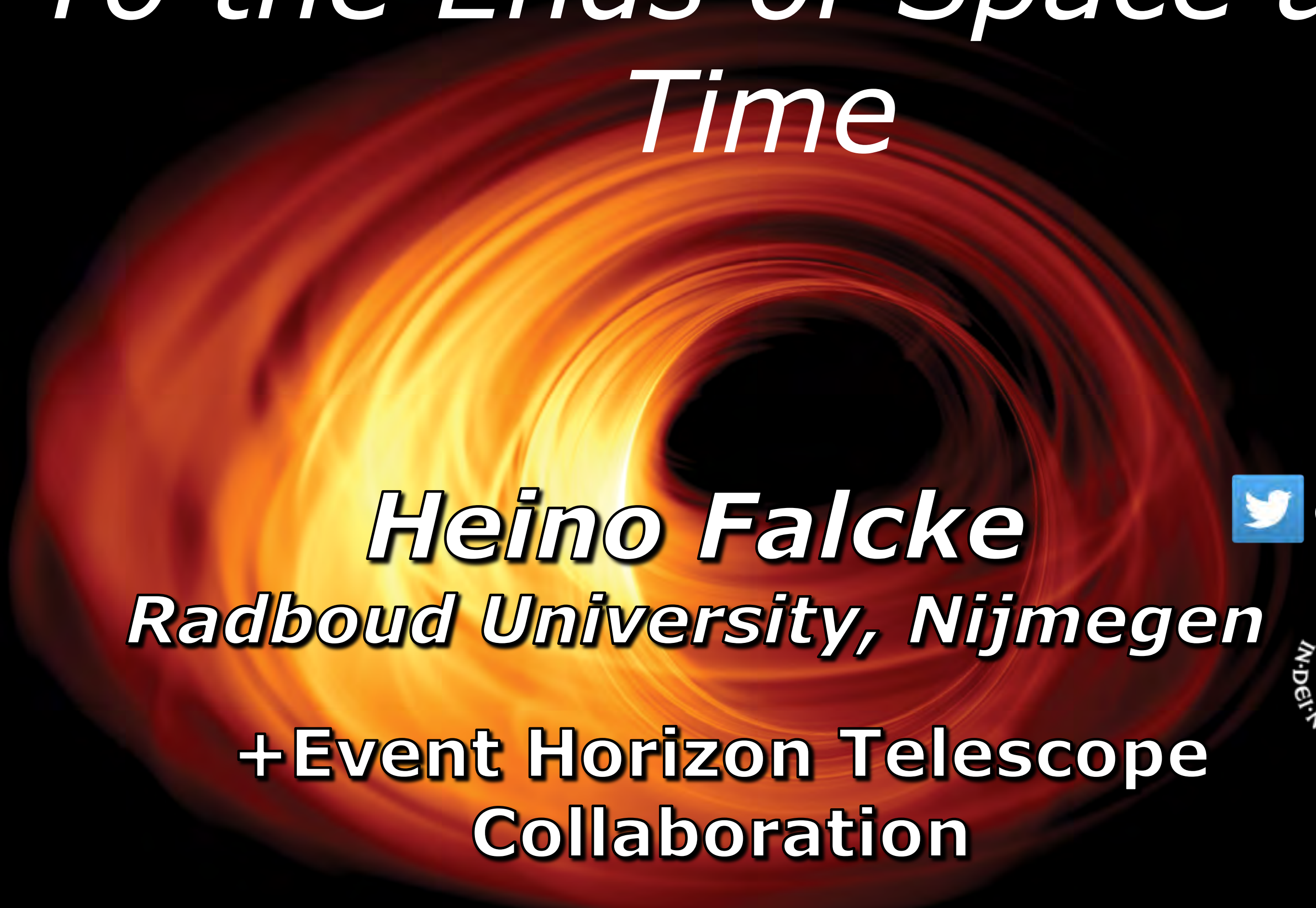
To the Ends of Space and Time



Heino Falcke

Radboud University, Nijmegen

@hfalcke

IN·DEI·NOMINE·FELICITER

+Event Horizon Telescope Collaboration

RADBOUD RADIO LAB

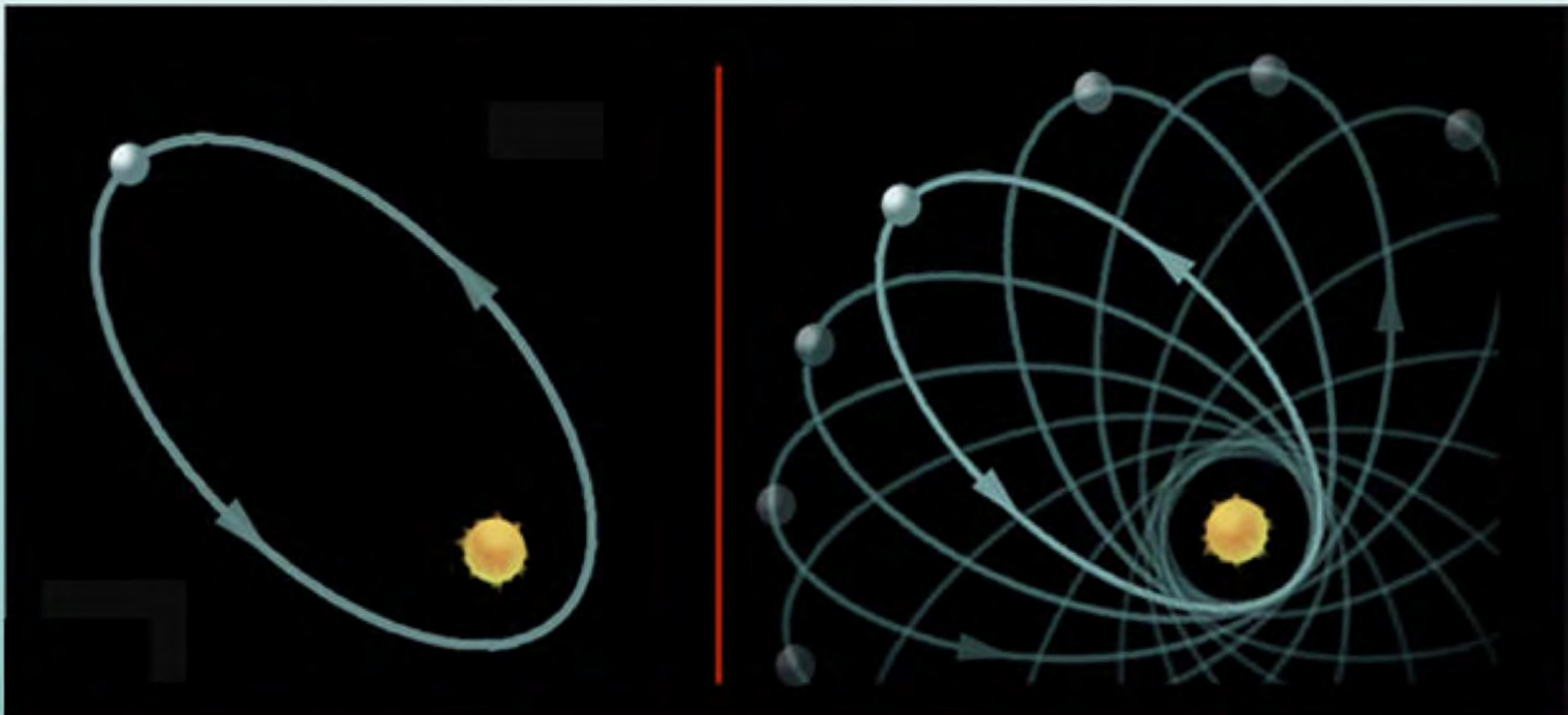
erc European Research Council

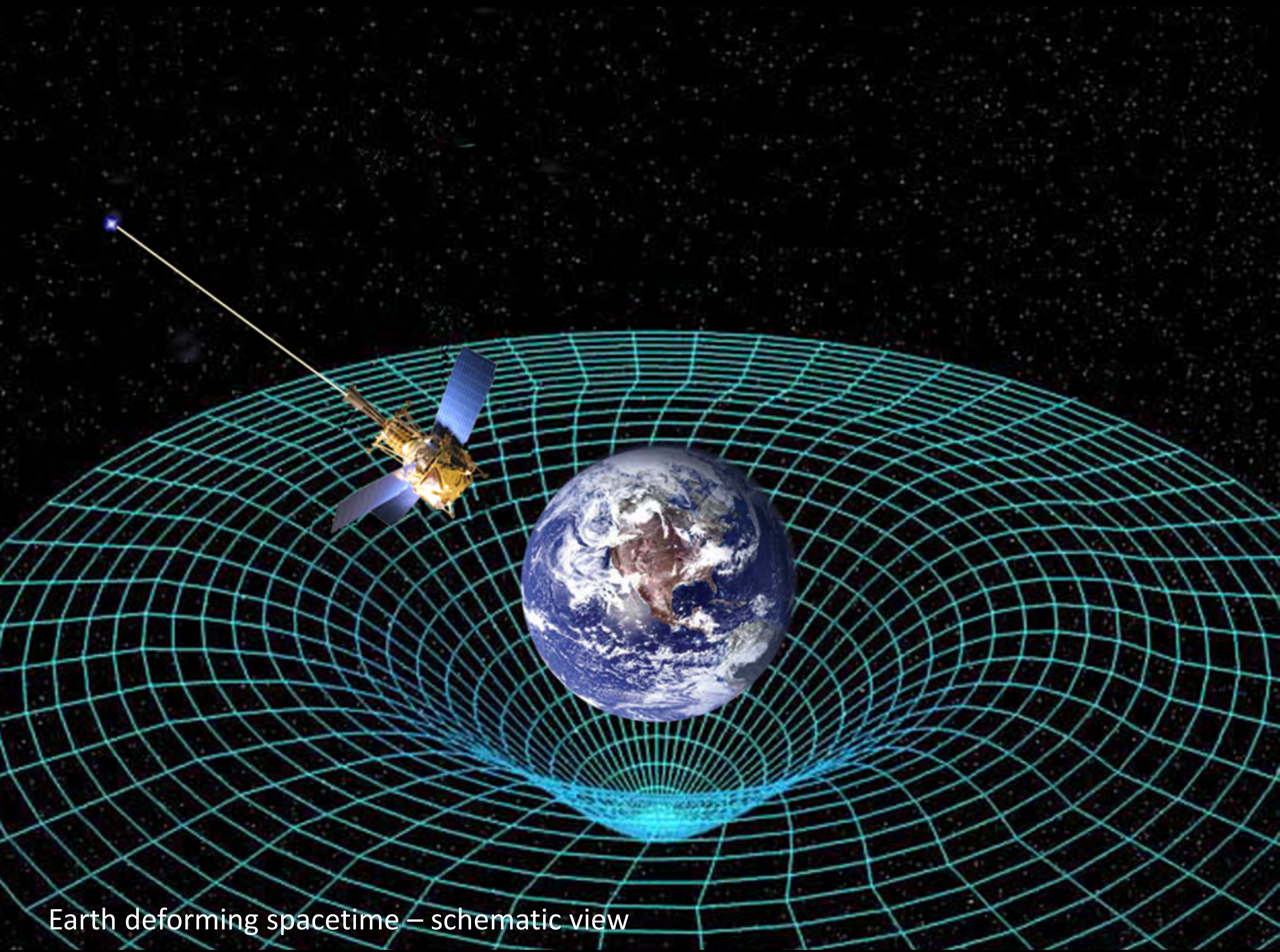
BLACK HOLE CAM

ERC Synergy Grant Co-PIs:
L. Rezzolla (U. Frankfurt)
M. Kramer (MPIfR Bonn)

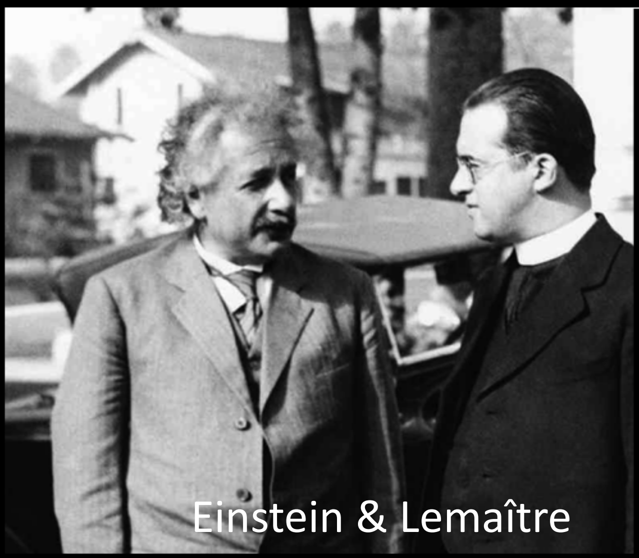
Disk of Nebra
~1600 BC

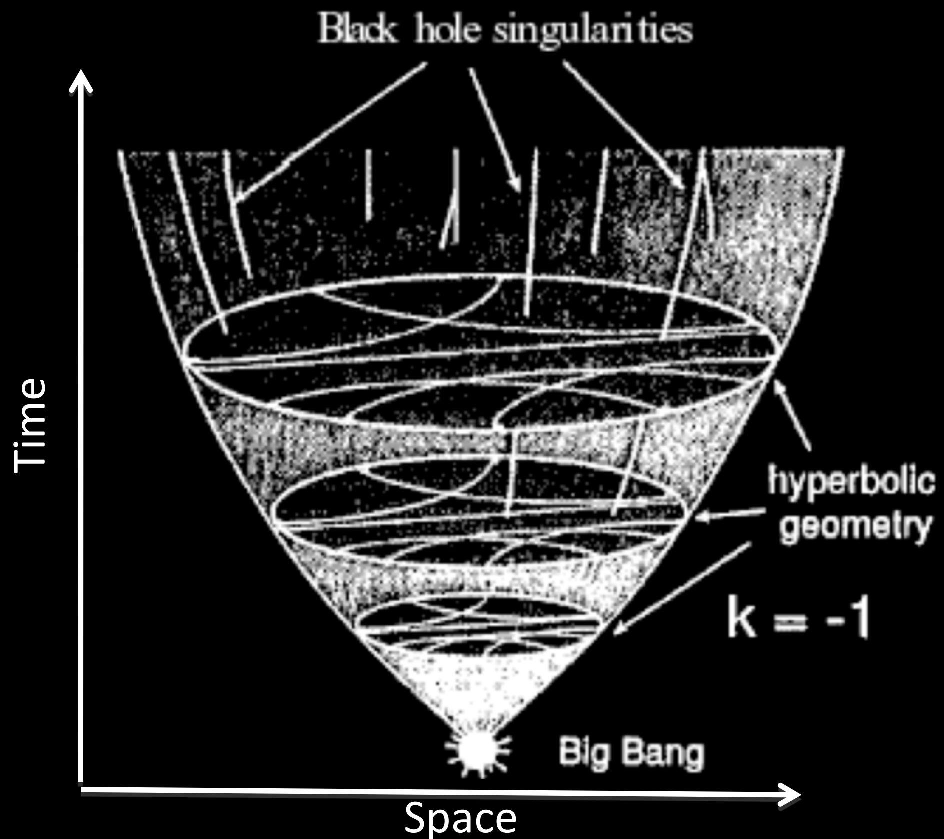
MERCURY'S ORBIT




Earth deforming spacetime – schematic view

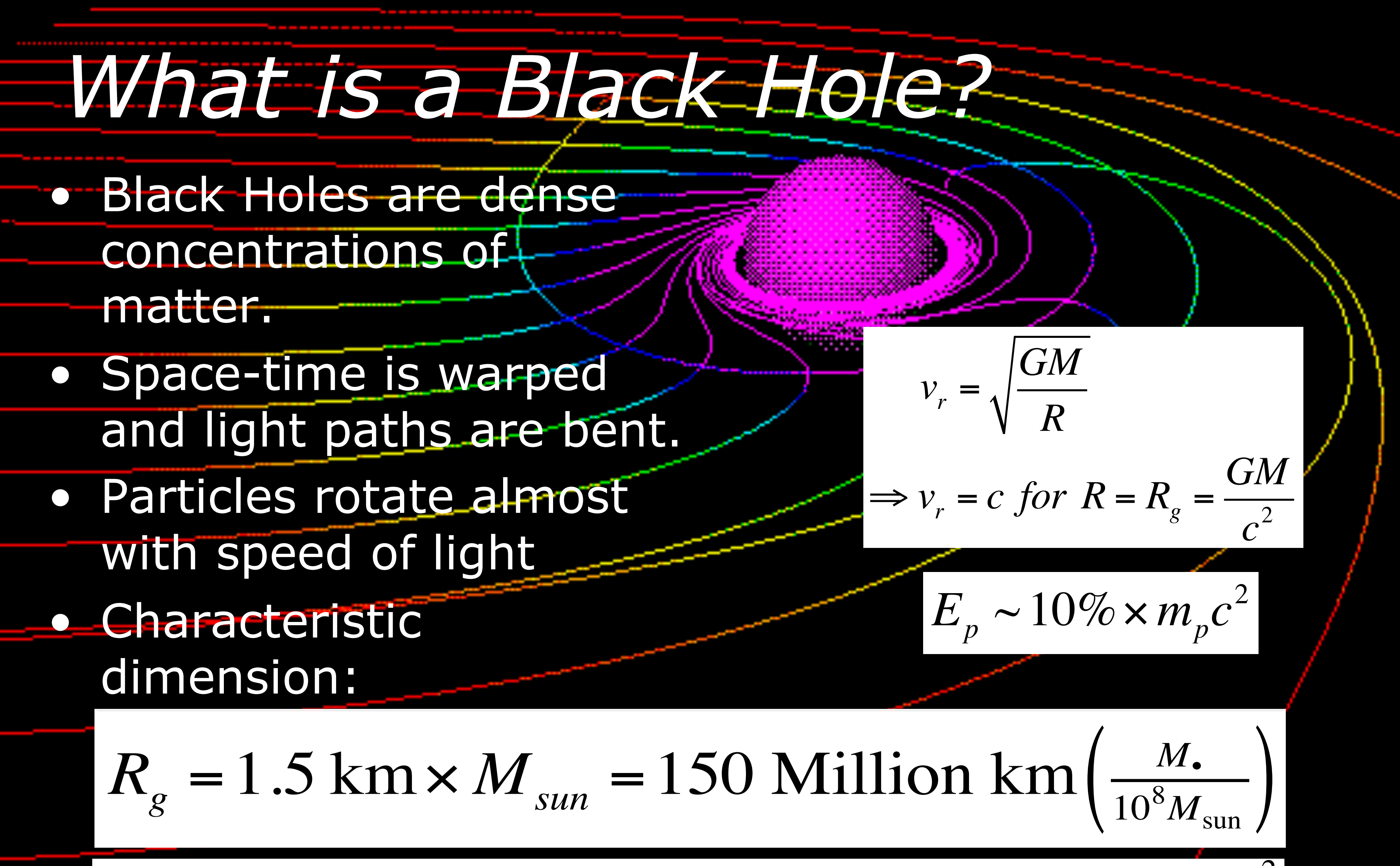
Singularities in the universe: Beginning and end of spacetime





Penrose (1996)

What is a Black Hole?



- Black Holes are dense concentrations of matter.
- Space-time is warped and light paths are bent.
- Particles rotate almost with speed of light
- Characteristic dimension:

$$v_r = \sqrt{\frac{GM}{R}}$$

$$\Rightarrow v_r = c \;\; for \;\; R = R_g = \frac{GM}{c^2}$$

$$E_p \sim 10\% \times m_p c^2$$

$$R_g = 1.5\,\mathrm{km} \times M_{sun} = 150\ \mathrm{Million\ km}\left(\frac{M_\bullet}{10^8 M_{\mathrm{sun}}}\right)$$

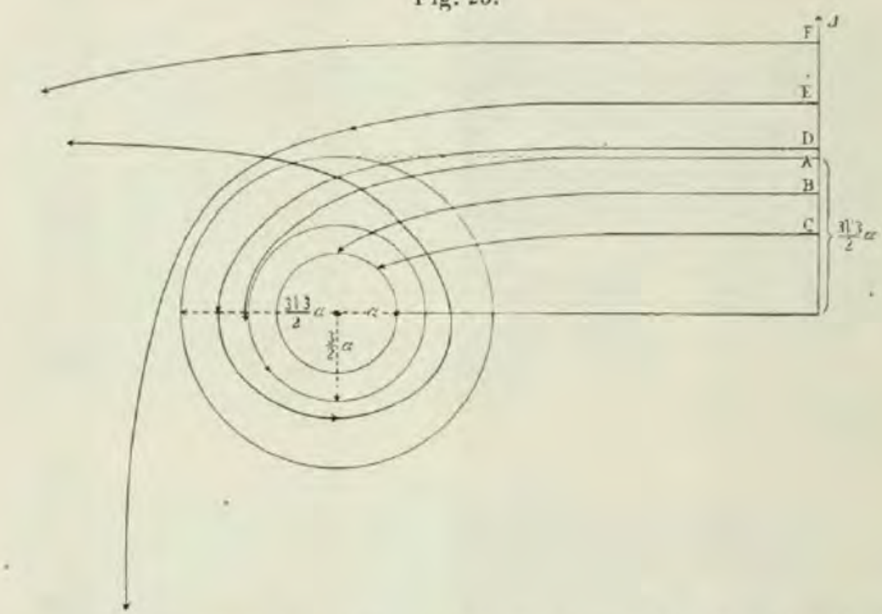
$$\rho_\bullet = \frac{M_\bullet}{4/3\,\pi\left(2R_{\mathrm{g}}\right)^3} \approx 10^{16}\, g\, cm^{-3} \times (\mathrm{M}_{sun})^{-2} \approx 2\, g\, cm^{-3}\left(\frac{M_\bullet}{10^8 M_{\mathrm{sun}}}\right)^{-2}$$

How a black hole looks like

Radboud University Nijmegen

Daraus ziehen wir in Anlehnung an Poincarés Zykeltheorie den überdies recht anschaulichen Schluß: Der Lichtstrahl, der im Unendlichen auf den Abstand $\varDelta = \frac{3\sqrt{3}}{2}\,\alpha$ hinzielt, biegt sich nach innen und nähert sich auf einer Spirale asymptotisch dem Kreise $r = \frac{3}{2}\alpha$. Dann ergibt sich für die Gesamtheit der betrachteten Strahlen die Fig. 23. Sie zeigt uns die Kreise $r = \alpha$,

Fig. 23.



an welchem jeder herankommende Lichtstrahl endigt (ist doch dort die Lichtgeschwindigkeit 0), ferner $r = \frac{3}{2}\alpha$ und $r = \frac{3\sqrt{3}}{2}\,\alpha$.

(HT: E. Ros)

Max von Laune (1921): "Die Relativitätstheorie. Zweiter Band", Vieweg, 1921

stabe der r, zwischen α und $\frac{3}{2}\alpha$ liegt, so vergrößert, daß sie ihm den Halbmesser $\frac{3\sqrt{3}}{2}\,\alpha$ zu haben scheint. Überhaupt alle Kugeln werden optisch vergrößert. Die im Text folgende Rechnung gibt für die rela-

Based on **David Hilbert (1916)**: lectures, "Die Grundlagen der Physik"

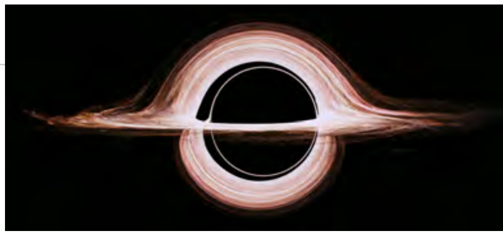
Black Hole "photon orbit":

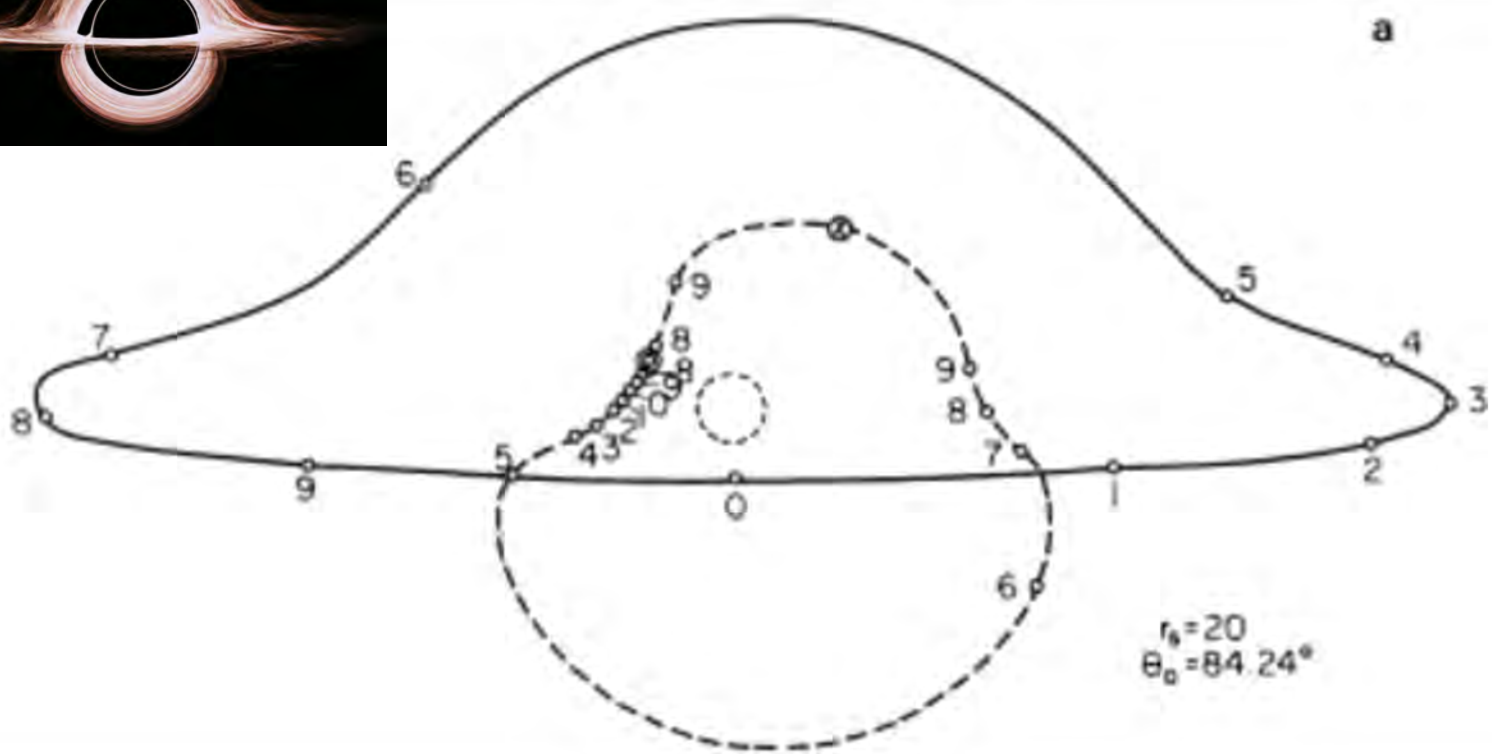
$$R_{ph} = \frac{3}{2} R_S$$

Black Hole "cross section":

$$D = 3\sqrt{3}R_S \sim 5.2 R_S$$

How a black hole looks like





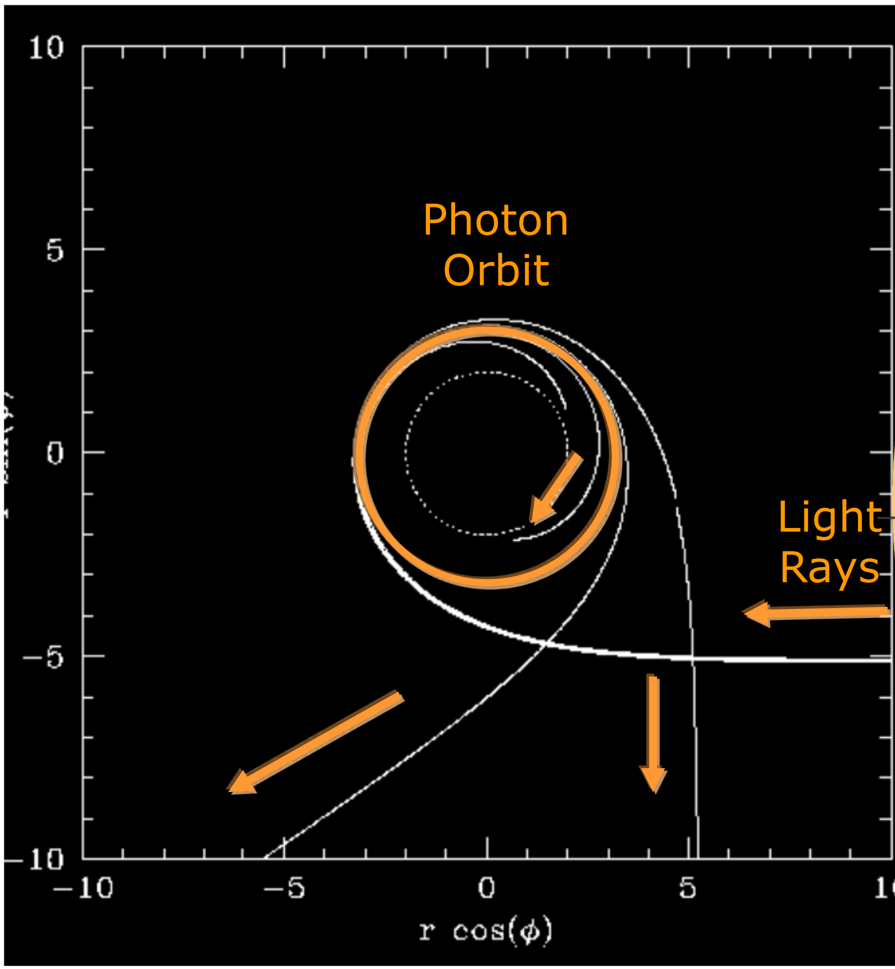
"Image of a star orbiting a black hole" Cunningham & Bardeen (1973)

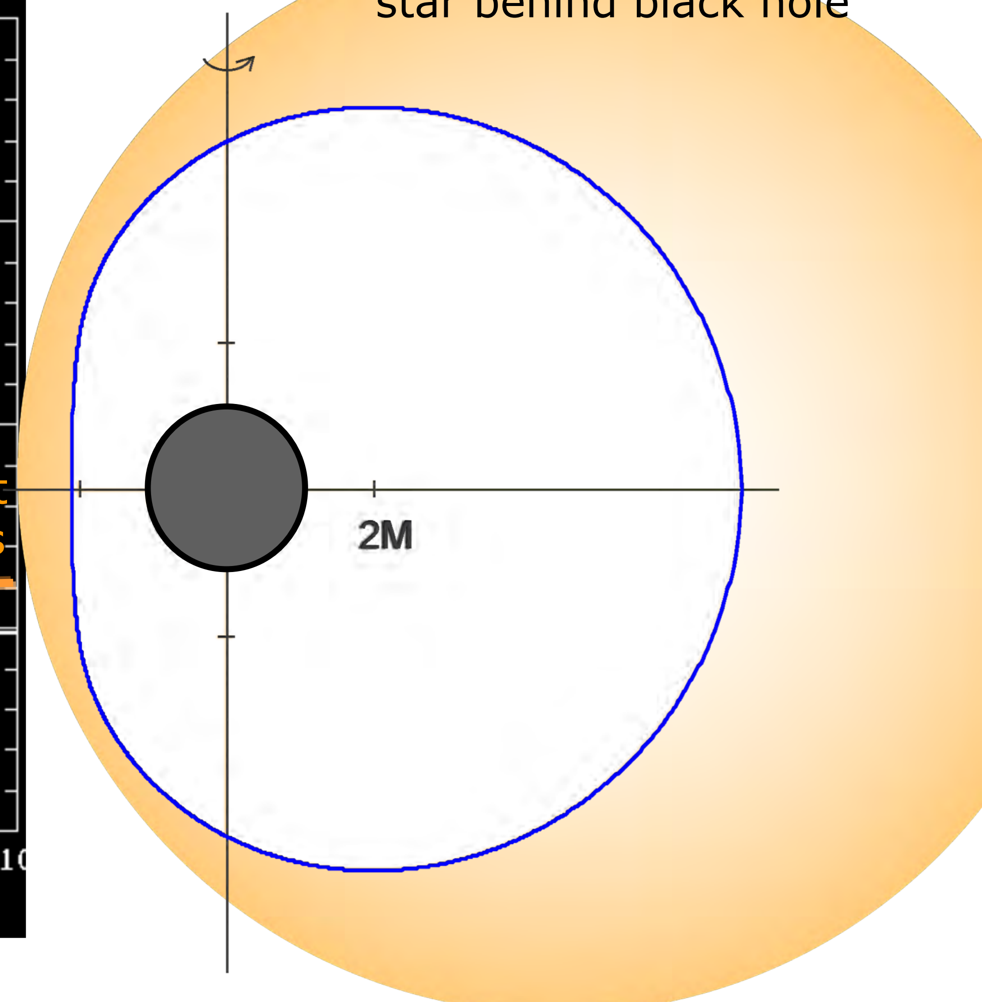
“Photos” of a black hole

Radboud University Nijmegen

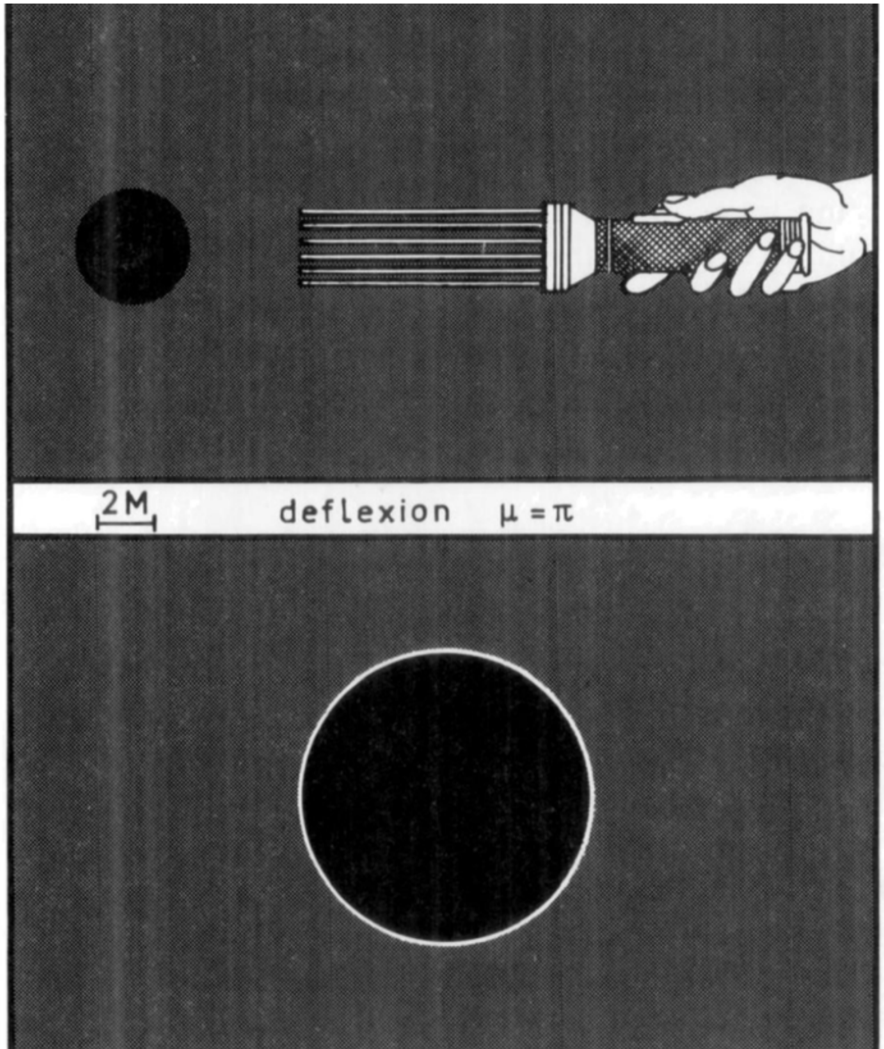
Circular photon orbit: Bardeen (1973)

“star behind black hole”

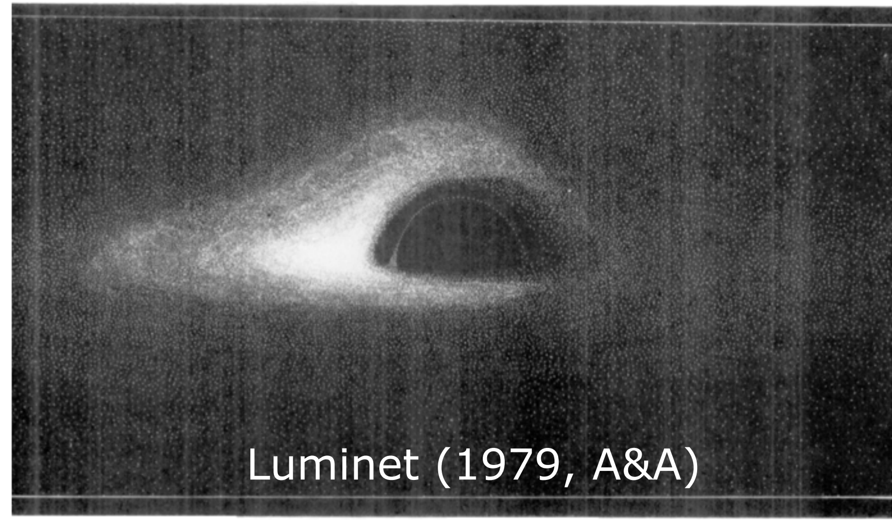




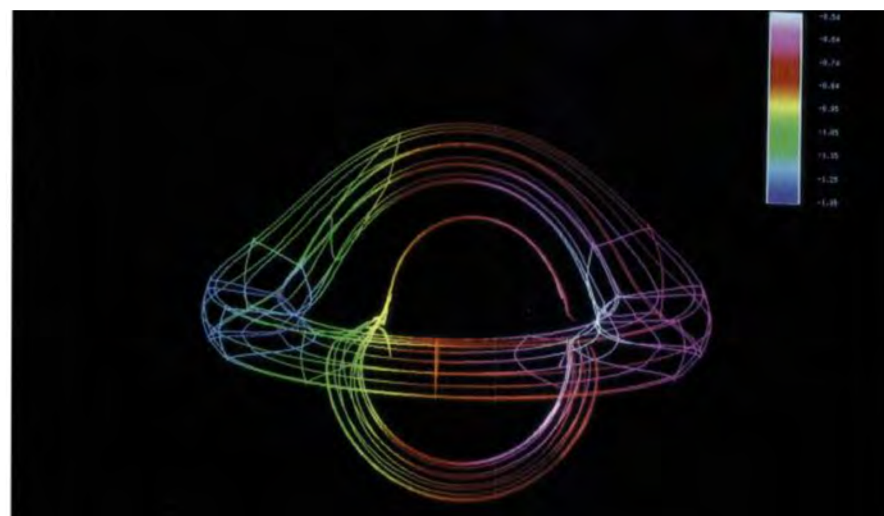
Photos of a black hole



Luminet (1979)



Luminet (1979, A&A)



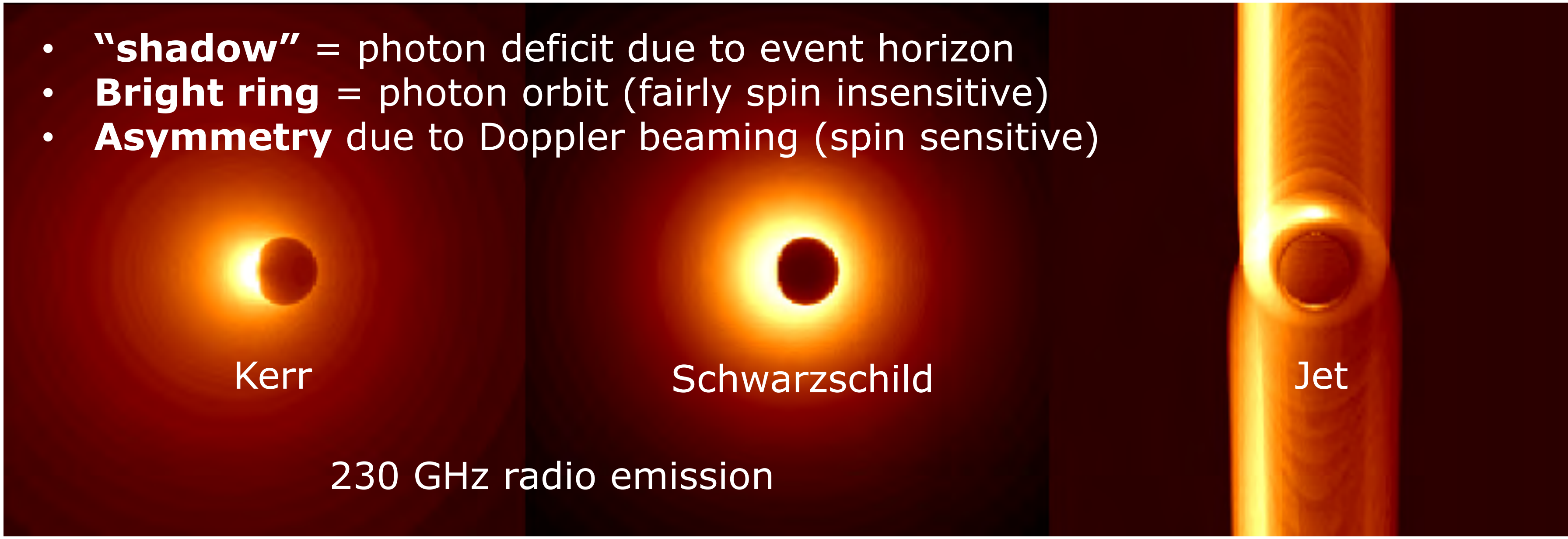
Viergutz (1993, A&A)

Black Hole Shadow

Falcke, Melia, Agol (2000, ApJ & AIPC 522, 317)

Radboud University Nijmegen

- **"shadow"** = photon deficit due to event horizon
- **Bright ring** = photon orbit (fairly spin insensitive)
- **Asymmetry** due to Doppler beaming (spin sensitive)



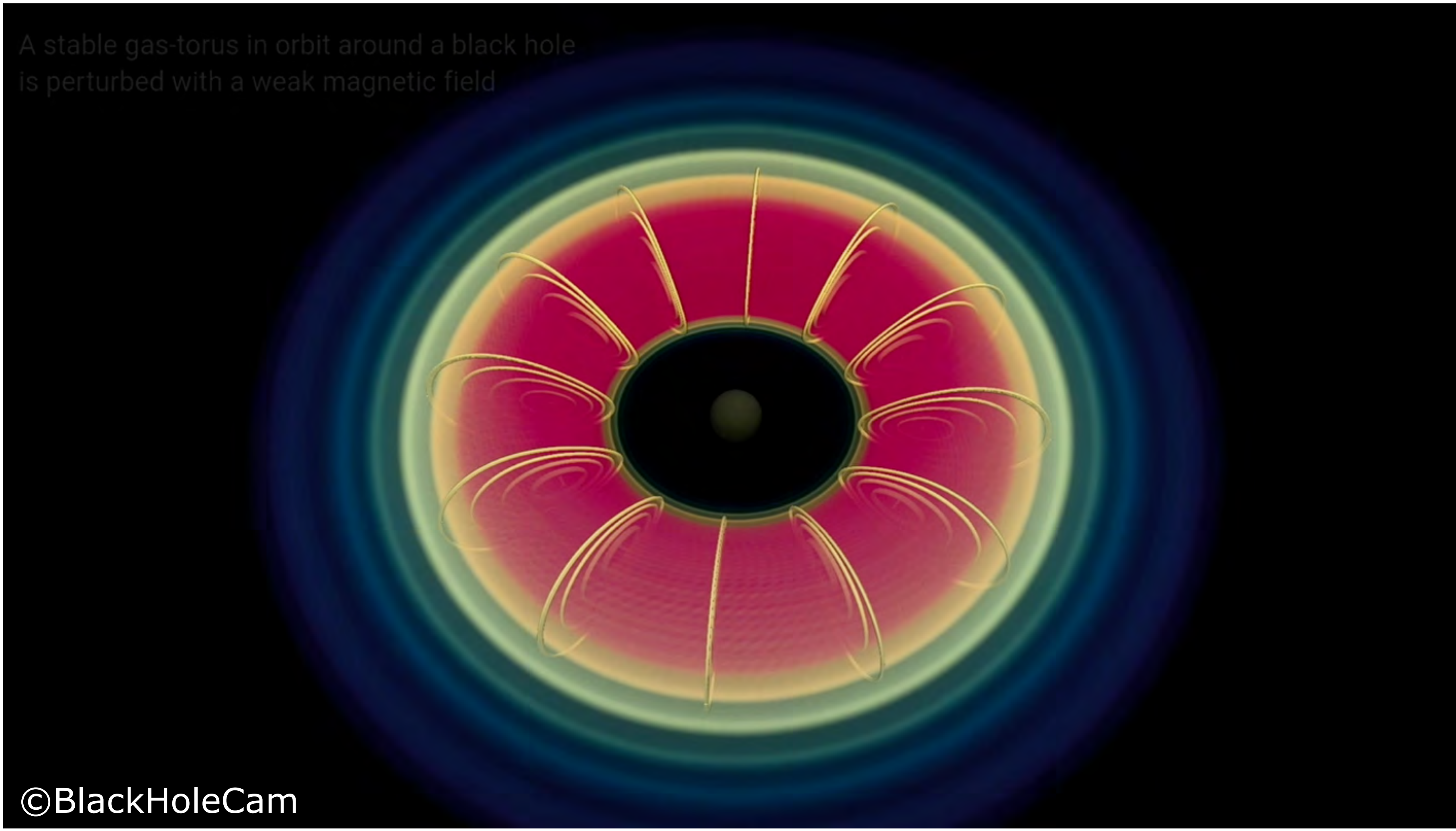
Regardless of the exact emission model we use, we find a characteristic structure in all models: a bright ring of emission with a pronounced deficit of emission inside of that (Fig. 1). We call the deficit in the inner region the "shadow" of the black hole since it is caused by the deficit of photons emitted near the black hole that have disappeared into the event horizon or are bent away from our line of sight. The circumference of the shadow is determined by the 'photon-orbit'—a theoretical orbit where photons can circle the black hole an infinite number of times, but when perturbed may escape to infinity (Bardeen 1973). Interestingly, the size of this

The exact intensity distribution of the bright ring depends significantly on the nature of the emission region, however. A rotating inflow would produce a slightly asymmetric ring due to Doppler-boosting of one side of the shells in Keplerian rotation. A jet would look even more asymmetric since boosting due to rotation

Prediction: Use global interferometry (VLBI at 230 GHz and higher to image the black hole shadow)!

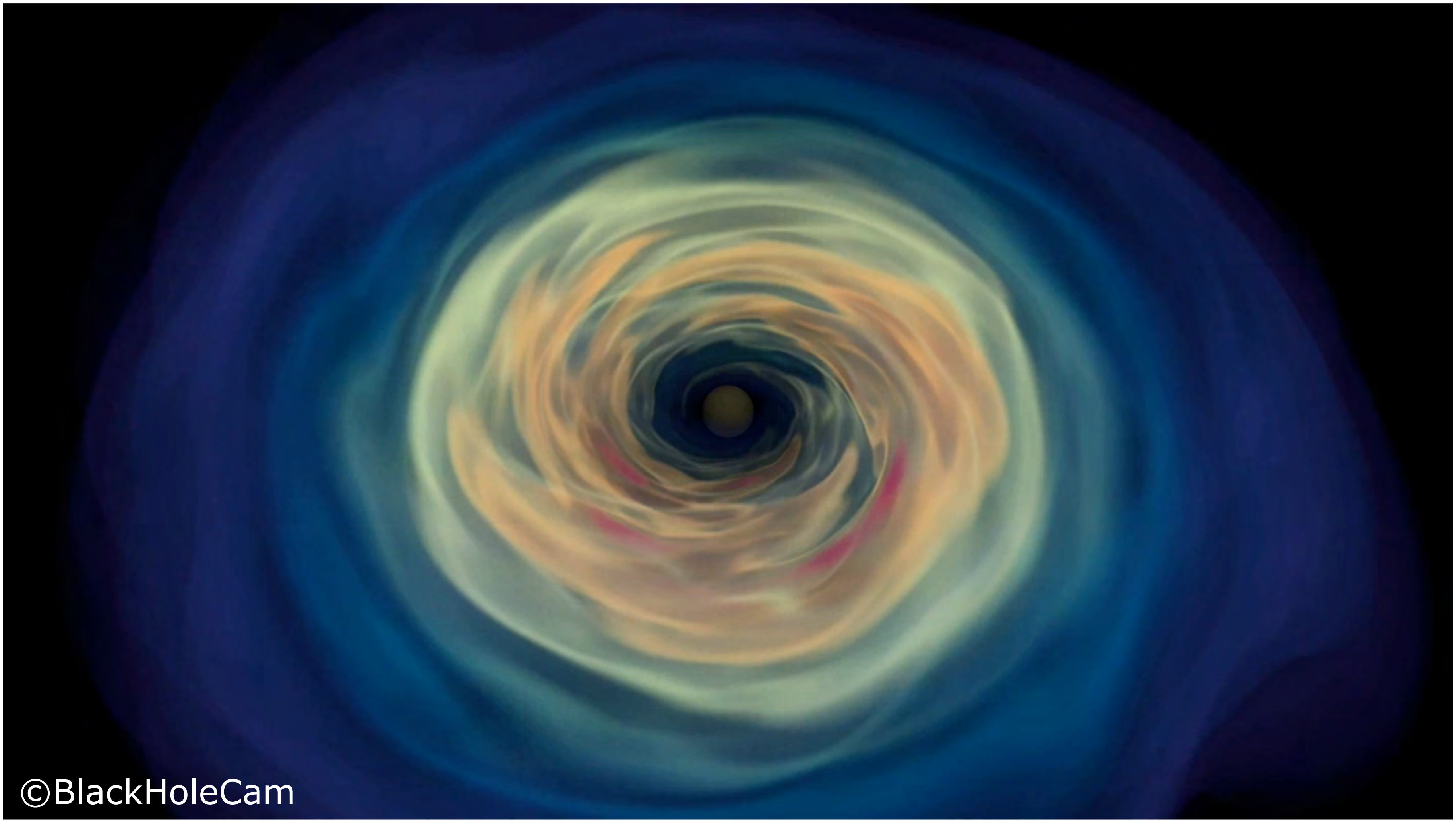
GRMHD Simulation

Radboud University Nijmegen



Mizuno, Porth, Rezzolla + (U Frankfurt)

GRMHD Simulation



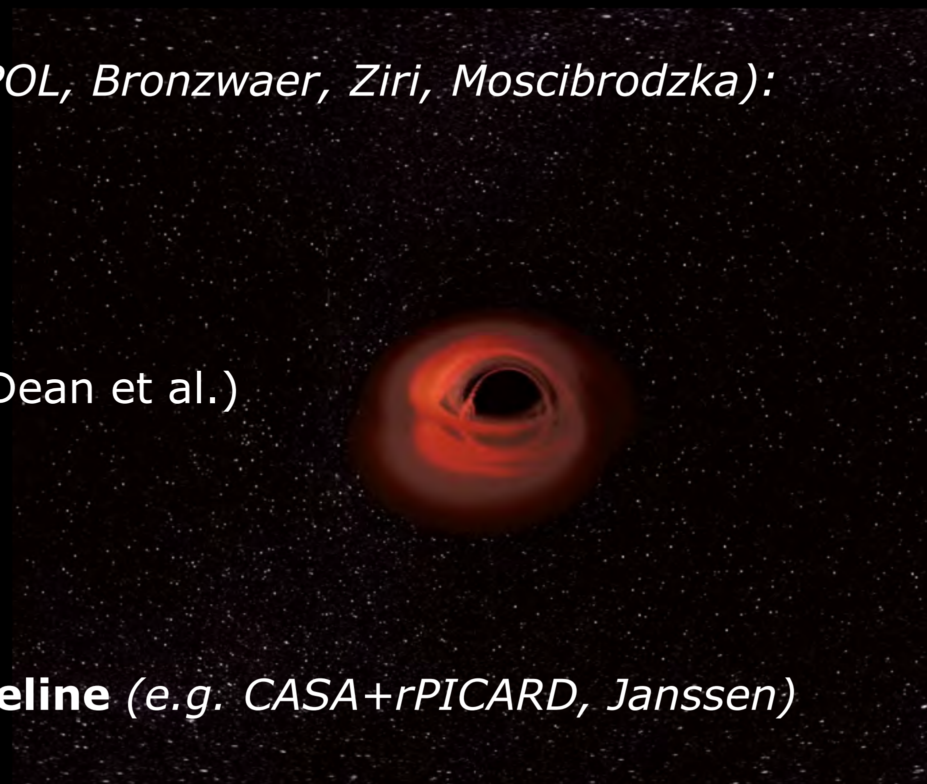
Comprehensive set of Advanced Simulation Tools

- Plasma simulations *(e.g. BHAC Code, Porth et al.):*

- Ideal (soon non-ideal) 3D GRMHD
- Multiple coordinate systems
- Adaptive GRID
- Arbitrary space times

- Ray Tracing *(RAPTOR/BHOSS/IPOL, Bronzwaer, Ziri, Moscibrodzka):*

- Arbitrary space times
- Synchrotron abs/emission
- Thermal & non-thermal particles
- Polarization, Faraday rotation



- VLBI Simulator (MeqSilhouette, Dean et al.)

- Thermal noise
- Troposphere fluctuations
- Pointing errors, Bandpass
- Actual observing schedule

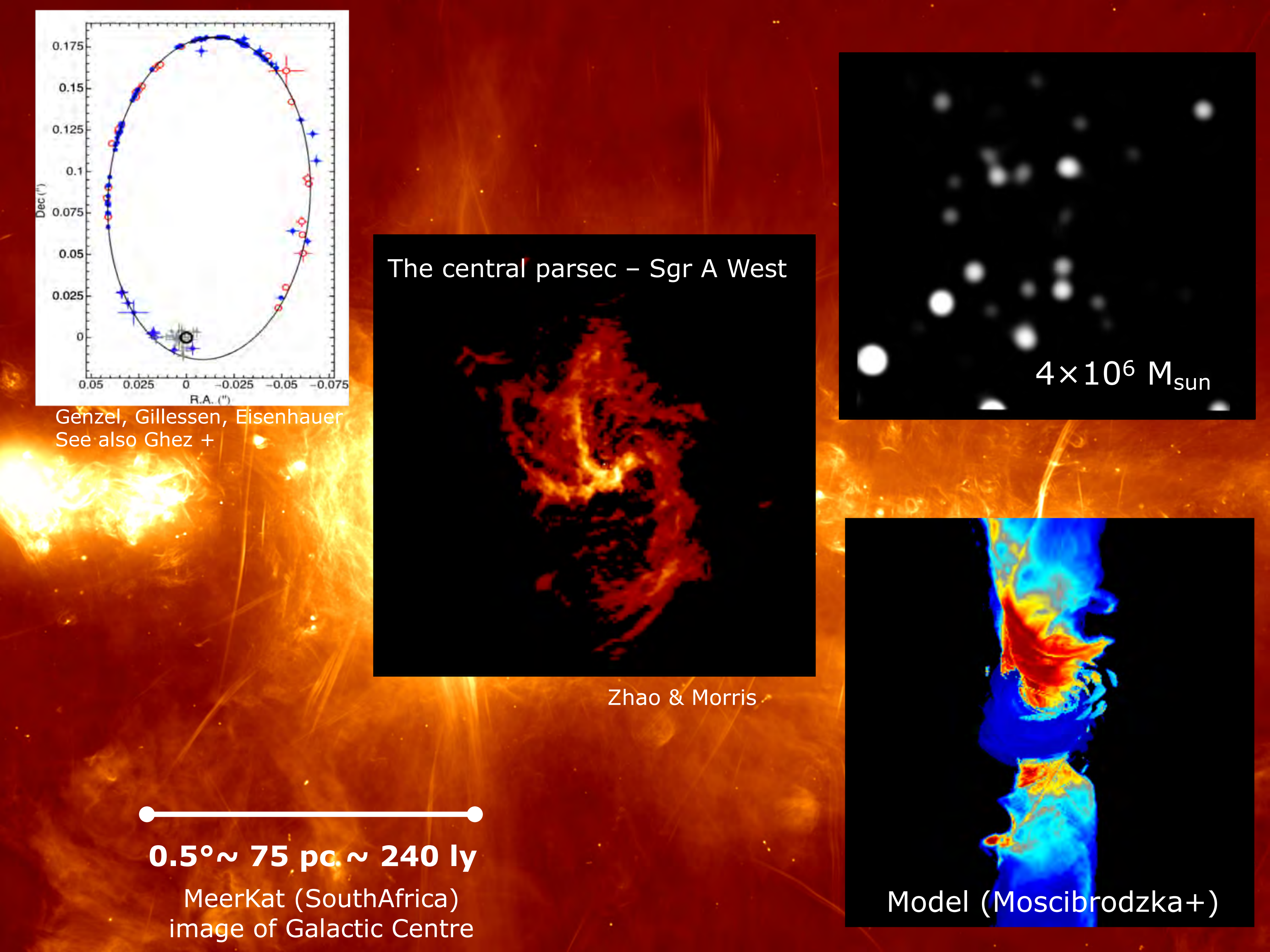
- Automatic VLBI Calibration Pipeline *(e.g. CASA+rPICARD, Janssen)*

- Multiple imaging algorithms

- Closure phase and Amplitude fitting, MEM (*EHT Imaging, Chael et al.)*
- *Sparse Imaging (Akiyama) et al.*

More codes within EHT: **code-comparison**

VR movie: J. Davelaar (BHAC/RAPTOR)

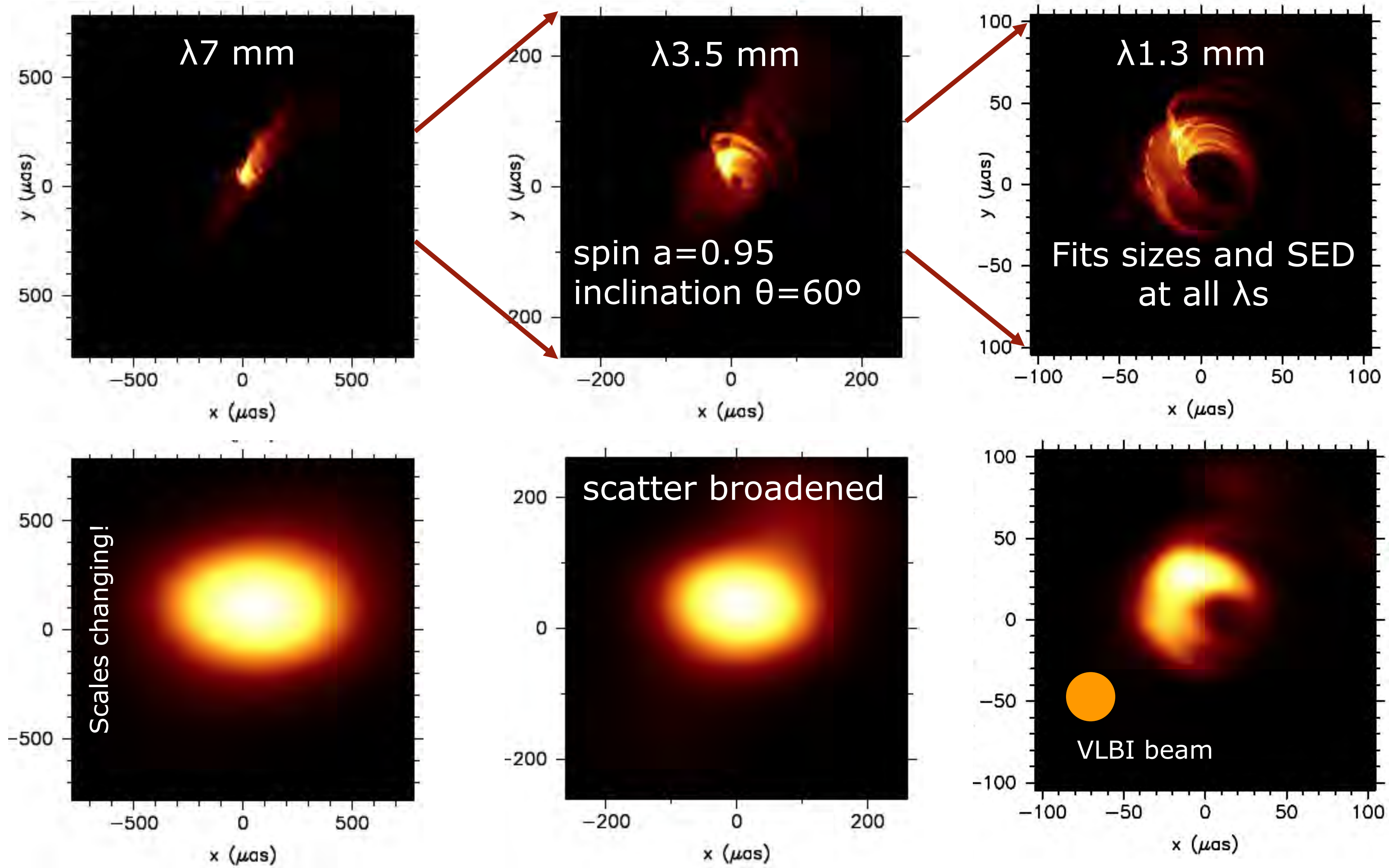


0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
Dec (")
0.05
0.025
0
−0.025
−0.05
−0.075
R.A. (")
Genzel, Gillessen, Eisenhauer
See also Ghez +
The central parsec – Sgr A West
Zhao & Morris
4×10⁶ Msun
Model (Moscibrodzka+)
0.5°~ 75 pc ~ 240 ly
MeerKat (SouthAfrica)
image of Galactic Centre

Galactic Center Jet Models

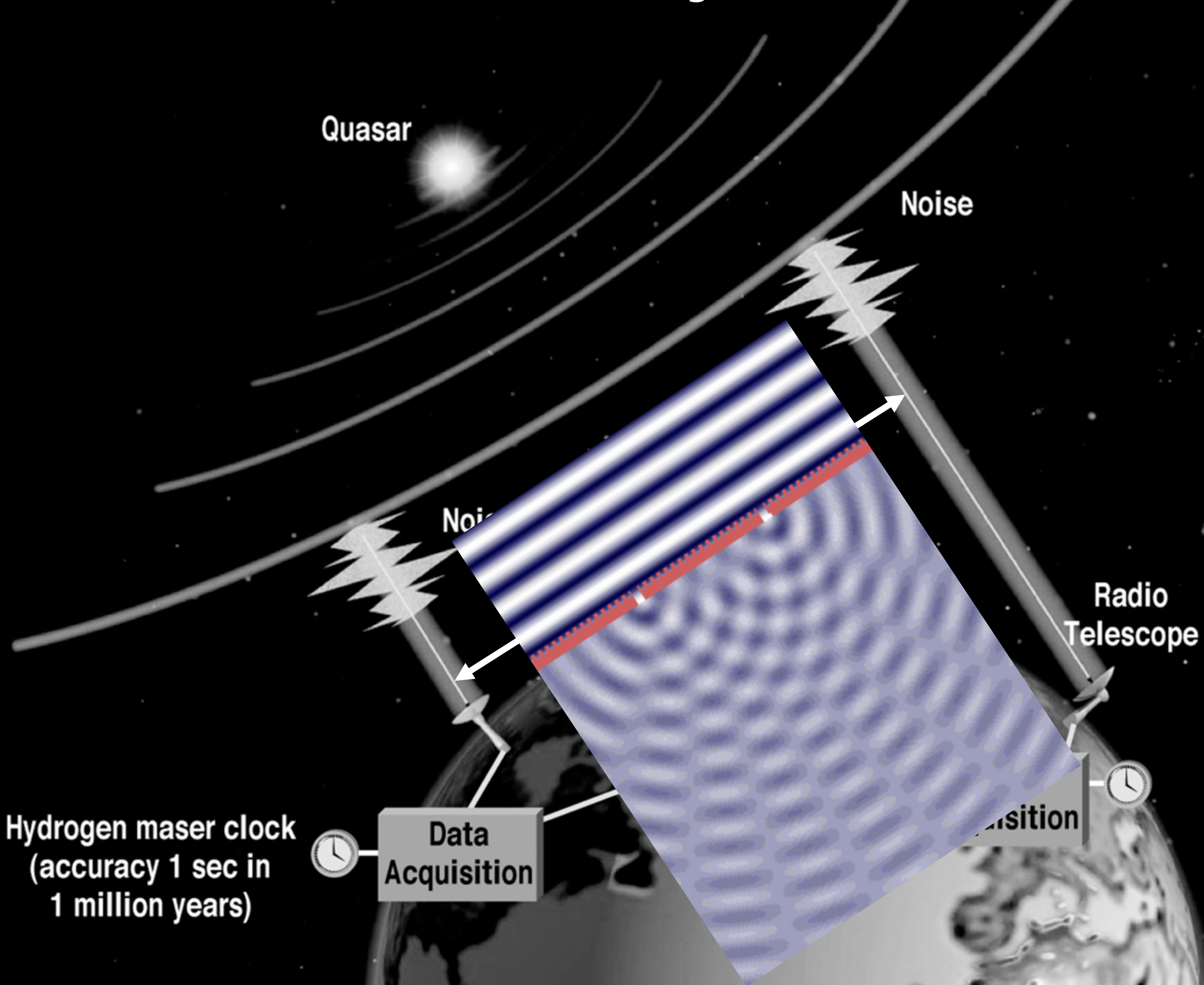
Radboud University Nijmegen

Moscibrodzka, HF et al. (2014)



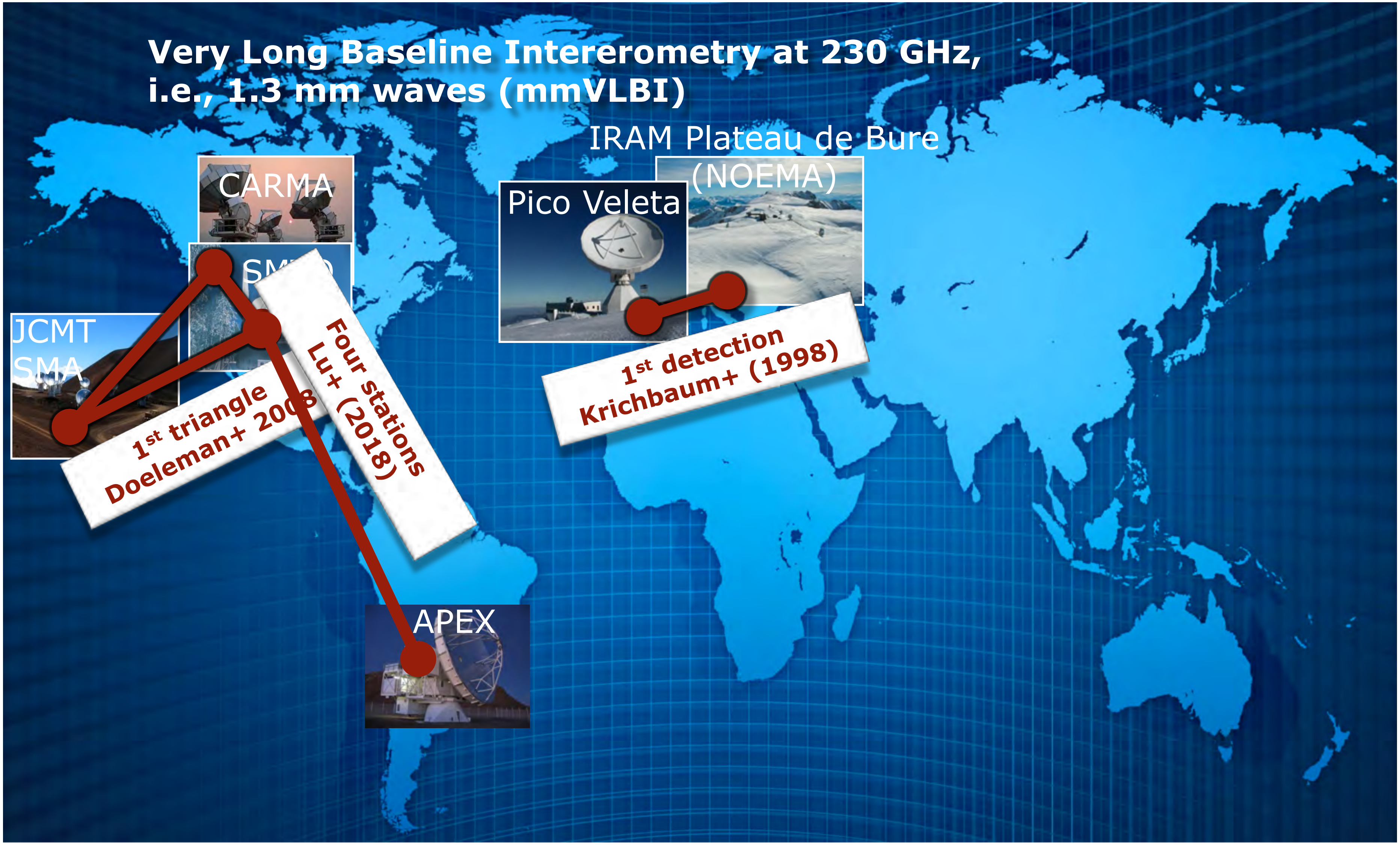
VLBI – Very Long Baseline Interferometry

Resolution: smallest angular scale: ~λ/D



The path towards event horizon imaging

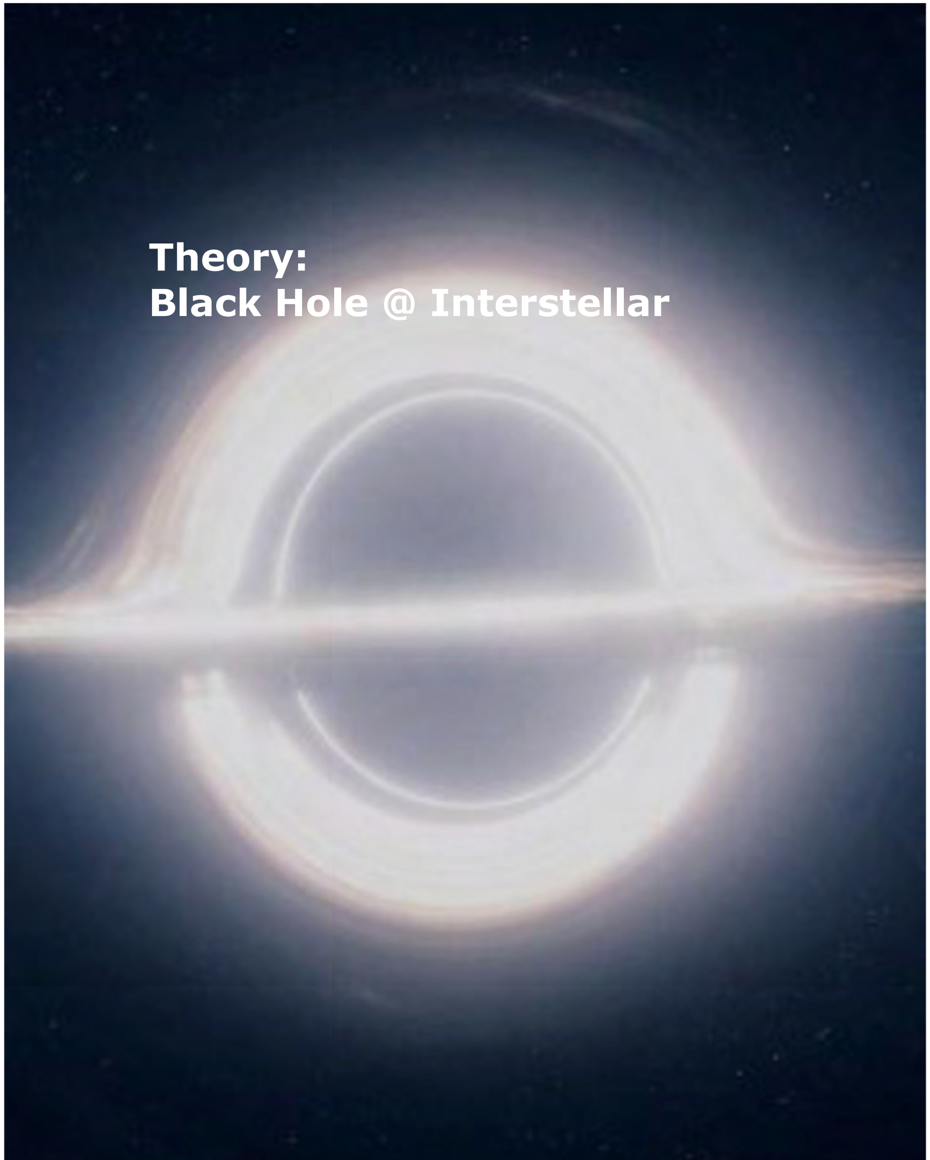
Radboud University Nijmegen

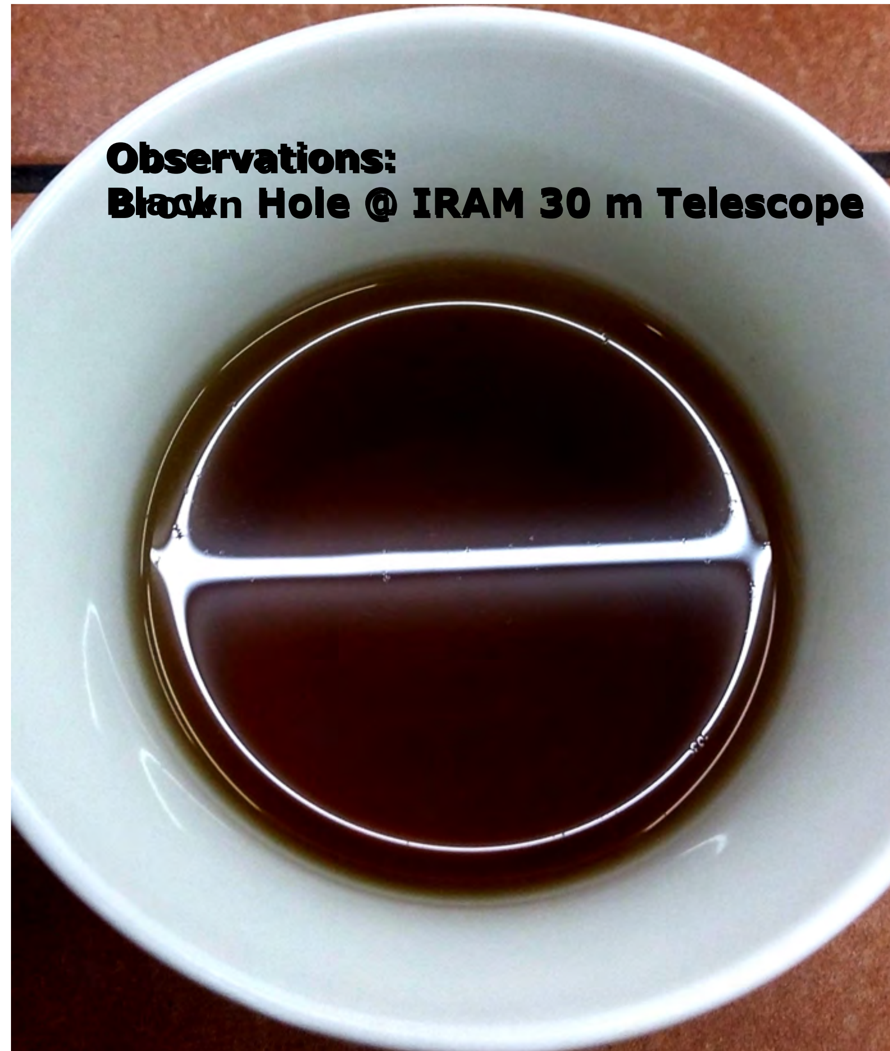


2017 global EHTC Campaign

- April 5 -11 2017
- 8 telescopes, 6 mountains (Largest 1mm VLBI experiment ever tried)
- 4 new stations, one dropped
- 6 observing nights in 10 day period (used all allocated time at ALMA)
- ~4 PB data raw data
- Overall good weather
- Only minor technical hiccups
- Data is correlated, of very good quality, and is being analyzed

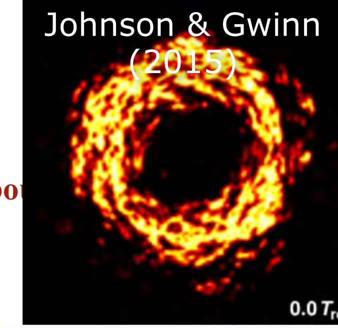
Scientists stunned by first image of black hole



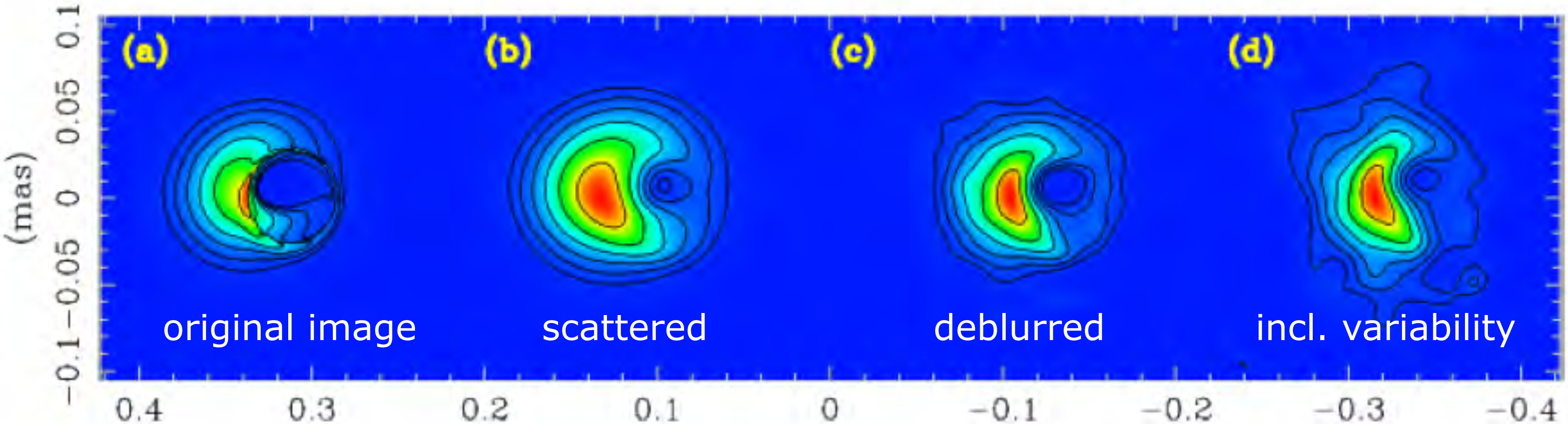


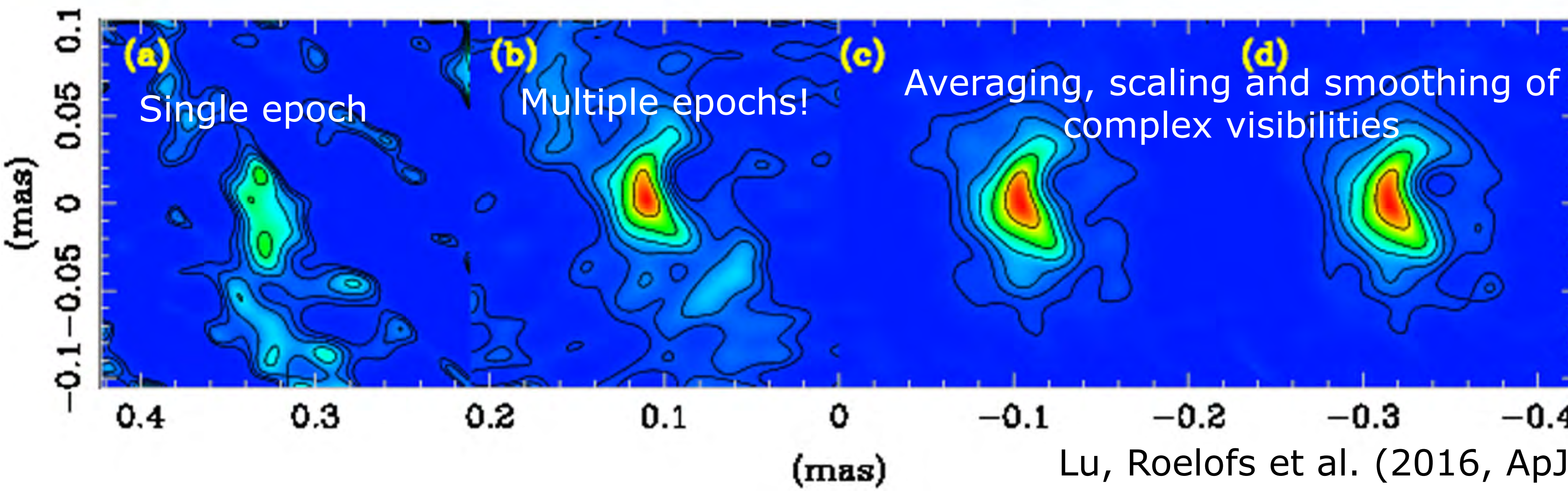
Ignacio Ruiz

What we **might** see



Challenges: troposphere (10 sec), sparse array (max 5 stations), refractive scattering substructures (days), source variability (hours)



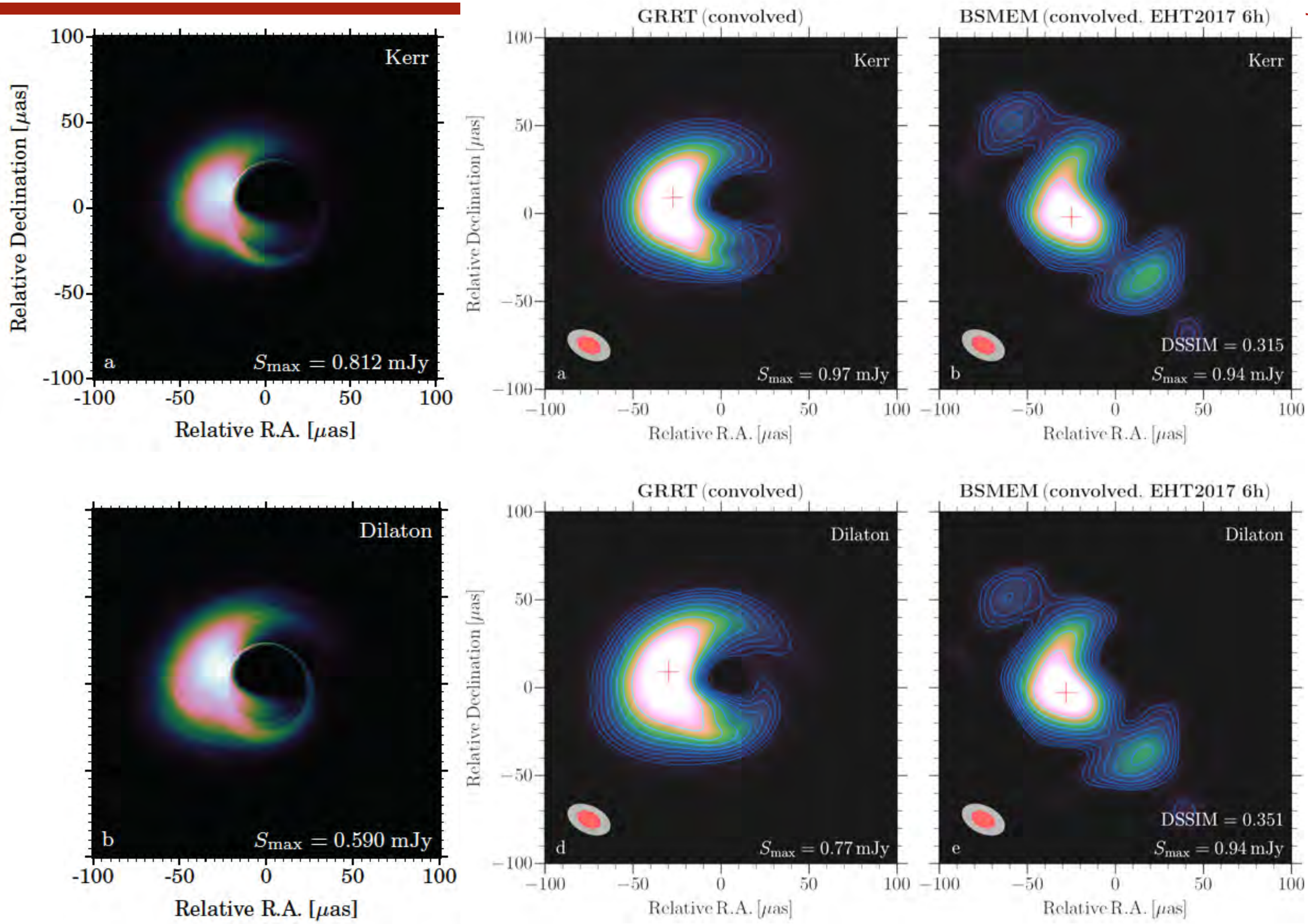


Lu, Roelofs et al. (2016, ApJ)

Non-standard spacetimes

Jniversity Nijmegen

Full resolution | interstellar scattering | 2017 experiment



Kerr BH

Dilaton BH

BHAC code

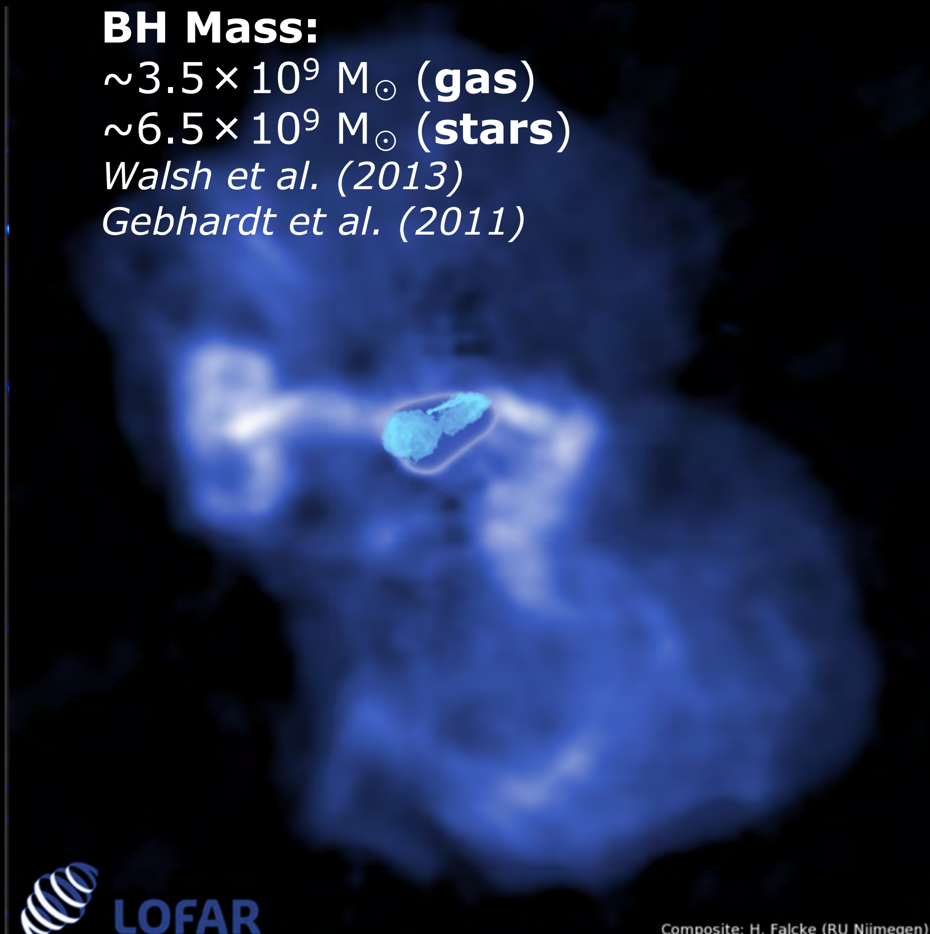
Mizuno et al. (2018, Nature Astronomy)

The radio jet in M87 (Virgo A)

Elliptical galaxy in center of Virgo cluster at d=17 Mpc

1000 × more massive, 1000 × more distant, 10^5 × more accretion than Sgr A*

⇒Same angular shadow size, same characteristic near-horizon frequency of emission



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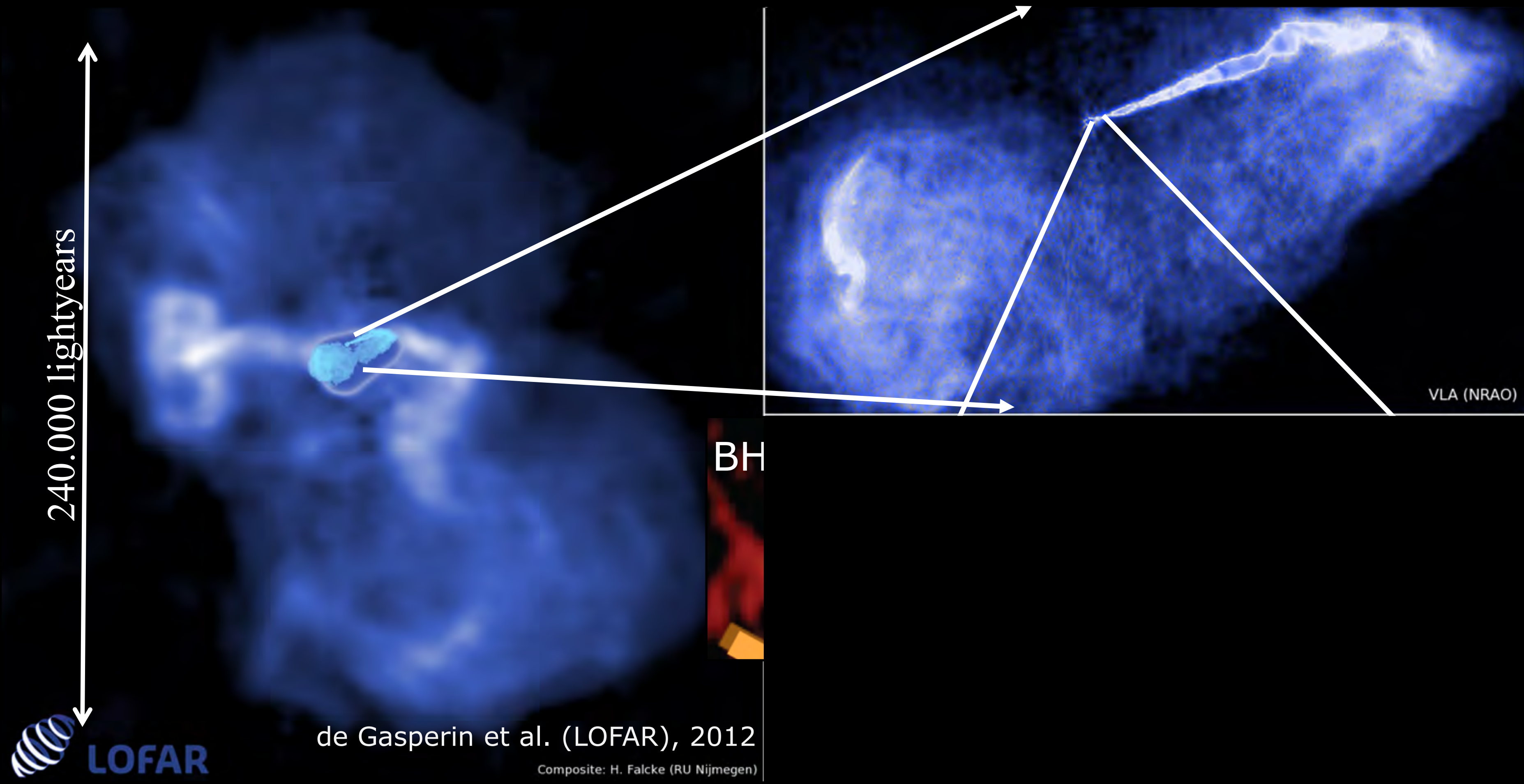
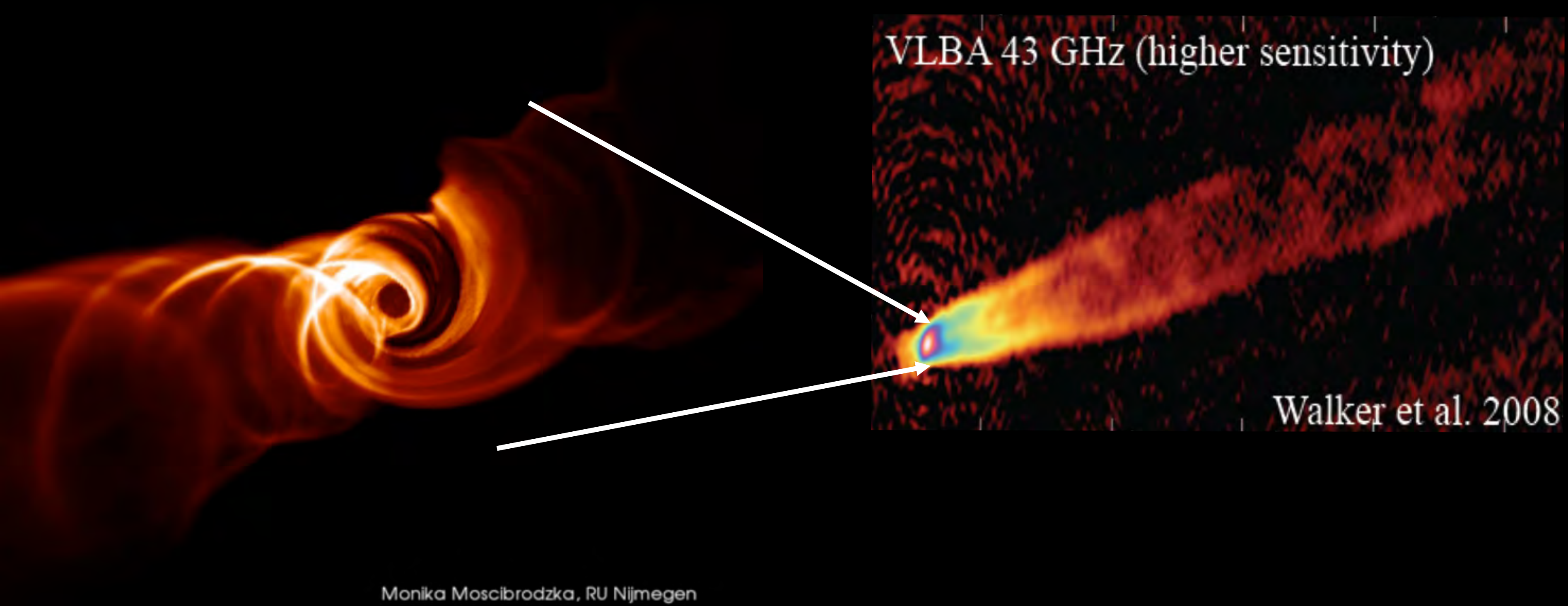


Black Hole Simluations of M87

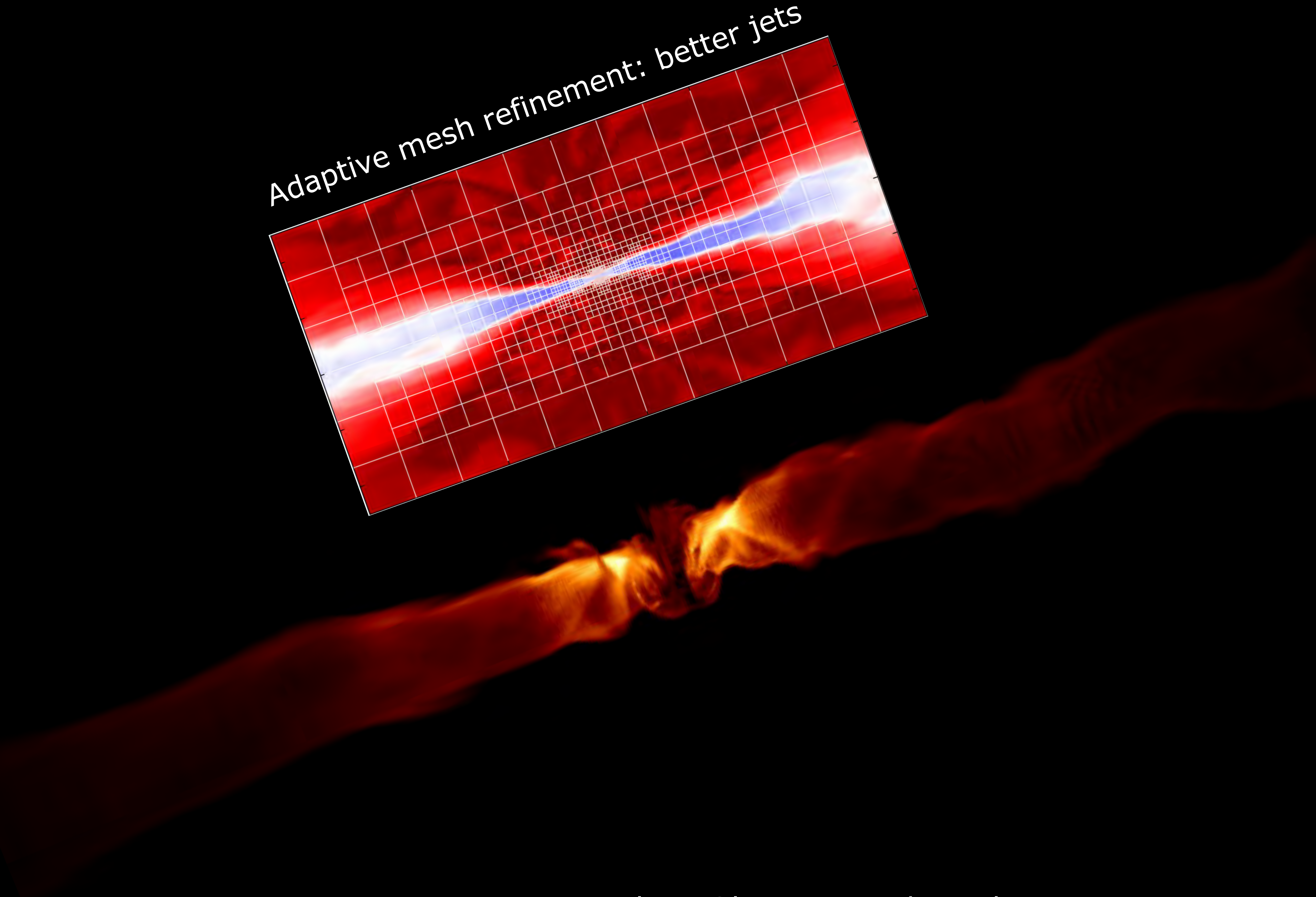
GRMHD Simulation

VLBI Observations

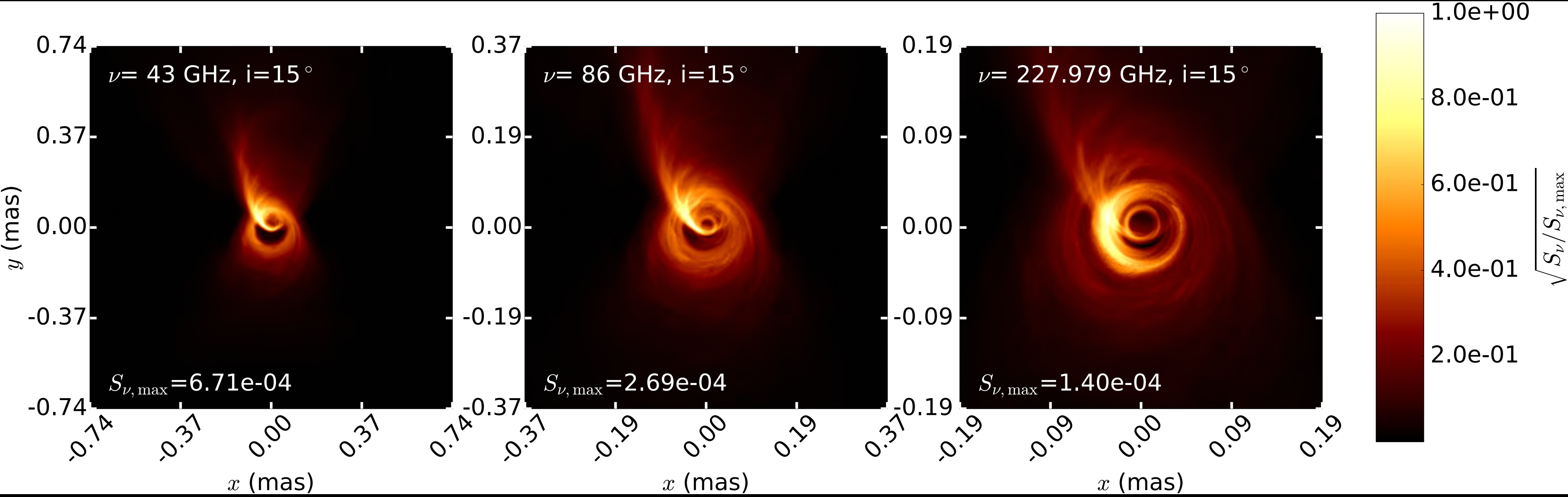


Moscibrodzka, Falcke, Shiokawa (2016, A&A)

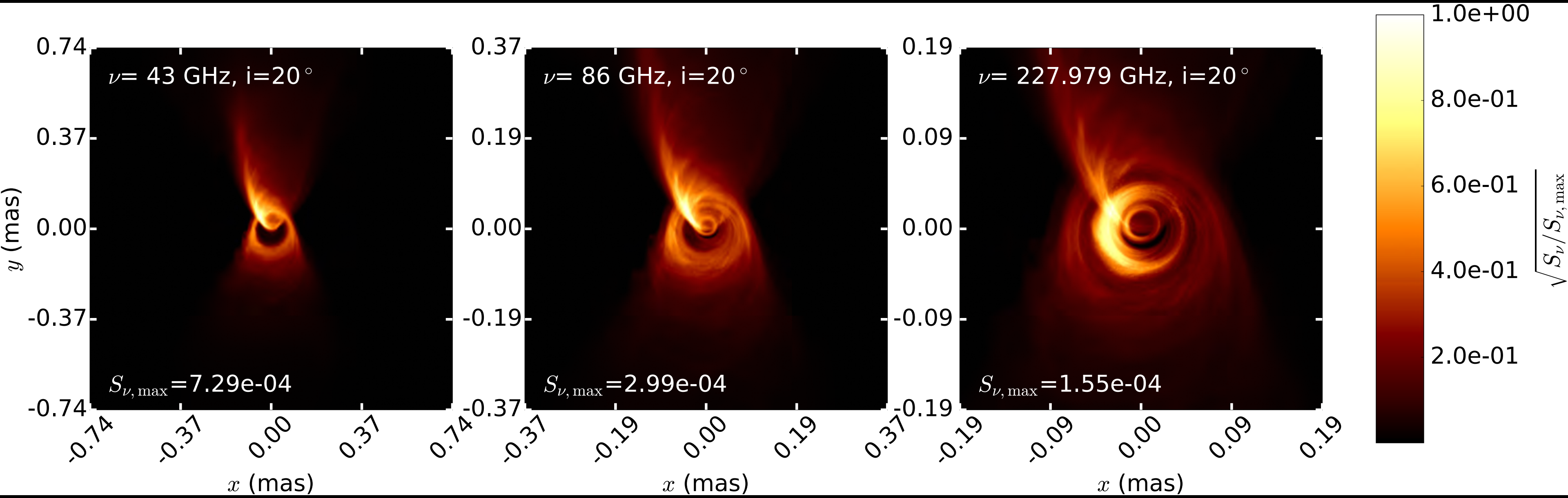
(Using Harm3D - Gammie et al.)



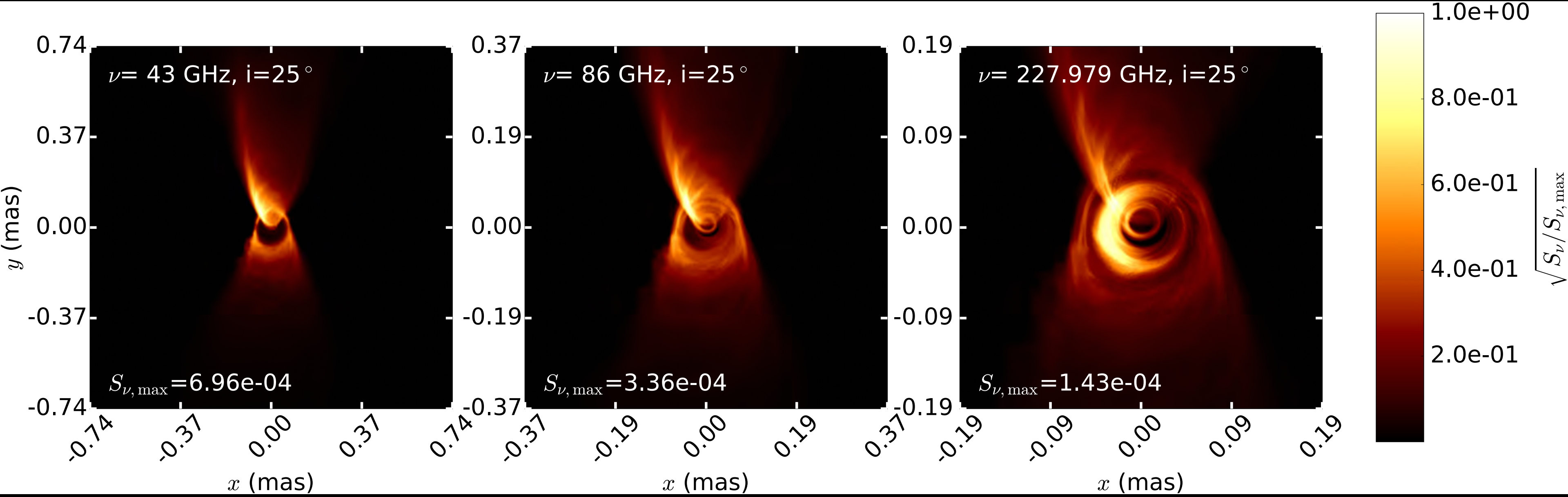
Davelaar, Olivarez, Porth et al., in prep.
(BlackHoleCam team)



Davelaar et al., in prep.



Davelaar et al., in prep.



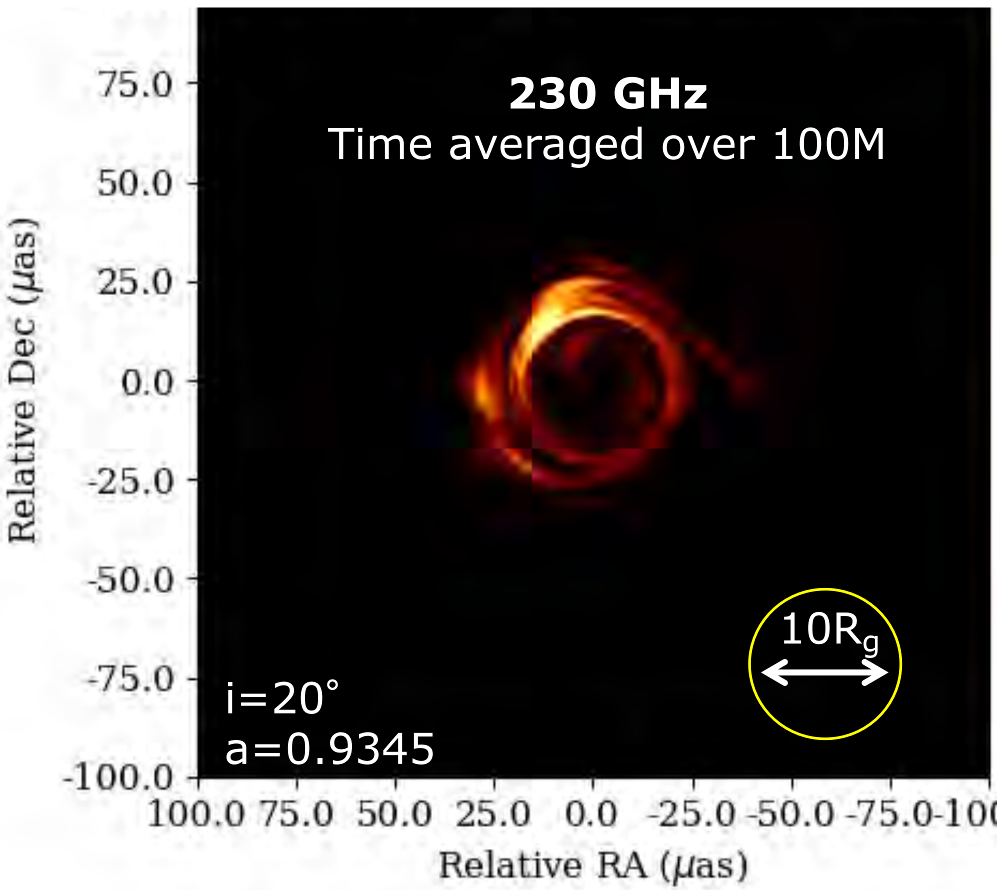
Davelaar et al., in prep.

VLBI Simulations of M87

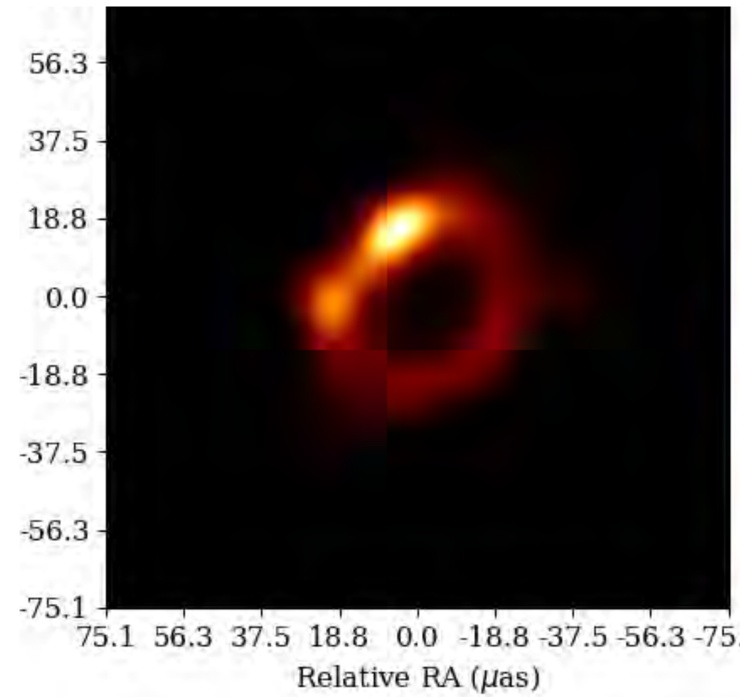
Radboud University Nijmegen

M87 GRMHD Simulations
(BHAC/Raptor)

Simulated EHT2017 observation
(MeqSilhouete/rPICARD/EHT Imaging)



Assumption: M87 mass is 6.5×10^9 M_{sol}



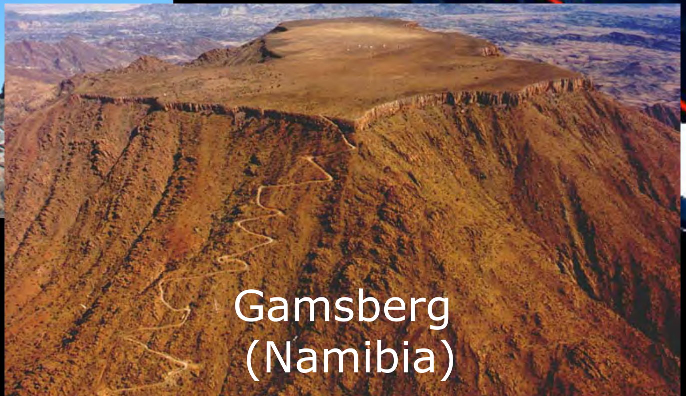
2017 layout & schedule, pointing errors, tropospheric phase and amplitude variations
Maximum Entropy (MEM) and closure quantity fitting

Davelaar et al., in prep.

Roelofs et al., in prep.

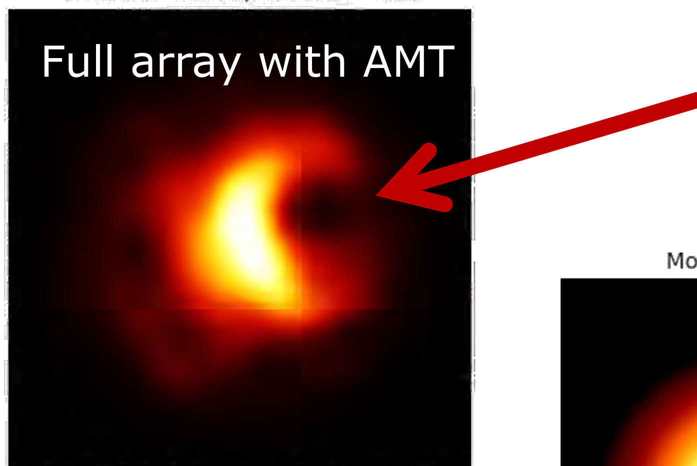
African mm-wave Telescope: Move SEST telescope to Namibia

A dedicated African mm-VLBI telescope for EHT, GMVA.
investment cost: ~5 M€ + operations …

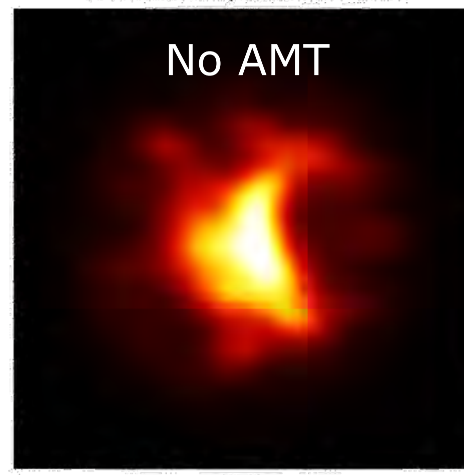


Imaging with Africa mm-wave telescope

EHT2017 + AMT, NRMSE = 0.26

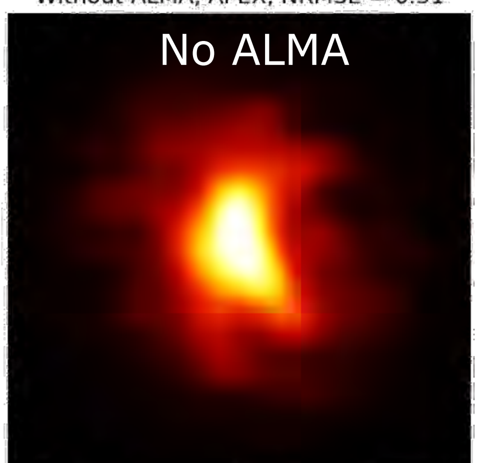


Without AMT, NRMSE = 0.28

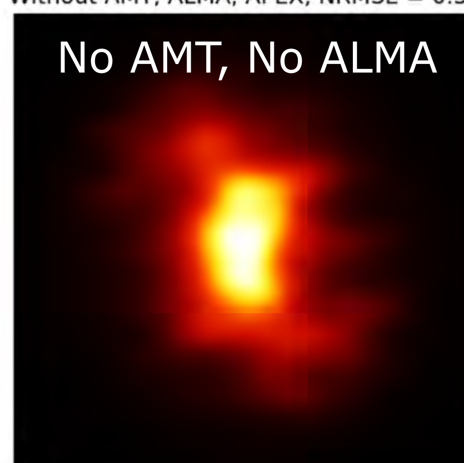


Model, time-averaged

Without ALMA, APEX, NRMSE = 0.31



Without AMT, ALMA, APEX, NRMSE = 0.34

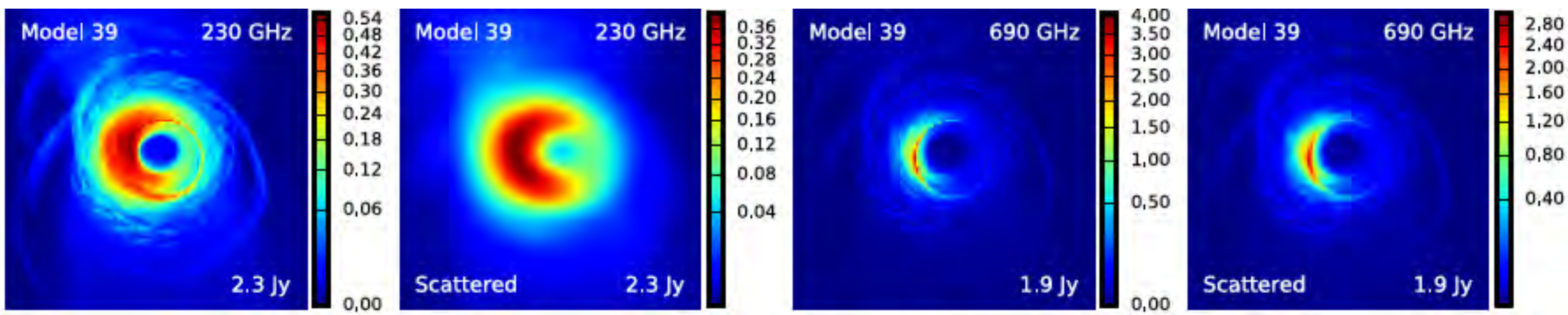


- Includes source variability
- 8 epochs
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering
- EHT imaging library

F. Roelofs

Black Hole Shadow Simulations at 690 GHz (!)

Optical depth included
Shadow size = 45 μas
Resolution at 10000 km baseline = 8.9 μas
Scattering blur kernel size = 2.5 μas

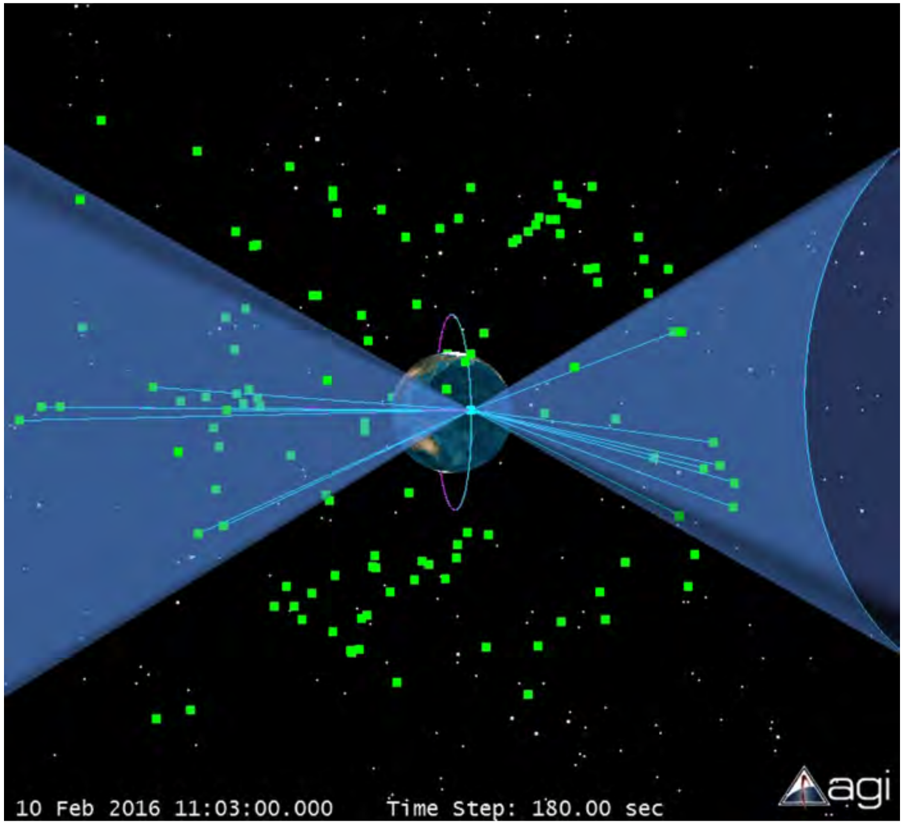


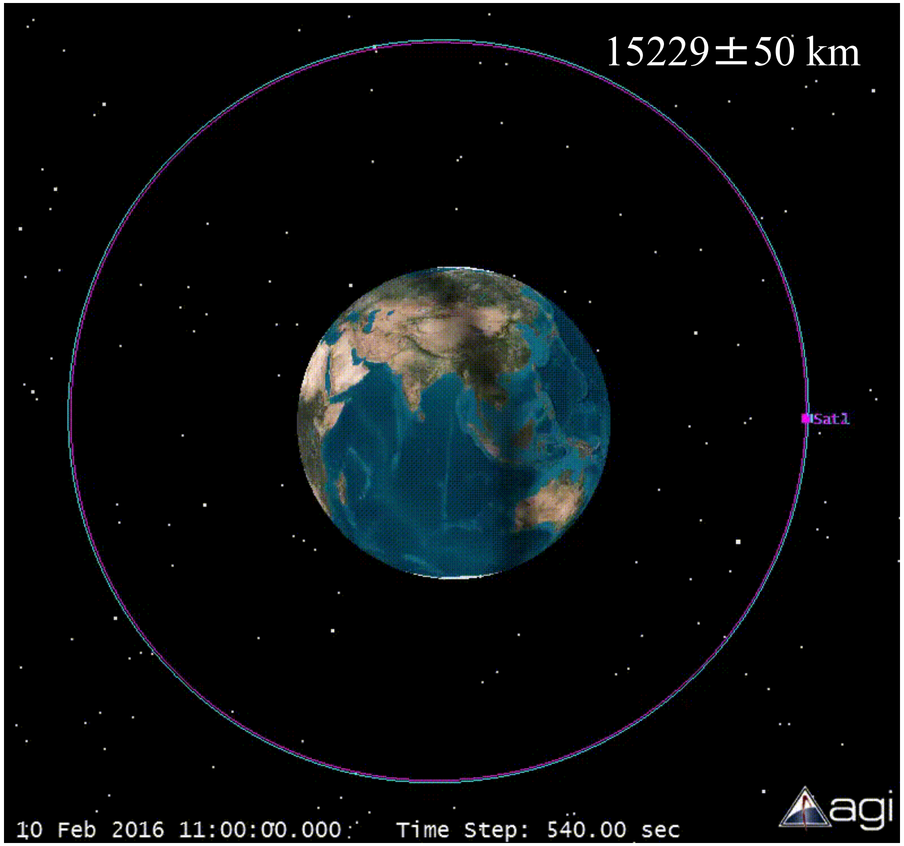
Moscibrodzka et al. (Radoud Univ)

Space Interferometry: Event Horizon Imager (EHI)

Radboud University Nijmegen

Idea: 2 or 3 S/C in Medium Earth Orbit (MEO) on slightly different orbits, to cover all possible separations and orientations. Use GPS/Galileo to get good locations.



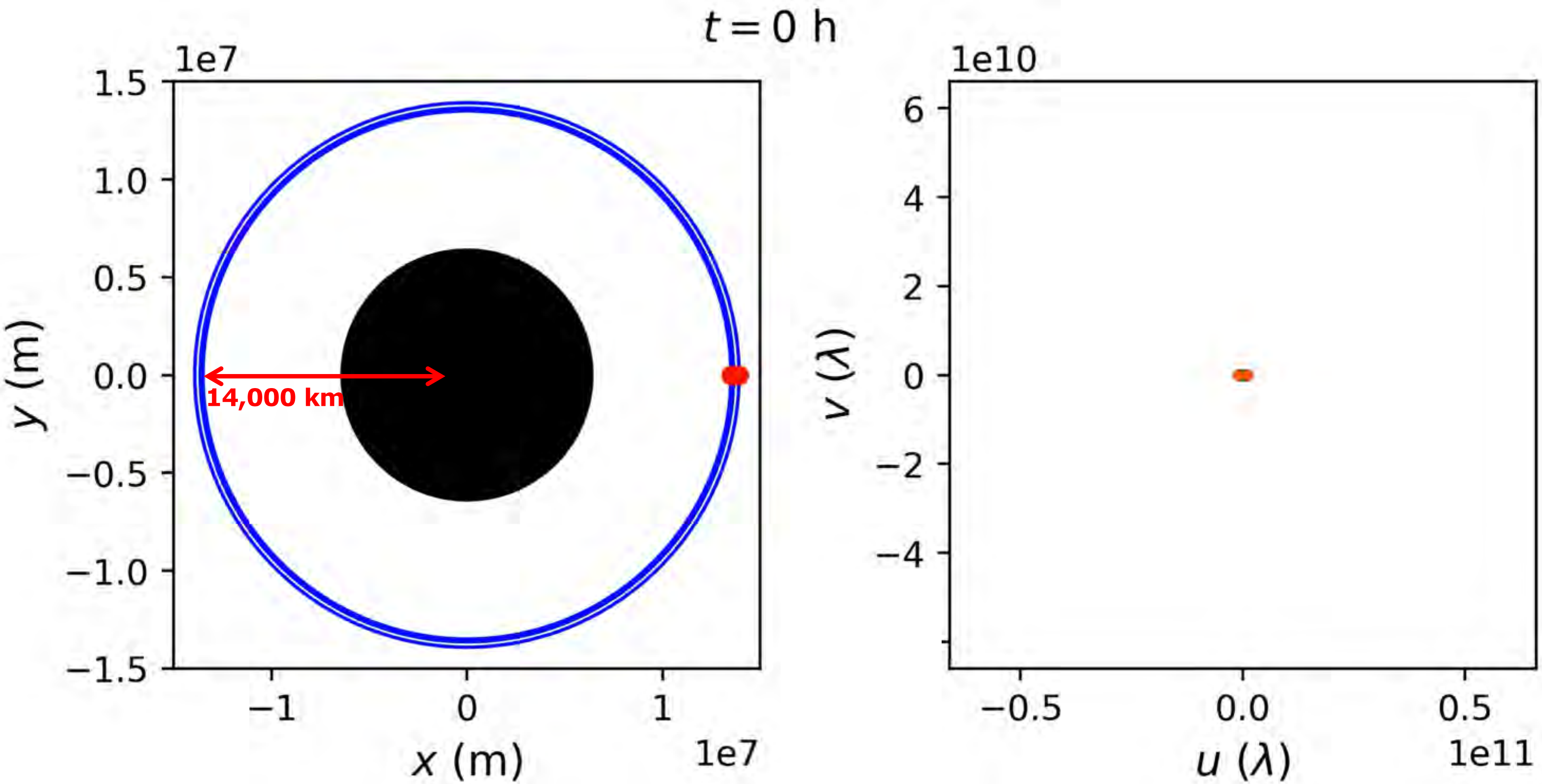


$\geq$3 GNSS transmitters in *common* visibility ,vA belts
=>Max Orbit Radius ~ 14000 km

Space Interferometry: Event Horizon Imager (EHI)

Radboud University Nijmegen

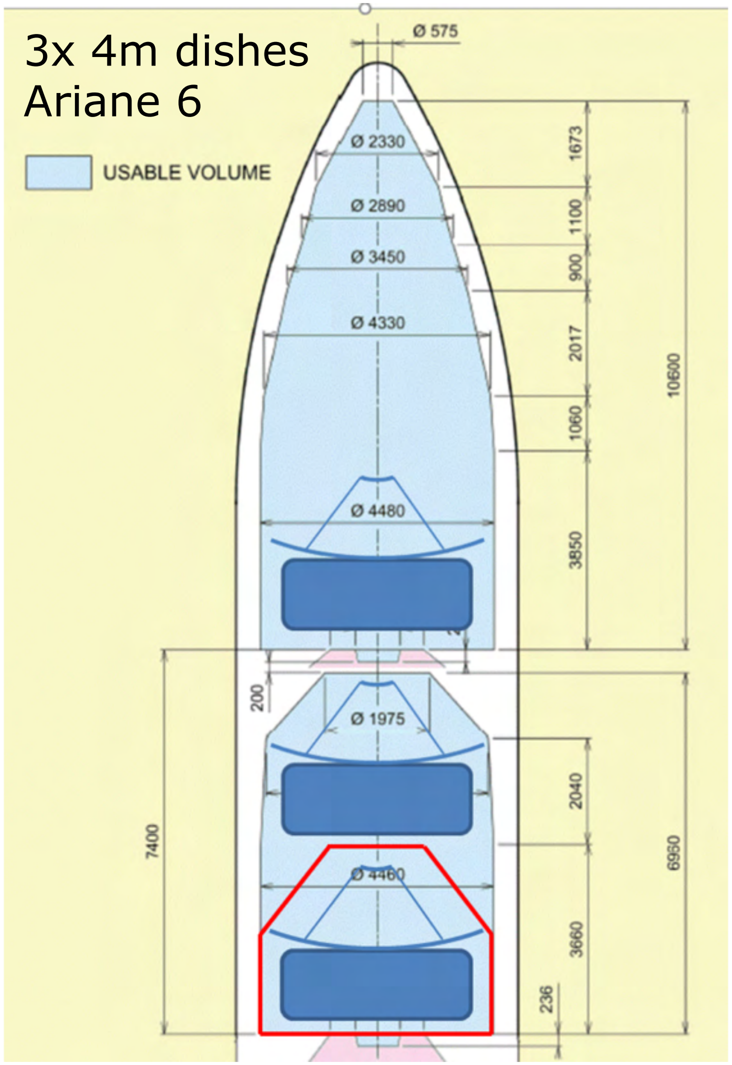
3×4 m dishes in medium earth orbit separated by 20 km



Martin-Neira, V.Kudriashov (ESTEC)

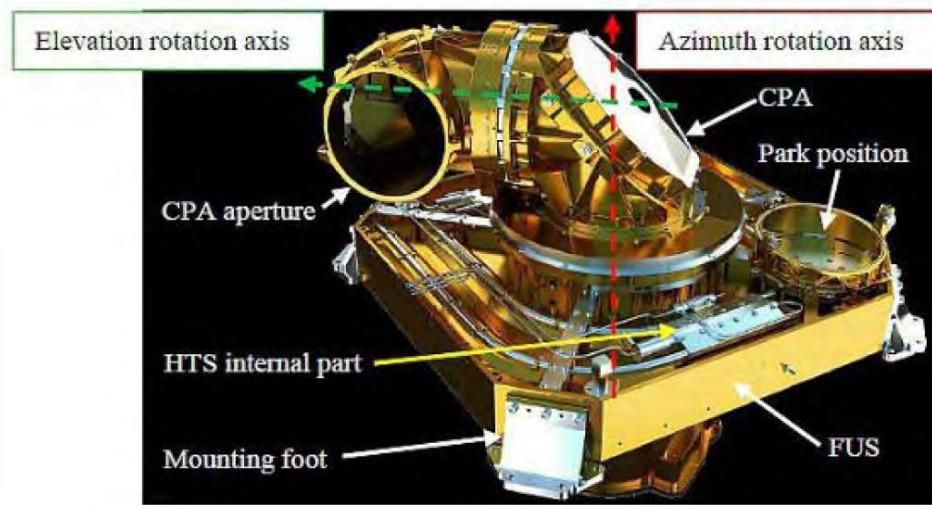
F. Roelofs et al. (2018, subm.)

Event Horizon Imager

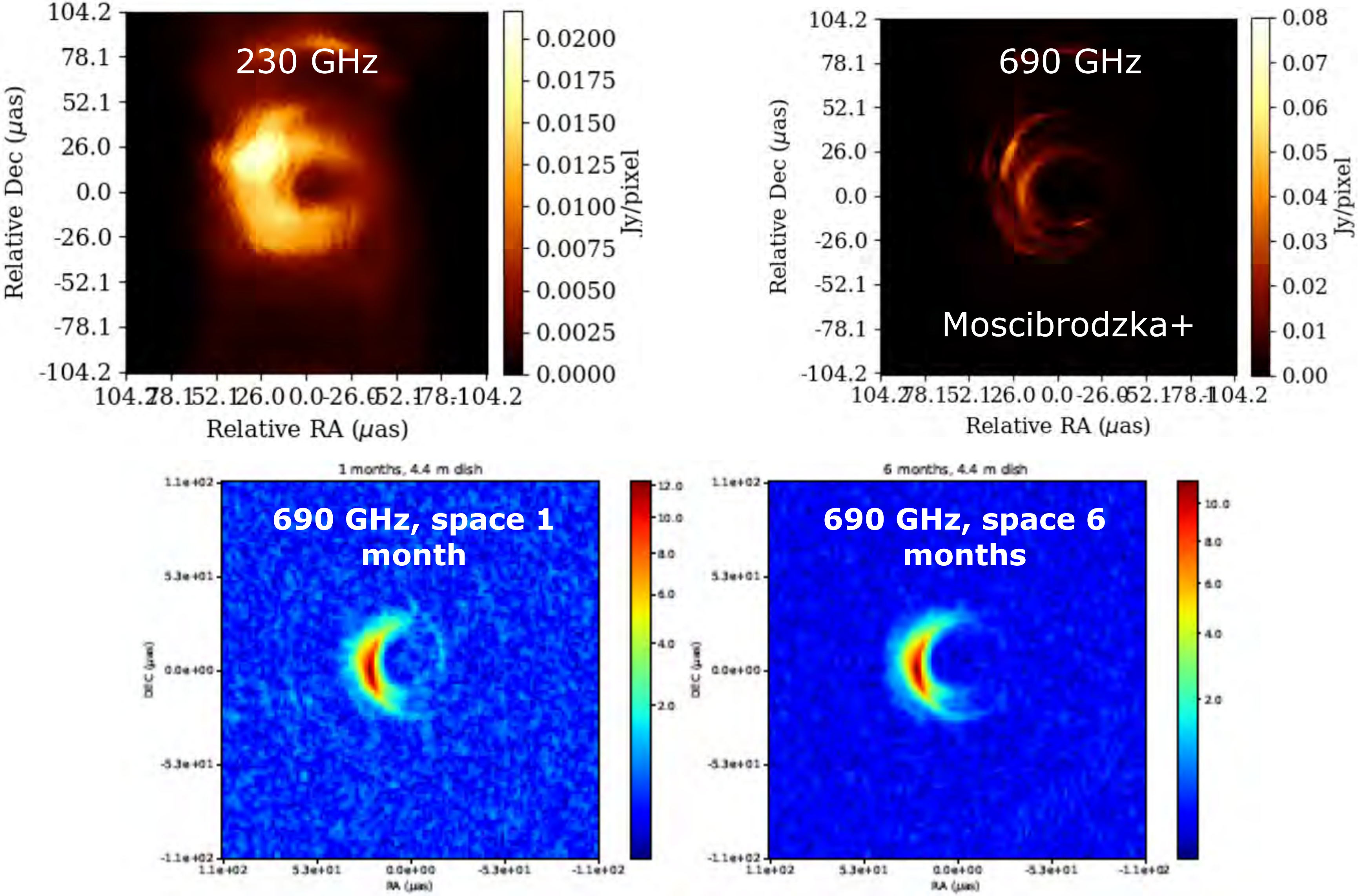


Laser link for
- multi TB/sec space-space link
- Clock exchange
- Donwlink for Space-ground VLBI?

The LCT is a product of TESAT Spacecom (Germany)



Imaging with variability & scattering



Roelof et al. (2018)

More black holes accessible

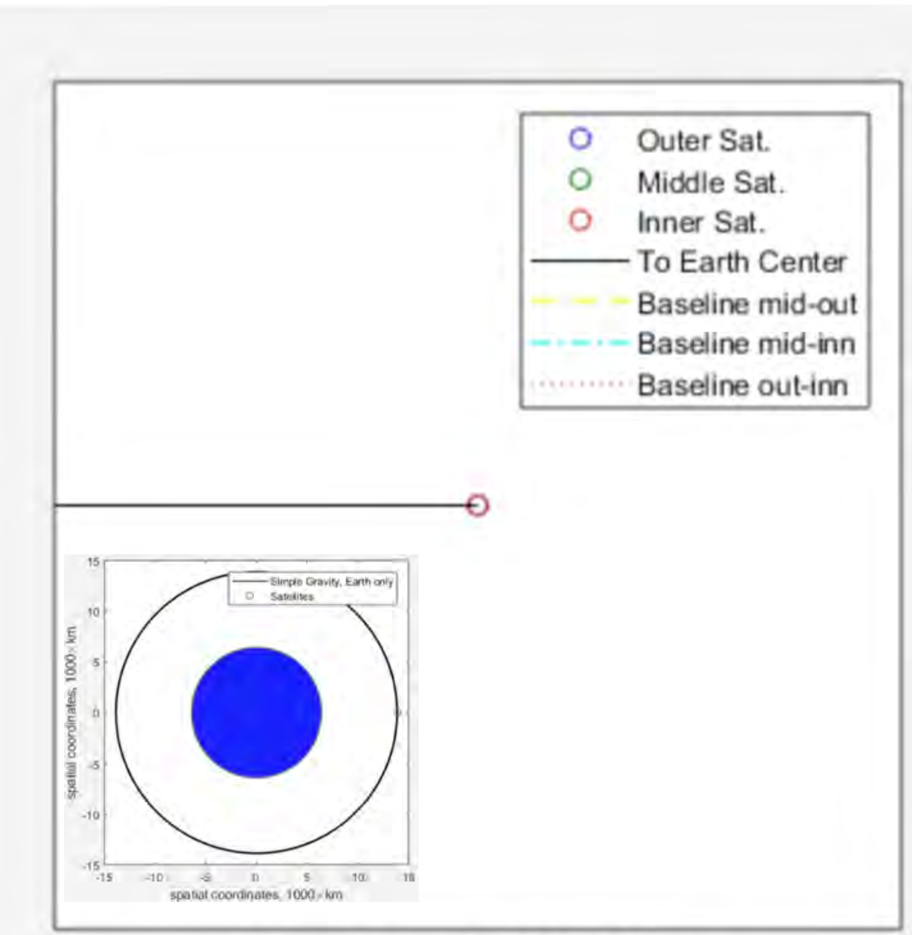
Sources for VLBI Observations

Source	θ_{ring} (μas)	Distance[a] (Mpc)	$\log(M_{BH})$[a] ($M_\odot$)	$\log(L_R)$[a] (erg s^{-1})	S_ν (Jy)
Sgr A*	53	0.008	6.61 ± 0.064	32.48	2.4
NGC 4486 (M87)	22	17.0	9.56 ± 0.126	39.83	0.897
NGC 0224 (M31)	19	0.8	8.17 ± 0.161	32.14	$\approx 3 \times 10^{-5}$
NGC 4649 (M60)	13	16.5	9.33 ± 0.117	37.45	<0.004
NGC 3115	9.6	10.2	8.98 ± 0.182	...	...
IC 1459	9.2	30.9	9.44 ± 0.196	39.76	0.264
NGC 4374 (M84)	9.1	17.0	9.18 ± 0.231	38.77	0.129
NGC 5128 (Cen A)	7.0	4.4	8.48 ± 0.044	39.85	6.9
NGC 4594 (M104)	5.7	10.3	8.76 ± 0.413	37.89	0.25
IC 4296	2.5	54.4	9.13 ± 0.065	38.59	0.155
NGC 1399	2.5	21.1	8.71 ± 0.060	...	≈ 0.04
NGC 4342	2.1	18.0	8.56 ± 0.185	...	...
NGC 3031 (M81)	2.0	4.1	7.90 ± 0.087	36.97	0.1812

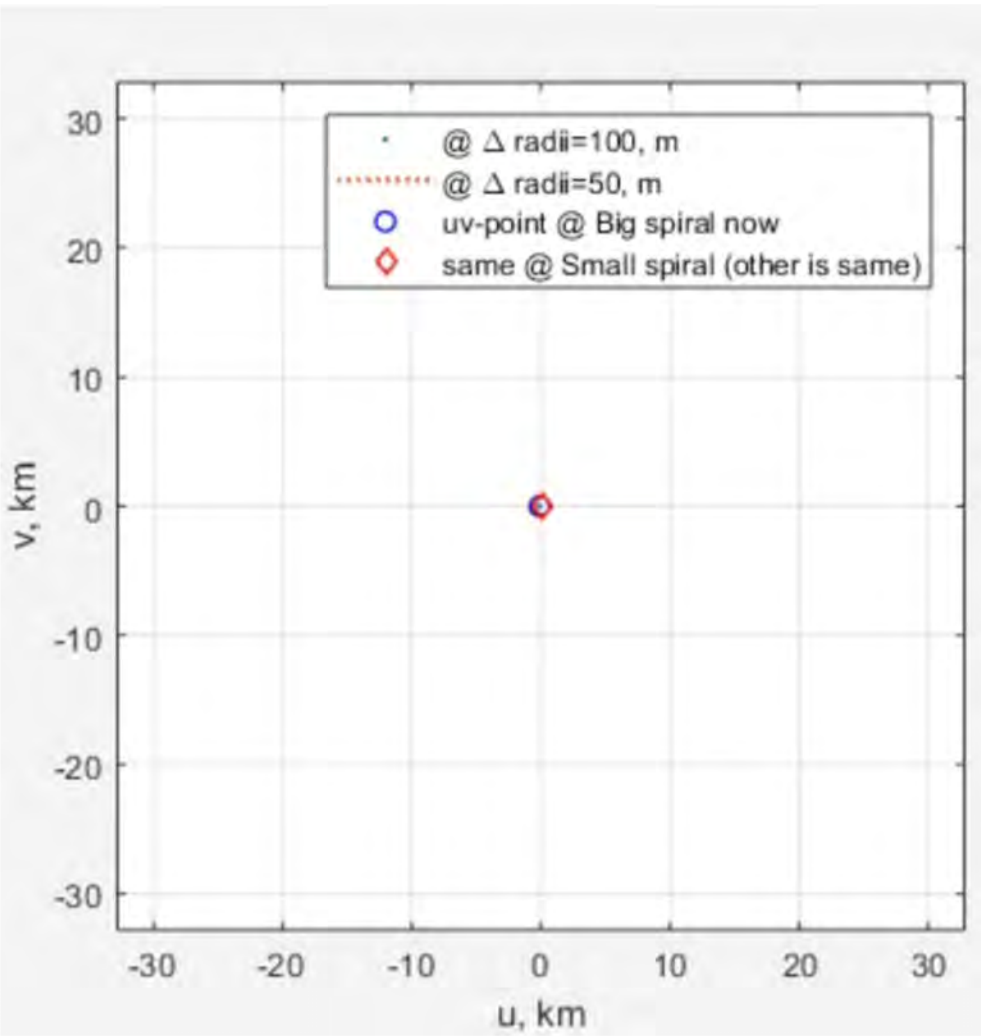
M81: 09h55m33.1730s, +69d03m55.061s
M84: 12h25m03.7433s, +12d53m13.139s
M87: 12h30m49.4233s, +12d23m28.043s
M104: 12h39m59.4318s, -11d37m22.996s
Cen A: 13h25m27.6152s, -43d01m08.805s
Sgr A*: 17h45m40.0383s, -29d00m28.069s
IC1459: 22h57m10.6068s, -36d27m44.000s

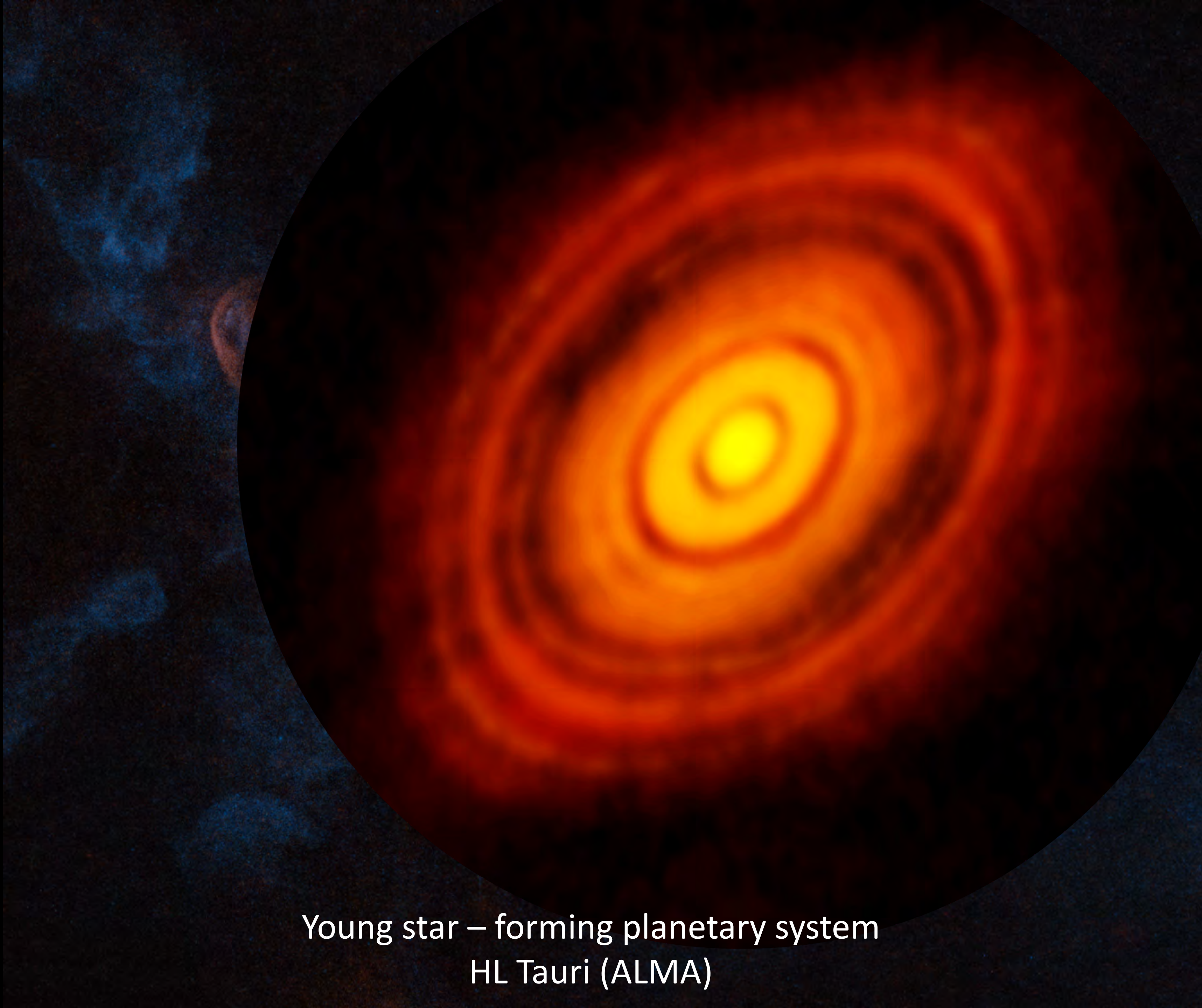
Johannsen et al. (2012)

Shorter Baselines: ALMA in space



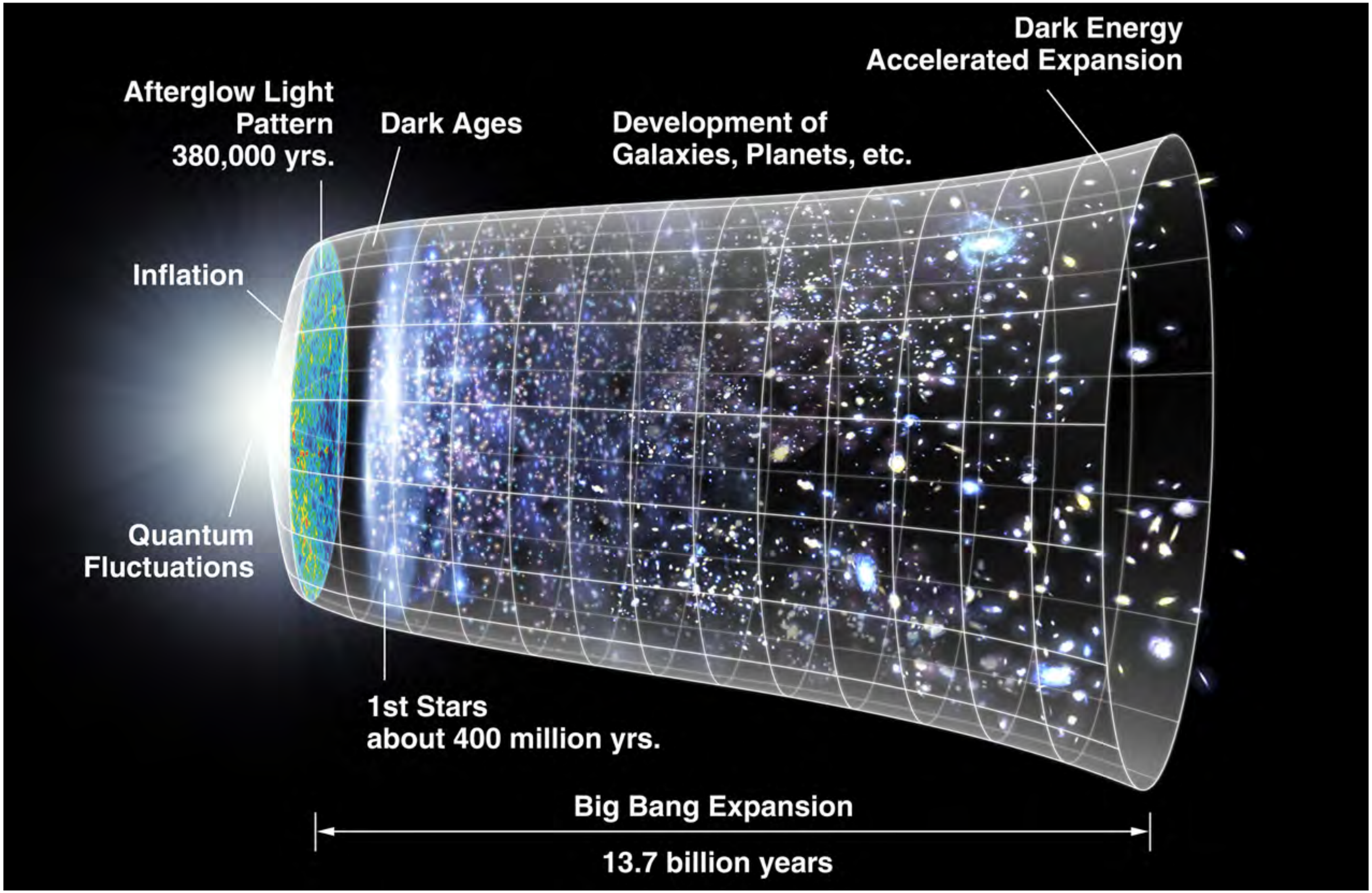
Field of View is of 66×66 km





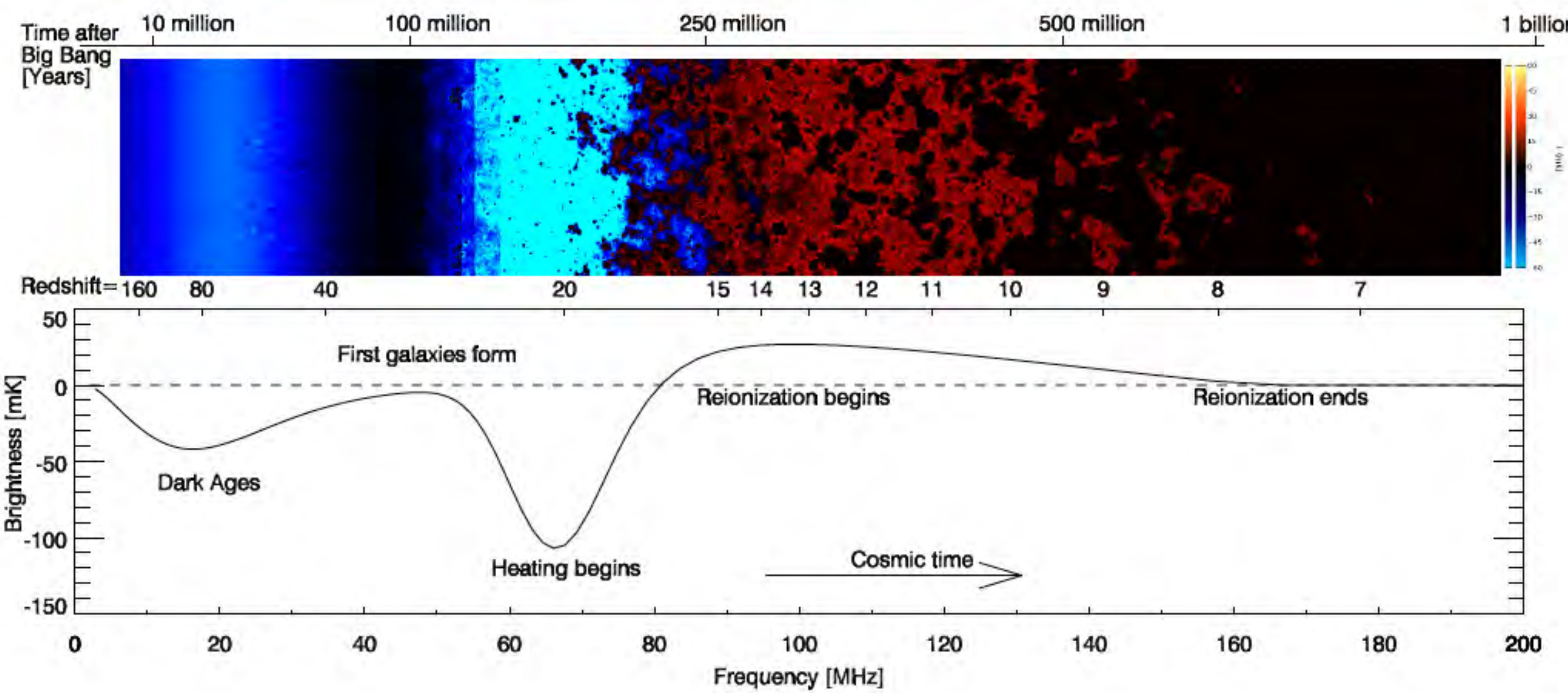
Young star – forming planetary system
HL Tauri (ALMA)

In the beginning …



Dark ages and cosmic dawn

Radboud University Nijmegen



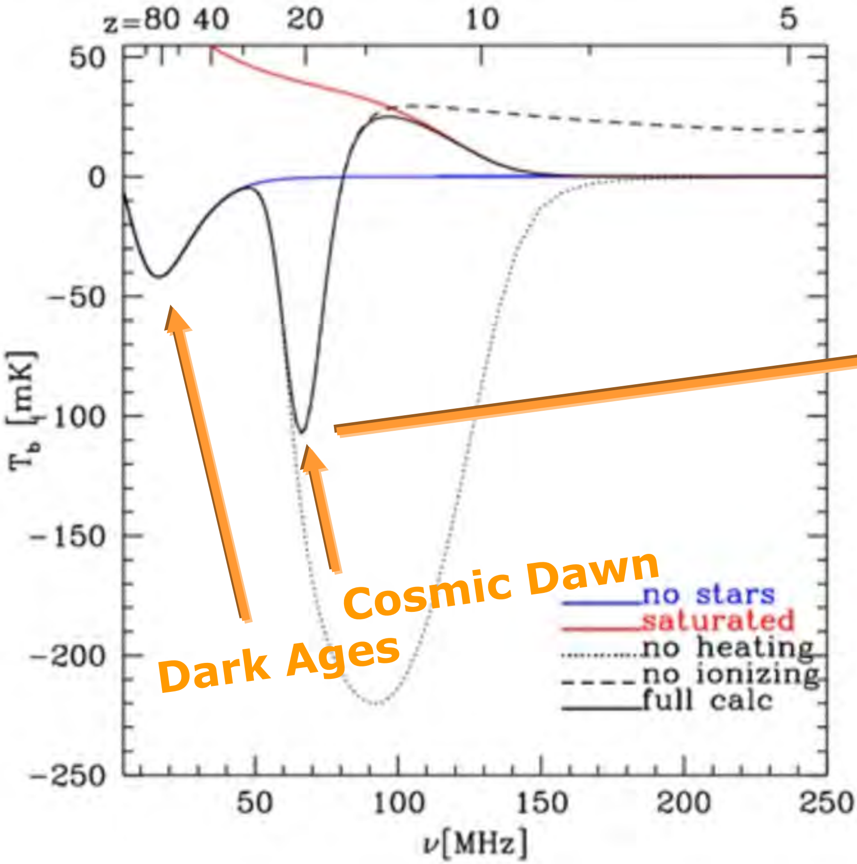
Pritchard & Loeb (2010)

Square Kilometre Array

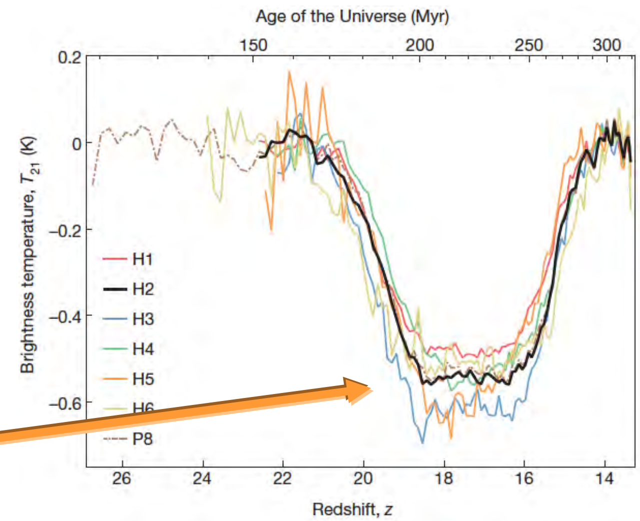
Radboud University Nijmegen

Cosmic Dawn Detection?

Radboud University Nijmegen



Pritchard & Loeb (2010)

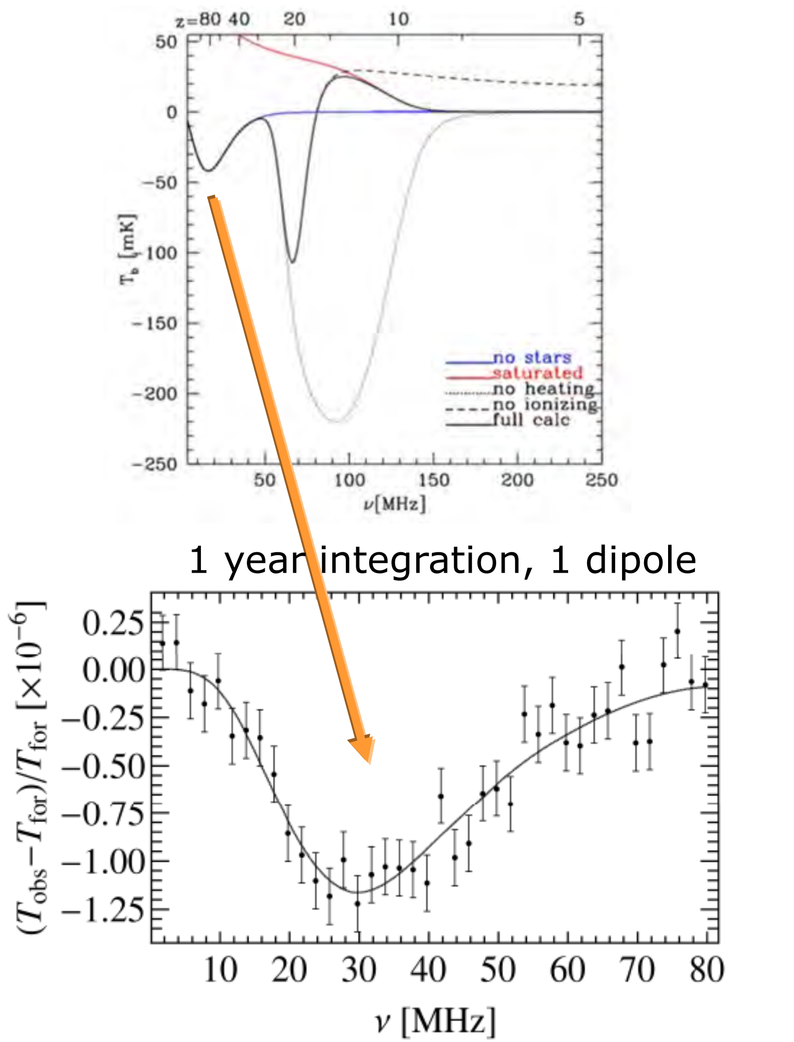


EDGES

Bowman et al. (2018, Nature)

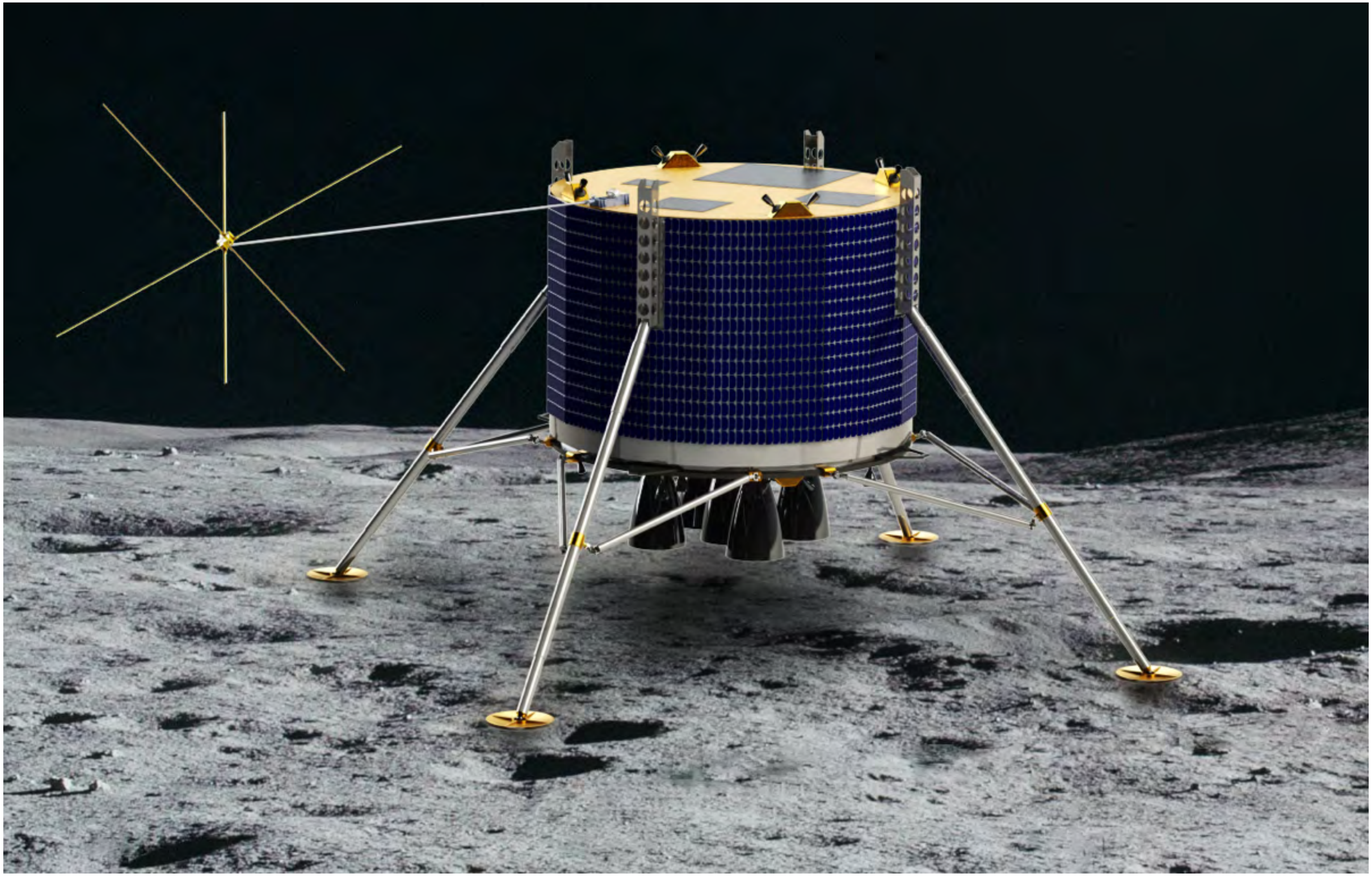
Global Dark Ages Signal

- HI global dark ages signal could be seen with one antenna.
- Integration time < 1 year at 37 MHz (i.e. z=37).
- Huge problem is the unknown foreground contamination and spectral „roughness“
- Signal is only 10^{-6} of foreground!
- Go to the Moon!



Jester & Falcke (2008, New Astronomy Rev.)

LRX – Lunar Radio Explorer (ESA Lunar Lander)



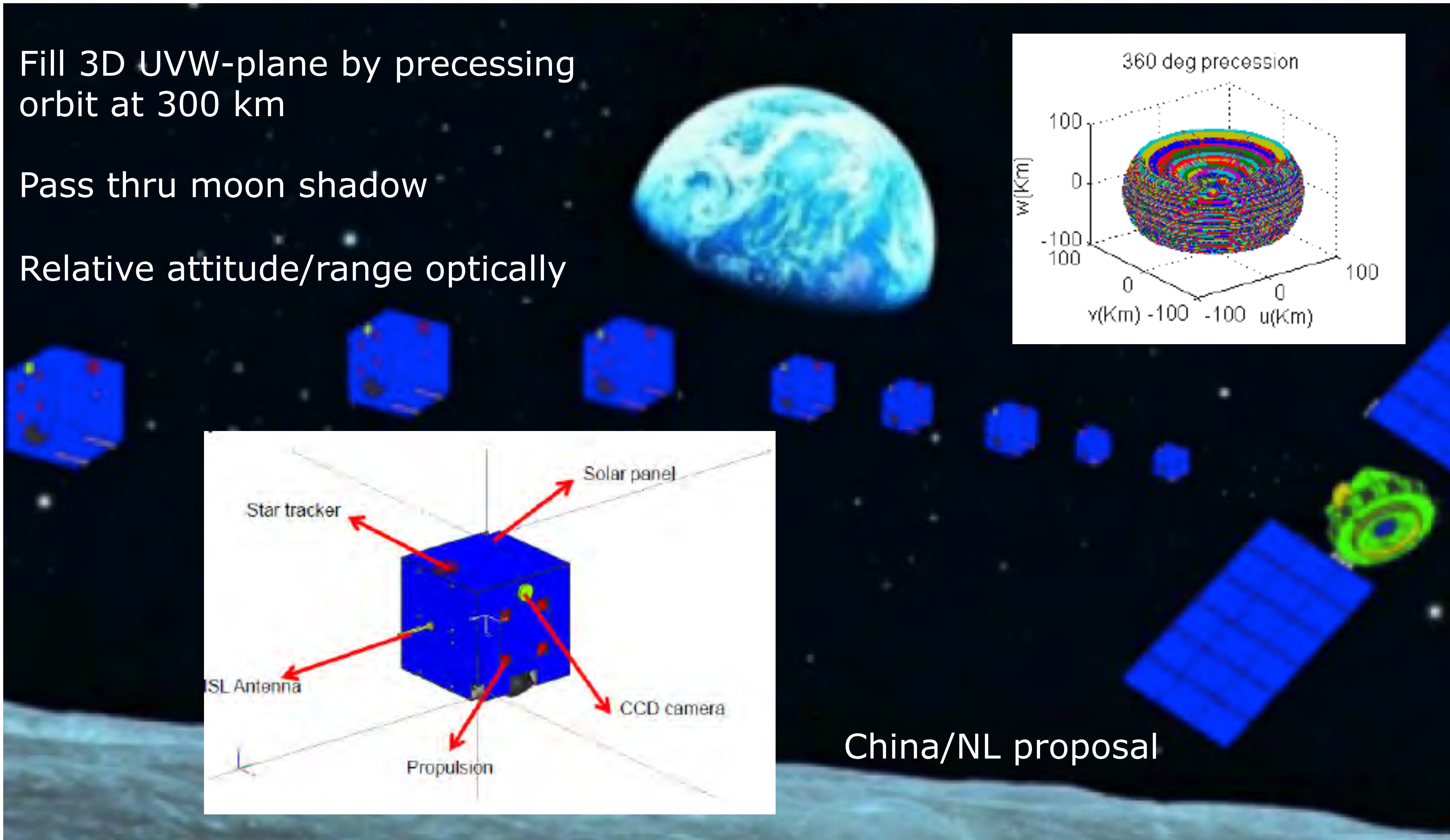
DSL – "cubesat train" Interferometer around moon

Radboud University Nijmegen

Fill 3D UVW-plane by precessing orbit at 300 km

Pass thru moon shadow

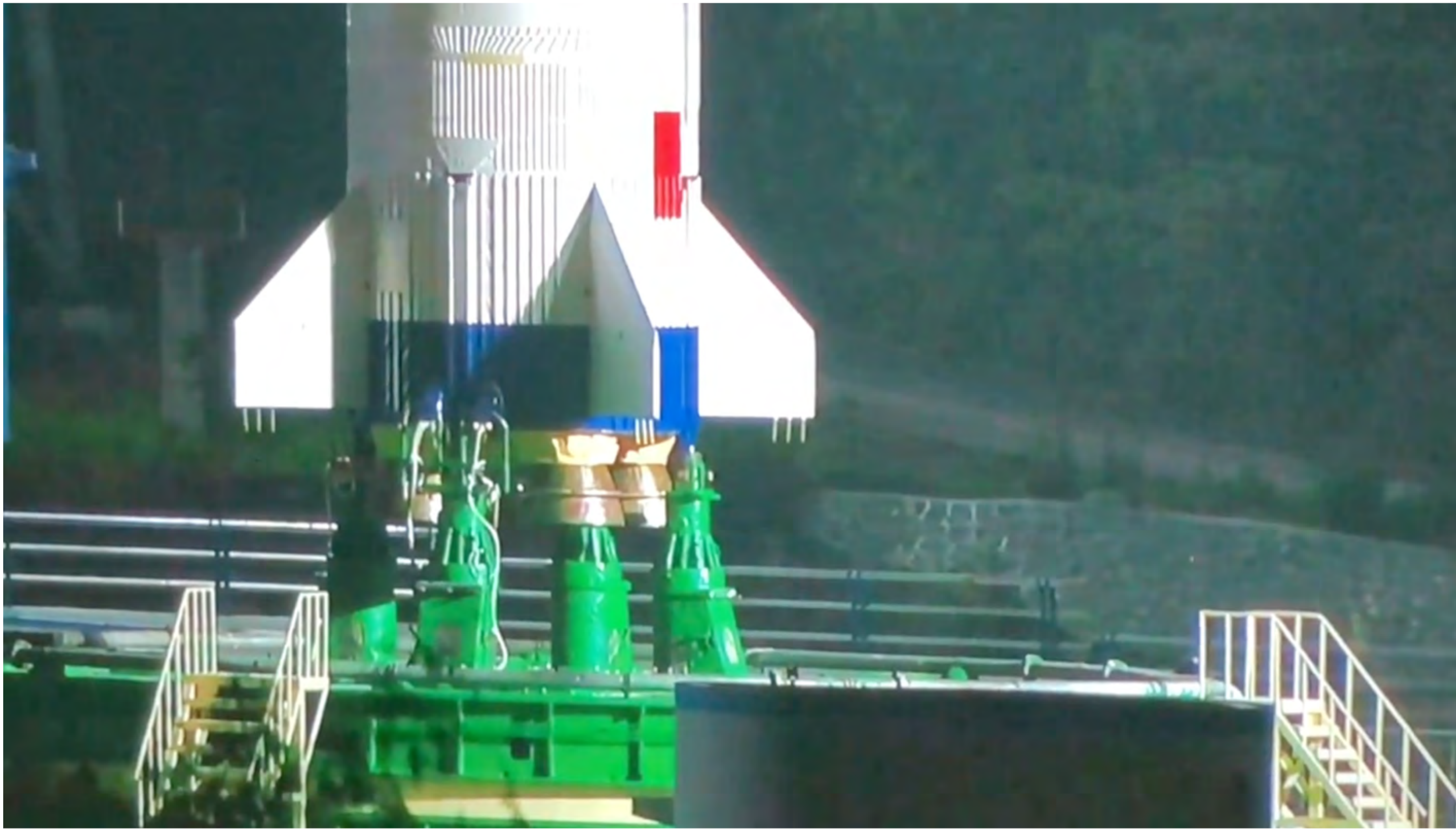
Relative attitude/range optically



China/NL proposal

Queqiao Launch May 20, 2018

Radboud University Nijmegen



NCLE: Netherlands-Chinese Low-Frequency Explorer onboard Chang’E4 relay Queqiao

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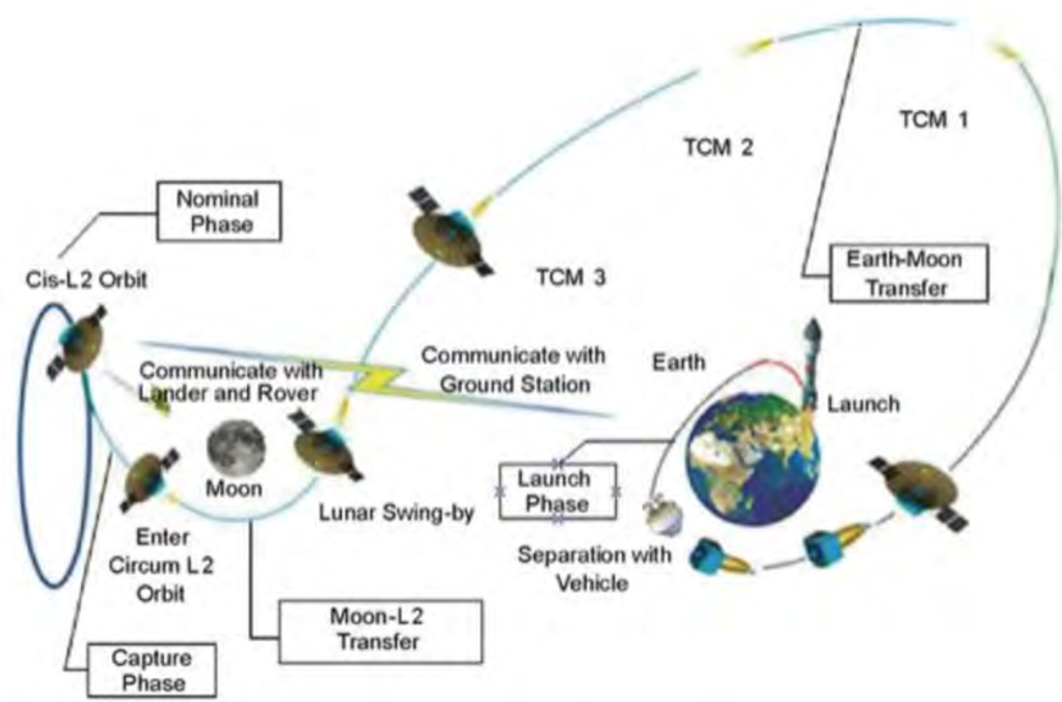
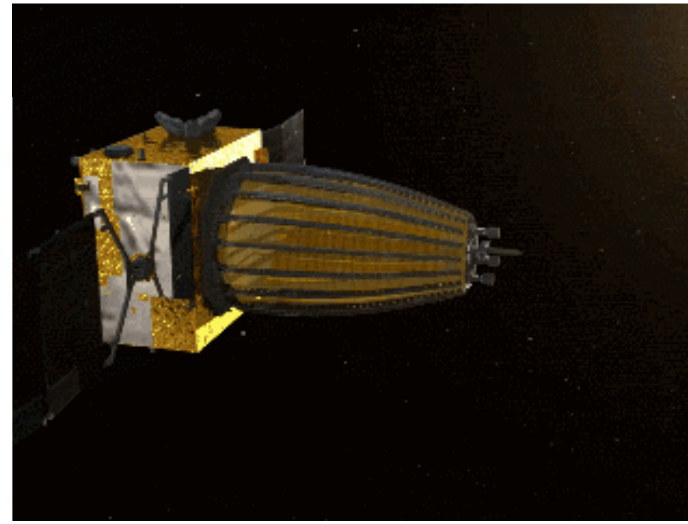
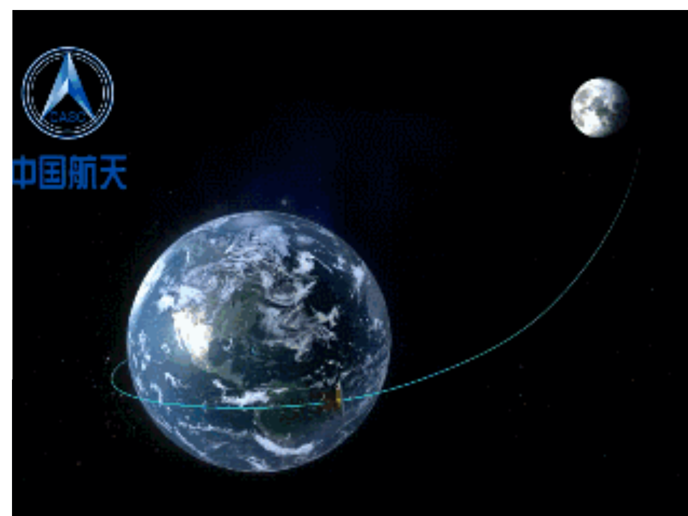


Launch profile for the Chang'e-4 communications relay satellite. *Chinese Academy of Sciences*





NCLE – Low-Frequency Explorer

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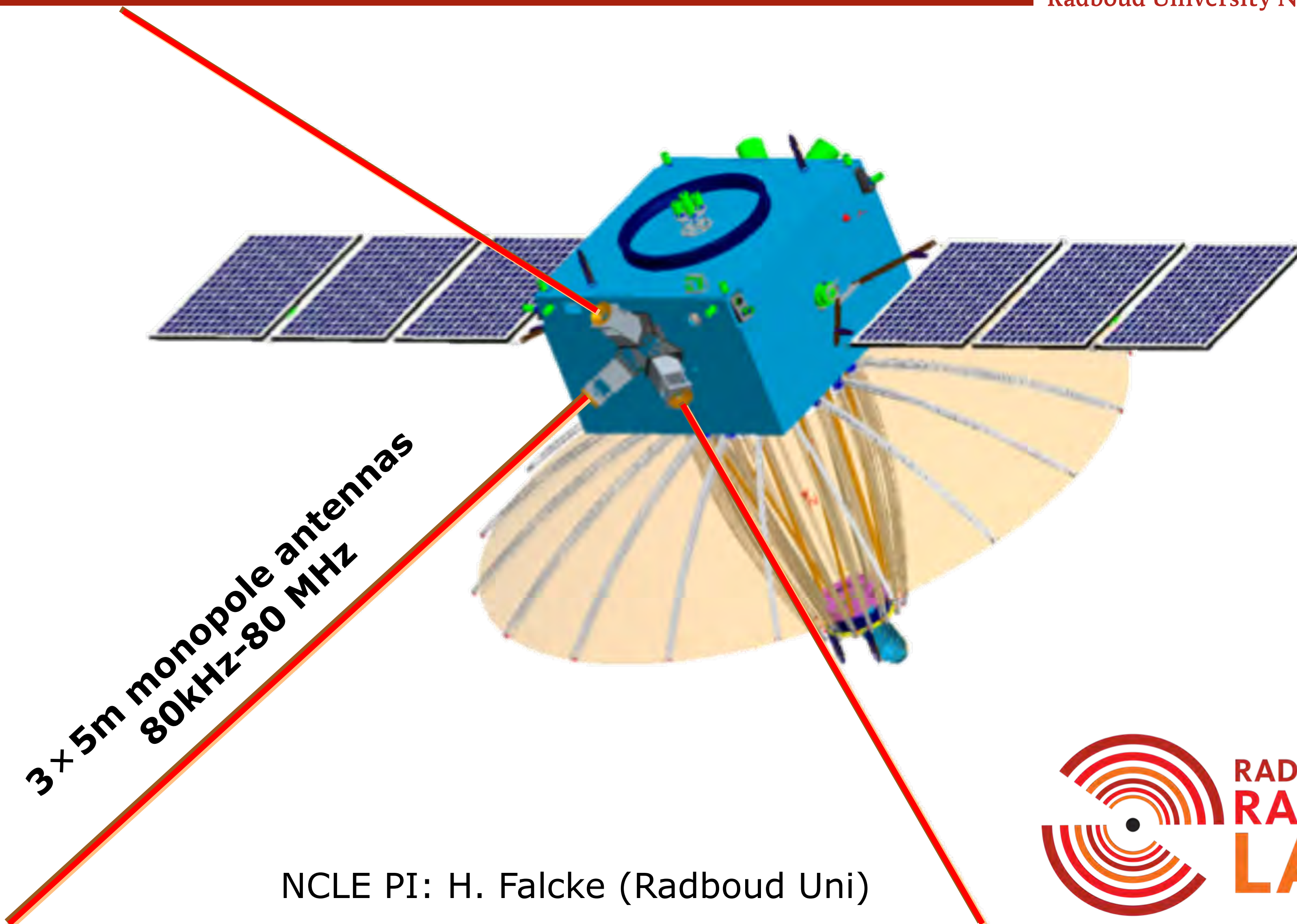


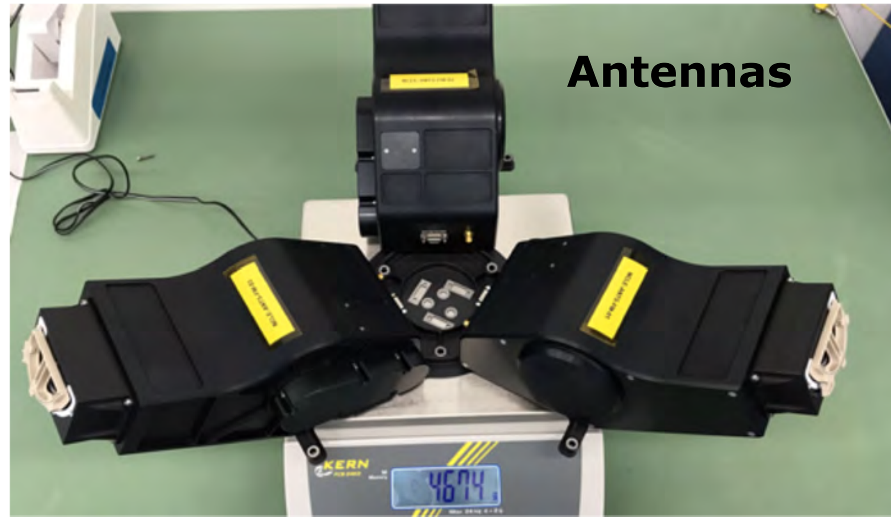
NCLE PI: H. Falcke (Radboud Uni)

RADBOUD RADIO LAB

NCLE components

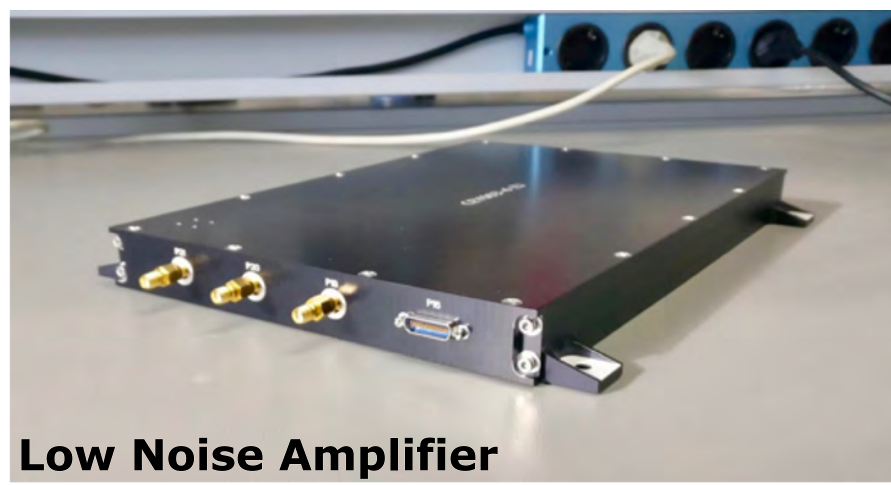
Radboud University Nijmegen

- **Three Monopoles**, 5m each
- **3 bands**: <3 MHz, 1-60 MHz, 60-80 MHz
- **16k chan**, 7.5-0.9kHz, 100 ms dump time
- **Sky noise limited** for 2-50 MHz
- **Full polarization**: XX, YY, ZZ, XY,XZ,YZ
- **14 bit ADC**: 4x, 120 MHz
- on-board memory: **250 GB**
- Downlink: < **10Mbps**
- Power: < **25W**
- Mass: < **10Kg**
- mission life time: **3 years**
- Antenna deployment: **March 2019**



Antennas

Digital Receiver & Control



Low Noise Amplifier

NCLE Sensitivity (3 bands)

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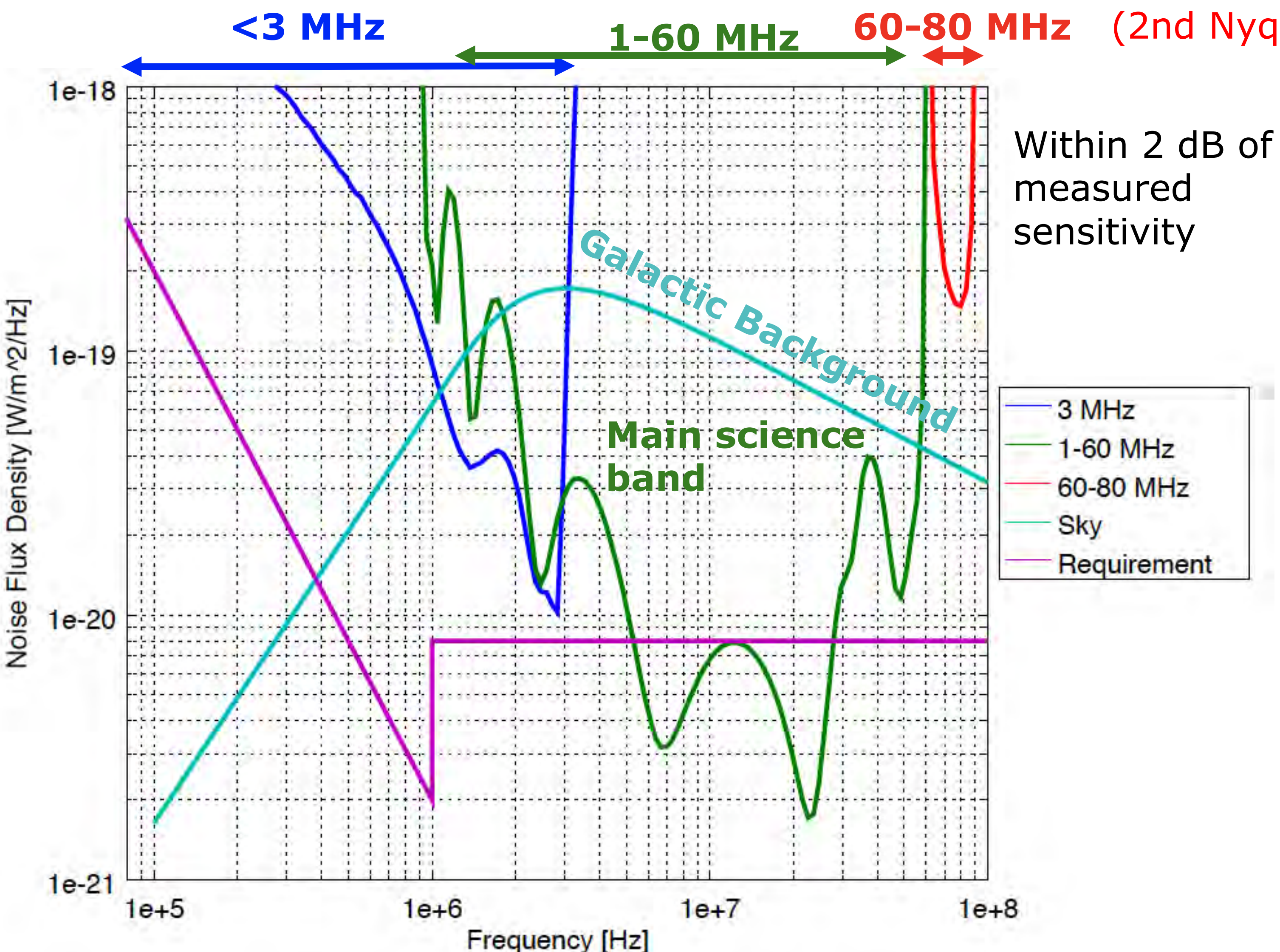

Within 2 dB of measured sensitivity

Conclusion

- End of Time:
  - The EventHorizonTelescope will deliver 1st images of black holes soon: rudimentary but precious!
  - M87: best to see shadow, Sgr A*: best to test GR
  - Images will become sharper with time: more data, higher frequency, +Africa, & Space Interferometry!
- Beginning of time:
  - Record of early universe and big bang is preserved in fluctuations of primordial hydrogen & 21 cm line (1.4 GHz) redshifted to 5-100 MHz
  - The lunar environment is an ideal location to detect this: infrastructure, shielding, stable ground

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