Imaging Black Holes: Past, Present, and Future

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@hfalcke

Event Horizon Telescope Collaboration

RADBOUD RADIO LAB

erc European Research Council

BLACK HOLE CAM

ERC Synergy Grant Co-PIs:
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M. Kramer (MPIfR Bonn)

How a black hole looks like

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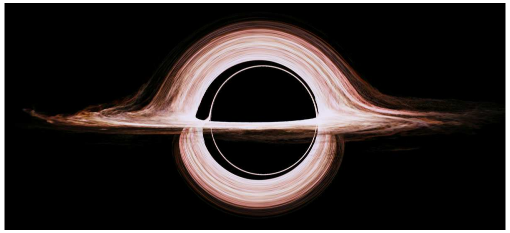
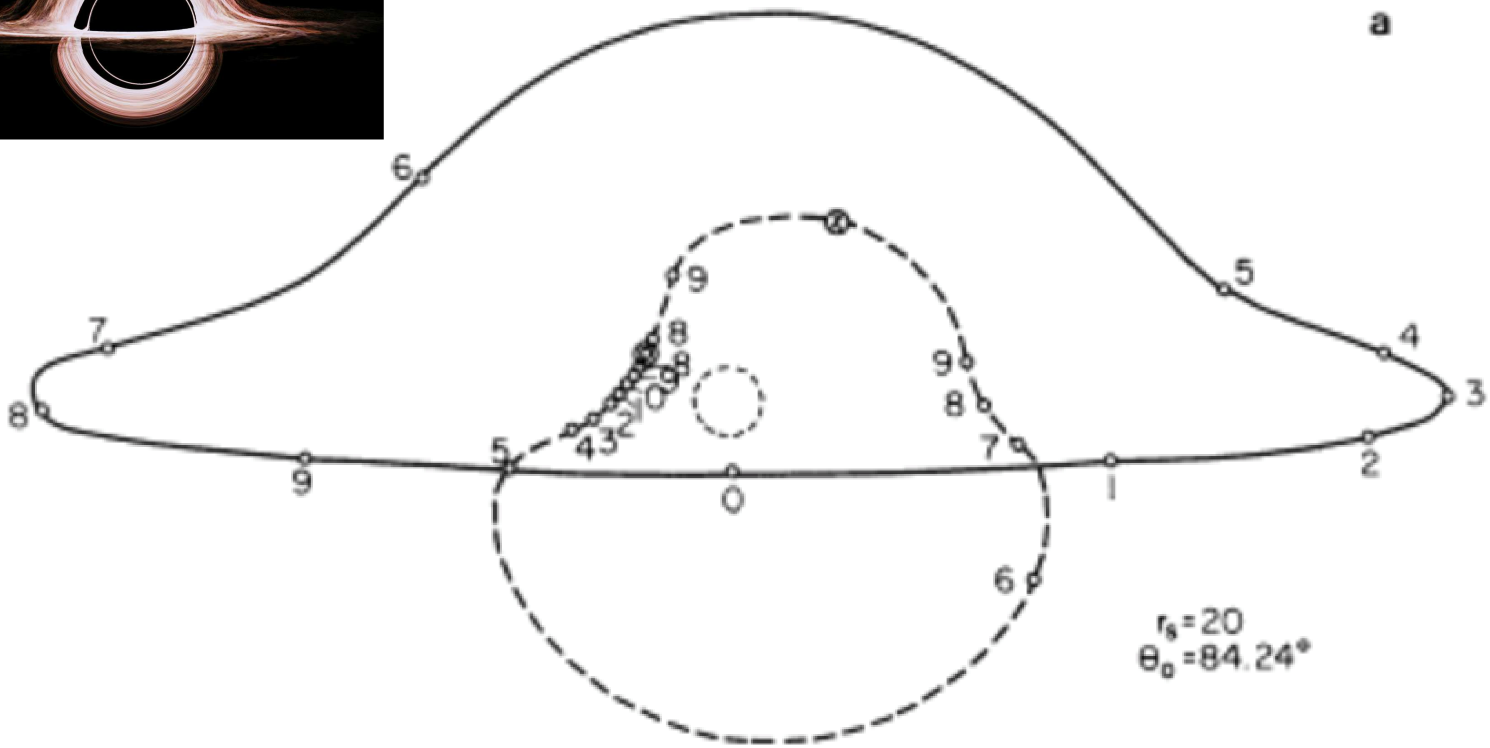
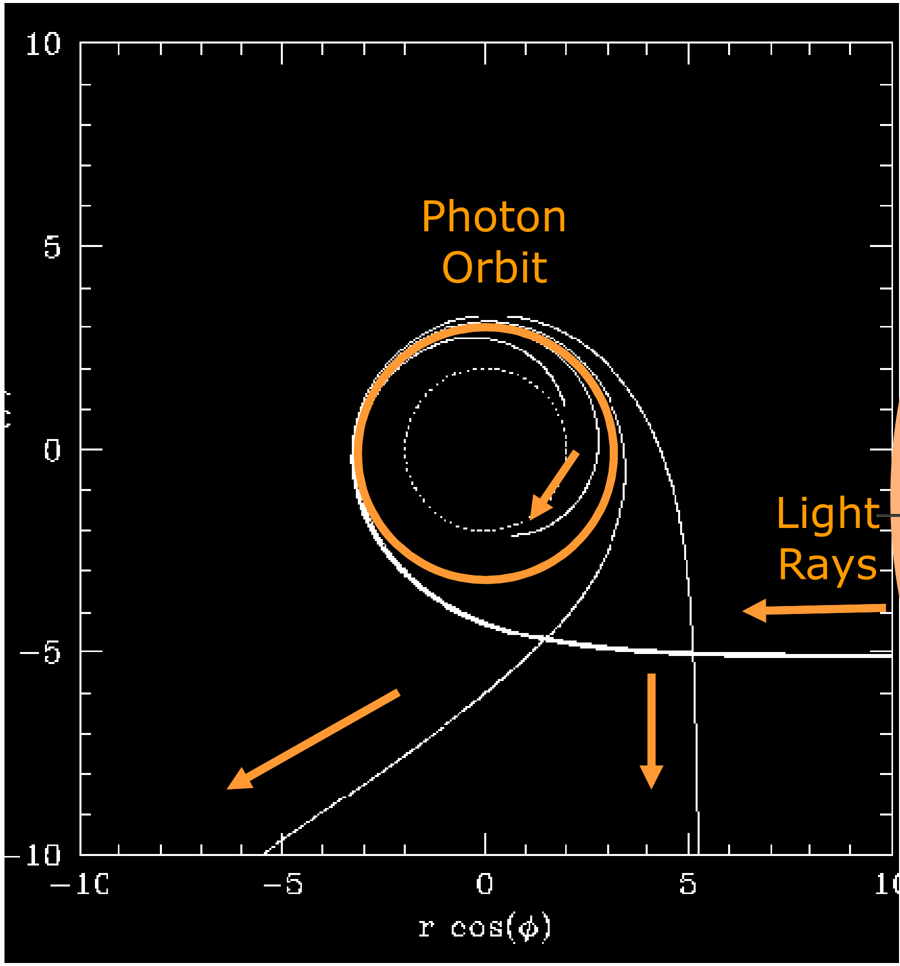




"Image of a star orbiting a black hole" Cunningham & Bardeen (1973)

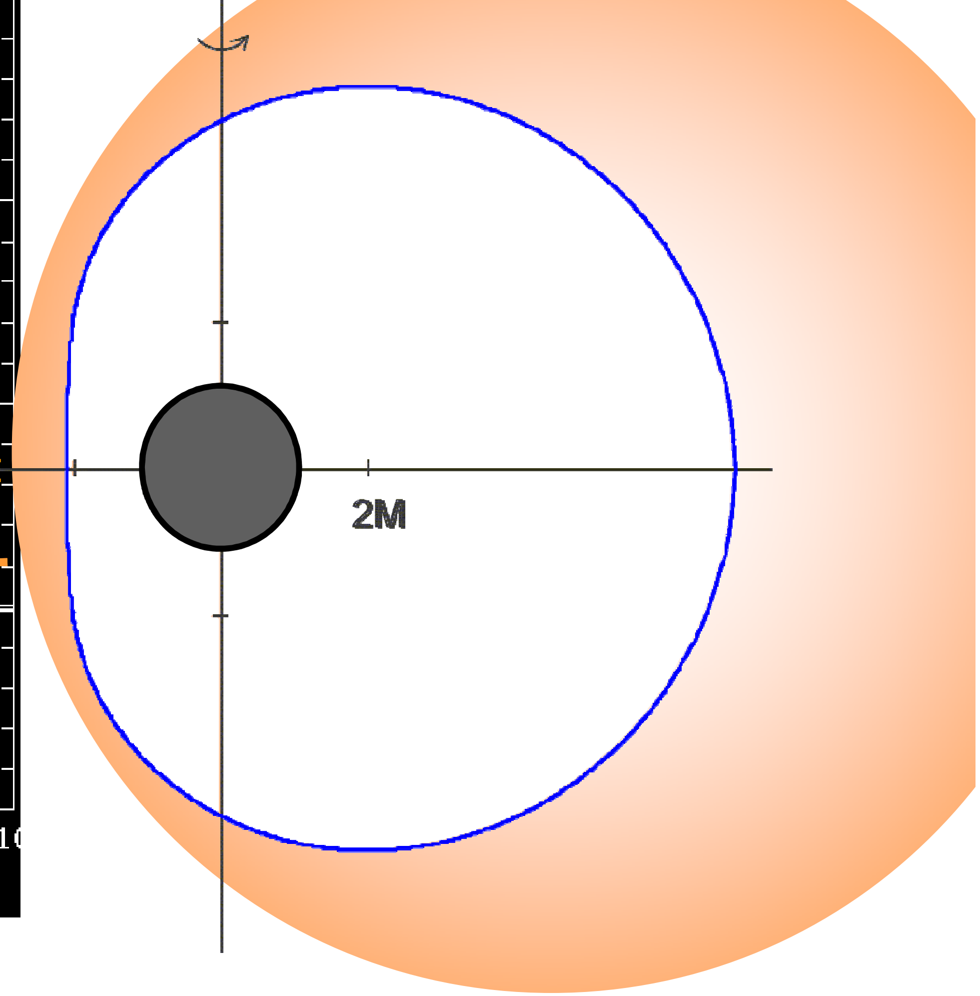
"Photos" of a black hole

Radboud University Nijmegen

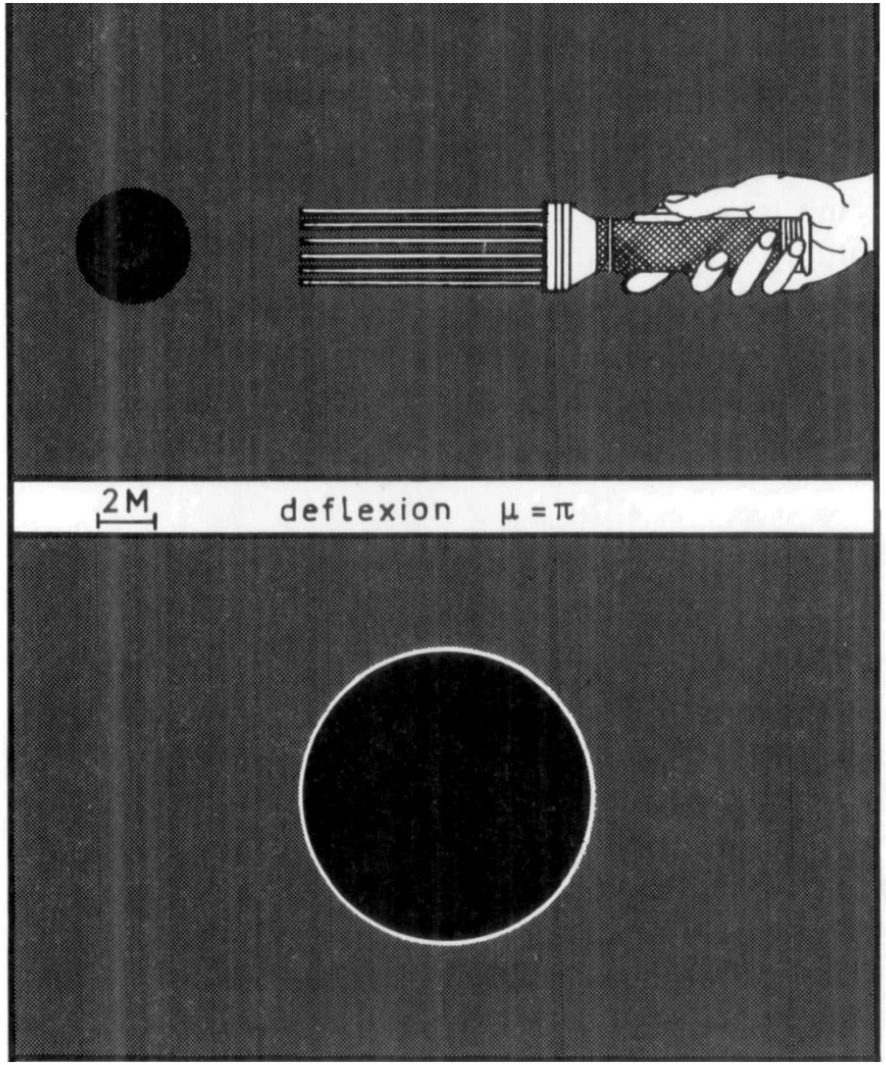


Circular photon orbit: Bardeen (1973)

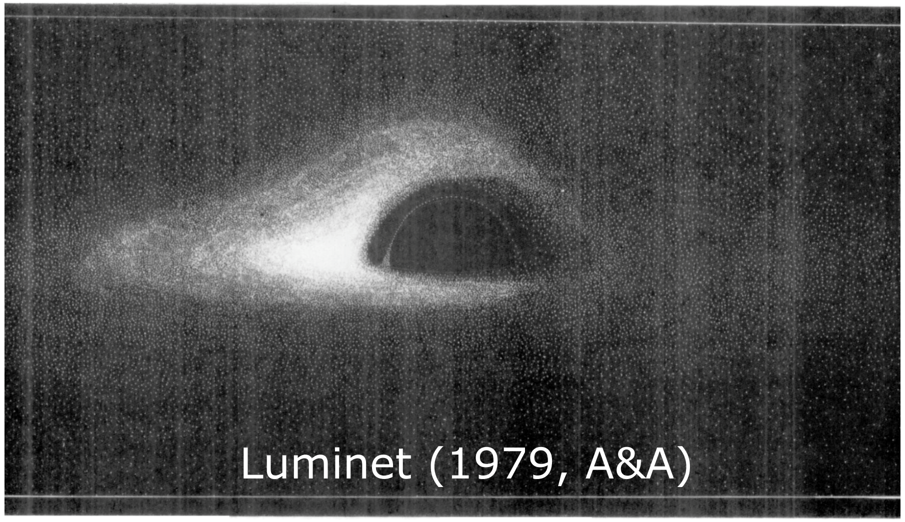
"star behind black hole"



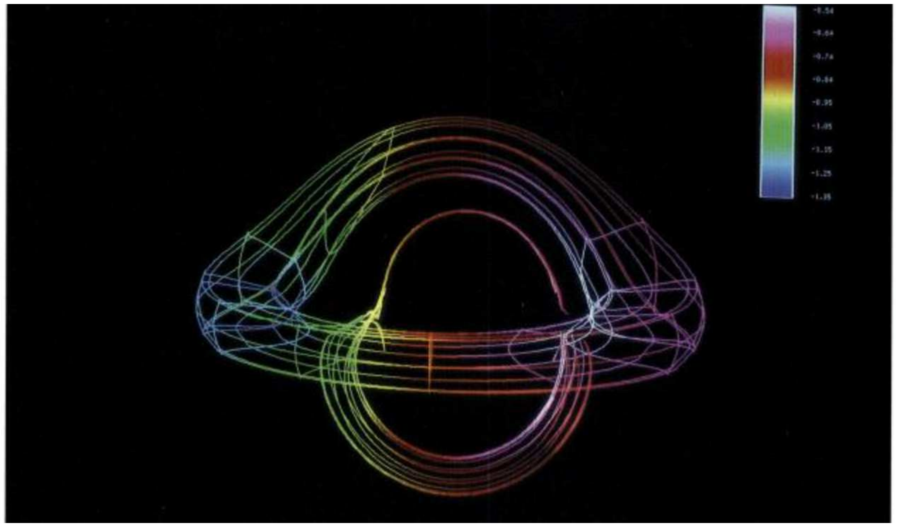
Photos of a black hole



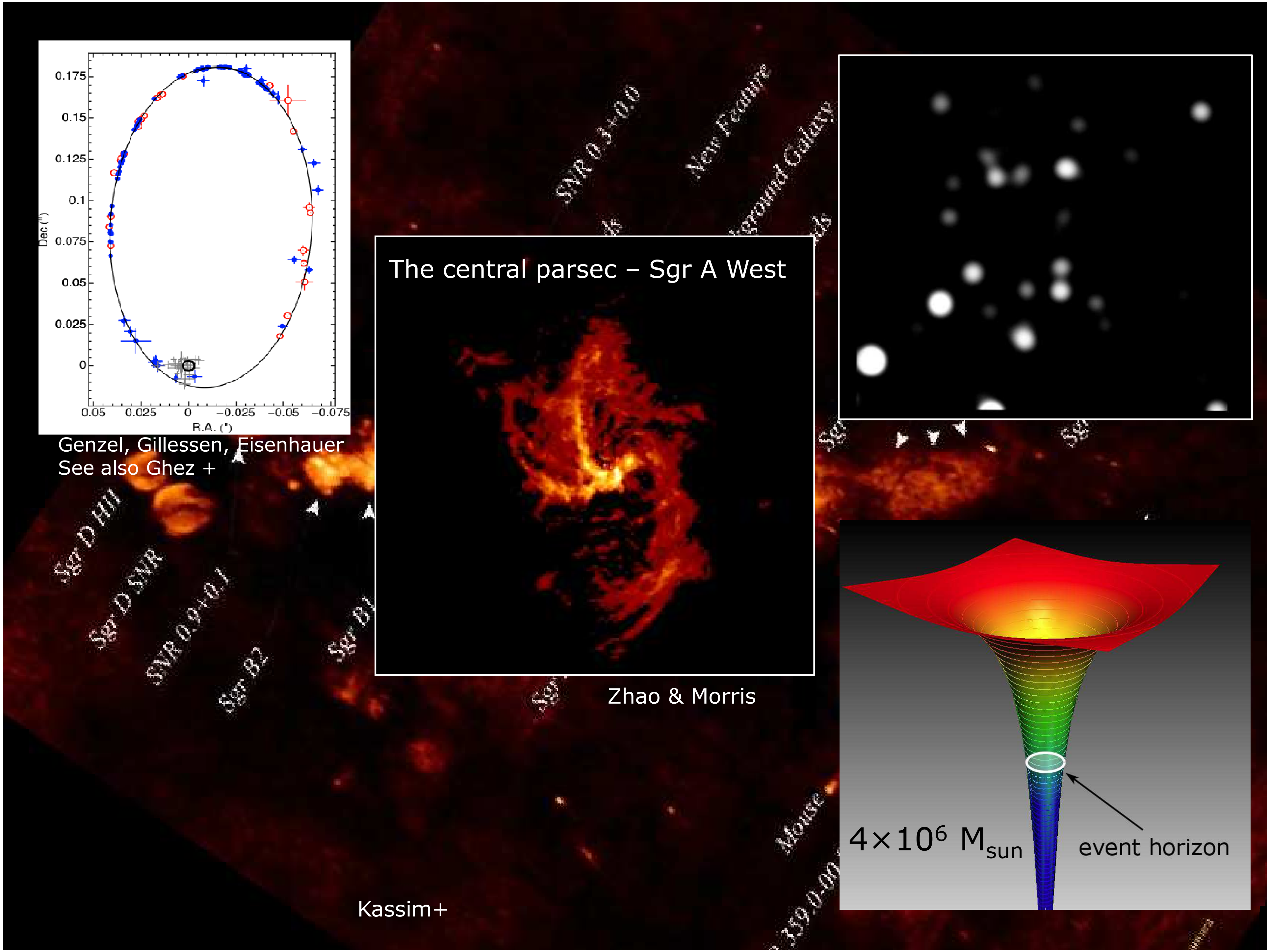
Luminet (1979)



Luminet (1979, A&A)



Viergutz (1993, A&A)



Dec (")
R.A. (")
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
0.05
0.025
0
−0.025
−0.05
−0.075
Genzel, Gillessen, Eisenhauer
See also Ghez +
The central parsec – Sgr A West
Zhao & Morris
Kassim+
SNR 0.3+0.0
New Feature
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Mouse
4×10⁶ M_sun
event horizon

Sgr A spectrum: starved black hole, jet, accretion flow, shadow*

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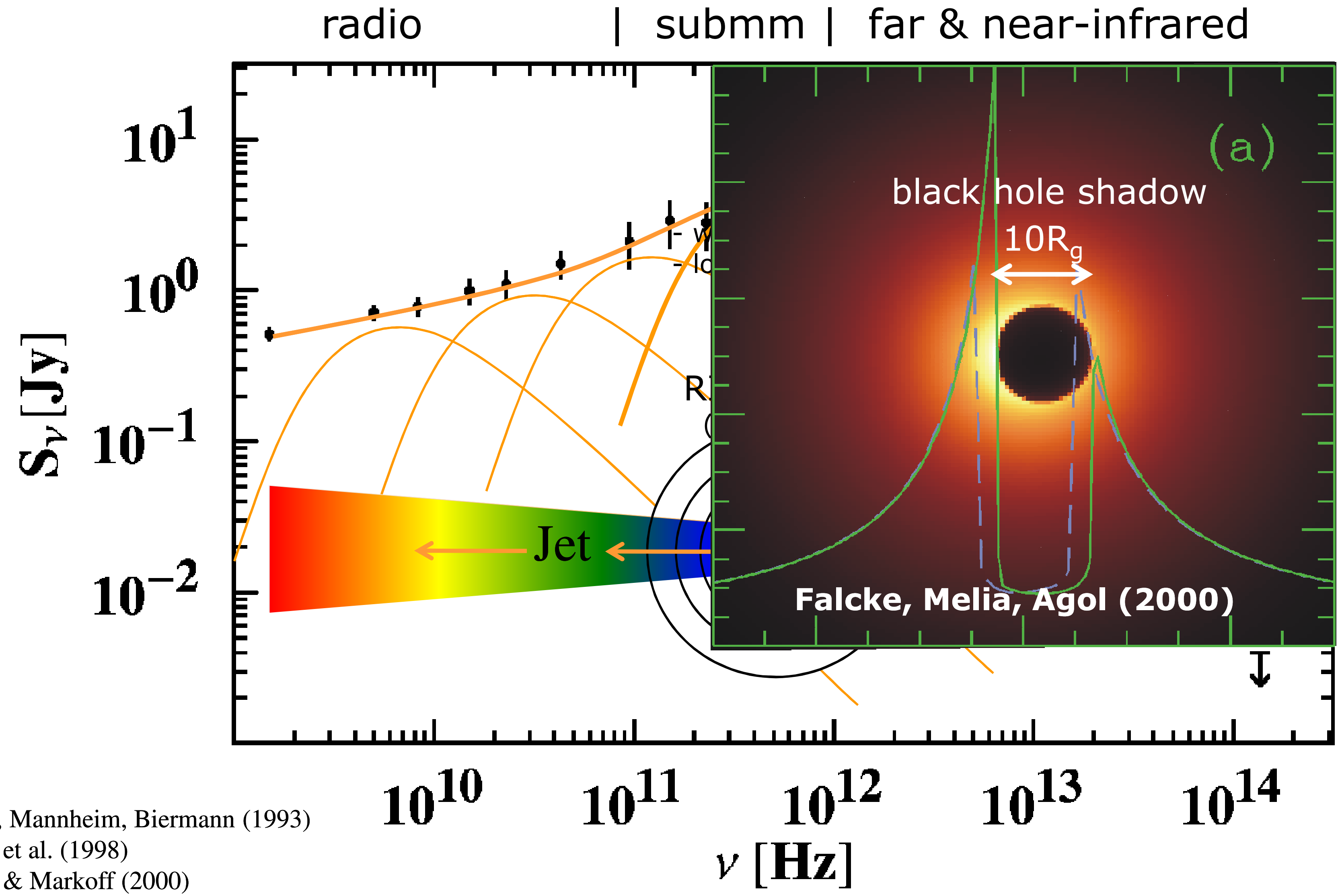

Falcke, Mannheim, Biermann (1993)
Falcke et al. (1998)
Falcke & Markoff (2000)

Different Theories of Gravity Different Shadows

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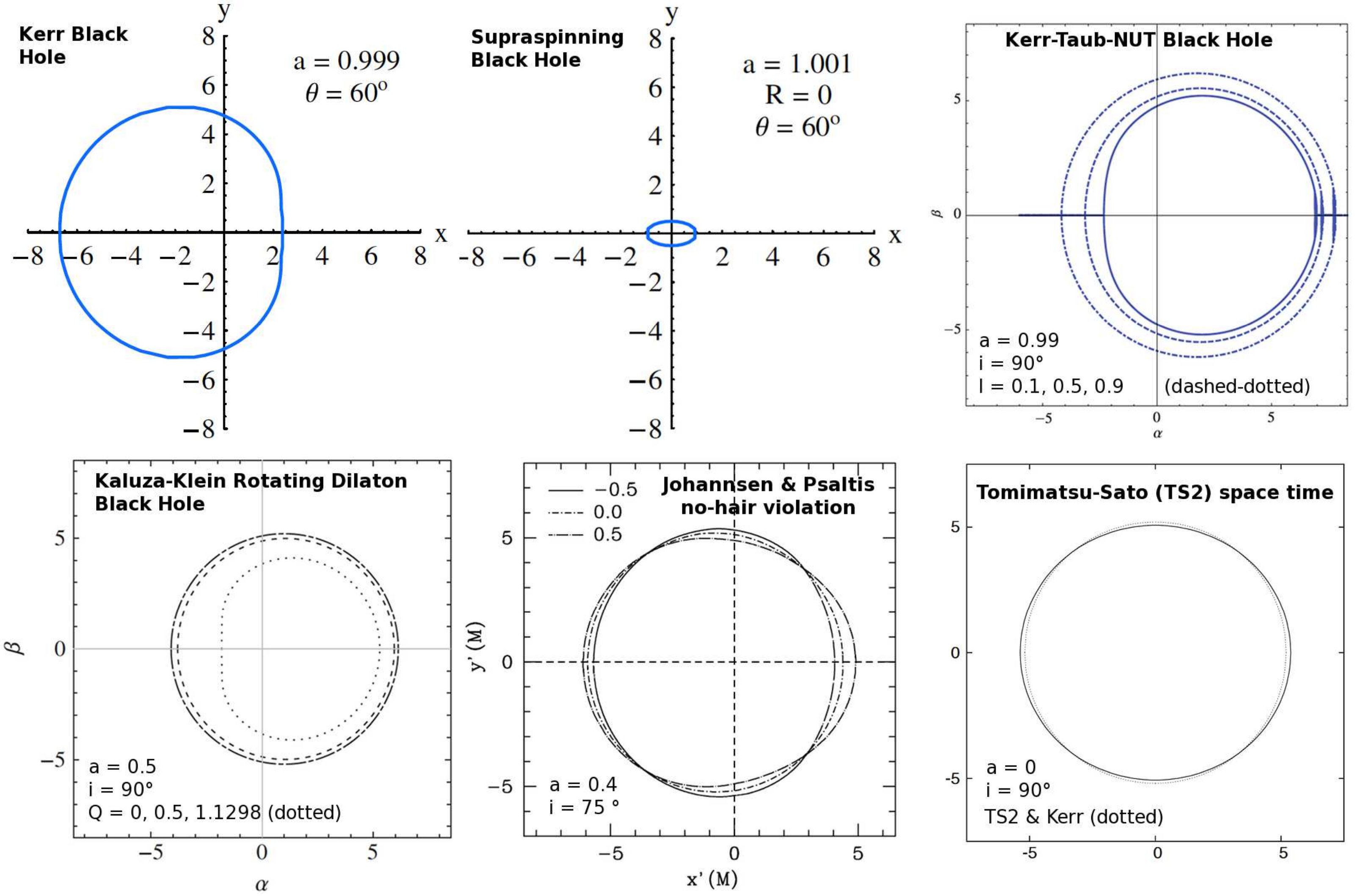

Falcke & Markoff, Class. & Quant. Gravity (2013, review)

The radio jet in M87 (Virgo A)

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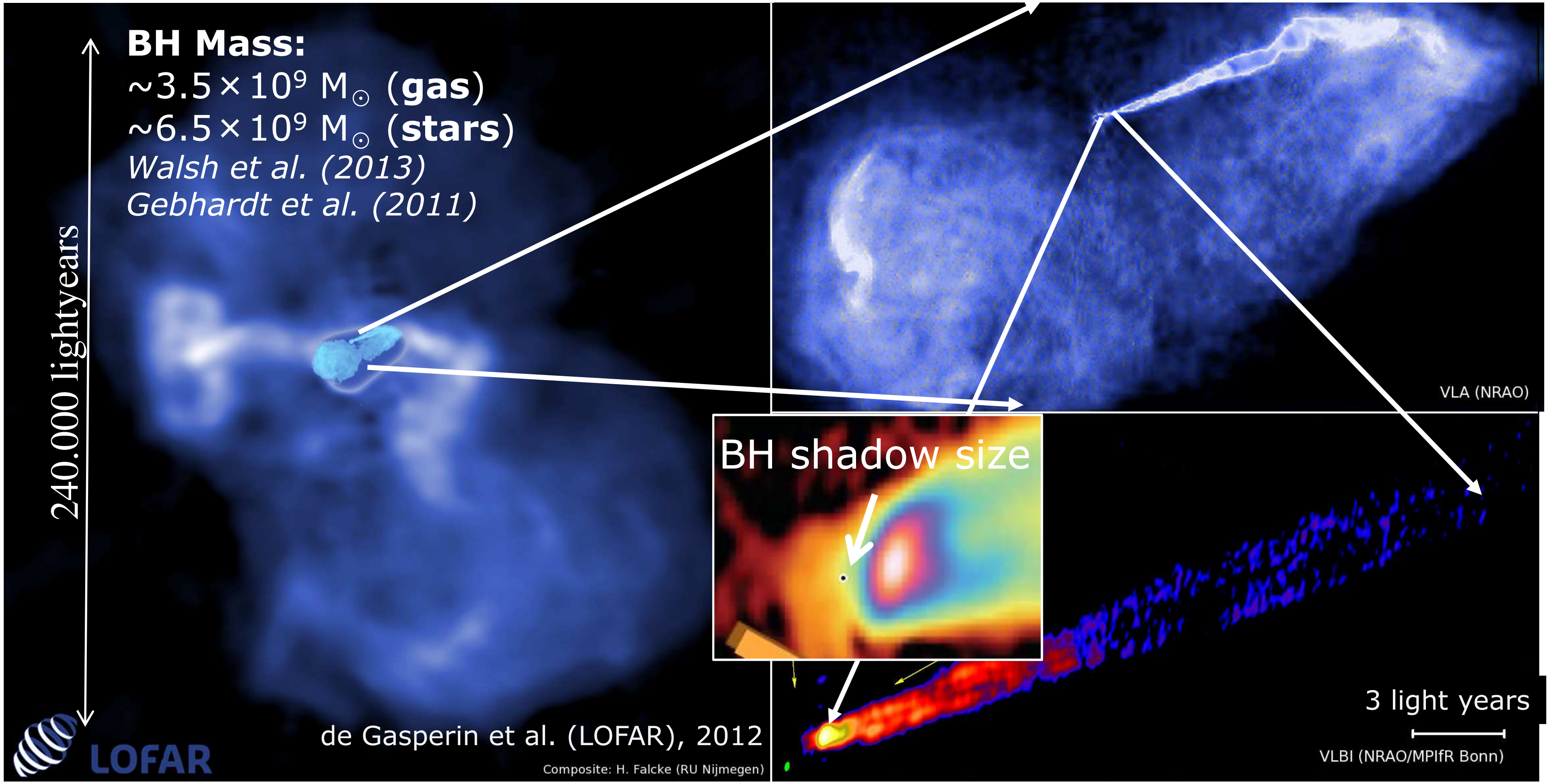
Elliptical galaxy in center of Virgo cluster at d=17 Mpc

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

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



Comprehensive set of Advanced Simulation Tools

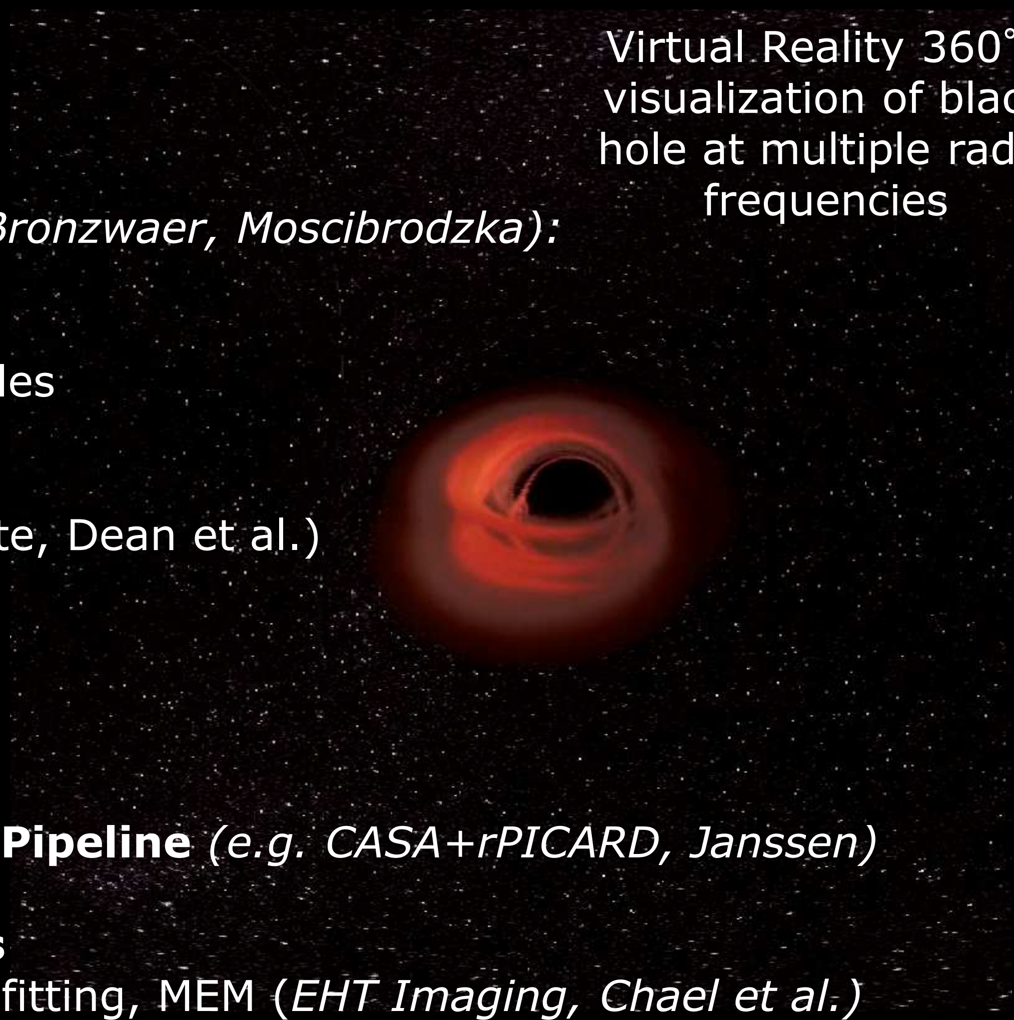
- **Plasma simulations** *(e.g. BHAC Code, Porth et al.):*
  - Ideal (soon non-ideal) 3D GRMHD
  - Multiple coordinate systems
  - Adaptive GRID
  - Arbitrary space times

- **Ray Tracing** *(e.g. RAPTOR, Bronzwaer, 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**

Davelaar, Bronzwaer, Moscibrodzka, HF, et al. ..

Jet Models with scattering

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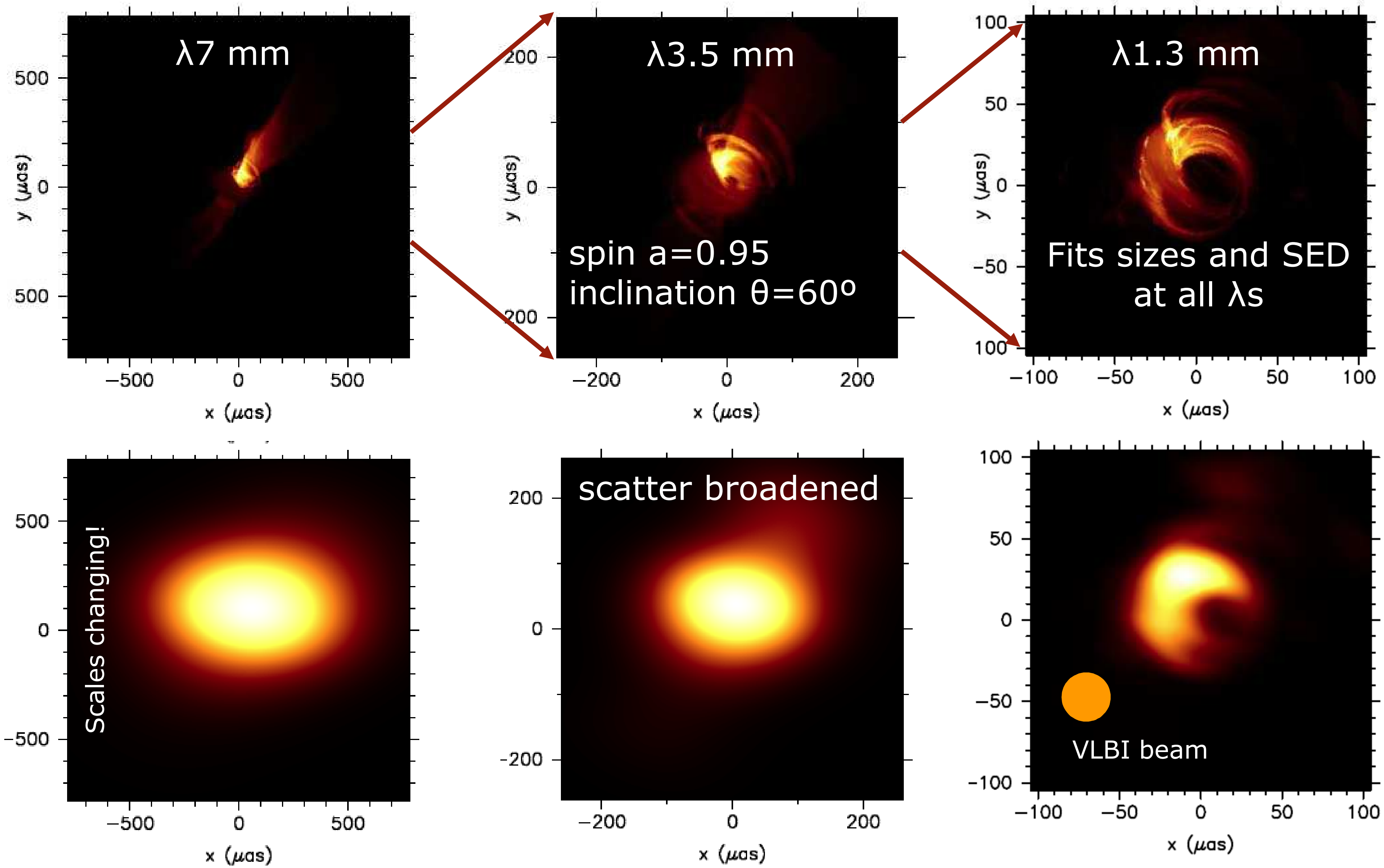
Moscibrodzka, HF et al. (2014)



The path towards event horizon imaging

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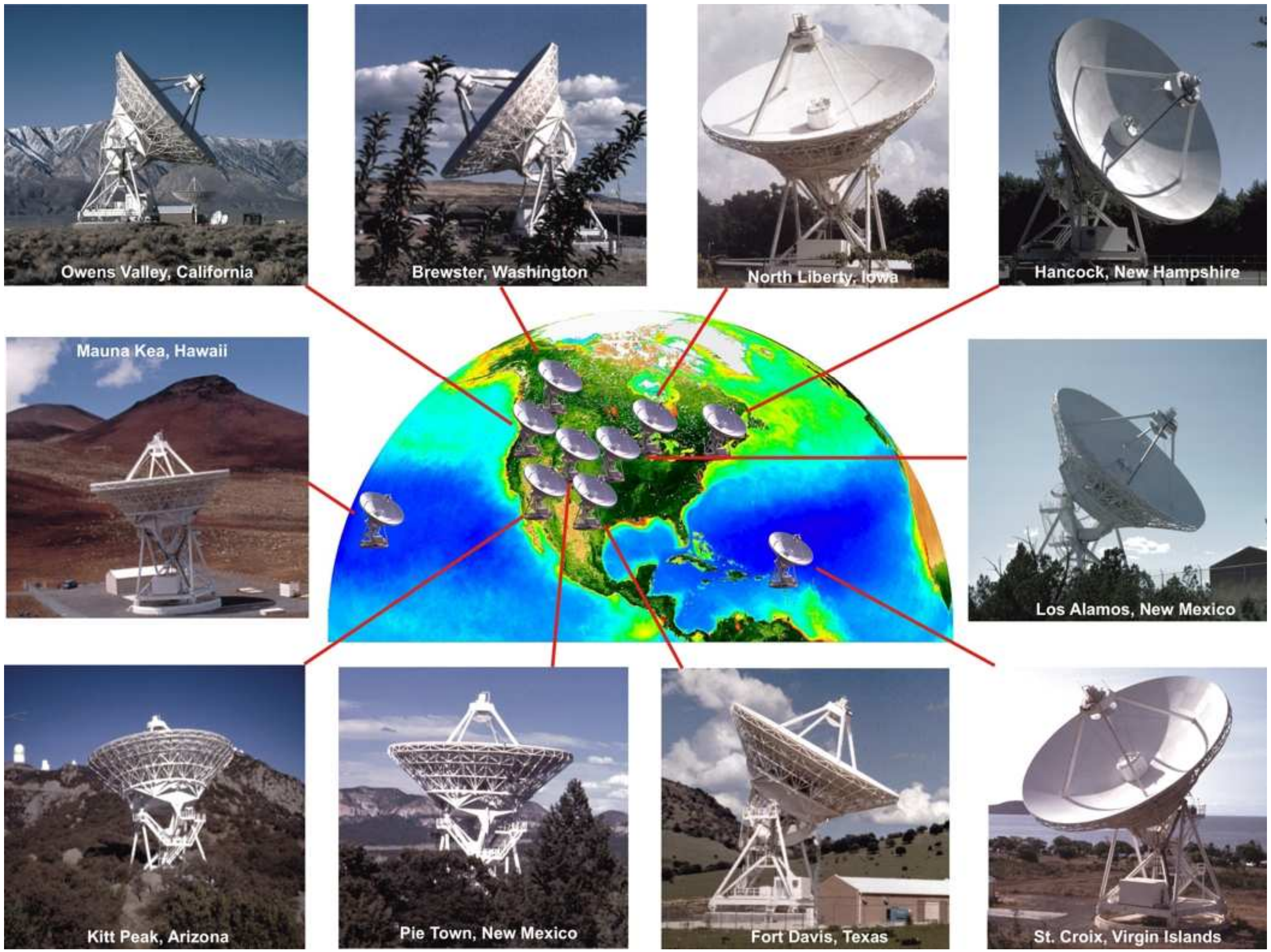
VLBA



VLBI from 3 cm to 3 mm

The path towards event horizon imaging

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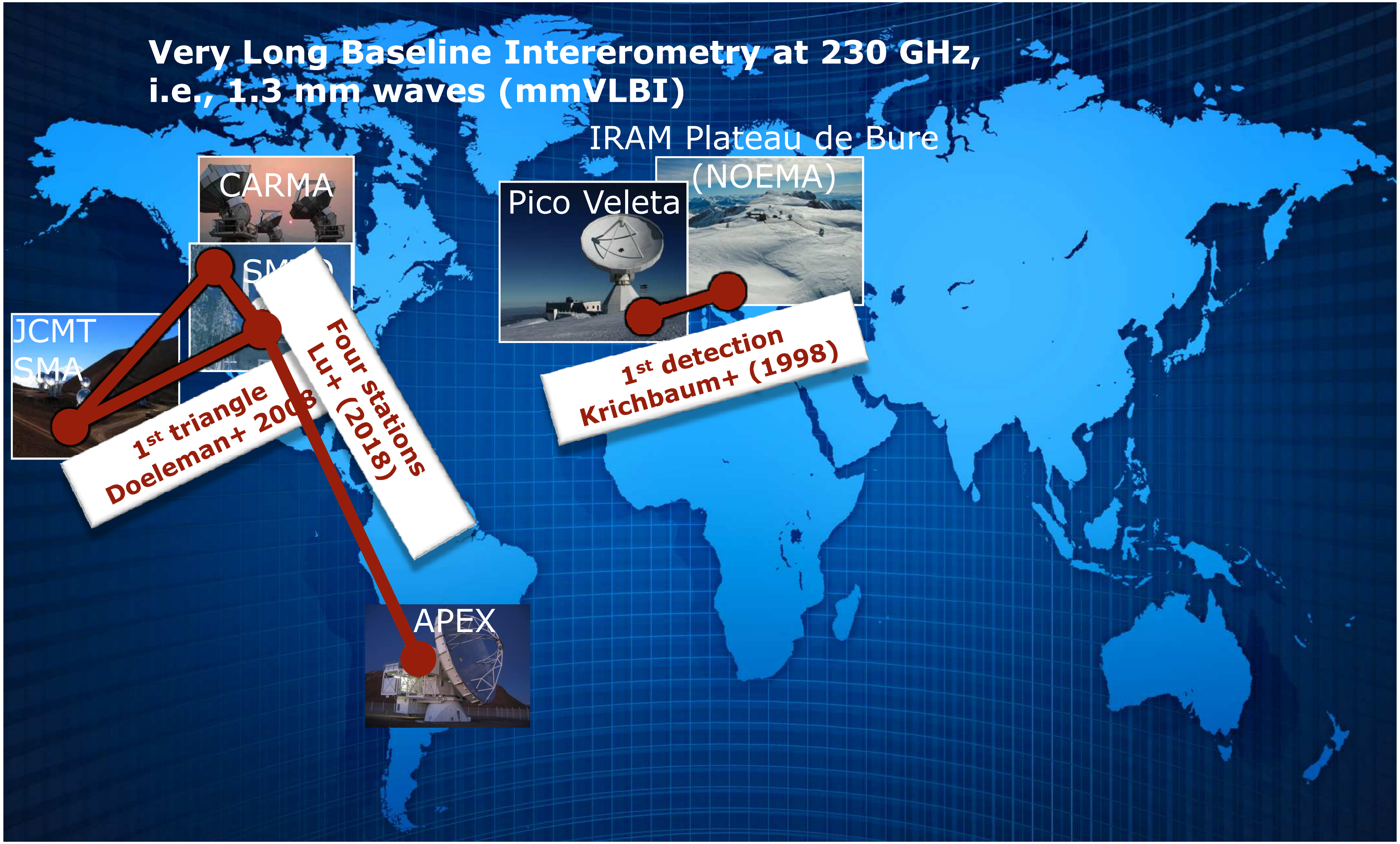

Intrinsic Radio Size of Sgr A*

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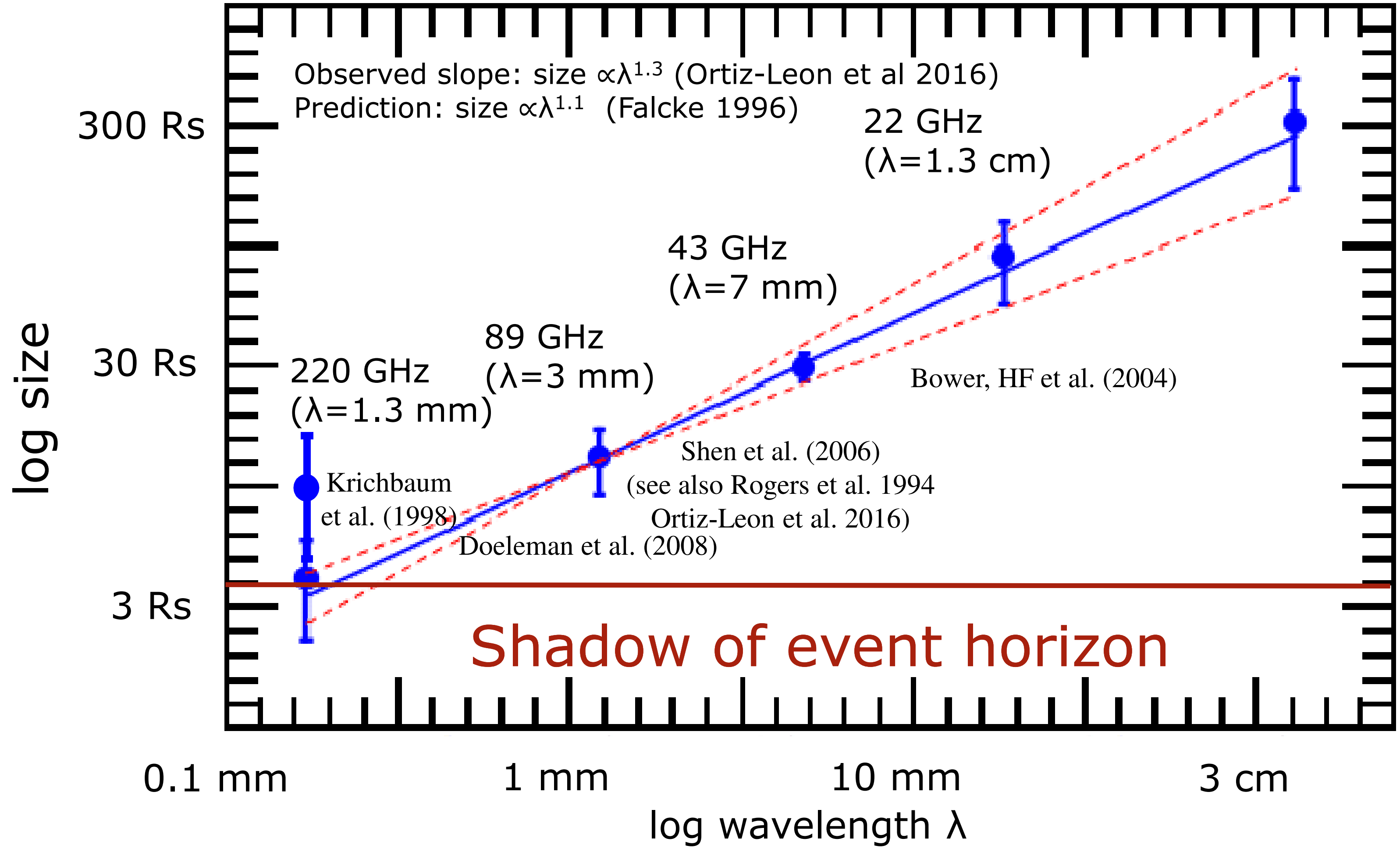
The higher the radio frequency – the closer to the black hole.
At 230 GHz the emission comes from the event horizon scale.



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

UV-Plots: Fouriertransforms

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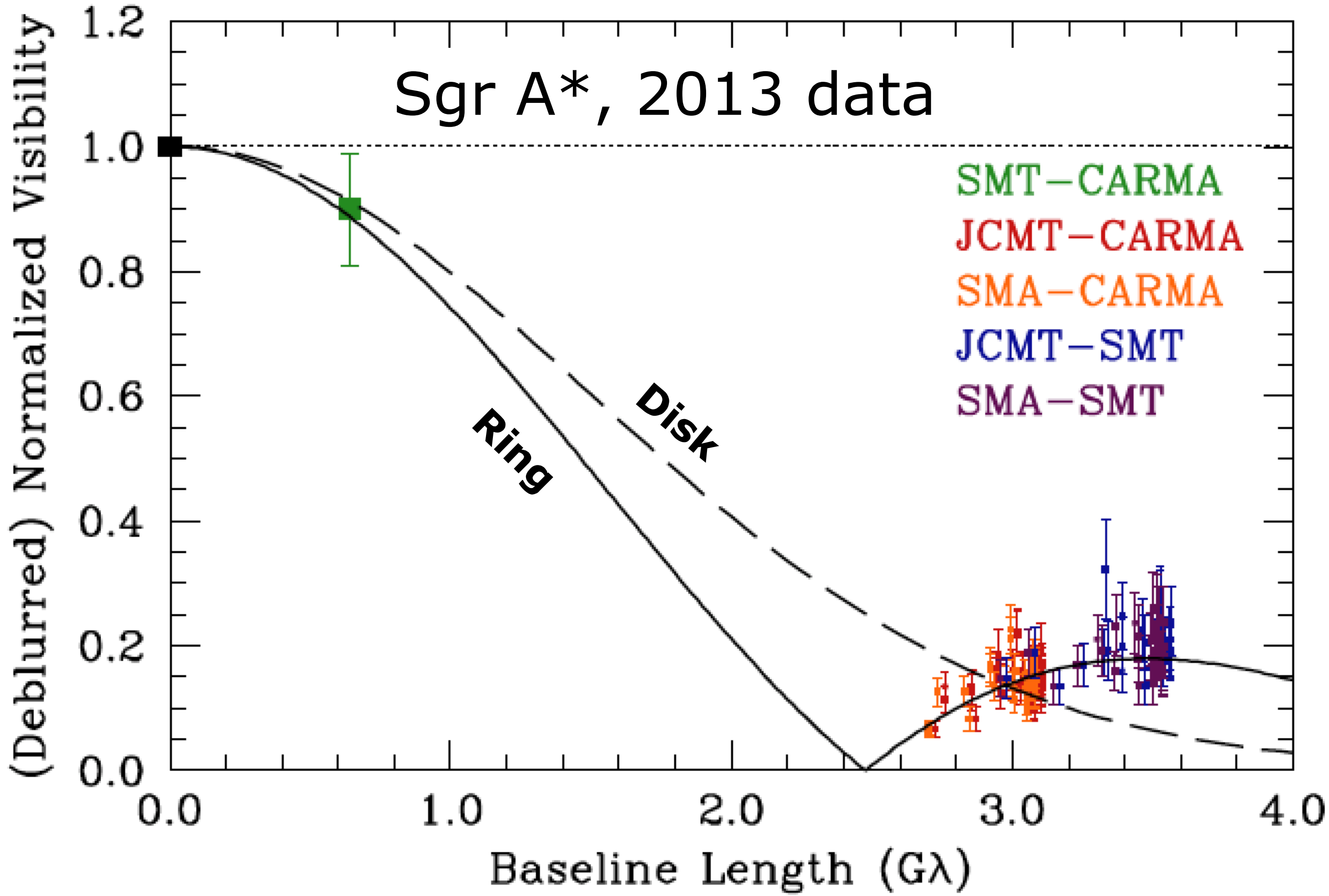

Johnson et al. (2015)

230 GHz VLBI with APEX (2013)

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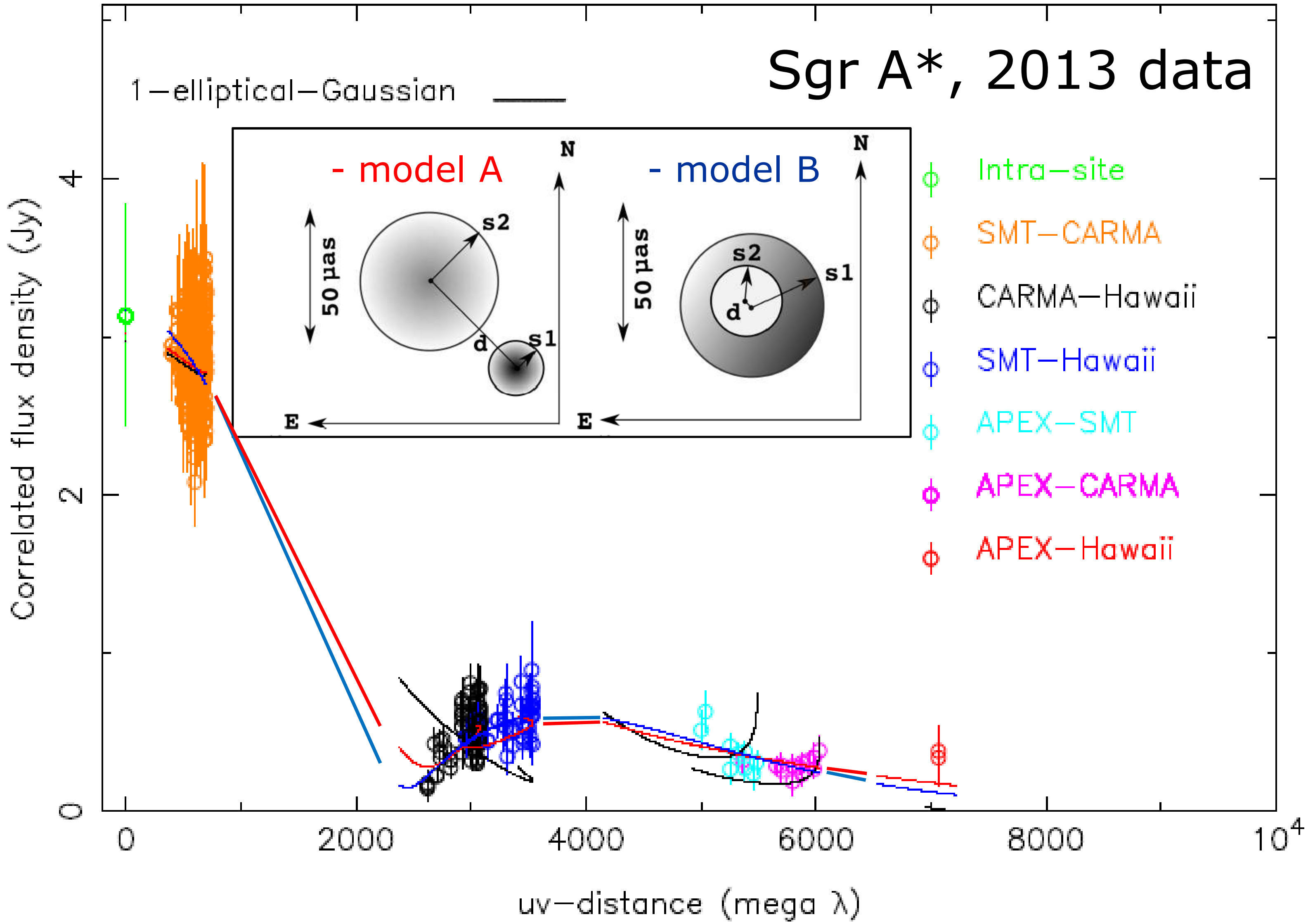


Lu et al. 2018, ApJ, in press

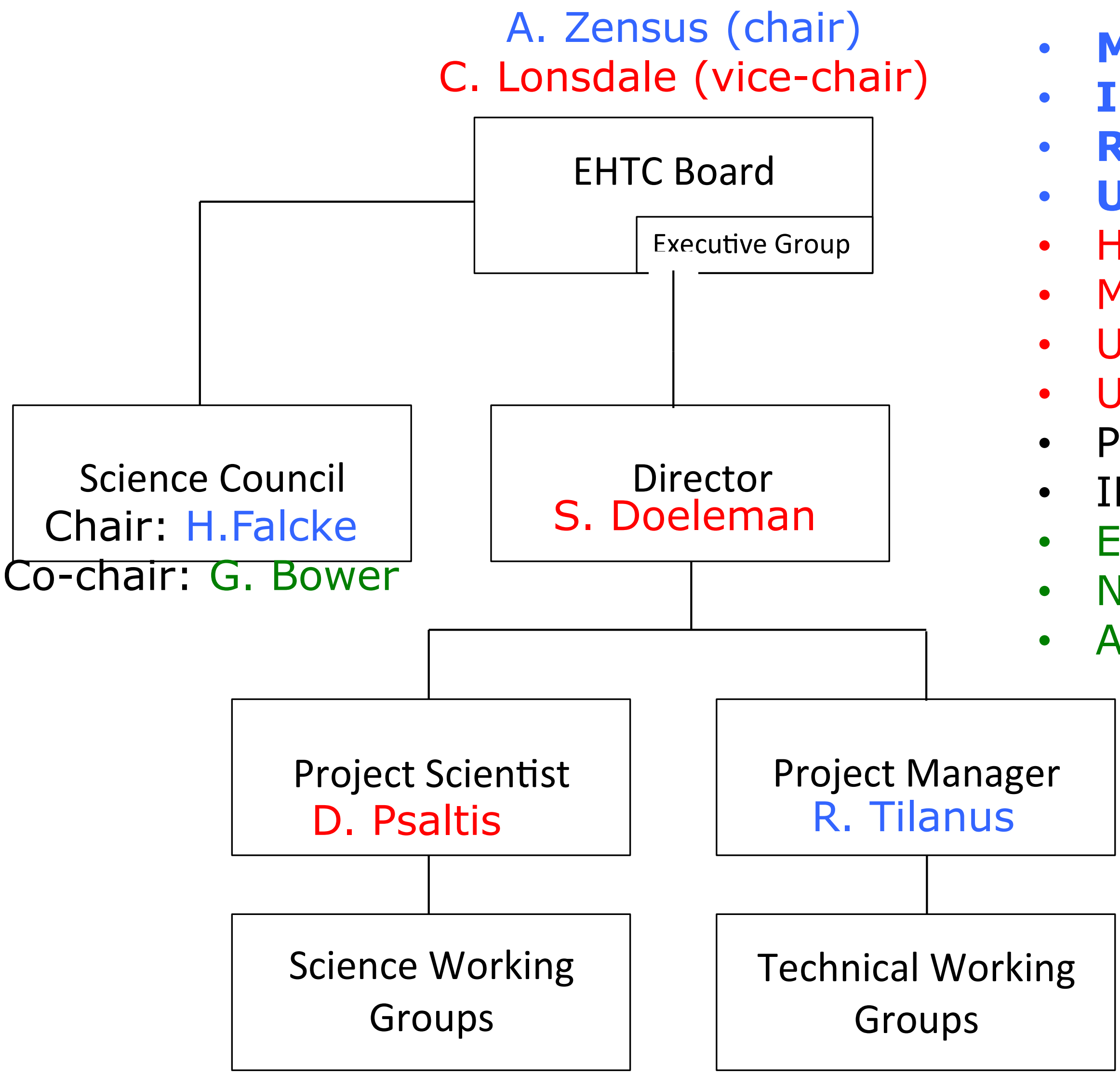
2017 global EHTC Campaign

Event Horizon Telescope

- 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
- All data arrived safely at correlation centers & is being processed
- **High SNR data and „fringes" to all stations!**


Mexico
Arizona
South Pole
Chile
Spain

Event Horizon Telescope Consortium



13 EHT Stakeholders

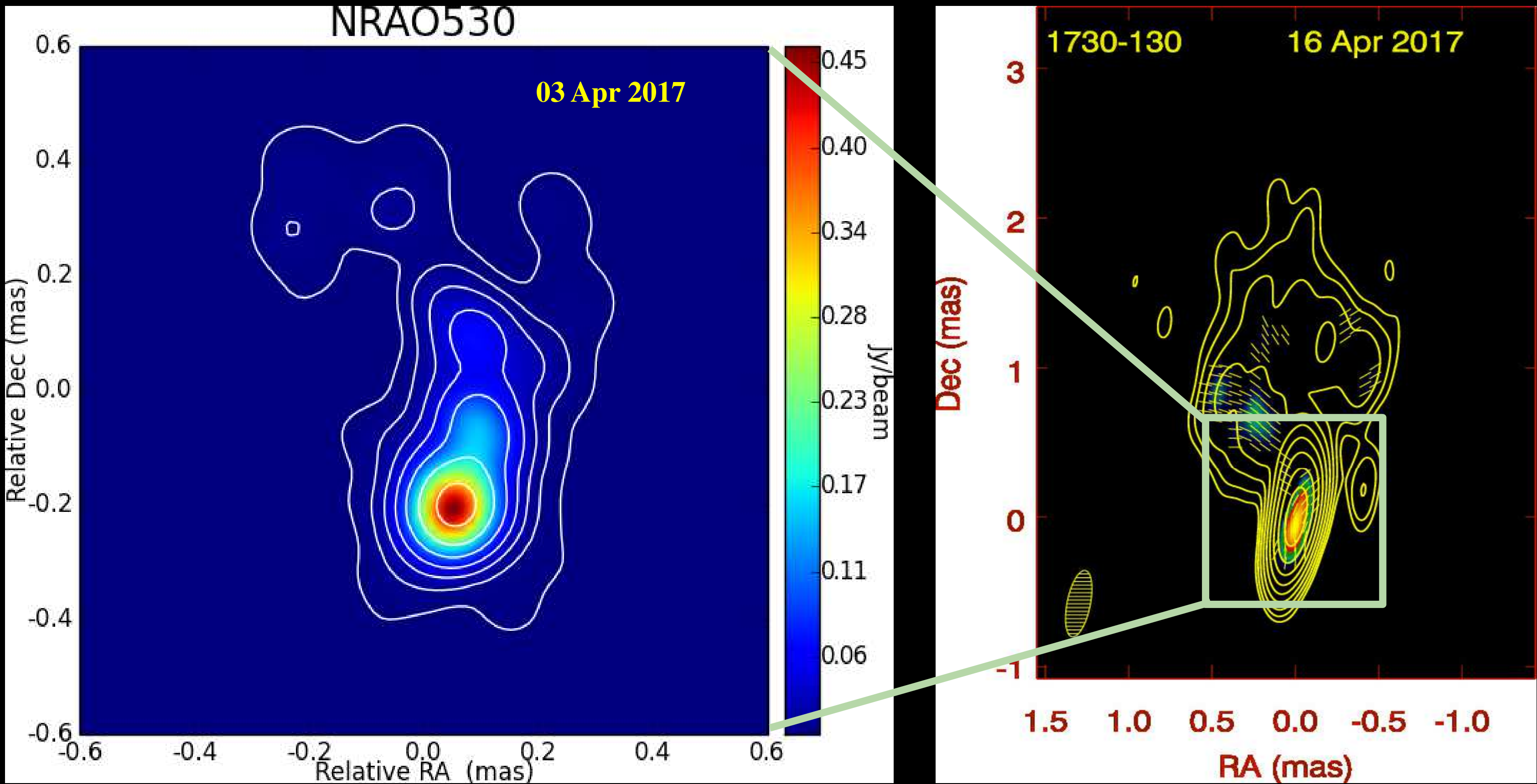
- **MPIFR Bonn (Germany)**
- **IRAM (D/F/E)**
- **Radboud Uni. (Netherlands)**
- **Univ. Frankfurt (Germany)**
- Harvard/SAO (USA)
- MIT Haystack Obs. (USA)
- Univ. Arizona (USA)
- Univ. Chicago (USA)
- Perimeter (Canada)
- INAOE (Mexico)
- EACOA (East Asia)
- NOAJ (Japan)
- ASIAA (Taiwan)

About 200 individual EHT members ...

EHT2017 Data Analysis

- 01/2017: EHT Dress Rehearsal
- 04/2017: observing run 6/10 days
- 06-07/2017: 1st Correlation pass
- 12/2017: SPT data arrives
- 01-04/2018: Correlation, Calibration & Engineering data release (Calibrators only)
  - 3 different VLBI software pipelines: HOPS, AIPS, CASA
- 05/2018: Engineering data release (Sgr A* & M87)
- 05-07/2018: Imaging Sgr A* and M87
  - 4 independent teams not talking to each other until joint workshop
- 08/2018: Science data (images) released for analysis …
- 11/2018: Collaboration meeting
- Q1/2019: Publication of results …

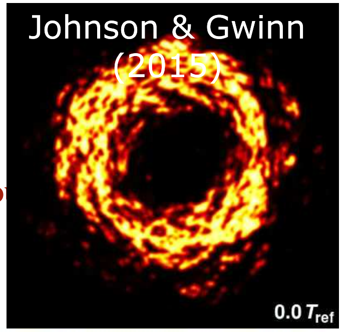
Calibrator image from VLBI with ALMA (at 3mm)



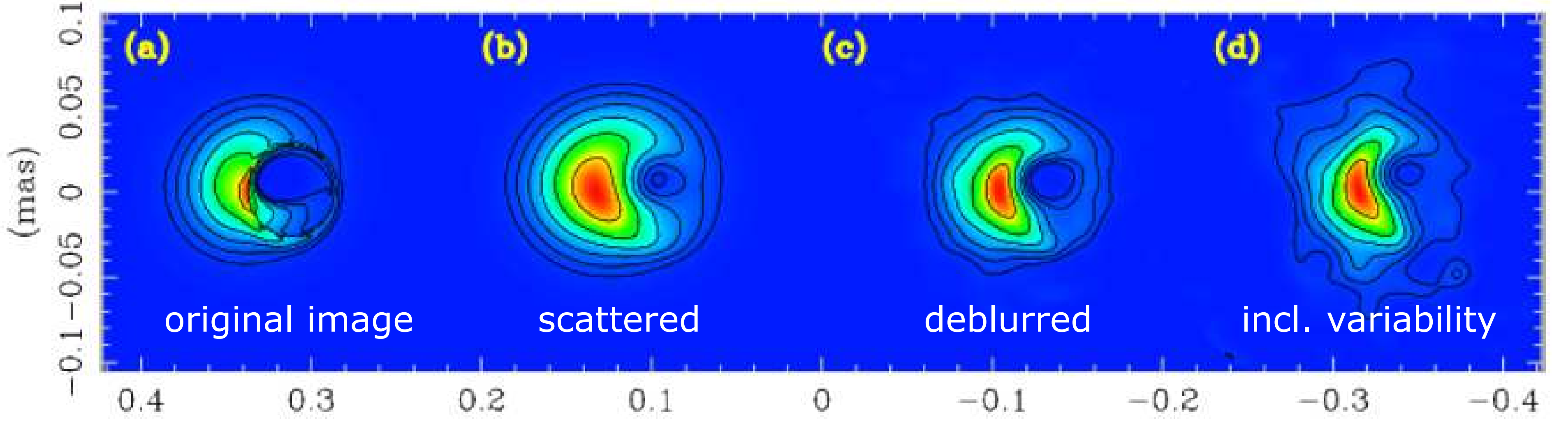
Closure imaging using MEM with the *EHT-imaging* library (Chael et al. 2018)

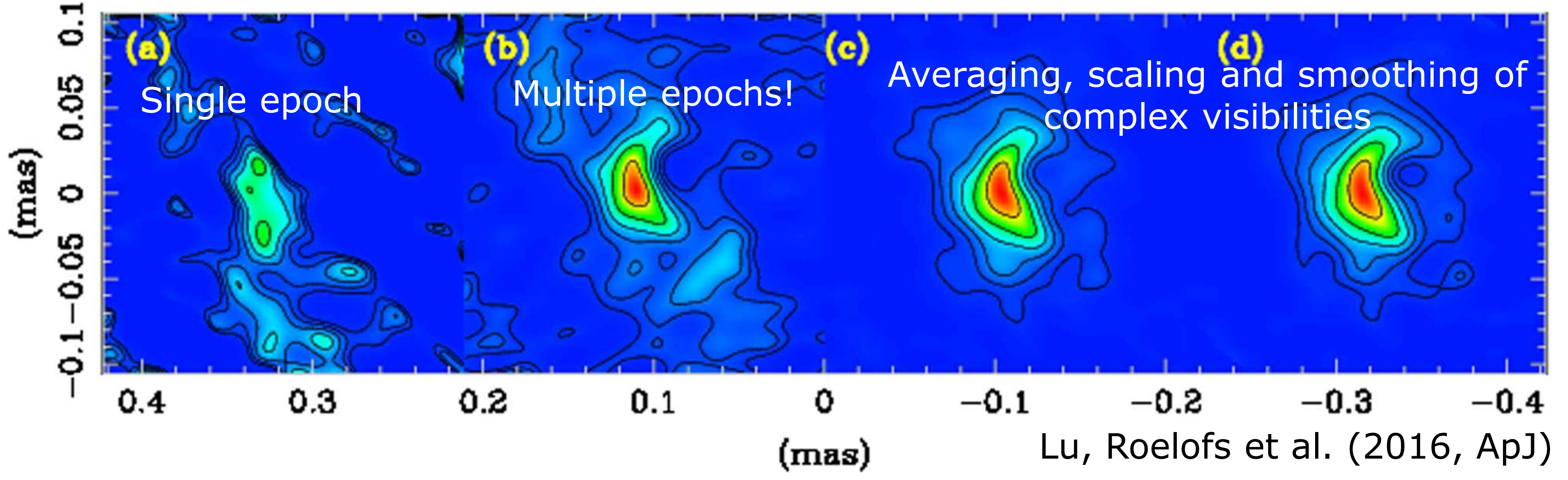
BU Blazar monitoring at 43 GHz with the VLBA (Jorstad & Marscher 2016)

What we **might** see



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



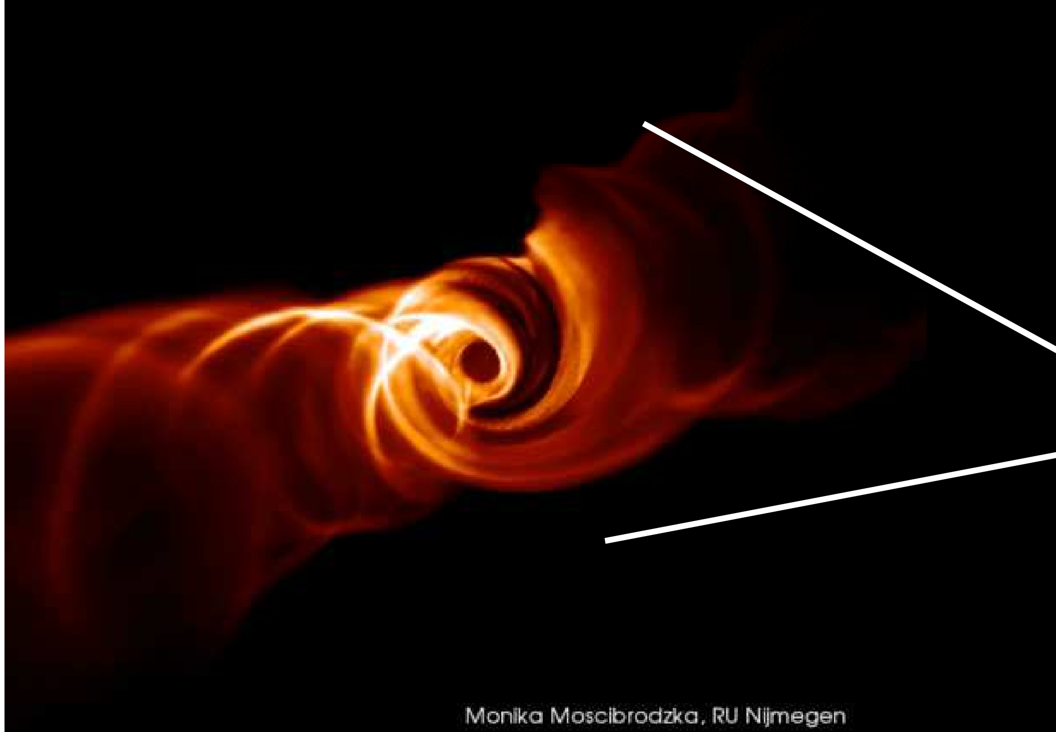


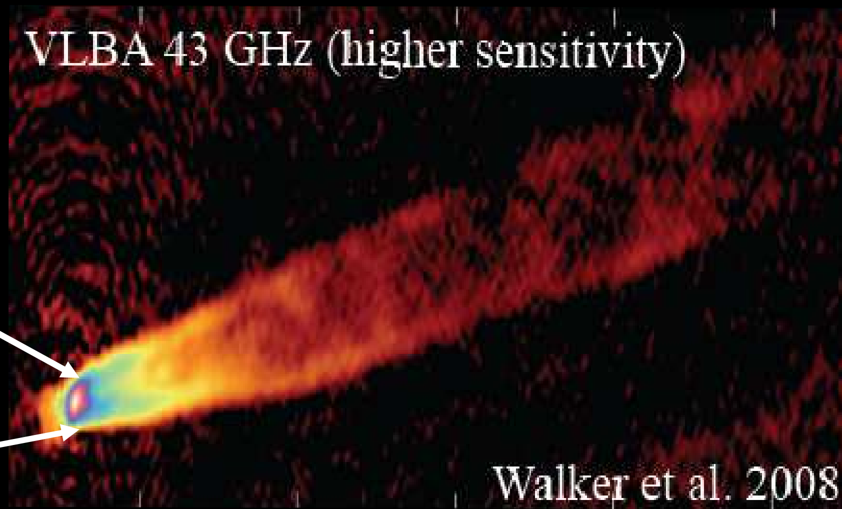
Lu, Roelofs et al. (2016, ApJ)

Black Hole Simluations of M87

GRMHD Simulation

VLBI Observations





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

(Using Harm3D - Gammie et al.)

VLBI Simulations of M87

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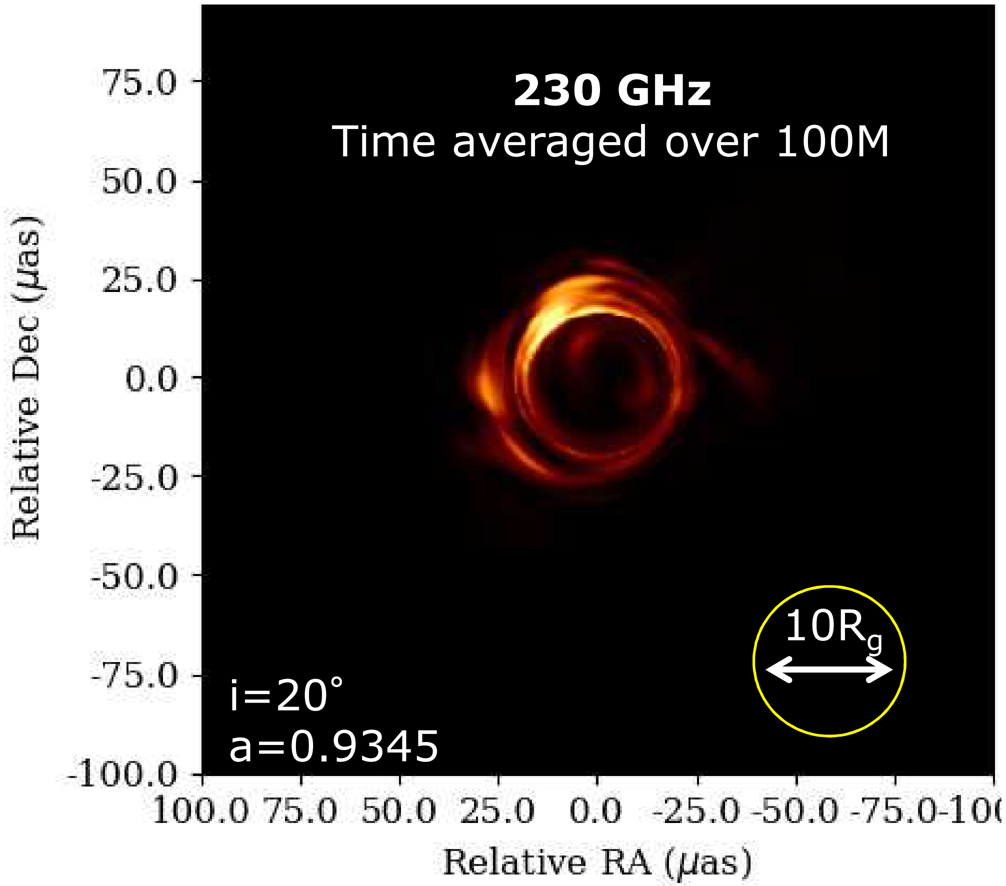
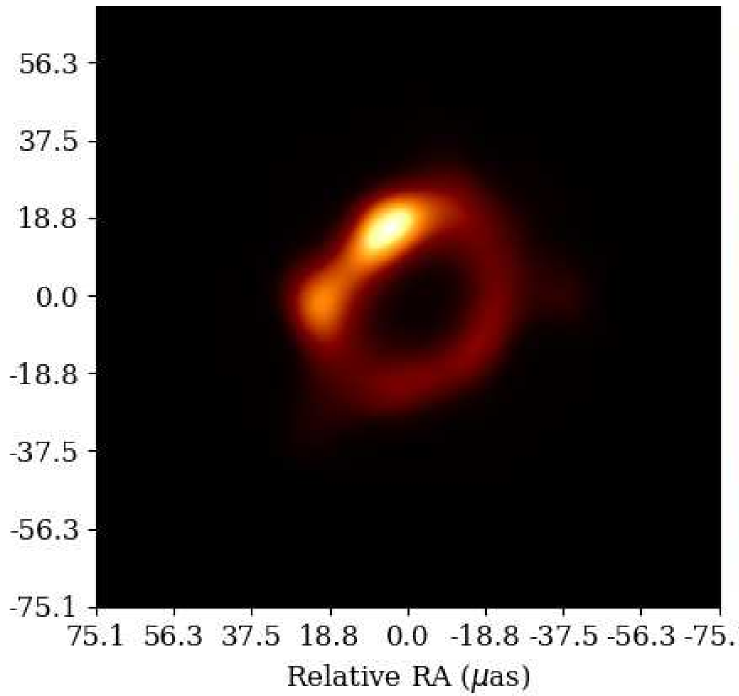
M87 GRMHD Simulations
(BHAC/Raptor)

Simulated EHT2017 observation
(MeqSilhouete/rPICARD/EHT Imaging)





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.

Rings in M87

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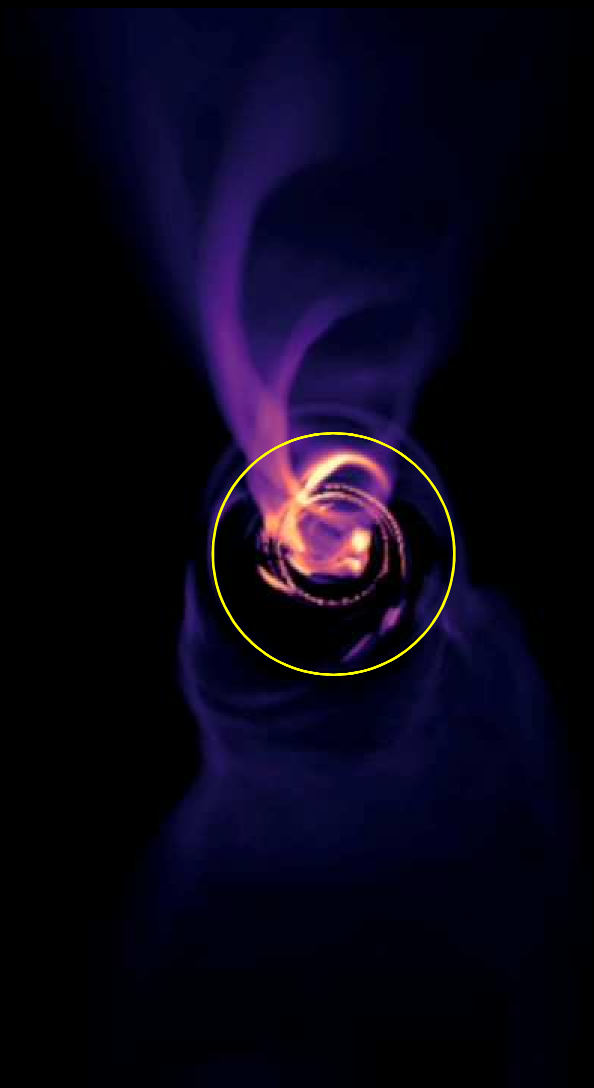

Non-standard spacetimes

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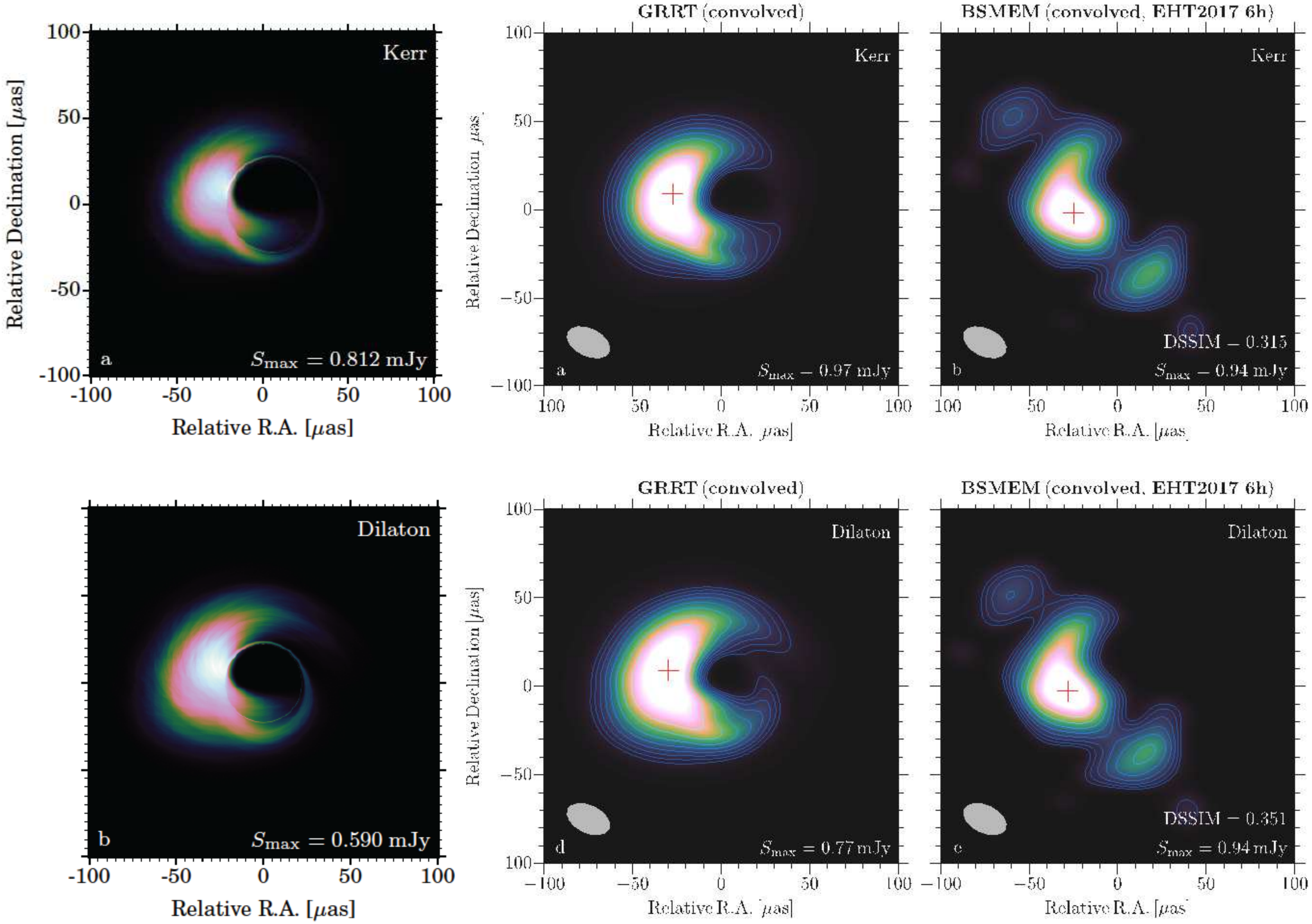
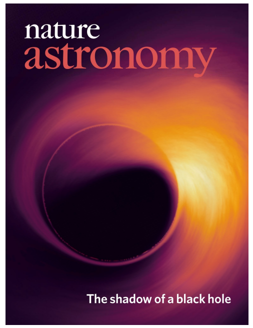
Full resolution | interstellar scattering | 2017 experiment



Kerr BH

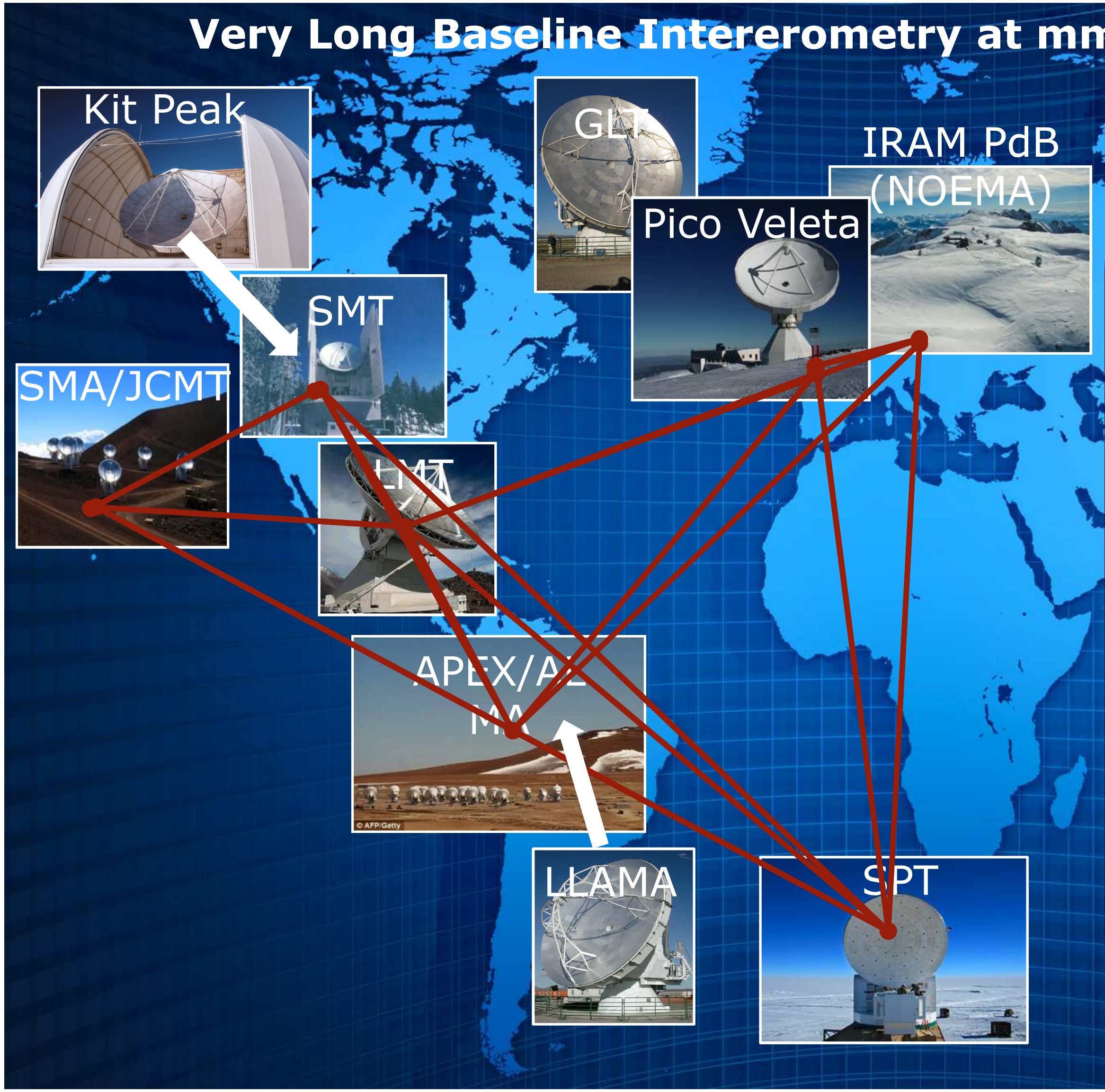


Dilaton BH

BHAC code

Mizuno et al. (2018, Nature Astronomy)

Event Horizon Telescope Upgrades



2018 run:

- April 16-30, 2018
- Double Bandwidth
- (8 GHz, 2 pol)
- Greenland Telescope (2018)
- Bad weather!

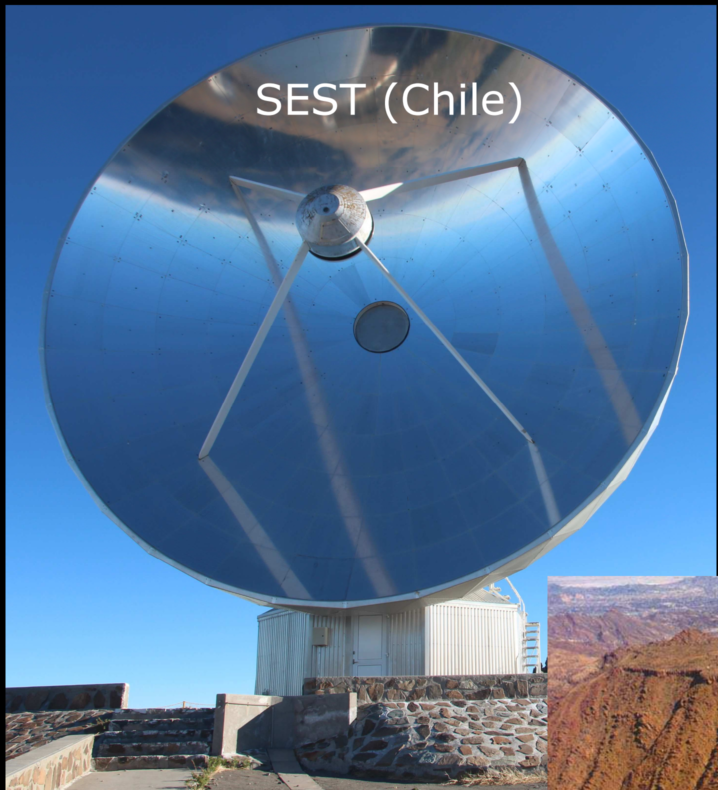
New Telescopes:

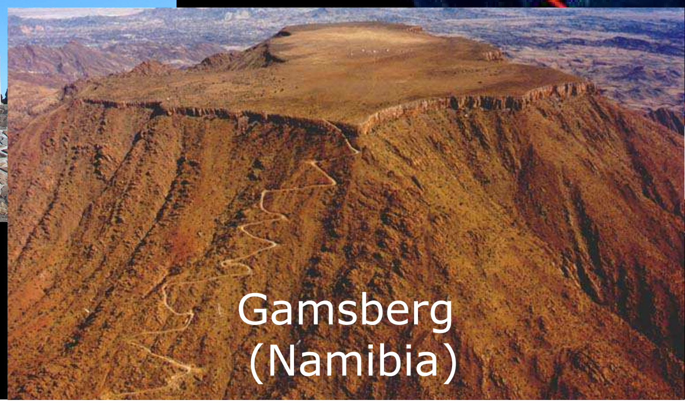
- Kit Peak (2019)
- NOEMA (2020) 10x15m dishes!

345 GHz ..

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

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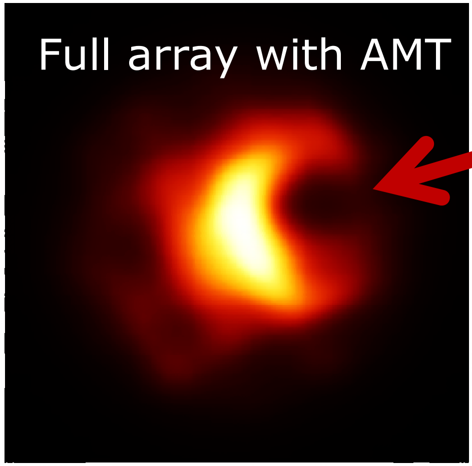
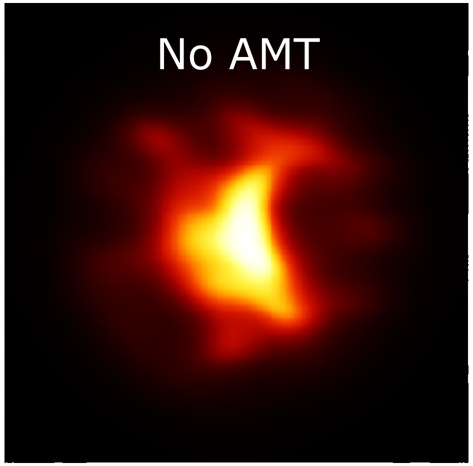
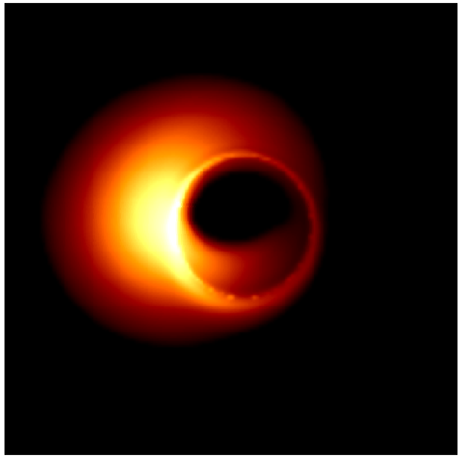
EHT2017 + AMT, NRMSE = 0.26



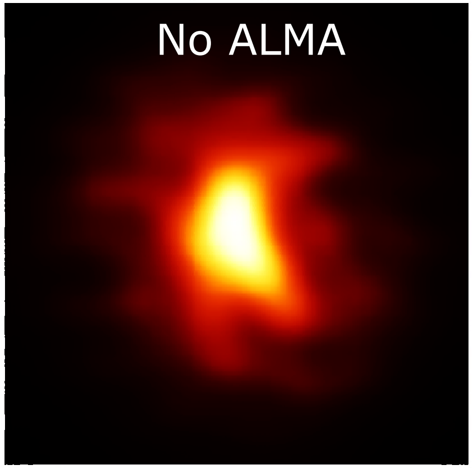
Without AMT, NRMSE = 0.28



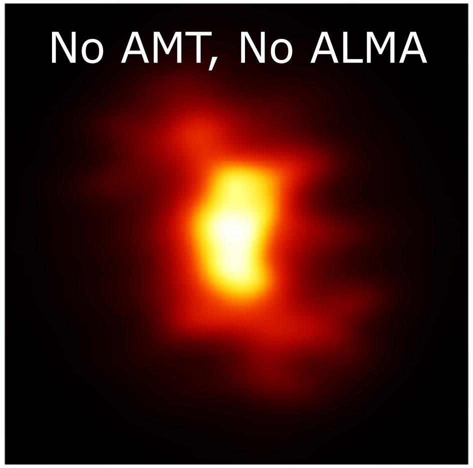
Model, time-averaged



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 (!)

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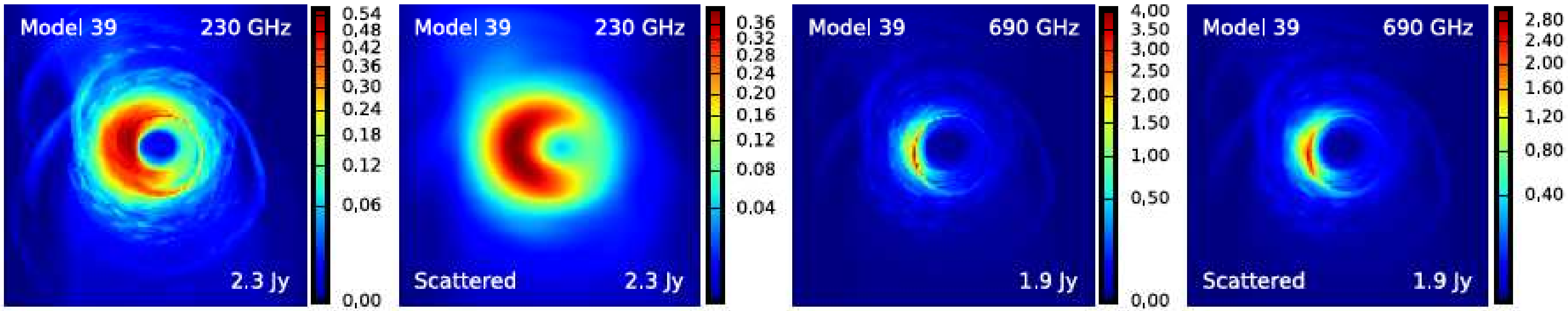
Optical depth included
Shadow size = 45 μas
Resolution at 10000 km baseline = 8.9 μas
Scattering blur kernel size = 2.5 μas



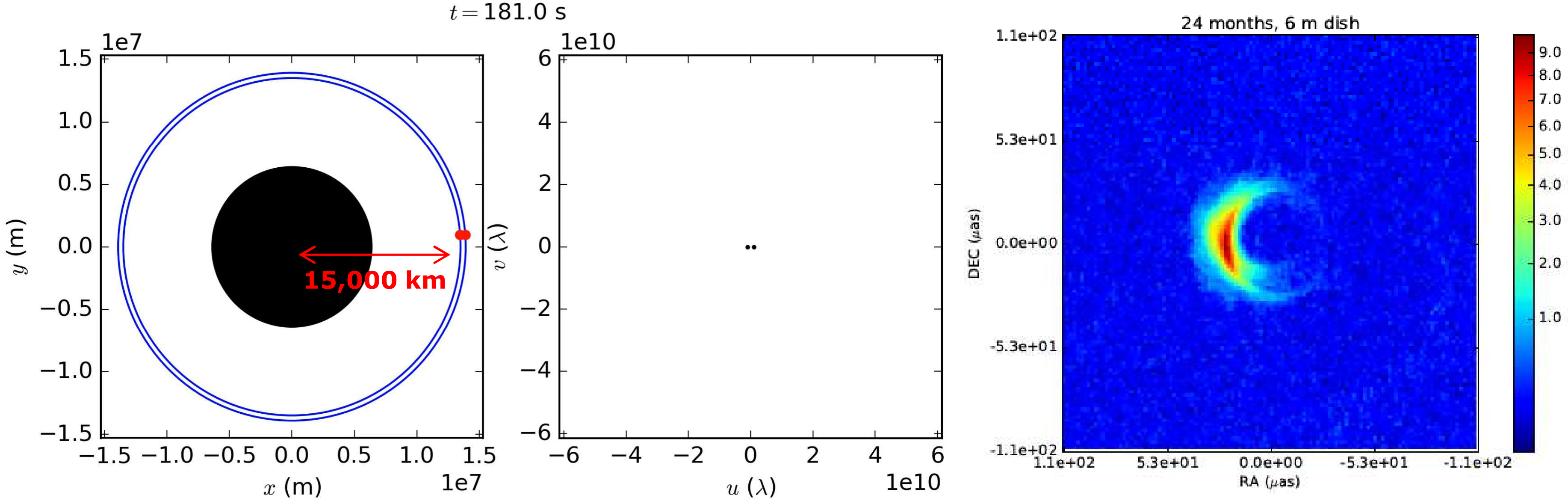
Moscibrodzka et al. (Radoud Univ)

Space Interferometry: Event Horizon Imager (EHI)

Radboud University Nijmegen

Reconstructed Space-VLBI image

Includes variability due to scattering and source variations



Martin-Neira, V.Kudriashov (ESA)

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

Using EHT Imaging library from Andrew Chael

Conclusion

BlackHoleCam

Radboud University

- Images of black holes shadows are no longer fantasy!
- Comprehensive tools exist to model black holes in GR (and alternatives) and match to observations.
- The EventHorizonTelescope will deliver images early 2019: rudimentary at first but still unique …
- Images will become sharper with time: multiple epochs, higher frequency, +France, +Africa, Space …
- A close pulsar would be great! Stars will constrain spin and mass better in any case (ESO GRAVITY).
- Sgr A* and M87 will stay around, allowing ever better tests of GR for centuries to come …

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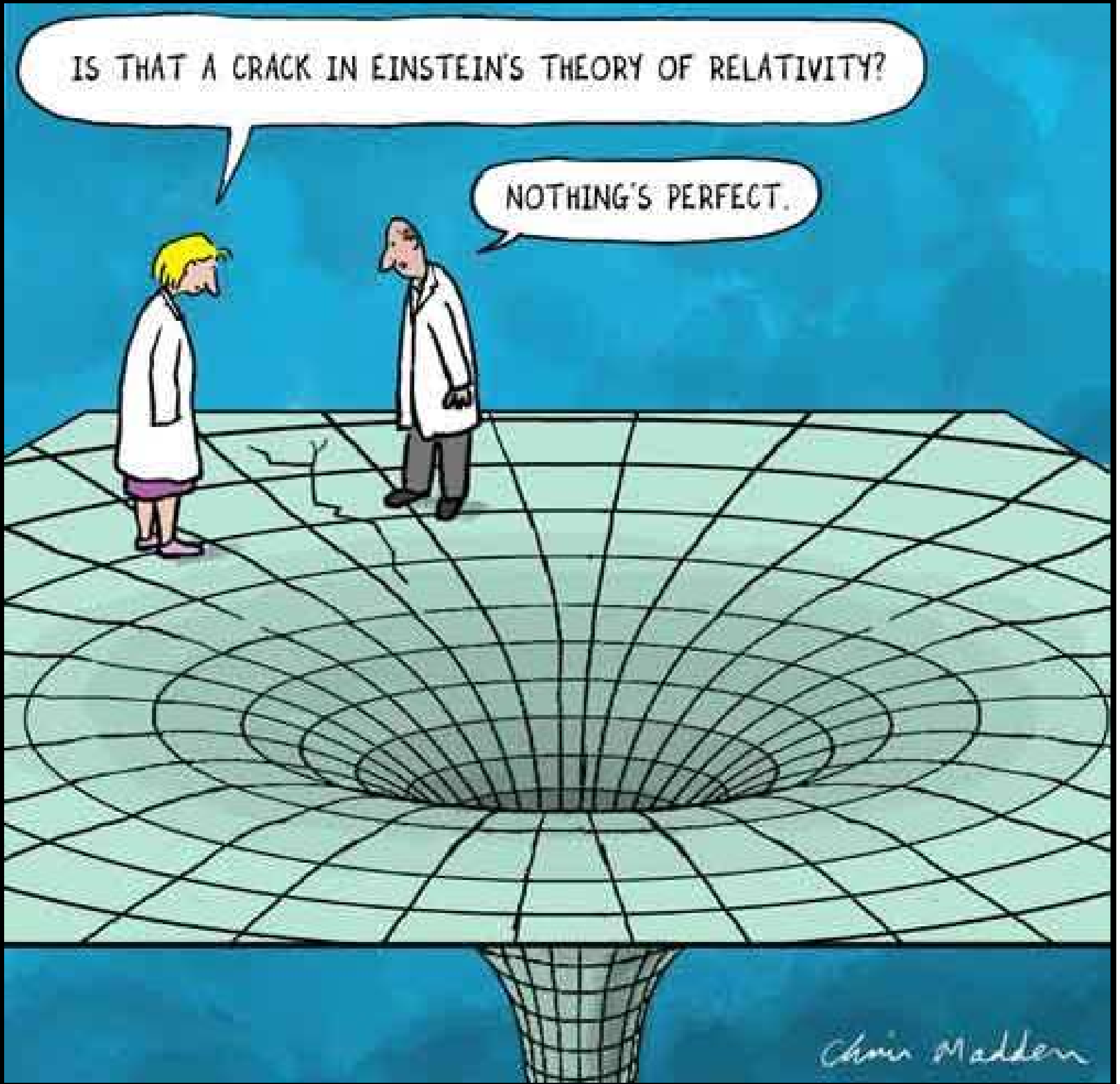
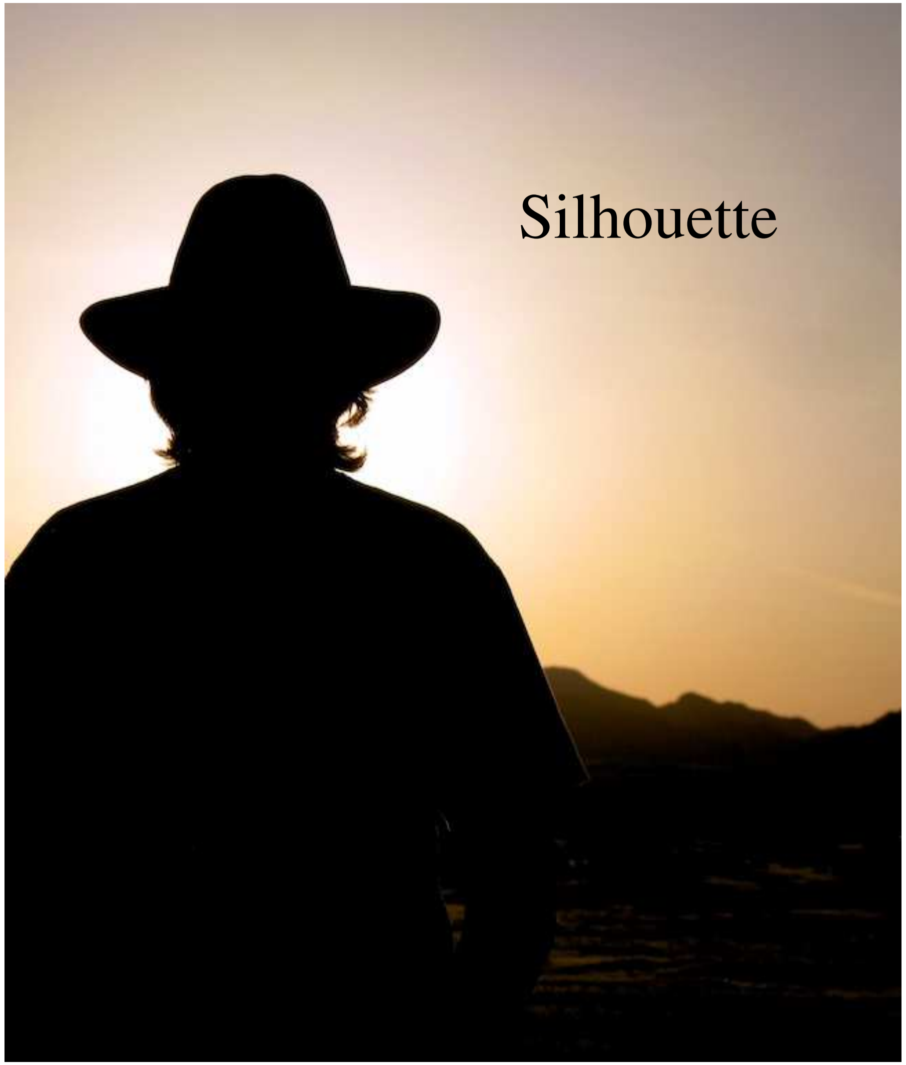
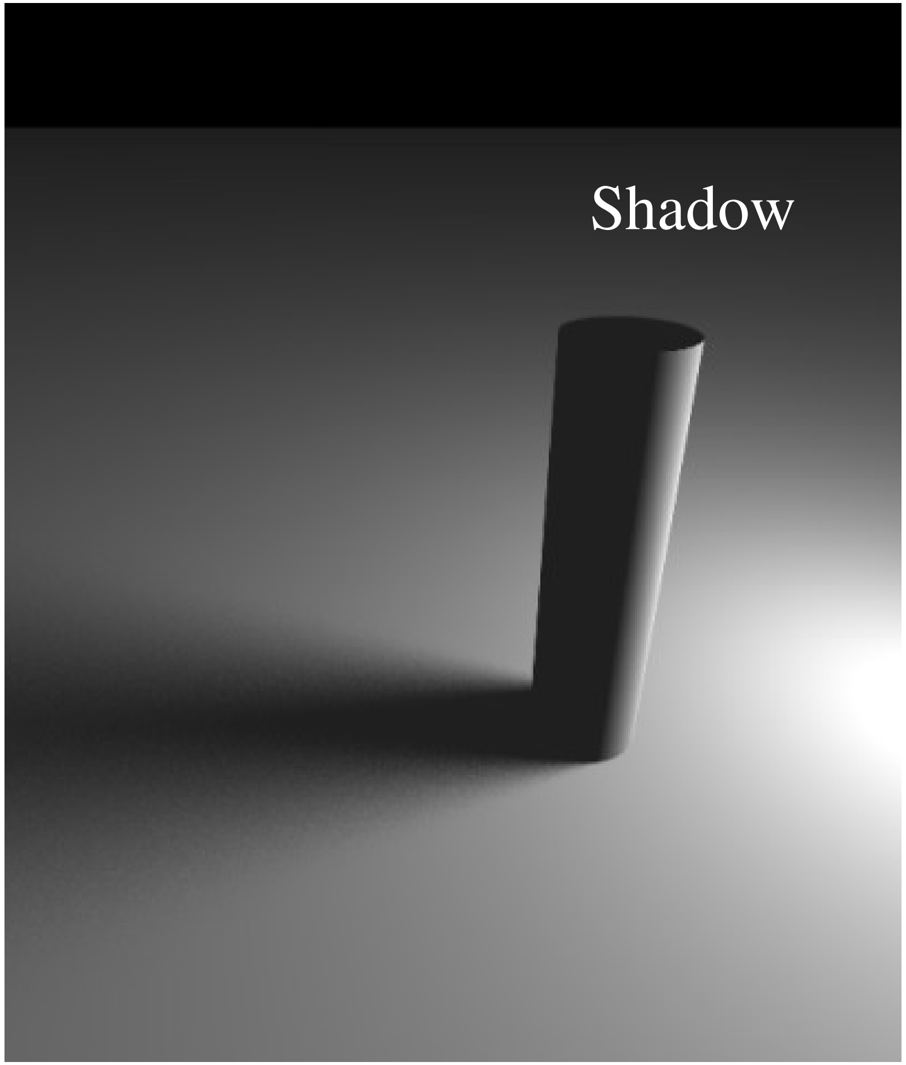


Silhouette vs Shadow





GRMHD Simulation

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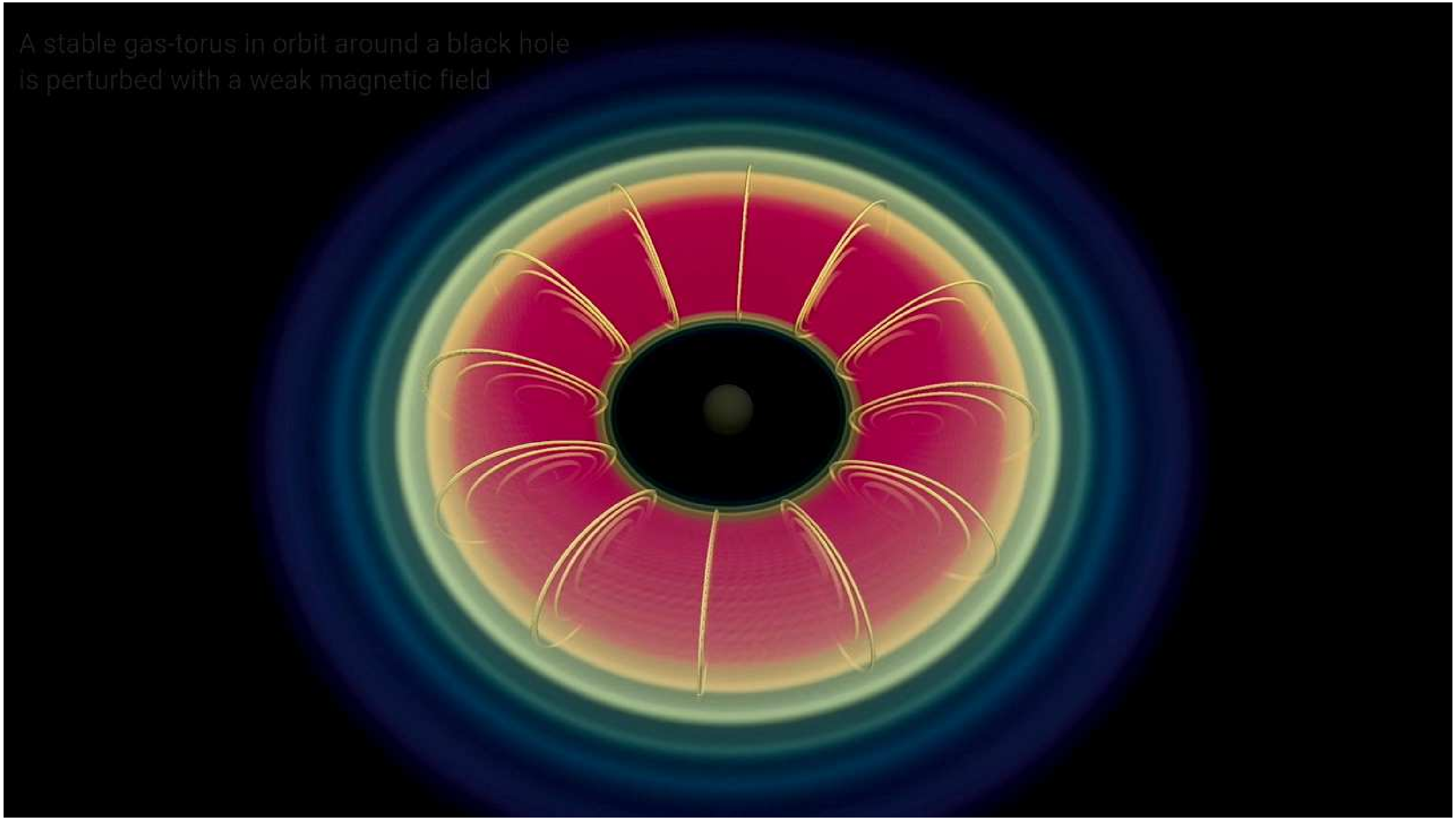
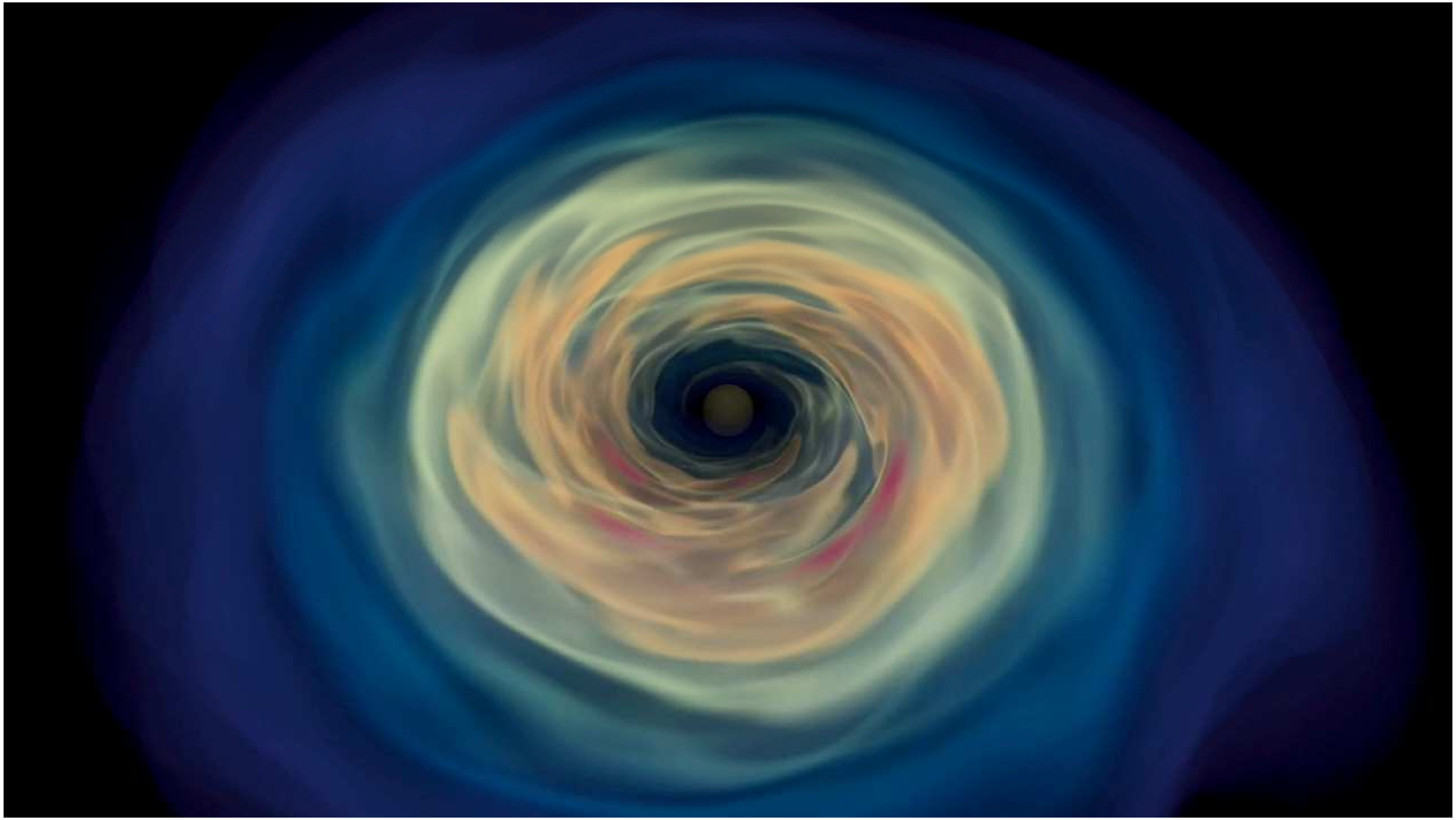


GRMHD Simulation



GRMHD with isothermal jet

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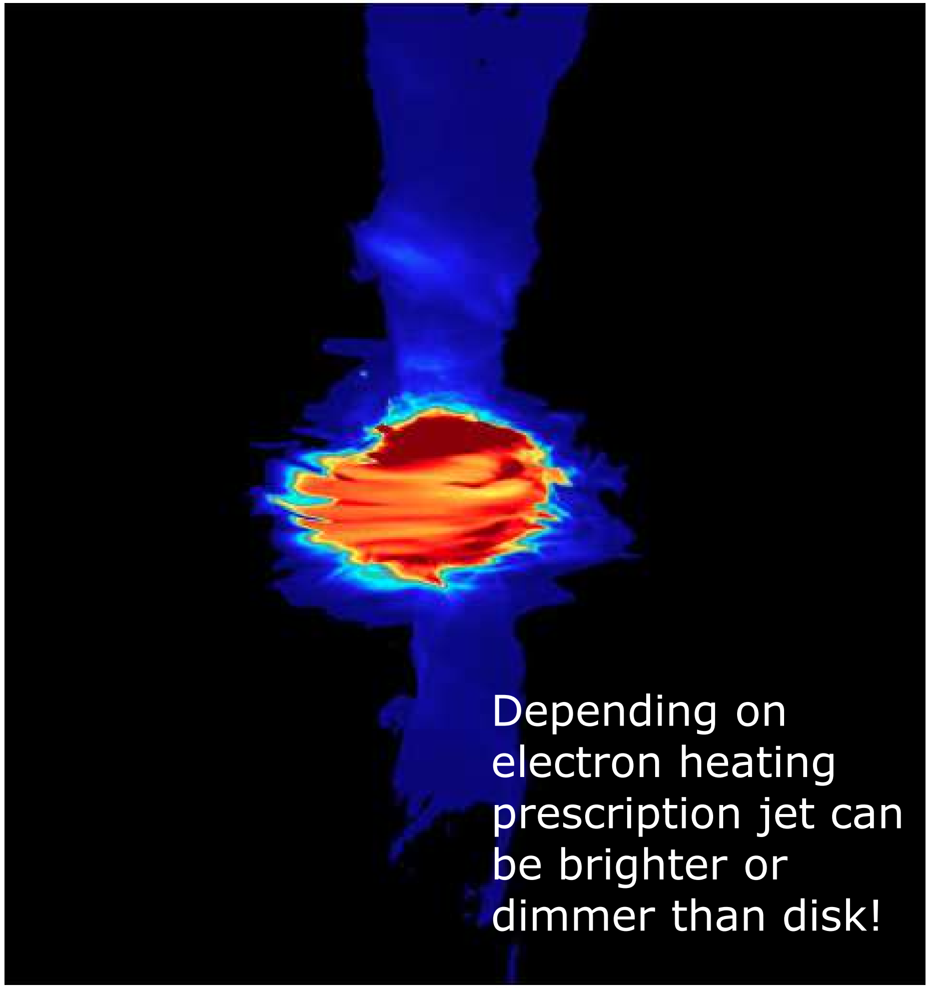
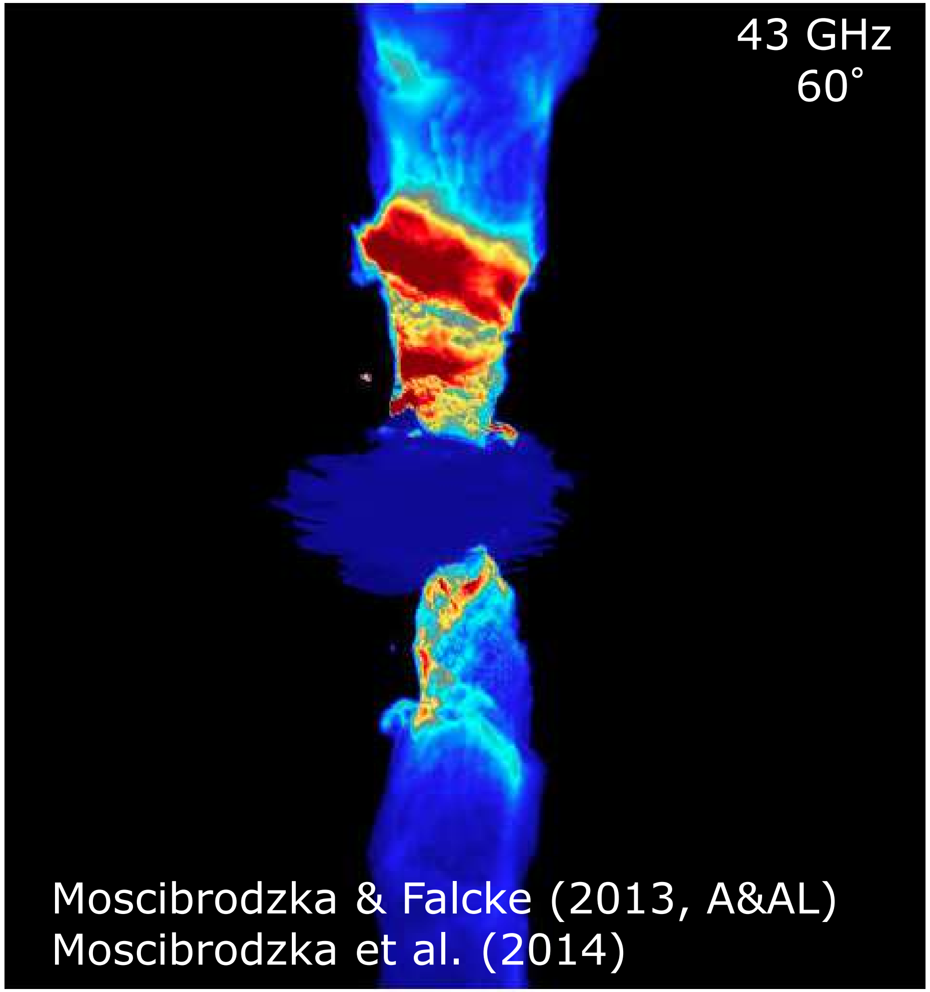
Jet: Tp/Te=1, Te~const
Disk: hot ADAF (Tp/Te~5)

Jet: Tp/Te=1, Te~const
Disk: "classical" 2-temperature ADAF (Tp/Te~25)





Sgr A* 3DGRMHD jet model

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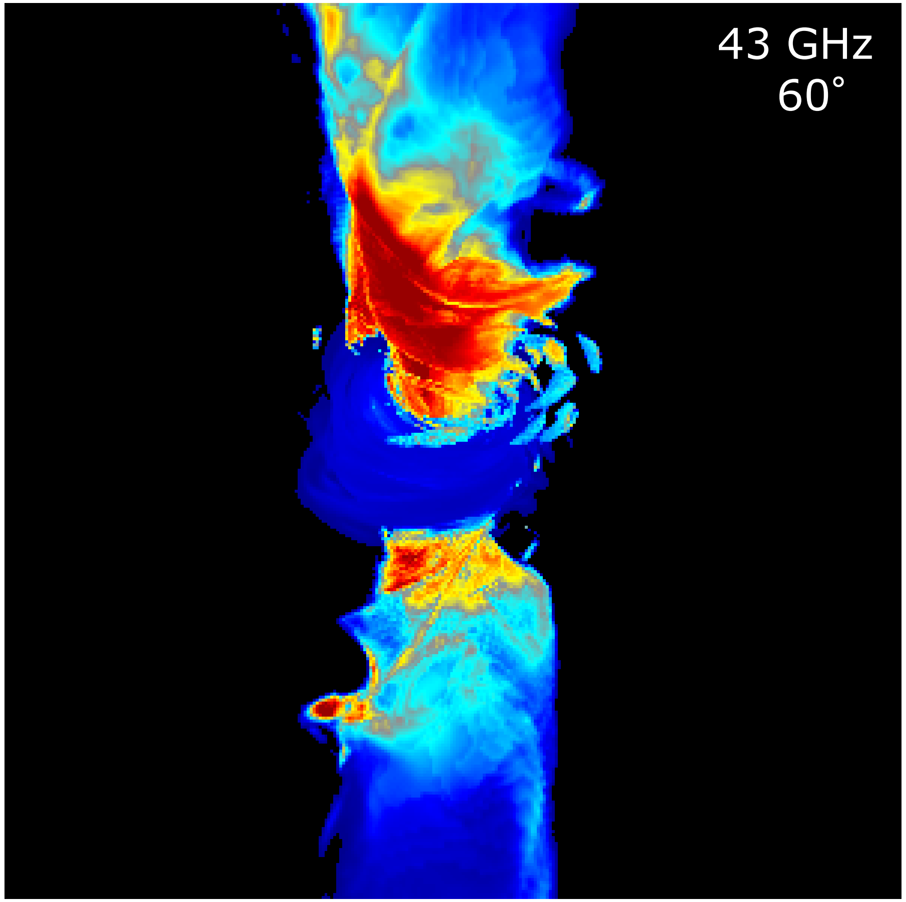
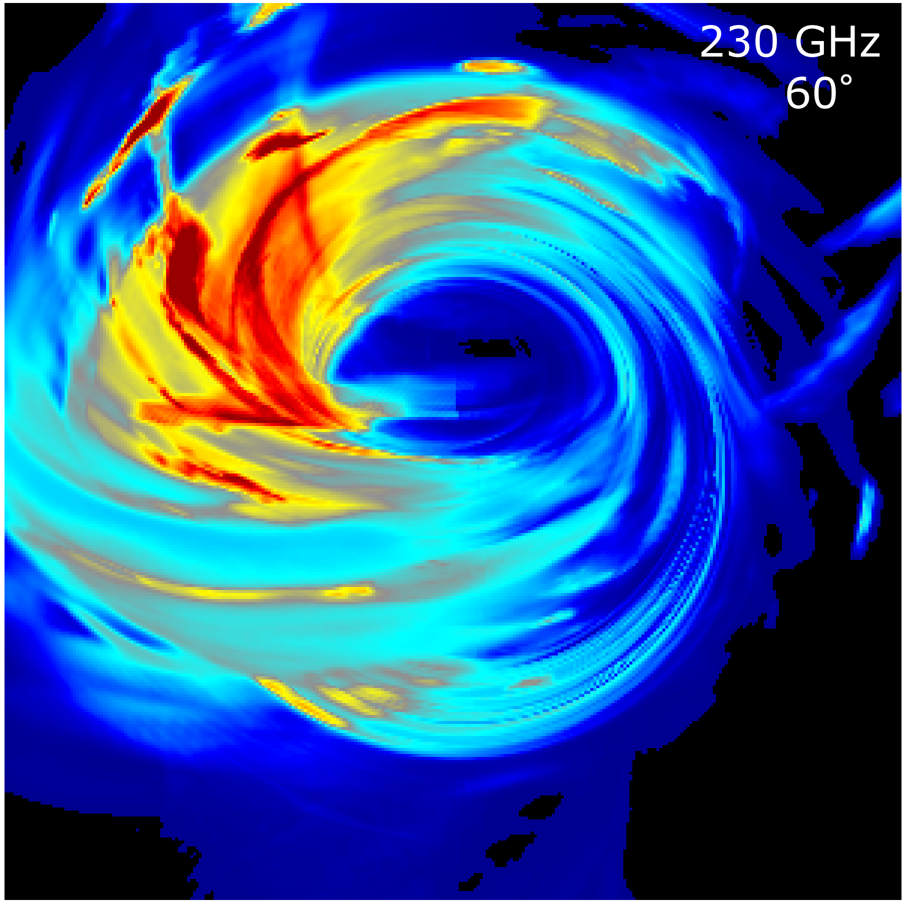
Three-dimensional general relativistic magneto-hydrodynamic fluid calculations with radiation transport





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

230 GHz Predictions

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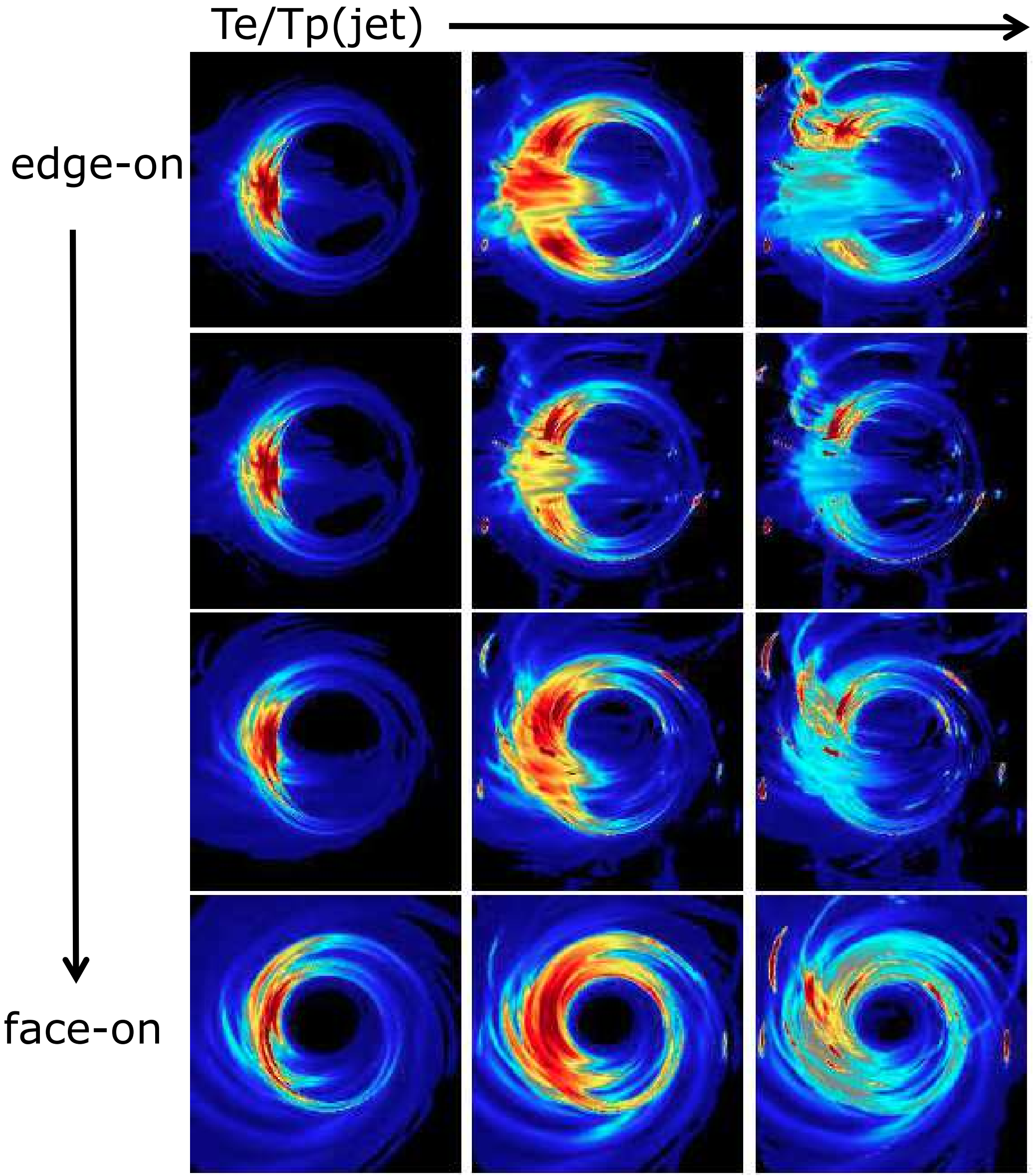
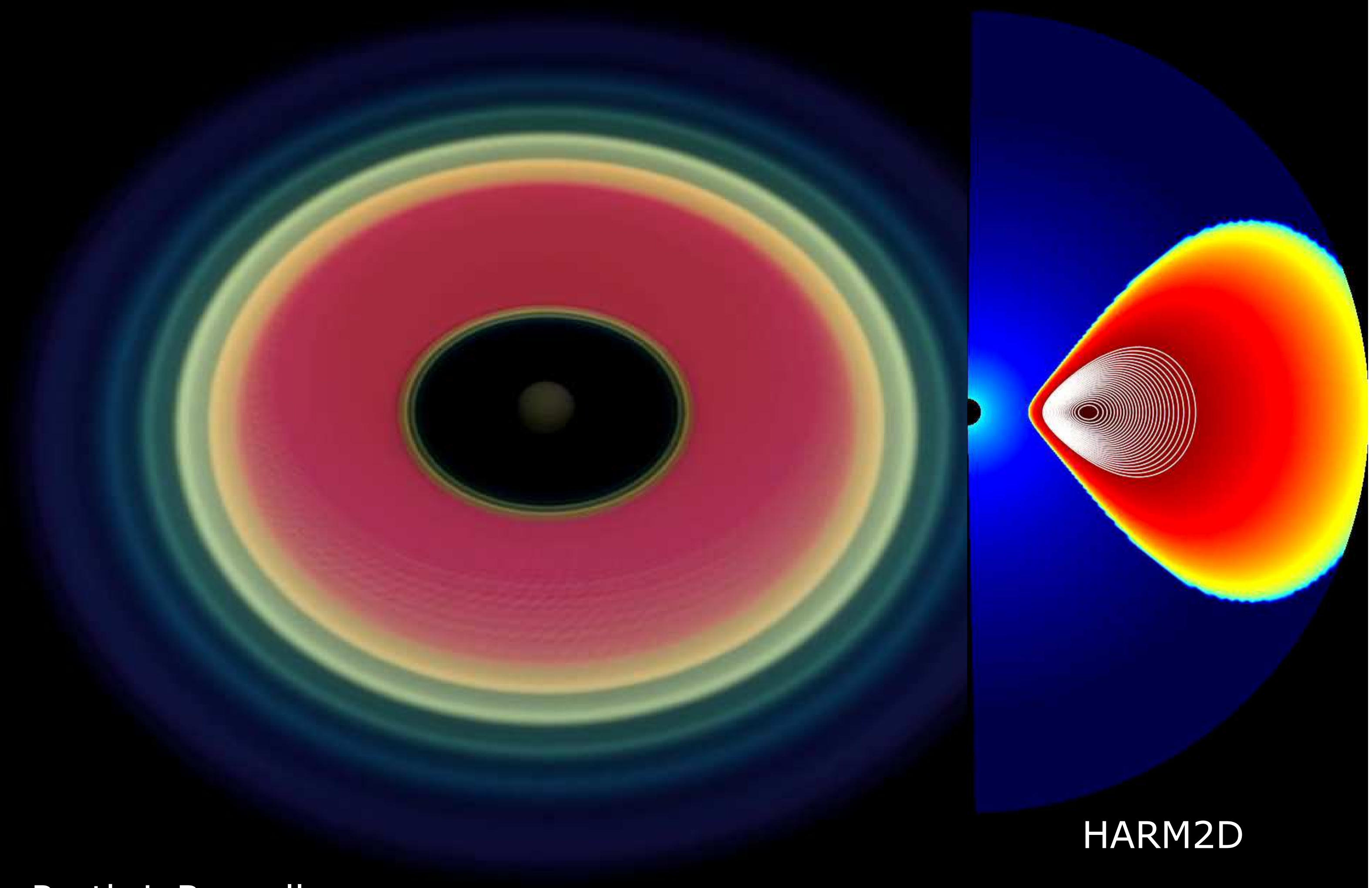


Moscibrodzka et al. (2014)

Goal:
constrain spin and orientation of black hole from shadow image!

GRMHD Simulations



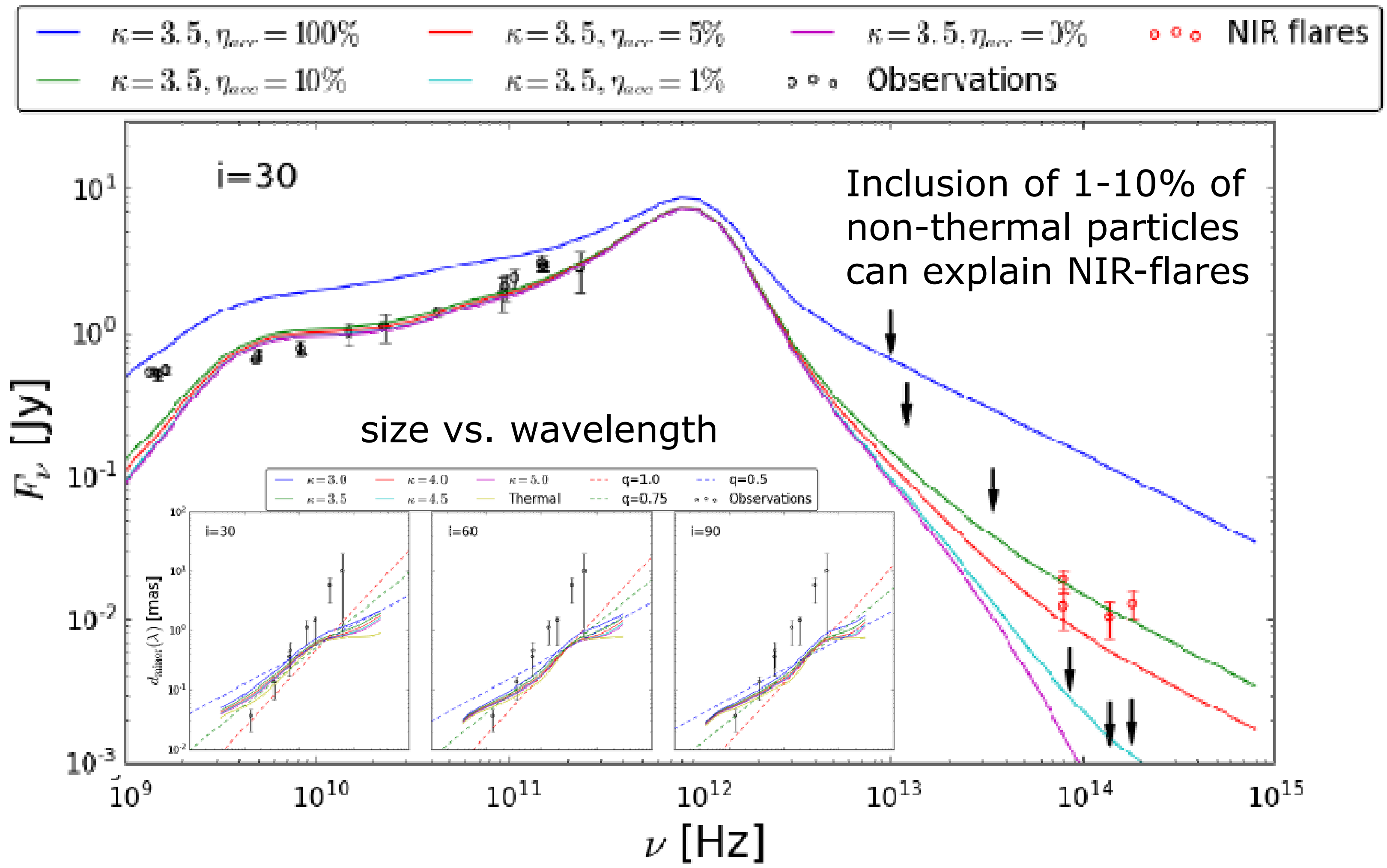
HARM2D

BHAC code O. Porth L.Rezzolla

Sgr A*: Jet-model SED

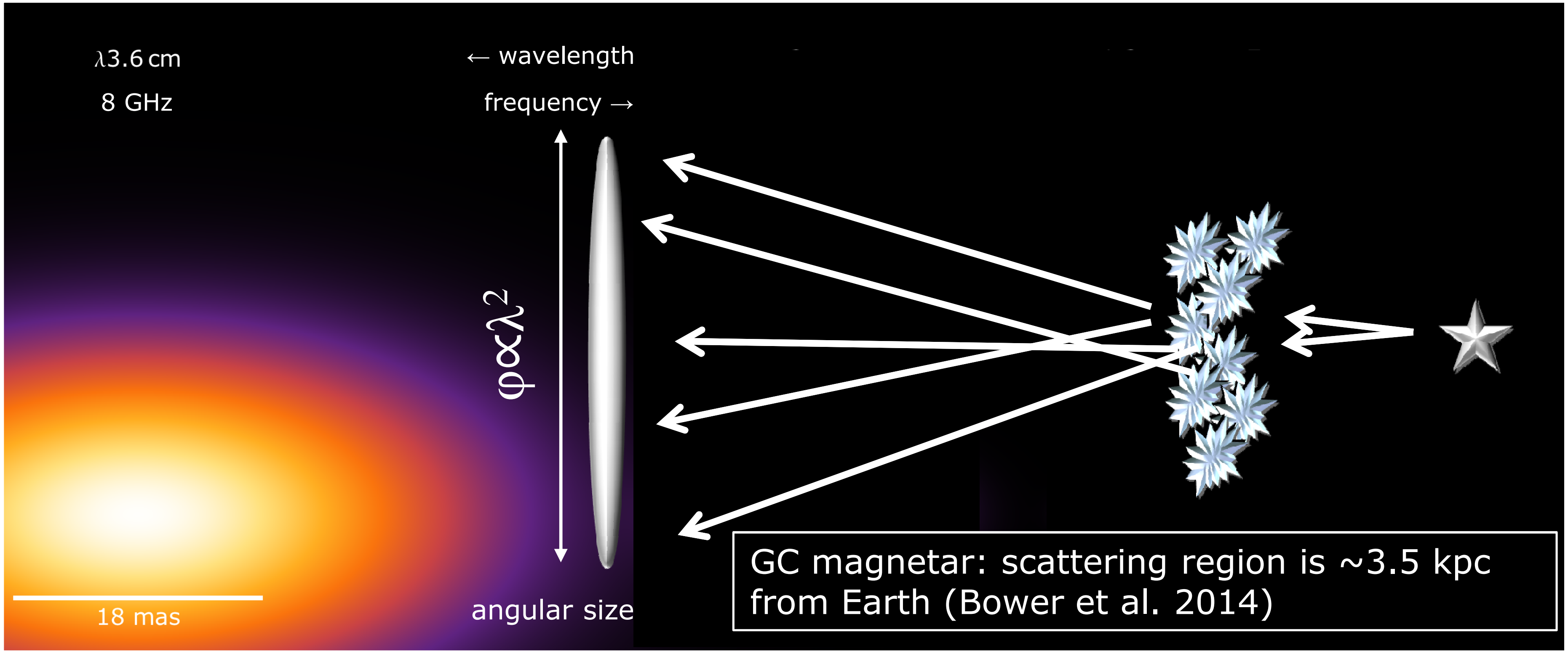
Radboud University Nijmegen

2D jet-model with a mix of thermal particle distribution
and non-thermal particles (kappa-distribution)



Davelaar, Moscibrodzka, Bronzwaer, Falcke A&A (2018), in press

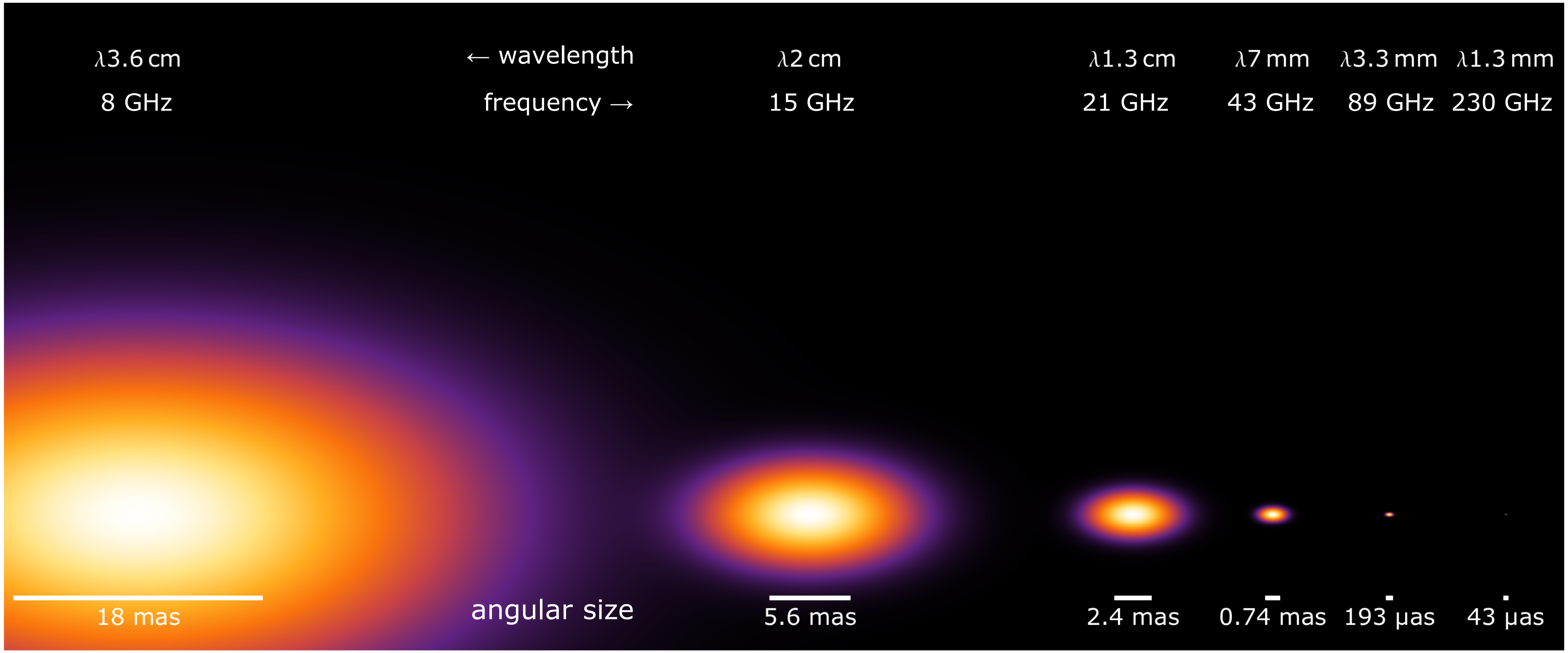
VLBI Images of Sgr A* (to scale)



- 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.

VLBI Images of Sgr A* (to scale)

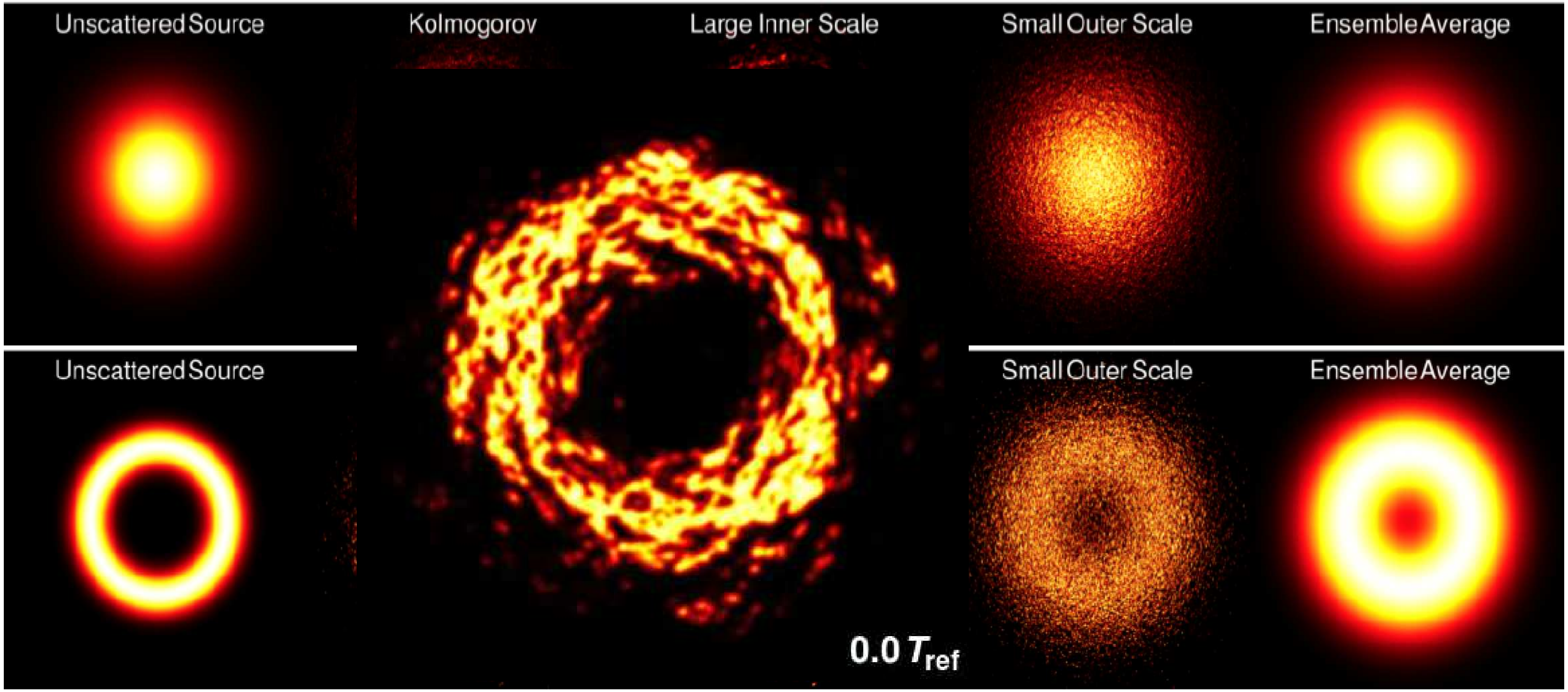
Radboud University Nijmegen



- 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.

Scattering

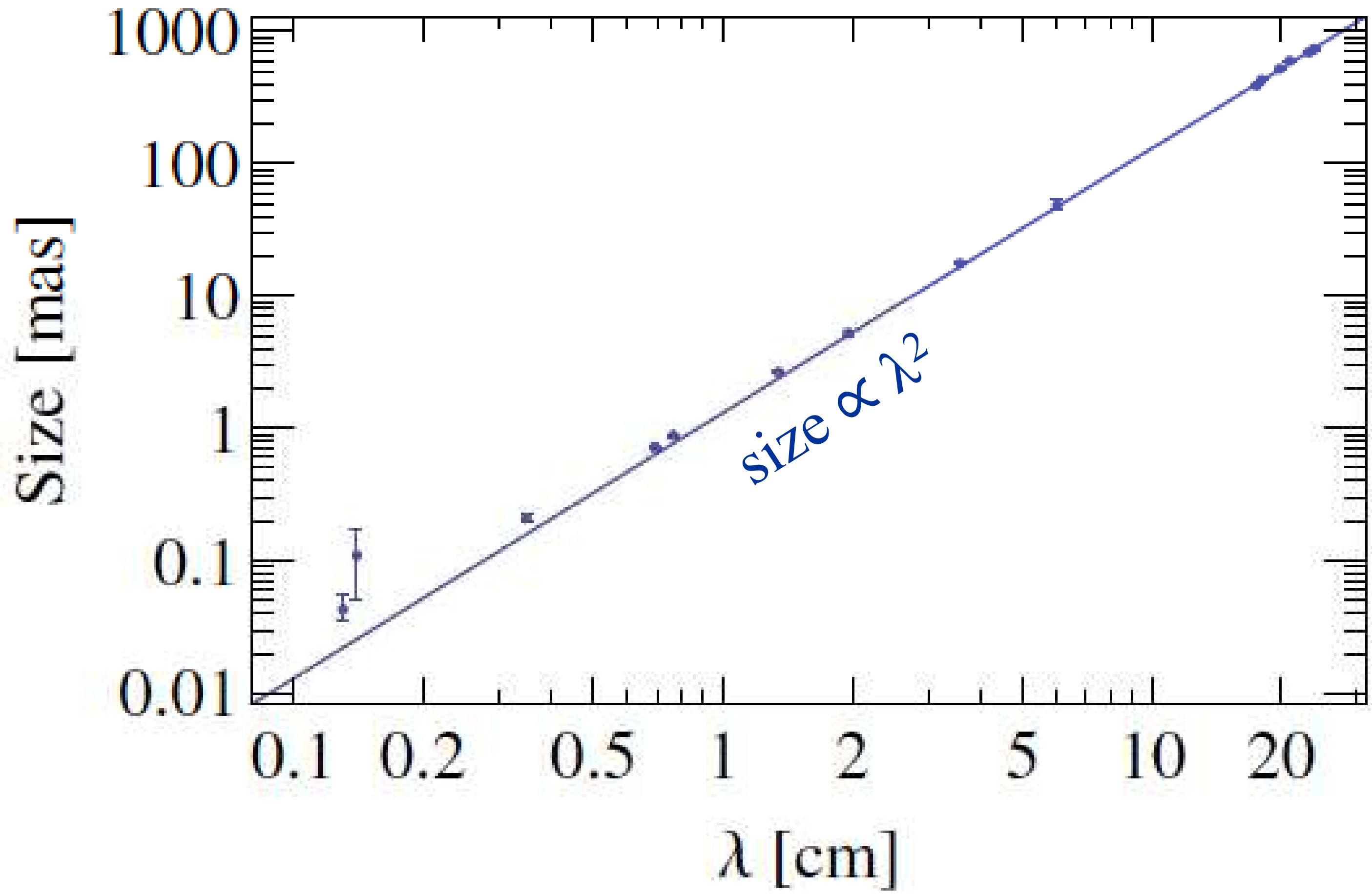
Radboud University Nijmegen



Johnson & Gwinn (2015)

Measured Size of Sgr A*

Radboud University Nijmegen

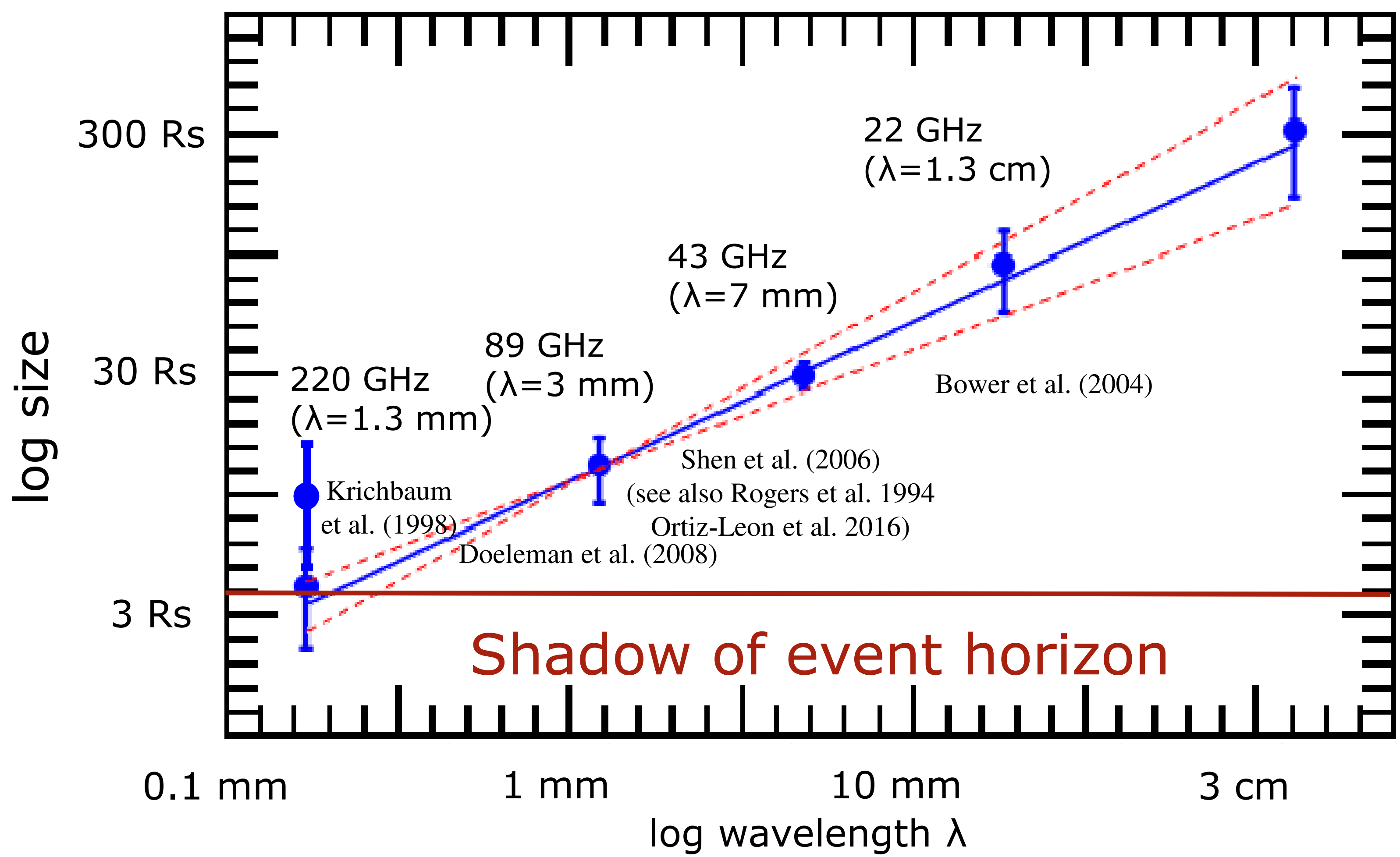


observing wavelength

Intrinsic Radio Size of Sgr A*

Radboud University Nijmegen

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

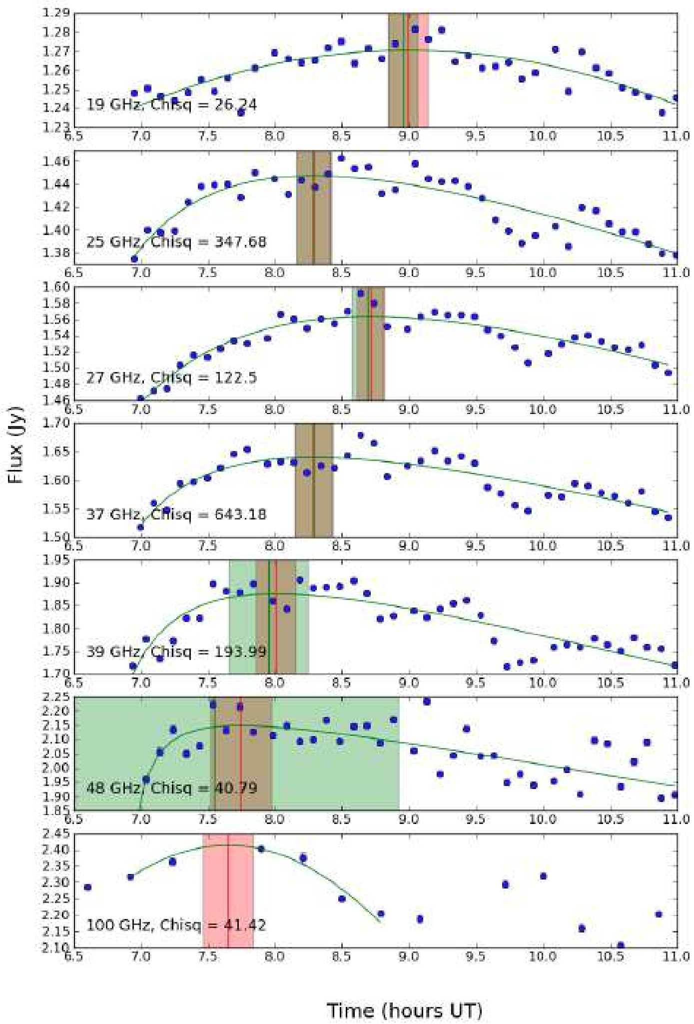


Falcke & Markoff, (2013, Class. & Quant. Gravity)

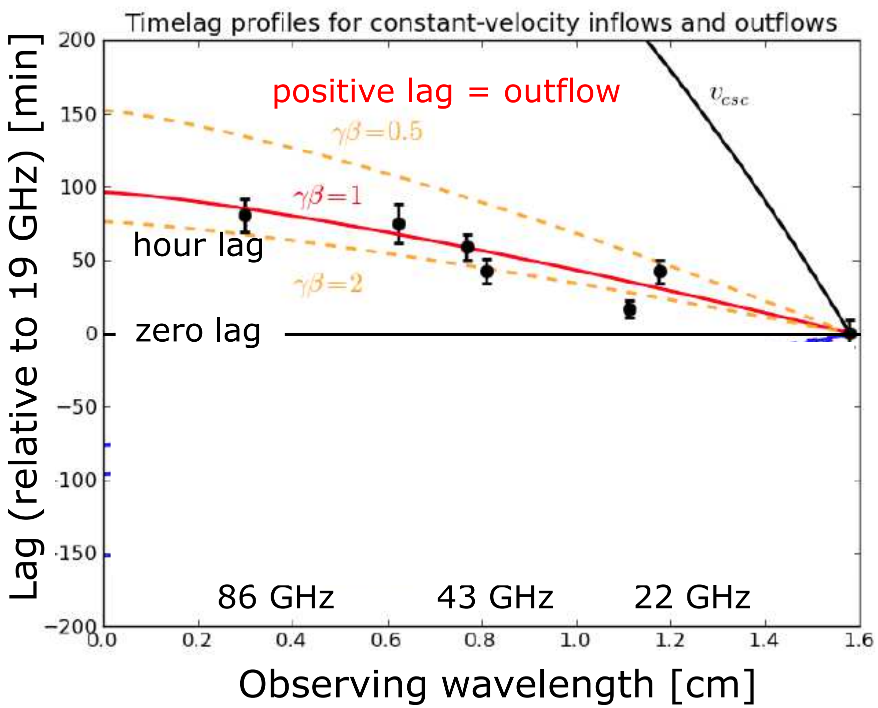
Radio Lags measured with ALMA & VLA

Radboud University Nijmegen

Flux evolution at different frequencies



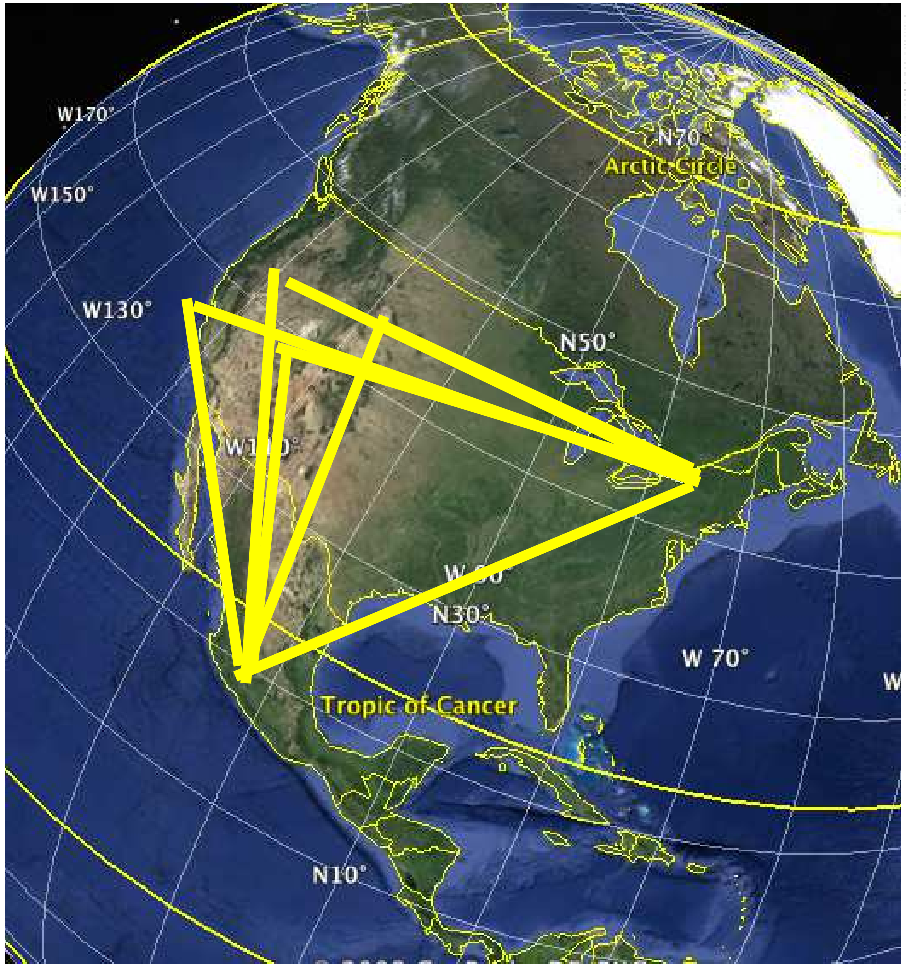
Higher frequencies, lead lower frequencies
delay is 30 – 90 min, size is ~1 light hour
⇒ **relativistic outflow**

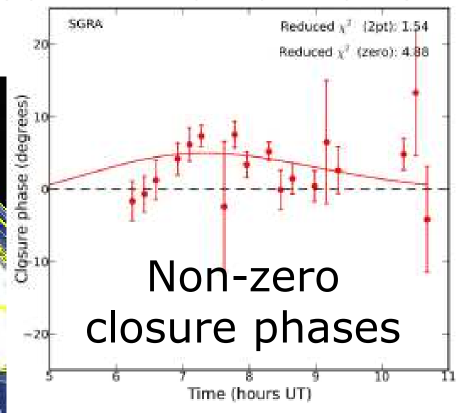


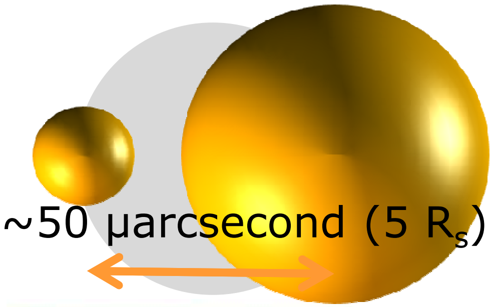
Brinkerink et al. (2015, A&A)
See also Yusef-Zadeh et al. (2009)

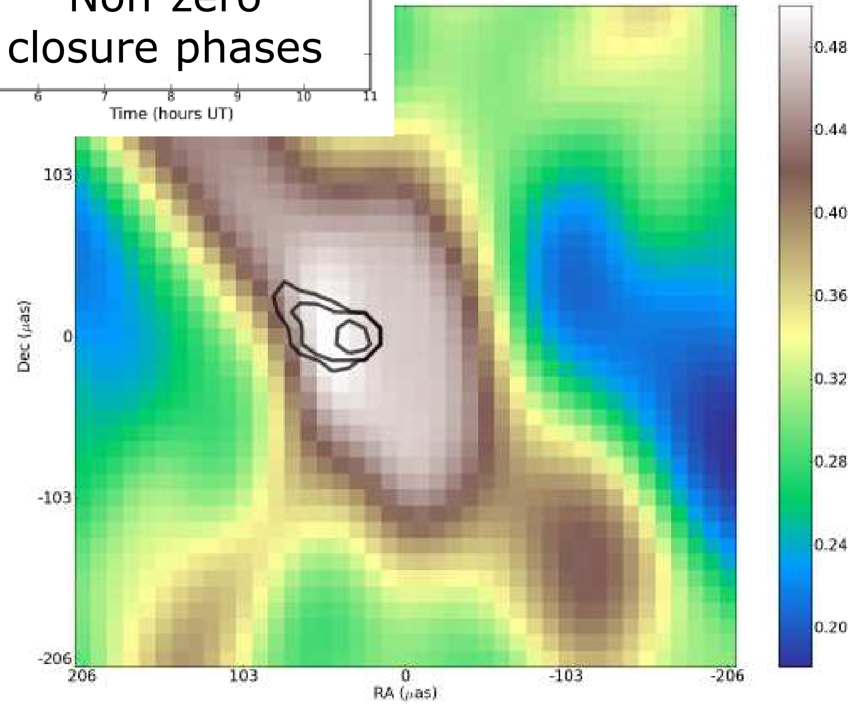
Asymmetric source structure at λ3mm (VLBA+LMT+GBT)

First indication of asymmetric source structure at 3m









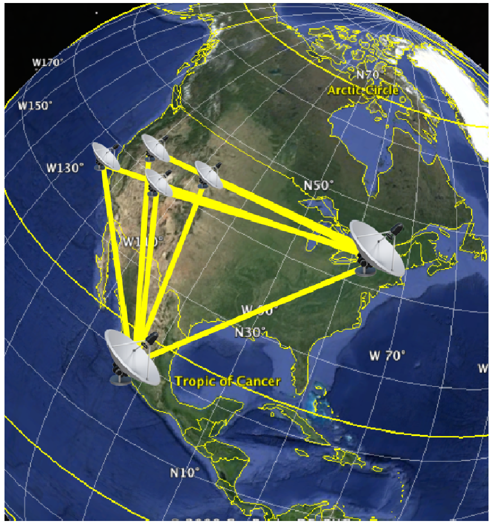
Brinkerink, Müller et al. (2016, MNRAS)

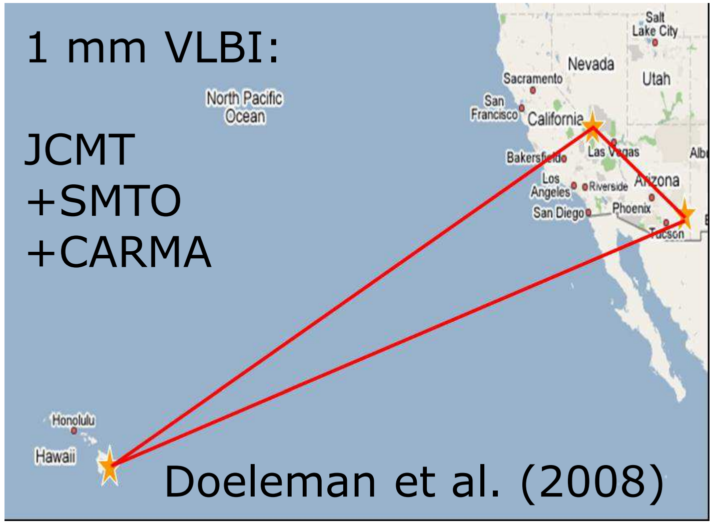
Asymmetric source structure: non-zero closure phases

Radboud University Nijmegen

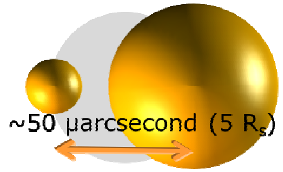
3mm-VLBI

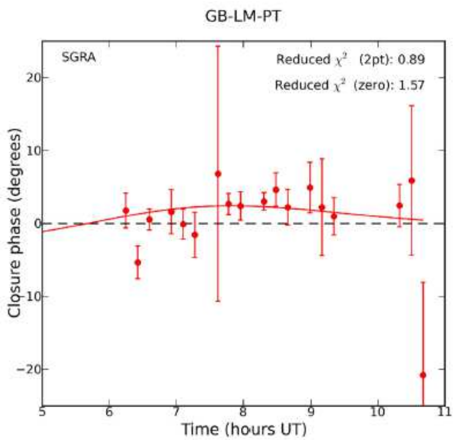
VLBA
+LMT
+GBT





Doeleman et al. (2008)

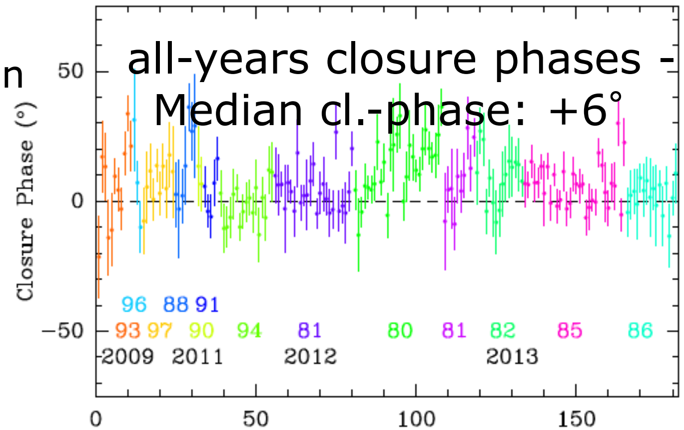




Brinkerink et al. (2016, MNRAS)
Ortiz-Leon et al. (2016)

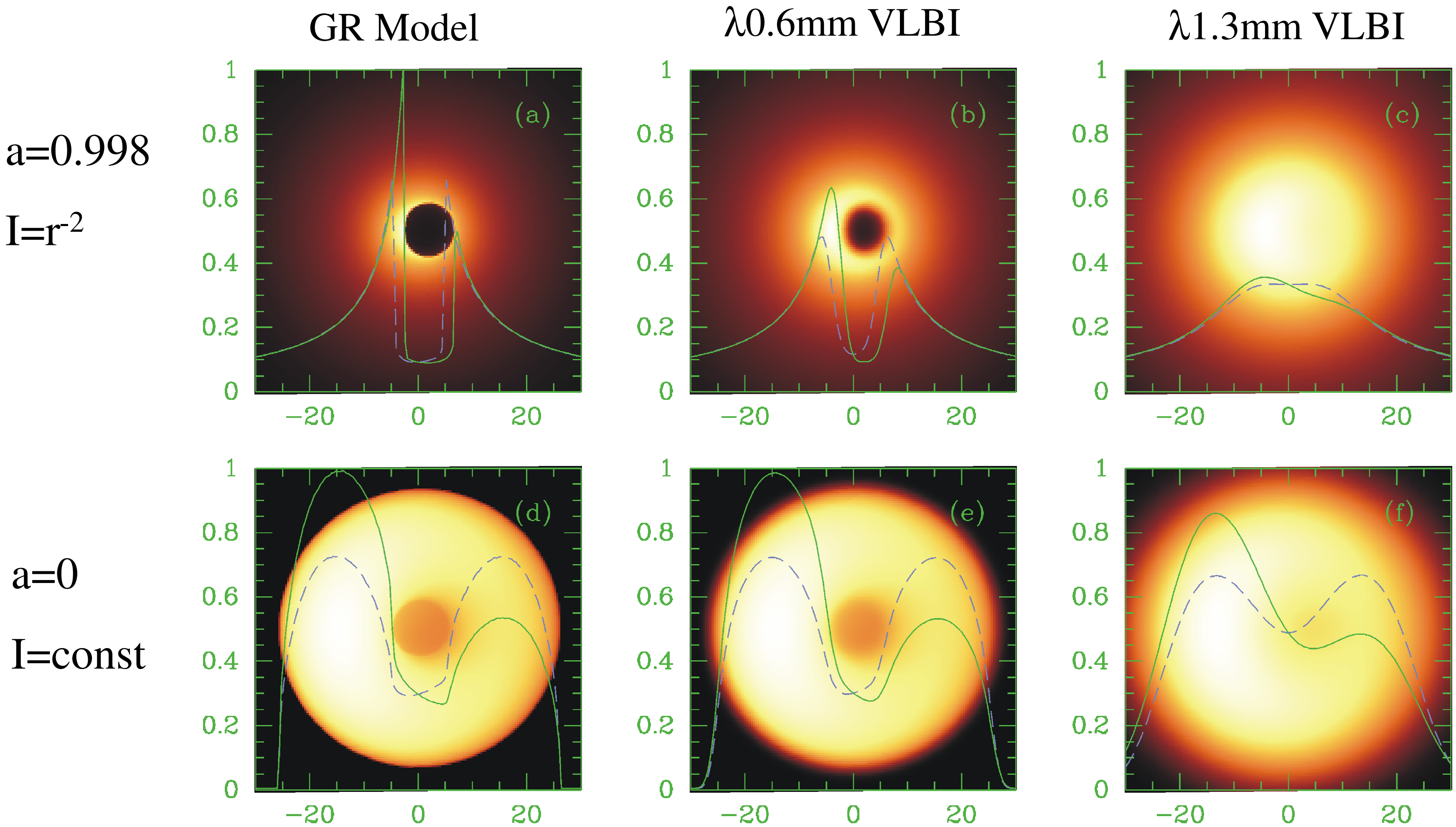
Both consistent with E-W extension

Scattering or intrinsic?



Fish et al. (2015, ApJ)

The Shadow of a Black Hole



(Falcke, Melia, Agol 2000, ApJL)

Predictions - Tucson 1998

Radboud University Nijmegen

The Central Parsecs of the Galaxy
ASP Conference Series, Vol. 186, 1999
H. Falcke, A. Cotera, W.J. Duschl, F. Melia, M.J. Rieke, eds.

The Jet Model for Sgr A*

H. Falcke
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
Steward Observatory, The University of Arizona, Tucson, AZ 85721

3.3. Predictions

A number of predictions from the jet model can be made that can be tested in the near future. Sgr A* should become resolved at 3 and 1 mm in the NS direction once a suitable mm-VLBI array is available. From analogy to other radio cores one would expect a polarization at the percent level at mm-wavelengths where interstellar propagation effects become negligible (Bower et al. 1999a&b). The most likely direction of the magnetic field is probably along the jet axis (NS?). Because the outflow travels from small to large scales and from small to large wavelengths one would expect that radio outbursts appear first at high frequencies and then propagate to longer wavelengths. The time scale for this delay could be relatively short. The model also predicts a certain level of x-ray emission, since the relativistic electrons in the nozzle will inverse-Compton scatter their own synchrotron radiation into the soft x-ray regime. The luminosity, however, will be relatively low, of the order $\lesssim 10^{34}$ erg/sec with a

4. Outlook

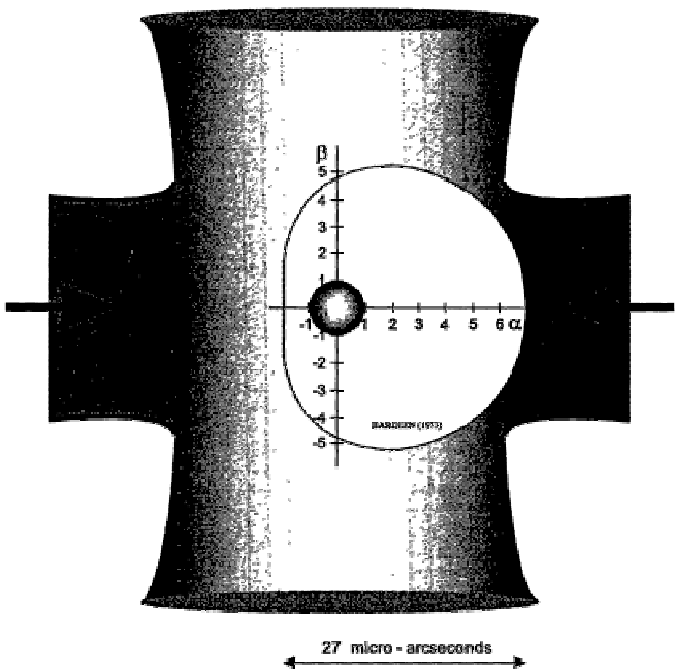


Figure 4. Sketch of the inner region of Sgr A* with accretion flow and nozzle surrounding the black hole. Overlaid is an appropriately scaled reproduction of a Figure from Bardeen (1973), showing the 'hole' of photons absorbed by the black hole if observed against a background source. A similar process could apply to Sgr A* and its compact, high-frequency emission component.

Simulating and quantifying non-Einstein gravity

Radboud University Nijmegen

- New 3DGRMHD code BHAC (U. Frankfurt, Rezzolla)
- Adaptive mesh and arbitrary space times
- Example: Non-Einstein gravity with „Dilaton parameter" b:

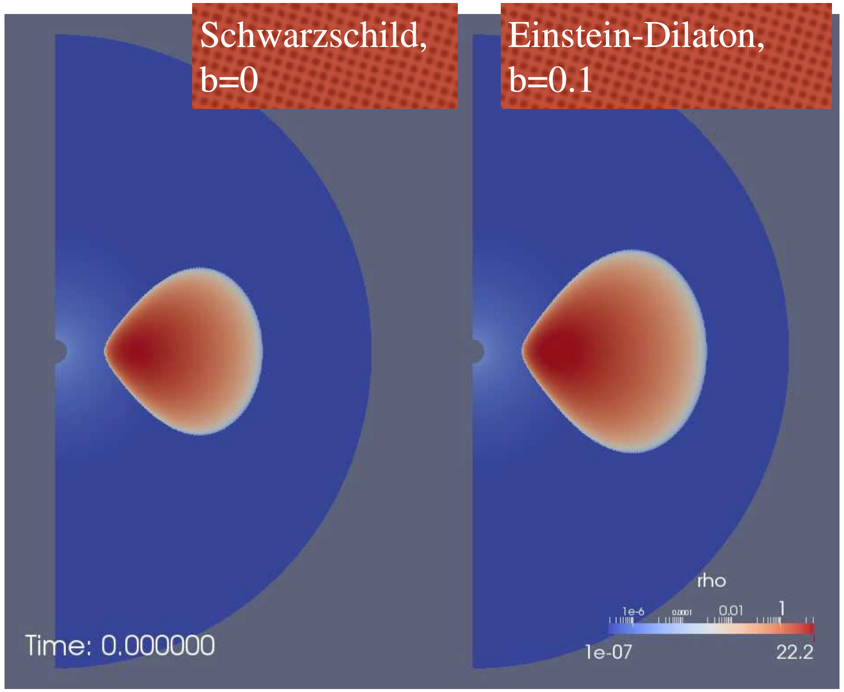
$$ds^2 = -\left(\frac{\rho - 2\mu}{\rho + 2b}\right)dt^2 + \left(\frac{\rho + 2b}{\rho - 2\mu}\right)d\rho^2 + (\rho^2 + 2b\rho)d\Omega^2 \qquad r^2 = \rho^2 + 2b\rho, \qquad M = \mu + b$$

Rezzolla & Zhidenko (2014) metric expansion:

$$ds^2 = -N^2(r)dt^2 + \frac{B^2(r)}{N^2(r)}dr^2 + r^2 d\Omega^2$$

yields high accuracy approximation e.g. error of 1e-4 in $g_{\mu\nu}$ with seven expansion parameters

General axisymmetric spacetime also available: Konoplya et al. (2016)



Simulation credit: Yosuke Mizuno

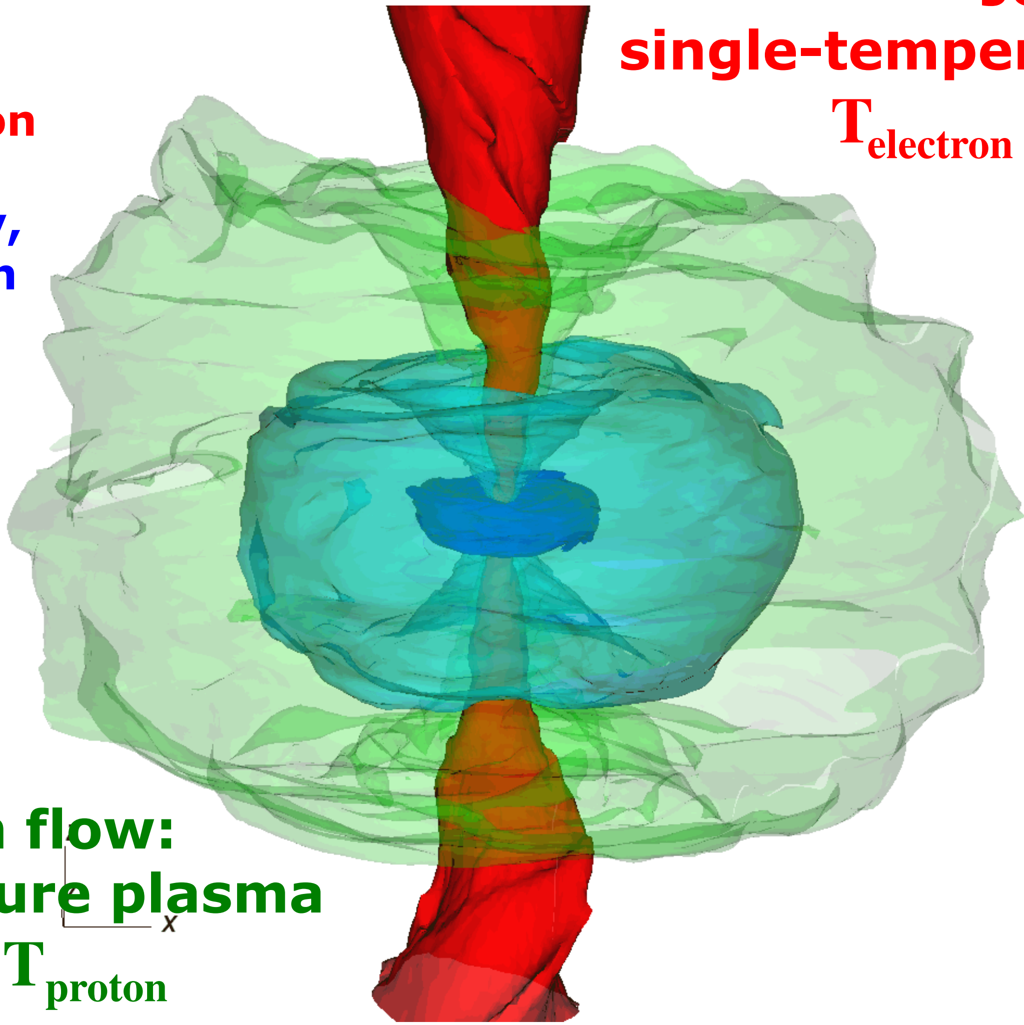
Importance of electron heating

Radboud University Nijmegen

3D GRMHD density regions:

Red: low density, high magnetization

Blue: high density, low magnetization



Jet: single-temperature plasma:
$T_{electron} \sim T_{proton}$

Jet is lower density than disk

$$\dot{M}_{jet} \ll \dot{M}_{disk}$$

Hence, needs to be hotter to radiate significantly:

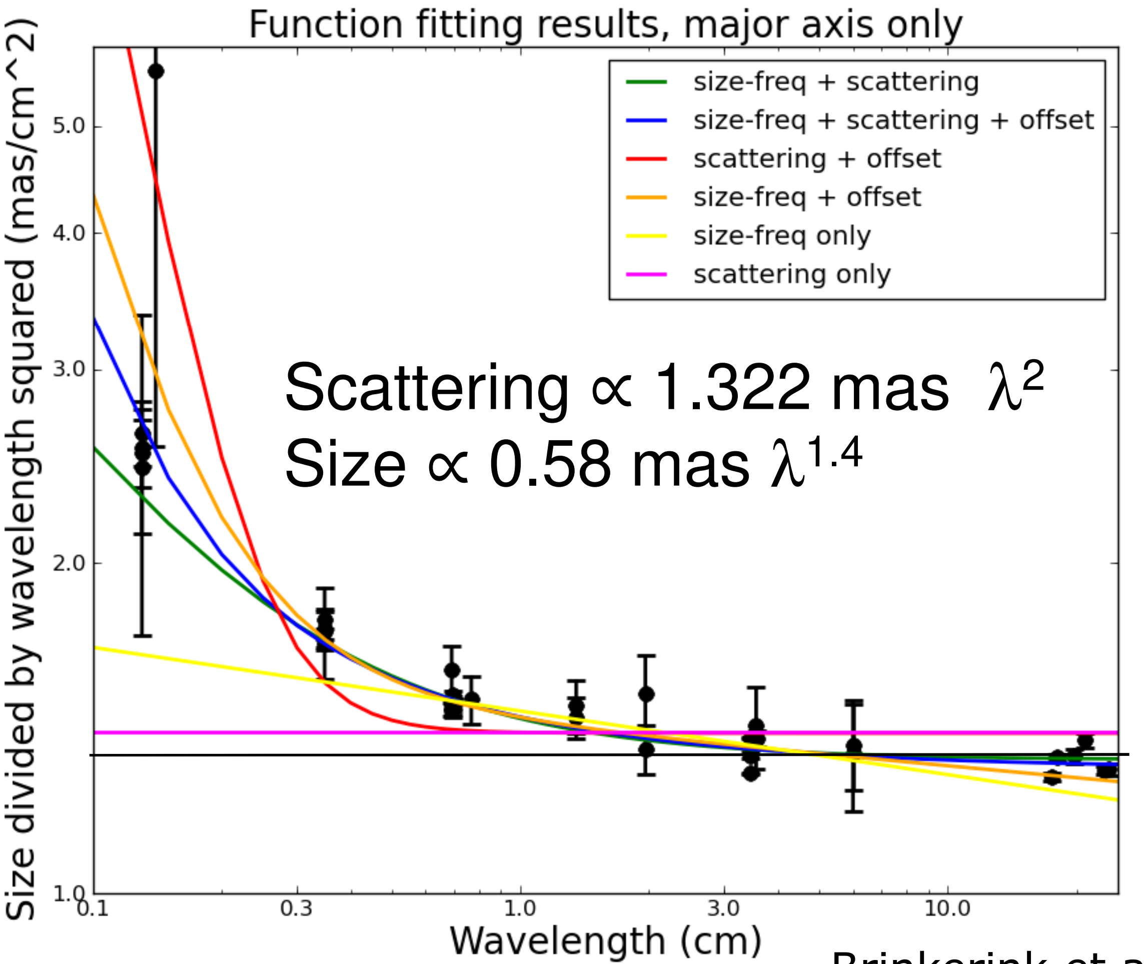
$$T_{e,jet} \gg T_{e,disk}$$

Accretion flow: two-temperature plasma
$T_{electron} \ll T_{proton}$

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

Sgr A radio size*

Radboud University Nijmegen



Scattering ∝ 1.322 mas λ^2

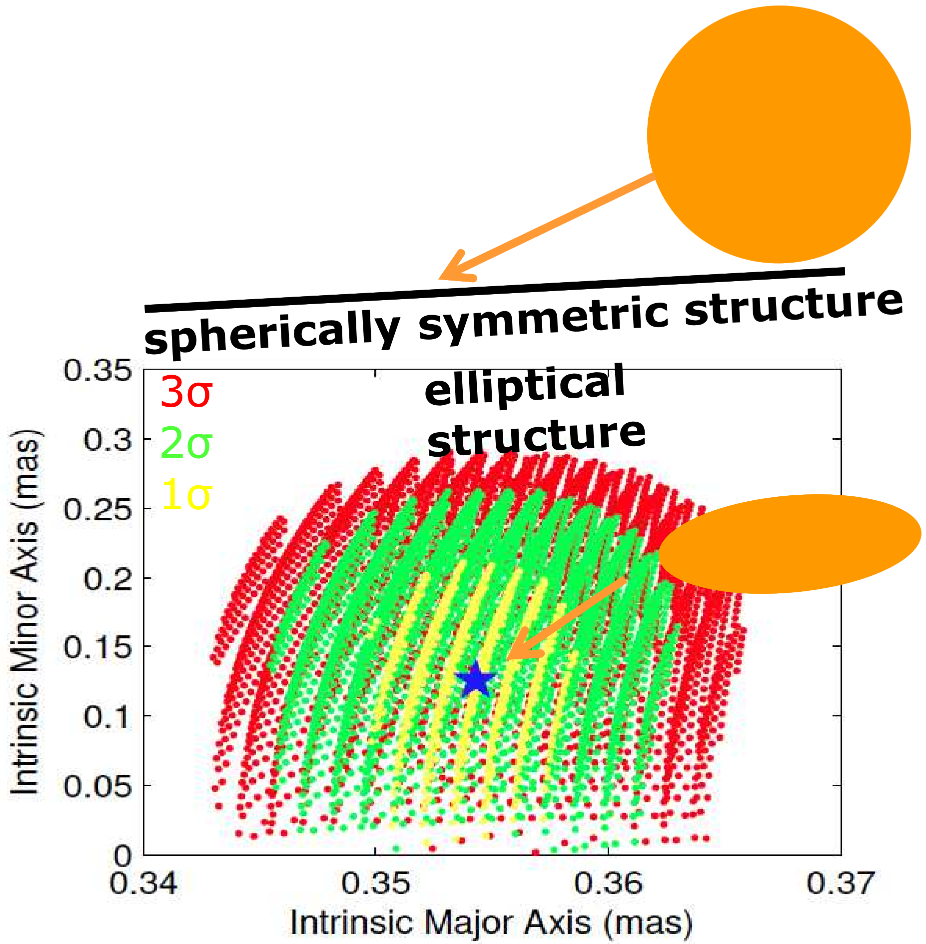
Size ∝ 0.58 mas $\lambda^{1.4}$

Brinkerink et al. (in prep)

Two-dimensional structure of Sgr A: fairly elongated*

Radboud University Nijmegen

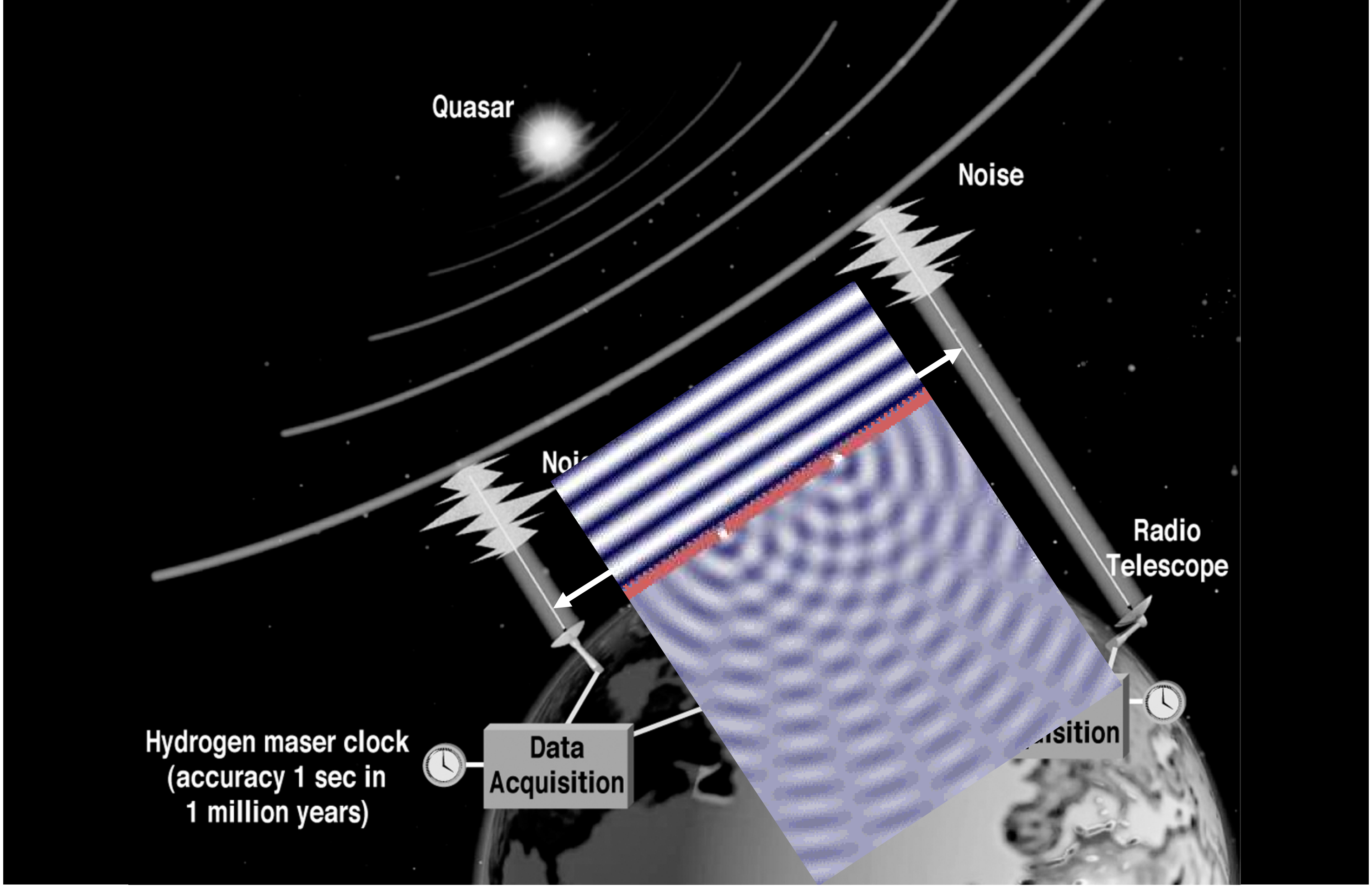
- Accurate closure amplitude measurements of 2D-size of Sgr A* with the VLBA.
- Size at 43 GHz: (35.4 ±0.4) Rs × (12.6±5.5) Rs at PA (95±4)°



Bower et al. (2014, ApJ)

VLBI – Very Long Baseline Interferometry

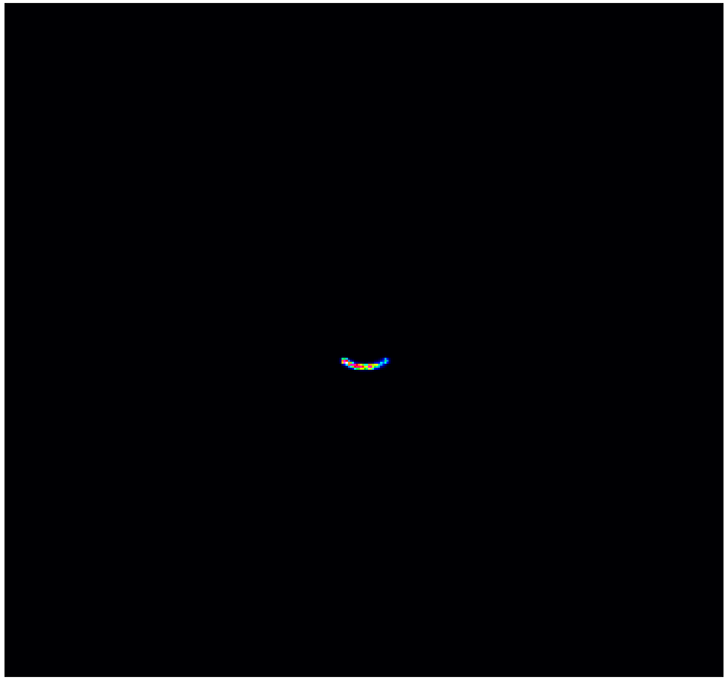
Resolution: smallest angular scale: ~λ/D

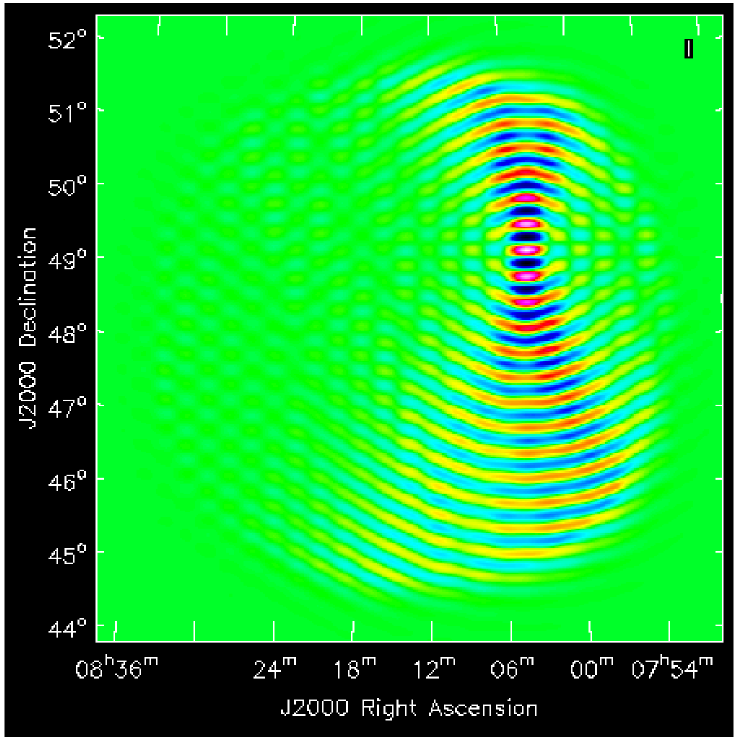


Interferometer Principle

Radboud University Nijmegen

- Each antenna-antenna baseline "draws" a ring on the sky
- Interference between signals produces interferometry fringes
- The superposition of the information of many baselines (fringes) "draws" the image.





Slide: C. Tasse

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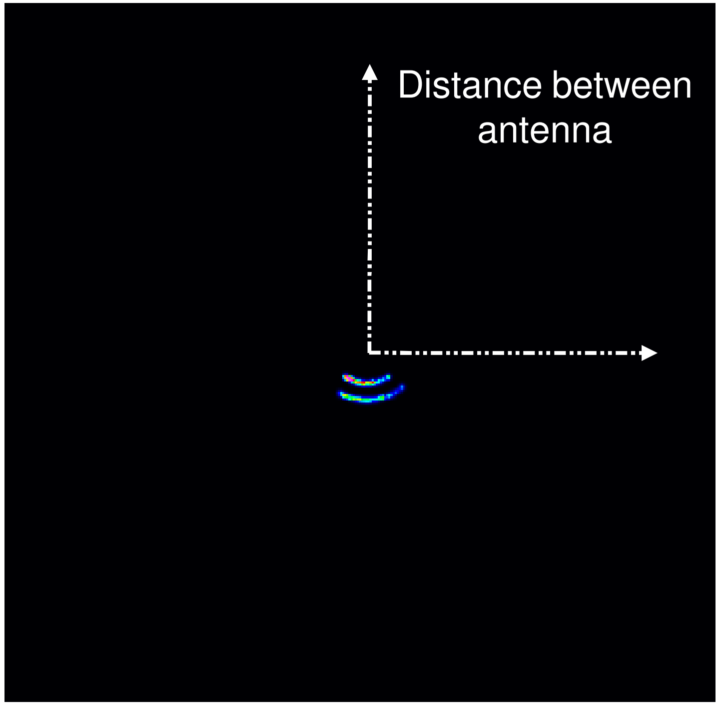

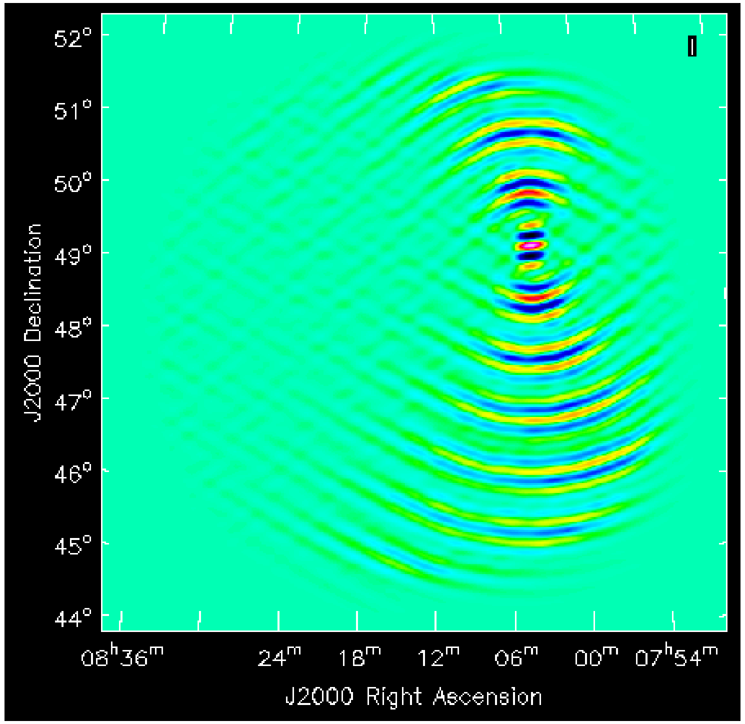

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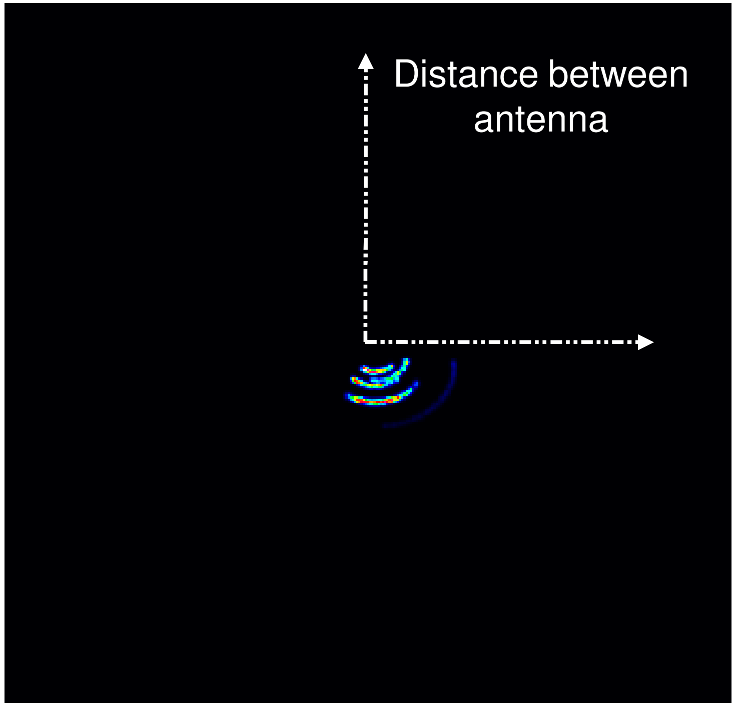

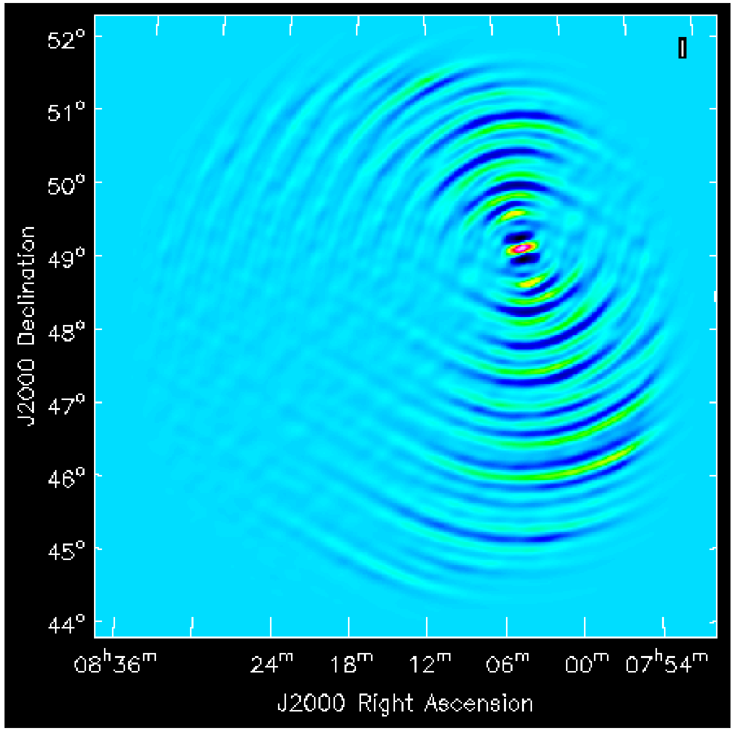

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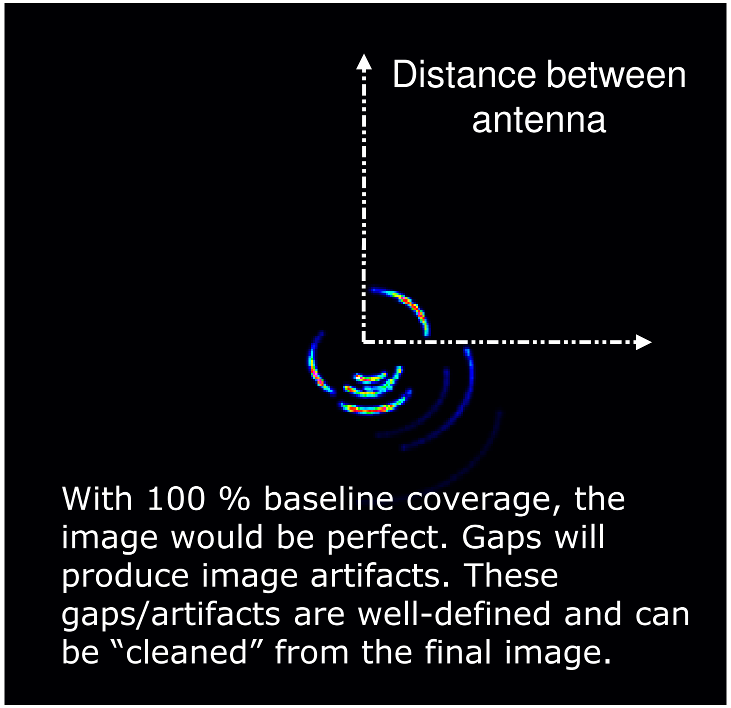
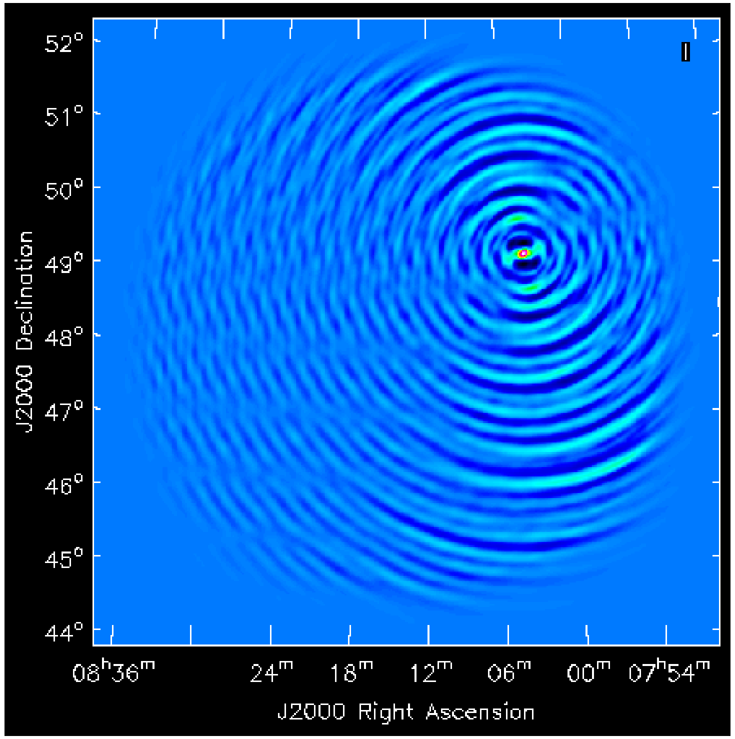
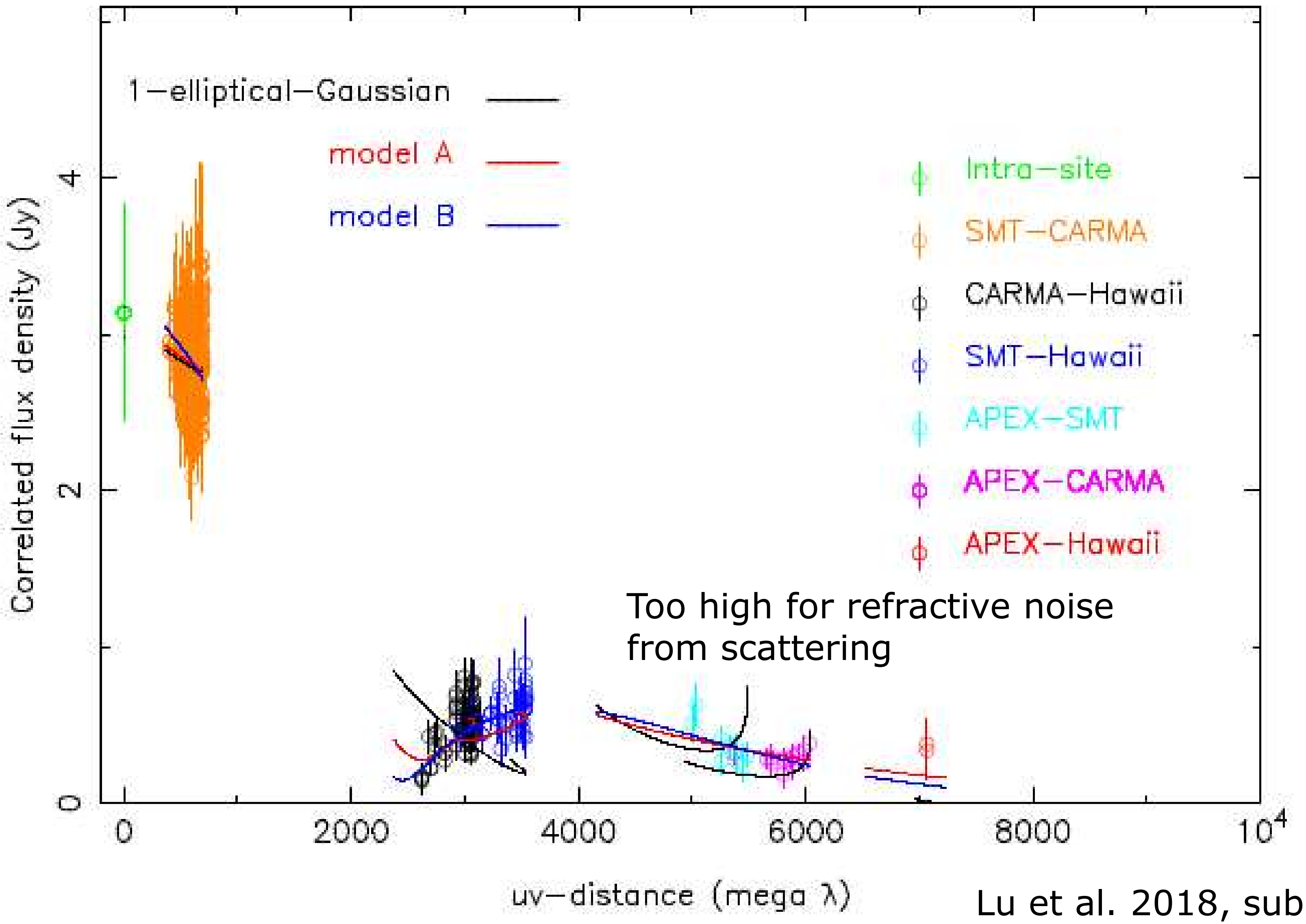




Slide: C. Tasse

First VLBI-Results from Apex

Radboud University Nijmegen



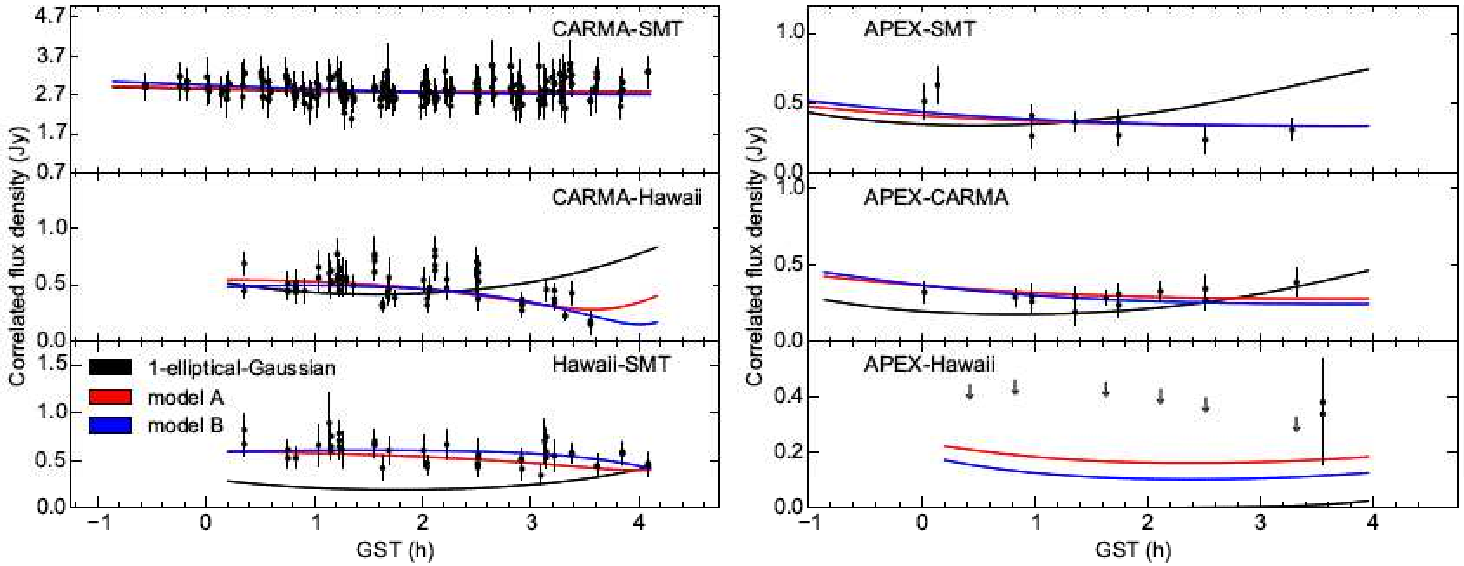
Too high for refractive noise from scattering

Lu et al. 2018, subm.

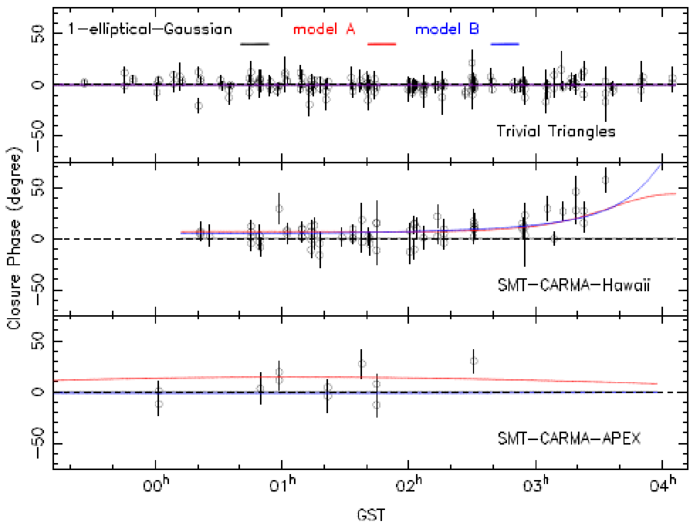
230 GHz VLBI with APEX

Radboud University Nijmegen

Correlated flux



Closure phases

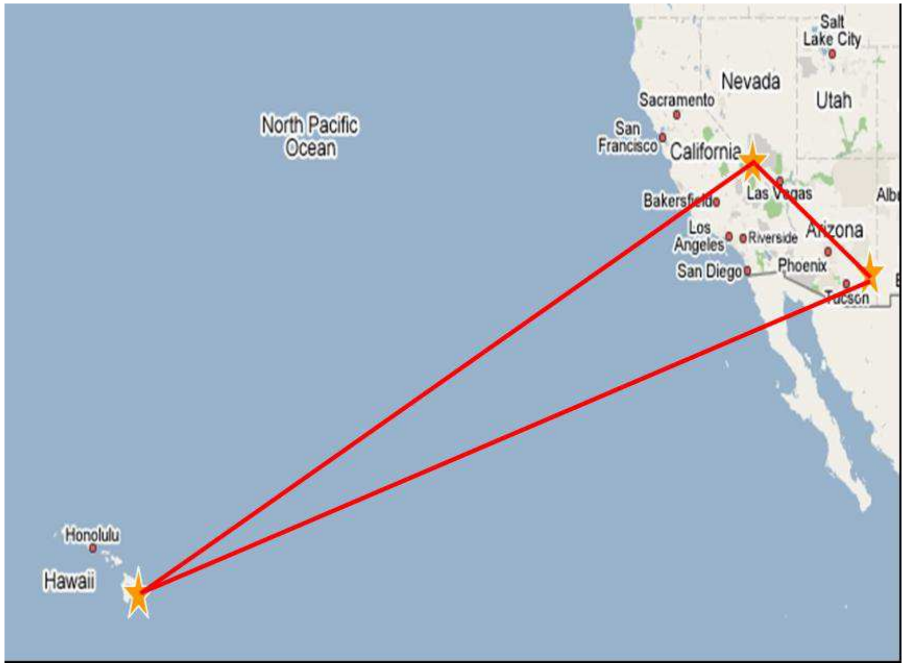


Lu et al. 2018, subm.

EHT Closure phases at 1 mm

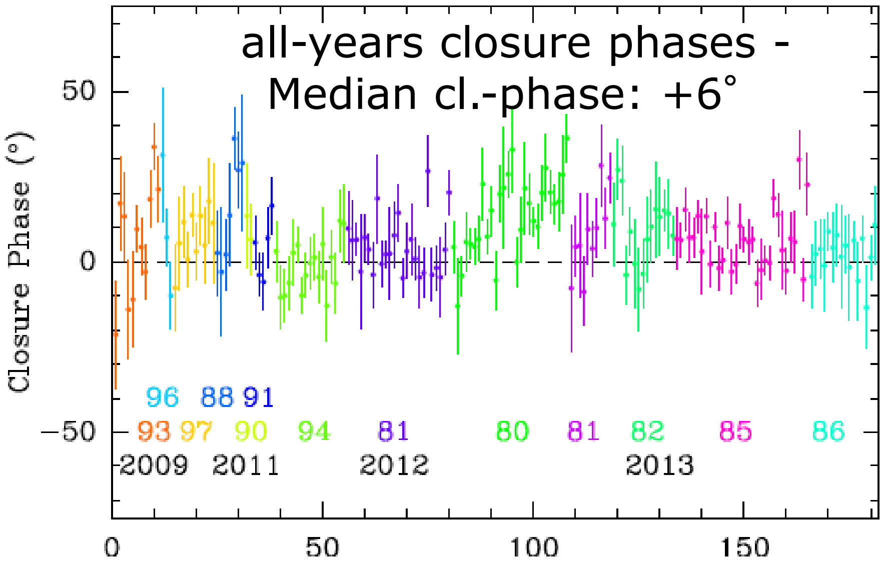
Radboud University Nijmegen

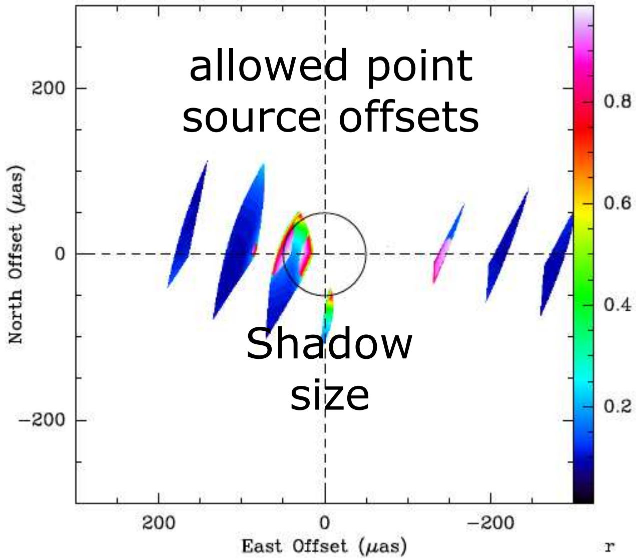
Hawaii-California-Arizona



Fish et al. (2015, ApJ subm.)

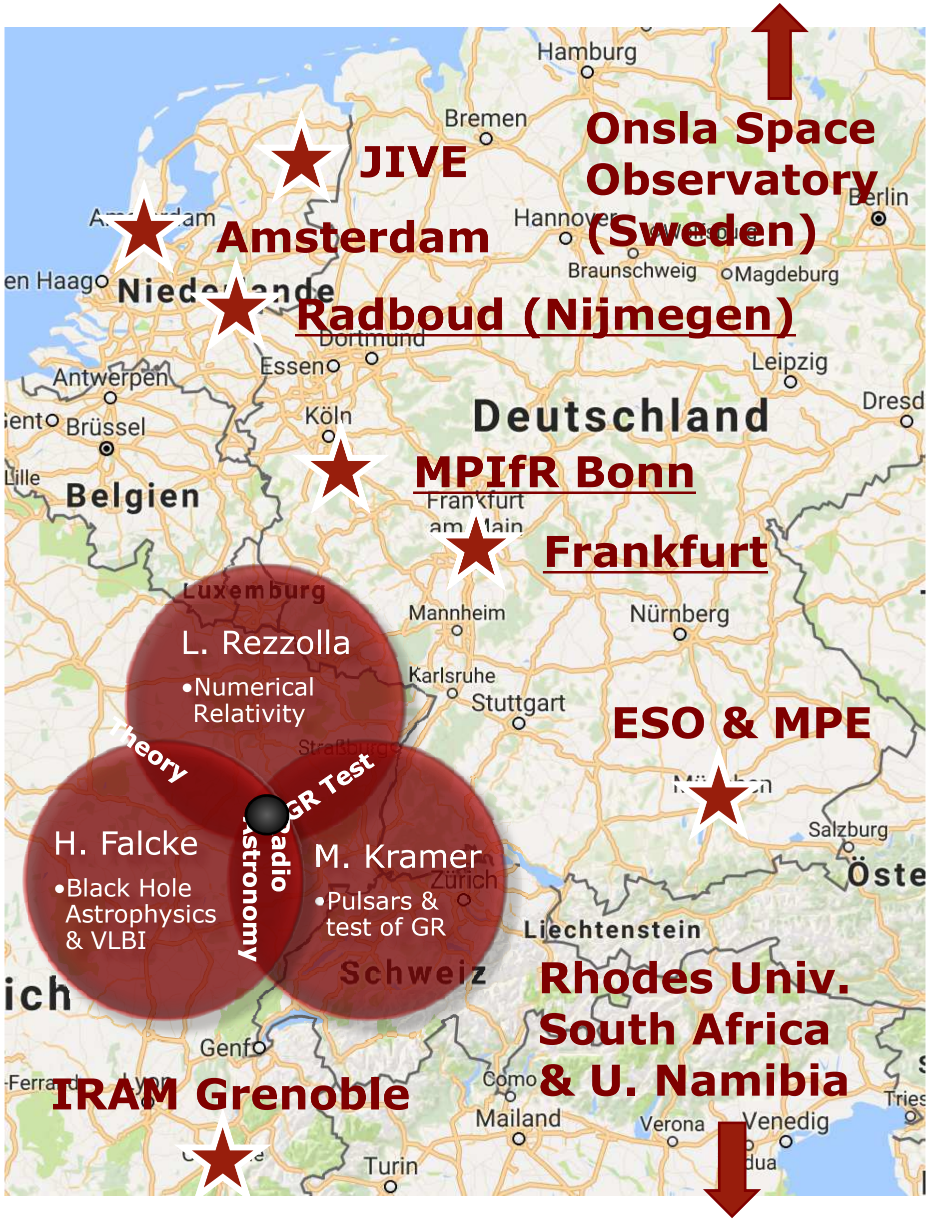
See also “Polarization on EH scales”:
Johnston et al. (2015, Science, in press)





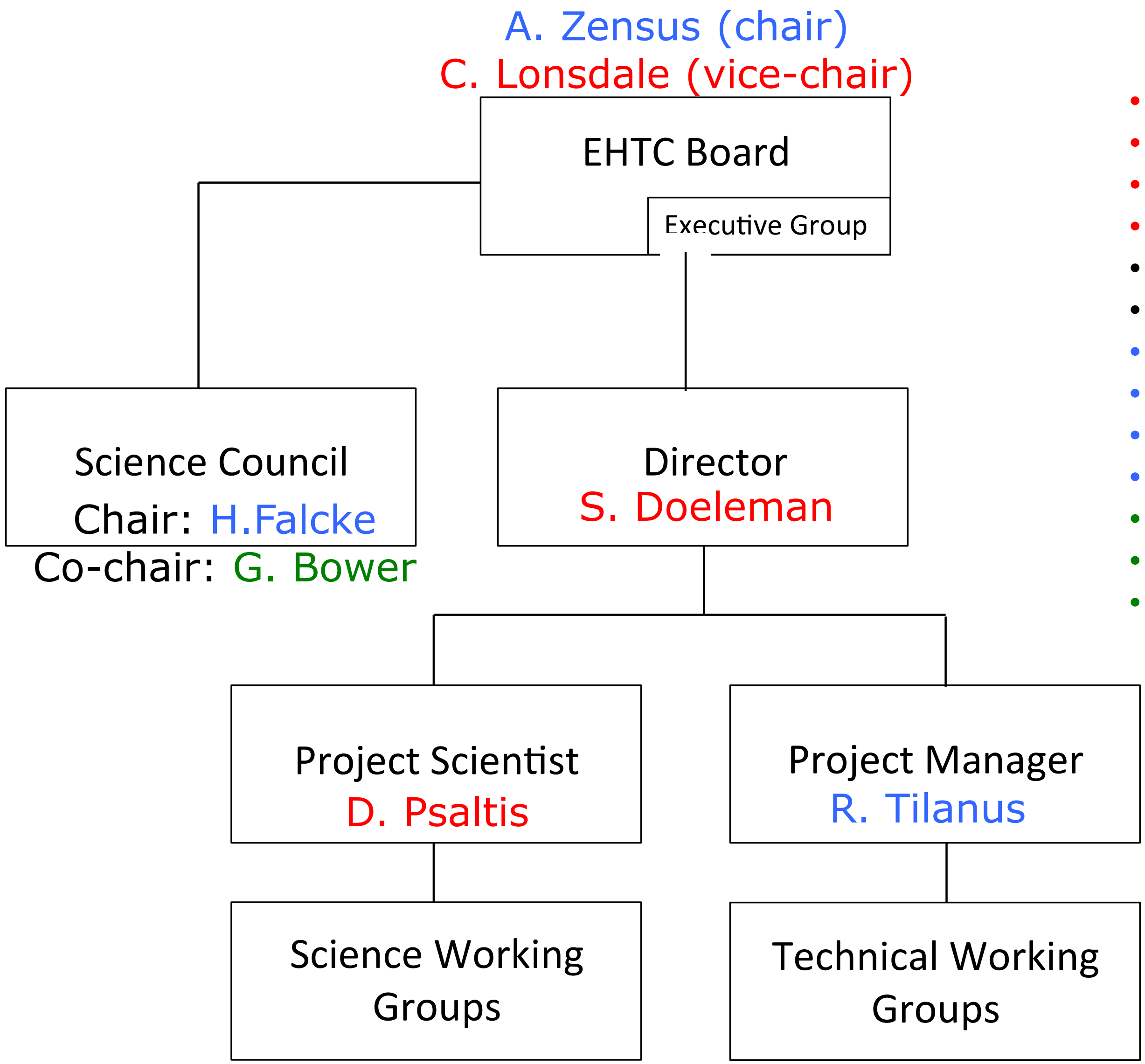
BHC Partners in Europe & Africa

Radboud University Nijmegen



- Amsterdam: Multi-wavelength observations
- Bonn VLBI: Data correlation, APEX telescope
- ESO: ALMA telescope
- IRAM: Pico Veleta & NOEMA telescopes
- JIVE: Open Science – VLBI analysis software
- Rhodes Univ.: VLBI Simulations
- Sweden: Polarisation calibration

Event Horizon Telescope Consortium



13 EHT Stakeholders

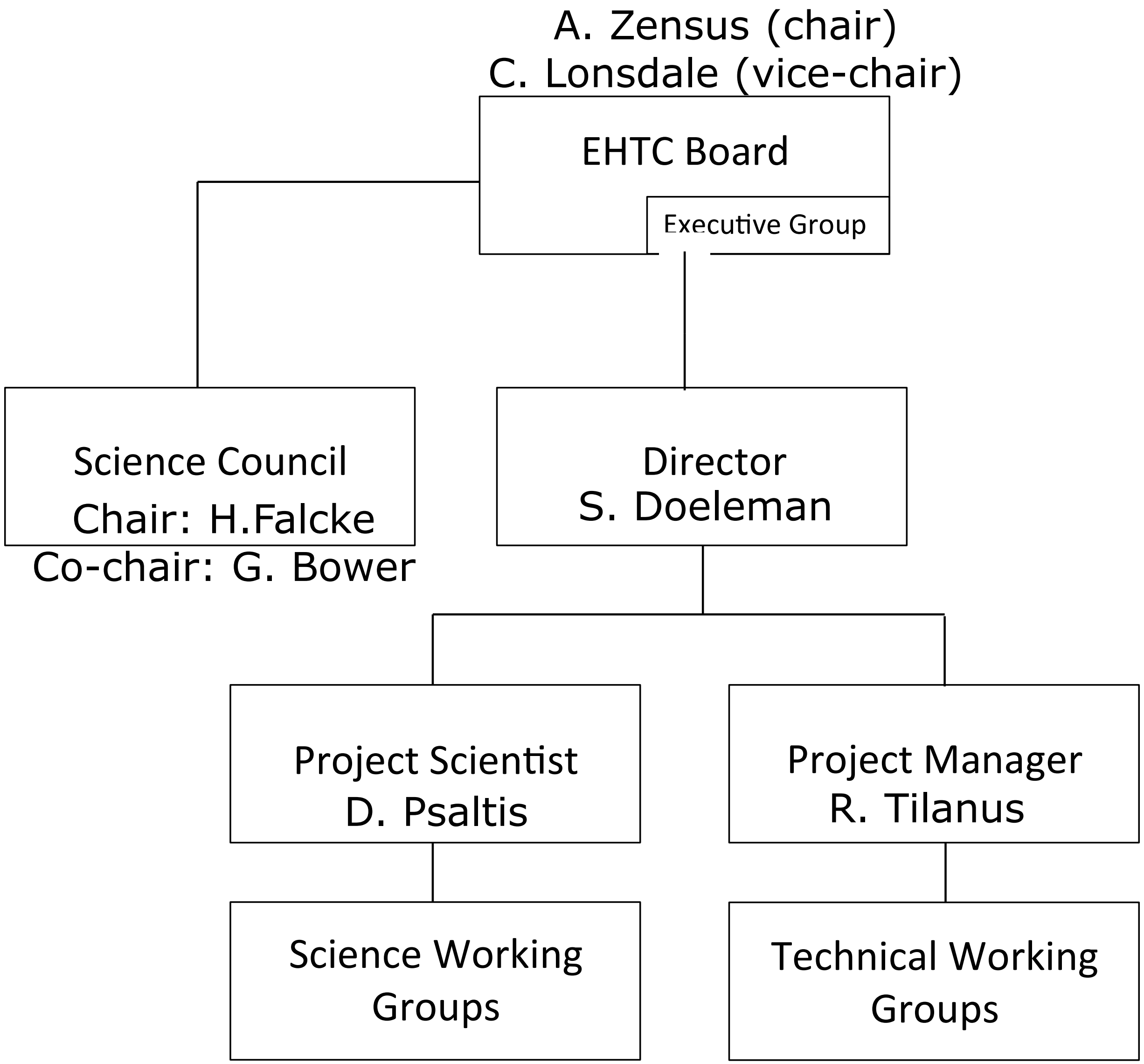
- Harvard/SAO (USA)
- MIT Haystack Obs. (USA)
- Univ. Arizona (USA)
- Univ. Chicago (USA)
- Perimeter (Canada)
- INAOE (Mexico)
- **MPIFR Bonn (Germany)**
- **IRAM (D/F/E)**
- **Radboud Uni. (Netherlands)**
- **Univ. Frankfurt (Germany)**
- EACOA (East Asia)
- NOAJ (Japan)
- ASIAA (Taiwan)

Main EU Contributions:

- BlackHoleCam/ERC
- MPG/IRAM
- ESO (ALMA)

About 150 individual EHT members ...

Event Horizon Telescope Consortium



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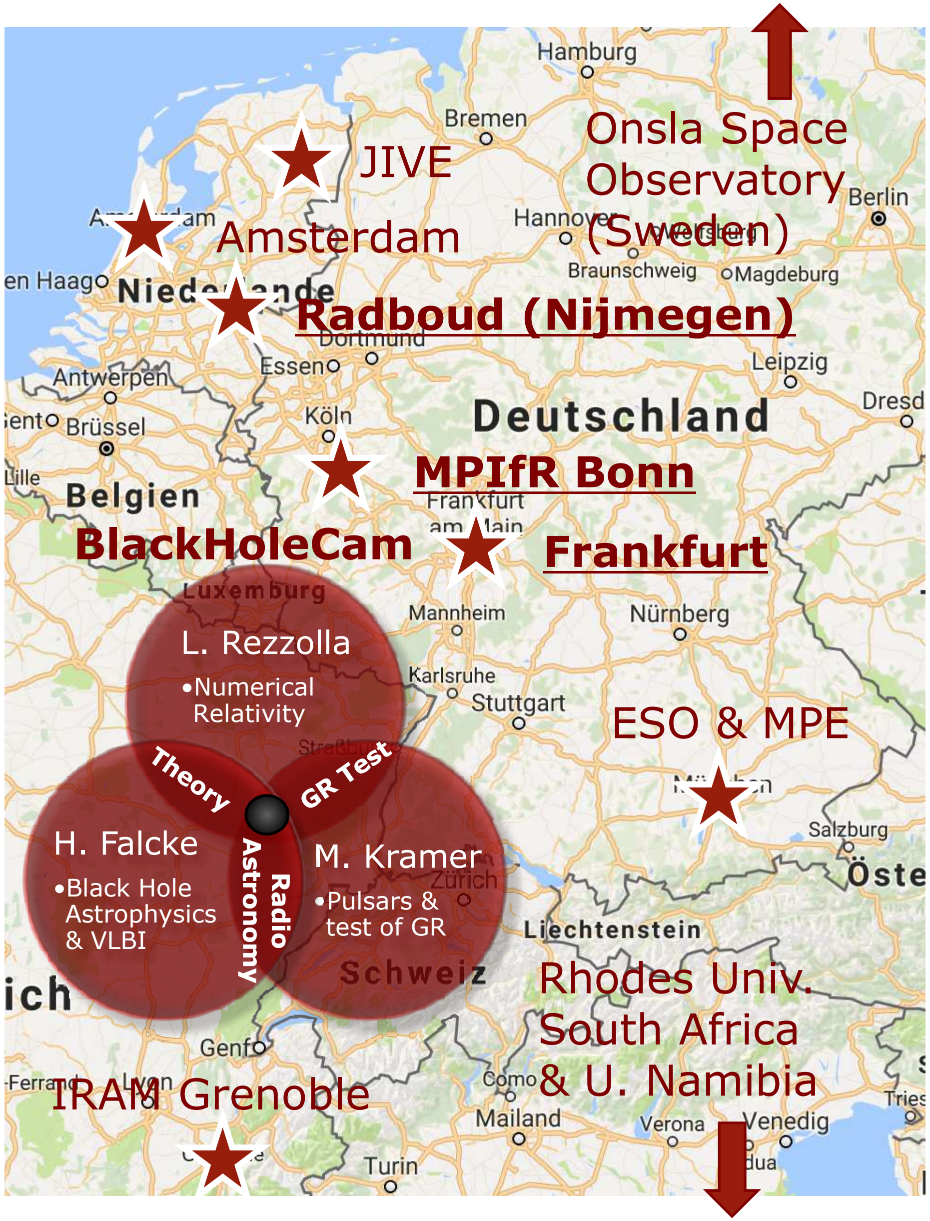
14 M€ ERC Synergy Grant BlackHoleCam & EU partners

BlackHoleCam

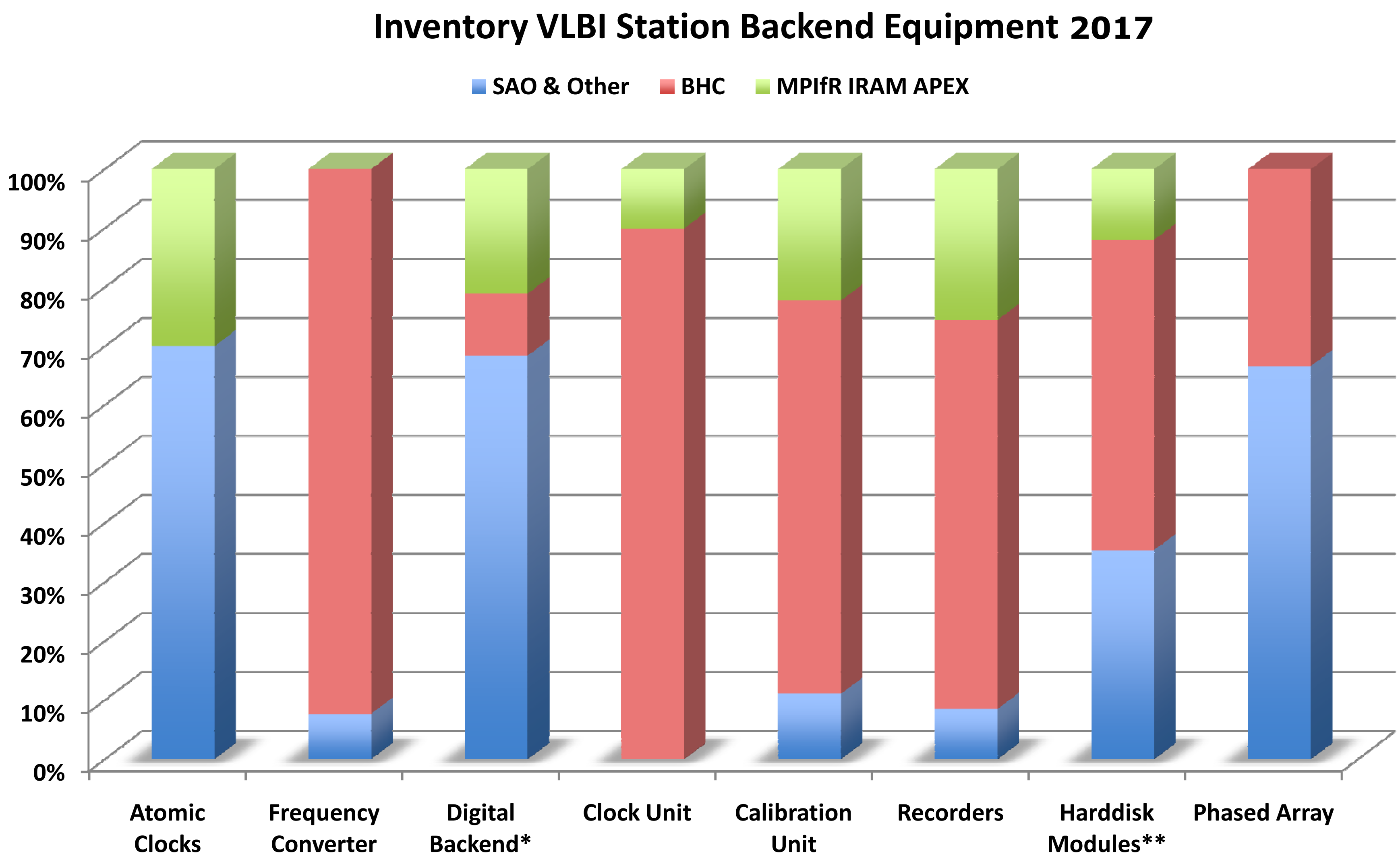


EU Players & Partners

- BlackHoleCam PIs:
  - Falcke (Radboud Nijmegen)
  - Rezolla (Frankfurt)
  - Kramer (MPIfR Bonn)
- BHC Partners
  - Zensus (MPIfR Bonn)
  - Markoff (Amsterdam)
  - ESO: ALMA telescope
  - IRAM: Pico Veleta & NOEMA telescopes
  - JIVE: CASA
  - Rhodes Univ: VLBI Simulations
  - Bologna: CASA

VLBI hardware contributions

Event Horizon Telescope



Note: not all columns are the same price …

Mark 6 Recording:

2017: 32 Gbit/sec
2018: 64 Gbit/sec

0.5-1 Pbyte/Telescope

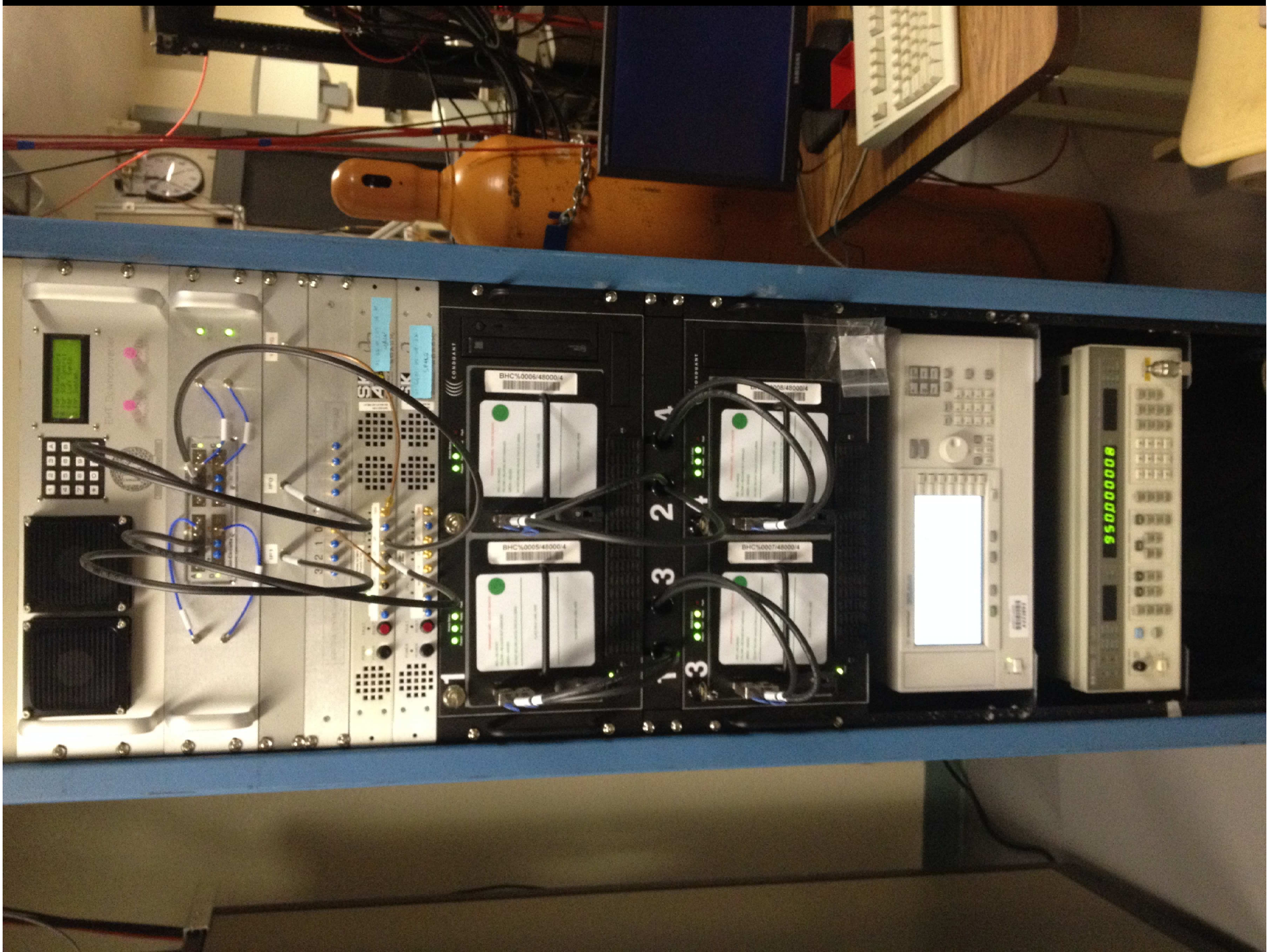
EHT VLBI equipment at
IRAM 30m Pico Veleta
(2017)

DBBC3 (parallel
recording)

DownConverter
+ R2DBE

2018: Control
Computer added

2019: Automatic
upload of schedules

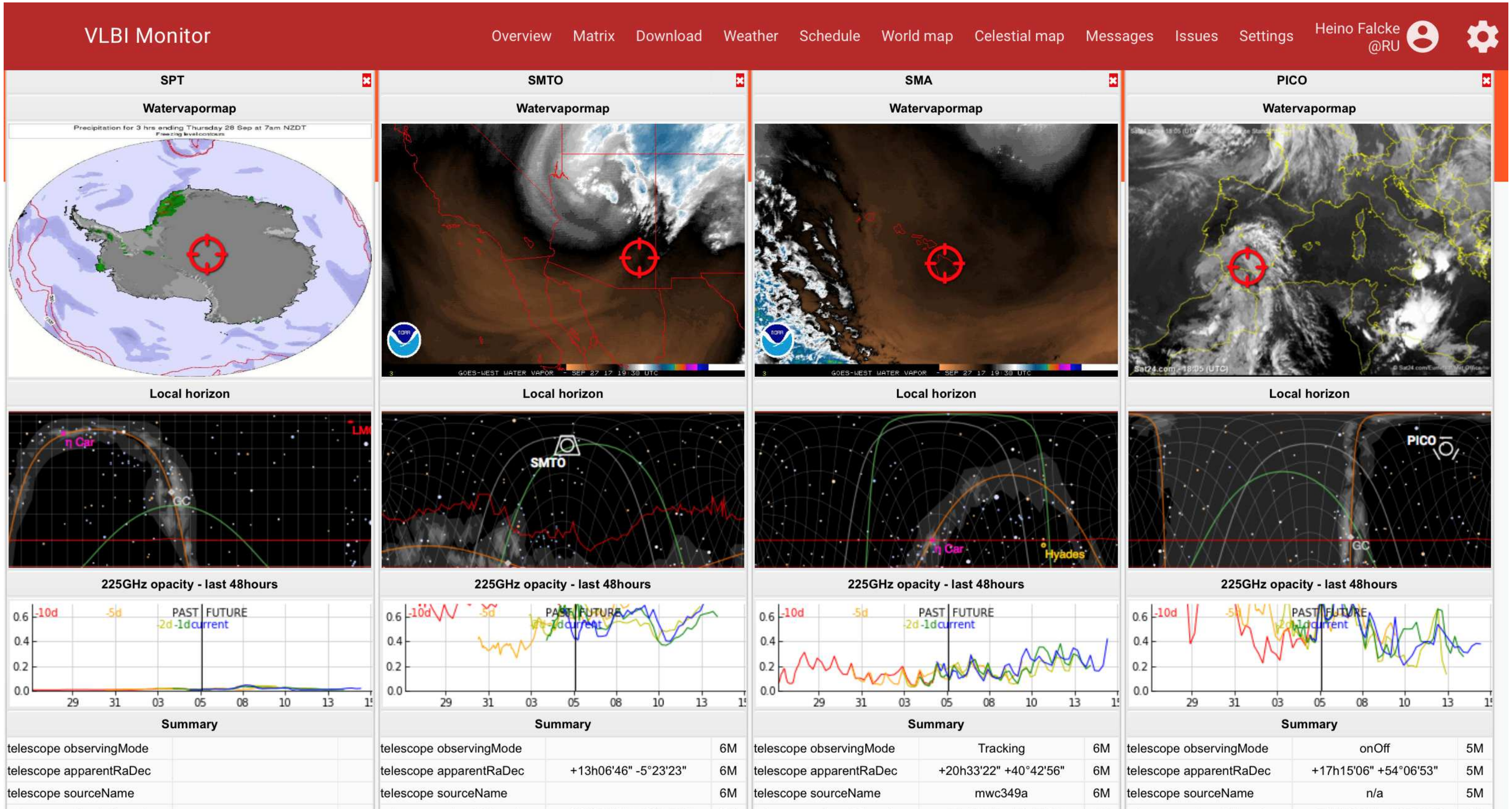



BHC%0008/48000/4
BHC%0007/48000/4

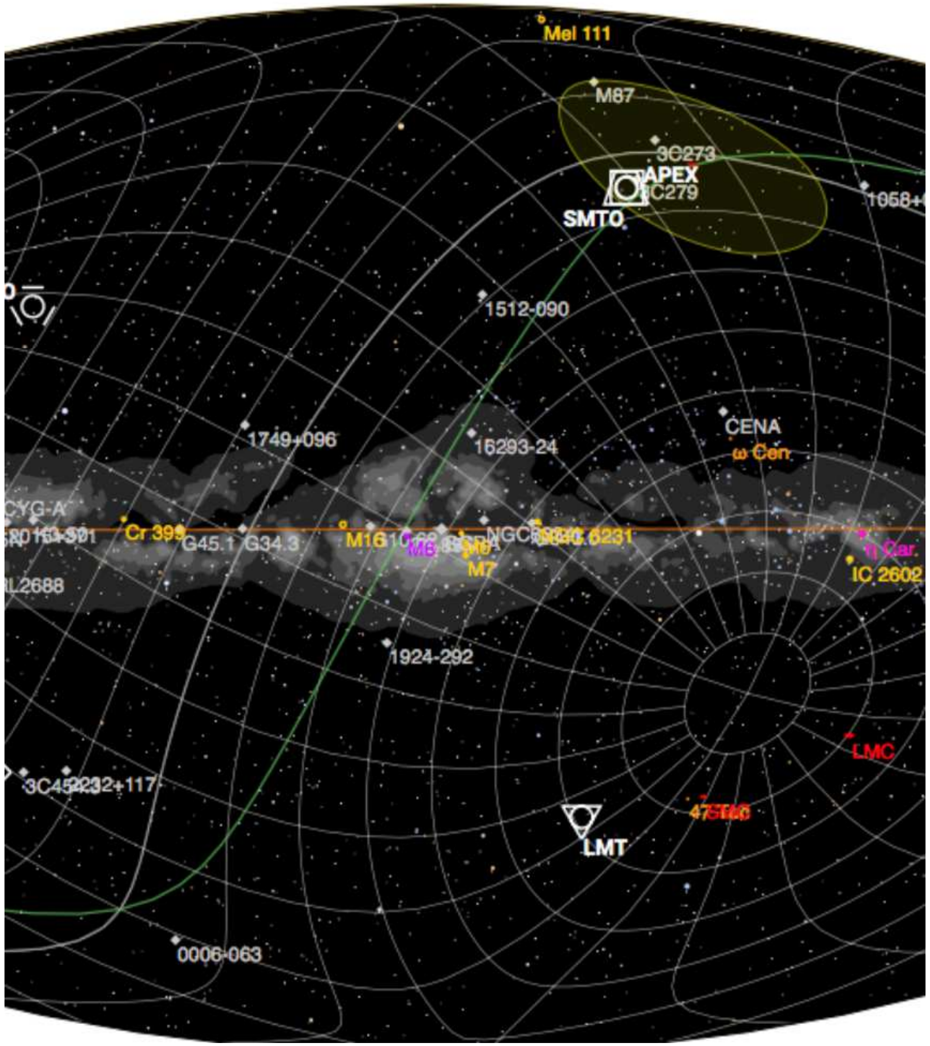
VLBI Real Time Monitor

Radboud University Nijmegen

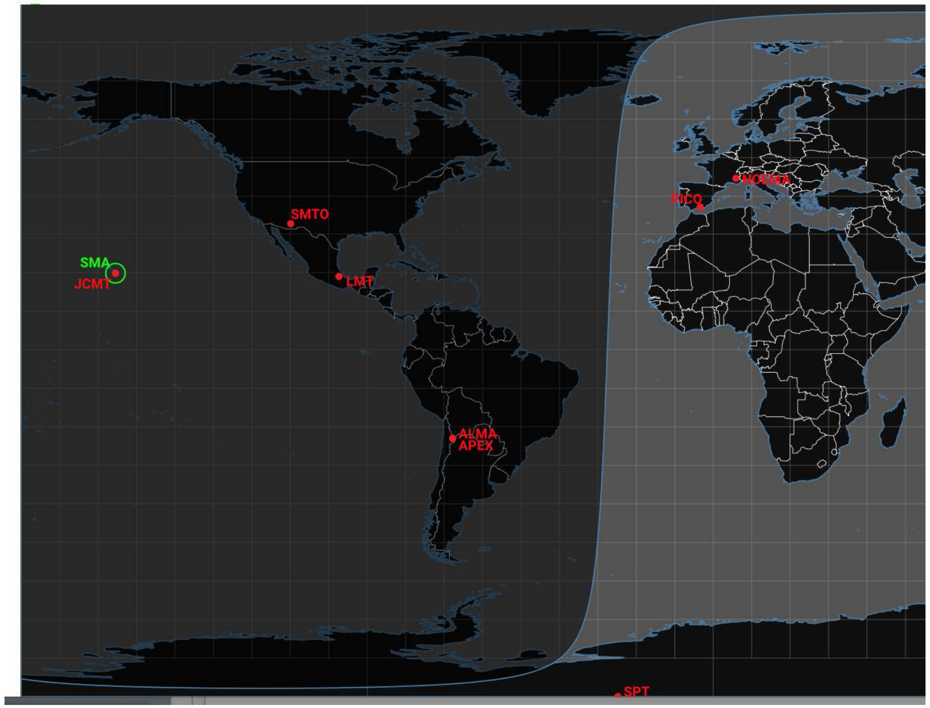
Daily weather forecast from Dutch meterorological servce (KNMI) for all sites



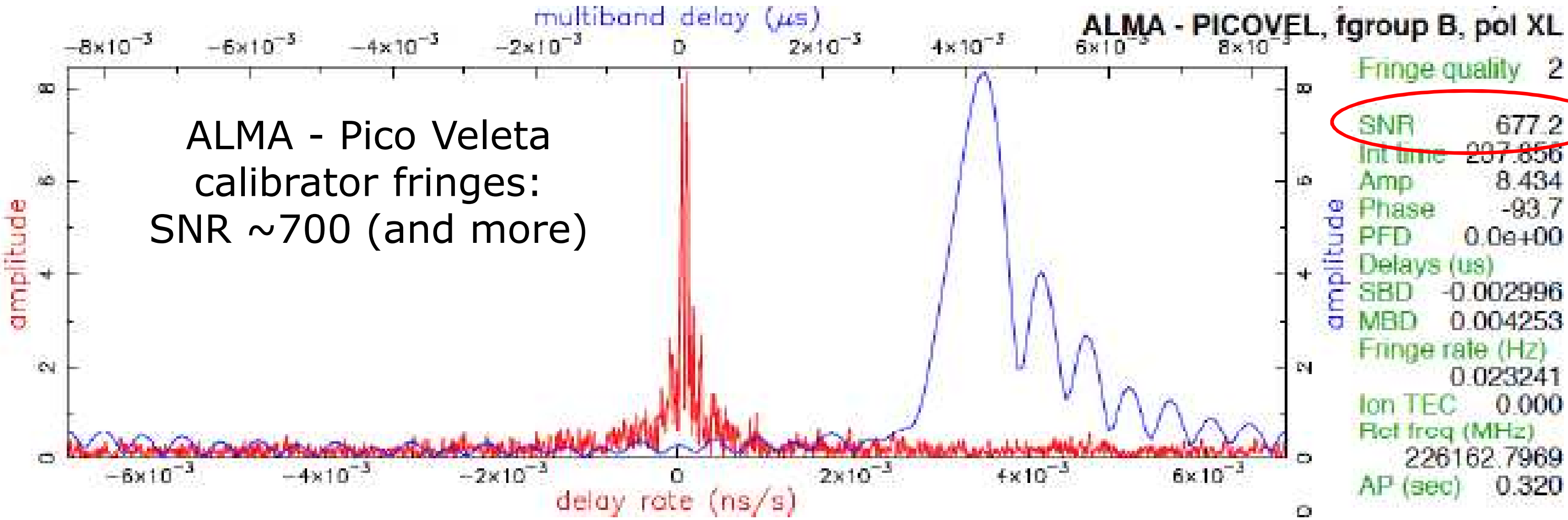
VLBI Monitor



EHT VLBI live world map

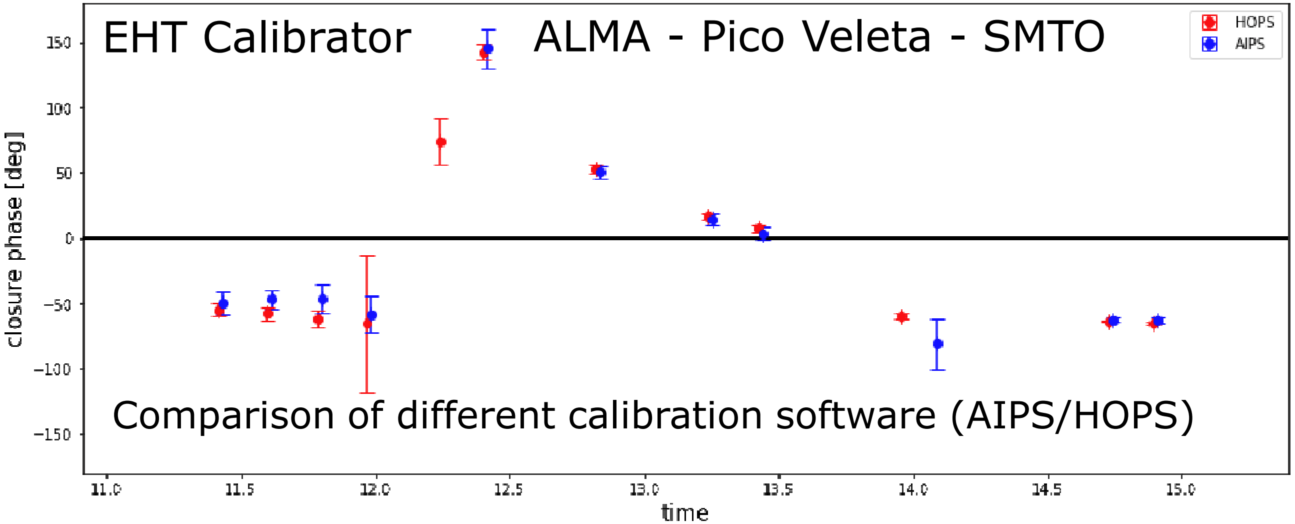


EHT 2017 – Data Quality

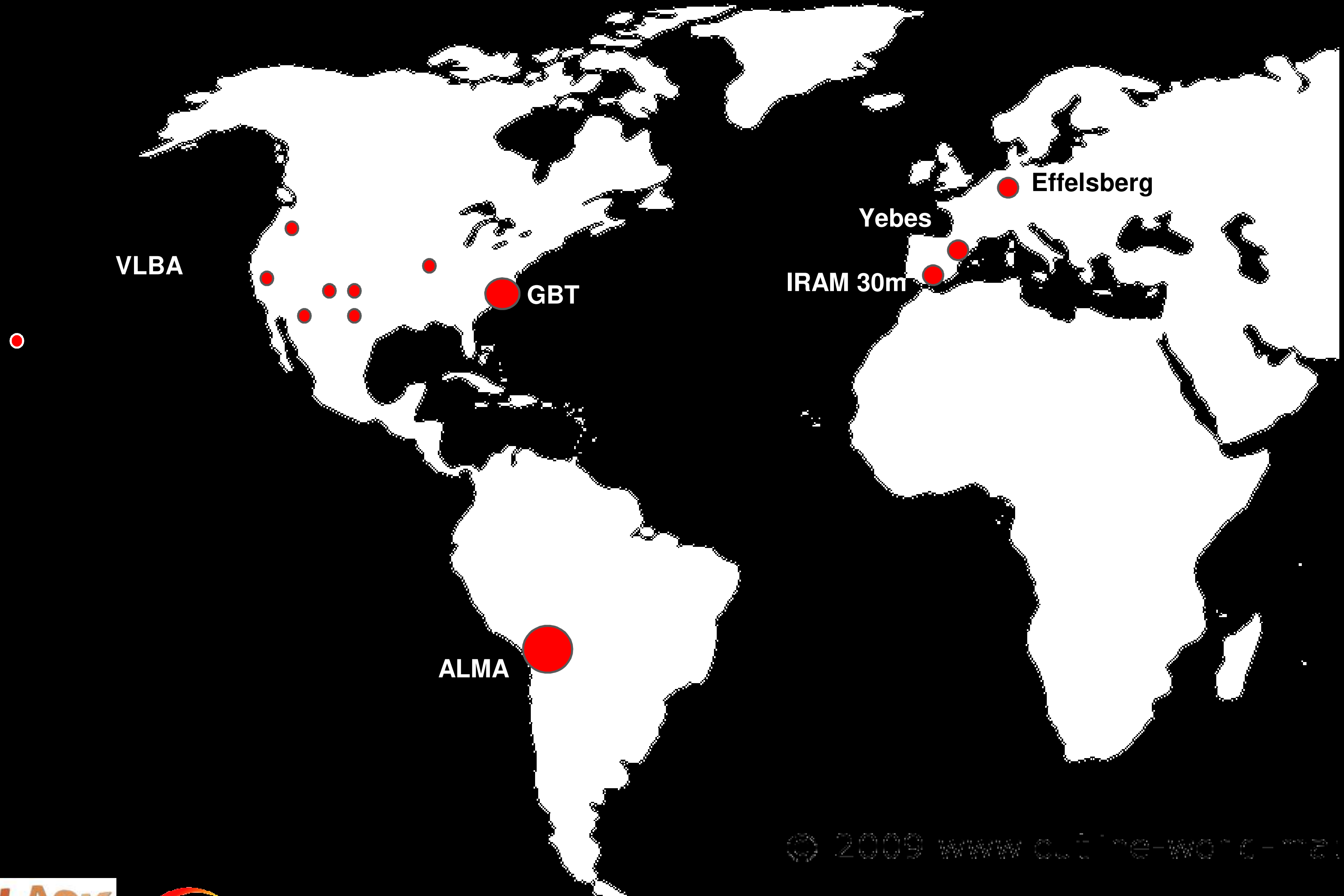


- Calibration and Error Analysis team working on 2017 data incl. South Pole
- Calibrator data now out for imaging
- Imaging Sgr A* not before May 2018
- Multiple imaging and calibration teams (AIPS/HOPS/CASA)

1mm closure phases



First VLBI with ALMA in April 2017

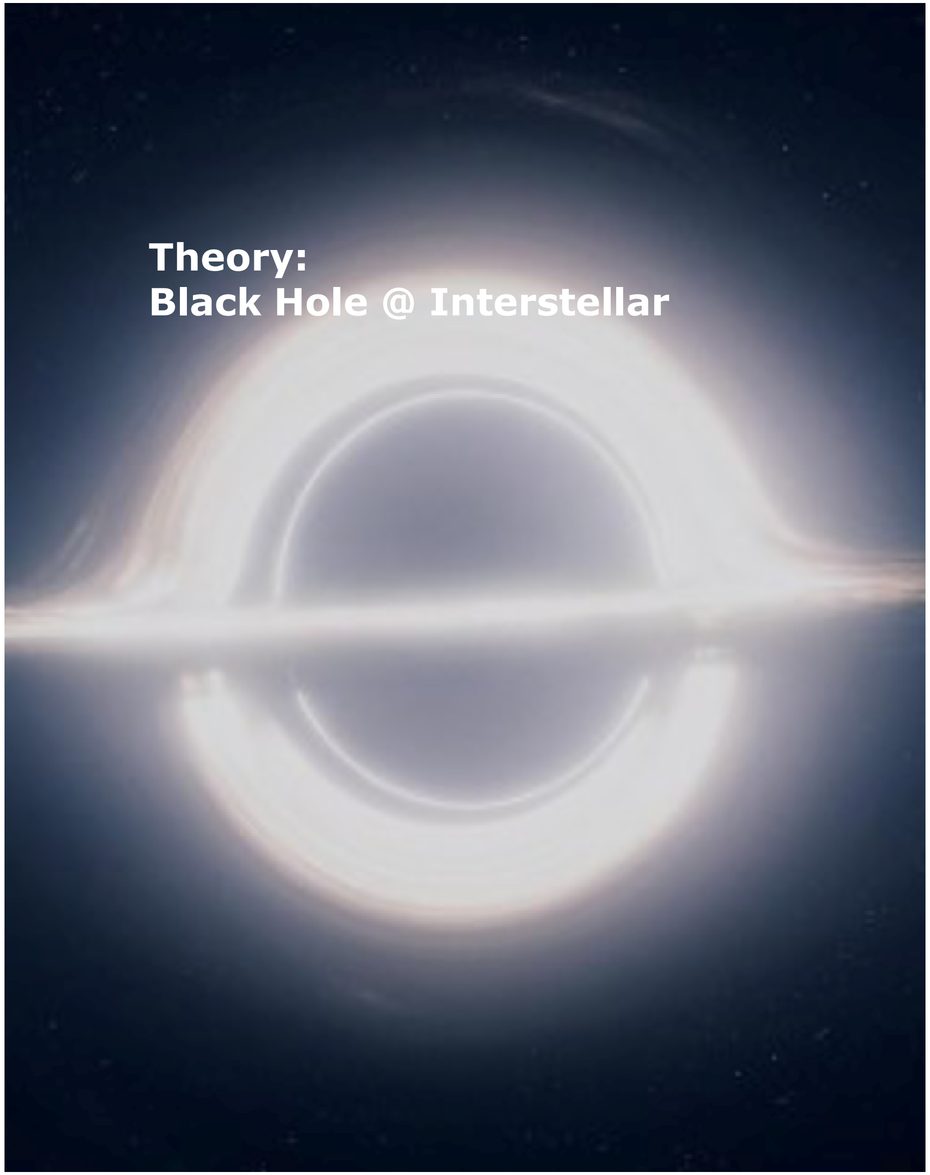


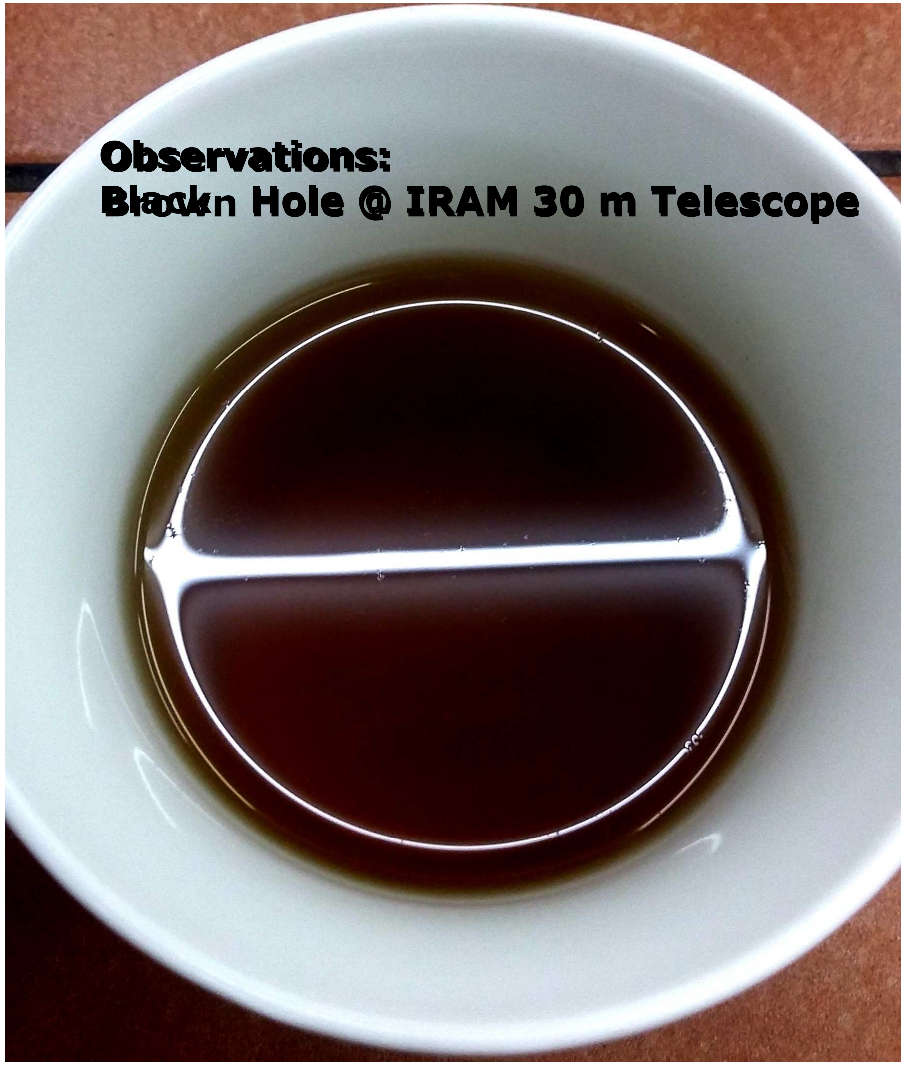
Radboud University

Issaoun, Brinkerink, Johnson et al. (in prep.)

Scientists stunned by first image of black hole

Radboud University Nijmegen

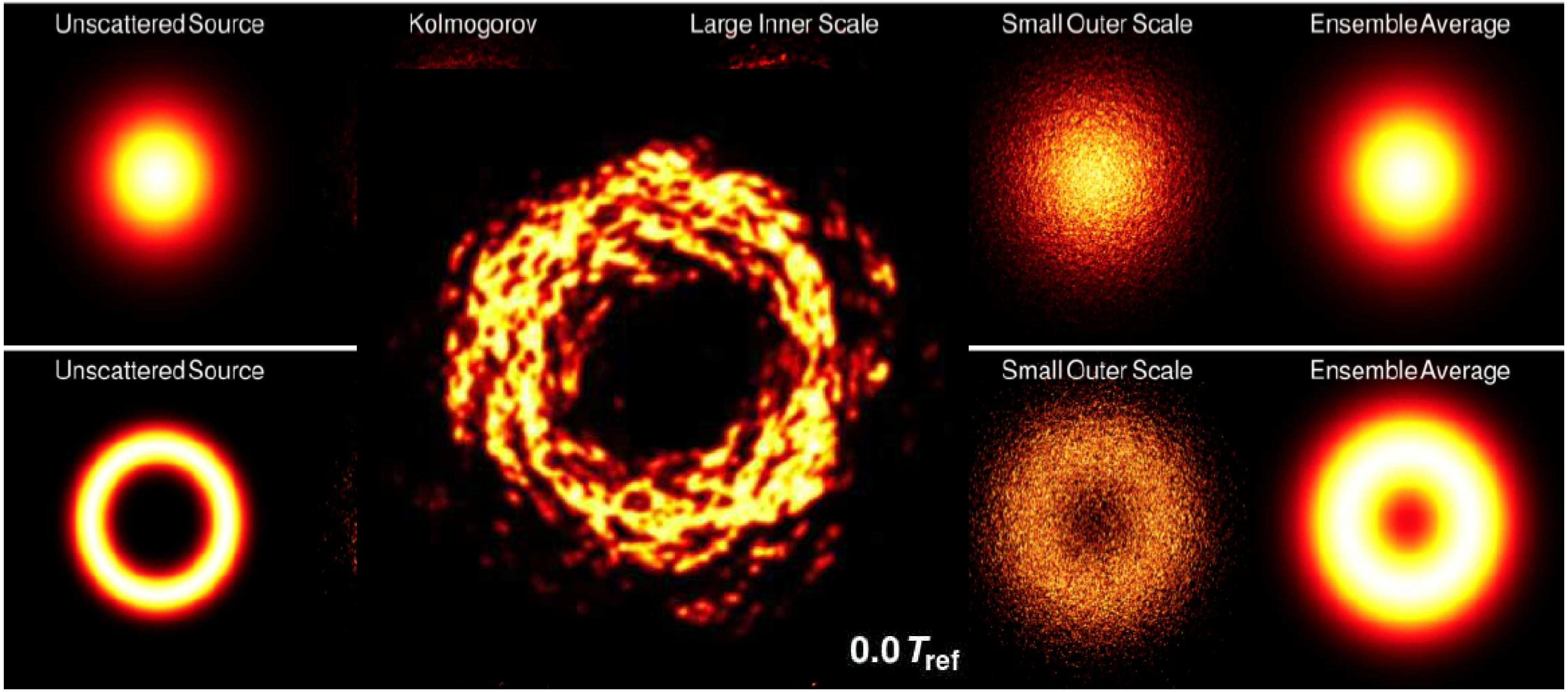




Ignacio Ruiz

Scattering

Radboud University Nijmegen



Johnson & Gwinn (2015)

EHT Data Analysis

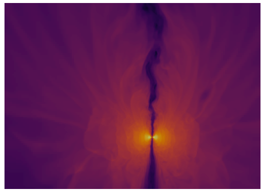
Radboud University Nijmegen

- 01/2017: EHT Dress Rehearsal
- 03/2017: Operation Readiness Review
- 04/2017: 1st observing run 6/10 days
- 06-07/2017: 1st Correlation pass
- 10/2017: 1st Engineering data release (Calibrators only) & Data issues review (multiple software tools, multiple imaging challenges)
- 12/2017: SPT data arrives
- 01-02/2018: 2nd Engineering data release (Calibrators only) & Data issues review
- 04/2018: 2nd observing run
- 05/2018: Engineering data release 3 of 2017 Sgr A* and M87 data for calibration and checks
- 06-07/2018: Start imaging of Sgr A* and M87
- 01-02/2019: First publications?

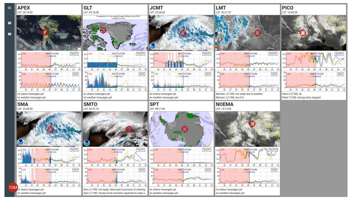
NL contributions

Radboud University Nijmegen

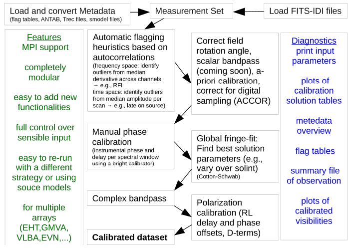
- Theory:
  - GRMHD simulations (M. Moscibrodzka, J. Davelaar)



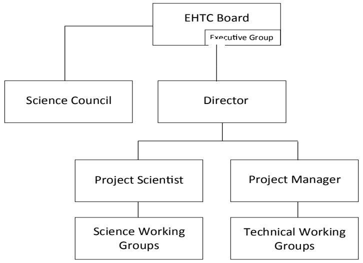
- Observing:
  - ~2/3 of VLBI equipment
  - Online Monitoring and Control of array (D. van Rossum)
  - Part of 5 telescope observing crews (e.g., S. Issaoun)



- Data Analysis Software:
  - New open source CASA VLBI functionality (JIVE/BlackHoleCam)
  - rPICARD: Automatic CASA-VLBI pipeline (**M. Janssen**) **Poster P30**
  - MeqSilhouette VLBI Simulations coupled to rPICARD (R. Dean, U. Pretoria with F. Roelofs)
  - Parameterextraction (Shan-Shan Zhao)



- Leadership:
  - Project management (R. Tilanus)
  - Science Council chair (H. Falcke)
  - EHT Board membership (W. Boland)
  - Multi-wavelength coordination (UA, S. Markoff)



Picard: CASA VLBI Pipeline

Load and convert Metadata
(flag tables, ANTAB, Trec files, smodel files)

Measurement Set

Load FITS-IDI files

Features
MPI support

completely modular

easy to add new functionalities

full control over sensible input

easy to re-run with a different strategy or using souce models

for multiple arrays (EHT,GMVA, VLBA,EVN,...)

Automatic flagging heuristics based on autocorrelations
(frequency space: identify outliers from median derivative across channels → e.g., RFI
time space: identify outliers from median amplitude per scan → e.g., late on source)

Correct field rotation angle, scalar bandpass (coming soon), a-priori calibration, correct for digital sampling (ACCOR)

Manual phase calibration
(instrumental phase and delay per spectral window using a bright calibrator)

Global fringe-fit: Find best solution parameters (e.g., vary over solint)
(Cotton-Schwab)

Complex bandpass

Polarization calibration (RL delay and phase offsets, D-terms)

Calibrated dataset

Diagnostics
print input parameters

plots of calibration solution tables

metedata overview

flag tables

summary file of observation

plots of calibrated visibilities

M. Janssen (Radboud Univ)

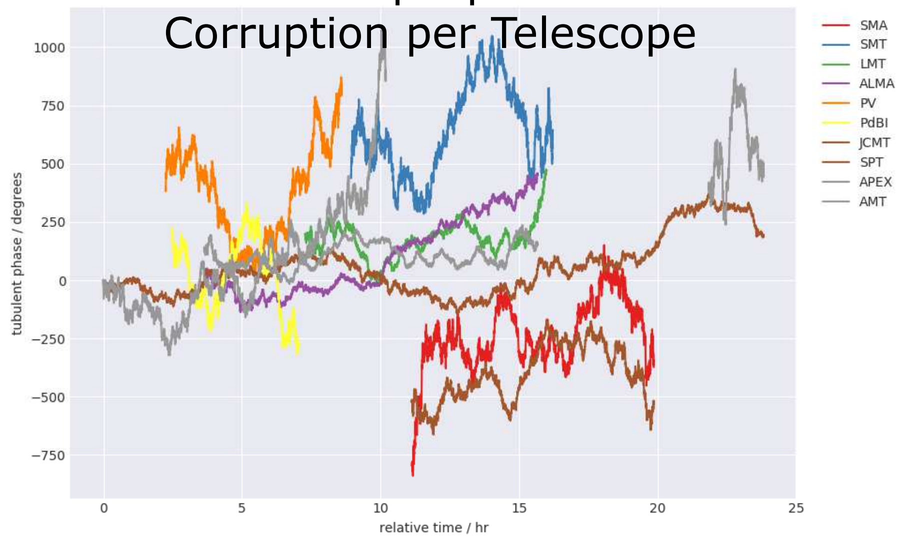
MeqSilhouette + CASA Pipeline

Radboud University Nijmegen

- New synthetic VLBI data generator based on MeqTrees (**R. Deane, I. Natarajan, T. Blecher**)
- Utilizes *atm* software to corrupt visibilities with atmospheric effects:
  - Turbulence
  - Attenuation
  - sky noise

  based on station weather
  - temperature
  - ground pressure
  - Water Vapor
  - coherence time)
- antenna pointing errors and bandpass effects
- full Stokes soon

Modelled Tropospheric Phase Corruption per Telescope

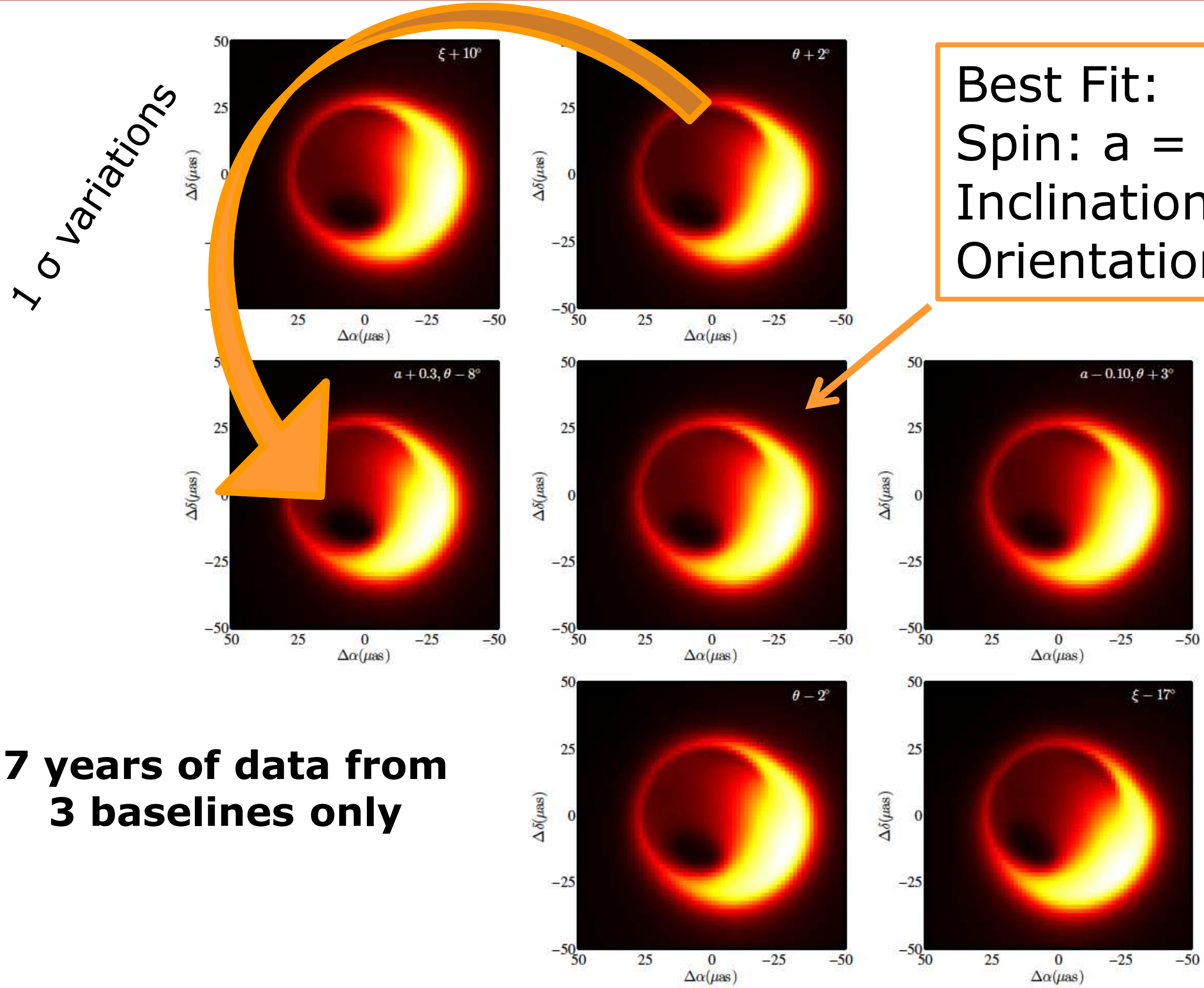


Current development

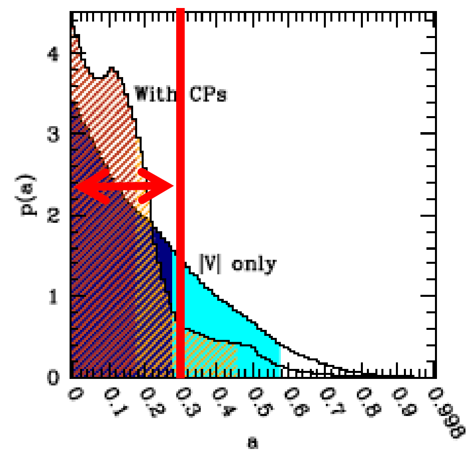
- MeqSilhouette + CASA Pipeline + Metadata from VLBI Monitor (**F. Roelofs**)
- Compare synthetic data to actual EHT data ⇒ quantify black hole parameter uncertainties

Fitting optimal shadow model to get BH parameters

Radboud University Nijmegen



Best Fit:
Spin: $a = 0.10_{-0.1}^{+0.3}$
Inclination $\theta = 60^o \pm 3^o$
Orientation: $\xi = 156^o \pm 15^o$



Spin

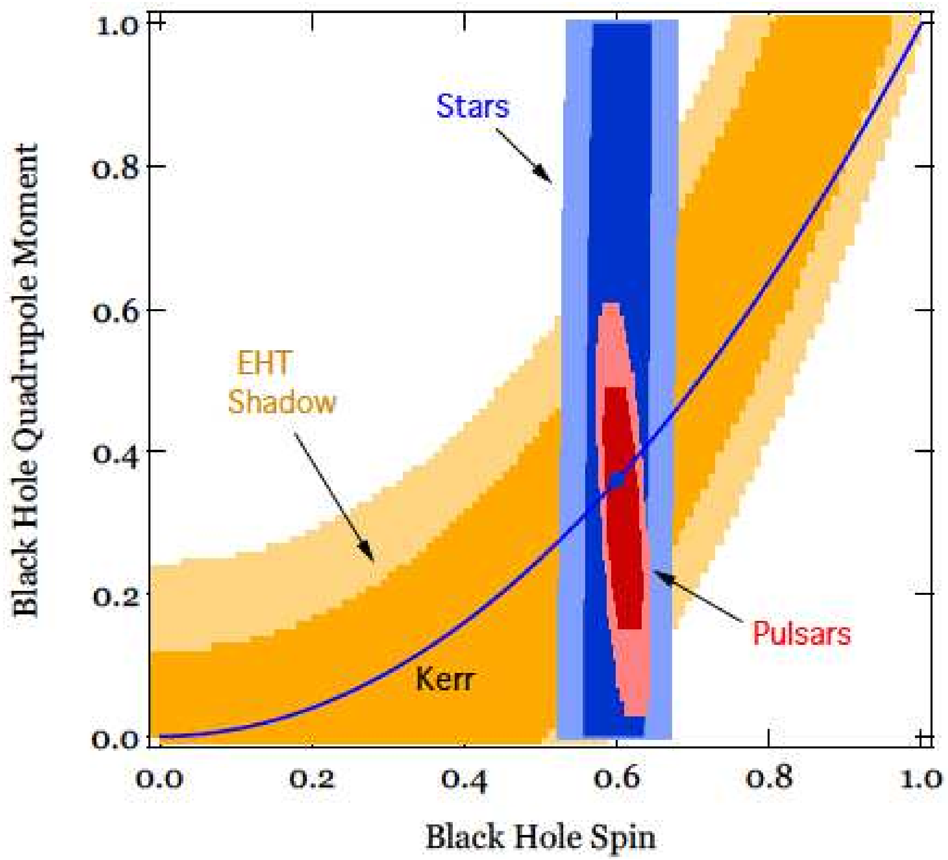
7 years of data from 3 baselines only

Broderick et al. (2016)

Multimessengers: Stars, Pulsars, EHT

Radboud University Nijmegen

- Shadow alone may not be enough
- Black-hole spin and quadrupole moment are ambiguous
- Add orthogonal constraint from orbits of stars and pulsars
- May allow tests of GR in strongly curved static space time.



Psaltis, Wex, Kramer (2016)

EHT and LIGO

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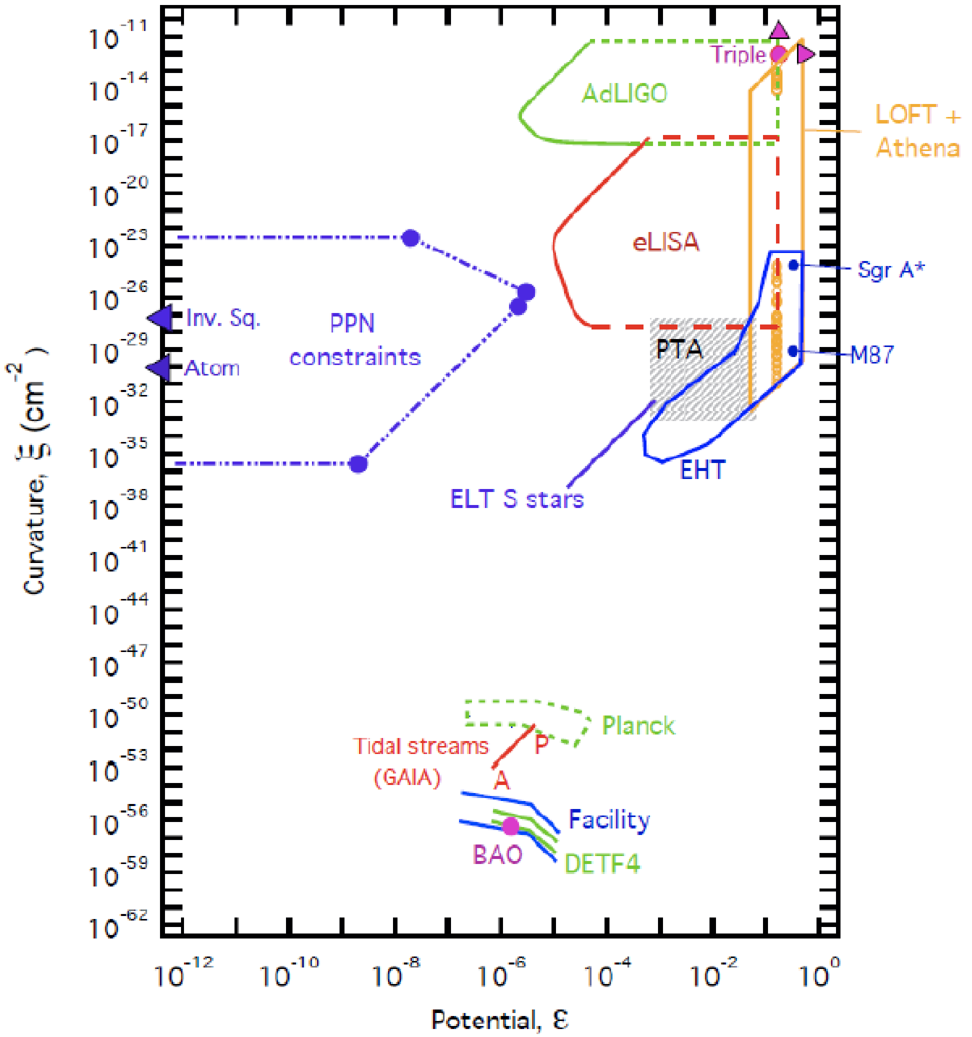


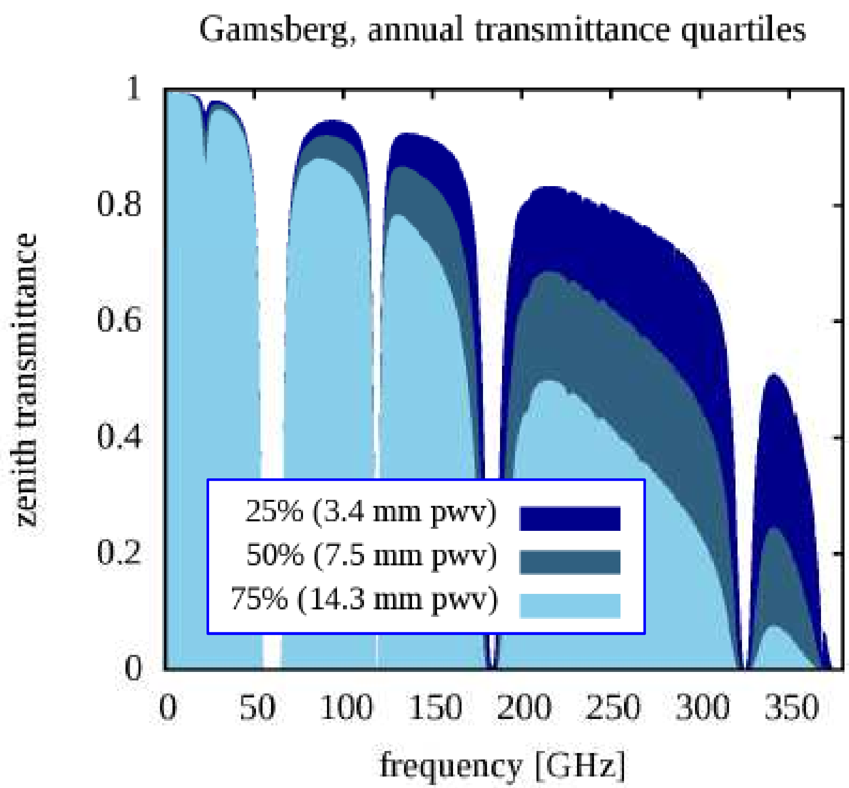
Baker, Psaltis, Skordis (2015)

Gamsberg – 2347 m

Gamsberg – Weather

Radboud University Nijmegen

1mm VLBI weather ~ 50% of the year



F. Roeolfs based on model from S. Paine (SAO)

- ESO site survey:
  - Benign weather
  - Water vapor comparable to Paranal in dry season.
  - Temp: 0-25°
  - Wind: 5.6m/s avg (no major storms)
  - Hardly any snow or icing
  - Wet season: Jan-March

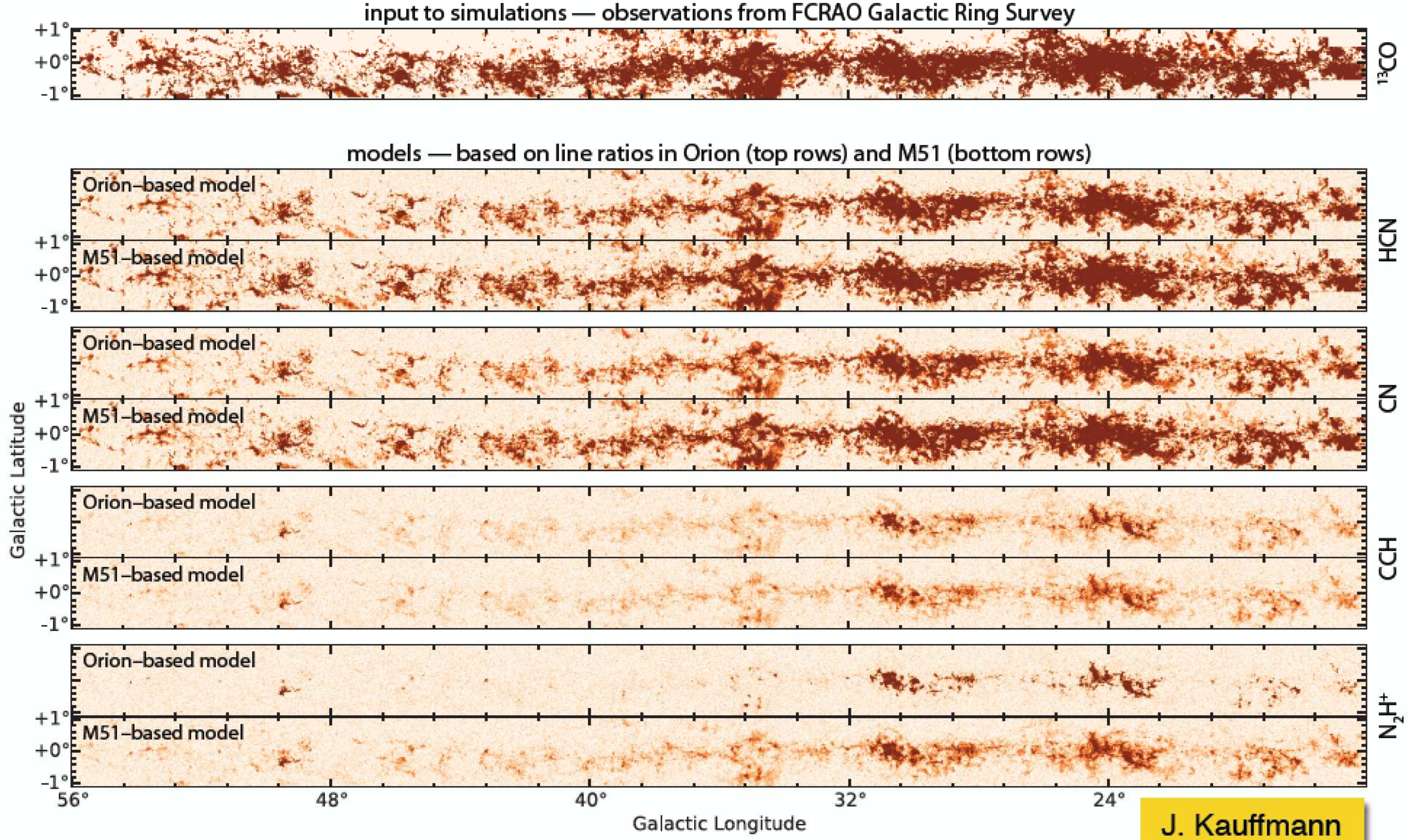
Sarazin (1994)


Dorob
National Park
Karibib
B1
Namibia
Henties Bay
Witvlei
B6
Windhuk
Swakopmund
Walfischbucht
Namib-Naukluft
National Park
H.E.S.S.
116 km
Rehoboth
GAMSBERG
Namibgrens
Gobabeb
Solitaire
Hoachanas
B1
Bullsport
Stampriet
Sesriem
Mariental

SEST 15m at La Silla in Chile

Radboud University Nijmegen

Feasibility: Imaging the Milky Way



J. Kauffmann

models suggest bright lines throughout Milky Way

could, e.g., map fraction of dense gas along spiral arm, shocks, feedback, etc.

time estimate:

could do $|\ell| < 60$ deg, $|b| < 1$ deg to reasonable depth in 3,000 h

“Infrastructure”

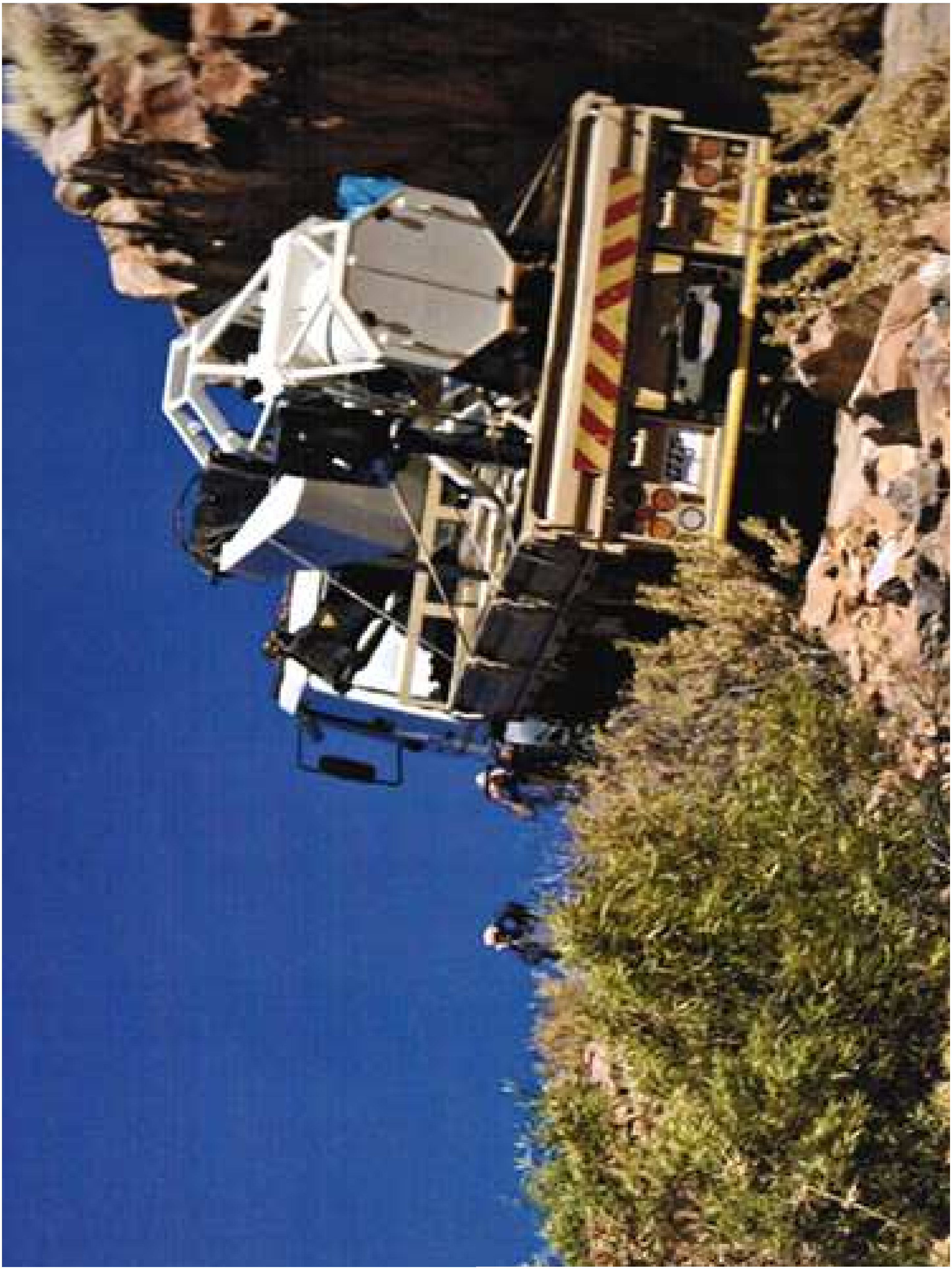
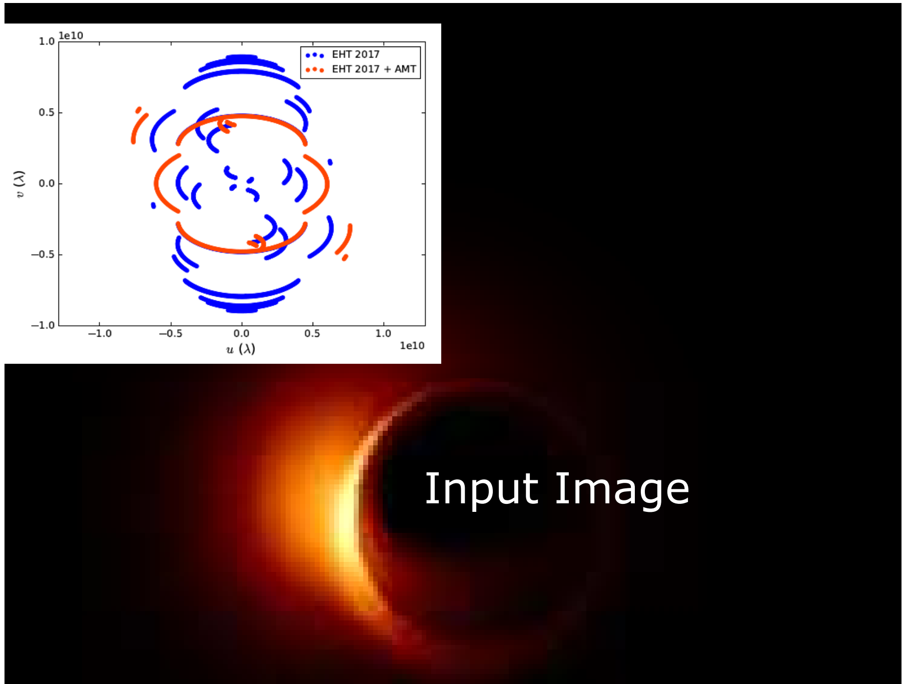
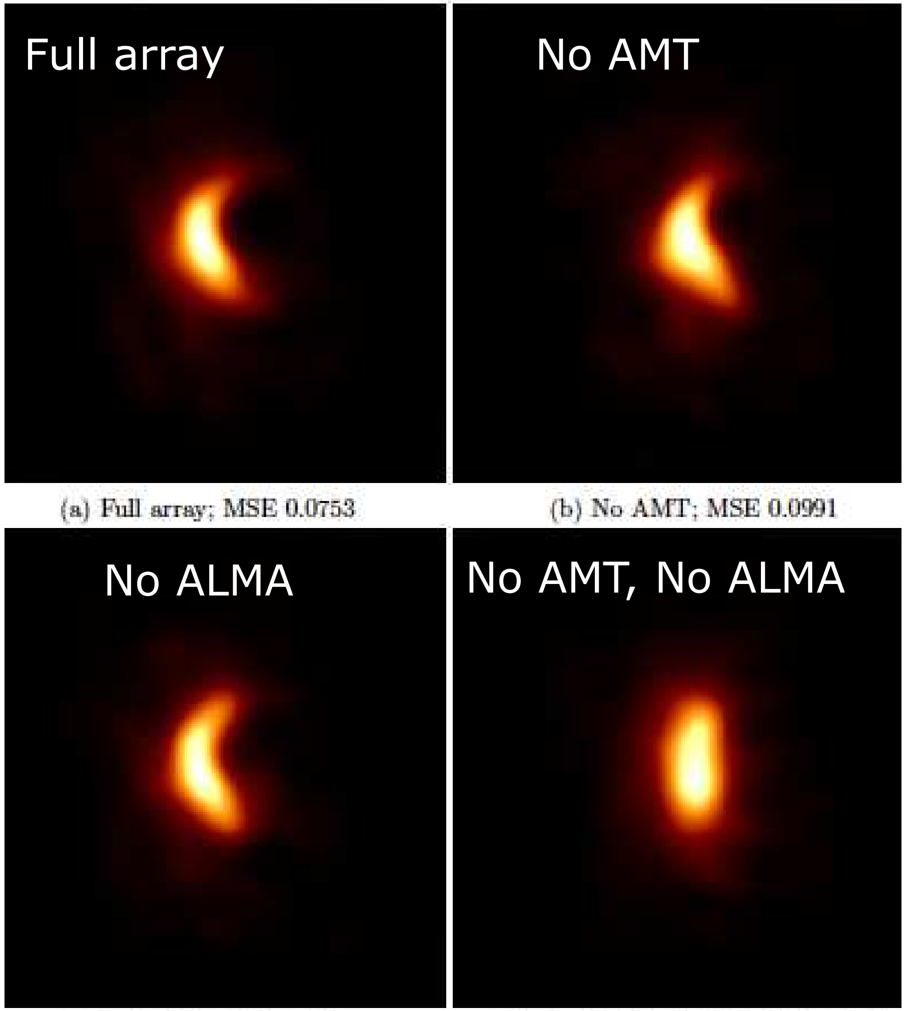


Image reconstruction

Radboud University Nijmegen



- Includes source variability
- Multiple days of observing
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering



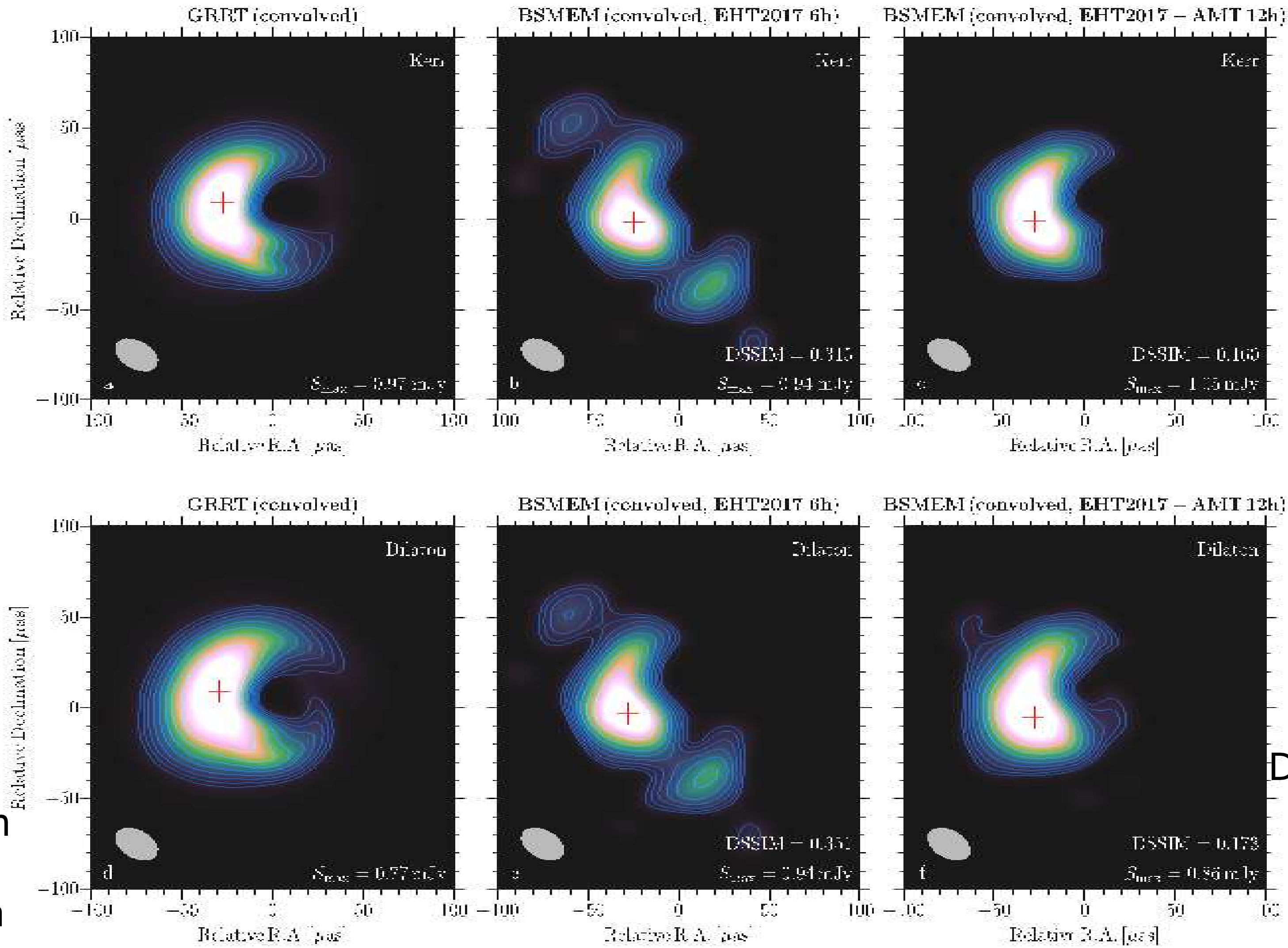
(a) Full array; MSE 0.0753
(b) No AMT; MSE 0.0991
(c) No ALMA; MSE 0.0887
(d) No ALMA, AMT; MSE 0.1130

Freek Roelofs (based on Lu, Roelofs et al. 2015, ApJ)

Non-standard BHs

Radboud University Nijmegen

GRMHD+Scattering EHT 2017 EHT 2018+AMT



Kerr BH

Dilaton BH

C. Fromm
Y. Mizuno
L. Rezolla
(BHAC)

Mizuno et al. (2018, Nature Astronomy)

Wide Field Mapping of Molecular Lines in the Milky Way

Jens Kauffmann

jens.kauffmann@mit.edu — Haystack Observatory, MIT

slide summary:

- emission lines essential to probe star formation throughout cosmos
- lines are observed to vary on scales $\geq$100 pc in galaxies
- straightforward and compelling to map large nearby clouds
- technically feasible and compelling to map Milky Way in many lines

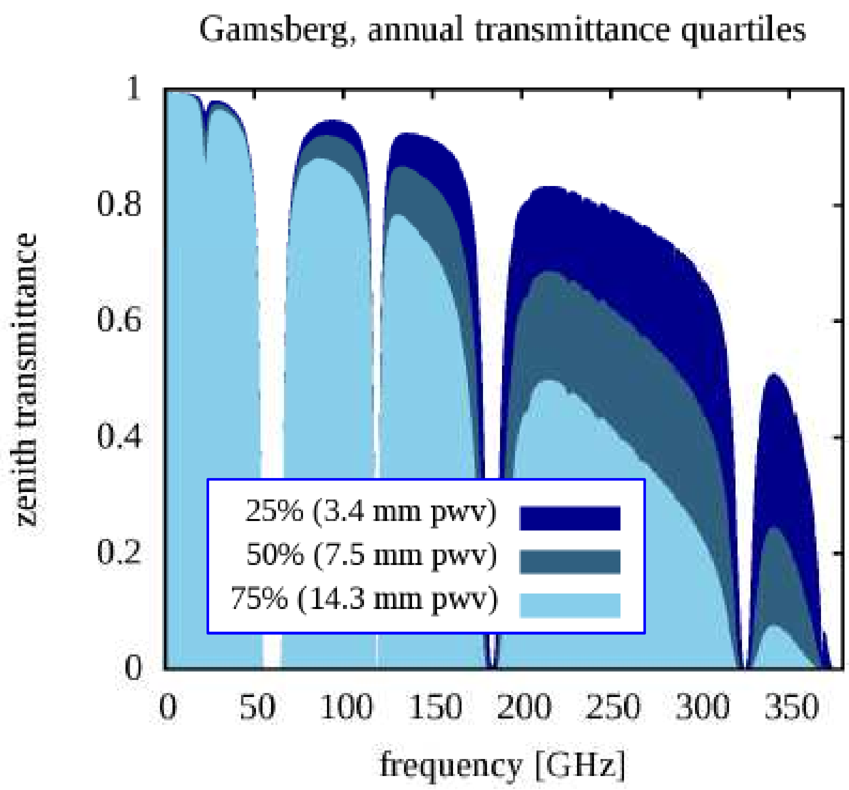
general science themes:

- Witnessing the Assembly of the Milky Way
  (baryons falling into Milky Way making stars)
- Uncovering the Structure of the Galaxy
  (where does gas pile up, and under what conditions?)
- Revealing the Life Cycle of Molecular Clouds
  (what controls the SF activity in clouds throughout the cosmos?)

Gamsberg – Weather

African mm-Wave Telescope

1mm VLBI weather ~ 50% of the year



F. Roeolfs based on model from S. Paine

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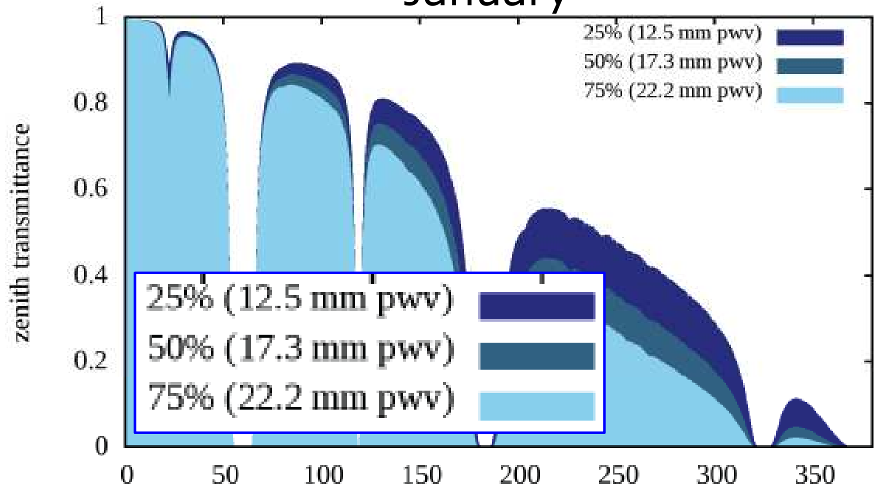
  - Benign weather
  - Water vapor comparable to Paranal in dry season.
  - Temp: 0-25°
  - Wind: 5.6m/s avg (no major storms)
  - Hardly any snow or icing
  - Wet season: Jan-March

Sarazin (1994)

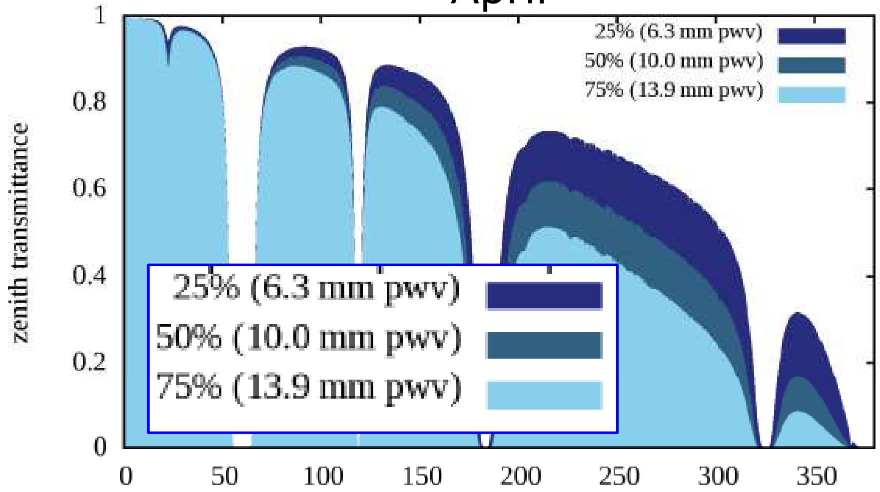
Gamsberg – Annual Variation

African mm-Wave Telescope

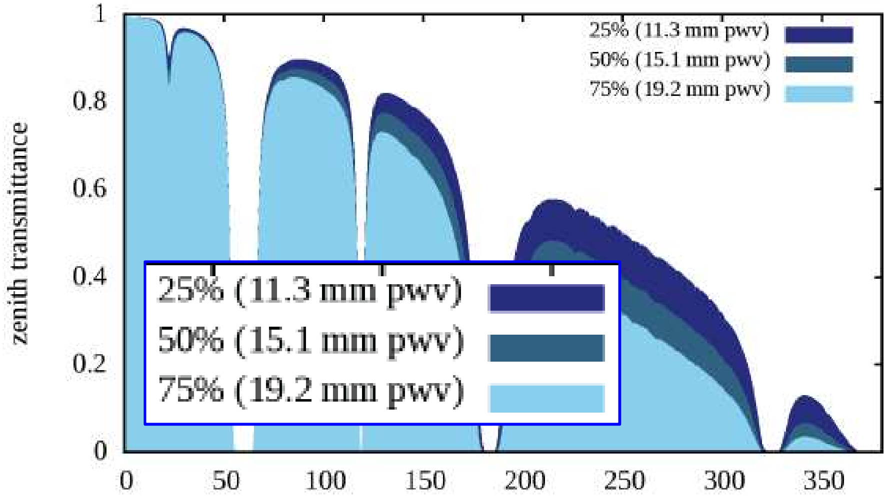
January



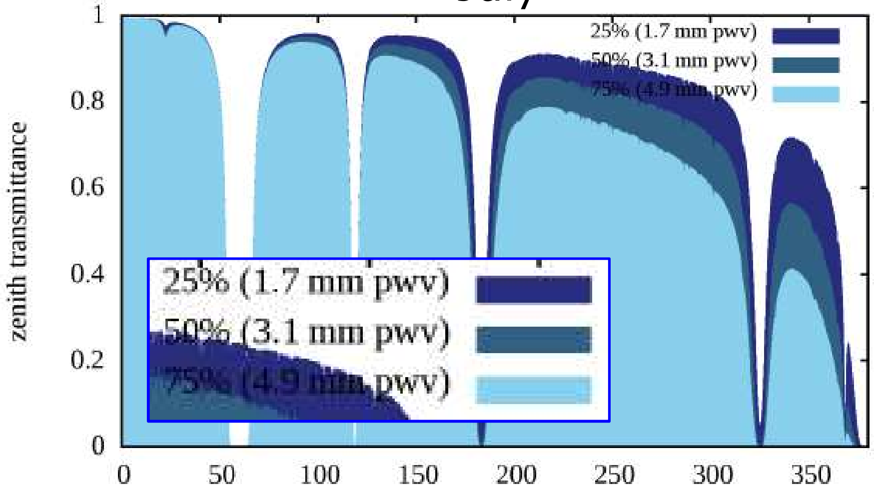
April



March

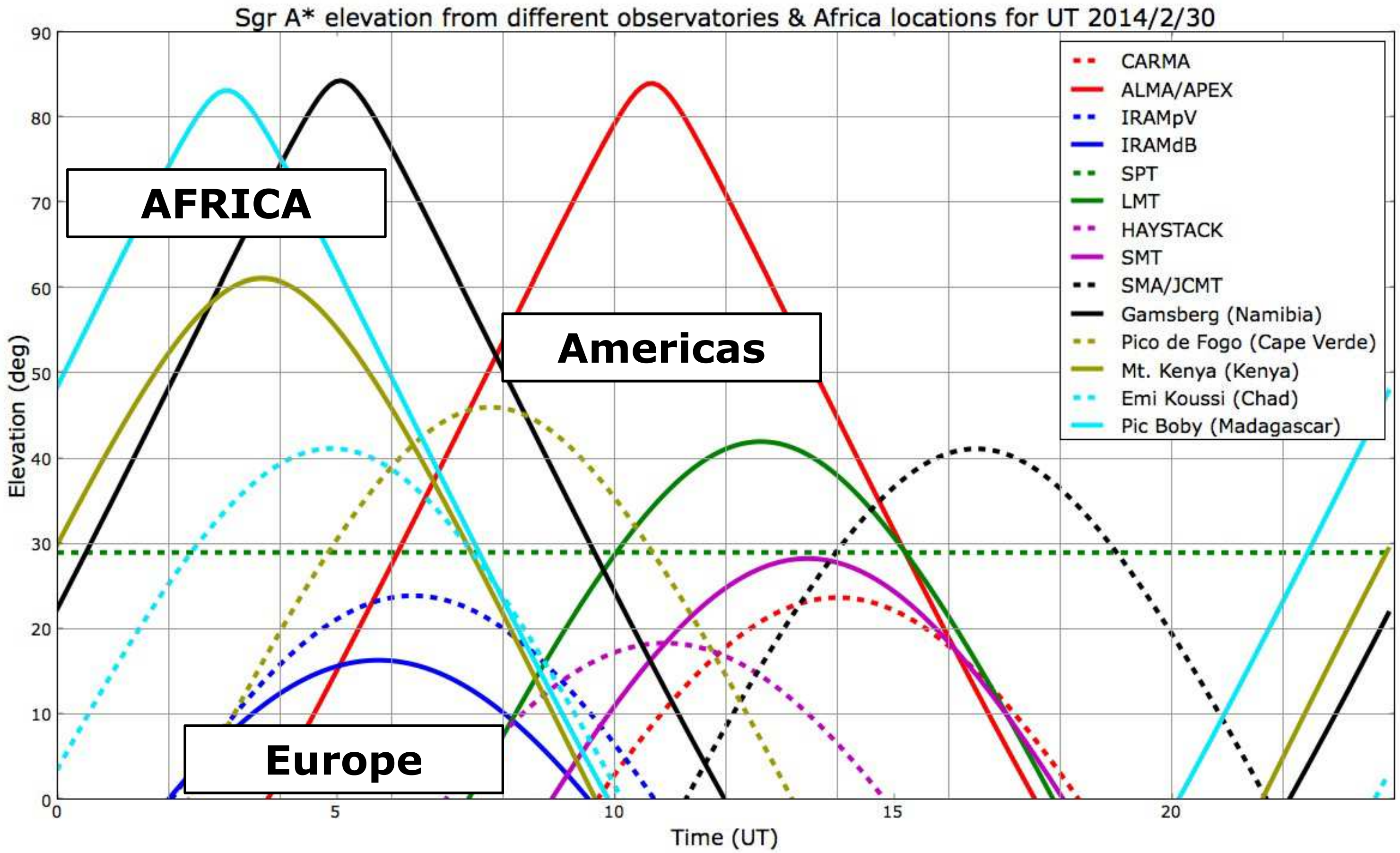


July



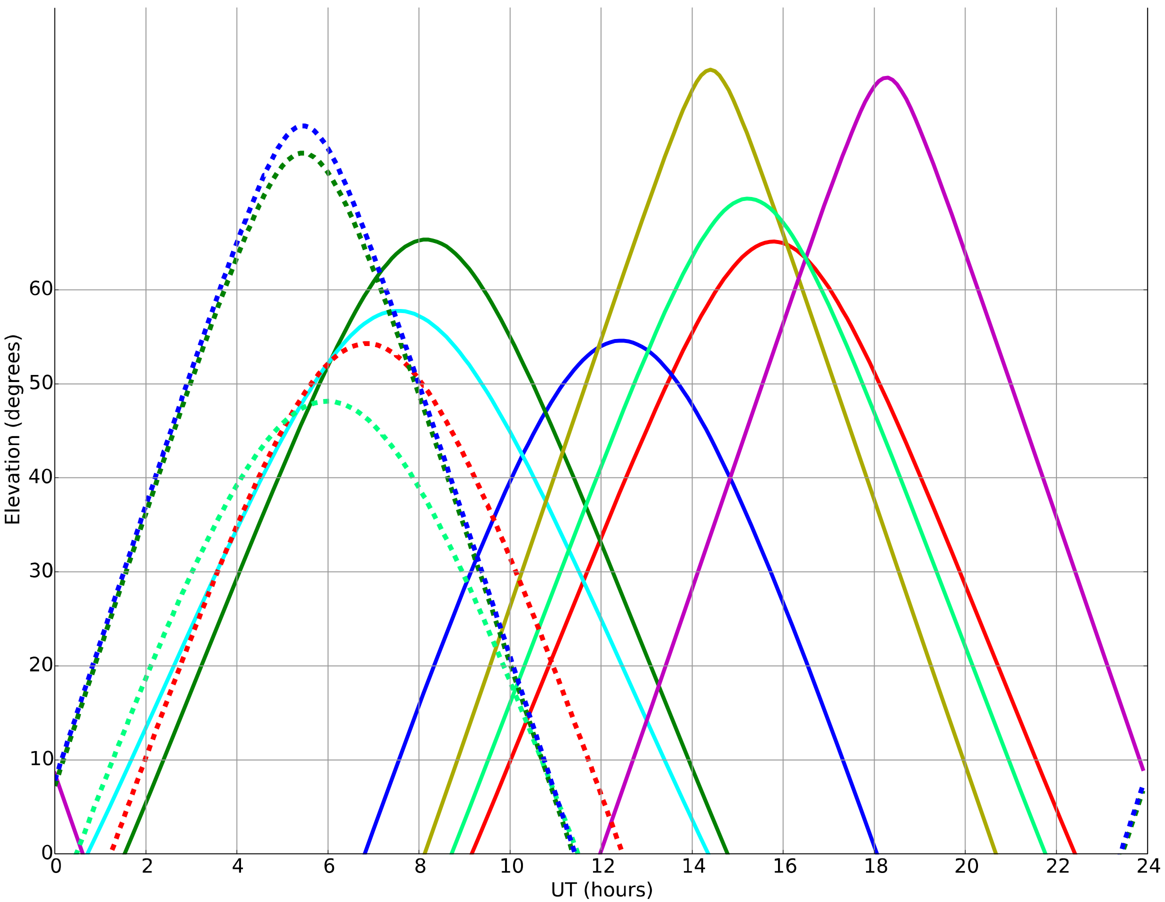
F. Roeolfs based on model from S. Paine

*Visibility for African sites: Sgr A**



M87 visibility for African sites

African mm-Wave Telescope



Gamsberg in-situ measurement

African mm-Wave Telescope

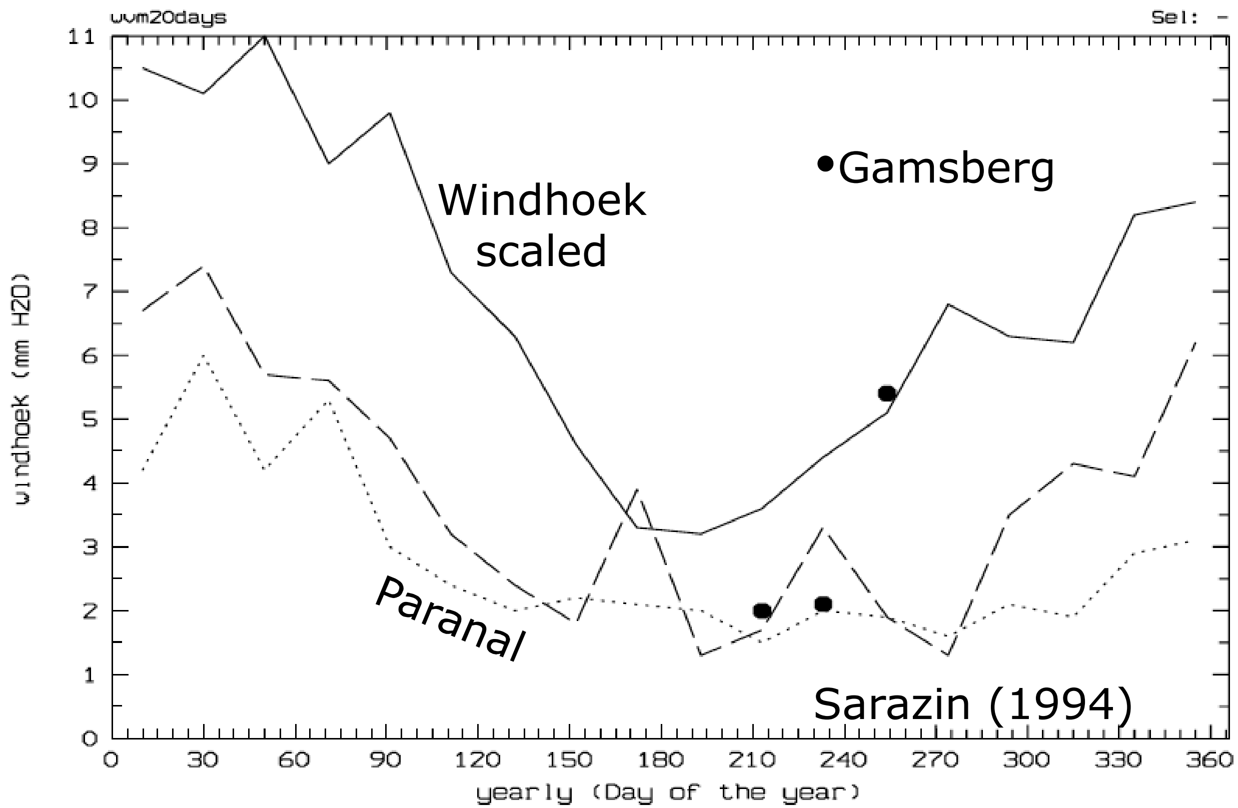


Figure 1: Seasonal variation of precipitable H_2O computed on the basis of 20 days median from 1985-1993 Windhoek radiosonde night flights (full line) from the altitude of Gamsberg compared to 1983-1989 in situ Paranal (dotted line) and La Silla (dashed line) nighttime statistics. The Gamsberg in situ measurements are overplotted as filled squares.