

Relativistic jets from black hole X-ray binaries: an observational review

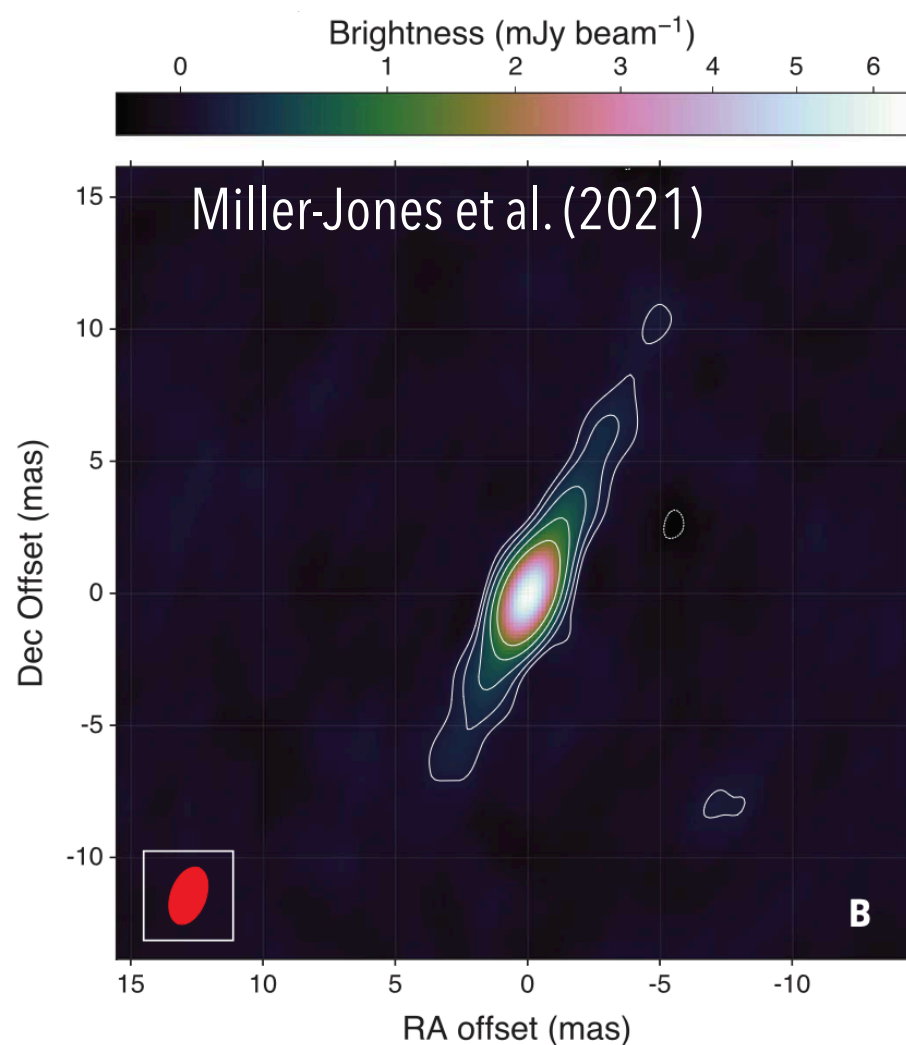
Francesco Carotenuto
INAF-OAR

11th Microquasar Workshop
17/09/2025

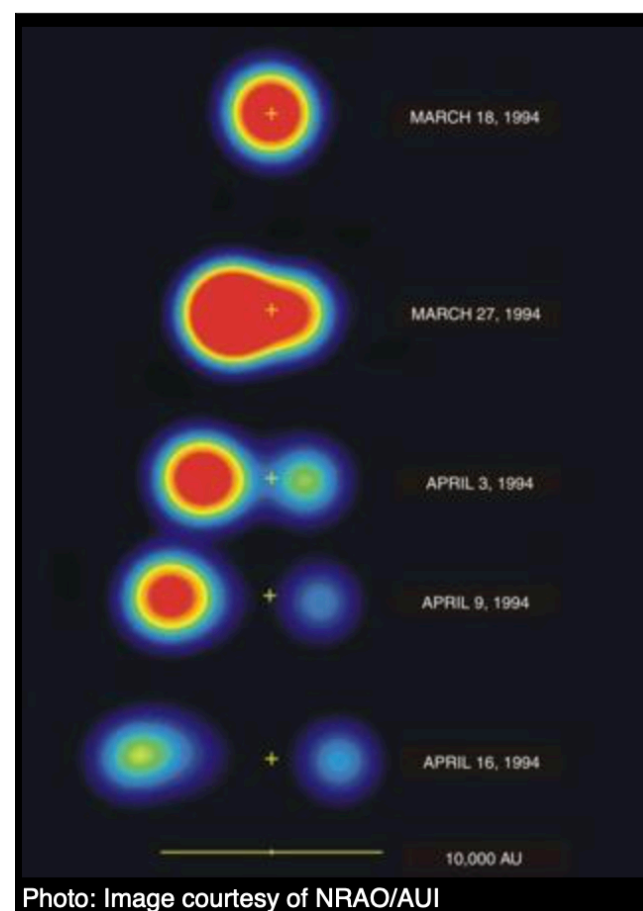


Different types of jets

Compact jets

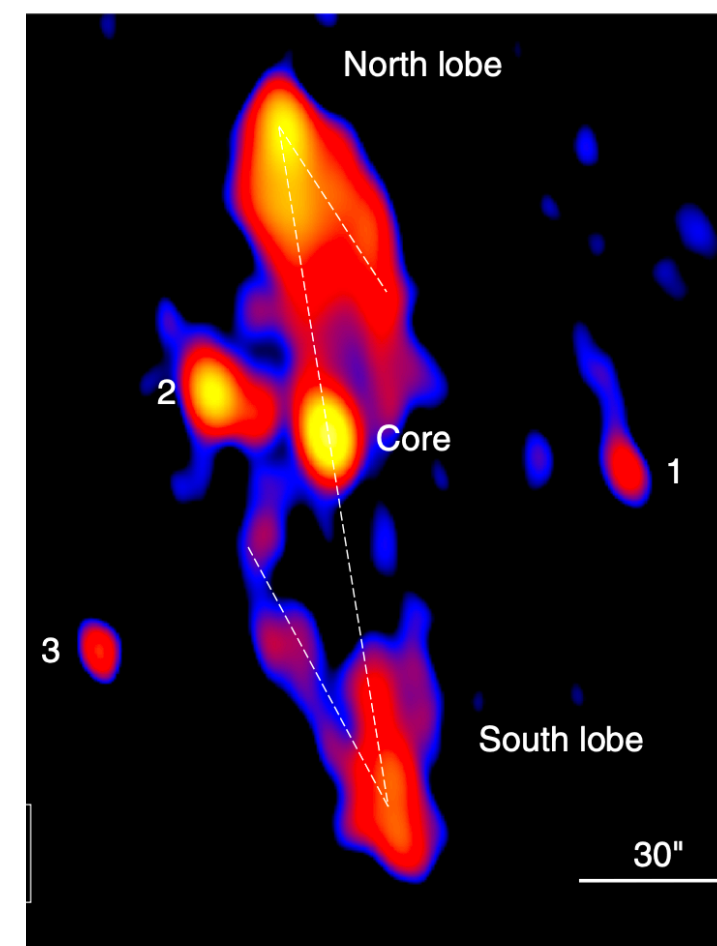


Discrete ejecta



Mirabel & Rodriguez (1994)

Large-scale persistent jets



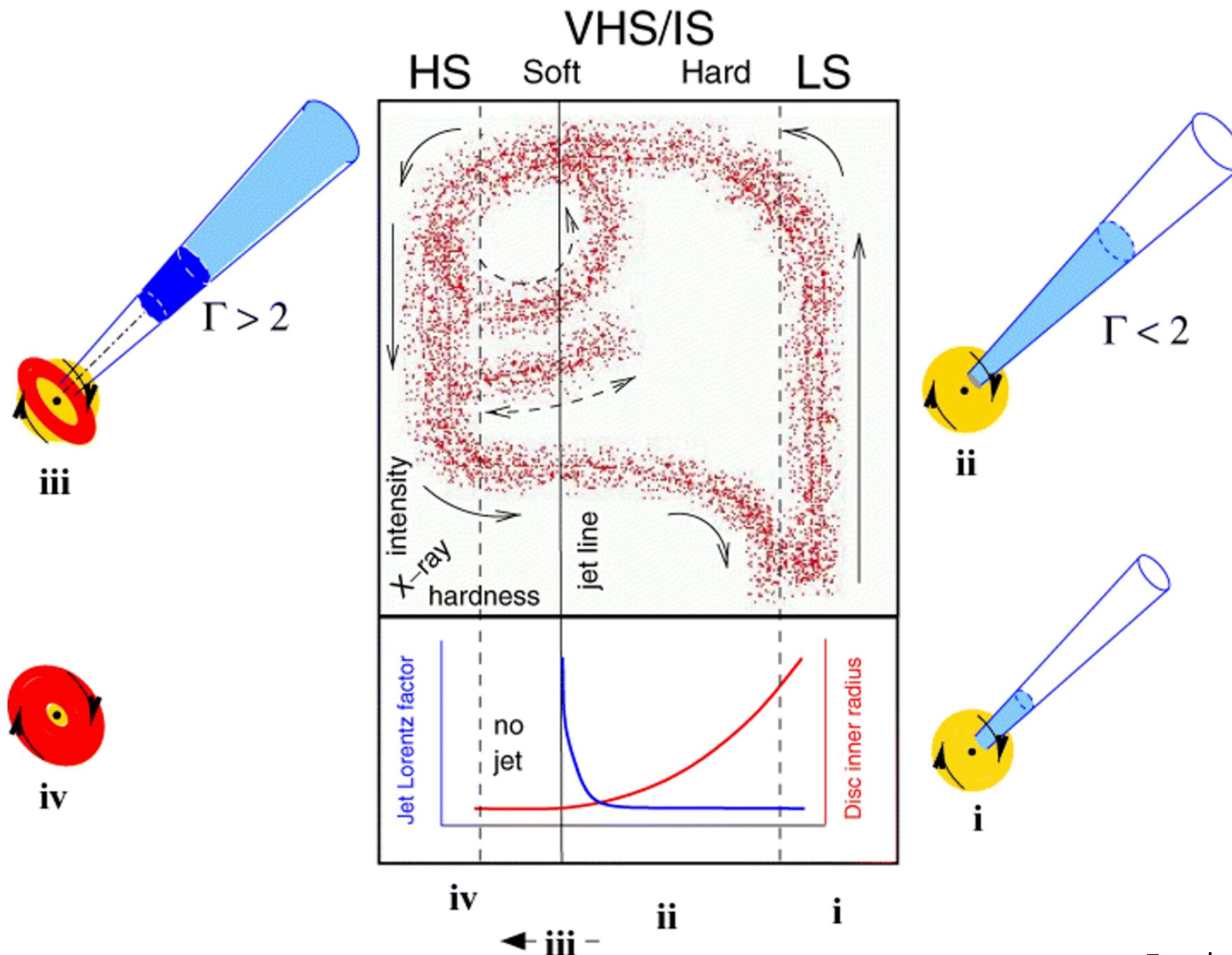
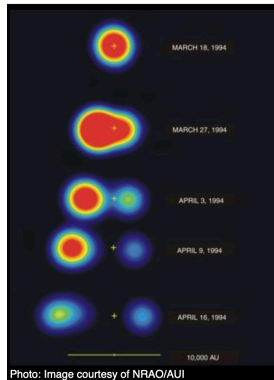
Martí et al. (2017)

See talk by **Isabella Mariani**!

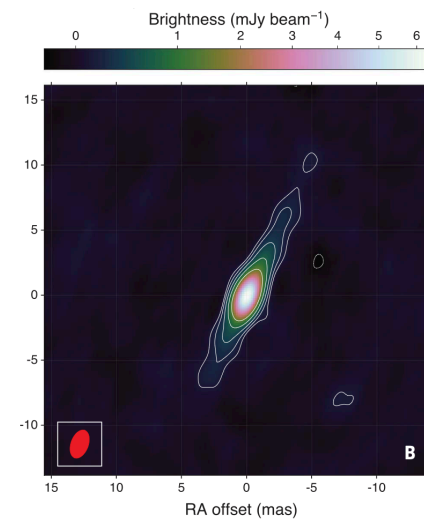
Outburst phenomenology

Compact jets and discrete ejecta are produced during different spectral/accretion states (Corbel et al. 2004, Fender et al. 2004).

Discrete ejections



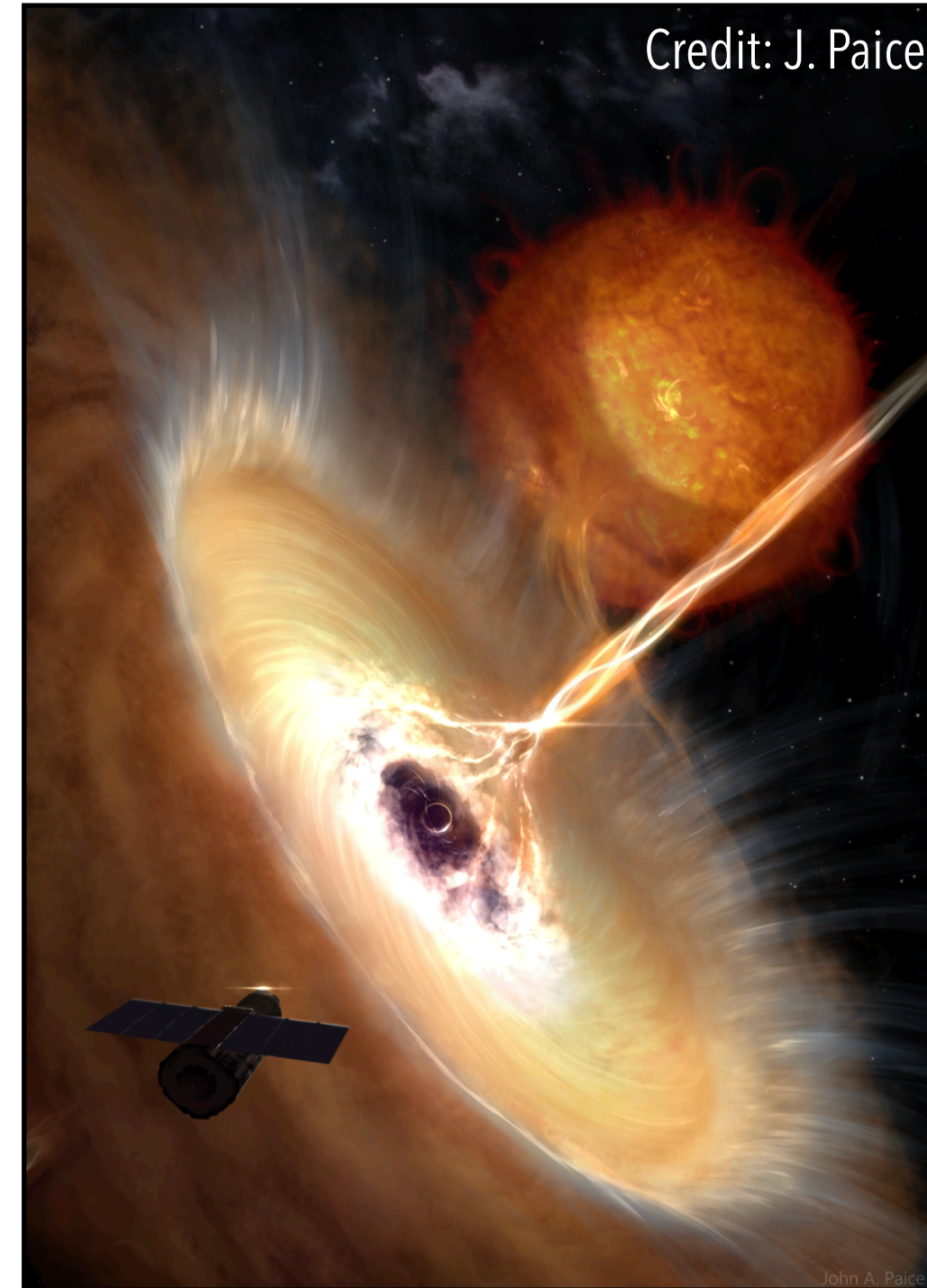
Compact jets

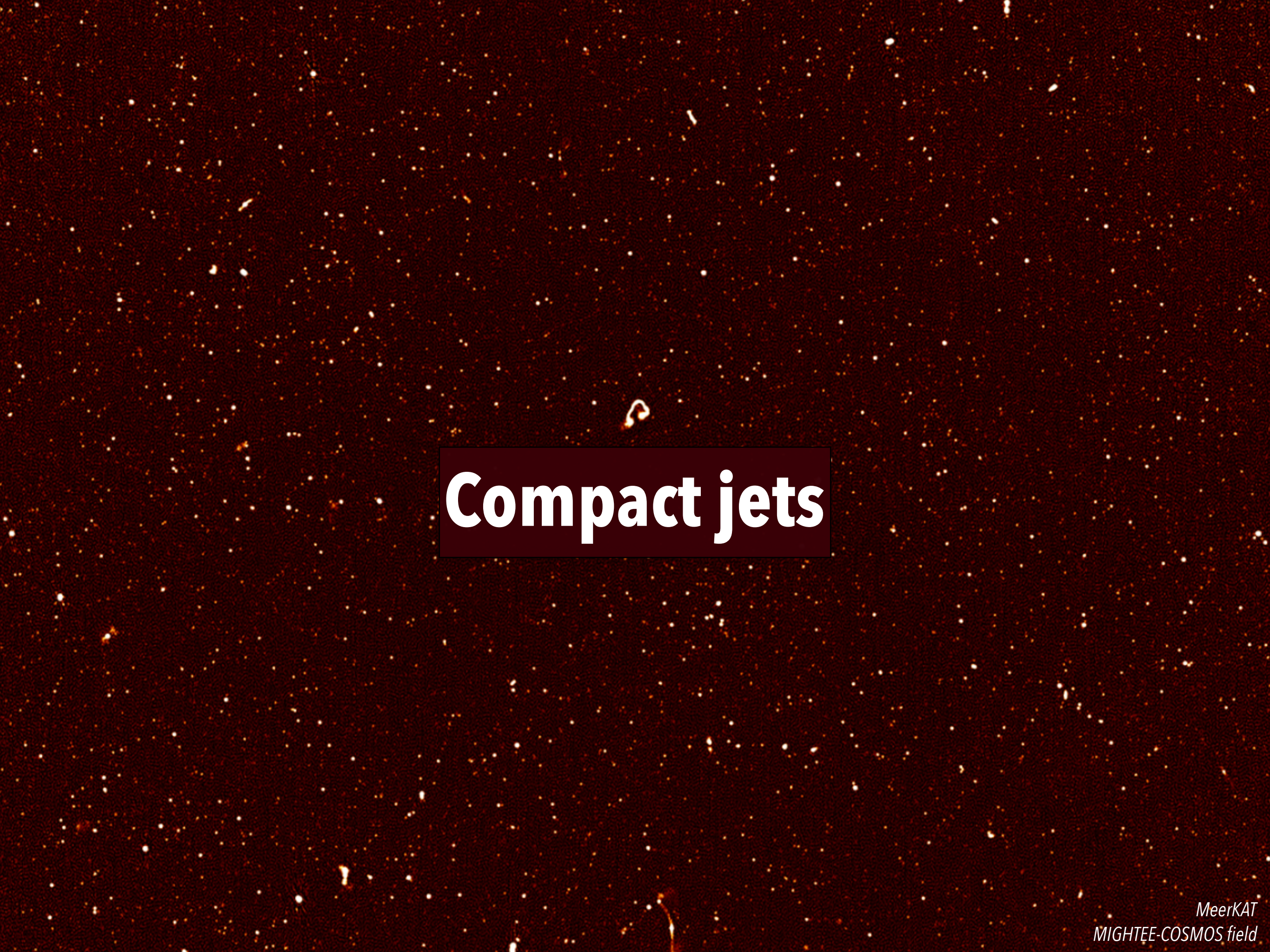


Fender, Belloni, Gallo (2004)

Some open questions

- What is the **jet powering mechanism**?
Blandford-Znajek, Blandford-Payne or a mixture of both?
- Are compact jets and discrete ejecta launched by two different physical mechanisms?
- What is the **composition** of the jet plasma?
- How much **energy** do they carry, and how do they deposit it in the ambient medium?
- Are jets linked to the LHAASO > 100 TeV detections?

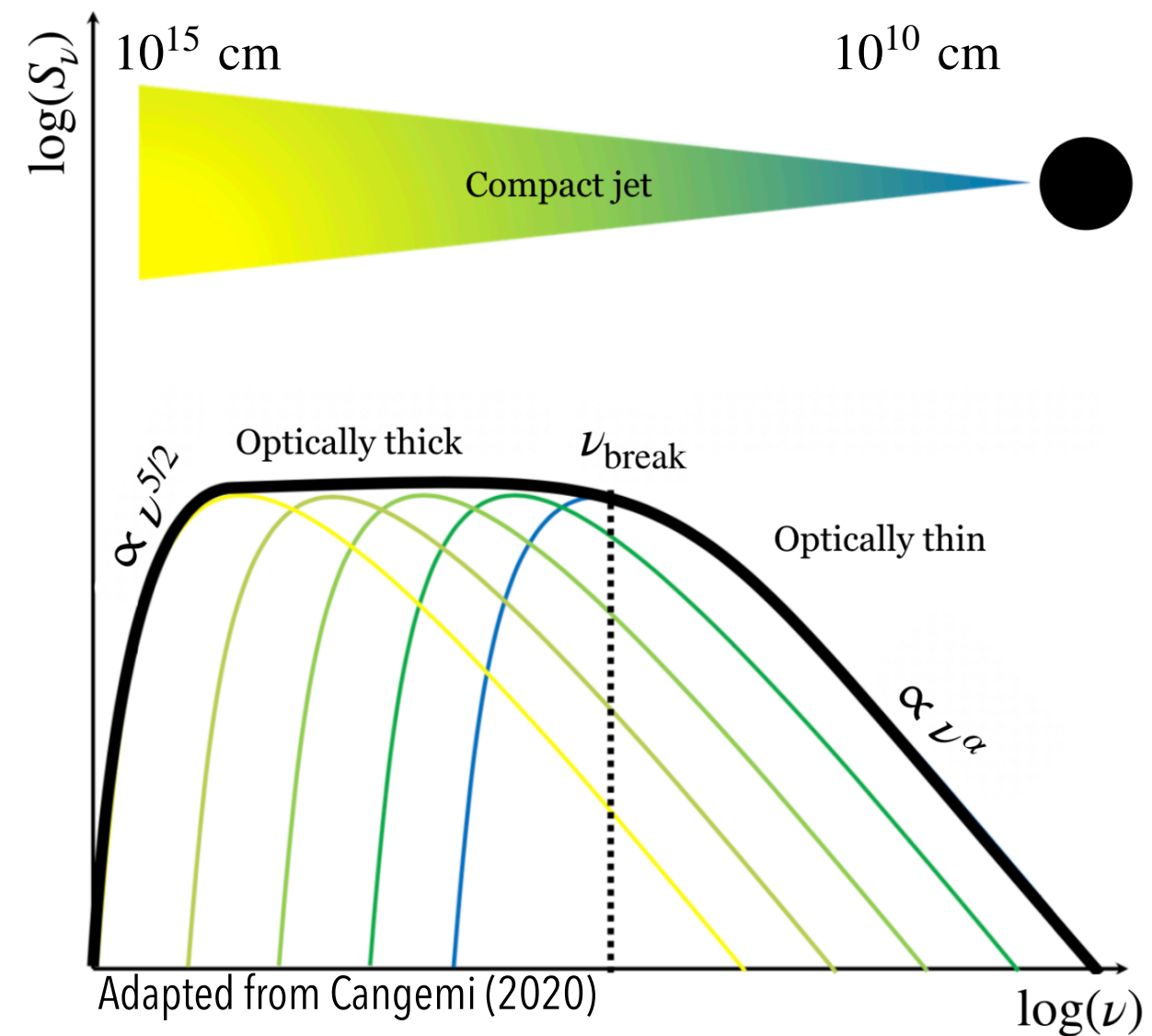




Compact jets

Compact jets from BH XRBs

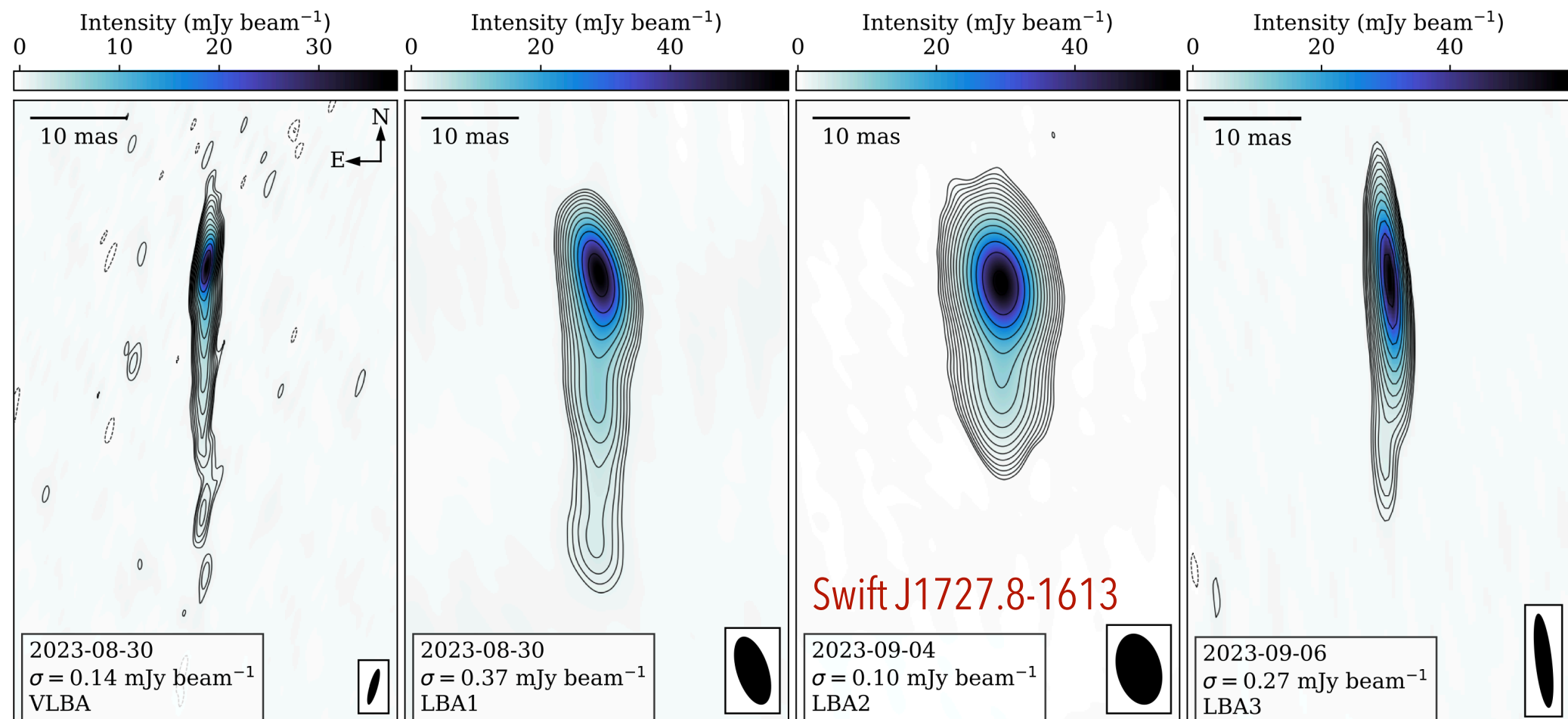
- Self-absorbed synchrotron emission from the radio to the IR/optical bands (e.g. Corbel & Fender 2002)
- If spatially unresolved, we observe a flat spectrum up to a break frequency located in the NIR band
- Higher frequencies emitted by plasma shells closer to the BH (Blandford & Königl 1979)
- Formation and quenching happen on hours-to-day dynamical timescales (e.g. Corbel et al. 2013, Russell et al. 2020) - See talk by **Thomas Russell**
- Re-heating from internal shocks between discrete shells with different velocity? (e.g. Malzac et al. 2014)



High-angular resolution observations

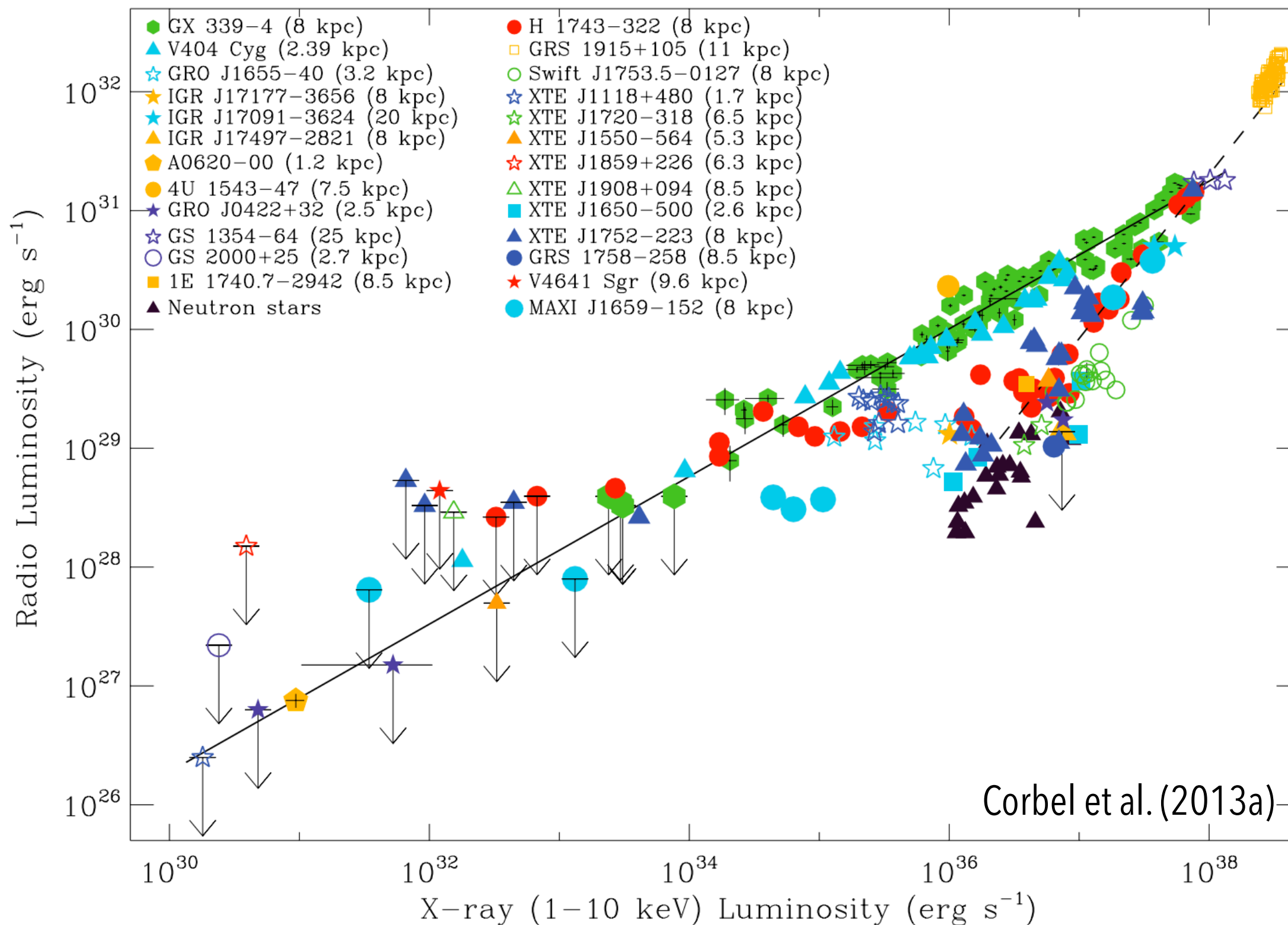
VLBI observations of compact jets provide us with unique information:

- Jet size, through direct imaging or core shifts at different frequencies
- Jet profile along its axis (e.g. Zdziarski et al. 2025)
- Jet axis direction, to be compared with IXPE X-ray polarisation results (e.g. Krawczynski et al. 2022)
- Parallax measurement $\rightarrow$ source distance (e.g. Atri et al. 2020)

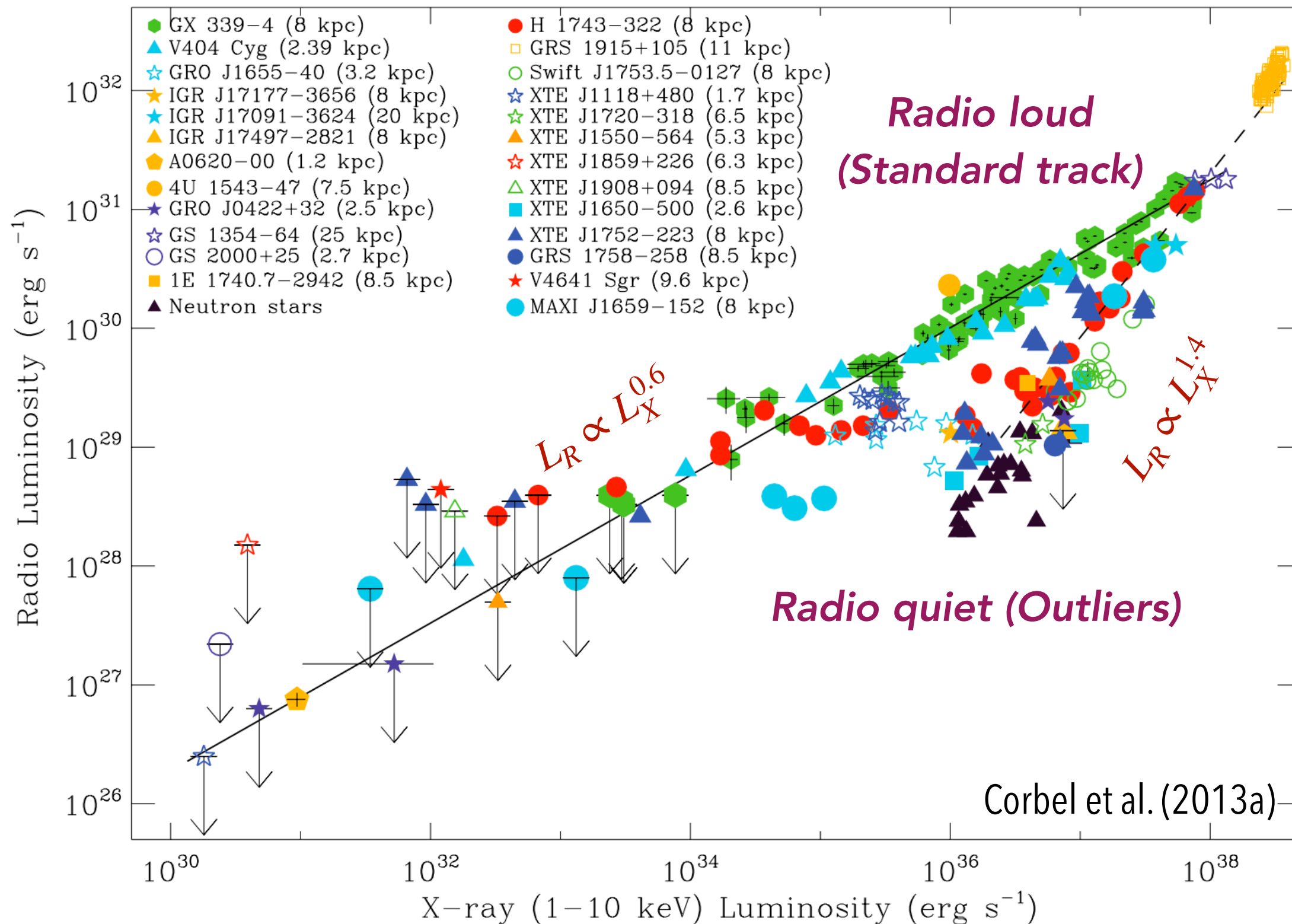


Wood et al. (2025)

The disk/jet connection in the hard state

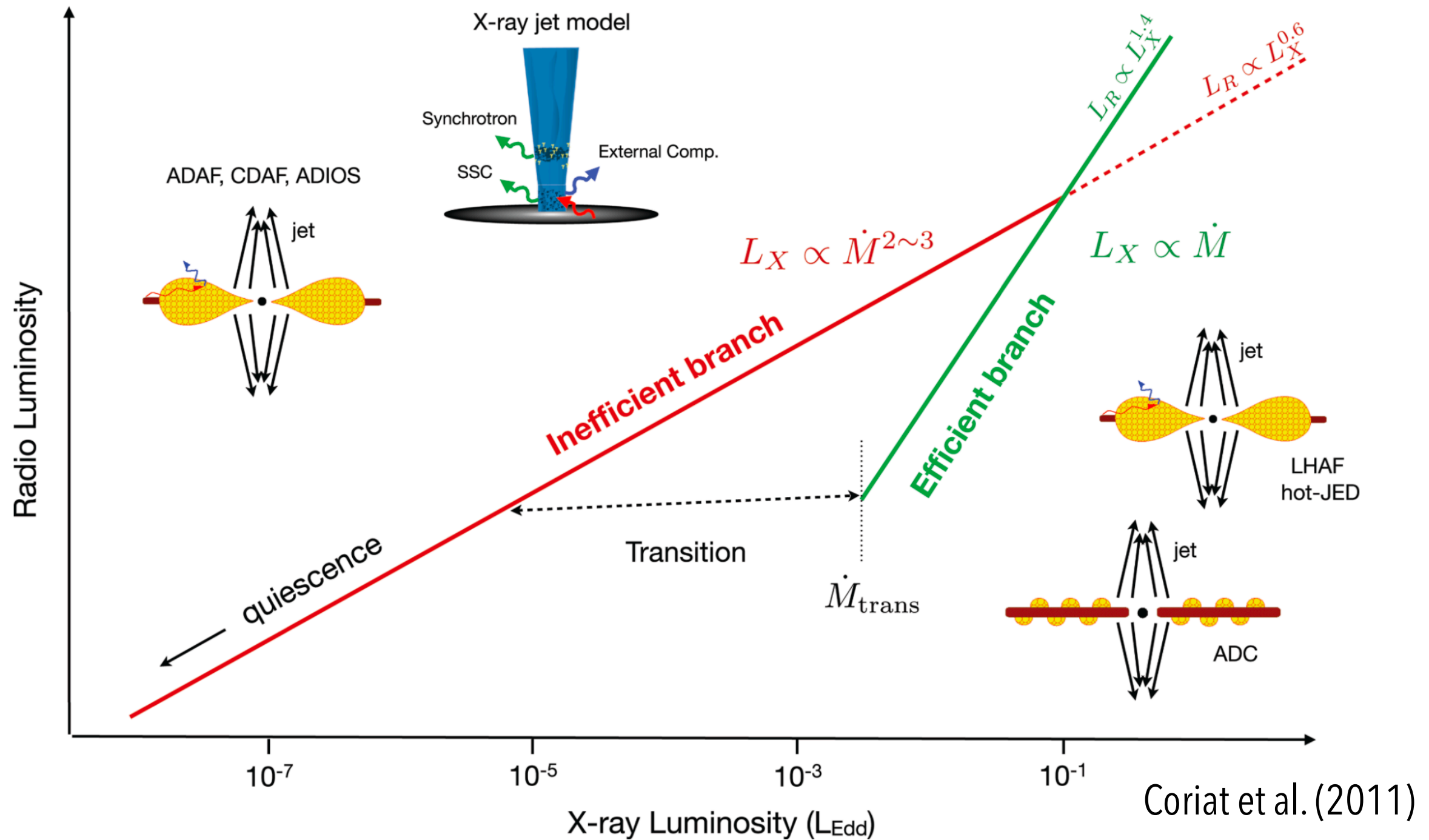


The disk/jet connection in the hard state



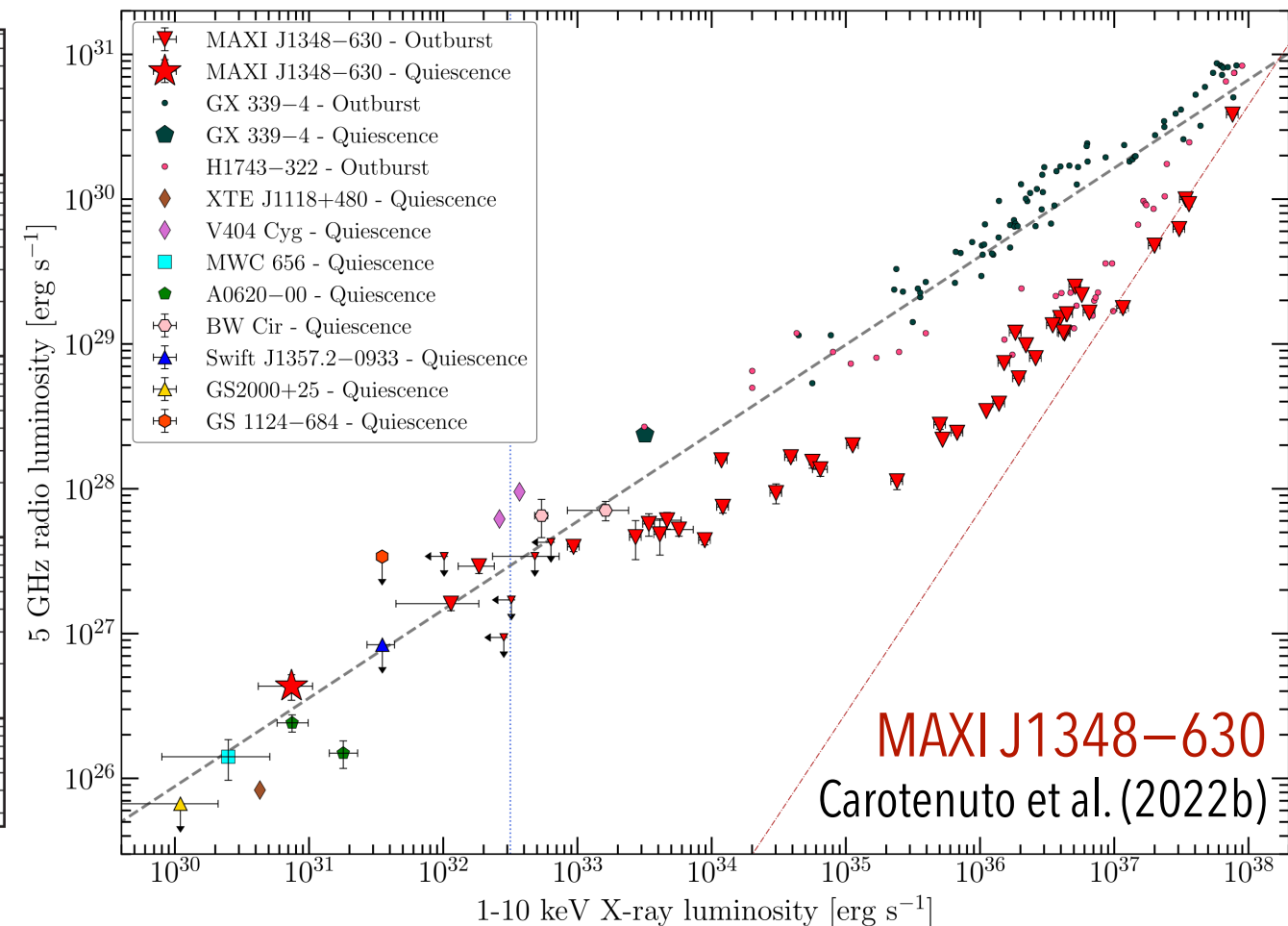
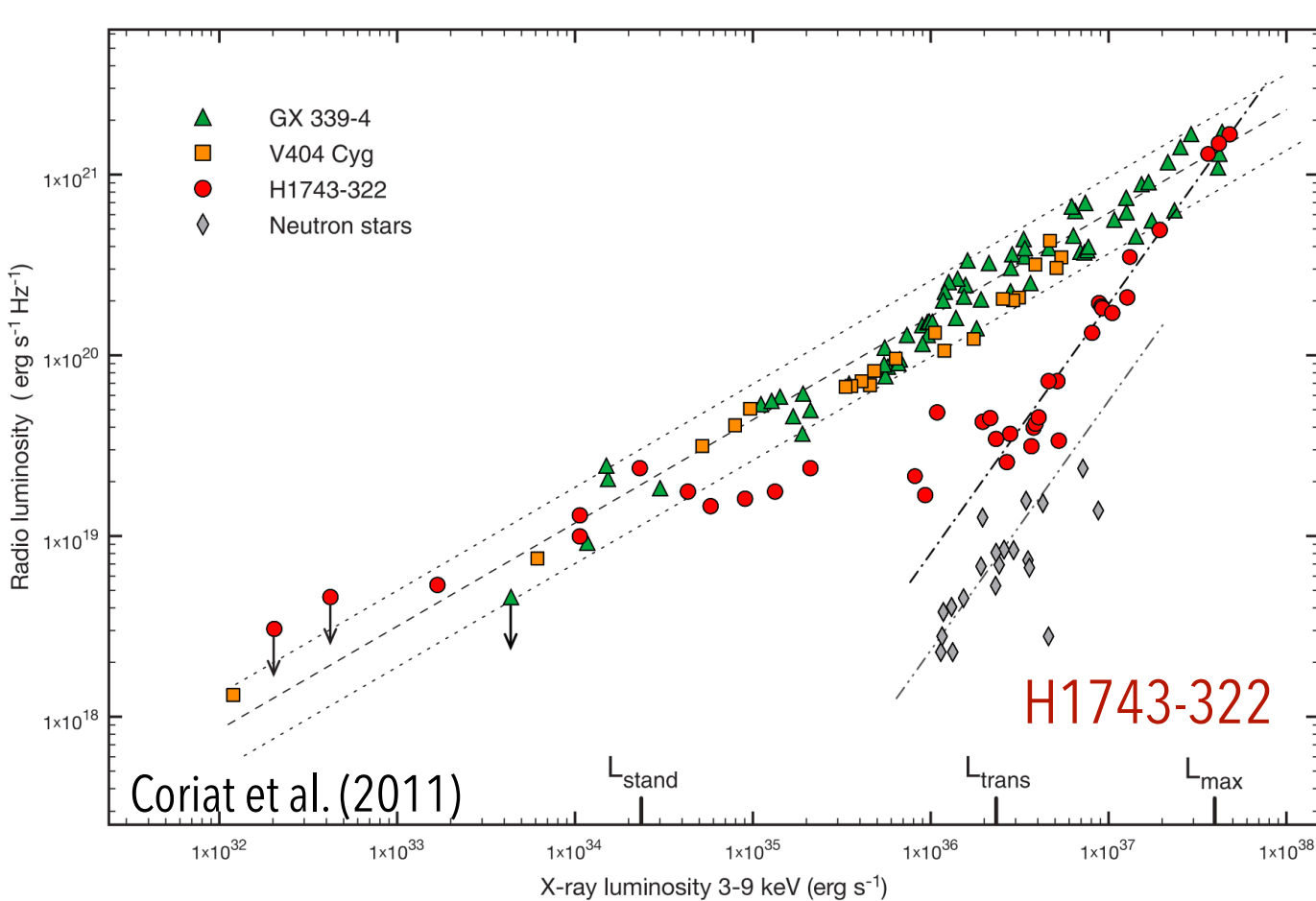
Different intrinsic jet properties? Geometry? Different properties of the accretion flow?

Radiatively efficient/inefficient accretion flows



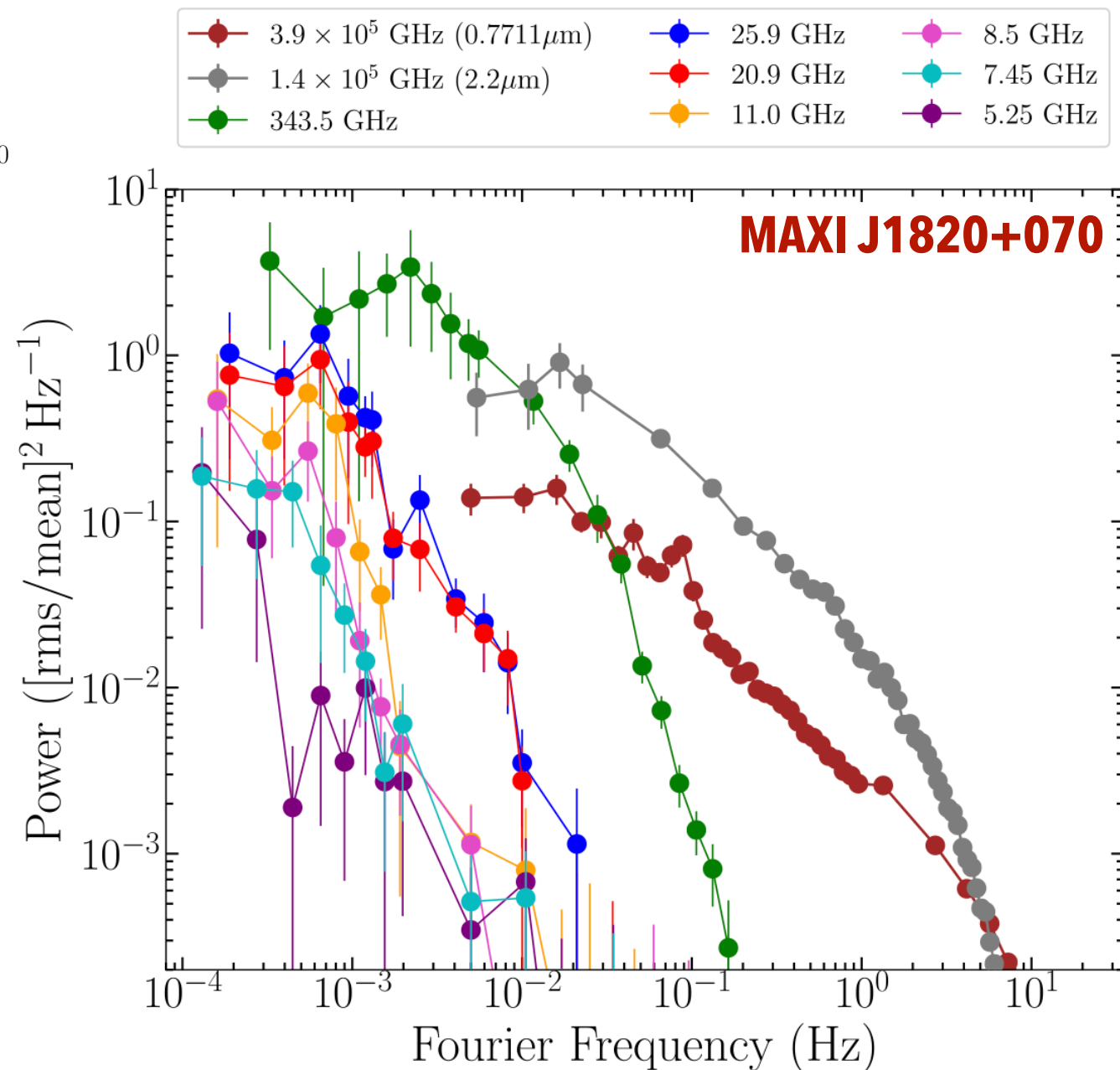
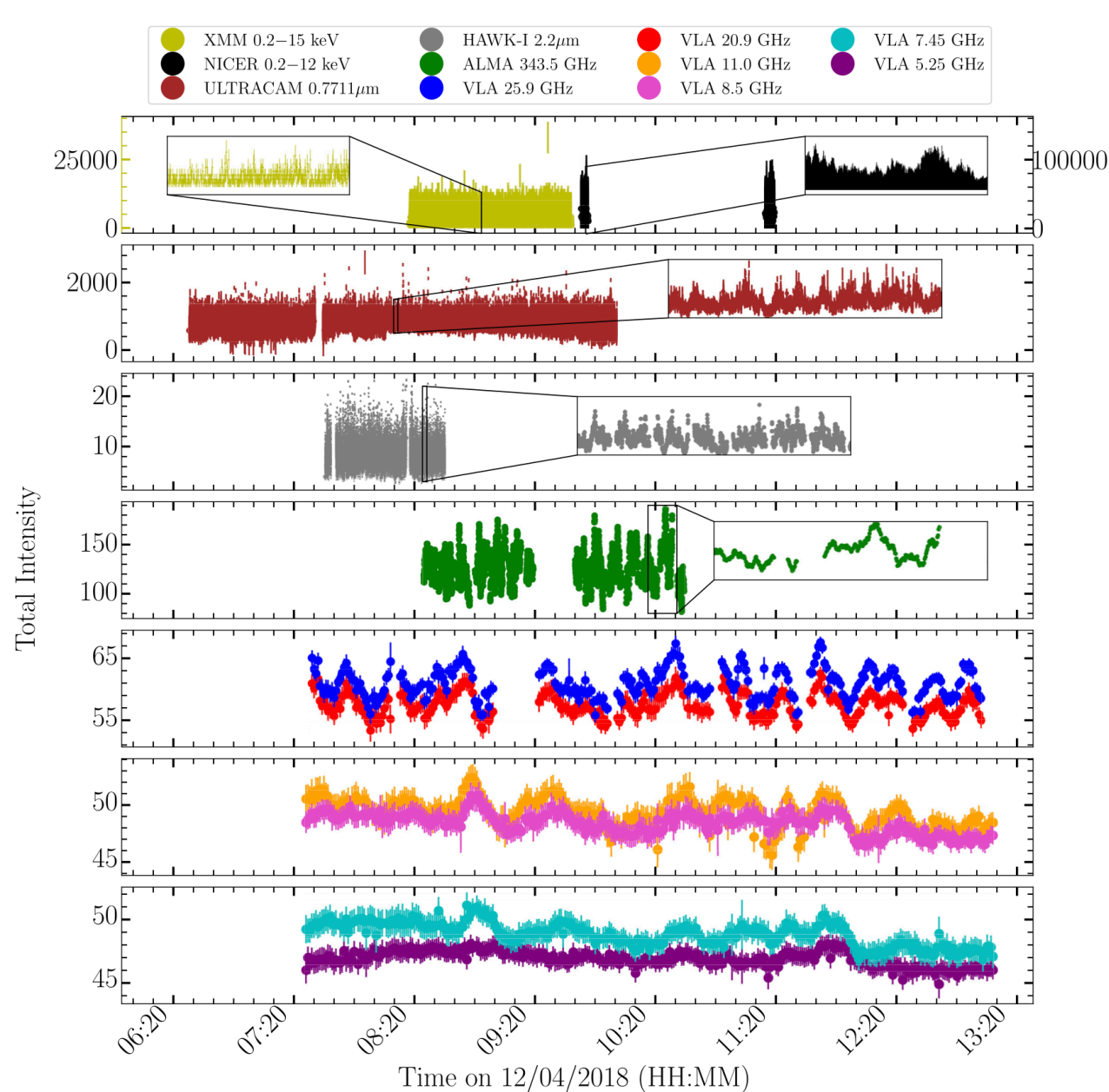
Hybrid correlation sources

Some of the radio-quiet sources were found to display a hybrid correlation, transitioning between the two tracks at different X-ray luminosities, at a fraction $10^{-4} \sim 10^{-3} L_{\text{Edd}}$ (Coriat et al. 2011; Carotenuto et al. 2021b, Hughes et al. 2025b)



See upcoming talks by **Justine Crook-Mansour** and **Andrew Hughes!**

Multi wavelength jet fast variability



Applying the standard Blandford-Königl model $\rightarrow$ constraints on the jet Lorentz factor $1.5 \lesssim \Gamma \lesssim 4.5$, its power ($\sim 10^{38}$ erg/s), the opening angle ($\sim 1.5^\circ$), the jet base ($\sim 10^{10}$ cm), and its magnetic field ($\sim 10^4$ G)

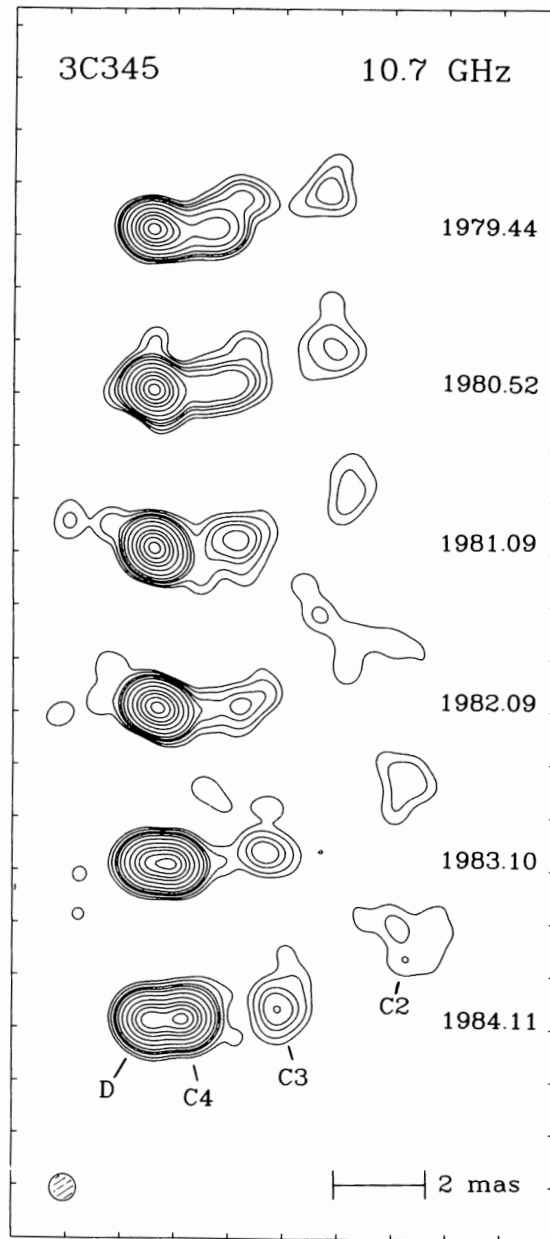
Tetarenko et al. (2021), Zdziarski et al. (2022)



Discrete ejecta

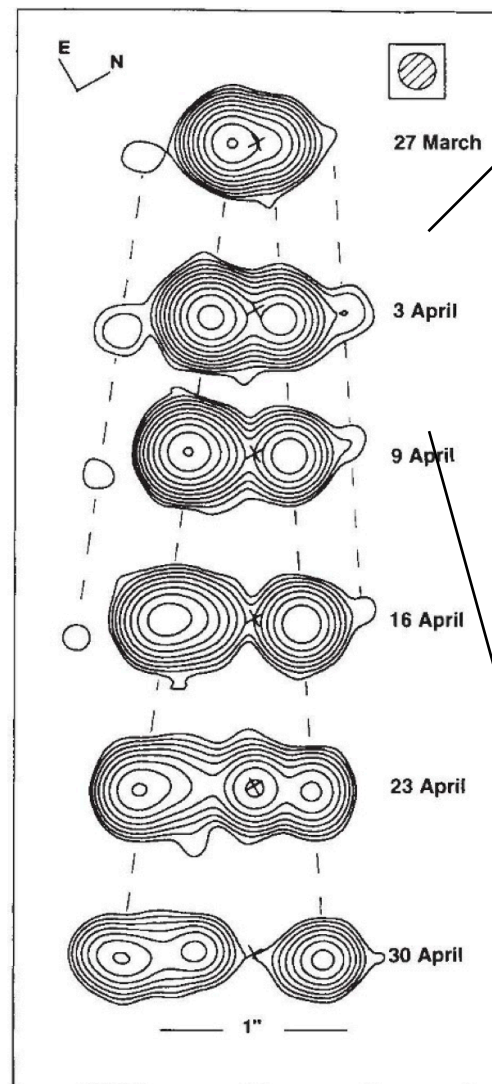
Superluminal motion in our Galaxy

Superluminal motion was already observed in AGN since the 70's with VLBI, but only at the milli-arcsec angular scales and on much larger timescales (e.g. Knight et al. 1971, Readhead & Wilkinson et al. 1978)

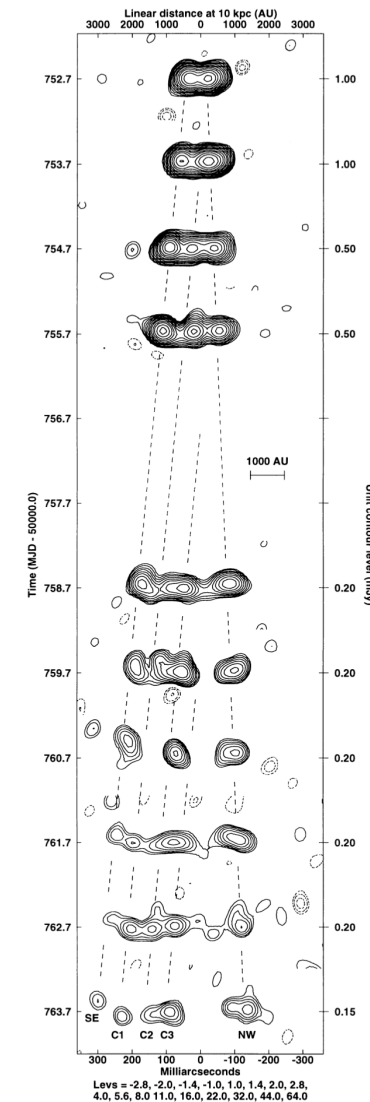


Biretta, Moore Cohen (1986)

GRS 1915+105

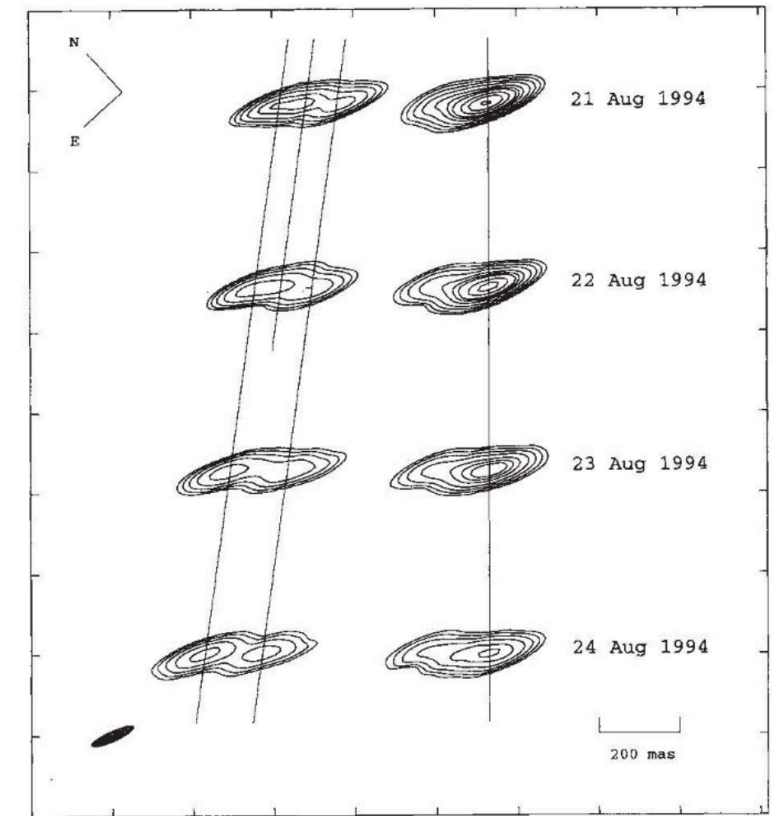


Mirabel & Rodriguez (1994)



Fender et al. (1999)

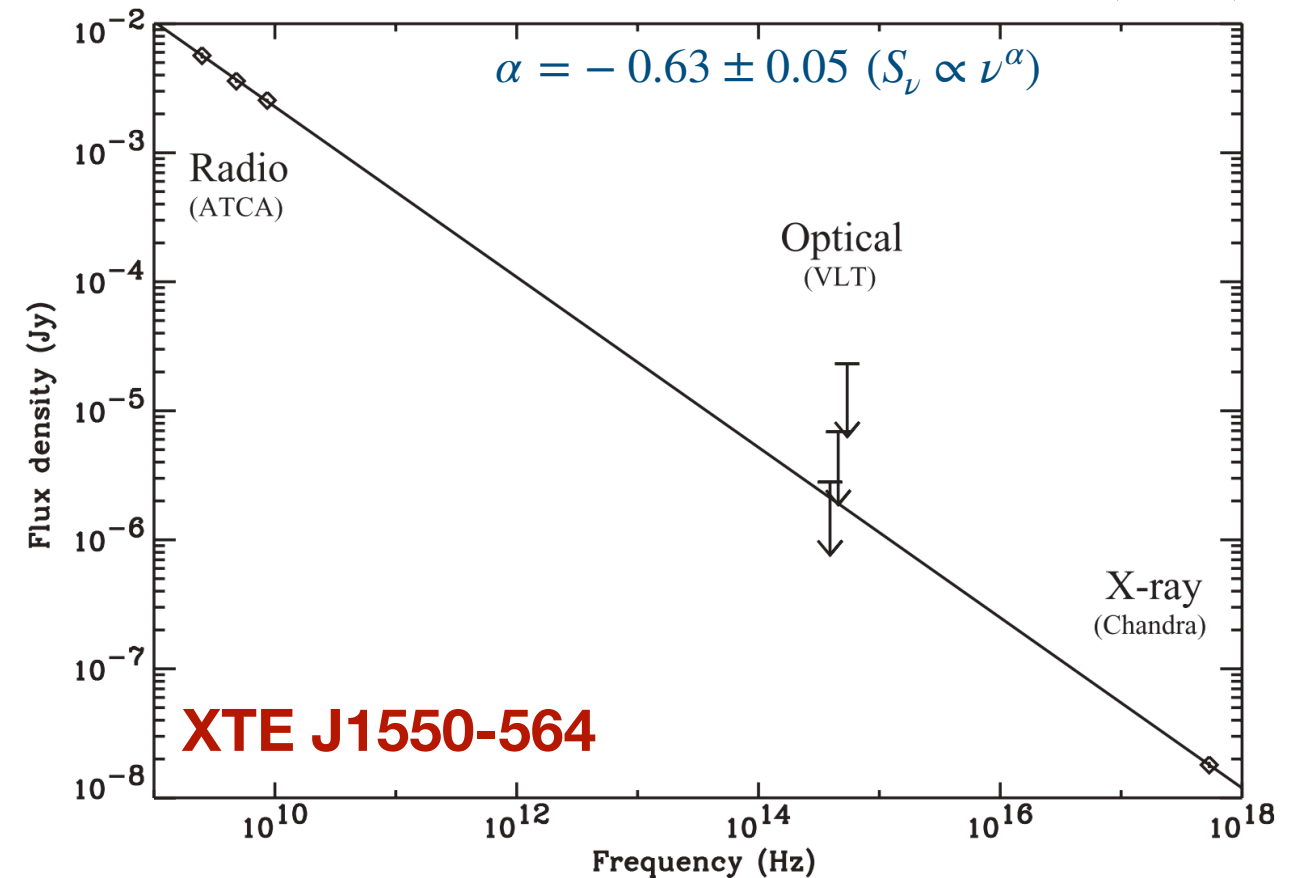
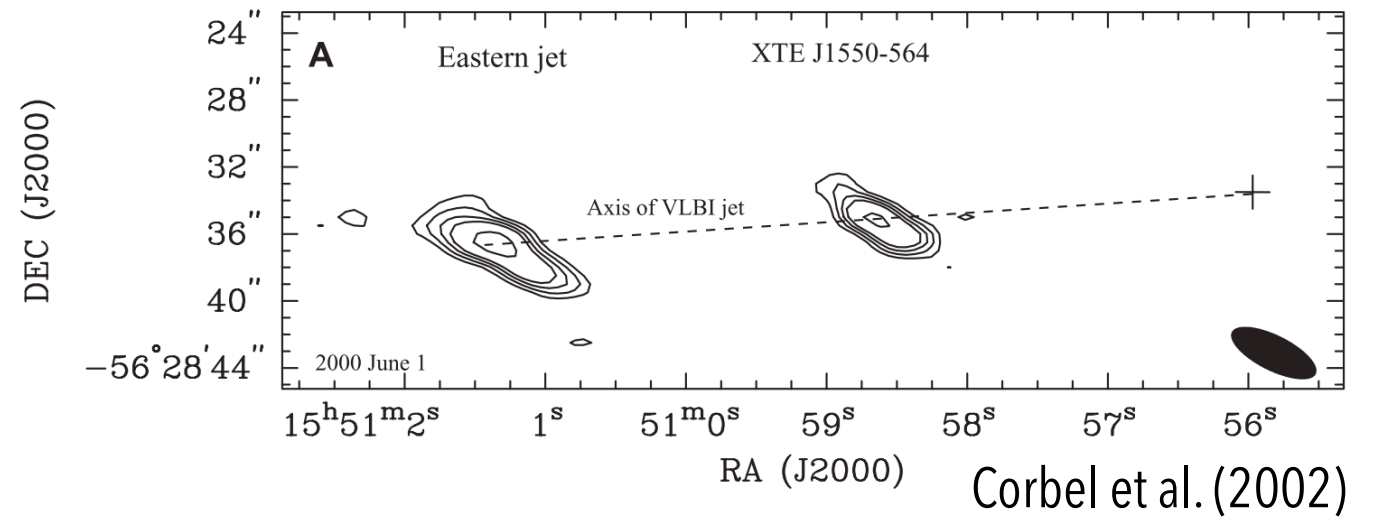
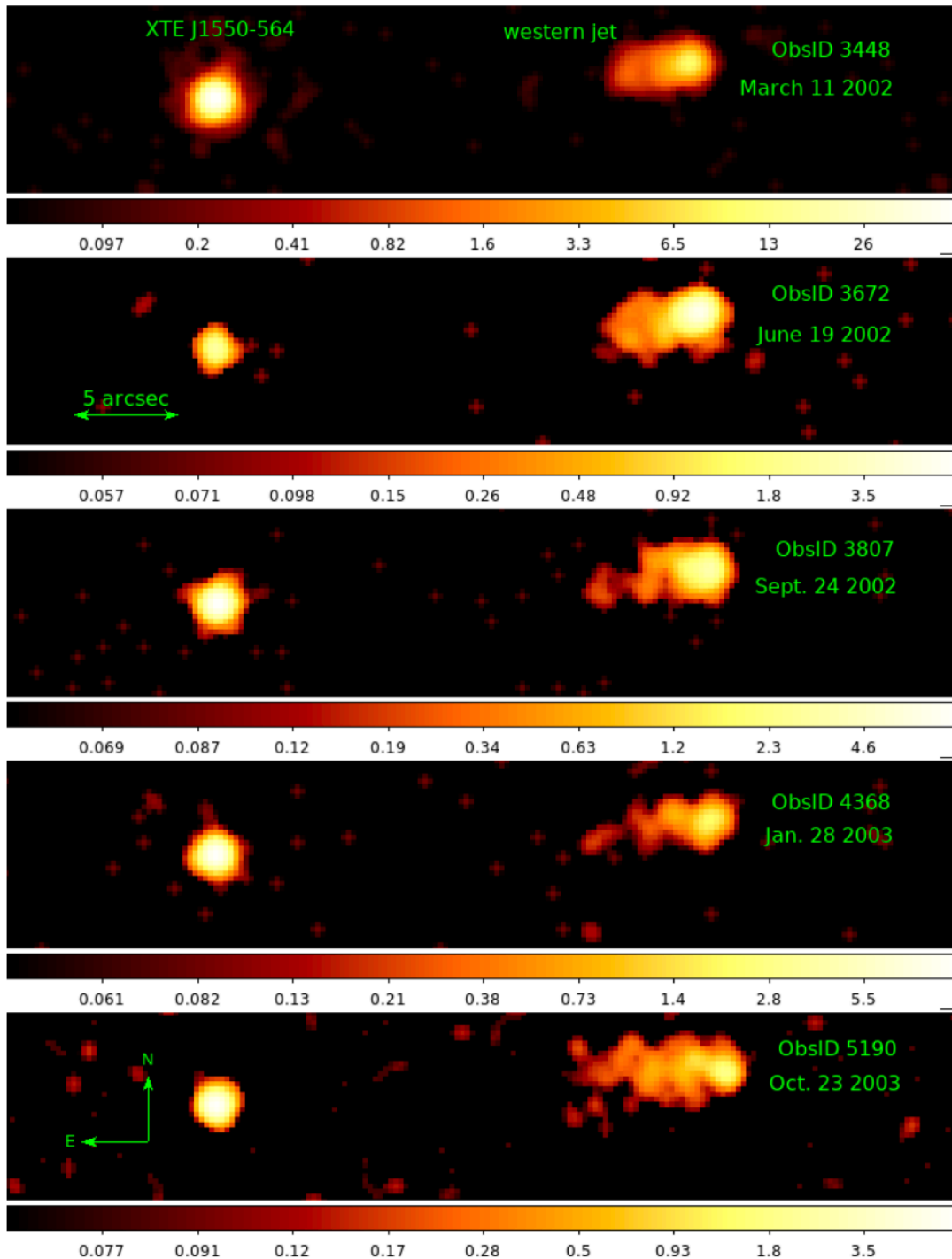
GRO J1655-40



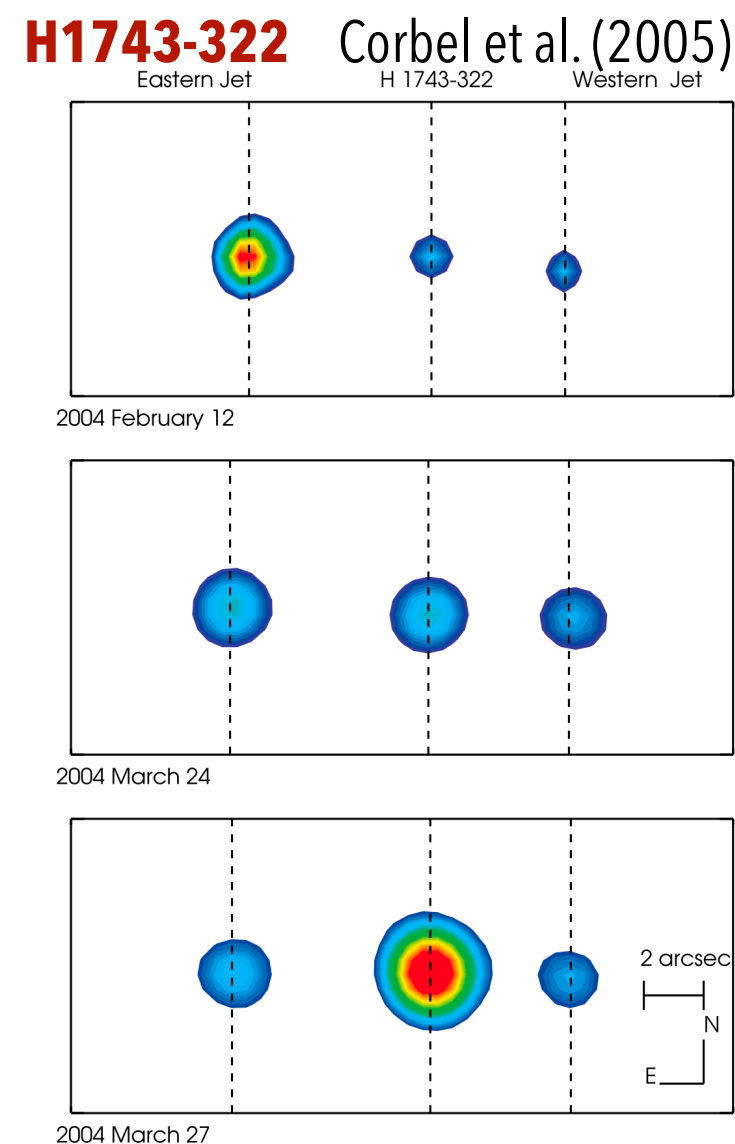
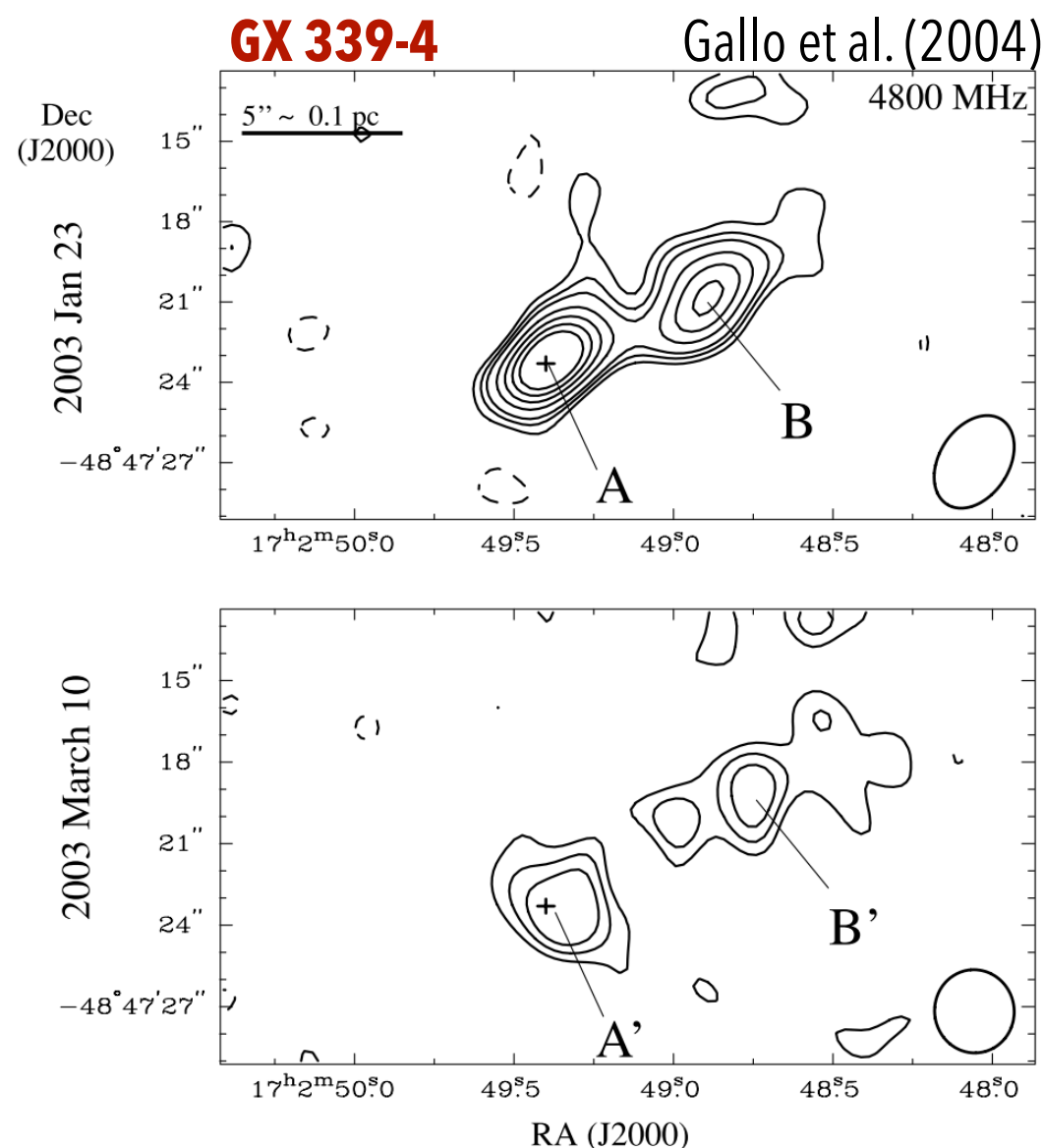
Tingay et al. (1995)

The first detections at large scales (XTE J1550)

Corbel et al. (2002), Migliori et al. (2017)



More detections at large scales



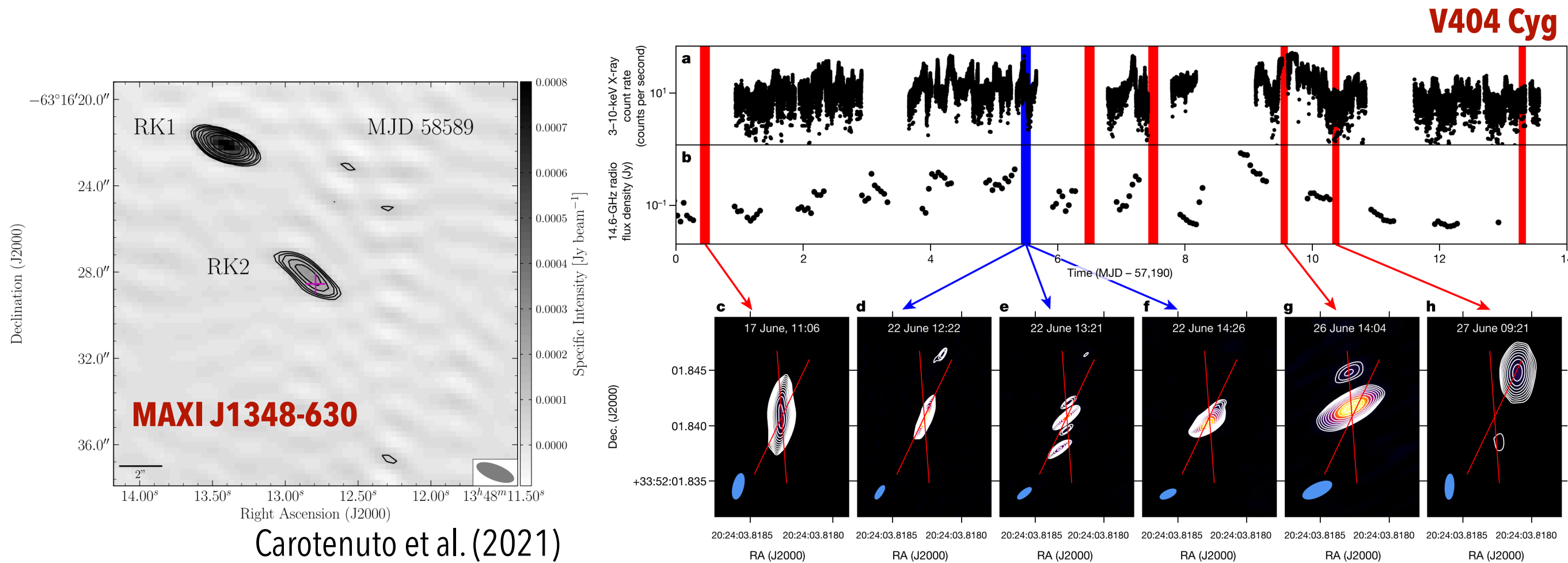
And now many more examples of large-scale jets detected with **MeerKAT** (ThunderKAT/X-KAT)
See following talk by **Sara Motta!**

Production of multiple jets

Multiple ejecta produced on timescales of hours, days, months.

Ejecta can also be launched along different directions. Is this driven by a precessing inner-disk?

Or are the jets aligned with BH spin and then 'redirected' by the flow? (e.g. Miller-Jones et al. 2019)

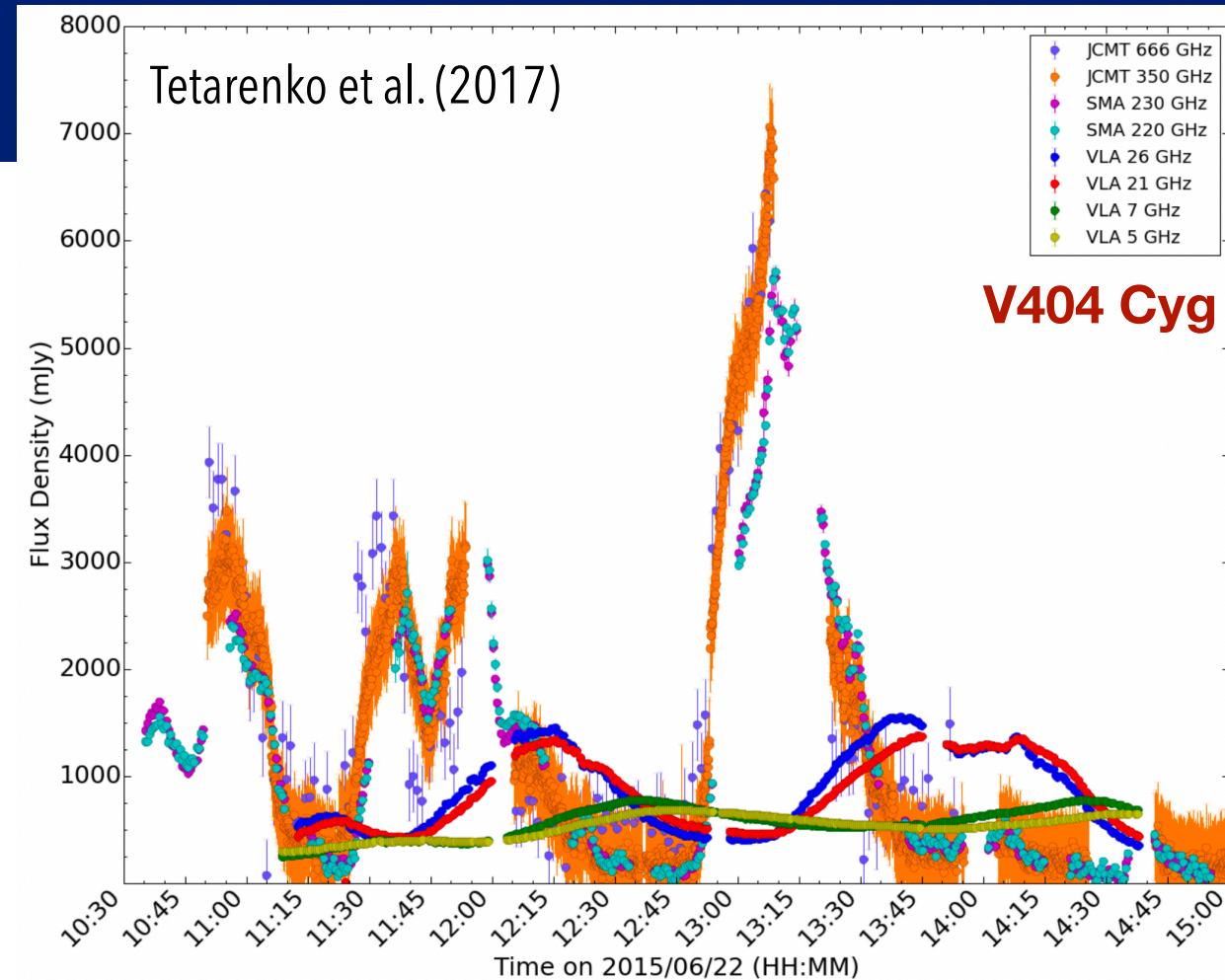


VLBI observations of ejecta are fundamental to resolve multiple jet components.

This is possible today also with new radio-interferometric techniques (see talk by **Callan Wood**)

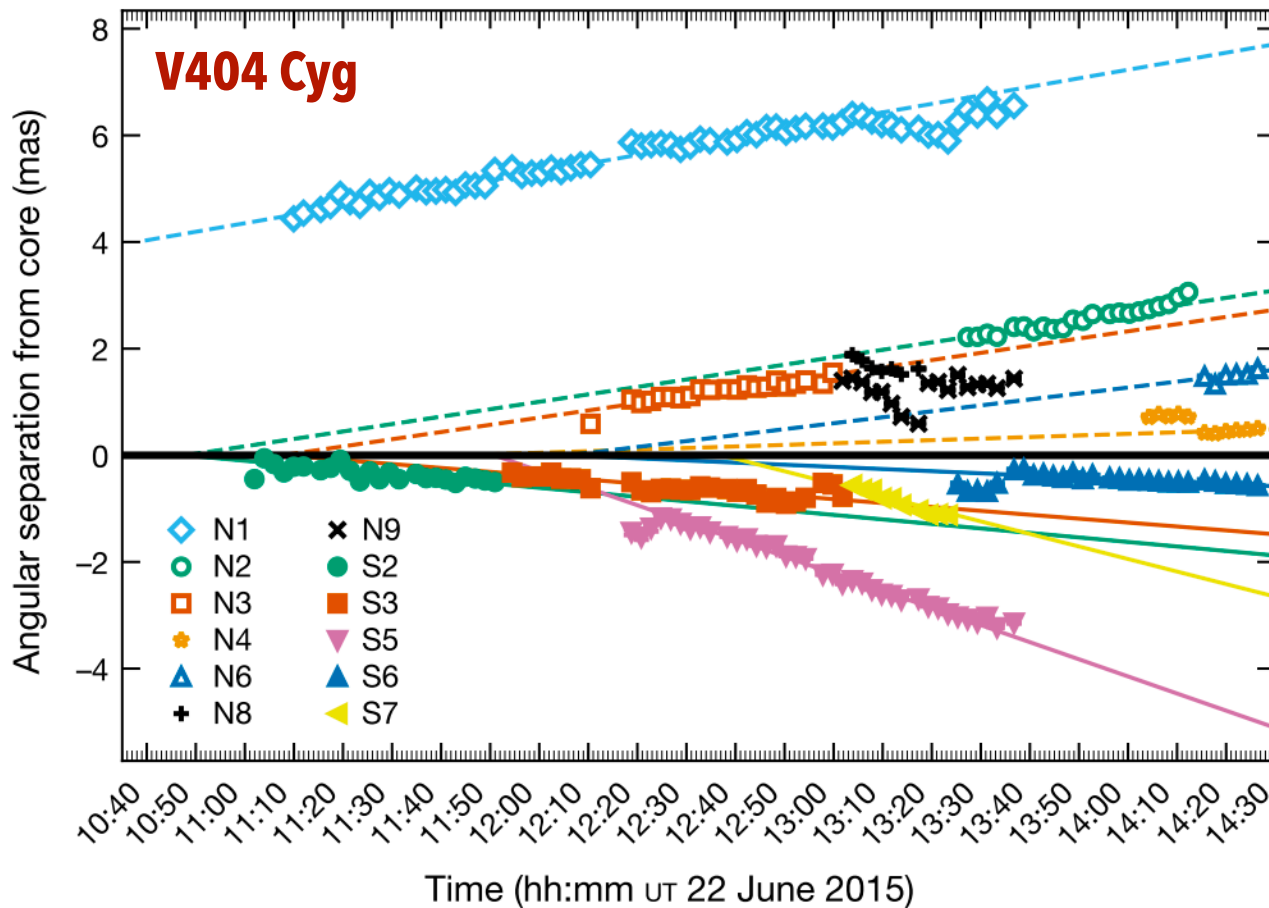
Ejections and radio flares

- Trigger and launching mechanism currently unknown
- Ejections produced at the transition from the hard to the soft state (Fender, Belloni, Gallo 2004)
- Strong radio flares generally observed at the jet launch
Adiabatic expansion? Collision with compact jet remnant?
First interaction with the ISM?
- Assuming the flare peak is due to decreasing optical depth to synchrotron self-absorption (Fender & Bright 2019):
 - typical minimum internal energies in the range $10^{38} \sim 10^{42}$ erg
 - Equipartition magnetic fields in the range $10^{-4} \sim 1$ G
- Connection with X-ray variability (Rodriguez et al. 2008)
Type-B QPOs? Hard/soft lags? (Homan et al. 2020, Mendez et al. 2022) - See talk by **Thomas Russell**



Jet kinematics

First phase of **ballistic** motion, often apparently **superluminal** (but Lorentz factor hard to measure)

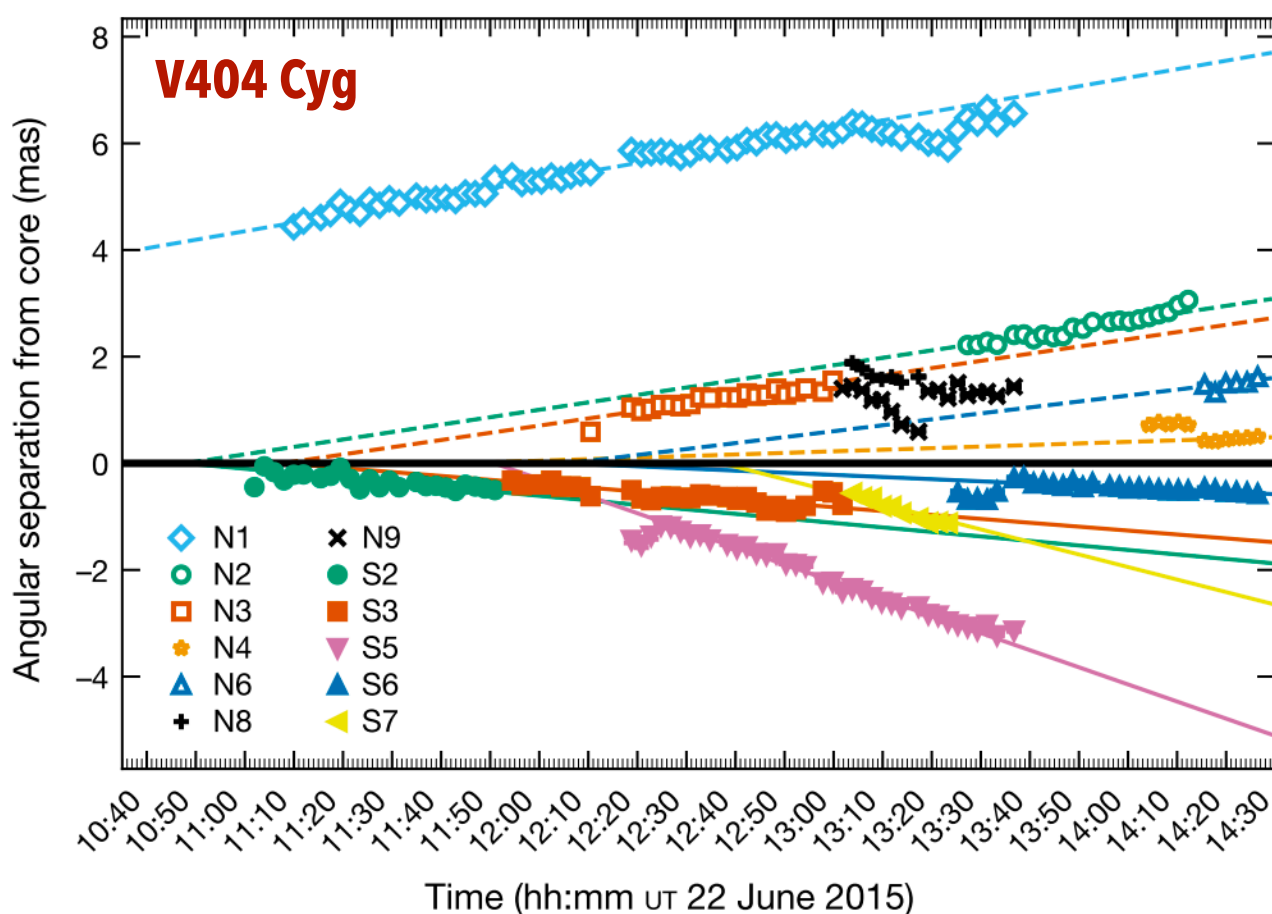


Miller-Jones et al. (2019)

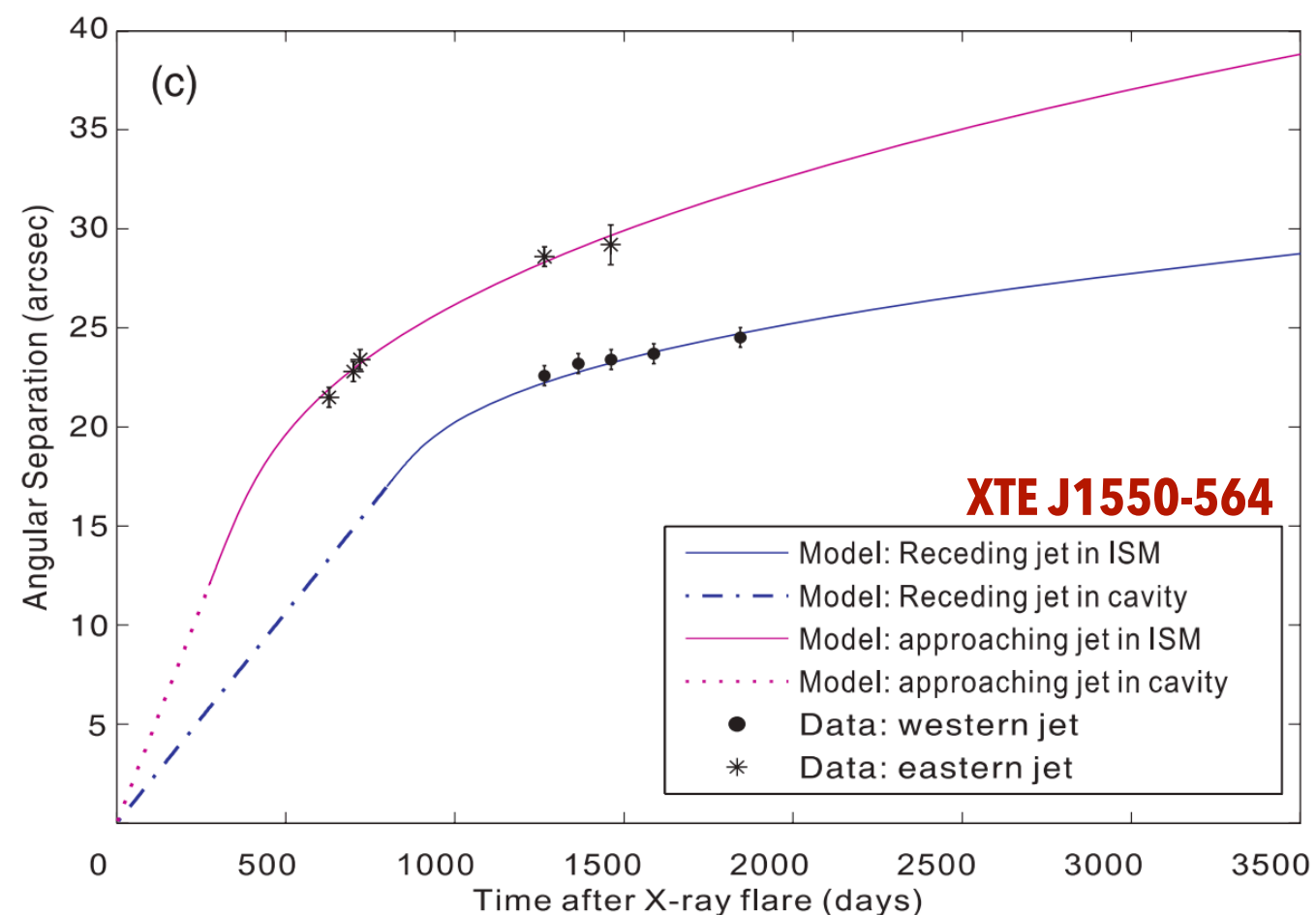
Jet kinematics

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Evidences for late-time **deceleration** of the jets due to the **interaction** with the ISM (Corbel et al. 2002)



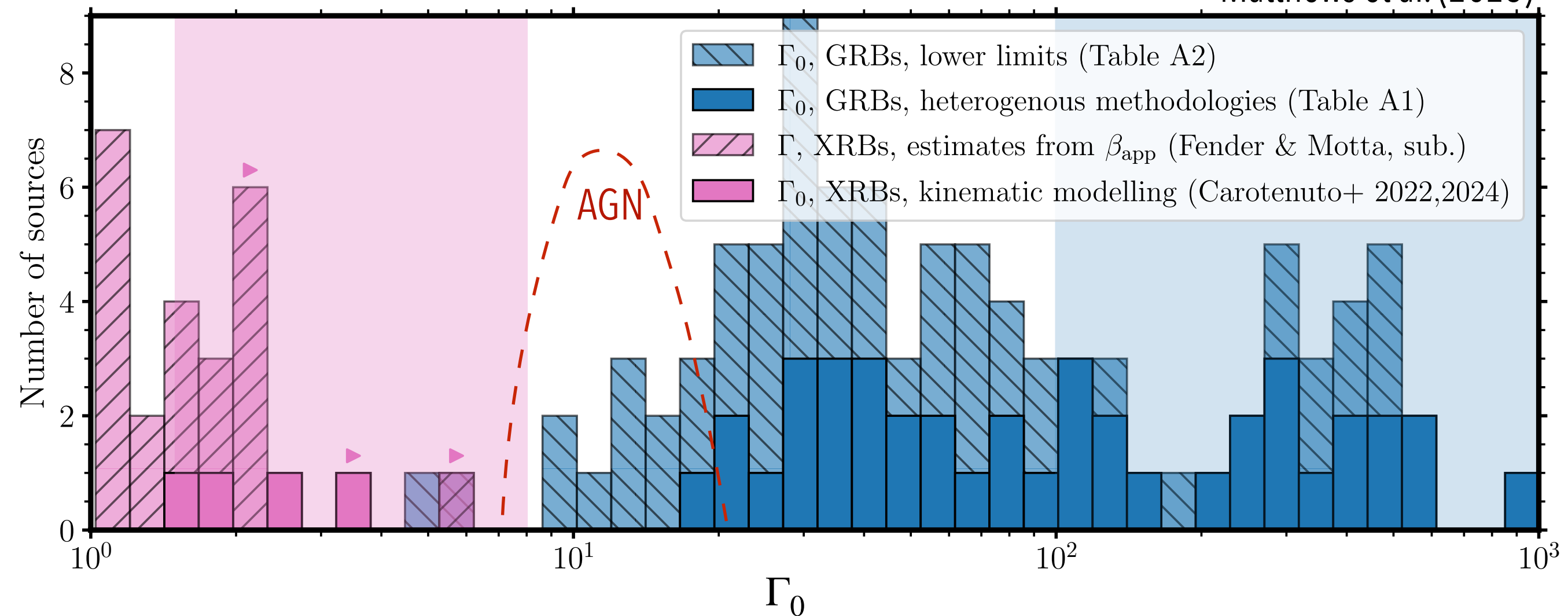
Miller-Jones et al. (2019)



Hao & Zhang (2009)

How relativistic are XRB jets?

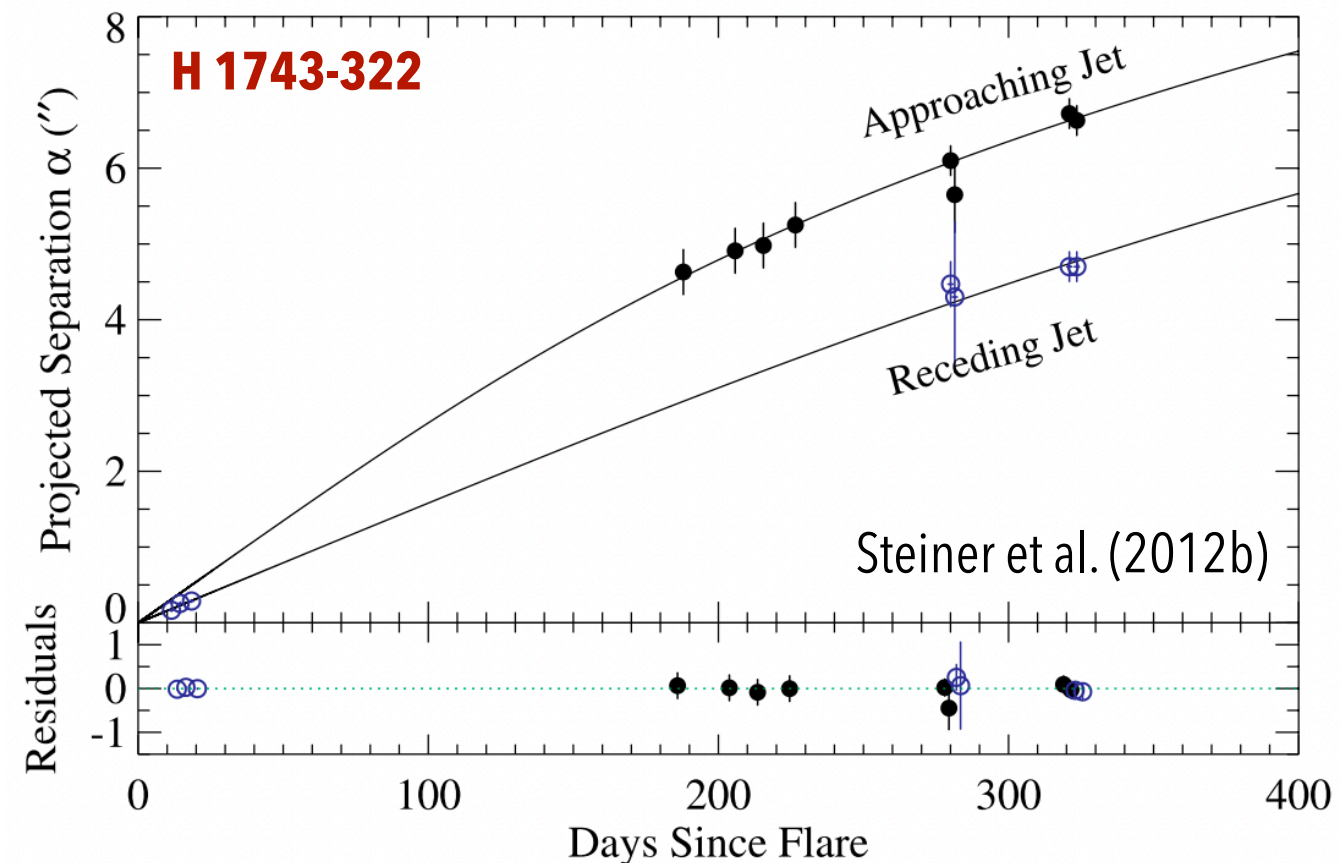
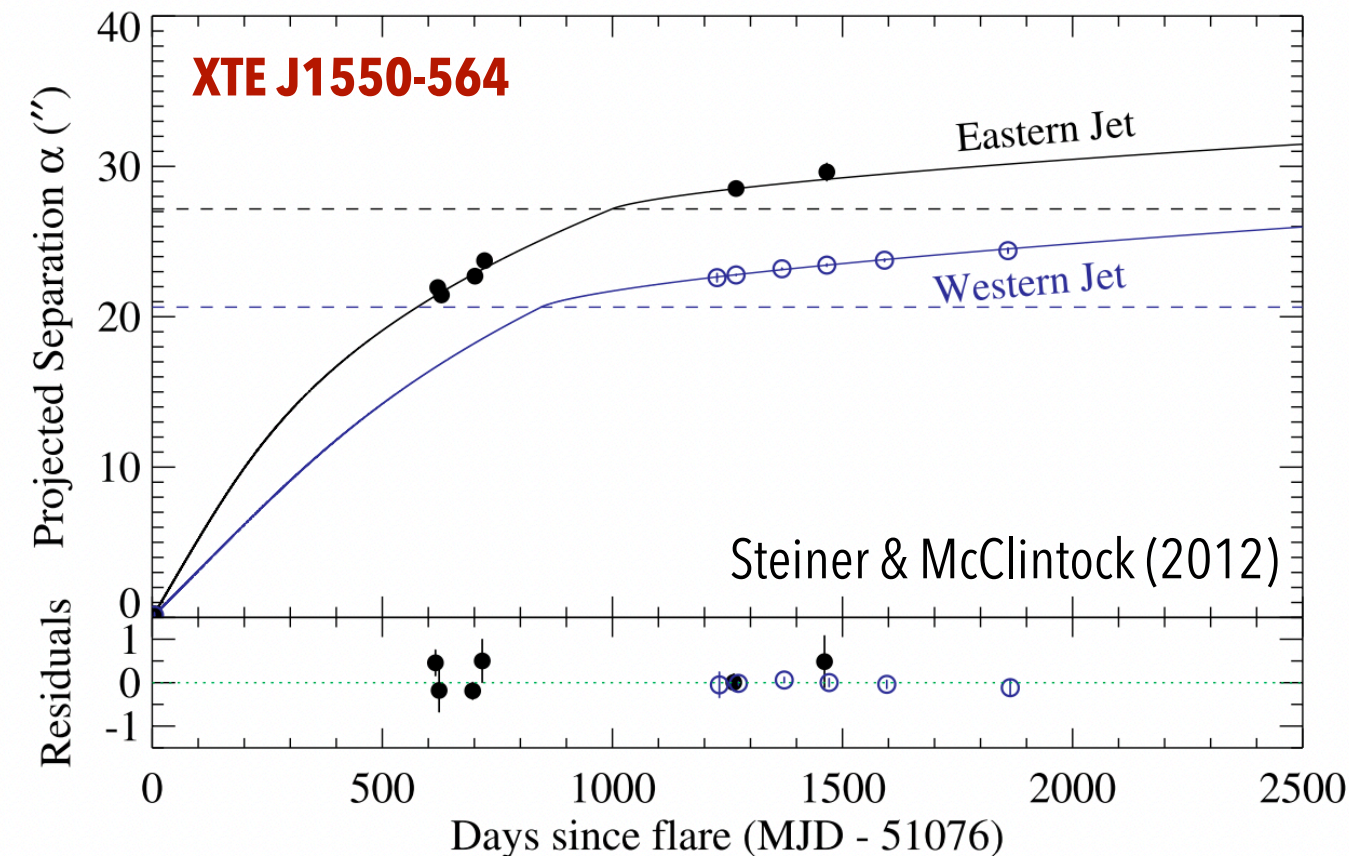
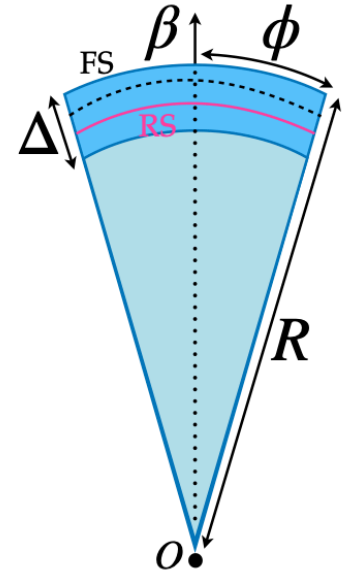
Matthews et al. (2025)



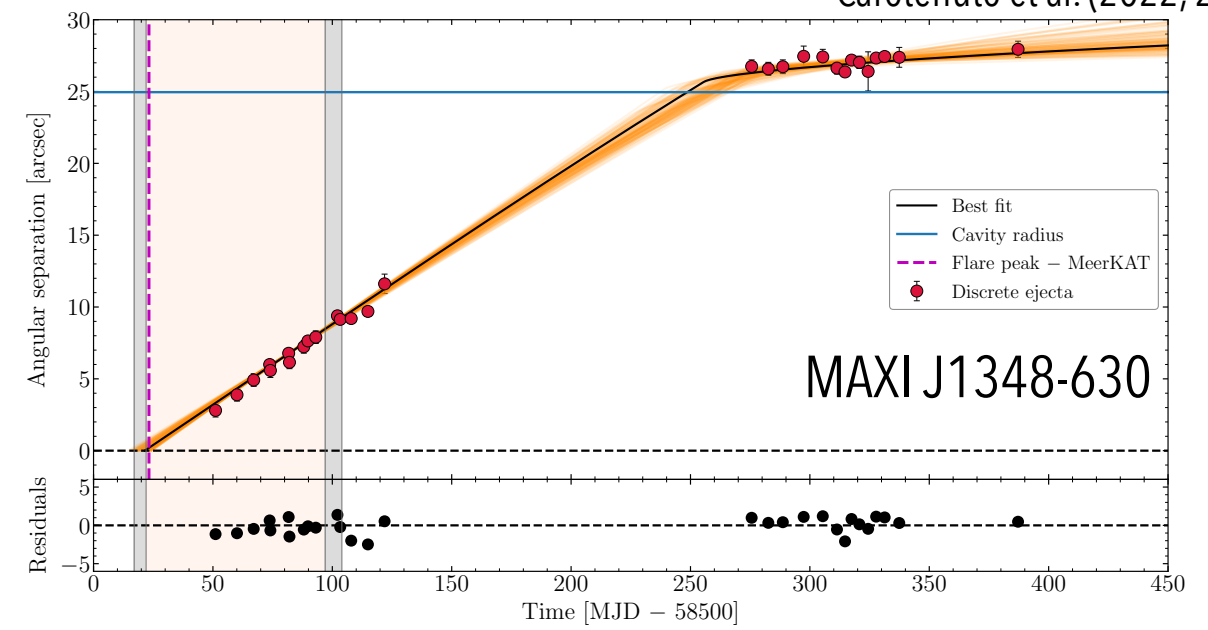
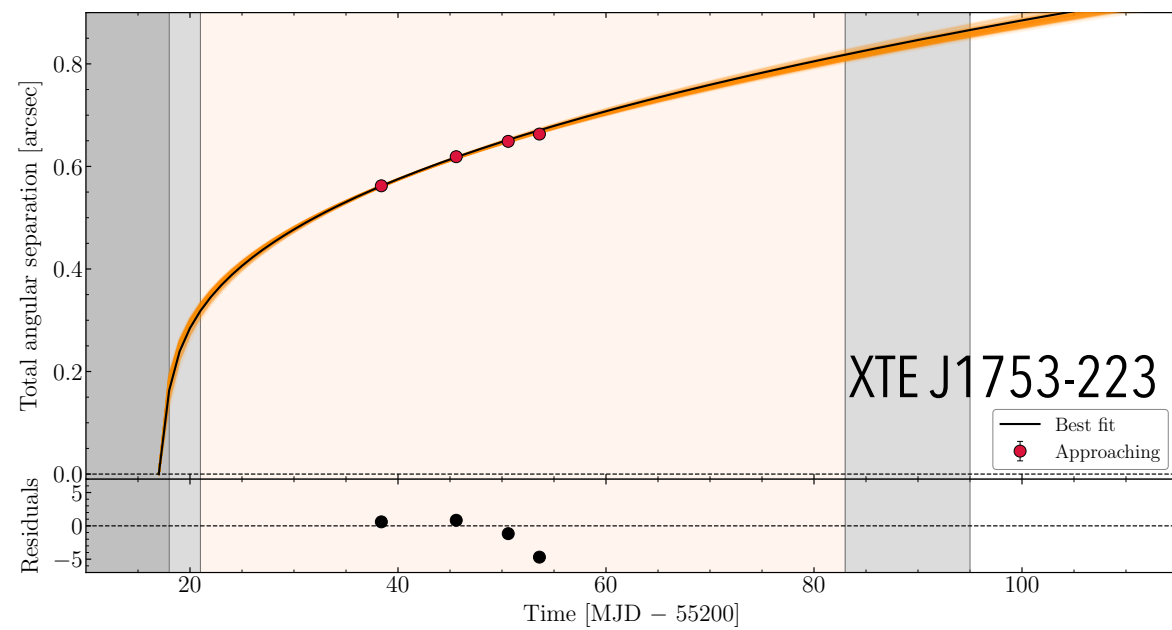
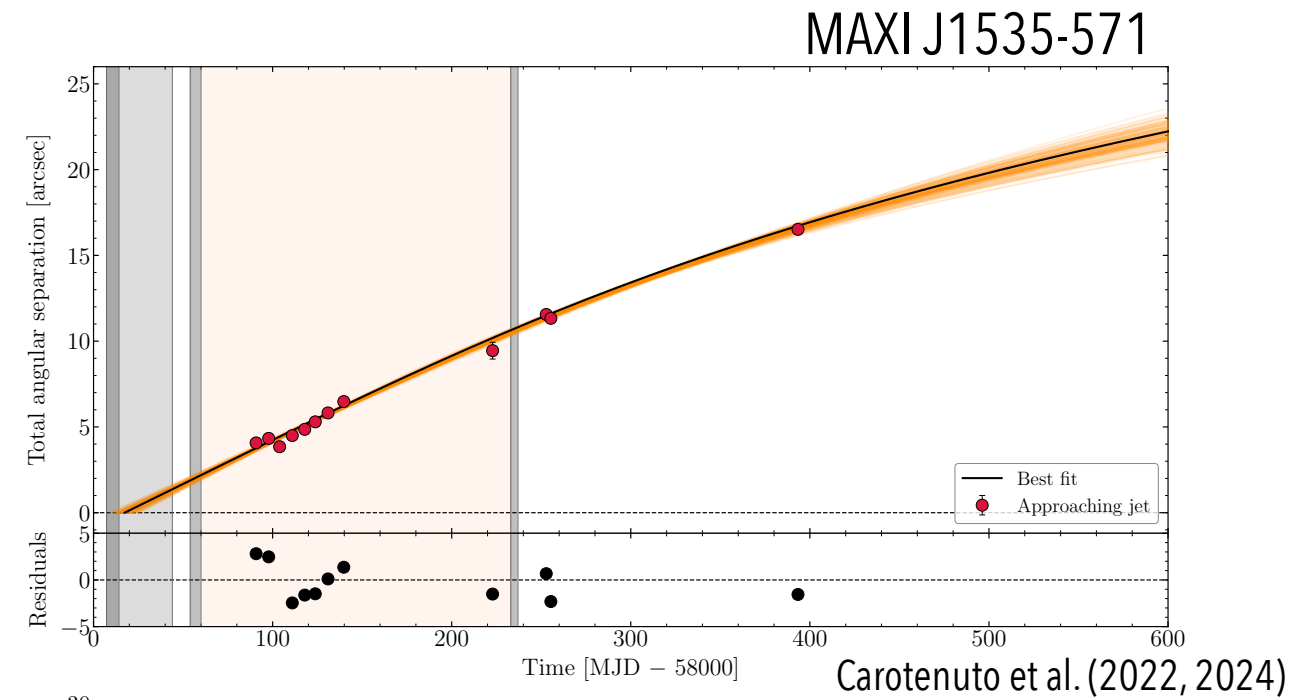
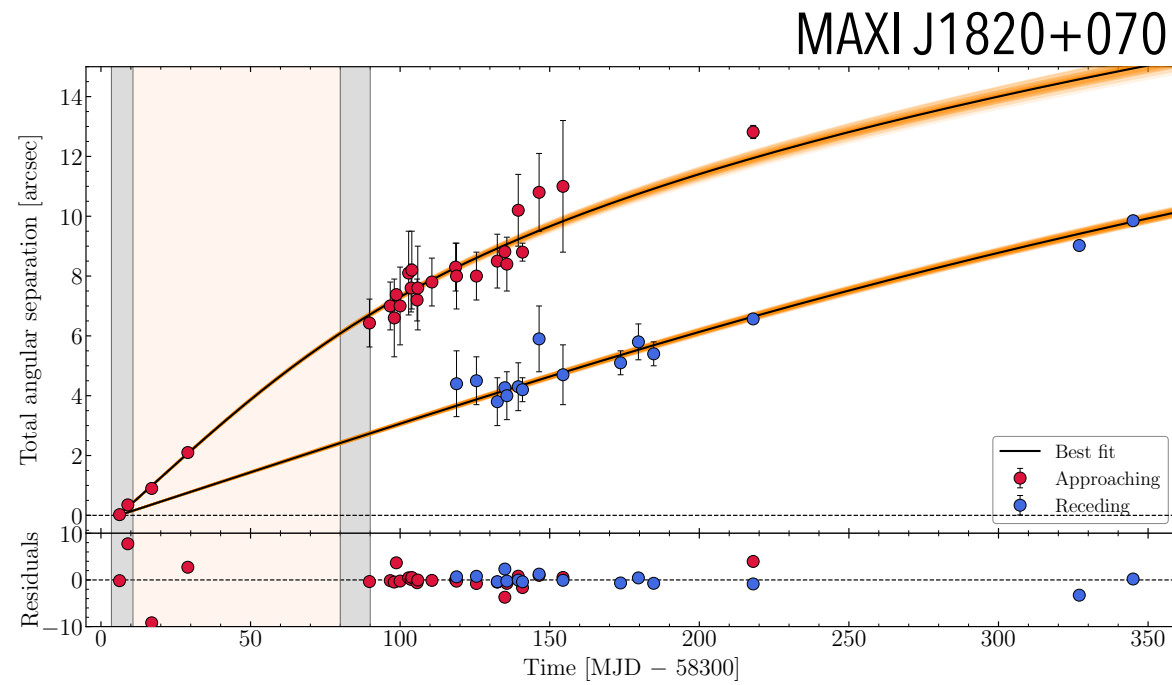
Applying GRB blast wave models to XRB jets

- BH XRBs display jets that can be observed off-axis, with resolvable core separations
- 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:

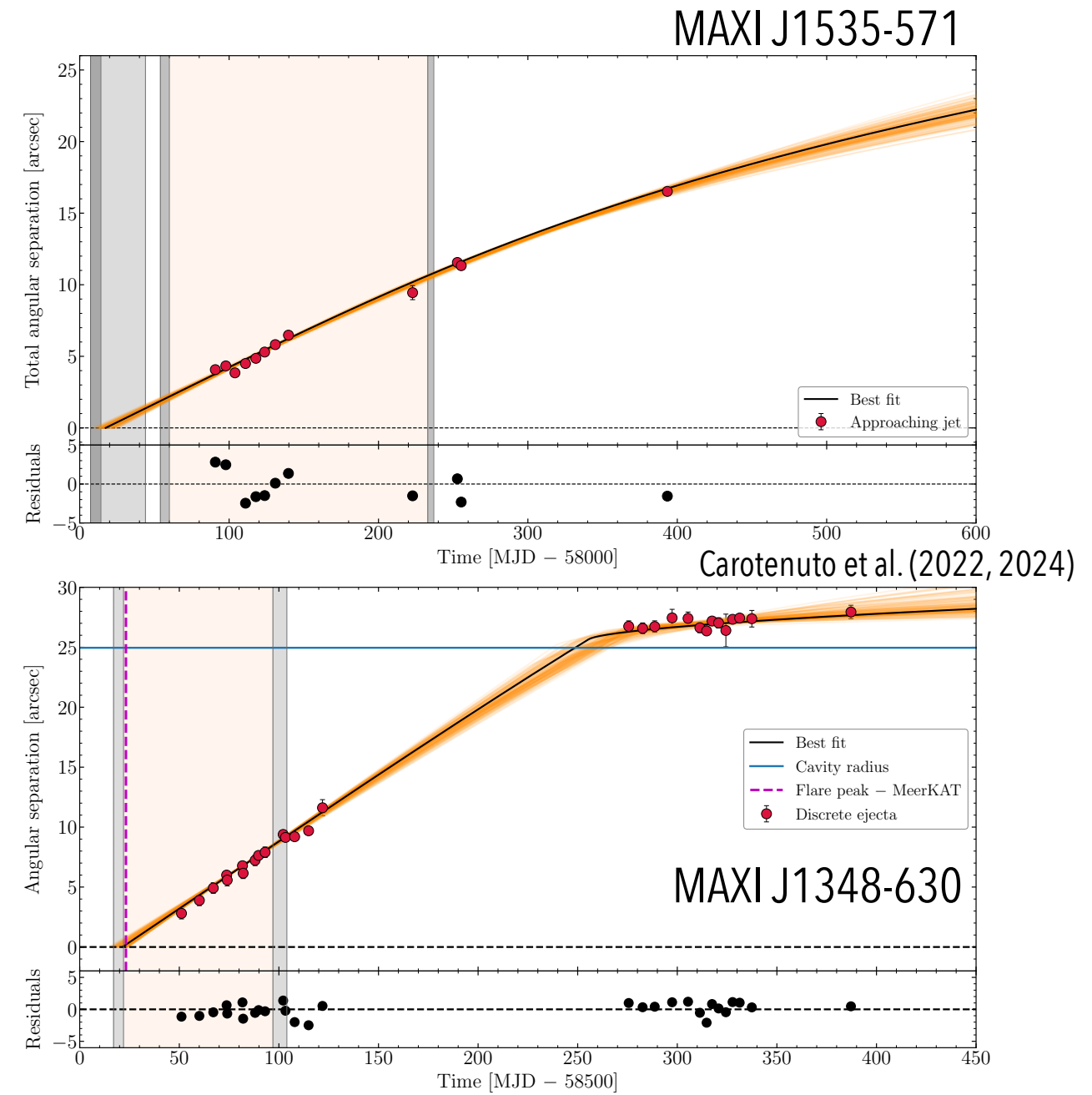
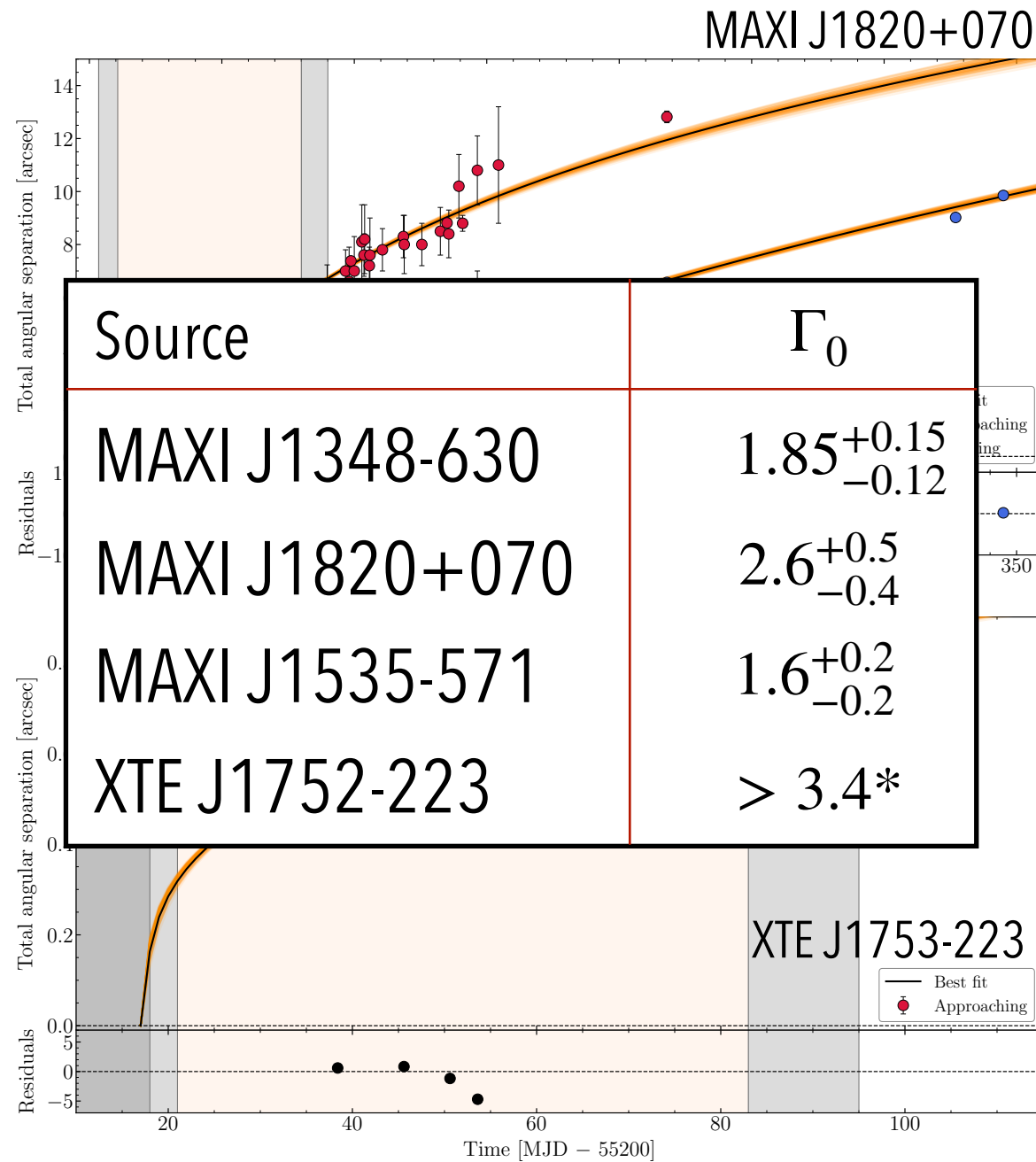
$$E_0 = [\Gamma(t) - 1] M_0 c^2 + \sigma [\Gamma_{sh}^2(t) - 1] m_{sw}(t) c^2$$



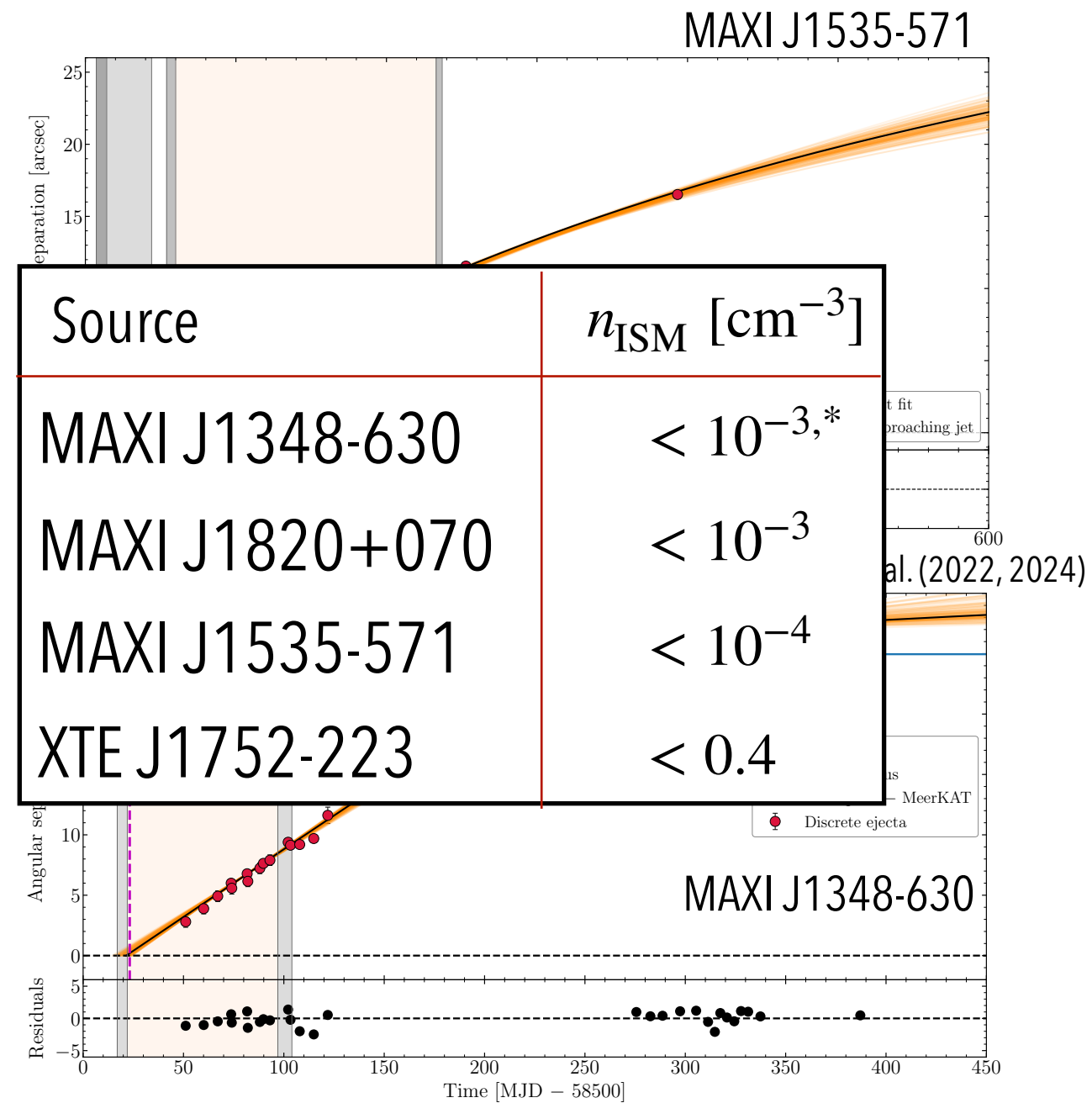
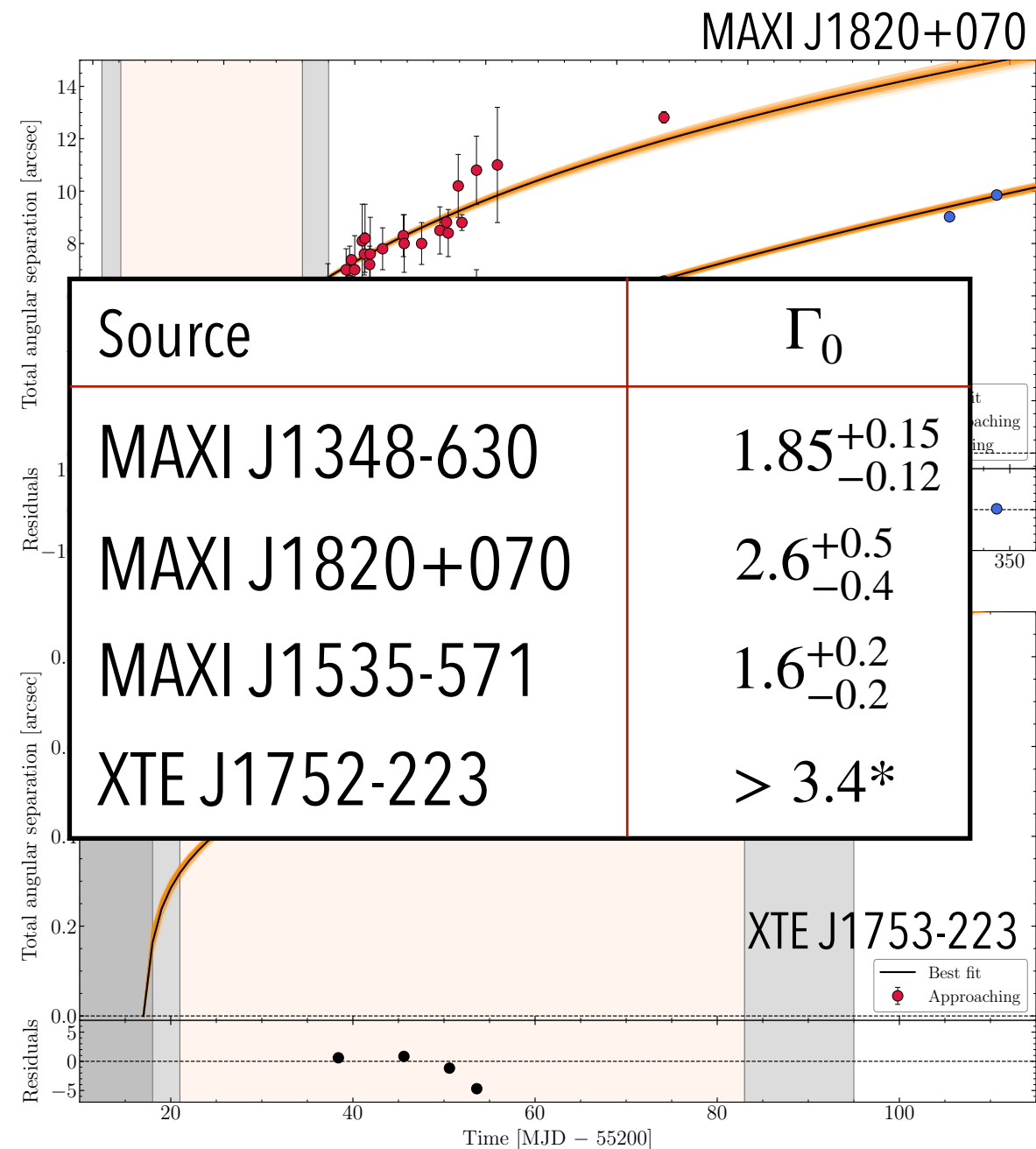
Applying GRB blast wave models to XRB jets



Applying GRB blast wave models to XRB jets

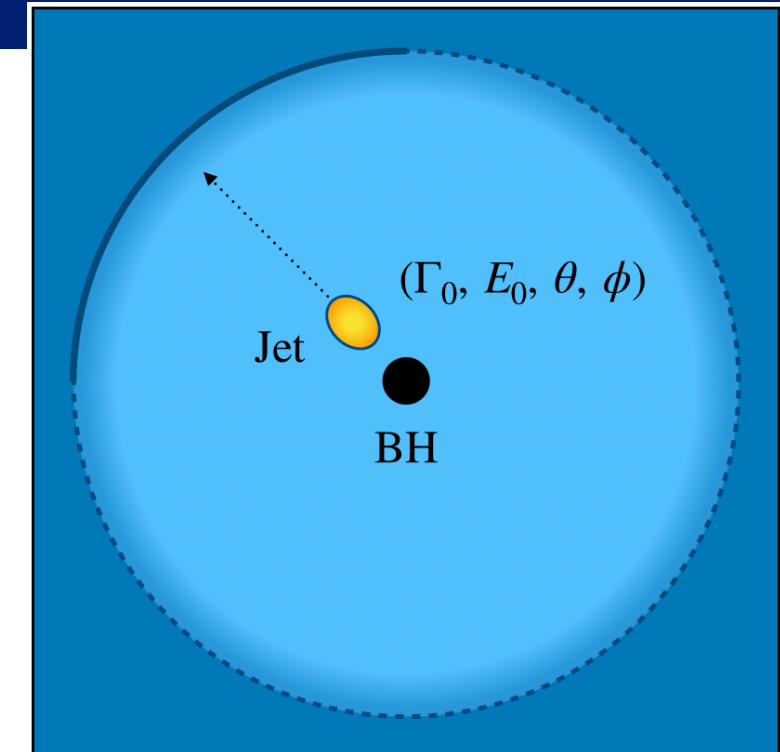


Applying GRB blast wave models to XRB jets



Discrete ejecta as probes of the BH environment

- Using discrete ejecta as “probes” of the environment surrounding BH XRBs is revealing the likely presence of under-dense cavities in which these sources could be embedded (e.g. Heinz 2002, Hao & Zhang 2009, Carotenuto et al. 2022, Sikora & Zdziarski 2023)
- What is producing these ISM cavities?
- Jet-produced under-dense environments are consistent with the first relativistic hydrodynamic simulations of these objects (Savard et al. 2025) - see talk by **Katie Savard**
- The jet feedback can be studied by mapping the molecular line emission from the shocked ISM with ALMA. See the Flash talk by **Pau Bosch-Cabot** for new results on MAXI J1348-630 and MAXI J1820+070!
- More information on the jet propagation can also be obtained from the evolution radio polarization (e.g. Fender et al. 1999, Hughes et al. *in prep.*), and also from the joint modelling of the jet motion and radiation. See the Flash talk by **Alex Cooper!**

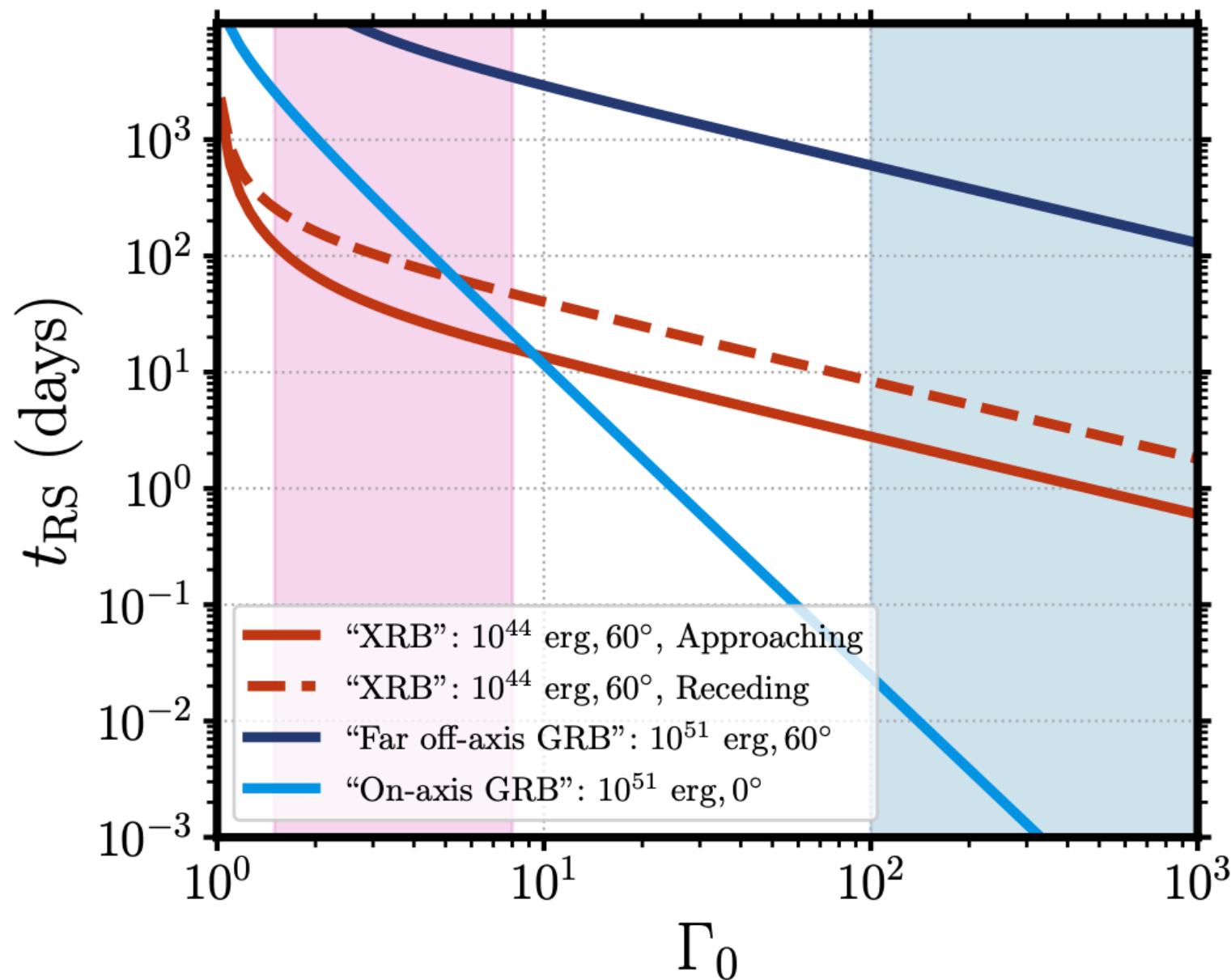


A visualization of the cosmic web, showing a vast network of dark matter filaments and galaxy clusters. The filaments are depicted as glowing orange and yellow structures against a dark background, with several bright, dense clusters of galaxies visible. The overall color palette is dominated by warm tones of orange, red, and yellow, suggesting high temperatures and intense gravitational forces.

**Thanks for
the
attention!**

Applying GRB blast wave models to XRB jets

We show that, for fixed blast wave or ejecta energy, reverse shocks cross the ejecta much later (earlier) on in the evolution for less (more) relativistic systems, and find that reverse shocks are much longer-lived in XRBs and off-axis GRBs compared to on-axis GRBs. Reverse shock crossing should thus typically finish after ~ 10 -100 of days (in the observer frame) in XRB ejections



Matthews et al. (2025)