The most complete multi-wavelength view of M87 to date: the 2017 campaign

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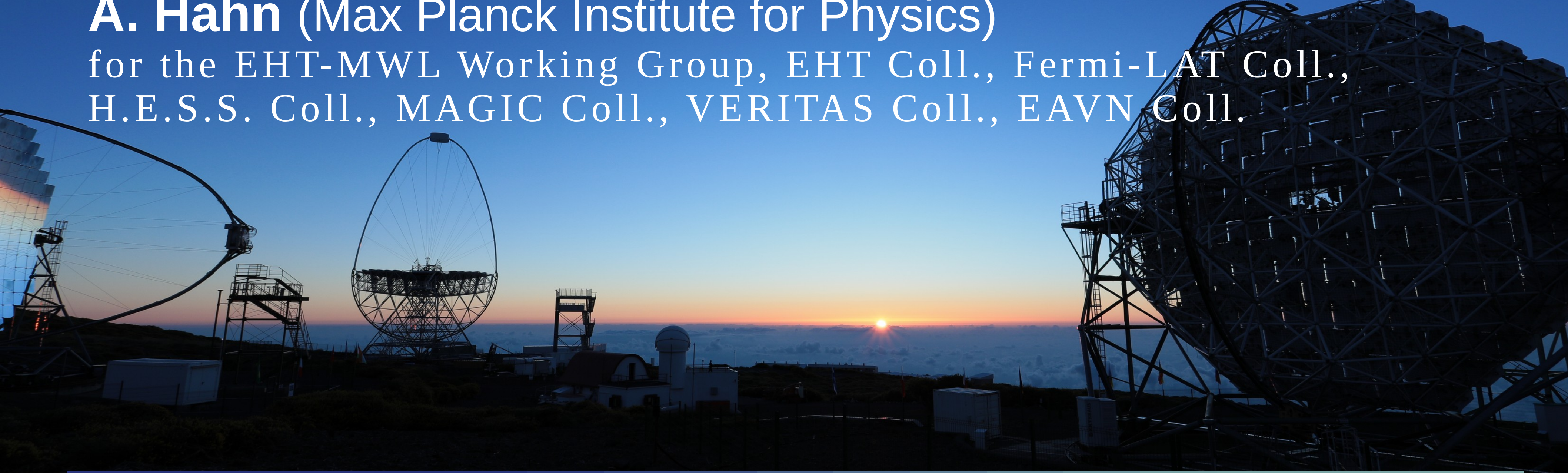
MAX-PLANCK-INSTITUT FÜR PHYSIK

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes



M87

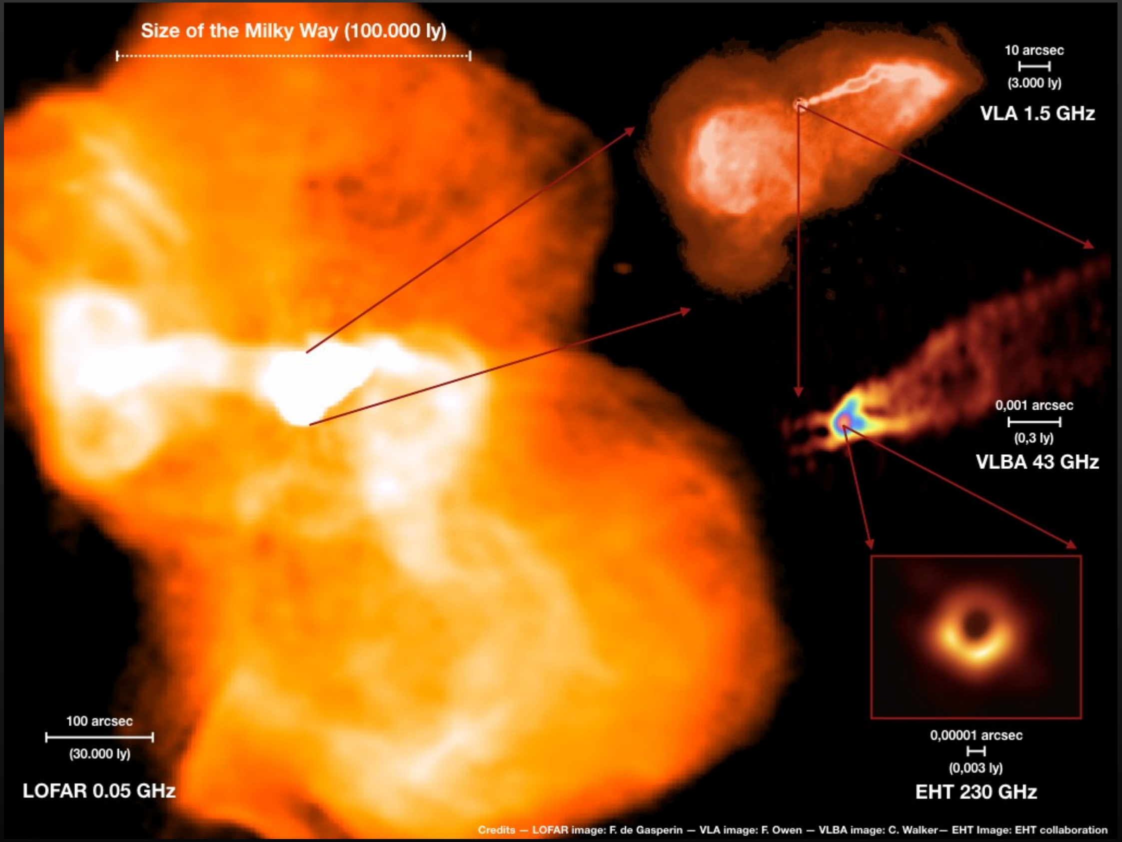
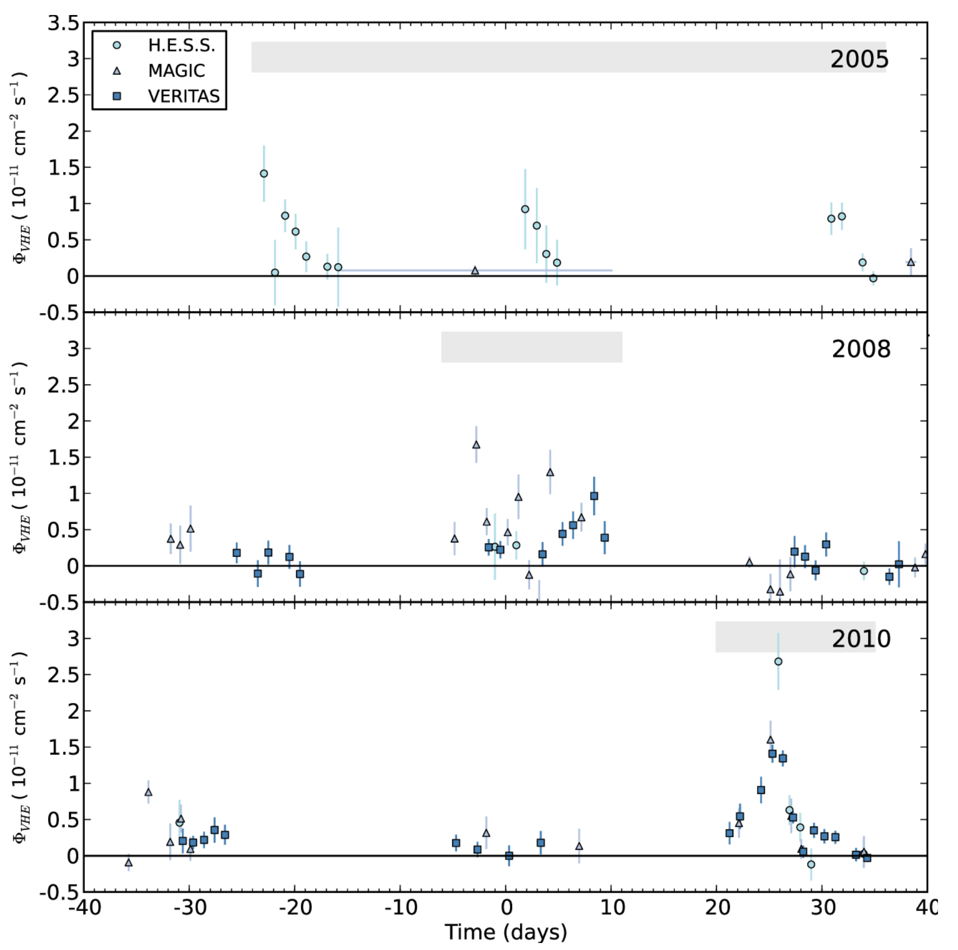


Image taken from glowconsortium.de

- Weakly accreting supermassive black hole (SMBH) M87*
- It's in the local universe:
  - Z = 0.00428
  - 16.8 Mpc from earth
- BH mass: $6.5 \pm 0.7 \times 10^9\ M_\odot$
- Viewing angle 163° (17°)
- No strong Doppler boosting
- Jet extends 65 kpc (~ 14")
- Jet age ~ 40 Myr
- Detected in all energy bands
- TeV flux variability coincided with different MWL behaviour

M87 at VHE gammas in the past

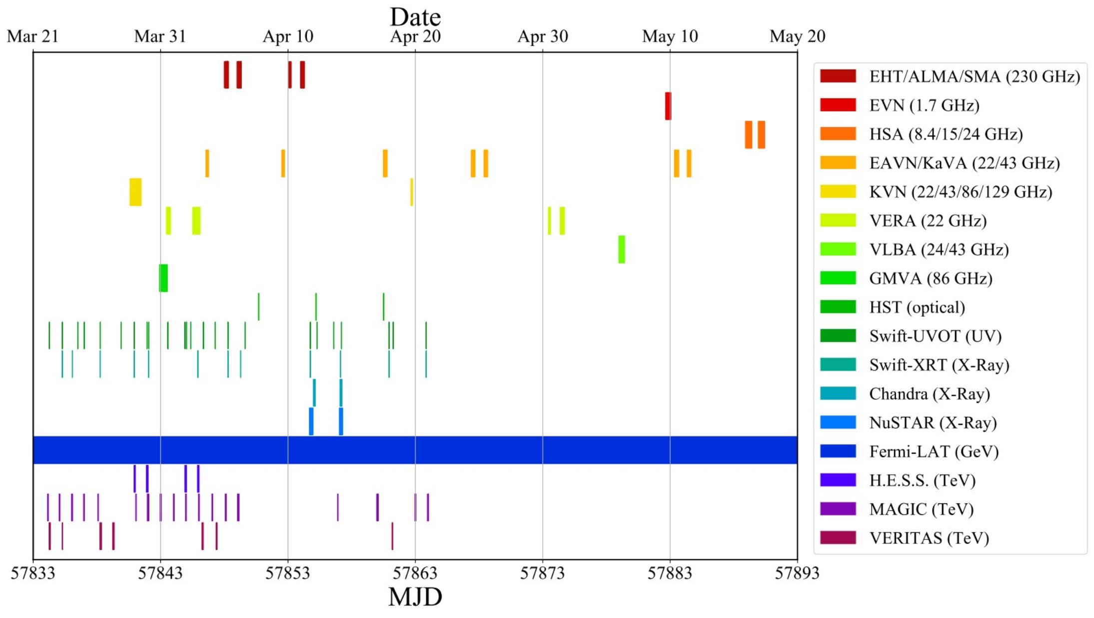


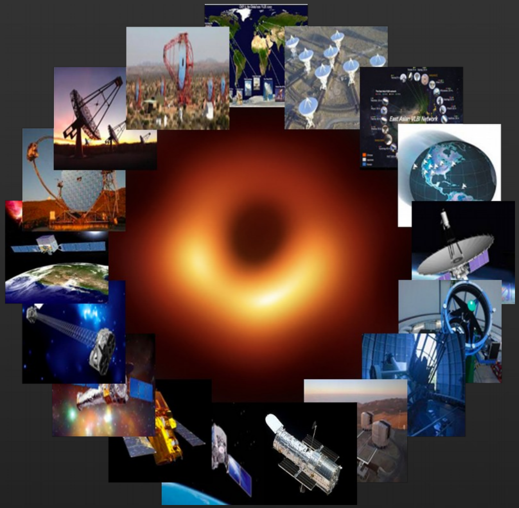
Abramowski et al. 2012; Integral fluxes E > 350 GeV

- 2005: TeV detection during increased X-ray and near-UV (HST) flux of HST-1
- 2008: TeV detection during X-ray core high flux, HST-1 low flux, start of increasing radio flux
- 2010: TeV detection with flux doubling time scale about 1 day, no increased radio flux at 43 GHz, but new radio blob appearing in HST-1, X-ray core bright

EHT-MWL
2017 campaign

- Purpose
  - Provide quasi-simulataneous MWL data
  - Combine EHT and MWL data to study SMBH vicinity in more detail
  - Serve as input for theoretical models of SMBHs and jets

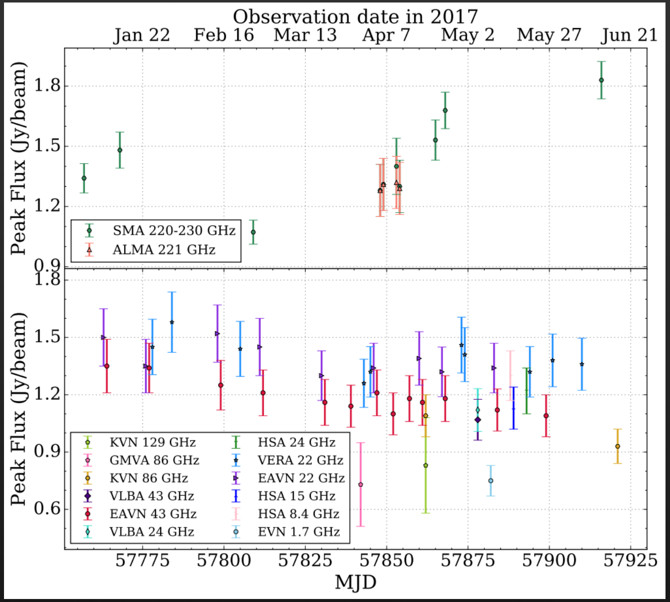




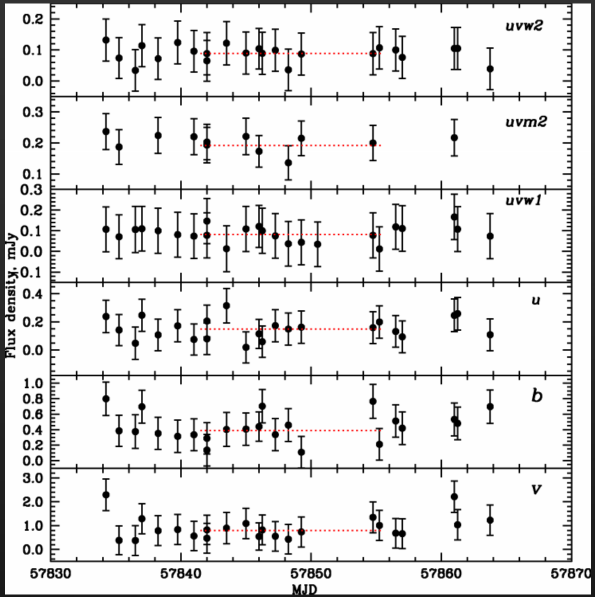
- MWL campaign on M87 2017:
  - Extensive, quasi-simultaneous
  - covering more than 15 decades in energy
  - 19 different facilities
  - Largest MWL campaign to observe a black hole
  - EHT collaboration et al., ApJ 911, L11 (2021)
  - 760 authors from 32 countries

EHT MWL
2017 LCs

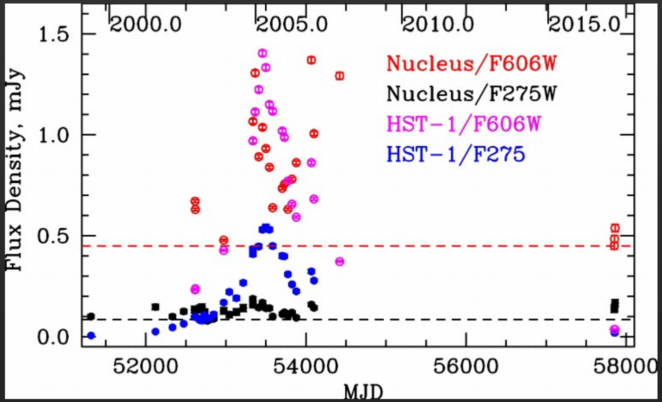
Radio



UV

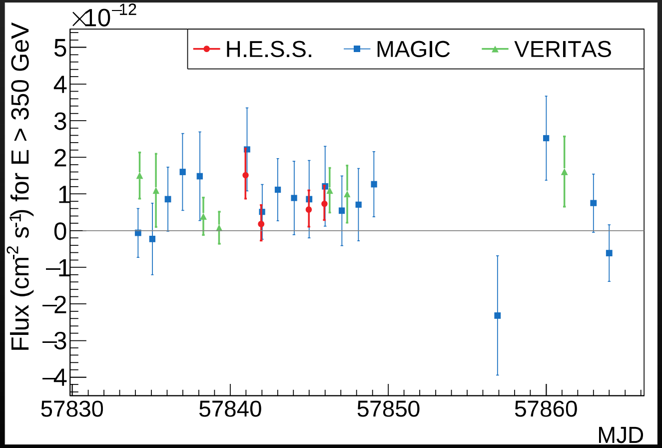


Optical



- Historically low state in 2017
- Insight into jet structure through variability

VHE



EHT-MWL
2017 images

- Resolved structures from radio to X-rays
- Straight, highly collimated jet
- Limb brightening, parabolic collimation profile
- Southern jet limb brighter than northern
- VLBA and GMVA: inner jet significantly offset from large scale jet (long-term periodic oscillations, Walker et al. 2018a)
- Core shift between 22 and 43 GHz Spectral index map show typical AGN jet (flat-spectrum radio core which progressively becomes optically thin)
- No component ejection detected

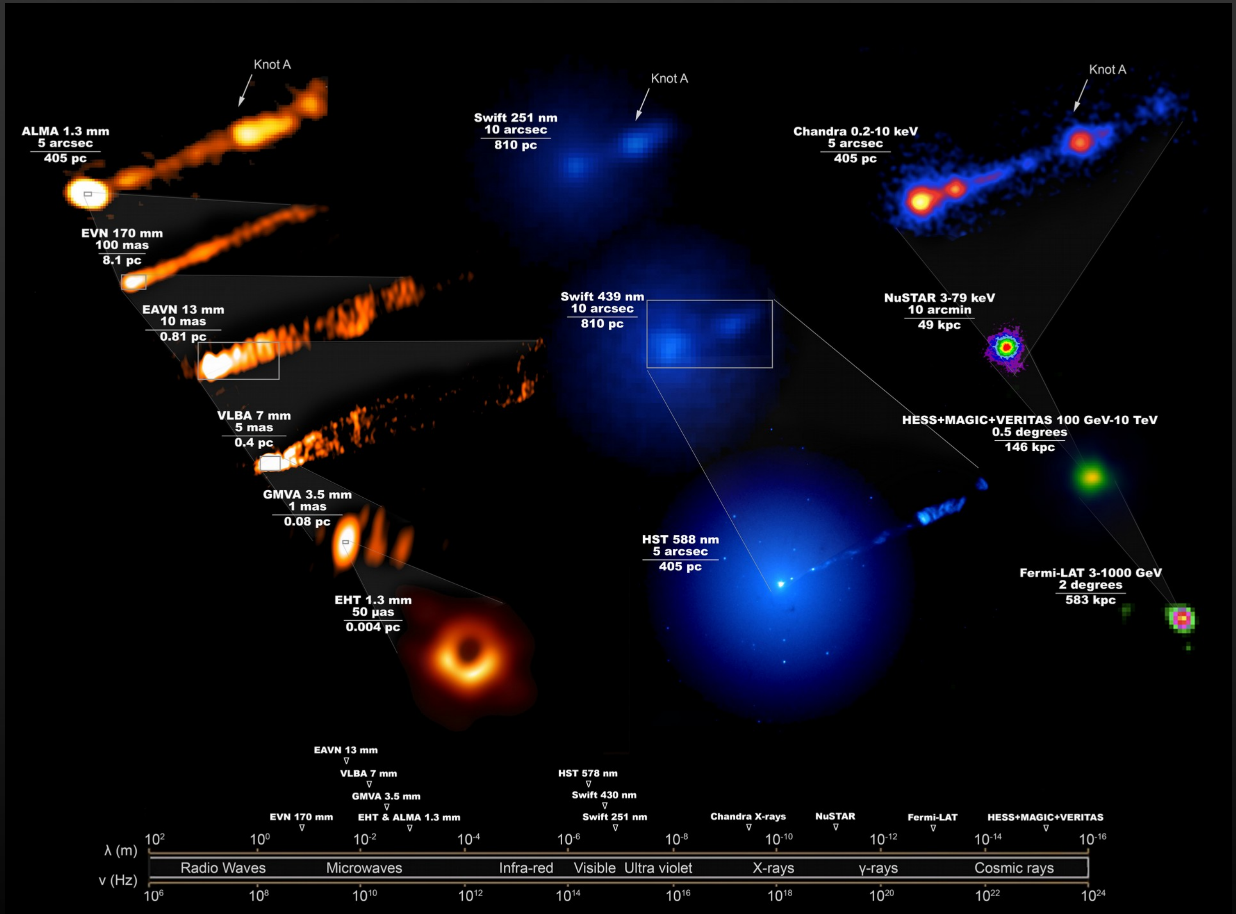
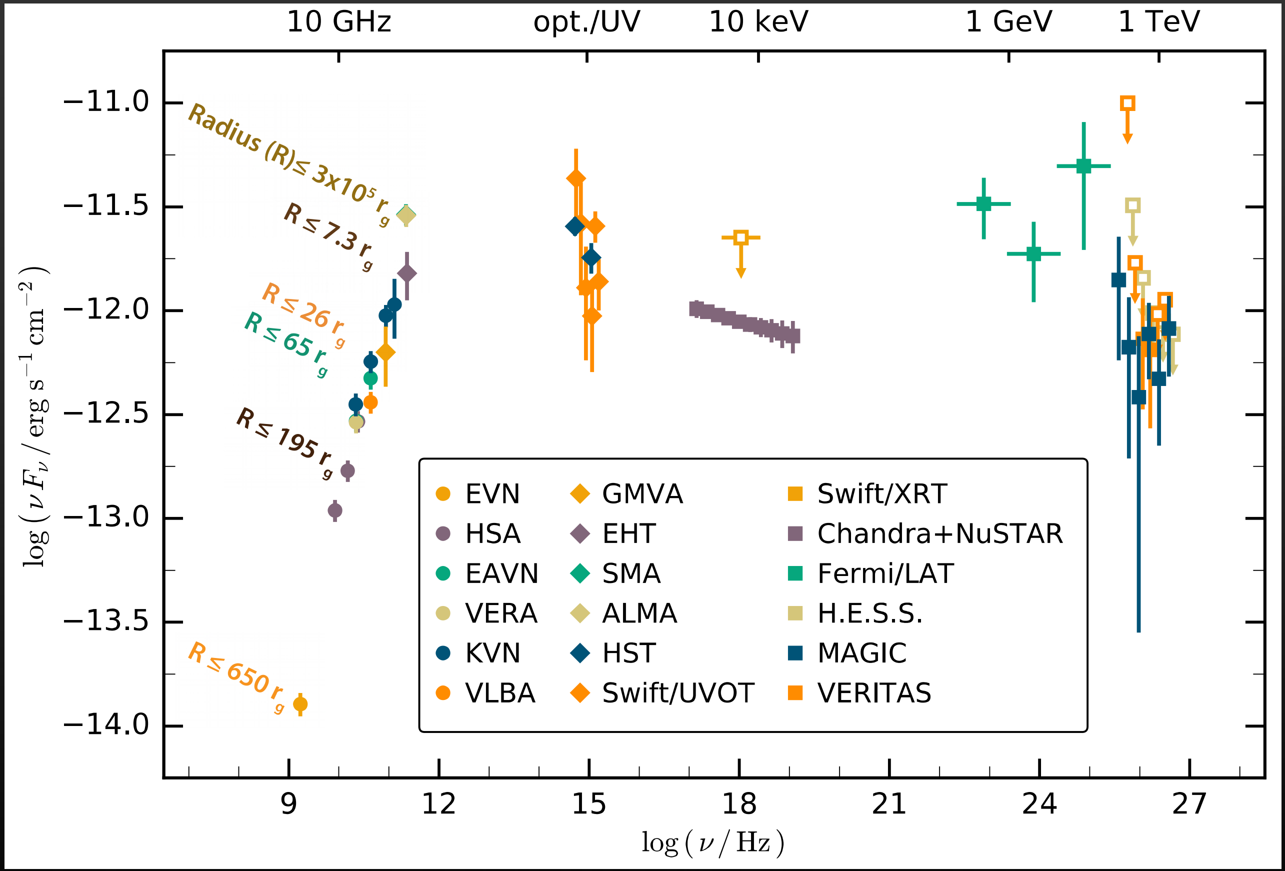


Image Credit: The EHT Multi-Wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope, the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S. collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J.C. Algaba.

EHT-MWL
2017 SED

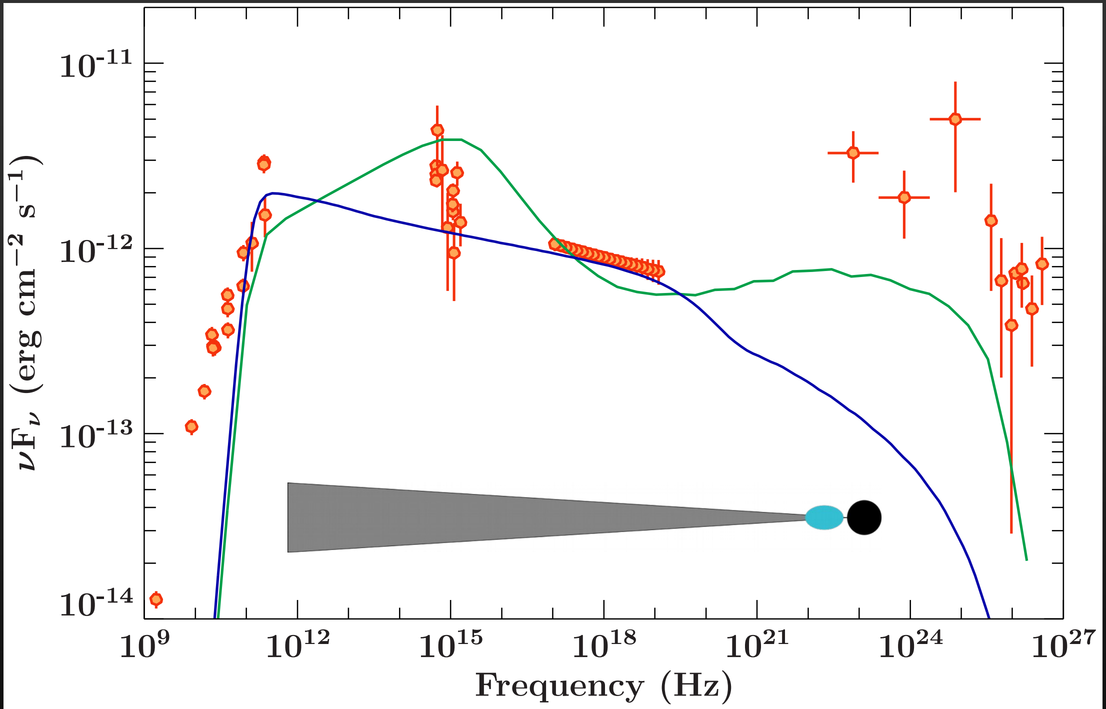
- MWL SED of the M87 core (in quiescent state)
- Near simultaneous data
- Spatial resolution of instruments ranging 20 µas – 2°



EHT MWL
2017 single-zone models

Model 1:

- **EHT oriented models**
  (hard constrain on emission region size)
- δ=1, bulk motion of emission region has likely not yet reached relativistic speed
  - **1a)** PL w/ rad. cooling (Kino)
    - uses parameters from MAGIC+20
  - **1b)** broken PL w/o rad. cooling (Kawashima)
    - does not well reproduce X-ray shape
  - Main difference in IR
- X-ray only by synchrotron
- Problematic in γ-rays
- GeV, TeV from more extended region



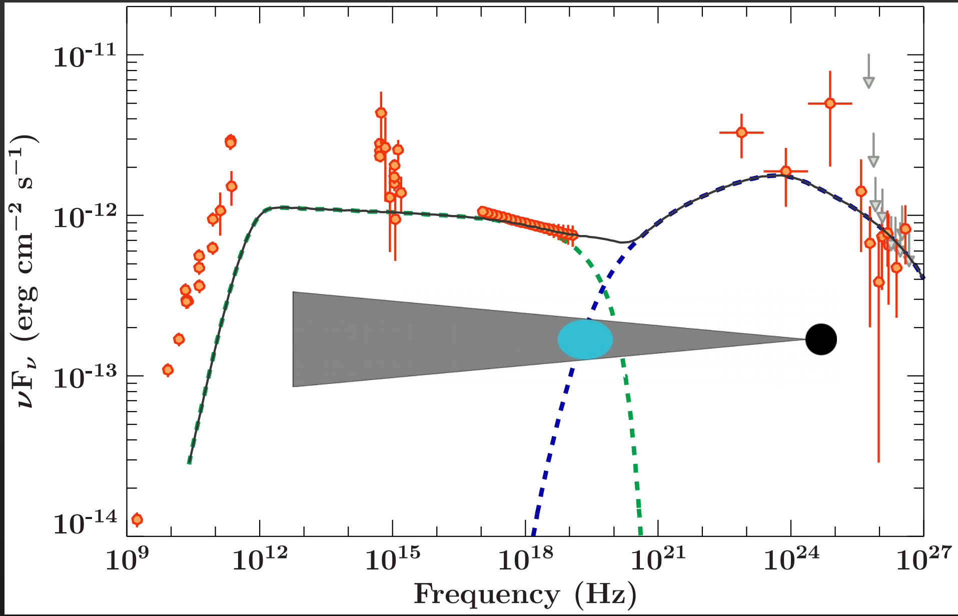
Model	L_j $[L_{\rm Edd}]^a$	δ	R $[r_g]^b$	n'_e [cm^{-3}]	c	B' [G]	$\gamma_{\rm min}$	$\gamma_{\rm br}$	$\gamma_{\rm max}$	p_1	p_2	U_e/U_B
model 1a	6×10^{-3}	1	5.6	3.6×10^5		4.7	1	–	3.5×10^6	2.2	–	2.3
model 1b	4.7×10^{-3}	1	5.2	8.0×10^5		5.0	1	1×10^4	2×10^6	2.7	3.8	1.6

EHT MWL

2017 single-zone models

Model 2 - VHE oriented model:

- Assume a sphere, radius R moving with bulk Lorentz factor Γ_j. Power divided between rel. electrons, non-rel. protons and a global magnetic field.
- Assume one cold proton per electron (no positrons), and that the eDF is described by a power-law with slope p_2 between Lorentz factors γ_{min} and γ_{max}.
- Assign the index to p_2 to allow better comparison to model 1b, as our steeper distribution is likely in the radiatively cooled regime, although we do not calculate γ_{br} explicitly.
- Modeling of X-ray emission in detector space to disentangle various jet and ICM components
- Without the strong EHT size constraint (1a/1b), model parameters are highly degenerate.
- Model 2 cannot fit the radio-mm VLBI core nor the VHE emission especially in the GeV range



Model	L_j $[L_{\rm Edd}]^a$	δ	R $[r_g]^b$	$n'_{\rm e}$ [cm^{-3}] [c]	B' [G]	$\gamma_{\rm min}$	$\gamma_{\rm br}$	$\gamma_{\rm max}$	p_1	p_2	$U_{\rm e}/U_{\rm B}$
model 1a	6×10^{-3}	1	5.6	3.6×10^5	4.7	1	–	3.5×10^6	2.2	–	2.3
model 1b	4.7×10^{-3}	1	5.2	8.0×10^5	5.0	1	1×10^4	2×10^6	2.7	3.8	1.6
model 2	$2.8^{+2.0}_{-1.4} \times 10^{-5}$	3.3	626^{+256}_{-301}	$9.5^{+7.5}_{-7.8} \times 10^{-3}$	$1.5^{+1.6}_{-0.9} \times 10^{-3}$	$4.1^{+2.1}_{-1.5} \times 10^3$	–	$6.4^{+2.6}_{-3.6} \times 10^{7}$ [d]	–	$3.03^{+0.03}_{-0.05}$	635^{+465}_{-288}

Concluding remarks

- Single-zone models fail to explain the M87 broadband SED
- Models 1a/b
  - EHT-mm and X-ray flux explained by mildly magnetically dominated sphere, but fails at gamma rays
  - In a ~5 G magnetic filed the synchrotron cooling time for X-ray producing electrons is ~30 s, which is in tension with the moderate X-ray variability
- Model 2
  - Particle-dominated larger zone describes X-rays well, but fails to fit radio and GeV emission
- Conclusion: structured jet model necessary to explain 2017 MWL observations

Concluding remarks

- Conclusion: structured jet model necessary to explain 2017 MWL observations
- Moderate magnetically dominated at jet base where EHT and possibly part of X-rays are produced
- Particle dominated, larger region further downstream seems necessary to explain gamma-ray emission
  - Either region not in the accelerating part of jet flow, or interacting with surrounding ICM
  - Might require additional seed photons than jet emission alone
- VHE emission also possible from even further downstream, from knots outwards of HST-1
  - Not covered by our radio and X-ray data but unresolved in gamma rays.
- Data available **DOI:10.25739/mhh2-cw46**
- Variability provides the key to test different scenarios
- Similar MWL campaigns performed in the following years
  ⇒ **stay tuned for EHT MWL data from 2018 !**

Thank you

Backup

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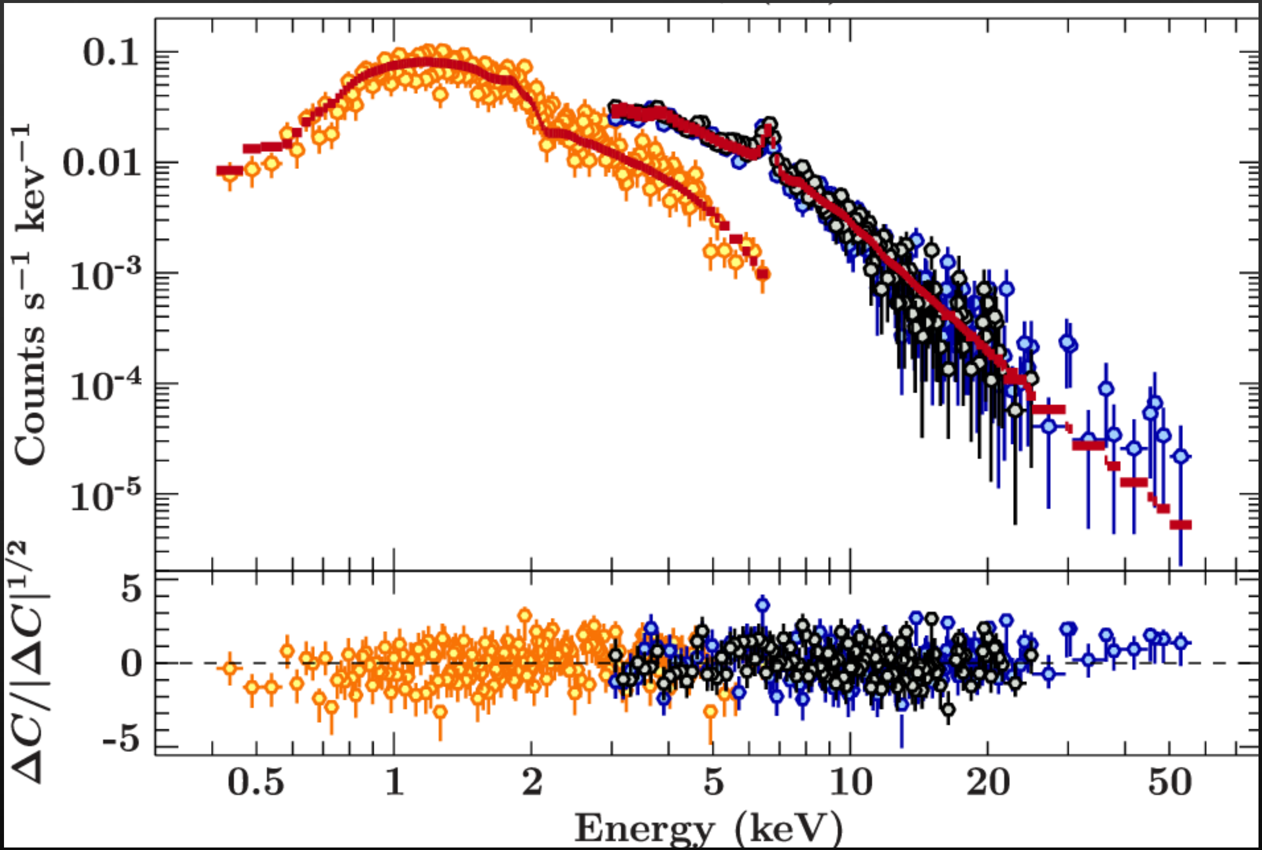
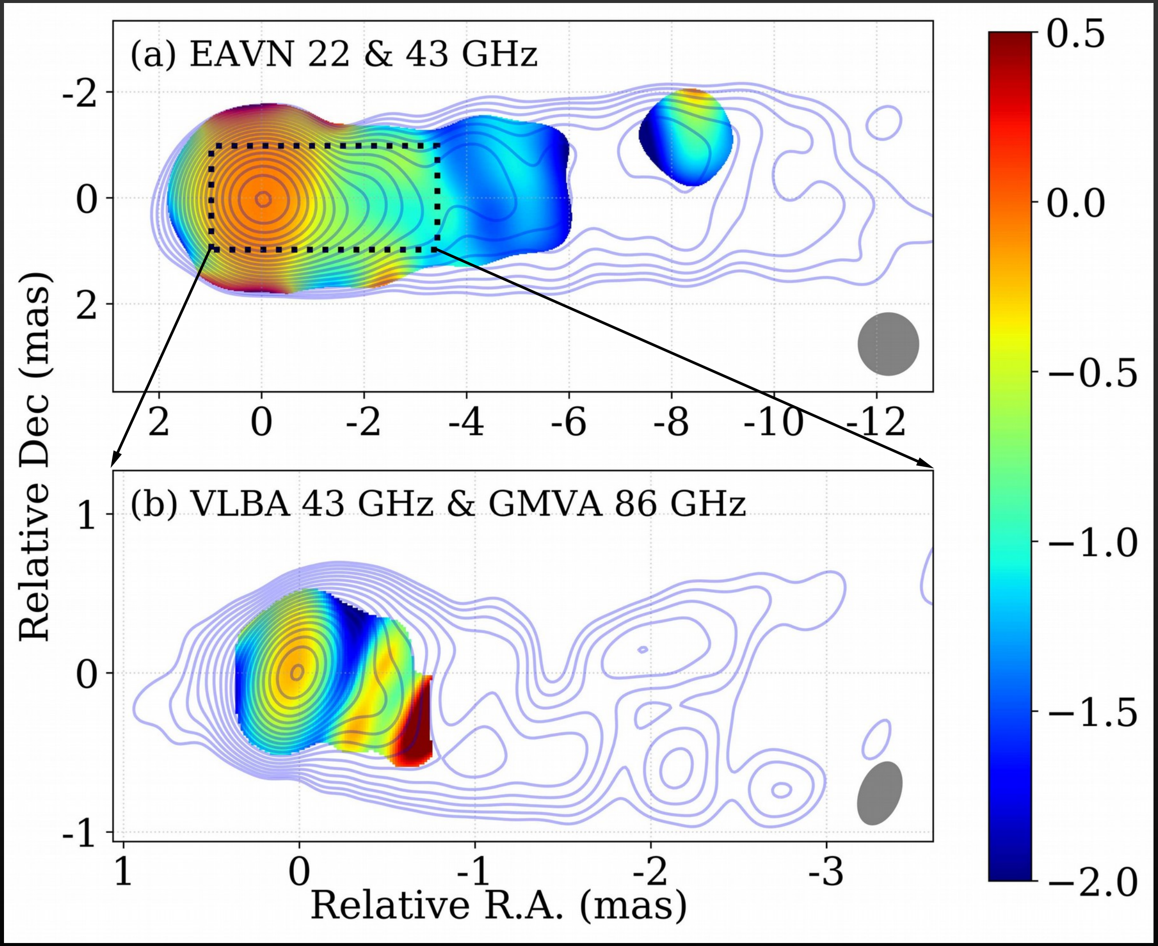
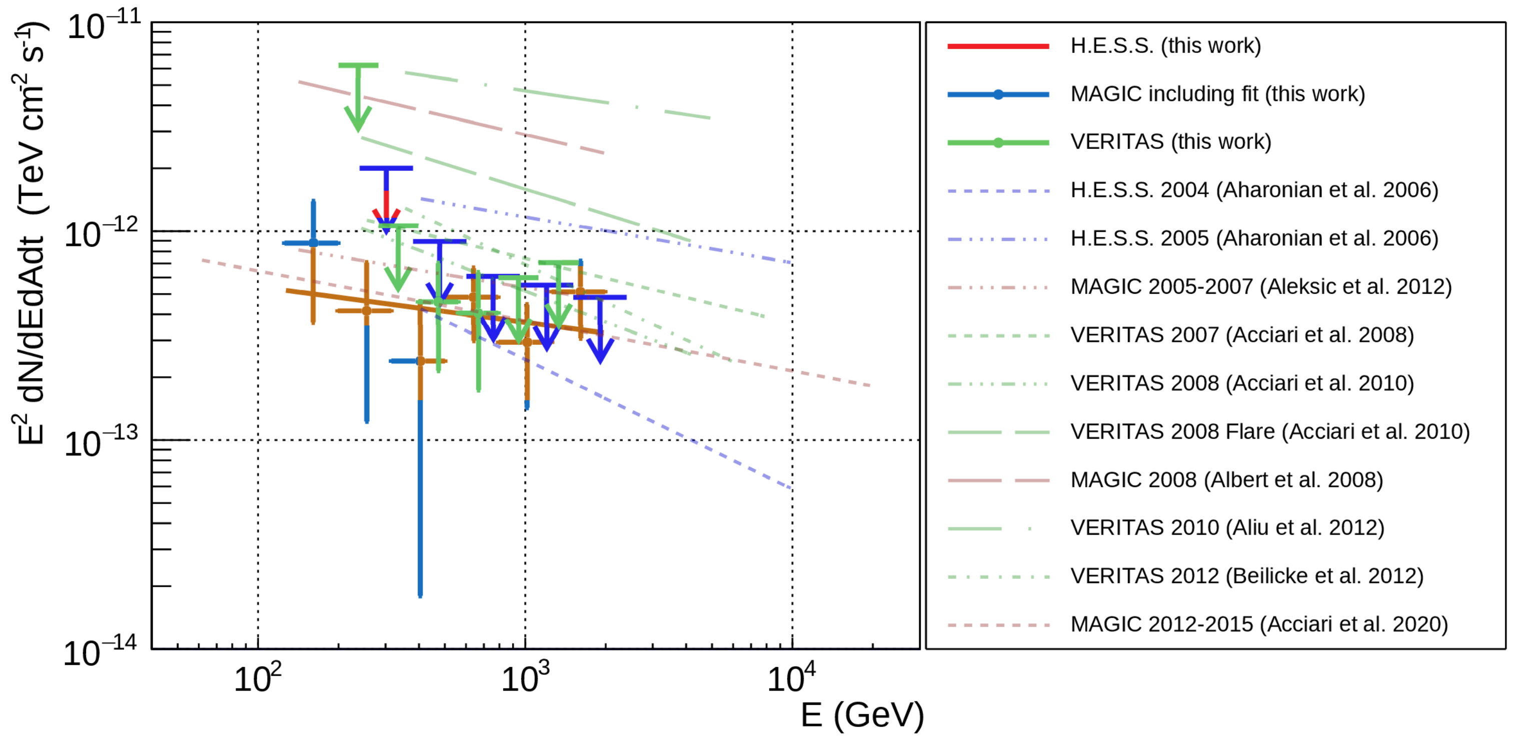
MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes



- Flat-spectrum radio core indicating presence of synchrotron self-absorbed component
- Extended regions become gradually optically thin. Typical for AGN jets




E^2 dN/dEdAdt (TeV cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^2
10^3
10^4
E (GeV)
H.E.S.S. (this work)
MAGIC including fit (this work)
VERITAS (this work)
H.E.S.S. 2004 (Aharonian et al. 2006)
H.E.S.S. 2005 (Aharonian et al. 2006)
MAGIC 2005-2007 (Aleksic et al. 2012)
VERITAS 2007 (Acciari et al. 2008)
VERITAS 2008 (Acciari et al. 2010)
VERITAS 2008 Flare (Acciari et al. 2010)
MAGIC 2008 (Albert et al. 2008)
VERITAS 2010 (Aliu et al. 2012)
VERITAS 2012 (Beilicke et al. 2012)
MAGIC 2012-2015 (Acciari et al. 2020)

- Two 17 m diameter Imaging Atmospheric Cherenkov Telescopes
- Canary island of La Palma at 2200 m a.s.l.
- MAGIC-I: since 2004
- MAGIC-II: since 2009
- 2012 major upgrade of readout and MAGIC-I camera
- Energy range ~50 GeV – ~50 TeV