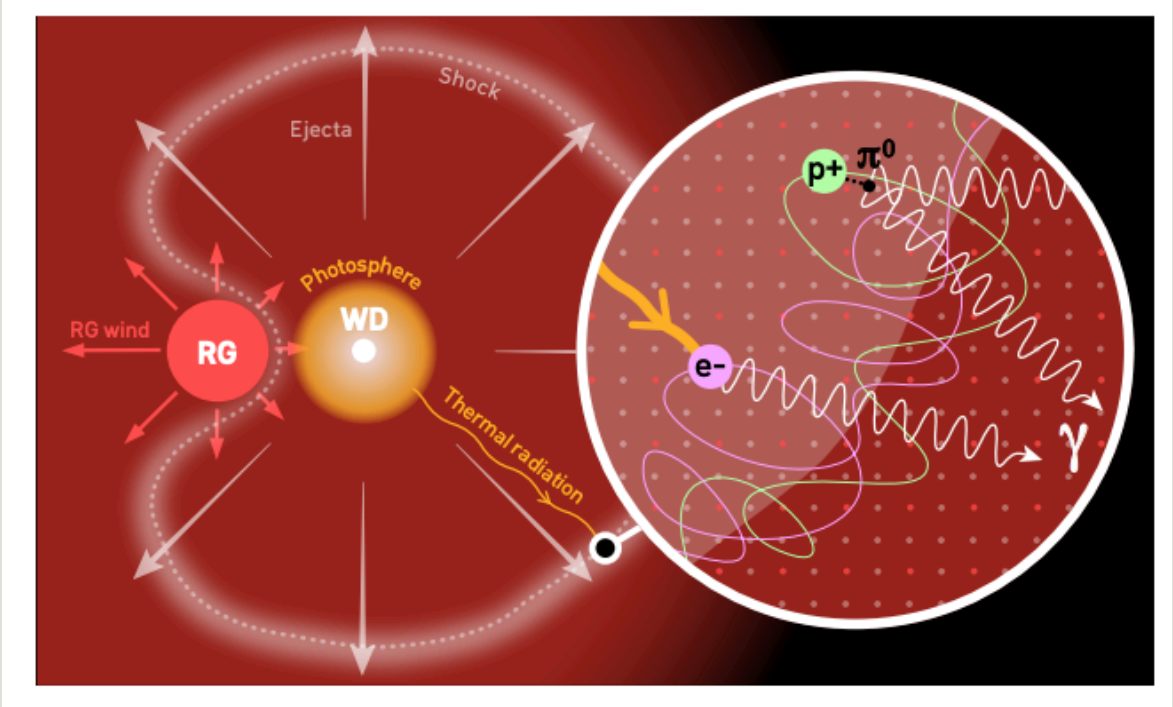
Multiwavelength Lightcurve

- Fast decay in the optical and Fermi.
- MAGIC photon flux is compatible with a constant.

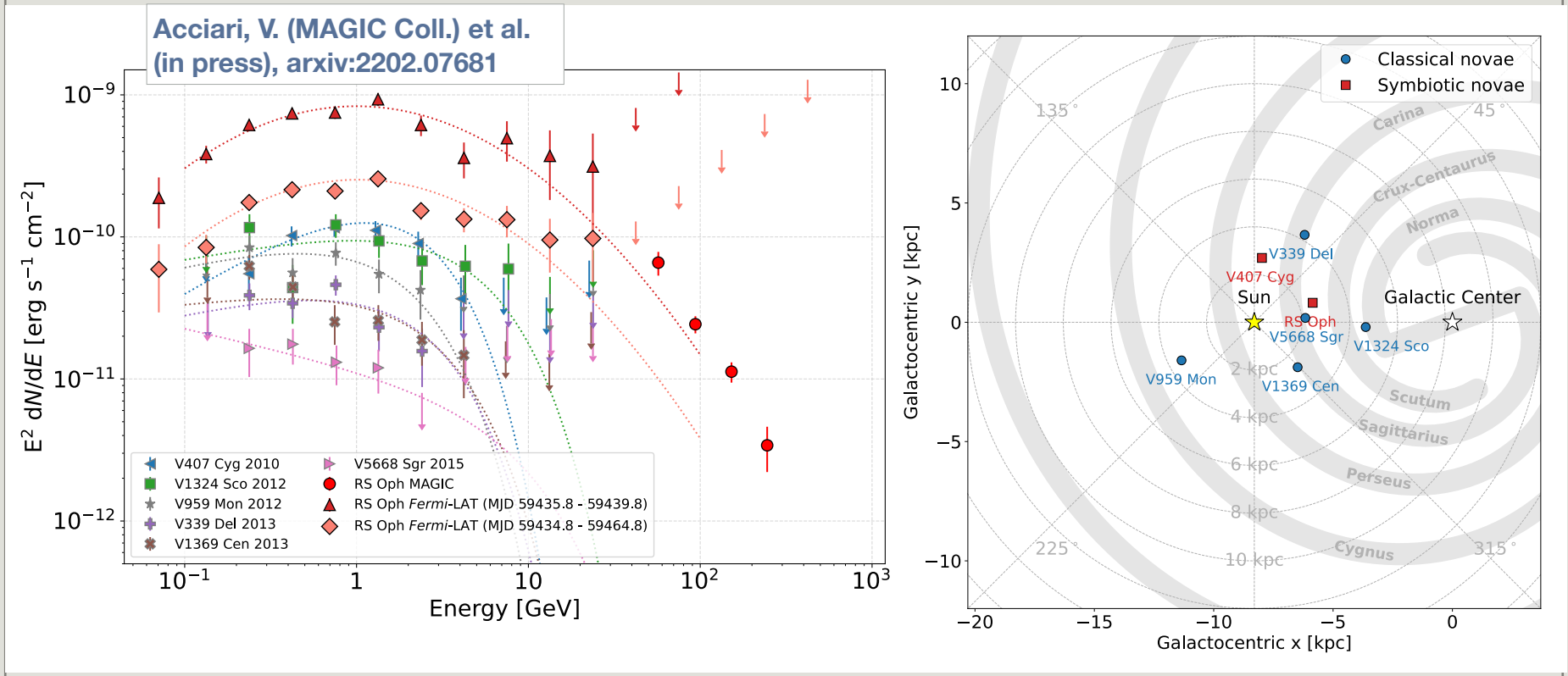


RS Oph in context

- What is happening in RS Oph so special? Why are we seeing it in VHE gamma rays and not all the other novae?

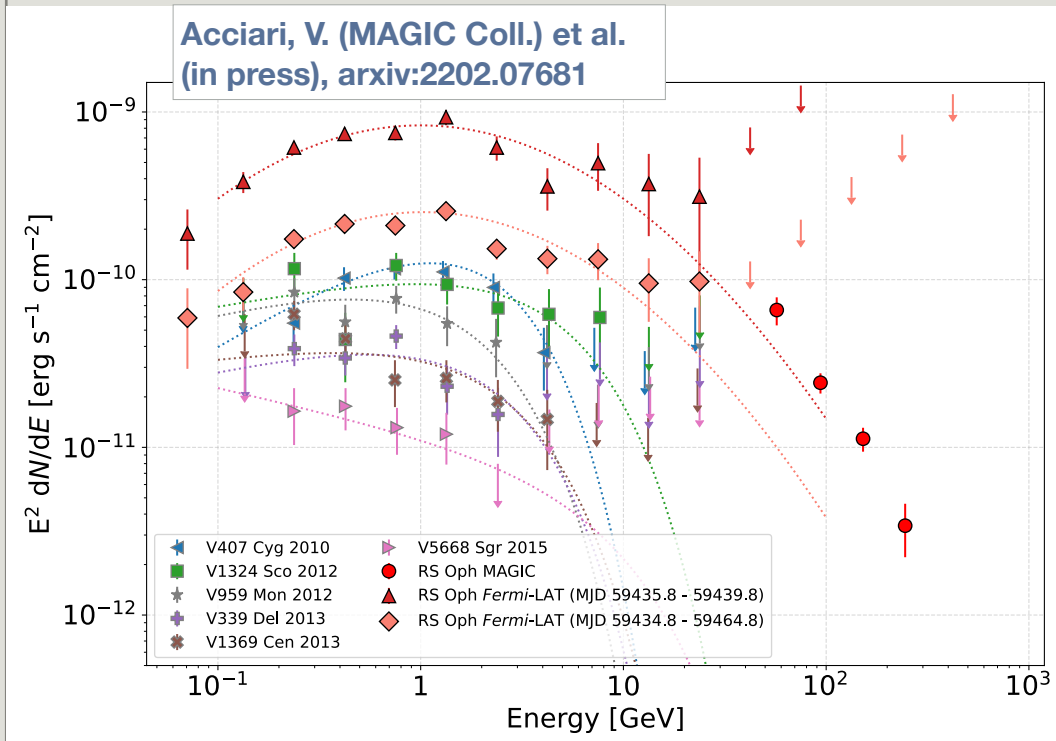


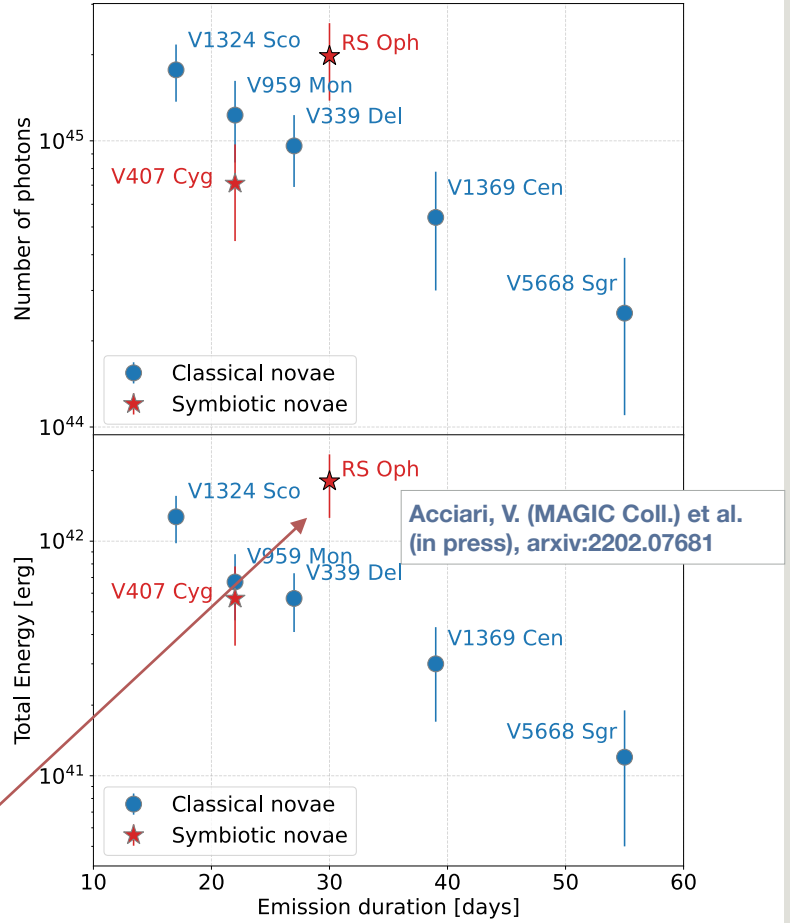
RS Oph in the context of other high energy novae



- Several novae detected by Fermi
  - RS Oph is the one with the highest flux

RS Oph in the context of other high energy novae

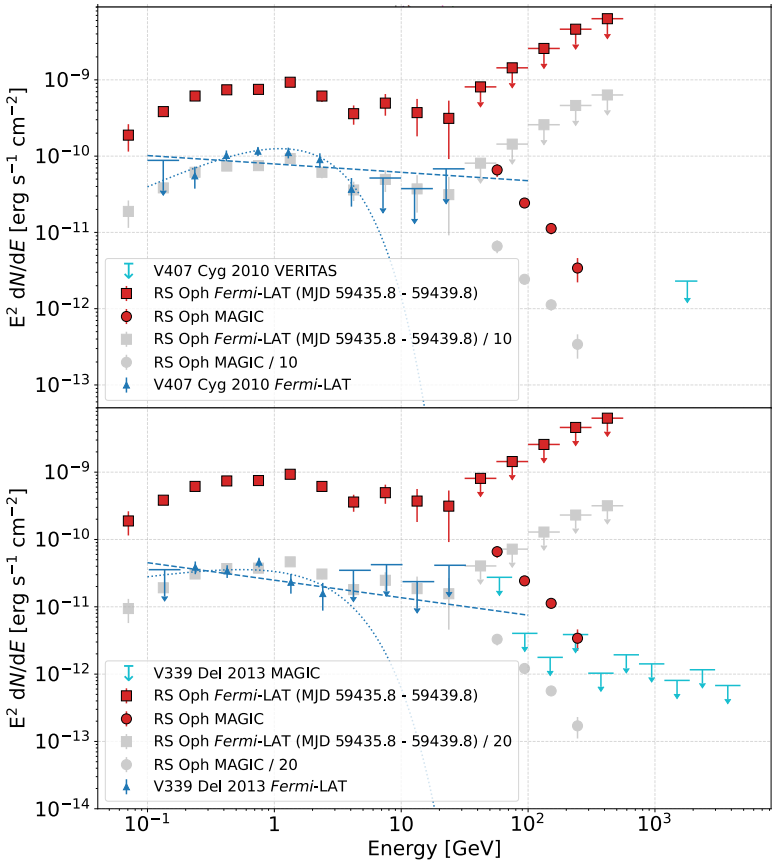




- Several novae detected by Fermi
  - RS Oph is the one with the highest flux
  - But it is also intrinsically the brightest!

Are other novae also emitting VHE gamma rays?

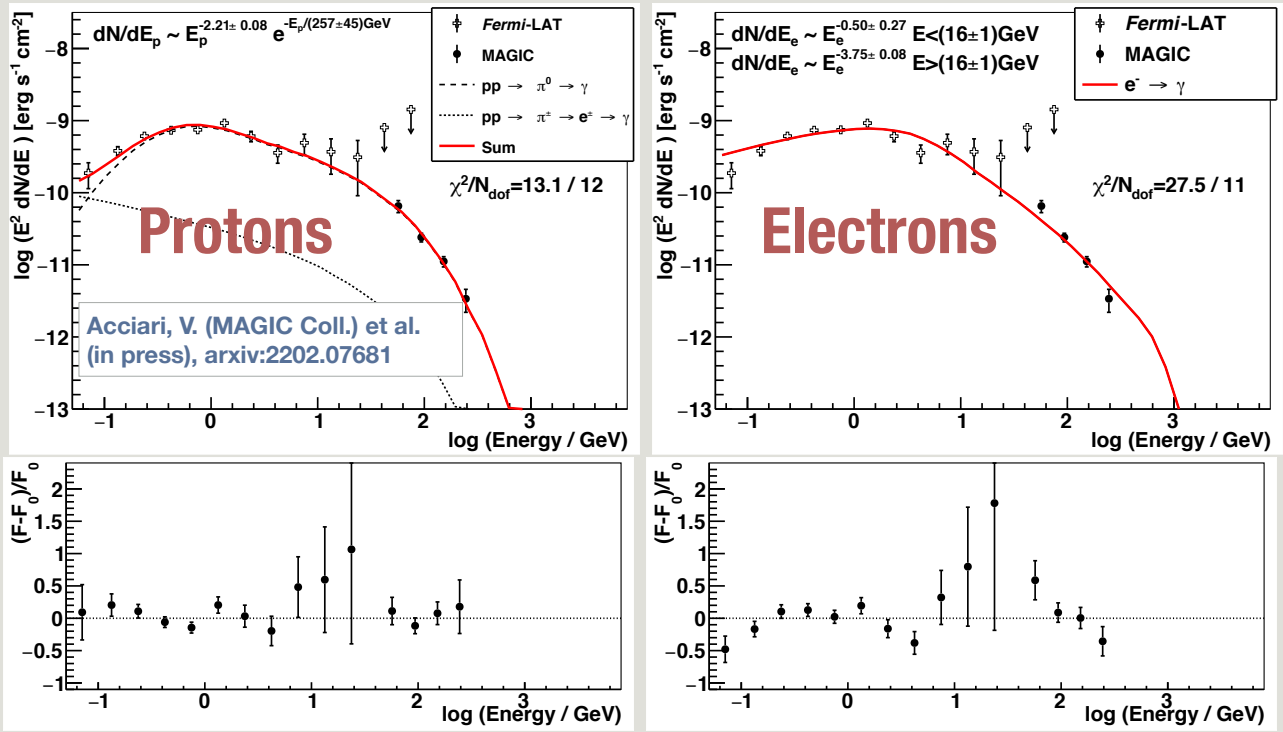
Acciari, V. (MAGIC Coll.) et al. (in press), arxiv:2202.07681



- The short answer is that we do not know:
  - Scaling V337 Del and V407 Cyg to the RS Oph level the previous MAGIC and VERITAS U.L. would not be able to constrain RS Oph-like emission.
  - It means that all previous novae may have been emitting at the same level RS Oph emitted, but we did not have the sensitivity to detect them.

Particle acceleration

- So there are some relativistic particles, but…
  - protons or electrons?

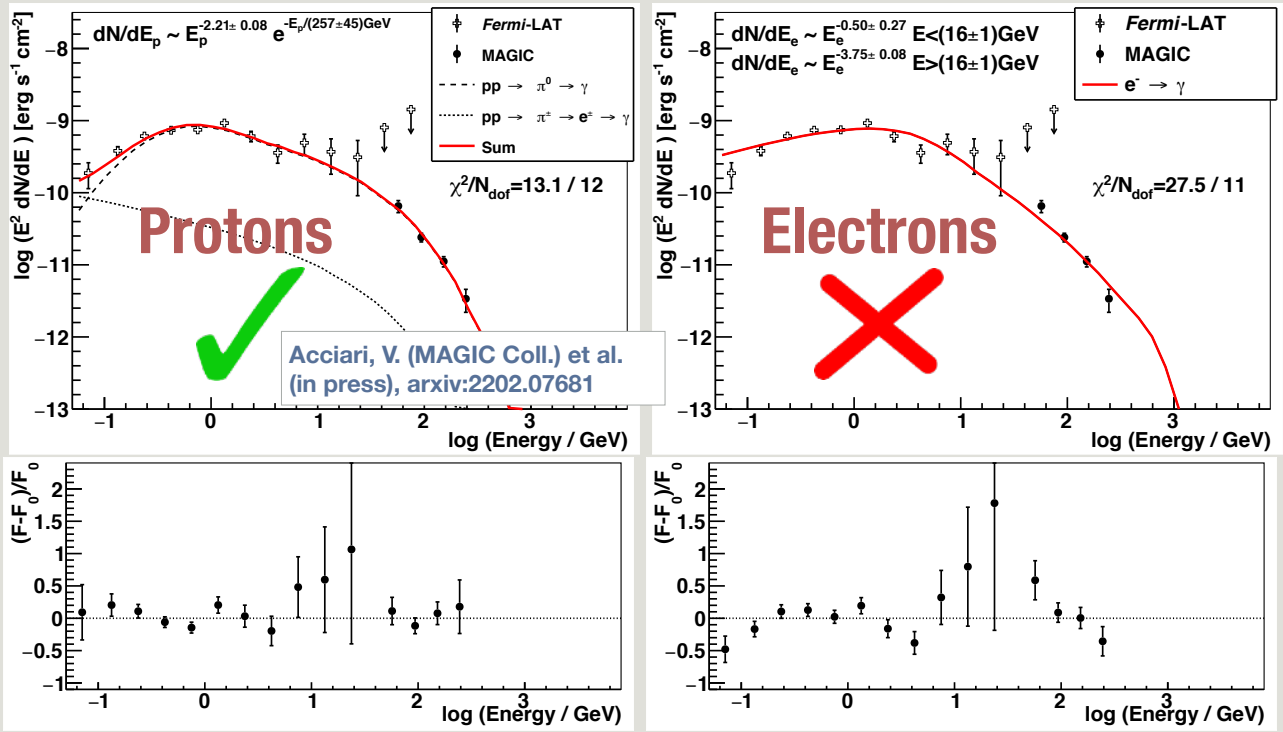


Proton acceleration

[Submitted on 15 Feb 2022 (this version), latest version 22 Feb 2022 (v2)]

Gamma rays reveal proton acceleration in thermonuclear novae explosions

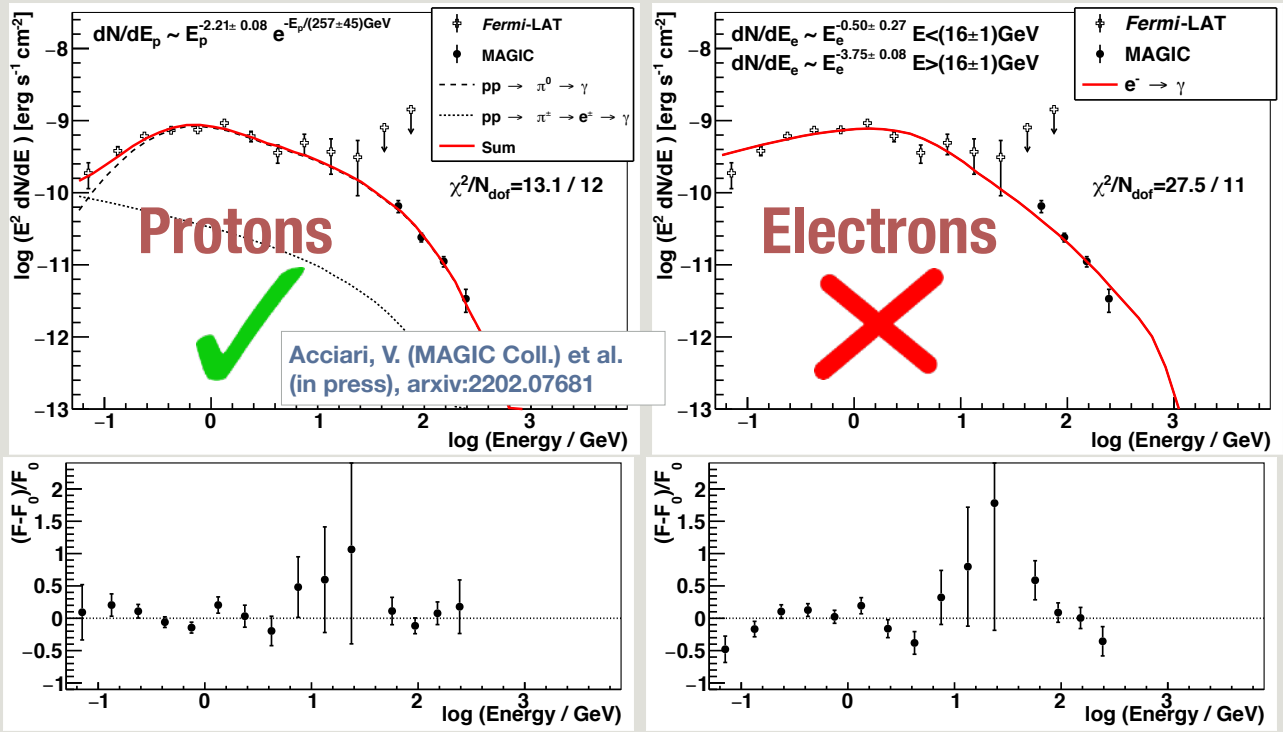
MAGIC Collaboration: V. A. Acciari (1), S. Ansoldi (2,42), L. A. Antonelli (3), A. Arbet Engels (4), M. Artero (5), K. Asano (6), D. Baack (7), A. Babić (8), A.



- Protons are favored over electrons because:
  - 1) they can be injected with a natural -2 spectral index, while electrons require an ad-hoc spectral break in the injection spectrum

Proton acceleration

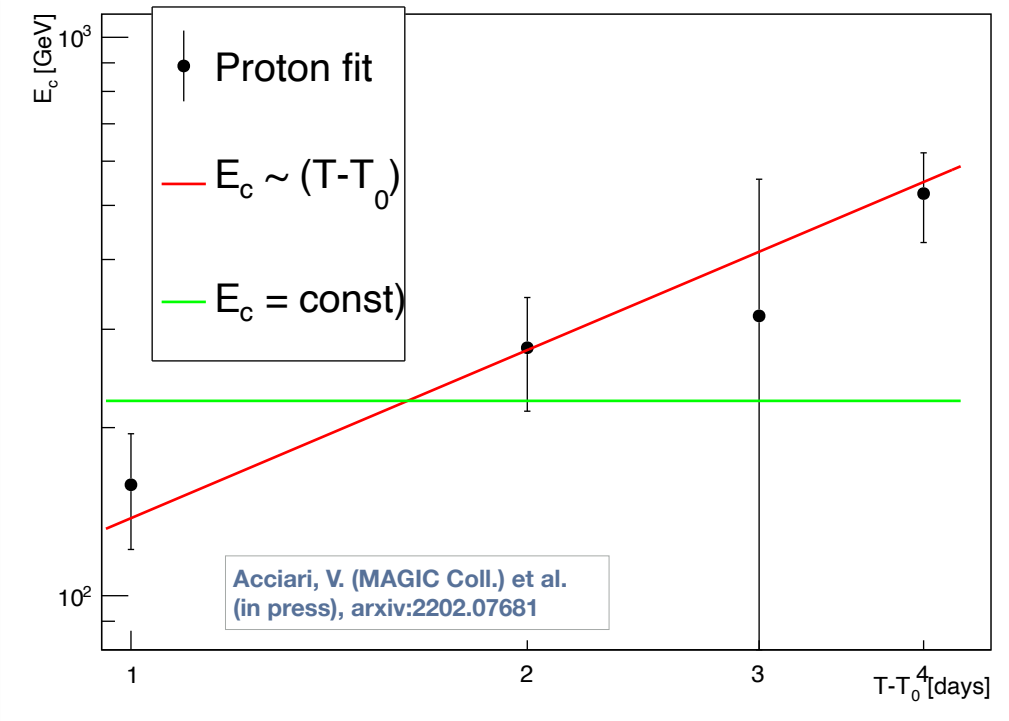
- So there are some relativistic particles, but…
  - protons or electrons?



- Protons are favored over electrons because:
  - 2) the chi2 of the fit is much better for protons over electrons

Proton acceleration

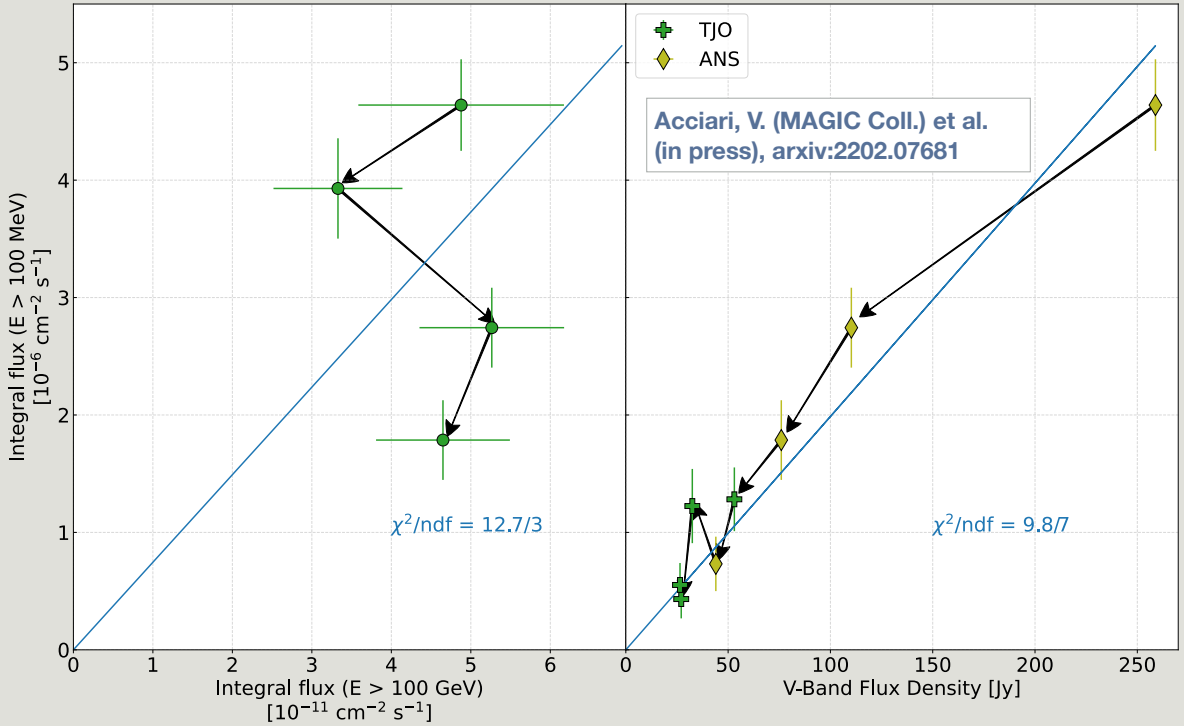
- So there are some relativistic particles, but…
  - protons or electrons?



- Protons are favored over electrons because:
  - 3) there is a hint of spectral hardening in the energy of the protons => protons do not cool down and their acceleration is not immediate.

Proton acceleration

- So there are some relativistic particles, but…
  - protons or electrons?



- Protons are favored over electrons because:
  - 4) optical and high energy emission follow a similar decay => IC emission should decay faster because of the photosphere expansion

Contribution to Galactic CRs

- These protons would contribute to the sea of CRs that we have in the galaxy.
  - The total contribution of novae is in any case < 0.2 % compared to that of supernovae (remnants)
- The region over which they can dominate over the CR sea is < 1 pc for one eruption.
  - <10 pc for multiple eruptions (recurrent novae)