Towards Imaging the Event Horizon

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European Research Council

BLACK HOLE CAM

IN·DEI·NOMINE·FELICITER

100 years of GR …

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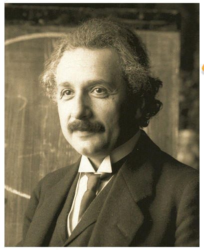
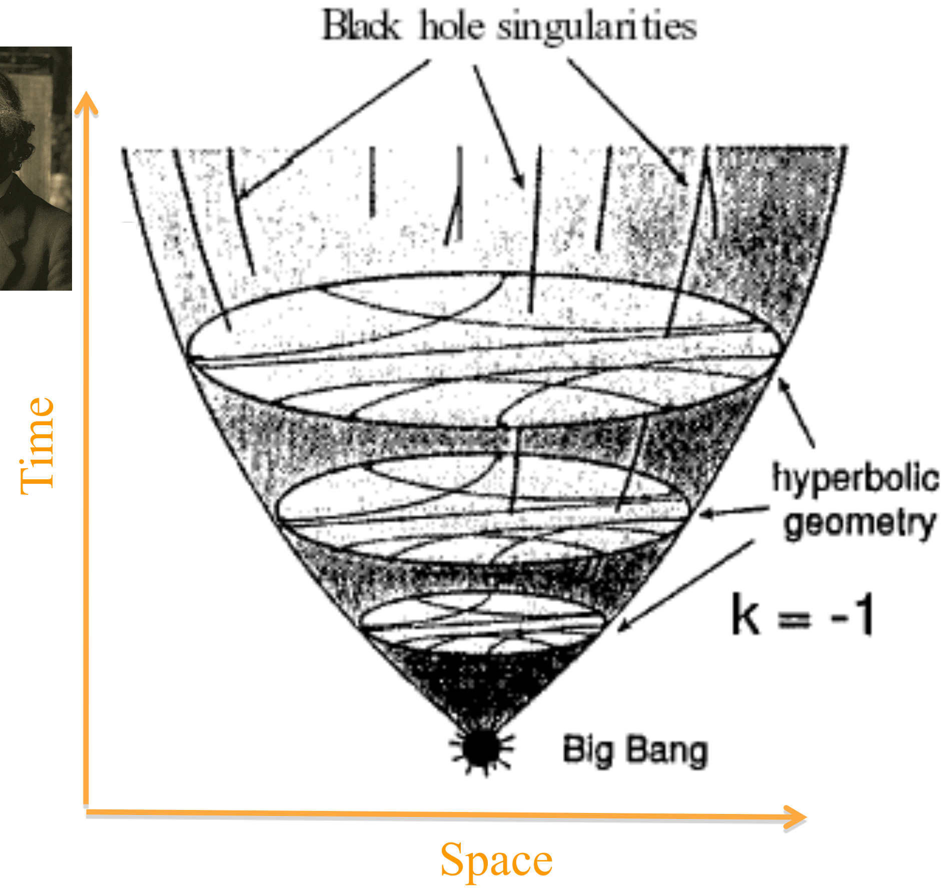
- **1915:** Einstein develops General Relativity



- **1916:** Schwarzschild metric, Basics for black holes
- Today the event horizon of black holes is point of intense debate: here quantum physics and GR collide.
- Black Holes are common place in astronomy – yet, we have never seen the event horizon!

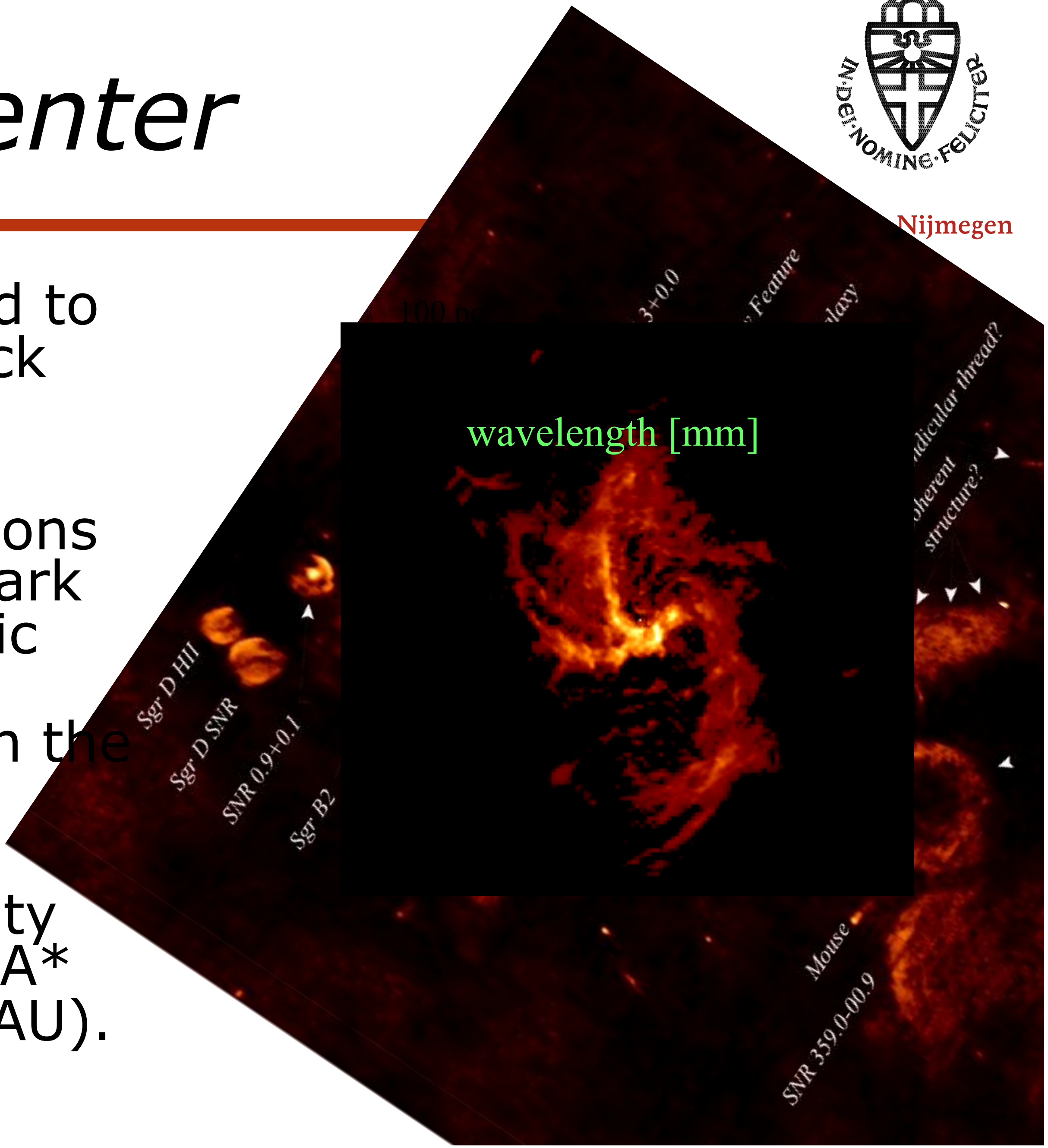


Penrose (1996)

Galactic Center

Nijmegen

- Sgr A* is suspected to be THE central black hole in the Milky Way.
- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 Rs (15 AU).



Sgr A radio proper motion: It's massive!*

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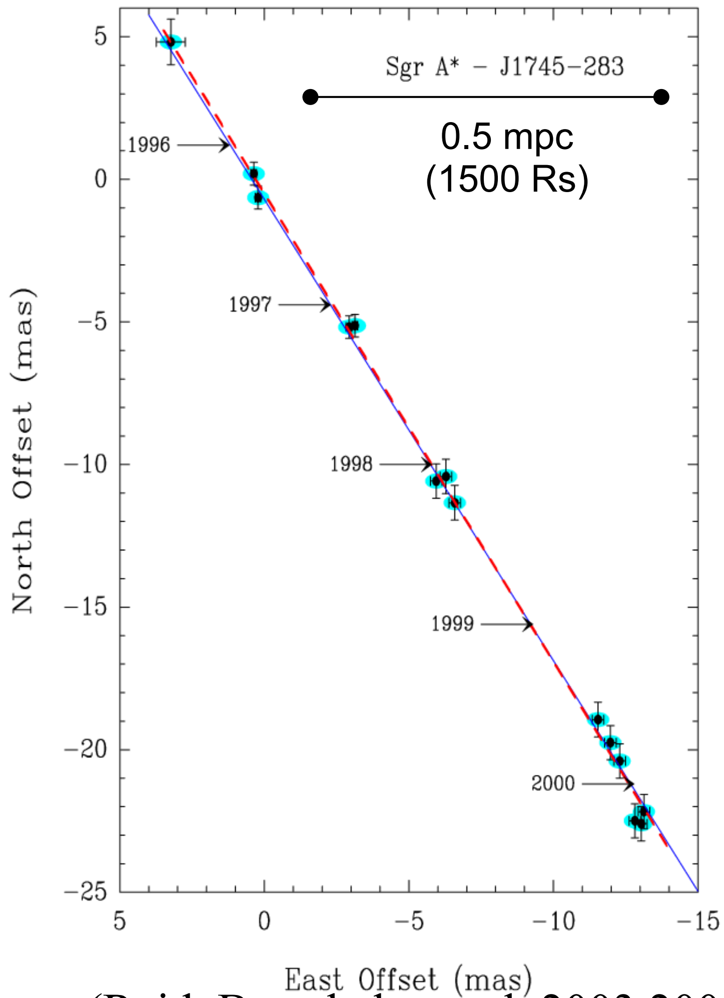
- High-resolution radio astrometry (VLBI): Sgr A* apparently moves along the Galactic Plane.
- Reflects motion of sun around Galactic Center!
- Unlike stars, Sgr A* does not move relative to the Galactic Center.
- $V_{Sgr A*} < 1$ km/s
- Mass limit: $M_\bullet > 4 \cdot 10^5 M_\odot$
- Most likely: all the mass is concentrated in the radio source – but, what is it?



(Reid, Brunthaler et al. 2003,2004)

*Structure of Sgr A**

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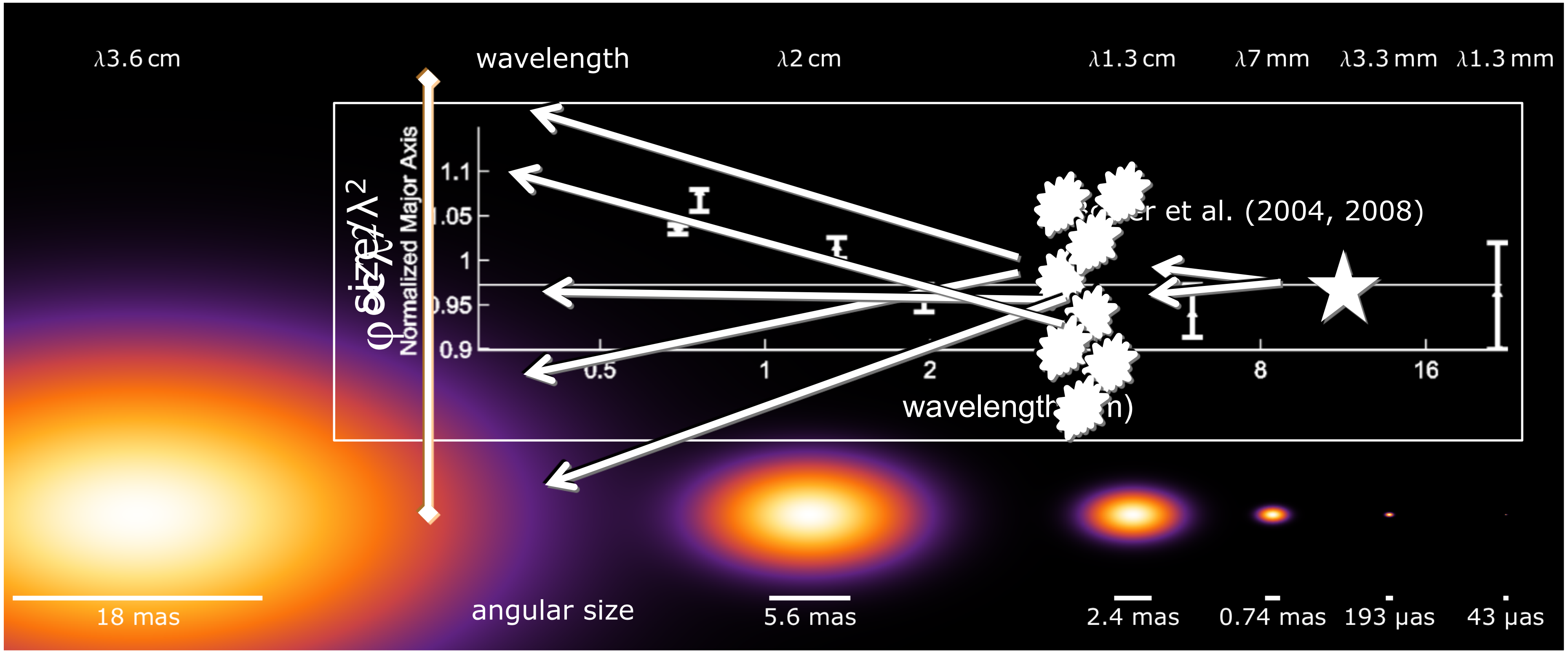

- The shorter the wavelength, the smaller the radio source.
- At low frequencies the structure is blurred by scattering with λ^2-law.
- At λ7 mm the radio source becomes slightly larger than the scattering.
- Intrinsic size at λ7 mm seems elliptical as well (~3:1 ratio, Bower+ 2014)

Two-dimensional structure of Sgr A: fairly elongated*

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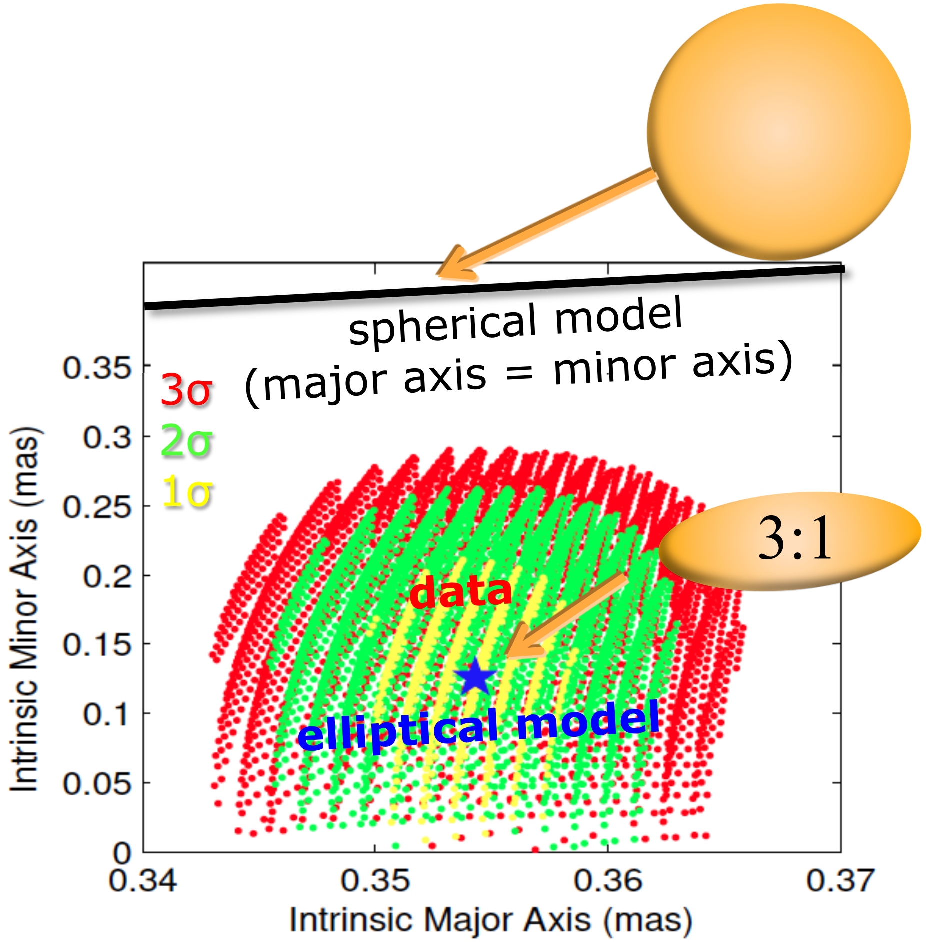
- Accurate closure amplitude measurements of 2D-size of Sgr A* with the VLBA.
- Size at 43 GHz: (35.4 ±0.4) Rs × (12.6±5.5) Rs at PA (95±4)°



Bower et al. (2014, ApJ)

First Galactic Center Pulsar

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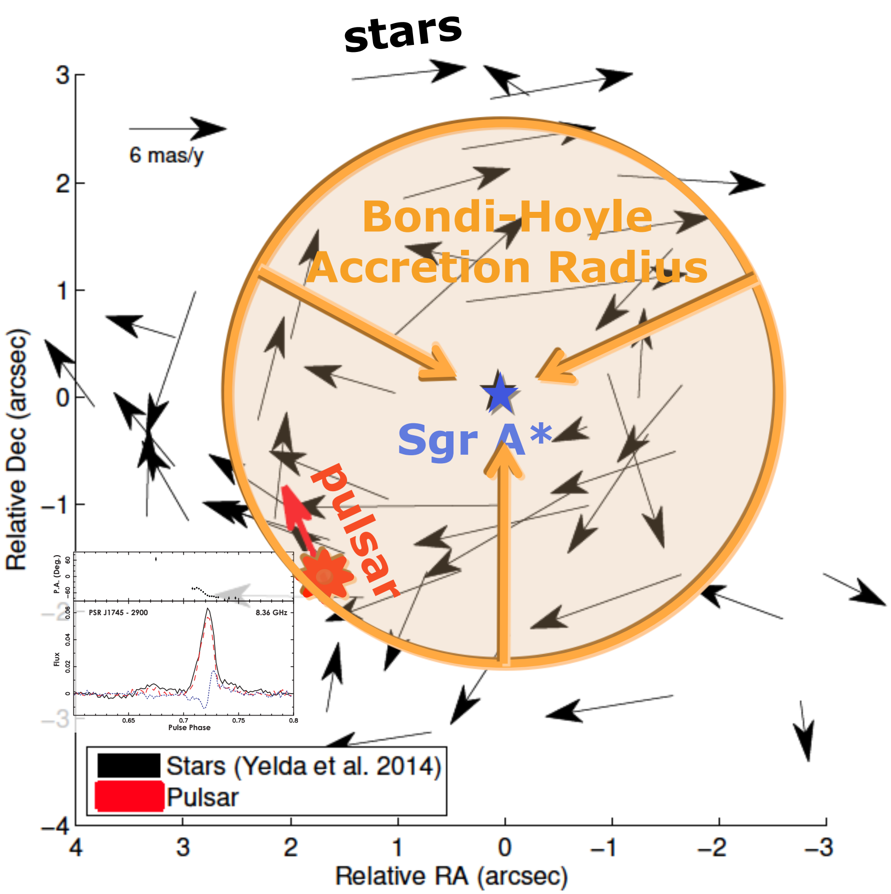


- X-ray transient (NuStar/Swift)
- ~2″ from Sgr A*= Bondi Radius!
- Period: P = 3.76354676(2) s
- period derivative (spindown)
  P/Pdot = 6.82(3)×10^{-12} (B~10^{14} G)
- Spin-down age ~ 9000 yrs
- Dispersion DM=1778+/-3 cm^{-3} pc
- spectrum ~flat, up to 200 GHz!
- Only 4th known radio magnetar
- Almost 100% linear polarization
- Rotation Measure:
  RM=-66,960 +/- 50 rad m^{-2}
  - Second only to Sgr A*
  - Effect local to Galactic Center!

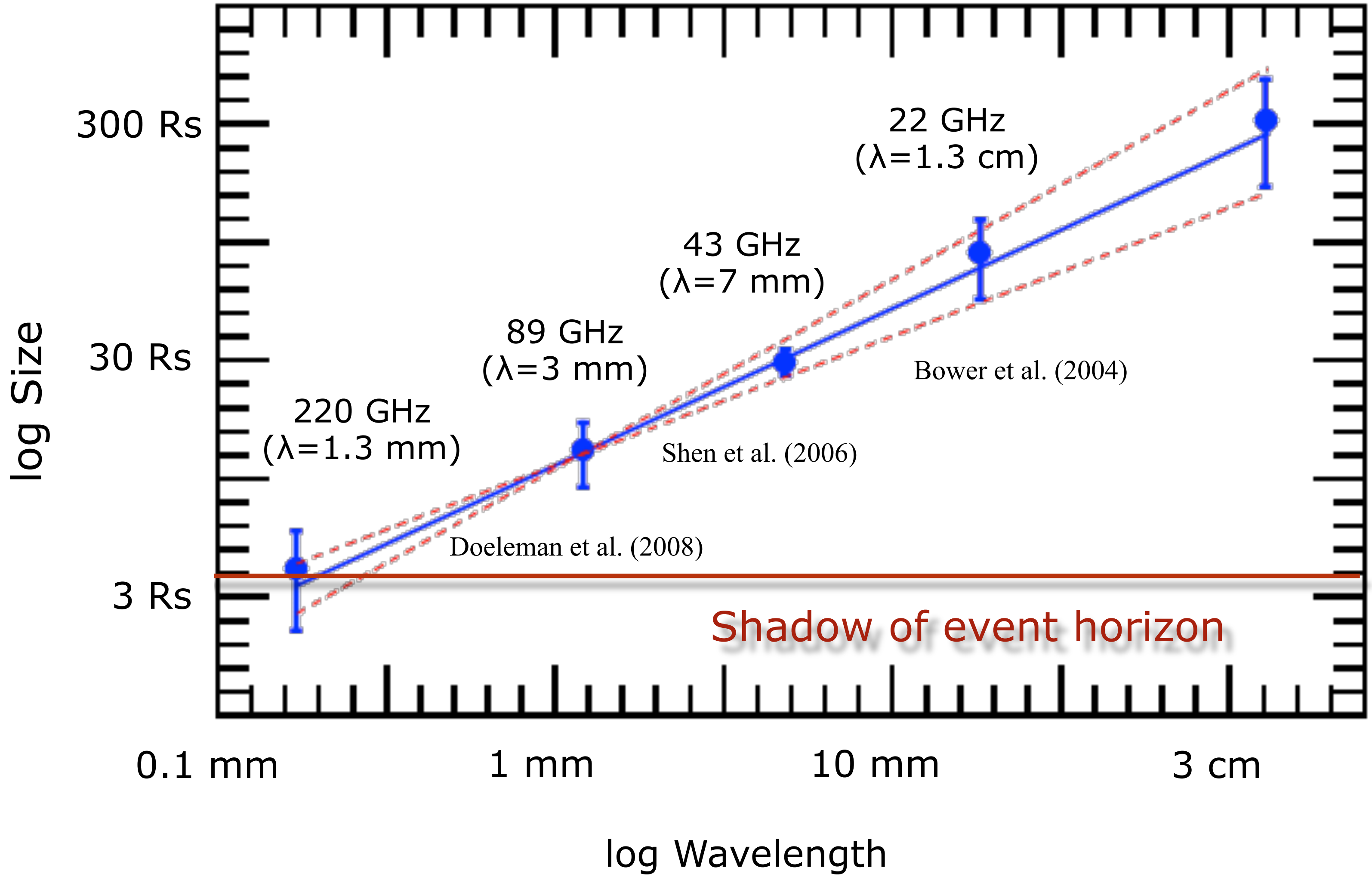
Radio proper motions:
Bower, Deller, Brunthaler, HF… (2015, ApJ)

Radio detection:
Eatough, Falcke et al. (2013, Nature)

Intrinsic radio size of Sgr A*

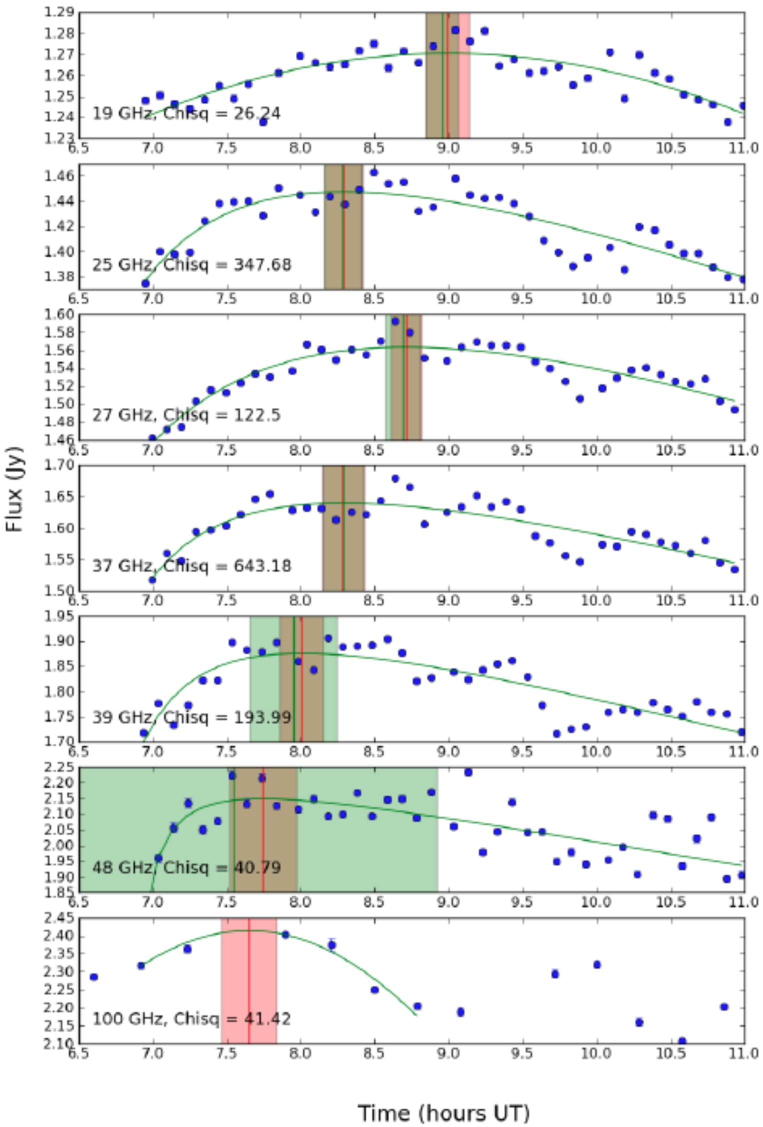
BlackHoleCam

The higher the radio frequency – the closer to the black hole.
At 230 GHz the emission comes from the event horizon scale.

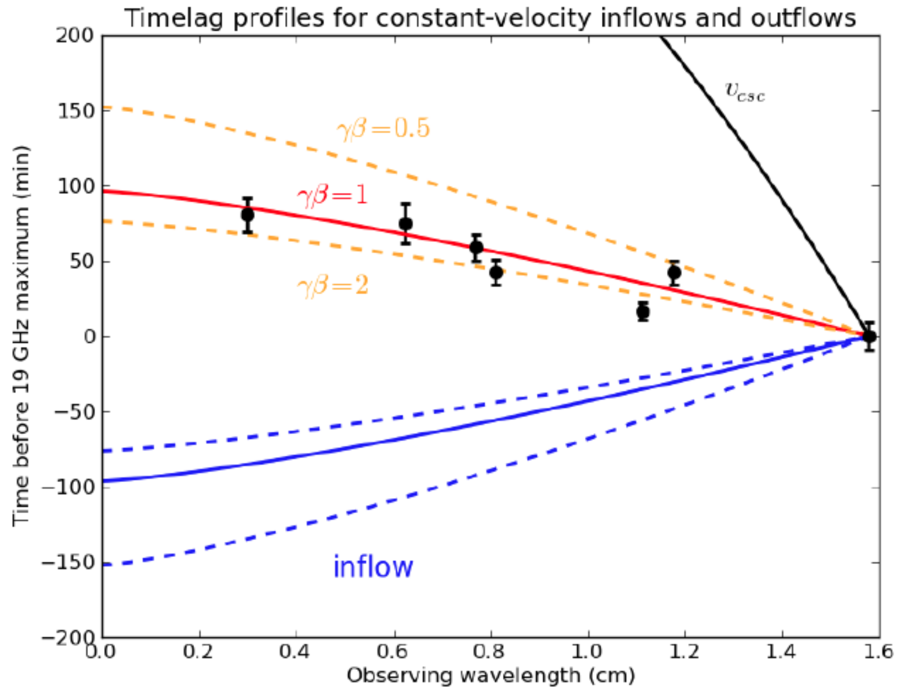


Falcke & Markoff, Class. & Quant. Gravity (2013)

ALMA+VLA Radio Lags



Higher frequencies, lead lower frequencies
⇒ **relativistic outflow**



Brinkerink et al. (2014, A&A, in press)

The Shadow of a Black Hole

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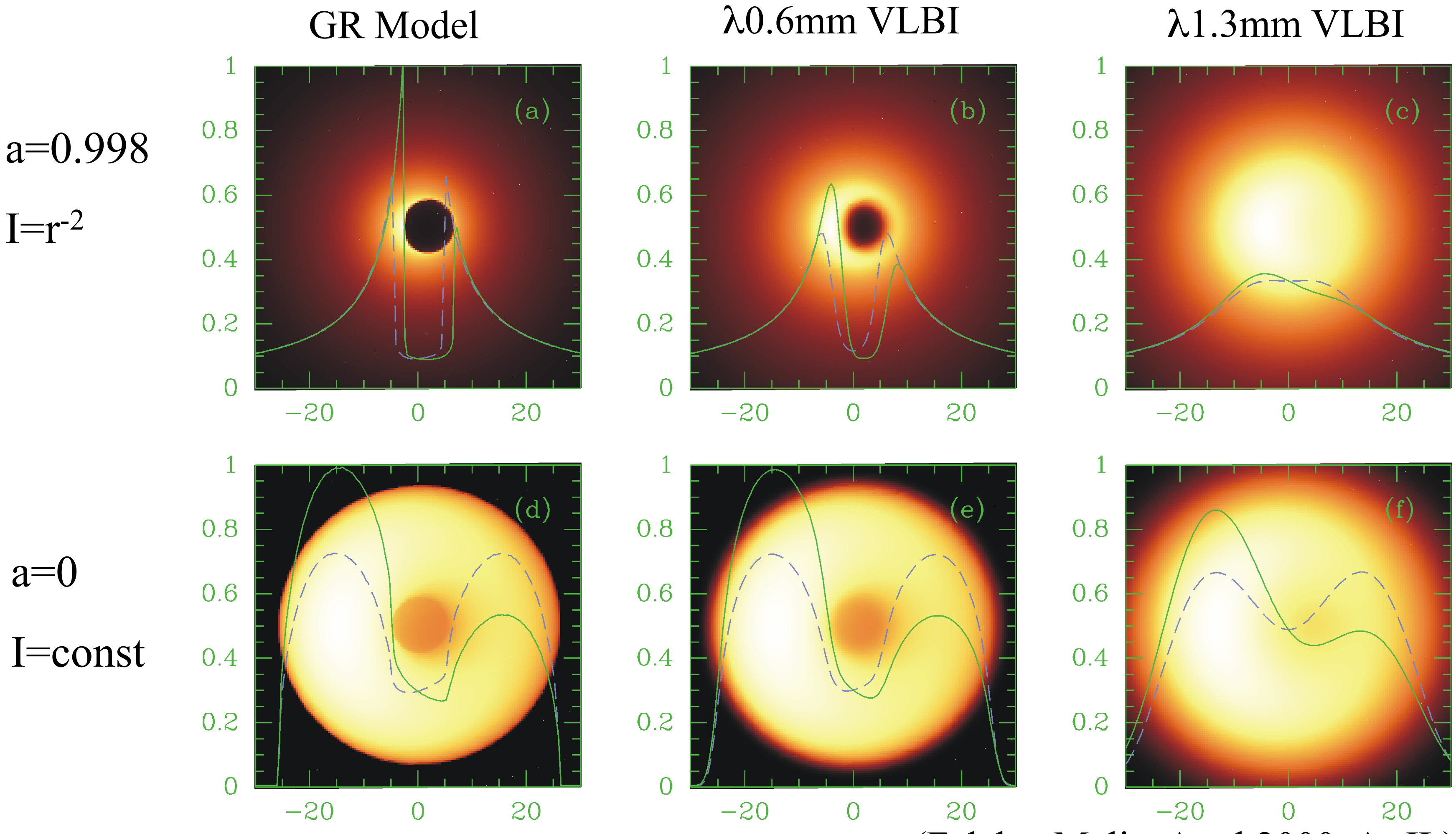

(Falcke, Melia, Agol 2000, ApJL)

Shadow industry: different spacetimes

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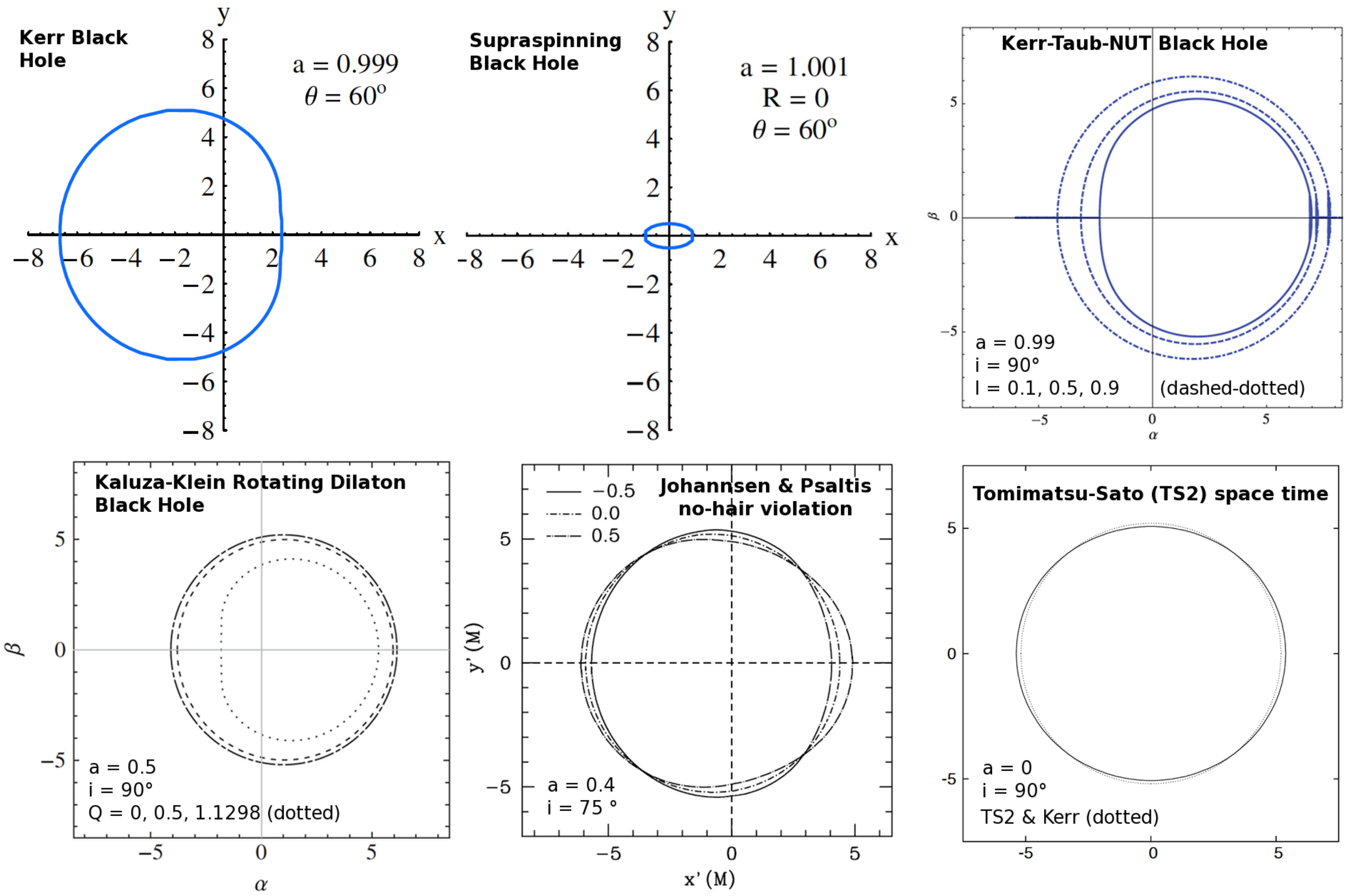
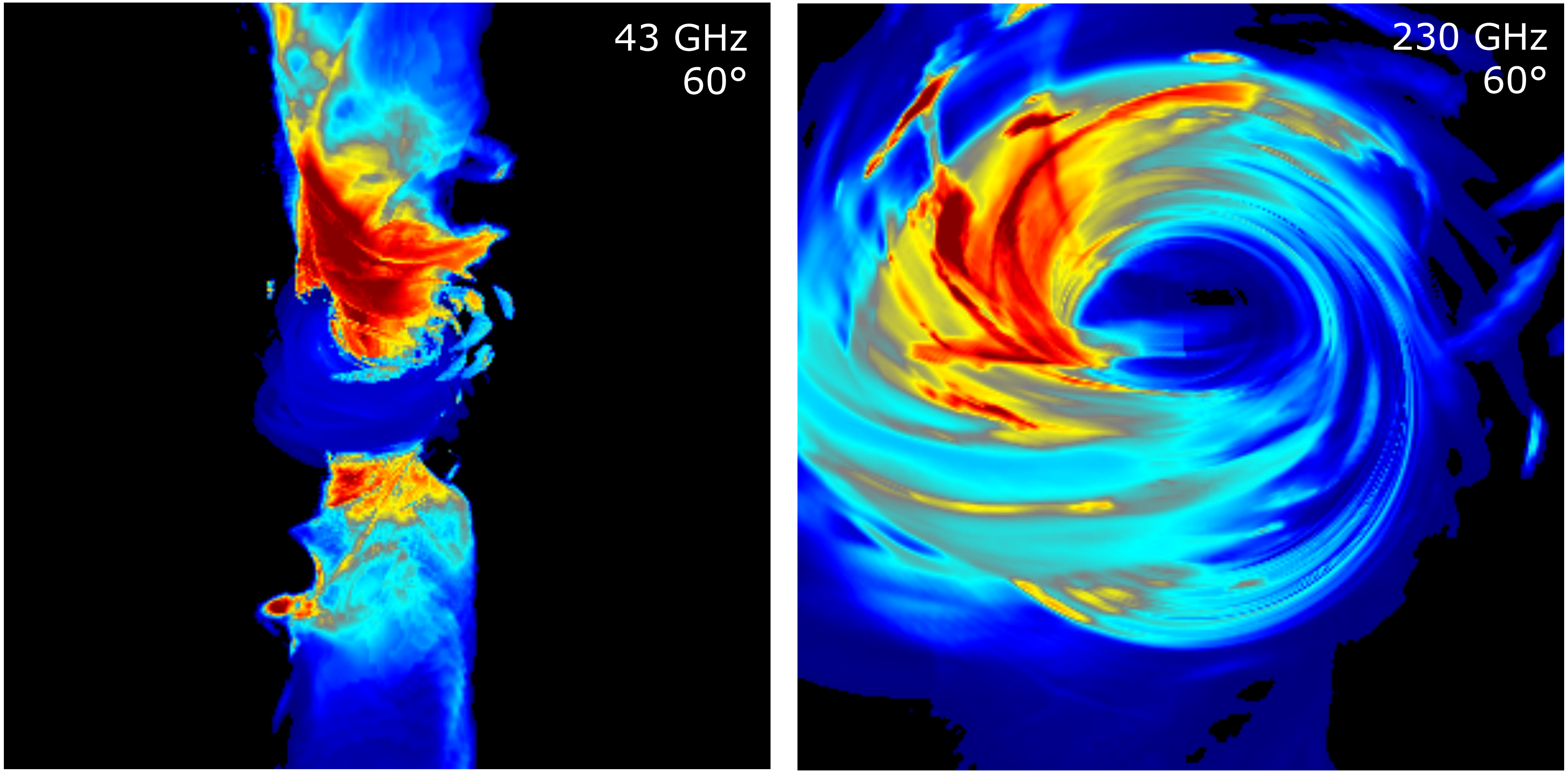


Falcke & Markoff, Class. & Quant. Gravity (2013, review)

GRMHD with isothermal jet

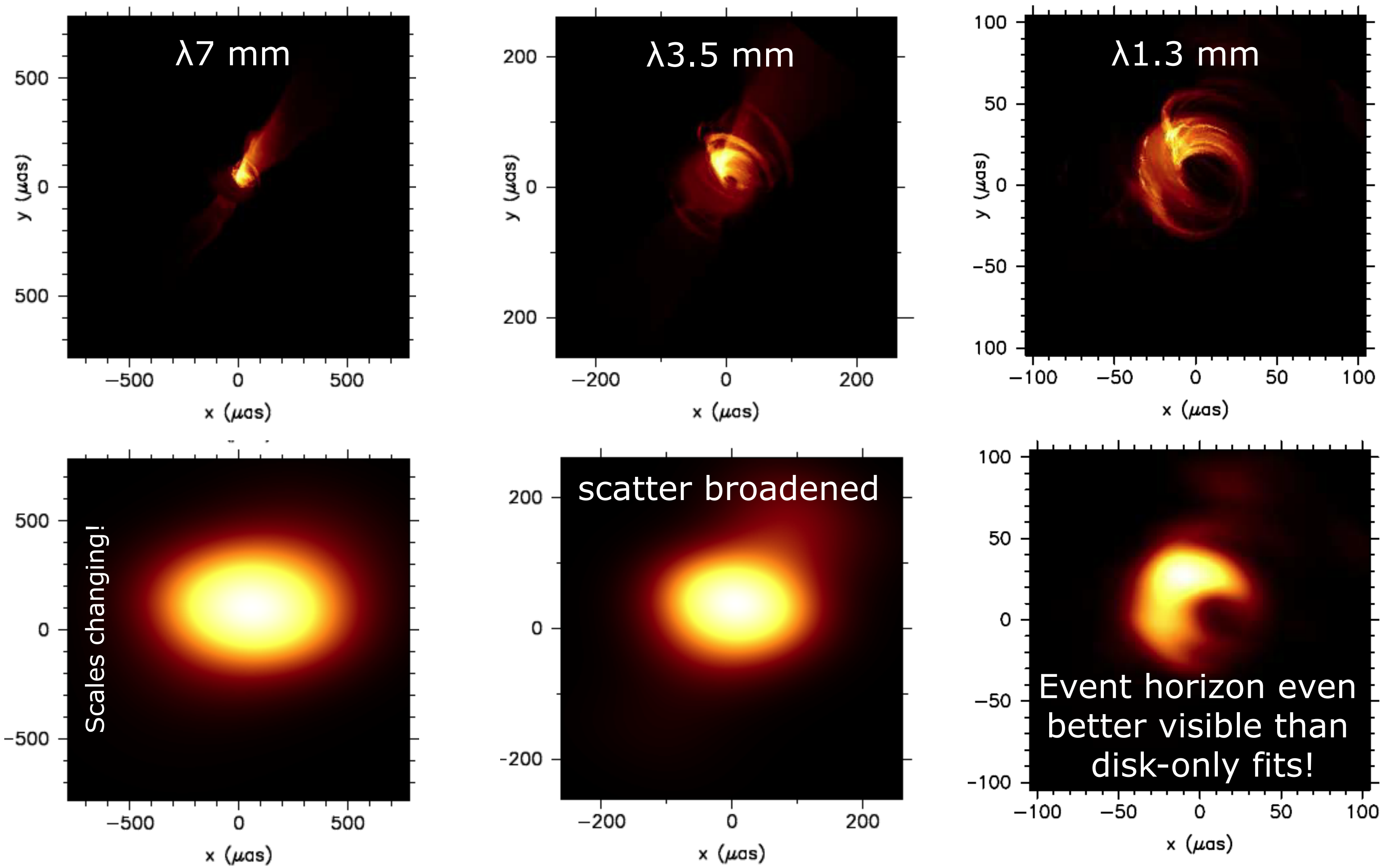
Jet: Tp/Te=1
Disk: two-temperature ADAF (Tp/Te>>1)



Moscibrodzka & Falcke (2013, A&AL)
Moscibrodzka et al. (2014, A&A)

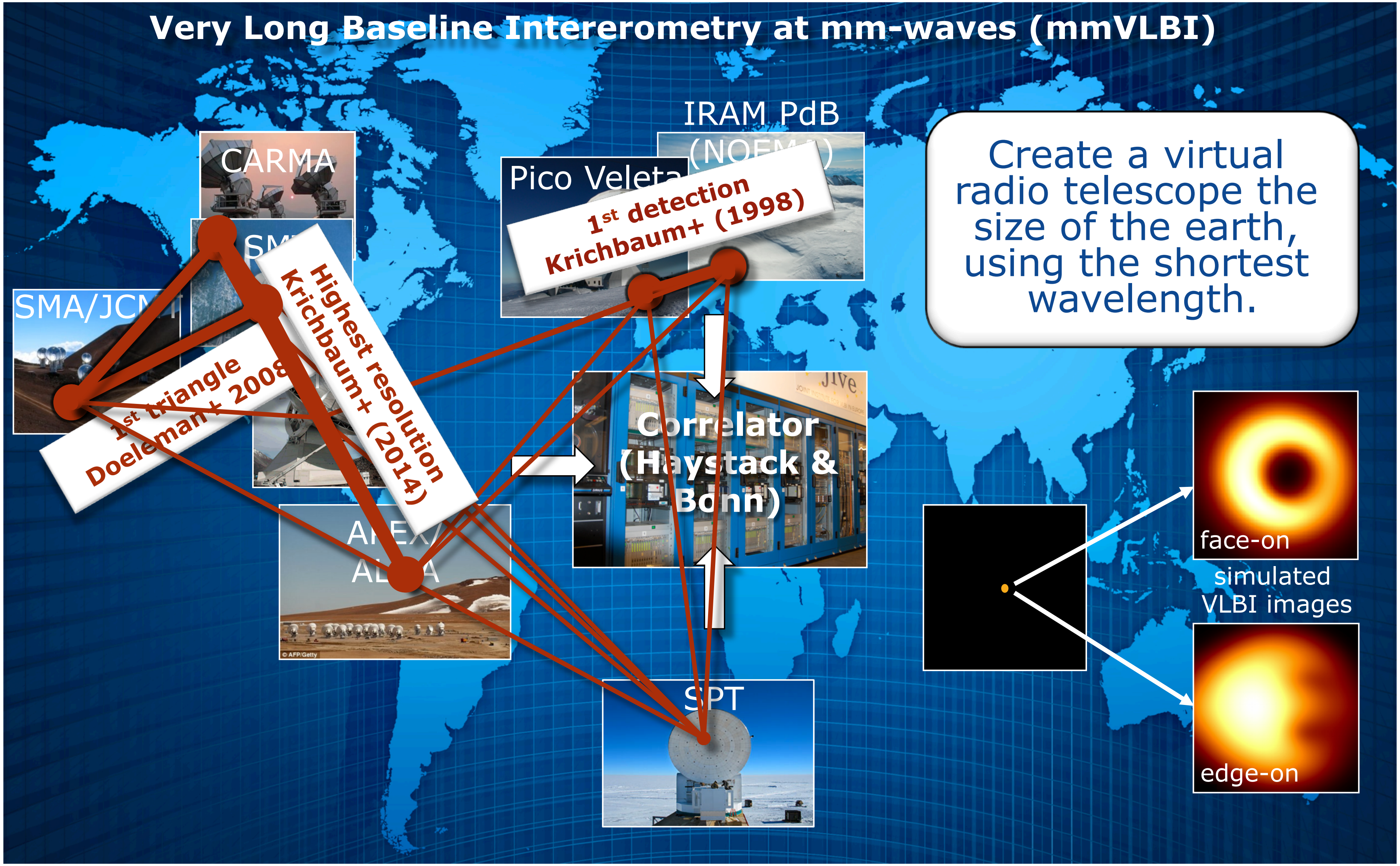
Effect of scatter broadening

BlackHoleCam



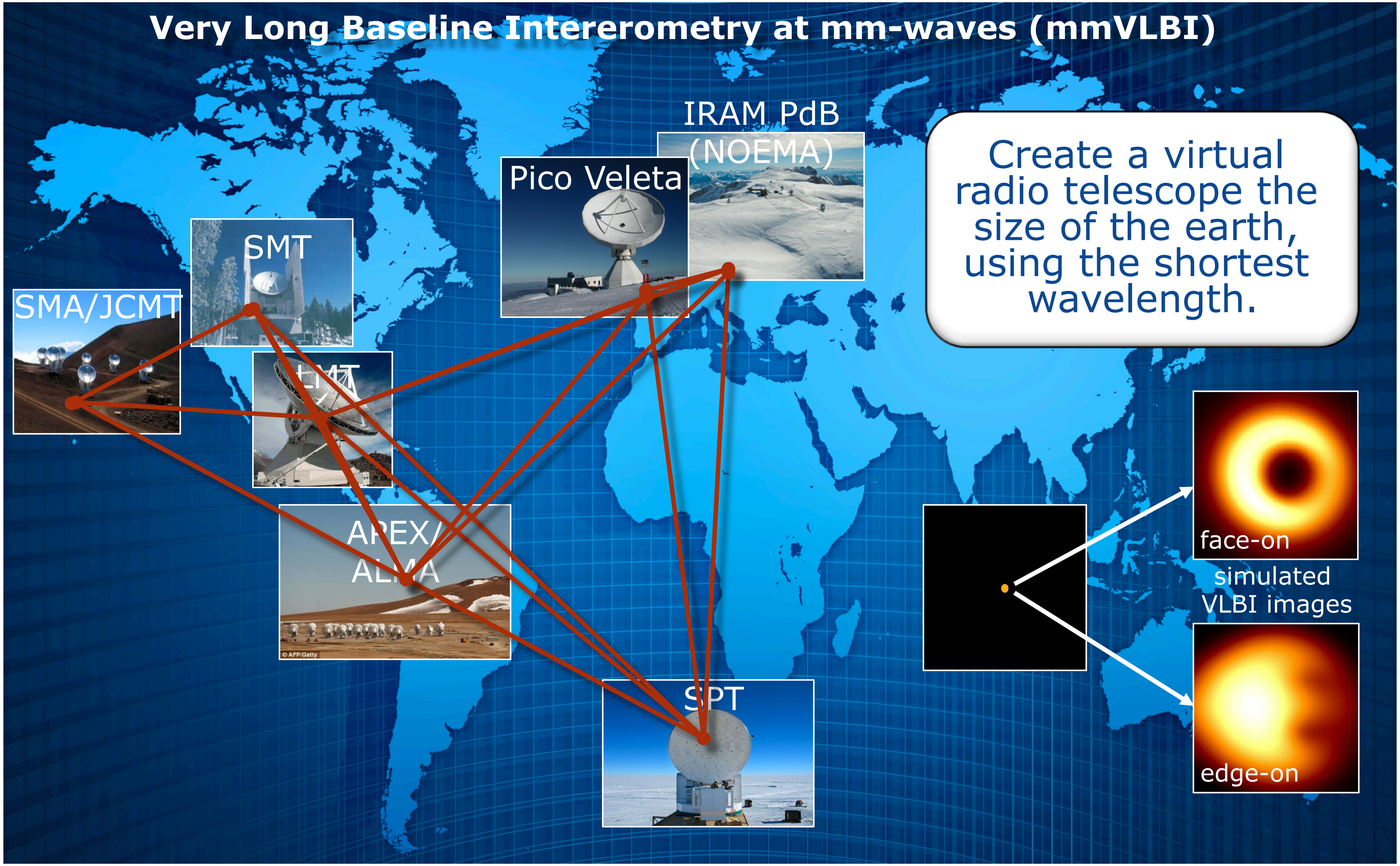
Event Horizon Telescope

BlackHoleCam



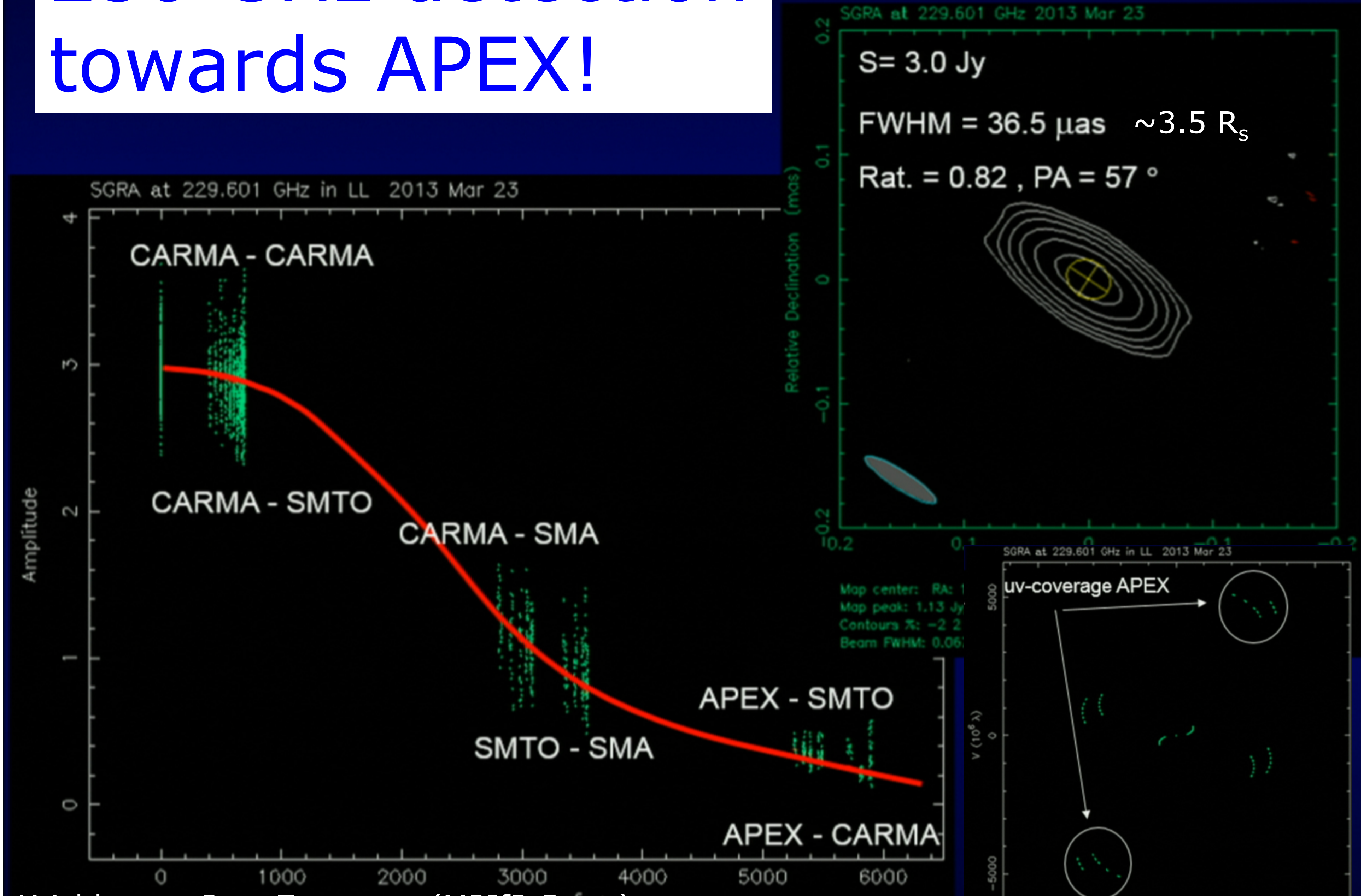
Event Horizon Telescope

BlackHoleCam



230 GHz detection towards APEX!

Preliminary!



Krichbaum, Roy, Zensus + (MPIfR Bonn)

EHT2015 Campaign

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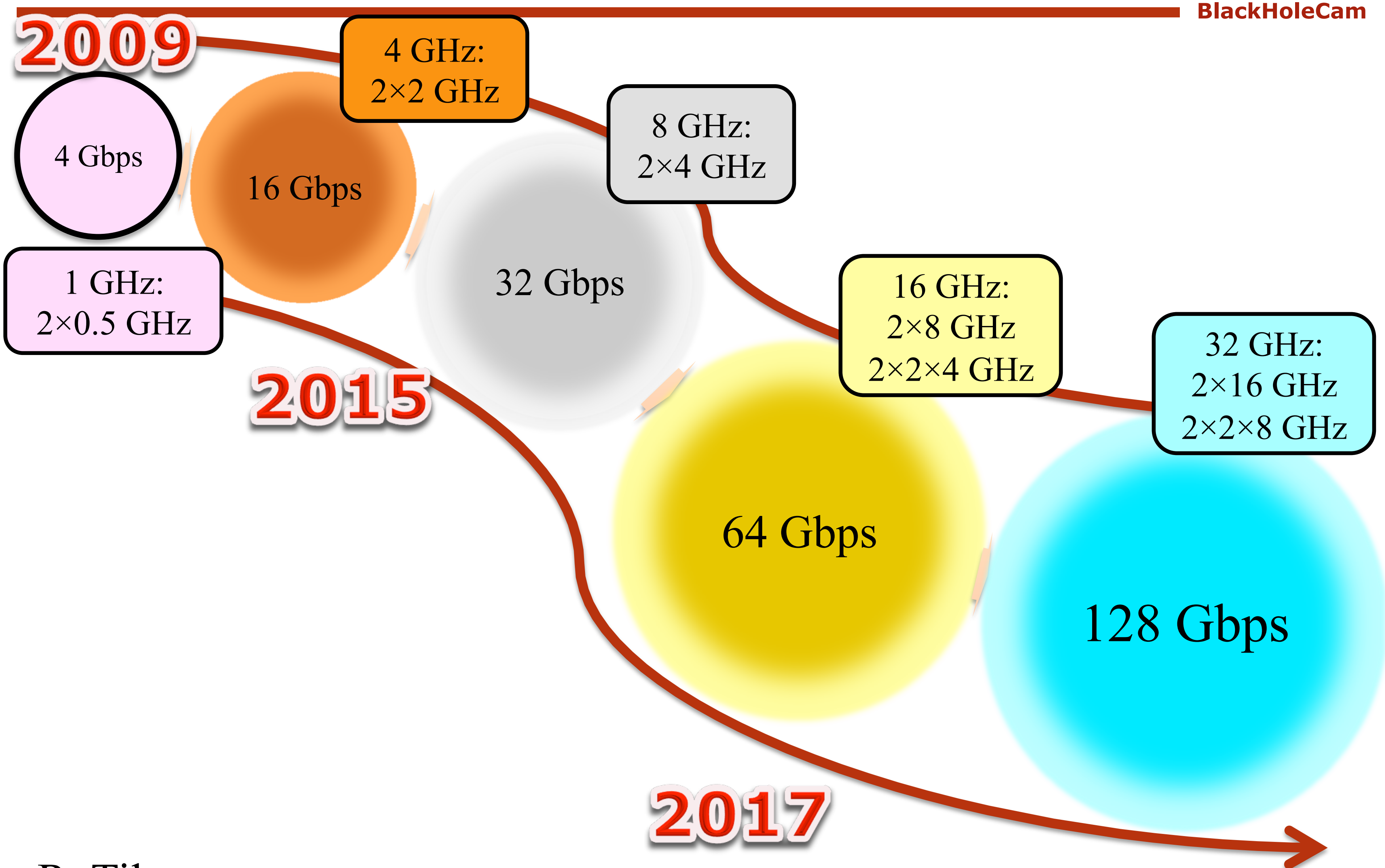
Future mmVLBI bandwidths

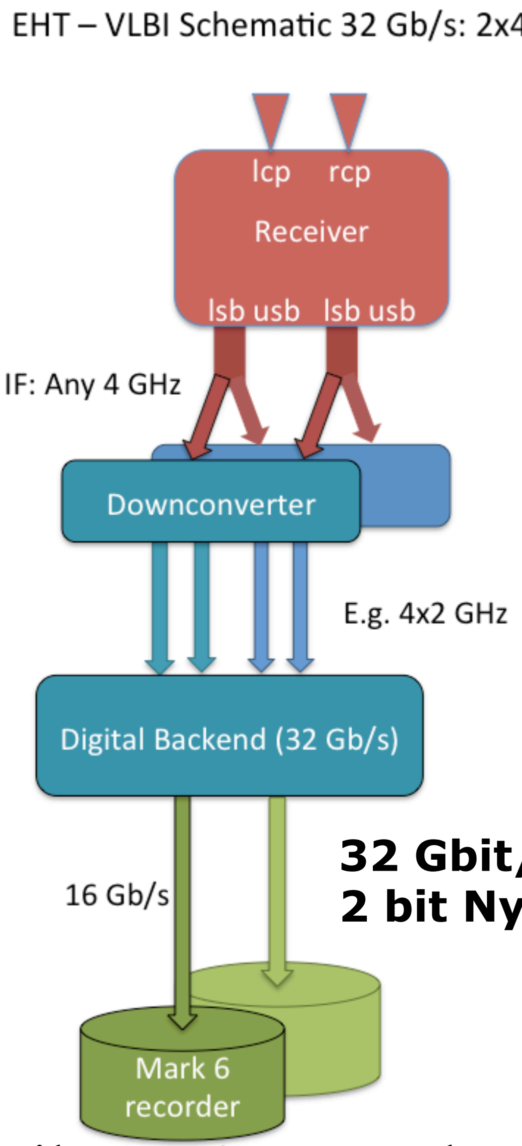
BlackHoleCam



R. Tilanus

Equipment for 32 Gbit/s version

BlackHoleCam



32 Gbit/s = 2x4 GHz
2 bit Nyquist sampled

R. Tilanus & M Hecht

- 7 downconverters supporting 2x4 GHz (4-8 or 5-9 GHz)
  - 6 constructed by NOVA/ALMA (Groningen) + filters from MPIfR
- 14 R2DBEs @ 16 Gb/s
  - 8 assembled on BHC budget, 4 owned by BHC
- 2 Mark 6 recorders per site
  - currently 10 purchased by BHC
- Needs 0.4 PB per site (4x8hr)
  - BHC purchesed ~3 PB
- For IRAM 30-m and APEX DBBC3 will replace R2DBEs

BHC software contributions to EHT

- End-to-end pipeline for mm-VLBI data reduction
  - CASA-based fringe-fitter for VLBI [JIVE]
- Robust turn-key VLBI operation
  - Scheduling and remote monitoring software [MPIfR Bonn]
  - Near real time calibration in snapshot mode [JIVE]
- Array simulation (MeqTrees, I. Bemmel) & comparison to GR/MHD models [Radboud]

EHT Interim Board

BlackHoleCam

MIT HAYSTACK OBSERVATORY

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Harvard-Smithsonian Center for Astrophysics

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Institute of Astronomy and Astrophysics

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Institut de Radioastronomie Millimétrique

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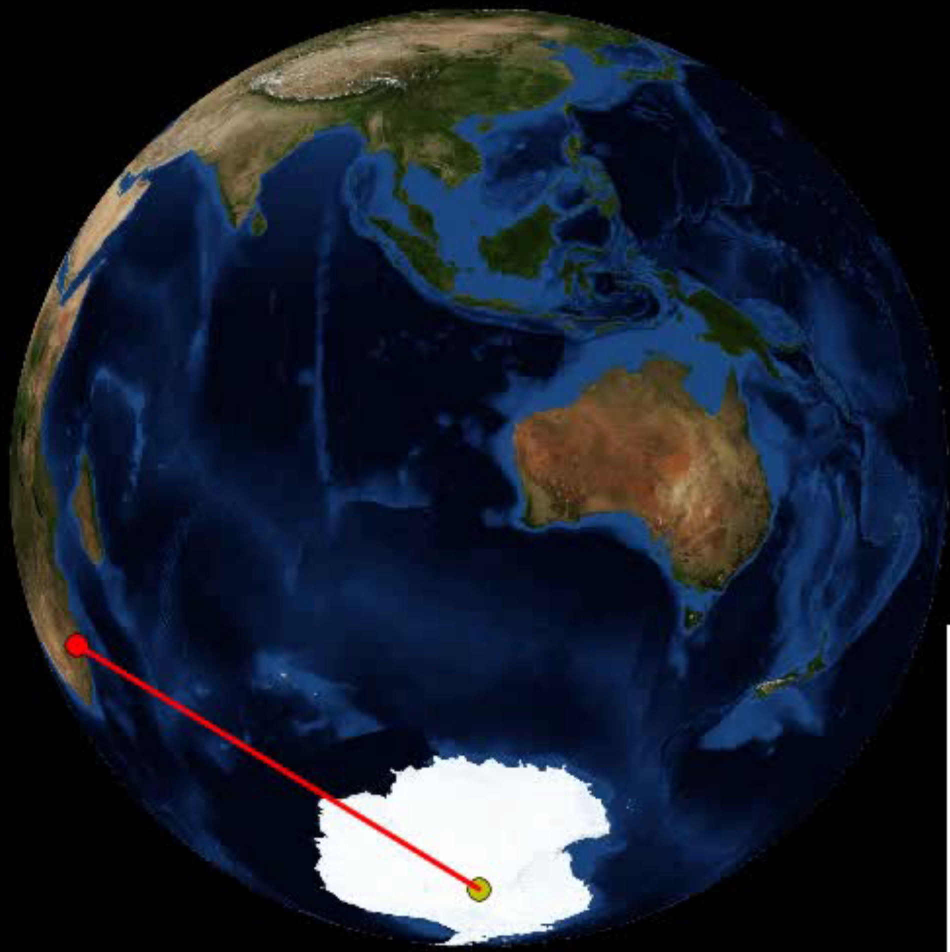
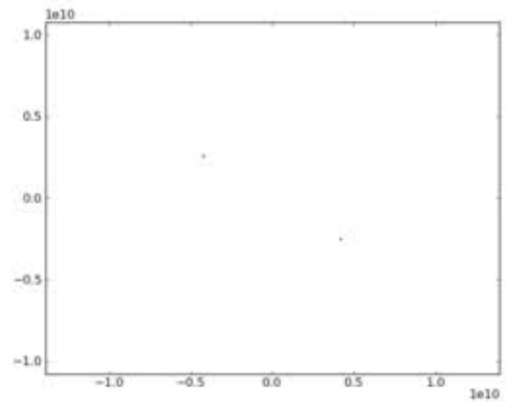
SOUTH POLE SPT TELESCOPE

African mm-wave telescope

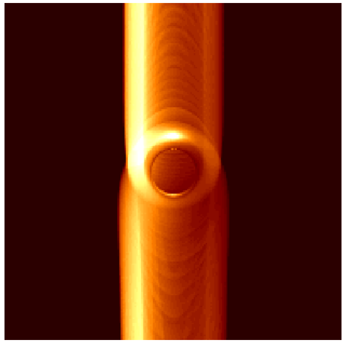
A dedicated African cm and mm-VLBI telescope for EHT/BHC, EVN, & SKA. investment cost: ~8 M€ + operations …



Earth seen from Sgr A*



VLBI 2010 antenna mount



Conclusions & Outlook

- Sgr A* is the best supermassive black hole candidate:
  - Mass and distance are accurately determined
  - sub-mm wave emission comes from event horizon scale
- If an event horizon exists, it will cast a shadow on the emission region, which is detectable by VLBI
- (sub)mm-wave VLBI is progressing well
  - NSF MSIP program & ERC Synergy “BlackHoleCam” project
  - Broad-band equipment 2015-2017
  - South pole: first fringes now, may join 2016
  - Alma phasing progressing, could join in 2017 (also for GMVA)
  - One Africa mm-wave telescope would be fantastic - three even better... Think of dedicated mm-wave VLBI network (with AVN?)!
  - Still needed:
    - software efforts, reliability, dynamical scheduling
    - Finalize organizational structure

⇒ Event horizon physics will become testable science!