GRAVITY and EHT: probing the suburb of supermassive black holes

Frédéric Vincent[1]

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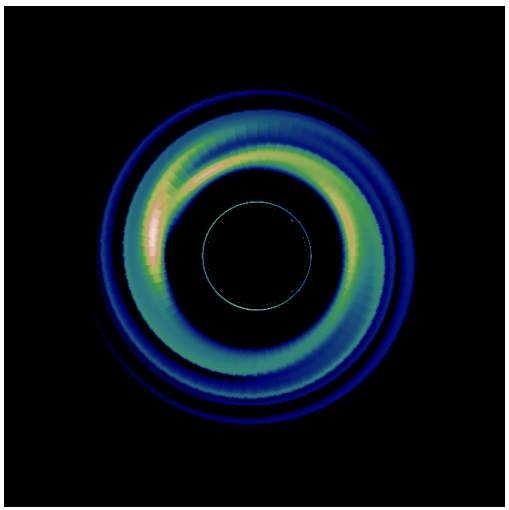
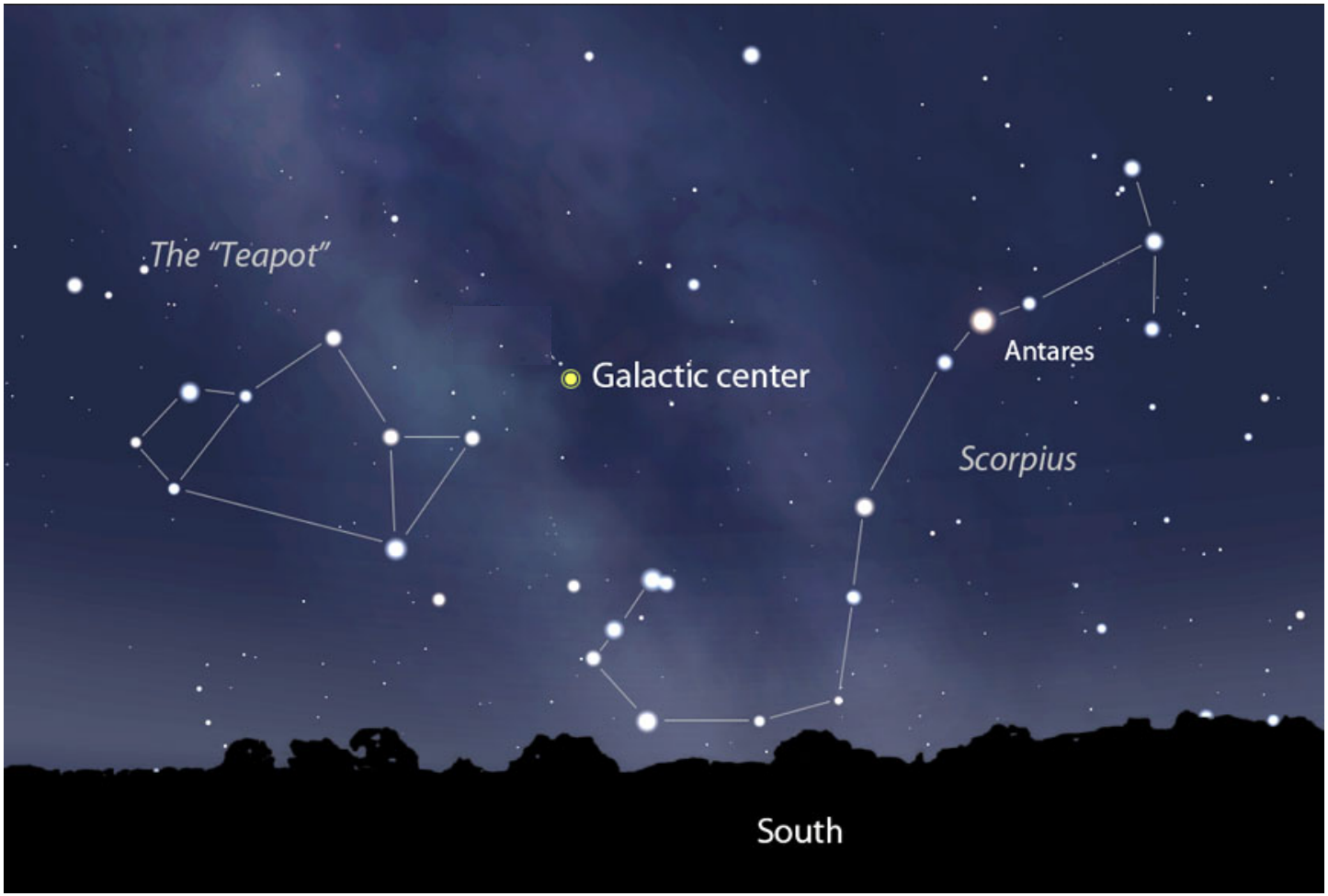
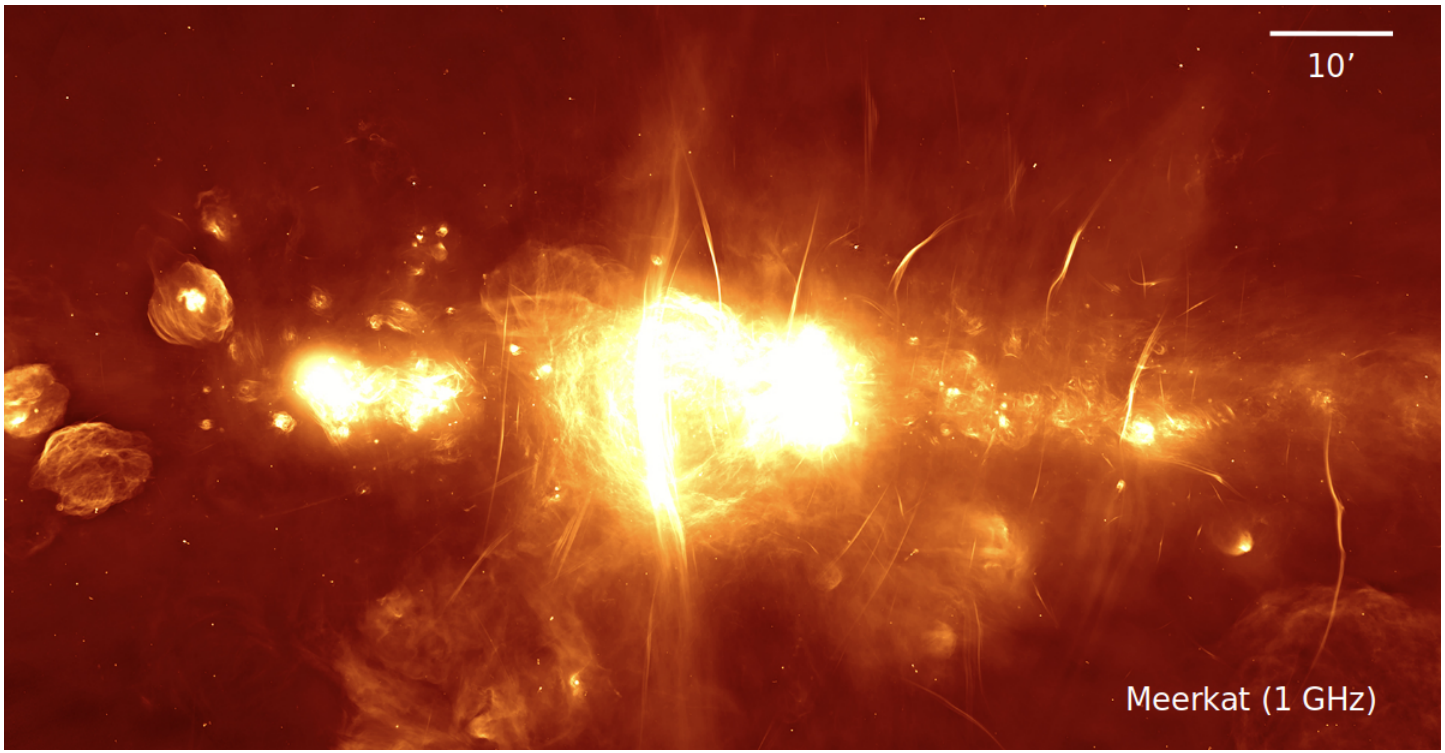
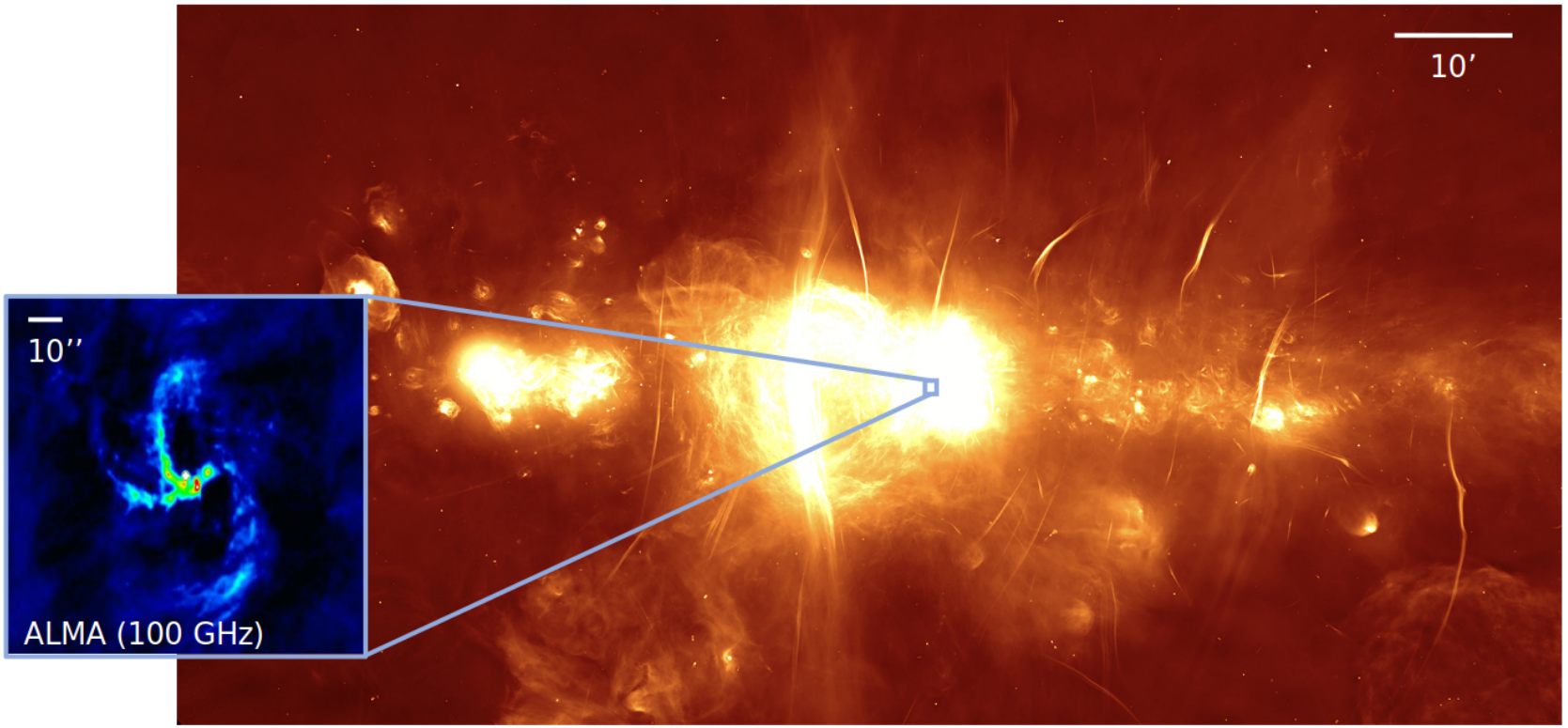
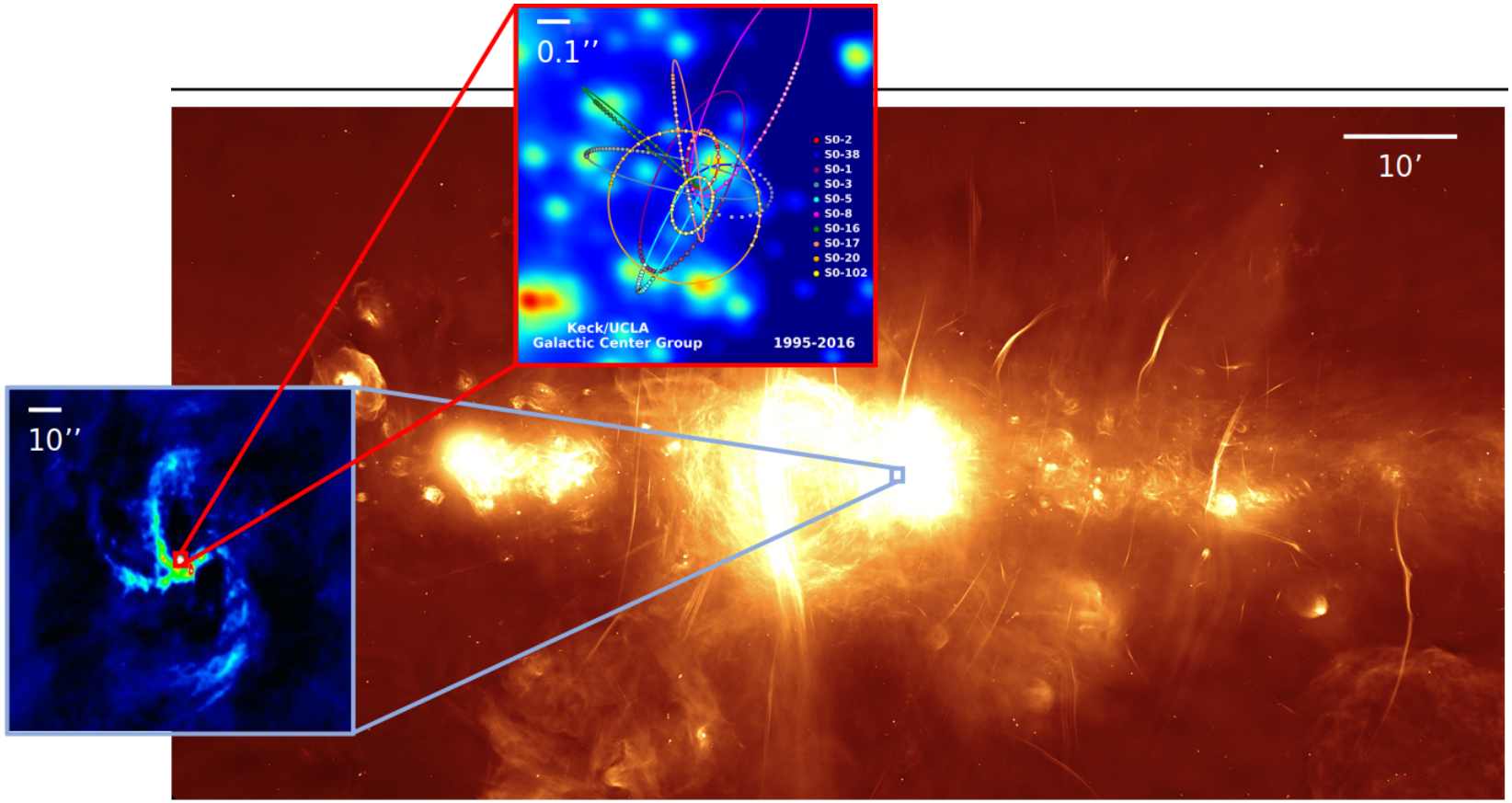
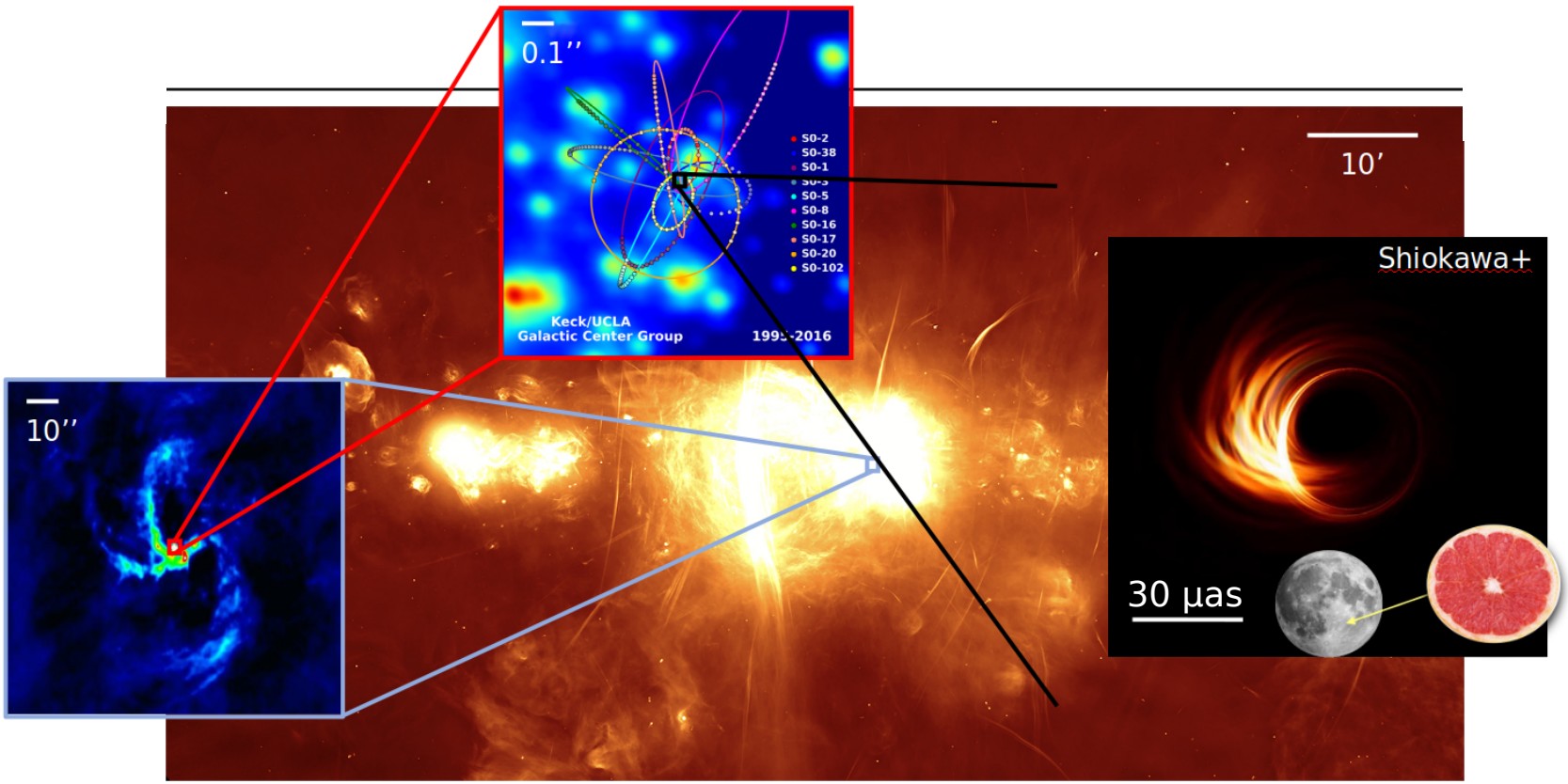



The "Teapot"
Galactic center
Antares
Scorpius
South

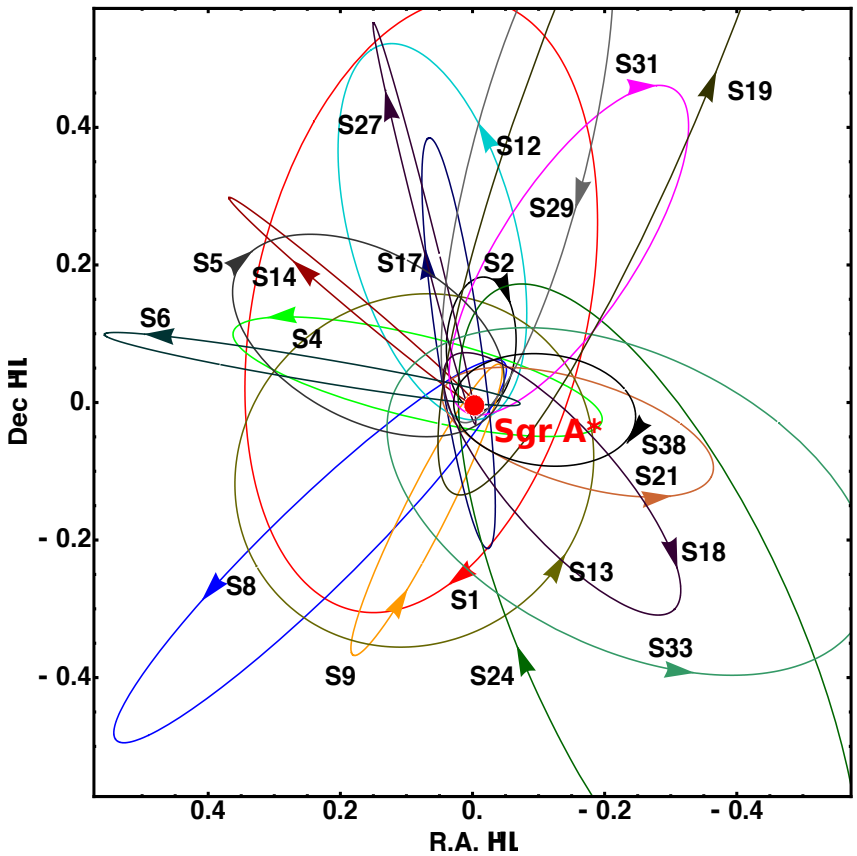

10′
Meerkat (1 GHz)


10’
10’’
ALMA (100 GHz)


0.1''
S0-2
S0-38
S0-1
S0-3
S0-5
S0-8
S0-16
S0-17
S0-20
S0-102
Keck/UCLA
Galactic Center Group
1995-2016
10''
10'



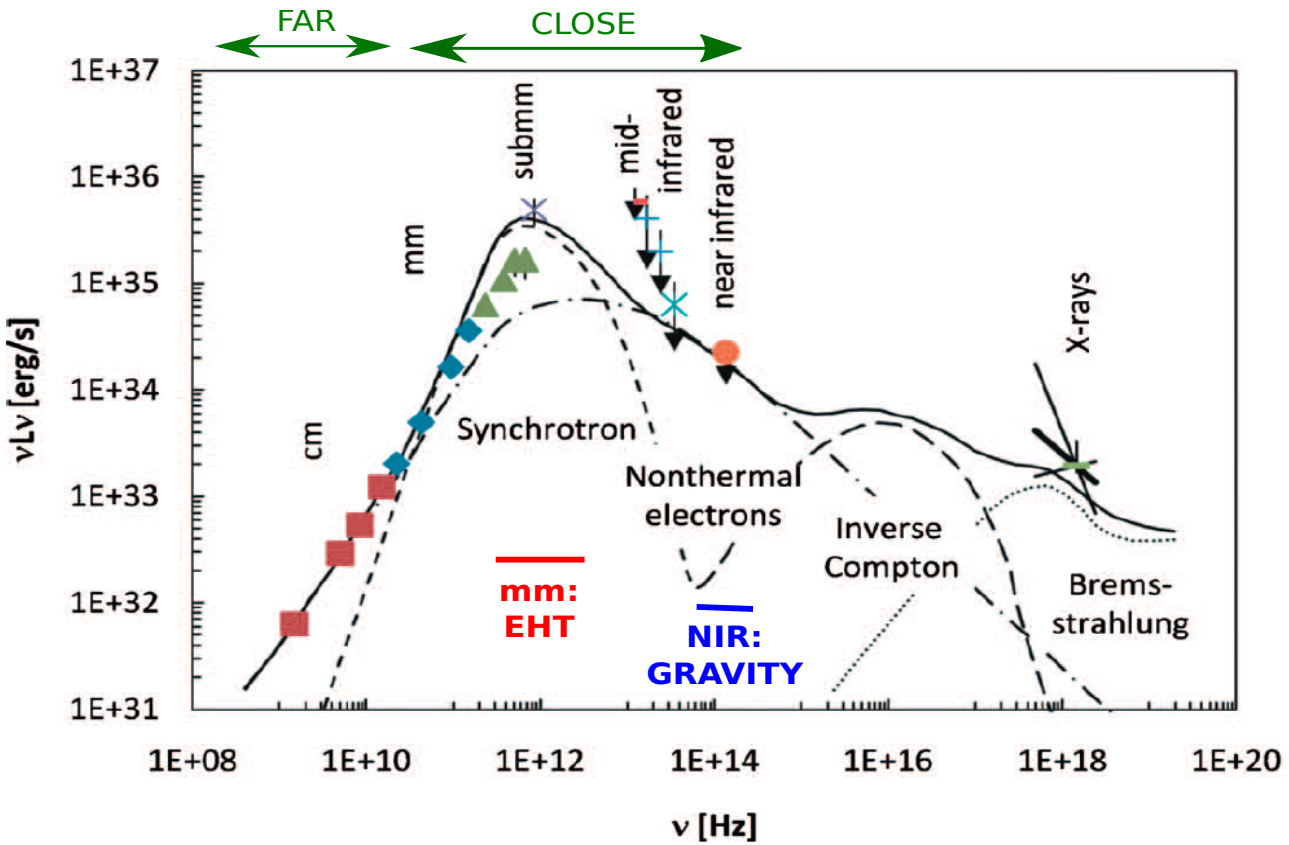
Credit: M. Wielgus



S-stars cluster (Gillessen+09): size = **1" ≈ 0.05 pc**

The central dark mass

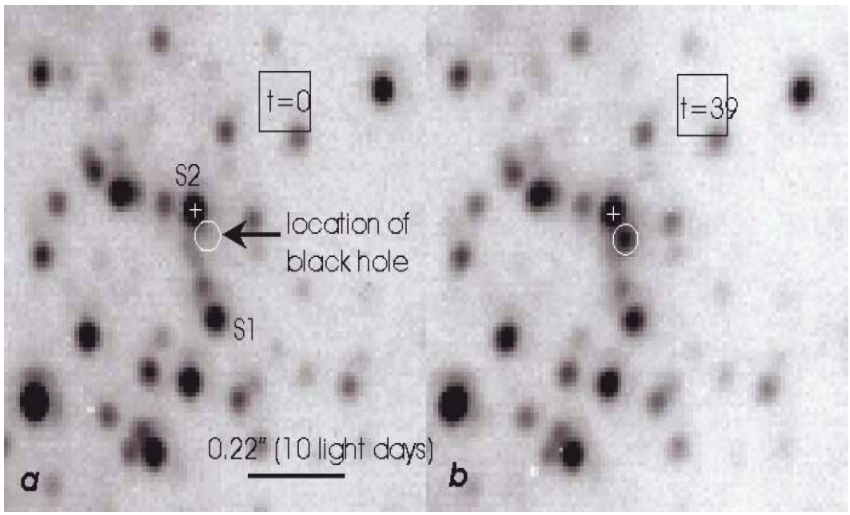
- Astrometric measurements of close stars → central mass.
- Sgr A* ≈ **SMBH of 4.1 10^6 $M_\odot$,** $\theta_{\mathrm{app,Sch}}$ **≈ 50 μas**



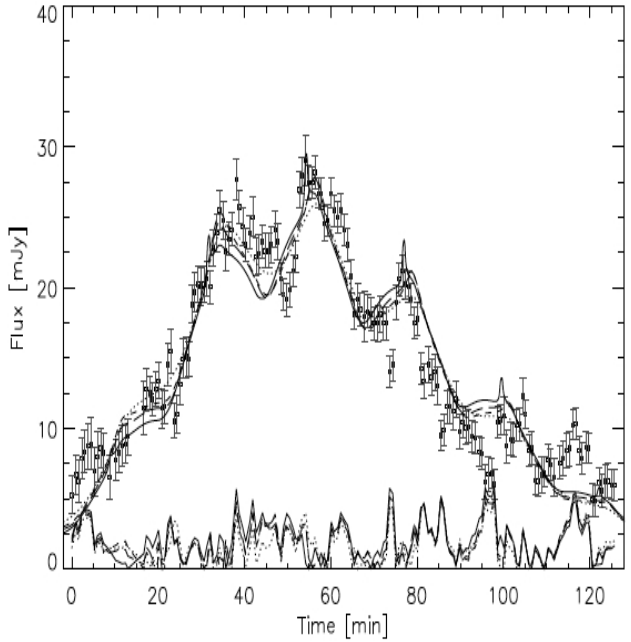
Genzel+10

Sgr A* spectrum

- Different $\nu \rightarrow$ different r
- **Optically thin synchrotron** emission at few 100 GHz
- **Innermost accretion flow**



Genzel+03



Hamaus+09

Sgr A* flares

- Sphere of gas orbiting around Sgr A*
- Jet / blob
- MHD instability
- ...

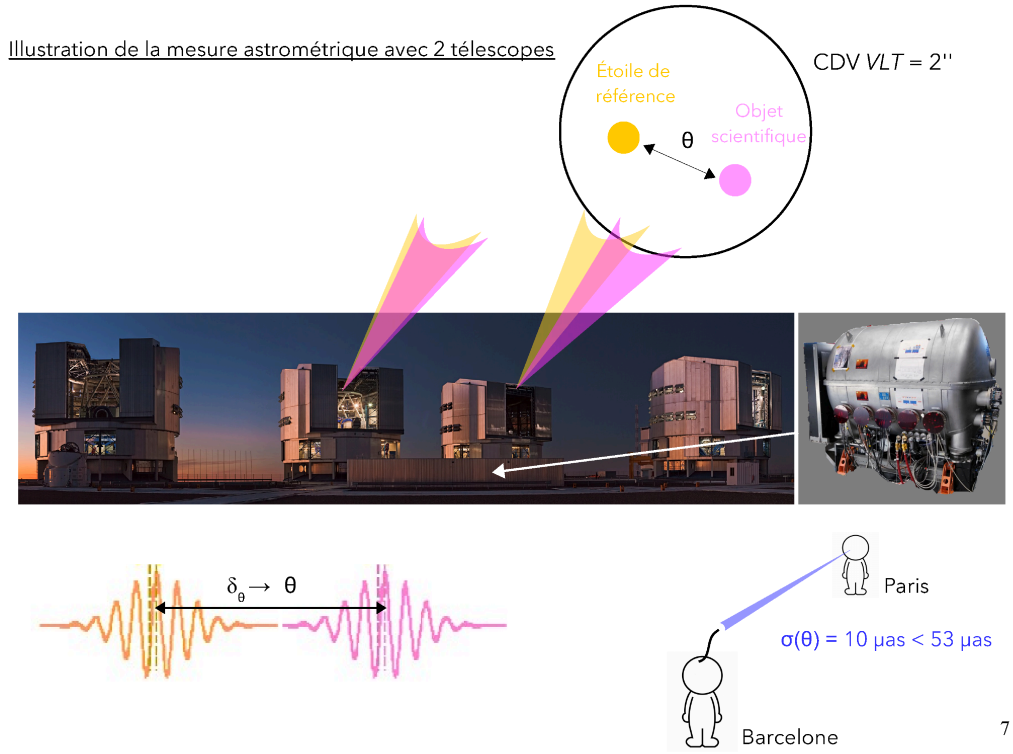
Goal: observing the vicinity of Sgr A*

- Follow stellar orbits...
- Understand flares...
- Observe shadow...
- ... and use all as probes of GR

Instrument challenge

- $\frac{GM/c^2}{D} = 10\,\mu$as
- Size of a grapefruit on the Moon!
- $\rightarrow$ GRAVITY, EHT

Introduction : L'instrument GRAVITY



GRAVITY (2016+)

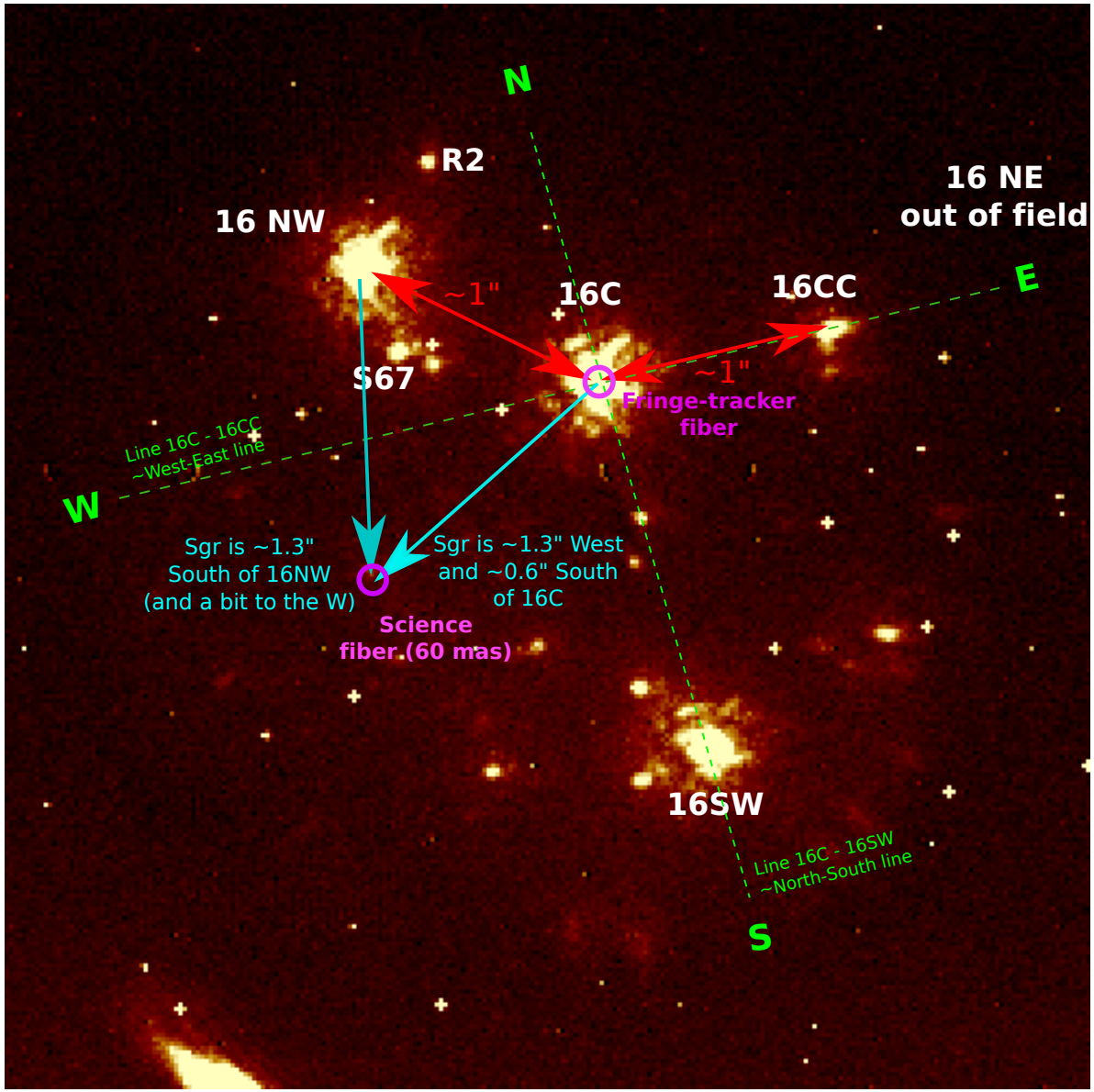
Courtesy M. Grould

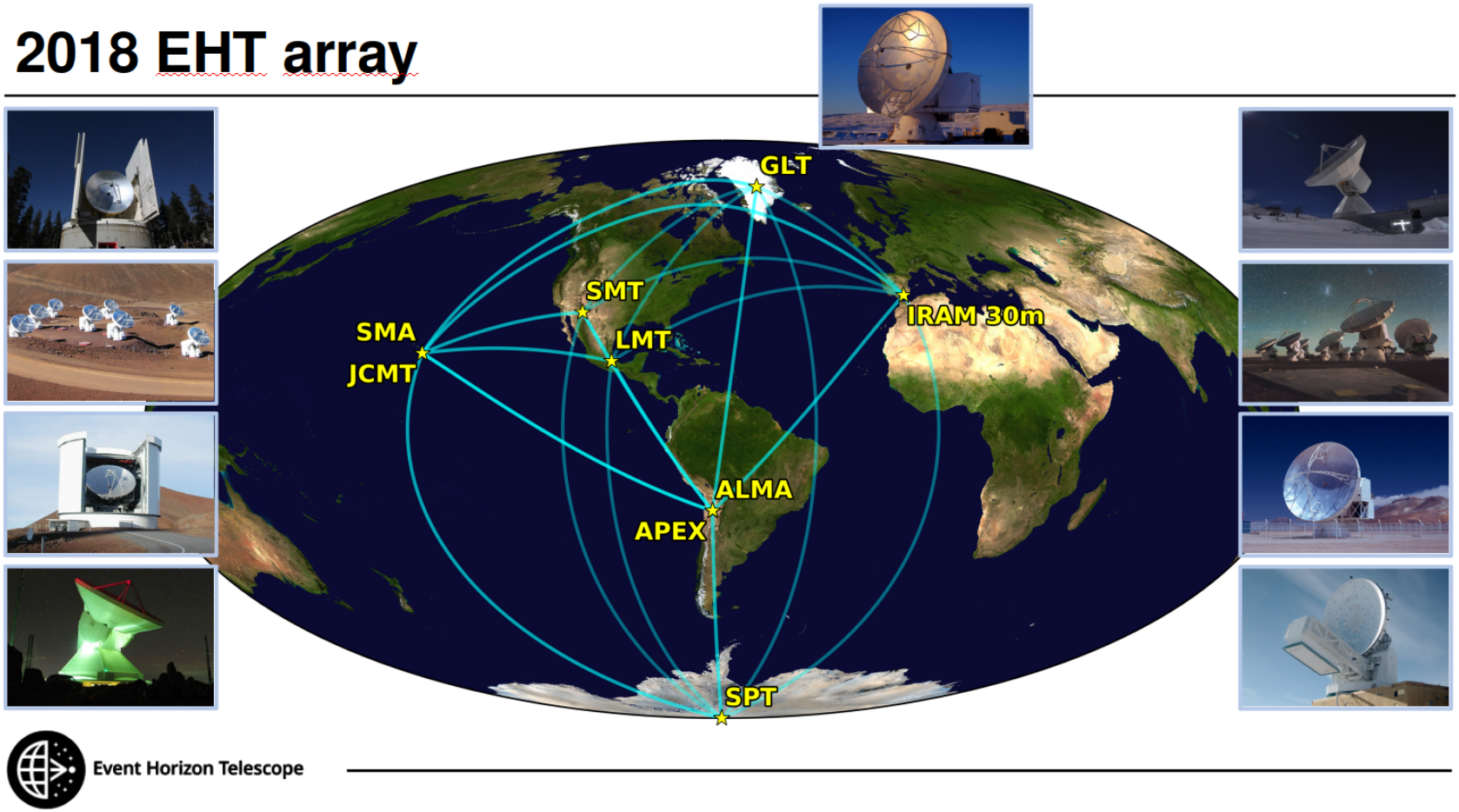
Stars follow-up + hot gas motion

- GRAVITY: **30 μas** astrometric precision (NIR; $\approx 2.2\,\mu$m)
- Goal: follow the motion of **stars** / **flares** around Sgr A*

$\rightarrow$ GRAVITY Collaboration 2017 *A&A 602 A94*

Gravity Acq Cam Image (29.03.2017)





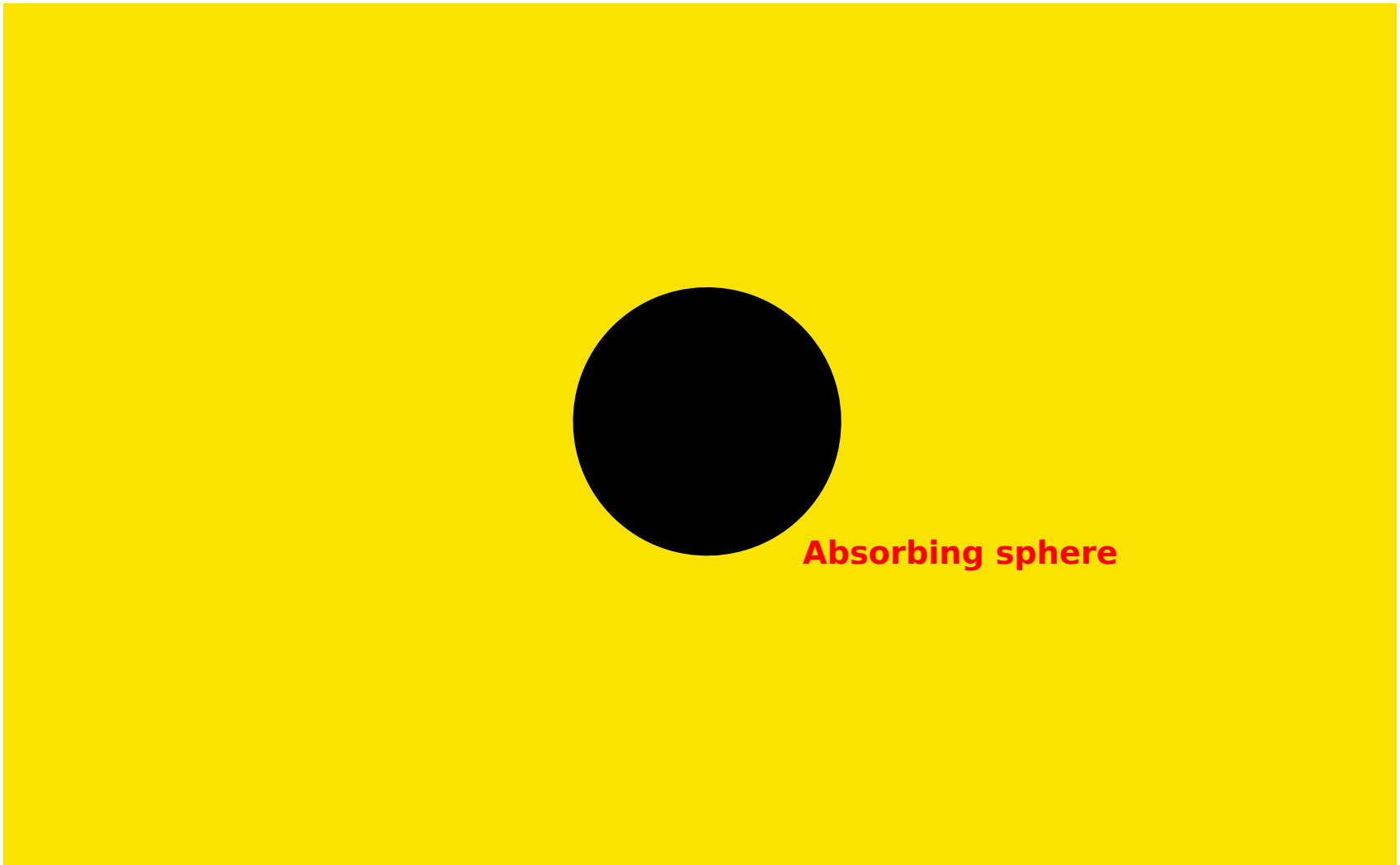
EHT: an array of millimeter antennas

Science cases

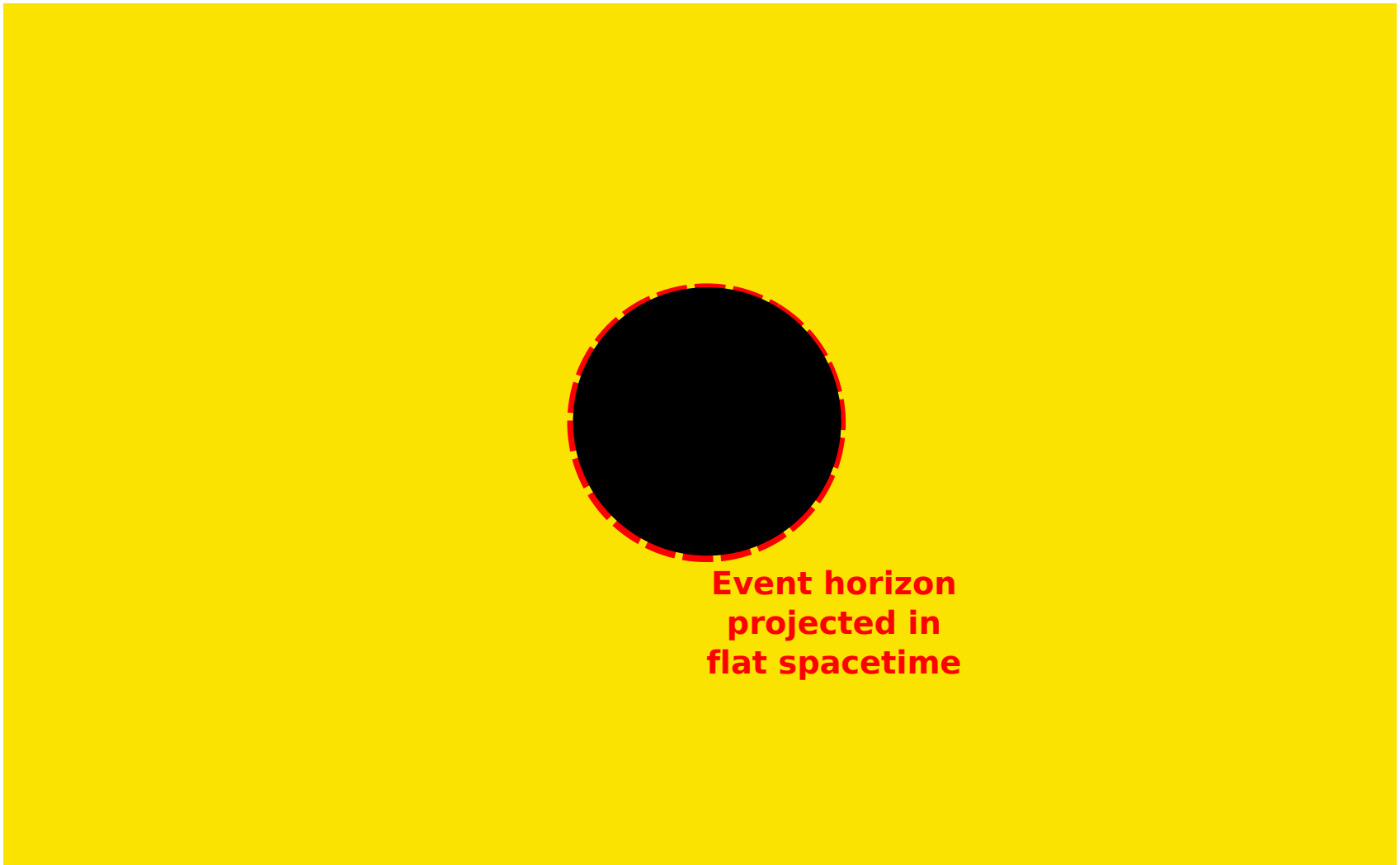
- EHT: $\frac{\lambda}{B} = \mathbf{25\ \mu as}$ resolution (mm; 230 and 345 GHz)
  (but superresolution allows to go further)
- Goal 1: image the **black hole shadow**
  of Sgr A* ($R_S = 10\,\mu$as) and M87* ($R_S \approx 5\,\mu$as)
- Goal 2: timing signatures of orbiting material

Black hole shadow

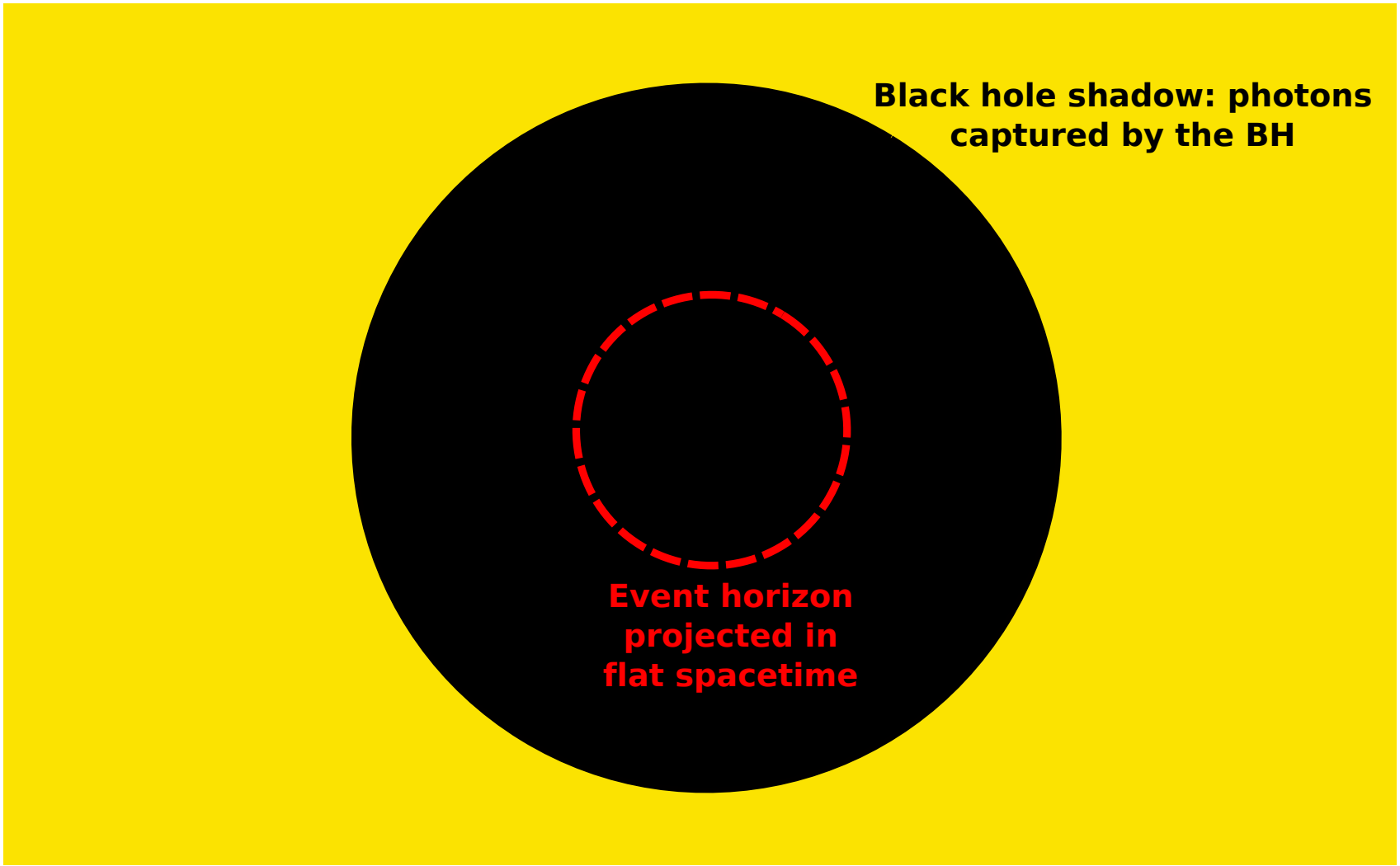
Black hole shadow



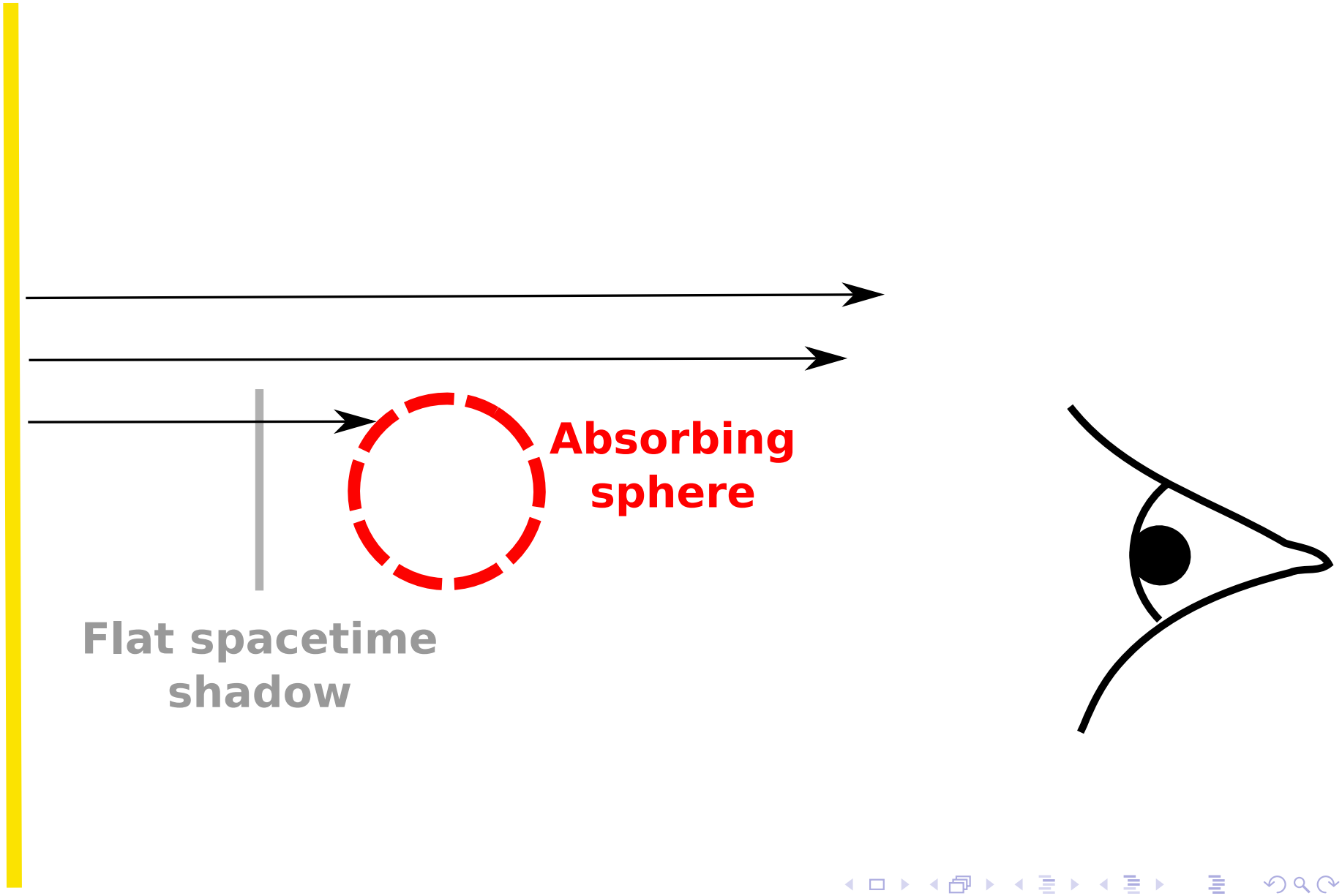
Black hole shadow



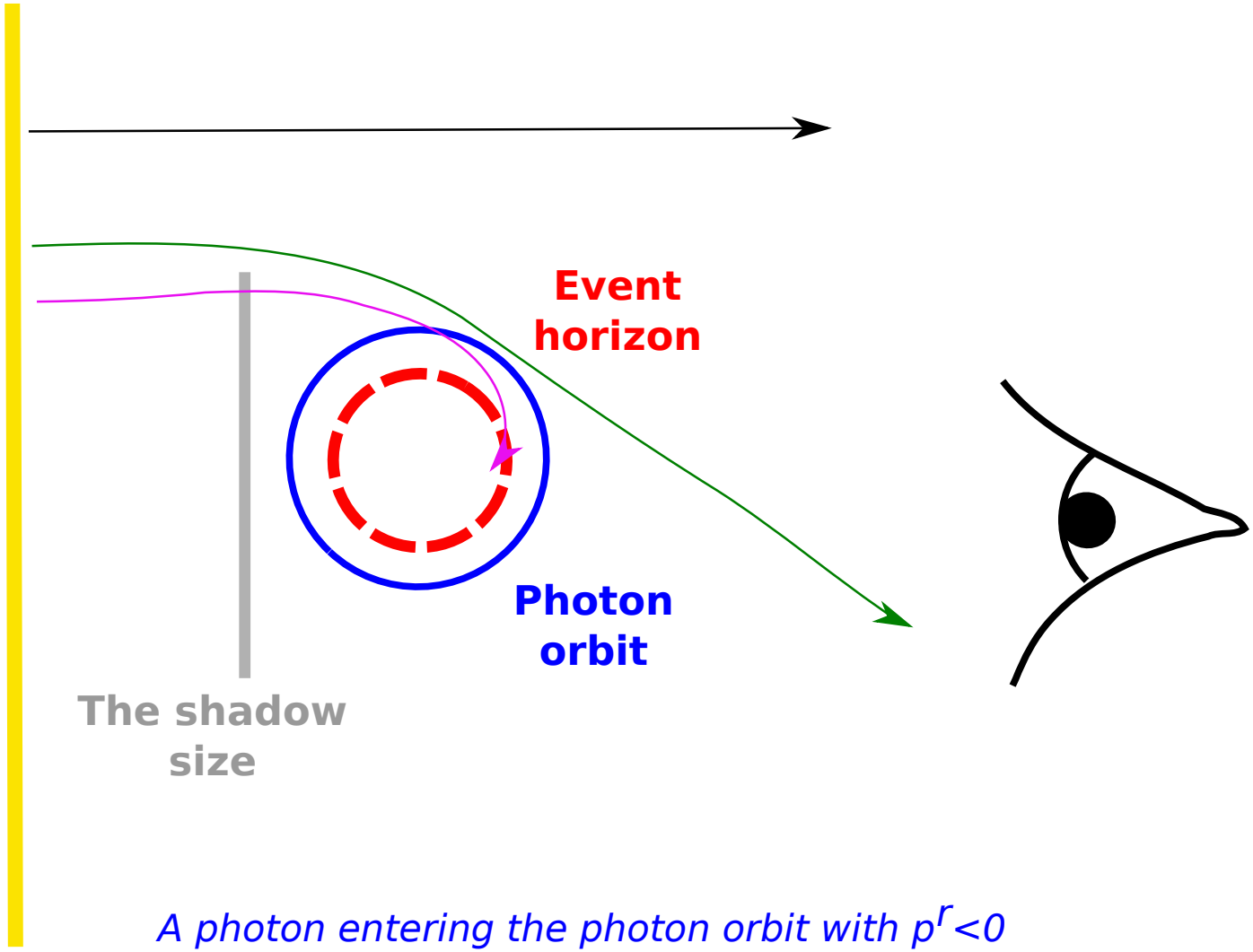
Black hole shadow



Flat spacetime shadow

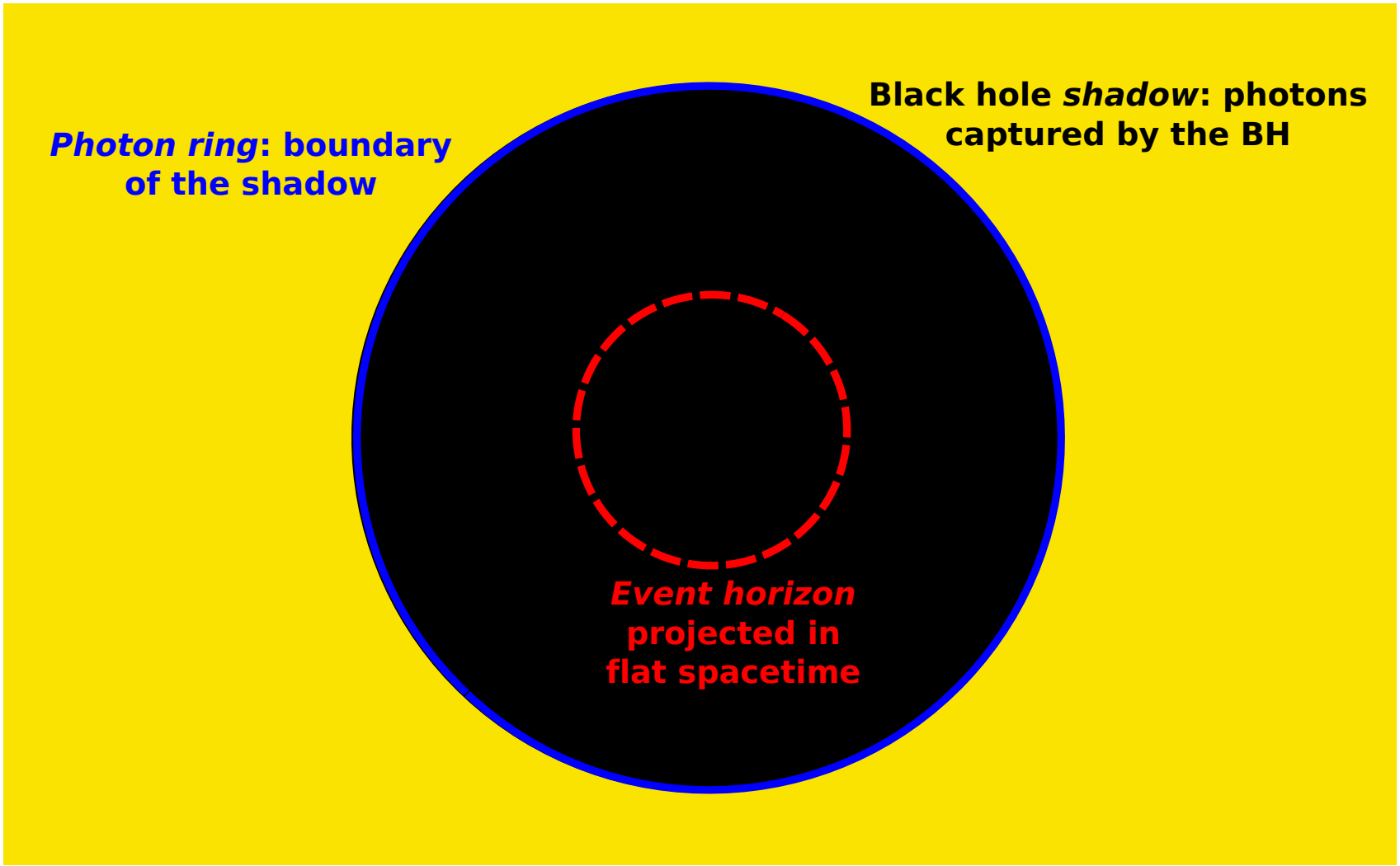


Black hole shadow

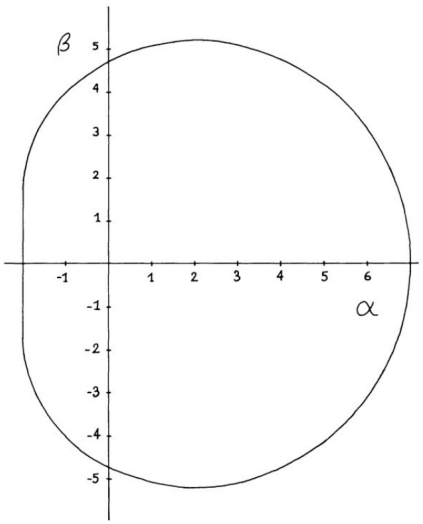


A photon entering the photon orbit with $p^r<0$
will fall into the event horizon.
So the boundary of the shadow coincides with
the image of the photon orbit, called the **photon ring**.

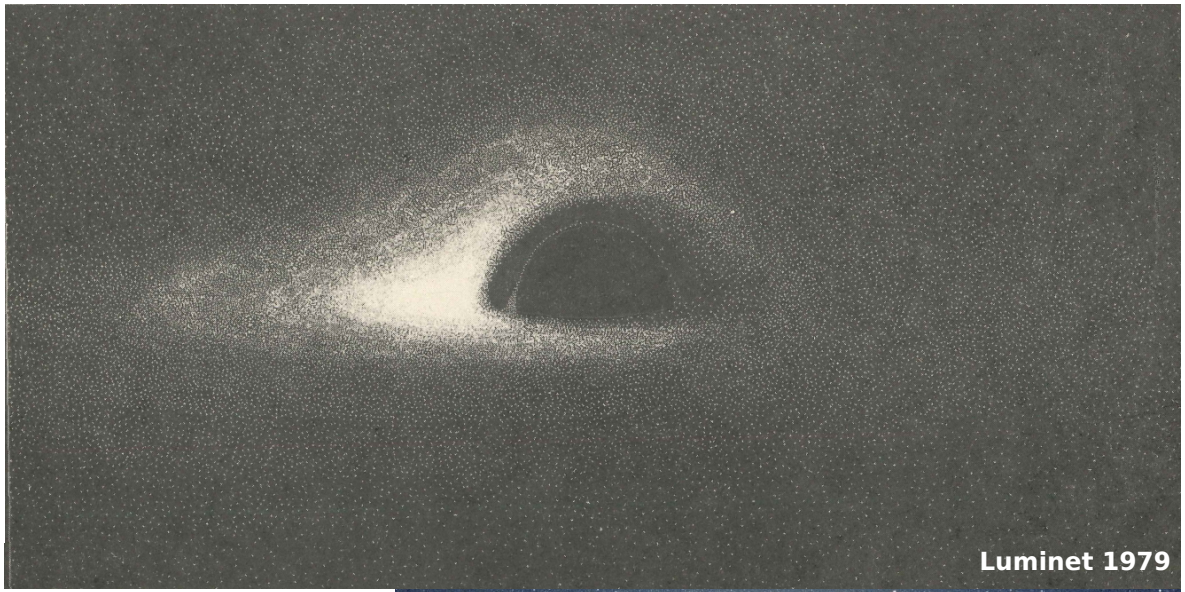
Black hole shadow



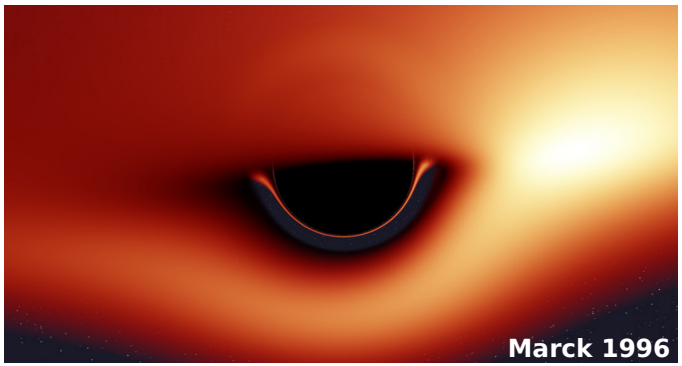
Black hole shadow in real life



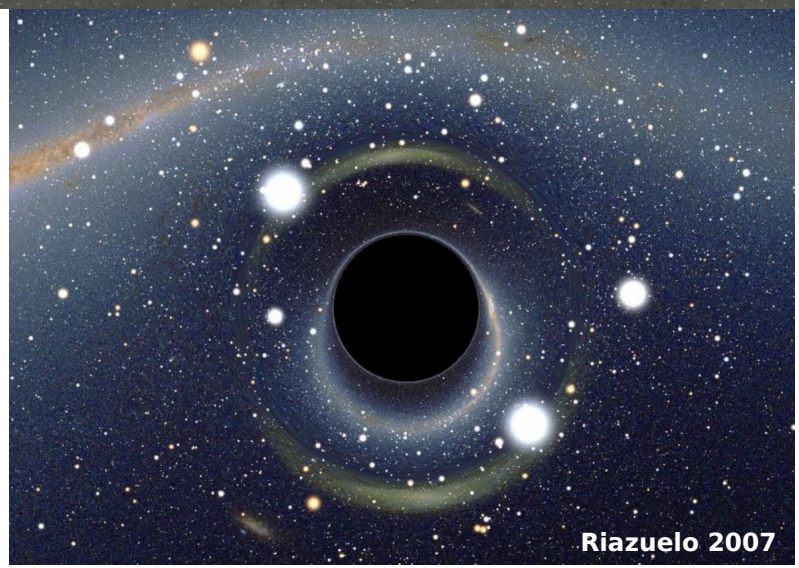
Bardeen 1972



Luminet 1979

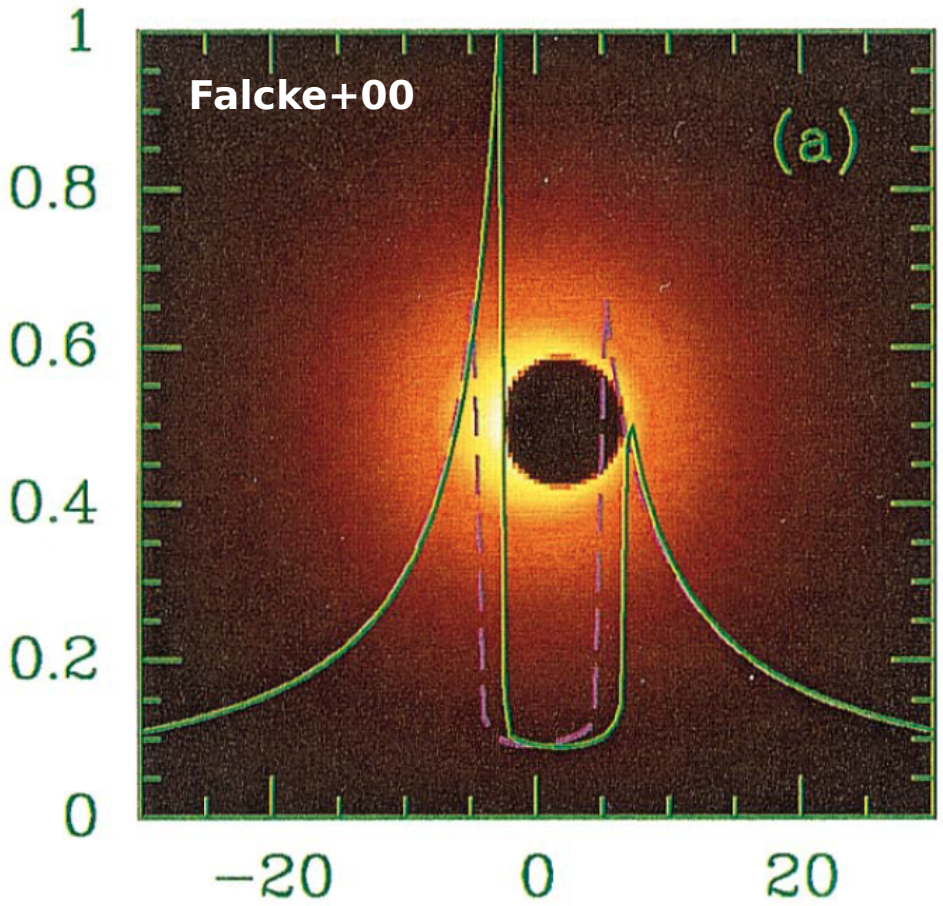


Marck 1996

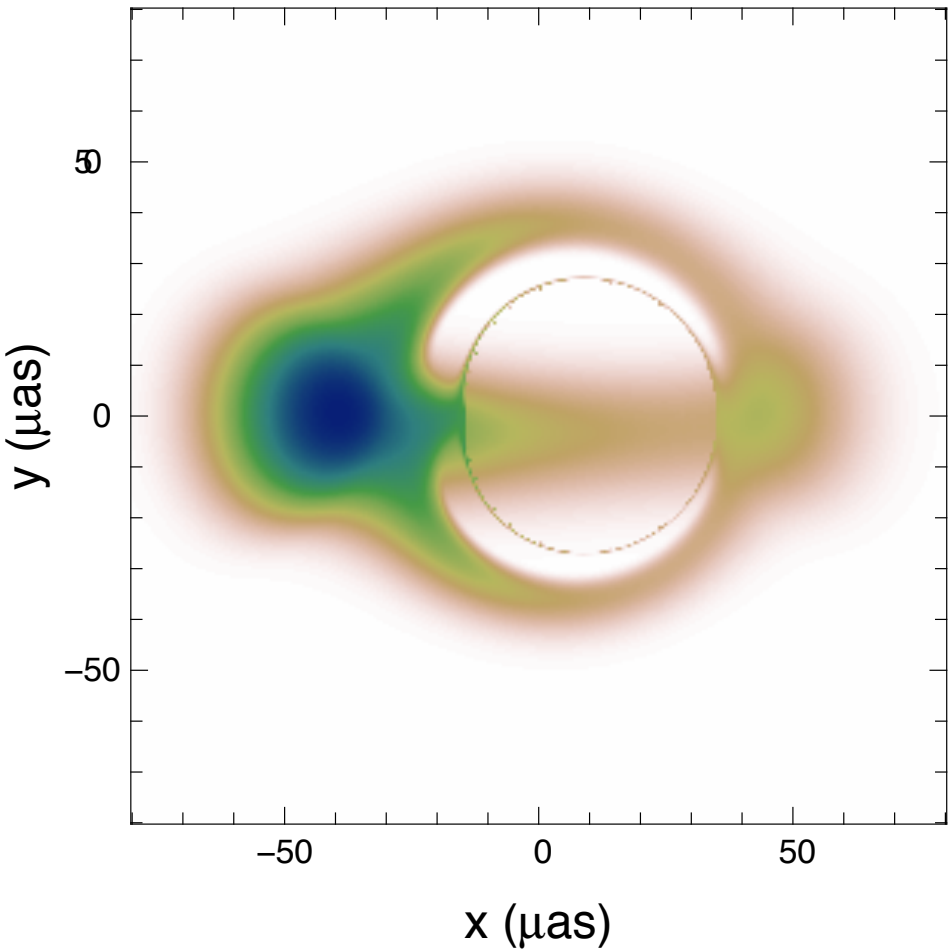


Riazuelo 2007

Black hole shadow in real life

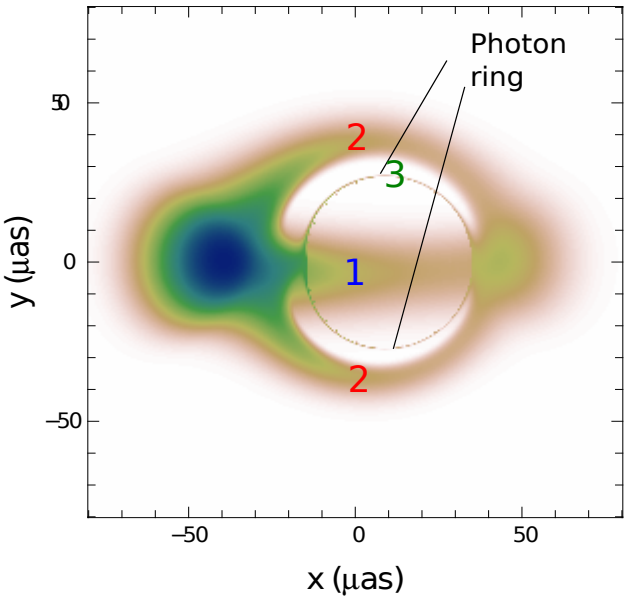


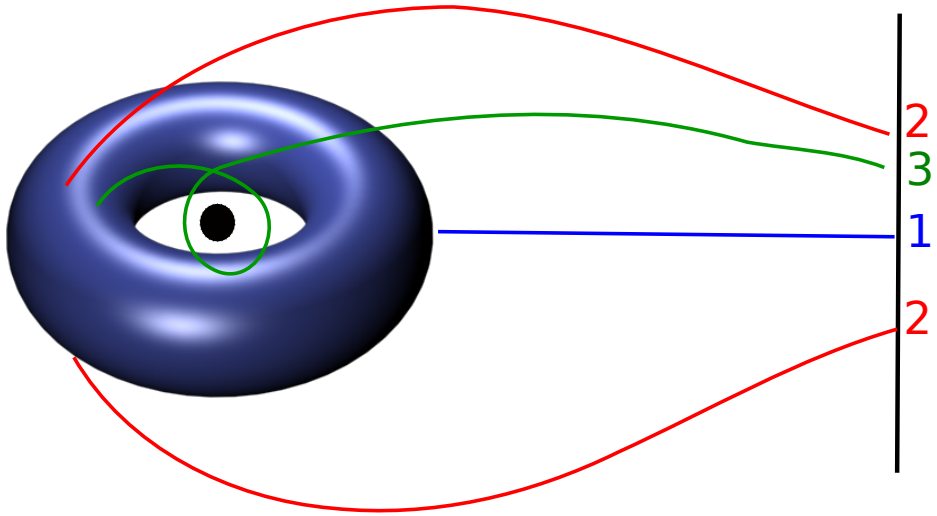
Black hole shadow in real life



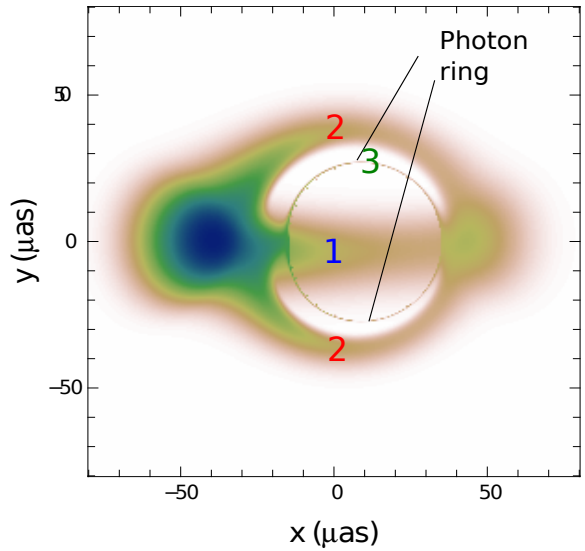
Understanding strong-field image

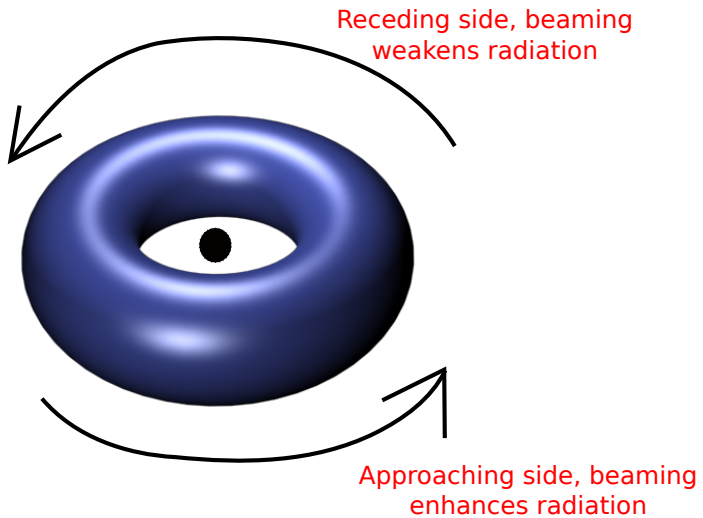
Edge-on view



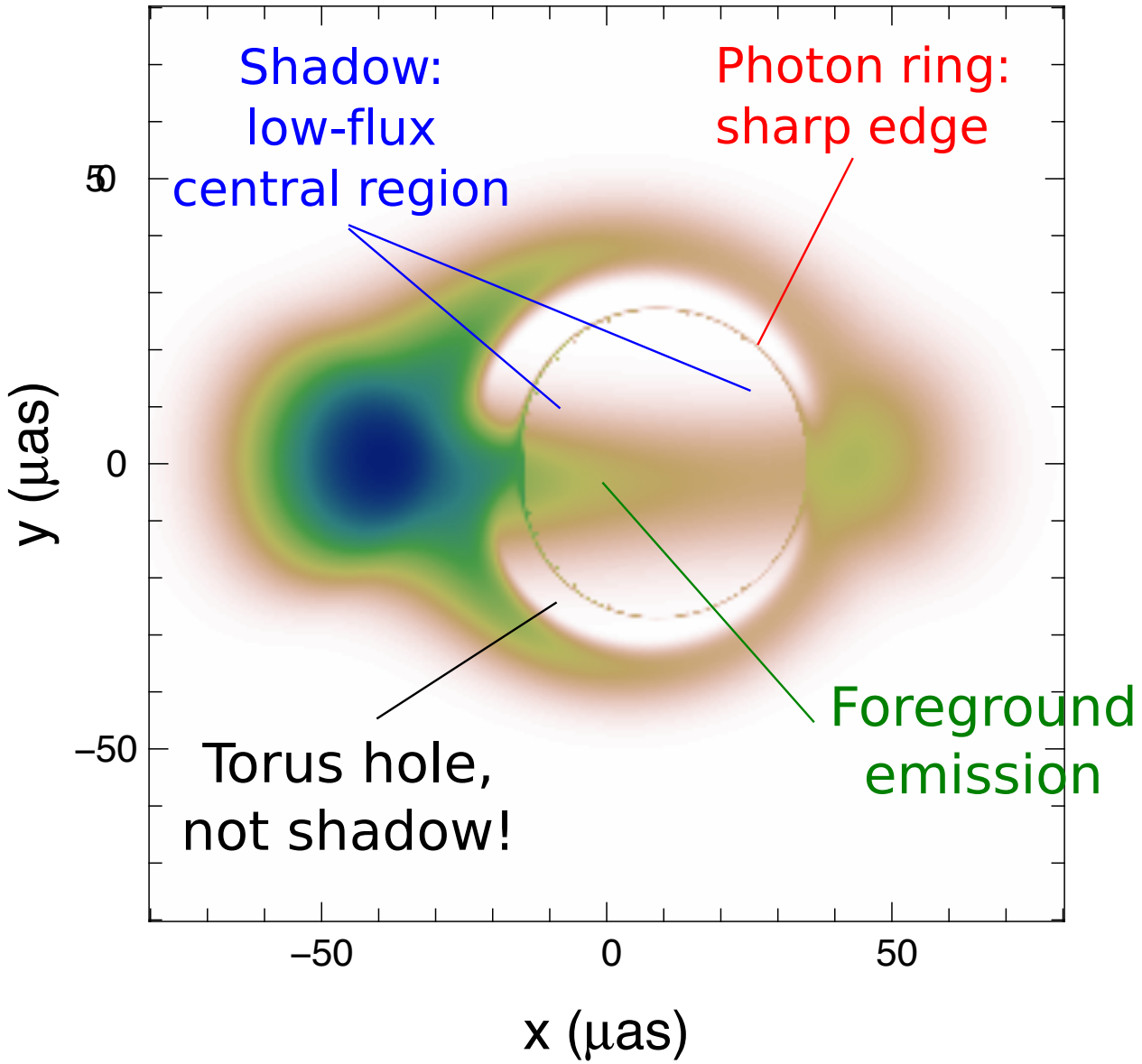


Understanding strong-field image

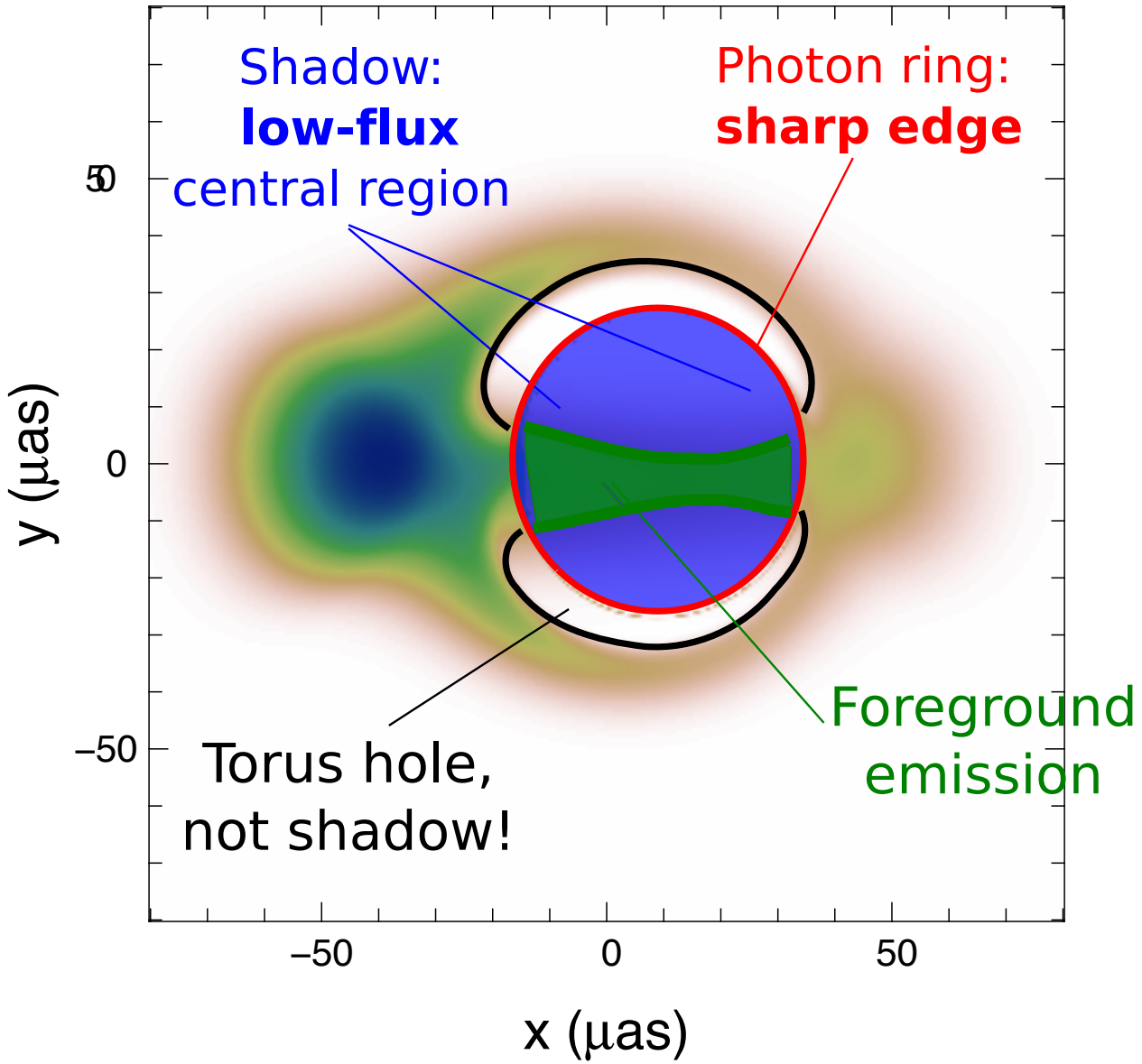




The shadow in a BH+torus spacetime



The shadow for an observer

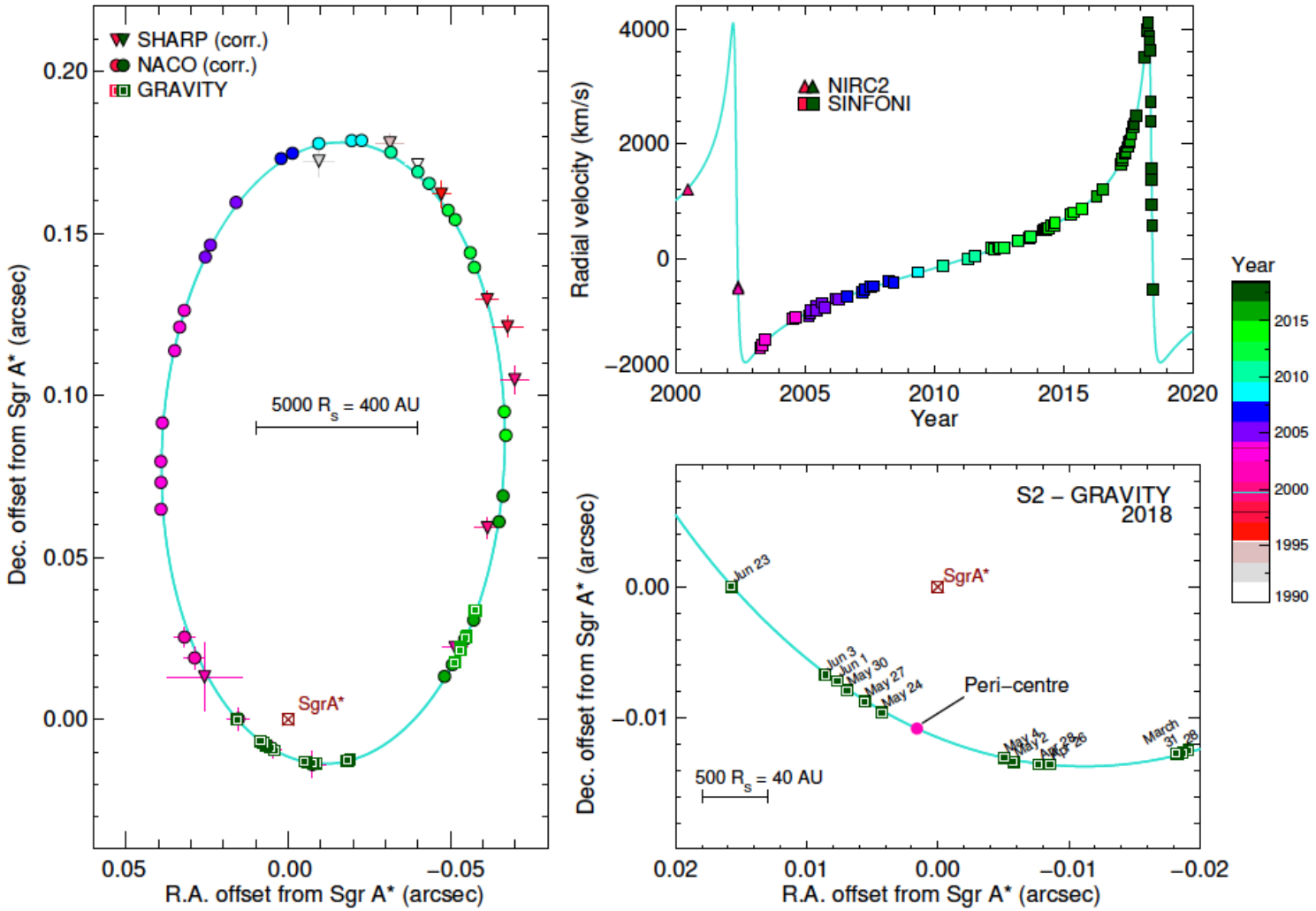


EHT final goal

- Image the shadow+photon ring of Sgr A*/M87*
- Hallmark of an event horizon (Falcke+00)
- Conclude that Sgr A*/M87* is a standard (Kerr) BH

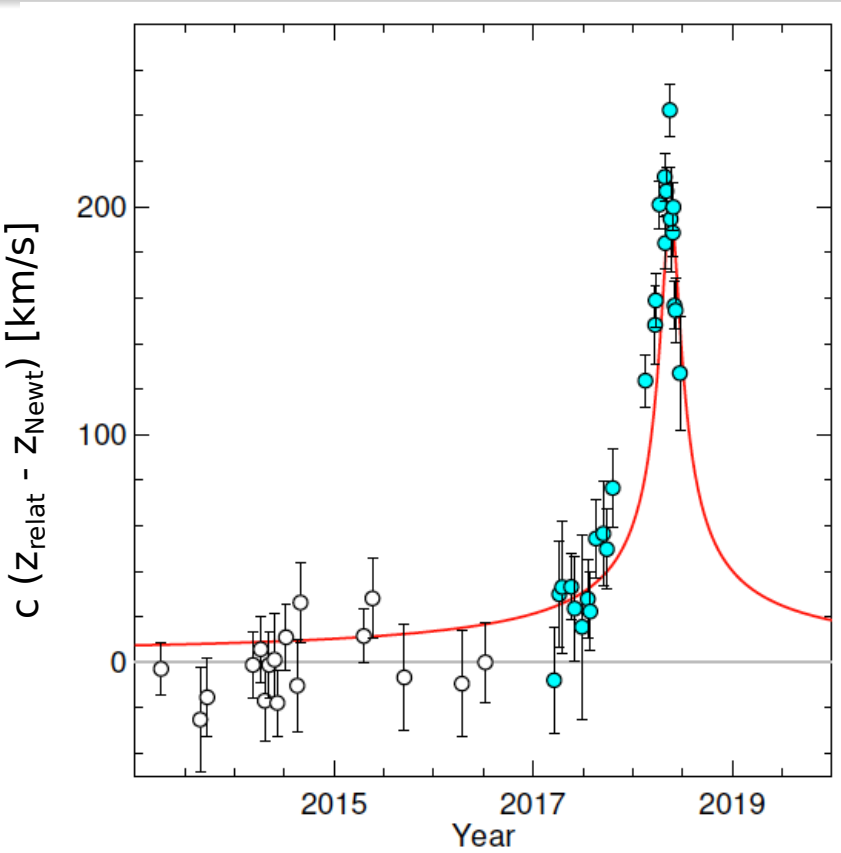
EHT intermediate goal

- Constrain accretion flow properties
- Constrain black hole parameters



GRAVITY Collaboration 2018

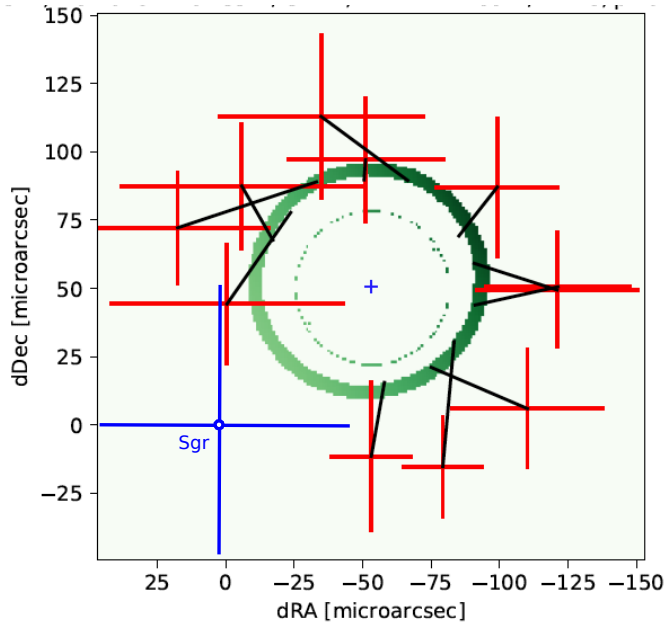
Following S2 at pericenter passage



GRAVITY Collaboration 2018

Newtonian vs. Parametrized Post-Newtonian (order 1 in v^2/c^2)

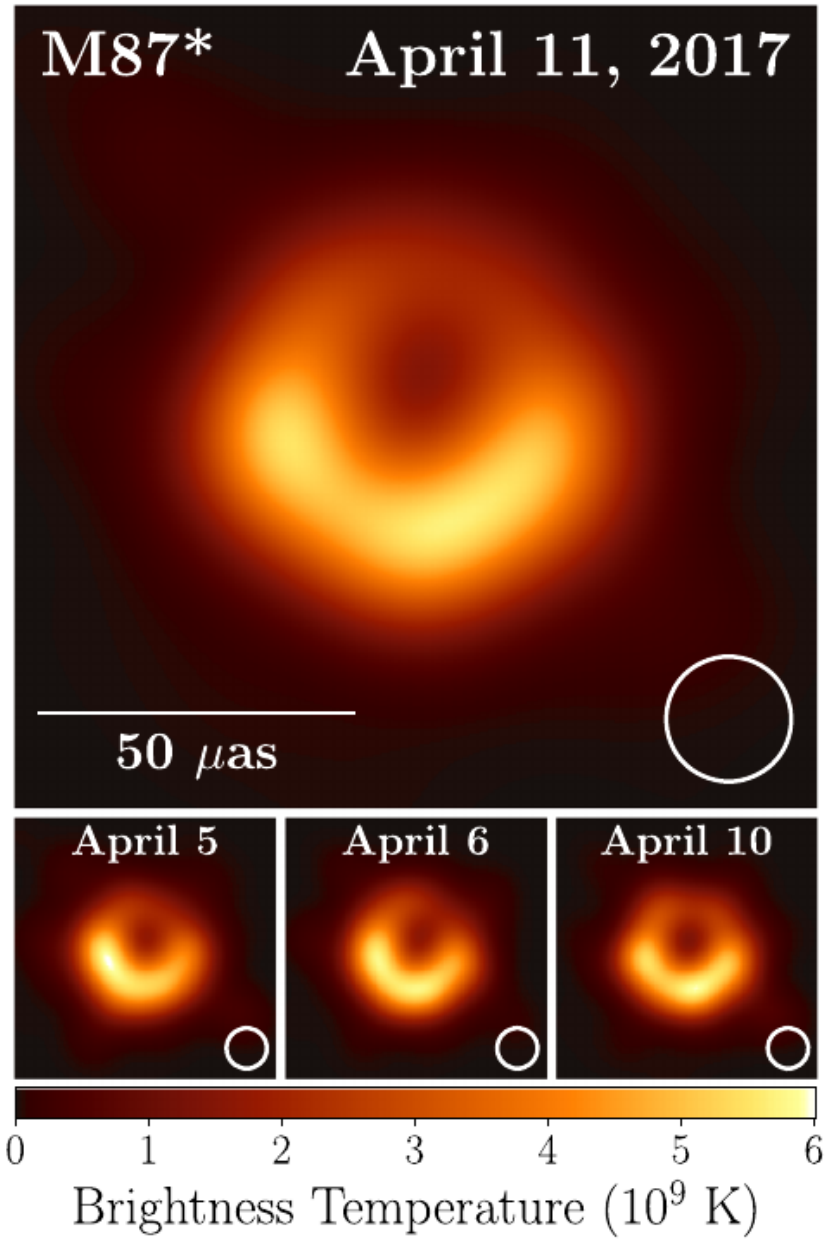
- $cz = \overbrace{c\,(z_0 + \text{Doppler} \times \beta)}^{\text{Newtonian}} + \overbrace{c\,(\text{Transverse Doppler} + \text{Grav. Redshift}) \times \beta^2}^{\text{Relativistic } \approx 200\,\text{km/s}}$
  ($\beta = v/c = 2.5\%$)



GRAVITY Collaboration 2018

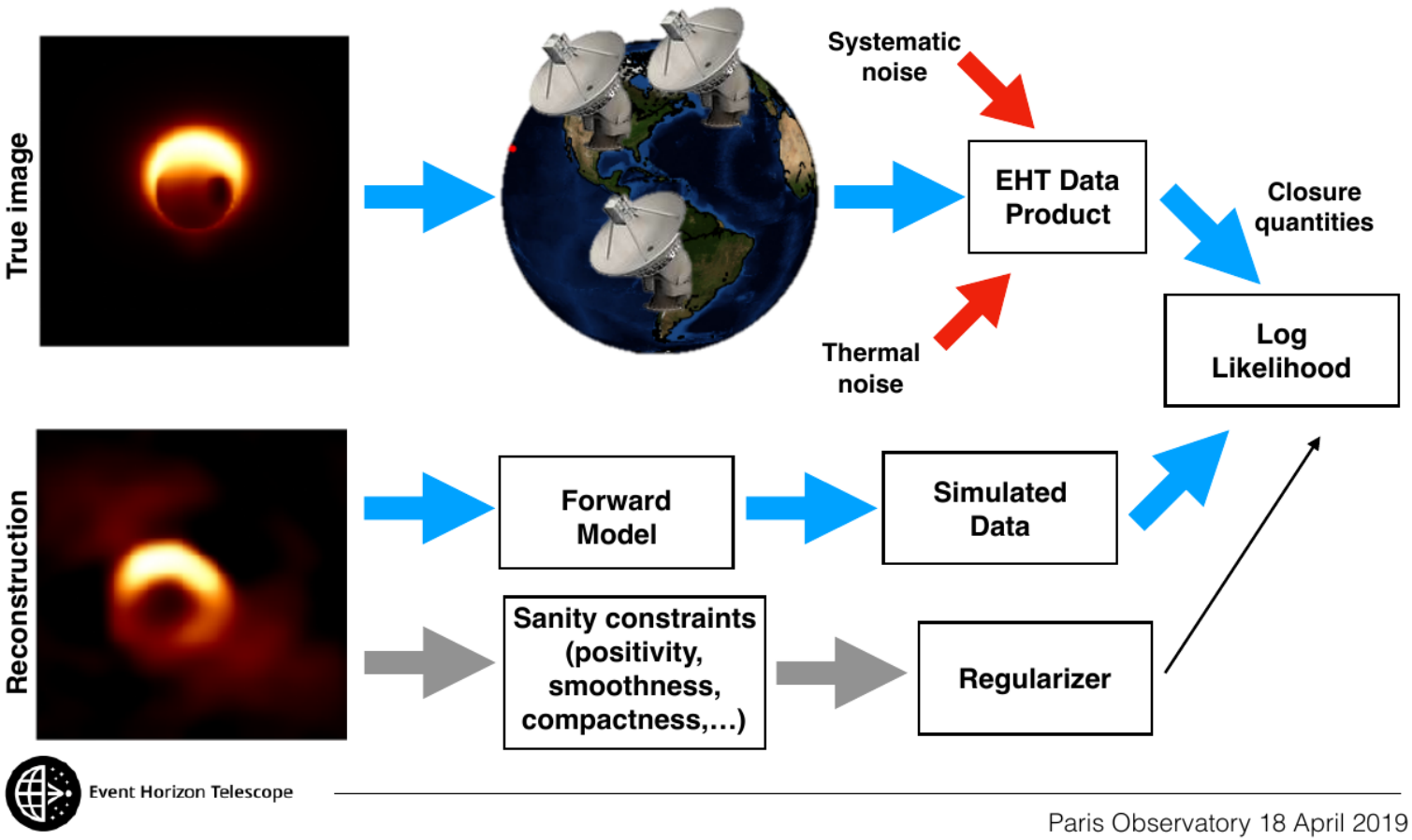
Orbital motion at the horizon

- Flare of July 22: $\Delta t = 30$ min, Flux $m_K = 14.5$ (quiescence: $m_K = 17$)
- Flare location **coincident with Sgr A***
- Motion consistent with **GR circular orbit at** $r \approx 7\,M$ **at spin** 0 with **low inclination** favored $\approx 20°$ (no spin constraint)



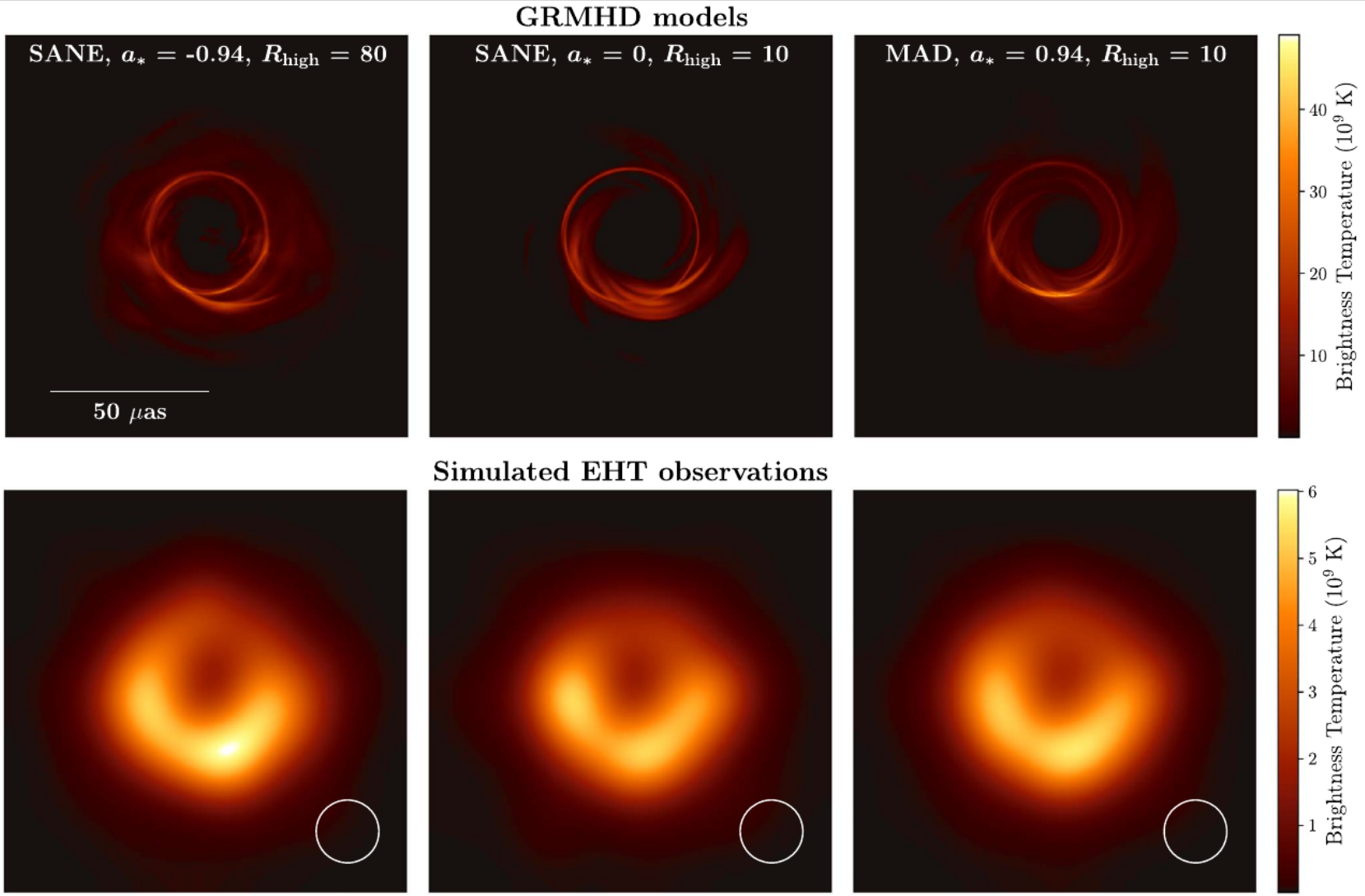
EHT Collaboration 2019

Regularized Maximum Likelihood



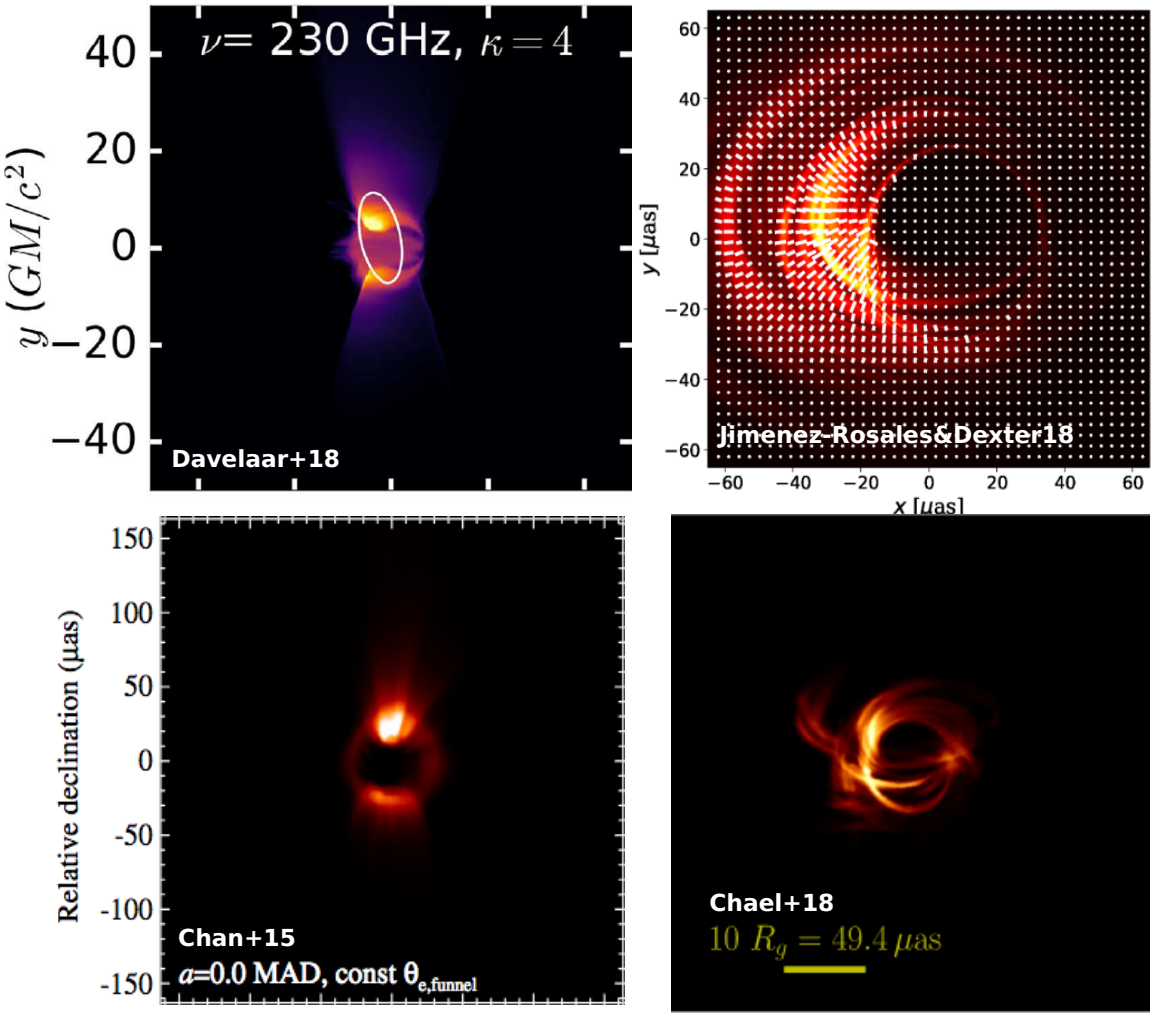
Credit M. Wielgus

Fitting model to EHT data

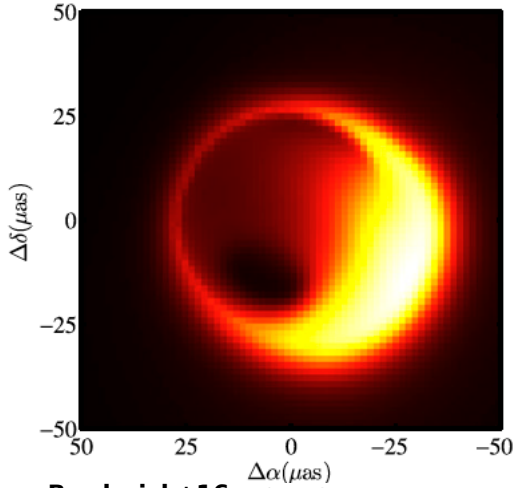


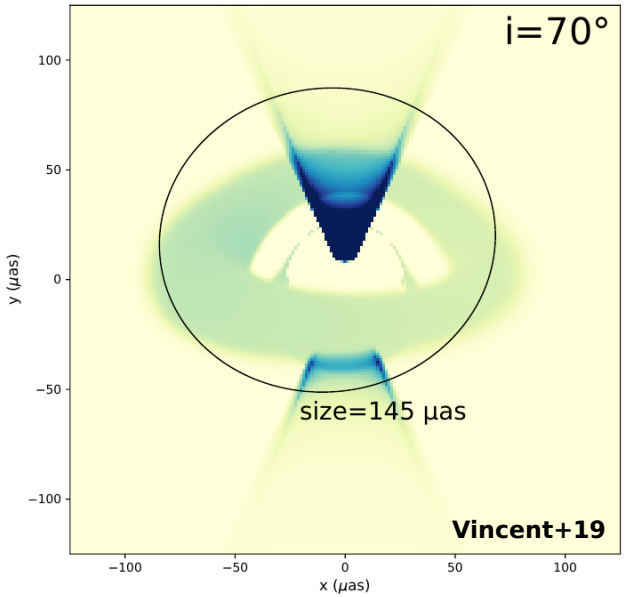
EHT Collaboration 2019

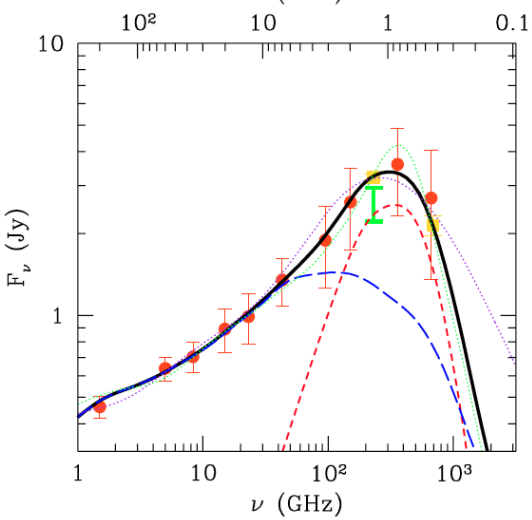
M87* accretion flow models

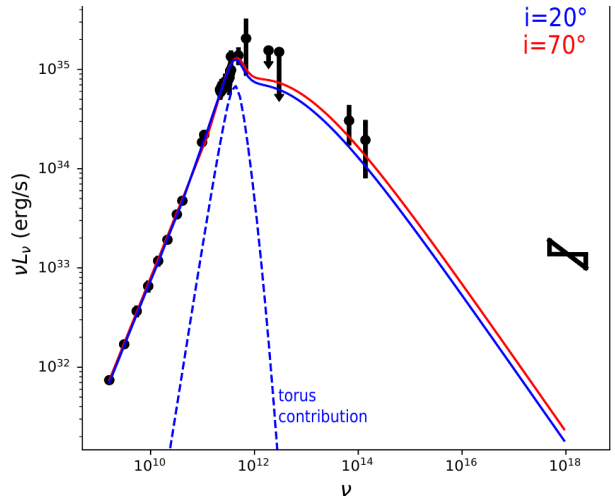


Sgr A* accretion flow models: GRMHD

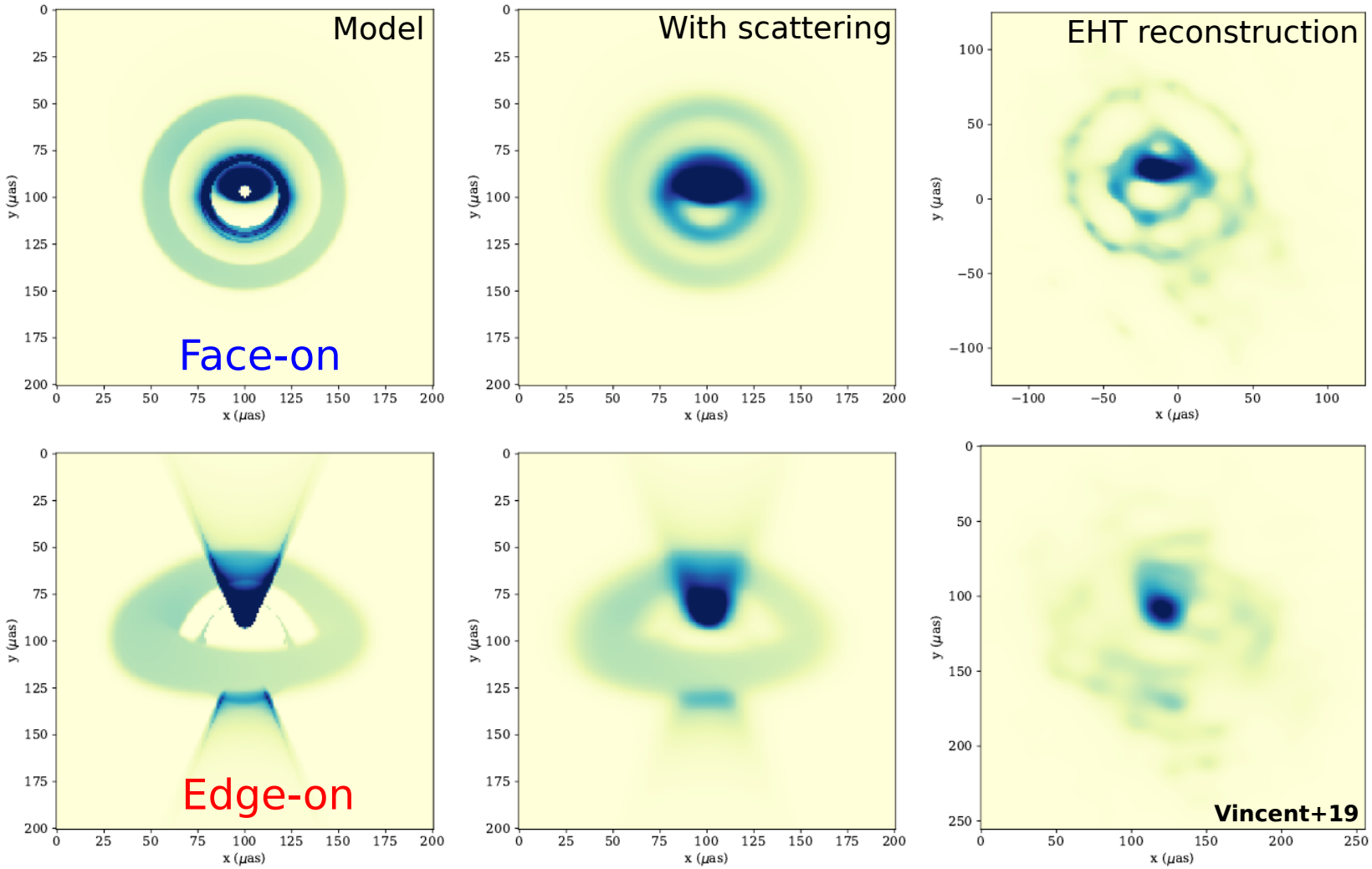


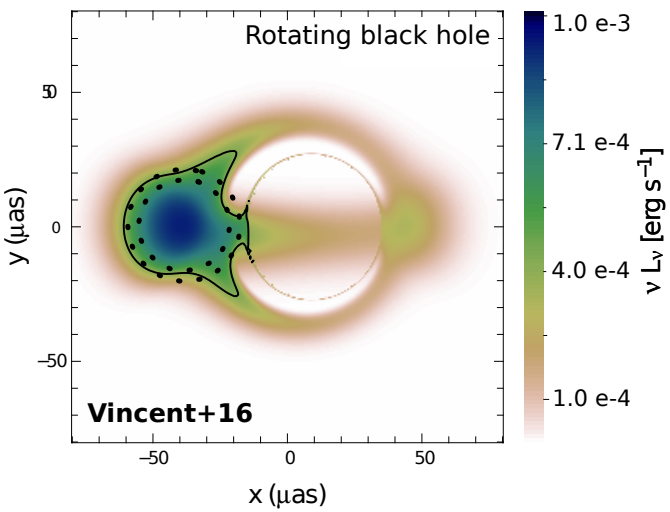


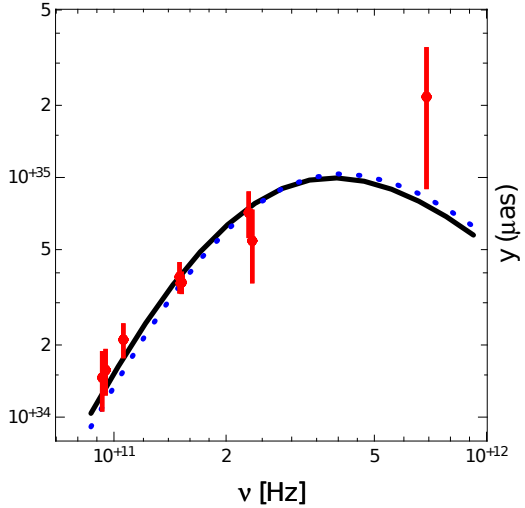


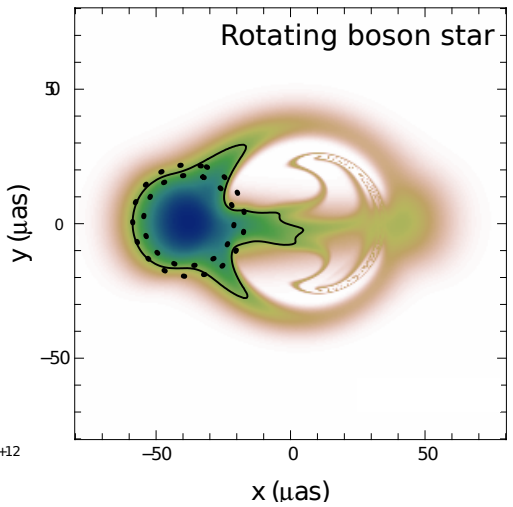


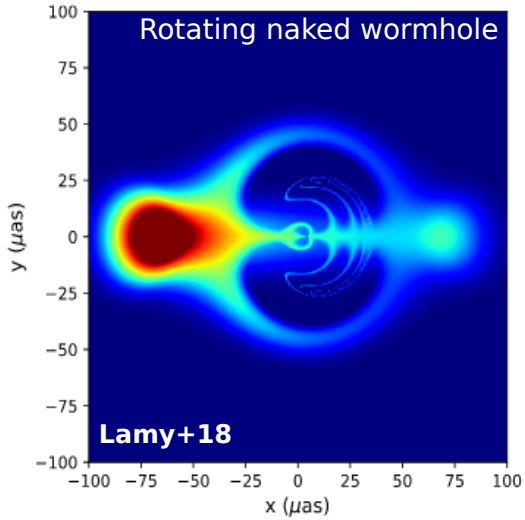
Sgr A* accretion flow models: analytic


Model
With scattering
EHT reconstruction
Face-on
Edge-on
Vincent+19
x (μas)
y (μas)

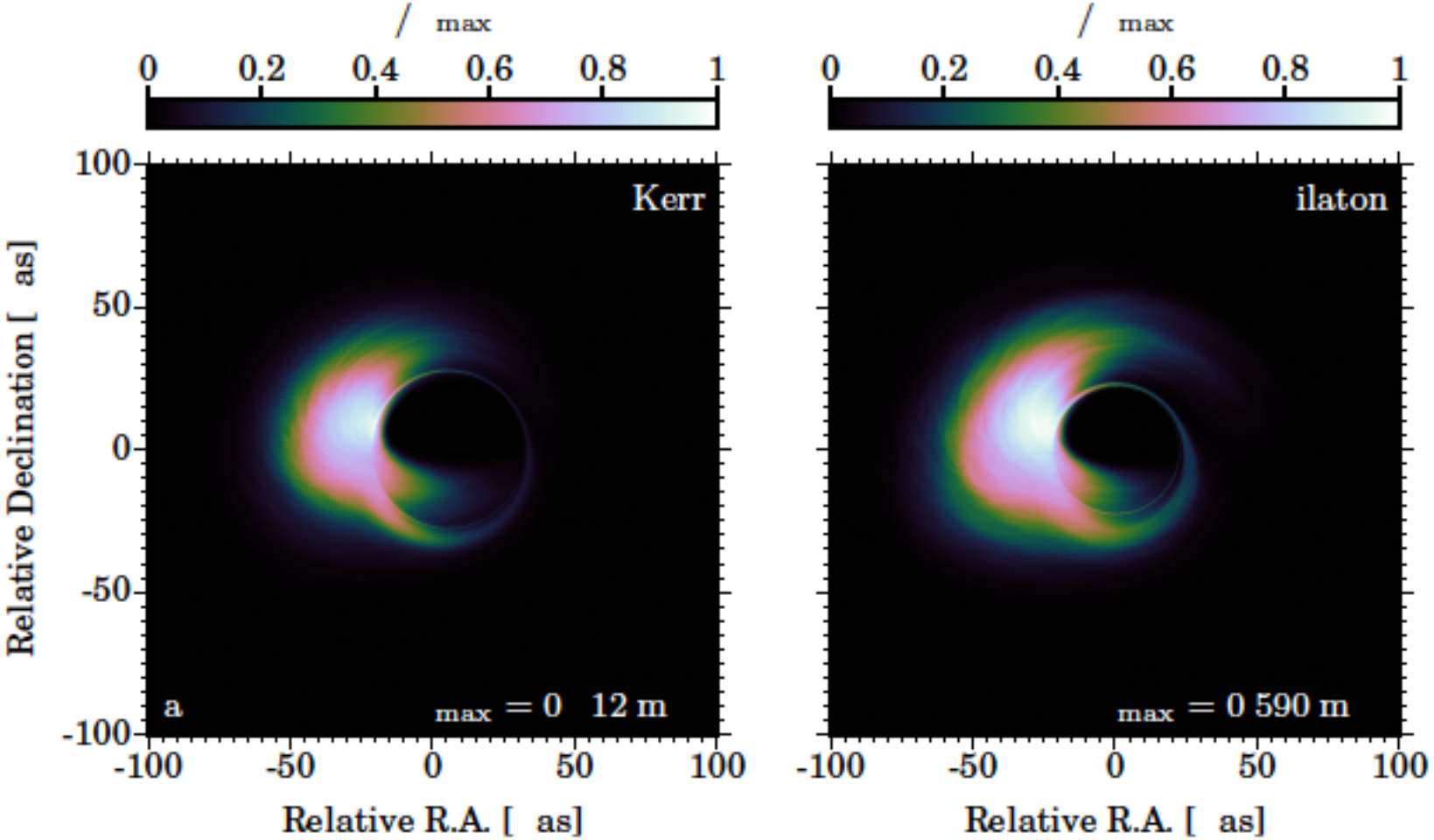








Testing the nature of Sgr A*?



Mizuno+18

Testing gravity?

Conclusion

- GRAVITY/EHT: event-horizon-scale monitoring of BH
- GRAVITY results:
  Kepler rejected, flares = orbiting strong-field events
- GRAVITY near future: pericenter advance, more flares
- EHT results:
  shadow imaged, first imaging constraints on accretion flow
- EHT near future: polarization, Sgr A*
- Test of black hole paradigm / gravity theory:
  a long way to go...
- Very promising short-term future with EHT + GRAVITY!

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