The multi-wavelength signature of the multi-zone jets of Markarian 421

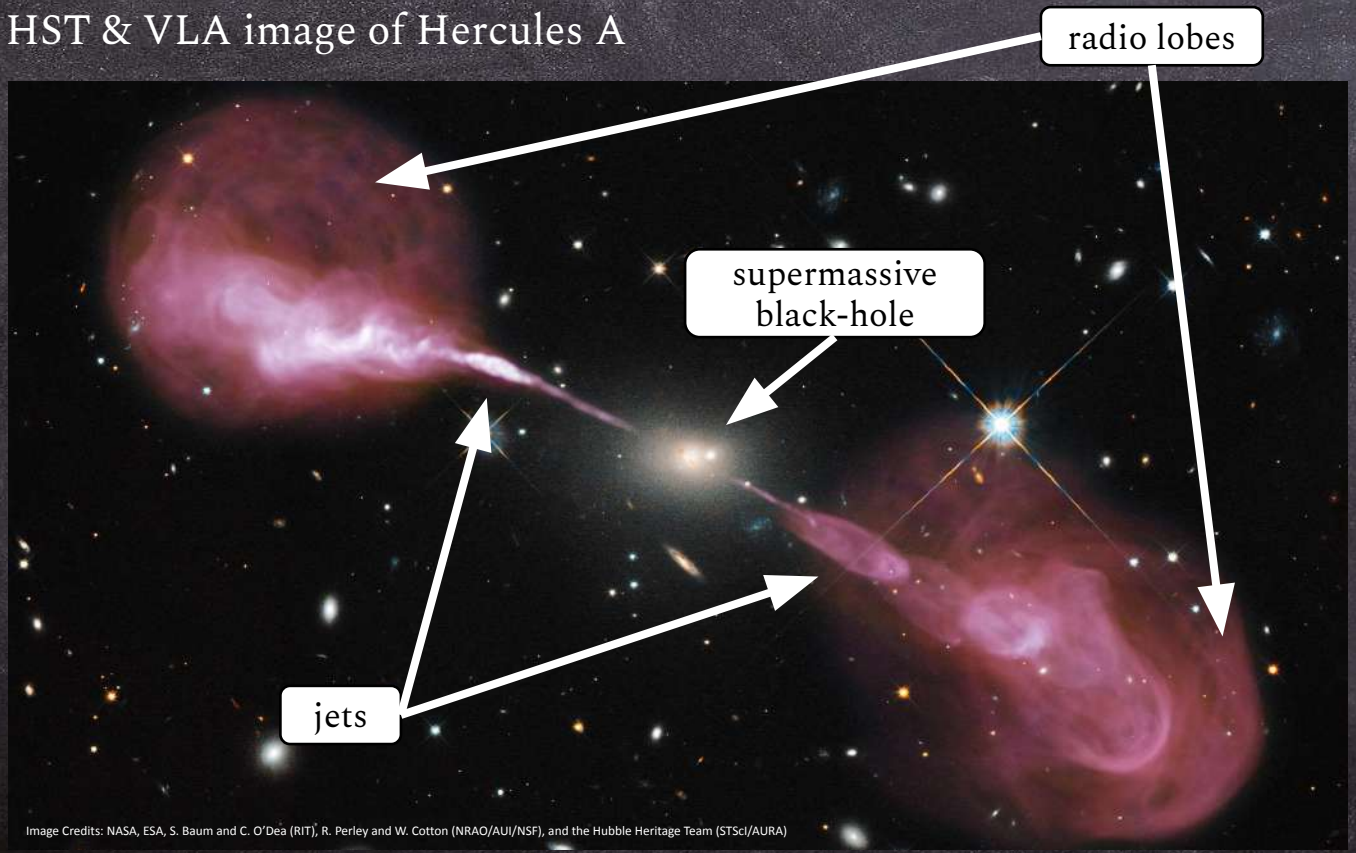
Dimitrios Kantzas (kantzas@lapth.cnrs.fr)
LAPTh/CNRS

with
Francesca Calore and Marco Chianese

Image Credit: NASA/JPL-Caltech

Active galactic nuclei (AGN)

HST & VLA image of Hercules A



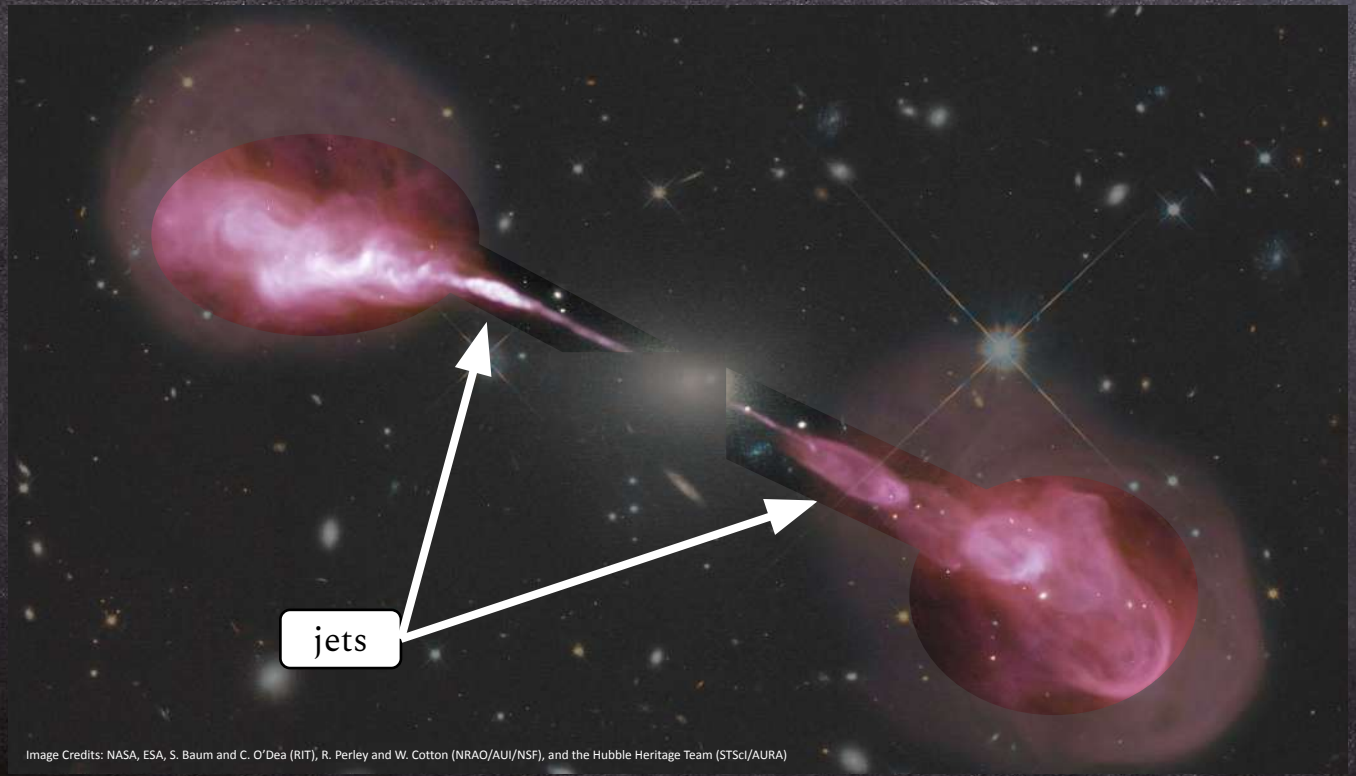
Supermassive BH
- powers jets

Jets
- accelerate CRs

Radio lobes
- feedback

AGN jets

HST & VLA image of Hercules A

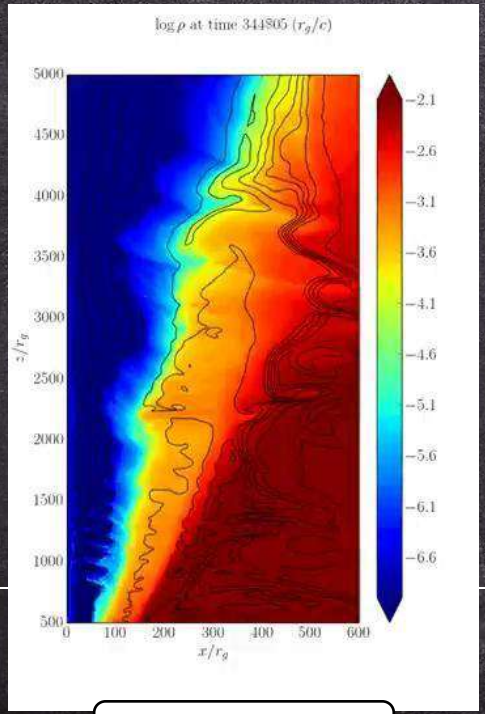


Jets ?

- magnetic field
- composition
- size

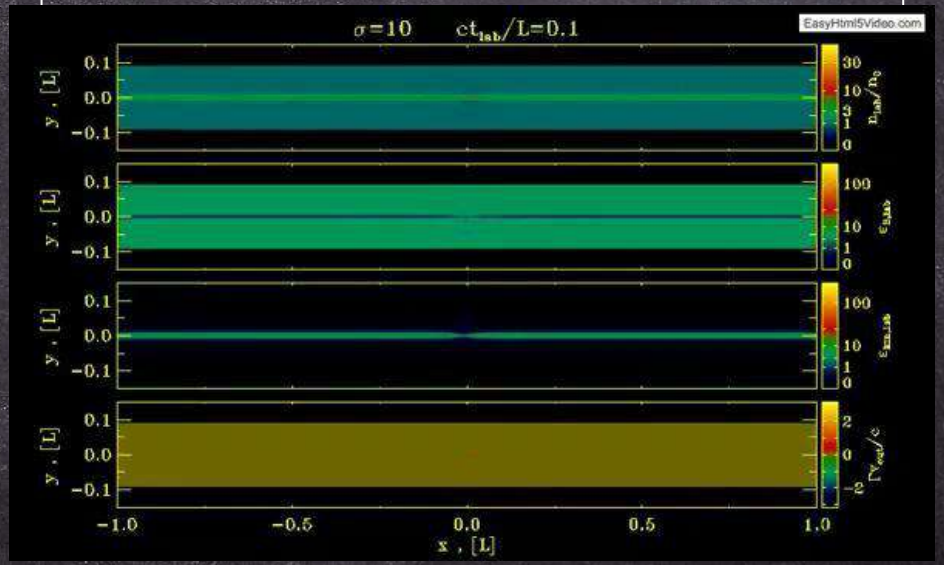
Theoretical studies of AGN jets (simulations)

General Relativistic MagnetoHydroDynamic
(e.g. Chatterjee et al. 2019)



$1r_g$ ~km $M_{bh}/M_\odot$

Particle-in-cell simulations
(e.g. Sironi et al. 2016)



1L ~5m (n/10^{10} particles per cc)$^{-1/2}$

Theoretical studies of AGN jets (simulations)

General Relativistic MagnetoHydroDynamic
(e.g. Chatterjee et al. 2019)

Pros

- Large-scale dynamics
- Morphology
- …

Cons

- No particle acceleration
- No radiation
- …

Particle-in-cell simulations
(e.g. Sironi et al. 2016)

Pros

- Fundamental equations
- Particle acceleration
- …

Cons

- Small scales
- Short timescales
- …

Theoretical studies of AGN jets (semi-analytical)

BHJet: a multi-zone model (Lucchini..., DK et al. 2022)

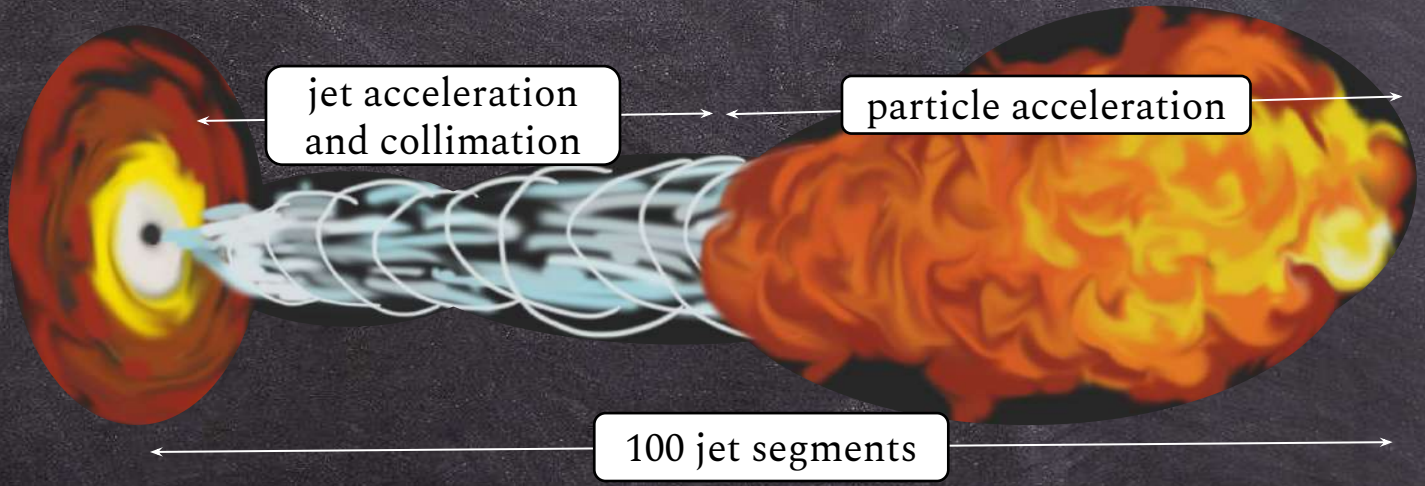


Image Credit: T. Revolta

BHJet: the main ingredients (I)

(Lucchini..., DK et al. 2022)

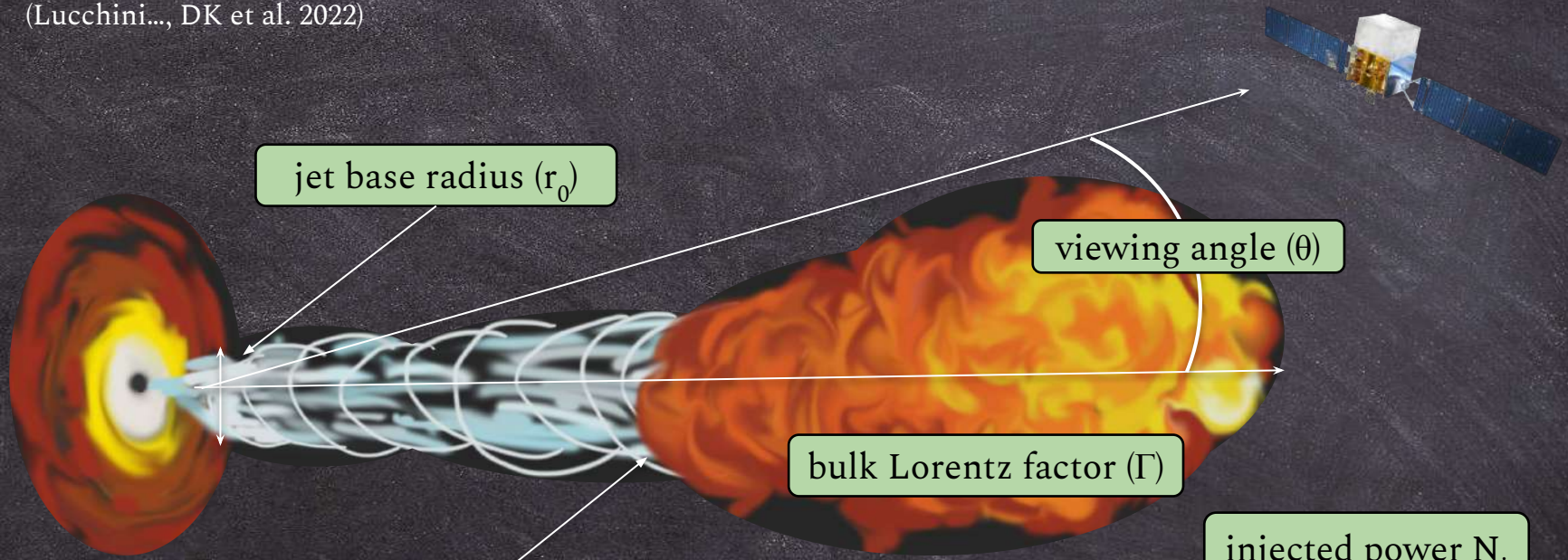


Image Credit: T. Revolta

BHJet: the main ingredients (II)

(Lucchini..., DK et al. 2022)

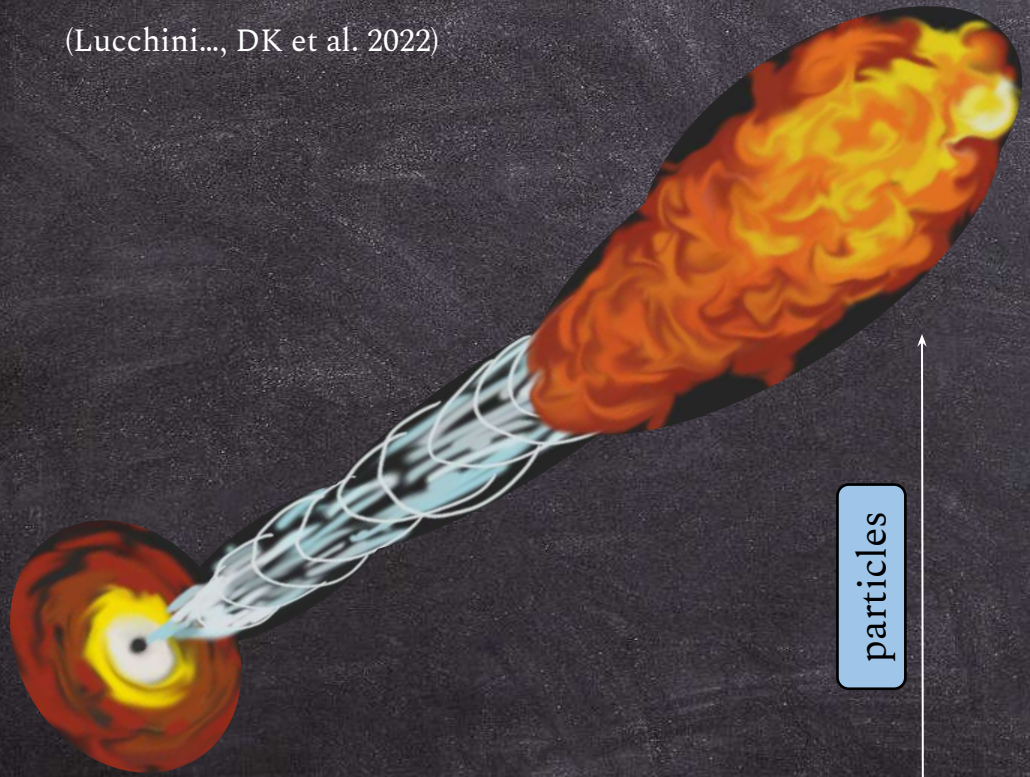
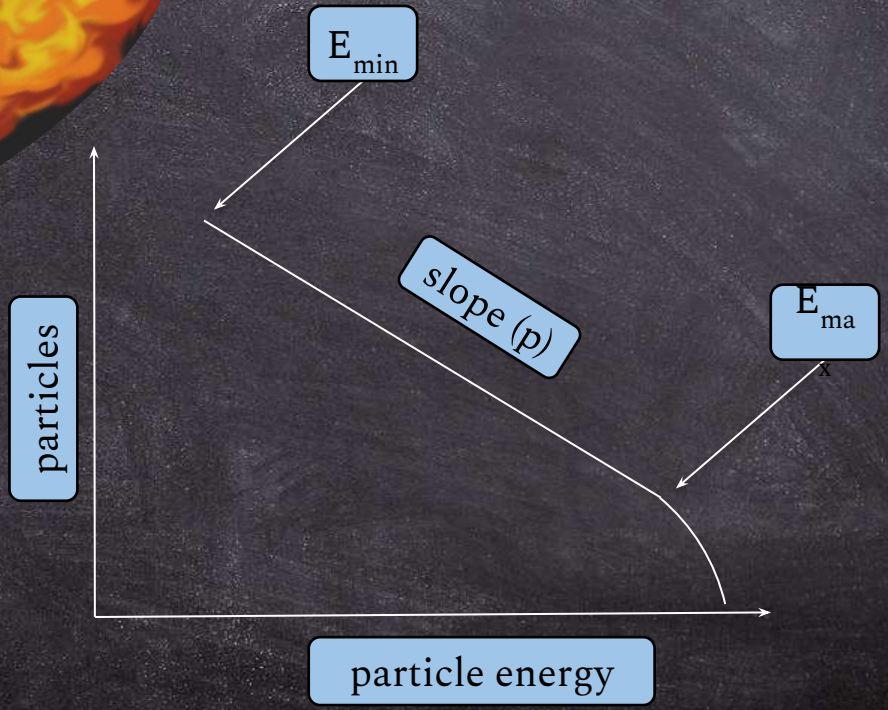


Image Credit: T. Revolta



Jet composition and radiative processes

Leptonic scenario

- Non-thermal electrons
  - protons carry the mass of the jet

- Synchrotron
  - thermal & non-thermal
- Inverse Compton
  - synchrotron-self & external
- Pair annihilation & production

See, e.g. Markoff et al. 2005; Lucchini et al. 2019; 2022

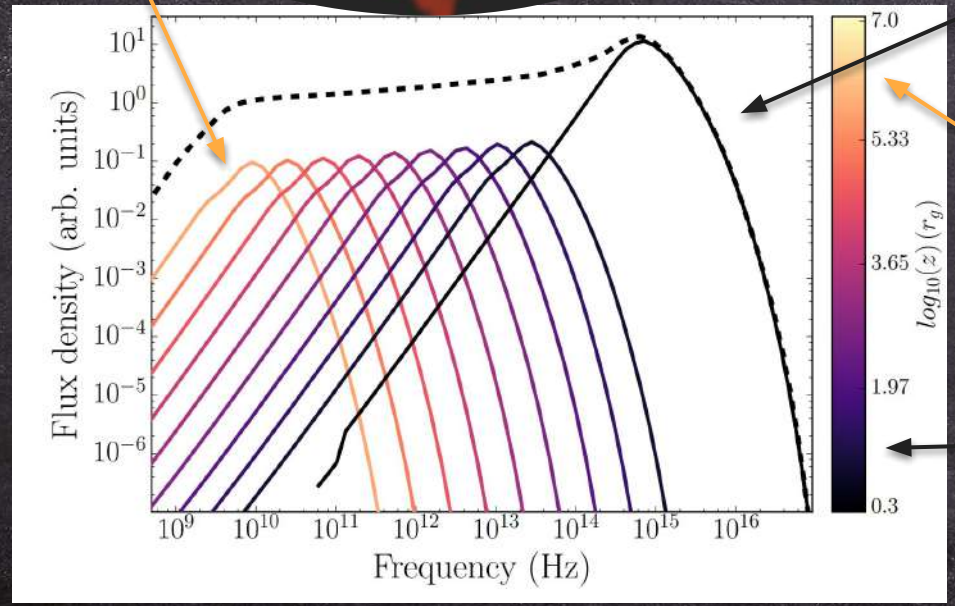
Lepto-hadronic scenario

- Non-thermal electrons & protons
  - uncertain lepton-to-proton ratio

- Synchrotron
  - thermal & non-thermal & protons
- Inverse Compton
  - synchrotron-self & external
- Pair annihilation & production
- Hadronic processes
  - Proton-proton, photomeson & Bethe-Heitler

See Kantzas et al. 2021; 2023

The multi-wavelength emission



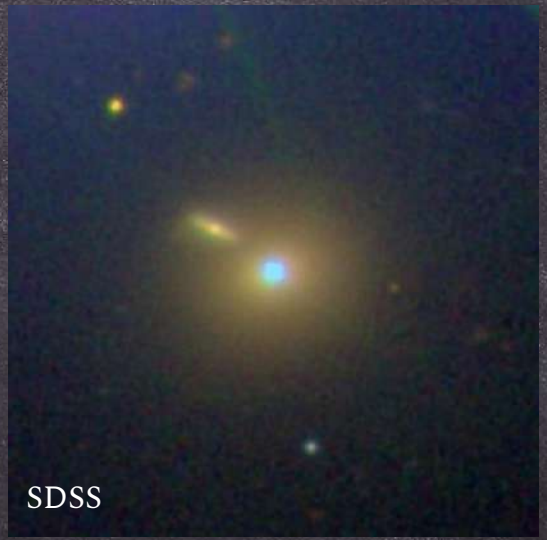
10^7 r_g

~few r_g ($1r_g \simeq 1.5\text{km}\ M_{bh}/M_\odot$)

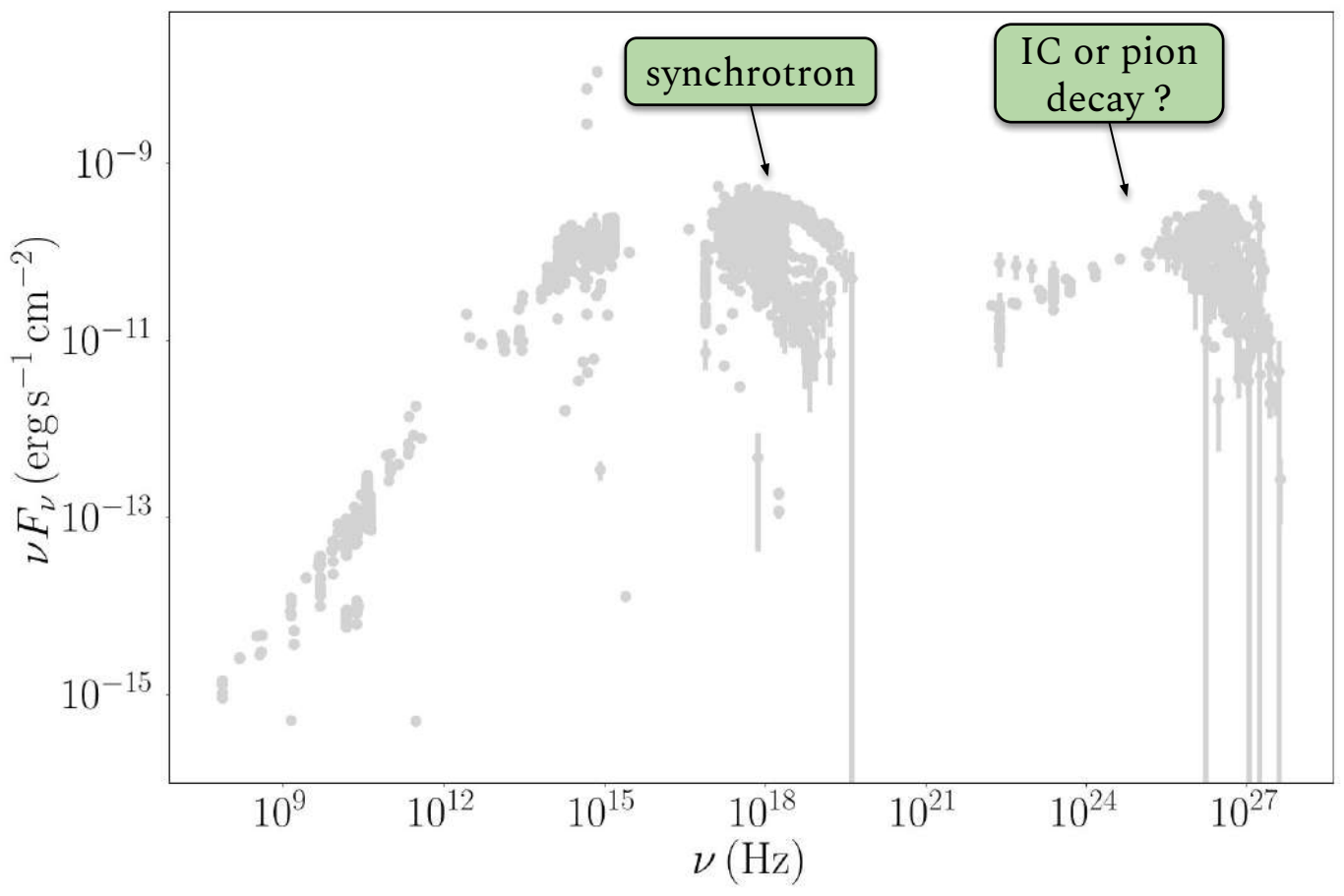
Lucchini..., DK et al. 2022

The study case of Markarian 421

- BL Lac object
- @122Mpc (z=0.0308)
- The 1st extragalactic TeV source (Punch et al. 1992)
- One of the brightest quasars



The multi-wavelength spectrum of Markarian 421



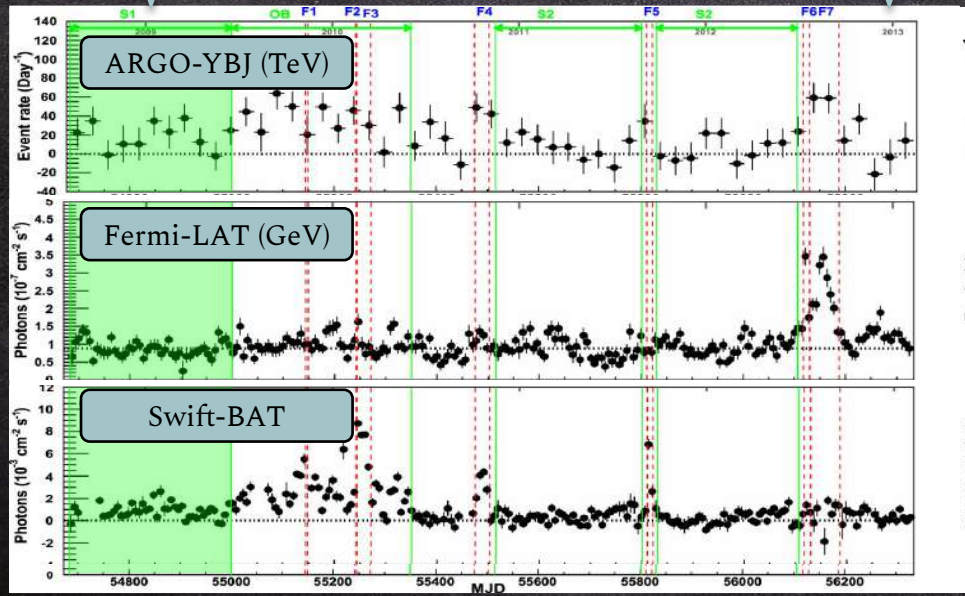
Archival data from SSDC SED builder

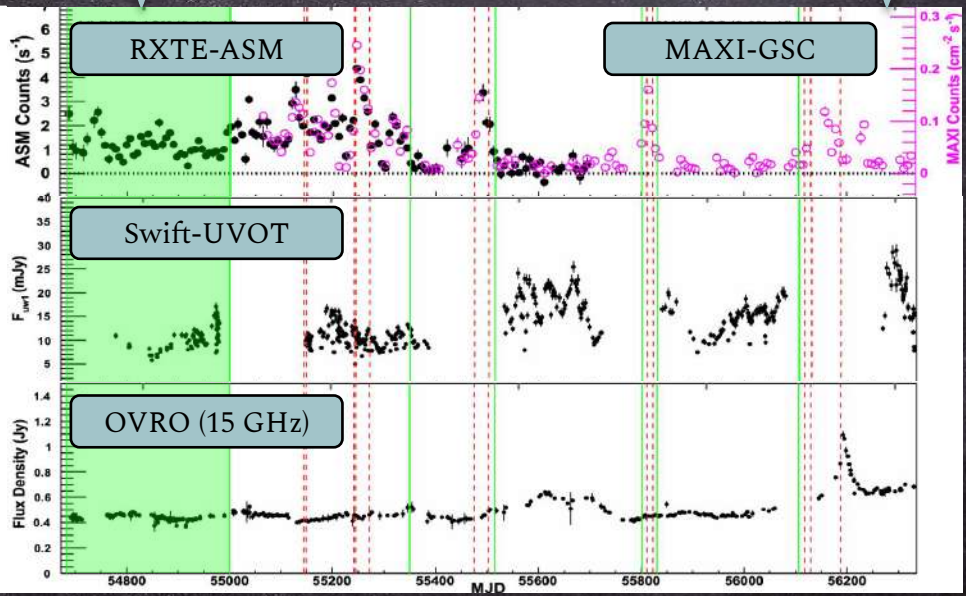
(e.g., BeppoSAX, VERITAS, TIBET, TACTIC, HESS, ARGO, MAGIC, EGRET, AGILE, Fermi, INTEGRAL, MAXI, XMM, RXTE, Swift, WISE, Sloan, NED et al.)

The multi-wavelength time-variability

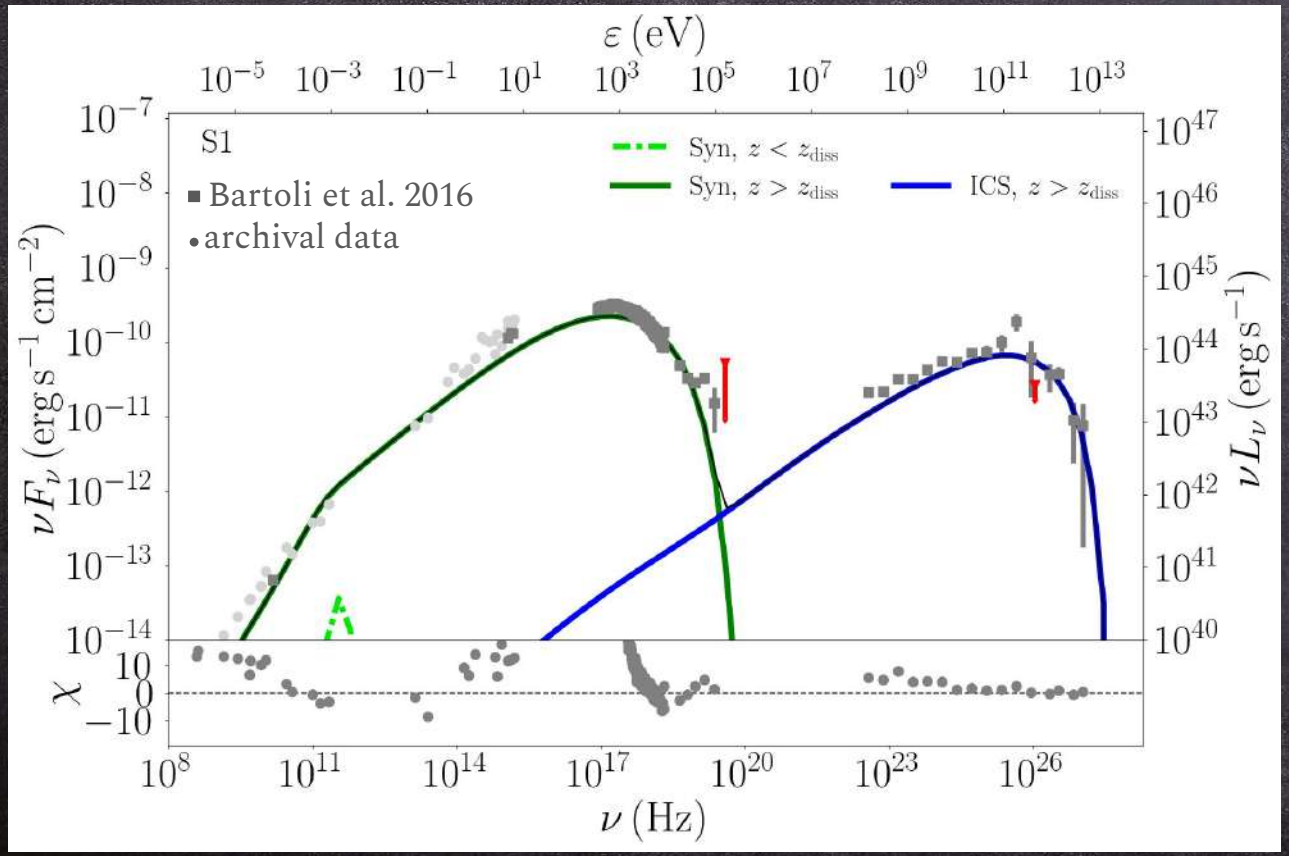
2009 2013 2009 2013

Bartoli et al. 2016





Best-fit of the Steady state with BHJet

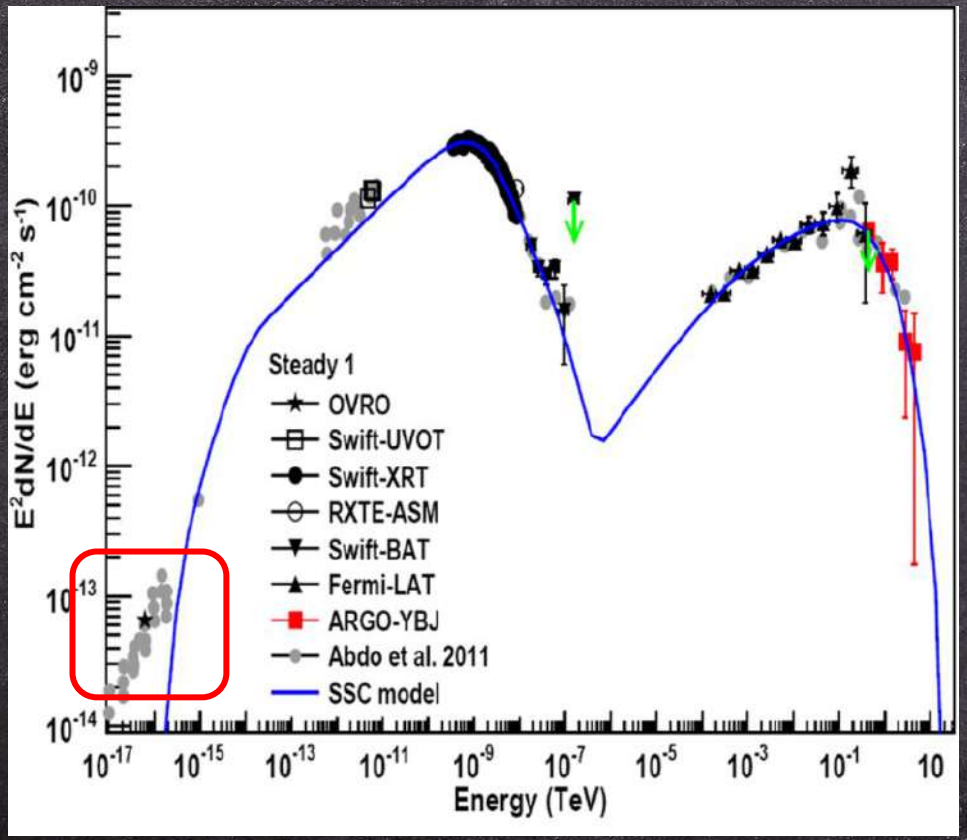


preliminary

parameter	value
p_1	1.83
E_{break} (GeV)	155
δ	42
B (G)	0.4
u_e/u_B	7.4
R (r_g)	36
z_{diss} (r_g)	435
N_j (L_{Edd})	0.0007

Kantzas et al. in prep

The Steady state



parameter	value
p_1	2.3
p_2	4.7
E_{break} (GeV)	100
δ	38
B (G)	0.048
u_e/u_B	70.6
R (r_g)	2

Bartoli et al. 2016

Comparison

parameter	value
p_1	2.3
p_2	4.7
E_{break} (GeV)	100
δ	38
B (G)	0.048
u_e/u_B	70.6
R (r_g)	2

Bartoli et al. 2016

particle acceleration mechanism ?

preliminary

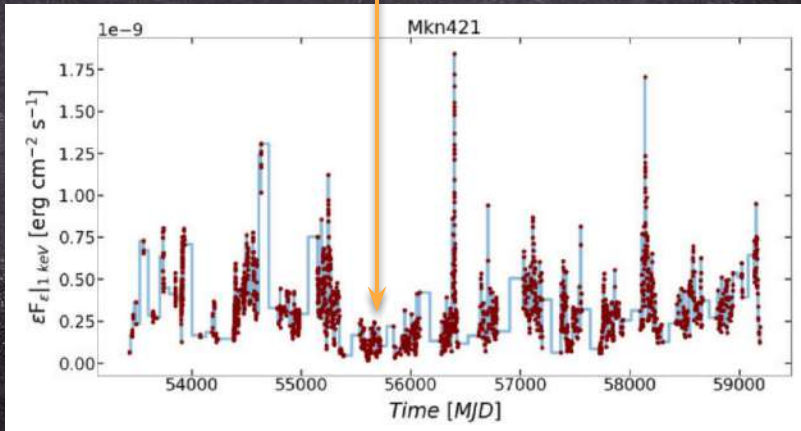
parameter	value
p_1	1.83
E_{break} (GeV)	155
δ	42
B (G)	0.4
u_e/u_B	7.4
R (r_g)	36
z_{diss} (r_g)	435
N_j (L_{Edd})	0.0007

Kantzas et al. in prep

Open questions and next steps

- Jet composition?
- Proton acceleration? (see e.g. Dimitrakoudis et al. 2014; Cerruti et al. 2015; Stathopoulos et al. 2022; …)
- Neutrino emission?
  (see Padovani & Resconi 2014 – possible neutrino counterpart while in steady state)

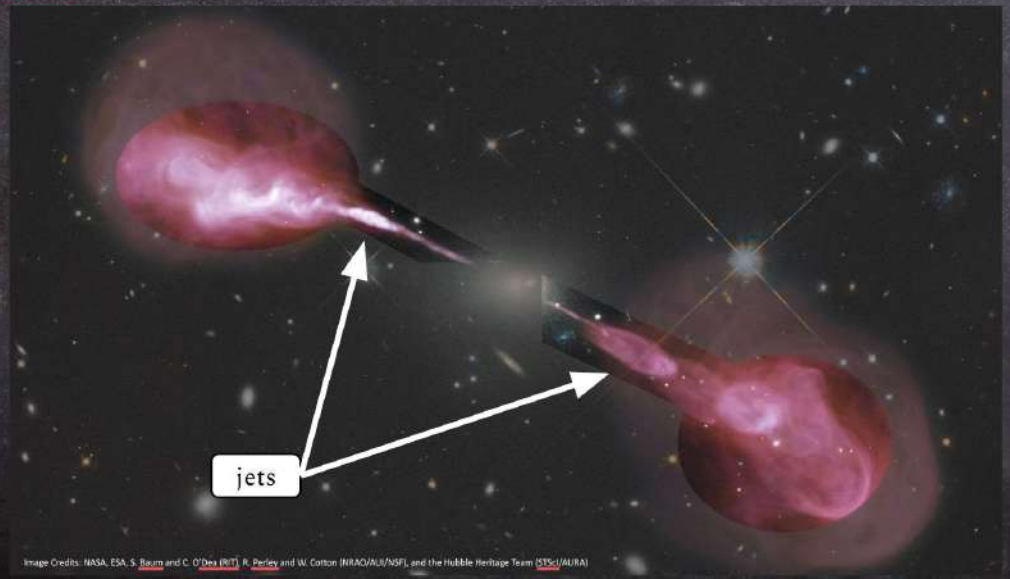
neutrino emission (2011 May 04)?



Conclusions

AGN jets

HST & VLA image of Hercules A



Jets ?

- magnetic field
- composition
- size

We understand better the magnetic field and the jet morphology, but we still struggle with the jet composition.