Highlights of Galactic observations with the MAGIC telescopes

Daniela Hadasch for the MAGIC Collaboration

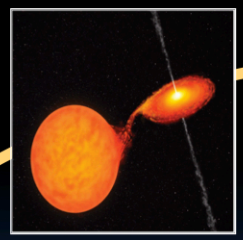
Overview
Infinite non-thermal Universe

MAGIC

Pulsars/PWN

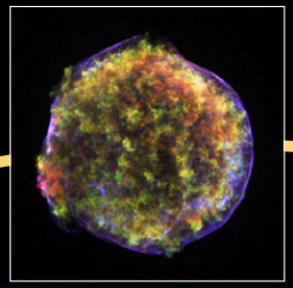
NS dynamo winds

Binaries



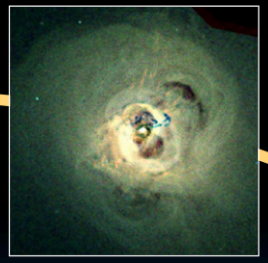
Jets, winds

SNRs



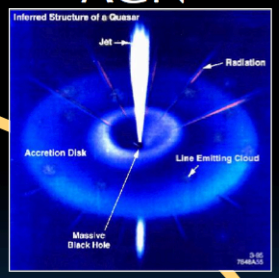
Shocks
Fermi Mech.

Starbursts



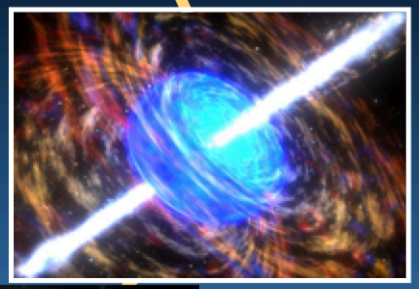
SN activity
Cosmic rays

AGN

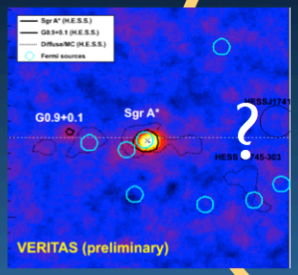


SMBH accretion, jets

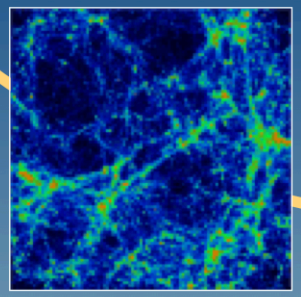
GRBs



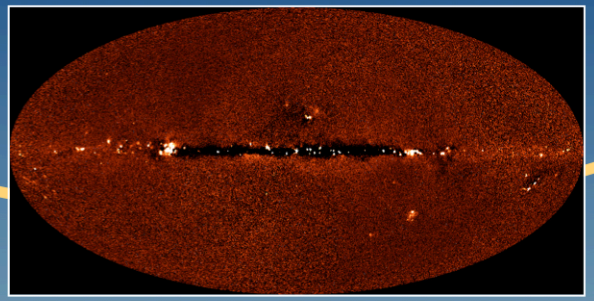
VHE γ-rays



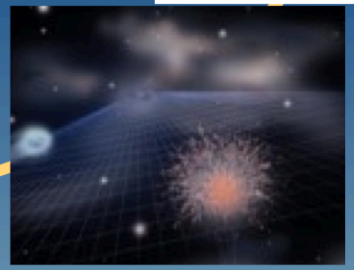
Unknowns
(Gal Center)



Dark Matter



Cosmological Fields



PBHs, QGrav

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Talk by Yusuke Suda on Wednesday!

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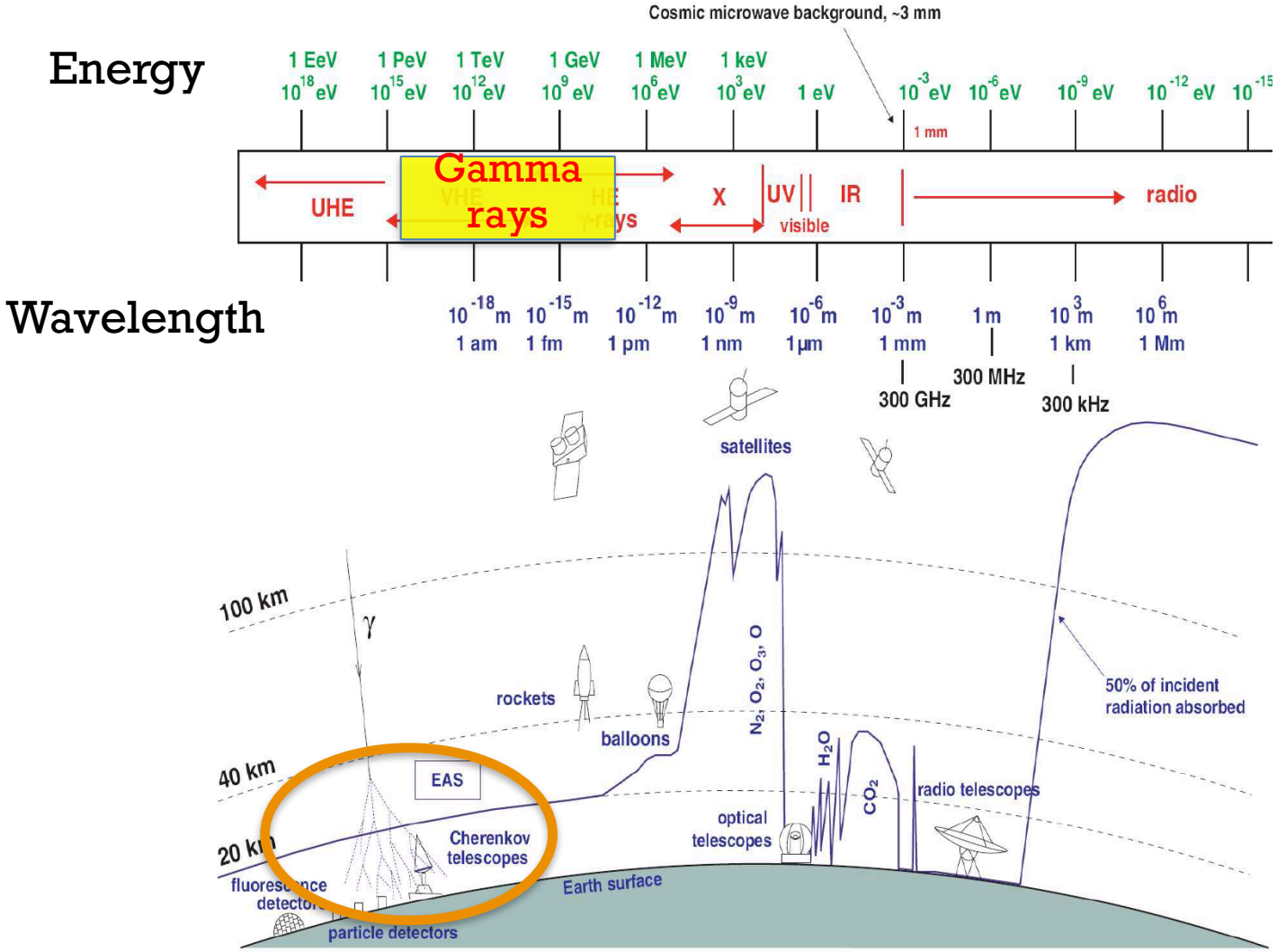
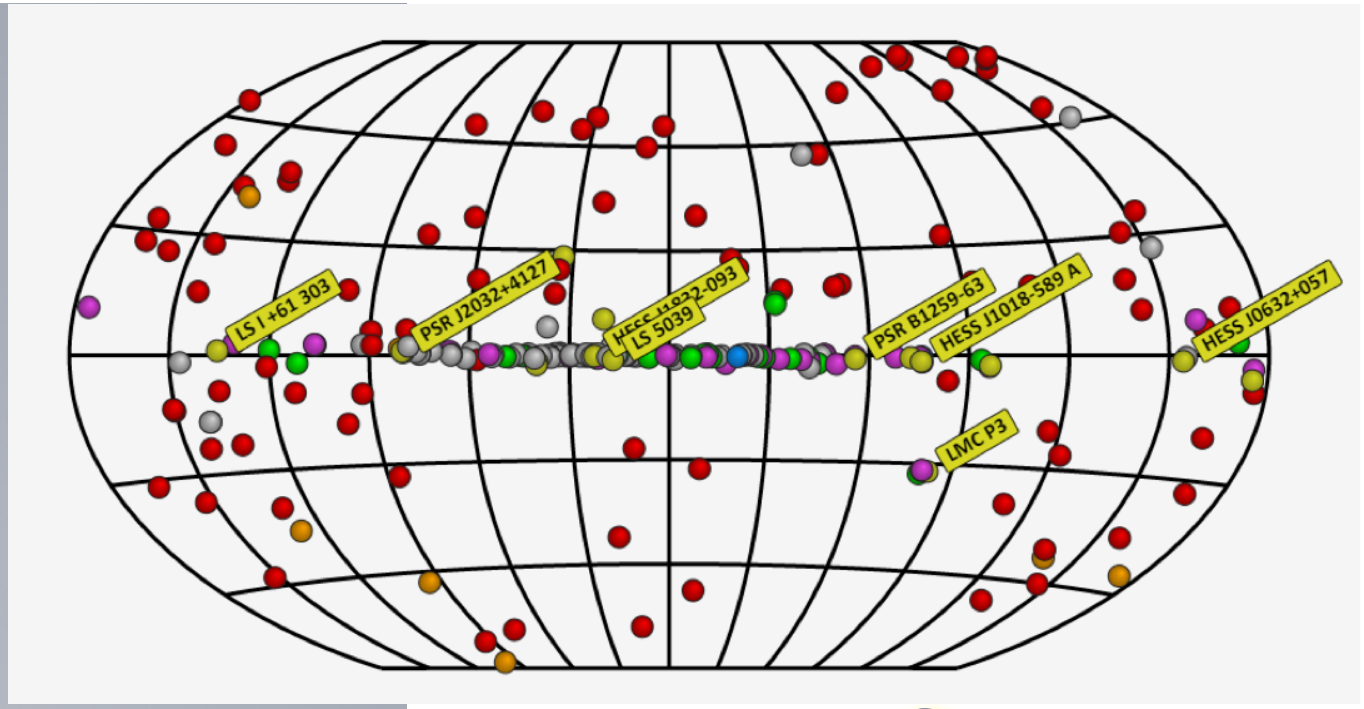
Observing the infinite Universe with Imaging atmospheric Cherenkov Telescopes



The MAGIC telescopes

- Located on La Palma (Spain), 2200 m above sea level
- 2 x 17 m diameter mirror dishes
- Energy threshold: 50 GeV (15 GeV with SUM-trigger)
- FoV: 3.5º, Angular resolution: 0.1°
- Energy resolution: 15% at 1TeV

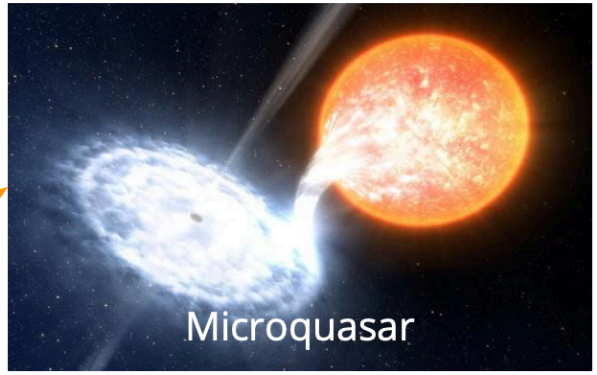


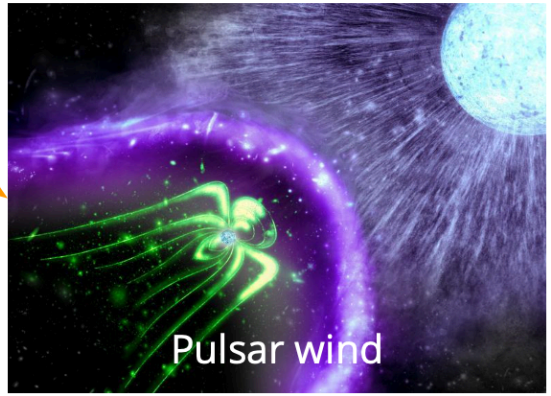
Gamma-ray binaries

MAGIC

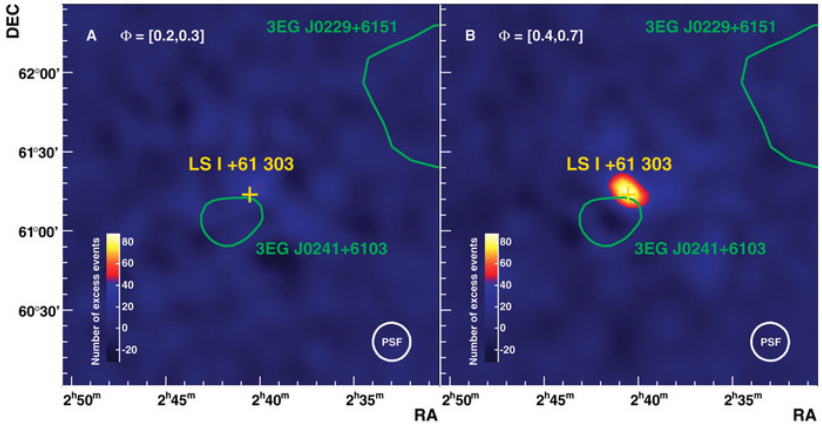
Gamma-ray binaries

- Systems consisting of a compact object and a companion star.
- Typically show broadband emission from radio up to X-rays and gamma rays.
- Two main scenarios to explain the observed emission.
  - Microquasar: compact object + star
  - Pulsar wind: non-accreting pulsar + massive star

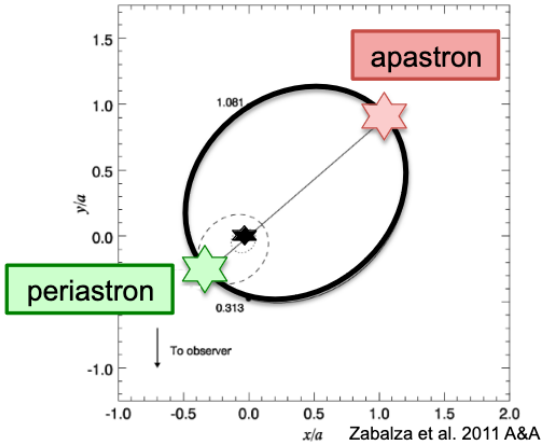




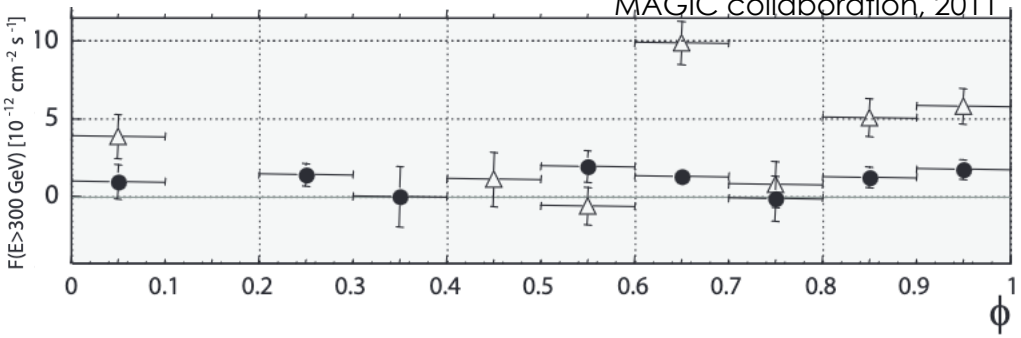
LS I +61 303



- System consists of compact object and Be star surrounded by decretion disk
  - Compact object recently discovered to be a pulsar (Weng et al. 2022)
- Discovery at Very High Energies by MAGIC
  [MAGIC Coll. Science 312, 5781 (2006)]
- Orbital period: (26.496 +/- 0.0028) days
  (Gregory et al. 2002)
- Superorbital period
  - First detected in radio: (1667 +/- 8) days (Gregory et al. 2002)

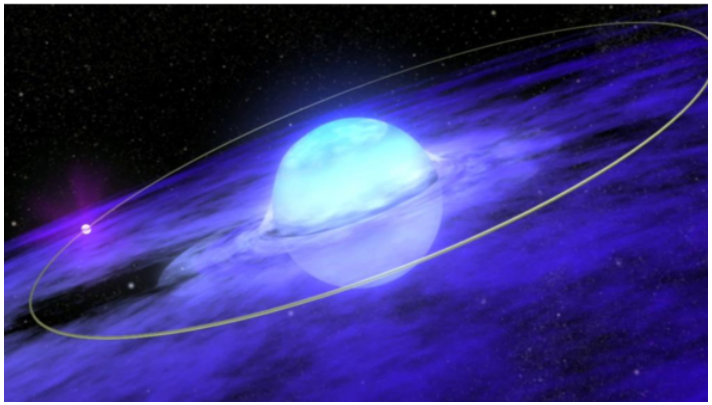


MAGIC collaboration, 2011

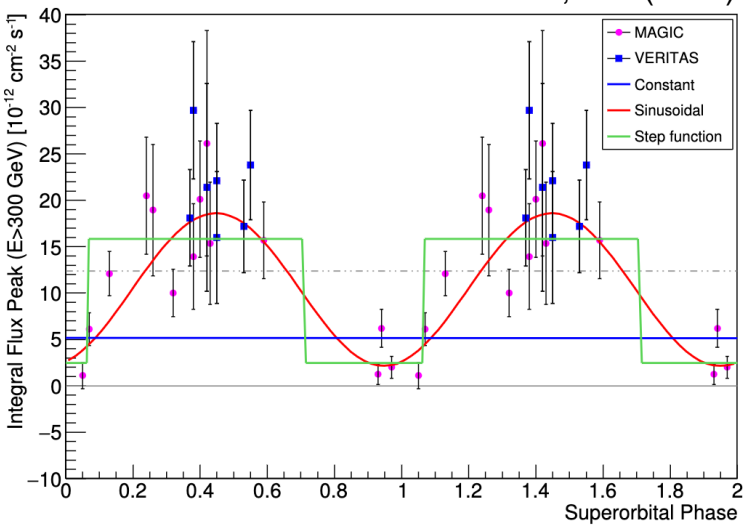


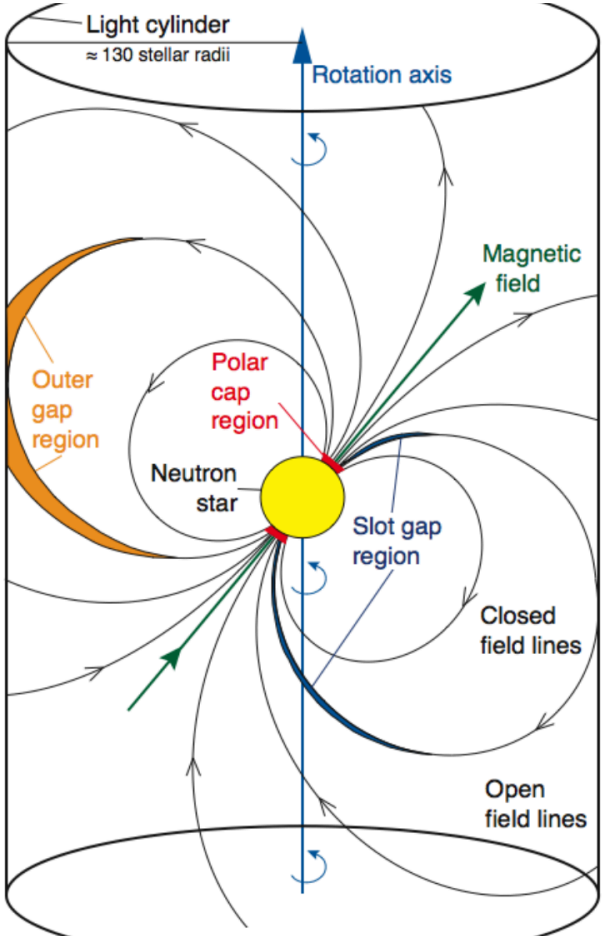
LS I +61 303

- TeV flux of the periodical outburst in orbital phases φ = 0.5–0.75 was found to show **yearly variability consistent with the long-term modulation** of ~4.5 years found in the radio band
  - The complete data span two super-orbital periods
- Modulation could be explained with flip-flop model (Torres et al. 2012)
- No evidence for a correlation between TeV emission and mass-loss rate of the Be star found
  - But this may be affected by the strong, short-timescale (as short as intra-day) variation displayed by the Ha fluxes
  - Maybe possible correlation in HESS J0632+057?



A&A 591, A76 (2016)

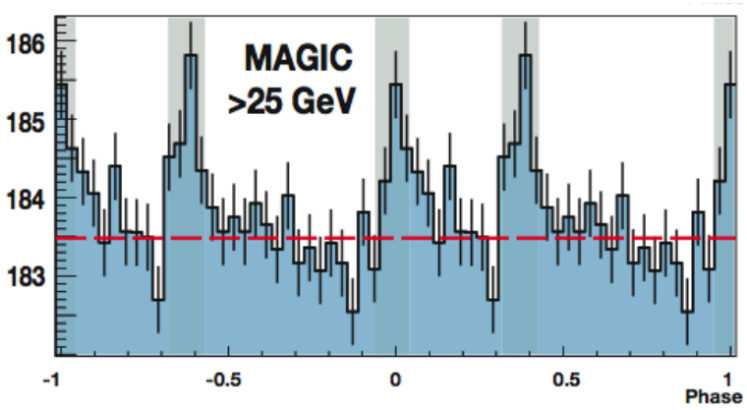




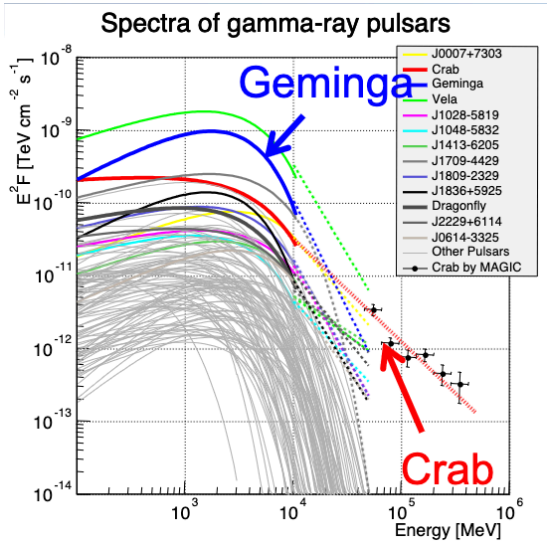
Pulsars

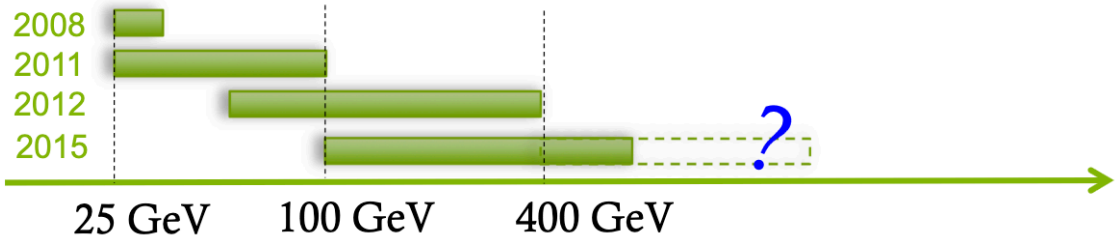
Fast rotating neutron stars

Pulsars - Crab pulsar



- Fast rotating neutron stars
  - **Crab pulsar**: 33ms & **Geminga pulsar**: 237ms
- 2008: **Detection of a pulsar at 25 GeV** with mono-MAGIC —> Polar Cap excluded (Science 322, 1221, 2008)
- 2011: VERITAS detected **pulsation >100 GeV**. (Science 334, 69, 2011)
- 2011/12: **spectral measurement 25-400GeV** (ApJ 742, 42, 2011)
  - Curvature Radiation questioned (A&A 540, A69, 2012)
- 2014: **Bridge emission** above 50 GeV. (A&A, 565, L12, 2014)



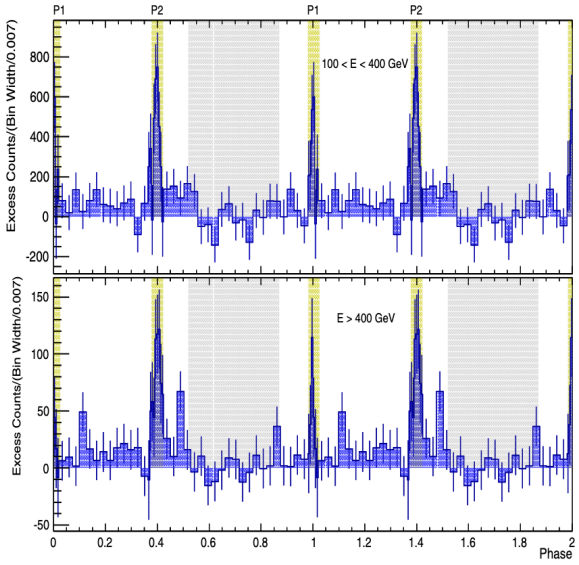


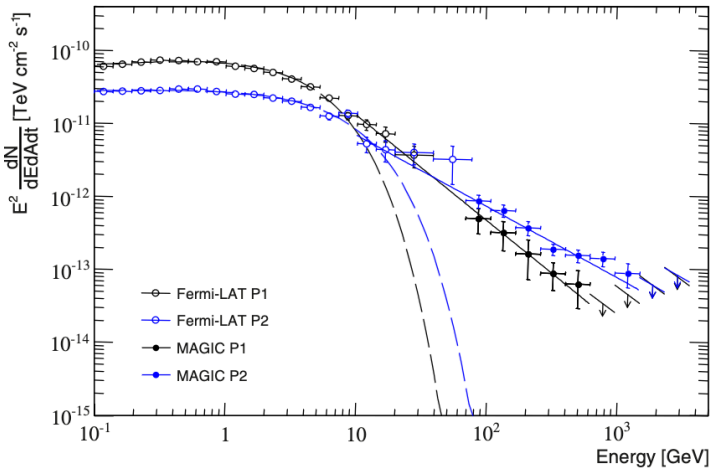
Crab pulsar (PSR J0534+220)

- **Most energetic pulsed emission ever detected up to 1.5 TeV** (A&A 585, A133 (2016))
- Spectra of two peaks follow two different power-law functions from 70 GeV to 1.5 TeV
  - Connect smoothly with spectra measured >10 GeV by the Fermi-LAT

➡ Inverse Compton scattering off low-energy photons as emission mechanism

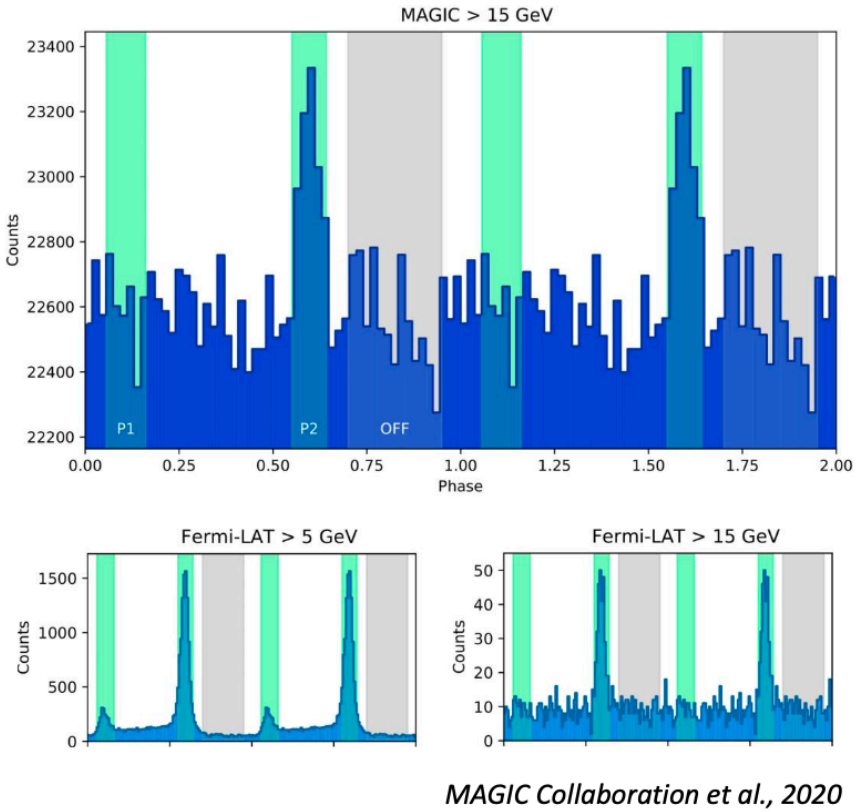
➡ Gamma-ray production region in vicinity of the light cylinder





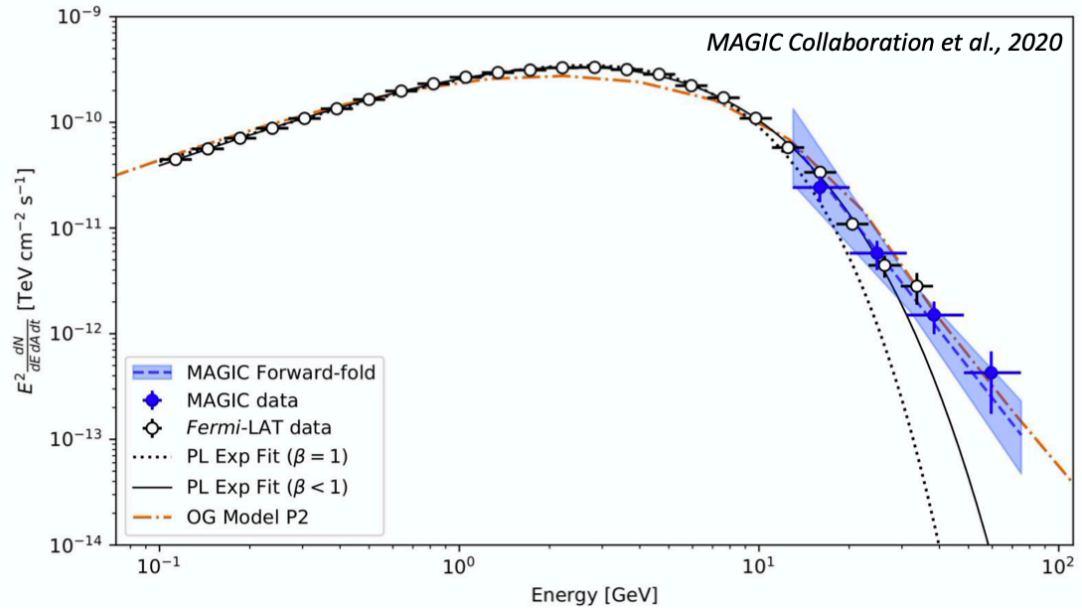
Geminga pulsar (PSR J0633+1746)

- Radio-quiet, 300 ky, d=250pc
- **Third known VHE pulsar** after Crab and Vela pulsar (A&A 643, L14 (2020))
  - Detection between 15 and 80 GeV
  - P2 detected with significance >6 sigma
  - First middle-age pulsar detached to emit at such high energies.



MAGIC Collaboration et al., 2020

Geminga pulsar: spectrum



- MAGIC measured P2 spectrum in 15 - 75 GeV range
  - Power-law like spectrum with spectral index Γ ~ 5.62
- Joint MAGIC/Fermi-LAT rules out sub-exponential cut-off at a 3.6 sigma level
  - Hinting a power-law tail emission at E > 15 GeV

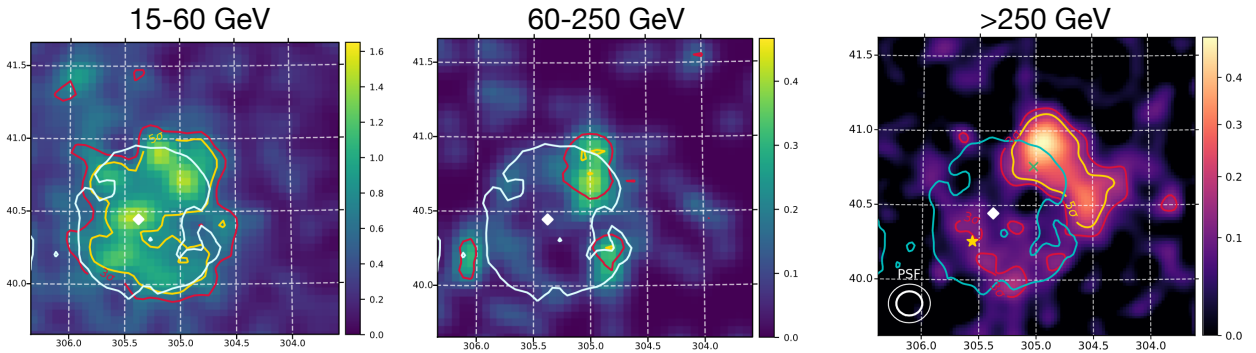
➡ **Transition from curvature radiation to Inverse Compton Scattering of particles accelerated in the northern outer gap**

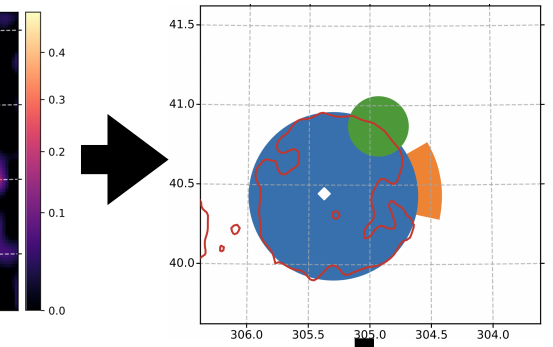
Supernova remnants

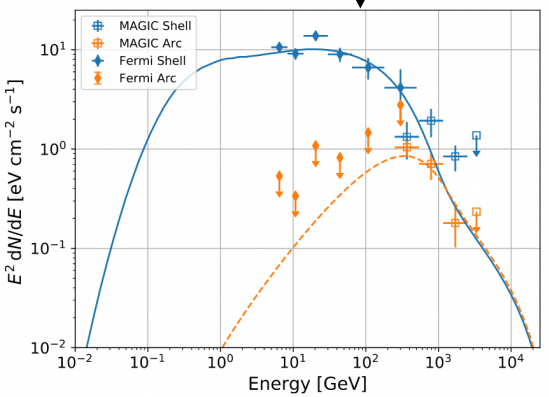
Evidence for cosmic ray escape

MAGIC

Gamma-cygni SNR G 78.2+2.1



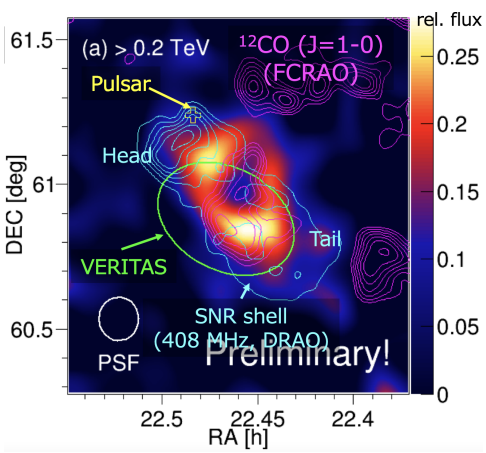


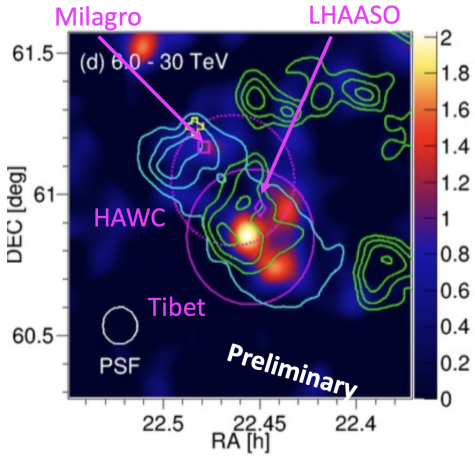


A&A 670, A8 (2023)

- Using MAGIC and *Fermi*-LAT, we studied energy dependent morphology and identified **there emission regions:**
  - Inside of the SNR (blue), region of escaped Cosmic Rays (CR, orange), potential SNR-MC interaction zone (green)
- Unique SNR as **low energy CR are still confined inside and high energy CR escaping**; in the SNR-Molecular Cloud zone also LE CR can escape due to wave damping.
- Hadronic, quasi linear diffusive shock acceleration model with CR escape can describe date in a constant way.
- Could determine that the level of turbulence has to decrease with time and the maximum energy follows $p_{\mathrm{max}} \propto t^{-2.55}$

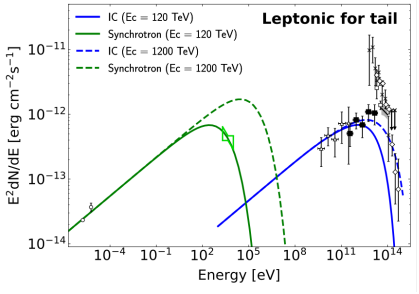
Boomerang PWN/SNR G106.3+2.7 Potential PeVatron

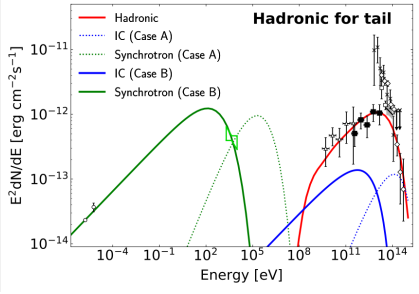




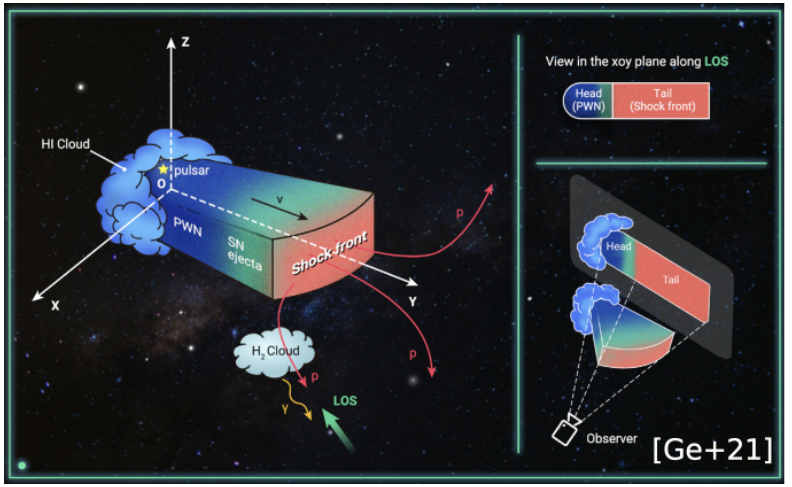
A&A 671, A12 (2023)

Leptonic scenario **cannot** explain
IACT and Air Shower array data with single population





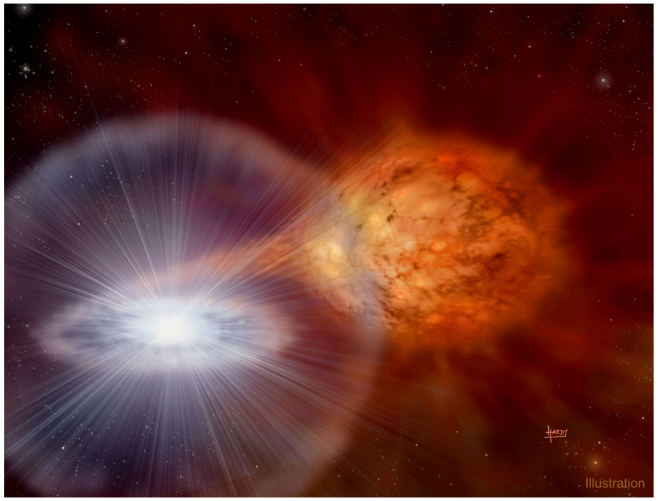
- MAGIC determined two emission regions associated with the SNR's so-called **head and tail**
- **At highest energies (~30TeV) only emission from tail** was detected; hence we associated the flux measured by air shower arrays with the tail
- **Emission from Head** can be modeled with either a leptonic or hadronic emission scenario
- **Emission from Tail** can only be modeled by a single particle population in the hadronic scenario



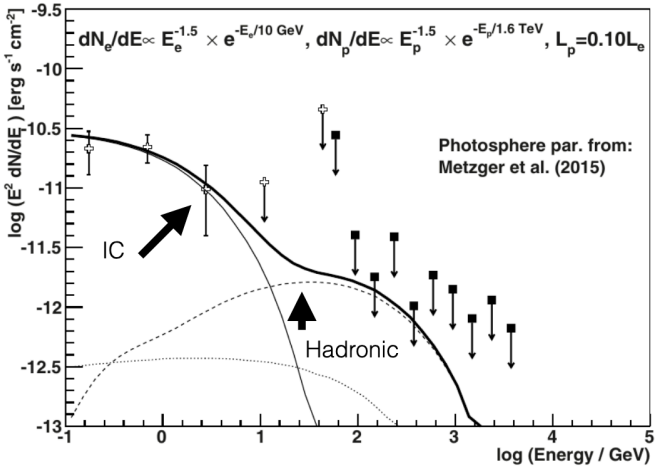
New VHE source class Novae

Recurrent nova in a symbiotic binary RS Ophiuchi

- **Thermonuclear explosions** caused by accumulation of material from a donor star on the surface of a white dwarf.
  - RS Oph: Major outbursts every ~15 years
- MAGIC initiated a **follow up program** on novae in 2012
  - No detection until RS Oph
- **VHE (>100 GeV) data is critical** to understand emission mechanisms
- **Latest outburst of RS Oph** on 2021.08.08 UT ~22:20
  - MAGIC observed it during its **peak emission**



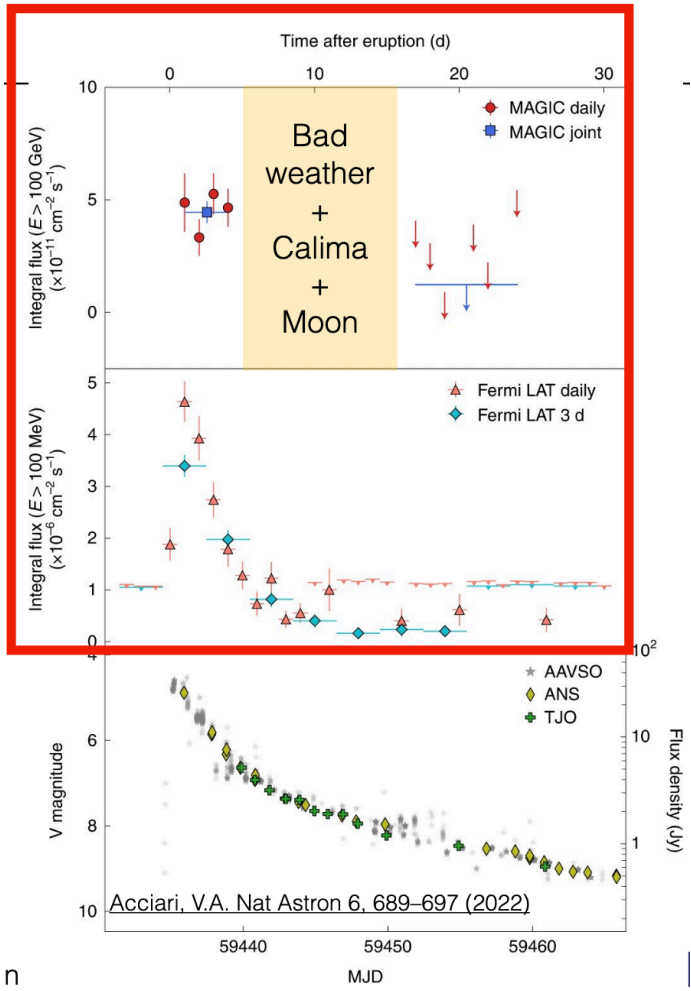
Credit: David A. Hardy



MAGIC Coll., A&A, 582 (2015)

Temporal development RS Ophiuchi

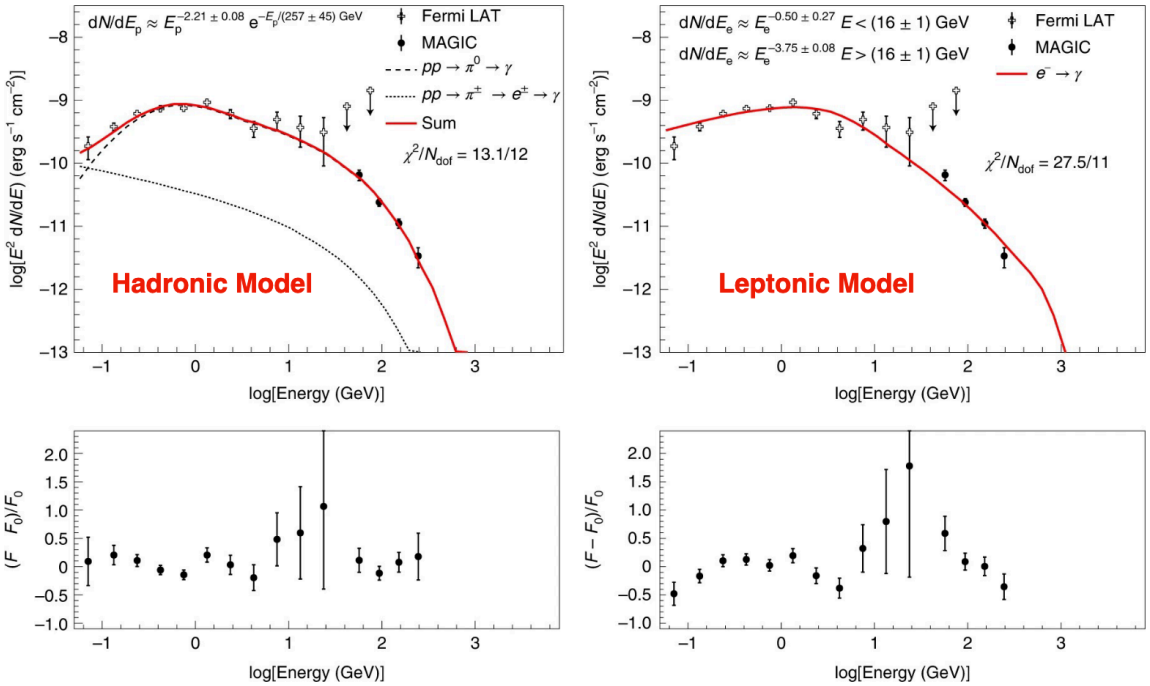
- HE shows **rapid rise & fall**: exponential halving time (2.20 ±0.18 days)
  - Brightest nova to date
- **First four days** of MAGIC observations (August 09-12) yield a VHE signal with a significance of 13.2σ
  - No MAGIC detection as after August 25th
- VHE photon flux >100 GeV **constant** over first 4 days while HE signal **decreases** by factor of <2
- **Photometry**: TJO and ANS **simultaneous** data with MAGIC
  - Emission described with T_{ph} 10800K ->7680 K and R_{ph} = 200 $R_\odot$



Gamma-ray modelling RS Ophiuchi

- **Time dependent modeling** based from MAGIC Coll., A&A, 582 (2015)
- **Hadronic model favored** over leptonic model
- Hadronic model has **natural Cosmic Ray index ~2**
- **Leptonic** requires ad hoc break and fits poorly
- **Hadronic emission favored** by Optical + Fermi-LAT + MAGIC modeling

Acciari, V.A. Nat Astron 6, 689–697 (2022)



Summary

- Extensive studies of few **gamma-ray binaries** known
  - Searching for similarities in emission mechanisms and studying the nature of the compact objects.
- Supernova remnants and pulsar wind nebulae studies
  - Evidence for Cosmic Ray escape
- Discovery of pulsed VHE emission from pulsars
  - More VHE gamma-ray pulsars to be discovered?
- Recurrent **nova RS Ophiuchi**
  - August 2021 outburst creates a **new class of VHE emitters.**
  - **First evidence for hadronic origin** of gamma-rays in novae.

➡**Infinite more questions to be answered and infinite more results to come!**

Summary

Thank you!

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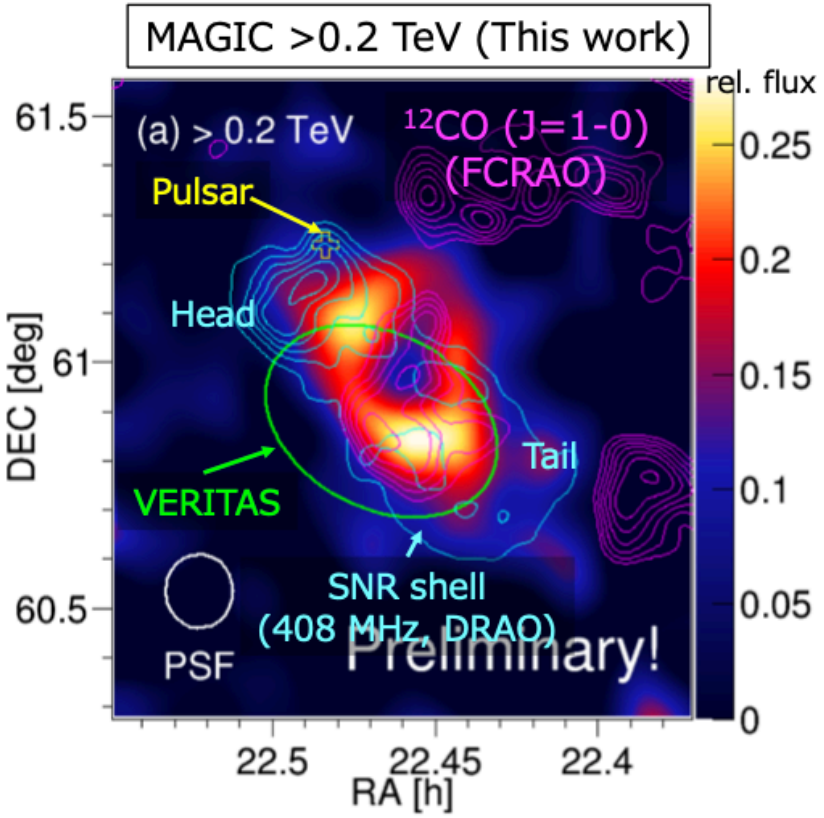
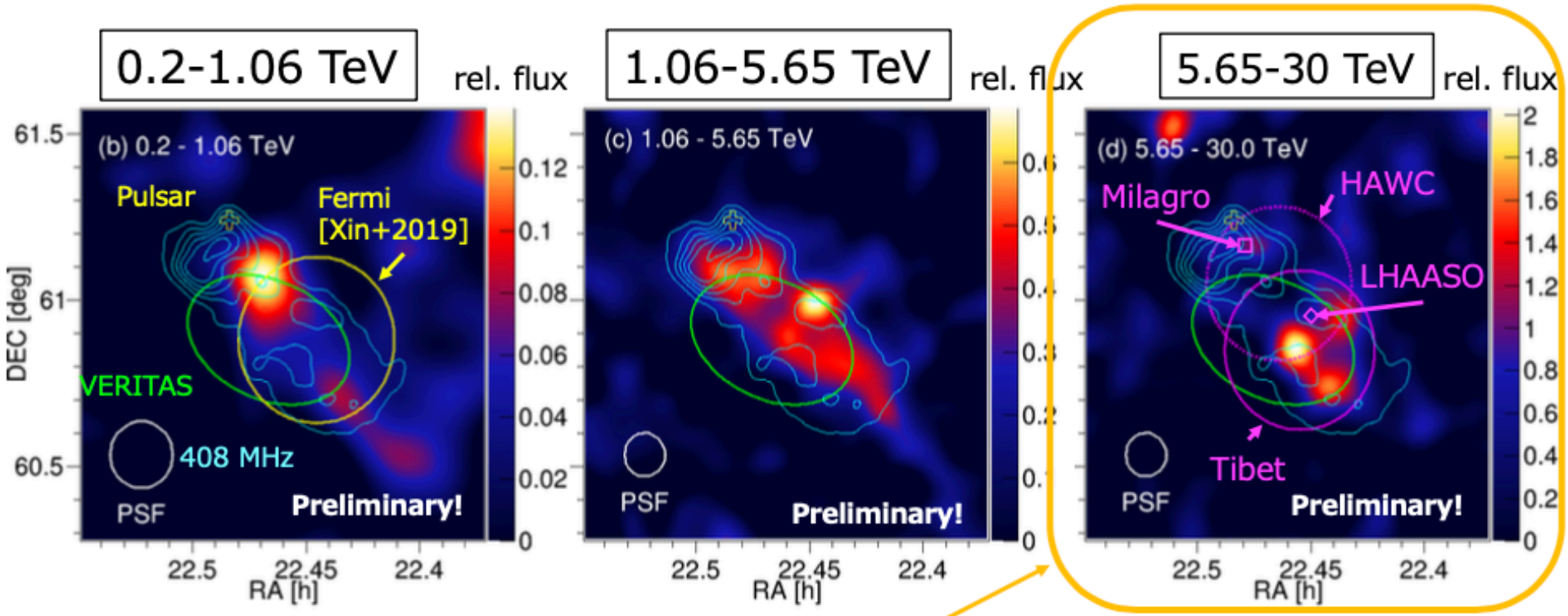
BACKUP

Boomerang PWN/ SNR G106.3+2.7

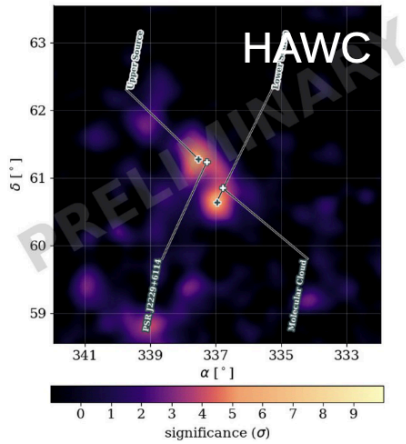
- **PeVatron candidate**
  - HAWC, TibetASγ, and LHAASO detected 100 TeV γ-ray emission [Albert+ 2020; Amenomori+ 2021; Cao+ 2021]
- Pulsar Wind Nebula (**PWN**) & Supernova Remnant (**SNR**) complex
  - Age: 4-10 kyr [Halpern+2001, Kothes+2006]
  - **The origin of the VHE emission is unclear:** PWN or SNR? Hadronic or leptonic?
- MAGIC observations performed with **best angular resolution** among previous γ ray observations in the vicinity of SNR G106.3+2.7
  - 122 hours between 2017-2019
  - 68% containment radius of PSF: **0.084°** (>0.2 TeV) & **0.072°** (>1 TeV)



Energy-dependent morphology



Milagro [Abdo+2009], HAWC [Albert+2020]
Tibet [Amenomori+2021], LHAASO [Cao+2021]



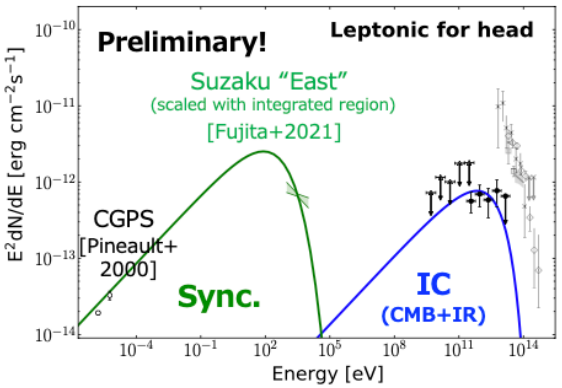
J. Goodman @ gamma 2022

- In the highest energy bin, γ-ray emissions are **offset from the pulsar position.**
- The position is in **good agreement** with other experiments.

Spectra of two regions & Interpretation

- Head
  - **Leptonic** emission can reproduce the MWL spectrum in the head region.
  - X-ray results for the head region (Ge+2021, Fujita+2021) suggest the **synchrotron emission originates in the Boomerang PWN**.
- Tail
  - **Leptonic**: Electrons of SNR-tail can reproduce the MAGIC spectrum but if assume gamma-ray >10TeV is only from tail —> tension.
  - **Hadronic**: Protons escaped from SNR in the past can explain PeV energies and the hard index at the middle-aged SNR (4-10kyr).

Modeling with naima [Zabalza 2015]



X-ray 1D profile [Ge+2021]