RELATIVISTIC JETS FROM STELLAR MASS BLACK HOLES

ROB FENDER (UNIVERSITY OF OXFORD)

AND MANY COLLABORATORS! INCLUDING AT OXFORD:

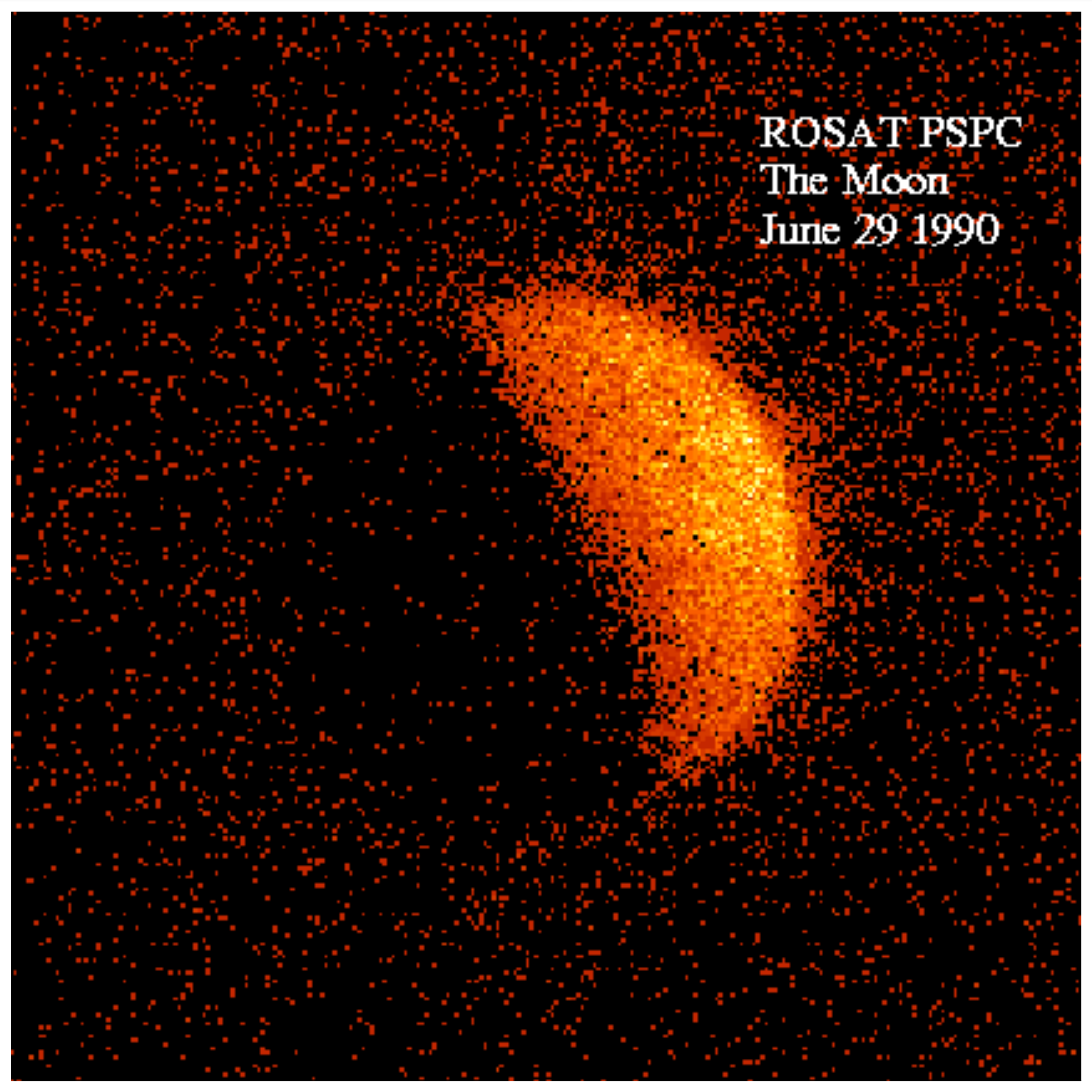
JOE BRIGHT, LAUREN RHODES, FRANCESCO CAROTENUTO, IAN HEYWOOD,
ALEX ANDERSSON, JAMES MATTHEWS, KATIE SAVARD

(LOTS OF WORK ON TDE / GRB AND OTHER TRANSIENTS NOT MENTIONED TODAY)

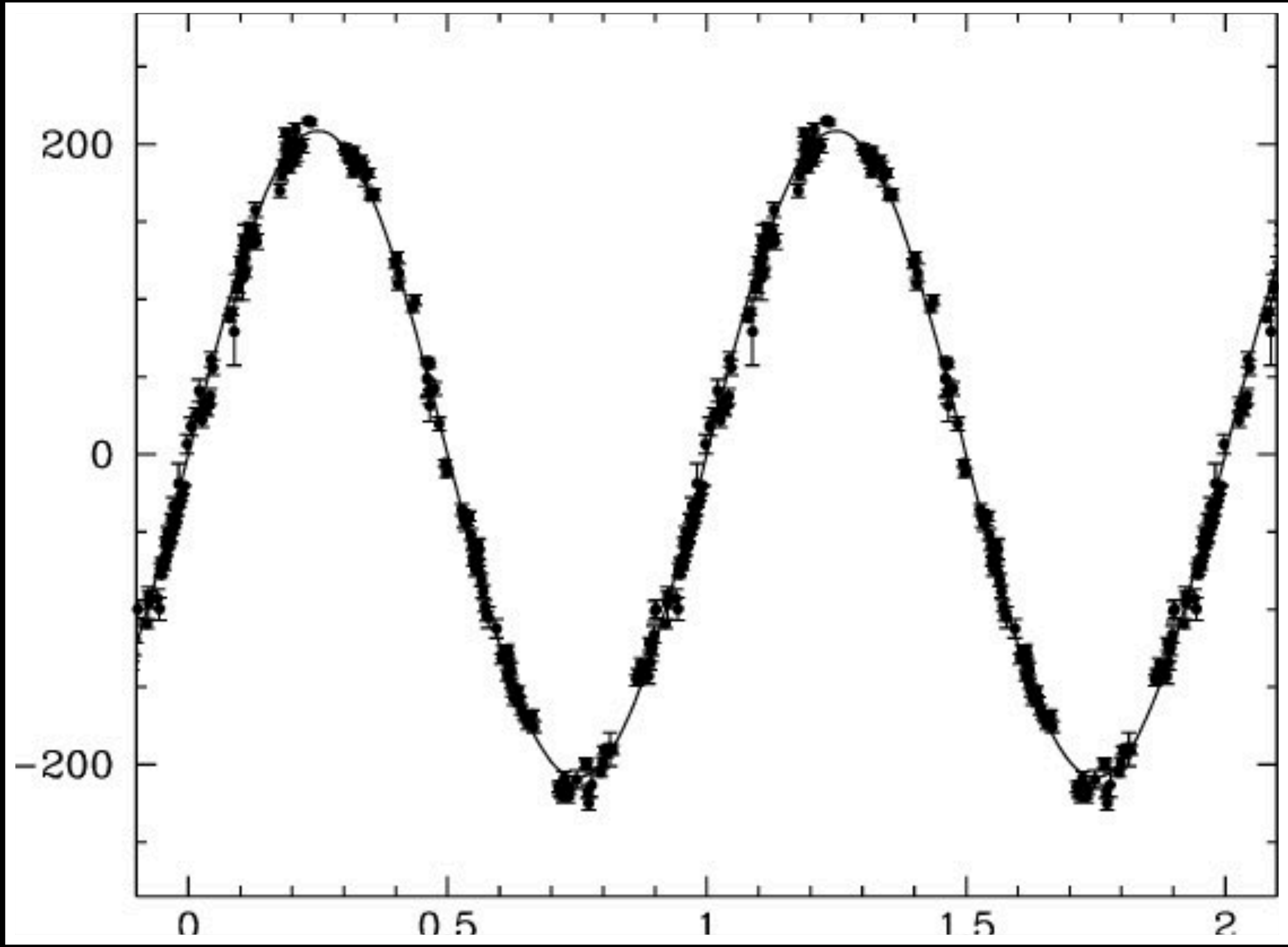
Oxford Astrophysics

EVIDENCE FOR ASTROPHYSICAL BLACK HOLES

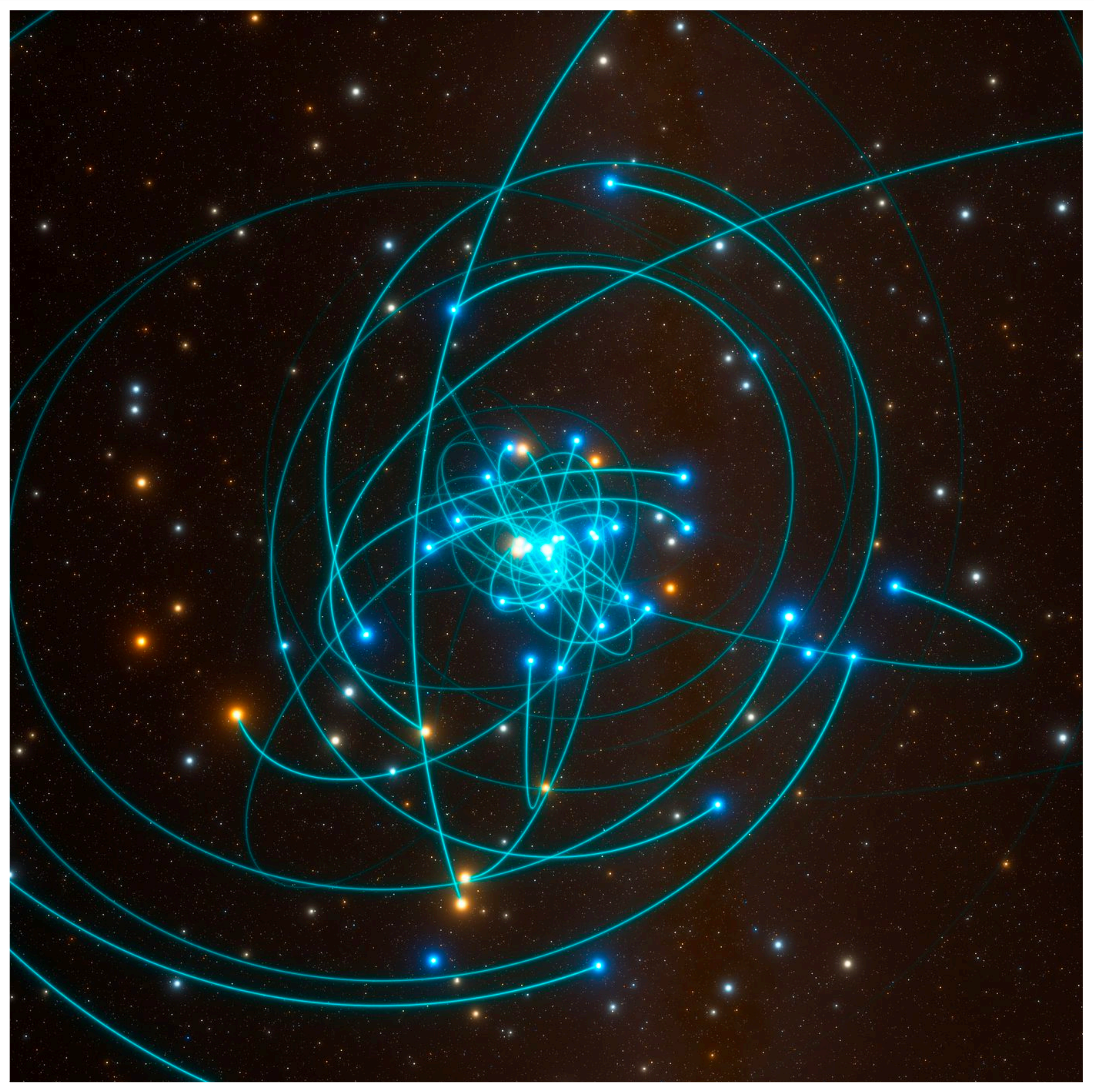
Extreme Luminosities



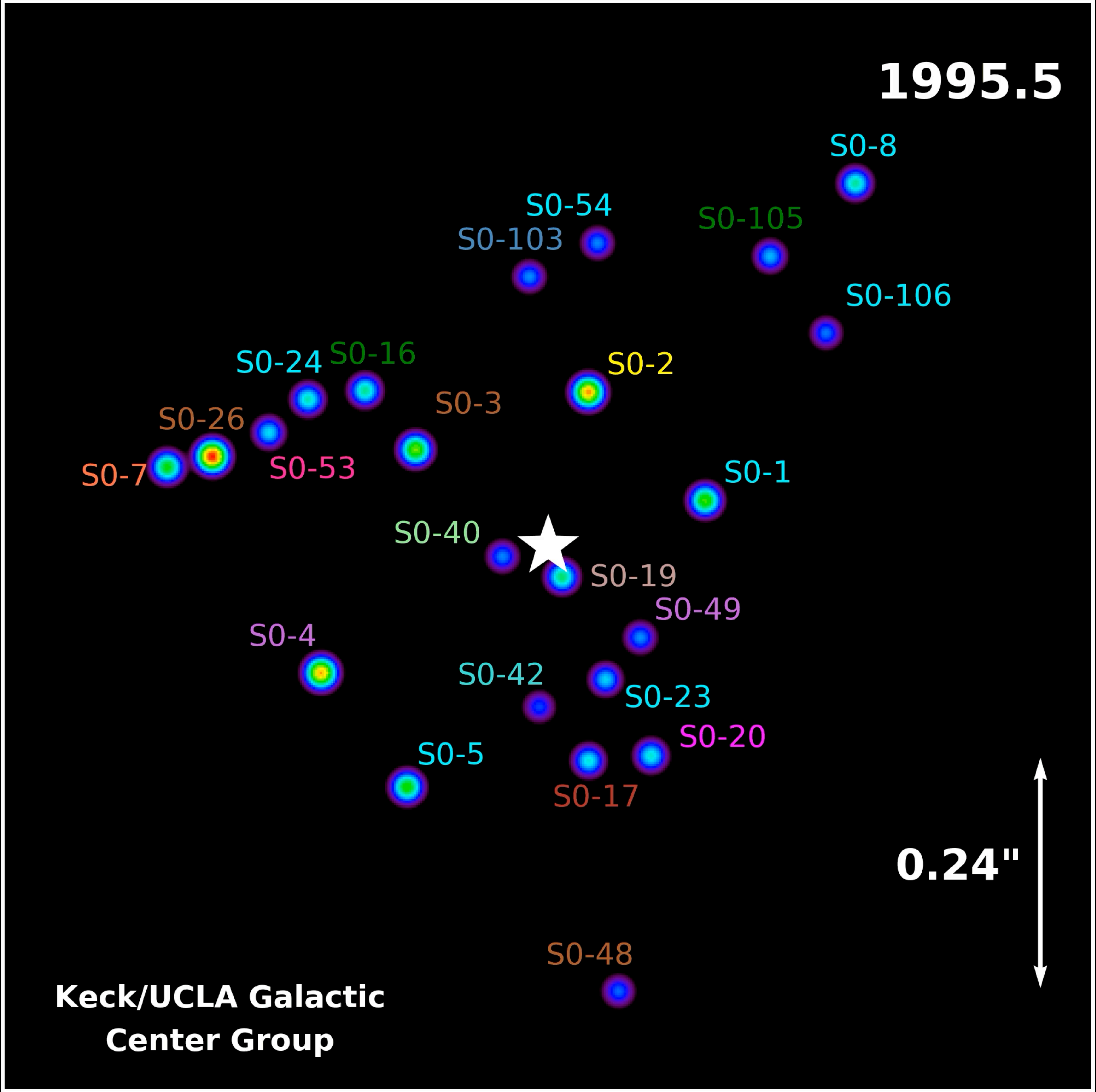
Massive unseen binary companions



Stellar motions in our galactic centre



Ghez et al.
(also Genzel et al.)

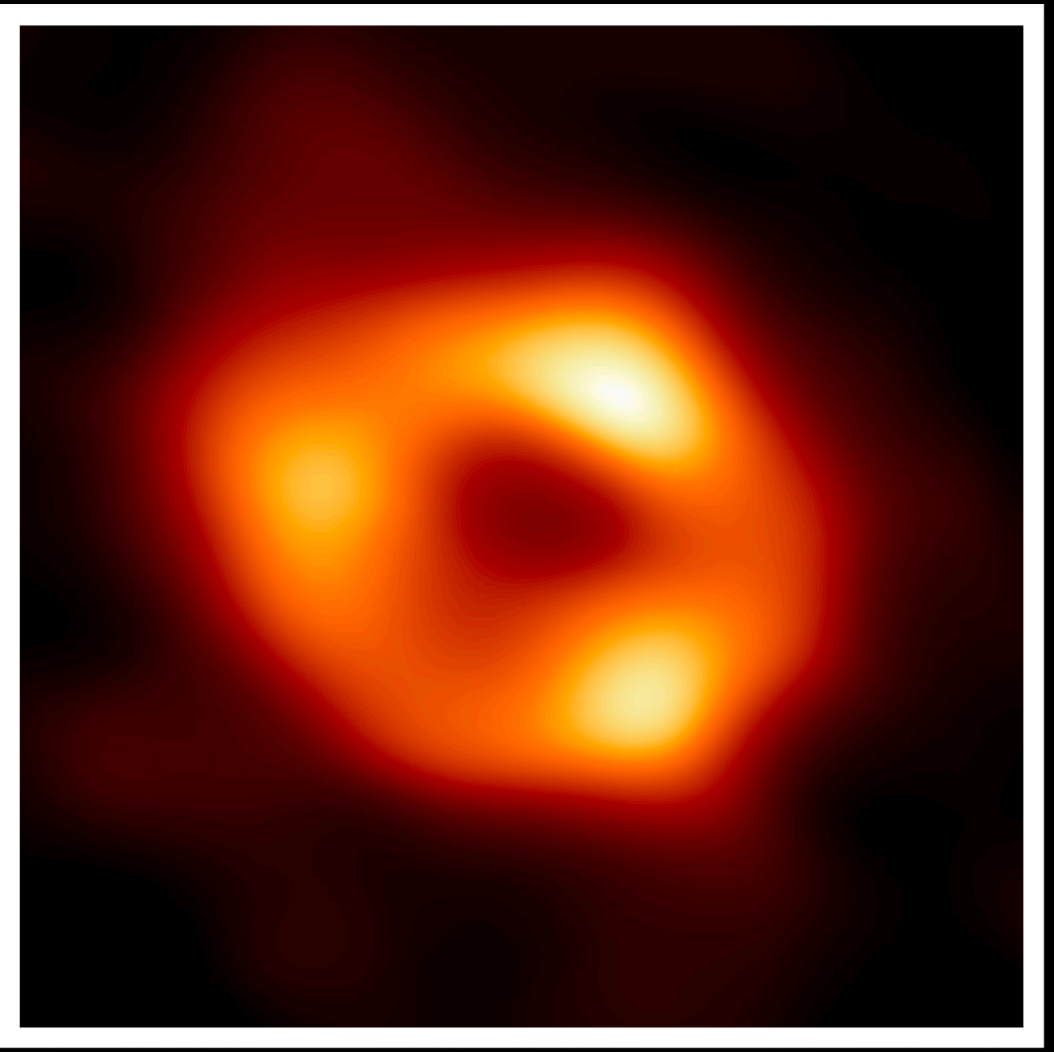


Direct imaging of event horizons

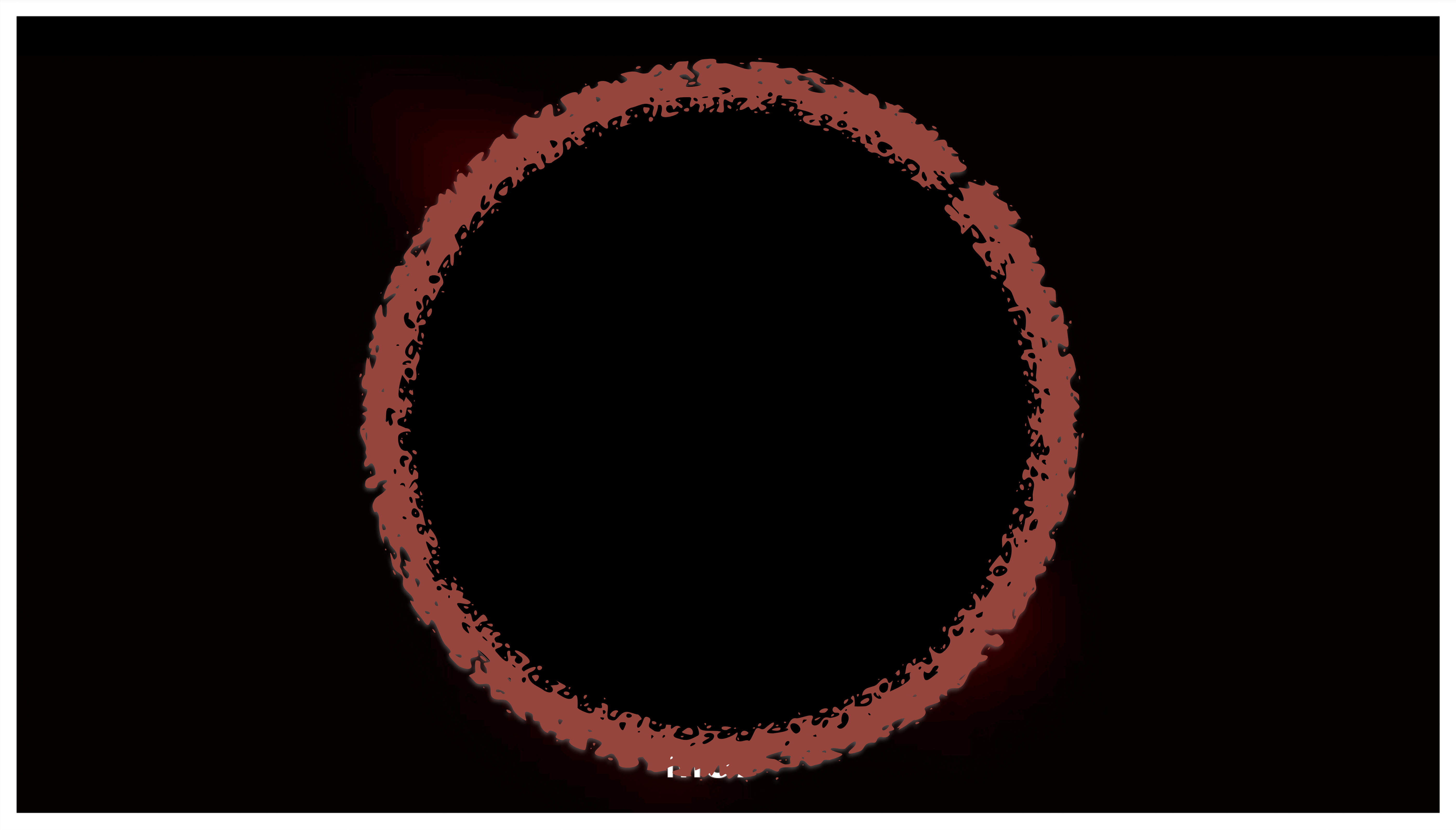
Huge range of scales

M87
6 x 10^9
solar
masses
(2019)

Sgr A*
3 x 10^6
solar
masses
(2022)



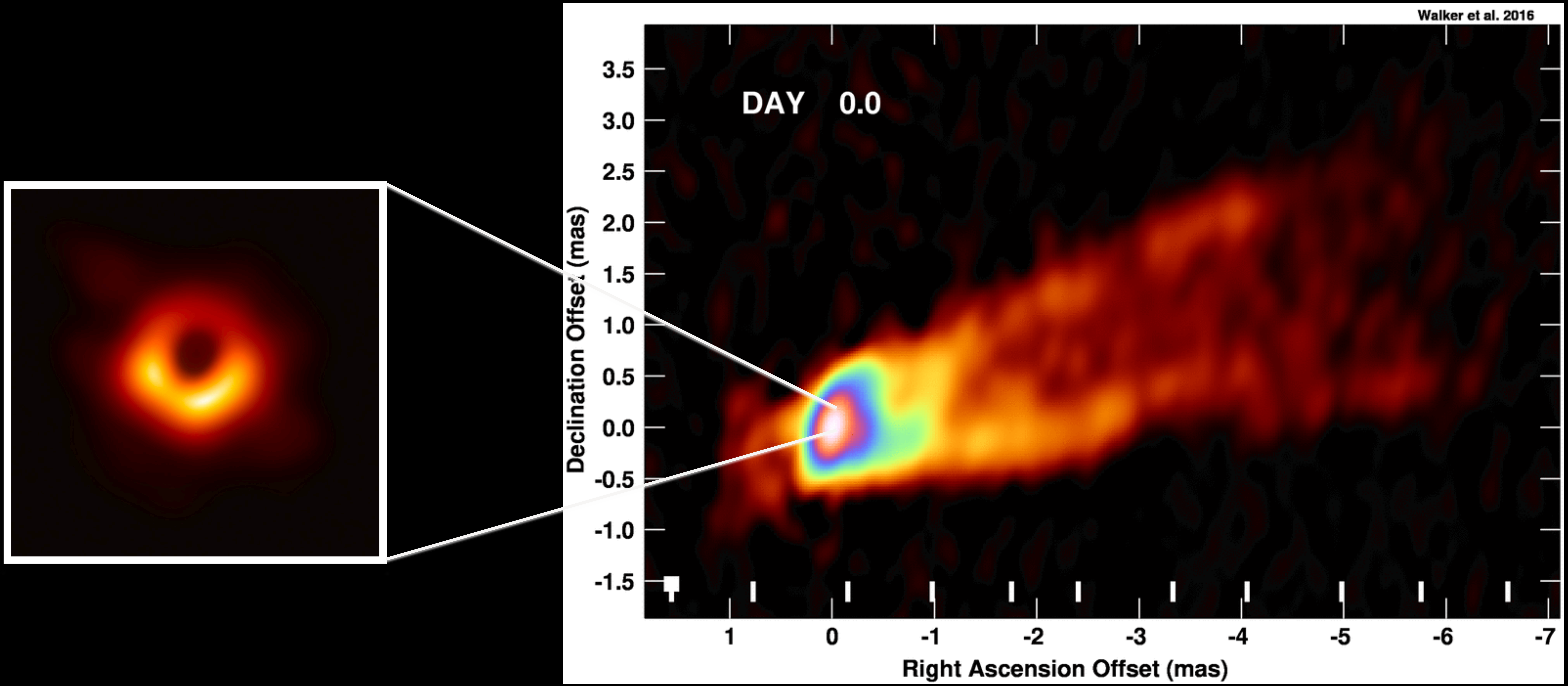
The EHT collaboration



Stellar mass black holes
10 solar masses

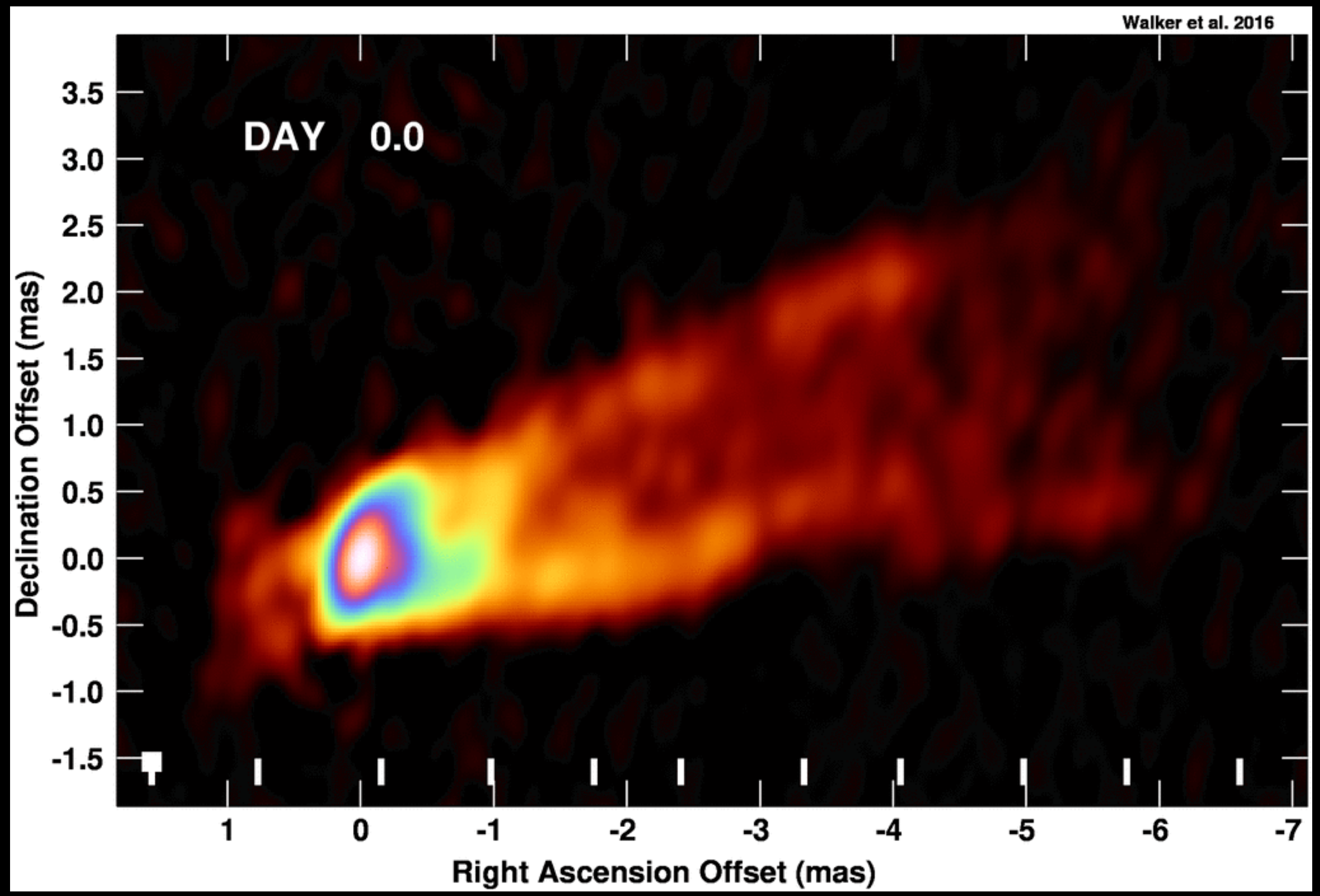
RELATIVISTIC JETS FROM BLACK HOLES

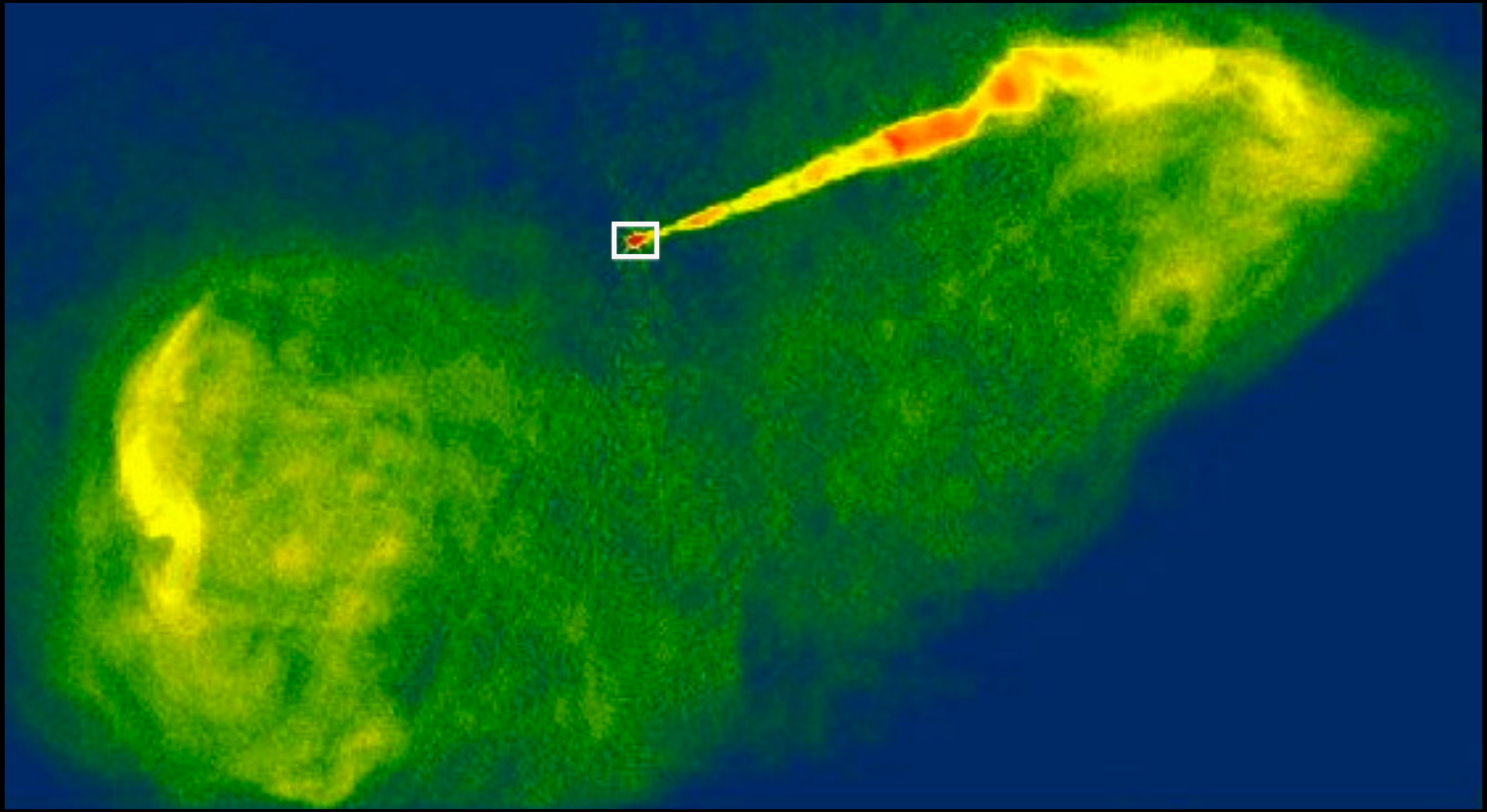

Cygnus A
Milky Way
100 kpc



M87 inner jet moves a few milliarcseconds in 200 days

1 arcmin (~6 kpc)





We will never be able to track M87 jets from launch to termination

M87 inner jet moves a few milliarcseconds in 200 days
Time to jet termination approximately 10,000 years

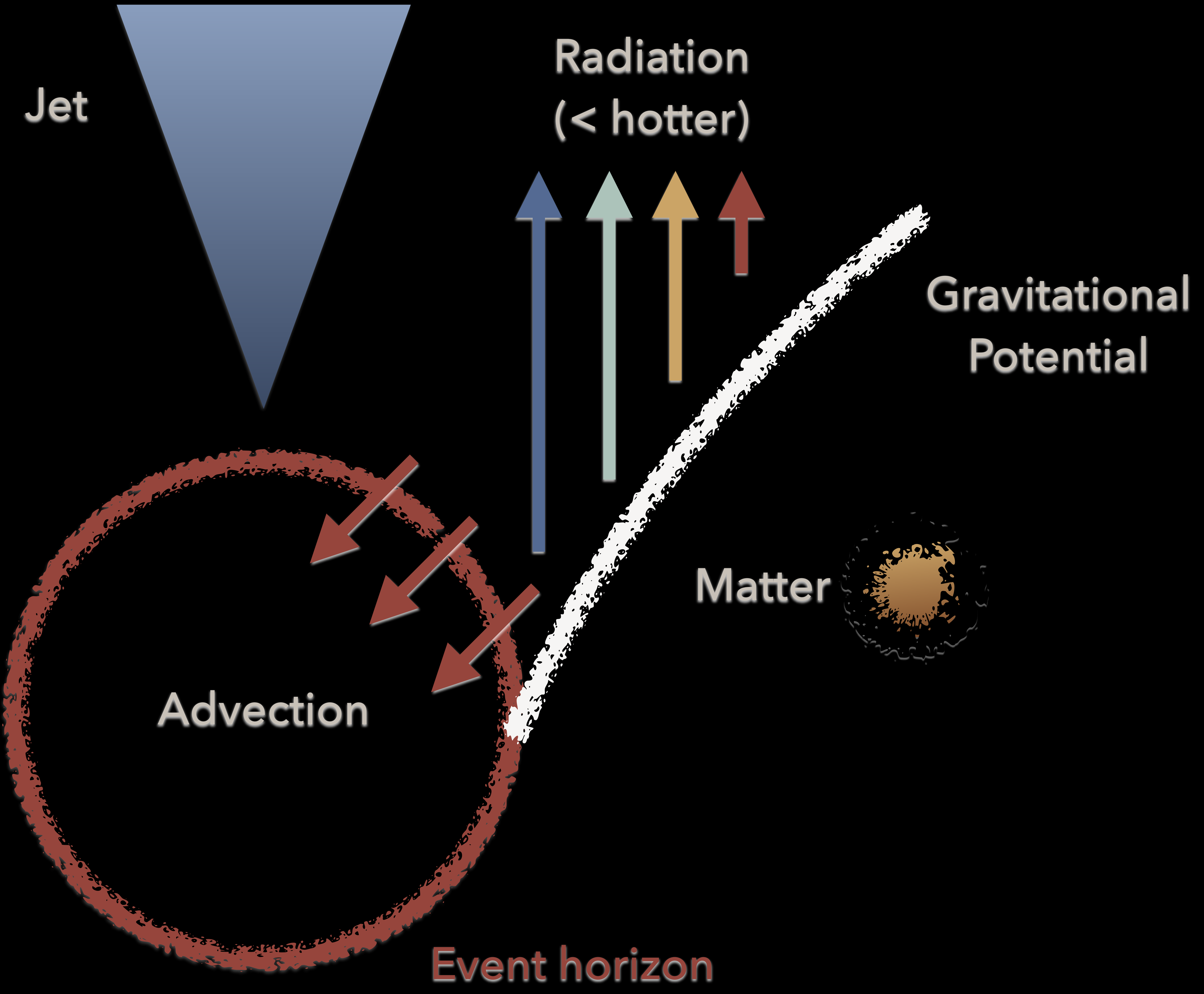
The power of jets: a fundamental question

The energy released in **radiation** is easy to measure (*instant release*)

The **mass accretion rate** is hard to measure

The **jet power** is very hard to measure (*slow release*)

The **advected** component cannot be measured, only inferred



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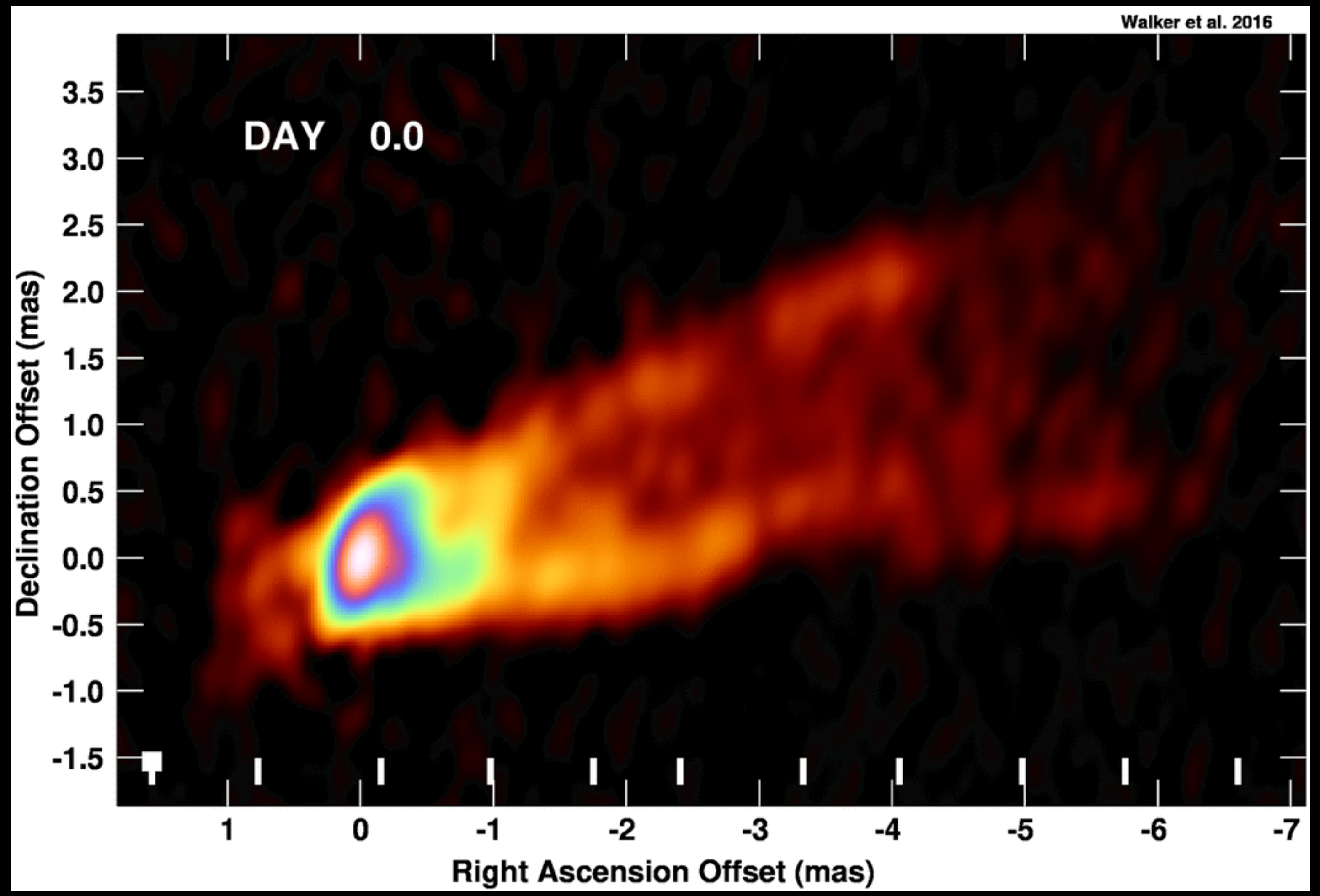
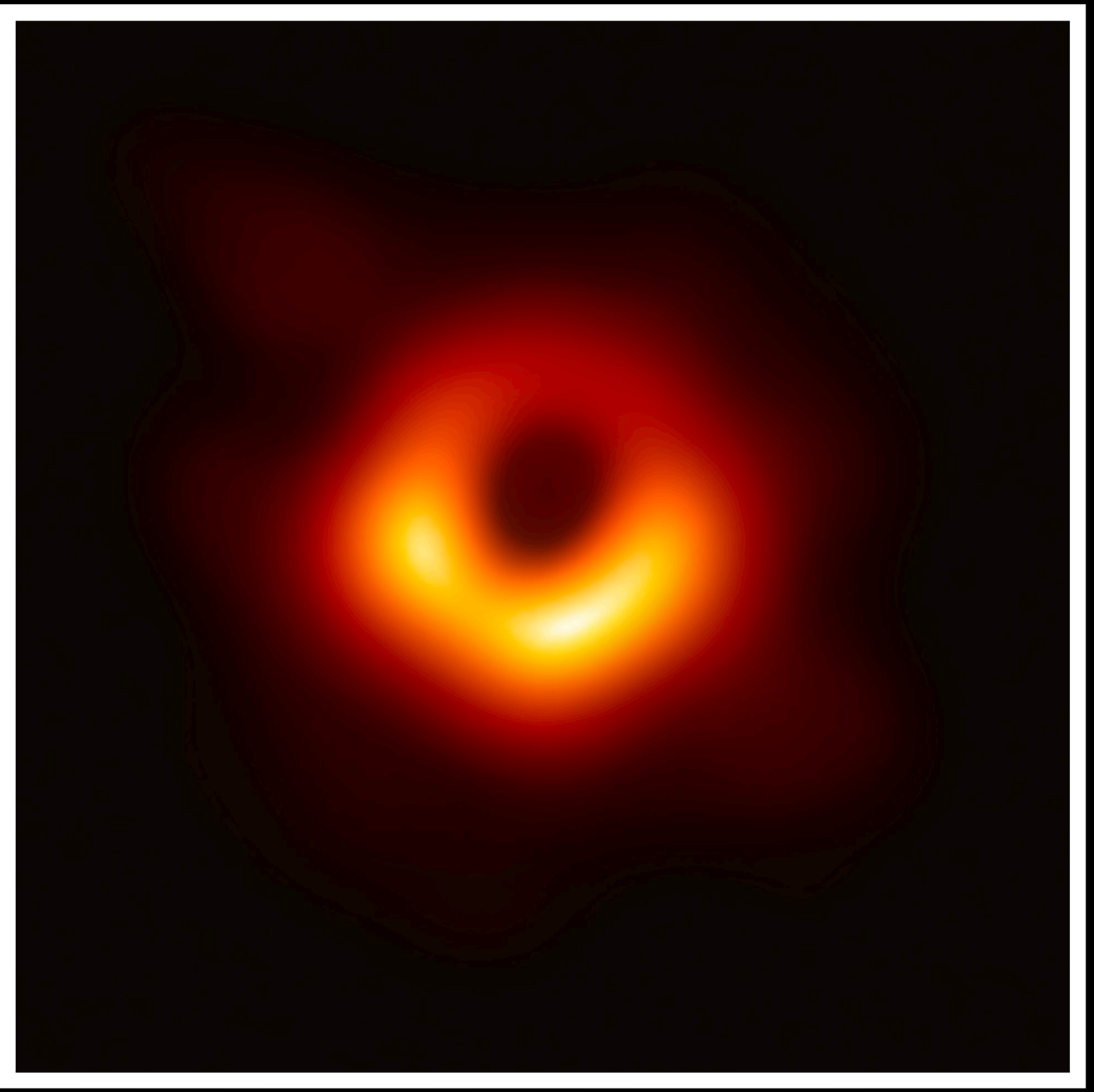
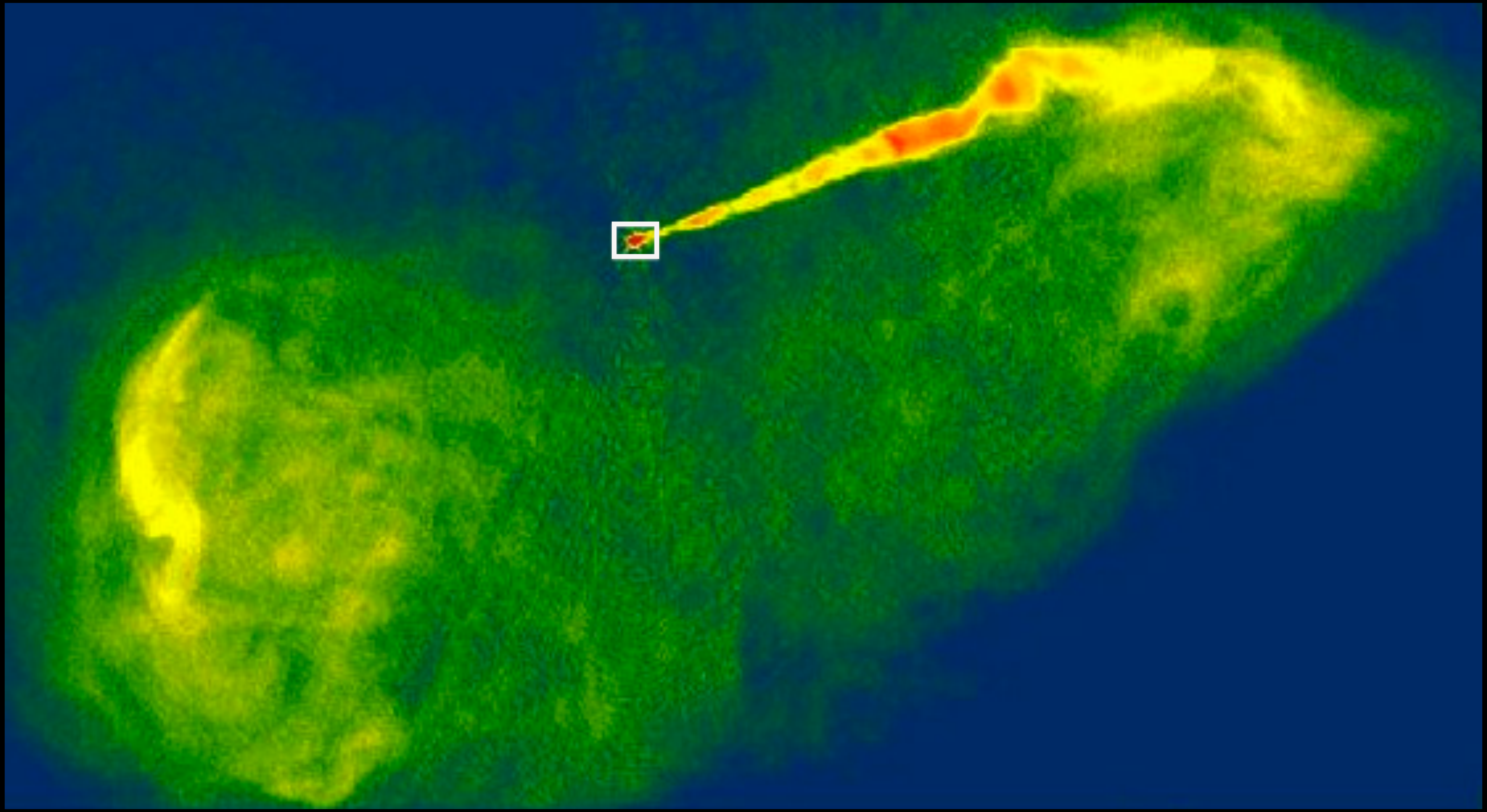






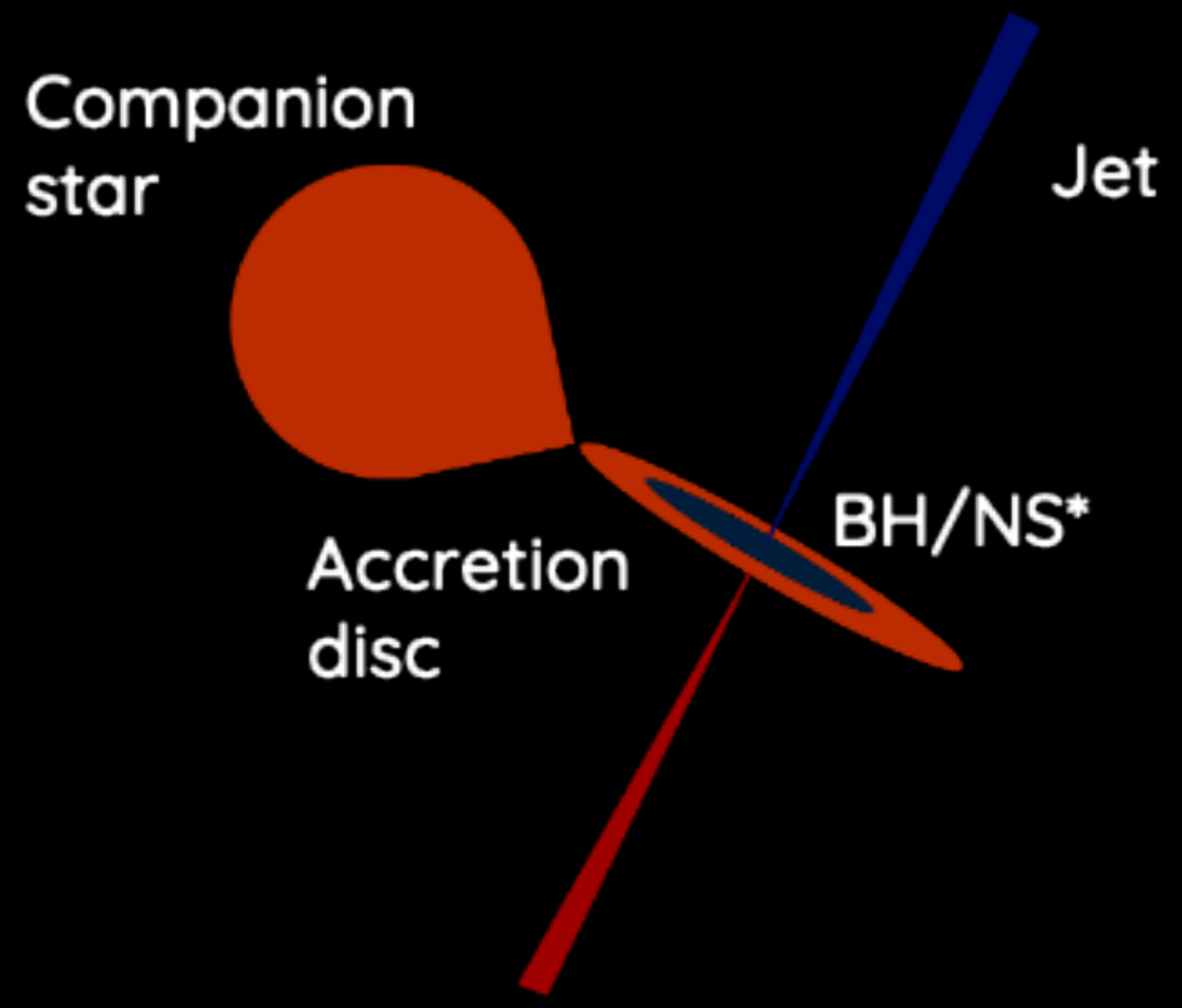
M87: arguably the best-studied jet from horizon to lobes

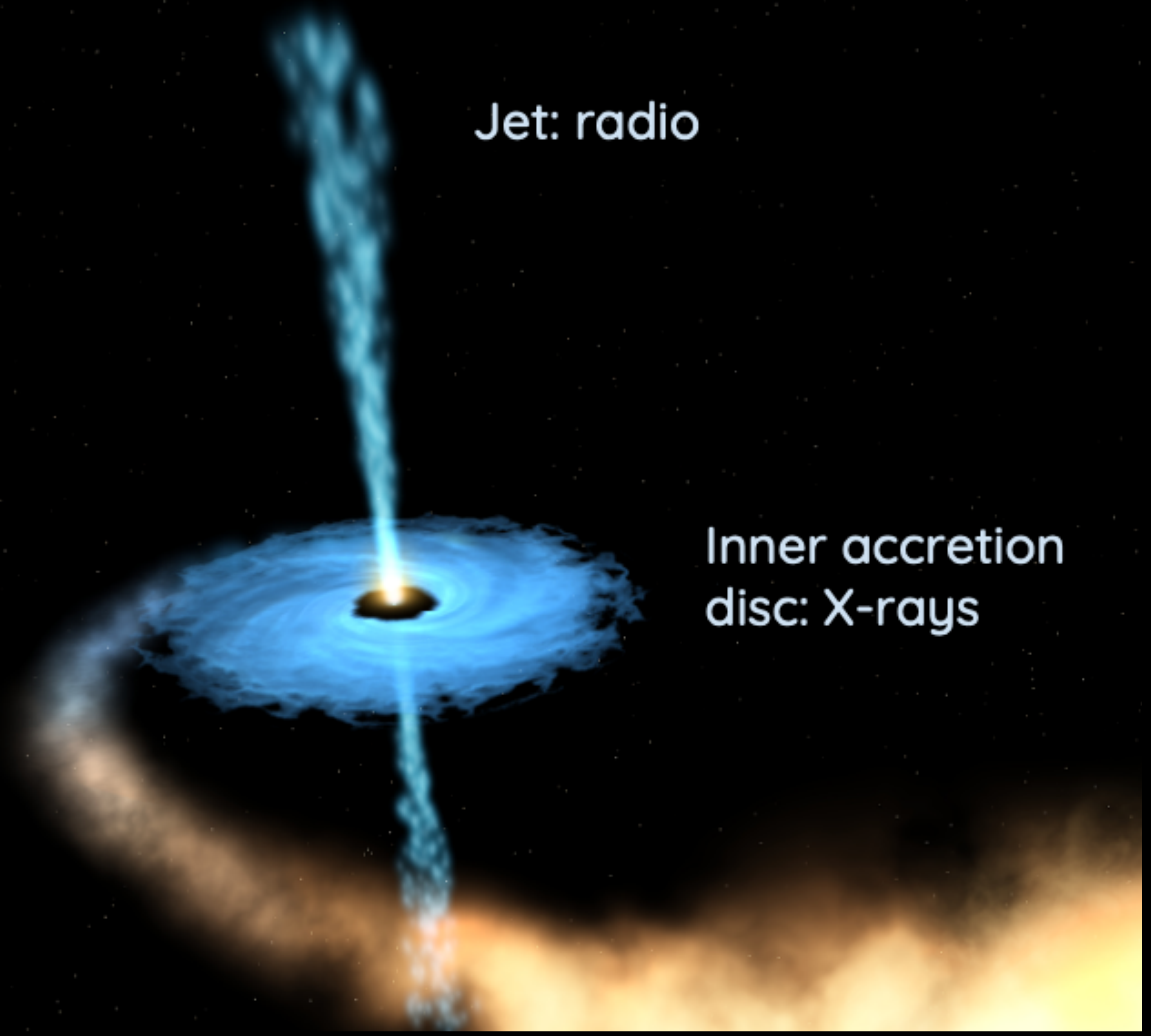
And yet: jet power estimates range from 10^{42} – 10^{45} erg s^{-1}

JETS FROM STELLAR MASS BLACK HOLES

X-ray binaries

(discovered via X-rays)

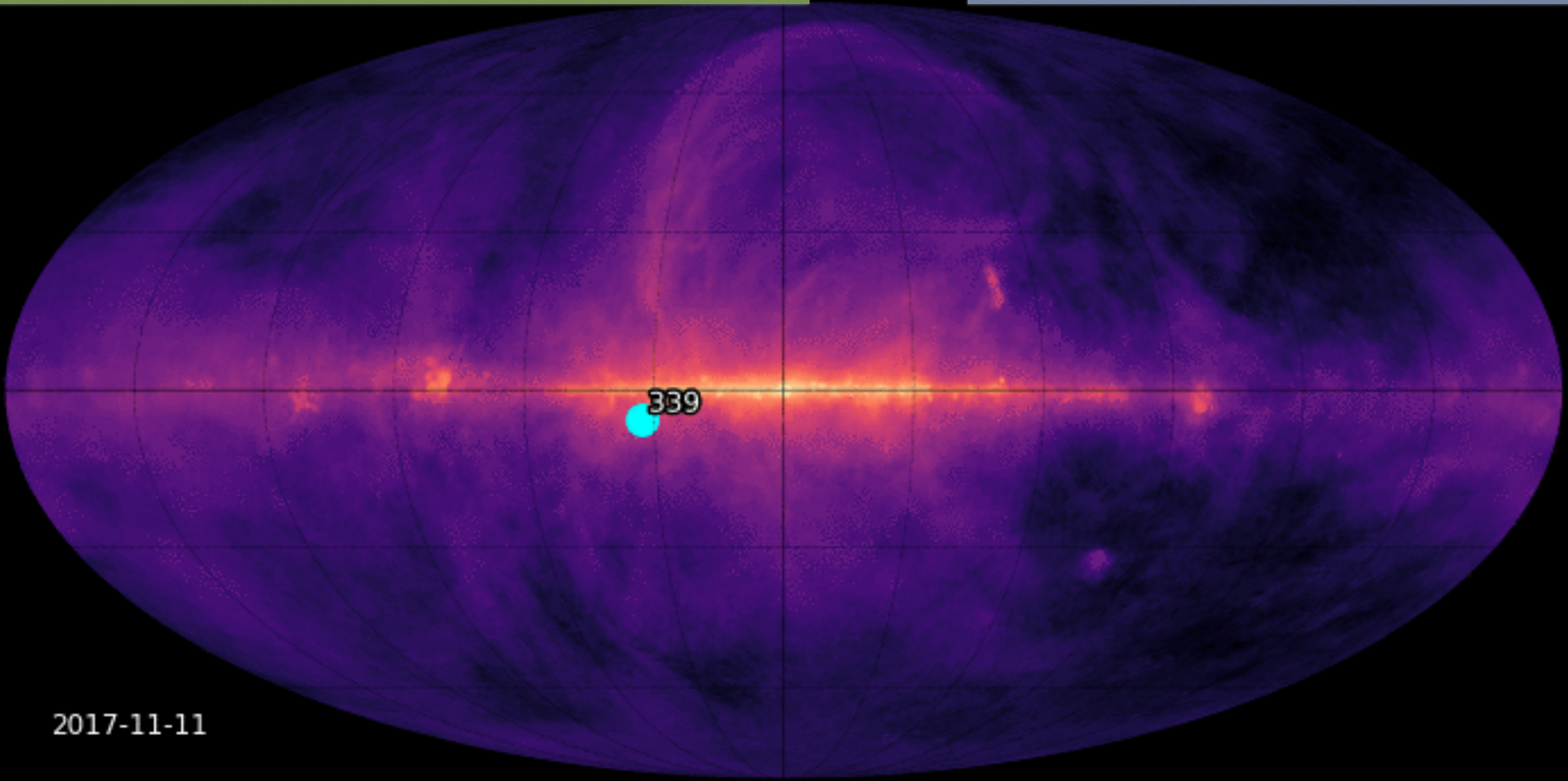




A binary companion star transfers mass to a relativistic accretor

ThunderKAT: monitoring relativistic jets and particle acceleration in our galaxy with MeerKAT

Led by Fender (Oxford) and Woudt (University of Cape Town)



Movie by Alex Andersson for ThunderKAT

On March 11, 2018, a new black hole X-ray transient, MAXI J1820+070, was discovered

We observed the source for approximately two years at weekly intervals with MeerKAT

To our surprise, after two months we began to spatially resolve the source, and this continued for ~2 years

Powerful, long-lived, superluminal ejections were observed

We were able to directly measure the internal energy of the ejecta 90 days after launch for the first time

Bright, RF et al. Nature Astronomy (2020)

MAXI/GSC detection of a probable new X-ray transient MAXI J1820+070

ATel #11399; T. Kawamuro (NAOJ), H. Negoro (Nihon U.), T. Yoneyama (Osaka U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, N. Isobe, R. Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, F. Yatabe, Y. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Yoshii, Y. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, M. Serino, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi (Osaka U.), M. Nakajima, T. Kawase, A. Sakamaki, W. Maruyama (Nihon U.), Y. Ueda, T. Hori, A. Tanimoto, S. Oda, T. Morita, S. Yamada (Kyoto U.), Y. Tsuboi, Y. Nakamura, R. Sasaki, H. Kawai, T. Sato (Chuo U.), M. Yamauchi, C. Hanyu, K. Hidaka (Miyazaki U.), K. Yamaoka (Nagoya U.), M. Shidatsu (Ehime U.) report on behalf of the MAXI team
on **11 Mar 2018; 16:41 UT**
Distributed as an Instant Email Notice Transients
Credential Certification: Hitoshi Negoro (negoro@phys.cst.nihon-u.ac.jp)

Subjects: X-ray, Black Hole, Neutron Star, Transient

Referred to by ATel #: 11400, 11403, 11418, 11421, 11423, 11424, 11425, 11426, 11427, 11432, 11437, 11439, 11440, 11445, 11451, 11458, 11480, 11488, 11490, 11510, 11533, 11539, 11540, 11574, 11576, 11578, 11609, 11723, 11820, 11831, 11833, 11887, 11899, 12057, 12061, 12064, 12128, 12157, 12534, 12596, 12608, 12688, 12988, 13066, 13502, 13530, 14492

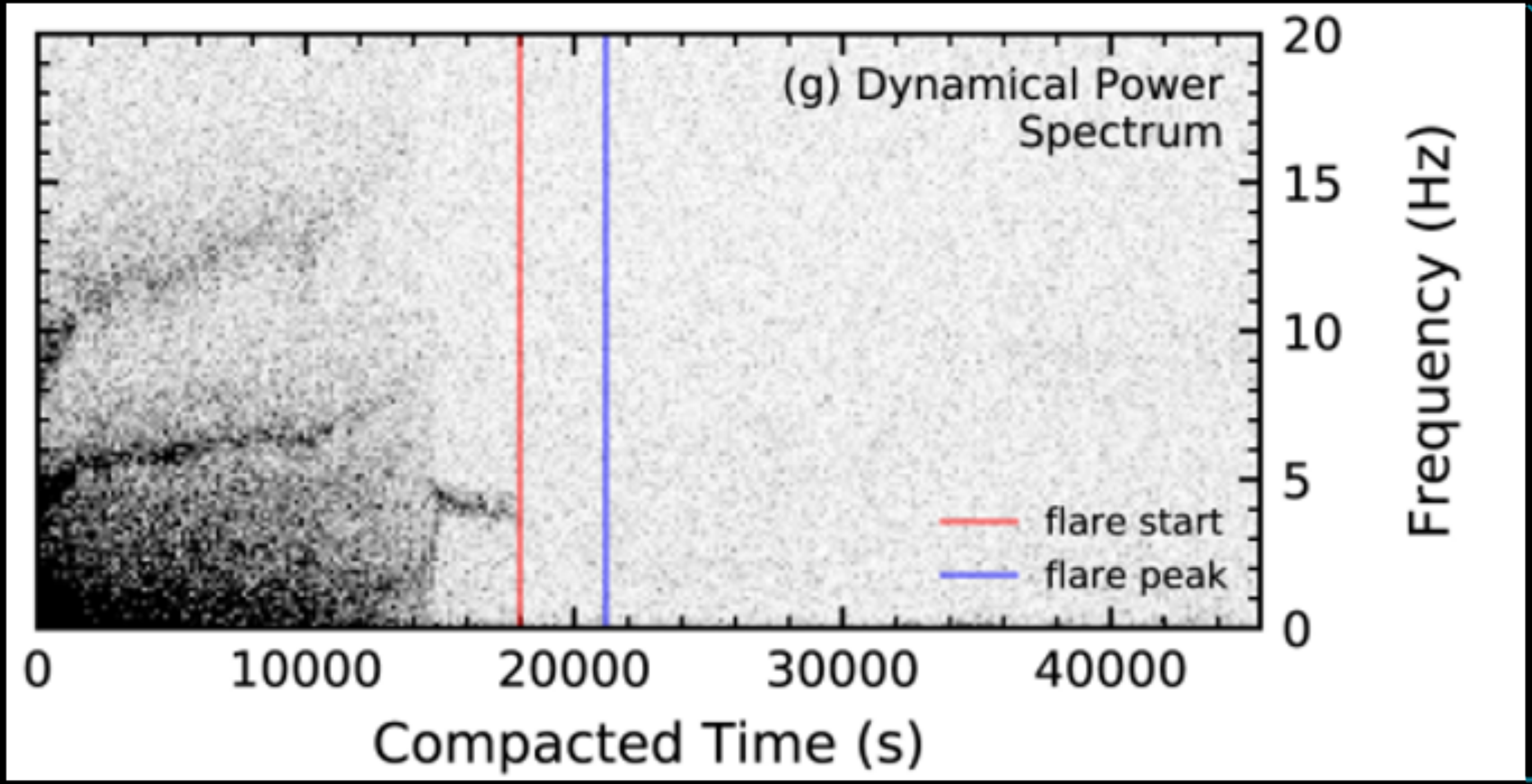
Tweet

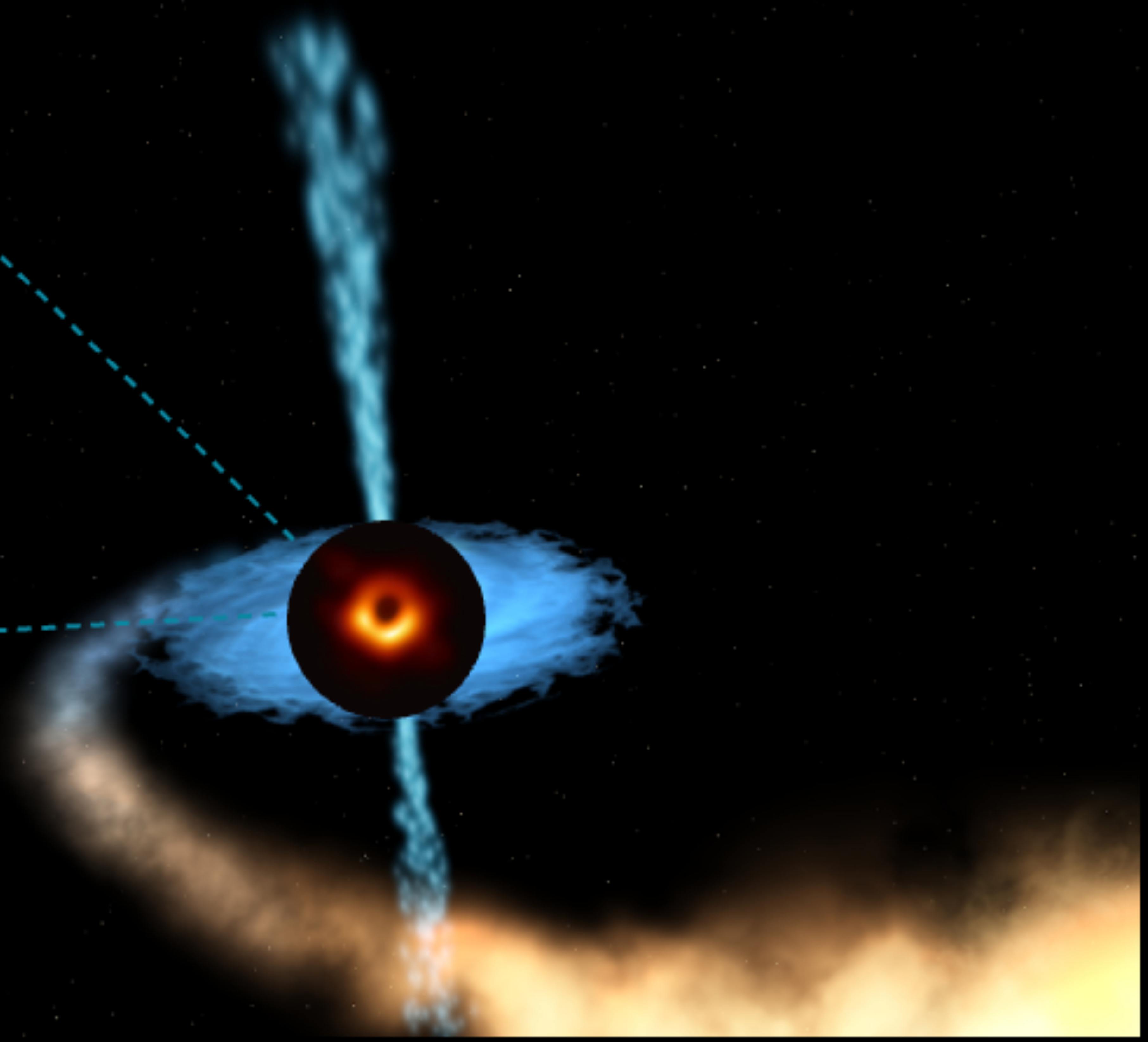
The MAXI/GSC nova alert system triggered on a bright uncatalogued X-ray transient source at 12:50 UT on 2018 March 11. Using GSC camera GSC_2 and GSC_7 data of 5 scan transits from 2018-03-11 19:48 to 2018-03-12 02:04, we obtain the source position at

(R.A., Dec) = (275.112 deg, 7.037 deg) = (18 20 26, +07 02 13) (J2000)

with a statistical 90% C.L. elliptical error region with long and short radii of 0.47 deg and 0.38 deg, respectively. The roll angle of the long axis from the north direction is 28.0 deg counterclockwise. There is an additional systematic uncertainty of 0.1 deg (90% containment radius). The X-ray flux averaged over the scan was 32 +- 9 mCrab (4.0-

MAXI J1820





We measured the variability of the inner X-ray emitting accretion flow at **exactly the moment of jet launch**

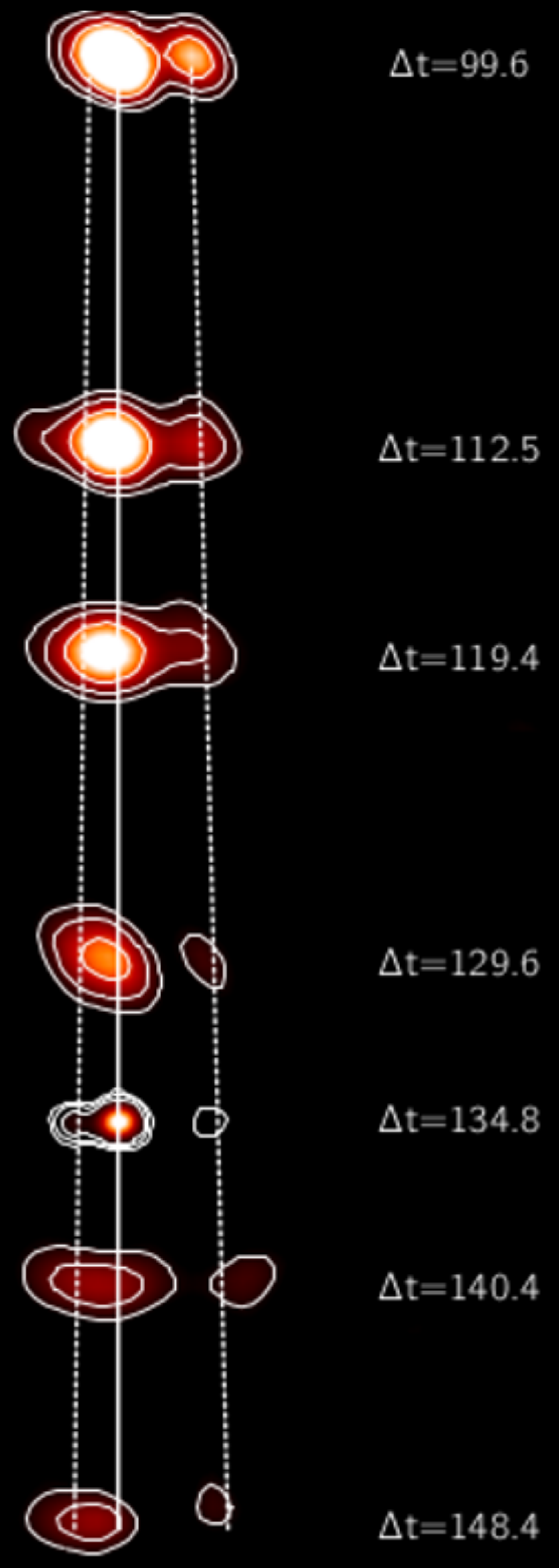
Stong broadband variability collapses to a quasi-periodic oscillation at ~5 Hz for ~3000 sec

Homan et al. (2020)

When scaled by mass, this is the same regime being directly imaged by EHT (to a few tens of event horizon radii)

MAXI J1820

Relativistic pseudo-ballistic phase



We track the jets propagating out for many weeks away from the central source 'superluminally' (→ at least mildly relativistic)

Previously we 'lost' ejecta typically in days – weeks with little or not sign of deceleration

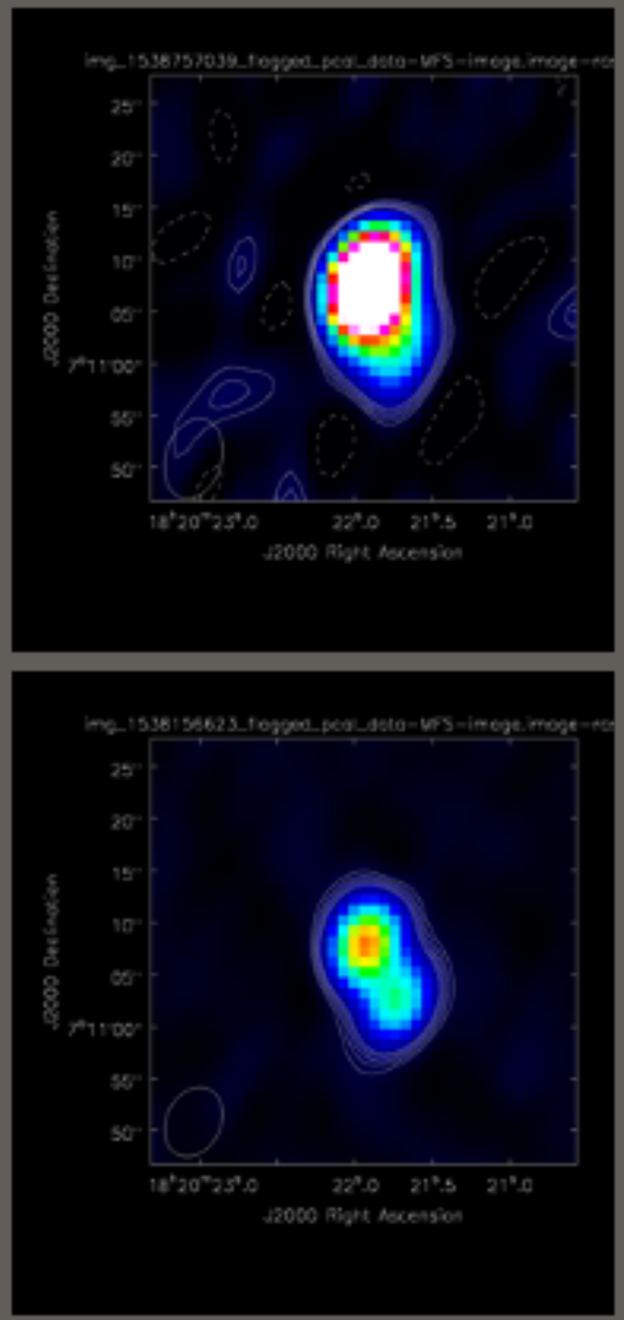
Quantitatively this is much further than previous studies, but qualitatively the same: proper motions are constant with no sign of slowing down.

Bright et al. (Nature Astronomy, 2020)

Measuring the energy in moving blobs

We cannot directly measure the bulk Lorentz factor Γ from proper motions for significantly relativistic flows

We can estimate the **internal** energy if we measure **size** and **luminosity** but as we don't know the doppler factor $\delta(\theta, \Gamma)$ we don't know the true luminosity



Why?

At large angles to the line of sight, Jet proper motions are a function of

$\beta = v/c$

not the Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$

For $\Gamma \gg 1$ changes in Γ do not result in changes in proper motion

For typical BH XRB jets we can only place a **lower limit** on Γ (and hence a lower limit on the jet energy)

Measuring the energy in moving blobs

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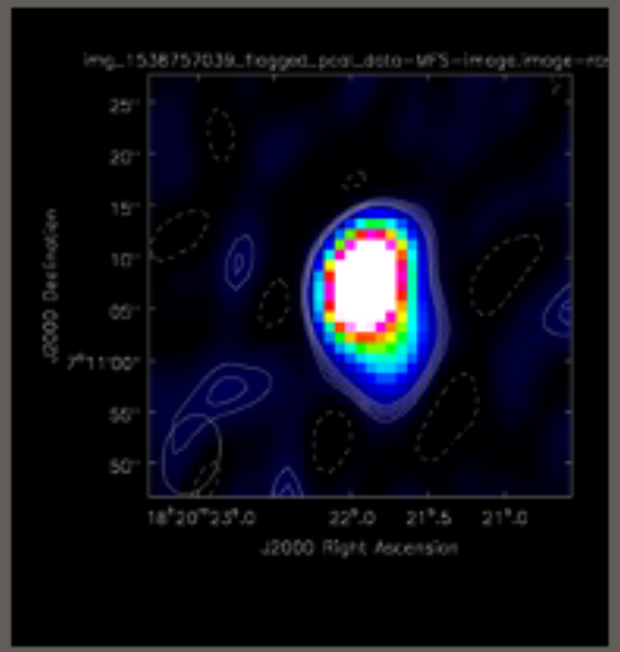
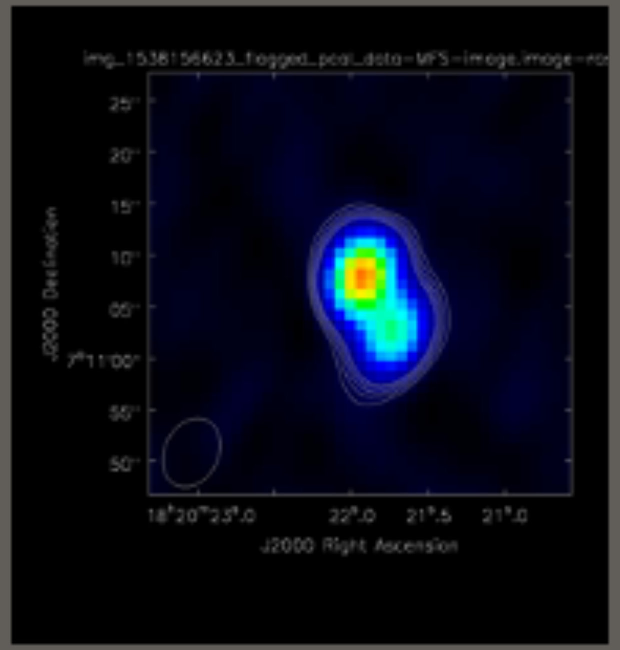
We can estimate the **internal** energy if we measure **size** and **luminosity** but as we don't know the doppler factor δ(θ, Γ) we don't know the true luminosity





How do we do this?

If we measure the size and luminosity of a synchrotron-emitting plasma at a given frequency, we can calculate the **minimum energy**.

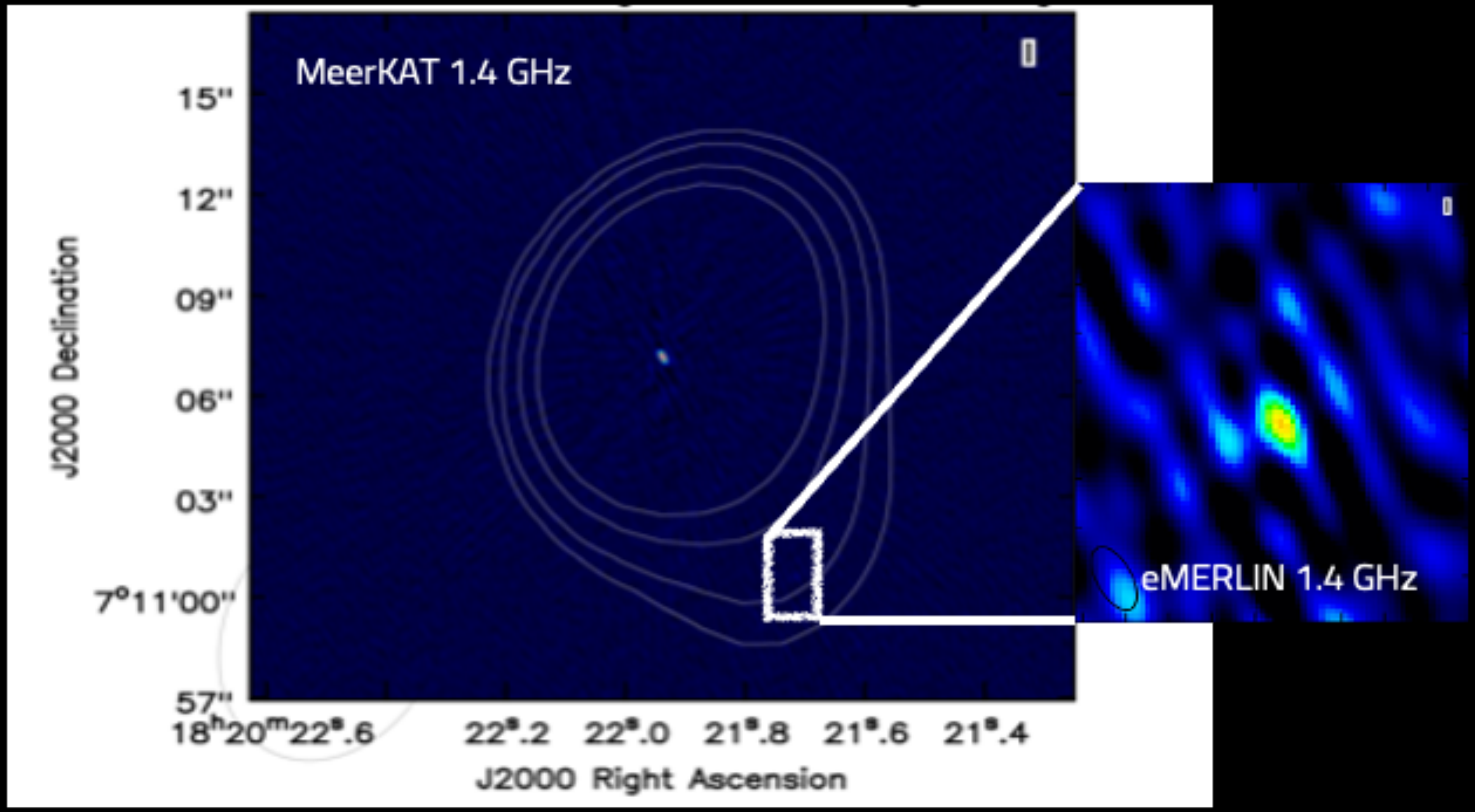
This minimum occurs as the energy in the electrons goes as $E^{-1.5}$ and the energy in the magnetic field goes as E^2

At this minimum the energies are very similar, hence it is called 'equipartition"

This method allowed Burbidge to establish the huge energy in AGN radio lobes in the 1950s

Even applied naively to XRB jets it demonstrates their large energy budgets

We achieved this size measurement at **one** epoch for MAXI J1820 at 90 days post-launch



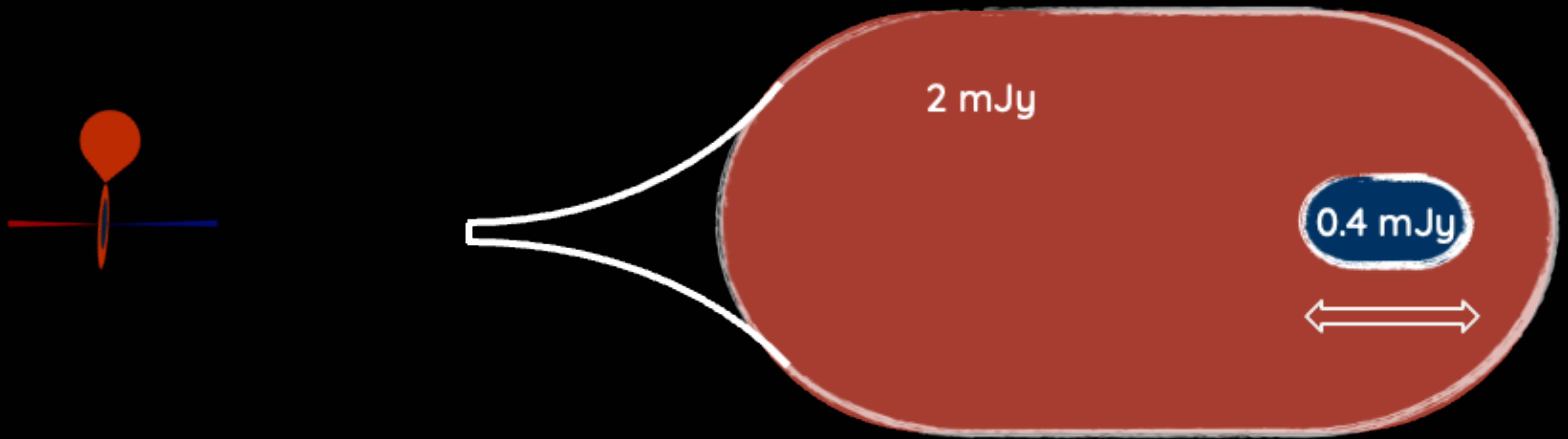
Size + luminosity → minimum (equipartition) energy

This gave us

E(Δt=90d) ≳ 10^{42} erg [!!]

(**and** ejecta still moving superluminally at this stage so **total** jet power much larger)

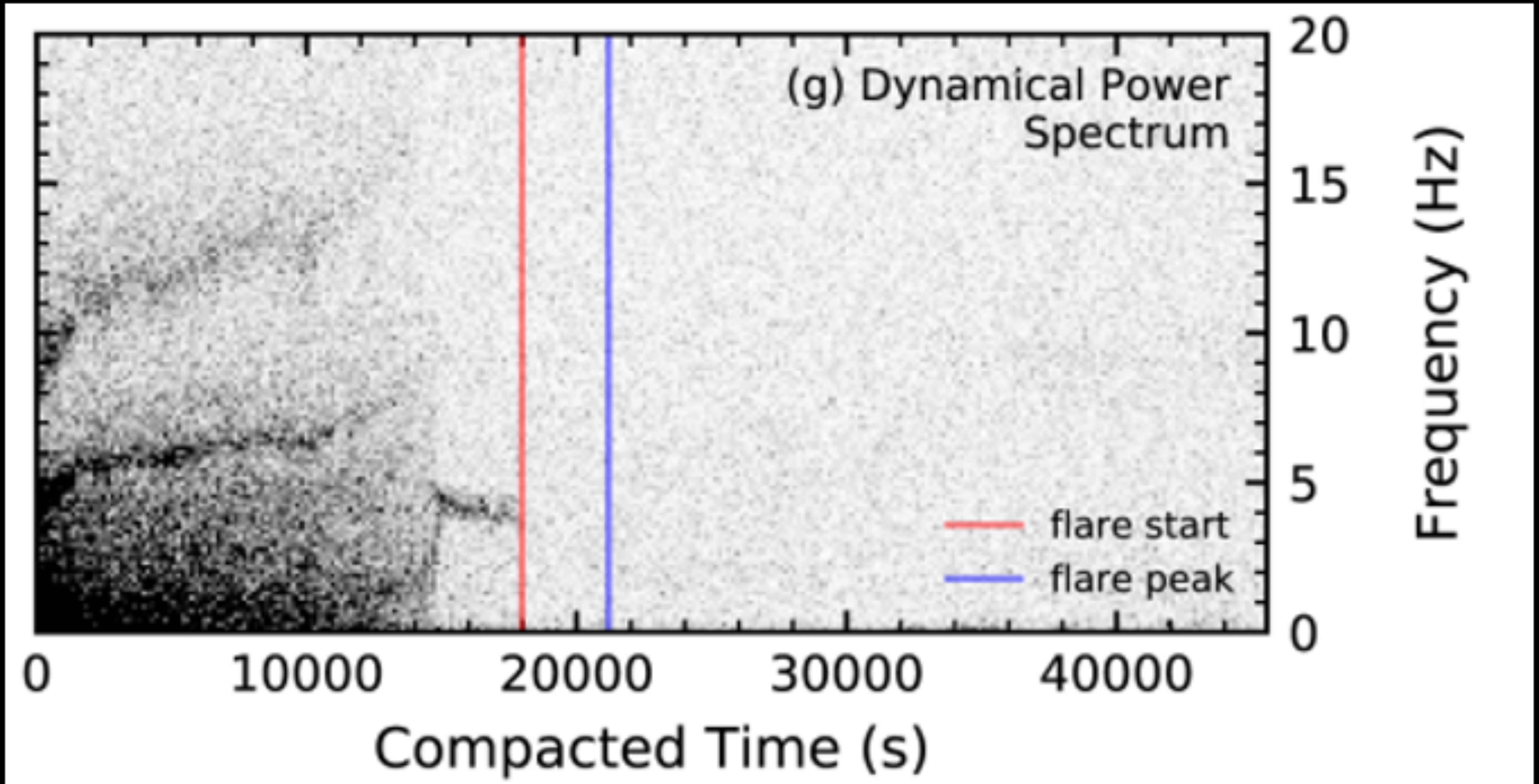
~2 arcsec (MeerKAT, unresolved)



~0.1 arcsec (eMERLIN)

MAXI J1820

MAXI J1820



If this energy were injected during the ~3000 sec duration of the 'type B QPO', this implies **jet power > Eddington luminosity** during jet launch (whereas X-ray luminosity was ~0.1 Eddington)

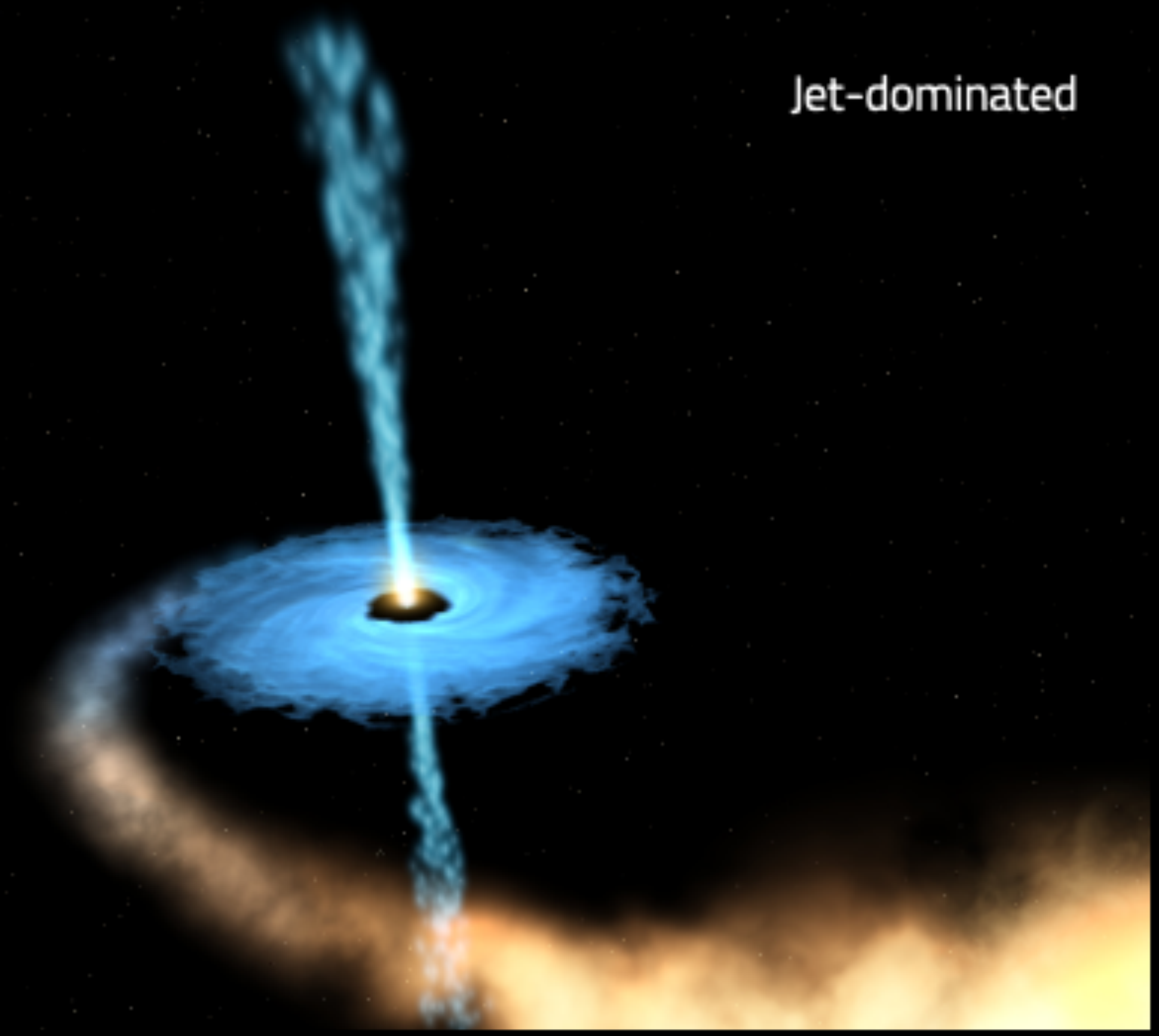
Accretion energy release is 'jet dominated' both at low accretion rates and also during some high luminosity phases

Size + luminosity → minimum (equipartition) energy

This gave us

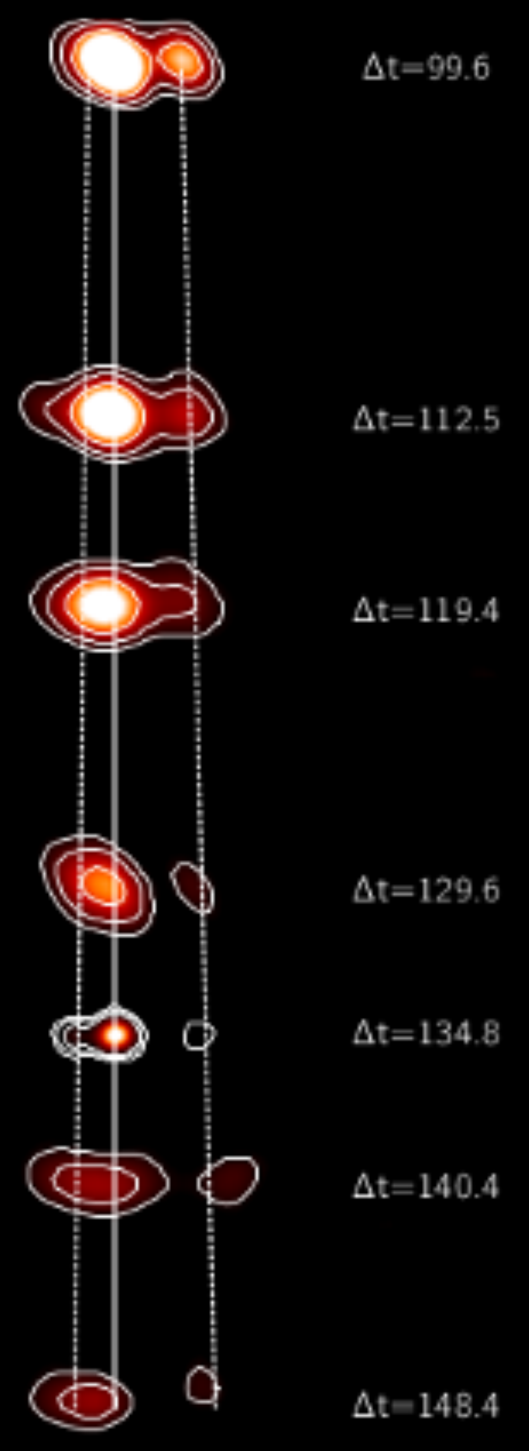
$$E(\Delta t=90d) \gtrsim 10^{42} \text{ erg [!!]}$$

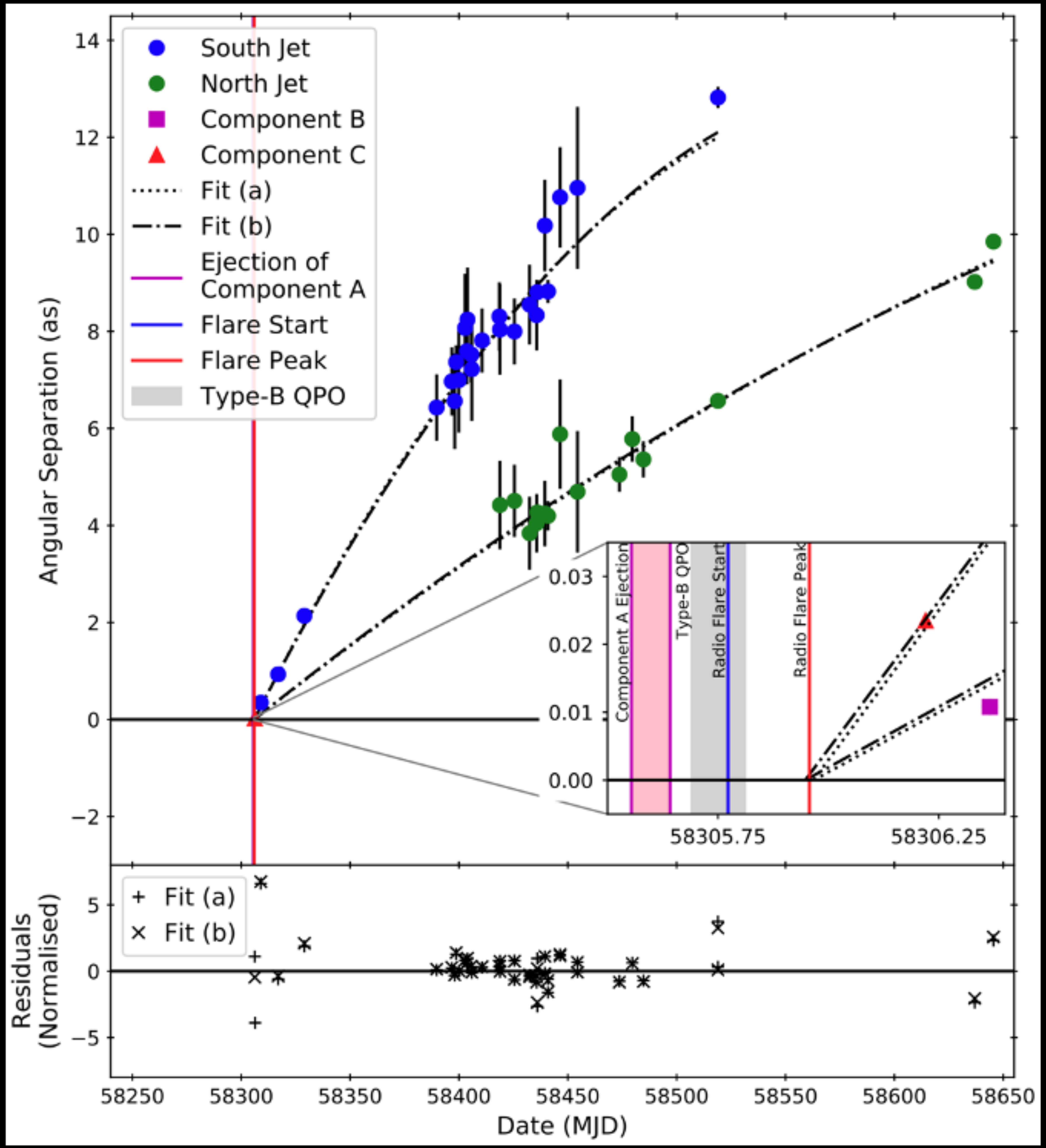
(**and** ejecta still moving superluminally at this stage so **total** jet power much larger)



So what happened next?

Deceleration!





We begin to see signs of deceleration

Important point: at point jet is observed to decelerate then $\Gamma_{bulk} \sim 2$

Bright et al. (2020)
Espinasse et al. (2020)
Wood et al. (2021)

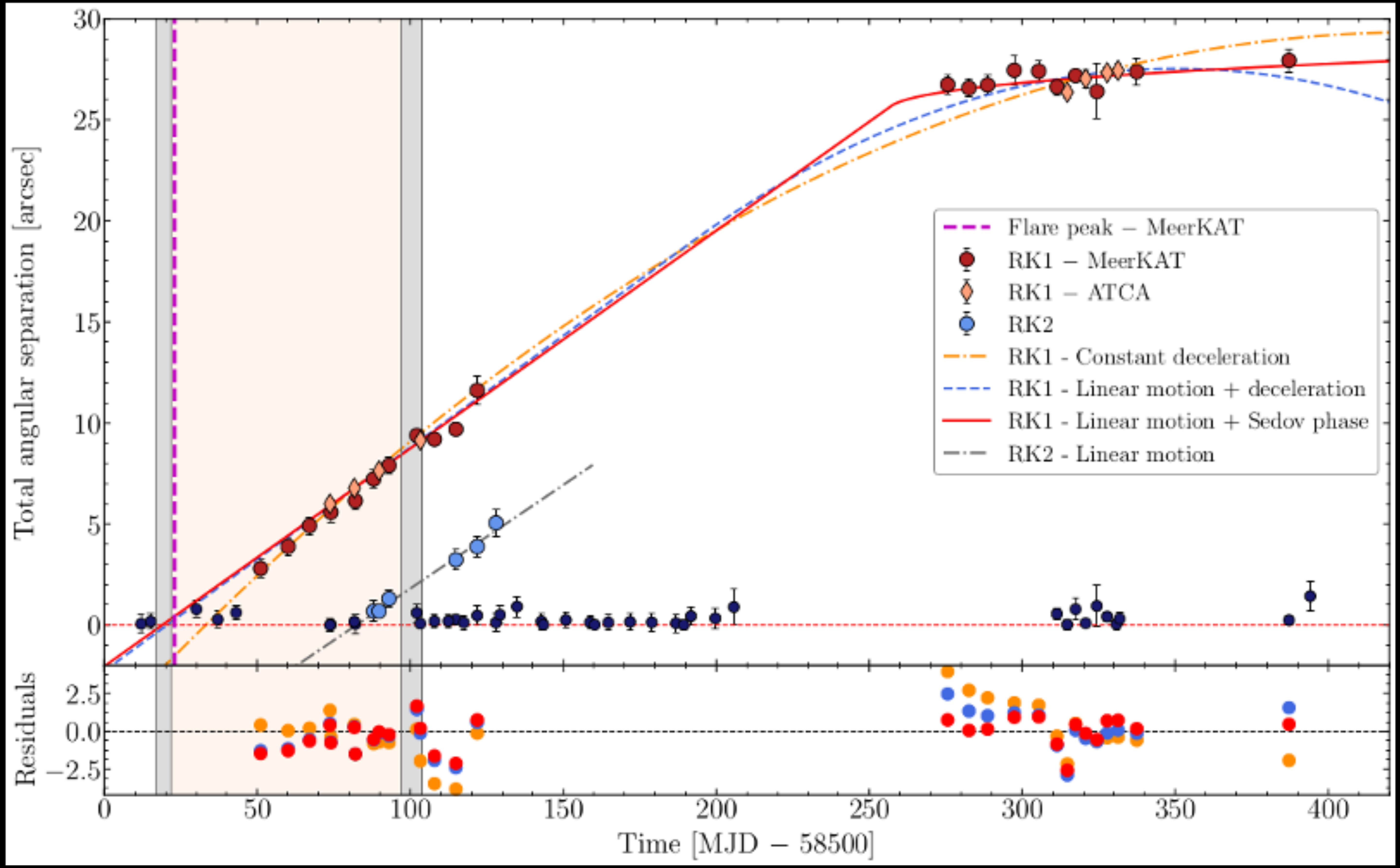
We now have multiple examples (1-2 per year) of jets traced from launch to termination

MAXI J1348
(Carotenuto et al. 2021, 2022)

MAXI J1348: strongest example of rapid deceleration in black hole XRB, associated with strong rebrightening of ejecta

Initial modelling suggests E_{jet} ~ 10^{46} erg ! (10^4 x MAXI J1820!)

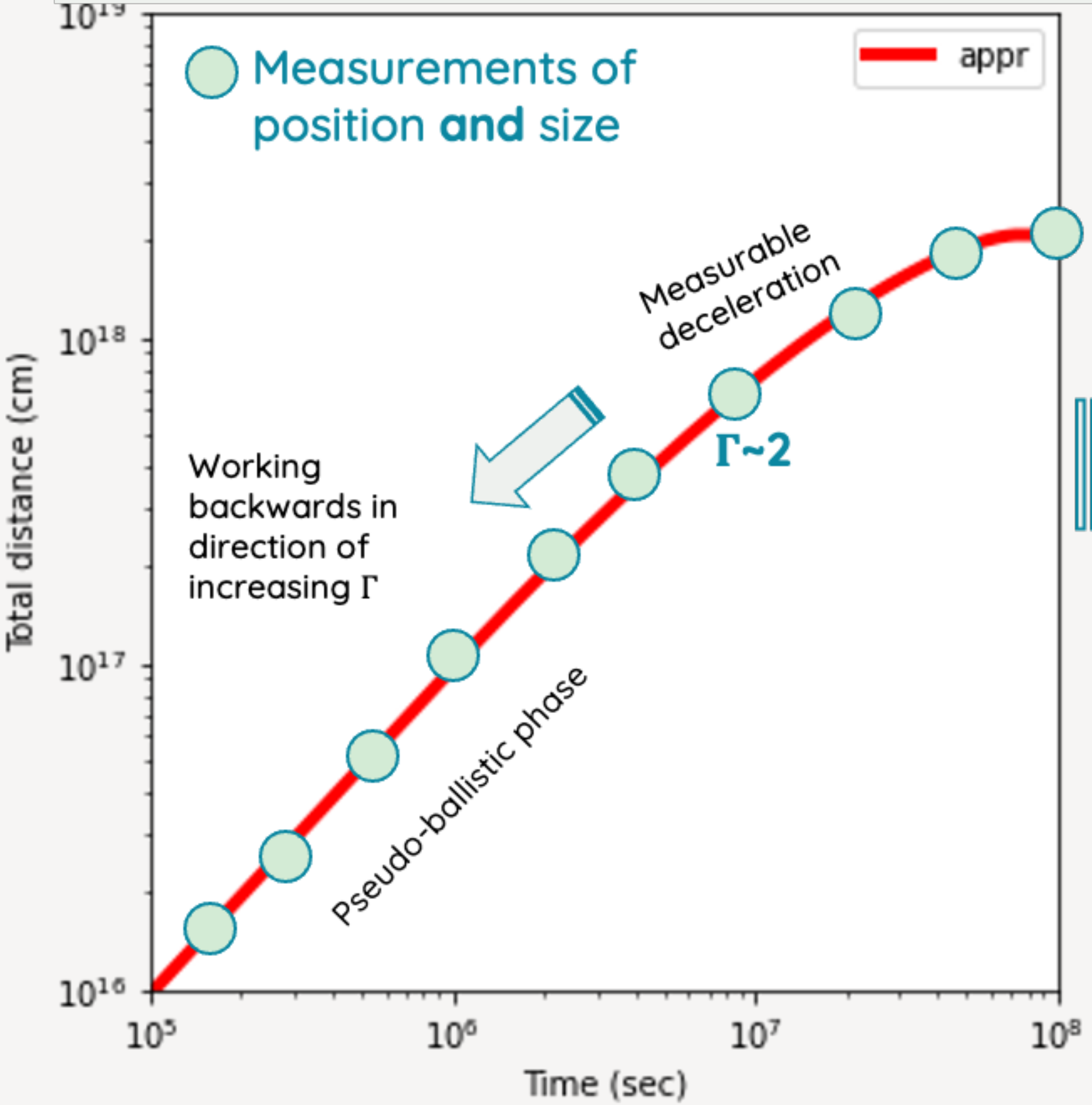
But we need much more data: **too model dependent!**



FUTURE PROSPECTS

A way to track total jet energy from launch to termination:

1. Measure size, flux, position at multiple epochs → internal energy
2. Connect Γ~2 to point of deceleration and work back towards launch

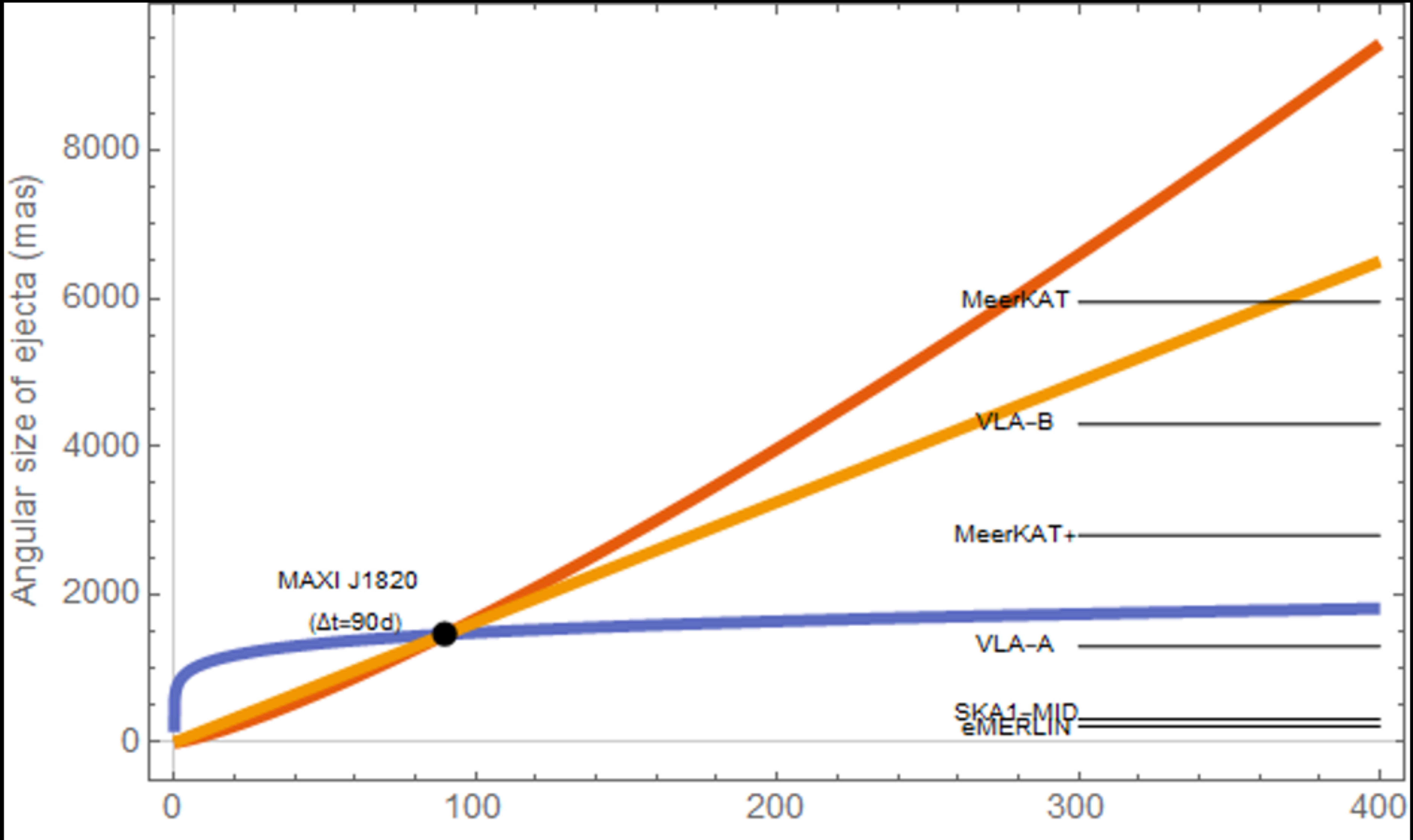


Leads to a continuous solution for **luminosity**, **proper motion**, **size** → E_{int} and K.E. → total energy as a function of time

Crucially some (significant) fraction of launch energy will be unobservable (e.g. K.E. → ISM turbulence) but we can model this extrapolating back from Γ~2 where we can measure ΔK.E.

Measuring the size

Red line is accelerating growth with time
Orange line is linear growth with time
Blue line is decelerating growth with time



Fender & Rhodes (in prep)

Bright et al. (2020) made **one** simultaneous measurement, with MeerKAT and eMERLIN

Measuring the size

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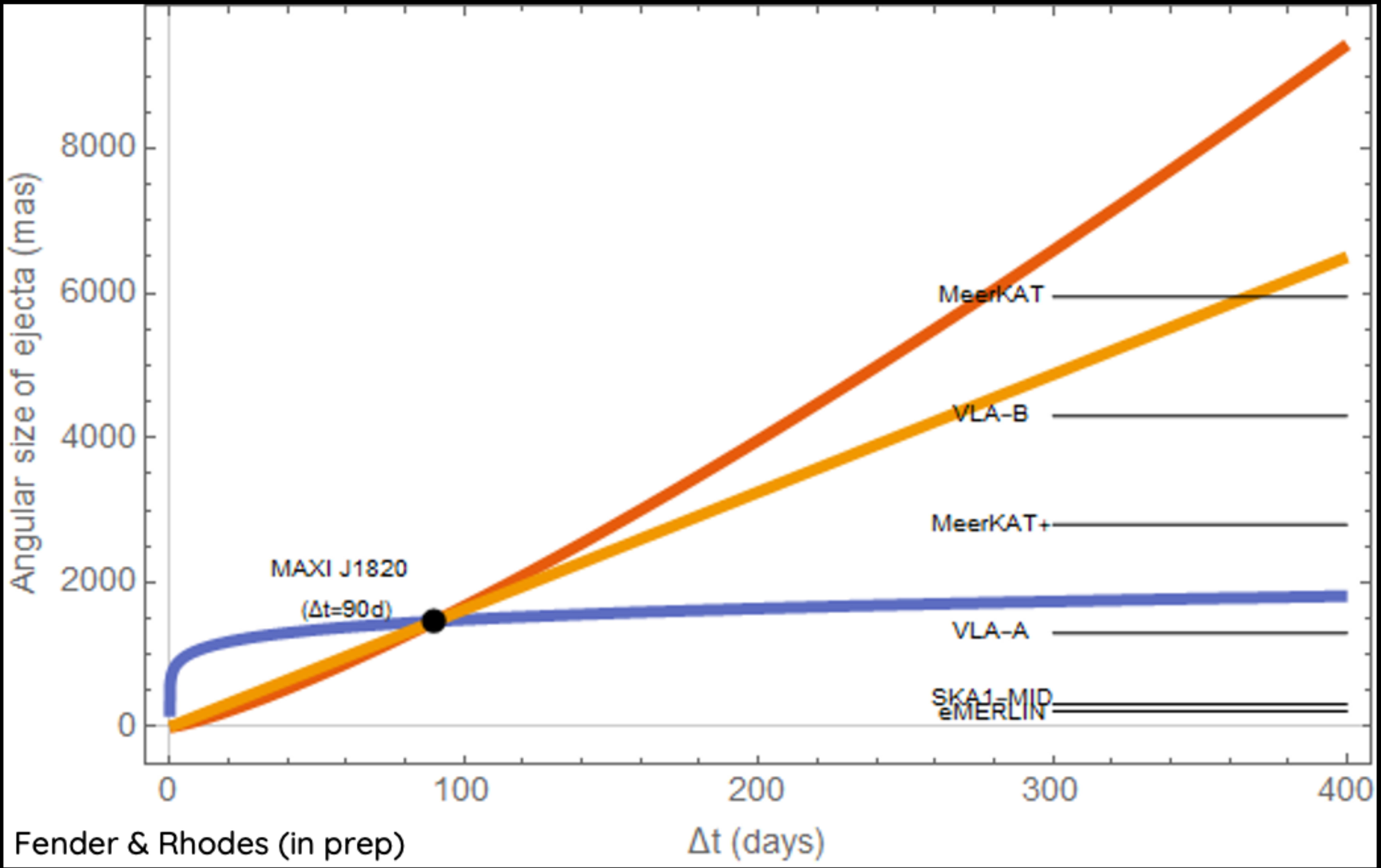


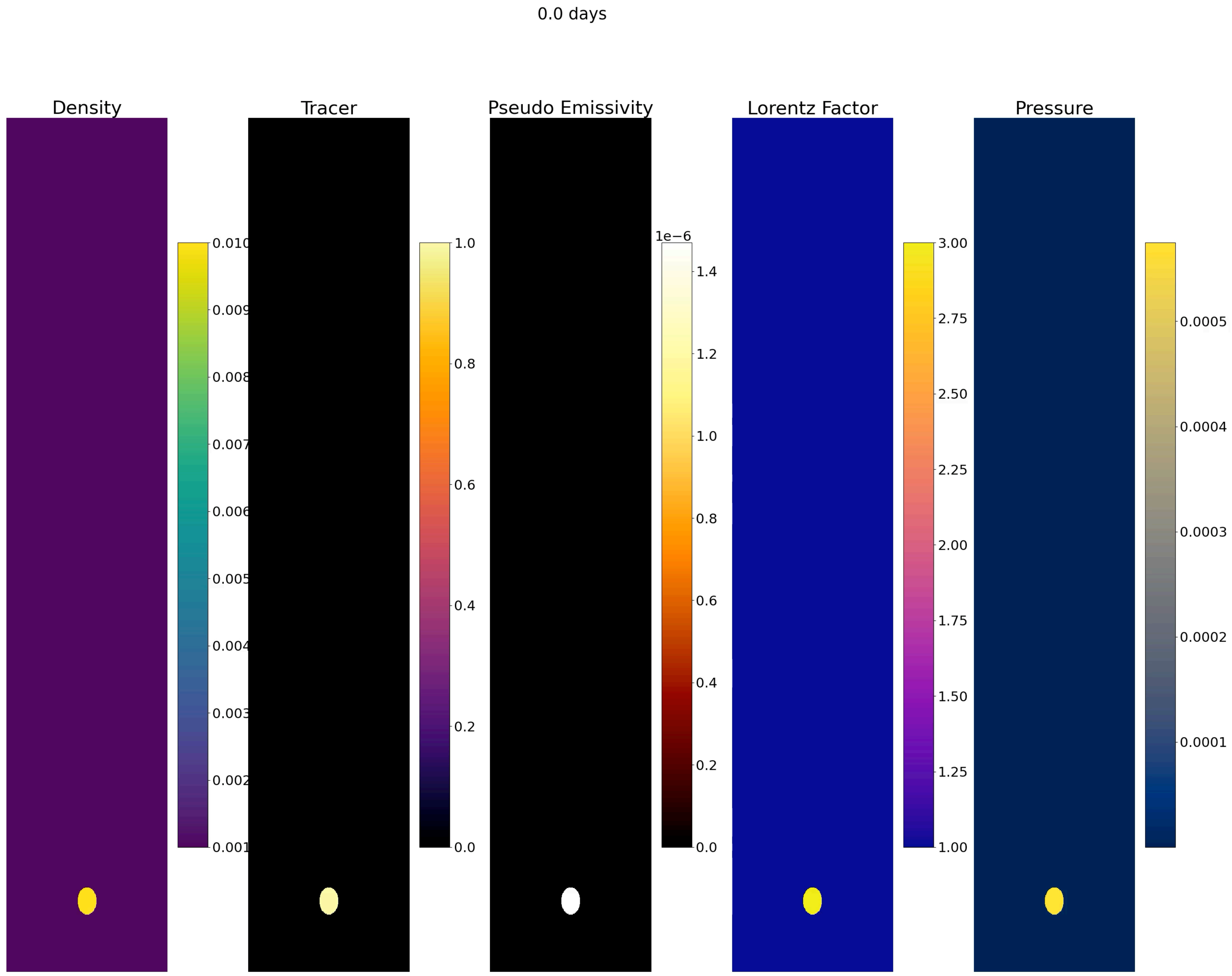
Fender & Rhodes (in prep)

SKA1-MID 'includes' MeerKAT:

a single observation will measure all baselines from MeerKAT to ~150 km

Continuously monitor size from ~**20 days**

(detection in minutes)

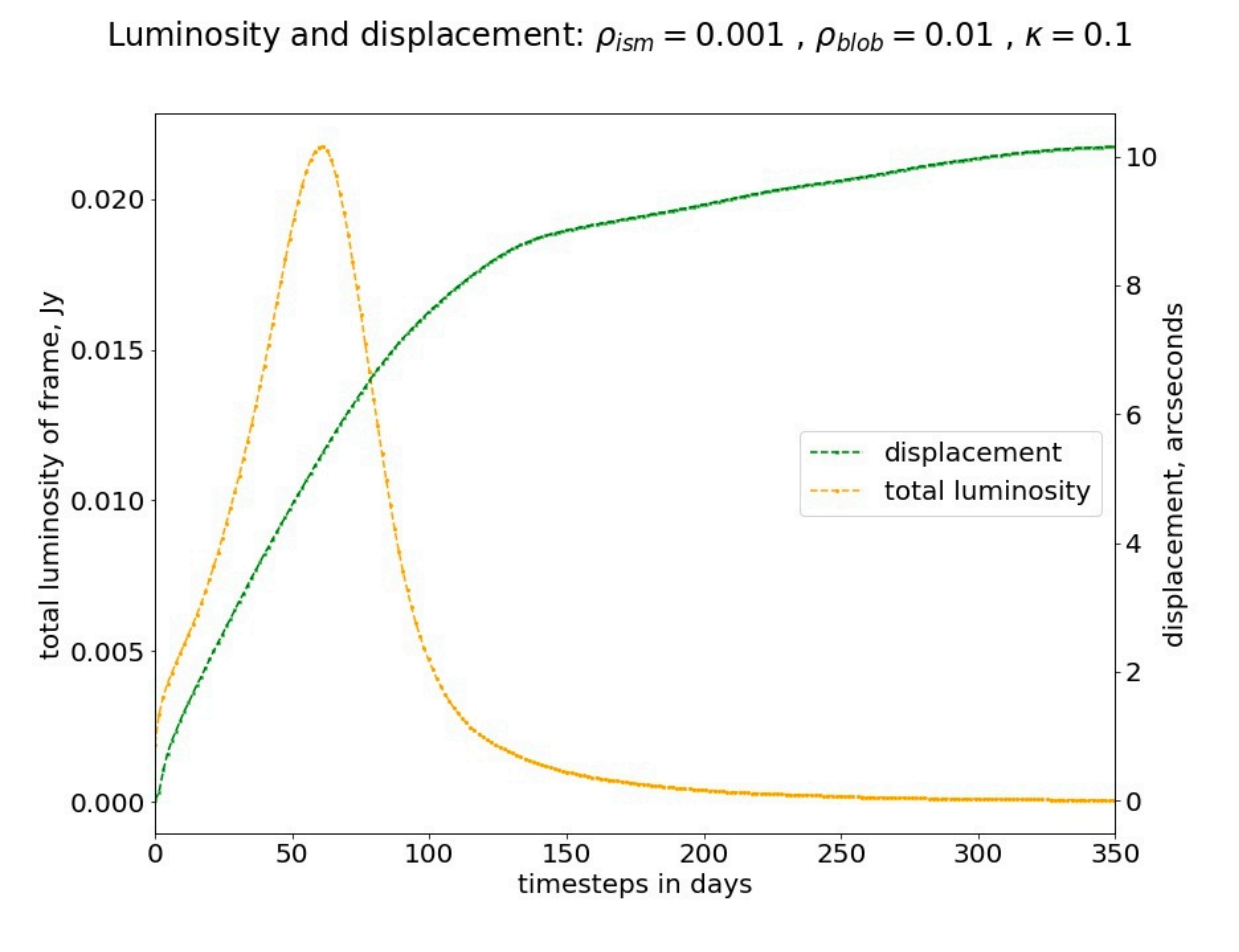


Beyond naive equipartition

PLUTO relativistic HD simulations

Initial conditions derived from observations of MAXI J1820 at 90 days (assuming Lorentz factor 3 at this time)

Savard, Matthews, RF et al. in prep



We are able to approximately reproduce size and timescale of deceleration, and observed synchrotron luminosity of blob (caveat degeneracies in initial conditions) <u>except</u> for an initial radio flare due to incorrect input structure)

Savard, Matthews, RF et al. in prep

Conclusions

Black holes produce relativistic jets whose large energy budget is hard to measures and hard to connect to horizon-scale properties at the moment of launch

In stellar-mass black holes we are now able to track jets from launch to termination

Rare size measurements confirm that jet power can exceed observed radiative luminosities at both low (always?) and high (intermittently) accretion rates

Relativistic MHD modelling and SKA-era observations will allow us to precisely measure jet energy and track how it is dissipated in the interstellar medium

Fin.