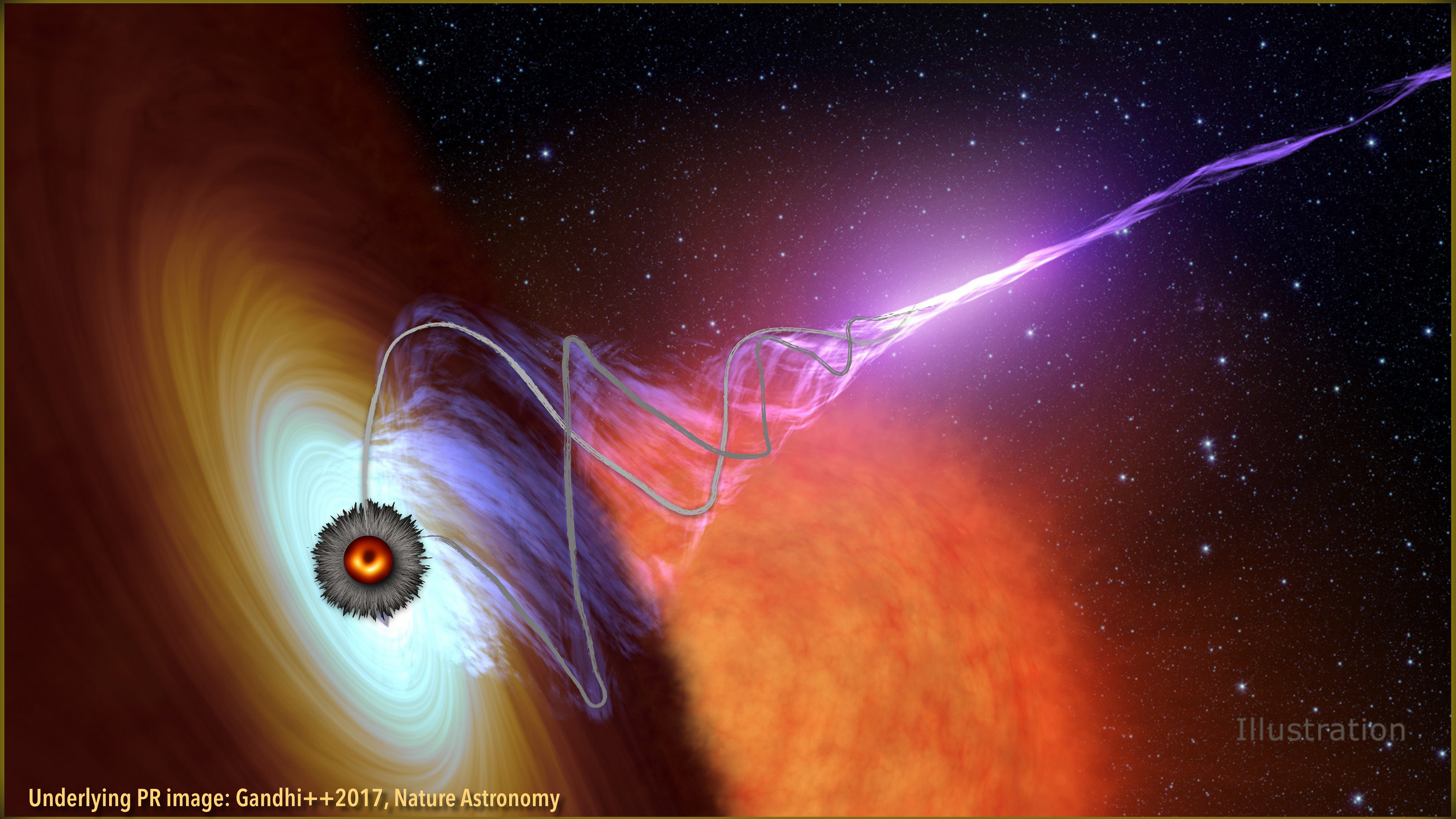
And then there was light: what black hole imaging w/EHT can teach us about particle acceleration

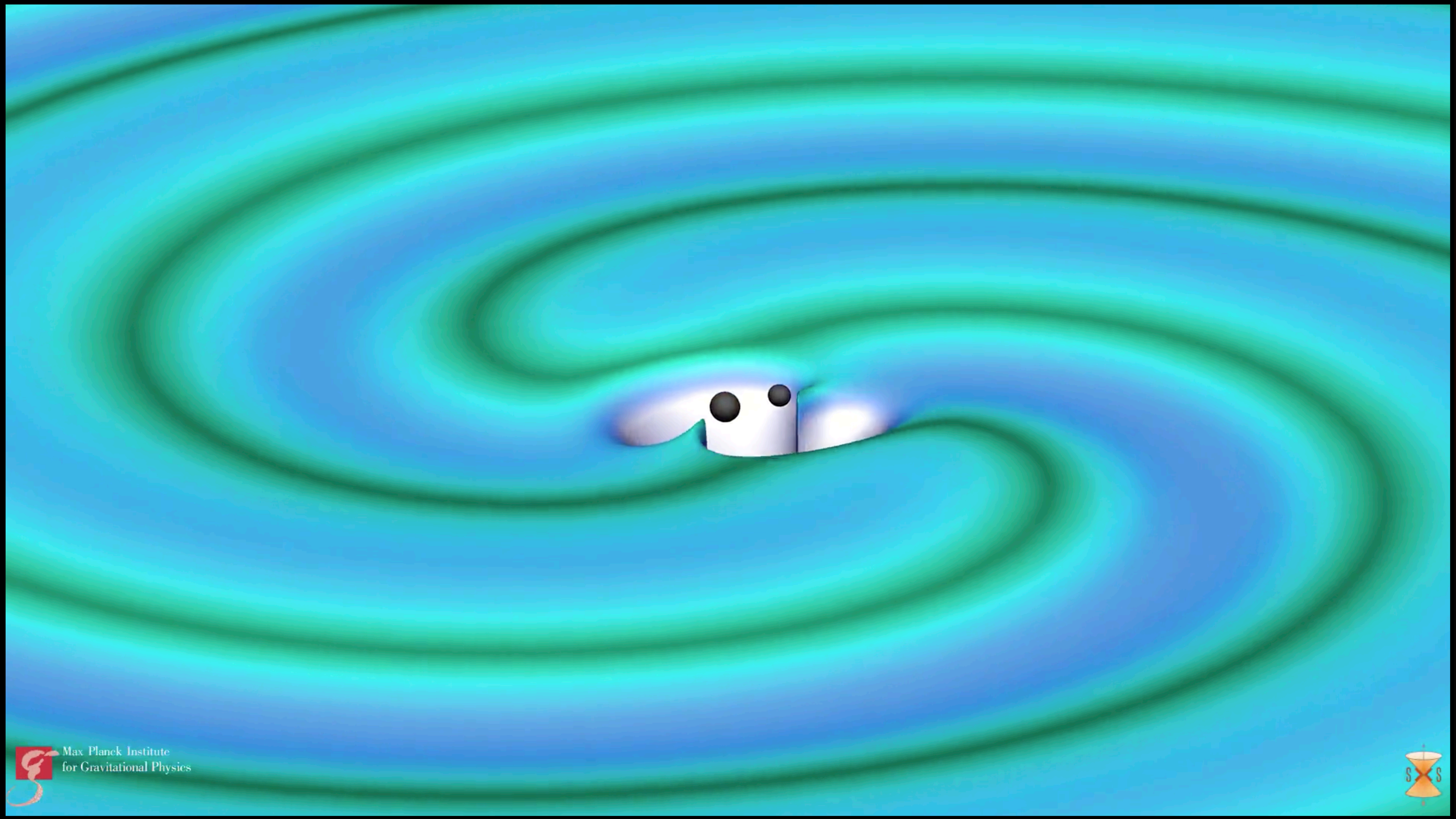


Underlying PR image: Gandhi++2017, Nature Astronomy

Sera Markoff + EHT MWL WG + EHTC/EAVN/FERMI/HESS/MAGIC/VERITAS + several current/former members of the 'jetsetters' group @ U Amsterdam (C. Ceccobello, K. Chatterjee, A. Chhotray, A. Cooper, P. Crumley, D. v. Eijnatten, C. Hesp, D. Kantzas, M. Liska, M. Lucchini, G. Musoke, T. Russell, D.-S. Yoon) + S. Phillipov, B. Ripperda, S. Tchekhovskoy, Z. Younsi (UCL!)

The new revolution in (astro)physics: "seeing" black holes

2015: **discovery of gravitational waves from merging black holes (*2017 Physics Nobel Prize*)**



LIGO/VIRGO collaboration

4/2019: **first image of a supermassive black hole in the heart of a galaxy**

Event Horizon Telescope Collaboration

The path to establishing ‘real’ black holes (1918-1963)

H. Curtis 1918: (on the M87 galaxy!!)

“A curious straight ray lies in a gap in the nebulosity in p.a. 20 deg, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11 arcsec, from the nucleus."

The path to establishing 'real' black holes (1918-1963)

(3C 273 in old optical plate image. Credit: Narlikar 1993)

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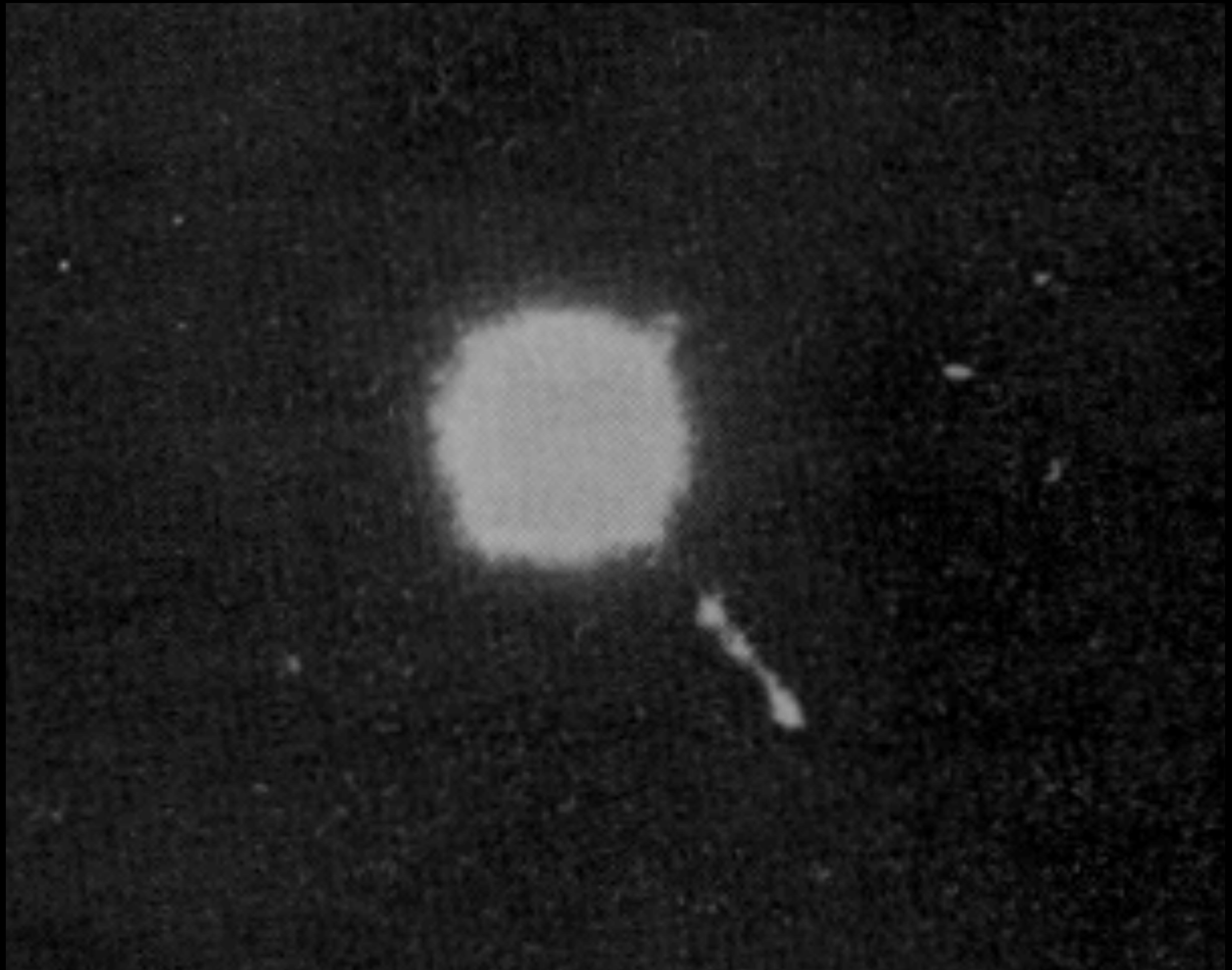
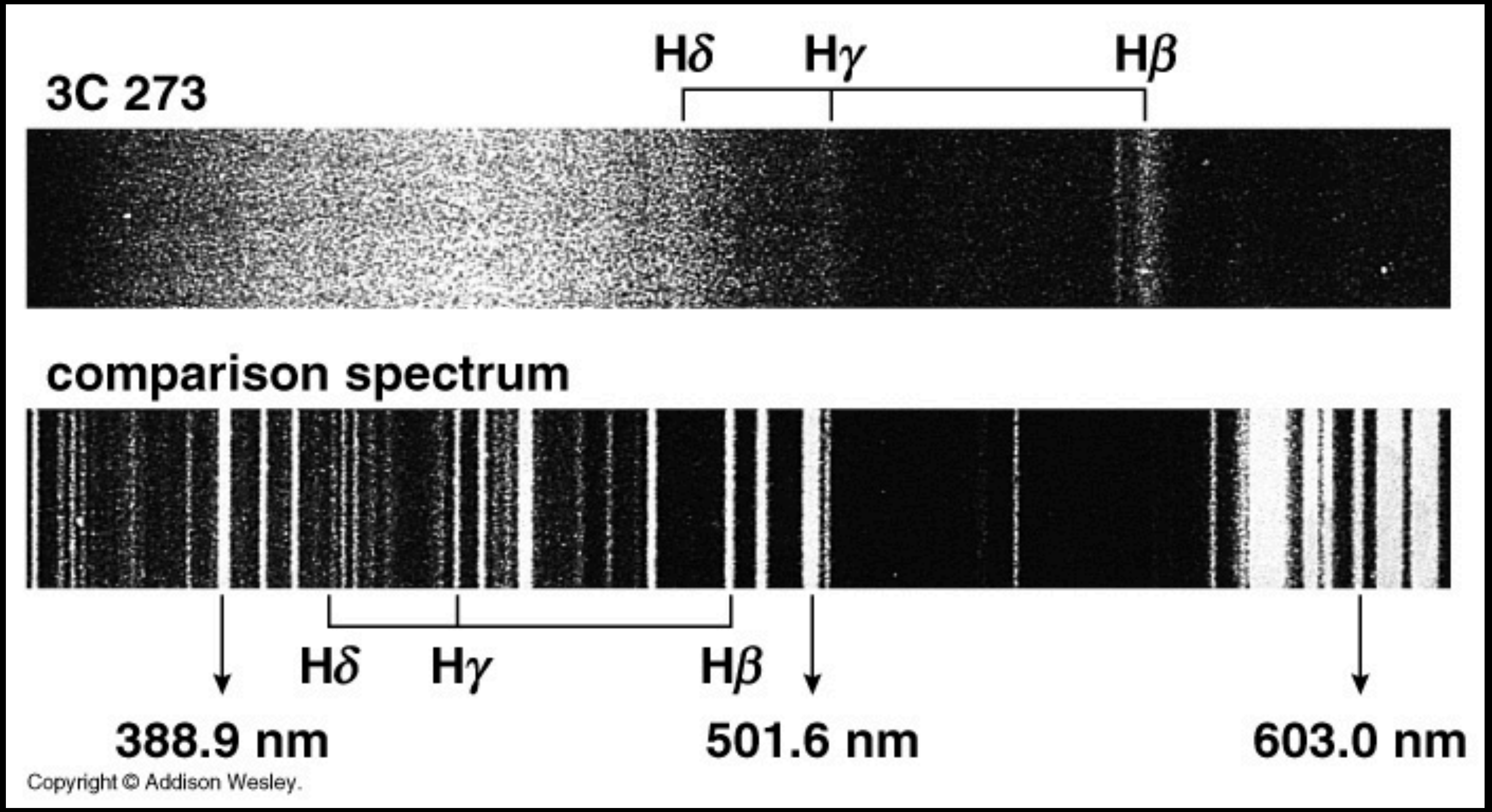


(3C 273 in old optical plate image. Credit: Narlikar 1993)



(Schmidt++1963)

★ "Quasar" = Quasi-stellar object, typically (hundreds of) trillions of times more luminous than our sun. $E=mc^2$ ☛ planet/second!

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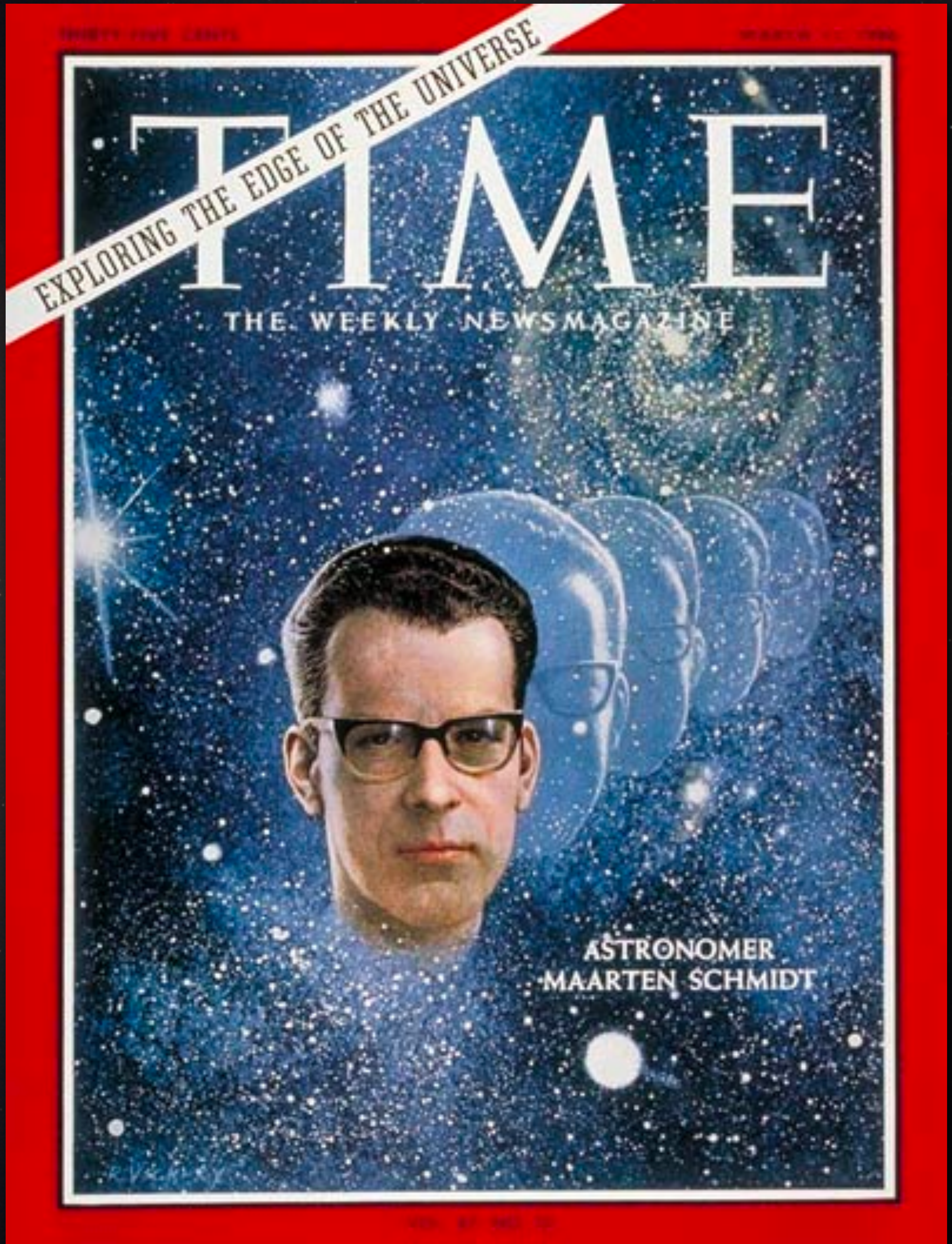

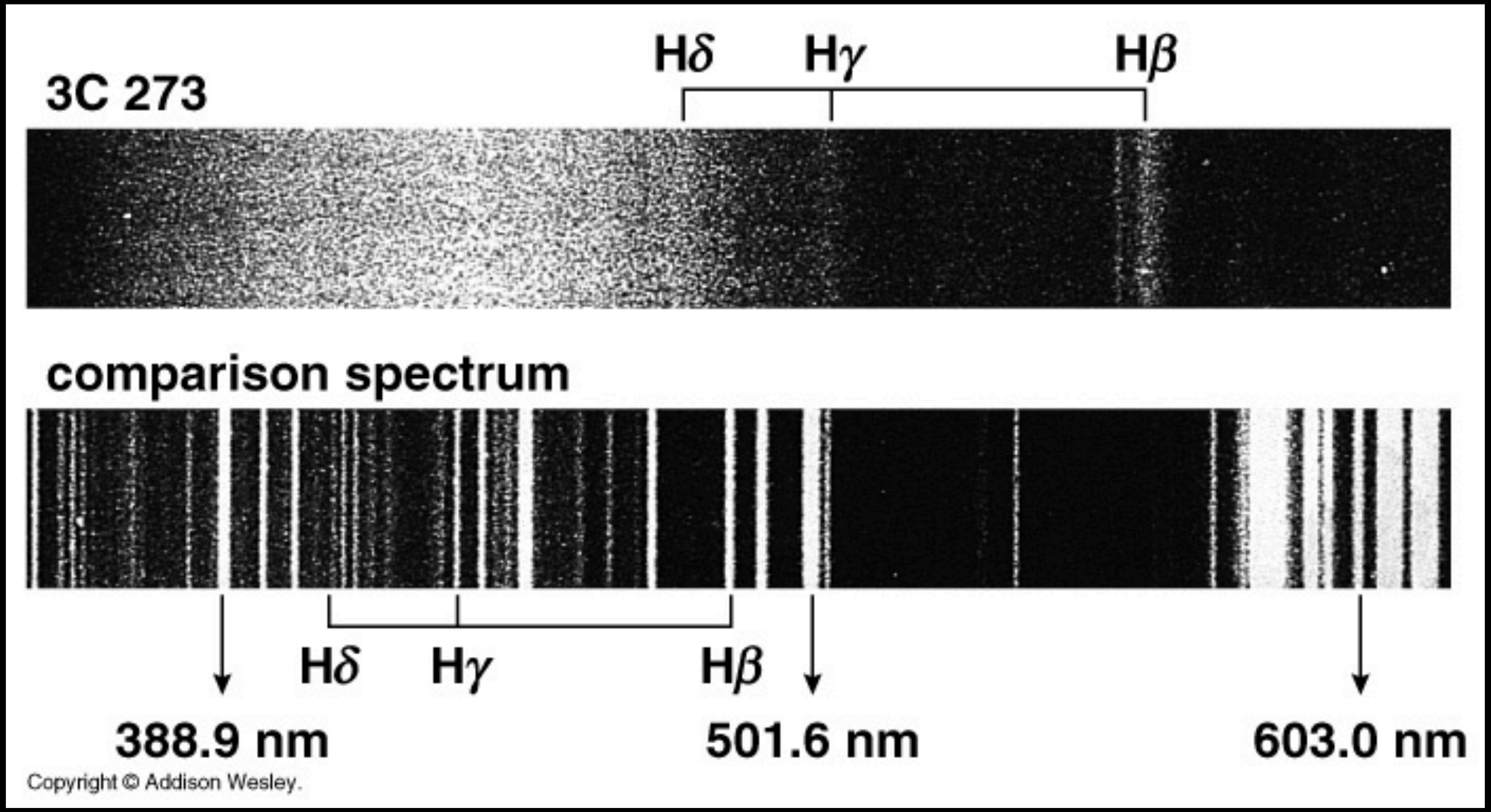

(Schmidt++1963)

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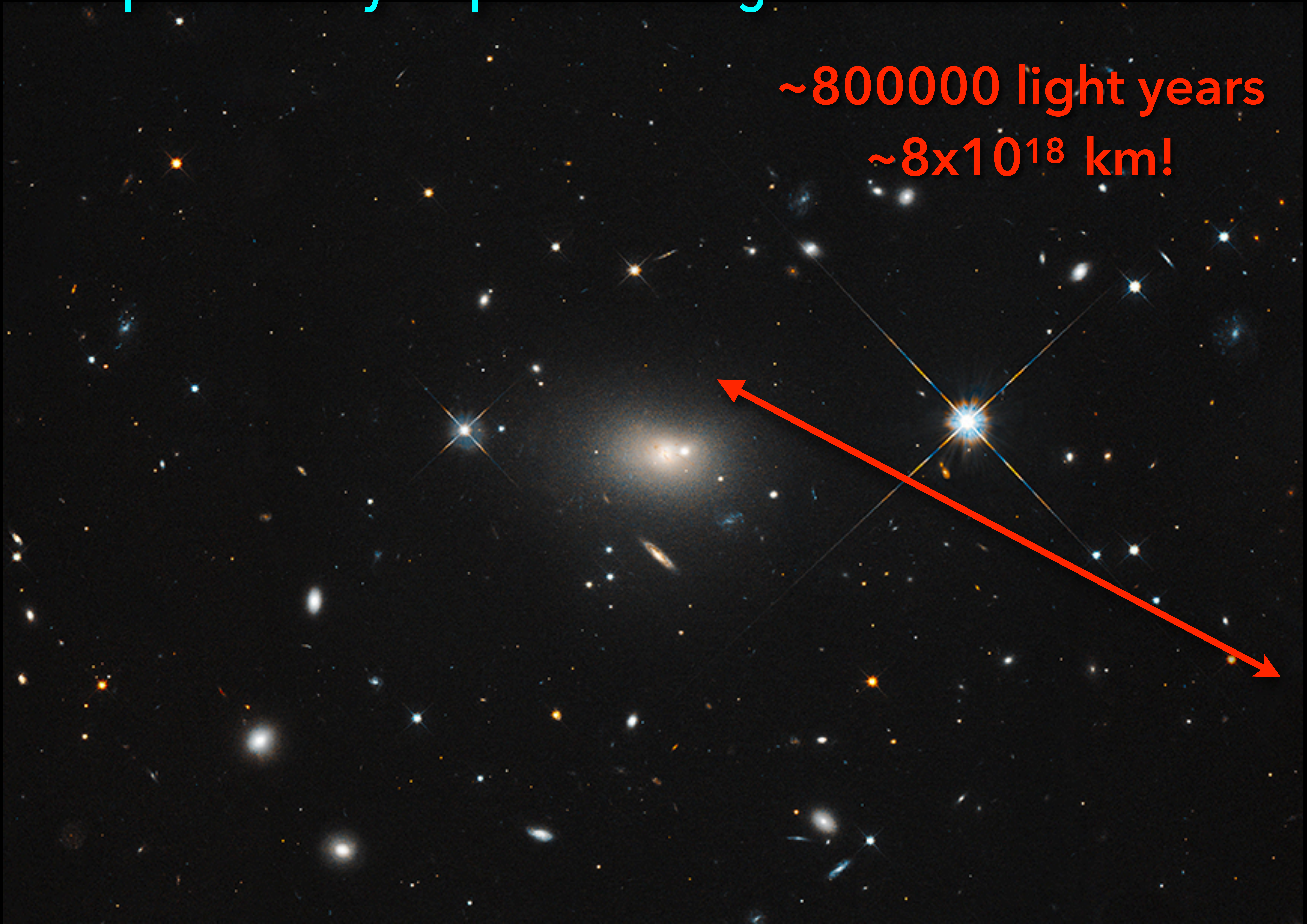
Black holes profoundly impact the largest structures in the Universe



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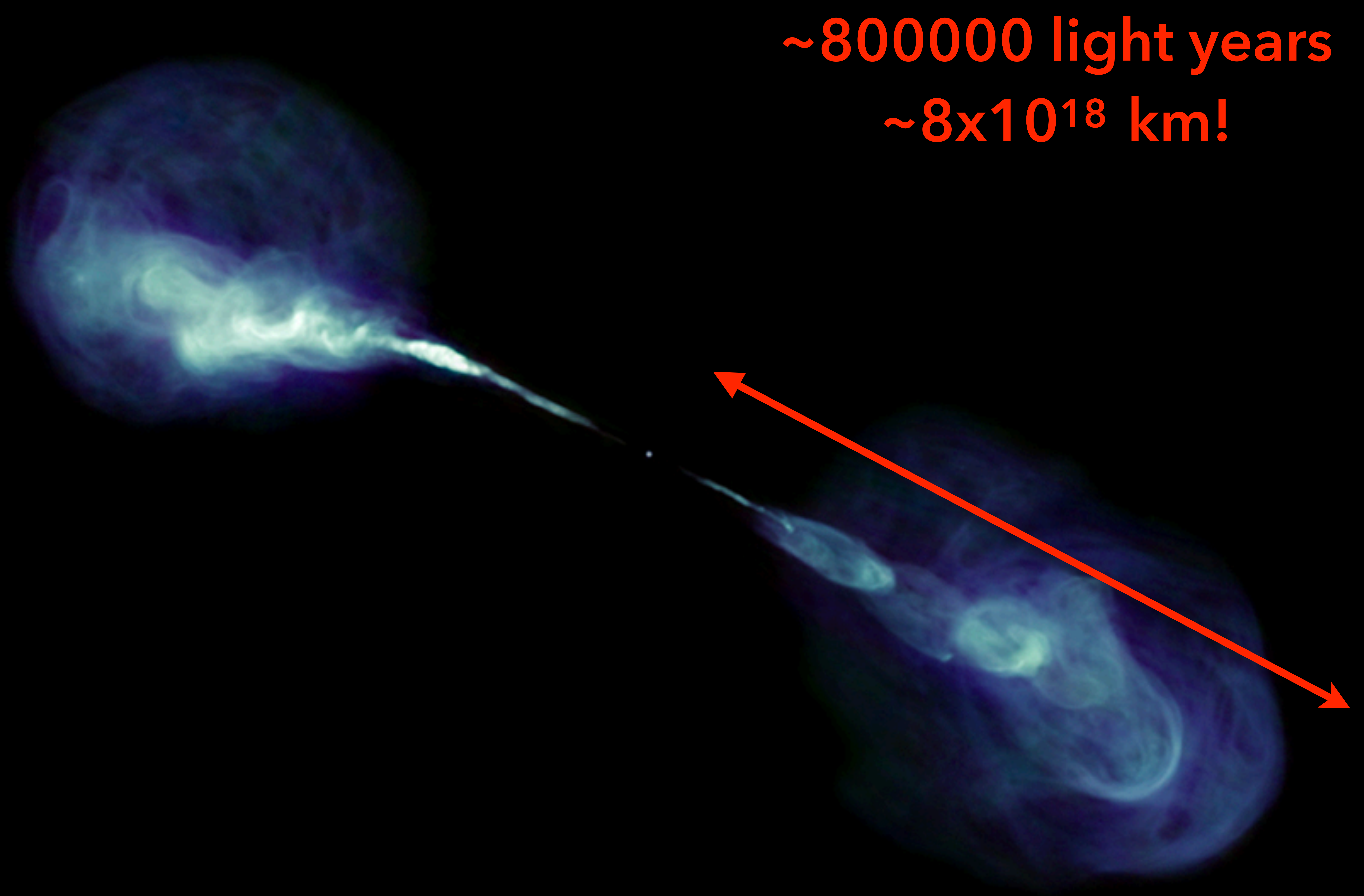

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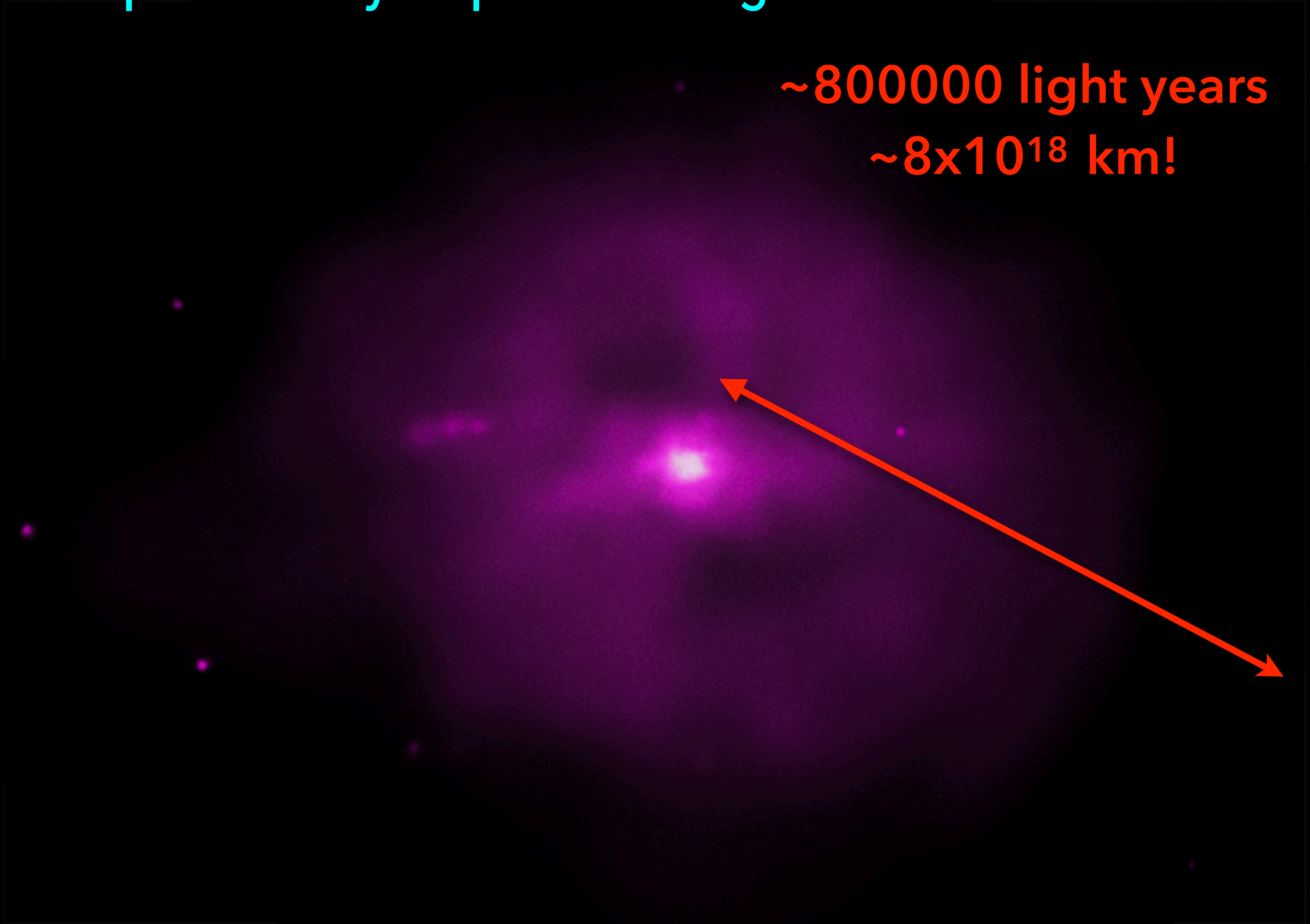

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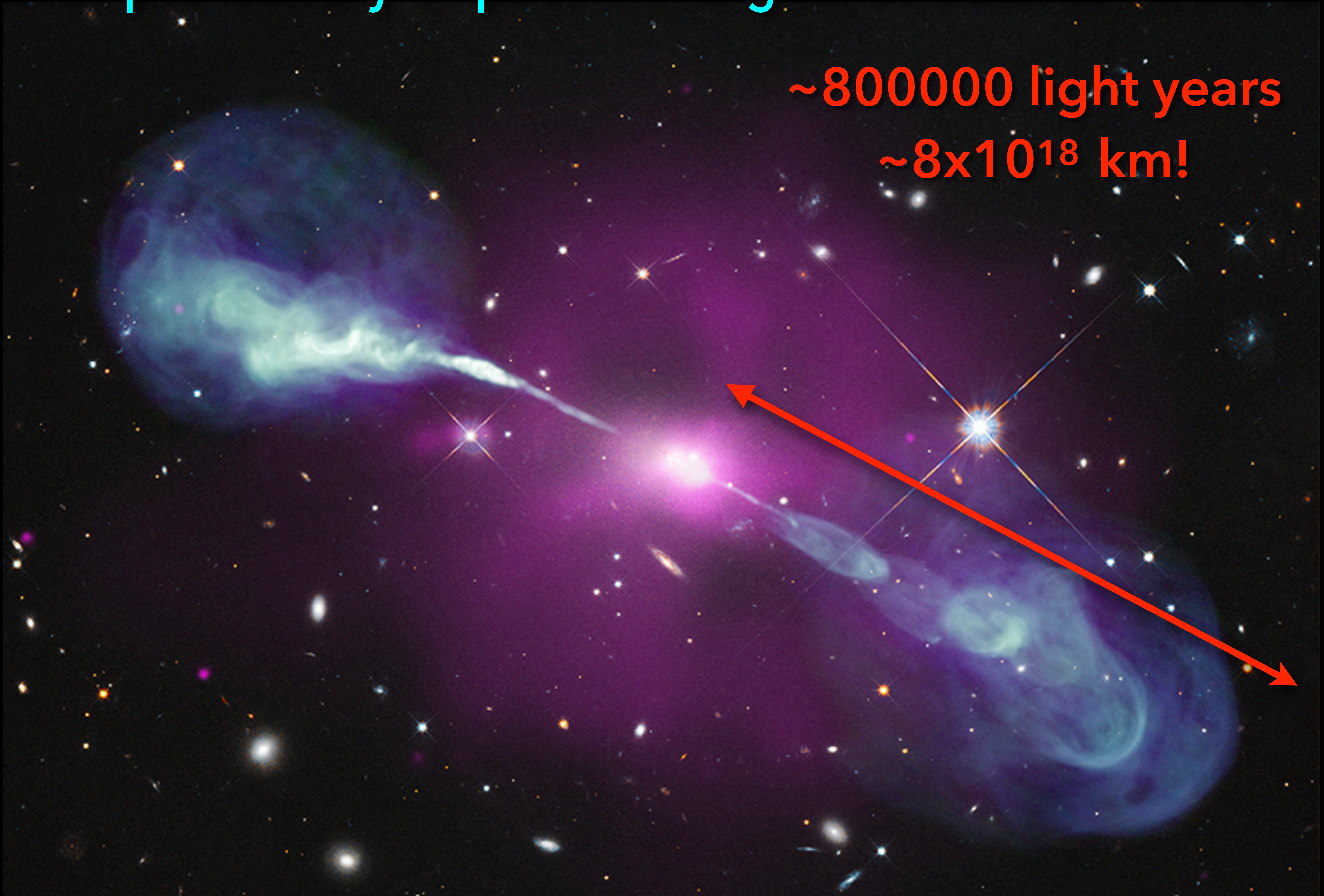

Hercules A galaxy, Credit: Xray (NASA/CXC/SAO), Optical (NASA/Hubble Space Telescope), Radio (NSF/NRAO/VLA)

New decade, same questions

Outline

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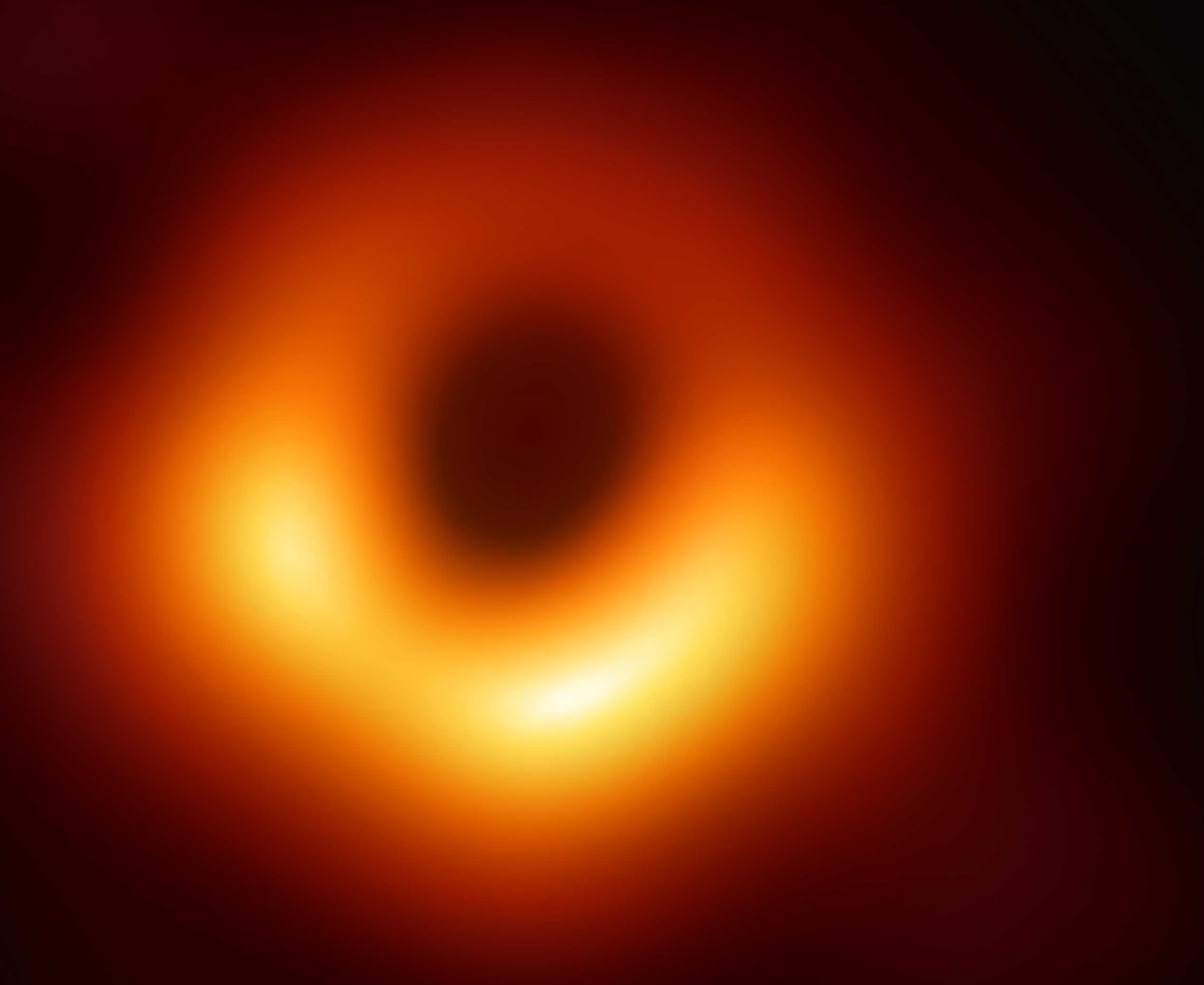
April 2017 results for M87's supermassive black hole

EHT December 2020: online collaboration meeting group photo

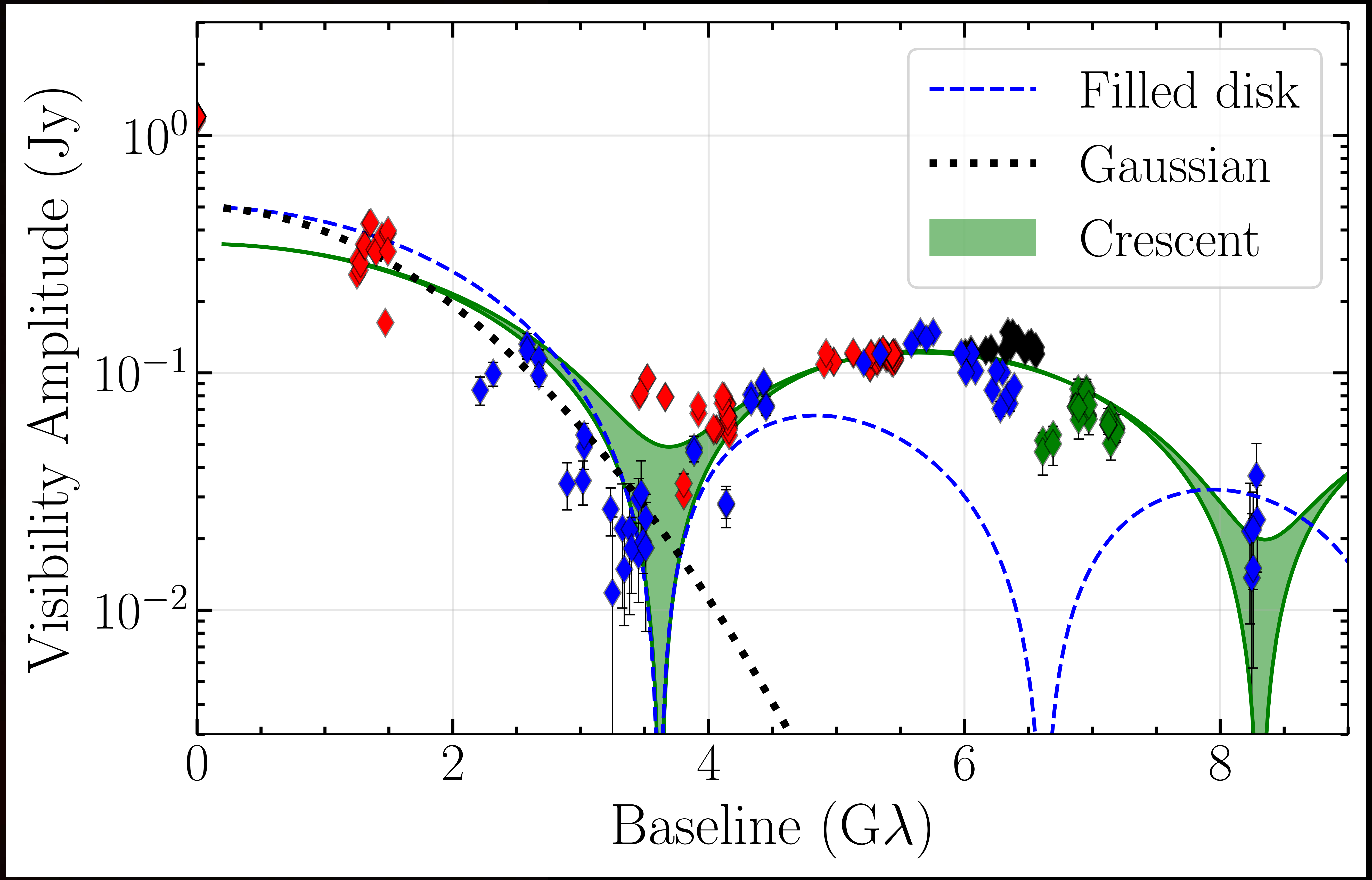
(EHT Collaboration 2019: Papers I - VI; Code comparison paper: Porth, Chatterjee++ 2019)

April 2017 results for M87's supermassive black hole

Reconstructed image



Measured structure on sky (Fourier power)



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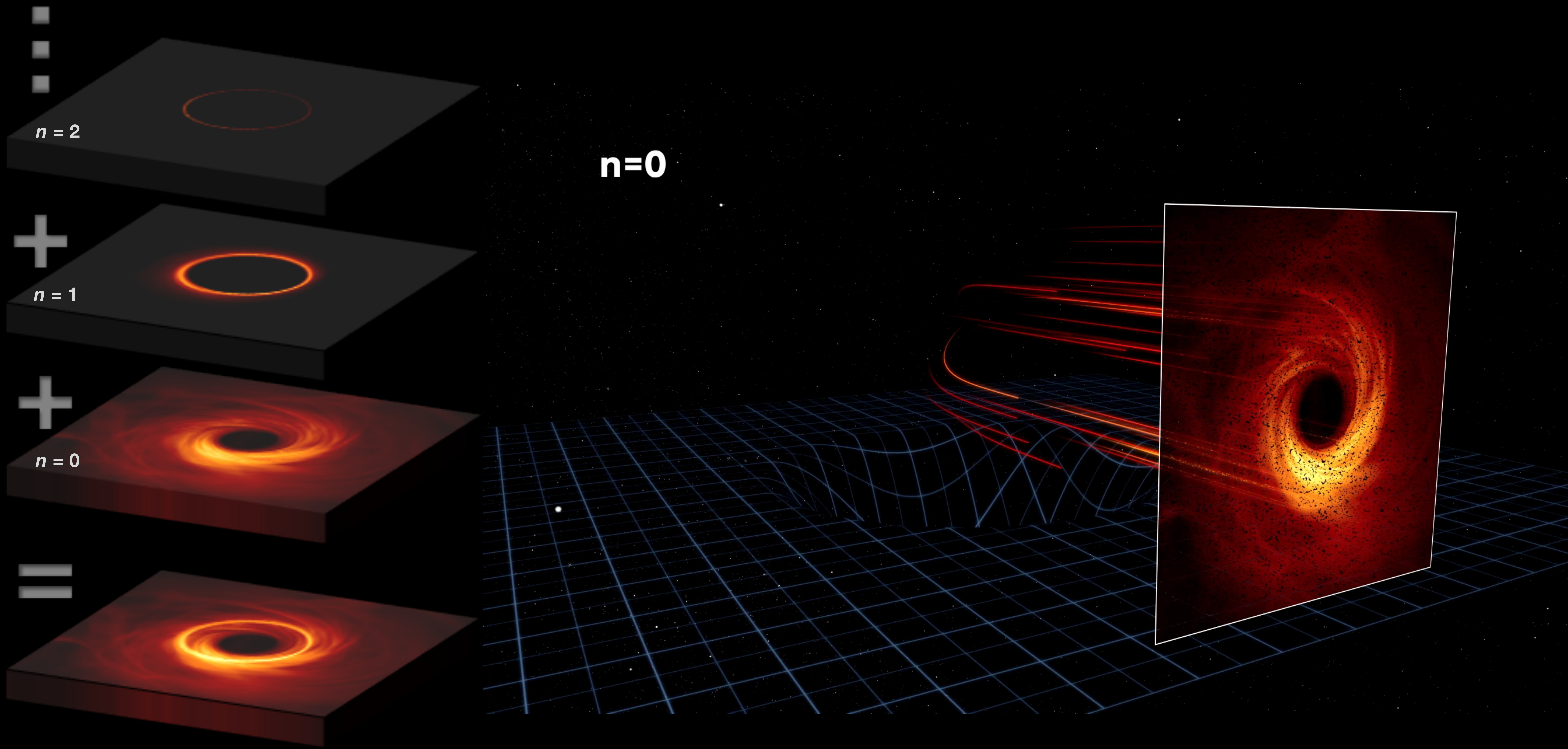
Decomposing the EHT image into photon half-orbit images



(see Johnson++2020; visualisations courtesy M. Johnson & G. Wong. See also e.g., Johannsen & Psaltis 2010; Gralla et al. 2019)

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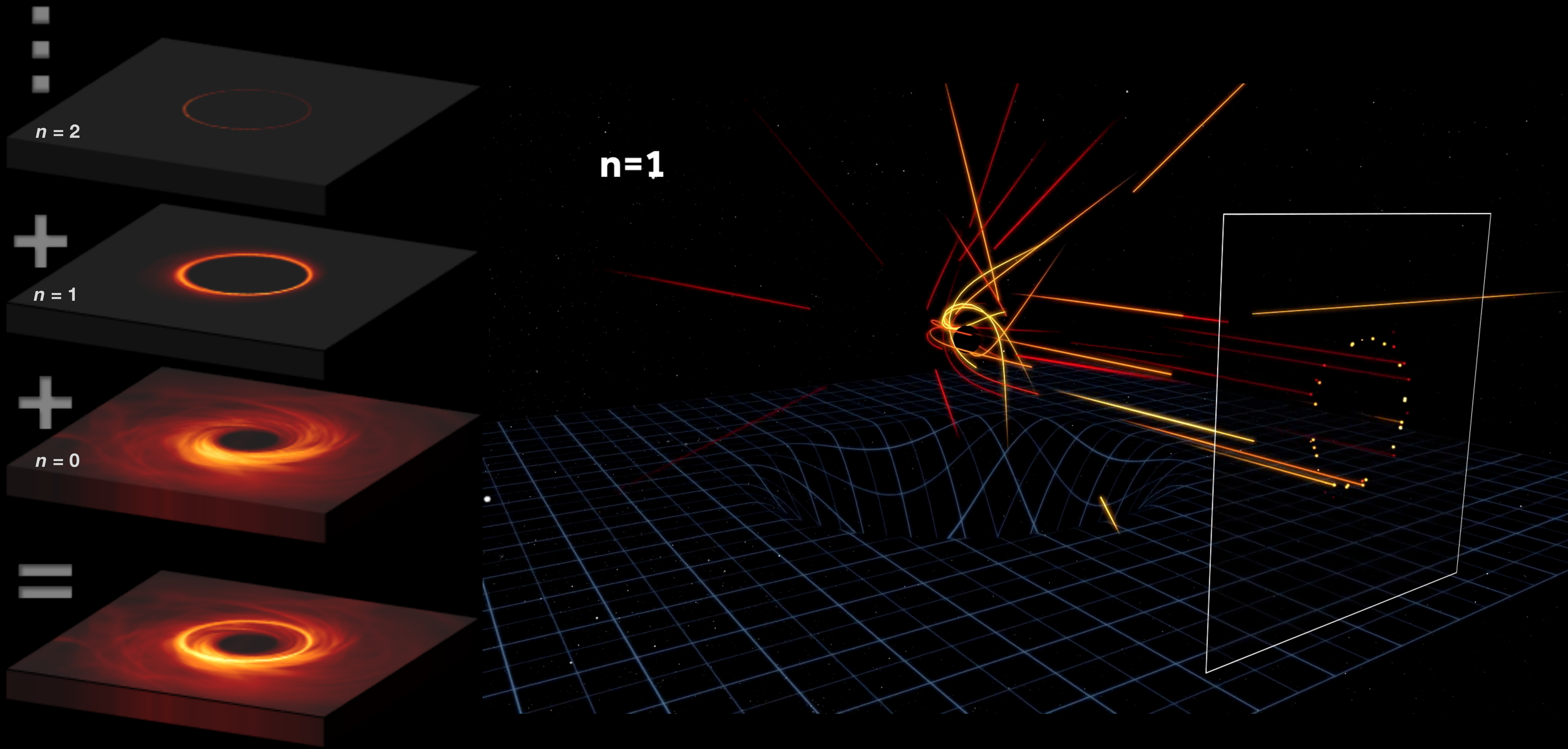

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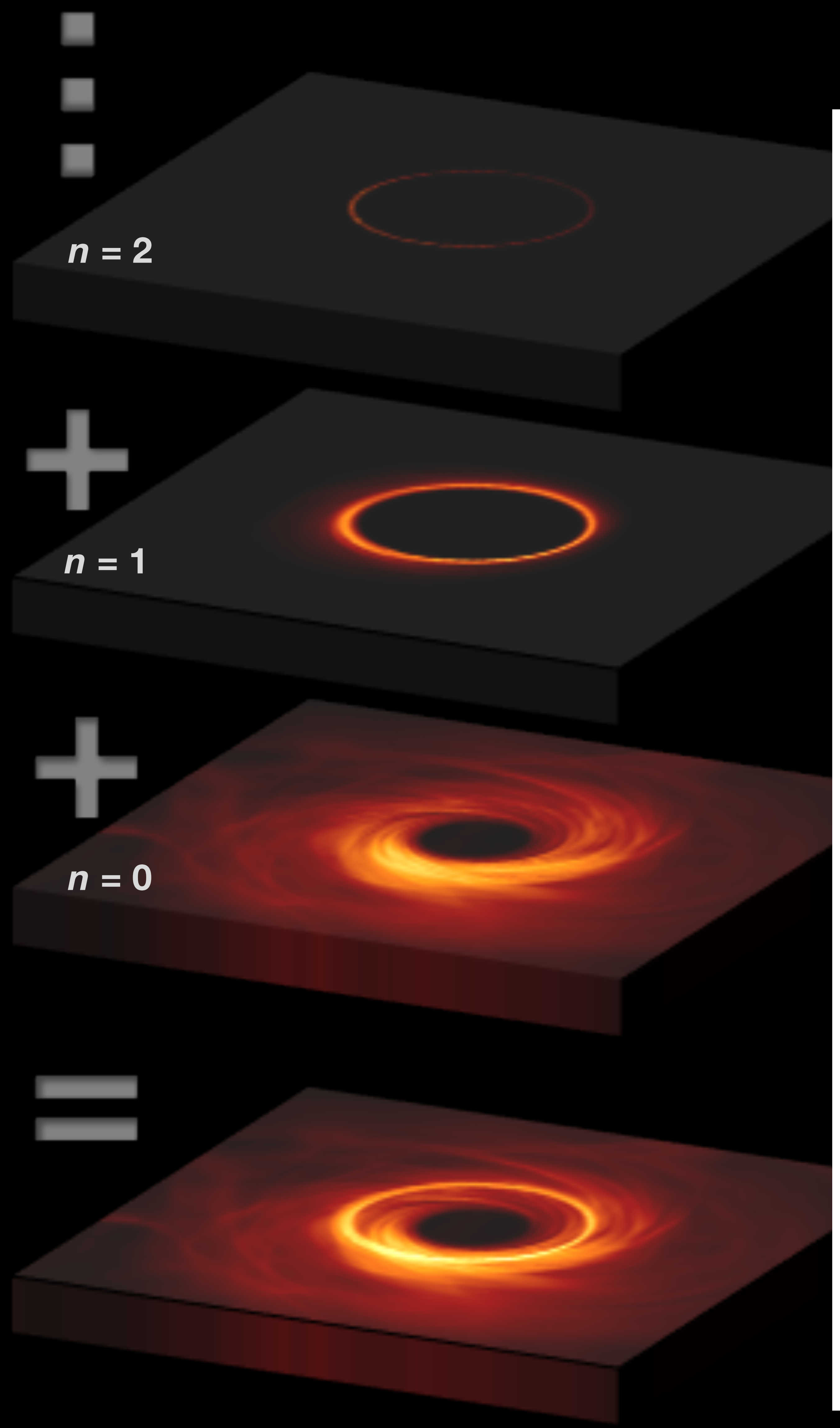
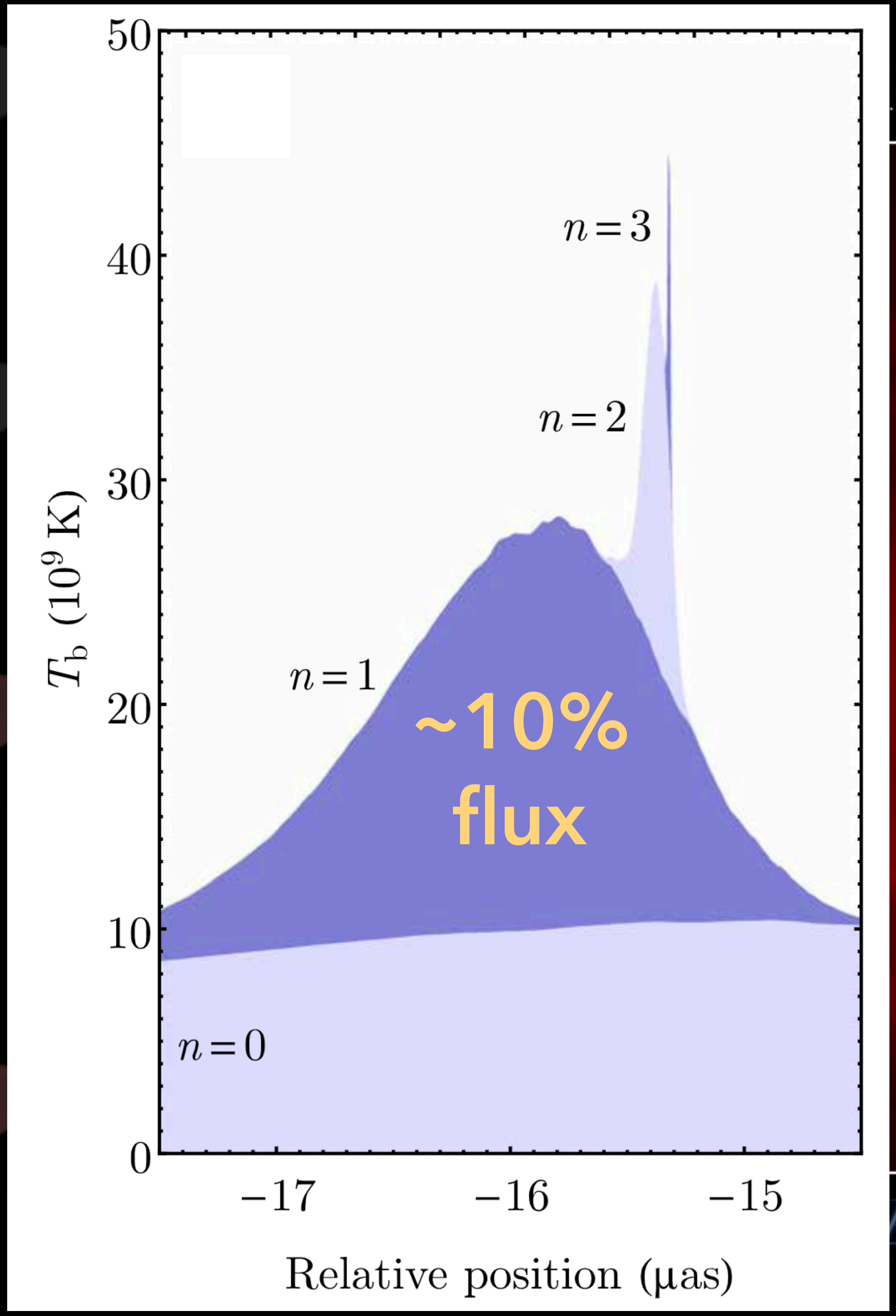
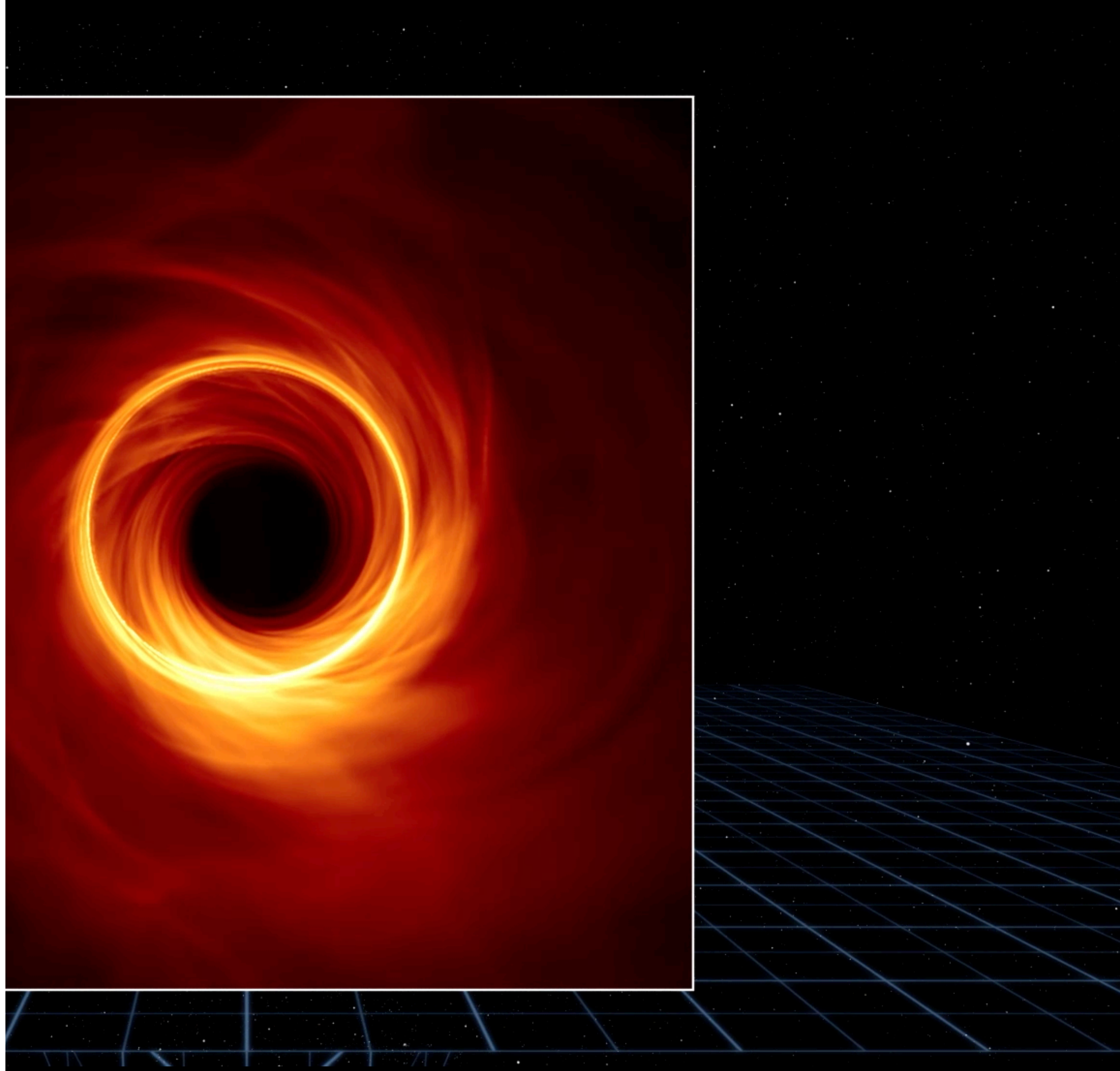
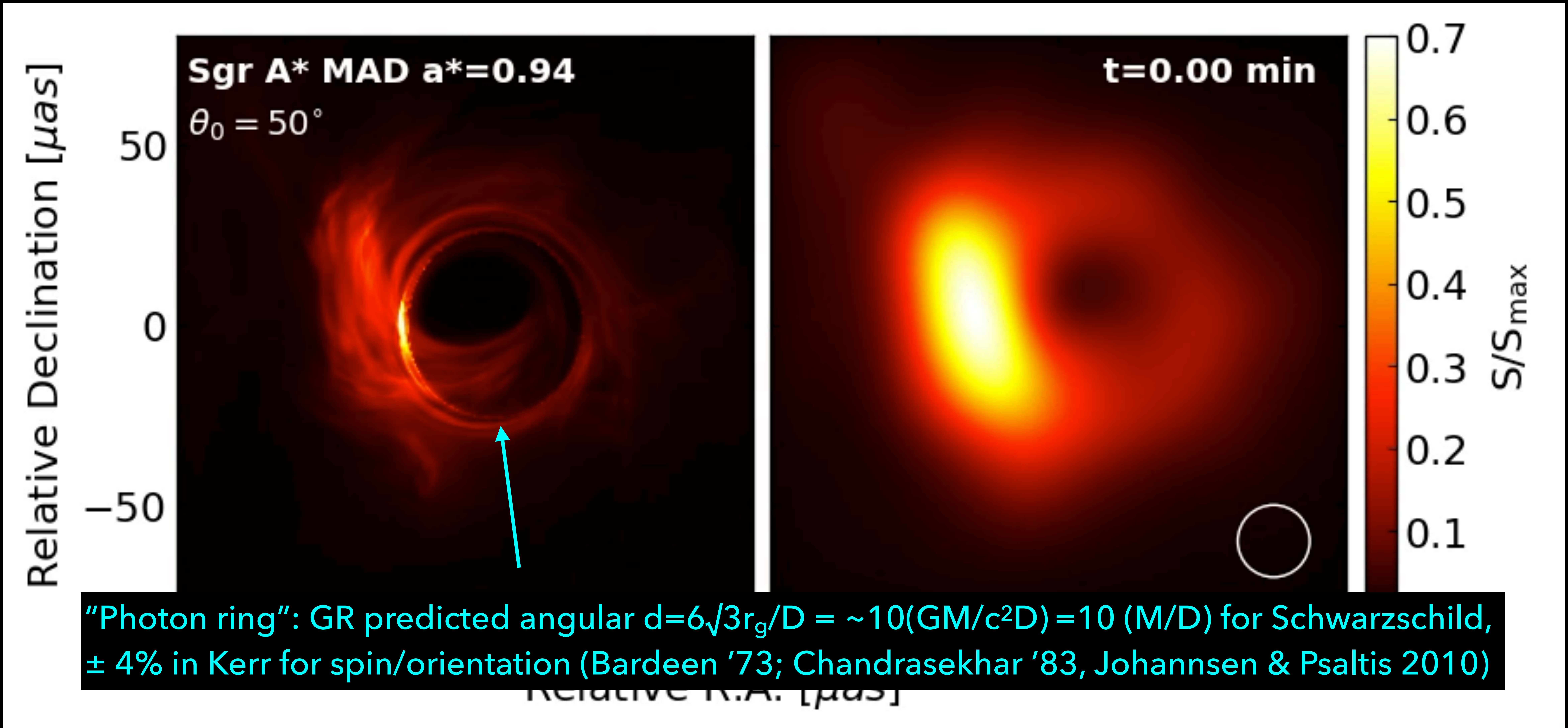






(see Johnson++2020; visualisations courtesy M. Johnson & G. Wong. See also e.g., Johannsen & Psaltis 2010; Gralla et al. 2019)

Decomposing the blurry ring into astrophysics + GR



"Photon ring": GR predicted angular $d=6\sqrt{3}r_g/D$ = ~$10(GM/c^2D)=10\ (M/D)$ for Schwarzschild, ± 4% in Kerr for spin/orientation (Bardeen '73; Chandrasekhar '83, Johannsen & Psaltis 2010)

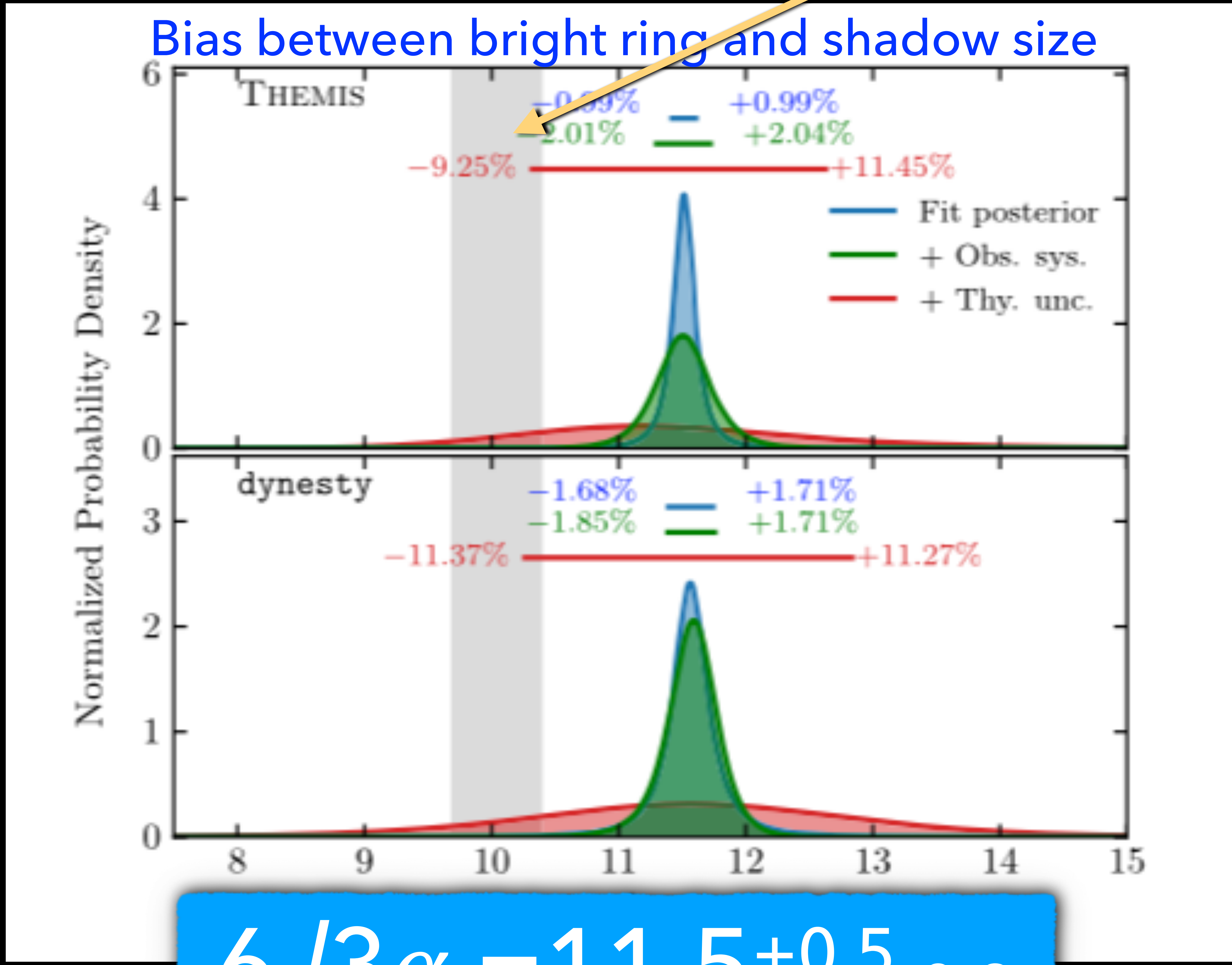
(GRMHD simulation D. Yoon; see Yoon, Chatterjee, SM++2020. Using our GPU-accelerated H-AMR code; Liska, Chatterjee++2019)

Conclusions regarding deviation from GR from 2017 results

$$d = 6\sqrt{3}\,\alpha\,(1+\delta)\left(\frac{GM}{Dc^2}\right)$$

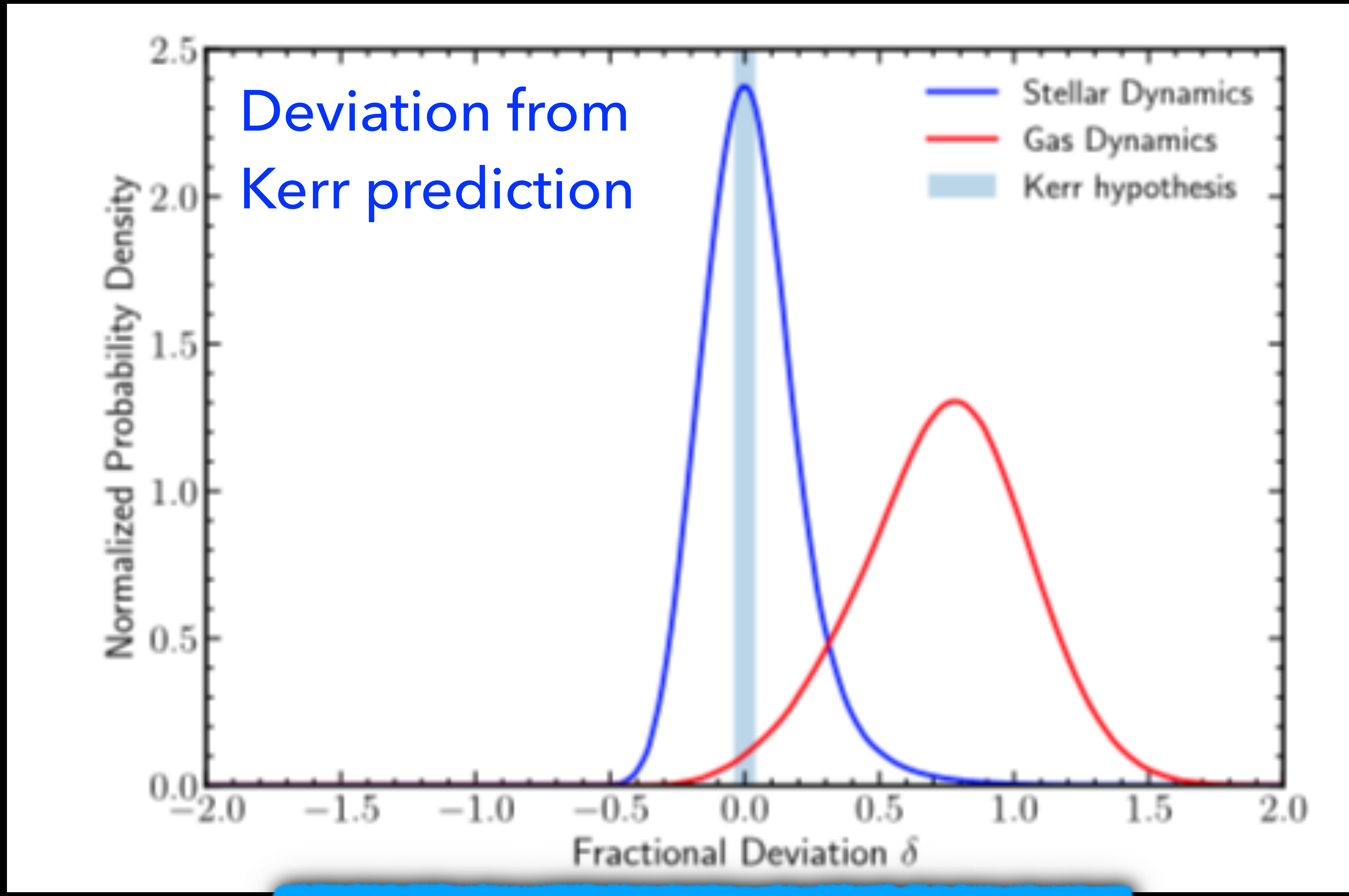
Prior (dynamical) mass + distance measurements

GR shadow size



$6\sqrt{3}\alpha = 11.5^{+0.5}_{-0.3}$

(see Model & Feature Extraction paper VI; EHT Collaboration 2019)



$\delta = -0.01 \pm 0.17$

(For more about GR tests, see: Psaltis, Talbot, Evans & Mandel, subm., arXiv: 2012.02117; Psaltis++ in prep.; see also Gralla++2019)

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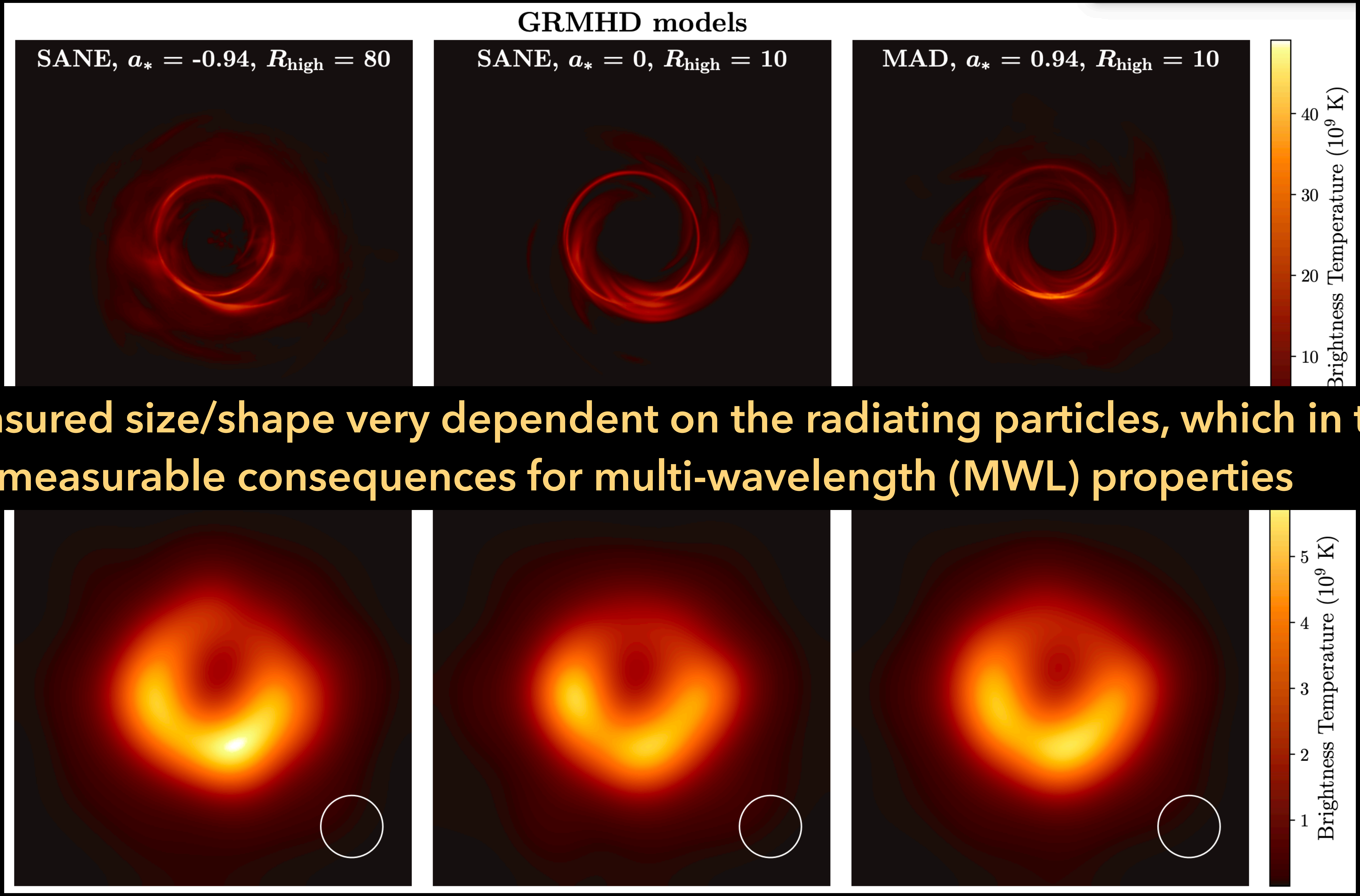
~10% theory ‘error’ introduced by uncertainties in particle properties



Measured size/shape very dependent on the radiating particles, which in turn has measurable consequences for multi-wavelength (MWL) properties

EHT Collaboration 2019, Papers V-VI

2017 M87 Quasi-simultaneous multiwavelength campaign

(EHT Multiwavelength WG, EHTC, EAVN, Fermi, HESS, MAGIC, VERITAS, ApJL, in press.)

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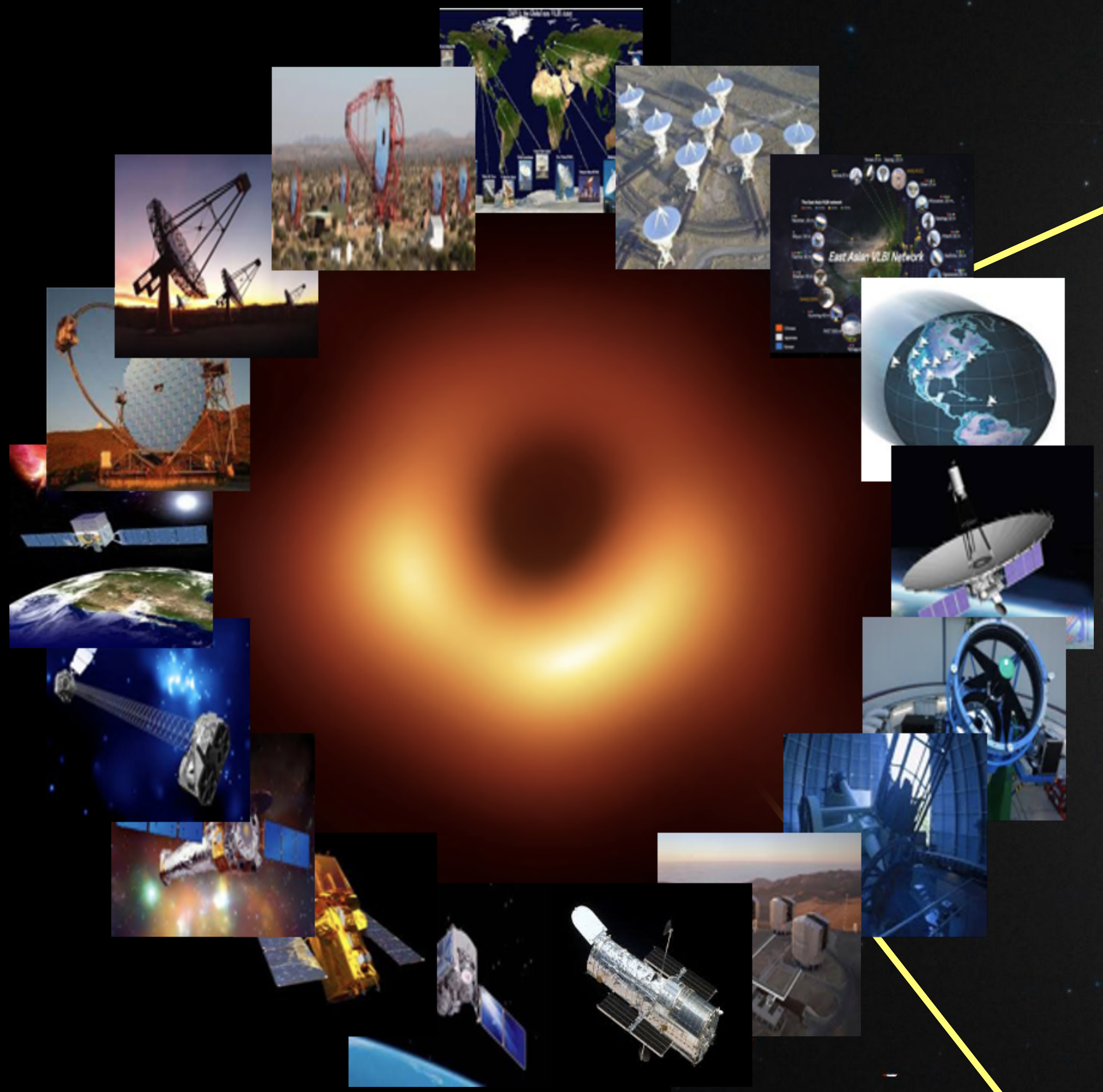

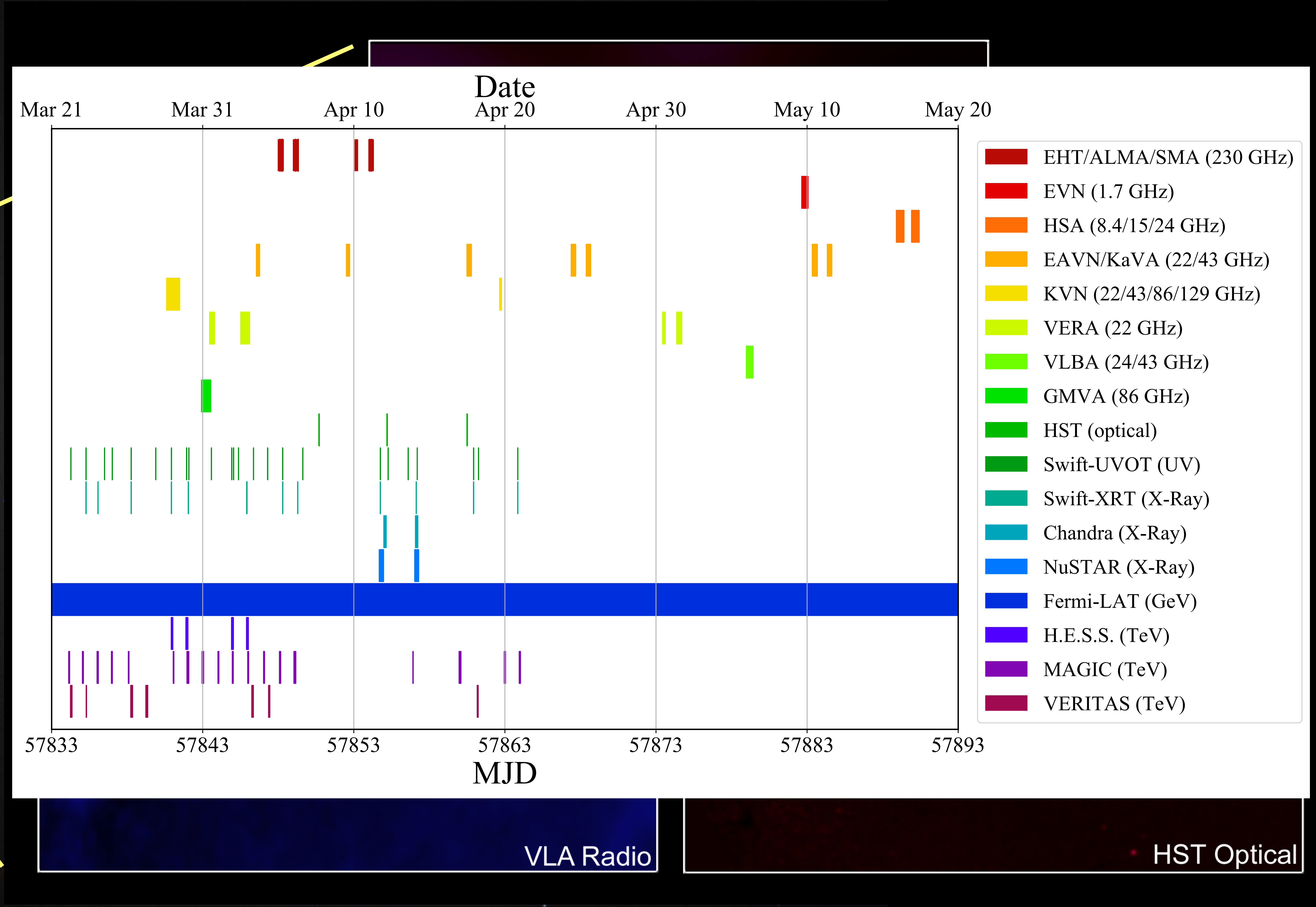

(EHT Multiwavelength WG, EHTC, EAVN, Fermi, HESS, MAGIC, VERITAS, ApJL, in press.)

2017 M87 Quasi-simultaneous multiwavelength campaign

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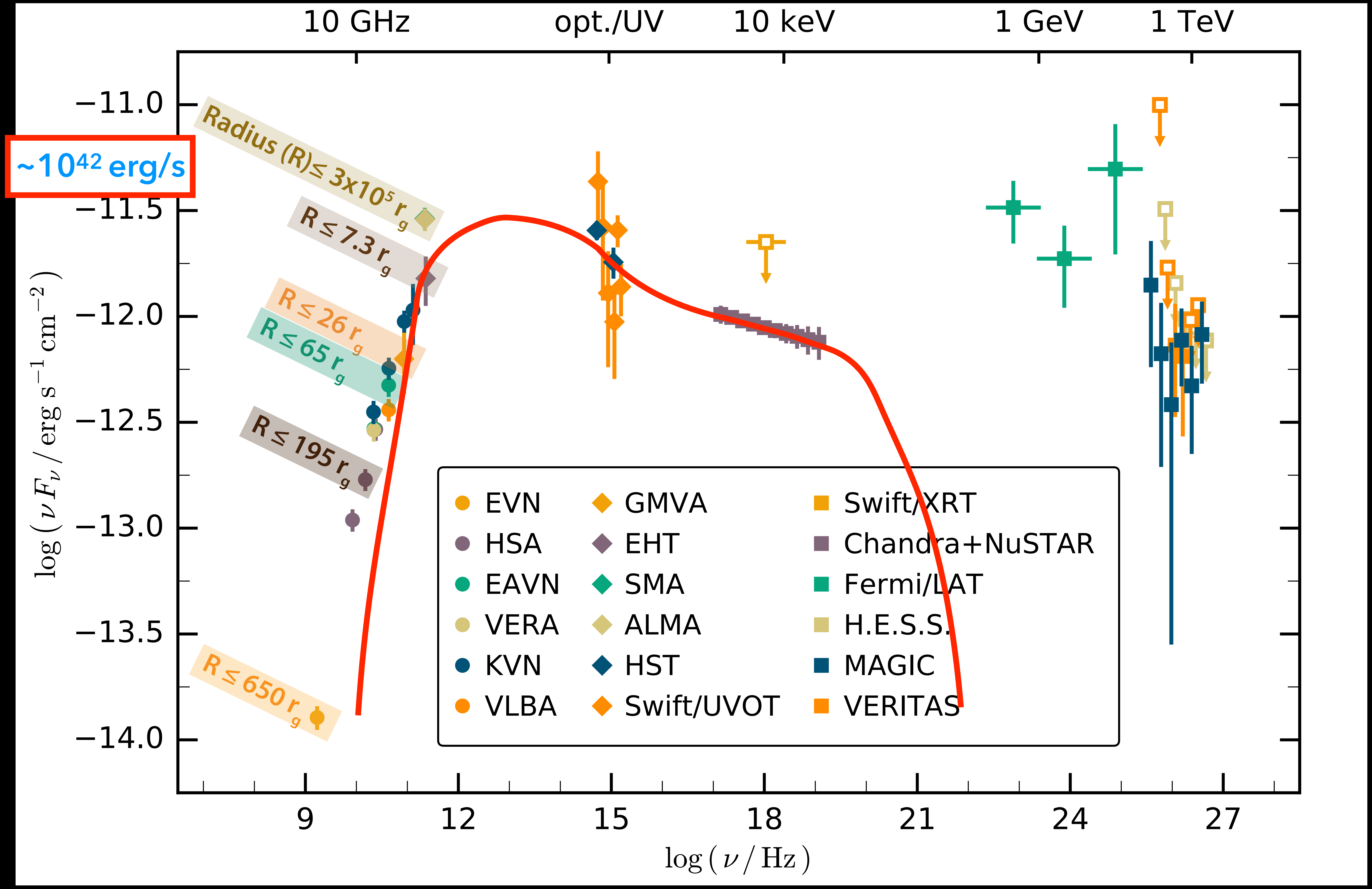
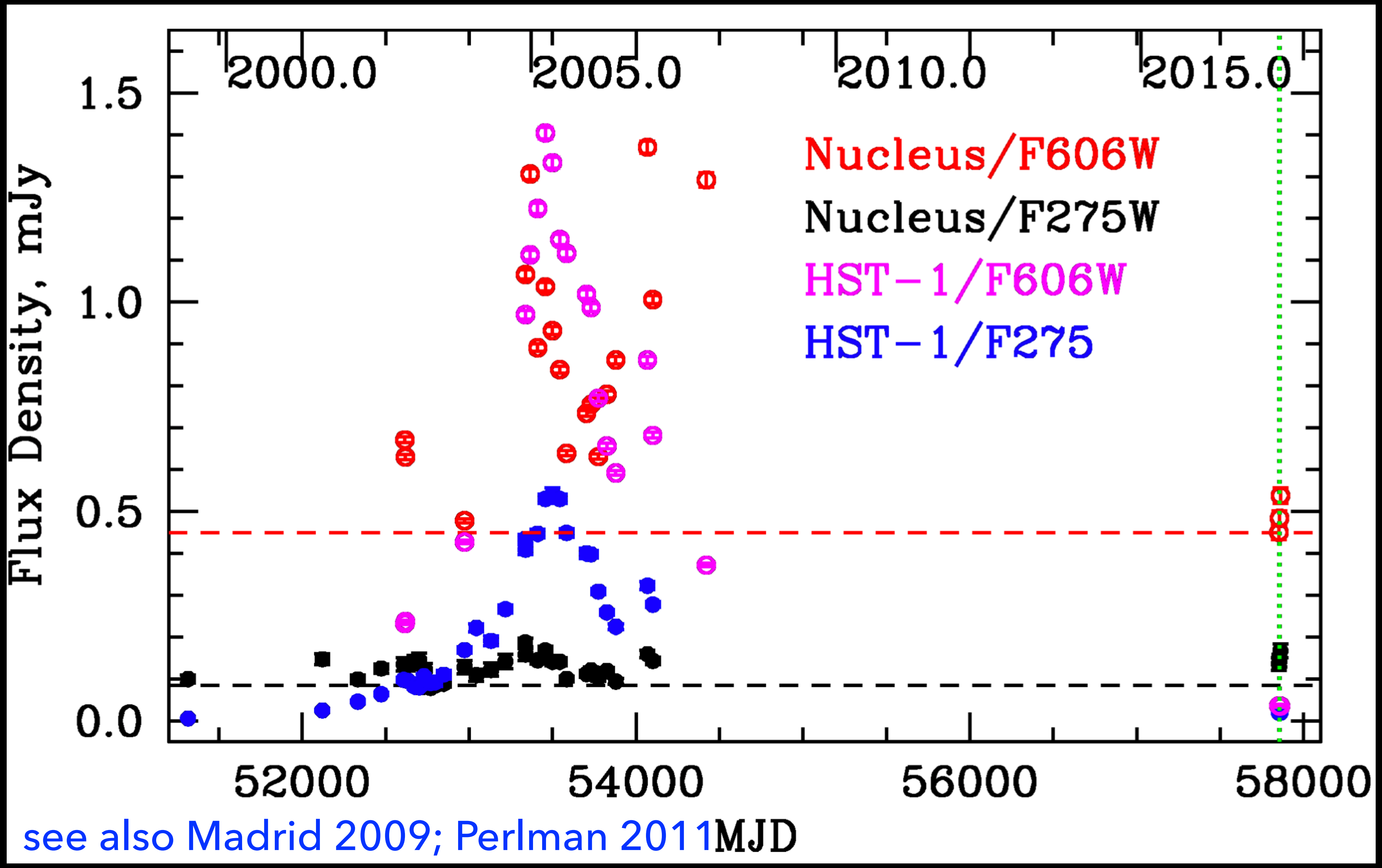
"Golden constraint" for M87's astrophysical output in 2017



(EHT Multiwavelength WG, EHTC, Fermi-LAT, HESS, MAGIC, VERITAS, EAVN, ApJL, in press)

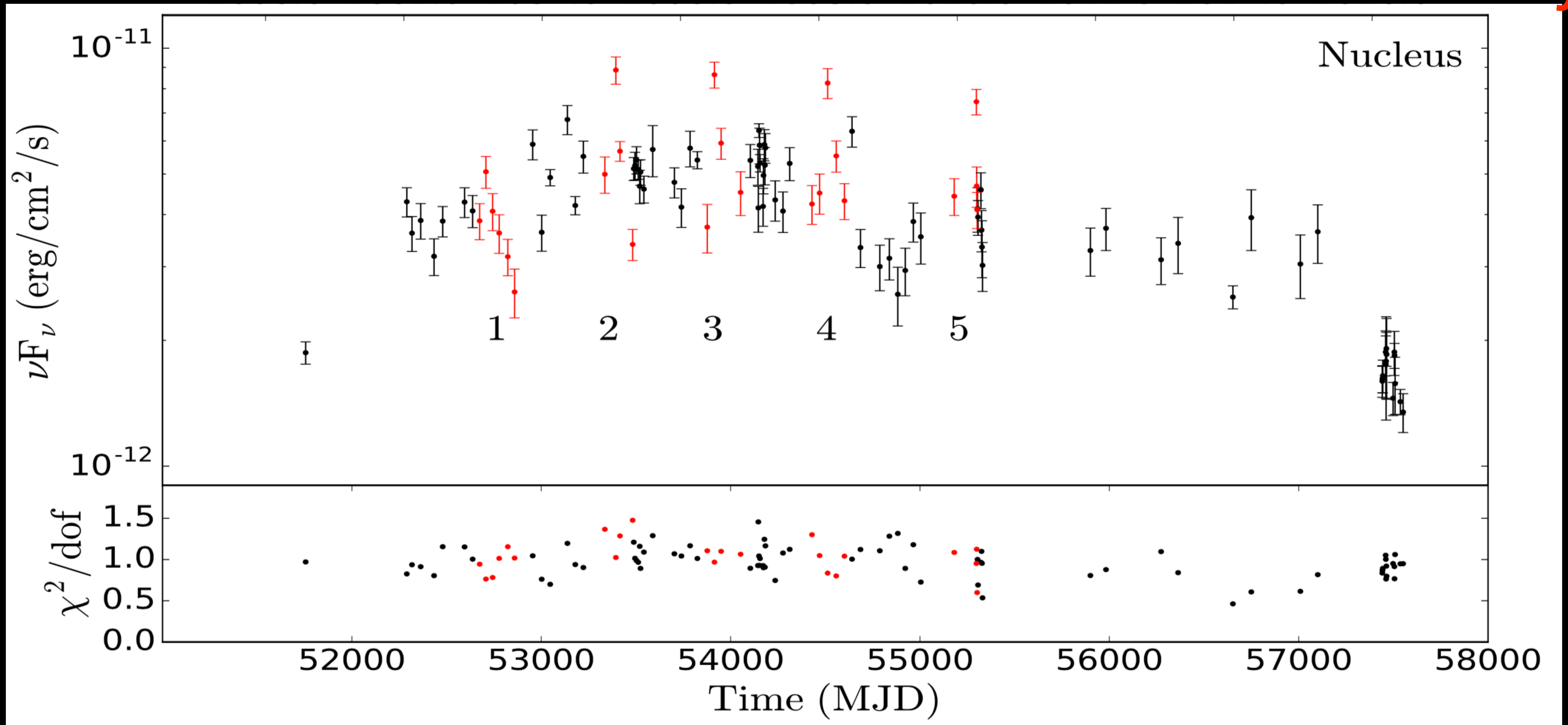
In 2017 we caught M87 in a historically low state

O/UV

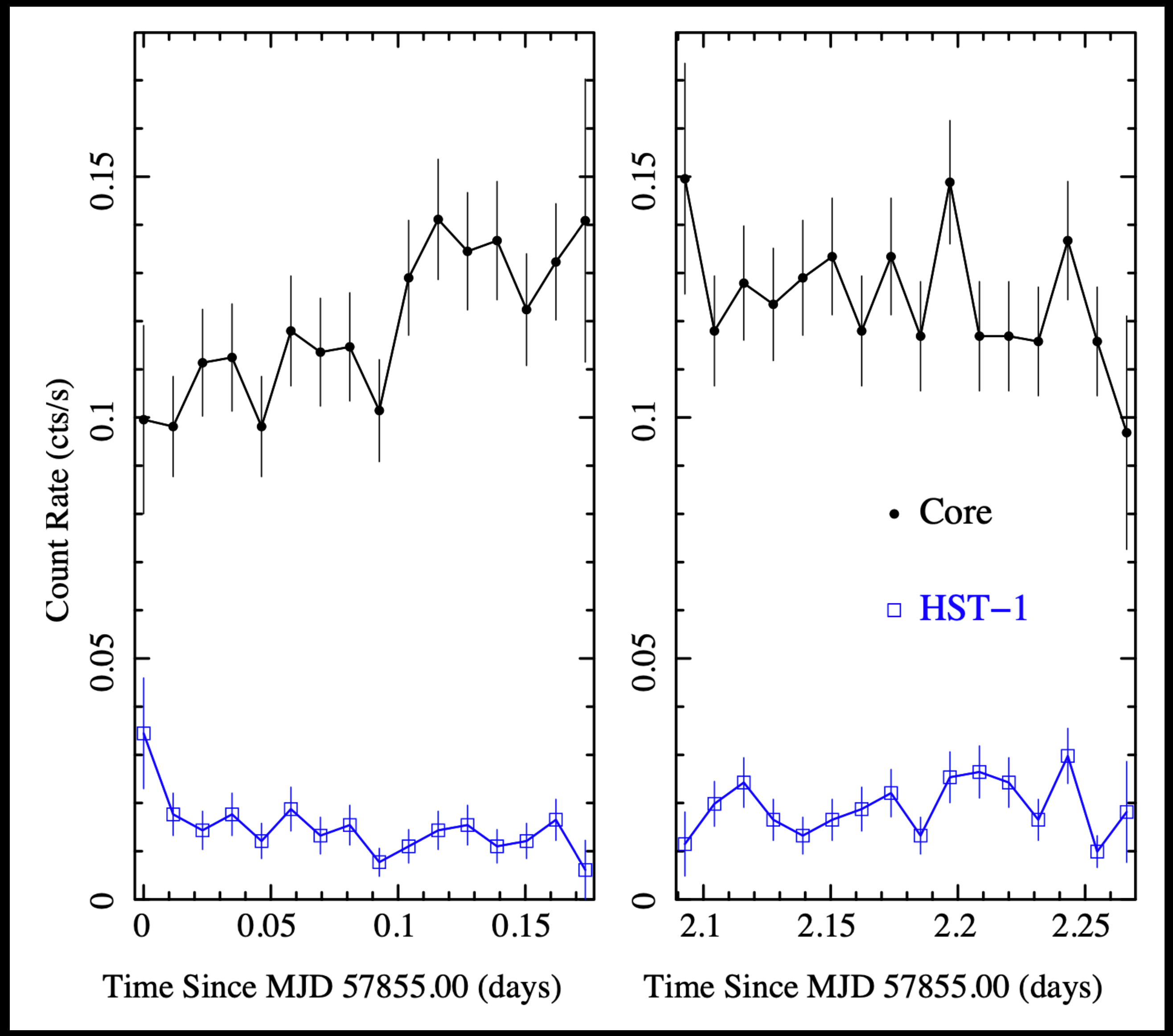


see also Madrid 2009; Perlman 2011

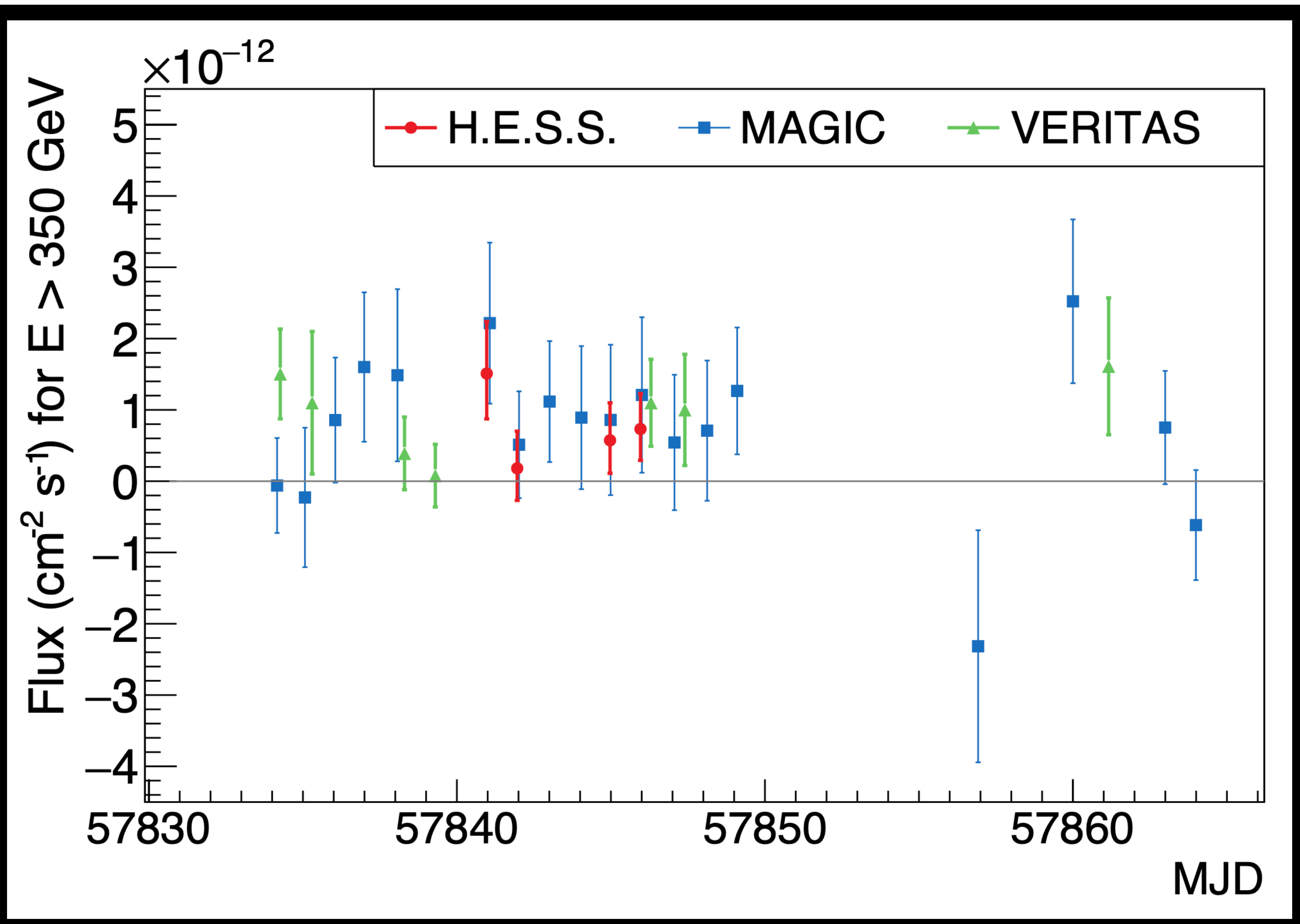
Chandra X-ray



Chandra X-ray: EHT 2017



VHE γrays: EHT 2017



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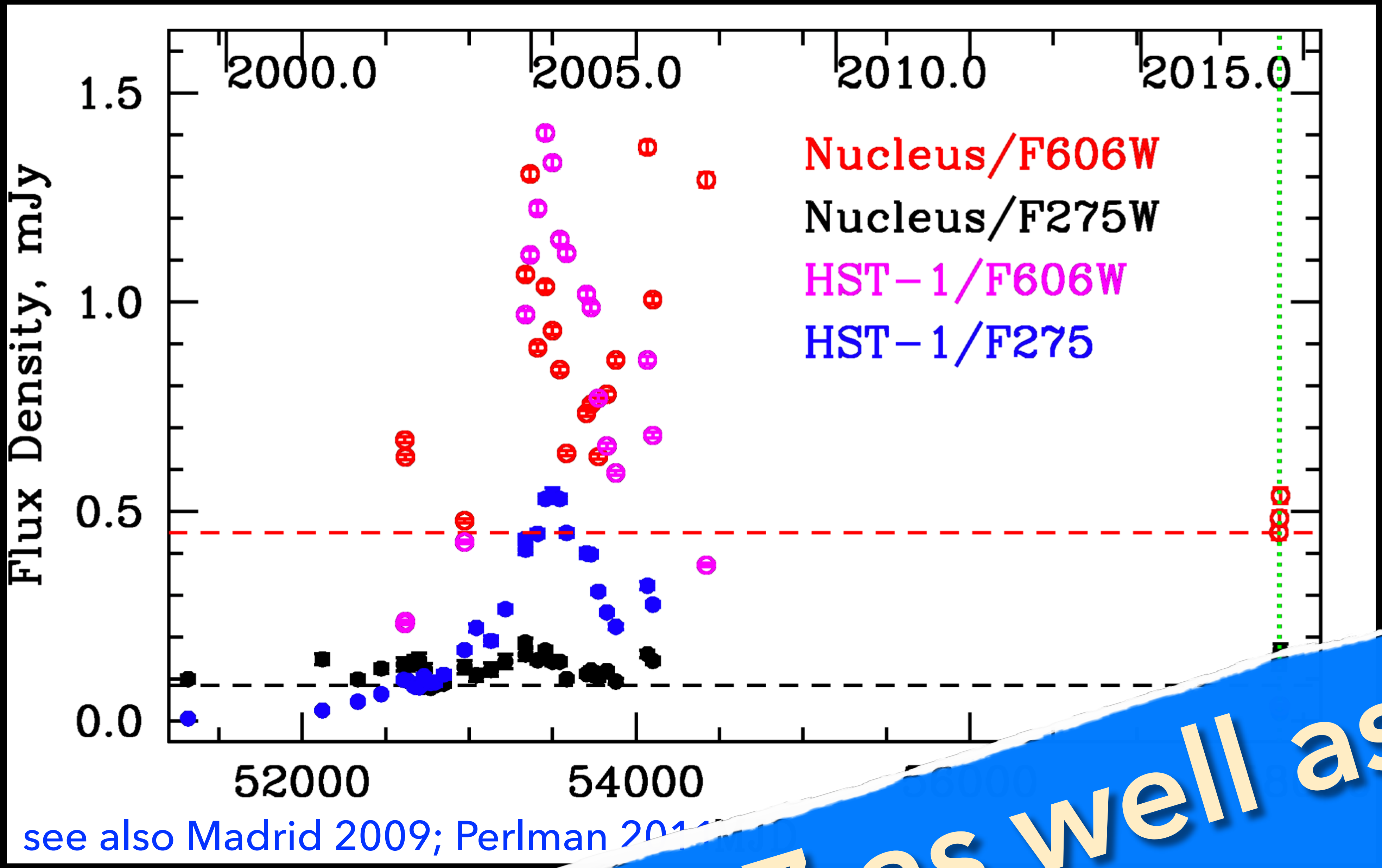

see also Madrid 2009; Perlman 201…

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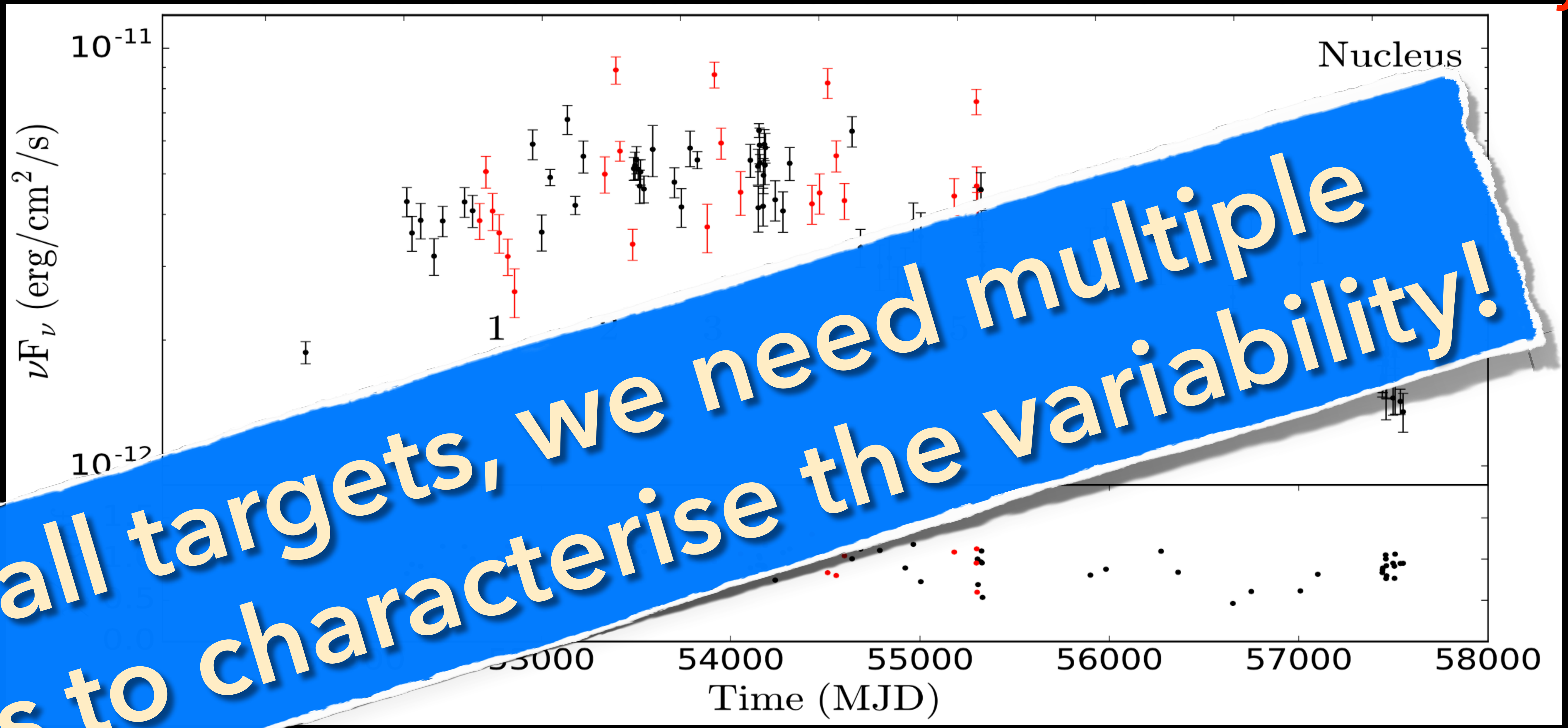
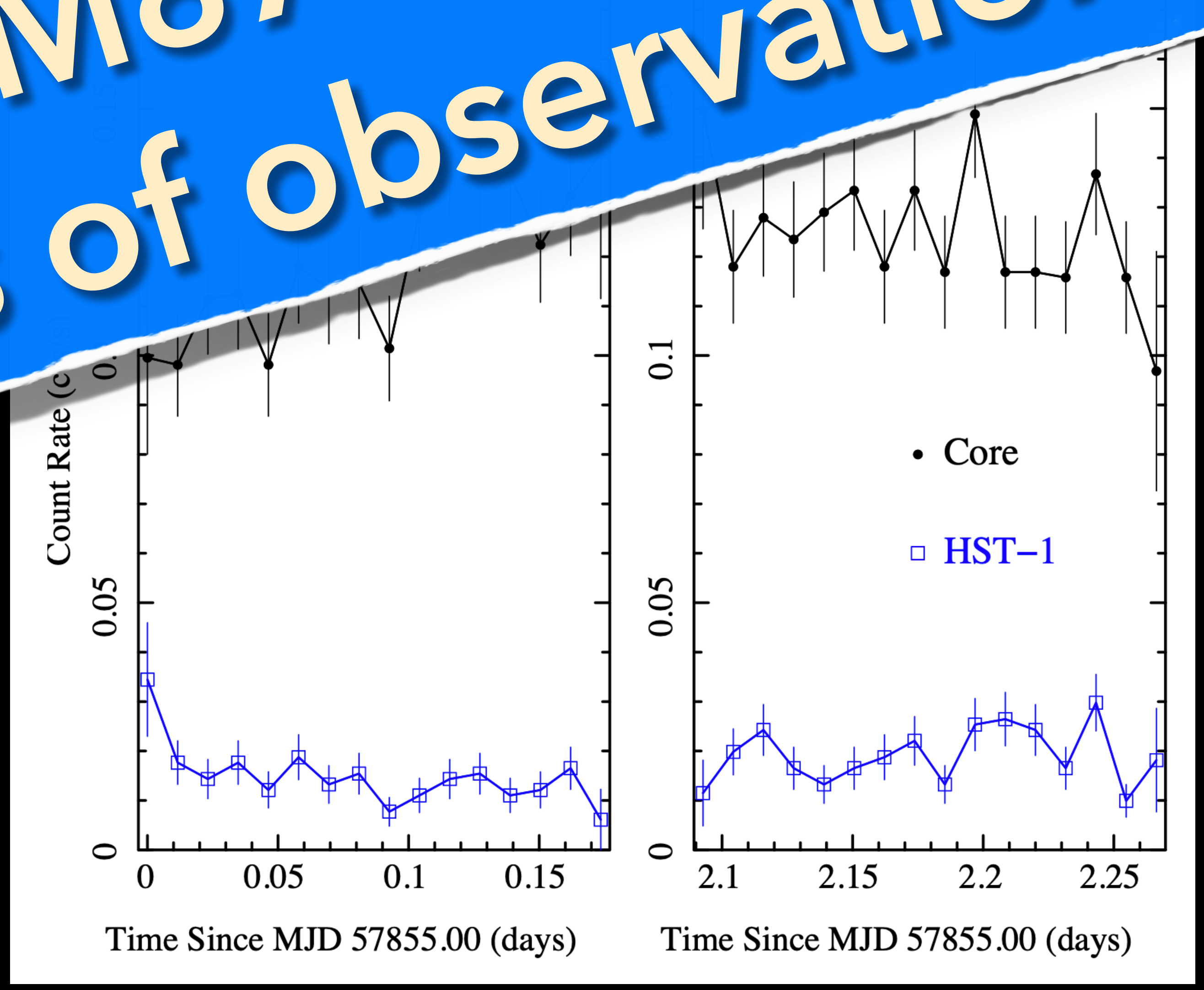
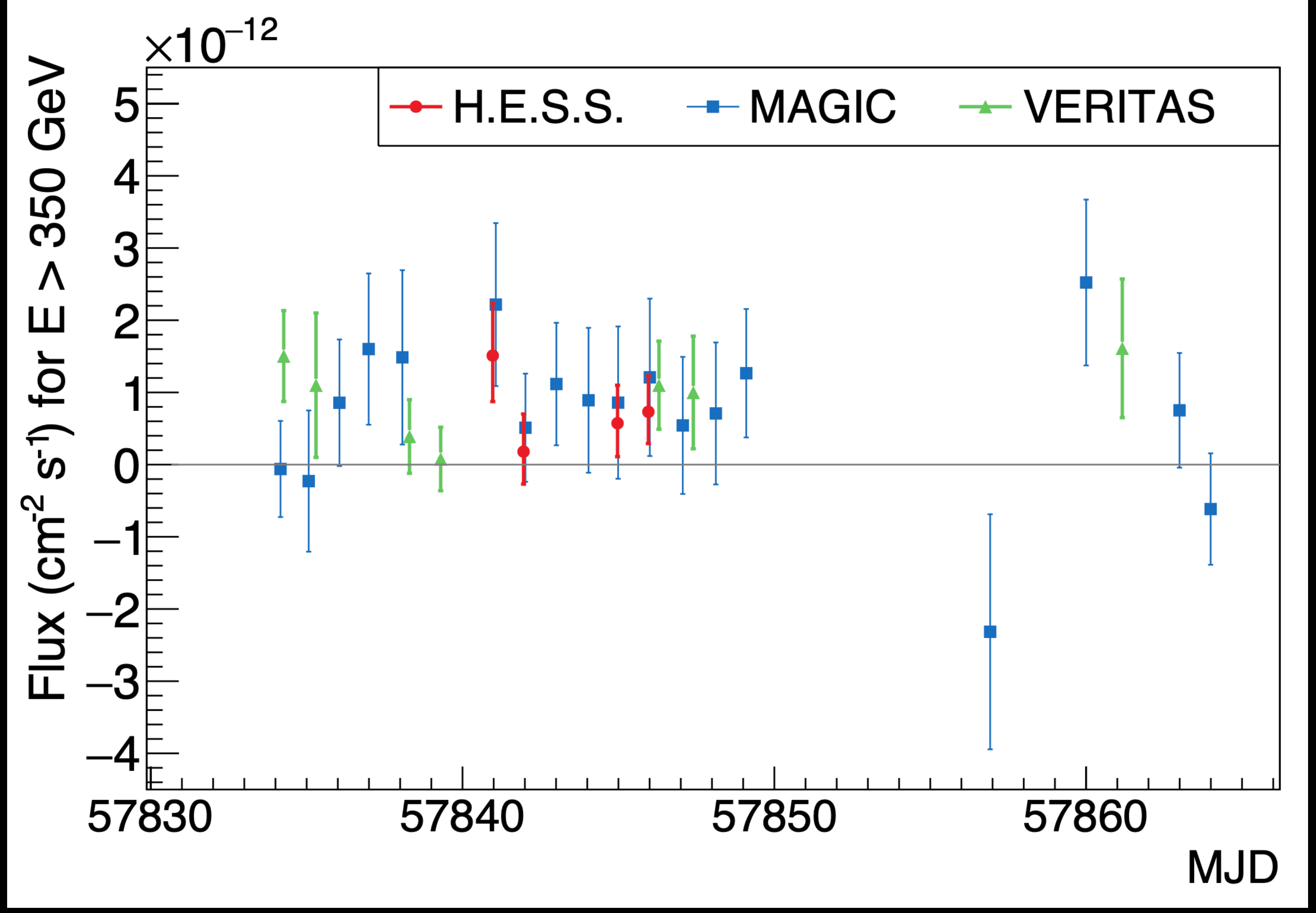


For M87 as well as all targets, we need multiple years of observations to characterise the variability!

Chand… EHT 2017



VHE γrays: EHT 2017



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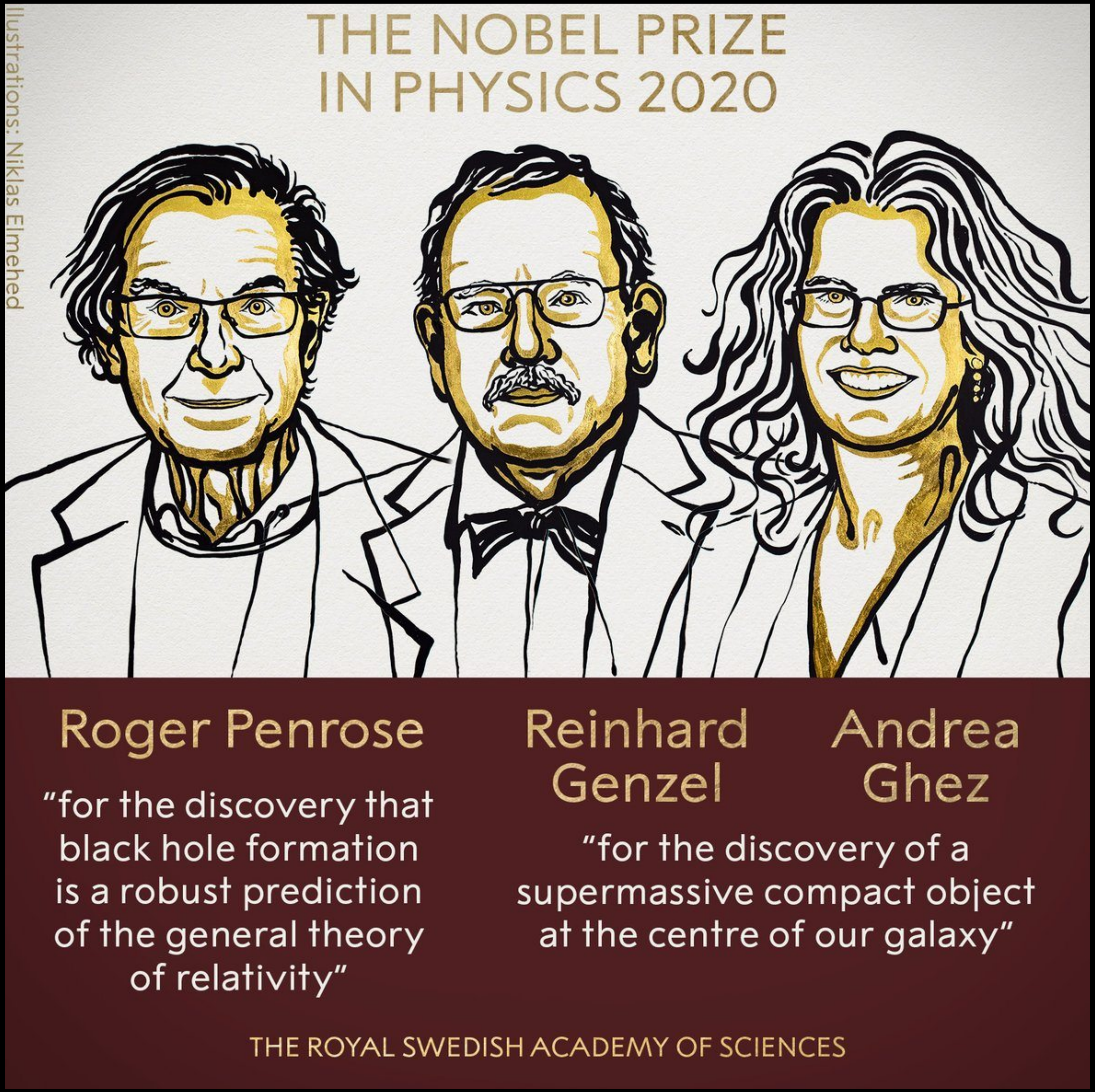
The second horizon target (and best studied black hole), Sgr A*!



Sgr A*: a clear sightline to the innermost accretion flow

2017 EHT MWL Campaign on Sgr A*

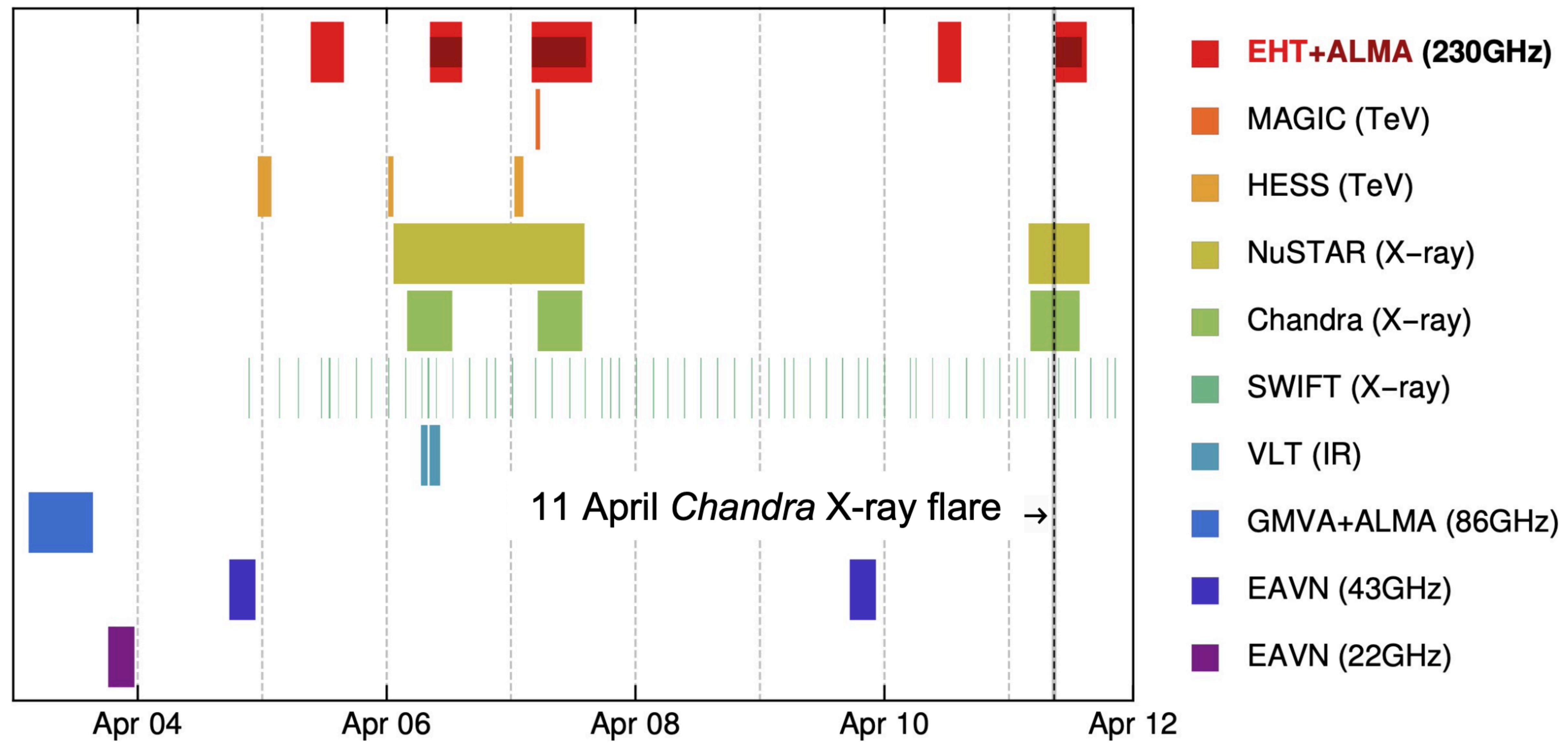
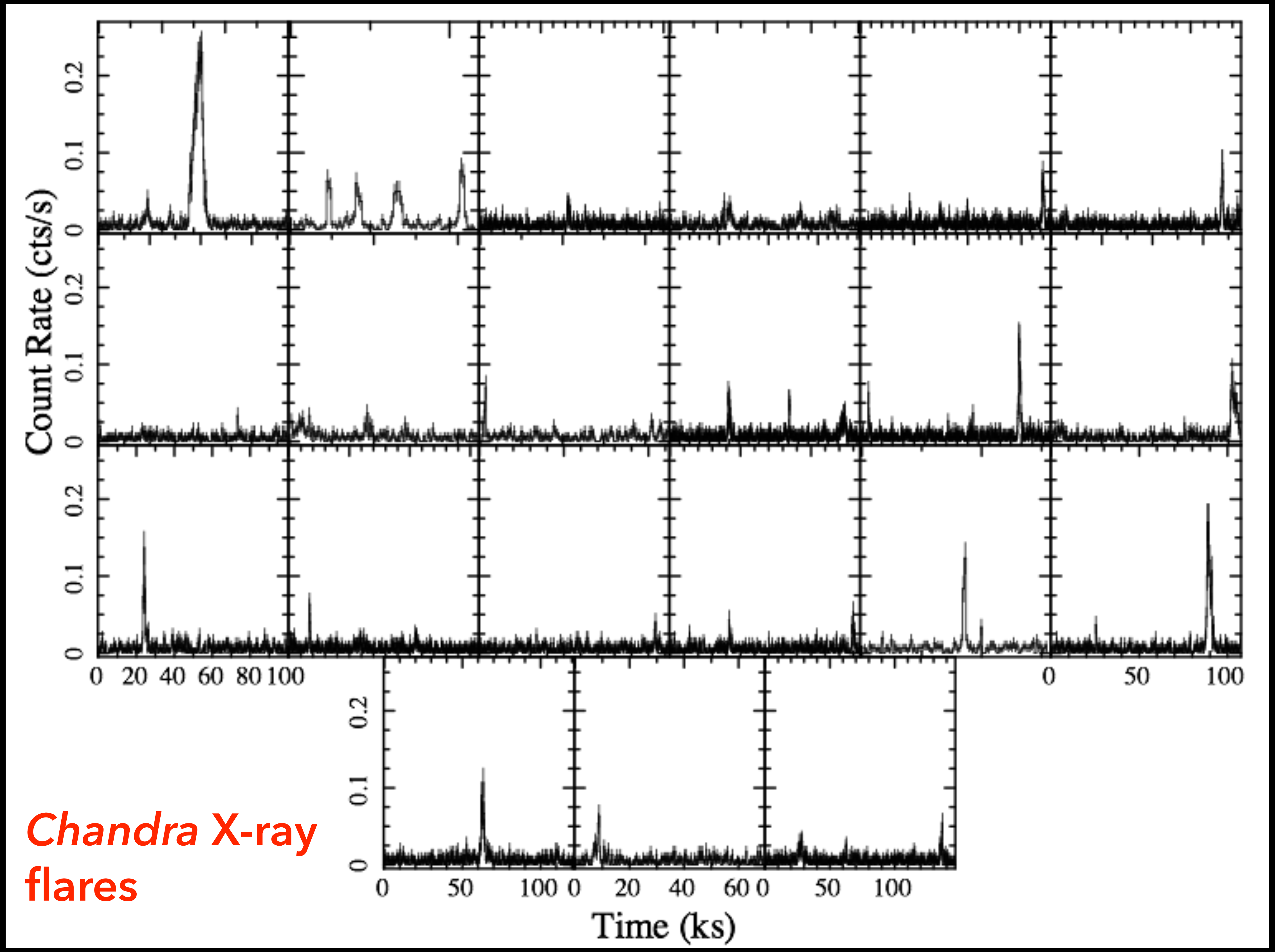
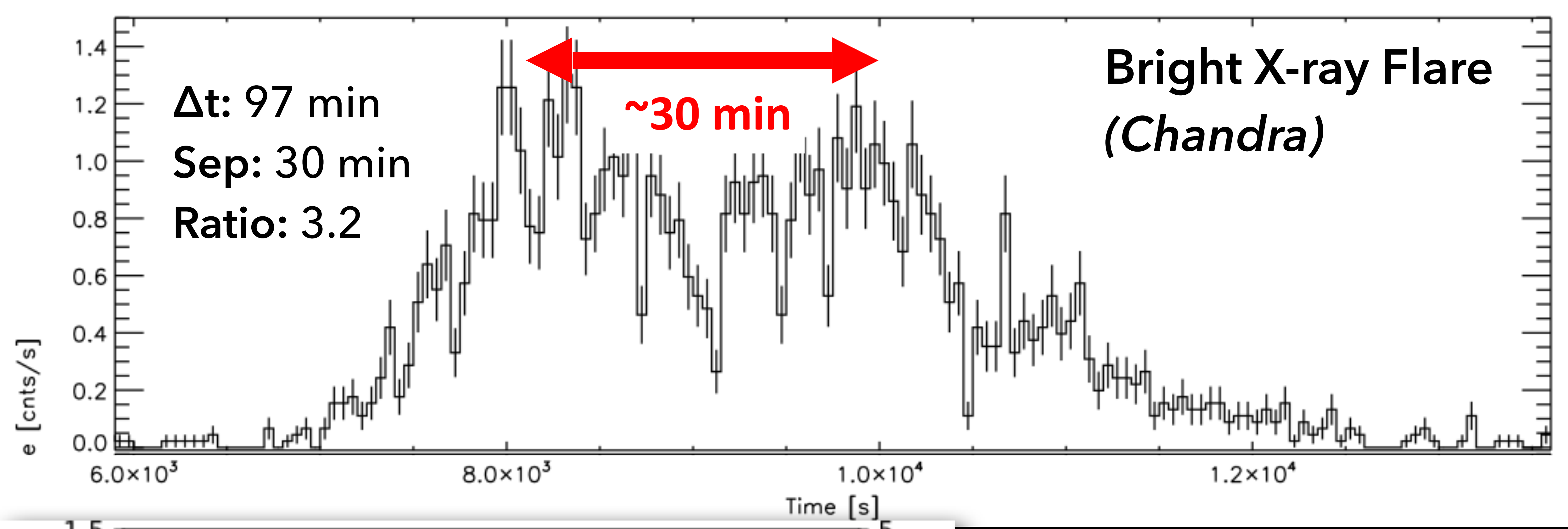


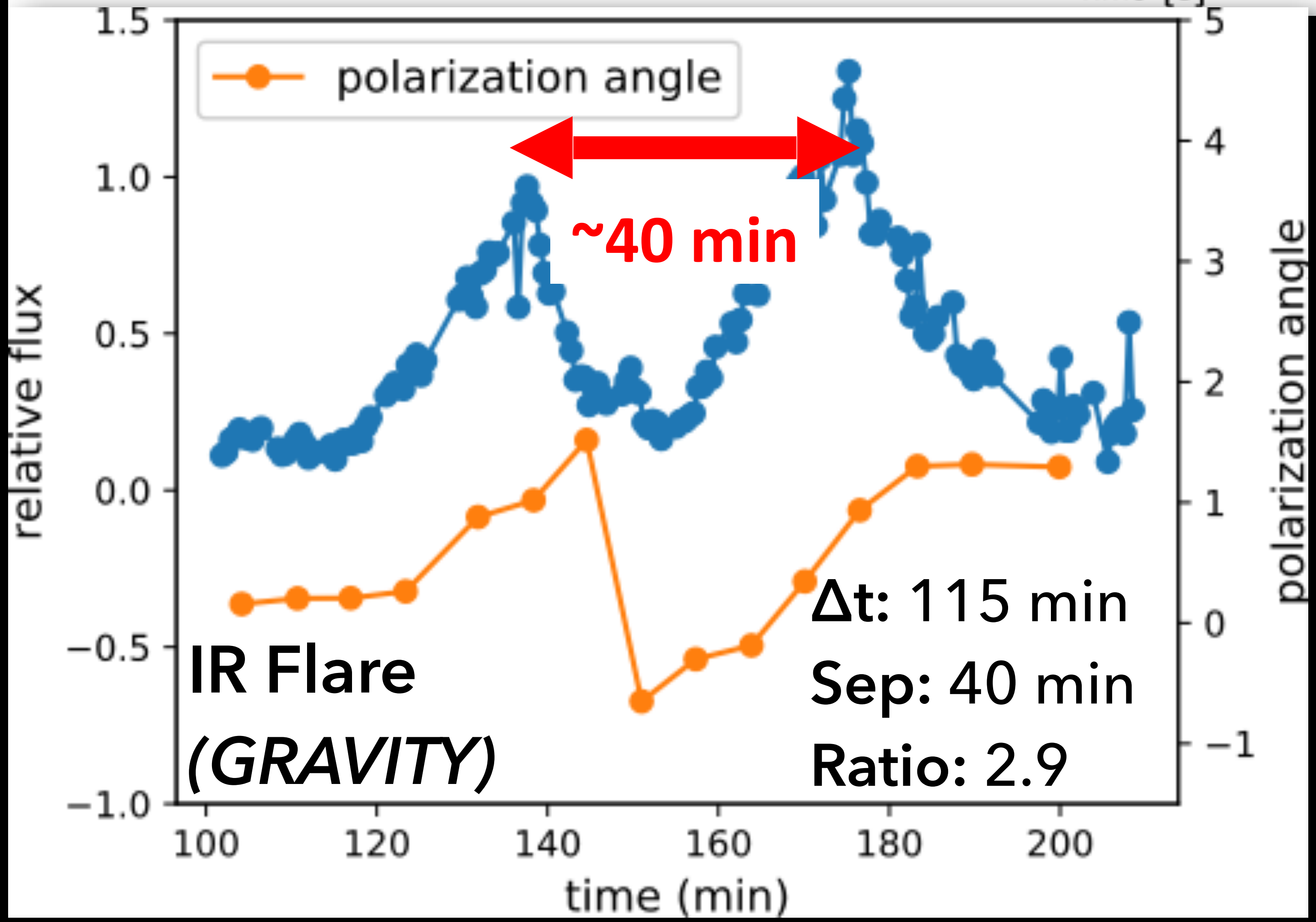
Figure courtesy of J.Farah and M.Johnson, on behalf of the EHT MWL WG.

Sgr A*: a clear sightline to the innermost accretion flow



(Dodds-Eden 2009; Witzel++ 2012; 18; Nielsen++ 2013, Nielsen, SM+ + 2015; Do++19)

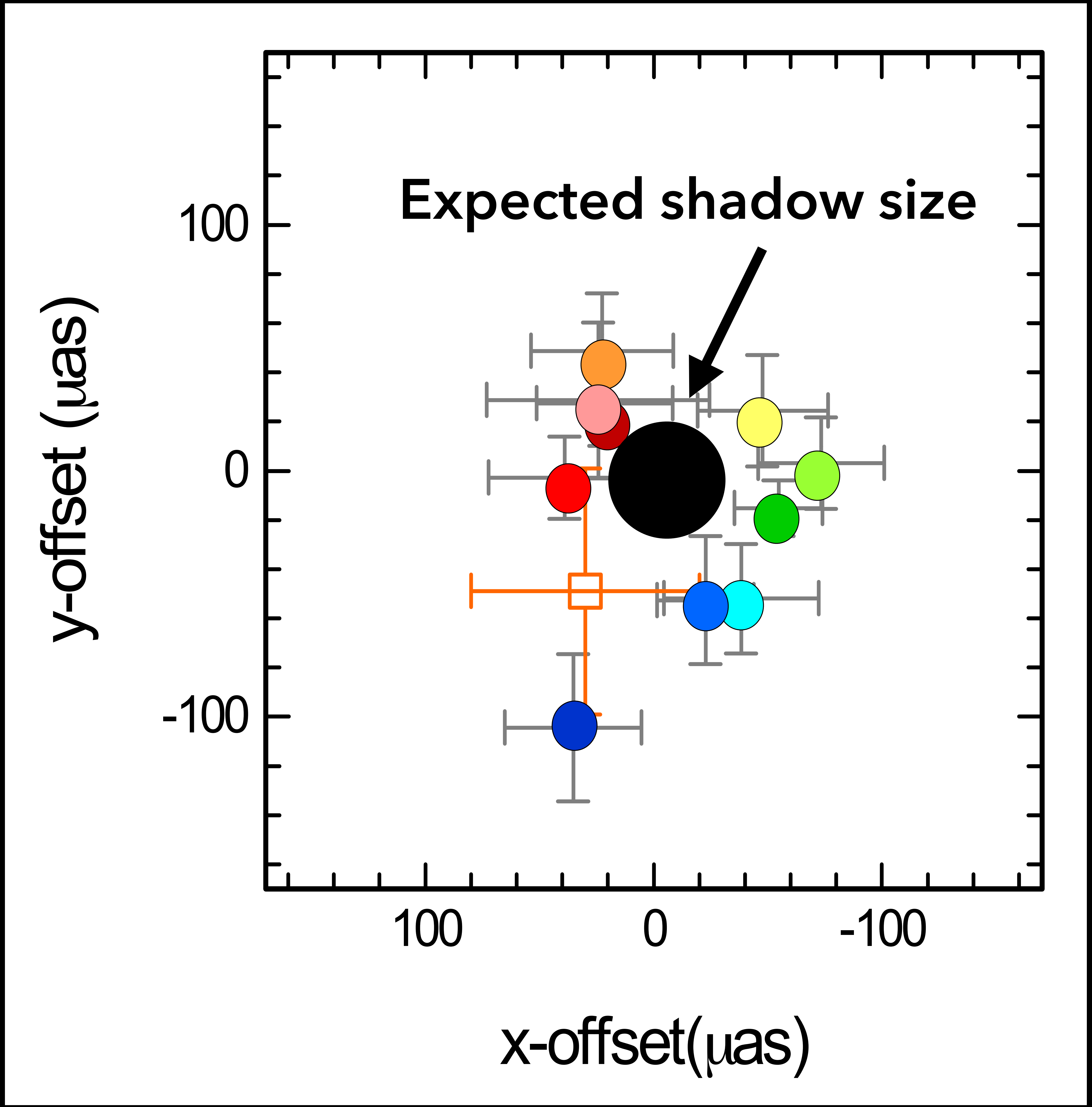




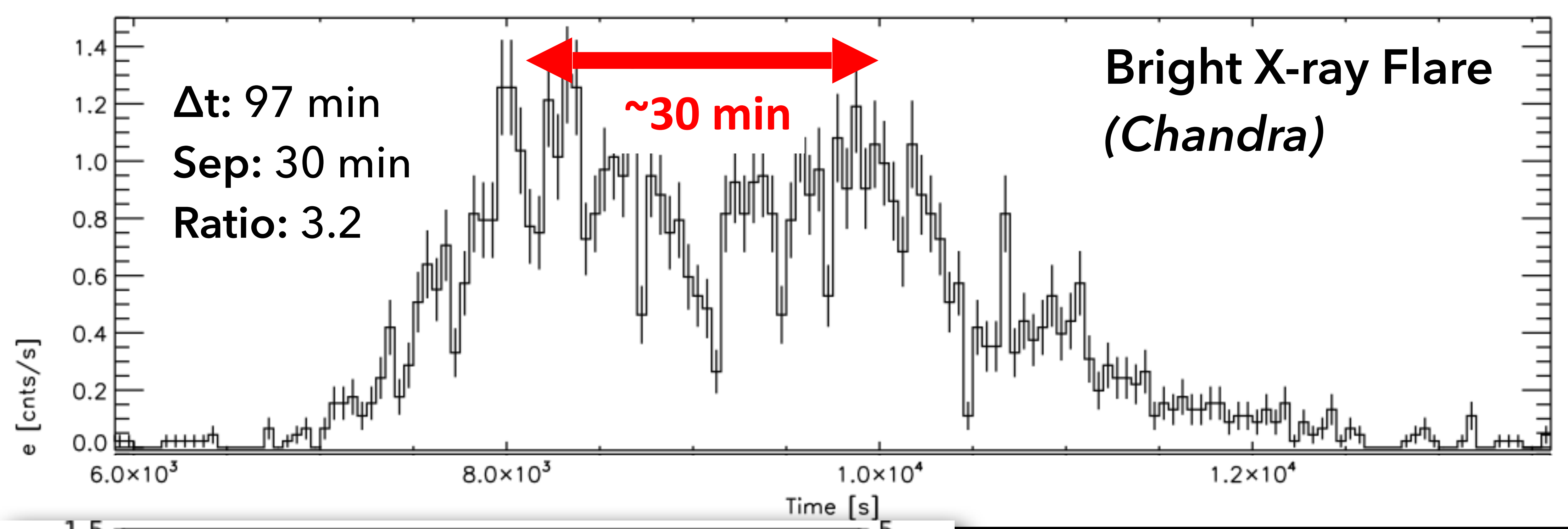
(GRAVITY Collaboration 2018; Haggard++2019)

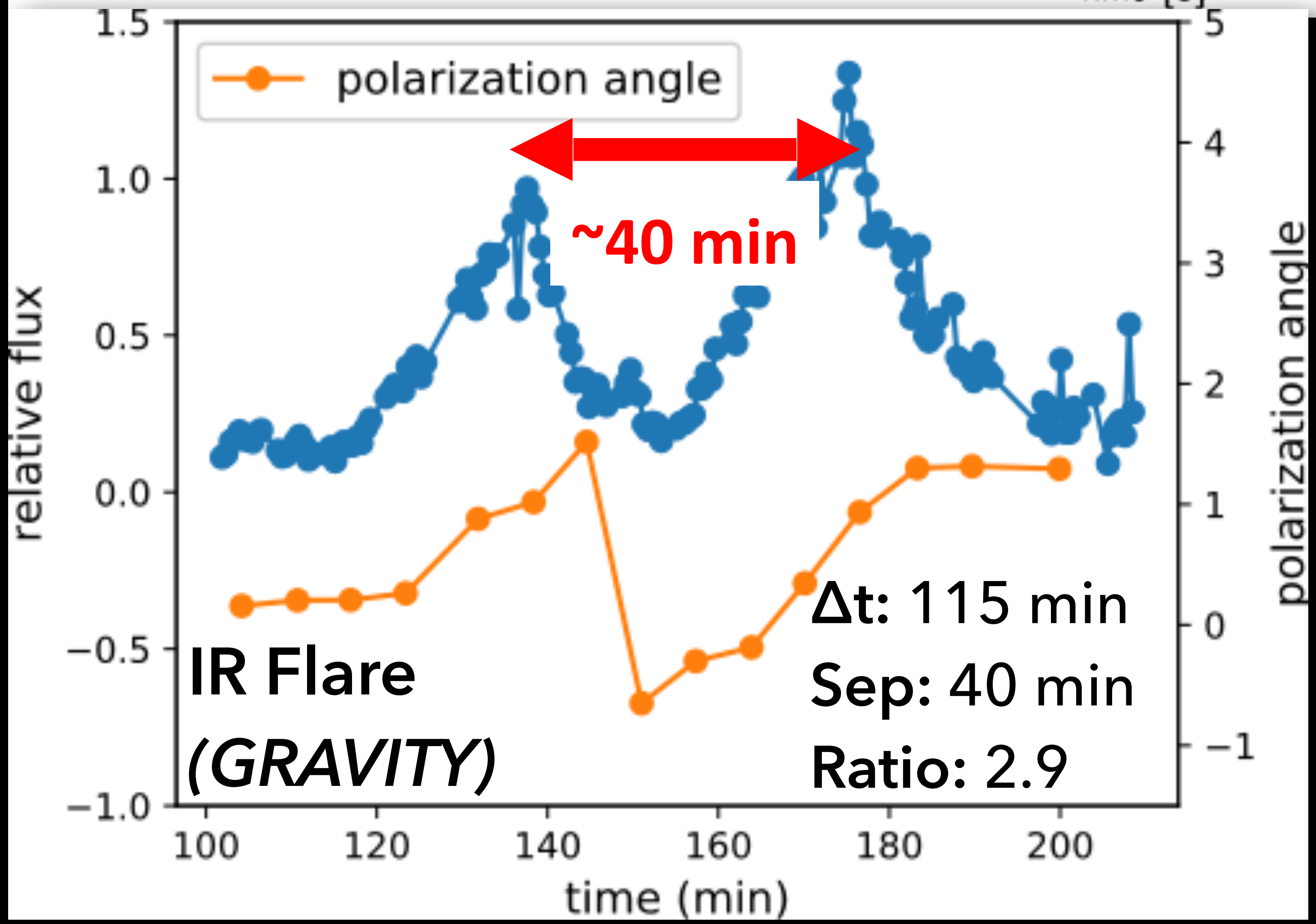
- Can we find the right combination of simulation + microphysics to explain images, MWL spectra and variability??

Sgr A*: a clear sightline to the innermost accretion flow



(GRAVITY++2018)





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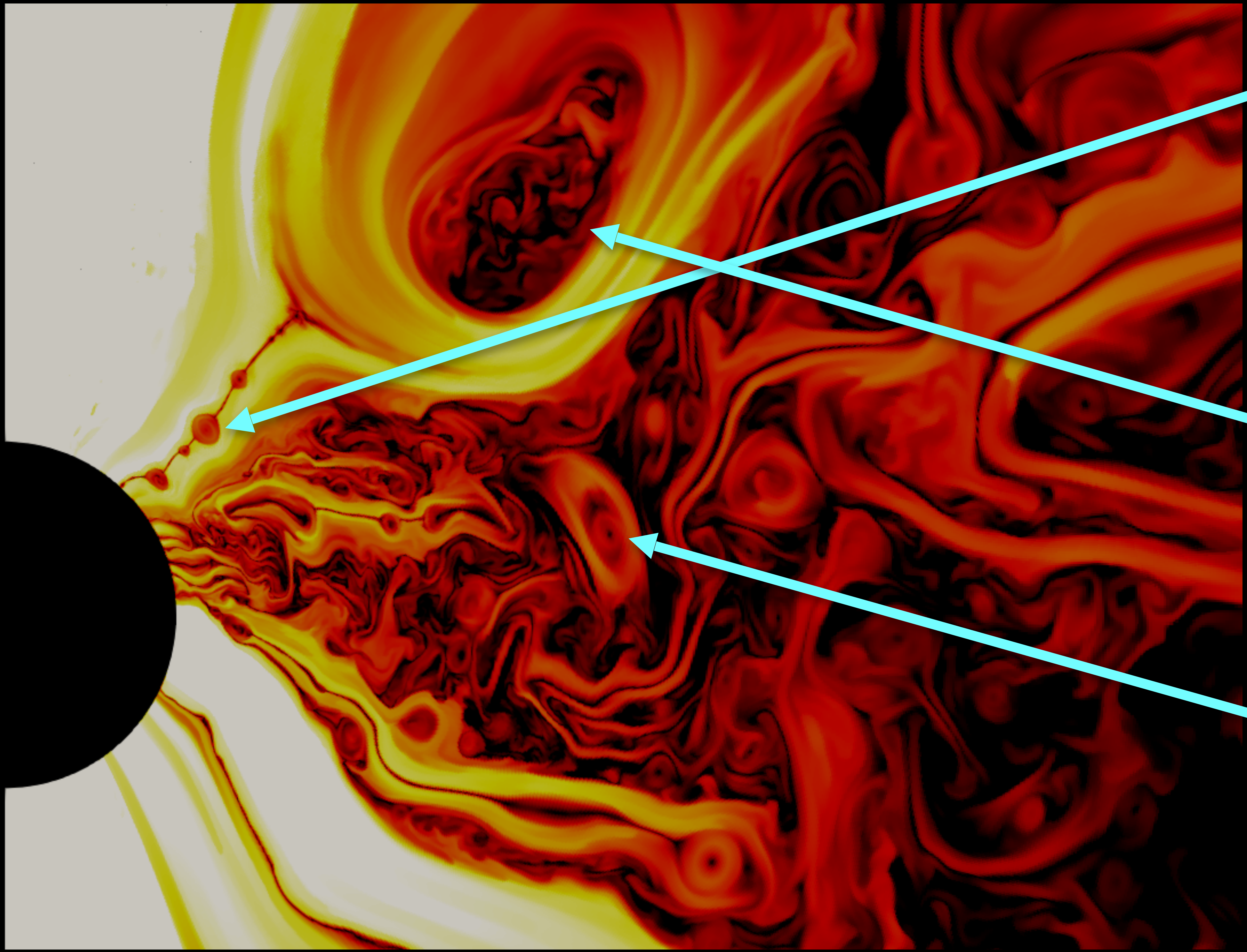
Recent developments focusing on turbulent plasmoid formation



- Plasmoids form from reconnecting current sheets at jet/disk interface
- Electrons inside get heated
- Merge into monster plasmoids or 'hotspots' and are expelled along jet sheath (which orbits in projection)
- and/or produce orbiting flares in inner disk

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

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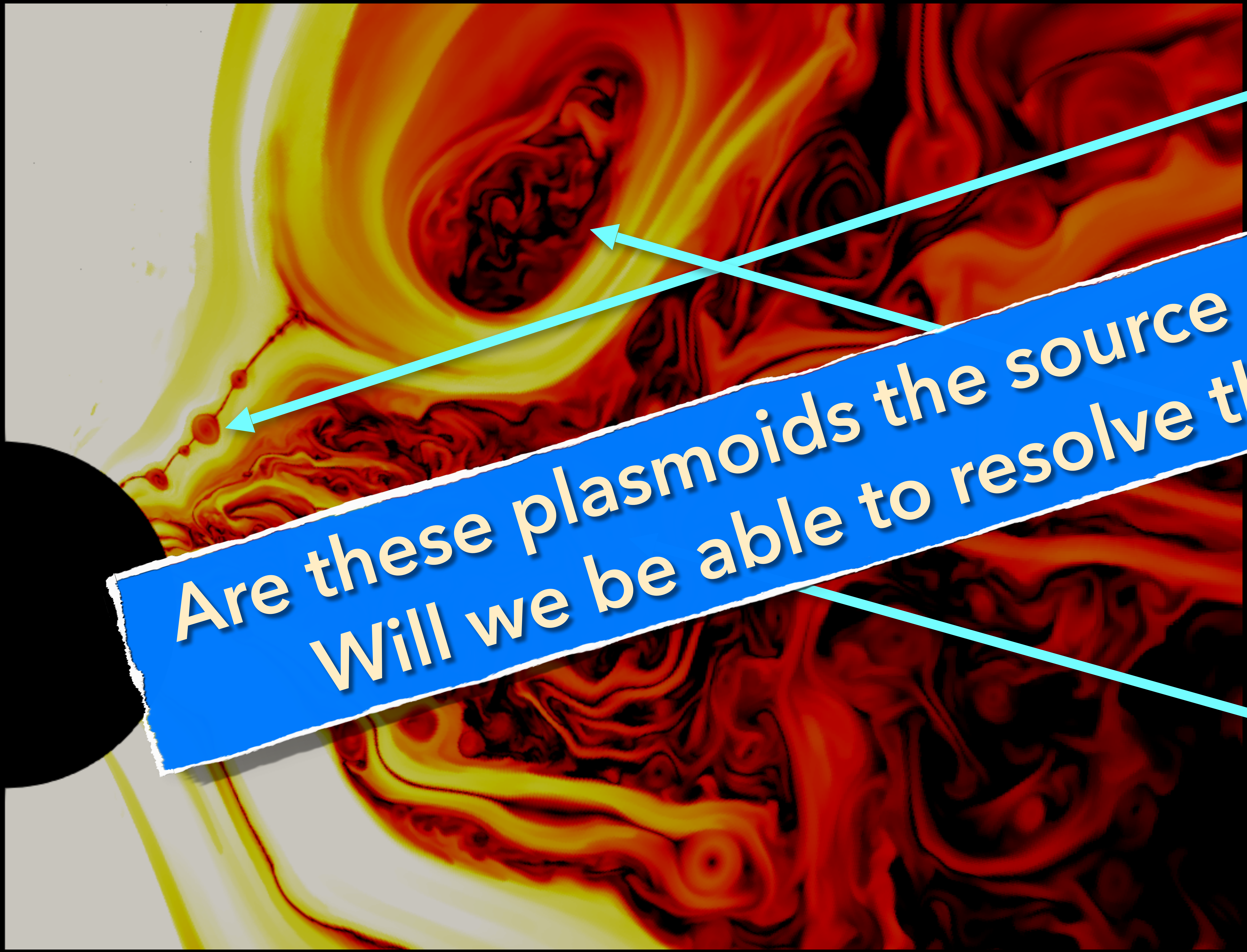

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  reconnec[…]ts
  […]get heated
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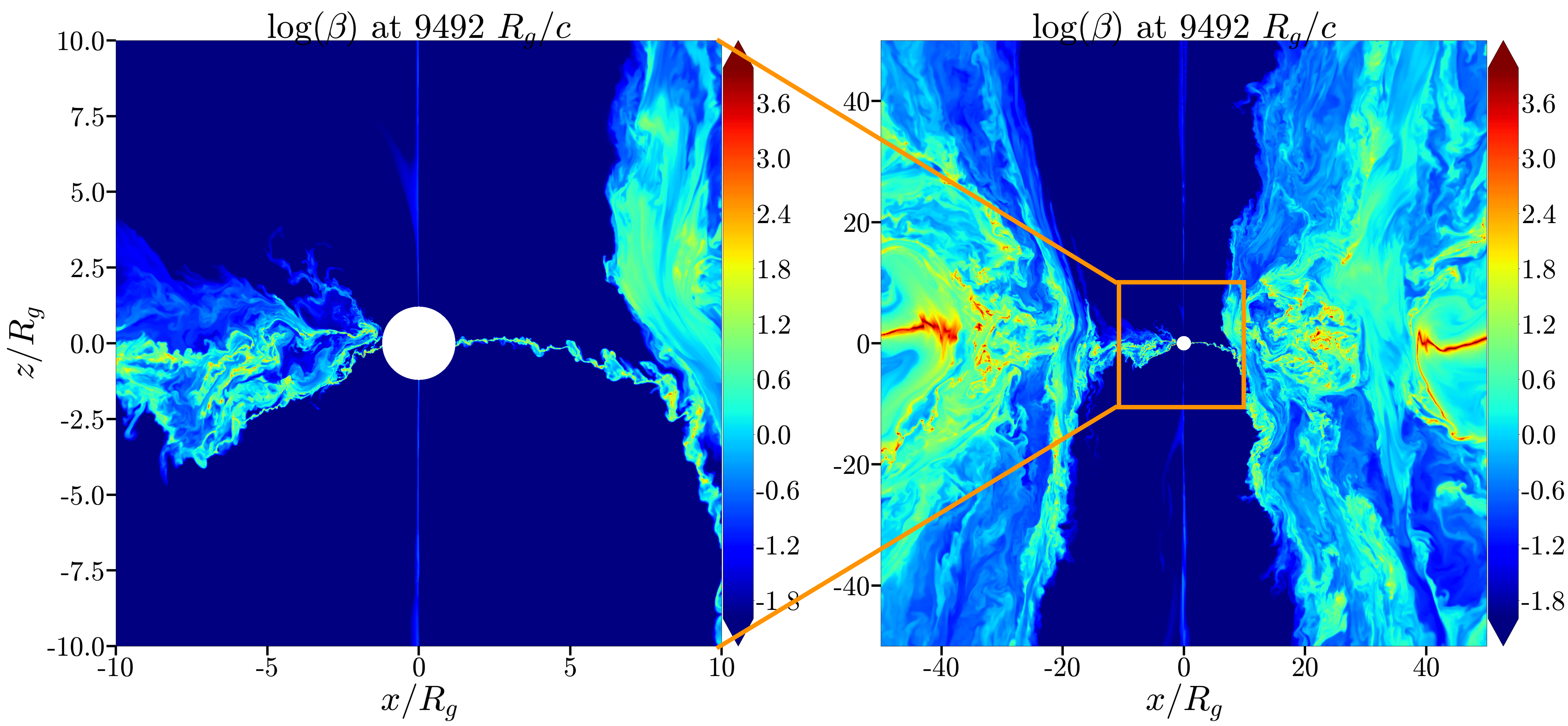
Are these plasmoids the source of Sgr A*'s flares?
Will we be able to resolve them with EHT?

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

New: plasmoid formation in *ideal* 3D-GRMHD on GPUs



5400x2304x2304 with H-AMR (Liska++ 2019) yields similar results as resistive 2D-GRMHD (Ripperda, Liska, Chatterjee, Musoke, Philippov, SM, Younsi, Tchekhovskoy, in prep.)

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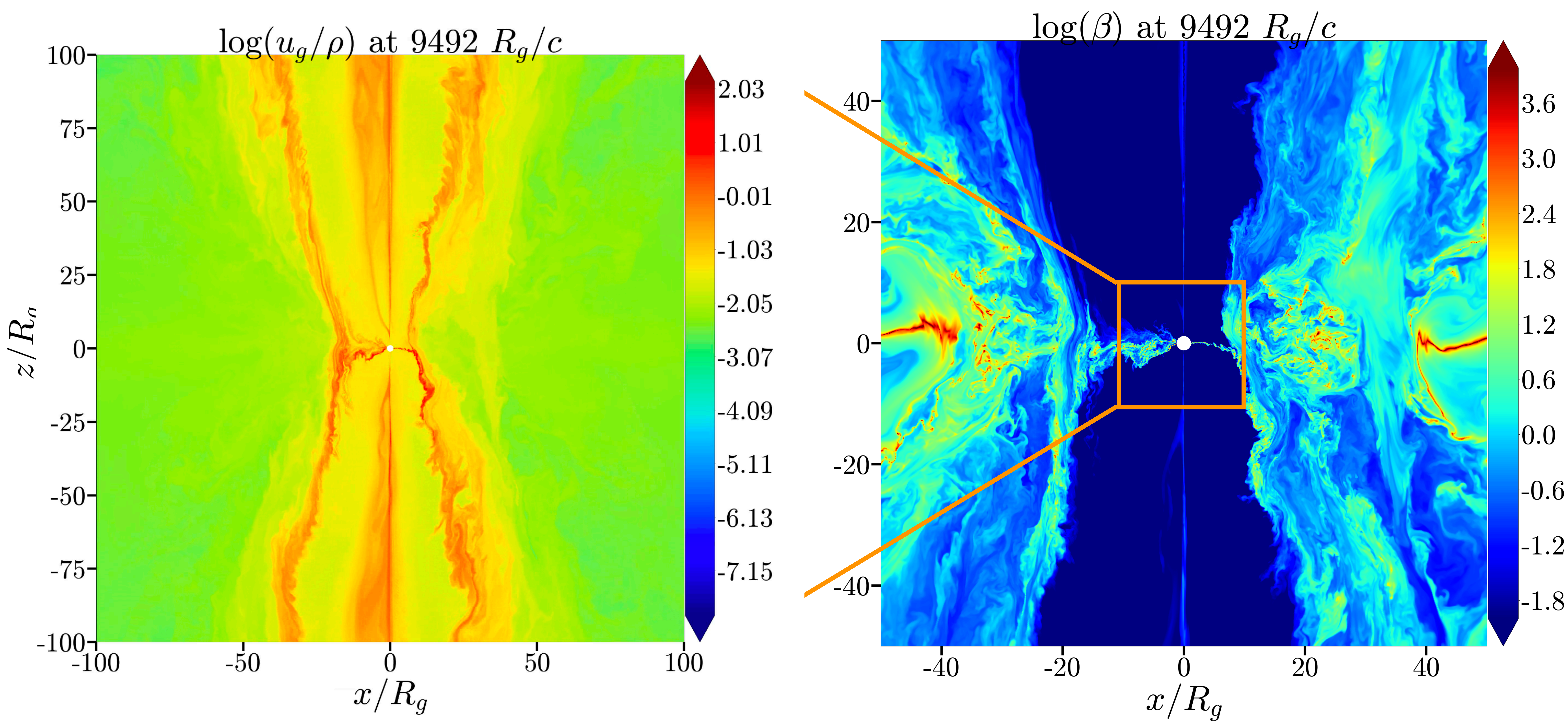

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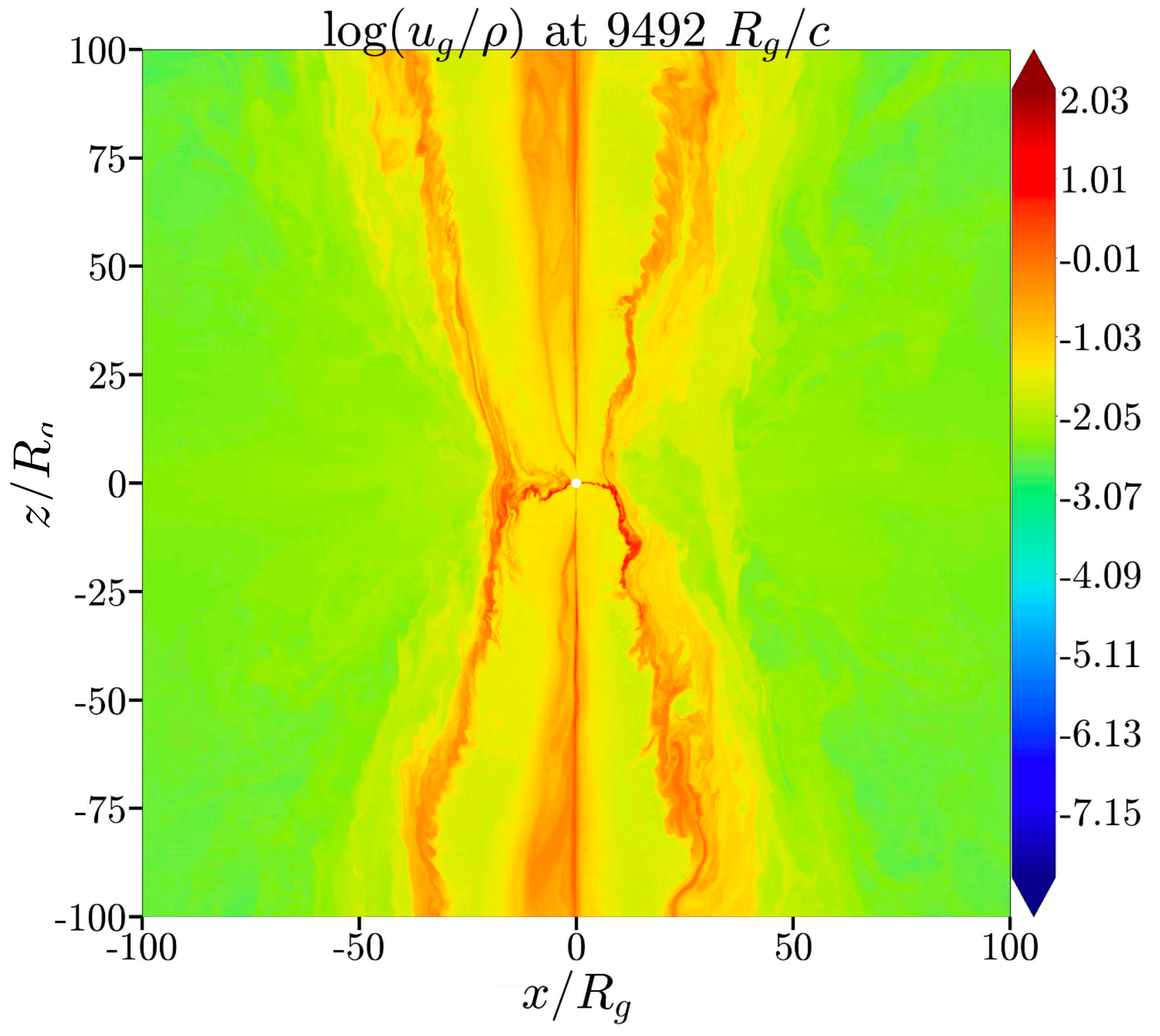

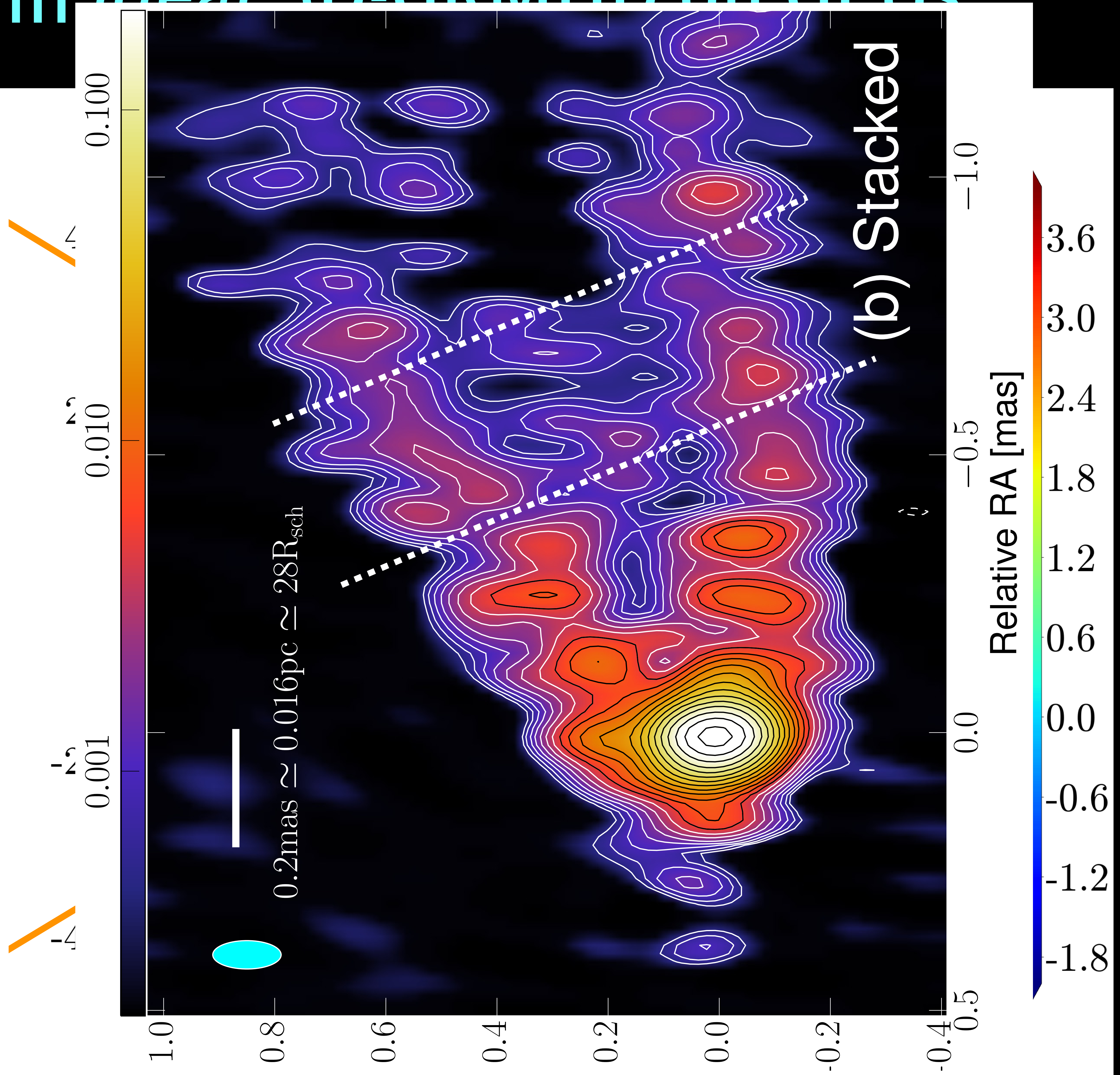

(Acciari++10; Abramowski++12; Kim++2018; Walker++2018;

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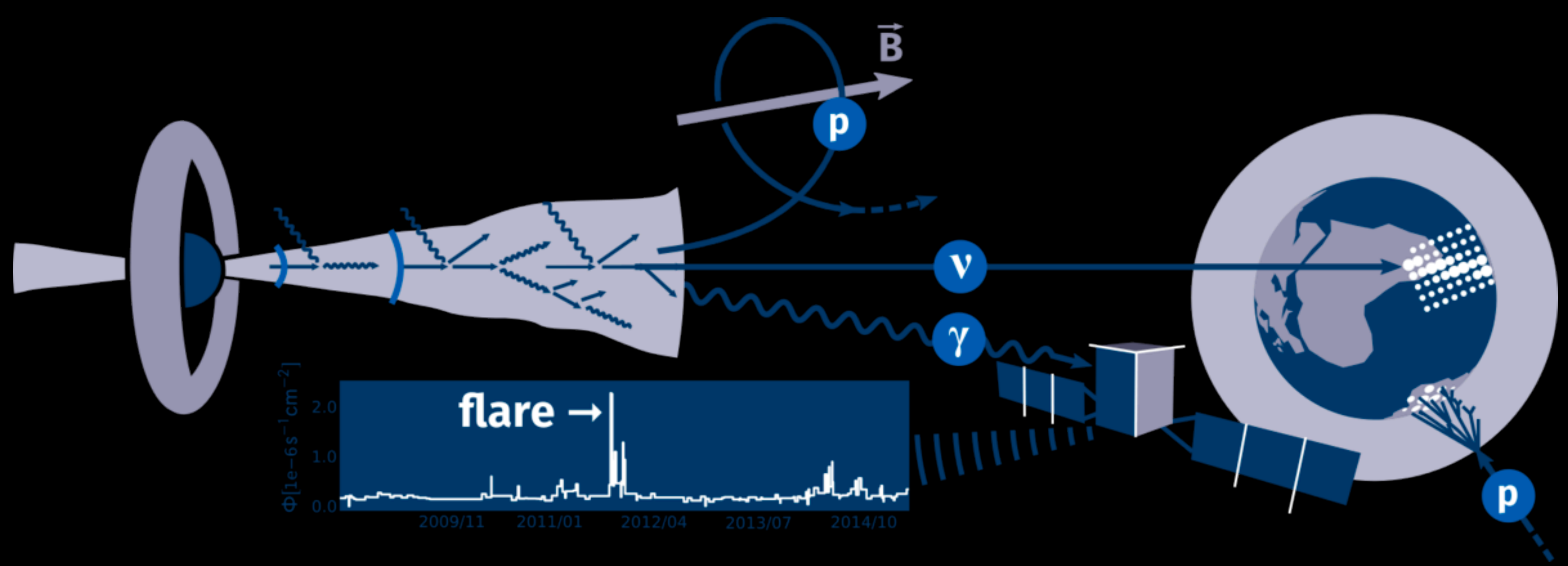
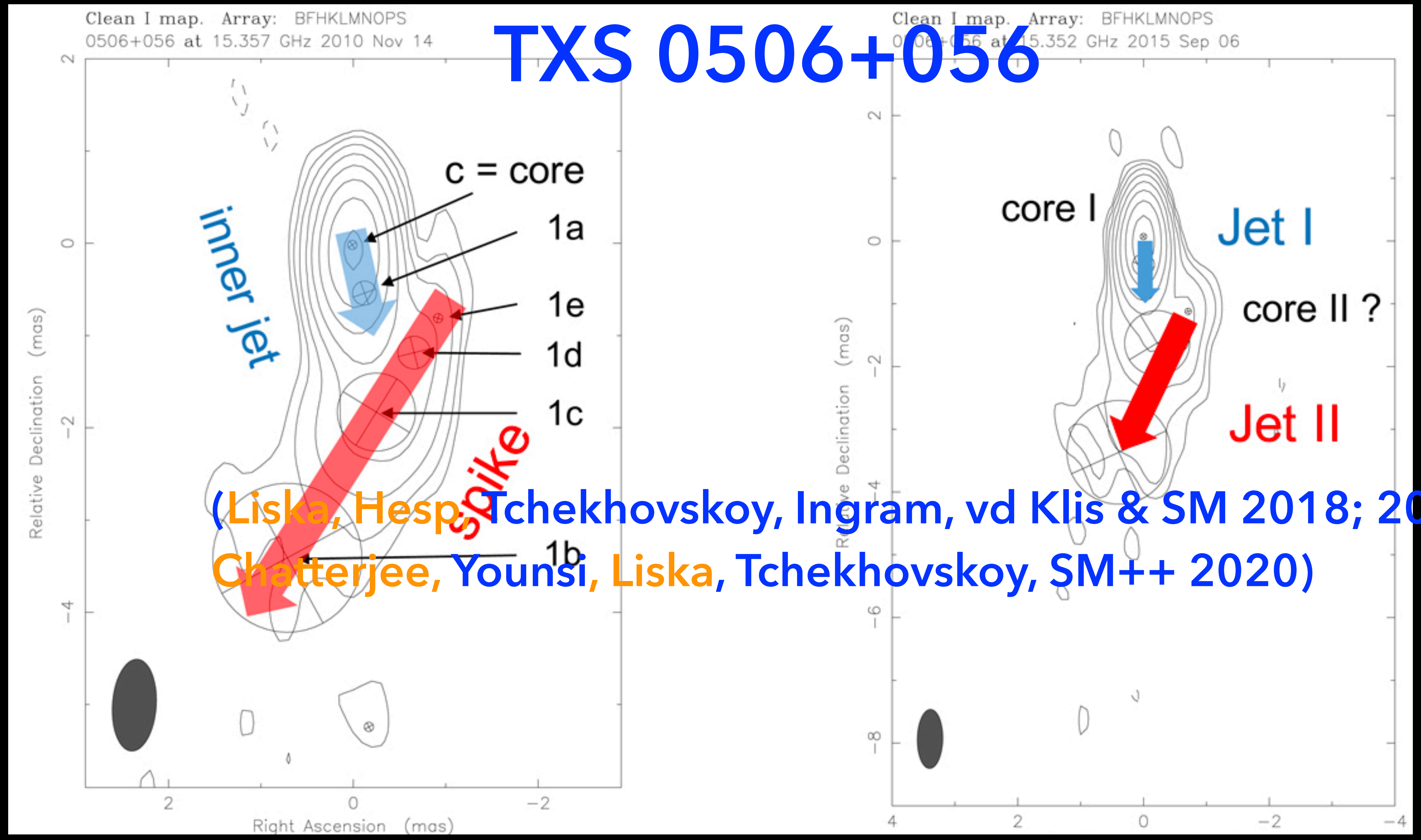
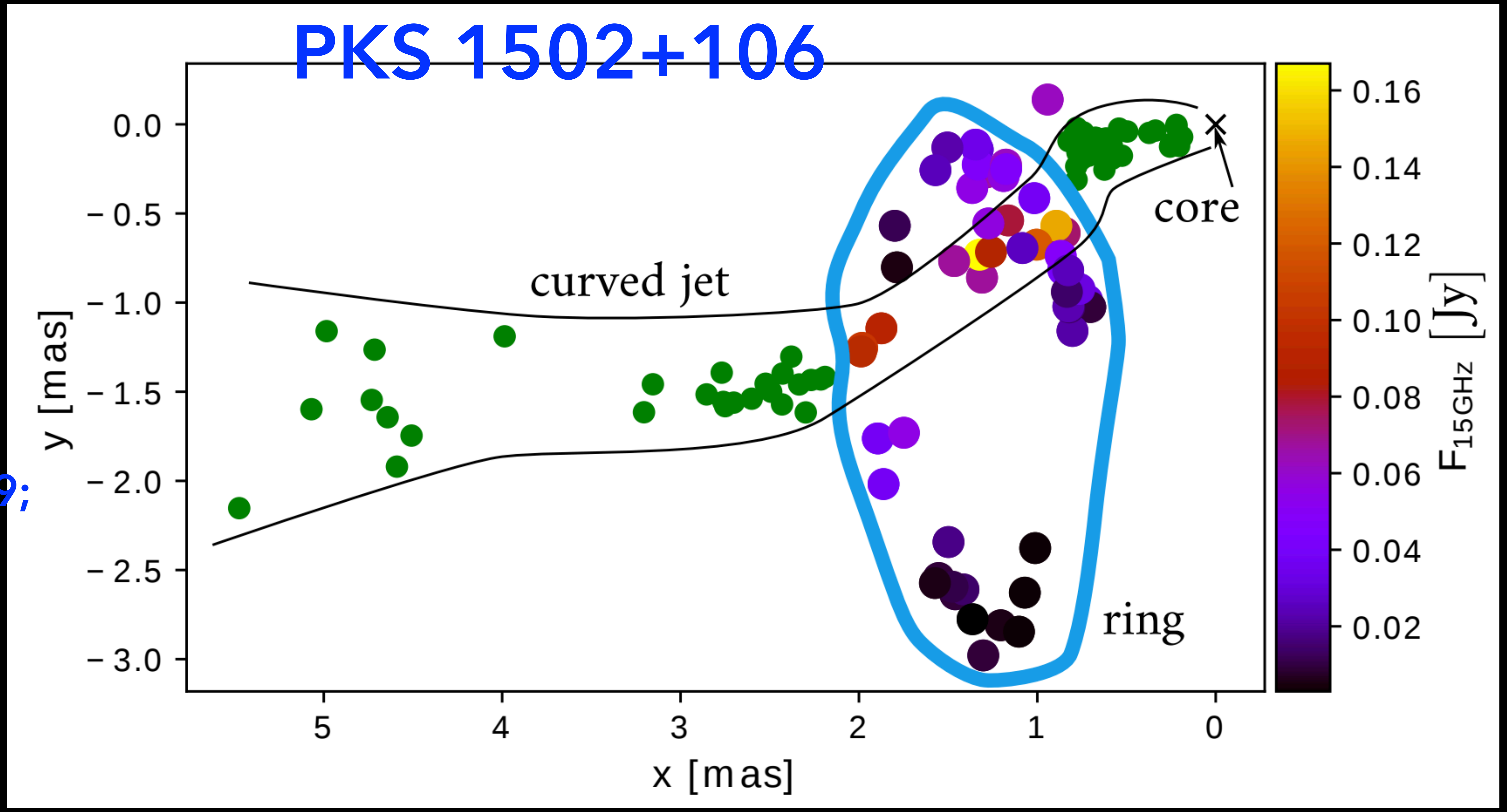
Strategy towards multi-messenger science w/(ng)EHT



- Only a few "coincidences" of neutrino+γ-ray sources, none particularly bright in γ-rays
- Something special in geometry/dynamics? Recent VLBI work by Britzen++2019, 2021 is suggestive:



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



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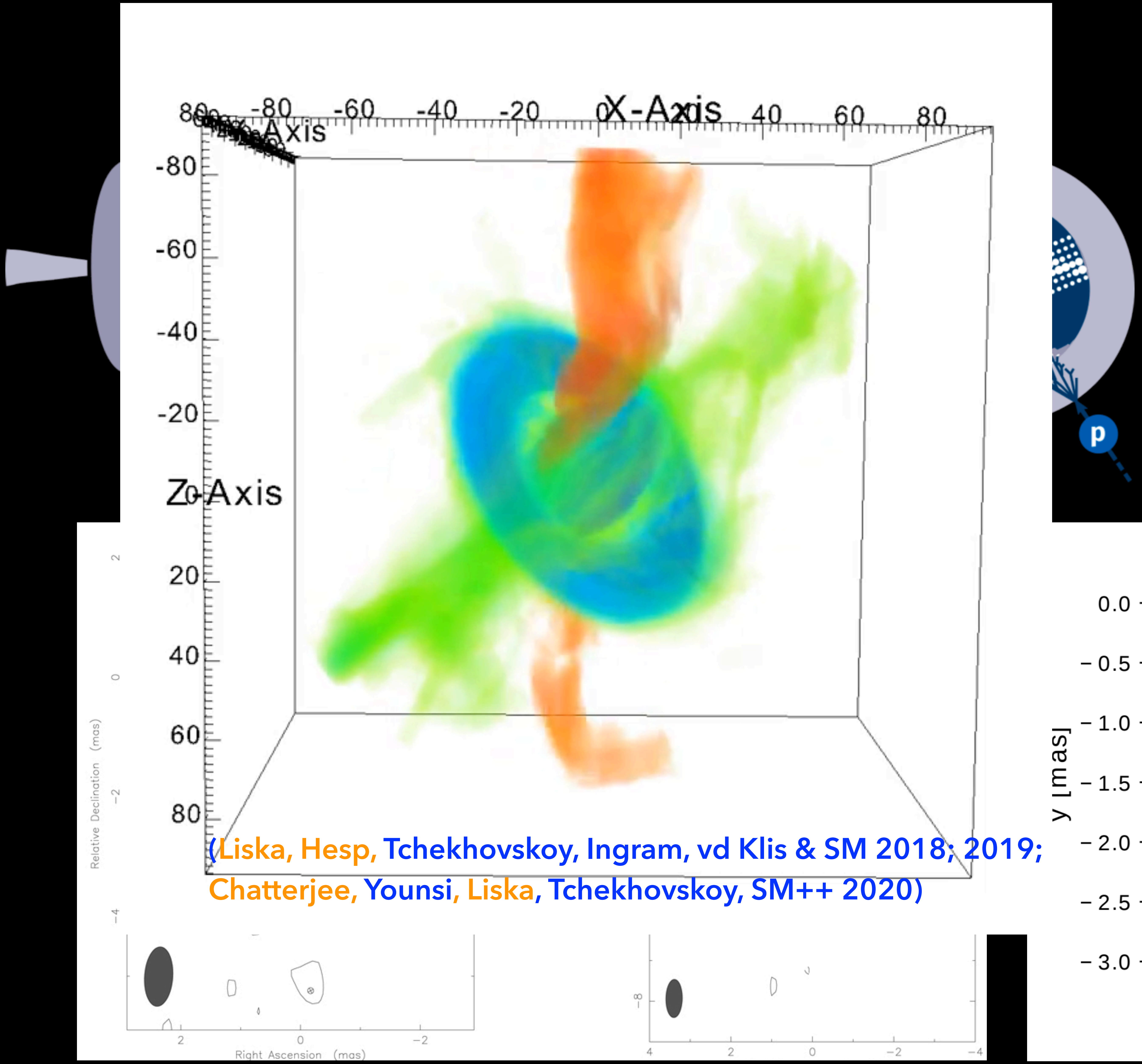
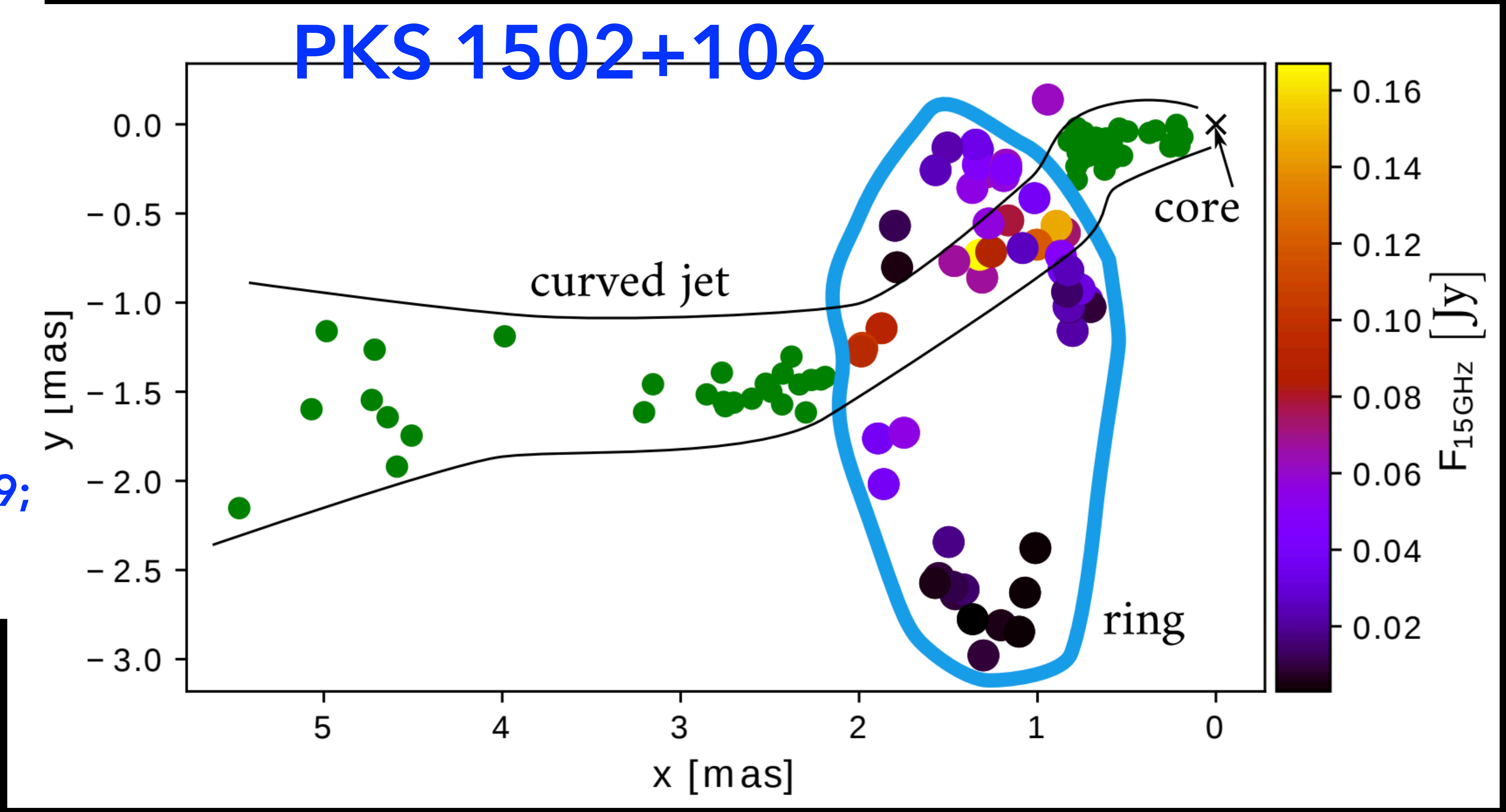


(Liska, Hesp, Tchekhovskoy, Ingram, vd Klis & SM 2018; 2019; Chatterjee, Younsi, Liska, Tchekhovskoy, SM++ 2020)



Strategy towards multi-messenger science w/(ng)EHT

ngEHT Concept Development

ngEHT
Science at the Horizon

Timeline:

- Phase I - design (2019-2024)
- Phase II - build out and commission (2024-2030)

- **New Stations:** ~10 small aperture (6-10m) dishes at optimized locations.
- **Bandwidth Expansion:** 256 Gb/s (x4)
- **Dual Band Observing:** 1.3mm/0.87mm
- **Data Volumes:** 10-100 PBytes
- **High speed data capture and transport:** leveraging COTS systems.
- **Data Processing:** x16 computational load
  - Cloud correlation: shifting all processing to a massively parallel platform.
- **Optimizing Algorithms:** Multi-frequency Synthesis, Dynamical Imaging, …

Astro2020 APC White Paper

Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Lindy Blackburn[1,2,*] Sheperd Doeleman[1,2,*], Jason Dexter[12], José L. Gómez[16], Michael D. Johnson[1,2], Daniel C. Palumbo[1,2], Jonathan Weintroub[1,2], Joseph R. Farah[1,2,21], Vincent Fish[4], Laurent Loinard[18,19], Colin Lonsdale[4], Gopal Narayanan[28], Nimesh A. Patel[2], Dominic W. Pesce[1,2], Alexander Raymond[1,2], Remo Tilanus[17,22,23], Maciek Wielgus[1,2], Kazunori Akiyama[1,3,4,5], Geoffrey Bower[6], Avery Broderick[7,8,9], Roger Deane[10,11], Christian Michael Fromm[13], Charles Gammie[14,15], Roman Gold[13], Michael Janssen[17], Tomohisa Kawashima[4], Thomas Krichbaum[29], Daniel P. Marrone[20], Lynn D. Matthews[4], Yosuke Mizuno[13], Luciano Rezzolla[13], Freek Roelofs[17], Eduardo Ros[29], Tuomas K. Savolainen[29,30,31], Feng Yuan[24,25,26], Guangyao Zhao[27]

Estimated Cost:

- Construction \$140M
- Operation \$13M/year

(Slide ‘borrowed’ from Shep Doeleman’s talk)

Strategy towards multi-messenger science w/(ng)EHT

M87: Transformative ngEHT imaging fidelity

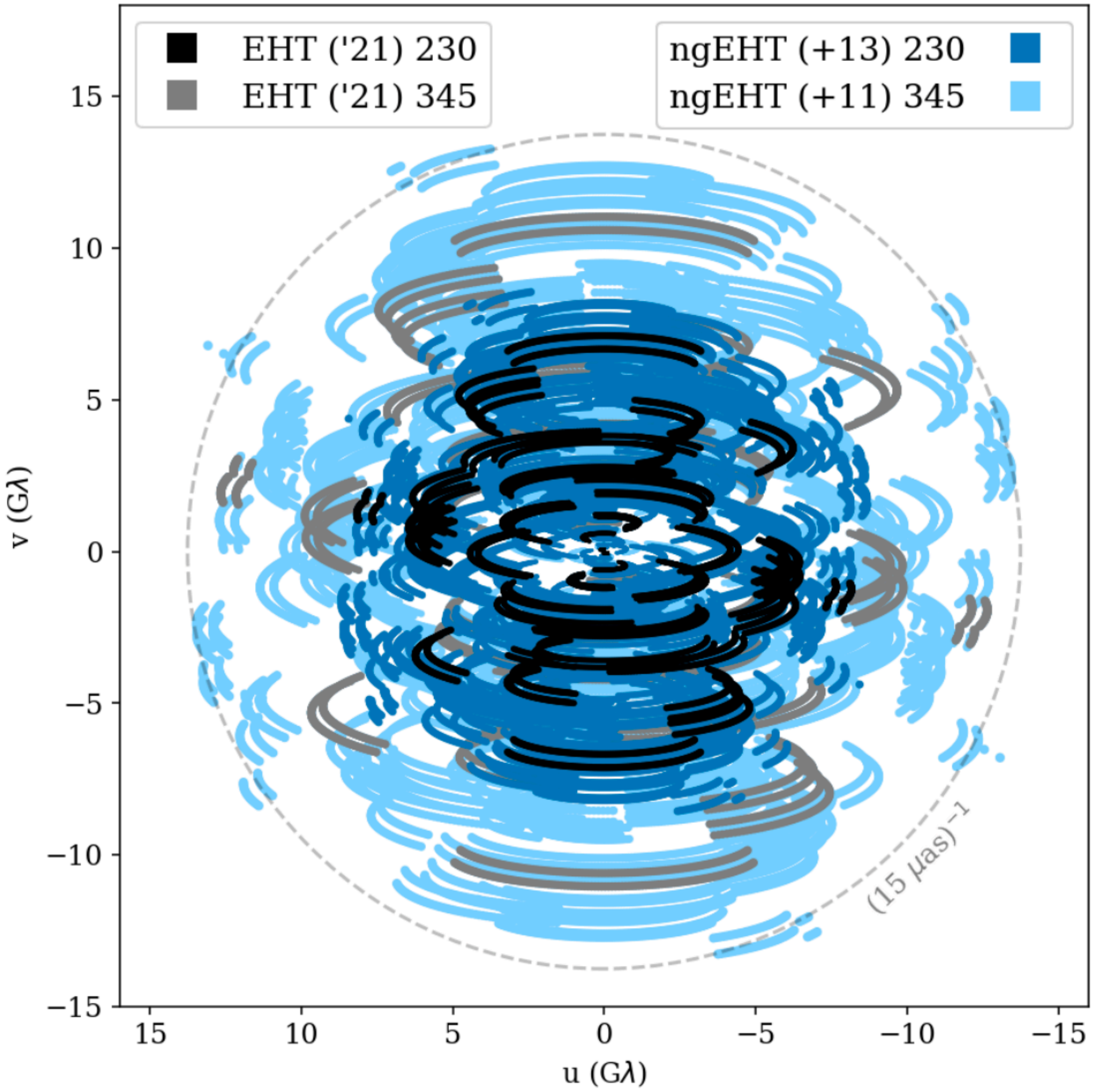
ngEHT
Science at the Horizon orizon

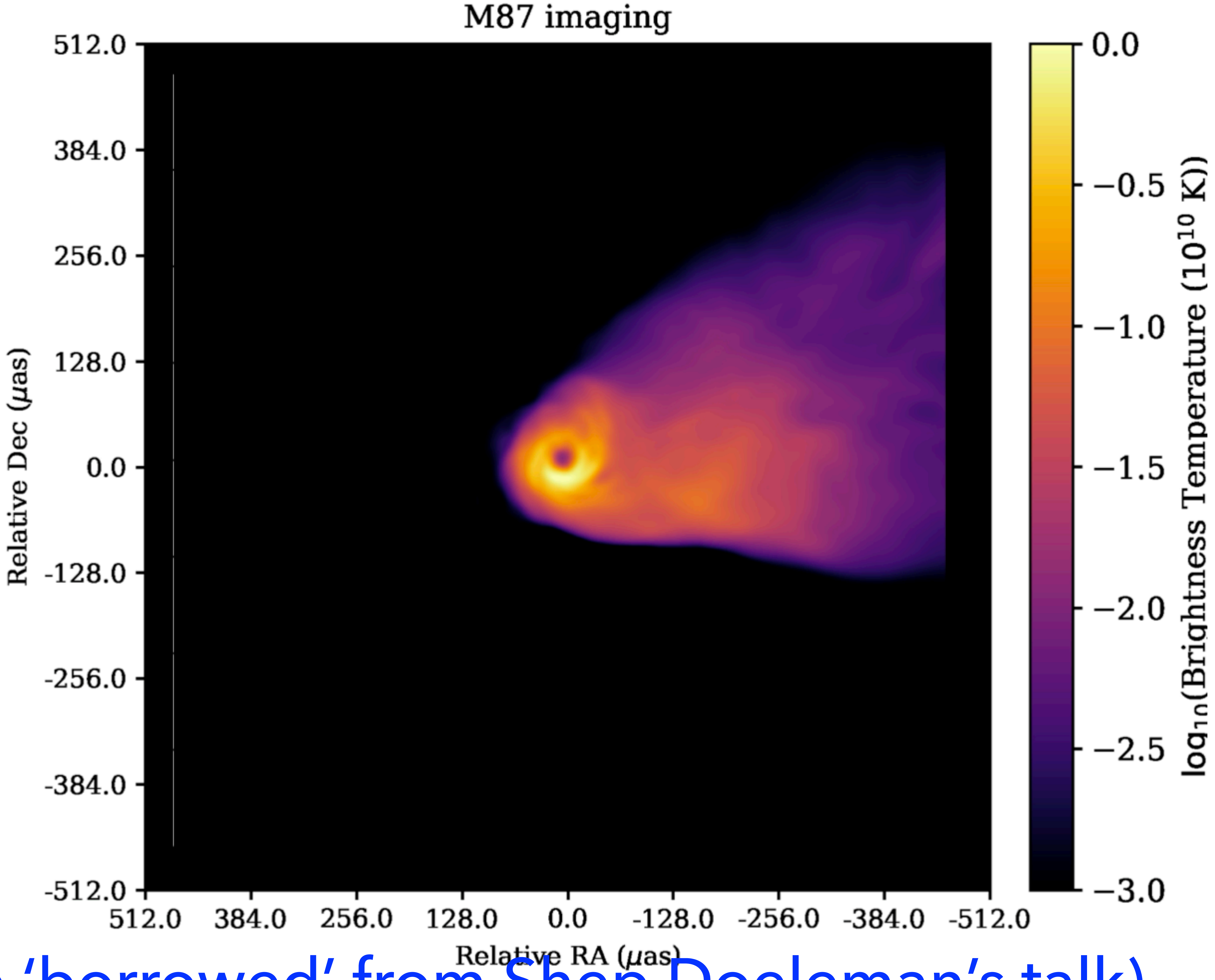
L. Blackburn & A. Chael

ngEHT (+13)

APEX SMA JCMT SMT LMT PV PDB SPT GLT [KP] (no ALMA)
SGO KEN NZ CNI CAT BMAC KILI BRZ GLT-S YBG SPX [HAY OVRO]
ngEHT sites with zenith $SEFD_{230}$ = 10,000 (8-10m)

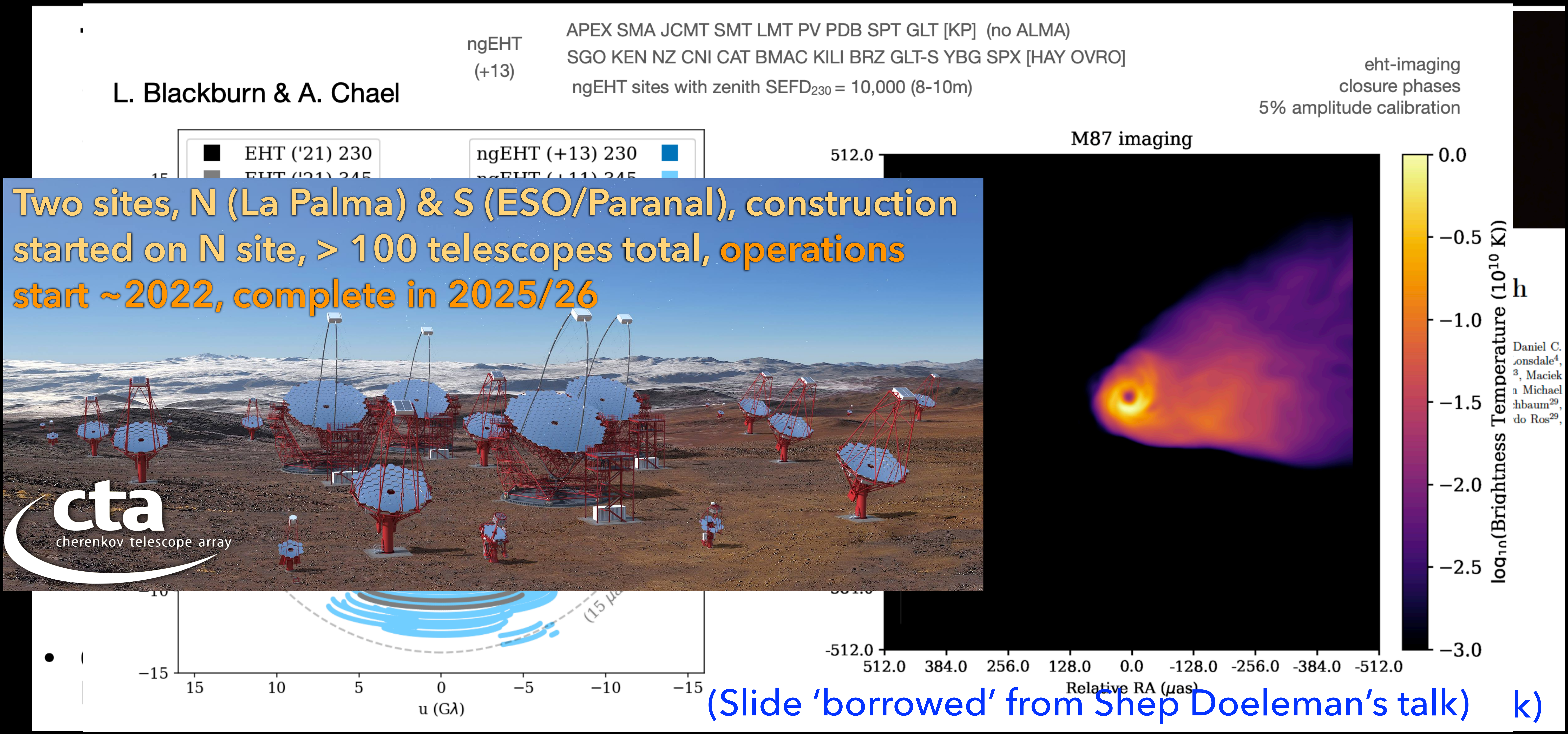
eht-imaging
closure phases
5% amplitude calibration





(Slide 'borrowed' from Shep Doeleman's talk)

Strategy towards multi-messenger science w/(ng)EHT



(Slide 'borrowed' from Shep Doeleman's talk) k)

An expanding horizon for testing physics:

- First MWL paper simultaneous with M87 in 2017 (just accepted!)
- Polarisation imaging and interpretation for M87 (imminent!)
- Sgr A*: very complicated because of variability but in progress
- Non-horizon AGN sources: 3C279, 3C273, OJ287, Cen A, Mrk501, calibrators…
- Multi-wavelength studies simultaneous with EHT runs
- 2018 data (more info on variability, albeit worse quality)
- Lots and lots of theory papers!! ➠ reduction of main error budget
- 2019 cancelled, 2020 run rescheduled for next month (hopefully)
- Future: larger array=better resolution (ngEHT, AMT, etc.), space VLBI !!

Summary

★ EHT's images probe 'hairy' accretion, jet launching, strong-field gravity effects at near horizon scales…*and particle acceleration!*

★ Ability to test GR closely linked to understanding how particles are energised in plasmas ➠ EHT + Multiwavelength (MWL)

★ Cutting edge in theoretical modelling: physical-scale simulations with extremely high resolution ➠ predict *multi-messenger* properties

★ (ng)EHT promises exciting times ahead: expanded ground array, space, movies of black holes, black hole demographics