Long-term monitoring of the radio-galaxy M87 in gamma rays:

joint analysis of MAGIC, VERITAS and Fermi-LAT data

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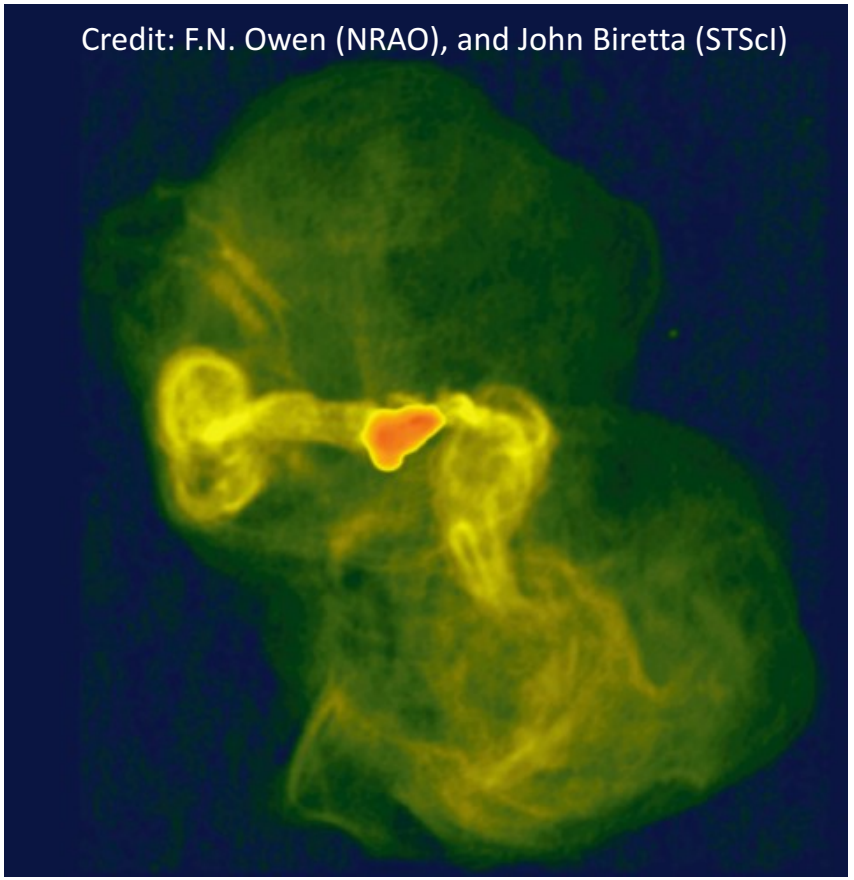
Motivation: Source

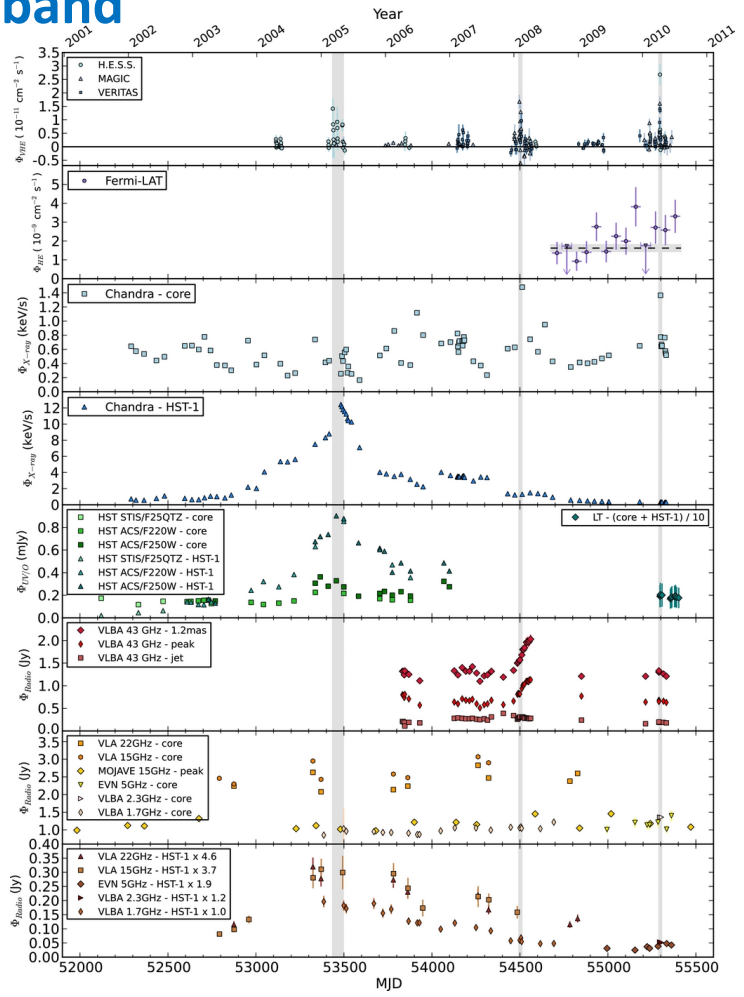
- Nearby giant radio galaxy, 16 Mpc, in the Virgo cluster with a central black hole of $\sim (6.5 \pm 0.7) \times 10^9$ $M_\odot$
- The jet has an opening angle of $\sim 30°$ that can be resolved from radio to X-rays
- The jet is variable: flares in radio, optical, X-rays and gamma rays
- First radio-galaxy detected in the VHE (>100 GeV) band by HEGRA in 2003



Motivation: VHE Band

M87 in the VHE band

- M87 is an unusual nearby source with a resolved jet in radio ⟹ Allows variability studies, not common in other VHE sources
- It is visible by the three big IACTs arrays (MAGIC, VERITAS and H.E.S.S.)
- It has been historically one of the most observed sources with 100s of hours of good quality data
- The source was detected in a flare state on several occasions (2005, 2008 and 2010)⟹ Nature of the emission still unknown, changing behavior from flare to flare
- Since the last flare, the source has been observed in a relatively low-state with the exception of small scale flares



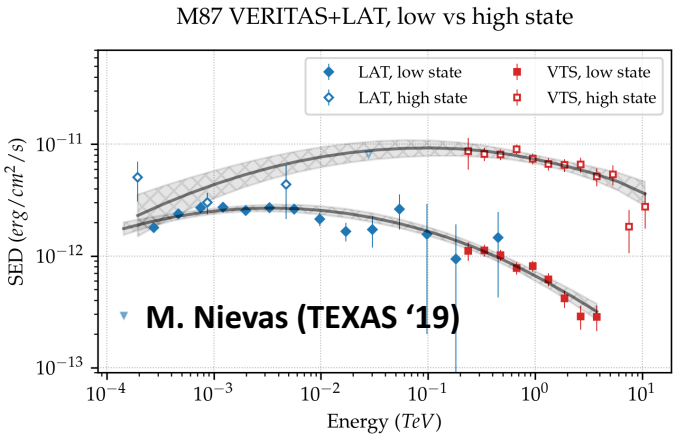
ApJ 746, 151 (2012)

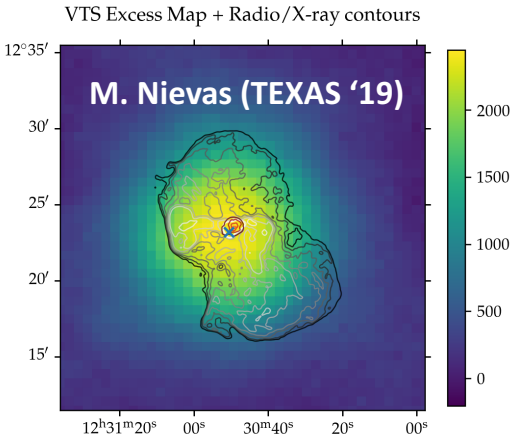
Motivation: Joint Analysis

The joint analysis of combined data from multiple IACT arrays could substantially improve the individual measurements

Possible scientific targets:

- **Legacy work:** historical evolution of the VHE emission and MWL correlations
- **Spectral variability:** Comparison between the low and high states
- **Location:** Locate and measure the extension of gamma-ray emission
- **Modeling of the data:** hadronic, leptonic or leptohadronic





MAGIC Telescopes

Performance details: Aleksić et al., AP (2016) 72, 76-94

- Two 17 m diameter Cherenkov Telescopes at the Roque de los Muchachos Observatory
- Energy range: > 50 GeV
- Energy Resolution: 17% at 1 TeV
- Point source sensitivity: 0.7% Crab in 50 h
- Field of view: 3.5 deg in 1039 PMTs/Telescope

VERITAS Telescopes

Performance details: C. B. Adams, A&A 658, A83 (2022)

- Array of four 12-m Cherenkov telescopes at the basecamp of FLWO, Arizona
- Energy range: > 85 GeV
- Energy resolution: 17% at 1 TeV
- Point-source sensitivity: 1% Crab in 25h
- Field of view: 3.5 deg in 499 PMTs/Telescope

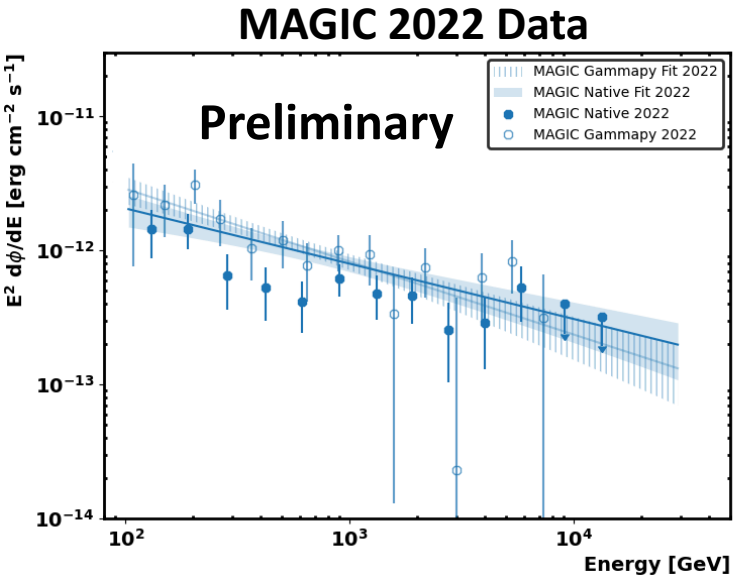
MAGIC and VTS Datasets

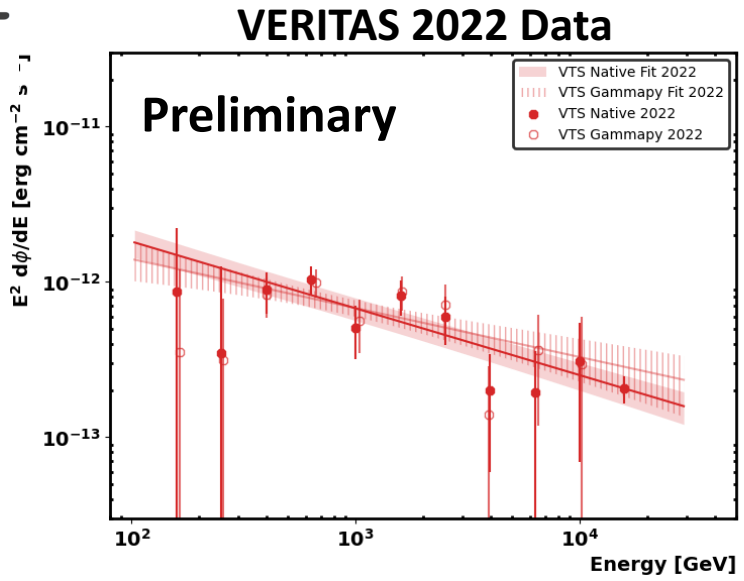
- Four full seasons from 2019 to 2022 have been analyzed by MAGIC and VERITAS
- A total of 113 and 61 hours of effective observation time was obtained for MAGIC and VERITAS

Year	$T_{\mathrm{Eff}}^{\mathrm{MAGIC}}[h]$	$T_{\mathrm{Eff}}^{\mathrm{VERITAS}}[h]$
2019	40	7
2020	16	4
2021	35	20
2022	22	30
2019-2022	113	61

DL3/Gammapy analysis

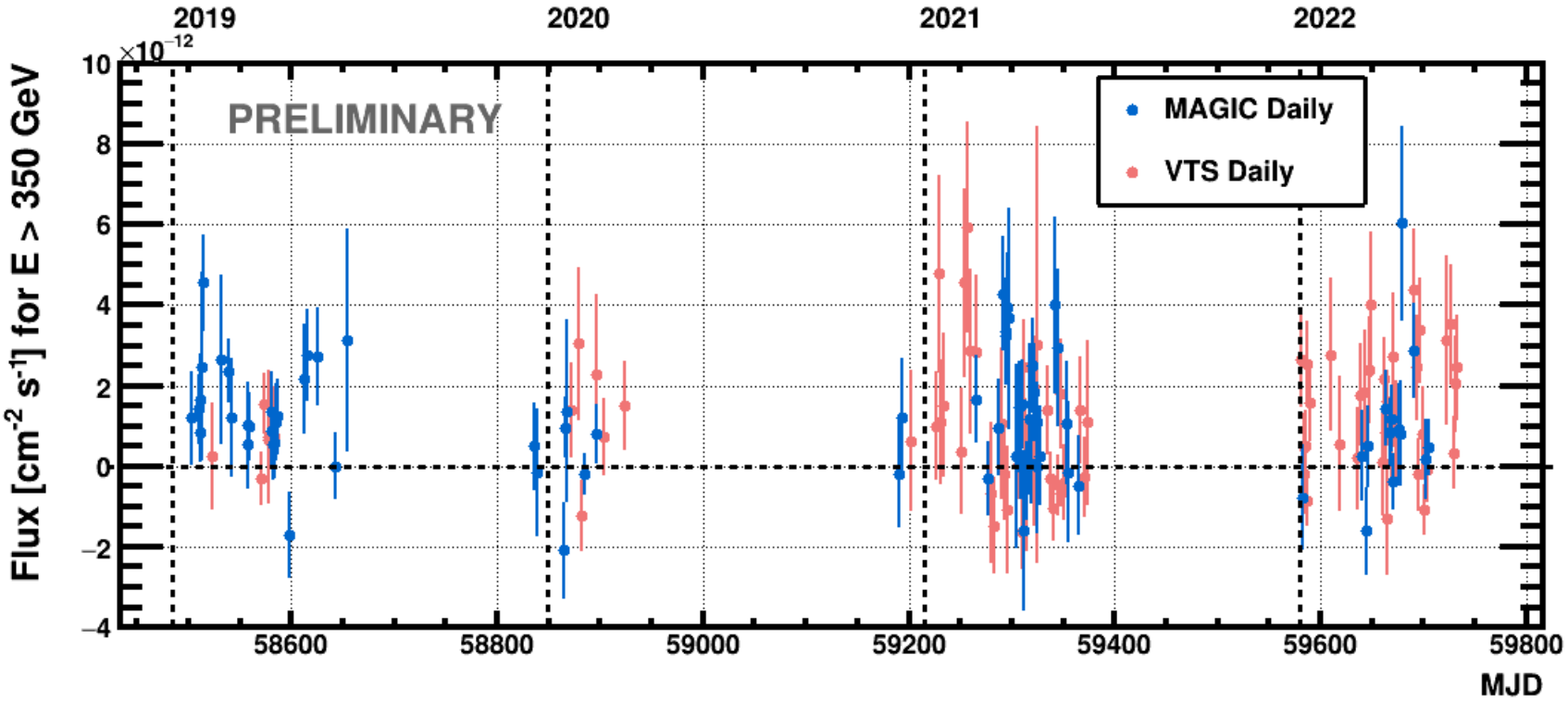
- Data have been analyzed independently for each period and instrument using their own collaboration softwares
- Then, files were exported to DL3 with the gamma-ray-like events and the associated instrument response functions
- DL3 files were analyzed by gammapy for each period and instrument and compared with the native analyses





Results: Light Curves Daily

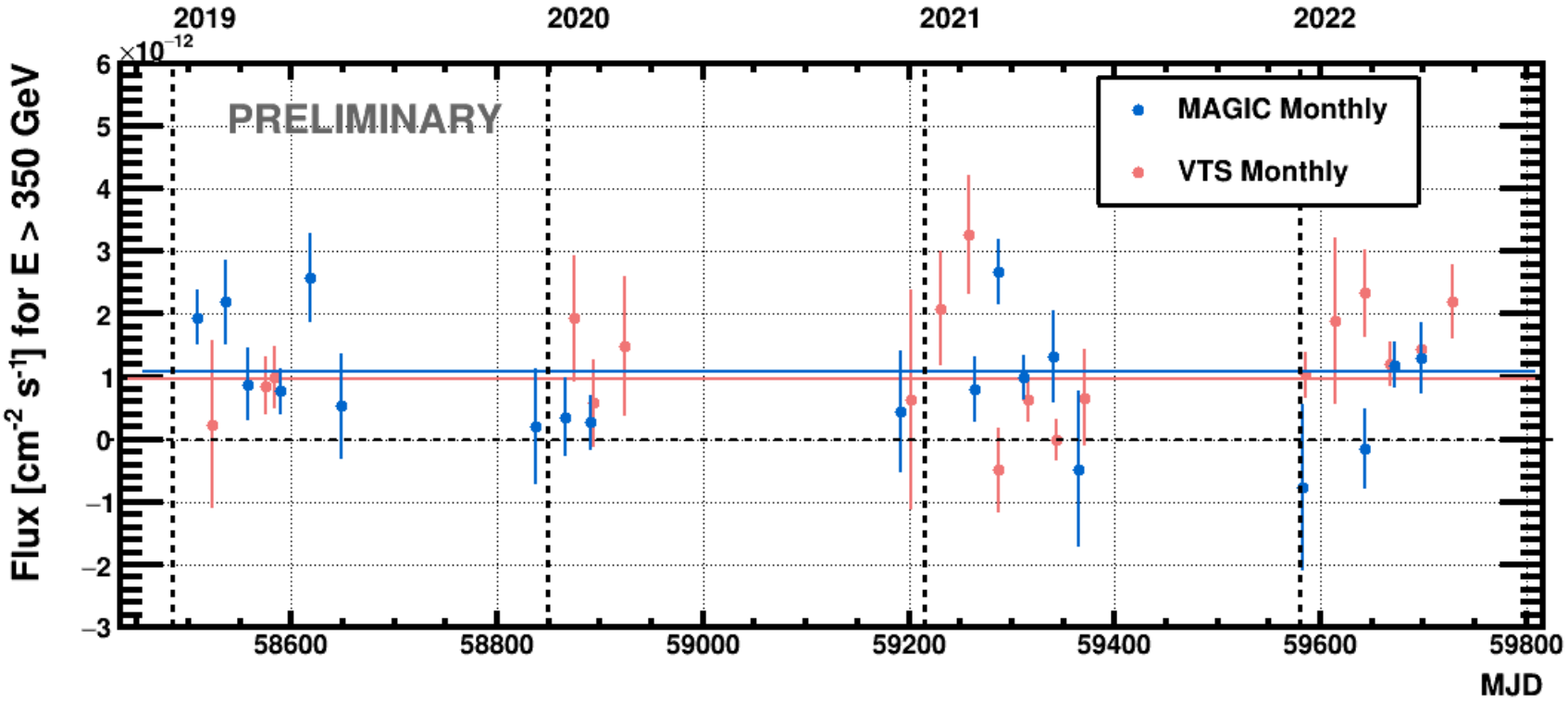
The time coverage is increased with the MAGIC and VERITAS data



Results: Light Curves Monthly

The mean integral flux is computed with the monthly light curves:

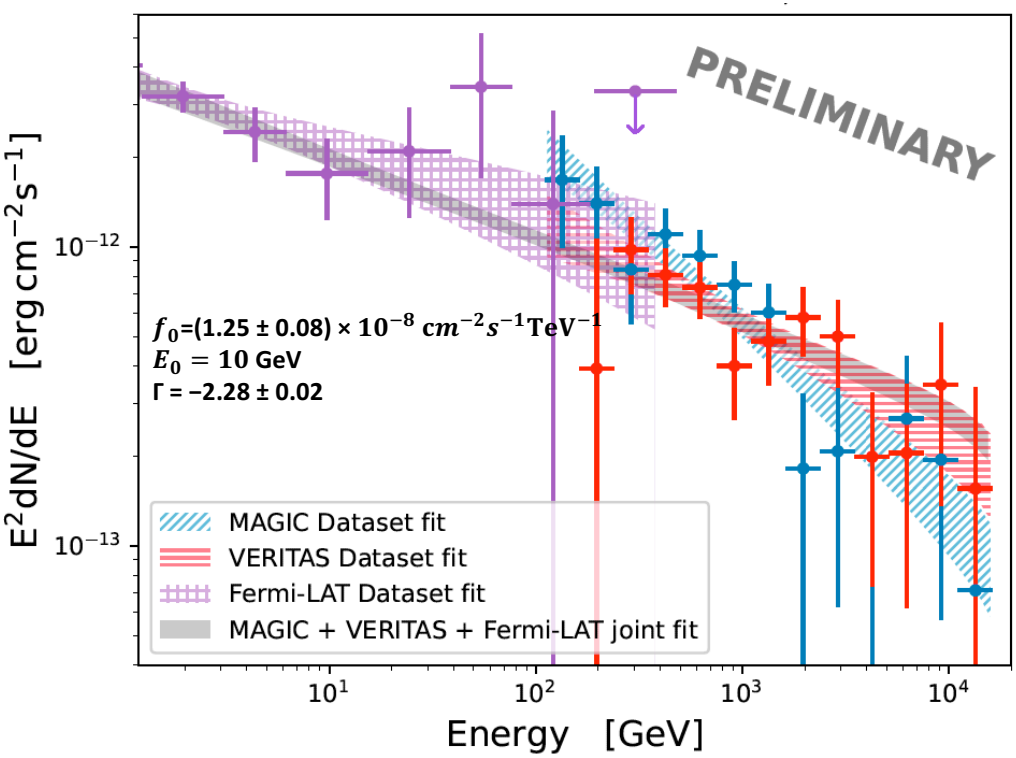
- **MAGIC:** $(1.07 \pm 0.13) \times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **VERITAS:** $(0.96 \pm 0.13) \times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



No significant variability is observed in the daily and monthly light curves

Results: Joint SED

Individual spectra and joint analysis can be well described by a power law of the form $E^2 dN/dE = f_0 (E/E_0)^{\Gamma}$



The spectral index in the joint analysis, $\Gamma = -2.28 \pm 0.02$, improves the statistical uncertainties obtained with the individual analysis

Conclusions

- M87 observations from 2019 to 2022 have been performed by MAGIC and VERITAS
- Total effective observation time of 113 and 61 h is obtained for MAGIC and VERITAS
- Gammapy and native analyses show compatible results for each period
- **Light Curves:**
  - Combined observations between MAGIC and VERITAS allow to increase the time coverage
  - Results show no significant variability at daily and monthly scales

  $\Longrightarrow$ Source in low flux emission state
- **Spectral Energy Distributions:**
  - Individual spectra and joint analysis can be well described by power law
  - The joint analysis substantially improves the statistical uncertainties with respect to the individual ones
- The extension of this work to more years could provide new insights in the historical evolution of M87 as well as in its spectral energy distribution in different emission states

Thank you for your attention

Interested in proposing observations with MAGIC?

Next MAGIC observing call (Cycle-19) will come very soon. It will be posted here:

https://magic.mpp.mpg.de/public/magicop/

(Deadline for submitting proposals in the end of October or beginning of November)