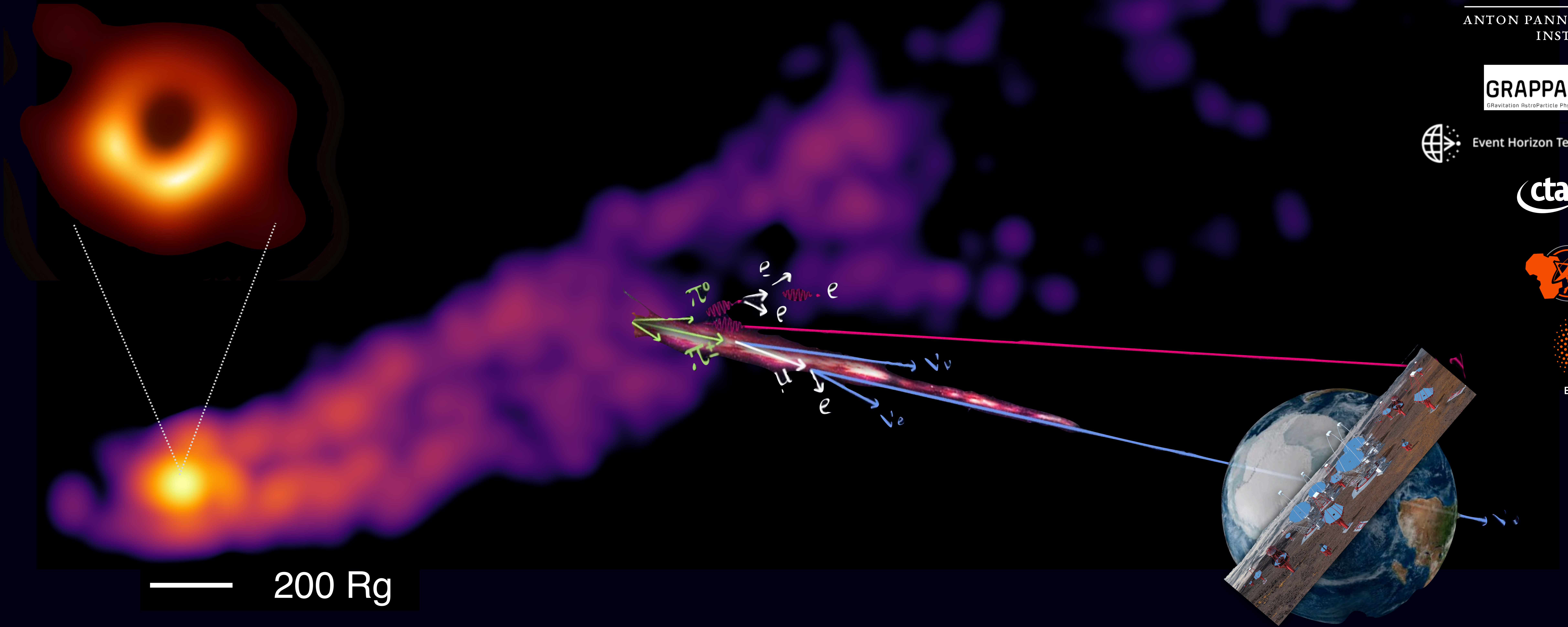
Black holes: new perspectives (in the EHT+MM era)



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

ANTON PANNEKOEK INSTITUTE

GRAPPA GRavitation AstroParticle Physics Amsterdam

Event Horizon Telescope

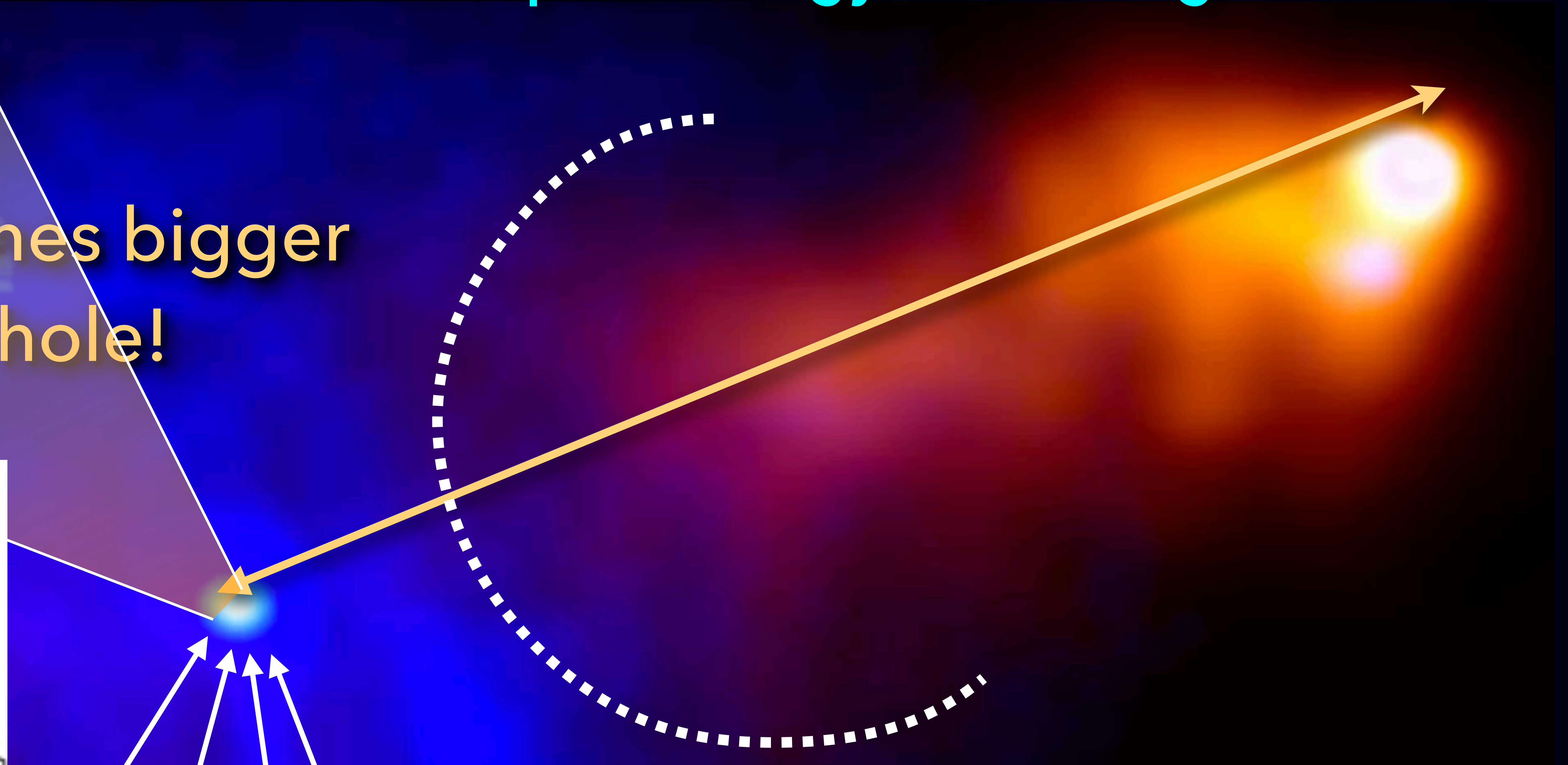
cta cherenkov telescope array

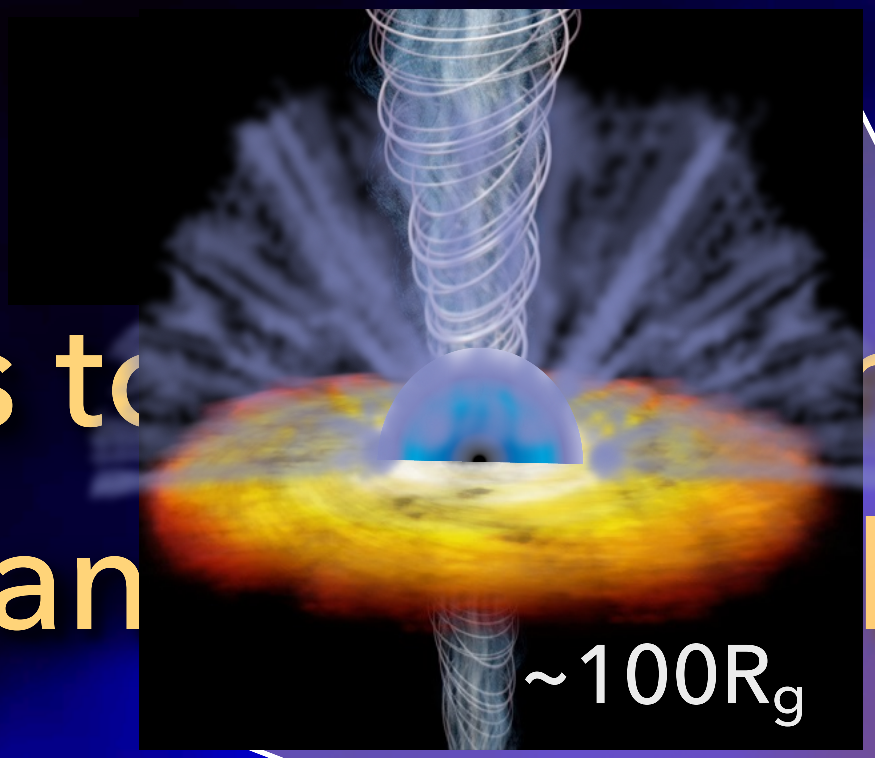
AFRICA MILLIMETRE TELESCOPE

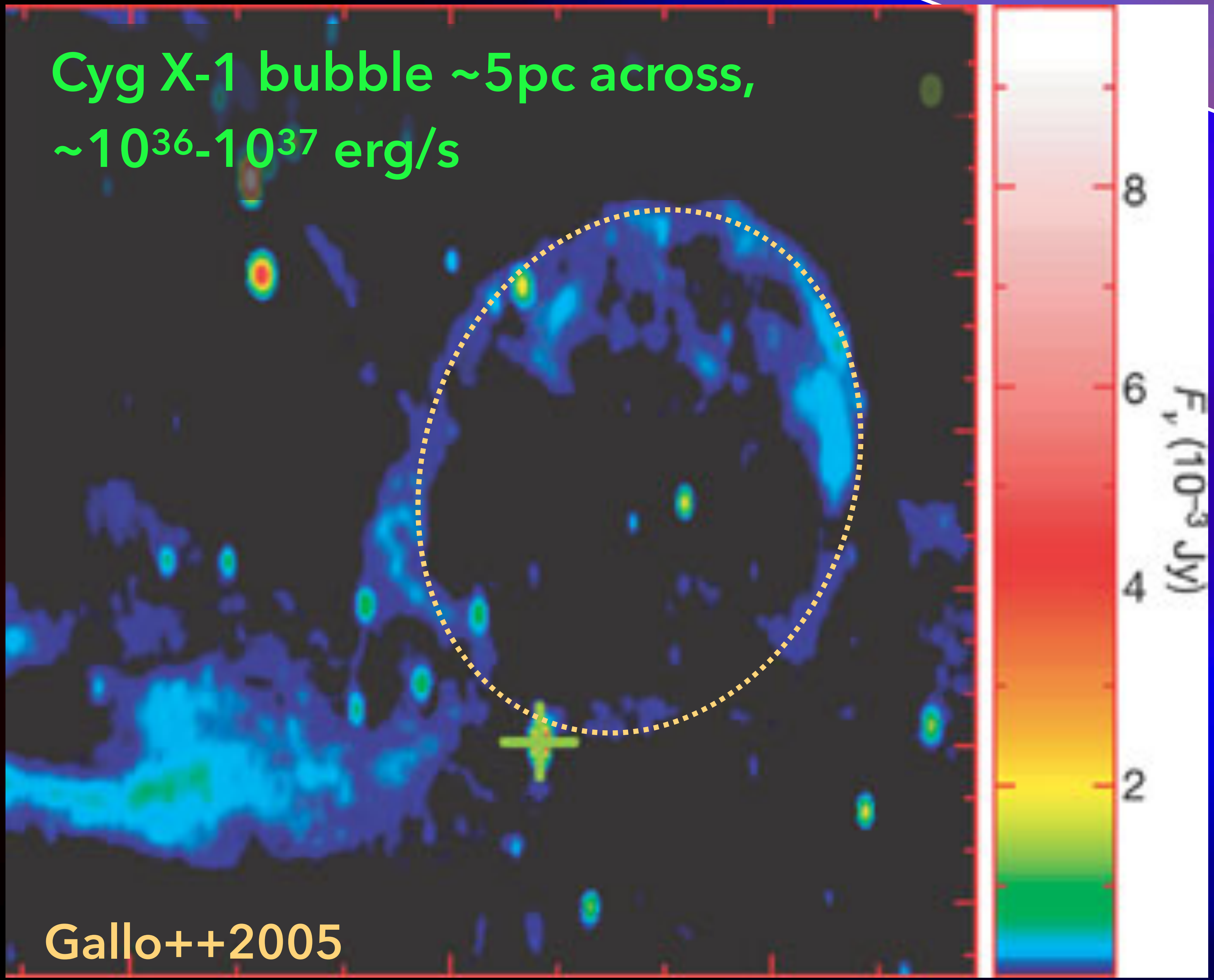
erc BlackHolistic

NWO

How do black holes grow, and release and transport energy to the largest scales?



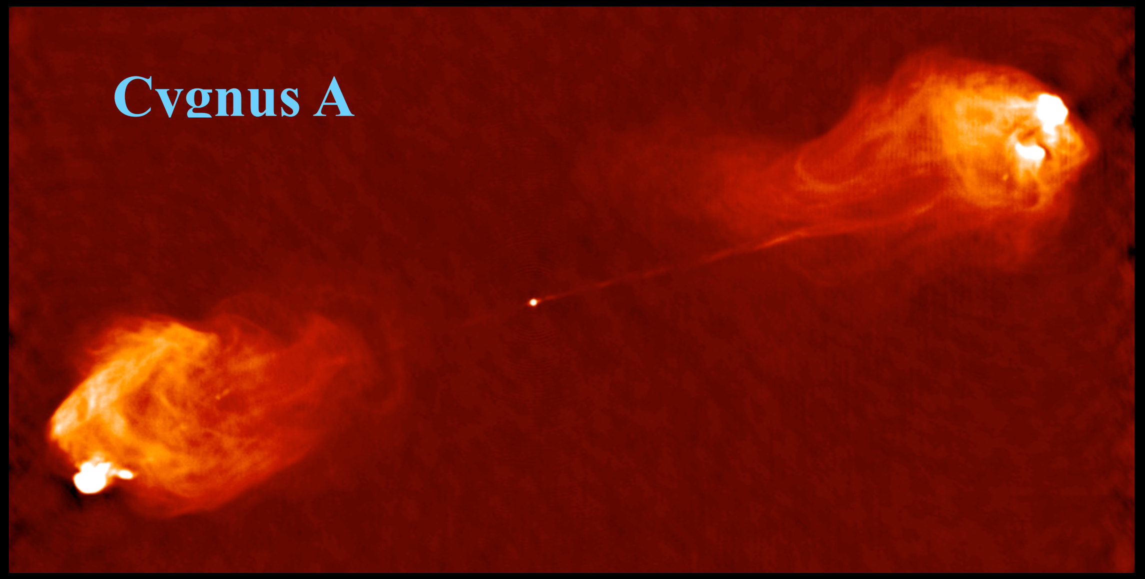


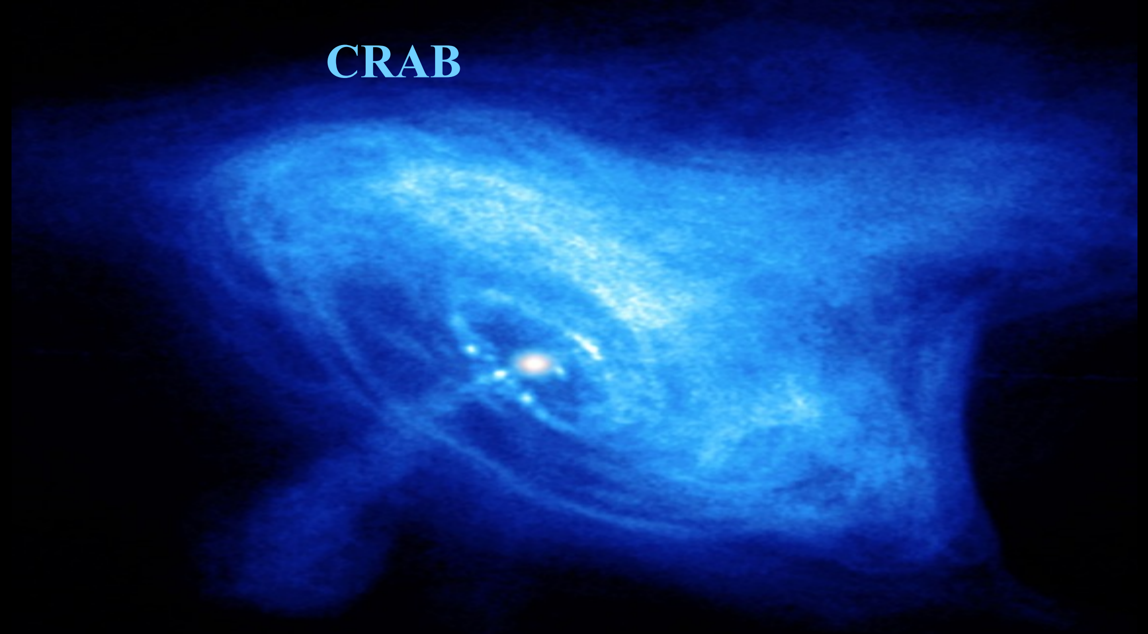


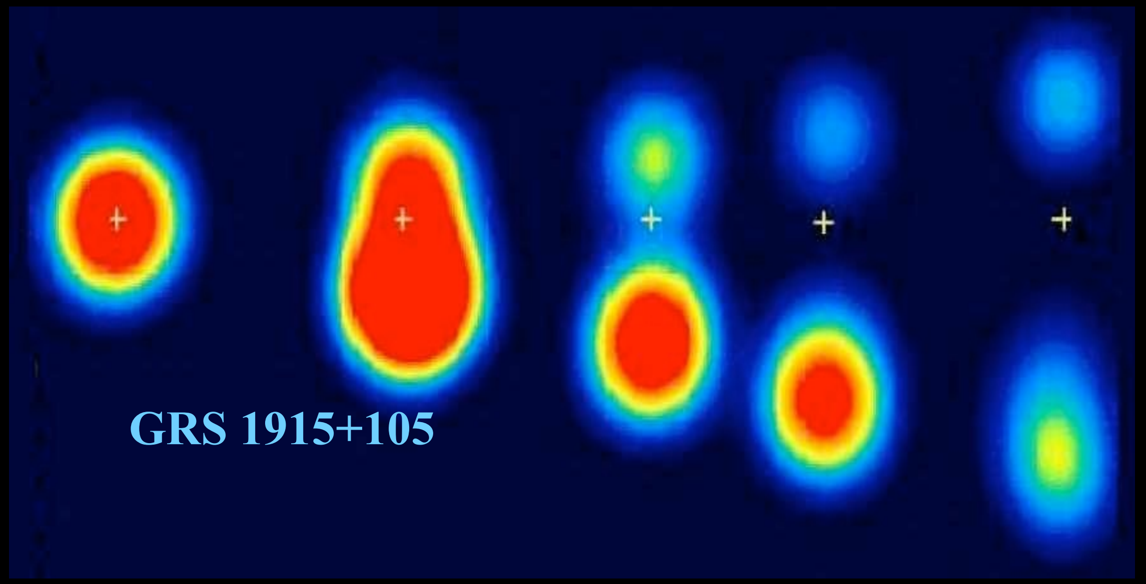
- Measure integrated jet power via lobes
- Feeding conditions? Duty Cycle?
- Inner accretion geometry?
- Black hole spin ➠ jet power?
- Jet composition/hadrons?
- Dynamics ➠ heat/accel ➠ light/particles?
- Relevant for stellar compact objects!

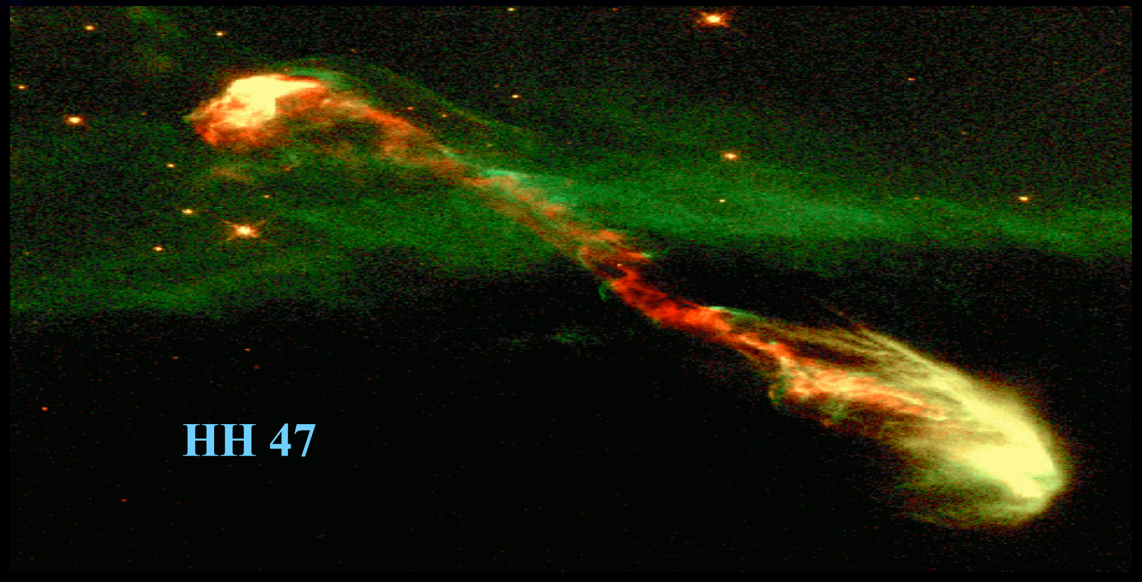
(Combined LOFAR radio + Chandra Xray image of Cyg A; Wise & McKean)

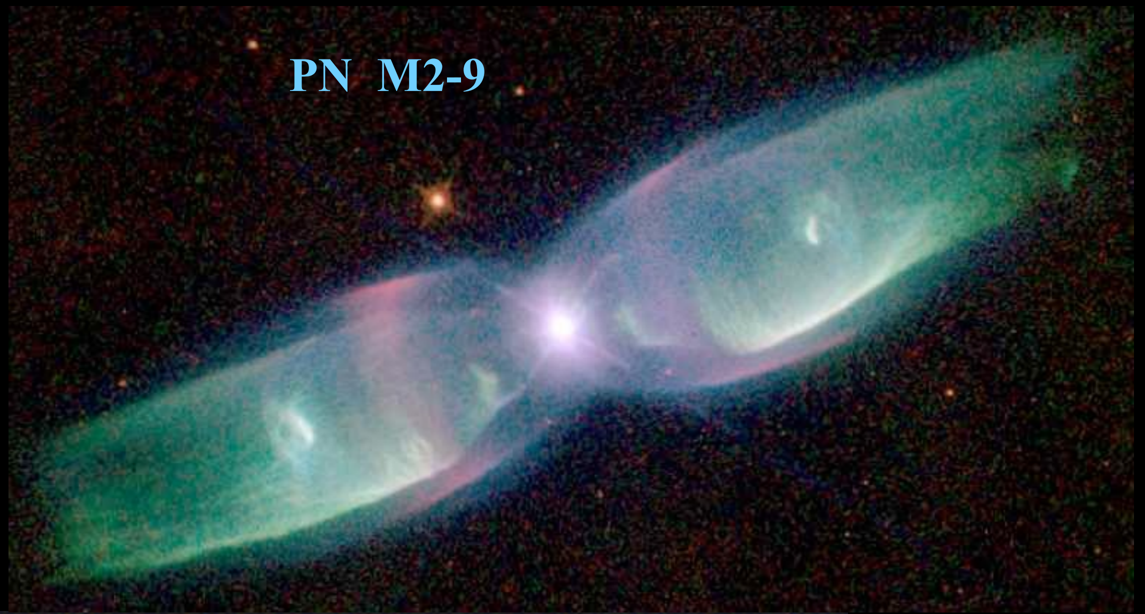
Physics of gravity-powered phenomena seems to be universal

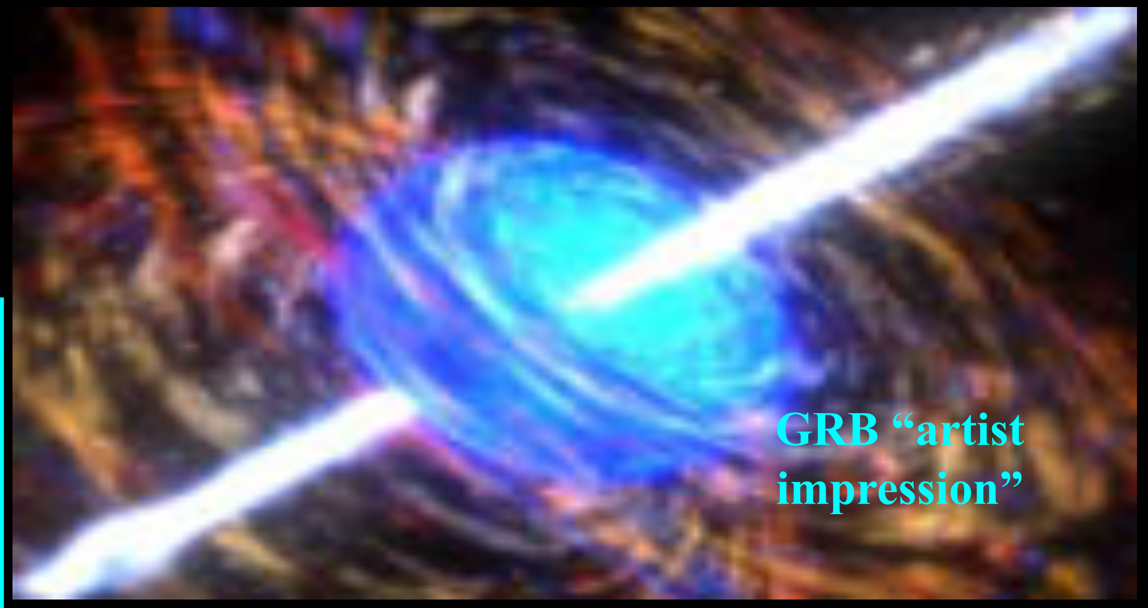


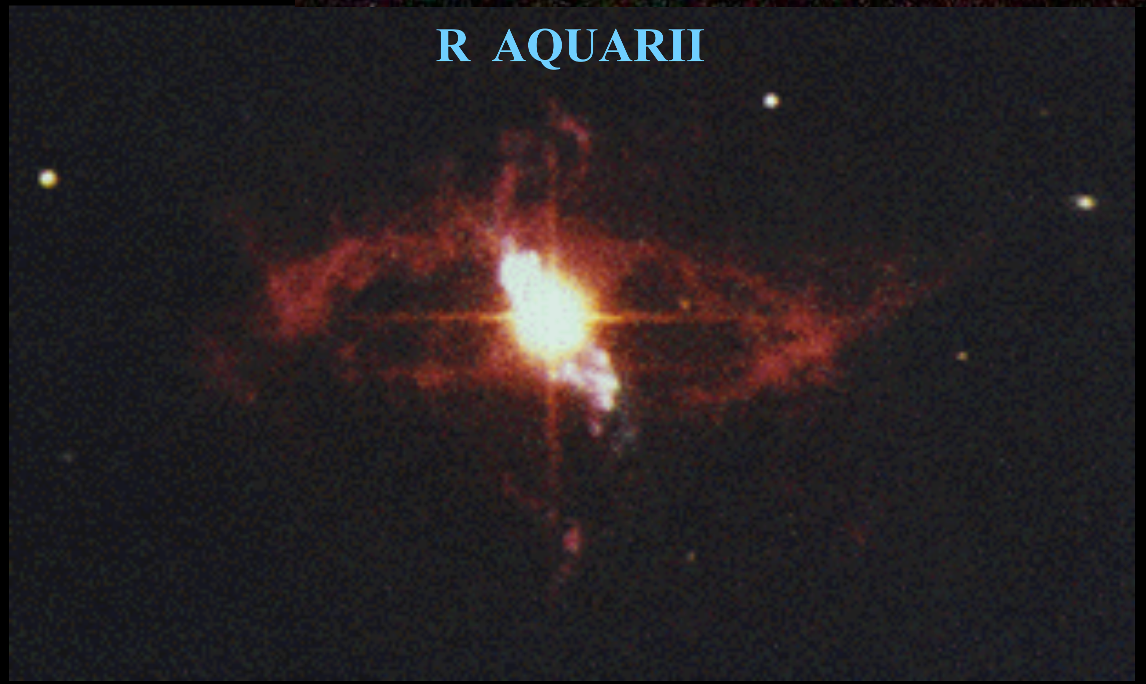


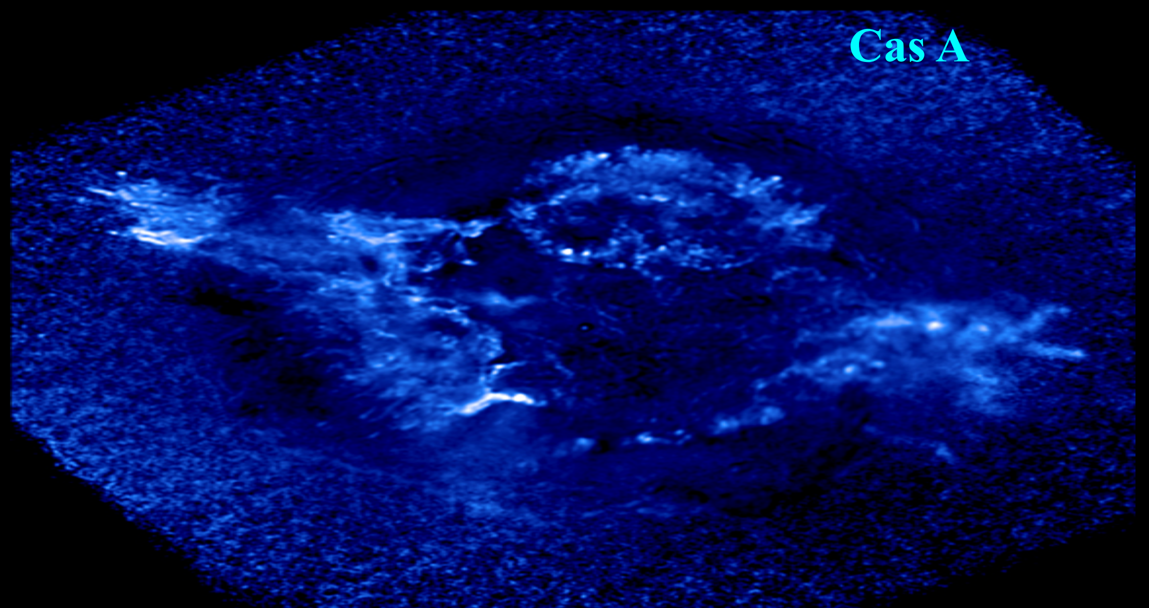


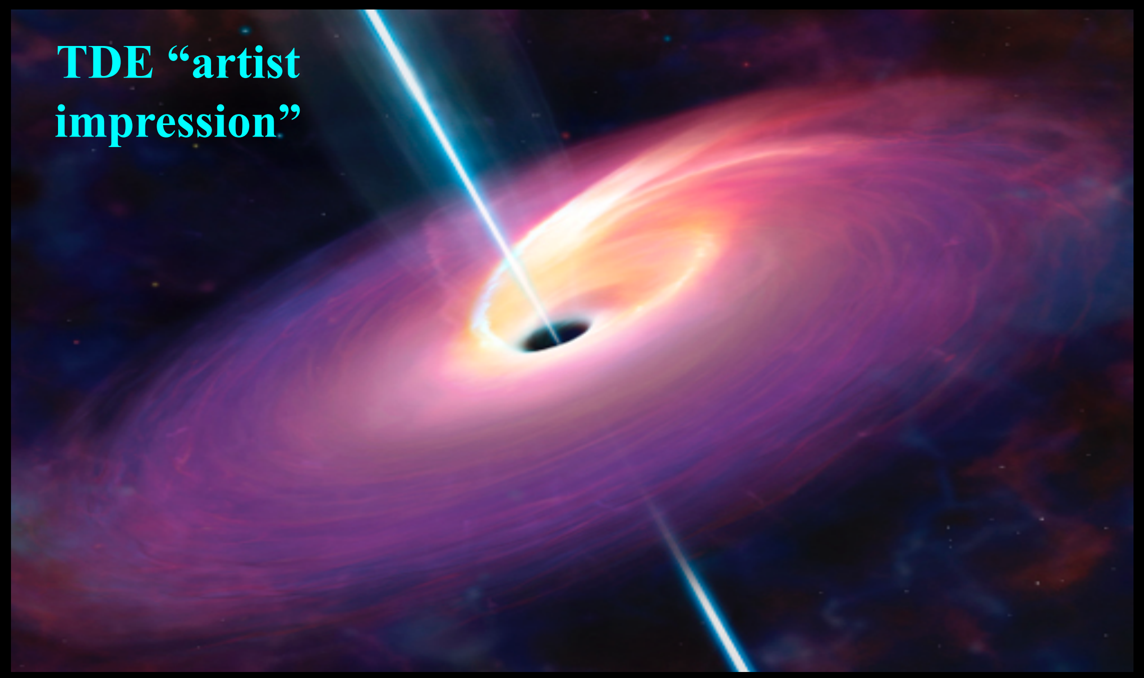






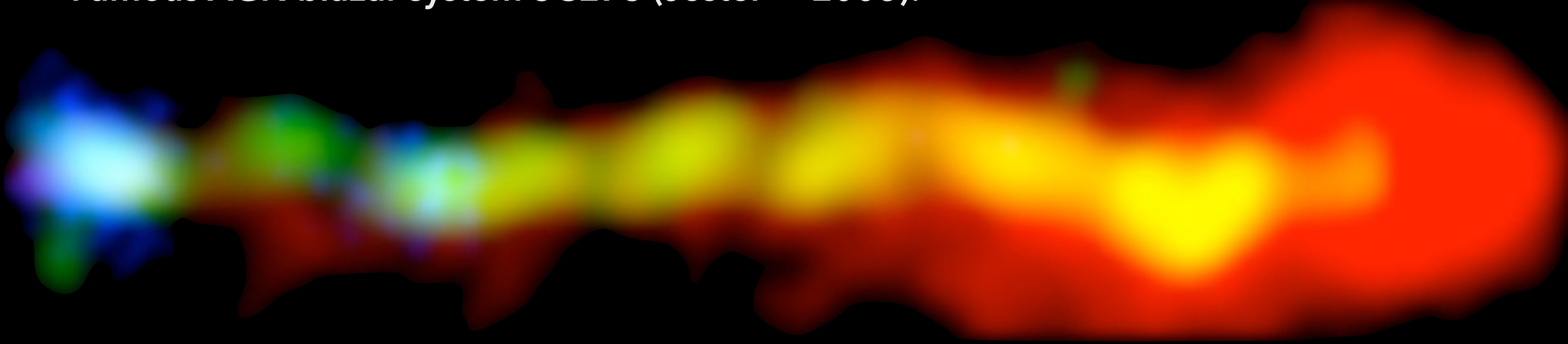




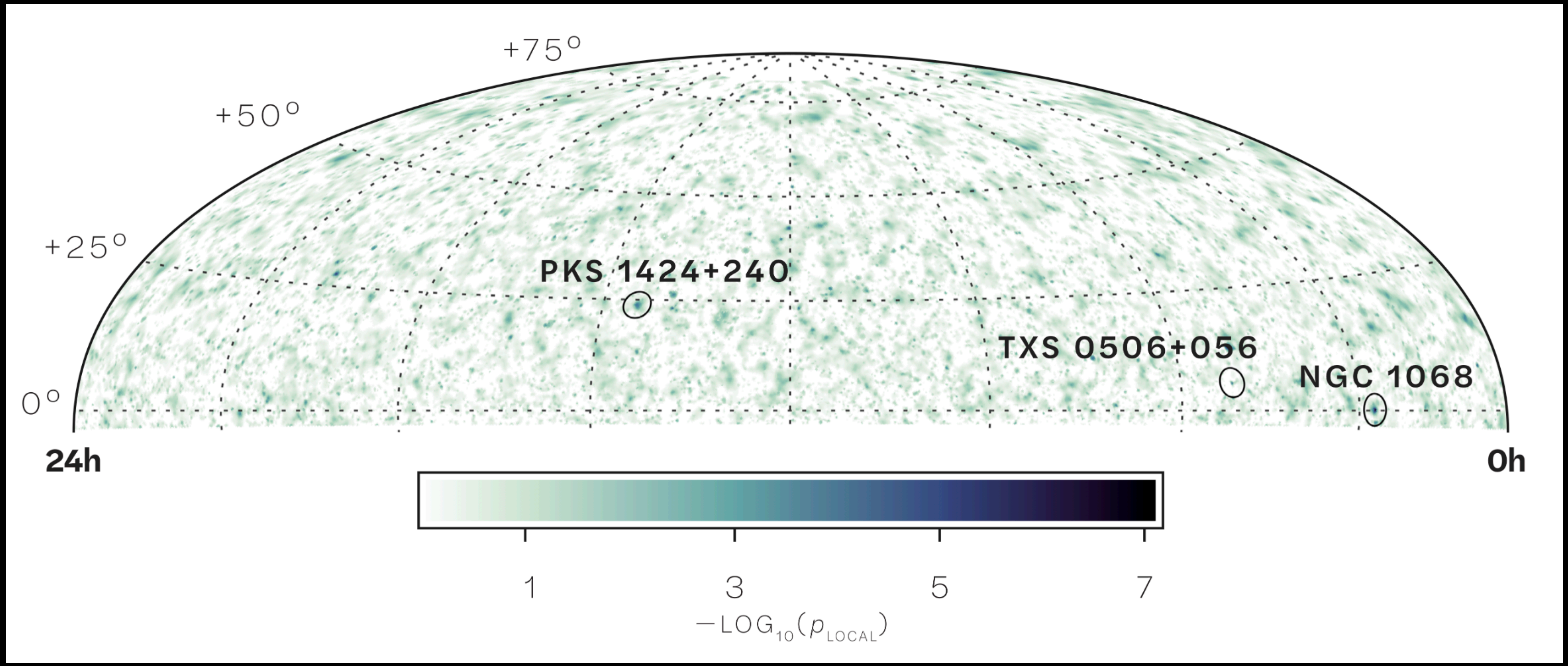


Supermassive black holes ⇔ CRs, neutrinos!

Famous AGN blazar system 3C273 (Jester++2006):



IceCube Collaboration 2018; 2022, Science



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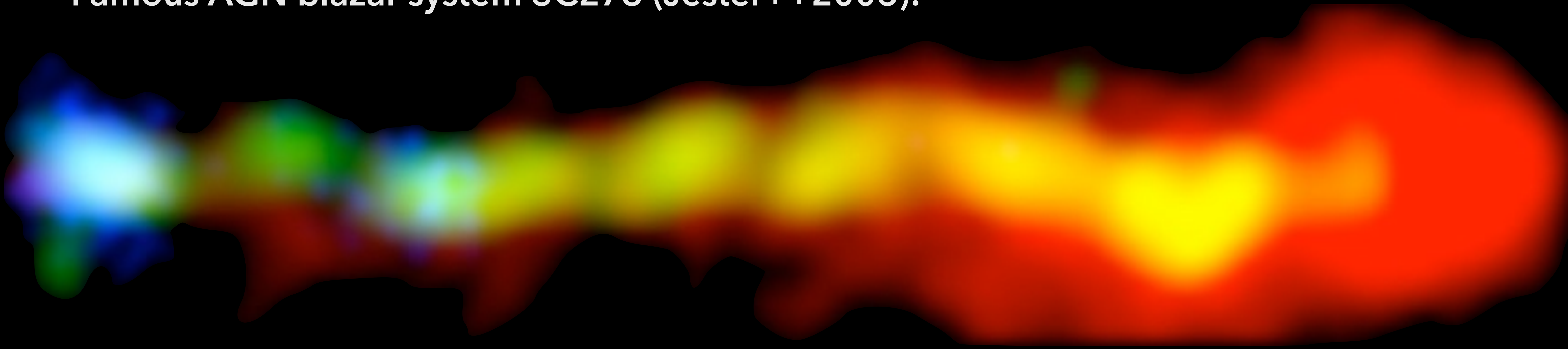
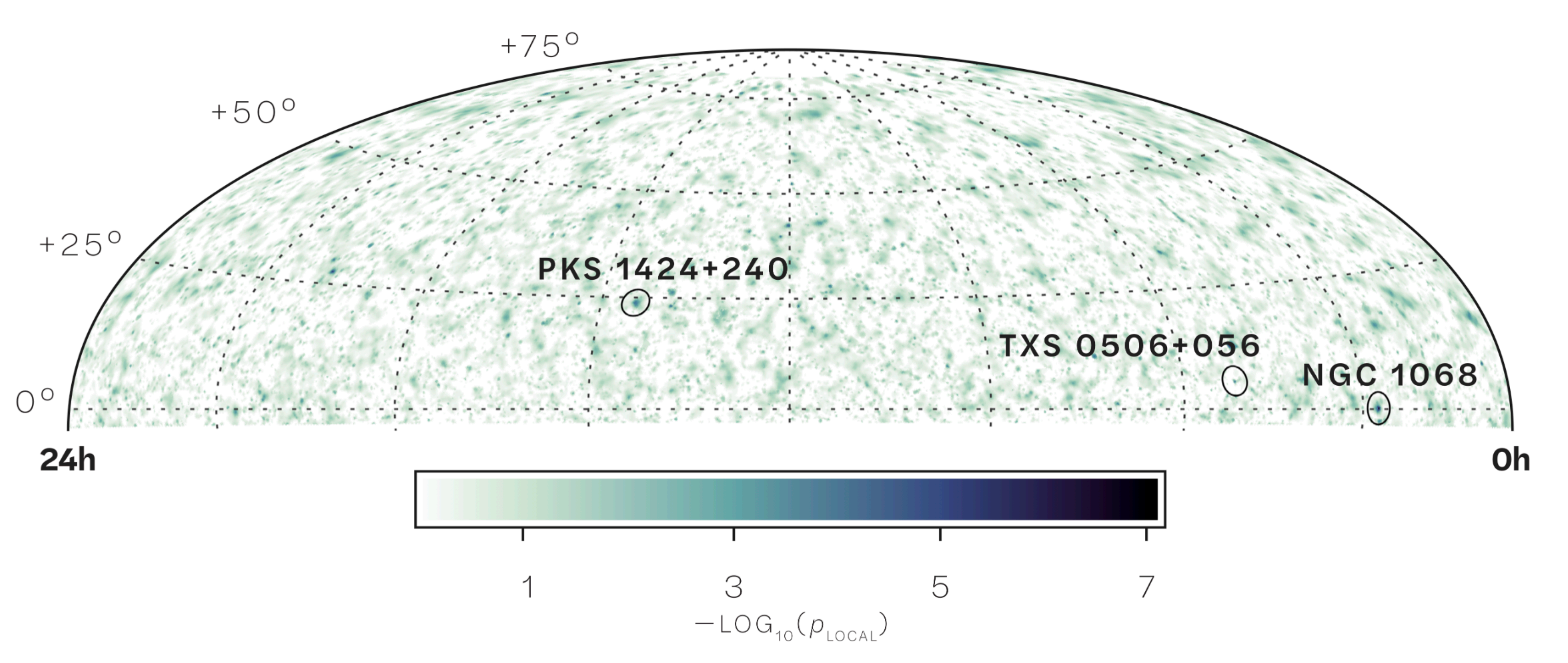


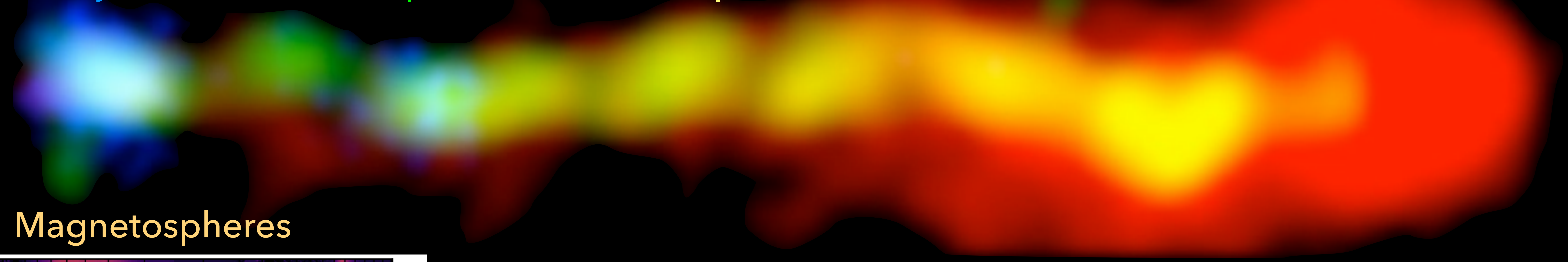


IceCube Collaboration 2018; 2022, Science

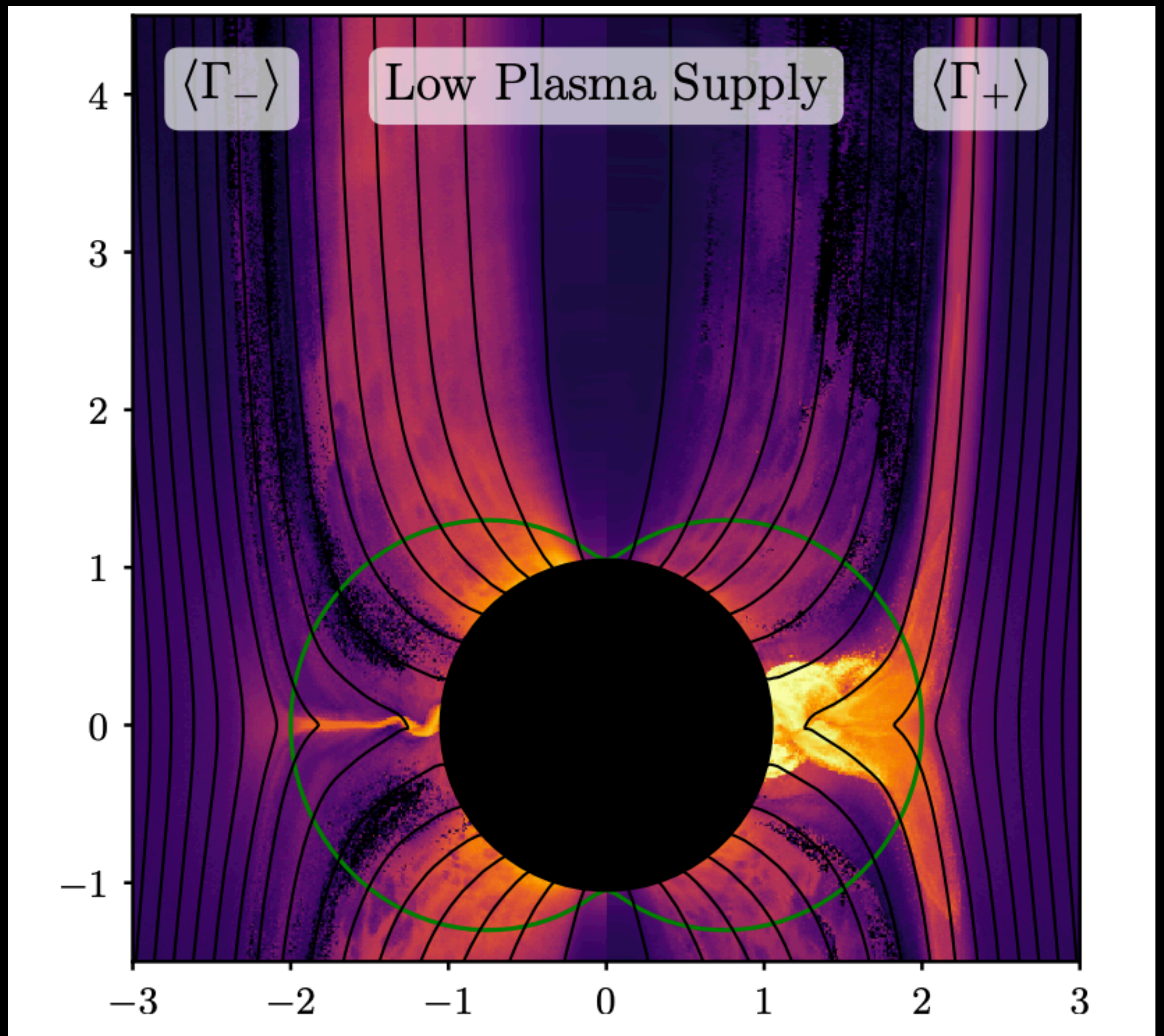
Understanding = localising: particle acceleration and VHE γ-rays

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

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

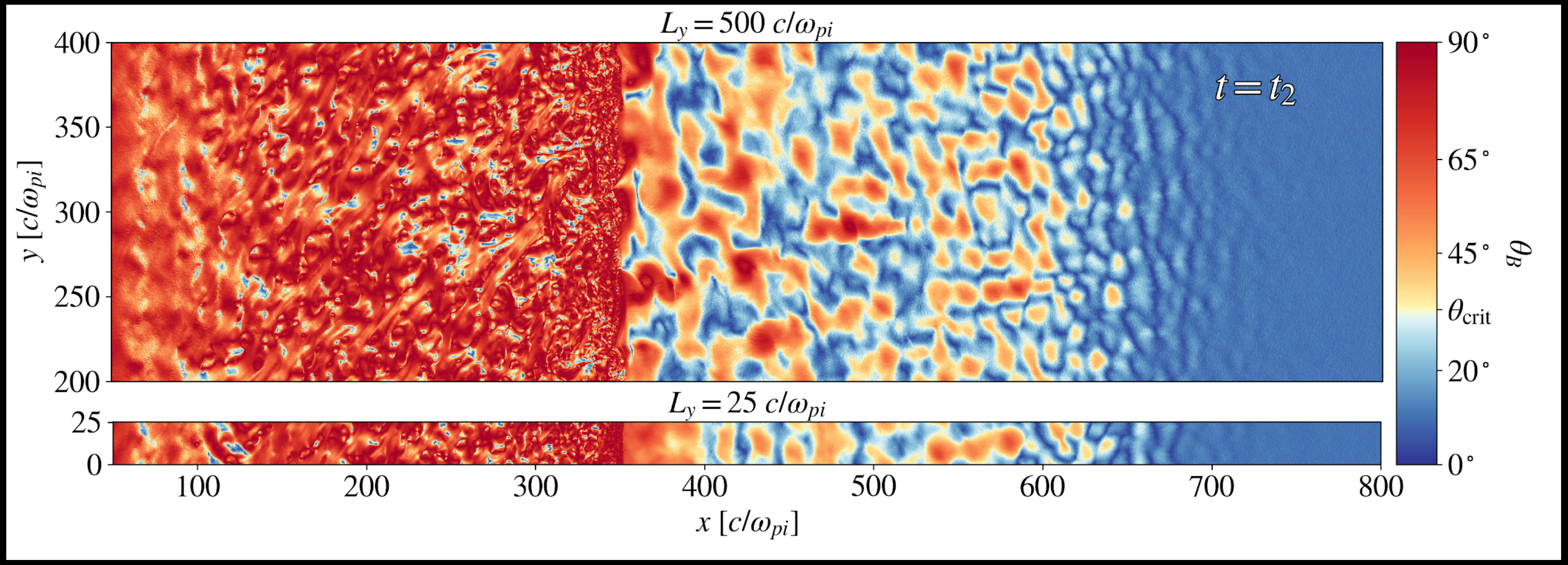


Magnetospheres



e.g. Rieger & Mannheim 2000; Rieger & Aharonian 2008; … Parfrey, Philippov & Cerutti 2019; Bransgrove, Ripperda & Philippov 2021; Hakobyan, Ripperda & Philippov 2023; + work by many others…

Shocks/shear/turbulence (umbrella terms for many mechanisms)

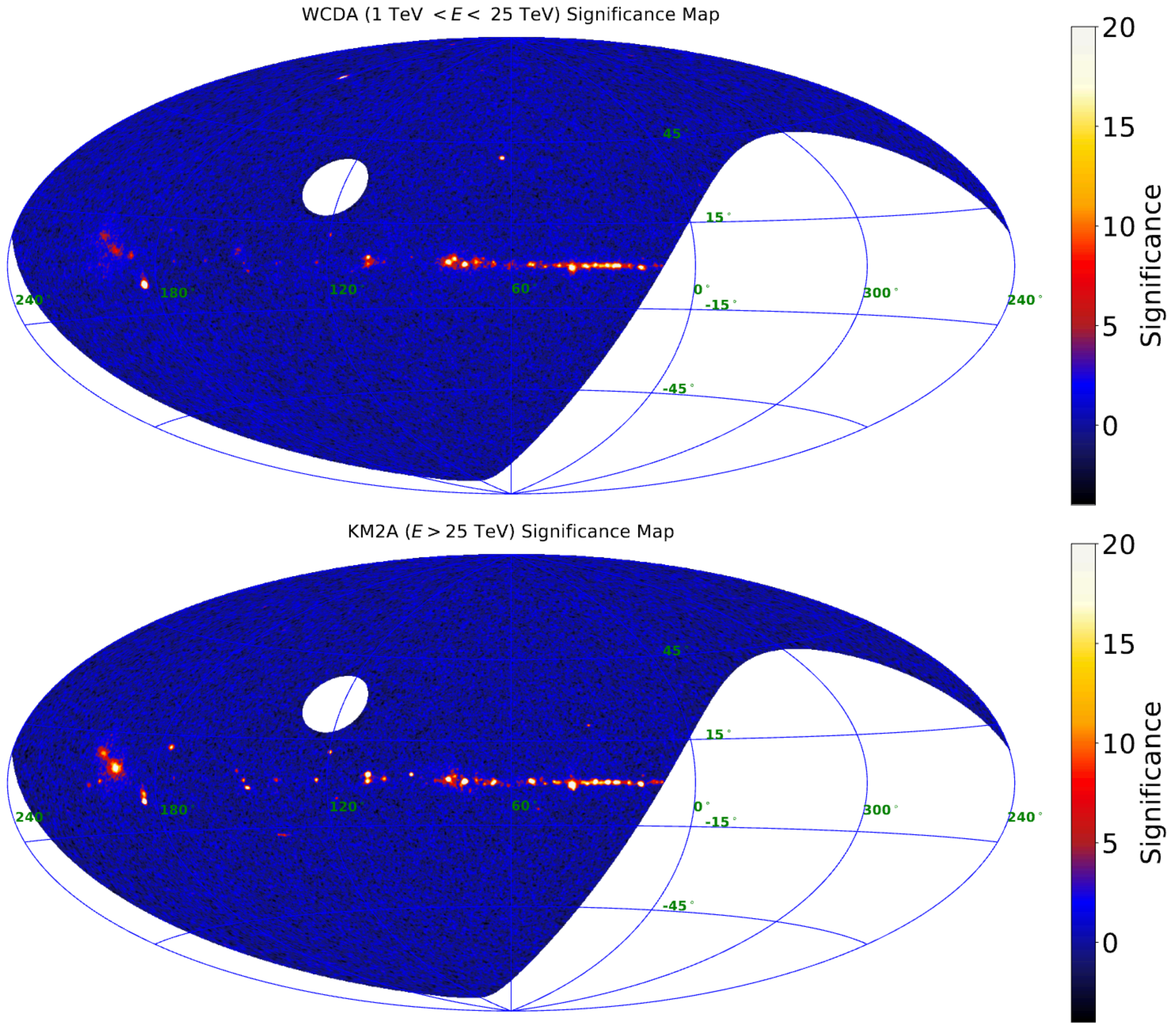


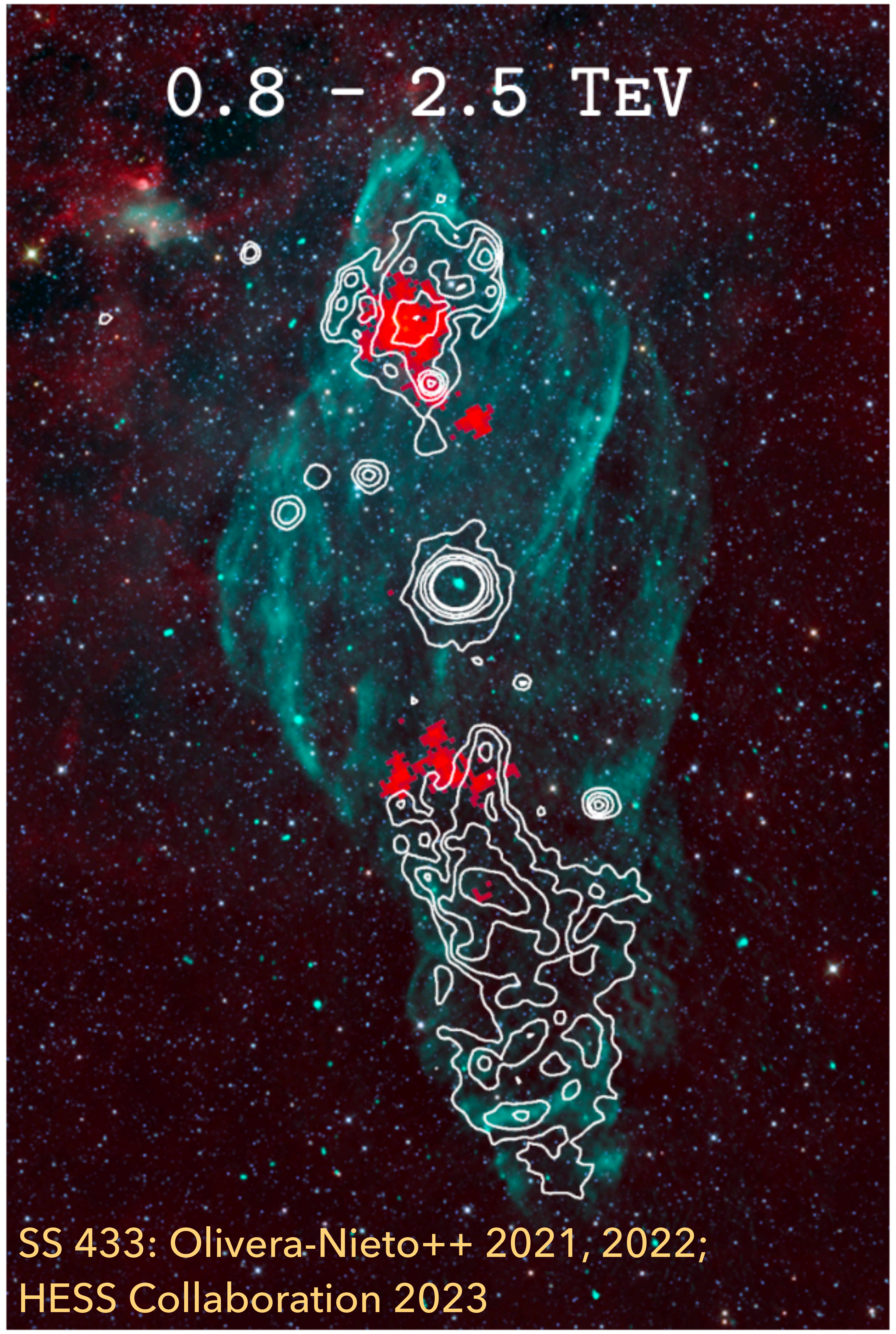
eg. Crumley++2019, Sironi++2021; and see numerical/semi-analytical work by eg, Aharonian; Bai; Bell; Böttcher; de Gouveia Dal Pino; Drury; Giannios; Jokipii; Kirk; Lazarian; Marscher; Oikonomou; Petropoulou; Reimer; Reville; Winter; ++ many many others…

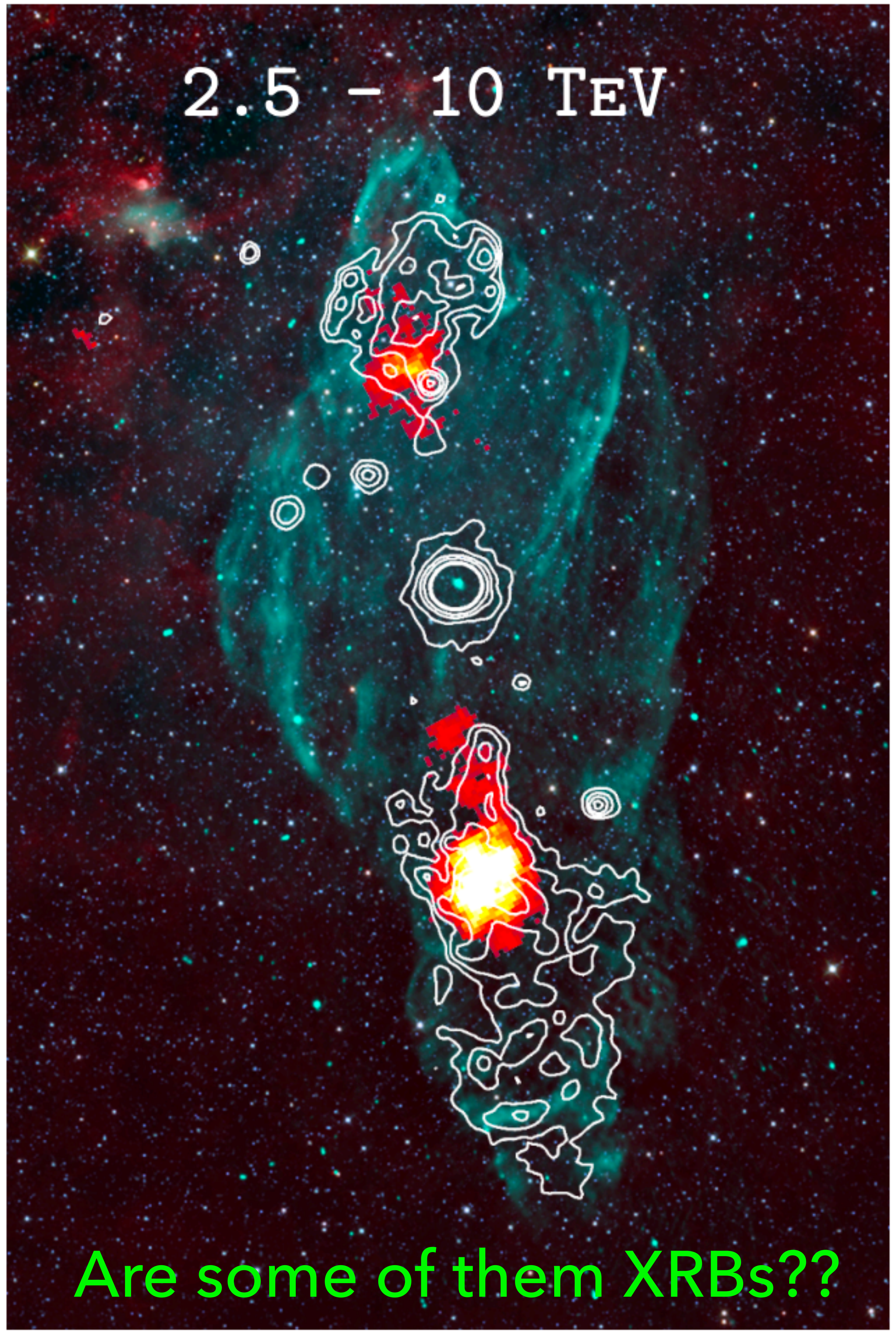
LHAASO revolution!

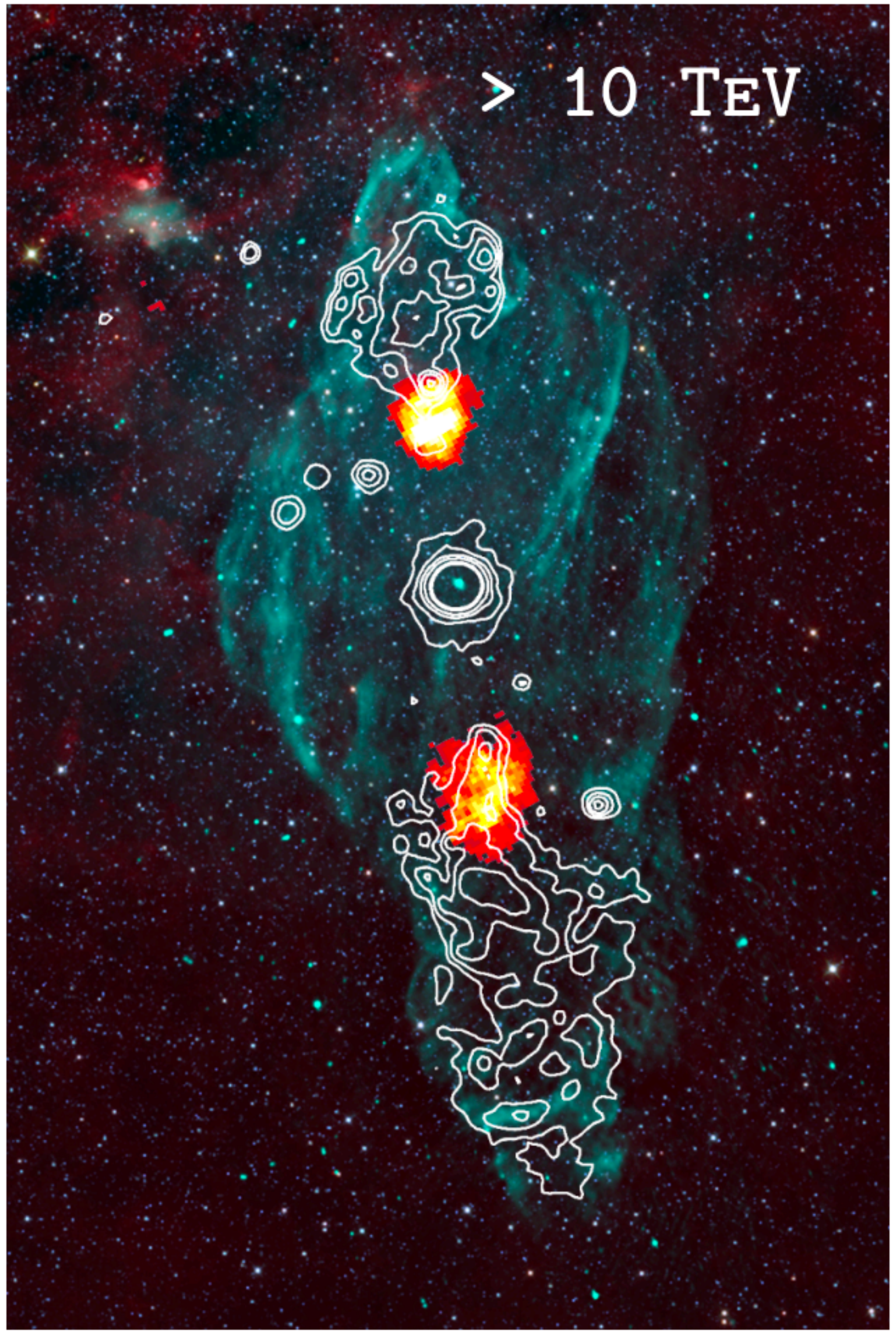
- ~100 sources so far
- ~30% never seen by any other instrument!
- ~50% have E>100 TeV
- New class of >25 TeV-only sources, weird bc of γ-γ opacity, you'd expect more at low energy!
- Milky Way is full of (non-ID'd) PeVatrons!

(LHAASO Collaboration; Cao++23)









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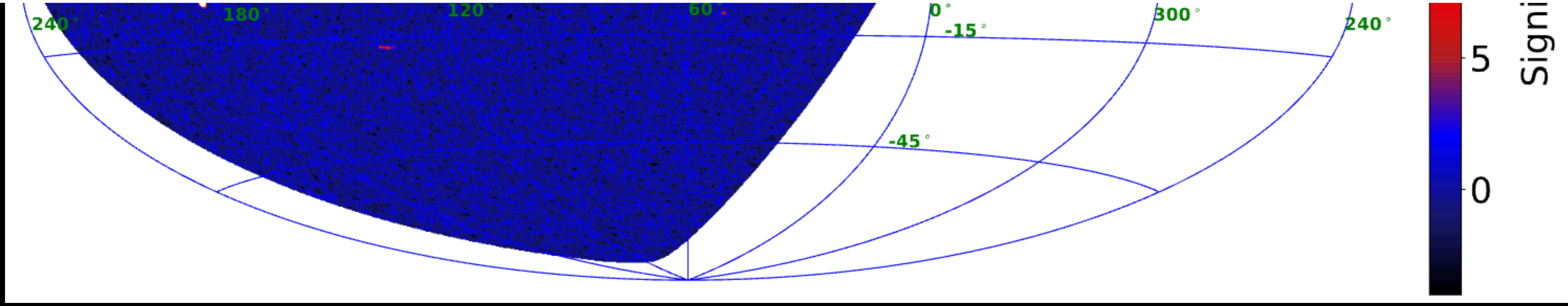
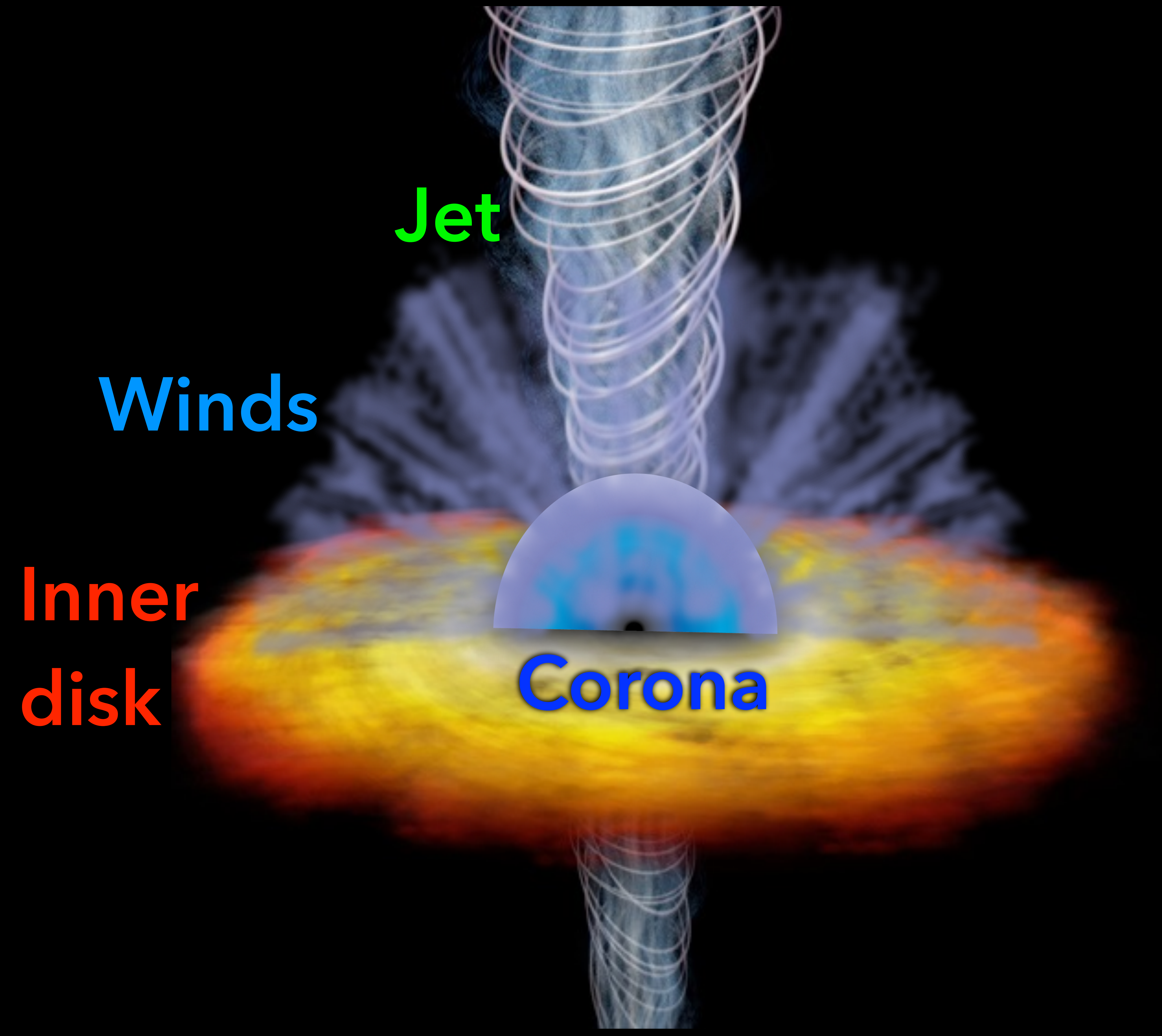
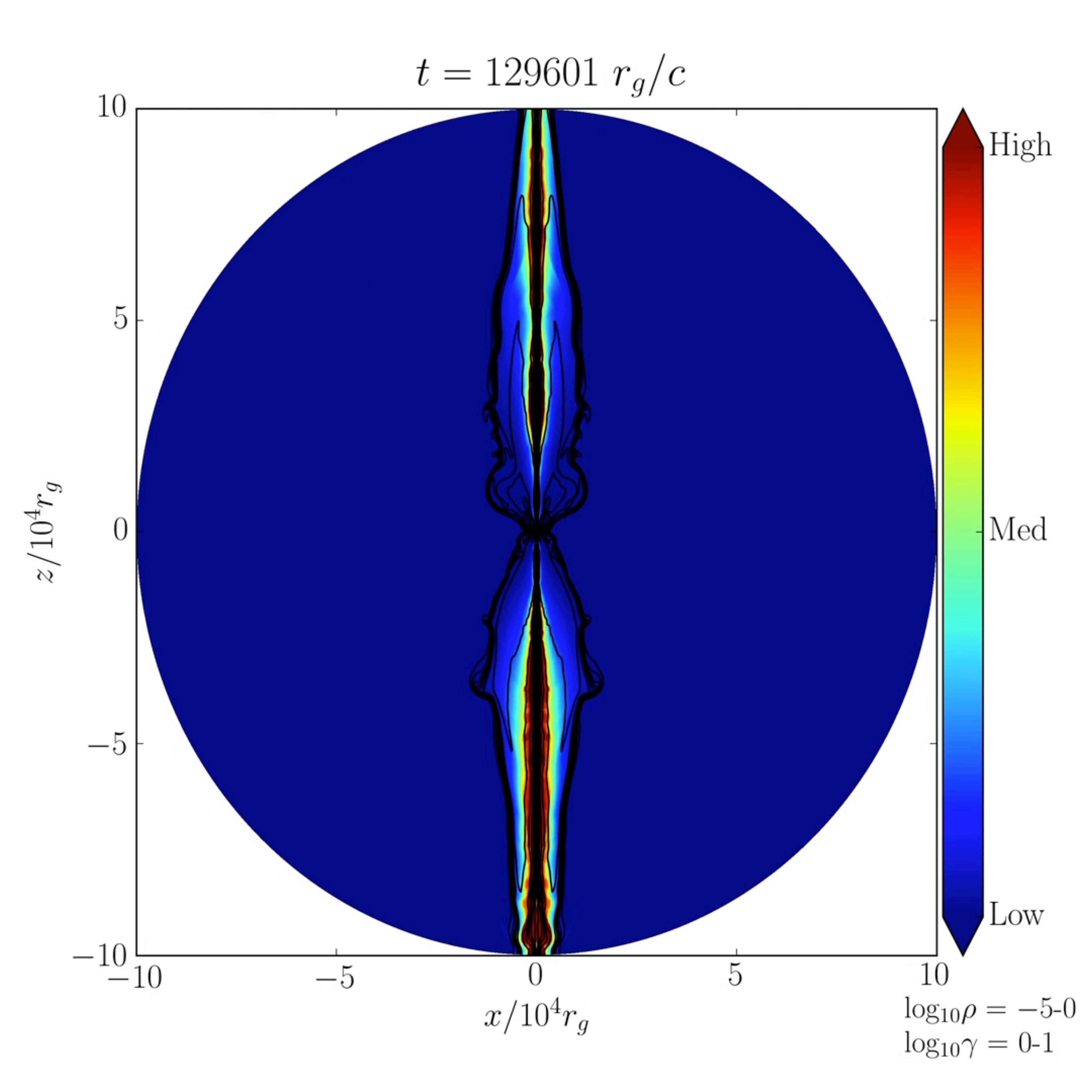


Does the older "cartoon" picture fit w/current theory?





GRMHD simulation with H-AMR: Chatterjee, Liska, Tchekhovskoy & SM 2019; Liska, Chatterjee++2022

Outline

- ★ Geometry ⇔ particle acceleration
- ★ The (evolving) perspective from EHT
- ★ Variability (EHT and beyond)
- ★ Advances in numerical modelling
- ★ Outlook for the future

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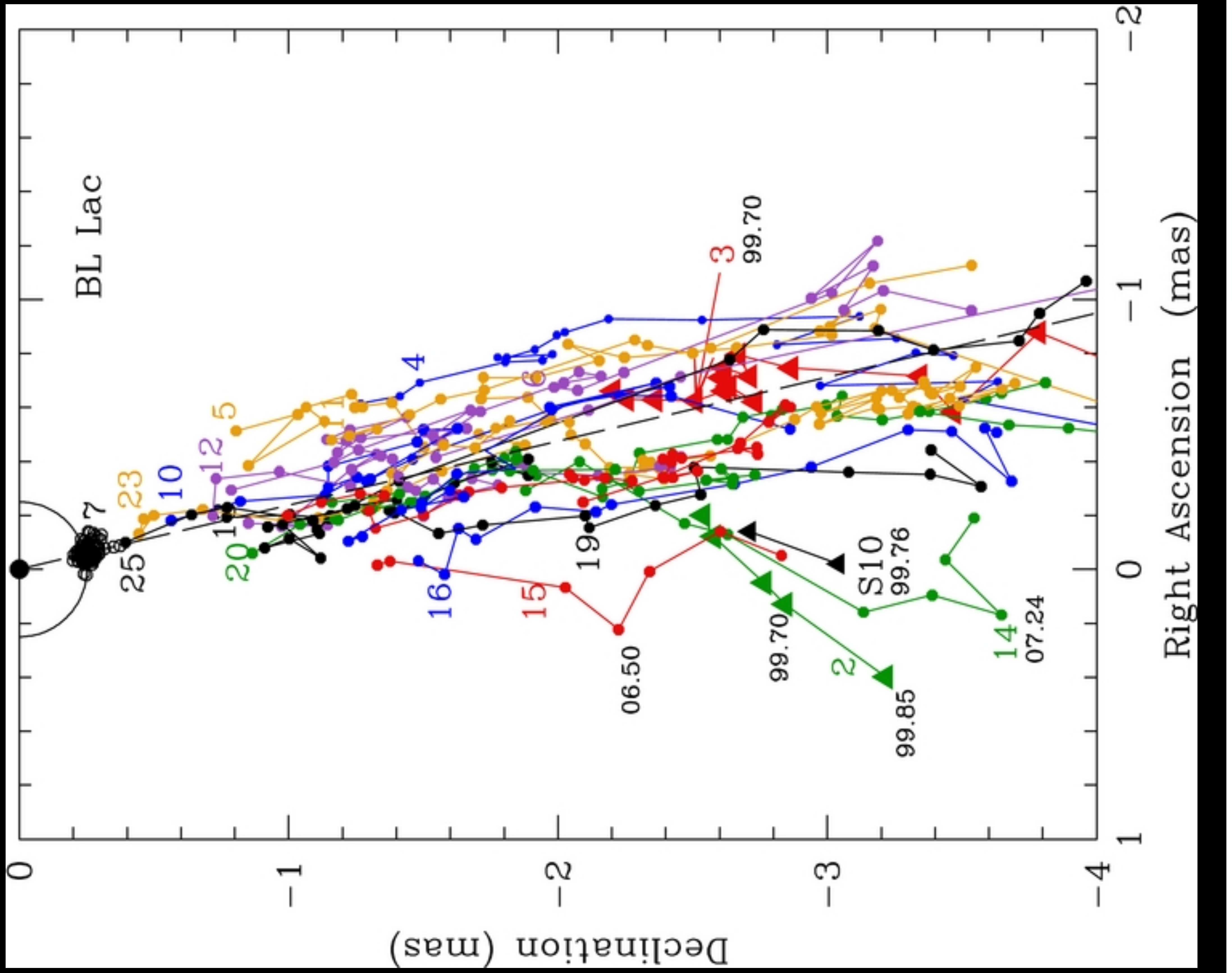
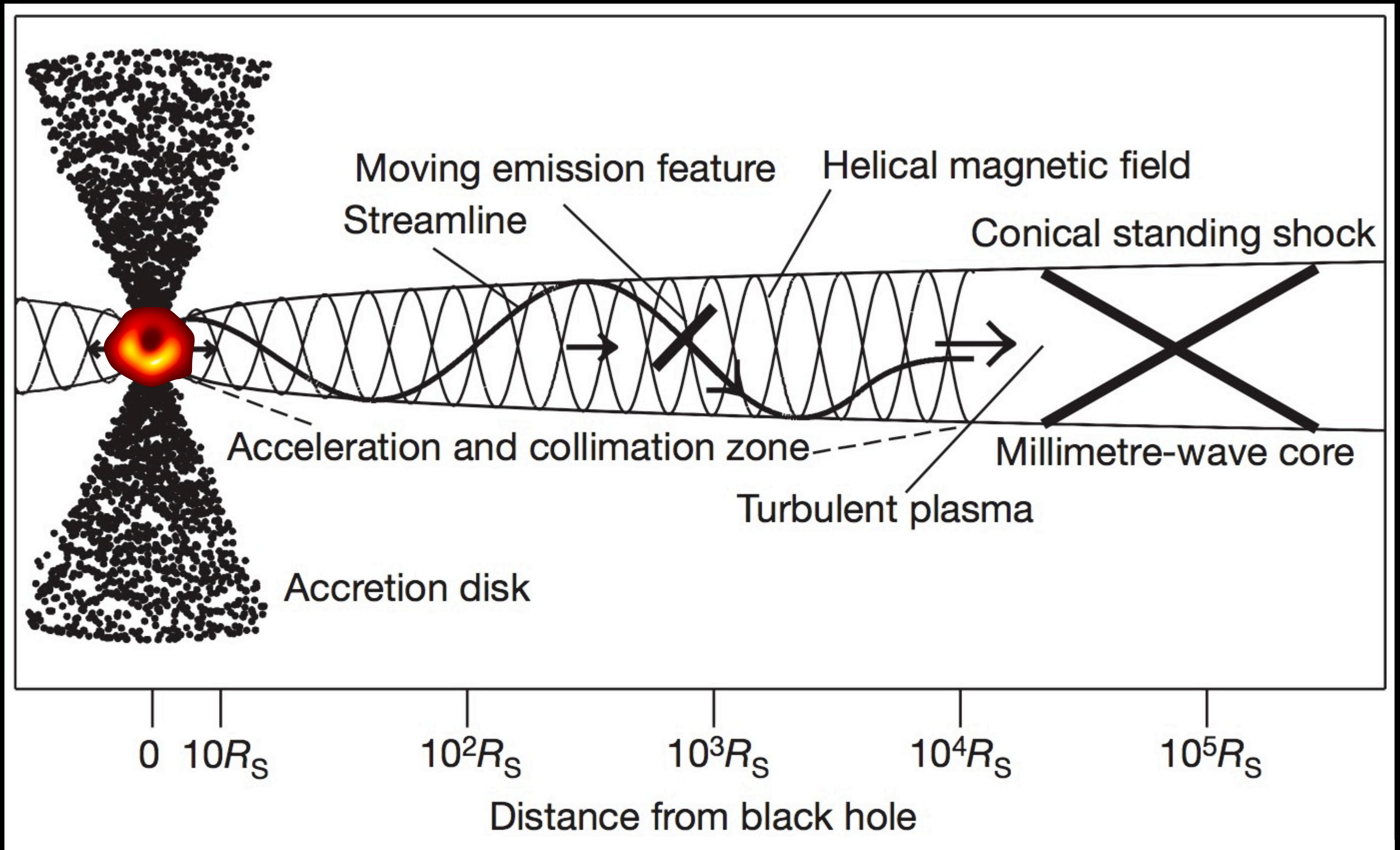
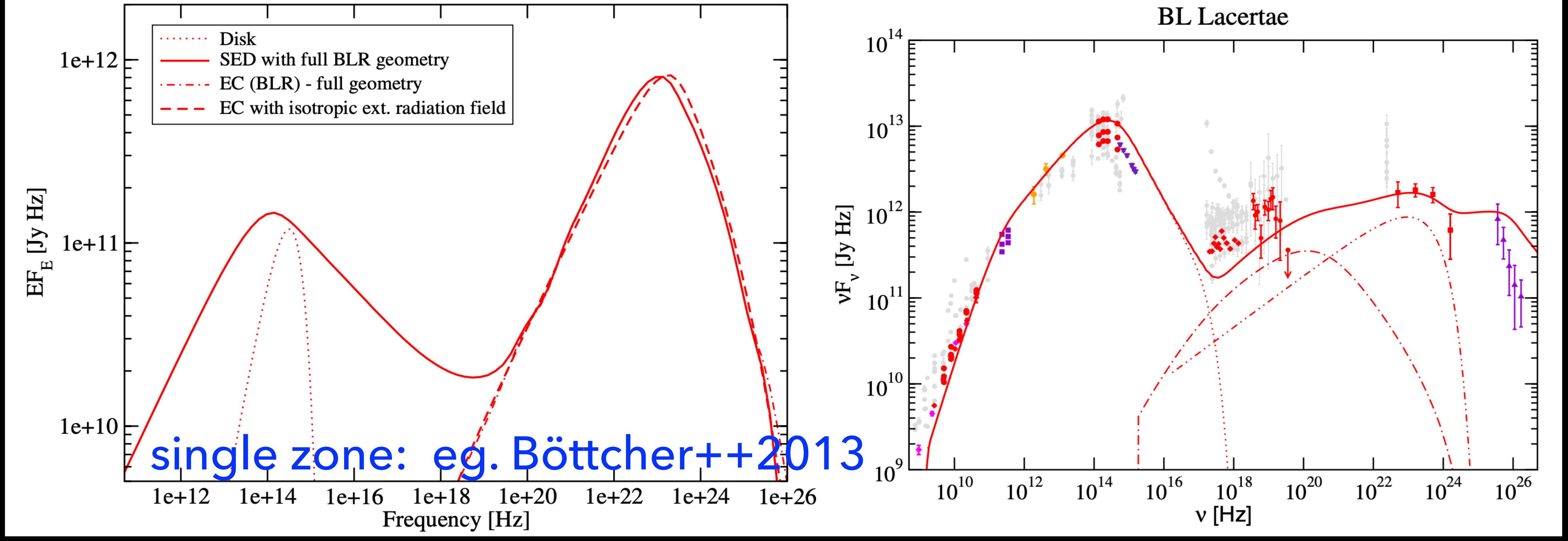
MWL modeling + VLBI ➠ localised dissipation zone far from BH

Marscher++2008, 2014; Cohen++ 2014 (MOJAVE/VLBI; Lister++2019):







single zone: eg. Böttcher++2013

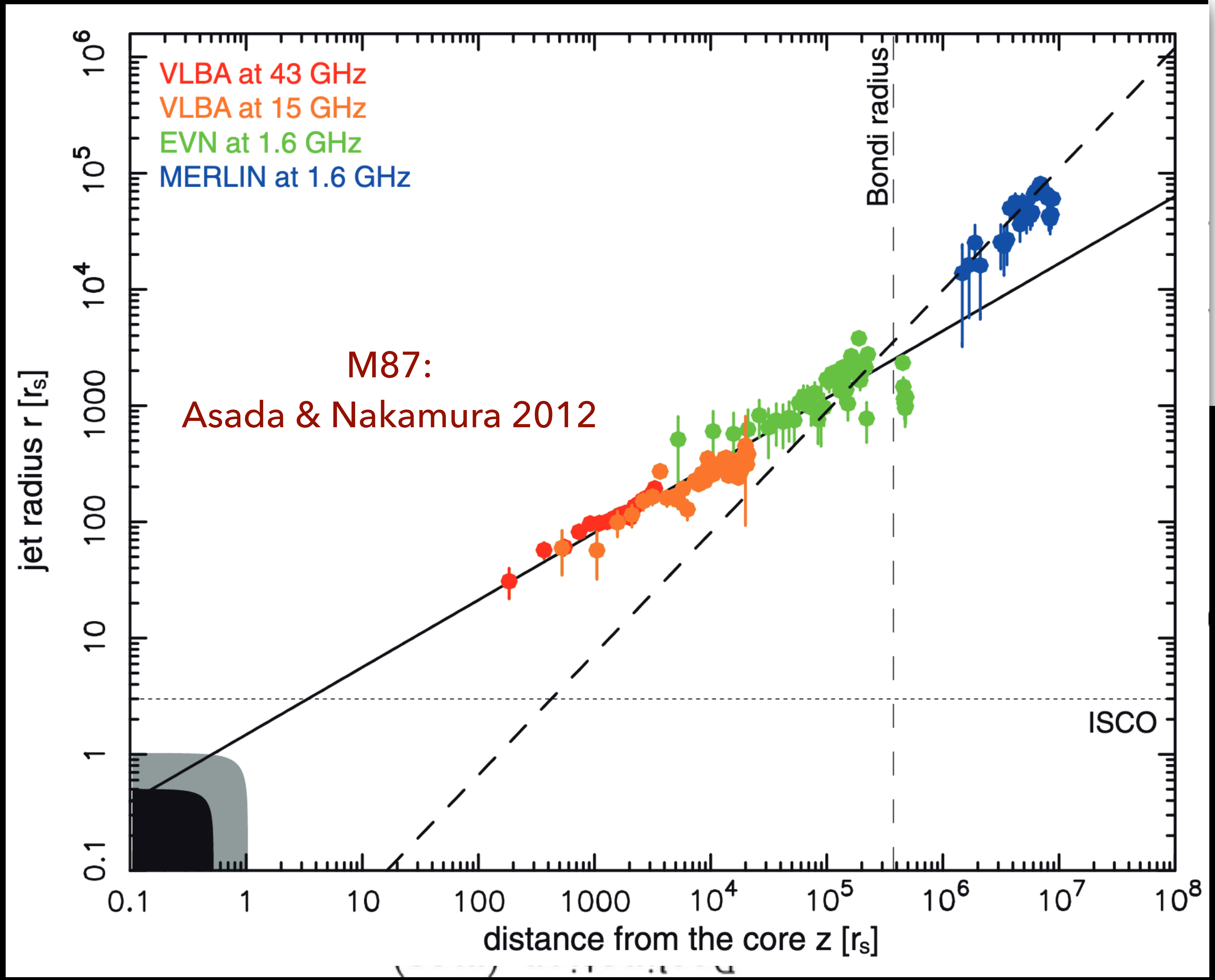
MWL modeling + VLBI ➠ localised dissipation zone far from BH

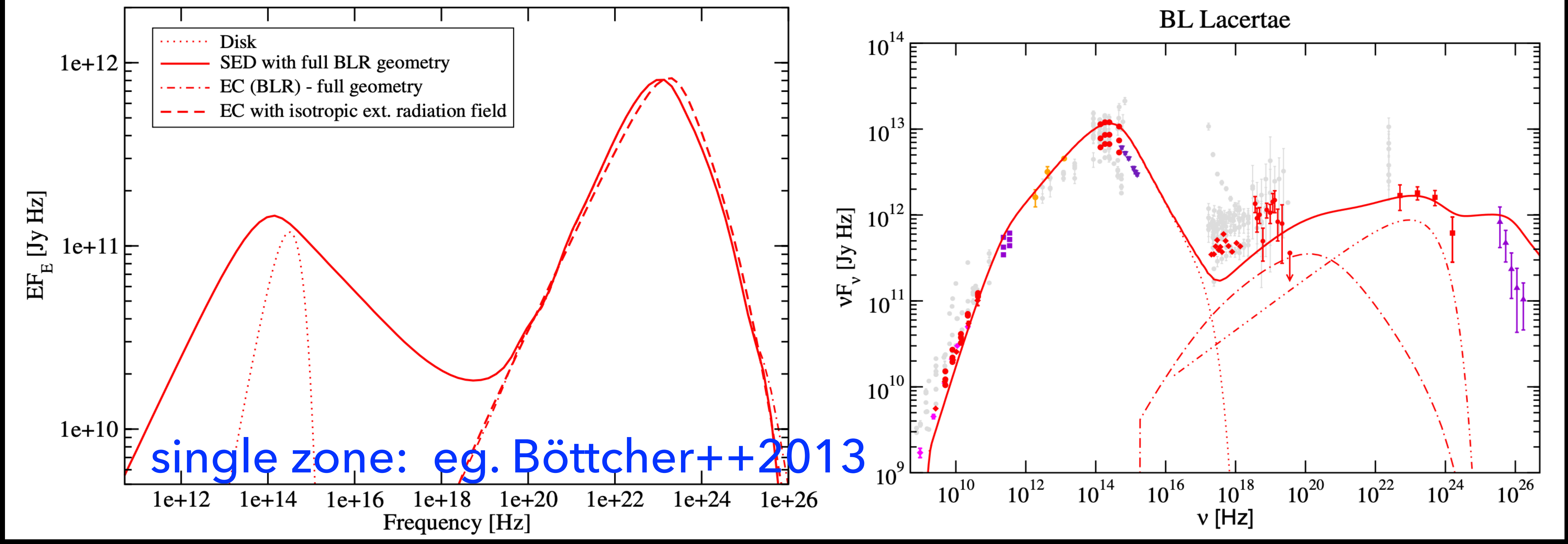
Marscher++2008, 2014; Cohen++ 2014 (MOJAVE/VLBI; Lister++2019):

Distance to Recollimation Shock

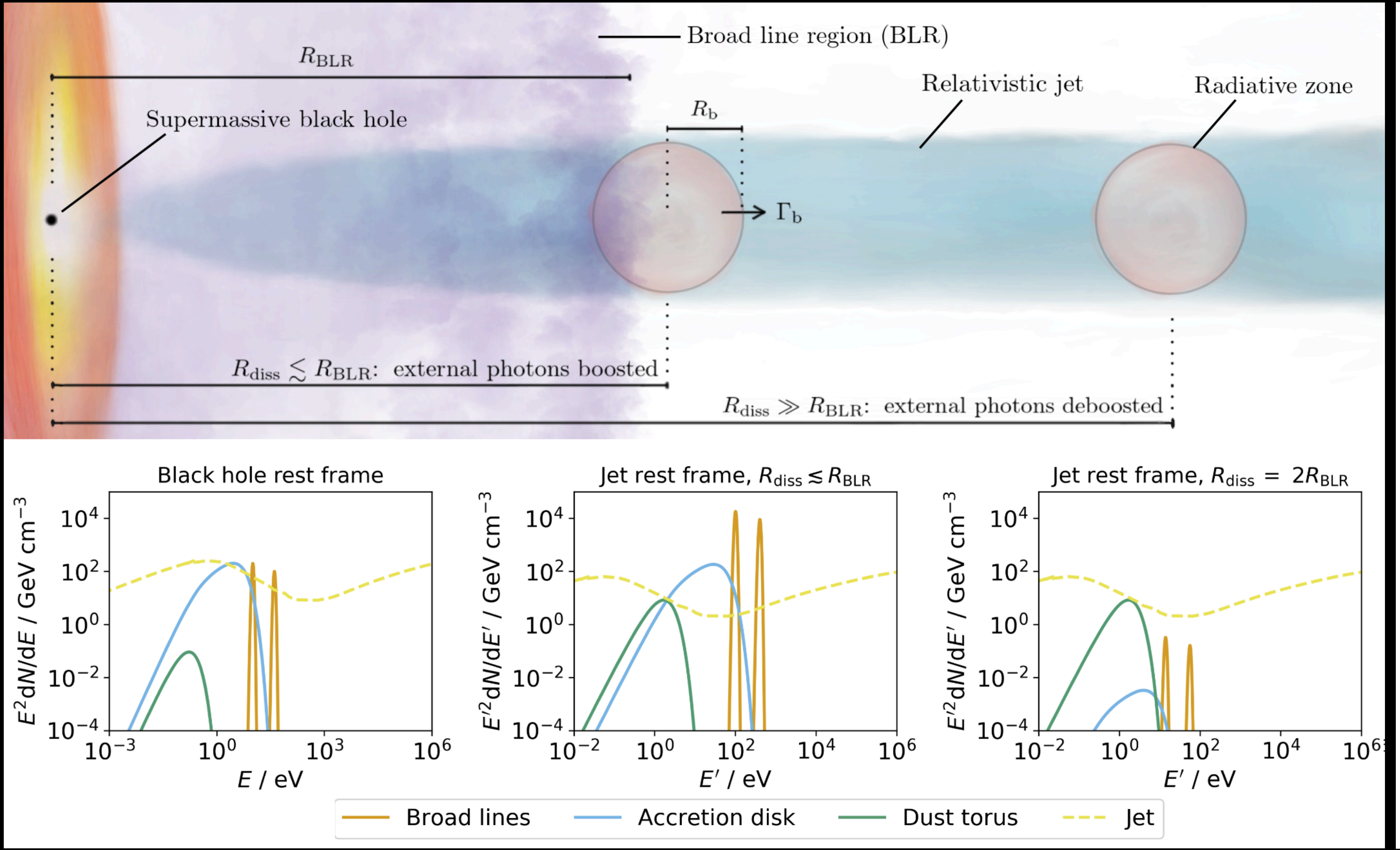
Name	z	Class	pc/mas	theta	Dist to Shock	log M_{BH}	log R	Ref.
BL Lac	0.0686	BLL	1.29	6	0.26	8.2	5.6	1, 2
M87	0.00436	FR I	0.08	13	860	9.5	6.0	1, 3, 4
3C 120 S1	0.033	FR I	0.65	16	0.7	7.8	5.7	5, 6
3C 120 C80	...	...	...	...	80	...	7.8	6, 7
3C 273	0.158	FSRQ	2.70	6	0.15	9.8	4.1	8, 9
3C 390.3 S1	0.0561	FR II	1.09	50	0.28	8.6	4.3	10, 11

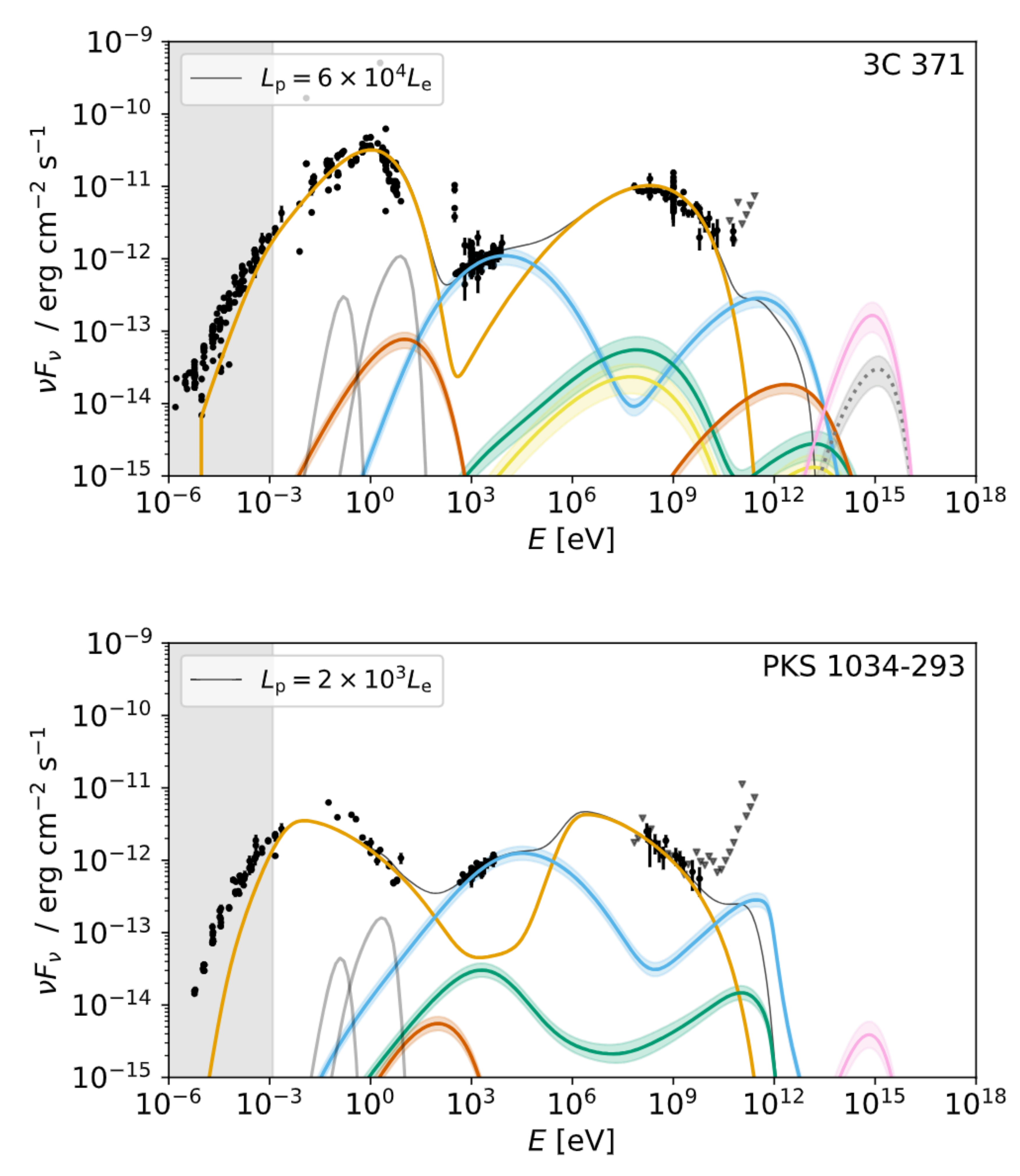
Distance from black hole





The field's "workhorse": time-dependent single-zone models





(from Rodrigues++2024 using AM³: Gao++2017 ➠ modelled 324 gamma-ray emitting blazars;
see also the hadronic code comparison Cerutti++2024)

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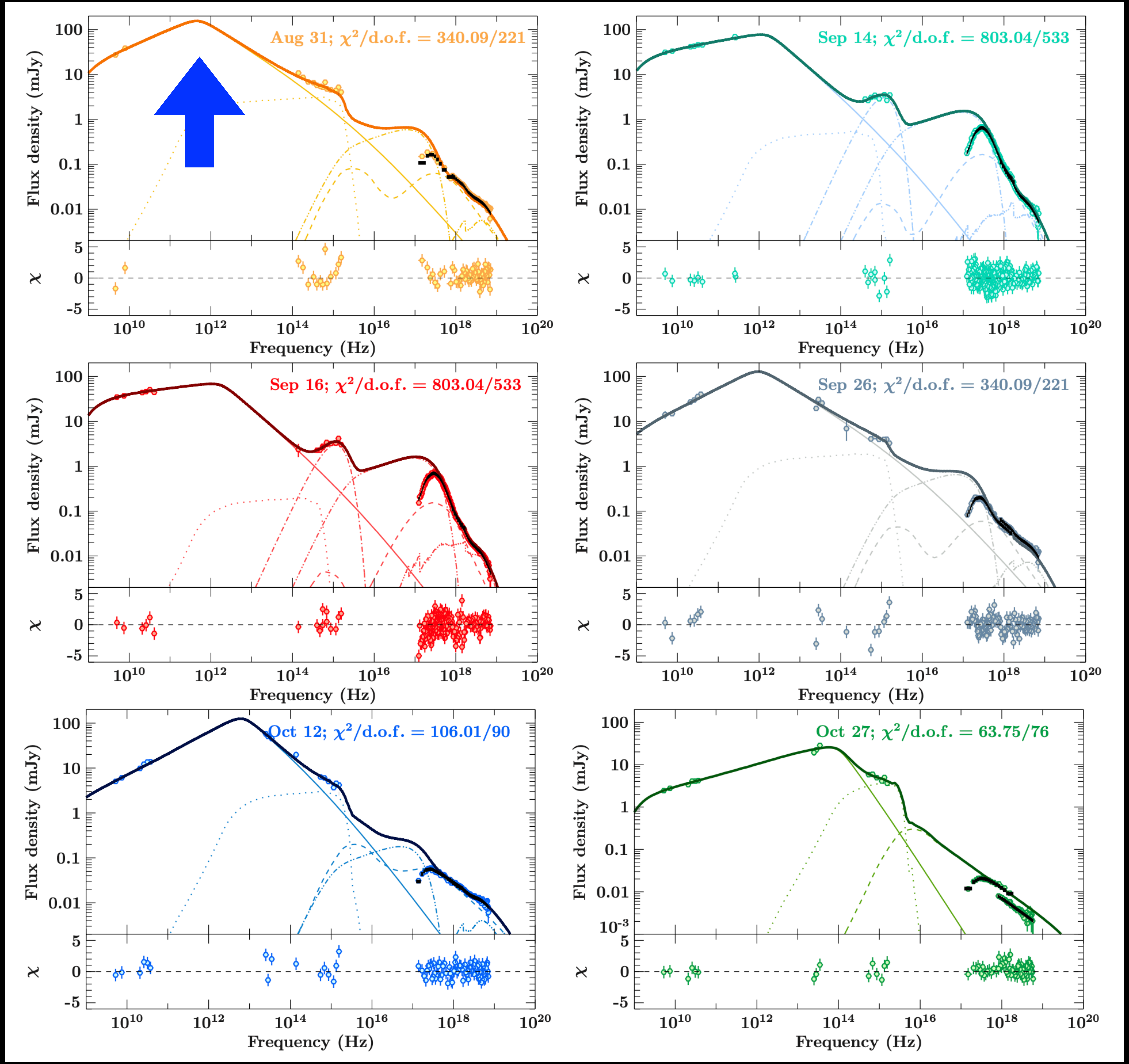
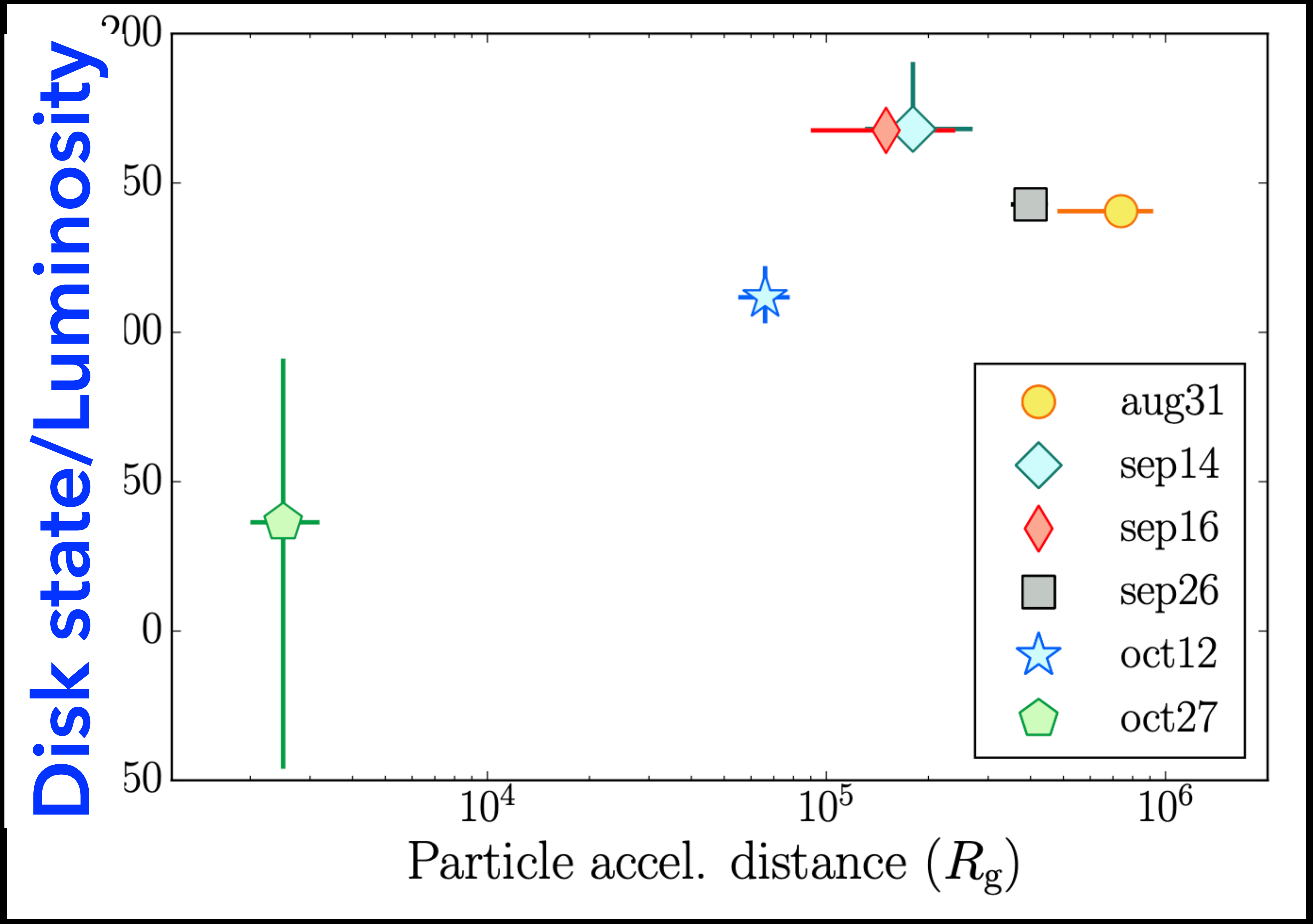
(from Rodrigues++2024 using AM³: Gao++2017 ➠ modelled 324 gamma-ray emitting blazars; see also the hadronic code comparison Cerutti++2024)

XRB spectral-timing: XTE J1836-194 "dissipation zone" responds to disk in realtime





- Jets respond to changes in accretion disk in real time!
- Dissipation 'zone' changes by 2 orders of magnitude over 2 months!

(Russell++ 2014; Lucchini, Russell, SM++ 2020; Cao, Lucchini, SM++2021)

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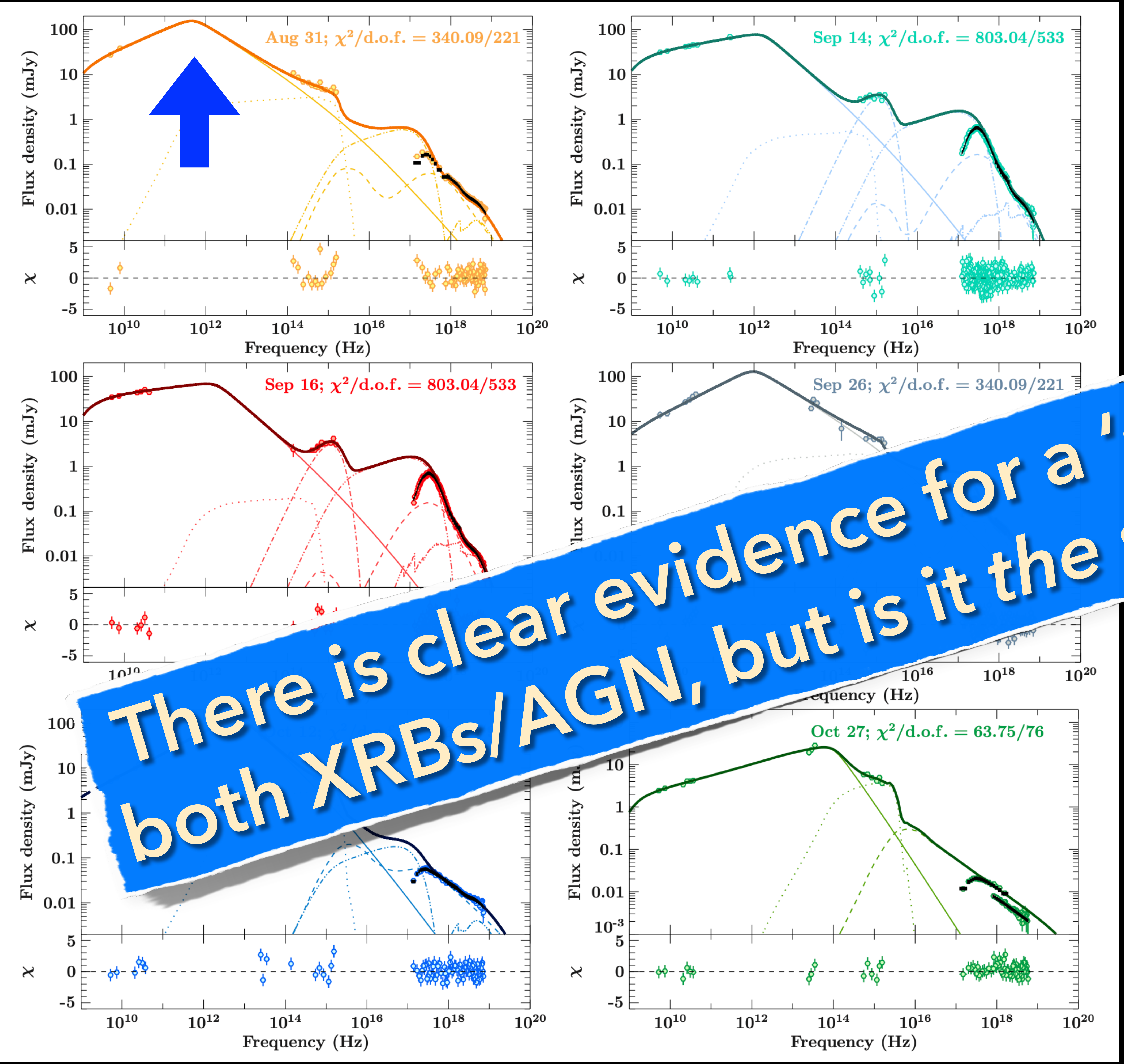
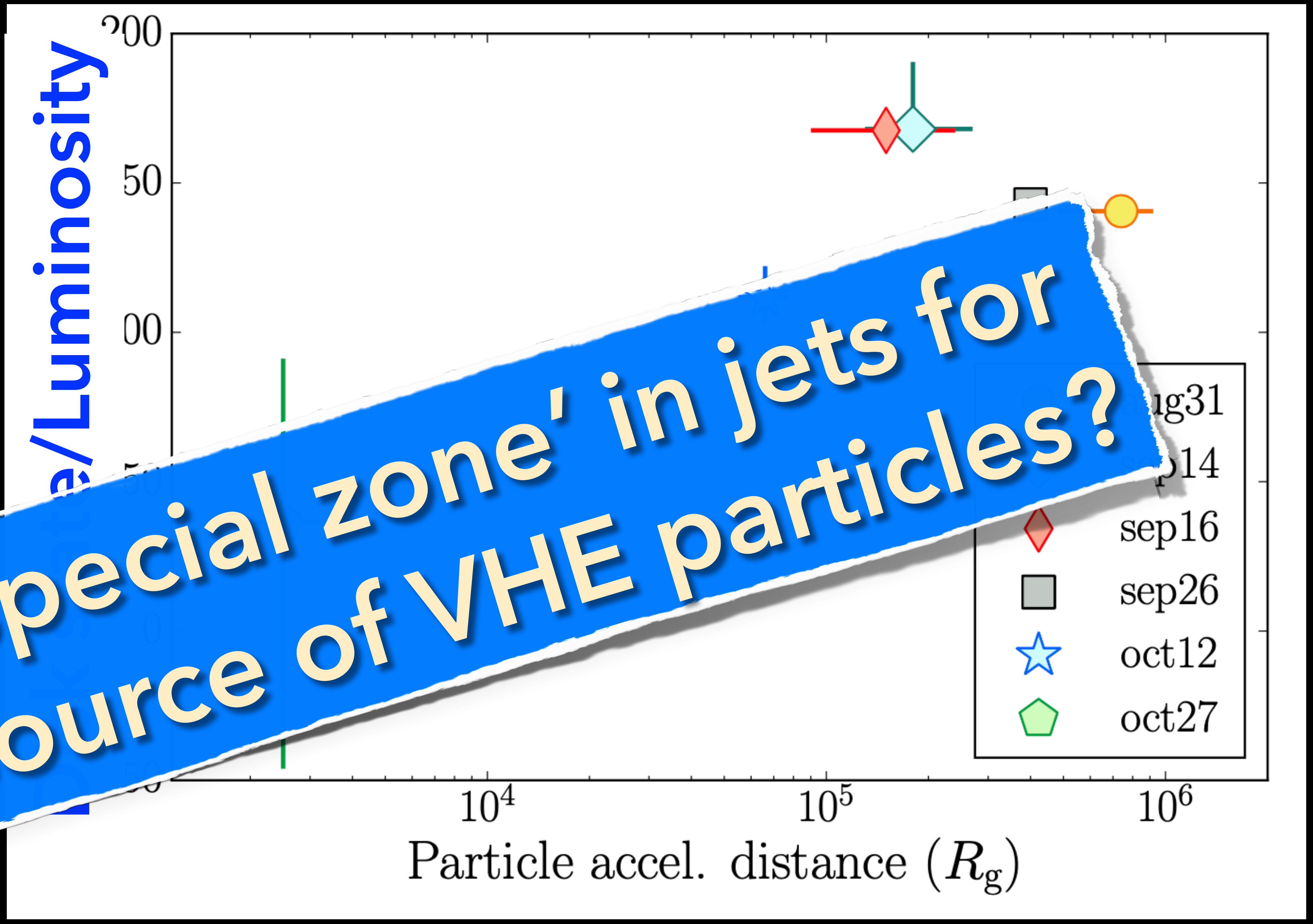


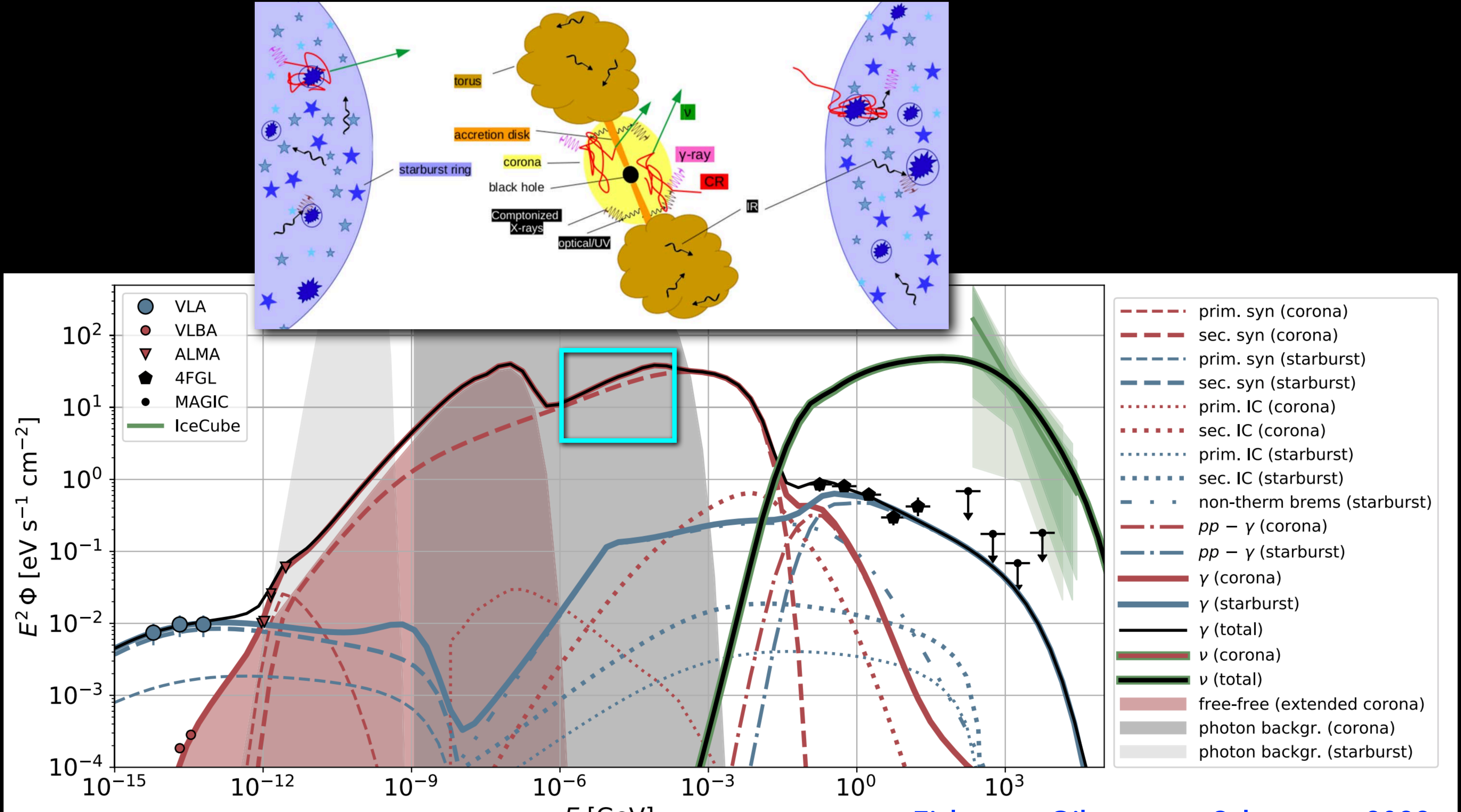


There is clear evidence for a 'special zone' in jets for both XRBs/AGN, but is it the source of VHE particles?

- Jets respond to changes in accretion disk in real time!
- Dissipation 'zone' changes by 2 orders of magnitude over 2 months!

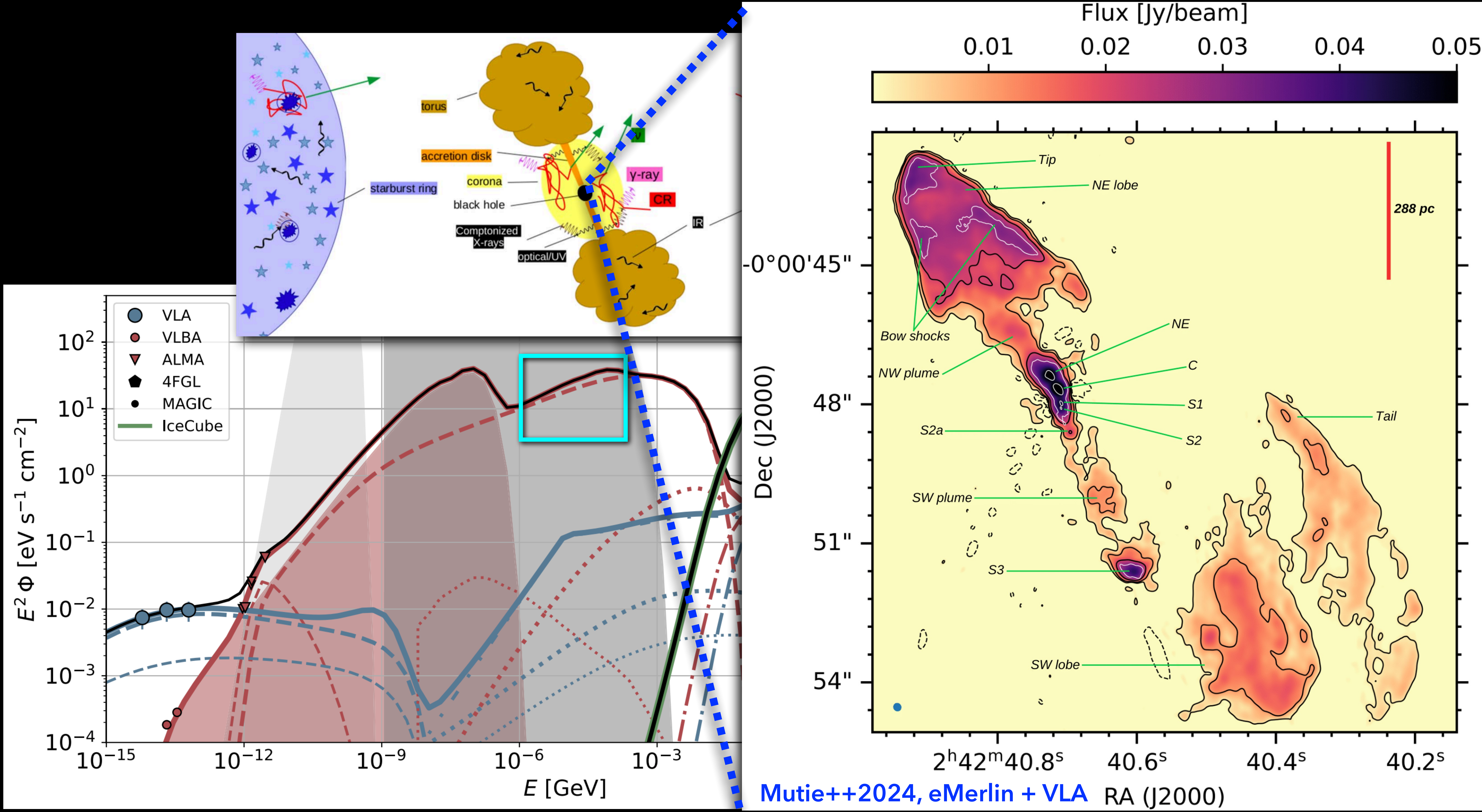
(Russell++ 2014; Lucchini, Russell, SM++ 2020; Cao, Lucchini, SM++2021)

NGC 1068: AGN Corona (=jet base?) + Starburst?

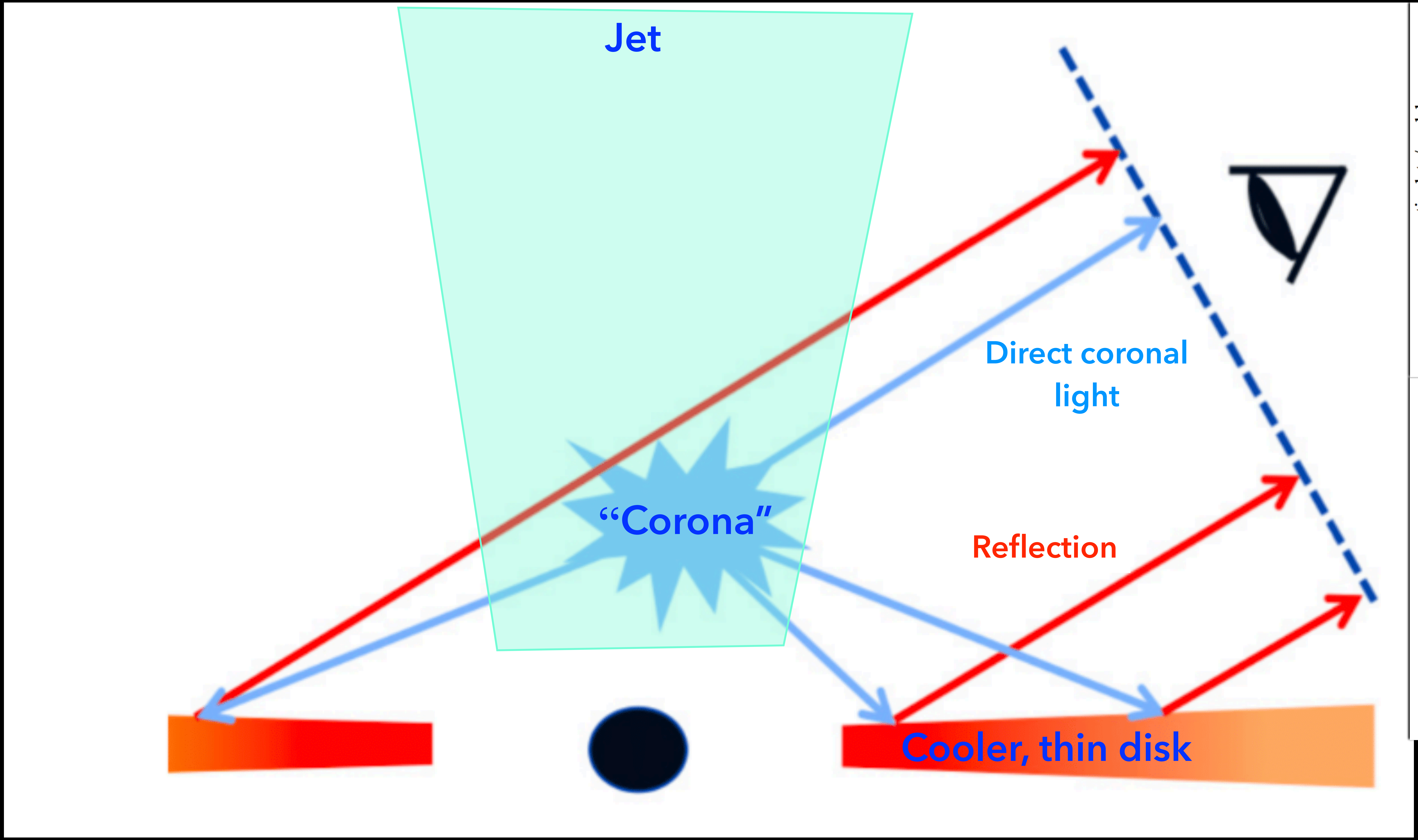


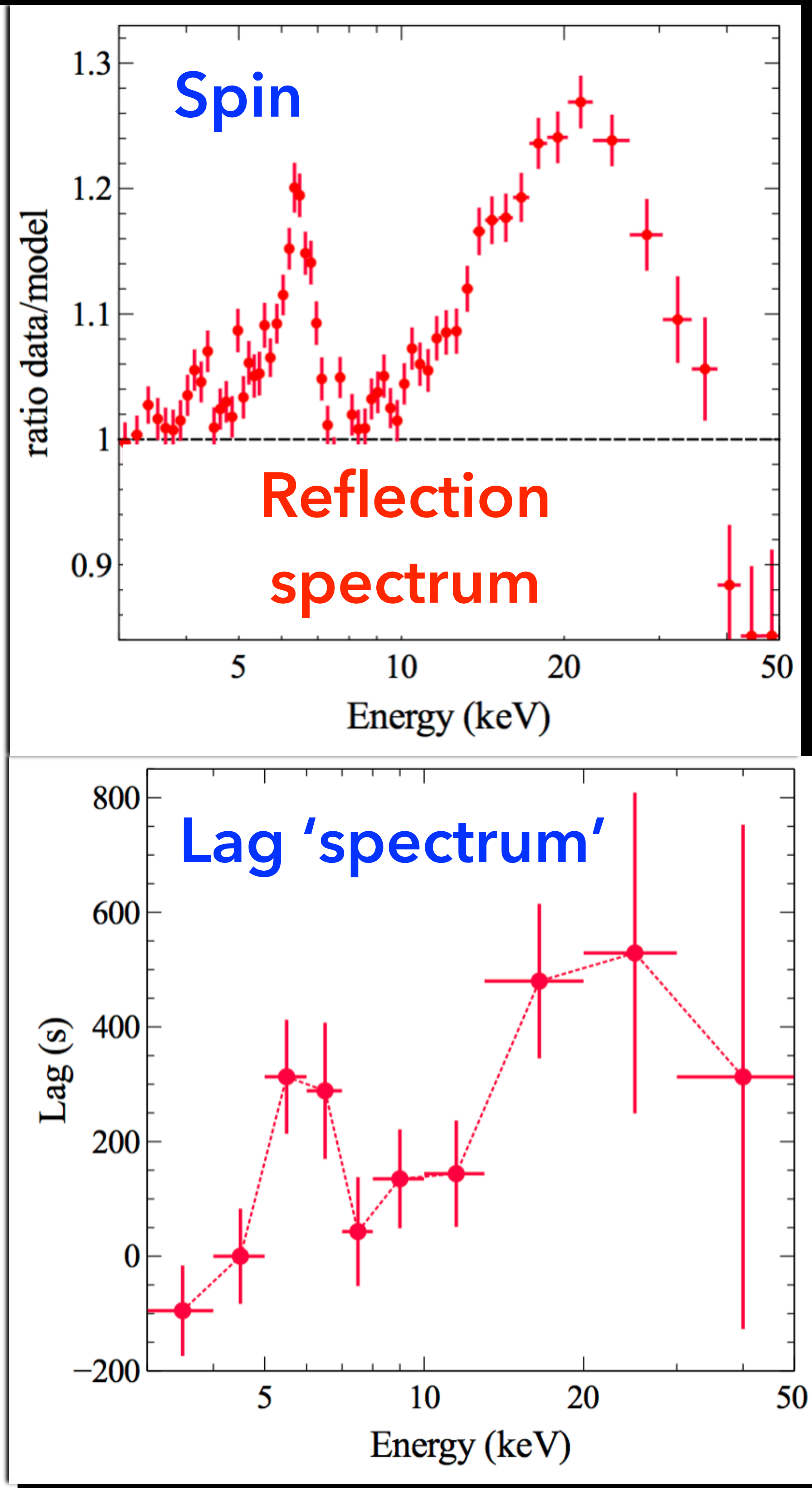
Eichmann, Oikonomou, Salvatore++2022

NGC 1068: AGN Corona (=jet base?) + Starburst?



Swap spatial ➠ time resolution: X-ray spectral reflection & lags

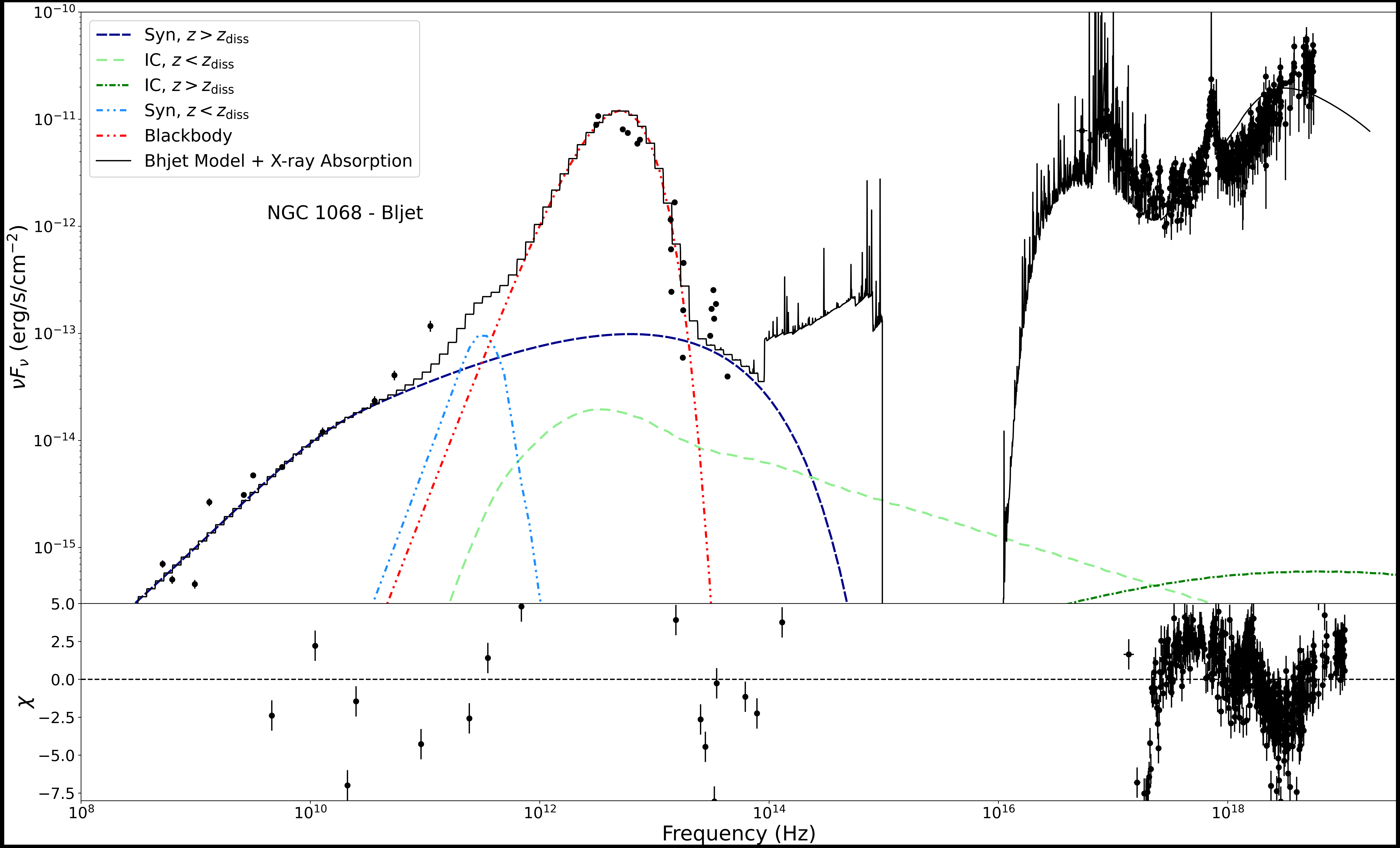




Kara++2015

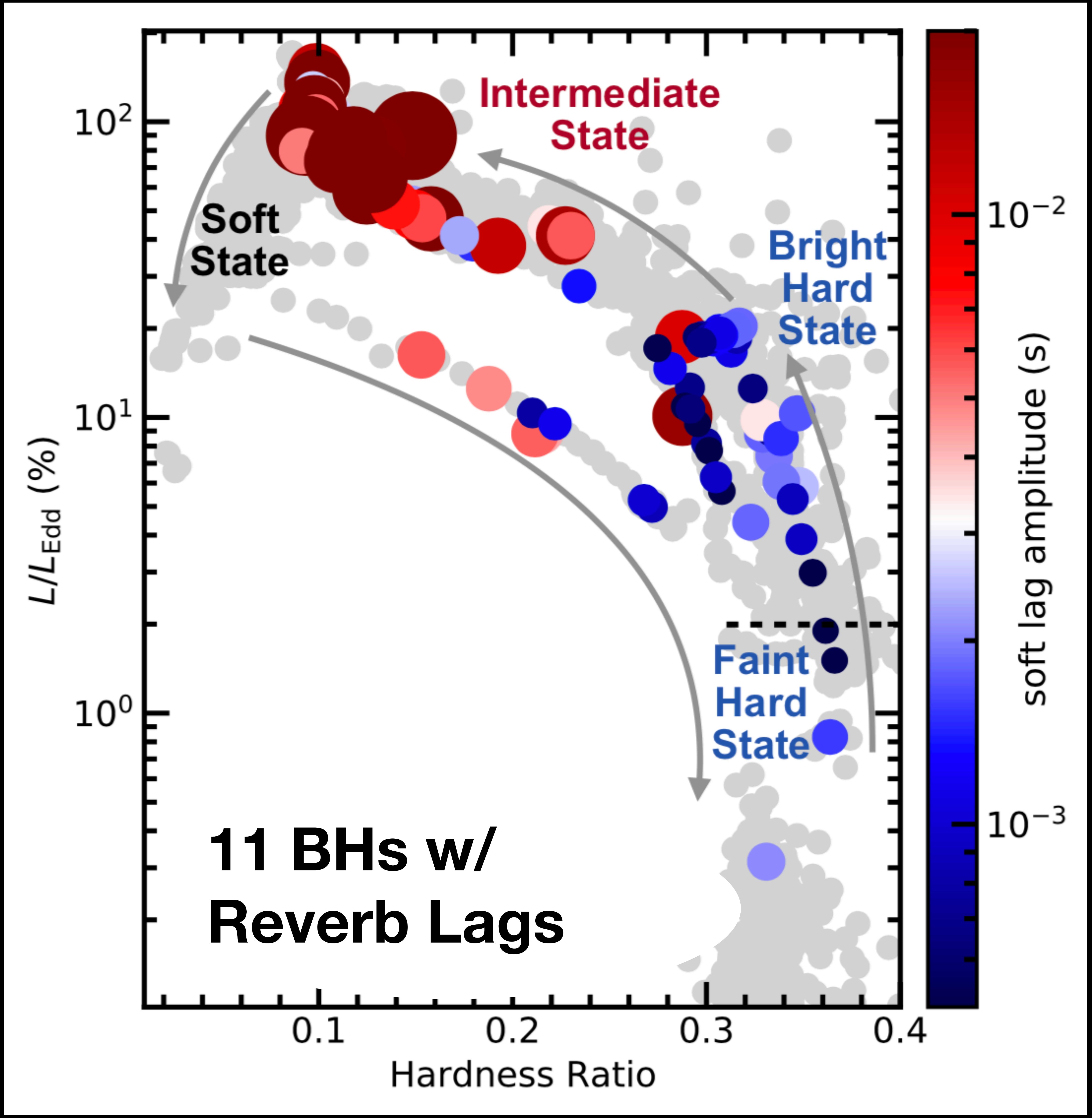
See eg. Fabian++2009; Zoghbi++2010; Uttley++2014 for reviews

NGC1068: complex absorption/reflection constrains geometry

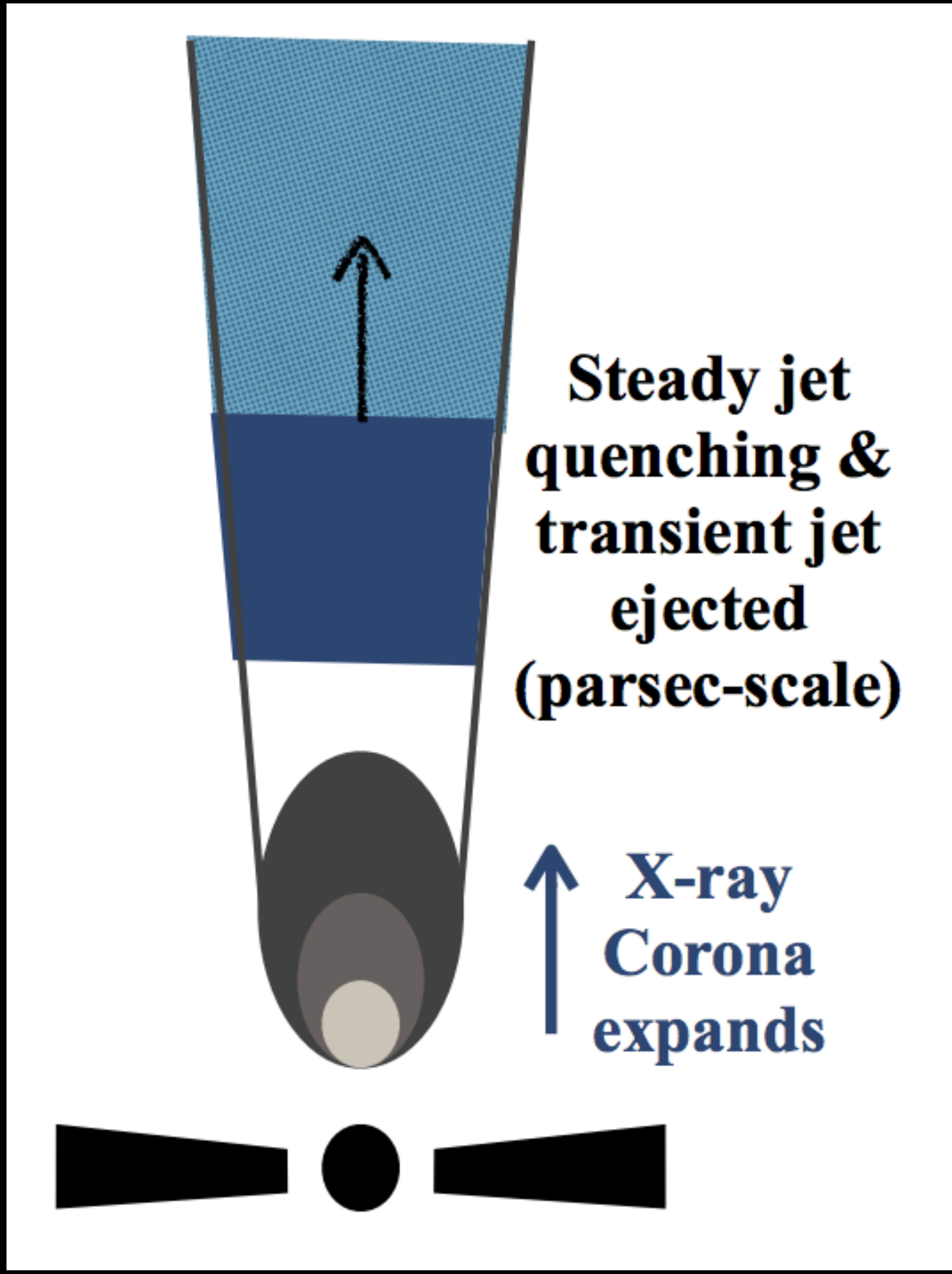


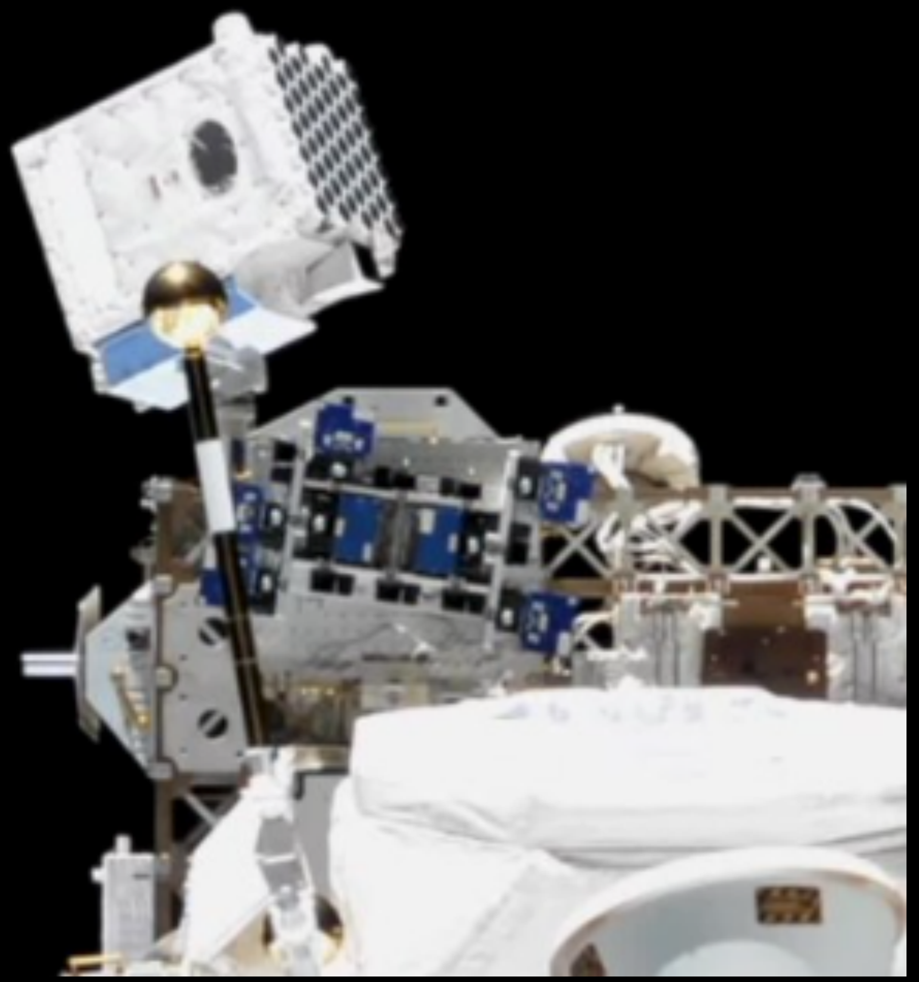
Duncan (MSc student), Lucchini, SM++, in prep.; see also Bauer++2015

NICER: Reverberation mapping "machine"



Wang, Kara++2022

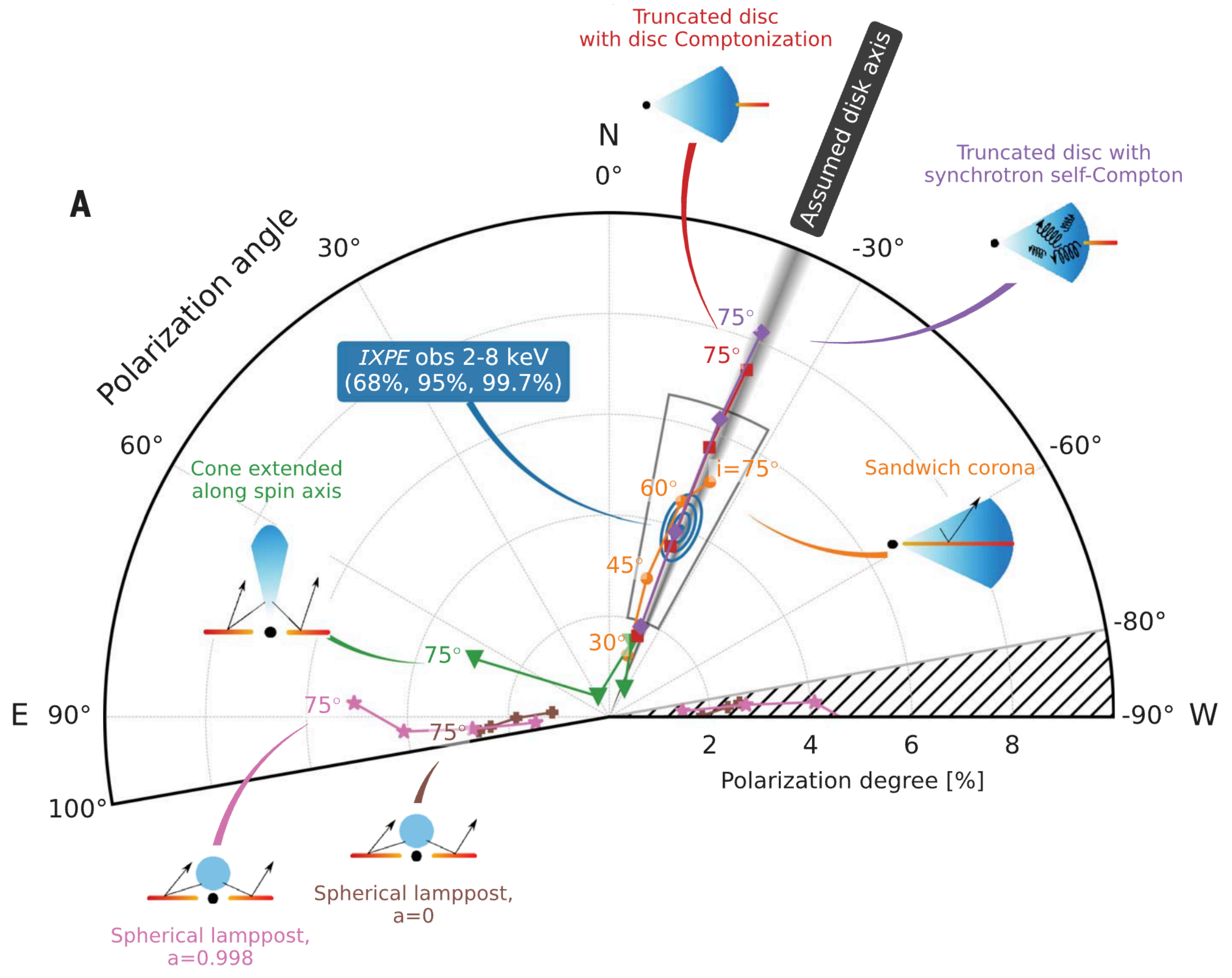




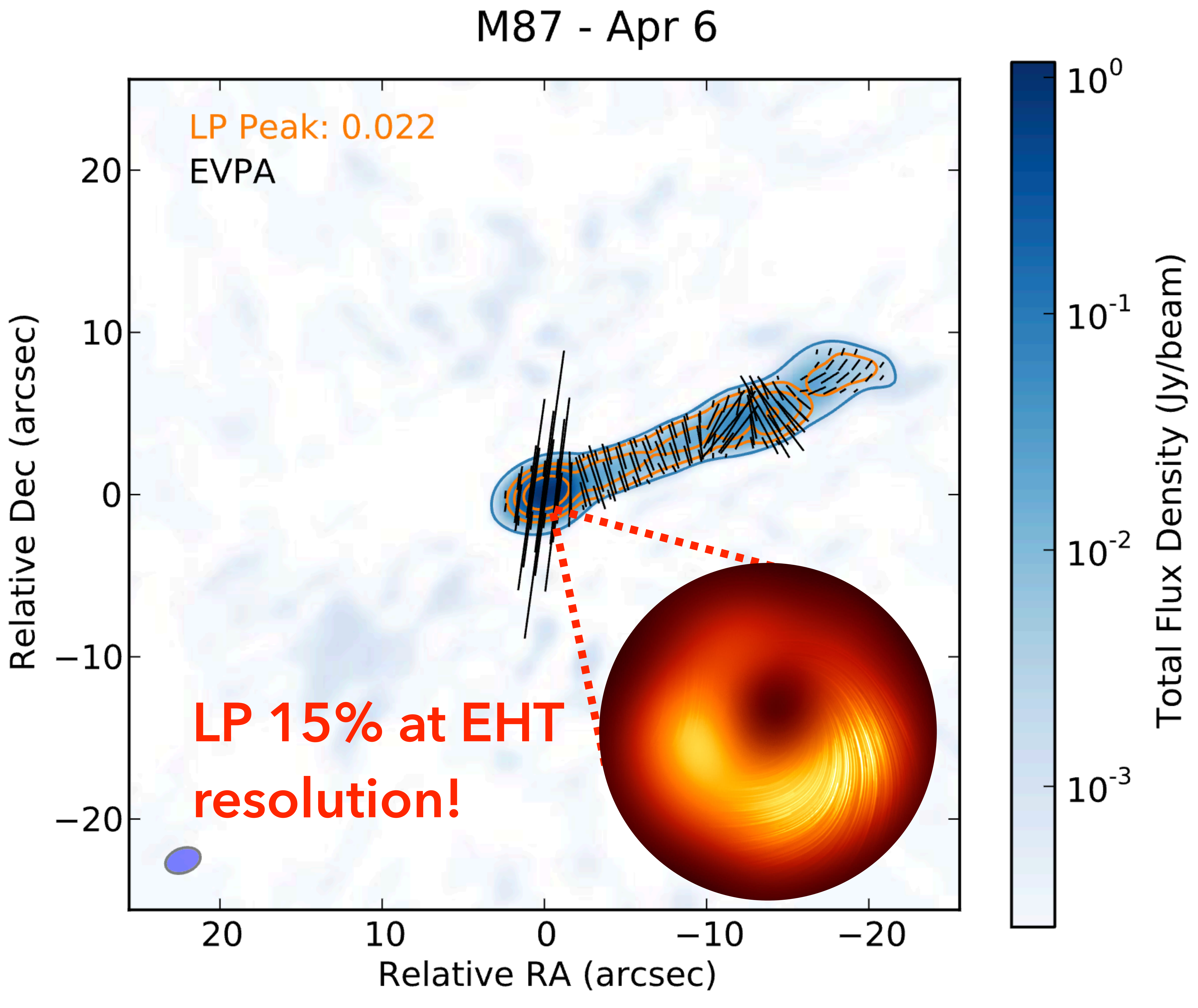
Kara+19

And see recent work by: Lucchini, Russell, SM++ 2021; Cao, Lucchini, SM++ 2021

Polarisation is a key new constraint with IXPE, but beware resolution!



Krawczynski++2022: Cyg X-1 constraints from IXPE



Goddi, EHT++2021 (ALMA subarray of the EHT array 2017)

Radiative 2T-3D-GRMHD simulations: corona as disk/jet interface layer?

Density | Ion Temperature | Electron Temperature

Disk threaded by large scale poloidal flux promotes 2T regions and truncation

Develop low density, thick hot corona with $T_i > T_e$.

Corona best described by radiative analog of a MAD

Corona flow has patches of cool gas floating through it.

Liska, Musoke, Tchekhovskoy++2022; Liska++2024

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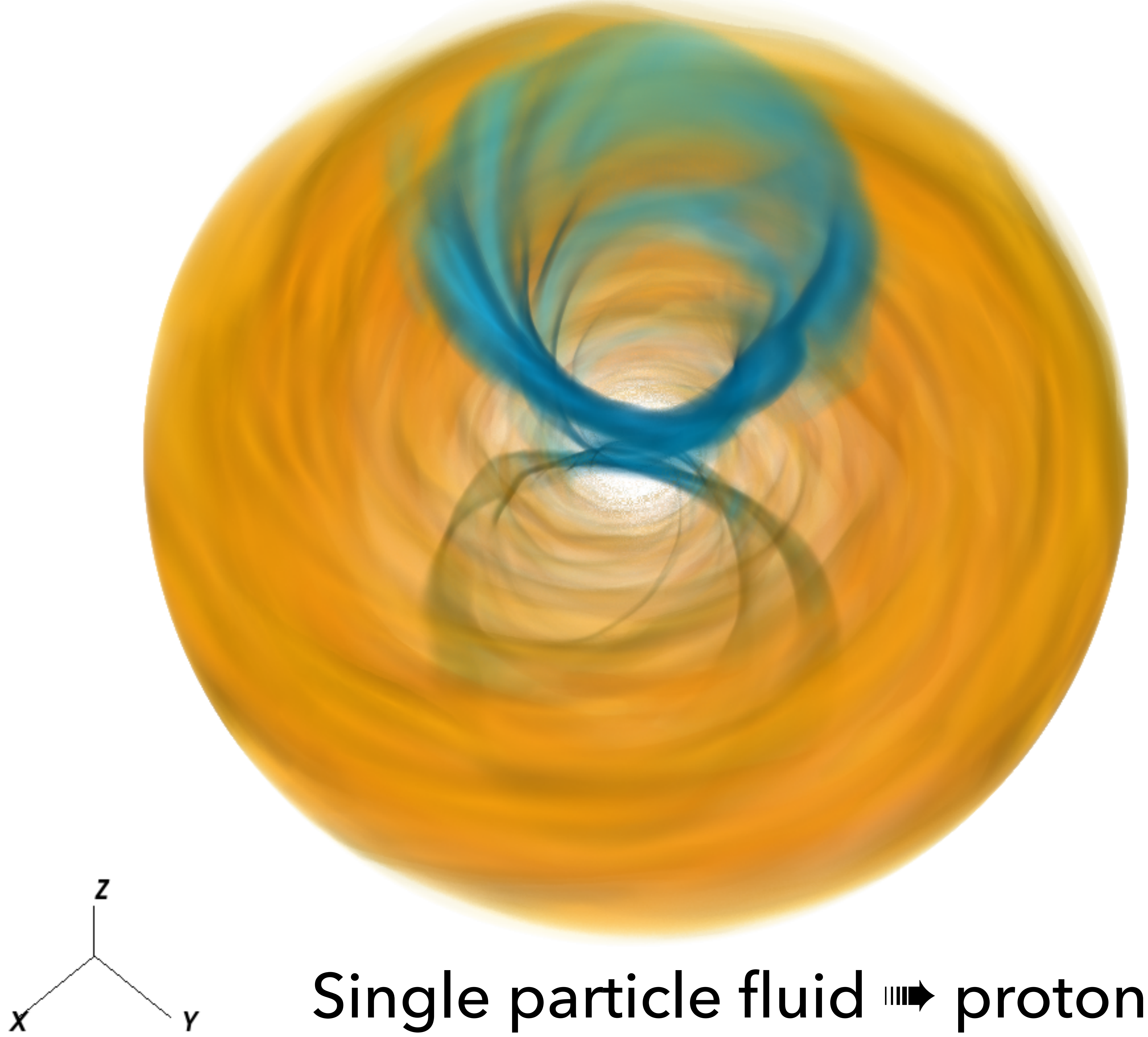
Model degeneracy introduced via particle "subgrid" models

GRMHD simulation: disk (orange), jets (blue)



Single particle fluid ➟ protons

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

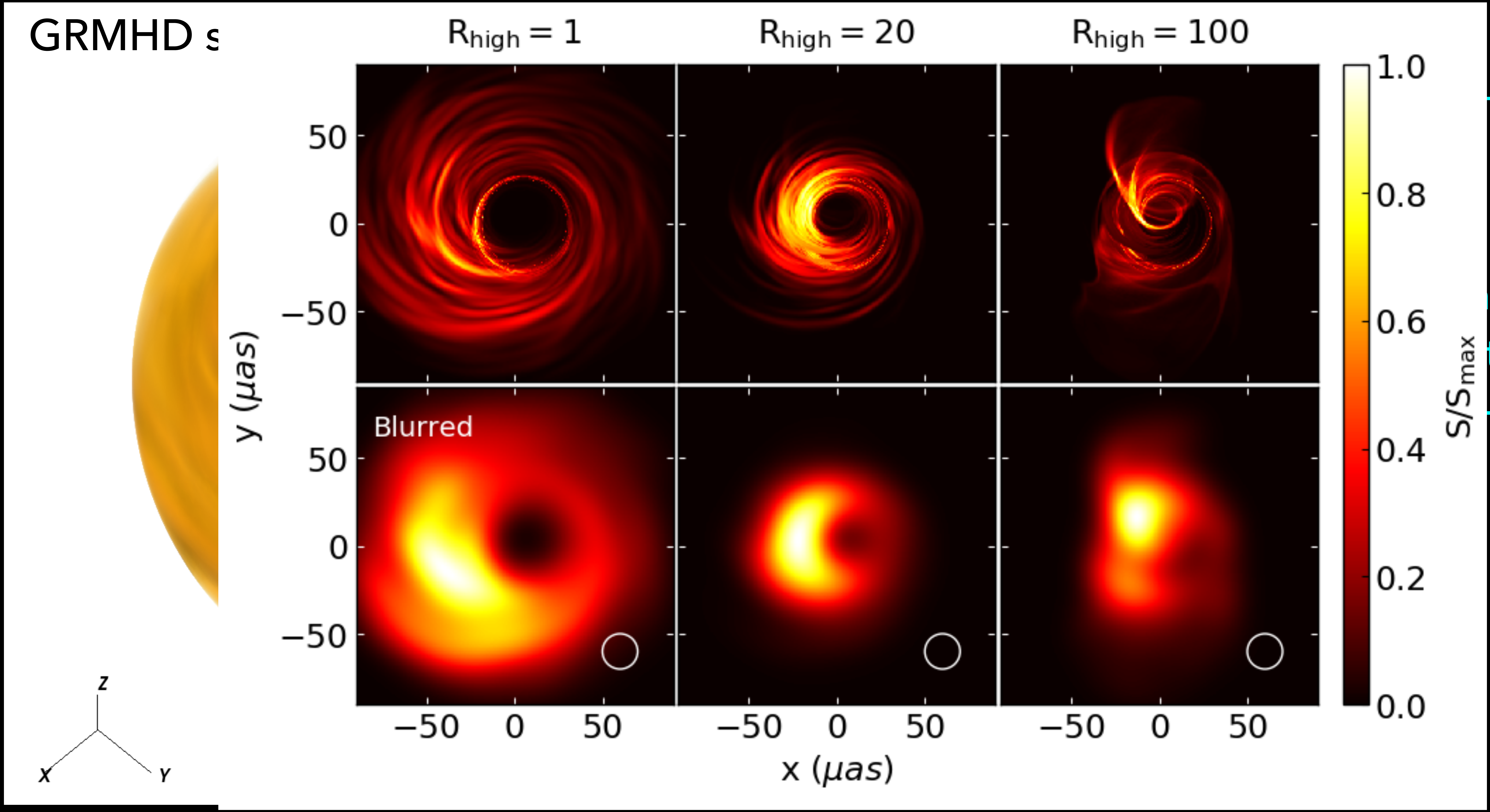
Heat electrons, example: from EHT/ Moscibrodzka++2016 (motivated by Alfvénic turbulent heating, eg. Howes 2010; Kawazura++2018)

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

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)

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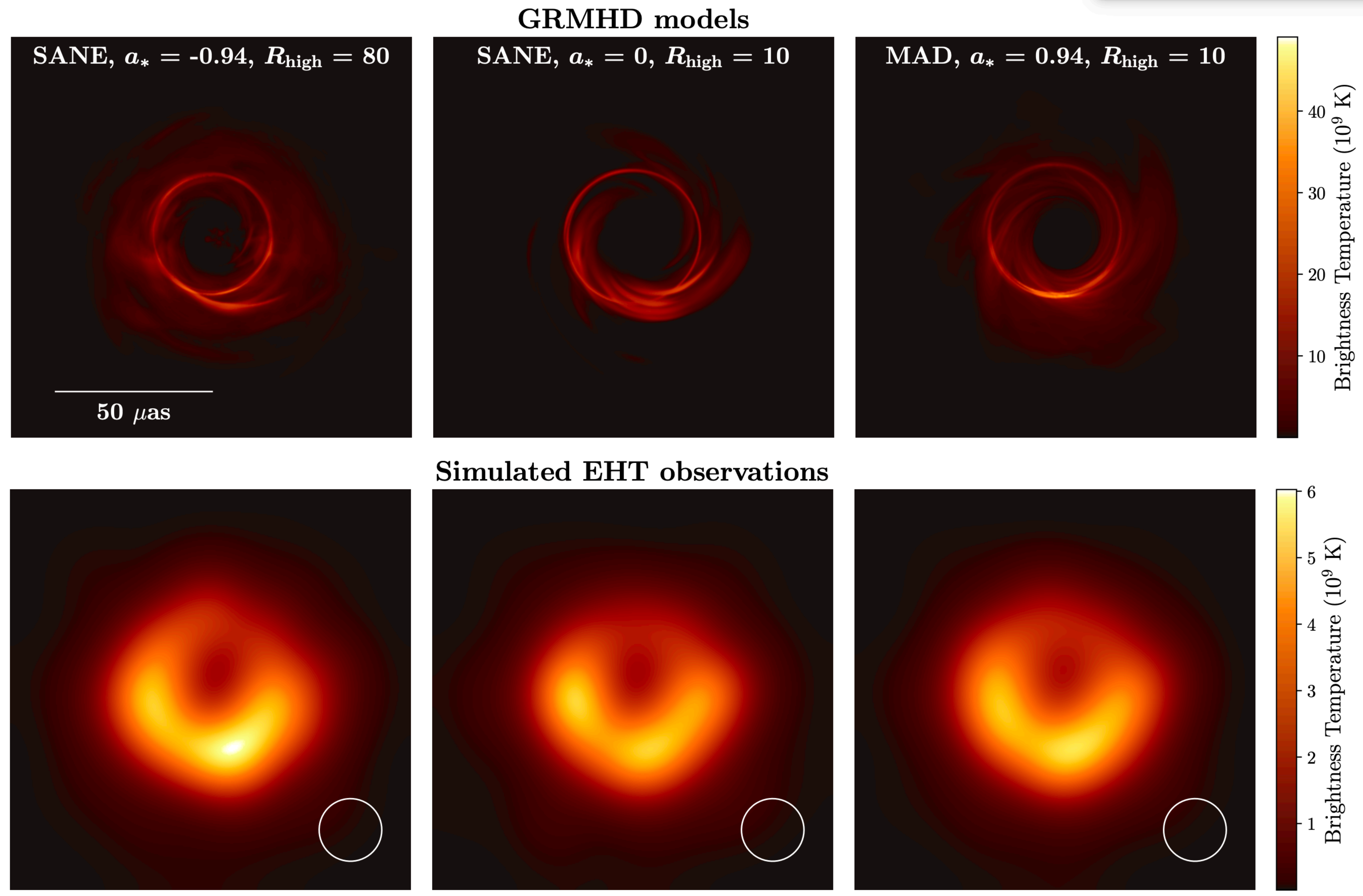
GRMHD s



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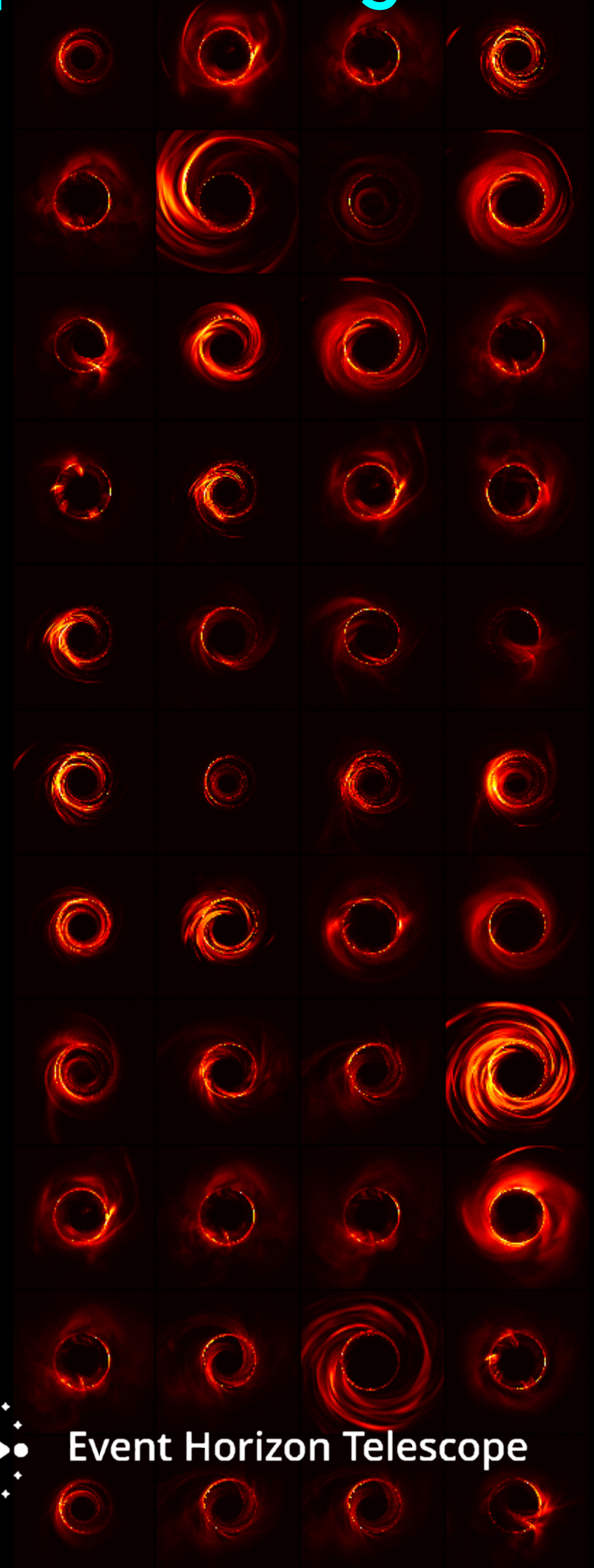
EHT's M87* Simulation Library: ~10x5 models, 23 TB, 60k snapshot images

Event Horizon Telescope

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

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



- Matching just the size/shape and minimum jet power (from MWL), could only rule out ~60% of models
- 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, unambiguously determine spin, or constrain particle acceleration regions/ mechanisms!

Event Horizon Telescope

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

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

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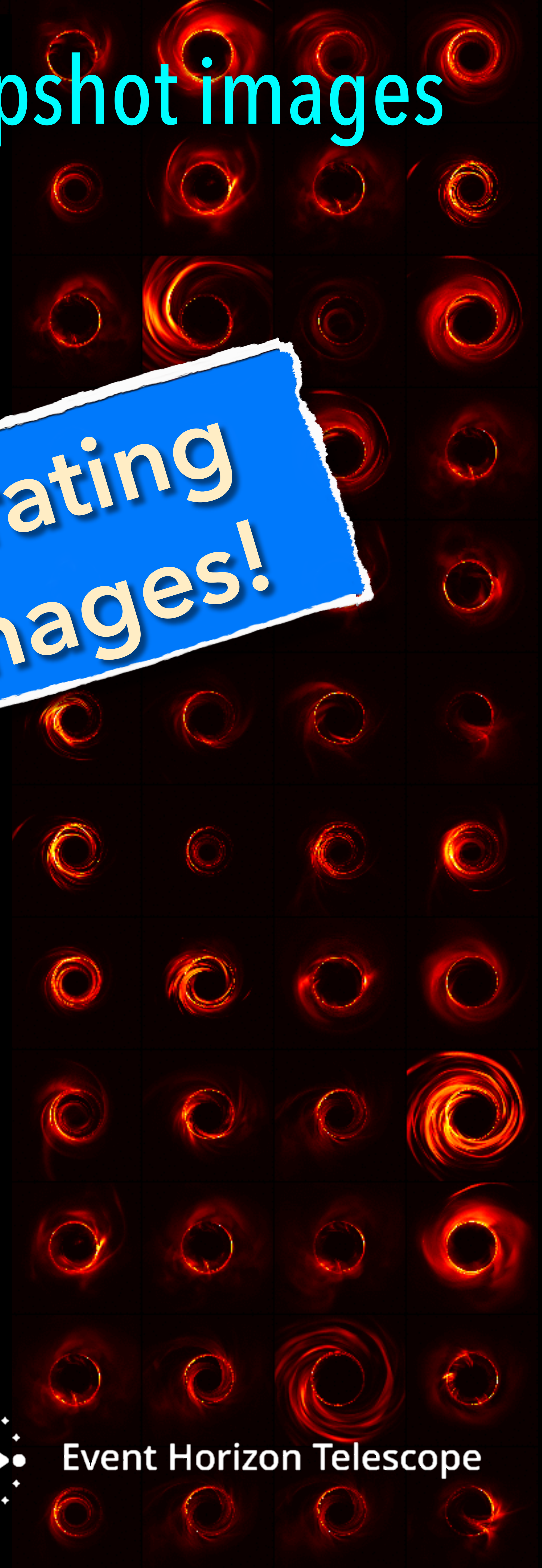
- Polarisation (EHTC 2021) prefers "M... dynamically strong, ord... fields ➠ ideal f...
- ... image of M87* ...biguously determine spin, or ...train particle acceleration regions/ mechanisms!

Now: breaking degeneracy requires incorporating information beyond EHT single-frequency images!



Event Horizon Telescope

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

Models need to explain not only images but also MWL spectra

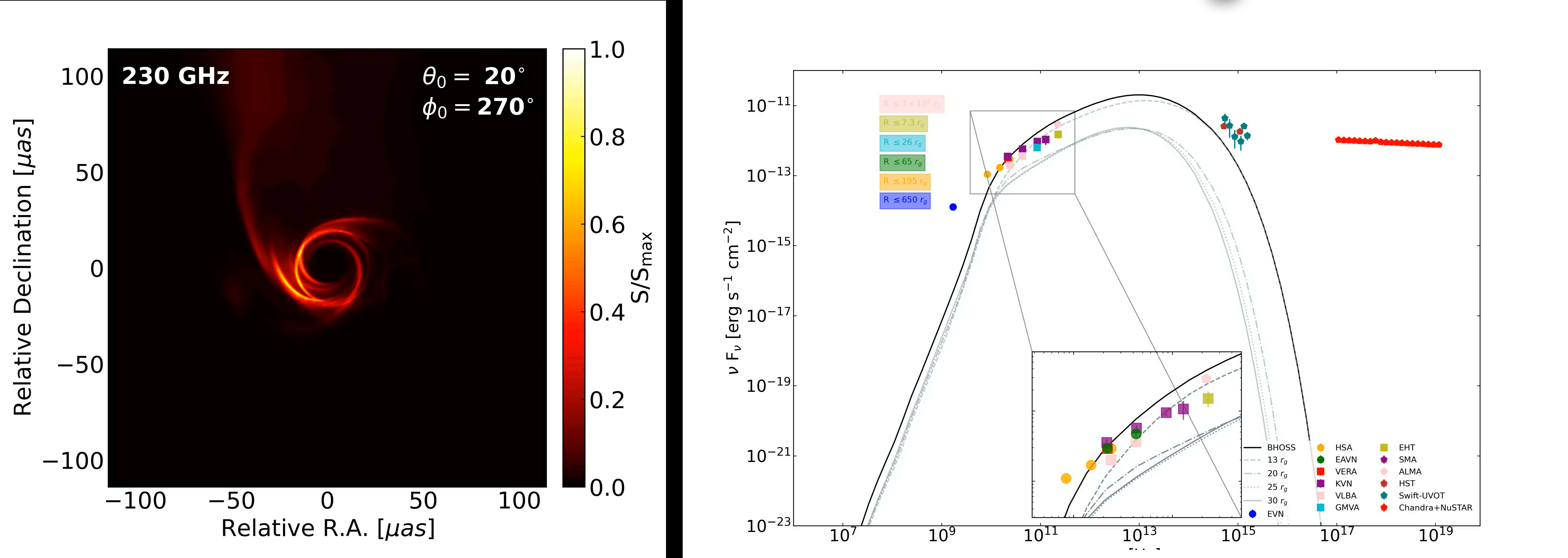
EHT 2017
M87 MWL
Campaign

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

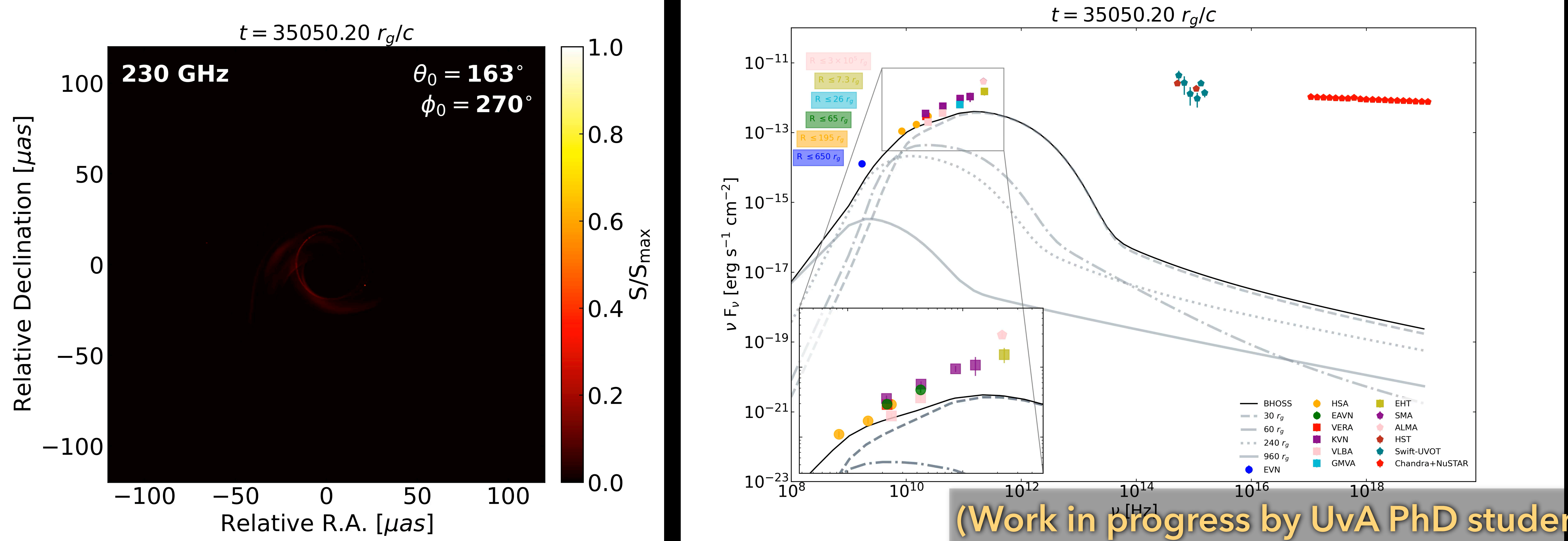
Models need to explain not only images but also MWL spectra

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

The new horizon: combined image + SED modelling



Thermal, inner 30r_g



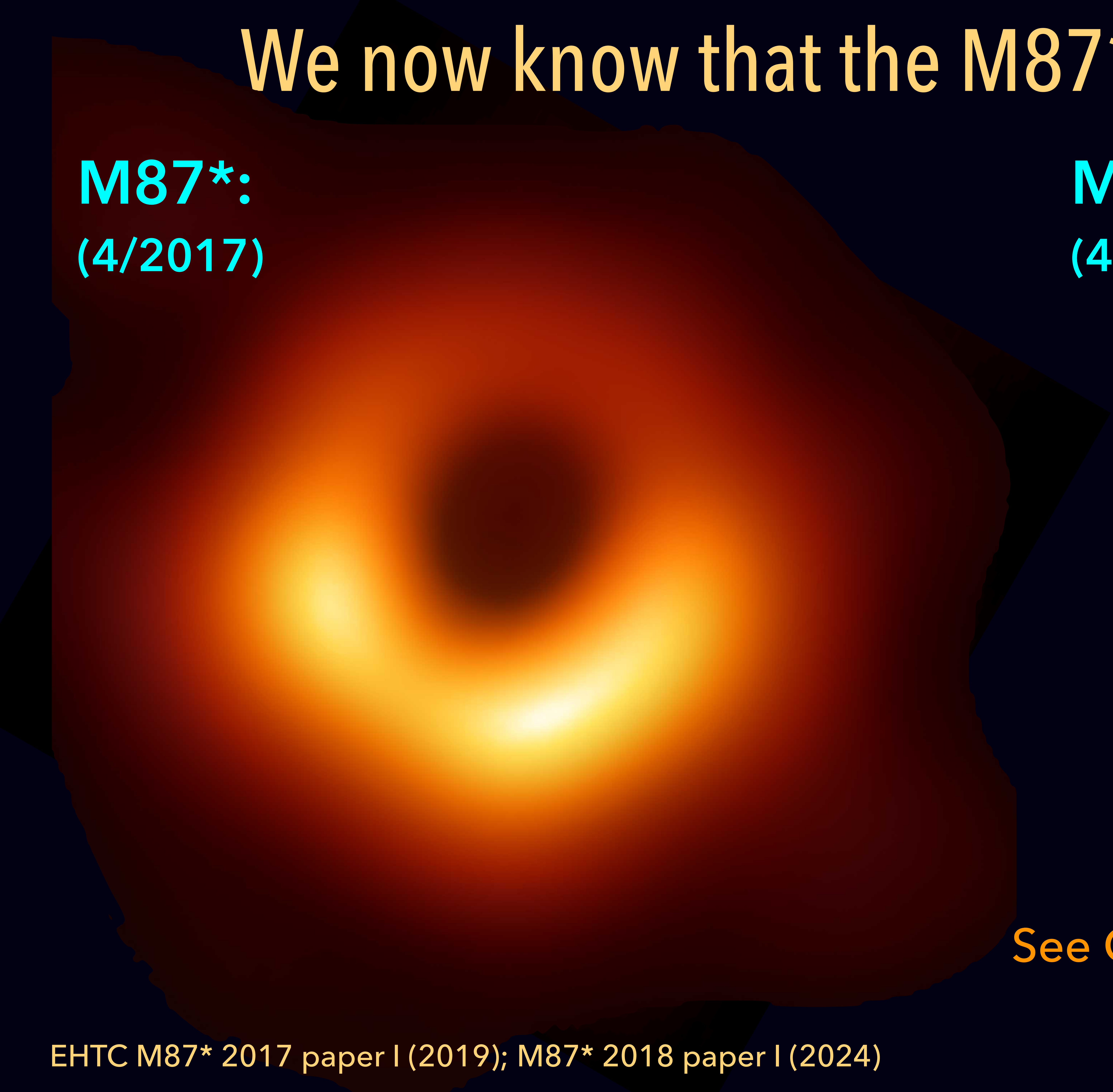
Non-thermal parameter-ised power-law, <960r_g

(Work in progress by UvA PhD students Wanga Mulaudzi & Rittick Roy)

Outline

- ★ Geometry ⇔ particle acceleration
- ★ The (evolving) perspective from EHT
- ★ Variability (EHT and beyond)
- ★ Advances in numerical modelling
- ★ Outlook for the future

We now know that the M87* ring is evolving!



M87*:
(4/2017)

M87*:
(4/2018)

See Giacomo Principe's talk on the 2018 EHT campaign for M87!

EHTC M87* 2017 paper I (2019); M87* 2018 paper I (2024)

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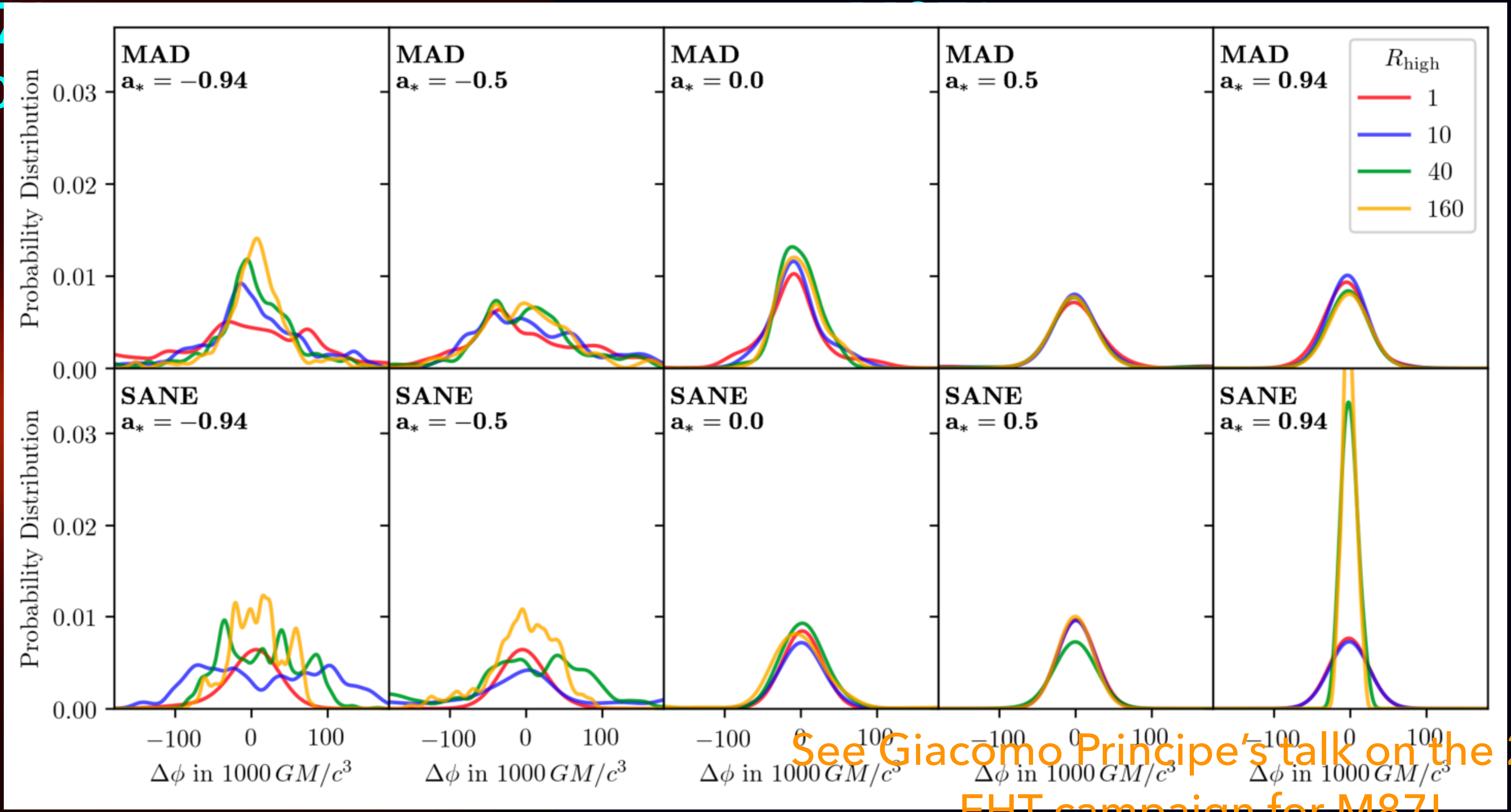
We now know that the M87* ring is evolving!

M87

(4/20



See Giacomo Principe's talk on the 2018 EHT campaign for M87!

EHTC M87* 2017 paper I (2019); M87* 2018 paper I (2024)

Courtesy Boris Georgiev, PhD thesis

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

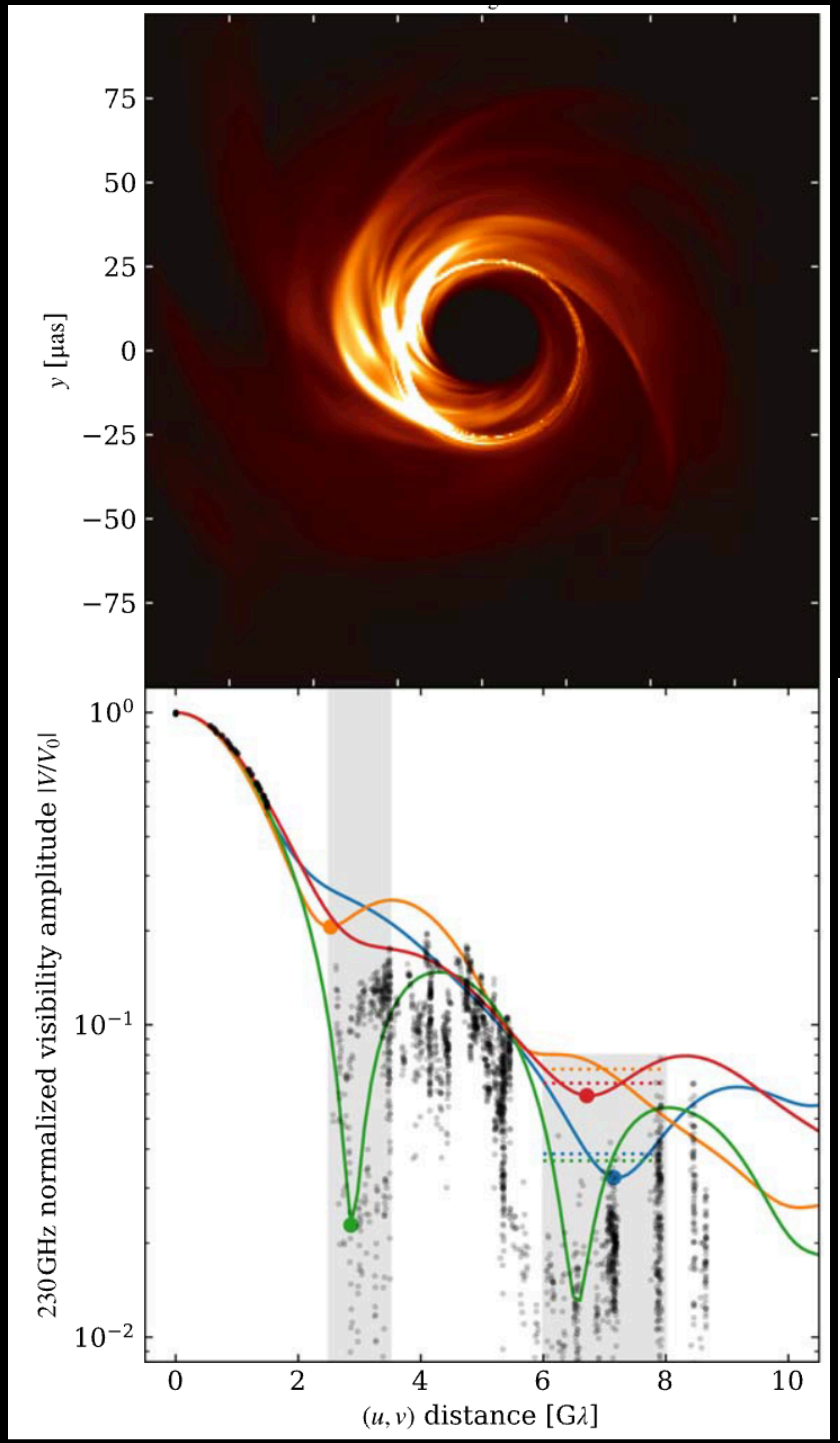
X-ray flare from NASA's Chandra X-ray Observatory, + NuSTAR & Swift (space)

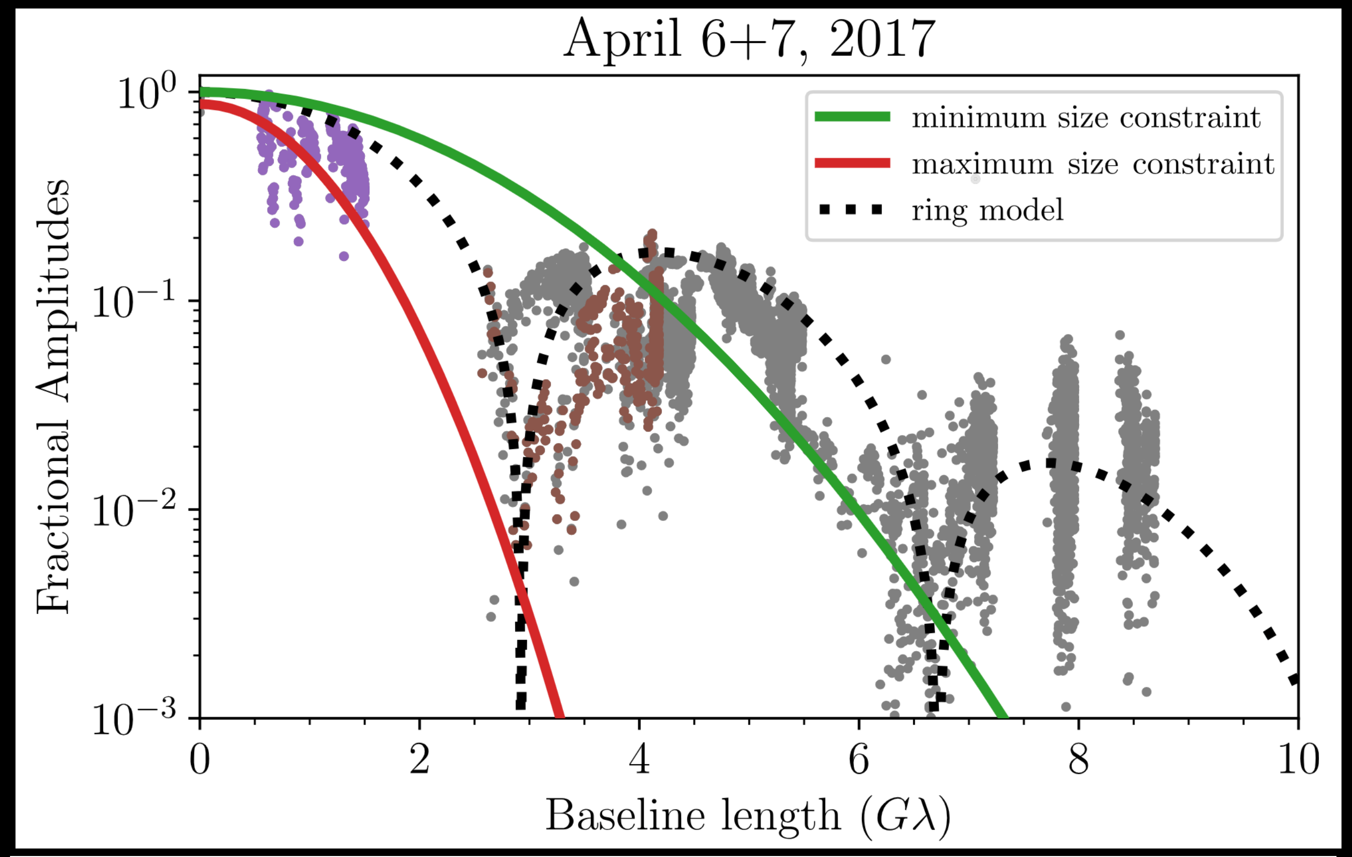
Credit: NASA/CXC/Amherst College/D.Haggard et al.

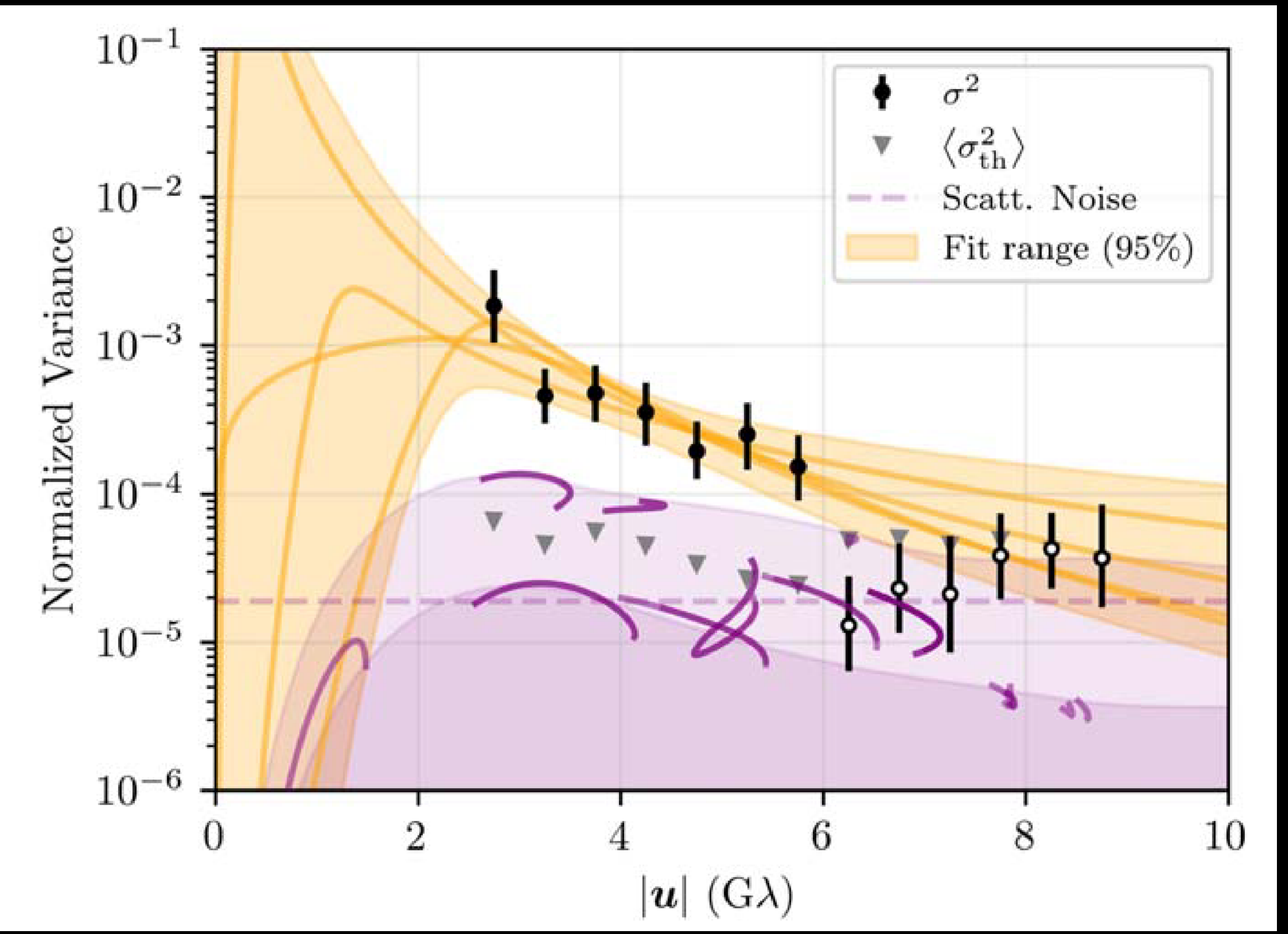
Infrared flare from the Keck Observatory + VLT/GRAVITY (ground)

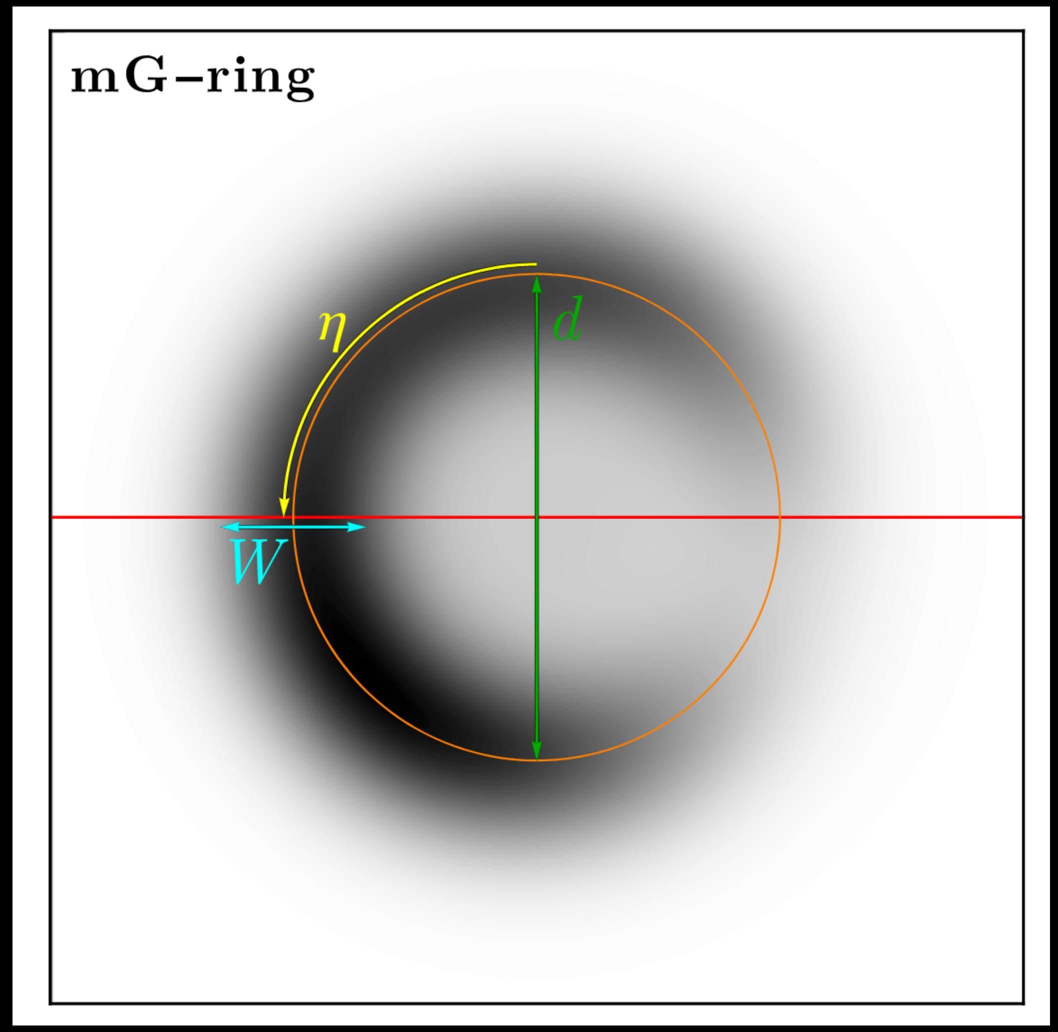
We applied a much greater set of constraints (11!) to Sgr A*

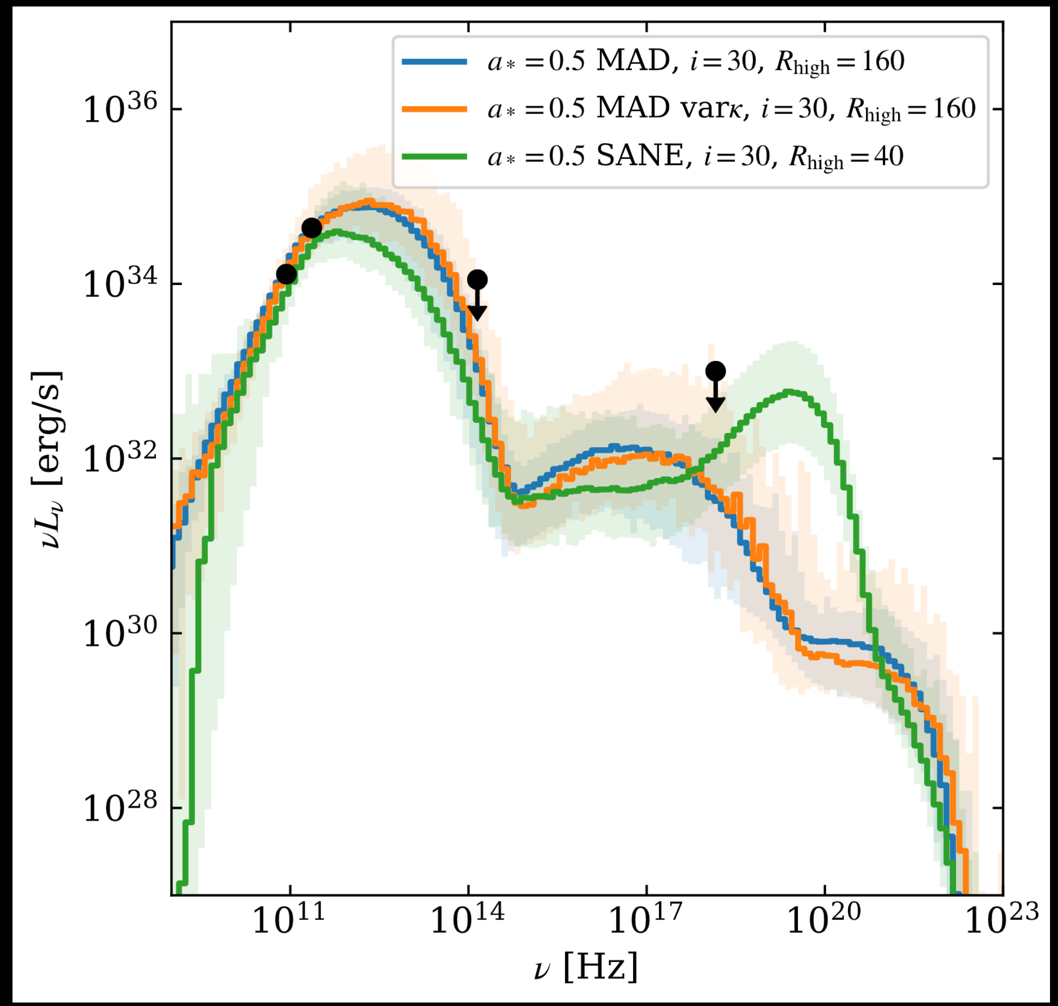
"Variability Crisis"??

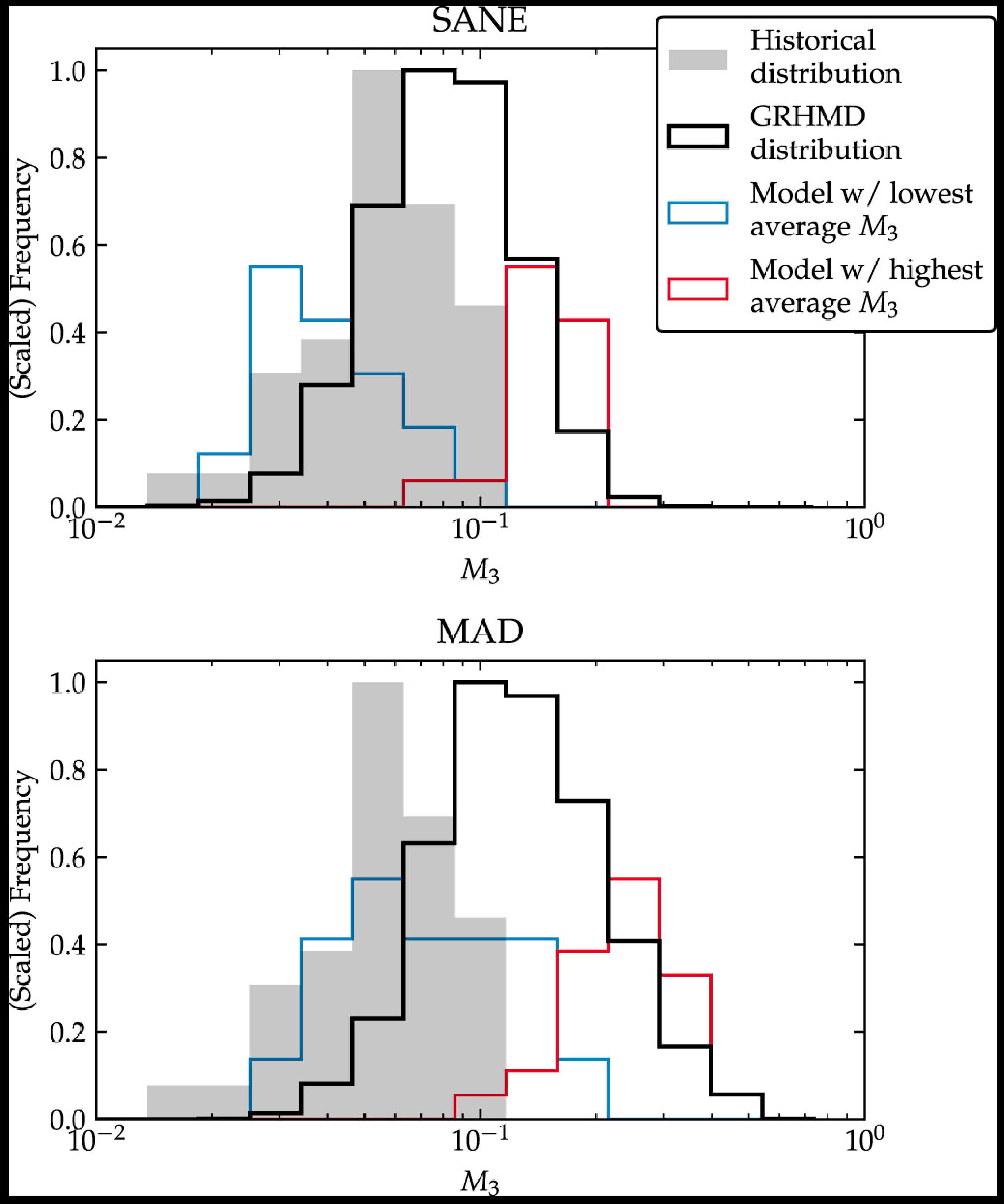








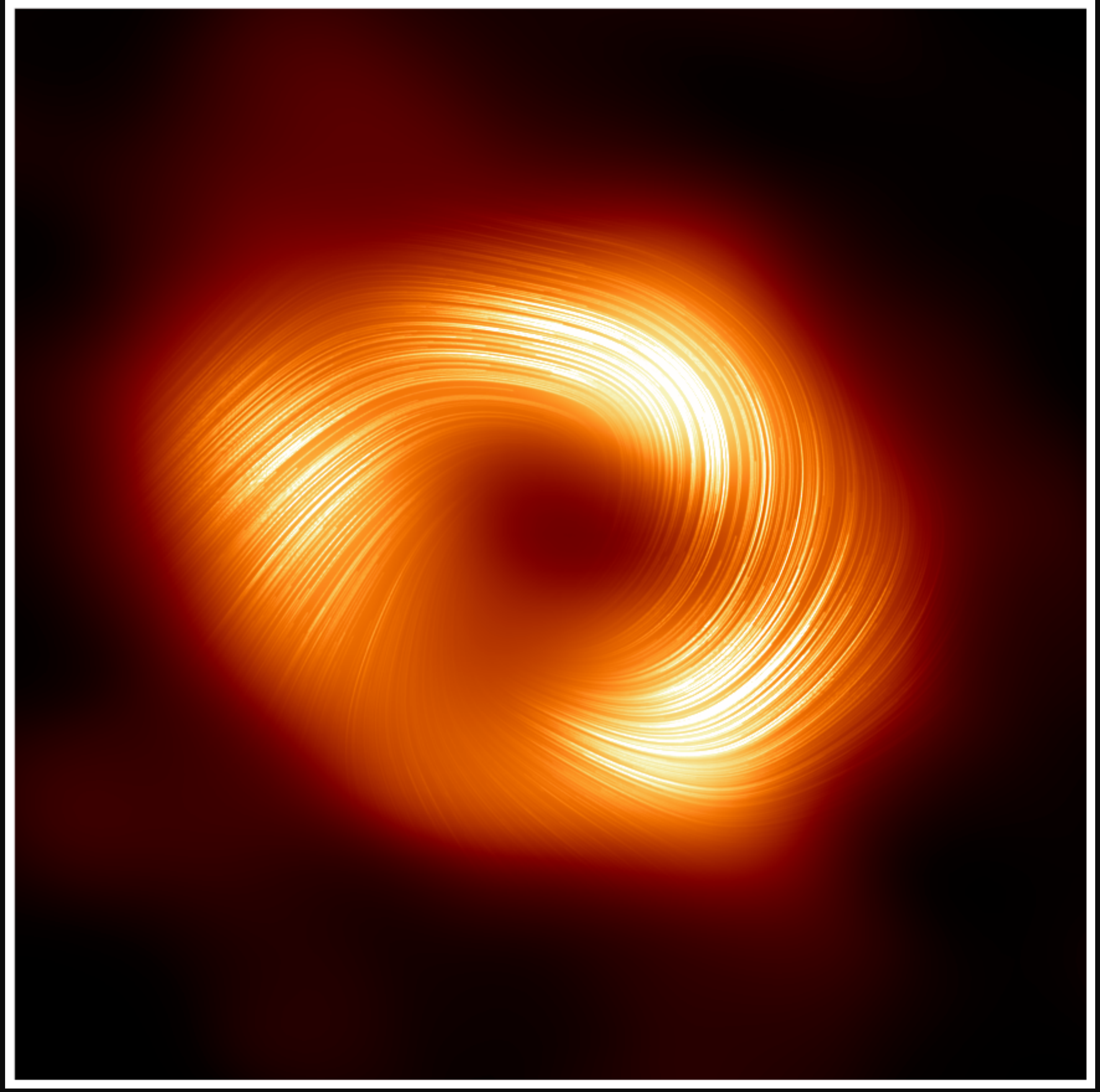


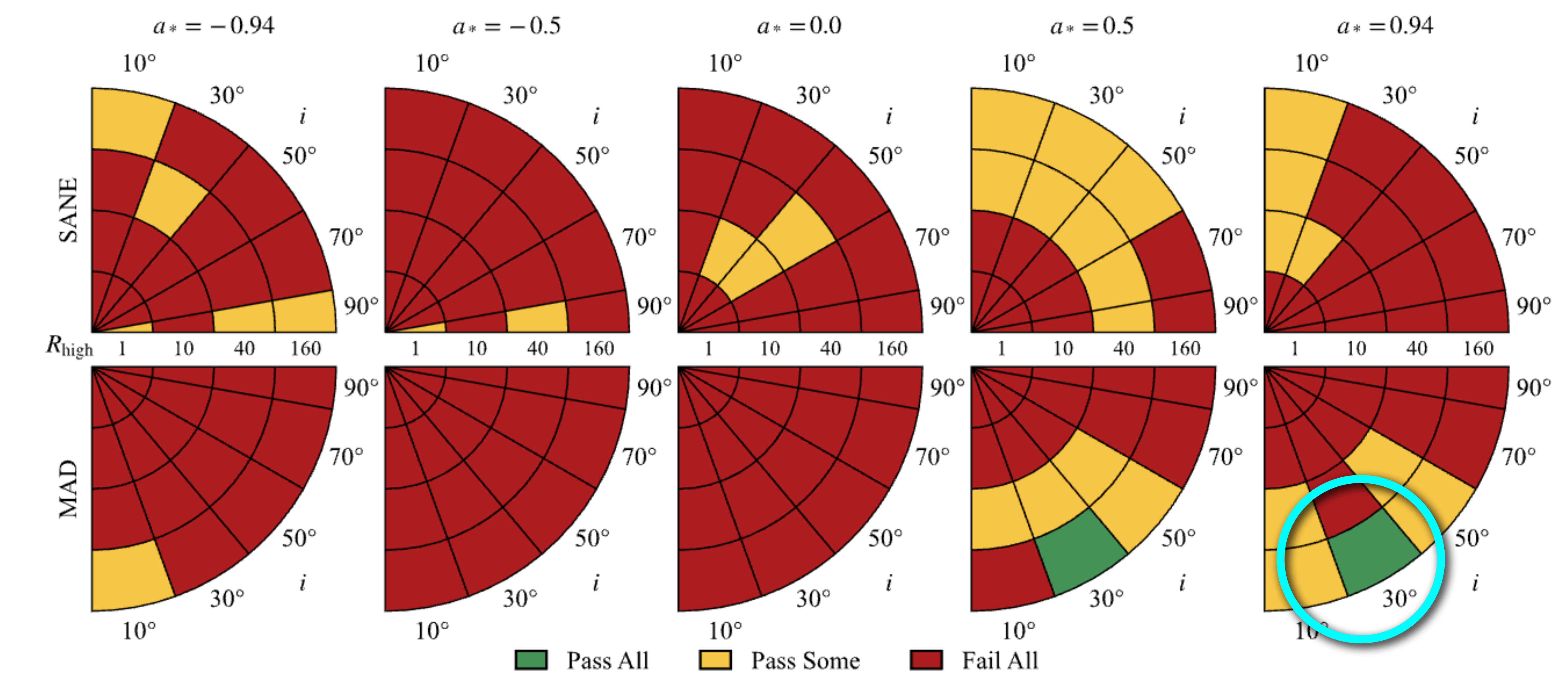


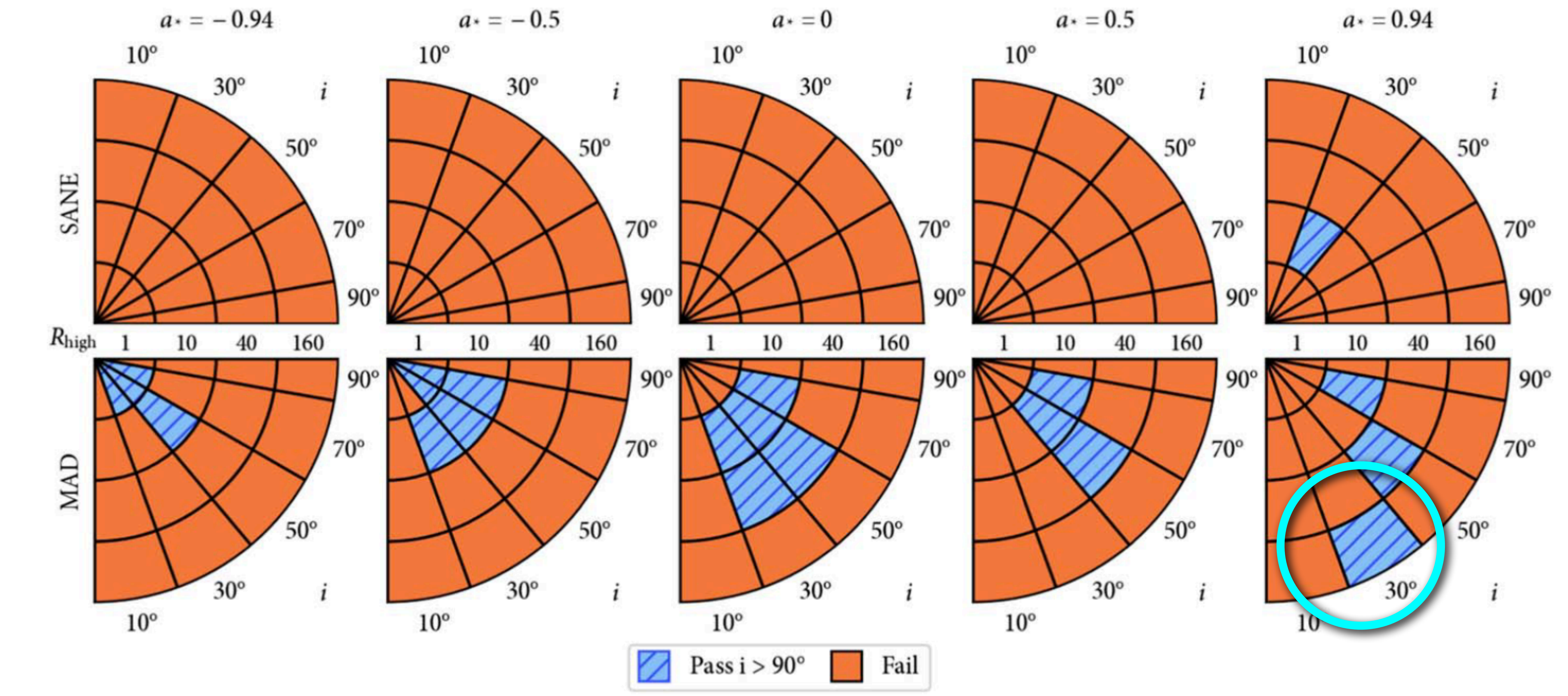
EHTC Sgr A* Papers I-VI (2022)

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

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

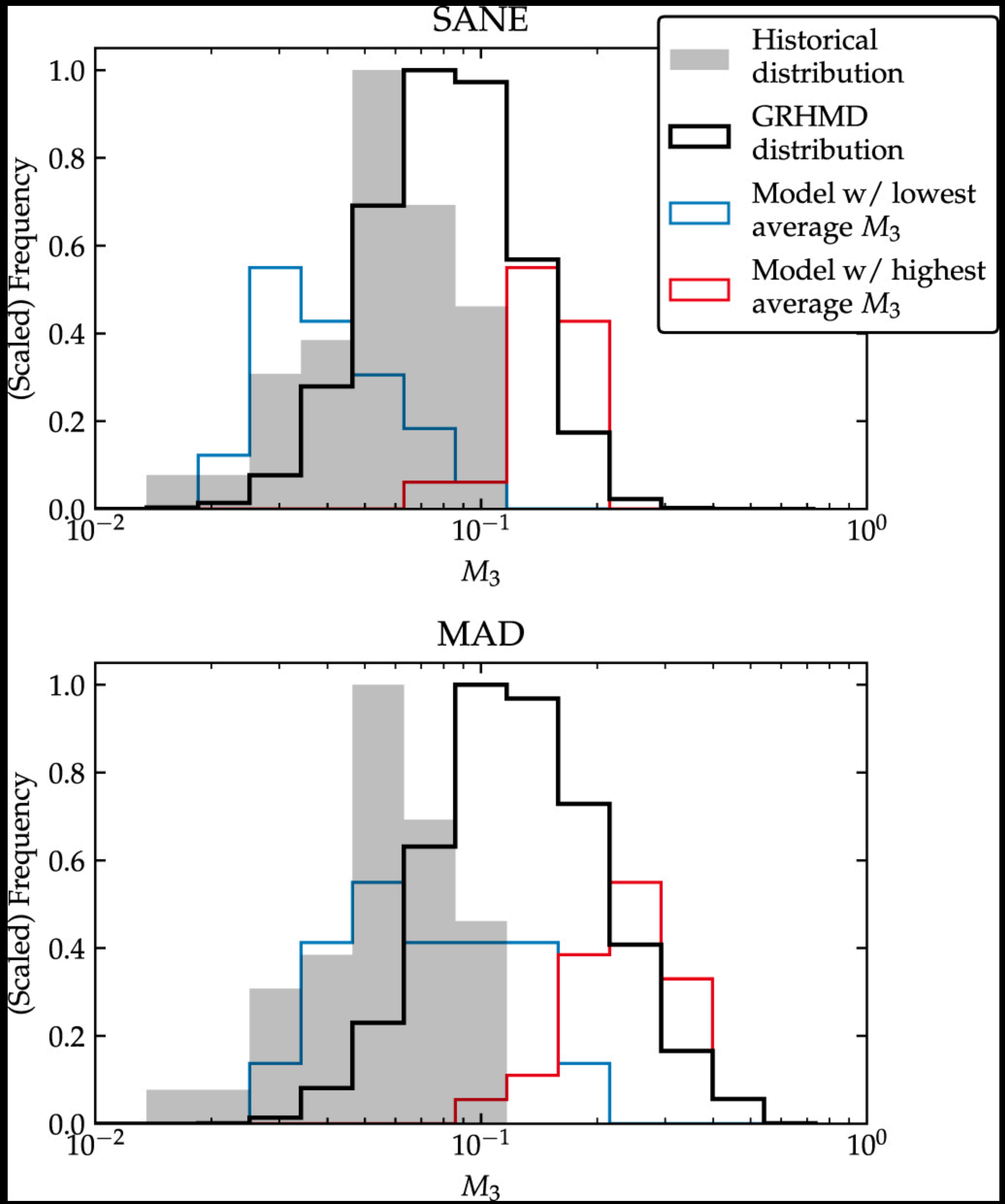


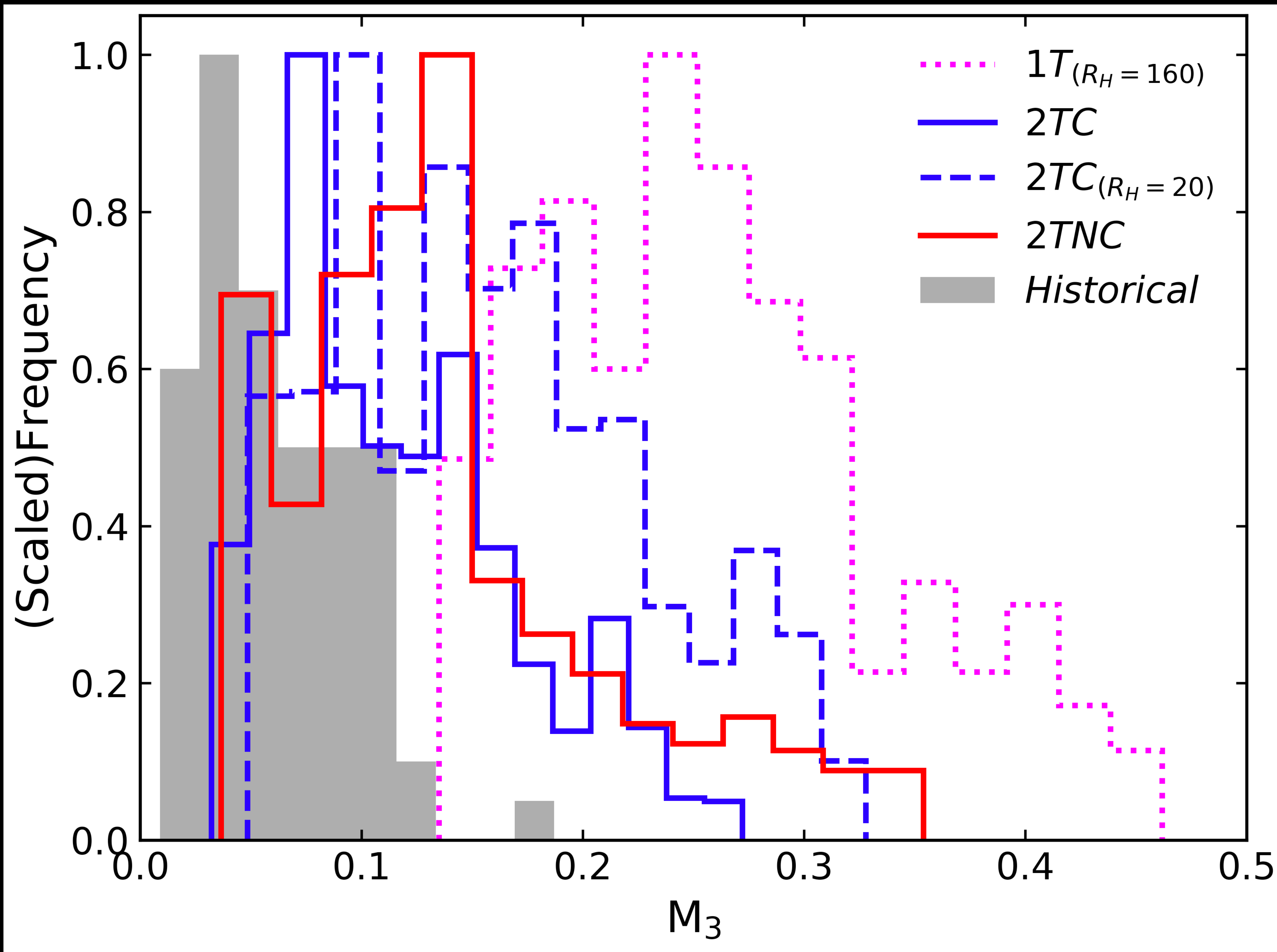




EHTC Sgr A* Paper I & Paper V (2022), Paper VII & VIII (2024)

Variability one of the biggest modelling challenges



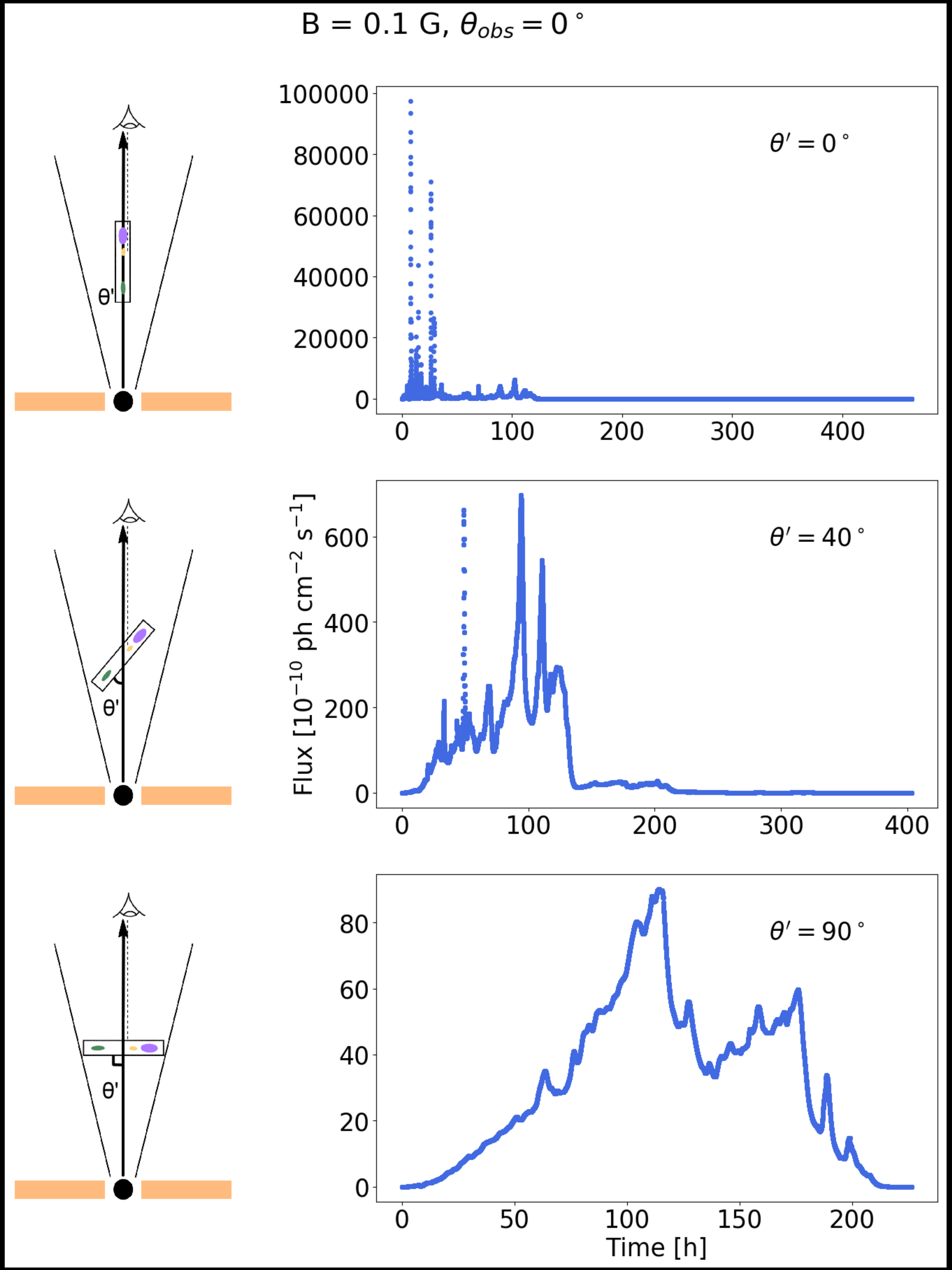


EHTC Sgr A* Paper V (2022); Salas, Chatterjee, Musoke, SM, Liska++, in prep.

Variability predictions to test e.g. magnetic reconnection models

- Based on simulations by Christie++2019 and Petropoulou++2016
- Varying 3 parameters to generate simulated light curves, compare w/data:
  - B-field strength
  - Jet viewing angle
  - Reconnection layer angle
- Optimised fits vs multiple constraints: flux distribution, fractional variability, fastest Δτ/rise τ

Jormanainen++2023



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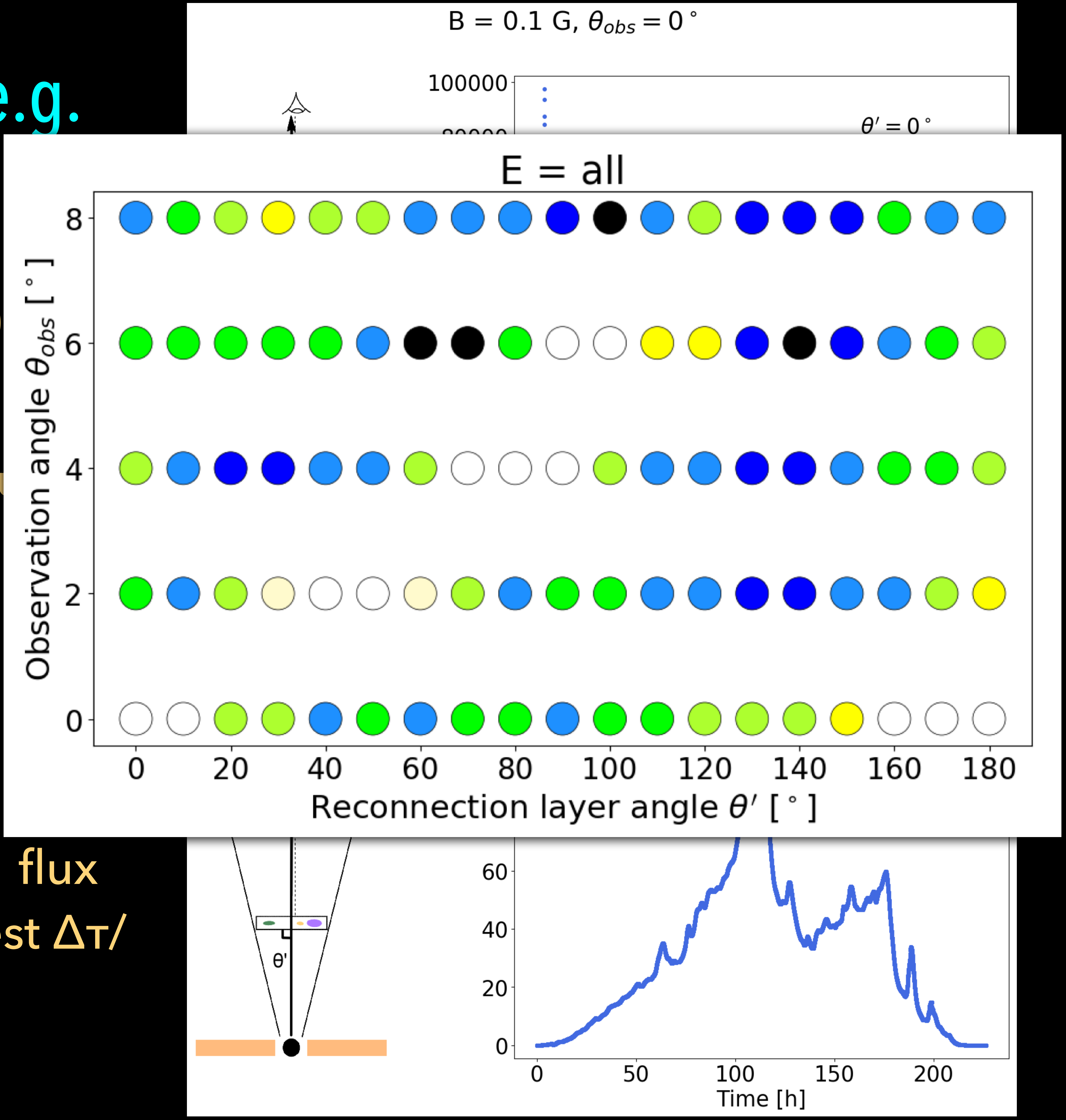

Jormanainen++2023

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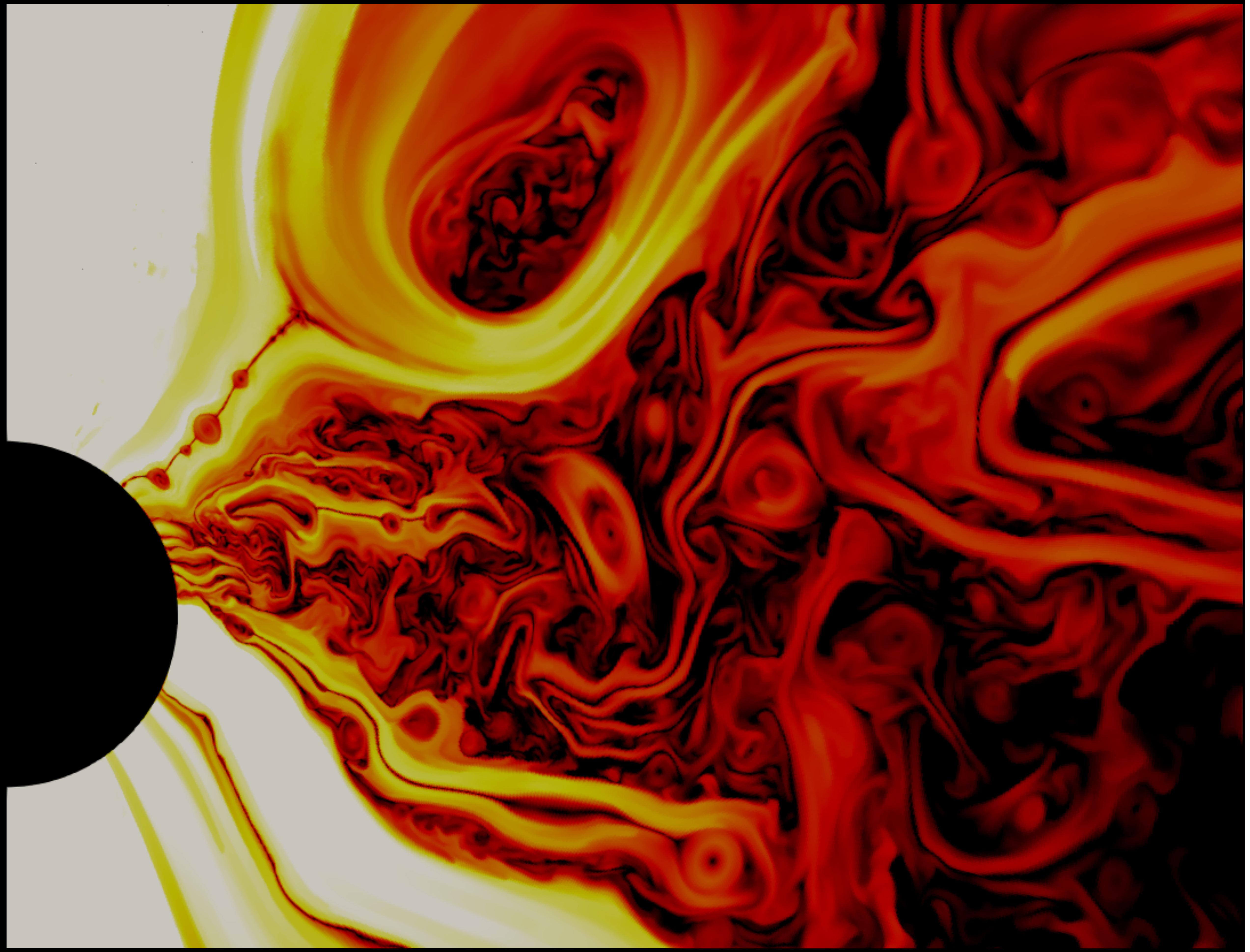
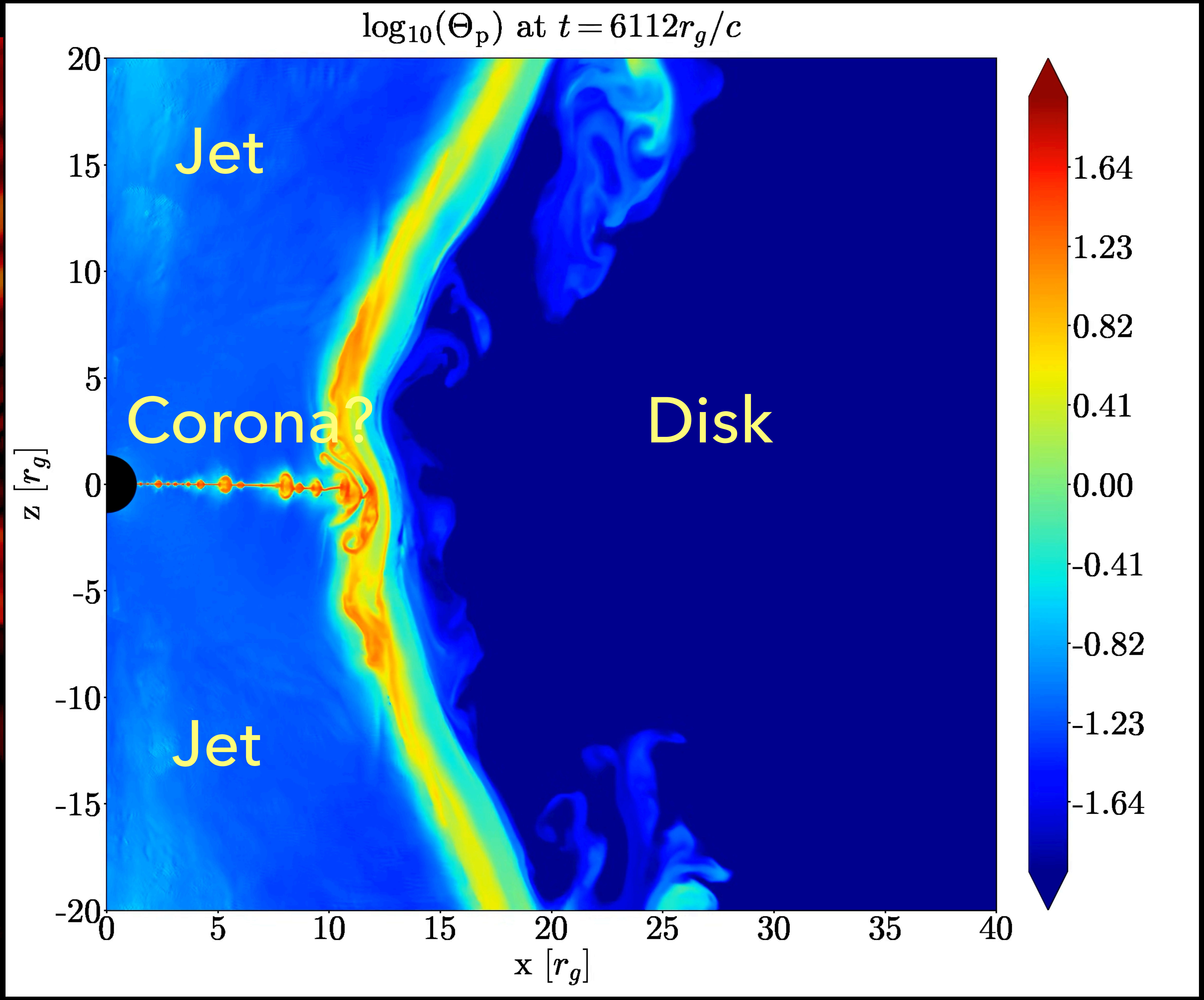
The newest generation high-res simulations will be put to the test



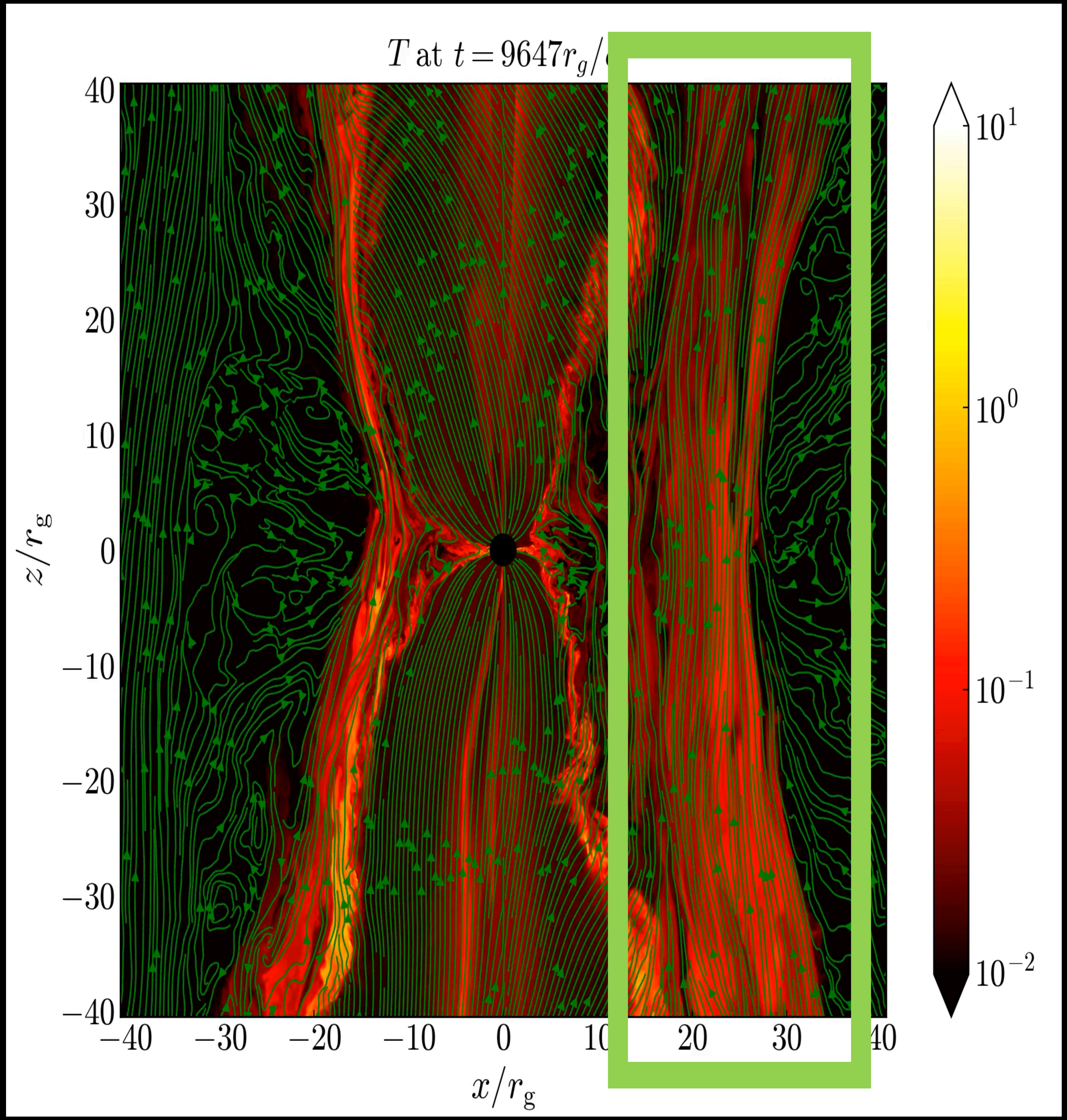


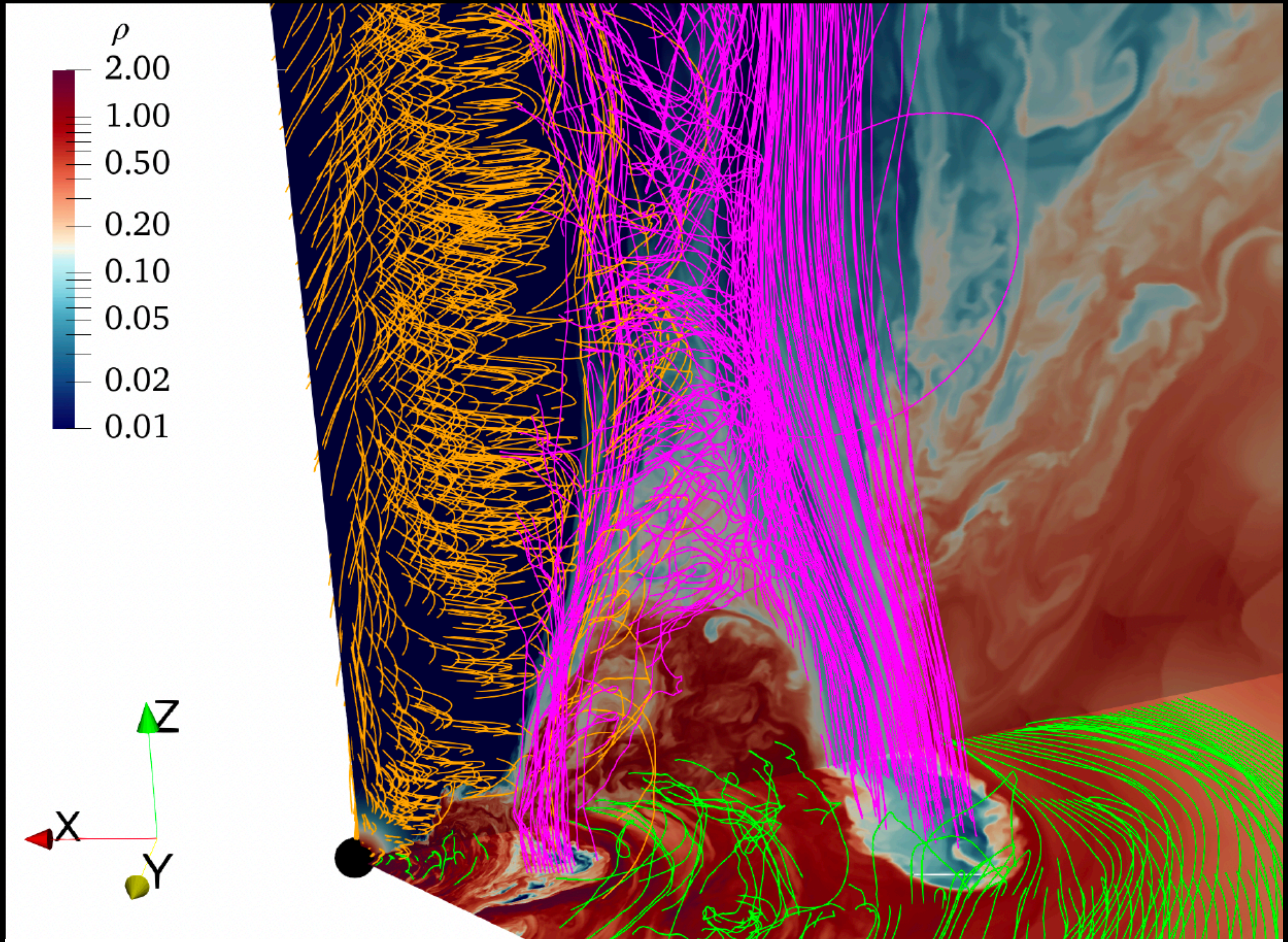
Ripperda, Bacchini & Philippov 2020, resistive 2D GRMHD w/ effective resolution of 12288x6144

(5400x2300x2300) with H-AMR (Liska++ 2019) yields similar results: Ripperda, Liska, Chatterjee, Musoke, Philippov, SM++ 2022


Components of the TeV signal:
IC = soft background + $e^{\pm}$
SSC = synchrotron + $e^{\pm}$
SSC2 = secondary synchrotron + $e^{\pm}$
repelled accretion flow
accretion flow
soft background radiation from the disk
($\sim 10^{-3}$ eV)
secondary synchrotron
(~ 0.1 eV)
secondary $e^{\pm}$
($\sim 200\ m_e c^2$)
synchrotron
(~ 20 MeV)
$B \sim 100$ G
magnetic reconnection
accelerating E-field
($e^{\pm}$ accelerated up to $\sim 10^8\ m_e c^2$)
transient current layer
$w \sim 10 r_g$
Note: all the numbers mentioned are for M87 parameters
Hakobyan, Ripperda & Philippov 2023

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



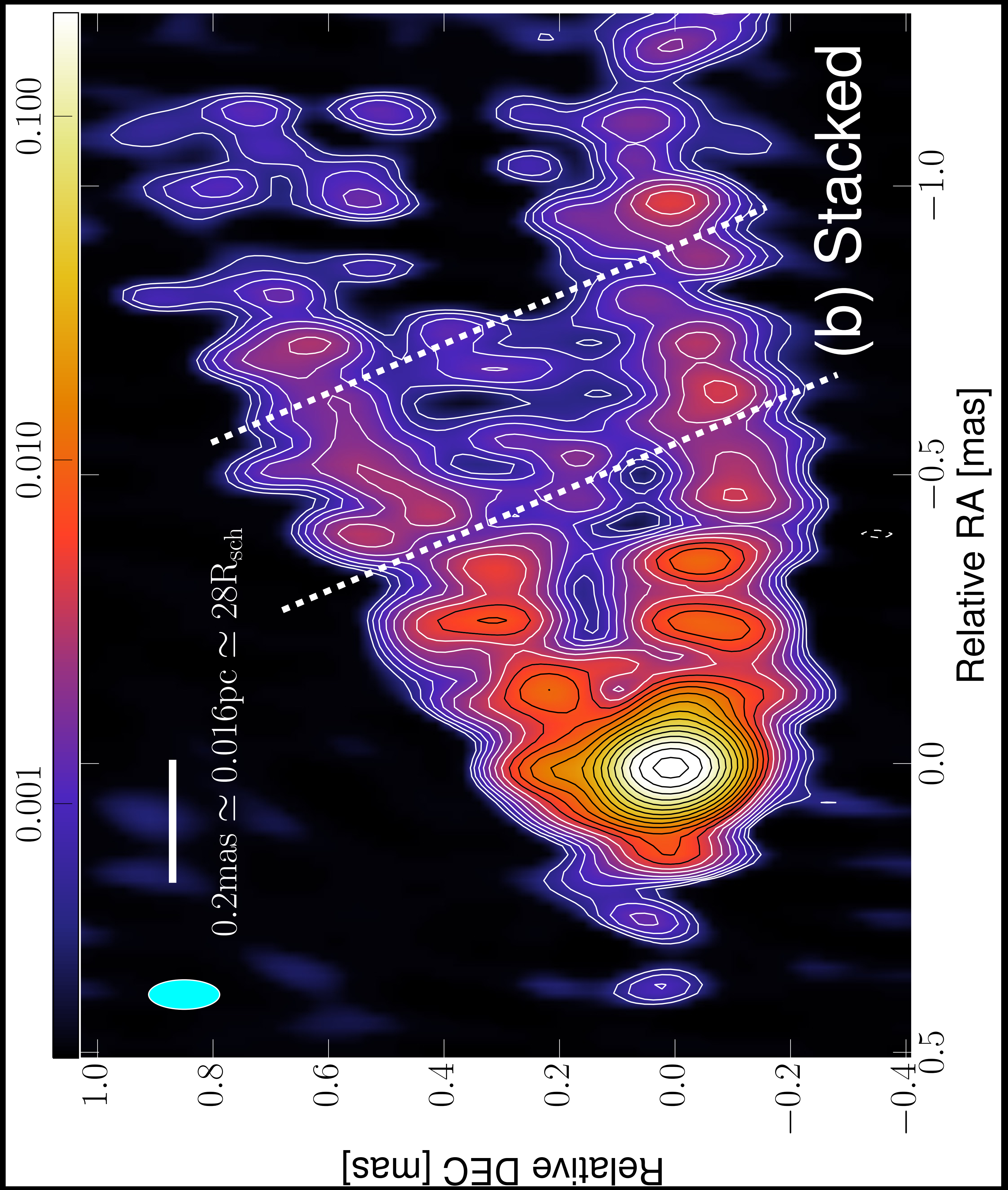


- Reconnection expels flux tubes with vertical field, consistent with IR/mm polarisation
- Can drive turbulence/instabilities leading to particle acceleration ➠ flares?

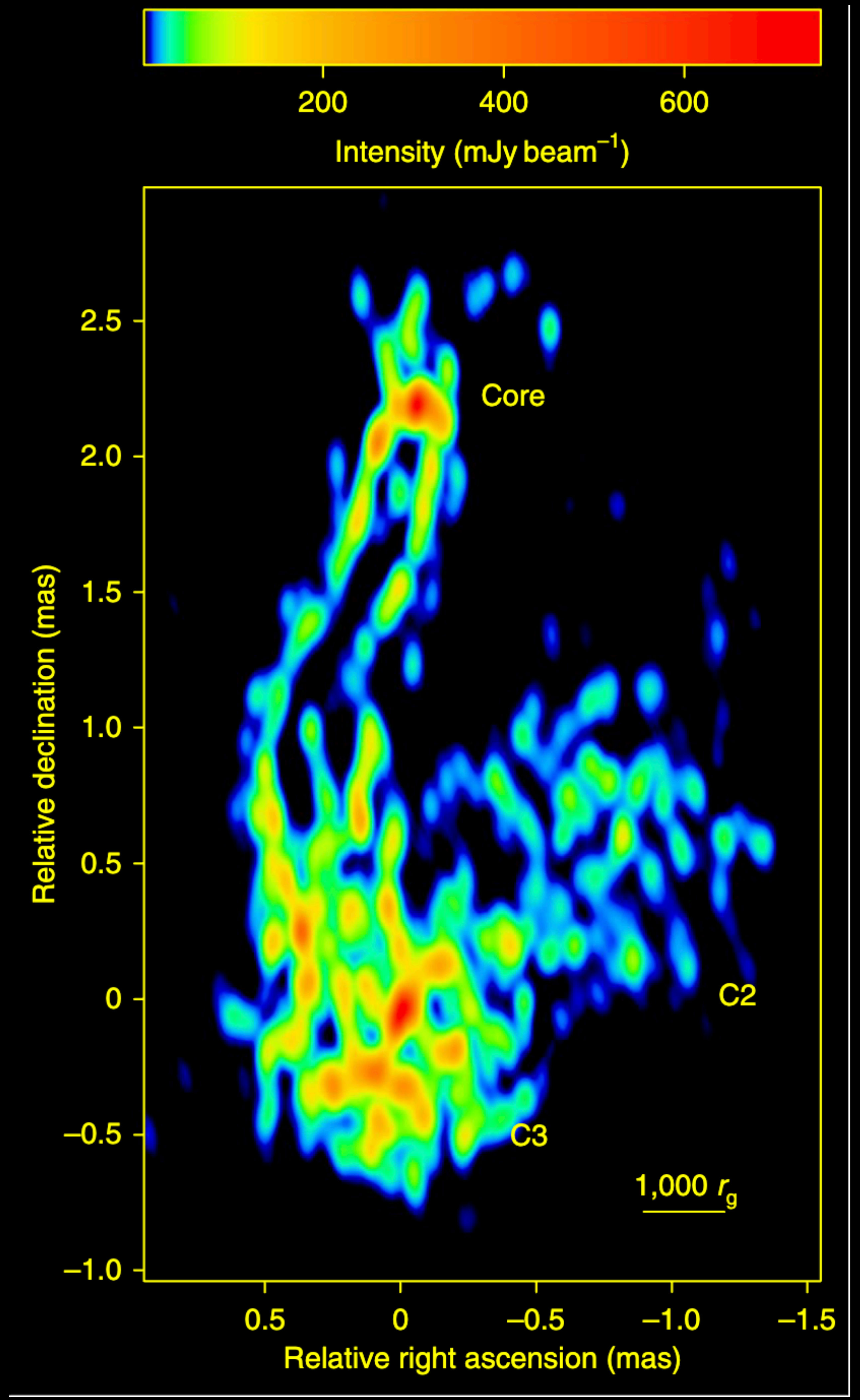
Ripperda, Liska, Chatterjee, Musoke, Philippov, SM 2022

see e.g., Porth++2021; Ripperda++2024

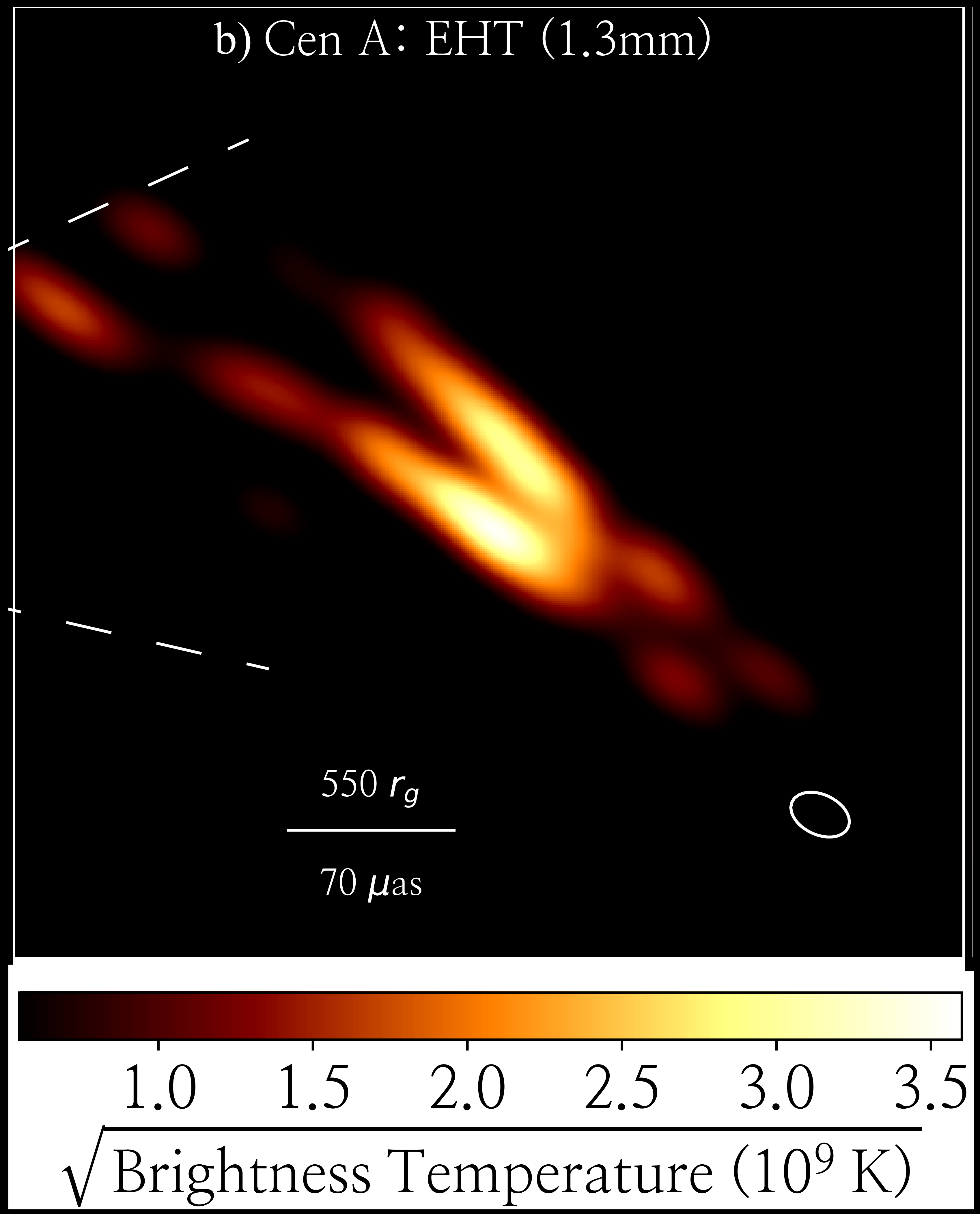
Interface region seems to be what shines for jets/corona



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

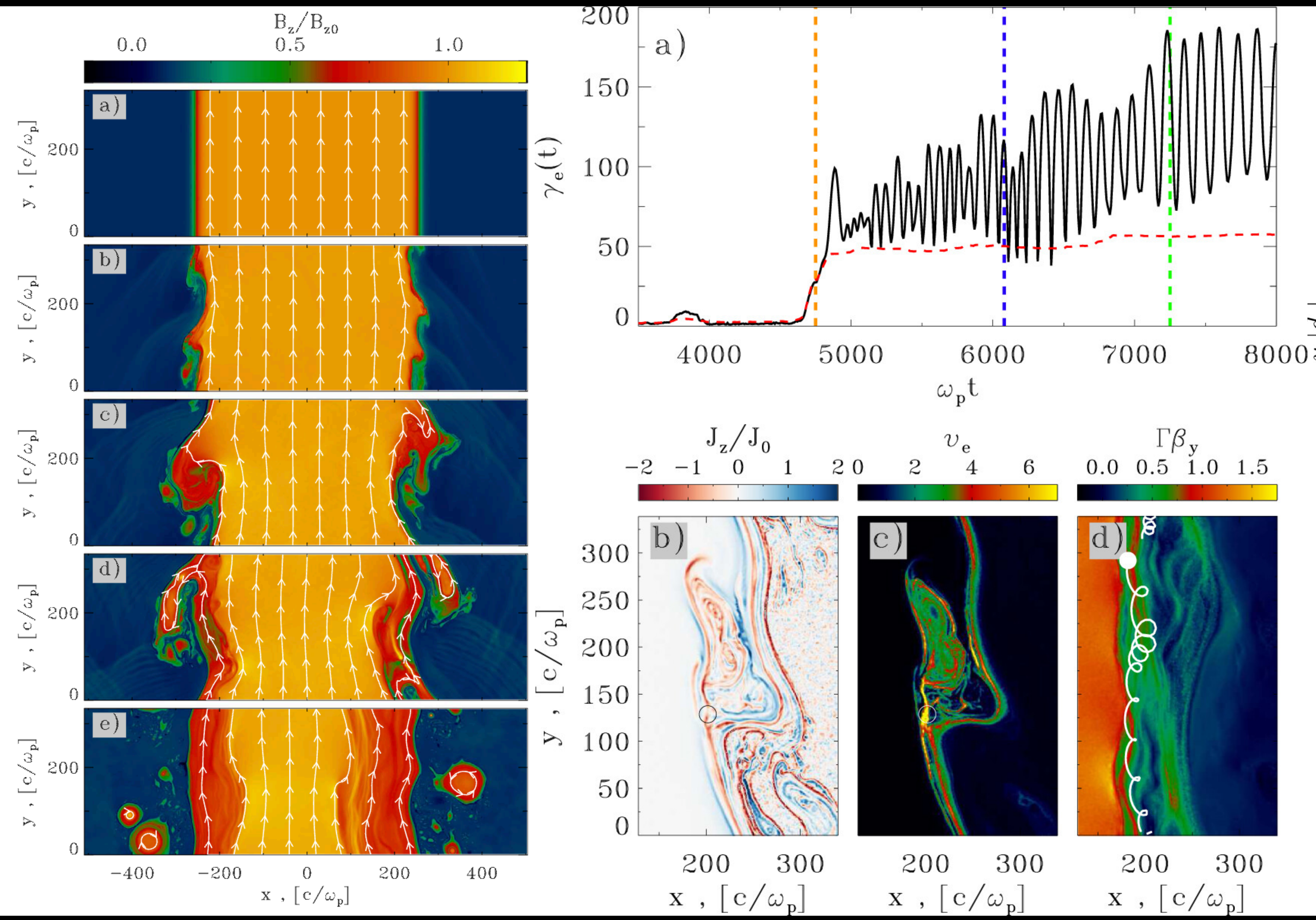


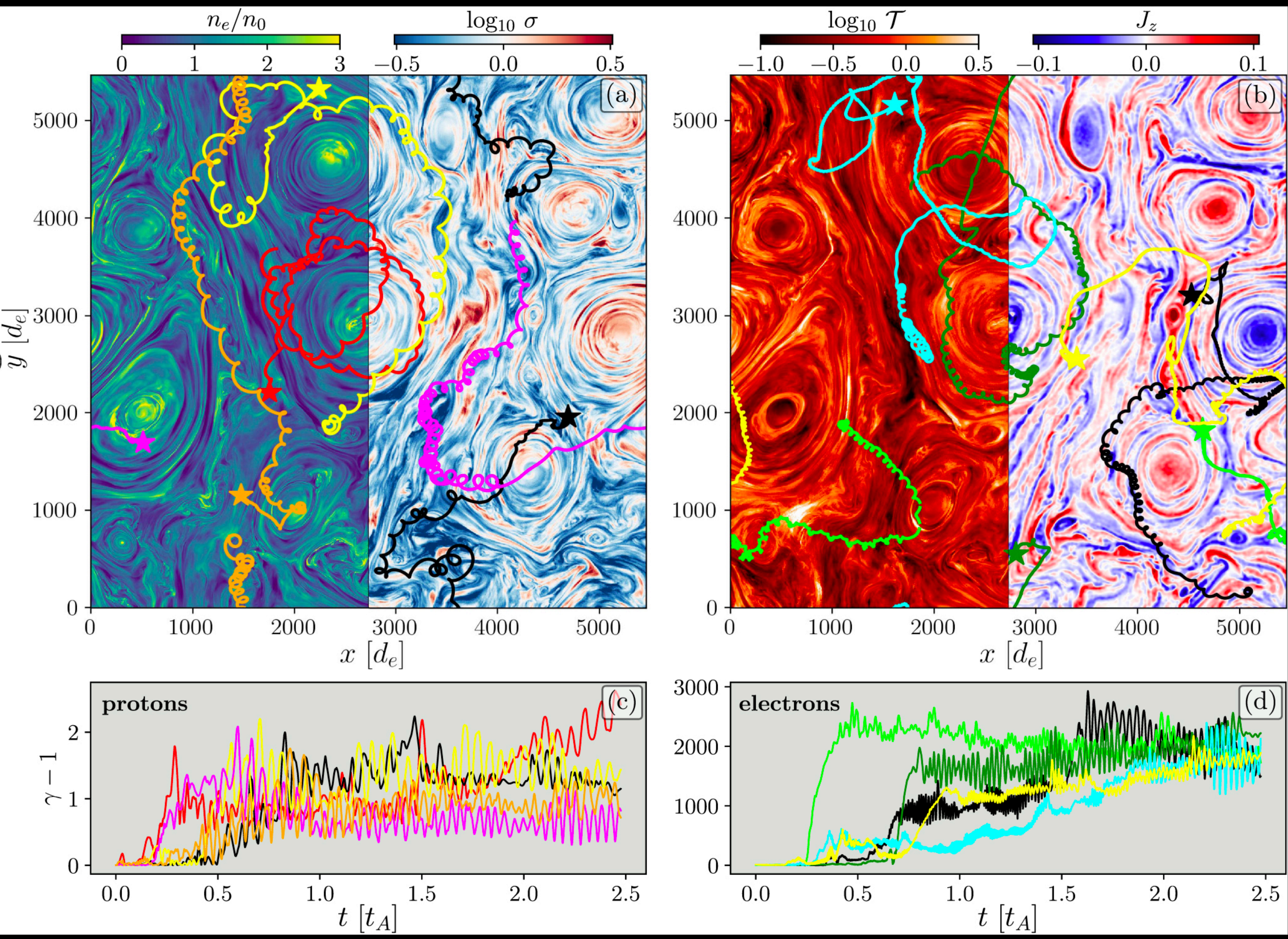
3C84 (VLBI+RadioAstron): Giovannini++2018, Nat.Astro



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

Bridging the gap between particle and dynamical flows





Two recent examples: (left) Sironi++2021, (right) Meringolo++2023; for new results with PIC+turbulence/comptonisation see Grošelj++2024

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★ Geometry ⇔ particle acceleration

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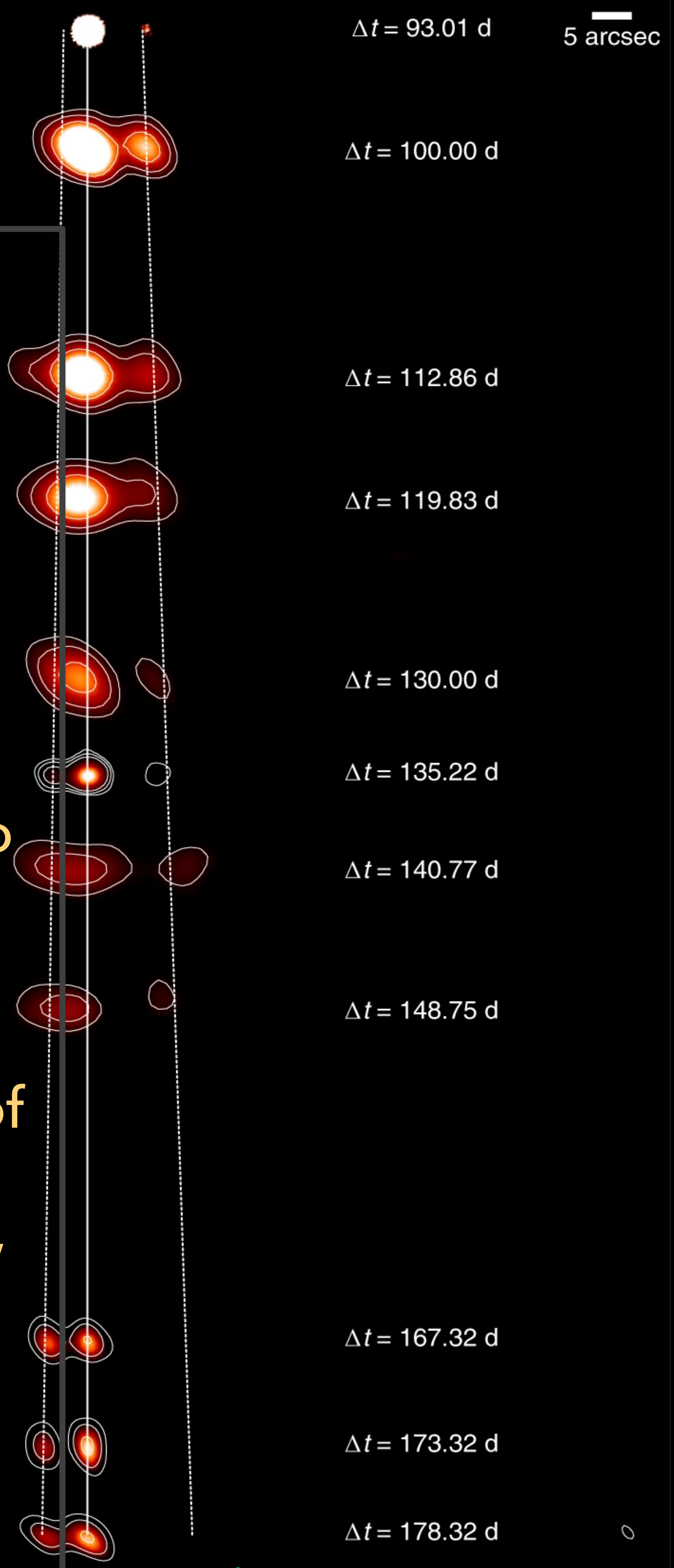
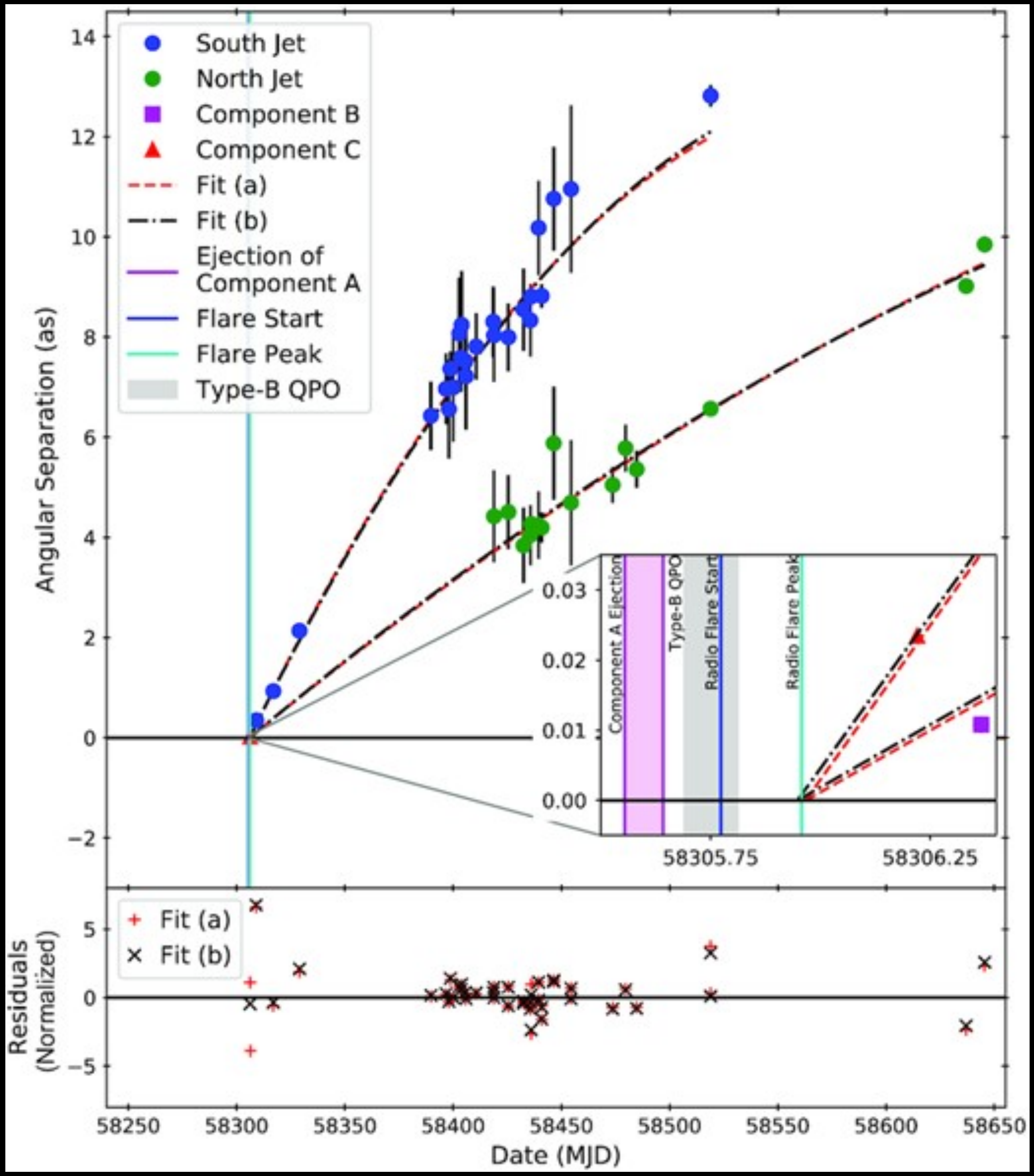
XRB dynamics

MAXI J1820+070:

- Large scale bipolar jets detected/tracked for entire year w/VLBA + DPCT, eMERLIN, VLA, MeerKAT, Chandra
- Direct measurement of radio source size at t ≳ 90 days ➠ internal energy
- Very precise measurement of launch conditions: 3000s duration of the 'type B QPO' implies $L_{jet} > L_{Edd}$ (whereas $L_X \sim 0.1\ L_{Edd}$) ➠ solves power problem?



Bright++2020



Wood++2021, see also Espinasse++2020; Tremou++2022; and Carotenuto++2021 for extreme deceleration in MAXI J1348

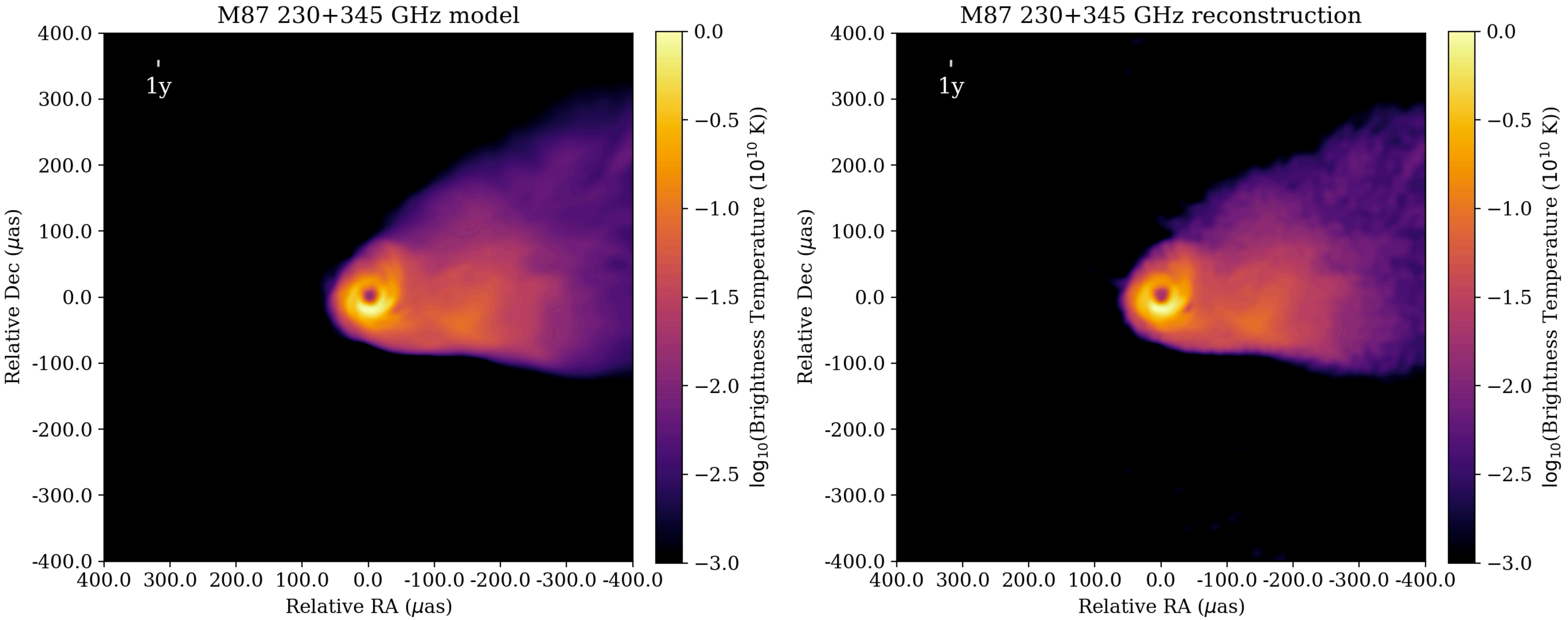
Next-gen EHT expansions in the planning/design phase on CTA timescale

Partnering with UNAM

ERC SyG “BlackHolistic”

see Johnson++2023: “Key Science Goa

Future: ngEHT dynamical imaging + MWL/MM monitoring!



Reconstructed ngEHT movie: L. Blackburn (SAO), site model: A. Raymond, jet simulation w/nonthermal reconnection heating model: Chael++2019

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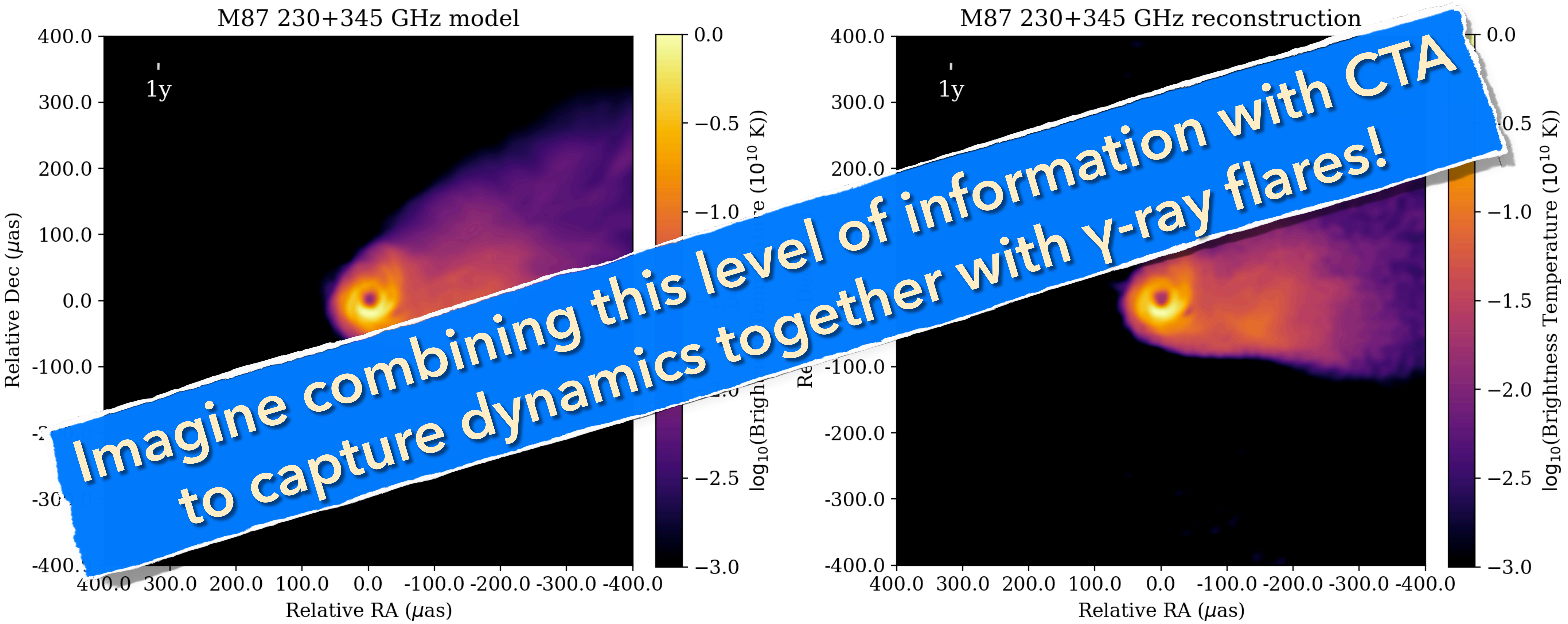

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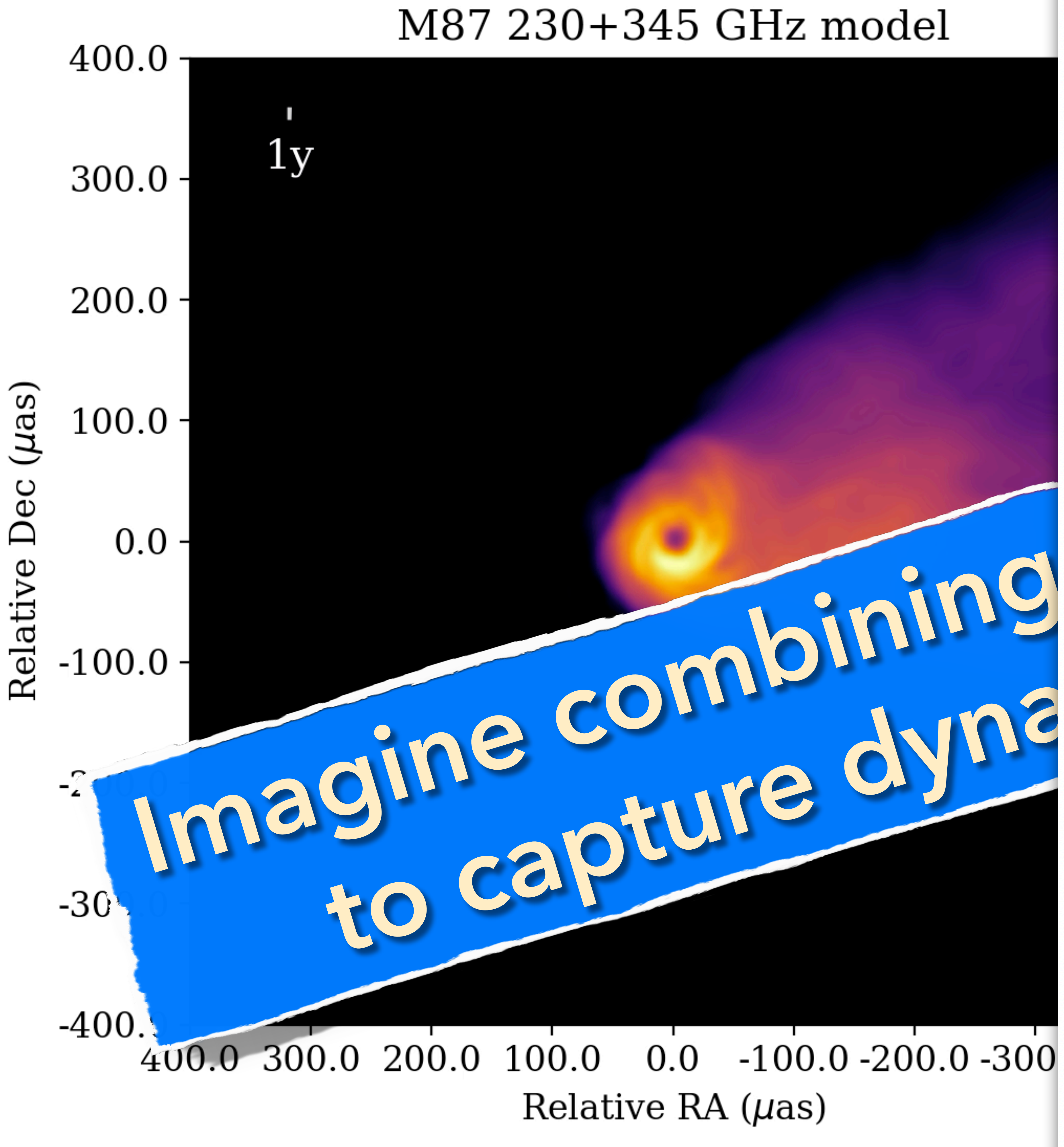
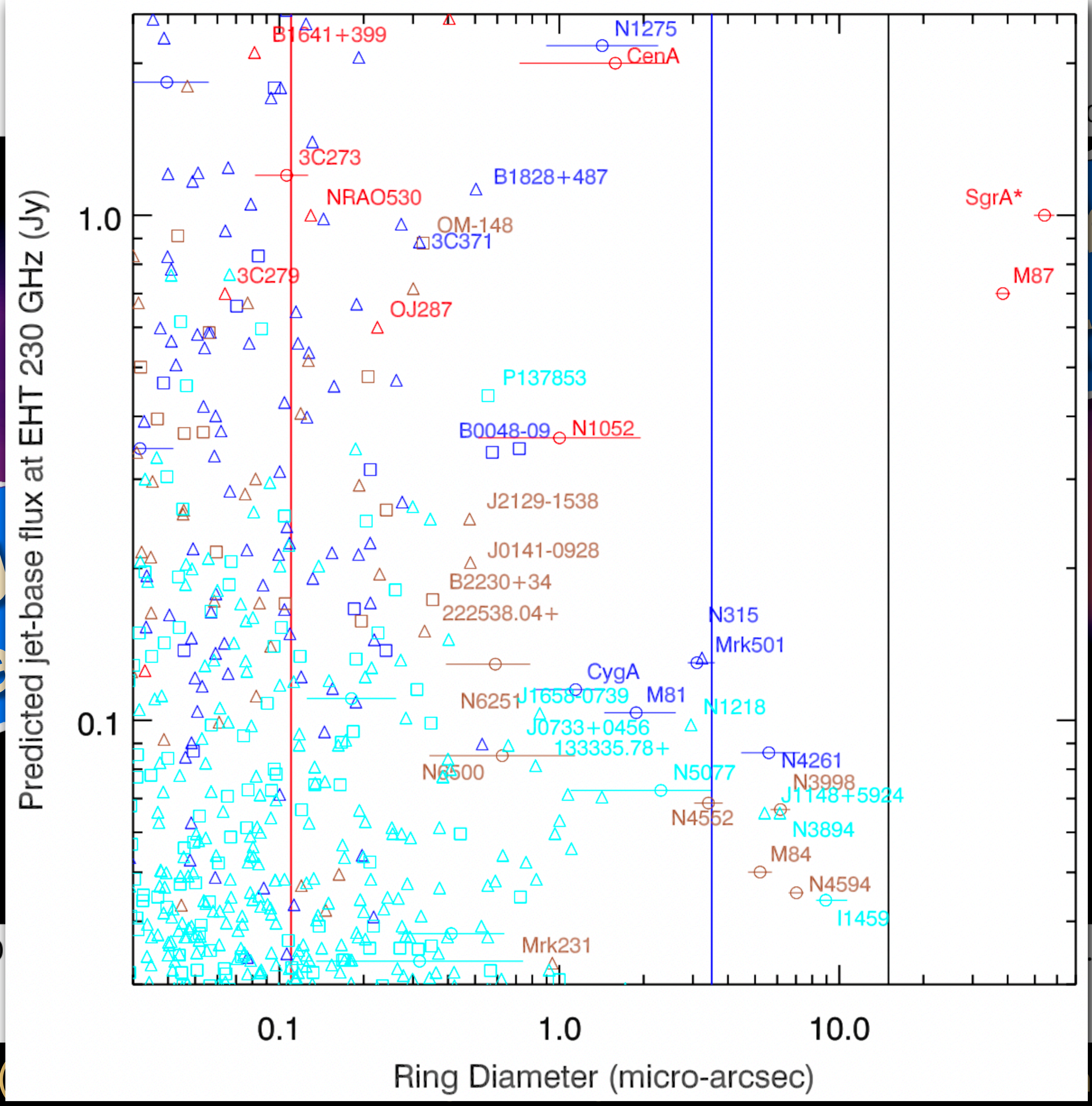
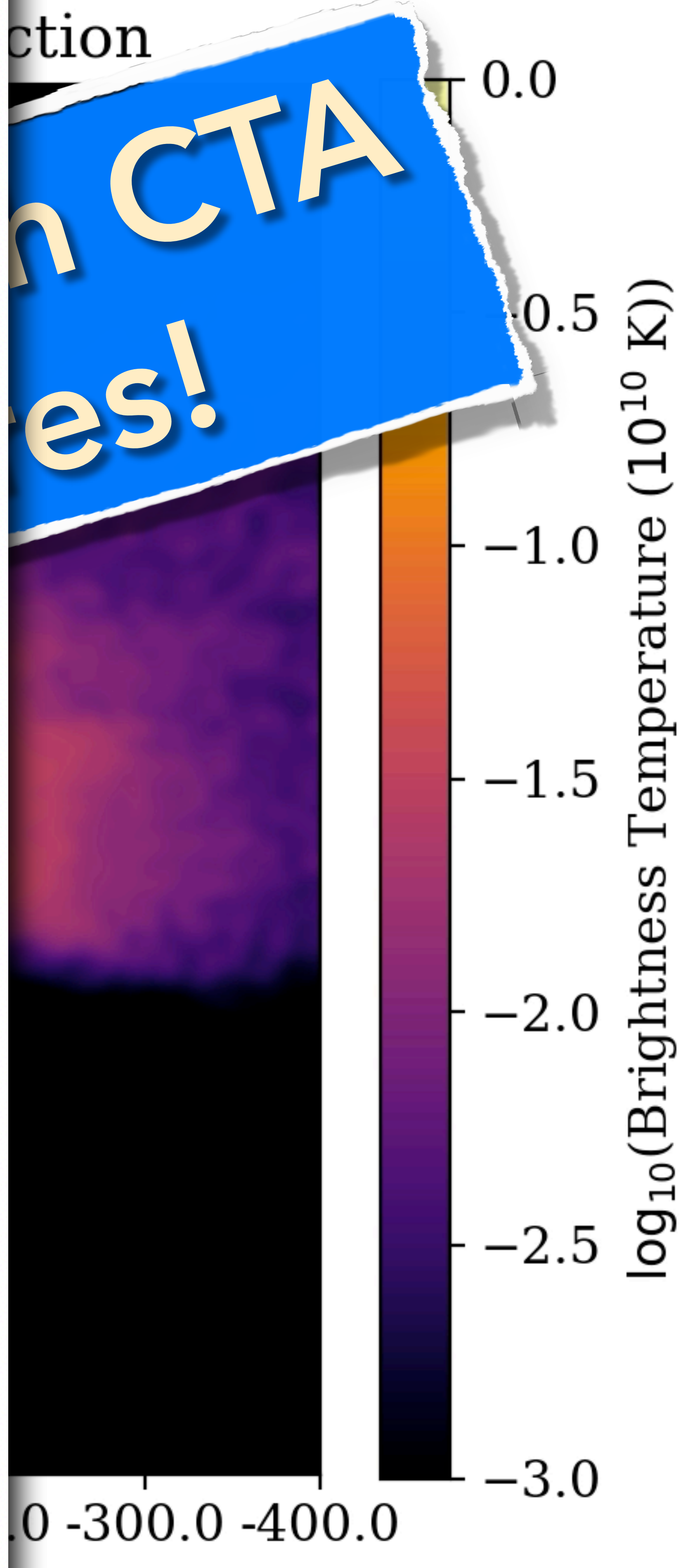






Reconstructed ngEHT movie: L. Blackburn (… al reconnection heating model: Chael++2019

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

Summary

- State-of-the-art data continue to support the paradigm that AGN and XRBs share similar central engine physics/geometry
- XRB timing, MWL correlations and EHT imaging all point towards a complex, magnetised, dynamical corona connected to the jets
- The challenge now is to incorporate/interpret the 'single-zone' picture within this complex phenomenology
- Future: combining EHT/imaging with MWL/MM monitoring will resolve the links between global dynamics and particle acceleration
- Extending these studies w/CTA to populations of black holes, lays a path towards the first *predictive models of black hole behaviour*

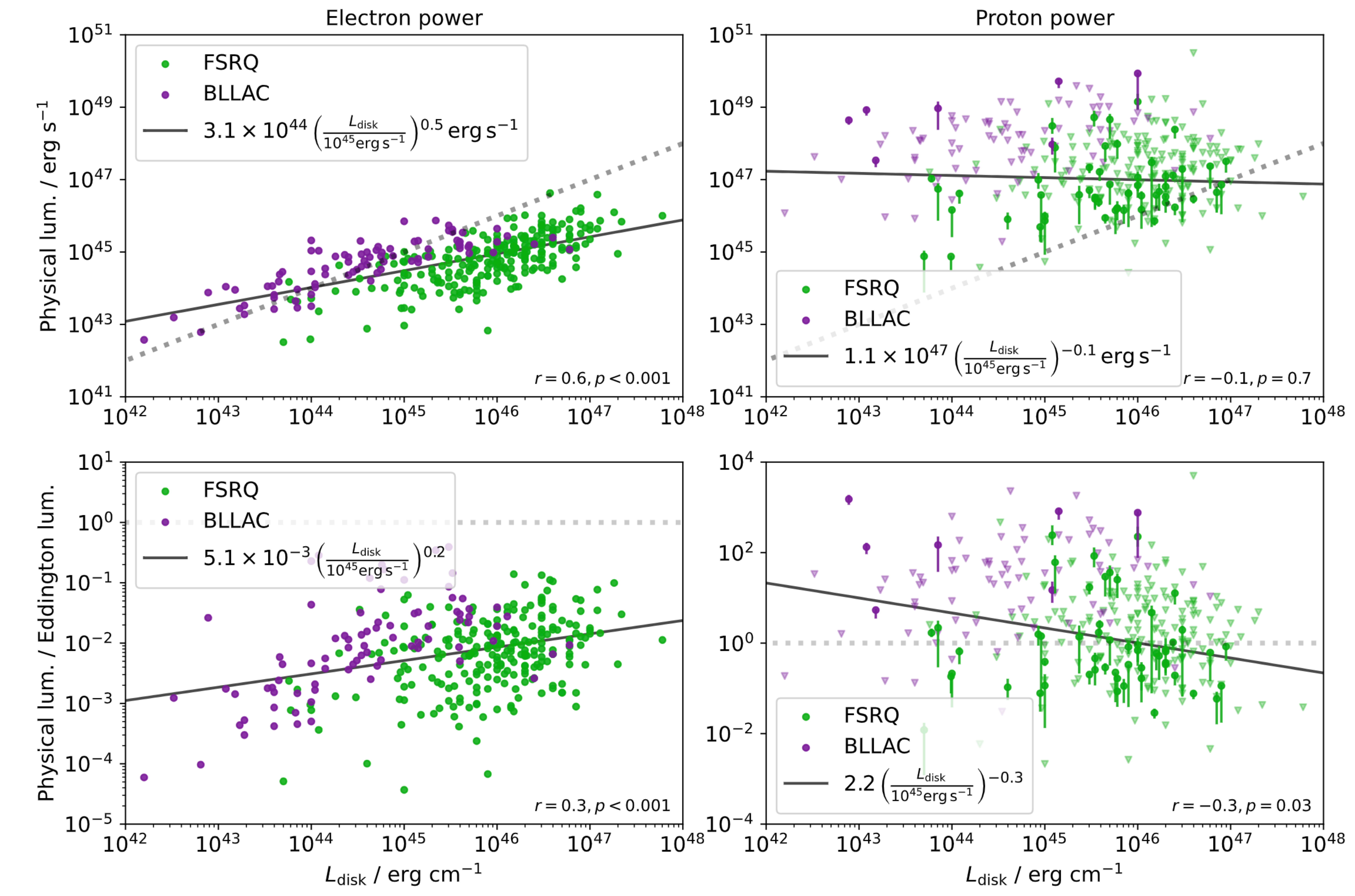
Extra slides

Variability encodes dynamics and particle acceleration properties

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

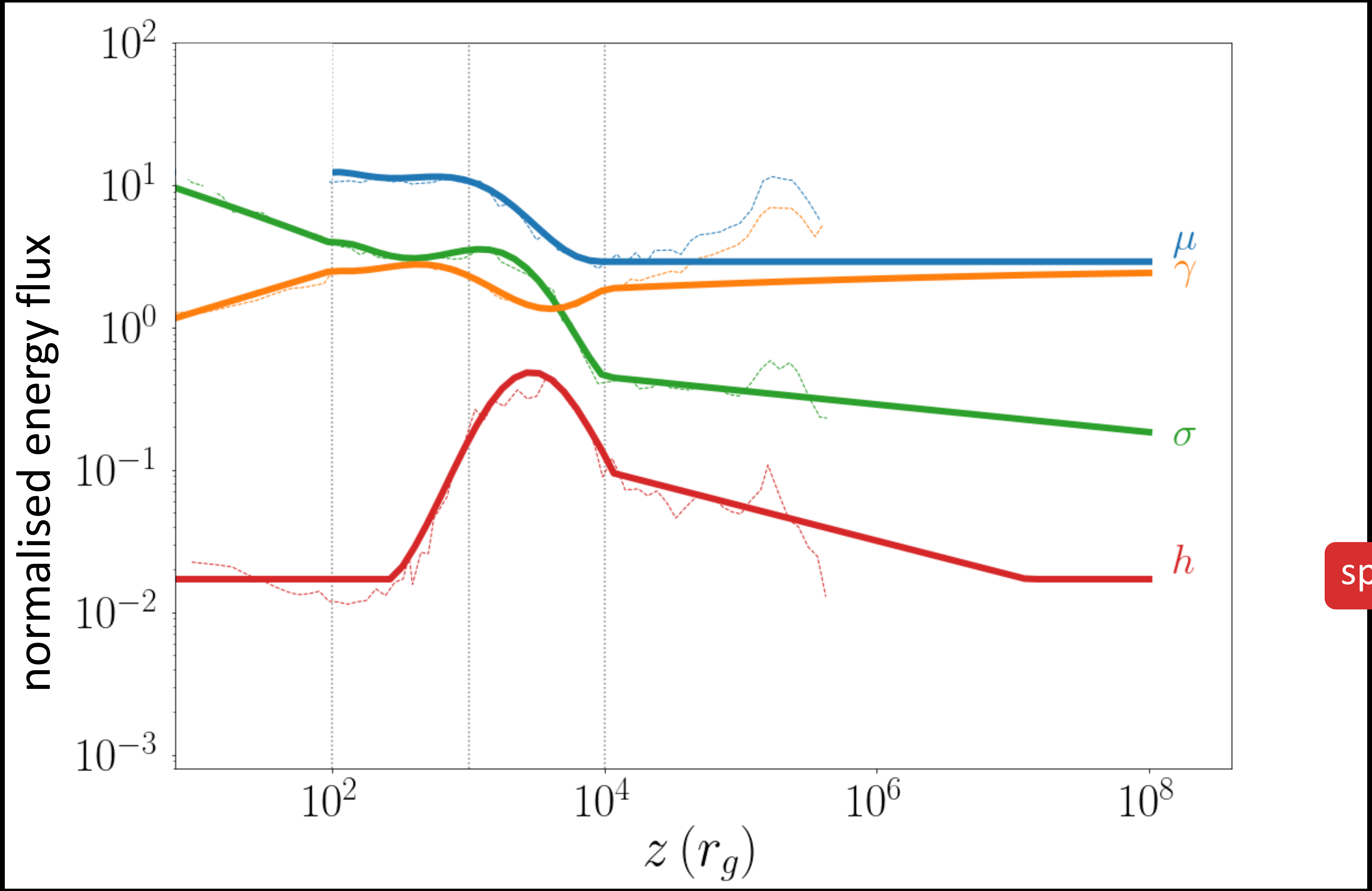
EHTC + Multiwavelength Partners, Sgr A* Paper II 2022; Wielgus, EHT++2022

The "power problem" of lepto-hadronic models



(from Rodrigues++2024; using AM³: Gao++2017 ➠ modelled 324 gamma-ray emitting blazars)

Mass loading can mitigate the hadronic power "crisis"



total energy flux/rest mass flux: μ=γ (σ+h+1)

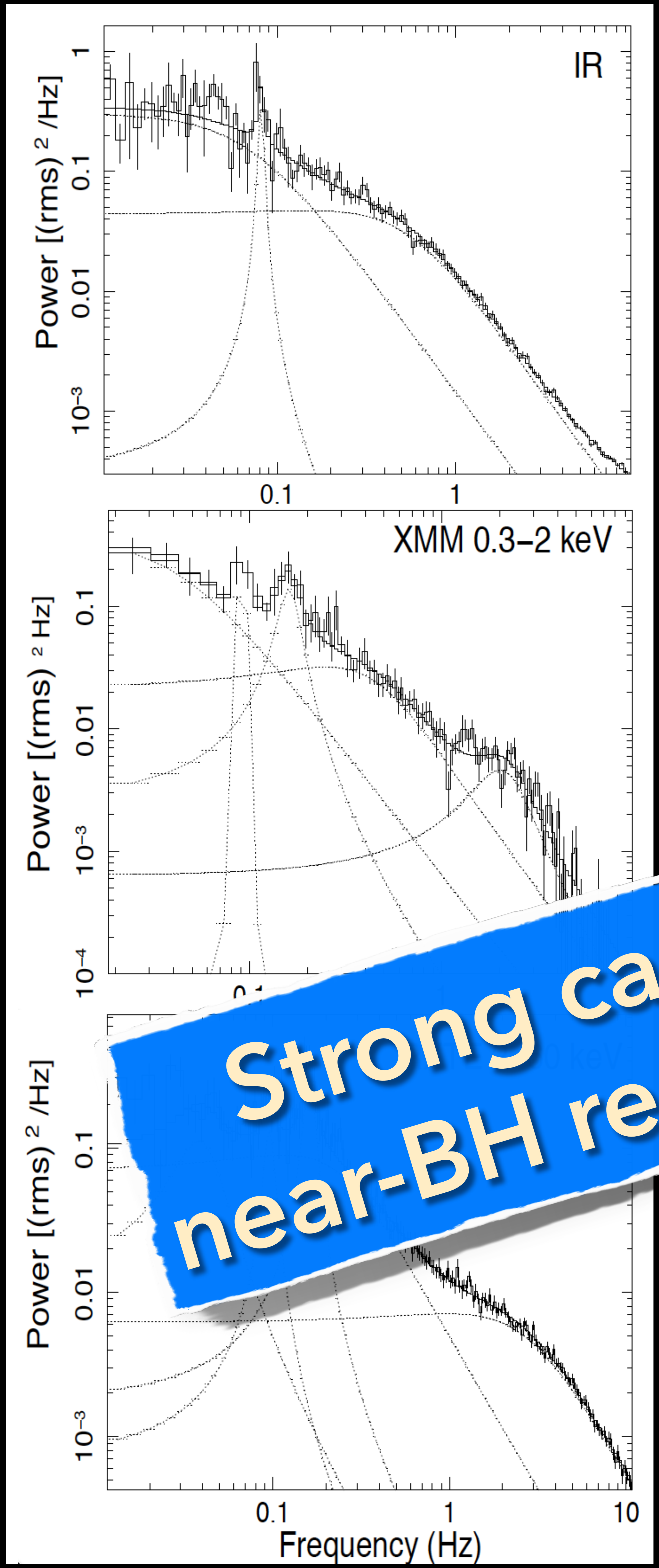
bulk Lorentz factor: γ

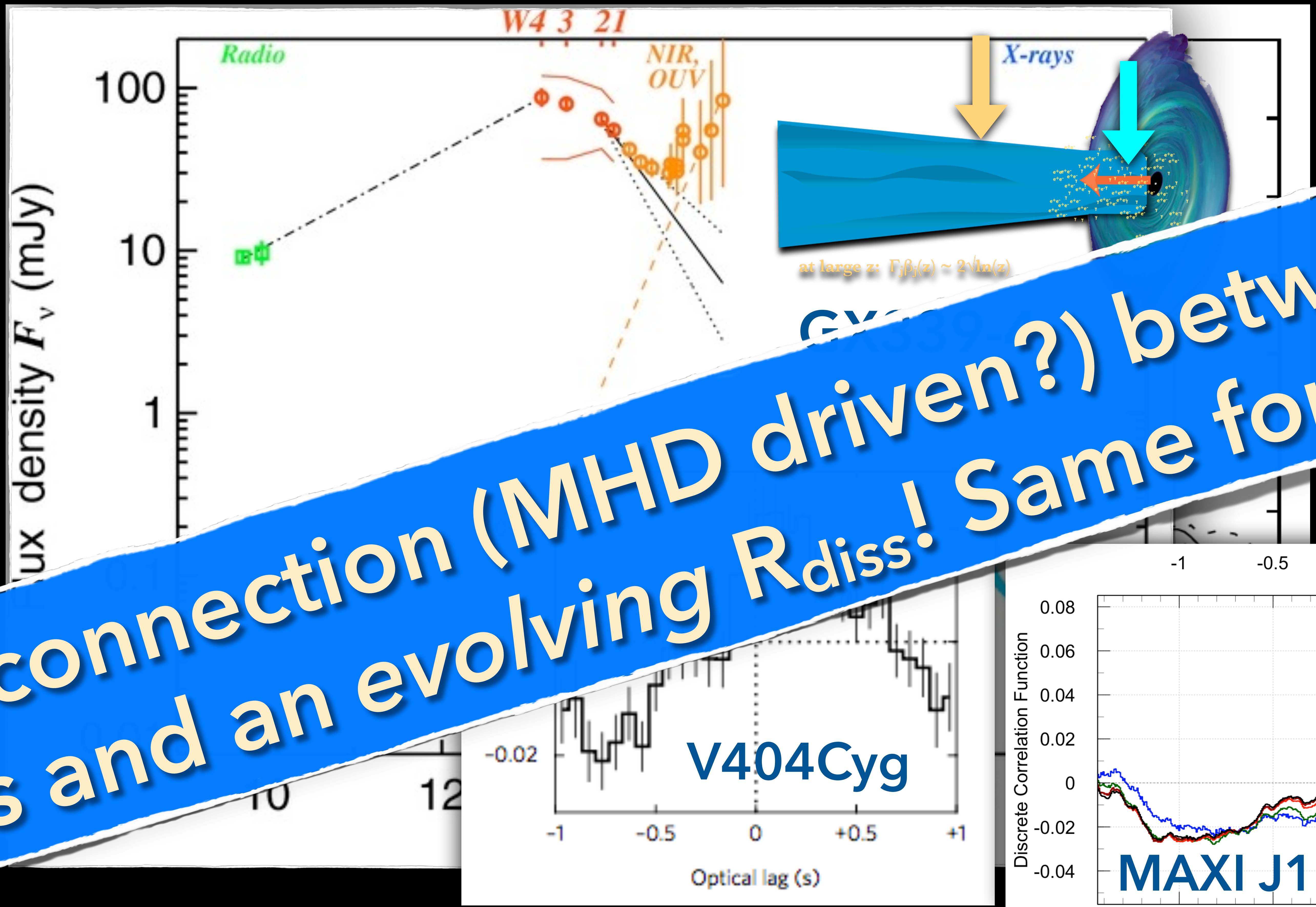
magnetisation: $\sigma = B^2/4\pi\rho c^2$

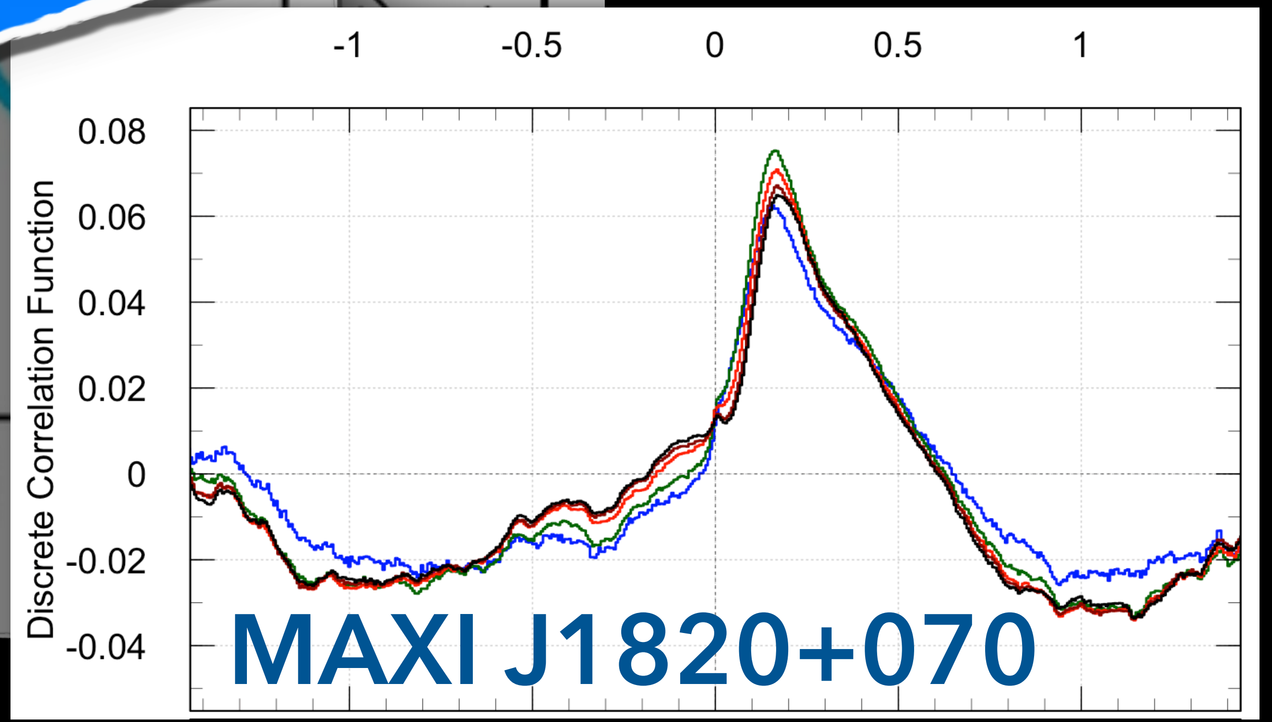
specific enthalpy: $h = (U_{gas}+P_{gas})/\rho c^2$

Kantzas, SM, Lucchini++2023a using simulations from Chatterjee, Liska, Tchekhovskoy & SM 2019; see also, e.g. Petropoulou++2023

Confirmation of geometry/distance for R_{diss}





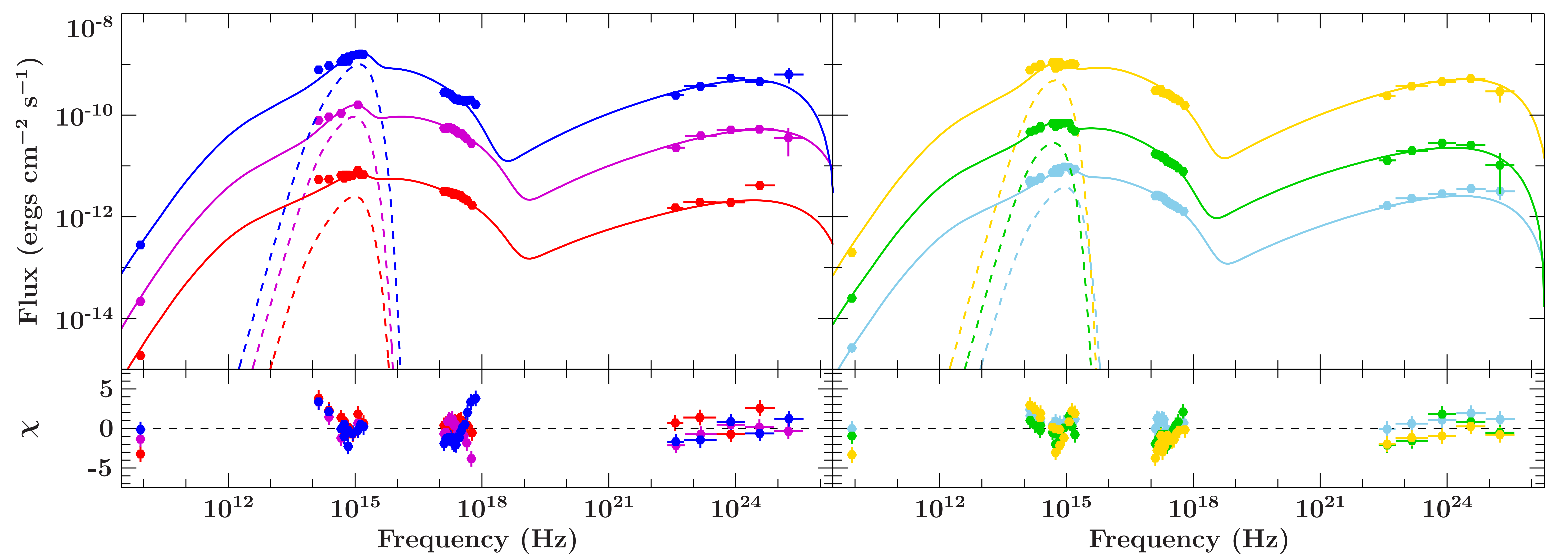


Strong causal connection (MHD driven?) between near-BH regions and an evolving R_{diss}! Same for AGN?

- Variability carried long distances along the jets from disk: IR jet synchrotron lags X-ray (corona) by ~100-300ms ➡ (10^3 -10^4 r_g)
- Now found in three XRBs: robust feature ➡ month to yrs in AGN?
- First IR low frequency QPO's! Harmonic (1:2) of Xray frequency

(Kalamkar++2016; Gandhi++ 2017; Paice, Gandhi++2019; Thomas++2022)

Full jet model + joint fitting: blazar PKS 2155-304, $R_{diss} < R_{Bondi}$?

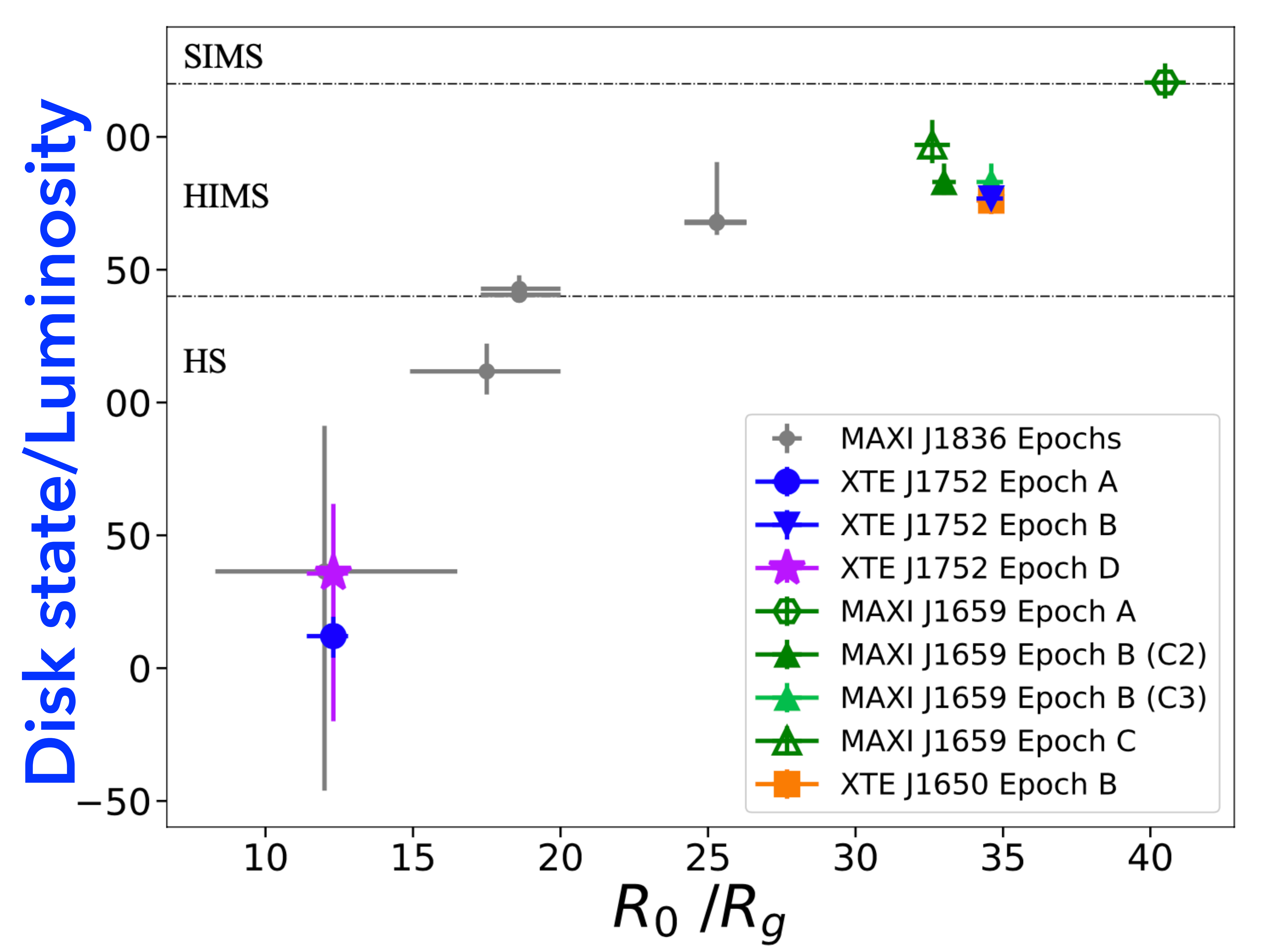


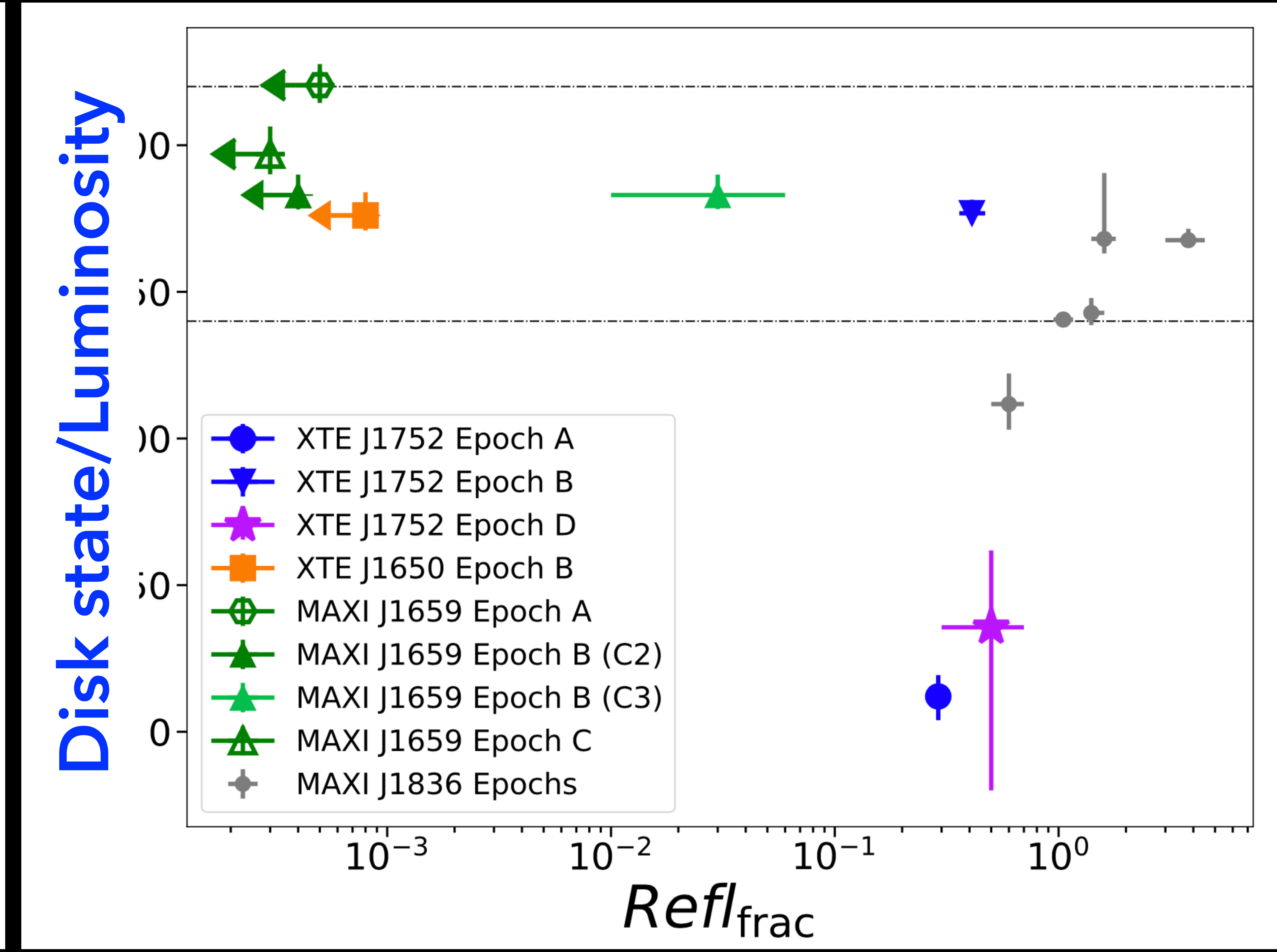
	$\dot{M}_{disc}$ [$\dot{M}_{Edd}$] 10^{-2}	R_{in} [R_g]	N_j [L_{Edd}] 10^{-2}	r_0 [R_g]	z_{diss} [R_g]	p	f_{heat}	f_b	f_{sc} 10^{-6}	σ_{diss} 10^{-2}	B [G]	$n(e)$ [cm^{-3}]	γ_{min}	γ_{brk} 10^2	γ_{max} 10^5	χ^2/dof
α	2.9	22	1.0	29	510	1.9	20	40	2.7	2.0	0.24	52.6	133	11	3.2	59.33/22
β	1.6	30	1.0	75	1360	1.8	10	22	2.5	3.2	0.30	17.3	63	7.1	2.7	38.51/15
γ	/	/	0.9	23	1700	1.9	11	30	2.0	5.6	0.37	56.6	72	7.1	2.4	58.3/21
δ	1.4	100	0.9	10	1170	1.6	8	86	1.2	2.0	0.23	97.3	51	7.3	1.8	66.05/24
ϵ	0.7	79	1.5	15	960	1.8	6	50	1.2	1.4	0.23	130	43	8.2	1.8	29.87/24
ζ	0.9	18	1.6	26	1720	1.9	8	43	1.6	1.6	0.28	90.1	55	8.1	2.3	33.72/25

Lucchini, SM, Crumley, Krauss & Connors 2018; data from Krauss++2006

Geometrical trends in XTE J1752-223, MAXI J1659-152, and XTE J1650-500

- ‘Corona’ expands as inner disk cools? Corona contracts along jet and/or is more beamed nearing state transition ➠ supports corona-only = failed jet?

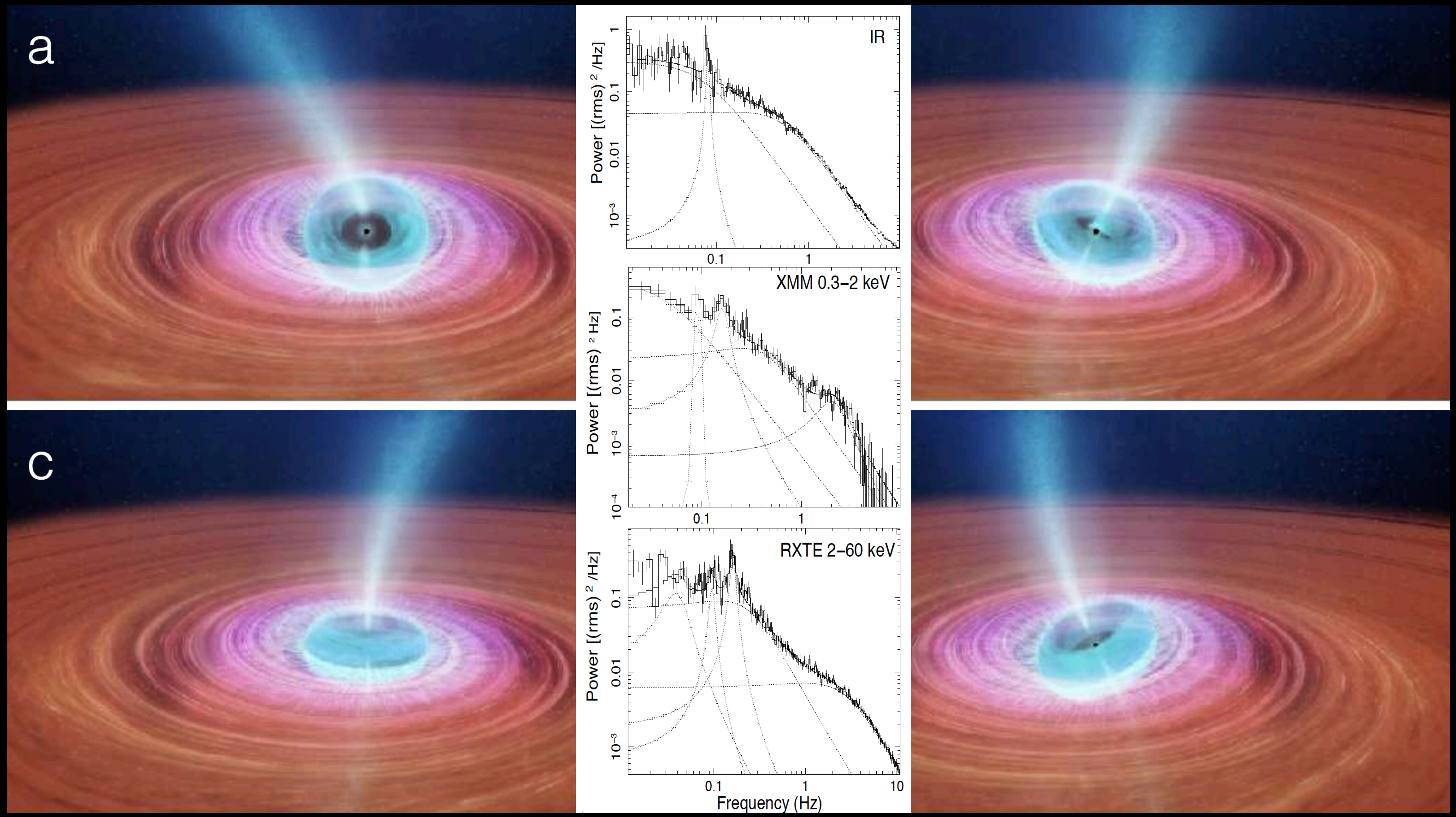




Lucchini, Russell, SM++ 2021; Cao, Lucchini, SM++ 2021

Tilted black holes may explain a variety of observed phenomena

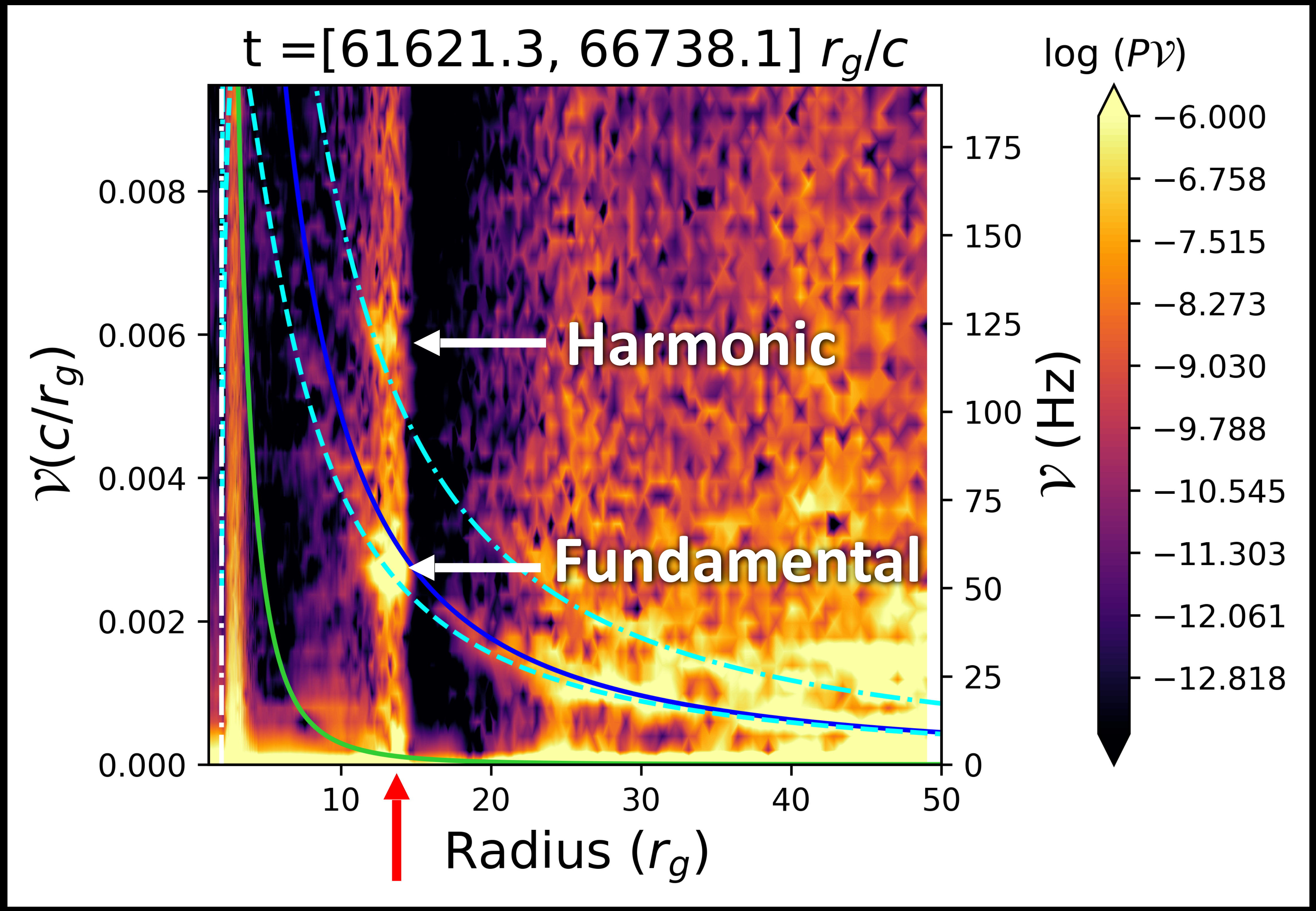
Precessing jets and low frequency QPOs



Kalamkar++2016:

Ingram & Motta 2019

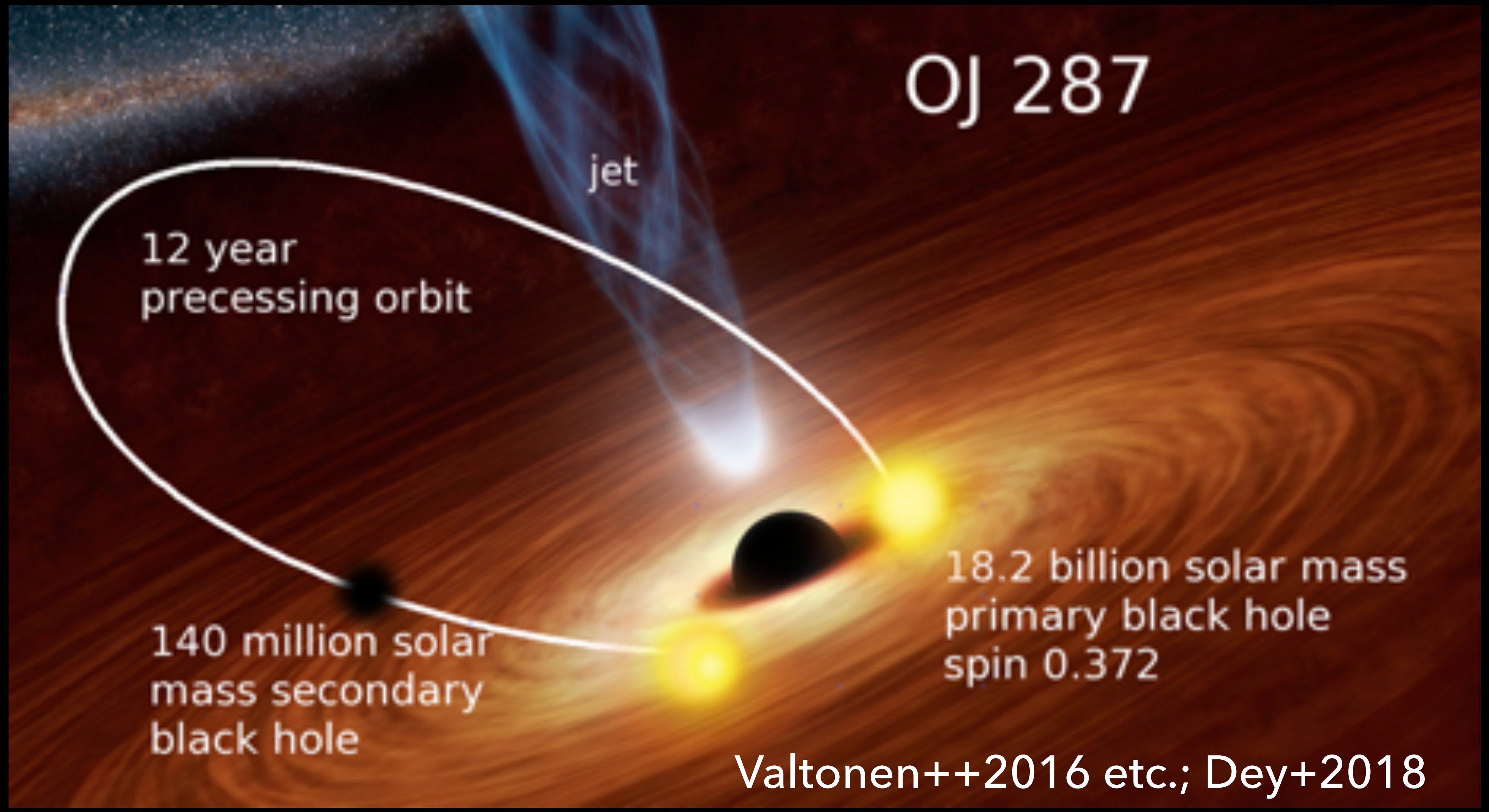
Radiation GRMHD: low & high frequency QPOs

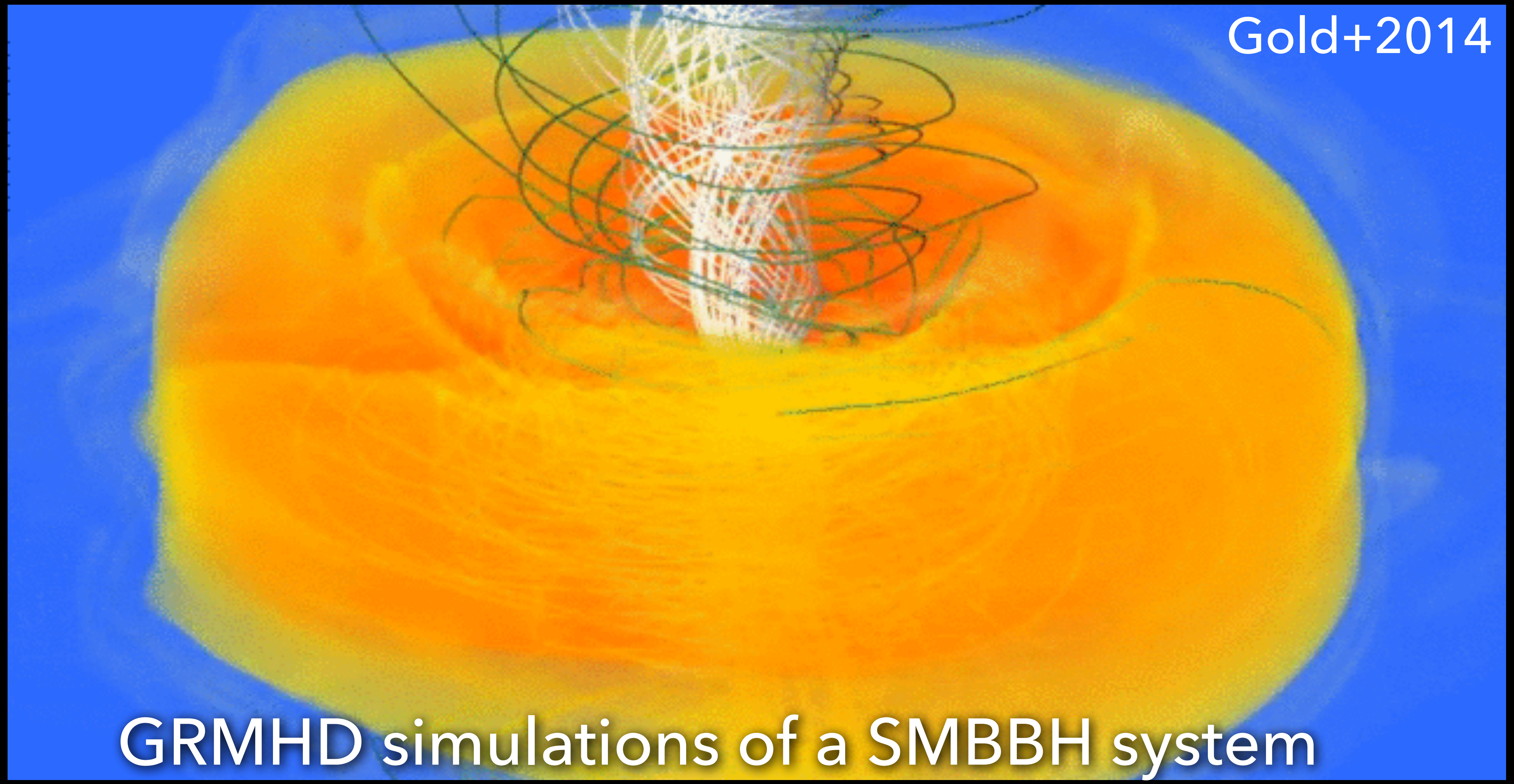


r = 13 r_g (disk tearing radius)

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

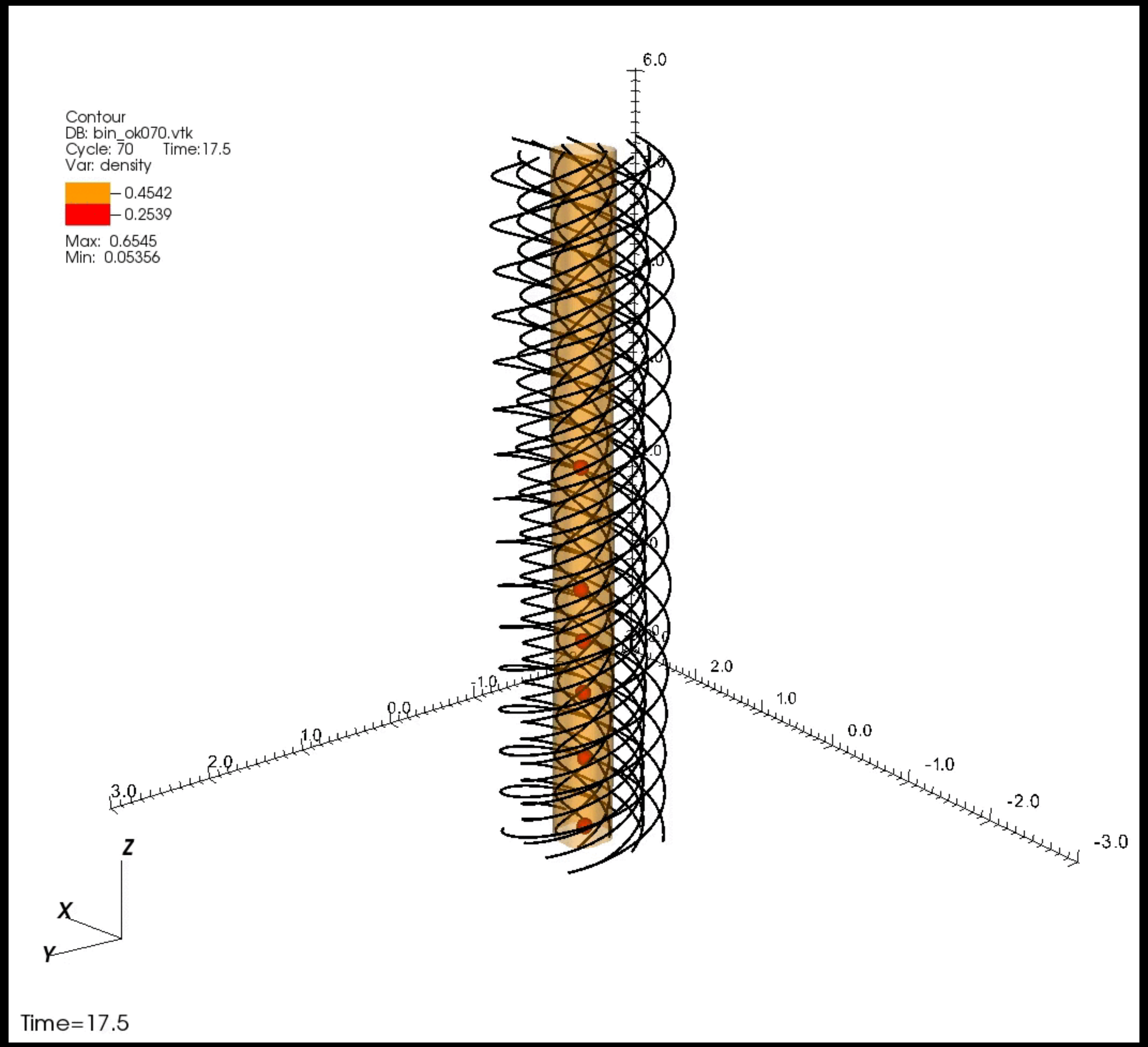
OJ 287: Is it really a binary black hole??

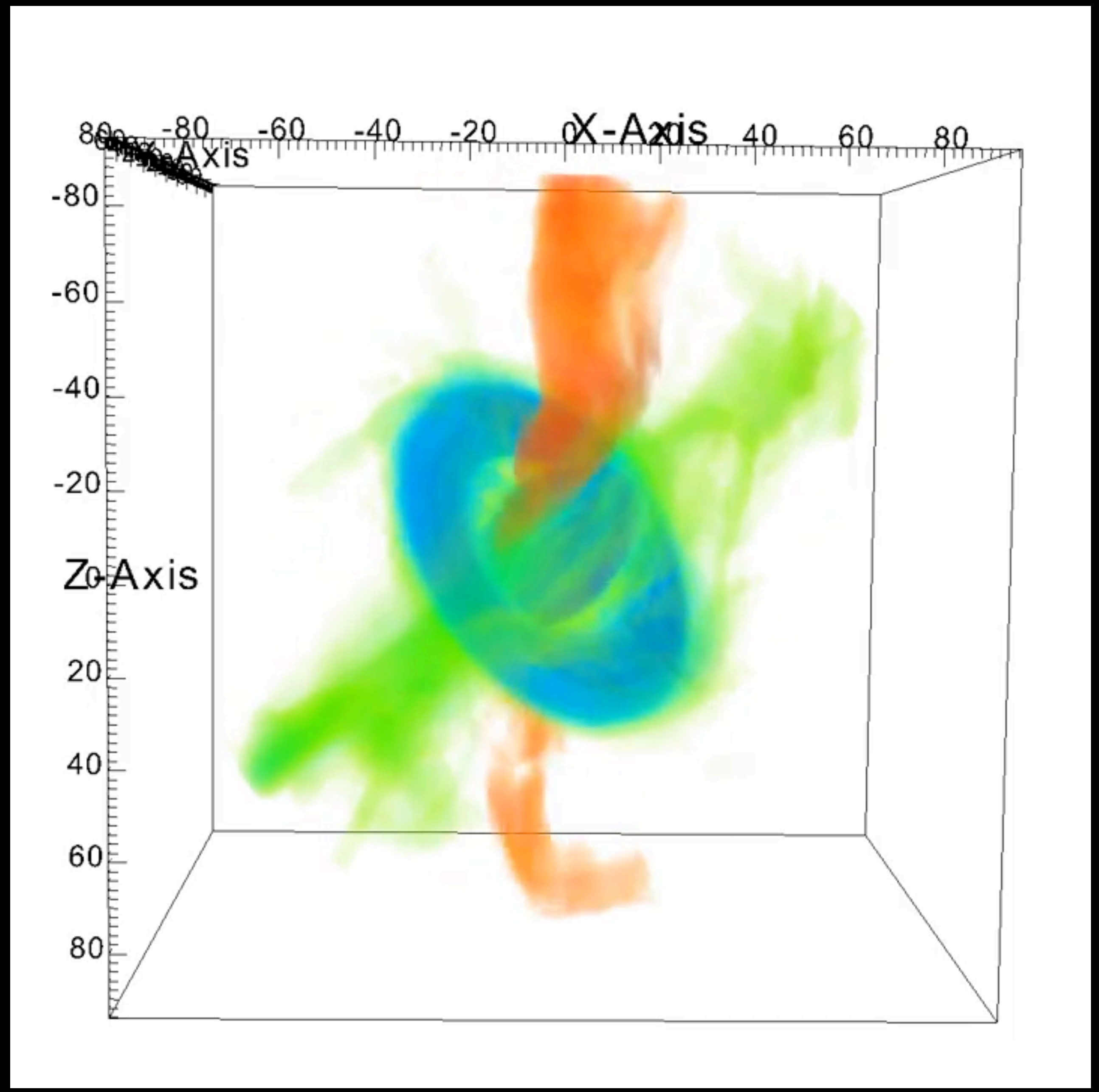




But other options do exist!

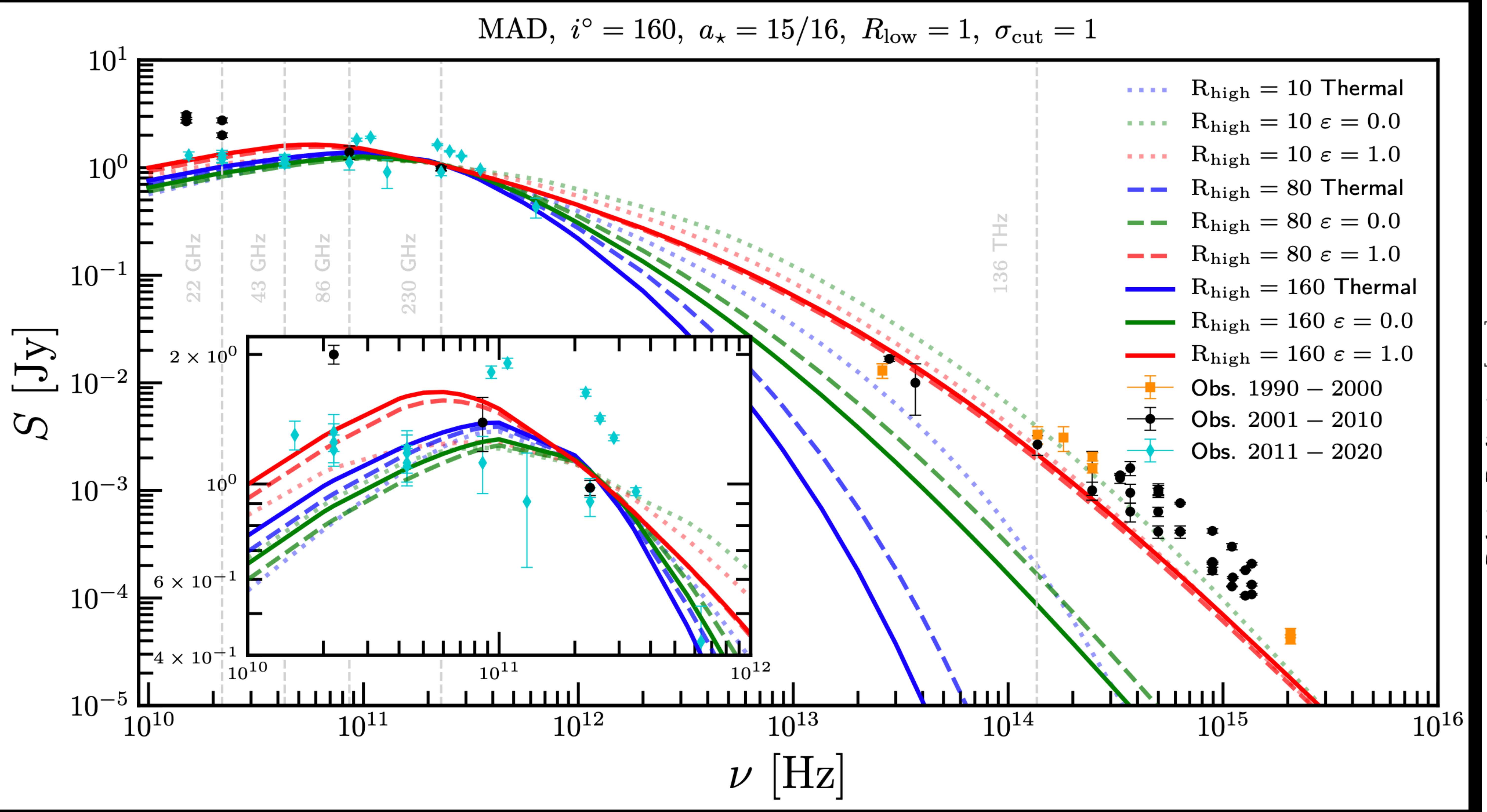
- Kink instabilities? (Y.Mizuno++2014; Singh, YM++2015, Kadowaki, YM++2020)
- Tilted accretion disk (Liska, Hesp, Tchekhovskoy, Ingram, vd Klis & SM 2018; Liska, Chatterjee++2019, 2022)

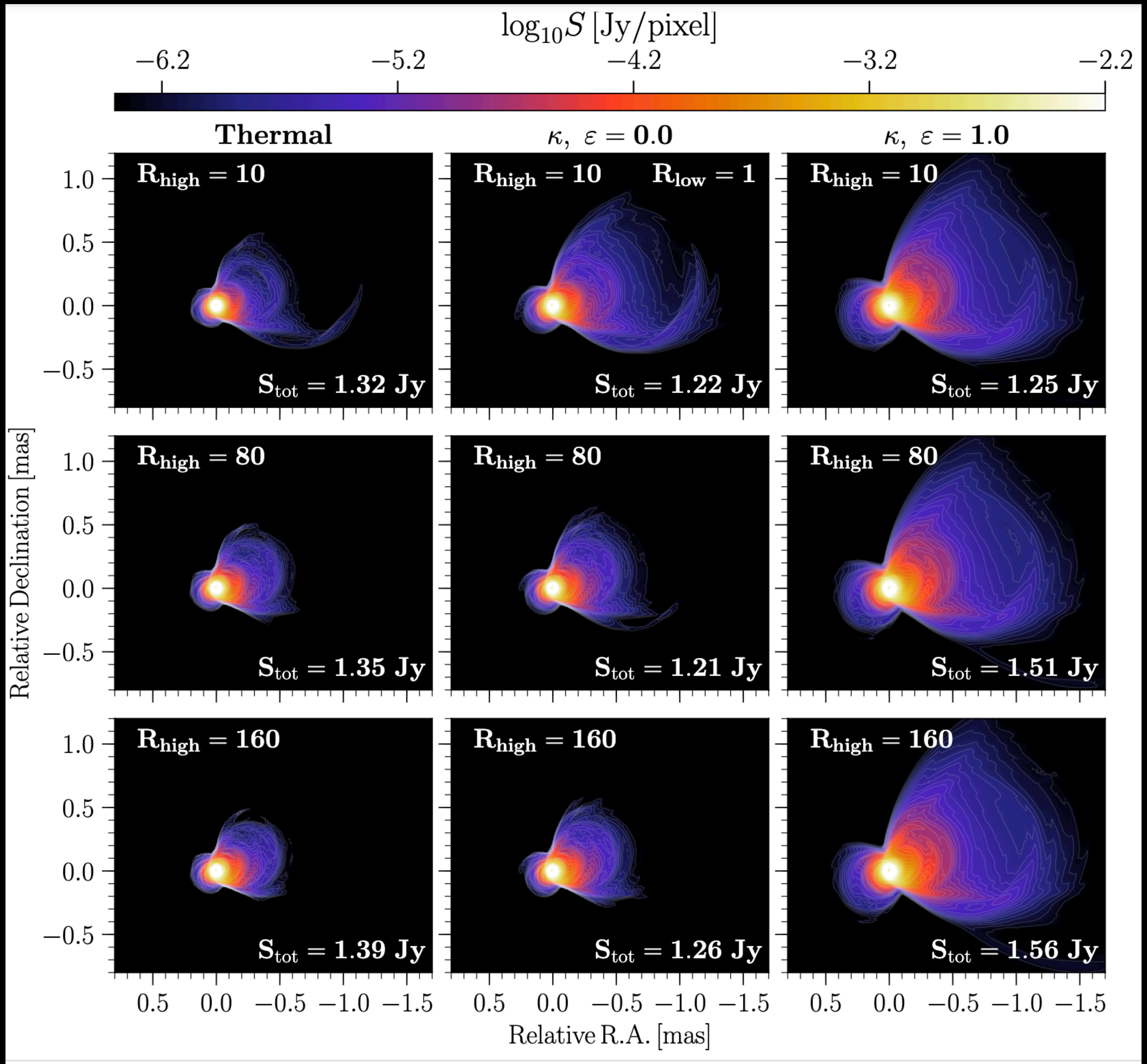




(Slide adapted from J.L. Gomez)

The new horizon: combined image + SED modelling





Radio to optical SED fitting + image modelling by Fromm++22