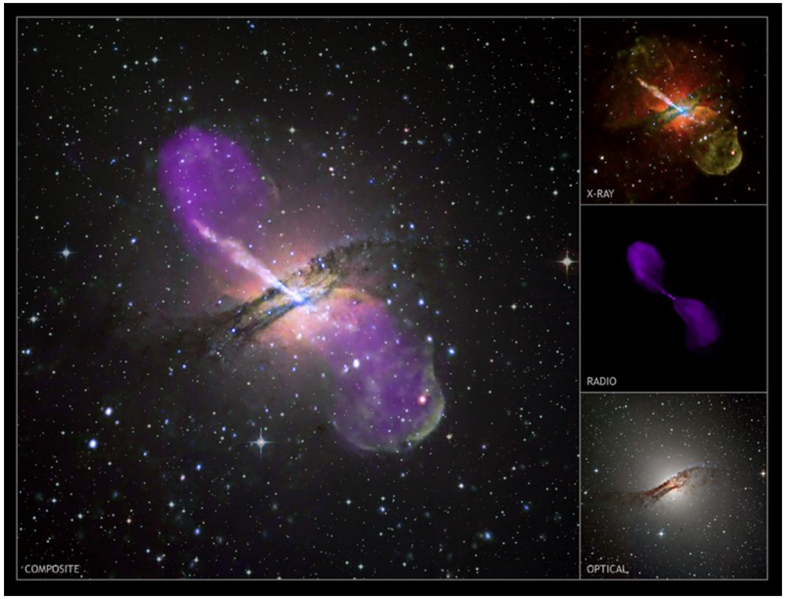
Resolving the kpc jet of Centaurus A in TeV γ-rays

M. de Naurois for the H.E.S.S. collaboration

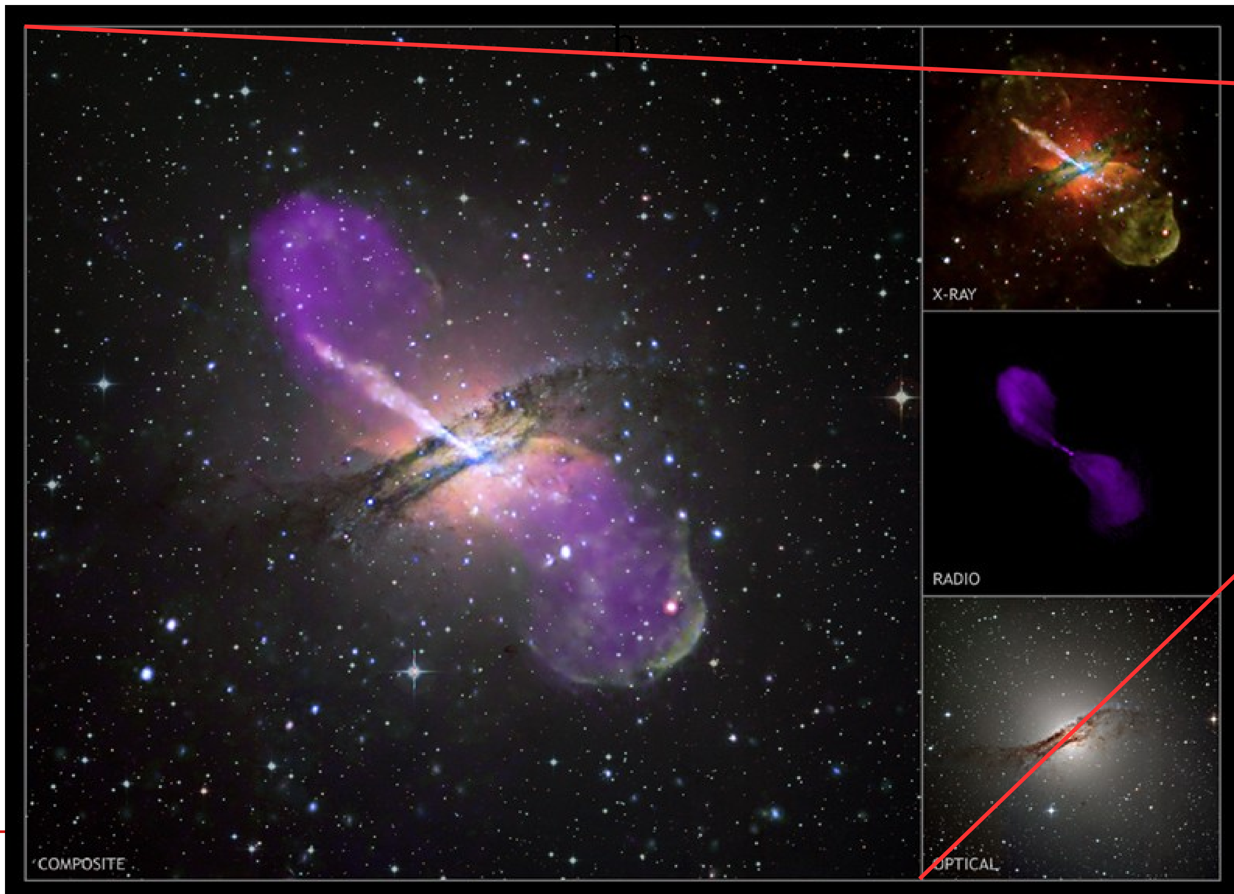


Centaurus A

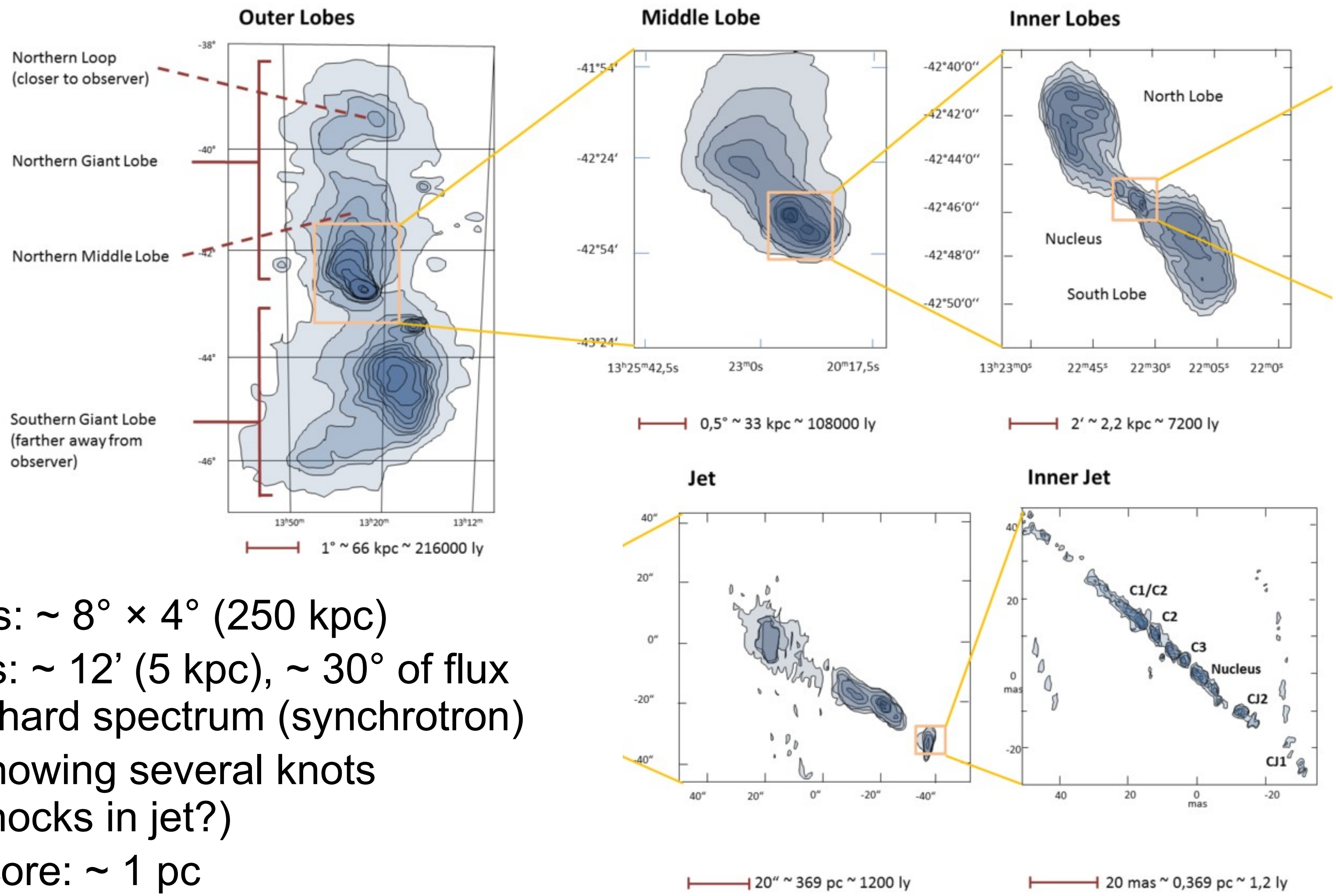
- Lenticular or elliptical galaxy at a distance of ~3.7 Mpc
  - Fifth brightest in optical
  - Contains a SMBH of ~ 55 × 10^6 $M_\odot$
  - Dust bar resulting from inclined *disk* component
  - Intense star formation rate in edges of dense dust disk, possibly linked to recent merger (UV observations) (started 50 Myrs ago)

Centaurus A - Radio

- Radio galaxy (NGC 5128) of FRI type (midly relativistic jets, moderate beaming effect)
  - Giant lobes covering ~ 8 degrees



Radio structure of Centaurus A



- Giant lobes: ~ 8° × 4° (250 kpc)
- Inner lobes: ~ 12' (5 kpc), ~ 30° of flux @ 5 GHz, hard spectrum (synchrotron)
- Inner jet showing several knots (internal shocks in jet?)
- Compact core: ~ 1 pc

arXiv:1001.0059

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Centaurus A – Gamma

- Large scale emission observed by Fermi-LAT (pink) on top of core emission
- Correlates well with giant lobes, represents > 50% of total γ-ray output
- γ-ray output ~ 10 × radio, attributed to IC scattering of electrons on CMB
- radio/γ ratio constrains magnetic field to ~ 0.9 μG in lobes
- requires electrons up to ~ 1 TeV, accelerated in situ or efficiently transported

Science 328, 2010

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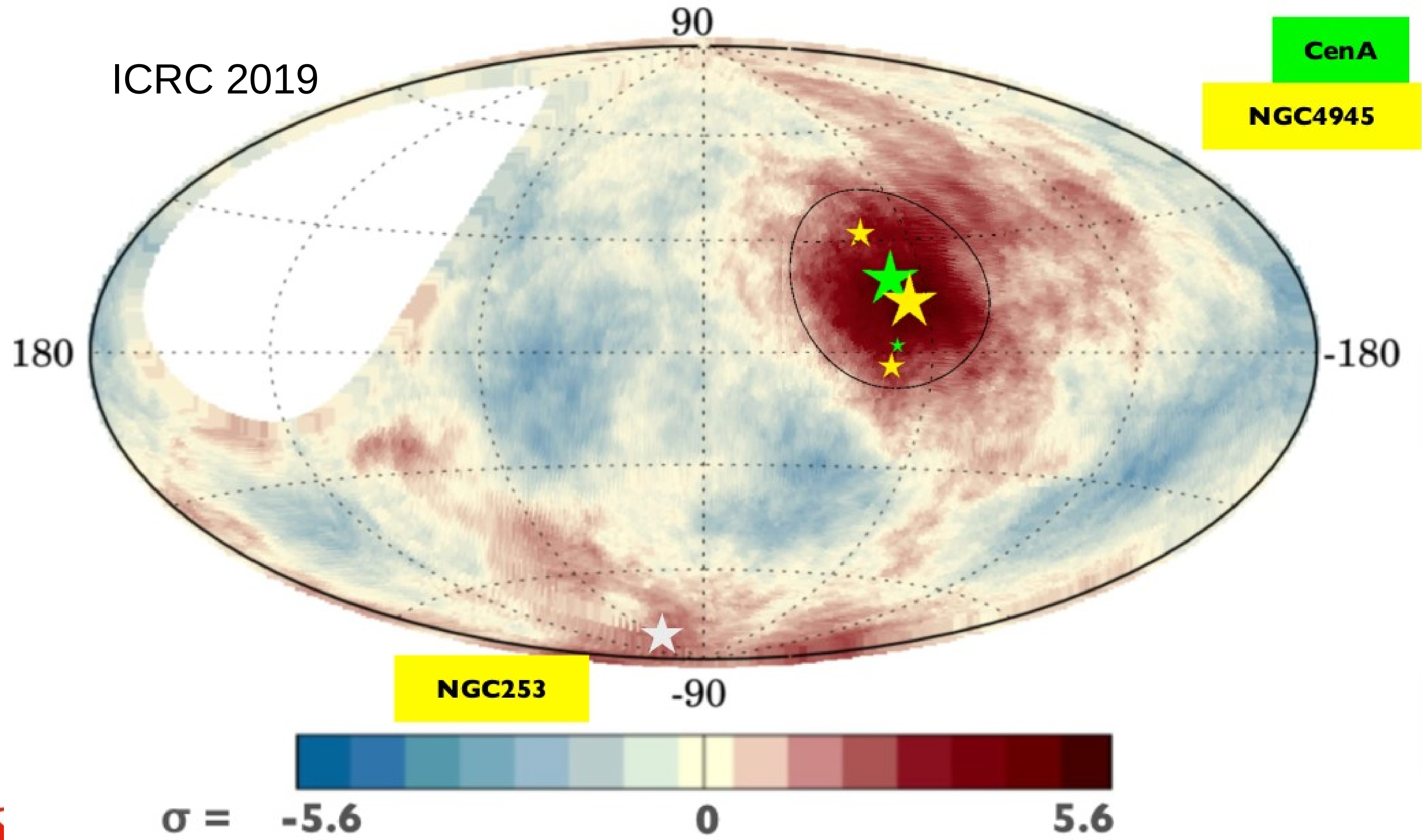
Centaurus A & UHECRs?

- Small scale anisotropies of UHECRs indicates possible correlation with Cen A region (or starburst galaxies) at ~ 3.9σ (post-trials)



High Energy Stereoscopic System (H.E.S.S.)

- Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia (1800 m)

- H.E.S.S. phase 1 (09-2002):
- 4 telescopes: Ø 12 m,107 m^2
- Stereoscopic reconstruction
- 960 PMTs/camera, Field of view : 5°
- Observations : ~1000h/year
- Source position : ~ 10''

- H.E.S.S. phase 2 (09-2012):
- a 5th telescope, Ø 28 m, 600 m^2 (largest IACT in the world)
- 2048 PMTs, Field of view : 3.5°
  → Energy threshold (zenith) ~ 30 GeV

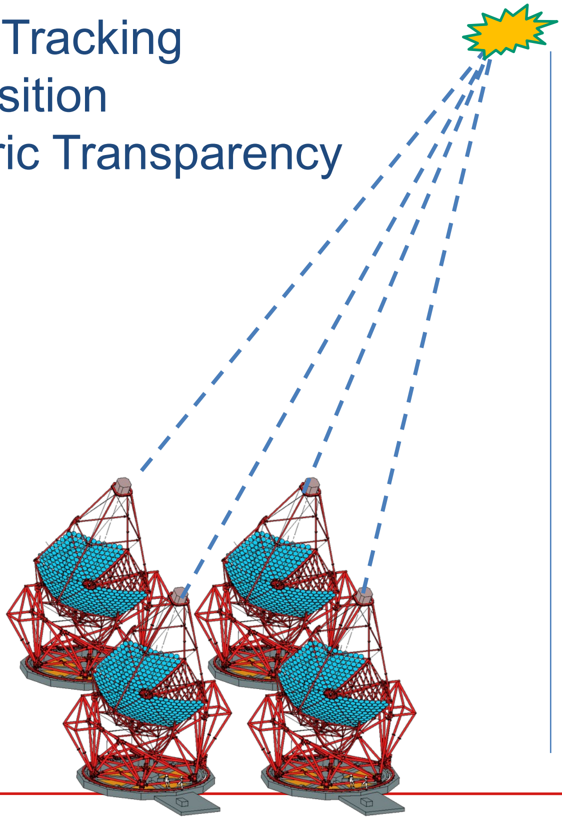
Advanced framework for simulations

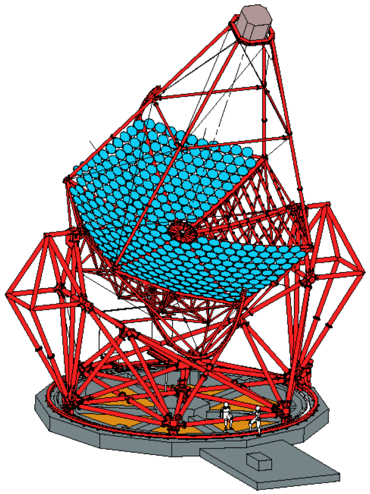
More realistic simulation approach (ICRC 2017)

- Simulating each observation run of a data set
- Using actual observation and instrument conditions

Array-wise

- Telescope Tracking
- Source Position
- Atmospheric Transparency



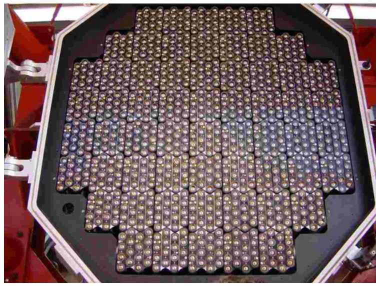


Telescope-wise

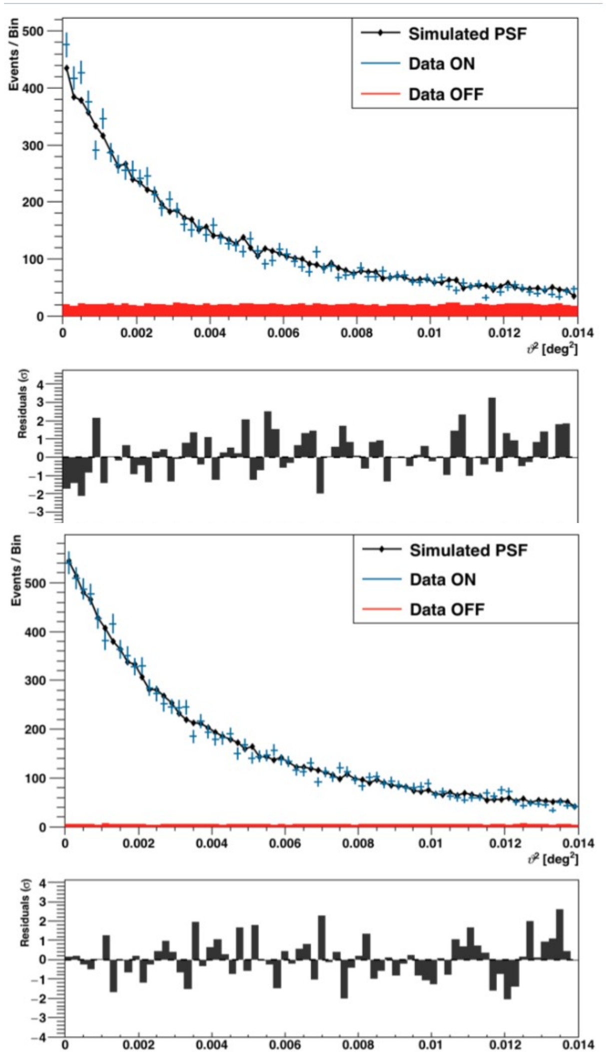
- Camera focus
- Trigger Settings
- Live-Time fraction
- Average reflectivity

Pixel-wise

- Broken Pixels
- PMT Gain
- HI-Lo ratio
- Flatfield Coeffient
- NSB (star field, …)

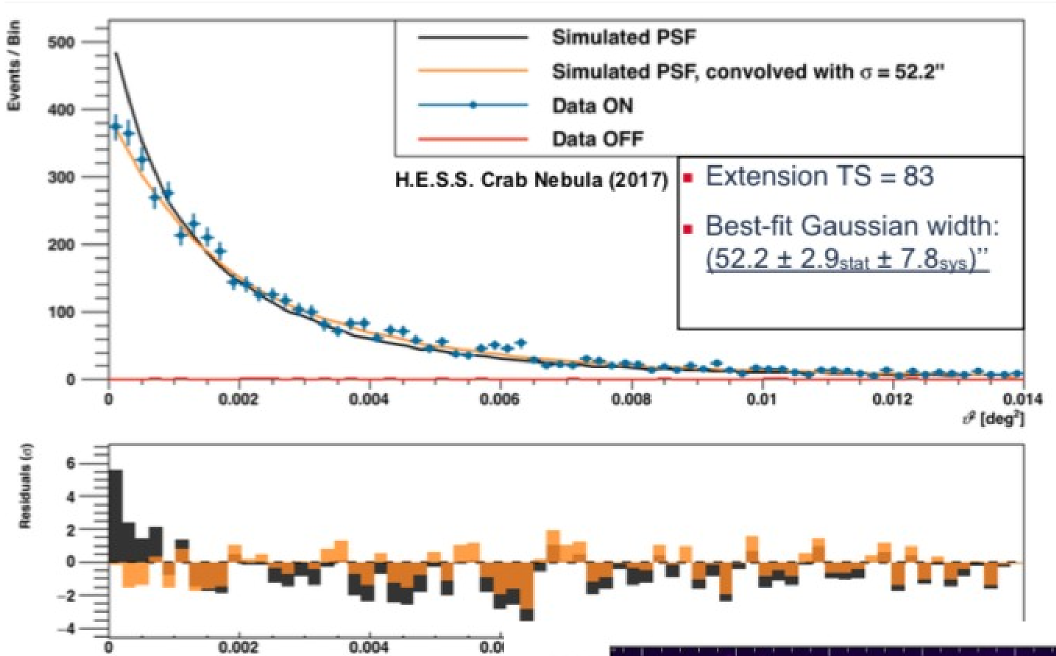


Outcome: Morphology of Point-Like Sources

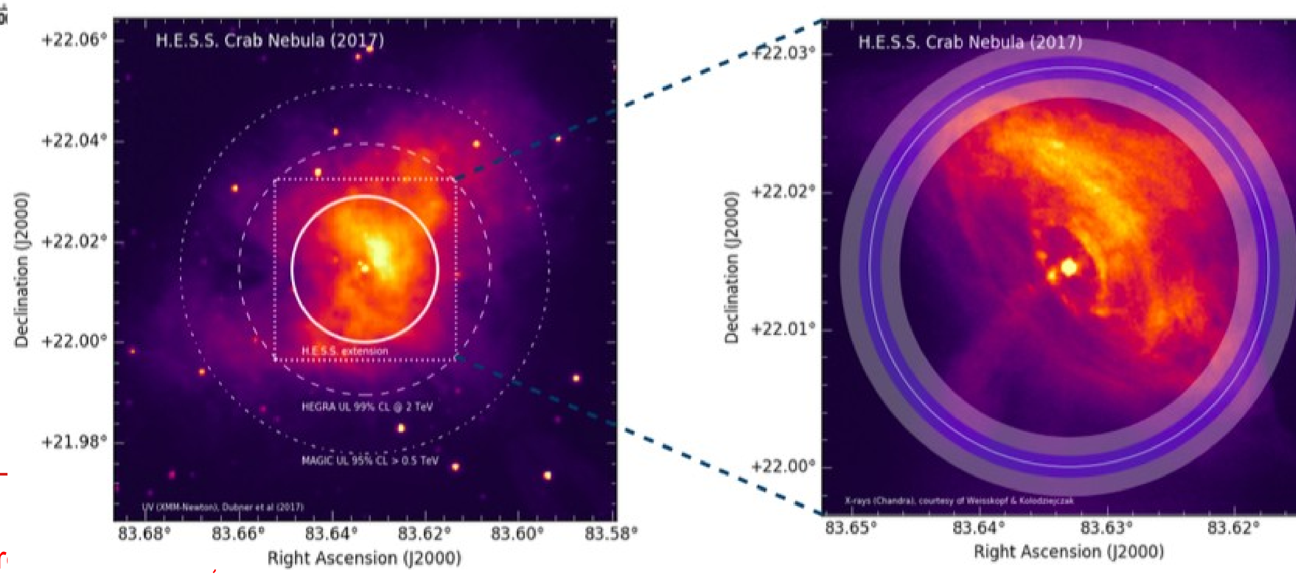


- PKS 2155-304
  - Detection significance: 125σ
  - S/B ratio: 6.9
  - Consistent with point-like
  - Extension upper limits (2D Gaussian width):
    - 13.7'' (1σ) ,
    - 23'' (3σ)
- Markarian 421
  - Detection significance: 196σ
  - S/B ratio: 35
  - No hints of systematics despite extremely large zenith angle
  - Extension upper limits (2D Gaussian width):
    - 23.4'' (1σ)
    - 33.5'' (3σ)

Outcome: New capabilities in morphology studies



Extension of the Crab Nebula 52'', comparable with X-ray Nebula

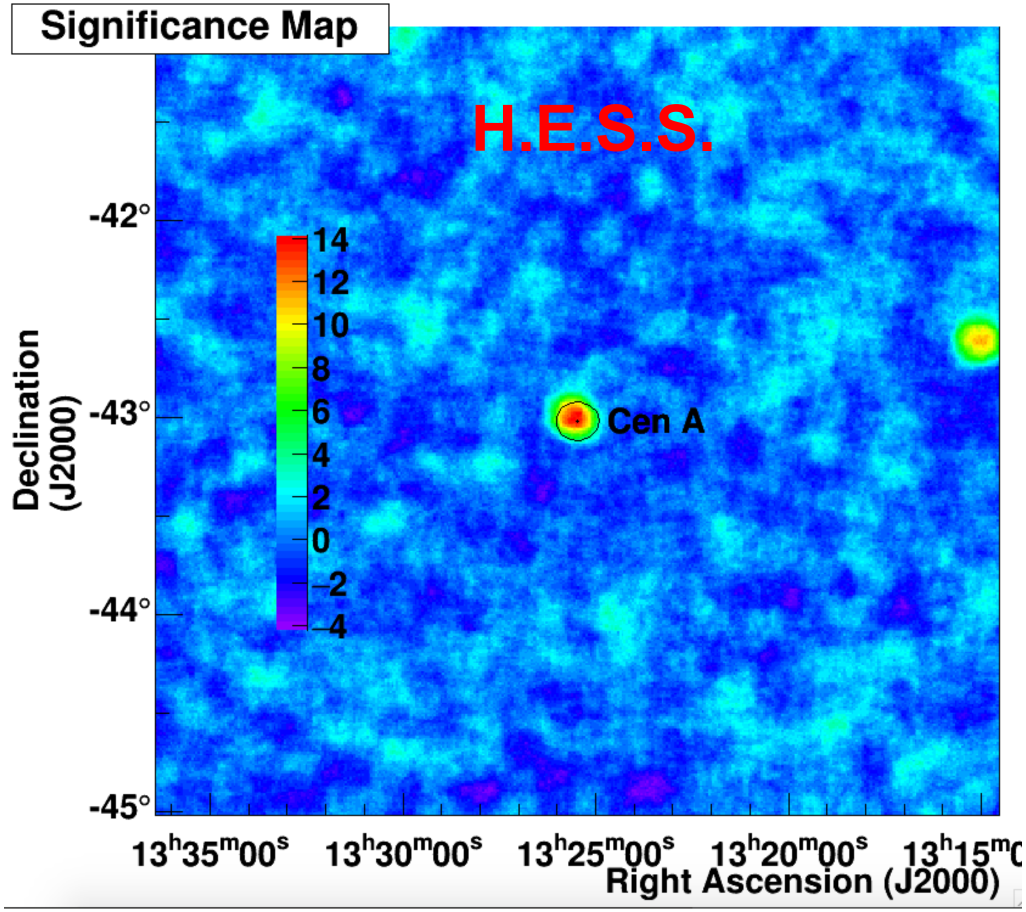


Nature Astronomy, 2019

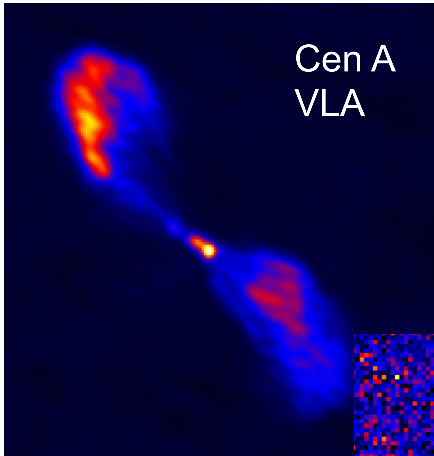
H.E.S.S.

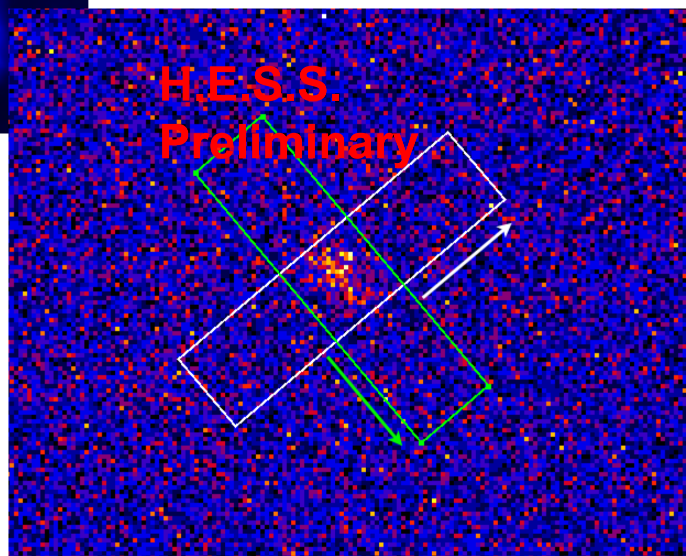
H.E.S.S. Re-analysis of the H.E.S.S. phase I data

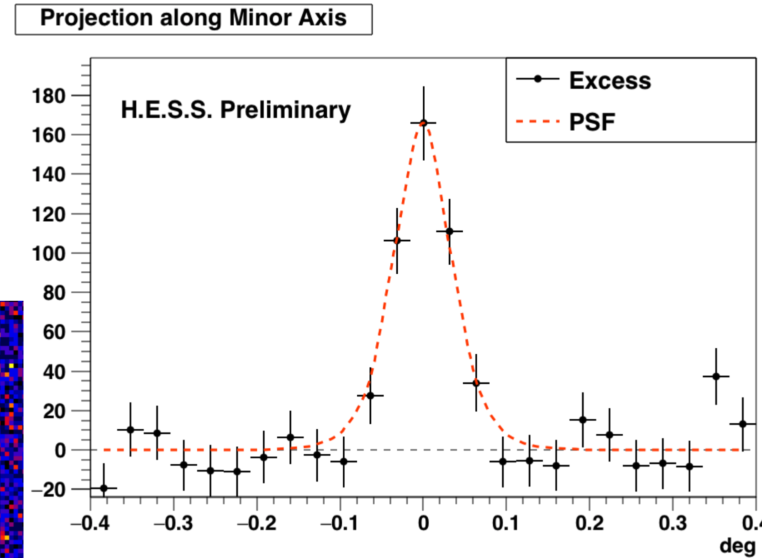
- Deep H.E.S.S. Observations from 2004 to 2013
  - 202 hours of live time
  - Change in hardware state, observation conditions
- Detection significance: 13.1σ
- S/B ratio: 0.5
- Challenging data set
  - Long exposure over several years
  - Different hardware states
  - Different obs. conditions
  - Low S/B ratio

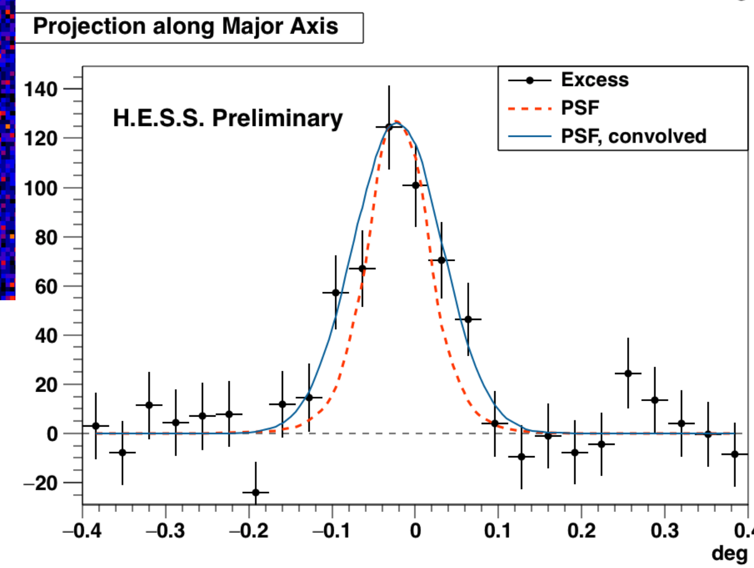


1D-projection of the raw event map







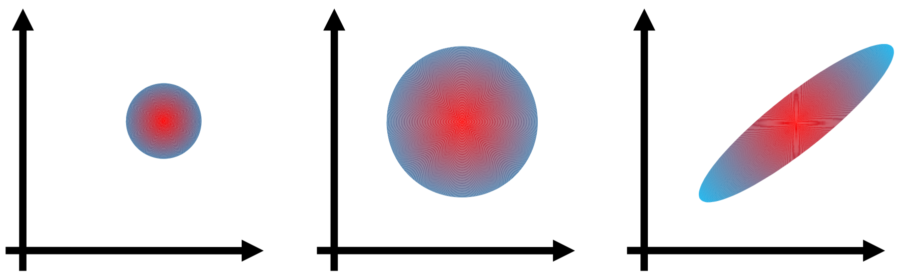


Projection along the radio jets

- Minor axis: no extension
- Major axis: PSF folded with the best-fit width from the 2D fit

2D study of the Cen A data set

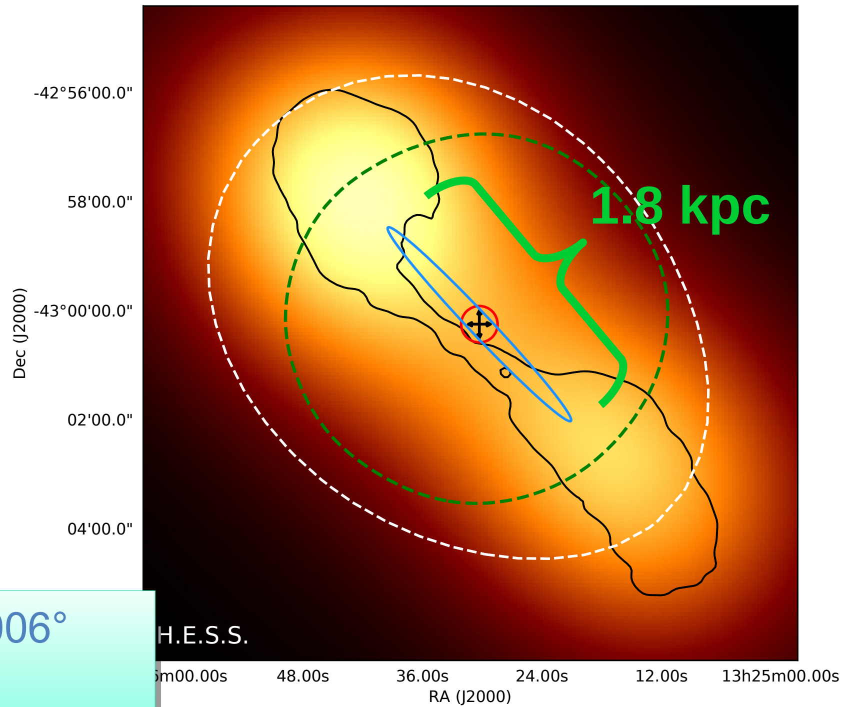
- Several morphological models invstigated
- Forward folding log-likelihood comparison (Sherpa)



Point-like   Sym-Gauss   Elliptic-Gauss

Sym. Gauss. vs. Point-Like	Elliptic. Gauss. vs. Point-Like
TS = 6.1	TS = 19.4

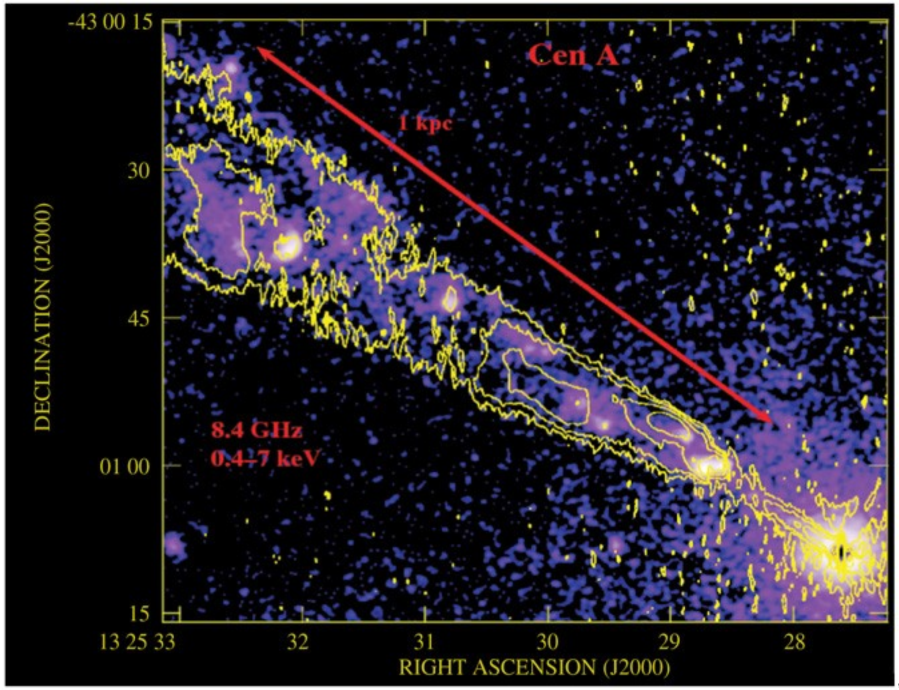
PSF
Best fit
Pointing uncertainties
Stat. uncertainties



- Gaussian width of semi-major axis: 0.041 ° ± 0.006°
- ~ Point-Like in the transverse direction
- Aligned with inner radio jets (43.4° + 7.7 – 7.2)

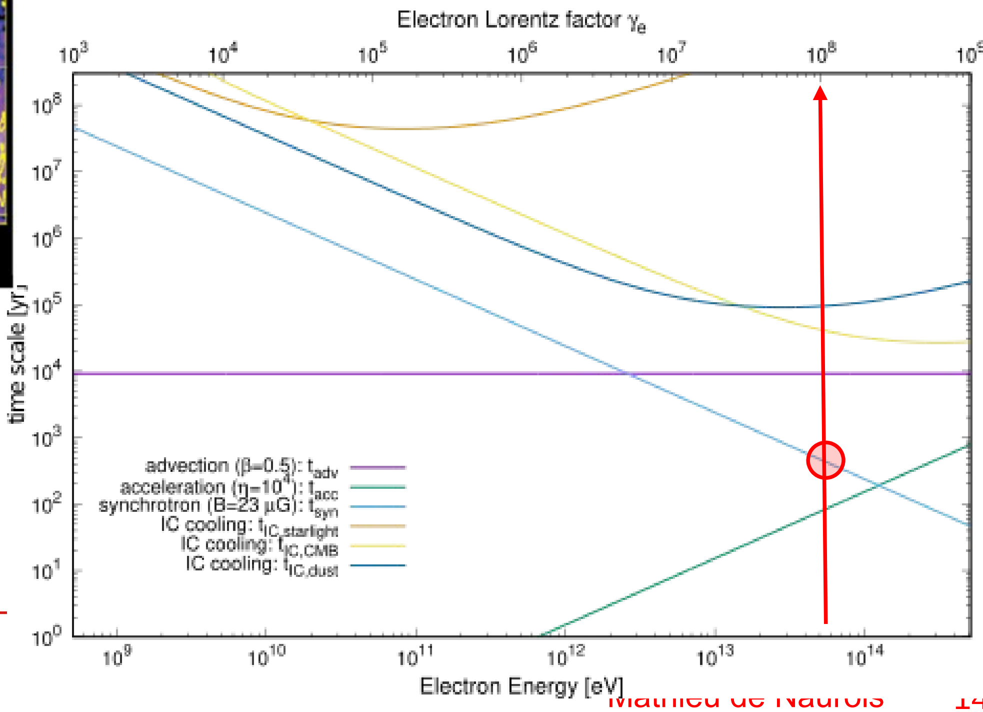
Extended VHE emission along the kpc-scale jet in Cen A?

Chandra X-ray image of the first kpc of Cen A's jet.



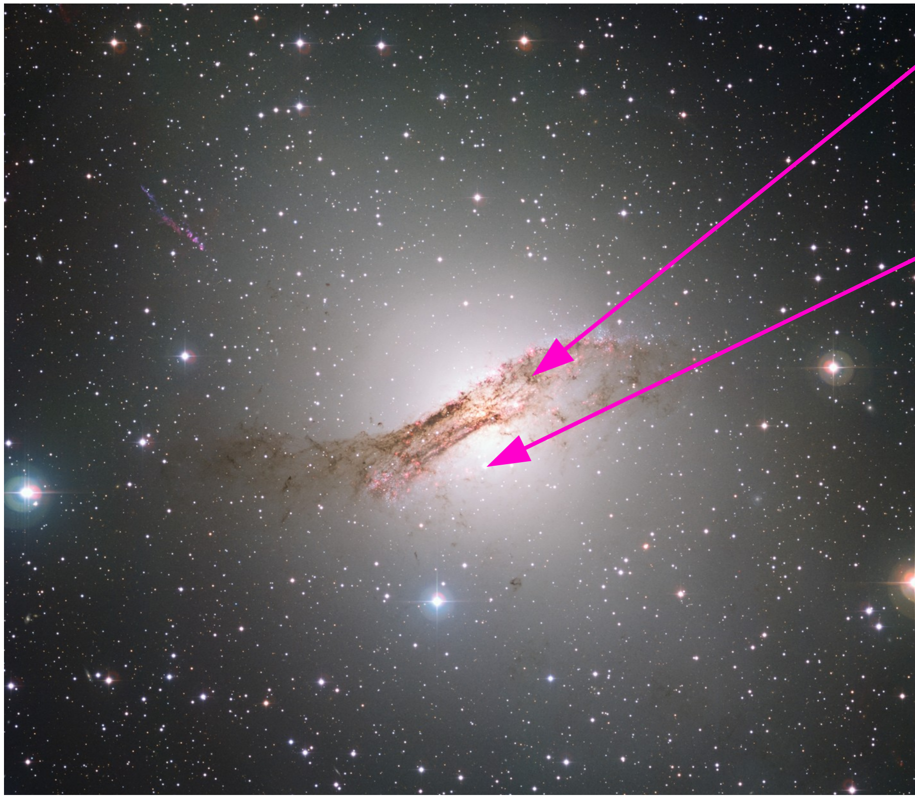
(Credit: Schwartz 2010, Hardcastle et al. 2003)

- Emitting particles ?
  - VLA radio (8.4 GHz) emission (contours) correlates with X-rays.
  - X-rays are continuously emitted throughout jet.
  - If X-rays are due to synchrotron, electrons need to be accelerated everywhere (short cooling timescale for $\gamma \sim 10^8$)



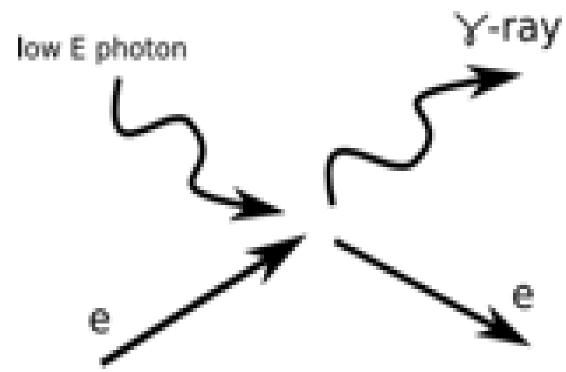
Extended VHE emission along the kpc-scale jet in Cen A?

Source of soft photon fields

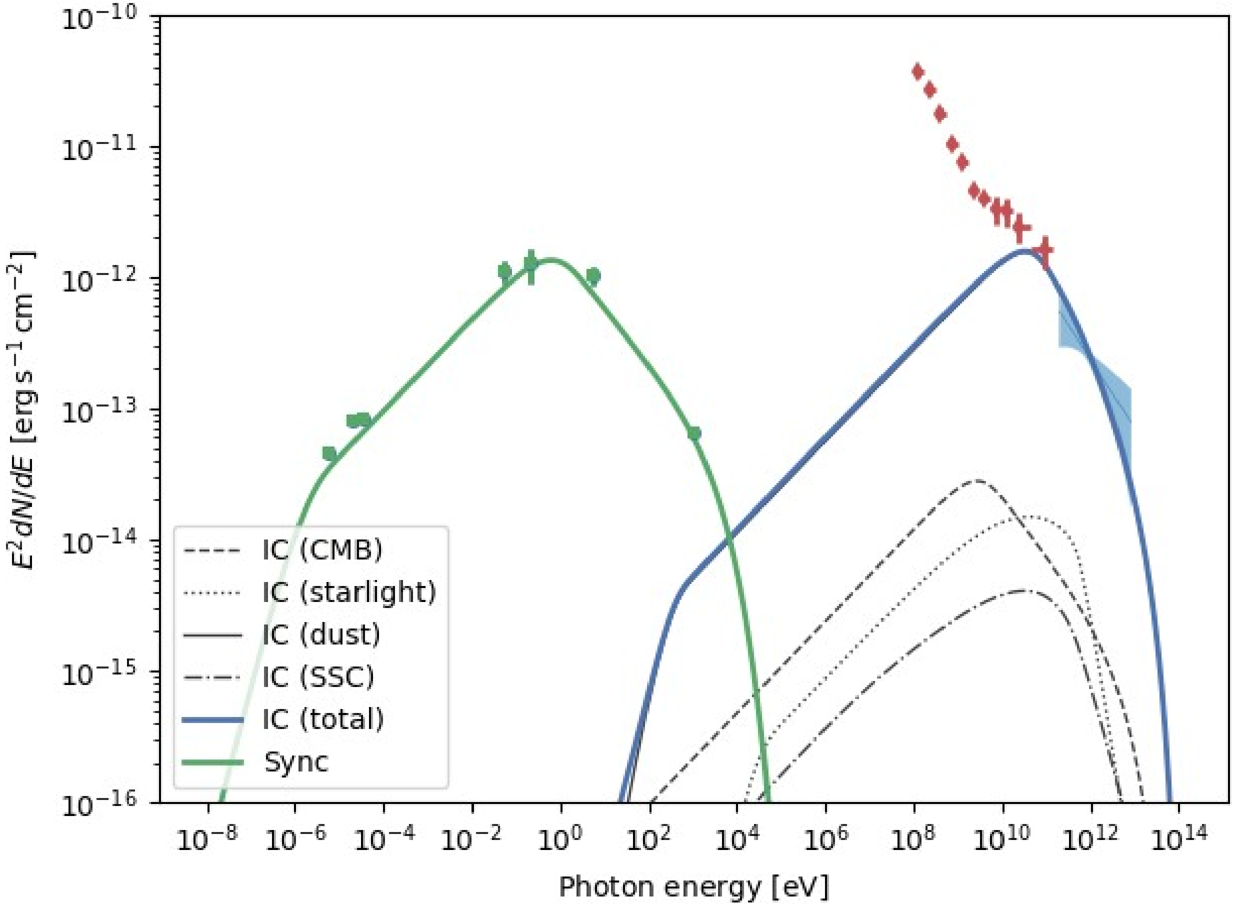


(Credit : ESO/WFI)

- External soft photon fields:
  - dust (peaking @ ν_p~3 × 10^{12} Hz):
    $\nu_{VHE} \sim \gamma^2 \nu_p$ (Thomson) □ $\gamma \sim 10^7$
  - host starlight ($\nu_p \sim 5 \times 10^{14}$ Hz):
    $\nu_{VHE} \sim \gamma\, m_e c^2$ (KN) $\Rightarrow \gamma \sim 10^6$
- CMB and SSC contribution negligible



SED



- IC on dust dominant component
- Synchrotron emission in 23 μG field explains X-ray emission
- GeV emission arising from the core, explains spectral hardnening @ 3GeV

Conclusions

- New era for morphology studies in VHE astronomy
- Centaurus A emission is not point-like at TeV
- First extragalactic extended source at VHE

- Morphology of Cen A:
  - Elliptical shape :
  - Gaussian width of semi-major axis:
  - 0.044 ° ± 0.012° (1.8 kpc)
  - Point-Like in the transverse direction
  - Aligned with radio jets
- Implies continuous acceleration along the jets
- Paper submitted to Nature