Imaging & modeling Super-Massive Black Holes

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ALMA EUROPEAN ARC ALMA Regional Centre || Allegro

**BHC is an ERC-funded project and partner of the Event Horizon Telescope Consortium*

BLACK HOLE CAM

Event Horizon Telescope

http://blackholecam.org
http://www.eventhorizontelescope.org

erc European Research Council

Outline

I. Introduction : General Relativity & Black Holes

II. Simulations of Black Holes

III. Event Horizon Telescope (EHT)

IV. Apr 2017 Observing Campaign

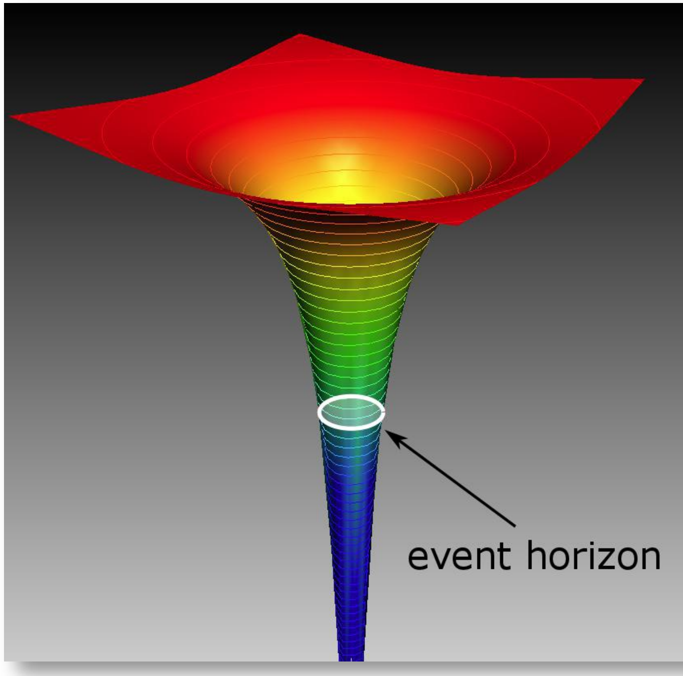
V. More than an image: stars/pulsars

VI. Outlook

I. General Relativity and Black Holes

BlackHoleCam

- Gravity is successfully described by Einstein's General Theory of Relativity (GR)
- Black holes (BHs) are one of the most fundamental predictions of GR
- Theoretically well studied - theory more advanced than observations (changing with GWs astronomy)
- The event horizon is the defining feature of a BH – and yet, we have never seen the event horizon



(LR/ITP)

✧ ***Are Black Holes observable astrophysical objects?***

✧ ***Does GR hold in its most extreme limit or are alternatives needed?***

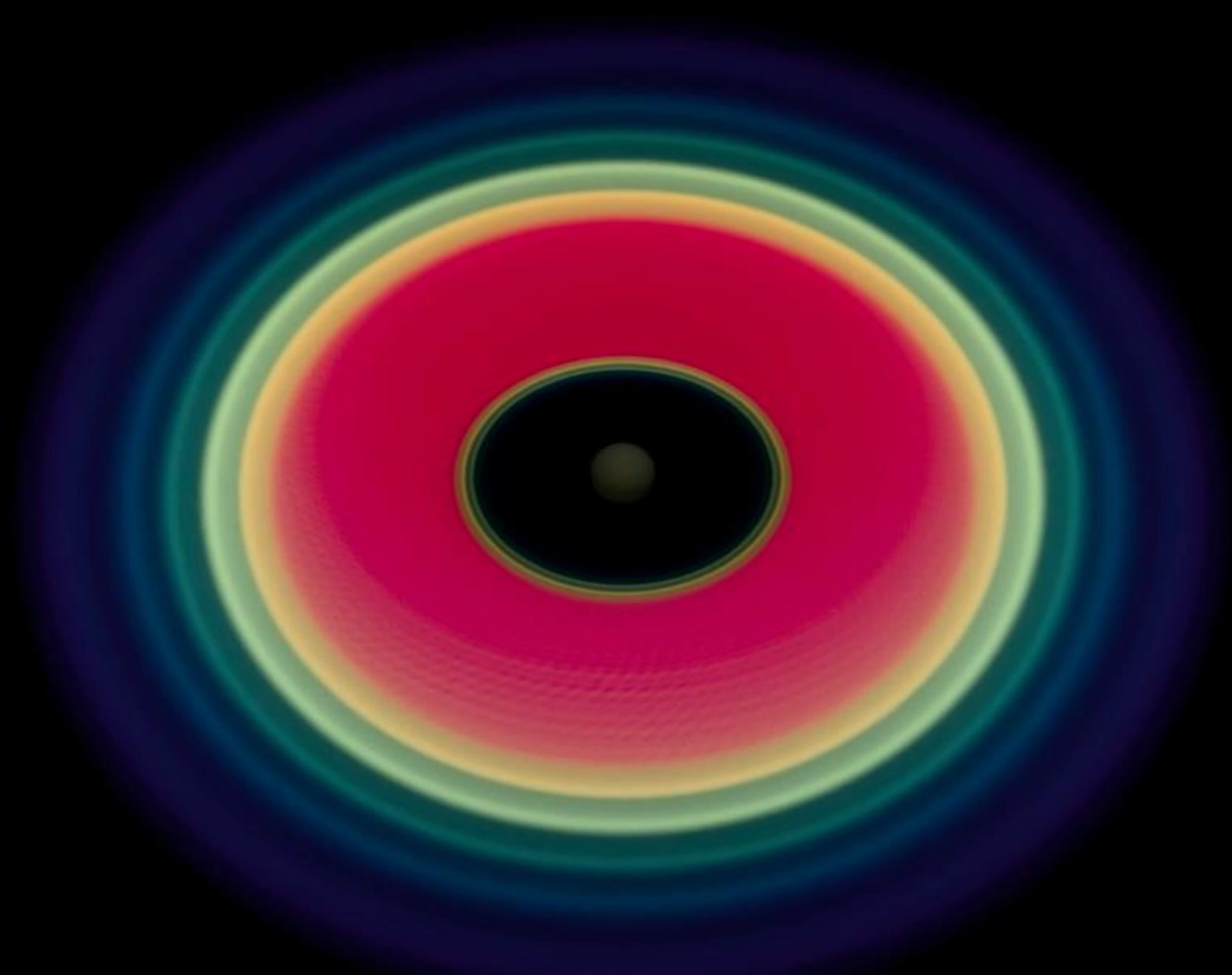
II. Simulations of Black Holes

1. theoretical modeling of the accretion onto SMBH
   - GRMHD Simulations

2. Modeling the corresponding EM emission
   - Radiative transfer models (ray tracing)

3. Tests of theories of gravity
   - GR and alternatives

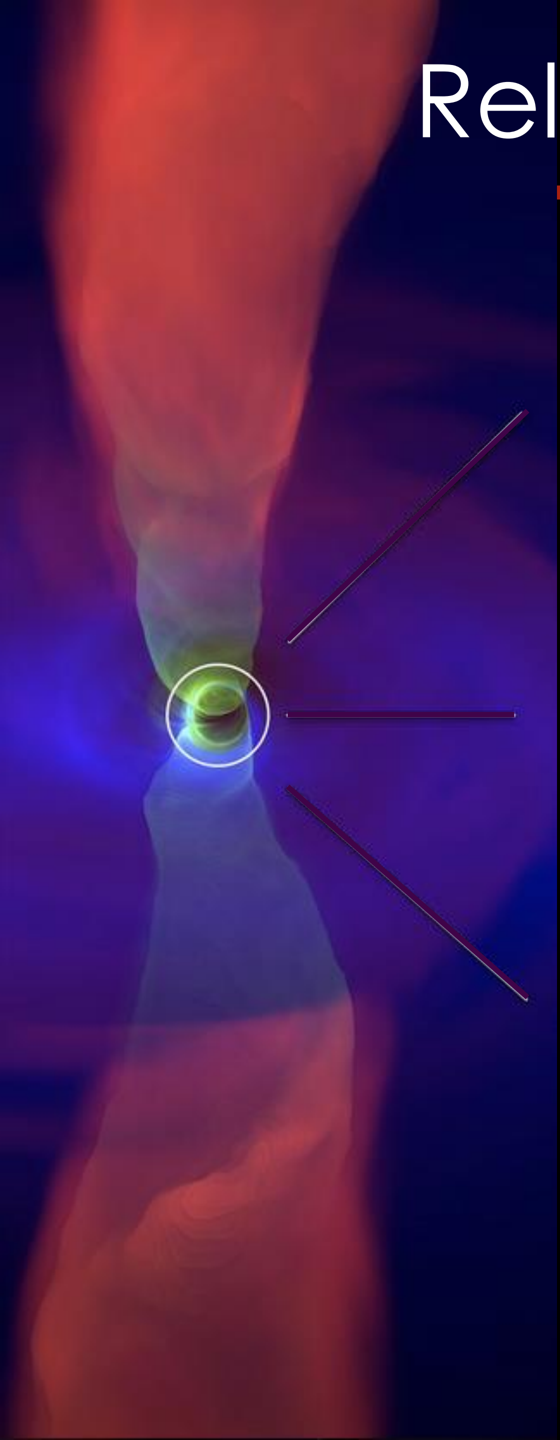
Modeling the accretion onto SMBHs
1. GRMHD Simulations



BHAC (Black Hole Accretion Code)

Porth, Rezzolla, et al., 2017

Relativistic jets and BHs



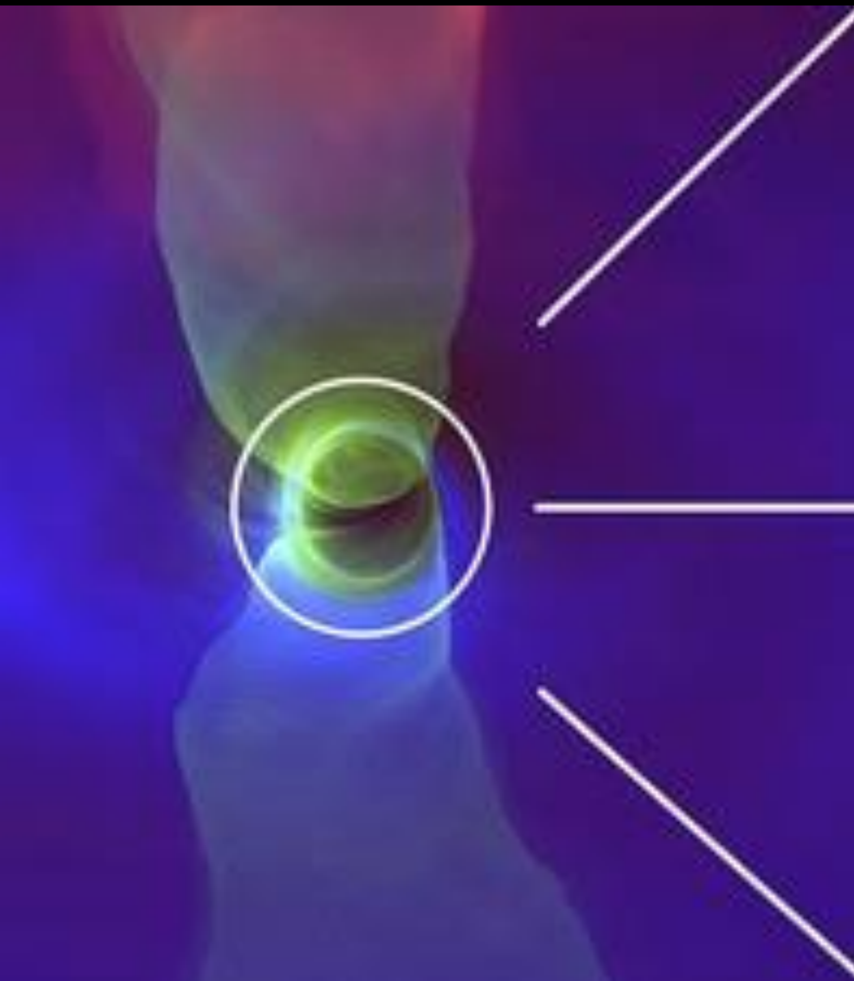
Boccardi et al. 2017

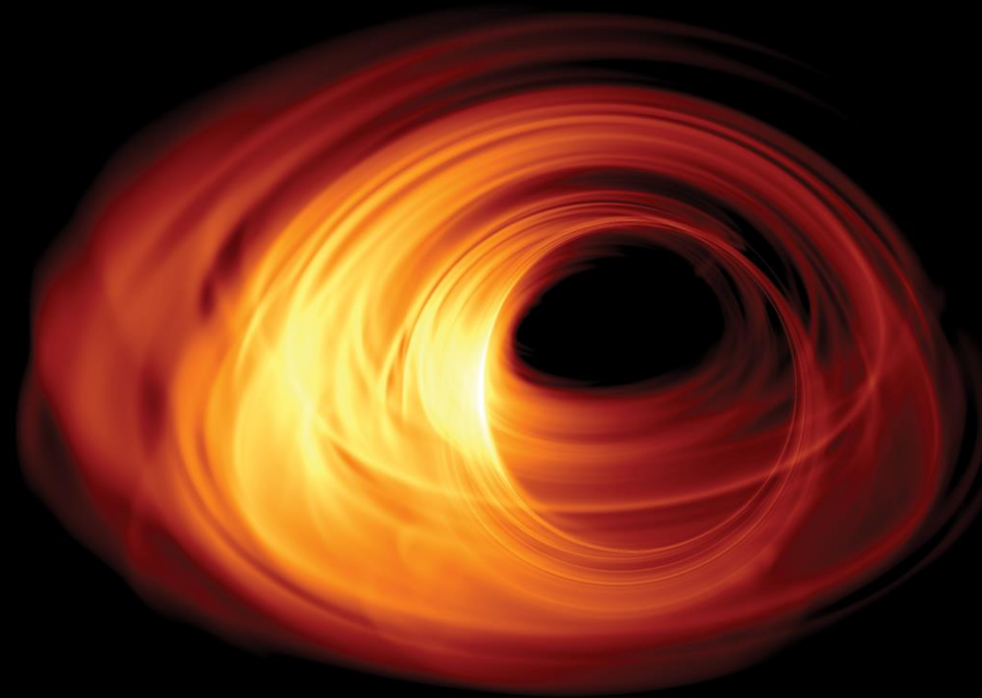
radio galaxy Hercules A

Credit: X-ray: NASA/CXC/SAO, Optical: NASA/STScI, Radio:

The Shadow of a Black Hole

BlackHoleCam





Bardeen 1973, Luminet 1979

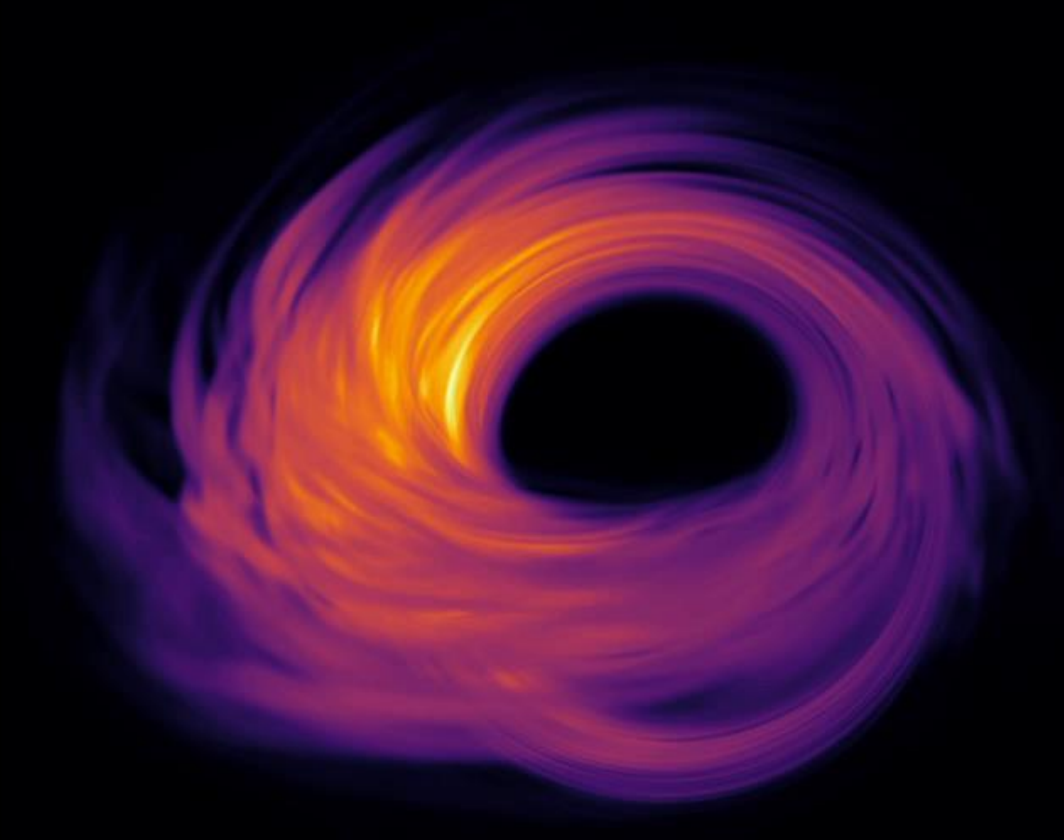
Falcke, Melia, Agol (2000)

Bronzwaer et al. 2018

The Shadow of a Black Hole

2. Radiative transfer models (ray tracing) to link to observations

BlackHoleCam



BHOSS (Black Hole Observations in Stationary Spacetimes)

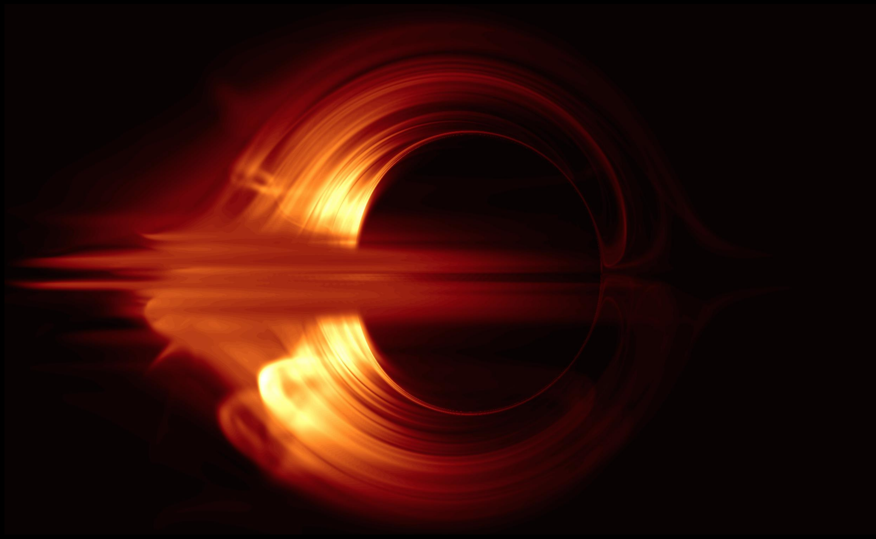
Younsi, Bronzwaer, Davelaar

The Shadow of a Black Hole

Constraining BH spin and inclination

BlackHoleCam

More face-on

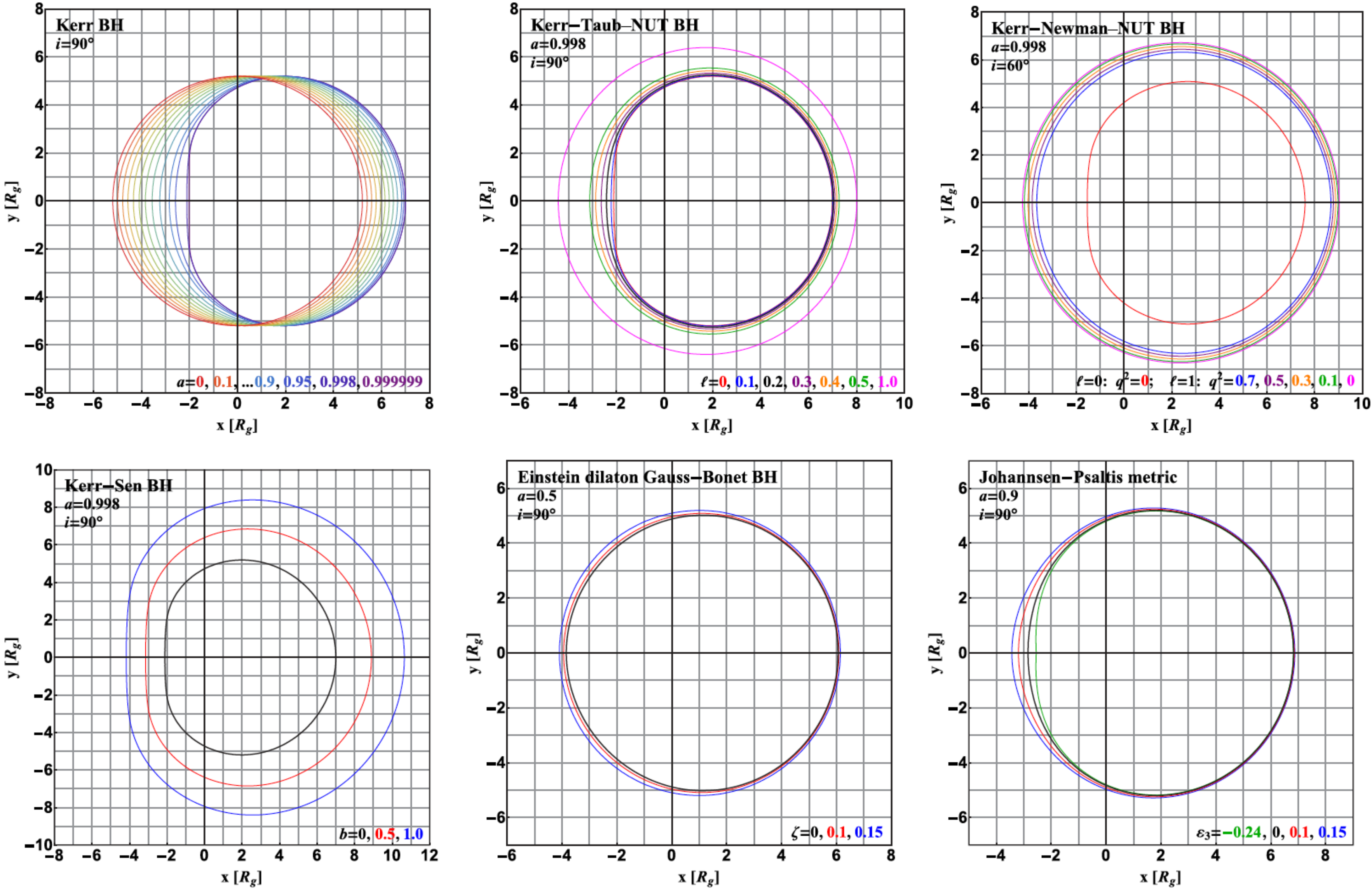


More edge-on

Younsi et al., Bronzwaer et al., Davelaar, et al.

The Shadow of a Black Hole
3. Testing theories of Gravity

BlackHoleCam



Goddi et al. 2017, Younsi et al. 2017

The Shadow of a Black Hole

Astrophysical Targets

$$R_{Sch} = 2\,GM_{BH}/c^2$$
$$\theta_{Sch} = R_{Sch}/D$$
$$\approx 0.02 \text{ nano-arcsec } (M_{BH}/M_{\odot})/(\text{kpc}/D)$$

Stellar mass BHs (D~1 Kpc, M_{BH} ~10 $M_{\odot}$)

Super-massive BHs (D~1 Mpc-1Gpc, M_{BH} ~10^6-10^9 $M_{\odot}$)

=> Both generally too small

Two notable exceptions:

Sgr A* : D~8 kpc, M_{BH} ~4×10^6 $M_{\odot}$ => $\boldsymbol{\theta_{Sch}}$ **~** 10 micro-arcseconds

M87 : D~17 Mpc, M_{BH} ~7×10^9 $M_{\odot}$ => $\boldsymbol{\theta_{Sch}}$ **~** 8 micro-arcseconds

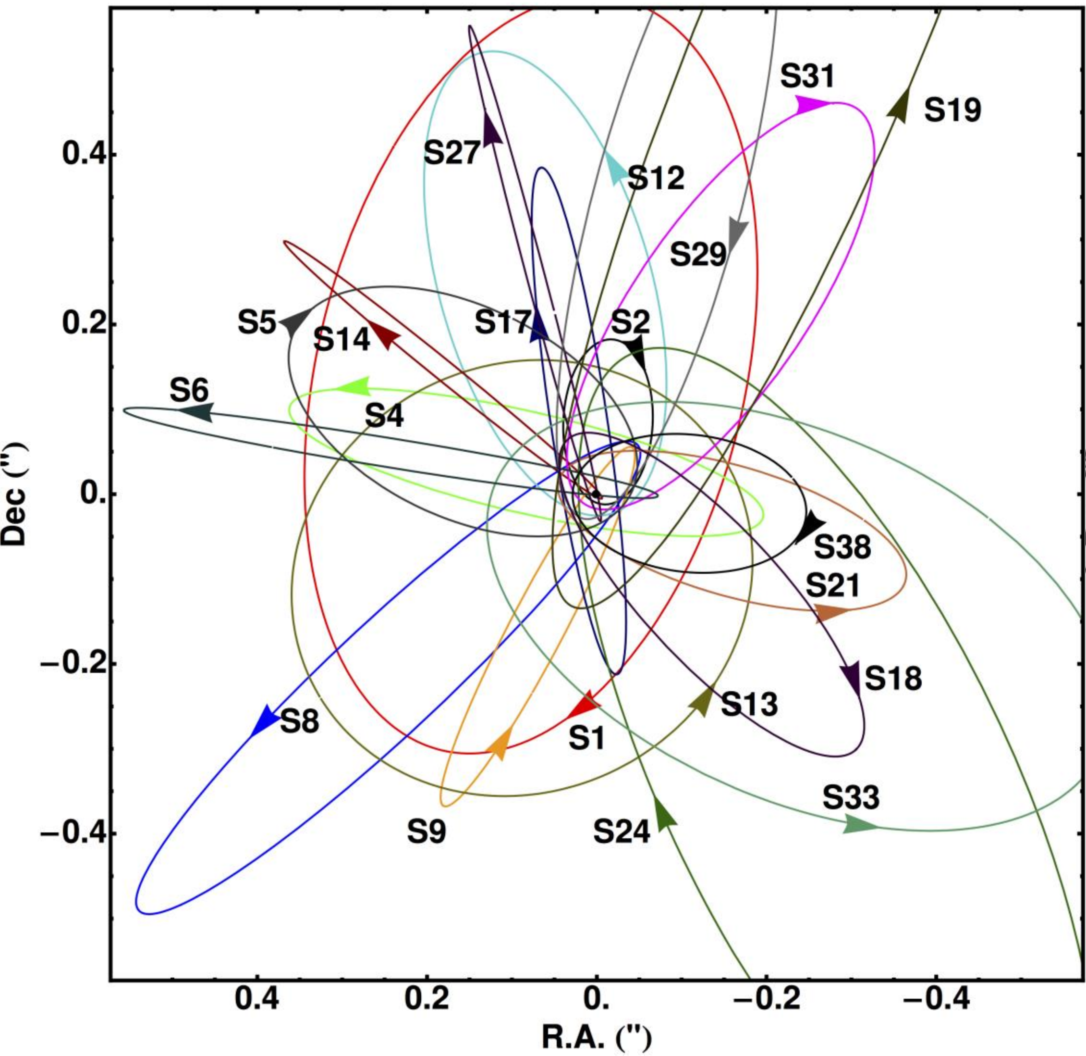
=> Gravitationally-lensed size ~**50 micro-arcseconds**

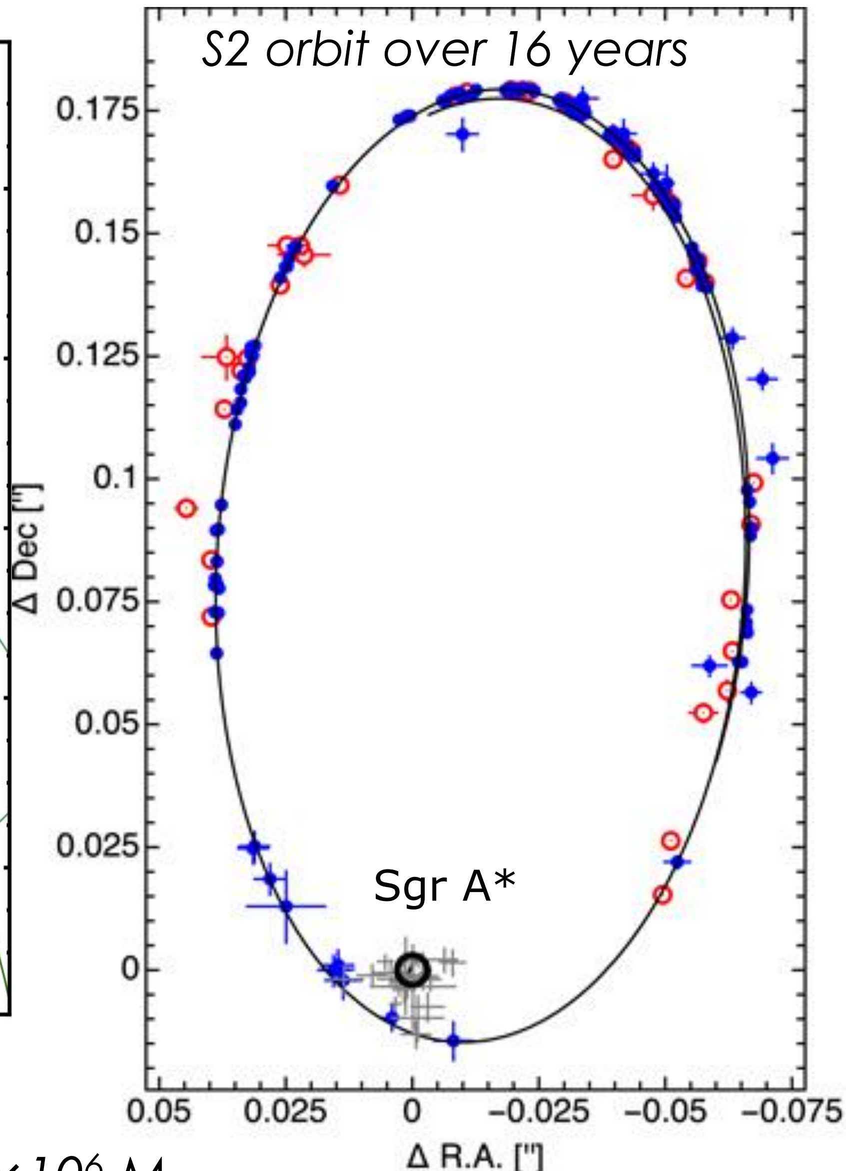
The Galactic Center contains the best and closest SMBH: Sagittarius A* (4×10^6 solar masses)

see also Ghez et al. (UCLA group)

The Galactic Center contains the best and closest SMBH: Sagittarius A* (4×10^6 solar masses)

BlackHoleCam





Stellar proper motions around Sgr A: 4.3×10^6 M_{sol}*

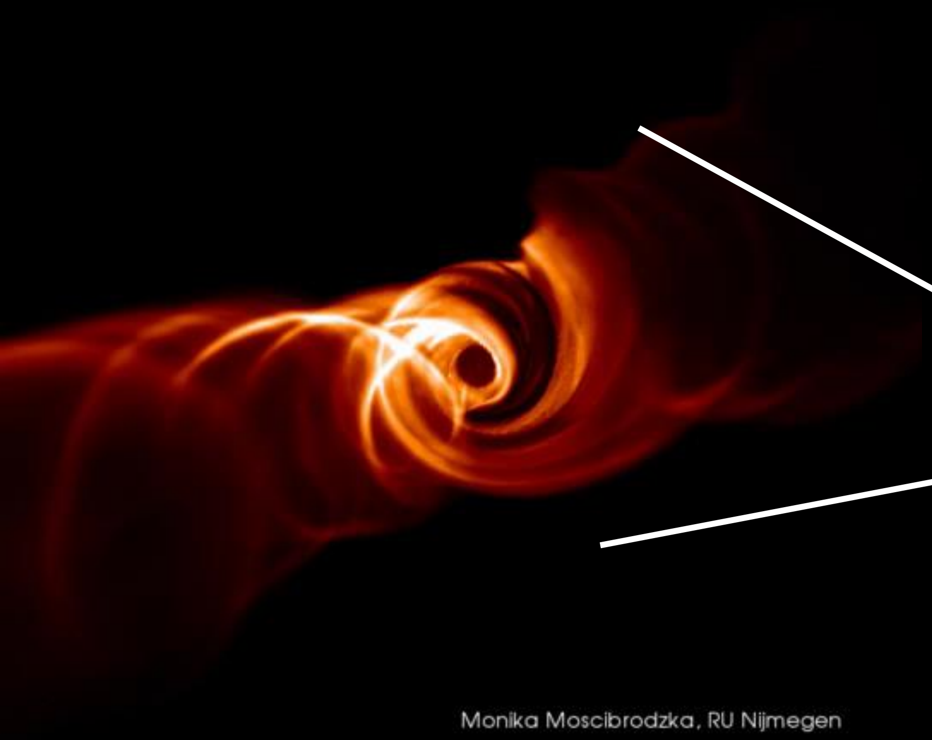
Gillessen et al. 2017

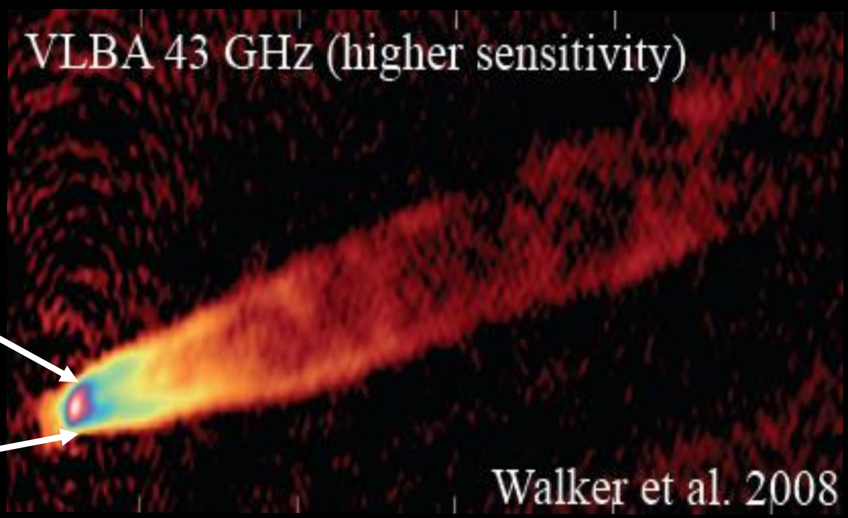
The SMBH and relativistic jet in M87

BlackHoleCam

GRMHD Simulation

VLBI Observations





Moscibrodzka, Falcke, Shiokawa (2016, A&A)

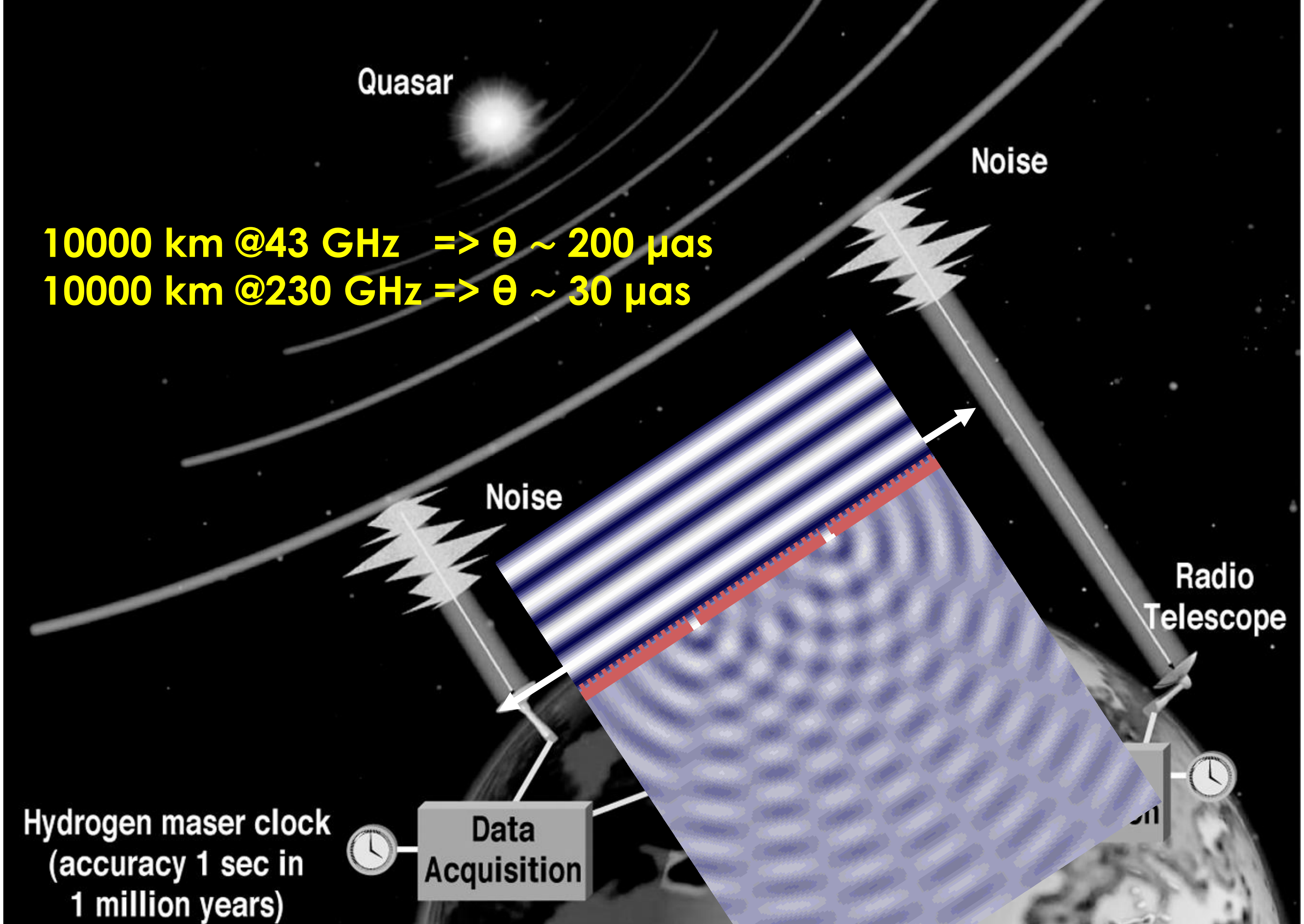
(Using Harm3D - Gammie et al.)

III. Event Horizon Telescope (EHT)

VLBI – Very Long Baseline Interferometry

Resolution: smallest angular scale: ~λ/D

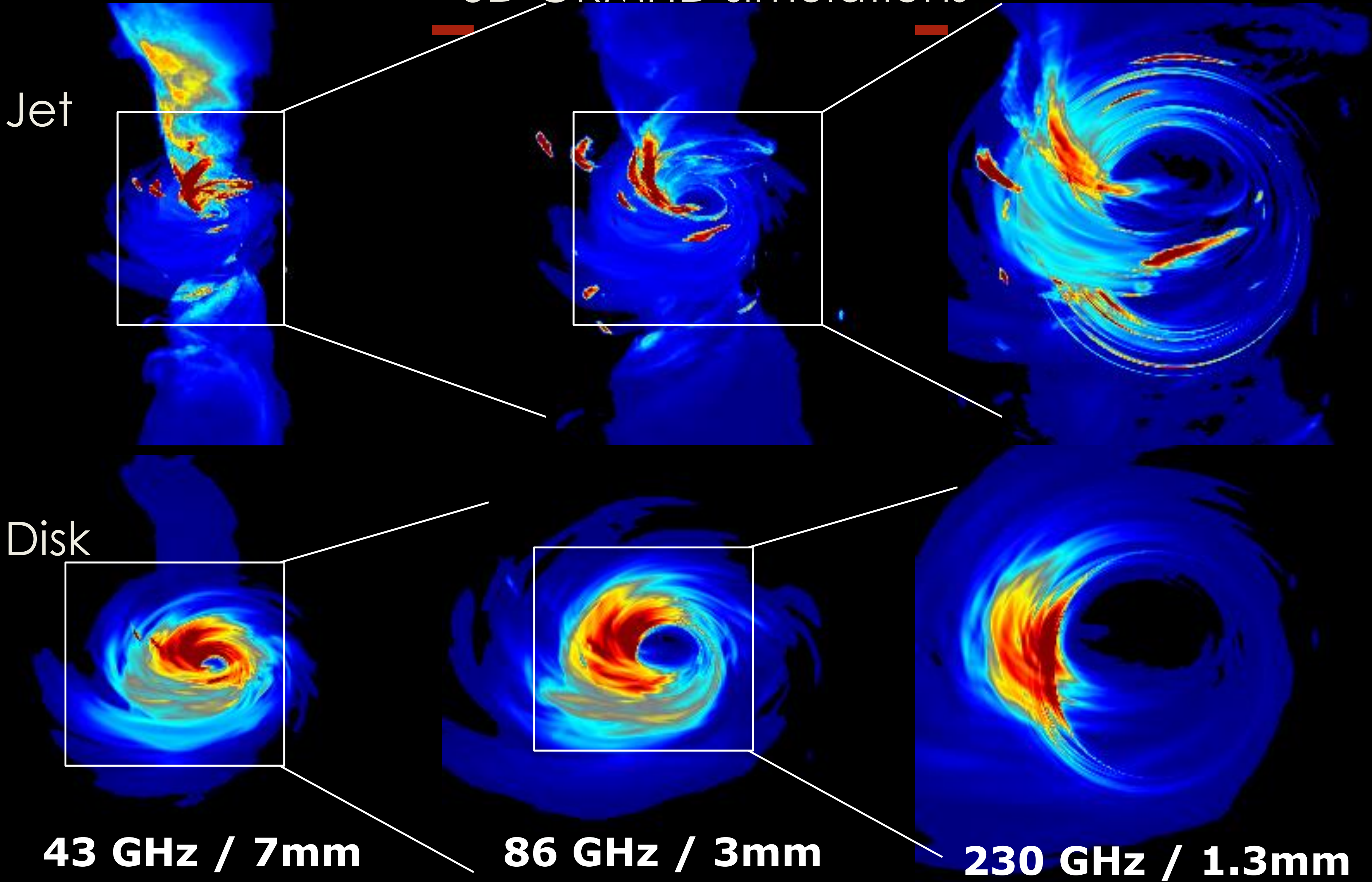
10000 km @43 GHz   => θ ~ 200 μas
10000 km @230 GHz => θ ~ 30 μas



Create a virtual radio telescope the size of the earth at mm-waves

The importance of high frequencies

3D GRMHD simulations



Moscibrodzka et al.

Very Long Baseline Intererometry at mm-waves (mmVLBI)

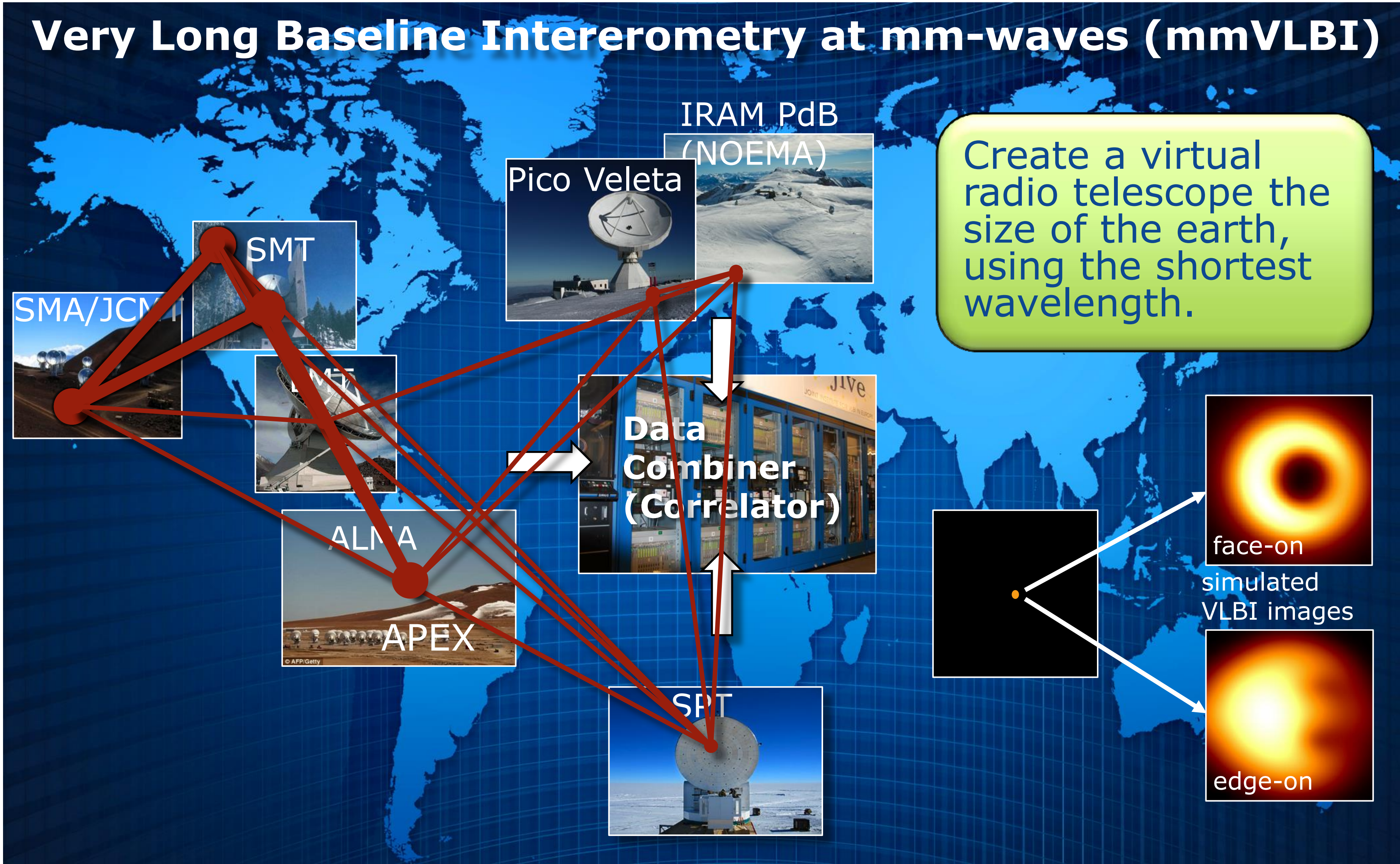
- VLBI is “routine” at cm-wavelengths

- VLBI at <3mm is still in an experimental phase, due to challenges of high frequencies:
  - stability of receiver chains
  - distortion effect of the wave fronts by the troposphere
  - small number of telescopes operating in this short wavelength range

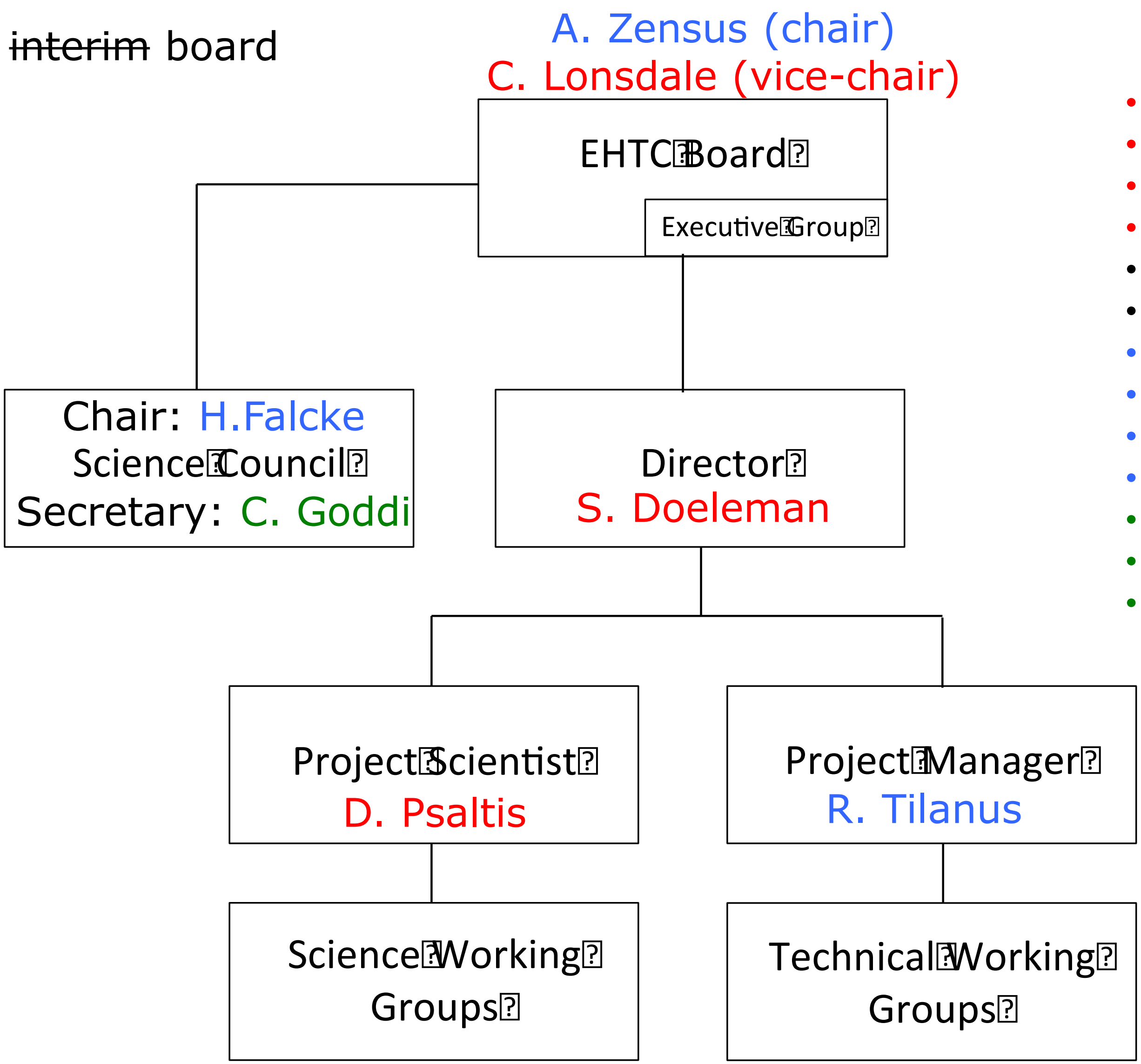
=> Till recently, mm-VLBI experiments have been conducted with a limited number of stations (3) which provided to few baselines and thus visibilities to make an image

The Event Horizon Telescope (EHT)

BlackHoleCam



Event Horizon Telescope Consortium



About 200 individual EHT members …

13 EHT Stakeholders

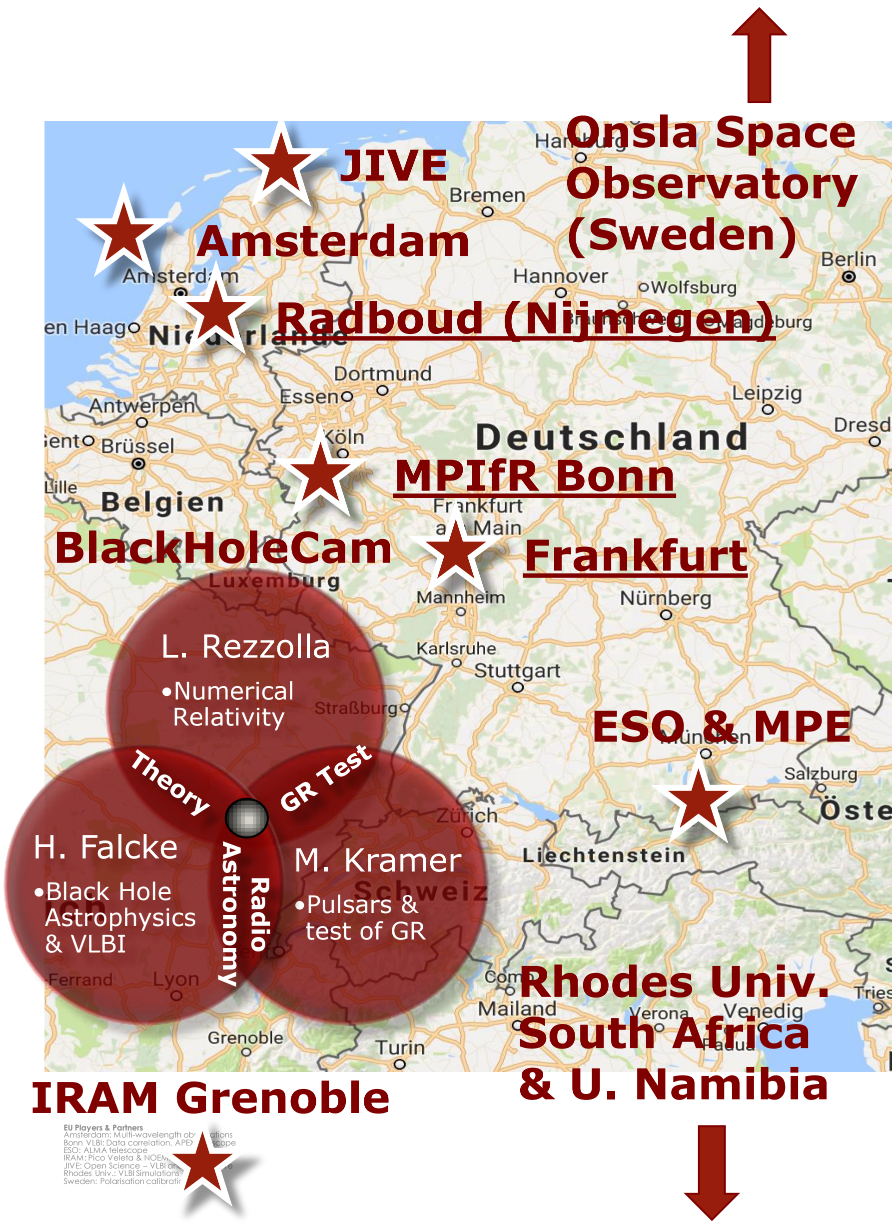
- Harvard/SAO (USA)
- MIT Haystack Obs. (USA)
- Univ. Arizona (USA)
- Univ. Chicago (USA)
- Perimeter (Canada)
- INAOE (Mexico)
- **MPIFR Bonn (Germany)**
- **IRAM (D/F/E)**
- **Radboud Uni. (Netherlands)**
- **Univ. Frankfurt (Germany)**
- EACOA (East Asia)
- NOAJ (Japan)
- ASIAA (Taiwan)

Interim Board since Jan 2015.

50 telecons …

Finally consortium agreement signed July 2017.

14 M€ ERC Synergy Grant BlackHoleCam



Pis: H. Falcke (Radboud), M. Kramer (MPIfR), L. Rezzolla (Frankfurt)

Project Scientist:

Ciriaco Goddi (Radboud/Leiden)

Project Manager:

Remo Tilanus (Radboud/Leiden)

EU Players & Partners

Amsterdam: Multi-wavelength observ.

Bonn VLBI: Data correlation, APEX tel.

ESO: ALMA telescope

IRAM: Pico Veleta & NOEMA telescopes

JIVE: VLBI analysis software

Rhodes Univ.: VLBI Simulations

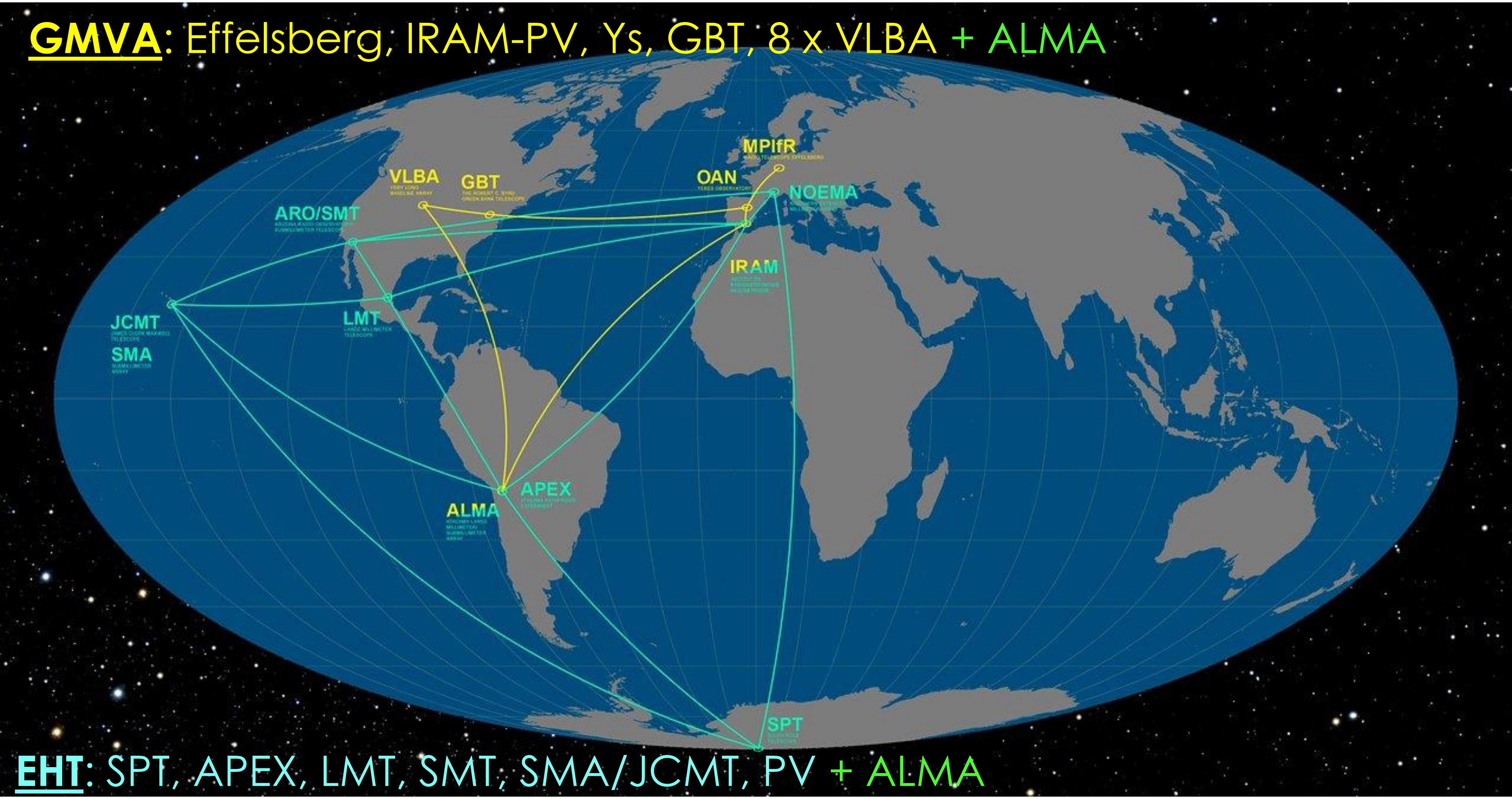
Sweden: Polarisation calibration

Bologna: VLBI Software

IV. April 2017 Observing Campaign

mmVLBI Networks with ALMA in 2017

GMVA: Effelsberg, IRAM-PV, Ys, GBT, 8 x VLBA + ALMA



EHT: SPT, APEX, LMT, SMT, SMA/JCMT, PV + ALMA

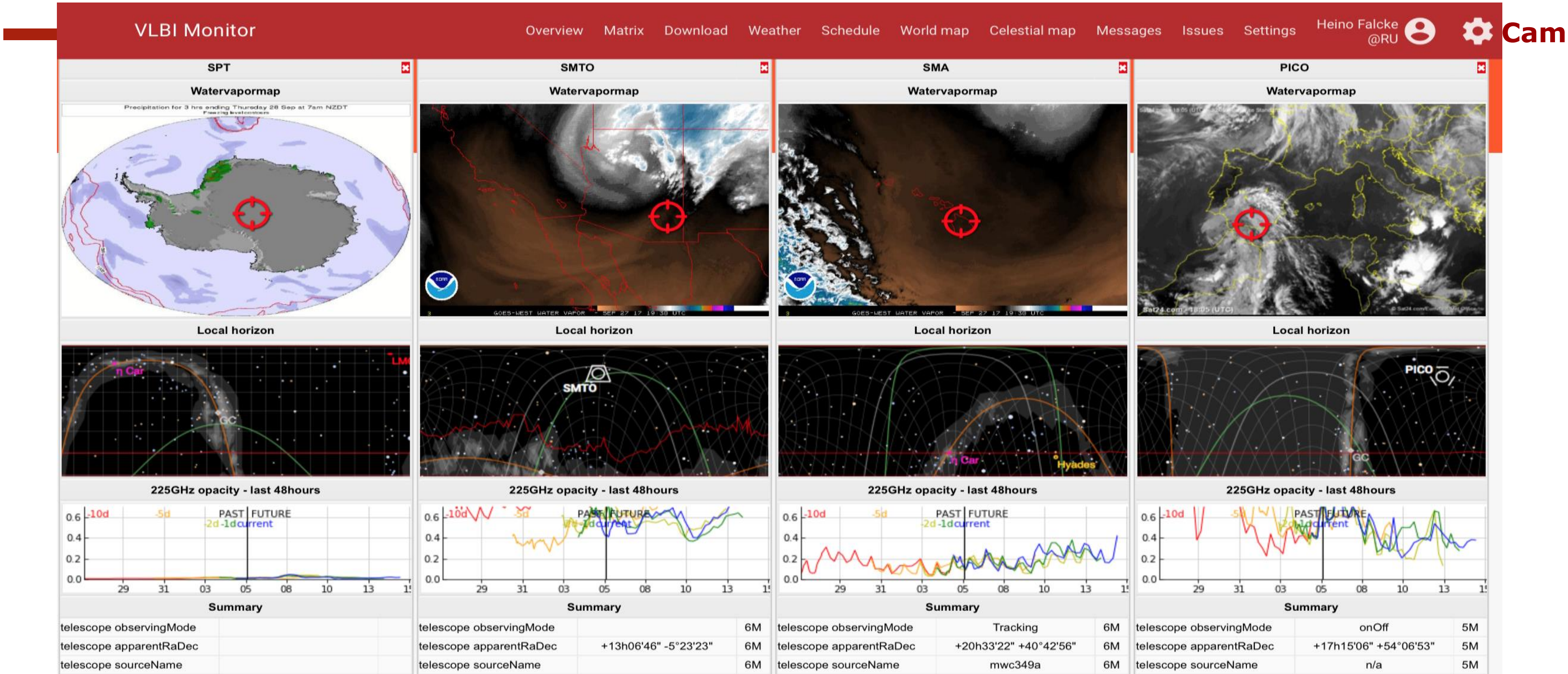
- GMVA @3mm (128 MHz BW, dual pol., 2 Gbps recording)
- EHT @1.3mm (~4 GHz BW, dual pol., 32 Gbps recording)

ALMA VLBI projects in Cycle 4

- **GMVA** (B3): fixed dates (Apr 2-4)
  1. 2016.1.01116.V // OJ287- April 02
  2. 2016.1.00413.V // **Sgr A***- April 03
  3. 2016.1.01216.V // 3C273- April 04

- **EHT** (B6): trigger 5 nights in 10 days (Apr 5-14)
  1. 2016.1.01404.V // **Sgr A***
  2. 2016.1.01114.V // OJ287
  3. 2016.1.01154.V // **M87**
  4. 2016.1.01176.V // 3C279
  5. 2016.1.01198.V // cen A
  6. 2016.1.01290.V // ngc1052

Triggering EHT Observations



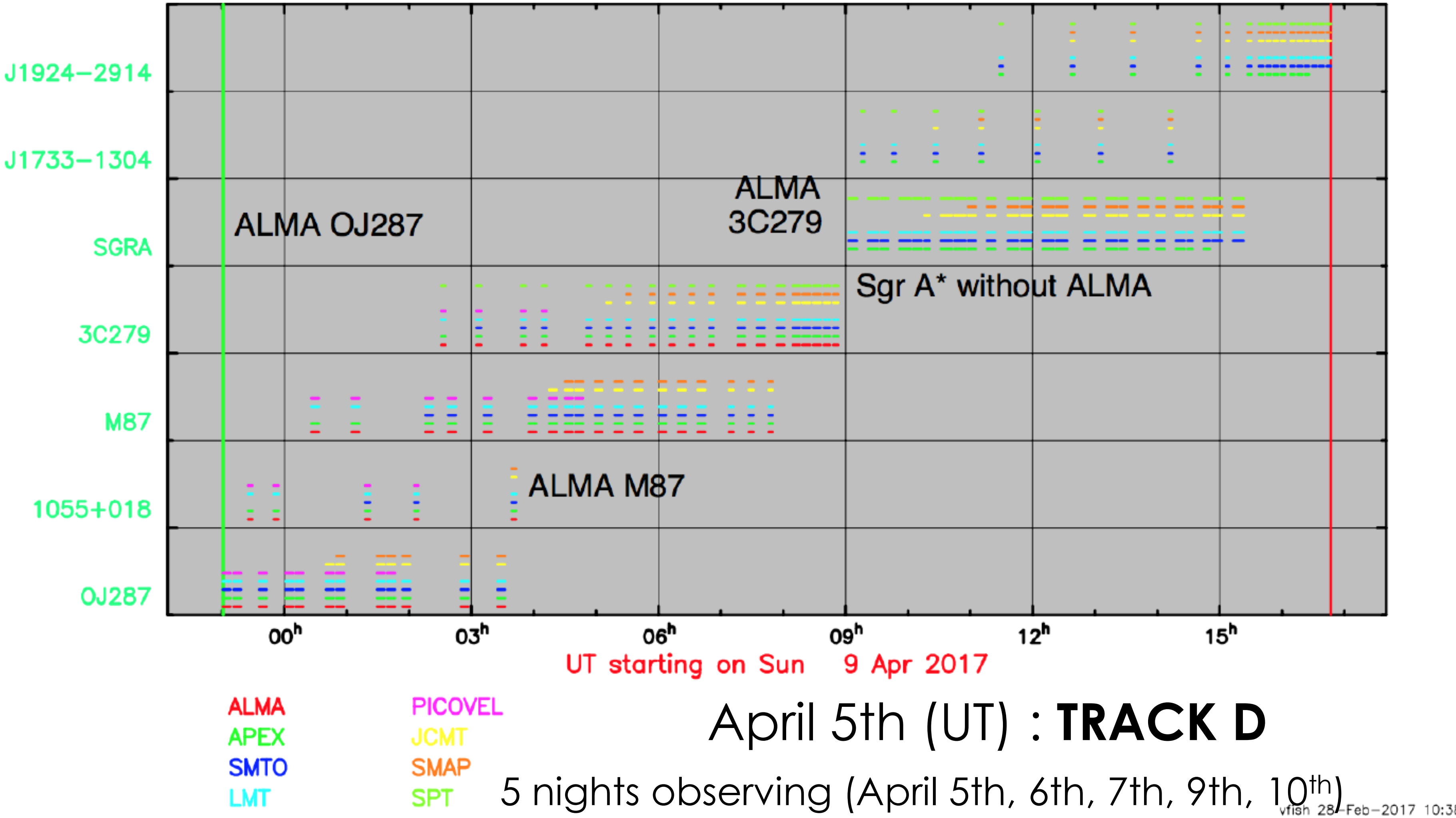
- Go/NoGo Decision (Each day, a few hours ahead of time)
  - Each station reports that is it *Ready* or *Not Ready*, based on weather and technical considerations.
  - VLBI Monitor developed at Radboud very useful
- For first 5 days, all stations (except APEX & JCMT) were required

2017 EHT Observations
Projects observed in "Tracks"

BlackHoleCam

10 days (Apr 5-14) during which trigger 4 "tracks": A,B,C,D

- SgrA* = Tracks B, C ; M87 = Tracks B, D



April 5th (UT) : **TRACK D**

5 nights observing (April 5th, 6th, 7th, 9th, 10th)

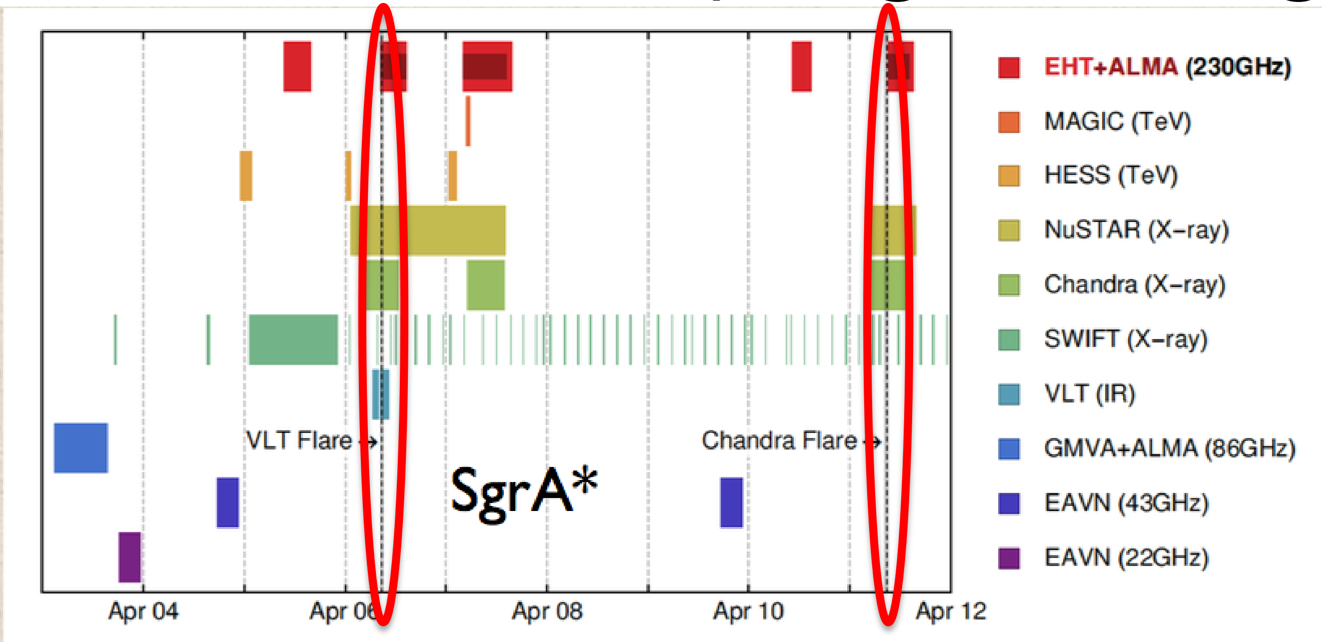
2017 EHT Campaign

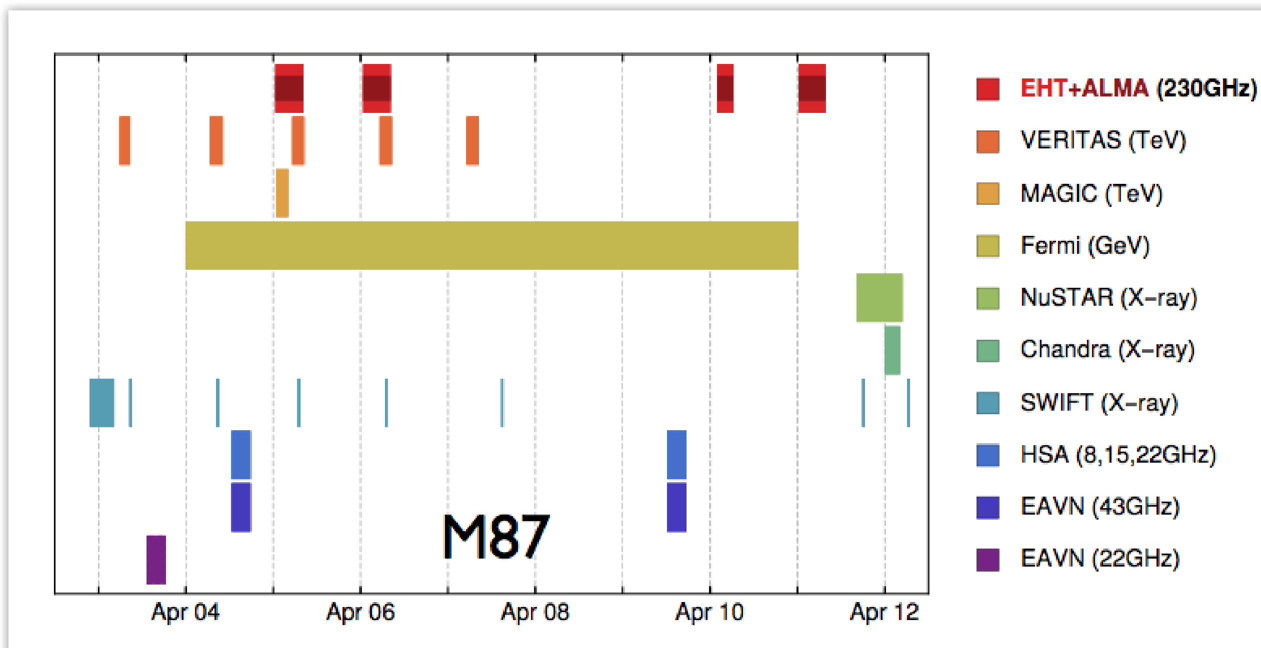
BlackHoleCam

- April 5 -11 2017
- 8 telescopes, 6 sites
  (Largest 1mm VLBI
  experiment ever tried)
- 3 new stations, one dropped
- 5 observing nights in 10 day period
- ~4 PB raw data
- Overall excellent weather!
- Only minor technical hiccups (fraction of lost data small)
- **„Fringes“ to all stations!**
  ⇒ Imaging is technically possible!

MWL Campaign during EHT run

April 2017 campaign

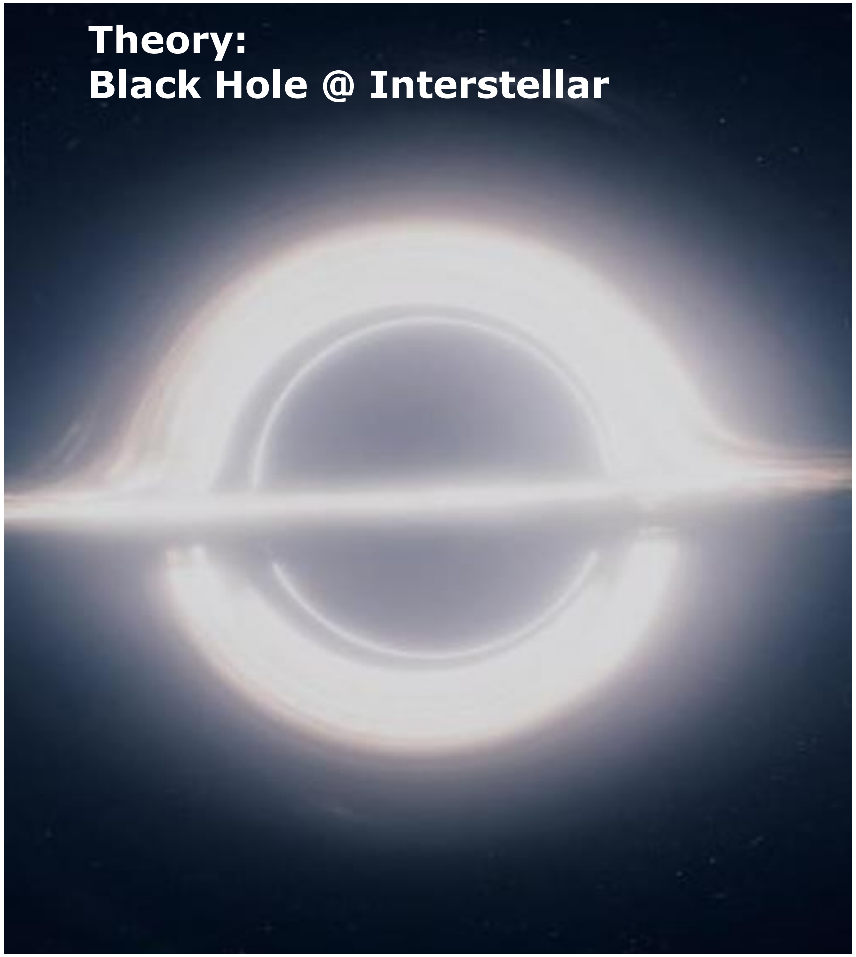


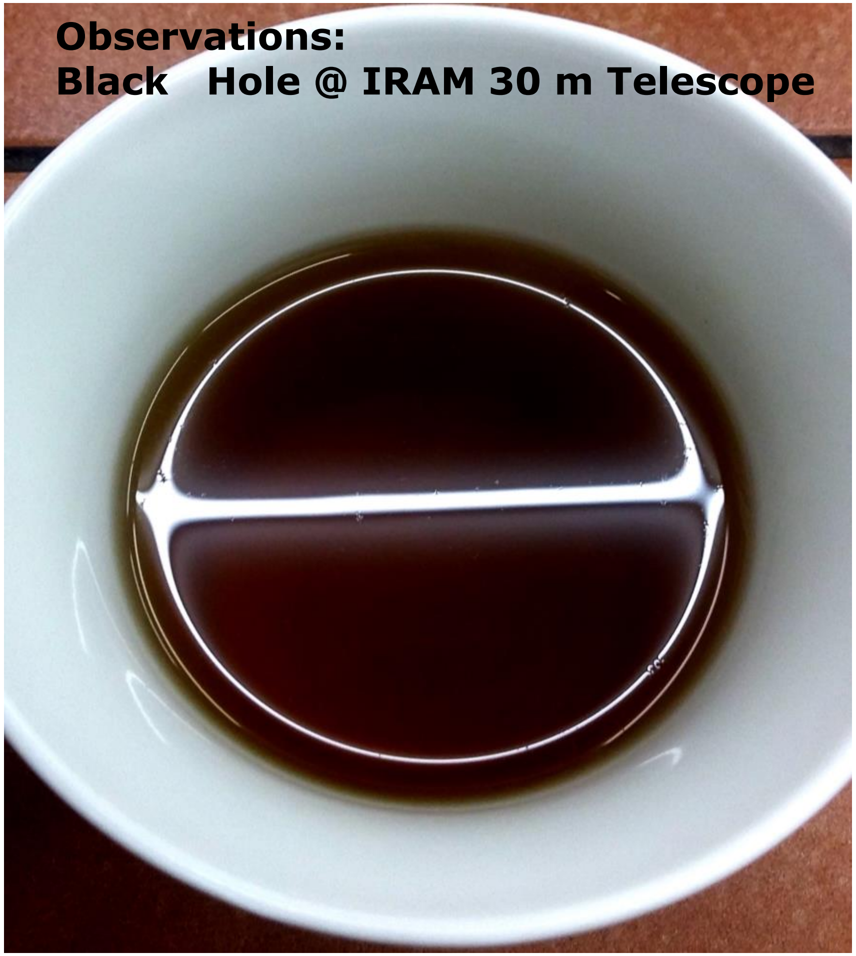


*So **when** are we gonna see the image of Sgr A*?*

First (preliminary!) image of a black hole

BlackHoleCam

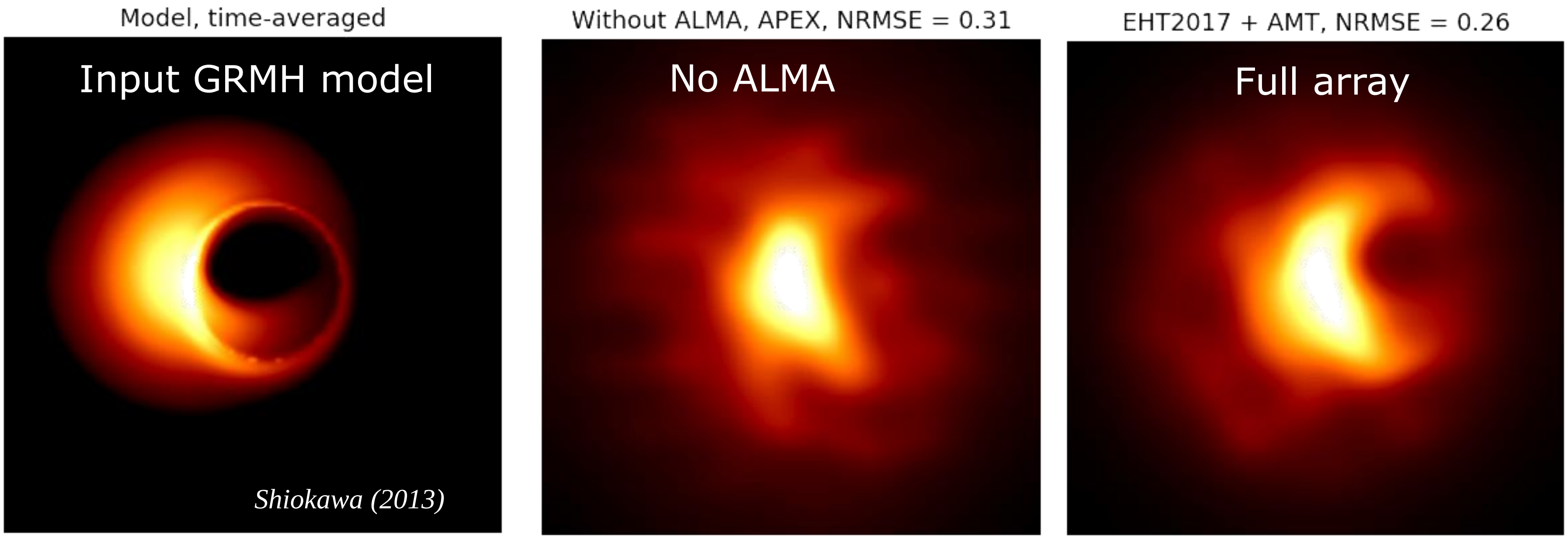




What we **might** actually see

BlackHoleCam

Challenges: troposphere (10 sec), sparse array (max 8 stations, 6 sites), refractive scattering substructures (days), source variability (hours)



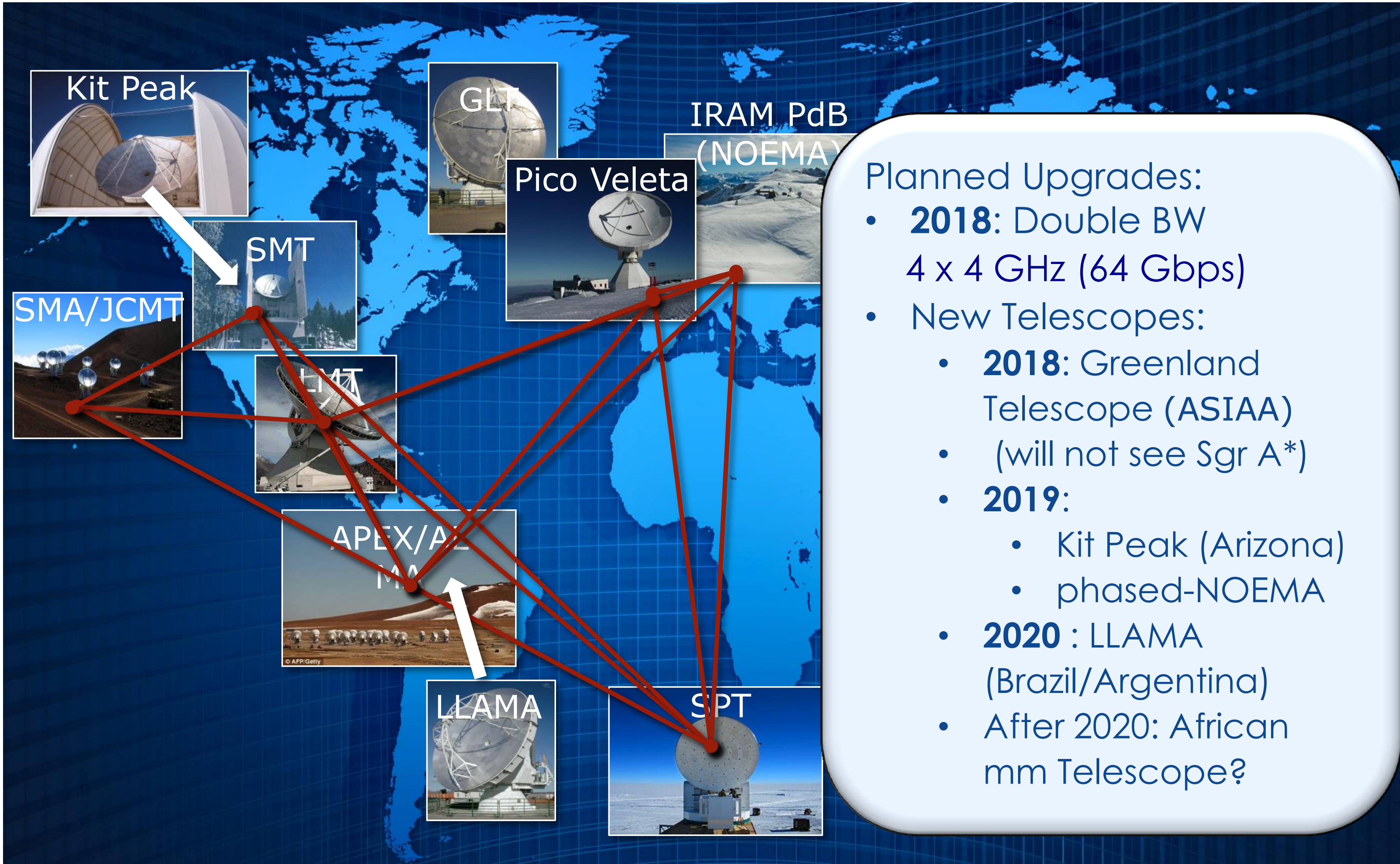
- Includes source **variability**
- 8 epochs
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering
- **EHT imaging** library

F. Roelofs

V. Outlook

Event Horizon Telescope Upgrades

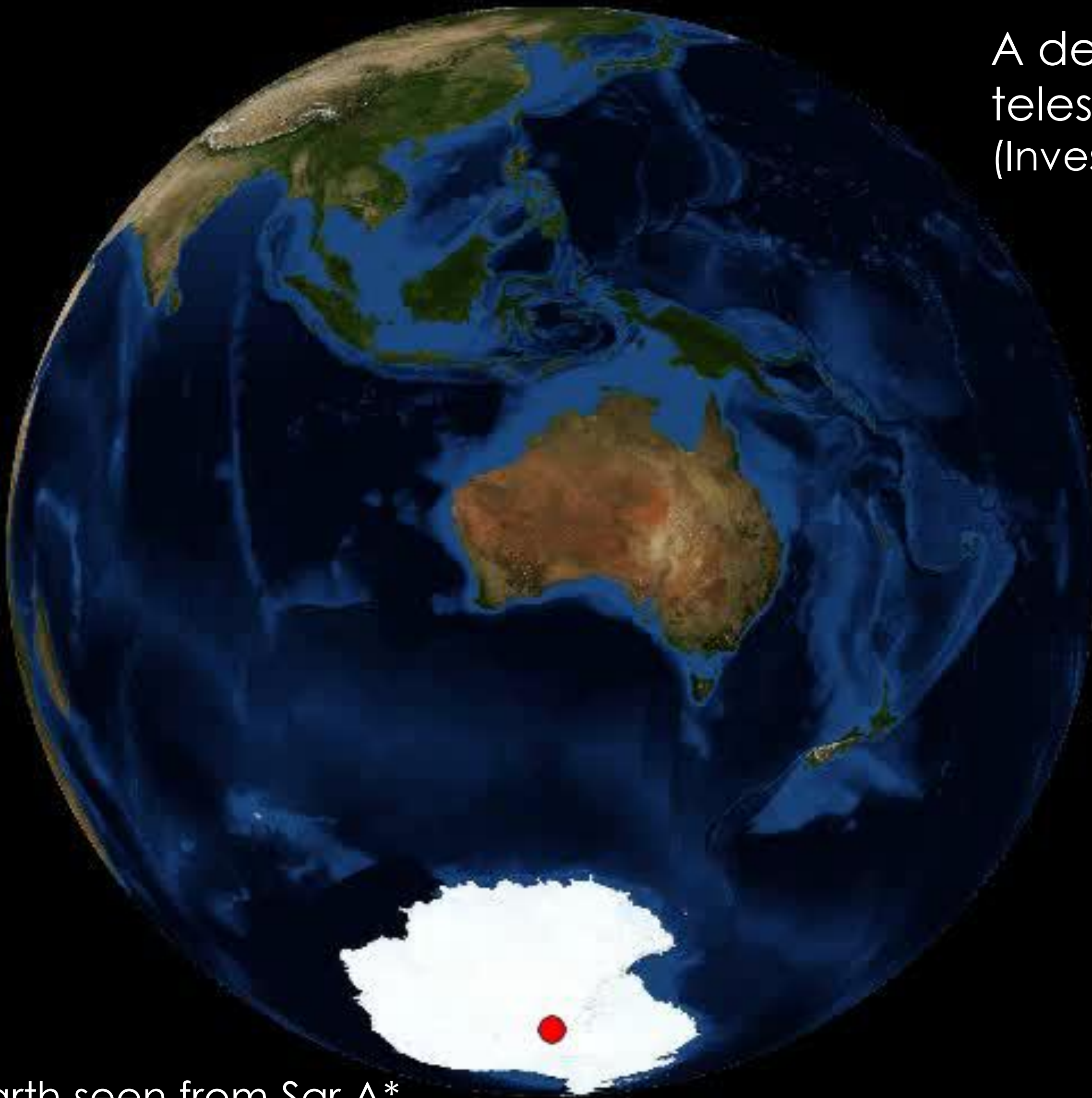
BlackHoleCam



Planned Upgrades:

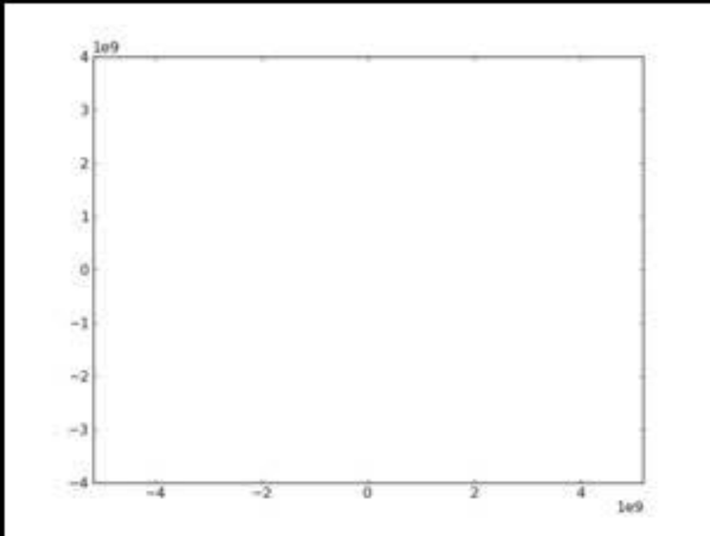
- **2018**: Double BW
  4 x 4 GHz (64 Gbps)
- New Telescopes:
  - **2018**: Greenland Telescope (ASIAA)
  - (will not see Sgr A*)
  - **2019**:
    - Kit Peak (Arizona)
    - phased-NOEMA
  - **2020** : LLAMA (Brazil/Argentina)
  - After 2020: African mm Telescope?

VLBI with Africa mm-telescope?



A dedicated African mm-VLBI telescope for EHT, GMVA & EVN
(Investment cost: ~8 M€ + ops …)

Earth seen from Sgr A*



Not only VLBI and shadow image…..

The image itself might not be able to identify deviations from a Kerr spacetime due to correlations with mass and spin magnitude and orientation

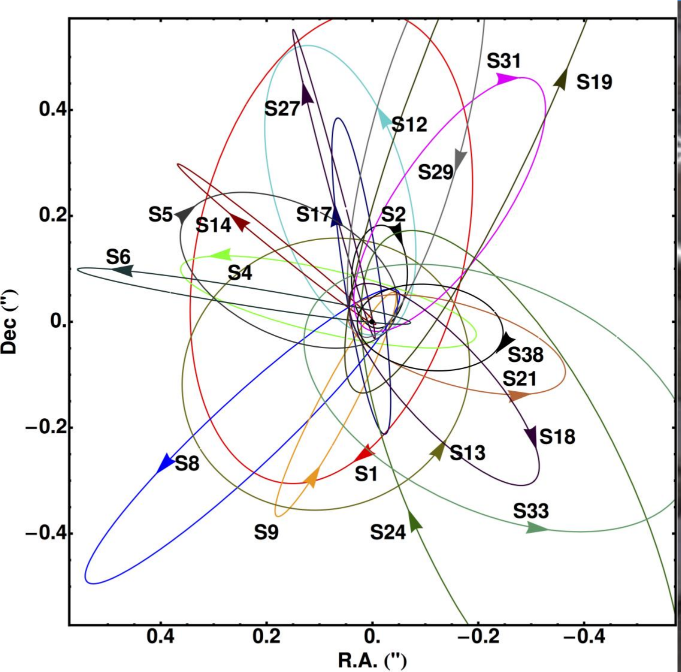
$\Rightarrow$*key to determine the BH parameters (mass, spin, inclination) independently from the imaging*

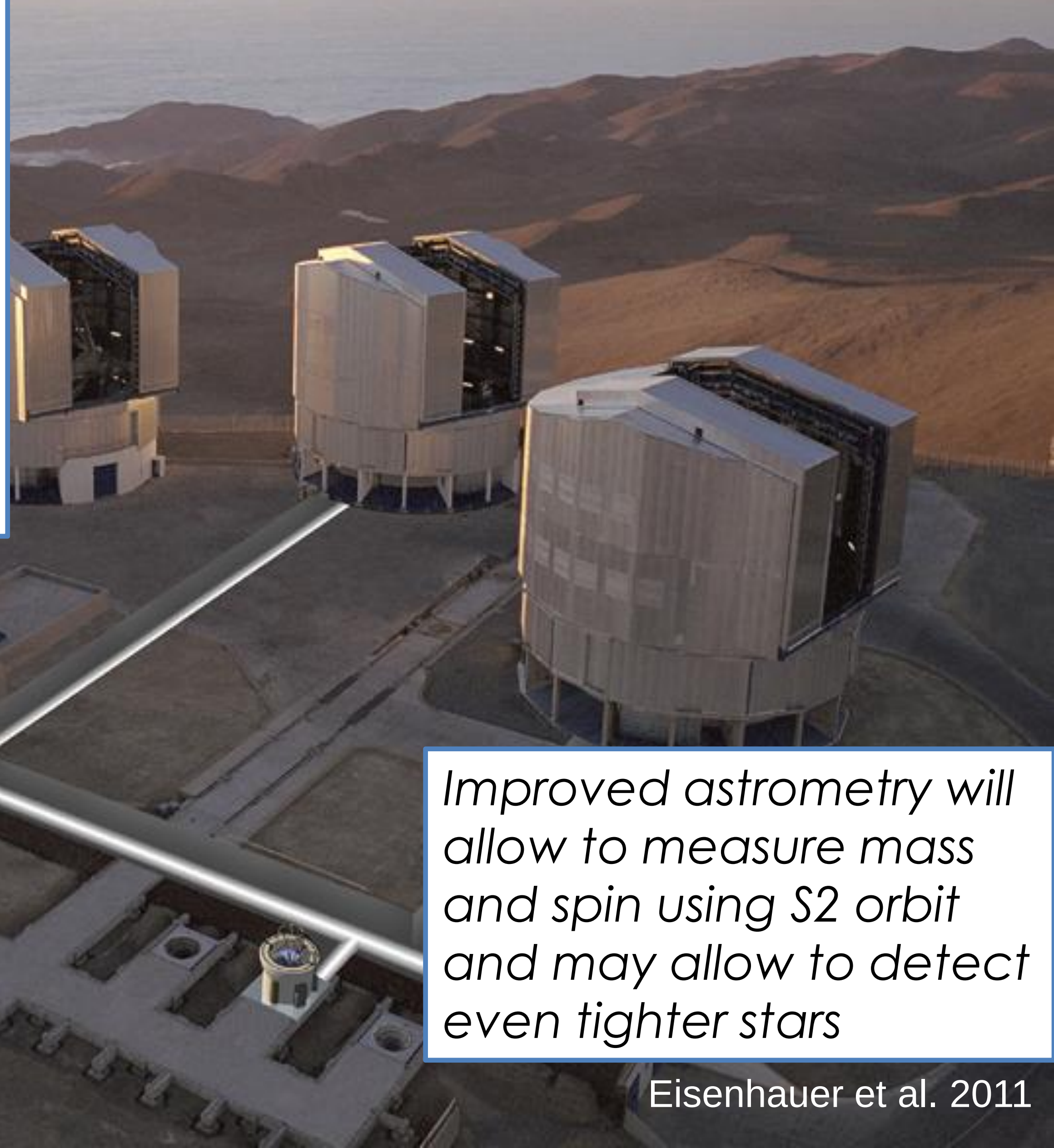
Stellar orbits with GRAVITY @ ESO VLTI

Milestones:
- First science light in 2017
- Measuring S2 periastron in May 2018

Astrometry:
- few 10 μas in 5 minutes

Interferometric Imaging:
- Few mas resolution

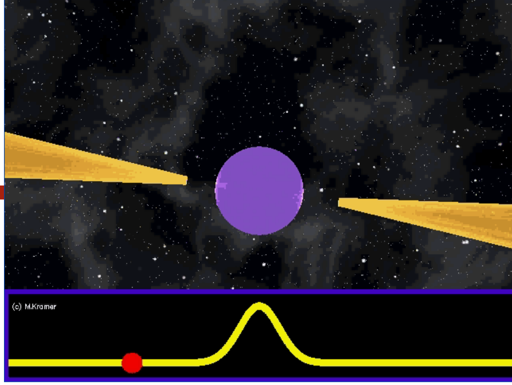




Improved astrometry will allow to measure mass and spin using S2 orbit and may allow to detect even tighter stars

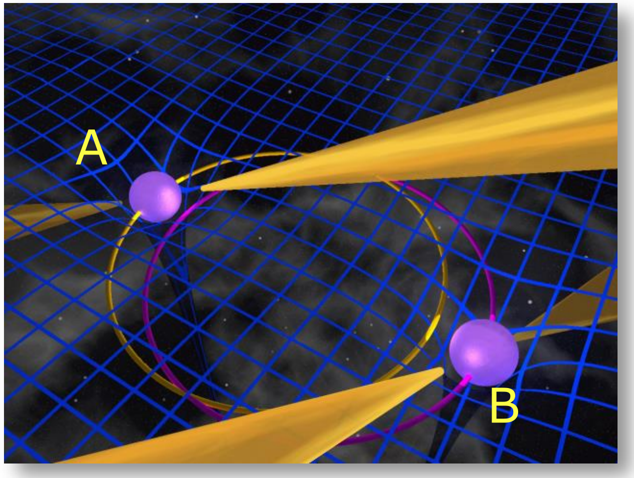
Eisenhauer et al. 2011

Even better a pulsar!



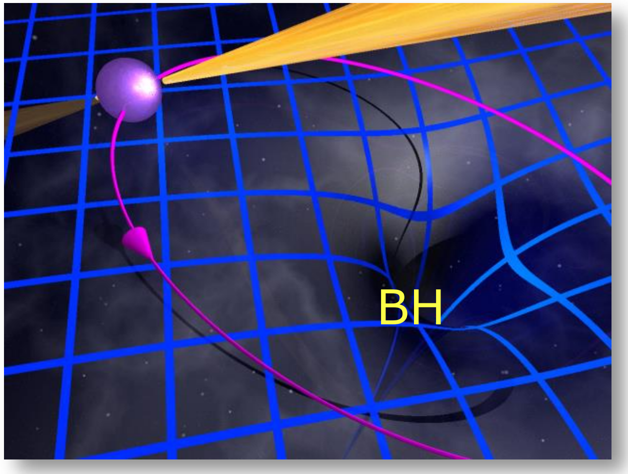
Why do we want to find a pulsar orbiting the SMBH in the centre of our Galaxy?

Binary pulsars



- gauge and weigh companion to test predictions of theories of gravity. E.g.:
  - Hulse-Taylor binary (Hulse & Taylor 1975)
  - Double Pulsar (Lyne et al. 2004)

Binary pulsar-BH

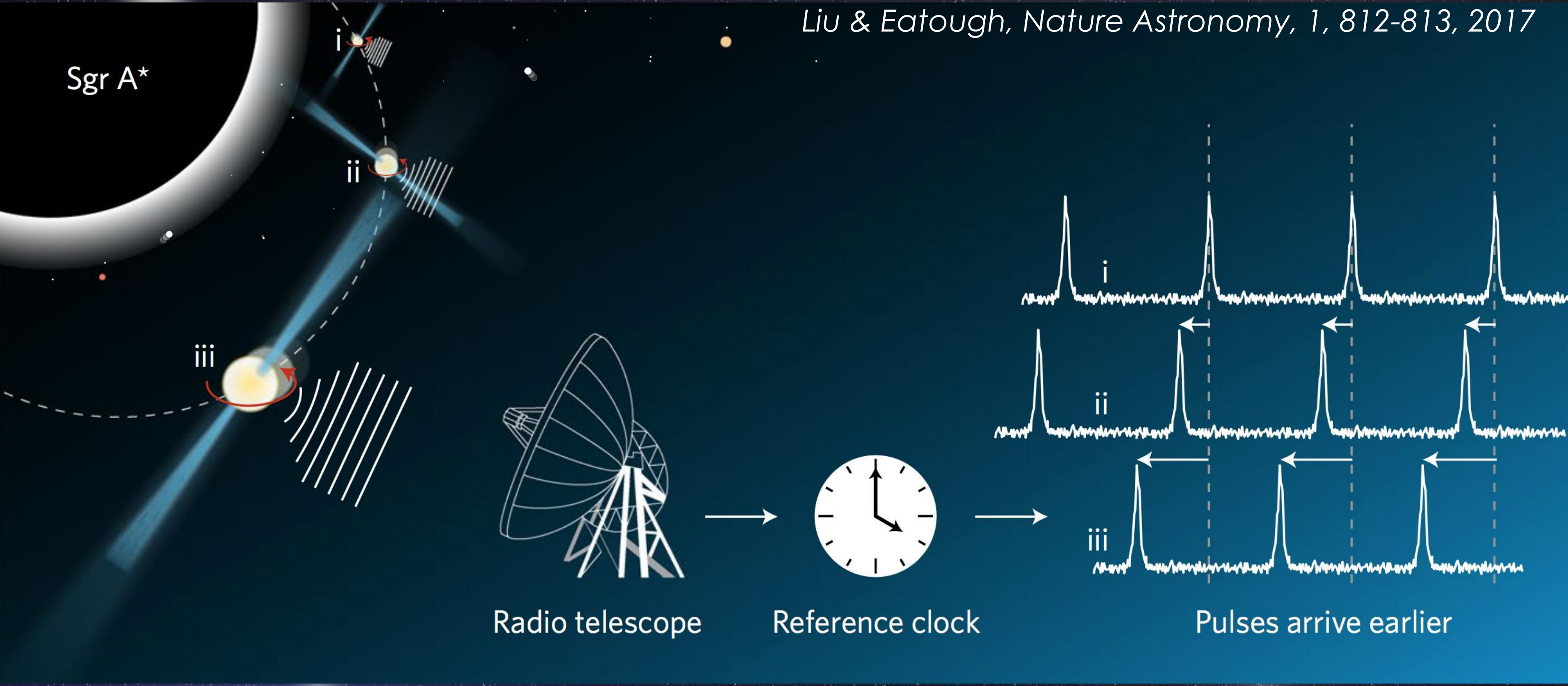


- Ability to measure BH properties scales with mass
- For few-million solar mass BH:
  - *Mass with precision of 1:1,000,000!*

M. Kramer

Pulsar orbiting Sgr A*

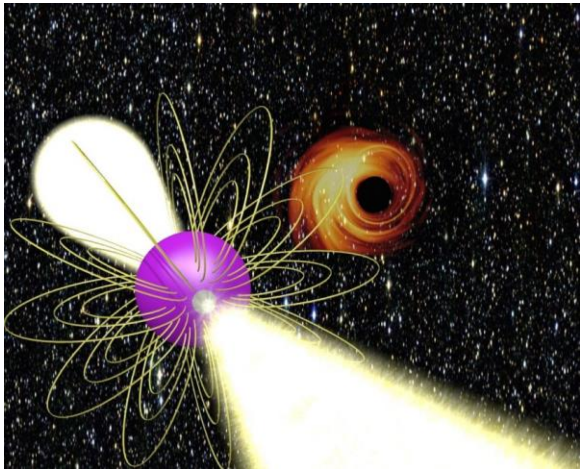
Pulsar in a 0.3 yr eccentric (e = 0.5) orbit
Semi-major axis: 72 AU = 860 $R_{Schwarzschild}$
Pericentre distance: 36 AU = 430 $R_{Schwarzschild}$
Pericentre velocity: 0.042 c



- Highly precise measurement of the black hole **mass** : ~ 0.001%
- Precise measurement of the **Lense-Thirring effect / spin**: ~ 0.1 … 1 % + spin orientatio
- **Testing GR** with a pulsar-black holes system and **the Kerr-hypothesis** (no-hair theoren test)

Complementarity to imaging

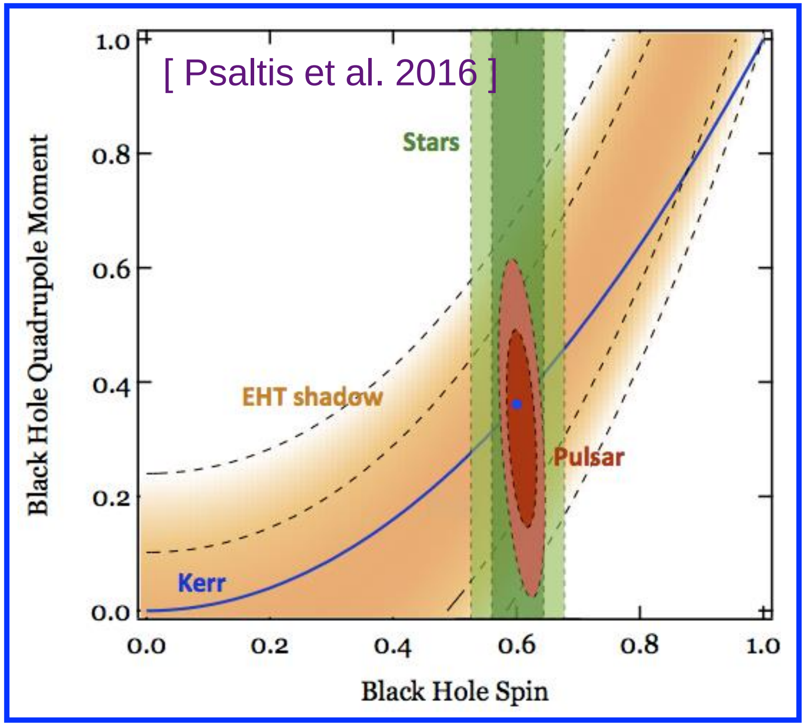
BlackHoleCam



1. Pulsars and stars probe the far-field (100-1,000s Rg), the shadow image probes the near-field (< 10s Rg)

1. The 3 different techniques are affected by very different systematics which can be characterized by cross-comparison

2. Uncertainties in measurements of BH spin and quadrupole moment using orbits of stars and pulsars are nearly orthogonal to those obtained from the image



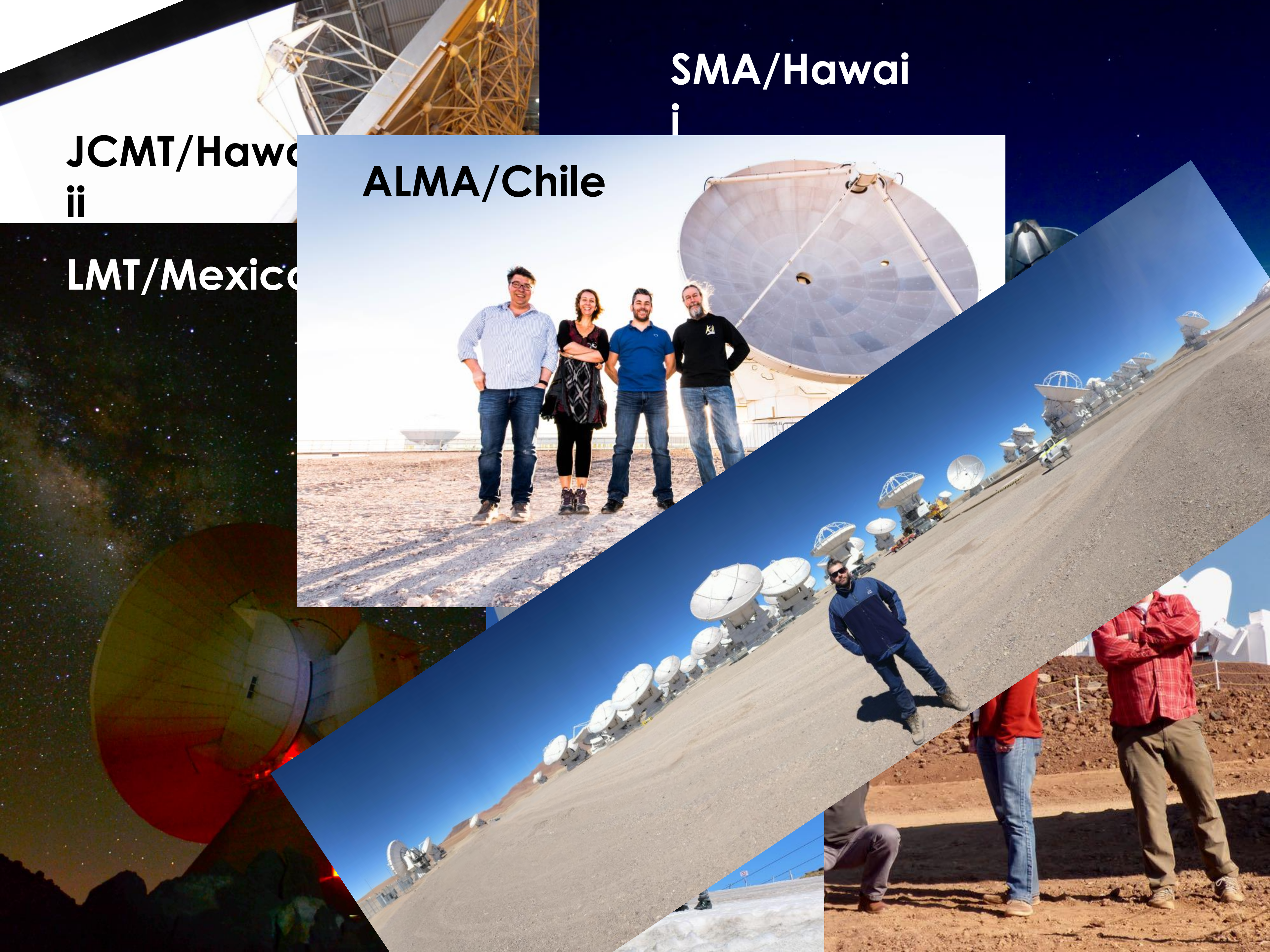
Conclusions & Remarks

BlackHoleCam

- Imaging the event horizon is possible for at least two SMBHs.
- First **EHT** campaign with ALMA conducted in April 2017
  - Data looks excellent so far, **imaging** is technically possible
- Images will look crappy at first, but they will become sharper with time: EHT, 345 GHz, Africa, Space …
- We have a powerful set of **theoretical tools** to compare data with and **test theories of gravity**
- **Stellar orbits** will constrain spin and mass better with **GRAVITY** @VLT
- **Pulsars** searches in the GC being conducted with radio and mm telescopes (Effelsberg, Pico-Veleta, LMT, **phased-ALMA**)

The Galactic center will allow precision tests of GR!

3D animation by Bronzwaer, Davelaar, Moscibrodzka et al. (BHC team)


SMA/Hawai
i
JCMT/Haw
ii
LMT/Mexic
ALMA/Chile