What can we learn from the picture of a black hole?

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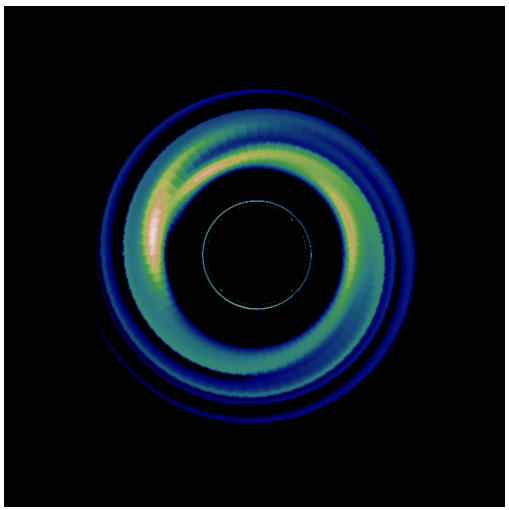
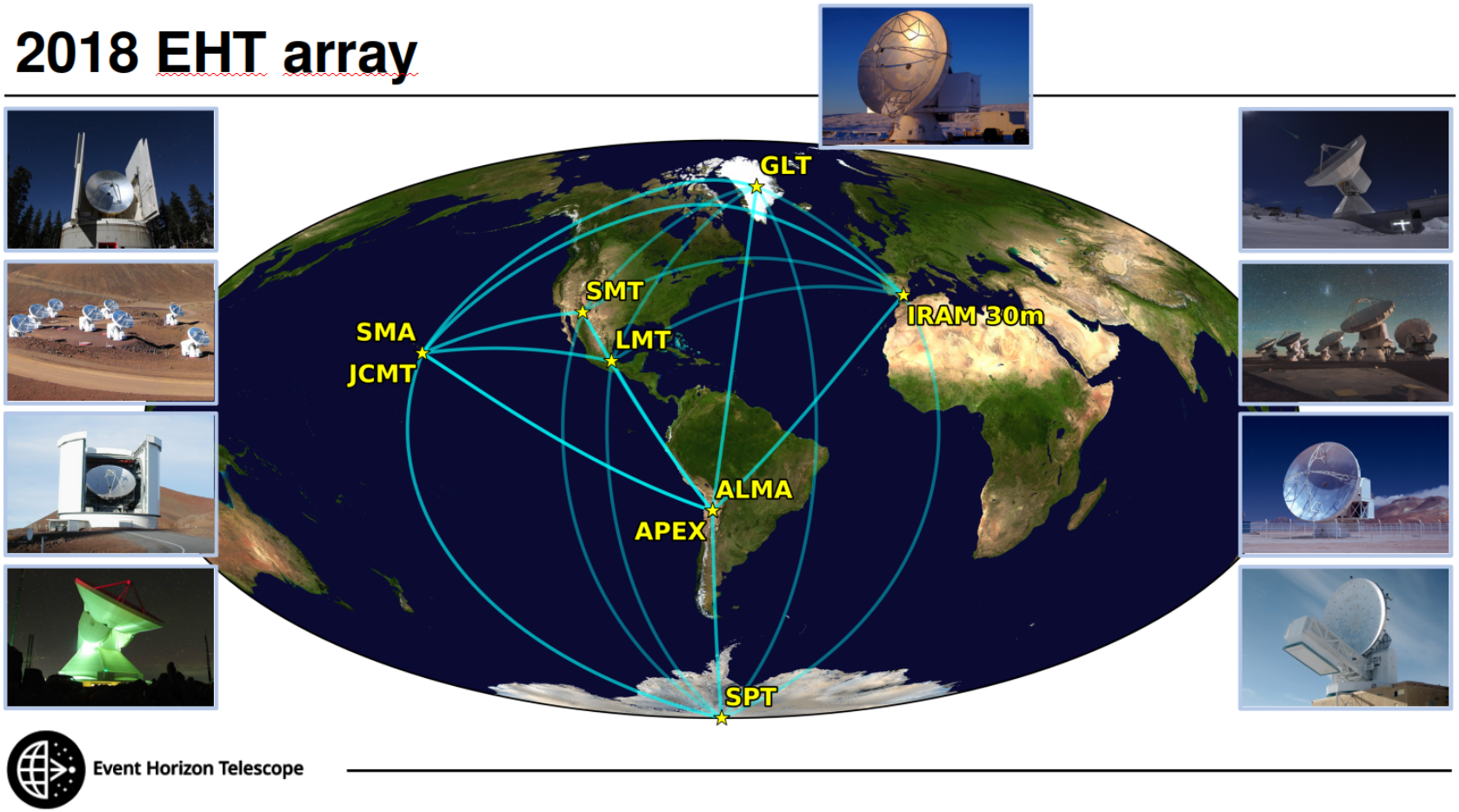




EHT: an array of millimeter antennas

Science cases

- EHT: $\frac{\lambda}{B} = \mathbf{25}\ \boldsymbol{\mu}\mathbf{as}$ 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

EHT funding support

Academia Sinica Institute of Astronomy and Astrophysics
University of Arizona
University of Chicago
East Asian Observatory
Goethe-Universität
Institut de Radioastronomie Millimétrique
Large Millimeter Telescope
Max Planck Institute for Radioastronomy
MIT Haystack Observatory
National Astronomy Observatory of Japan
Perimeter Institute for Theoretical Physics
Radboud University
Smithsonian Astrophysical Observatory

Event Horizon Telescope

EHT institutional board

EHT people

- Doeleman (Director), Psaltis (Proj. Scientist), Tilanus (Proj. Manager)
- Science Council (Falcke, chair)
- 20 Working Groups
- $\approx$ 200 people worldwide
- In Europe: *Black Hole Cam* Synergy ERC grant (Falcke, Kramer, Rezzolla) $\rightarrow$ EHT+pulsars+stars

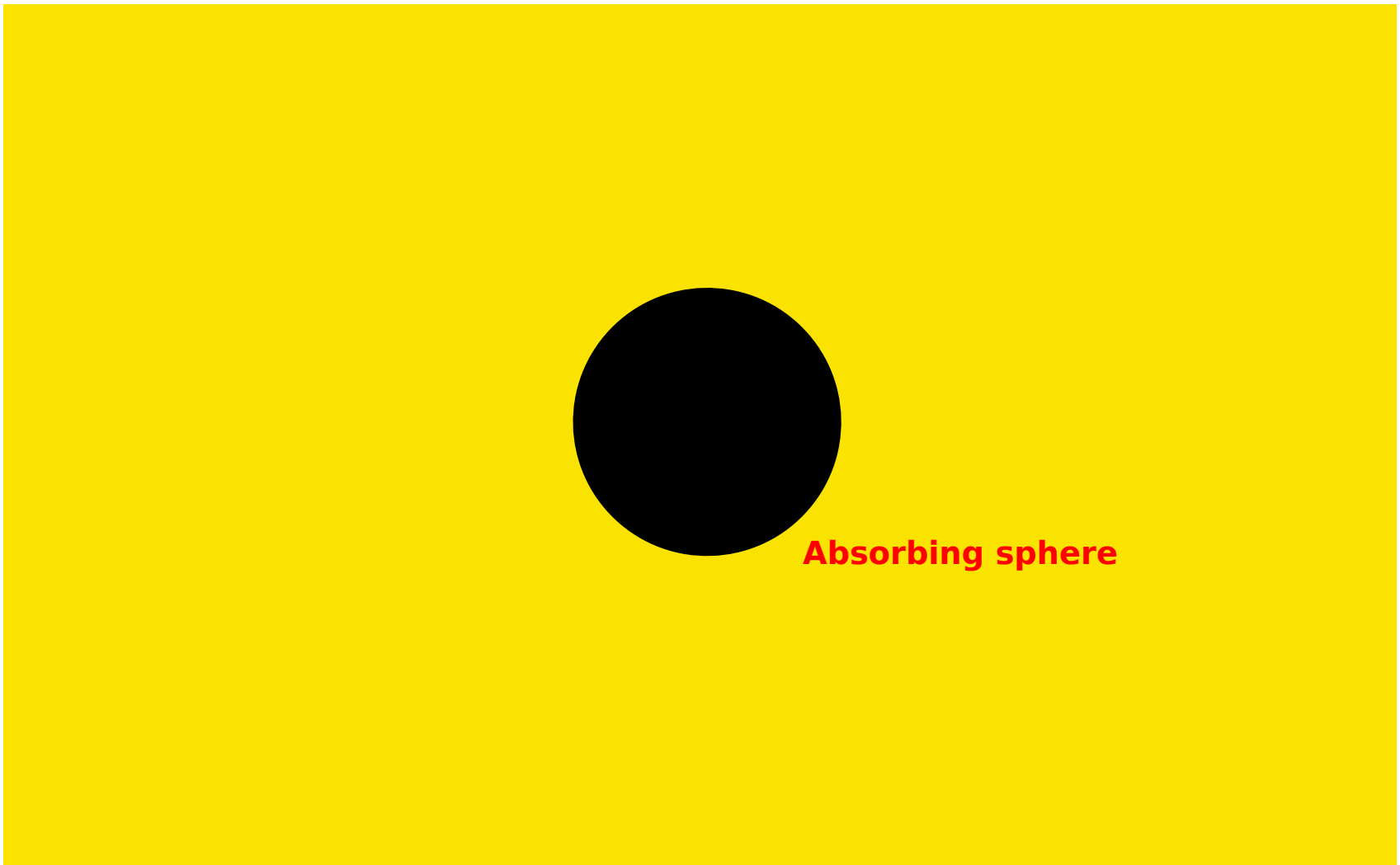
  $\approx$ 40 people

Involvment in France

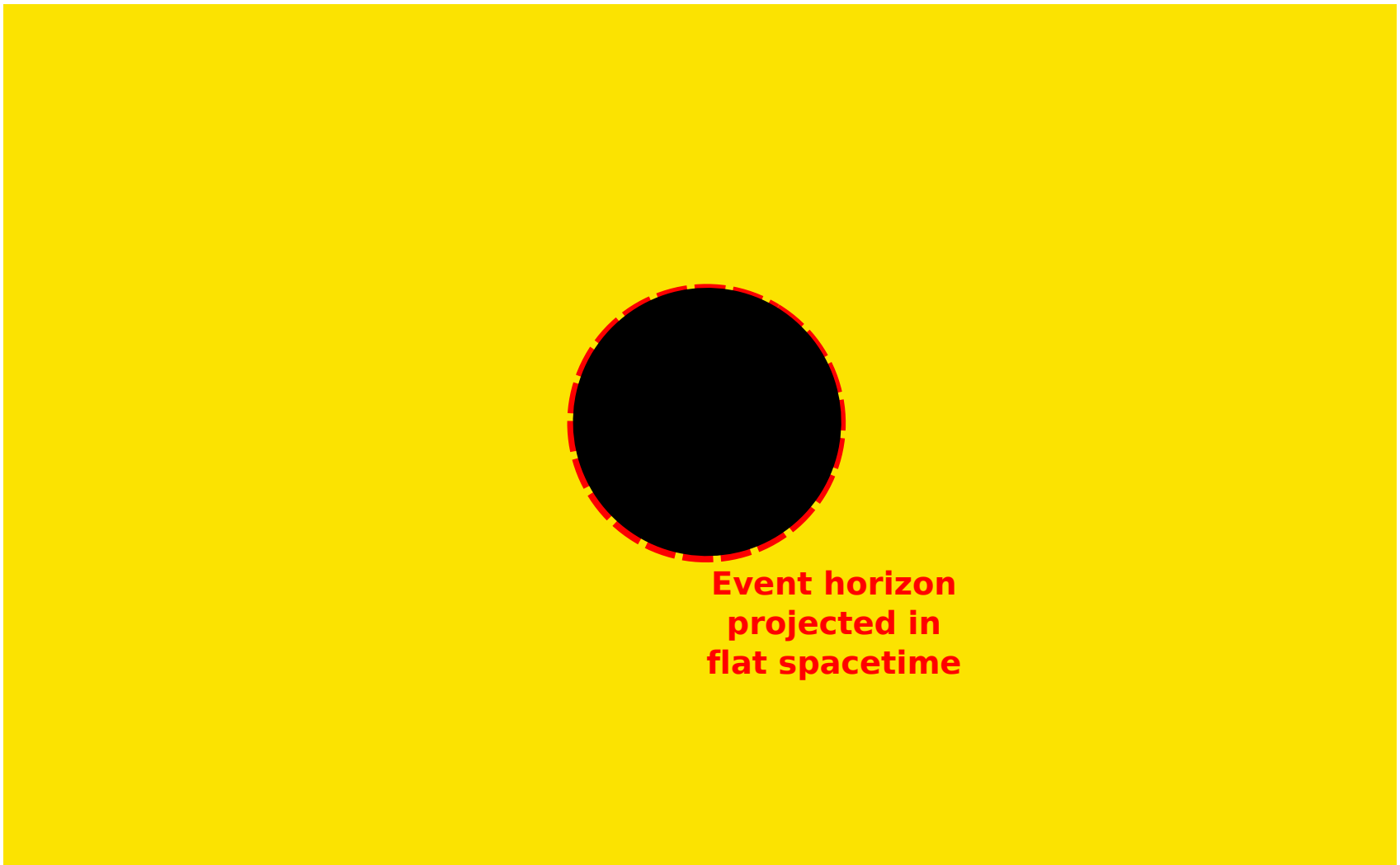
- via ESO through ALMA
- via IRAM through Pico Veleta
- via IRAM through NOEMA being commissioned
- LESIA entering Synergy grant (Desvignes joining team)
- Obs. Paris:
  LESIA (Paumard, Perrin, Vincent)
  LUTh (Gourgoulhon, Grandclement, Meliani)

Black hole shadow

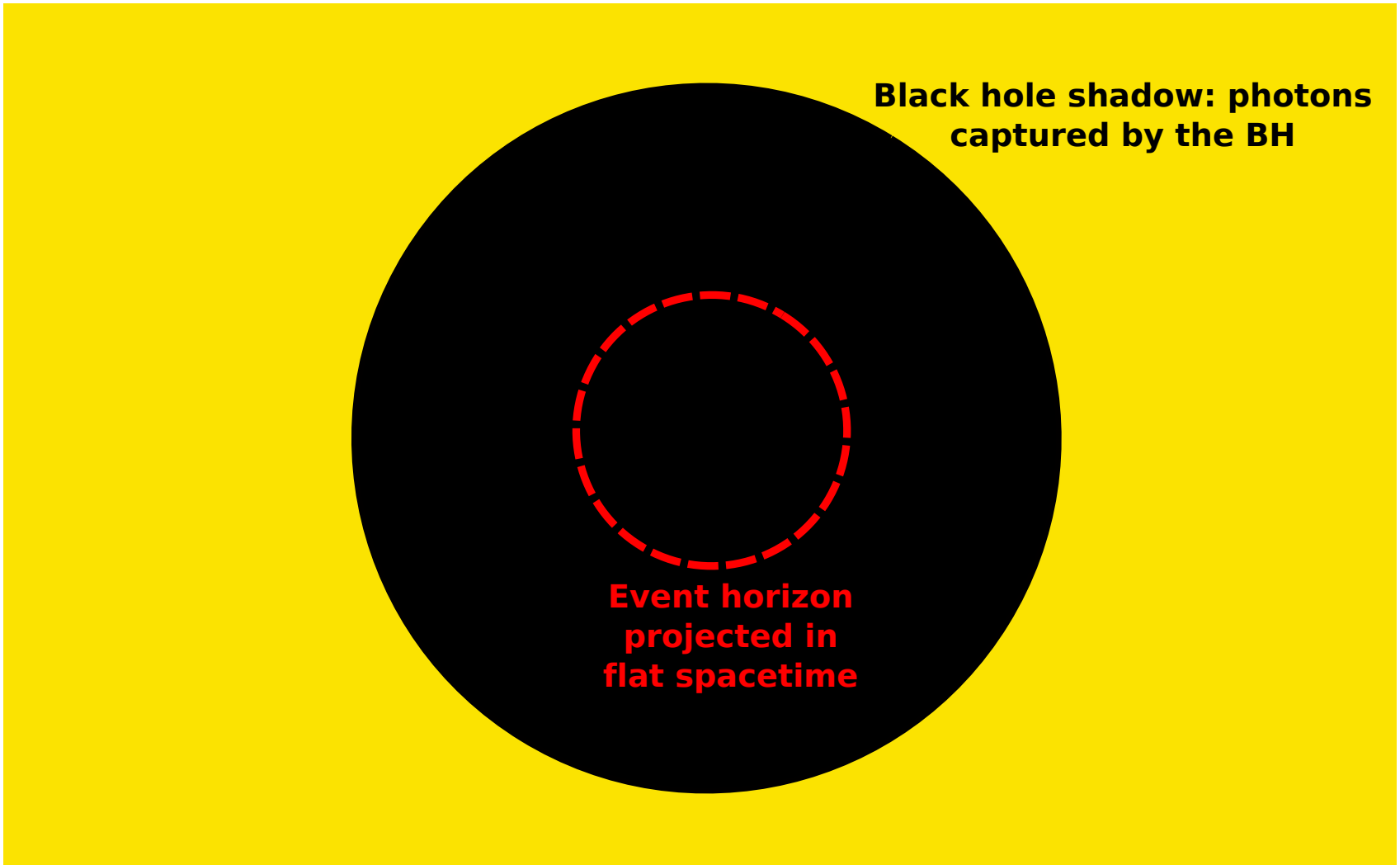
Black hole shadow



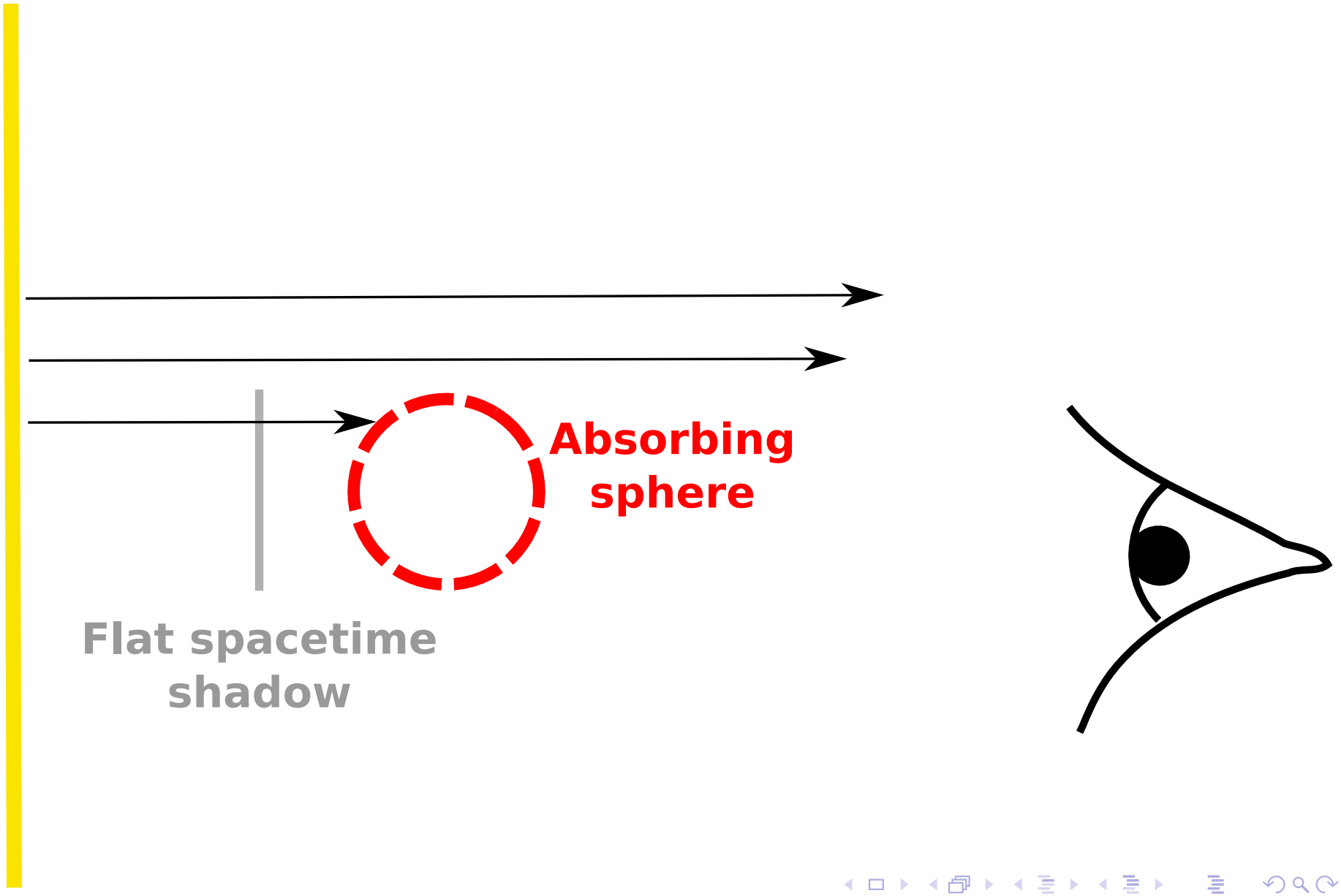
Black hole shadow



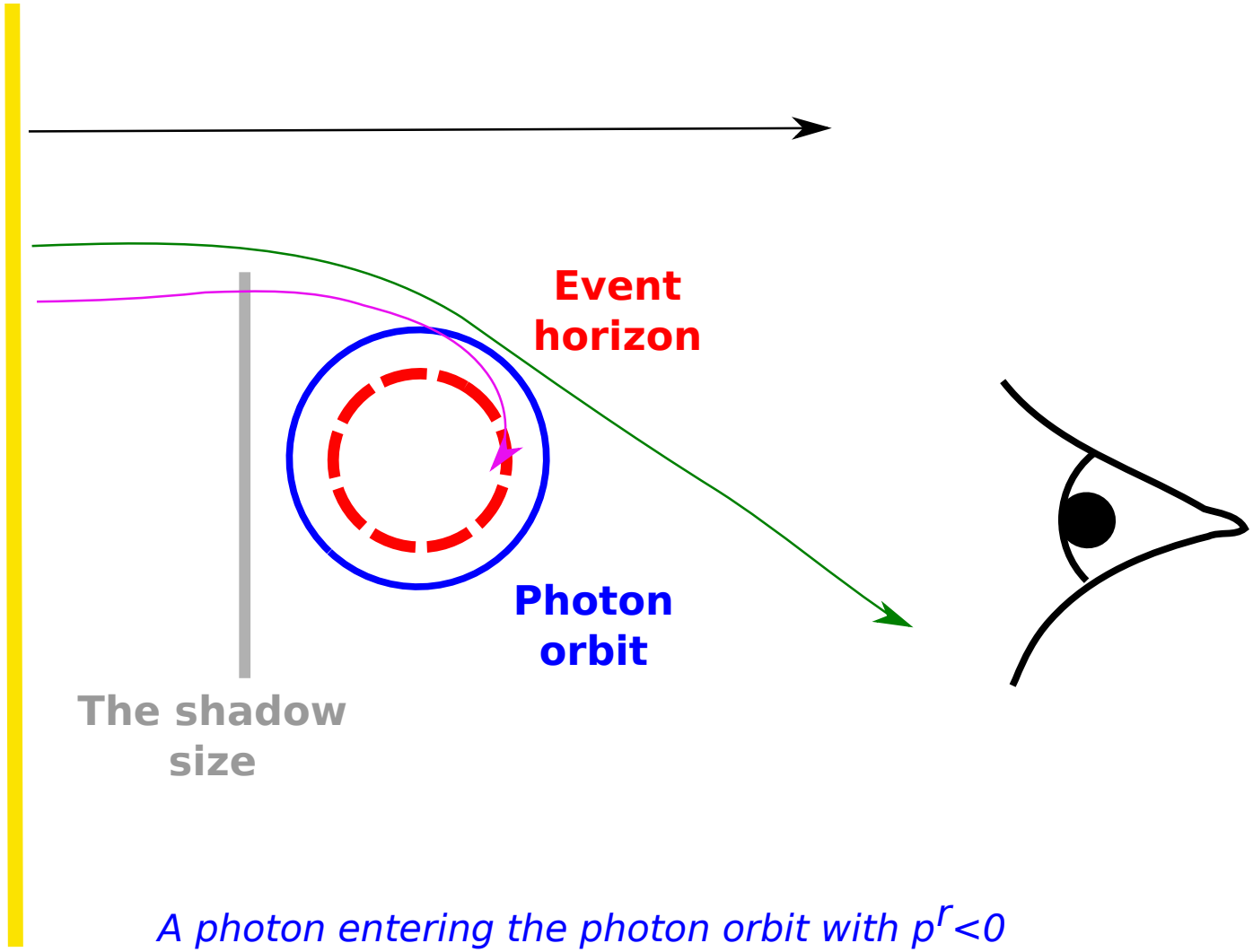
Black hole shadow



Flat spacetime shadow

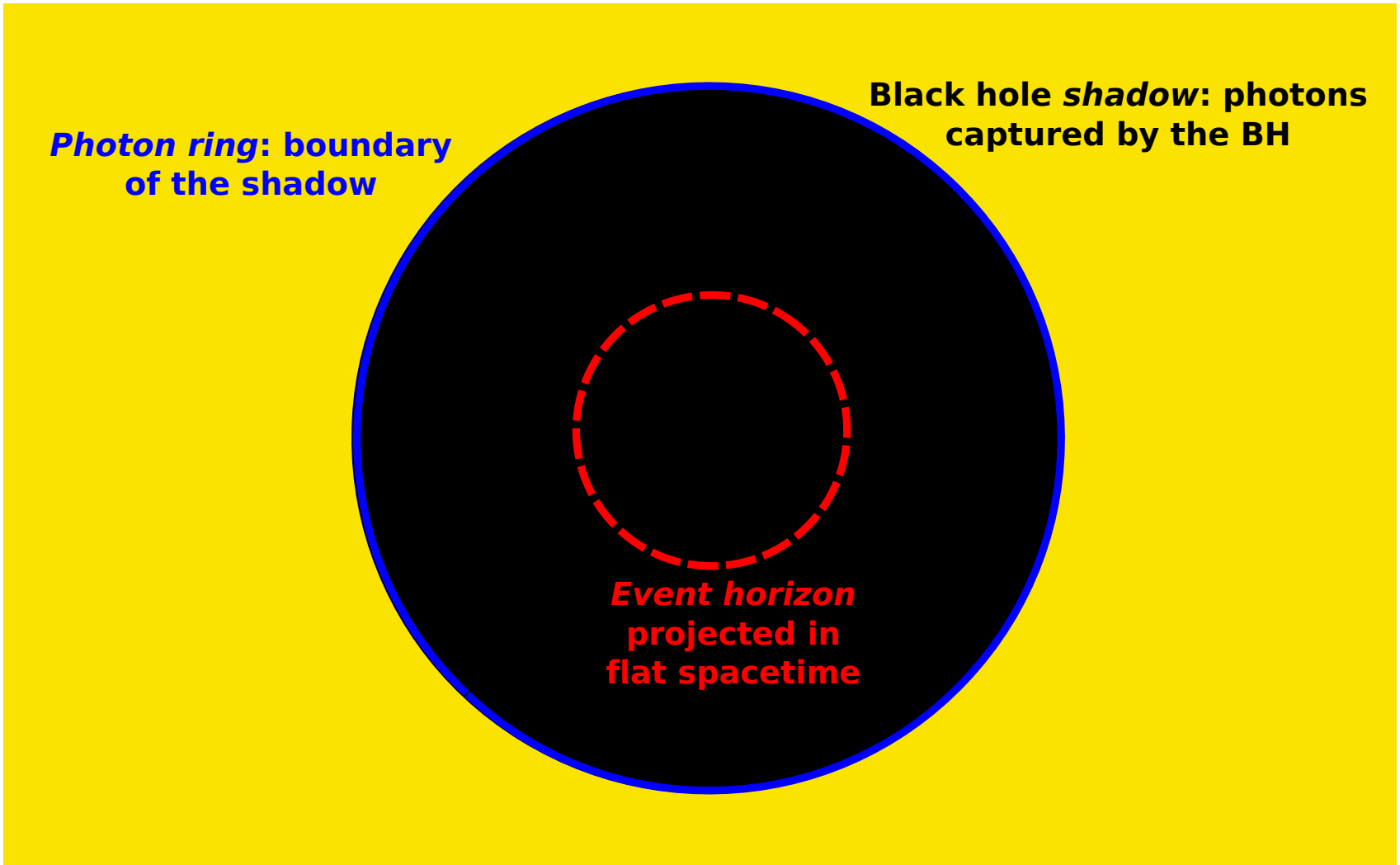


Black hole shadow

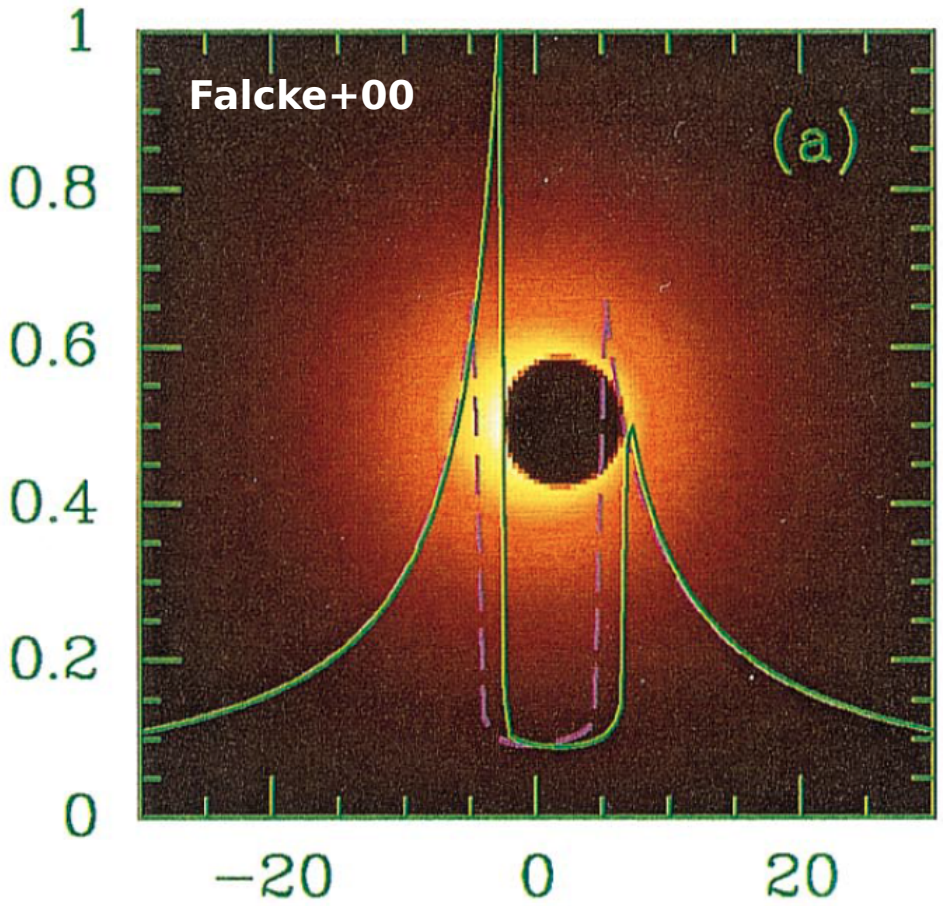


A photon entering the photon orbit with $p^r<0$
will fall into the event horizon.
So the boundary of the shadow coincides with
the image of the photon orbit, called the **photon ring**.

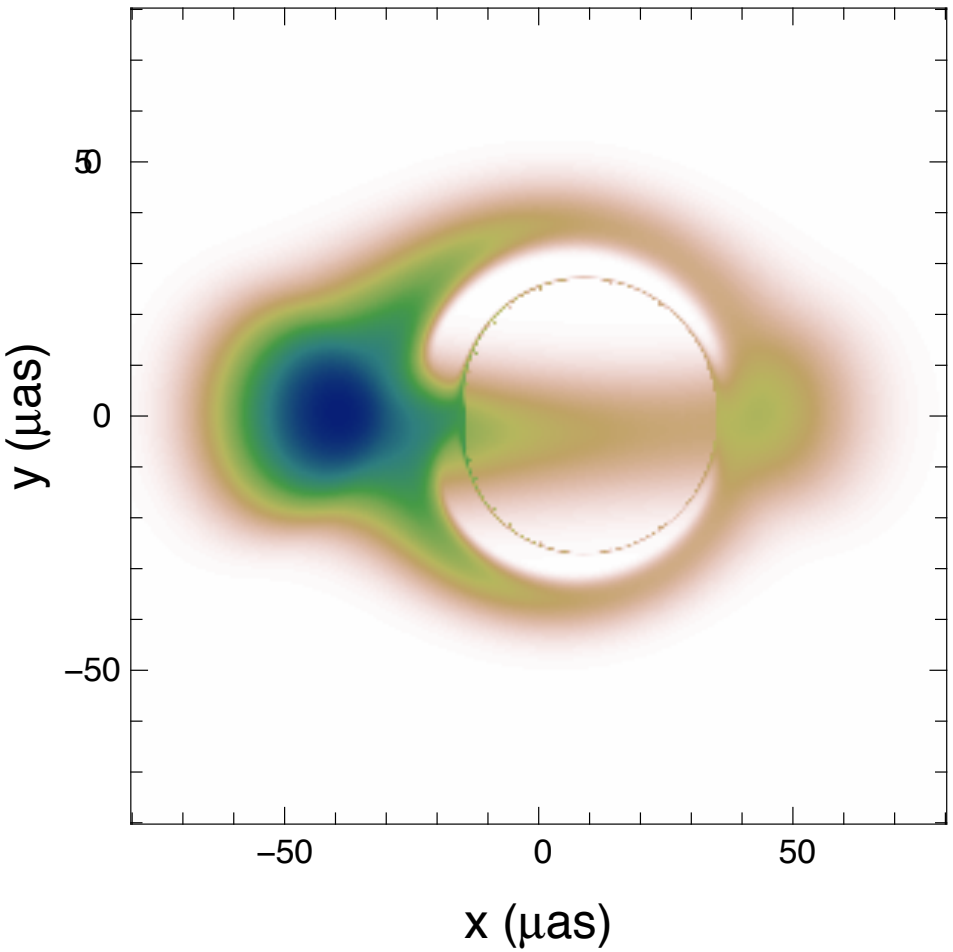
Black hole shadow



Black hole shadow in real life

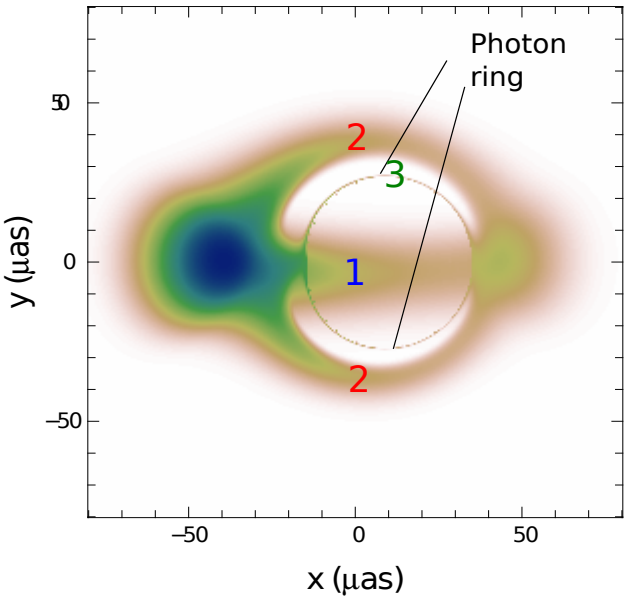


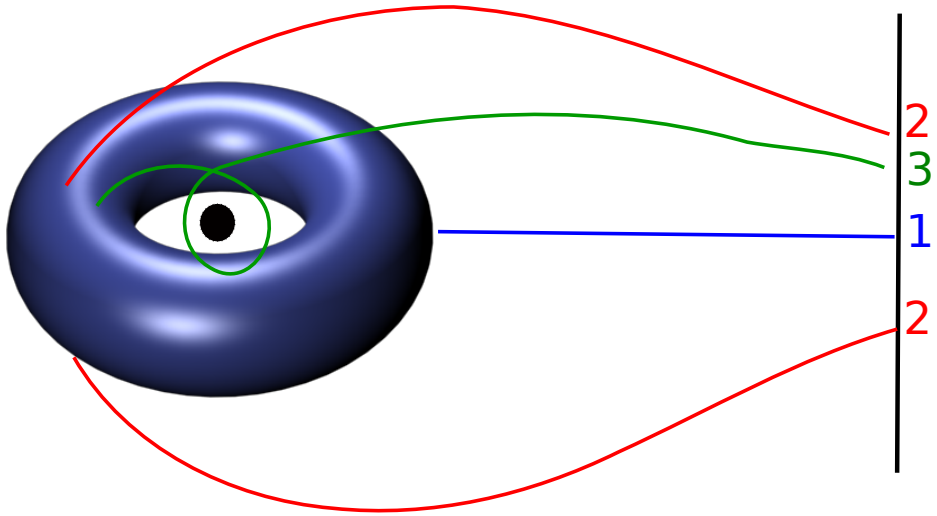
Black hole shadow in real life



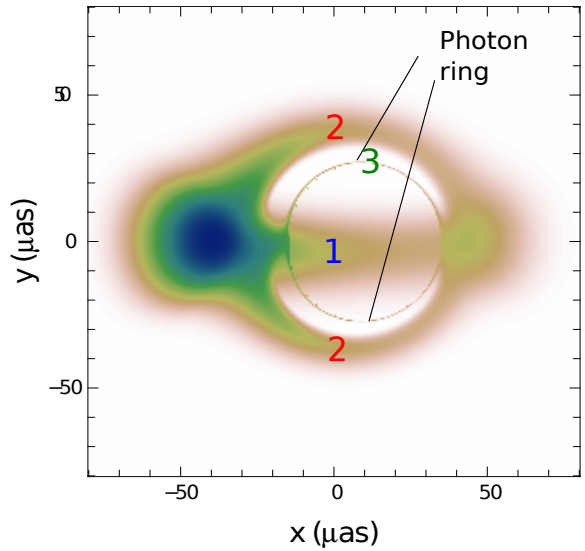
Understanding strong-field image

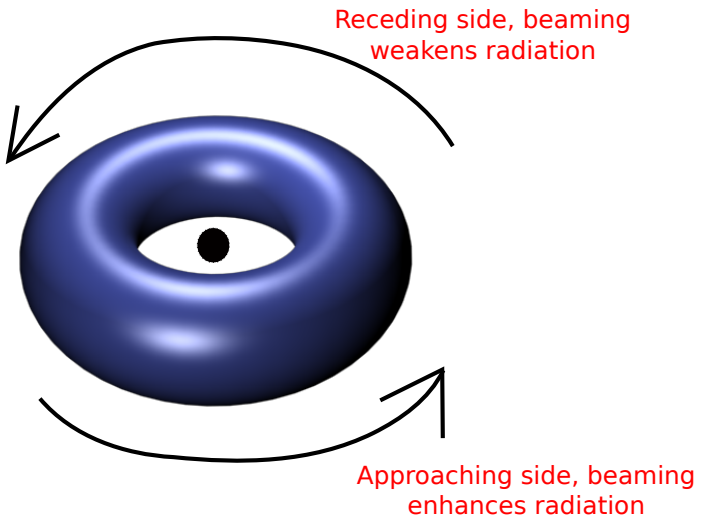
Edge-on view



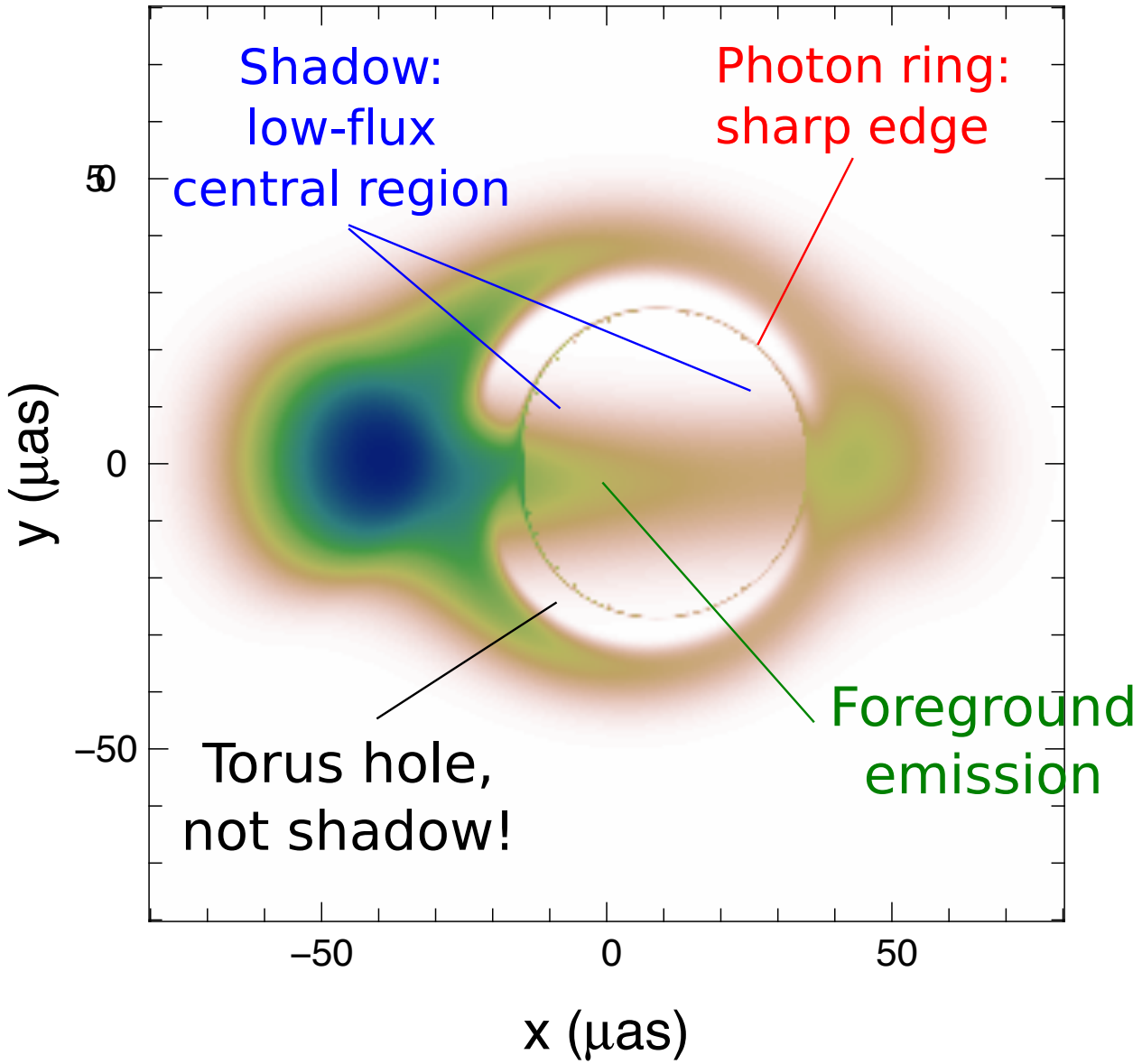


Understanding strong-field image

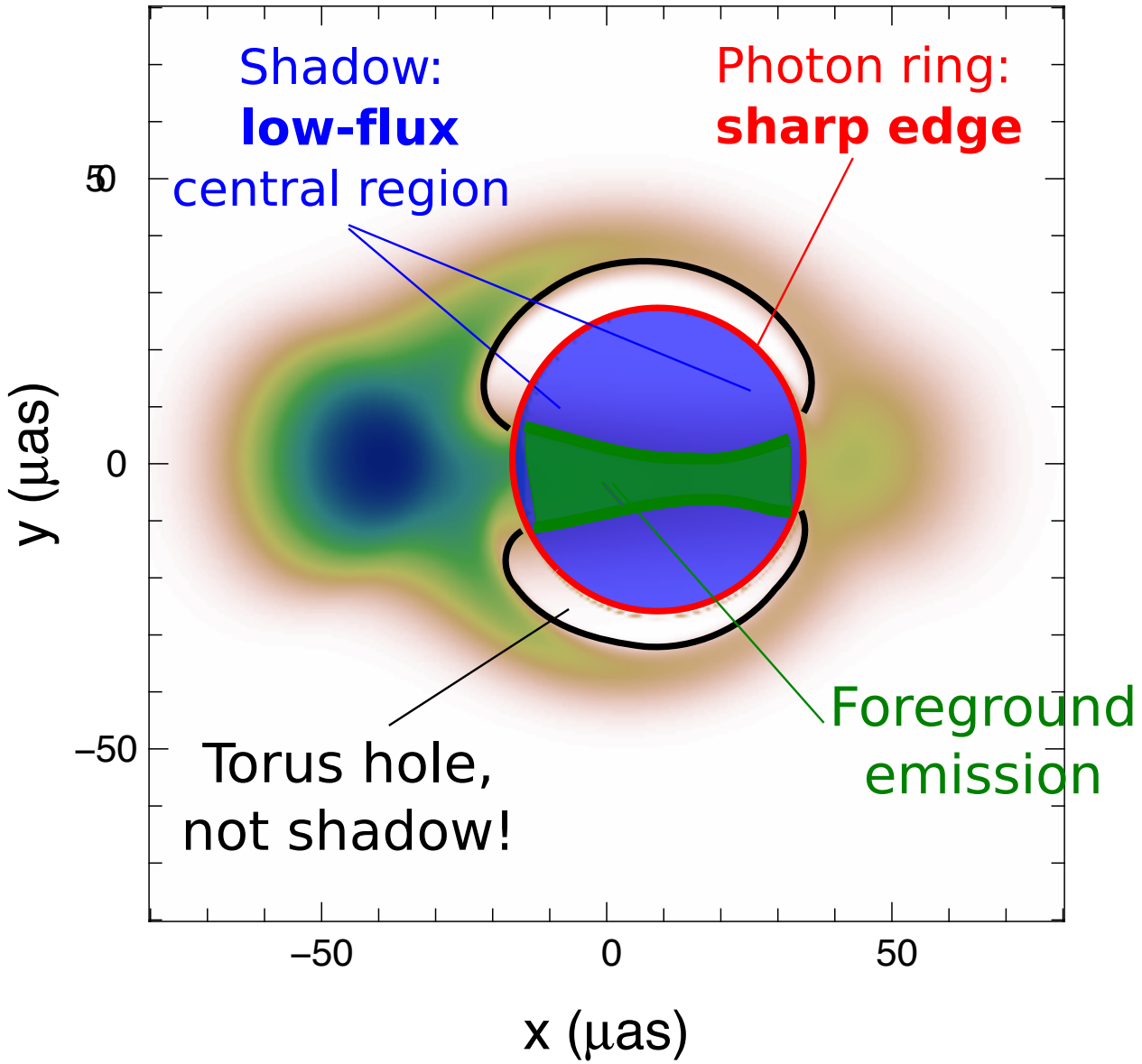




The shadow in a BH+torus spacetime



The shadow for an observer

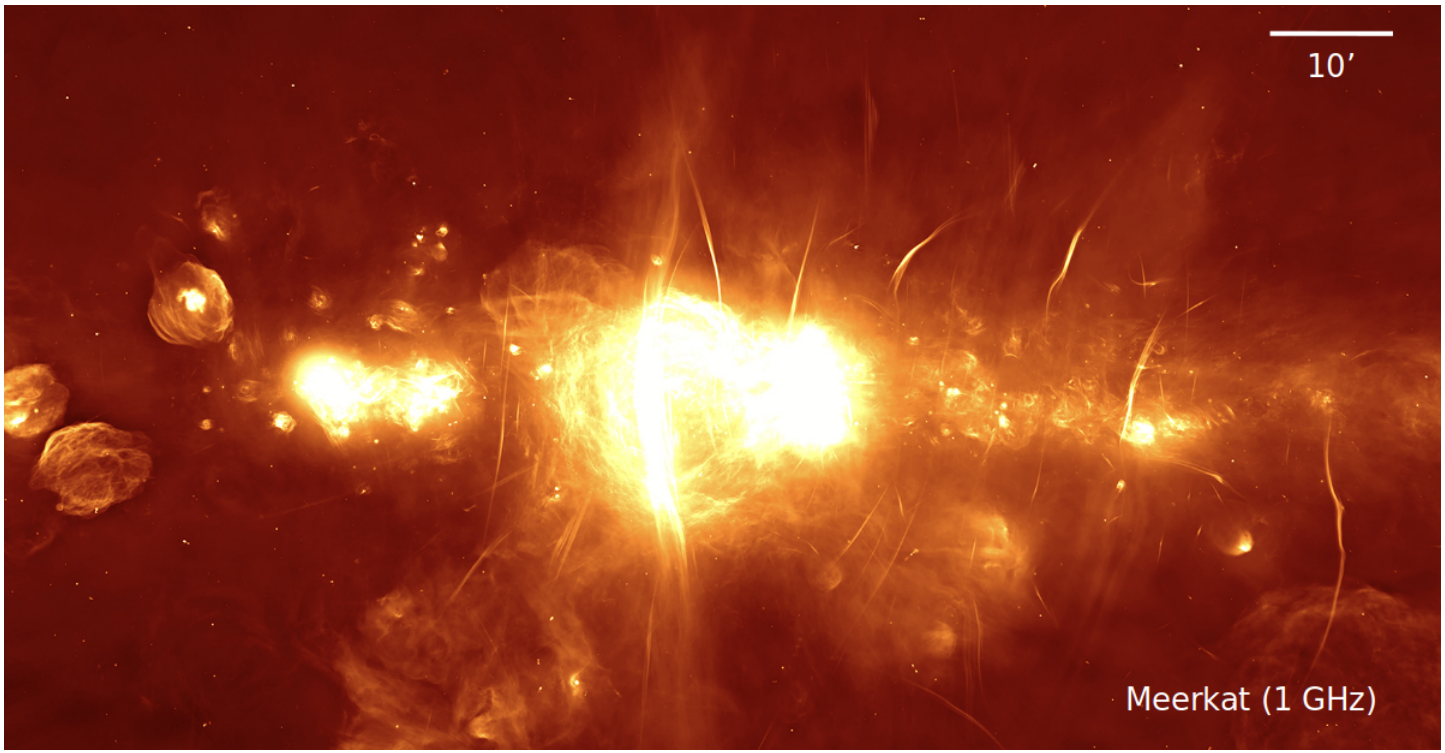


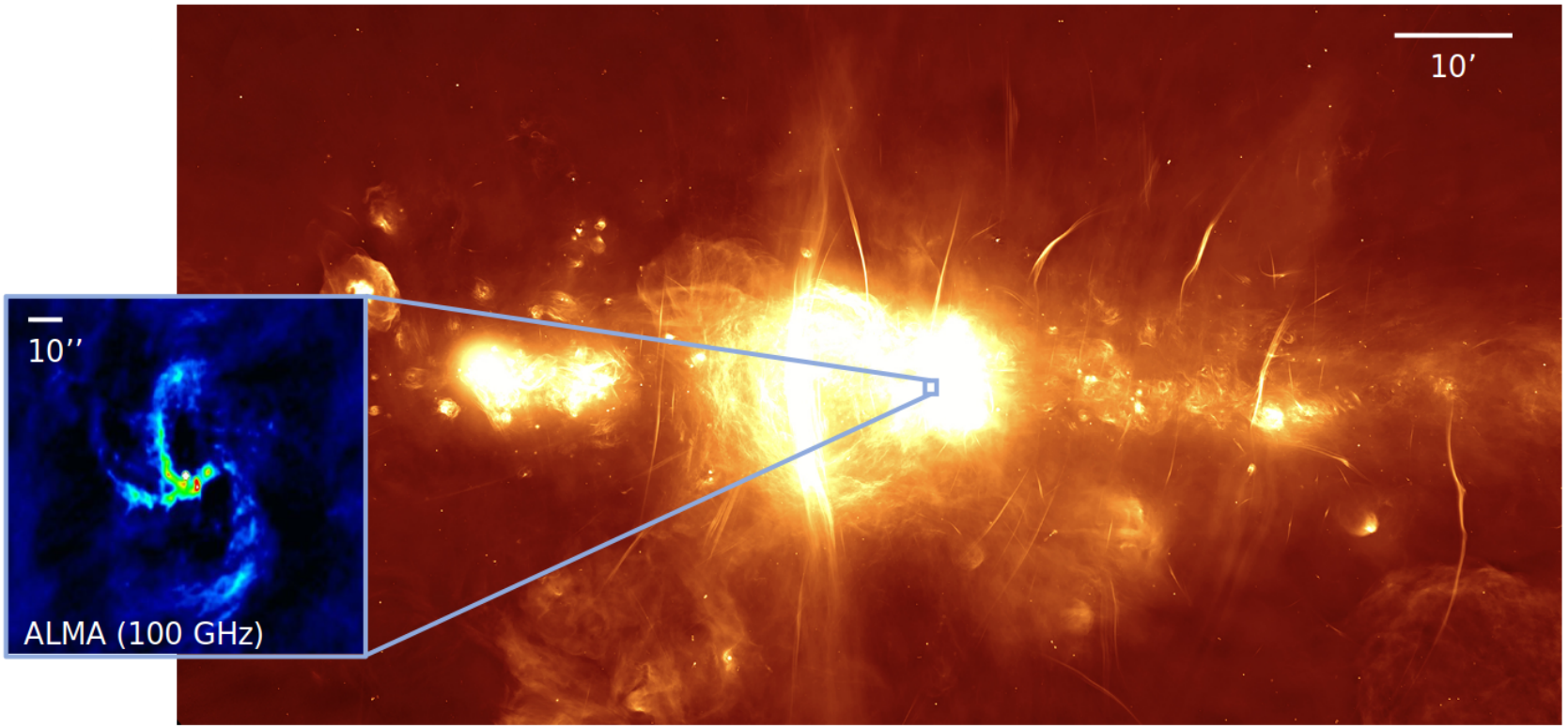
EHT final goal

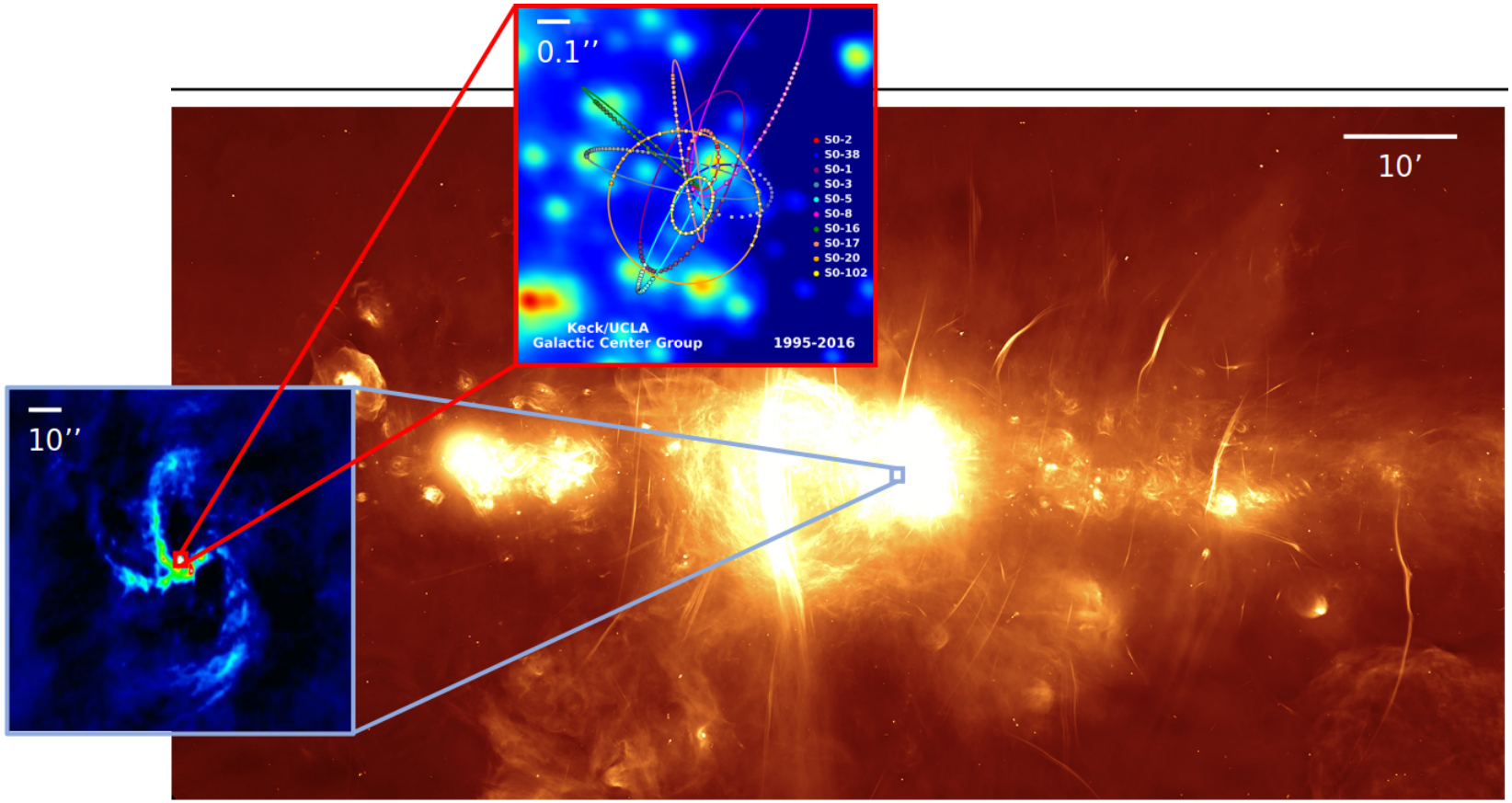
- Image the shadow+photon ring of Sgr A*/M87*
- Hallmark of an event horizon (Falcke+00)
- Conclude that Sgr A*/M87* is a standard (Kerr) BH

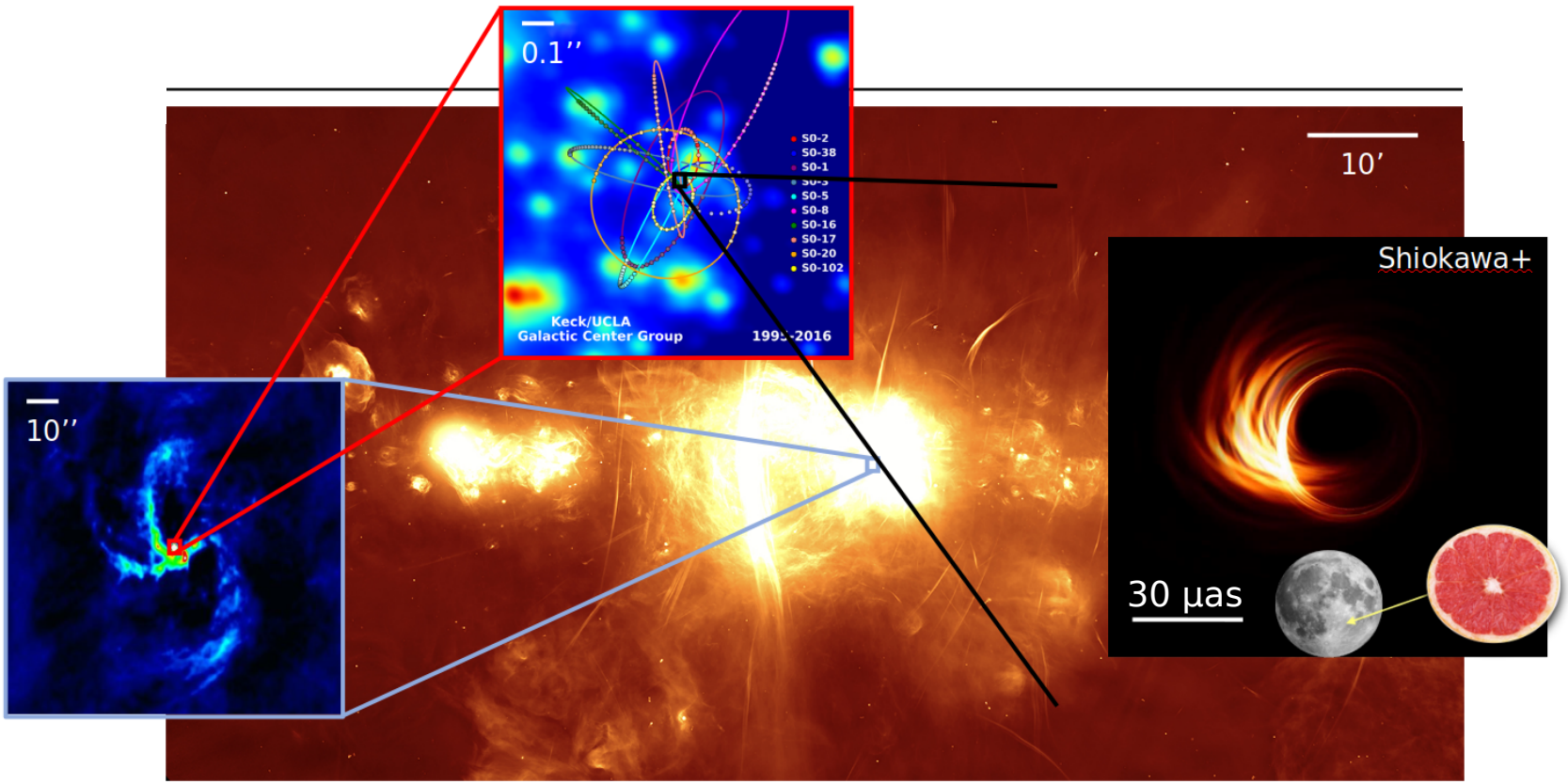
EHT intermediate goal

- Constrain accretion flow properties
- Constrain black hole parameters

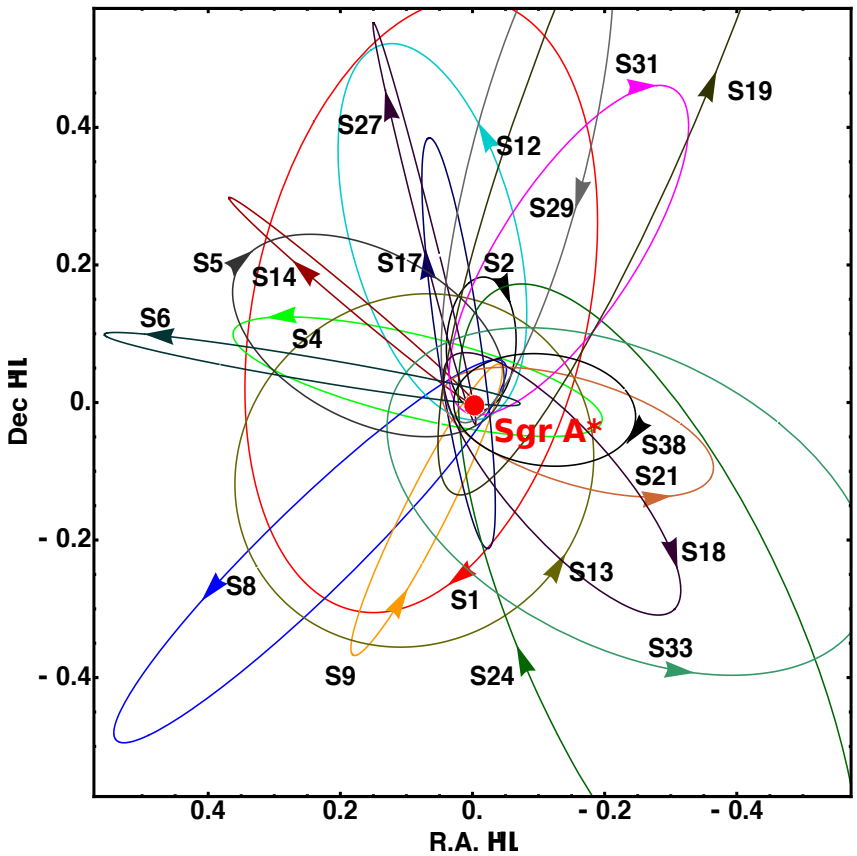

10′
Meerkat (1 GHz)


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'



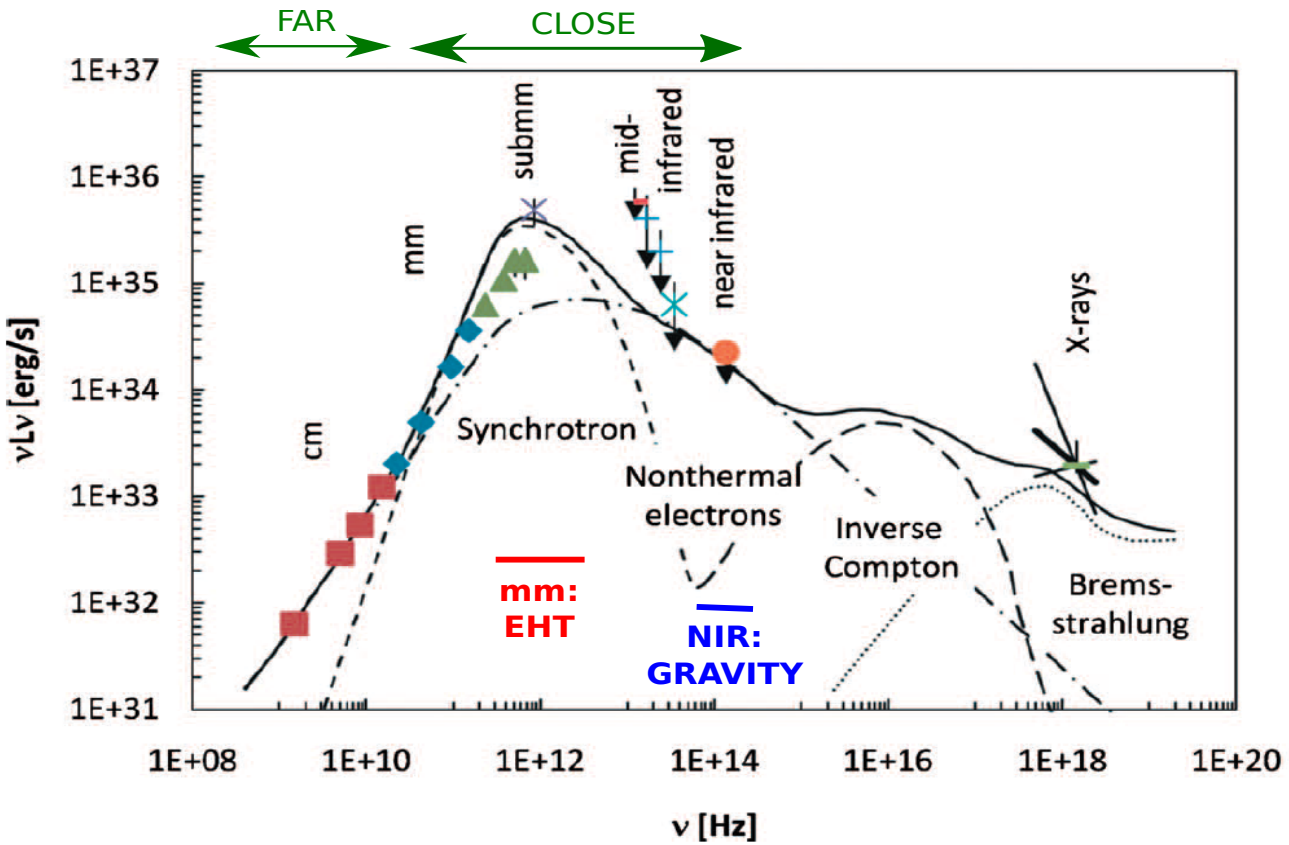
Credit: M. Wielgus



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

The central dark mass

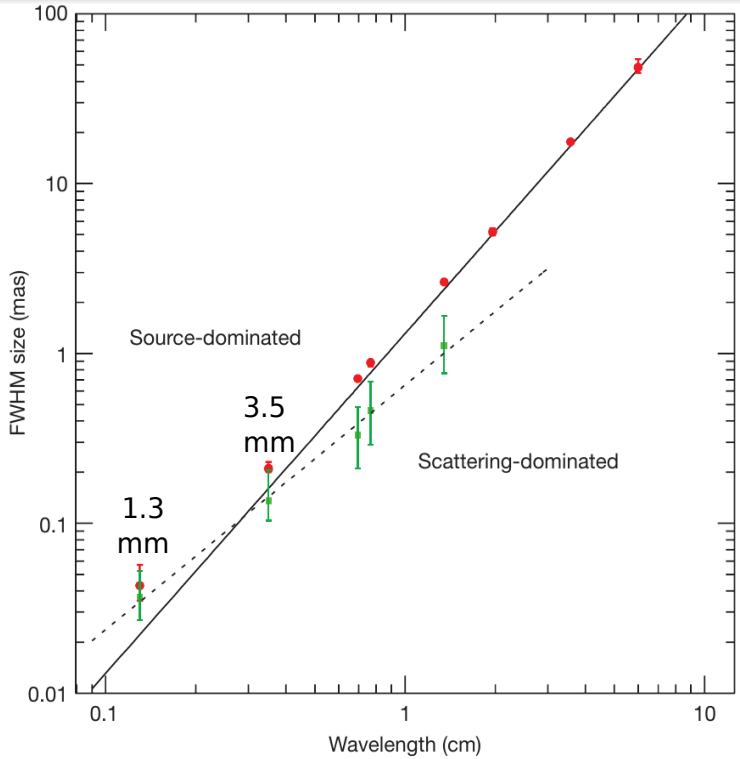
- Astrometric measurements of close stars → central mass.
- Sgr A* ≈ **SMBH of 4.1 10^6 $M_\odot$,** $\theta_{\mathrm{app,Sch}}$ ≈ **50 μas**



Genzel+10

Sgr A* spectrum

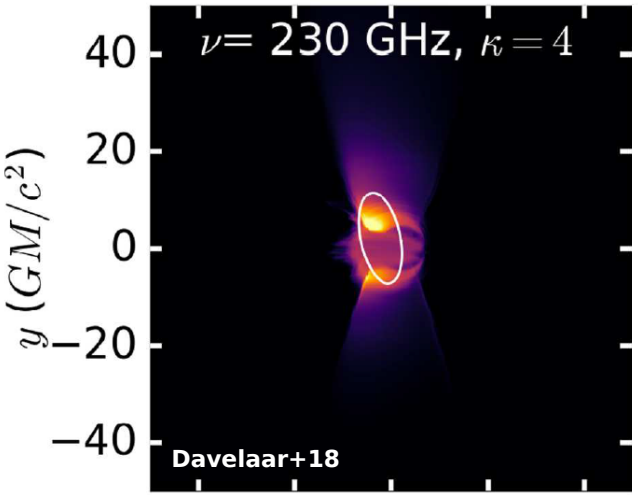
- Different $\nu \rightarrow$ different r
- **Optically thin synchrotron** emission at few 100 GHz
- **Innermost accretion flow**

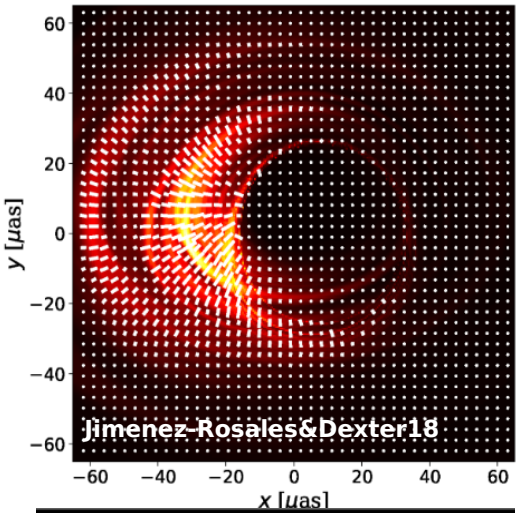


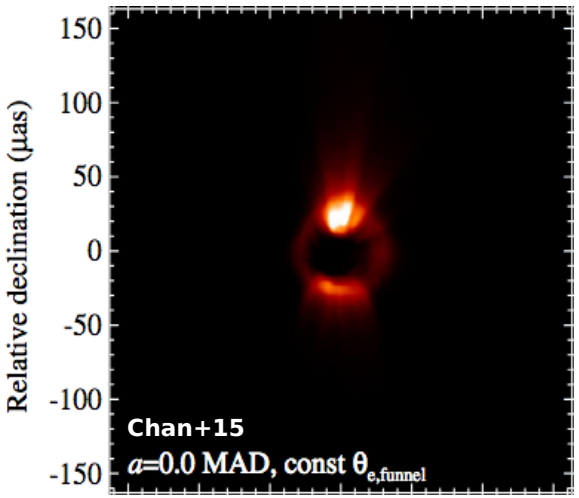
Doeleman+08

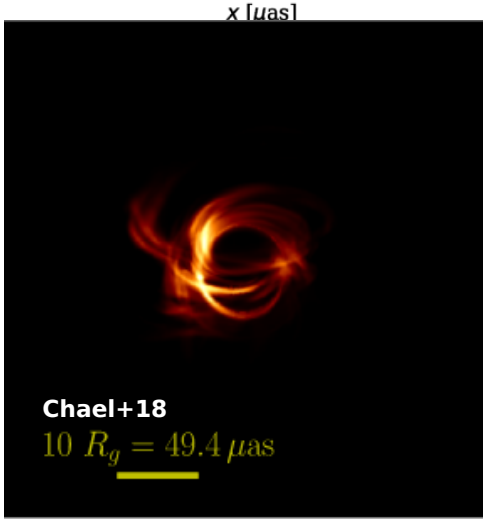
Scattering

- Index of refraction of plasma depends on density
- ISM density inhomogeneities $\rightarrow$ blurring of image
- 1.3 mm: scattering subdominant
- 3.5 mm: scattering starts to dominate

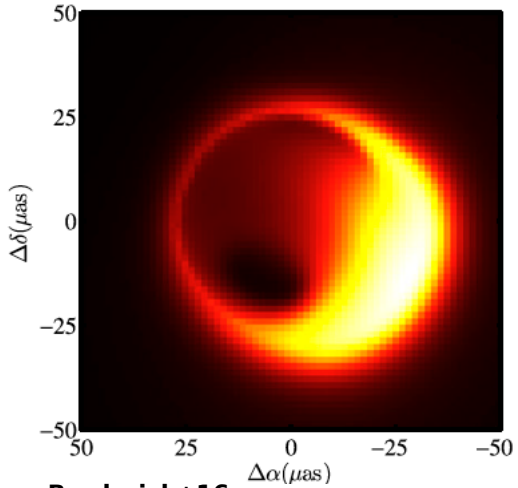


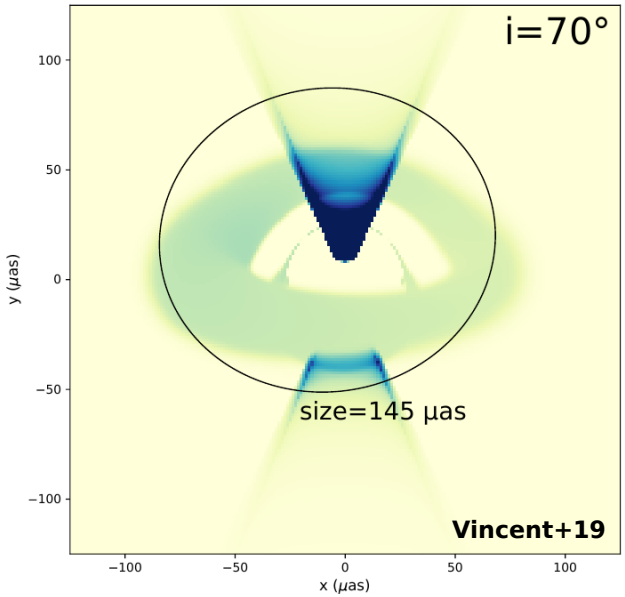


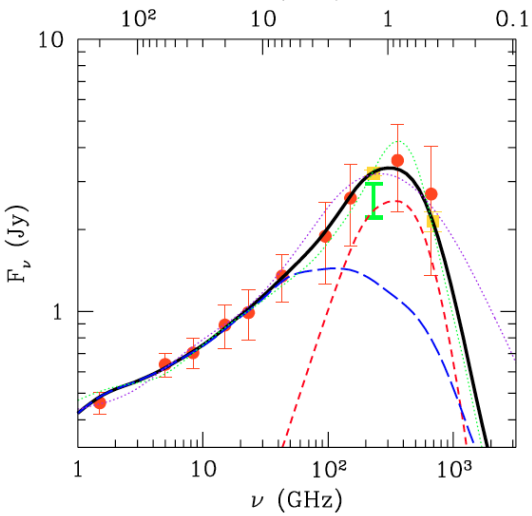


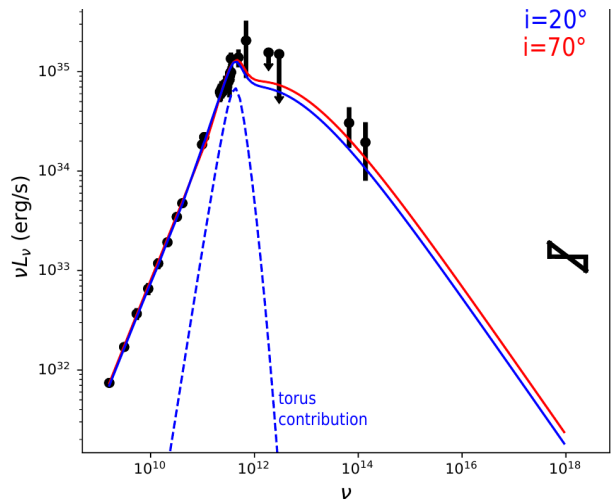


Models: GRMHD

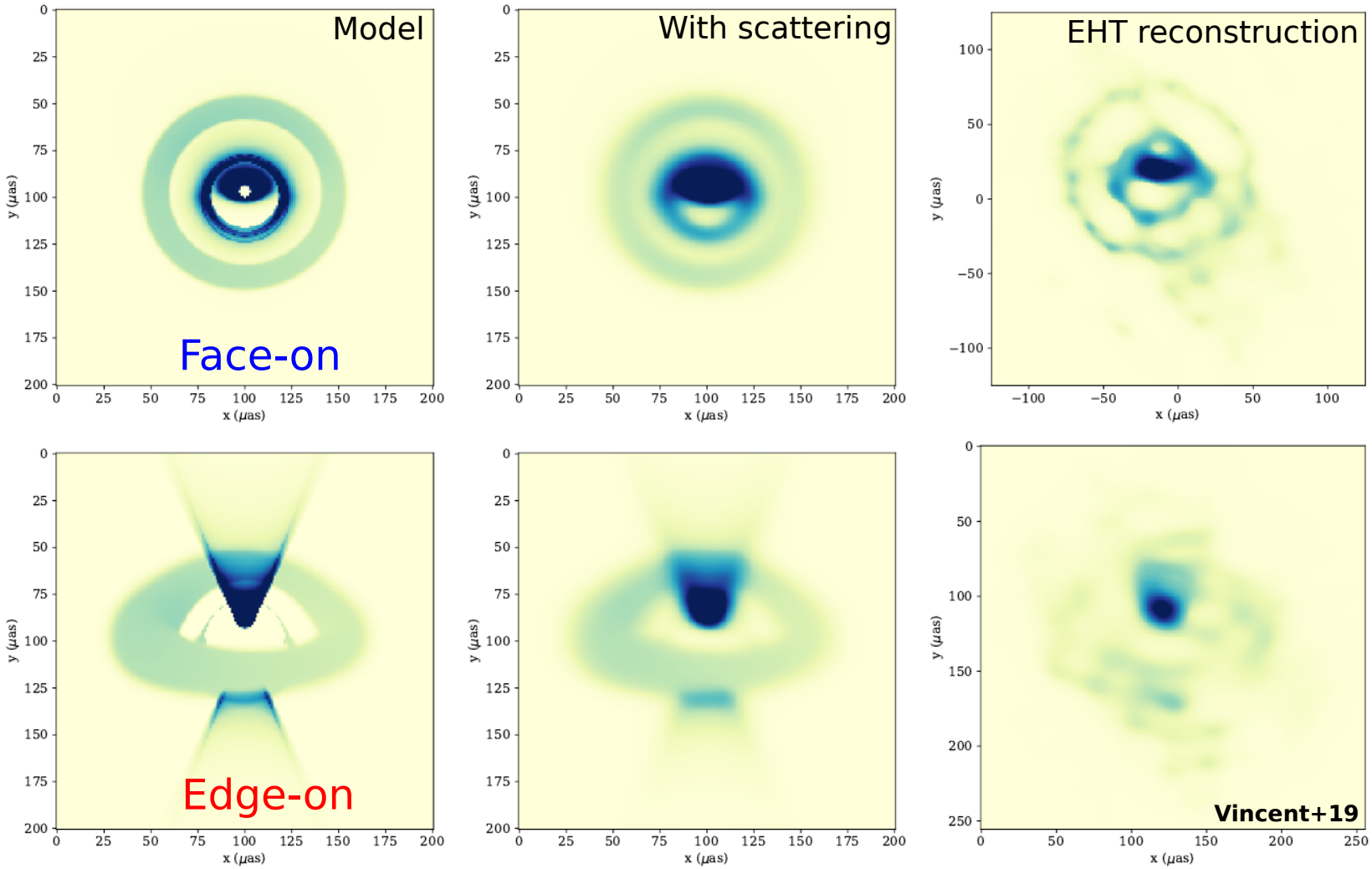


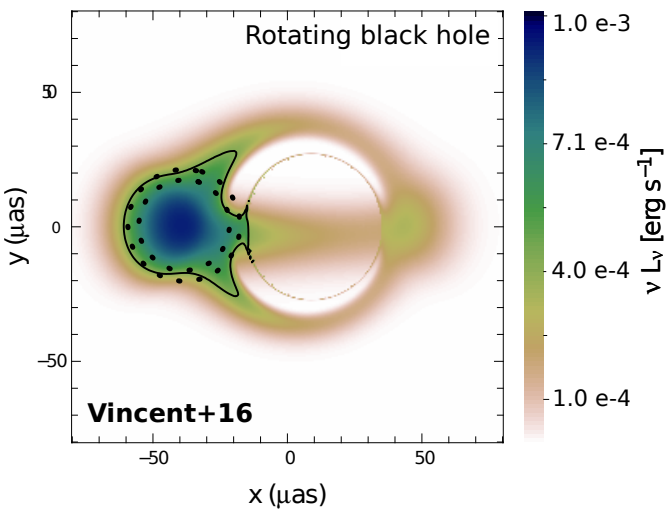


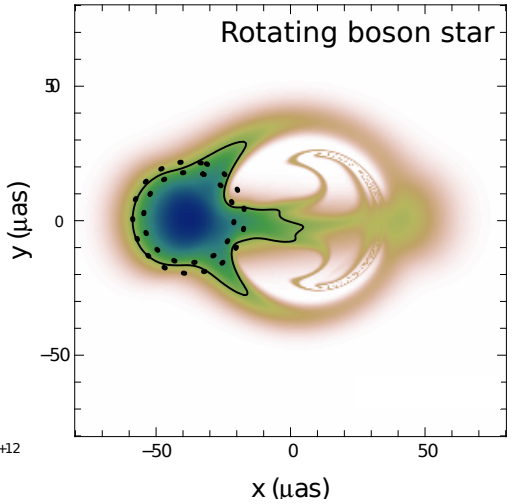


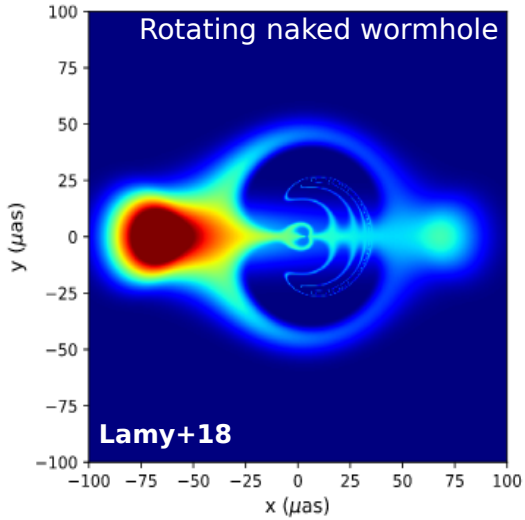


Models: analytic

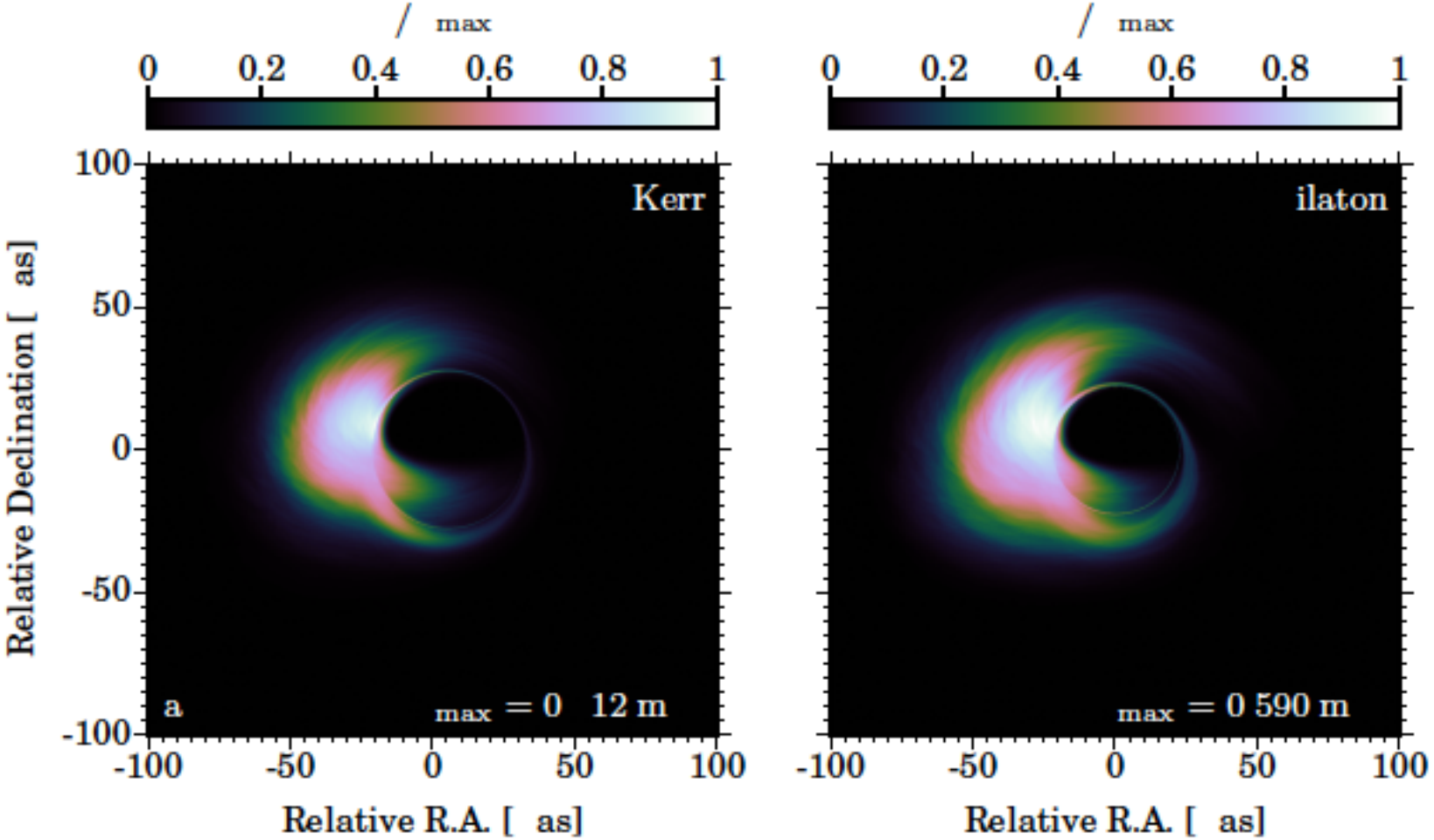

Model
With scattering
EHT reconstruction
Face-on
Edge-on
Vincent+19
x (μas)
y (μas)





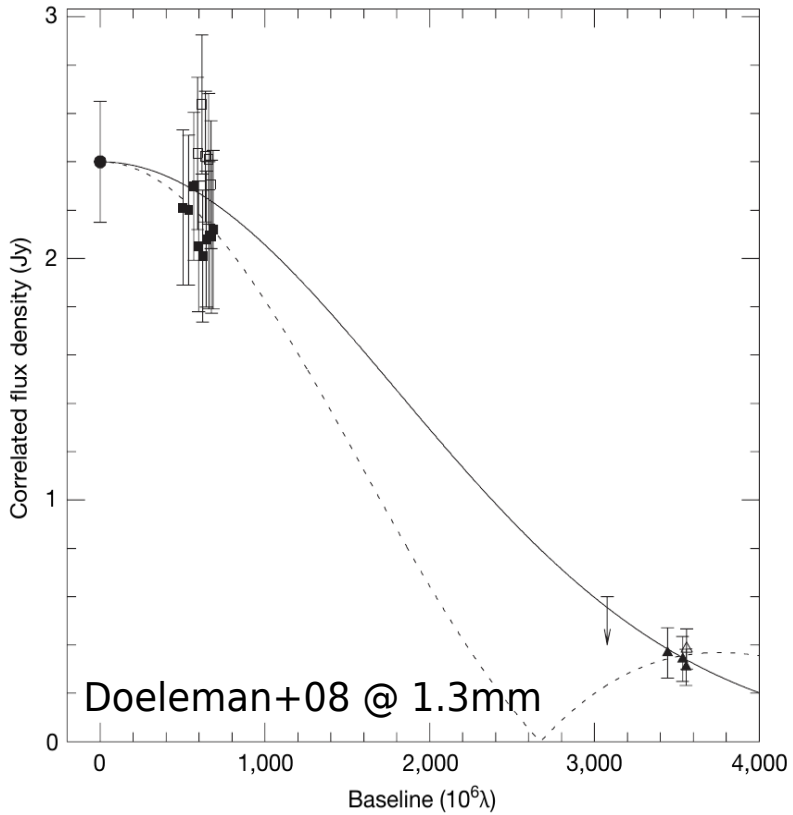


Testing the nature of Sgr A*?



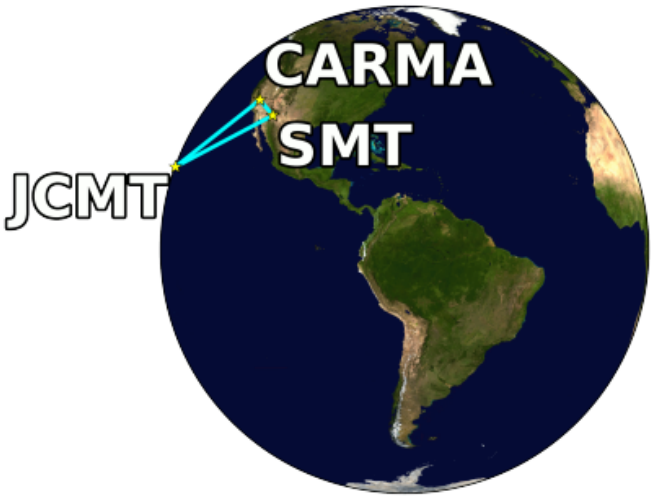
Mizuno+18

Testing gravity?

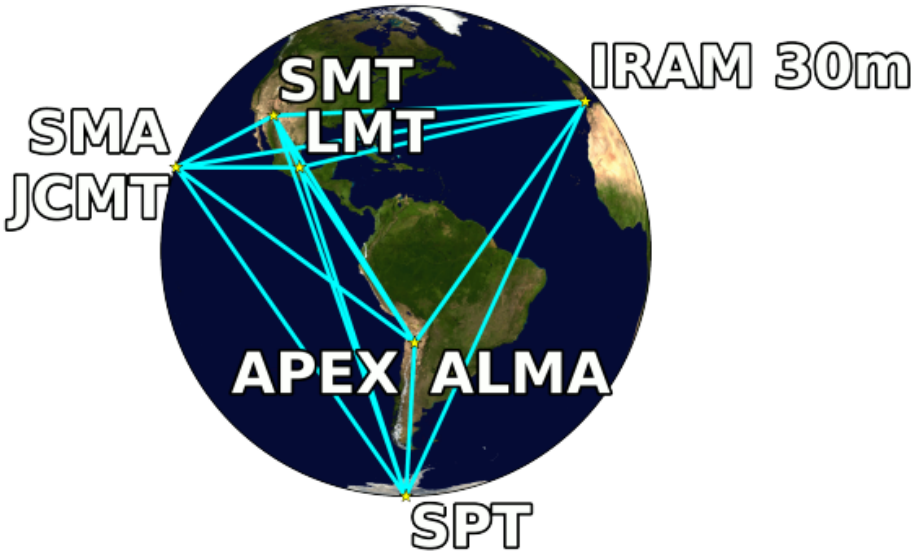


2007 early detection

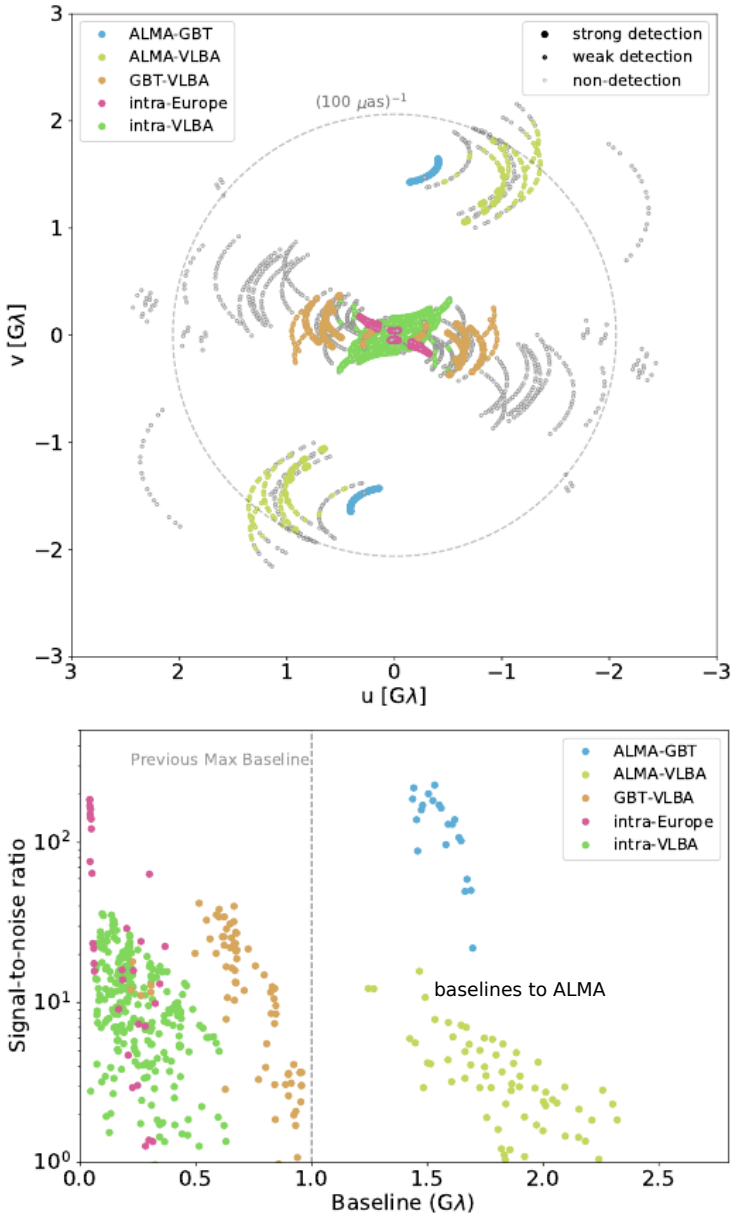
- 1.3 mm intrinsic size $37^{+16}_{-10}\,\mu$as
- Gaussian and ring models are good fit
- Need more baselines!



2007

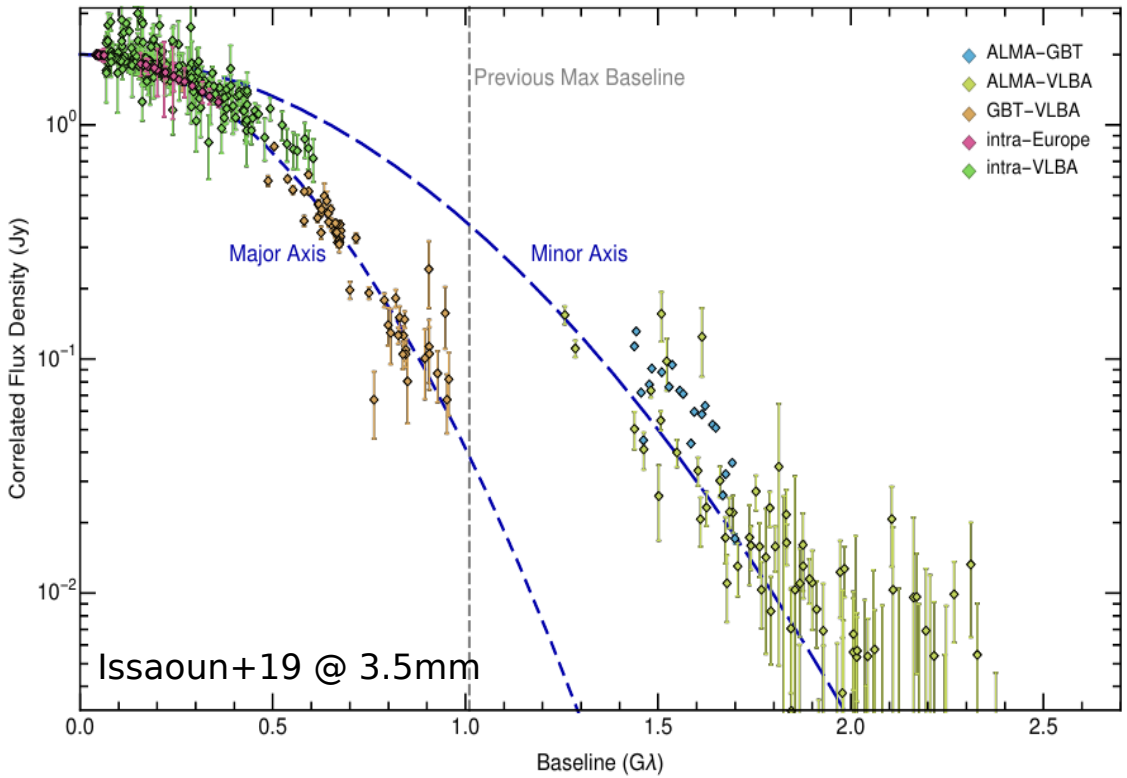


2017



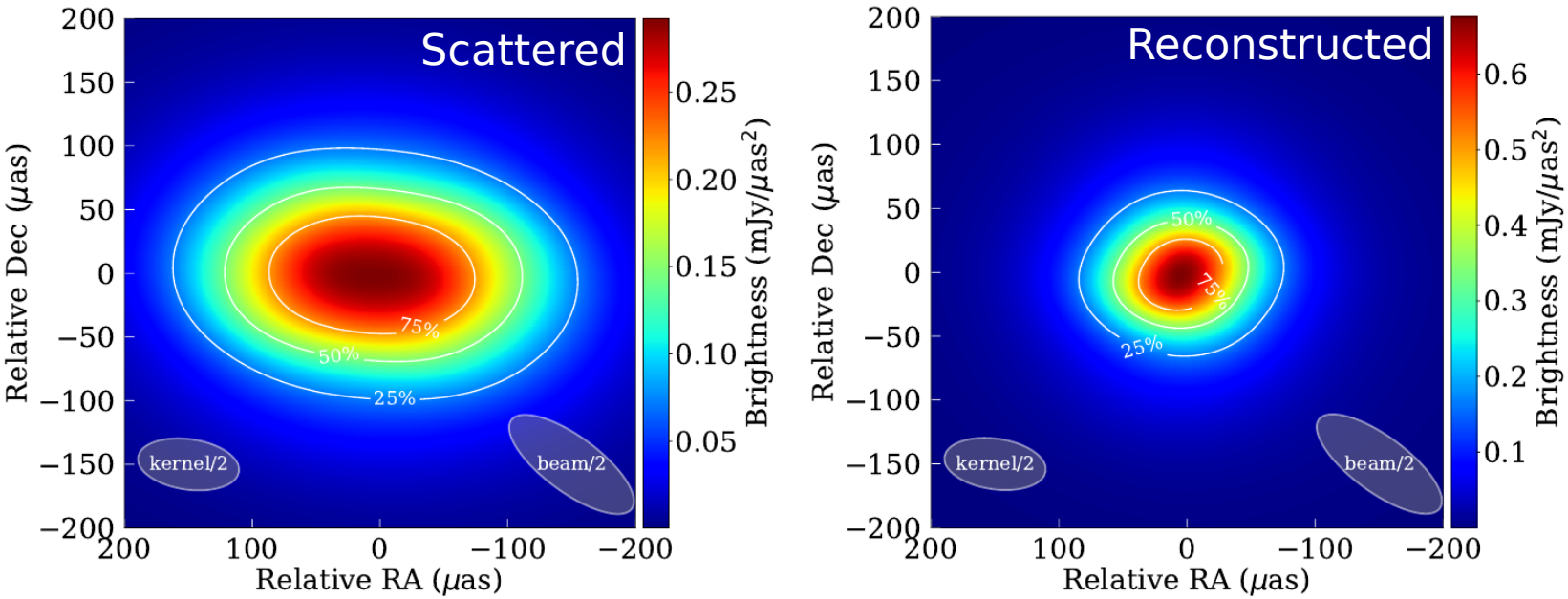
2017 latest data: Issaoun+19

- 3.5 mm data, 87 μas resolution
- Best λ to differentiate models (disk/jet...)
- {VLBA + Green Bank + Yebes + IRAM + Effelsberg } + ALMA
- Good detection on colored baselines
- Observing conditions not-so-good for VLBA and IRAM



Correlated flux

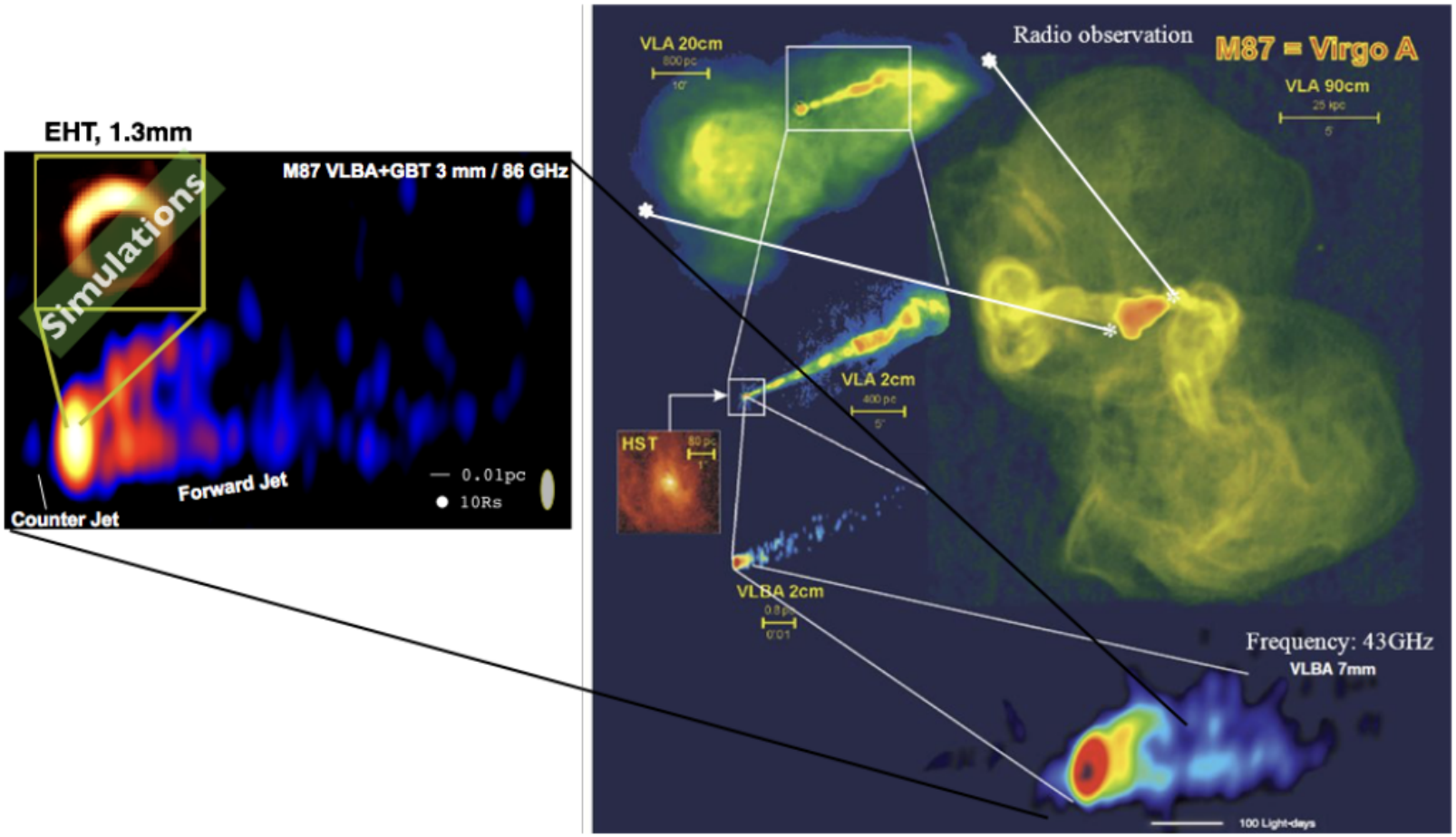
- Model = anisotropic Gaussian
- $215 \times 140\,\mu$as (from scattering model)
- Large-baseline (to ALMA) data inconsistent with Gaussian
- Could be intrinsic or scattering substructure...



Issaoun+19

Reconstructed image

- Scattering kernel from Johnson+18
- Intrinsic image very symmetric
- Consistent with face-on jet,
  or disk+jet whatever the orientation
- Face-on geometry favored by recent GRAVITY flare detection



Credit: M. Wielgus

More news coming soon on M87*...

- ... stay tuned!

What did/will we learn from the picture of a BH?

- EHT: horizon-scale black hole imager, on sky
- 2017 Sgr A* data:

  Data not consistent with pure Gaussian

  First weak constraint on source geometry & nature of accretion flow

  Fundamental physics tests still a long way
- 2017 M87* data:

  Coming soon...
- Very promising short-term future with EHT + GRAVITY!