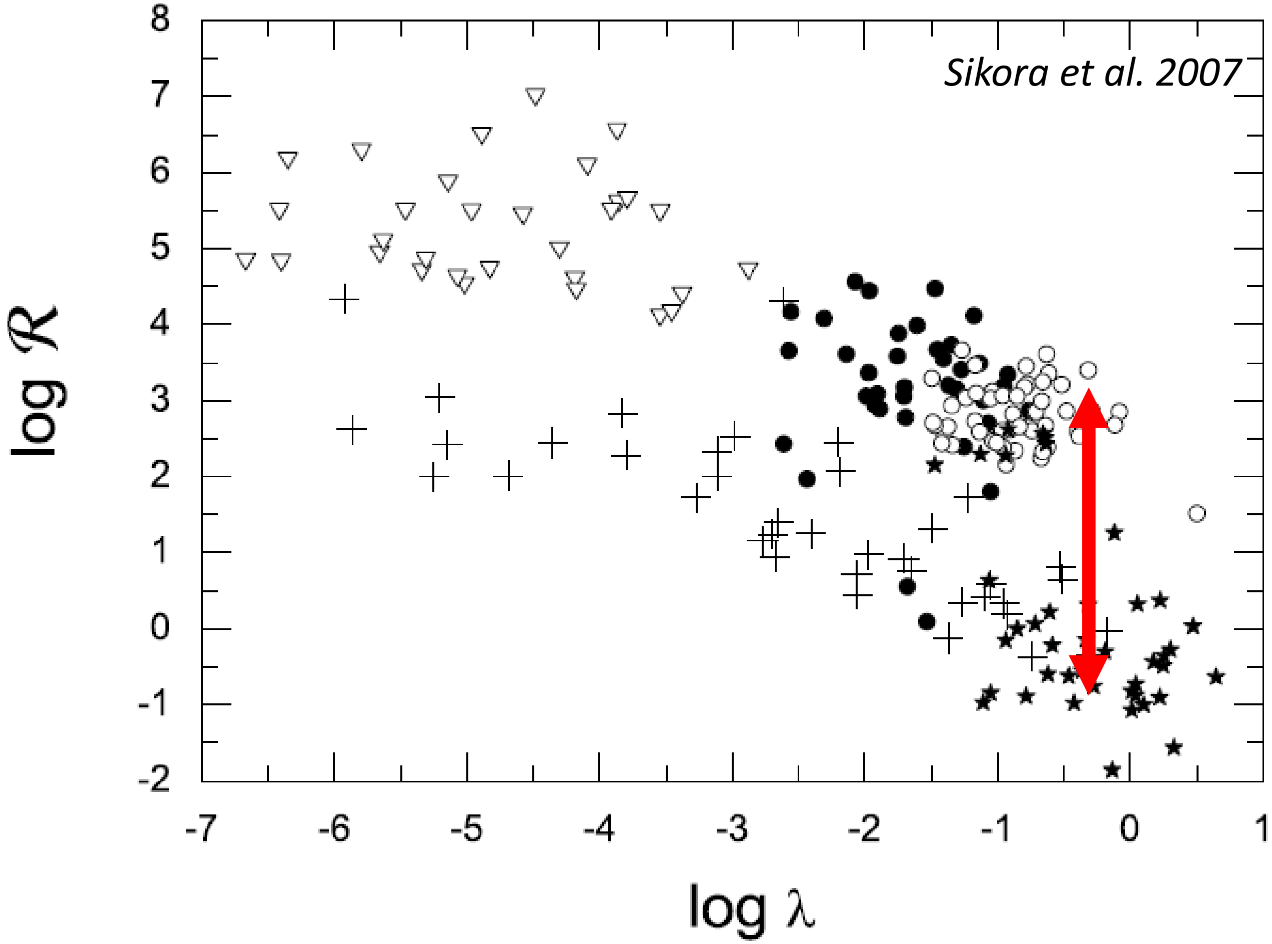
MAD accretion and AGN jets – an observational perspective

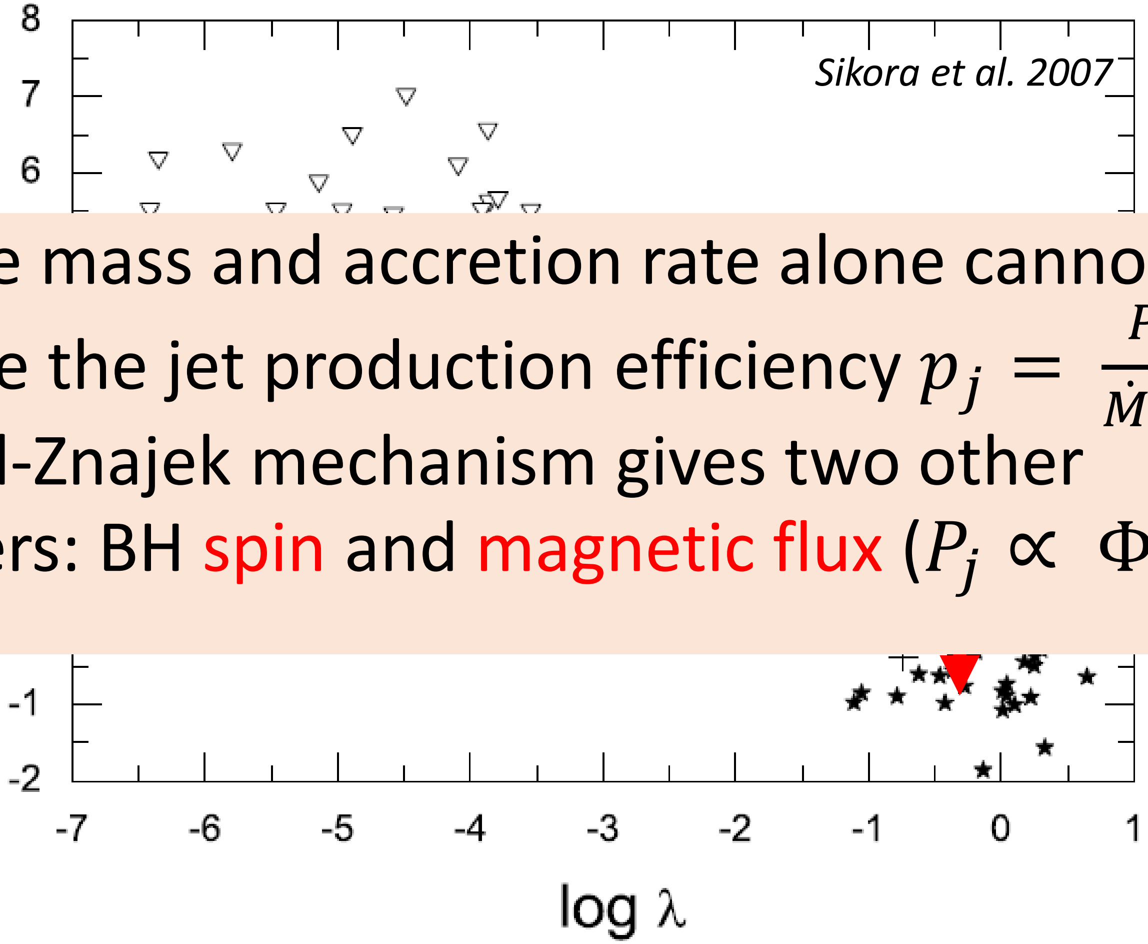
Tuomas Savolainen[1] & Wara Chamani[2]

[1]Aalto University, Finland; [2]GFZ-Potsdam, Germany

A fundamental question: why only some AGN produce jets efficiently?



A fundamental question: why only some AGN produce jets efficiently?



Black hole mass and accretion rate alone cannot determine the jet production efficiency $p_j = \frac{P_j}{\dot{M}c^2}$. Blandford-Znajek mechanism gives two other parameters: BH spin and magnetic flux ($P_j \propto \Phi_{BH}^2 \Omega_H^2$).

Spin vs. magnetic flux as a controlling parameter

Spin

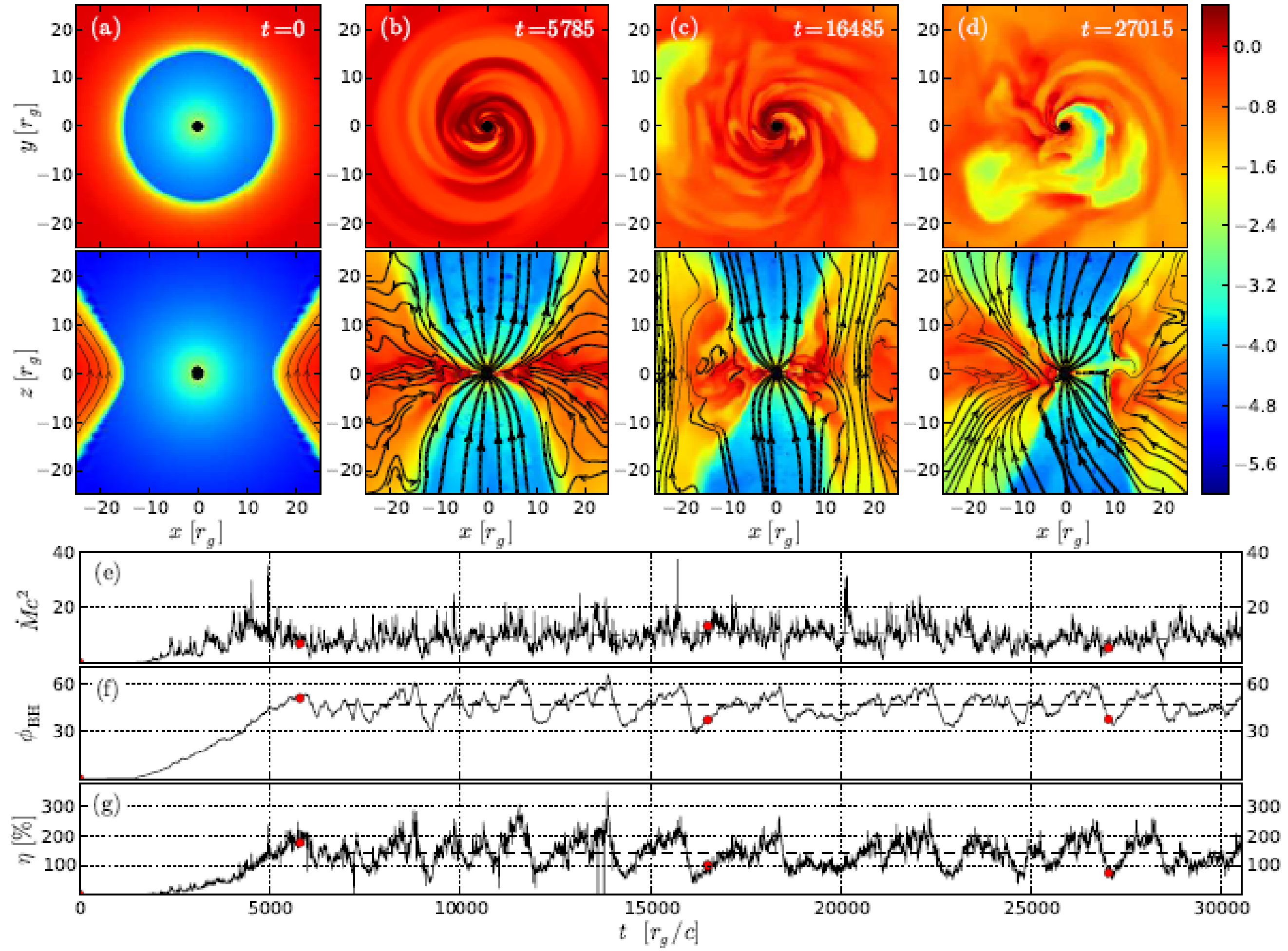
- The range in jet production efficiency is due to a range in BH spin values
- For thick accretion disks, power variations of ~1000x are possible for realistic spin distributions (Tchekhovskoy et al. 2010)
- However, modelling X-ray reflection spectra of radio-quiet AGN finds large spin values

Magnetic flux

- High efficiency jets require both high spin and large magnetic flux threading the BH, and it is the magnetic flux that typically controls the jet production (Sikora & Begelman 2013)
- AGN jet production depends on the accretion history, i.e., whether the system had enough time and correct conditions to accrete high enough magnetic flux

High jet efficiencies in simulations of MADs

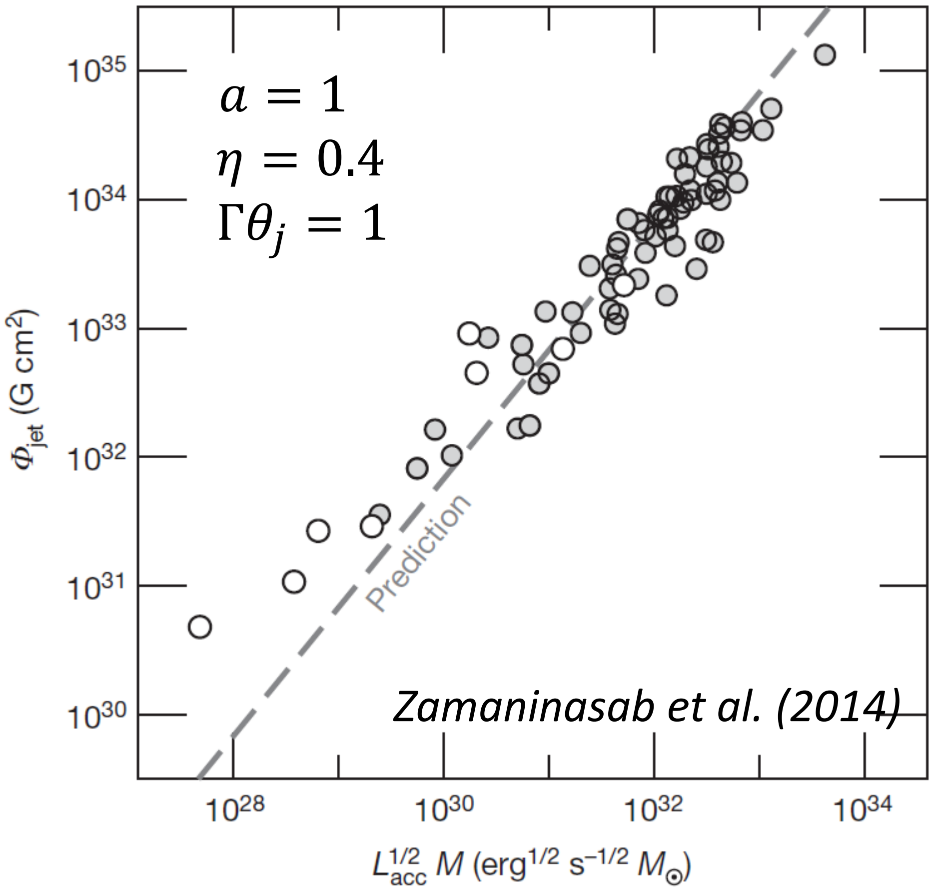
Tchekhovskoy et al. (2011)



- GRMHD simulations with a large initial magnetic flux produce >100% jet efficiency for spins of a>0.9 and lead to a saturation of the magnetic flux at $\Phi_{BH} \sim 50\left(\dot{M} r_g^2 c\right)^{1/2}$
- B-field becomes dynamically important and a "magnetically arrested disk" (MAD) is formed
- Jet power for a given accretion rate is maximized for MADs. So, are sources with high p_j MADs?

Zamaninasab et al. (2014): Testing the MAD scenario in radio-loud AGN

- For MADs: $\Phi_{BH} = \varphi_{BH}\left(\dot{M} r_g^2 c\right)^{1/2} \propto L_{\rm acc}^{1/2} M_{\rm BH}$ with $\varphi_{BH} \approx 50$
- Measuring the magnetic field strength in the jet from e.g., core shift allows one to estimate the jet poloidal magnetic flux, $\Phi_{\rm jet}$. Assuming flux freezing gives $\Phi_{\rm jet} = \Phi_{BH}$.
- $M_{\rm BH}$ and $L_{\rm acc}$ can be estimated from scaling relations using optical broad emission lines or stellar velocity dispersion and SED modelling
- In Zamaninasab et al. (2014) a correlation was found for a sample of 68 blazars + 8 nearby AGN (incl. M87). Measured $\varphi_{BH} = 52 \pm 5$ matches with the MAD prediction. AGN with powerful jets seem to be often MADs.



What about sources that produce jets less efficiently?

- High-p_j sources appear to have MAD-level magnetic fluxes. What about low-p_j sources? Can we create an observational test if the magnetic flux is the controlling parameter?
- Yes: measure magnetic flux (from VLBI core-shift or spectral turnover) for sources with significantly lower jet production efficiencies than in Z14
- Even better: try to also measure their BH spin from X-ray reflection spectroscopy

A VLBA + XMM/NuSTAR pilot program

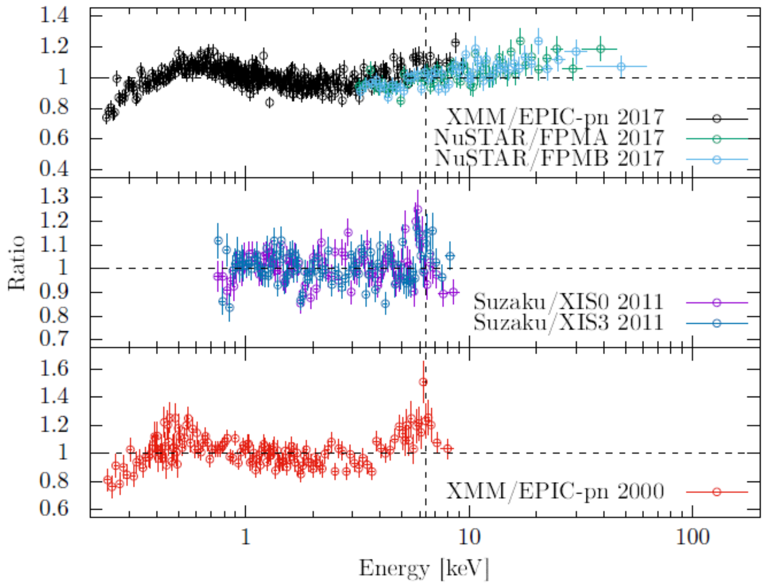
- A pilot sample of four low-to-intermediate R (1.5 – 195; RQQ/RIQ) jetted sources were observed with the VLBA:
  - III Zw 2 (VLBA + new XMM/NuSTAR obs.)
  - PG1309+355 (VLBA)
  - H1821+643 (VLBA + archival X-ray data)
  - PG2209+185 (VLBA + new XMM/NuSTAR obs.)
- VLBA obs. at four freqs. in phase-ref. mode for relative astrometry. Geoblocks for improved tropospheric calibration.

A case study: III Zw 2

Wara Chamani's PhD thesis

XMM/NuSTAR observations of III Zw 2

Residuals of absorbed power-law model



Chamani et al. 2020

- Signs of a reflection spectrum: soft excess, potential Fe Kα line, Compton hump
- Can be also fit with a warm absorber + black body, but the required BB temperature appears too high (~140eV)
- Reflection model fit with VLBI-kinematics-constrained inclination yields a high BH spin value

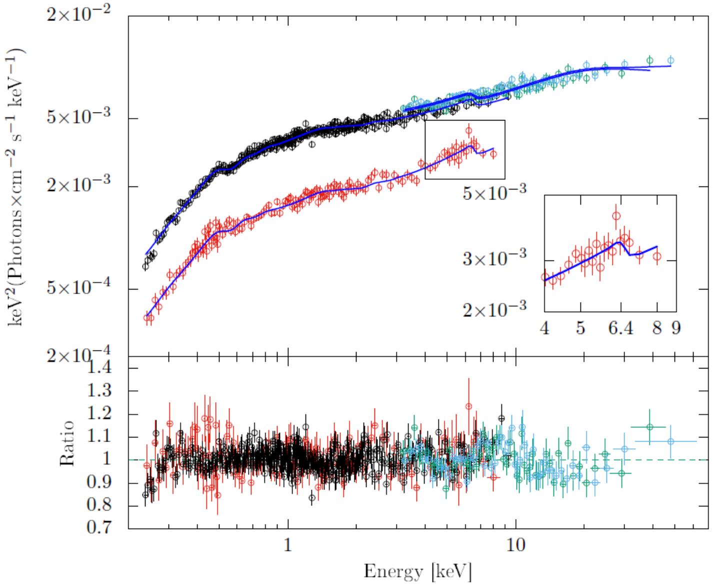
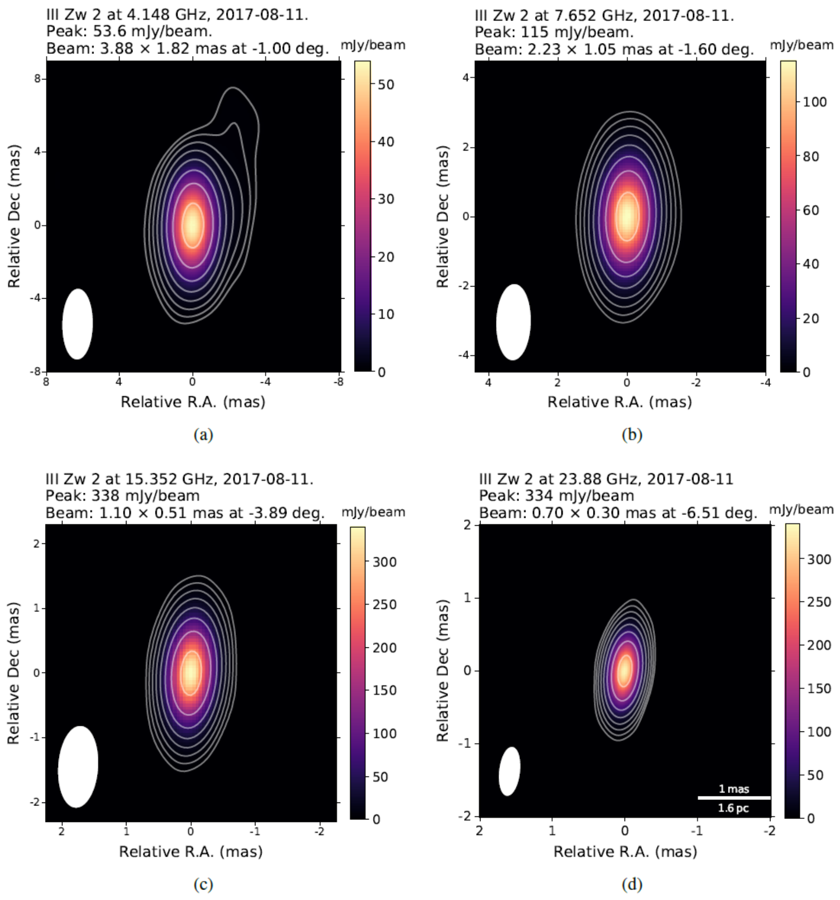


Table 4. RELXILL joint-fit parameters of the combined XMM-2000 and XMM+*NuSTAR* 2017 spectra.

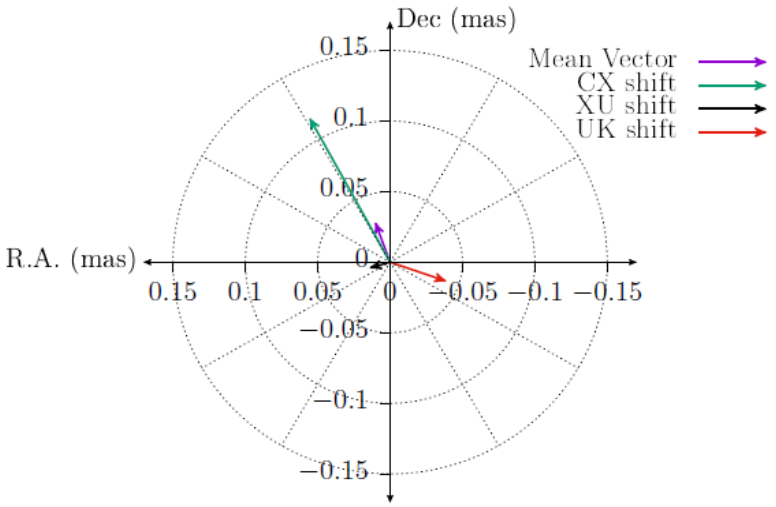
Linked parameters				
θ	a	N_H	$\log(\xi)$	A_{Fe}
$41^{\circ}{}^{+0^{\circ}}_{-1^{\circ}}$	≥ 0.98	$0.10^{+0.04}_{-0.03}$	$2.70^{+0.02}_{-0.05}$	2.0 ± 0.6
Unlinked parameters				
Epoch	Normalization	Γ	R	
2000	$3.32^{+0.25}_{-0.26}$	$1.77^{+0.02}_{-0.03}$	0.92 ± 0.14	
2017	$7.25^{+0.28}_{-0.36}$	$1.87^{+0.01}_{-0.02}$	0.48 ± 0.05	
χ^2/d.o.f.	696.6/598 (1.16)			

Multi-frequency VLBA astrometry of III Zw 2

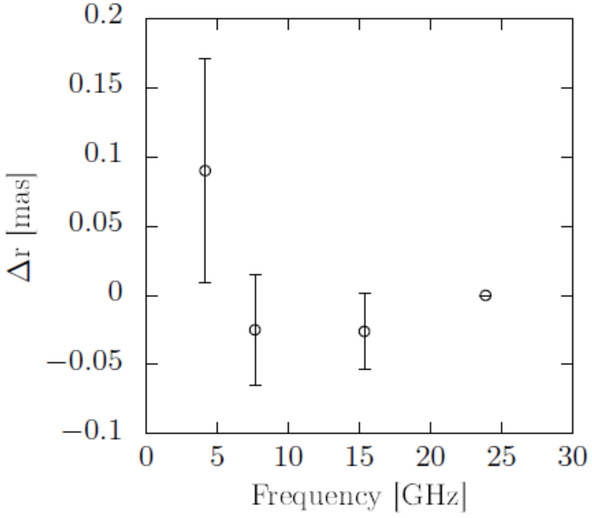
Chamani et al. 2021



- Quasi-simultaneous 4/8, 15 and 24 GHz phase-referencing observations of point-like III Zw 2 and three nearby calibrators, with resolved jet structures (sep. 0.82, 0.98 and 1.91 deg)
- Special care to estimate the error budget (therm., tropo., iono., core-ident.)
- No core-shift for III Zw 2 detected. 1-σ upper limit: **0.16 mas** between 4 and 24 GHz.



(a)

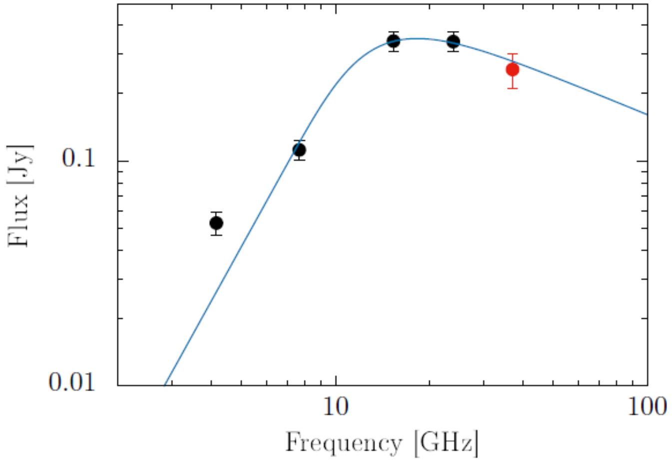


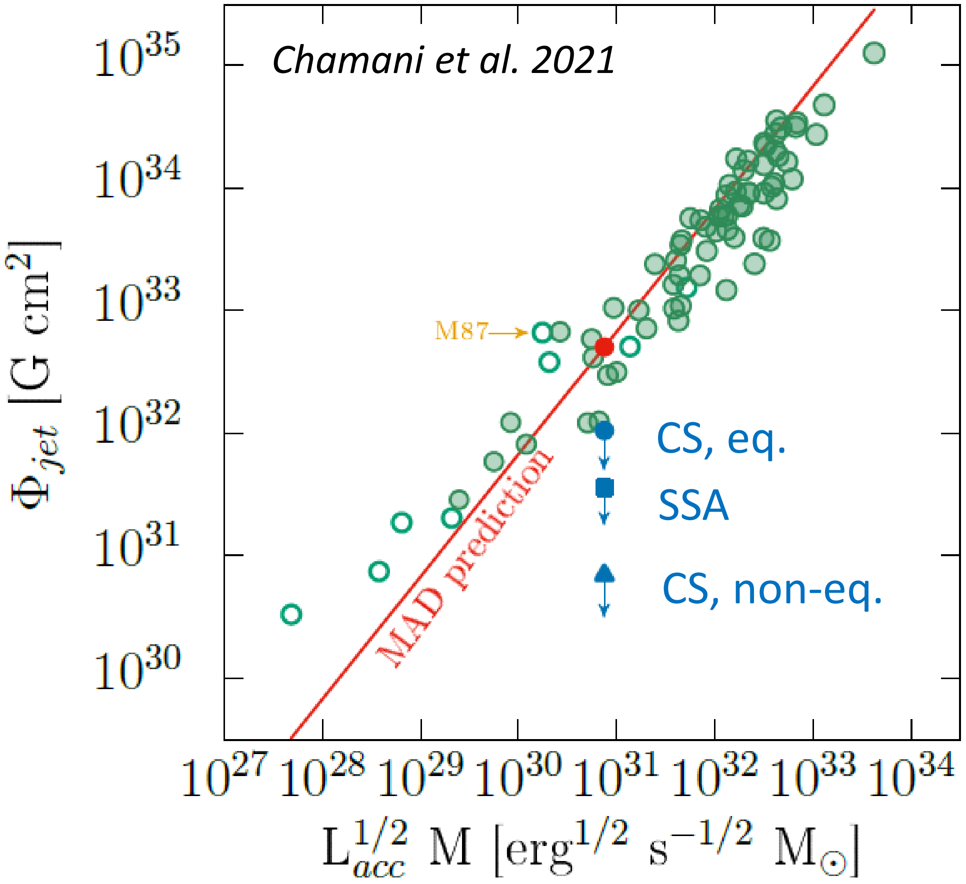
(b)

III Zw 2 magnetic field strength limits – MAD or not?

B- field strength limits:

- $B_1' \lesssim 60$ mG (from core-shift assuming equipartition)
- $B_1' \lesssim 4$ mG (from core-shift not assuming equipartition)
- $B_1' \lesssim 20$ mG (from turnover of the synchrotron spectrum)





- The highest upper limit for $\Phi_{\rm jet}$ is five times lower than the predicted $\Phi_{\rm BH,MAD}$, other upper limits are lower
- III Zw 2 seems to be a failed MAD, which can explain its relatively low jet production efficiency, despite the high BH spin

Summary

- Observational evidence indicates that AGN with powerful, high-efficiency jets are often MADs. This is compatible with the idea that BH magnetic flux is a parameter controlling AGN jet production efficiency.
- A new observational test: find sources with low-efficiency jets and measure their magnetic flux using multi-frequency VLBI. If possible, obtain high-SNR X-ray spectra to estimate BH spins. Are the magnetic fluxes below the MAD level? Are the BH spins high or low?
- A pilot study has been carried out and the results for III Zw 2 demonstrate that the approach is feasible (although laborious and challenging in terms of building a large sample). The high spin and sub-MAD magnetic flux in this source are compatible with the magnetic flux being the parameter controlling the jet production efficiency.