Large-scale jets from black hole X-ray binaries in the SKA era

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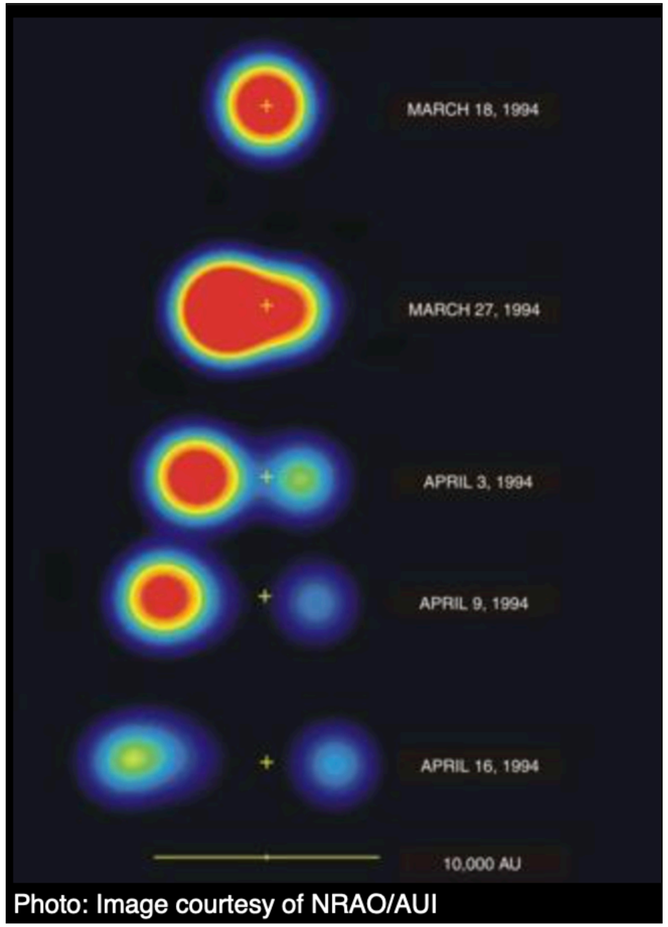
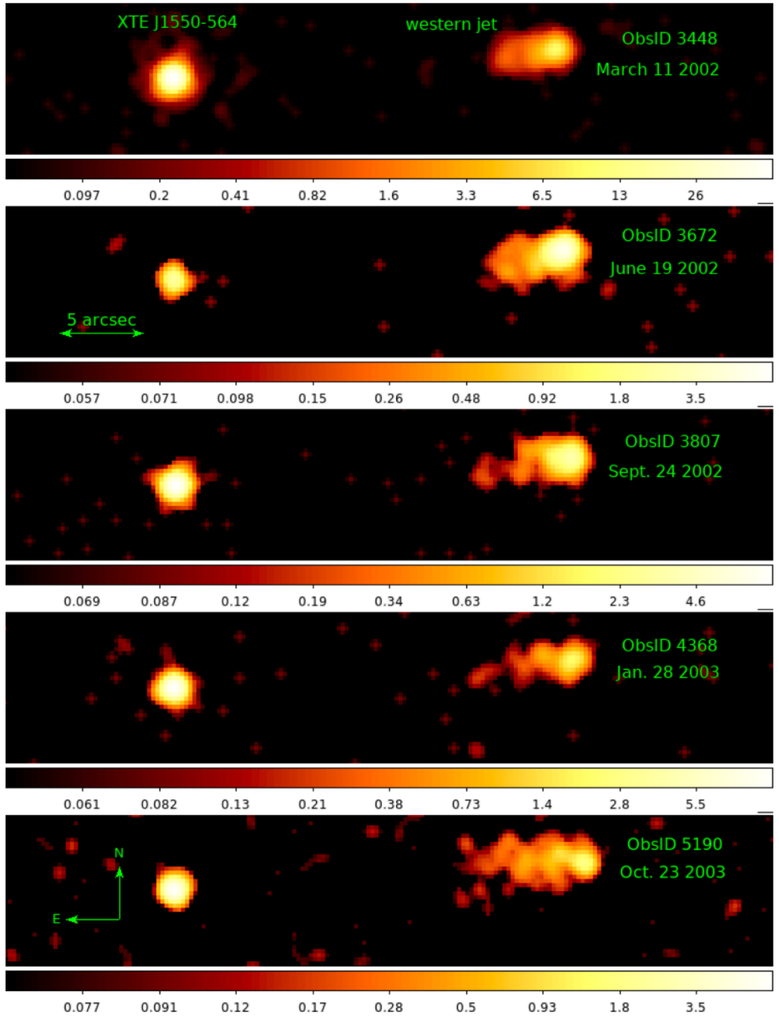
The Fifth National Workshop on the SKA project
27/11/2025

Credit: J. Paice

Discrete ejecta from BH XRBs





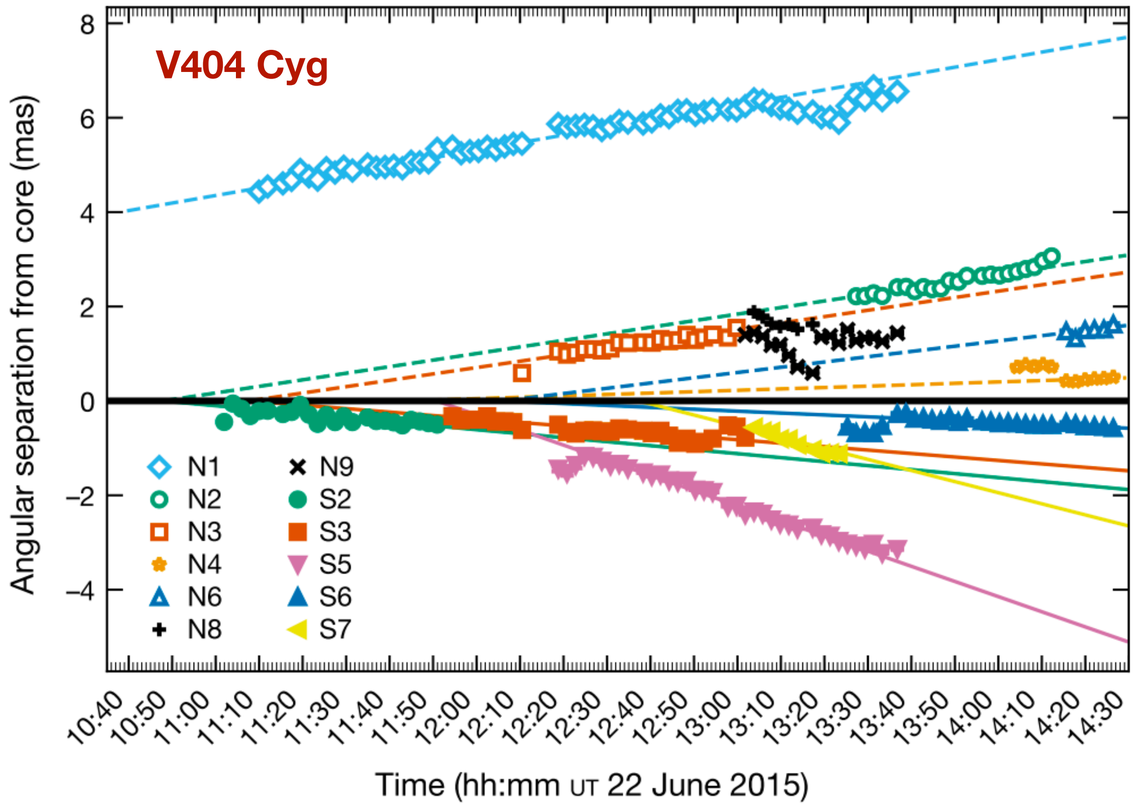
Main open questions

- What is the **jet powering mechanism**?
- How much **energy** do they carry, and what is their **composition**?
- What triggers the ejection of discrete components?
- Can we use the ejecta as **probes of the environment** surrounding the BH?

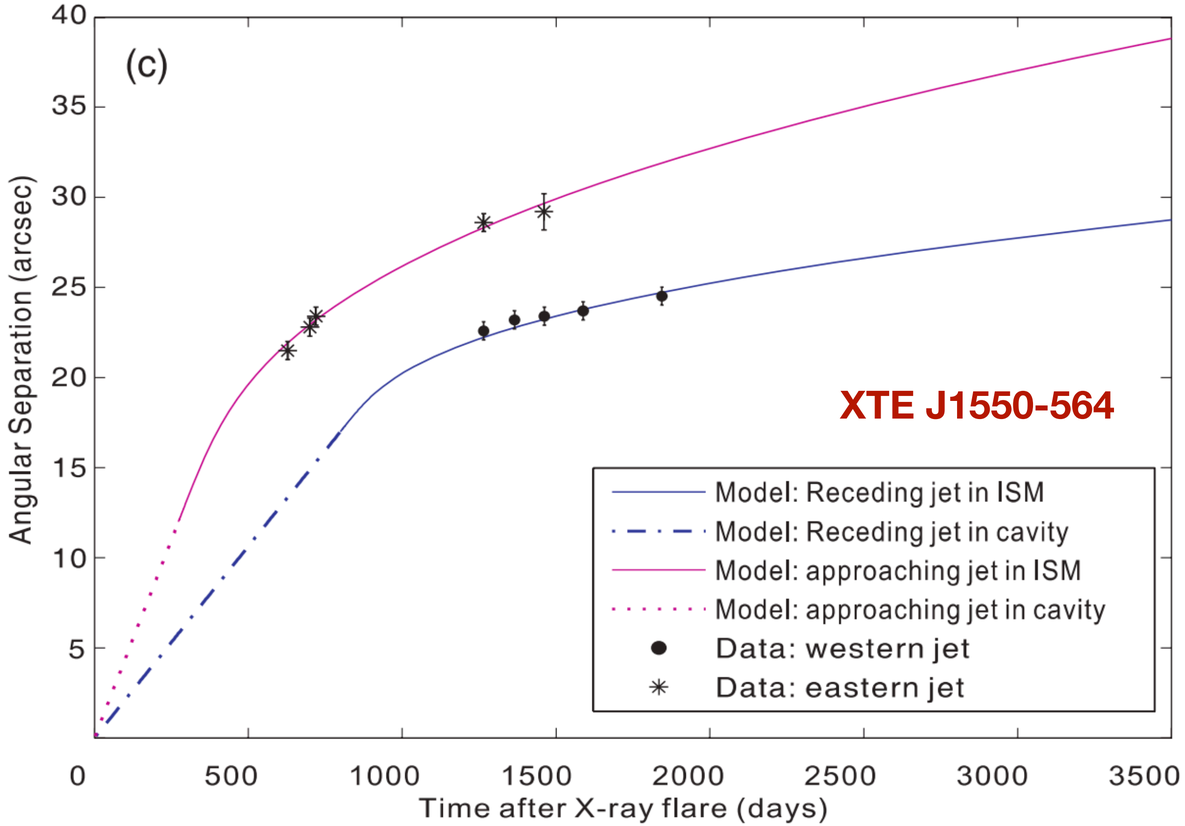
Mirabel & Rodriguez (1994), Migliori et al. (2017)

Jet kinematics

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



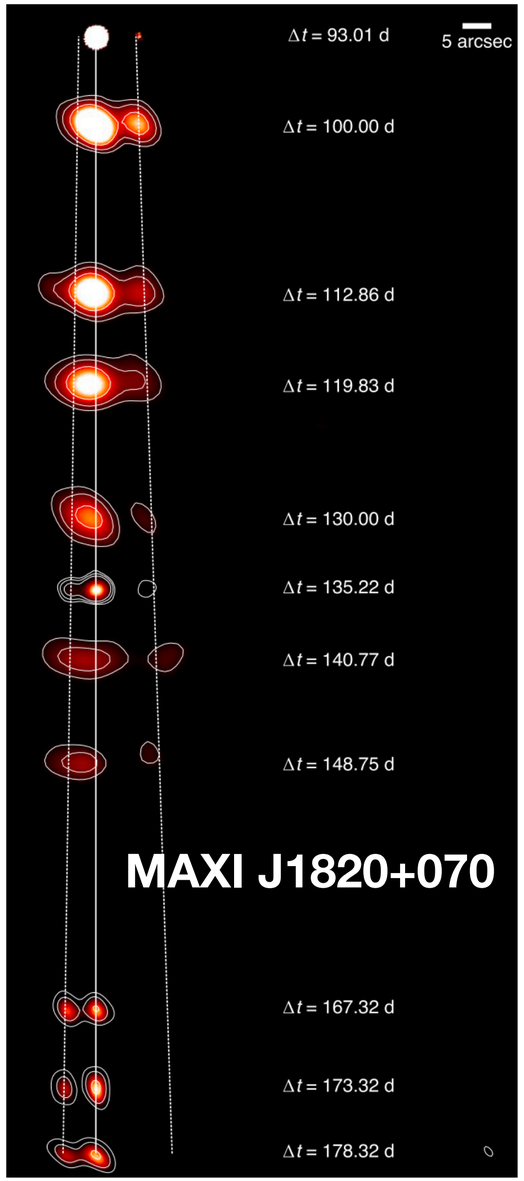
Evidences for late-time **deceleration** of the jets due to the **interaction** with the ISM

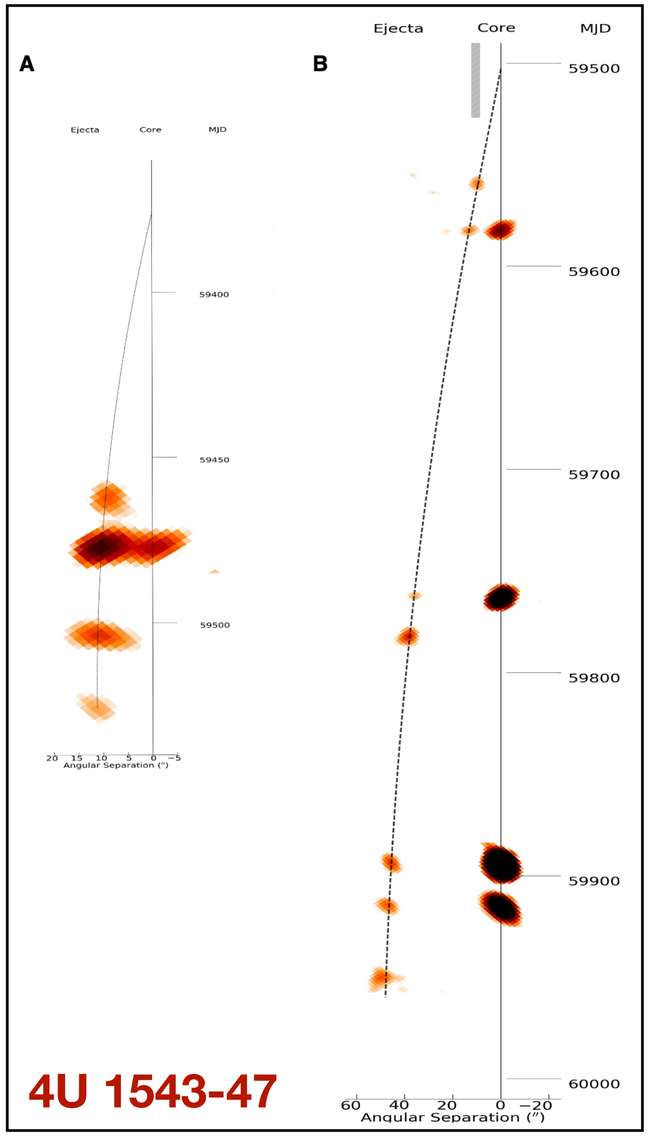


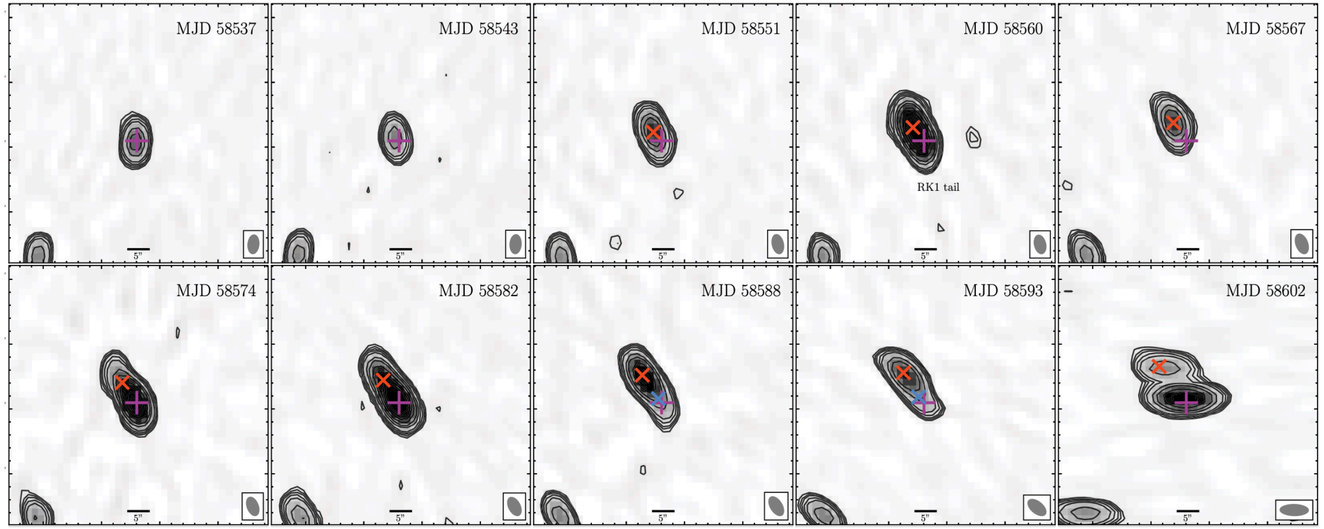
Corbel et al. (2002), Hao & Zhang (2009), Miller-Jones et al. (2019)

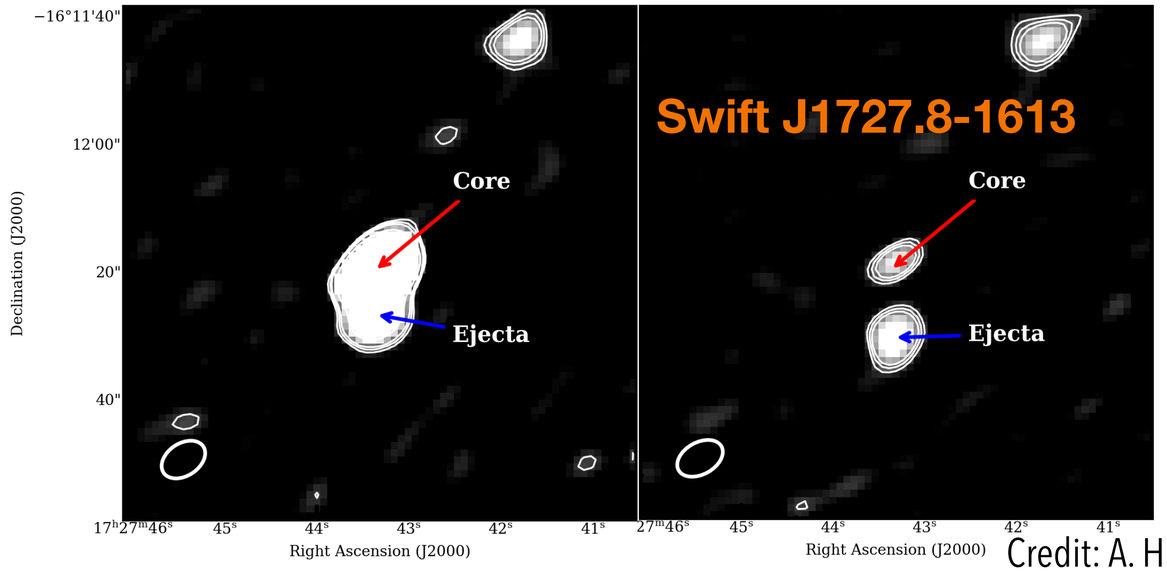
Large-scale jets from ThunderKAT and X-KAT

MAXI J1348-630







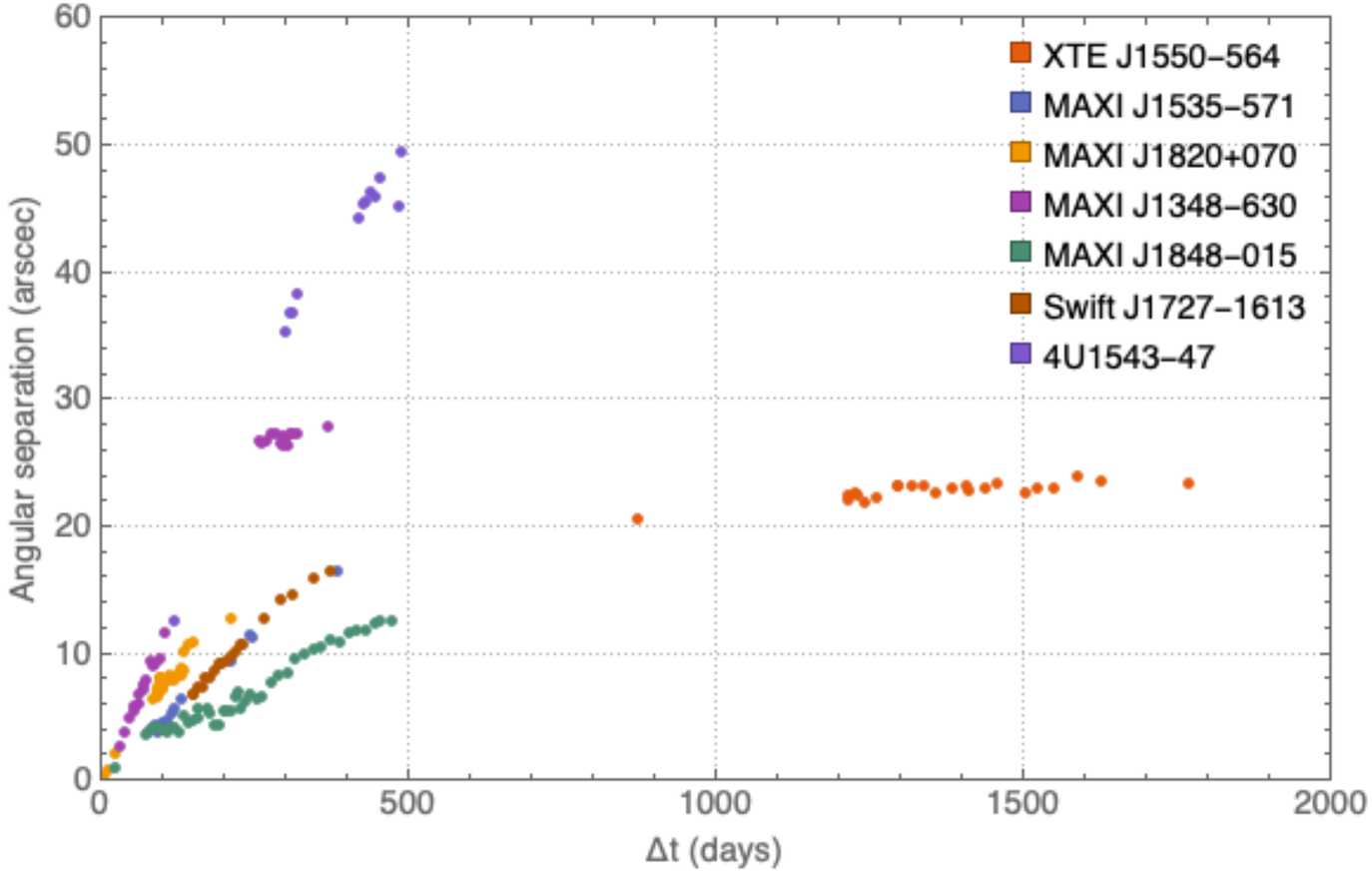


Credit: A. Hughes

Bright et al. (2020), Carotenuto et al. (2021 and in prep.), Zhang et al. (2025)

Large-scale jets from ThunderKAT and X-KAT

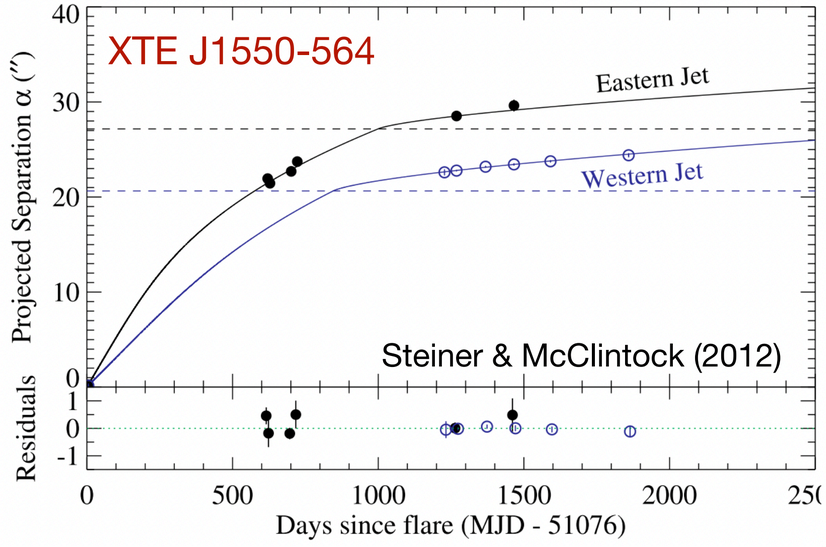
MeerKAT has revealed a new population: the majority of bright BH XRBs produce powerful ejections which propagate for > 1 year and decelerate in the ISM

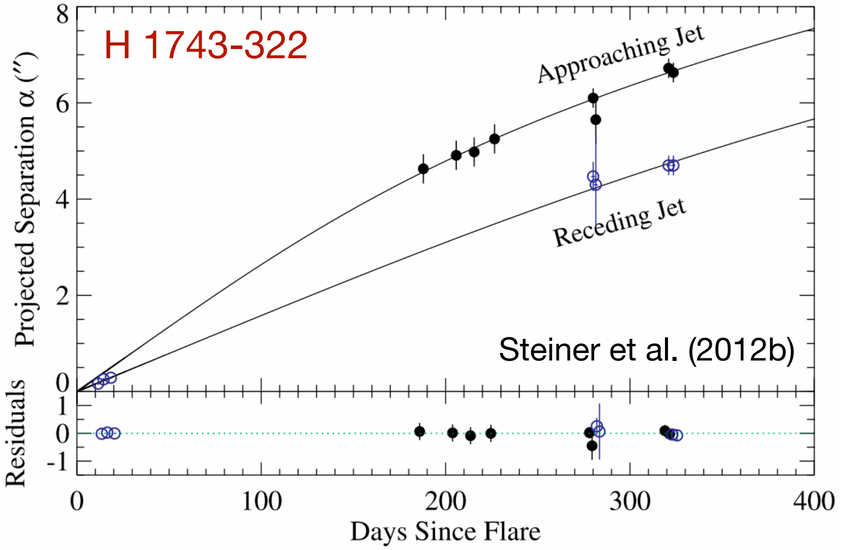


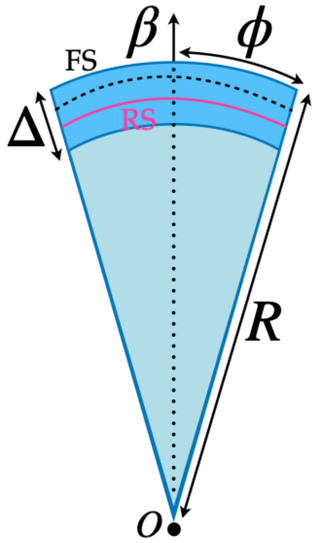
Credit: R. Fender

The blast-wave model

- Jet deceleration data can be fit with a numerical version of the GRB blast-wave model
- Jet dynamical model based on plasmon adiabatic expansion
- Kinetic energy is transferred to the swept up material via external shocks, in analogy with GRB afterglows
- $E_0 = \left[\Gamma(t) - 1\right] M_0 c^2 + \sigma\left[\Gamma_{sh}^2(t) - 1\right] m_{sw}(t) c^2$



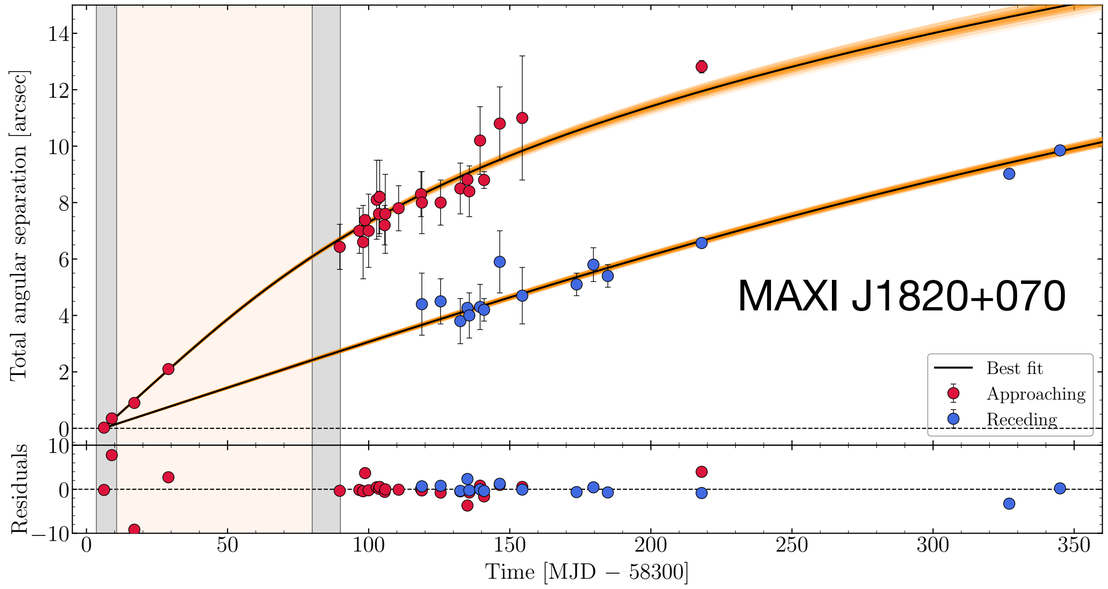


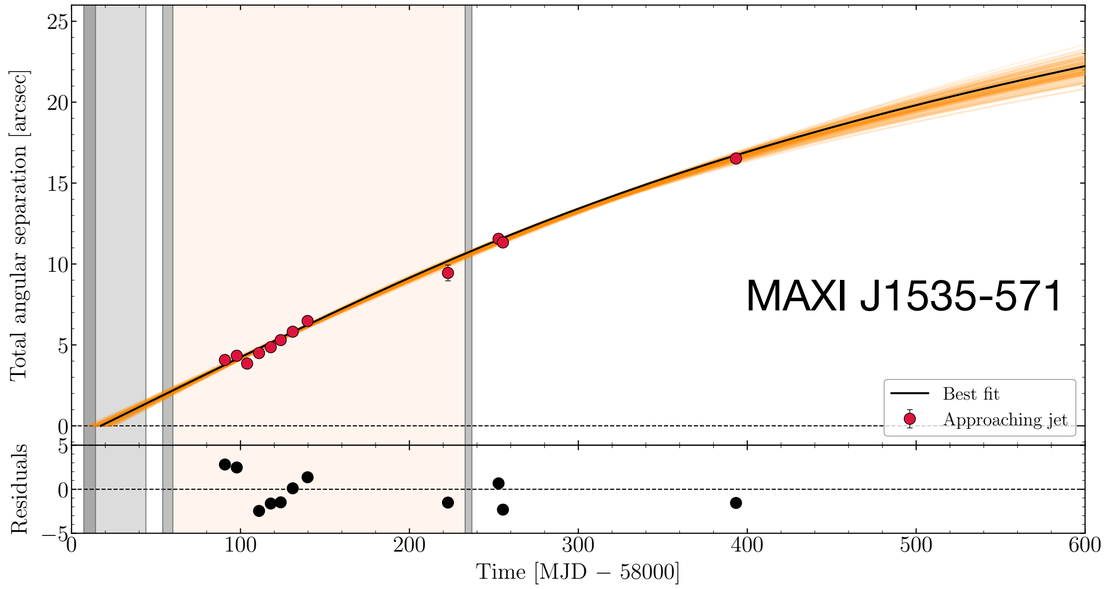


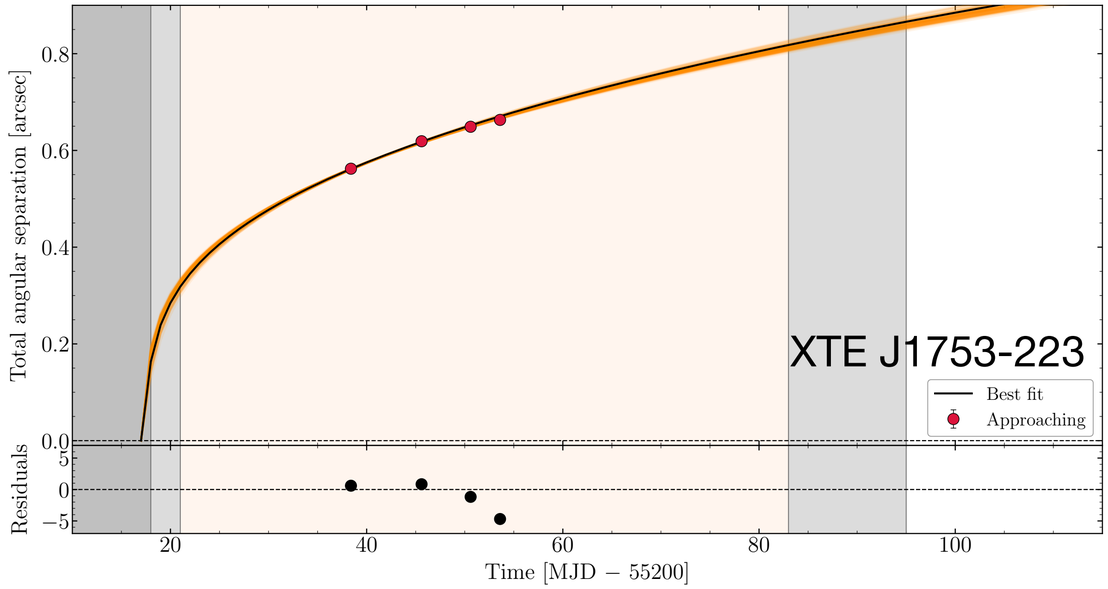
Degeneracy between E_0, $n_{\rm ISM}$, ϕ

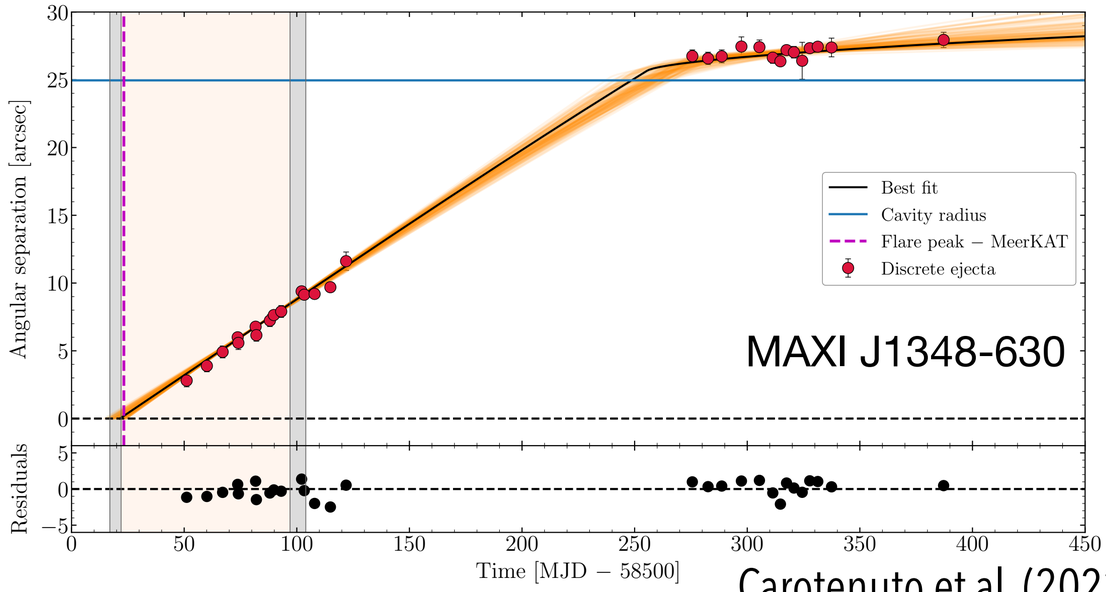
Wang et al. (2003), Hao & Zhang (2009)
Steiner & McClintock (2012)
Steiner et al. (2012)

Applying GRB blast wave models to XRB jets







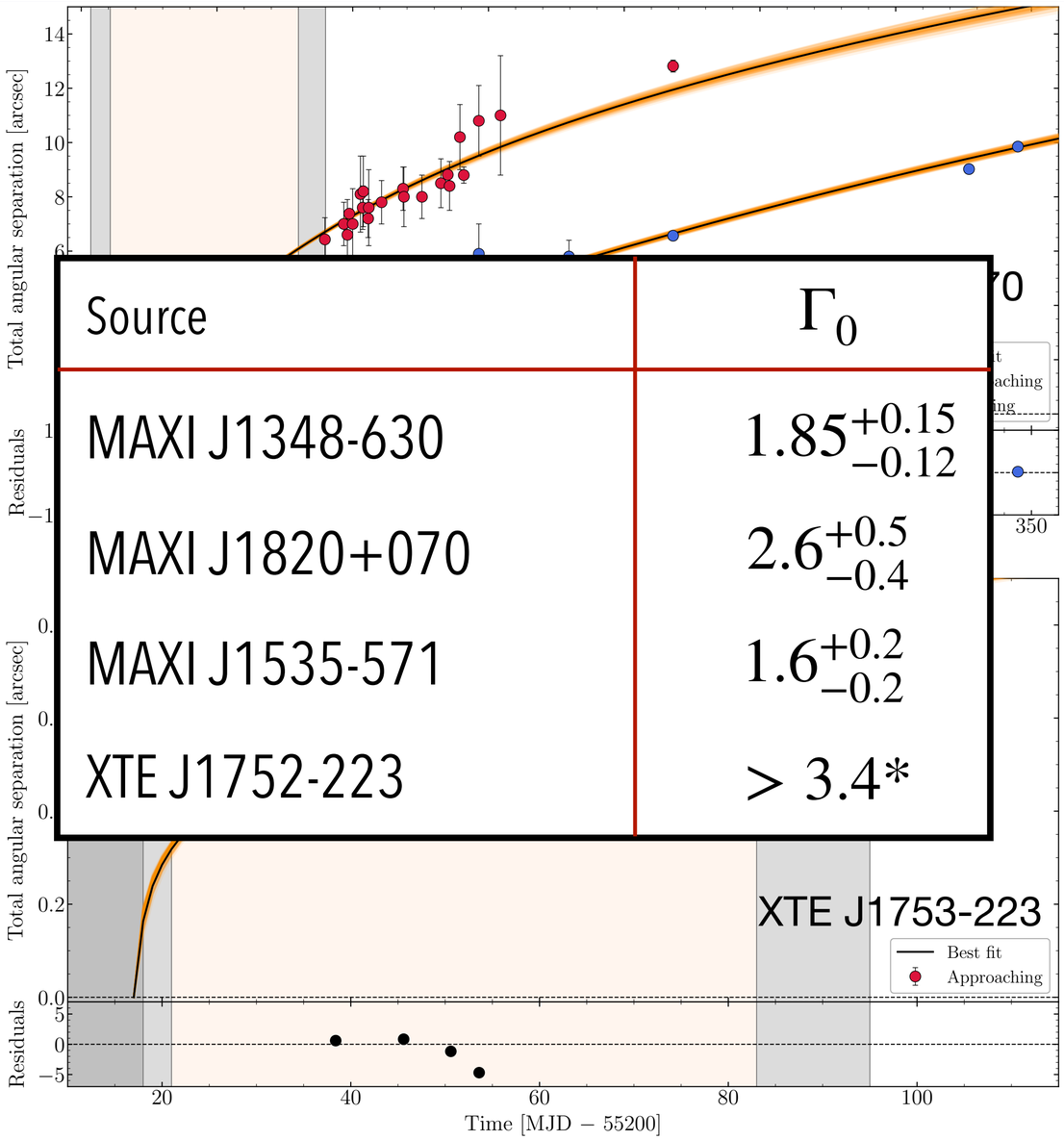


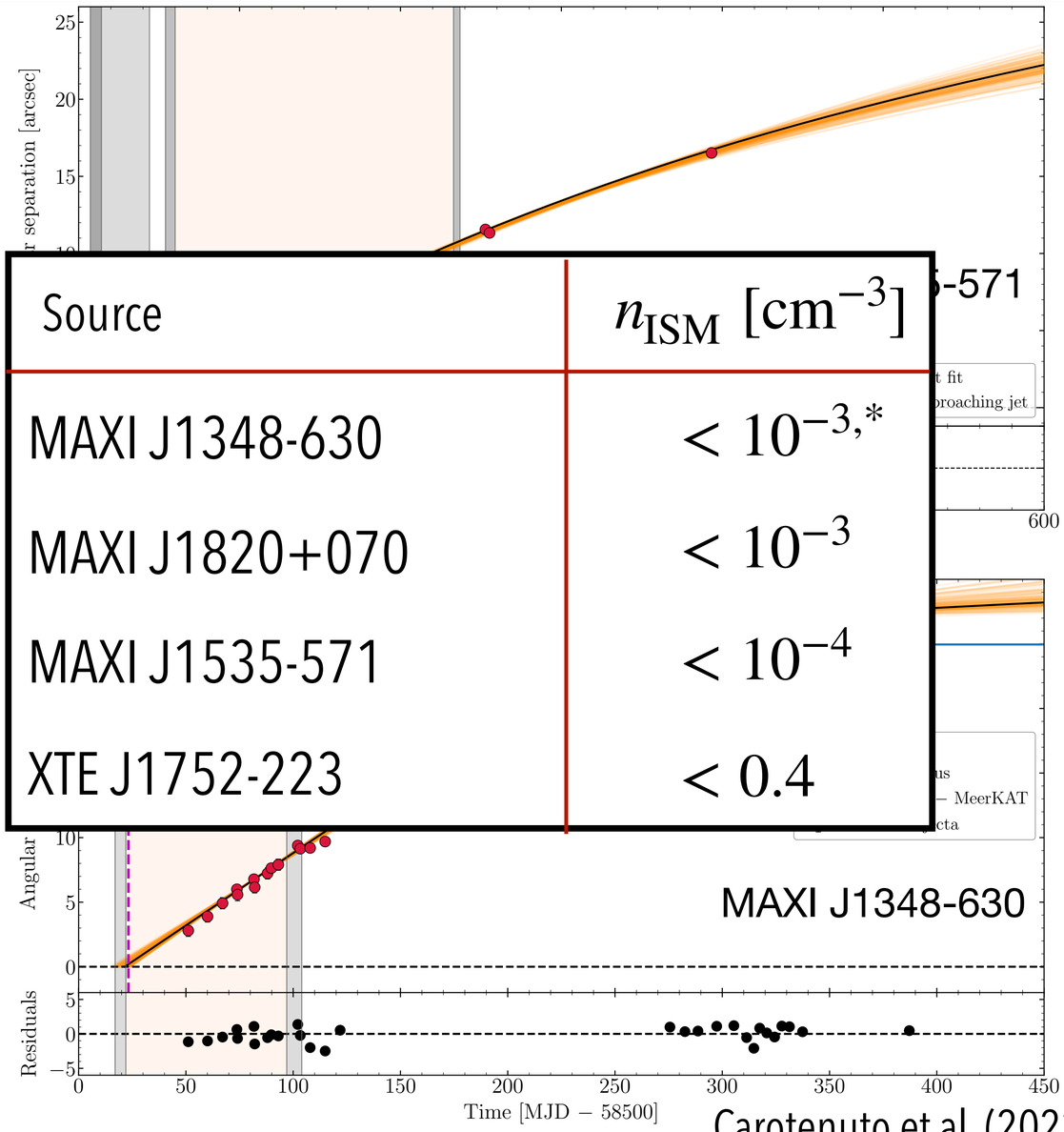
Carotenuto et al. (2022, 2024)

Applying GRB blast wave models to XRB jets

Source	Γ_0
MAXI J1348-630	$1.85^{+0.15}_{-0.12}$
MAXI J1820+070	$2.6^{+0.5}_{-0.4}$
MAXI J1535-571	$1.6^{+0.2}_{-0.2}$
XTE J1752-223	> 3.4*

Source	$n_{\rm ISM}$ [cm^{-3}]
MAXI J1348-630	$< 10^{-3,*}$
MAXI J1820+070	$< 10^{-3}$
MAXI J1535-571	$< 10^{-4}$
XTE J1752-223	< 0.4

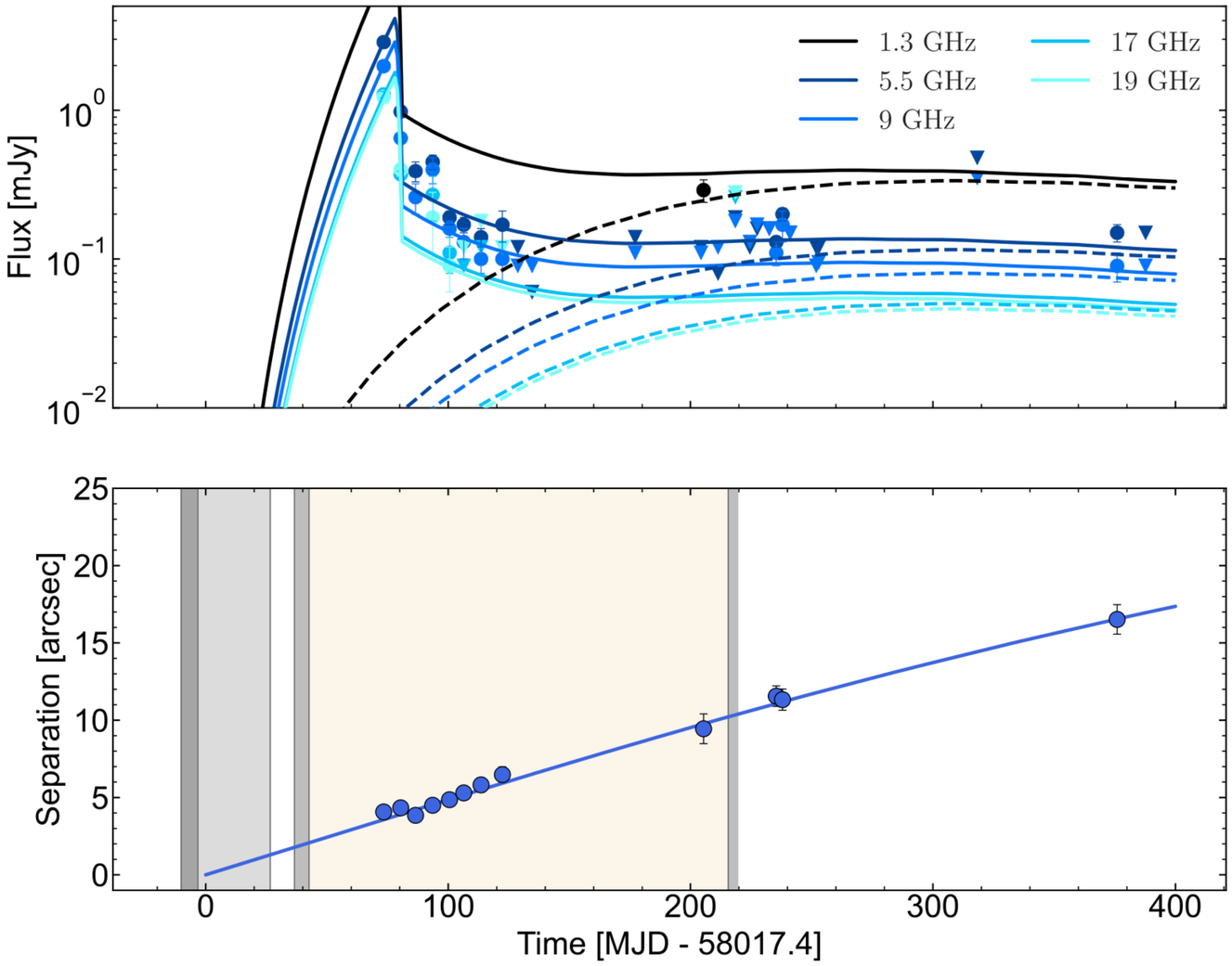




Carotenuto et al. (2022, 2024)

Joint radiation+kinematics modelling

MAXI J1535-571



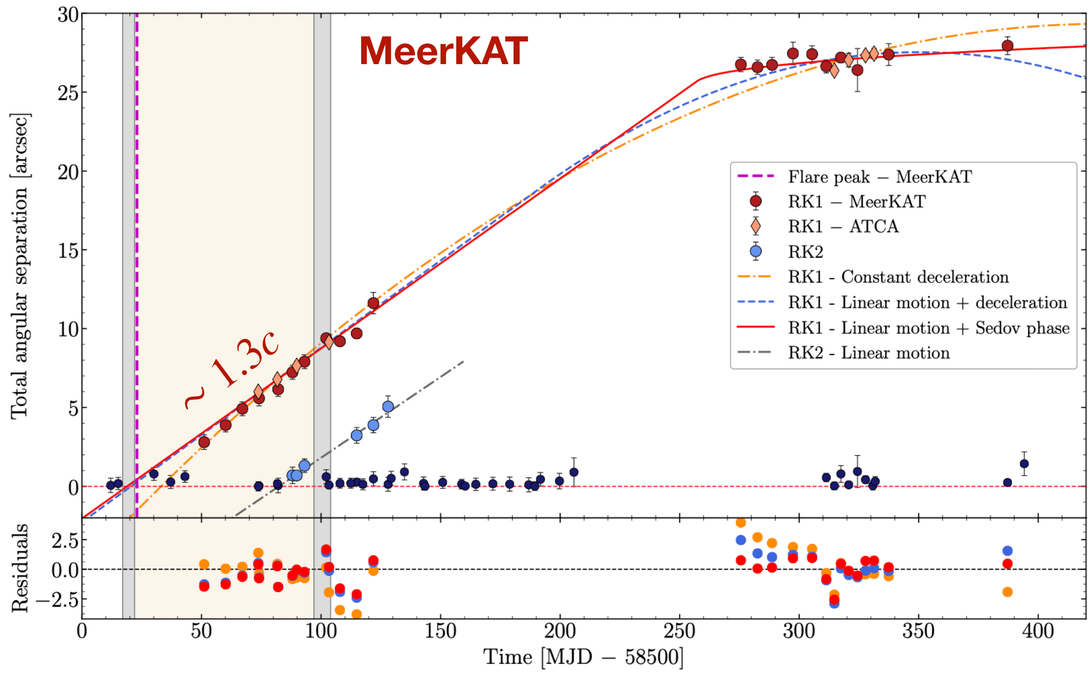
Combining **flux and separation data** allows us to **break the key degeneracy** $E_0, \phi, n_{\rm ISM}$

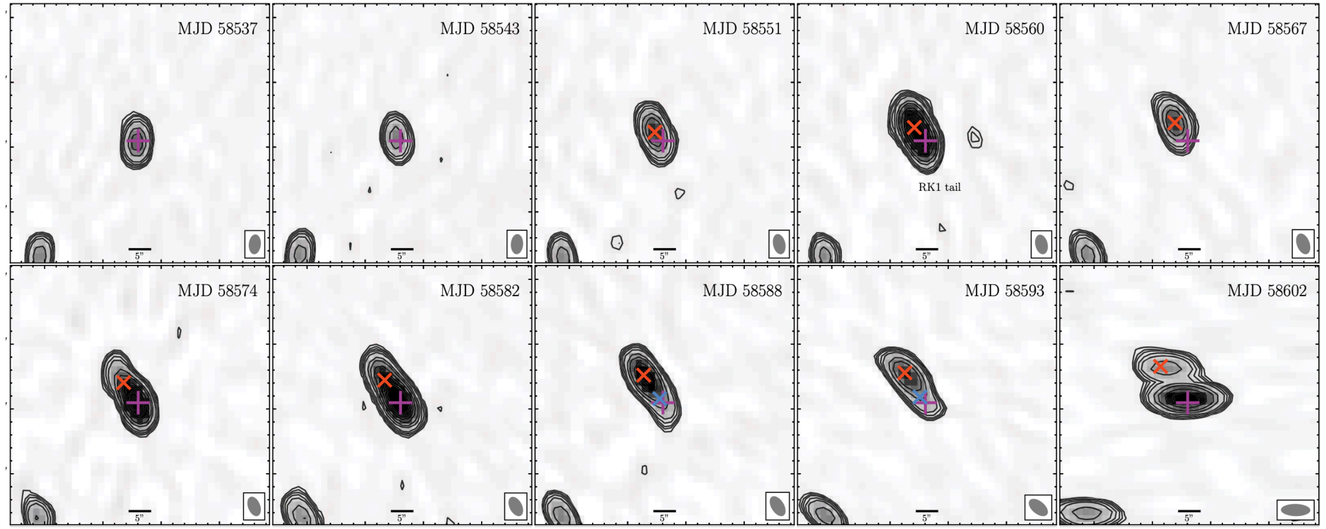
From a pilot study on the ejecta from MAXI J1535-571:

- The reverse shock dominates the ejecta emission at early times and is characterized by either low magnetization or inefficient particle acceleration.
- The jet has a moderate initial Lorentz factor $\Gamma_0 \simeq 1.4$ and does not undergo significant lateral spreading,
- The initial ejecta energy is $E_0 = (3 \sim 5) \times 10^{43}$ erg and may be powered by the accretion disk alone.
- The ejecta propagate into a low $n_{\rm ISM} = 10^{-5} \sim 10^{-4}$ cm^{-3} density environment.

Cooper et al. (2025)

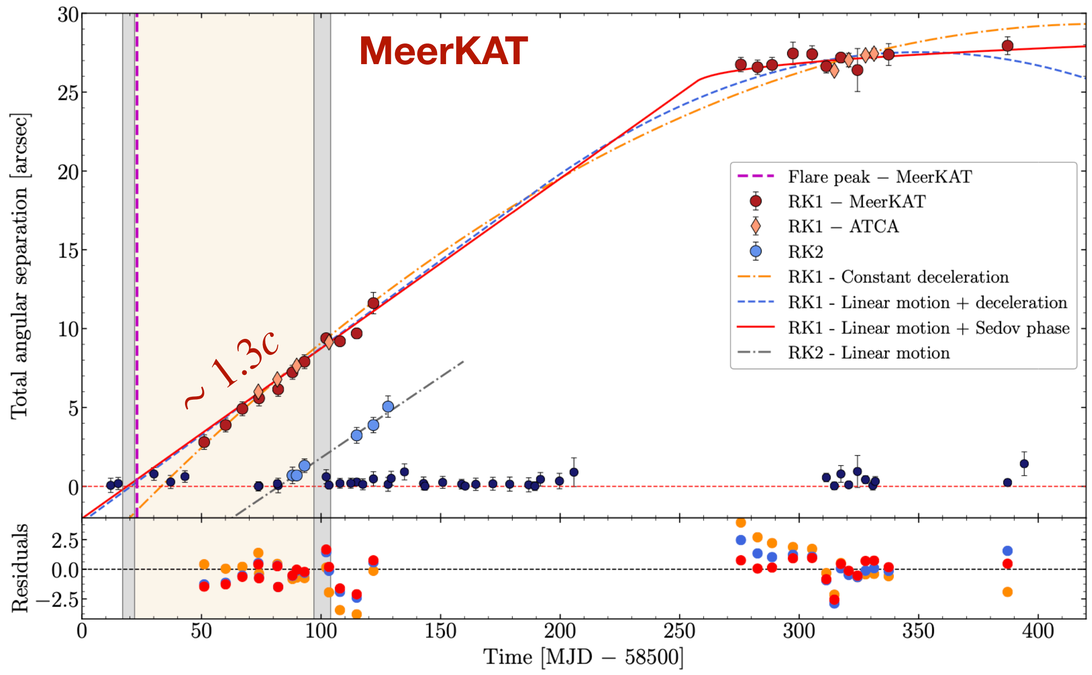
The BH environment: MAXI J1348-630 with MeerKAT and ALMA

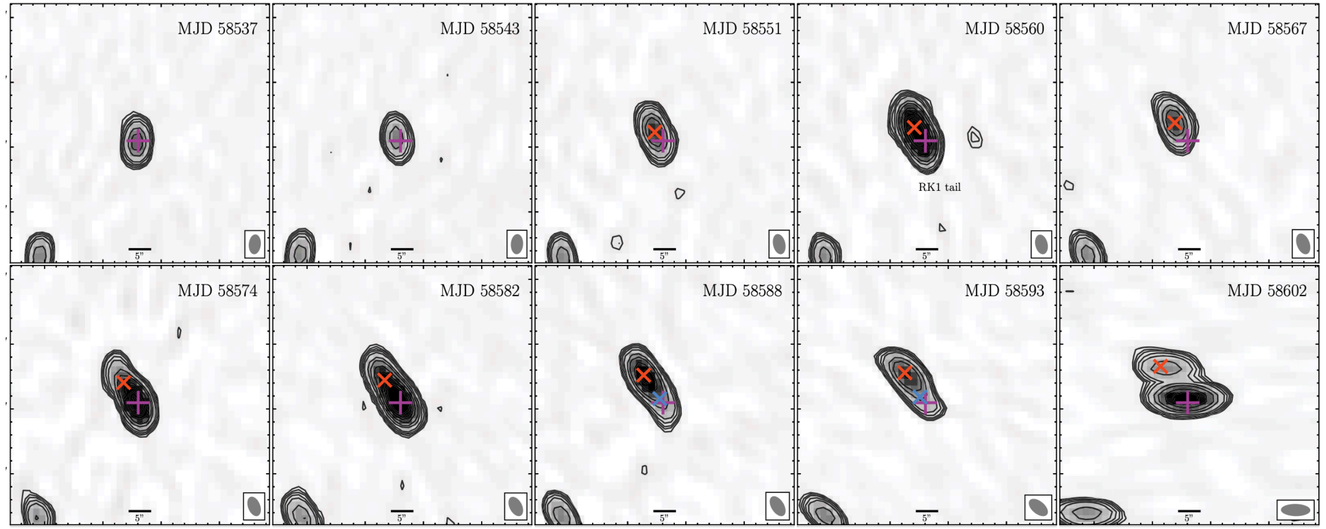


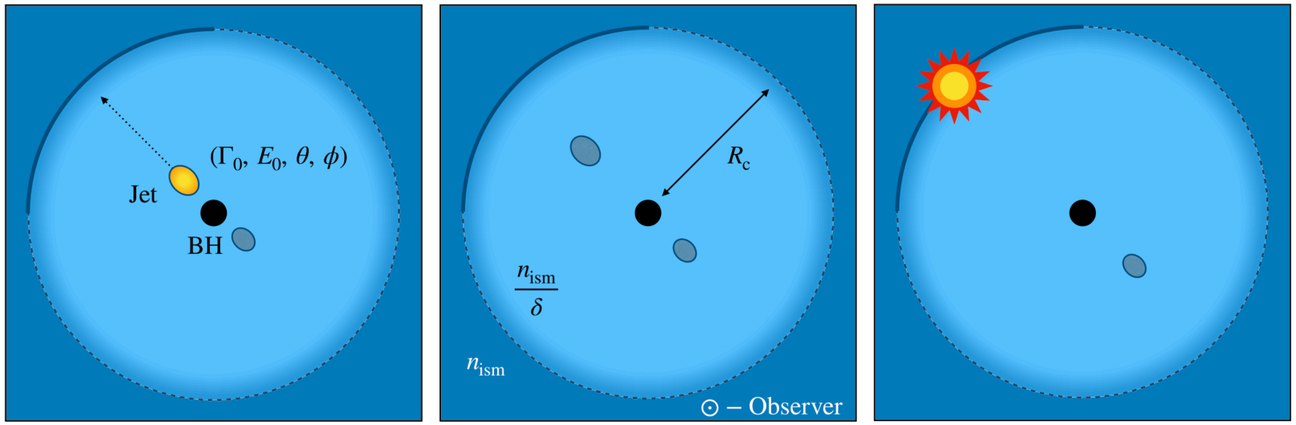


Carotenuto et al. (2021, 2022), Bosch-Cabot et al. (2025)

The BH environment: MAXI J1348-630 with MeerKAT and ALMA







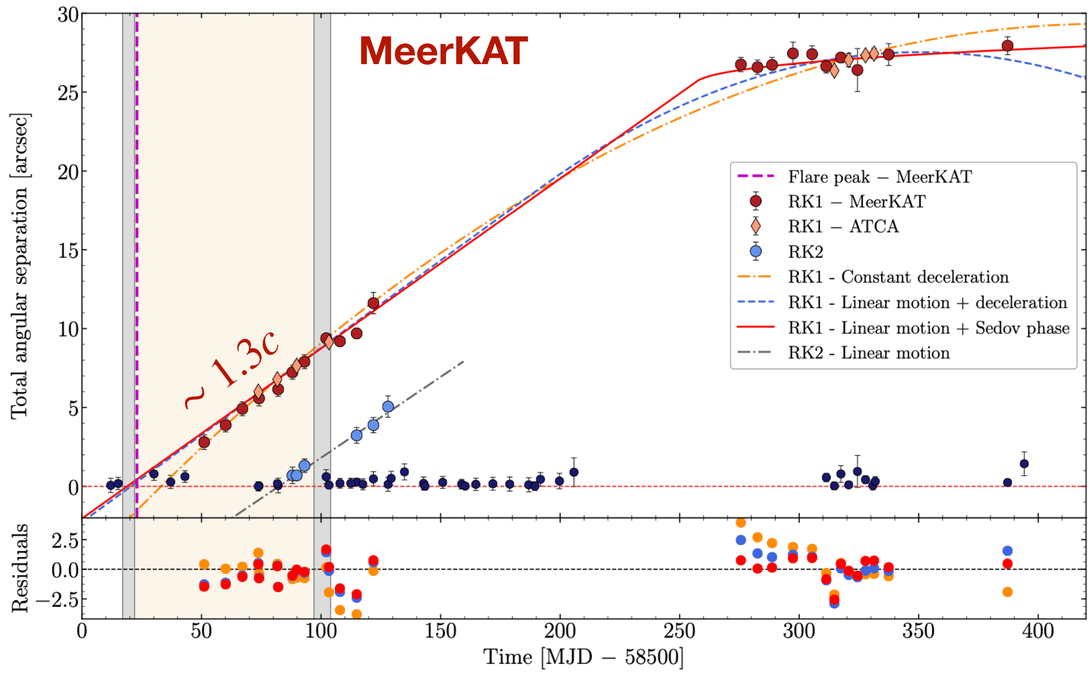
Ballistic phase
Feb - May 2019

Non-detection phase
May - Oct 2019

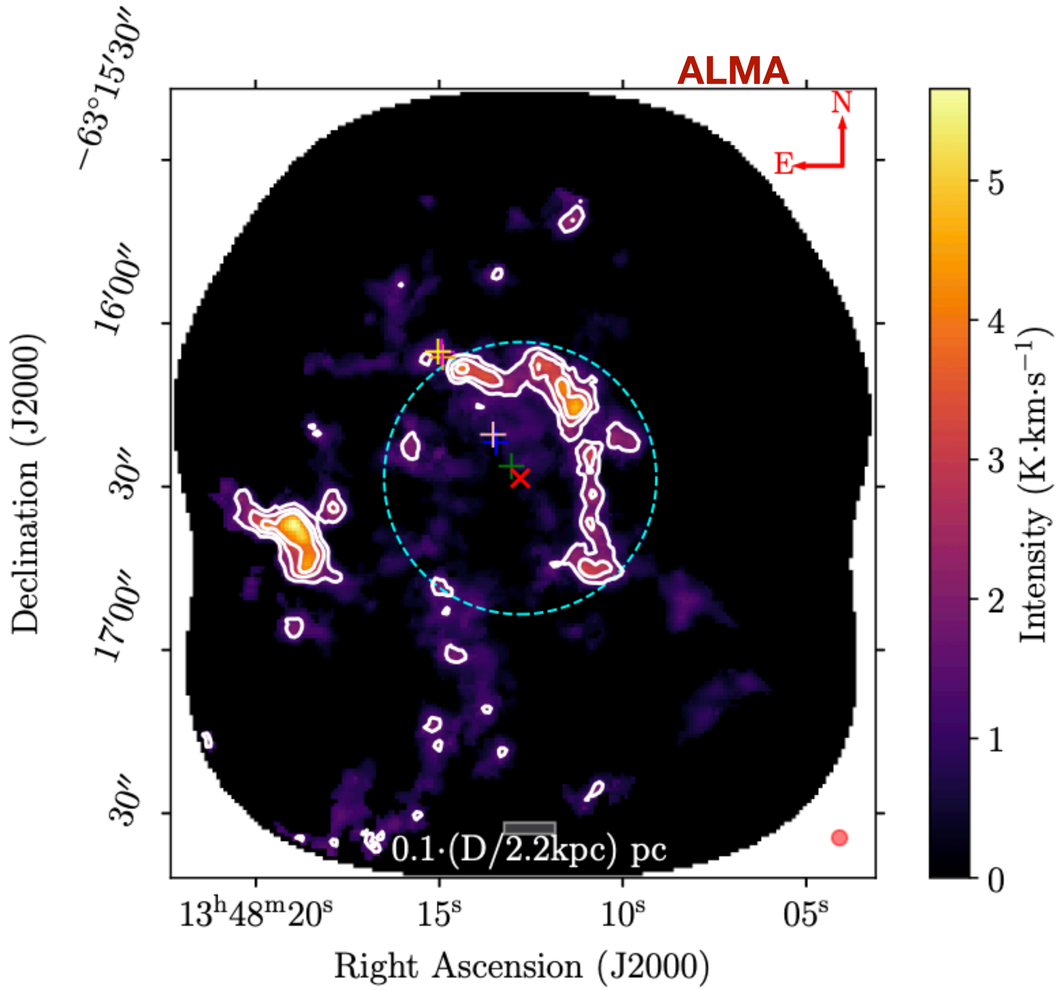
Deceleration phase
Oct 2019 - Feb 2020

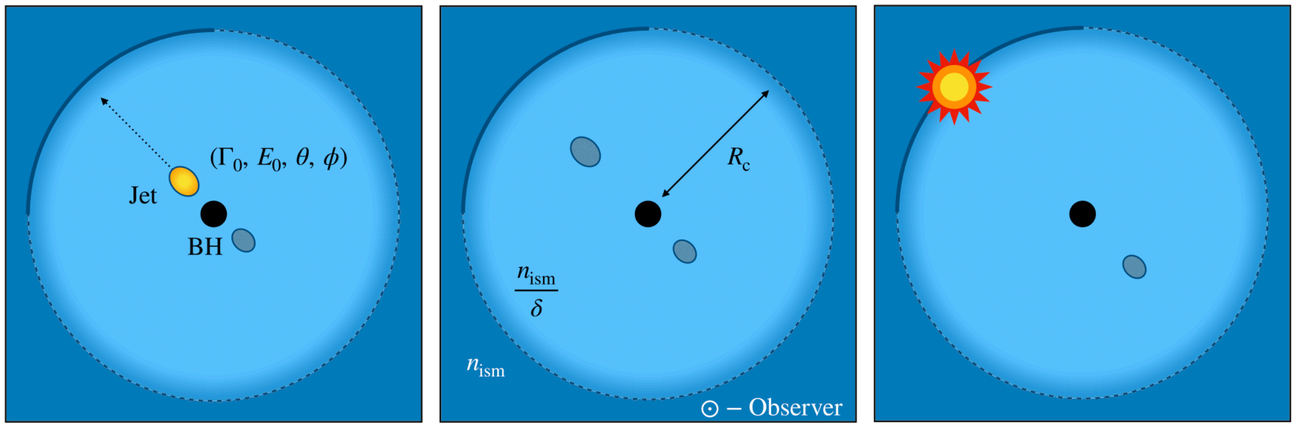
Carotenuto et al. (2021, 2022), Bosch-Cabot et al. (2025)

The BH environment: MAXI J1348-630 with MeerKAT and ALMA



ALMA identification of a ^{13}CO $(J = 1 - 0)$ molecular structure that provides compelling evidence for a jet-driven cavity in the environment of MAXI J1348-630





Ballistic phase
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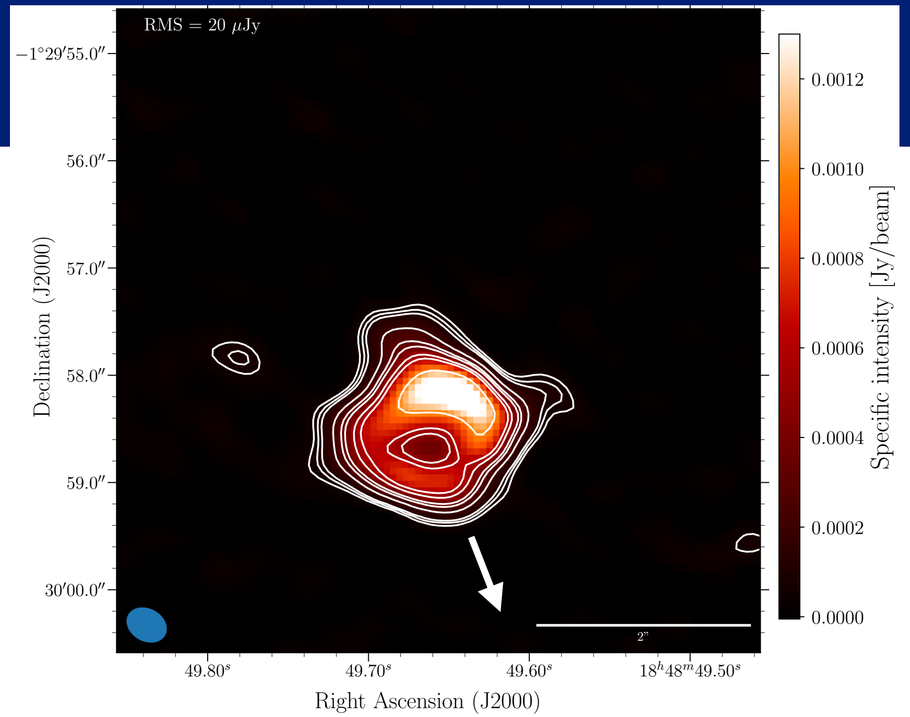
Carotenuto et al. (2021, 2022), Bosch-Cabot et al. (2025)

Perspectives with the SKA



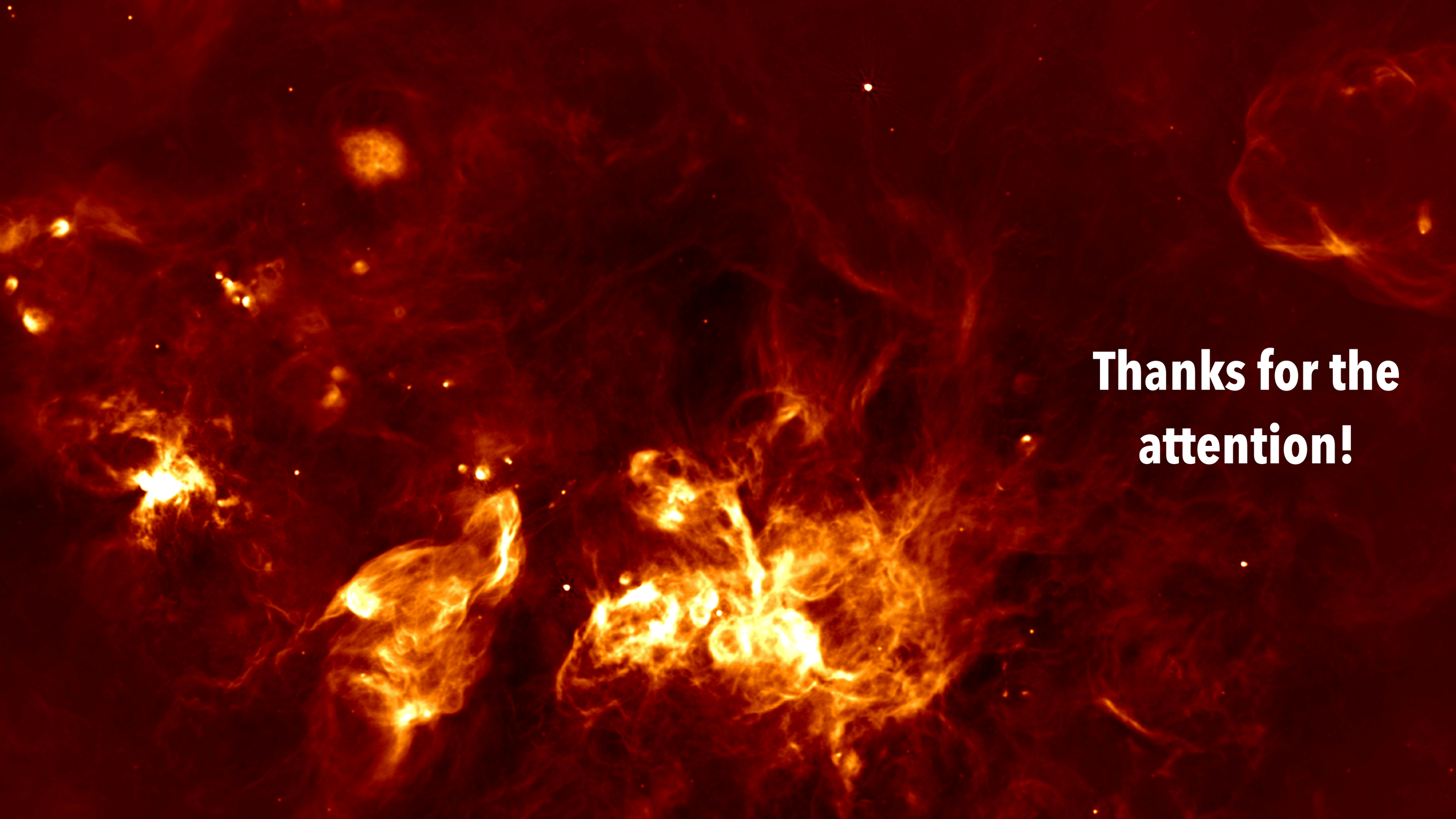
What can we do with the SKA in its AA* array?

- **Increased sensitivity:**
  Better coverage of the termination phase, improving the modelling of jet kinematics, more detections of receding jets

- **Increased frequency range:**
  More complete radio spectral coverage (up to band 5B) through the jet propagation, essential for the full kinematic+radiation modelling **–> jet energetics and BH feedback**

- **Sub-arcsec angular resolution:**
  - Resolving multiple components, observing ejecta much closer to the **moment of launch** (ejection date)
  - Accessing the jet **morphology** –> following the evolution of different shock components and comparison with relativistic hydrodynamic jet simulations (Savard et al. 2025)

Cooper et al. (2025), Savard et al. (2025), Corbel et al. (in prep.)


Thanks for the
attention!