Sagittarius A* as a testing laboratory

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Event Horizon Telescope

Columbia University
in the City of New York

Flatiron Institute
Center for Computational Astrophysics

The galactic center

Credit: X-Ray: NASA/CXC/UMass/D. Wang et al.; Radio: SARAO/MeerKAT

Credit: X-Ray: NASA/Chandra.; Radio: NRAO/VLA

The galactic center

Credit: X-Ray: NASA/CXC/UMass/D. Wang et al.; Radio: SARAO/MeerKAT

Credit: X-Ray: NASA/Chandra.; Radio: NRAO/VLA

The galactic center

Strong radio source discovered in 1974, by Balick and Brown

Additionally stars in close orbits, observed for many years by Keck/UCLA and GRAVITY

S2 star: period of 12 years

Constraints the mass of a compact mass of 4.31 million solar mass

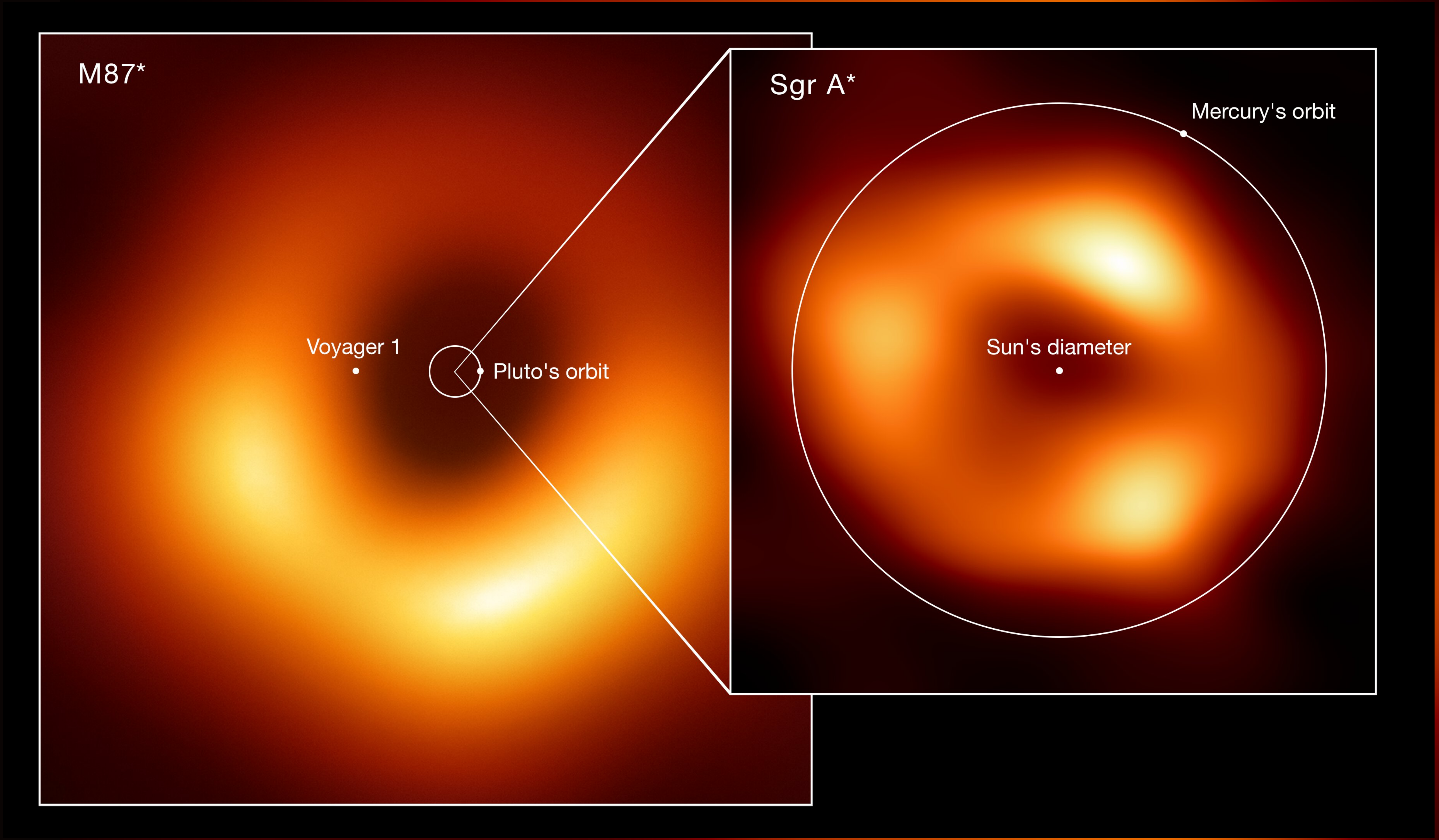
Credit: GRAVITY/Keck

A new era in black hole astronomy

Black hole images at event horizon scales.

Both images not in disagreement with GR

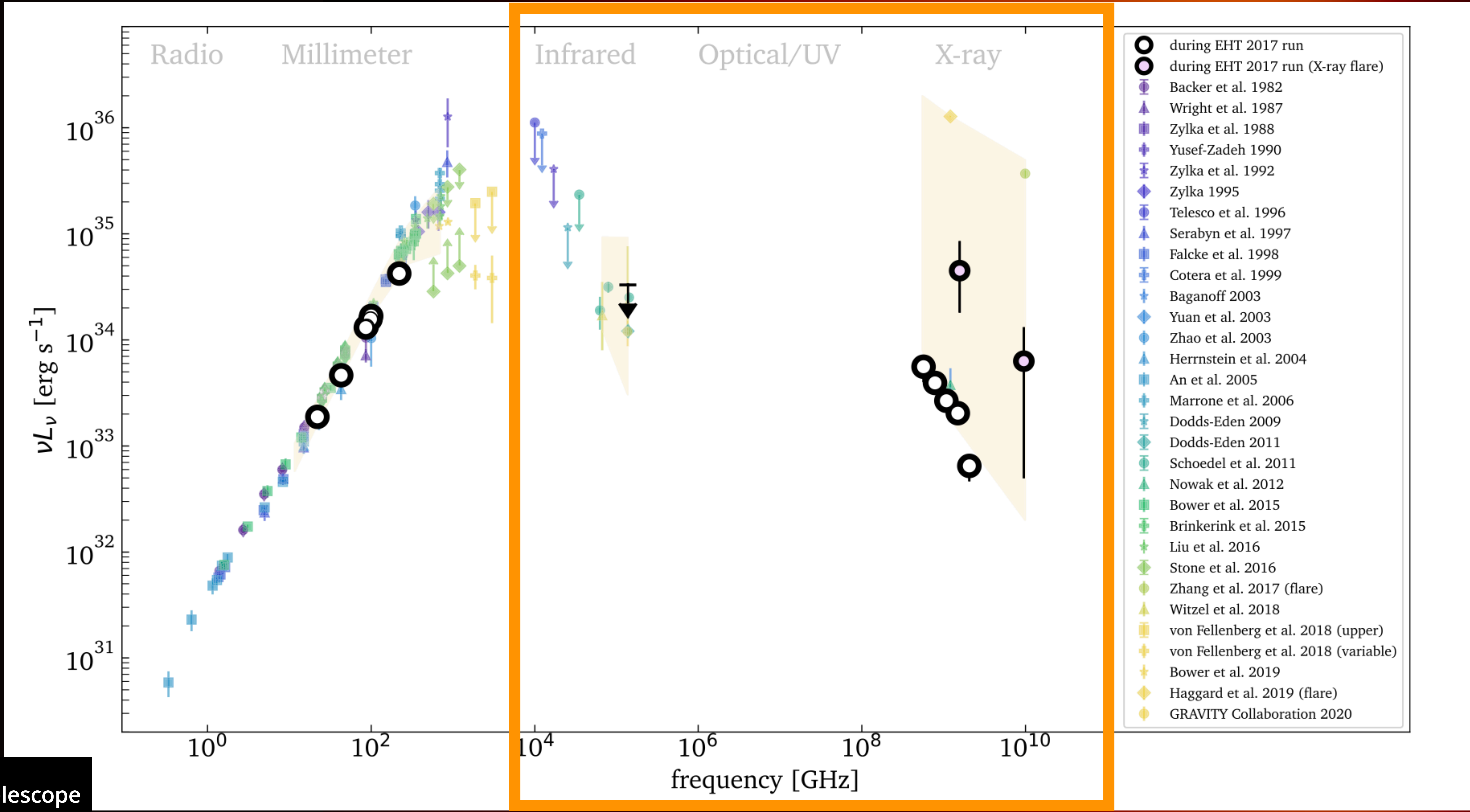
SgrA* is thousand times less massive than M87, vastly different timescales!



credit: EHTC /xkcd

Event Horizon Telescope

Sagittarius A* - Xray/NIR



Event Horizon Telescope

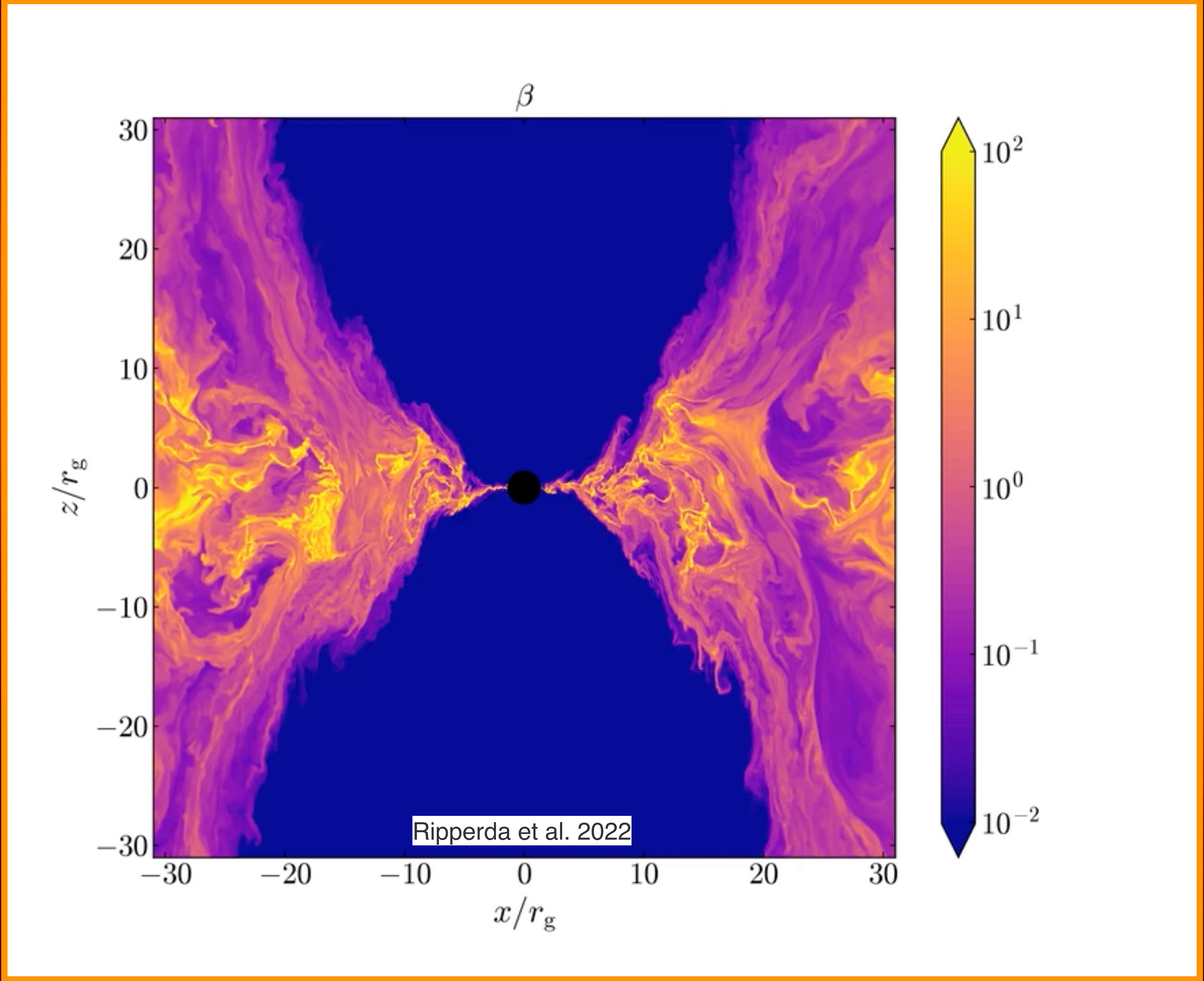
Magnetically Arrested Disks

Large accretion disk with poloidal fields.

Typically produce strong jets powered by Blanford-Znajek mechanism (Tchekhovskoy+2011)

Saturated state; maximum magnetic flux on horizon. If exceeded field is reconnected, triggers strong variability at the jet base.

Favored by EHTC for M87* based on linear and more recently also circular polarization.



Reconnection in the mid plane (Ripperda et al. 2020,2022)

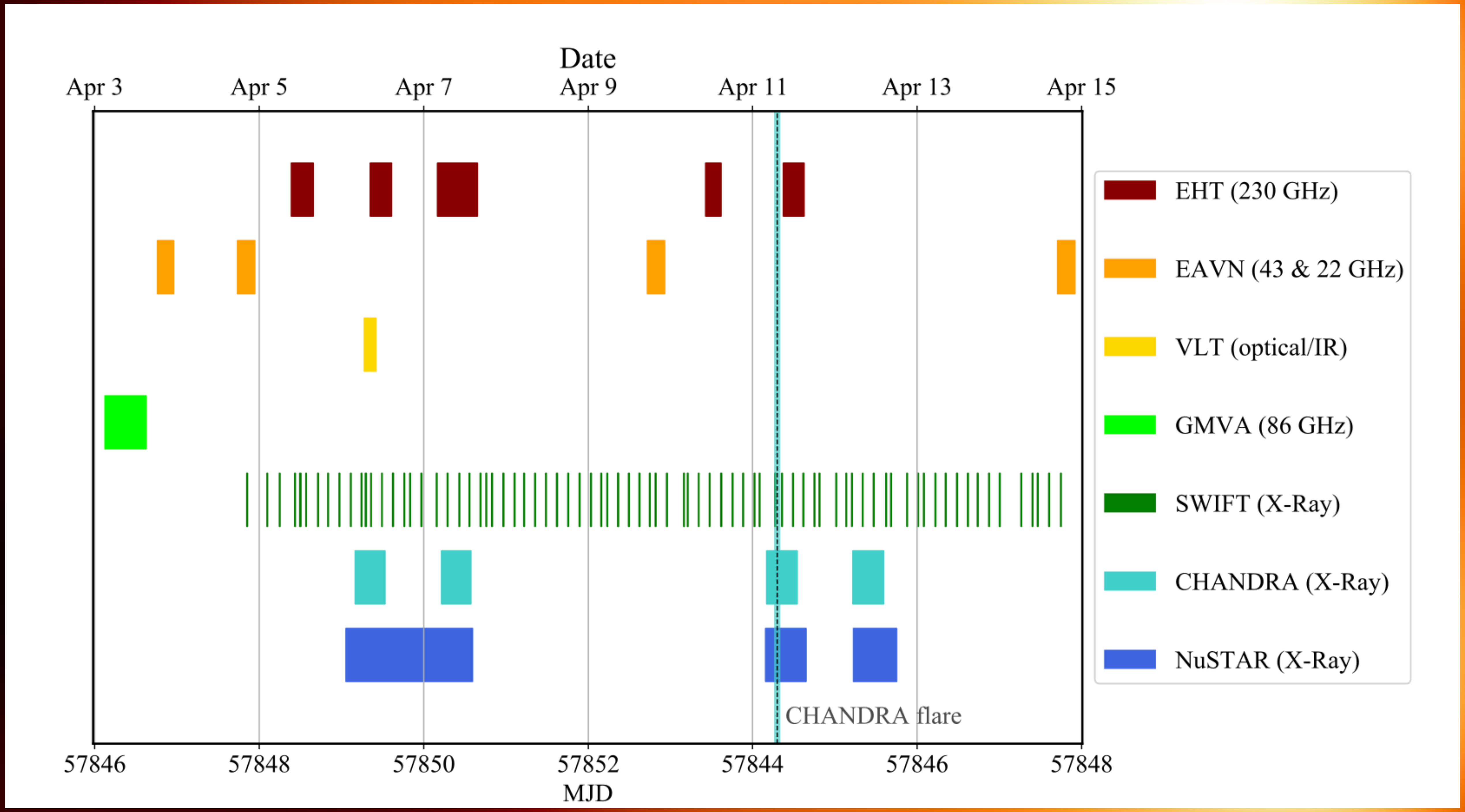
Shown to be tearing unstable, efficient sight of particle acceleration

Potentially behind ultra high energy emission, e.g. for M87* (Hakobyan et al. 2023)

credit: Bart Ripperda

April 11 2017

An X-ray flare was observed during the 2017 EHT observational campaign

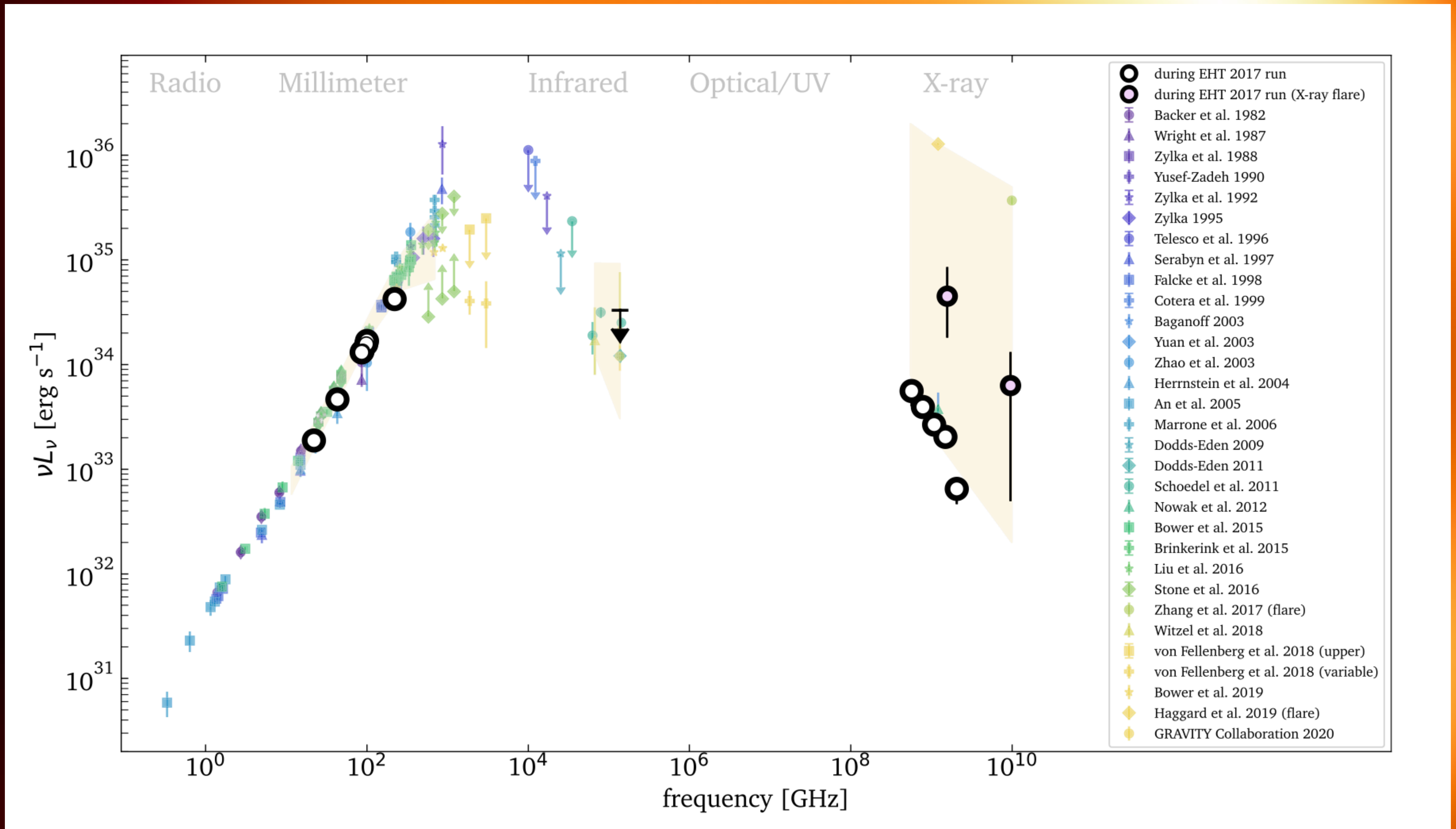


April 11 2017

An X-ray flare was observed during the 2017 EHT observational campaign

Flux goes up by an order of magnitude

No images for April 11 yet…

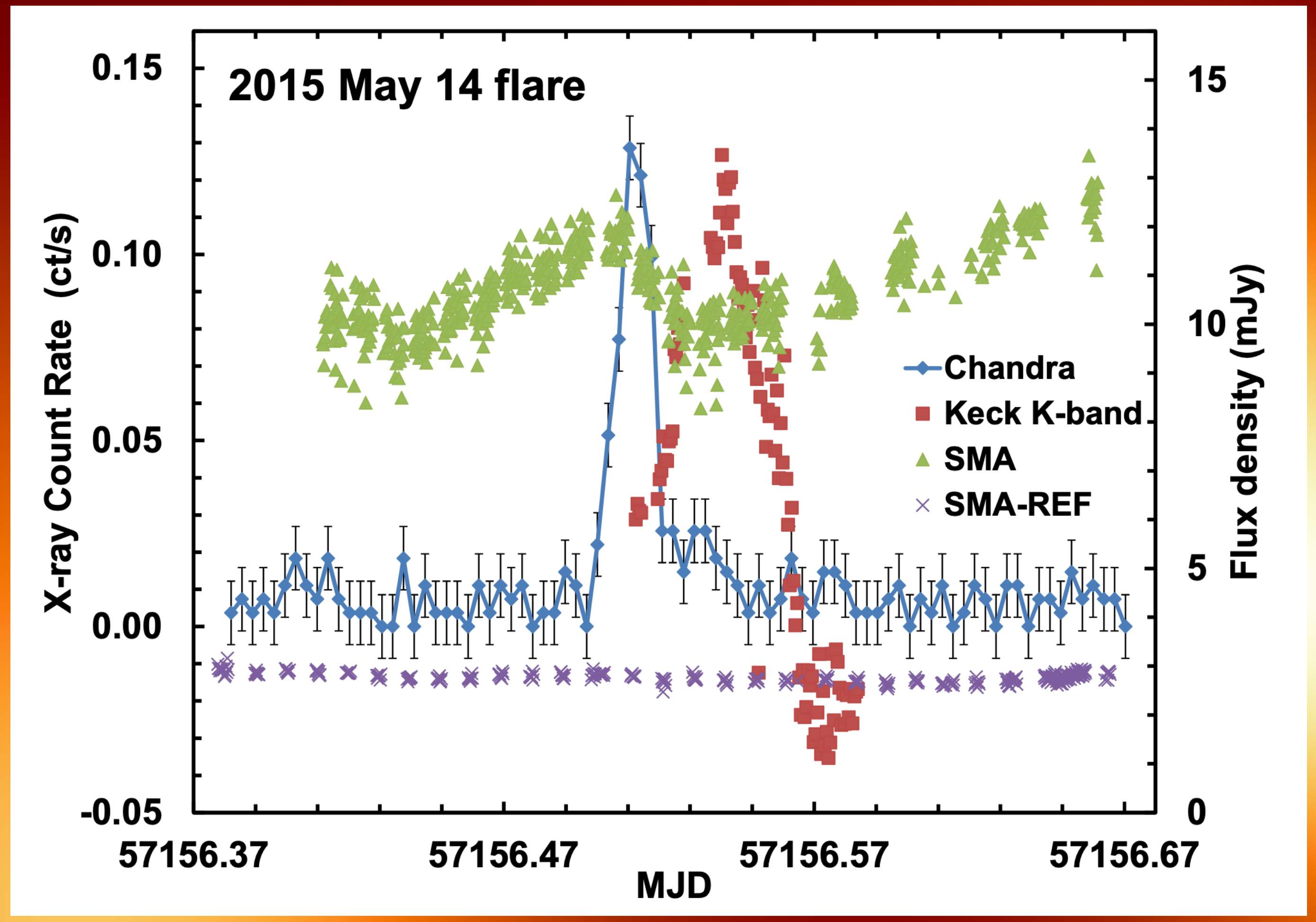


Event Horizon Telescope

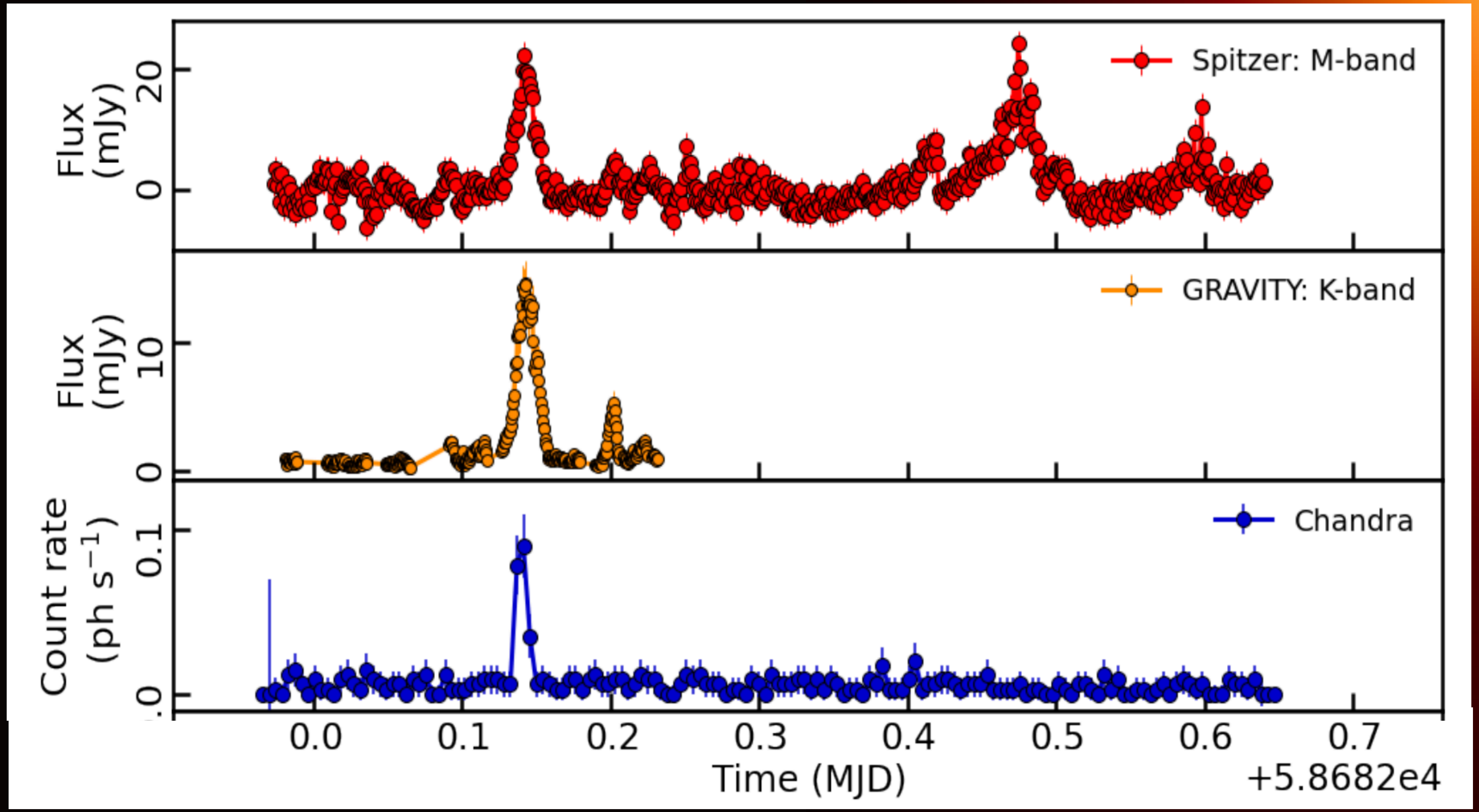
NIR flares by GRAVITY and Keck

- Flares last for ~ 30 min, minute-long sub-variability
- Once/twice per day
- Radio, near-infrared (NIR) and X-ray components
- NIR sometimes isolated, sometimes seem delayed..
- Submm often delayed, and dimmed during X-ray

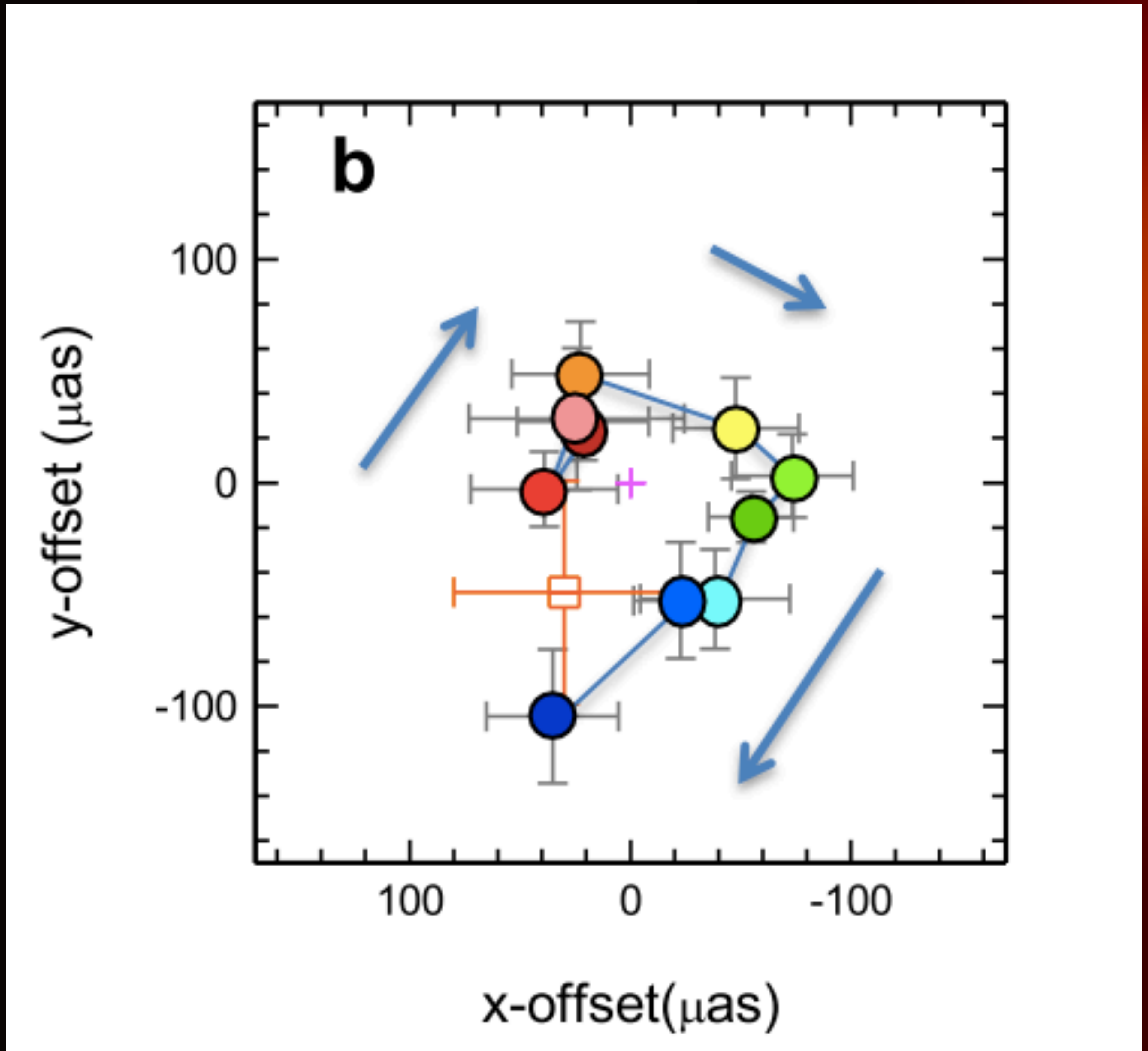
[Fazio et al, ApJ, 2018]

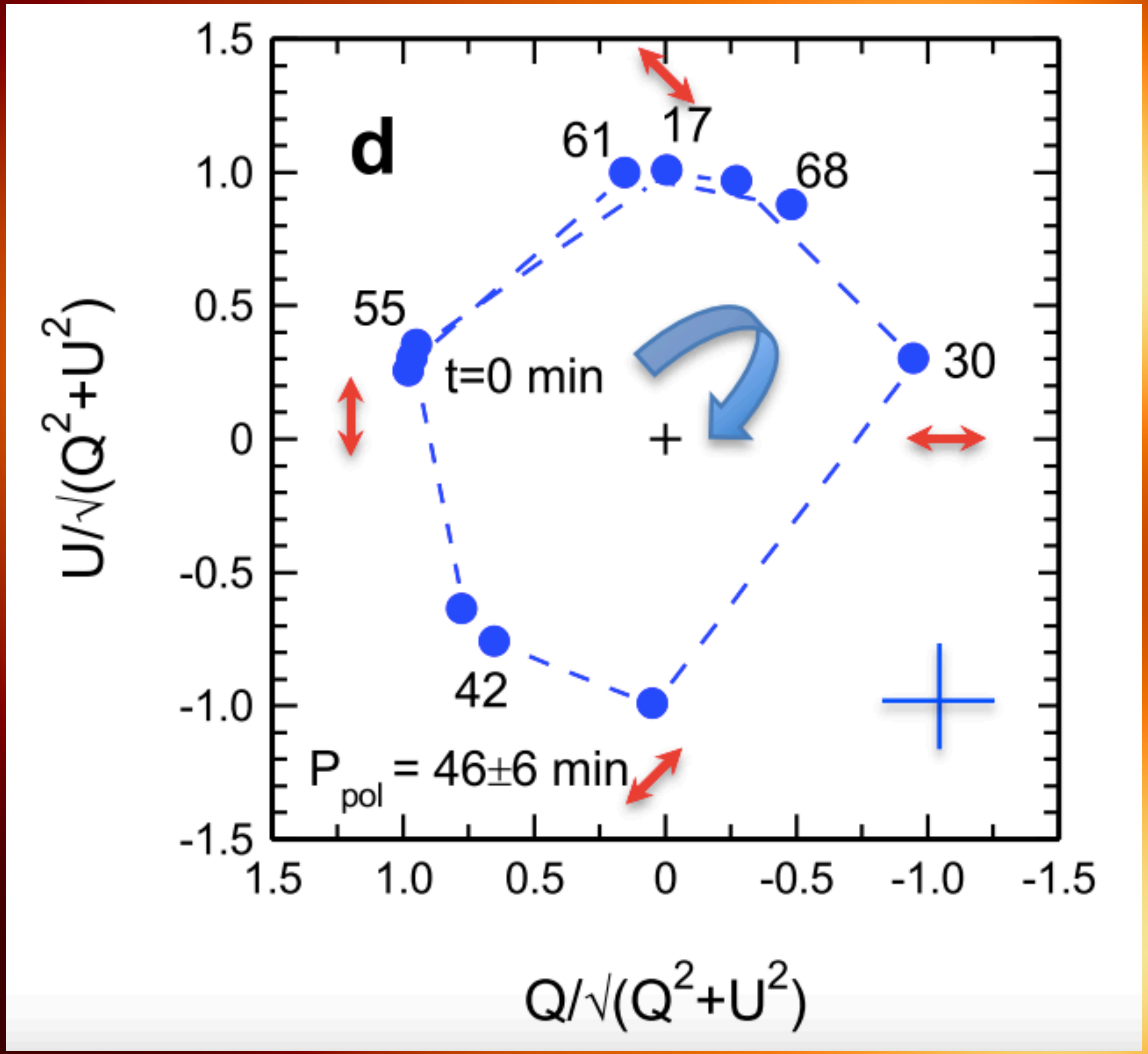


[GRAVITY, A&A, 2021]



NIR loops by GRAVITY



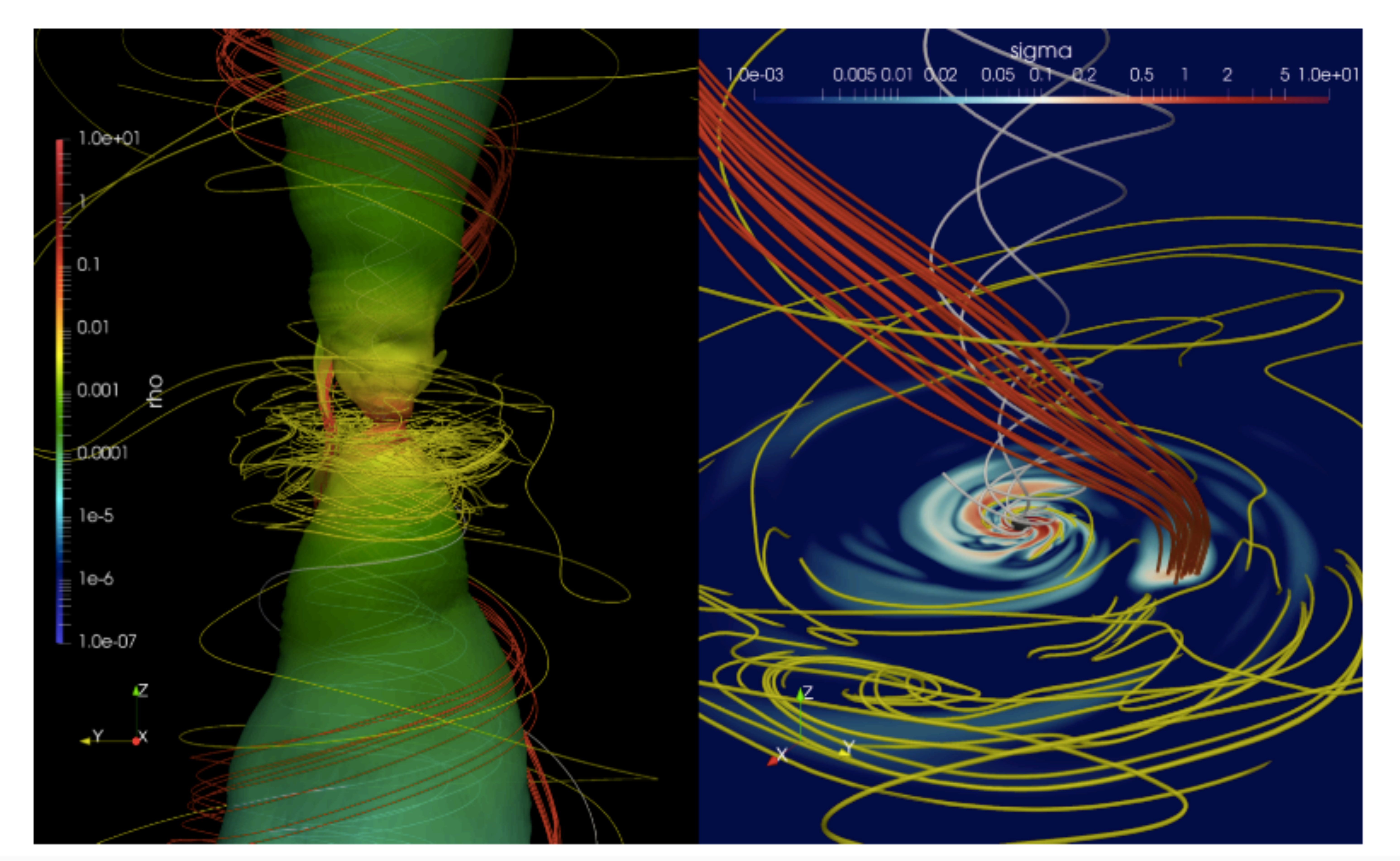


Credit: GRAVITY

Origin of NIR hot spots?

Exhaust of the current sheet generates vertical magnetic field.

This field partially arrestees the disk creating a “flux tube” that orbits the black hole.



Porth et al. 2021

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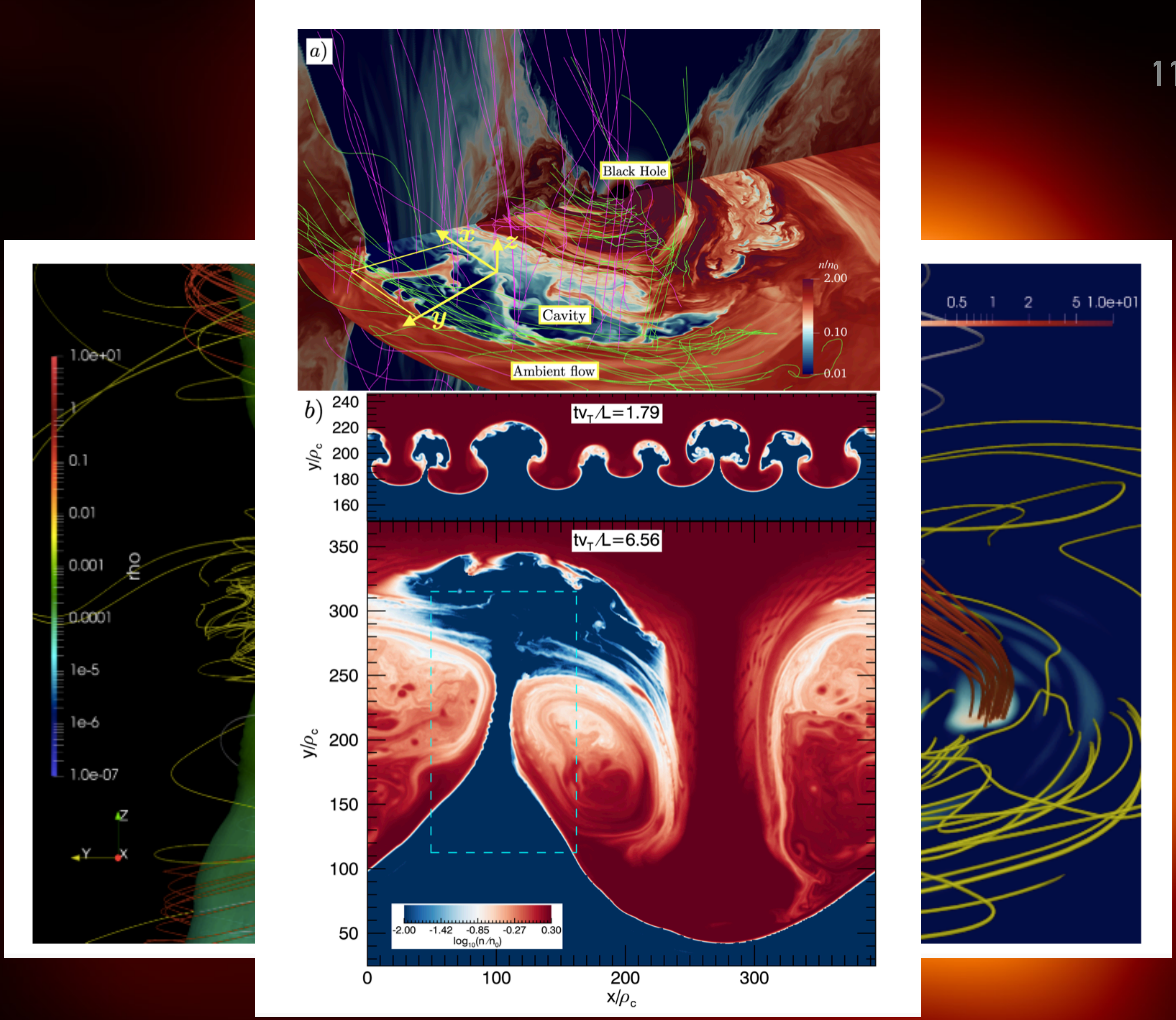
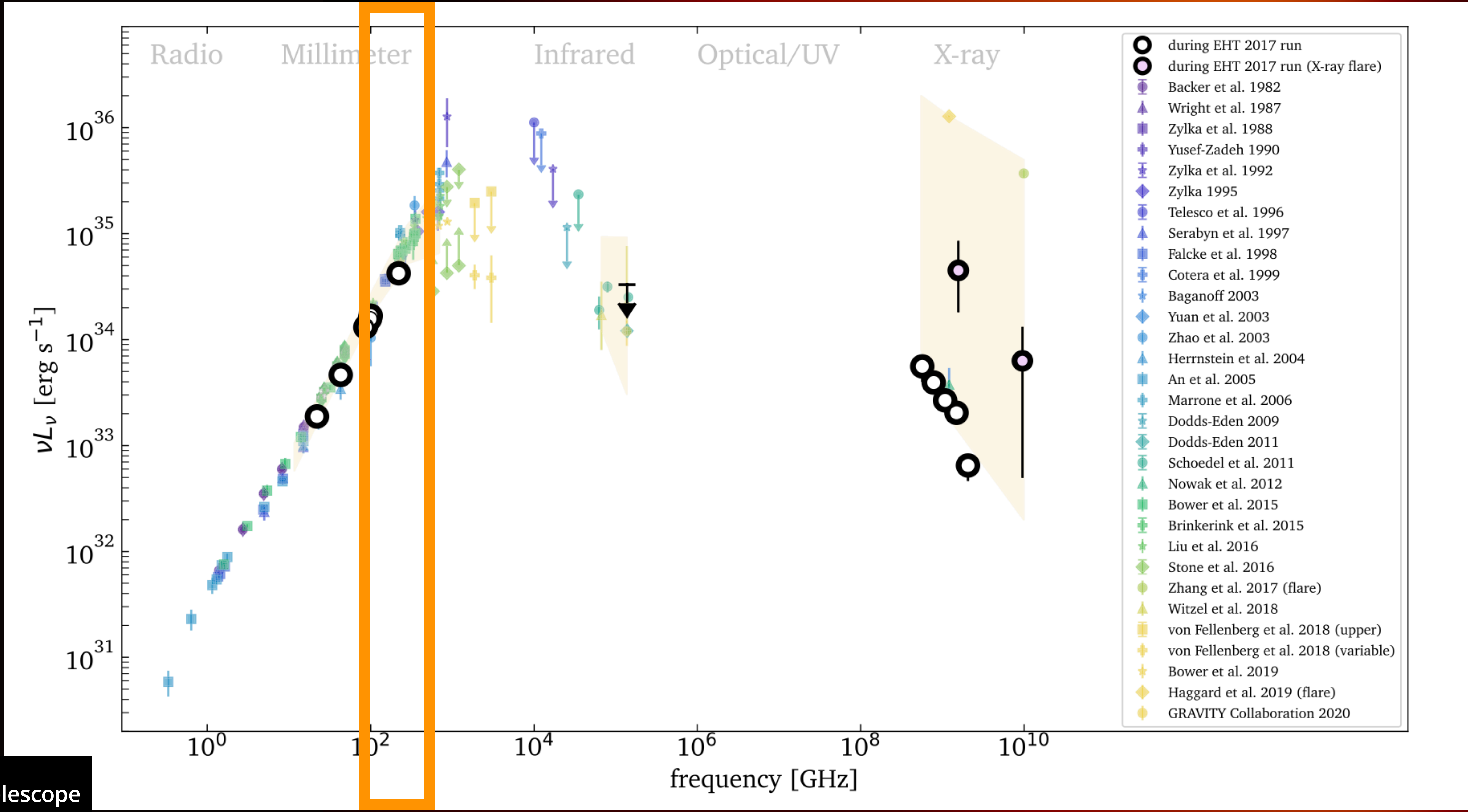


Porth et al. 2021

Zhdankin et al. 2023

Sagittarius A* - mm



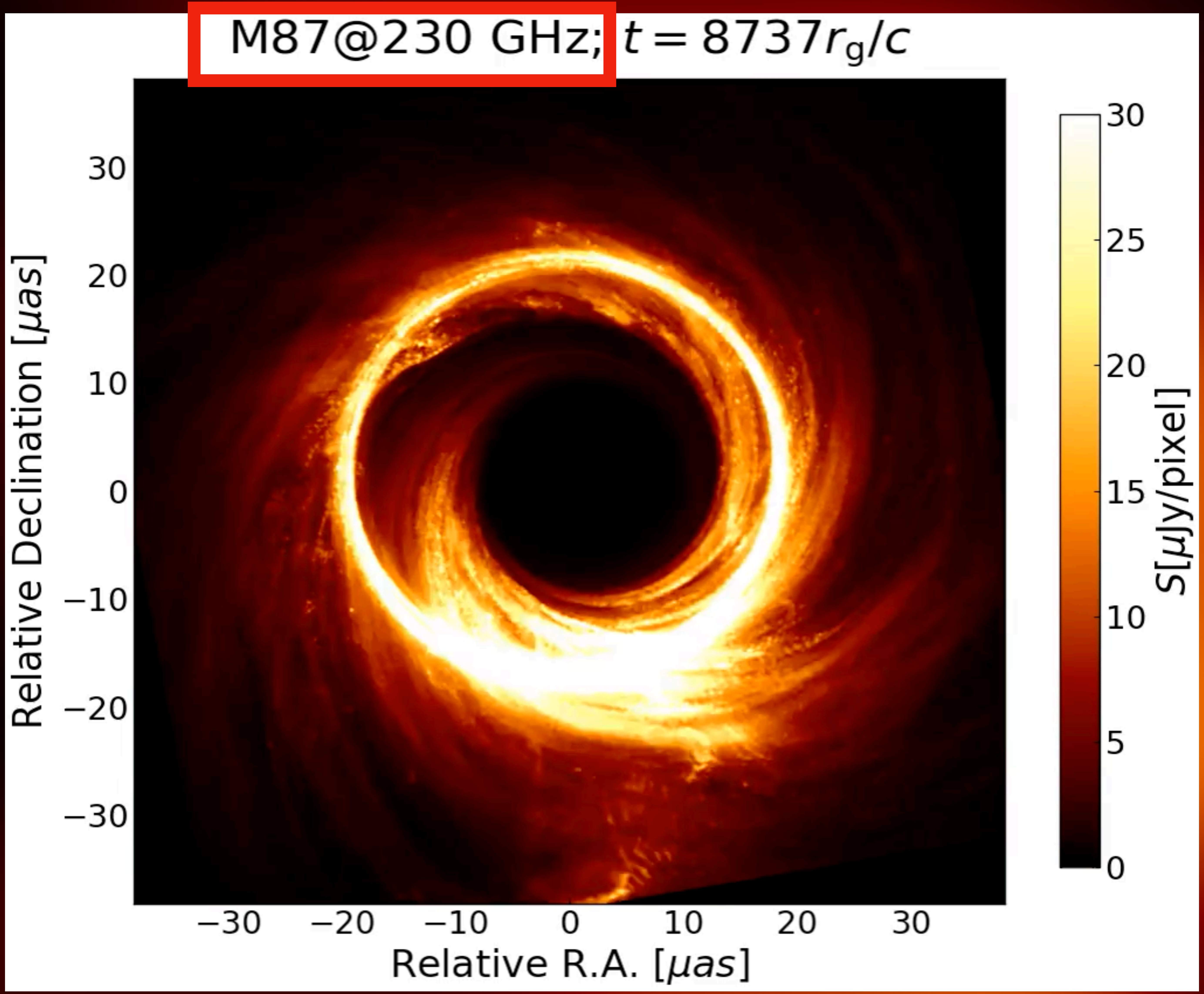
Event Horizon Telescope

April 11 2017

Unsolved; no images for April 11 yet…

Some work done for M87

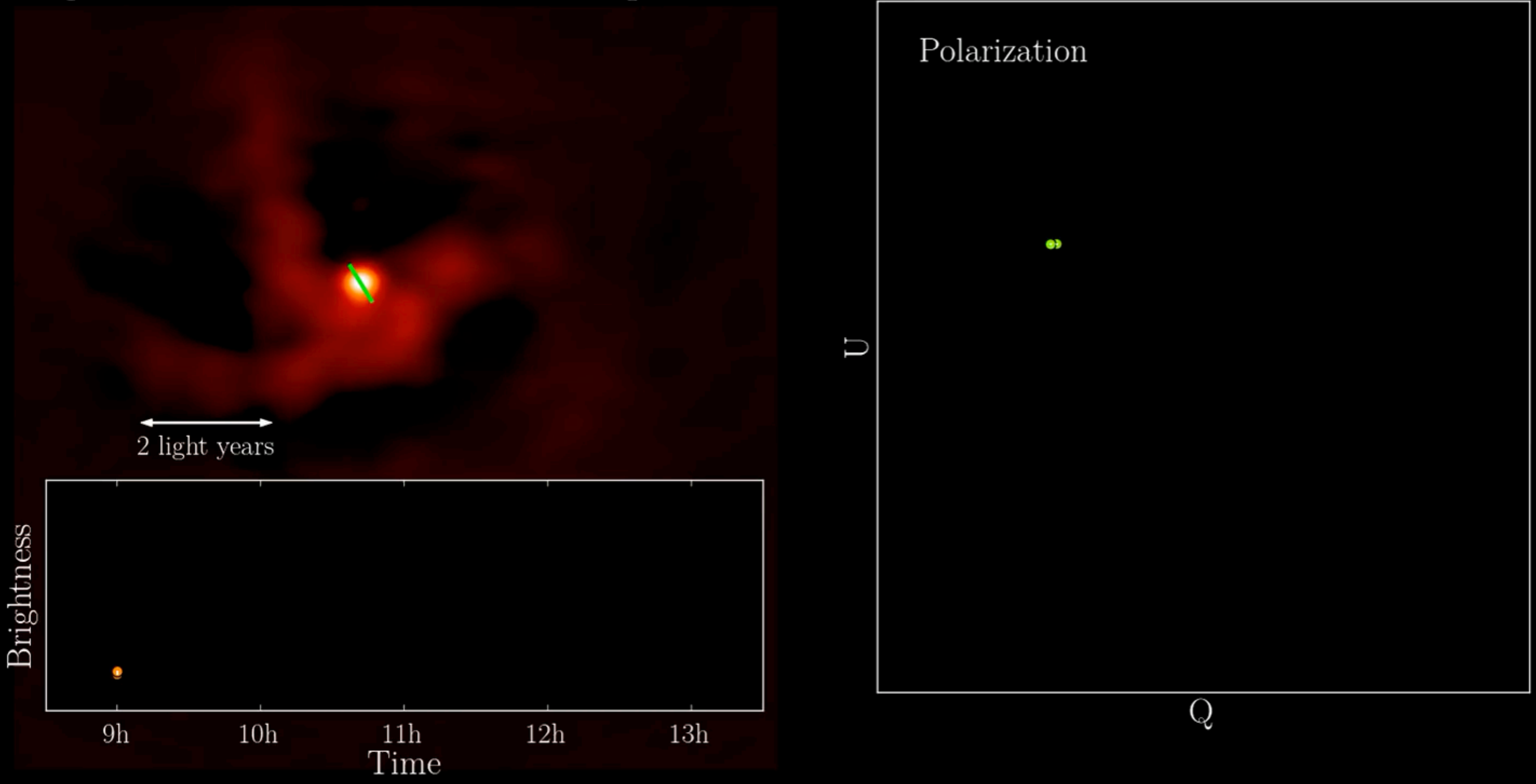
For SgrA* this effect might be even larger, optical depth at 230 GHz is larger!



Jia et al. 2023, credit: Koushik Chatterjee

Event Horizon Telescope

SgrA* with ALMA on 2017 April 11



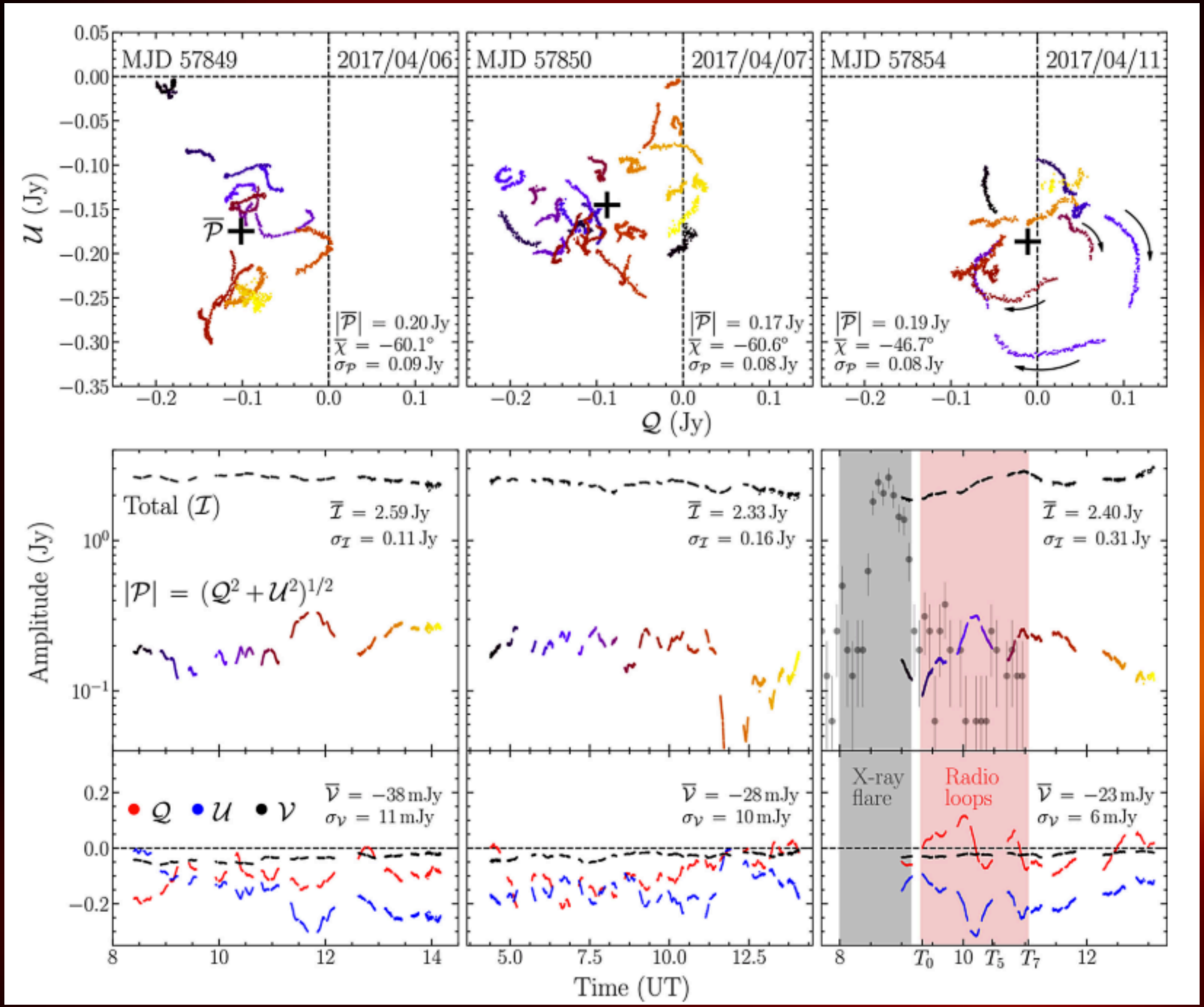
Animation credit: I. Marti-Vidal (Univ. Valencia)

Q-U loops in mm band

Incidental X-ray flare during the EHT observation of 2017

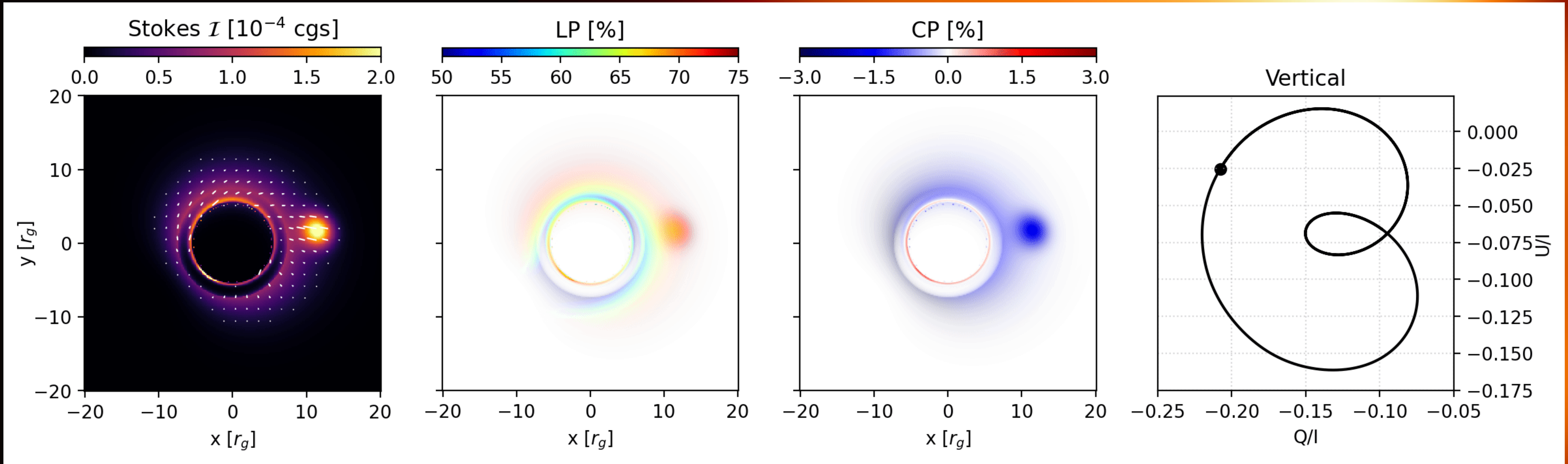
ALMA light curve, high temporal resolution

Polarized! Q-U diagram shows coherent loops similar to as seen by GRAVITY



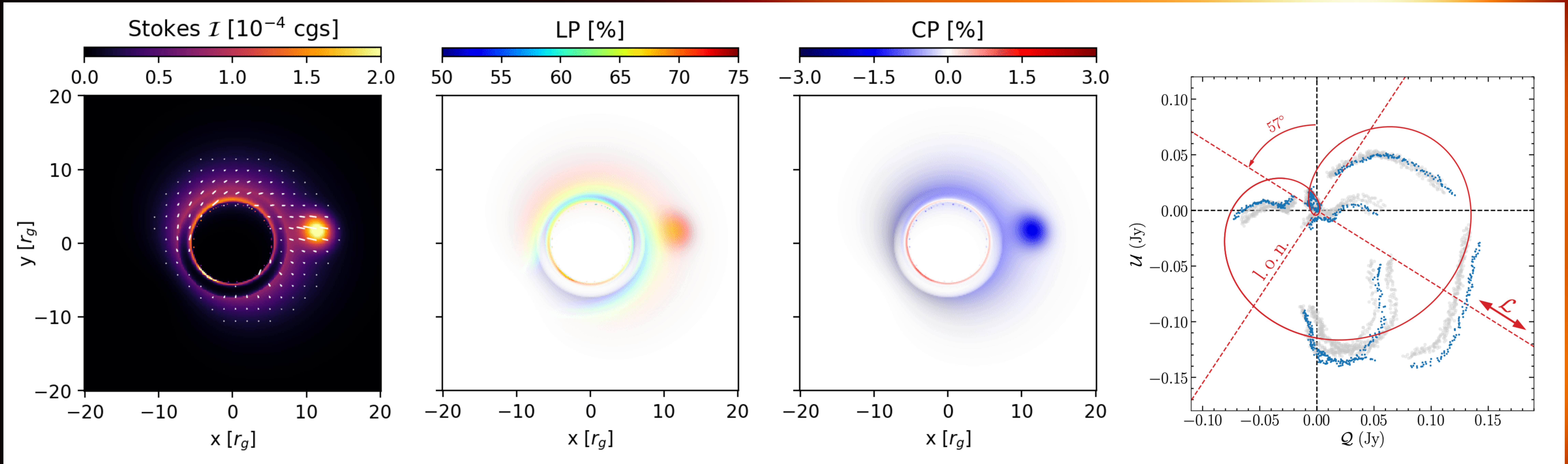
Credit: Wielgus et al. 2022

Modeling of Q-U loops in mm band



Credit: Vos et al. 2022

Modeling of Q-U loops in mm band



Credit: Vos et al. 2022

RAPTOR: Polarized General Relativistic Ray Tracing

GitHub: jordydavelaar/raptor

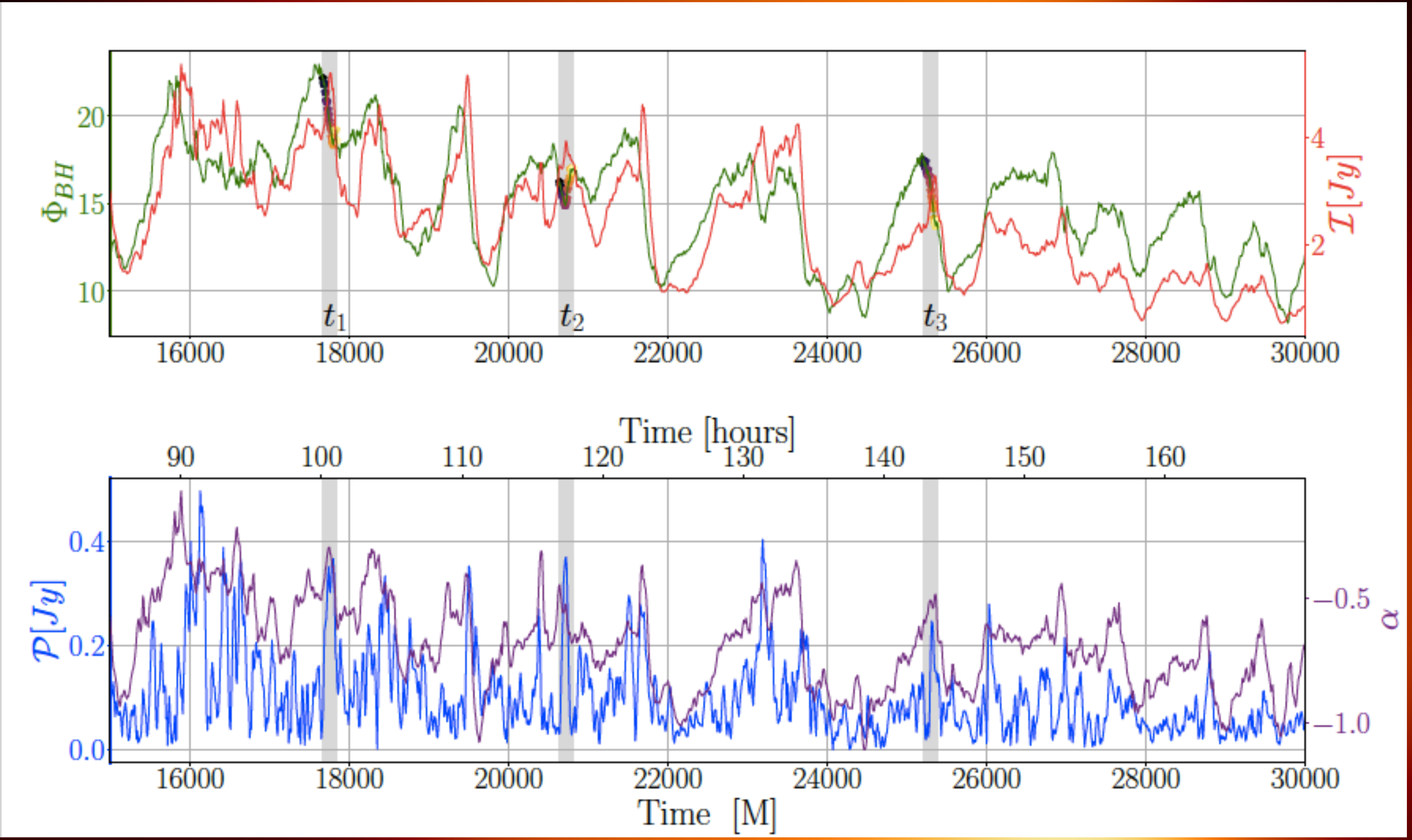
Animation: Davelaar, Radboud University/ESO

Q-U loops by MAD accretion models

MAD, a* = -0.9375, Rhigh =1, i =10

Increase in intensity directly after eruption

Followed by a decrease in intensity as the cavity expands



Najafi-Ziyazi, Davelaar et al. **2023**

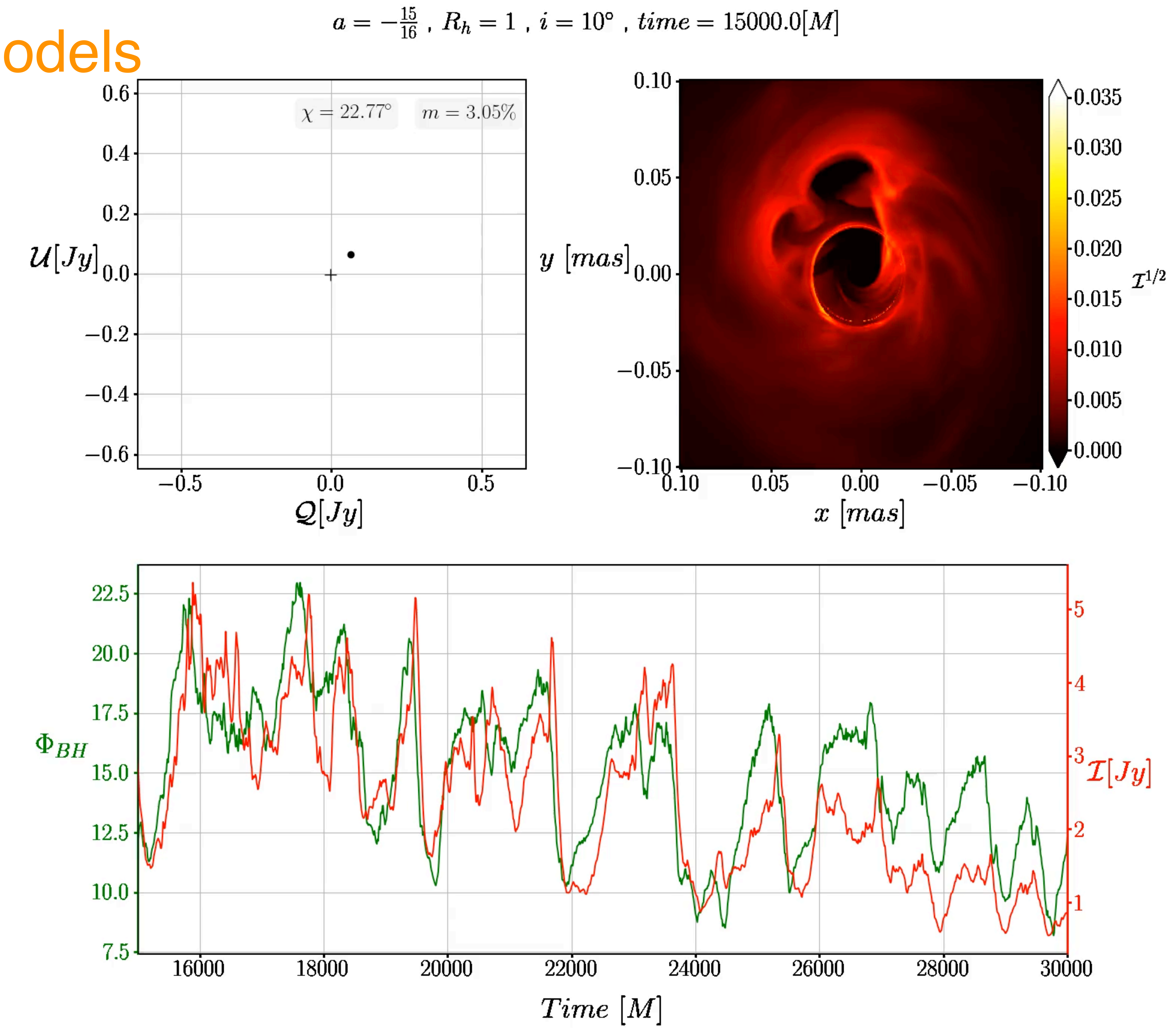
Q-U loops by MAD accretion models

MAD flux eruption disrupt the flow

Rotates around the black hole at 5-10 gravitational radii

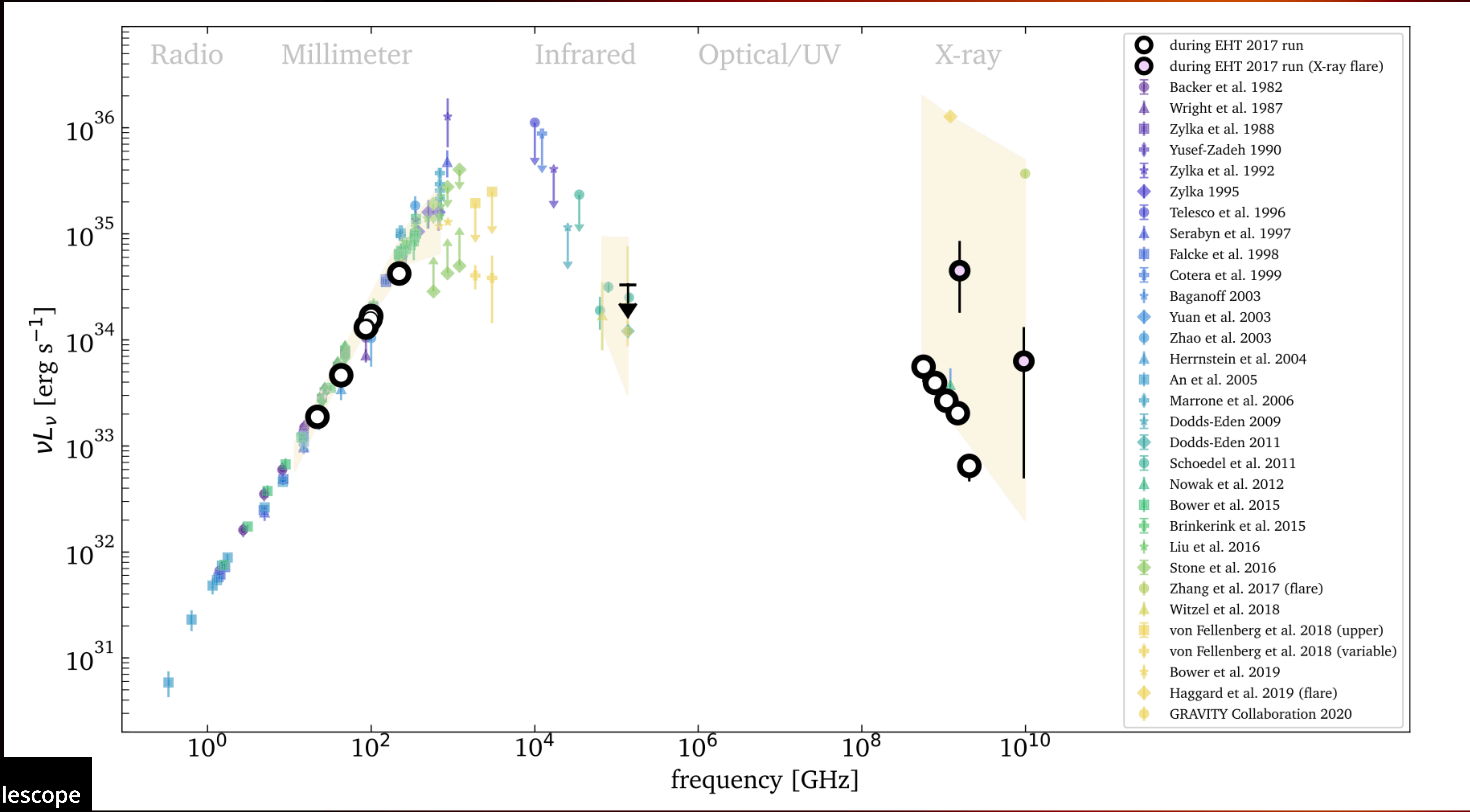
Expansion of the exhaust leads to heating in mm band

Heated material enhances the polarization



Najafi-Ziyazi, Davelaar et al. **2023**

Sagittarius A* - radio



Event Horizon Telescope

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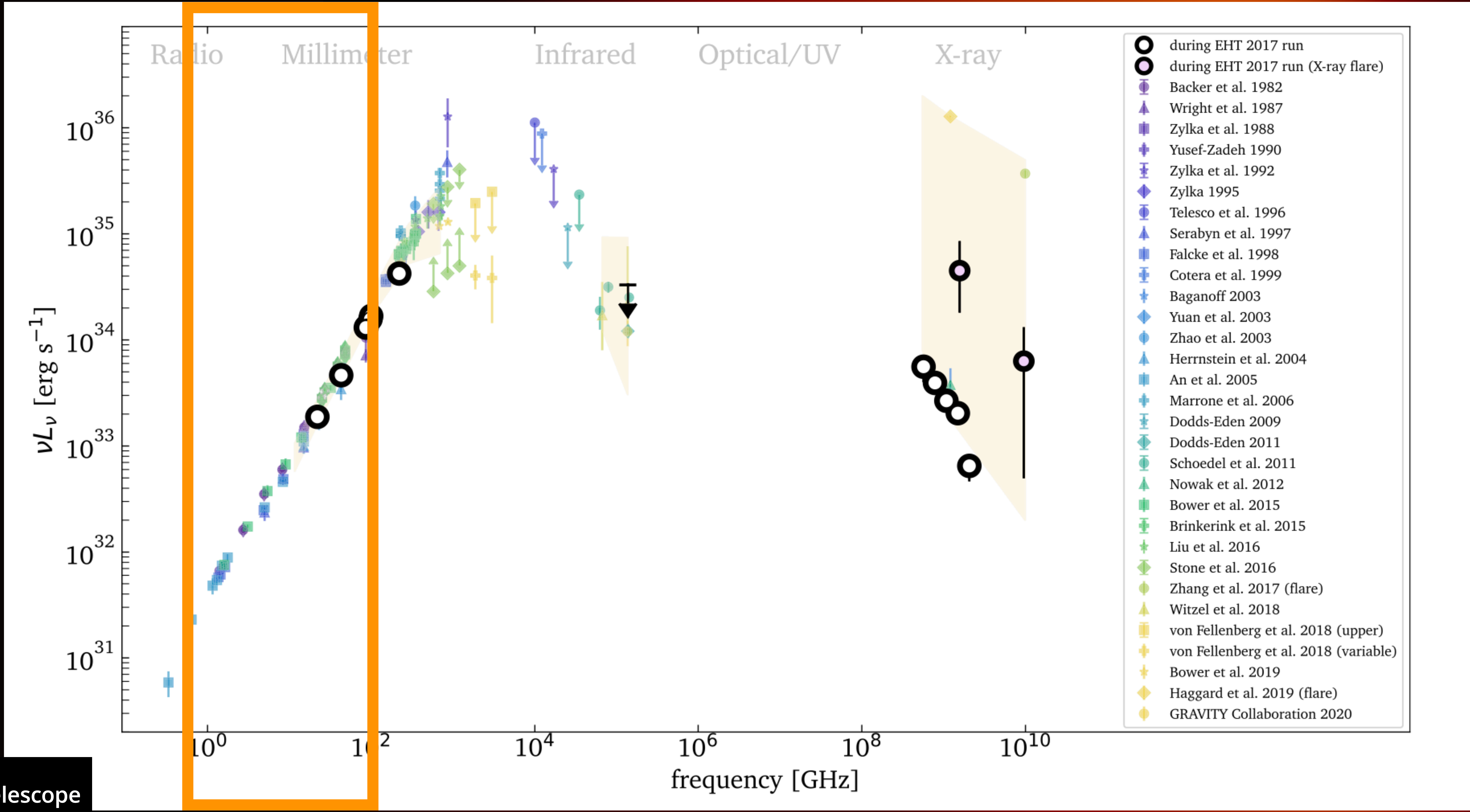


SgrA* flares at cm wavelengths

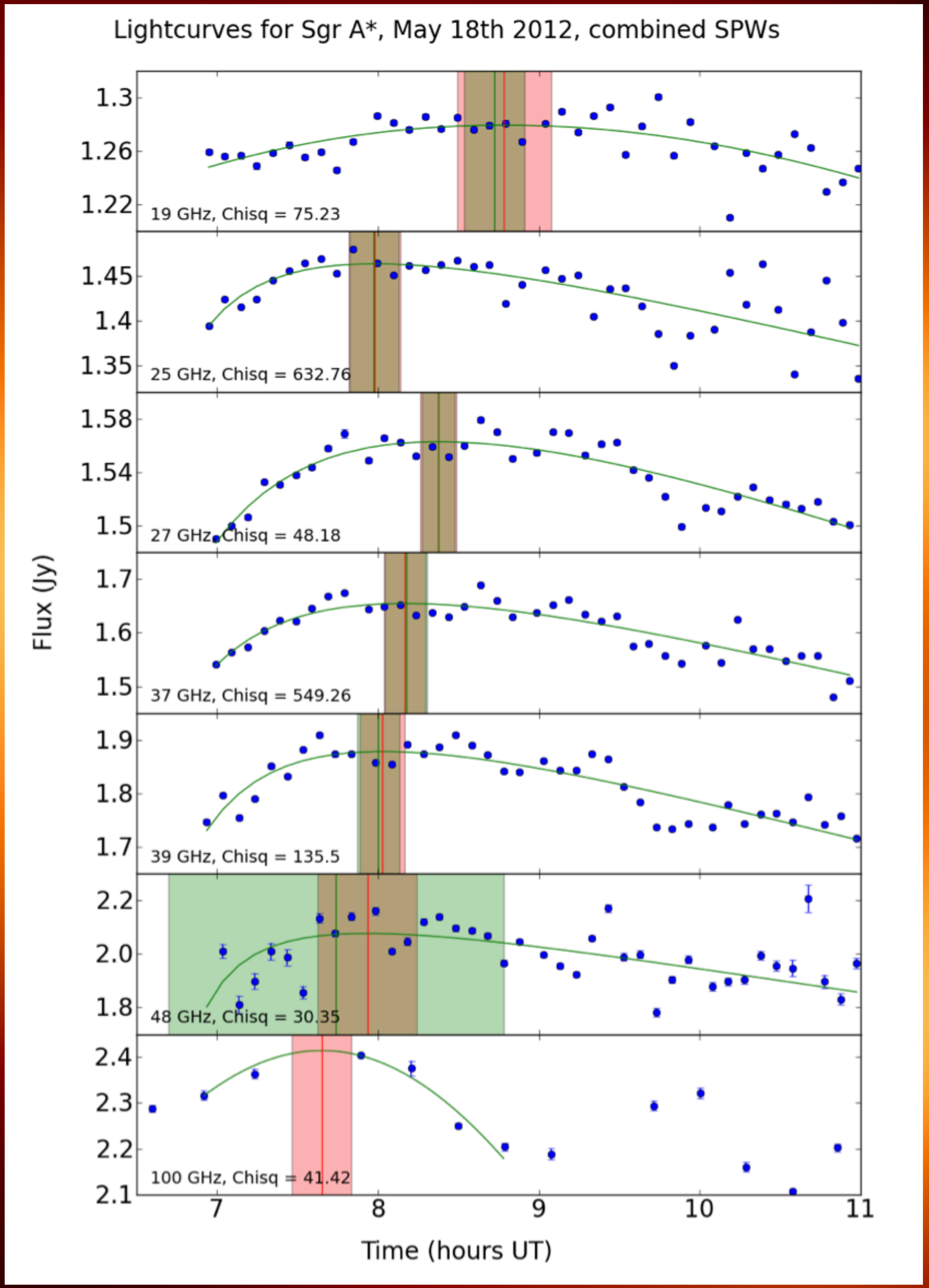
At even lower frequencies flares are observed in the radio

Brinkerink et al. 2015 observed SgrA* between 20 GHz en 100 GHz.

Flare was seen on May 18th 2012

Flare arrival time is time dependent, lower frequency arrives later, 30 minutes delay

Vos, Davelaar et al. **2023**



Credit: Brinkerink et al. 2015

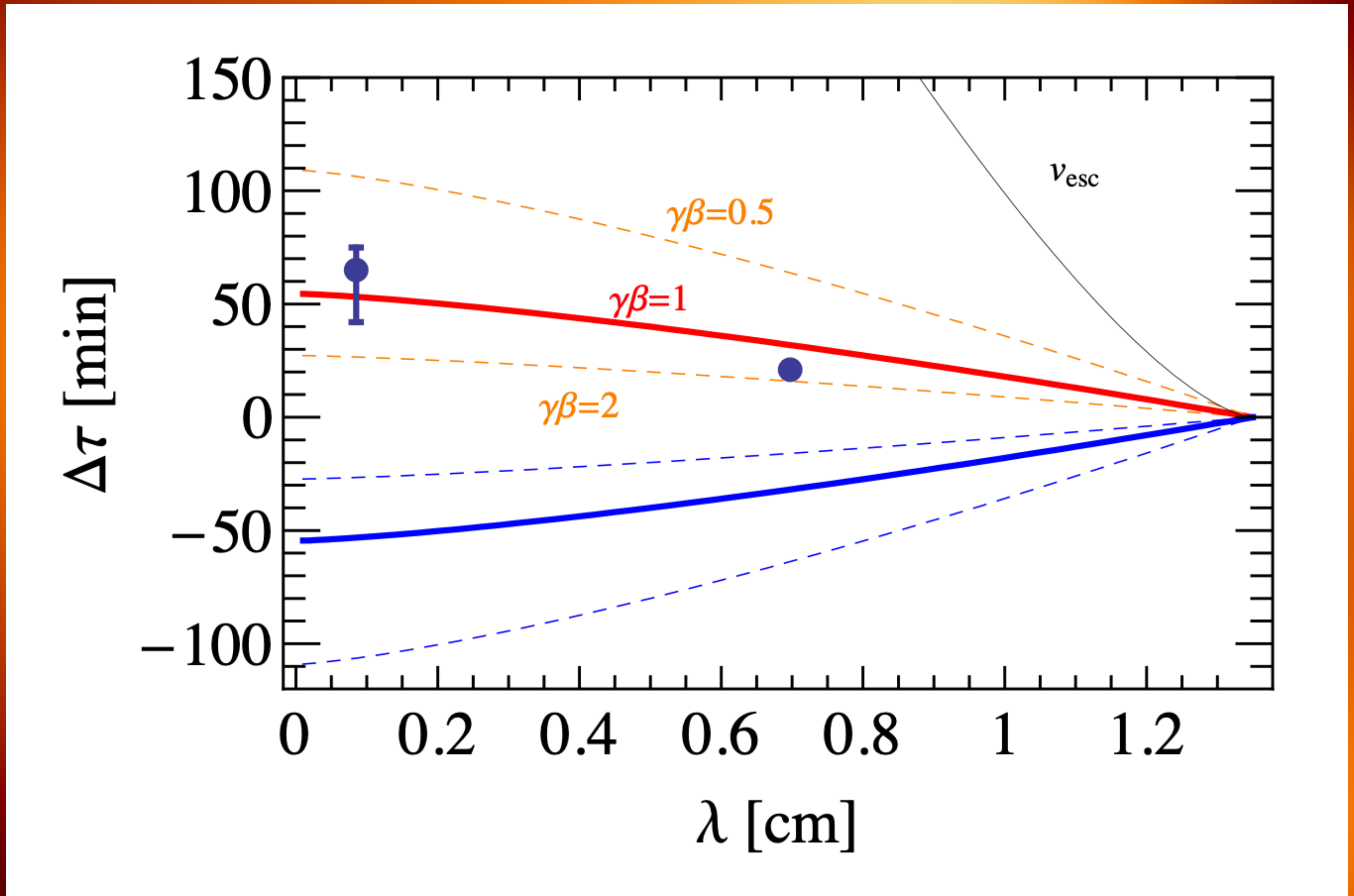
Modeling of time-lags

In the context of SgrA*, Falcke et al. 2008 modeled shifts like this.

IF the low frequency is arriving before the high frequency -> gas is inflowing and heating

IF the high frequency is arriving before the low frequency -> gas is outflowing and cooling

Velocity of the emission region sets the delay time



Credit: Falcke et al. 2008

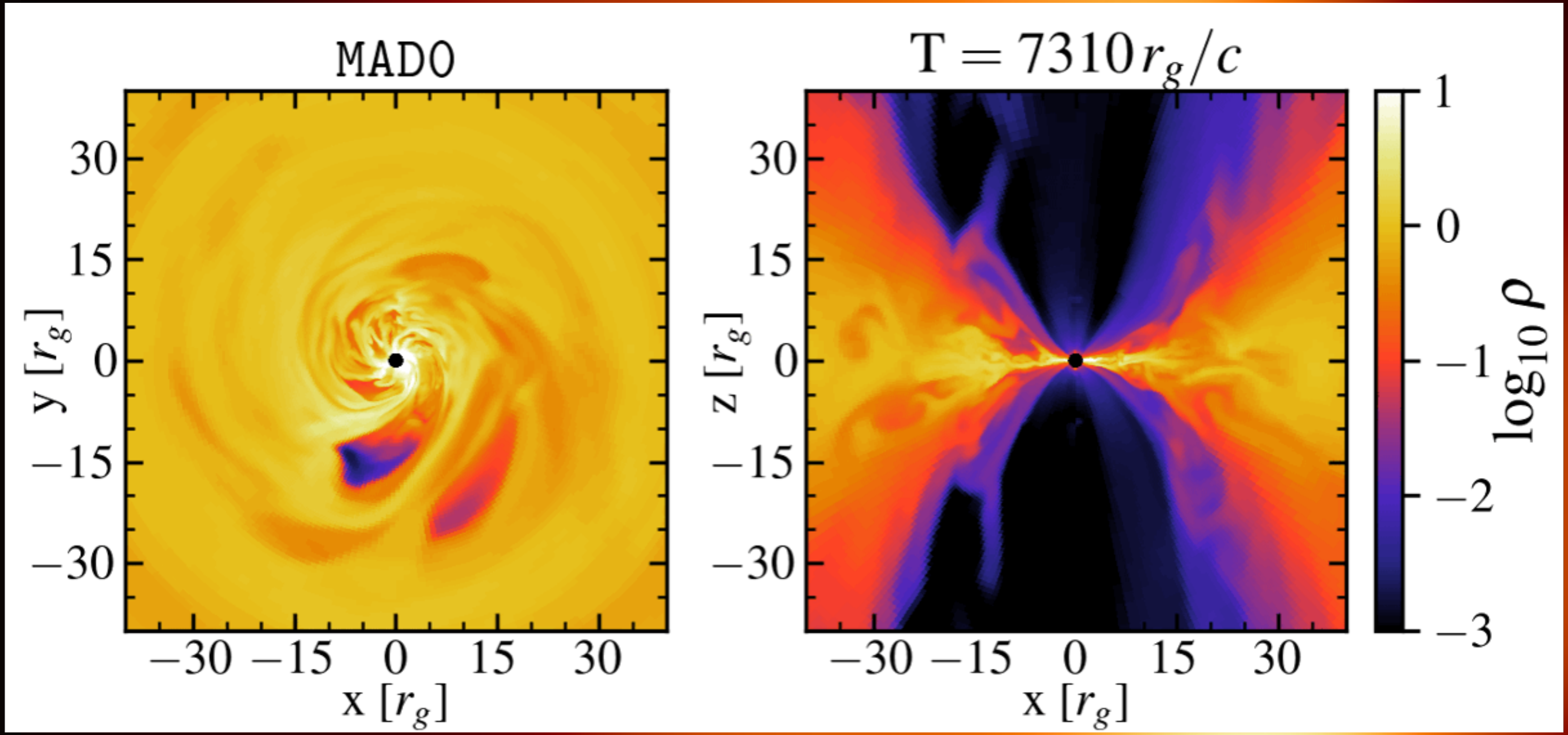
Vos, Davelaar et al. **2023**

Time-lags by magnetic flux erruptions

High resolution MAD simulations, for three spin values a=0,±15/16

High temporal output of data, every 1 rg/c

Light curves at 19-47 GHz



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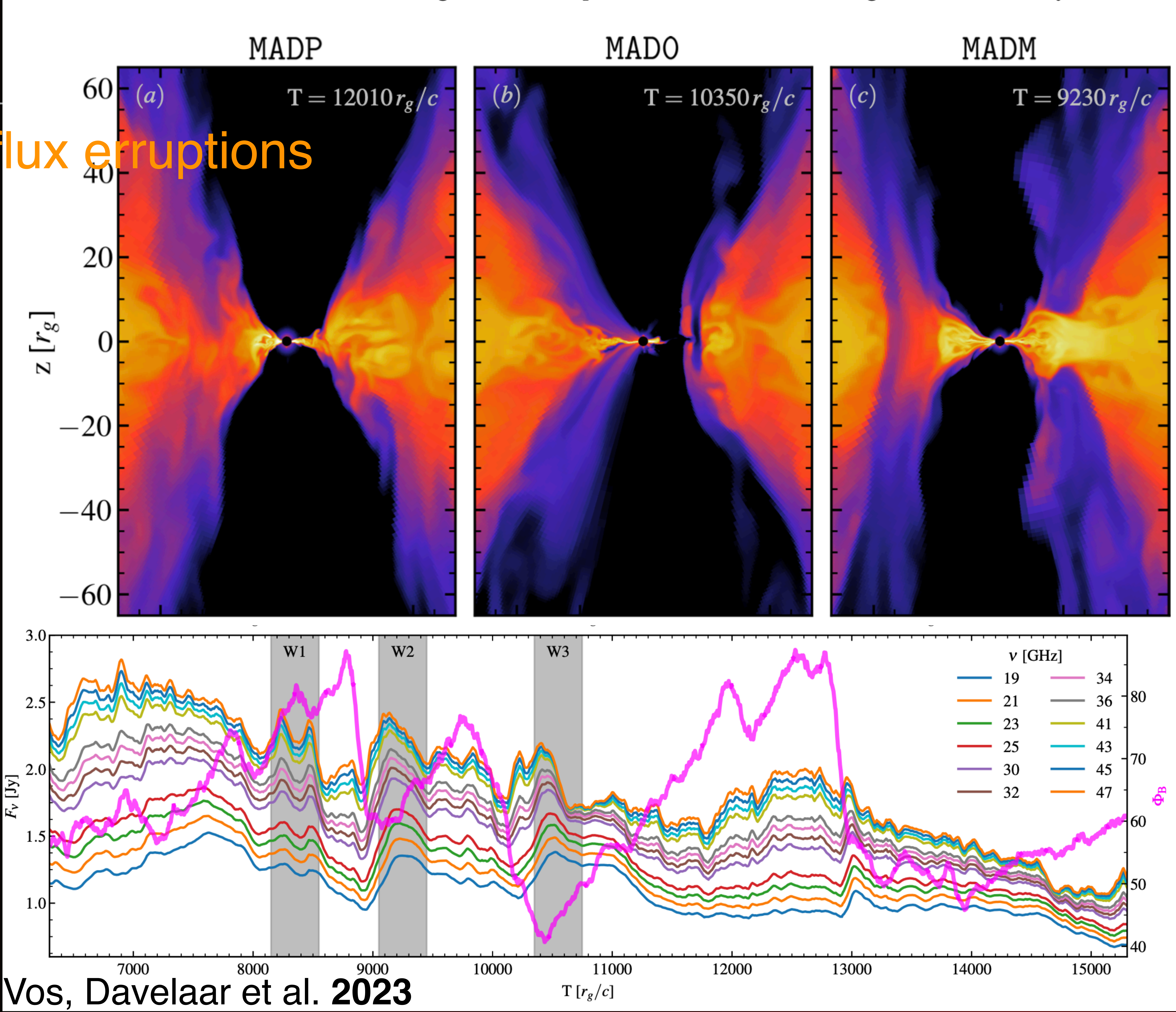
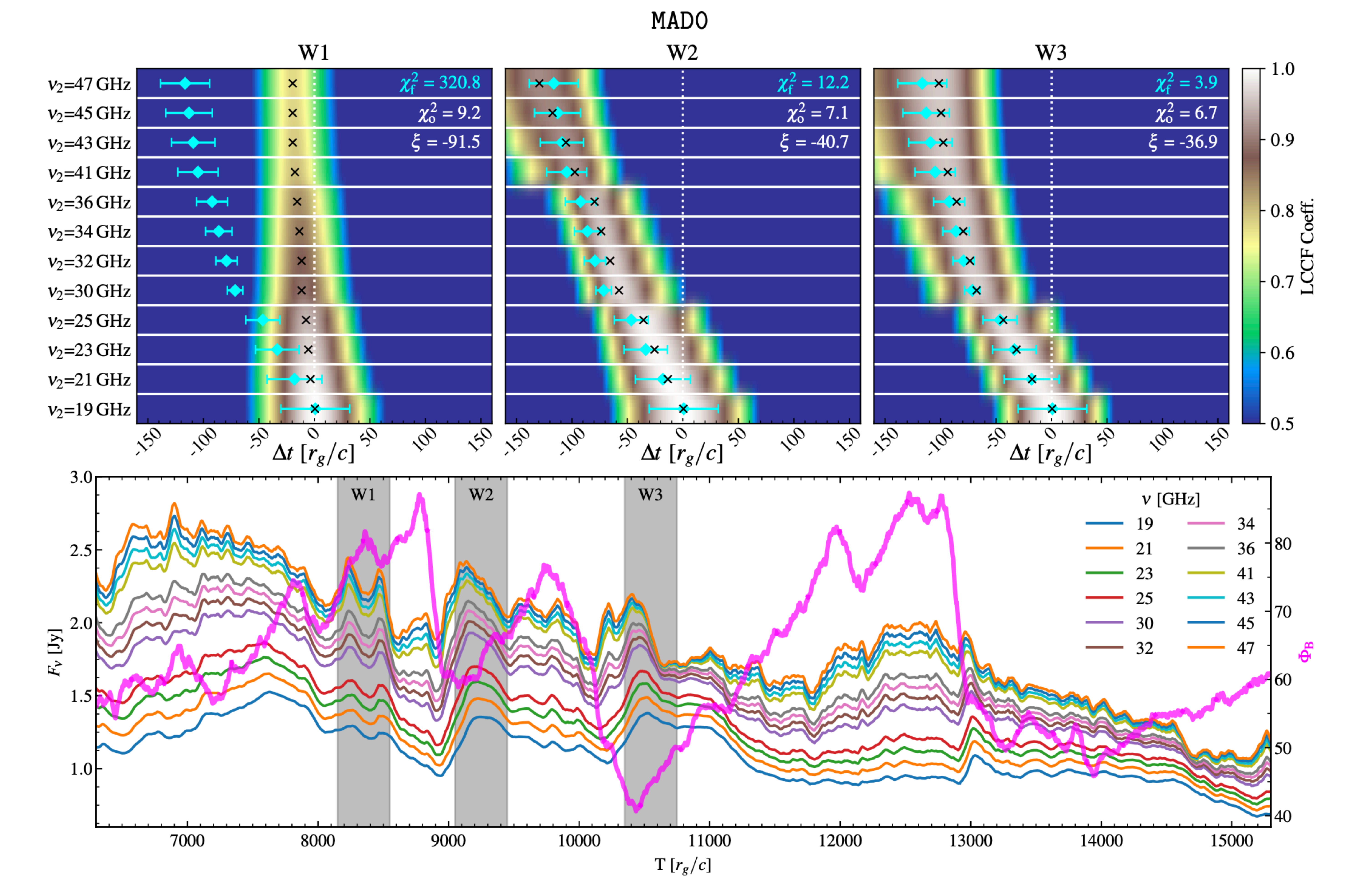


Vos, Davelaar et al. **2023**

Time-lags by magnetic flux erruptions

Moving window cross correlation with the19 GHz as baseline frequency

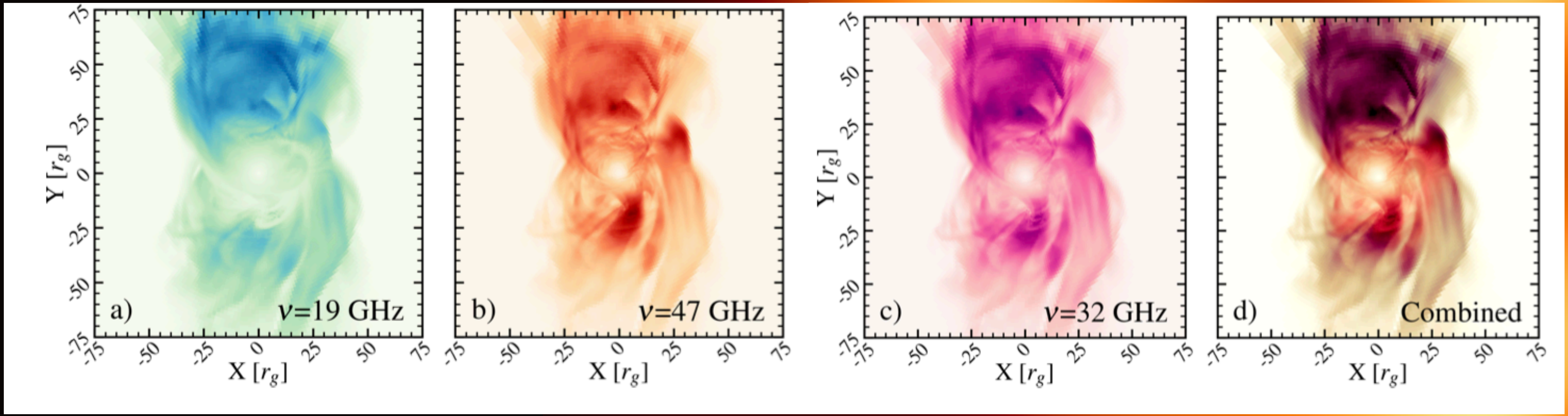
Flares and shifts are seen in the light curve that find similar slopes as the trends found by Brinkerink et al. 2015



Vos, Davelaar et al. **2023**

Its a MAD, MAD, MAD world

Composite images to understand how different frequency get brighter during the flare



Vos, Davelaar et al. **2023**

Its a MAD, MAD, MAD world

Vos, Davelaar et al. **2023**

Summary

- Sagittarius A* shows X-ray/NIR/mm/radio flares
- Interpretation of EHT observations suggests the flow is best describe as a MAD accretion flow
- Magnetic flux erruptions could potentially drive the mm/radio flares
- Flux erruptions also drive wave along the wind-jet shear layer