MAXI SOURCES AND RELATIVISTIC JETS

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With main collaboration from F. Carotenuto, G. Migliori, R. Fender, P. Kaaret, A.K. Tzioumis, J. Miller-Jones, L. Tremou, A. Bahramian,… and the ThunderKAT/XKAT MeerKAT LSP

Special thanks to Hitoshi

Université Paris Cité

Observatoire de Paris | PSL

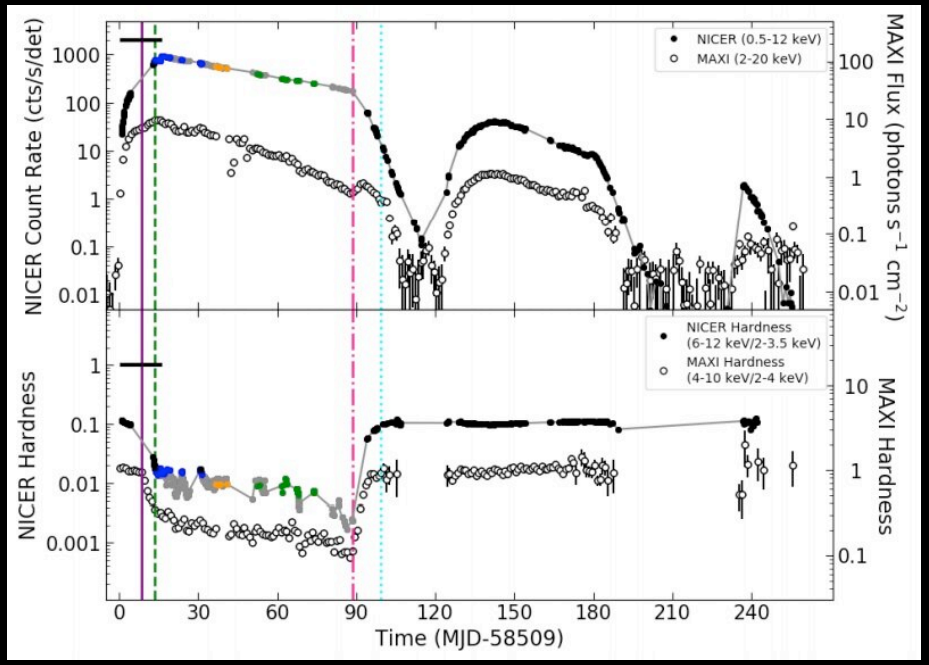
cnrs dépasser les frontières

cea

OUTLINE

- Accretion, jets and X-ray binaries in outburst
- The state transition under the microscope
- On the jets fate after ejection ?
- Specific focus on some recent MAXI sources (which is good as it was the most interesting targets) including a very unique one.
- Large scale jets as cosmic rays accelerators ?

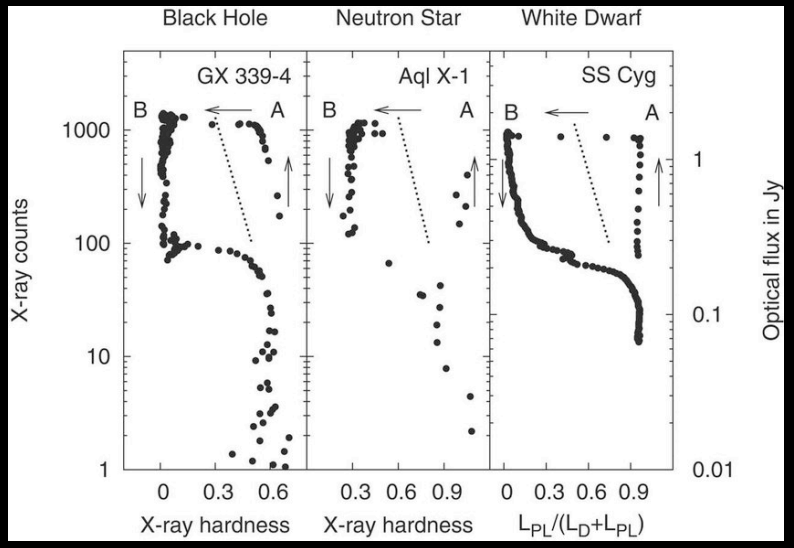
MICROQUASARS IN OUTBURST



MAXI J1348-630 in outburst (Zhang et al. 2020)

- **Regular outbursts** with different timescales (CV, NS, BH)
- **Key role of MAXI** for detection and follow up of new transients !
- **Spectral states** variations with **timing** signatures (Hard —> Soft —> Hard)
- **Multi-wavelength** emission
- Strong connection with **jets/winds** emissions

See the various talks during the conference

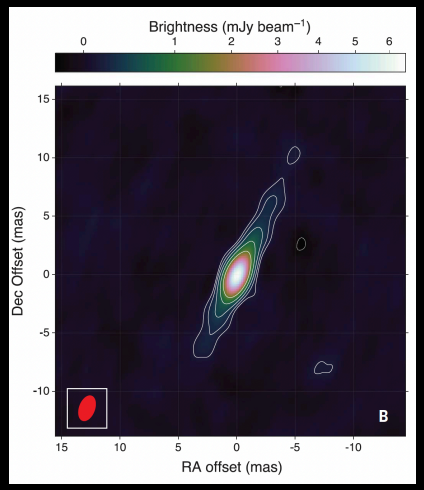


Hardness Intensity Diagram (HID)

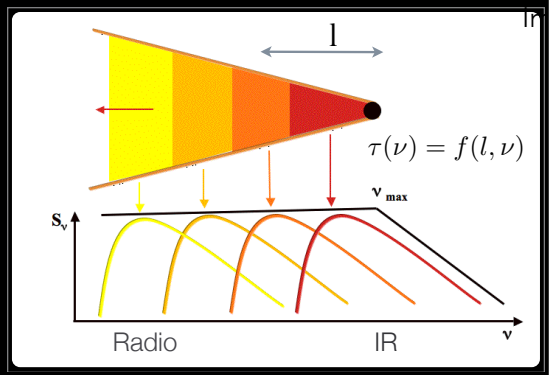
Koerding et al. 2008

VARIOUS FLAVOURS OF JETS

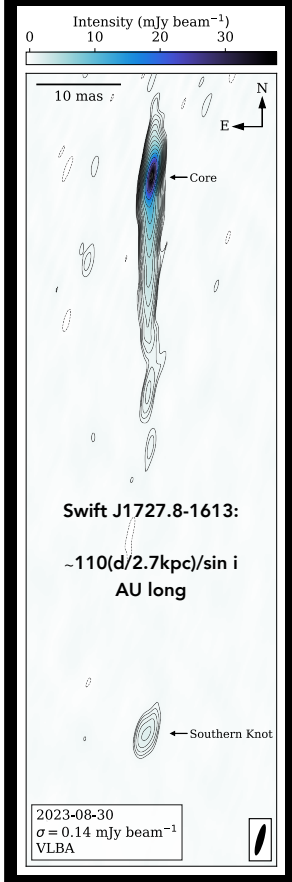
Compact jets in the hard state

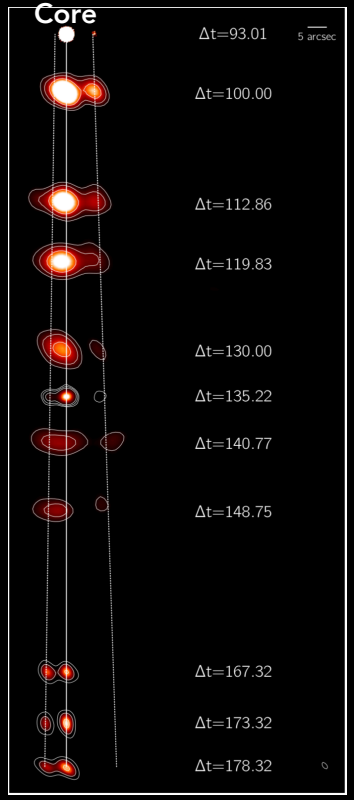


Stirling et al. 2001, Miller-Jones et al. 2021
Wood et al. 2024



Discrete ejection event(s) at state transition

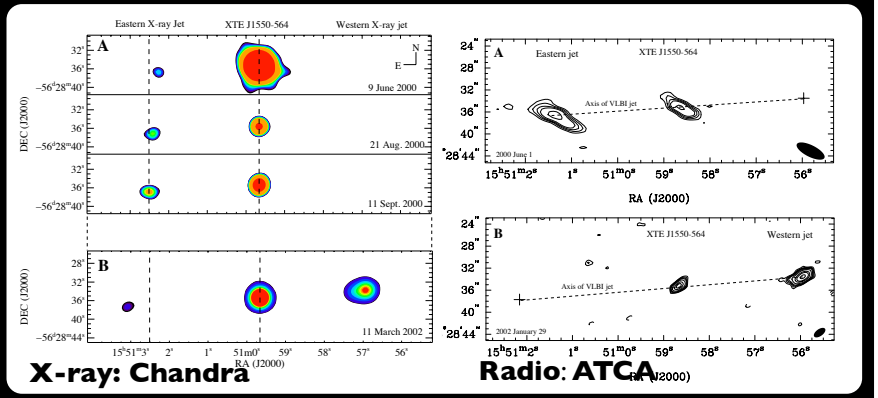




Bright et al. 2020

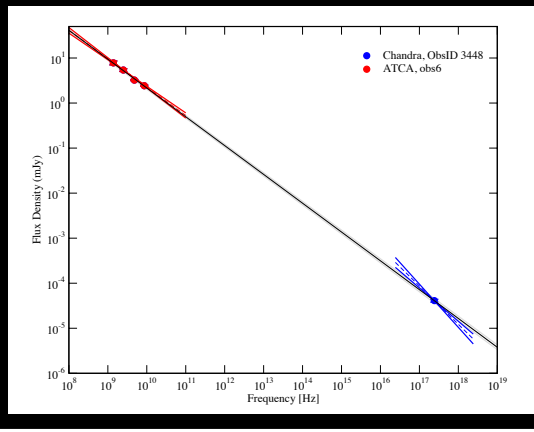
I will focus on extended jets

Large scale jets —> interaction with surroundings



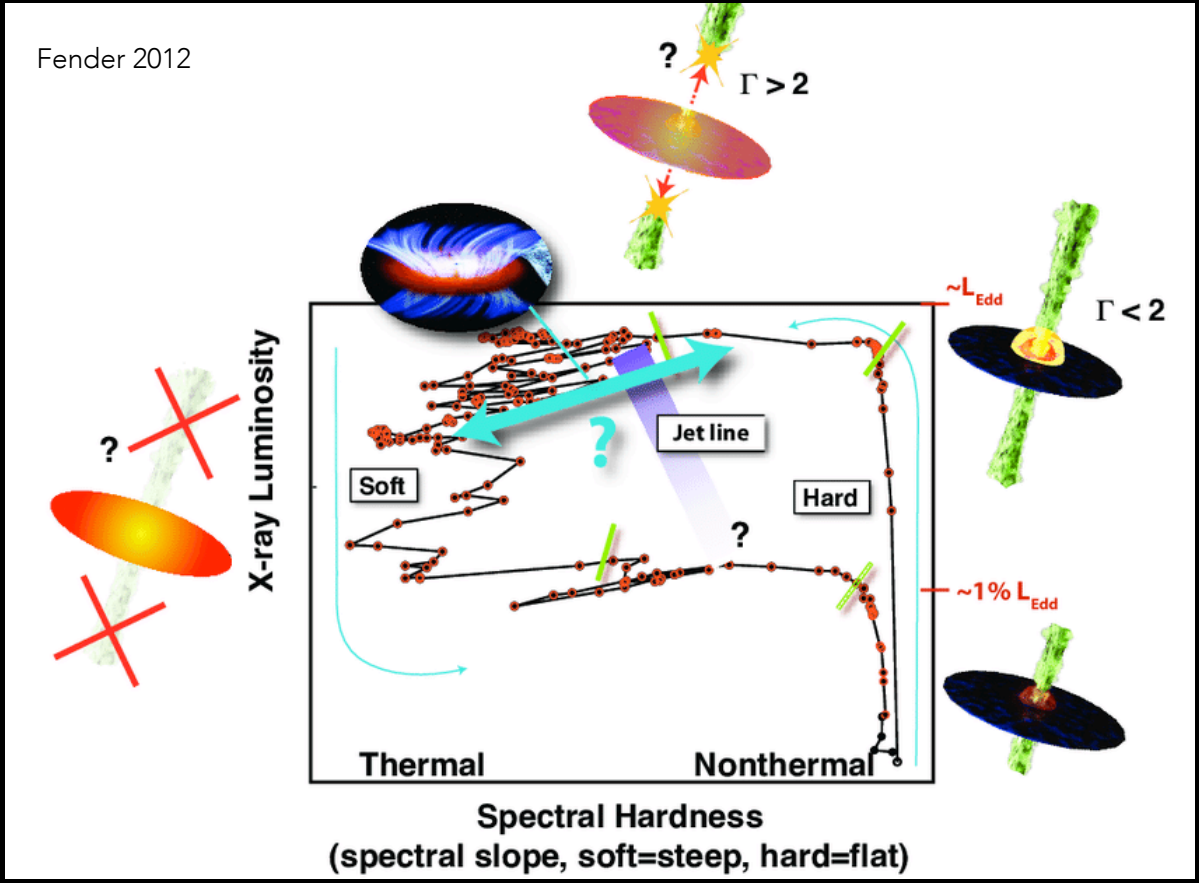
Synchrotron, synchrotron…

from radio to … X-rays



Corbel et al. 2002; 2005; Migliori et al. 2017; Espinasse et al. 2020

THE UNIFIED PICTURE OF JET EJECTION



- **Unification** (Corbel et al. 2004; Fender et al. 2004)
- Global picture also almost works for CV and NS XRBs
- Many questions on the jet « line » !
- Universality, GR effect ?
- But do not forget about winds (some talks today and Thursday morning).

SOME OPEN QUESTIONS

- Behind this **unification** scheme, **causality** of events around jet ejection, connection with corona ? Nature of the corona ?

- Nature of the **microquasars emission** across the electromagnetic spectrum and associated physical processes/geometry ? **See second review later by A. Tetarenko.**

- Jets **feedback** ? **Interactions** with surrounding environment ? Jets energetics ? Maximum energy of particles acceleration ?

- **New major sources** these recents years: MAXI J1820+070, MAXI J1348-630, MAXI J1535-571 and Swift J1727.8-1613 for example and V404 Cyg, it changes from GX 339-4 and GRS 1915+105 ! **Thanks to All Sky Monitors like MAXI**, we need them !

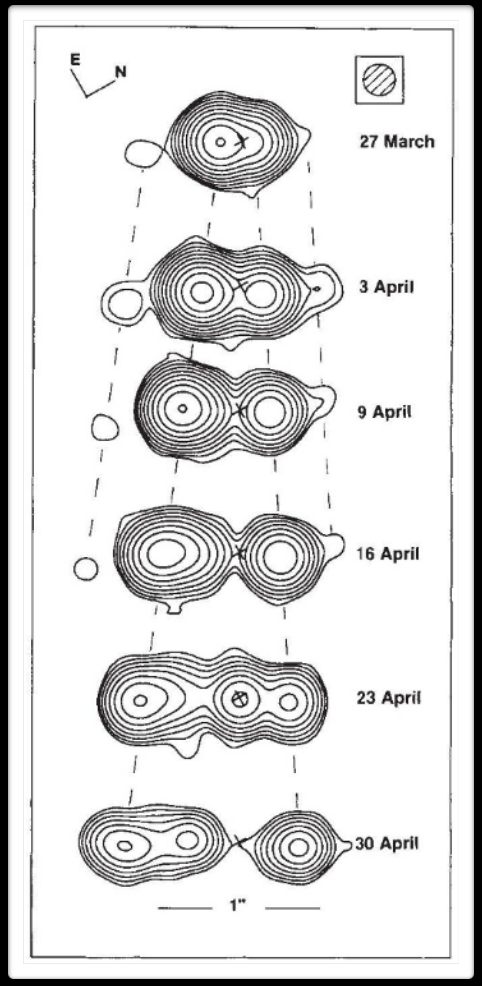
- + **new** major **technics** and observing **campaigns** (and the way, these have been done).

The dynamic radio sky: Five years of radio monitoring X-ray binaries with MeerKAT

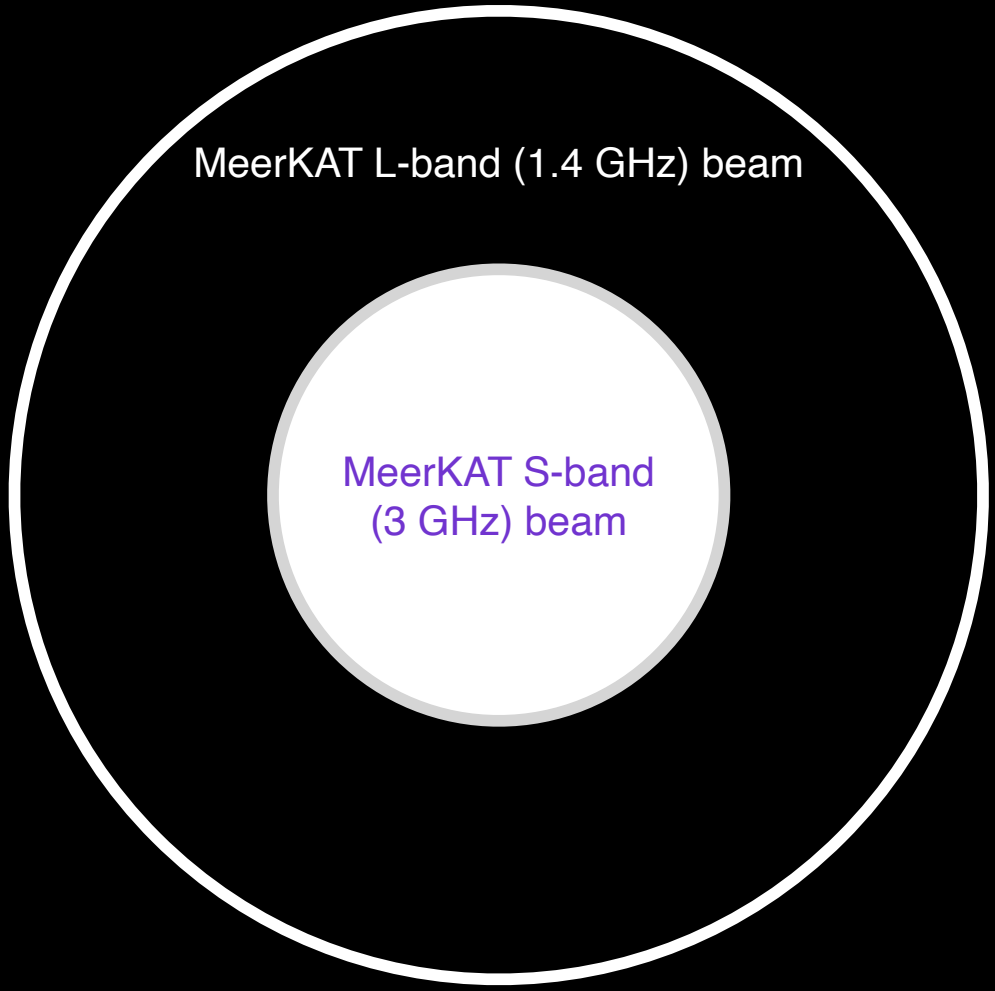
Part of the ThunderKAT project (PIs Rob Fender [Oxford])
and Patrick Woudt [Cape Town])

Movie credits Alex Andersson and Fraser Cowie, Oxford

RESOLVING JETS WITH MEERKAT

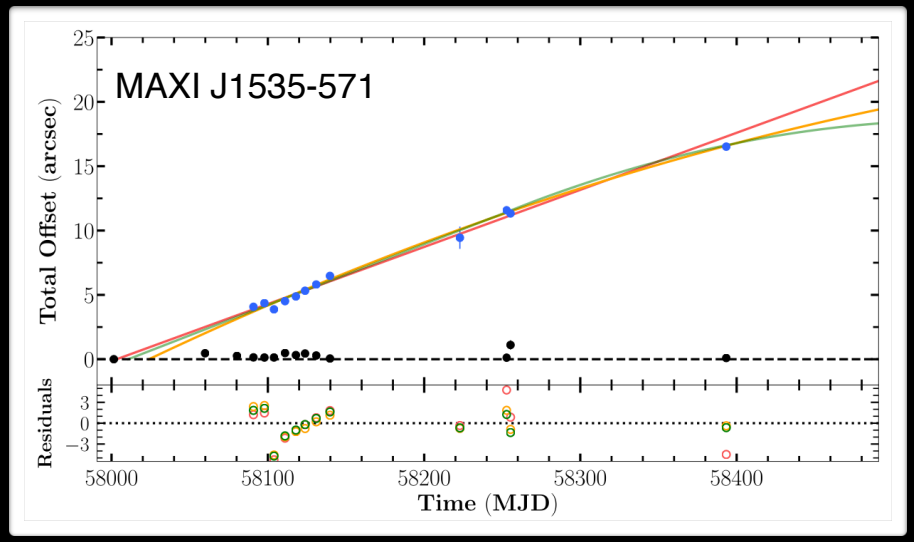


Mirabel & Rodríguez (1994)

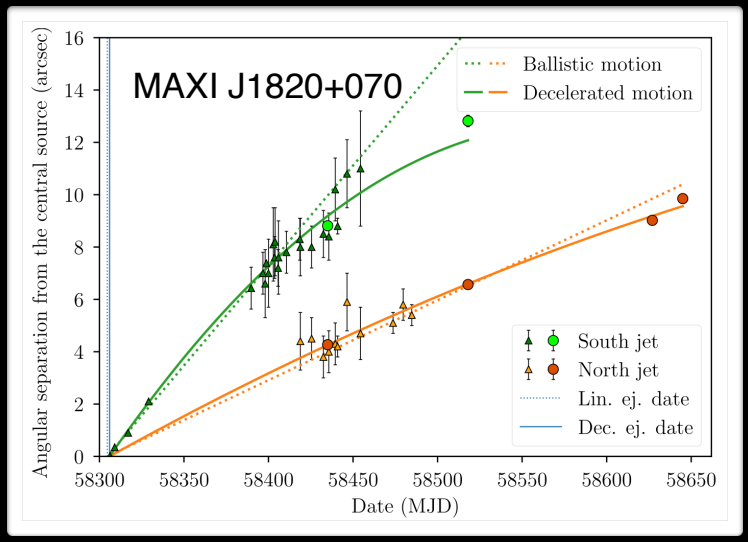


THUNDERKAT LARGE-SCALE JETS

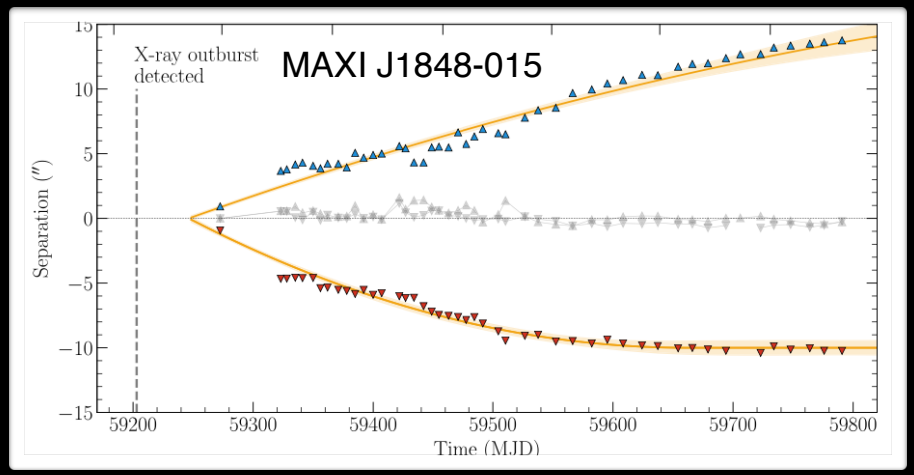
→ Omnipresence of large-scale jets from black hole X-ray binaries



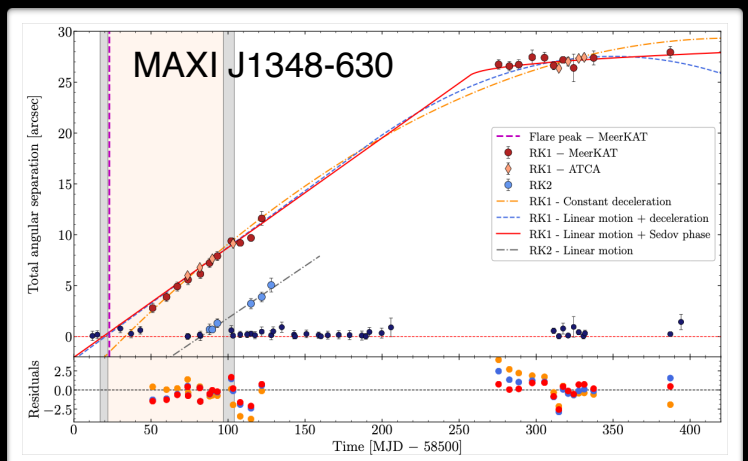
Russell et al. (2019)



Espinasse et al. (2020)

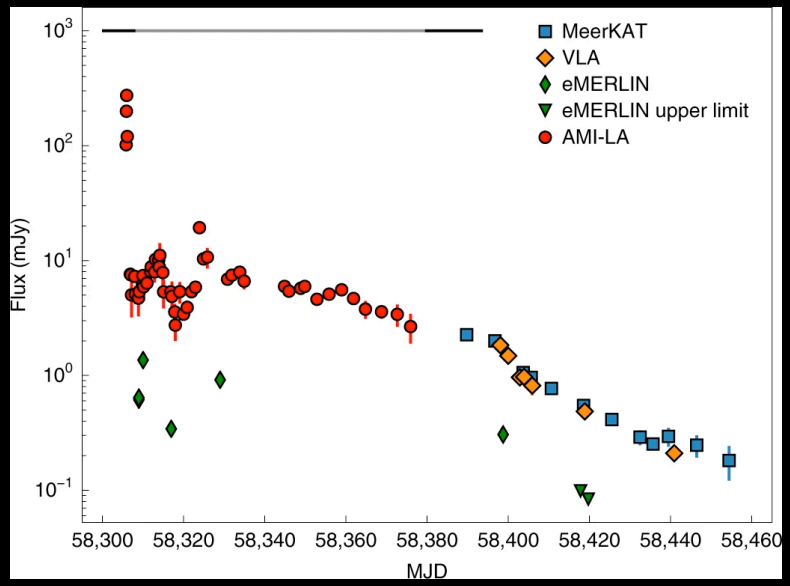


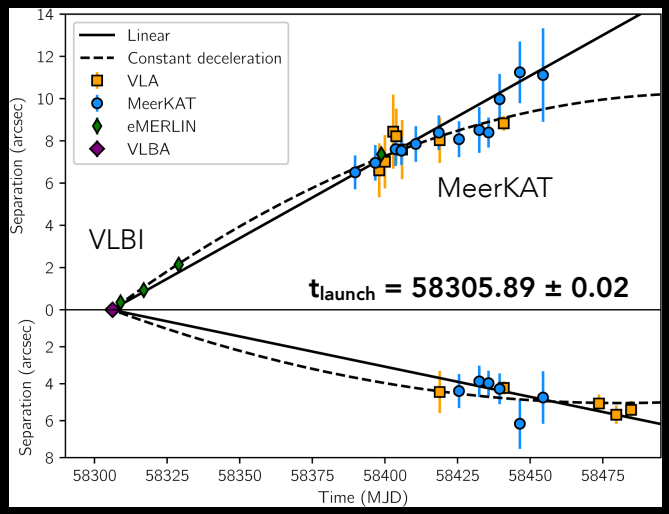
Bahramian et al. (2023)



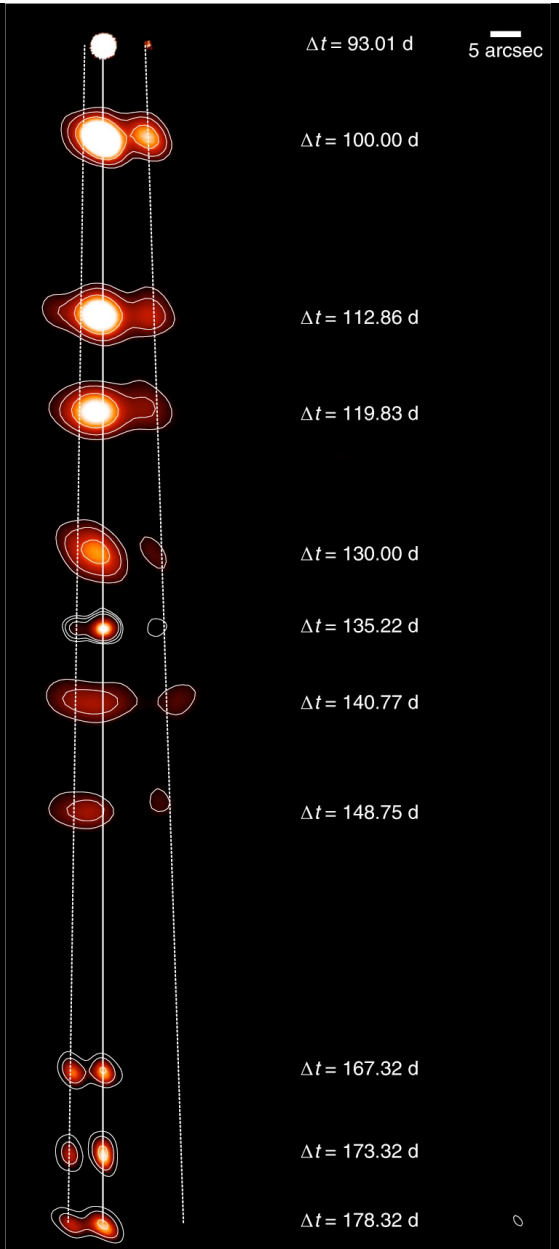
Carotenuto et al. (2021)

AN EXTREMELY POWERFUL LONG-LIVED SUPERLUMINAL EJECTION FROM THE BLACK HOLE MAXI J1820+070



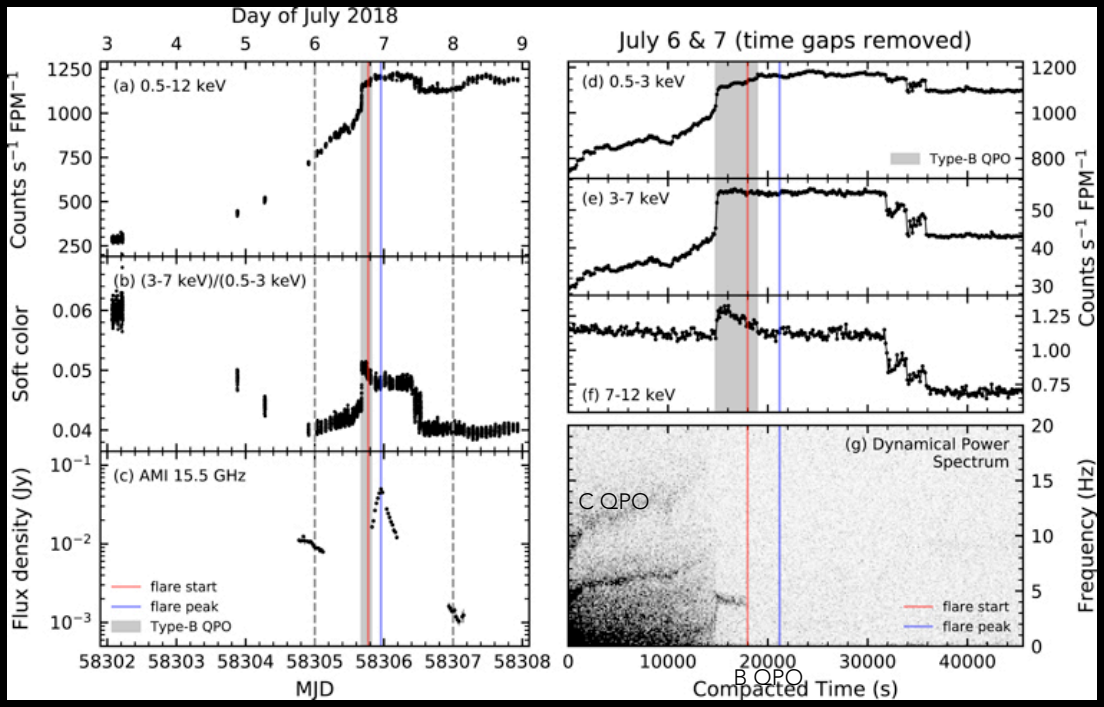


Bright et al. 2020

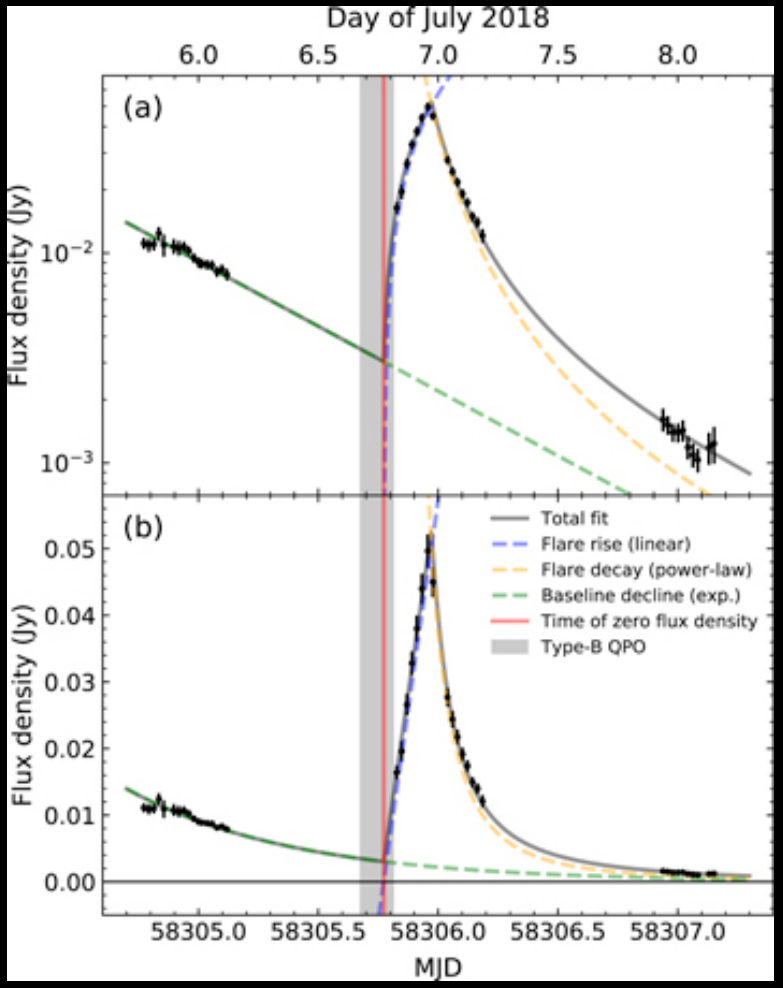


- An isolated radio flare, resolved over 200 days timescale, superluminal, $\Gamma > 1.7$ ($v > 0.8c$)
- Size —> lower lim. to the internal energy : 2.1×10^{41} erg < E < 1.5×10^{43} erg: **orders of magnitude larger than the internal energy associated with the radio flare**

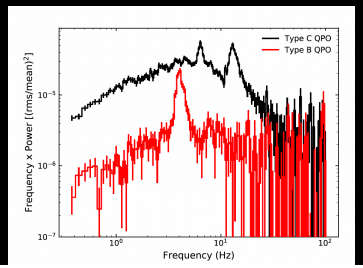
X-RAY VARIABILITY AND EJECTION



Homan et al 2020



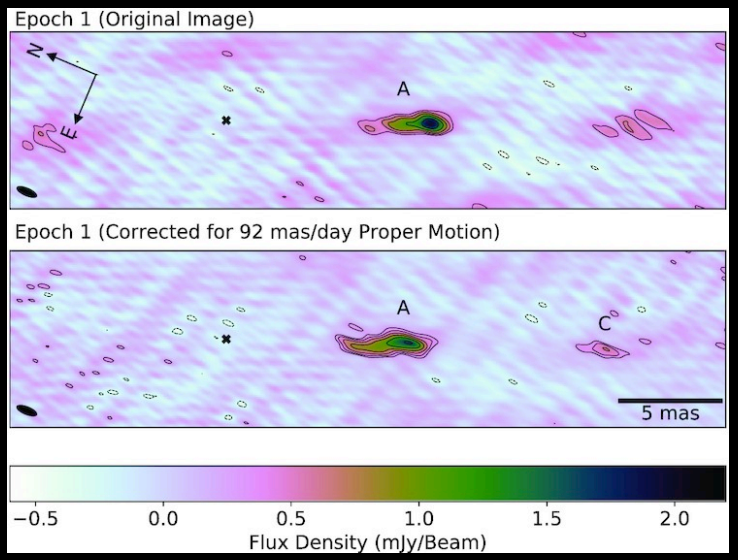
- **NICER**: Hard to soft state transition with QPO evolution type C to B + drop in rms variability + brief flare
- The most promising observational X-ray markers of discrete jet ejections in transient BH LMXBs ? See also Miller-Jones et al. (2012) and Russell et al. (2019) for H1743-322 and MAXI J1535-571.

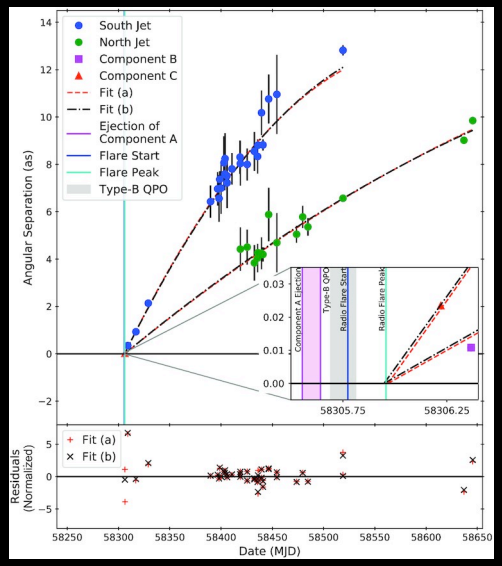


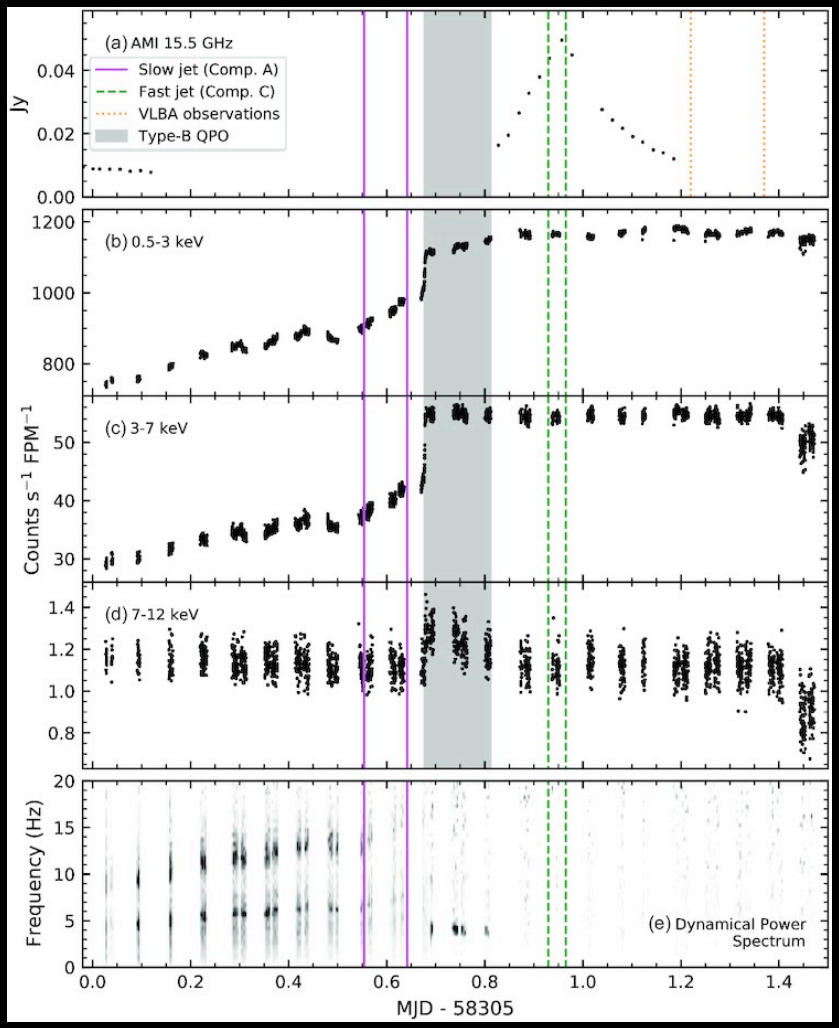
See also P28 from K. Yamaoka

FAST VLBI IMAGING

Wood et al. 2021



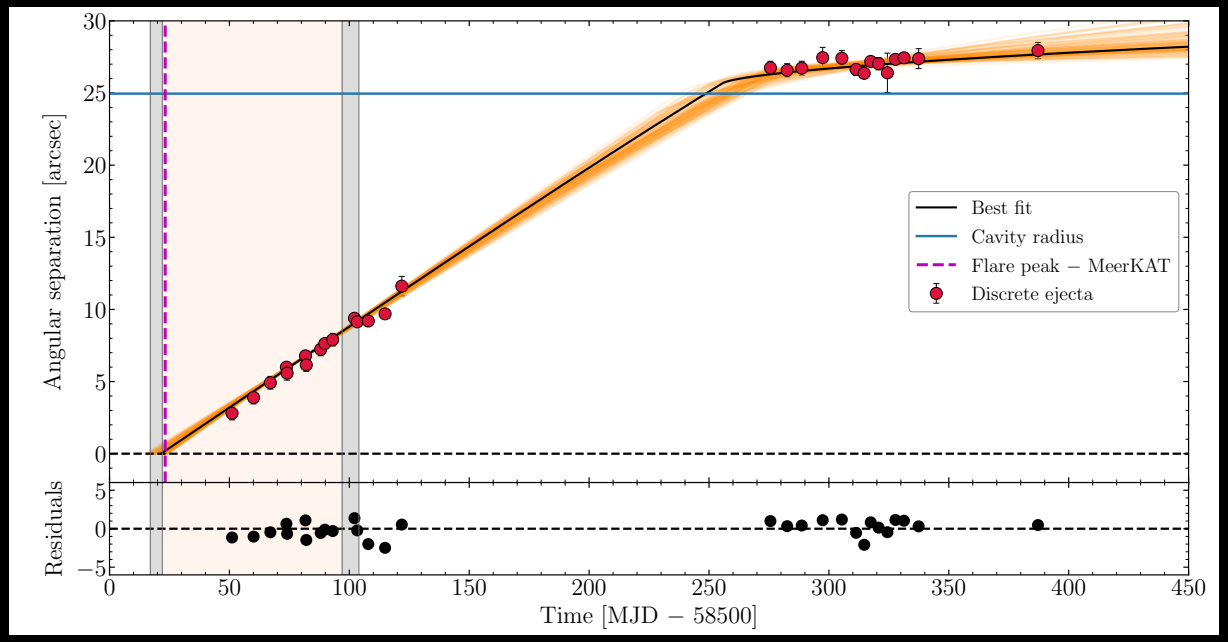


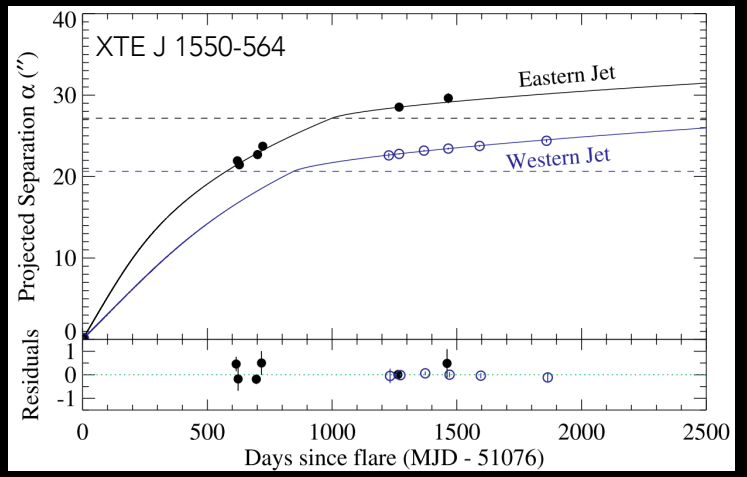


- New VLBI technic for fast imaging (Wood et al 2021). See AT
- Identification of an earlier and slower ejection (0.30c) and 0.97c for the fastest one ($\Gamma > 2.1$)
- Approaching slow-moving component —> radio flare, likely linked to the switch from type-C to type-B QPOs.
- No definitive signature for the fast moving ejecta !

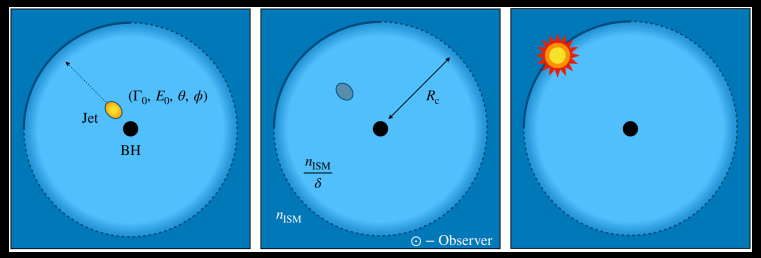
Wood et al. 2021

MORE POWERFUL JETS BASED ON LARGE SCALE JETS DETECTION





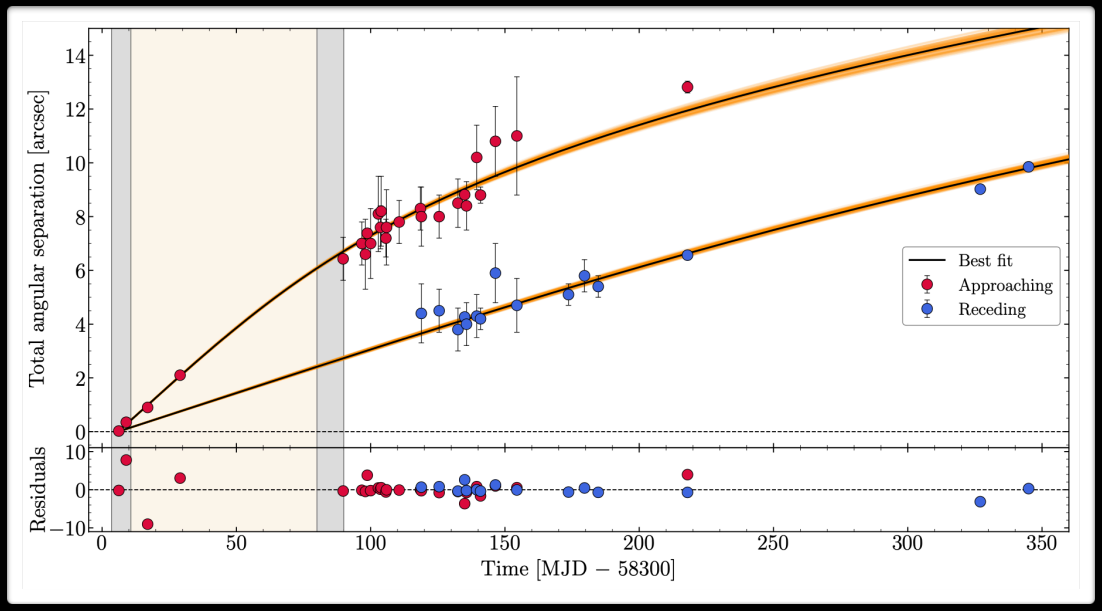
Corbel et al. 2002, Steiner et al. 2012



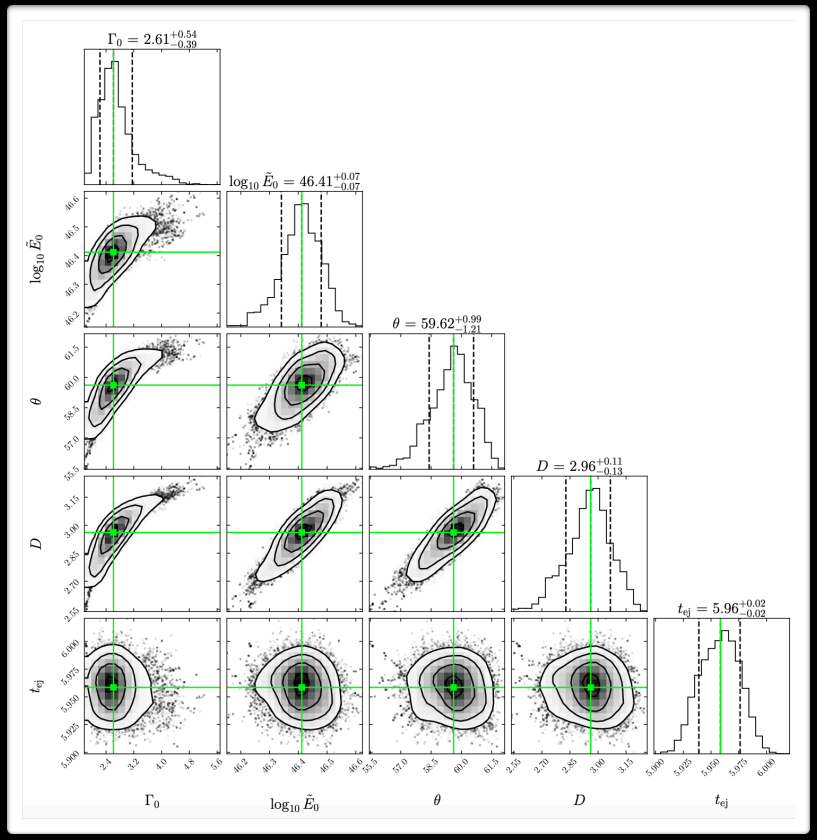
- Powerful jets in MAXI J1348-630 (Carotenuto et al. 2022b) , but ~ n_{ISM} . Φ^2 !
- Jet initial Lorentz factor $\Gamma_0 = 1.85^{+0.15}_{-0.12}$. We infer that MAXI J1348–630 is likely embedded in an ISM cavity with low internal density (similar to XTE J1550-564).

MODELING THE JET DYNAMICS

- **Jet dynamical model** based on **plasmon adiabatic expansion** (Wang et al. 2003)
- **Kinetic energy** is transferred to the swept up material via **external shocks**, in analogy with GRB afterglows
- Bayesian approach to fit the proper motion and infer physical parameters

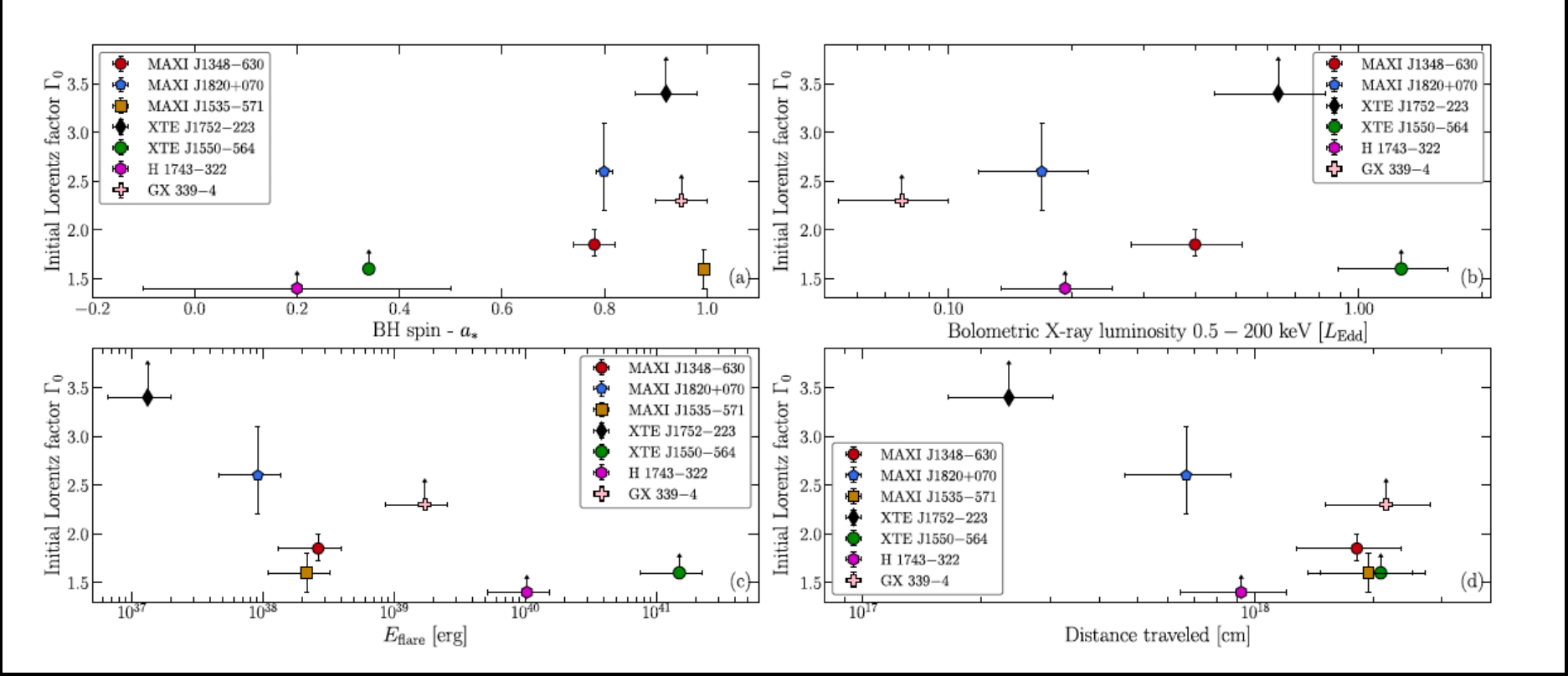


Carotenuto et al. (2024)



$\Gamma_0 = 2.6^{+0.5}_{-0.4}$ + geometrical parameters

$n_{\rm ISM} \leq 1 \times 10^{-3}$ cm^{-3} → **Low-density cavity?**

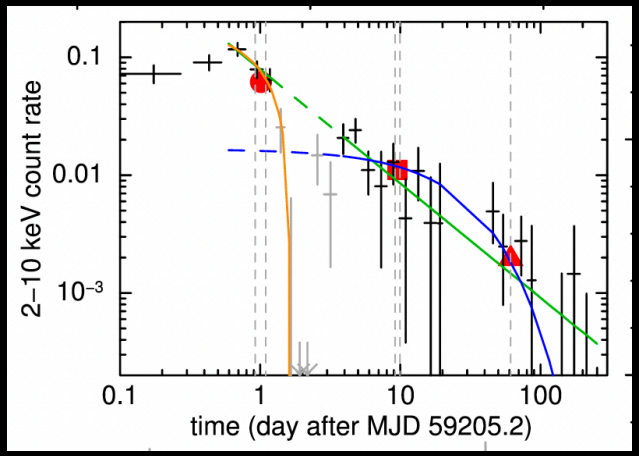


- **Comparison between the inferred initial Lorentz factor Γ_0 of the ejecta** in our sample of large-scale jets the **dimensionless spin parameter**, the **bolometric X-ray luminosity**, the **jet frame internal energy flare** inferred from the radio flare associated to each ejection, the **de-projected distance** traveled by the jet. We find **no clear correlation and more sources are needed to increase the sample of large-scale jets.**

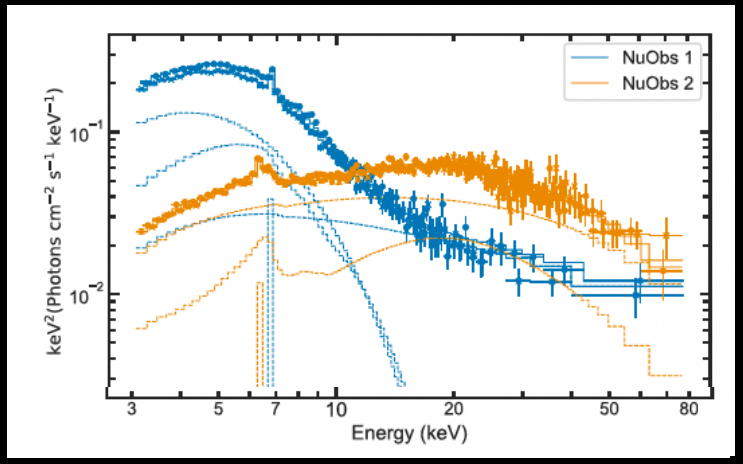
MAXI J1848-015

- **X-ray binary**, discovered in outburst in **December 2020** by **MAXI** (Takagi et al. 20) (while the source was Sun-constrained for almost all other telescopes).

MAXI Lightcurve



Pike et al. 2022



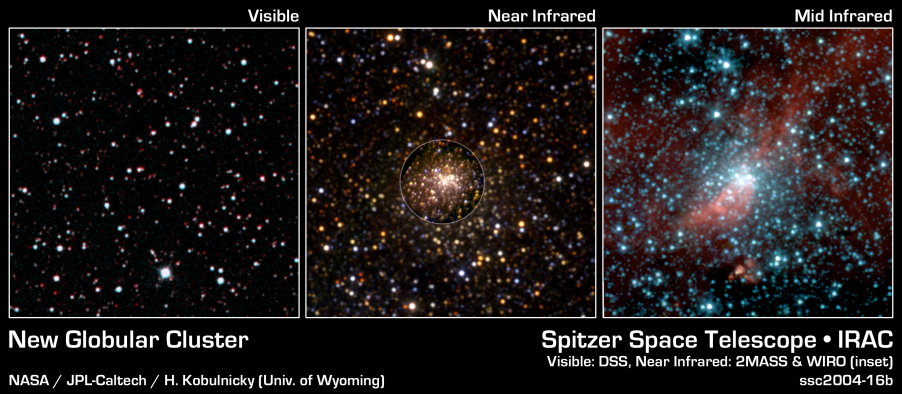
- **NuSTAR** observations (Pike et al. 2022) : State transition (soft, hard), relativistic reflection features, high spin (a = 0.967 +/- 0.013) —> **A black hole candidate ?**

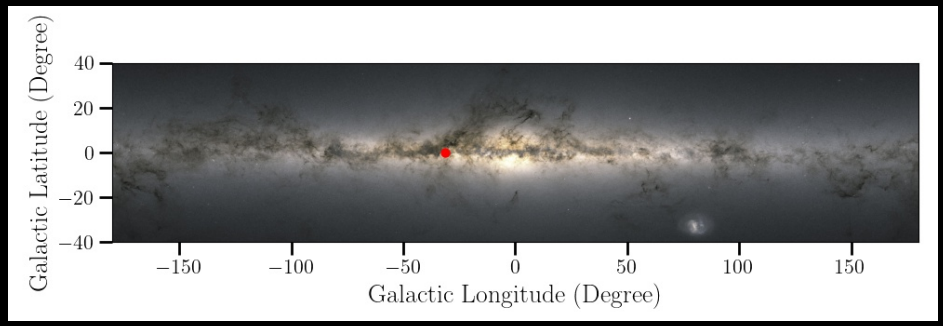
- Early February 2021: **Swift+Chandra** follow-up -> **located in the core of the cluster GLIMPSE-C01** but not coincident with any of the X-ray sources (e.g. Chakrabarty et al. 21).

- Short duration outburst. Radio counterpart (Tremou et al. 21) —> likely radio jets

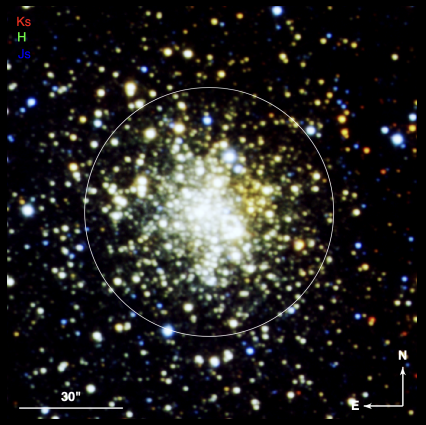
GLIMPSE-C01

- **GLIMPSE-C01**: A poorly understood globular cluster in the Galactic plane with Spitzer (Kobulnicky et al. 05).

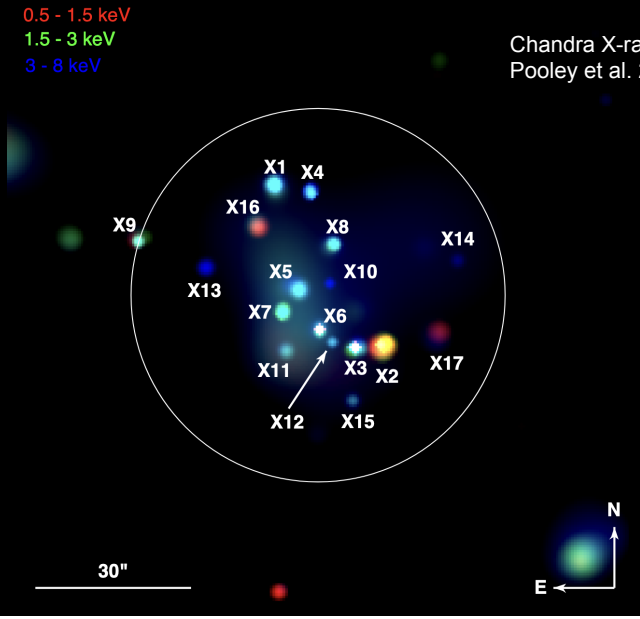




- Distance from us ~3.3 kpc , from the midplane ~ 6pc.
- Heavily extinguished (Av ~15 mag.), ~10^5 $M_\odot$
- Large population of X-ray sources (Chandra)
- A GC passing through the Galactic plane ?
- More compact than typical GC
- A rare intermediate age cluster ?



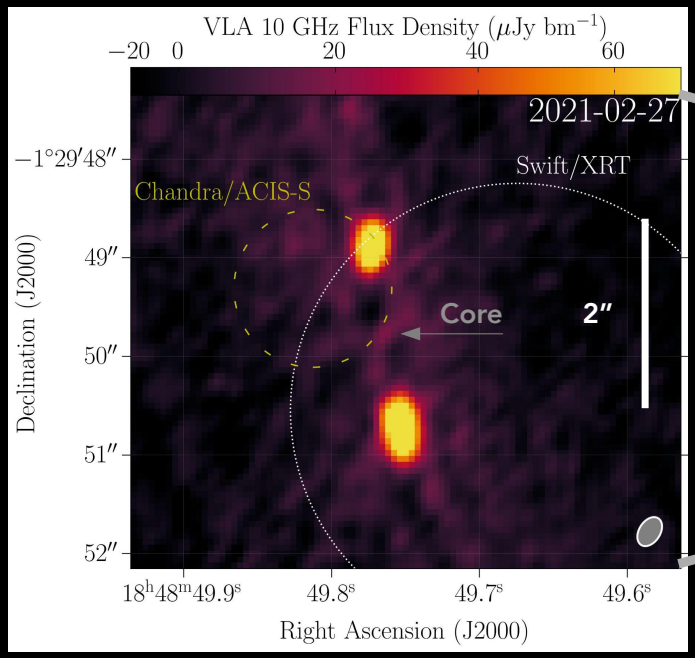
NNT-NIR
Ivanov et al. 2005

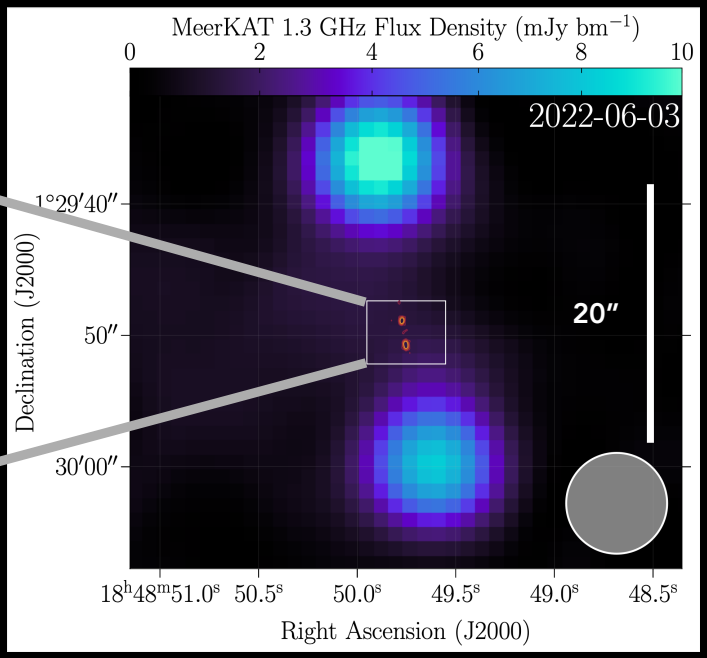


Chandra X-rays
Pooley et al. 2007

MAXI J1848-015

- Late February 2021: VLA observation, beginning of MeerKAT monitoring
- Detection of two moving jets over more than 2 years (active for 3 years)

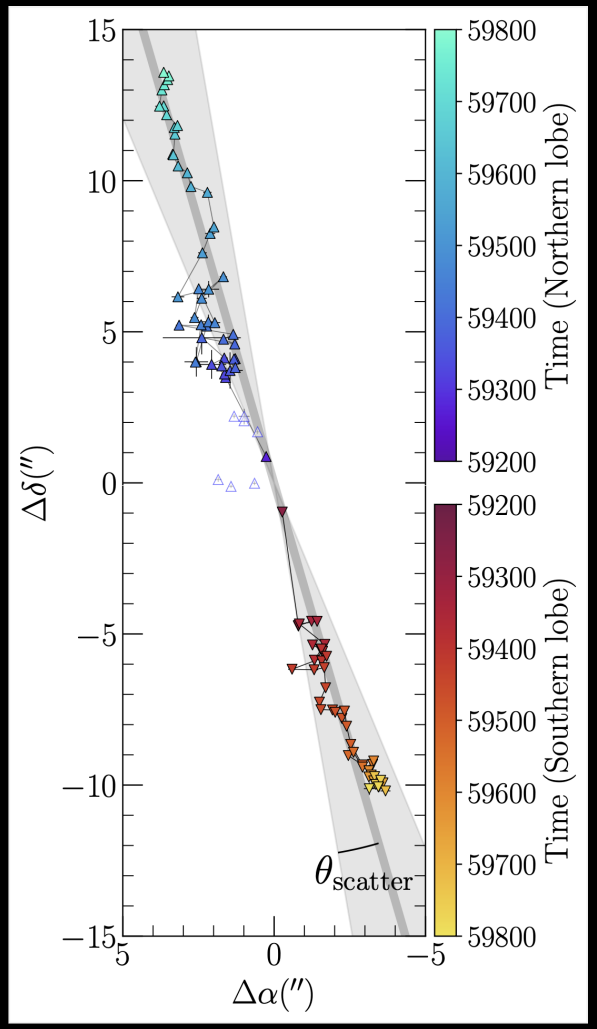


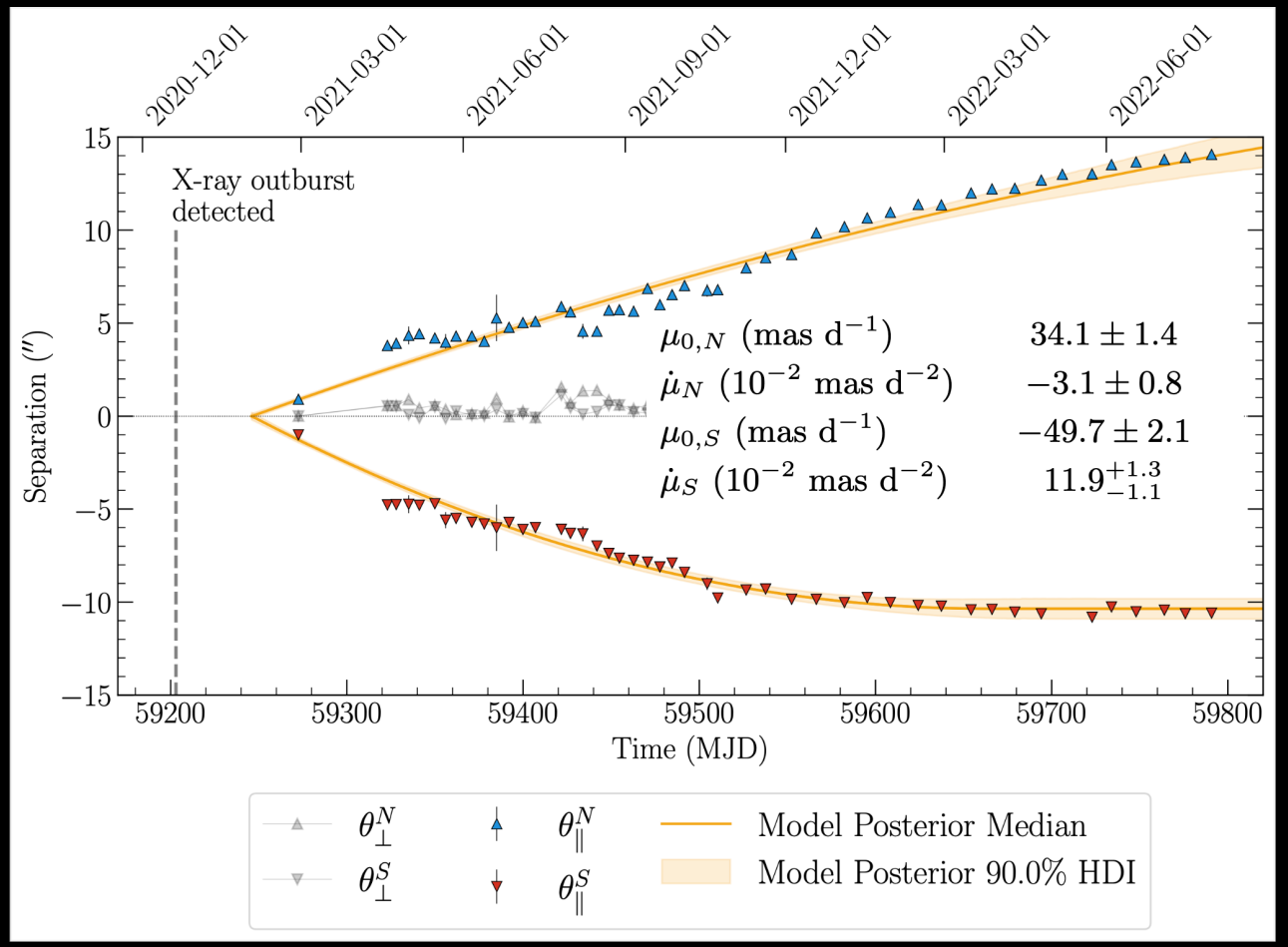


VLA A-config obs in Feb 2021

Bahramian et al., in press

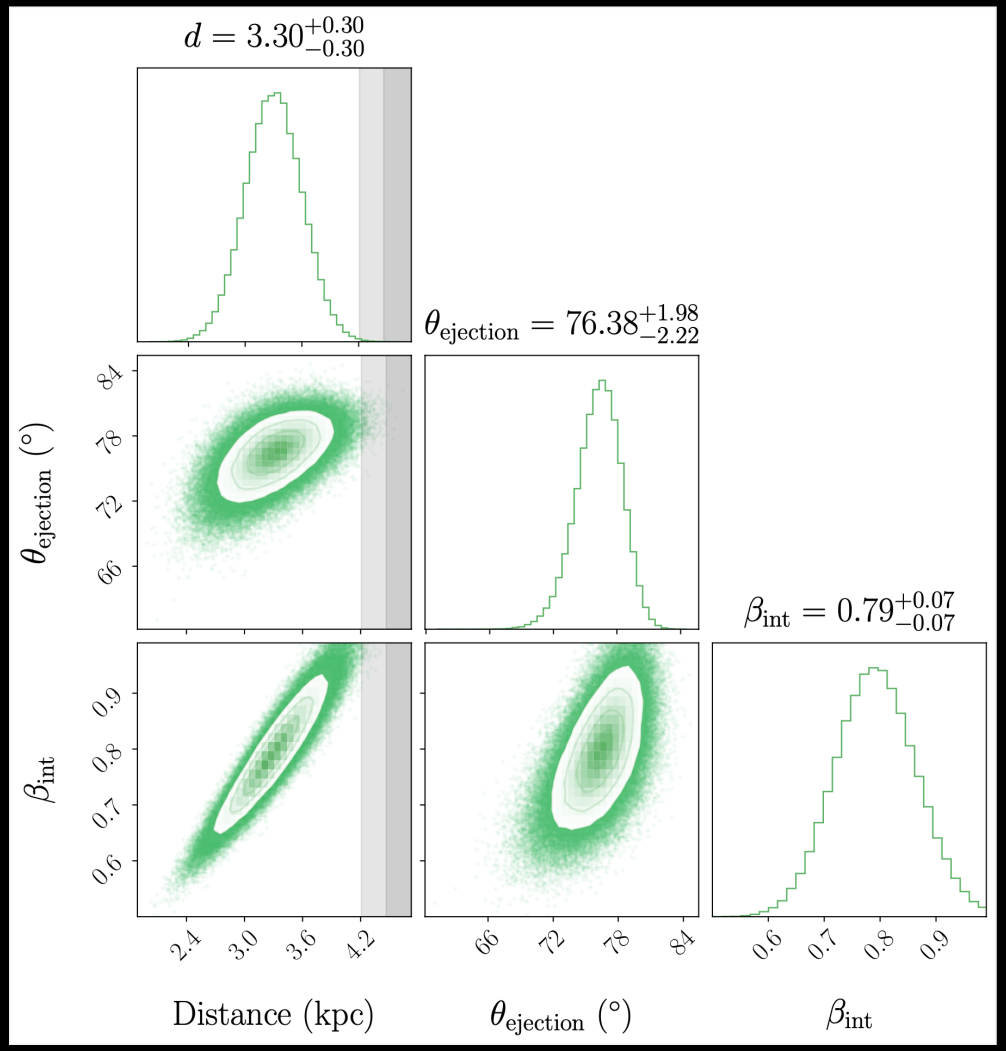
MODELLING THE JETS PROPER MOTION





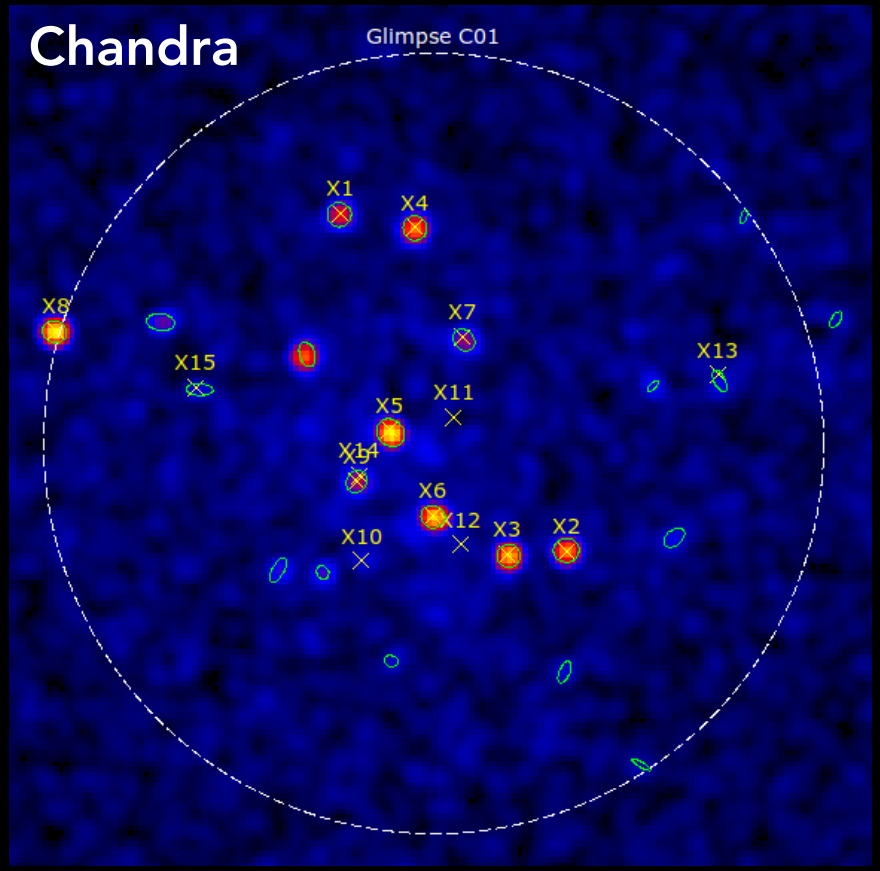
Bahramian et al. 2023

- Max **distance** from the jets : 4.2 kpc
- Assuming 3.3 kpc (distance to Glimpse-01):
  - Jet angle: 76 degrees
  - **Intrinsic β = 0.79**
- First conclusions from the MeerKAT monitoring:
  - **First relativistic jets detected from an XRB in a GC (Bahamian et al. 2023)**
  - Probing Jet-ISM interaction in an exotic environment
  - **Extended campaign with Chandra and VLA (4 to 18 GHz) (PI: Corbel) + archival Chandra data**

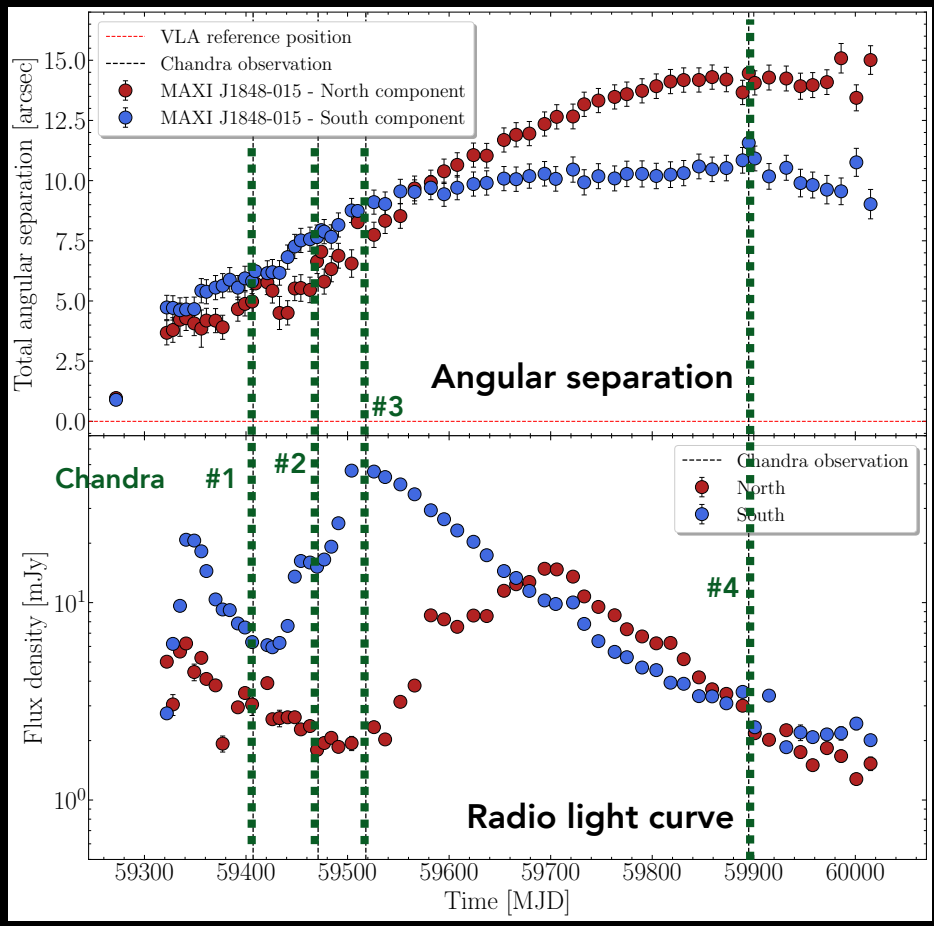


Bahramian et al. 2023

GLOBAL CONTEXT OF THE CHANDRA/VLA CAMPAIGN



Archival 180 ks Chandra ACIS-S with X sources from Hare et al. (2018)
Some new X-ray sources, but no X-ray source at core location
New Chandra data registered to X1, X2, X3, X4 and X5 sources
Sub-pixel analysis

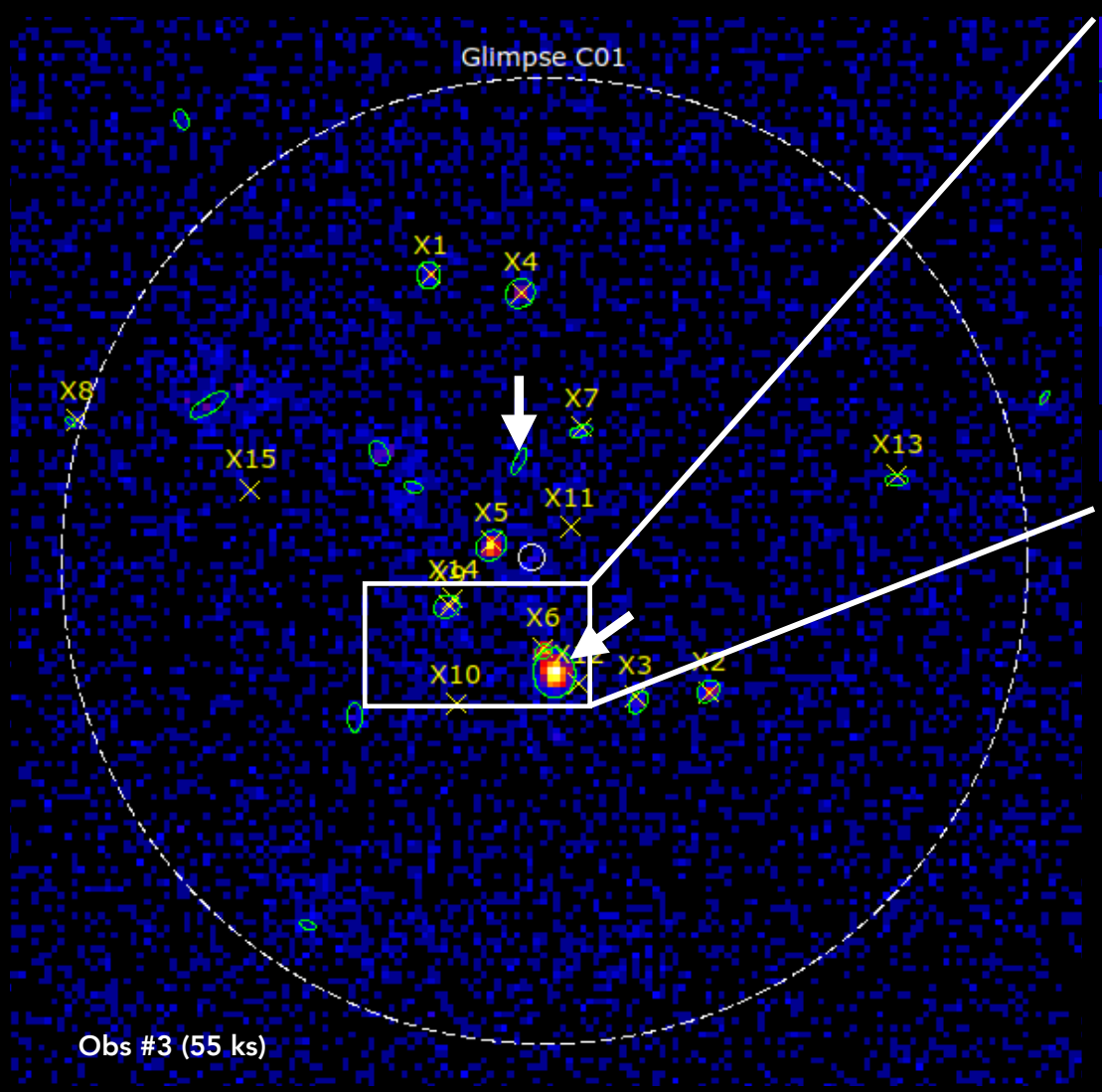


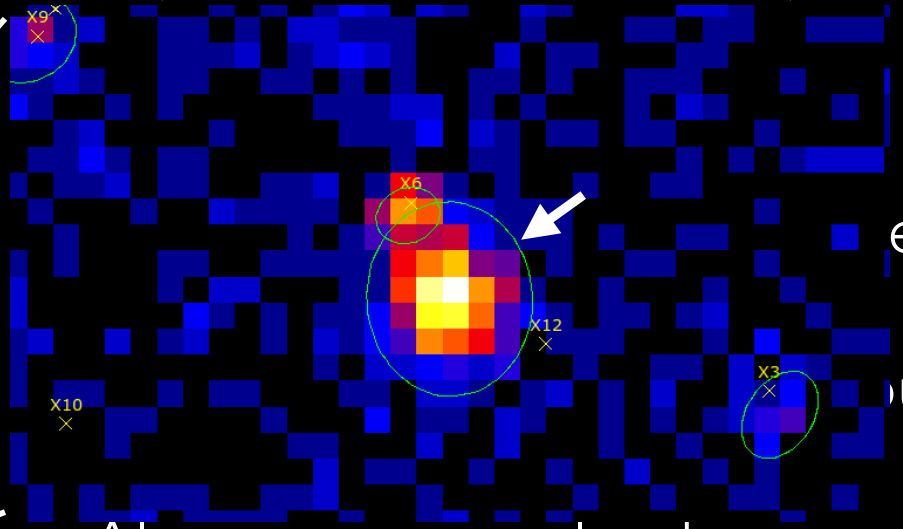
2021 2023

MeerKAT

Tremou et al. (in prep.)

MOVING X-RAY JETS (ONE EXAMPLE)





ets

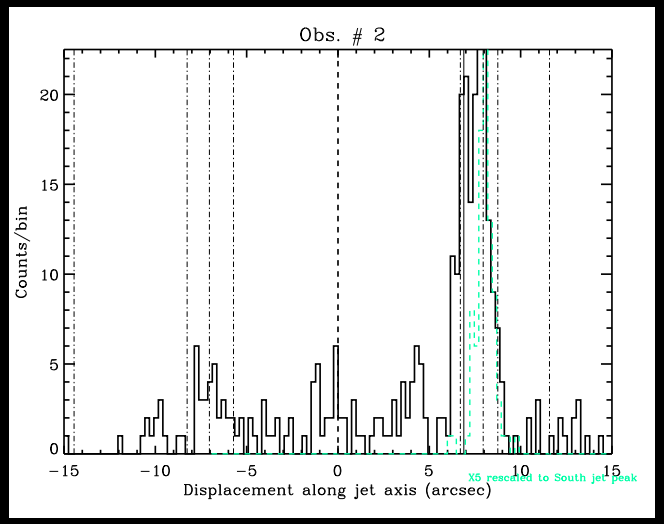
urces

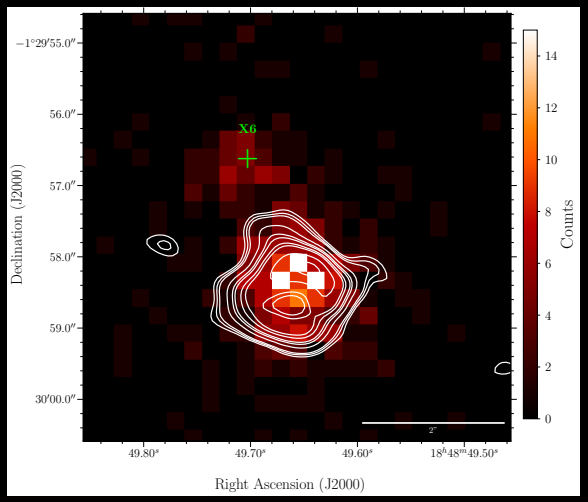
- Also appear resolved
- Discovery of moving X-ray sources associated with both radio jets, extended ?

Corbel et al. (submitted)

THE JETS ARE RESOLVED

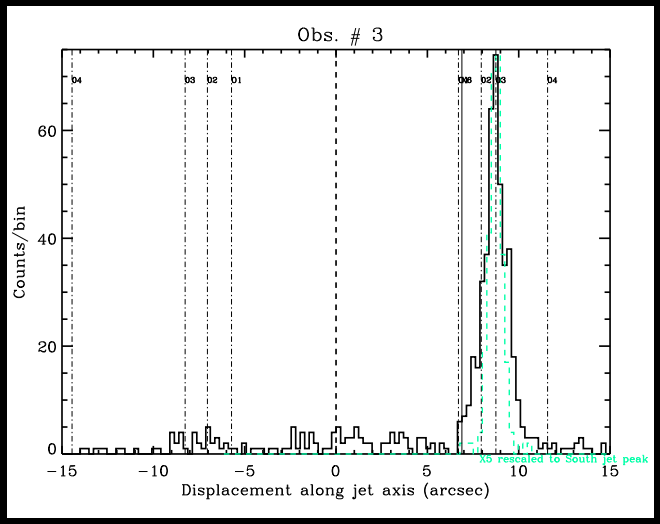
X-ray profile for South jet in Obs #2

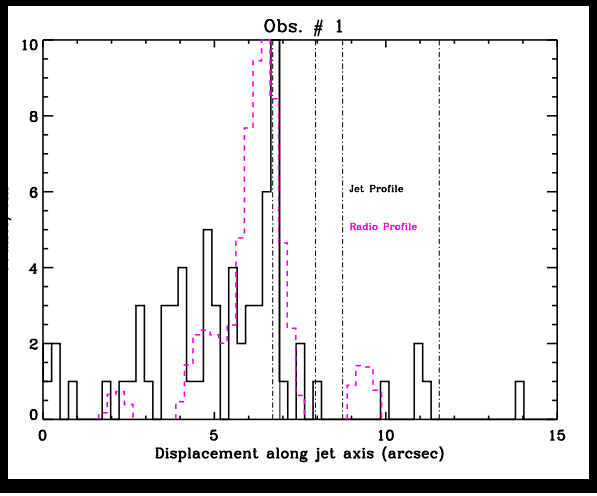




VLA / Chandra South Obs #3

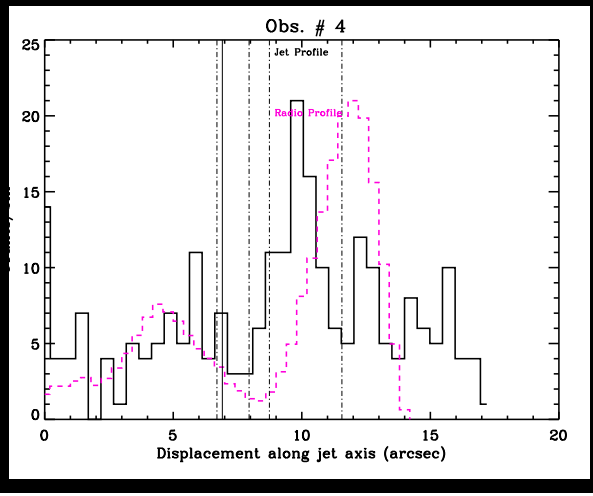
X-ray profile for South jet in Obs #3



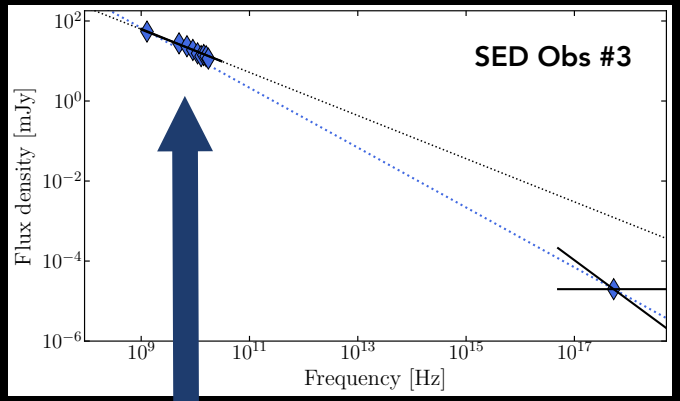


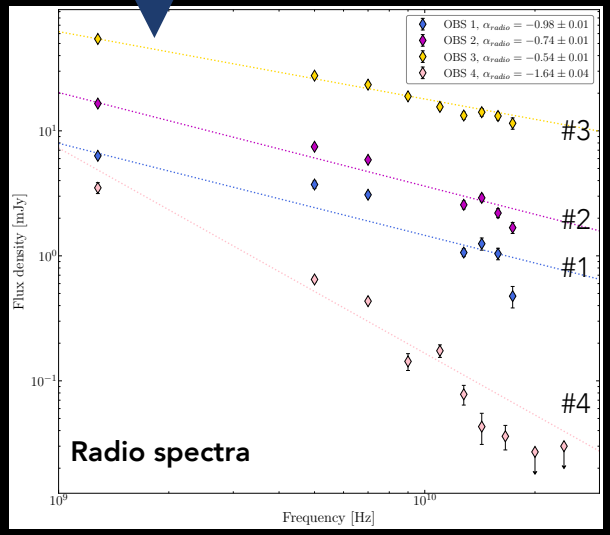
- X-ray jets = a head + a 3″ extended tail
- Complexe evolution of the radio to X-ray profiles

Corbel et al. (submitted)



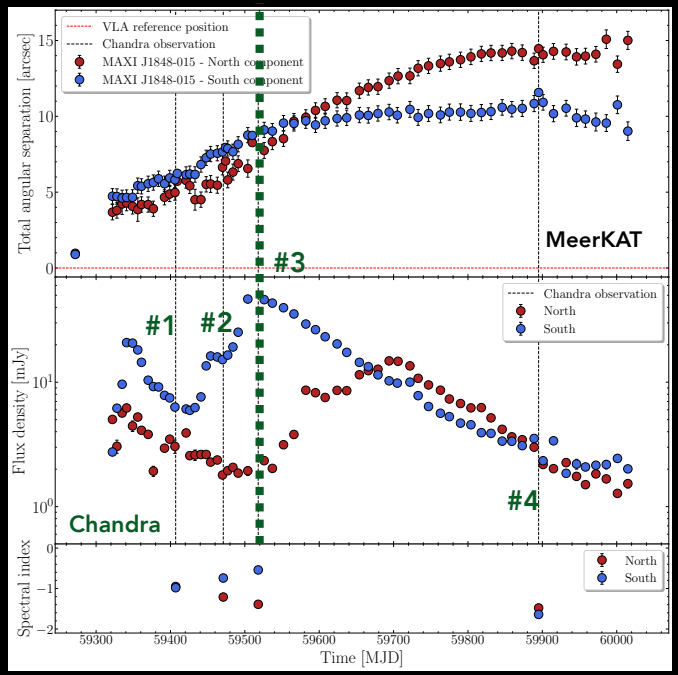
SED ON OBS #3 (SOUTH JET)





Corbel et al. (submitted)

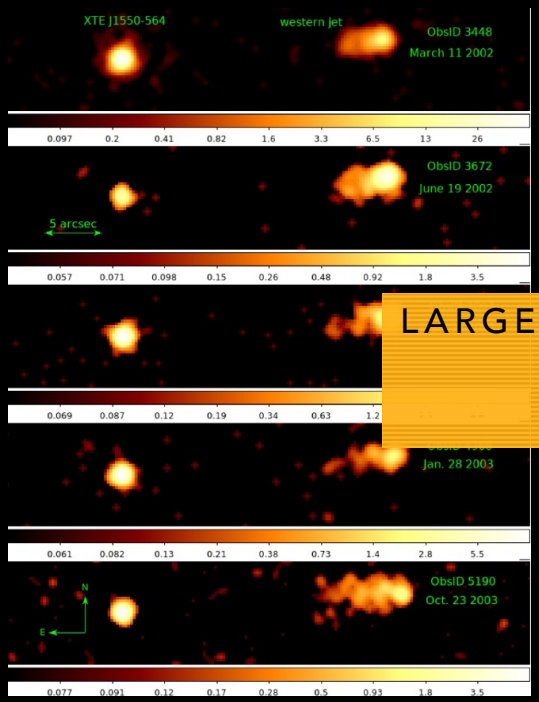
- SED for Obs #3 is consistent with **synchrotron emission**
- Under **equipartition**:
  - Minimum internal energy ~10^{43} erg
  - Magnetic field ~0.5 mGauss
- X-rays synchrotron —> **electrons with E ~ 10s TeV**
- But some more **complicated and steep radio spectra** for the others observations and North jet —> May need 2 diff. populations of electrons, consistent with reverse and forward shocks.



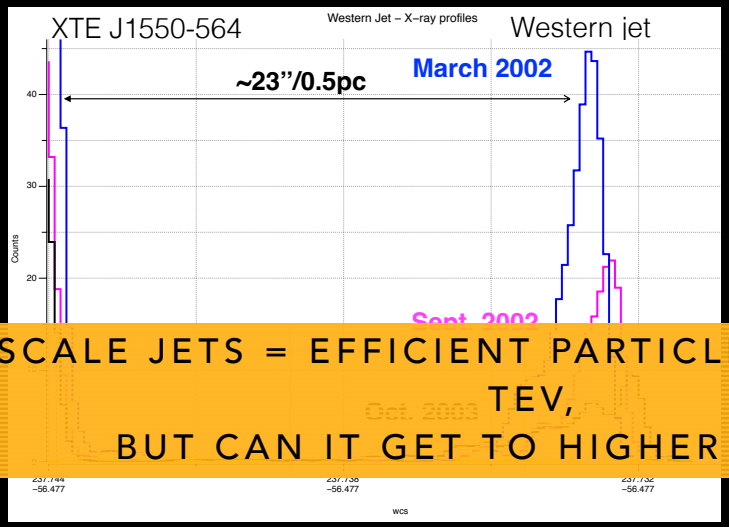
Tremou et al. in prep

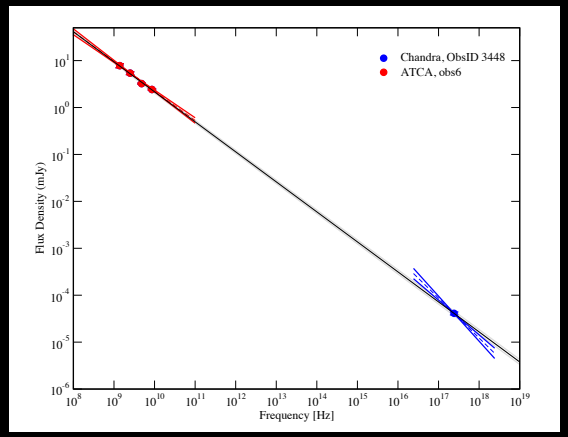
COMPARISON WITH OTHER SOURCES

XTE J1550-564

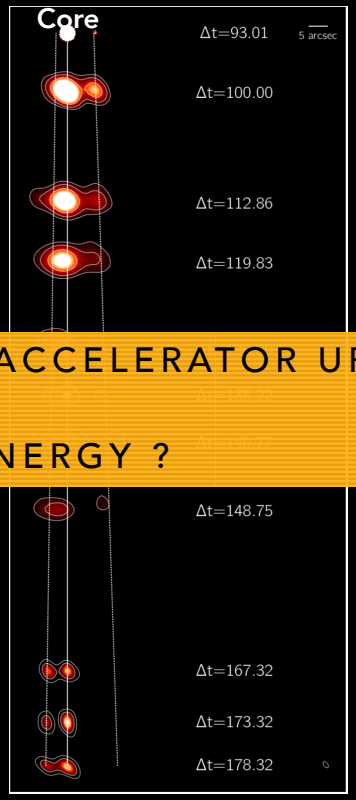


Corbel et al. 2002, Migliori et al. 2017



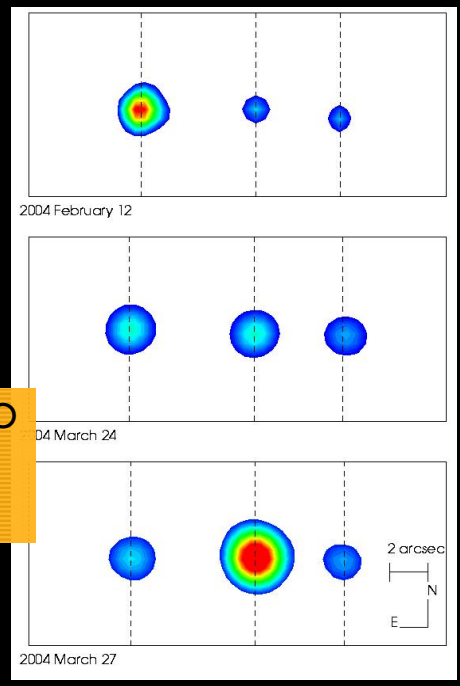


Bright et al. 2020



S. J **N. J** MAXI J1820+070

H 1743-322



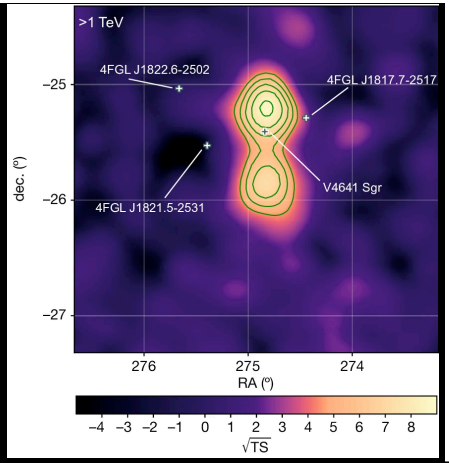
Corbel et al. 2005

LARGE SCALE JETS = EFFICIENT PARTICLE ACCELERATOR UP TO TEV,
BUT CAN IT GET TO HIGHER ENERGY ?

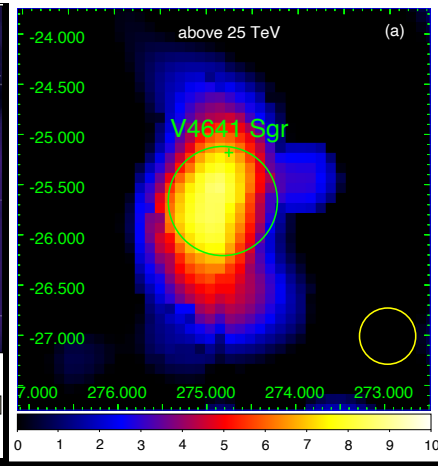
Derived numbers (Obs #3) consistent with all previous examples, but differing behaviour for other dates

LARGE SCALE JETS AS COSMIC ACCELERATORS ?

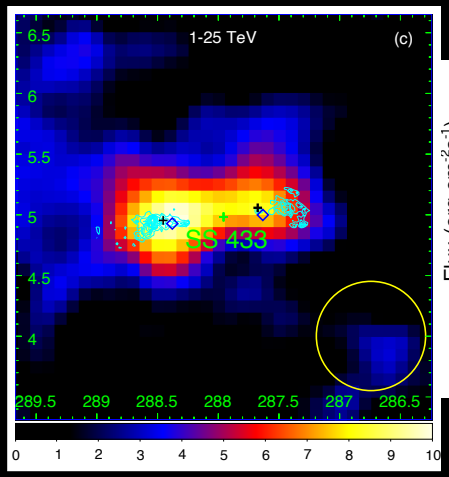
- **Ultra-high-energy gamma-ray bubble** around microquasar V4641 Sgr from **HAWK** (Alfaro et al. 2024) —> very hard spectrum up to 200 TeV.
- **LHAASO** Collab (Subm.):
  - V4641 Sgr : An extended source consistent with South HAWK source up to 0.8 PeV: « **super PeVatron** »,
  - SS433: Détection of VHE associated with jets interaction zones, **hadronic process** needed !
  - + detection of Cyg X-1, GRS 1915+105, MAXI J1820+070.
- **Large scale jets from microquasars as efficient cosmic accelerator up or even beyond the so called « knee » of the CR spectrum.**

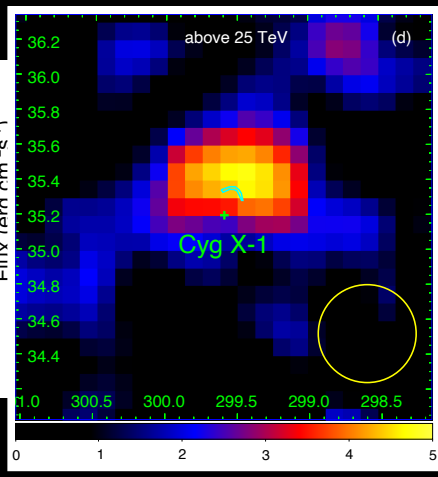


Alfaro et al. 2024 (**HAWK** cola.)



LHAASO Collaboration, subm.





LHAASO Collaboration, subm.

TAKE-AWAY MESSAGES

- Black hole (all ?, but not only NS too) X-ray binaries produce transient relativistic jets.
- MeerKAT, following Chandra and radio, has revealed the omnipresence of large-scale jets.
- **X-ray markers of the relativistic ejection(s) ?** Not there completely yet.
- **Powerful jets** based on calorimetry with ISM ? Probing feedback on environment?
- **First relativistic jets** detected from an **outbursting black hole candidate XRB in a globular cluster.**
- **Key role of MAXI** (as well as Swift/BAT) for detected those new transients.
- Large scale jets as efficient **cosmic accelerators** ? **Cosmic PeVatron** ?


Questions ?
質問 ?