Modelling supermassive black holes on event horizon scales

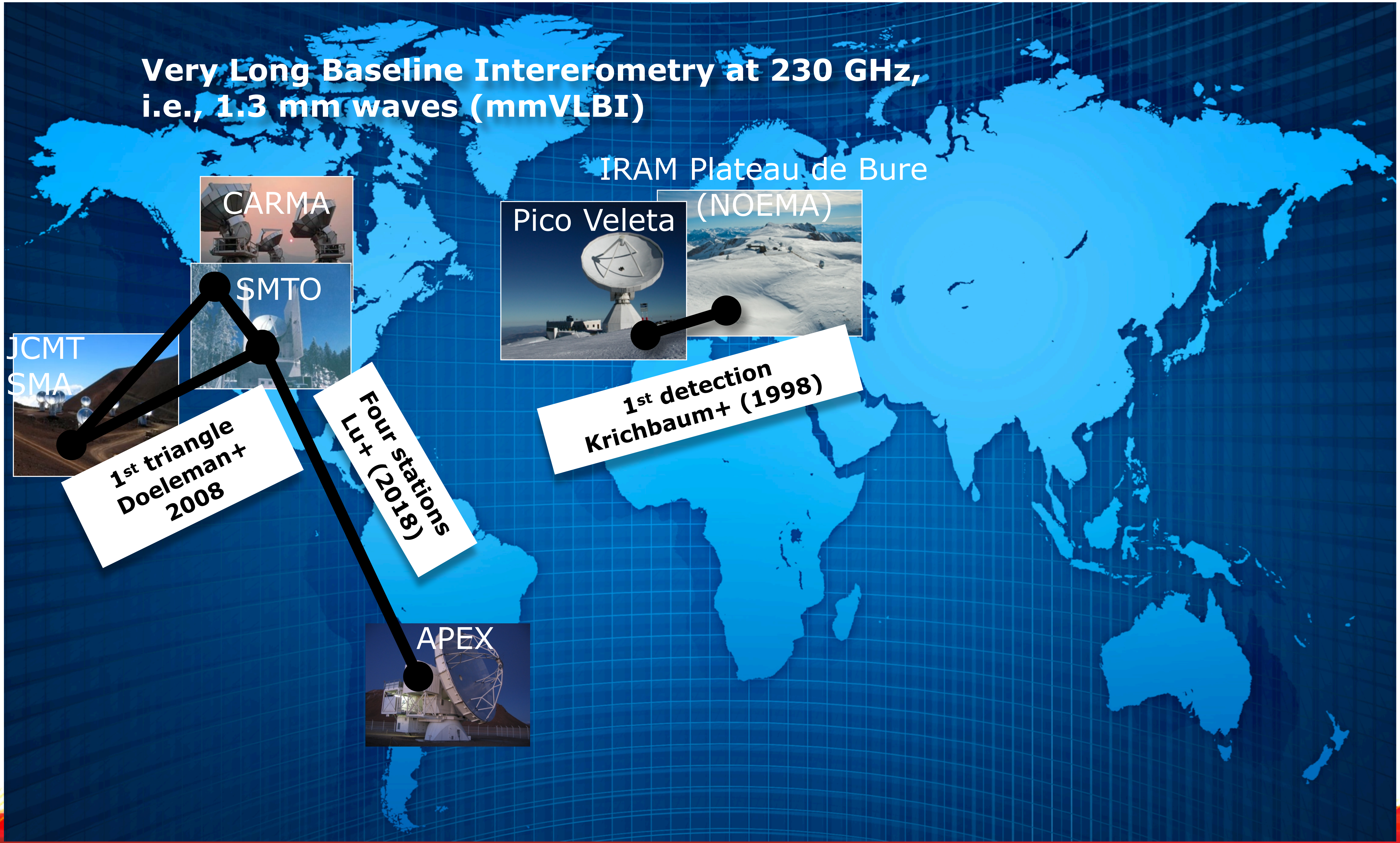
Multimessengers, Prague

Jordy Davelaar
On behalve of the Event Horizon Telescope Collaboration

Netherlands Organisation for Scientific Research
BLACK HOLE CAM
European Research Council
Event Horizon Telescope
Radboud Universiteit


ΤΥΠΟΣ
«Τον καταδίωξαν και τον σκότωσαν»
The New York Times
Frankfurter Allgemeine
THE TIMES
Blackmailers threaten release of Assange embassy 'sex secrets'
May defies Tory rebels with pledge to stay on
LE FIGARO
Européennes: Macron veut orchestrer la campagne
THE WALL STREET JOURNAL
EL PAÍS
La clase media se reduce en los países desarrollados por el declive de ingresos
deVolkskrant
O ESTADO DE S. PAULO
Süddeutsche Zeitung
Netanjahu holt mehr Stimmen
Le Télégramme
VERTIGINEUX !
FOLHA DE S.PAULO
General-Anzeiger
ΕΘΝΙΚΟΣ ΚΗΡΥΞ
Clarín
Preparan un acuerdo para frenar los precios en medio de una pulseada interna
DE TIJD
DERSTANDARD
ST. LOUIS POST-DISPATCH
DARKNESS VISIBLE, FINALLY
Η ΚΑΘΗΜΕΡΙΝΗ
THE BALTIMORE SUN
Judge: A 'crisis' engulfs the city
FINANCIAL TIMES
Microsoft under fire over AI work with Chinese military university
黑洞照片首曝光
GAZETA wyborcza
ŻYCIE PO UDARZE
EGZAMIN Z KSIĘDZEM I TELEFONEM
DIE WELT
Rechnungshof kritisiert Steuervorteile für ARD und ZDF
The Guardian
May defies critics with vow to stay on and see Brexit deal through
Los Angeles Times
la Repubblica
Italia-Libia il negoziato segreto
L'Echo
The Boston Globe
theindependent
DER TAGESSPIEGEL
Union-Tribune
CHINA DAILY
HOSPODÁŘSKÉ NOVINY
Miliardová žaloba proti Vítkovi
EL MUNDO
Casado envía a Aznar a las provincias que le disputa Vox
ブラックホール 初撮影
THE IRISH TIMES
MORGENAVISEN Jyllands-Posten
Det sorte hul
The Dallas Morning News
GOP leaders seek 1-cent sales tax hike

The path towards event horizon imaging



The first observing run

Five observing days in a ten day window

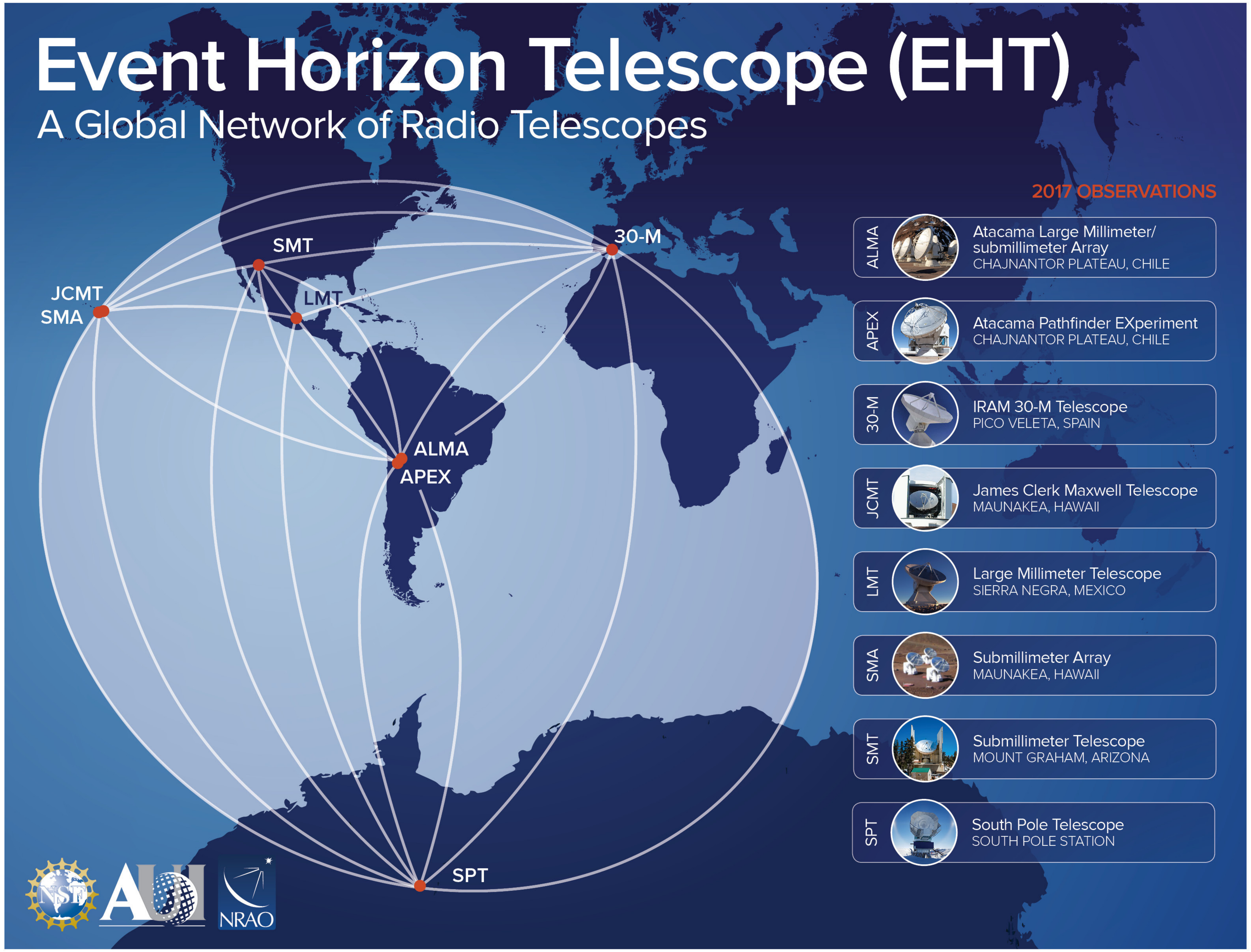
8 Telescopes on 6 sites

First EHT run including ALMA

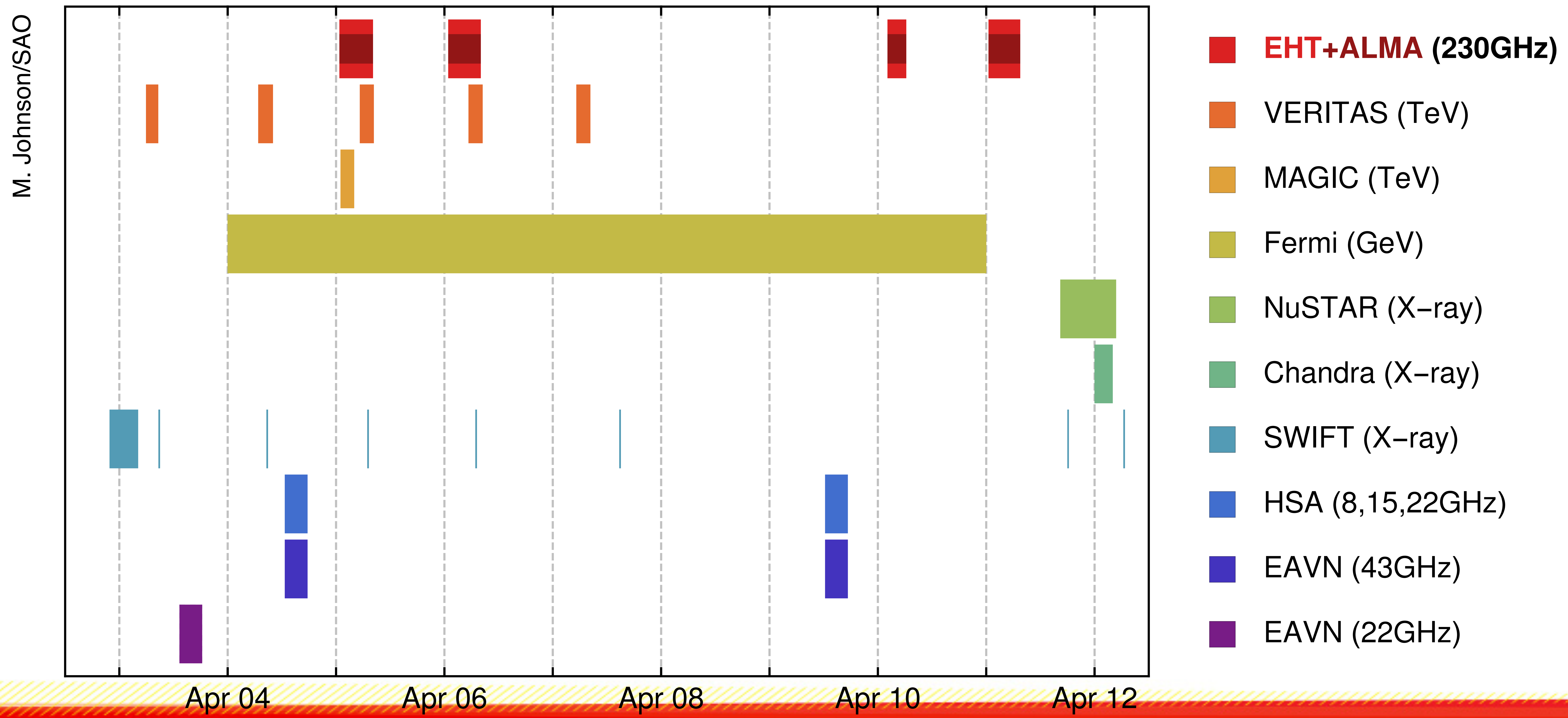
5 Pb of data recorded

Exquisite weather conditions

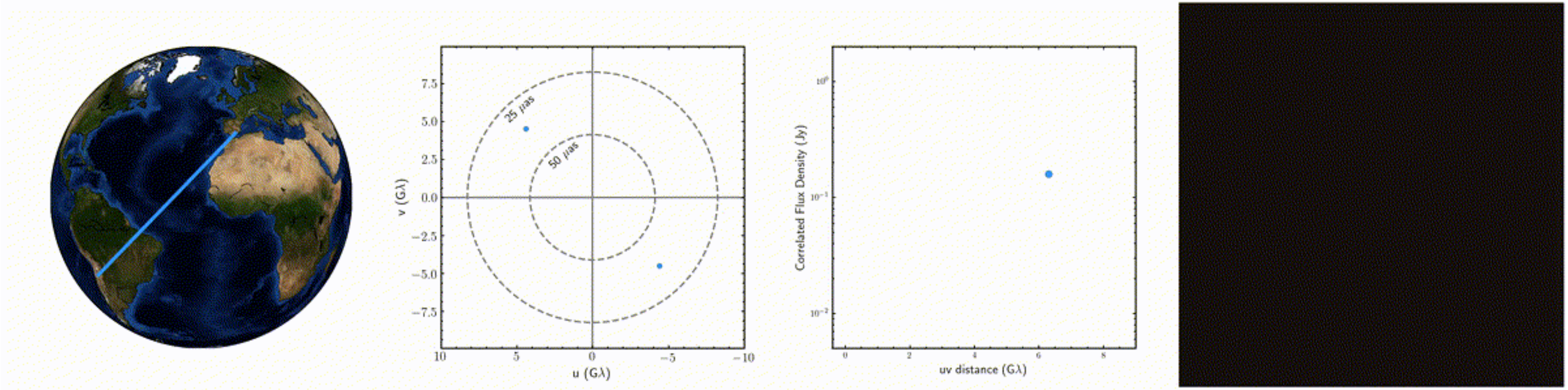
Detections on all baselines



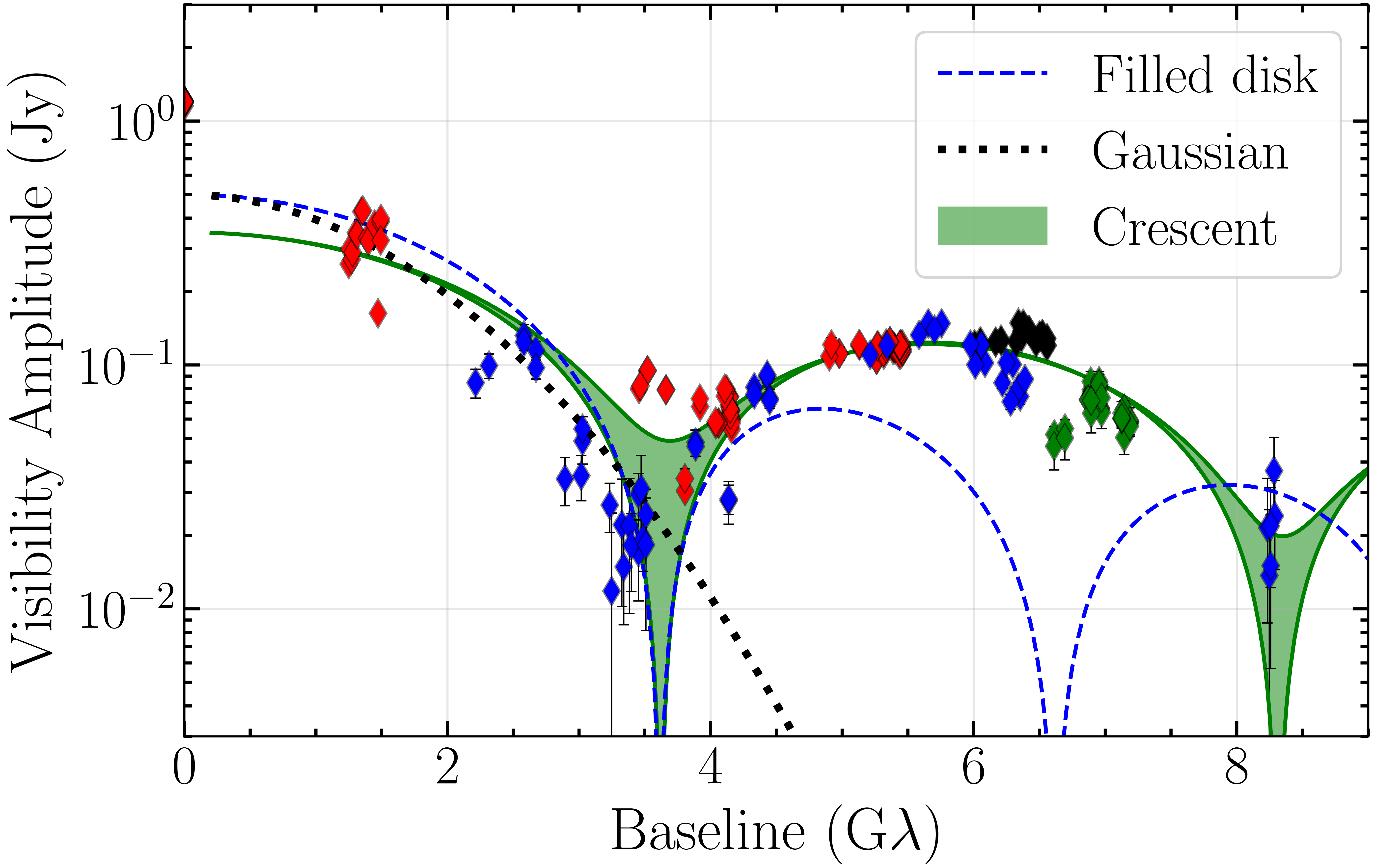
Multi-Wavelength Coverage: M87 in April 2017



The earth as a telescope



A shadow in disguise



The First EHT Images of M87

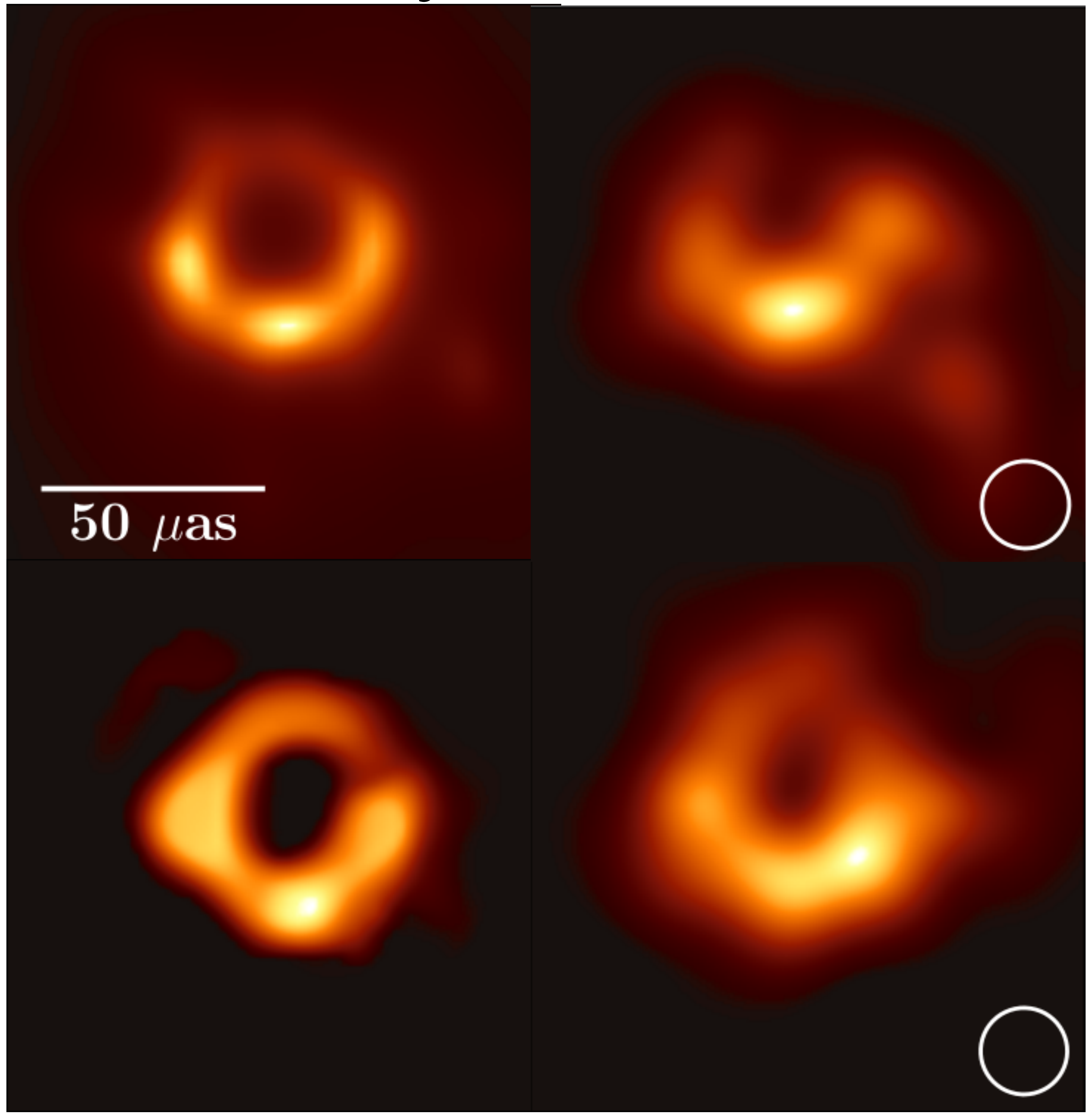
July 24, 2018

Team 1

Region:
The Americas
(SAO, UoA, U.Concepcion)

Team 4

Region:
East Asia (ASIAA, KASI, NAOJ)



Team 2

Region:
Global
(MIT Haystack, Radboud U, NAOJ)

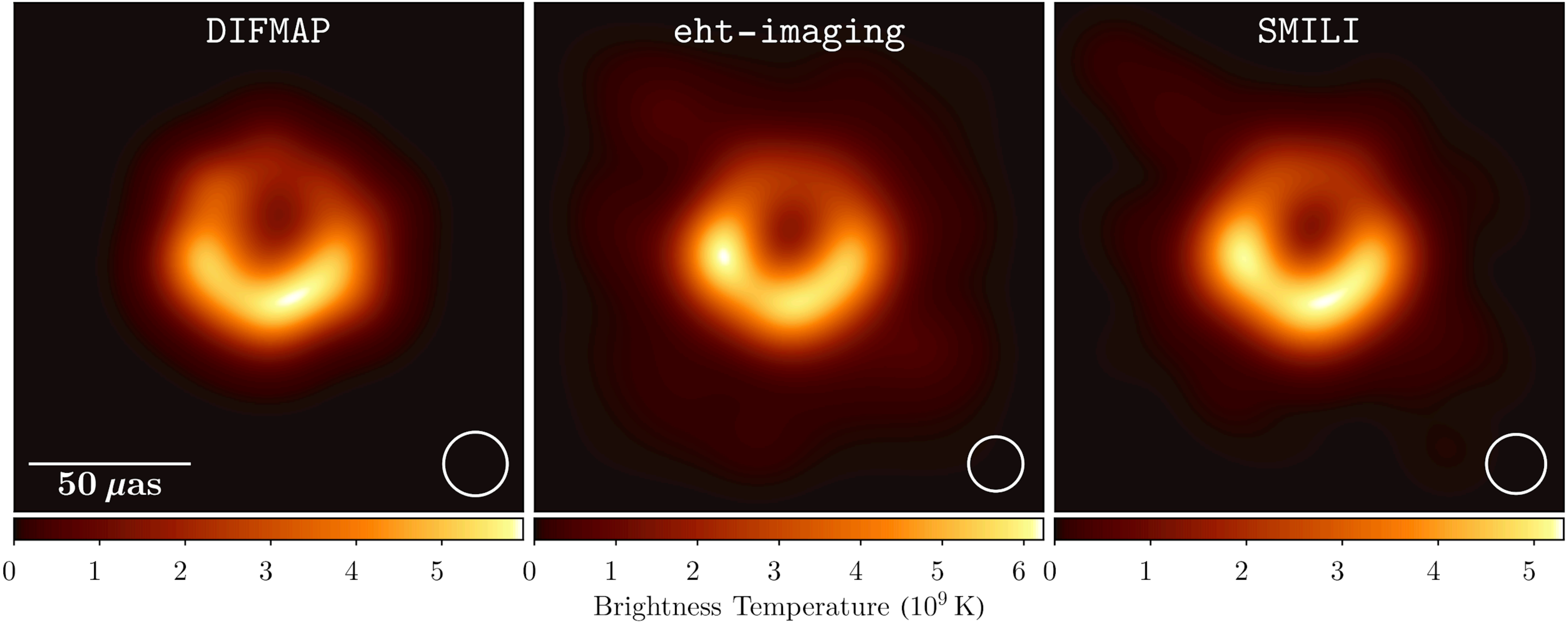
Team 3

Region:
Cross-Atlantic
(MPIfR, Boston U, IAA, Aalto)

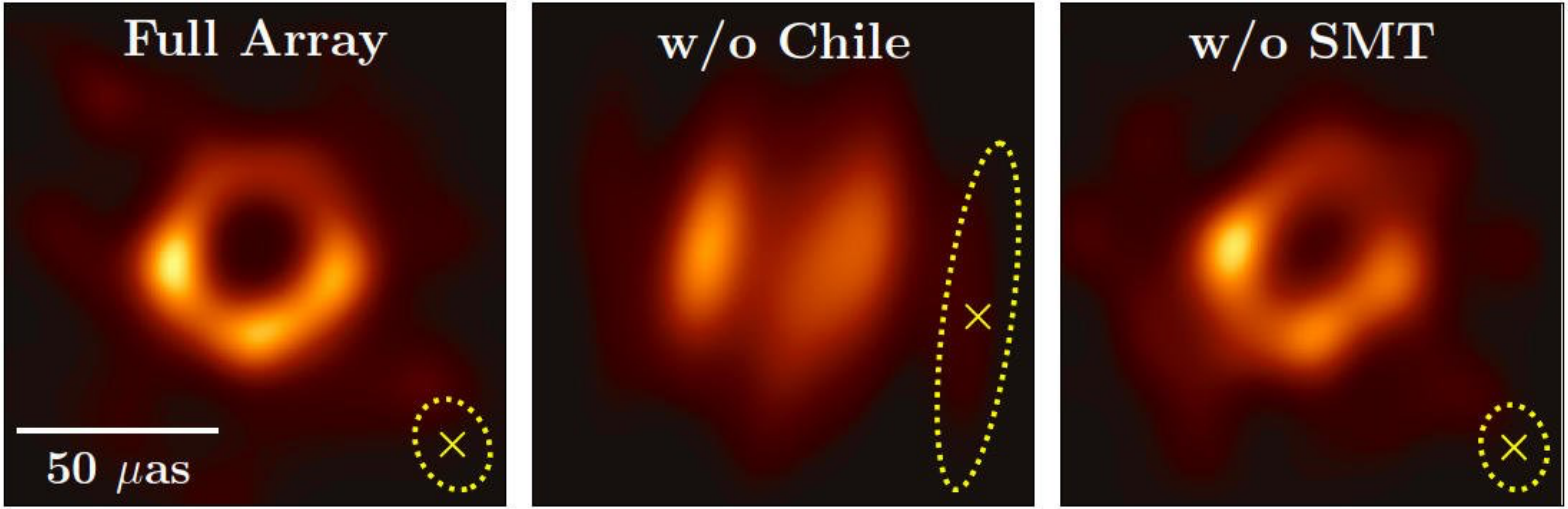
Each team blindly reconstructed images

Goal: Assess human bias

Different methods, same answer



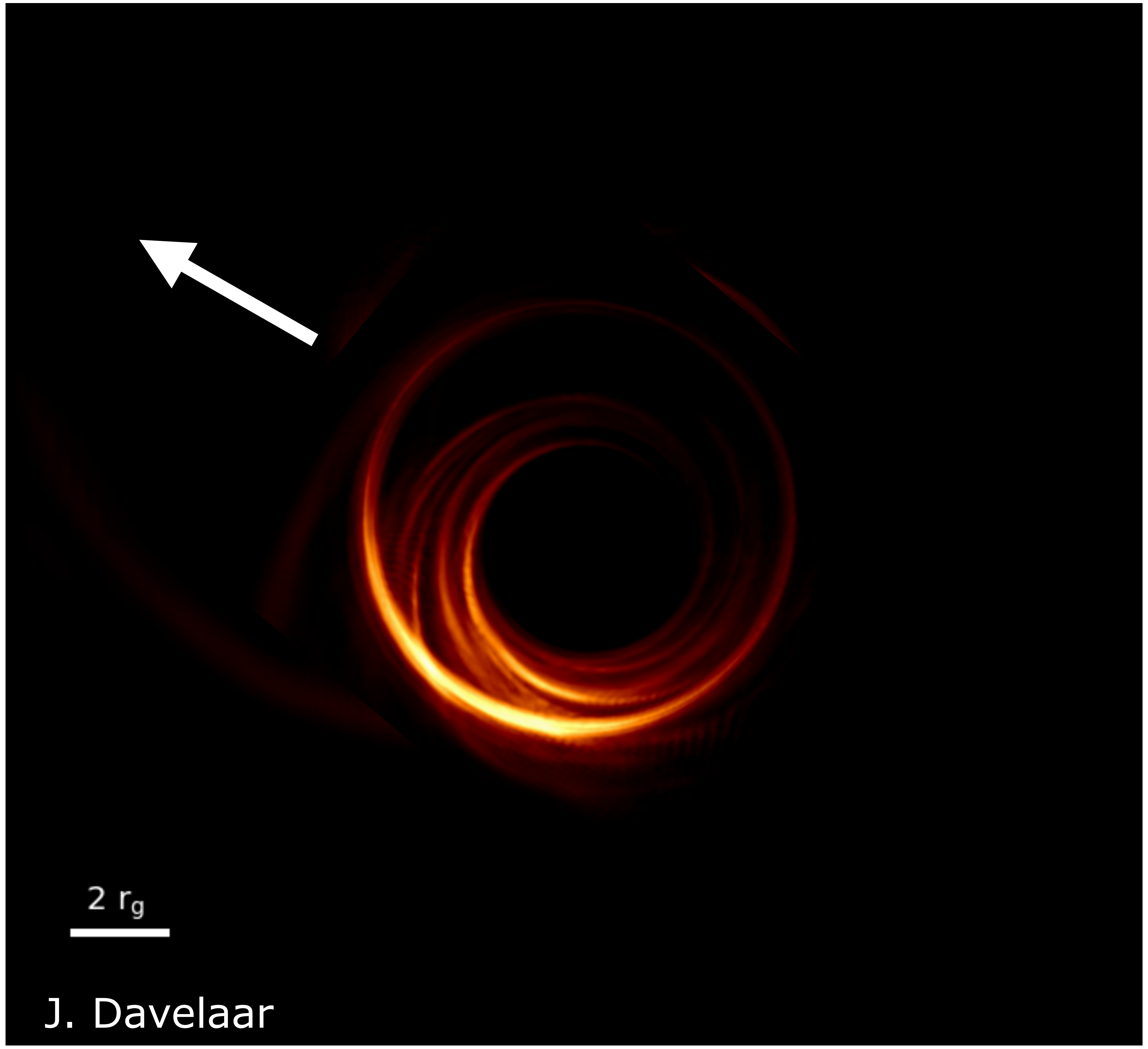
The Power of ALMA



Event Horizon Telescope

Credit: O. Porth, L.Rezzolla

General Relativistic Ray Tracing 101

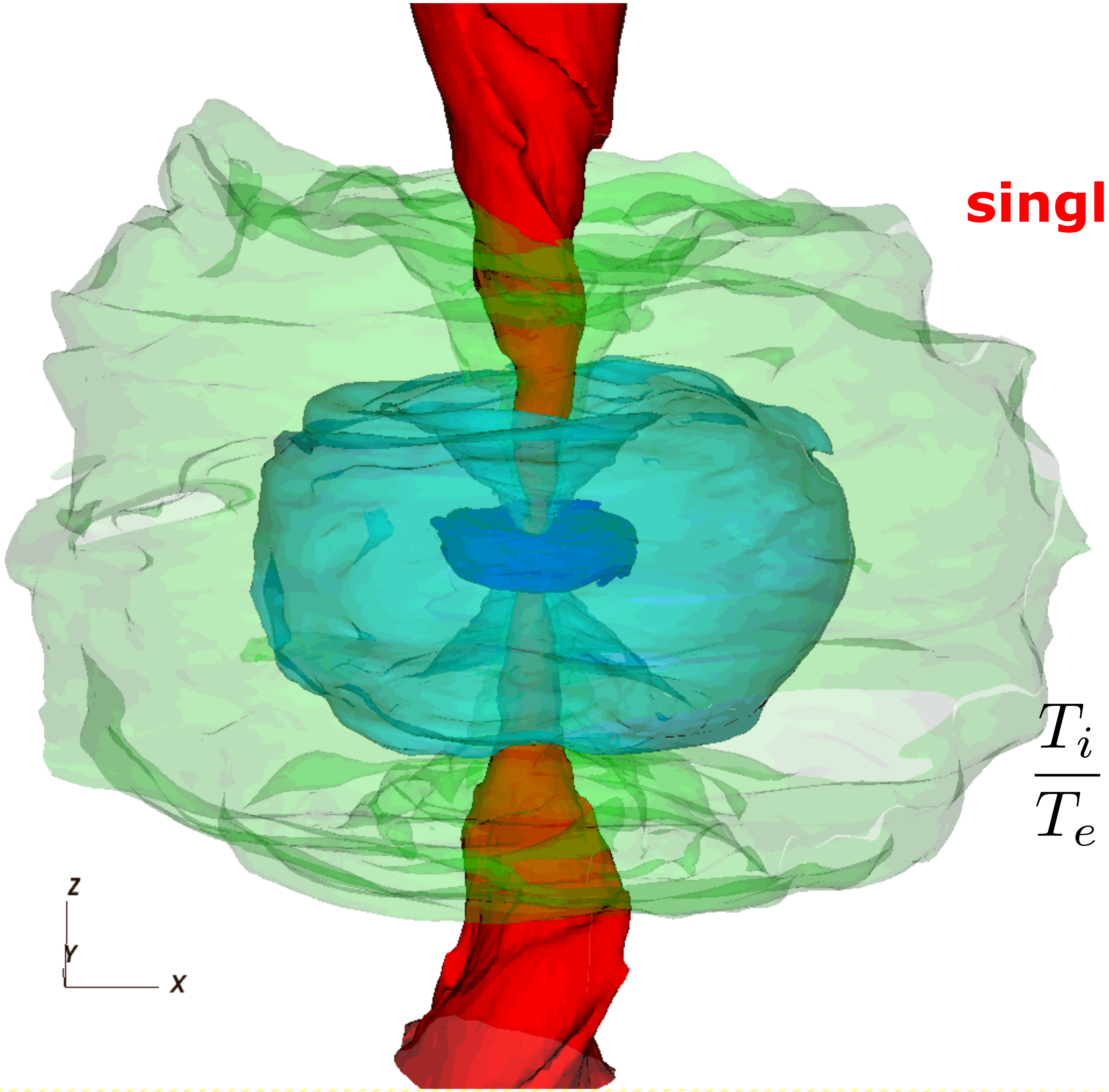


Modeling accreting black holes: "the standard model"

3D GRMHD density regions:

Red: low density, high magnetization

Blue: high density, low magnetization



Jet: single-temperature plasma:
$T_{electron} \sim T_{proton}$

Accretion flow: two-temperature plasma
$T_{electron} \ll T_{proton}$

$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$

$$\beta = \frac{P_{gas}}{P_{mag}} = \frac{u(\gamma - 1)}{B^2}$$

Moscibrodzka et al. (2016, A&A)

Simulation Library: 43 GRMHD numerical simulations

- 3D GRMHD simulations from: `BHAC, iharm3d, KORAL, H-AMR`

- Two accretion states according to accumulated magnetic flux on horizon:
  - SANE (Standard and Normal Evolution)
  - MAD (Magnetically Arrested Disk)

- BH spin parameter:
  - SANE: -0.94, -0.5, 0, 0.5, 0.75, 0.88, 0.94, 0.97, 0.98
  - MAD: -0.94, -0.5, 0, 0.5, 0.75, 0.94

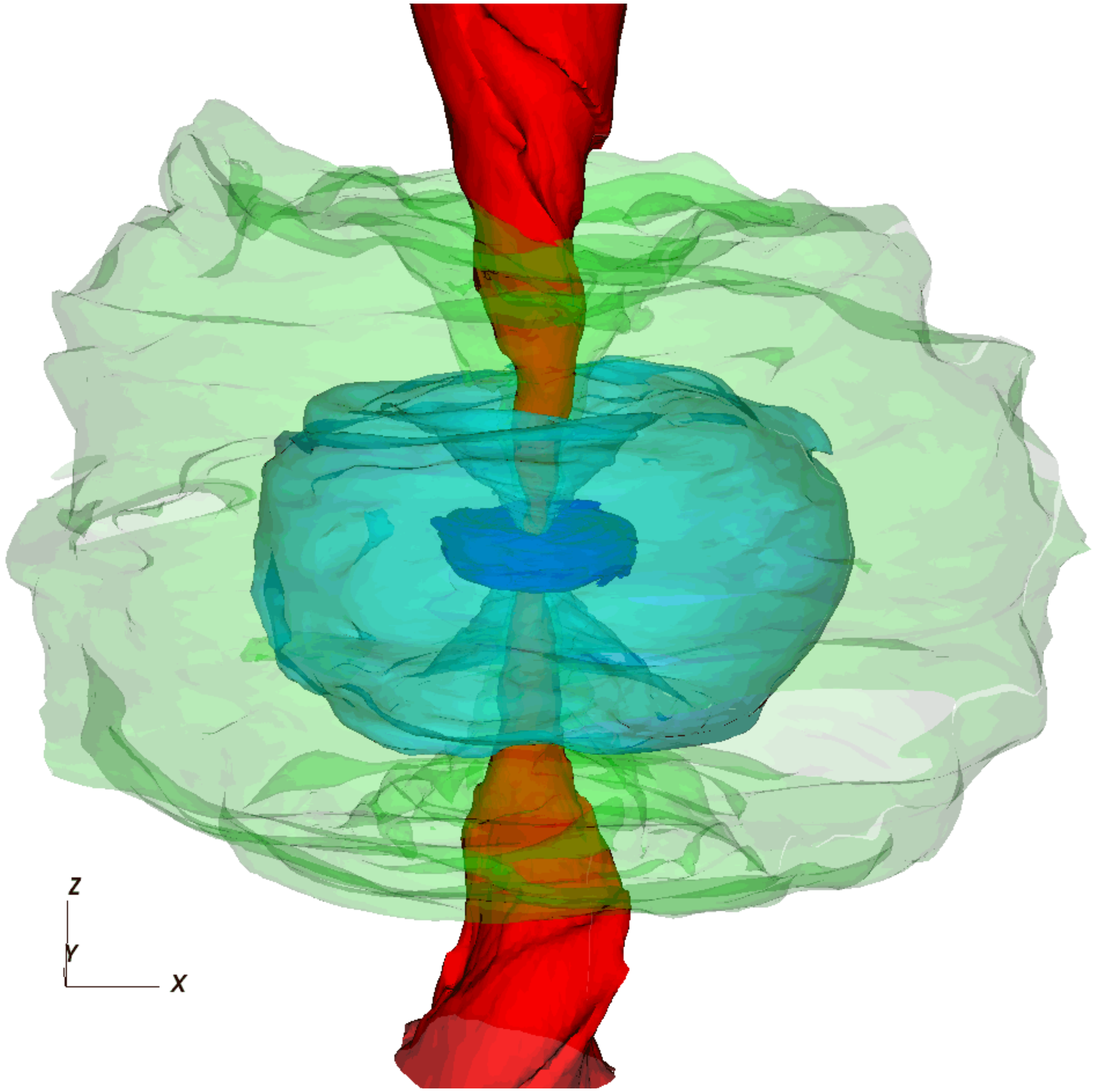
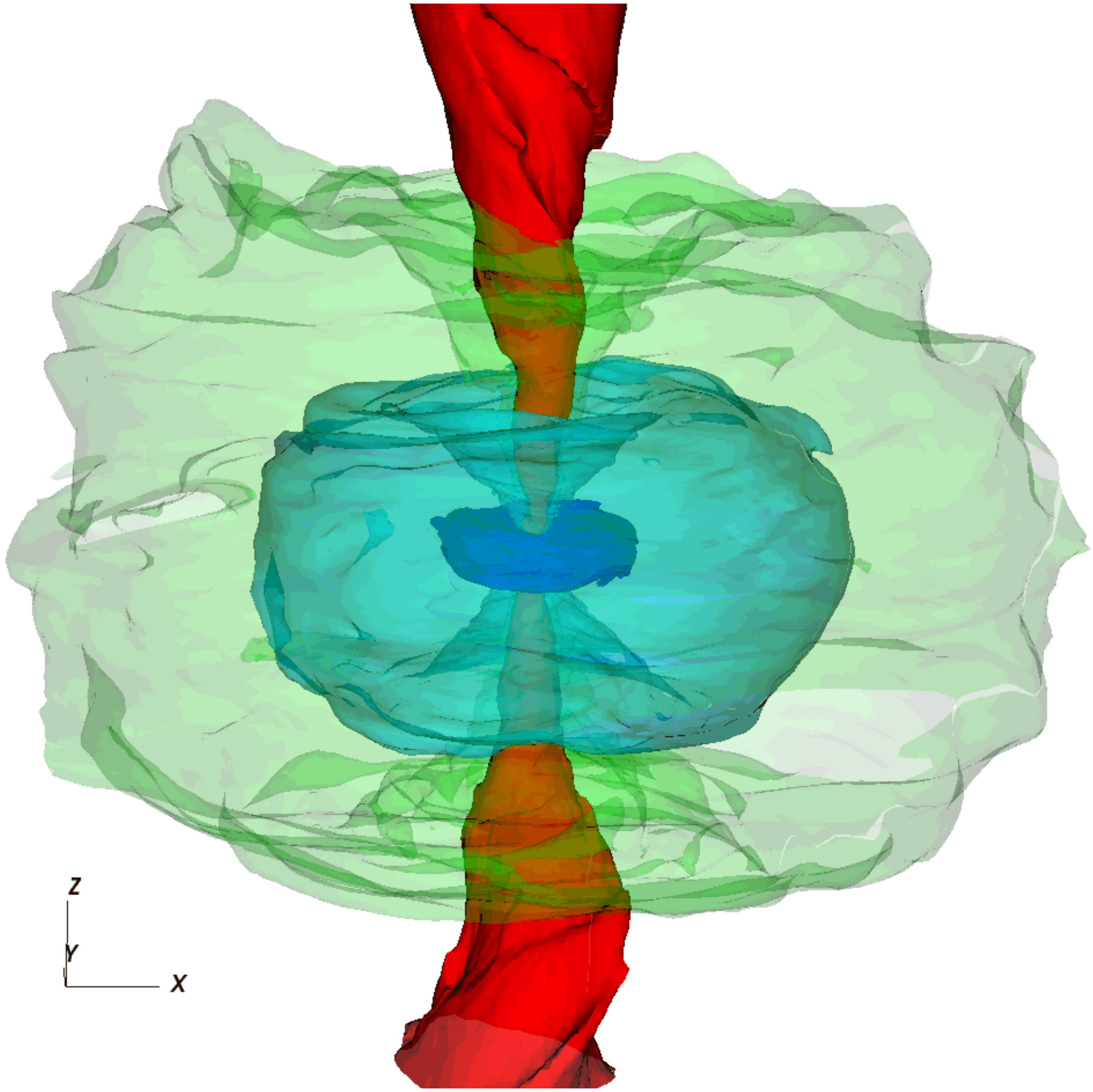


Image Library: > 60,000 images

- 1.3mm modeled images from: `ipole`, `RAPTOR`, `BHOSS`
- Observer inclination angles: i=12, 17, 22, 158, 163, 168 deg
- Thermal electron distrbution in full domain: R_{high}=(1, 10, 20, 40, 80,160),



Event Horizon Telescope

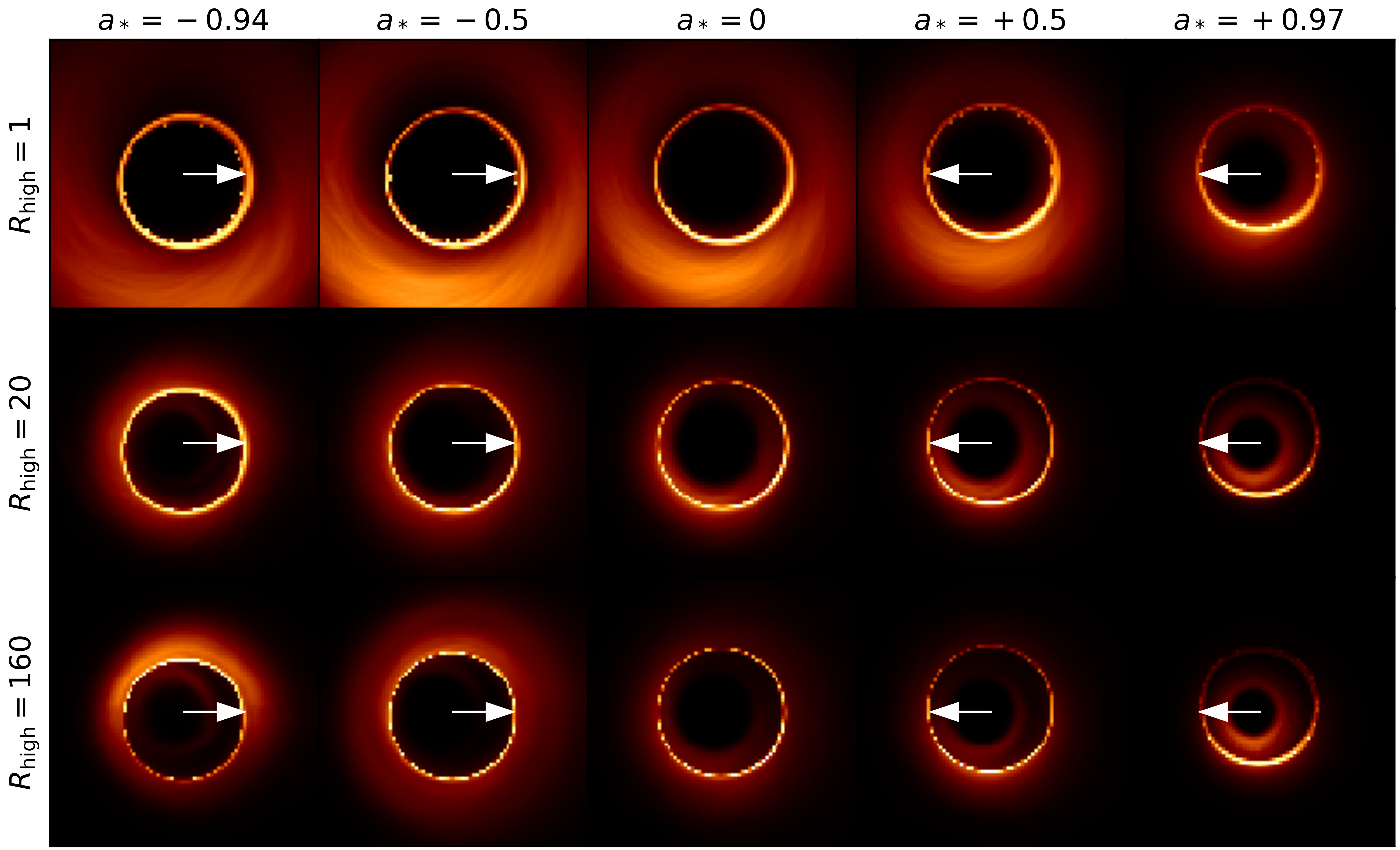
Radboud Universiteit


Event Horizon Telescope

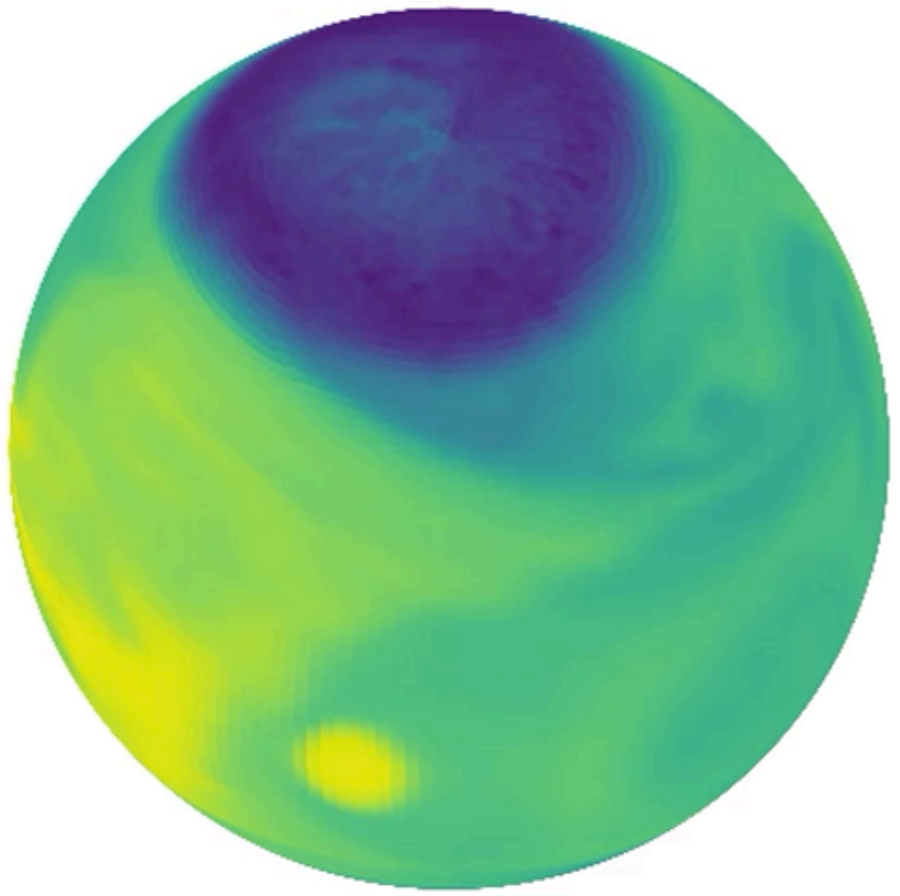
Overview of image library: Time-averaged Images (SANE)

black hole
rotational axis

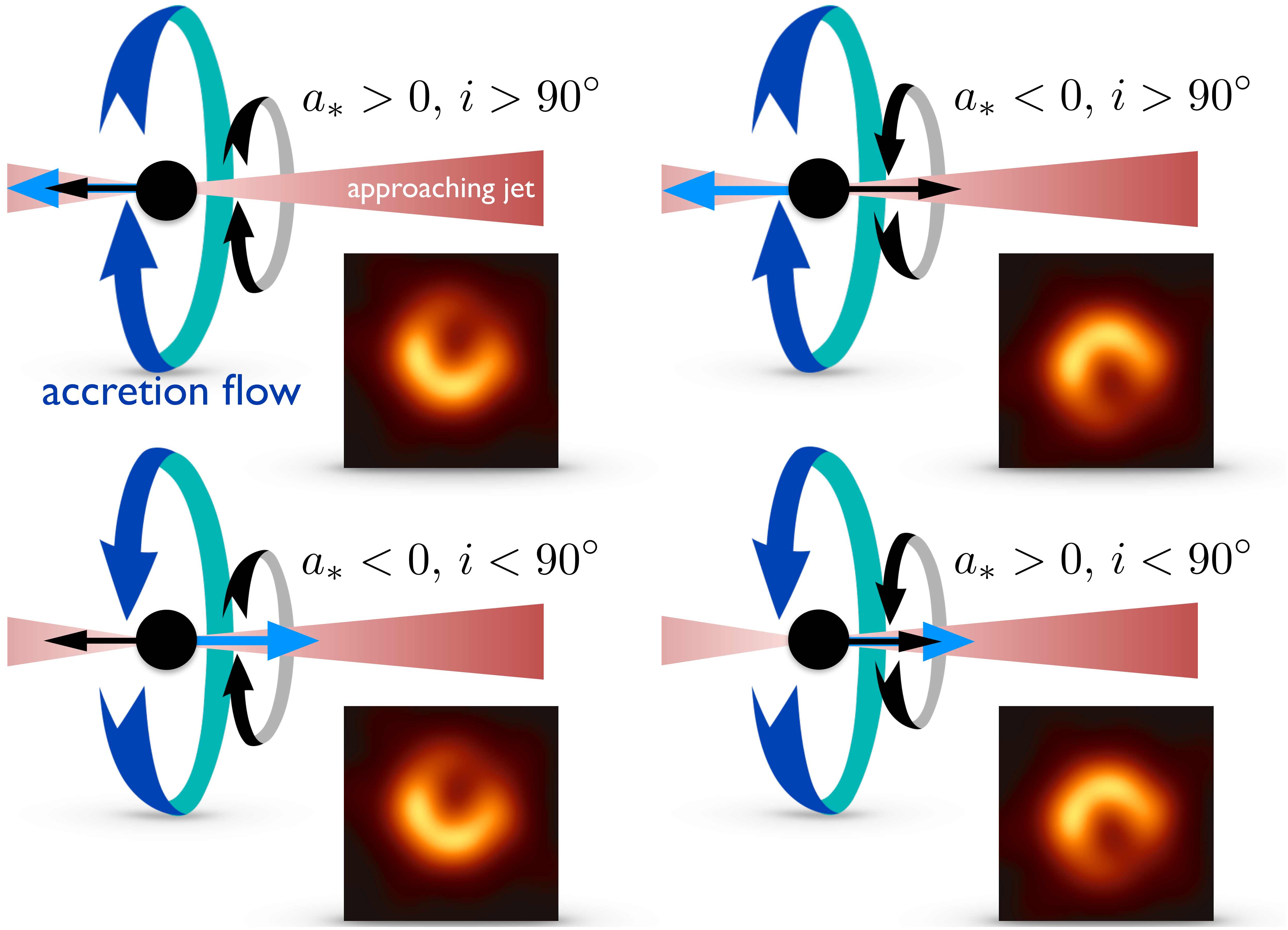
**the forward jet is pointed to the right in all panels*



Ring Asymmetry and Black Hole Spin



G. Wong, B. Prather, C. Gammie (Illinois)



Model constraints

Four constraints

1. Average Imaging Score
2. Radiative efficiency must be small
3. Must not overproduce X-rays
4. Must produce jet power > minimal jet power = 10^{42} erg/sec

Constraint Summary

- Applied Average Imaging Score (AIS), consistency of radiative equilibrium, max X-ray luminosity, and minimum jet power
- SANE models that pass; a = -0.94 and a = 0.94 models with large R_{high}
- MAD models that pass, a = ±0.5, and a=0.94, models with large R_{high}

SANE

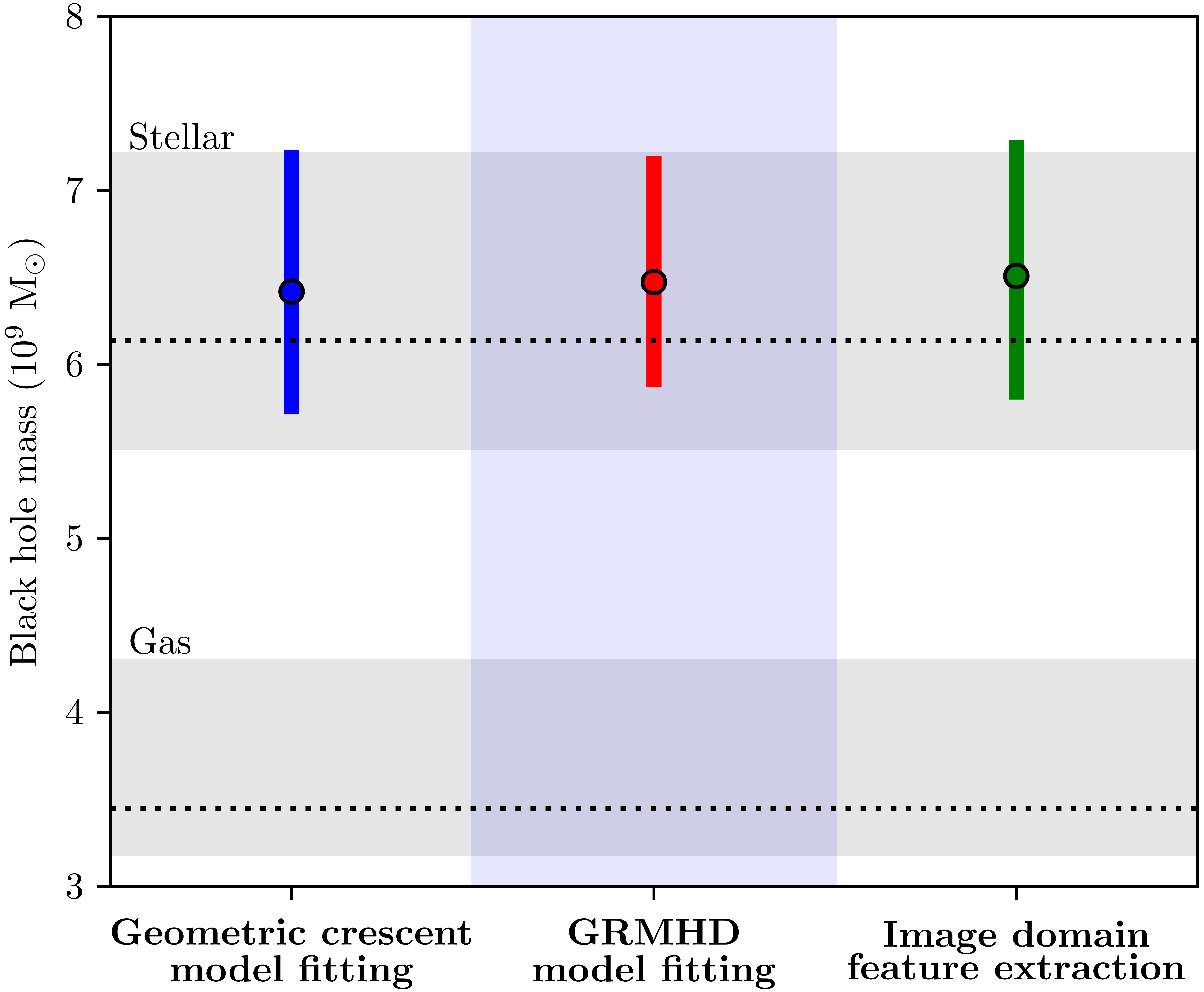
flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
SANE	-0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	-0.94	10	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	20	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	40	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	160	Fail	Pass	Pass	Pass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

MAD

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

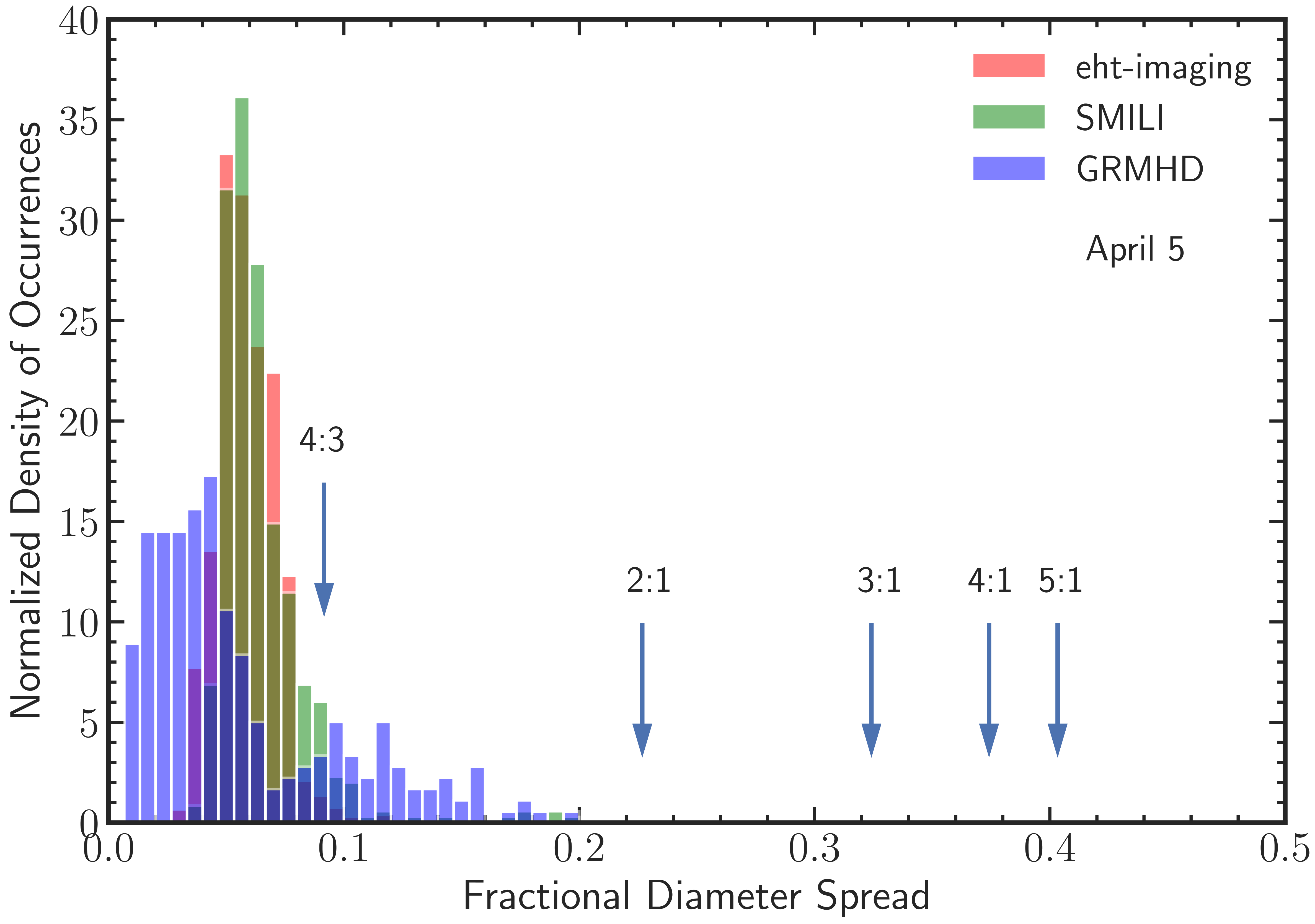
The mass of M87*

- Using D = 16.8 +/- 0.7 Mpc
- M = 6.5 +/- 0.7 x 10^9 Msun
- Three methods in excellent agreement
- Excellent agreement with recent stellar dynamics mass estimate (Gebhardt+2011)



Towards tests of GR: image circularity

- At low inclination of M87, shadow shape should be extremely circular for all values of black hole spin (e.g. Chan+2013)
- From reconstructed images, we measure an emission region that is circular to within ~4:3 in axis ratio
- Given limited resolution, result is consistent with expectations from GRMHD models of M87
- Future: get to circularity of shadow and photon ring



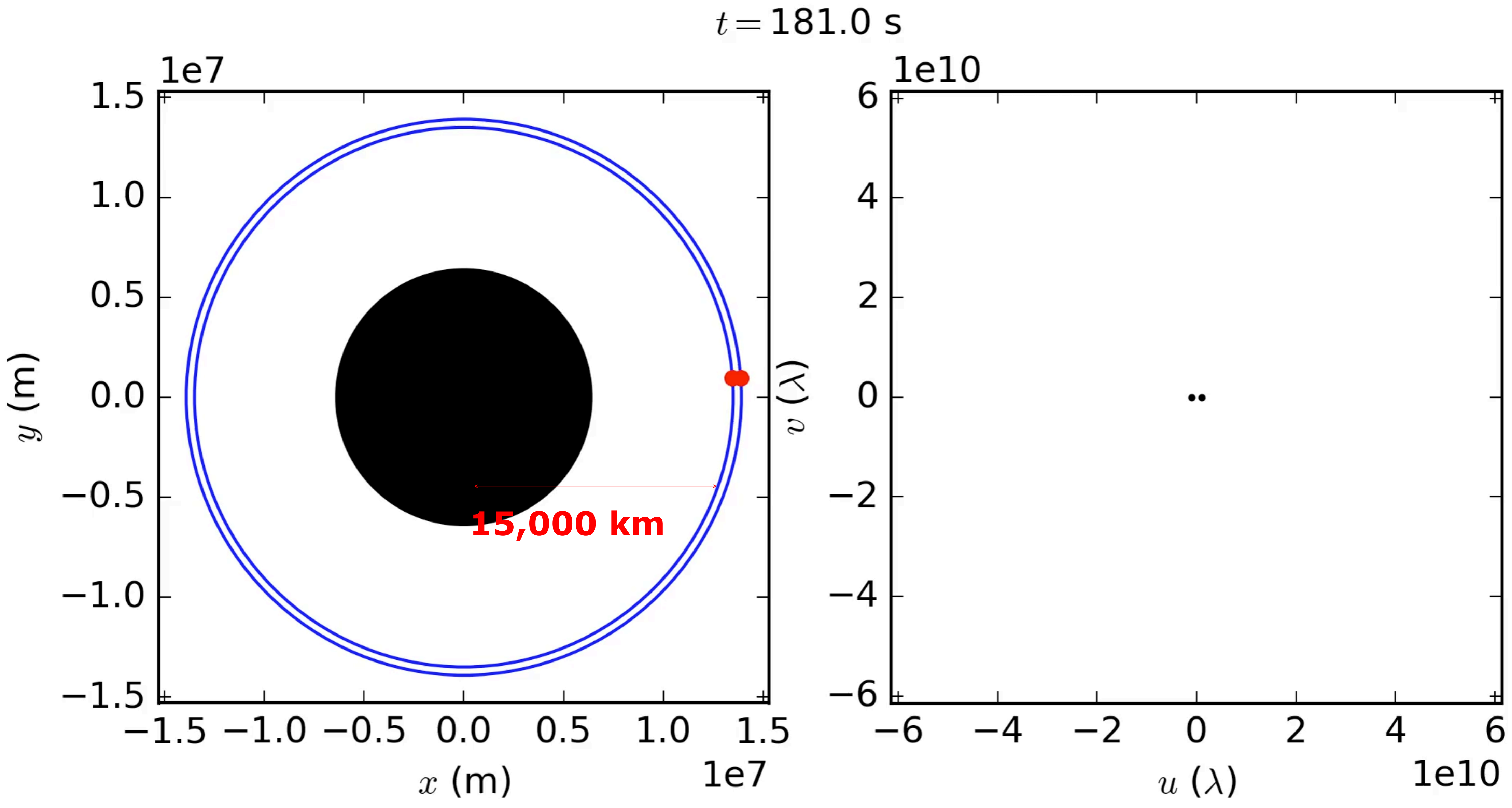
The future of EHT

1. EHT is being upgraded to include the 345 GHz band.

2. Next science goals: imaging SgrA*, polarization, time variability

3. EHT the next generation: new telescopes (NOEMA, Kitt Peak, GLT)
   + space-VLBI (to boldly go…, see white papers for NSF and ESA)

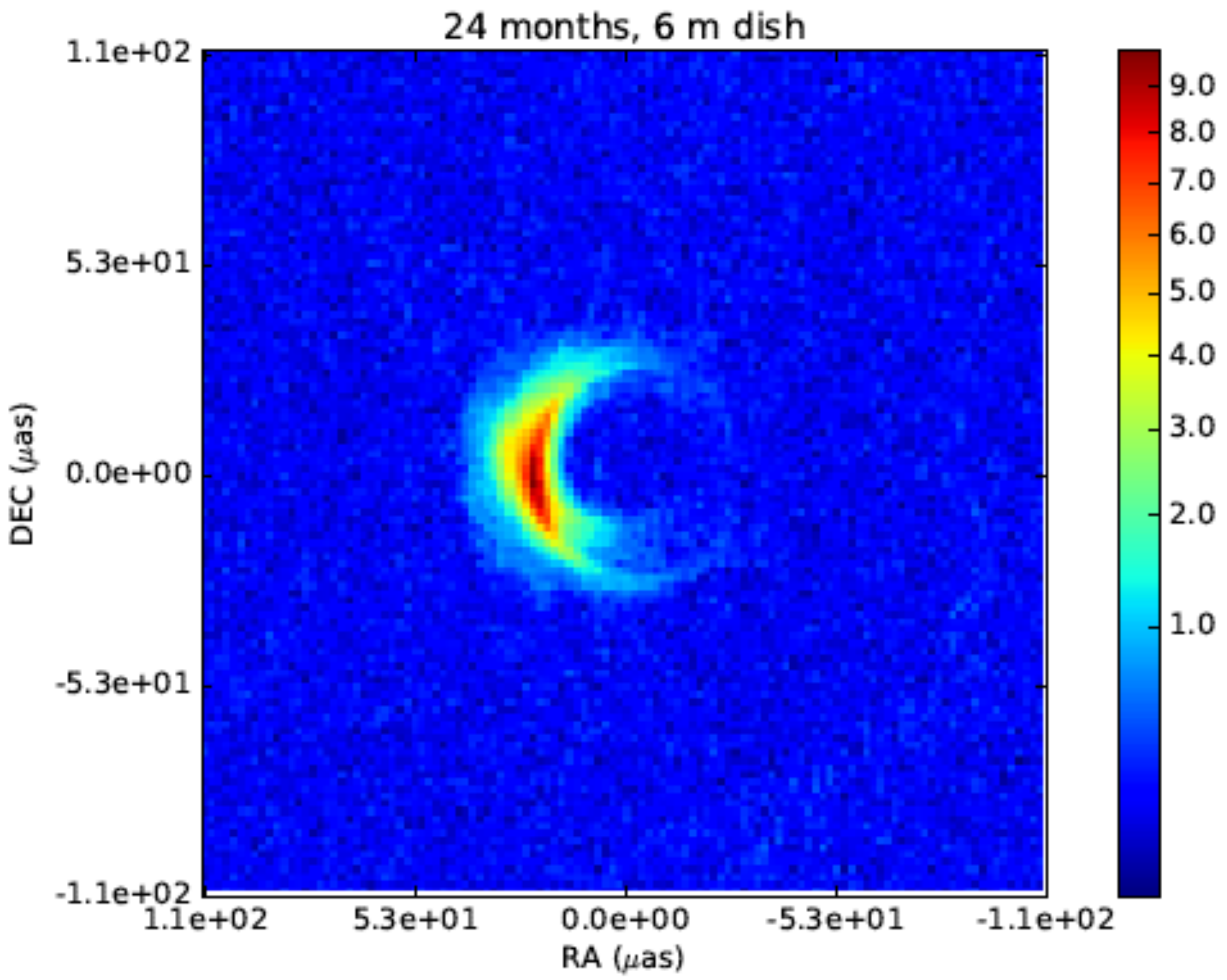
Future of the EHT: space VLBI, razor sharp shadow images



Martin-Neira, V.Kudriashov (ESA)

Reconstructed Space-VLBI image

Includes variability due to scattering and source variations



F. Roelofs et al. (2018, subm.)

ESA 2050 White paper, THEZA, Gurvits et al. 2019 arXiv:1908.10767

How to improve theory?

1. Highly resolved GRMHD simulations

2. Non-thermal electron distribution functions

Davelaar, Olivares, Porth, et al. 2019, A&A
Olivares, Porth, Davelaar, et al. 2019, A&A

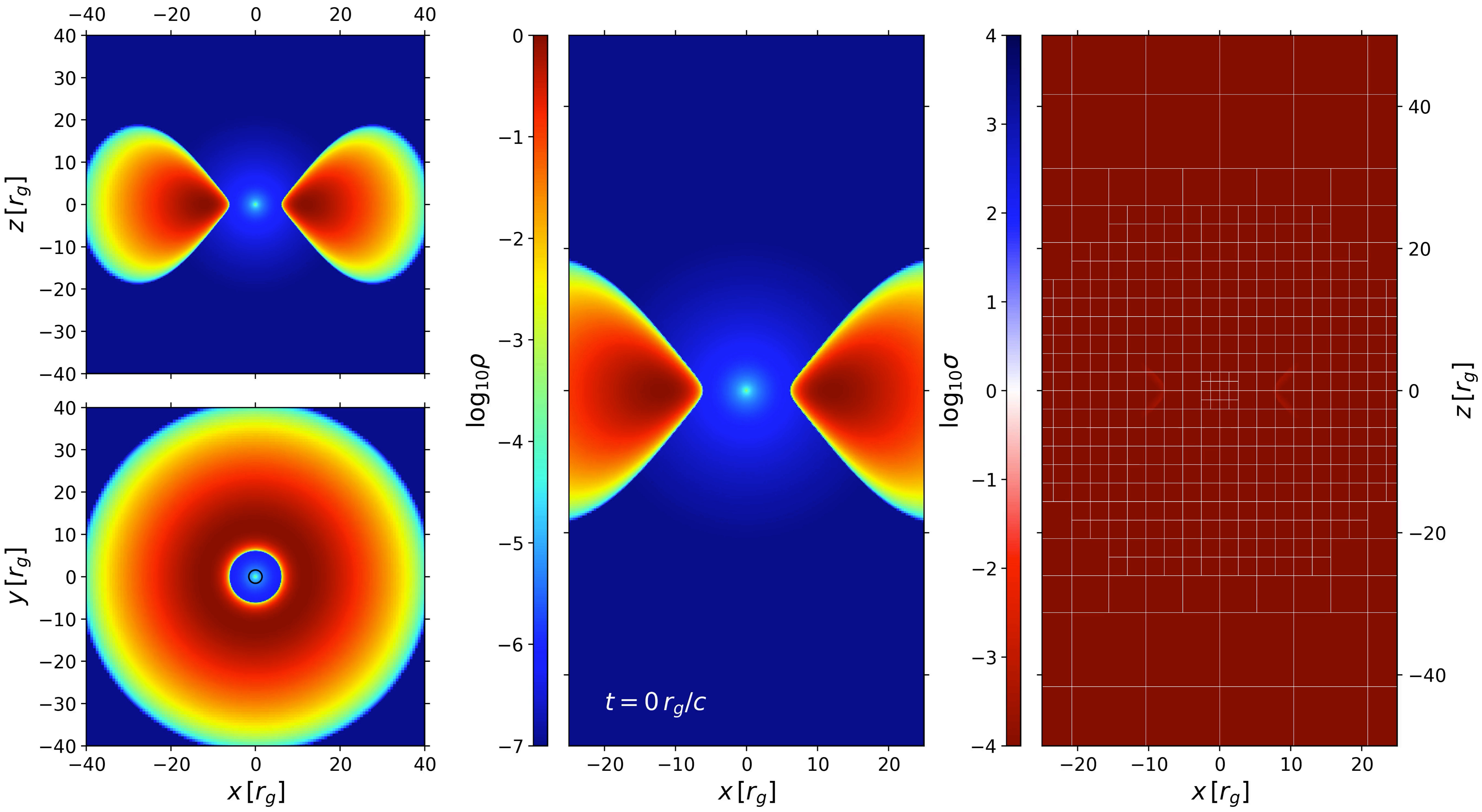
Cartesian AMR simulations

High resolution cartesian simulations to avoid numerical dificulties at the polar region

Includes adaptive mesh refinement

70 million grid cells

Simulation performed with **BHAC** (Porth et al. 2017)



Olivares, Porth, Davelaar et al. 2019, A&A
Davelaar, Olivares, Porth et al. 2019, A&A

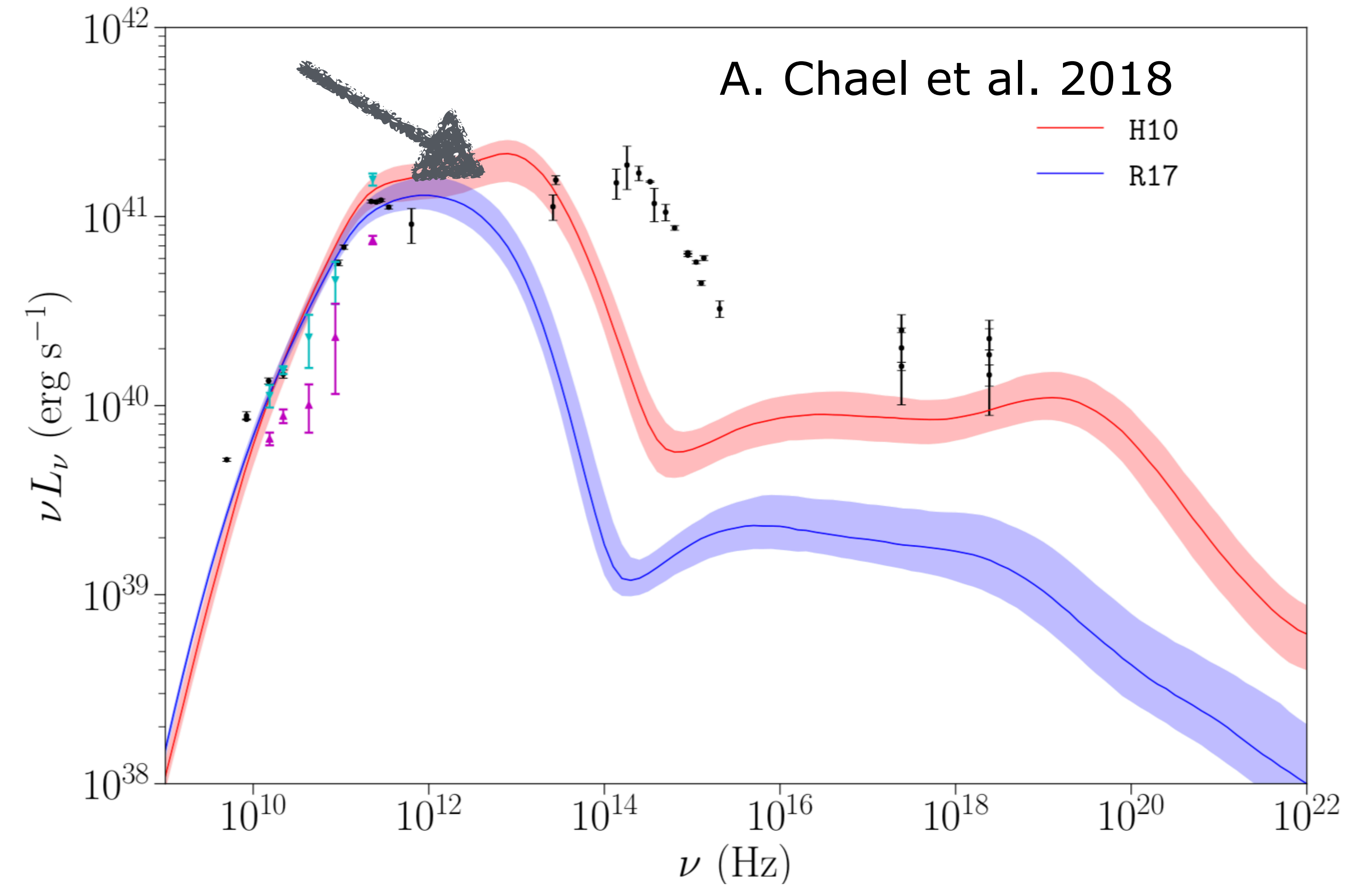
A skeleton in the closet

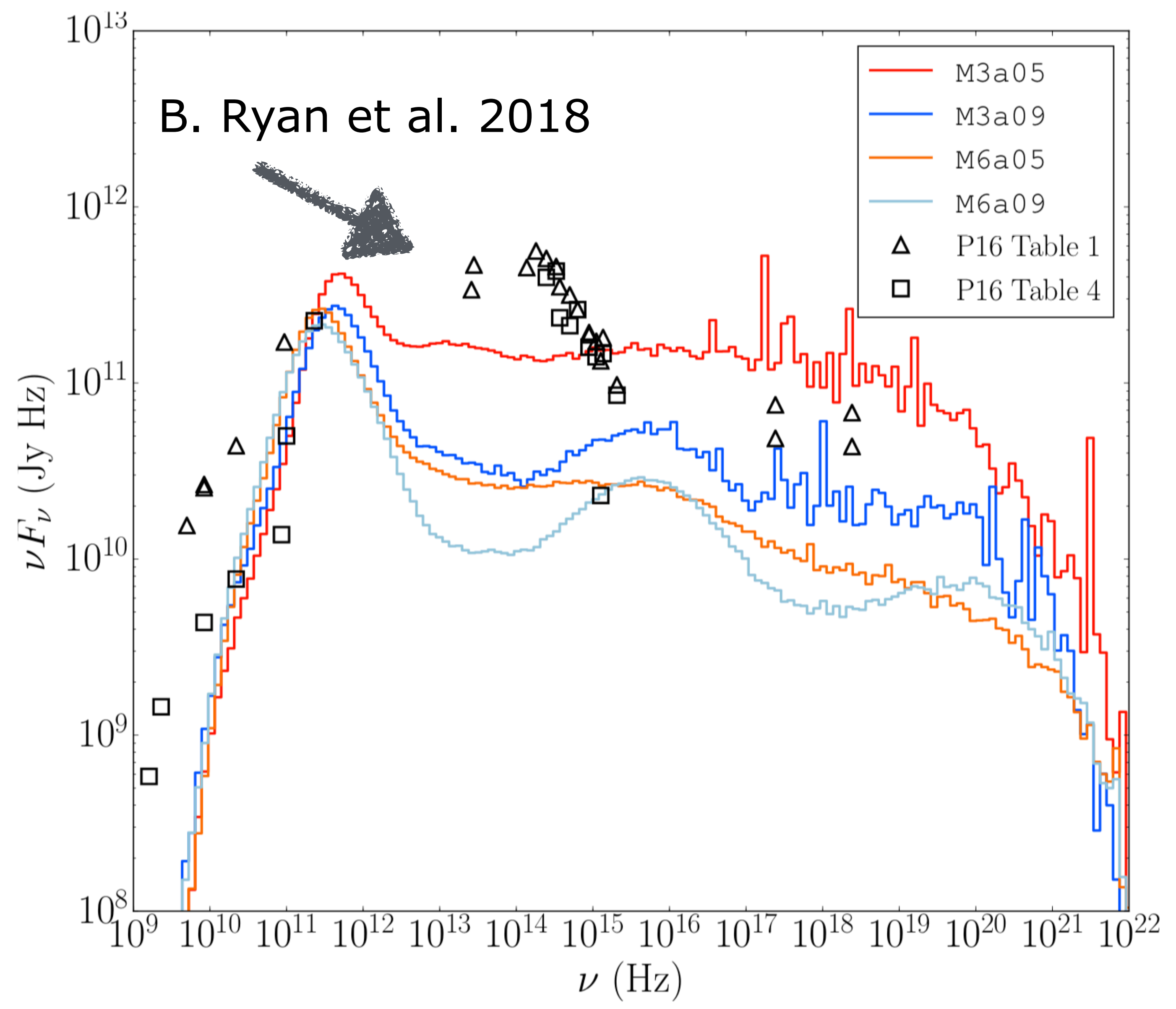
- Currently models only consider electrons in a thermal distribution function. but…

  Mean free path of electron > 10^8 radius of the event horizon
  → Plasma is collisionless → Kinetic effects important

- **Chael et al. 2018** and **Ryan et al. 2018**; SED modeling of M87*, thermal electrons only
- Fit the radio and X-ray, but an excess at NIR

  → Powerlaw in observations suggest electron acceleration



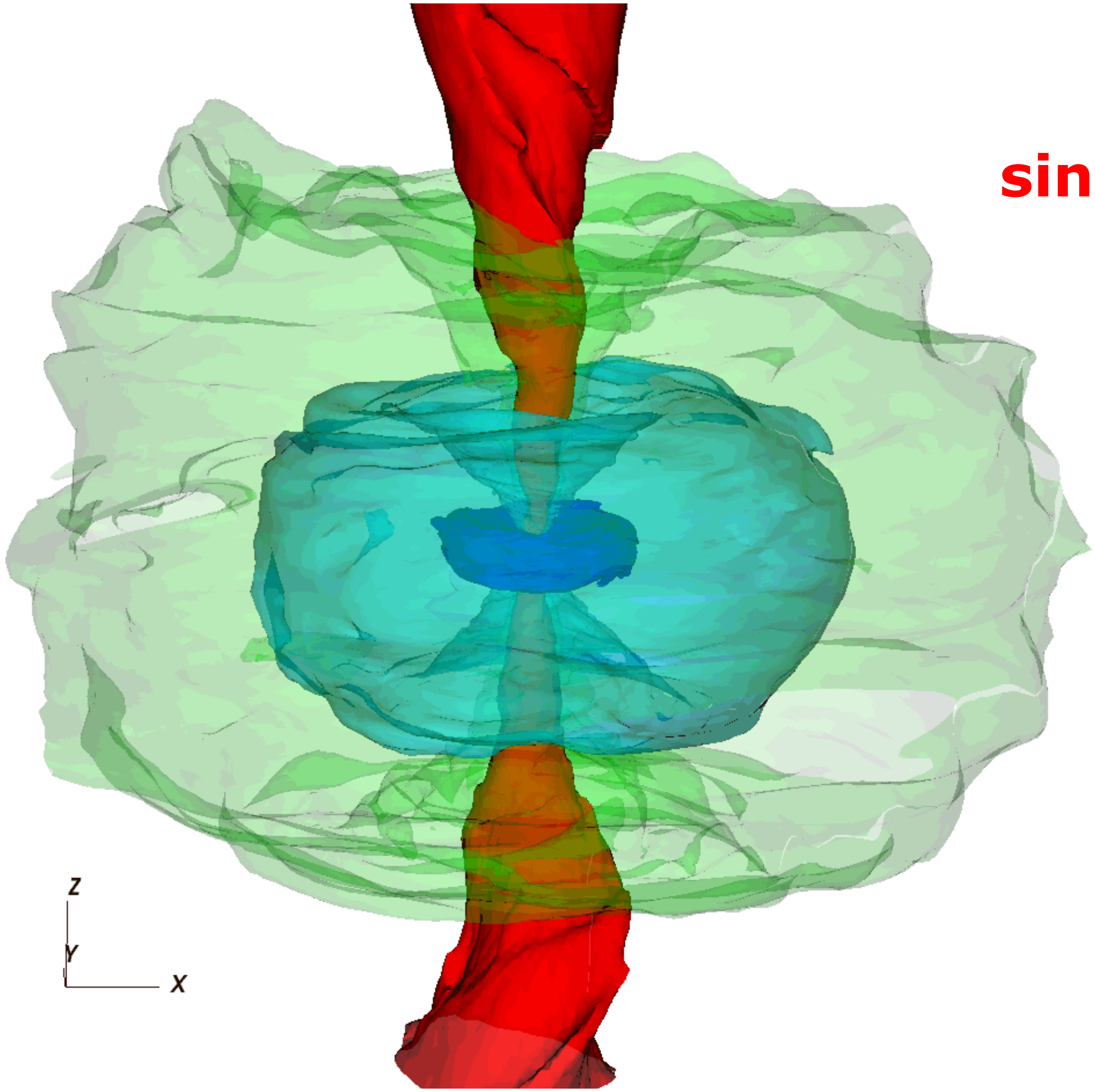


Modeling accreting black holes: "the standard model"

3D GRMHD density regions:

Red: low density, high magnetization

Blue: high density, low magnetization



Jet: single-temperature plasma:

$T_{electron} \sim T_{proton}$

Electrons are partially accelerated?

kappa-distribution

$$\frac{dn_e}{d\gamma} = N\gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa w}\right)^{-(\kappa+1)}$$

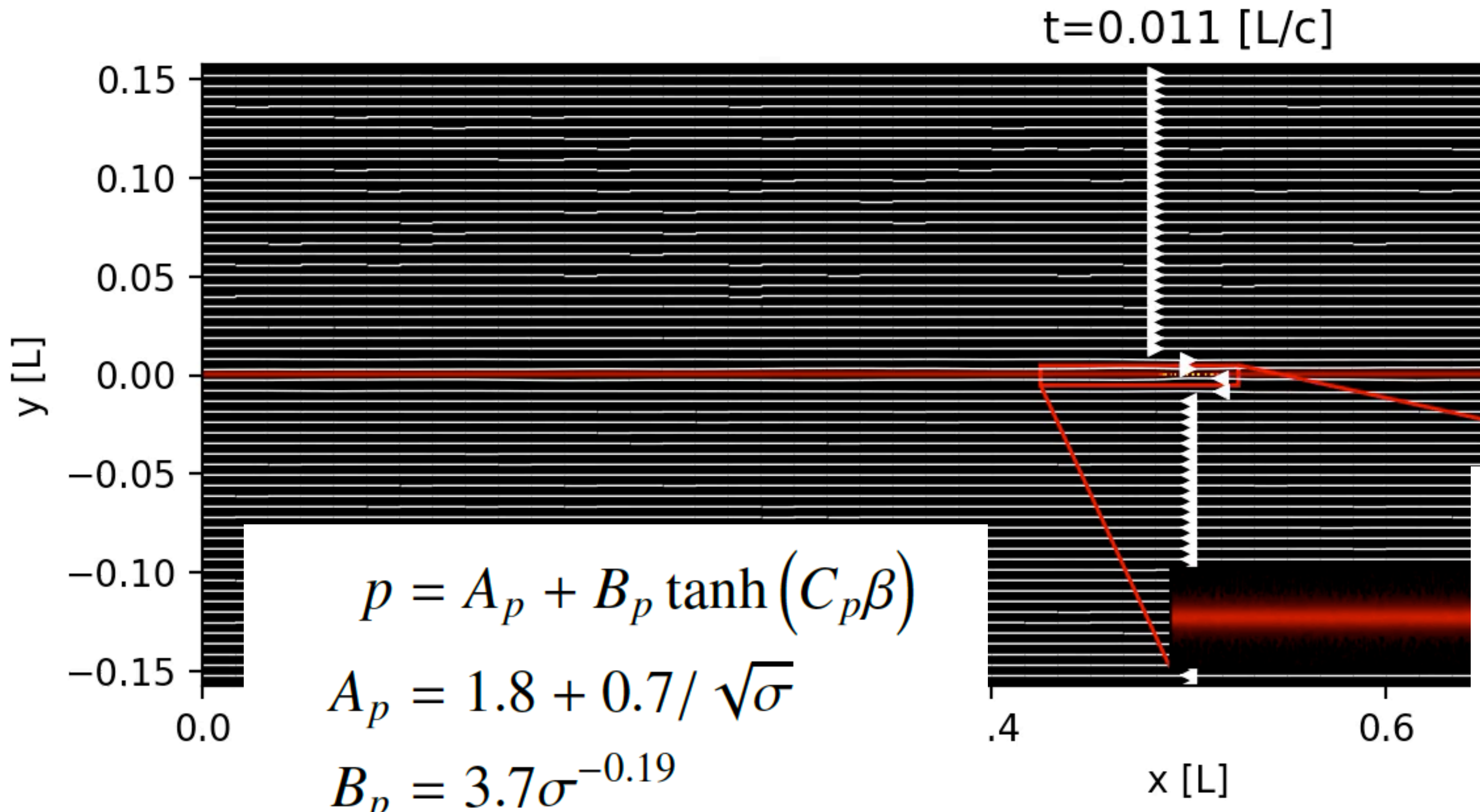
$$p = \kappa - 1$$

Accretion flow: two-temperature plasma

$T_{electron} \ll T_{proton}$

Davelaar, Olivares, Porth et al. 2019, A&A

Reconnection as the source of electron acccelaration

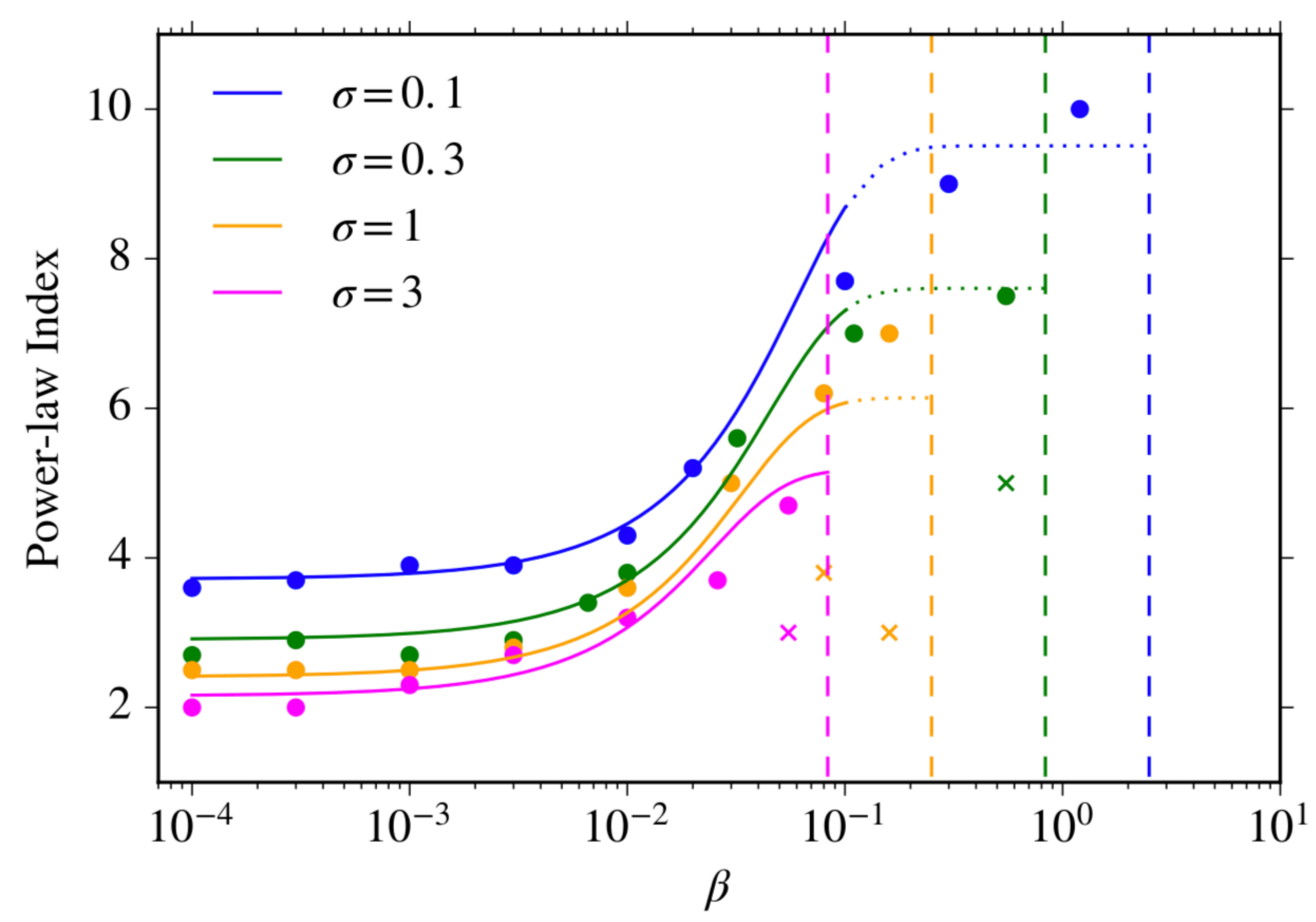


$$p = A_p + B_p \tanh\left(C_p\beta\right)$$

$$A_p = 1.8 + 0.7/\sqrt{\sigma}$$

$$B_p = 3.7\sigma^{-0.19}$$

$$C_p = 23.4\sigma^{0.26}$$



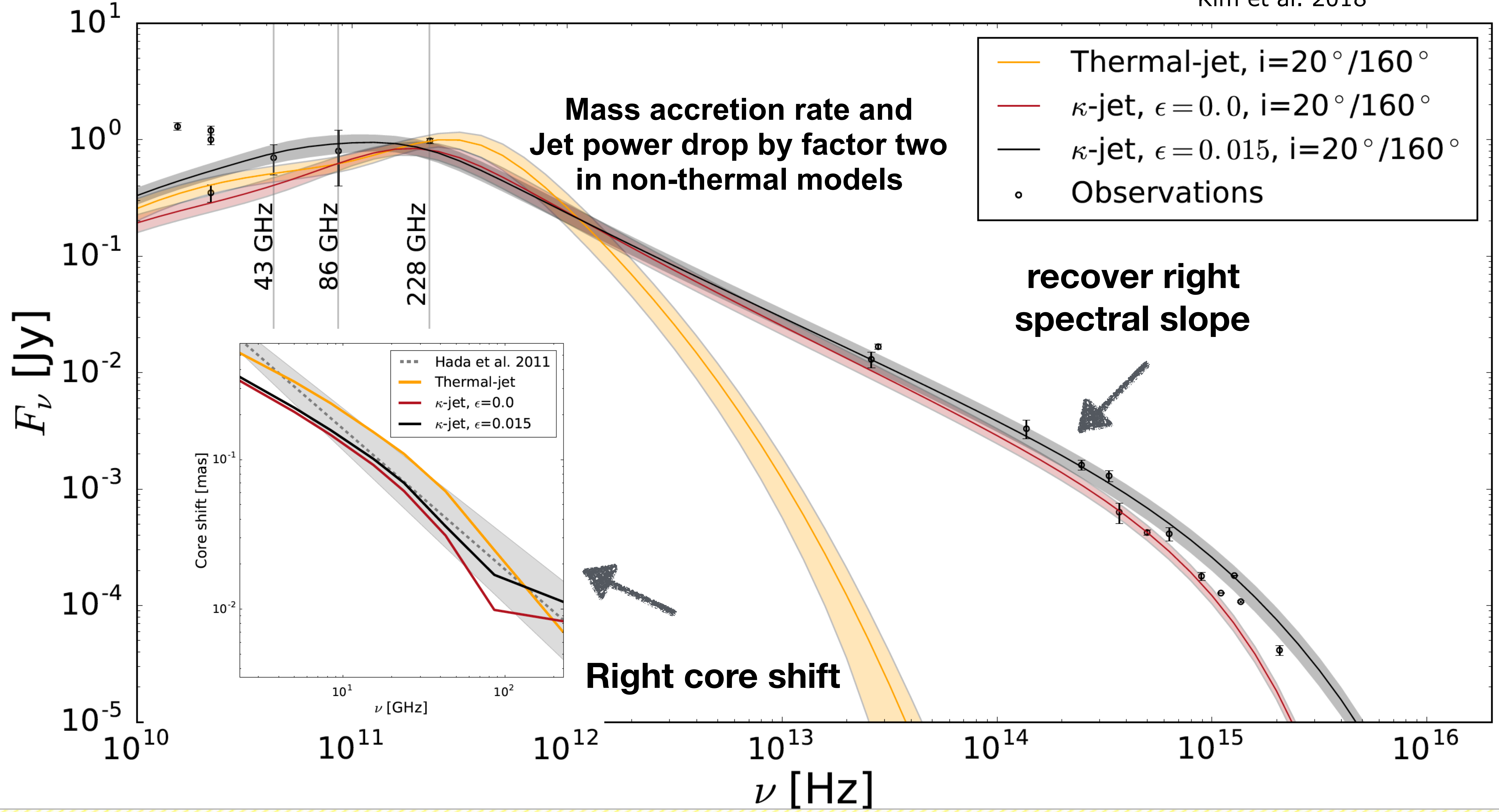
Werner et al. 2017

Ball et al. 2018

Davelaar et al. 2020 in prep

SED fitting of M 87*

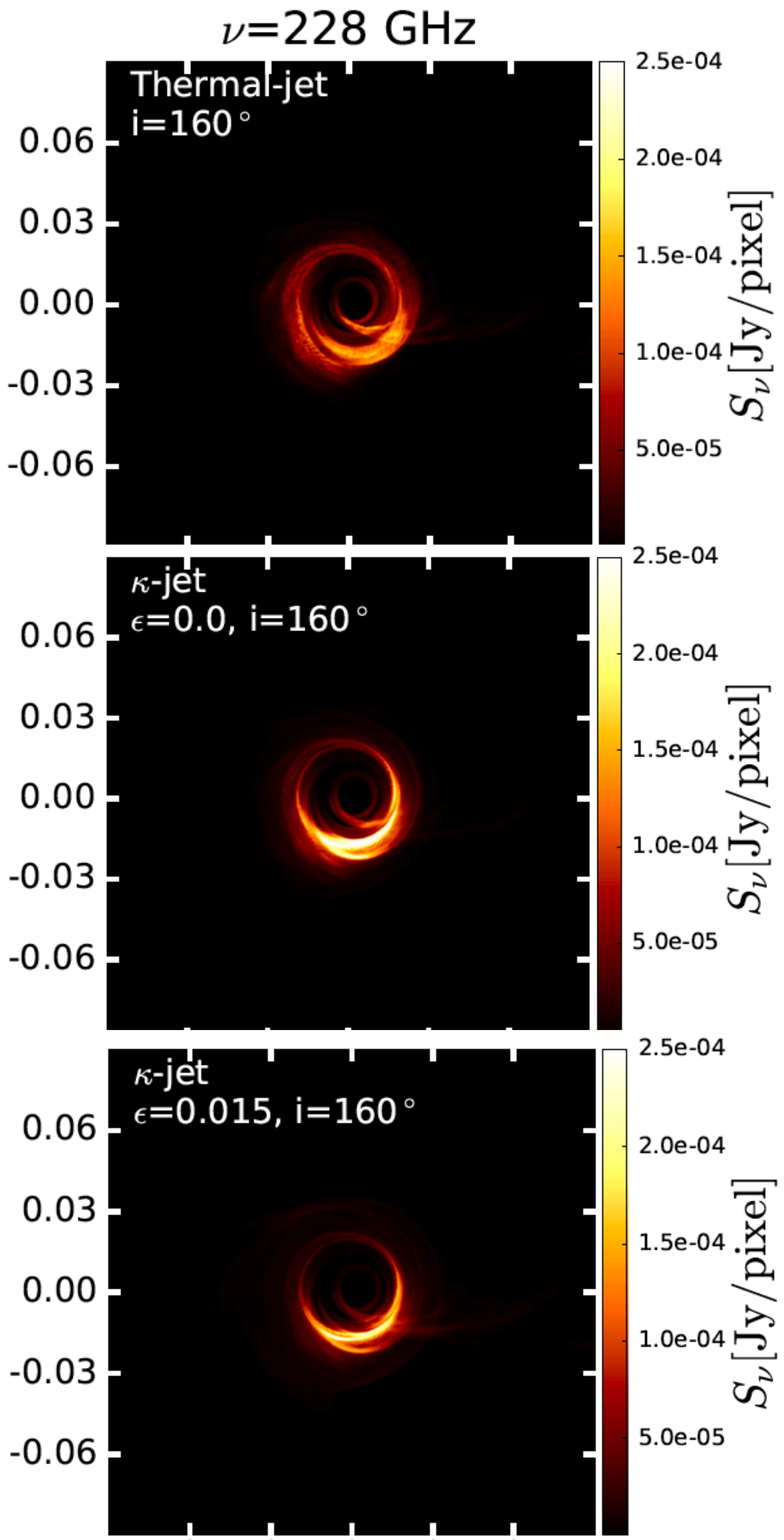
Observational data:
Hada et al. 2011
Doeleman et al. 2012
Prieto et al. 2015
Walker et al. 2018
Kim et al. 2018



Davelaar, Olivares, Porth et al. 2019, A&A, in press

Images of M87*

- non-thermal models are optically thinner
- Could exclude some models based on lower jet powers?
- No direct comparison with EHT date done yet (work in progress…)



Davelaar, Olivares, Porth et al. 2019, A&A

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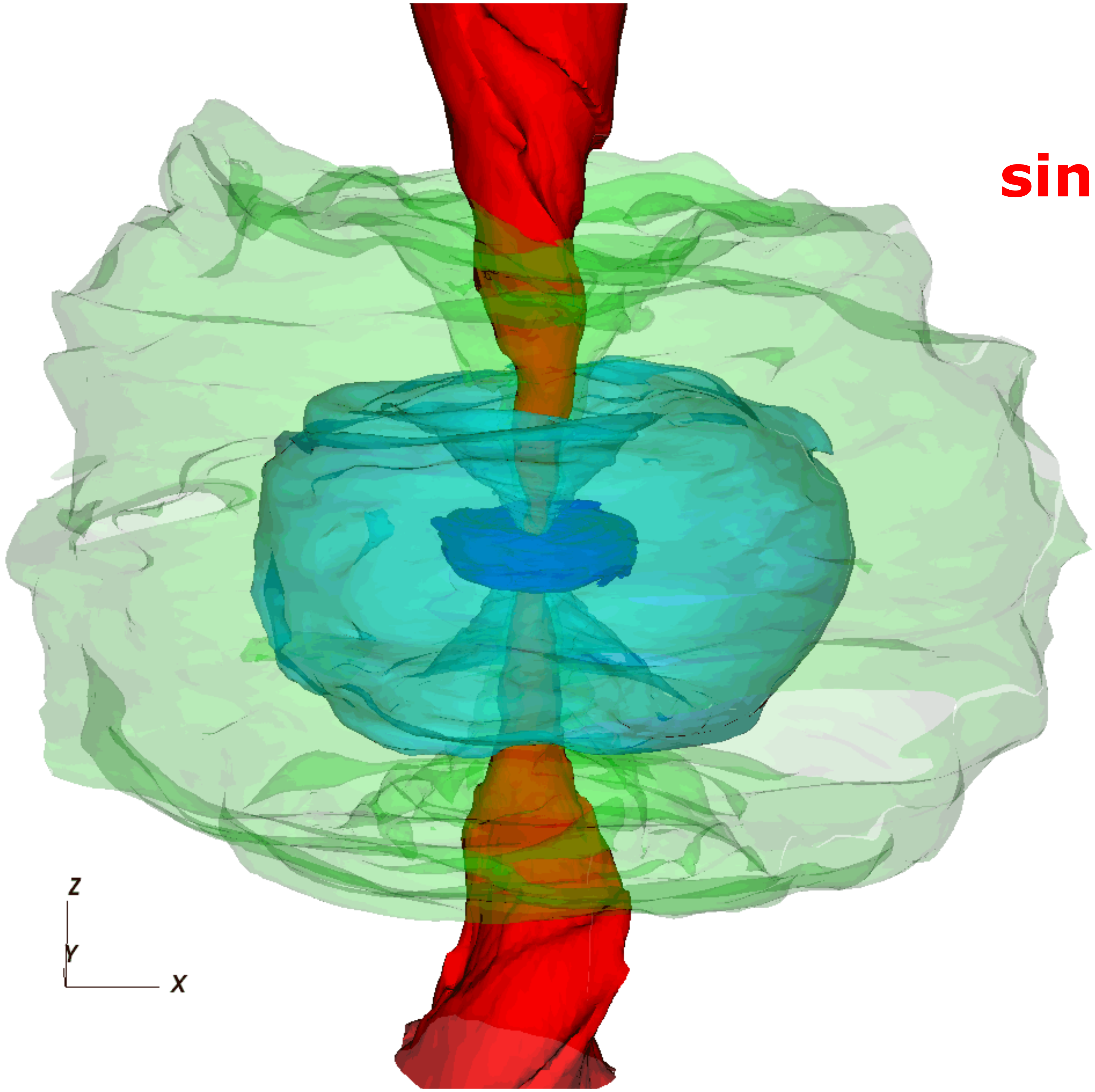


Jet: single-temperature plasma:
$T_{\text{electron}} \sim T_{\text{proton}}$

Electrons are partially accelerated?

in plasmoid unstable current sheets? In shear layers?

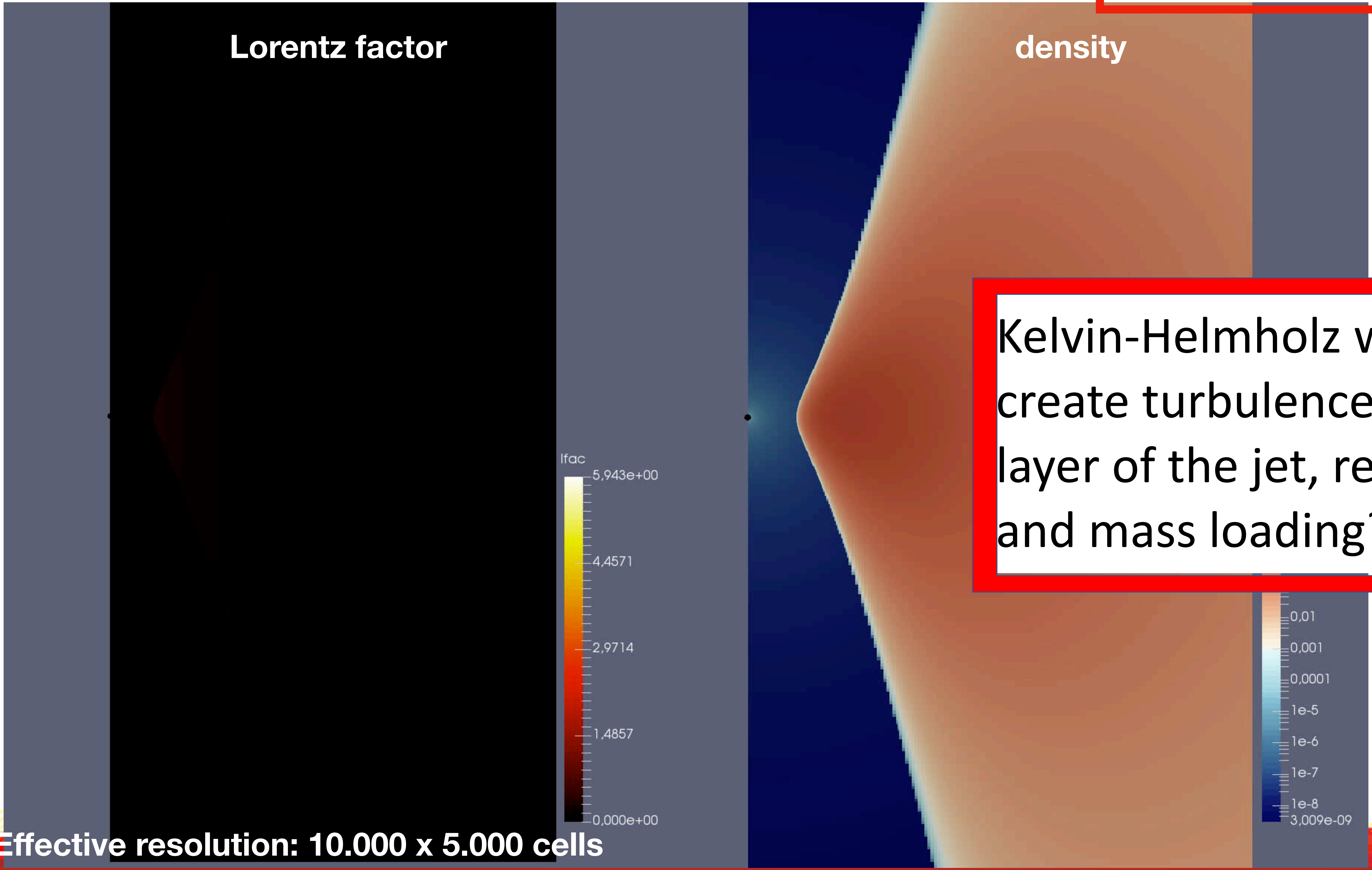
$$\frac{dn_e}{d\gamma} = N\gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa w}\right)^{-(\kappa+1)}$$

Accretion flow: two-temperature plasma
$T_{\text{electron}} \ll T_{\text{proton}}$

Davelaar, Olivares, Porth et al. 2019, A&A

Highly resolved GRMHD

Work in progress



Kelvin-Helmholz waves create turbulence in shear layer of the jet, reconnection and mass loading?

Effective resolution: 10.000 x 5.000 cells

Davelaar, Ripperda, Biachini et al. in prep
Ripperda, Biachini, Davelaar et al. in prep

Summary

EHT

- First image of the shadow of a black hole
- Mass around 6.5 +/- 0.7 x 10^9 Msun
- Asymmetry constrains rotation direction

Non-thermal modeling

- Performed high resolution Cartesian GRMHD simulation
- Trans-relativistic reconnection can explain the NIR power law seen in the SED of M87
- comparison with EHT observation in progress

Future work

- Effect on polarisation
- Resistive GRMHD to identify reconnection events
- more sophisticated electron injection criterion