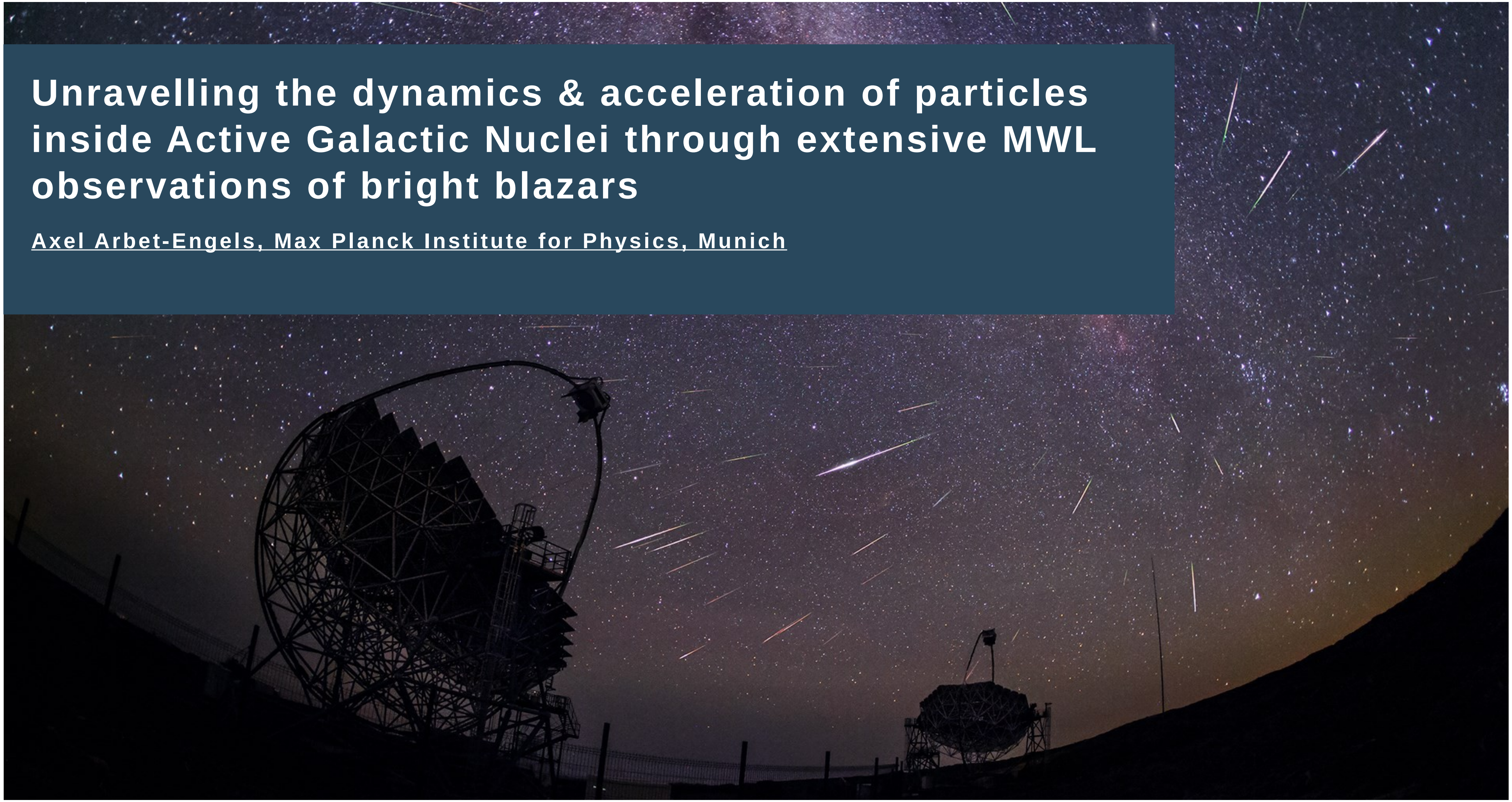
MAX-PLANCK-INSTITUT
FÜR PHYSIK

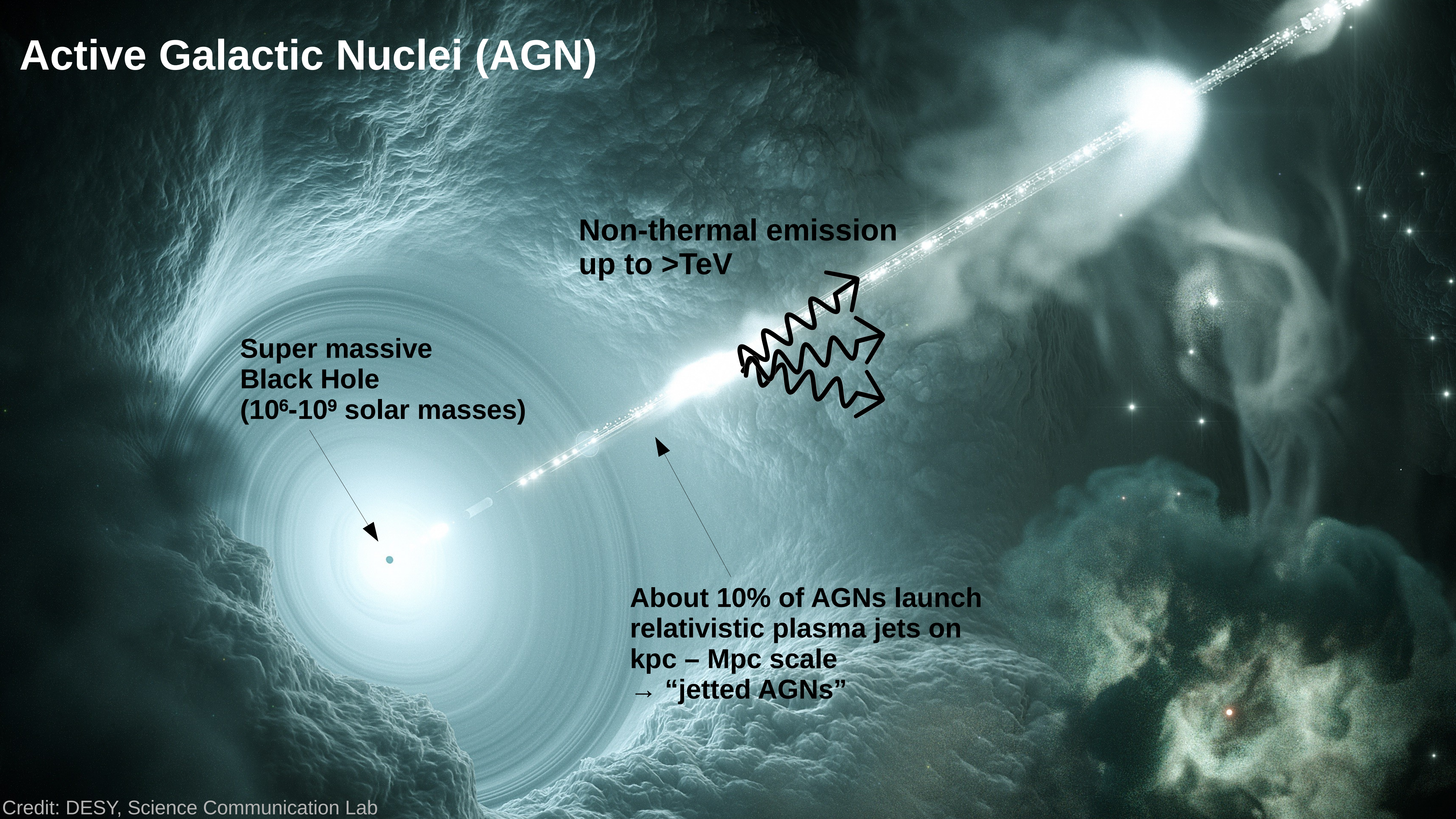


Unravelling the dynamics & acceleration of particles inside Active Galactic Nuclei through extensive MWL observations of bright blazars

Axel Arbet-Engels, Max Planck Institute for Physics, Munich

Image credits: Daniel Lopez

Active Galactic Nuclei (AGN)

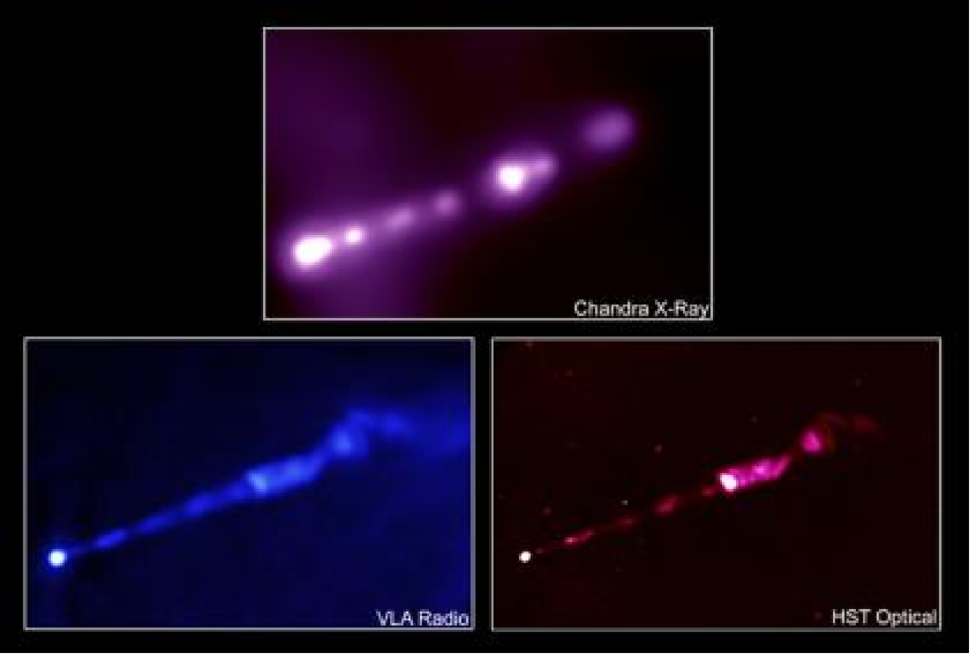


Non-thermal emission
up to >TeV

Super massive
Black Hole
(10^6-10^9 solar masses)

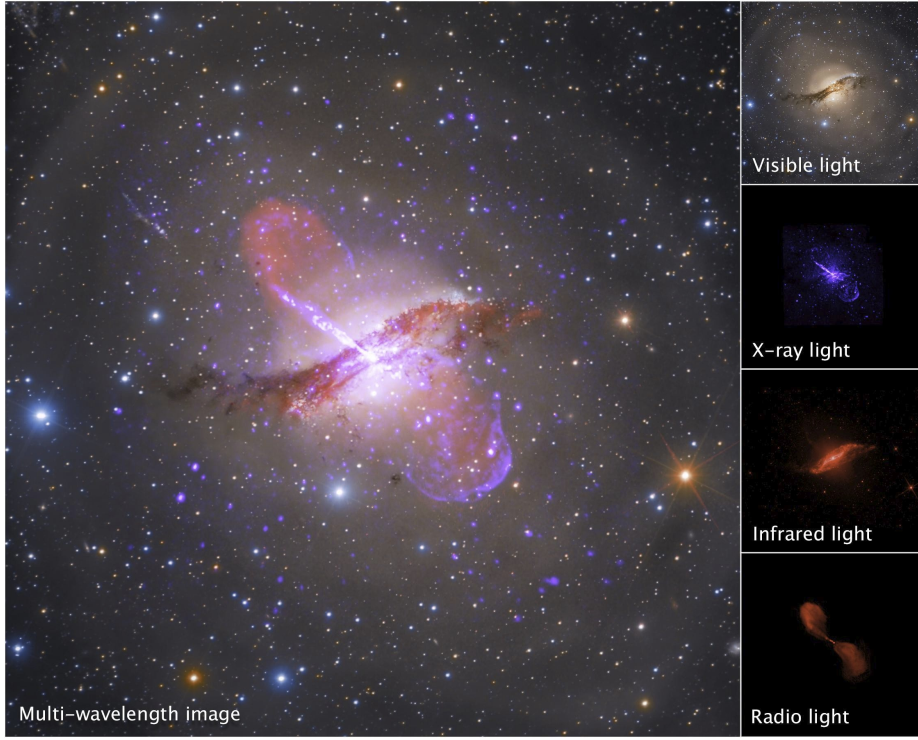
About 10% of AGNs launch
relativistic plasma jets on
kpc – Mpc scale
→ “jetted AGNs”

Credit: DESY, Science Communication Lab



Credit: X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F. Zhou, F.Owen (NRAO), J.Biretta (STScI) Optical: NASA/STScI/UMBC/E.Perlman et al.

AGN jets resolved from radio to X-ray!



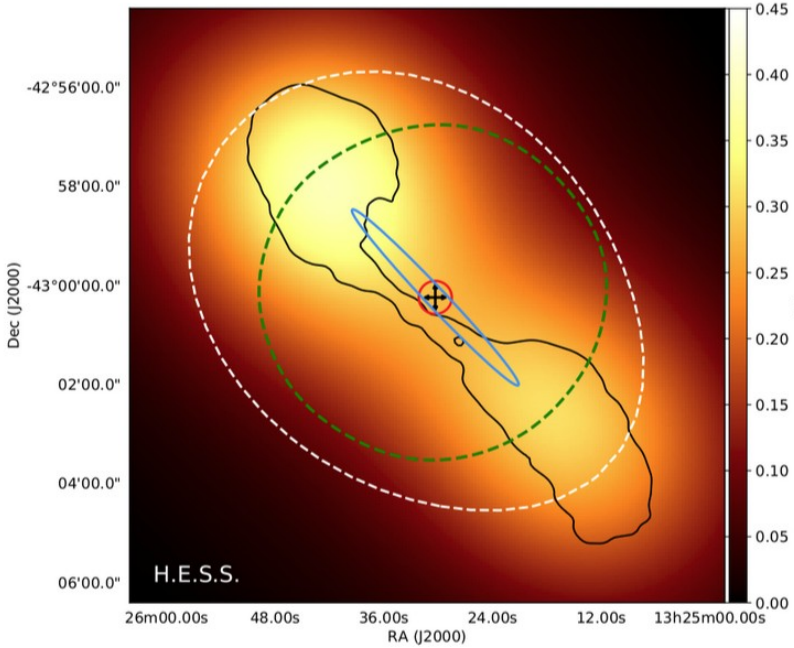
Credit: ESO

$$h\,\nu_{synch} \;\propto\; \gamma_e^2\, B$$

$$h\,\nu_{synch} \;\approx\; 1-10\,keV$$

$$\rightarrow \gamma_e \;\sim\; 10^{5-6}$$

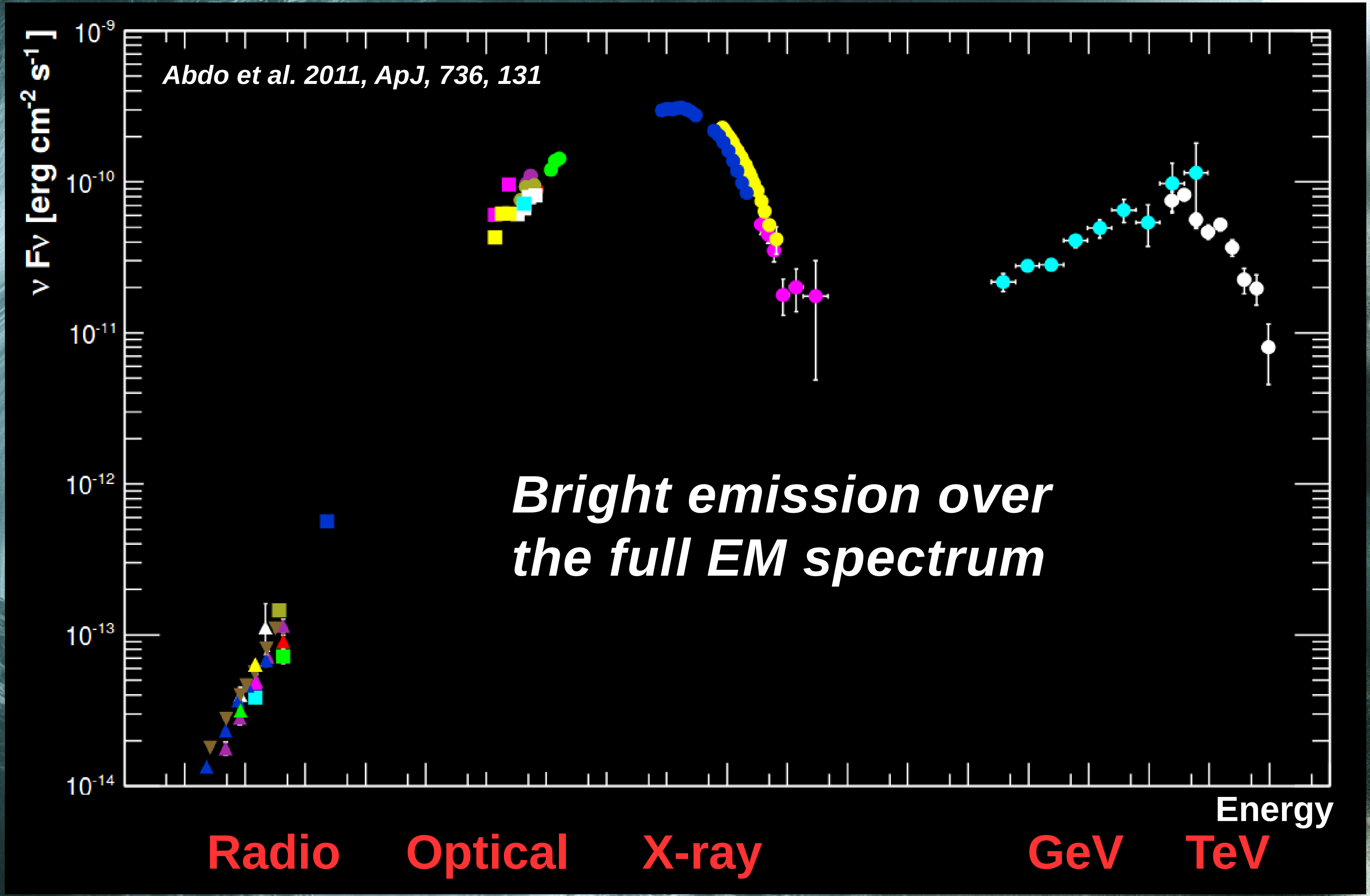
AGNs are efficient particle accelerators



And since recently even at VHE (>100GeV)!

H.E.S.S. Collab, et al. 2020, Nature

Spectral energy distribution (SED) – “jetted” AGNs

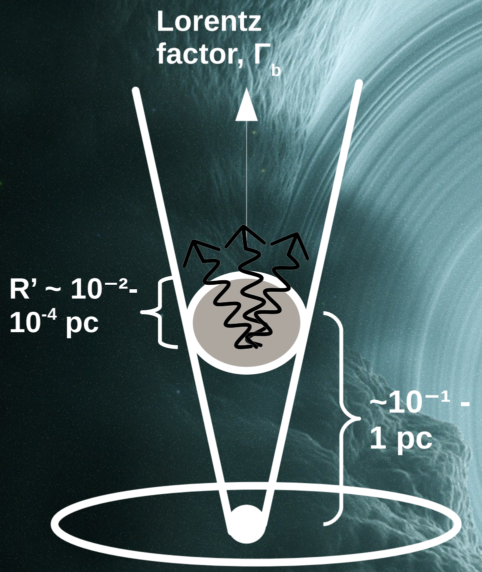


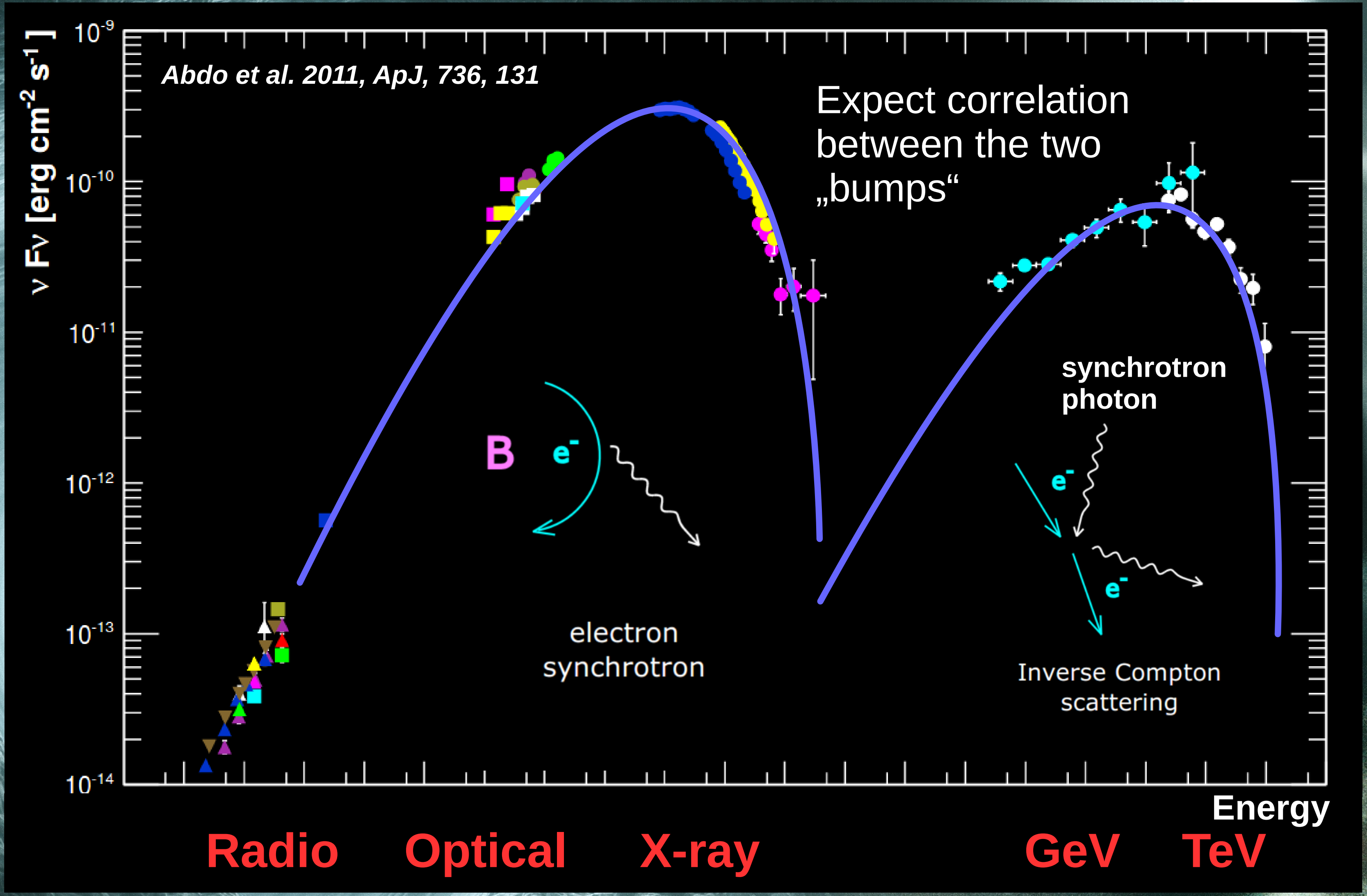
Abdo et al. 2011, ApJ, 736, 131

Bright emission over the full EM spectrum

Credit: DESY, Science Communication Lab

Leptonic model



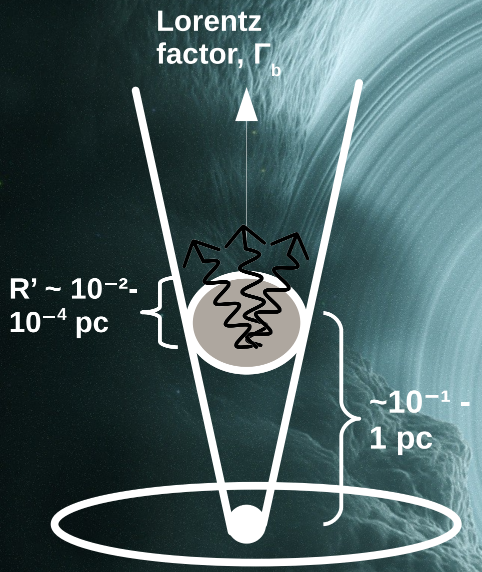


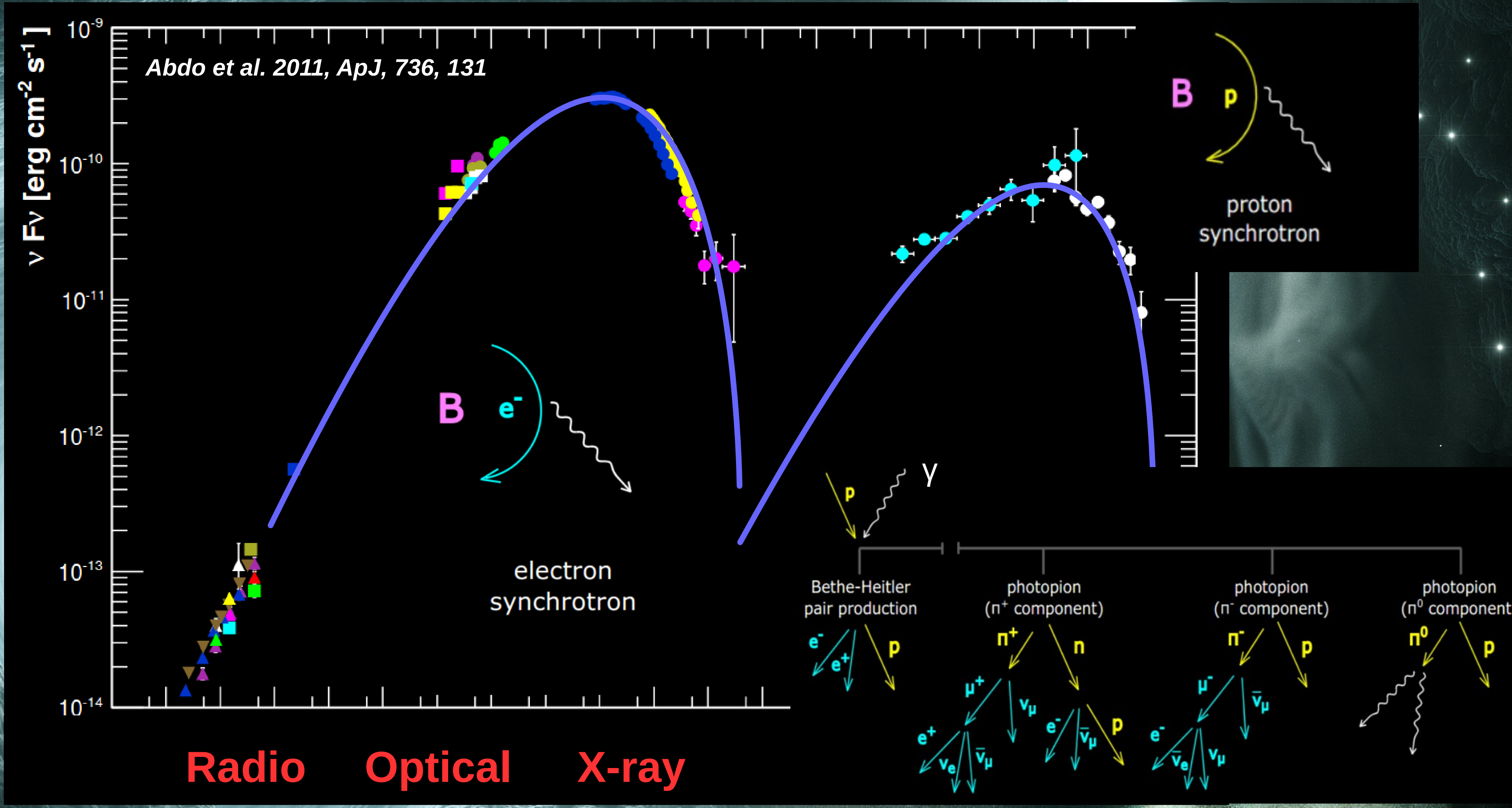
Abdo et al. 2011, ApJ, 736, 131

Expect correlation between the two „bumps“

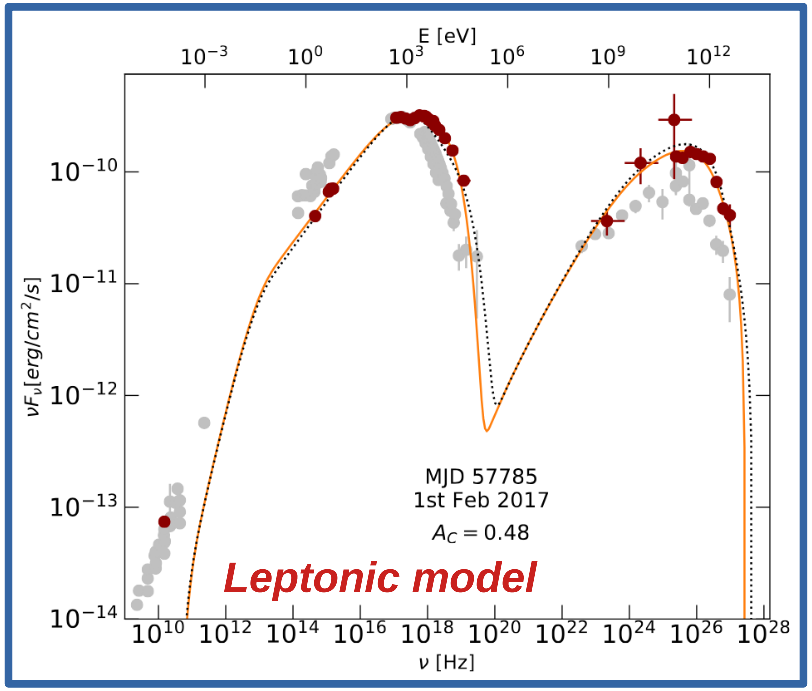
Credit: DESY, Science Communication Lab

Hadronic models

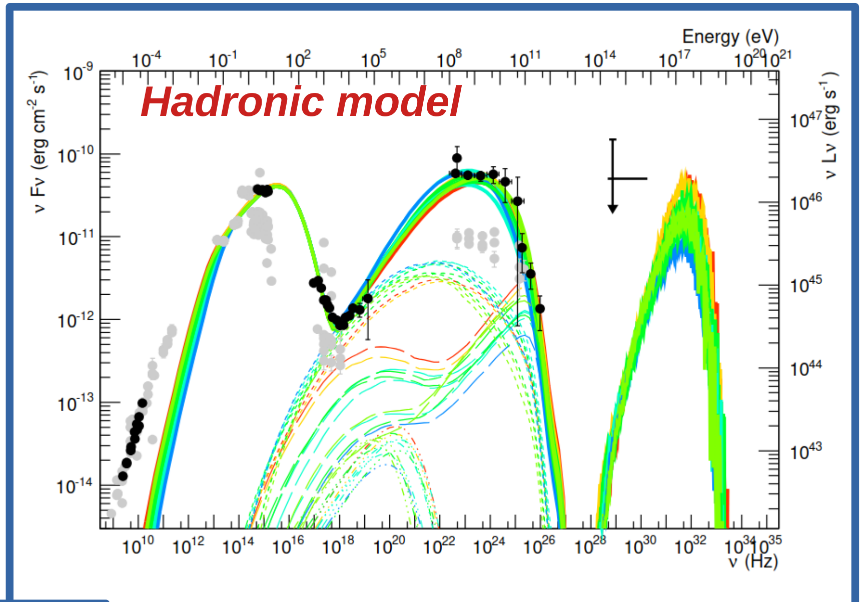



Abdo et al. 2011, ApJ, 736, 131

Credit: DESY, Science Communication Lab



MAGIC Collaboration et al. 2021

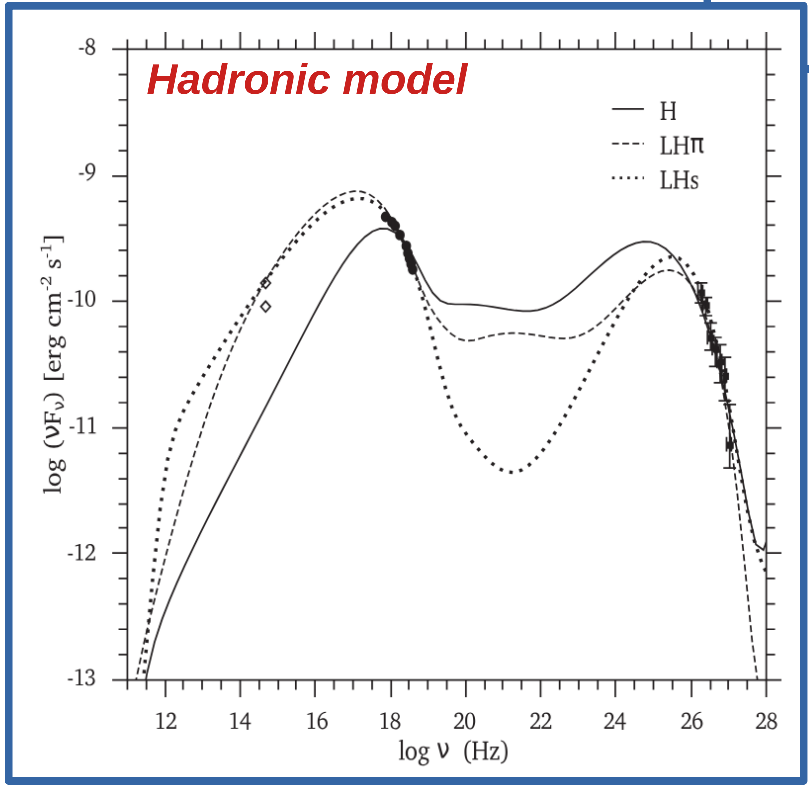


Lepto-hadronic modeling of TXS 0506+056

Cerruti et al. 2019

Leptonic & hadronic models usually able to describe the SED

(important note: hadronic models can be challenging for the energetic)

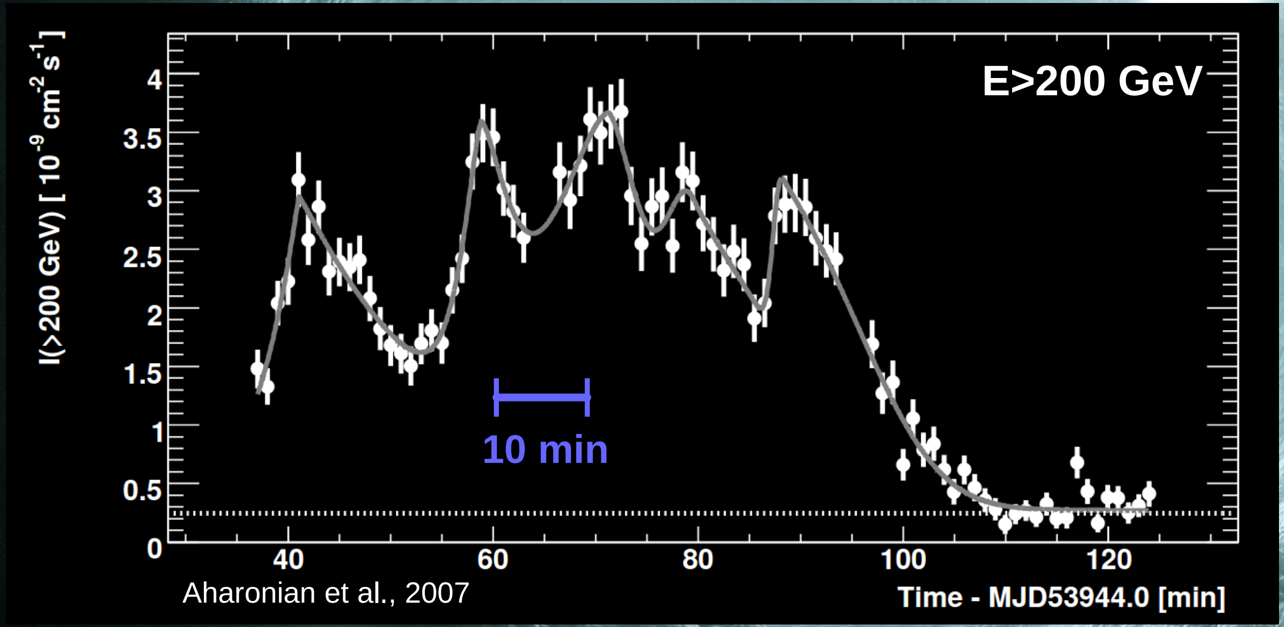


Mastichiadis et al. 2013

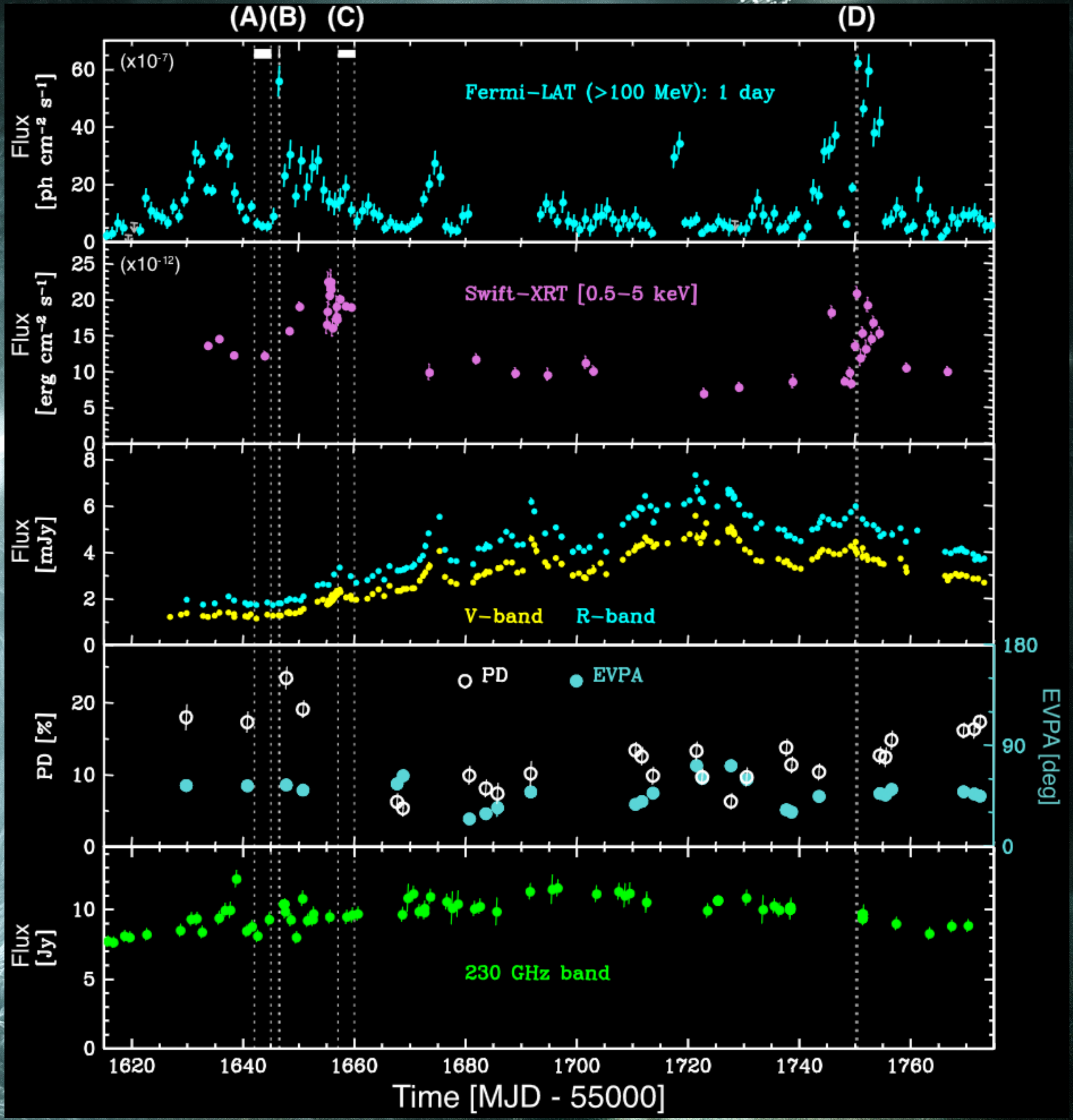
Many more examples in literature..

Variability

Variability on all timescales
From years, down to minutes



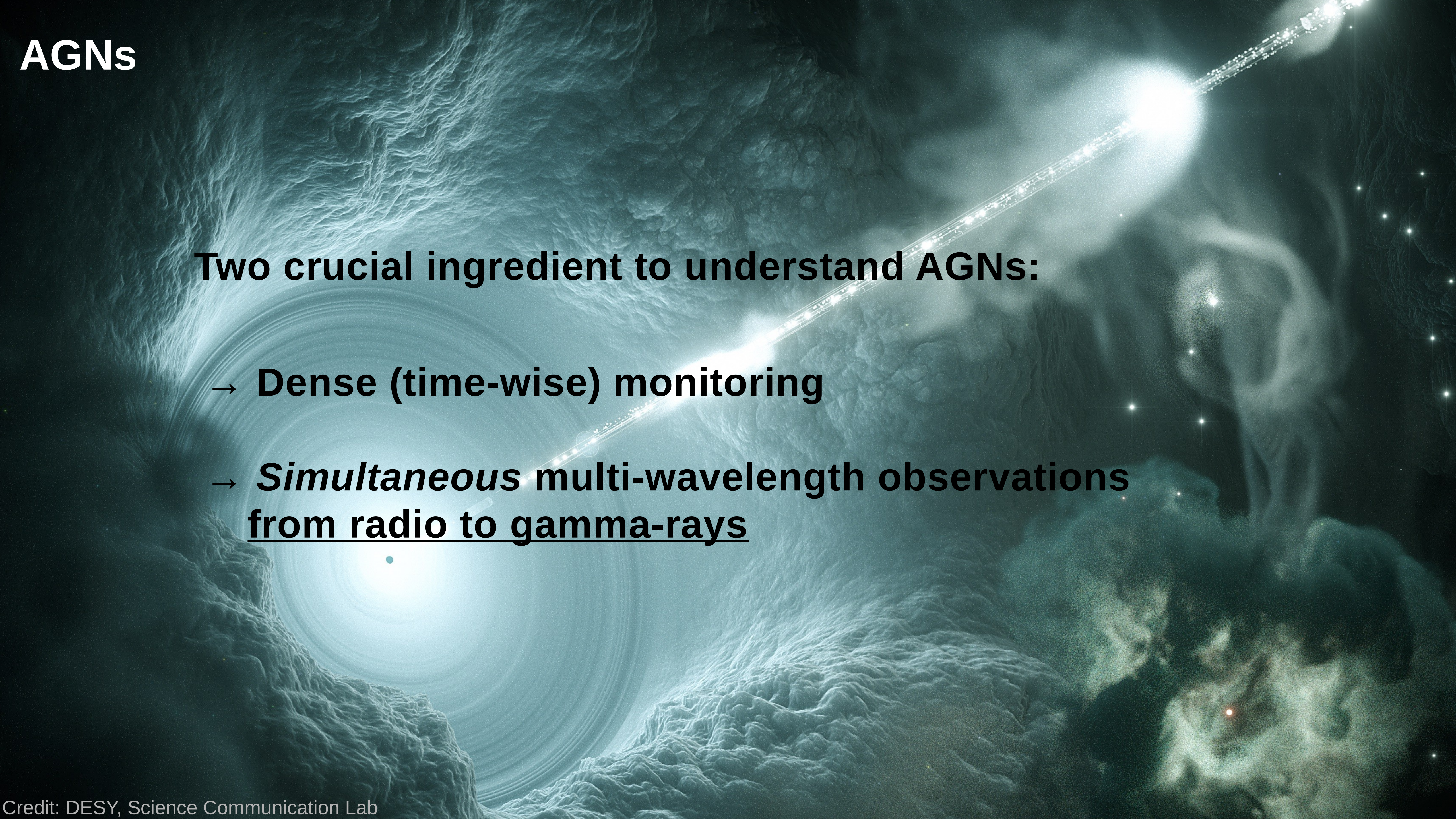
Aharonian et al., 2007



M. Hayashida et al 2015 ApJ 807 79

Credit: DESY, Science Communication Lab

AGNs



Two crucial ingredient to understand AGNs:

→ Dense (time-wise) monitoring

→ *Simultaneous* multi-wavelength observations
<u>from radio to gamma-rays</u>

Credit: DESY, Science Communication Lab

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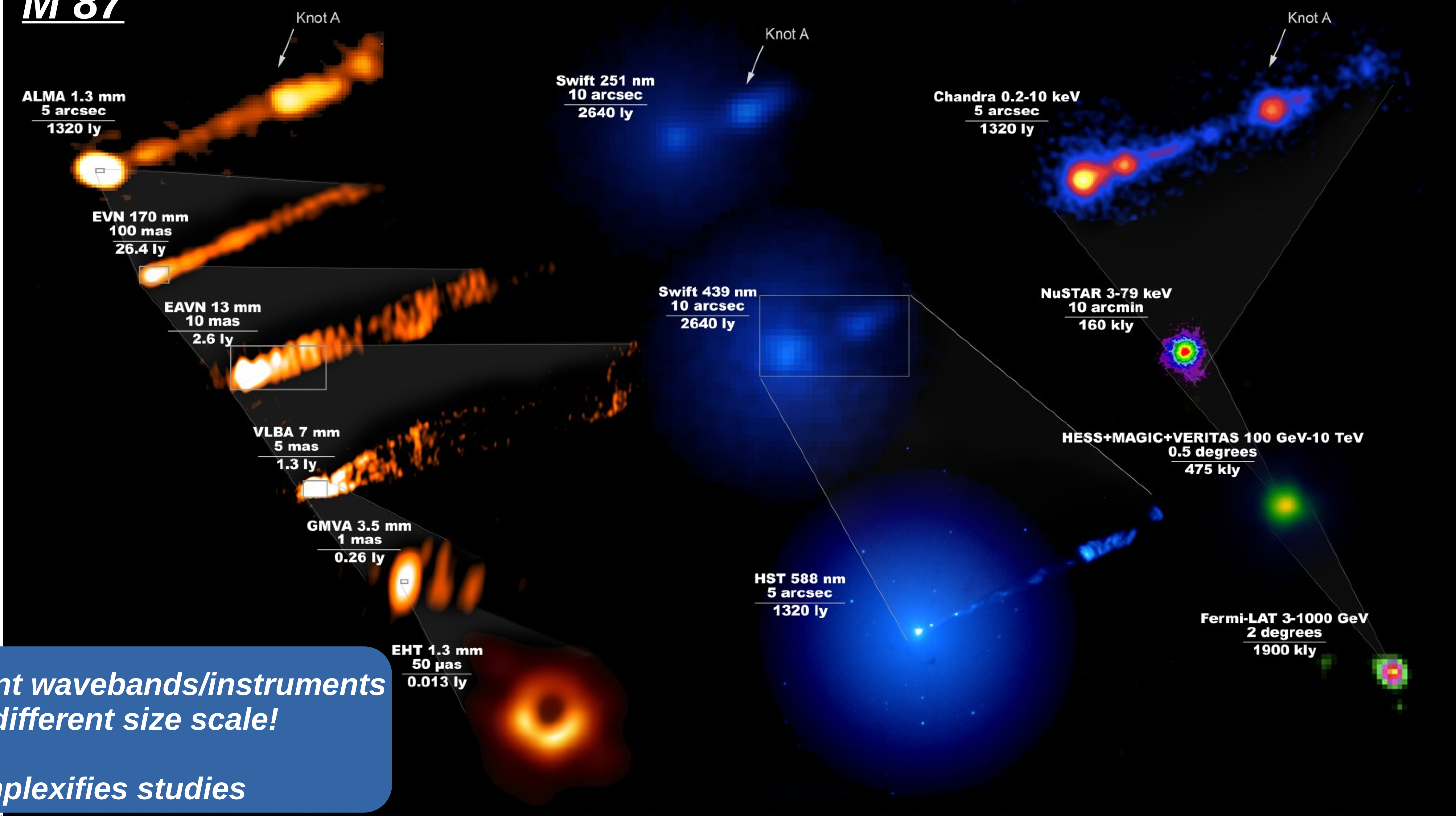


Different wavebands/instruments probe different size scale!

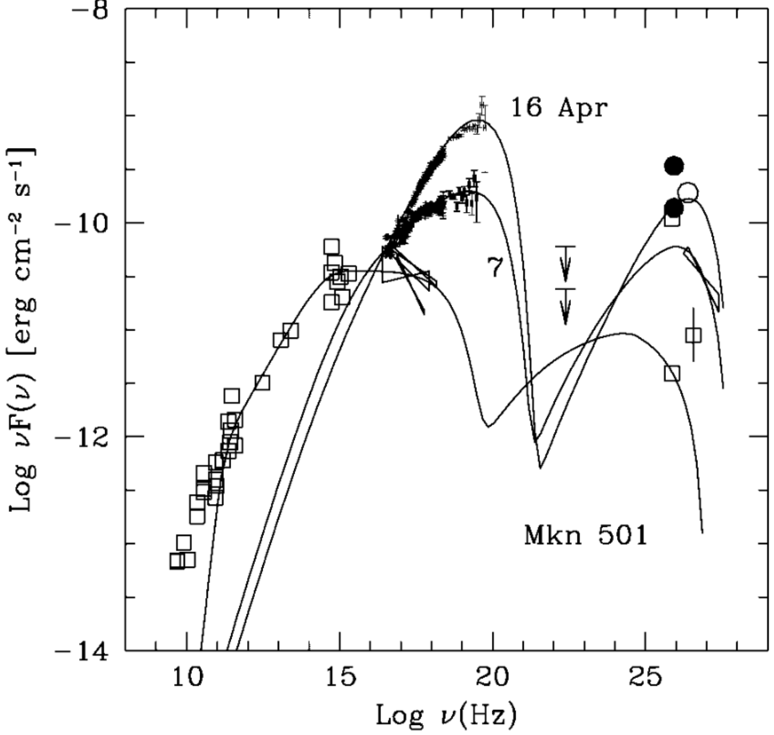
→ Complexifies studies

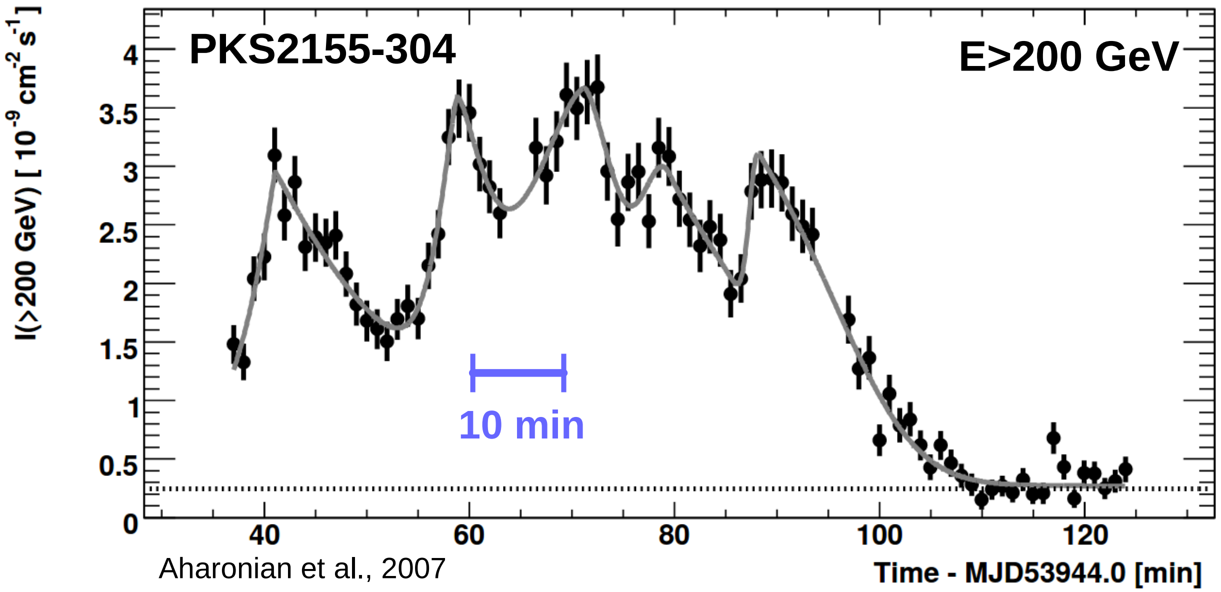
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array;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

AGNs – some open questions

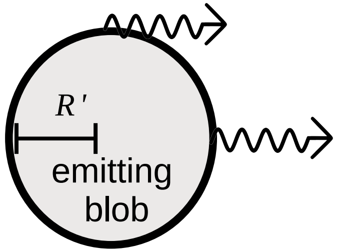
- **Particle acceleration mechanisms?**
- **Origin of fast/strong spectral+flux variability?**
- **Jet composition?**
  Origin of gamma-ray emission?
- **….**

Pian et al. 1997





Aharonian et al., 2007

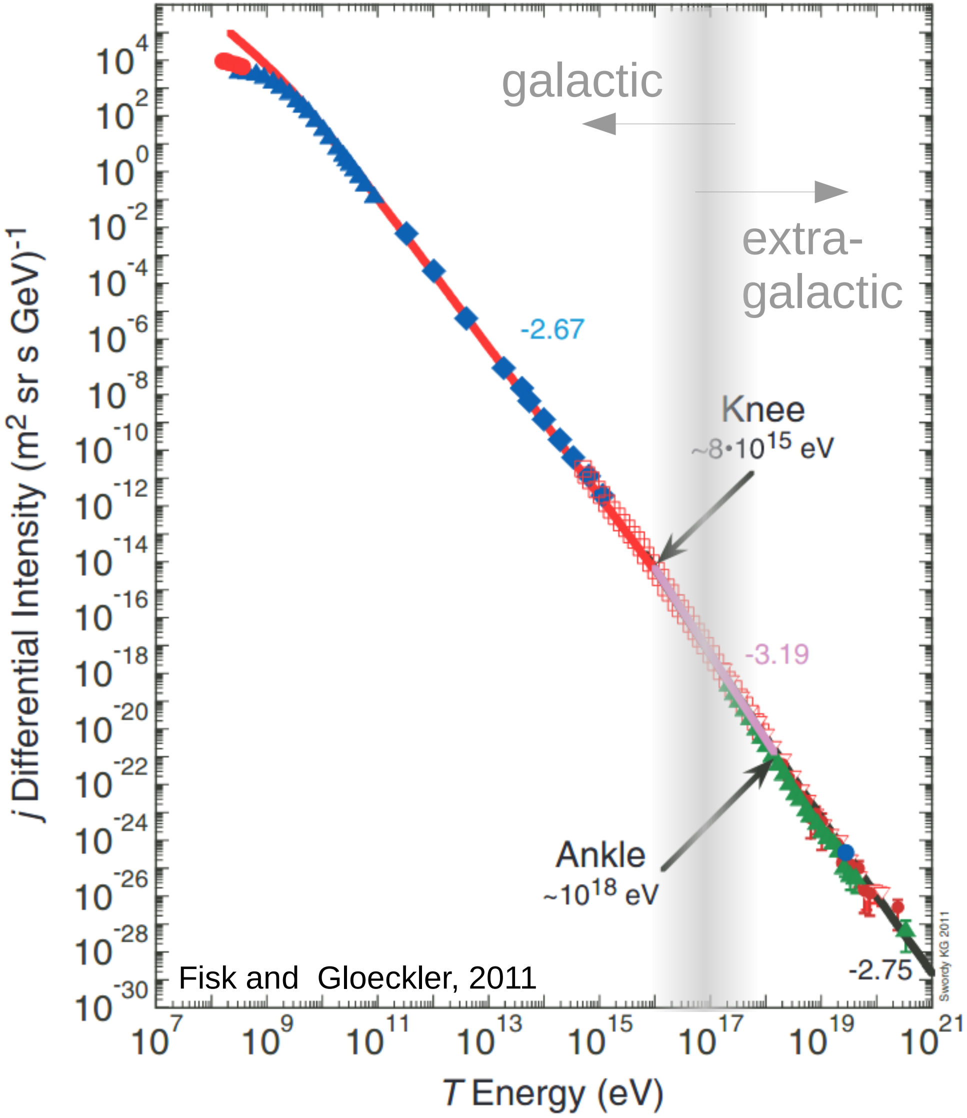


$R' \leqslant t'_{var}\, c$

$t_{var} \sim 1$ min $\Leftrightarrow$
$R' \sim$ Schwarzschild radius

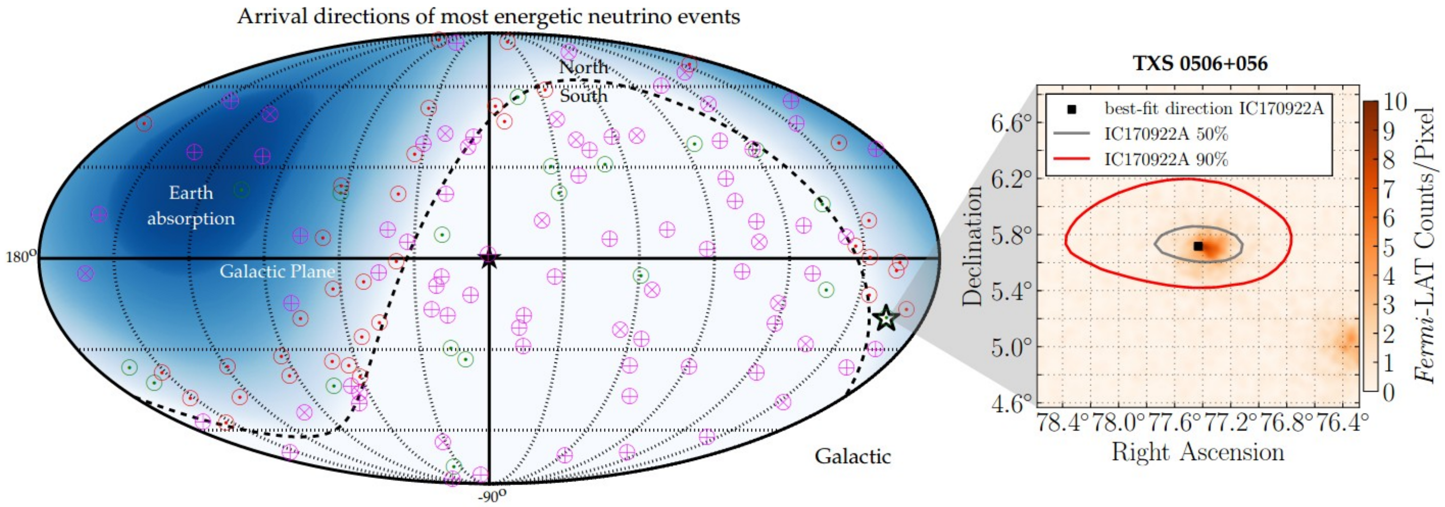
AGNs – some open questions

Sources of >10^{18} eV cosmic rays?

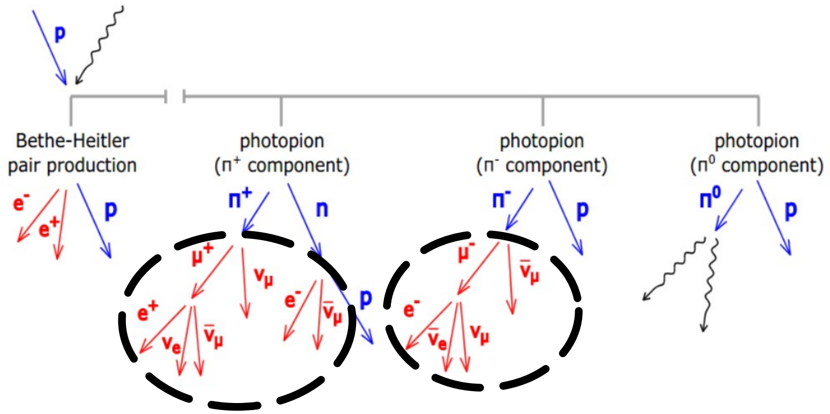


Fisk and Gloeckler, 2011

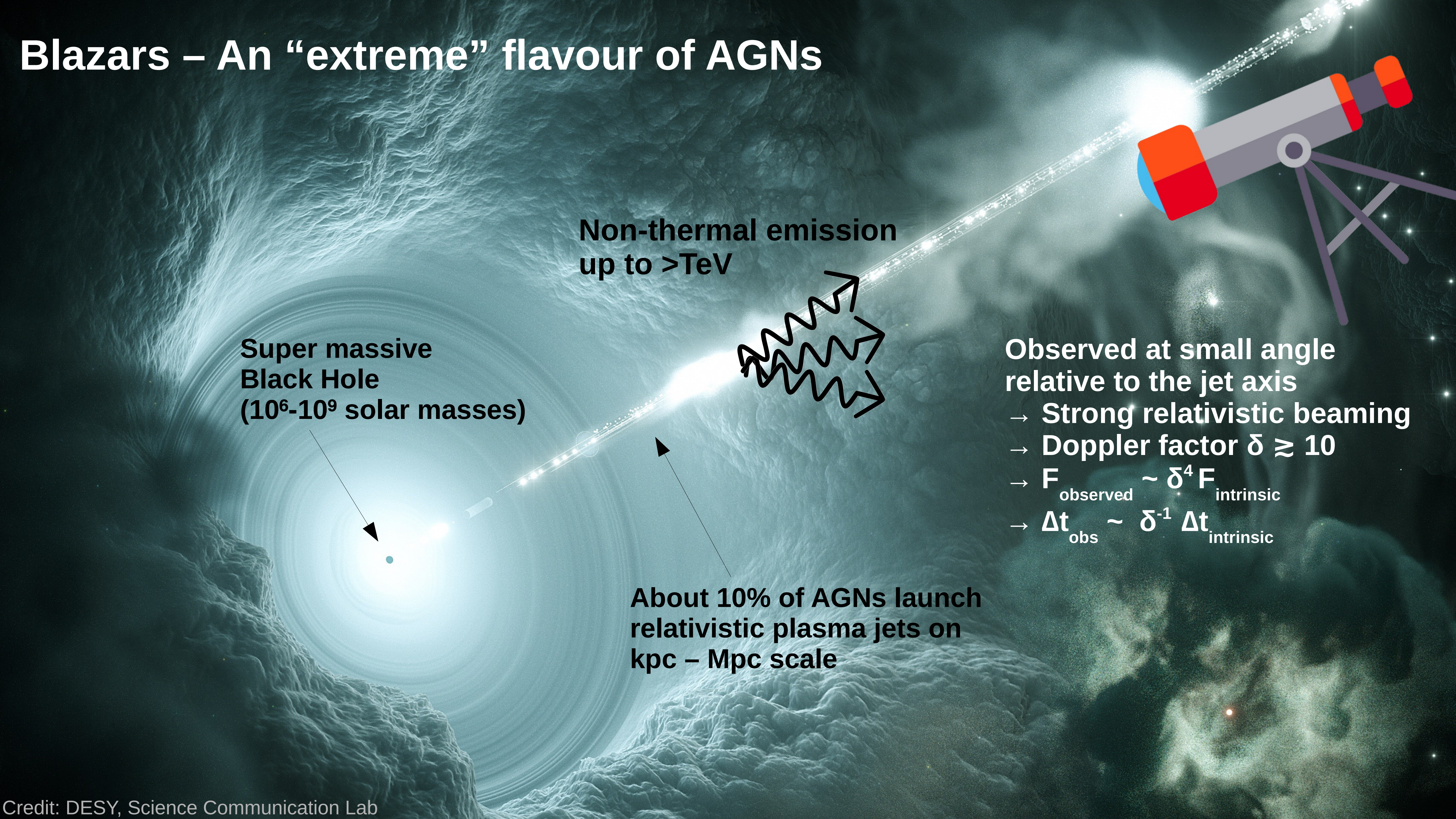
Sources of PeV neutrinos detected by IceCube?



Aartsen et al., 2019



Blazars – An “extreme” flavour of AGNs



Non-thermal emission
up to >TeV

Super massive
Black Hole
(10^6-10^9 solar masses)

About 10% of AGNs launch
relativistic plasma jets on
kpc – Mpc scale

Observed at small angle
relative to the jet axis
→ Strong relativistic beaming
→ Doppler factor $\delta \gtrsim 10$
→ $F_{observed} \sim \delta^4 F_{intrinsic}$
→ $\Delta t_{obs} \sim \delta^{-1} \Delta t_{intrinsic}$

Credit: DESY, Science Communication Lab

the MAGIC telescopes

La Palma, Canary Islands, Spain

Credit: Daniel Lopez, IAC

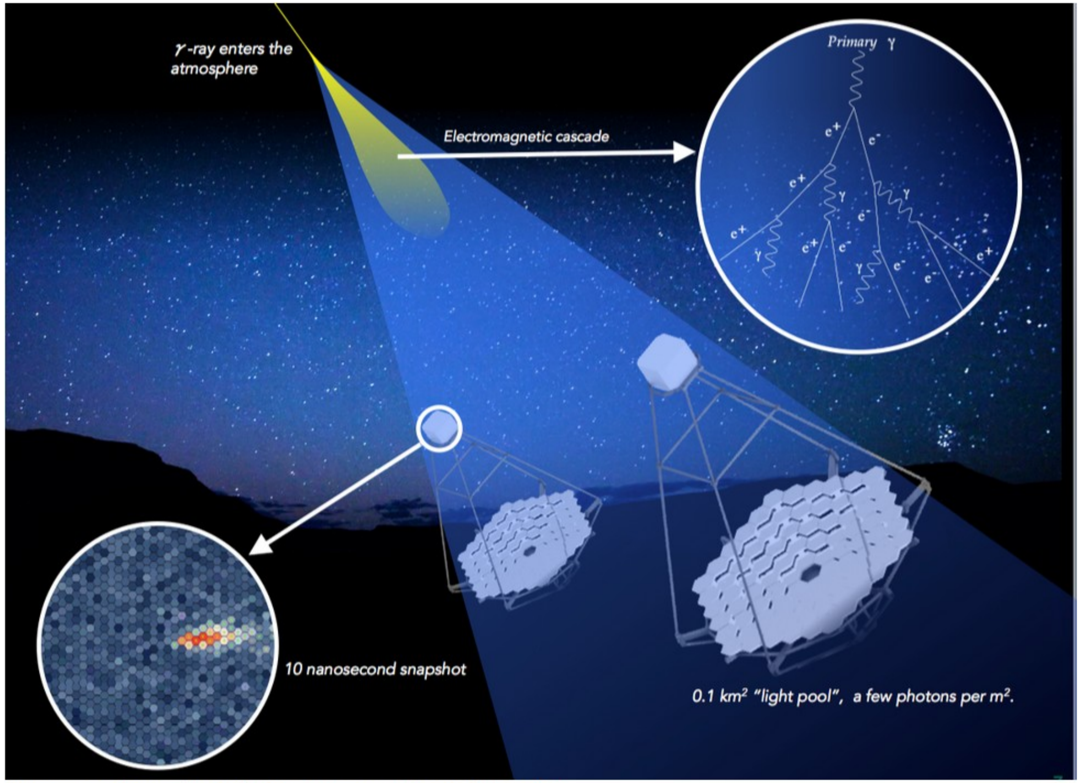
MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

the MAGIC telescopes

20 years MAGIC anniversary last year!


Credit: Daniel Lopez, IAC

the MAGIC telescopes

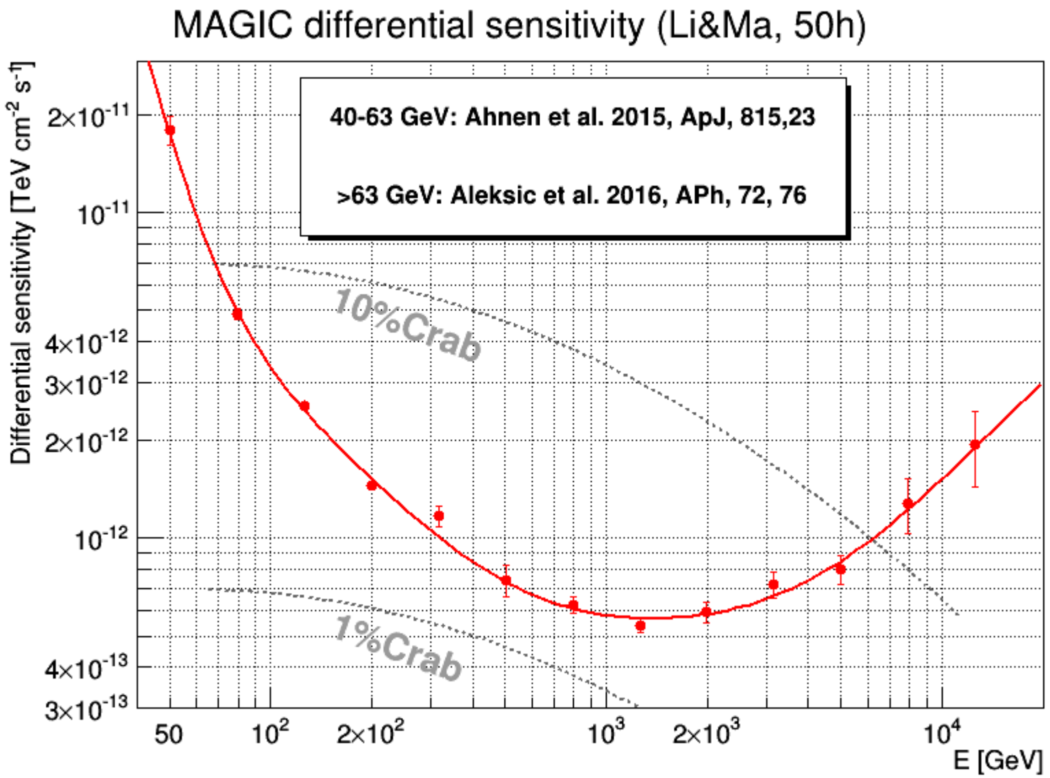


Credit: R. White (MPIK) / K. Bernlohr (MPIK) / DESY

Credit: Daniel Lopez, IAC

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

the MAGIC telescopes

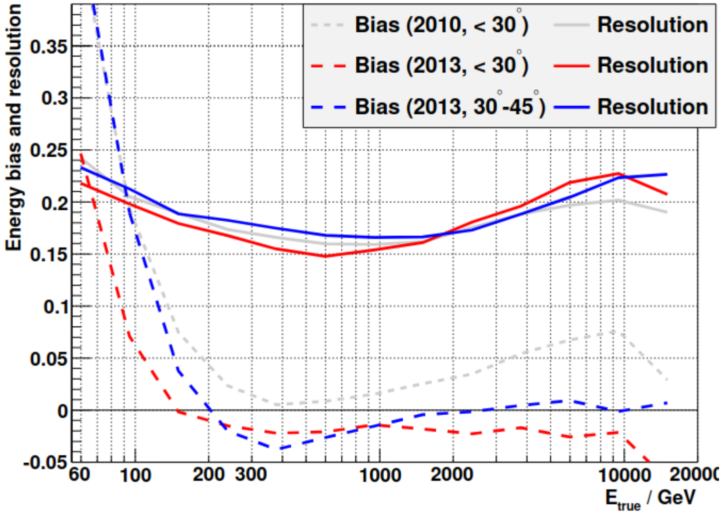


40-63 GeV: Ahnen et al. 2015, ApJ, 815,23

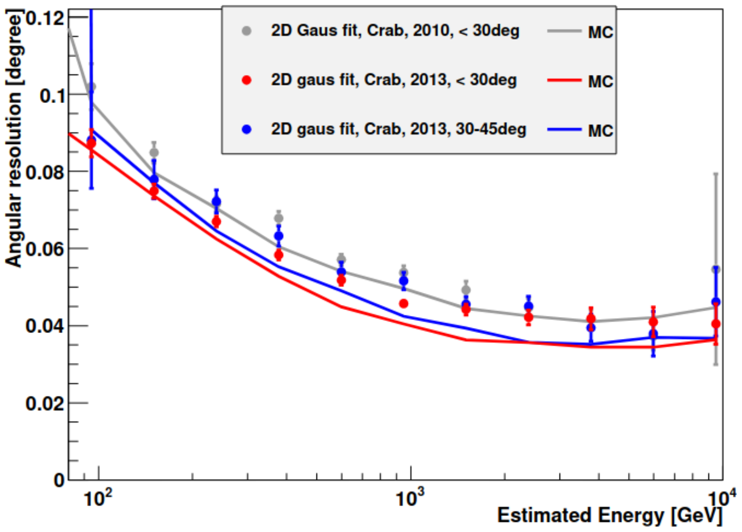
>63 GeV: Aleksic et al. 2016, APh, 72, 76

Aleksic et al. 2016, APh, 72, 76.

Energy resolution



Angular resolution



*Energy range: **~15 GeV to ~100 TeV***

*Energy resolution: **~15-25%***

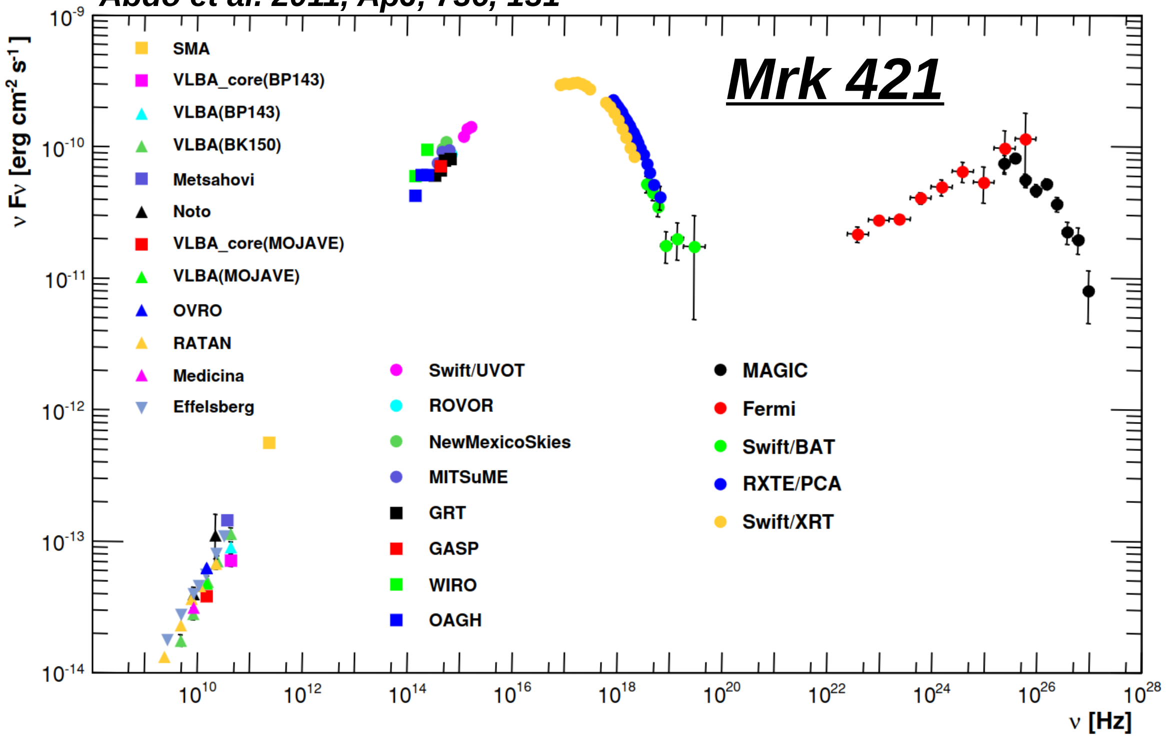
*Field of view: **~3.5 deg***

*Angular resolution: **0.05 -0.10 deg***

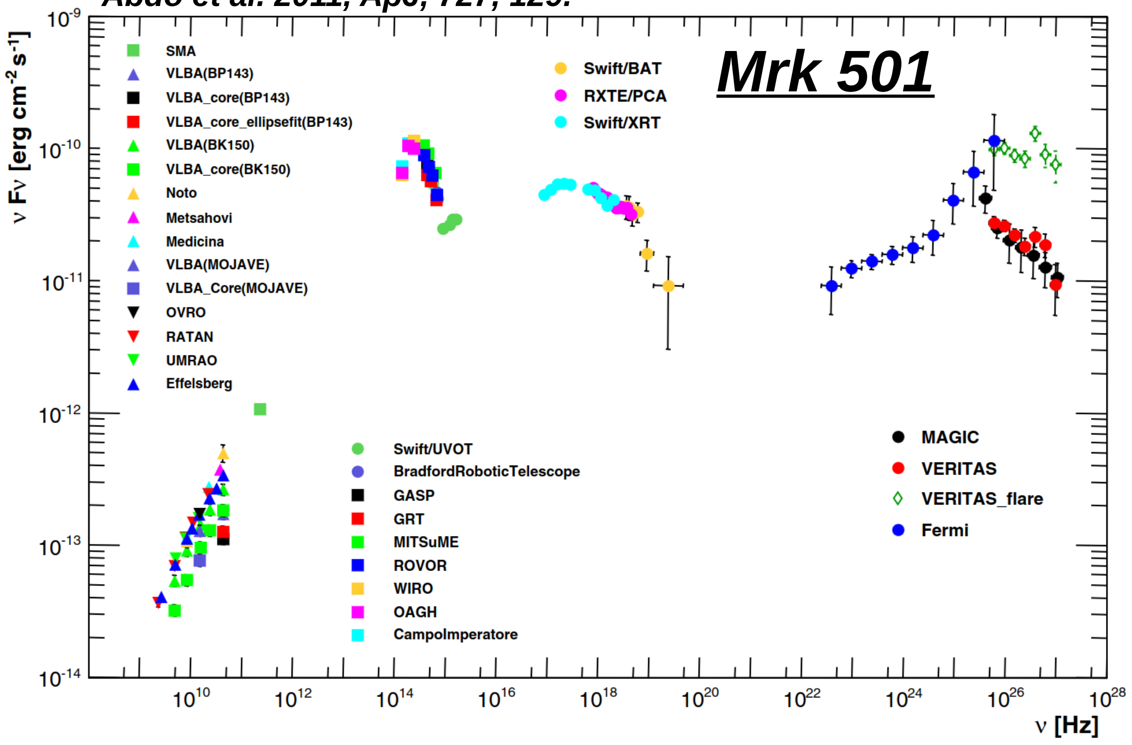
MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

Bright blazars in our neighbourhood: Markarian 421 & Markarian 501

Abdo et al. 2011, ApJ, 736, 131



Abdo et al. 2011, ApJ, 727, 129.



1) Bright sources:
→ “Easily” detectable from radio to TeV

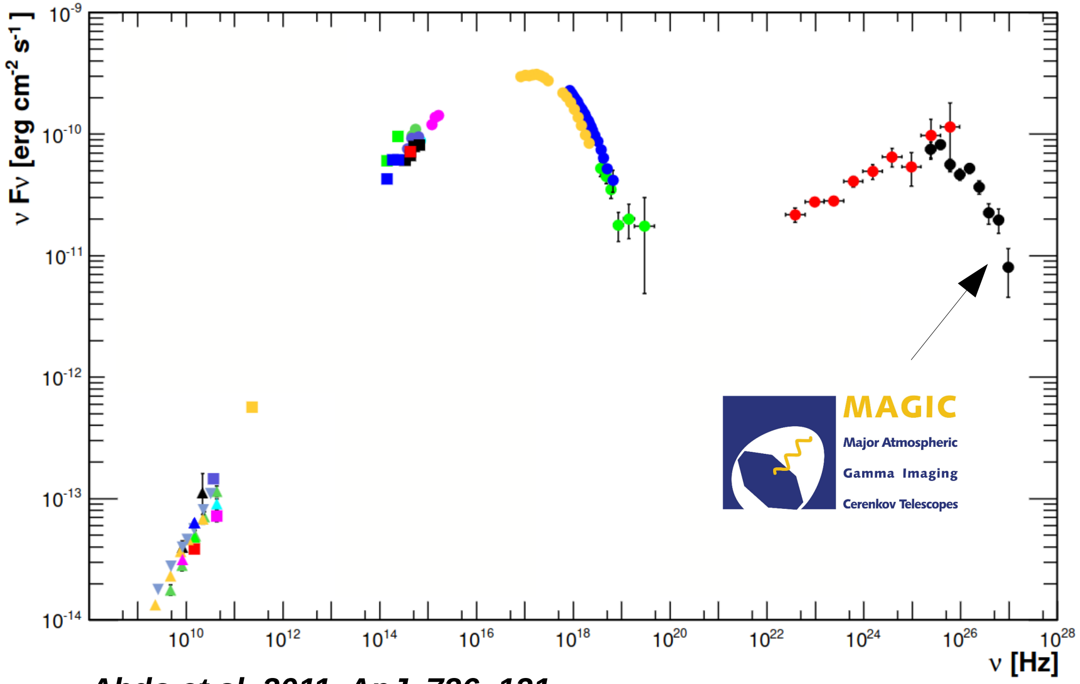
2) Proximity (130-140 Mpc; ~4x10^8 light years):
→ Small attenuation of gamma rays
due to pair creation with optical/IR background

Variability studies on short timescales
→ *Probe particle acceleration & cooling*

Detailed intra-band correlation
→ *Crucial to constrain models*

Observing campaigns of Mrk421 & Mrk501 with the MAGIC telescopes

- **Monitoring of Mrk421 & Mrk501 since ~2009**
  (current P.I.: A. Arbet-Engels)
  → observe every 2/3 days; “Unbiased”



Abdo et al. 2011, ApJ, 736, 131

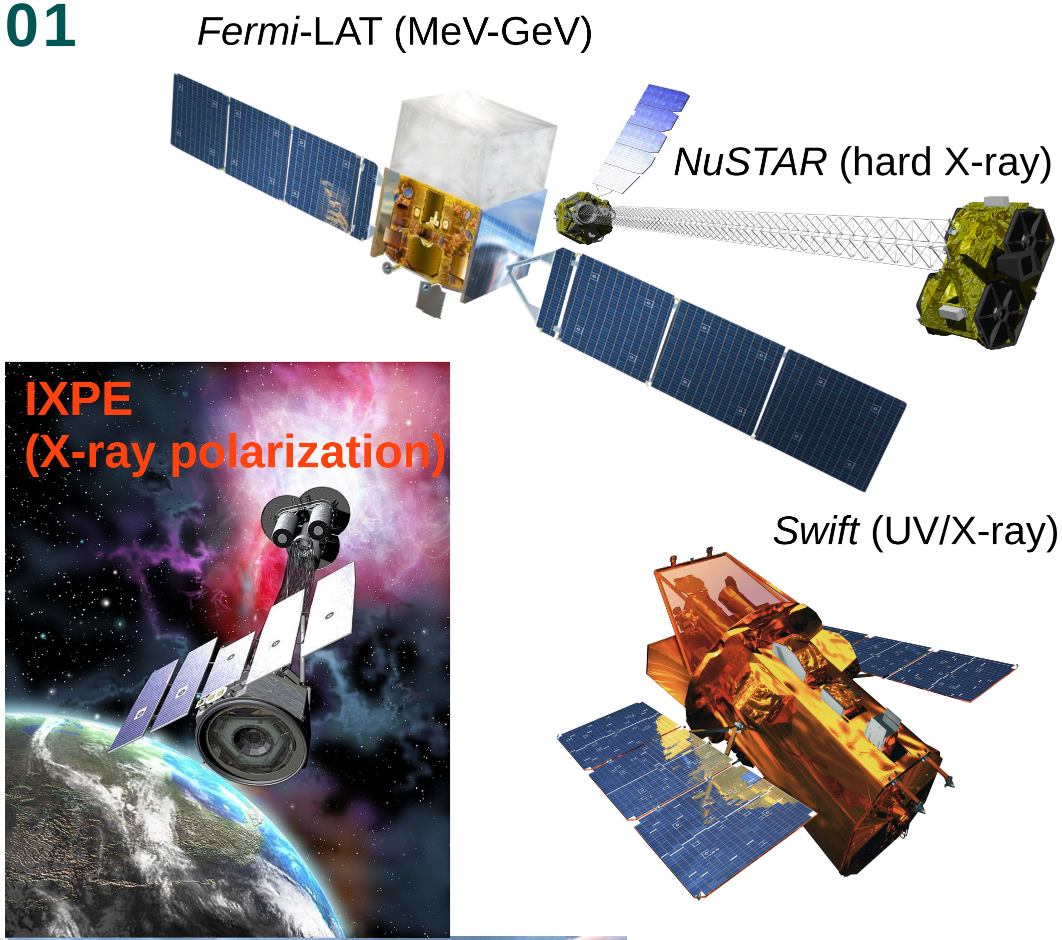
Credit: Daniel Lopez, IAC

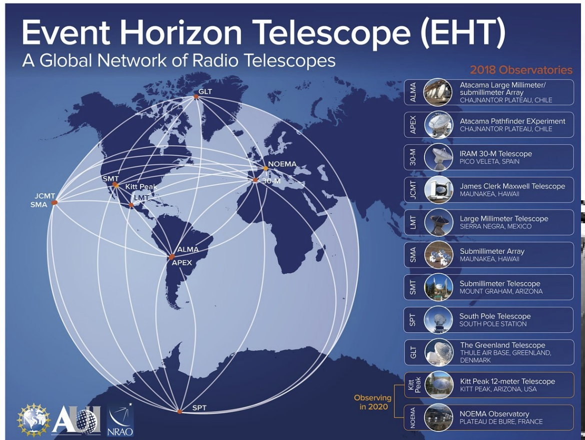
Observing campaigns of Mrk421 & Mrk501 with the MAGIC telescopes

- **Monitoring of Mrk421 & Mrk501 since ~2009**
  (current P.I.: A. Arbet-Engels)
  → observe every 2/3 days; “Unbiased”

- **Coordinated with > 20 instruments**
  → Simultaneous radio-to-VHE coverage

- **Synergy with “cutting-edge” instruments**
  → Mrk 421 & 501 are prime targets for new telescopes
  First blazars with X-ray polarization data from the new *IXPE* satellite (see later)



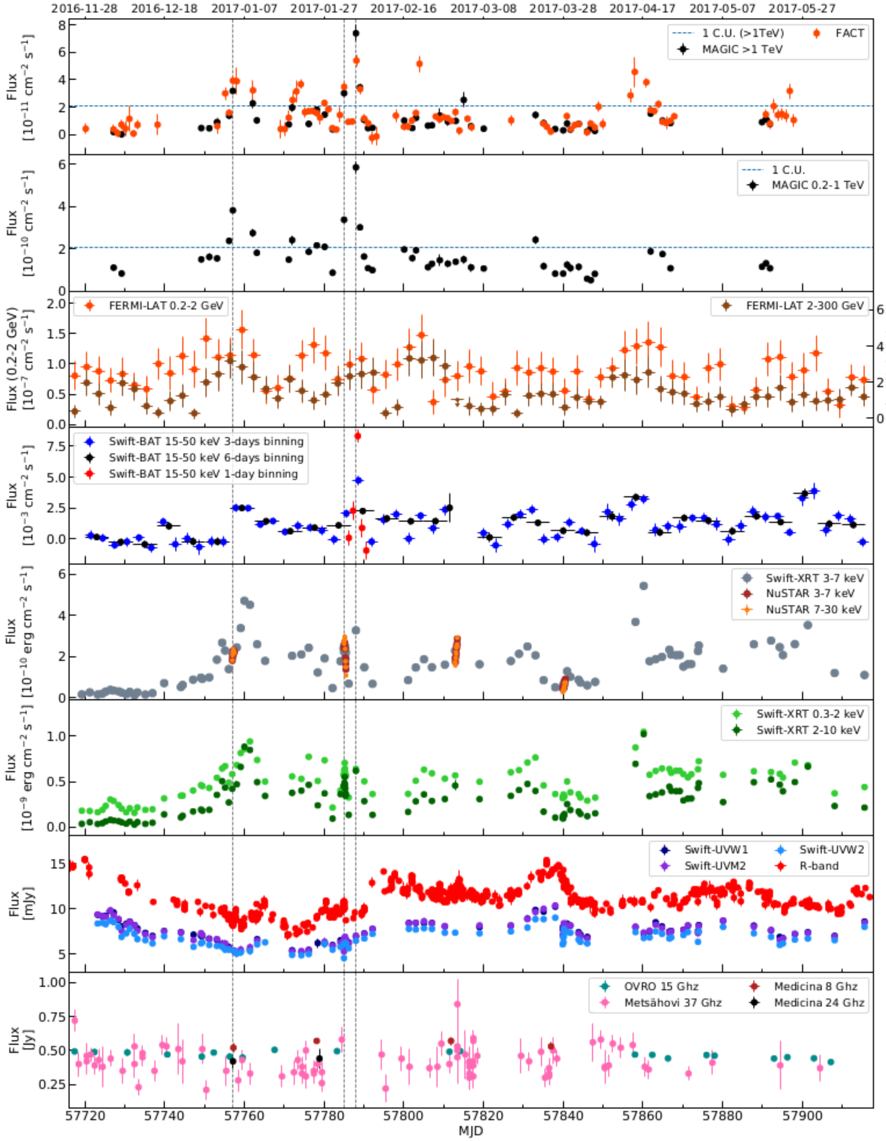


And many more...

Multi-wavelength observing campaigns of Mrk421 & Mrk501

Mrk421 in 2017

Acciari et al. 2021, A&A 655, A89



>1TeV (MAGIC)

0.2-1TeV (MAGIC)

MeV-GeV

X-ray

X-ray

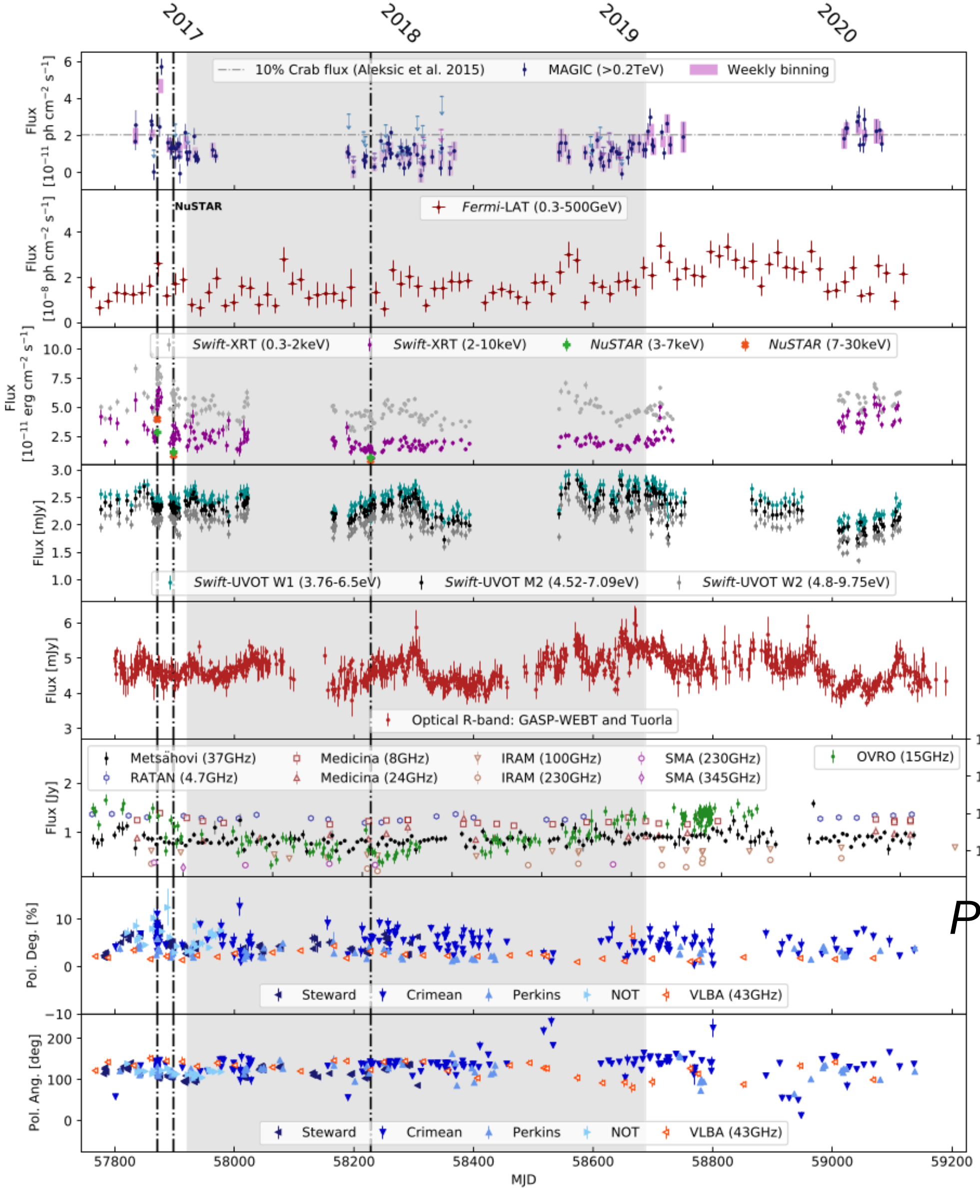
X-ray

Optical/ UV

radio

Mrk501 from 2017 to 2020

Abe et al. 2023, ApJS, 266, 37



>0.2TeV (MAGIC)

MeV-GeV

X-ray

UV

optical

Radio

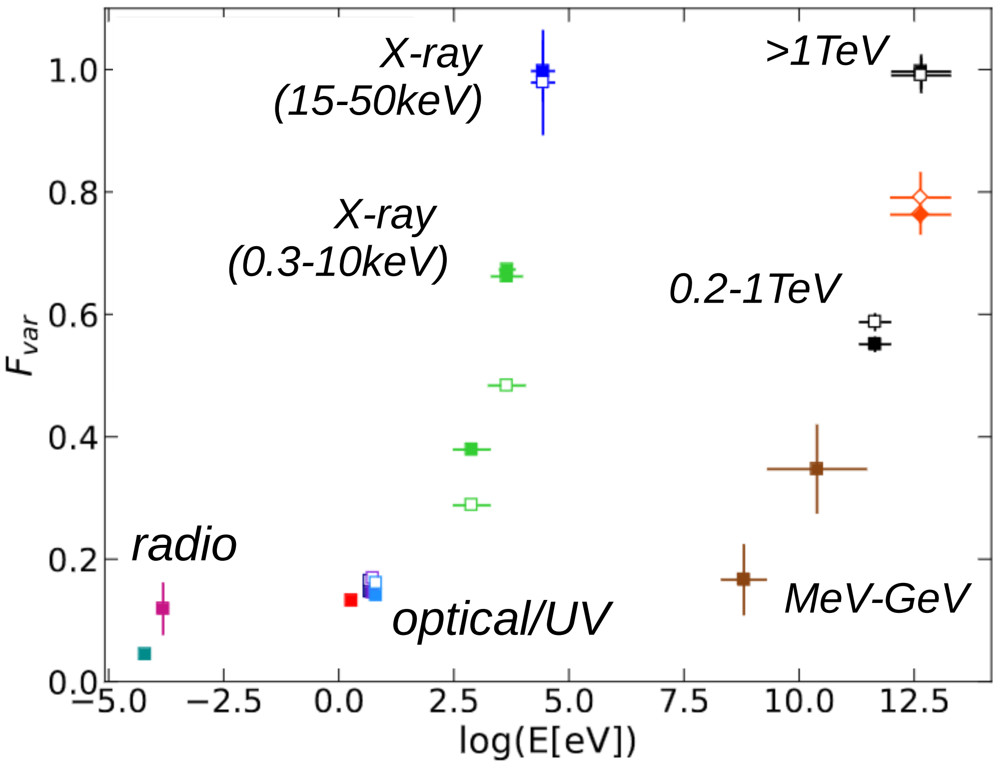
Polarization

Multi-wavelength observing campaigns of Mrk421 & Mrk501

- Variability quantified using **Fractional Variability (F_var)**

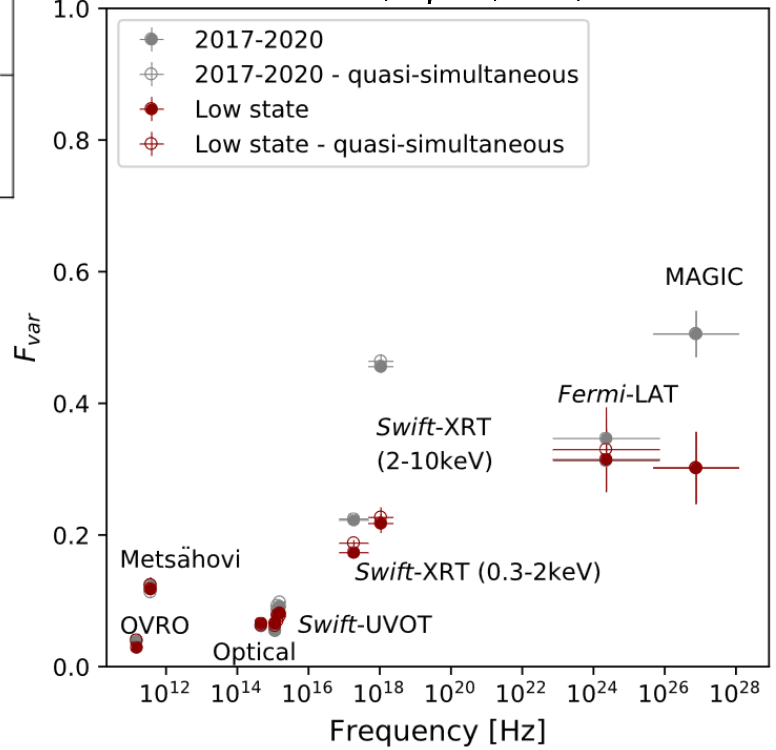
$$F_{\mathrm{var}} = \sqrt{\frac{S^2 - \langle \sigma_{err}^2 \rangle}{\langle x \rangle^2}}$$

- **Strongest variability in X-ray & VHE**



Mrk421 in 2017
Acciari et al. 2021, A&A 655, A89

Mrk501 from 2017 to 2020
Abe et al. 2023, ApJS, 266, 37



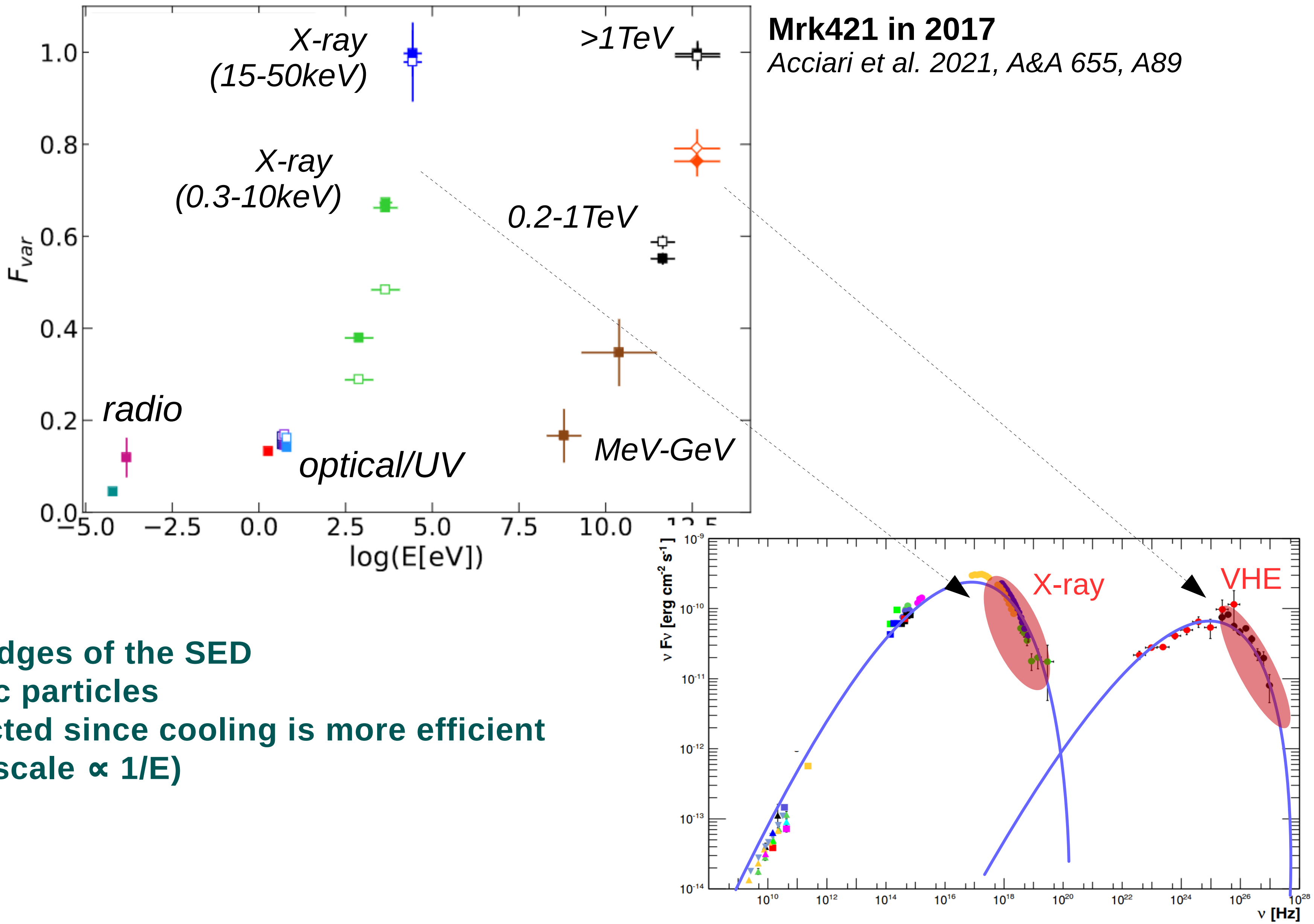
Multi-wavelength observing campaigns of Mrk421 & Mrk501

- Variability quantified using **Fractional Variability (F_var)**

$$F_{\rm var} = \sqrt{\frac{S^2 - \langle\sigma_{err}^2\rangle}{\langle x\rangle^2}}$$

- **Strongest variability in X-ray & VHE**

- **Corresponds to the falling edges of the SED**
  → Emitted by most energetic particles
  → Stronger variability expected since cooling is more efficient (synchrotron cooling timescale ∝ 1/E)

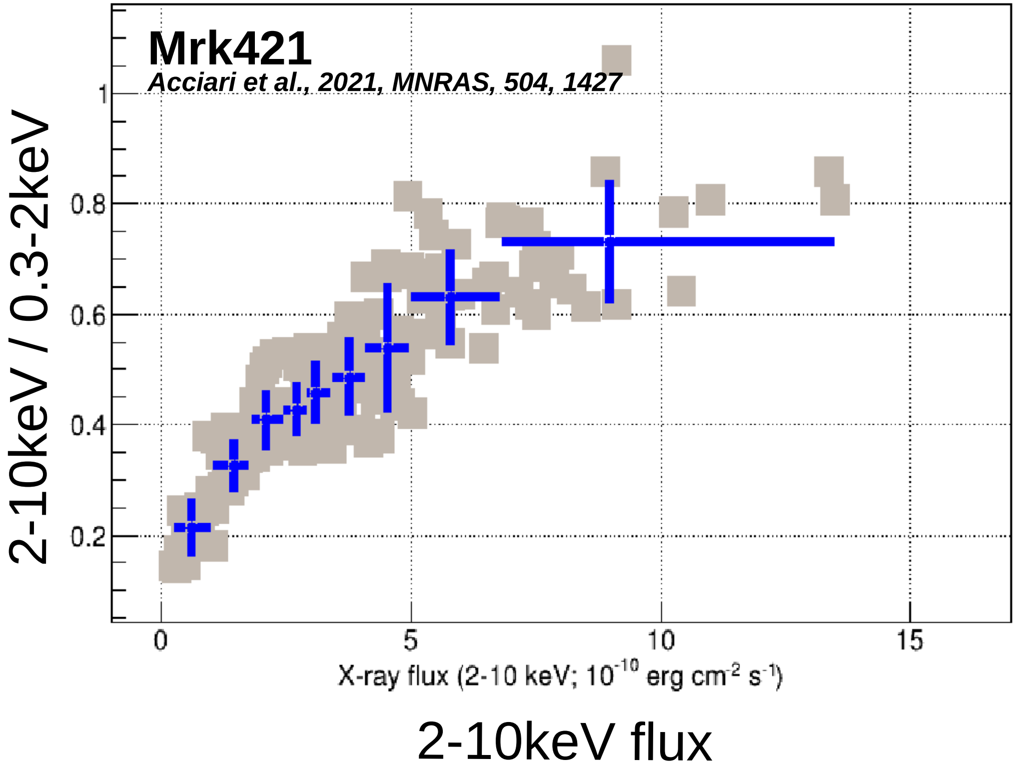


Mrk421 in 2017
Acciari et al. 2021, A&A 655, A89

Spectral evolution

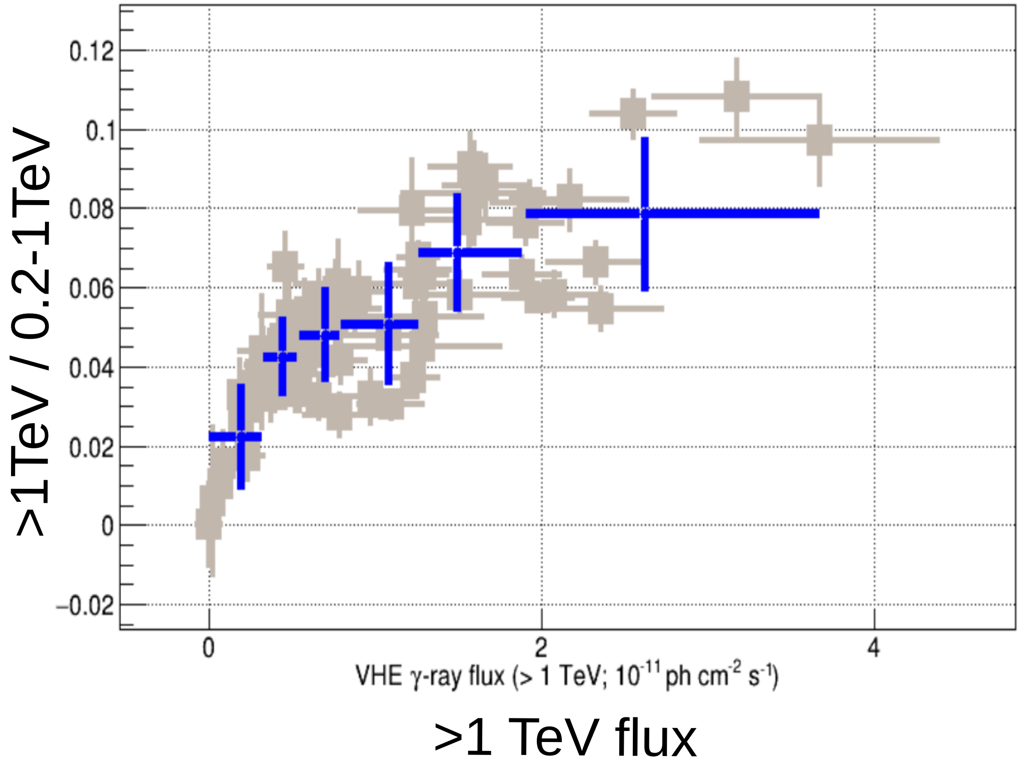
- Hardness (higher-energy flux / lower-energy flux) correlated with flux
  → **“harder when brighter”**
- **Flux increase driven by injection of freshly accelerated particles**

X-ray



Acciari et al., 2021, MNRAS, 504, 1427

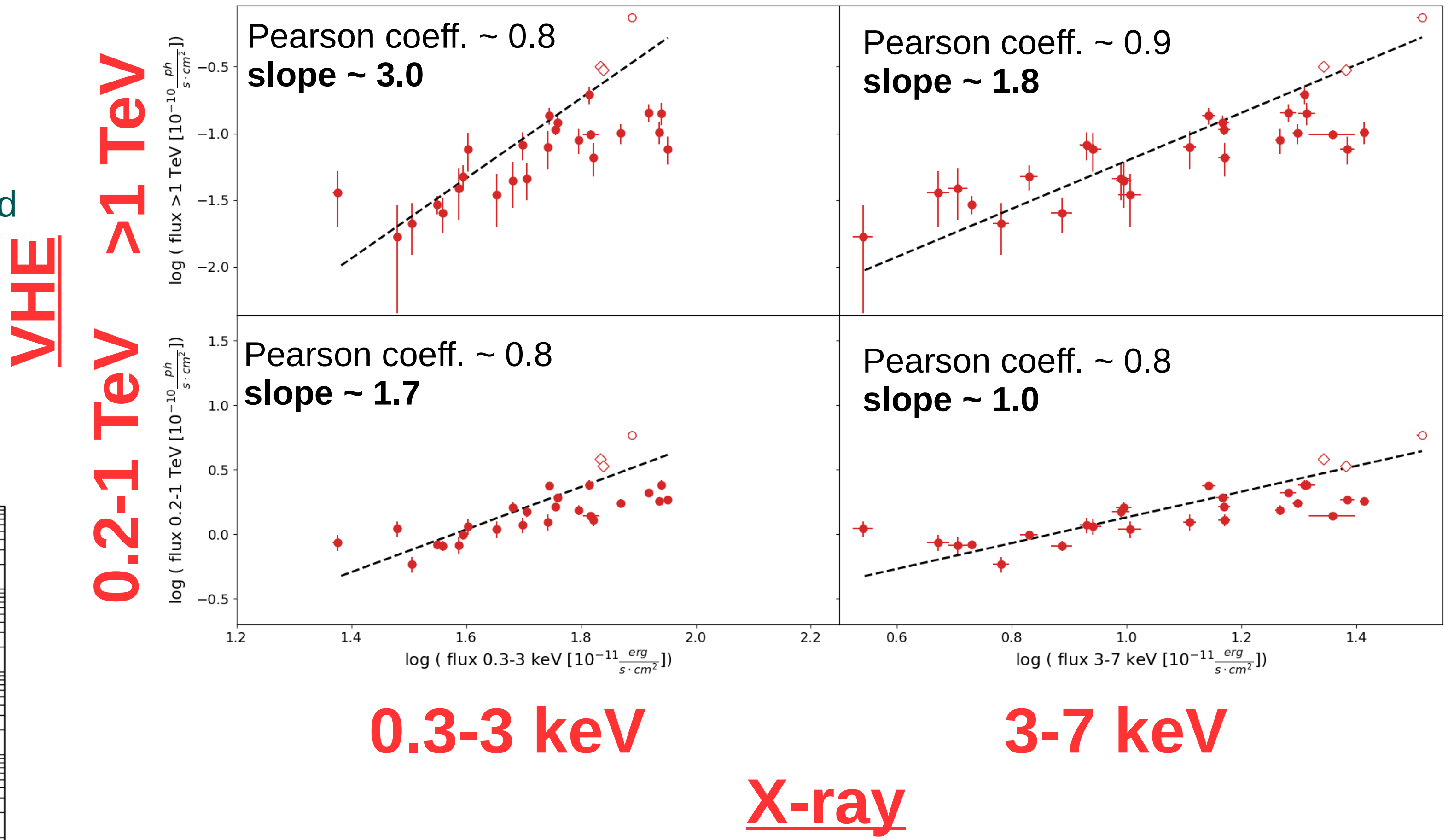
VHE

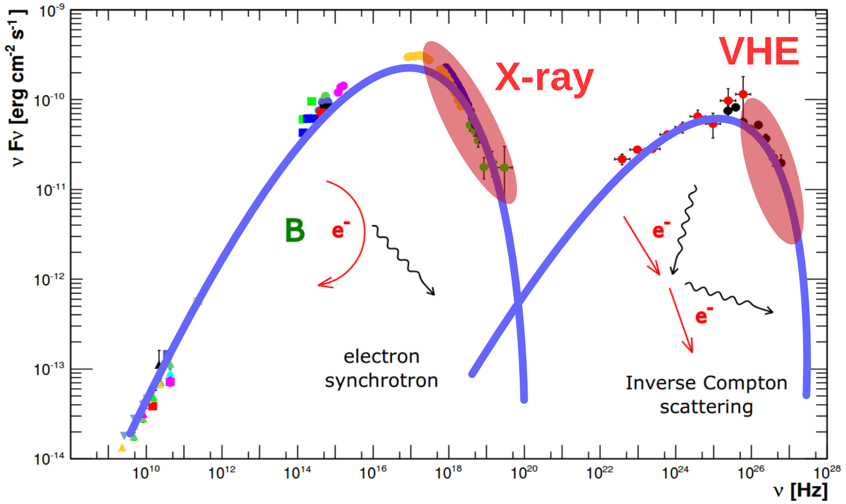


Detailed view on correlation patterns

- **Tight <u>VHE / X-ray</u> correlation**
  → during low activity & flares
  → consistent with leptonic models
- **Correlation slope is energy dependent**
  → Such TeV/X-ray complexity only probed in bright targets like Mrk 421 & 501

Acciari et al., 2021, A&A, 655, A89





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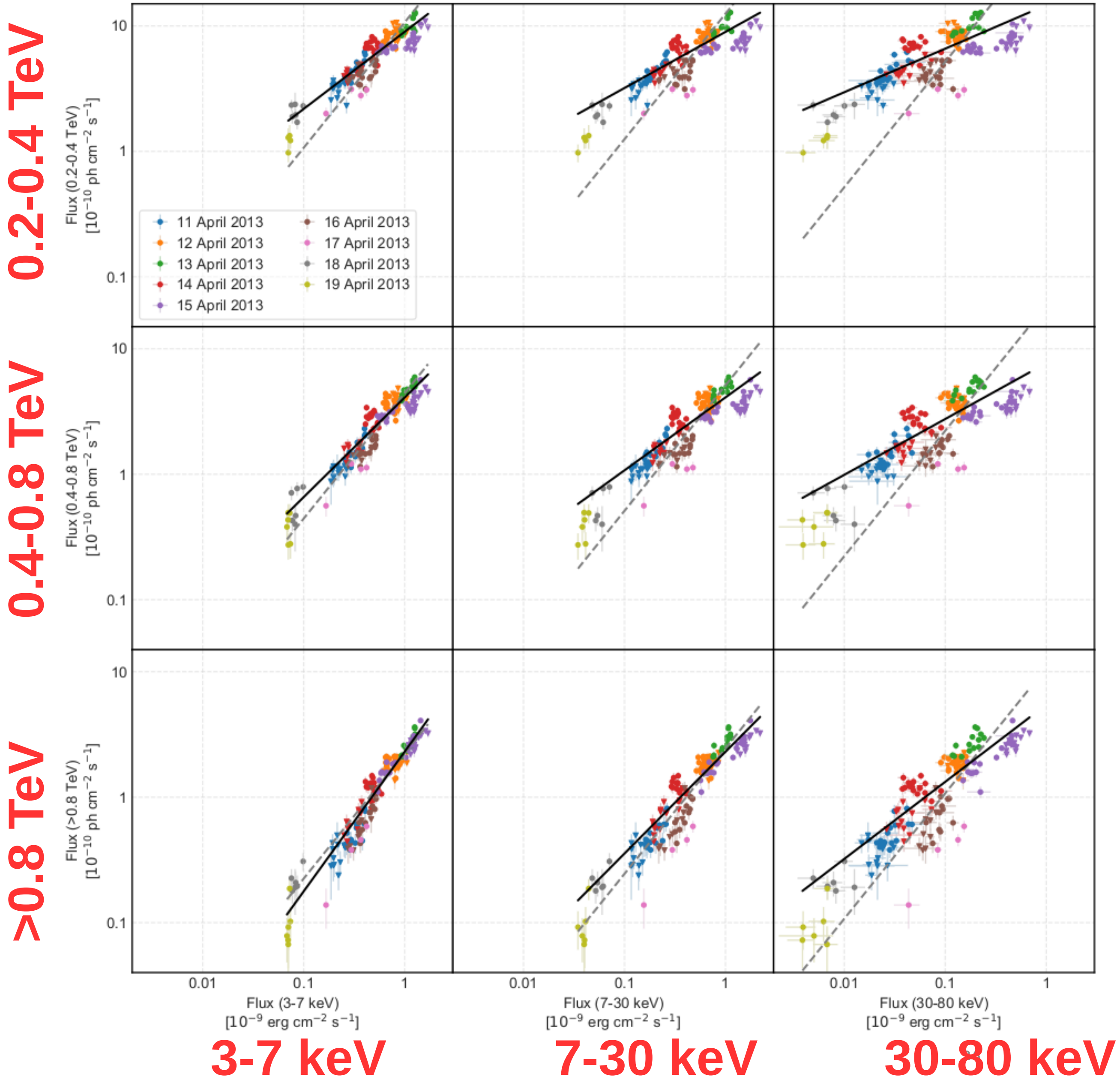
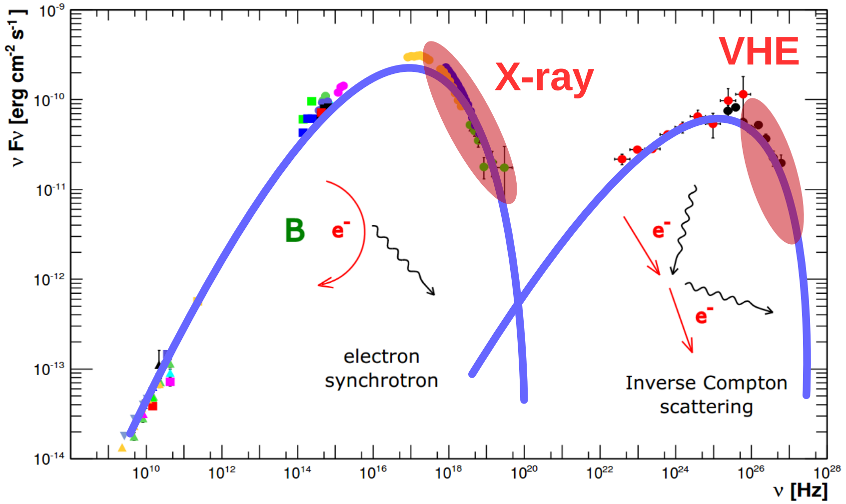
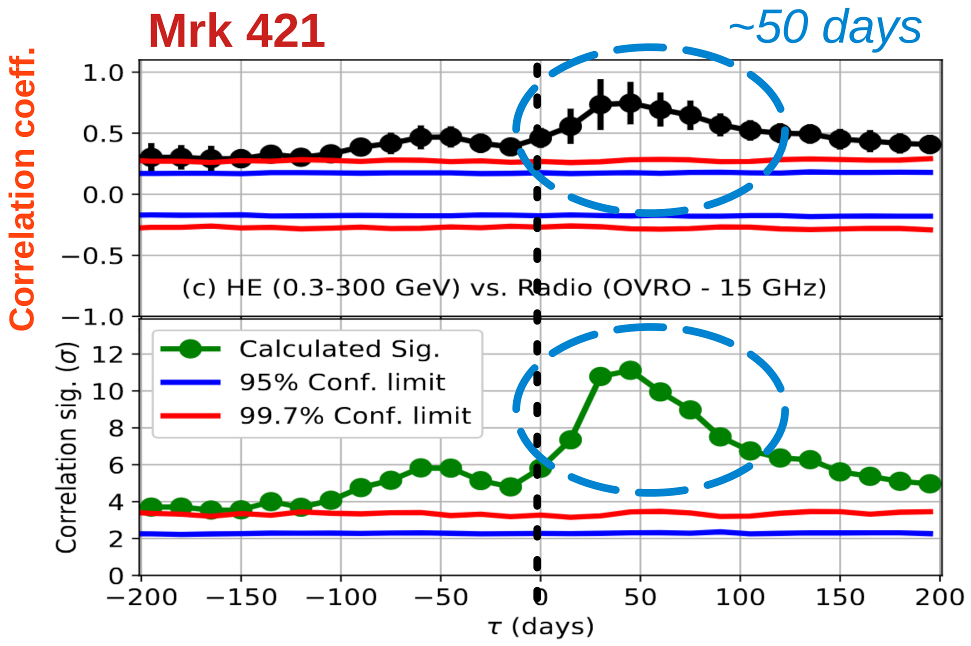
Acciari et al., 2020 ApJS 248 29

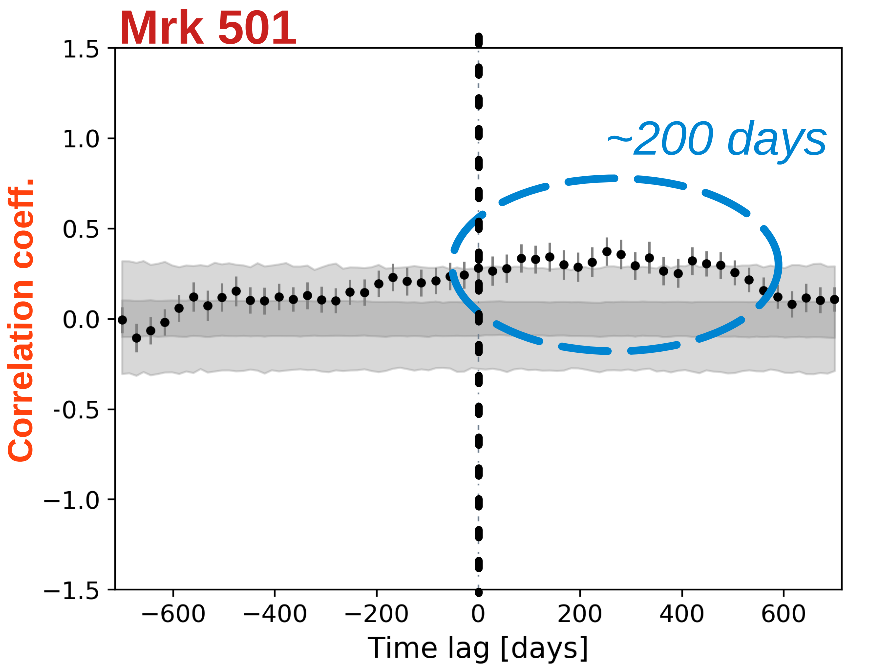




Detailed view on correlation patterns



Acciari et al., 2021, MNRAS, 504, 1427



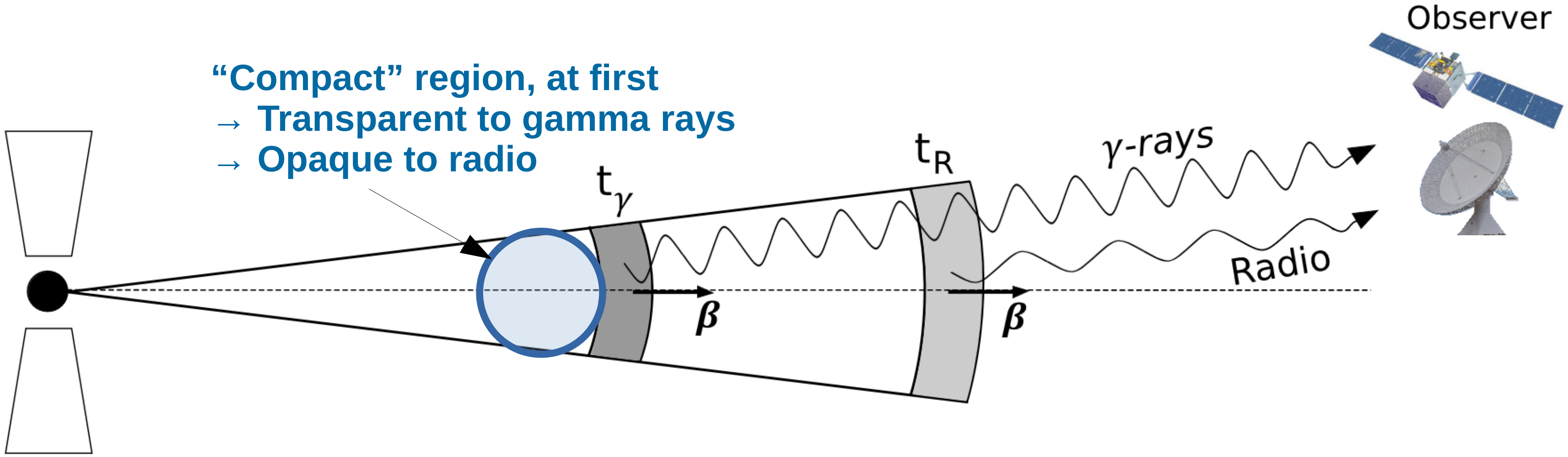
Abe et al., 2023, ApJS, 266, 37

- **Radio delayed w/ respect to MeV / GeV on monthly timescales**

  → observed in high & low emission states: **intrinsic behaviour of the source**

  → MeV / GeV region separated from radio zone?

Detailed view on correlation patterns



“Compact” region, at first
→ Transparent to gamma rays
→ Opaque to radio

Max-Moerbeck 2014, MNRAS, 445, 428

- **Radio delayed w/ respect to MeV / GeV on monthly timescales**

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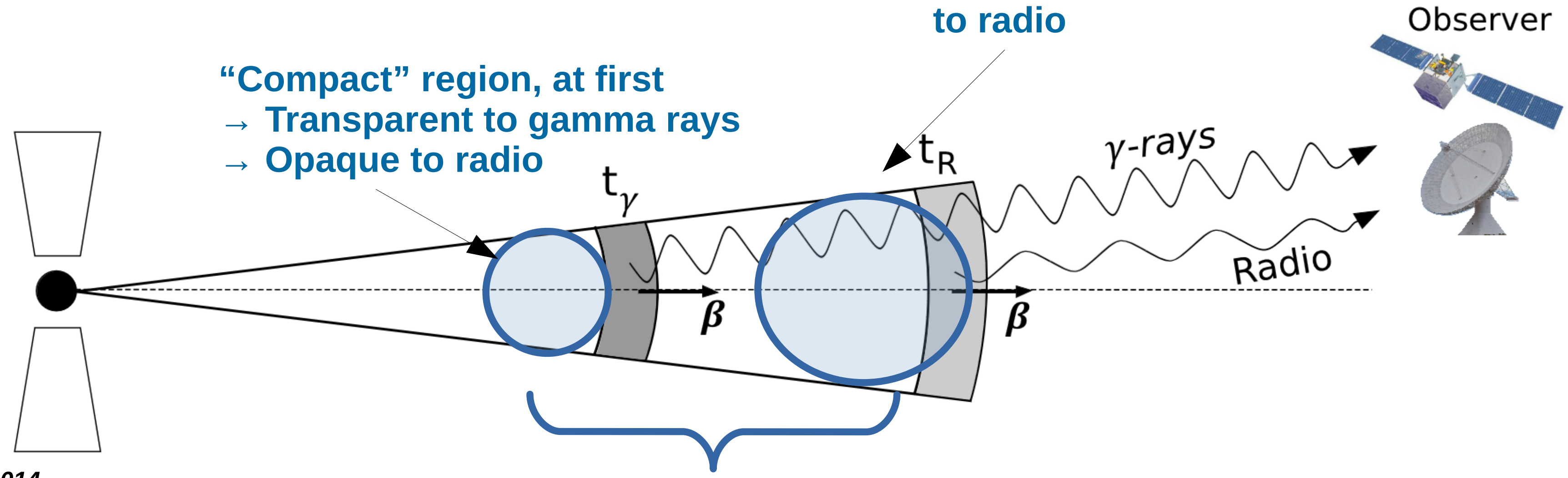
Detailed view on correlation patterns



Region expands
→ Becomes transparent to radio

“Compact” region, at first
→ Transparent to gamma rays
→ Opaque to radio

Max-Moerbeck 2014, MNRAS, 445, 428

~0.2-0.5 pc separation (1pc ~ 3e18cm)
(exact values depends on delay & jet parameters)

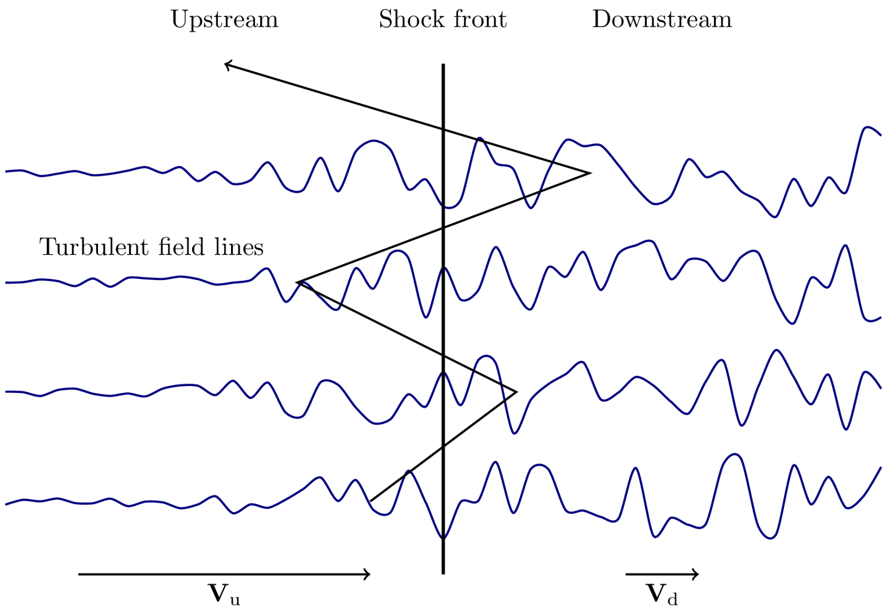
- **Radio delayed w/ respect to MeV / GeV on monthly timescales**

  → observed in high & low emission states: **intrinsic behaviour of the source**

  → MeV / GeV region separated from radio zone?

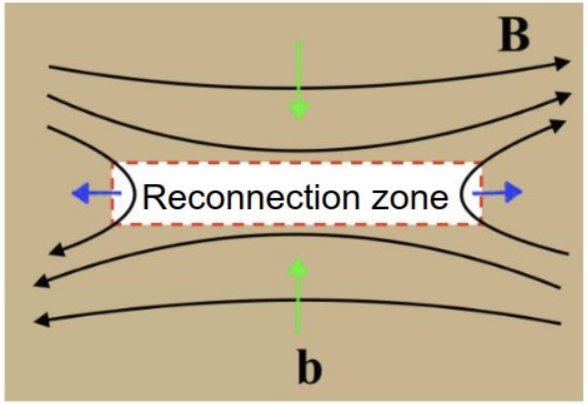
Particle acceleration in AGN jets?

- **"Diffusive shock acceleration"** (DSA) a.k.a. Fermi acceleration

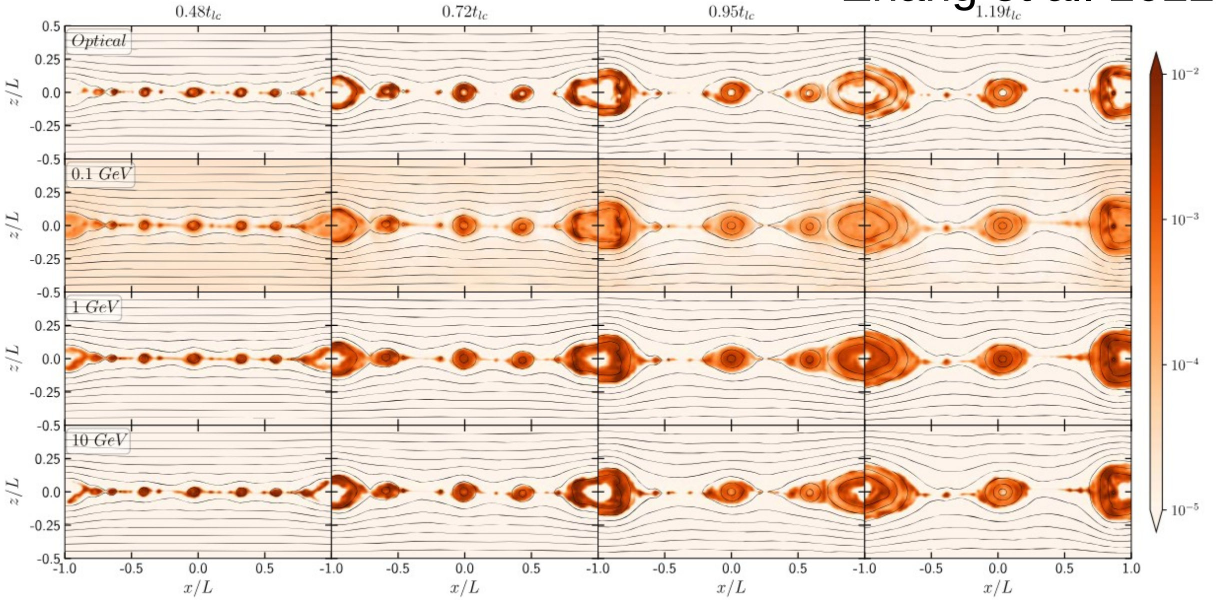


courtesy of Dr. Mark Pulupa

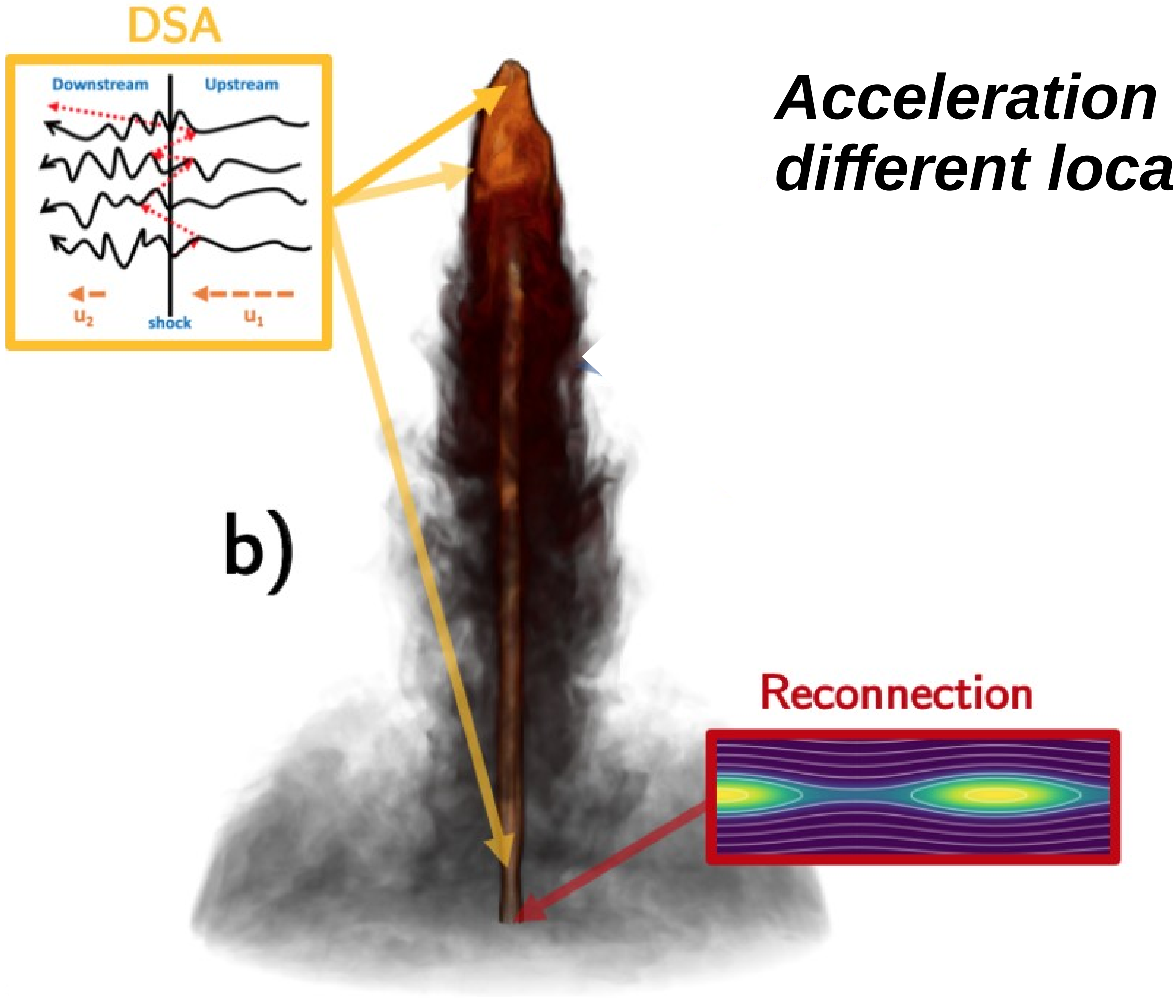
- **Magnetic re-connection**



Zhang et al. 2022



Particle acceleration in AGN jets?



Acceleration possibly at different location in the jet...

Matthews et al. 2020

Synchrotron polarization as a probe

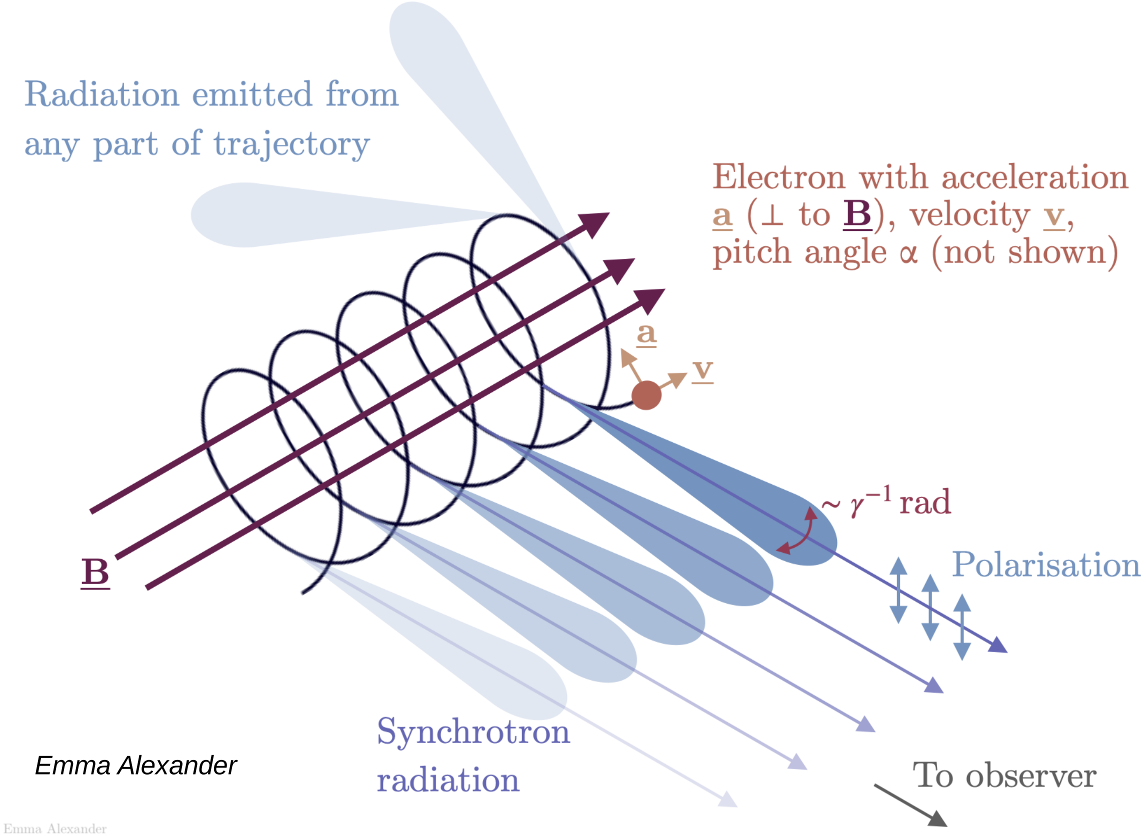
- **(Electric vector) polarization angle perpendicular to magnetic field**

- For electron power-law distribution with slope **p**, **maximum degree of linear polarization** (i.e., polarised / non-polarised flux ratio) :

$$Pol_{deg,max} = \frac{(3p+3)}{(3p+7)}$$

- For **p** ~ 2: $Pol_{deg,max} \approx 70\%$

- Magnetic turbulence can lower the polarization

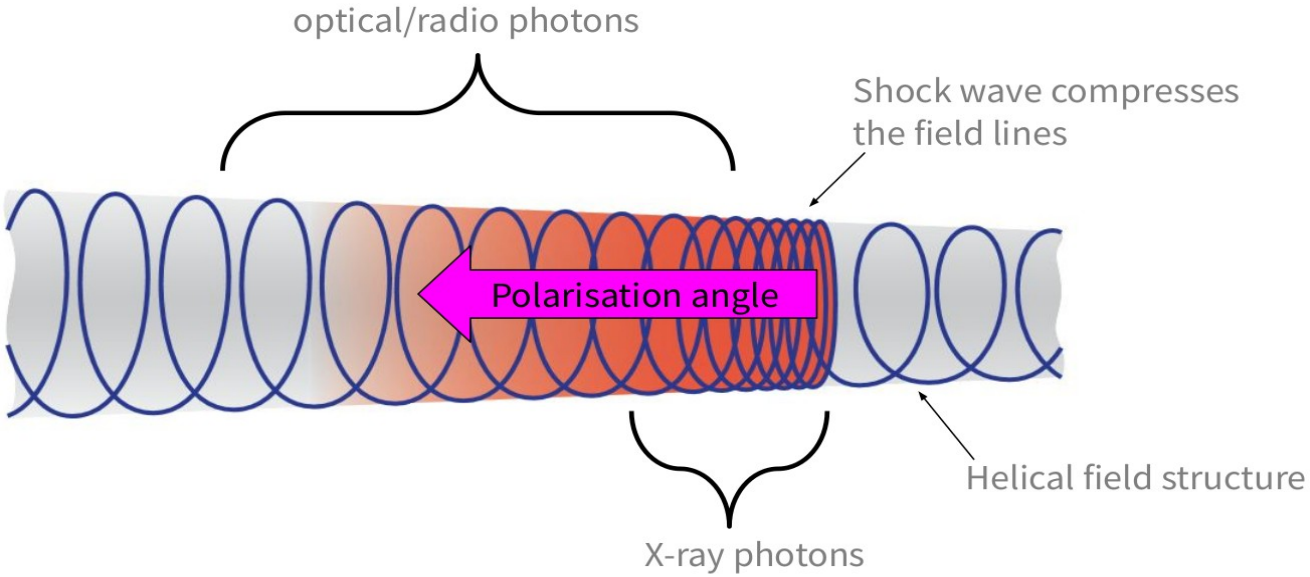


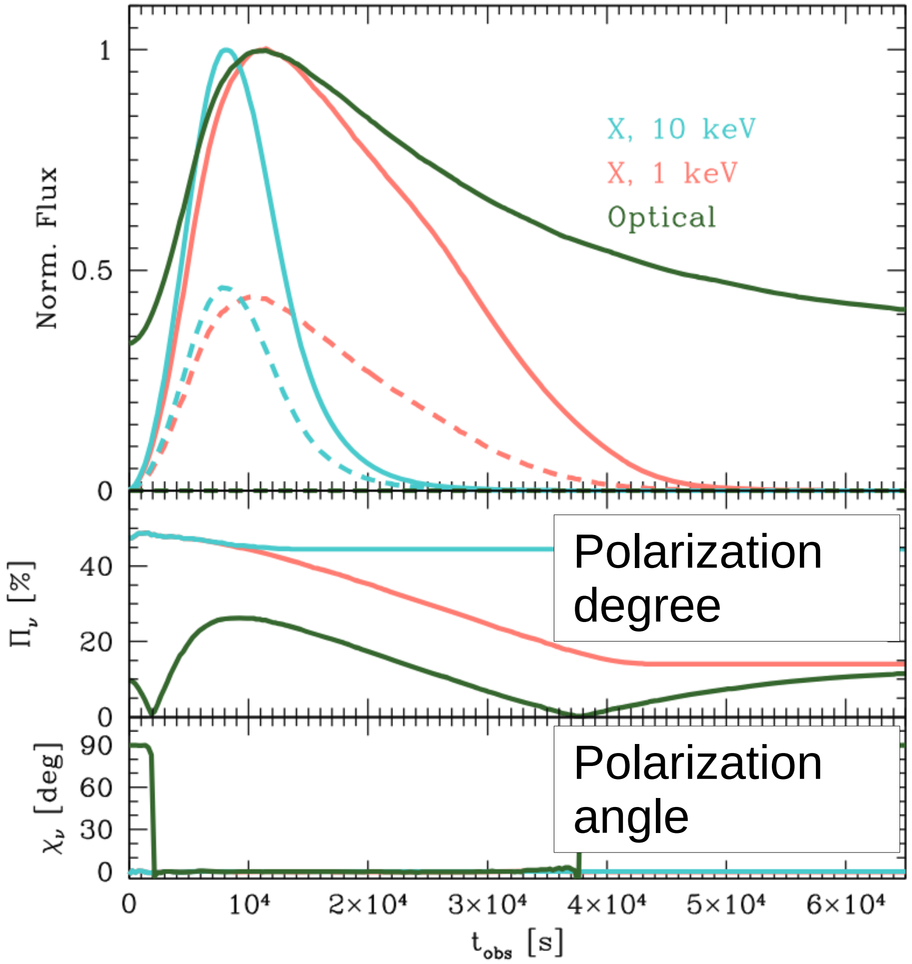
Emma Alexander

Particle acceleration in AGN jets?

- **“Diffusive shock acceleration”** (DSA)
  a.k.a. Fermi acceleration

  > pol. angle similar among energies (and ~ jet’s axis)
  > pol. degree increases with energy
  > pol. degree & angle variable on ~day timescales
  (if turbulence, stronger variability)



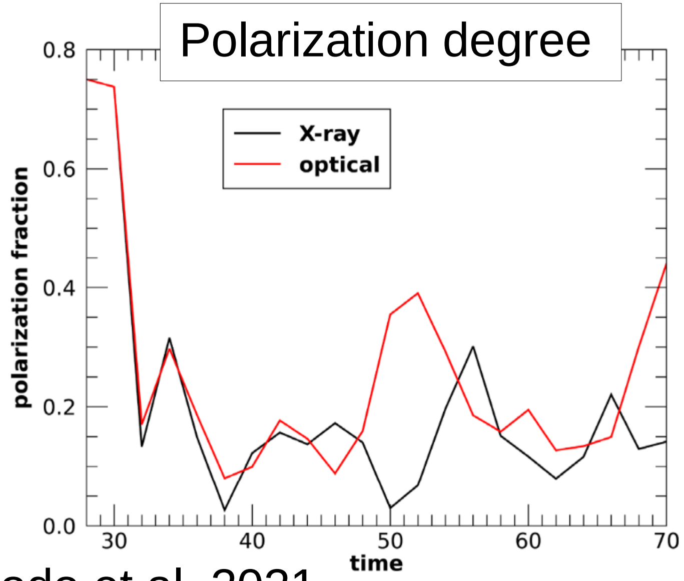


Tavecchio et al. 2020

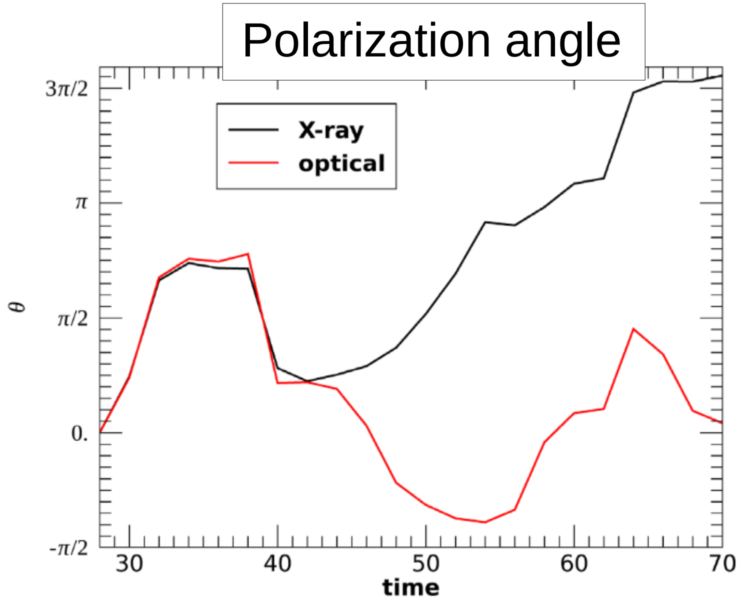
Particle acceleration in AGN jets?

- **Magnetic re-connection**

  > Strong and fast pol. variability
  > pol. degree comparable among with energy
  > pol. angle can be in any direction, its variations
  are usually coincident with flares

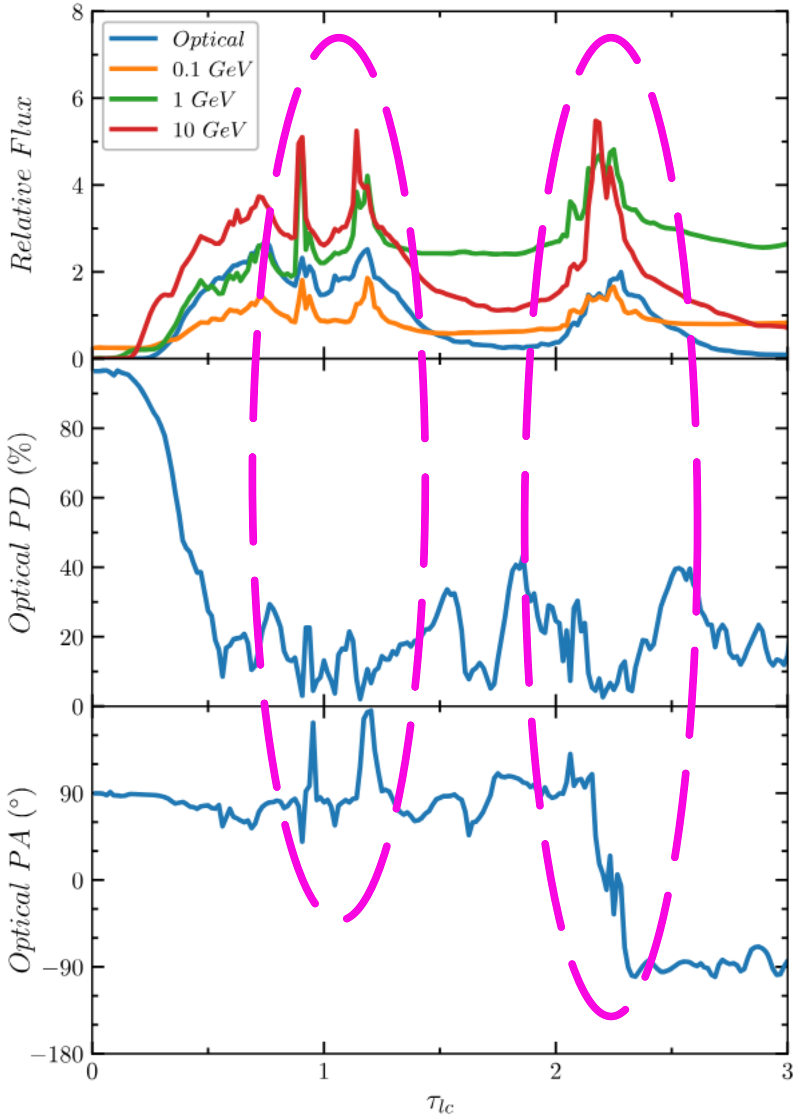


Polarization degree



Polarization angle

Bodo et al. 2021



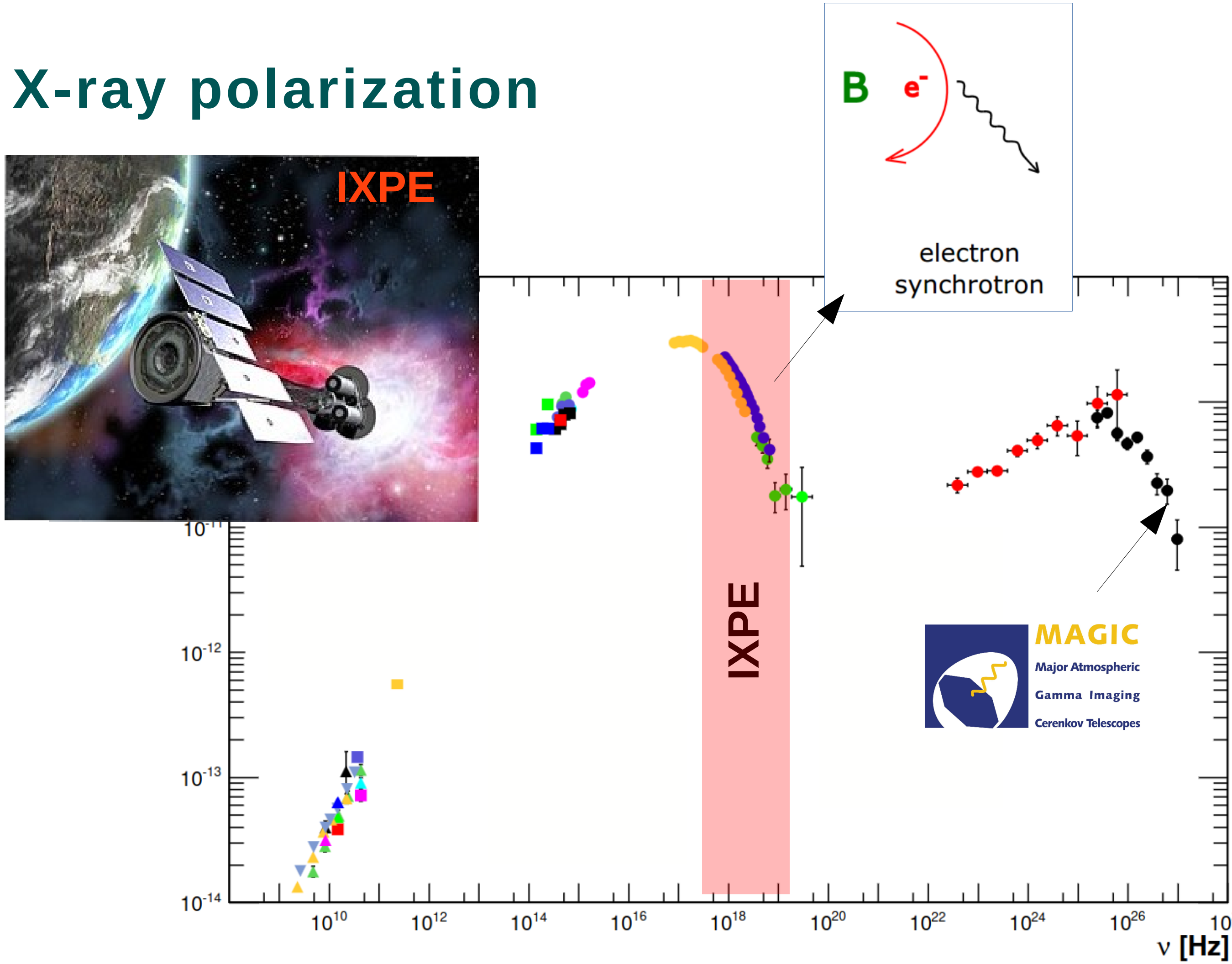
Zhang et al. 2022

A new view on TeV blazars – X-ray polarization

- ***IXPE :*** **1st instrument measuring X-ray polarization in extragalactic jets**
  → Launched in 2021
  (observations started in 2022)

- **Probe freshly accelerated particles in the jet**

- **Important synergies with MAGIC:**
  → X-ray / VHE tightly correlated
  → electrons emitting in IXPE band
  expect to emit in MAGIC band (in leptonic models)

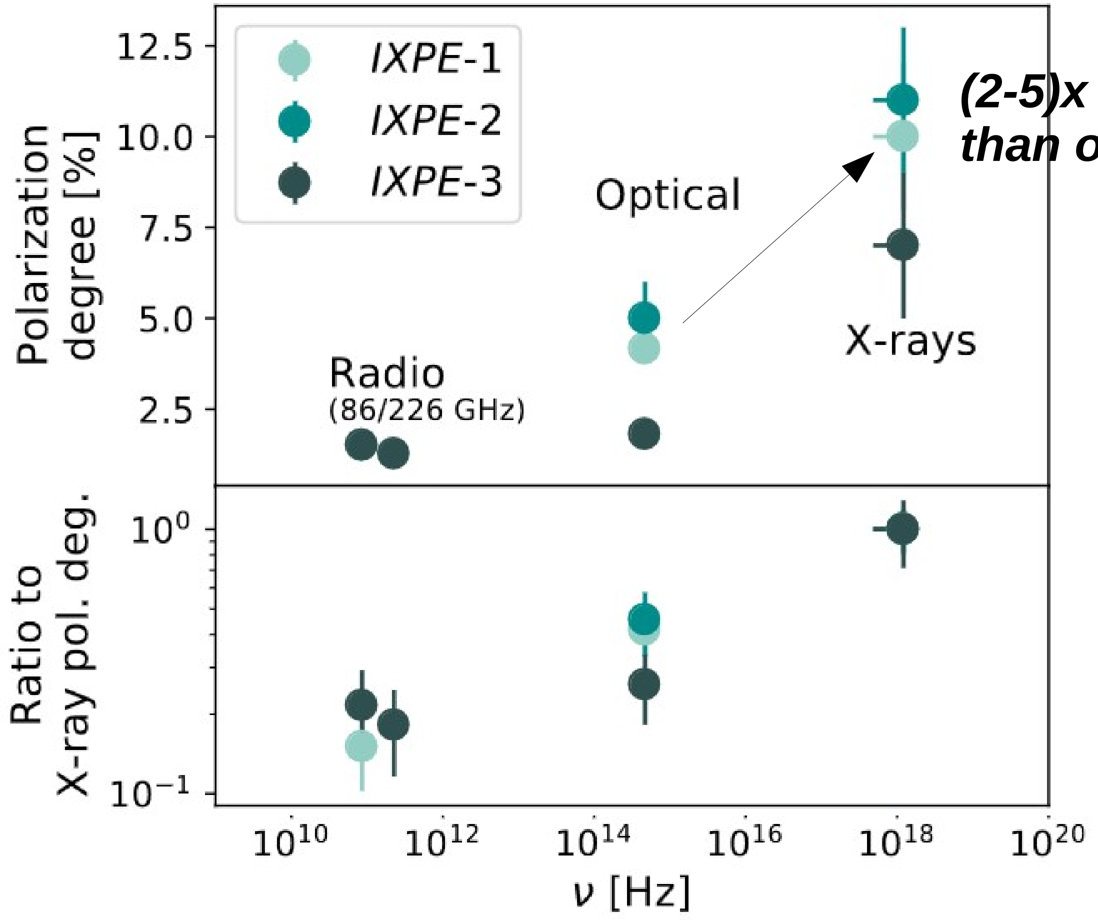


Abdo et al. 2011, ApJ, 736, 131

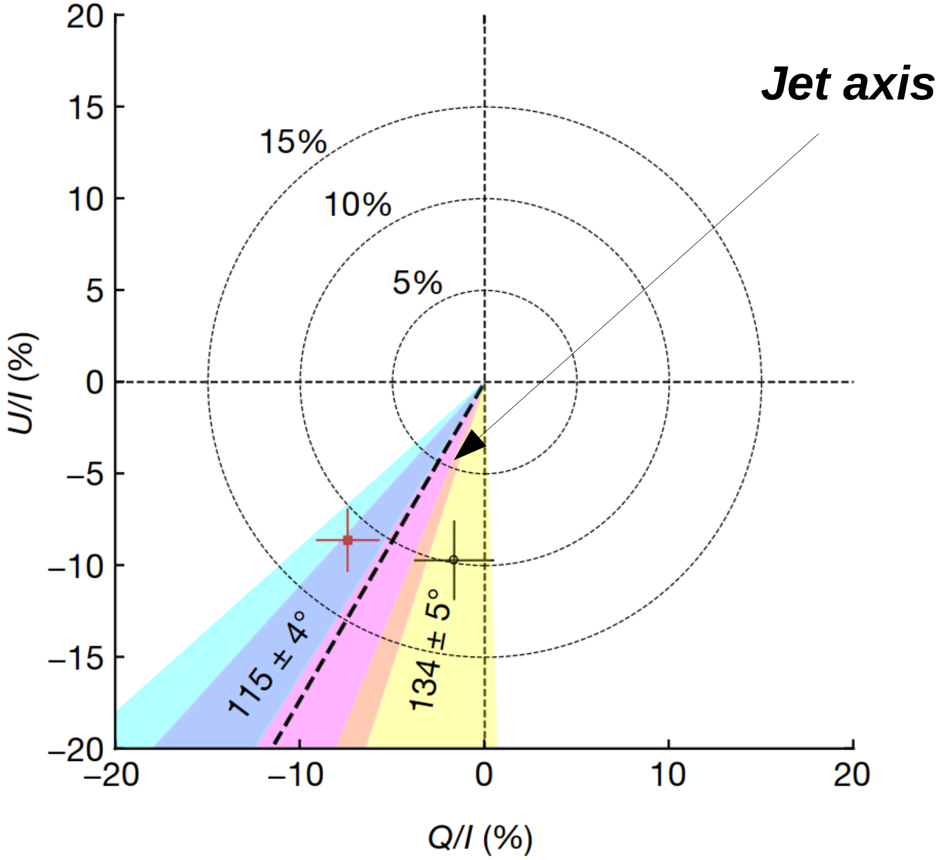
Blazars – from radio to TeV, including X-ray polarisation

Mrk501

Liodakis et al. 2022, Nature 611, 677–681
MAGIC Collab. et al., 2024, A&A, 685, A117



(2-5)x higher than optical



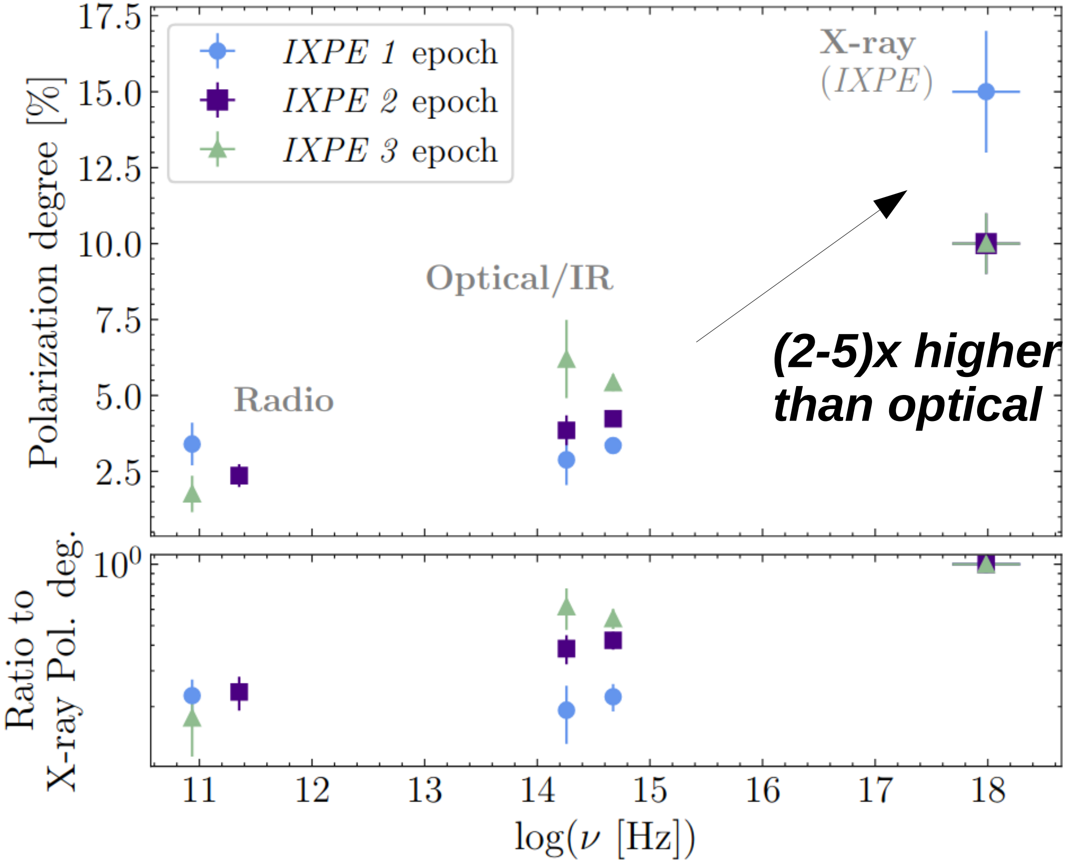
Jet axis

1) Polarization increases with energy
2) X-ray angle // optical+radio
3) Polarization slowly variable

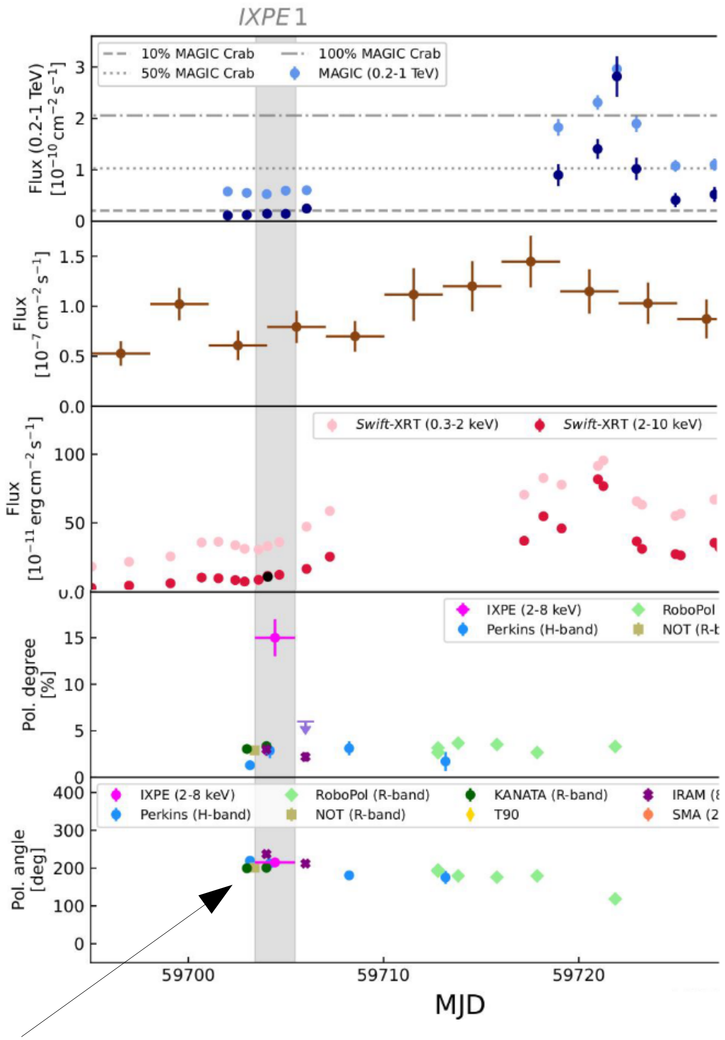
Blazars – from radio to TeV, including X-ray polarisation

Similar results for Mrk421 !

MAGIC Collab. et al., 2024, A&A, 684, A127
Di gesu et al, 2022, ApJL, 938, L7



(2-5)x higher than optical



MAGIC

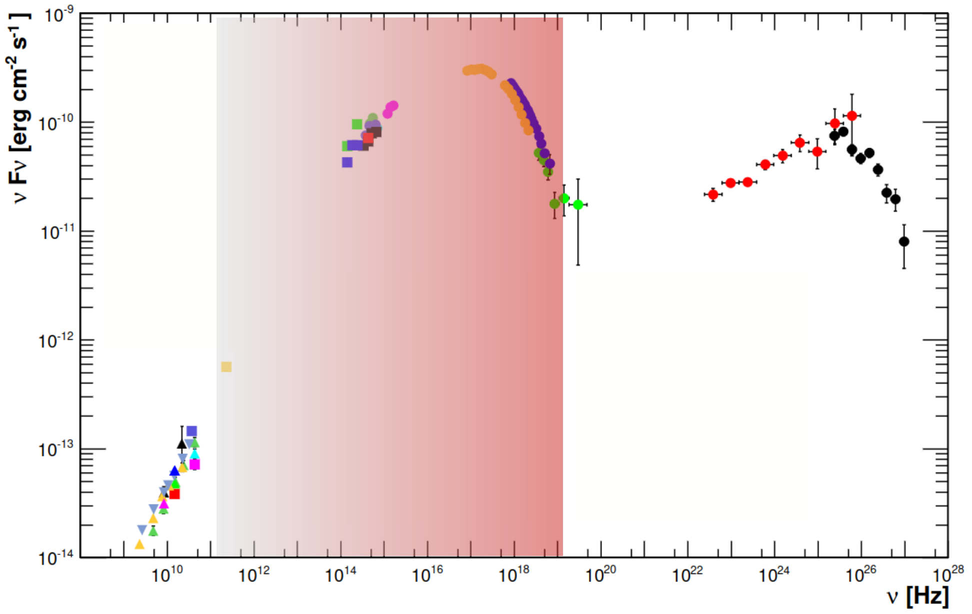
Fermi-LAT

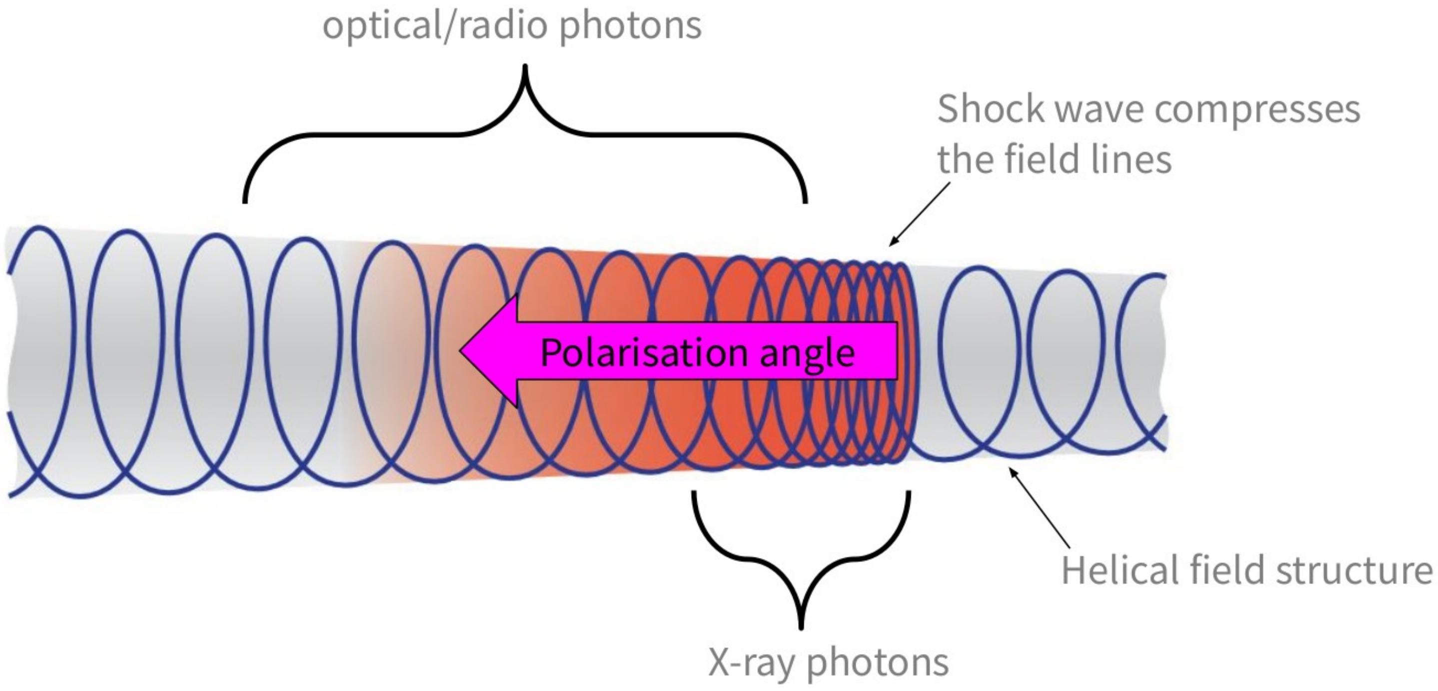
Swift-XRT

IXPE & optical+radio

X-ray angle // optical+radio

Blazars – from radio to TeV, including X-ray polarisation





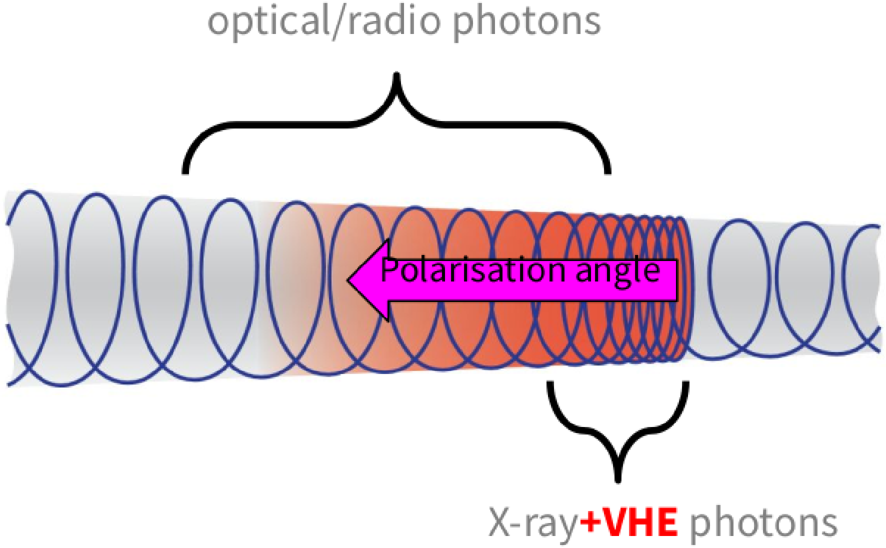
Electrons accelerated by a shock
→ *emission in "Energy stratified region"*

Blazars – from radio to TeV, including X-ray polarisation

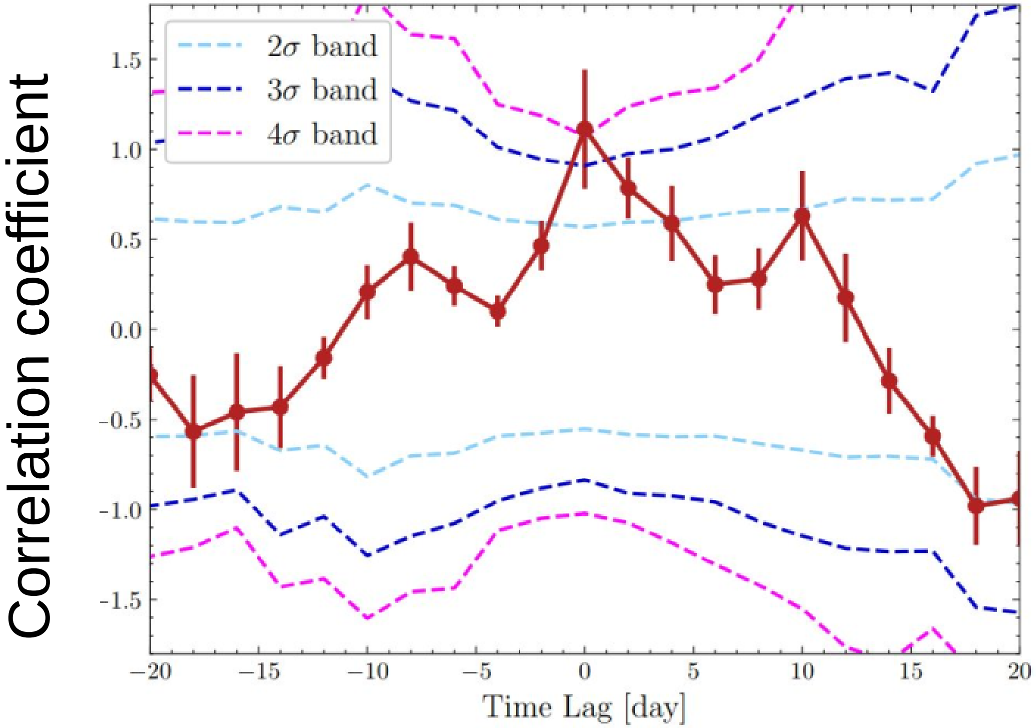
4σ VHE vs X-ray correlation,

No time lag

→ VHE photons emitted at the shock front

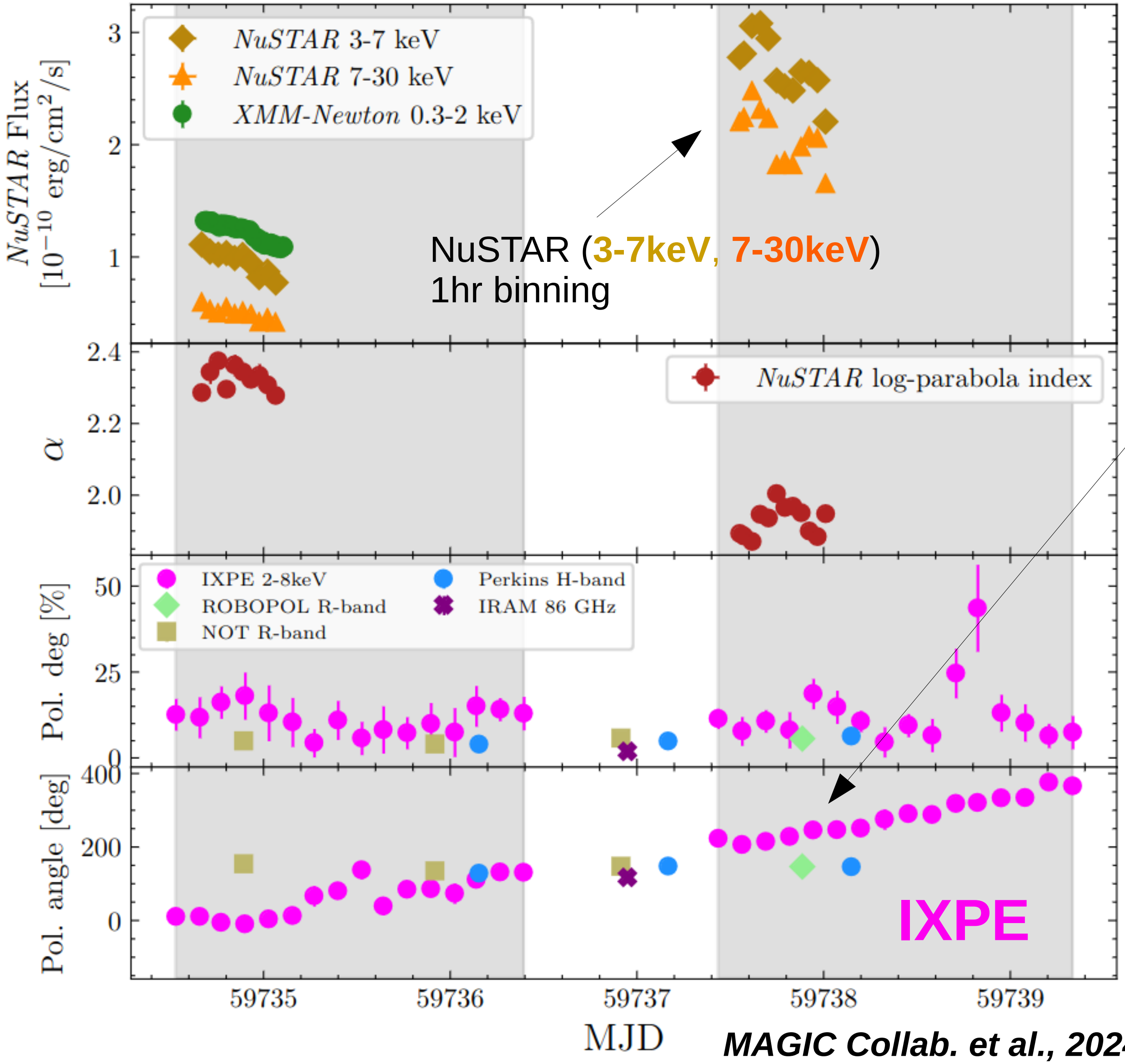


MAGIC Collab. et al., 2024, A&A, 684, A127



X-ray polarization angle rotation in Mrk421

June 5th '22 June 7th '22 June 9th '22

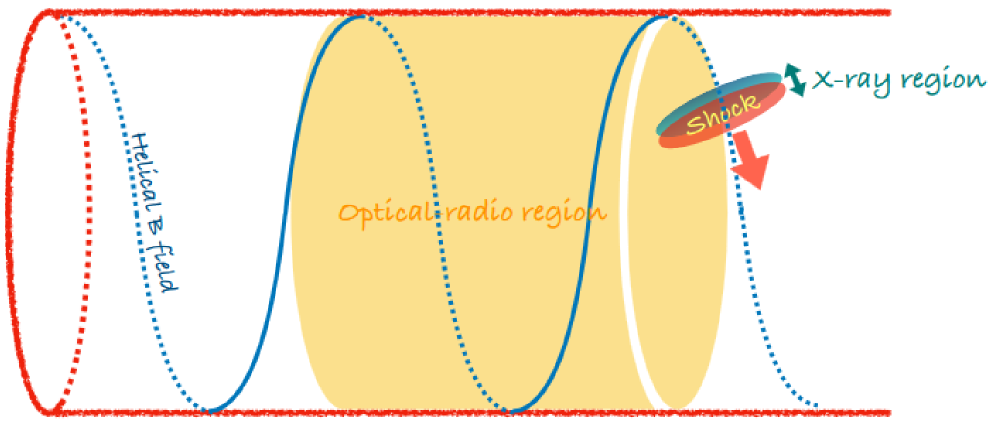


NuSTAR (3-7keV, 7-30keV)
1hr binning

IXPE

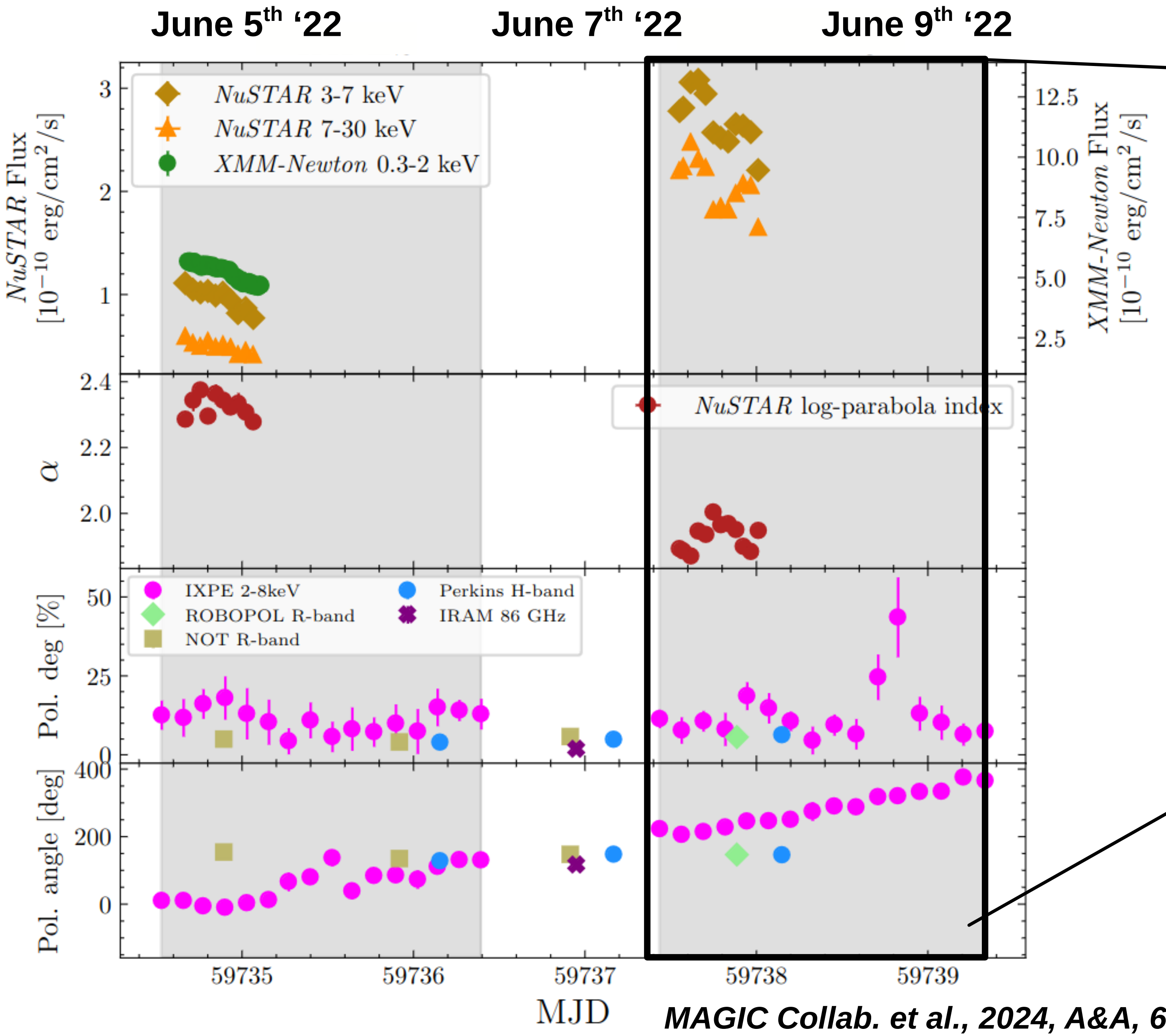
MAGIC Collab. et al., 2024, A&A, 684, A127

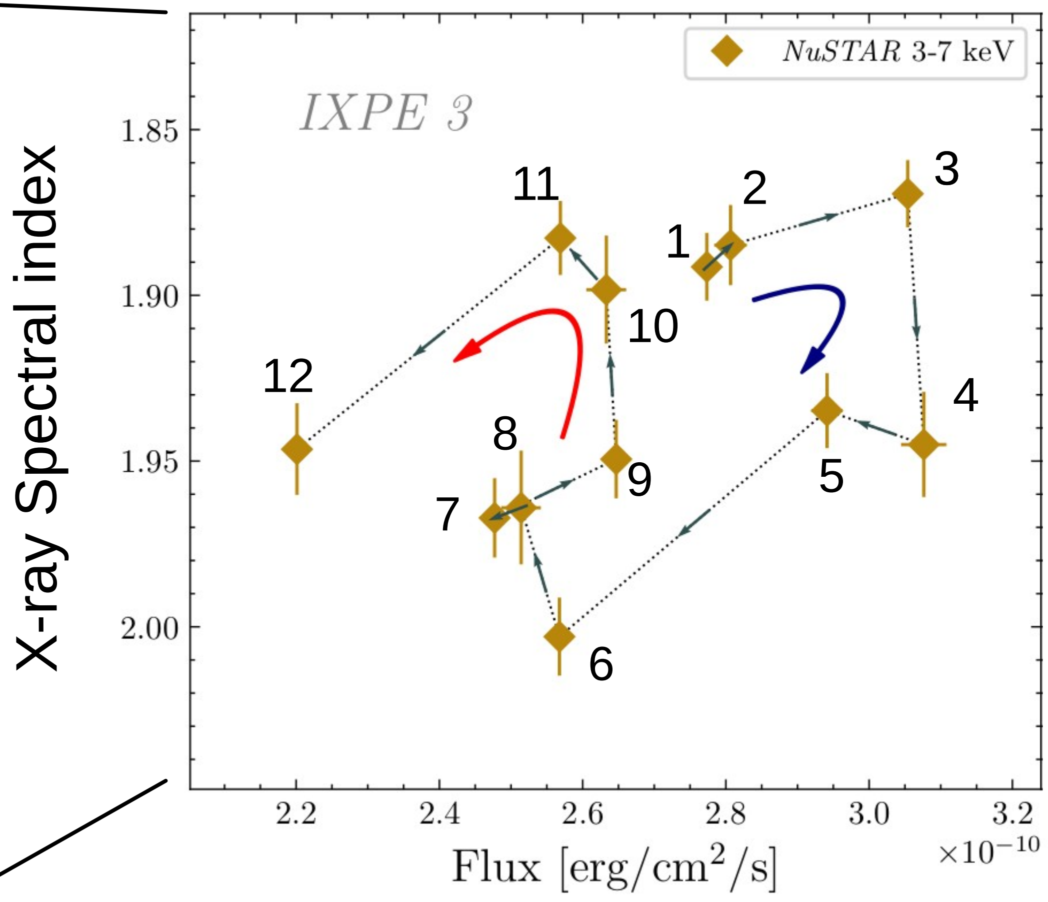
- **X-ray angle rotation in X-ray during June 2022**
- **X-ray emitting region rotating in jet ?**



Di Gesu L. et al., 2023, NatAs, 7, 1245

X-ray polarization angle rotation in Mrk421





→ Hysteresis loops **clock-wise** and **counter clock-wise** direction

MAGIC Collab. et al., 2024, A&A, 684, A127

X-ray polarization angle rotation in Mrk421

- **Clock-wise loop** *:*
  low-energy lags behind high-energy
  Suggests variability driven by synchrotron cooling
  (Kirk, et al. 1998)*:*

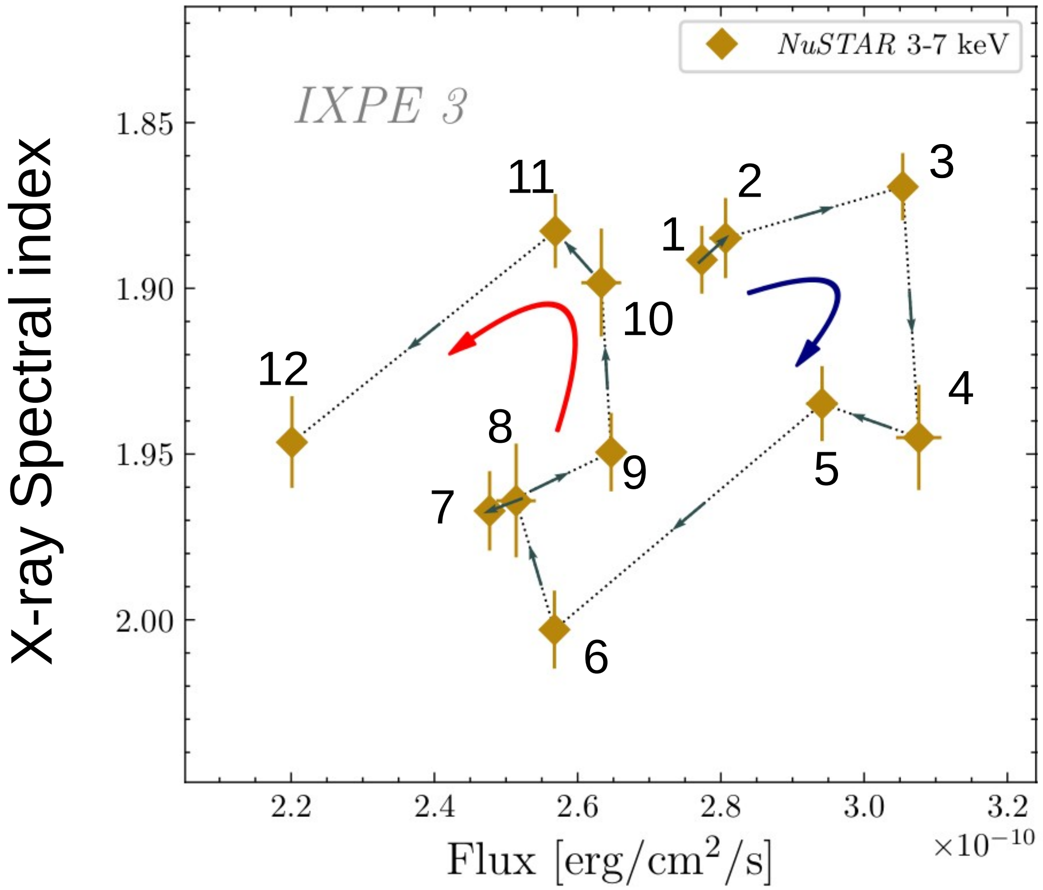
  $t_{acceleration} << t_{synch,cool}$

- **Counter clock-wise loop** *:*
  high-energy lags behind low-energy
  Suggests cooling and acceleration timescales ~similar
  (Kirk, et al. 1998)*:*

  $t_{acceleration} \sim t_{synch,cool}$

- *Contiguous clock-wise and counter clock-wise loops suggest* **decrease in shock acceleration efficiency during rotation**

MAGIC Collab. et al., 2024, A&A, 684, A127



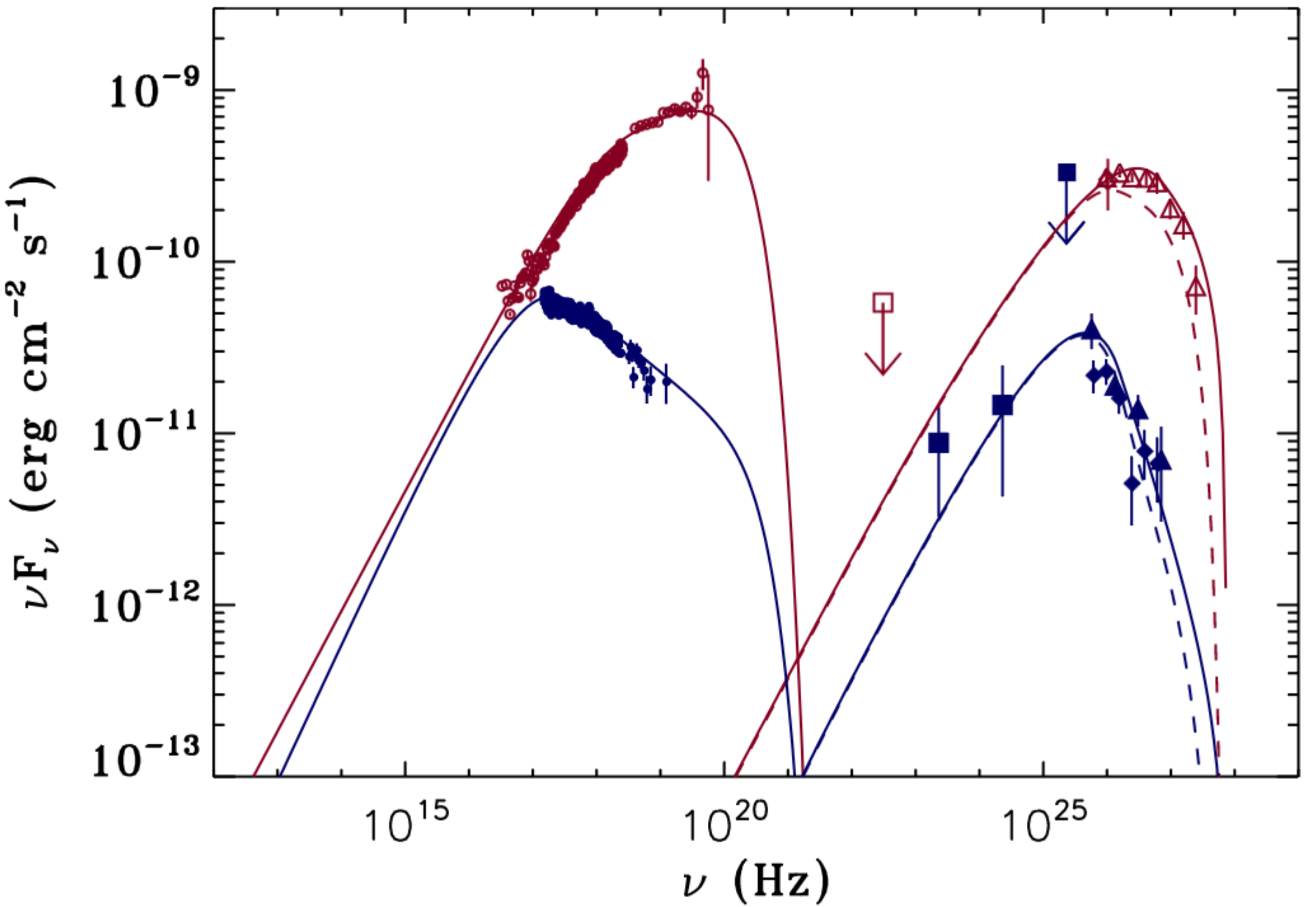
→ Hysteresis loops
clock-wise and **counter clock-wise** direction

X-ray polarization during blazar flares

IXPE only observed blazars in “quiescent” states (so far!)

Spectral hardening during flares imply particle (re)acceleration … but via which process?

IXPE is crucial to determine the origin of flares



Acciari et al. 2011
Pian et al. 1998

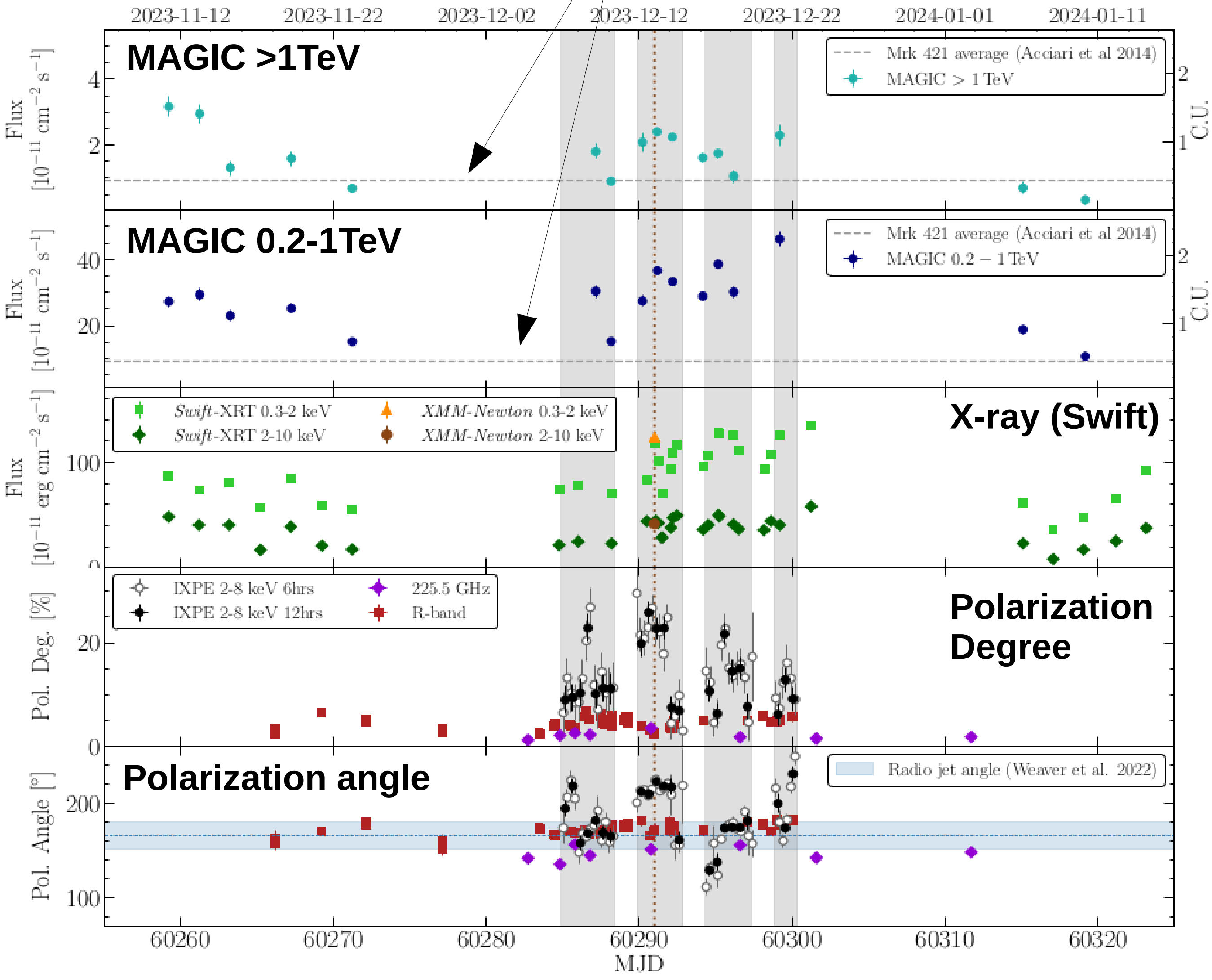
X-ray polarization during blazar flares

Flare of Mrk421 observed in **December 2023 with MAGIC & IXPE (and many other instruments)**

> 4 times the average flux at VHE

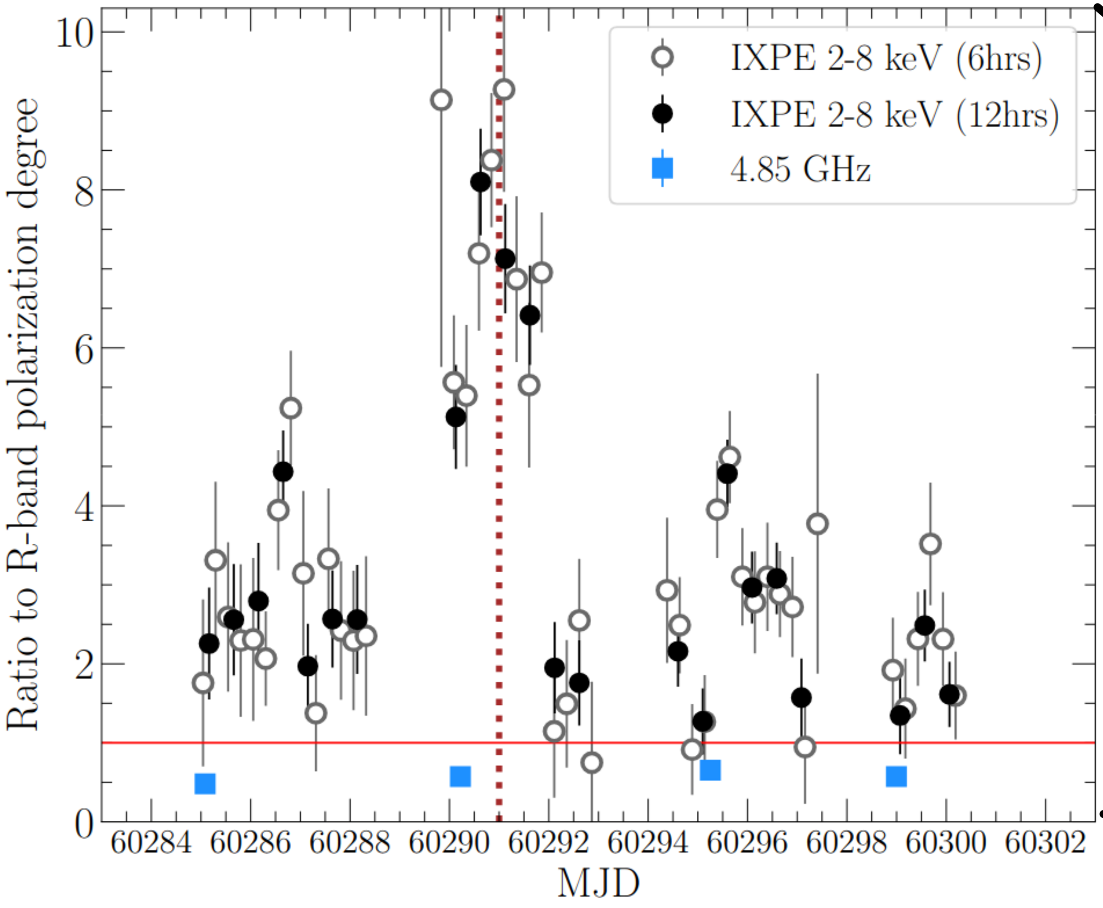
Significant X-ray polarisation variability during the flare!

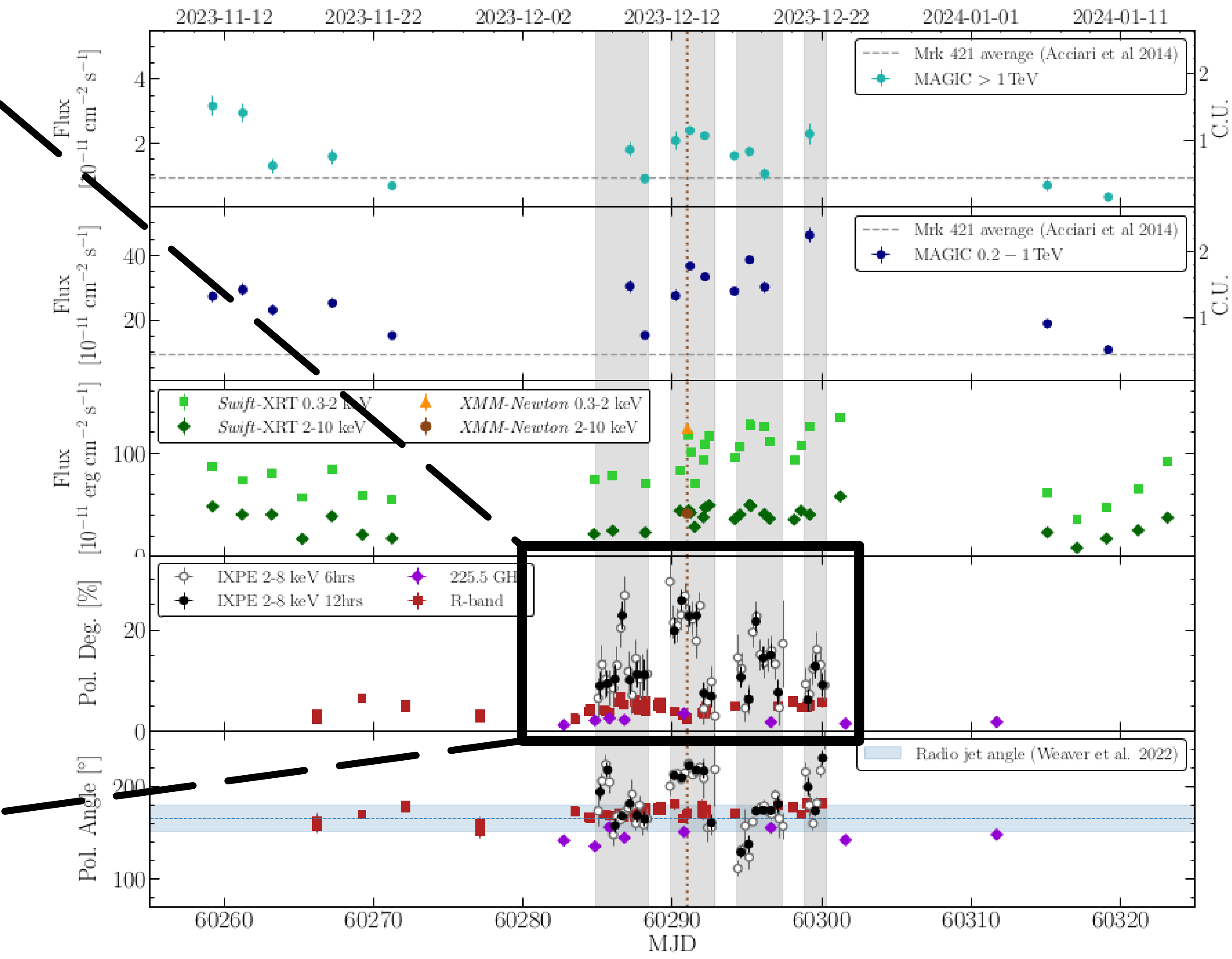
Average state at VHE



MAGIC Collab. et al., 2024, arXiv:2410.23140

X-ray polarization during blazar flares

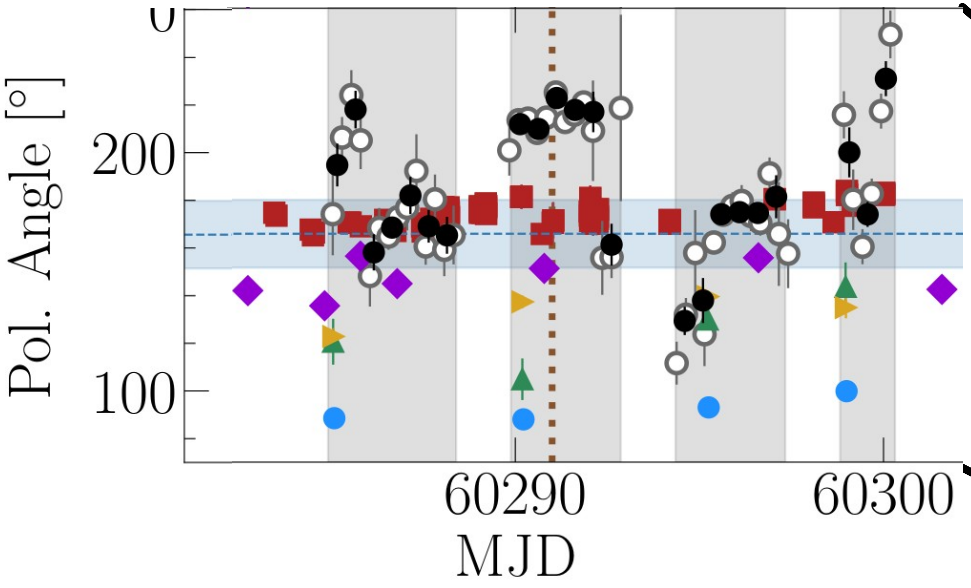




MAGIC Collab. et al., 2024, arXiv:2410.23140

Strong chromaticity:
$\mathrm{Pol}_{X\text{-}ray} \sim 10 \times \mathrm{Pol}_{visible}$

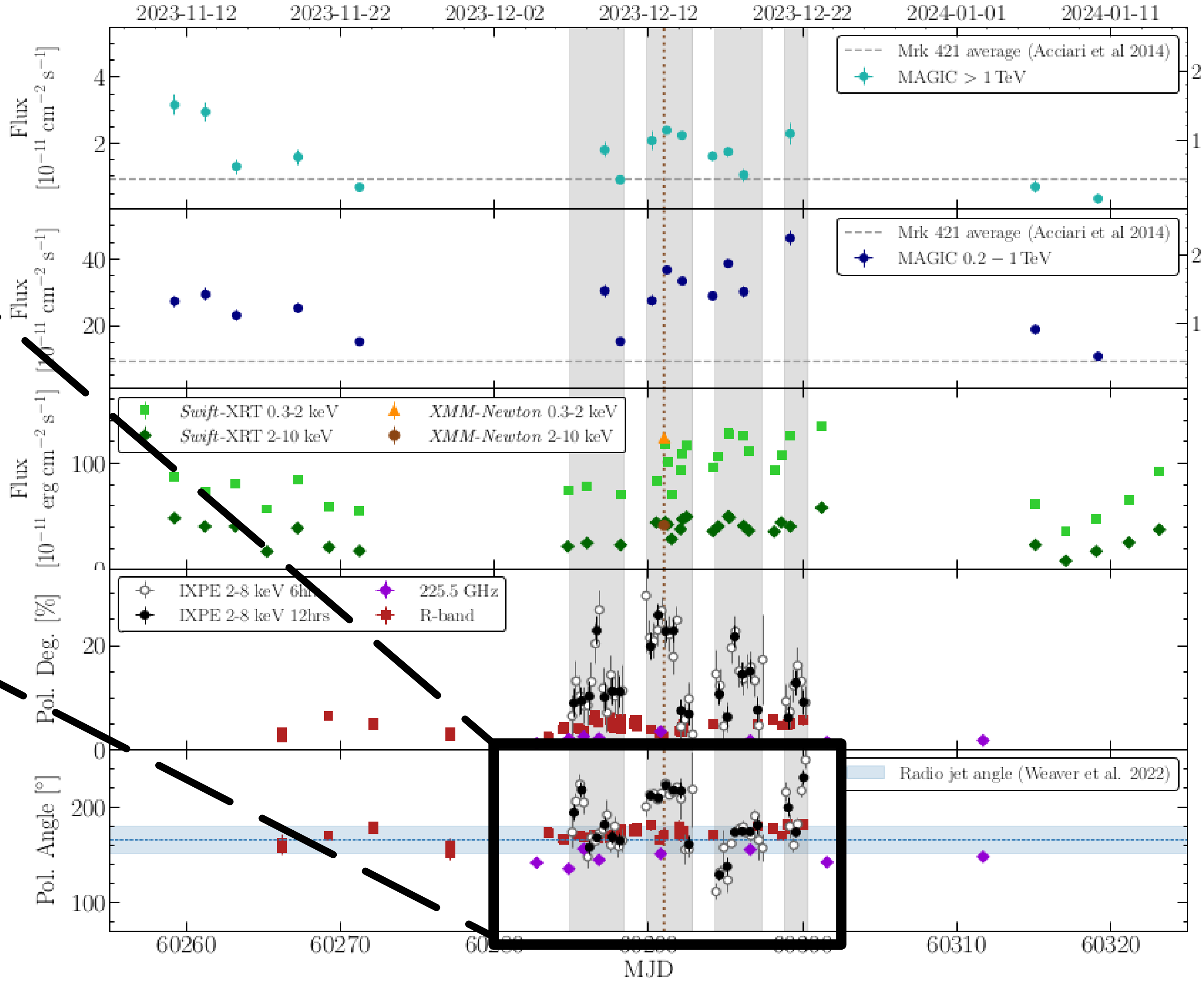
X-ray polarization during blazar flares



Erratic X-ray polarization angle variations (unlike rotation in 2022)

X-ray angle remains within 50deg from jet's axis and visible band

Average X-ray angle // visible band & jet's axis

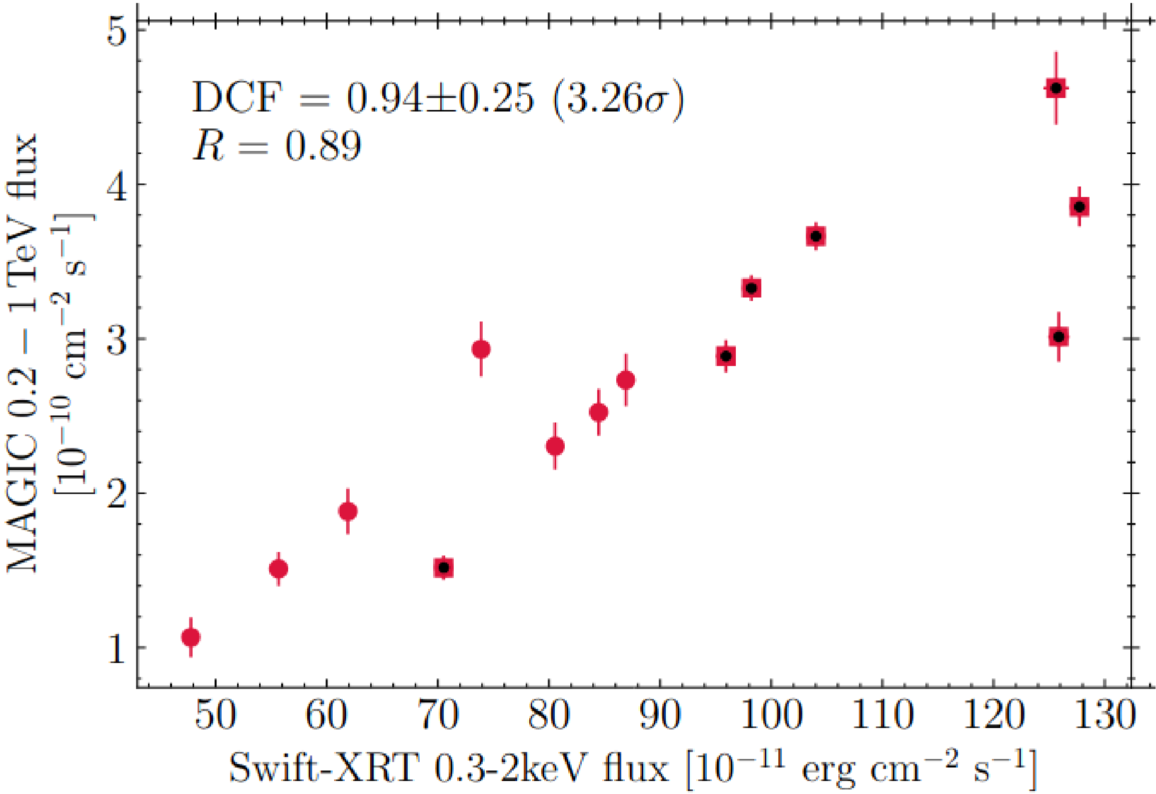


MAGIC Collab. et al., 2024, arXiv:2410.23140

X-ray polarization during blazar flares

X-ray vs VHE correlation

→ Co-spatial emission



Scatter in measurements

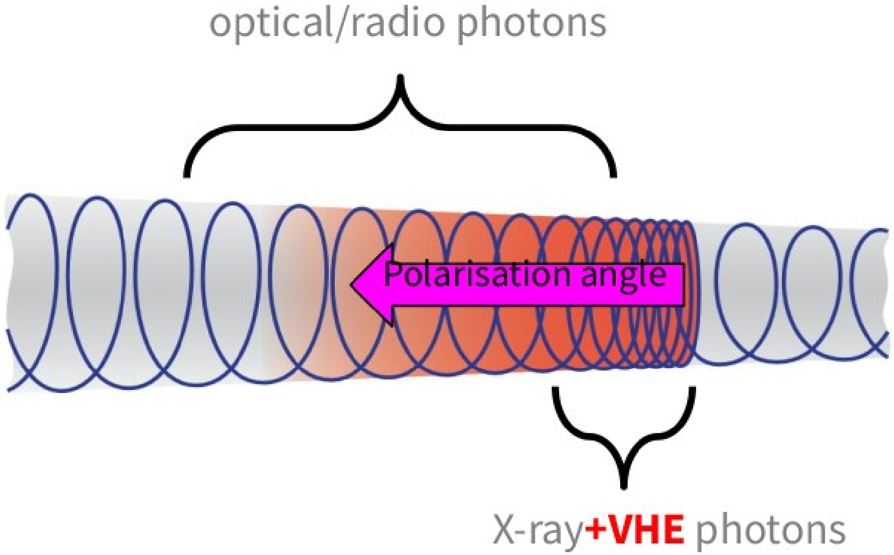
Suggests several source parameters varying simultaneously (magnetic field, particle density, radius)

MAGIC Collab. et al., 2024, arXiv:2410.23140

X-ray polarization during blazar flares

- **Average X-ray pol. angle // jet's axis**
  and
  Strong chromaticity of the polarisation degree

  → *tends to favor shock acceleration*



X-ray polarization during blazar flares

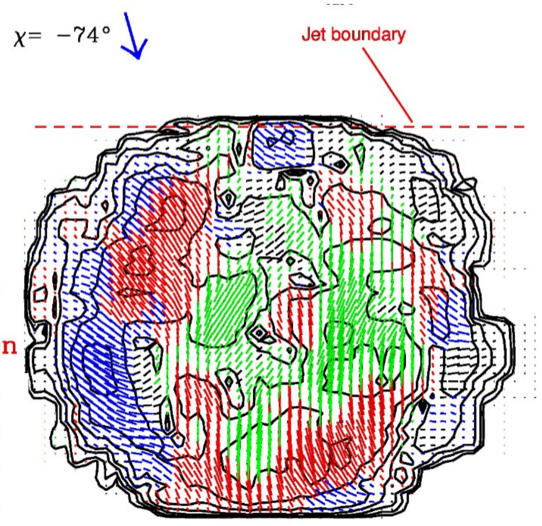
- **Average X-ray pol. angle // jet's axis**
  and
  Strong chromaticity of the polarisation degree

  → *tends to favor shock acceleration*

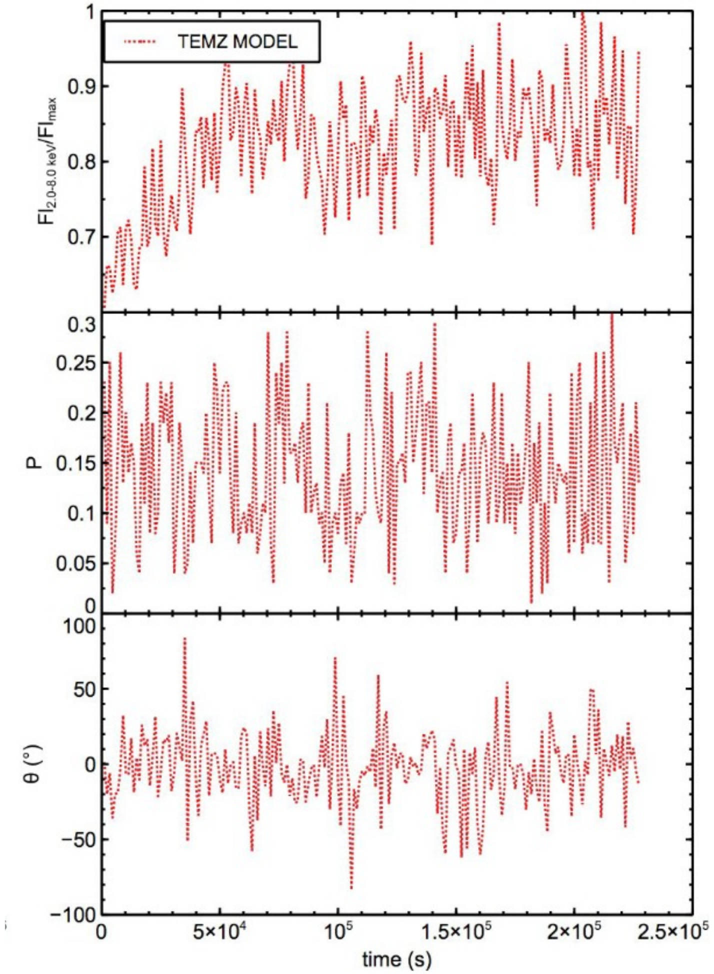
- **Polarization variability**

  → *magnetic turbulence*

  Plasma turbulent before crossing the shock?



Marscher et al. 2014



Di Gesu et al. 2022

X-ray polarization during blazar flares

- **Average X-ray pol. angle // jet's axis**
  and
  Strong chromaticity of the polarisation degree

  → *tends to favor shock acceleration*

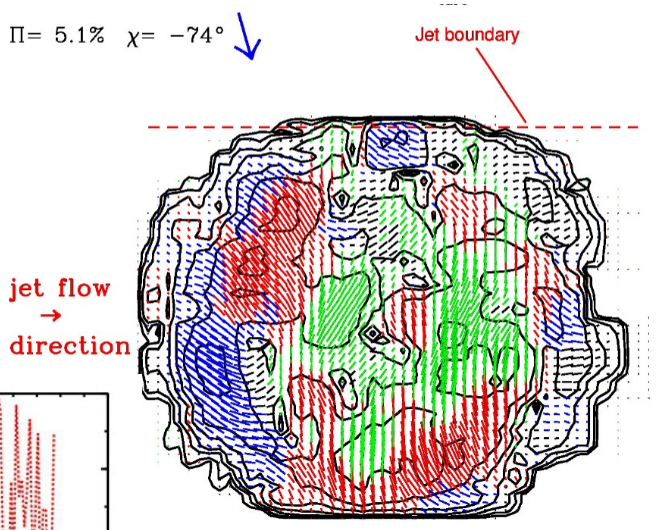
- **Polarization variability**

  → *magnetic turbulence*

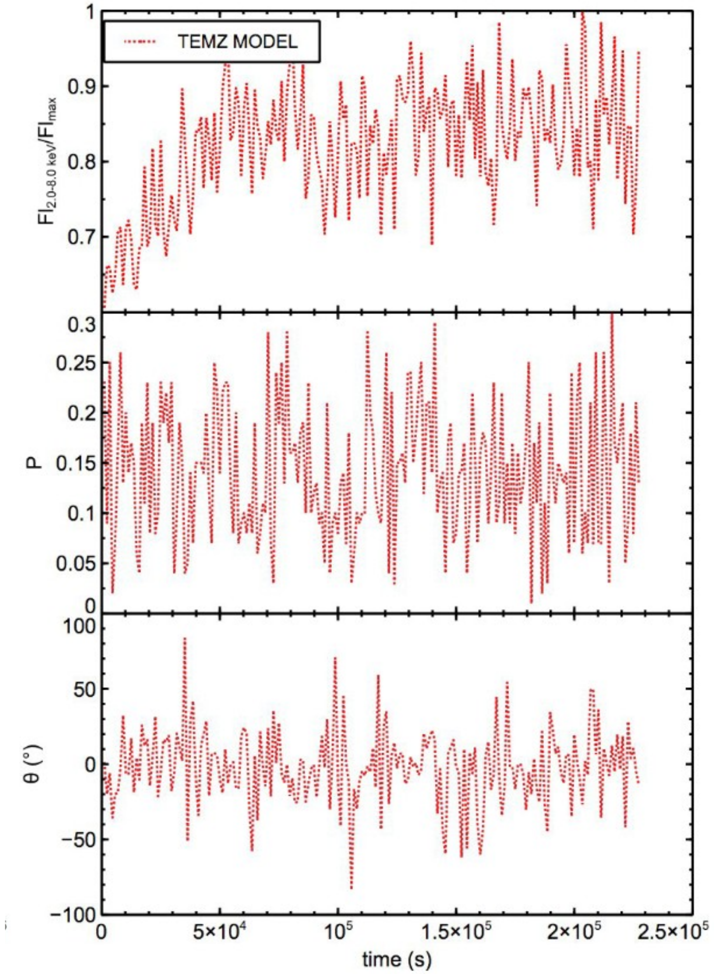
  Plasma turbulent before crossing the shock?

  Magnetic reconnection not fully ruled out, yet

  (more simulations and observations are needed)



Marscher et al. 2014



Di Gesu et al. 2022

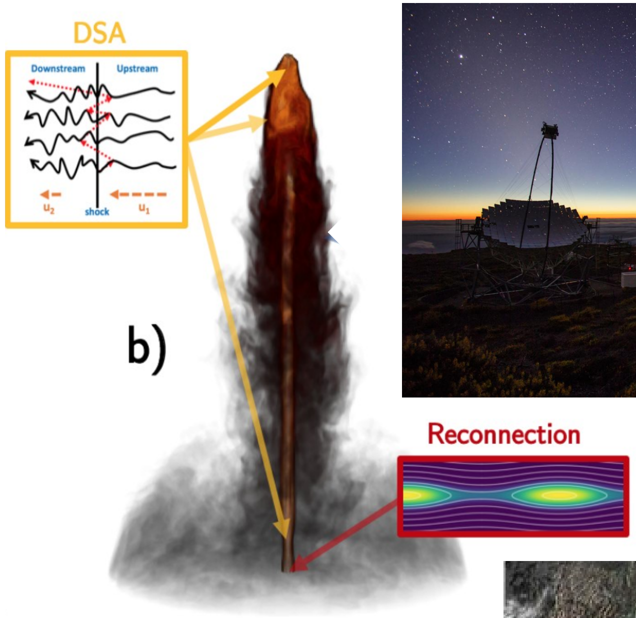
Conclusions

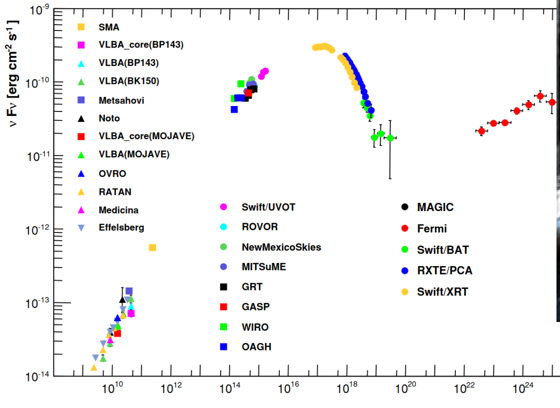
- **Blazars as tools to study cosmic accelerators**
  → Bright sources such as Mrk421/Mrk501
  are ideal sources to probe the particle dynamics

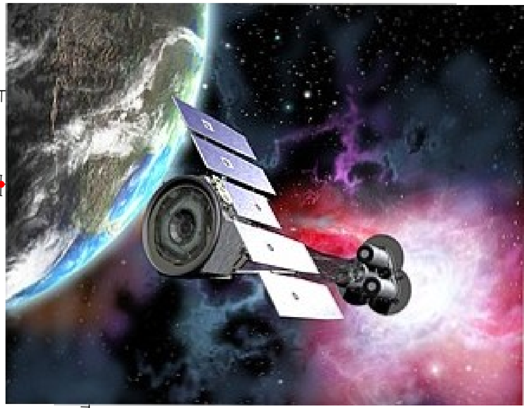
- **Complex variability behaviours**
  → *revealed thanks to dense MWL campaigns*

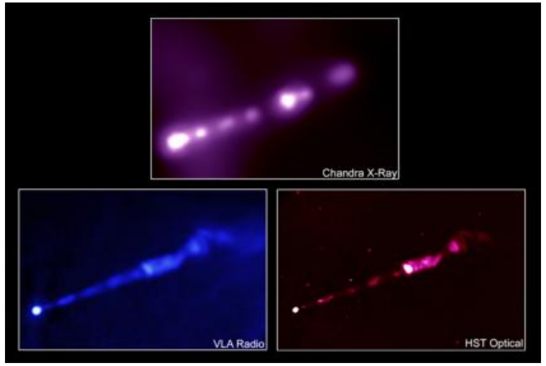
- **New window recently opened with X-ray polarization**
  → *suggest shock acceleration, turbulences possibly play important roles during flares*
  → ***We are only scratching the surface!***
  Further observations/simulations crucial

- **Increase effort to fit data with time-dependent model**
  → *complementary step to make progress particle acceleration in jets*
  → *data are bright blazars are optimal targets for this*







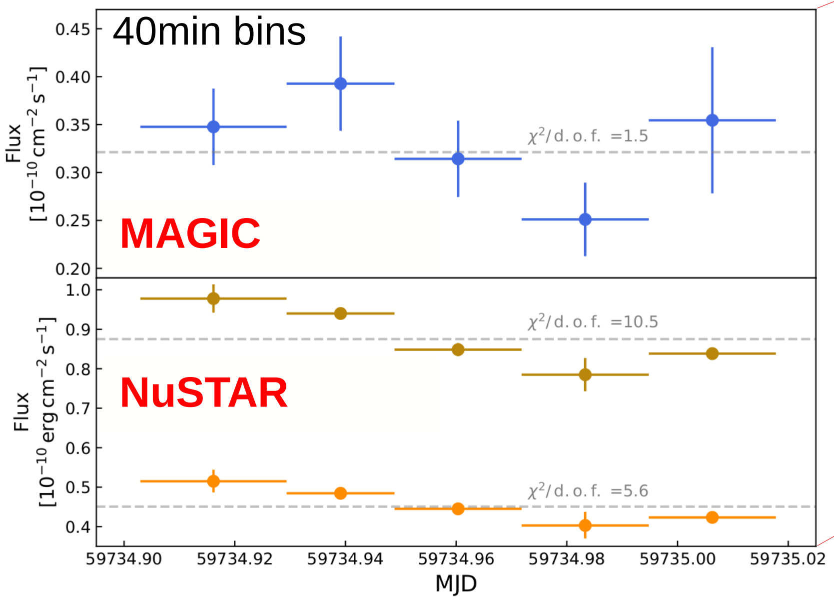


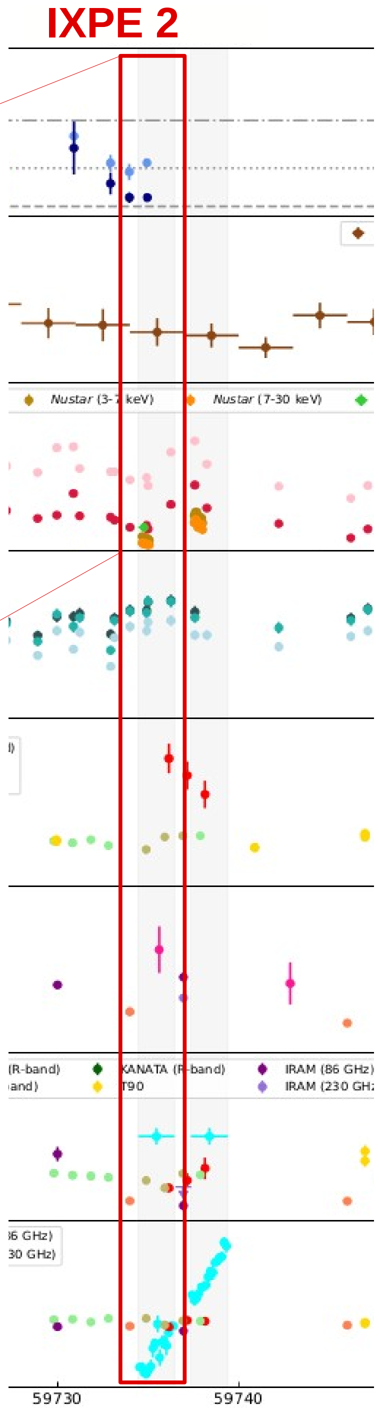
Thank you!

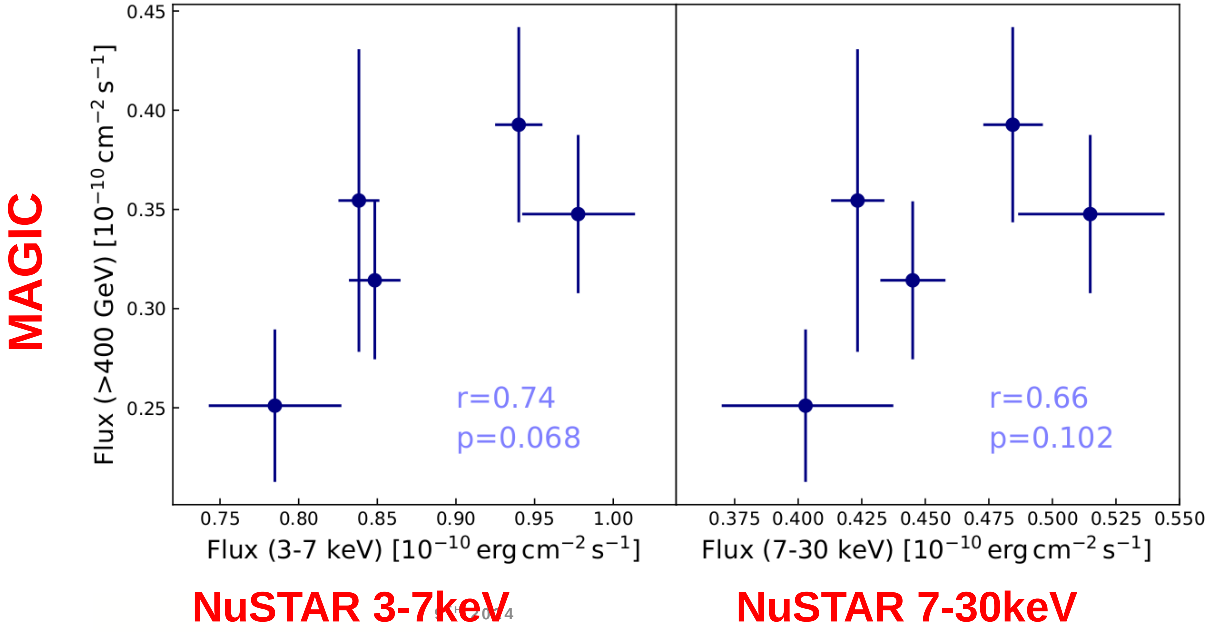
Back-up slides

VHE versus X-ray Correlation

In ***IXPE 2 epoch****, start of rotation,*
→ ~ 2σ VHE/X-ray correlation
using MAGIC/NuSTAR



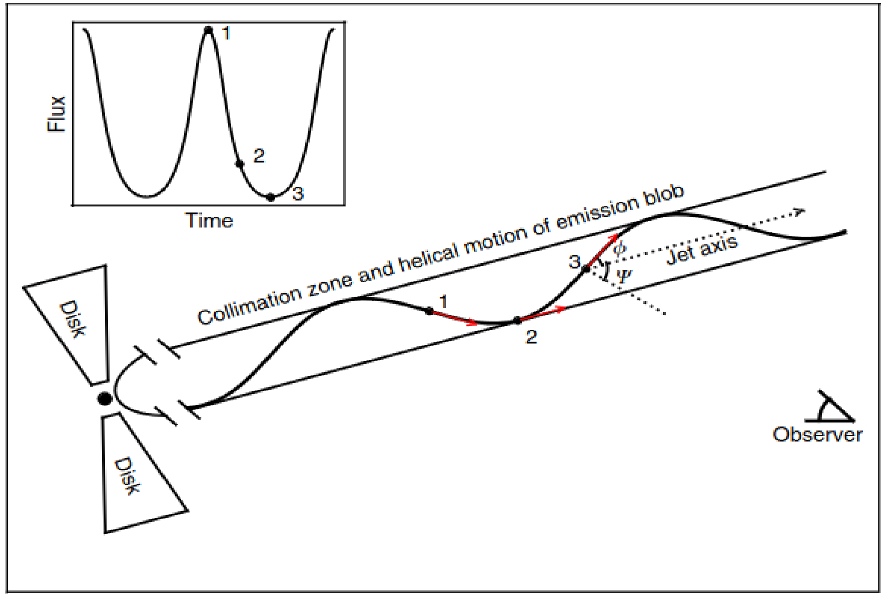




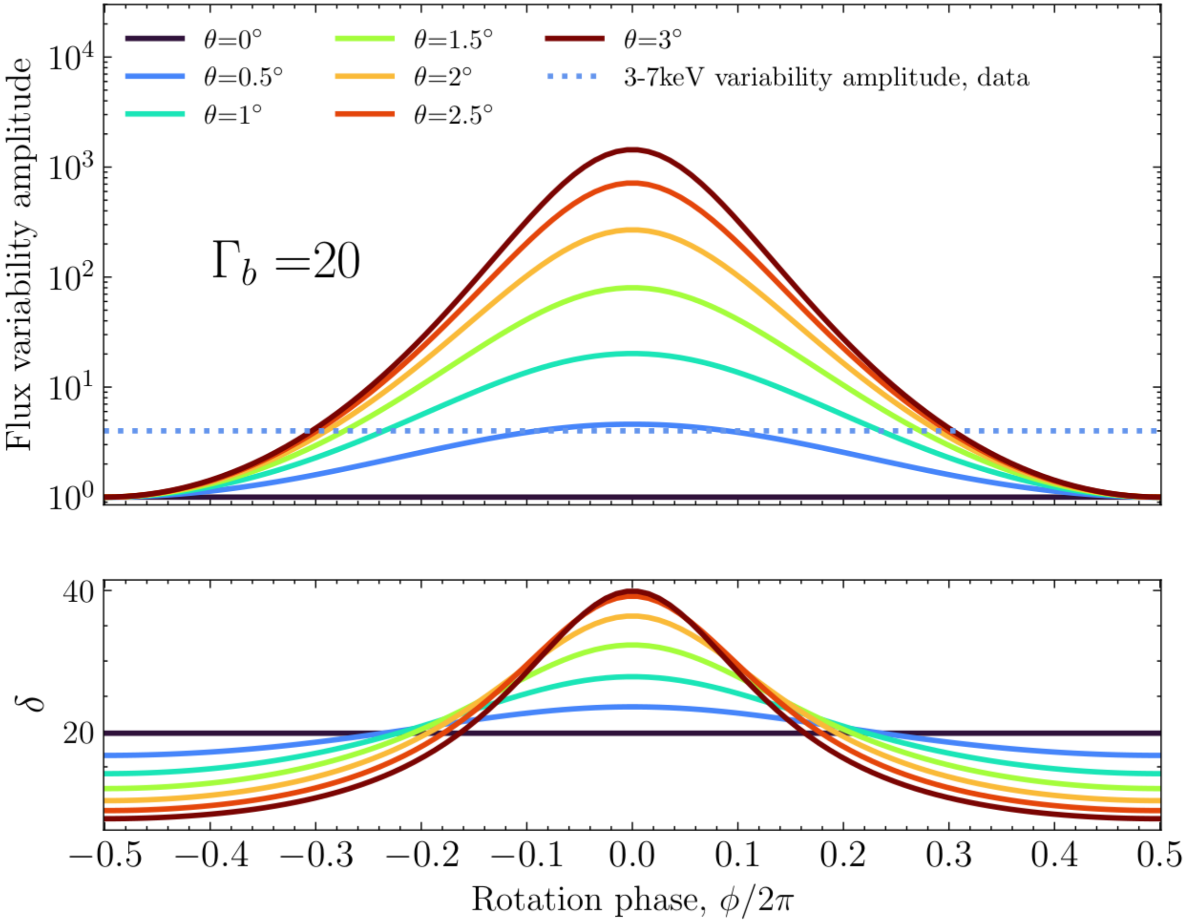
X-ray variability during polarization angle rotation

- *Pol. angle rotation due to blob moving in a helical path?*
  → Change of doppler factor δ
  → Expect strong flux modulation, F_obs $\propto \delta^{3}$ F_intrinsic
  does this contradicts observations?

- *Assuming* **bulk Lorentz factor ~ 20** *&*
  jet viewing angle of ~0.5deg
  → Expected variability solely caused by δ evolution
  in agreement with NuSTAR variability

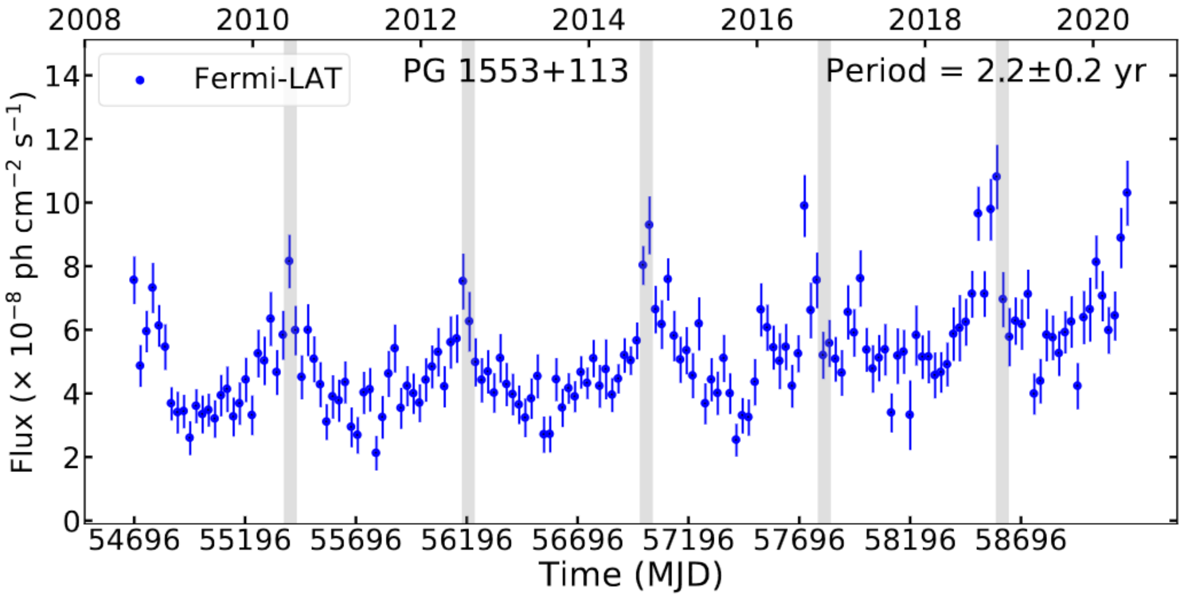


Sketch credits: Zhou et al. 2018

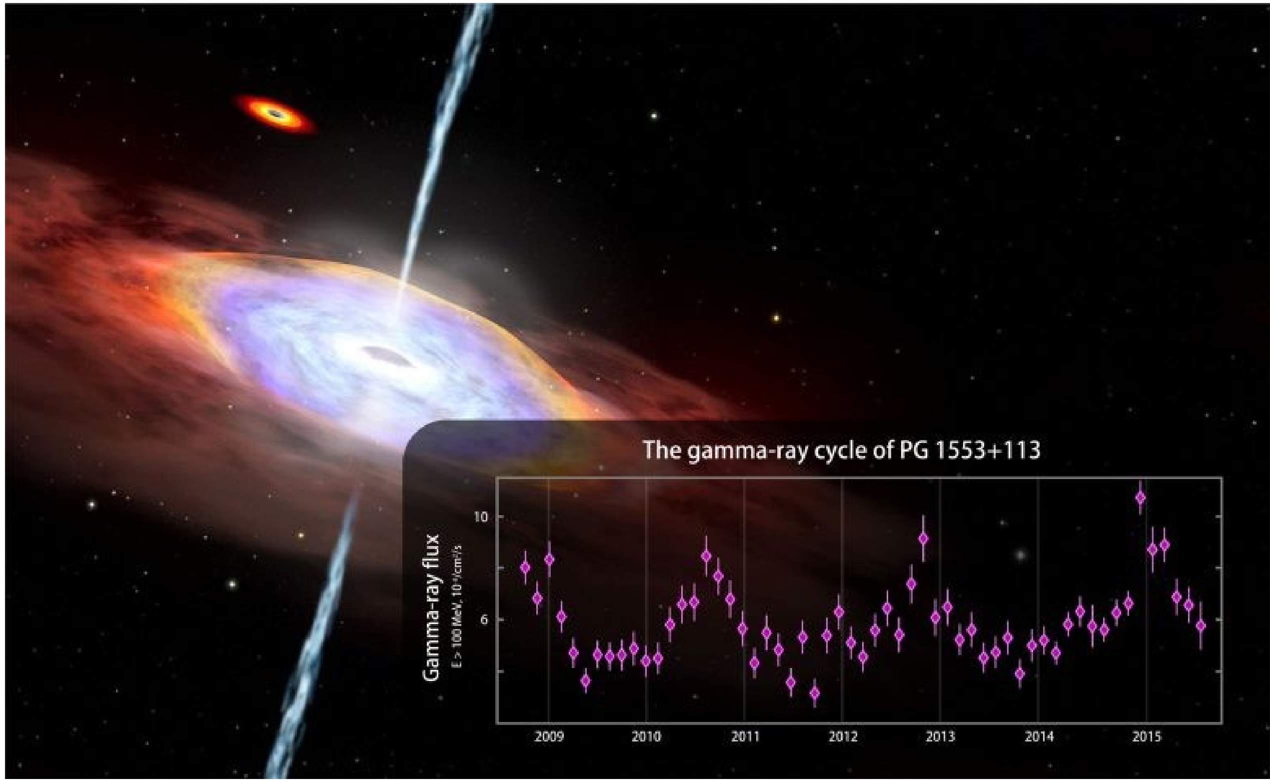


Other targets monitored by MAGIC: The “periodic” blazar PG1553+113

- Periodic flux variation, period: ~ 2 yrs



Penil et al., 2022, arXiv, arXiv:2211.01894.

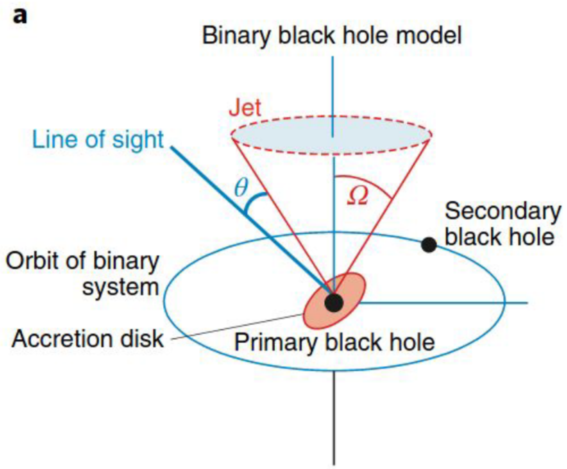


Ackermann et al 2015 ApJL 813 L41

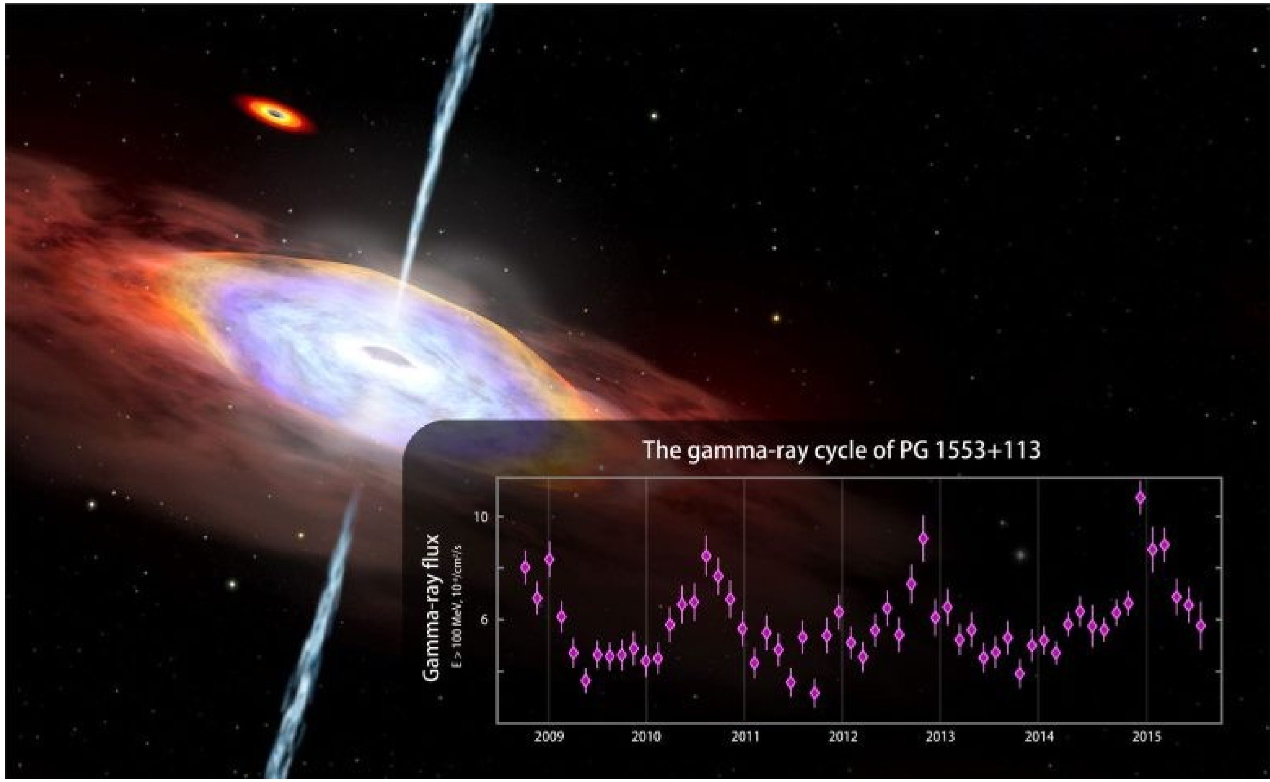
Other targets monitored by MAGIC:
The “periodic” blazar PG1553+113

- Periodic flux variation in gamma rays,
  → period: ~ 2 yrs

Jet precession?



Caproni+2017, Abraham 2018



Ackermann et al 2015 ApJL 813 L41

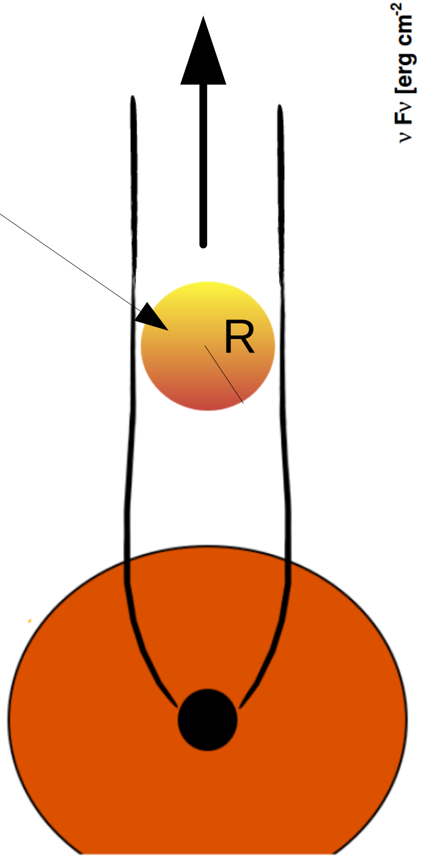
Modelling blazar SED – simplest & most common approach

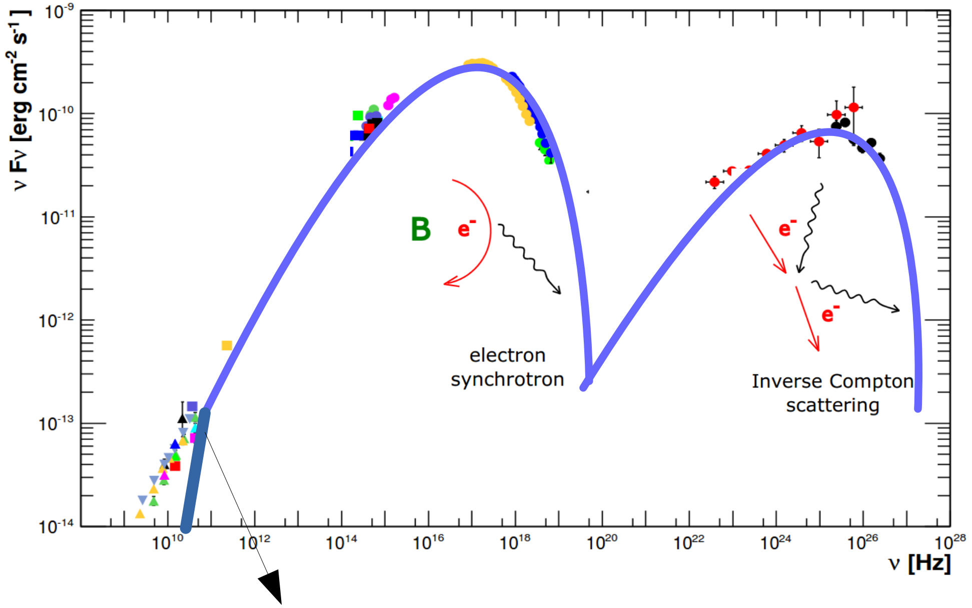
<u>“Inject” $e^{+/-}$ distribution</u>
Power law (4 parameters)
Broken power law (6 parameters)

<u>Other parameters:</u>
Doppler (~10-50),
B (~0.1-0.01 G),
R (~1e15-1e17 cm)

→ 7-9 free parameters

Doppler factor
$f(\Theta , \Gamma_b)$





Synchrotron
self-absorption

Sketch credits: F. Tavecchio

Modelling blazar SED – simplest & most common approach

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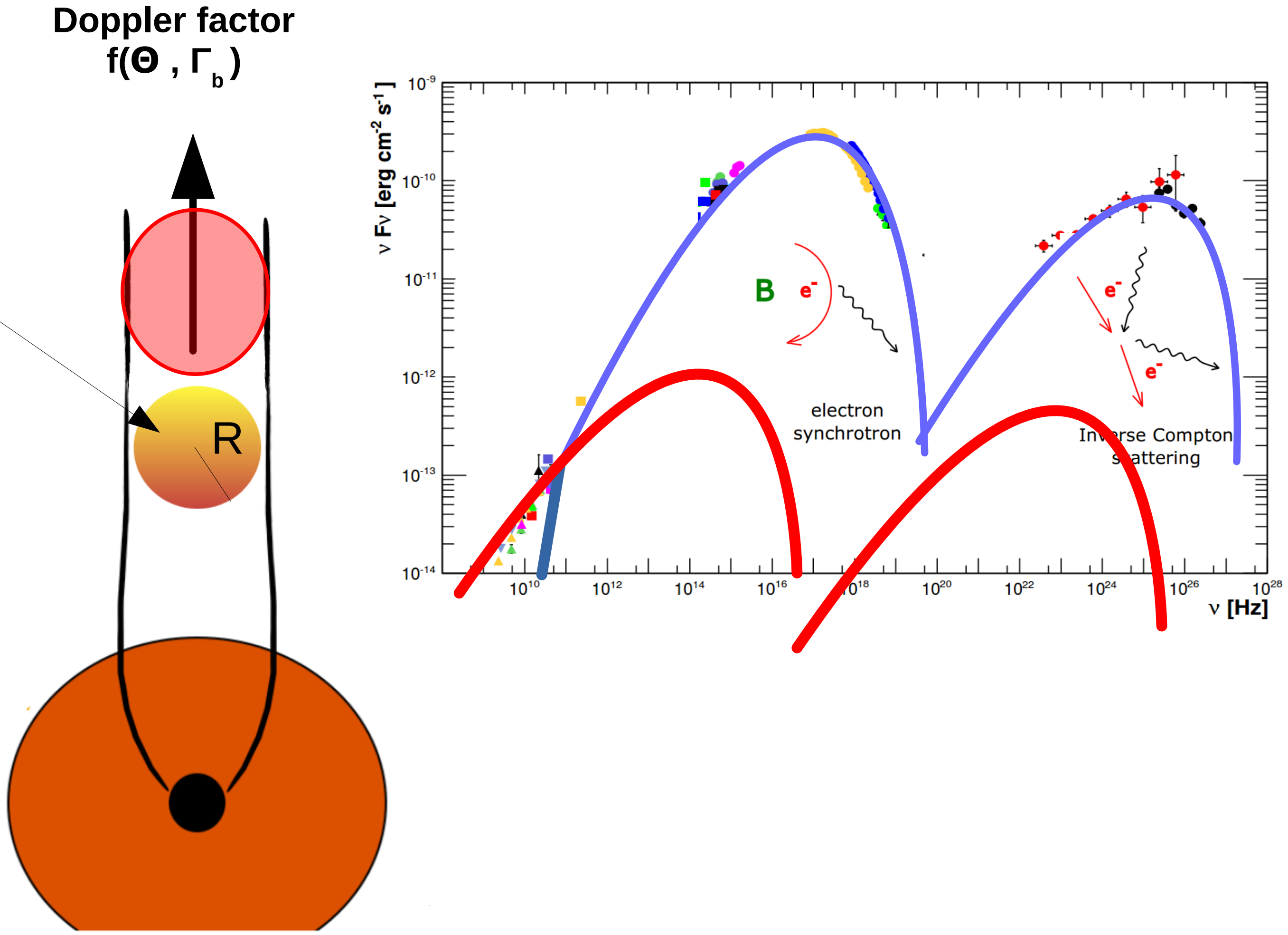
Broken power law (6 parameters)

<u>Other parameters:</u>
Doppler (~10-50),
B (~0.1-0.01 G),
R (~1e15-1e17 cm)

→ 7-9 free parameters

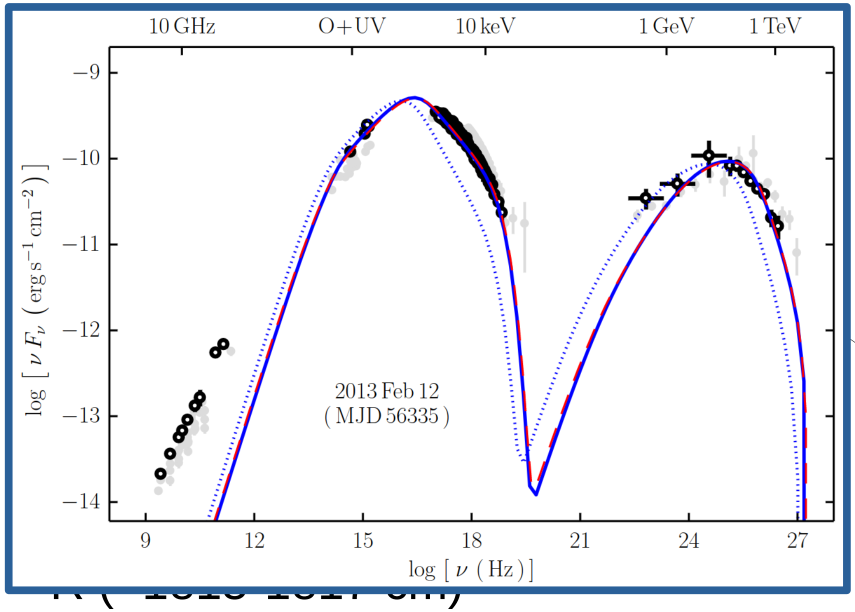
2nd zone often needed to model radio:

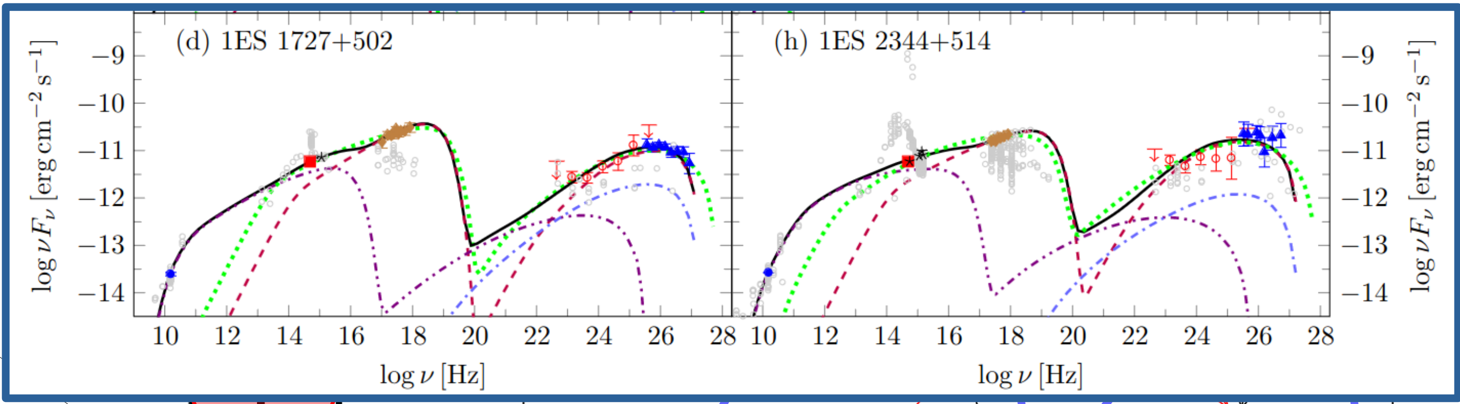
→ ~14-18 free parameters

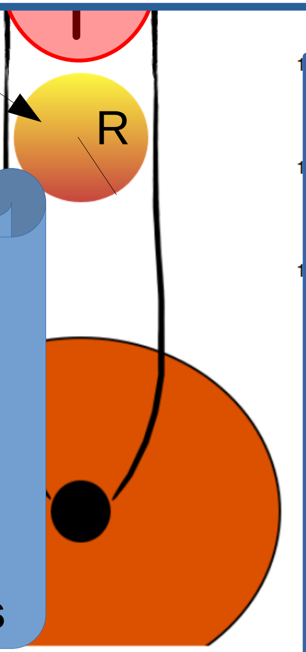


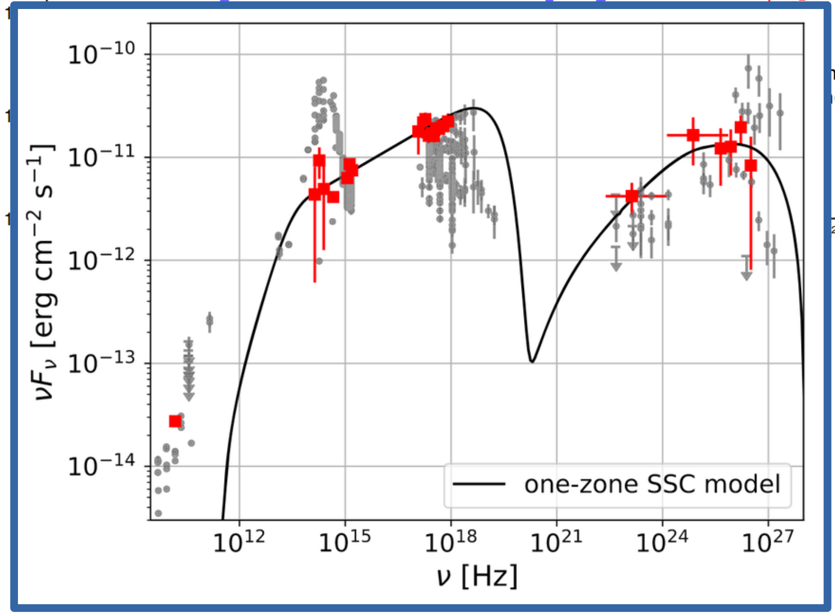
Sketch credits: F. Tavecchio

Modelling blazar SED – simplest & most common approach









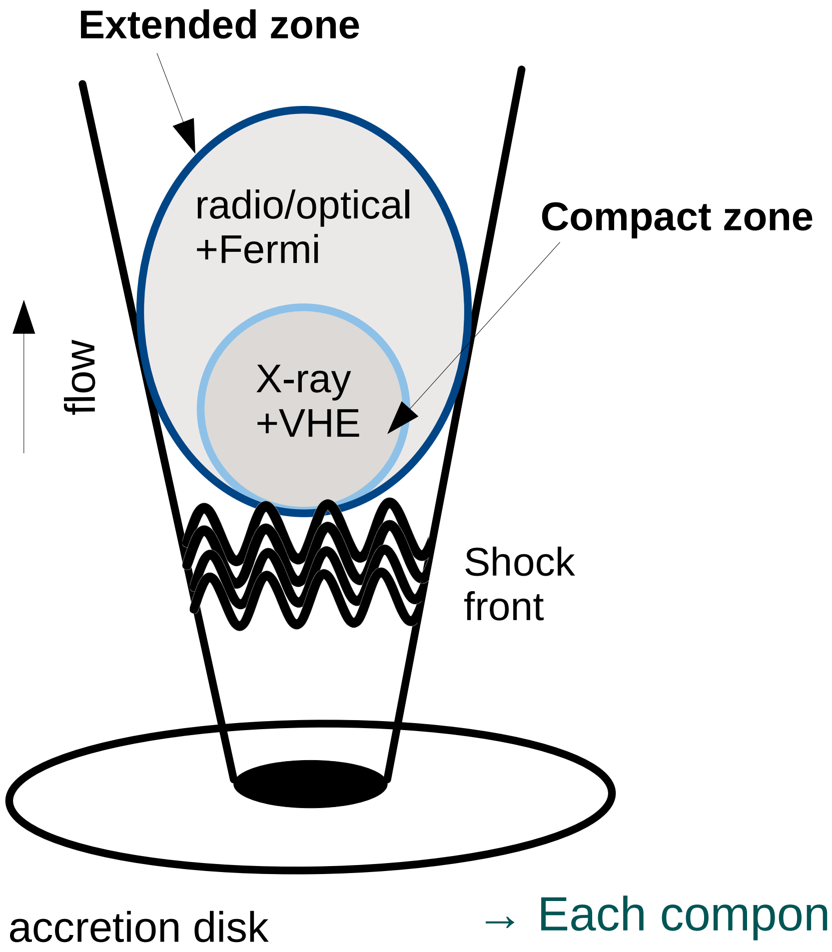
Describes the SED well

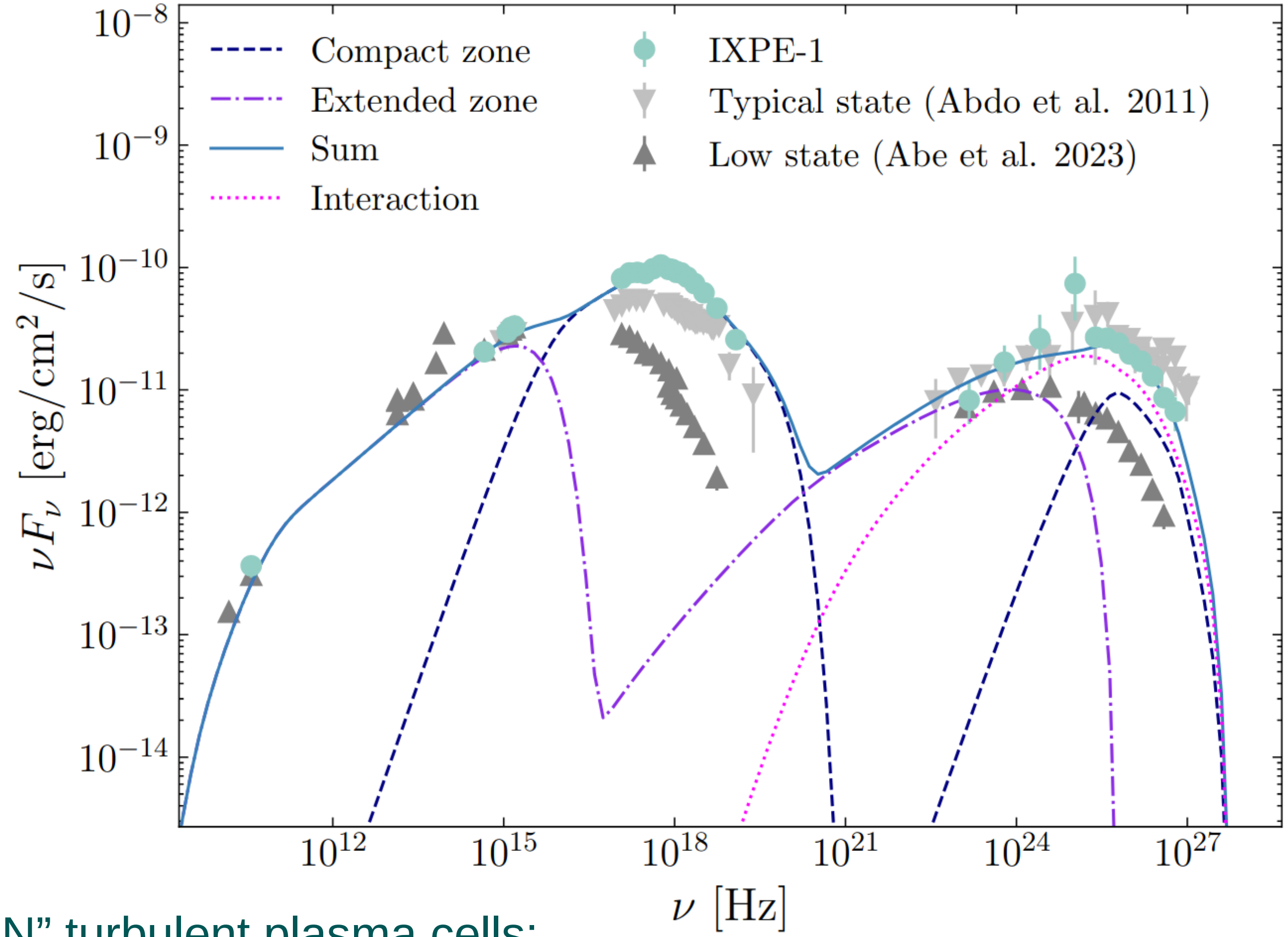
But… so far modelling is *very often* **time independent**…

Now have sufficiently constraining datasets to explore time dependent models

Sketch credits: F. Tavecchio

Modelling of Mrk501 with polarization constraints

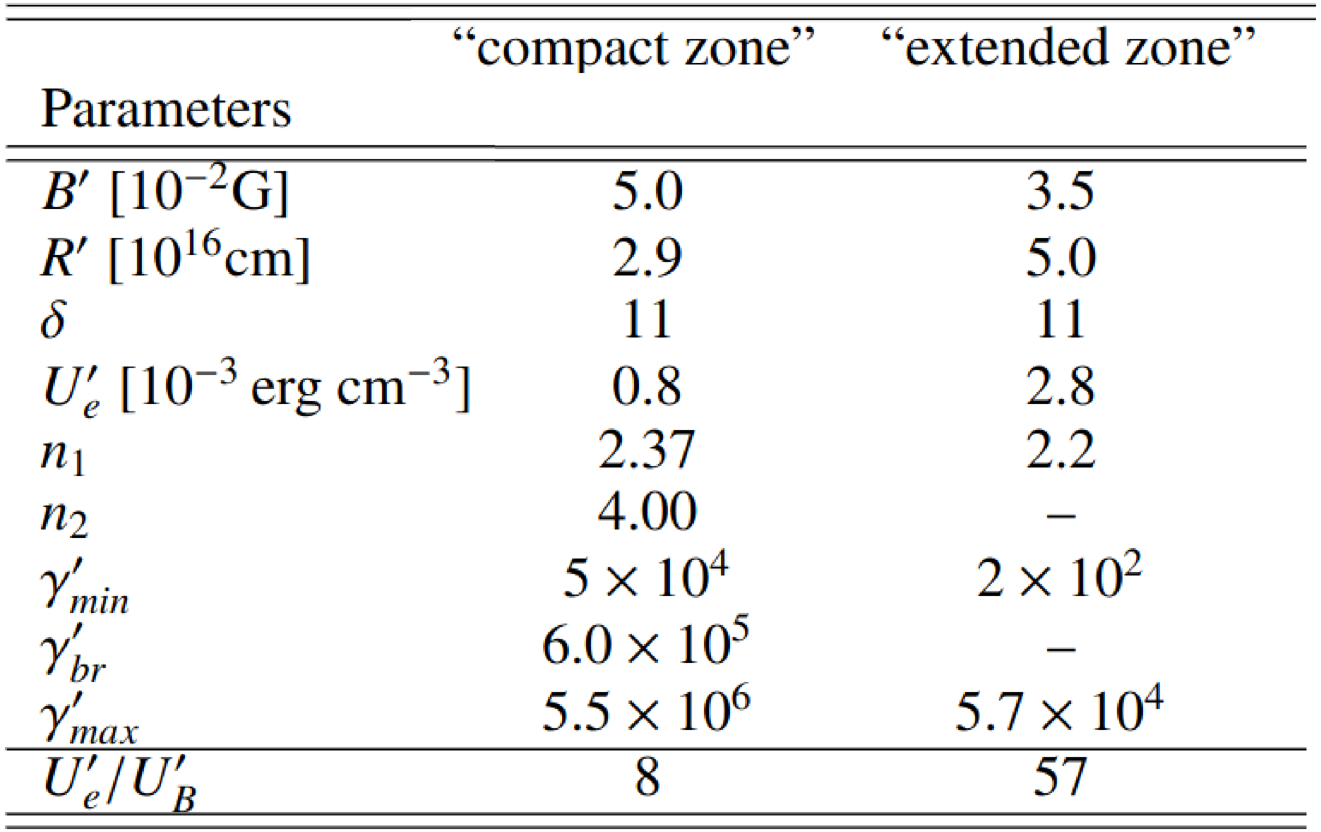




→ Each component made of “N” turbulent plasma cells: $\langle P_{deg} \rangle \sim 70\% * N^{-0.5}$ (see e.g. Marscher et al. 2014)

→ Relative size tuned to match observed optical/X-ray polarization

Modelling parameters



Parameters	"compact zone"	"extended zone"
B' [10^{-2}G]	5.0	3.5
R' [10^{16}cm]	2.9	5.0
δ	11	11
U'_e [10^{-3} erg cm^{-3}]	0.8	2.8
n_1	2.37	2.2
n_2	4.00	–
γ'_{min}	5×10^4	2×10^2
γ'_{br}	6.0×10^5	–
γ'_{max}	5.5×10^6	5.7×10^4
U'_e/U'_B	8	57