Connecting the branches to the roots: confronting long-standing questions about jet physics in the global VLBI/EHT era

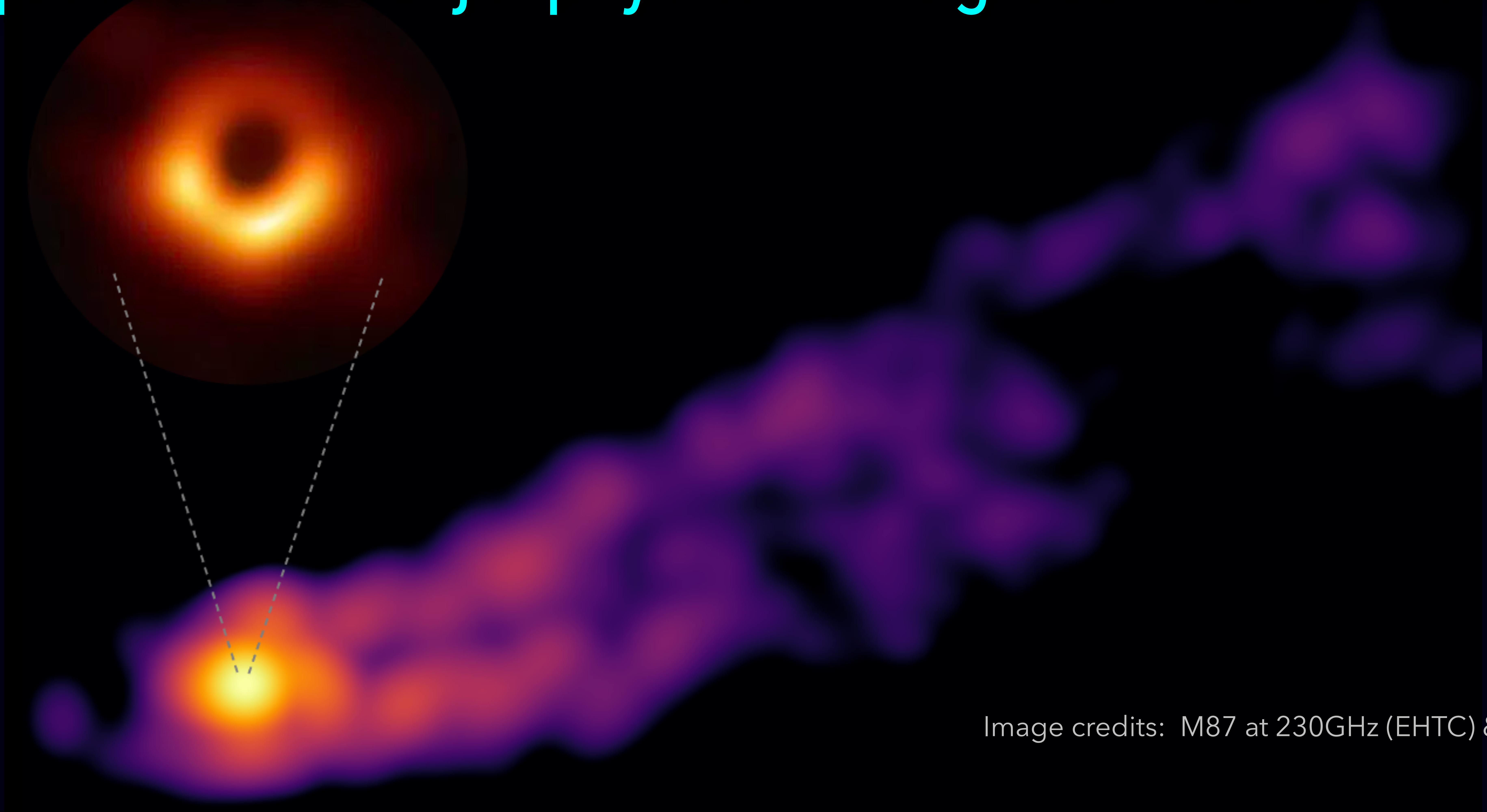

Image credits: M87 at 230GHz (EHTC) & 43 GHz (EAVN)

Sera Markoff (U Amsterdam) + EHTC & EHT MWL WG + ngEHT + CTAC + several current/former members of the 'jetsetters' group @ U Amsterdam (K. Chatterjee, R. Connors, D. v. Eijnatten, C. Hesp, M. Liska, M. Lucchini, W. Mulaudzi, G. Musoke, R. Plotkin, L. Sosapanta Salas, D.-S. Yoon) + J. Davelaar, S. Phillipov, B. Ripperda, S. Tchekhovskoy, Z. Younsi

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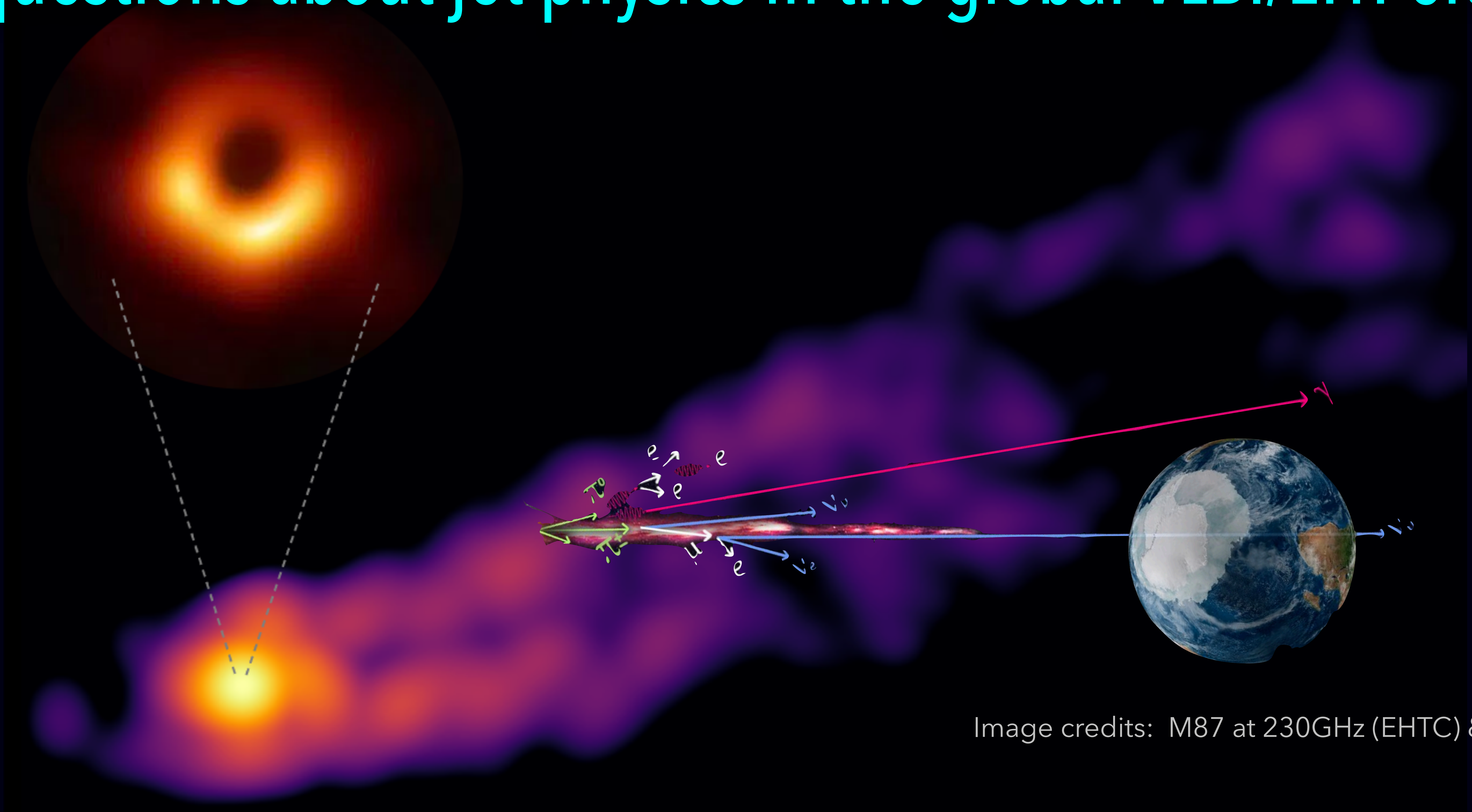

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(Cygnus A galaxy, combined LOFAR radio (red/orange) + Chandra Observatory X-ray image (blue); Wise & McKean)

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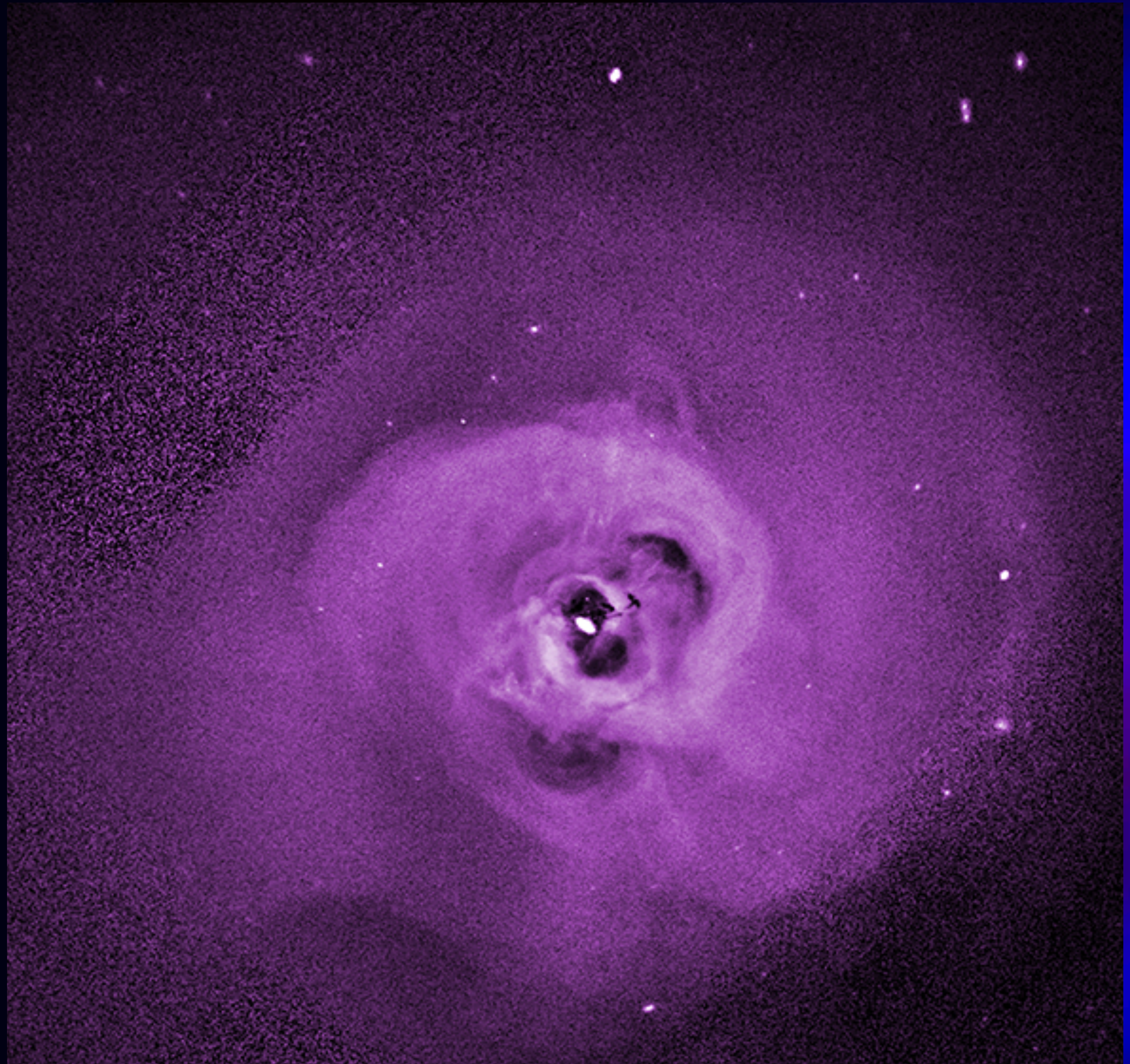
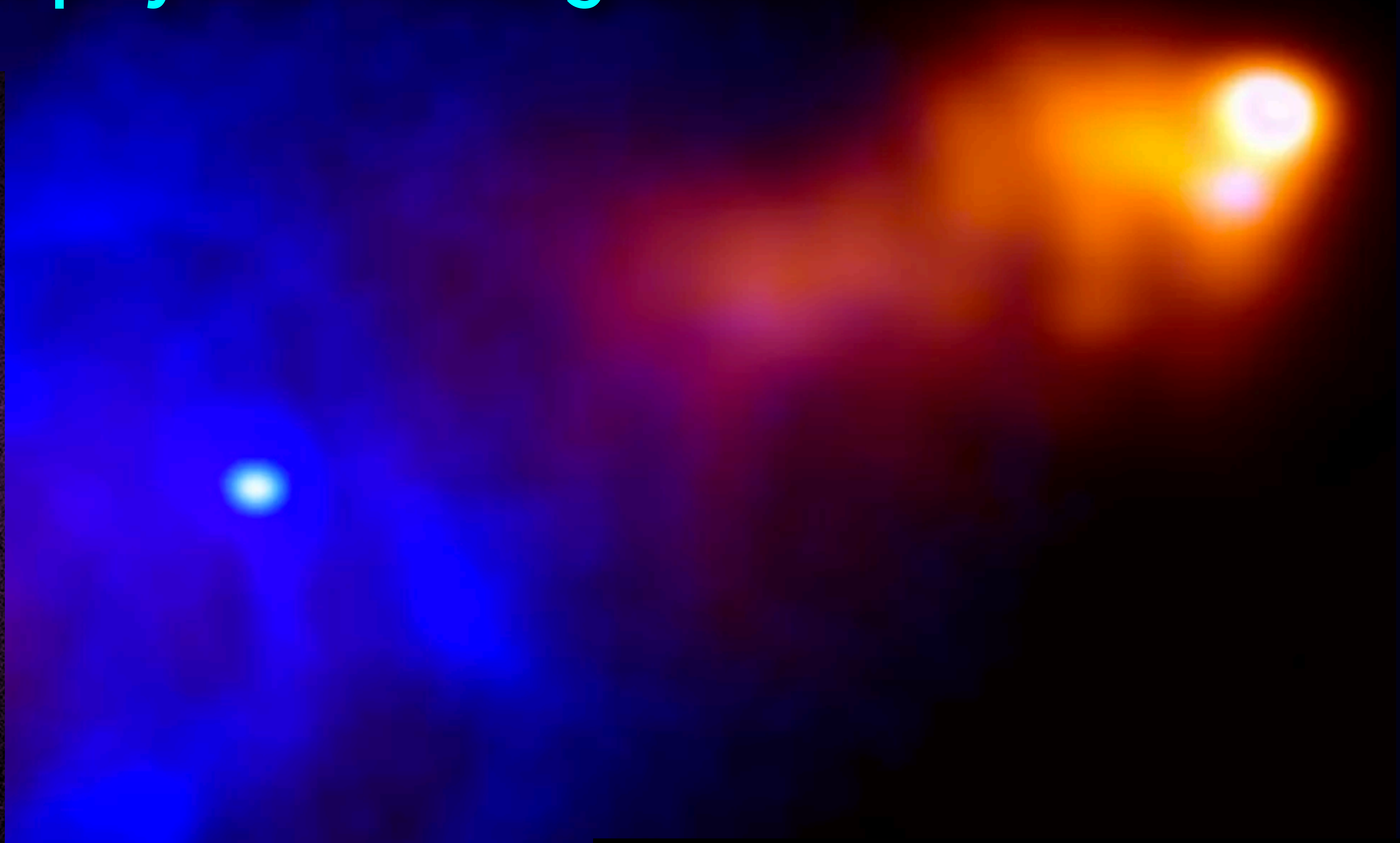


(Perseus Cluster; Fabian++ 2005)



(Cygnus A galaxy, combined LOFAR radio (red/orange) + Chandra Observatory X-ray image (blue); Wise & McKean)

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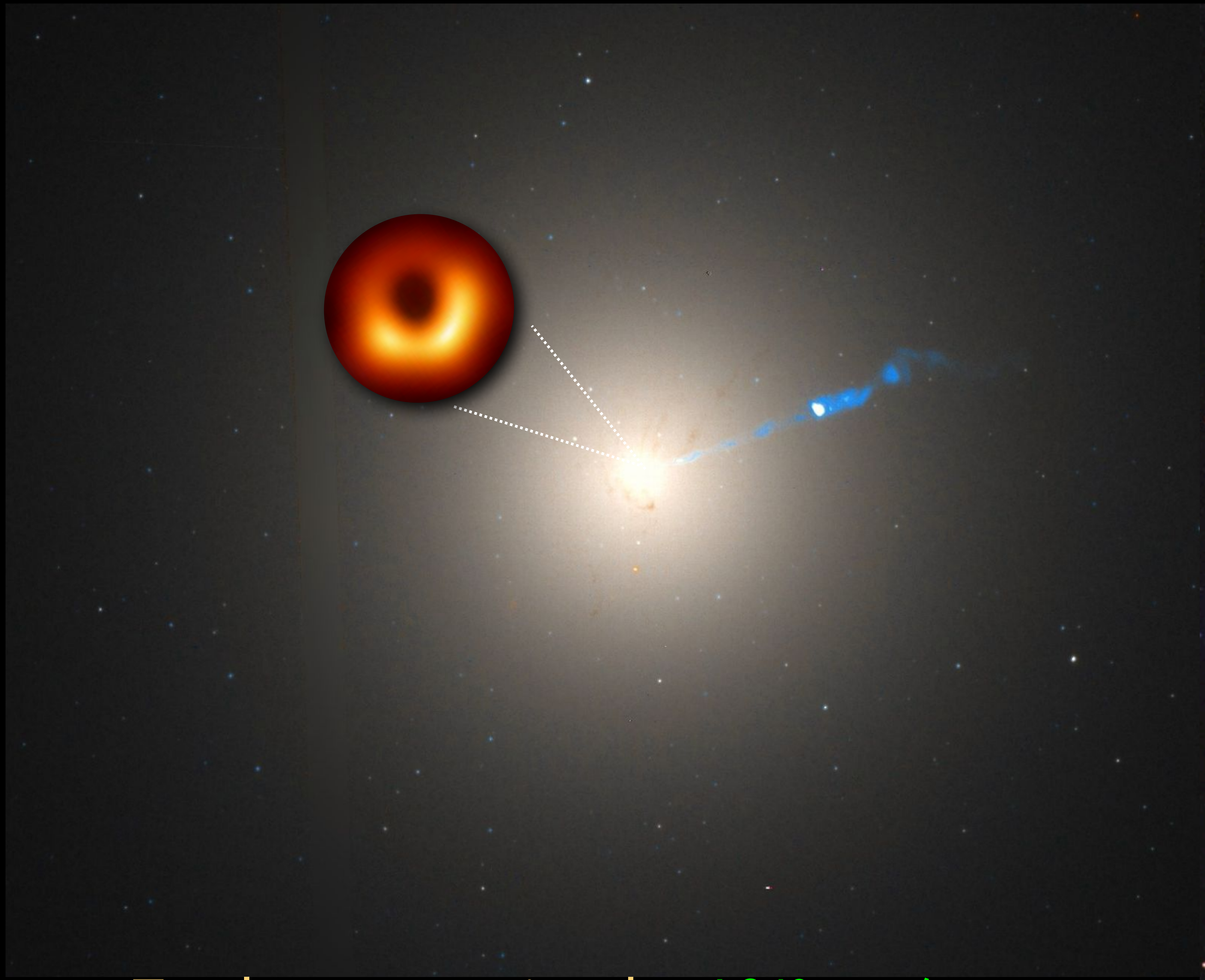
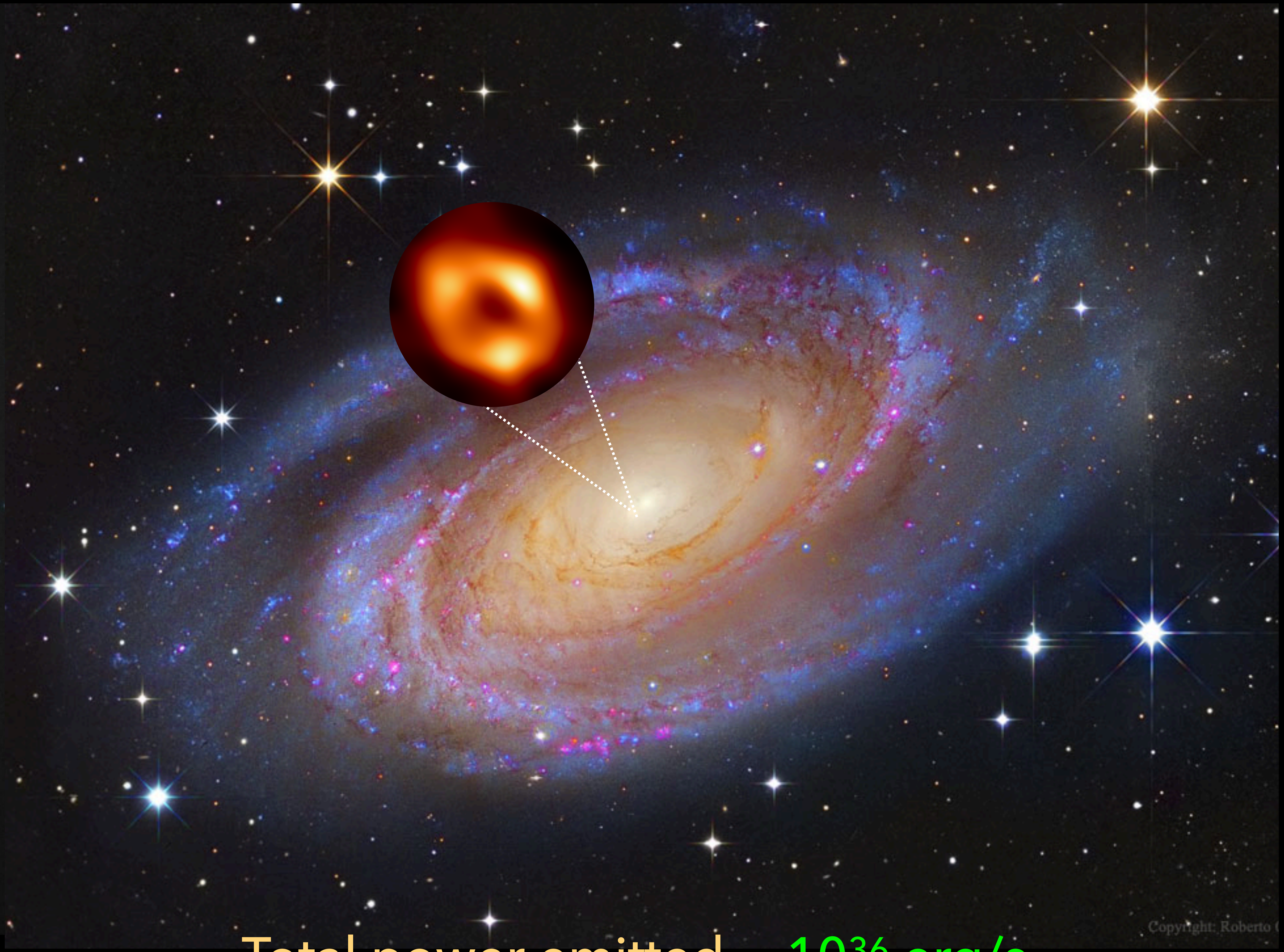
The EHT "horizon" sources embody two different BH/jet states

M87: Elliptical Galaxy, in a weakly active state (LLAGN; e.g. Ho 2008), launches a huge jet



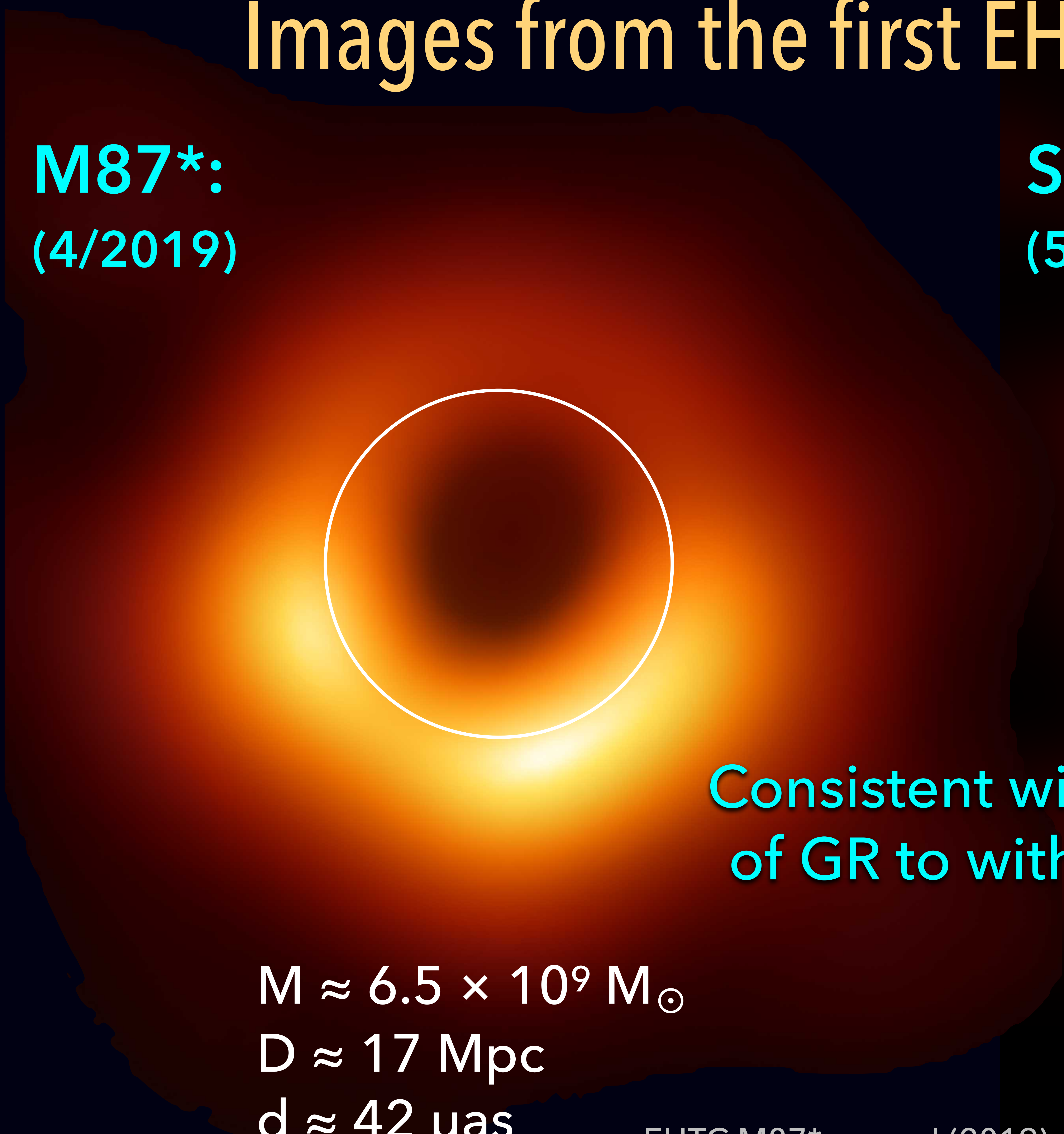
Total power emitted ~ 10^{42} erg/s

M81 (as proxy for Milky Way): Spiral Galaxy, Sgr A* is quiescent, has no (obvious) jet



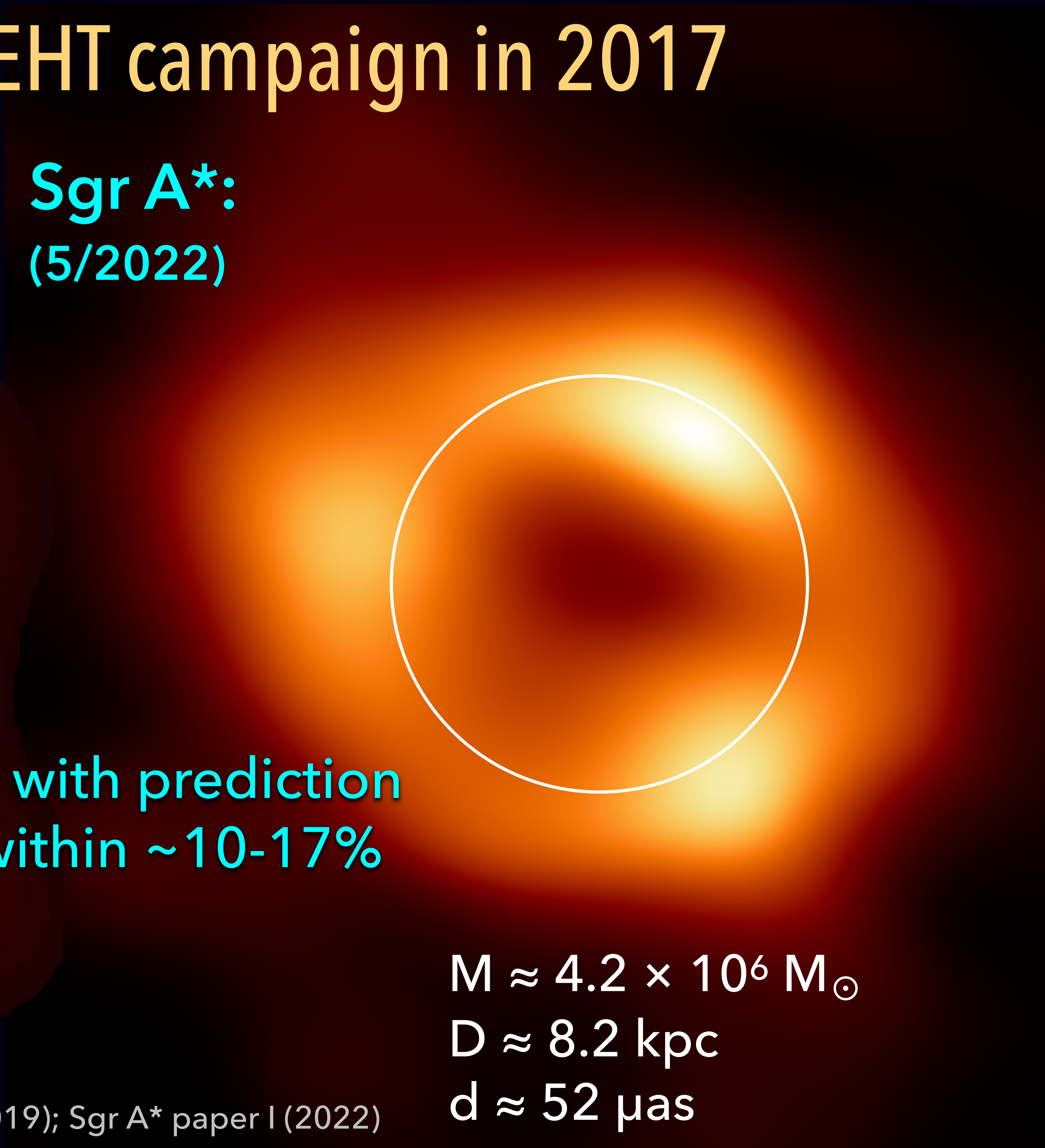
Total power emitted ~ 10^{36} erg/s

Images from the first EHT campaign in 2017



M87*:
(4/2019)

$M \approx 6.5 \times 10^9 M_\odot$
$D \approx 17$ Mpc
$d \approx 42$ μas



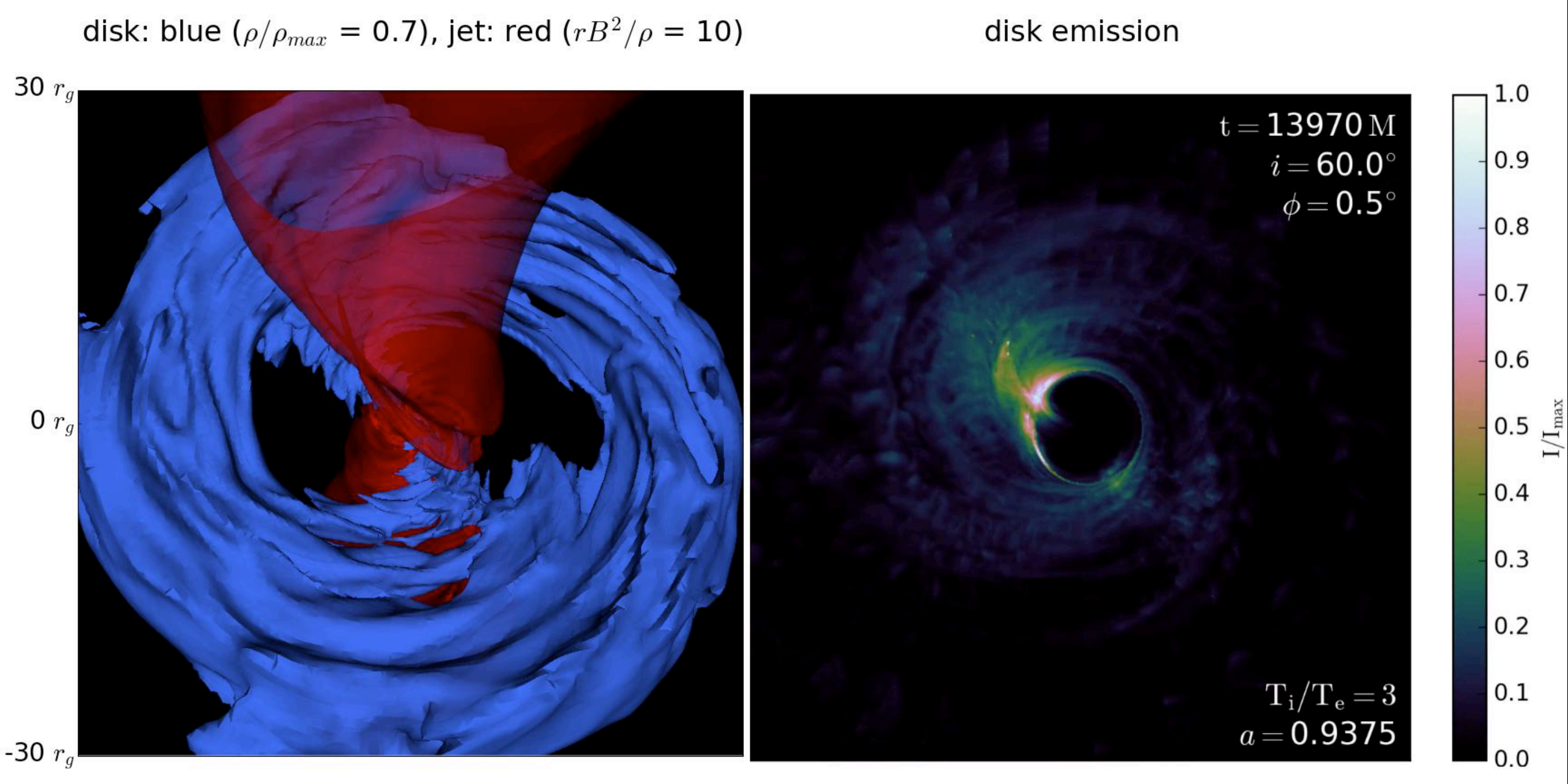
Sgr A*:
(5/2022)

$M \approx 4.2 \times 10^6 M_\odot$
$D \approx 8.2$ kpc
$d \approx 52$ μas

Consistent with prediction of GR to within ~10-17%

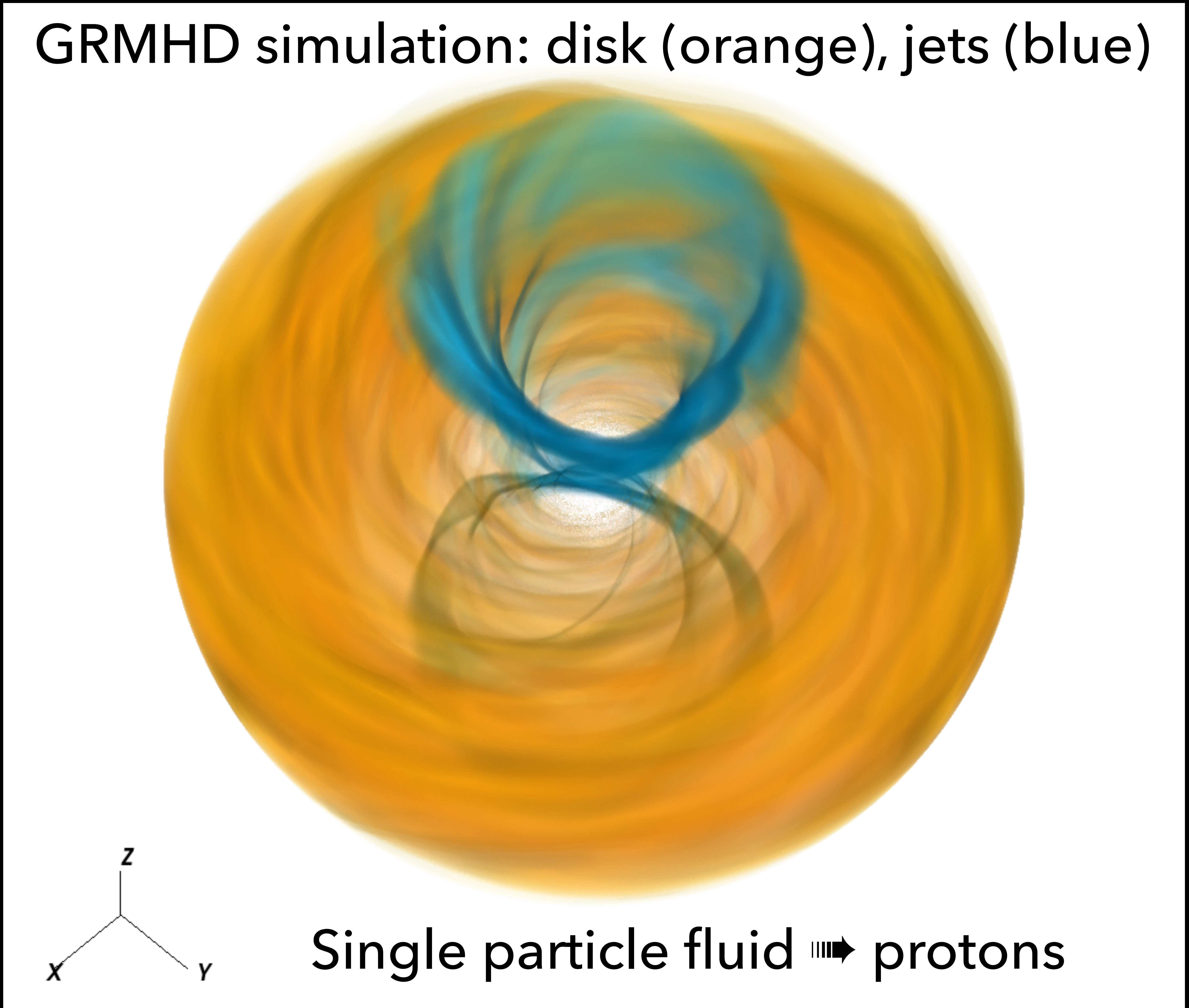
EHTC M87* paper I (2019); Sgr A* paper I (2022)

GRMHD simulations + GR ray-tracing ➠ synthetic EHT images



(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis, SM++ 2018; Chatterjee, Younsi, Liska, Tchekhovskoy, SM 2020, using H-AMR, Liska++22)

Model degeneracy introduced via particle "subgrid" models



Assume 100% H (n_e=n_p), thermal distributions

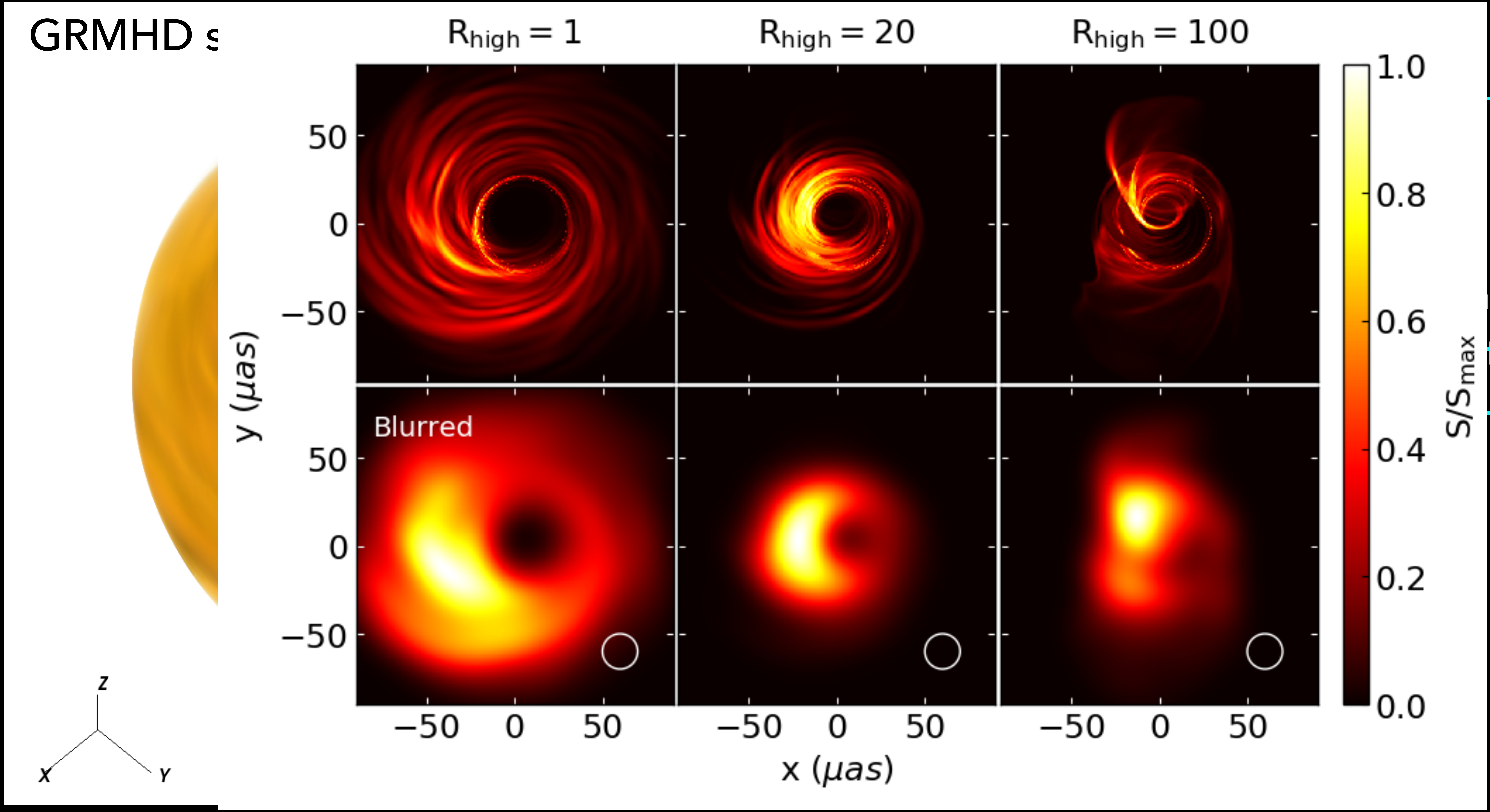
Heat electrons, example: from EHT/ Moscibrodzka++2016 (motivated by Alfvénic turbulent heating, eg. Howes 2010; Kawazura++2018)

$$T_p/T_e = \frac{R_{\rm low} + R_{\rm high}\beta^2}{1+\beta^2}$$

Where $\beta = P_{gas}/P_{mag}$

Visualisations by DooSoo Yoon w/H-AMR & GRRT/BHOSS (Younsi++2016; 2020) and see EHT Collaboration 2019 Papers I-VI

Model degeneracy introduced via particle "subgrid" models



thermal

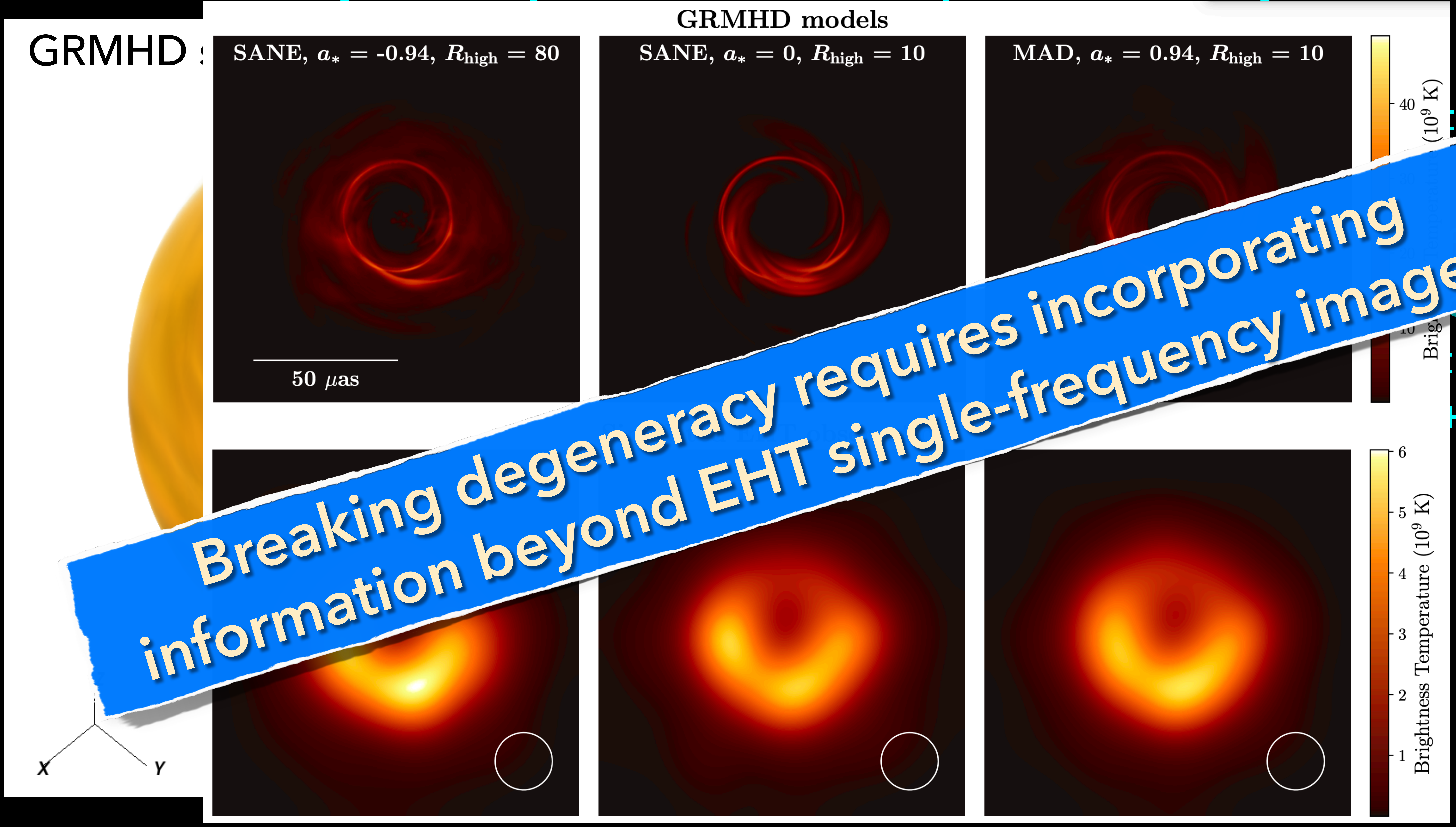
from EHT/
otivated
ting, eg.
+2018)

Visualisations by DooSoo Yoon w/H-AMR & GRRT/BHOSS (Younsi++2016; 2020) and see EHT Collaboration 2019 Papers I-VI

Model degeneracy introduced via particle "subgrid" models

Visualisations by DooSoo Yoon w/H-AMR & GRRT/BHOSS (Younsi++2016; 2020) and see EHT Collaboration 2019 Papers I-VI

Model degeneracy introduced via particle "subgrid" models



Breaking degeneracy requires incorporating information beyond EHT single-frequency images

thermal
EHT/
otivated
ing, eg.
+2018)

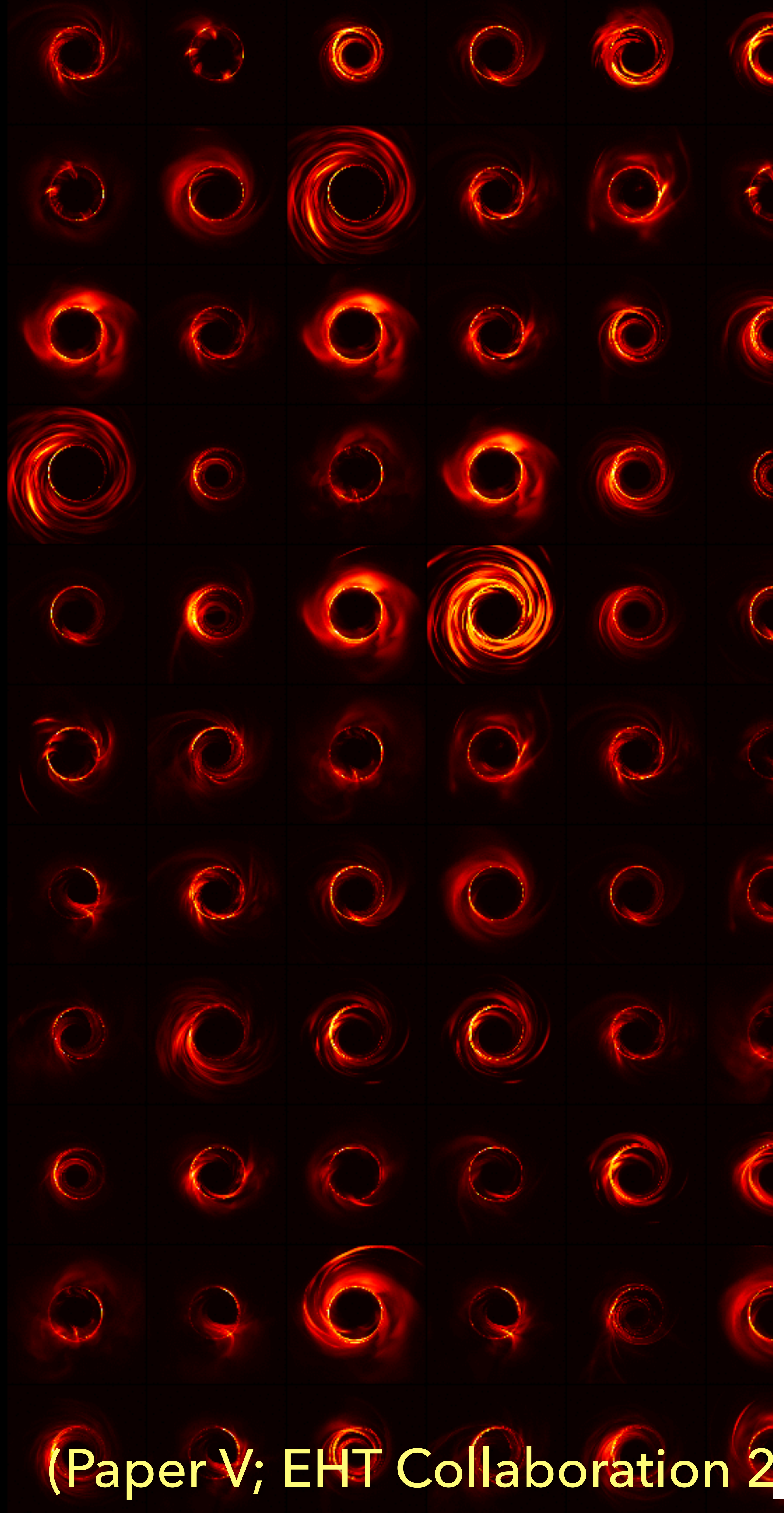
Visualisations by DooSoo Yoon w/H-AMR & GRRT/BHOSS (Younsi++2016; 2020) and see EHT Collaboration 2019 Papers I-VI

EHT's M87* Simulation Library: ~10x5 models, 23 TB, 60k snapshot images

Event Horizon Telescope

(Paper V; EHT Collaboration 2019. Slide credit: A. Broderick)

EHT's M87* Simul … k snapshot images



(EHT Paper V pass/fail table)

Table 2. Rejection Table

flux[1]	a_*[2]	$R_{\rm high}$[3]	AIS[4]	ϵ[5]	L_X[6]	$P_{\rm jet}$[7]	
SANE	-0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	-0.94	10	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	20	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	40	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	-0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	-0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	+0.94	160	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.94	1	Fail	Fail	Pass	Pass	Fail
MAD	-0.94	10	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	20	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	40	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	80	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	160	Fail	Pass	Pass	Pass	Fail
MAD	-0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	-0.5	10	Pass	Pass	Pass	Fail	Fail
MAD	-0.5	20	Pass	Pass	Pass	Pass	**Pass**

Table 2 *(continued)*

flux[1]	a_*[2]	$R_{\rm high}$[3]	AIS[4]	ϵ[5]	L_X[6]	$P_{\rm jet}$[7]	
MAD	-0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	160	Pass	Pass	Pass	Pass	**Pass**

[1] flux: net magnetic flux on the black hole (MAD, SANE).

[2] a_*: dimensionless black hole spin.

[3] $R_{\rm high}$: electron temperature parameter, see equation (8).

[4] Average Image Scoring (THEMIS-AIS), models are rejected if $p \leq 0.01$, see Section 4 and Table 1.

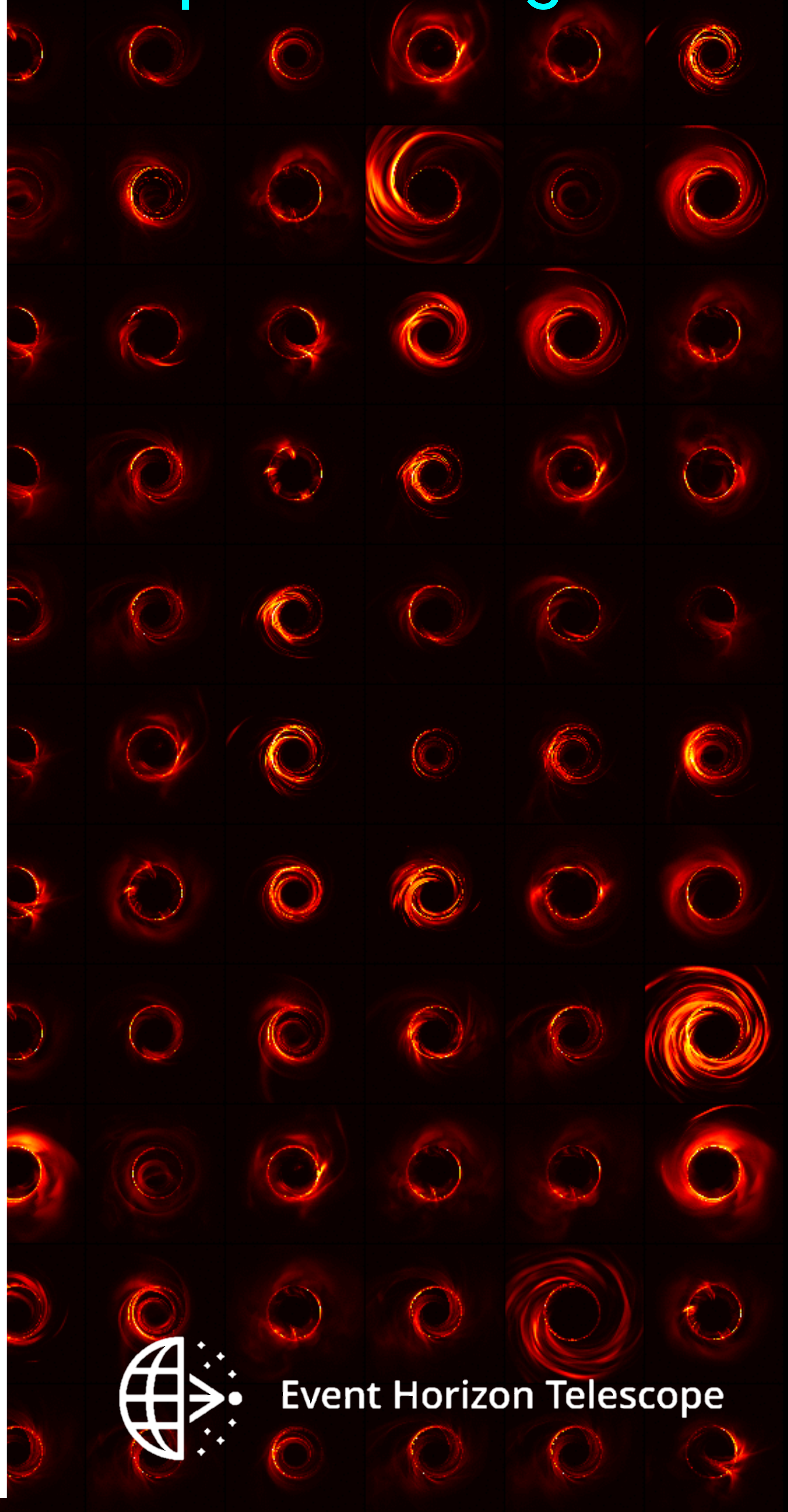
[5] ϵ: radiative efficiency, models are rejected if ϵ is larger than the corresponding thin disk efficiency, see Section 6.1.

[6] L_X: X-ray luminosity; models are rejected if $\langle L_X \rangle 10^{-2\sigma} > 4.4 \times 10^{40}$ erg sec^{-1}. See Section 6.2.

[7] $P_{\rm jet}$: jet power, models are rejected if $P_{\rm jet} \leq 10^{42}$ erg sec^{-1}, see Section 6.3.

7. DISCUSSION

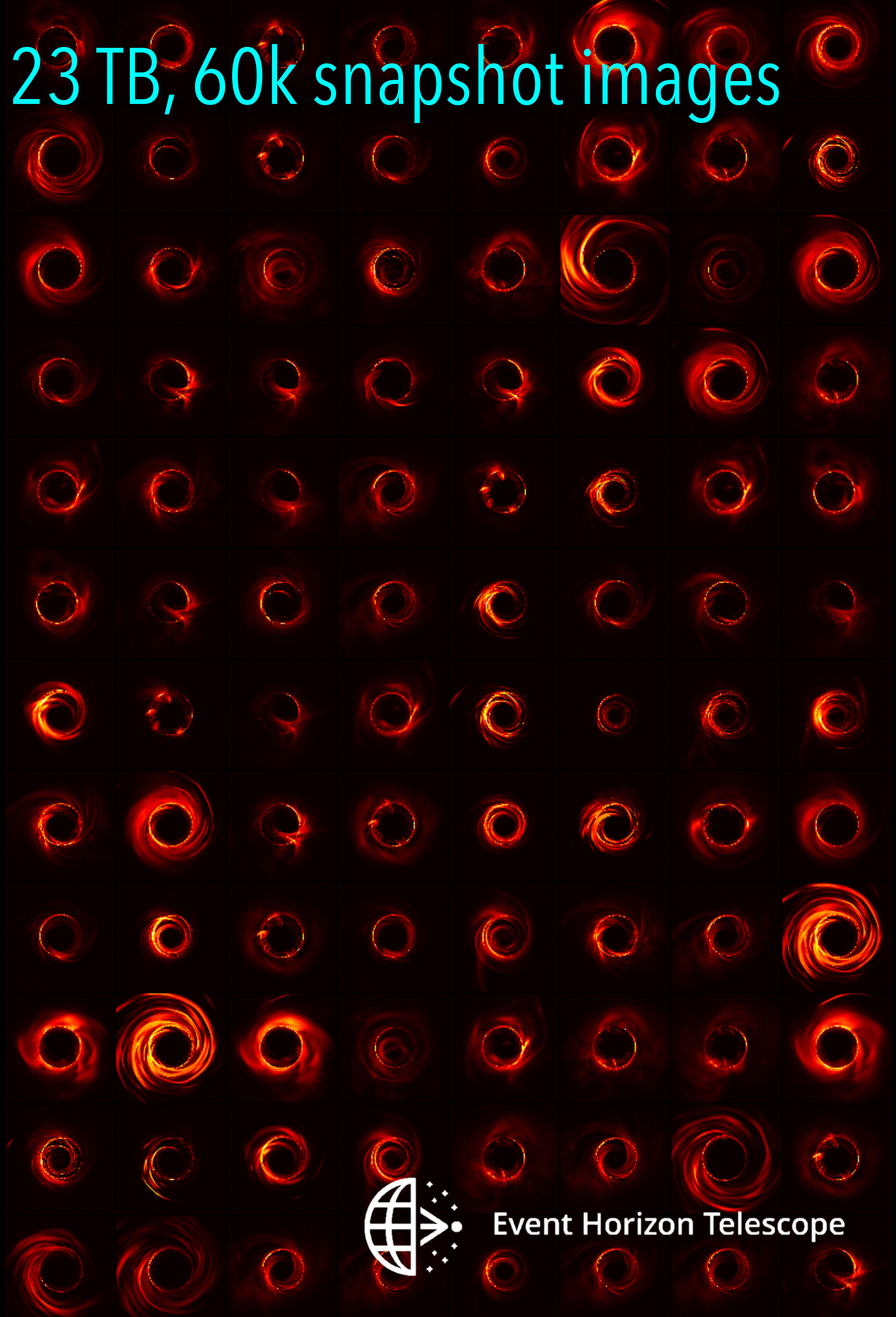
We have interpreted the EHT2017 data using a limited library of models with attendant limitations. Many of the limitations stem from the GRMHD model, which treats the plasma as an ideal fluid governed by equations that encode conservation laws for particle number, momentum, and energy. The eDF, in particular, is de-



Event Horizon Telescope

(Paper V; EHT Collaboration 2

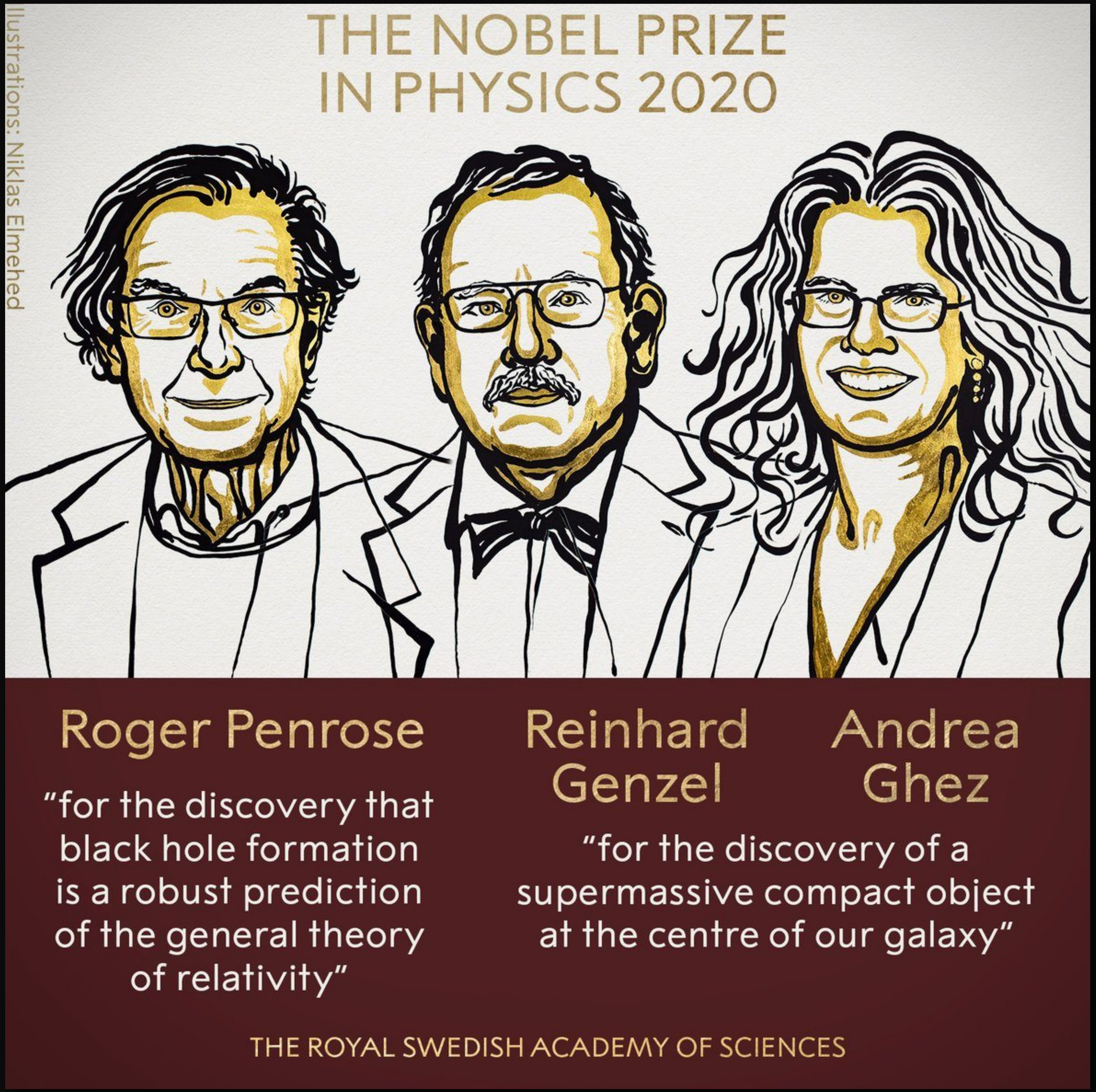
EHT's M87* Simulation Library: ~10x5 models, 23 TB, 60k snapshot images

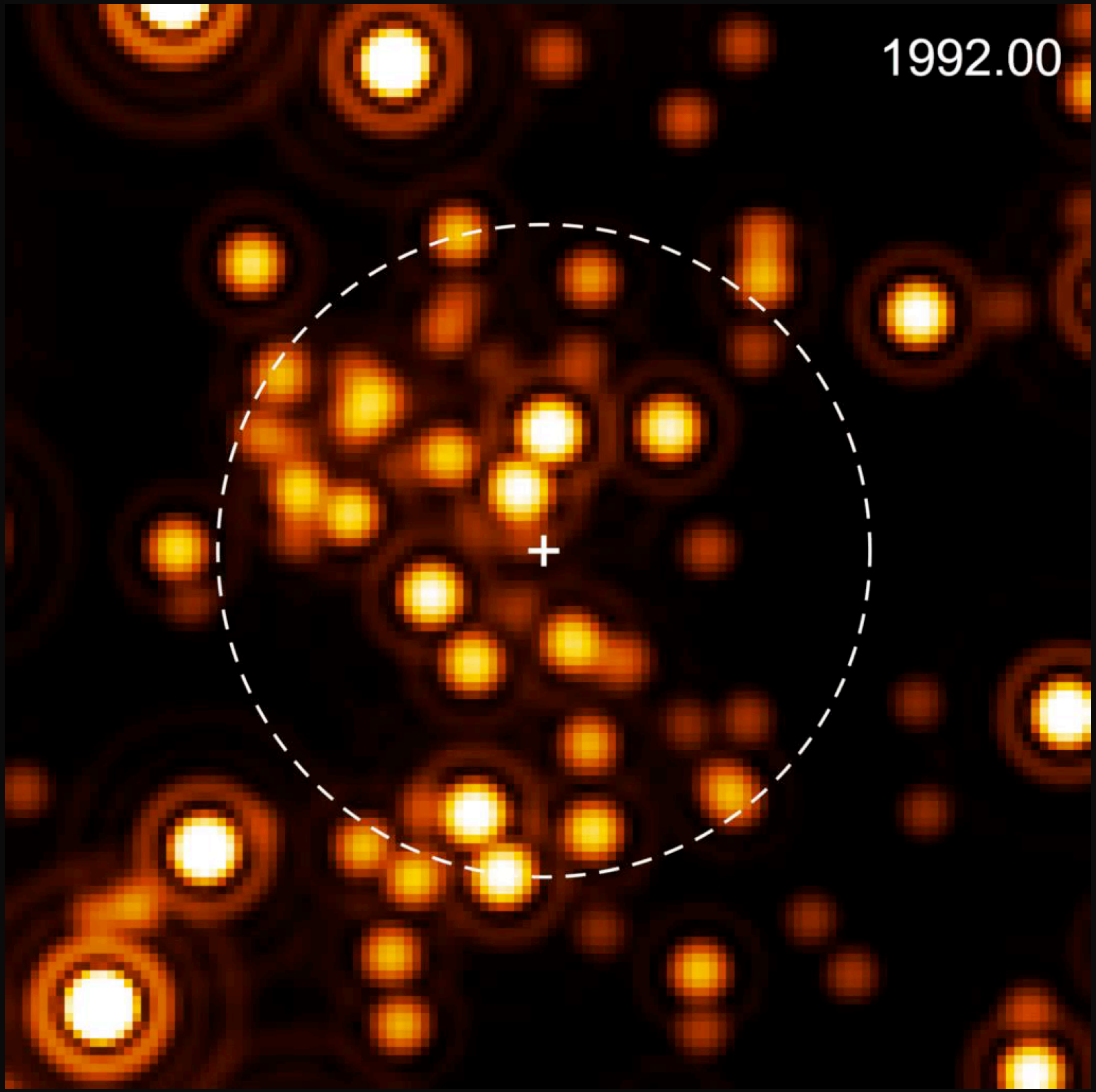


- Size/shape of shadow is consistent with predictions of GR to ~17%
- Brightness asymmetry due to Doppler
- Polarisation (EHTC 2021) prefers "MAD": dynamically strong, ordered, poloidal B fields ➠ ideal for launching jets!
- Cannot yet connect the EHT image of M87* to its jets, or constrain particle acceleration regions/mechanisms

(Paper V; EHT Collaboration 2019. Slide credit: A. Broderick)

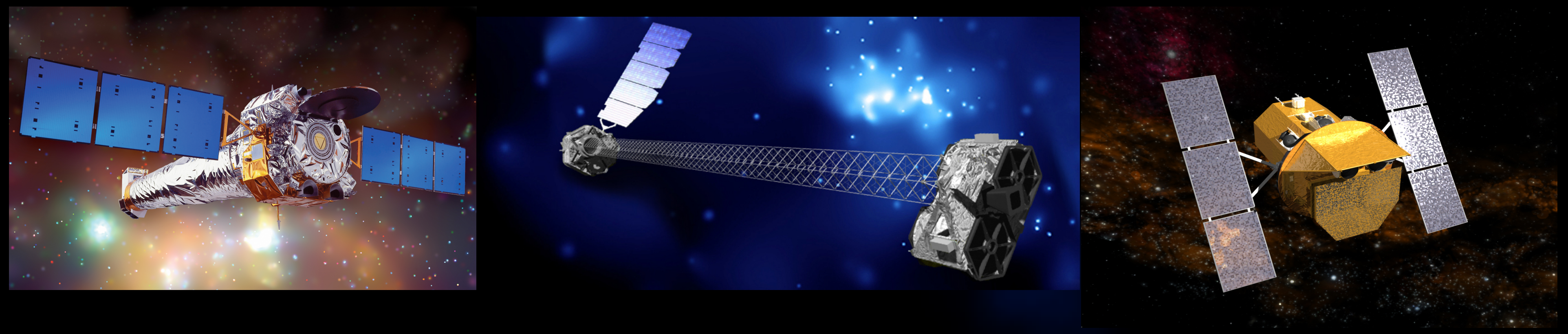
Sgr A*: more difficult to analyse but better priors

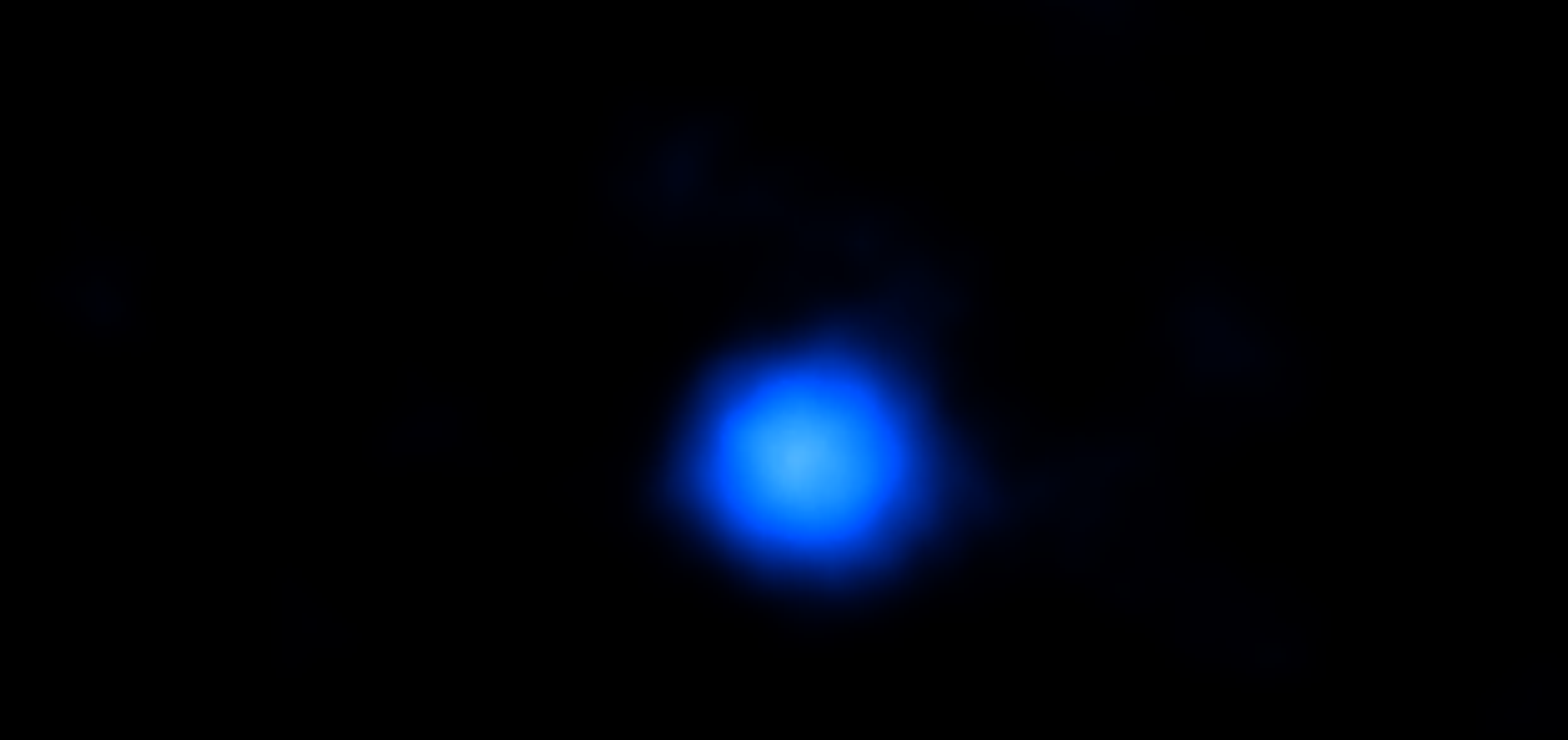




Sgr A* gives us a direct view of coronal-like activity

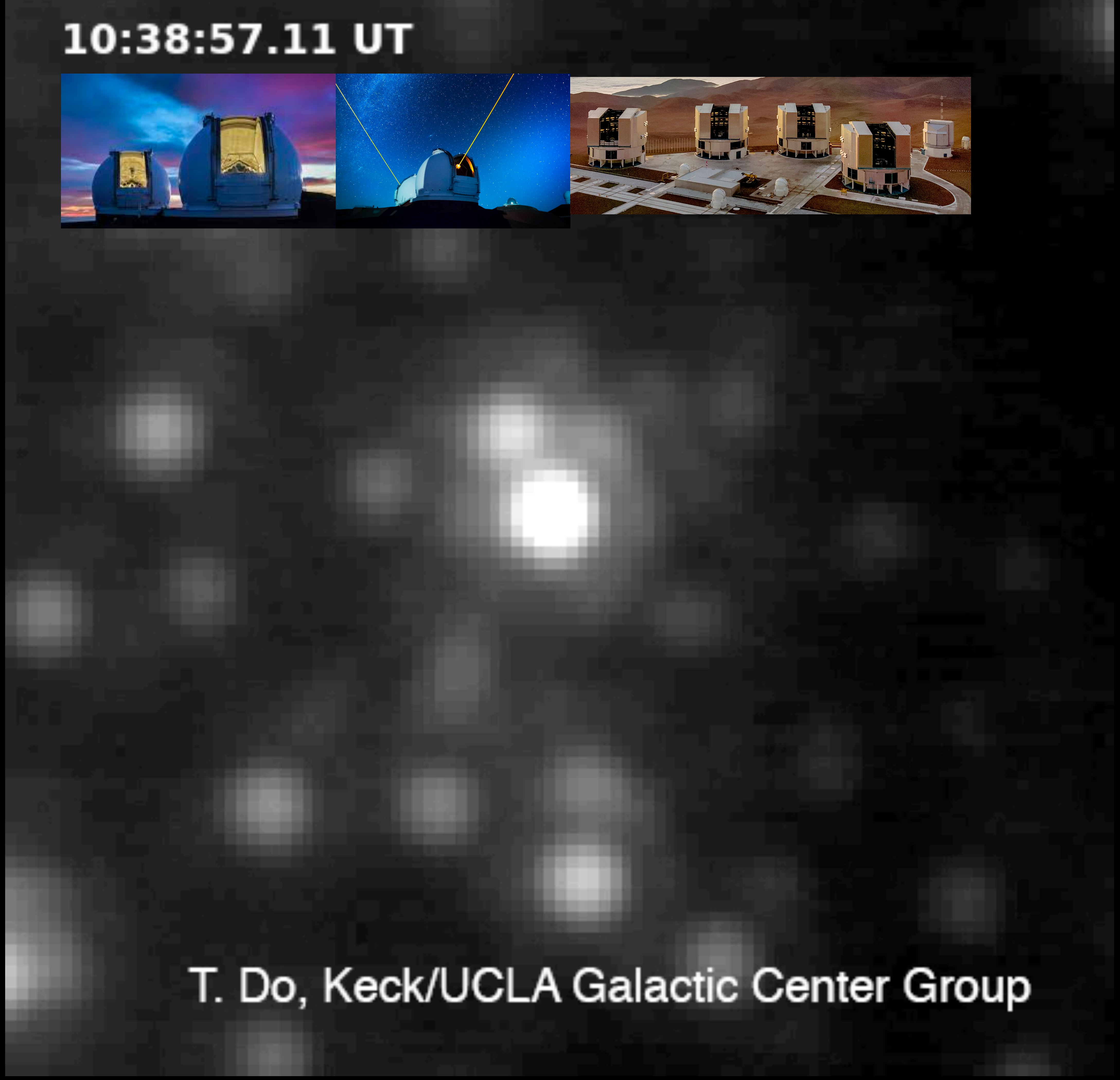
X-ray flare from NASA's Chandra X-ray Observatory, + NuSTAR & Swift (space)





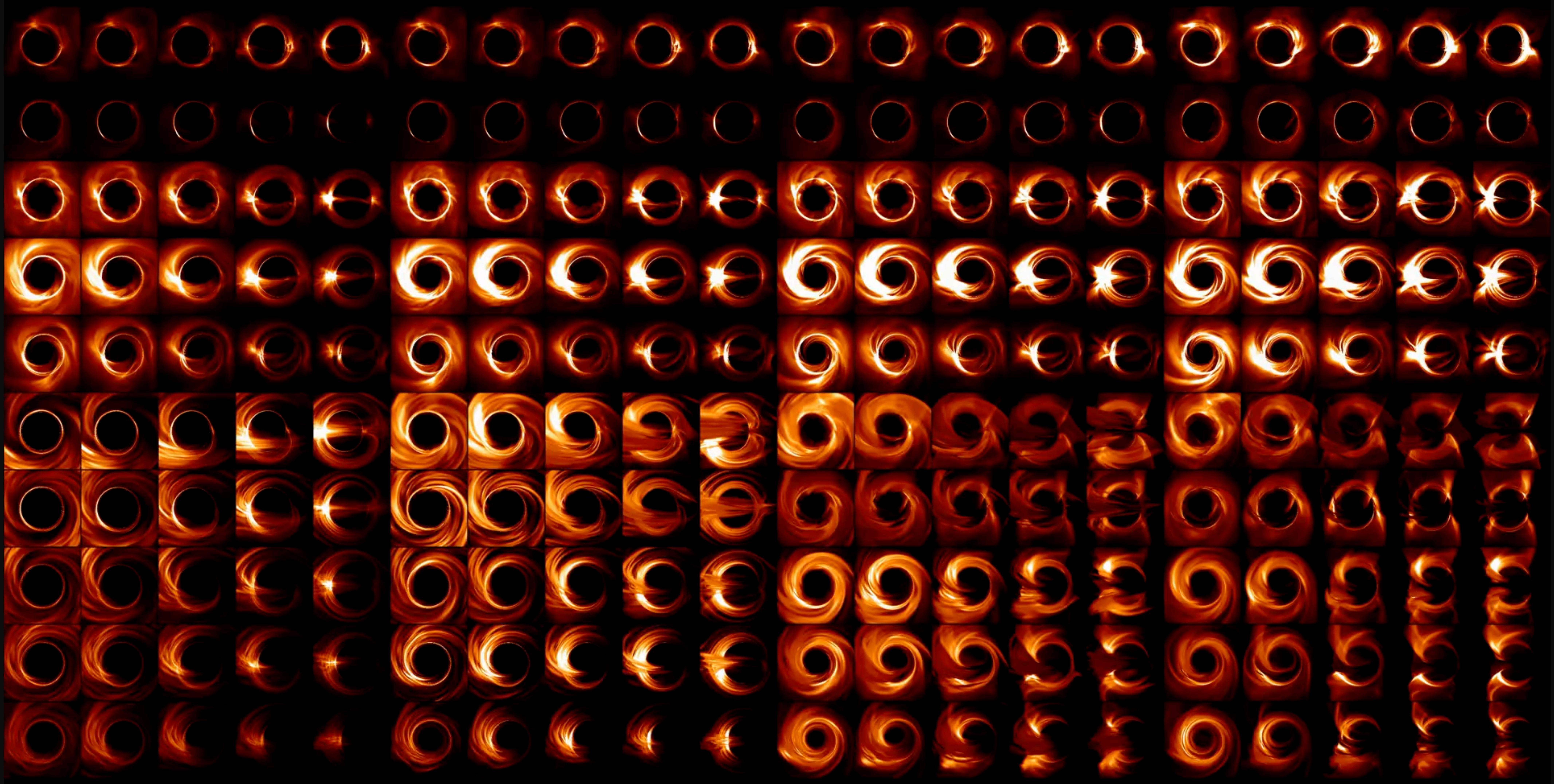
Credit: NASA/CXC/Amherst College/D.Haggard et al.

Infrared flare from the Keck Observatory + VLT/GRAVITY (ground)



Sgr A*: Over 200 models, 1.8 Million images, ~PByte of data!

11 Constraints of 3 types : EHT images + Multi-wavelength + Variability



Visualization credit: Ben Prather, University of Illinois at Urbana-Champaign.
Image library credit: EHT Theory Working Group, CK Chan. EHTC Sgr A* Paper I, Paper V (2022)

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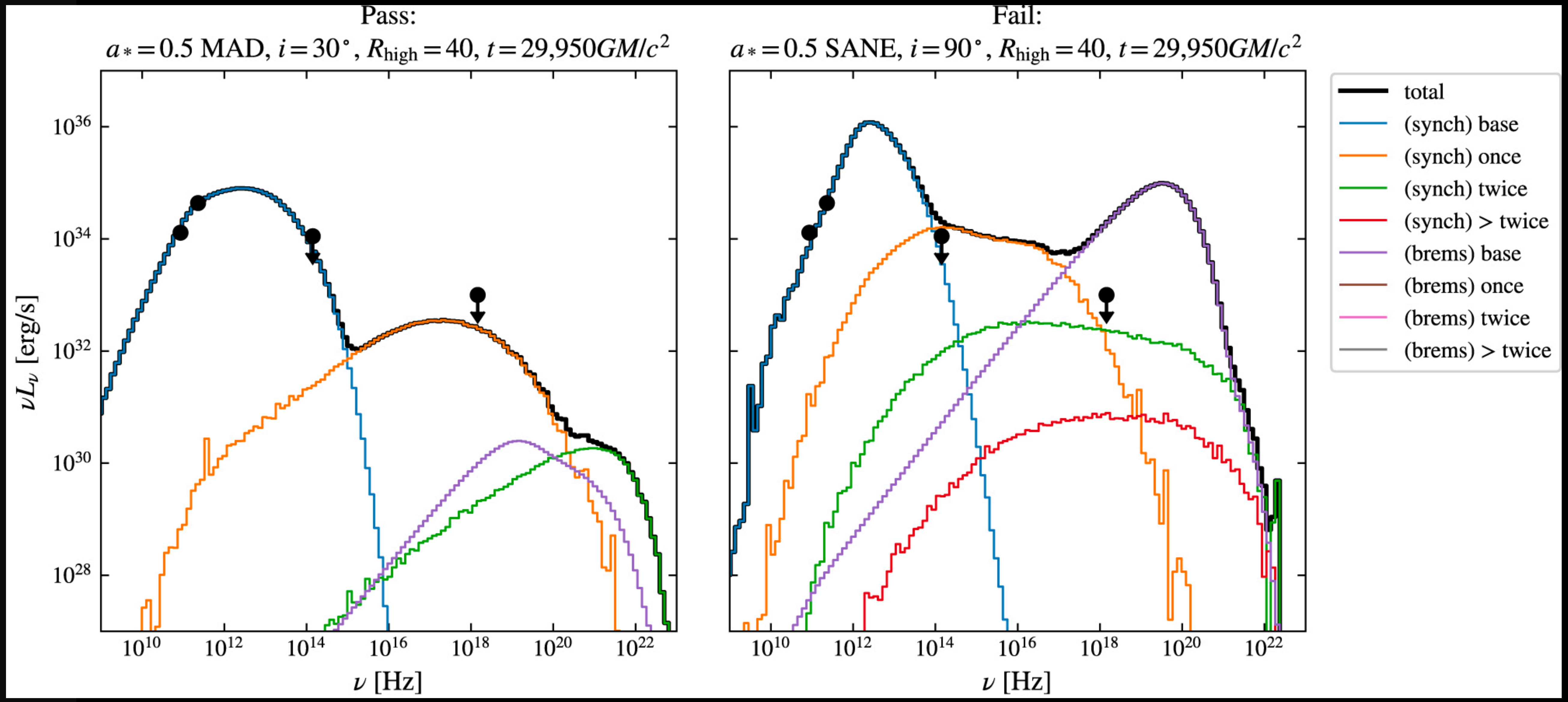

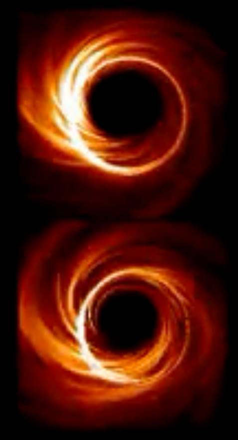

Visualization credit: Ben Prather, University of Illinois at Urbana-Champaign.
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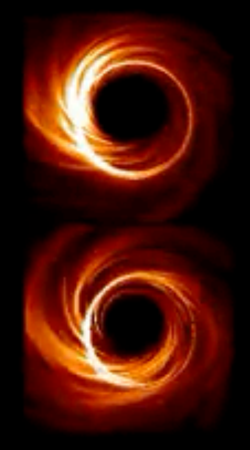
Sgr A*: Over 200 models, 1.8 Million images, ~PByte of data!

11 Constraints of 3 types : EHT images + Multi-wavelength + Variability

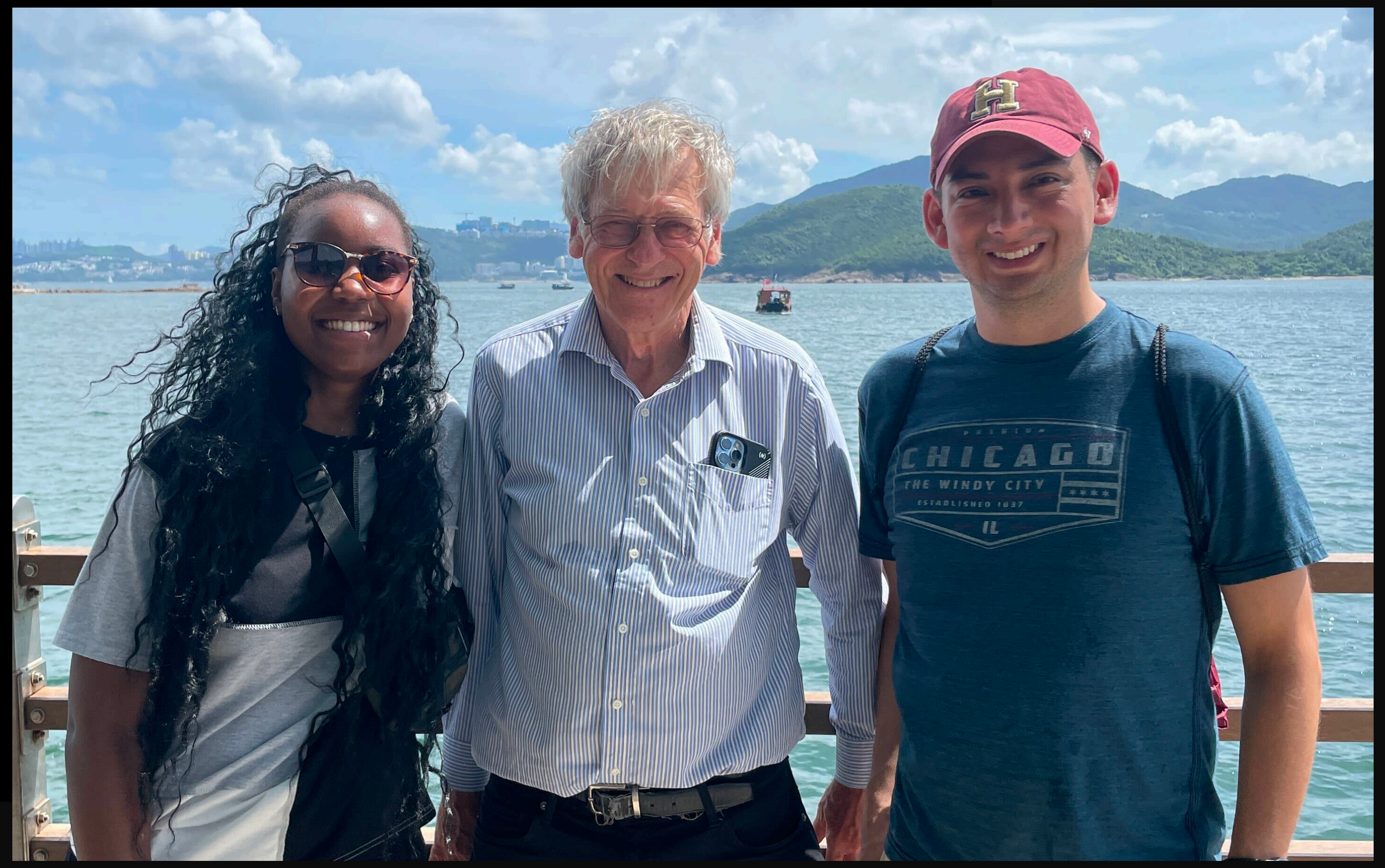
- "Best bet models": favour prograde spin (a~0.5-9.4), lower inclination (≤ 30°), weak coupling between electrons and ions, very strong magnetic fields ("MAD")
- M87* and Sgr A* seem remarkably (puzzlingly) similar ➠ why doesn't Sgr A* show similar jets??
- Key difference may be in the mechanism/location for particle acceleration that lights up jets



▸ Theoretical progress now hinges on figuring out:

I. Does Sgr A* actually have a jet??

II. Interpretation of Sgr A*'s and M87*'s *spectrum* and variability*† *[*Wanga Mulaudzi's (NT particles/MWL) & †León S. Salas' (2T + cooling) talks]*

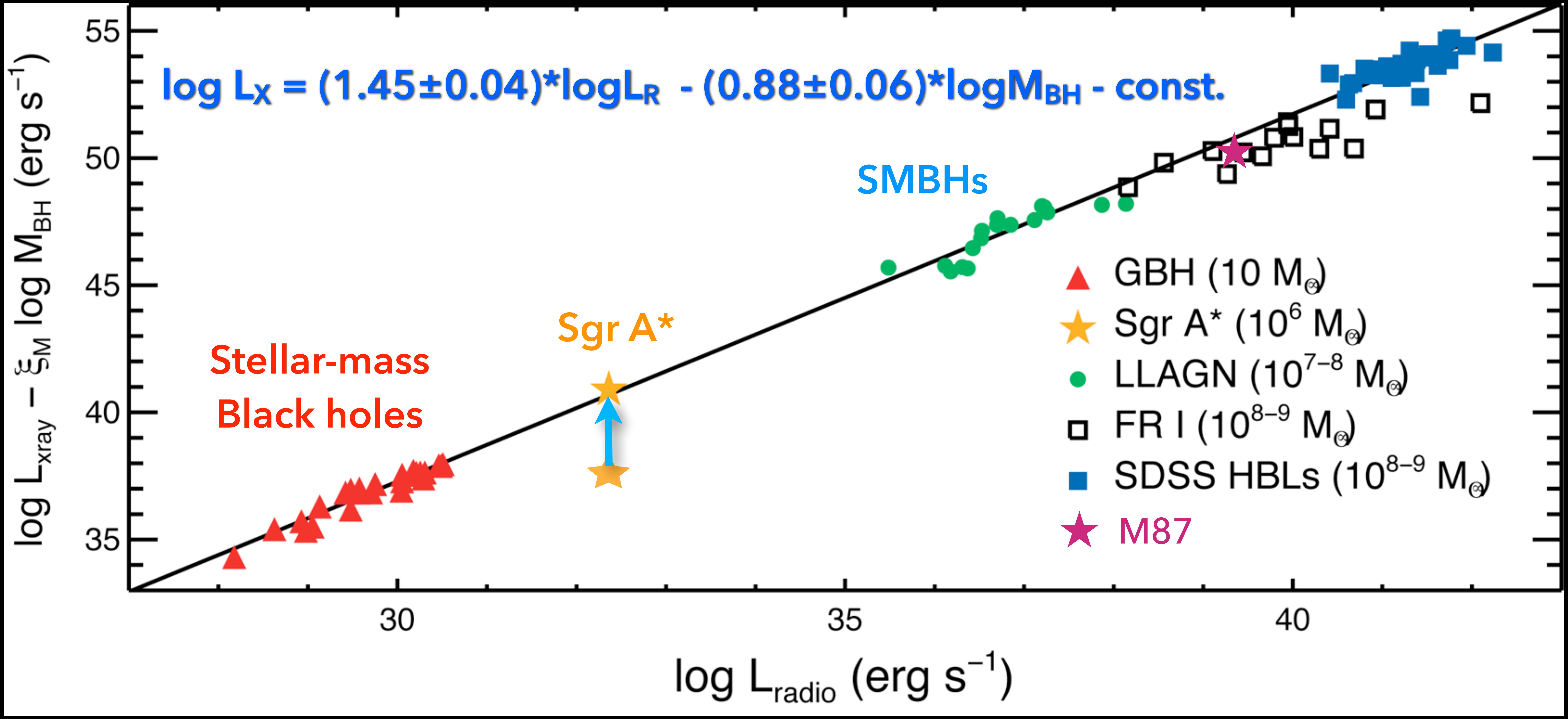


Visualization credit: Ben Prather, University of Illinois at Urbana-Champaign.
Image library credit: EHT Theory Working Group, CK Chan. EHTC Sgr A* Paper I, Paper V (2022)

Does Sgr A* have a jet?

(if so, why don't we see one??)

Sgr A*'s flares may be the key to the differences with M87*



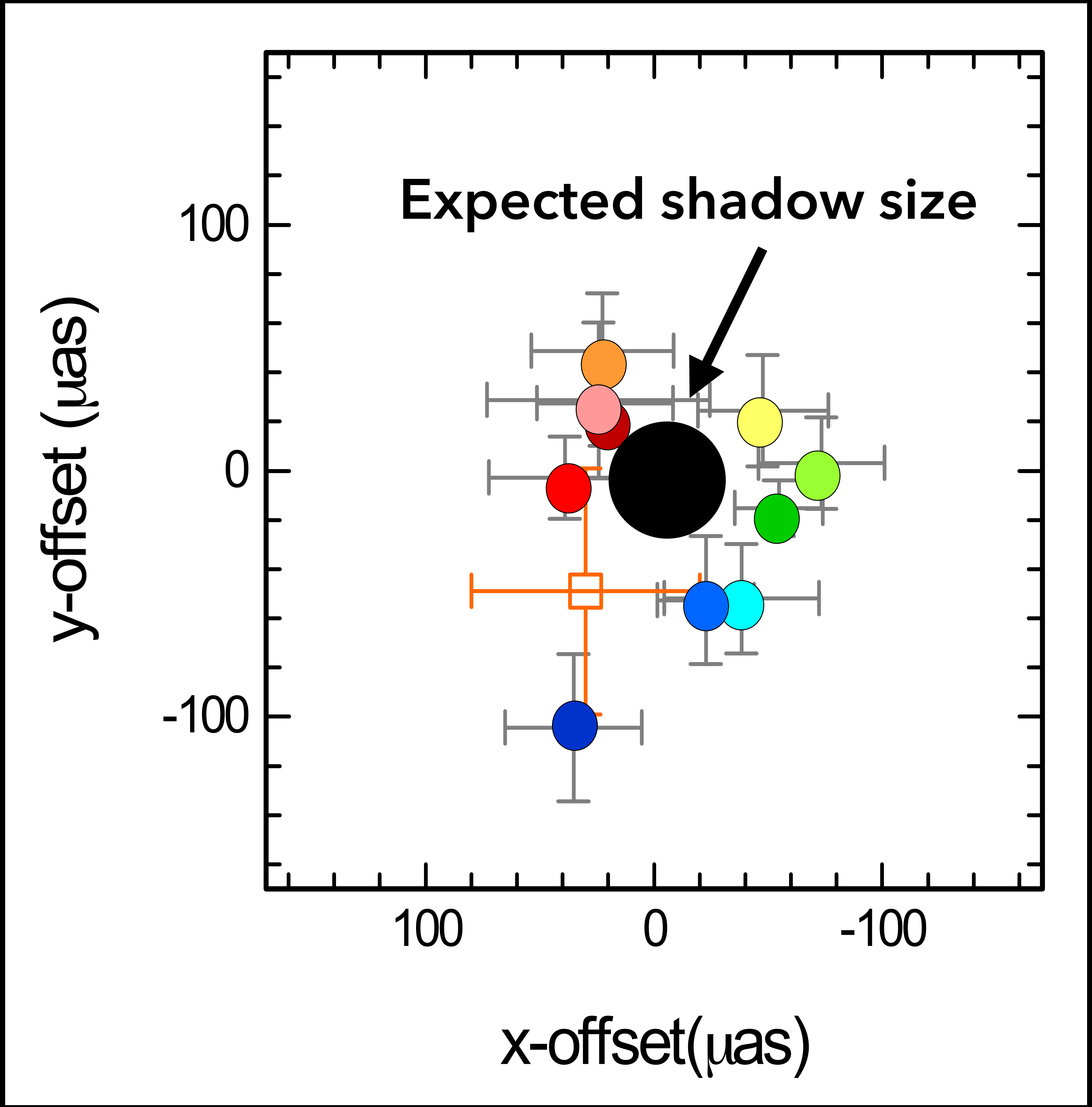
(SM++01,03,05; SM 05; Corbel++2008; Hynes++2009; Plotkin, SM++2012, Corbel++2013; Gallo++2014; Rana++2016; Plotkin++2016)

Variability encodes dynamics and particle acceleration properties

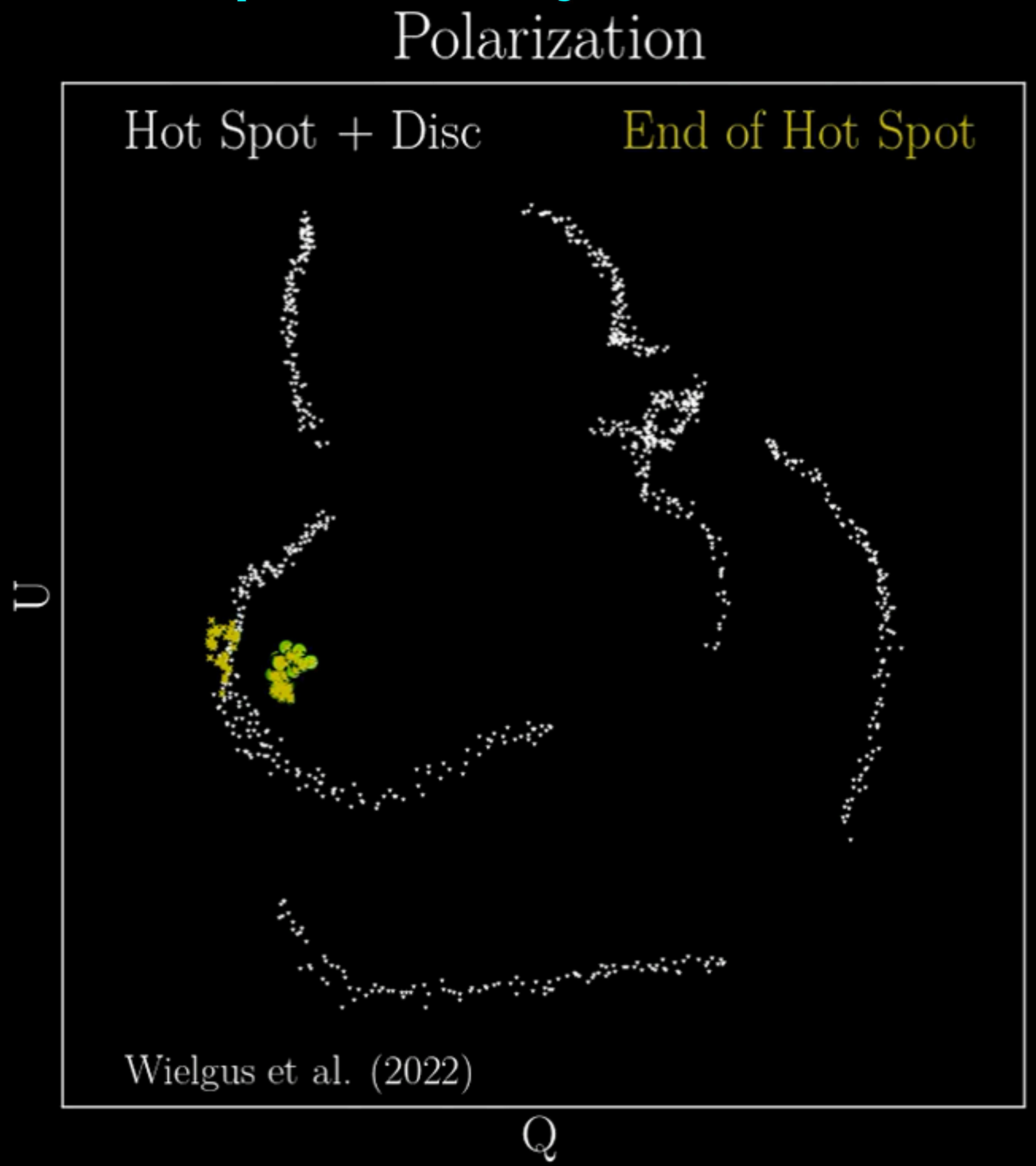
2017 campaign: mm-variability shows clear change after a X-ray flare (lucky!!):

EHTC + Multiwavelength Partners, Sgr A* Paper II 2022; Wielgus, EHT++2022

Sgr A* flares clearly associated with plasma dynamics

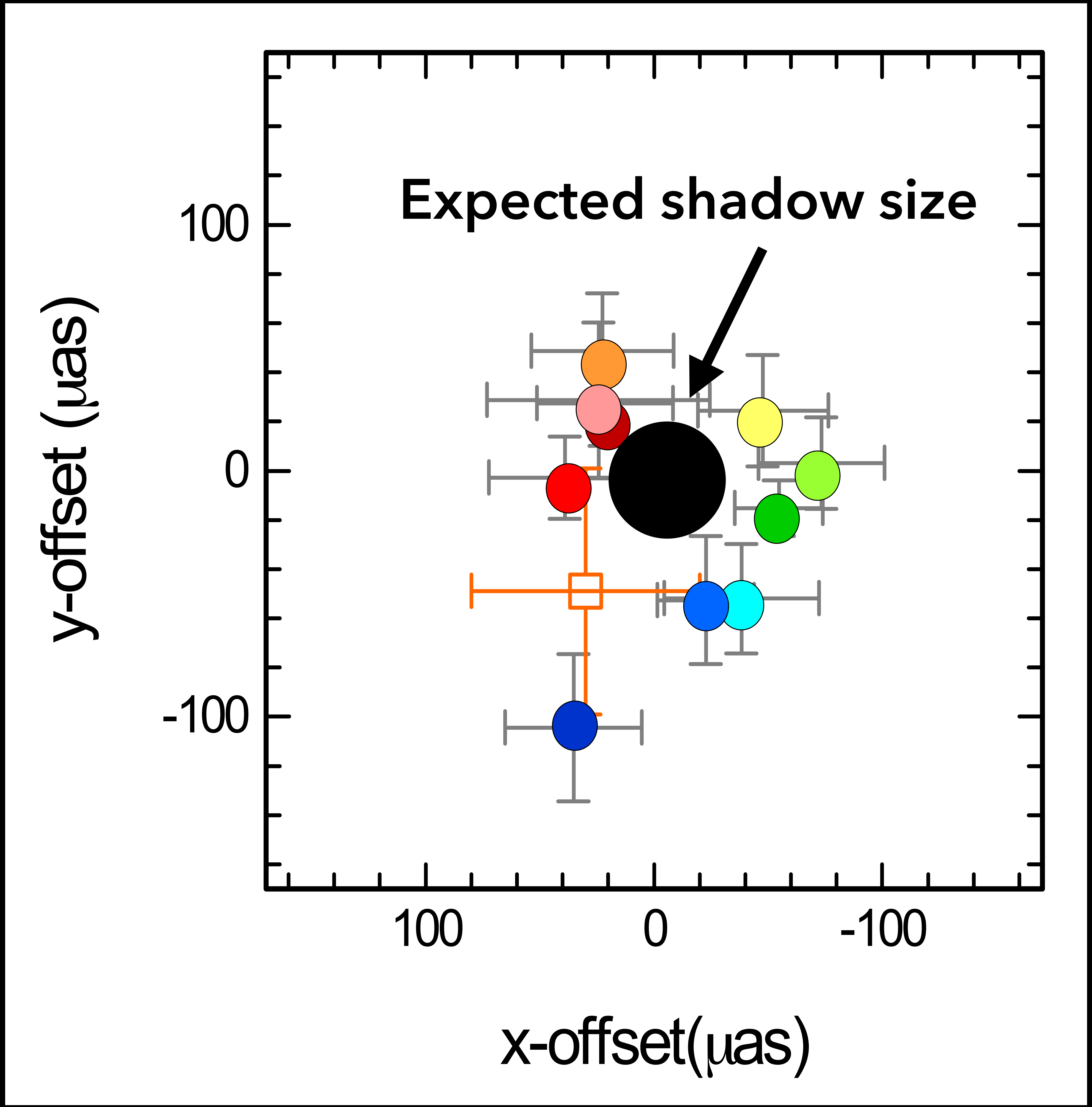


Infrared flares move around the BH (GRAVITY++2018)



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

Sgr A* flares clearly associated with plasma dynamics



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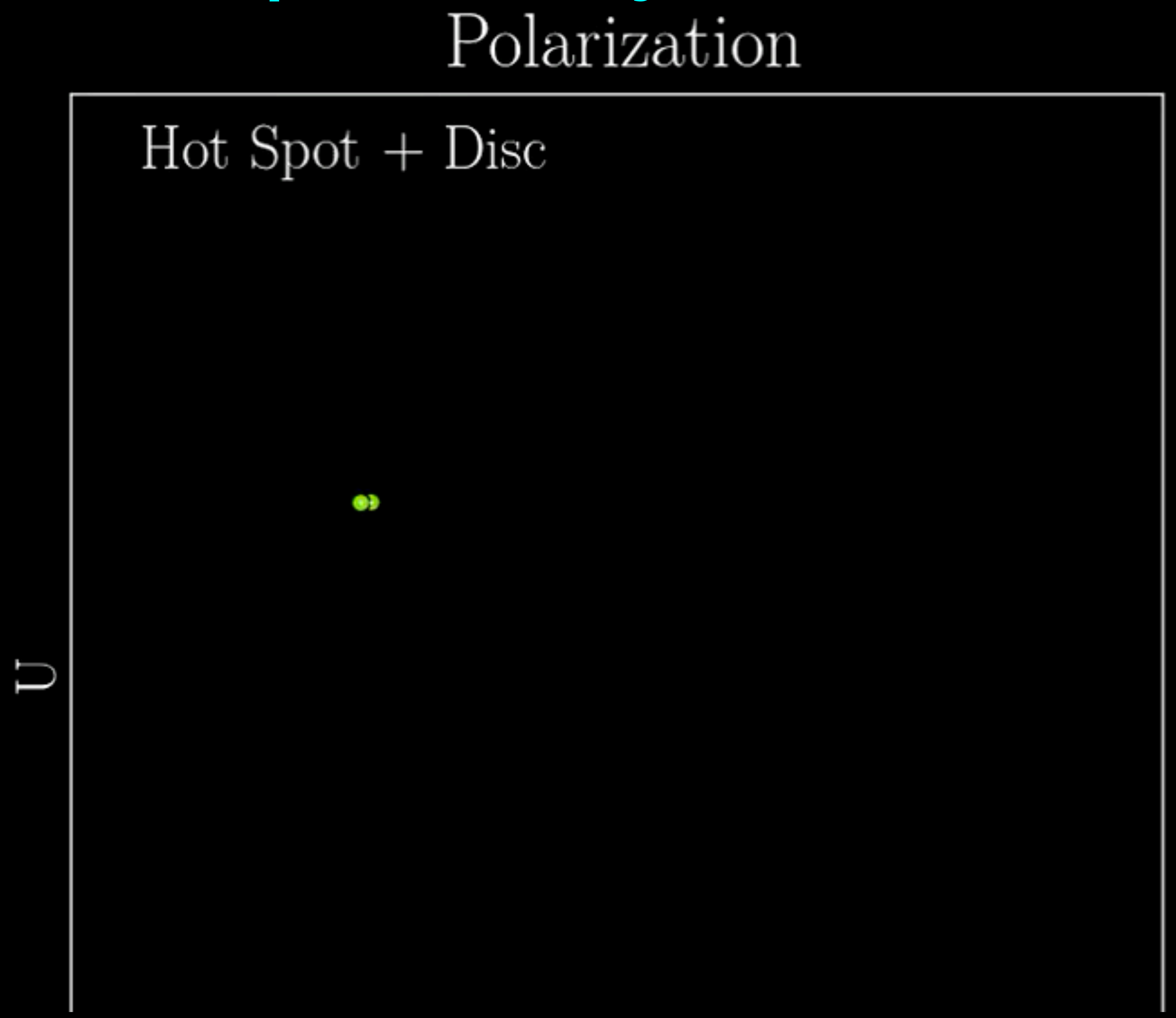
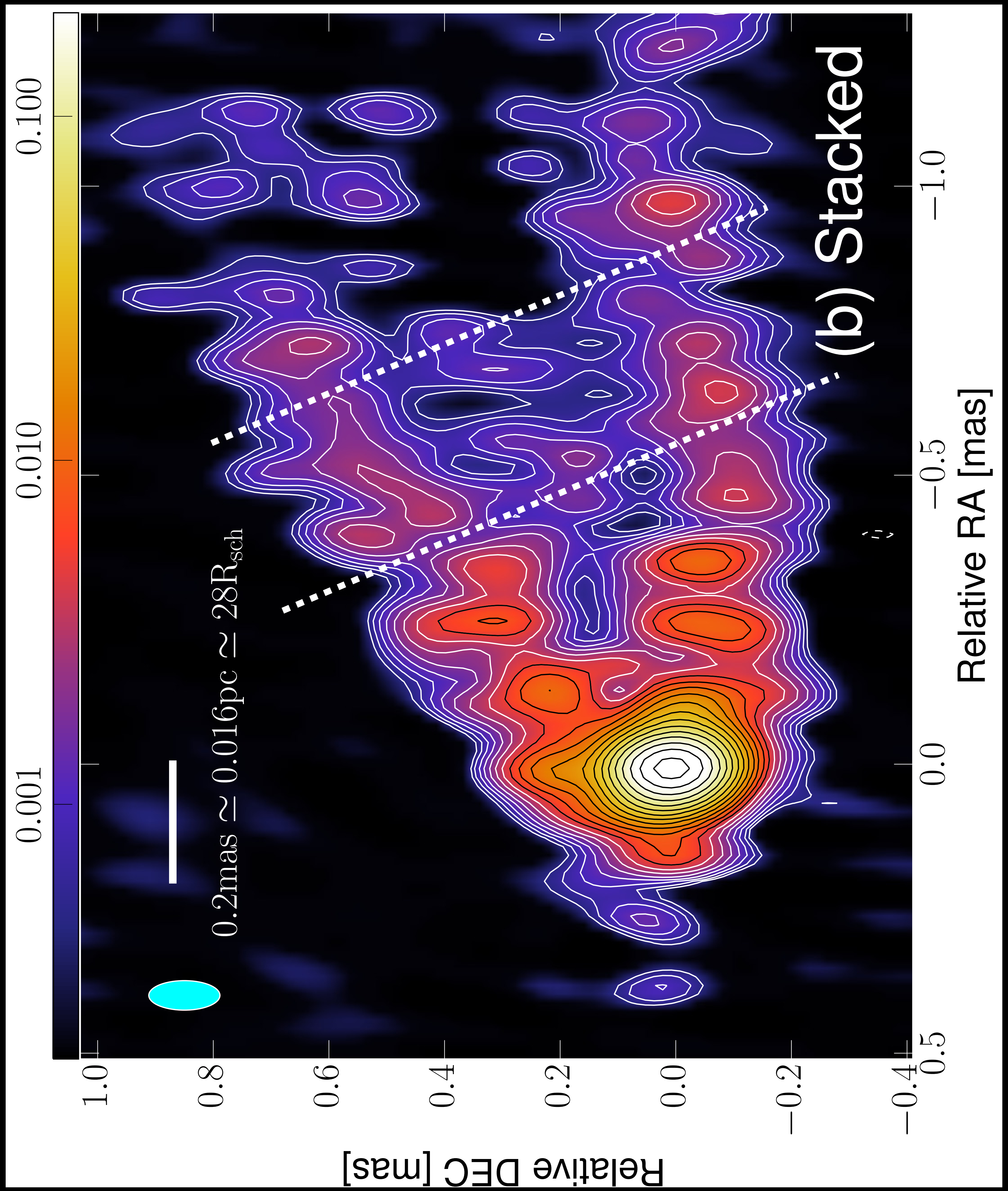


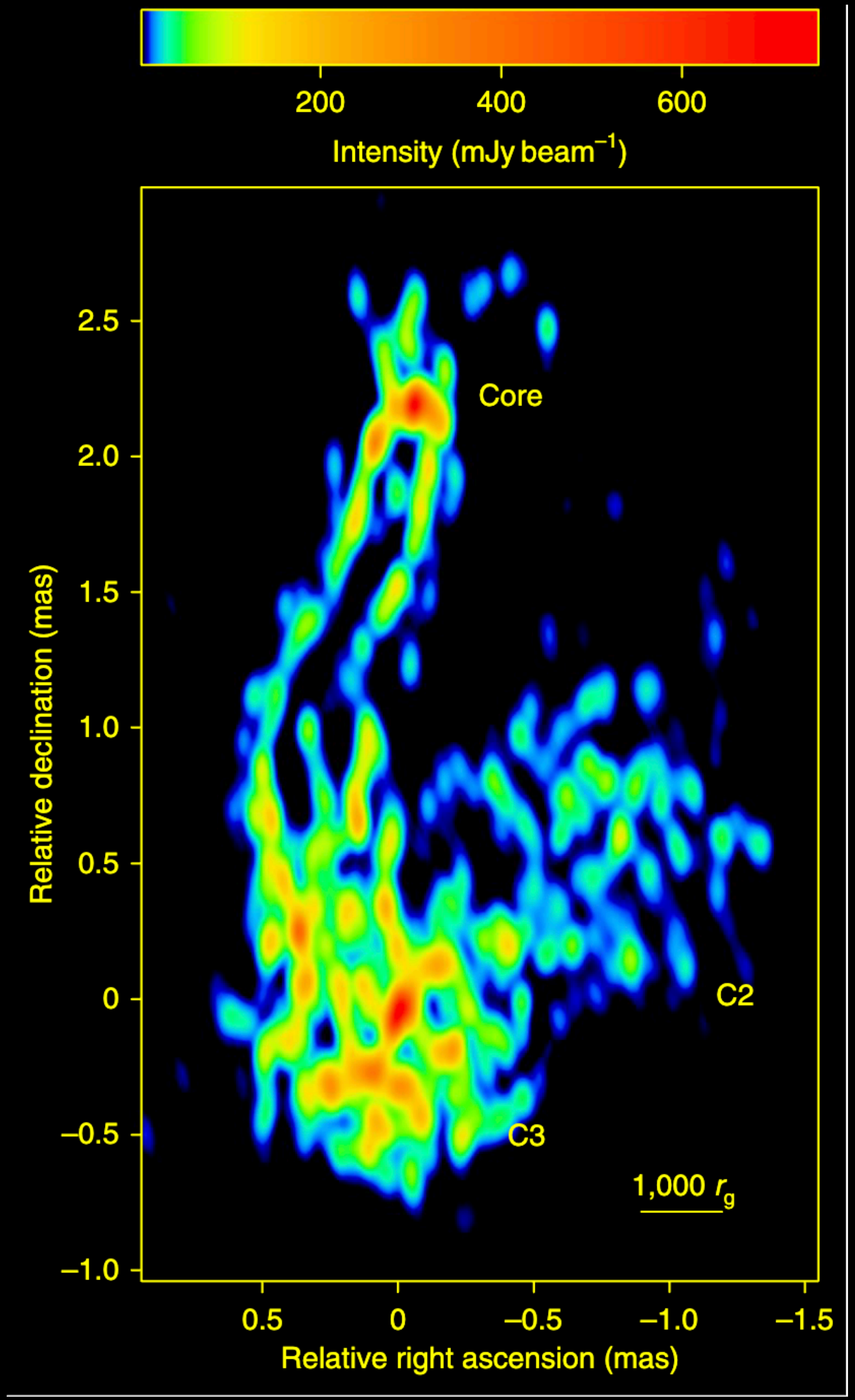
- Can we find the right combination of dynamics + microphysics to explain images, spectra and variability??

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

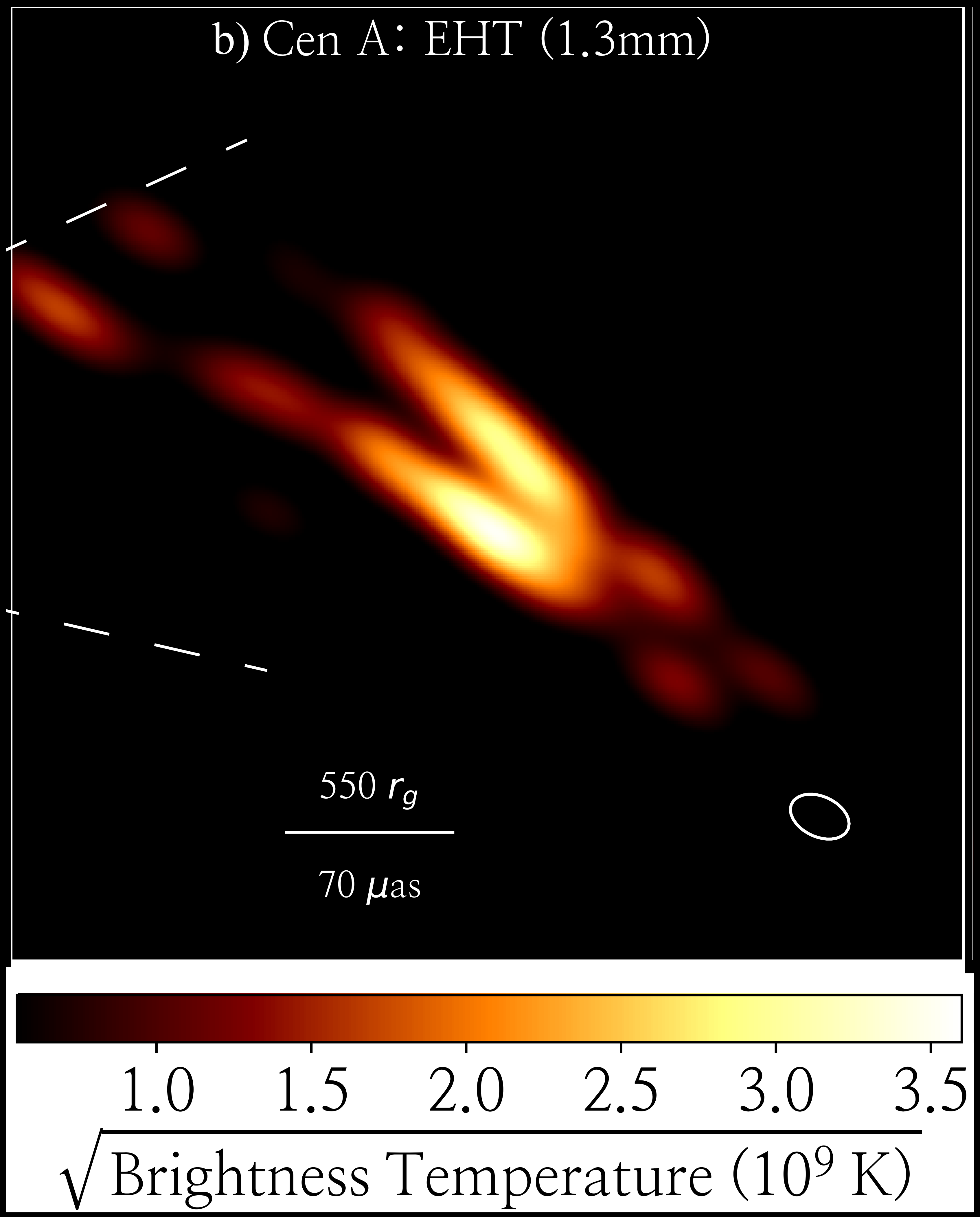
What lights up the jet core?



M87 (VLBA/VLBI): Kim++2018; Walker++2018; Hada++14,16,18

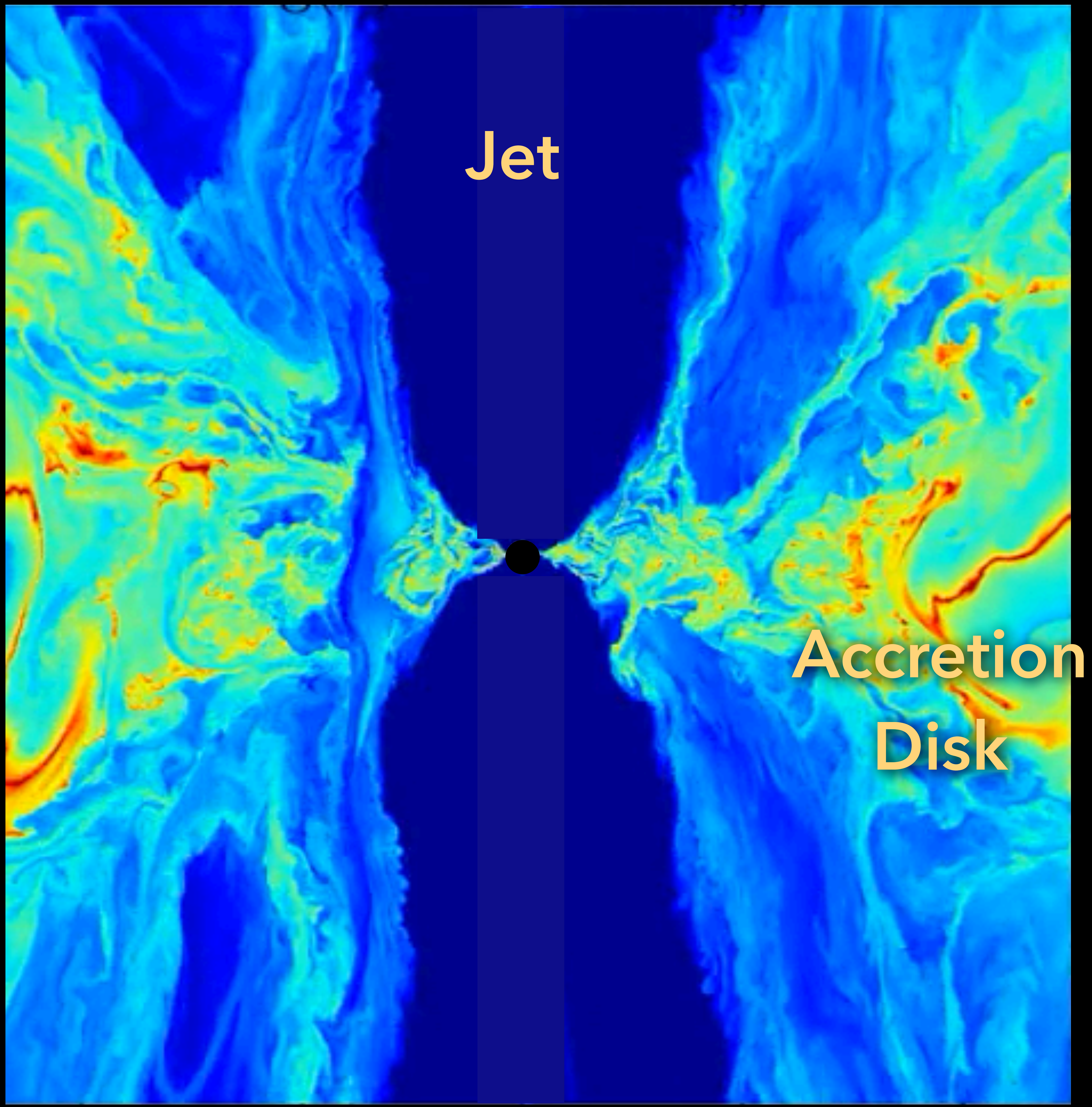


3C84 (VLBI+RadioAstron): Giovannini++2018, Nat.Astro



Cen A (EHT): Janssen++2021, Nat.Astro

Very high resolution 3D GRMHD gives insights into flares/dissipation



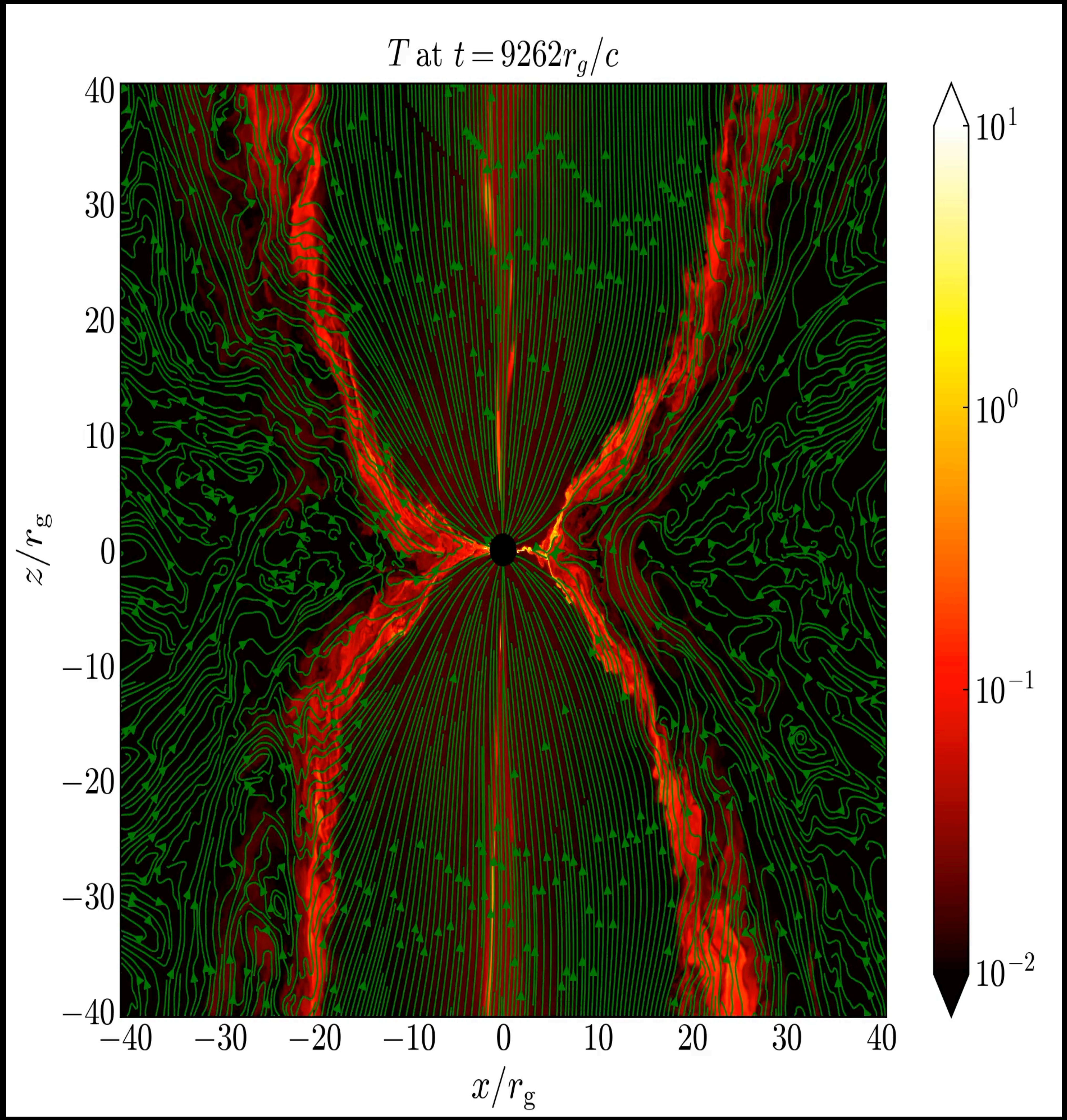
(5400x2300x2300) with H-AMR (Liska++ 2019;2022) yields similar results as resistive 2D-GRMHD; Ripperda, Liska, Chatterjee, Musoke++2022

Very high resolution 3D GRMHD gives insights into flares/dissipation

- Plasmoids only form with resolutions ≳ (6000x2000x2000), ~10x10x10x > than EHT “fiducial” simulations
- Plasmoids merge ➠ hotspots with roughly the right size/ timescales (~100 r_g/c~hour every ~2000r_g/c~day)
- Need kinetic treatment to study more realistically the timescales (faster) and radiative properties

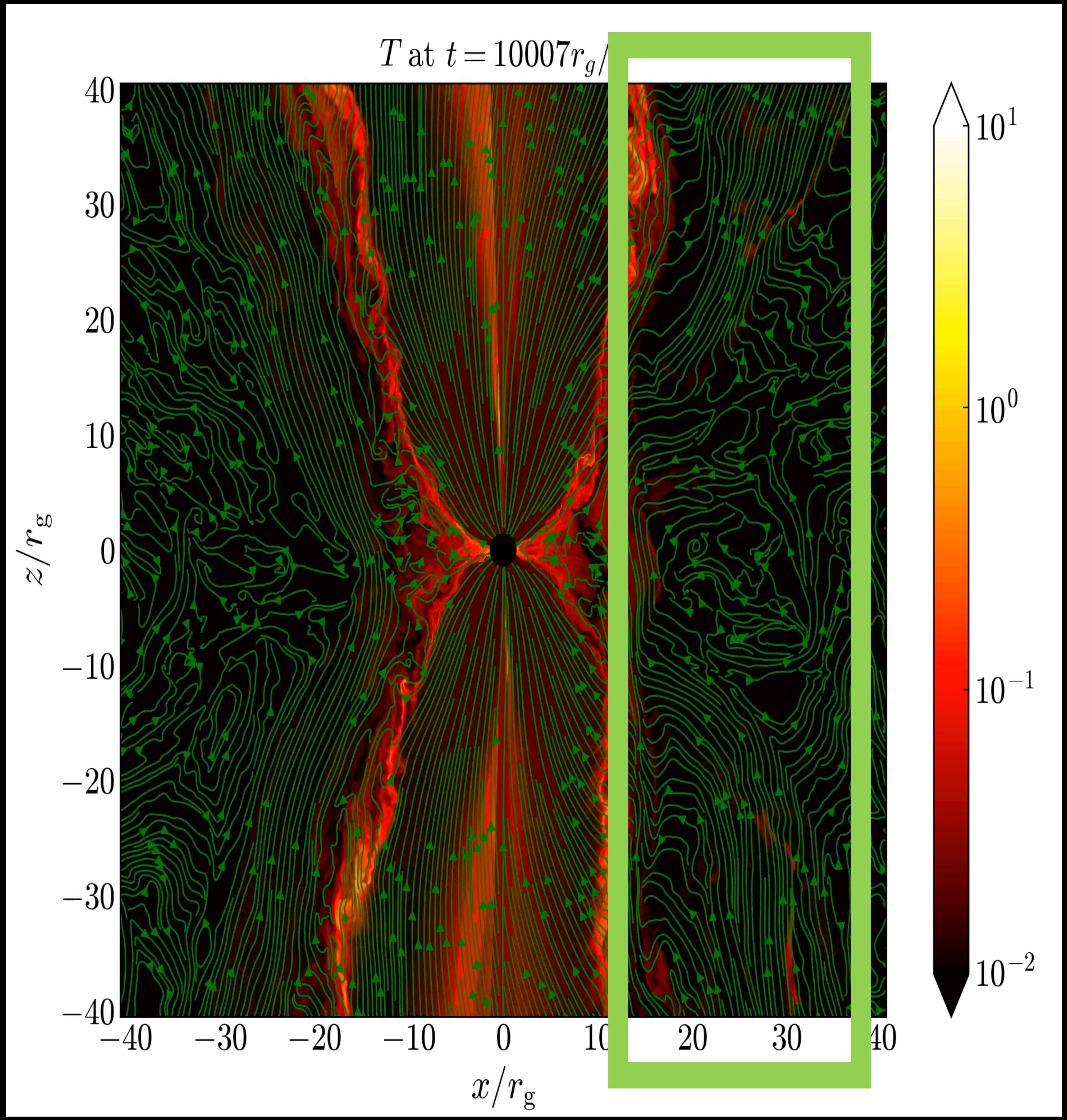
(5400x2300x2300) with H-AMR (Liska++ 2019;2022) yields similar results as resistive 2D-GRMHD; Ripperda, Liska, Chatterjee, Musoke++2022

Very high resolution 3D GRMHD gives insights into flares/dissipation

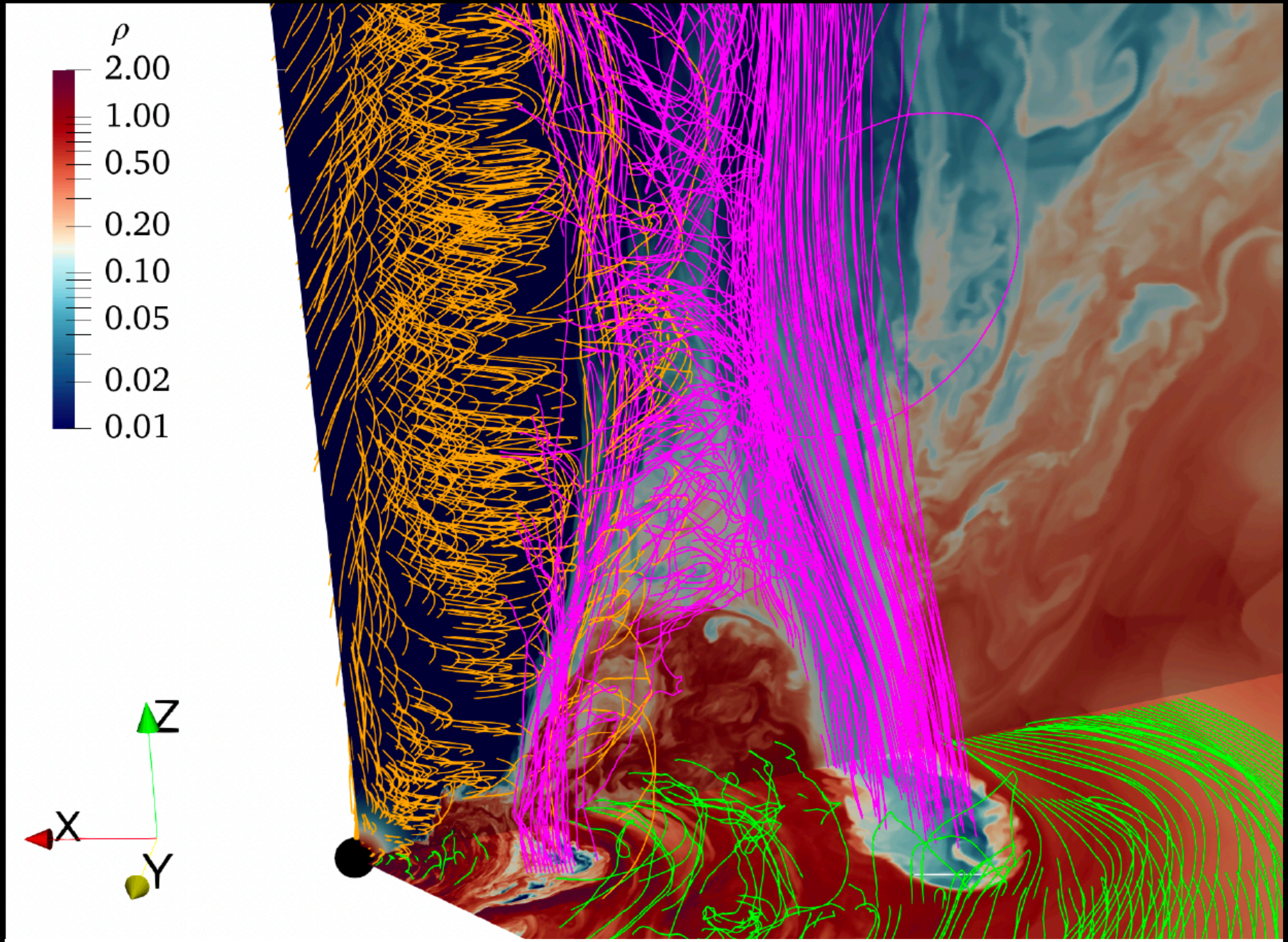


Ripperda, Liska, Chatterjee, Musoke++2022

Very high resolution 3D GRMHD gives insights into flares/dissipation



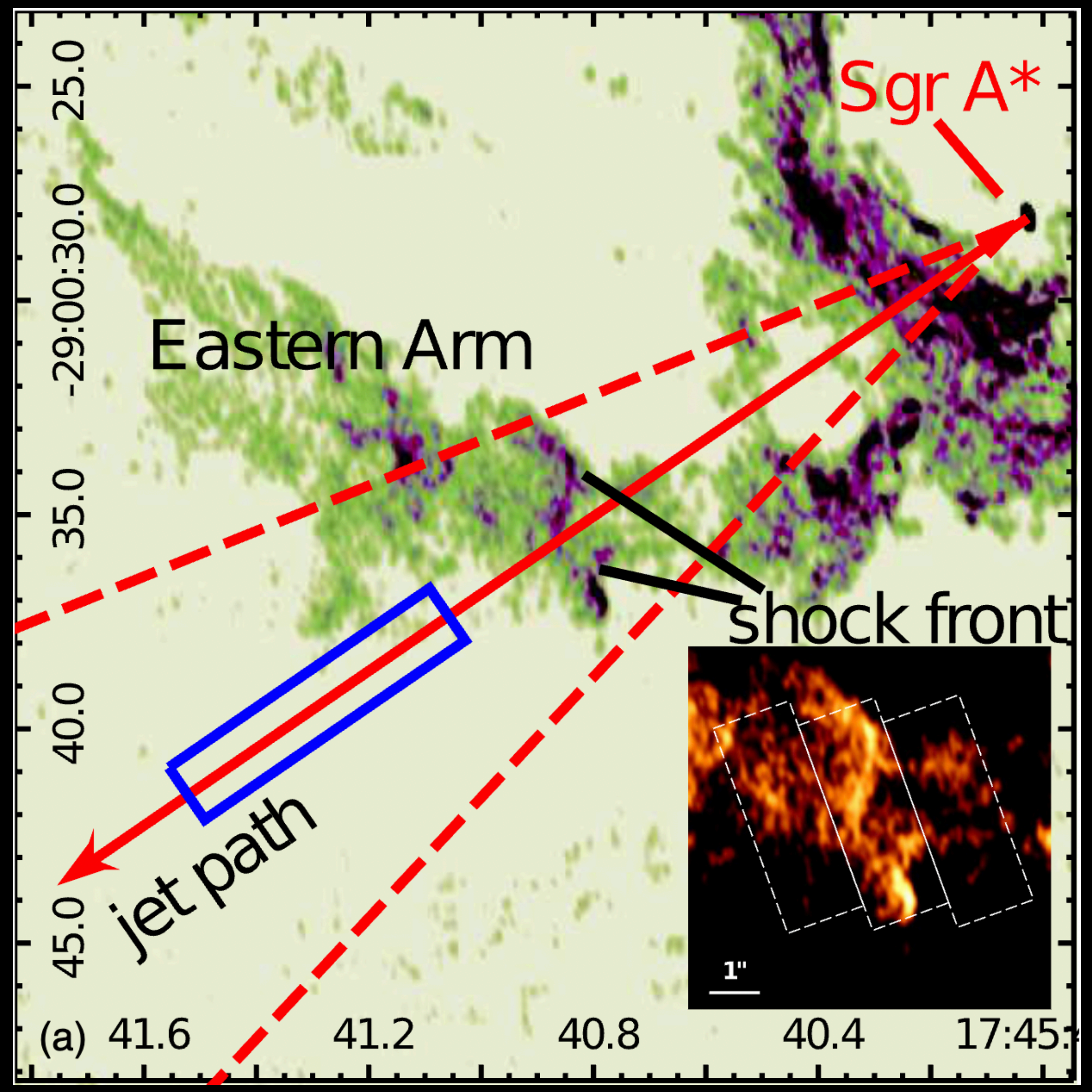
Ripperda, Liska, Chatterjee, Musoke++2022



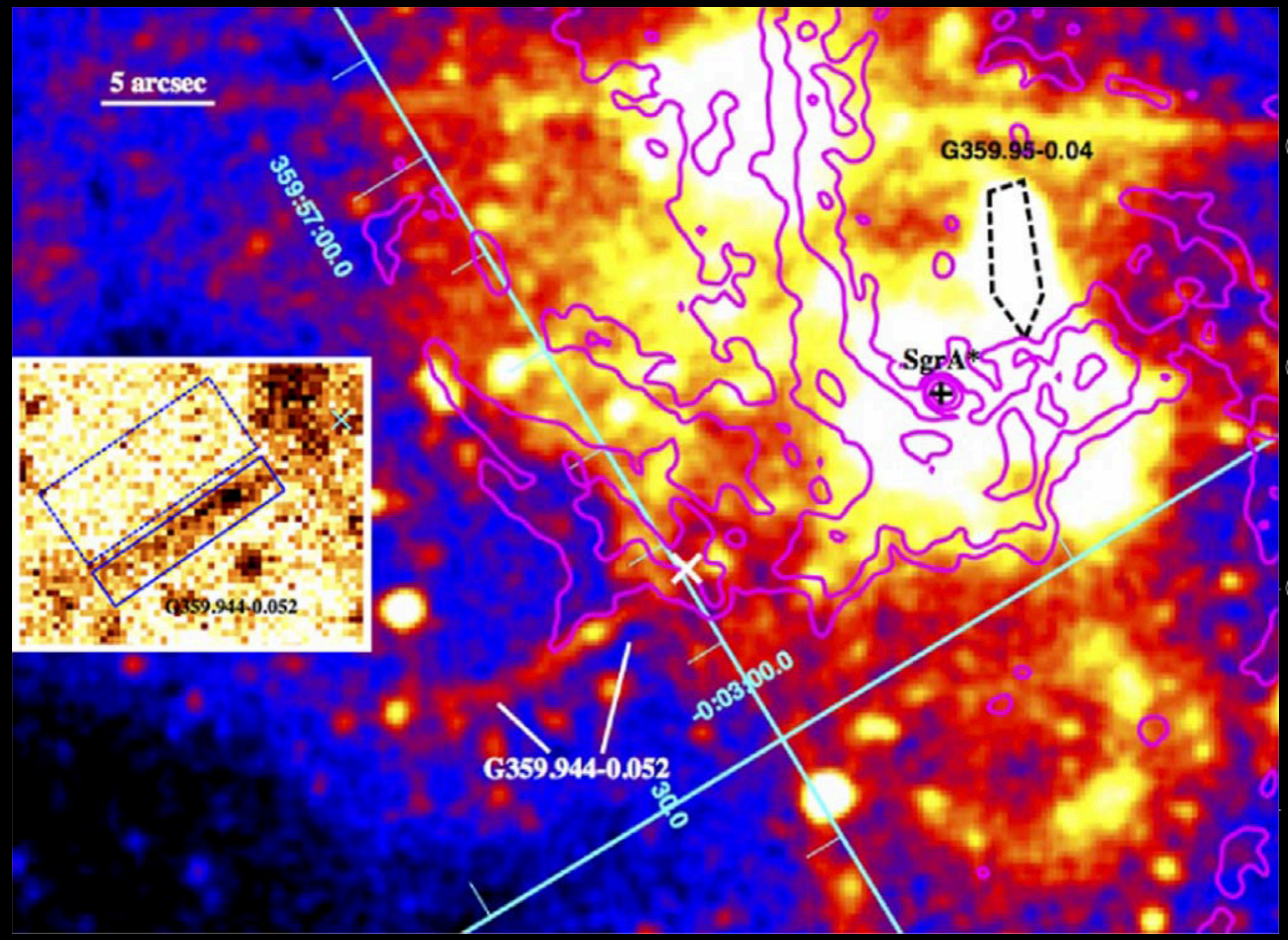
- Reconnection expels flux tubes with vertical field, consistent with IR/mm polarisation
- Can drive turbulence/instabilities leading to particle acceleration ➠ flares?

see e.g., Porth++2021; Ripperda++, in prep.

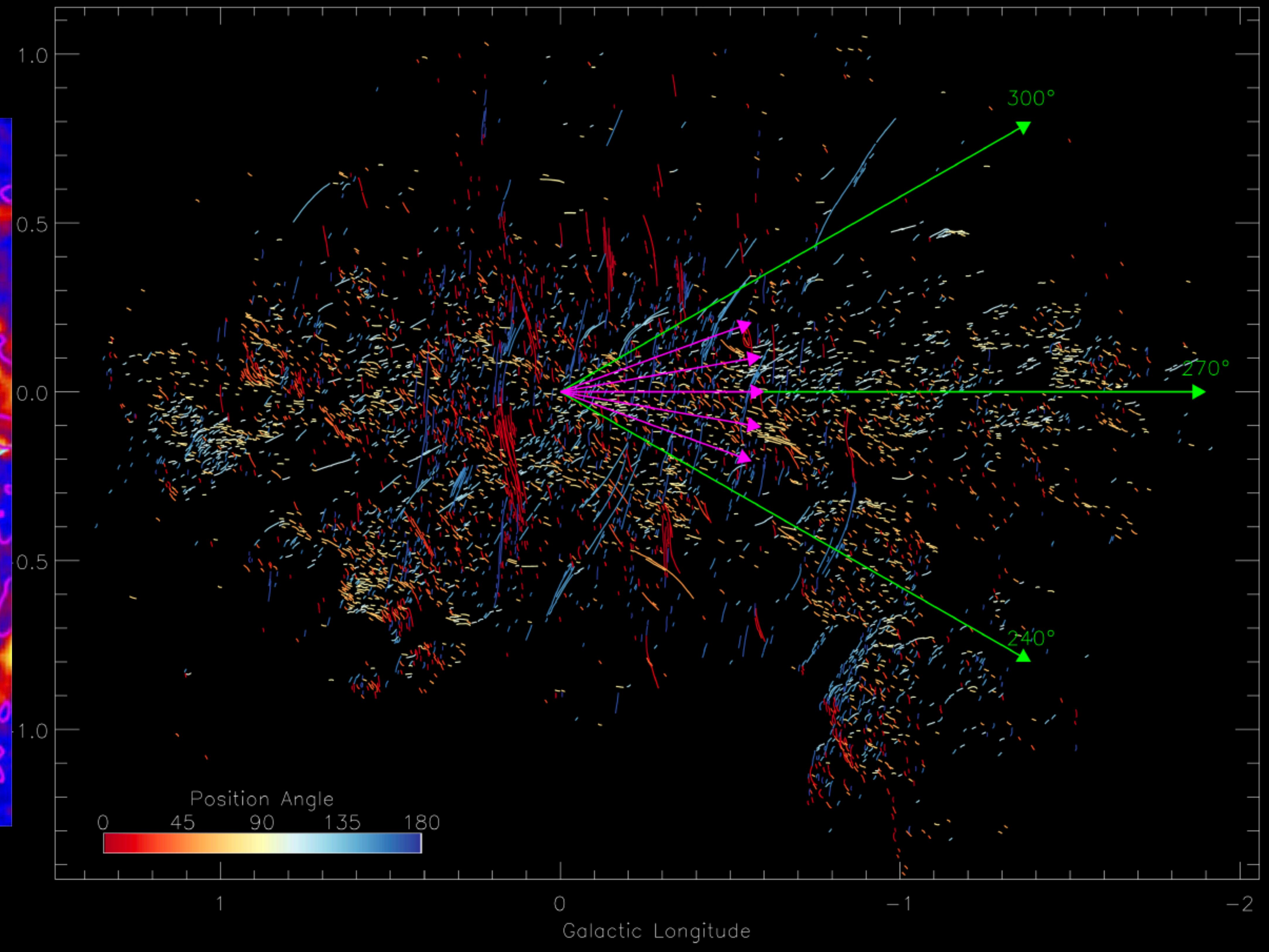
Is there any circumstantial evidence for Sgr A* having a jet??



Li++2013

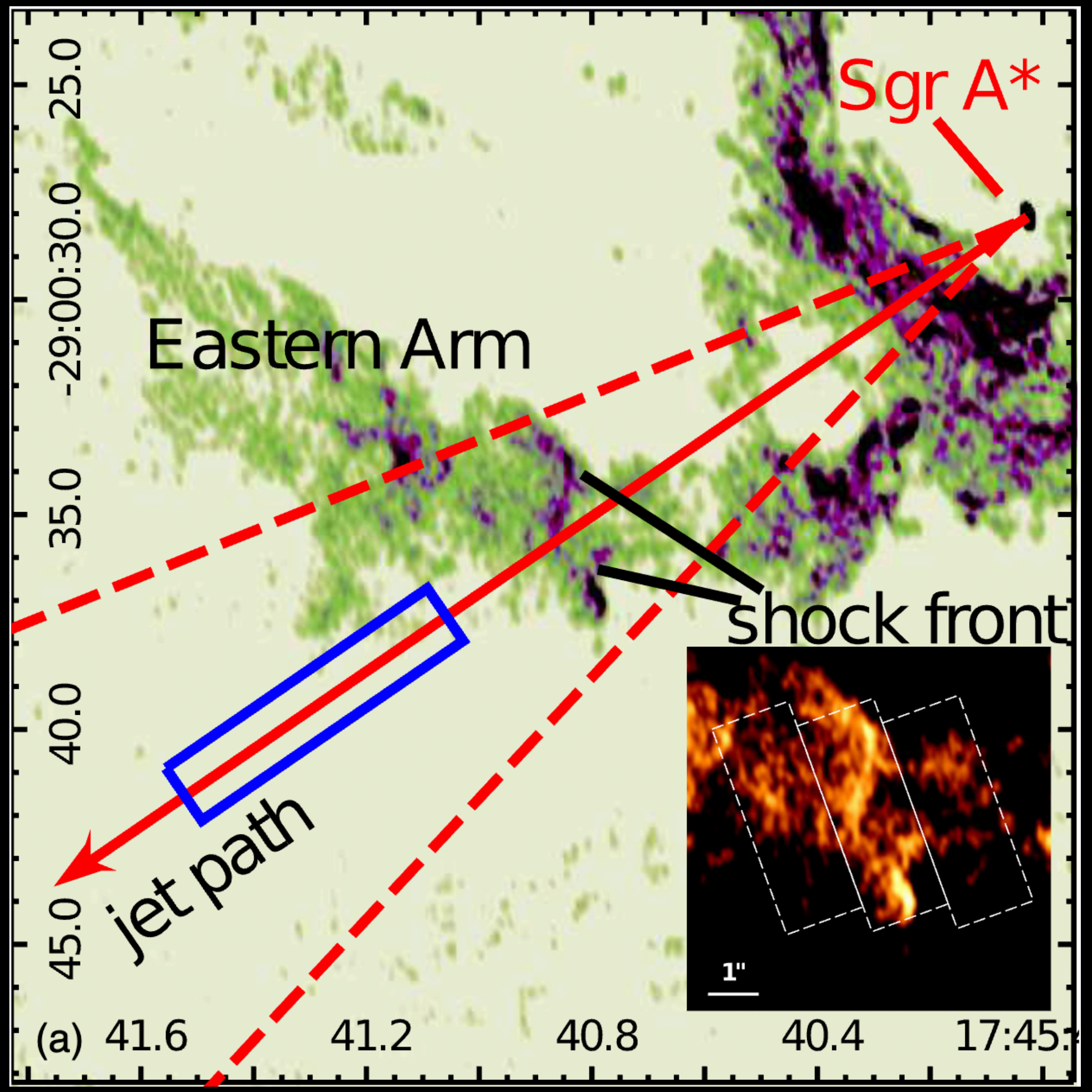


Zhu++2019

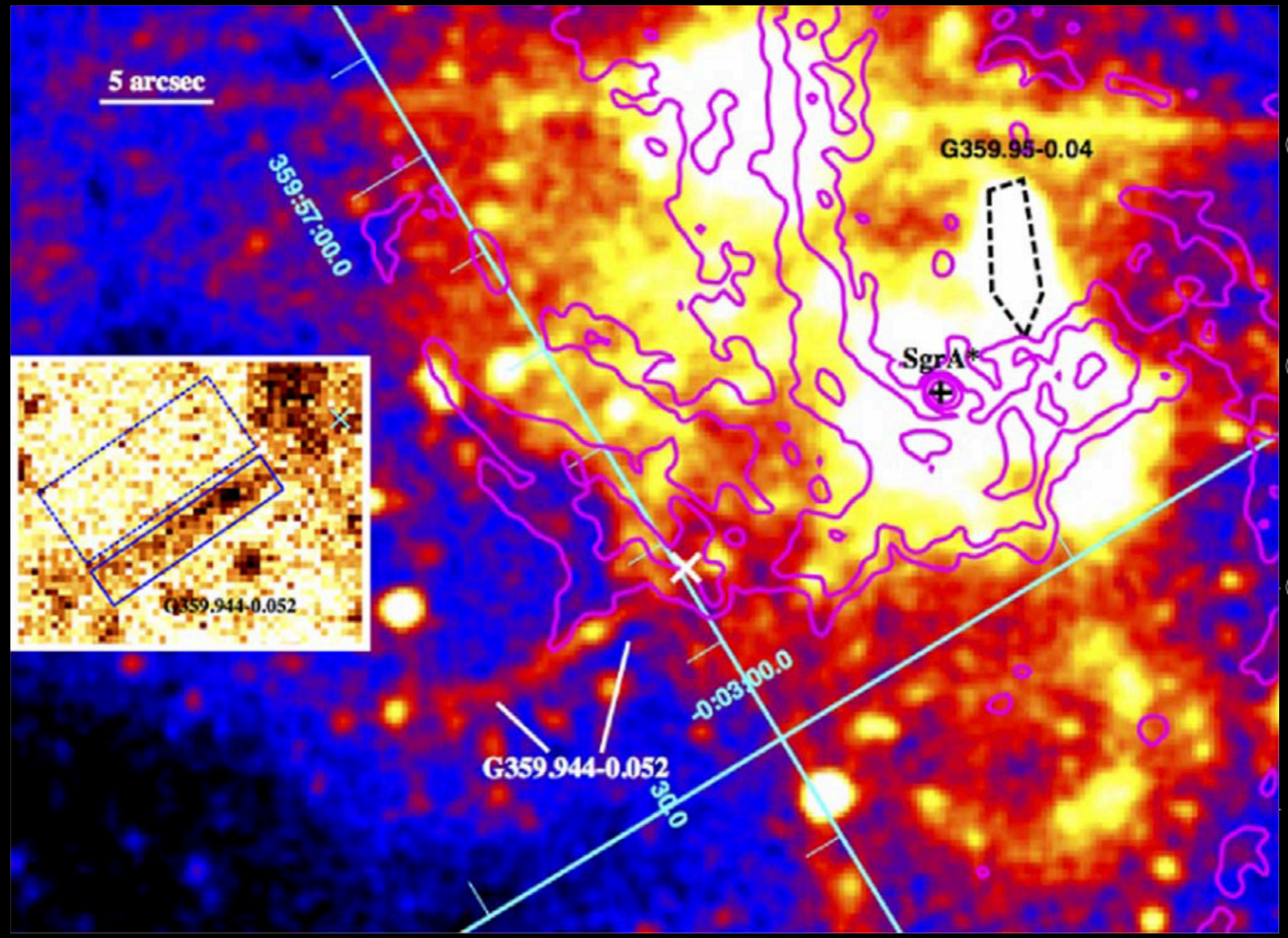


Yusef-Zadeh++2023

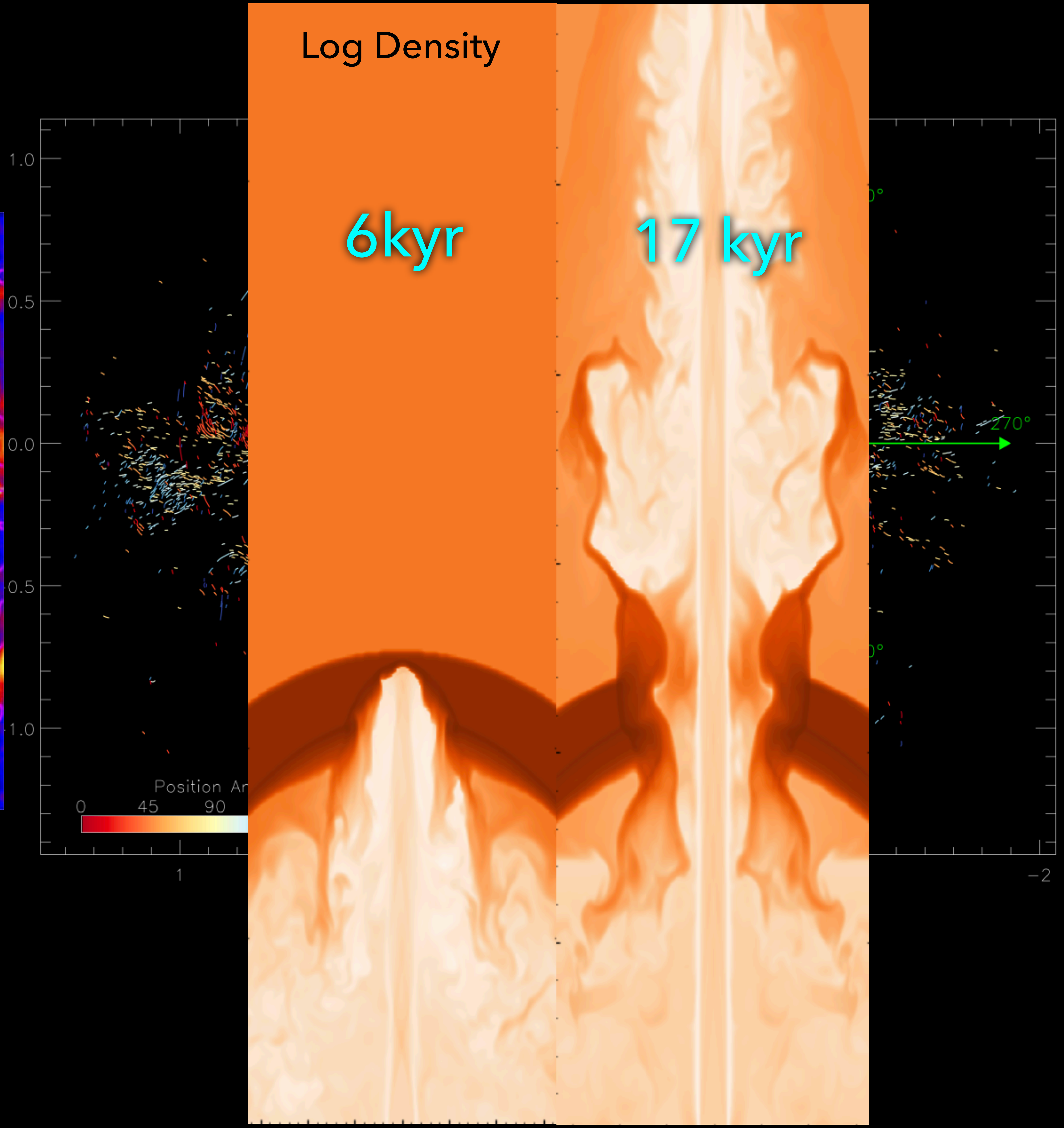
Is there any circumstantial evidence for Sgr A* having a jet??



Li++2013

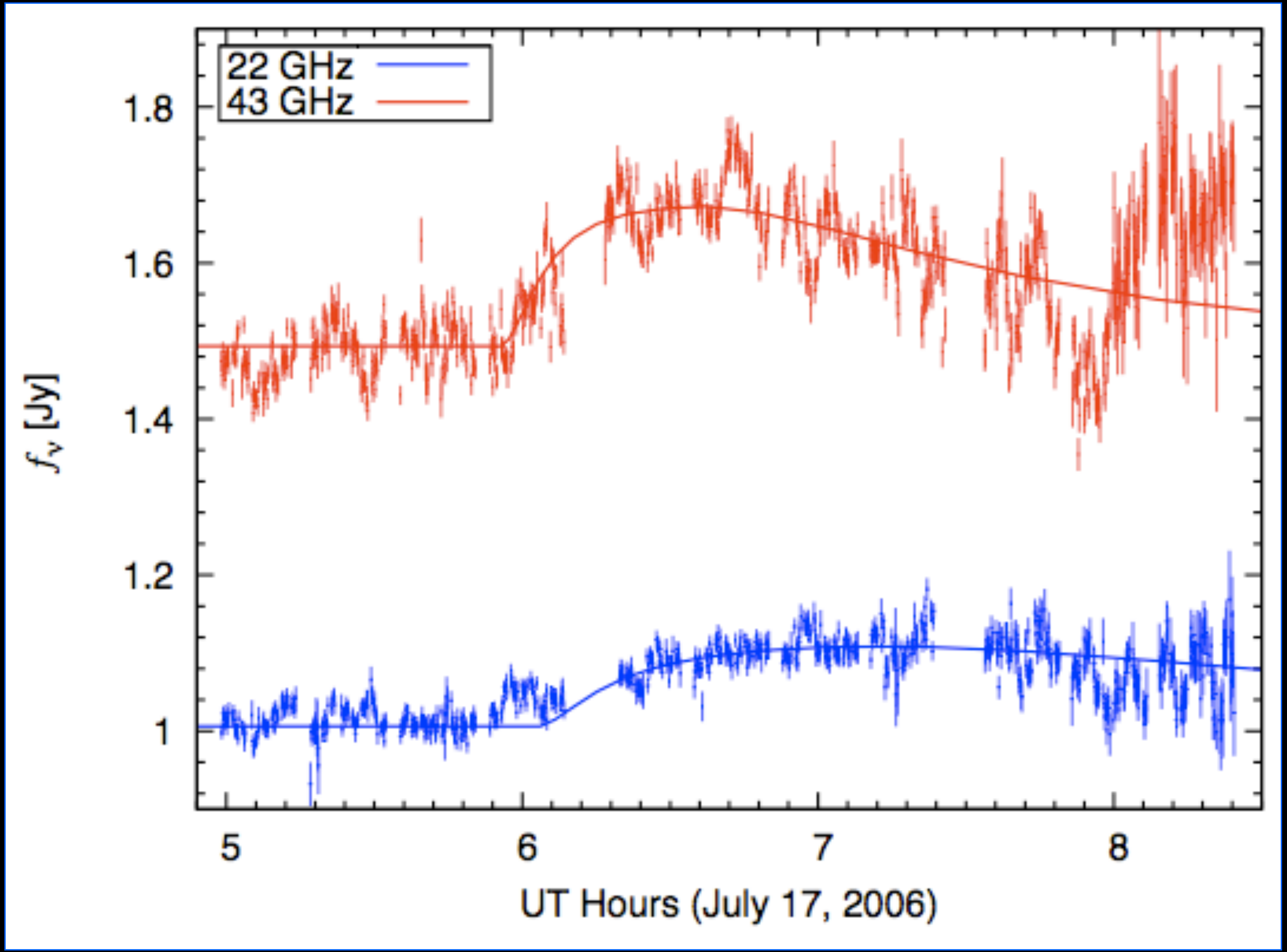


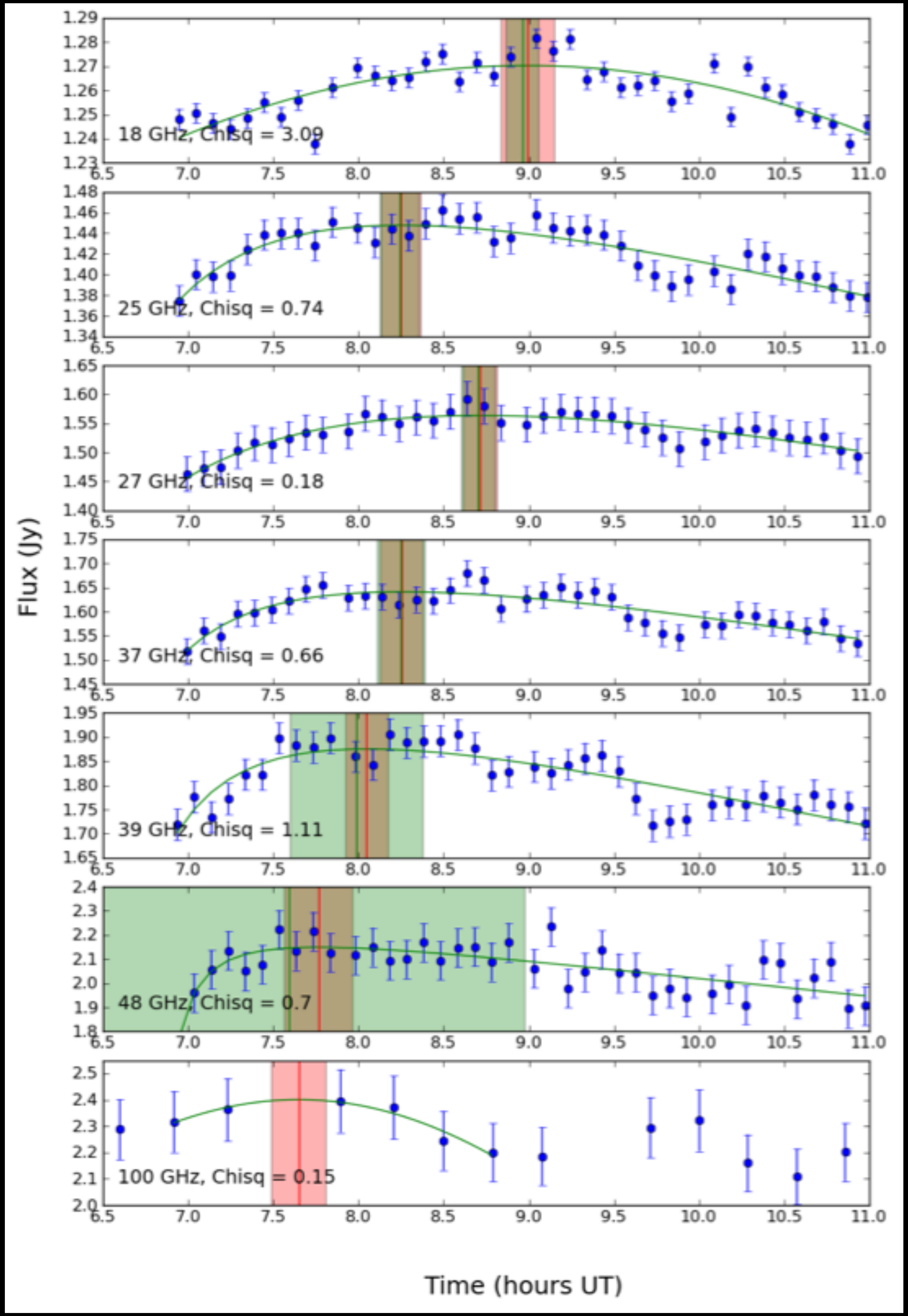
Zhu++2019



AMRVAC Simulations in progress led by UvA VIA PD Fellow G. Musoke

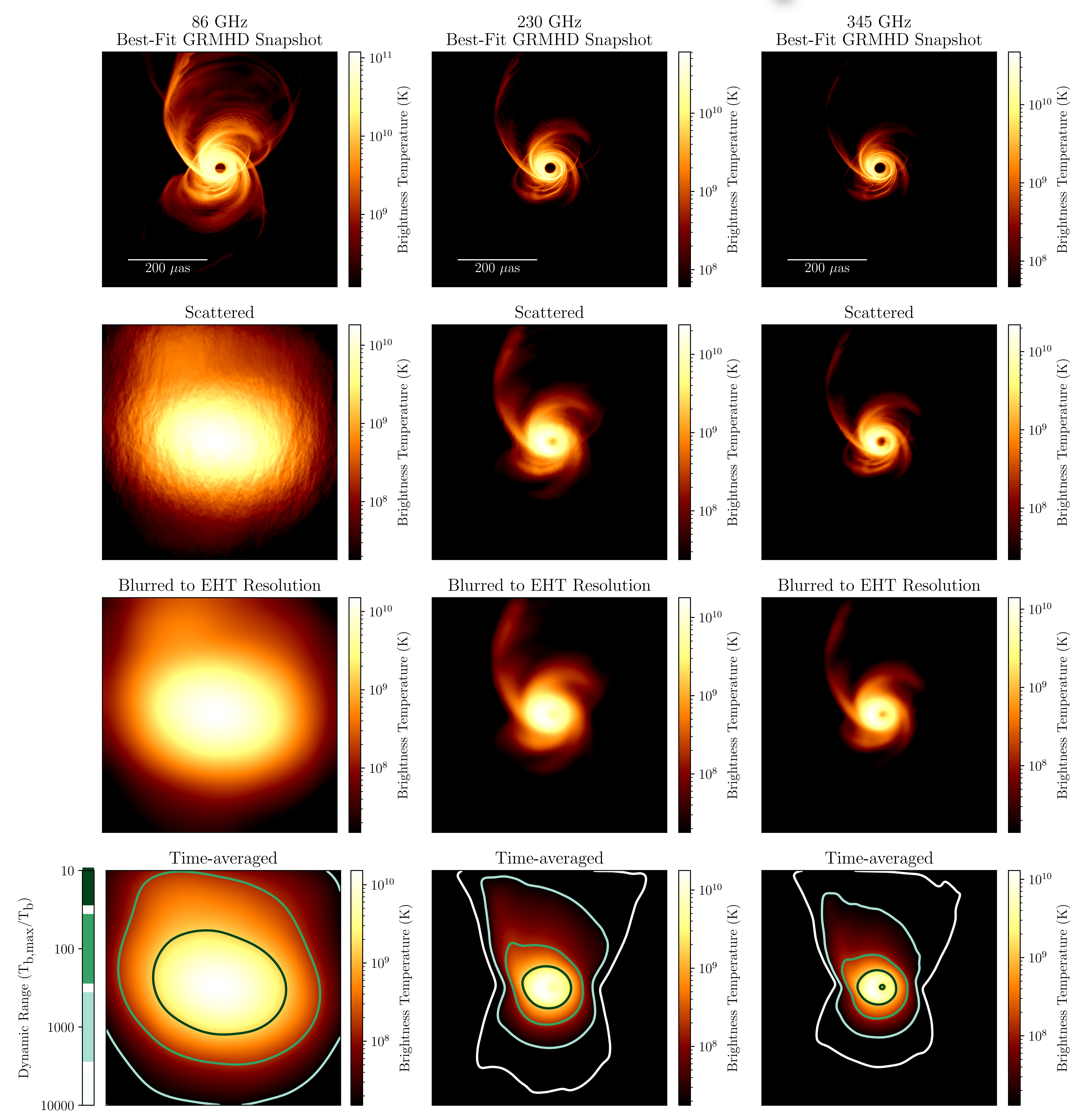
Evidence for an outflow from multi-wavelength variability





(Maitra, SM & Falcke 2009; Brinkerink++ 2015; Brinkerink++2021)

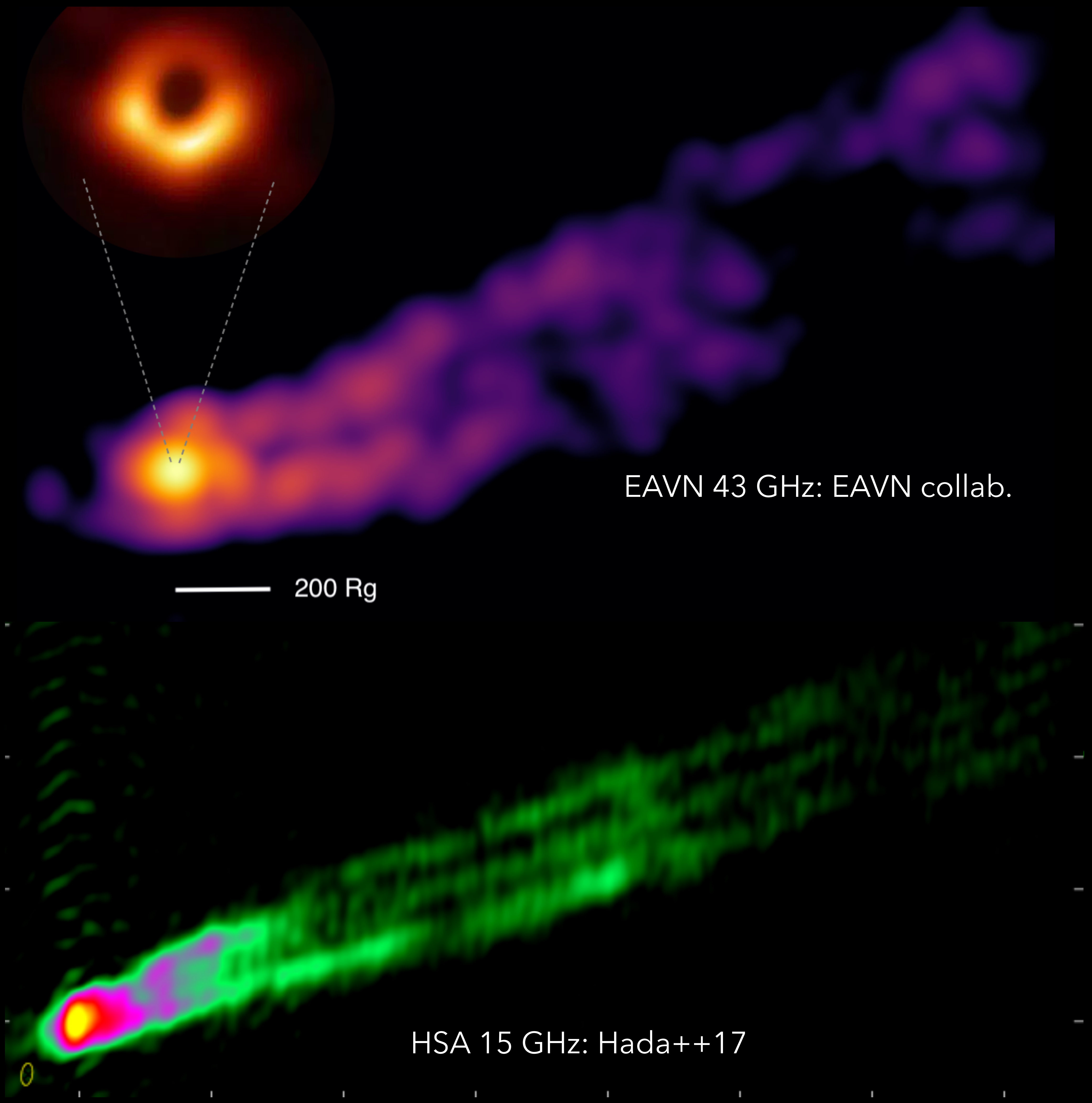
Future expansions of EHT should help resolve this question

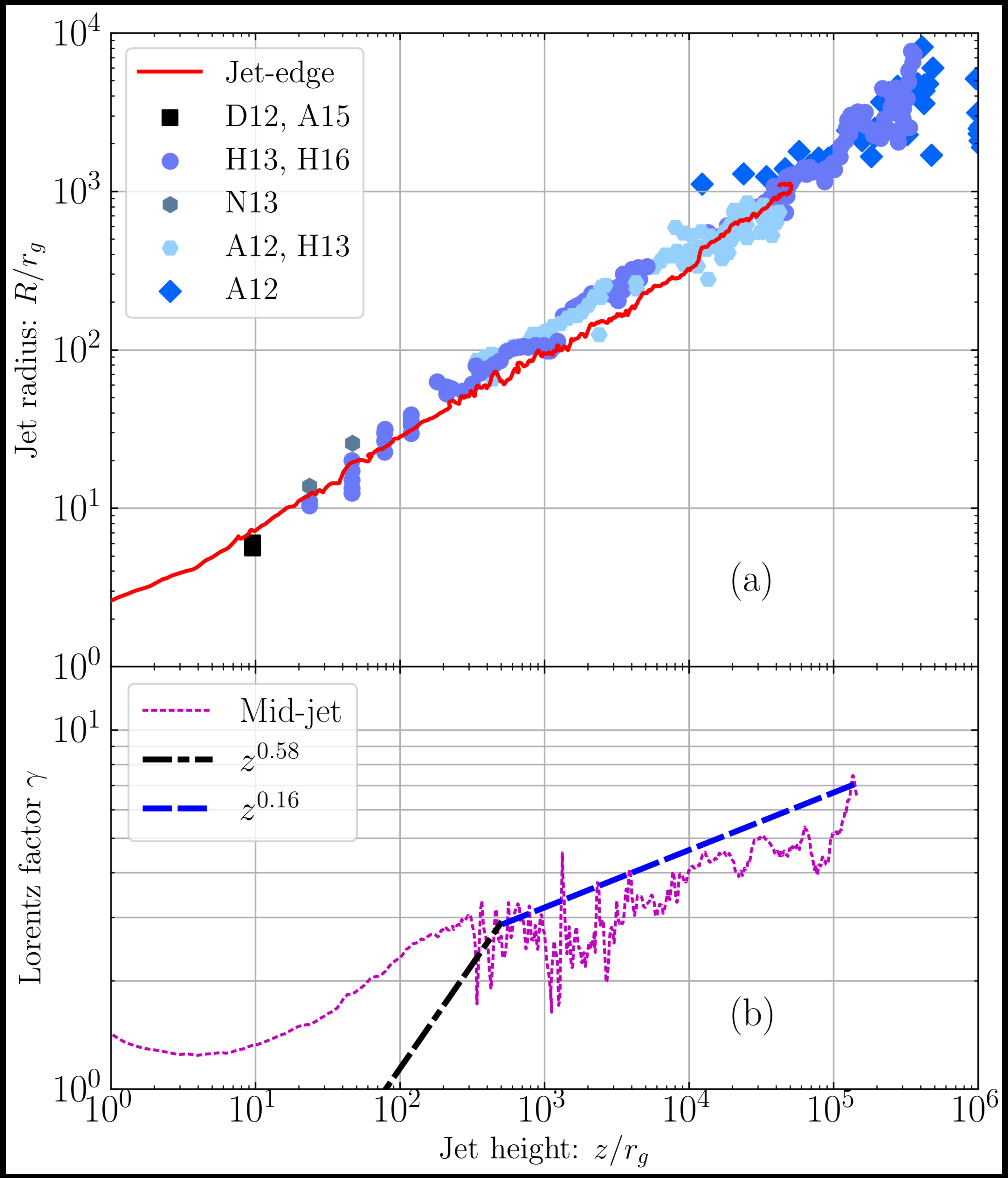


Chavez, Johnson, Issaoun, Fromm, Tiede++ in prep.

M87 dynamics, SED and VHE flares

Any model should fit both the image *and* the larger jet structure/dynamics





(Acciari++10; Abramowski++12; Kim++2018; Walker++2007-2018; Hada++14,16,18; EHT Collaboration 2019a-f, 2021ab)

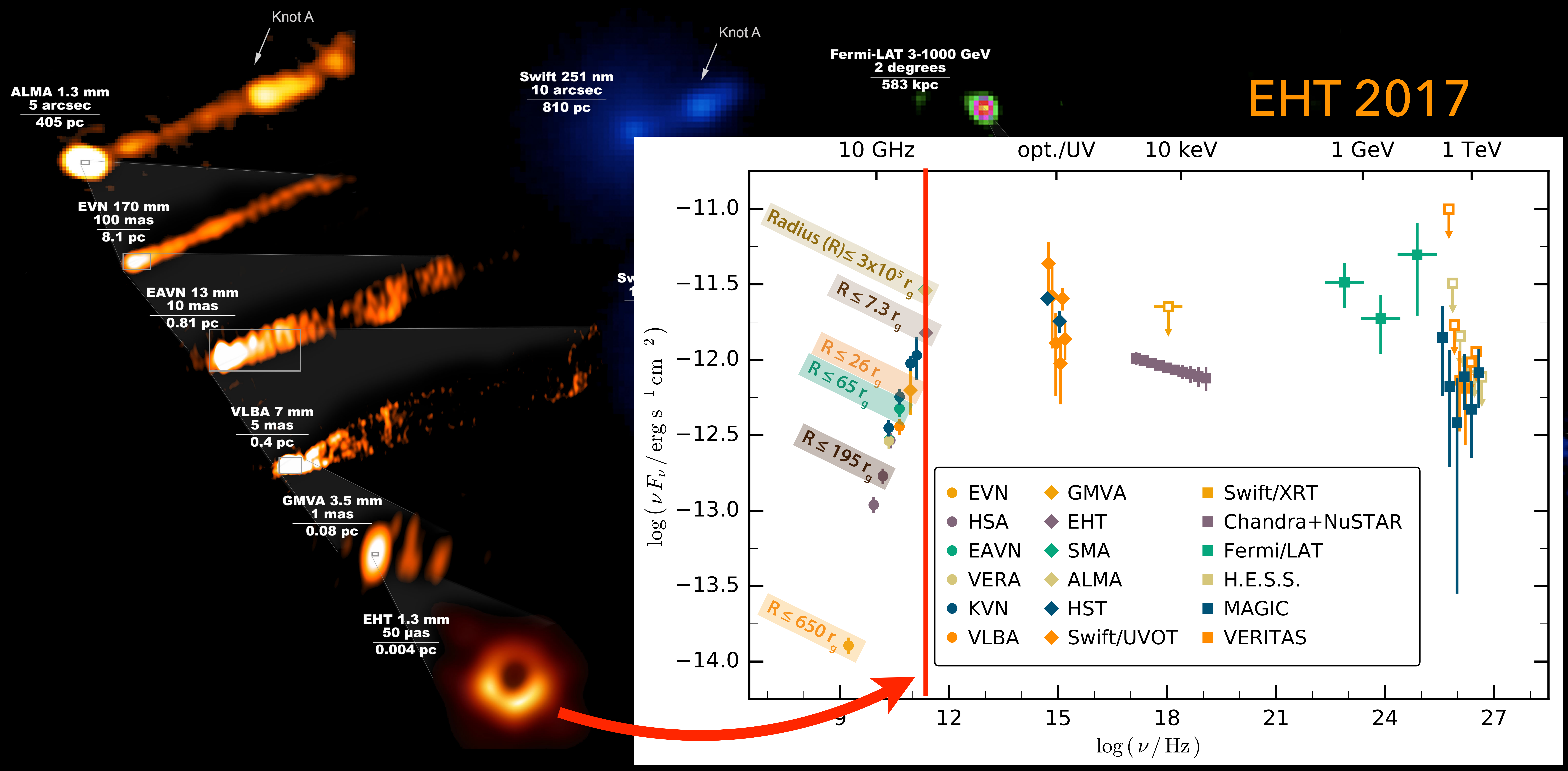
(2D 6000x800x1 resolution: Chatterjee, Liska, Tchekhovskoy & SM 2019 using H-AMR: Liska, Chatterjee, Tchekhovskoy++ 2019)

And…each model should also describe core shift and the broadband SED!

(EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN++ 2021, ApJL)

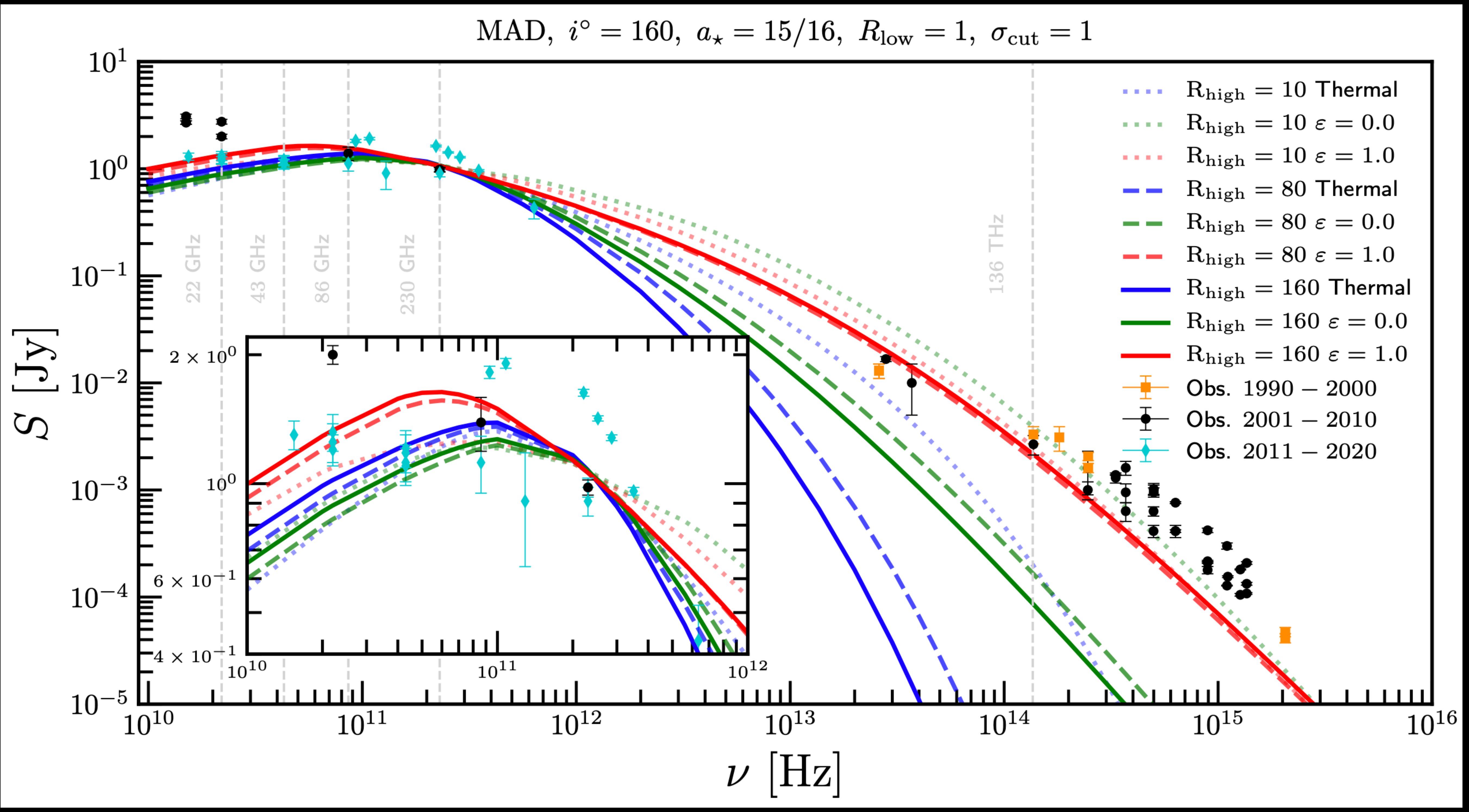
And…each model should also describe core shift and the broadband SED!

EHT 2017

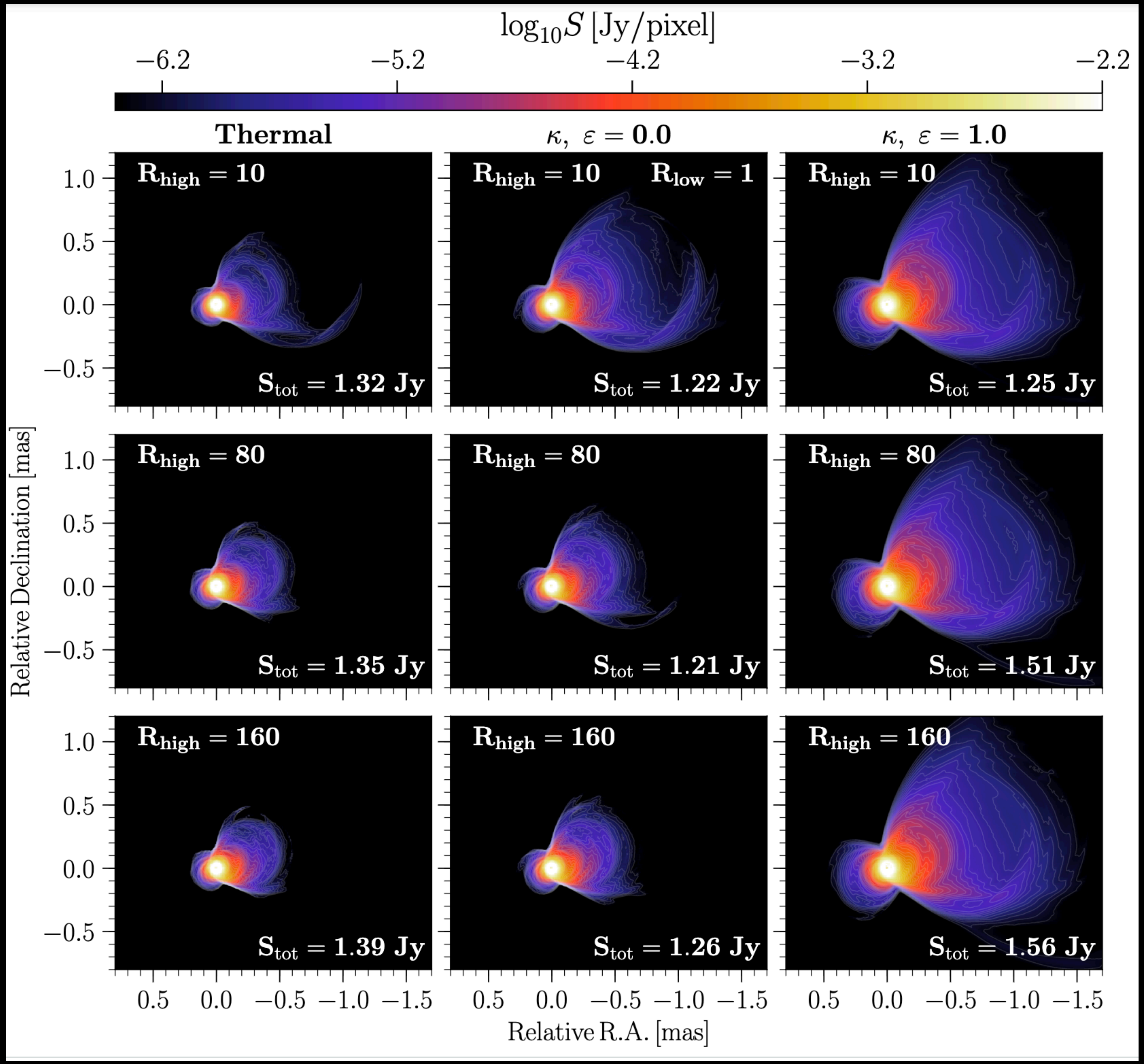


(EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN++ 2021, ApJL)

The new horizon: combined image + SED modelling



Radio to optical SED fitting by Fromm++22



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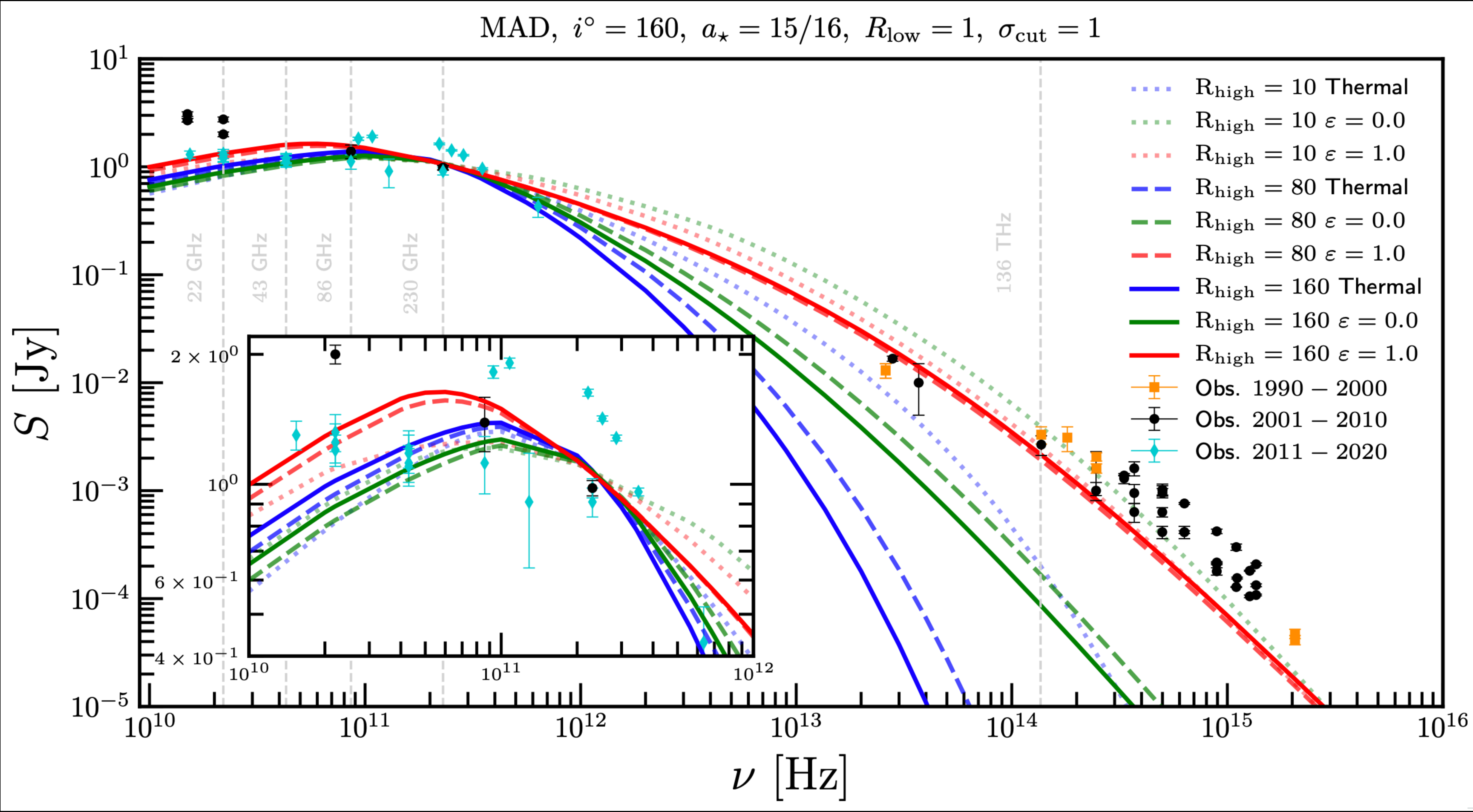

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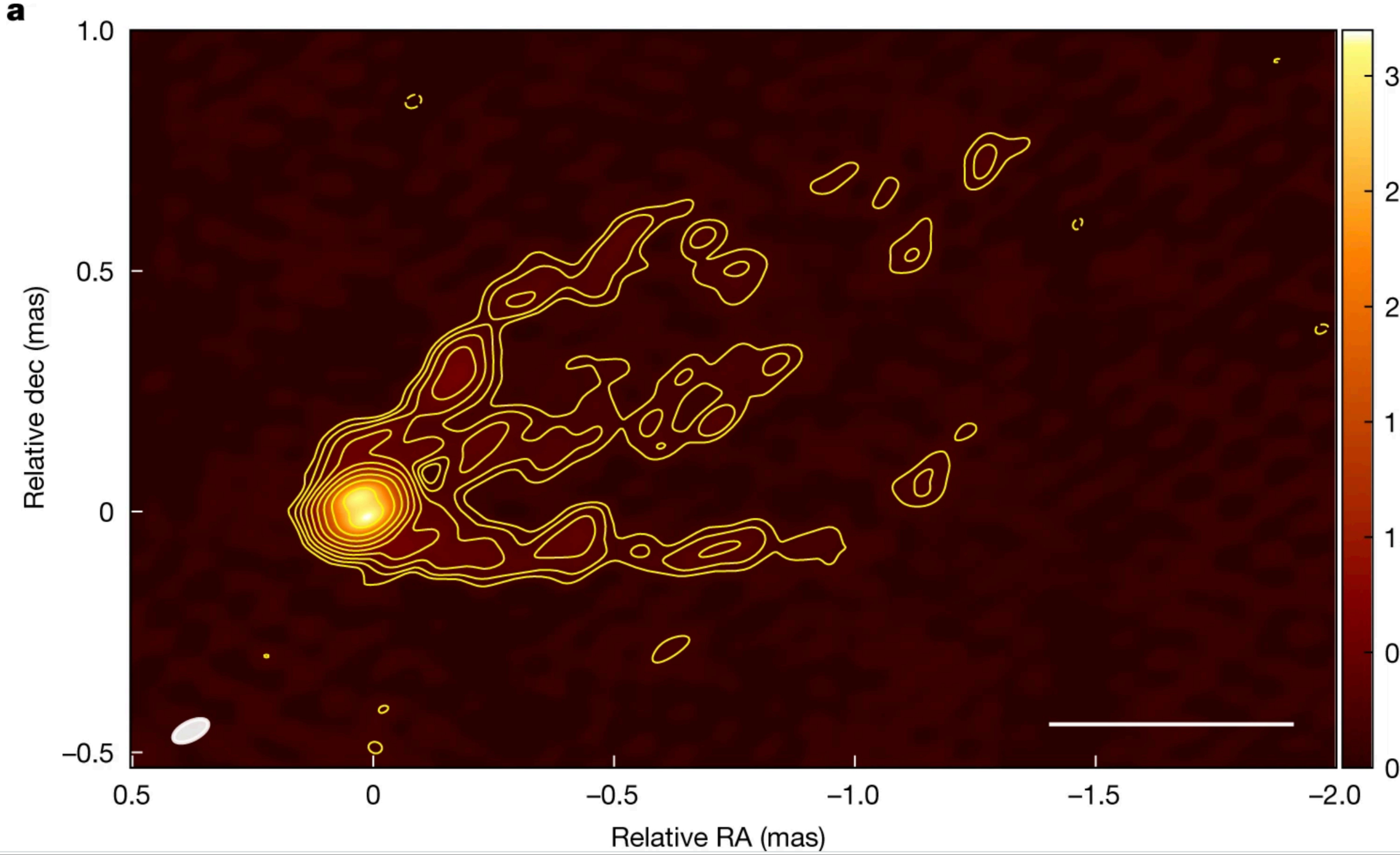
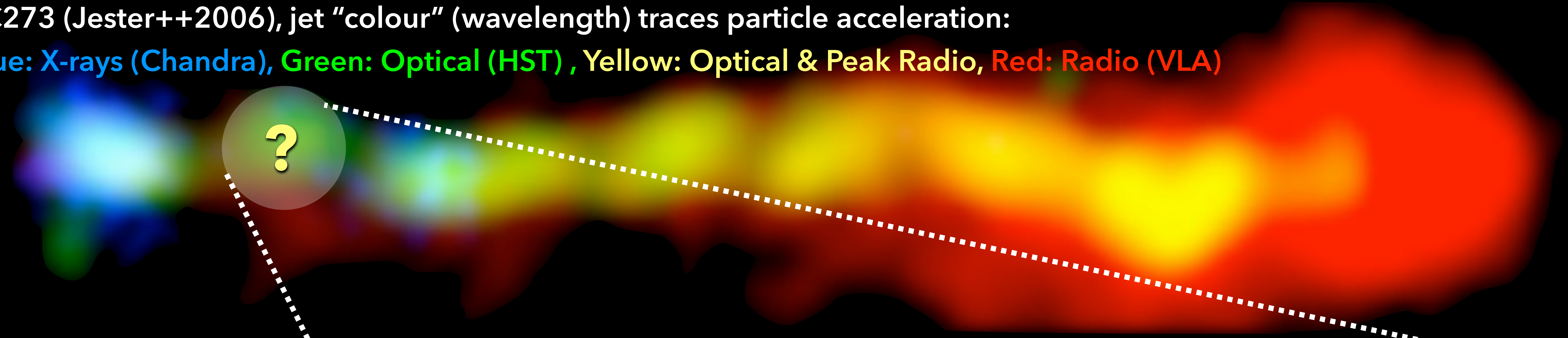


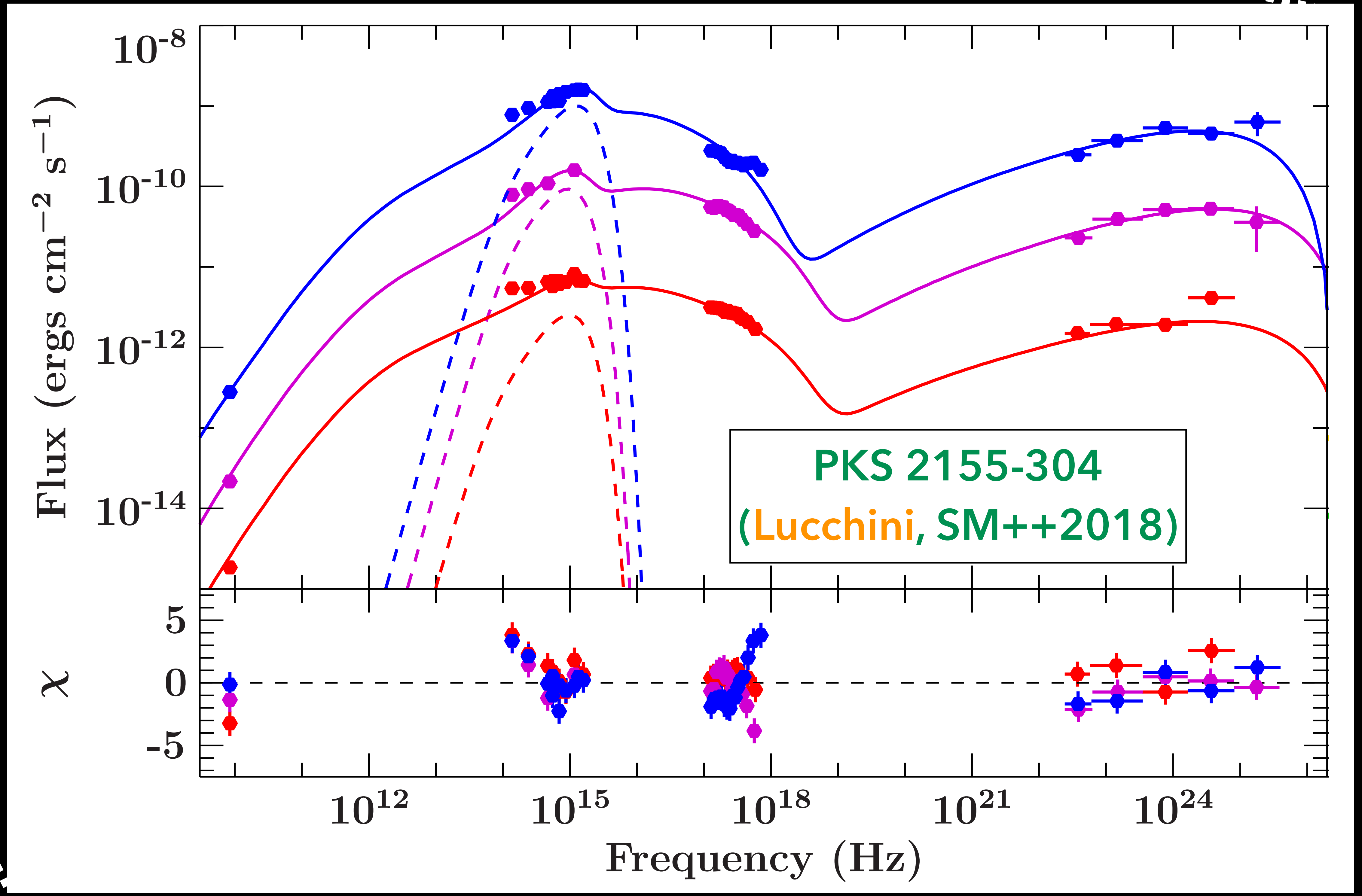
86 GHz radio image from Lu++2023, Nature

Understanding = localising: particle acceleration and VHE γ-rays

3C273 (Jester++2006), jet "colour" (wavelength) traces particle acceleration:

Blue: X-rays (Chandra), Green: Optical (HST) , Yellow: Optical & Peak Radio, Red: Radio (VLA)





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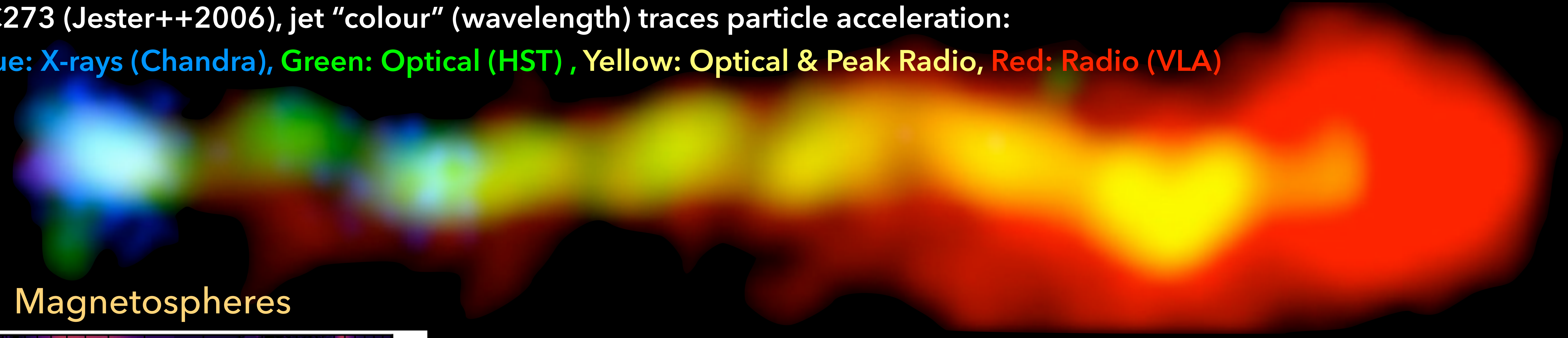
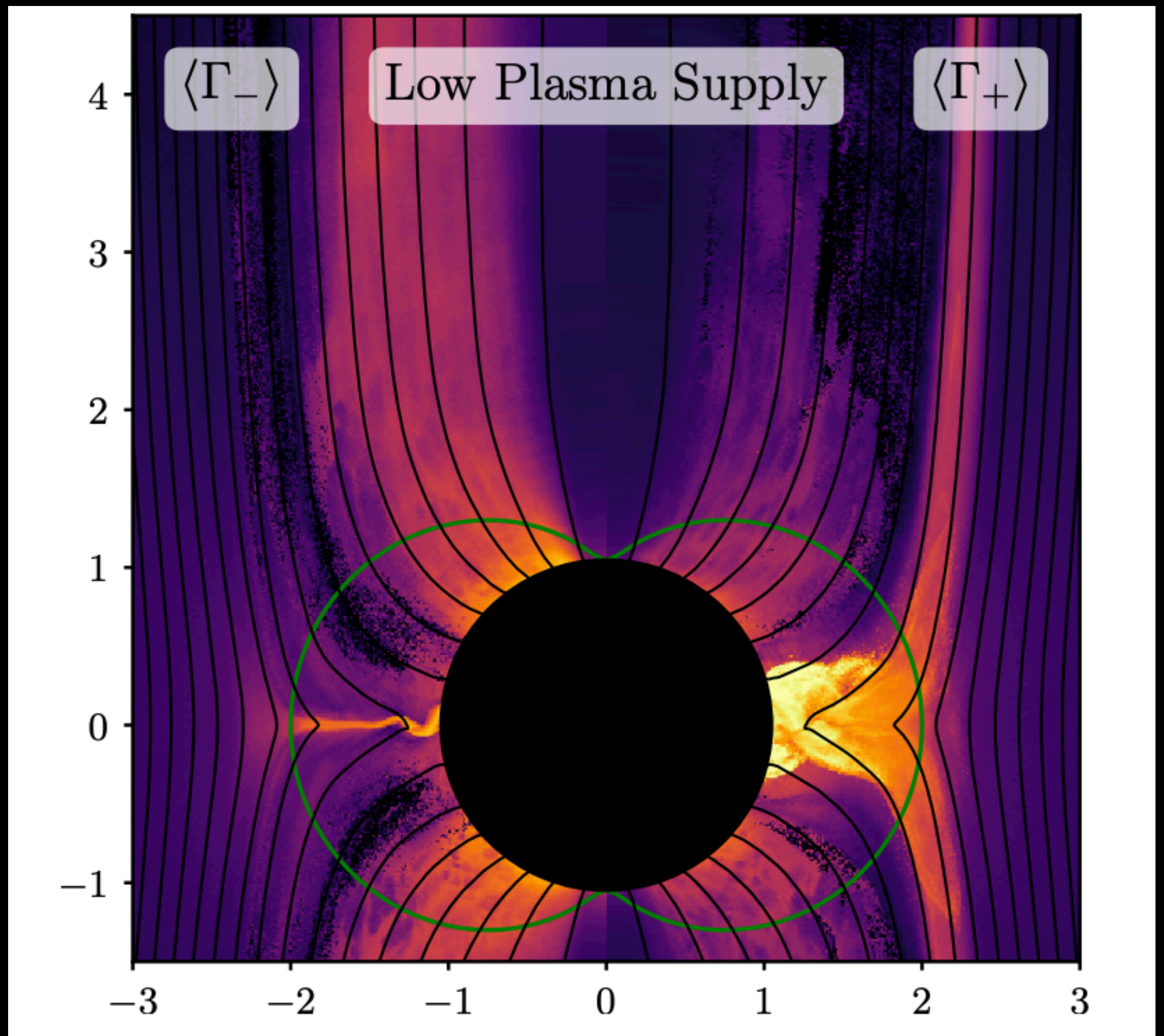
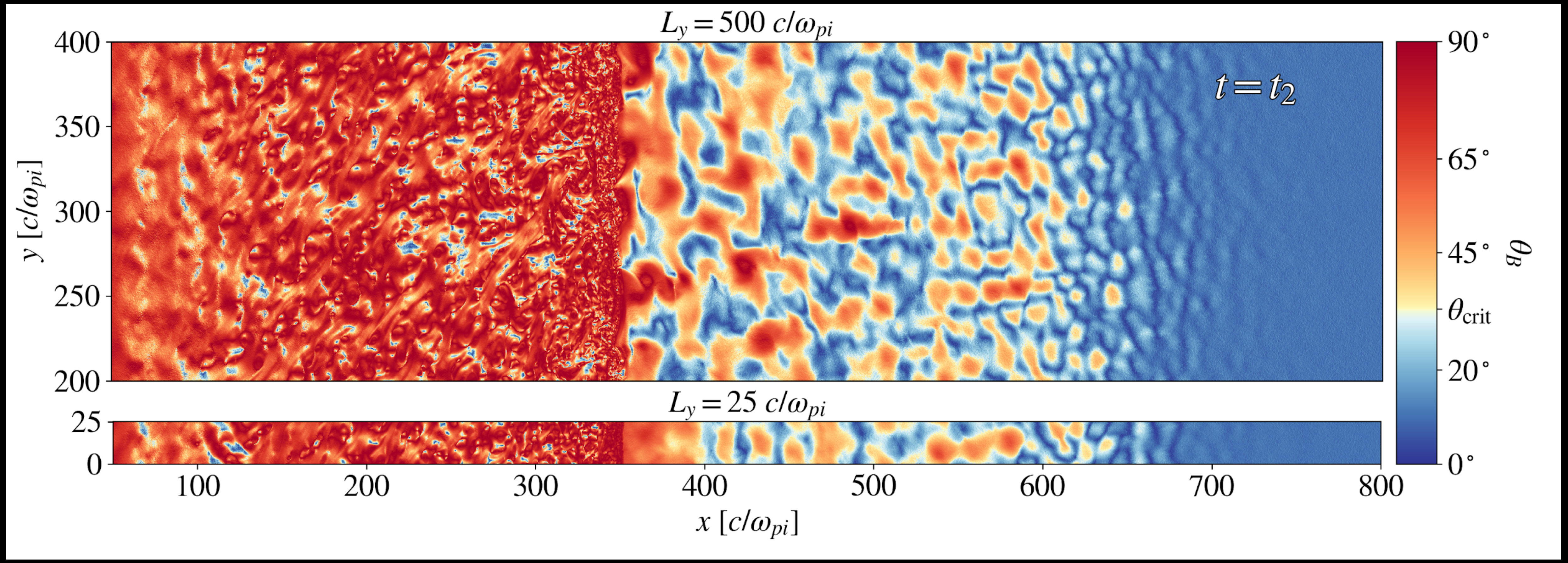


Magnetospheres



Parfrey, Philippov & Cerutti 2019
Bransgrove, Ripperda & Philippov 2021
Hakobyan, Ripperda & Philippov 2023
and many others...

Shocks/turbulence (umbrella terms for many mechanisms)



Crumley++2019, Sironi++2021; and see work by eg:
Bell; Jokipii; Drury; Marscher; Böttcher, and many others...

M87 2018 MWL campaign: localising γ-ray flares?

- Most significant γ-ray flare since 2010!
- Enhanced activity in higher energy bands overall compared to 2017, while radio/mm seems fairly unchanged (see e.g. Hakobyan++2023 for one scenario)
- Offers a chance to test jet/particle acceleration link with an unprecedented set of constraints ➠ value of monitoring

EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN, in prep.

Next decade(s): EHT++ and multiwavelength monitoring of many AGN!

Credits: (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss++(Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)+ Janssen, EHT++21, Nat Astro) , (NGC 1265: M. Gendron-Marsolais++; S. Dagnello, NRAO/AUI/NSF; SDSS),(3C279, EHT),(3C293, Chandra),(Mrk501, Giroletti/VLBA/HO/RO/HALCA),(NGC1068; Kadler/VLBA), (NRAO530, Zhao++/JVLA + Jorstad, Wielgus+EHT++23) , (OJ287, Marscher&Jorstad/Chandra/VLA)

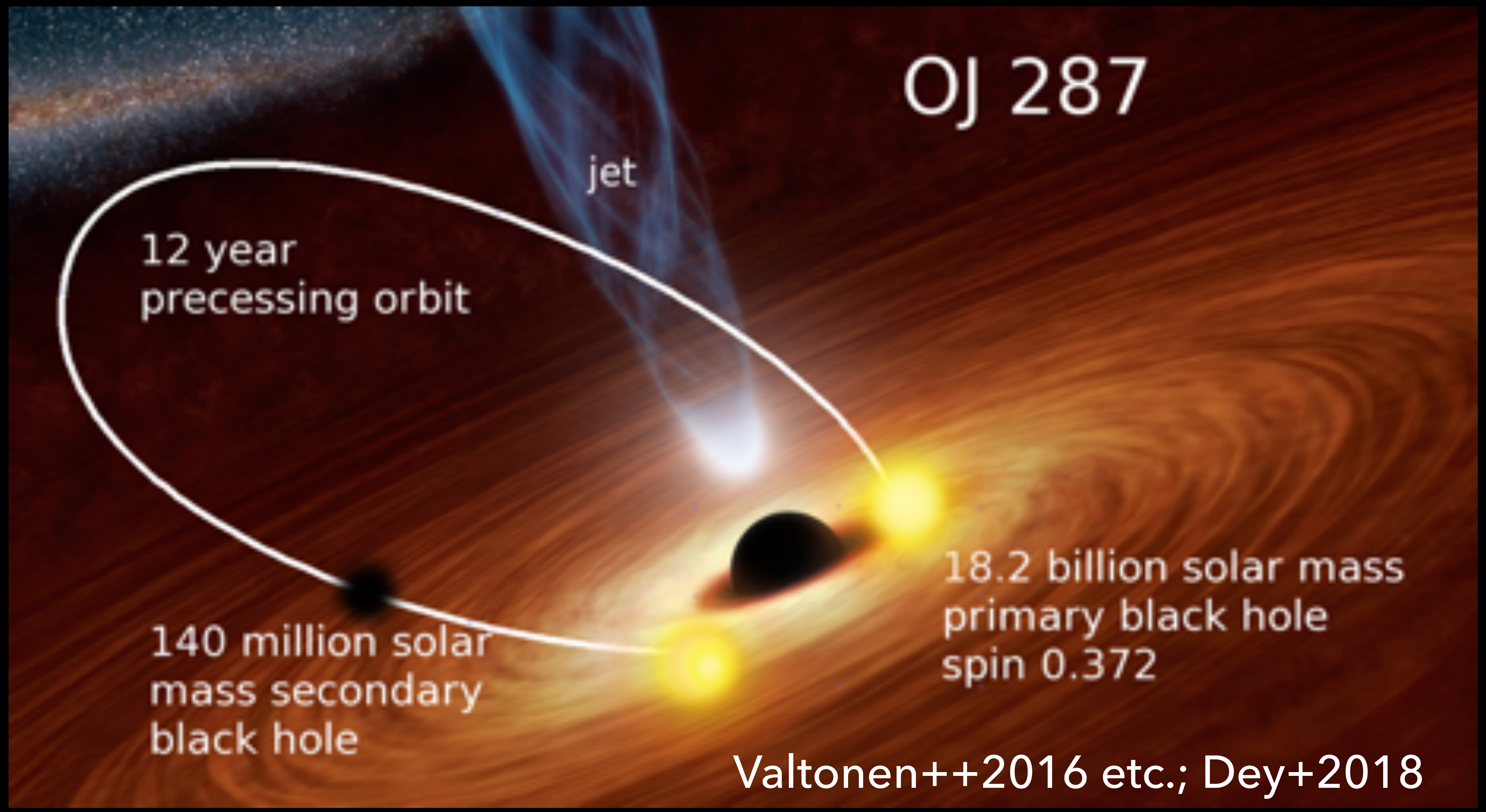
(Slide adapted from M. Moscibrodzka)

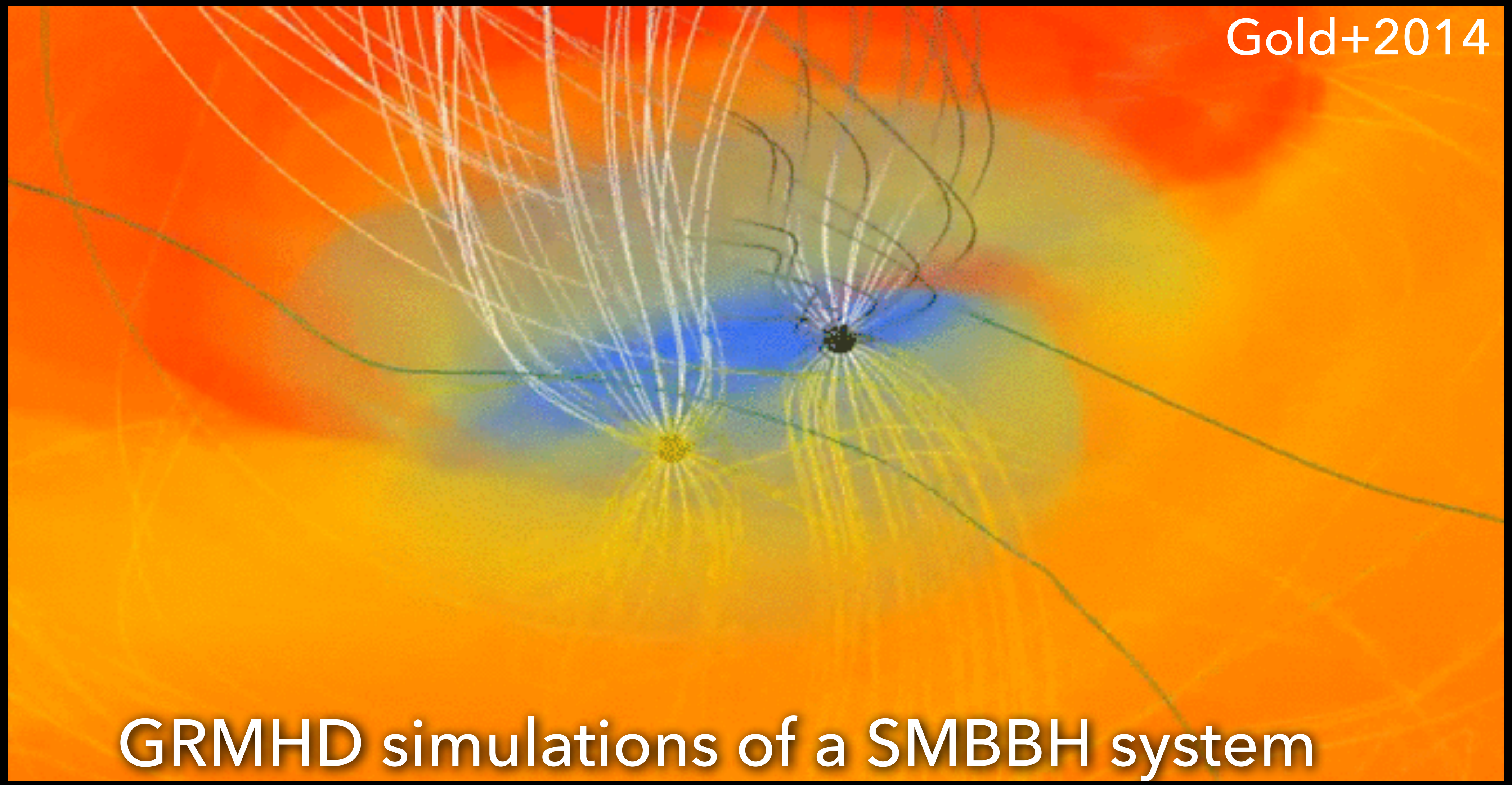
Next decade(s): EHT++ and multiwavelength monitoring of many AGN!

Credits: (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss++(Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)+ Janssen, EHT++21, Nat Astro) , (NGC 1265: M. Gendron-Marsolais++; S. Dagnello, NRAO/AUI/NSF; SDSS),(3C279, EHT),(3C293, Chandra),(Mrk501, Giroletti/VLBA/HO/RO/HALCA),(NGC1068; Kadler/VLBA), (NRAO530, Zhao++/JVLA + Jorstad, Wielgus+EHT++23) , (OJ287, Marscher&Jorstad/Chandra/VLA)

(Slide adapted from M. Moscibrodzka)

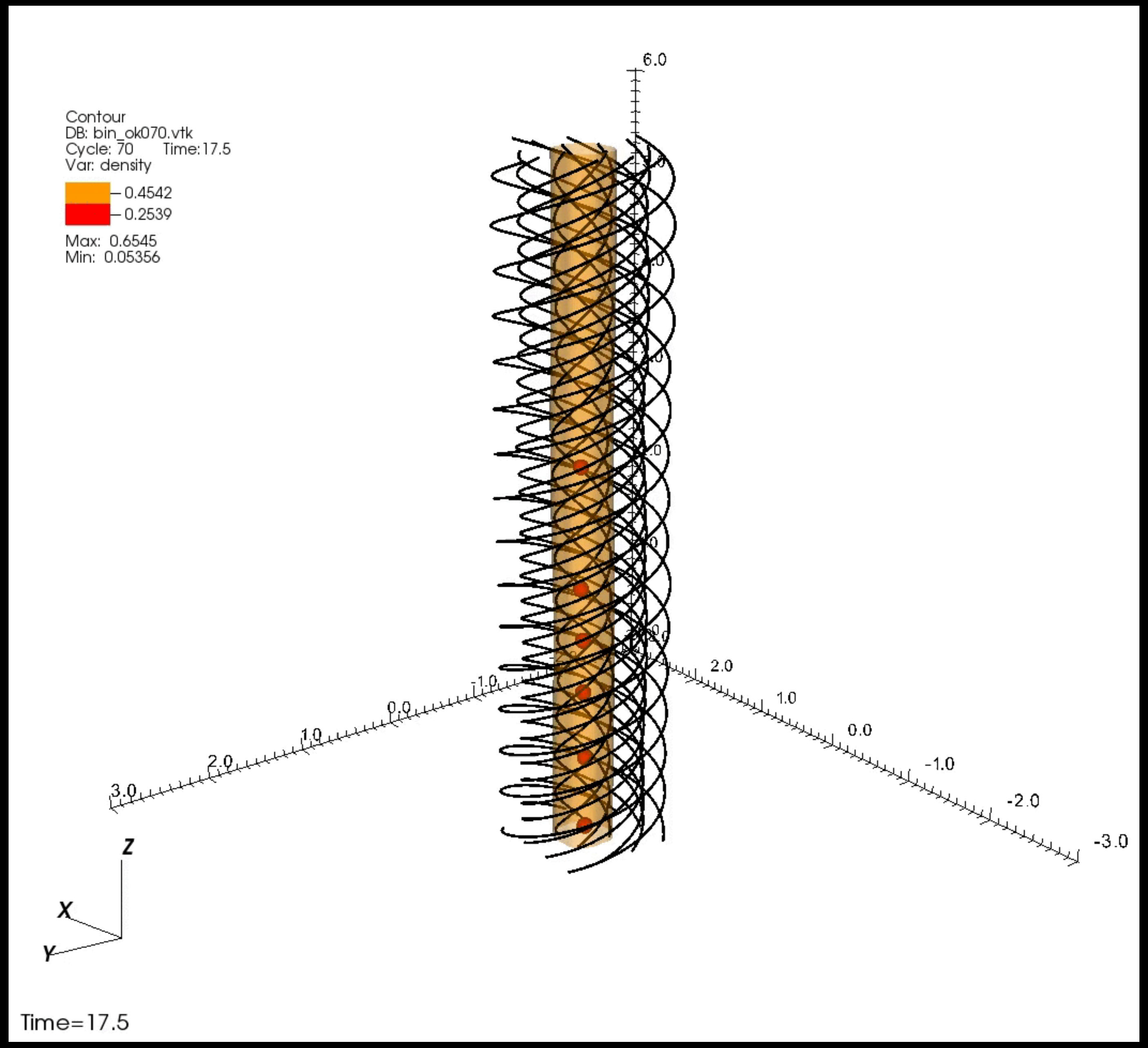
OJ 287: Is it really a binary black hole??

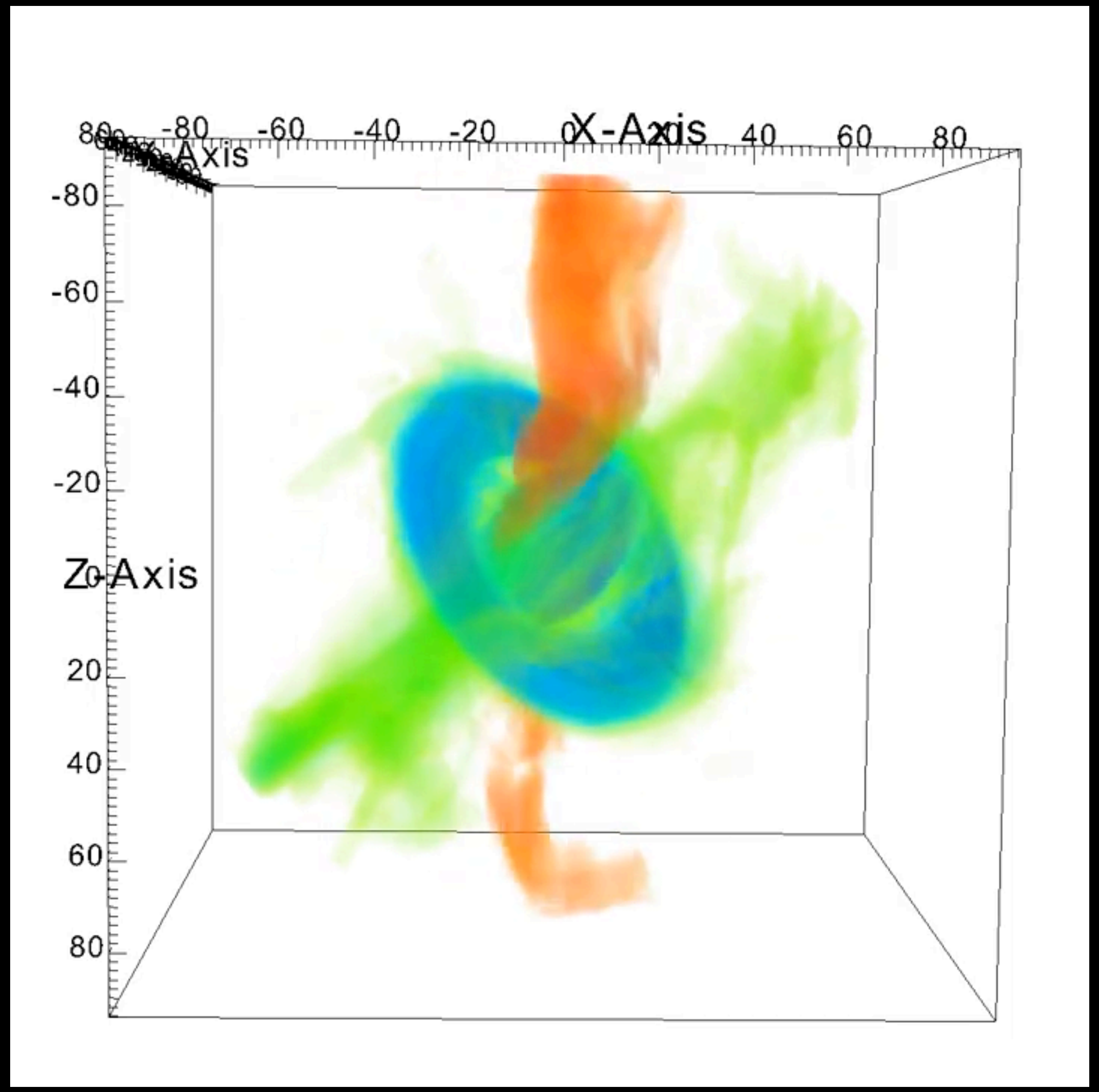




But other options do exist!

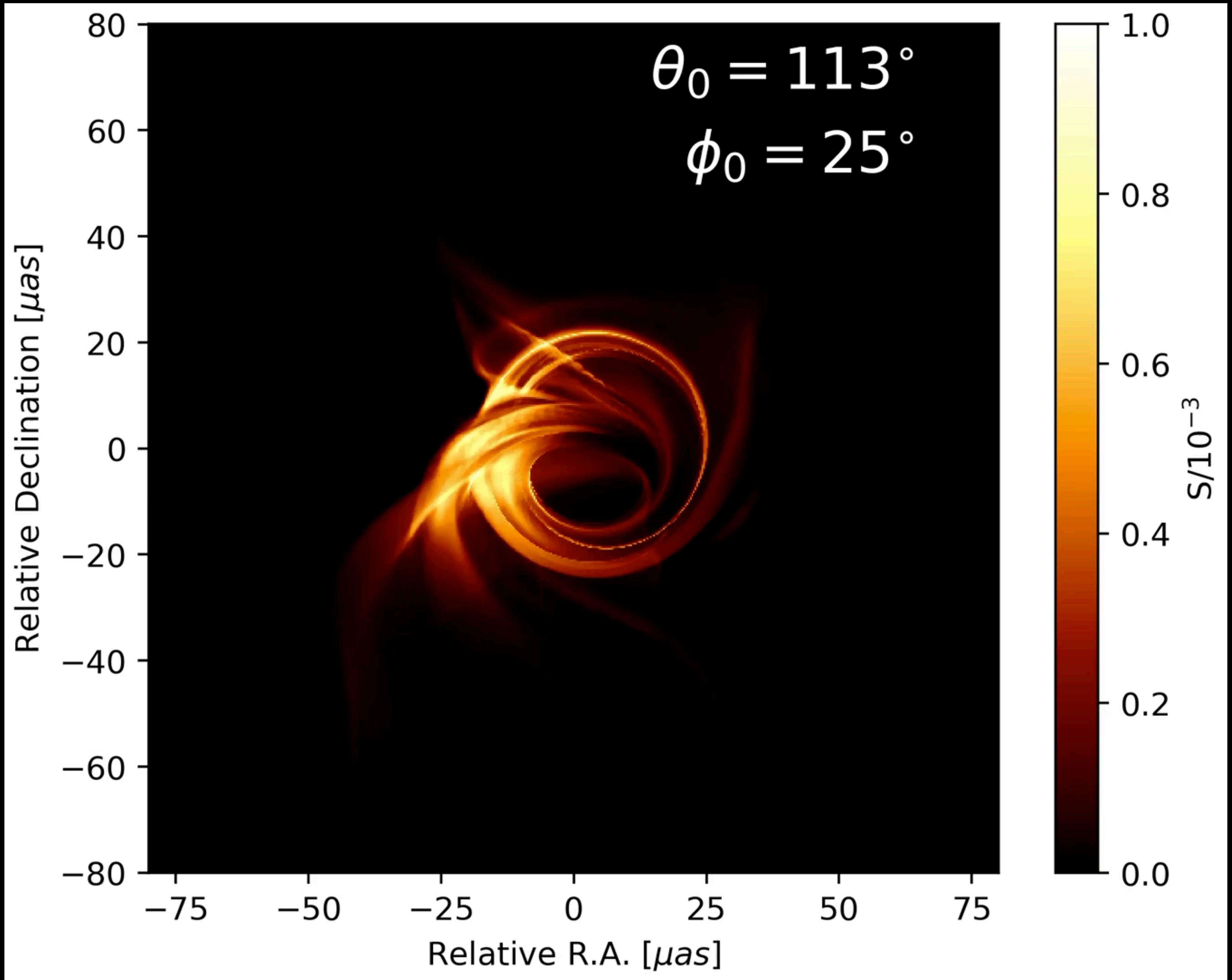
- Kink instabilities? (Y.Mizuno++2014; Singh, YM++2015, Kadowaki, YM++2020)
- Tilted accretion disk (Liska, Hesp, Tchekhovskoy, Ingram, vd Klis & SM 2018; Liska, Chatterjee++2019)

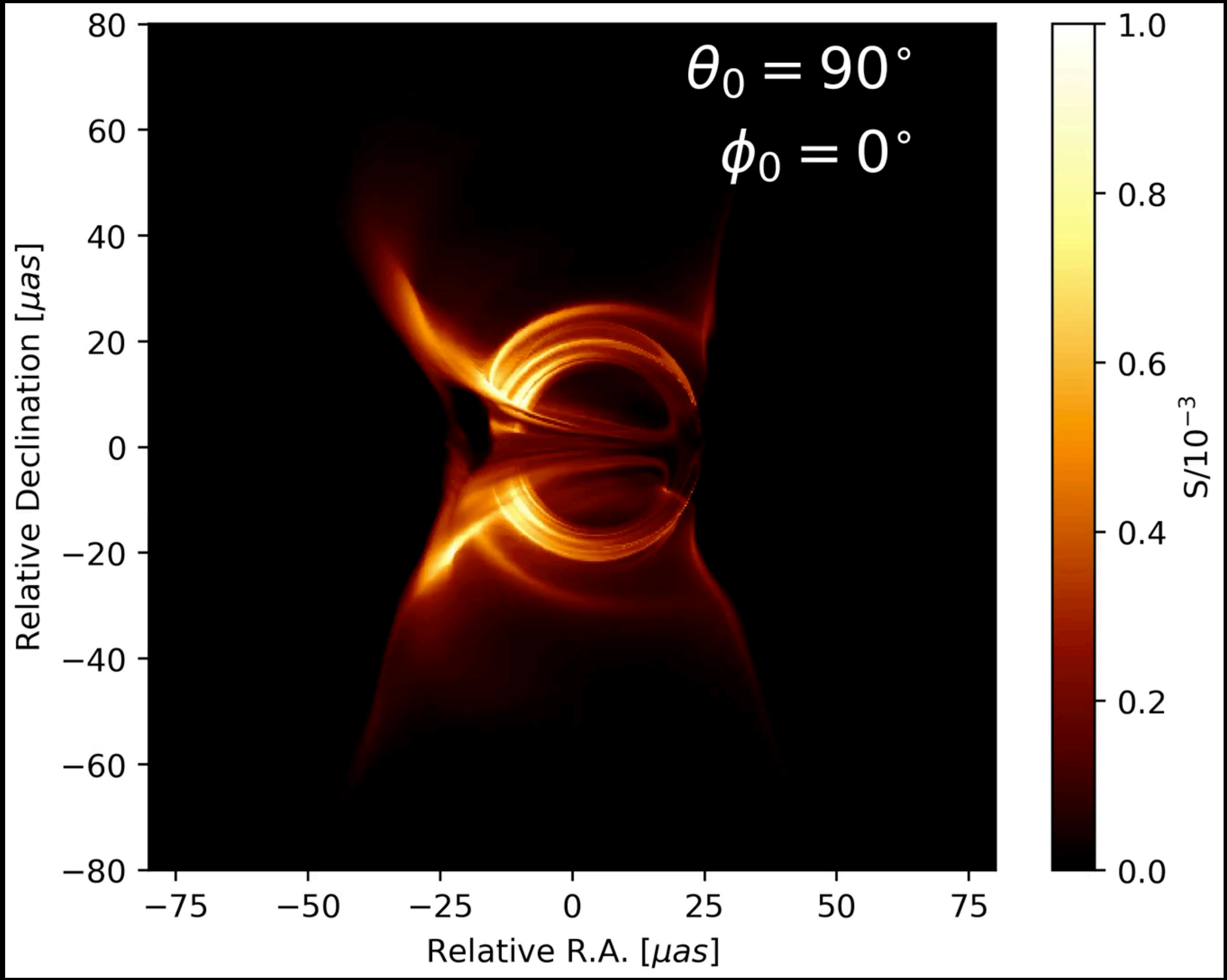




(Slide adapted from J.L. Gomez)

Exploring the effect of tilted disks (w/r/t black hole spin axis)

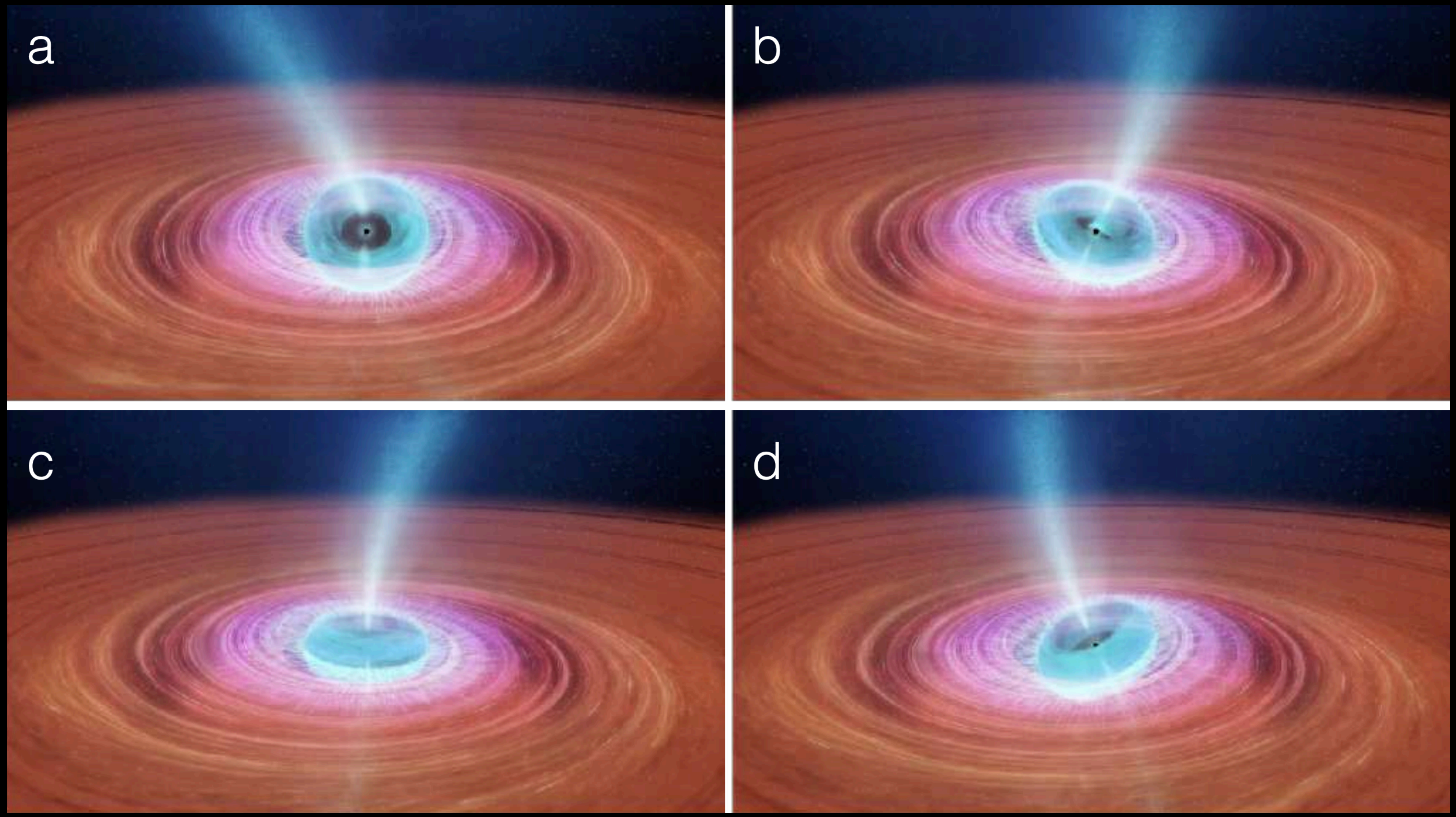




(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis & SM 2018; 2019; Chatterjee, Younsi, Liska, Tchekhovskoy, SM++ 2020)

Tilted black holes may explain a variety of observed phenomena

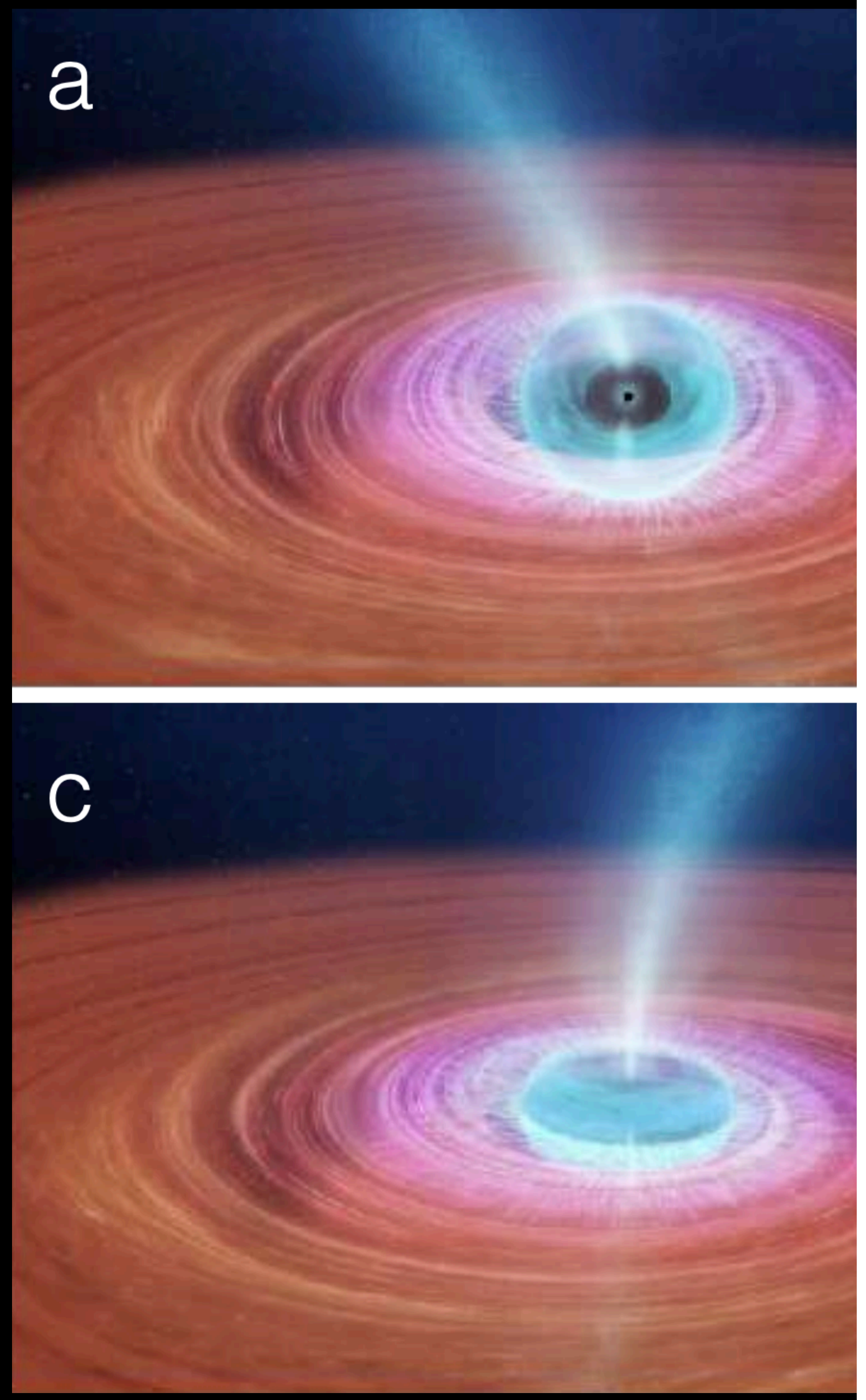
Precessing jets and low frequency QPOs



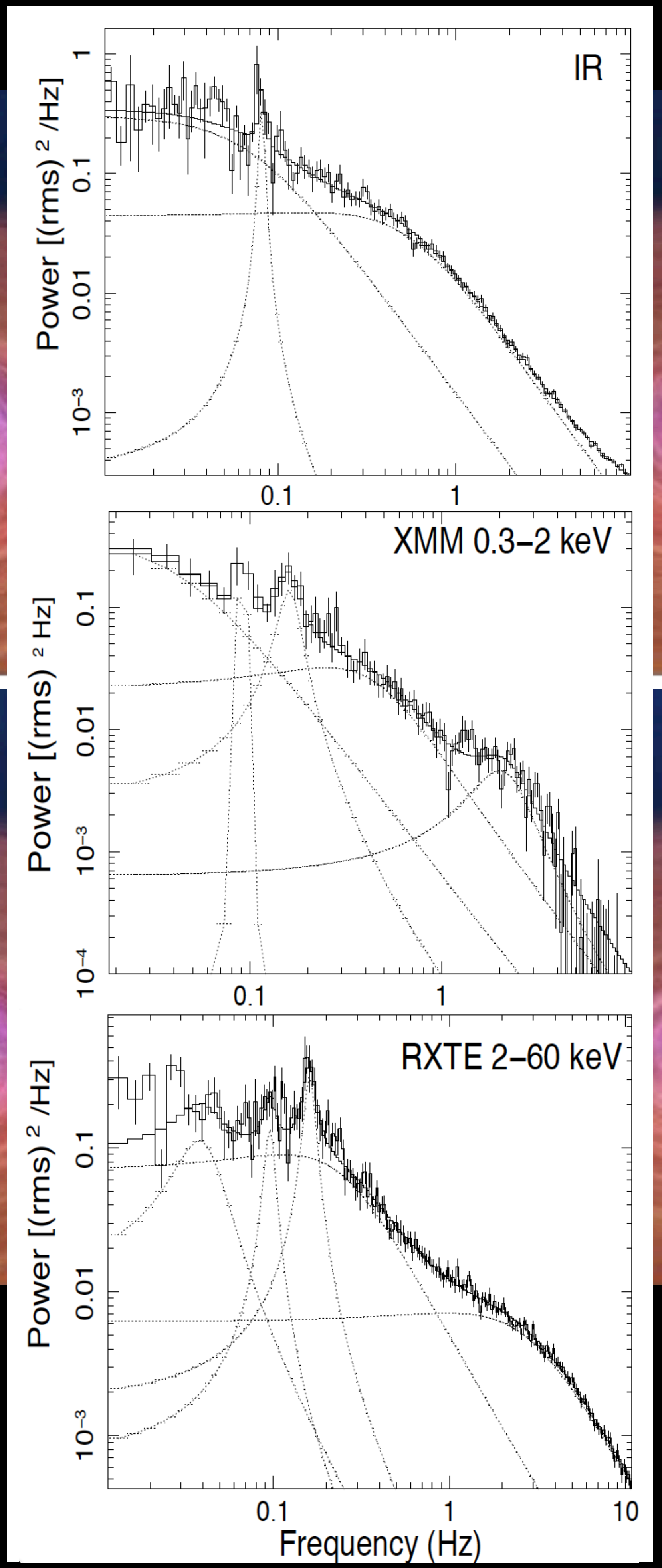
Ingram & Motta 2019

Tilted black holes may explain a variety of observed phenomena

Precessing jets and low frequency QPOs



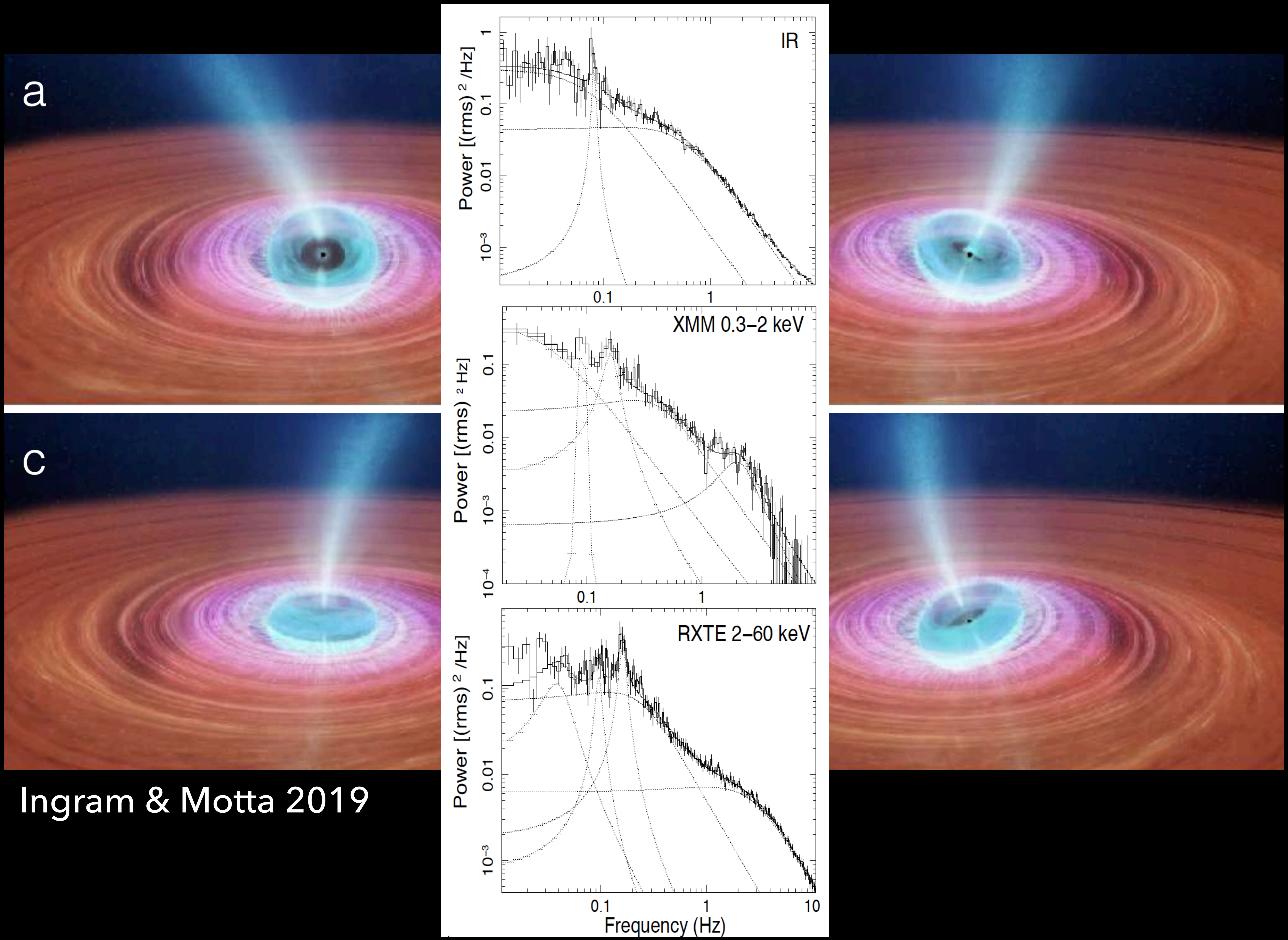
Ingram & Motta 2019



Kalamkar++2016

Tilted black holes may explain a variety of observed phenomena

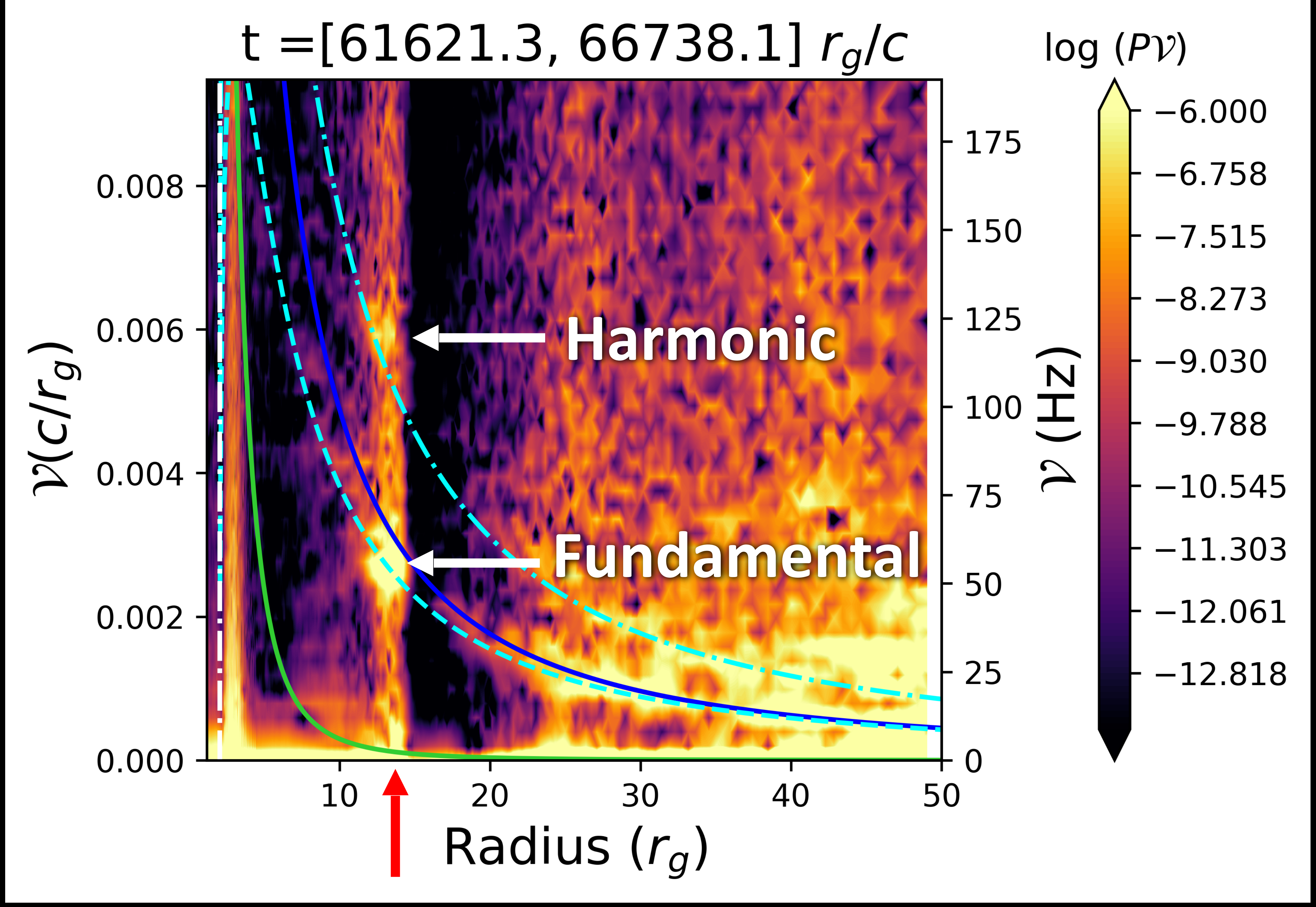
Precessing jets and low frequency QPOs



Ingram & Motta 2019

Kalamkar++2016

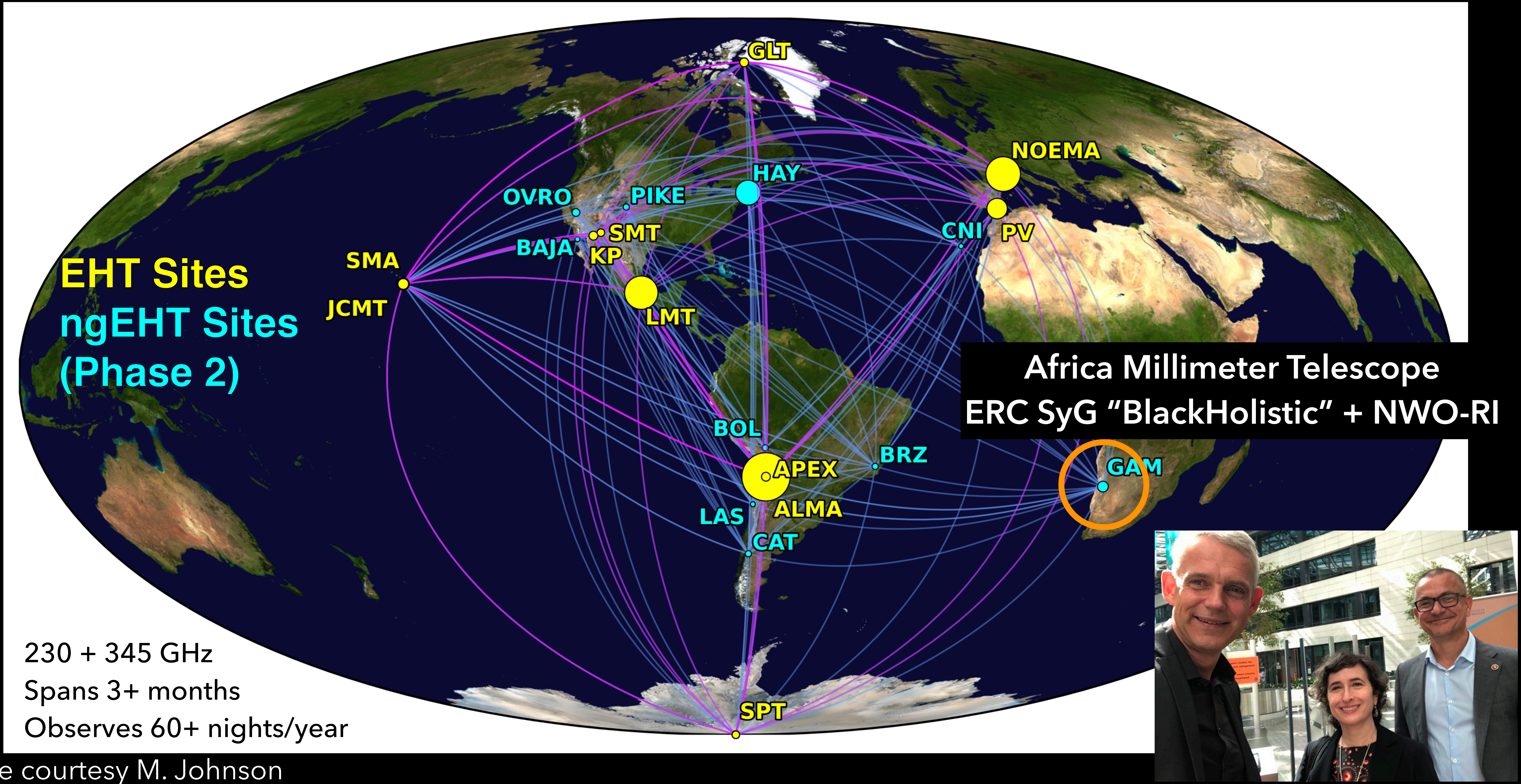
Radiation GRMHD: low & high frequency QPOs



r = 13 r_g (disk tearing radius)

Mishra++2017; Musoke, Liska, Porth++2023

Next generation EHT expansions in the planning/design phase



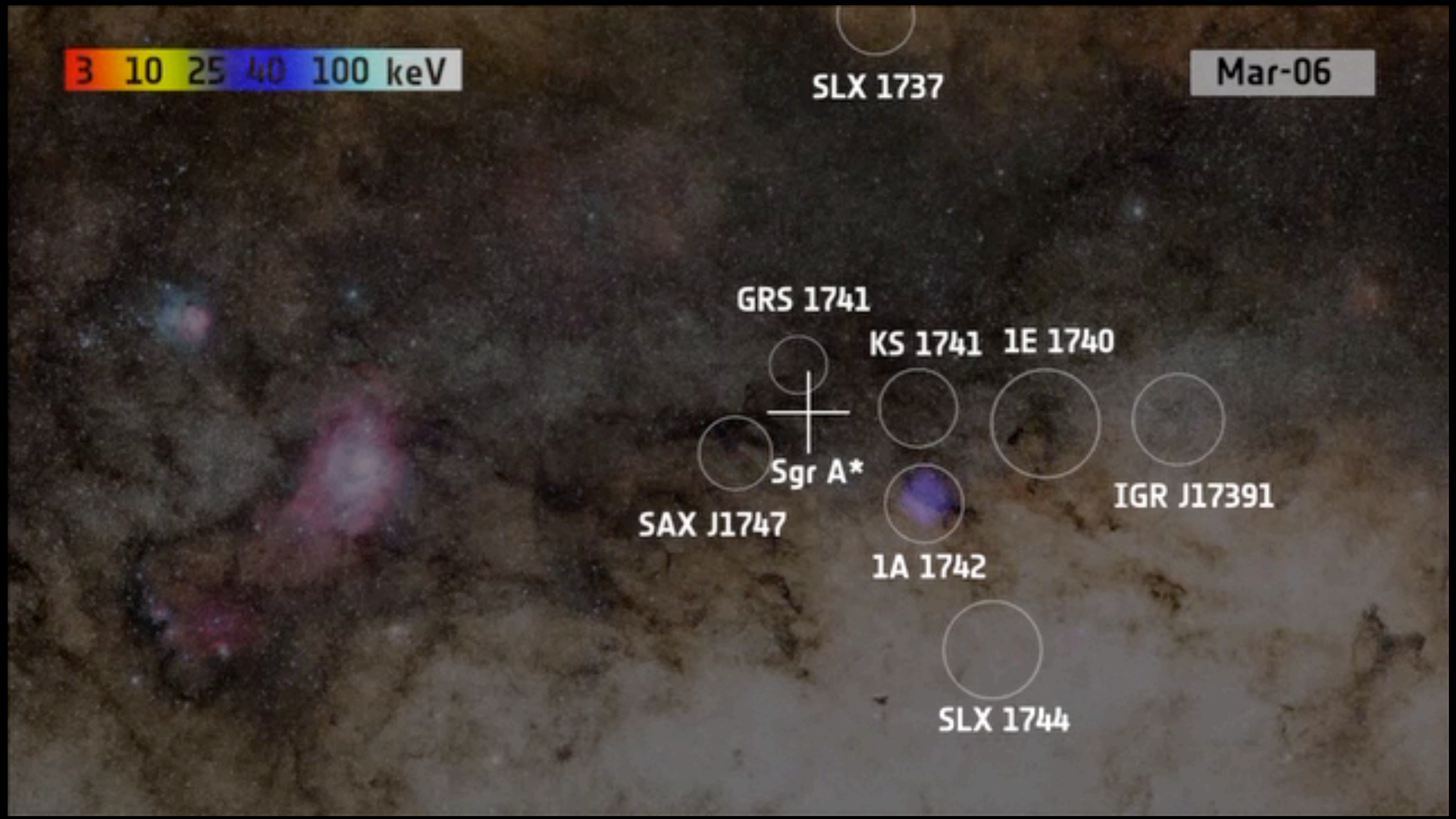
EHT Sites
ngEHT Sites
(Phase 2)

Africa Millimeter Telescope
ERC SyG “BlackHolistic” + NWO-RI

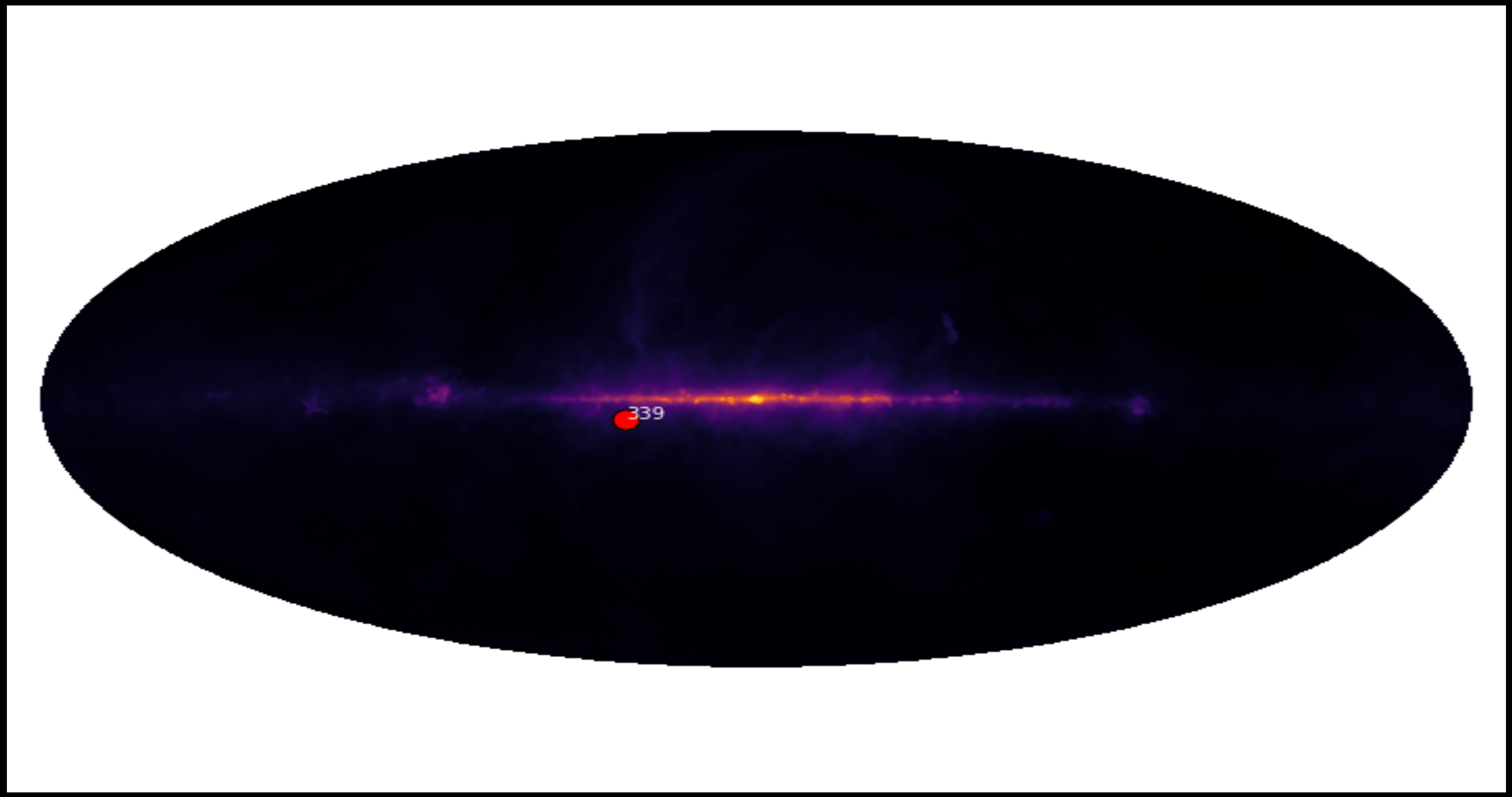
230 + 345 GHz
Spans 3+ months
Observes 60+ nights/year

Slide courtesy M. Johnson

AMT/EHT will discover and monitor new transients and AGN



The X-ray/gamma-ray transient sky from *INTEGRAL*



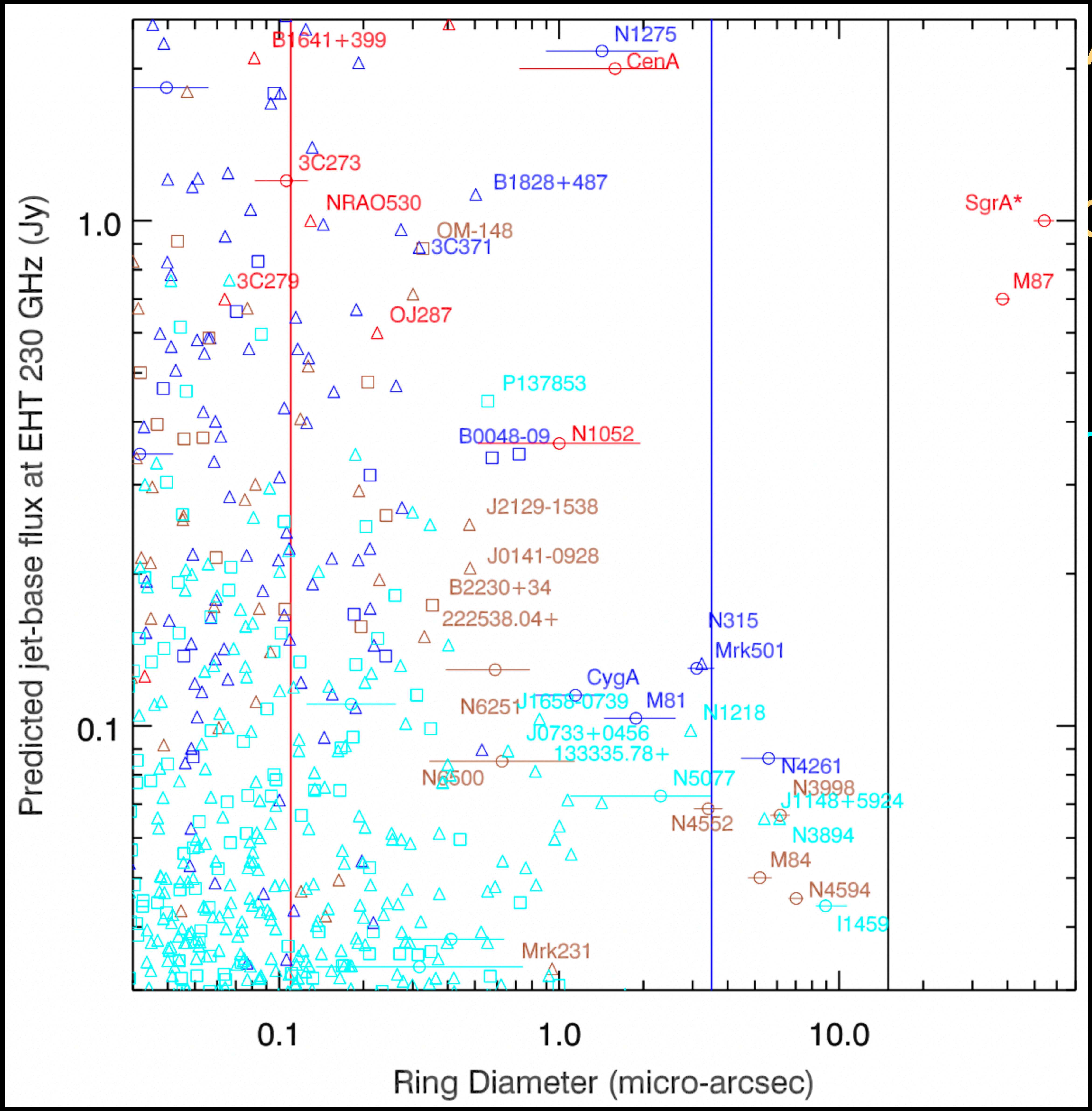
New radio transient monitoring with MeerKAT, co-led by ERC SyG Co-PI Fender (Oxford U)

AMT will enable the *first real-time census of black hole activity and explosive events* in the millimetre band, and AMT+EHT can actually resolve some of their jets!

Cherenkov Telescope Array (CTA): Full N/S sky coverage with unprecedented sensitivity

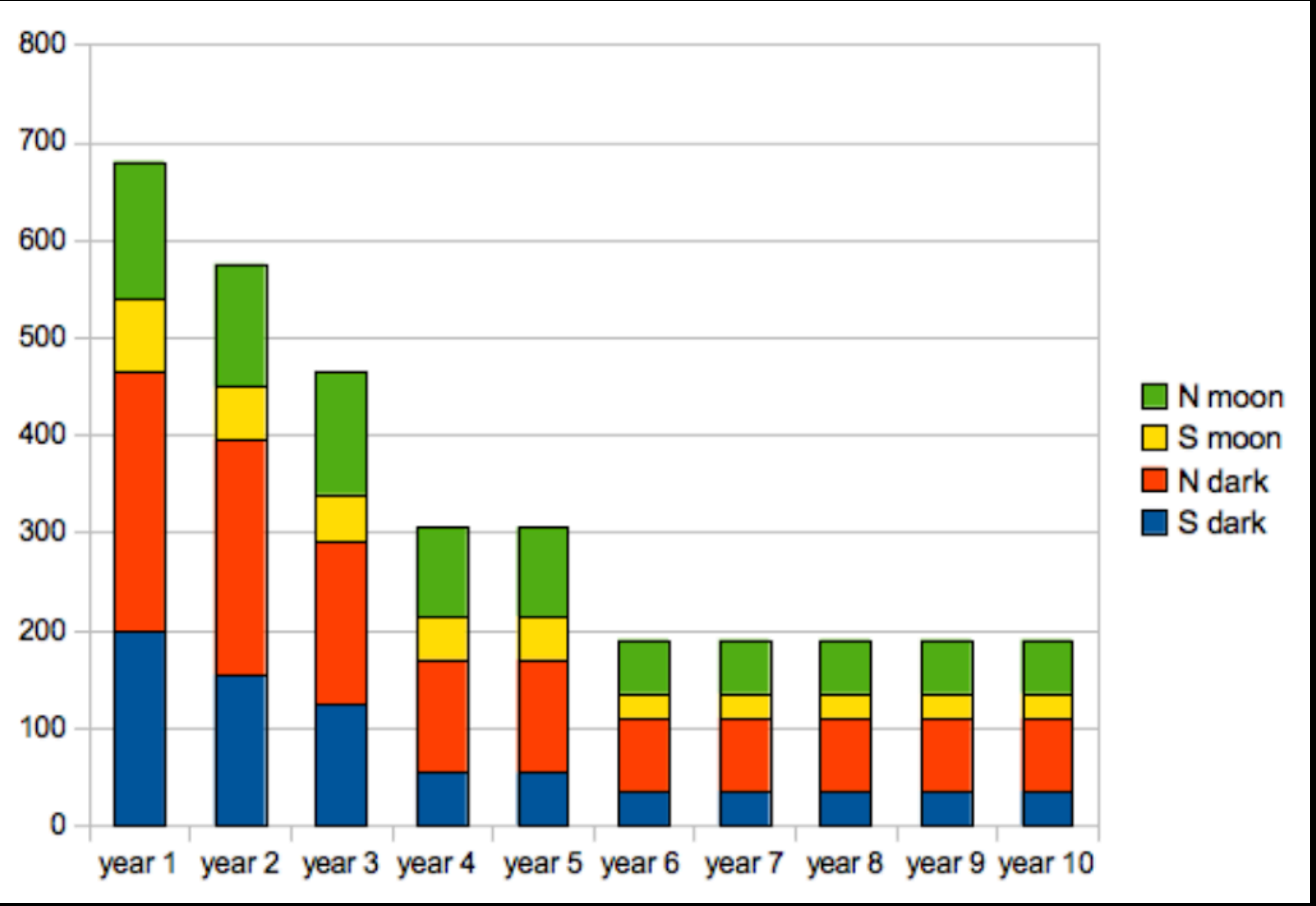
- 10x more sensitive, 3-5x better pointing accuracy, 2.5x larger FoV, and many orders of magnitude better at detecting fast transients!
- Largest (open) observatory in the VHE gamma-rays with two sites in both hemispheres for full sky access (~2029)

CTA AGN KSP: a decade of intense VHE γ-ray monitoring (w/AMT/EHT!)



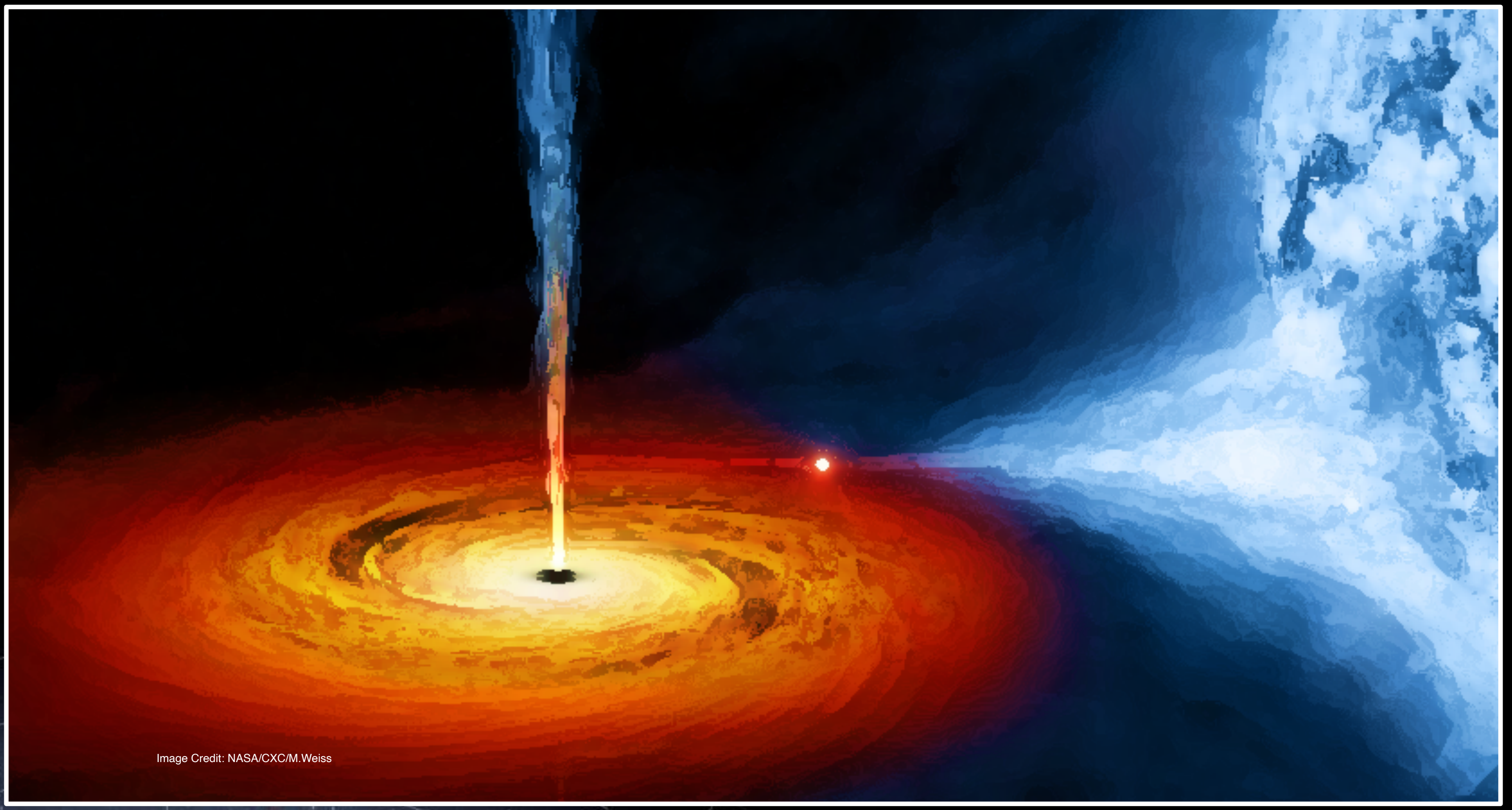
See "Science with CTA" ebook: arXiv:1709.07997

Programme	total N [h]	total S [h]	duration [yr]	observation mode
Long-term monitoring	1110	390	10 †	full array
AGN flares				
snapshots	1200	475	10 *	LSTs
snapshots	138	68	10 *	MSTs (assuming 10 sub-arrays)
verification ext. trig.	300	150	10 *	LSTs or MST sub-arrays
follow-up of triggers	725	475	10 *	full array
High-quality spectra				
redshift sample	195	135	3	full array
M 87 and Cen A	100	150	3	full array



(EvenT Horizon and EnviRons=ETHER sample; Ramakrishnan, Nagar++2023)

X-ray binaries as CR/γ-ray/ν sources



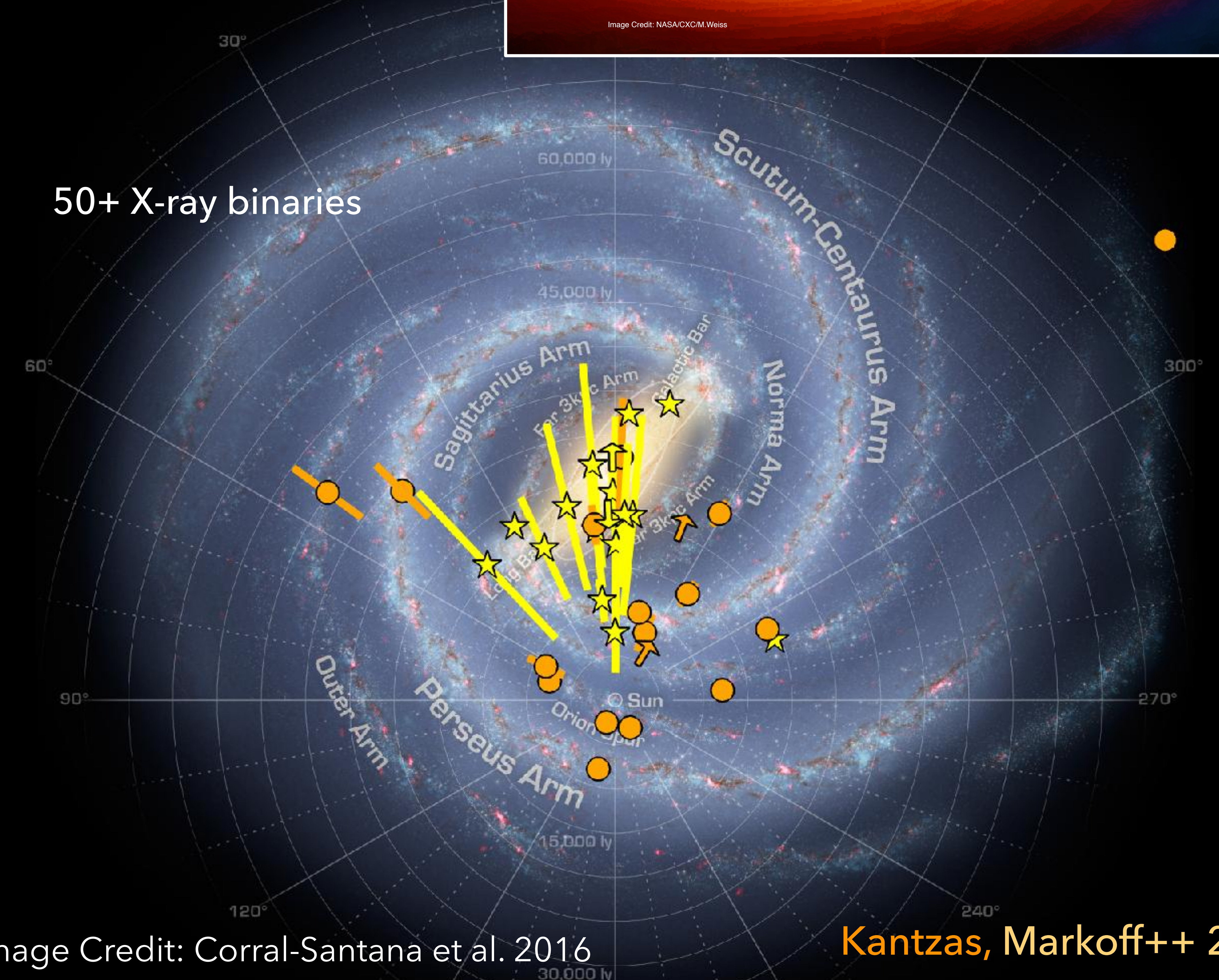
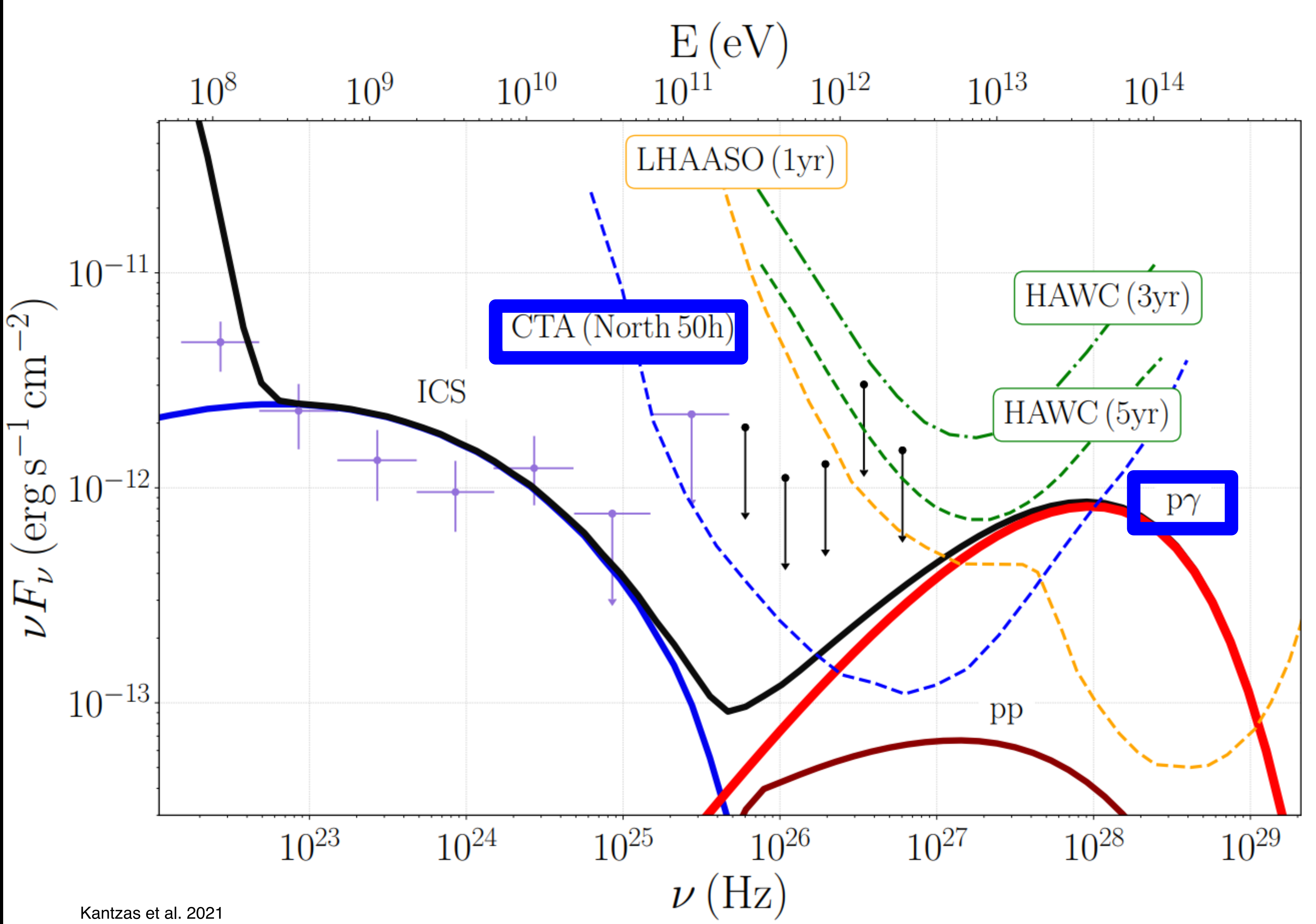
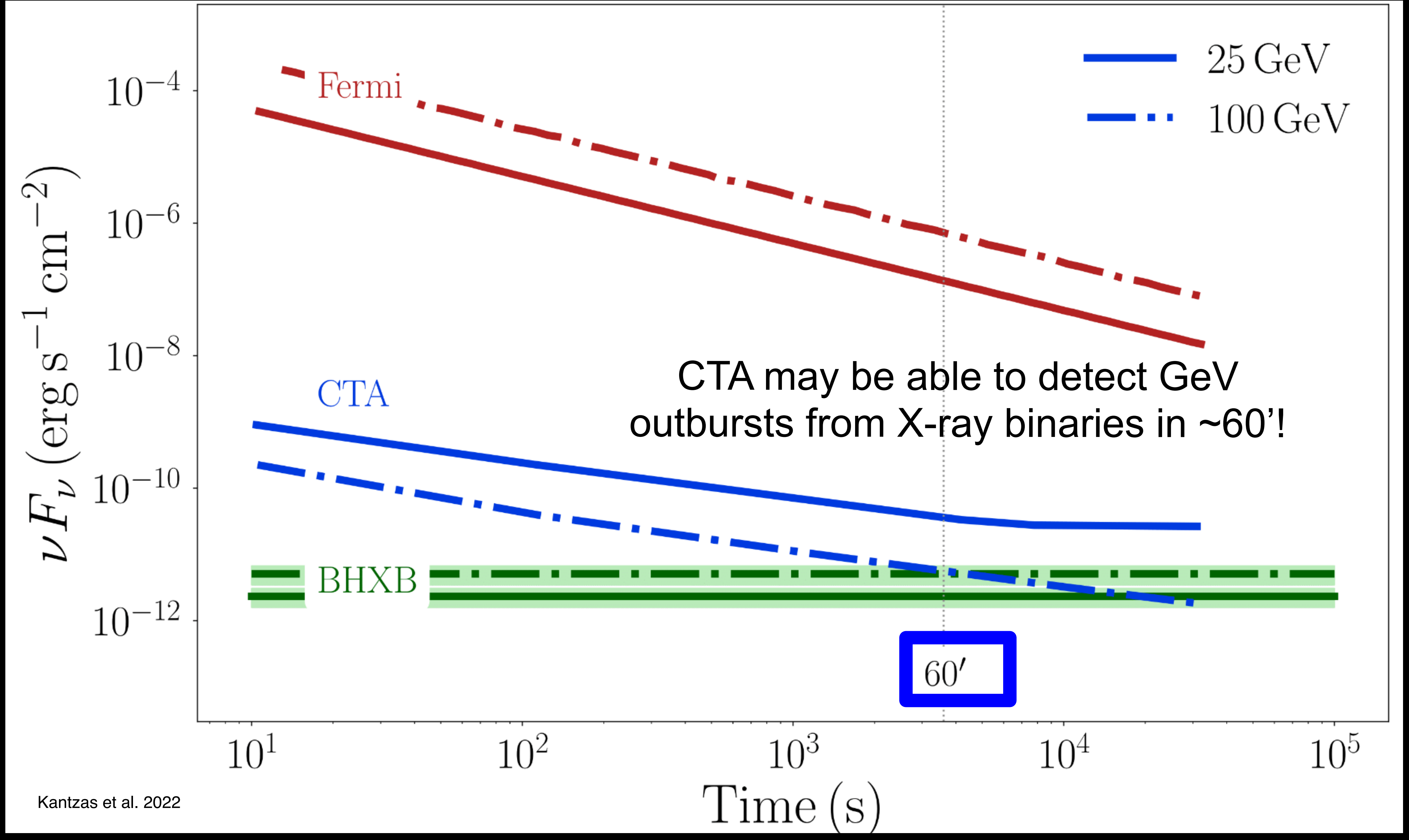


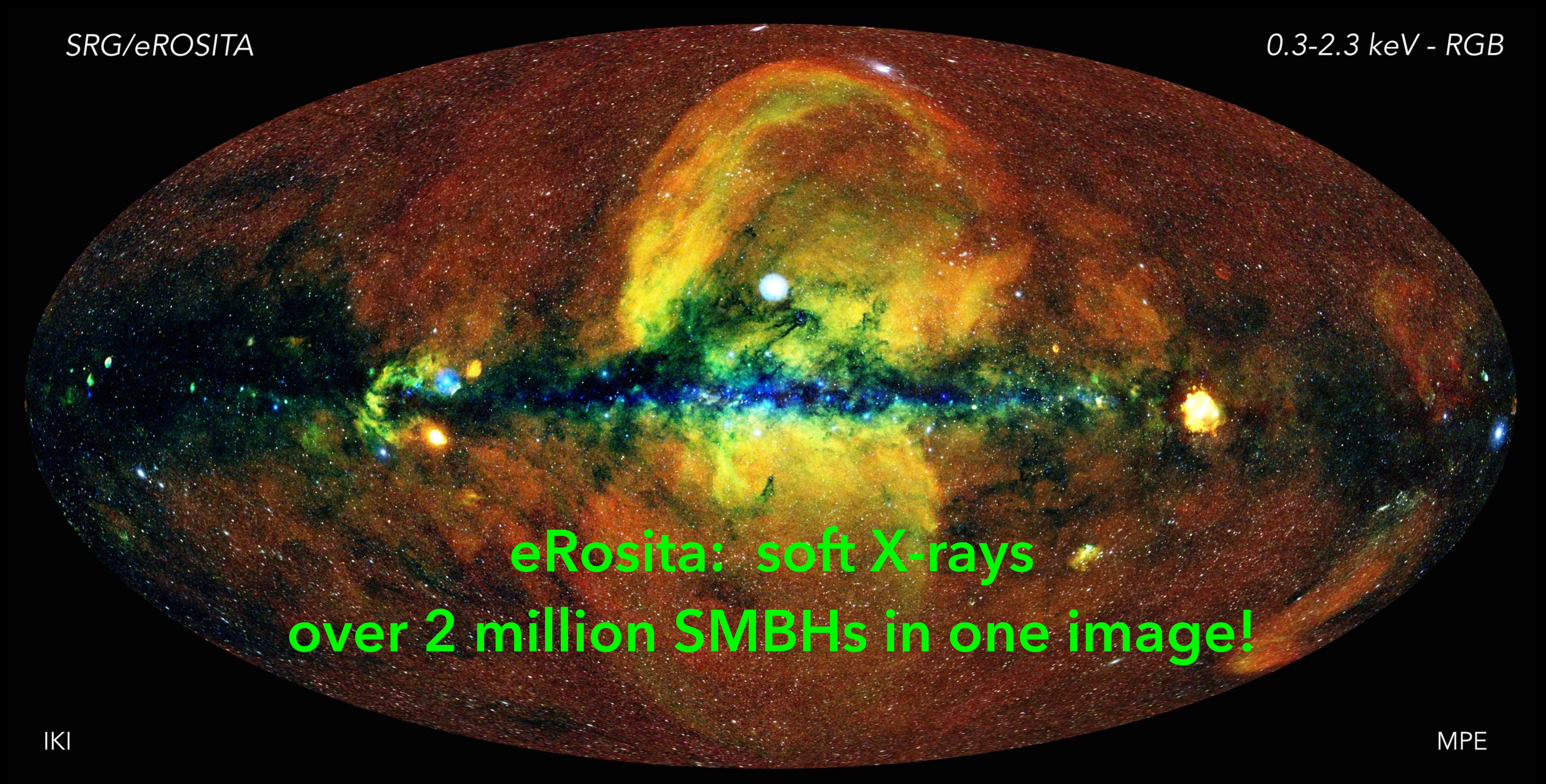
Image Credit: Corral-Santana et al. 2016





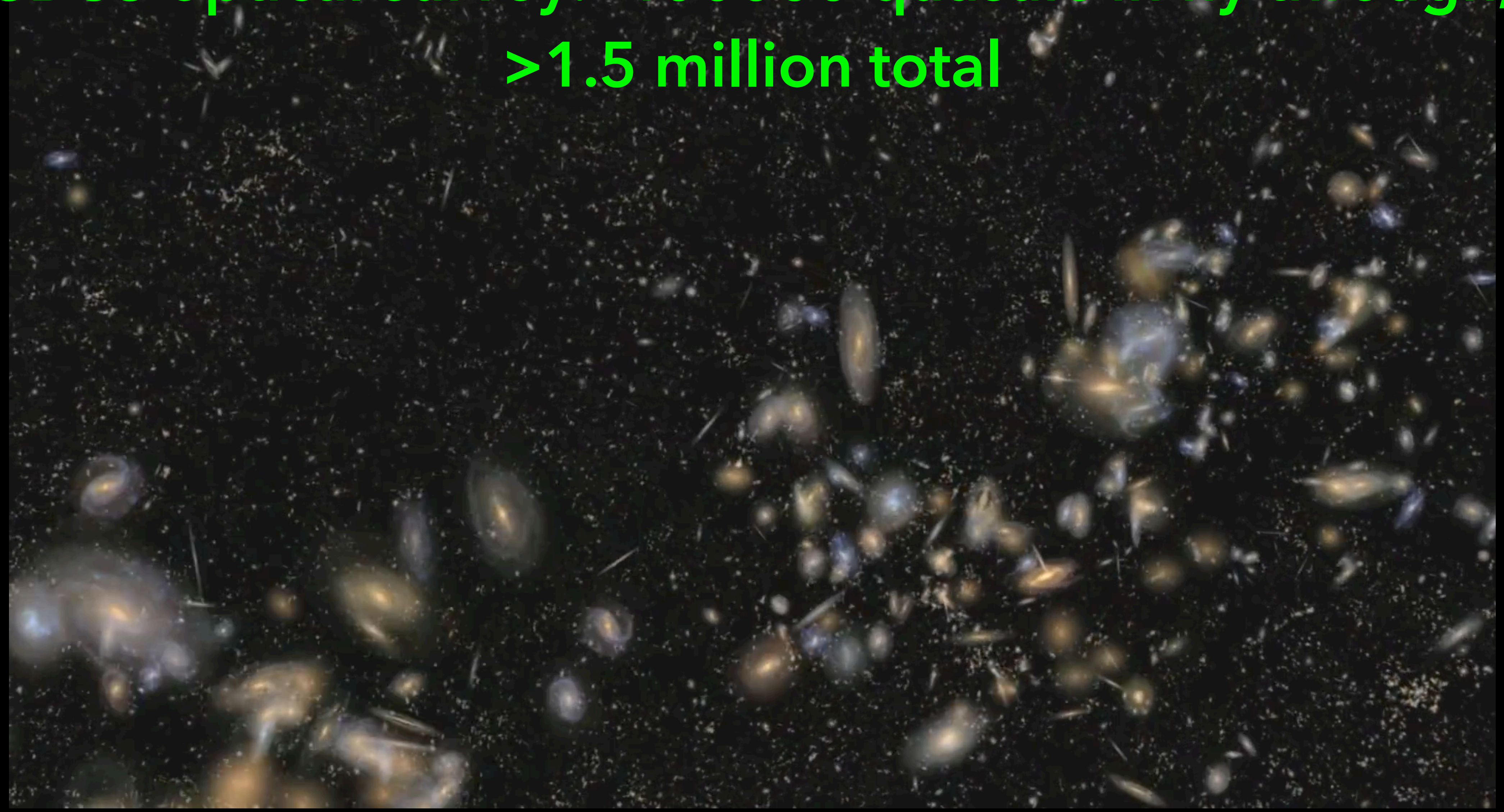
Kantzas, Markoff++ 2021;2022;2023

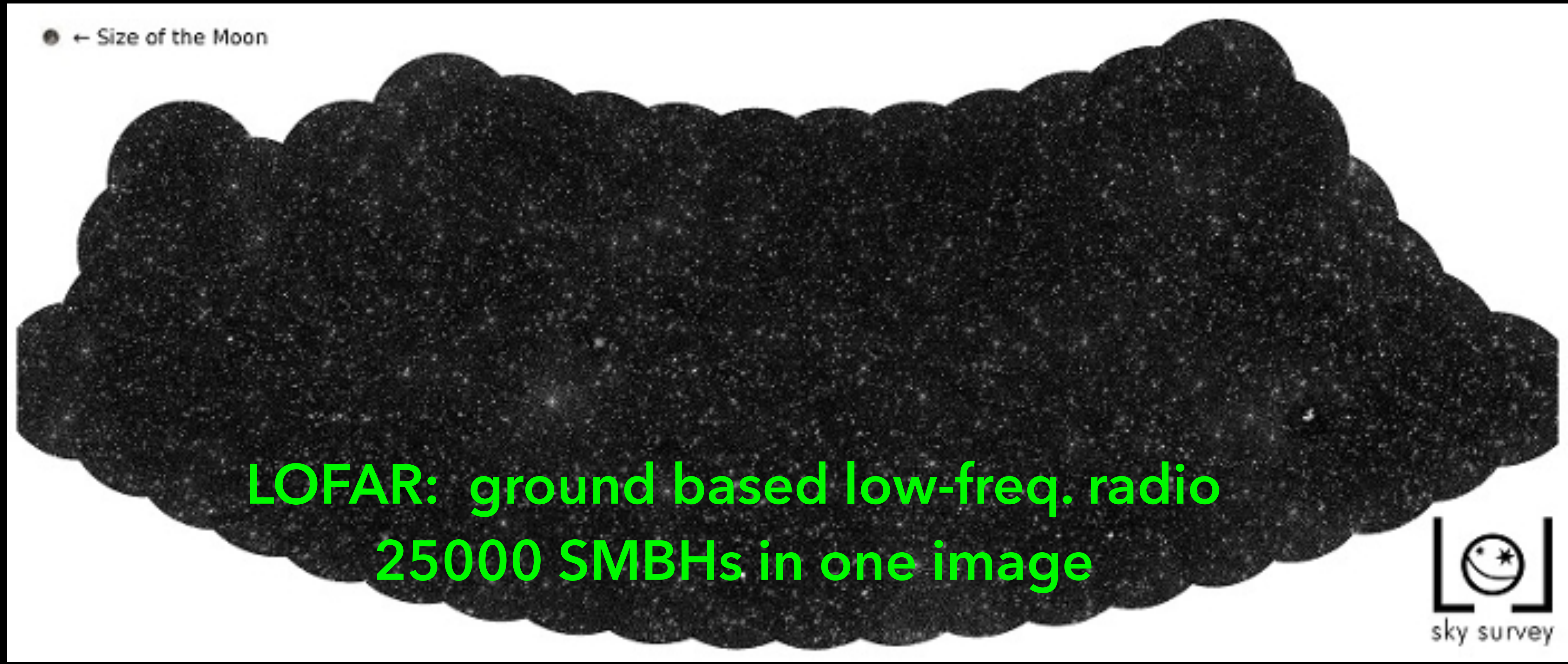
Into the future: characterising black hole populations



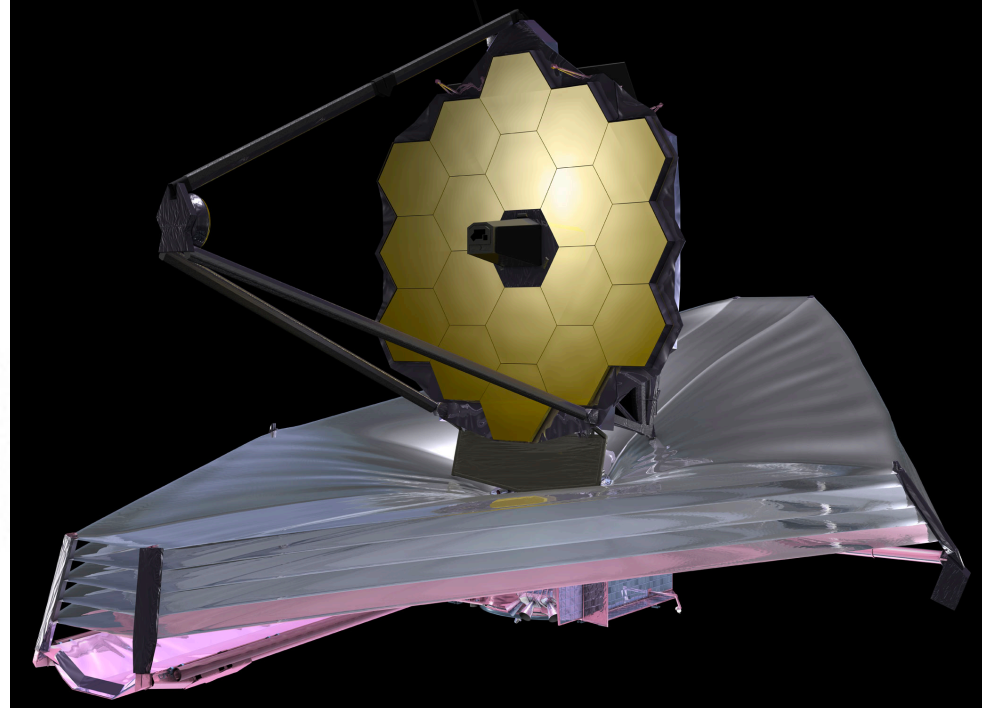
eRosita: soft X-rays
over 2 million SMBHs in one image!

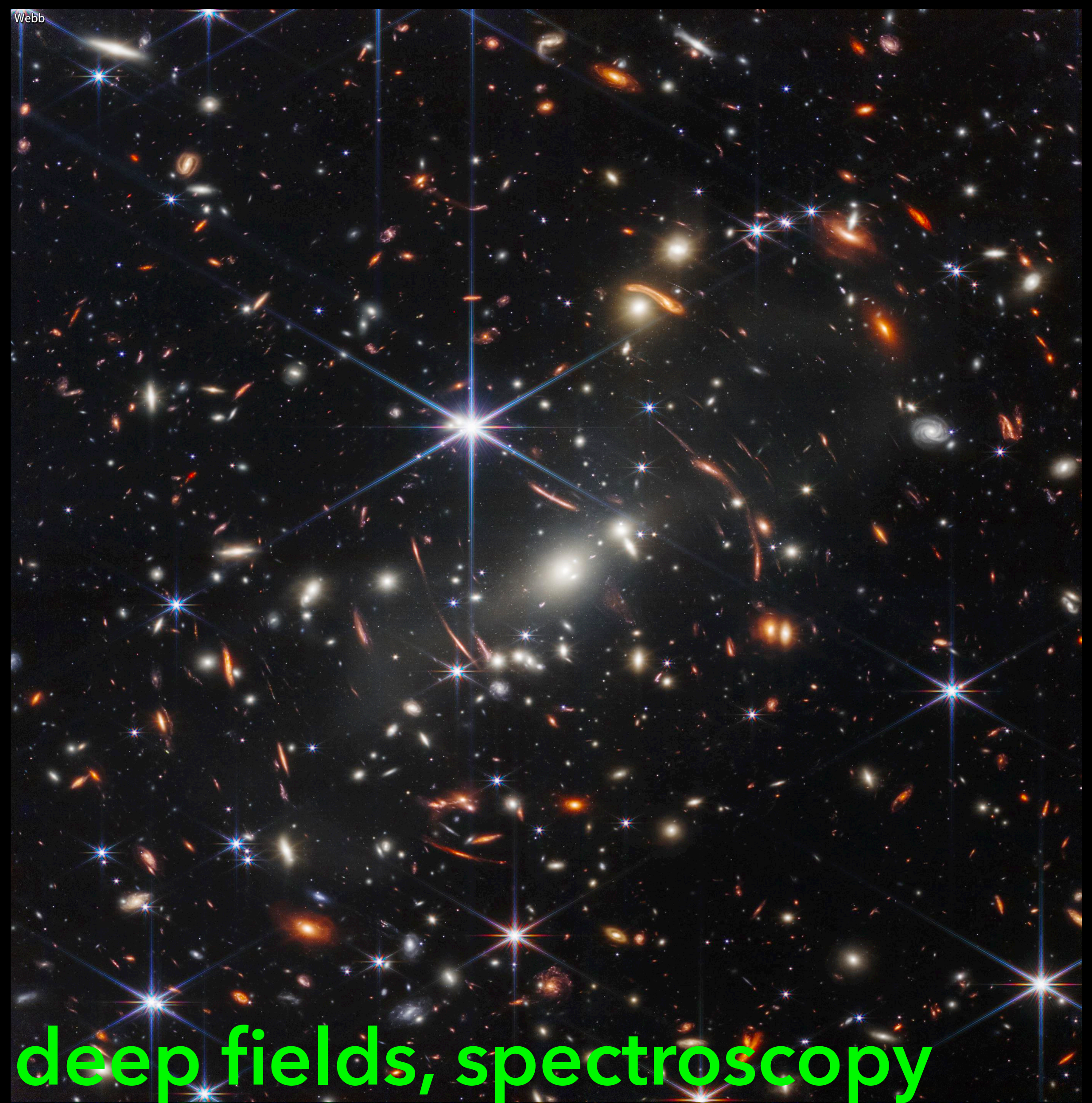
SDSS optical survey: 400000 quasars in fly through,
>1.5 million total





LOFAR: ground based low-freq. radio
25000 SMBHs in one image





JWST: Opt/MIR, deep fields, spectroscopy

Summary

★ EHT reveals two extremes of BH cyclic activity, Sgr A* and M87*, to be remarkably similar, *but Sgr A*'s lack of jets remains a puzzle for theory*

★ Combined constraints from EHT/VLBI + MWL have the power to reveal the link between global dynamics and particle acceleration

★ 2018 results imminent, 2021-2023 (+KP and NOEMA) in pipeline. Near term: Sgr A* dynamical movies, connecting M87* to its jets

★ Coming decade builds these studies out to population of nearby non-horizon sources, *what we learn will be relevant for all jetted sources*

★ Exciting future including AMT+(ng)EHT+, multi-messenger transient science, and eventually space-based VLB (in radio and X-ray!)