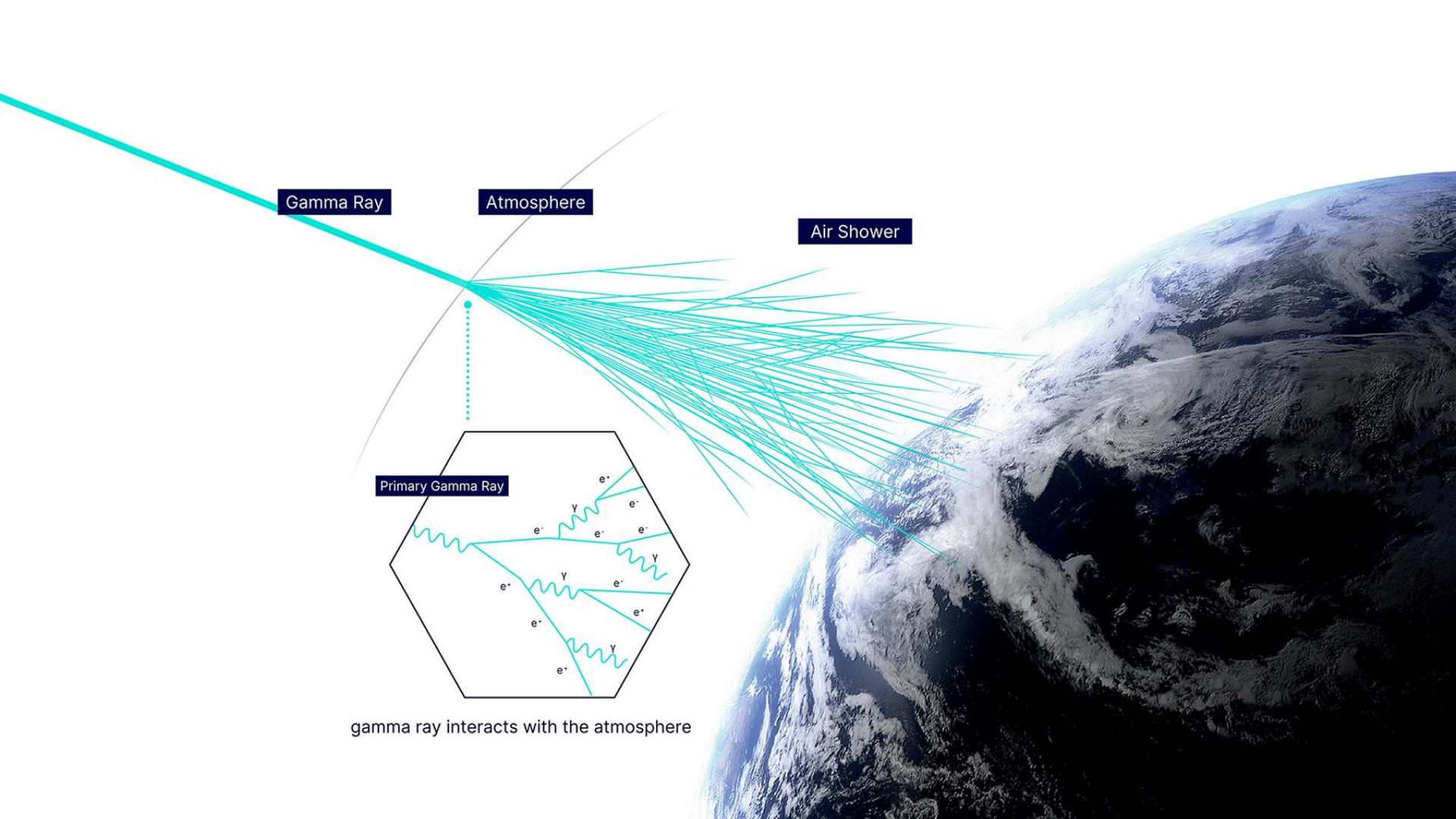
Extragalactic VHE gamma-ray sky

Elina Lindfors, University of Turku, Finland

TURUN YLIOPISTO

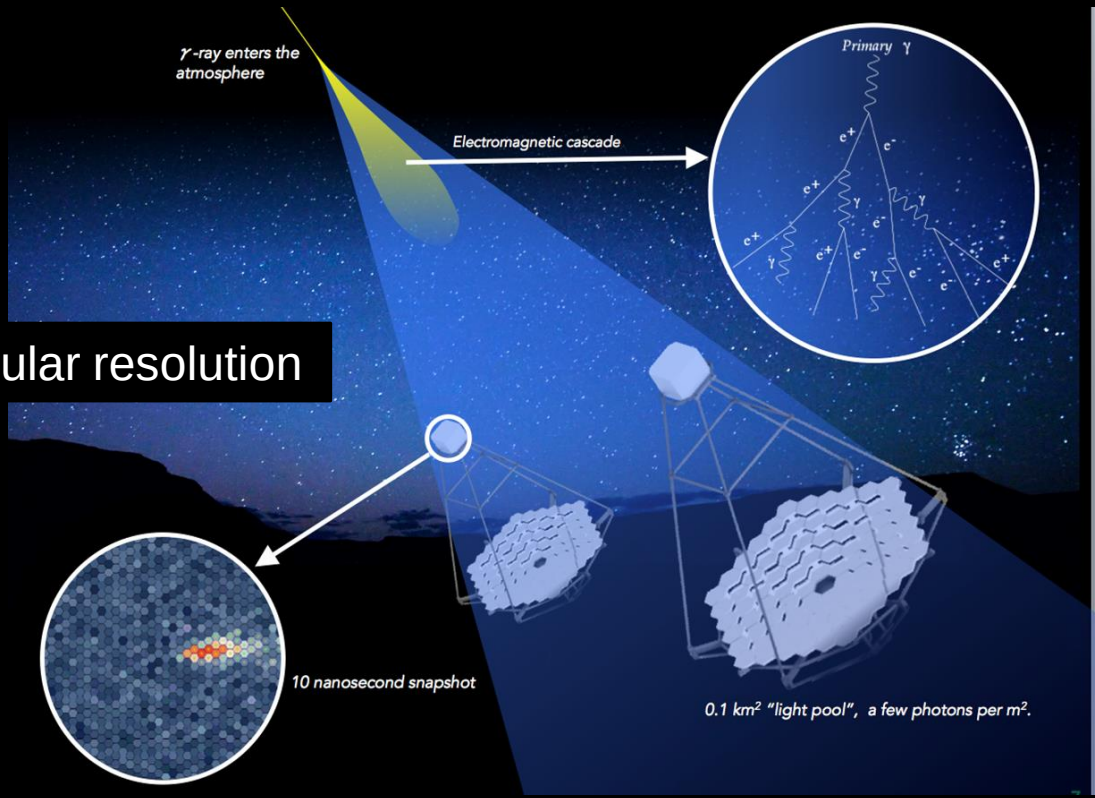
Observing VHE gamma-ray sky



Observing VHE gamma-ray sky

- Pointing instruments Imaging Air Cherenkov Telescopes: MAGIC, H.E.S.S., VERITAS

Lower energy threshold, better angular resolution

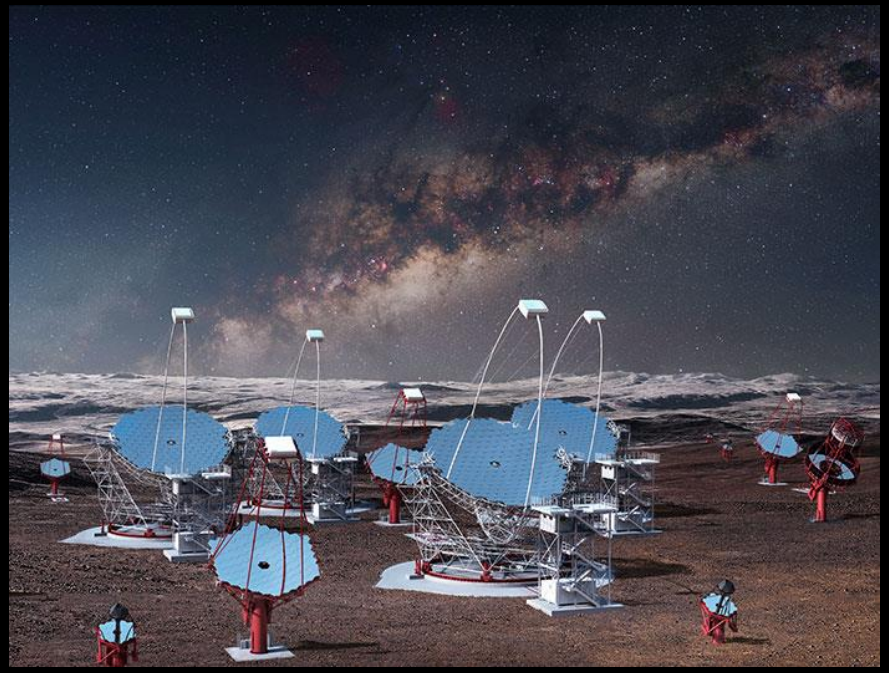


CTAO | CONSORTIUM

First Open Observatory for VHE gamma-rays

CTAO

- Two Observatories: North @La Palma, South @Paranal
- Three different telescope sizes to drive the sensitivity in different energy ranges
- Order of magnitude better sensitivity, energy resolution, angular resolution, extends energy range in both ends.
- Performance: https://www.ctao.org/for-scientists/performance/

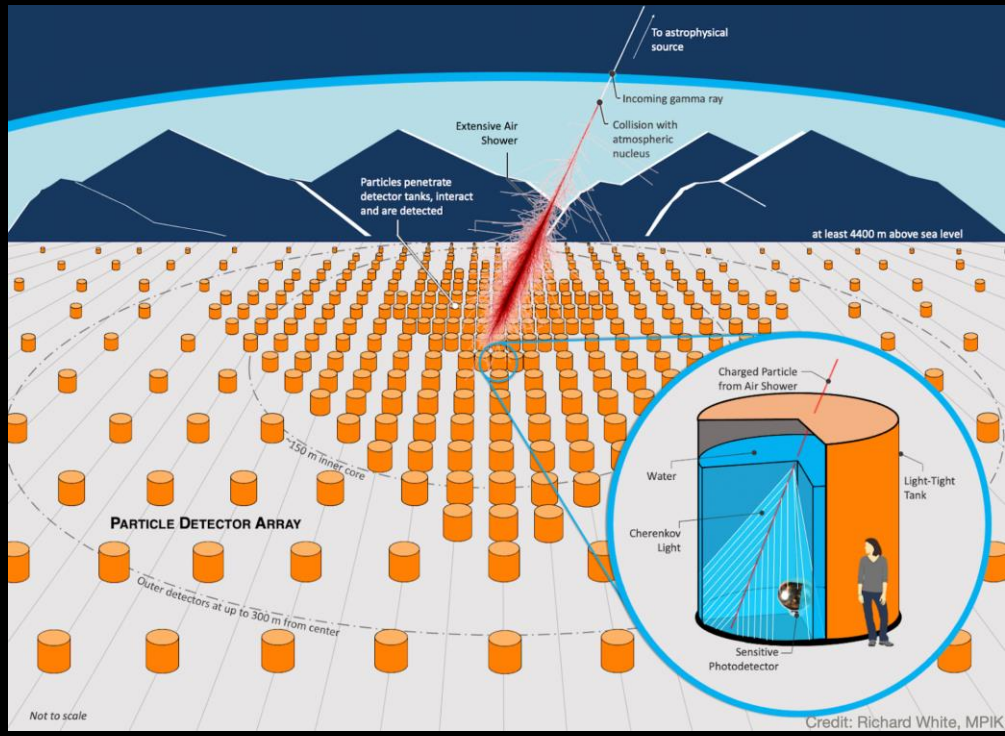


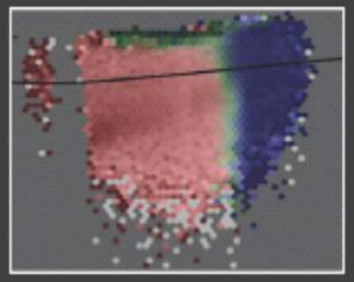
Observing VHE gamma-ray sky

- Pointing instruments
  Imaging Air Cherenkov Telescopes: MAGIC, H.E.S.S., VERITAS

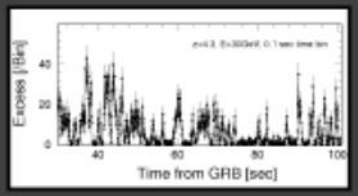
- ”All”-sky instruments
  Water Cherenkov: HAWC and LHAASO, upcoming SWGO

  ”All” sky view, higher duty cycle

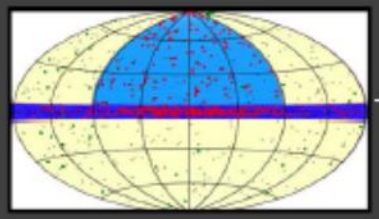




Dark Matter Programme



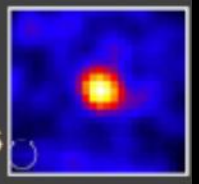
Transients

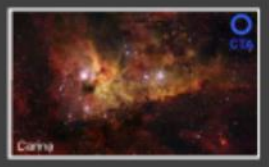


ExGal Survey

Extragalactic

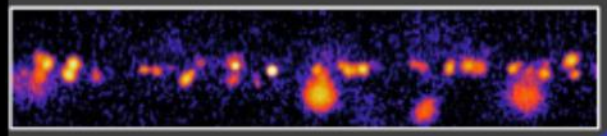
Galaxy Clusters





Star Forming Systems

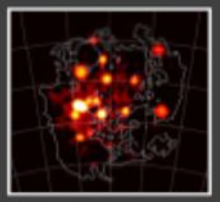
AGN



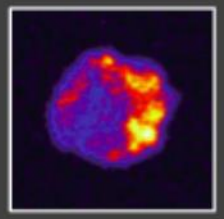
Galactic Plane Survey

Galactic

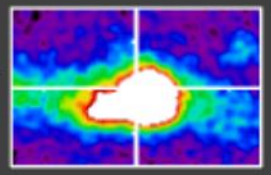
LMC Survey



PeVatrons

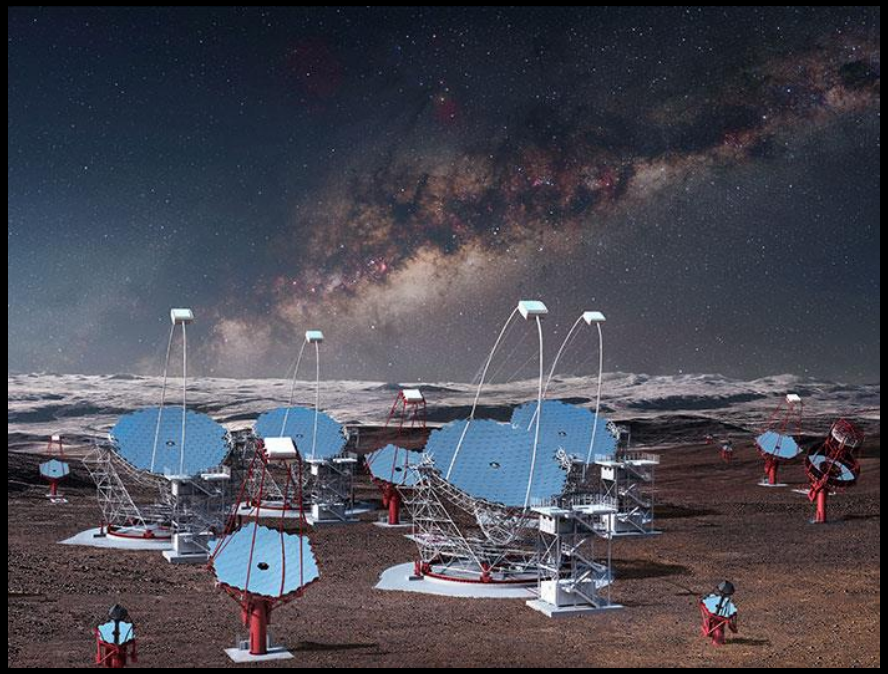


Galactic Centre



Extragalactic VHE sky

- Currently ~100 sources, with CTAO we expect order of magnitude increase
- Handful of nearby starburst (NGC253, M82) and radio galaxies (M87, Cen A)



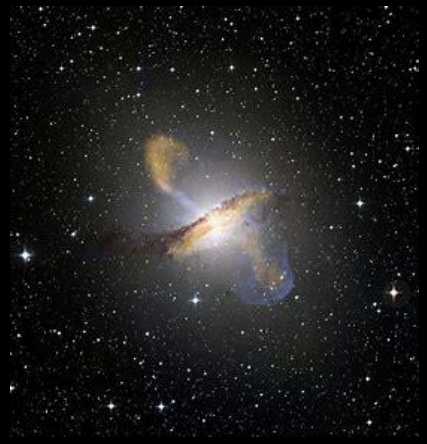
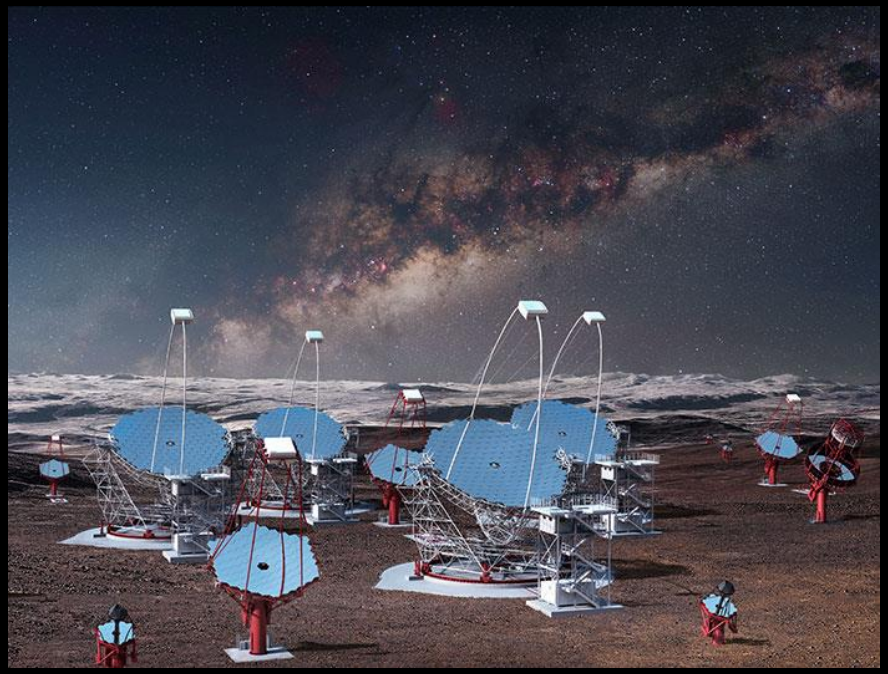


Image credit: ESO

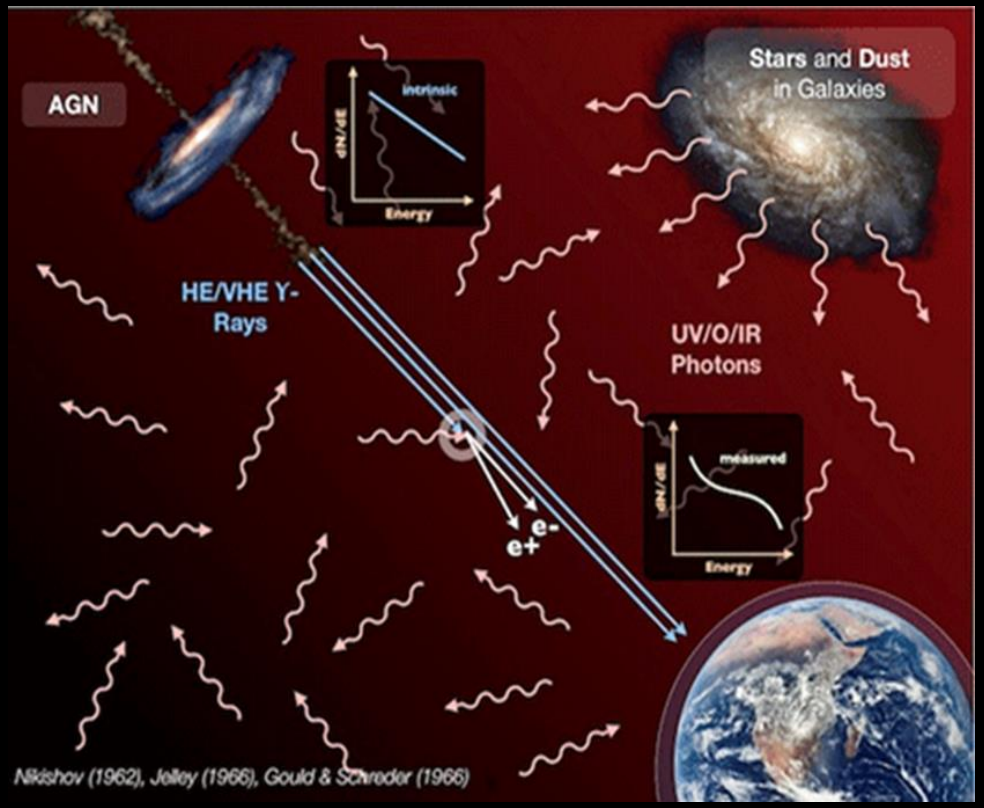
Extragalactic VHE sky

- Currently ~100 sources, with CTAO we expect order of magnitude increase
- Handful of nearby starburst (NGC253, M82) and radio galaxies (M87, Cen A)
- GRBs (5)
- Majority: extragalactic jets pointing at us.



Extragalactic VHE sky: the horizon

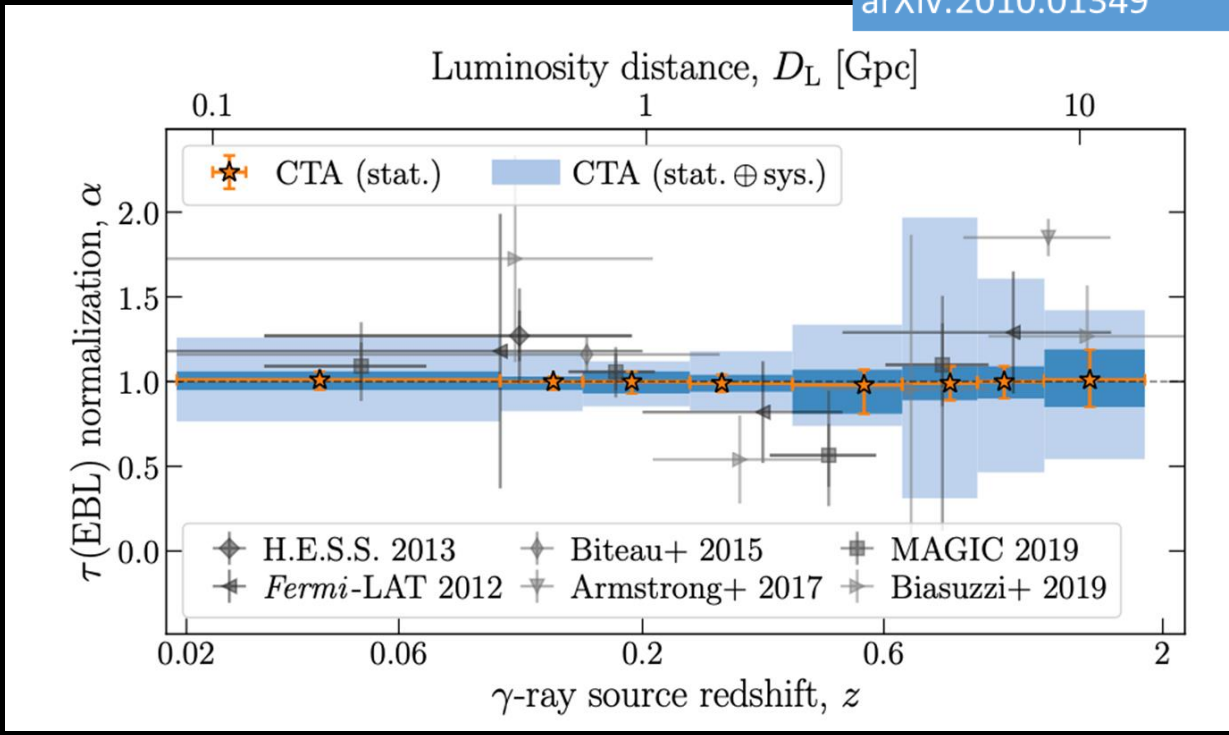
- VHE gamma-rays pair produce with optical and IR-photons of the extragalactic background light (EBL)
- Most distant VHE gamma-ray sources currently at z~1, with CTAO we expect to see up to z~2



Extragalactic jets in gamma-rays

- At z>0.4 there is a deficit of sources because many candidate sources lack redshifts.
- The further we go in redshift the more likely we are to significantly detect the sources only during the gamma-ray flares.

CTA consortium, 2021
arXiv:2010.01349



Ongoing work to update this study, stay tuned!

CTAO CONSORTIUM

VHE gamma-rays and Gravitational Waves

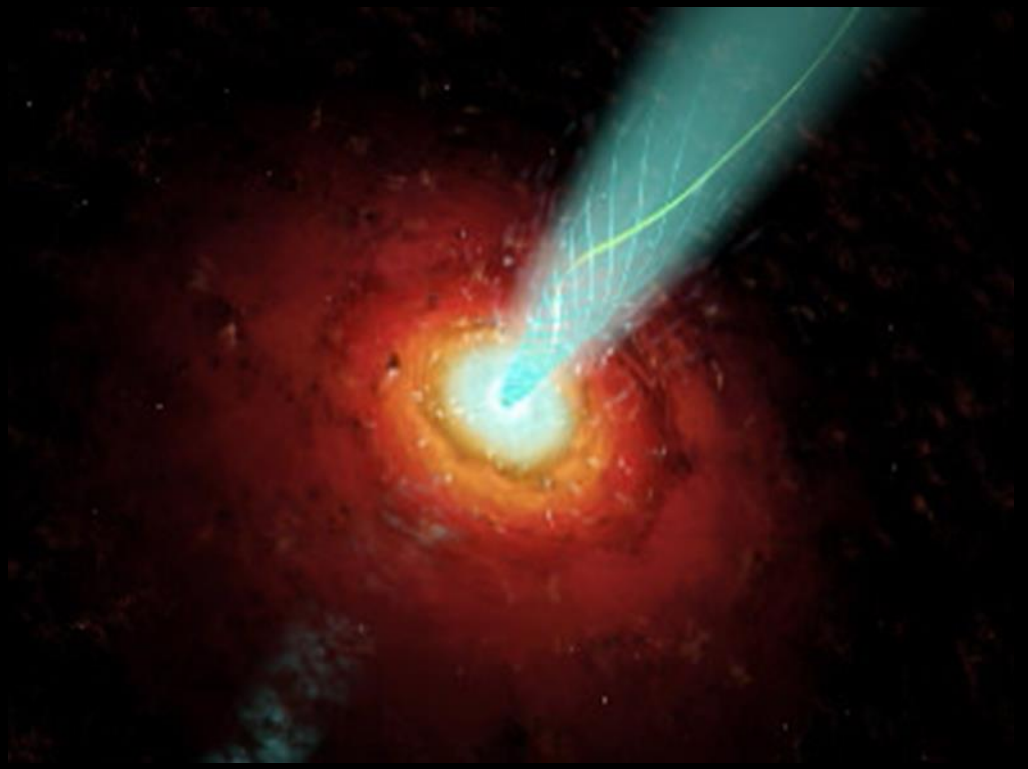
Supermassive black hole binaries

- All that other variability from the jet: noise for searching for periodicities
- VHE sources that are SMBH binary candidates
- SMBH candidates that could be interesting for VHE in the future

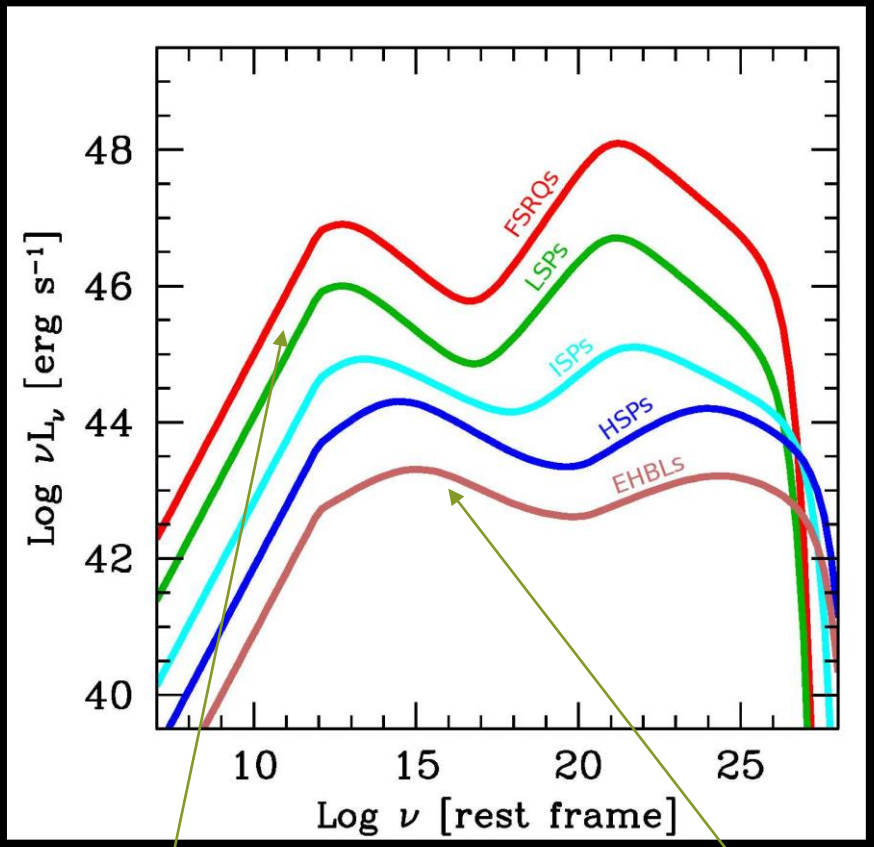
Short gamma-ray bursts

Extragalactic jets in gamma-rays

- Relativistic jets launched by supermassive black holes are the most extreme particle accelerators
- Pointing at us: blazars
- Bright *and variable* in all wavelengths: the most numerous sources in the gamma-ray sky



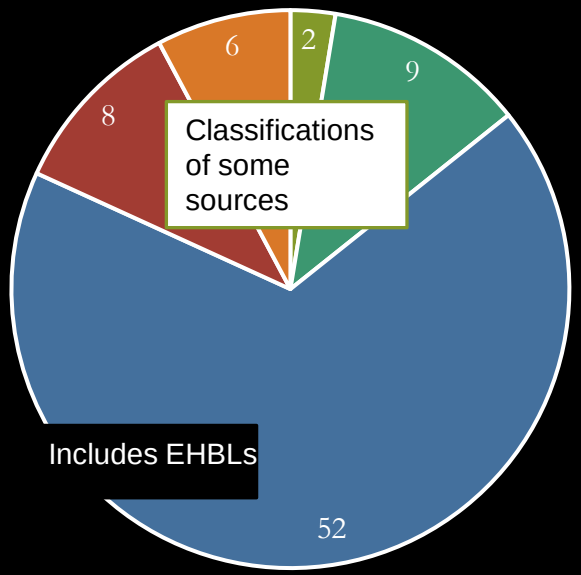
Very High Energy gamma-ray AGNs



LSPs = LBLs + FSRQs

EHBL = synchrotron peak above 10^{17} Hz

sub-classes



- HSPs most numerous objects
- Only handful: EHBLs, LSPs , Radio galaxies
- Discovery space: NlSy1, LLAGN

Extragalactic jets in gamma-rays

- Relativistic jets launched by supermassive black holes are the most extreme particle accelerators
- Pointing at us: blazars
- Bright *and variable* in all wavelengths
- Variability: *all bands* at time scales from minutes (in gamma-rays) to years, polarized emission (radio, optical, X-rays)

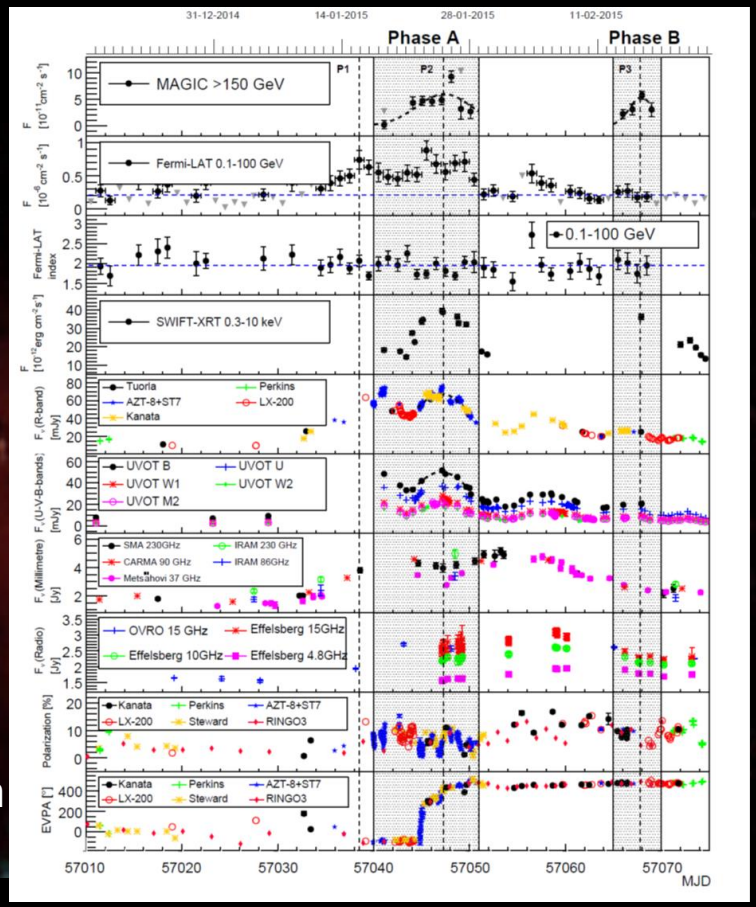
Gamma

X-rays

Optical

Radio

Polarization

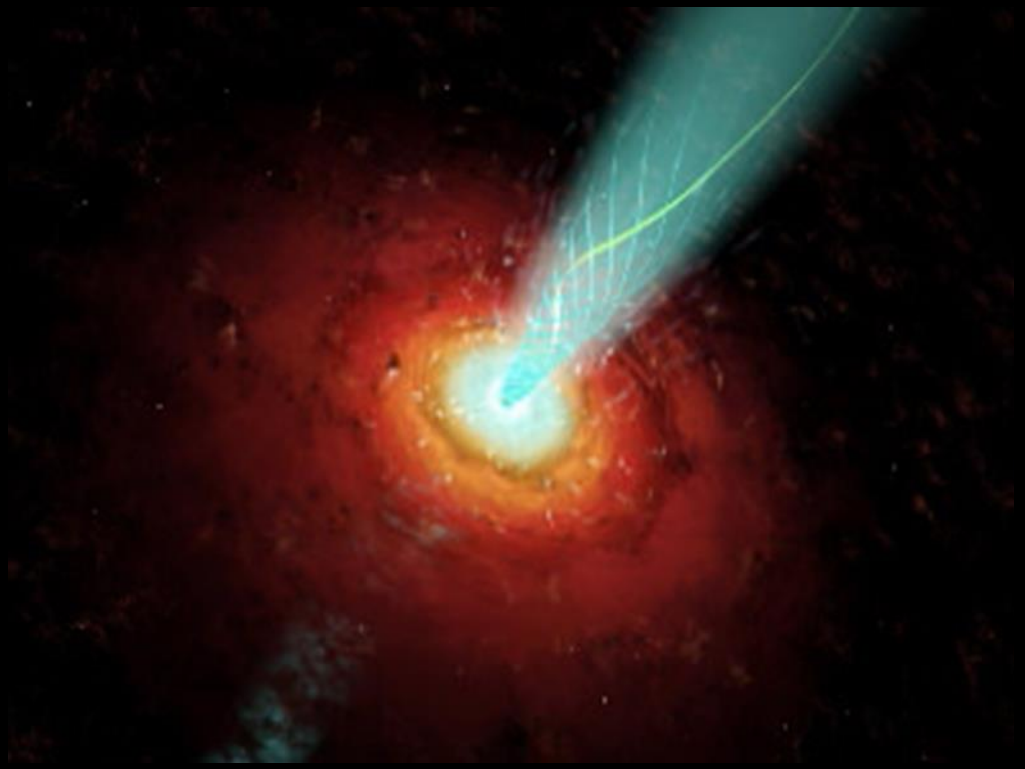


~2 months

MAGIC Collaboration (including EL) et al. 2018, S50716+714

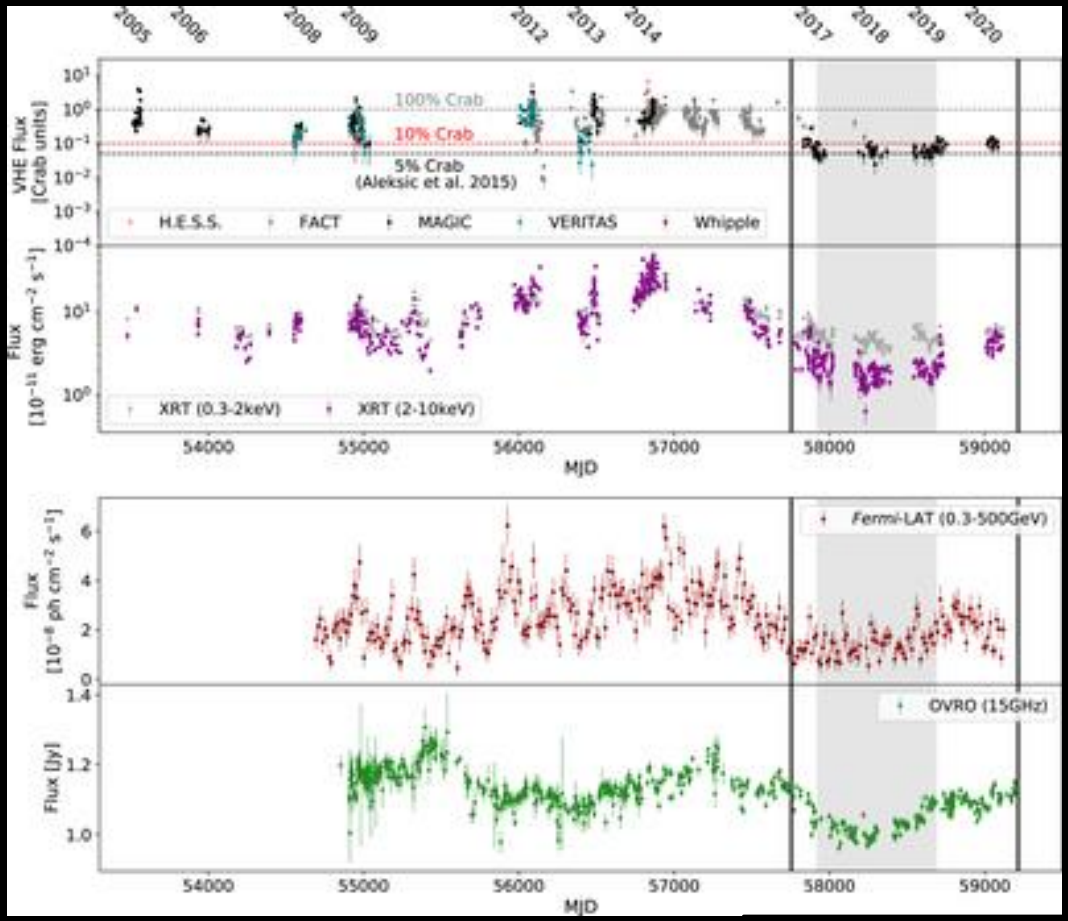
Extragalactic jets in gamma-rays: Open Questions

- Mechanism of the variability (shocks, magnetic reconnection?)
- Hosting SMBHBs?
- Location, external seed photon fields and physical conditions of the emission region/emission regions
- Composition of the jet: are there protons in the jet? (suggested sources of neutrinos and UHECRs)



Extragalactic jets in gamma-rays: Variability

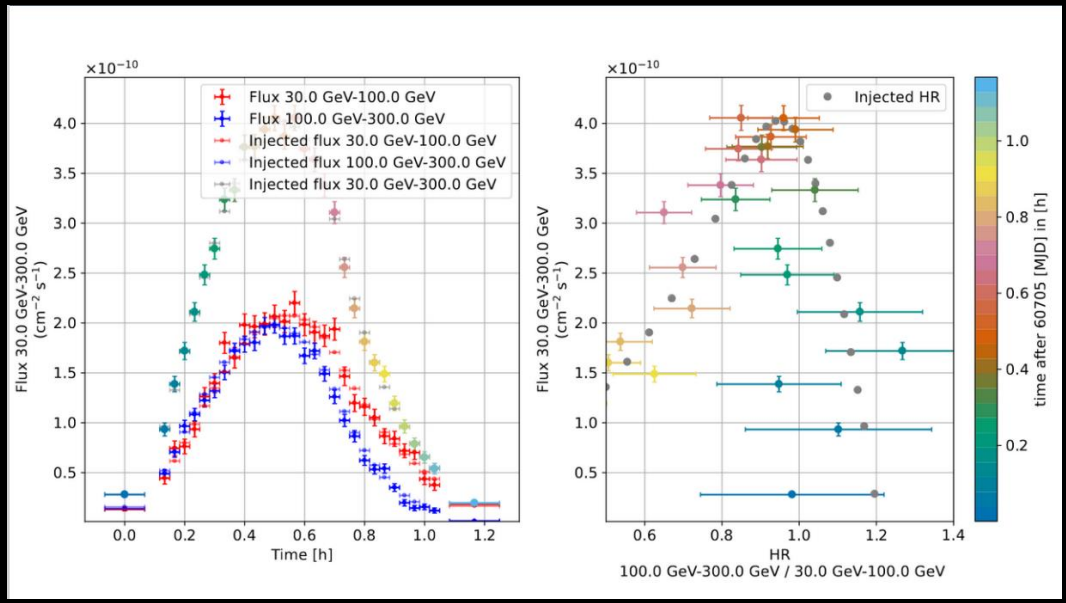
- Emission at VHE gamma-rays variable from time scales of years to hours and even minutes
- VHE gamma-rays: very long light curves like this one: only for handful of sources
- IACTs are not optimal monitoring devices
- CTAO KSP foresees long-term monitoring of 15 blazars (see Grolleron et al. Including EL on behalf of the CTAO consortium, ICRC2023)



MAGIC Collaboration et al. 2023, ApJS, 266, 37 Mrk 501

Extragalactic jets in gamma-rays: Variability

- Emission at VHE gamma-rays variable from time scales of years to hours and even minutes.
- Mechanism of the ”flares” (shocks, magnetic reconnection?) result in different spectral evolution at VHE, can be differianted with CTAO
- Stochastic variability from the jet, periodic signals very difficult to detect.



Cerrutti et al. (including EL, on behalf of the CTAO Consortium), ICRC 2023

CTAO CONSORTIUM

SMBHB candidates
Famous Examples

- OJ287: The optical light curve of 130 years shows a 12-year quasi-periodic pattern → A supermassive black hole (SMBH) binary with a precessing orbit?
- The impact flares have been predicted and observed since the 1980s
- More data: more difficult to see?

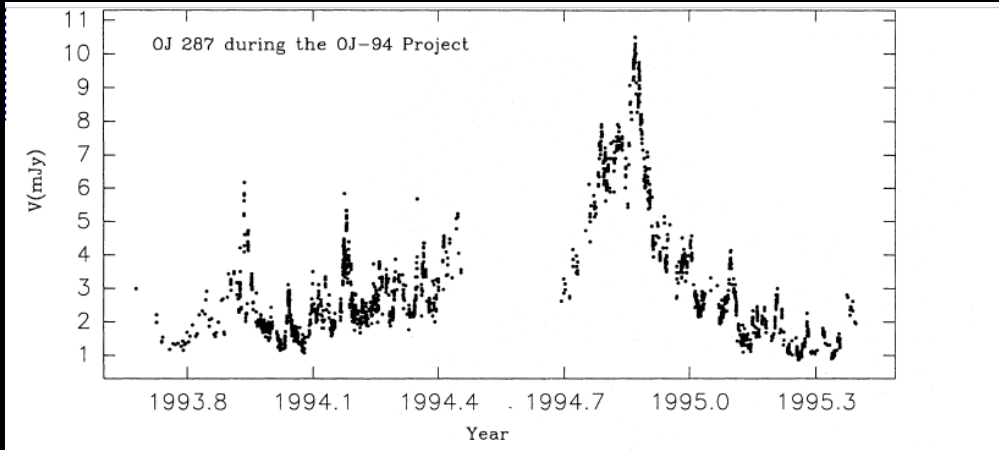


Fig. 1. The V-band light curve of OJ 287 based on the observations taken during the OJ-94 project.

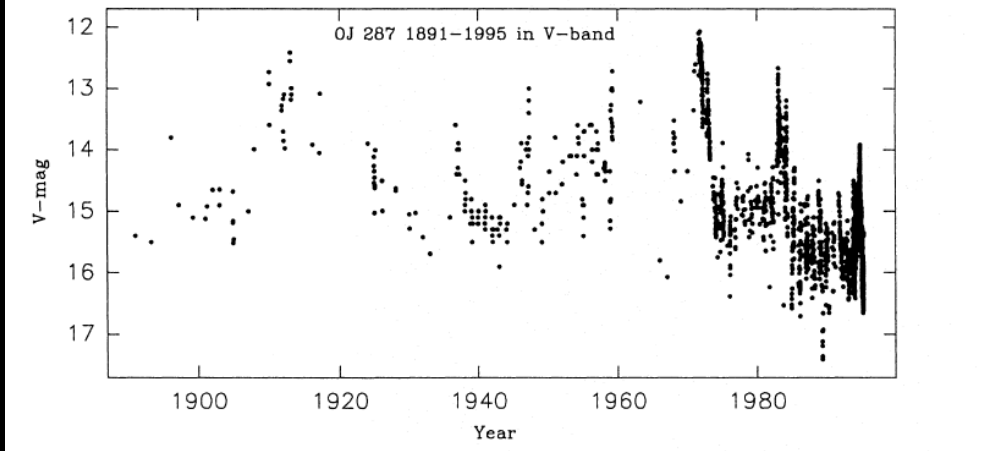
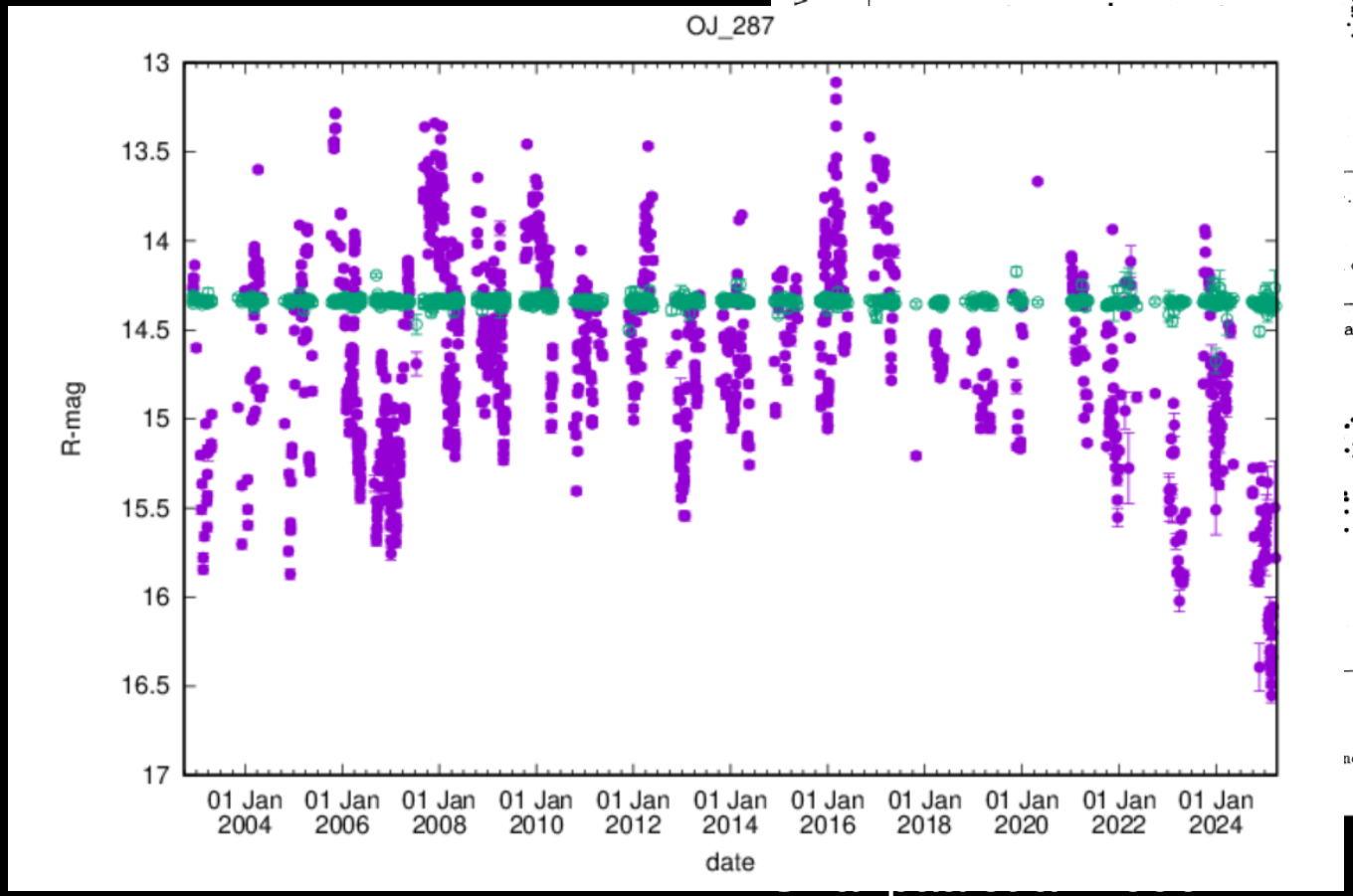


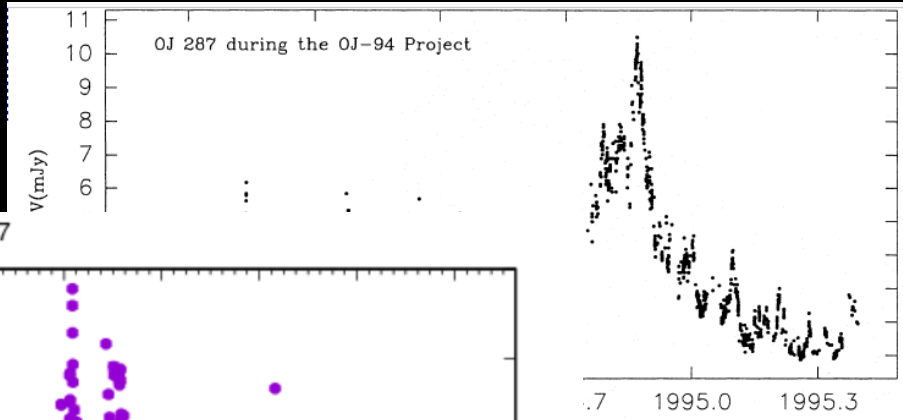
Fig. 2. The historical light curve (in magnitudes) of OJ 287 in the V-band over the interval 1891-1995 showing eight major outbursts with a time difference of about 12 years.

Sillanpää et al. 1996

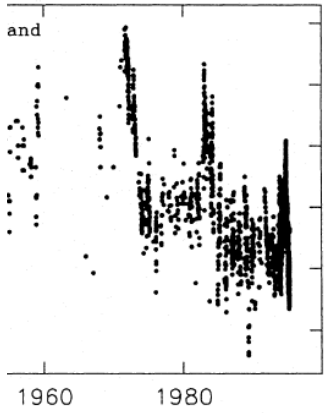
SMBHB candidates
Famous Examples

- OJ287: a 12 year





during the OJ-94 project.



nd over the interval 1891-1995 showing eight major

Tuorla blazar monitoring program: https://tuorlablazar.utu.fi/OJ_287.html

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SMBHB candidates
Famous Examples

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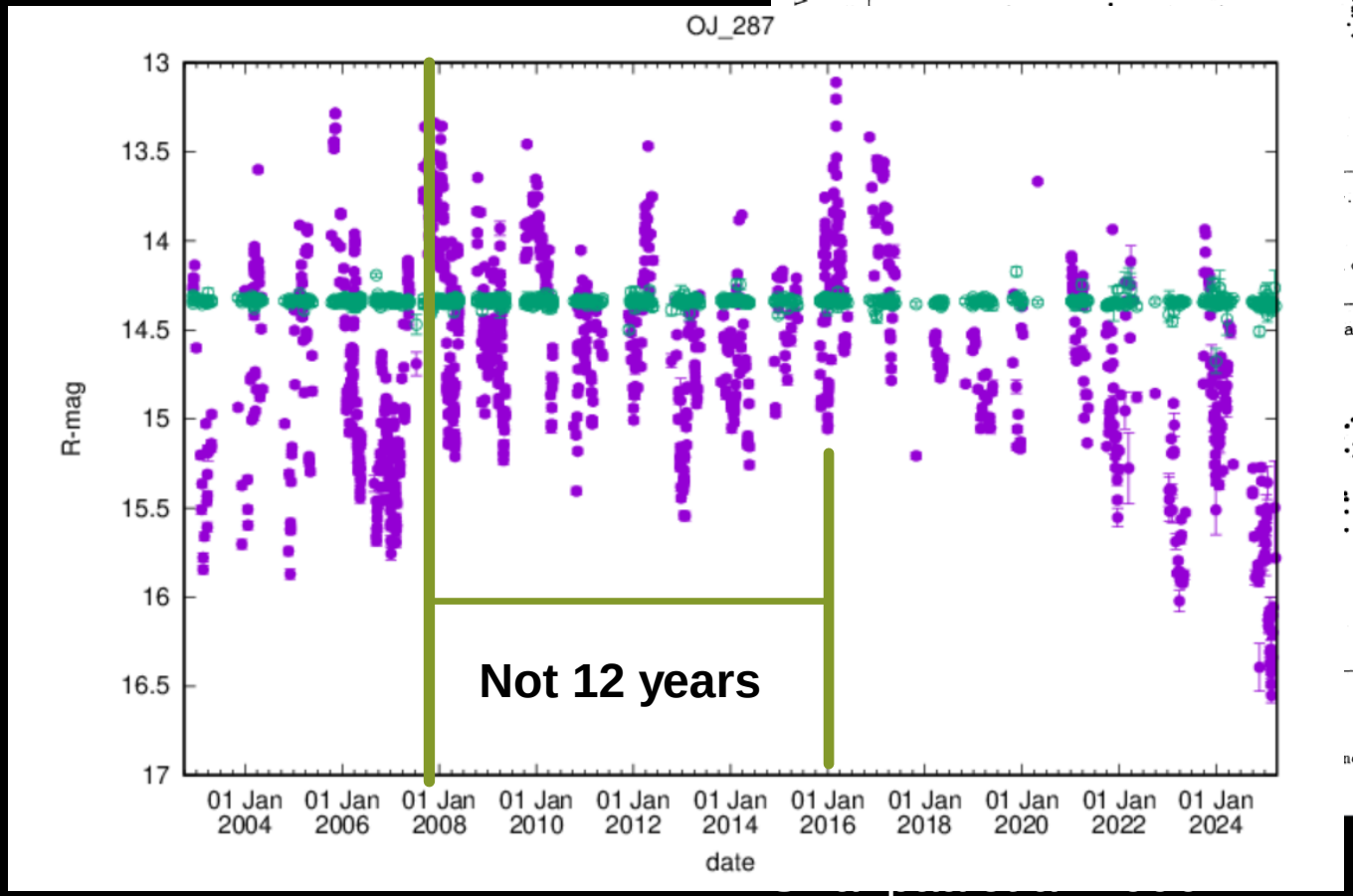

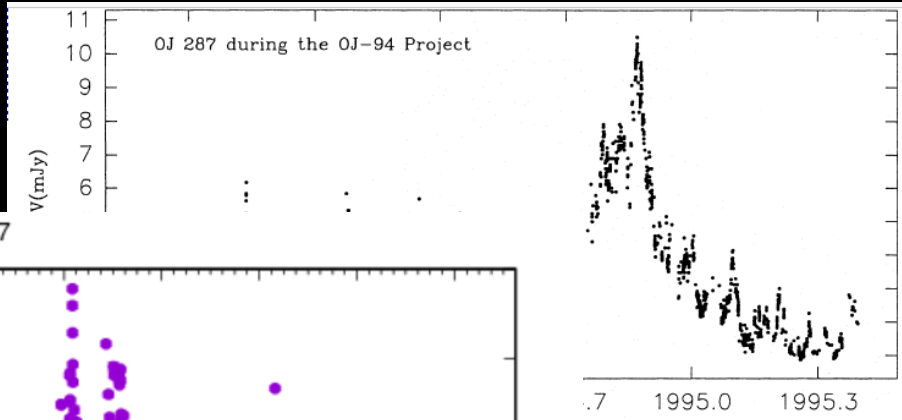

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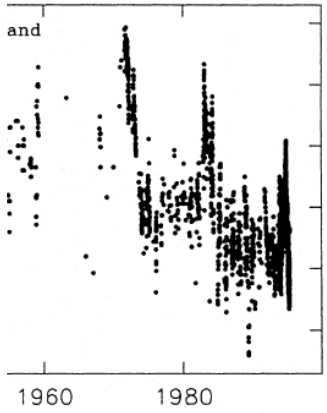

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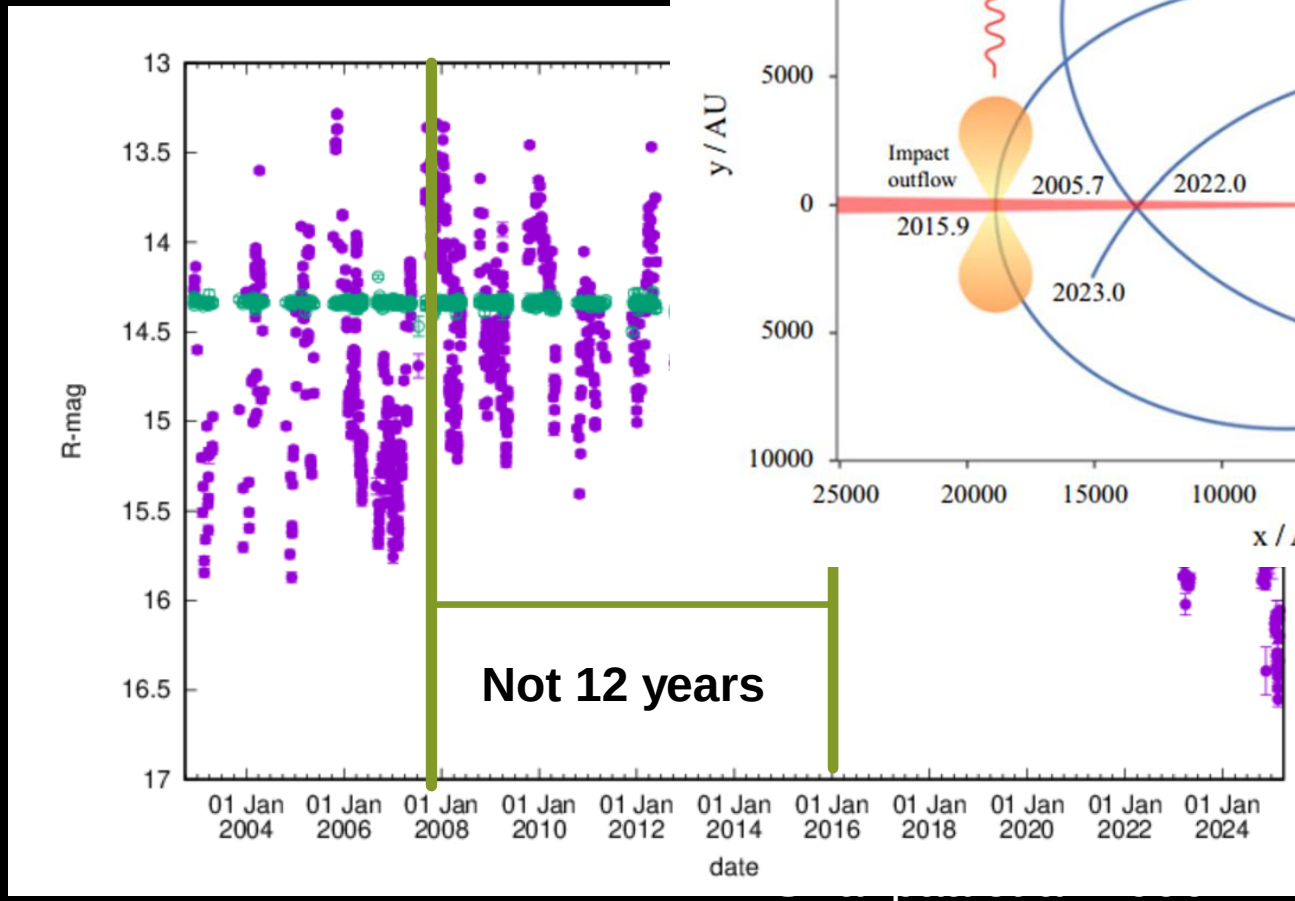

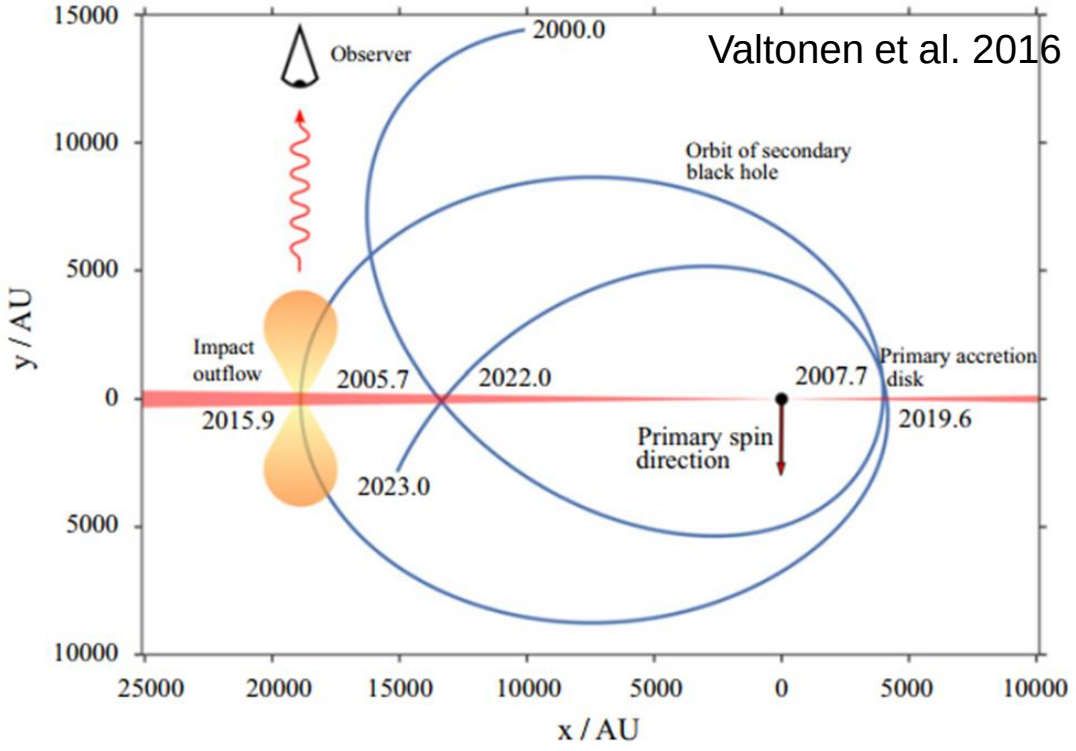

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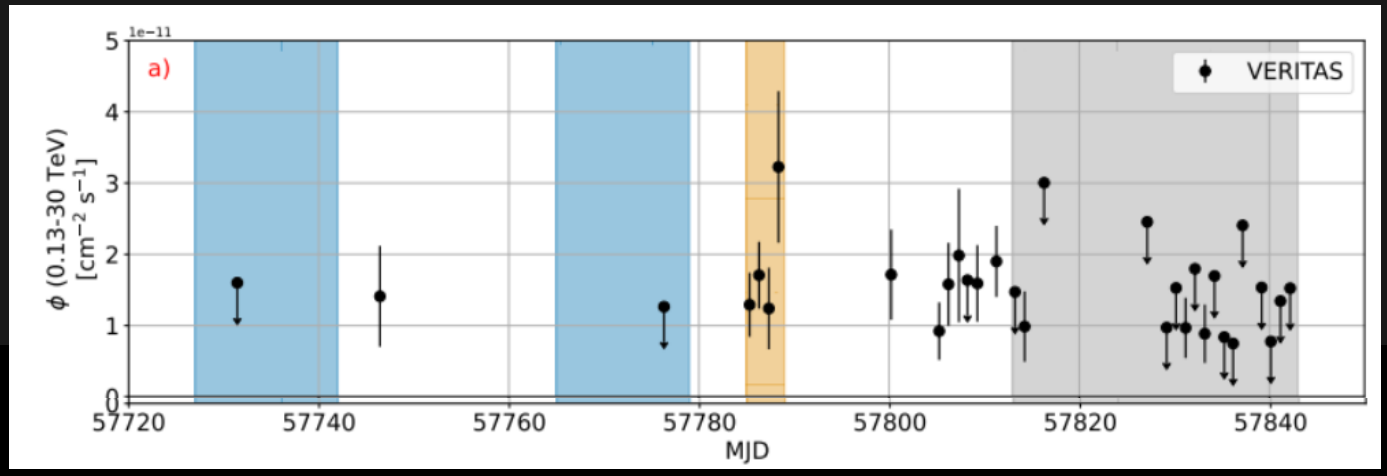
SMBHB candidates: Famous Examples

First VHE flare in 2017

- OJ287 is LSP, only detectable during flares
- In February 2017, OJ 287 was detected flaring in the very-high-energy gamma-rays for the first time with VERITAS (Archaryya et al. 2024)
  - Lico et al. 2022 suggested a possible link between the moving component K that they see emerging from VLBA core in March 2017 and passing through a stationary component **S1 and the VHE flare**
  - **Jormanainen, Hovatta, EL et al. 2025 investigated the polarization behaviour**

Archaryya et al. 2024



SMBHB candidates: Famous Examples

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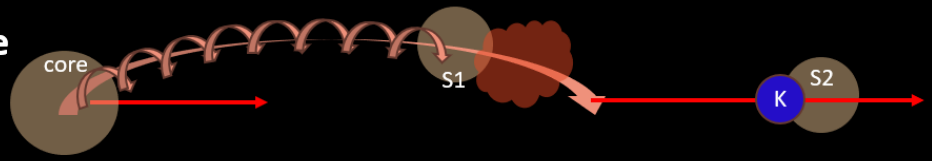
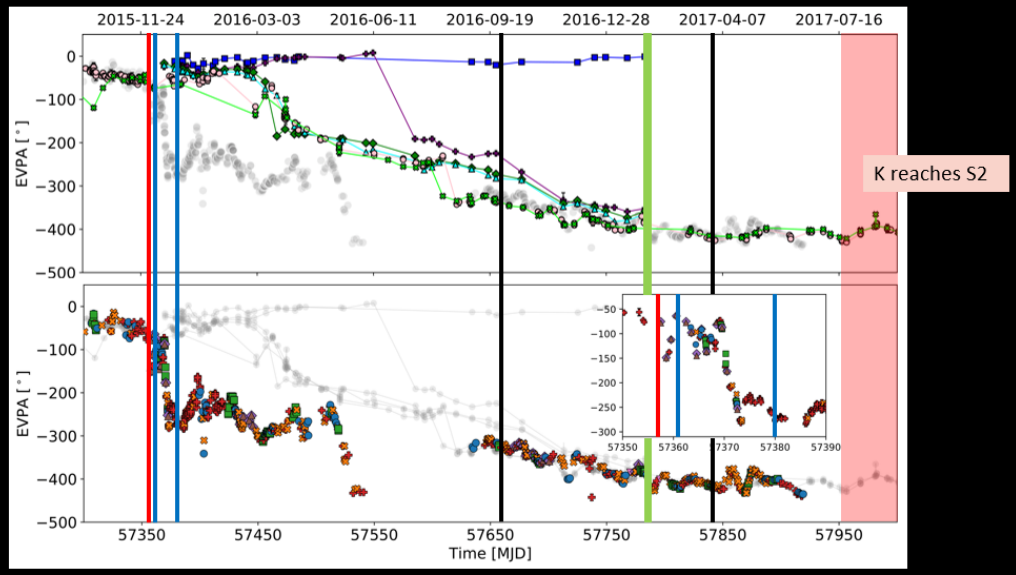
Bigger picture





Myserlis et al. 2018 and Jormainen et al. 2025: Something already pre-impact sets something to move in the jet, flare in VHE related to shock-shock interaction

Famous Examples

- OJ287: The optical light curve of 130 years shows a 12-year quasi-periodic pattern → A supermassive black hole (SMBH) binary with a precessing orbit?
- The impact flares have been predicted and observed since the 1980s, nowdays with very accurate MWL glasses including VHE!
- If the SMBHB model and masses correct: nHz GW source

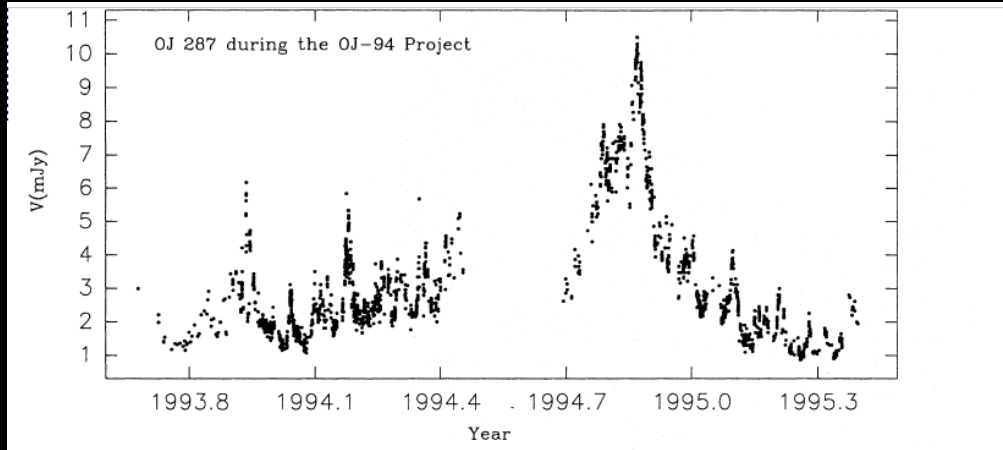


Fig. 1. The V-band light curve of OJ 287 based on the observations taken during the OJ-94 project.

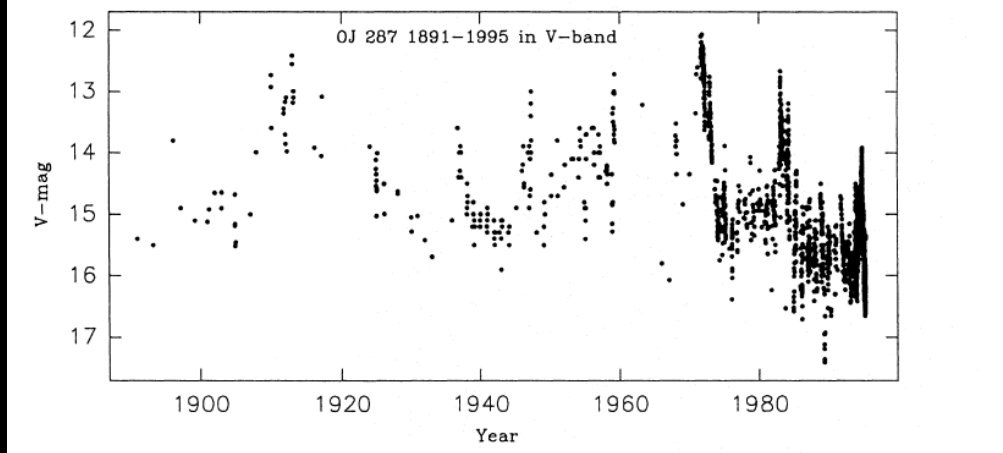


Fig. 2. The historical light curve (in magnitudes) of OJ 287 in the V-band over the interval 1891-1995 showing eight major outbursts with a time difference of about 12 years.

Sillanpää et al. 1996

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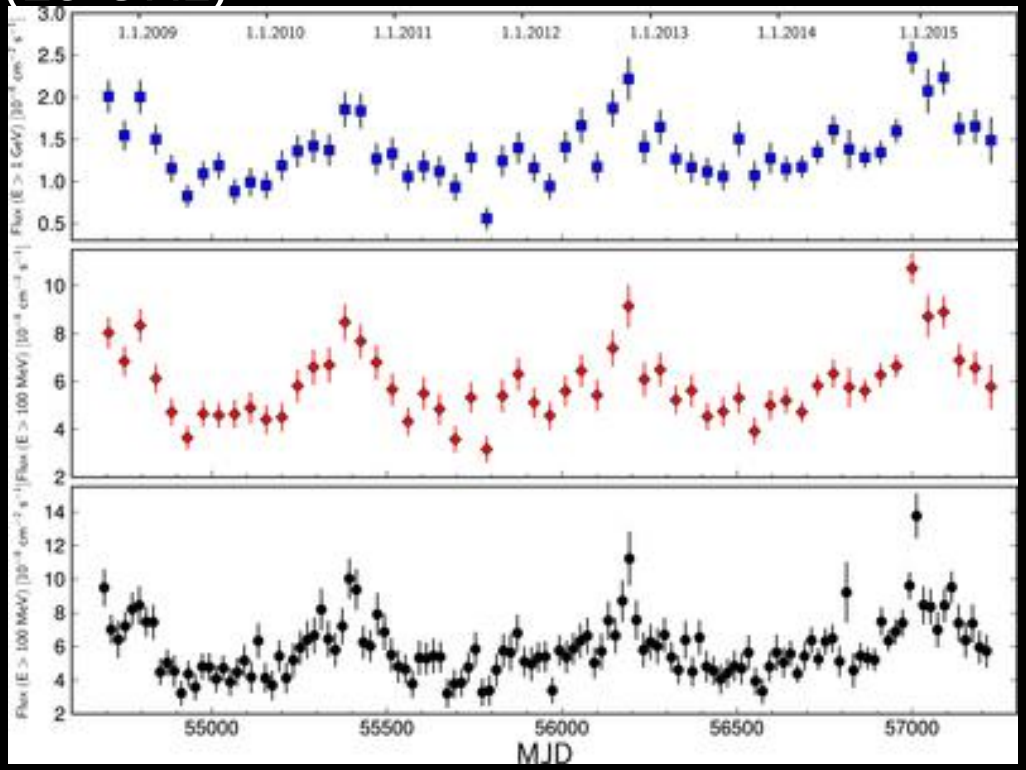
Famous Examples

- PG1553+113: two year periodicity in the gamma-ray and optical bands (Ackermann et al. 2015, still there Abdollahi et al. 2024), maybe also seen at radio (15 GHz)



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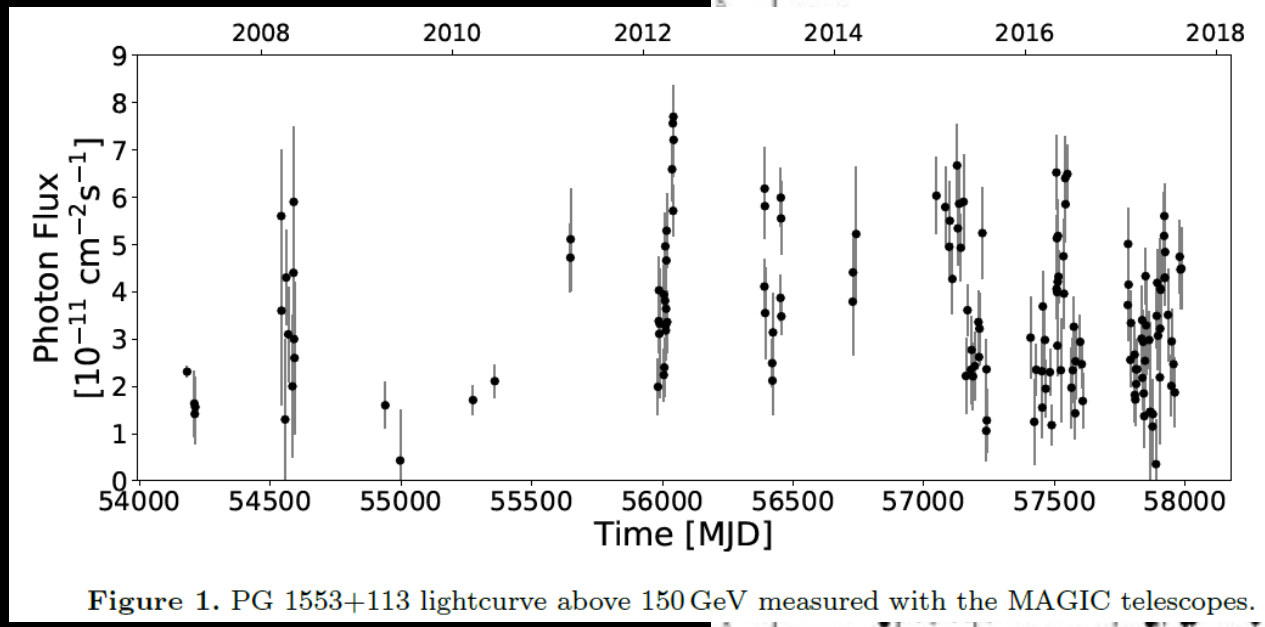
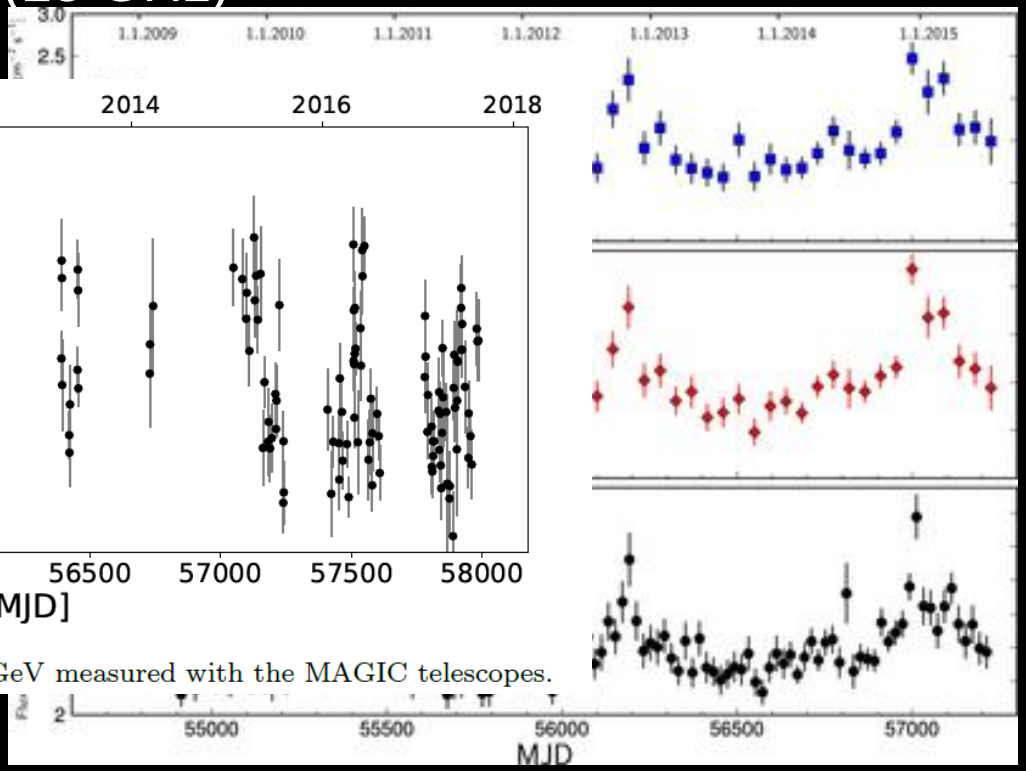
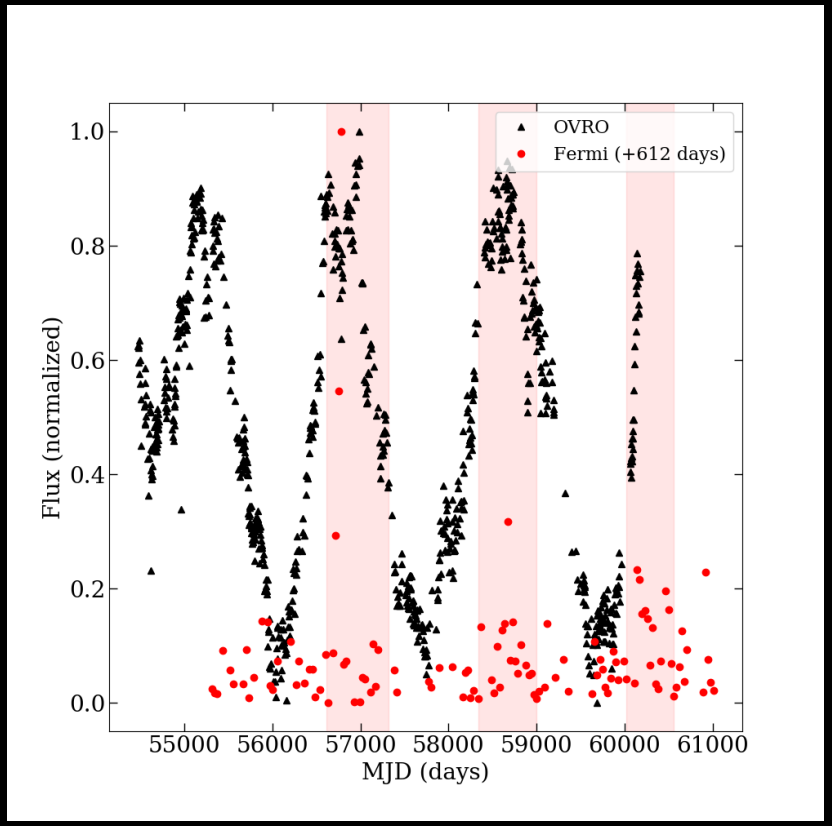


Figure 1. PG 1553+113 lightcurve above 150 GeV measured with the MAGIC telescopes.



Not there at VHE gamma-rays, MAGIC Collaboration et al. 2024

Interesting candidate (not yet VHE): PKS 2131−021

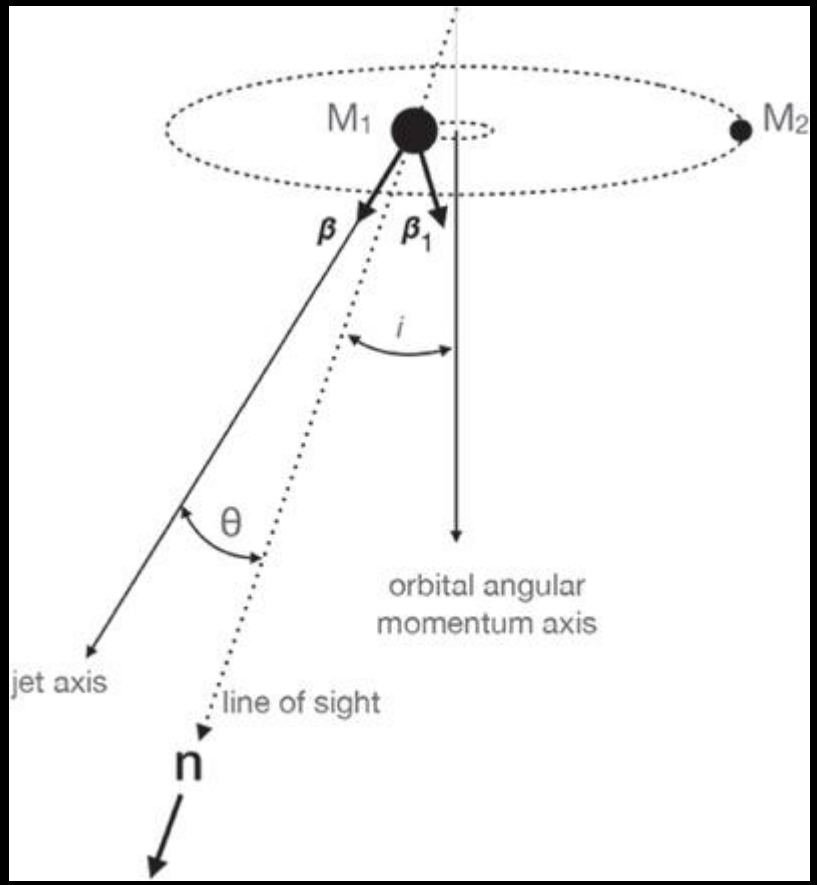


- z = 1.283, during the flares detectable with CTAO?
- Quasi-periodicity at radio (15GHz, Owens Valley Radio Observatory) ~1740 days (4.77 years), O'Neill et al. 2022,
- Sinusoidal signal also present in optical, smoothly varying monotonic phase-shift
- Hint of this sinusoidal signal also in the Fermi-LAT

Kiehlmann et al. 2025, ApJ, *in press*

Interesting candidate (not yet VHE): PKS 2131−021

- Why would SMBH with a relativistic jet produce sinusoidal variations?
- Kinetic Orbital model: one of the SMBHs in the binary system produces a jet, and aberration of this jet due to orbital motion has a large effect on the observed emission from the highly relativistic emitting material.
- Suggested independently by Sobacchi et al. (2017) and by O'Neill et al. (2022)



O'Neill, Kiehlmann et al. 2022

Summary of SMBHB at VHE gamma-rays

- VHE is not the main band where to look for the periodicities BUT
- Many already known VHE gamma-ray blazars are candidate SMBHB, many more will be within the reach of CTAO
- Ongoing debate on what fraction of the (gamma-ray) blazars show periodicity
- ”Normal activity” makes the search of the periodicities more difficult

Gamma-Ray Bursts at VHE gamma-rays

- GRBs were driving force for the design of the current generation of IACTs, but still it took 15 years to catch the first one
- VHE observations of GRBs from 2002-2018

➢ Hundreds of observations

➢ Detections > 100 GeV:

GRB130427A: 90 GeV photon Fermi-LAT

GRB160821B: ∼ 3σ hint of signal from MAGIC

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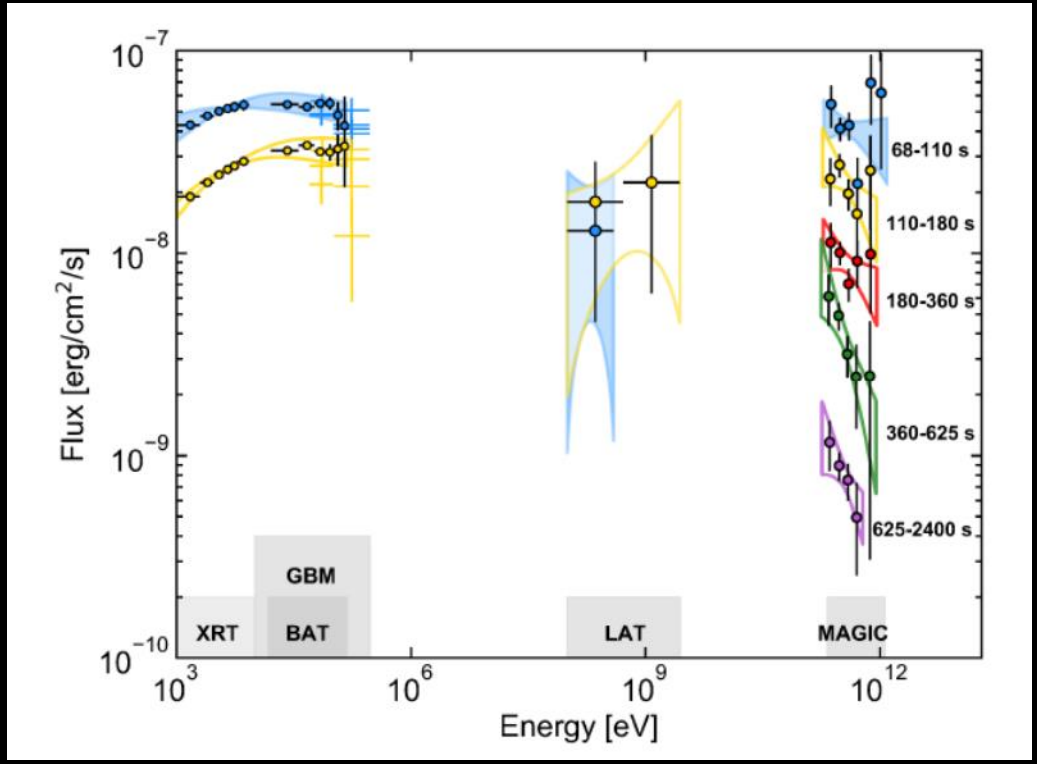
GRB160821B: ∼ 3σ hint of signal from MAGIC

Short GRB, z=0.162

MAGIC Collaboration et al. 2021: “MAGIC started observing GRB 160821B at the Swift-BAT position on 2016 August 21, 22:29:37 UT, 24 s after T0. The observation started from a zenith angle of 34°, and continued until 4 hr after T0 (August 22, 2:29 UTC), reaching a zenith angle of 55°. The level of the night sky background (NSB) light was relatively high, due to the presence of the Moon”

Gamma-Ray Bursts at VHE gamma-rays

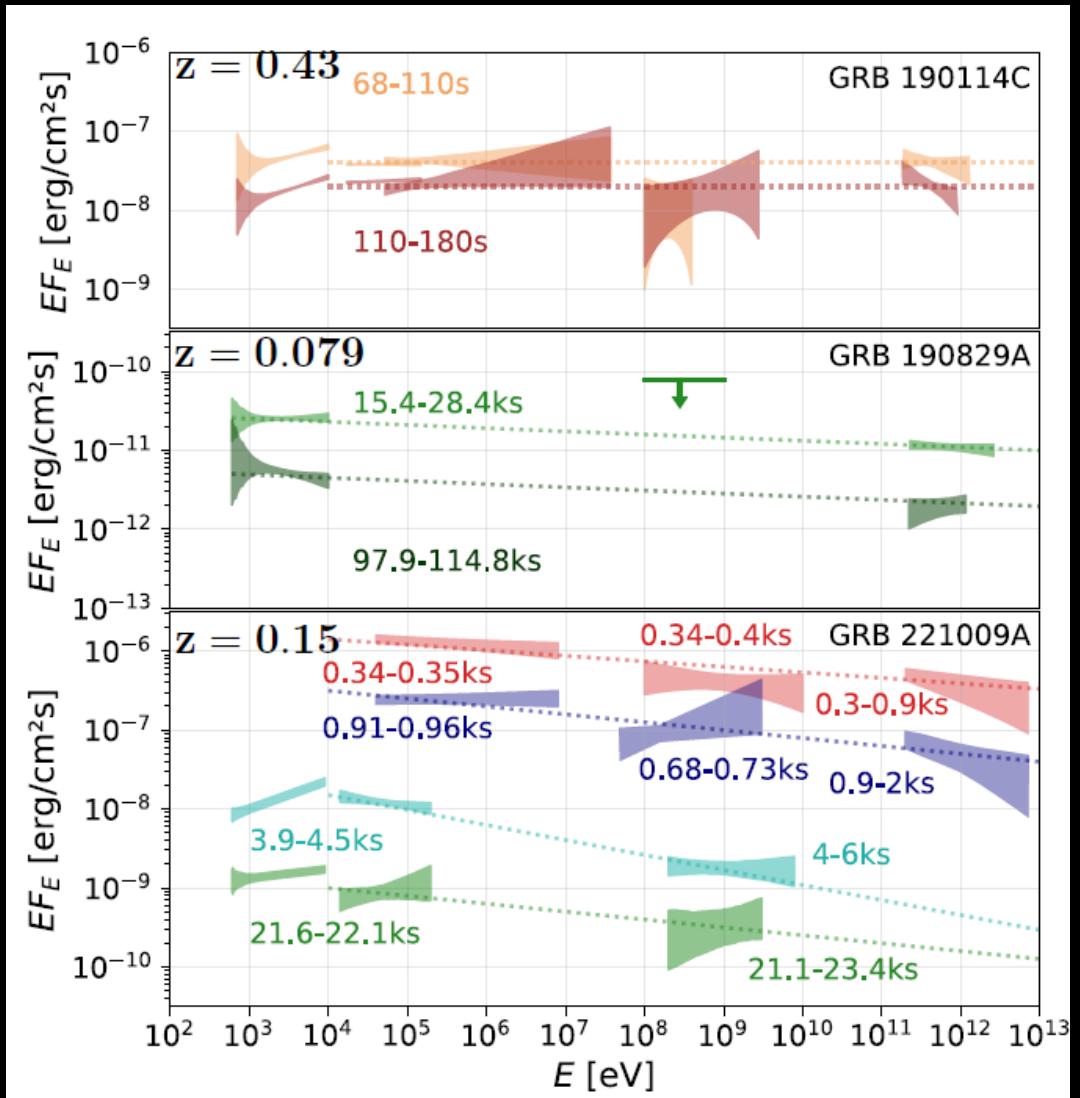
- GRB190114C: Very High Energy gamma-rays from inverse Compton scattering: New emission component



MAGIC Collaboration 2019, Nature

Gamma-Ray Bursts at VHE gamma-rays

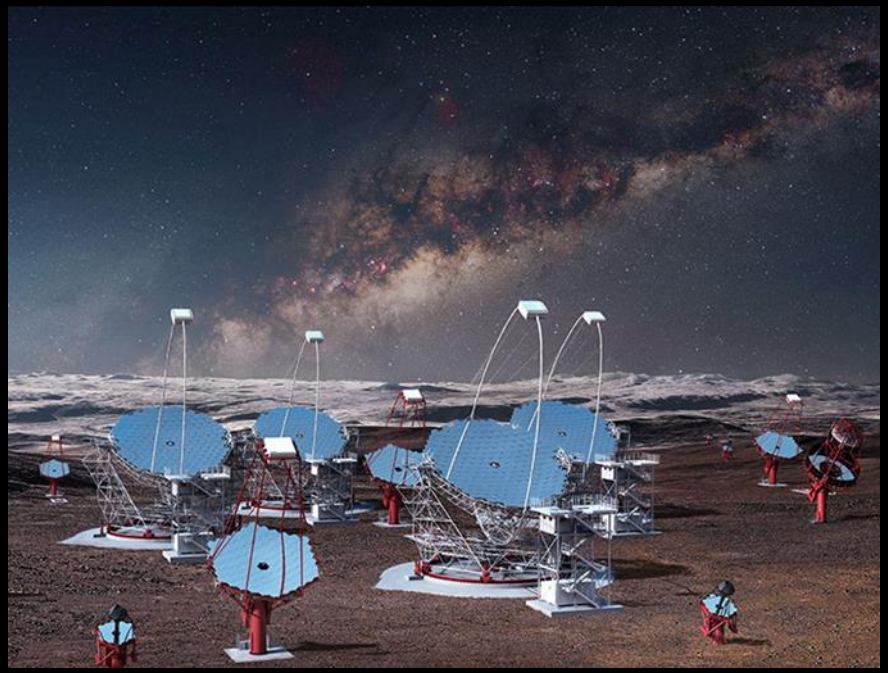
- GRB190114C: Very High Energy gamma-rays from inverse Compton scattering: New emission component
- Debated as the photon spectra are rather flat: The SSC model predicts a curved spectrum which “may be contradiction with these observations”



MAGIC Collaboration Nature 2019
HESS Coll. Science 2021
LHAASO Coll., Science 2023
Klinger et al. arxiv:2403.13902

What to expect from CTAO

- Fast automatic reaction
- Slewing speed <20s to any point in sky with LSTs
- Potential to detect GRBs at z=2 and beyond!
- Few GRBs per year

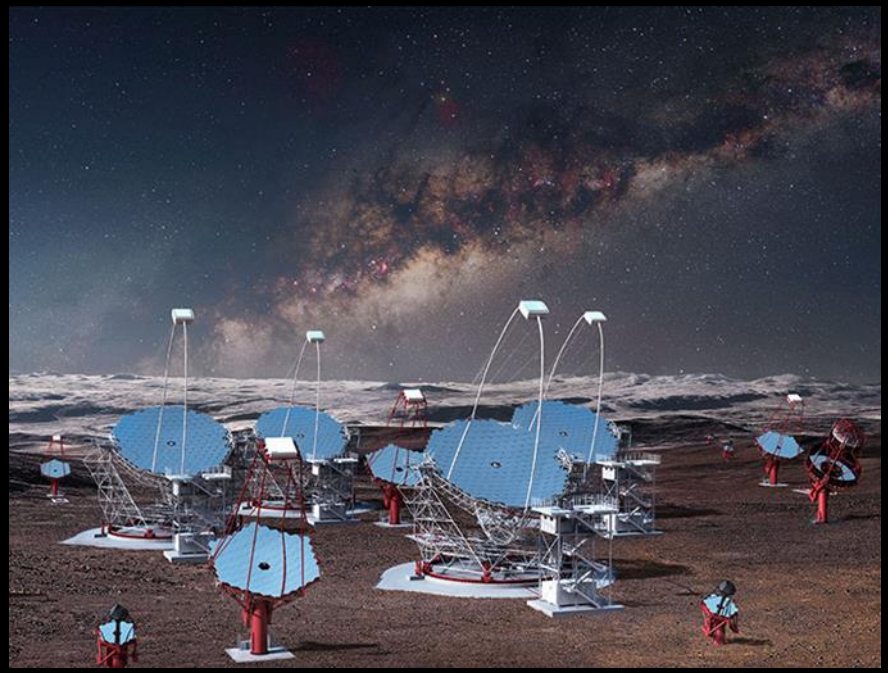


CTAO | CONSORTIUM

Work in progress…

What to expect from CTAO

- Fast automatic reaction
- Slewing speed <20s to any point in sky with LSTs
- Potential to detect GRBs at z=2 and beyond!
- Few GRBs per year
- Follow-up of GW alerts



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Work in progress…

What to expect from CTAO

- Simulated GRB emission from 2000+ BNS mergers

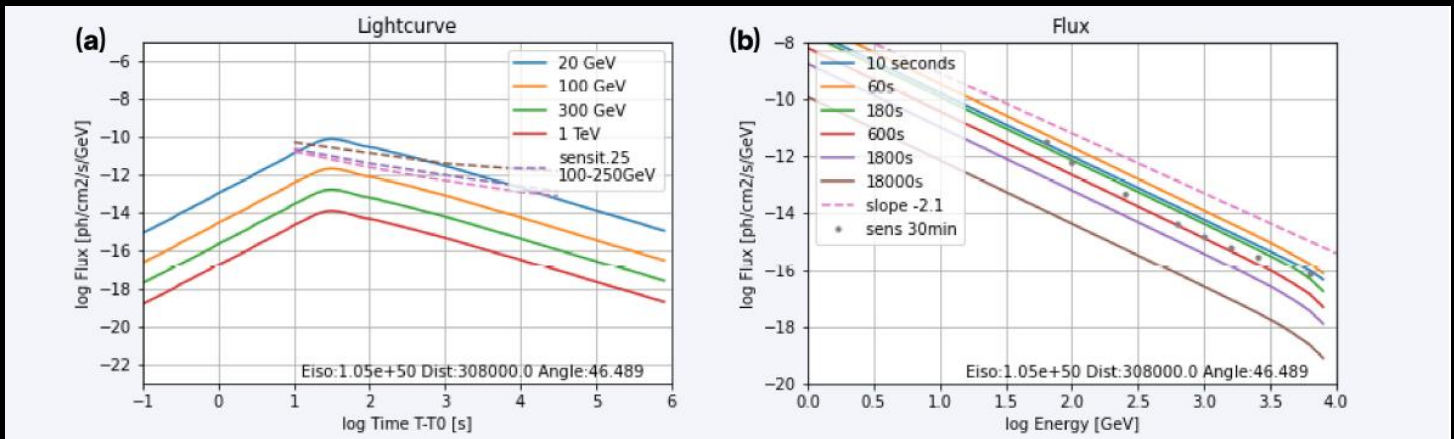

Figure 1 Panel (a): Lightcurves at different energies for a simulated short GRB associated to a GW event. Panel (b): spectra at different latencies for the same event. For reference, the sensitivities of CTA are reported: in (a) the dashed lines show the CTA sensitivities at energies of 25, 100 and 250 GeV; in (b) the points represent the CTA differential sensitivity for an integration time of 30 minutes.

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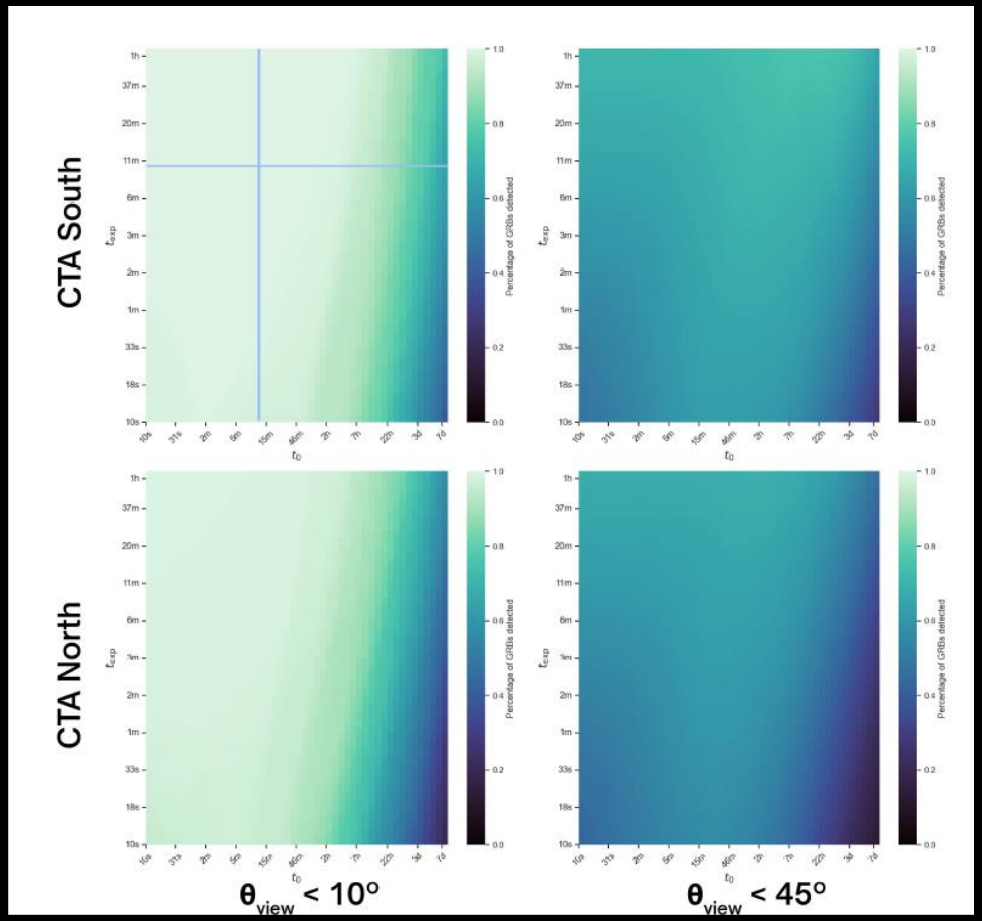
J.G.Green et al. on behalf of the CTAO consortium
ICRC 2023

What to expect from CTAO



- X-axis: the delays before CTAO will observe (alert arriving, pointing, searching the large uncertainty region)
- Y-axis: the exposure time
- The lighter the color the larger fraction of the simulated GRBs gets detected

CTAO CONSORTIUM

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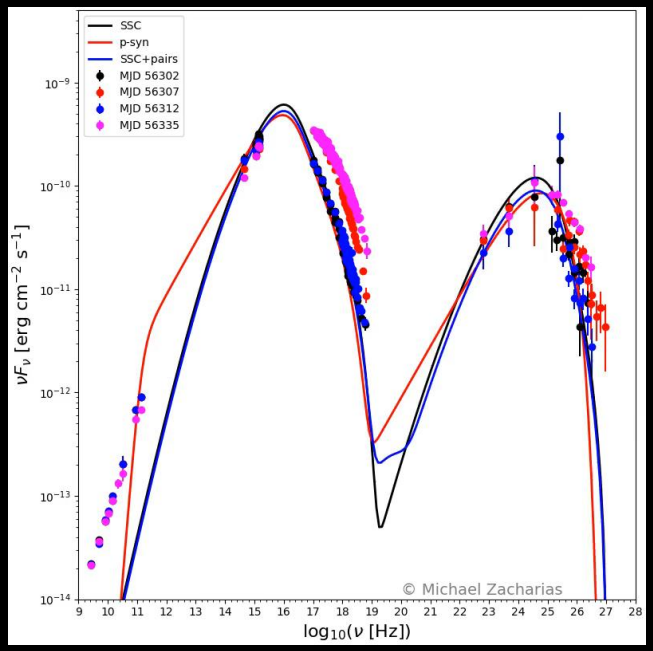
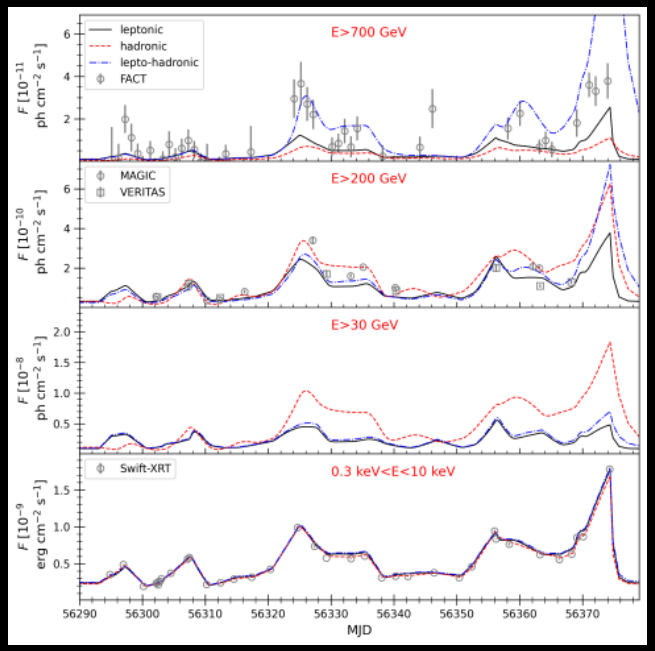
Thank you

(2 Slides on composition of the jet in back-up)

Composition of the jets

- Pure electron-positron or protons as well? Composition affects on how efficiently the jet heats the environment (e.g. Perucho et al. 2014)
- Variability patterns at VHE gamma-rays will be different: black is SSC, blue SSC+pairs.





Zacharias, M. OneHaLe

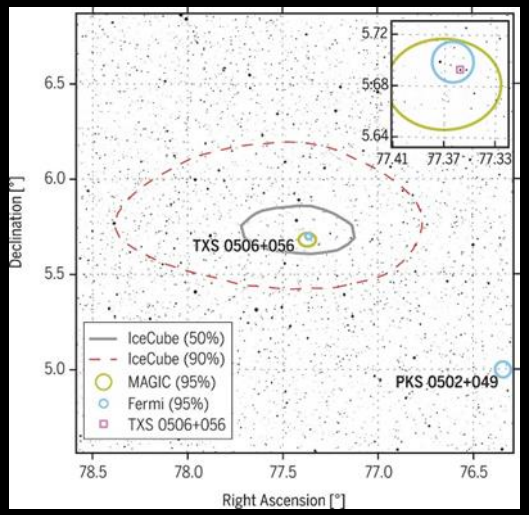
Zacharias, M. et al. (including EL) Gamma2024

TURUN YLIOPISTO

Composition of the jets

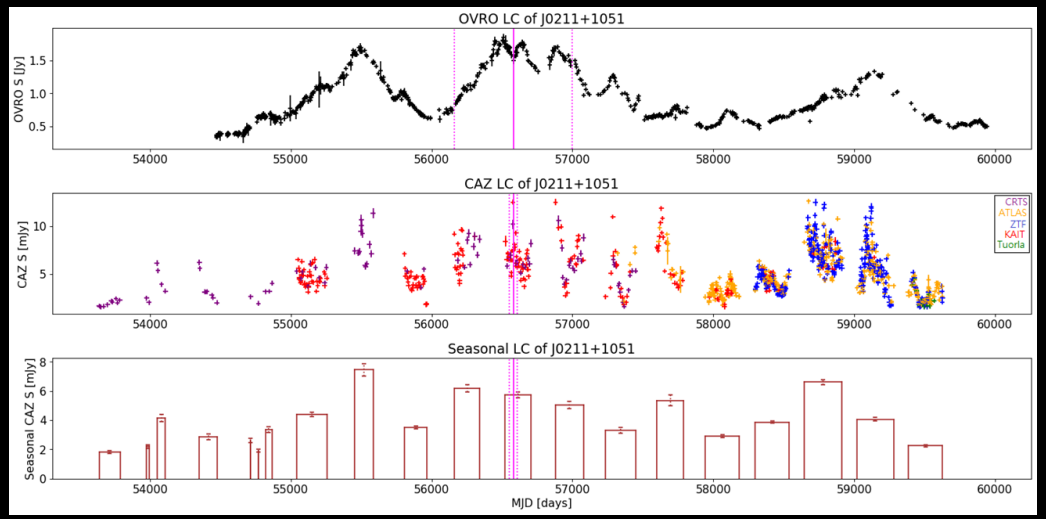
- Pure electron-positron or protons as well?
- Several hints that jets would be sources of astrophysical neutrinos

TXS0506+056



IceCube collaboration et al. 2018, Science

Flaring blazars



Kouch, Lindfors et al. 2024, A&A

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