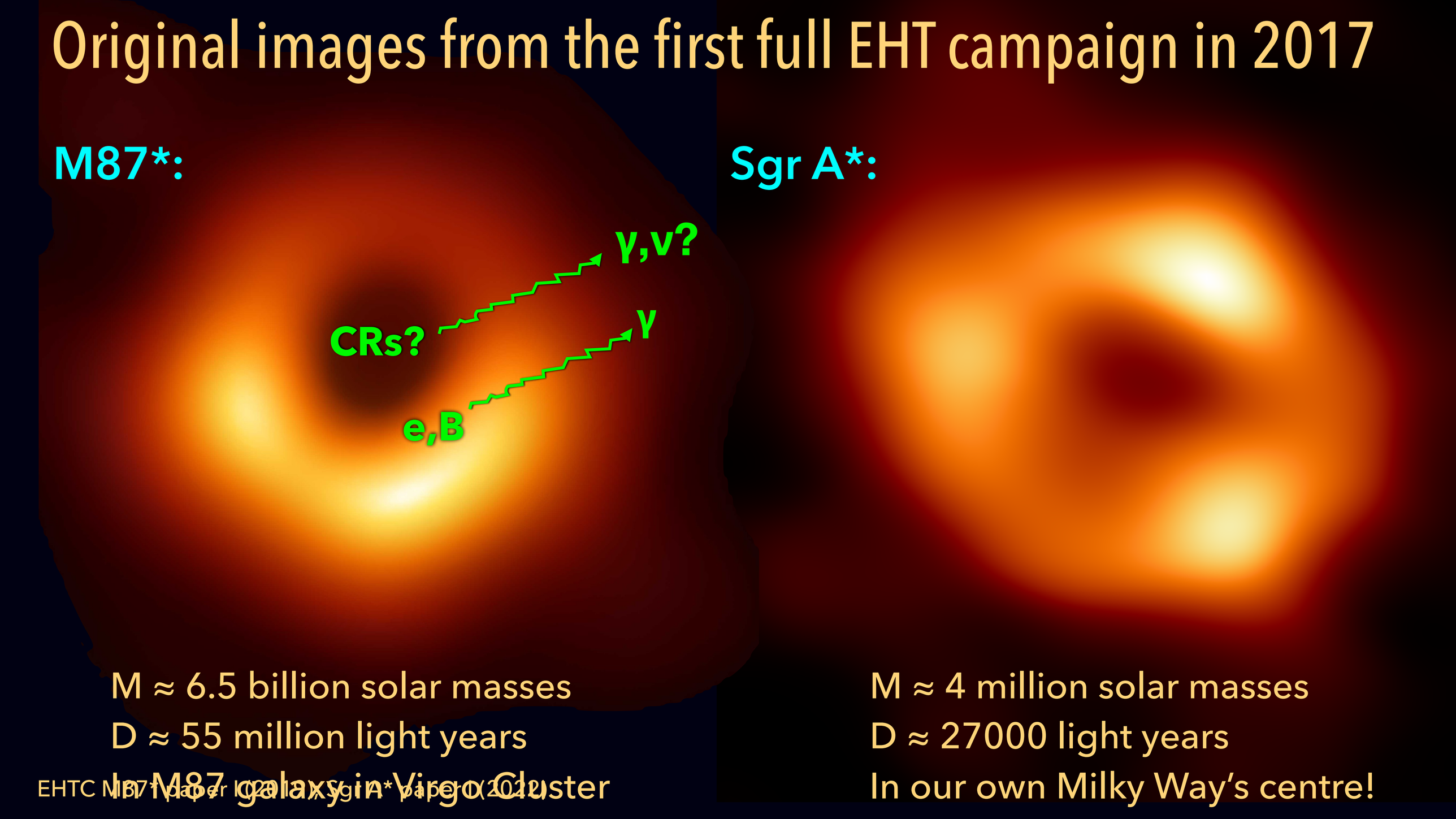
A multi-messenger view of black holes in the Event Horizon Telescope (EHT) era

Sera Markoff (U Amsterdam) + EHT Collaborations + EHT SB & MWL/TS WGs + CTAO + several current/former members of the 'jetsetters' group @ U Amsterdam (K. Chatterjee, R. Duncan, D. Kantzas, M. Liska, M. Lucchini, W. Mulaudzi, G. Musoke, S. Praharaj, R. Roy, L.S. Salas, D.-S. Yoon) + Collaborators: J. Davelaar, S. Philippov, B. Ripperda, P. Tiede, S. Tchekhovskoy, Z. Younsi

Original images from the first full EHT campaign in 2017



M ≈ 6.5 billion solar masses
D ≈ 55 million light years
In M87 galaxy in Virgo Cluster

M ≈ 4 million solar masses
D ≈ 27000 light years
In our own Milky Way's centre!

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

Outline

- ★ Black hole jets as particle accelerators and the search for the VHE emission region
- ★ The Event Horizon Telescope to date
- ★ Latest EHT/MWL results and implications
- ★ Near/far-term outlook

Outline

★ Black hole jets as particle accelerators and the search for the VHE emission region

★ The Event Horizon Telescope to date

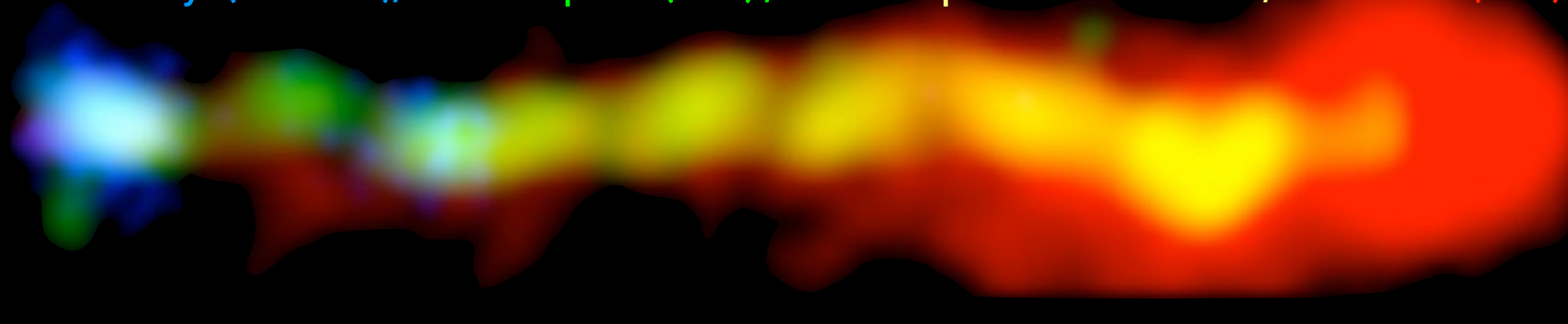
★ Latest EHT/MWL results and implications

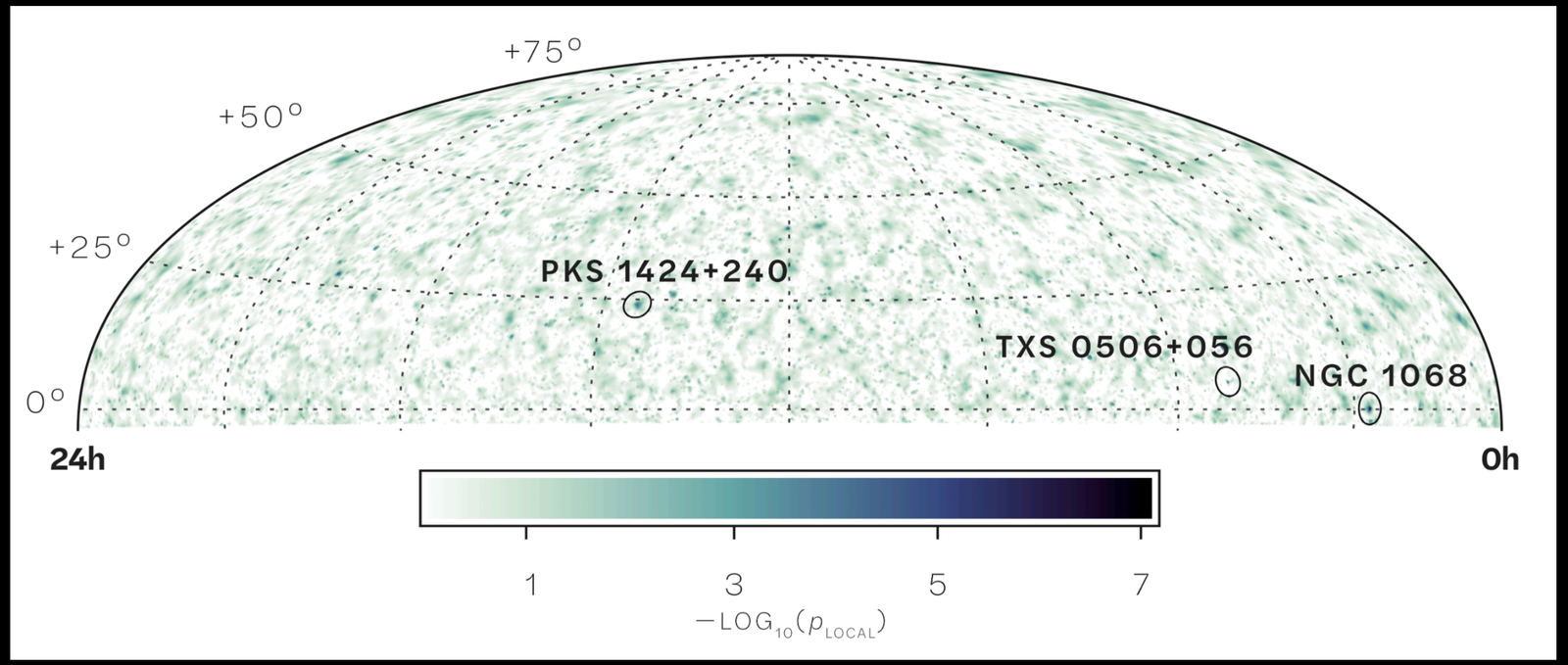
★ Near/far-term outlook

The “classic” jet picture for CRs looks to be too simplistic

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

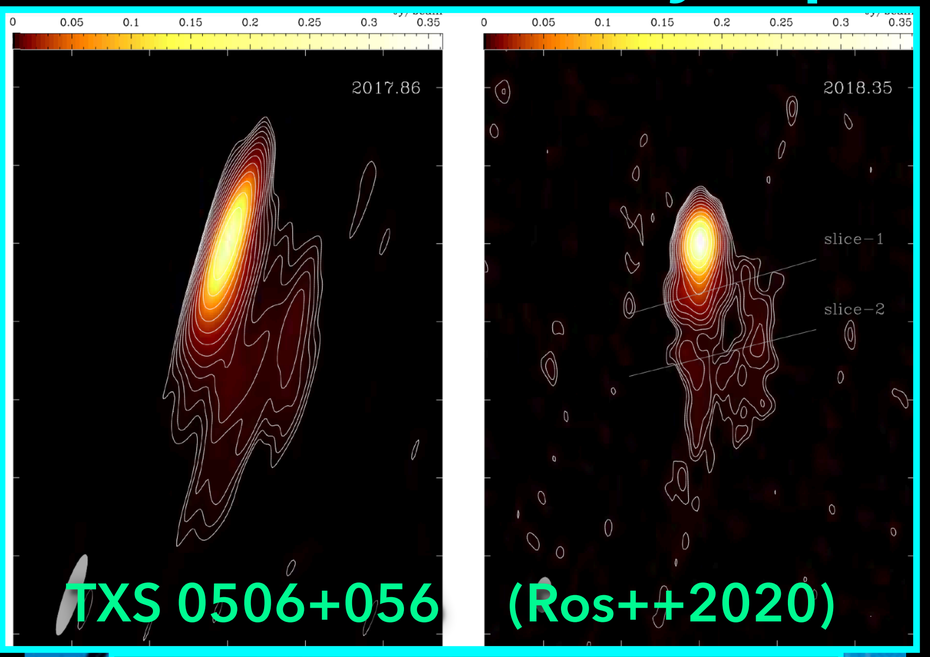
Blue: X-rays (Chandra), Green: Optical (HST) , Yellow: Optical & Peak Radio, Red: Radio (VLA)





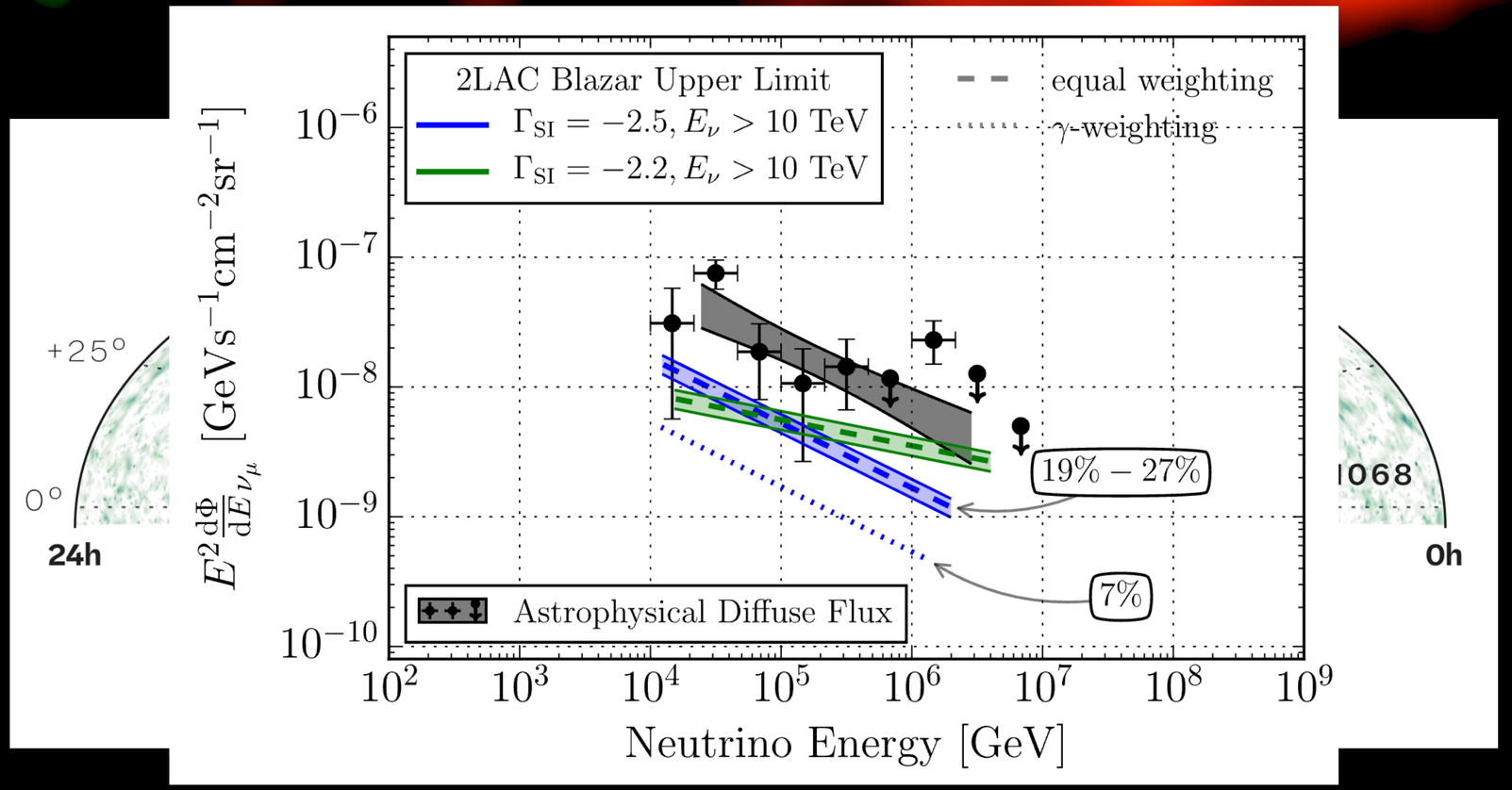
IceCube Collaboration 2018; 2022, Science

The “classic” jet picture for CRs looks to be too simplistic



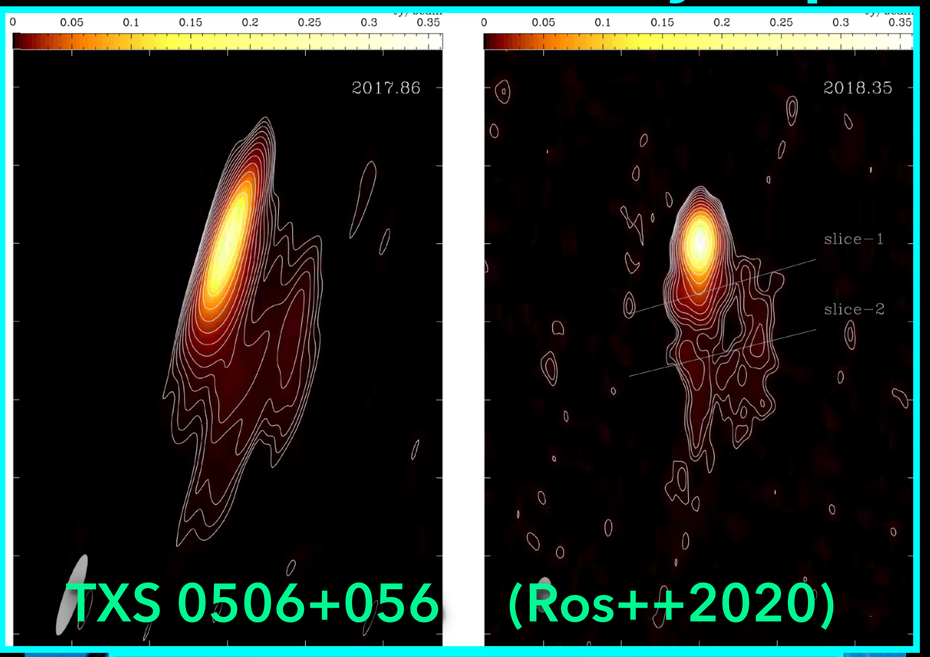
3C273 (Jester++2006), jet “colour” (wavelength) traces particle acceleration:
Blue: X-rays (Chandra), Green: Optical (HST) , Yellow: Optical & Peak Radio, Red: Radio (VLA)

IceCube Collaboration 2018; 2022, Science



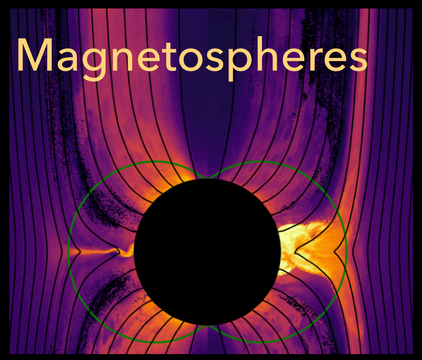
IceCube Collaboration 2017

The “classic” jet picture for CRs looks to be too simplistic

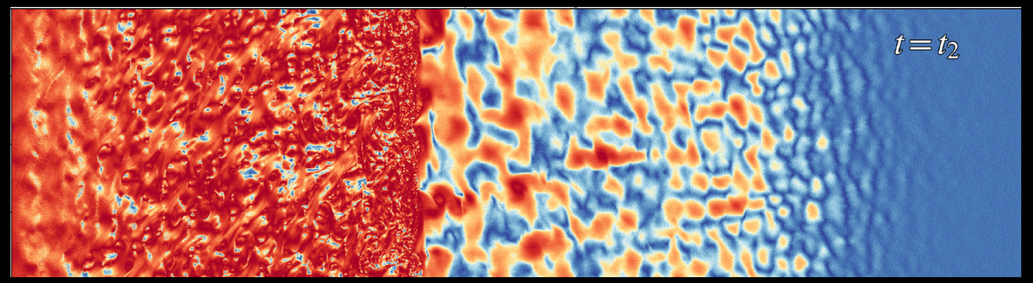


TXS 0506+056 (Ros++2020)

Magnetospheres

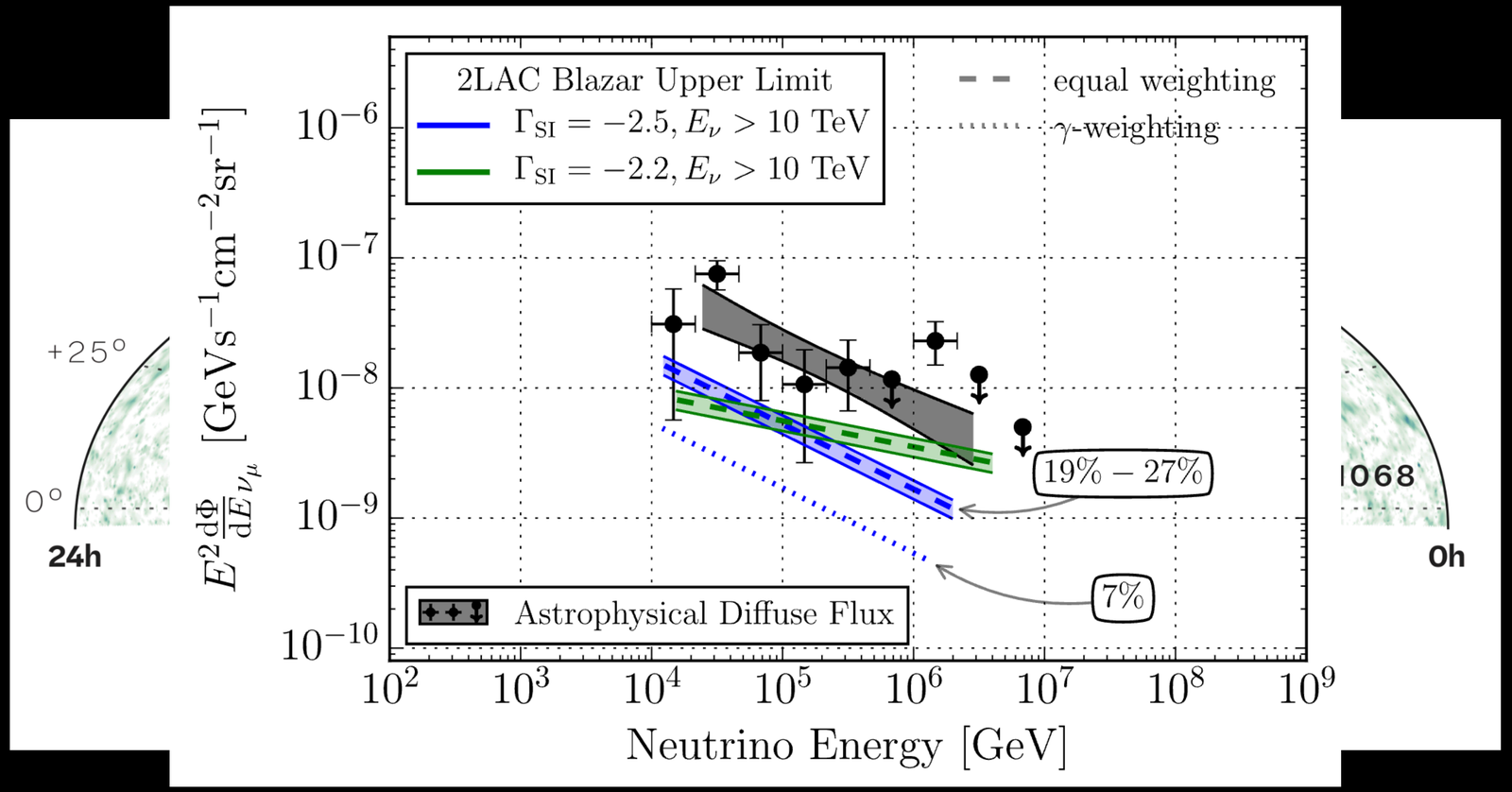


Stochastic/shear/turbulence



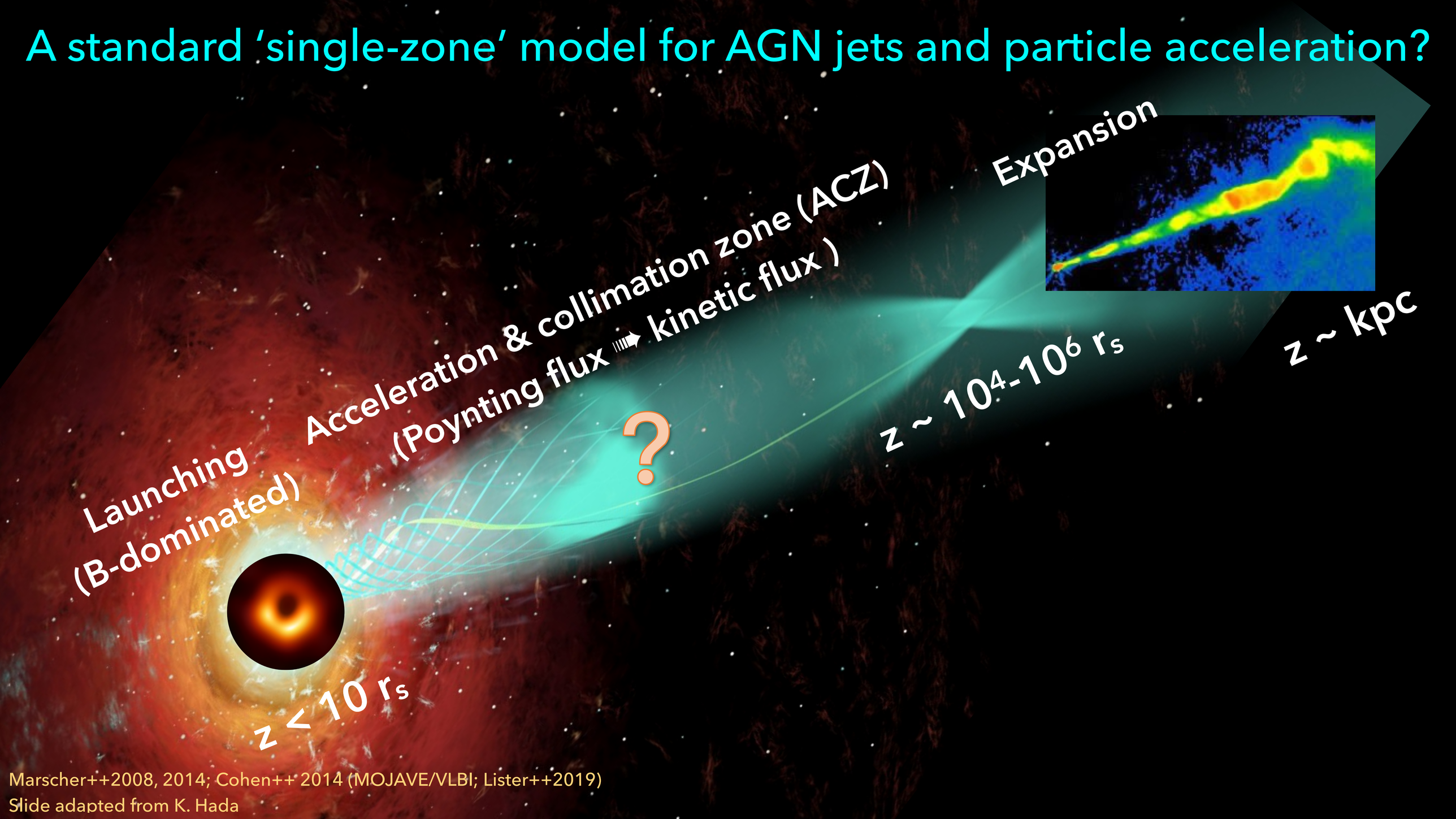
NGC 1068 = Seyfert II…?!

IceCube Collaboration 2018; 2022, Science



IceCube Collaboration 2017

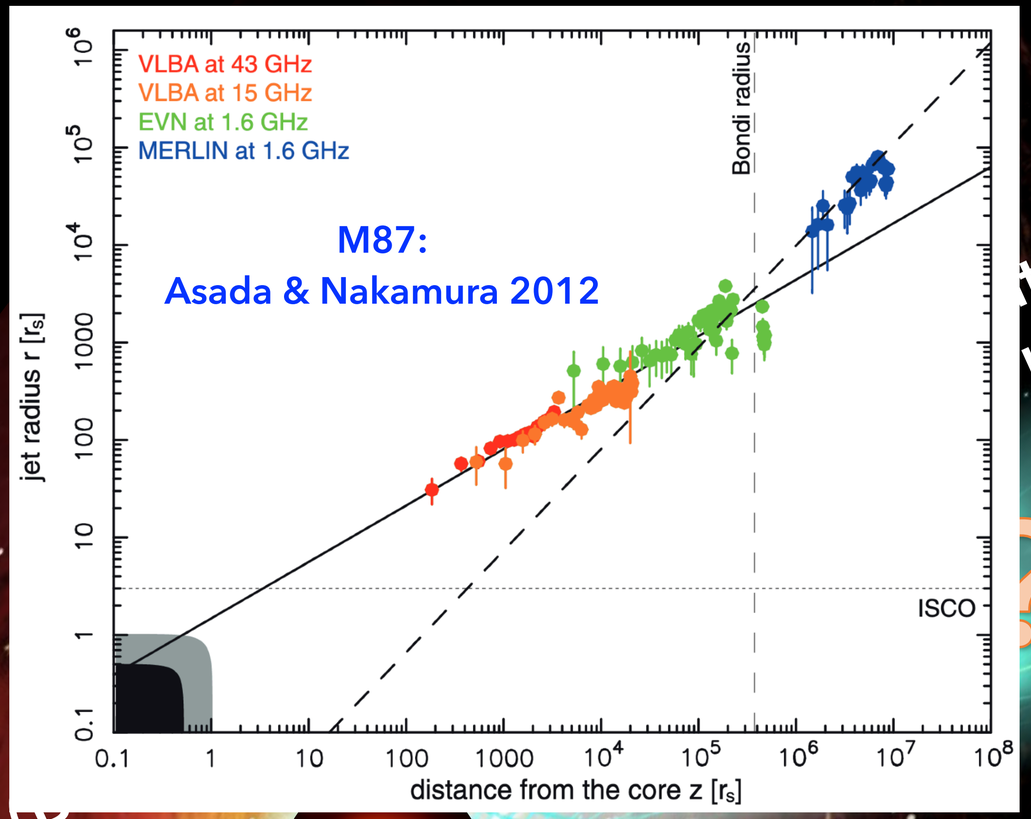
A standard ‘single-zone’ model for AGN jets and particle acceleration?



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

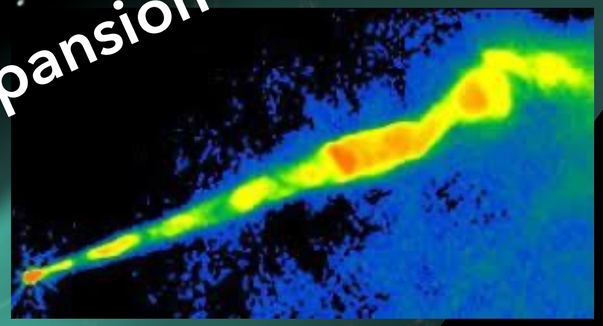
Slide adapted from K. Hada

A standard ‘single-zone’ model for AGN jets and particle acceleration?



tion zone (ACZ)
kinetic flux)

Expansion



$z \sim 10^4$-10^6 r_s

$z \sim$ kpc

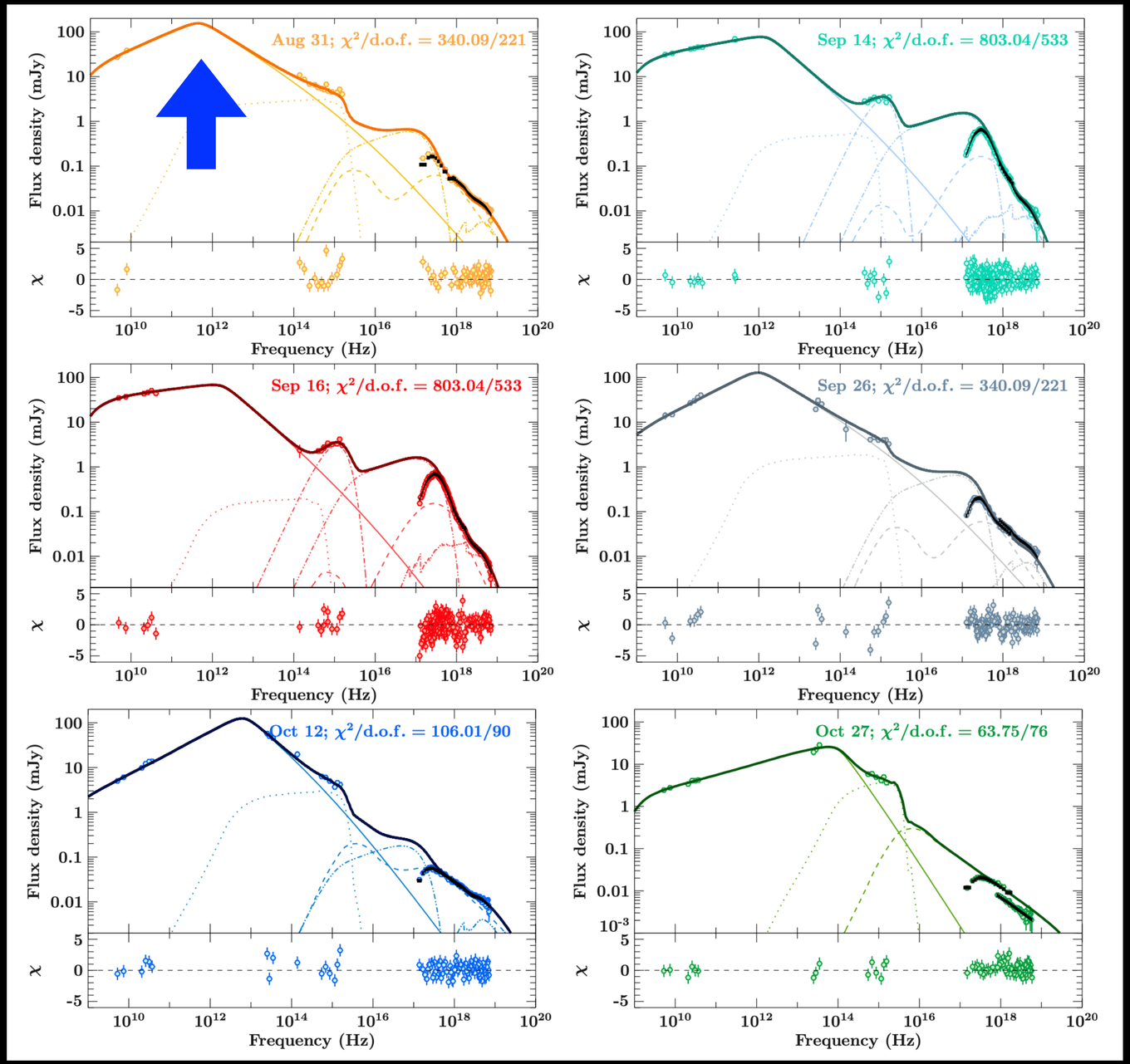
$z < 10$ r_s

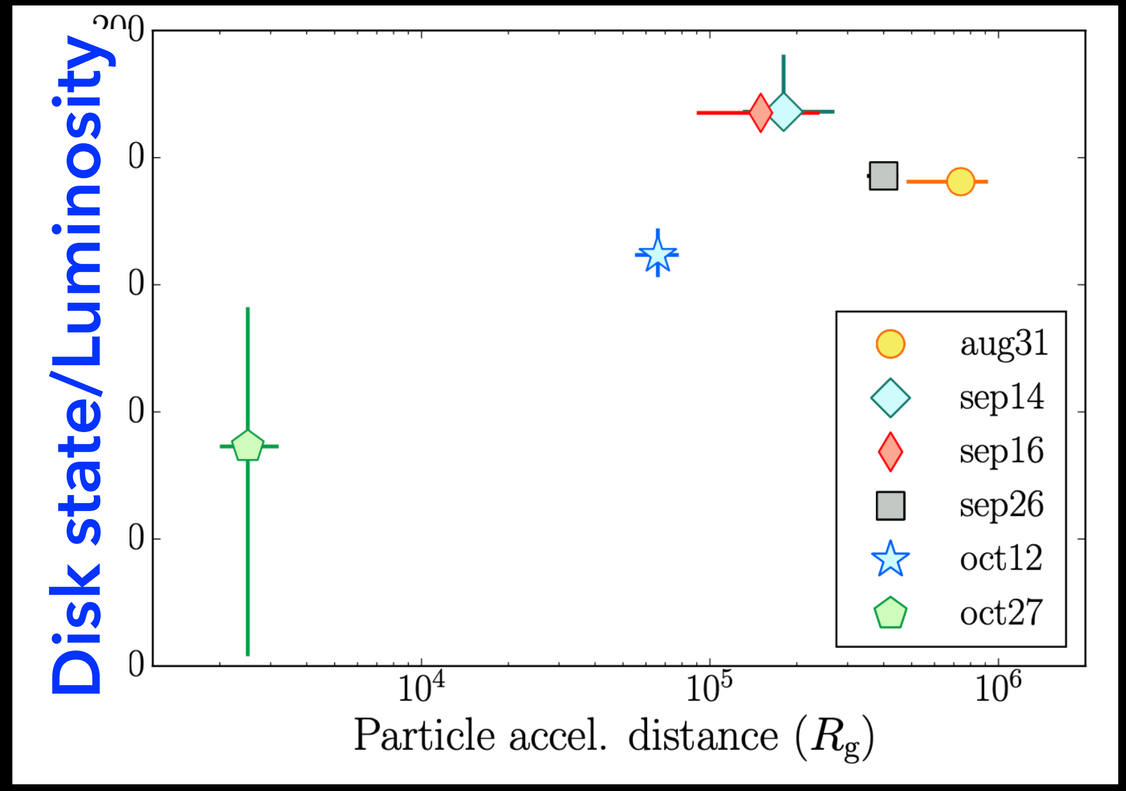
Distance to Recollimation Shock

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

Marscher++2008, 2014; Cohen++ 2014 (MOJAVE/VLBI; Lister++2019)
Slide adapted from K. Hada

XRB spectral-timing: XTE J1836-194 "ACZ equivalent" responds to $\dot{M}$ in realtime

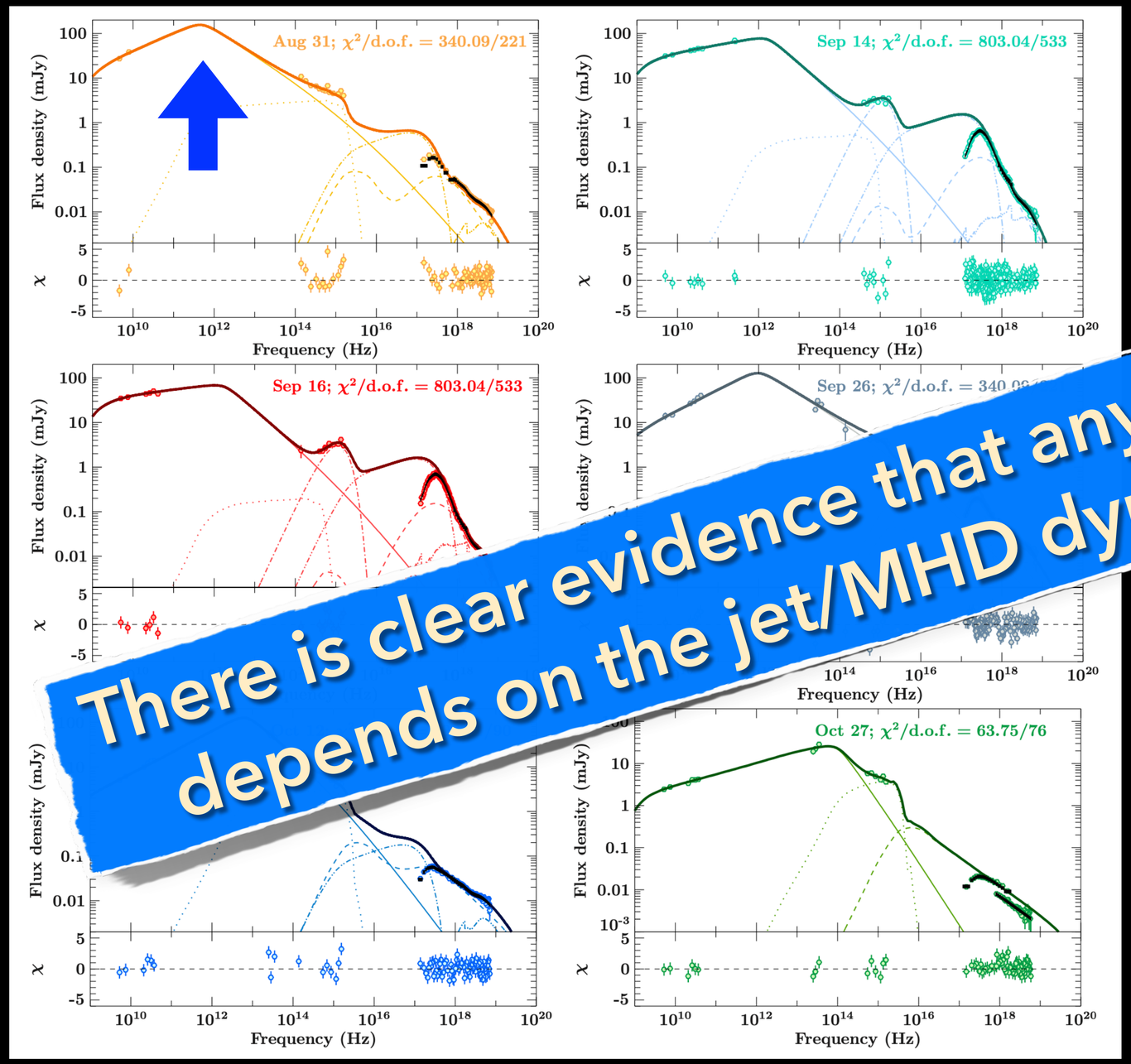


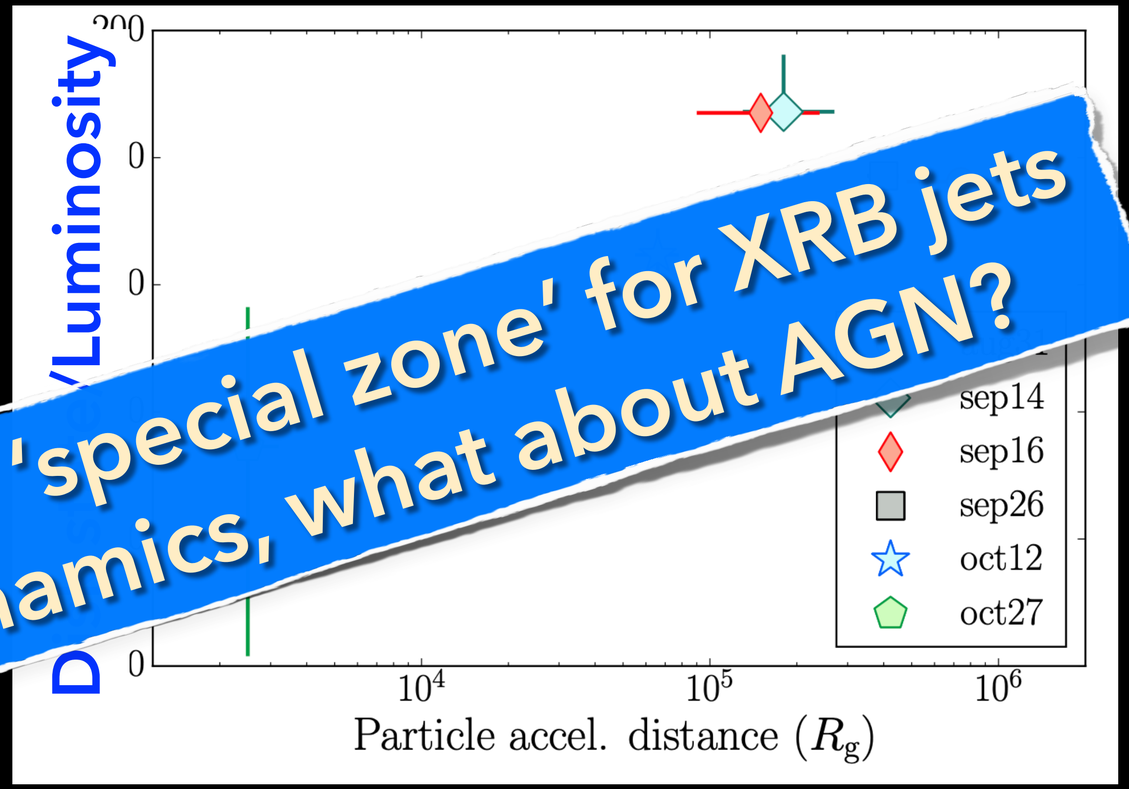


- Jets respond to changes in accretion rate/disk in real time!
- Dissipation 'zone' changes by 2 orders of magnitude over 2 months!

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

XRB spectral-timing: XTE J1836-194 "ACZ equivalent" responds to $\dot{M}$ in realtime



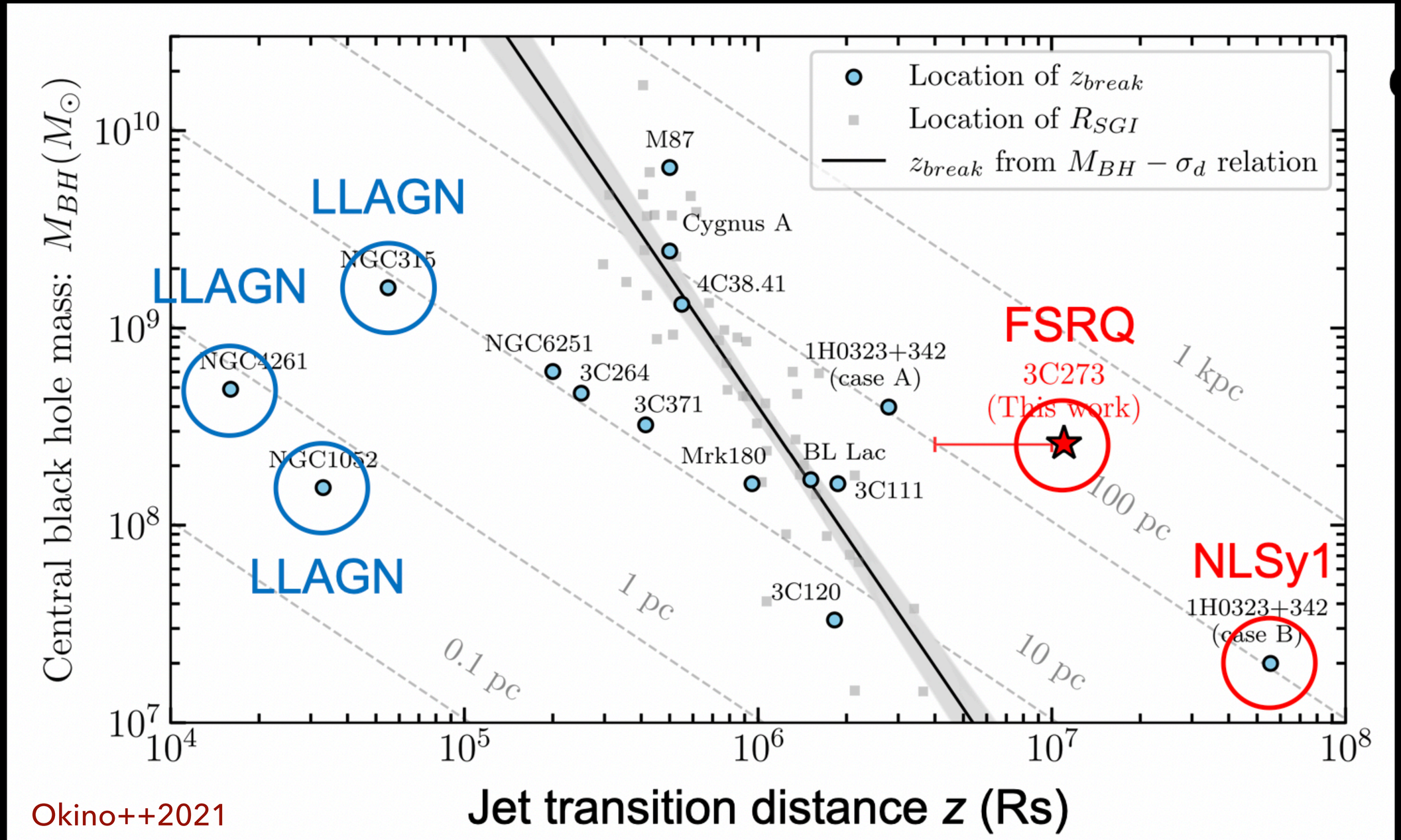


There is clear evidence that any 'special zone' for XRB jets depends on the jet/MHD dynamics, what about AGN?

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

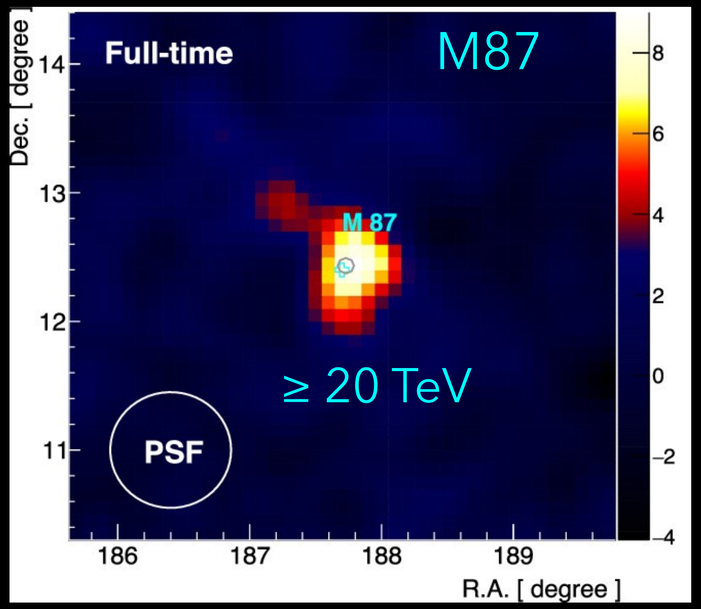
(Russell++ 2014; Lucchini, Russell, SM++ 2020; Cao, Lucchini, SM++2021)

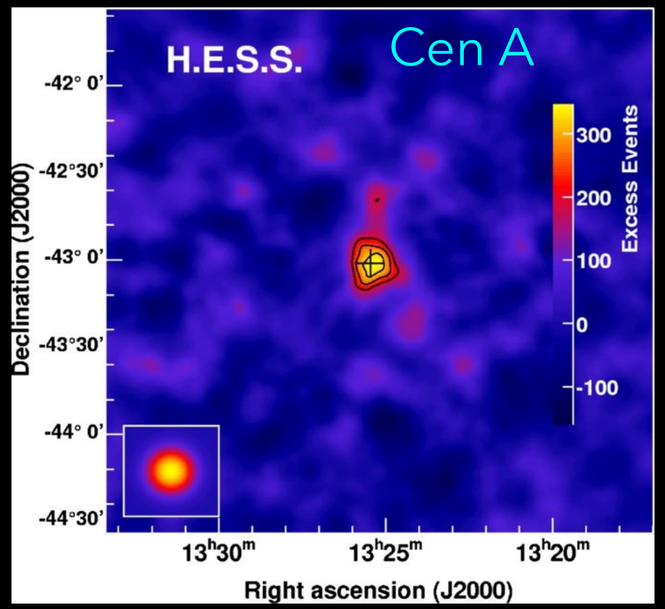
Growing evidence that AGN jets also respond to $\dot{M}$ in realtime (=years/decades)!!

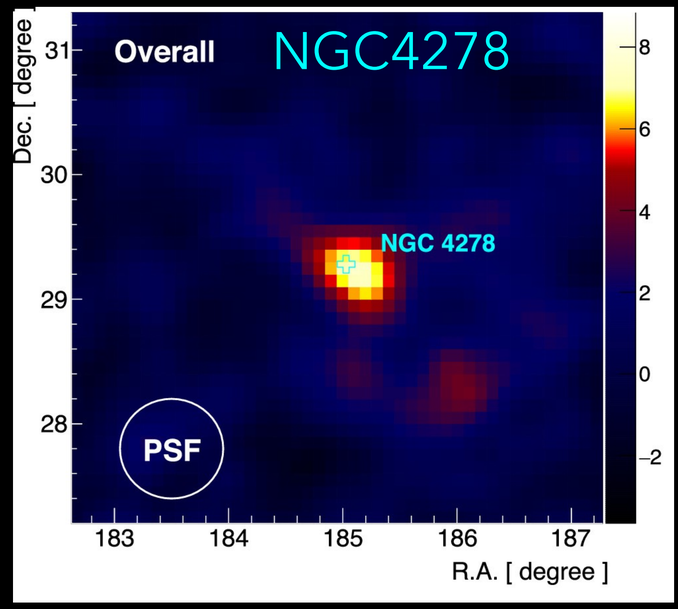


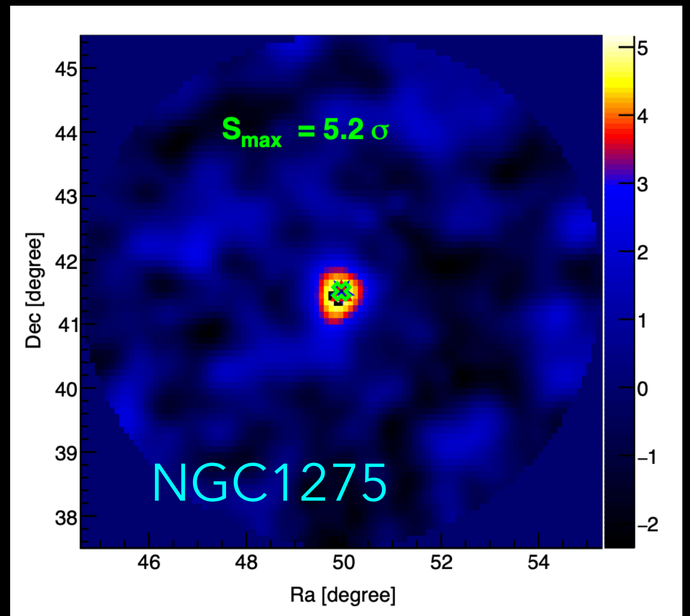
Okino++2021

VHE γ-ray revolution underway also for LLAGN



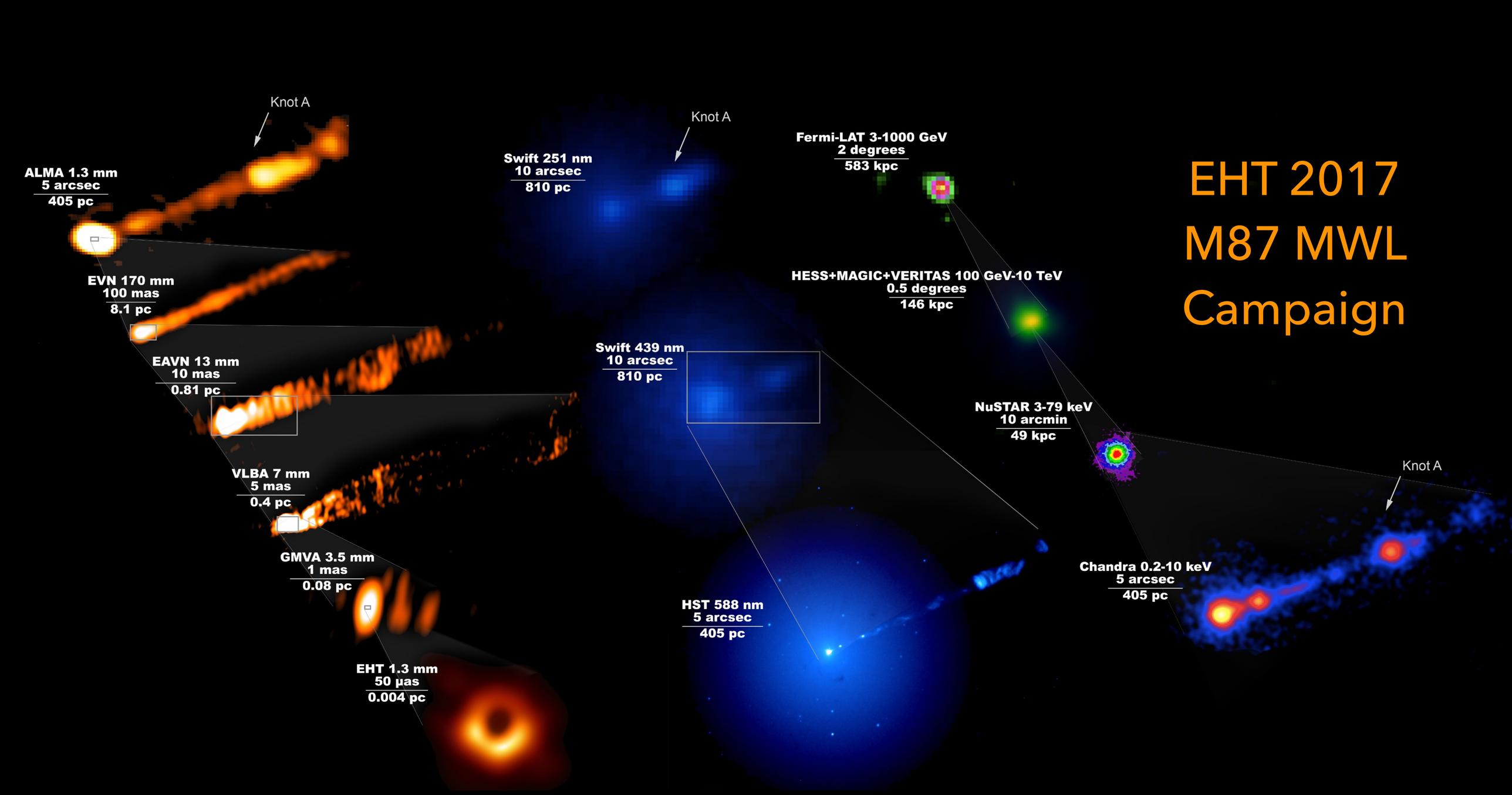






(LHAASO Collaboration; Cao++23; Cao++24ab)

- Are non-blazar LLAGN another population responsible for UHECRs?
- If so, are we looking at the same acceleration processes, eg the “blazar zone”, or something closer to the black hole?



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

Outline

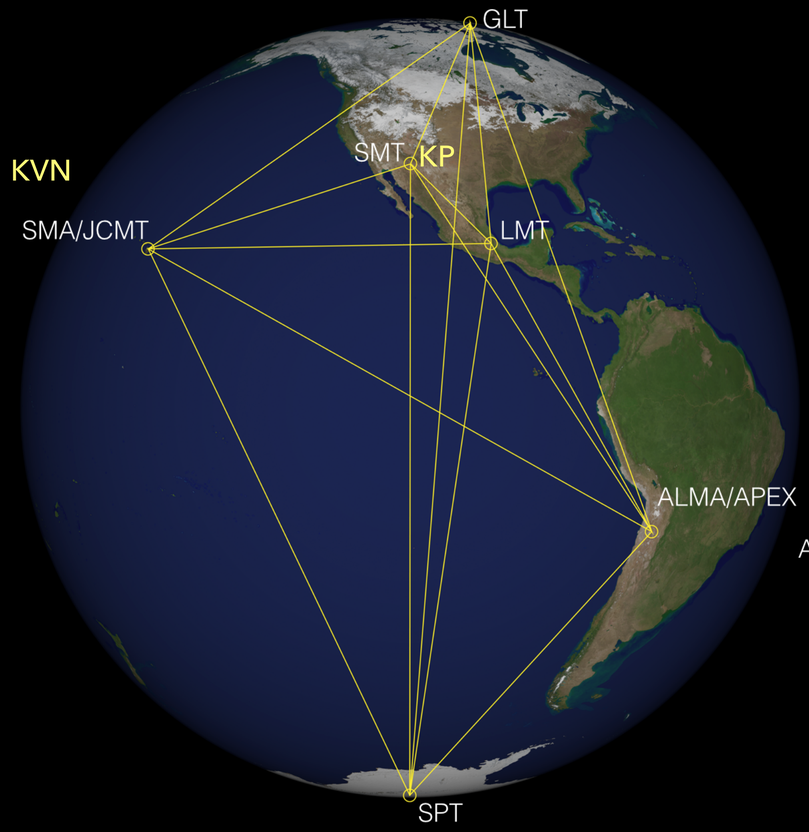
- ★ Black hole jets as particle accelerators and the search for the VHE emission region
- ★ The Event Horizon Telescope to date
- ★ Latest EHT/MWL results and implications
- ★ Near/far-term outlook

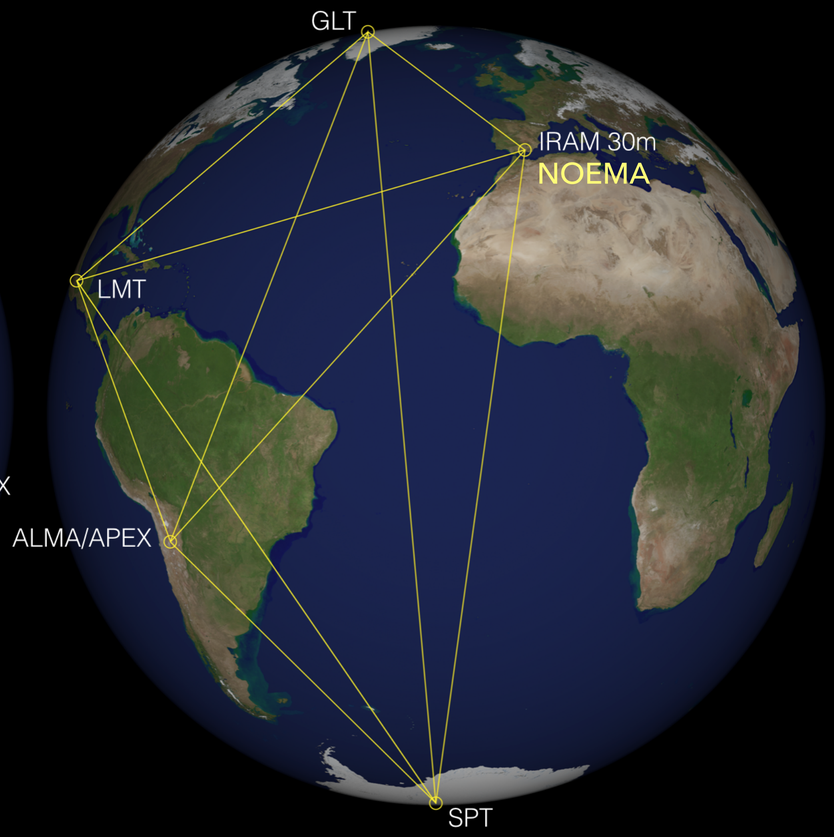
The Event Horizon Telescope (EHT) Collaboration is comprised of >400 members from >80 institutes....

...across 19 time zones!

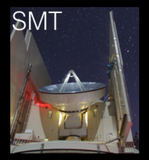
“Living on borrowed time”: EHT’s annual campaigns

Event Horizon Telescope





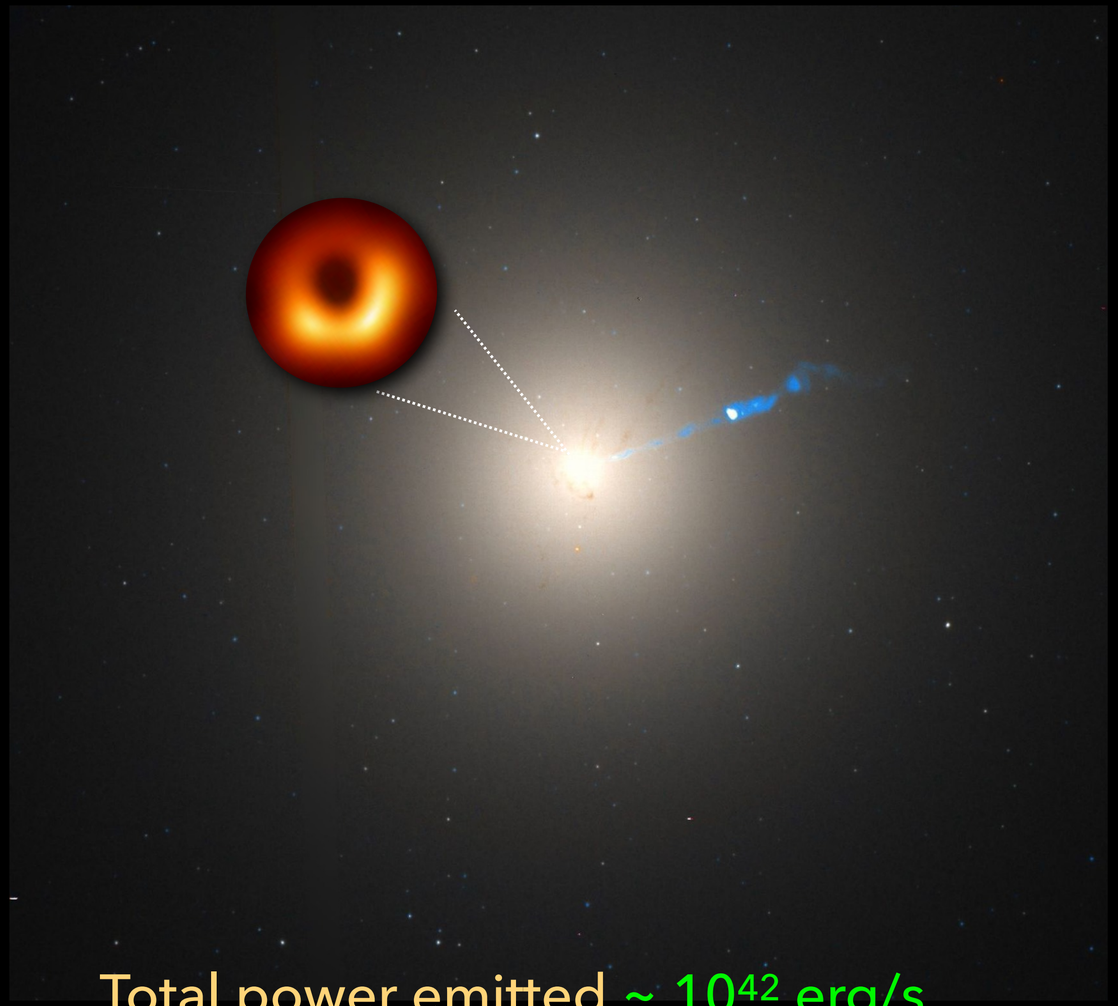
- We write competitive proposals to use the EHT for ~6/14 days annually
- 8 facilities in 2017, 9 in 2018 (+GLT)
- 2021-2023: added Kitt Peak dish + NOEMA array
- 2024, 2025: KVN & 0.8mm added/tested*



*Doeleman++2024

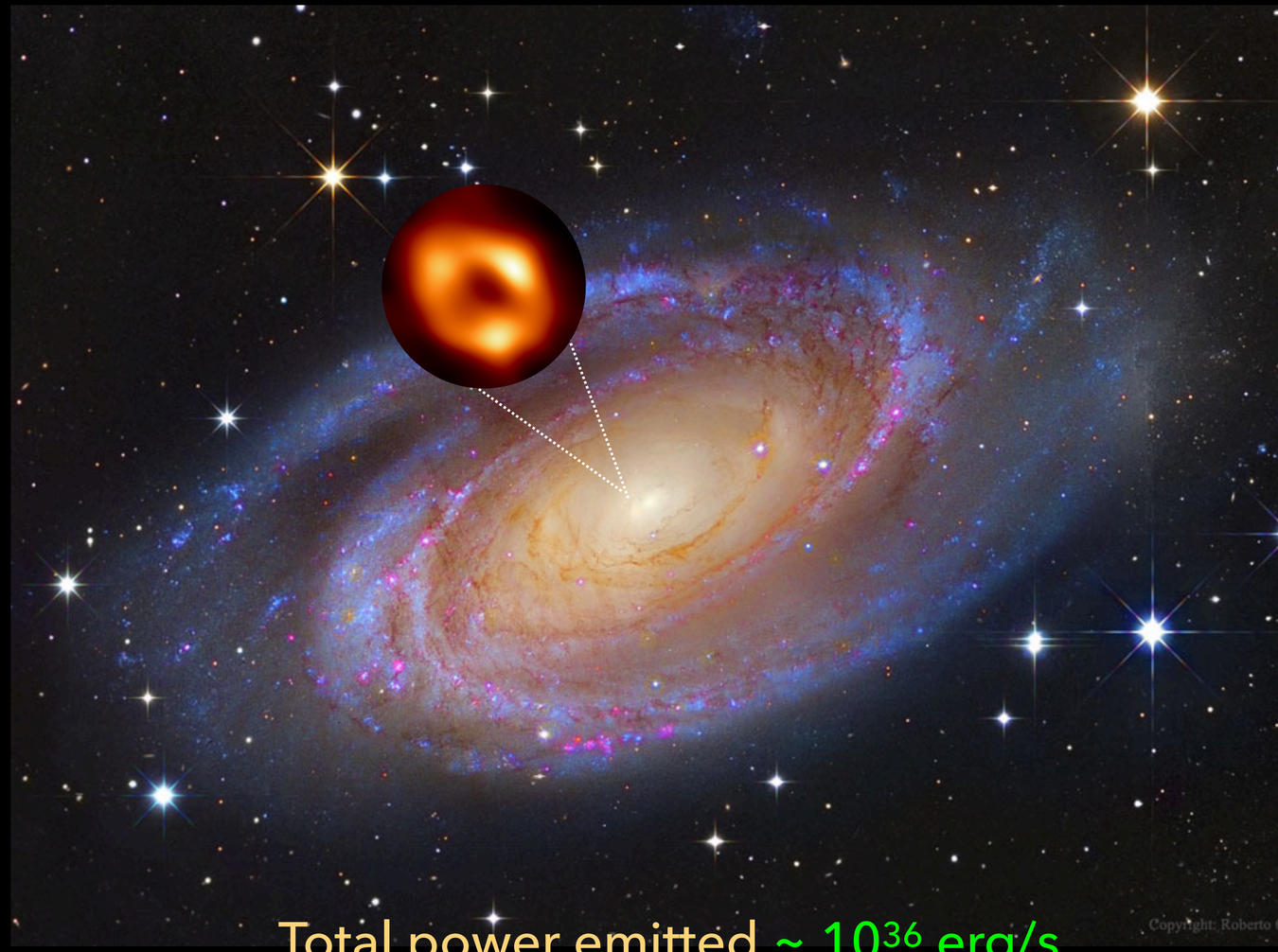
The EHT "horizon" sources embody two different BH/jet states

M87: Elliptical Galaxy, black hole mass ~6.5 billion times the sun's mass, launches a huge jet



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

M81: Spiral Galaxy (proxy for Milky Way): Sgr A*'s mass is ~4 million times the sun's mass, and has no (obvious) jet

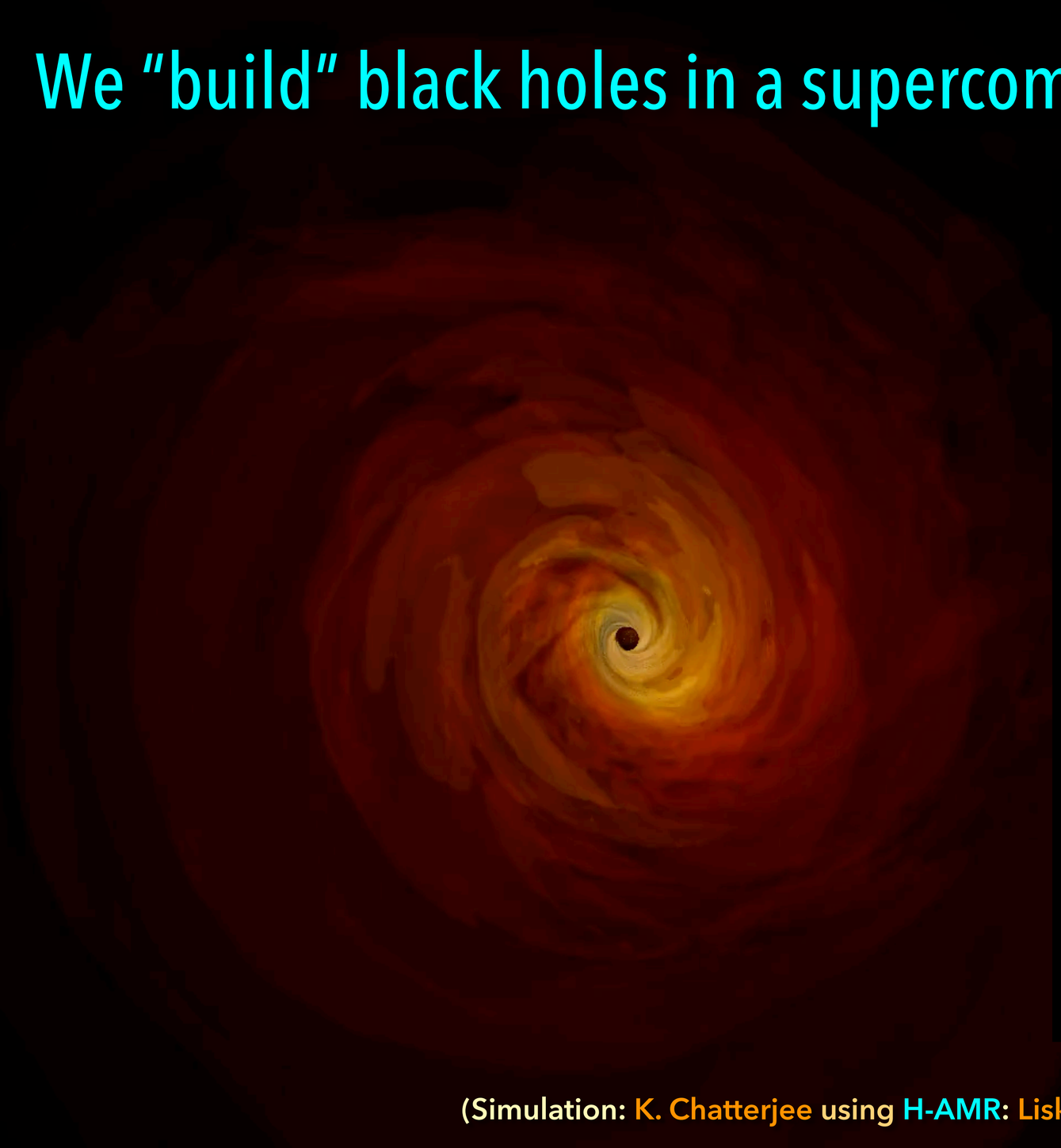


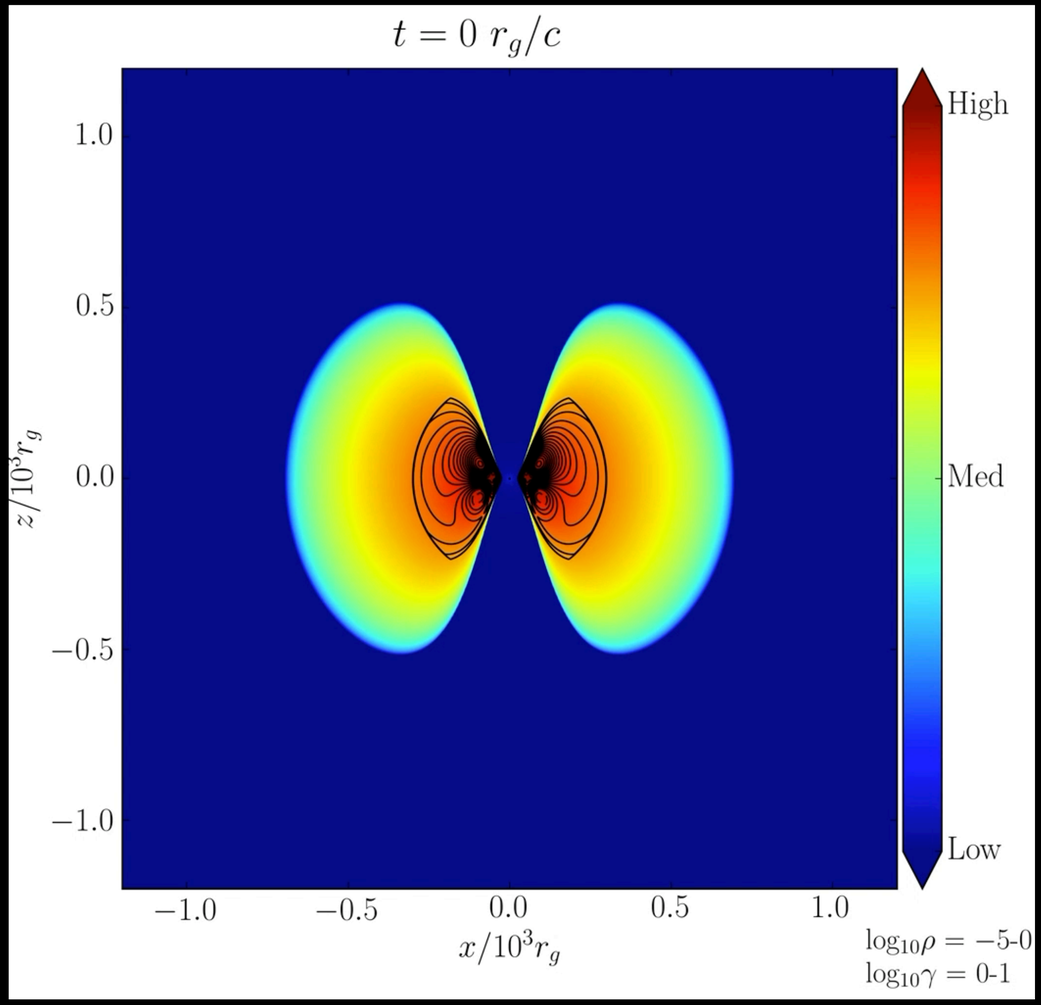
Total power emitted ~ 10^{36} erg/s

M87 is the ideal source to explore particle acceleration

- Nearby LLAGN/FRI with a huge jet, known to be a steady VHE γ-ray emitter (*last big flare in 2010, but flared in 2018 during our EHT campaign!*)
- One of EHT's main targets so we can try to link questions of particle acceleration to jet/accretion properties we can probe via direct imaging (*Spring 2026: the first real-time monitoring!*)
- We coordinate (via the EHT MWL Science WG) simultaneous multi-wavelength coverage including VHE γ-rays during our annual campaigns
- Prototype to extend to other VHE/EHT sources: e.g., Cen A, BL Lac, Mrk501, 3C273/3C279, OJ287, etc. (see Sasikumar, Nagar++ ETHER Gold sample) ➠ *increasing focus on EHT AGN science!*
- Help develop strategy for CTAO AGN KSP, which involves MWL monitoring

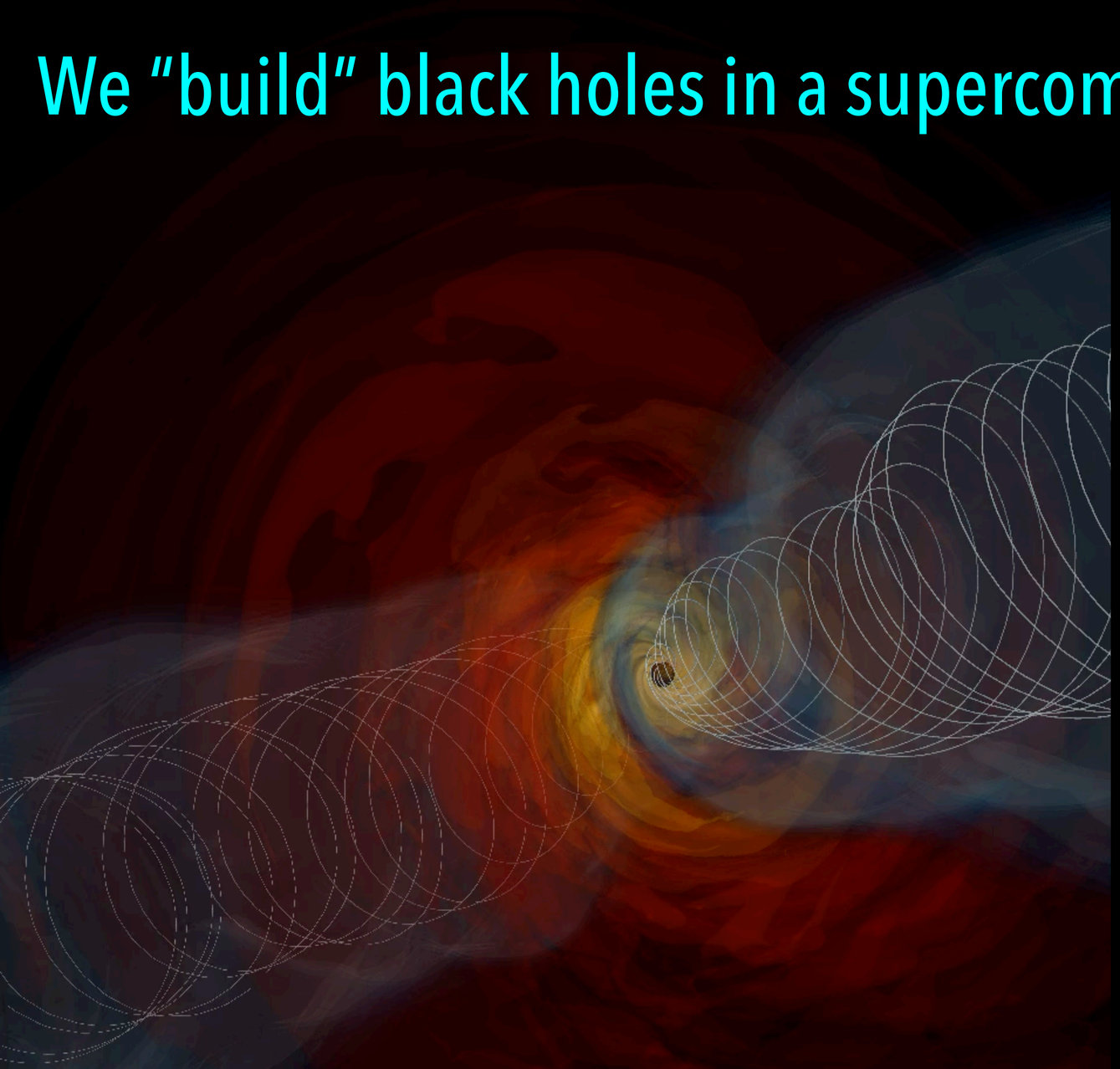
We “build” black holes in a supercomputer to model/interpret our data

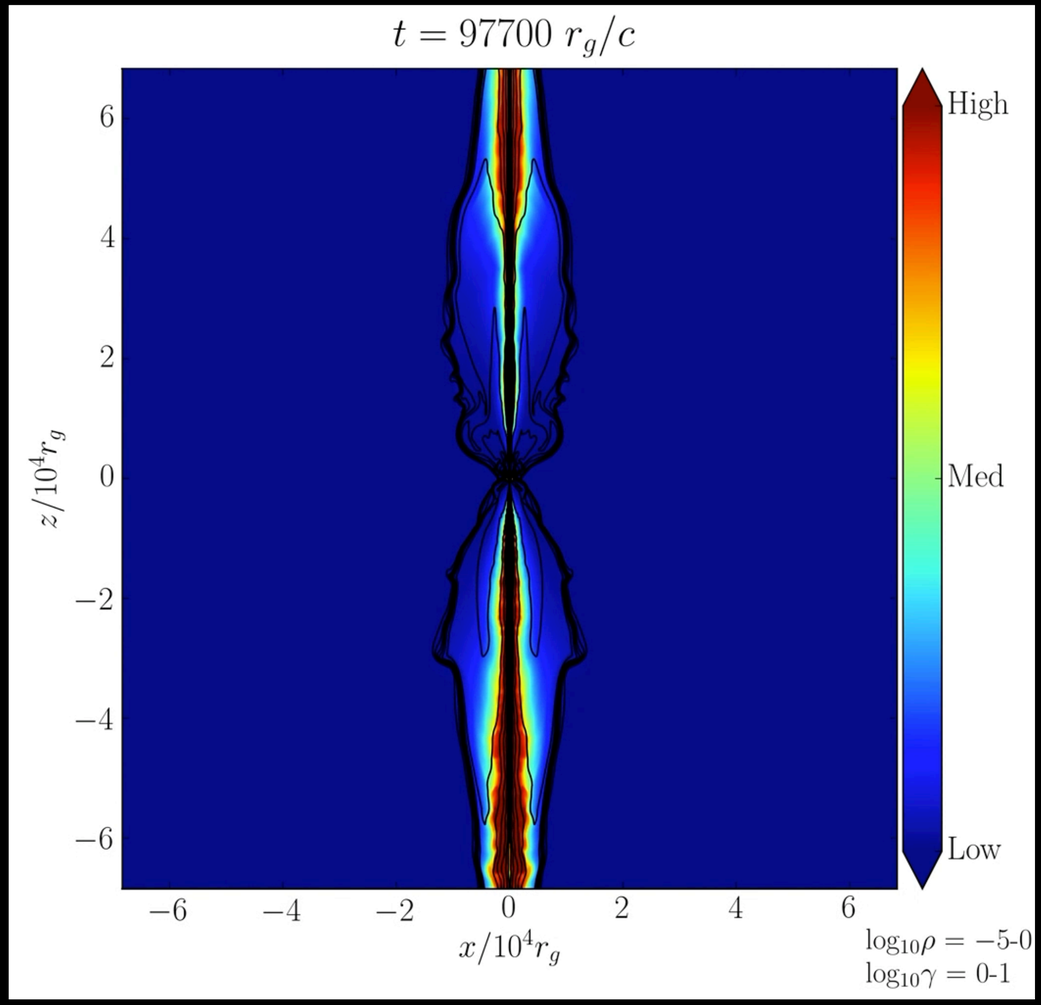




(Simulation: K. Chatterjee using H-AMR: Liska, Chatterjee, Tchekhovskoy++ 2022)

We “build” black holes in a supercomputer to model/interpret our data

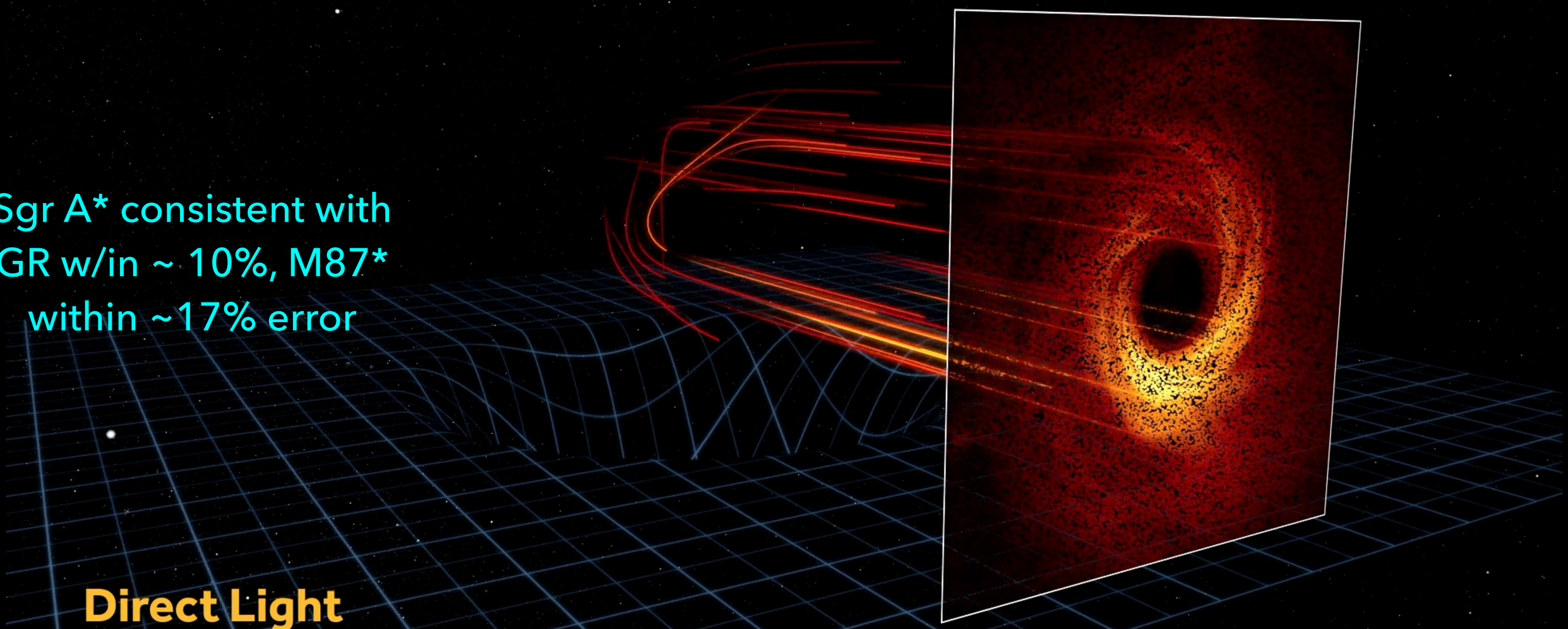




(Simulation: K. Chatterjee using H-AMR: Liska, Chatterjee, Tchekhovskoy++ 2022)

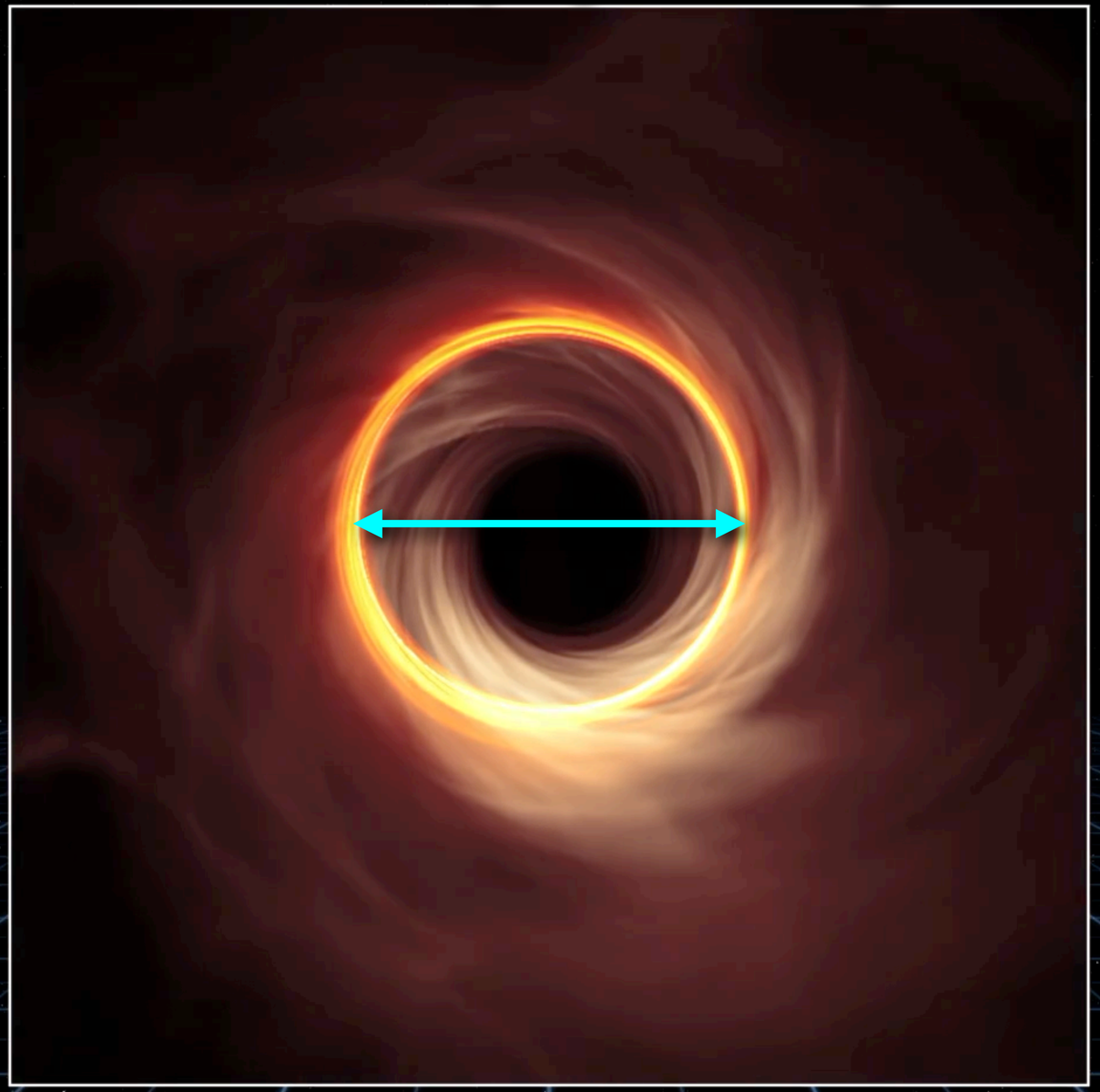
Image comprised of astrophysics + gravitational effects

Sgr A* consistent with GR w/in ~ 10%, M87* within ~17% error



Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen ‘73; Chandrasekhar ‘83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc…, For degeneracies see EHT Collaboration Paper V 2019

Image comprised of astrophysics + gravitational effects



Sgr A* consistent with GR w/in ~ 10%, M87* within ~17% error

Physics of General Relativity predicts: "Photon ring" ~5x bigger than the event horizon

Exact shape and size of the photon ring tells us about the nature of spacetime!

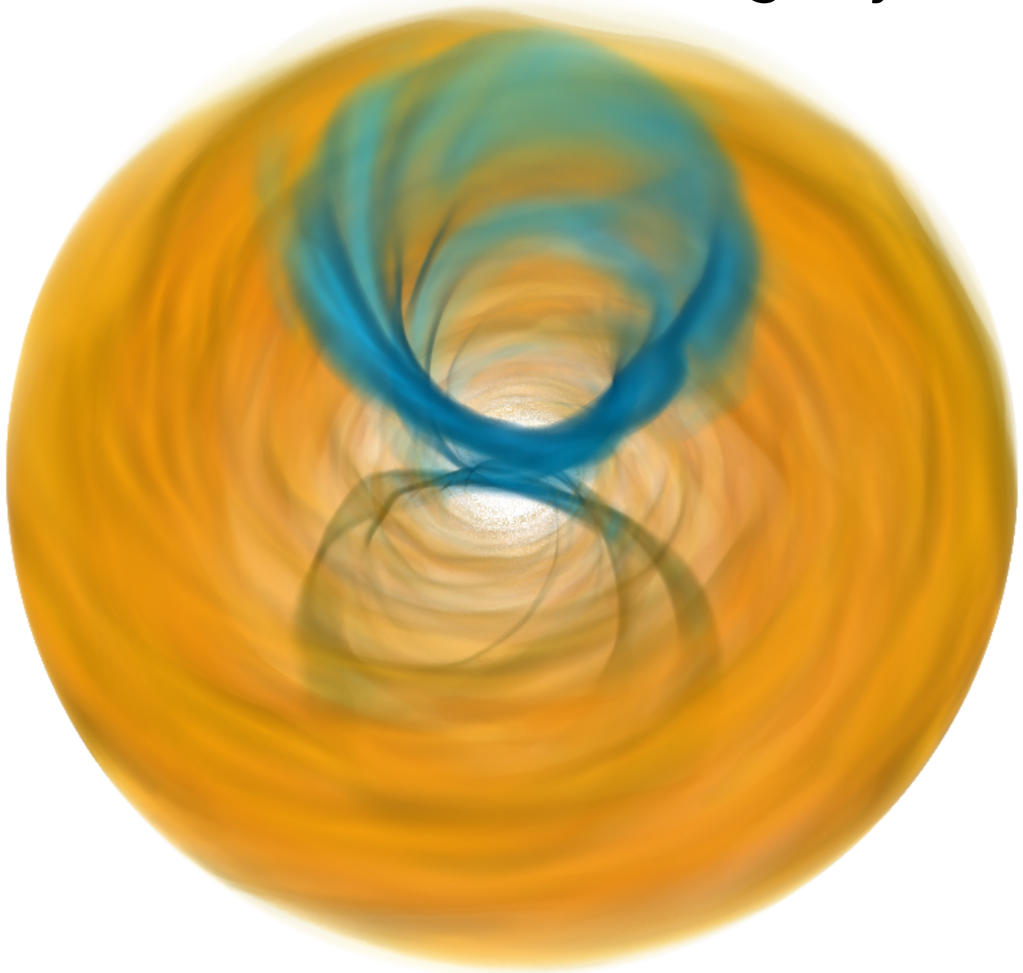
Orbiting Light

Direct Light

Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen '73; Chandrasekhar '83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc…, For degeneracies see EHT Collaboration Paper V 2019

Model degeneracy introduced via radiating electrons

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



Single particle fluid ➠ protons

Assume 100% H (n_e=n_p)

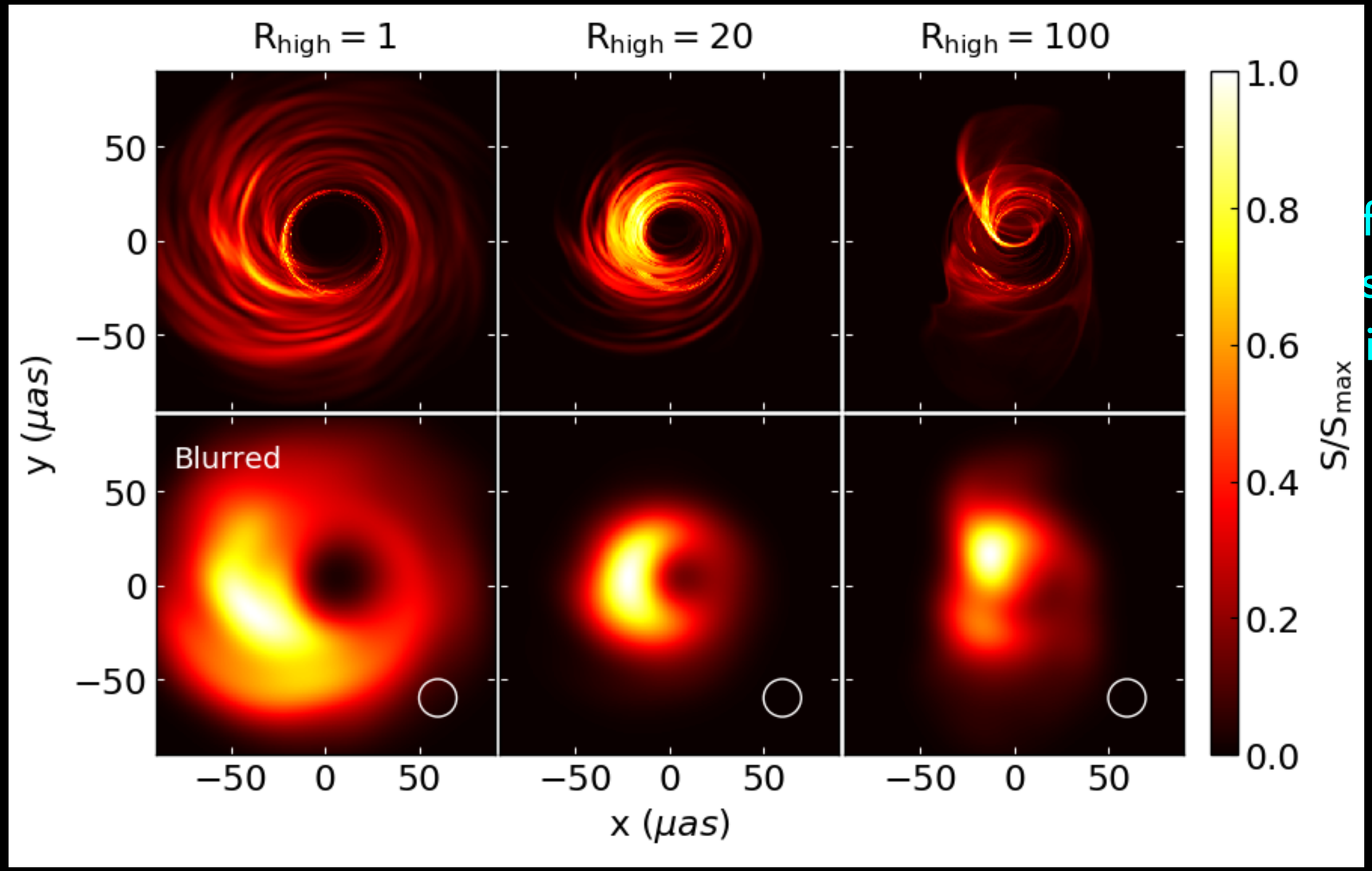
Heat electrons, example: from Moscibrodzka++2016 based on PIC models for turbulent heating

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

Where β = P_{gas}/P_{mag}

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

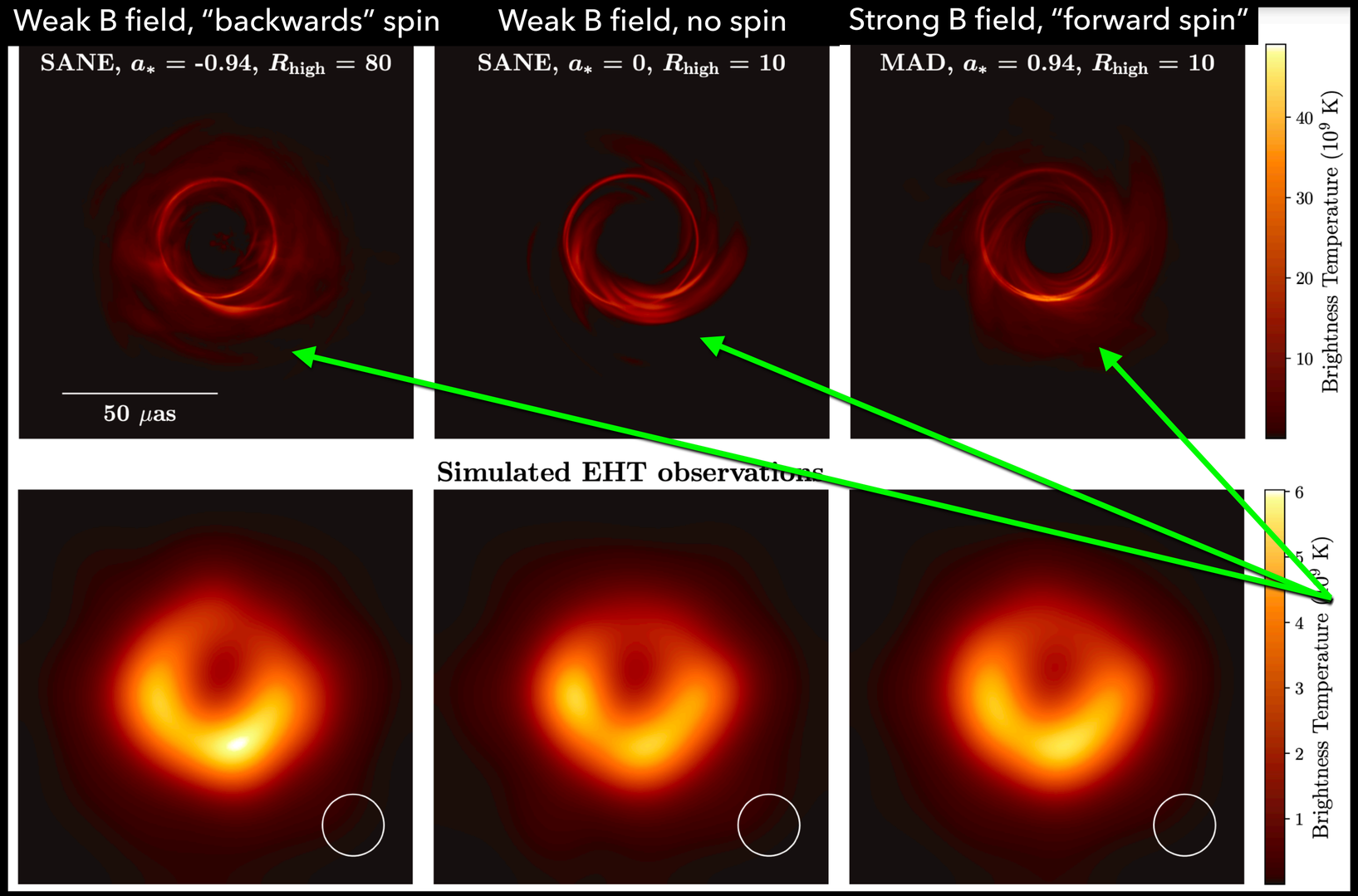
Model degeneracy introduced via radiating electrons

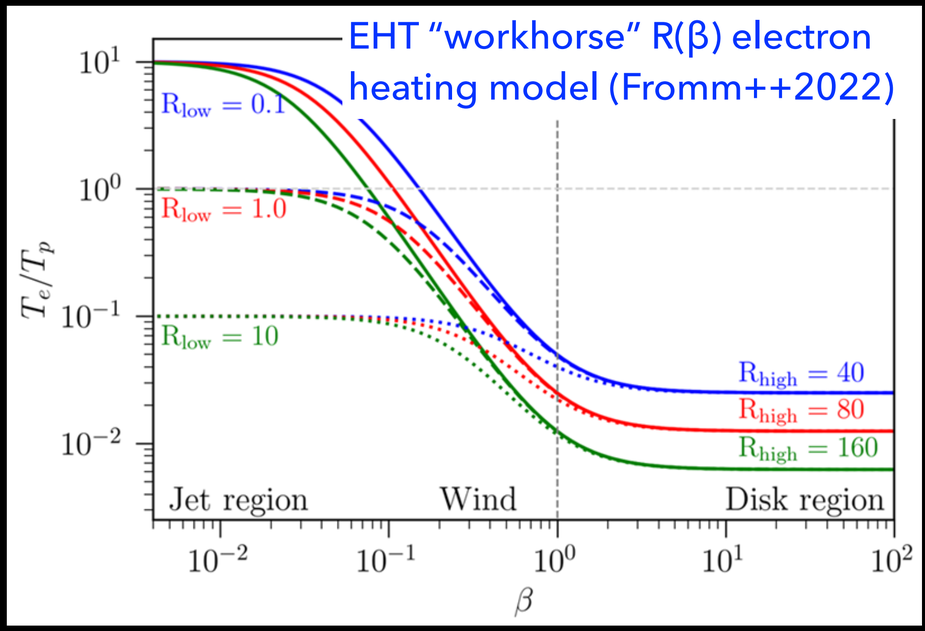


from
sed on PIC
ing

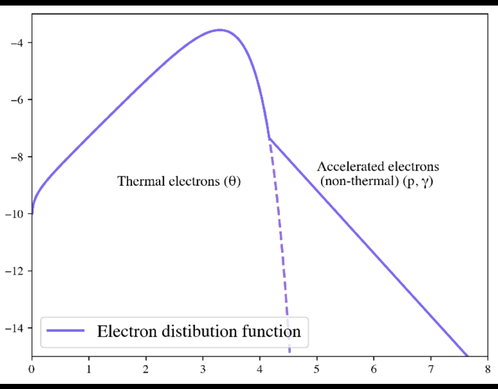
Visualisations by DooSoo Yoon w/H-AMR & GRRT/BHOSS (Younsi++2016; 2020) and see EHT Collaboration 2019 Papers I-VI

The biggest uncertainty for testing GR is the particle physics





Differences in the pattern of direct light depend on a mix of geometry and the *particle acceleration model*



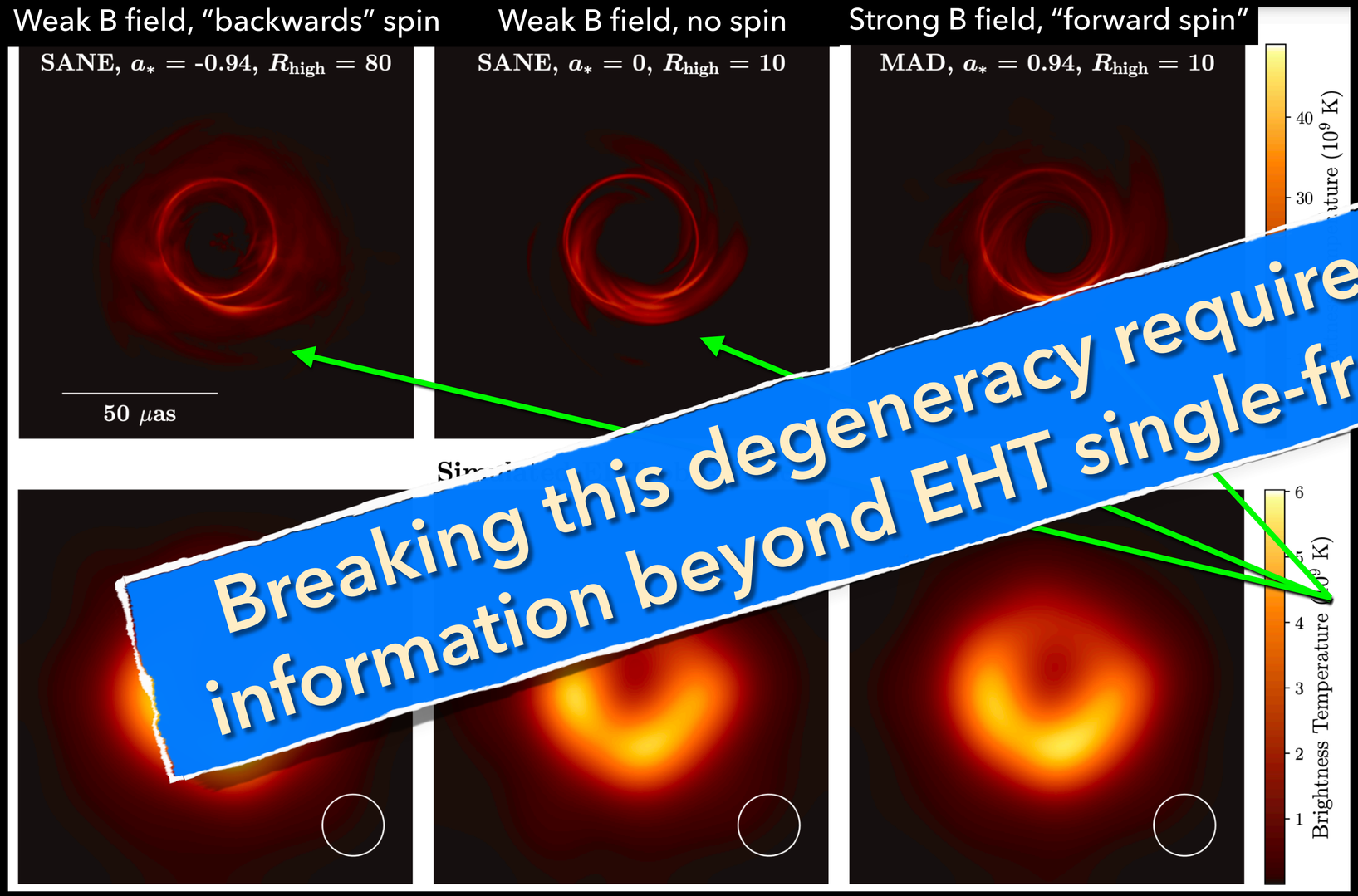
Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen '73; Chandrasekhar '83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc…, For degeneracies see EHT Collaboration Paper V 2019

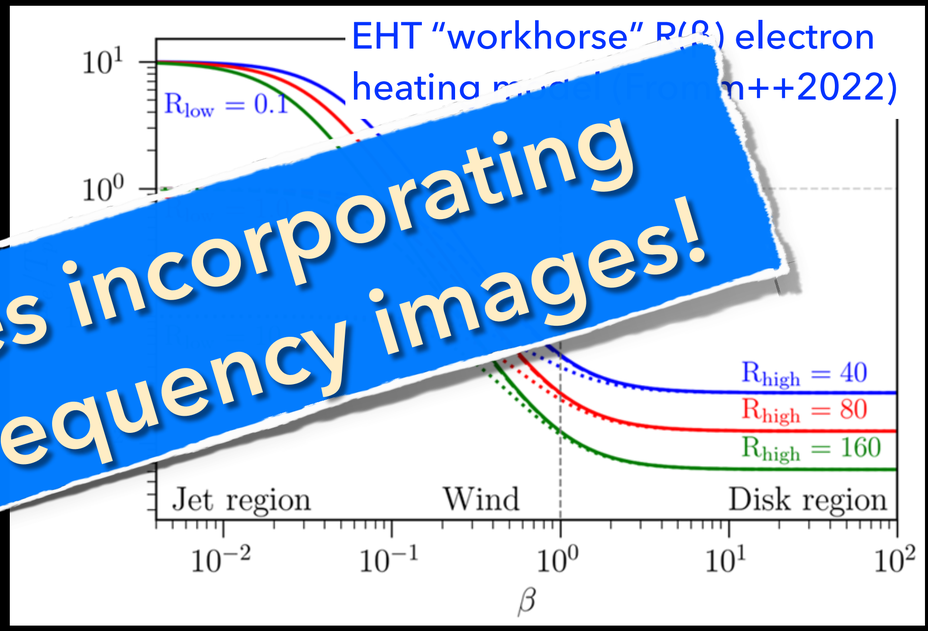
The biggest uncertainty for testing GR is the particle physics

Weak B field, "backwards" spin

Weak B field, no spin

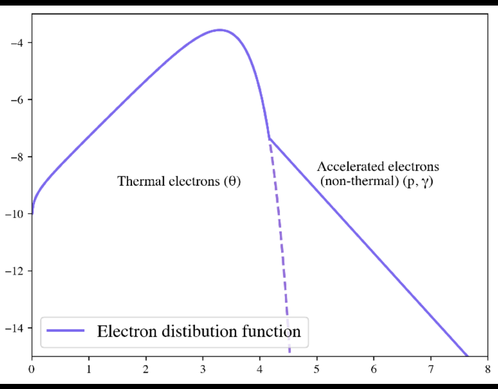
Strong B field, "forward spin"





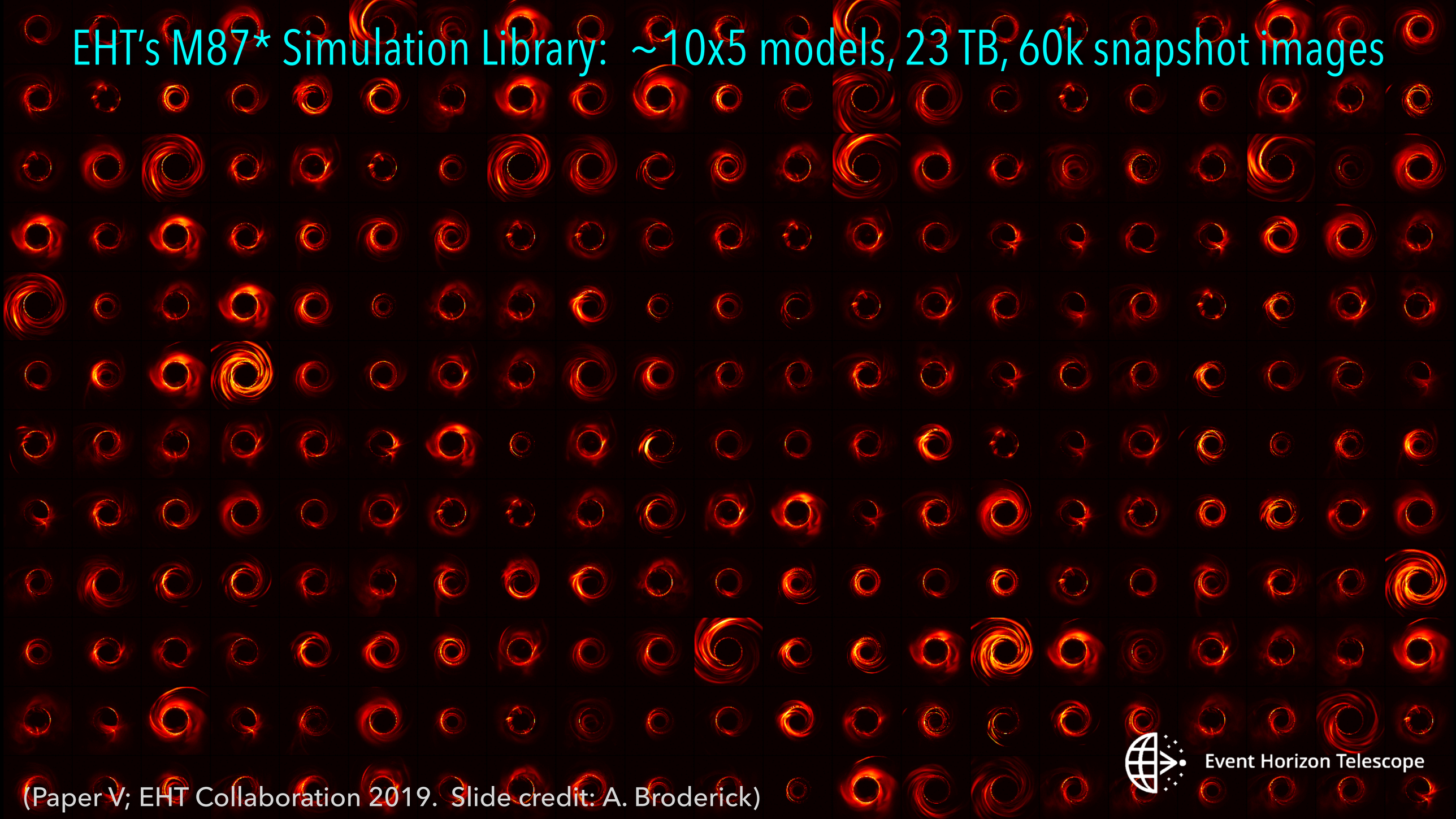
Breaking this degeneracy requires incorporating information beyond EHT single-frequency images!

Differences in the pattern of direct light depend on a mix of geometry and the *particle acceleration model*



Visualisation: M. Johnson & G. Wong/SAO/Crazybridge Studios. See also e.g., Hilbert 1916; von Laue 1920; Bardeen '73; Chandrasekhar '83; Johannsen & Psaltis 2010; Gralla++2019, Johnson++2020; etc…, For degeneracies see EHT Collaboration Paper V 2019

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

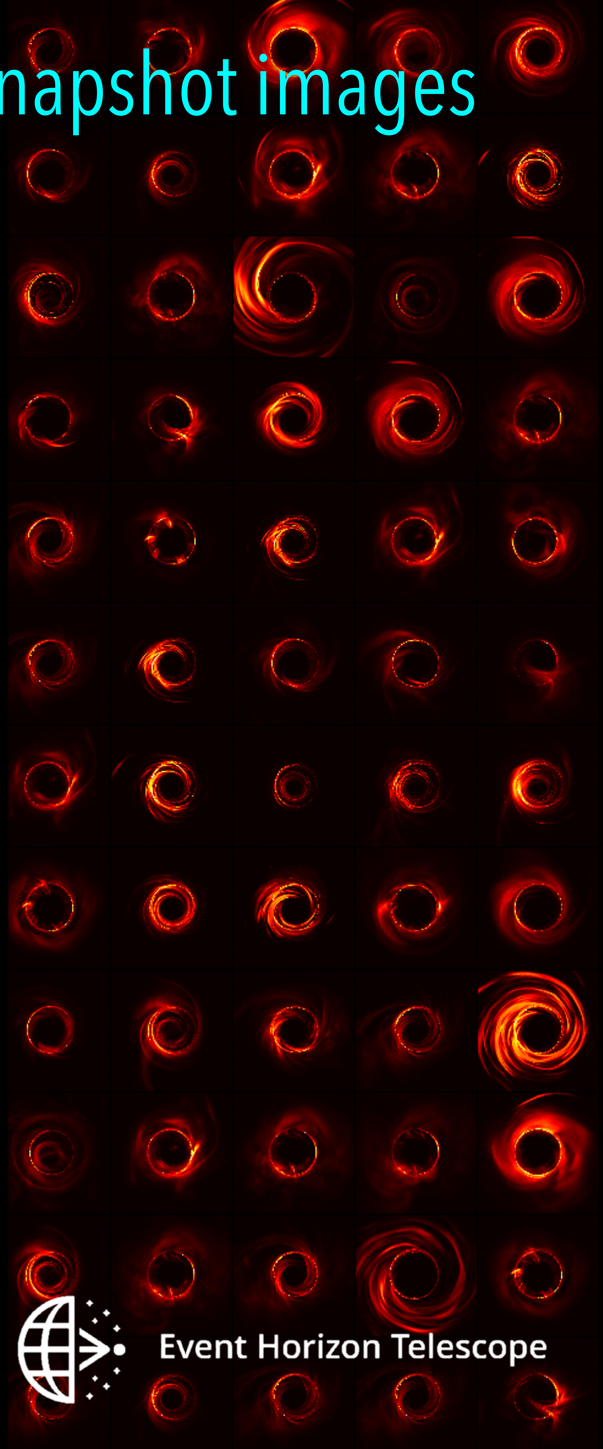


(Paper V; EHT Collaboration 2019. Slide credit: A. Broderick)

Event Horizon Telescope

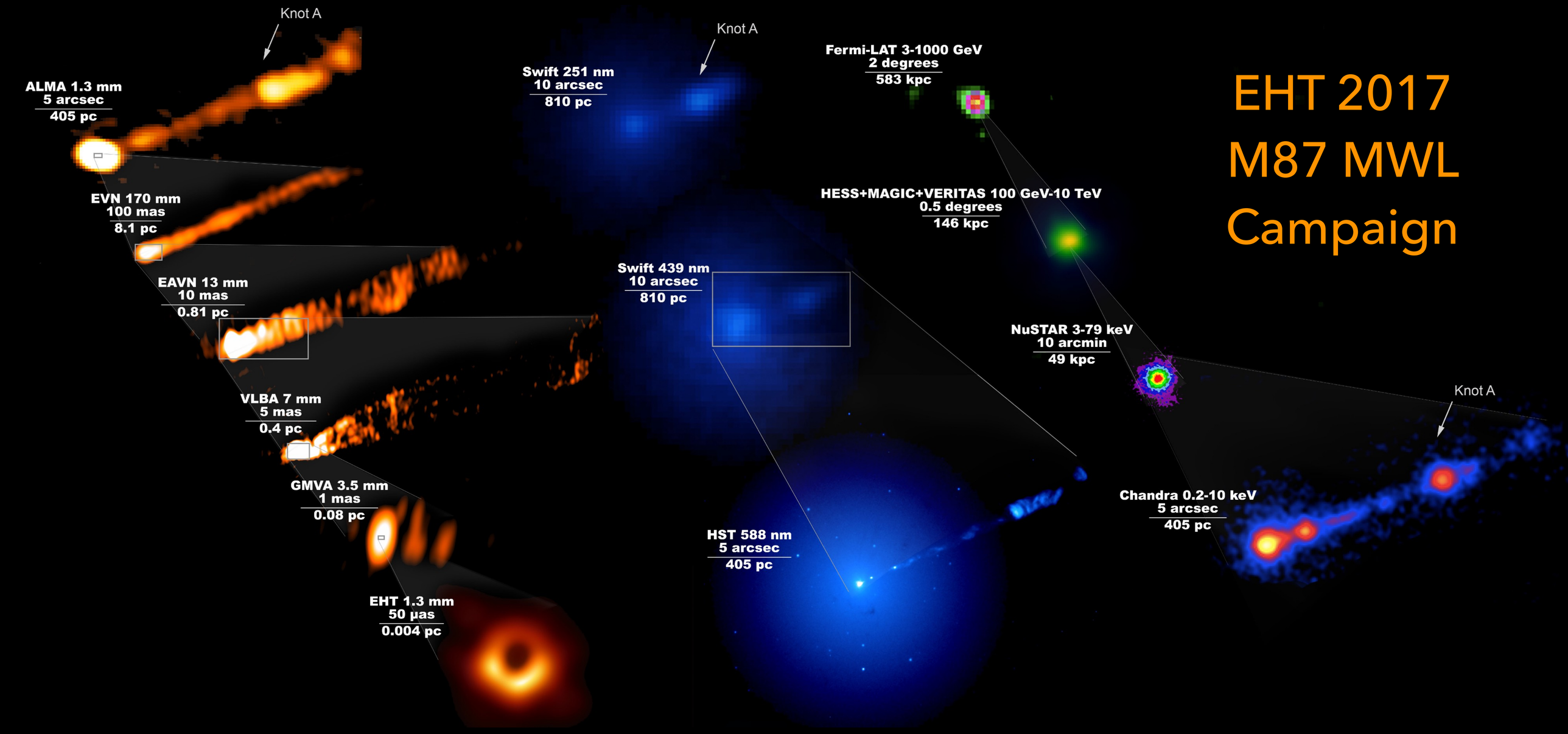
EHT's M87* Simulation Library: ~10x5 models, 23 TB, 60k snapshot images

- Matching just the size/shape and minimum jet power (from MWL), only rules out ~60% of models
- Polarisation in 2017 (EHTC 2021) prefers "MAD": dynamically strong, ordered, poloidal B fields
  ➠ ideal for launching jets!
- BUT, these projects only accounted for thermal particles (no particle acceleration), so many of the models will need to be revisited with more sophisticated treatments



Event Horizon Telescope

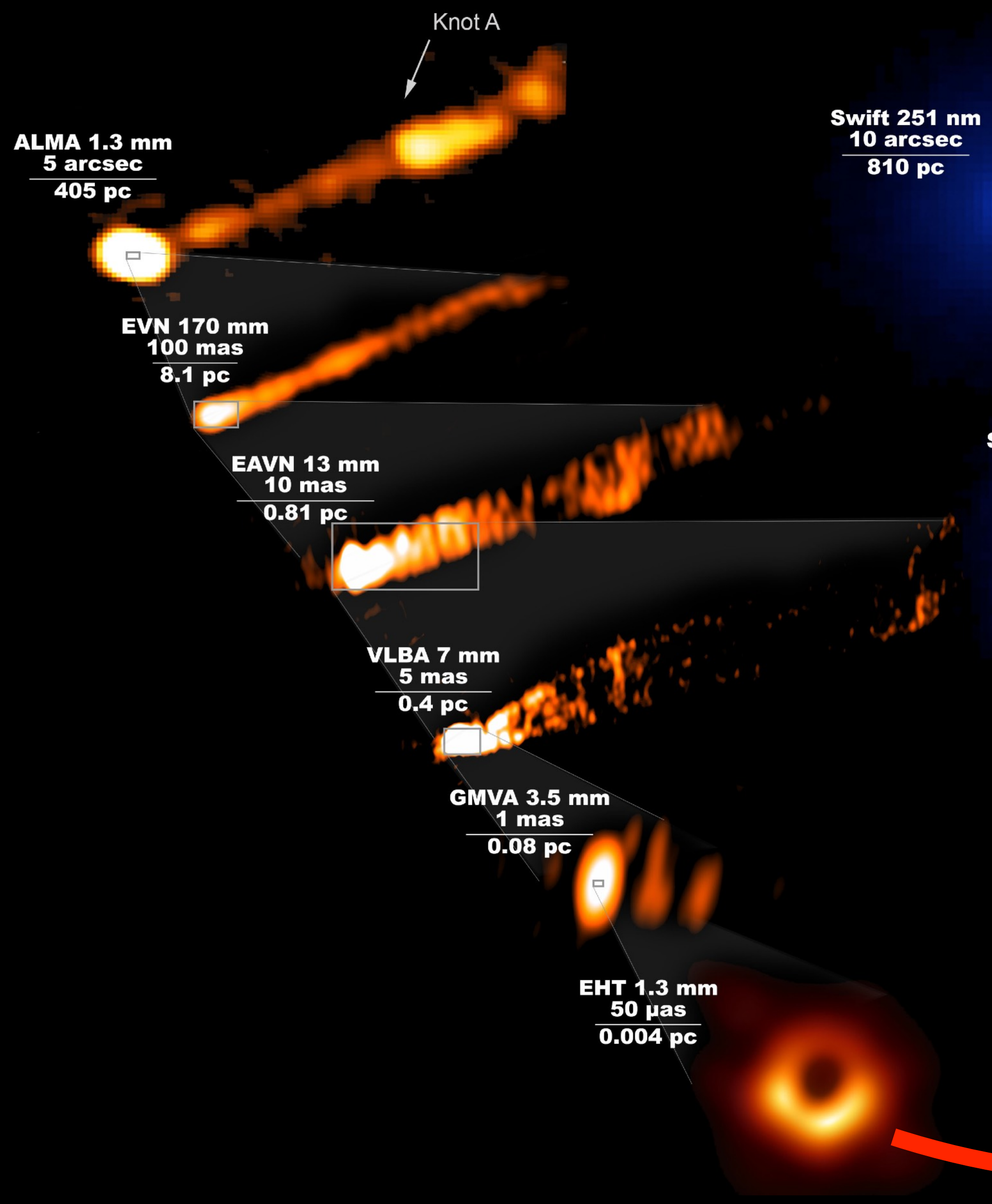
Models need to explain not only images but also MWL spectra

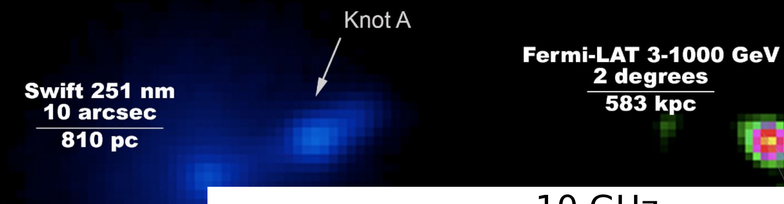


EHT 2017
M87 MWL
Campaign

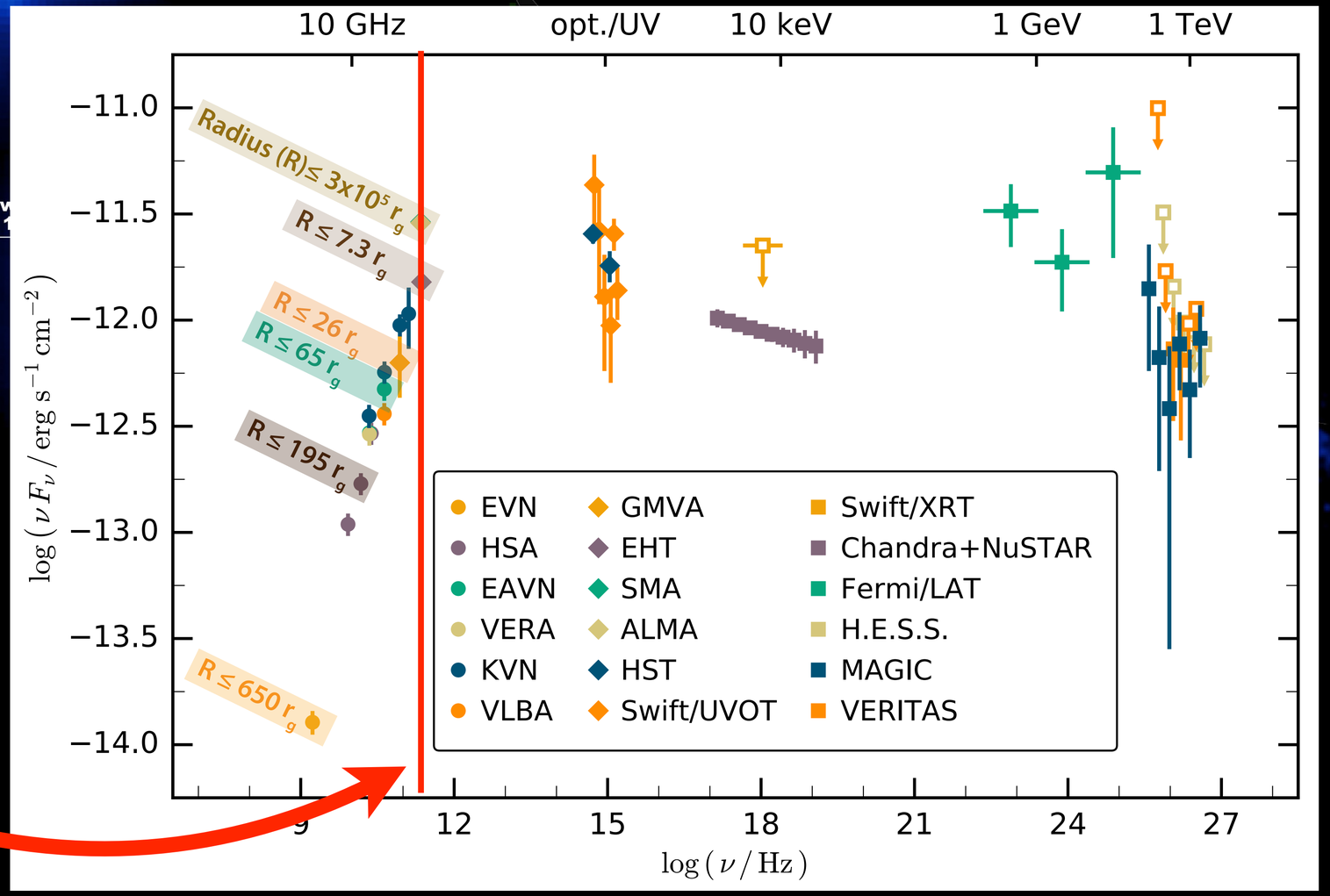
(EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN++ 2021, ApJL)

Models need to explain not only images but also MWL spectra



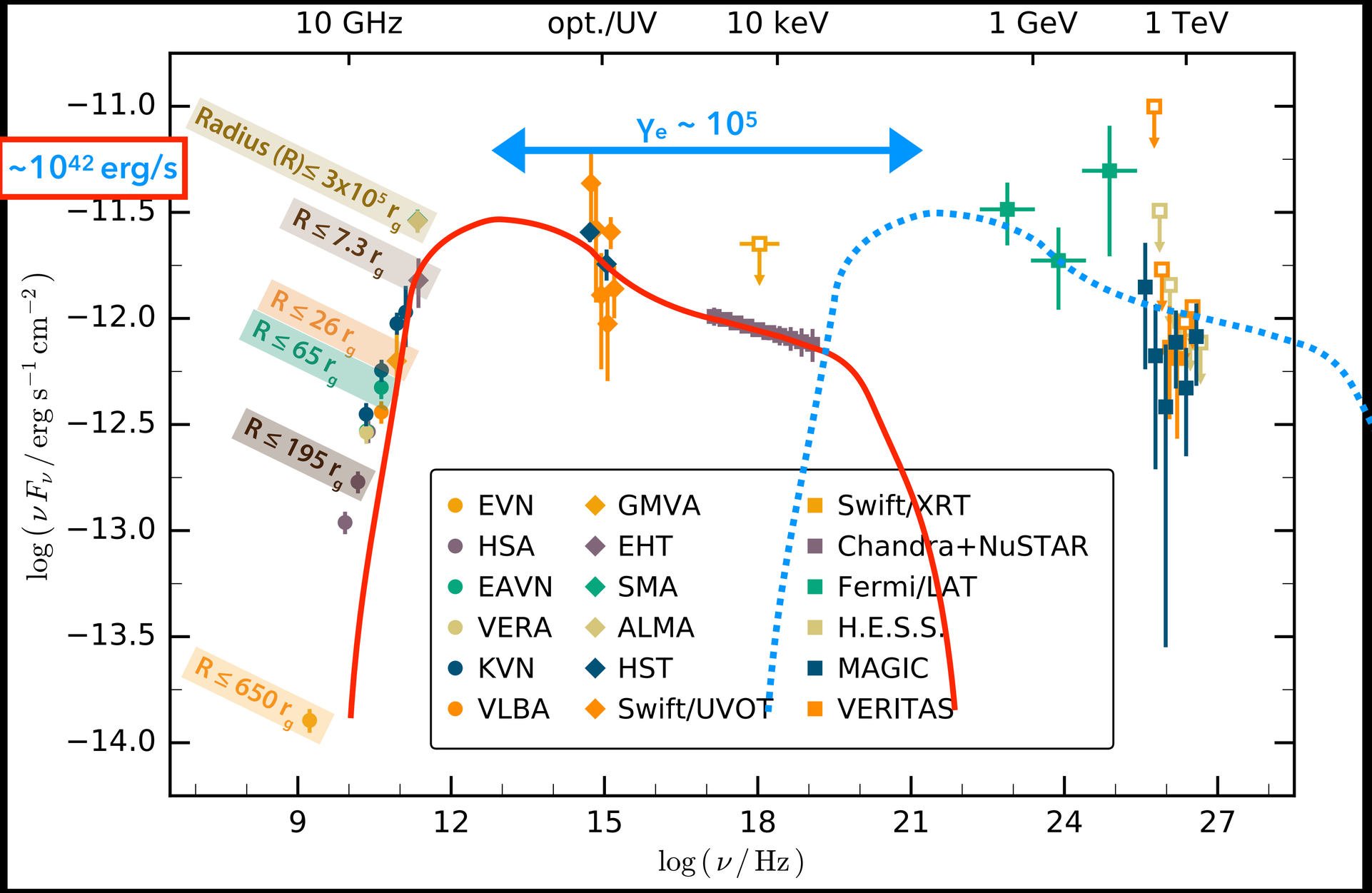


EHT 2017



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

"Golden constraint SED" for M87's astrophysical output in 2017



- SSA break above 86 GHz (core shift) restricts B>mG
- $\tau_{sc} = n\sigma_T R \sim 1$ gives $n > 10^8$ /cm^3, way too big to reconcile with synchrotron!
- If pack 10^{42} erg/s TeV gamma-rays into max $7r_g$, interaction with 10^{41} erg/s optical gives $\tau_{\gamma\gamma}$ >3.5, or 97 % attenuation

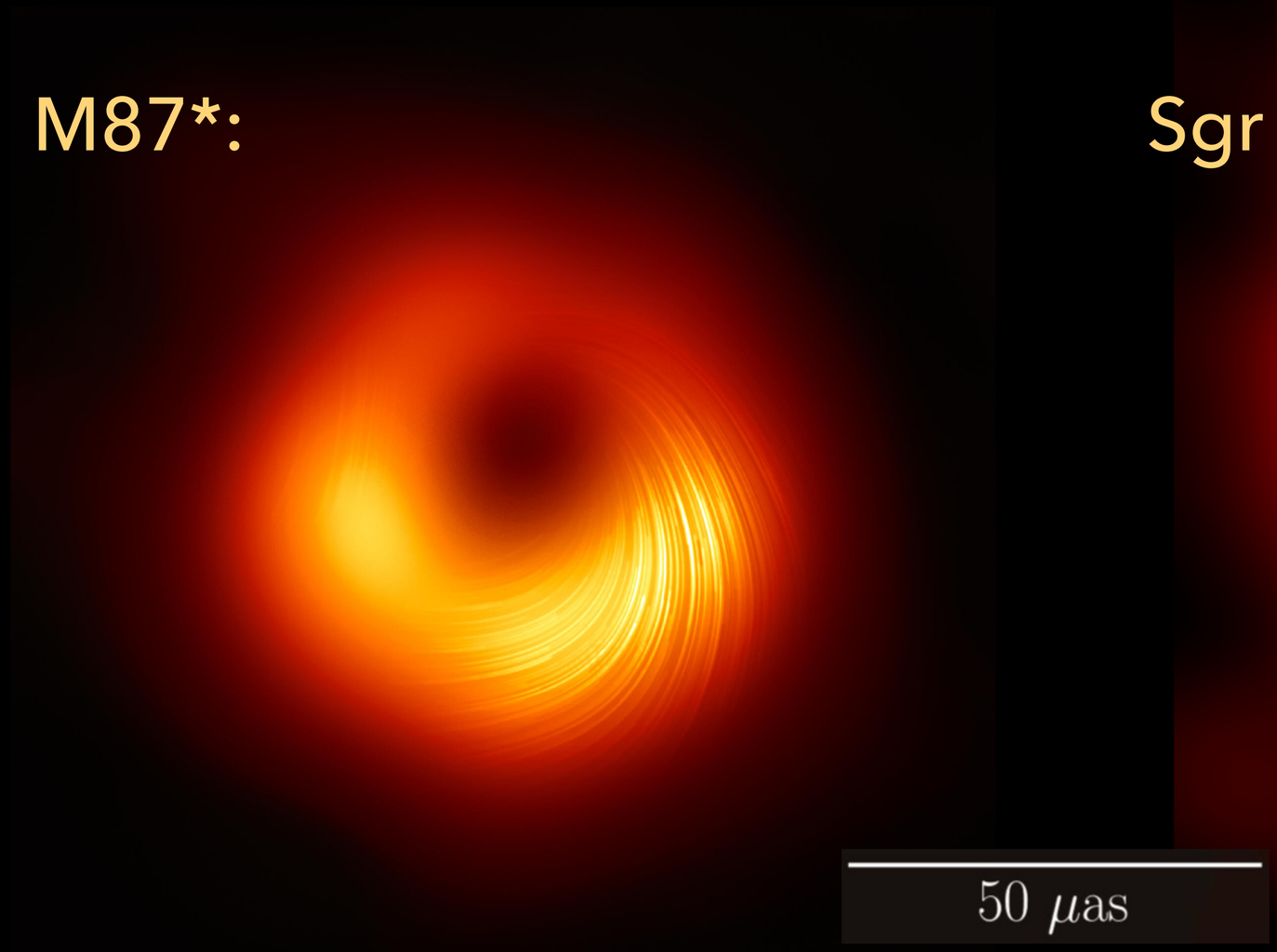
EHT Multiwavelength WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN, EAVN 2021, ApJL

Outline

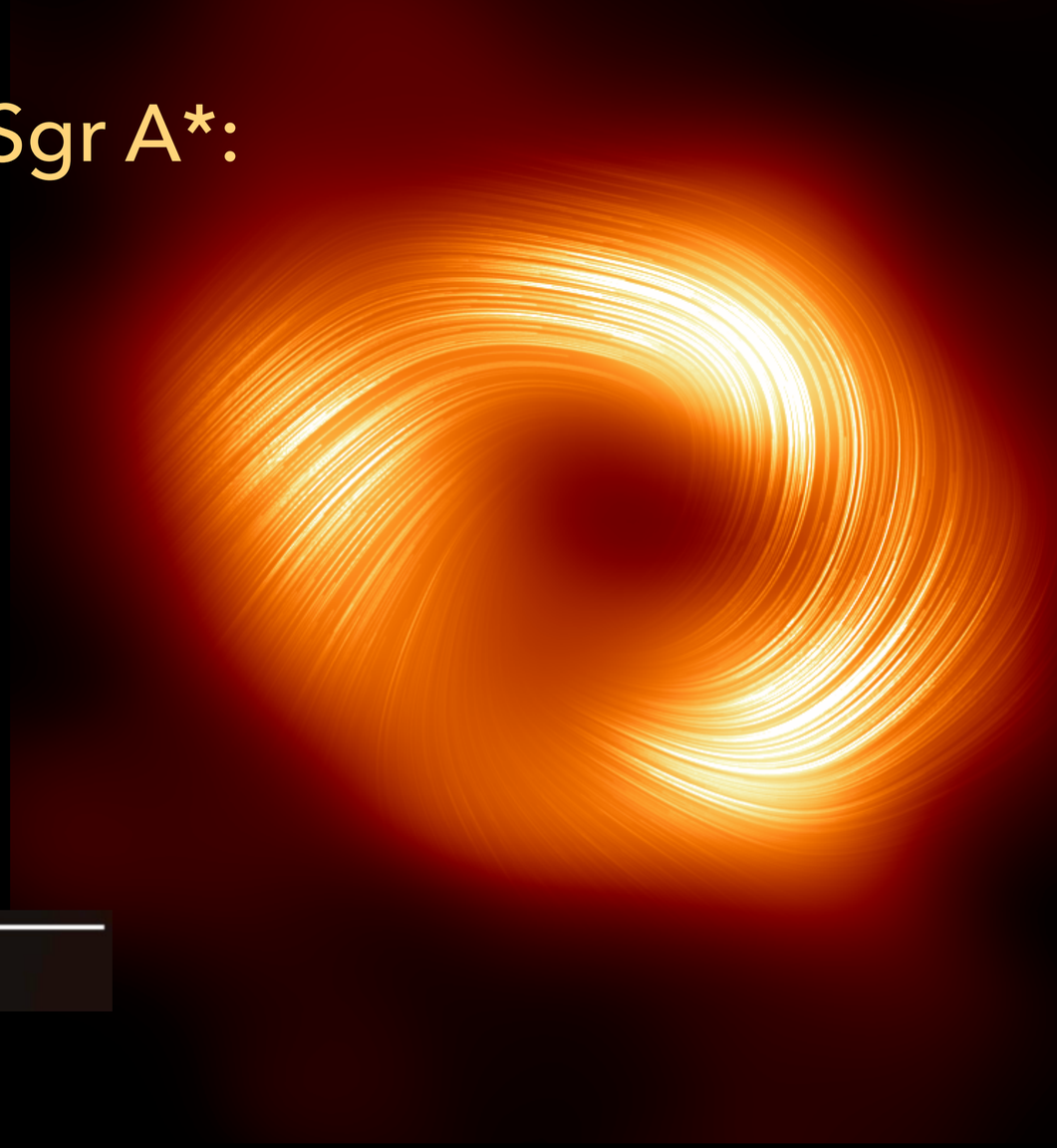
- ★ Black hole jets as particle accelerators and the search for the VHE emission region
- ★ The Event Horizon Telescope to date
- ★ Latest EHT/MWL results and implications
- ★ Near/far-term outlook

State of the art: images with polarisation (= magnetic fields)

M87*:



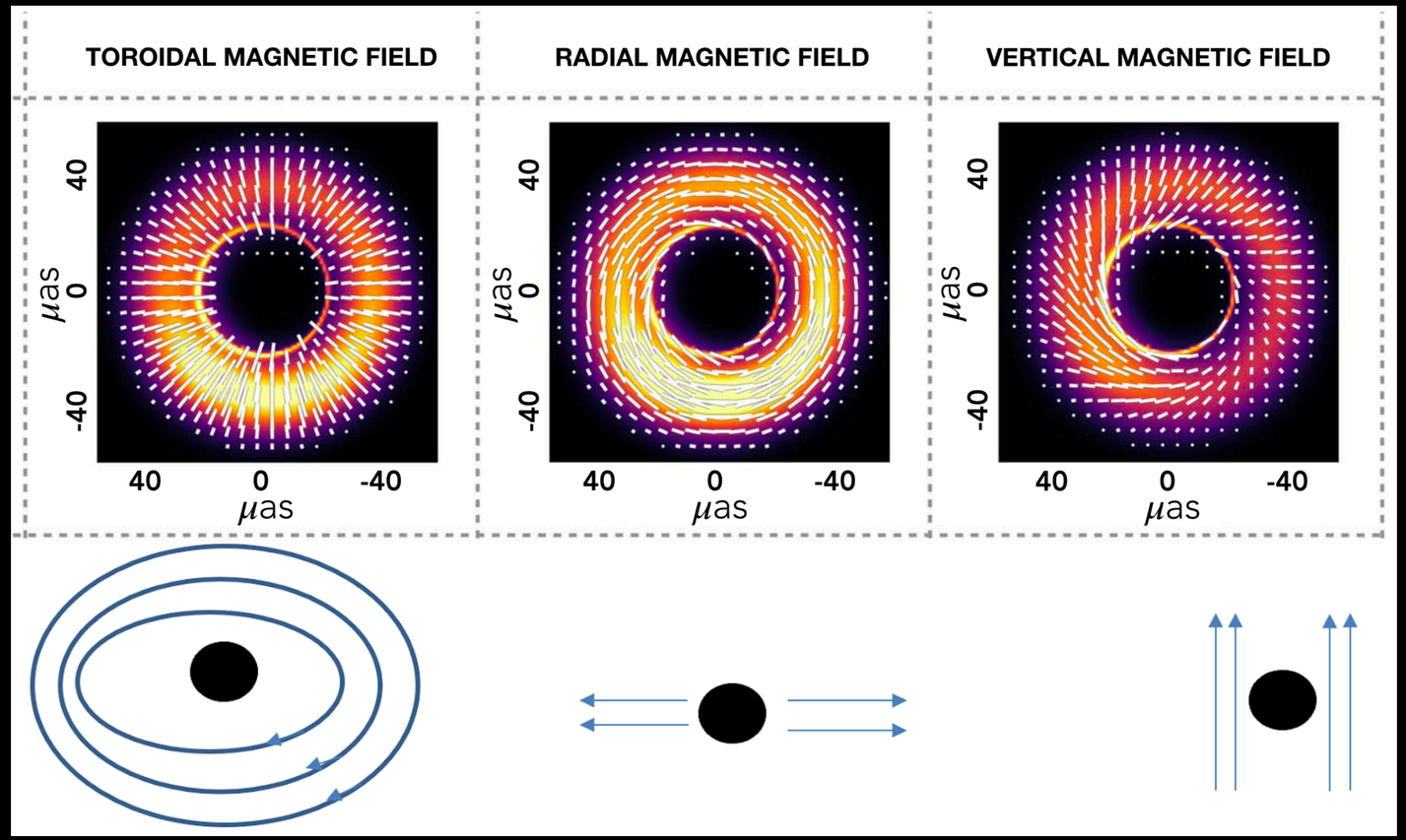
Sgr A*:

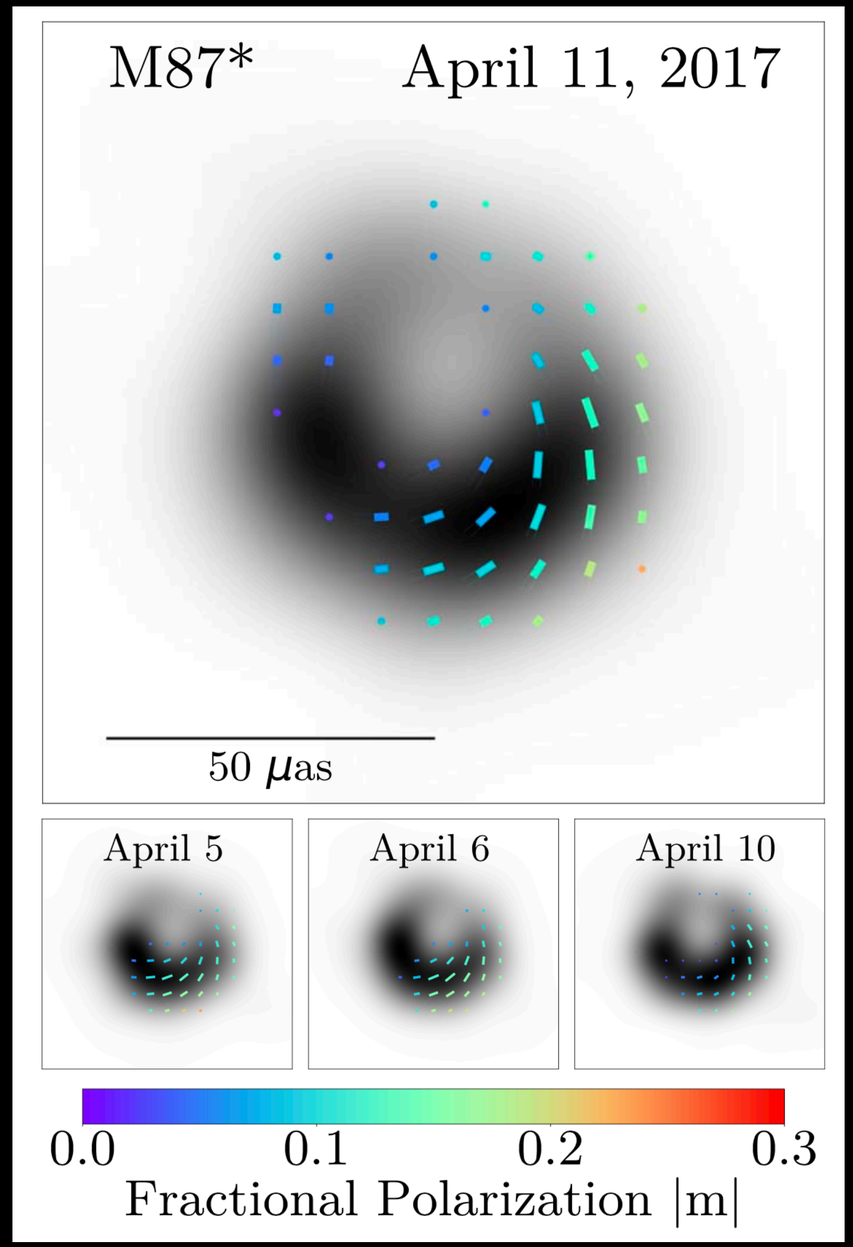


EHTC M87 Paper VII (2021); Sgr A* Paper VII (2024)

Polarisation imaging provides a much more powerful constraint

- "Twisting" polarization tick (EVPA) pattern
- linear polarization fraction ~10-20%, Faraday rot.
- $T_e \sim 10^{10\text{-}11}$ K, $n_e \sim 10^{4\text{-}7}$ cm^{-3}, B ~ 1-30 G

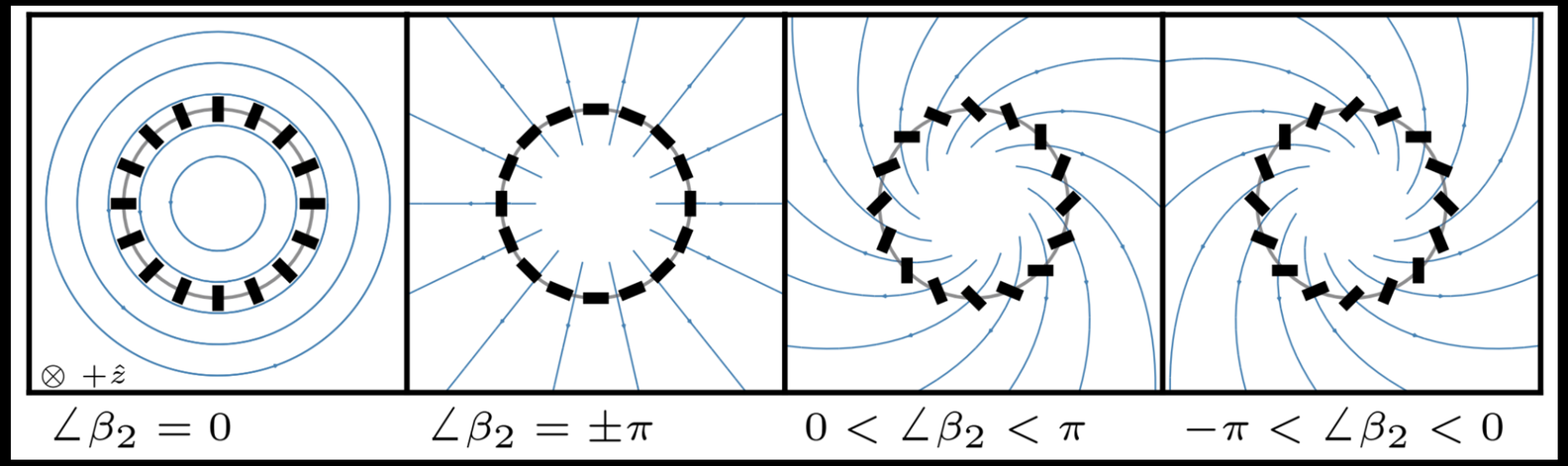


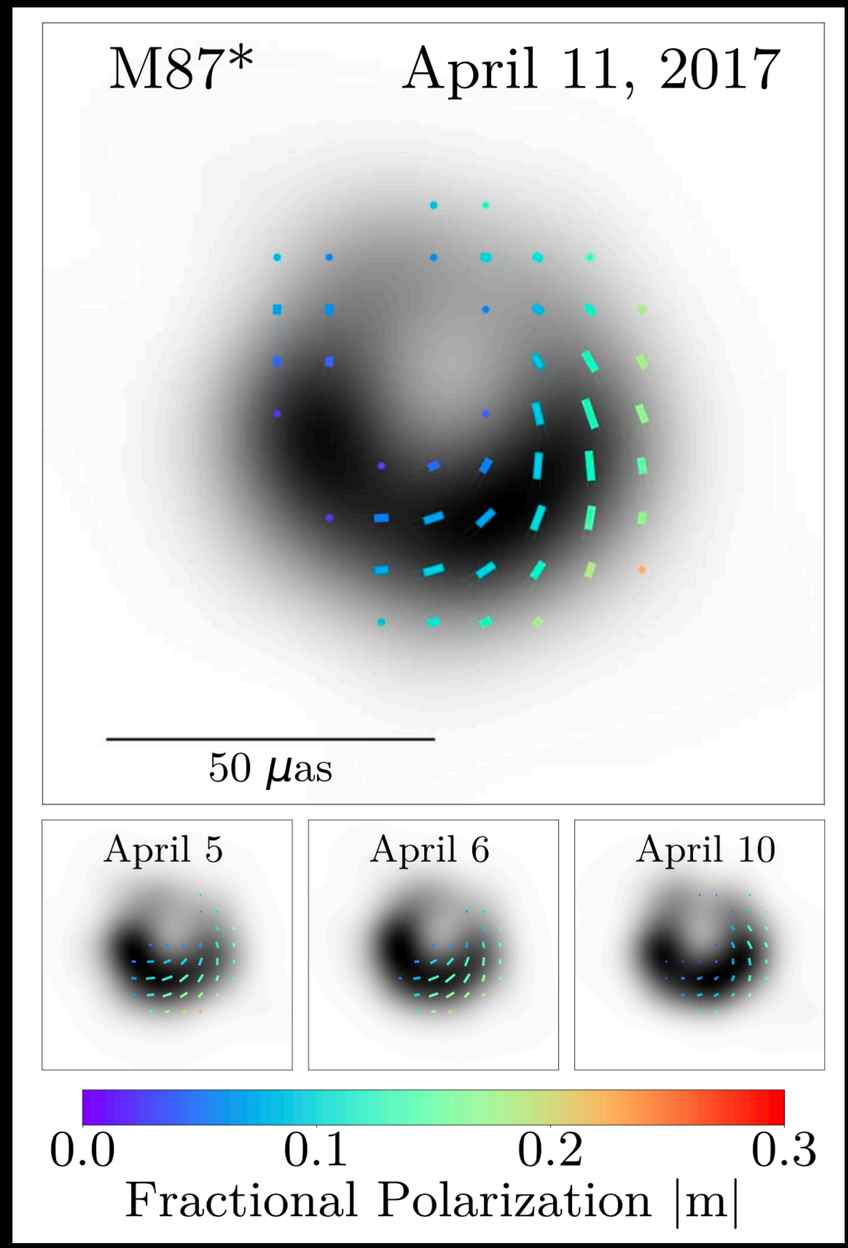


(M87* Polarisation Papers VII & VIII; EHT Collaboration 2021)

Polarisation imaging provides a much more powerful constraint

- "Twisting" polarization tick (EVPA) pattern
- linear polarization fraction ~10-20%, Faraday rot.
- $T_e \sim 10^{10\text{-}11}$ K, $n_e \sim 10^{4\text{-}7}$ cm^{-3}, B ~ 1-30 G
- EVPA helicity turns out to be a major constraint

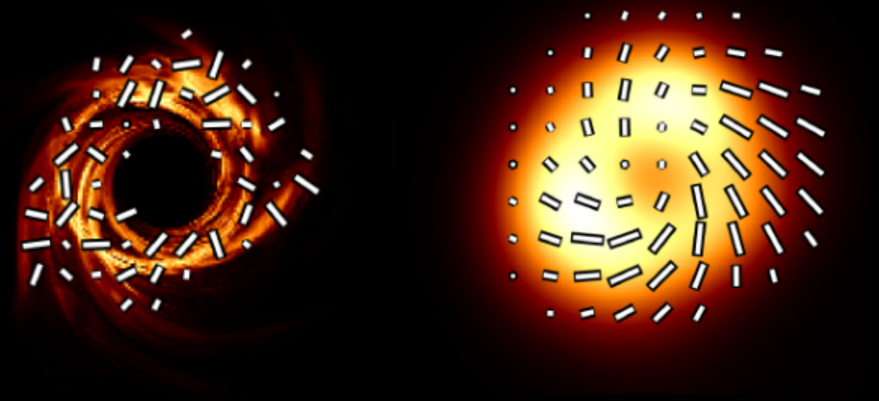




(M87* Polarisation Papers VII & VIII; EHT Collaboration 2021)

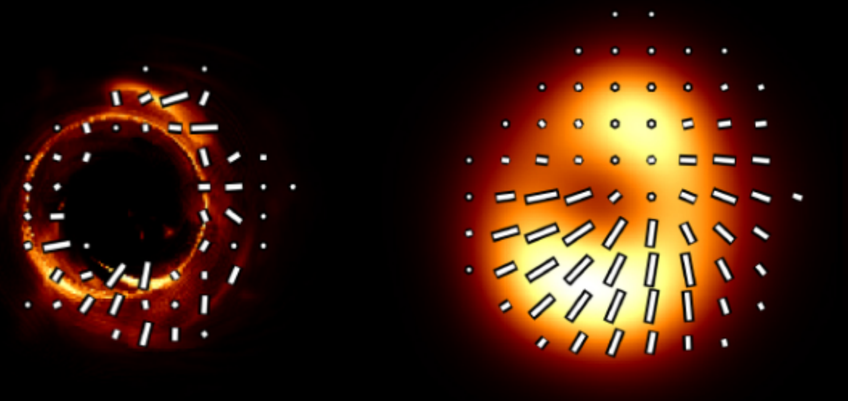
Polarisation can distinguish between accretion/magnetisation states

"MAD"



- Magnetically arrested disks
- High (saturated) magnetization near the horizon
- Strong polarization (vertical fields)

"SANE"

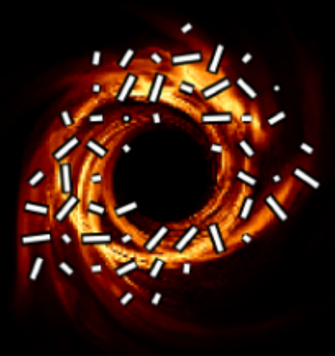


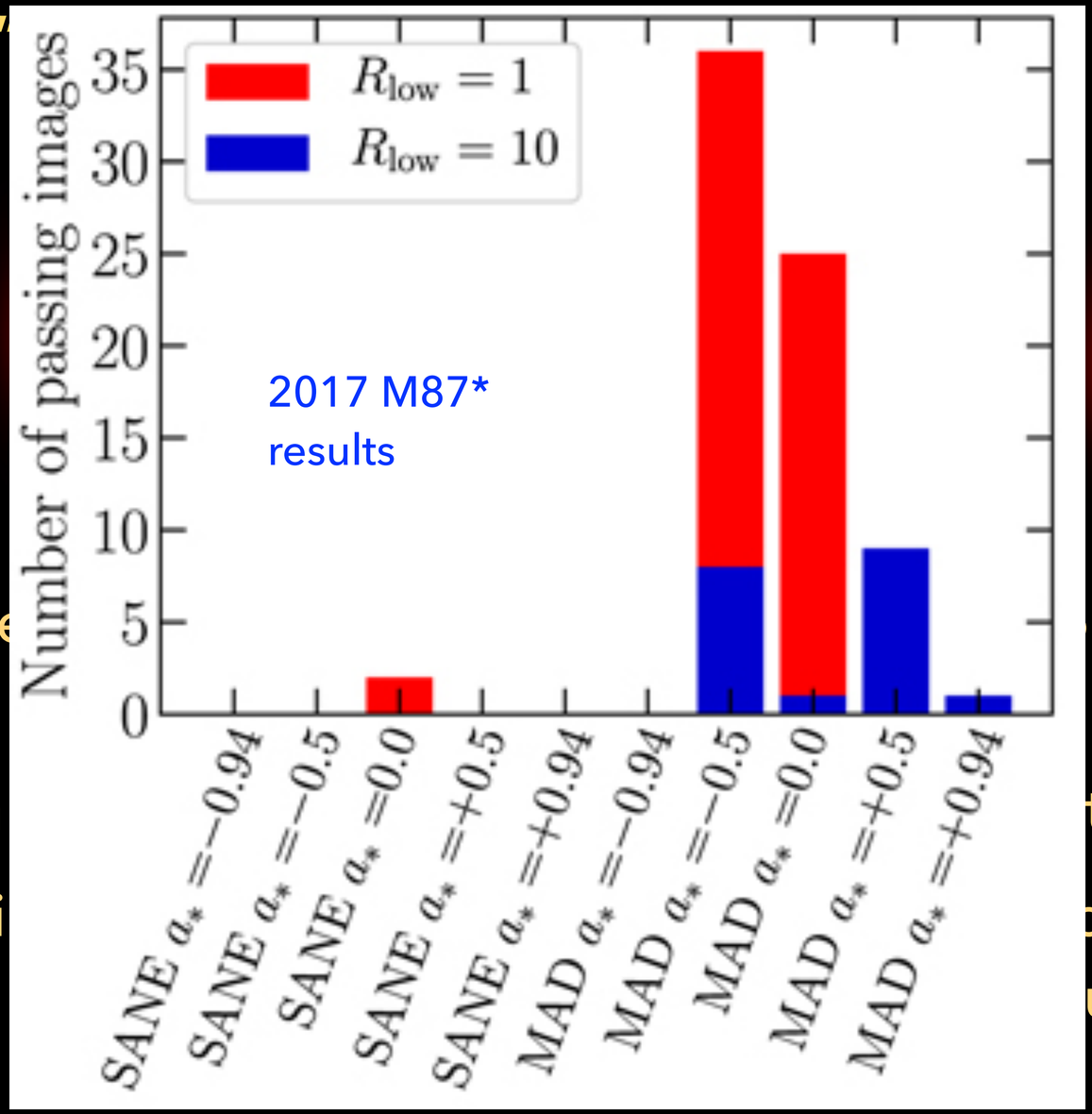
- Standard and normal evolution
- Low polarization with less coherent magnetic fields
- Lower polarization (toroidal or generally more turbulent fields)

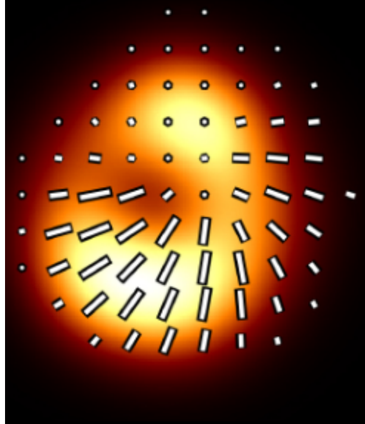
M87* 2017 Polarisation Papers VII & VIII (EHT Collaboration 2021) & M87 Multi-year Polarisation (2025), slide courtesy P. Tiede

Polarisation can distinguish between accretion/magnetisation states

"MAD"







- Magnetically arre rmal evolution
- High (saturated) with less near the horizon tic fields
- Strong polarizati on (toroidal or fields) urbulent fields)

M87* 2017 Polarisation Papers VII & VIII (EHT Collaboration 2021) & M87 Multi-year Polarisation (2025), slide courtesy P. Tiede

New: three “frames” in 5 years = more info but also challenges

11 April 2017

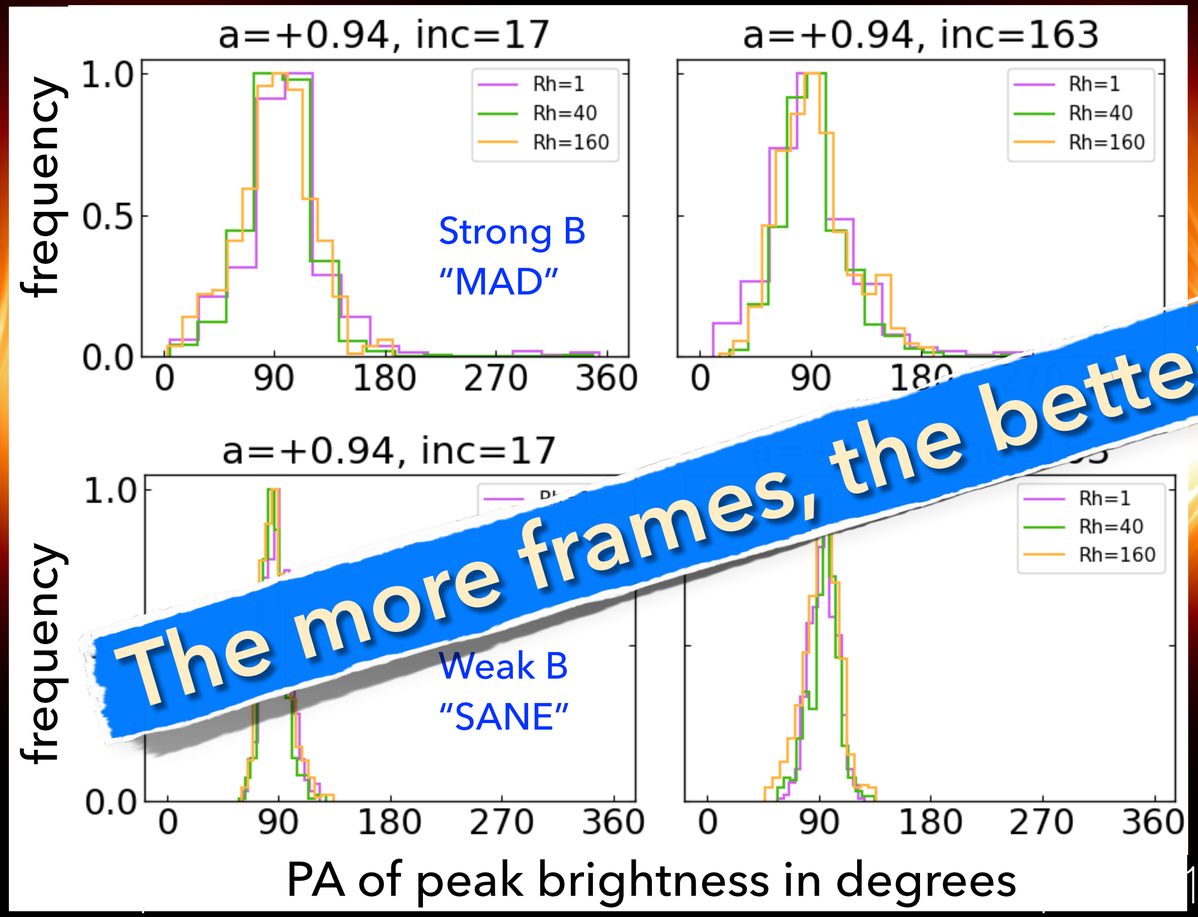
21 April 2018

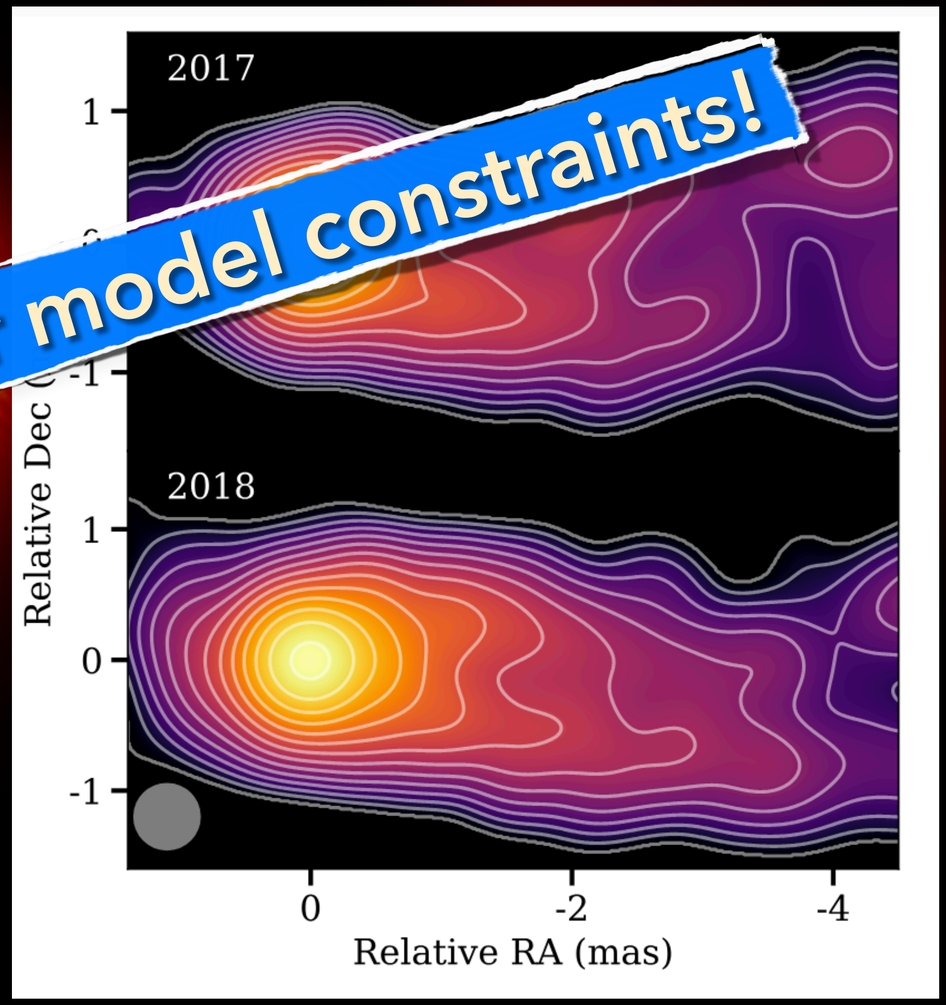
18 April 2021

Event Horizon Telescope Collaboration 2025

Event Horizon Telescope collaboration

New: three "frames" in 5 years = more info but also challenges



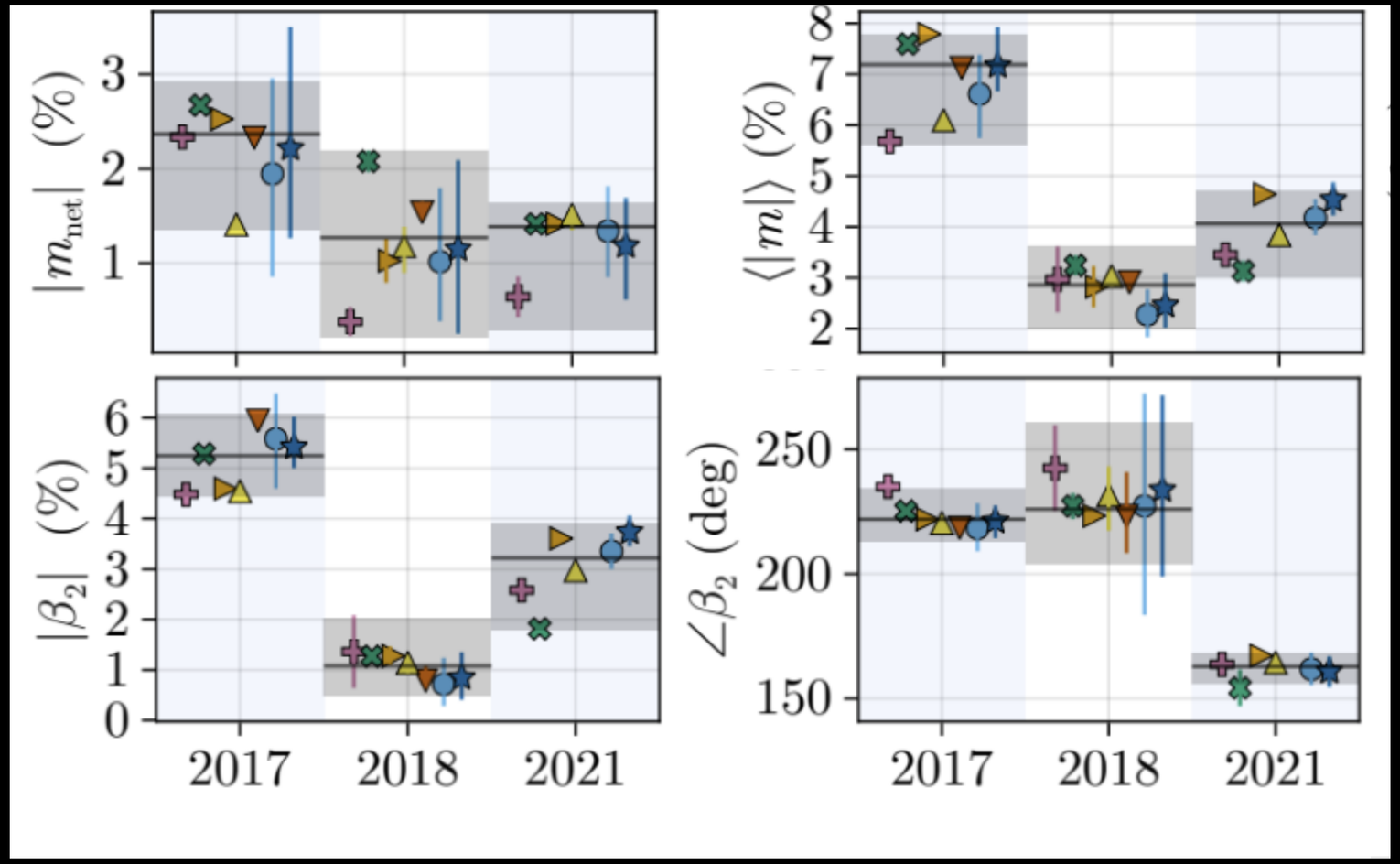


The more frames, the better our model constraints!

EHTC M87* 2017 paper I (2019); M87* 2018 paper I (2024); BSc Thesis project Marin Kruis!

Cui++2023

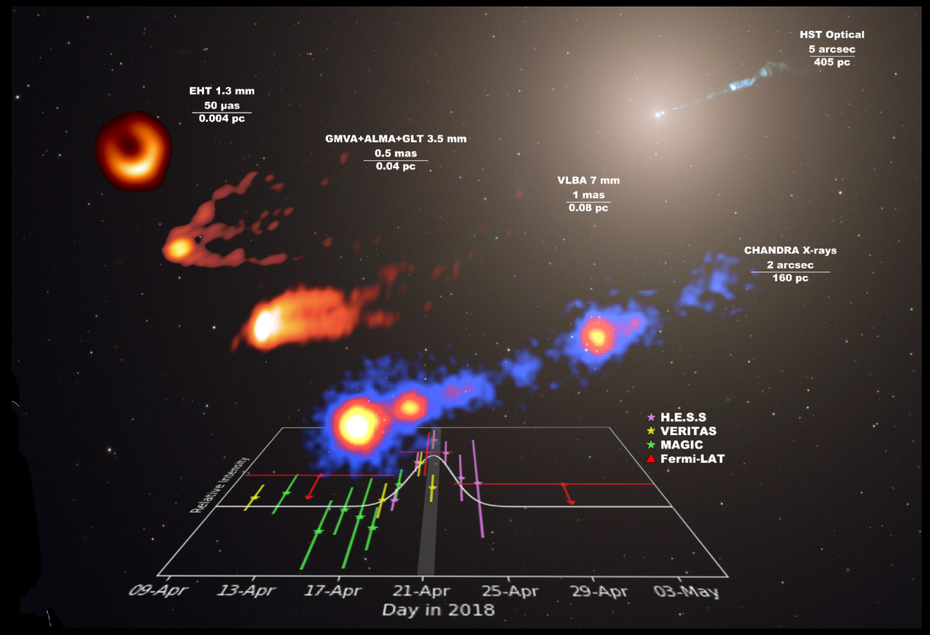
M87*'s image and polarisation seem decoupled?

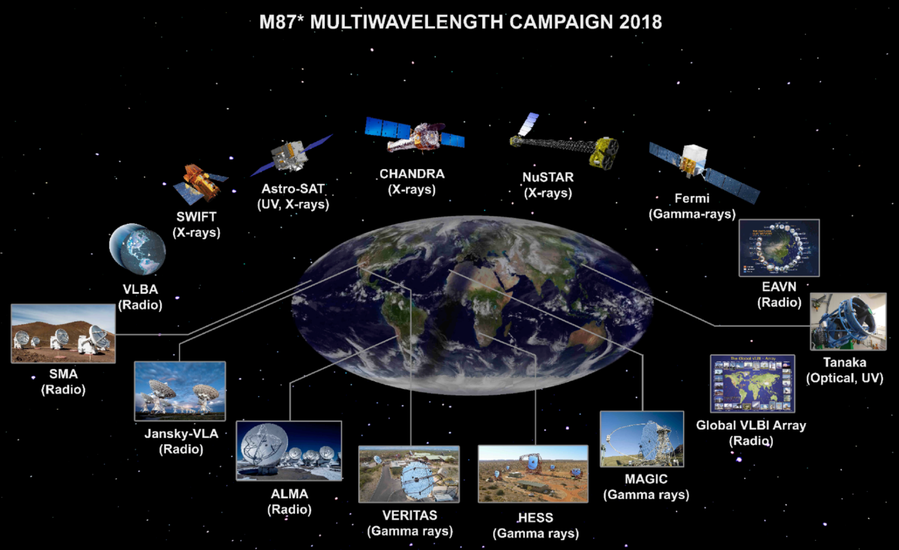


- Mismatch btw peak polarisation and peak brightness in 2018, 2021
- Peak polarisation fraction over whole image <10% in 2018 & 2021 (~15% in 2017)
- Average polarisation fraction decreased by 2x from 2017 to 2018/2021
- Average helicity decreased by a factor of 2–4 from 2017 to 2018
- Helicity flip between 2018 to 2021

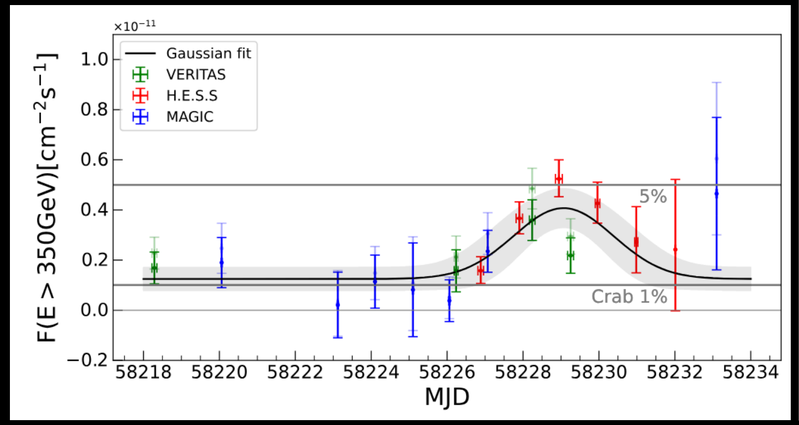
Event Horizon Telescope Collaboration 2025, slide adapted from P. Tiede

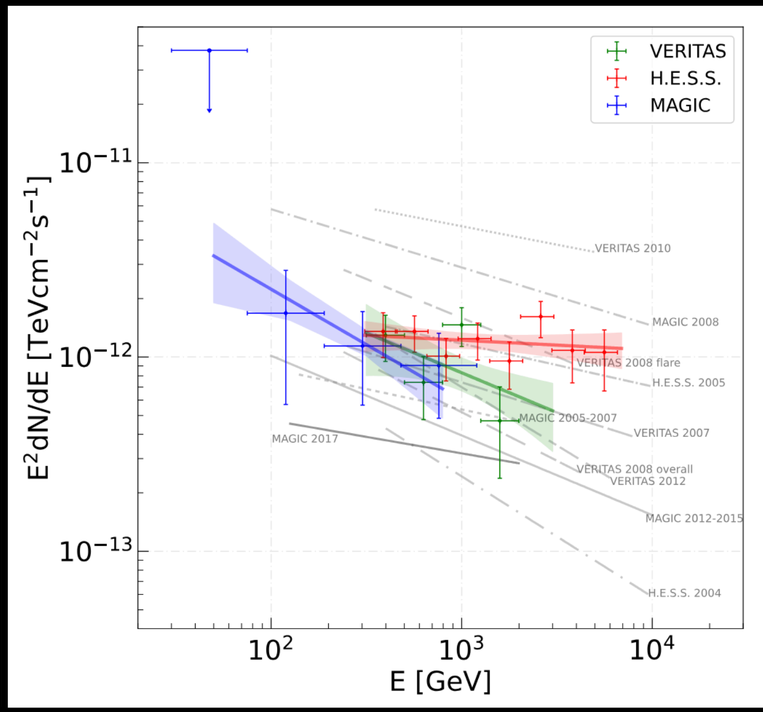
EHT M87 2018 MWL campaign: first VHE γ-ray flare since 2010!





- Most significant γ-ray flare since 2010!





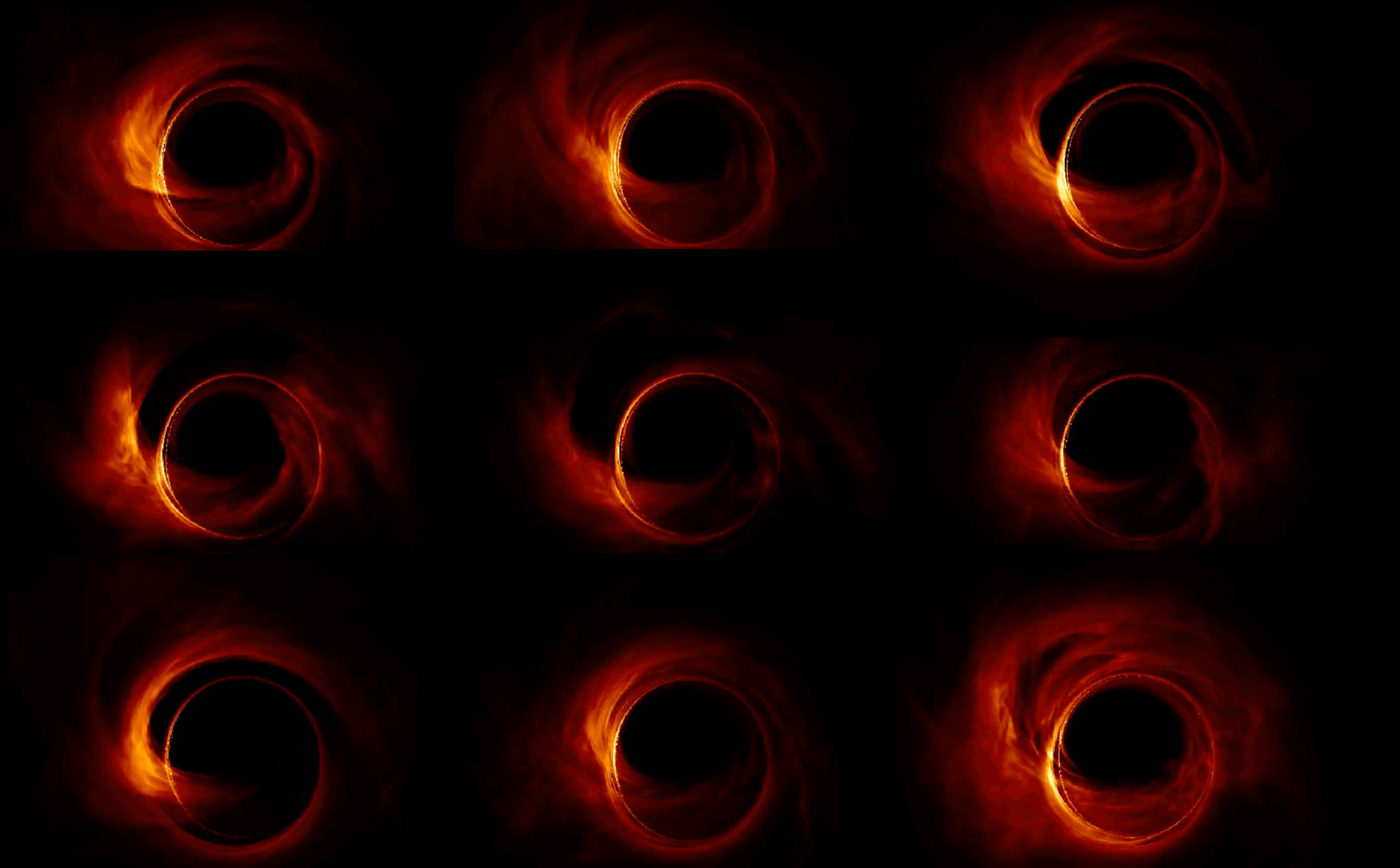
- Offers chance to test particle acceleration scenarios via an unprecedented set of constraints ➠ value of monitoring, link to neutrino results & puzzle over UHECRs

EHT Multiwavelength Science WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN++ A&A 2024 (arXiv: 2404.17623)

Outline

- ★ Black hole jets as particle accelerators and the search for the VHE emission region
- ★ The Event Horizon Telescope to date
- ★ Latest EHT/MWL results and implications
- ★ Near/far-term outlook

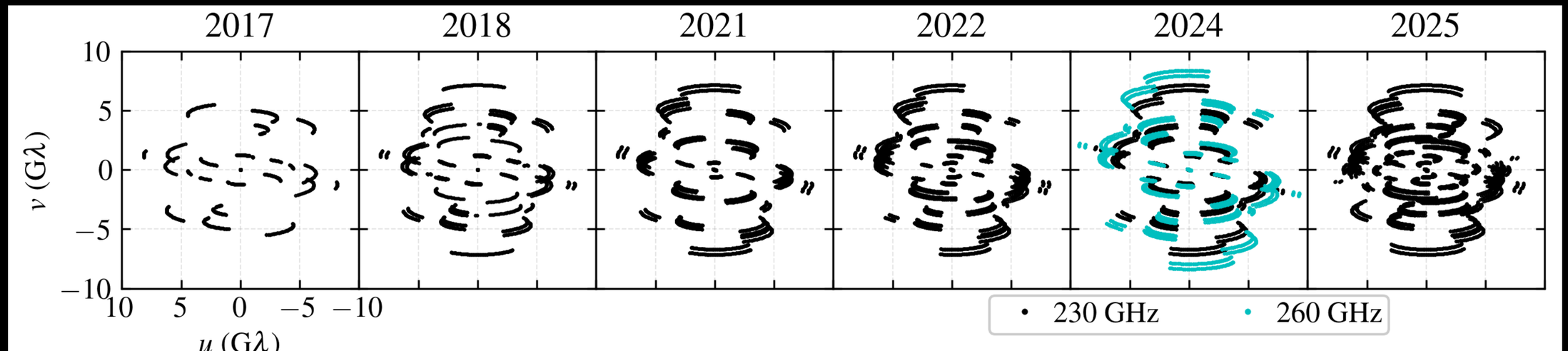
Why a “movie” is better than annual snapshots: statistics!



(GRMHD simulation by PhD student L. S. Salas; see Salas, Liska, SM++2025. Using H-AMR code; Liska, Chatterjee++2019;2022 & BHOSS: Younsi++)

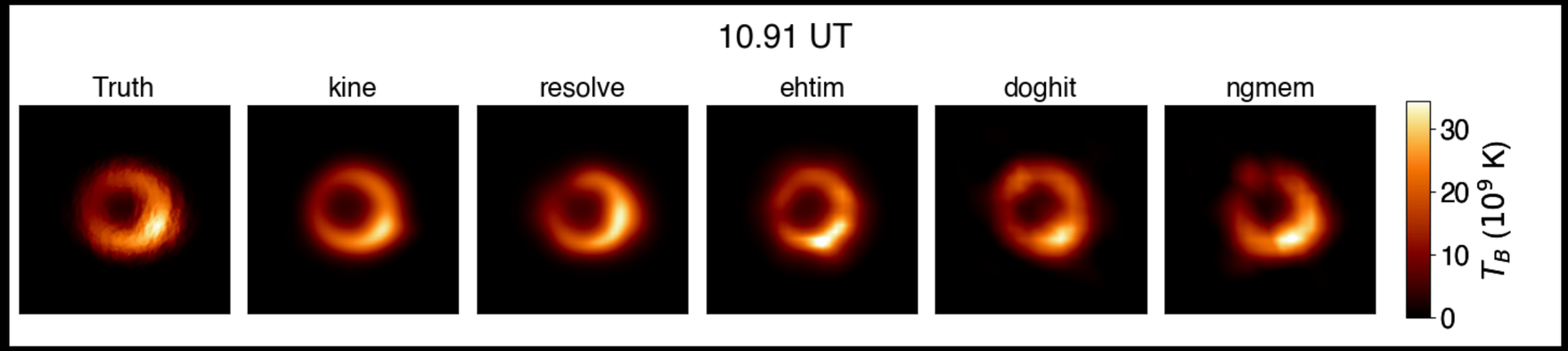
The next big thing: Spring 2026 EHT M87 "movie" campaign!

- We (EHTC) are conducting a groundbreaking ~2 month VLBI campaign in March/April 2026, on M87* (plus calibrators: 3C273, 3C279)!!
- Baseline schedule is every 3-4 days for 4 hours w/ALMA, some days longer with the rest of the array not including ALMA
- We have significant cm/mm-radio VLBI through VHE γ-ray multi-wavelength coverage lined up, including Chandra, NuSTAR, Fermi, HESS, MAGIC, VERITAS and the *first CTAO 23m element LST-1!!*



The next big thing: Spring 2026 EHT M87 "movie" campaign!

- We (EHTC) are conducting a groundbreaking ~2 month VLBI campaign in March/April 2026, on M87* (plus calibrators: 3C273, 3C279)!!
- Baseline schedule is every 3-4 days for 4 hours w/ALMA, some days longer with the rest of the array not including ALMA
- We have significant cm/mm-radio VLBI through VHE γ-ray multi-wavelength coverage lined up, including Chandra, NuSTAR, Fermi, HESS, MAGIC, VERITAS and the *first CTAO 23m element LST-1!!*
- Sgr A* will give us some idea what to expect!

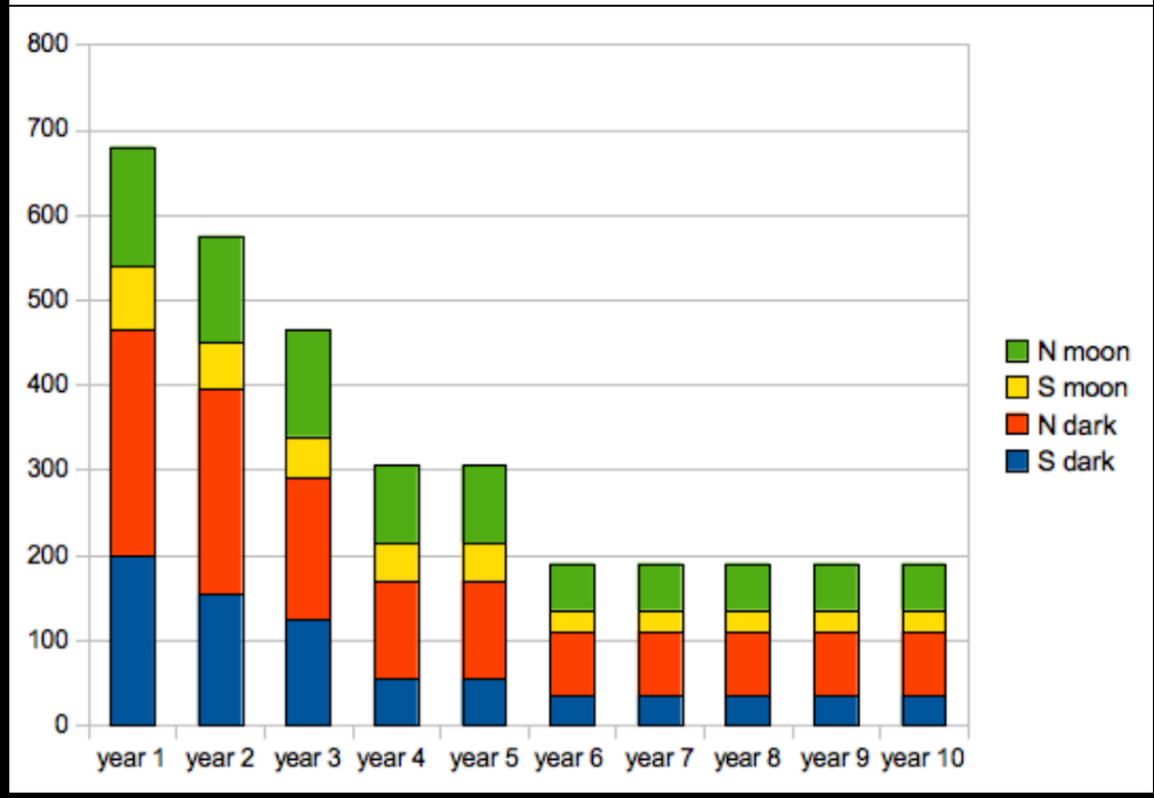


CTOA AGN KSP: a decade of intense VHE γ-ray monitoring (w/AMT/EHT!)

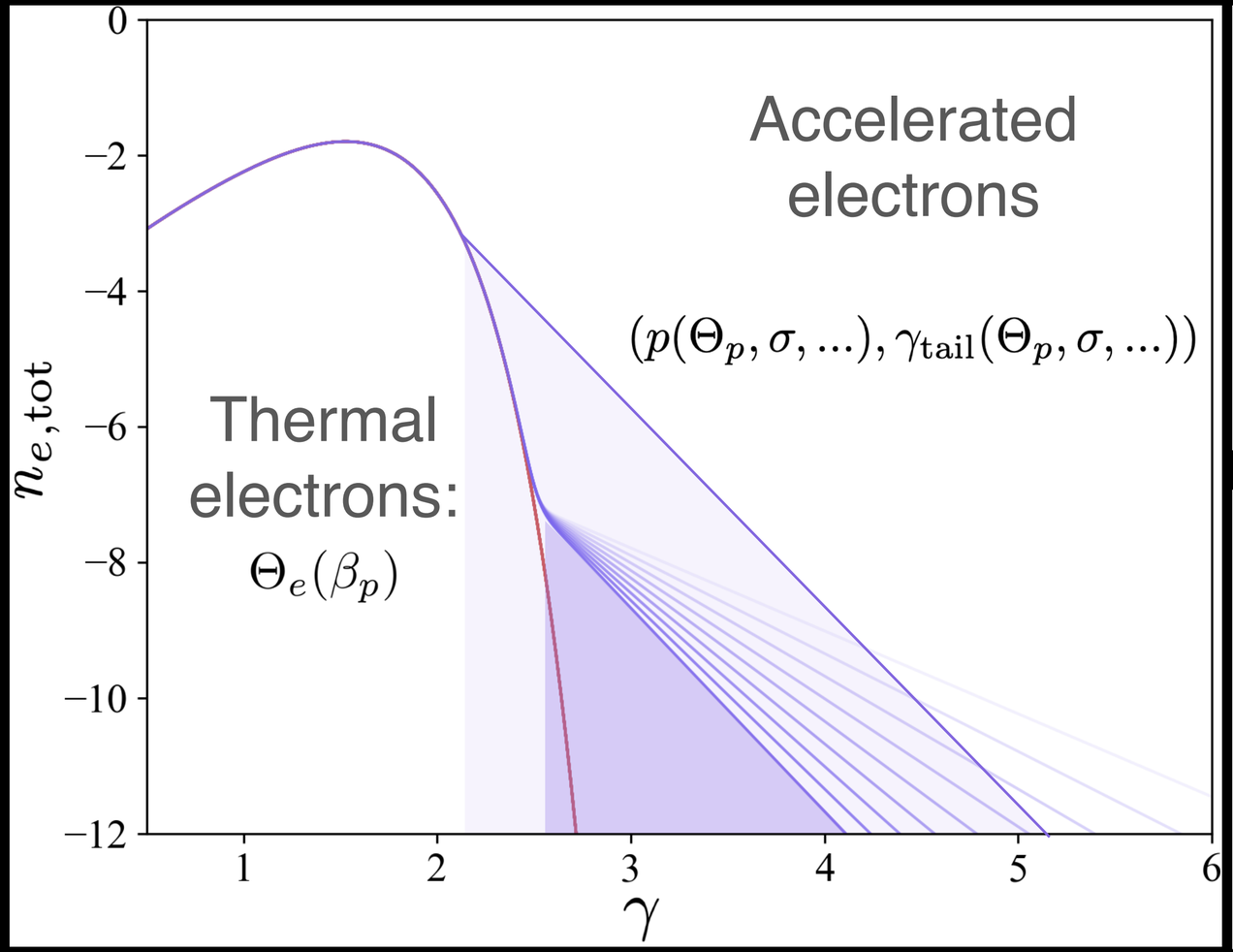
- Deep exposures: M87 (100 hrs) and Cen A (150 hrs)
- Longterm monitoring: 2-3 sources per AGN class, 15-20 total "prominent" VHE AGN (mostly blazars/radio galaxies/LLAGN), spectra at least weekly for 30 minutes, for ~10 years
- AGN Flares: triggered externally or internally (CTA realtime analysis mode, regular 12min snapshots of ~80 AGN)
- High quality spectra: ~80 sources
- Many of these also potential neutrino sources monitored by eg. MOJAVE

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

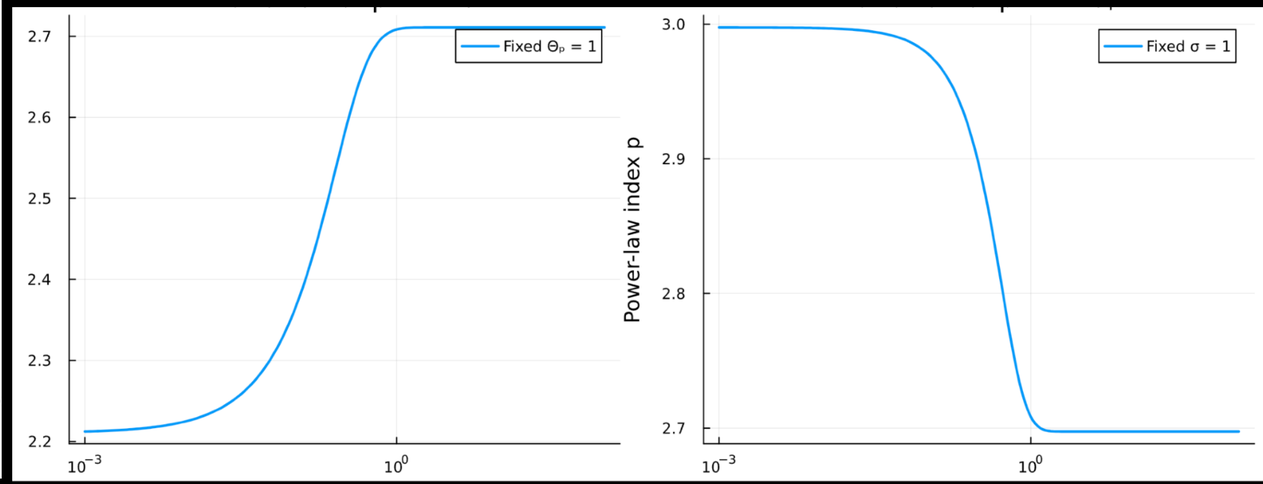


Prototype: Bayesian parameter inference approach to EHT modelling



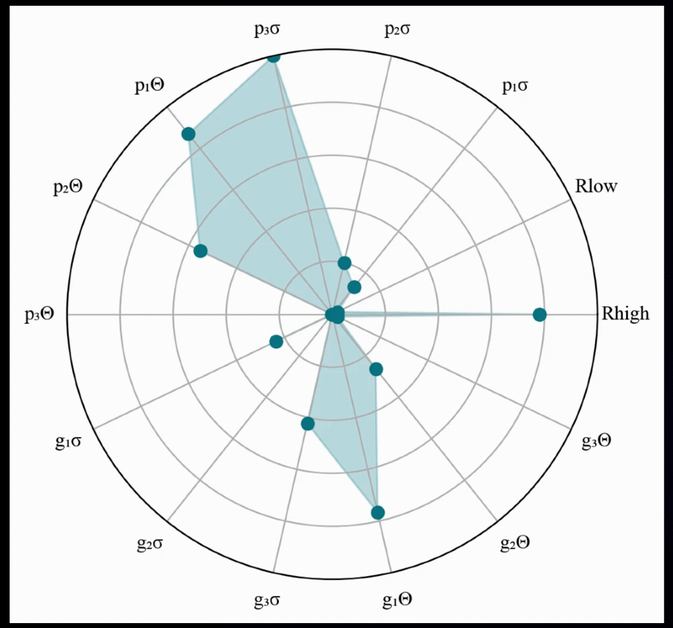
$$p_{\rm ind} = p_{\rm max} - \left(\frac{p_{\rm max} - p_{\rm min}}{n}\right) \sum_{\alpha_i=\sigma,\Theta_p\ldots}^{n} \left(p_1^{\alpha_i} \tanh p_2^{\alpha_i} \left(\frac{\alpha_i}{p_3^{\alpha_i}}\right)^{p_4^{\alpha_i}} \right),$$

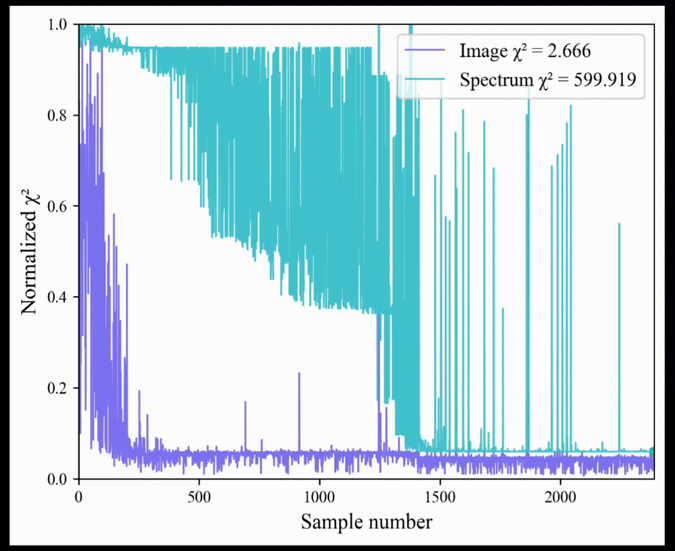
$$\gamma_{\rm tail} = \gamma_{\rm max} - \left(\frac{\gamma_{\rm max} - \gamma_{\rm min}}{n}\right) \sum_{\alpha_i=\sigma,\Theta_p\ldots}^{n} \left(\gamma_1^{\alpha_i} \tanh \gamma_2^{\alpha_i} \left(\frac{\alpha_i}{\gamma_3^{\alpha_i}}\right)^{\gamma_4^{\alpha_i}} \right),$$

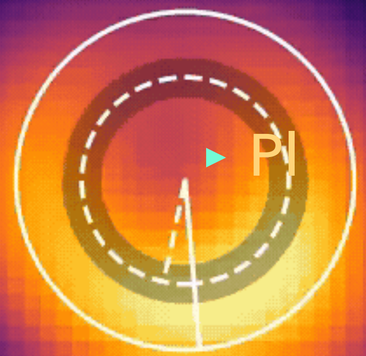


Roy, Tiede, SM++ in prep ➠ will eventually be on Github and become part of the EHT "toolkit"

New Bayesian parameter inference approach to EHT modelling

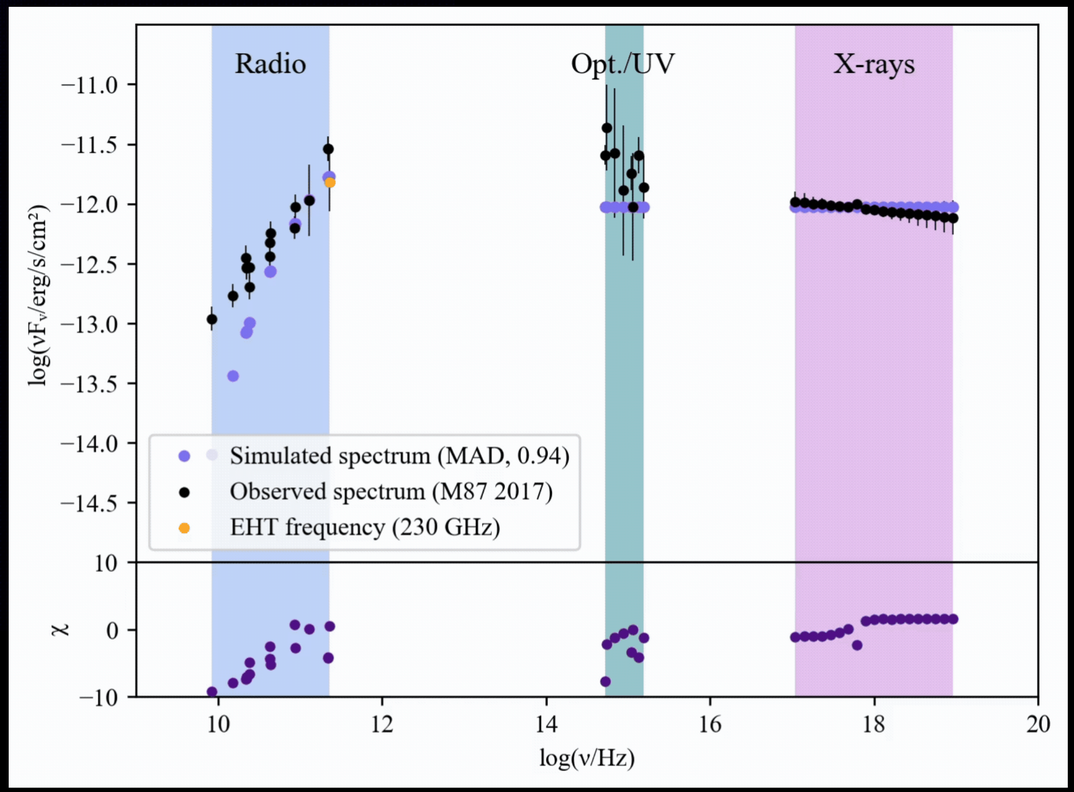






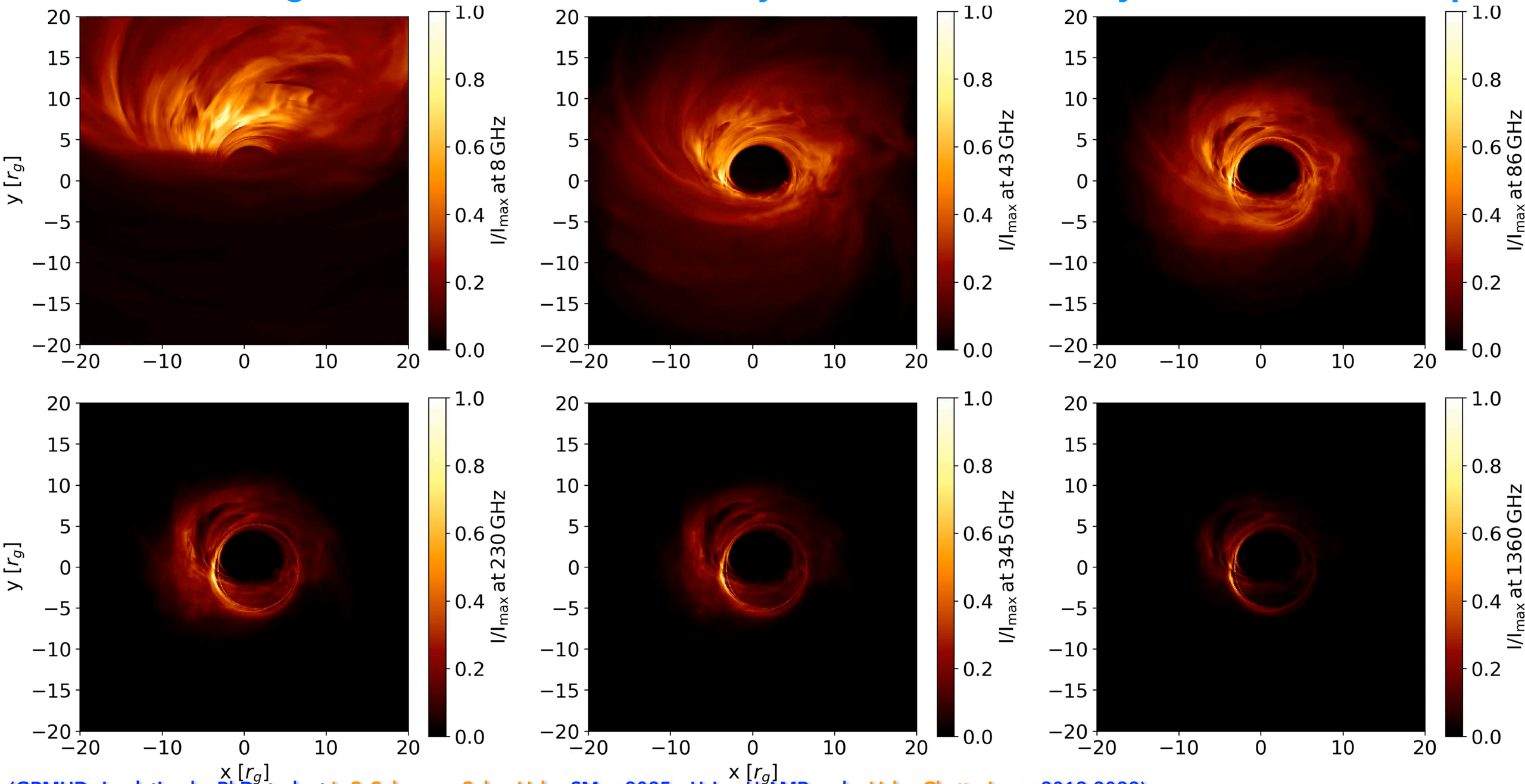
- Prototype!
- Bayesian approach with nested/sliced sampling
- Simultaneous image/ MWL spectral fitting
- PICASSO/POLLOCK (Roy, Lattimer++ in prep.)

- - - - Simulated data (MAD, a=0.94)
——— Observed data (M87 2017)



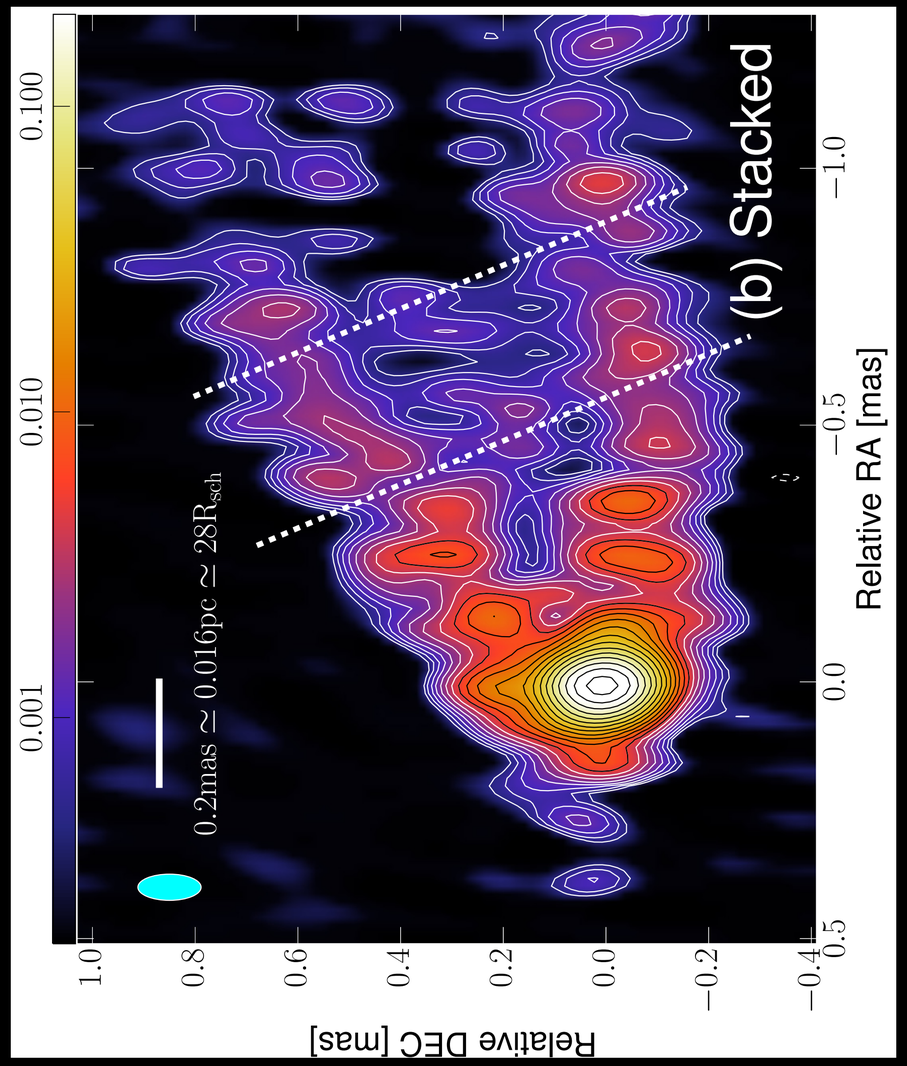
Roy, Tiede, SM++ in prep ➠ will eventually be on Github and become part of the EHT "toolkit"

Connecting the black hole to the jets is another key theoretical step

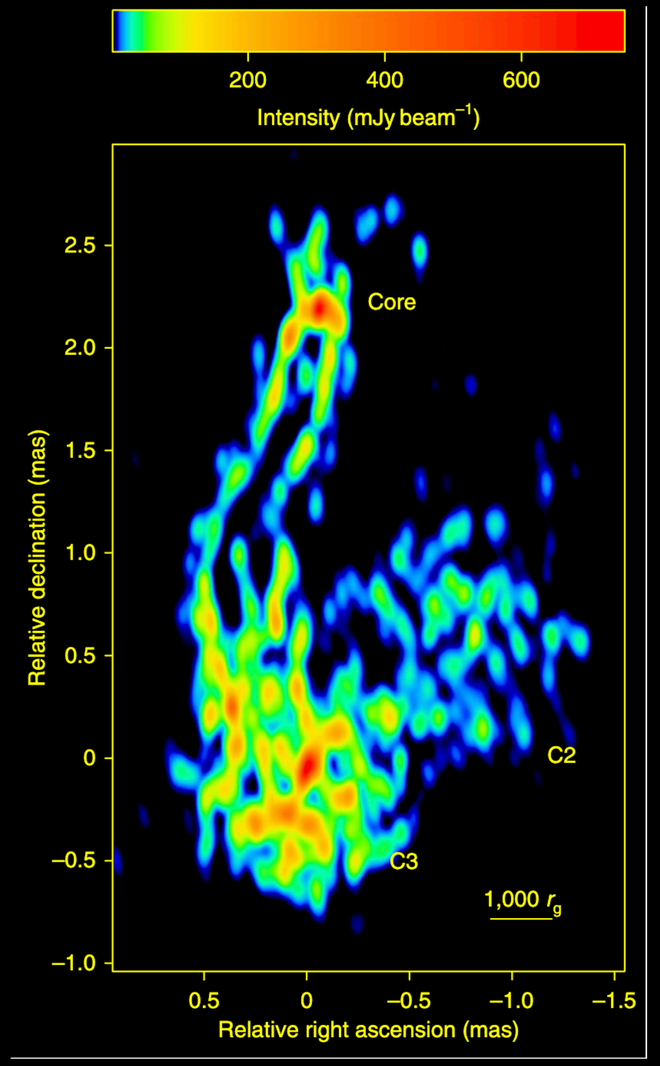


(GRMHD simulation by PhD student L. S. Salas; see Salas, Liska, SM++2025. Using H-AMR code; Liska, Chatterjee++2019;2022)

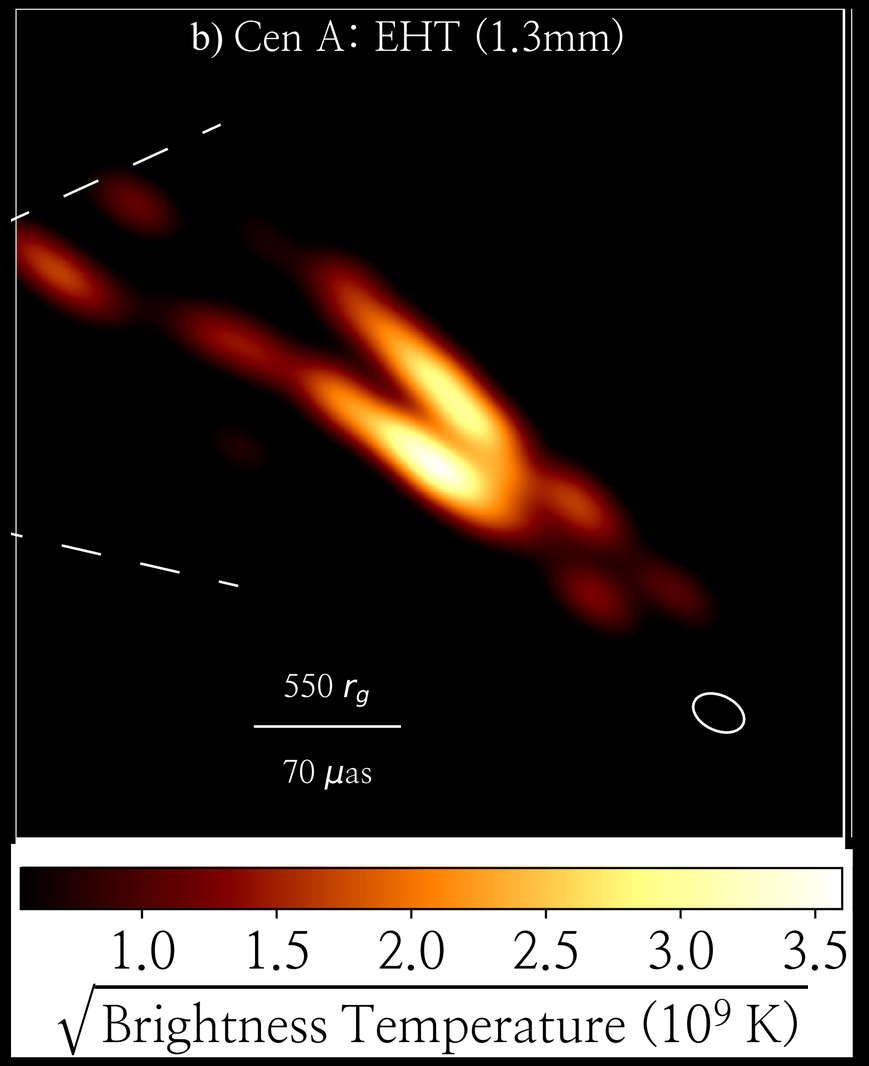
Jet edge/sheath seems to be what radiates < 10^5 r_g



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

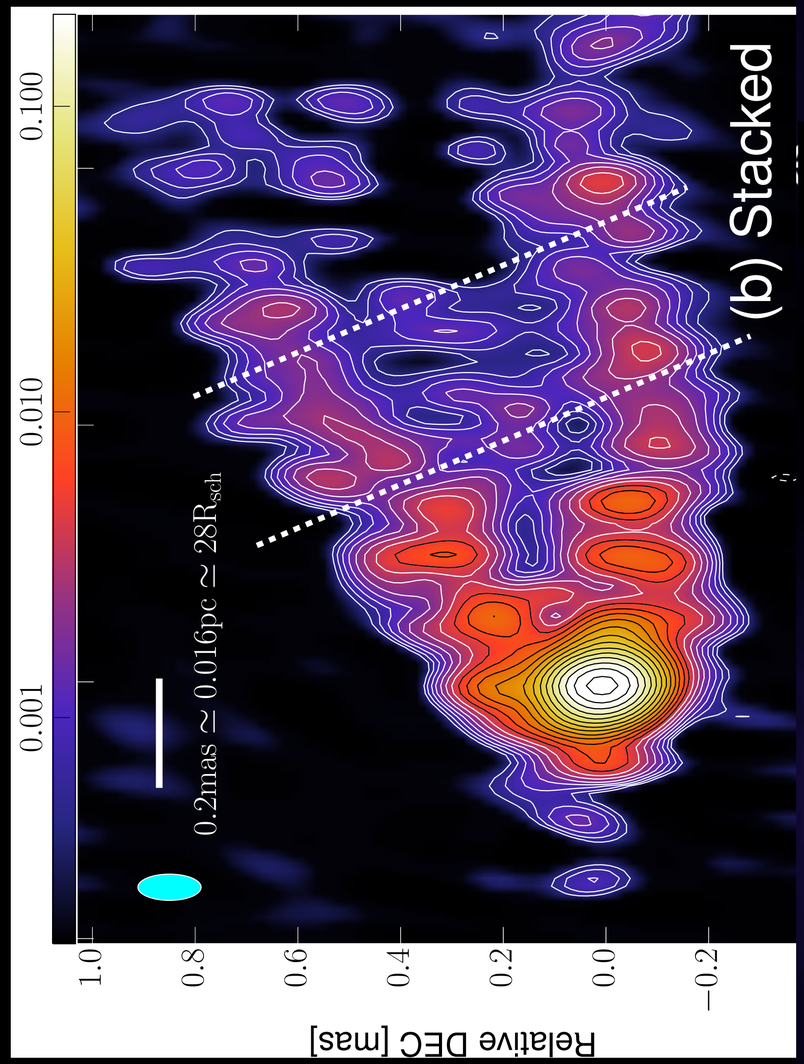


3C84 (VLBI+RadioAstron): Giovannini++2018, Nat.Astro



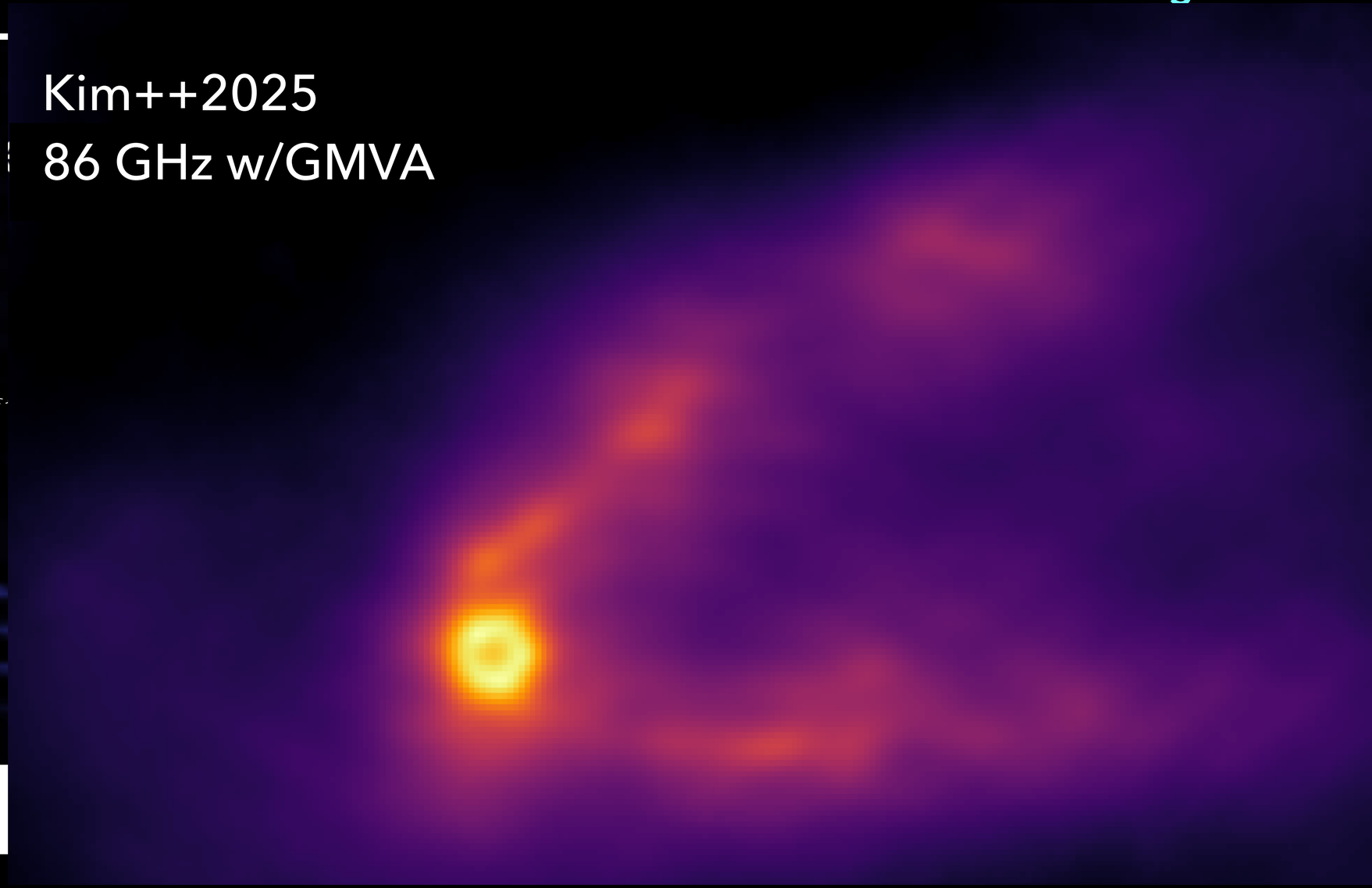
Cen A (EHT): Janssen++2021, Nat. Astro

Jet edge/sheath seems to be what radiates < 10^5 r_g



Kim++2025

86 GHz w/GMVA

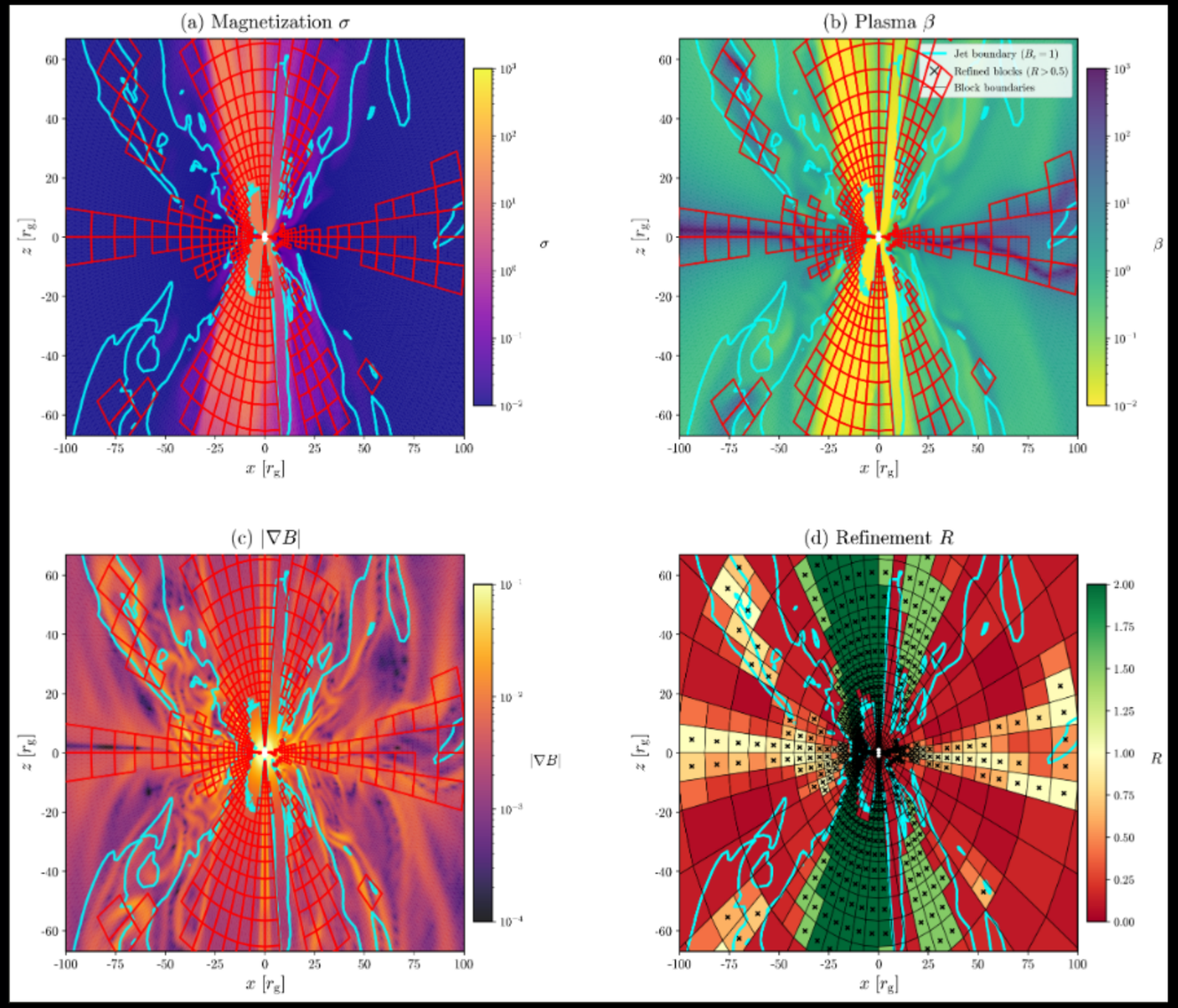


M87 (VLBA/VLBI): Kim++2018; Walker+ +2018; Hada++14,16,18

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

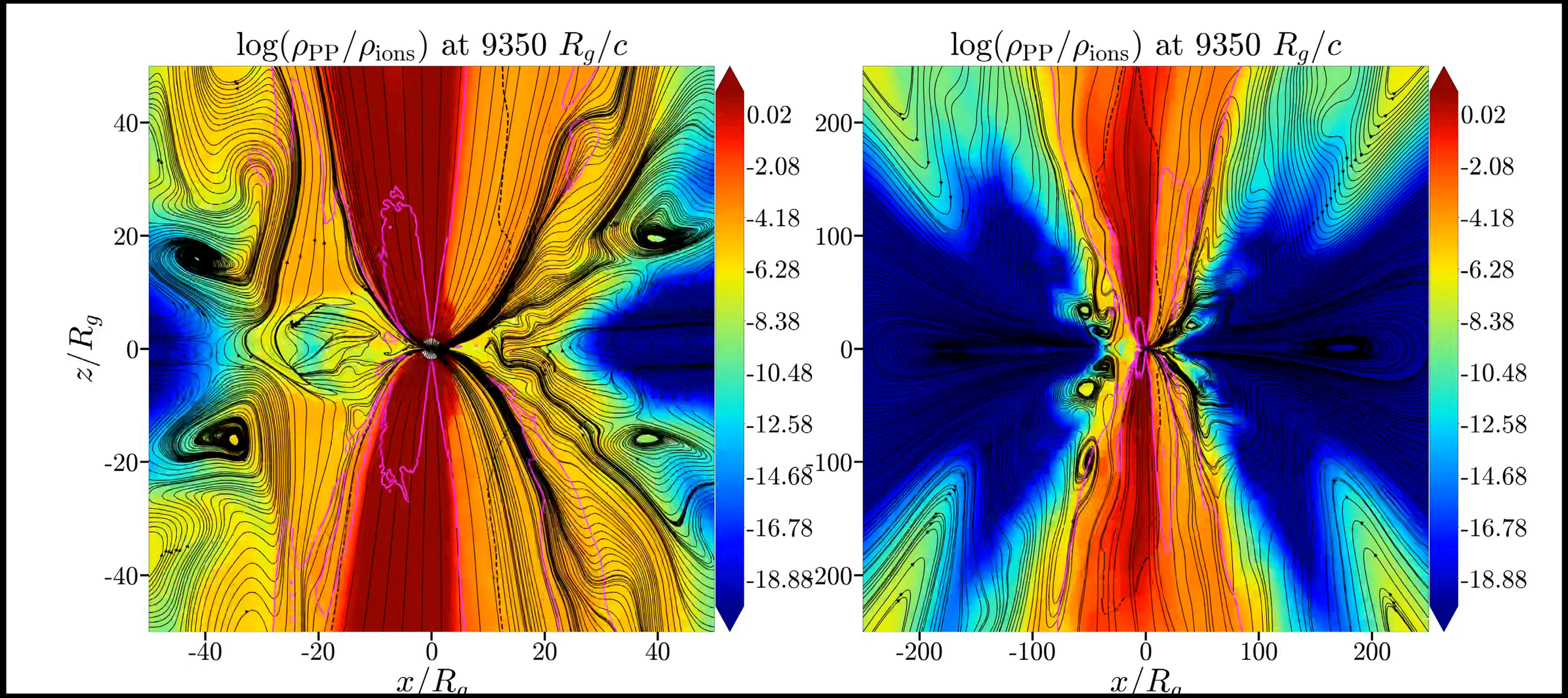
Cen A (EHT): Janssen++2021, Nat. Astro

New: tracing ‘hadronic mixing‘ and variability in 3D GRMHD



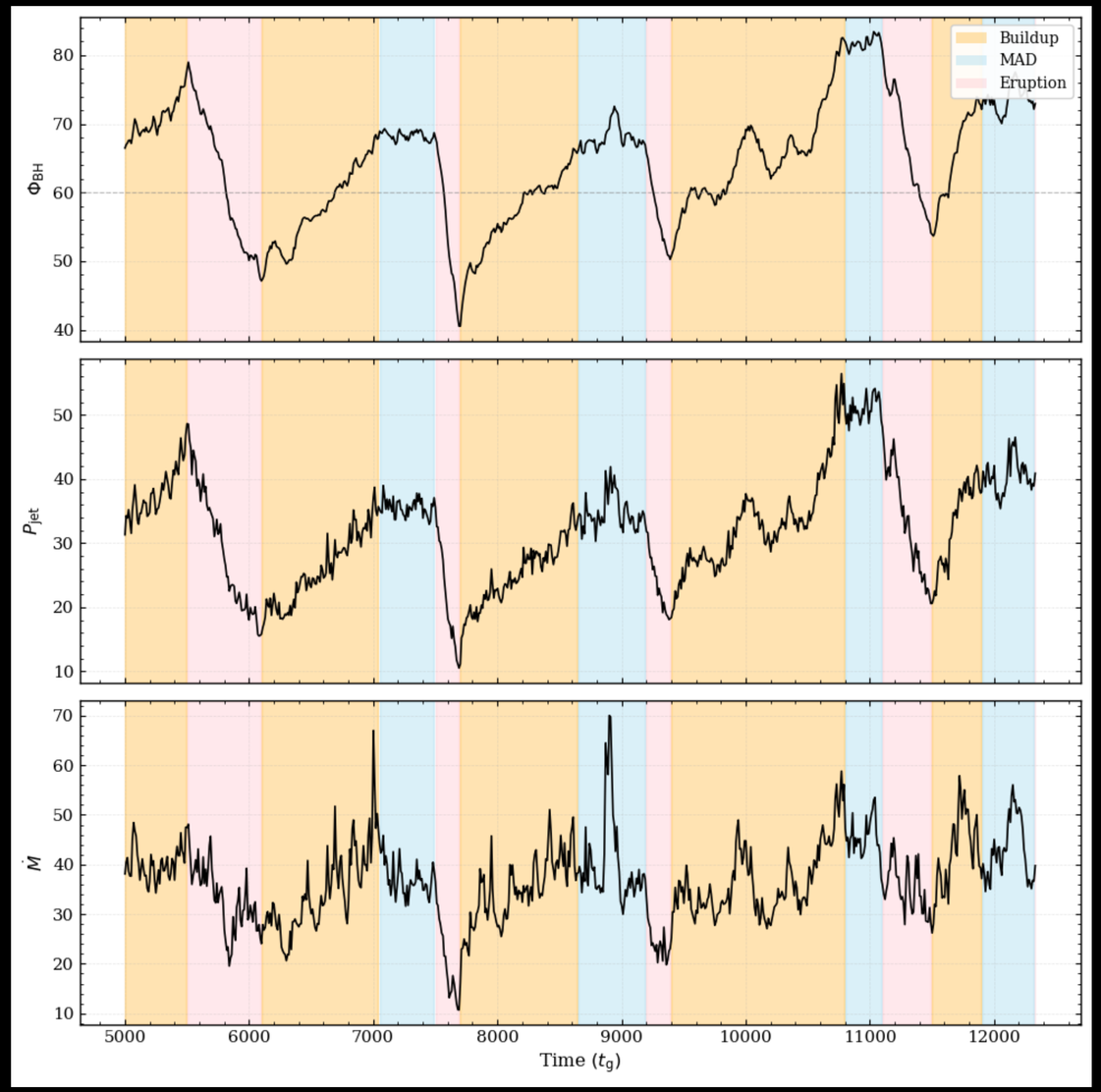
Praharaj, Liska, SM++ in prep. using H-AMR (Liska, Chatterjee++2022)

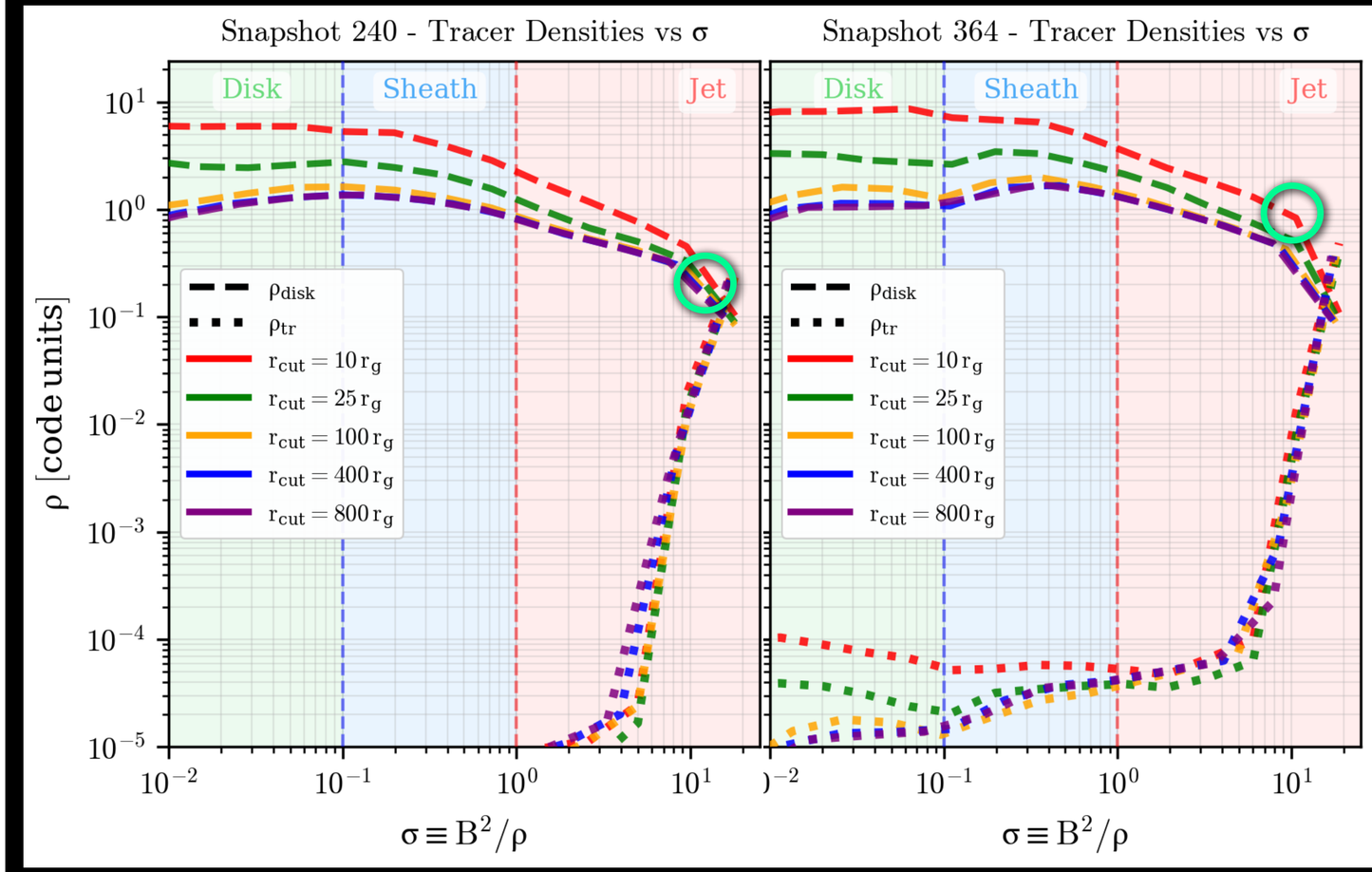
New: tracing ‘hadronic mixing‘ and variability in 3D GRMHD



Praharaj, Liska, SM++ in prep. using H-AMR (Liska, Chatterjee++2022)

New: tracing ‘hadronic mixing‘ and variability in 3D GRMHD

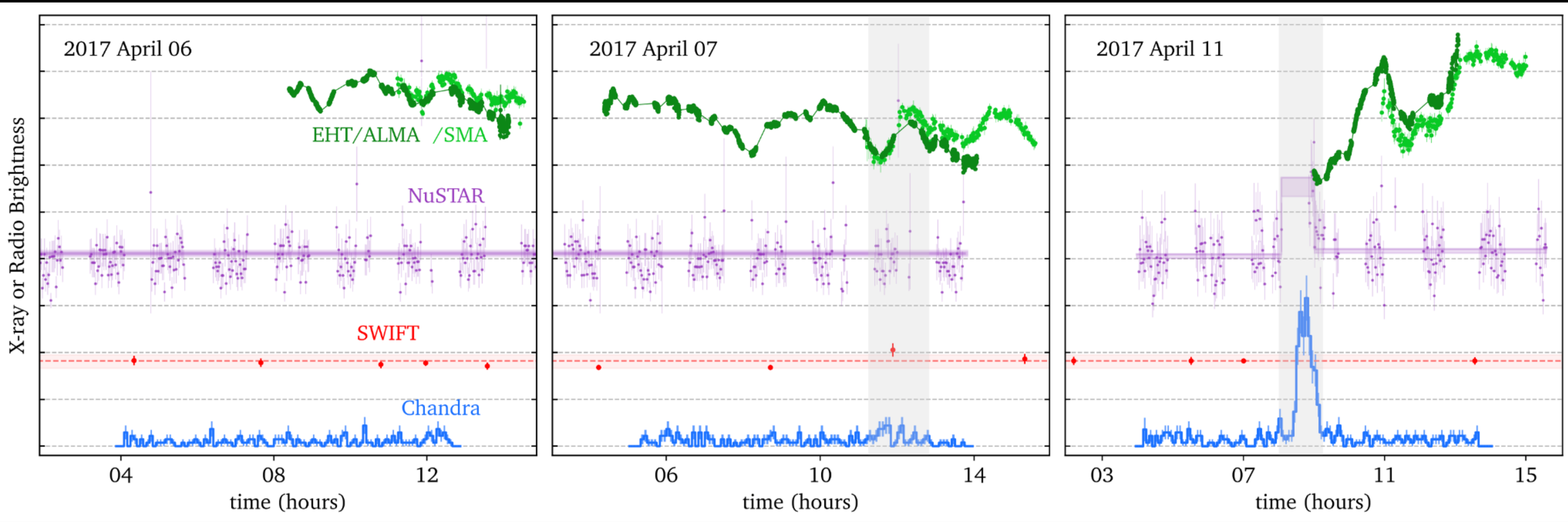




Praharaj, Liska, SM++ in prep. using H-AMR (Liska, Chatterjee++2022)

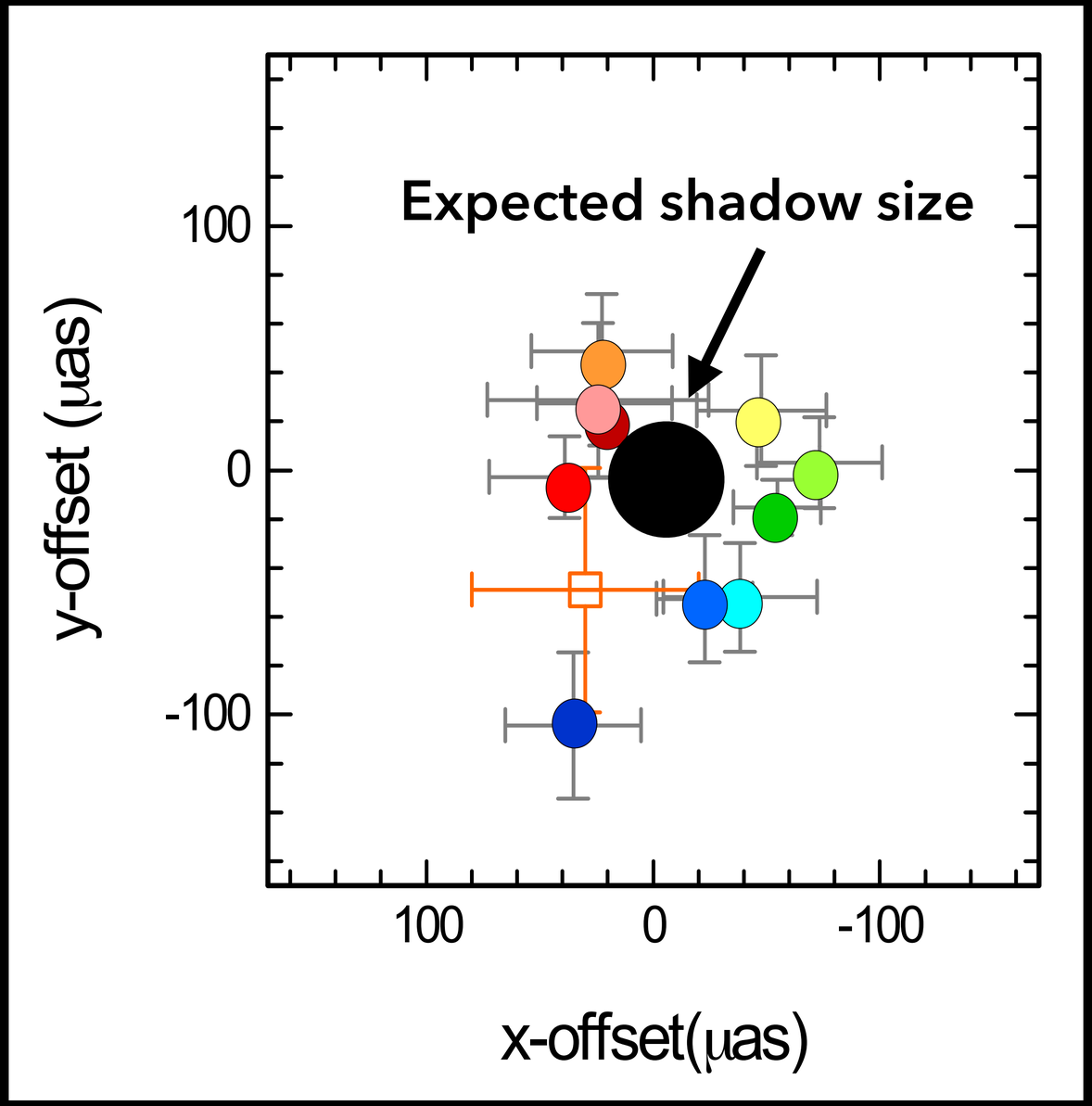
Sgr A* variability also encodes dynamics and particle acceleration properties

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

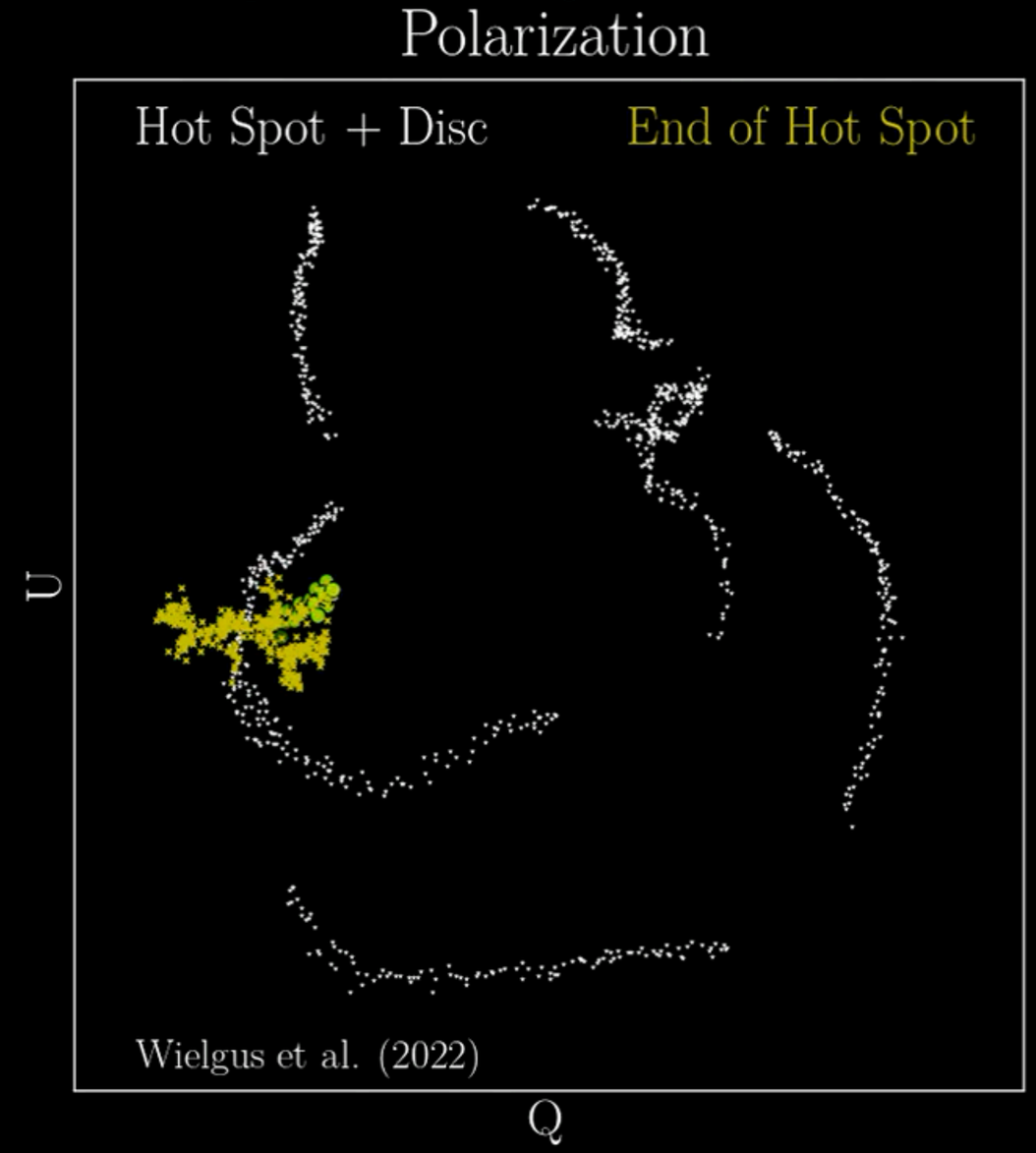


EHTC + Multiwavelength Partners, Sgr A* Paper II 2022; Wielgus, EHT++2022

Sgr A* flares clearly associated with plasma dynamics



Infrared flares move around the BH (e.g., GRAVITY++2018)

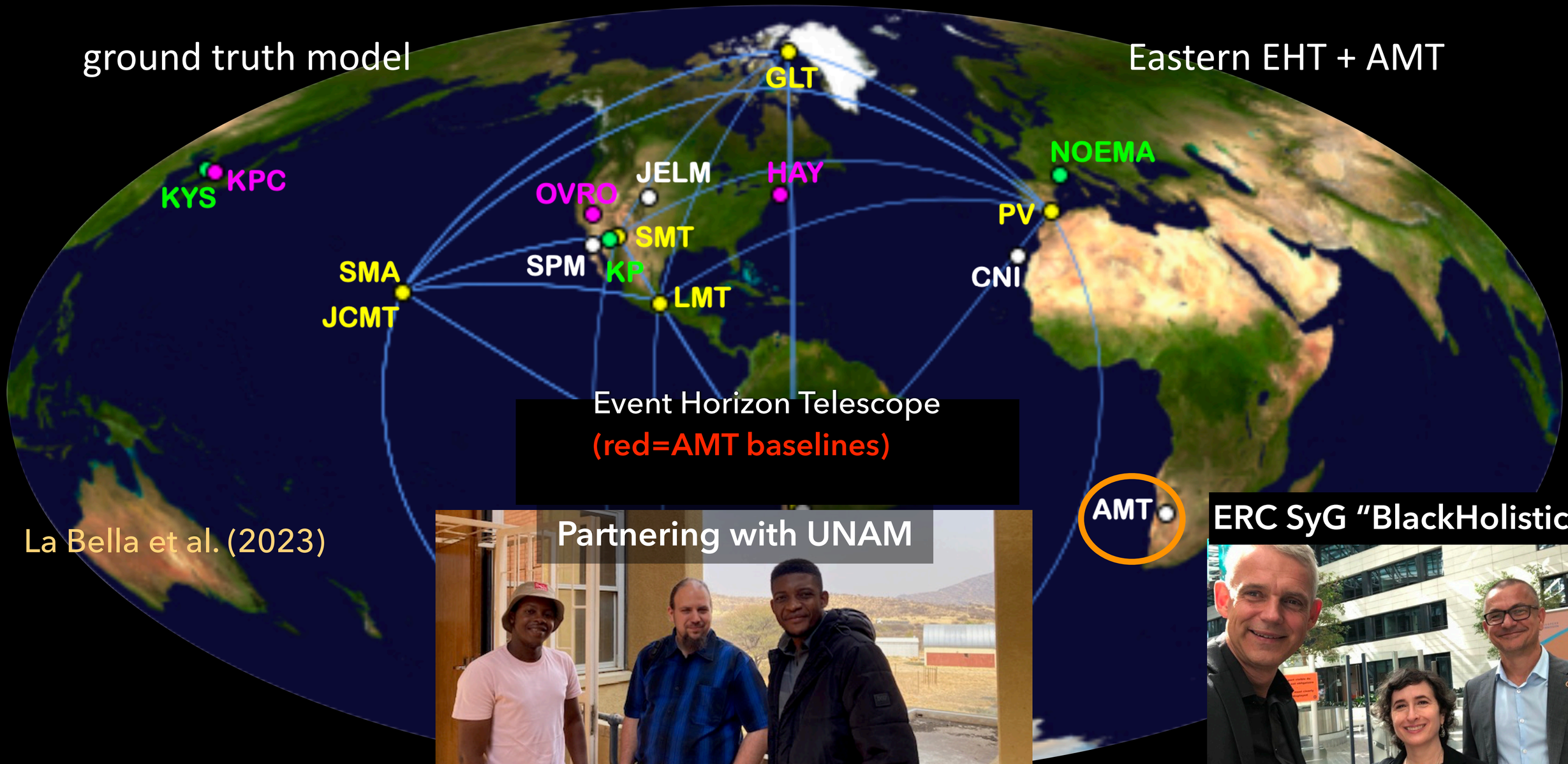


Animation credit: I. Marti-Vidal (Univ. Valencia)

EHT expansions on the ground in the coming ~5-10 yrs

ground truth model

Eastern EHT + AMT



Event Horizon Telescope
(red=AMT baselines)

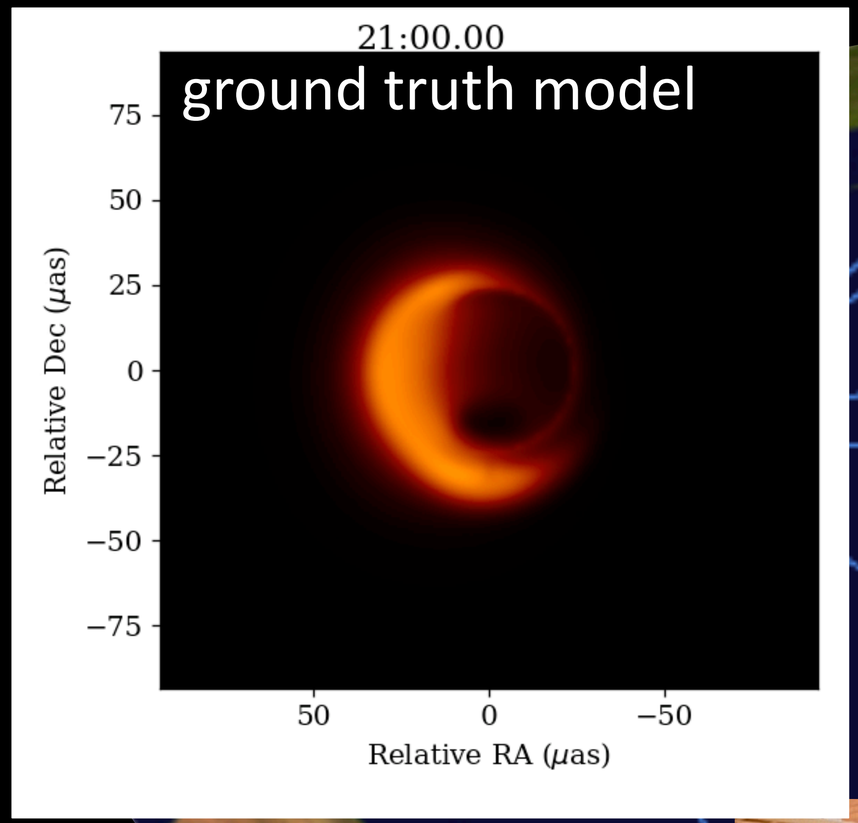
La Bella et al. (2023)

Partnering with UNAM

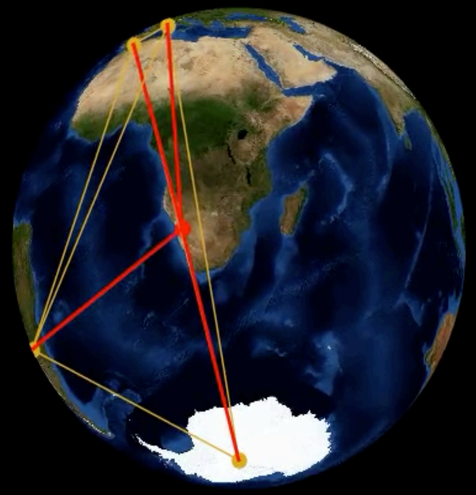
ERC SyG “BlackHolistic”

Johnson++2023: “Key Science Goals fo

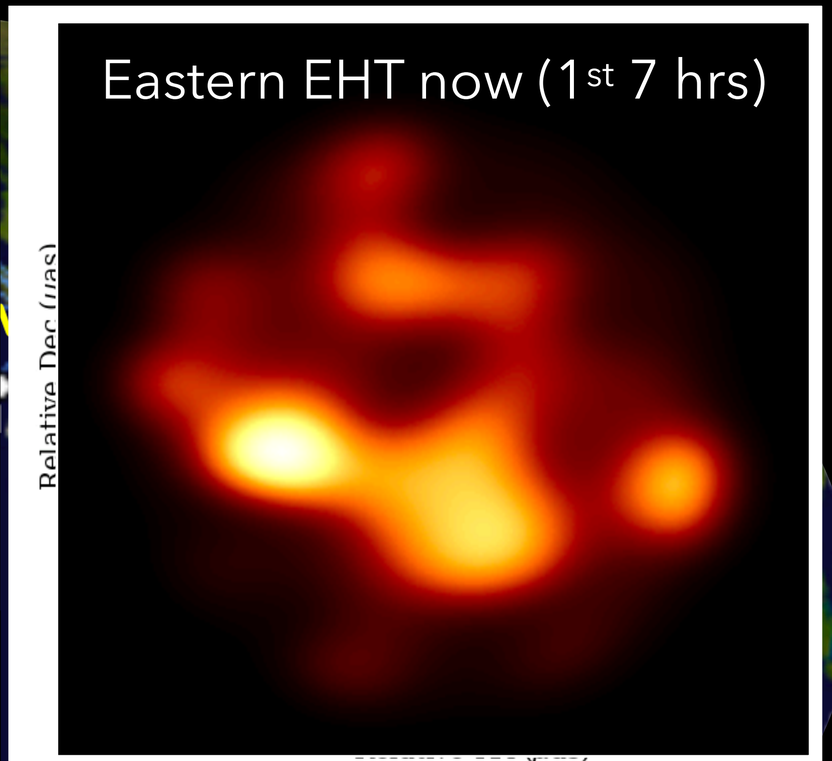
EHT expansions on the ground in the coming ~5-10 yrs



La Bella et al. (2023)



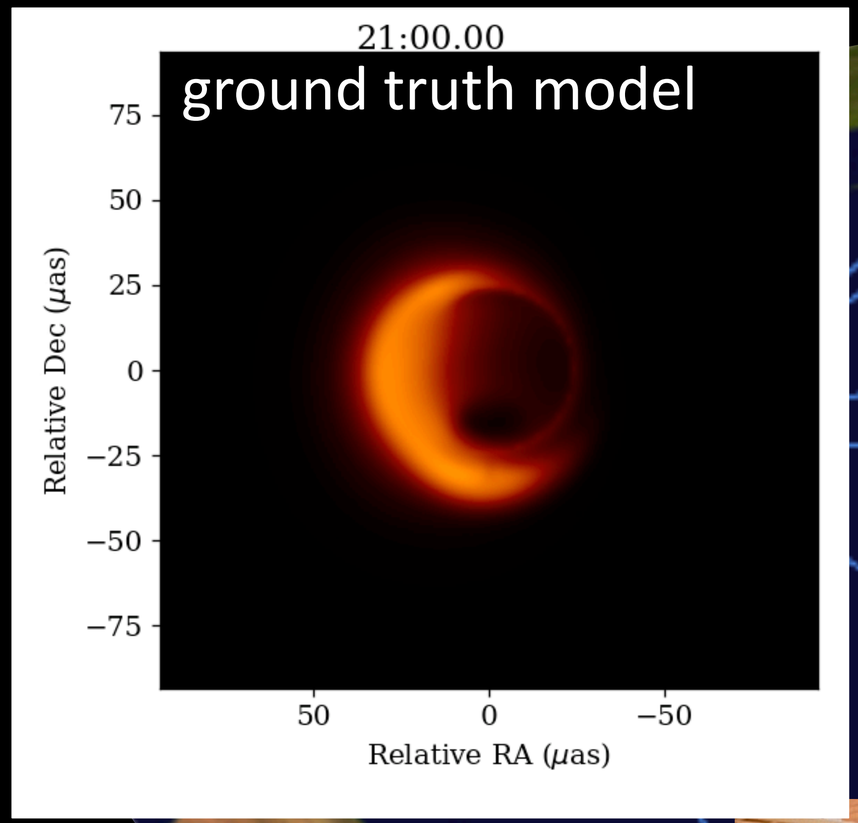
Event Horizon Telescope
(red=AMT baselines)



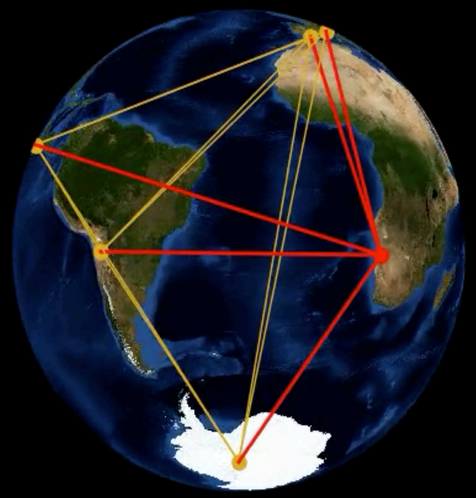
Partnering with UNAM

Johnson++2023: "Key Science Goals fo

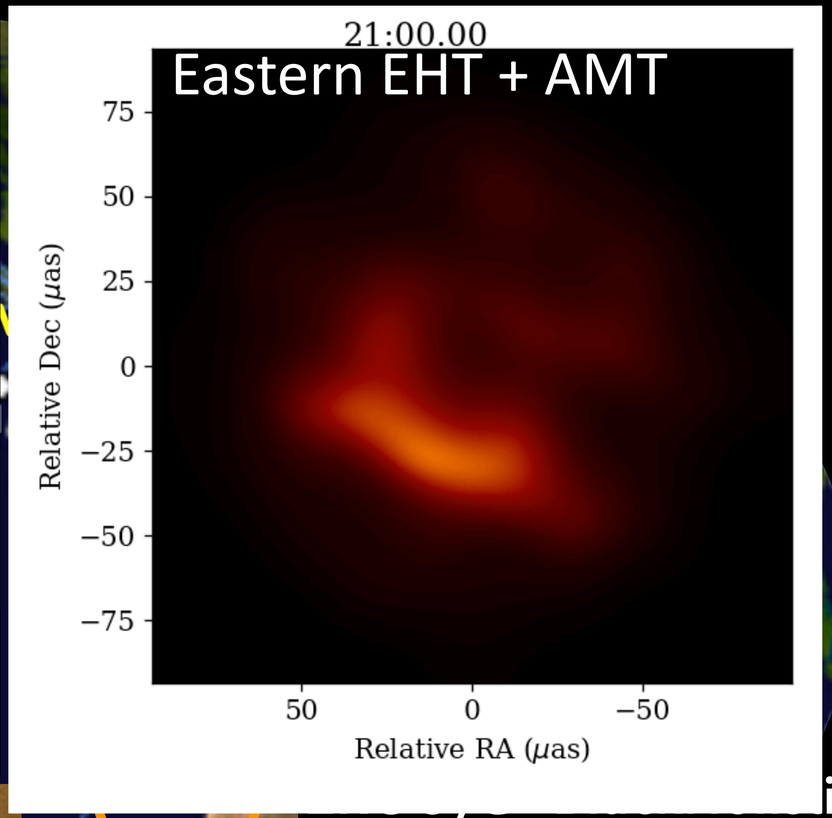
EHT expansions on the ground in the coming ~5-10 yrs



La Bella et al. (2023)



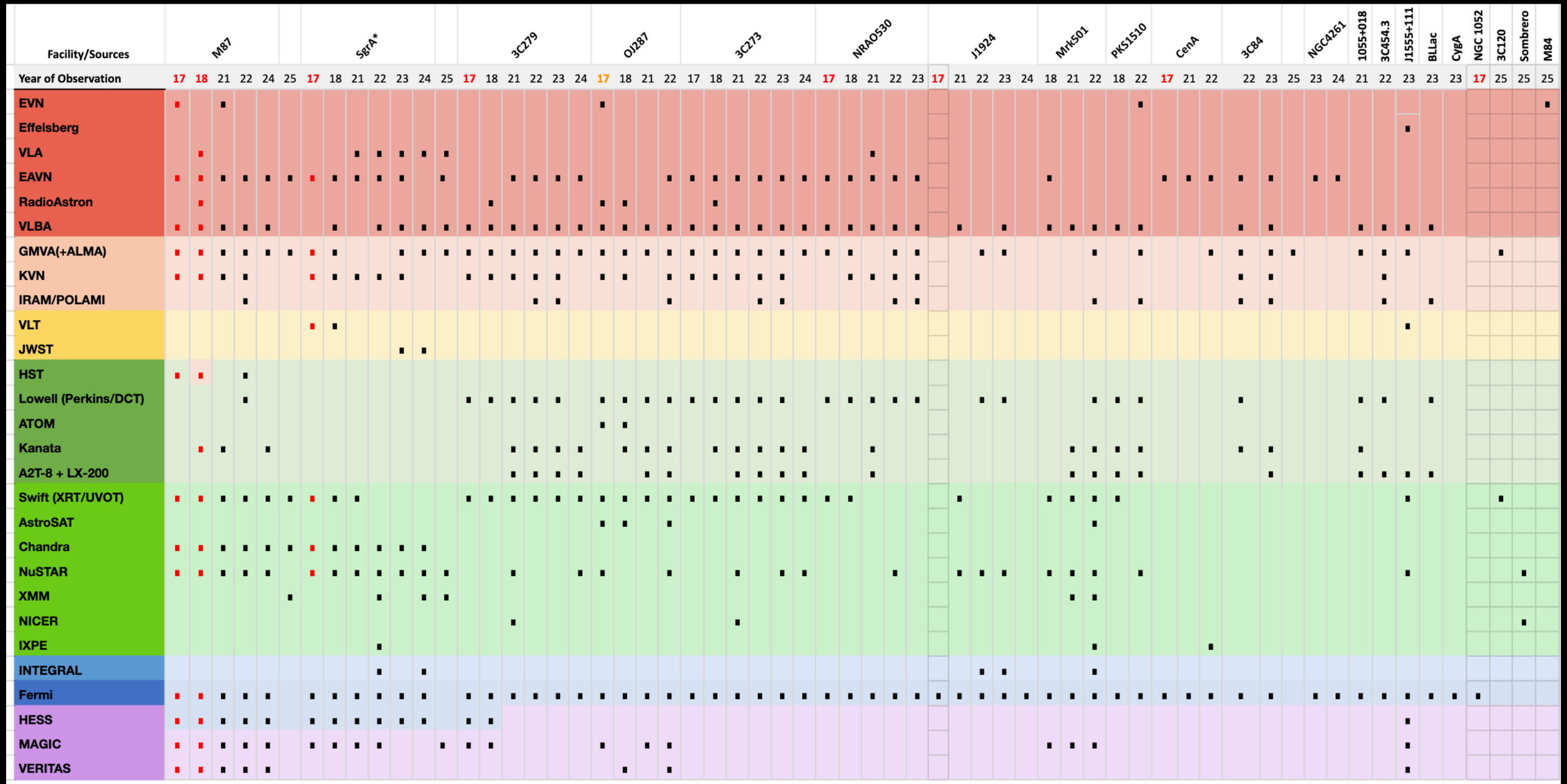
Event Horizon Telescope
(red=AMT baselines)



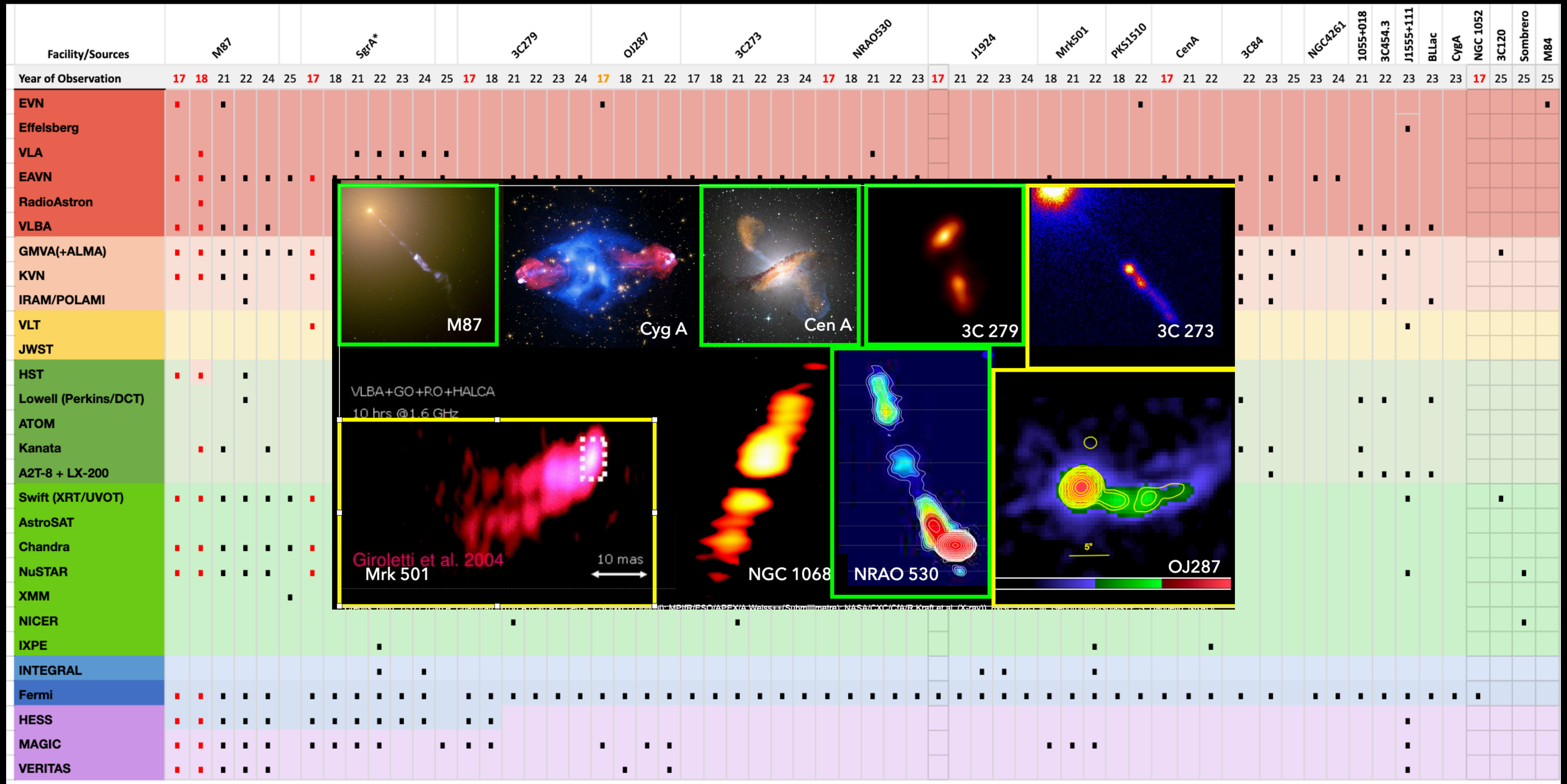
Partnering with UNAM

Johnson++2023: "Key Science Goals fo

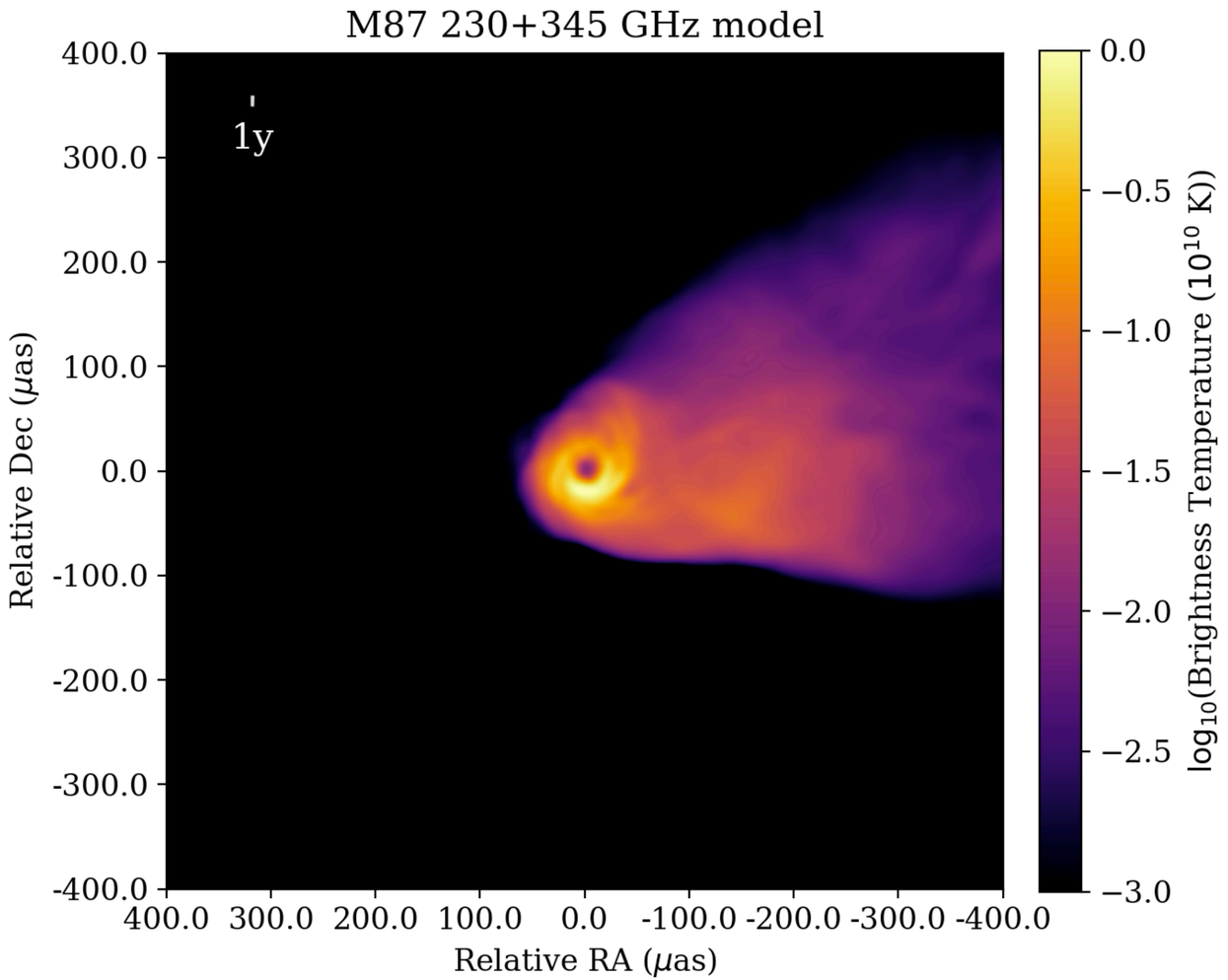
A sense of what's to come….

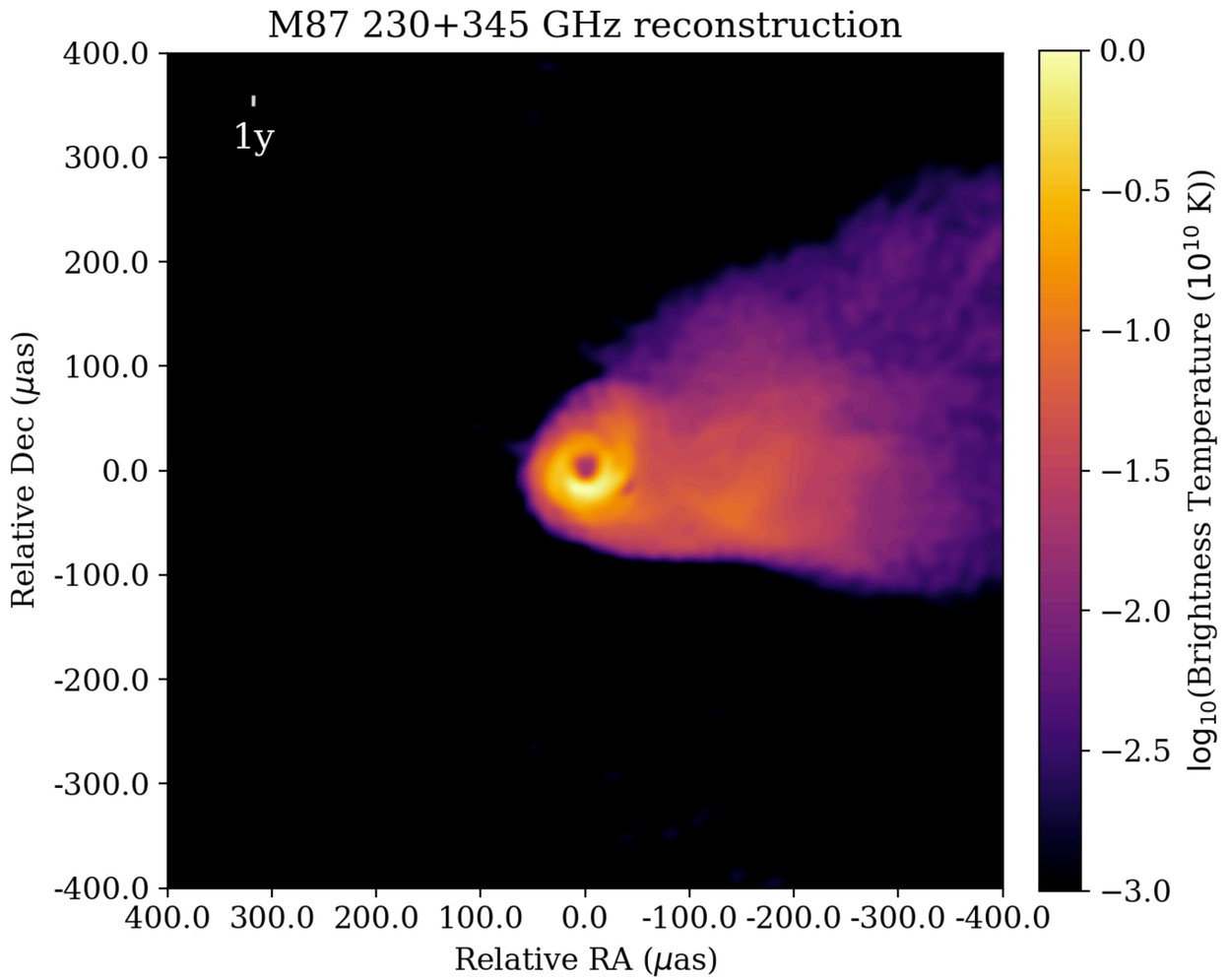


A sense of what's to come….



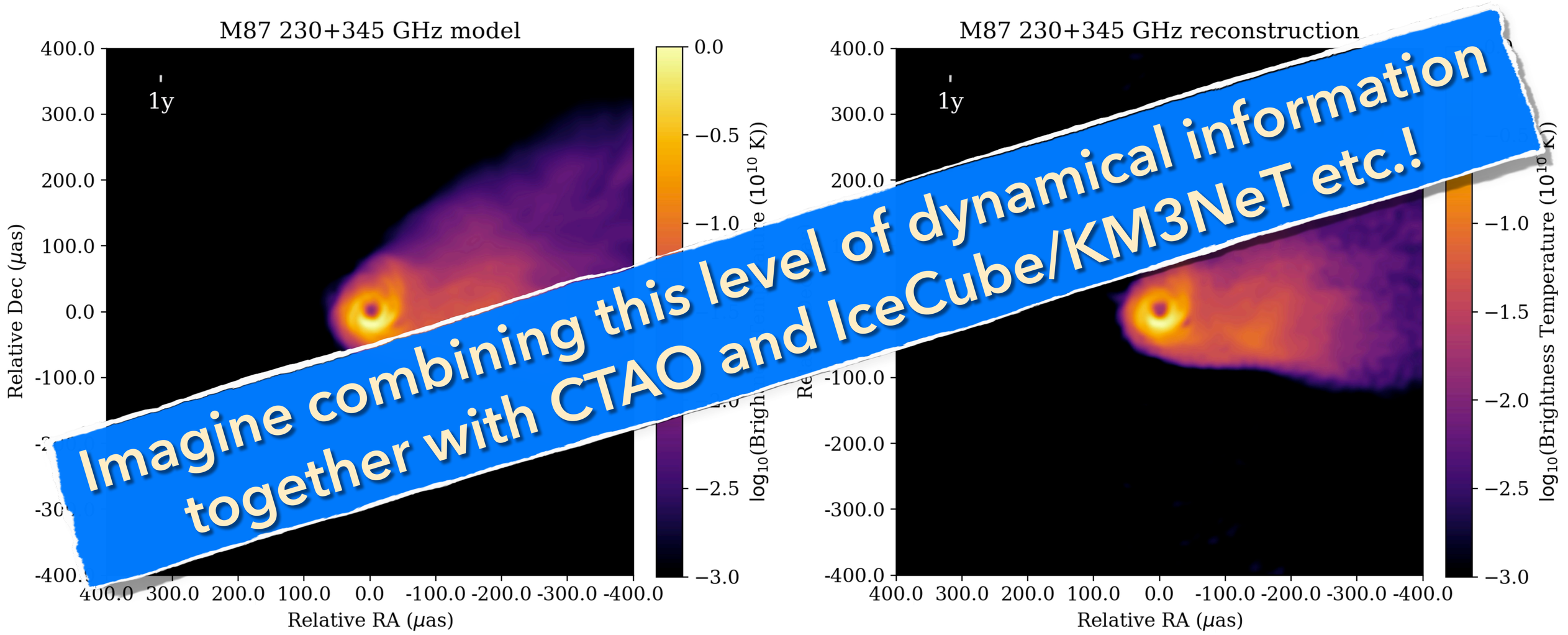
Future: ngEHT dynamical imaging + MWL/MM monitoring!





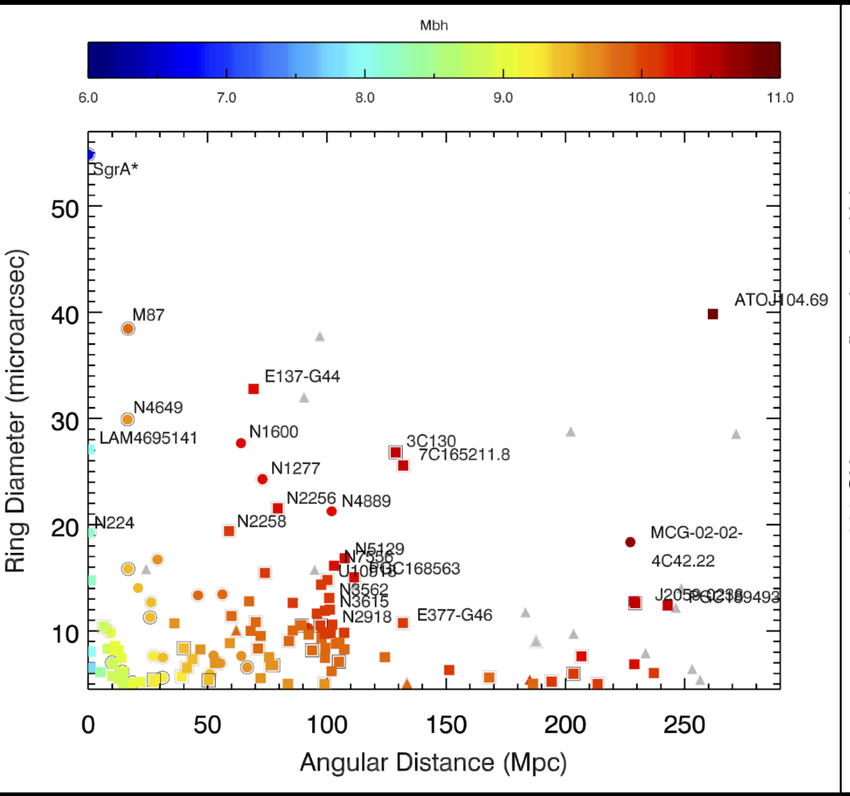
Reconstructed ngEHT movie: L. Blackburn (SAO), site model: A. Raymond, jet simulation w/nonthermal reconnection heating model: Chael++2019

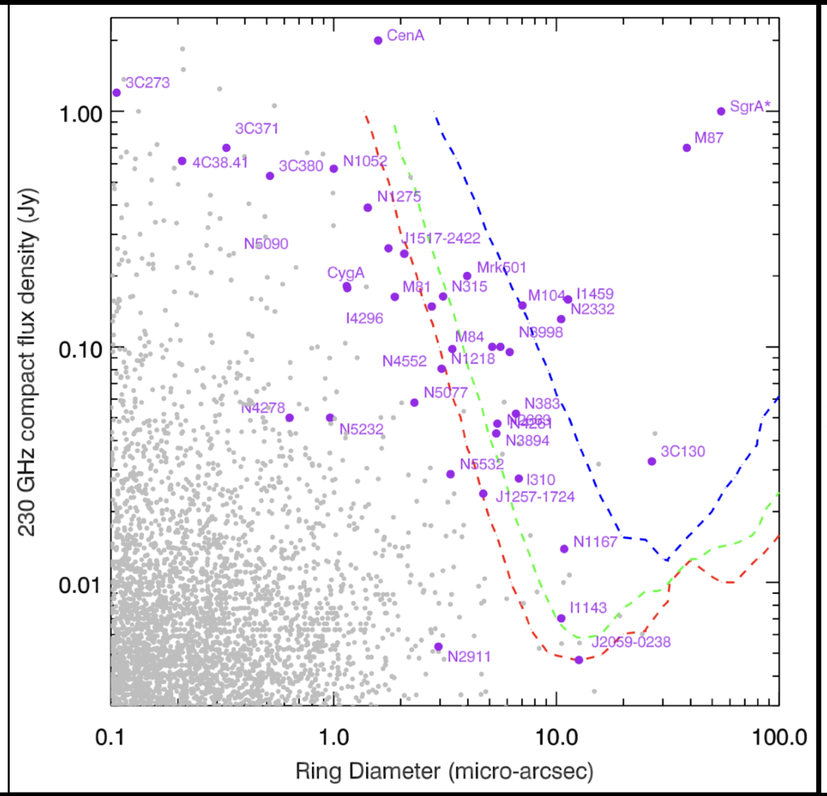
Future: ngEHT dynamical imaging + MWL/MM monitoring!

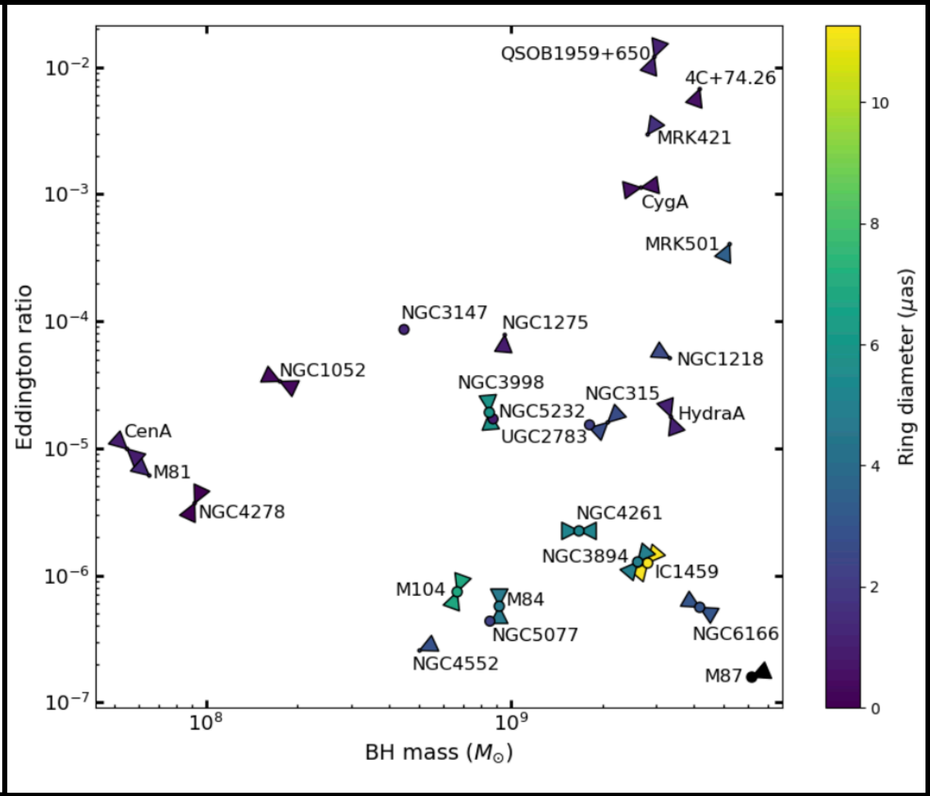


Reconstructed ngEHT movie: L. Blackburn (SAO), site model: A. Raymond, jet simulation w/nonthermal reconnection heating model: Chael++2019

ETHER sample: thinking ahead to EHT++ (and space VLBI)







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

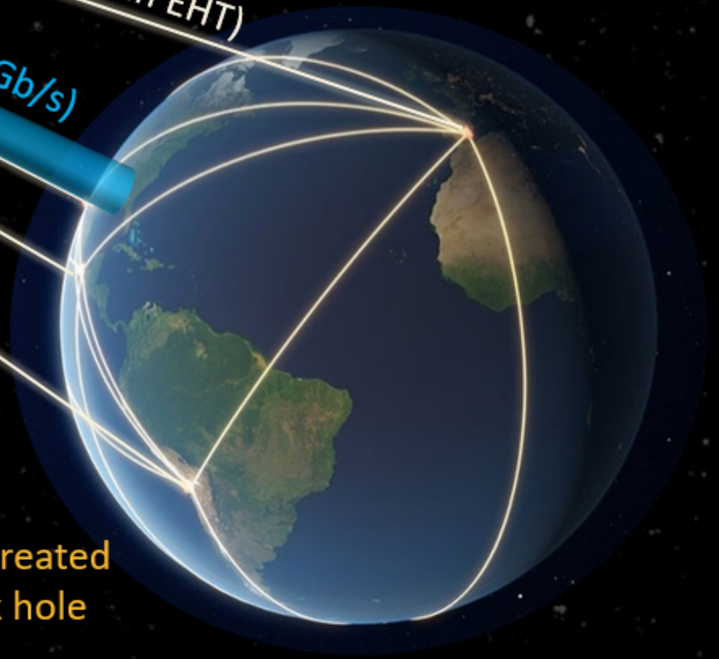
Future is space: BHEX

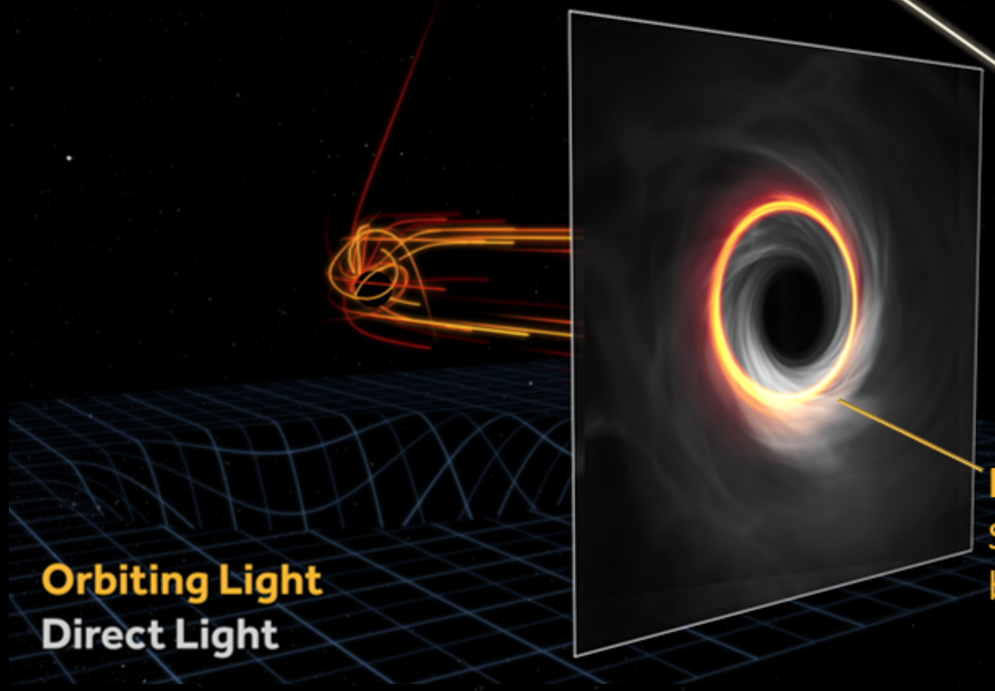
Ground Only

Ground + Space

Space-Ground Baselines (3x Longer than EHT)

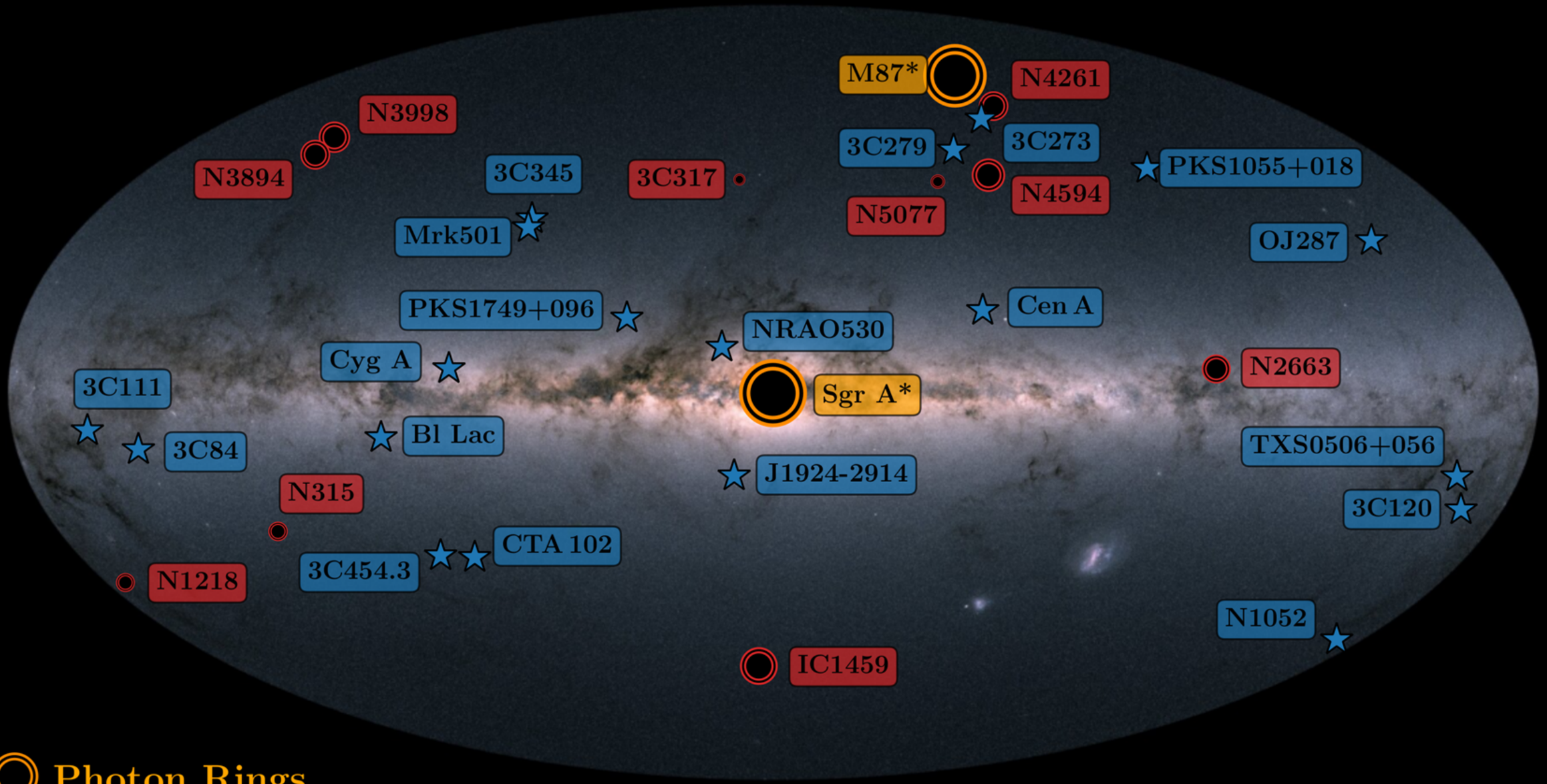
High-Speed Laser Downlink (100 Gb/s)





Photon ring
Sharp circular feature created by light orbiting a black hole

Orbiting Light
Direct Light



Johnson+2024 - Black Hole Explorer https://arxiv.org/pdf/2406.12917

Summary

★EHT provided the first “close-up” view of the extremes of BH cyclic activity, Sgr A* and M87*, and is starting to tackle their time evolution

★CR paradigm radically shifting: *combining EHT + MWL/MM can finally reveal the links between global dynamics and particle acceleration*

★2018-2022 (+KP and NOEMA) results out/imminent. Near term milestones: Sgr A* dynamical movies, connecting M87* to the jets

★M87’s 2018 flare is already a major focus for theoretical investigation, but the 2026 EHT “movie” campaign + VHE will be groundbreaking!

★EHT is expanding on Earth and in space, stay tuned for the first movies of black holes, better tests of GR, acceleration and a wide range of new science