Imaging Black Holes

Heino Falcke

Radboud University, Nijmegen

ASTRON, Dwingeloo

Event Horizon Telescope Collaboration

IN·DEI·NOMINE·FELICITER

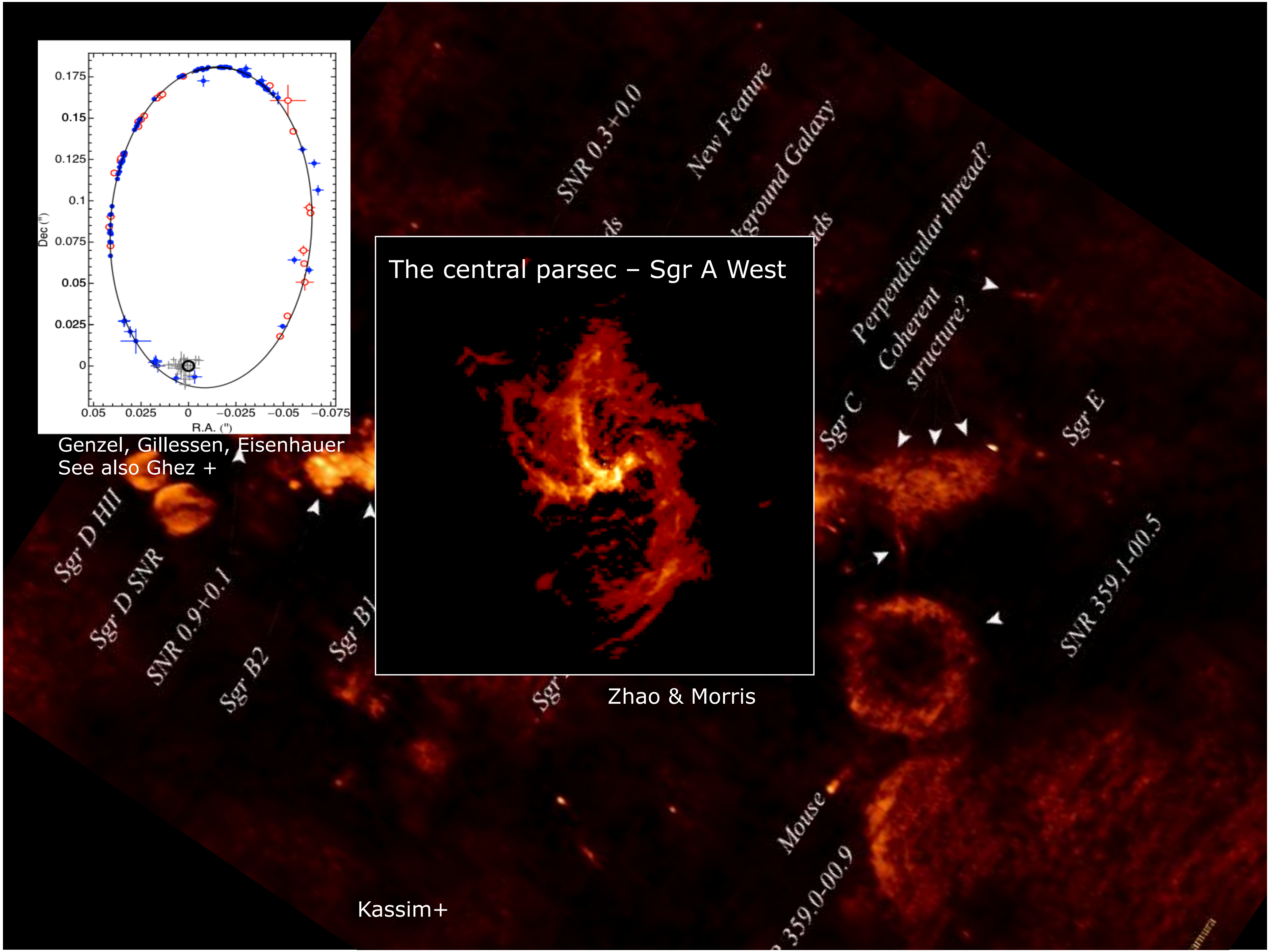
@hfalcke

RADBOUD RADIO LAB

erc European Research Council

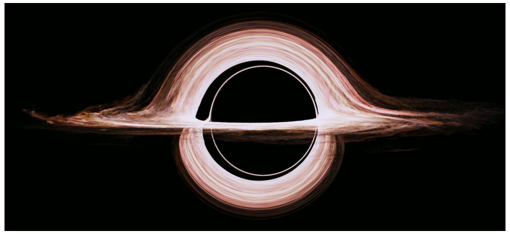
BLACK HOLE CAM

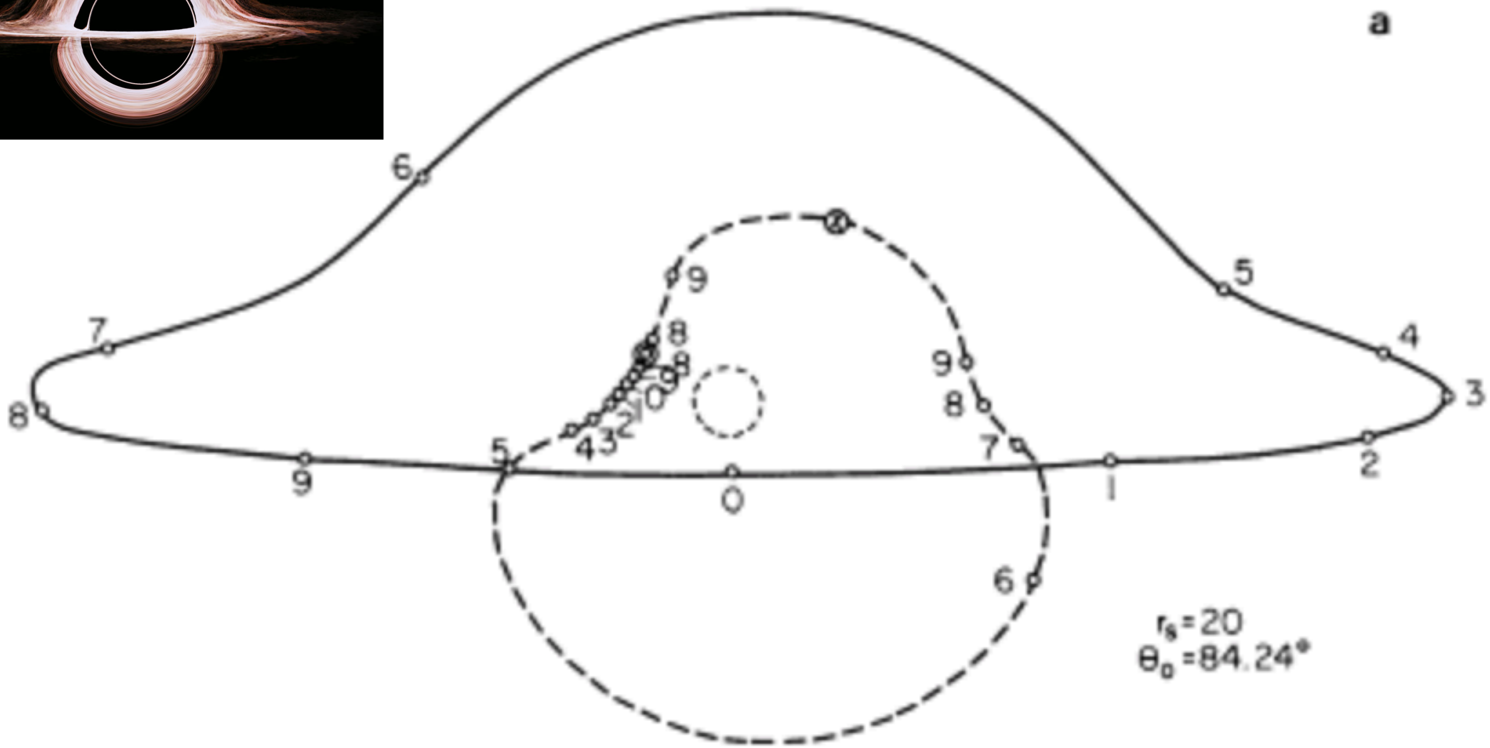
Co-PIs:
L. Rezzolla (U. Frankfurt)
M. Kramer (MPIfR Bonn)


The central parsec – Sgr A West
Zhao & Morris
Genzel, Gillessen, Eisenhauer
See also Ghez +
Kassim+
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
SNR 0.3+0.0
New Feature
Perpendicular thread?
Coherent structure?
Sgr C
Sgr E
SNR 359.1-00.5
Mouse
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2

How a black hole looks like

Radboud University Nijmegen



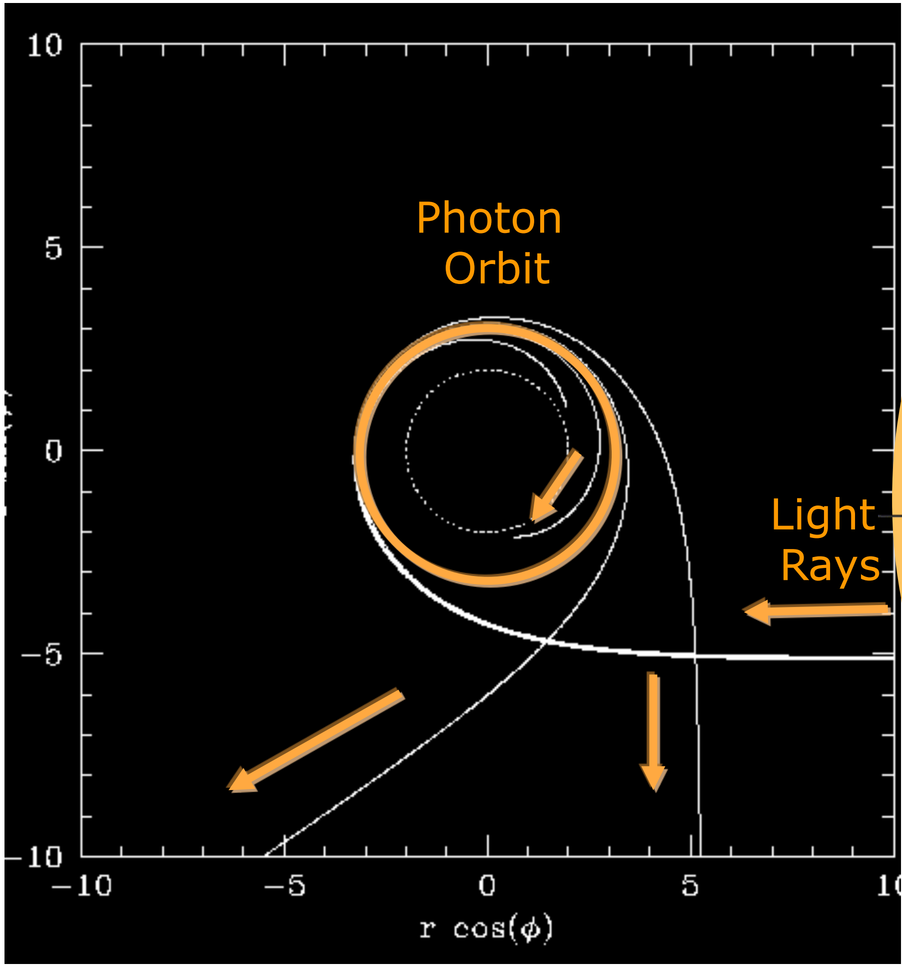


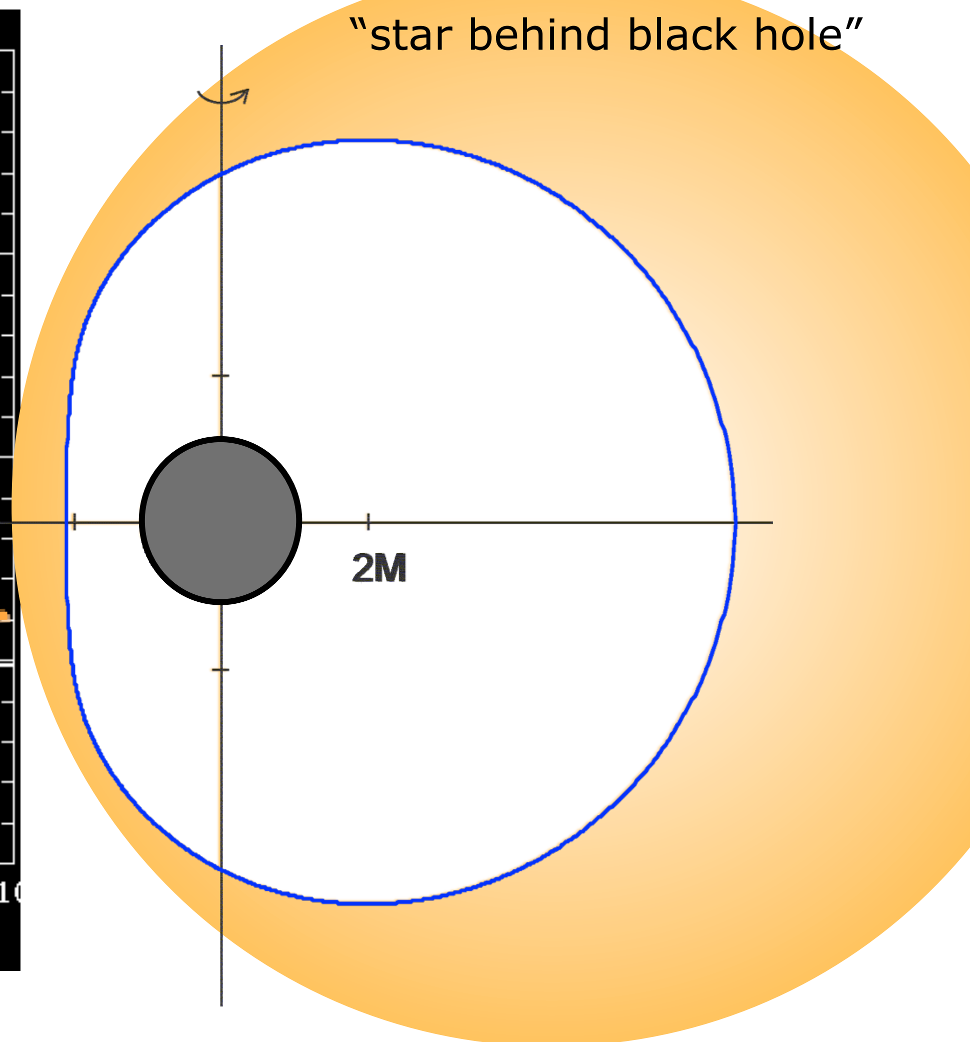
"Image of a star orbiting a black hole" Cunningham & Bardeen (1973)

"Photos" of a black hole

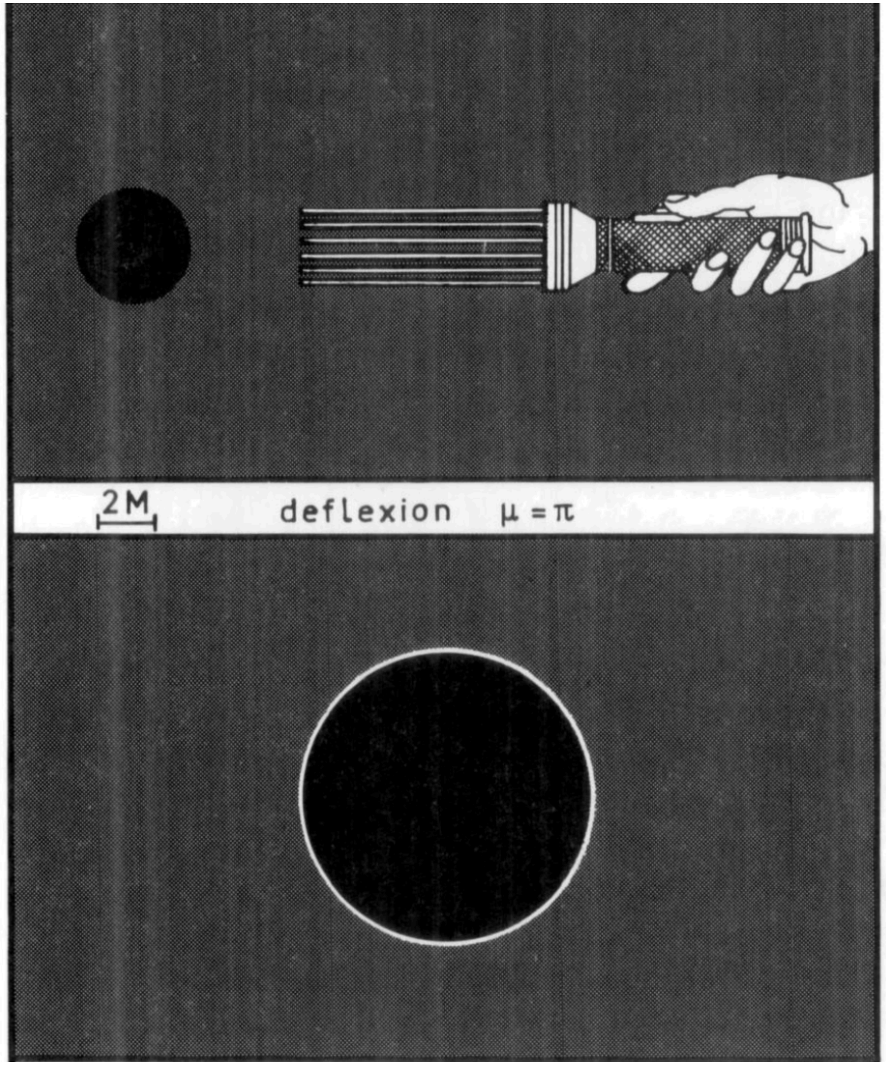
Radboud University Nijmegen

Circular photon orbit: Bardeen (1973)

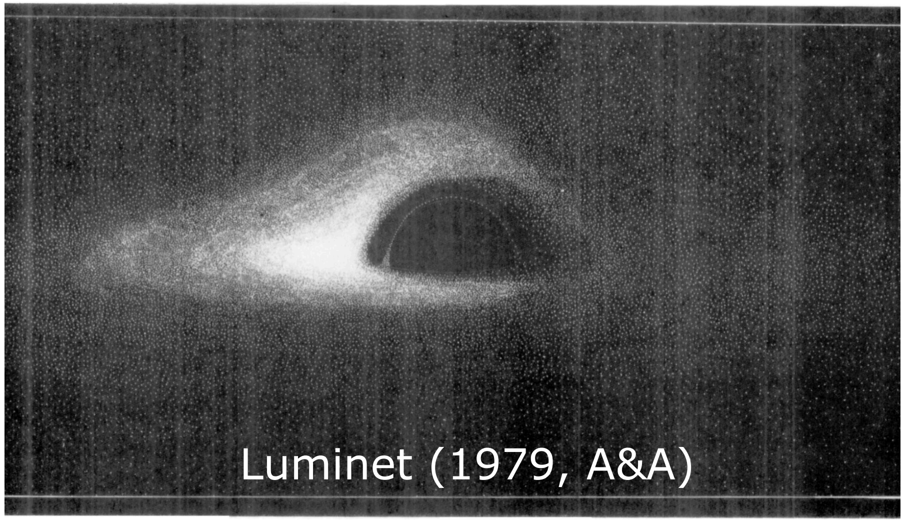




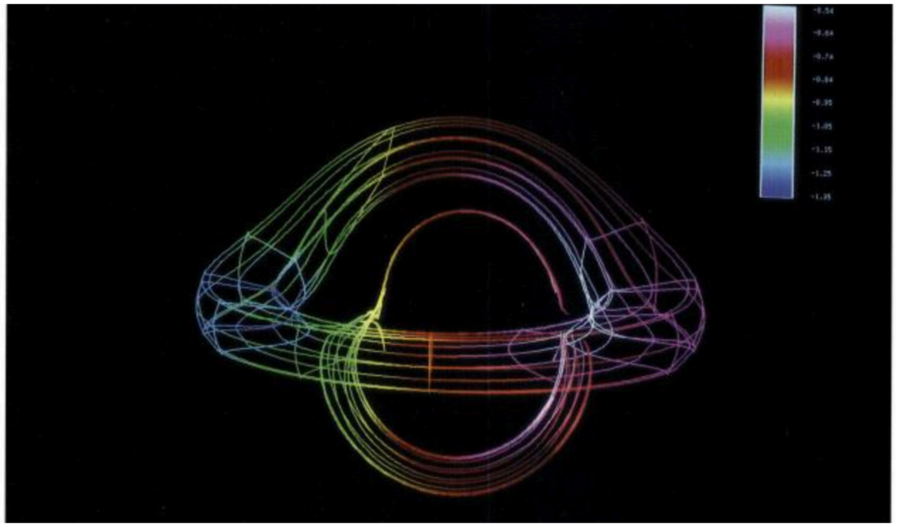
Photos of a black hole



Luminet (1979)



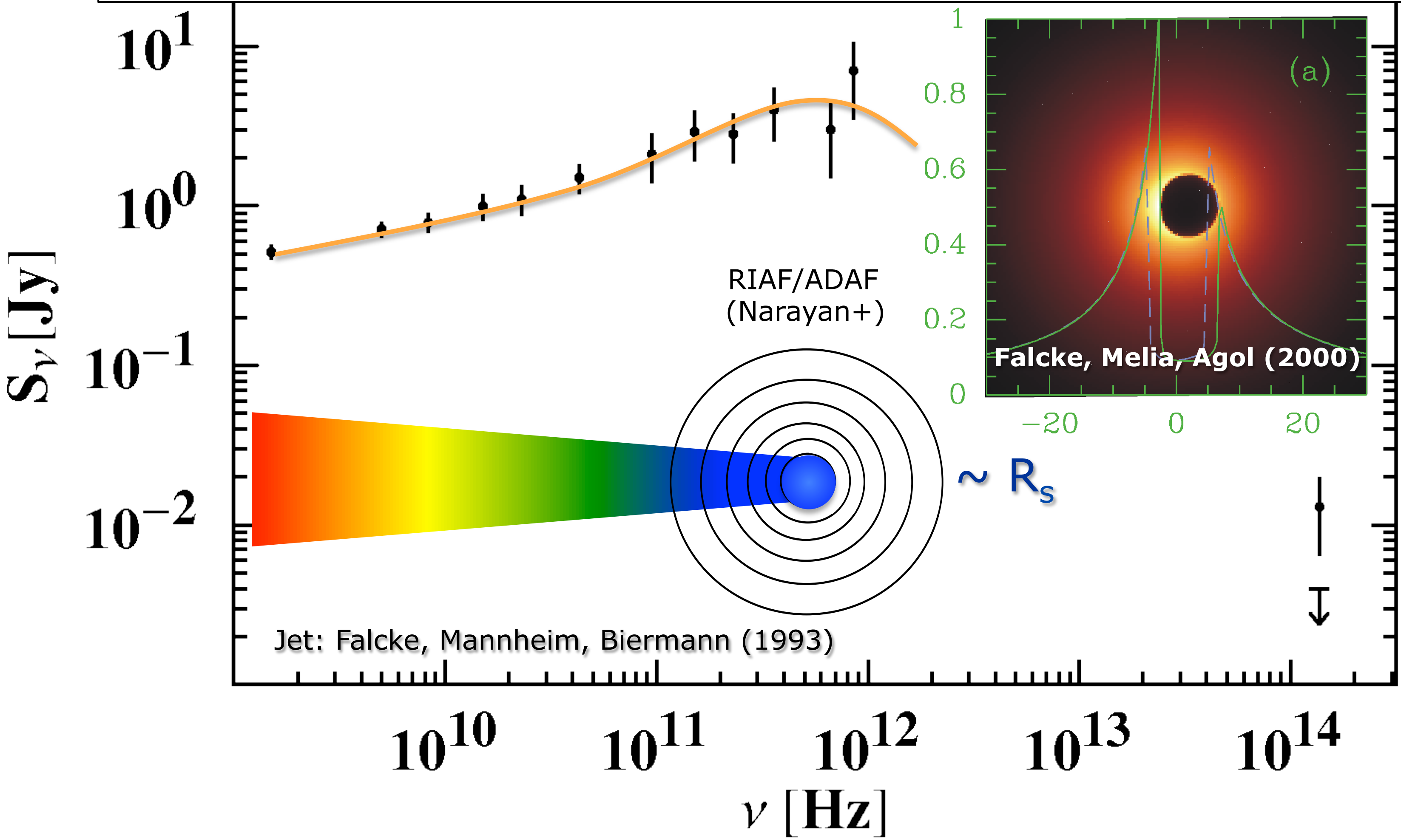
Luminet (1979, A&A)



Viergutz (1993, A&A)

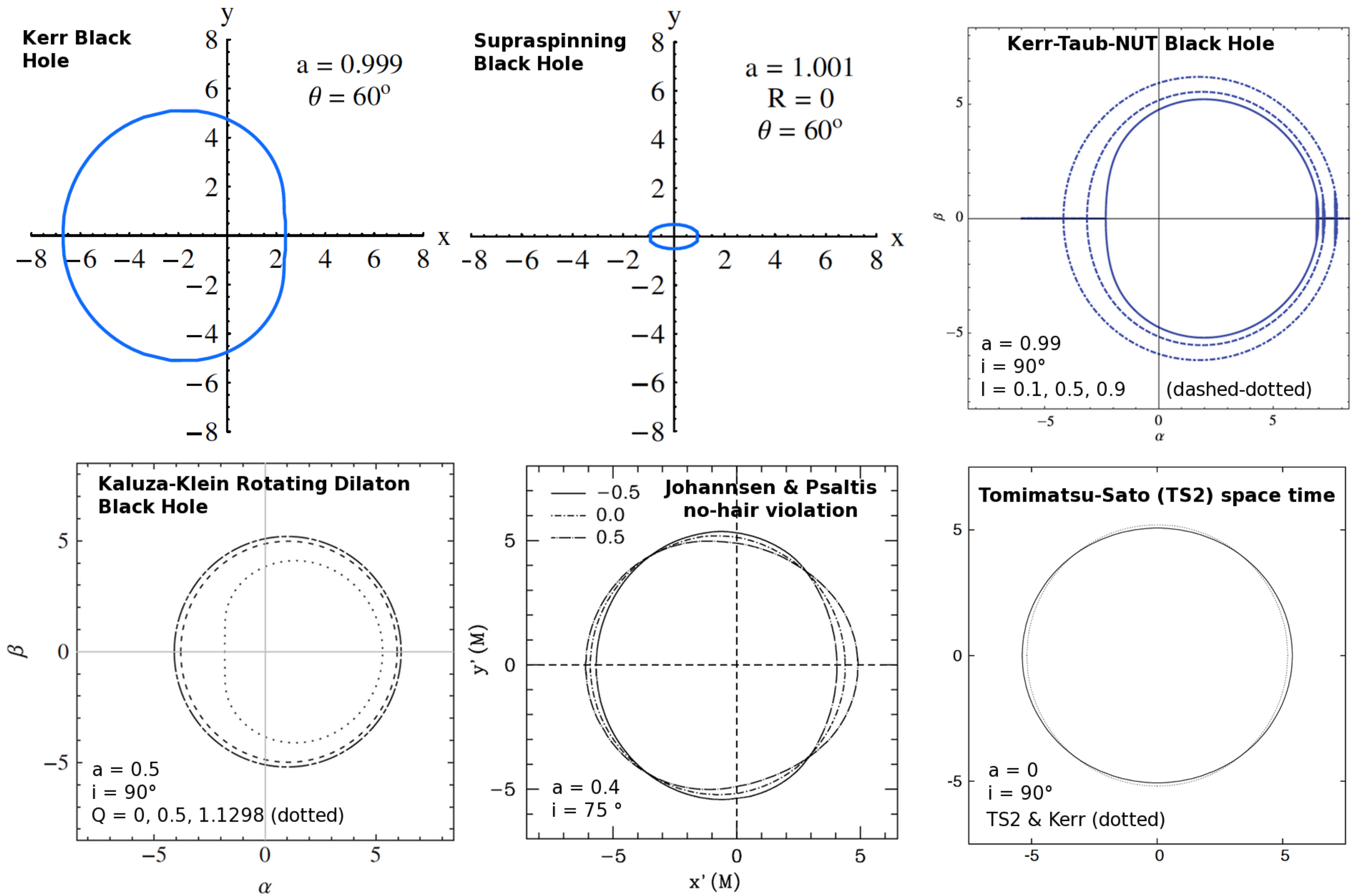
Sgr A: submm-bump & black hole shadow*

Predicted size of shadow today: ~50 µas +/- 10% for all spins, larger than ISM blurring and resolvable by global VLBI at 230 GHz!



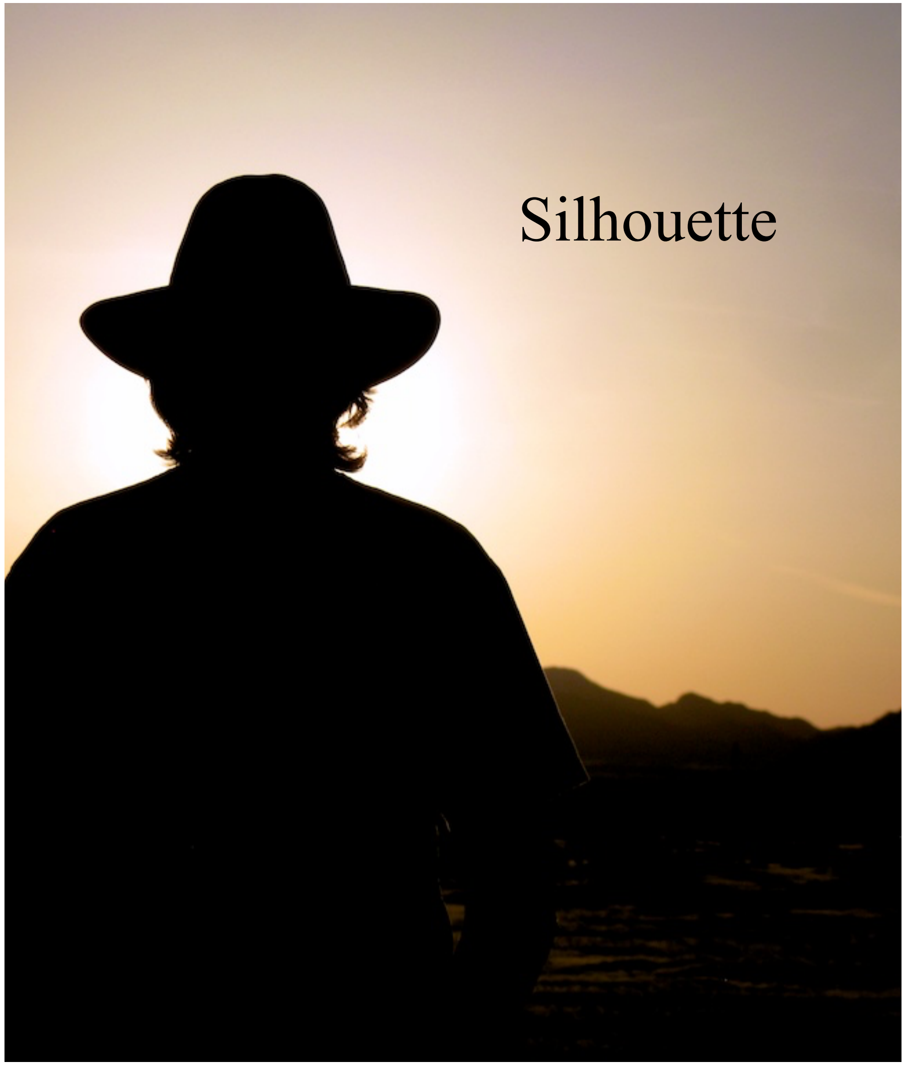
Different Theories of Gravity Different Shadows

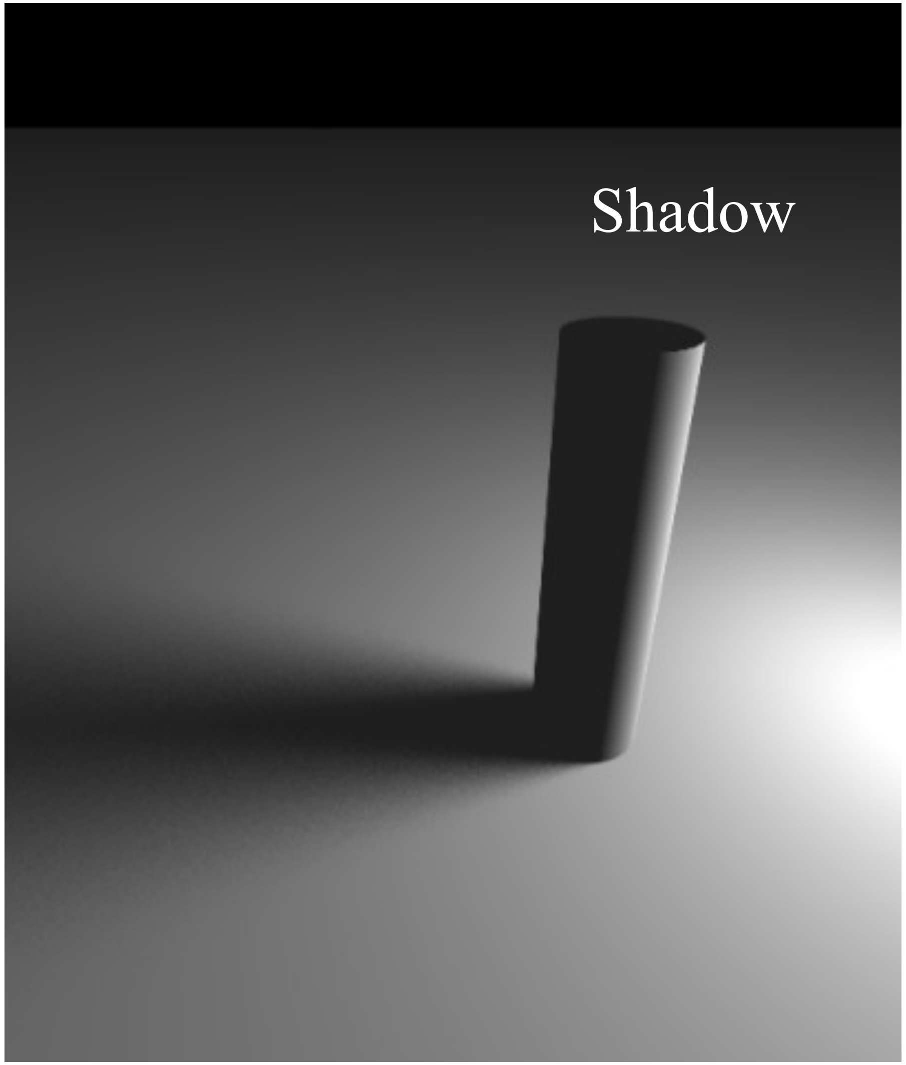
Radboud University Nijmegen



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

Silhouette vs Shadow

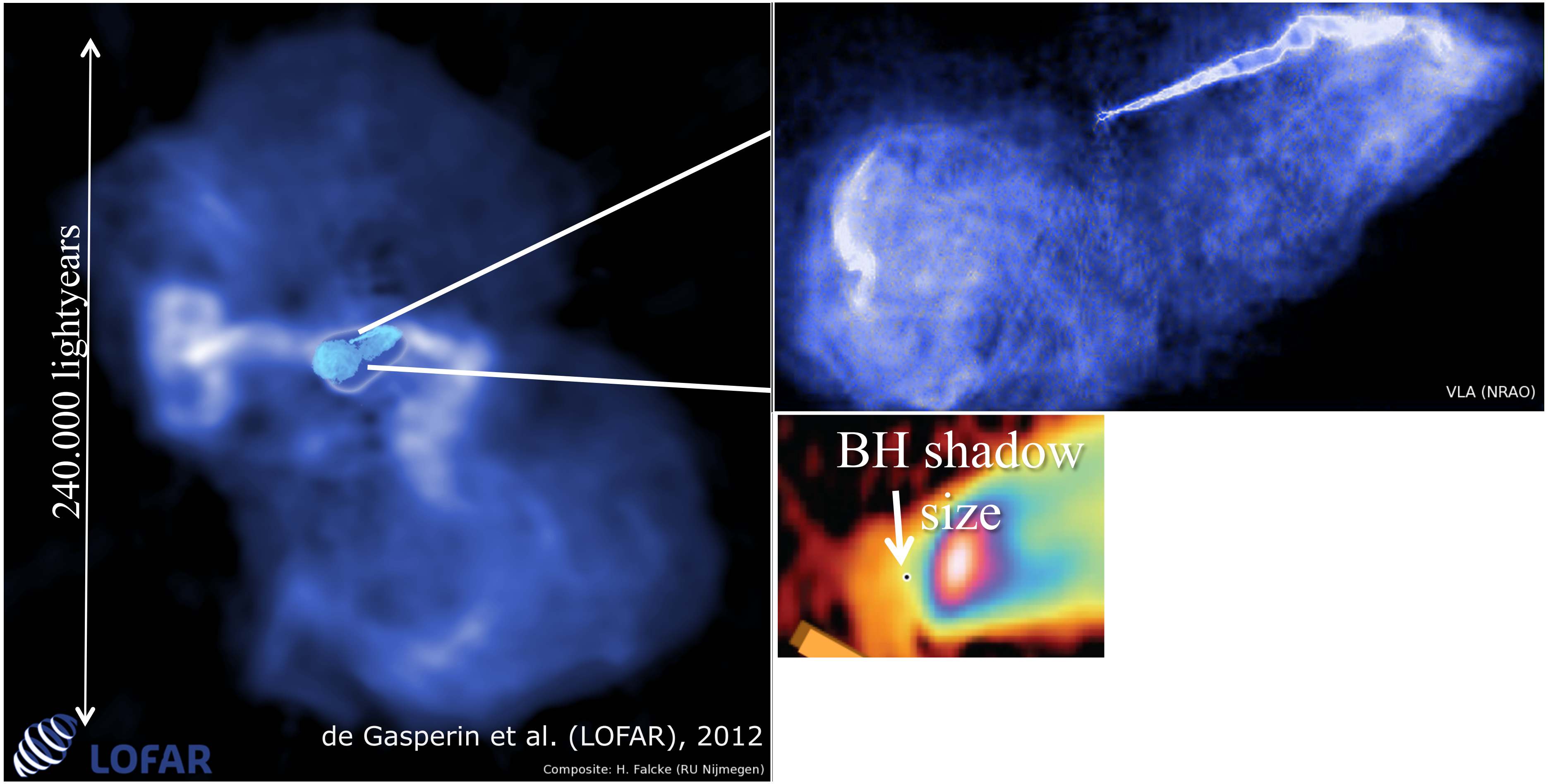




The radio jet in M87 (Virgo A)

Radboud University Nijmegen

Elliptical galaxy in center of Virgo cluster at d=17 Mpc, with $6\times10^{9}\ M_{\odot}$ black hole



General Relativistic Magnetohydrodynamic simulations with GR ray tracing

BHAC Code (AMRVAC heritage):
- ideal (soon non-ideal) MHD
- 2&3D
- Multiple coordinate systems
- Adaptive GRID
- Arbitrary space times

RAPTOR:
- Ray tracing, GPU-enabled
- Arbitrary space times
- Synchrotron abs/emission
- Thermal & non-thermal particles
- Polarization to come

IPOLE:
- Polarization
- Faraday rotation and conversion

KappaMonty:
- Inverse Compton

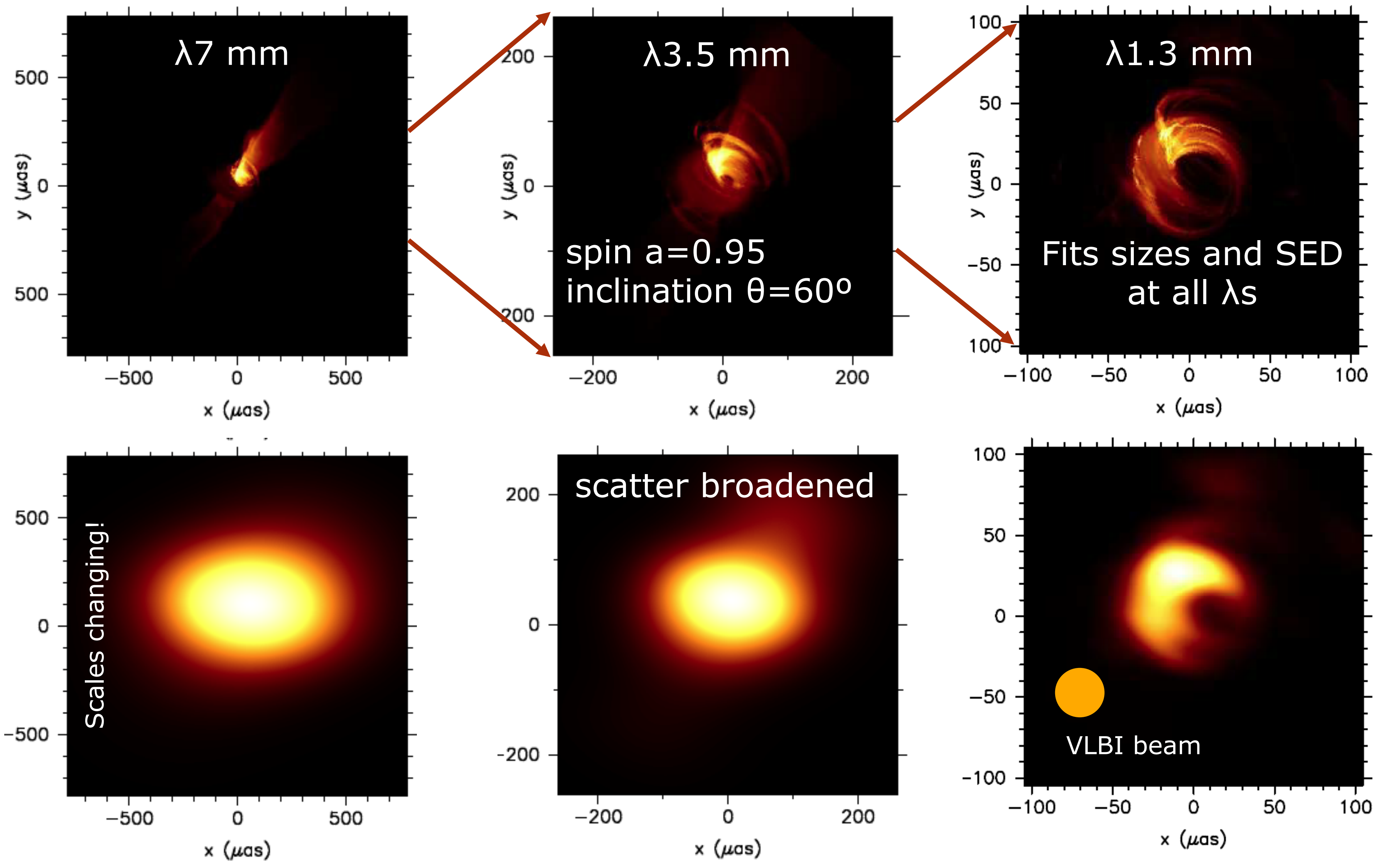
More codes in EHT: **code-comparison**

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

Jet Models with scattering

Radboud University Nijmegen

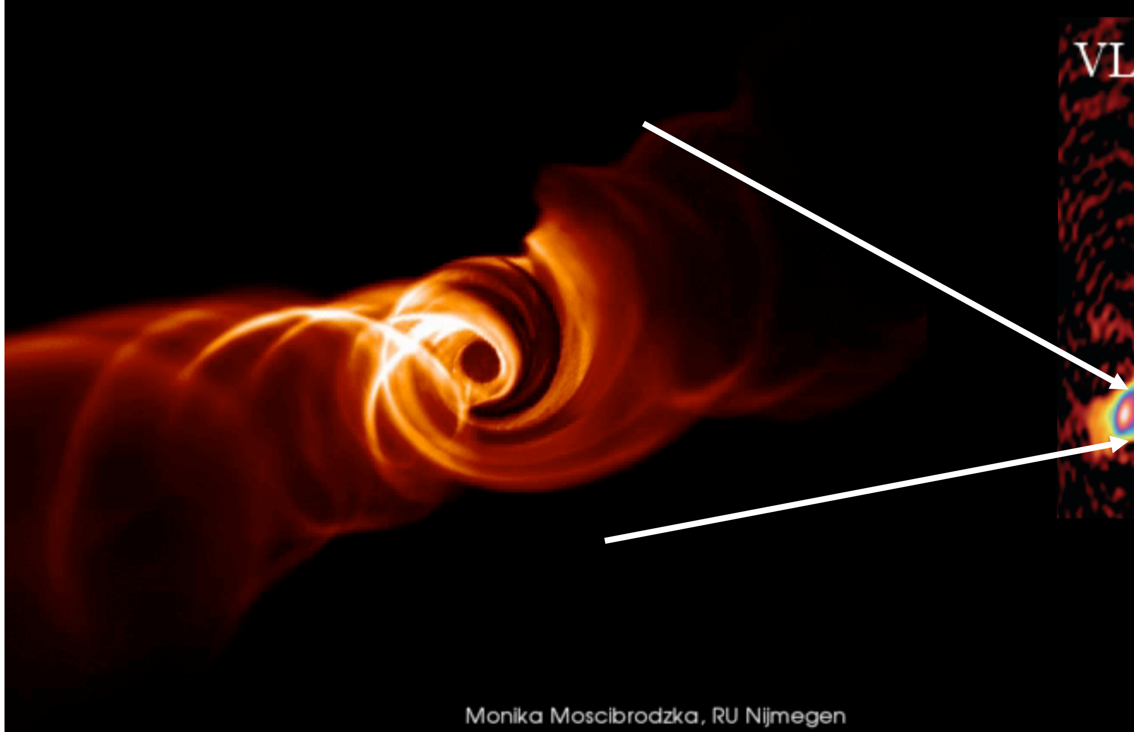
Moscibrodzka et al. (2014)

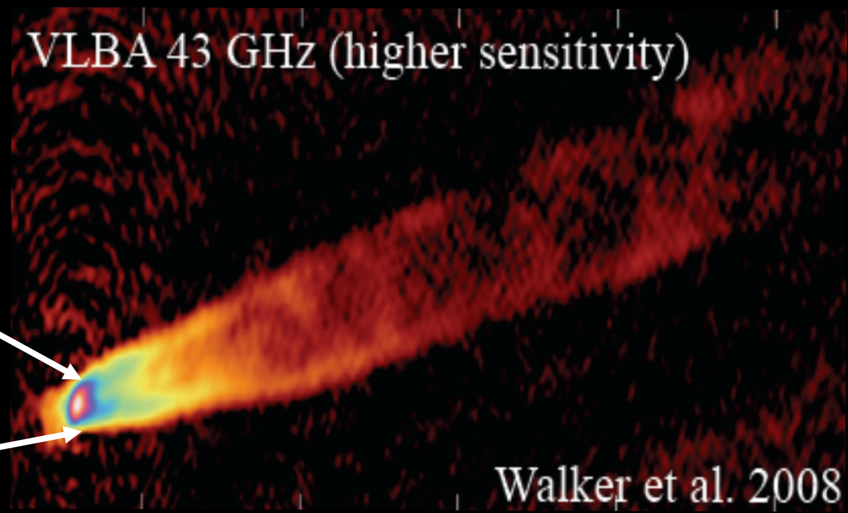


Black Hole Simluations of M87

GRMHD Simulation

VLBI Observations





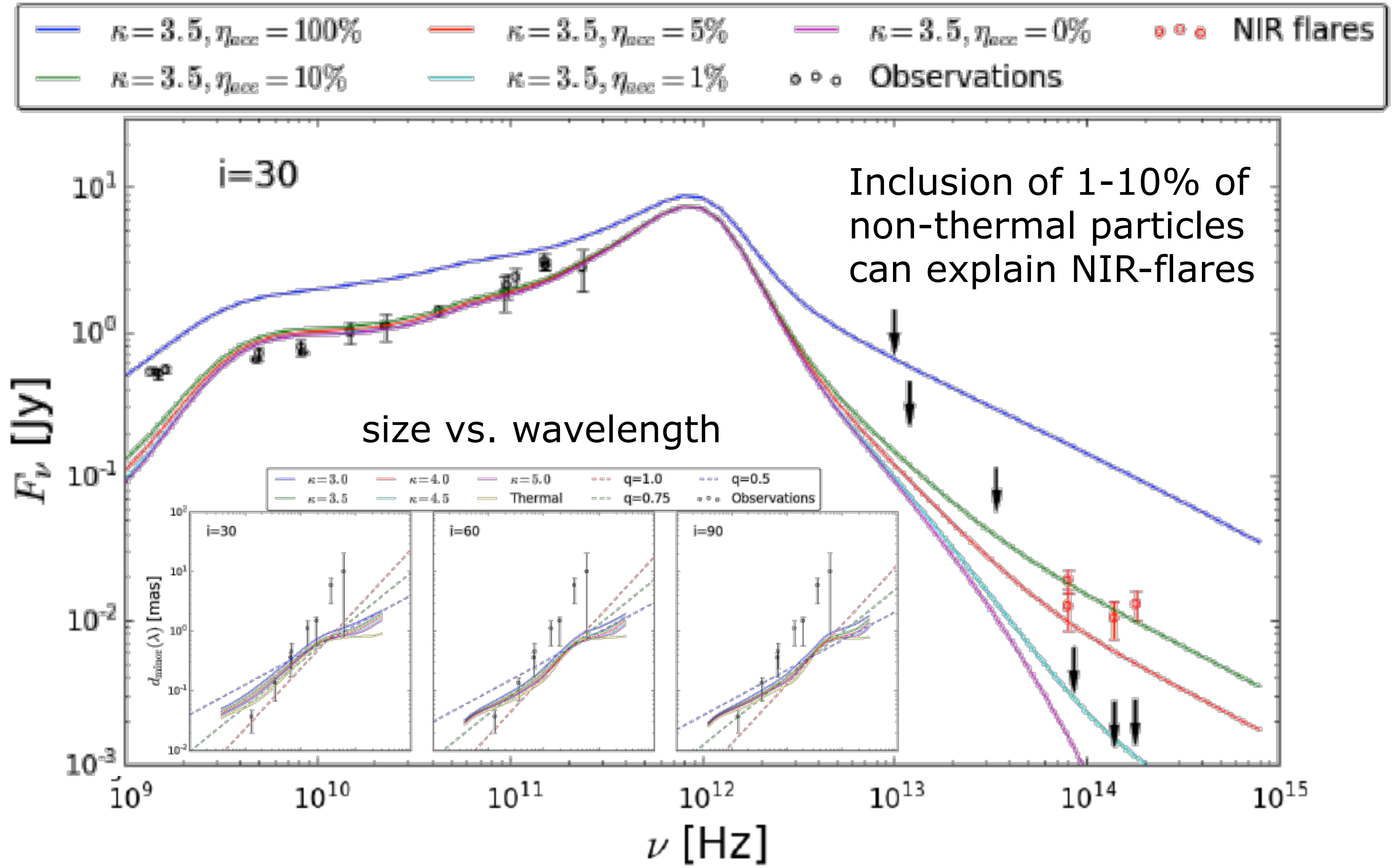
Moscibrodzka, Falcke, Shiokawa (2016, A&A)

(Using Harm3D - Gammie et al.)

Sgr A*: Jet-model SED

Radboud University Nijmegen

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

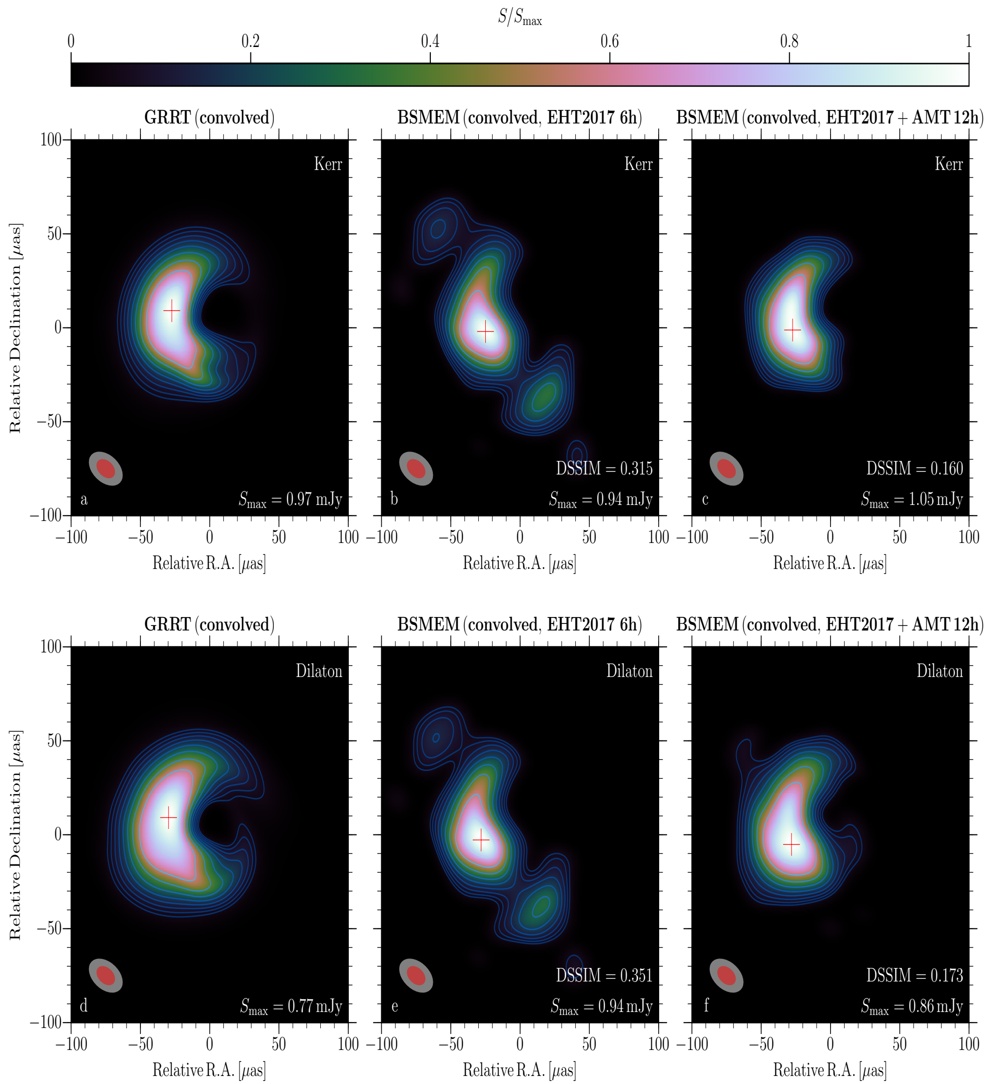


Davelaar, Moscibrodzka, Bronzwaer, Falcke A&A (2018), in press

Non-standard spacetimes

Radboud University Nijmegen

GRMHD+Scattering EHT 2017



Kerr BH

Dilaton BH

BHAC code

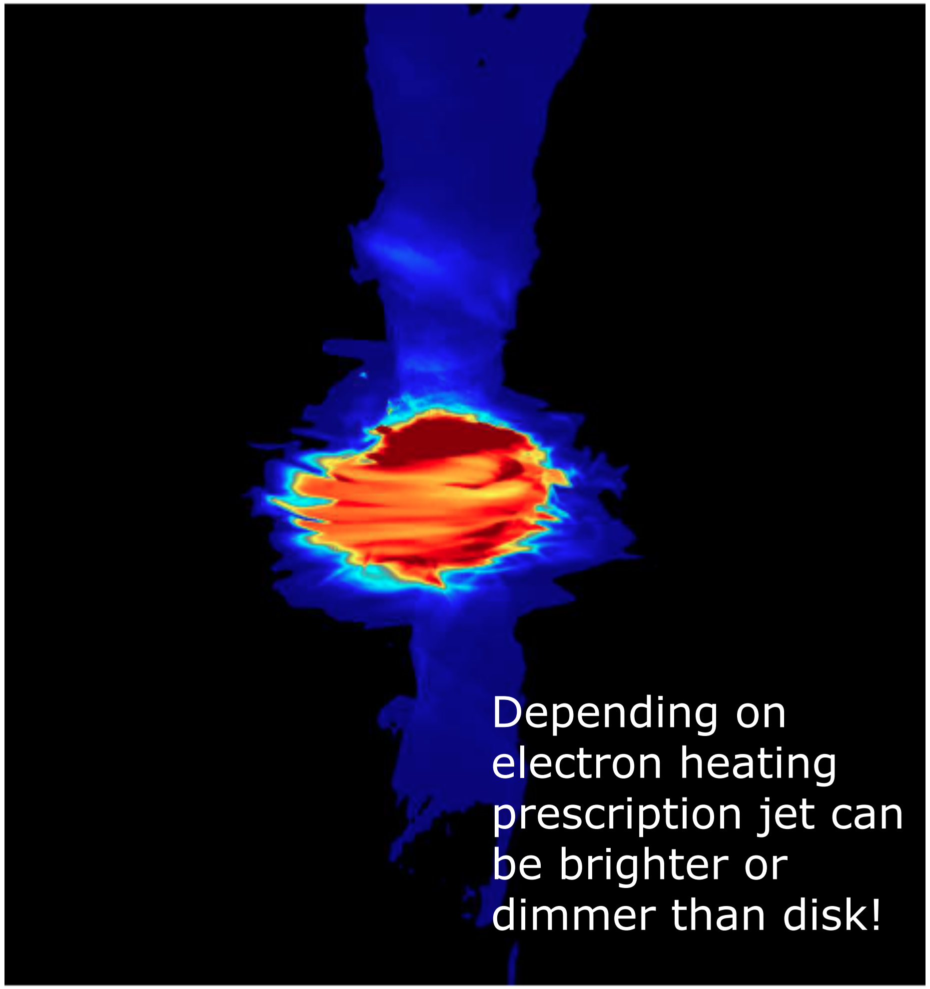
Mizuno et al. (2018, Nature Astronomy)

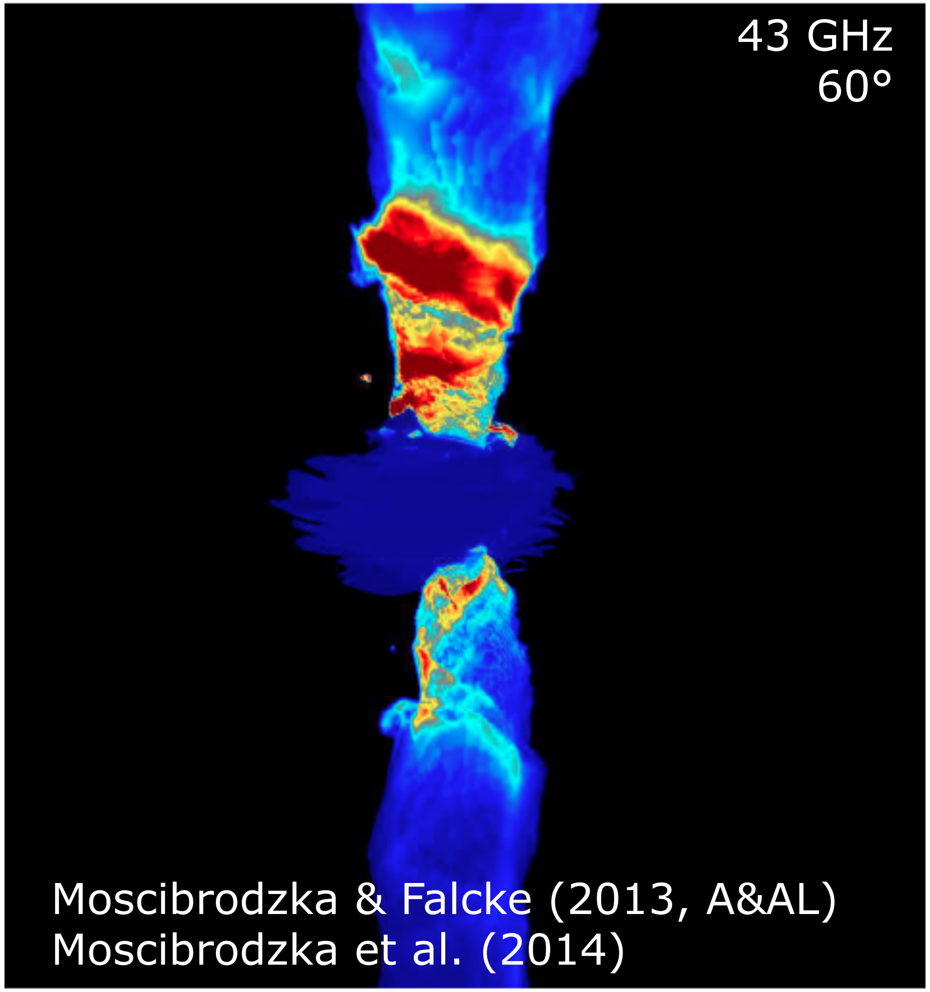
GRMHD with isothermal jet

Radboud University Nijmegen

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)

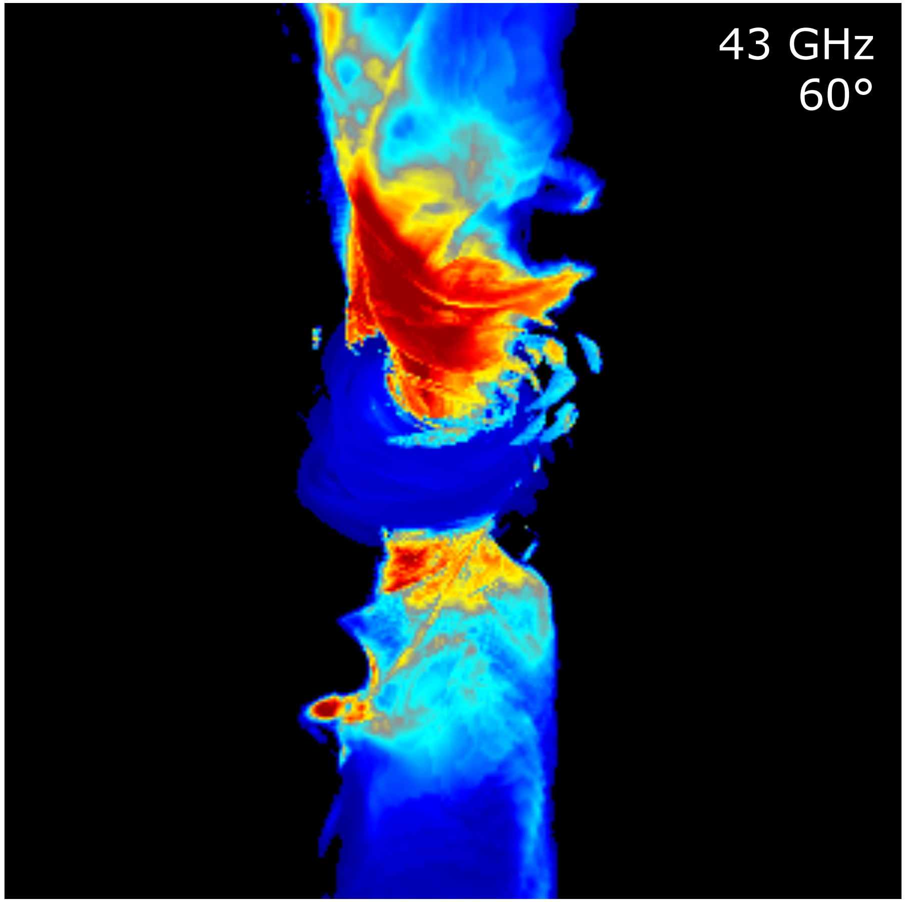


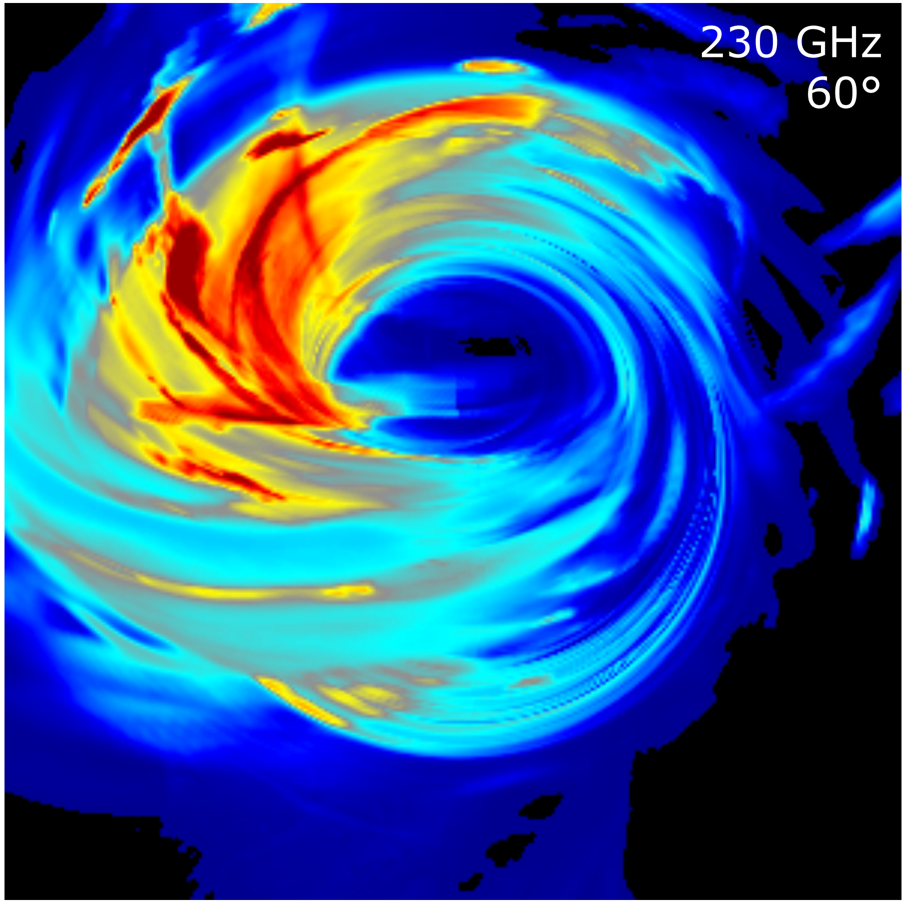


Sgr A* 3DGRMHD jet model

Radboud University Nijmegen

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





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

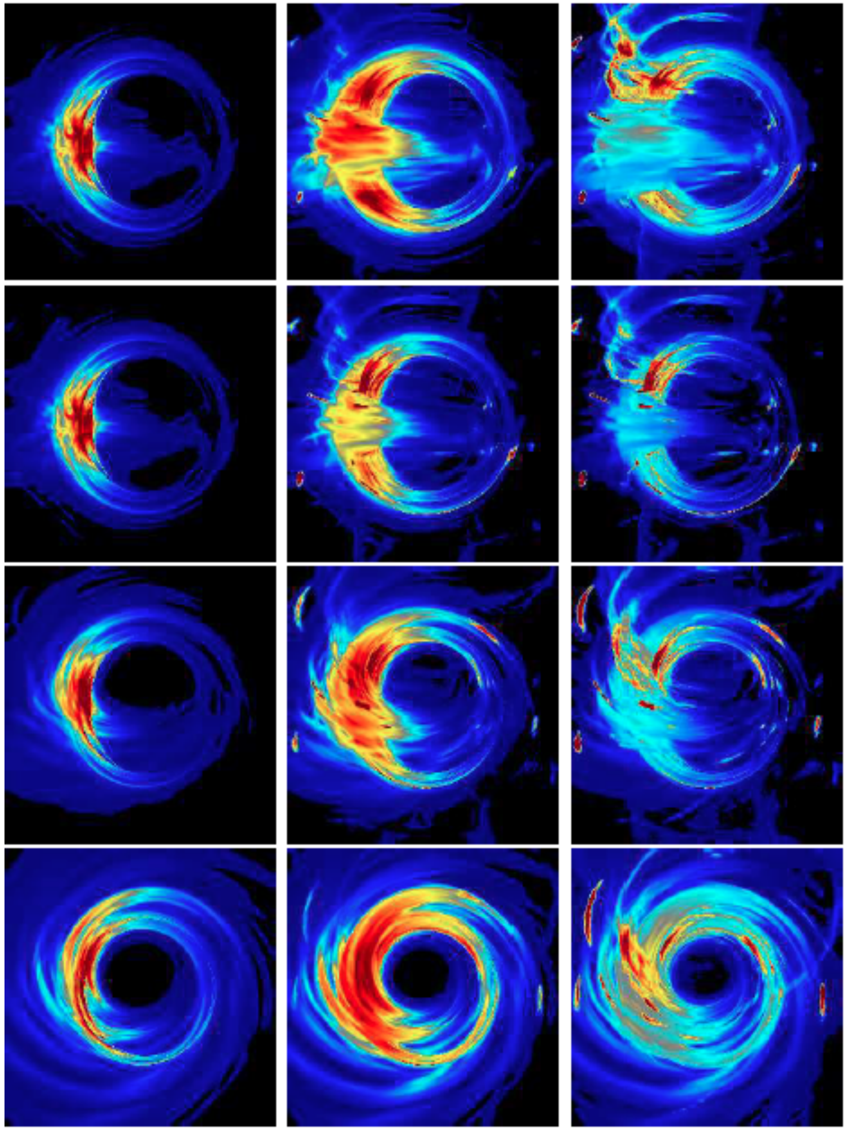
230 GHz Predictions

Te/Tp(jet) →

edge-on

↓

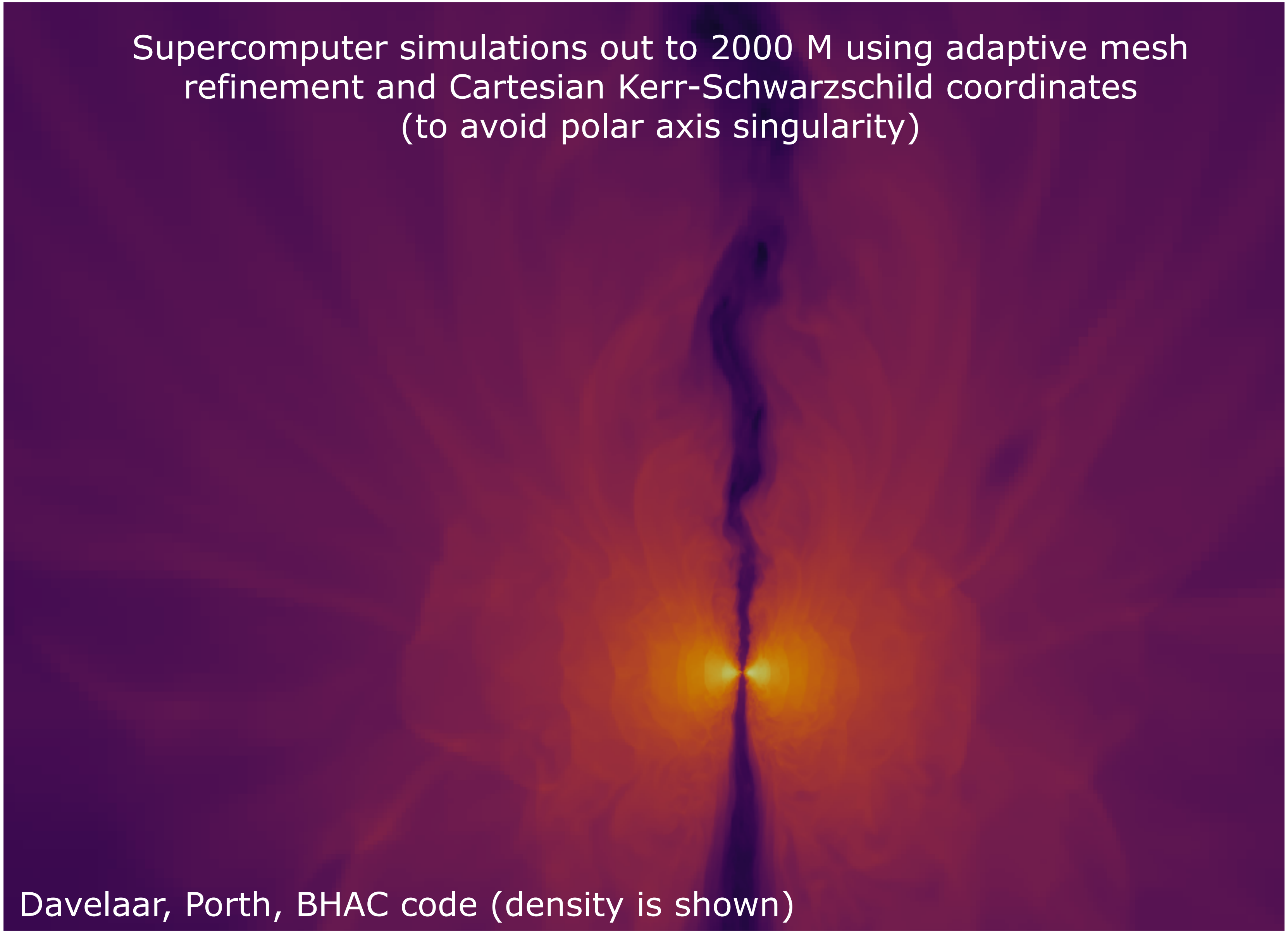
face-on



Moscibrodzka et al. (2014)

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

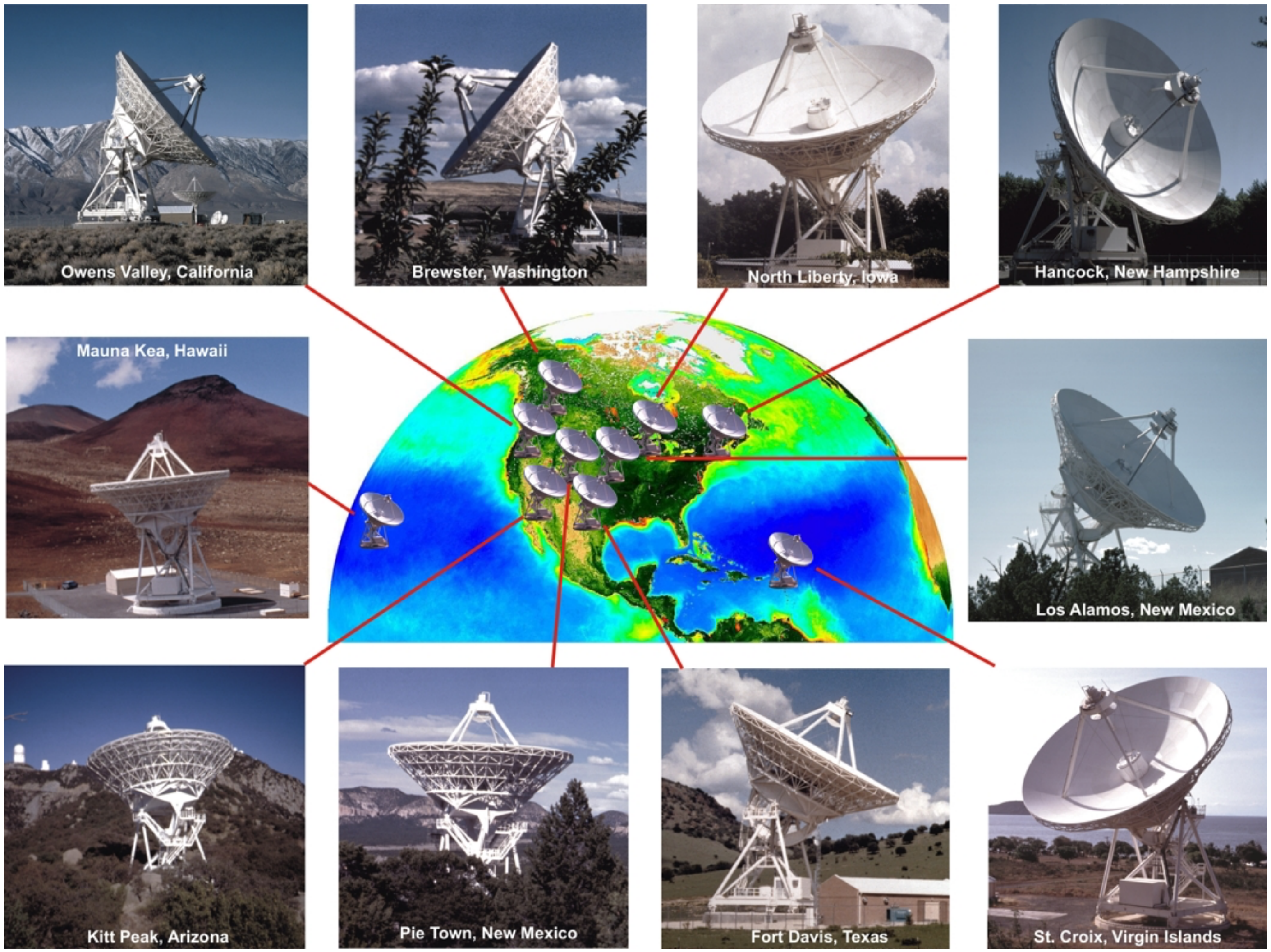
Next step: Large scale 3D



The path towards event horizon imaging

Radboud University Nijmegen

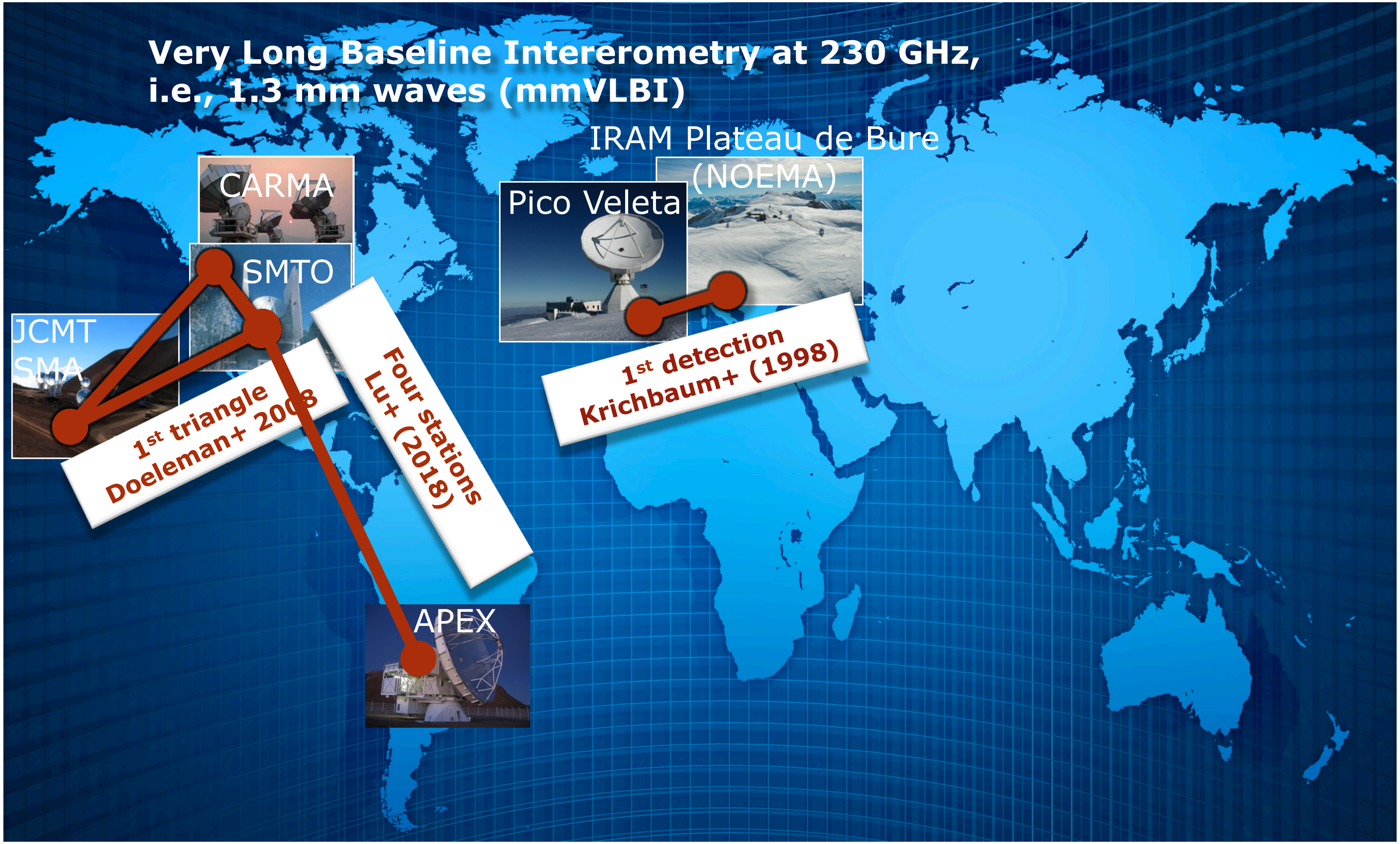
VLBA



VLBI from 3 cm to 3 mm

The path towards event horizon imaging

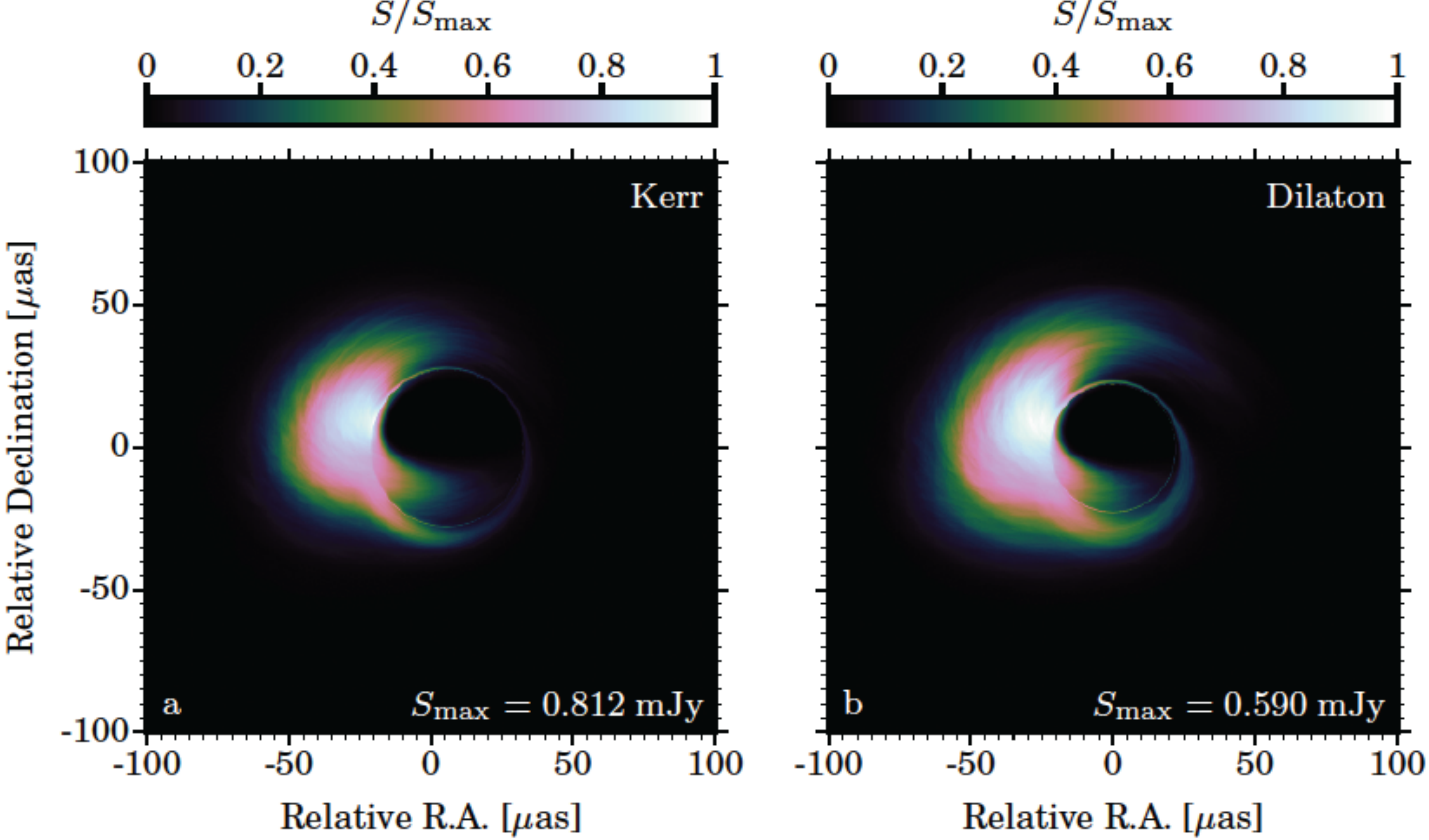
Radboud University Nijmegen



Full Non-GR MHD Simulations

Radboud University Nijmegen

Dilaton Black Holes

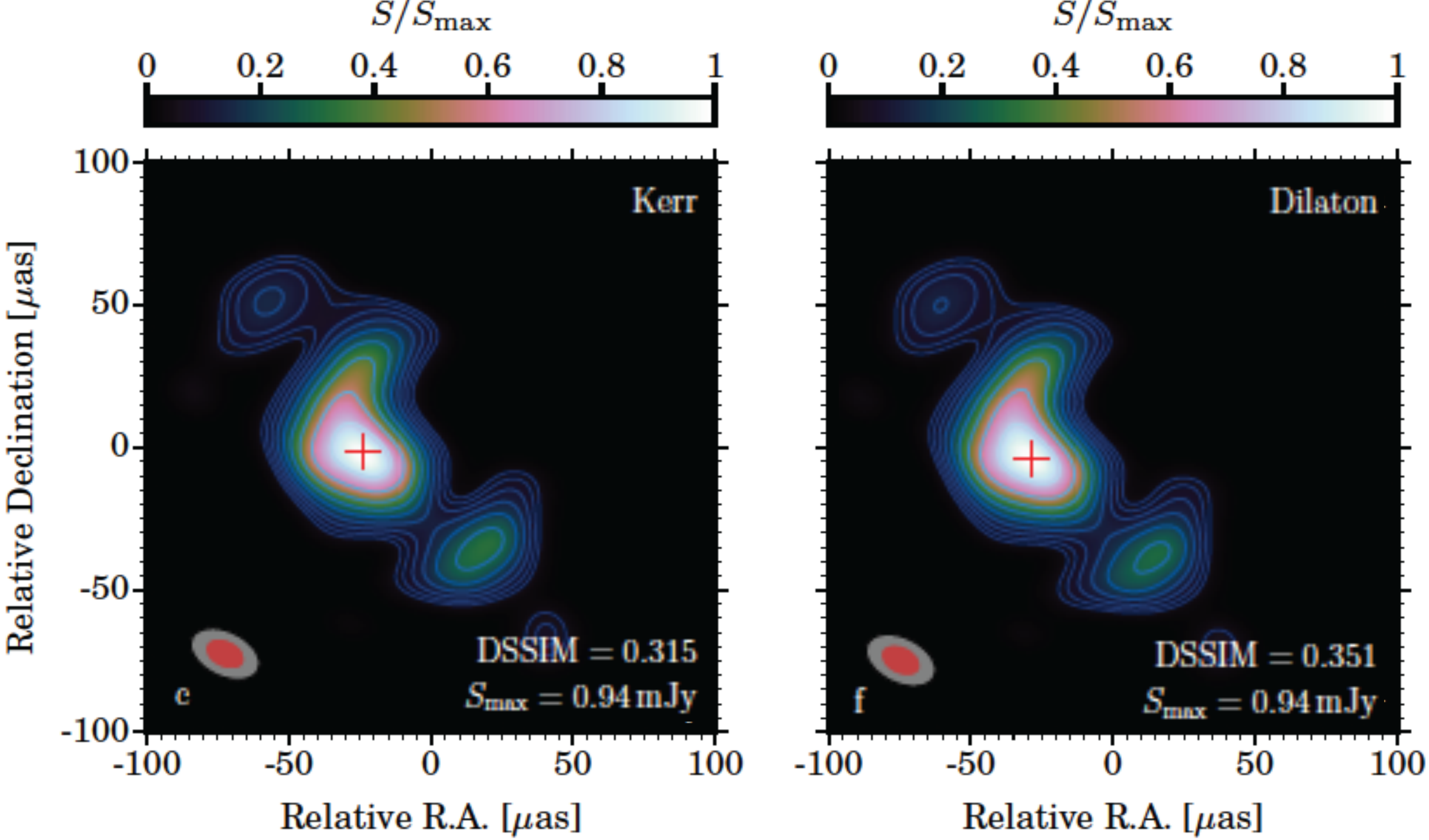


Mizuno et al. (2018, Nature Astronomy, subm.)

Full Non-GR MHD Simulations

Radboud University Nijmegen

Dilaton Black Holes



Mizuno et al. (2018, Nature Astronomy, subm.)

The submm-Bump: Event Horizon-Scale Emission

Radboud University Nijmegen

Multi-wavelength campaign:
Four Telescopes simultaneously …

THE ASTROPHYSICAL JOURNAL, 499:731–734, 1998 June 1

THE SIMULTANEOUS SPECTRUM OF SAGITTARIUS A* FROM 20 CENTIMETER TO 1 MILLIMETER AND THE NATURE OF THE MILLIMETER EXCESS

HEINO FALCKE,[1,2] W. M. GOSS,[3] HIROSHI MATSUO,[4] PETER TEUBEN,[1] JUN-HUI ZHAO,[5] AND ROBERT ZYLKA[6]
Received 1997 November 6; accepted 1998 January 12

ABSTRACT

We report results of a multiwavelength campaign to measure the simultaneous spectrum of the supermassive black hole candidate Sgr A* in the Galactic center from centimeter to millimeter wavelengths using the Very Large Array, the Berkeley-Illinois-Maryland Array (BIMA), the Nobeyama 45 m, and the Institut de Radioastronomie Millimetrique (IRAM) 30 m telescopes. The observations confirm that the previously detected millimeter excess is an intrinsic feature of the spectrum of Sgr A*. The excess can be interpreted as and effect of the presence of an ultracompact component of relativistic plasma with a size of a few Schwarzschild radii near the black hole. If so, Sgr A* might offer a unique possibility to image the putative black hole against the background of this component with future millimeter VLBI experiments.

Modeling Sgr A: Black Hole Jet & Shadow*

Radboud University Nijmegen

Jet Model for Sgr A* predictions:

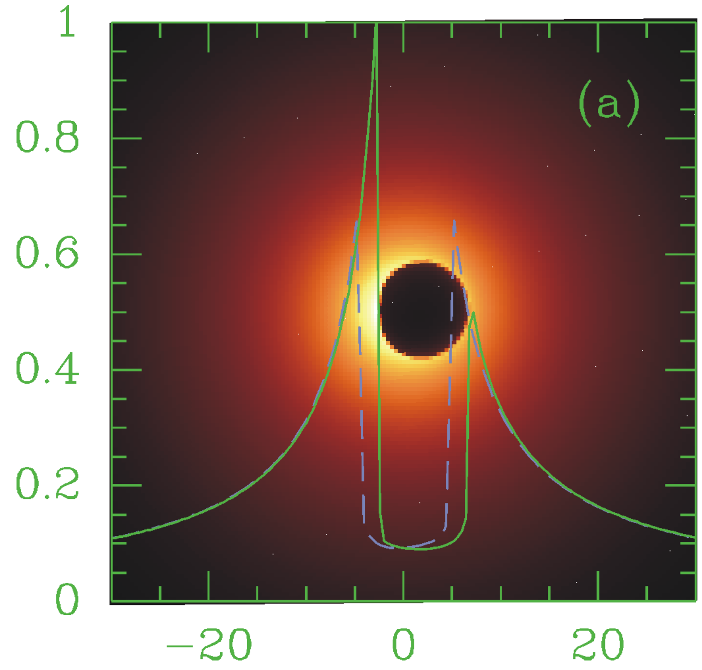
wavelength-dependent size & low accretion rate

$$z_{\tau_\nu=1,\mathrm{obs}} = 2\cdot10^{13}\,\mathrm{cm}\left(\frac{43GHz}{\nu}\right) \cdot\left(\frac{\gamma_\mathrm{j}\beta_\mathrm{j}}{\sqrt{1+(\gamma_\mathrm{j}\beta_\mathrm{j})^2}}\sqrt{\frac{9}{\Lambda}\frac{3}{\mathcal{M}}}\,\frac{q_\mathrm{m}}{3\%}\,\frac{\dot{M}_\mathrm{disk}}{10^{-7}M_\odot/\mathrm{yr}}\right)^{2/3}. \quad (7)$$

Model: Falcke, Mannheim, Biermann (1993)

see also Falcke & Markoff (2000)

⇒ Black Hole Shadow

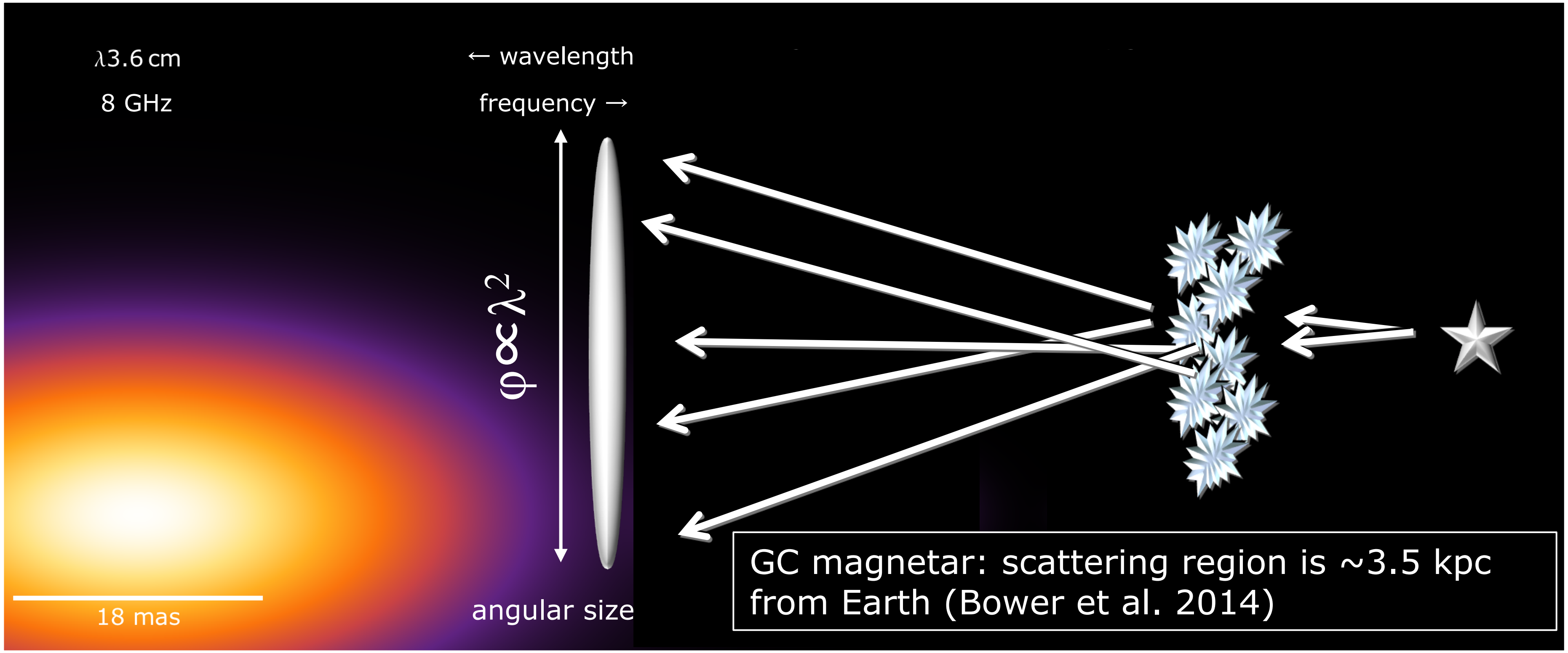


BH Shadow: Falcke, Melia, Agol (2000)

shadow will be offset by ~8 μas from the center of mass and will be slightly flattened on one side. Taking into account the scatter broadening of the image in the interstellar medium and the finite achievable telescope resolution, we show that the shadow of Sgr A* may be observable with very long baseline interferometry at submillimeter wavelengths, assuming that the accretion flow is optically thin in this region of the spectrum. Hence, there exists a realistic expectation of imaging the event horizon of a black hole within the next few years.

Predicted size of shadow today: ~50 μas +/- 10% for all spins
resolvable by global VLBI at 230 GHz!

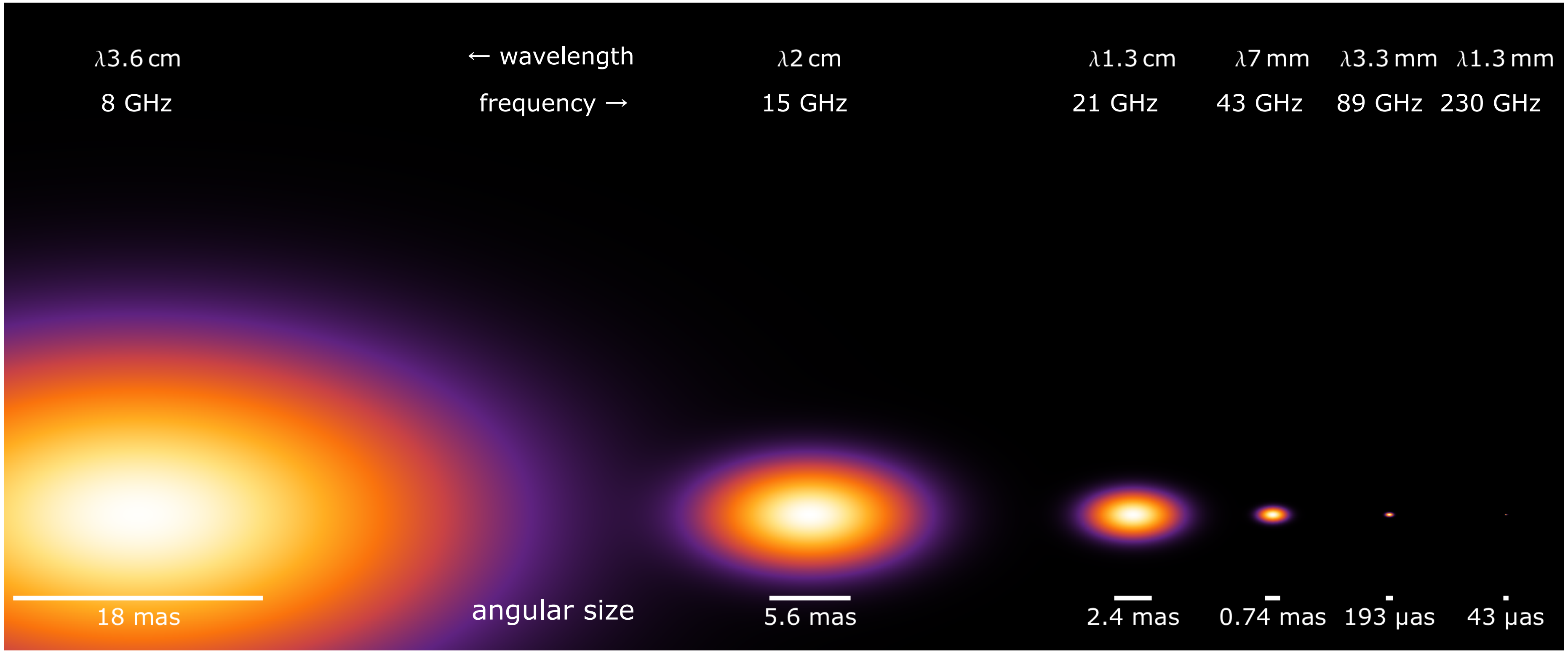
VLBI Images of Sgr A* (to scale)



- 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)

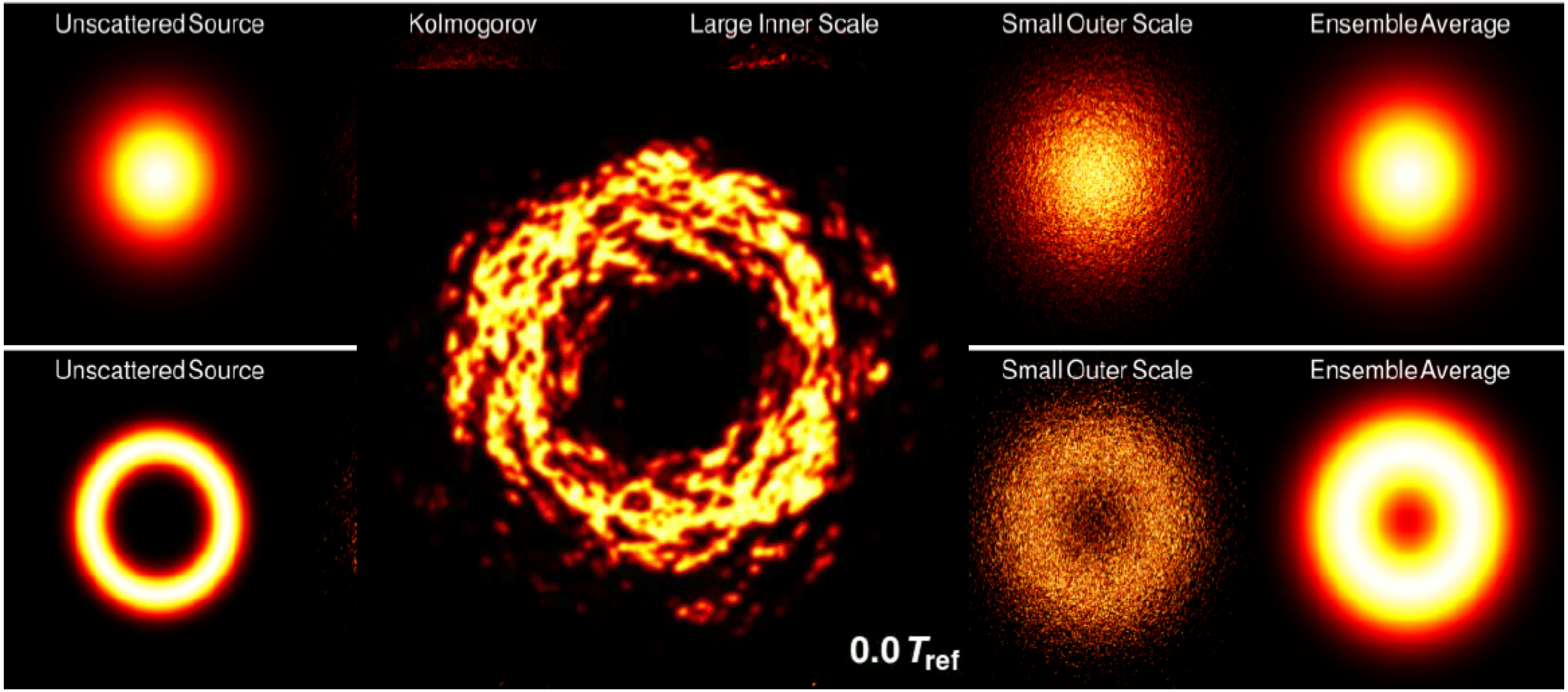
Radboud University Nijmegen



- 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.

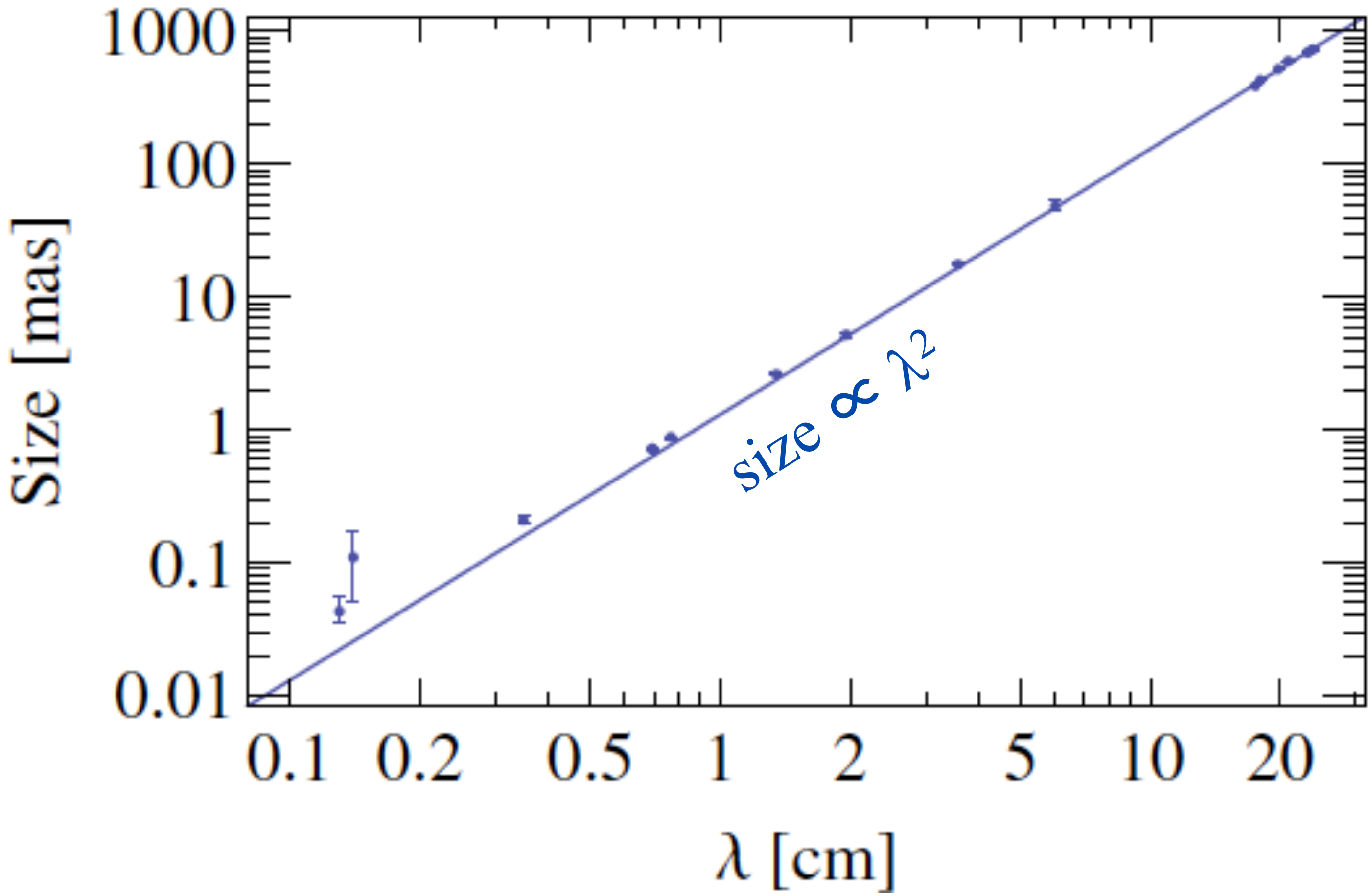
Scattering

Radboud University Nijmegen



Johnson & Gwinn (2015)

Measured Size of Sgr A*

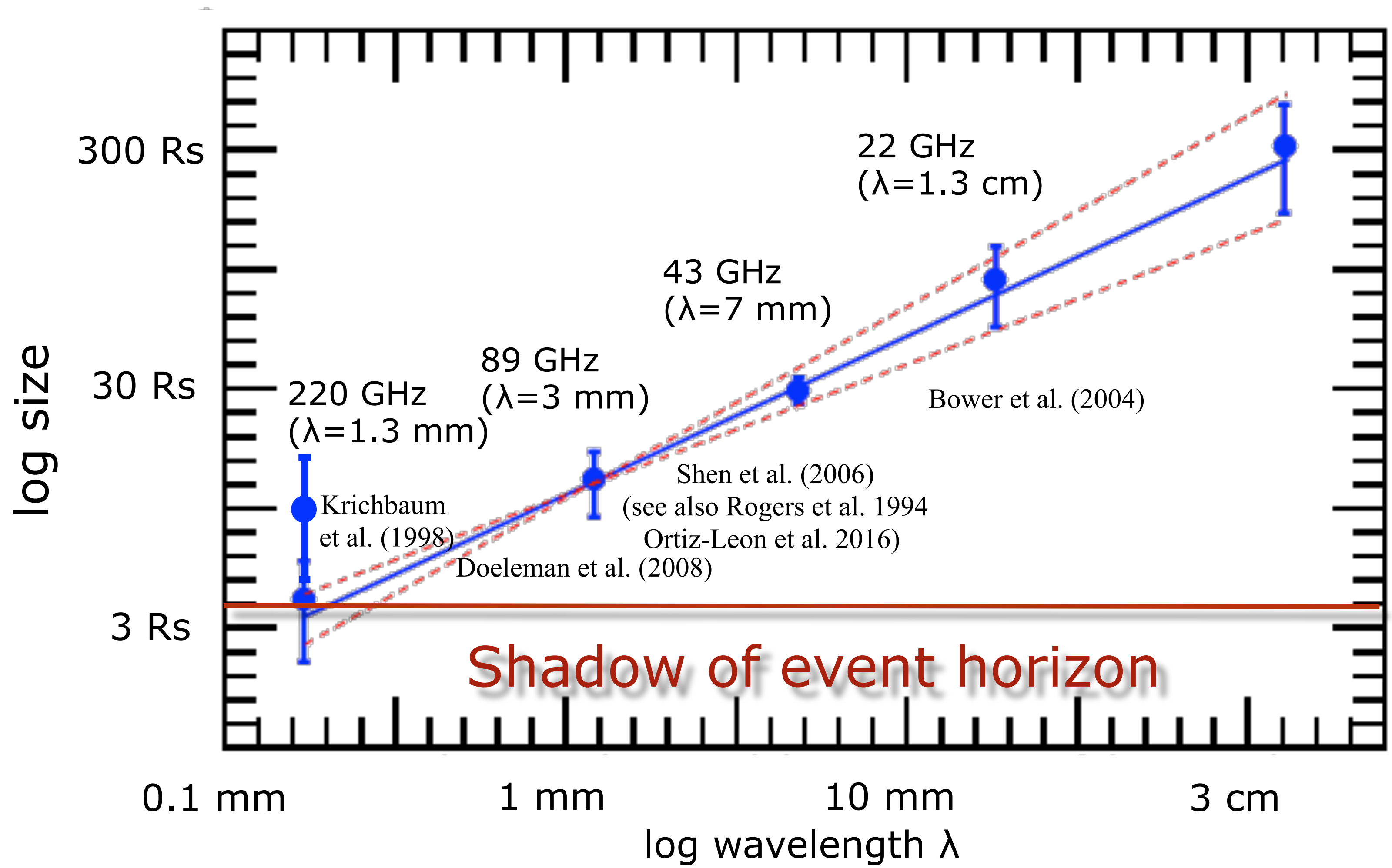


observing wavelength

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.

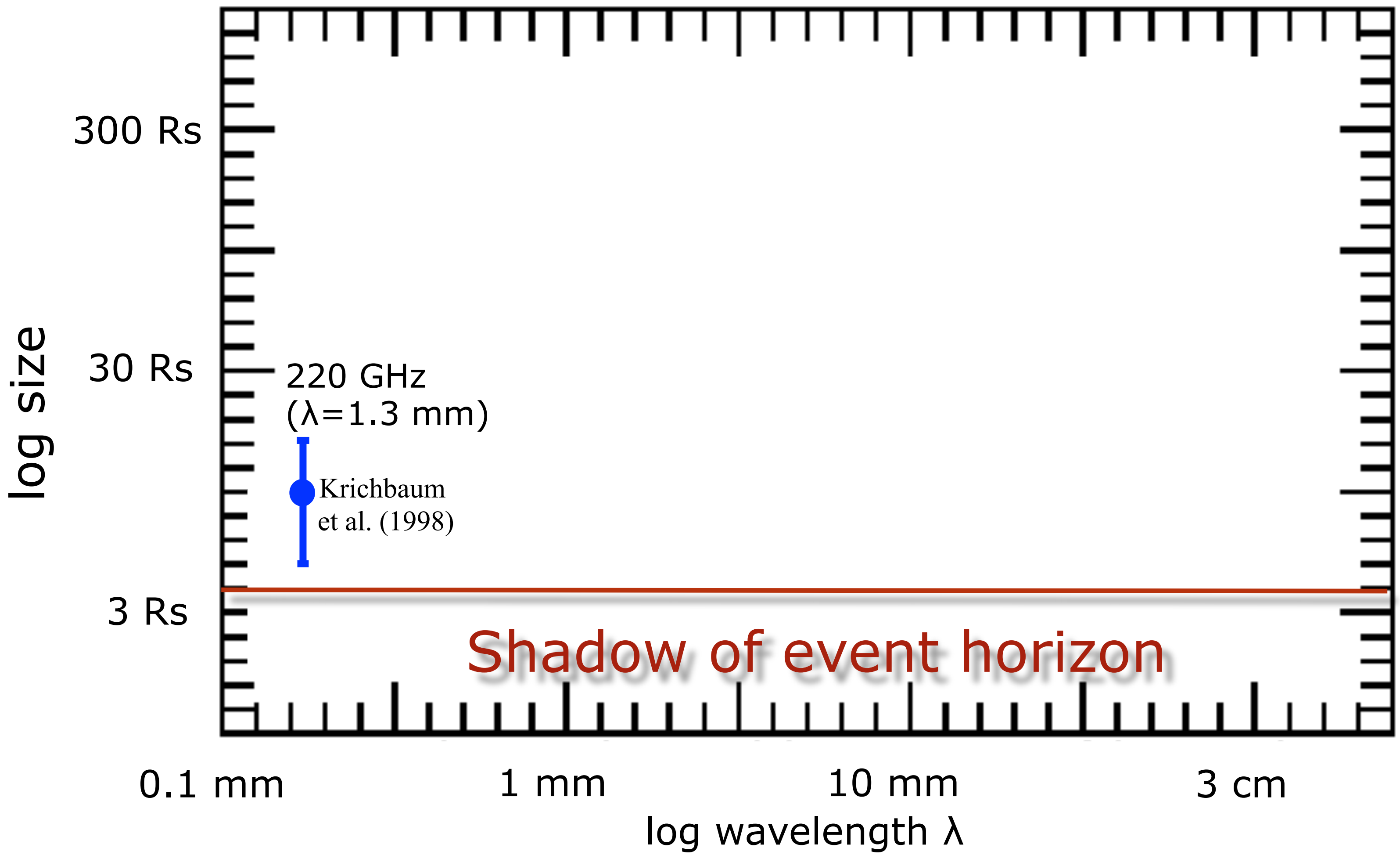


Falcke & Markoff, (2013, Class. & Quant. Gravity)

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.

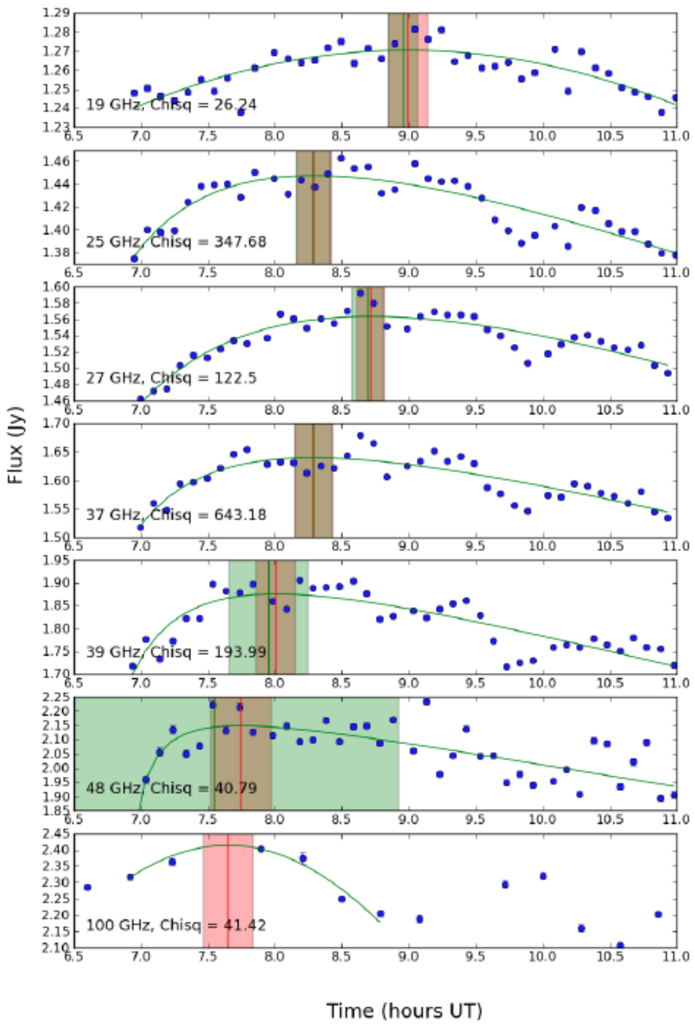


Falcke & Markoff, (2013, Class. & Quant. Gravity)

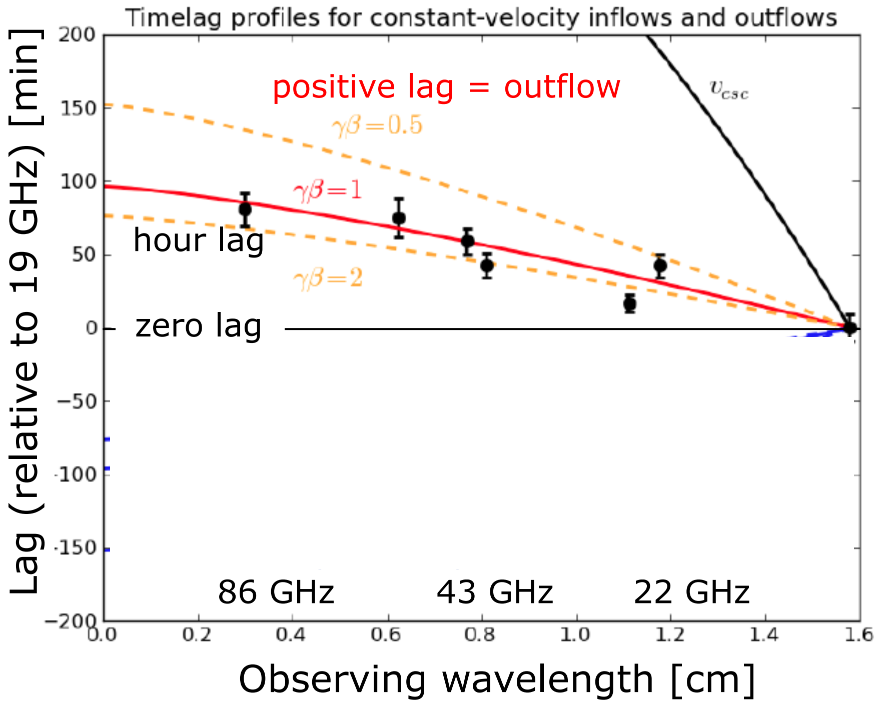
Radio Lags measured with ALMA & VLA

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**

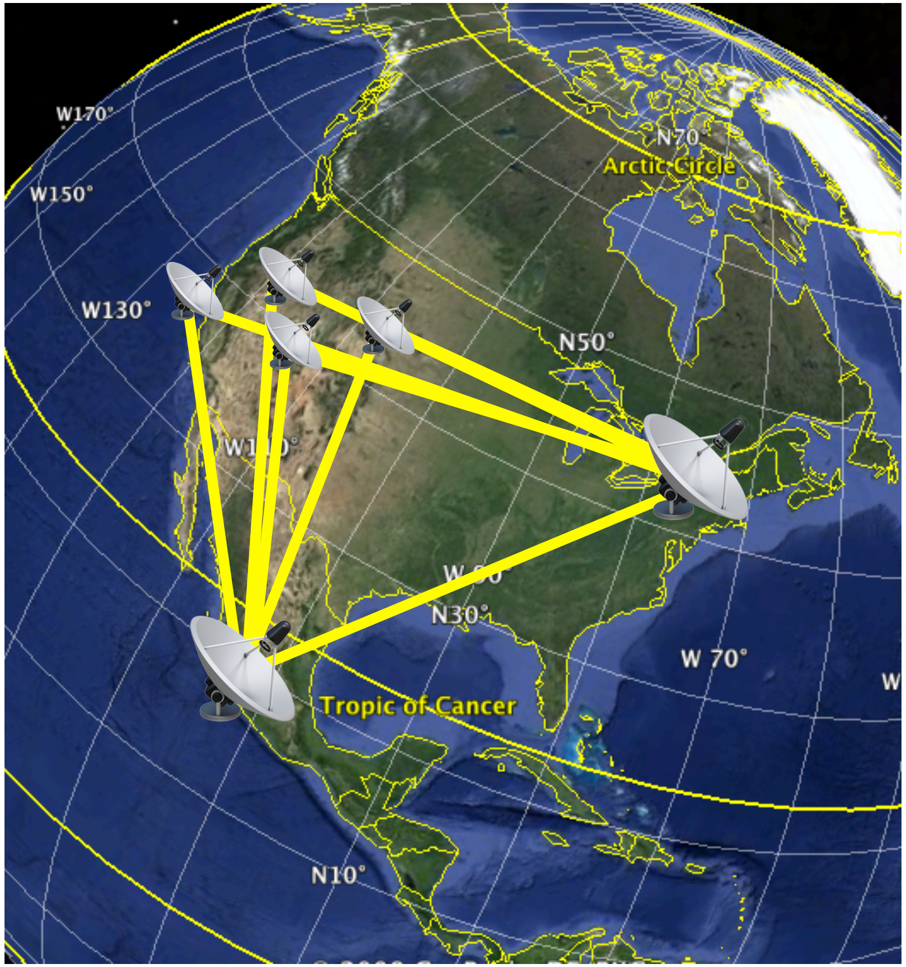


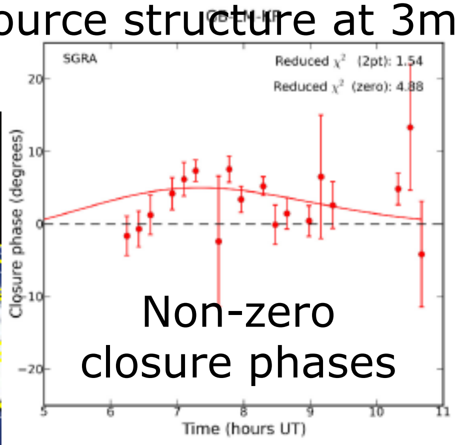
Brinkerink et al. (2015, A&A)
See also Yusef-Zadeh et al. (2009)

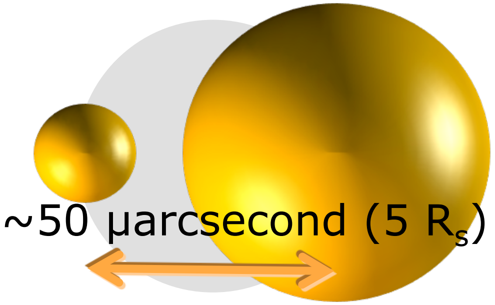
Asymmetric source structure at λ3mm (VLBA+LMT+GBT)

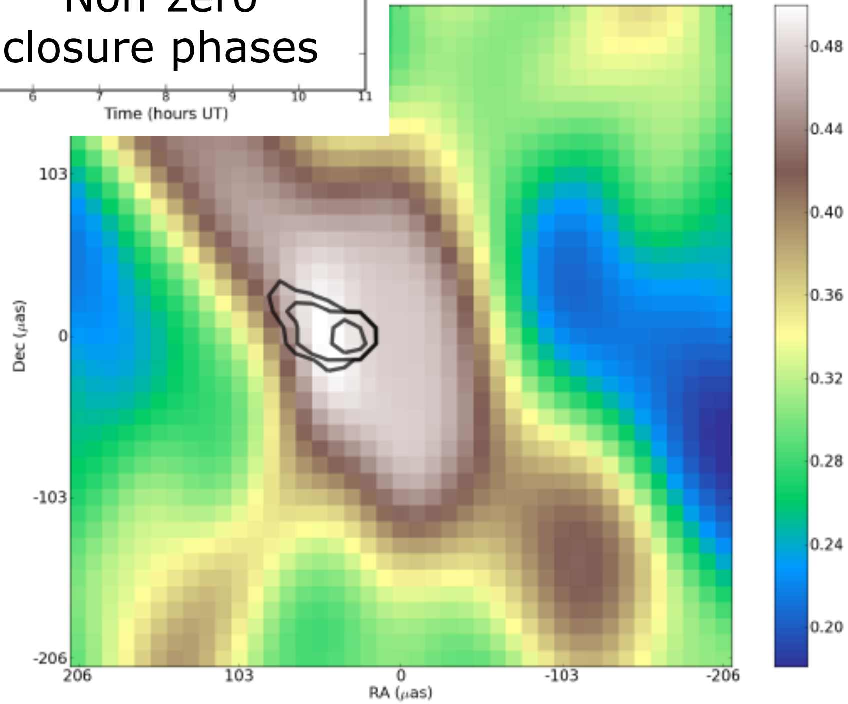
Radboud University Nijmegen

First indication of asymmetric source structure at 3m









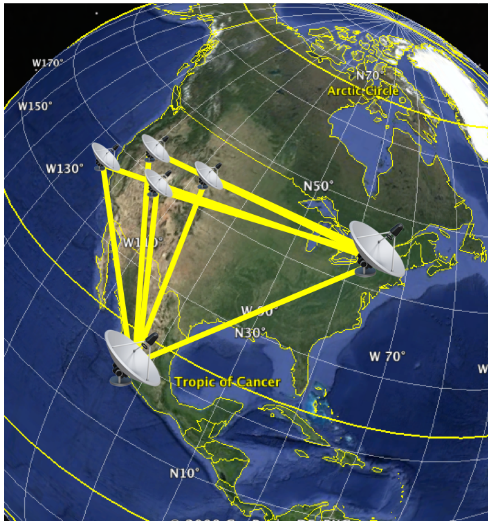
Brinkerink, Müller et al. (2016, MNRAS)

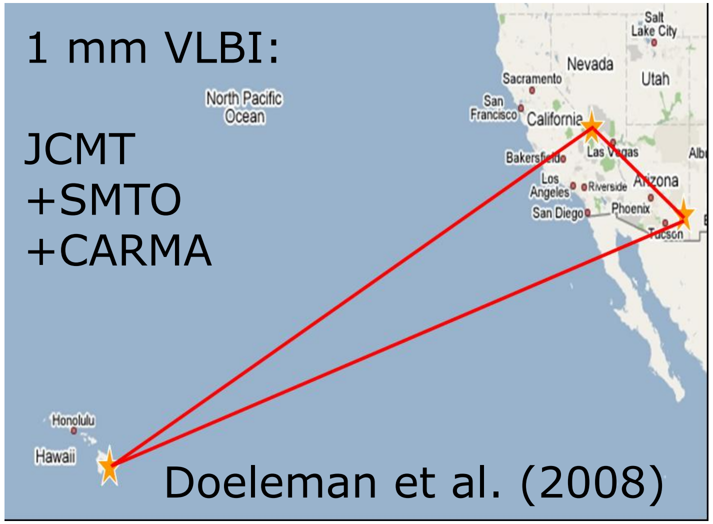
Asymmetric source structure: non-zero closure phases

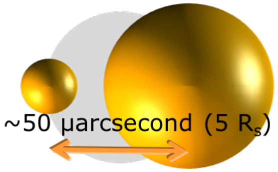
Radboud University Nijmegen

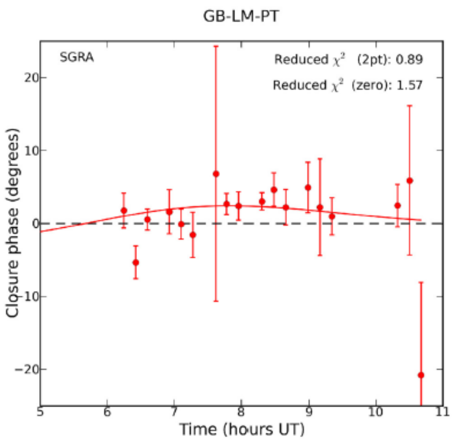
3mm-VLBI

VLBA
+LMT
+GBT





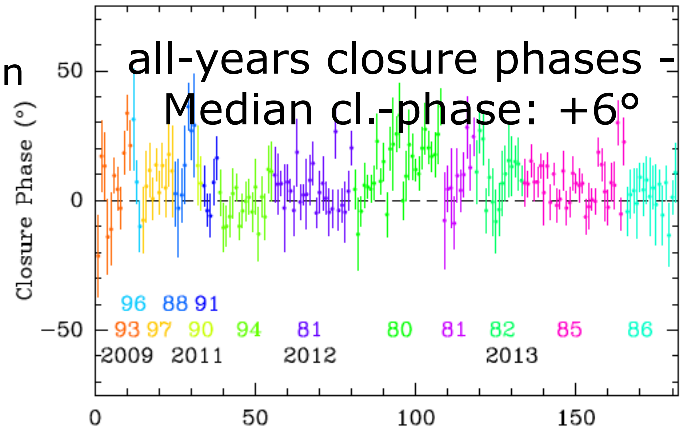




Brinkerink et al. (2016, MNRAS)
Ortiz-Leon et al. (2016)

Both consistent with E-W extension

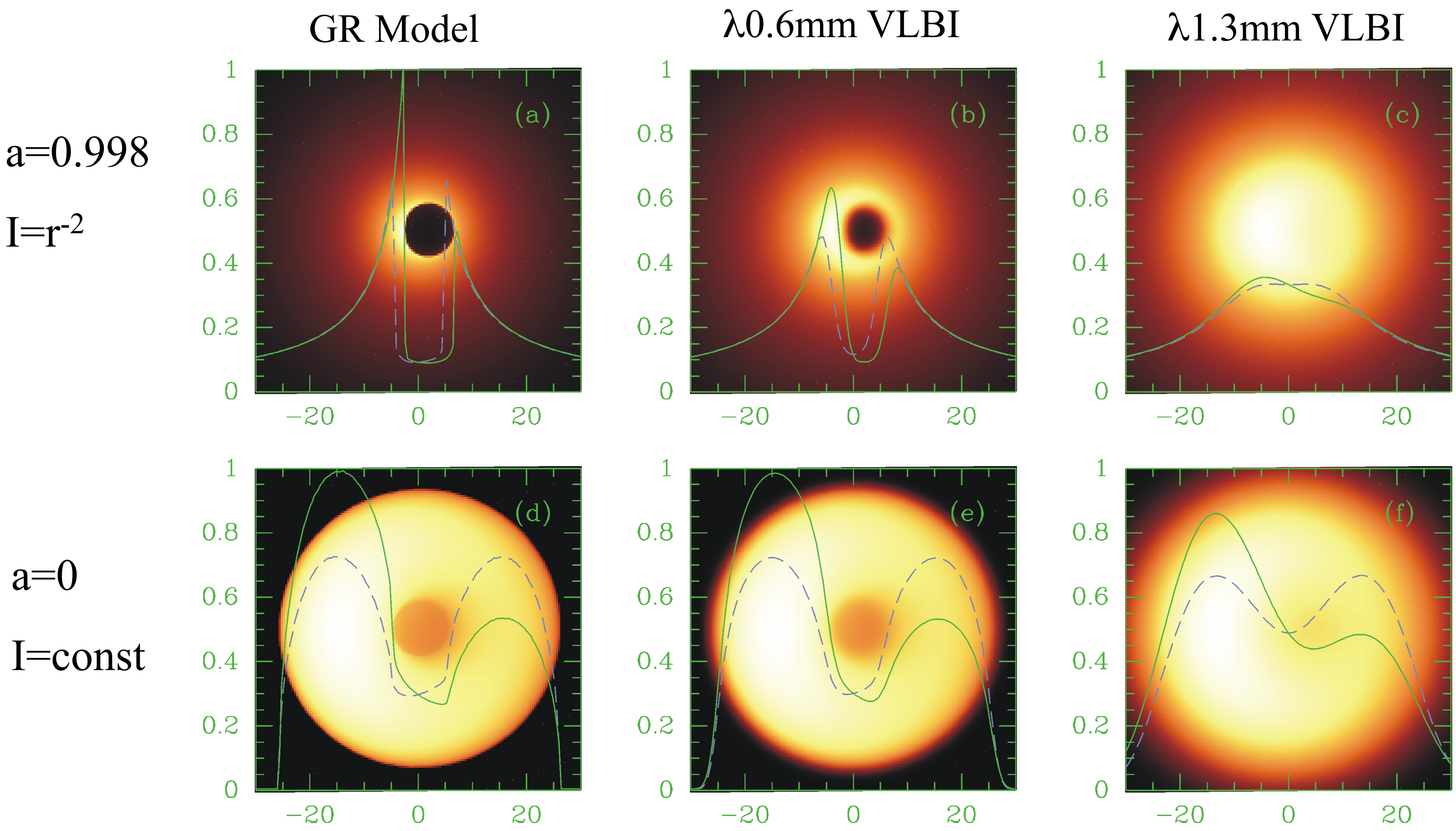
Scattering or intrinsic?



Fish et al. (2015, ApJ)

The Shadow of a Black Hole

Radboud University Nijmegen



(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

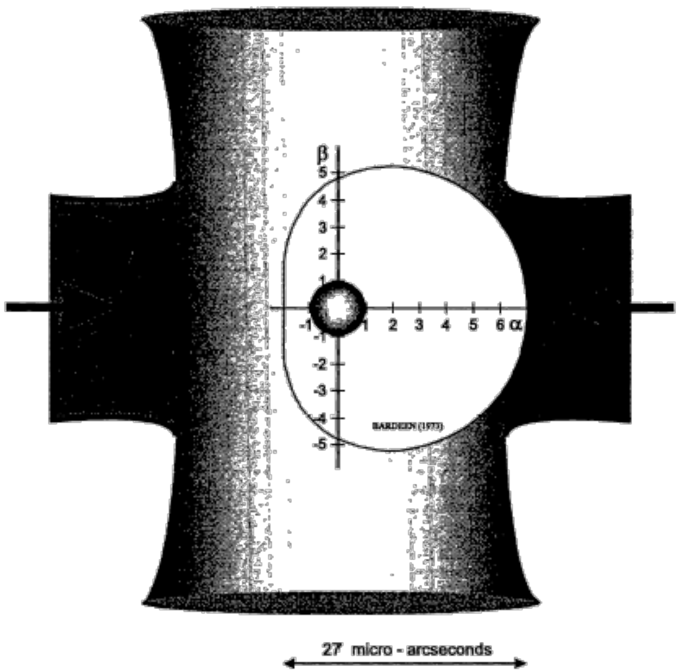


Figure 4. Sketch of the inner region of Sgr A* with accretion flow and nozzle surrounding the black hole. Overlaid is an appropriately scaled reproduction of a Figure from Bardeen (1973), showing the 'hole' of photons absorbed by the black hole if observed against a background source. A similar process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

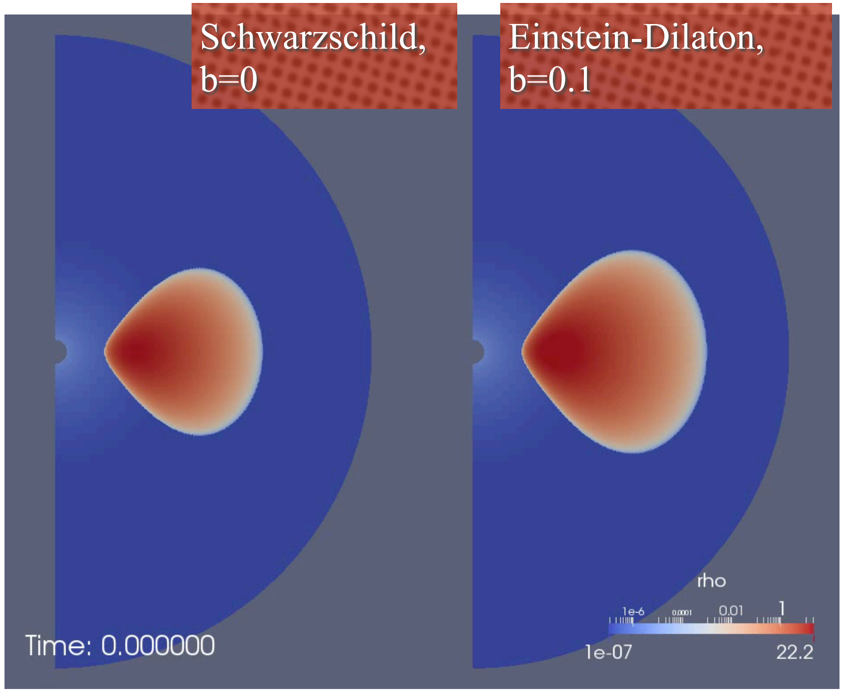
$$ds^2 = -\left(\frac{\rho - 2\mu}{\rho + 2b}\right)dt^2 + \left(\frac{\rho + 2b}{\rho - 2\mu}\right)d\rho^2 + (\rho^2 + 2b\rho)d\Omega^2 \qquad r^2 = \rho^2 + 2b\rho, \qquad M = \mu + b.$$

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)



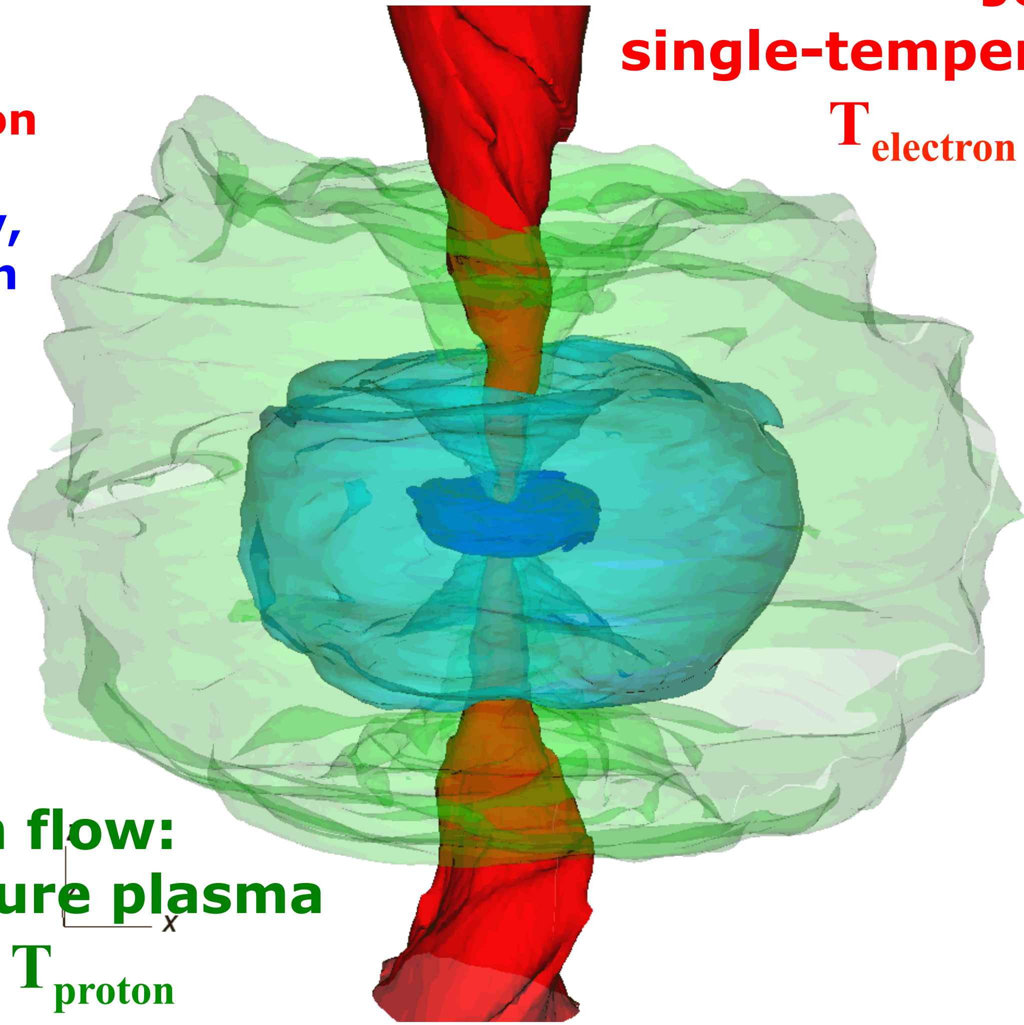
Simulation credit: Yosuke Mizuno

Importance of electron heating

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:

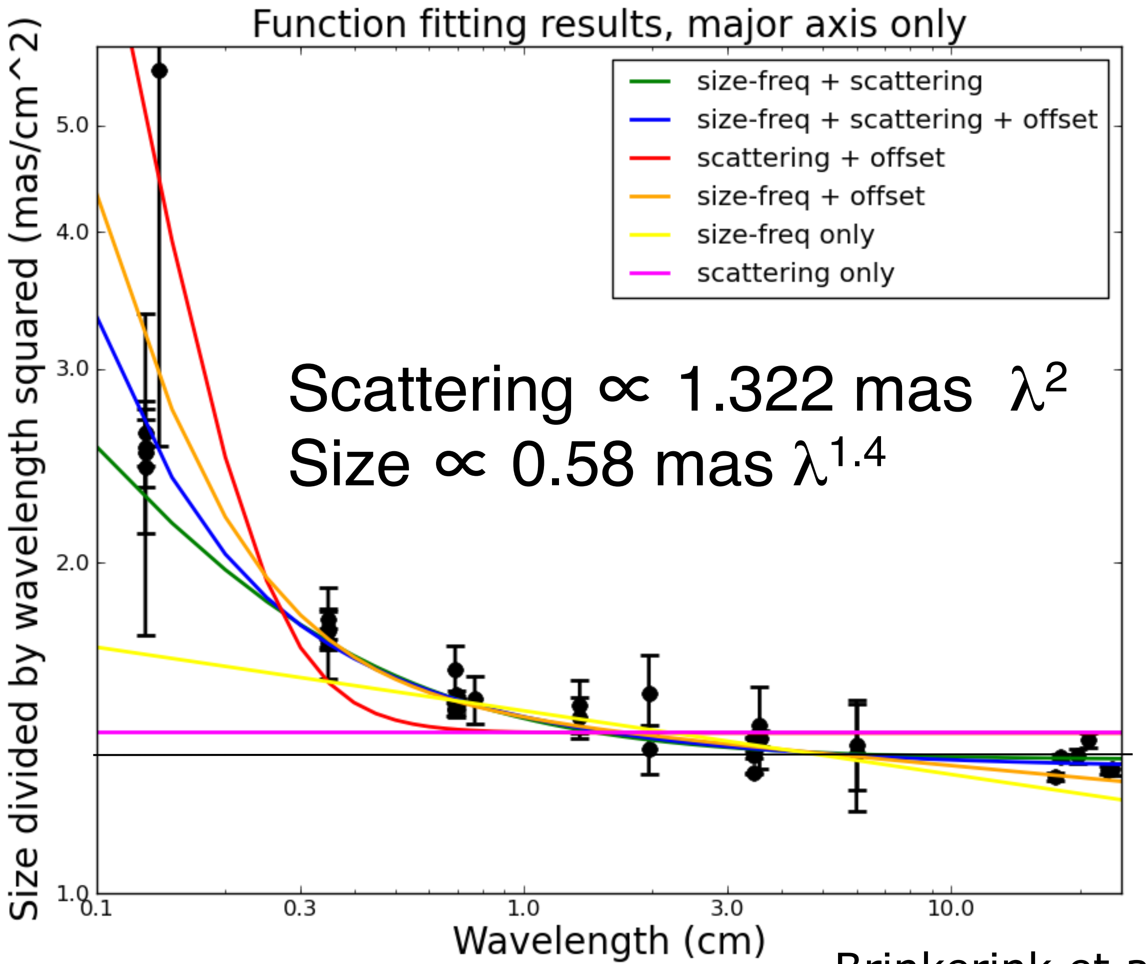
$$T_{e,jet} \gg T_{e,disk}$$

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*

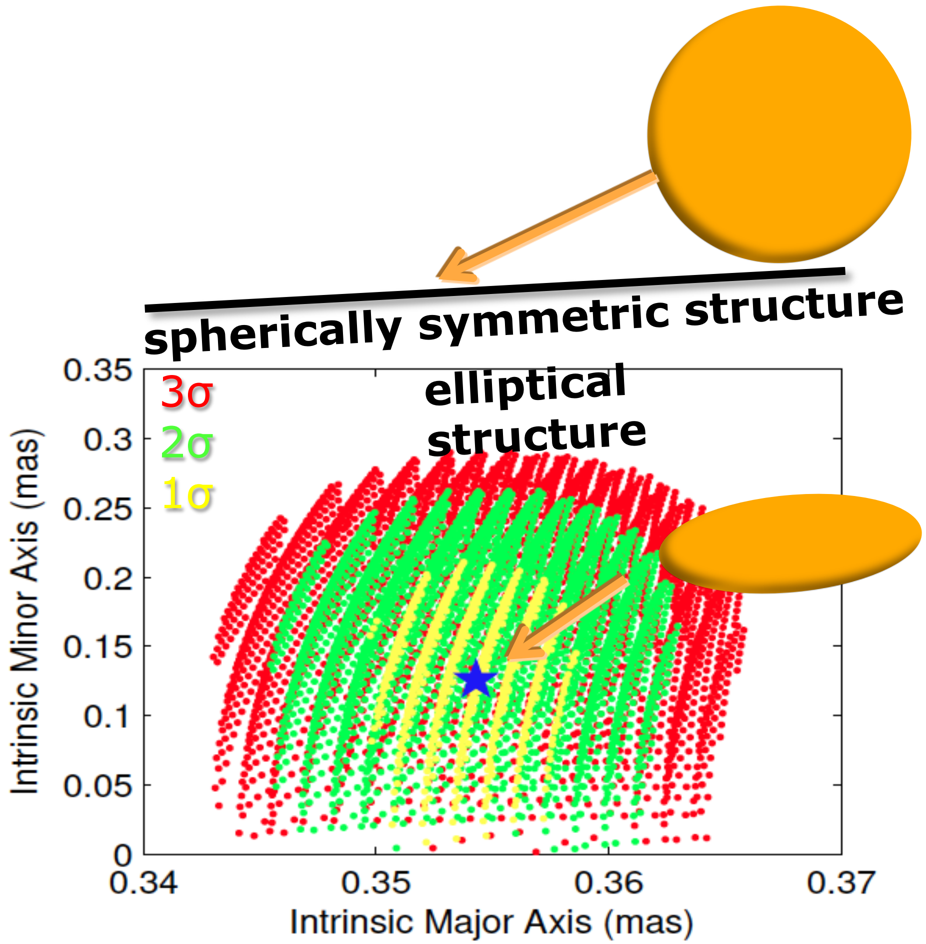


Brinkerink et al. (in prep)

Two-dimensional structure of Sgr A: fairly elongated*

Radboud University Nijmegen

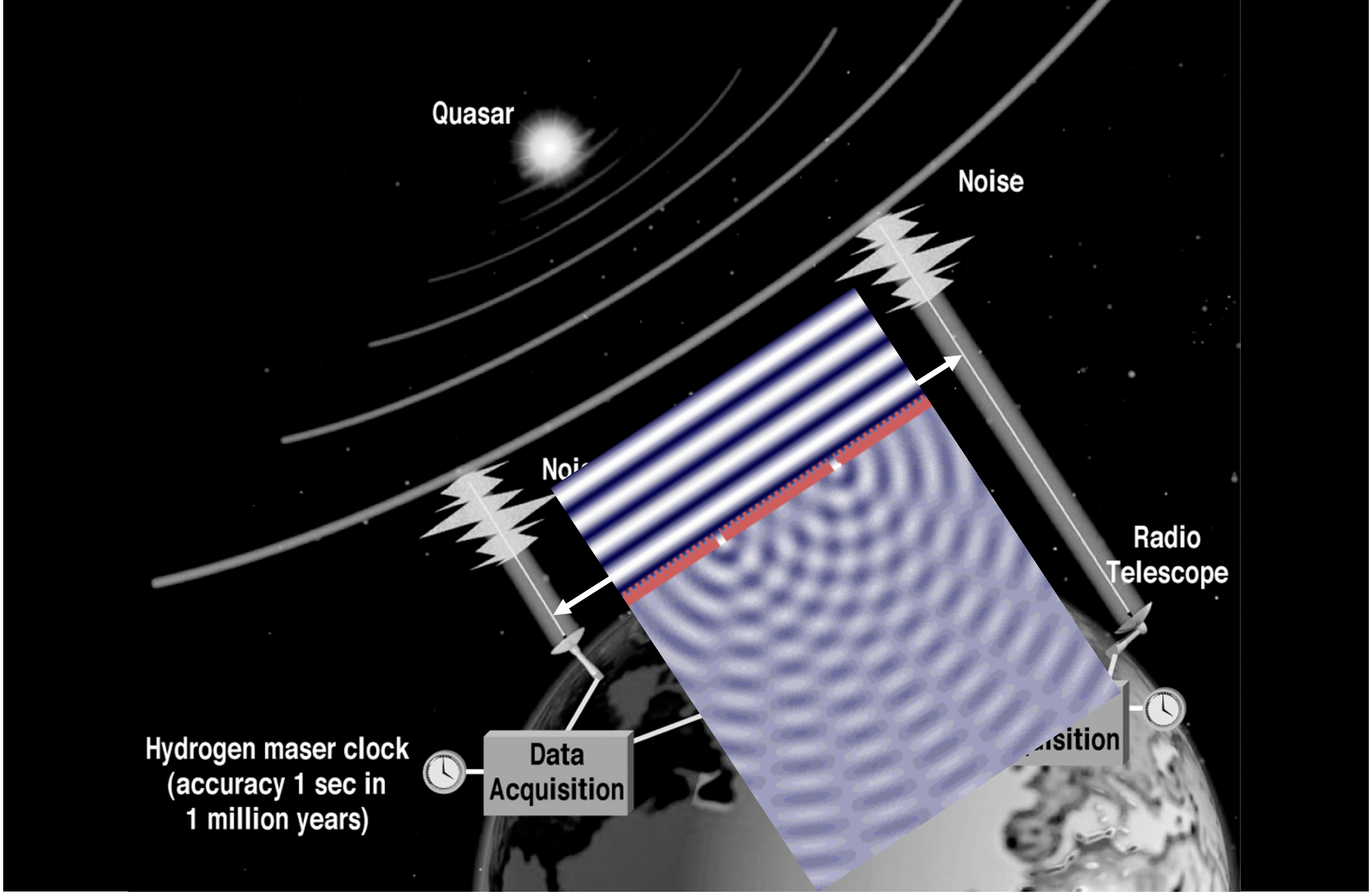
- Accurate closure amplitude measurements of 2D-size of Sgr A* with the VLBA.
- Size at 43 GHz: (35.4 ±0.4) Rs × (12.6±5.5) Rs at PA (95±4)°



Bower et al. (2014, ApJ)

VLBI – Very Long Baseline Interferometry

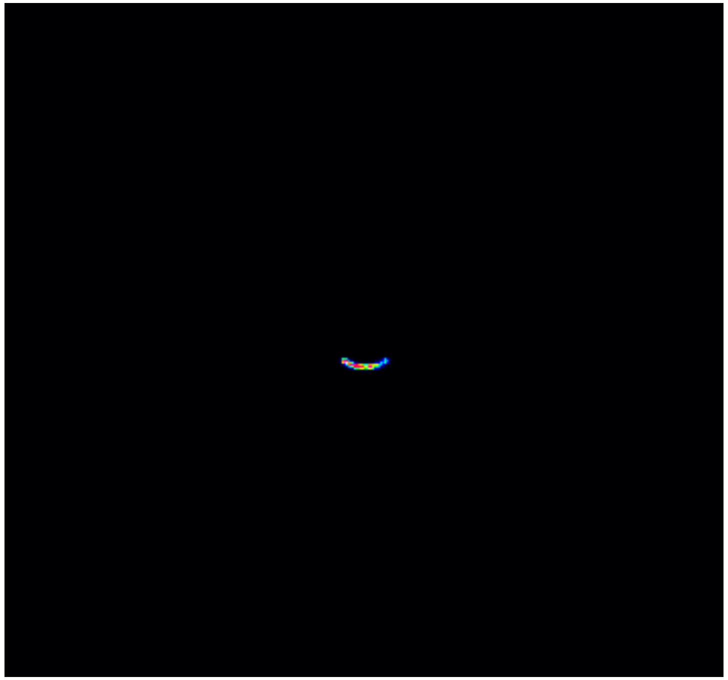
Resolution: smallest angular scale: ~λ/D

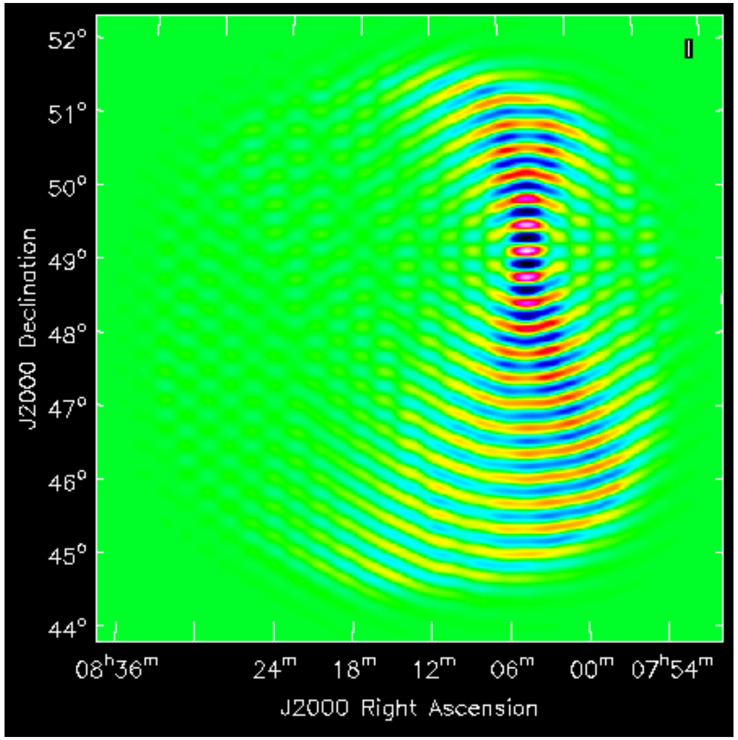


Interferometer Principle

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.



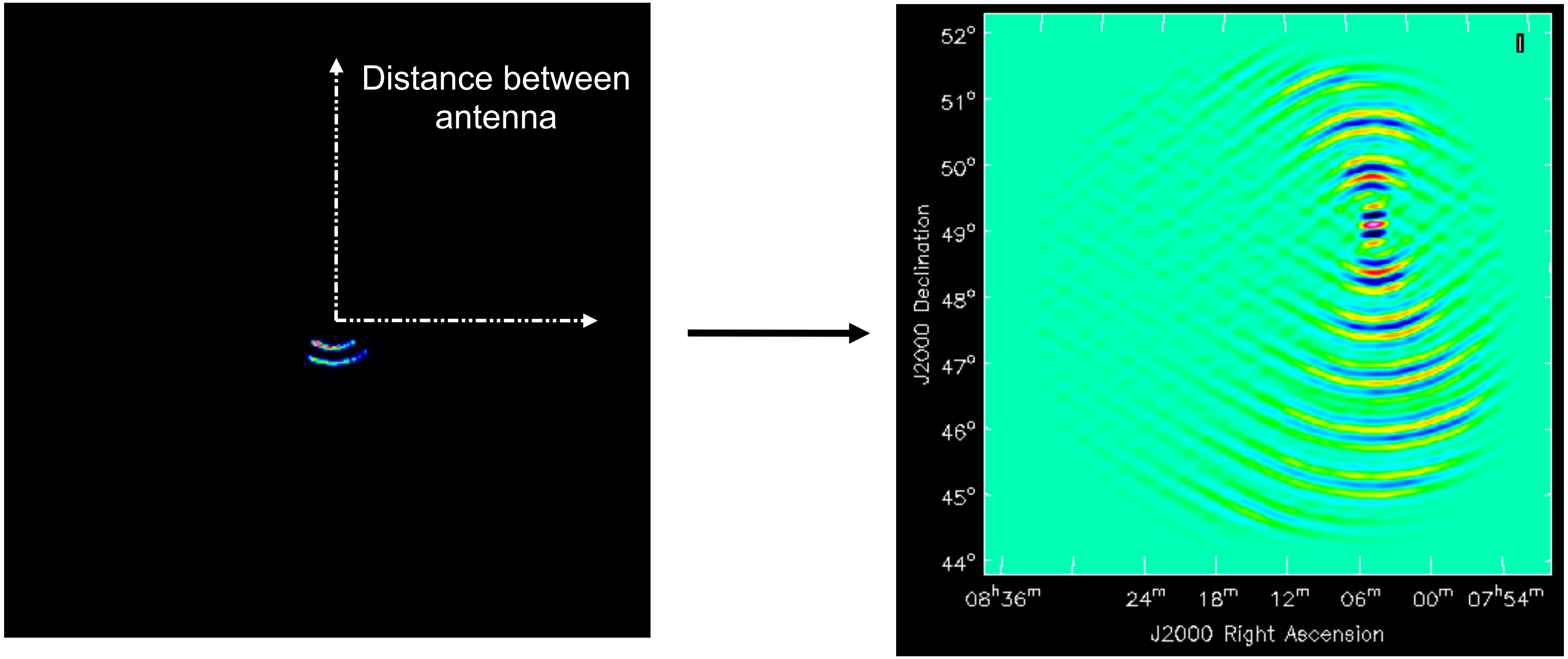


Slide: C. Tasse

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.

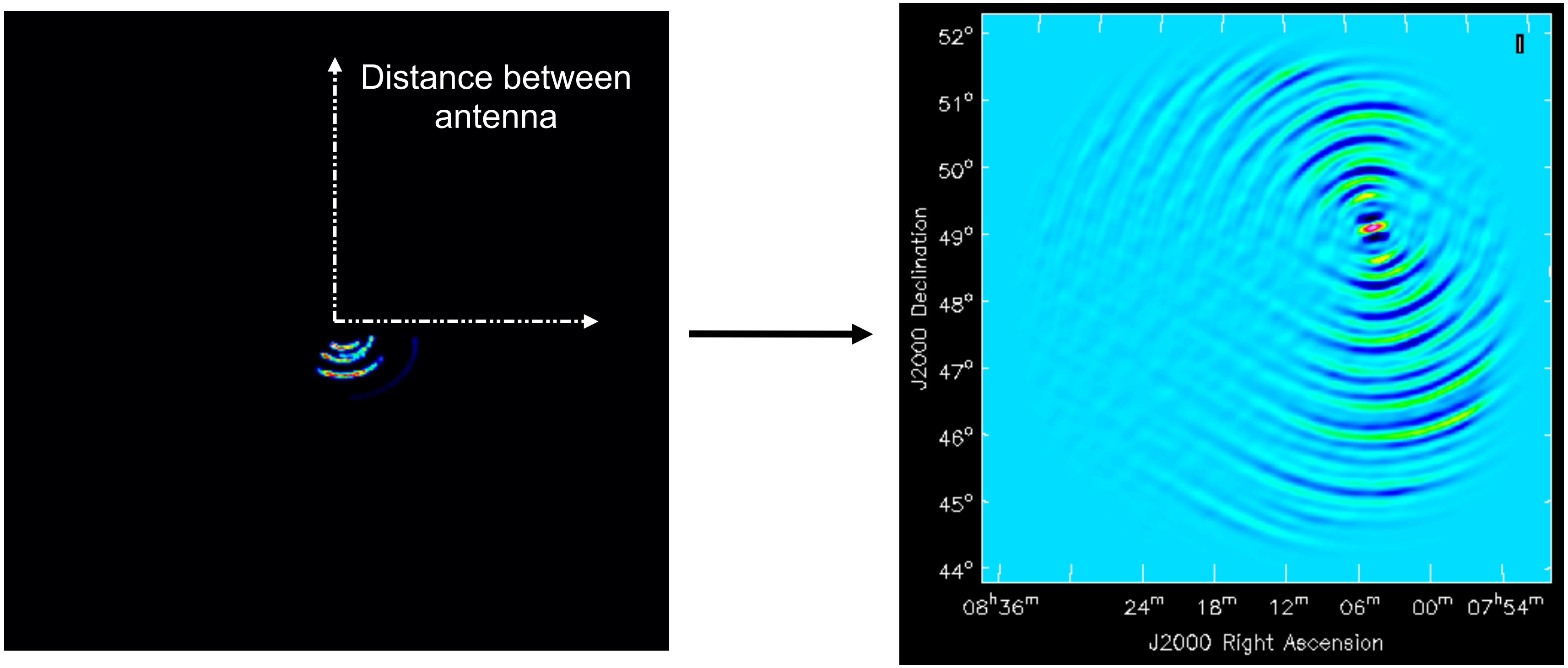


Slide: C. Tasse

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.

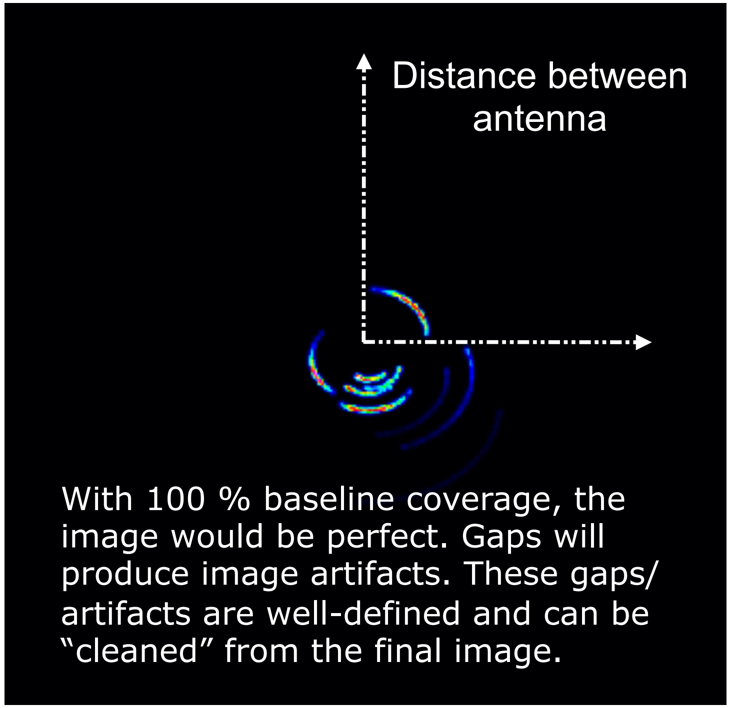


Slide: C. Tasse

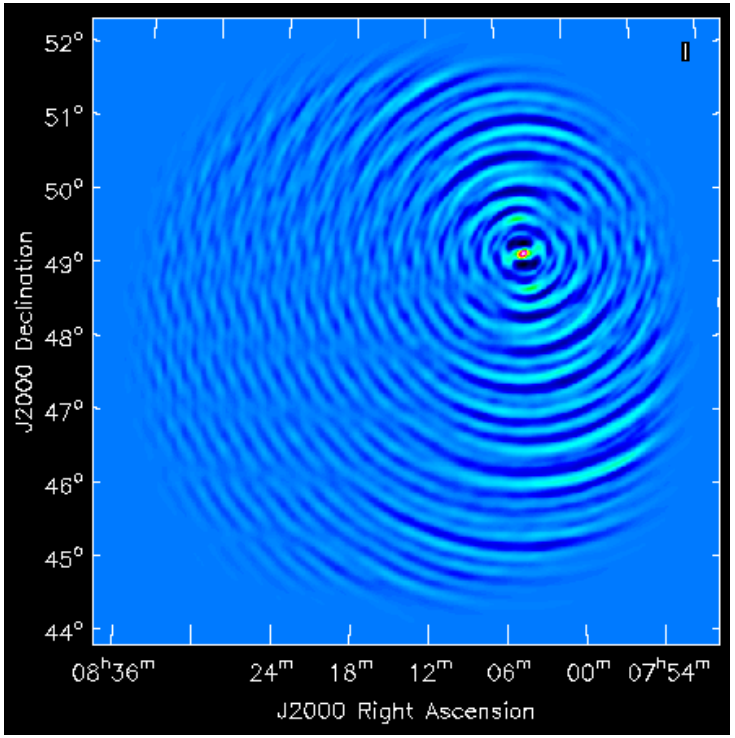
Interferometer Principle

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.



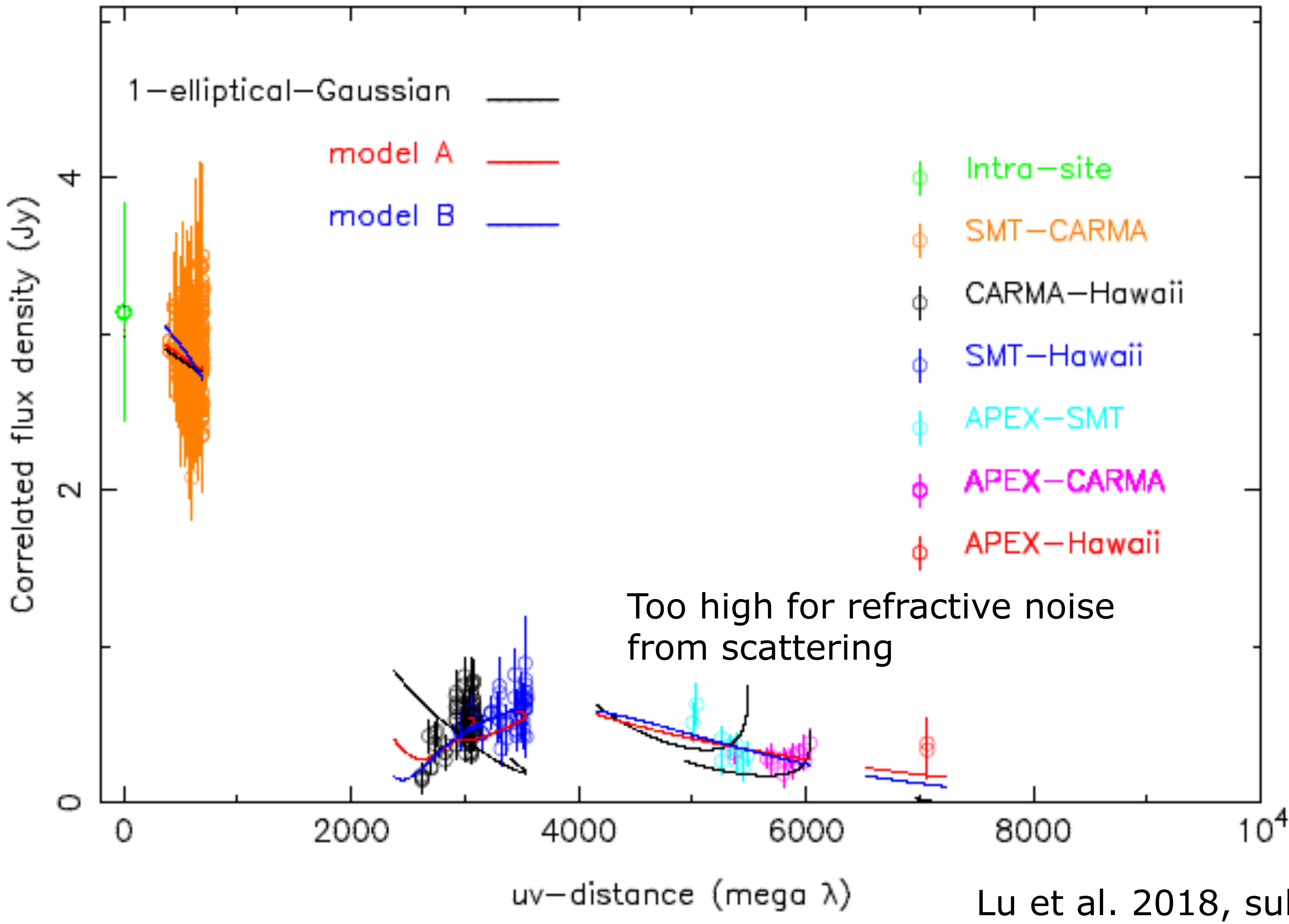
→



Slide: C. Tasse

First VLBI-Results from Apex

Radboud University Nijmegen



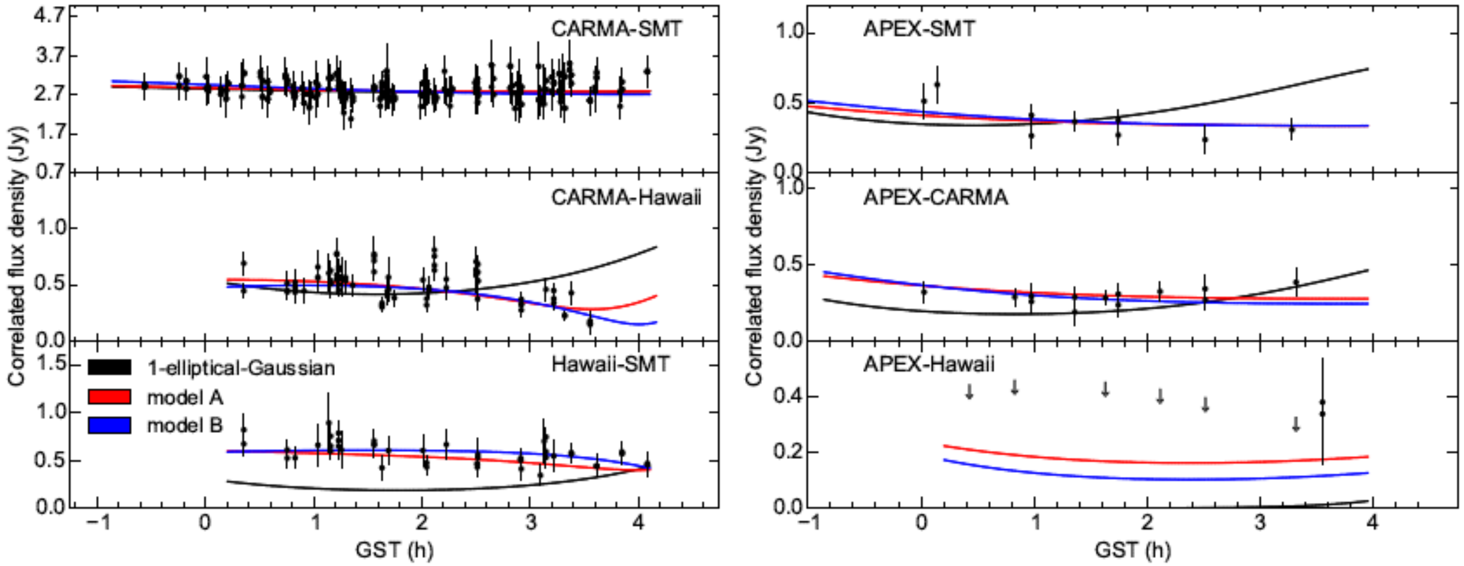
Too high for refractive noise from scattering

Lu et al. 2018, subm.

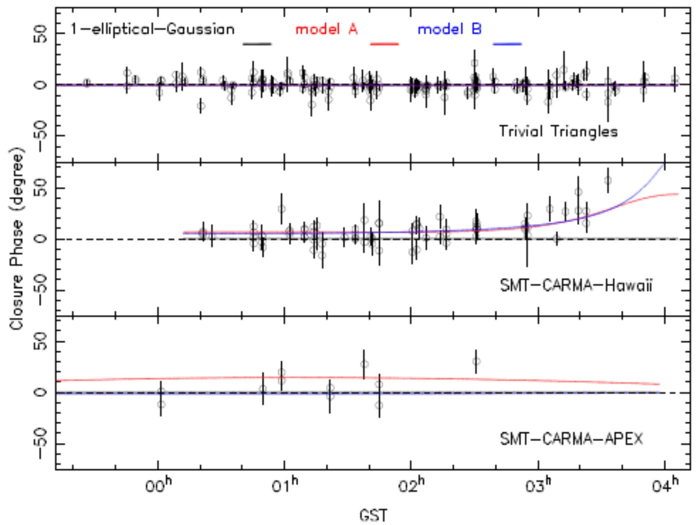
230 GHz VLBI with APEX

Radboud University Nijmegen

Correlated flux



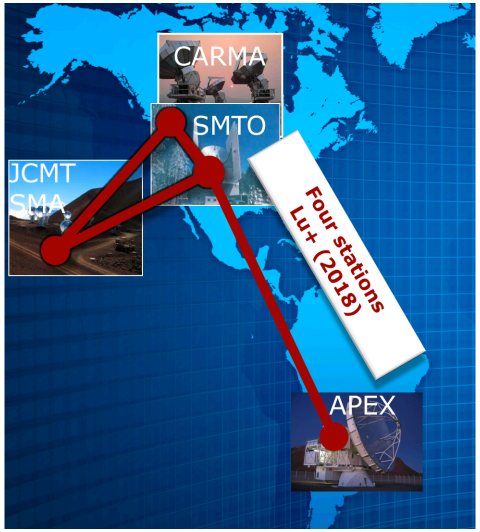
Closure phases

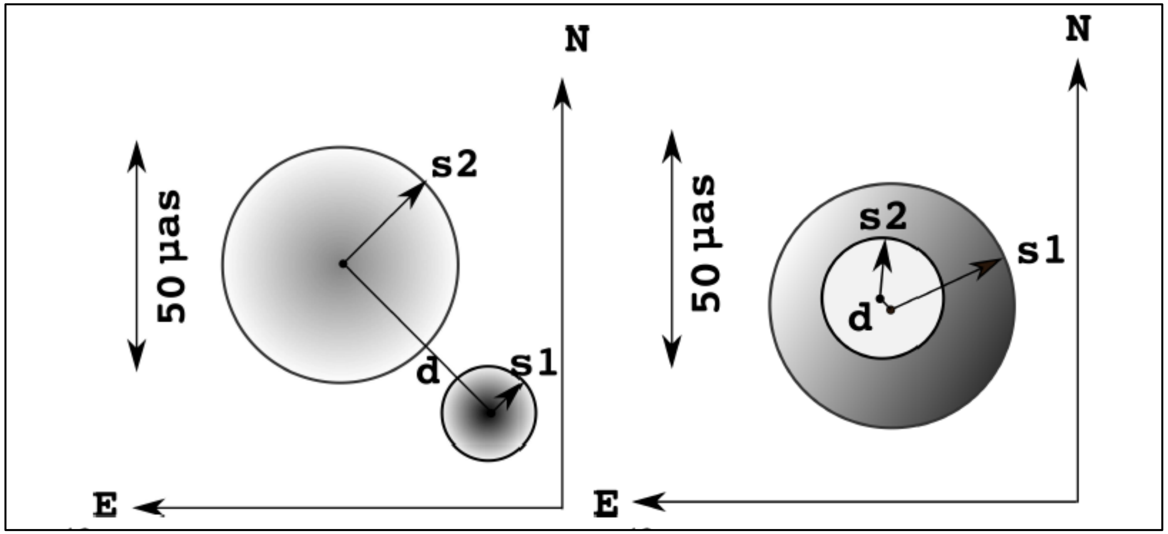


Lu et al. 2018, subm.

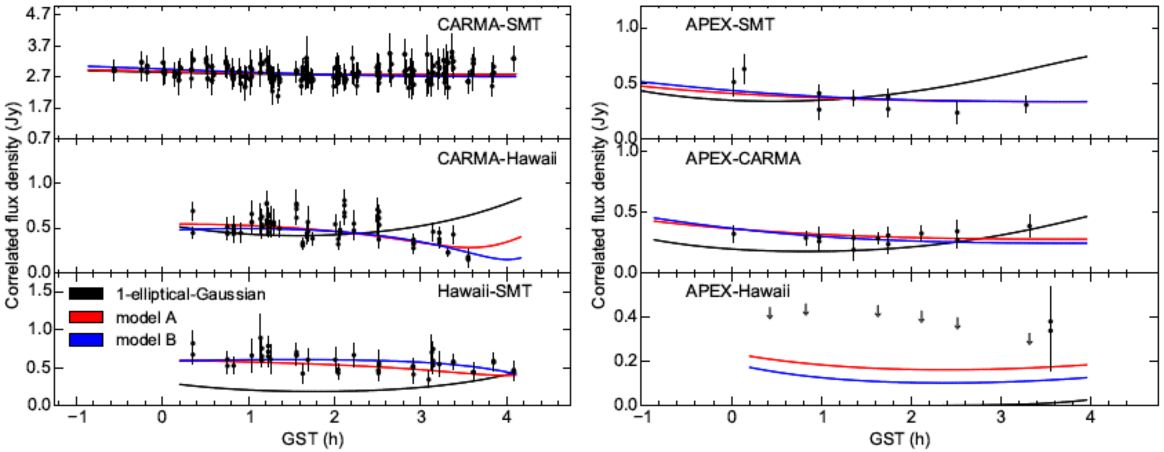
230 GHz VLBI with APEX

Radboud University Nijmegen

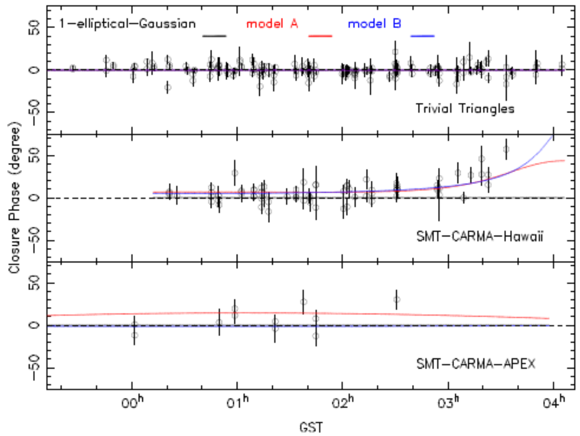




Correlated flux



Closure phases

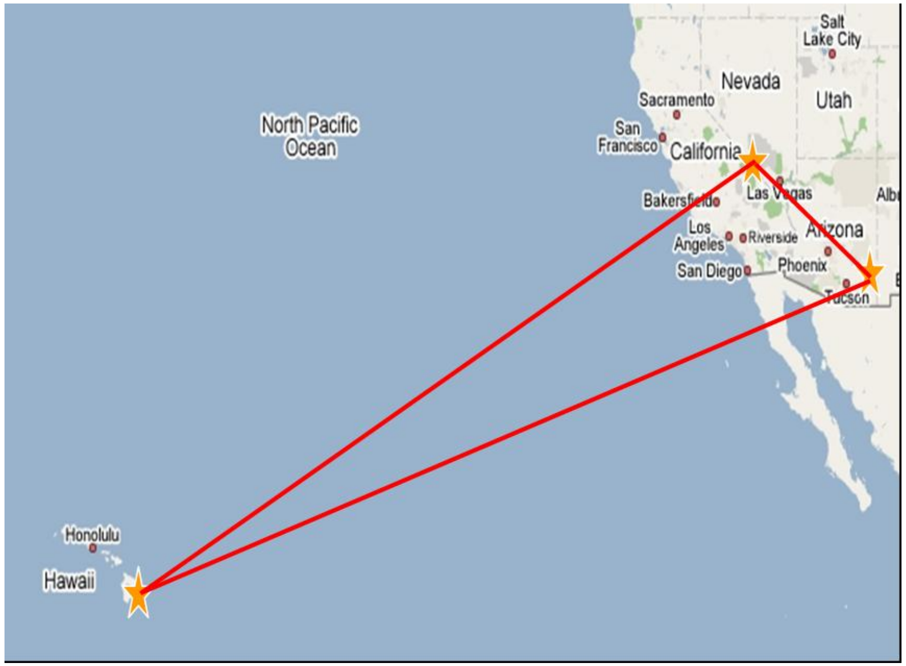


Lu et al. 2018, ApJ, subm.

EHT Closure phases at 1 mm

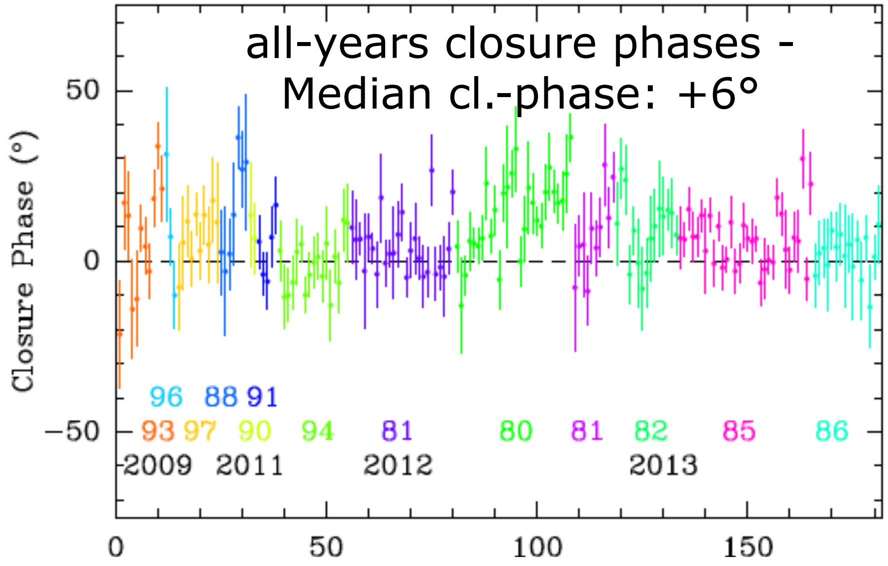
Radboud University Nijmegen

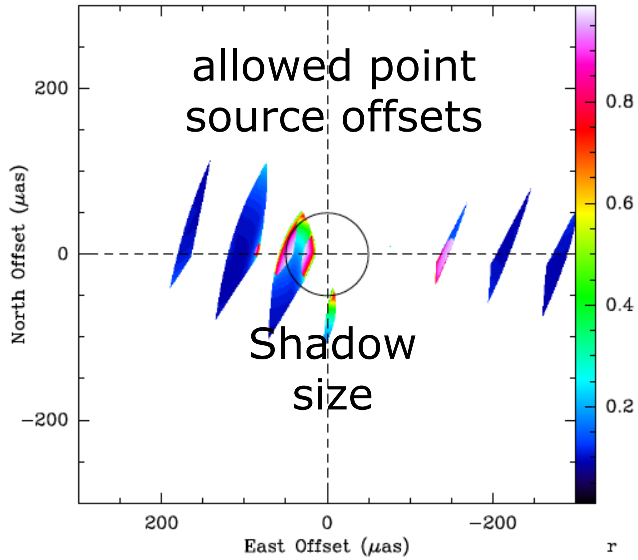
Hawaii-California-Arizona



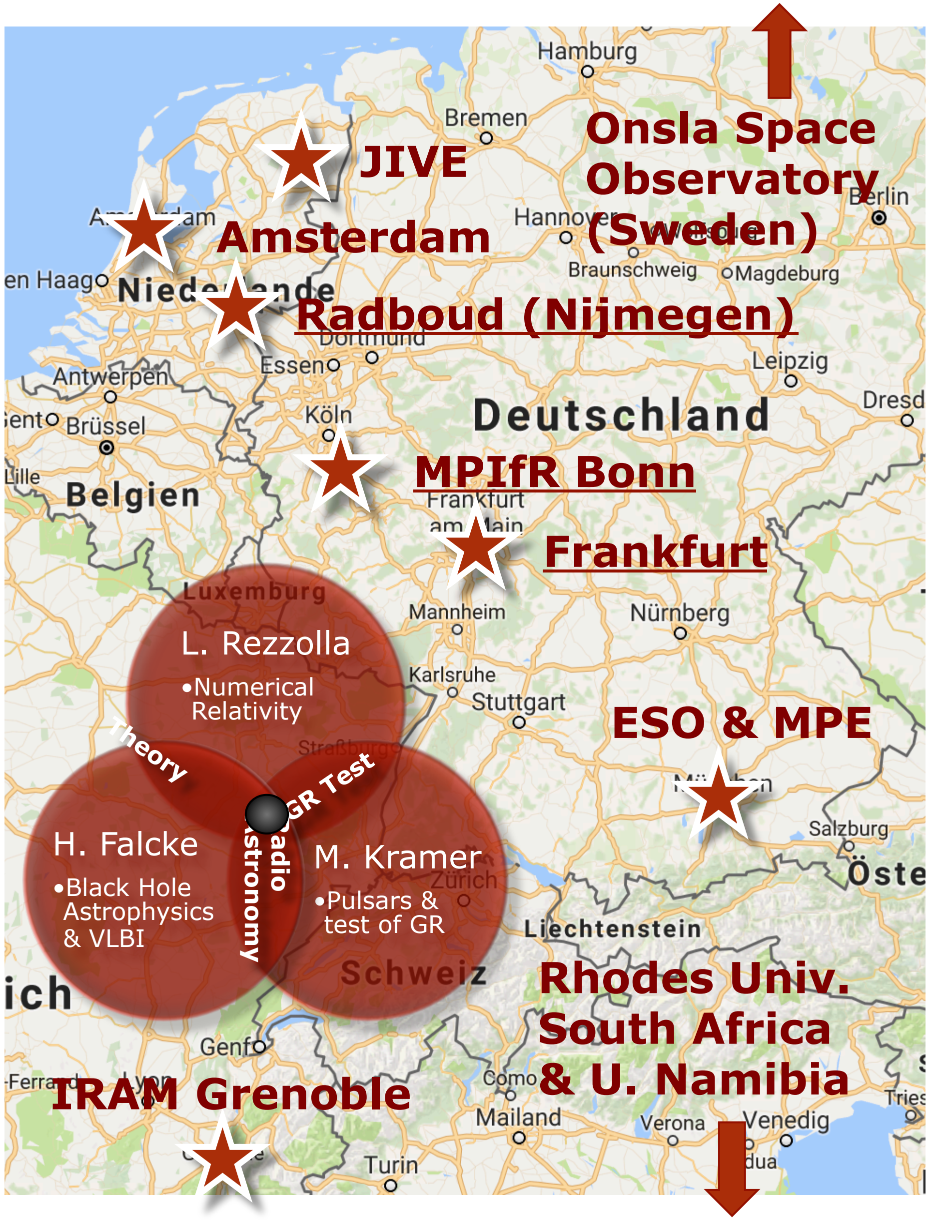
Fish et al. (2015, ApJ subm.)

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



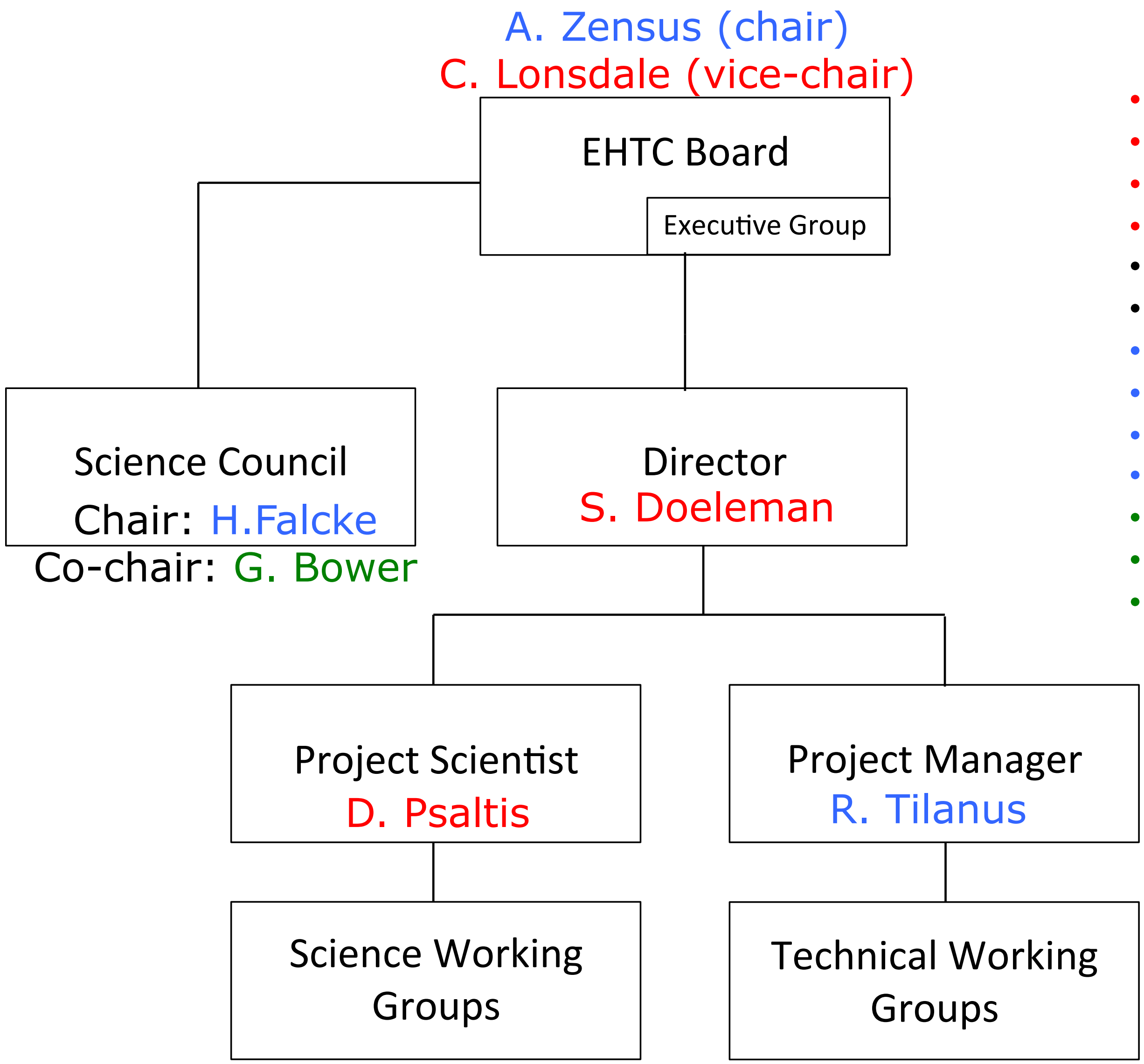


BHC Partners in Europe & Africa



- 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



About 150 individual EHT members ...

13 EHT Stakeholders

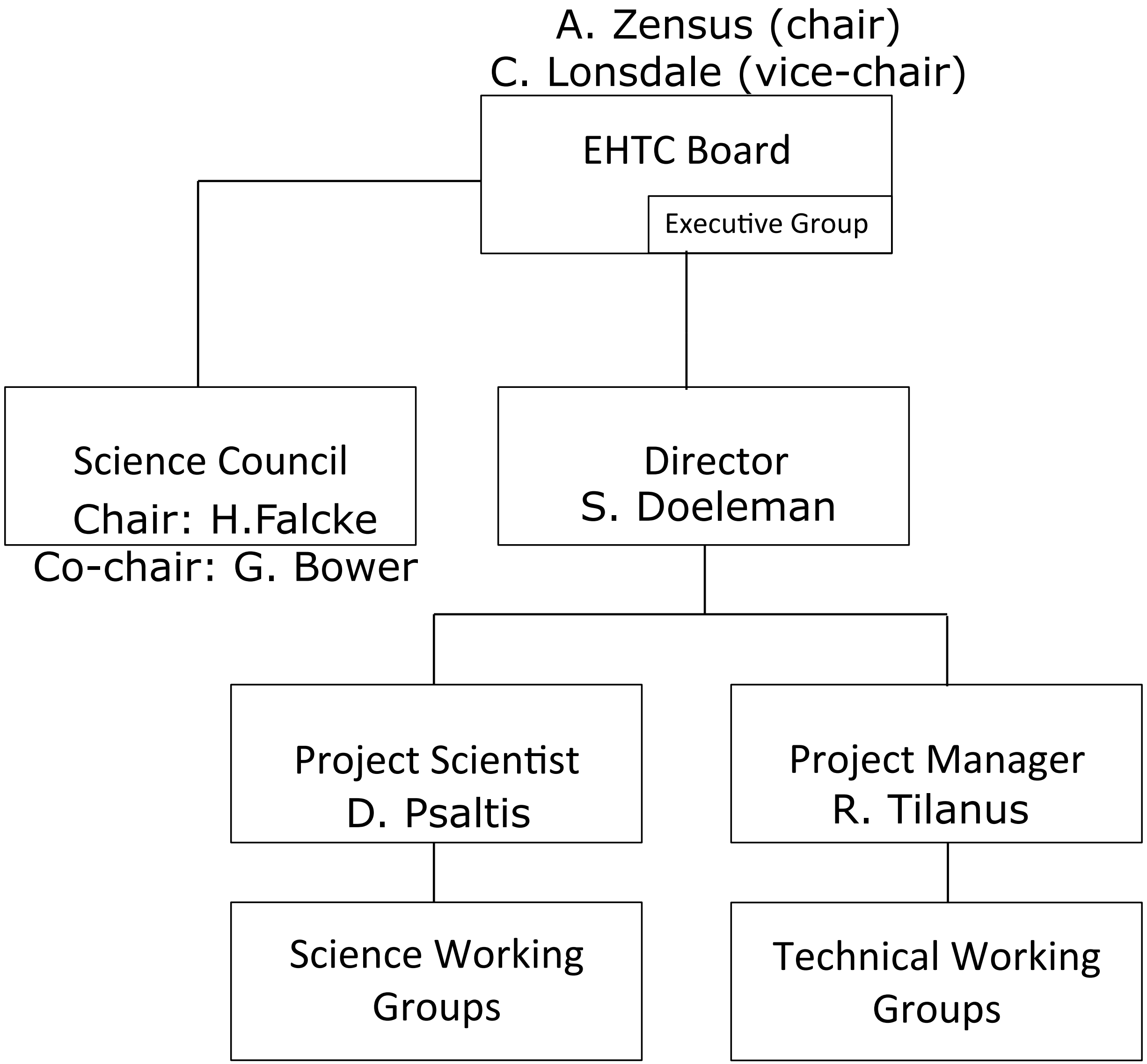
- Harvard/SAO (USA)
- MIT Haystack Obs. (USA)
- Univ. Arizona (USA)
- Univ. Chicago (USA)
- Perimeter (Canada)
- INAOE (Mexico)
- **MPIFR Bonn (Germany)**
- **IRAM (D/F/E)**
- **Radboud Uni. (Netherlands)**
- **Univ. Frankfurt (Germany)**
- EACOA (East Asia)
- NOAJ (Japan)
- ASIAA (Taiwan)

Main EU Contributions:

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

Event Horizon Telescope Consortium

Event Horizon Telescope



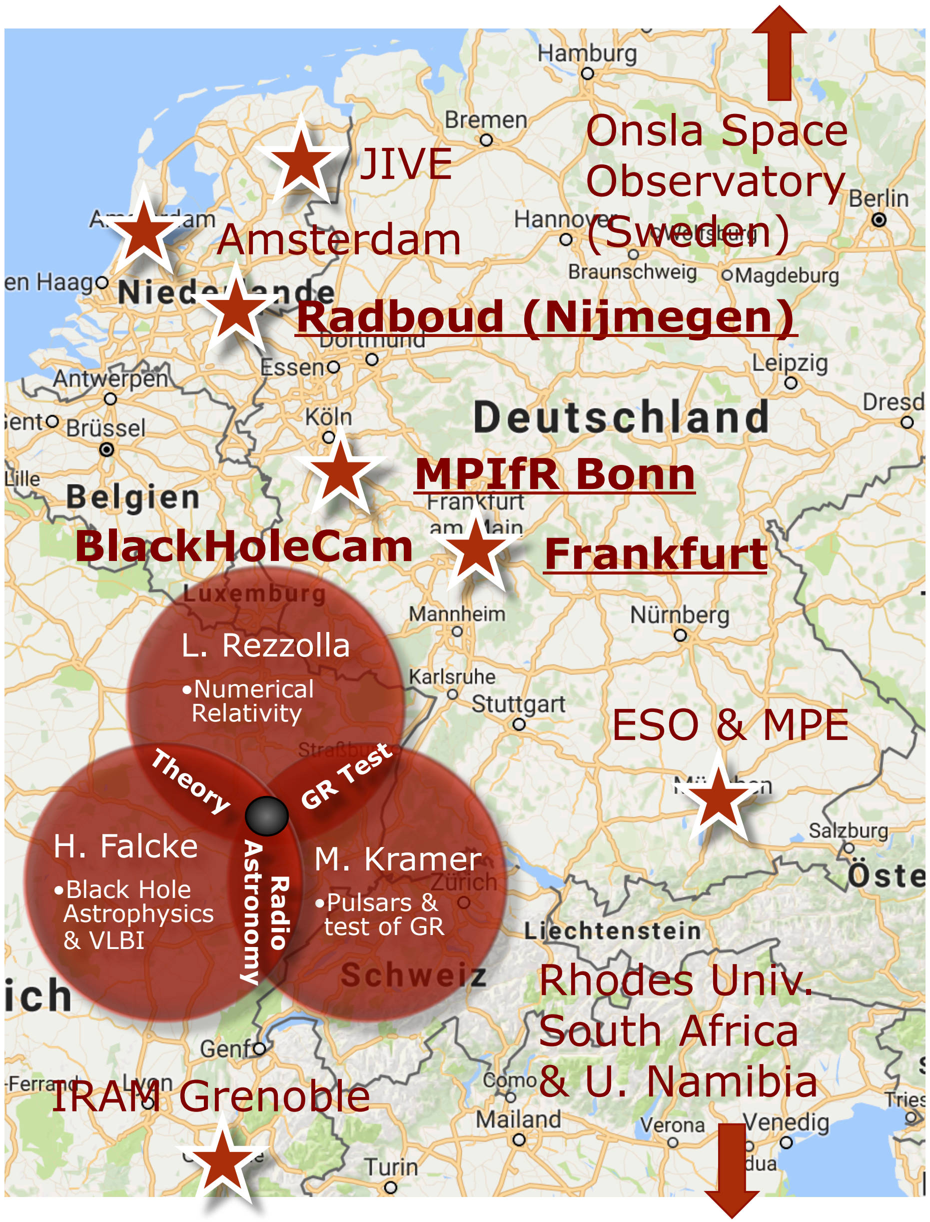
About 150 individual EHT members ...

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)

14 M€ ERC Synergy Grant BlackHoleCam & EU partners

BlackHoleCam

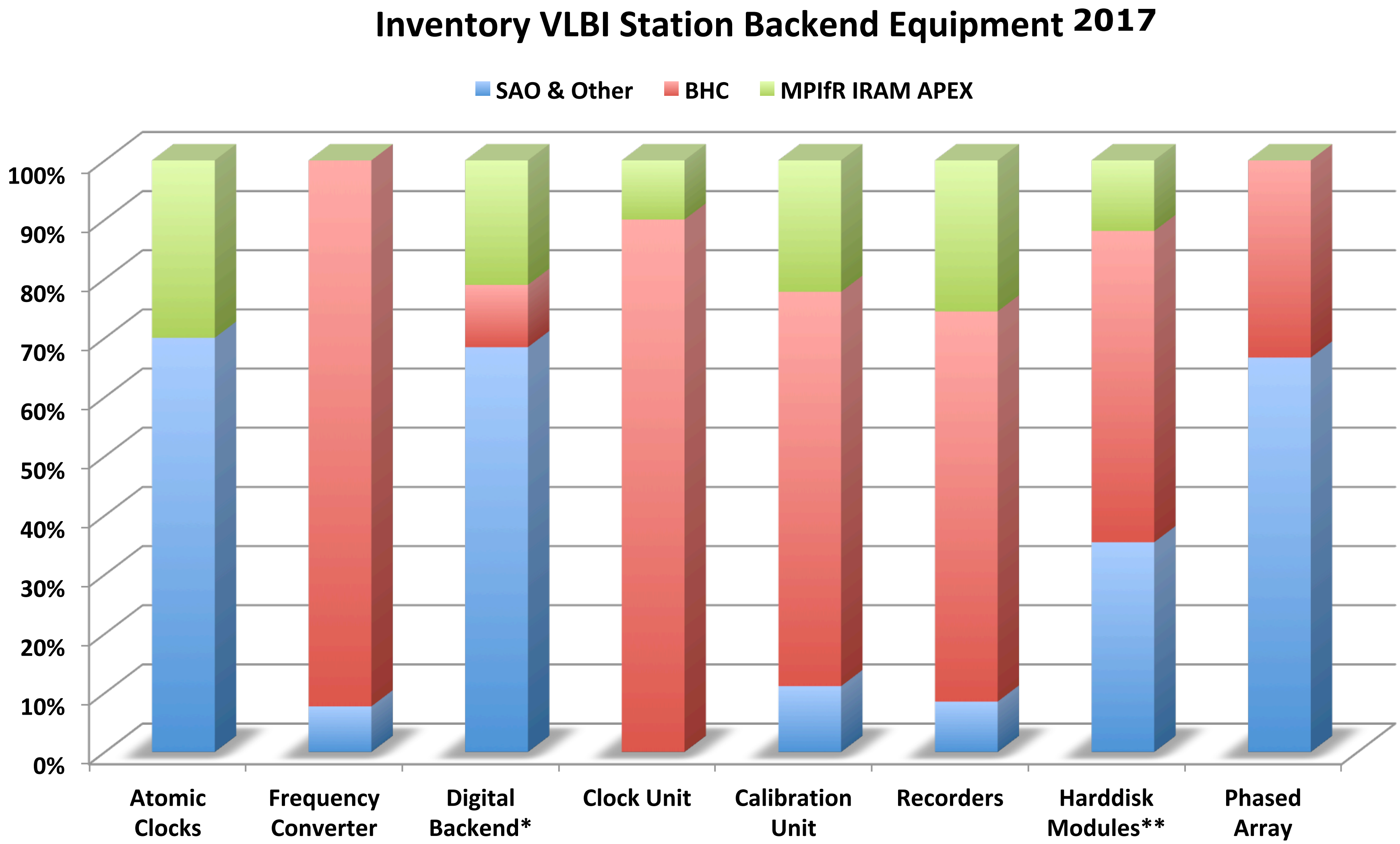


EU Players & Partners

- 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

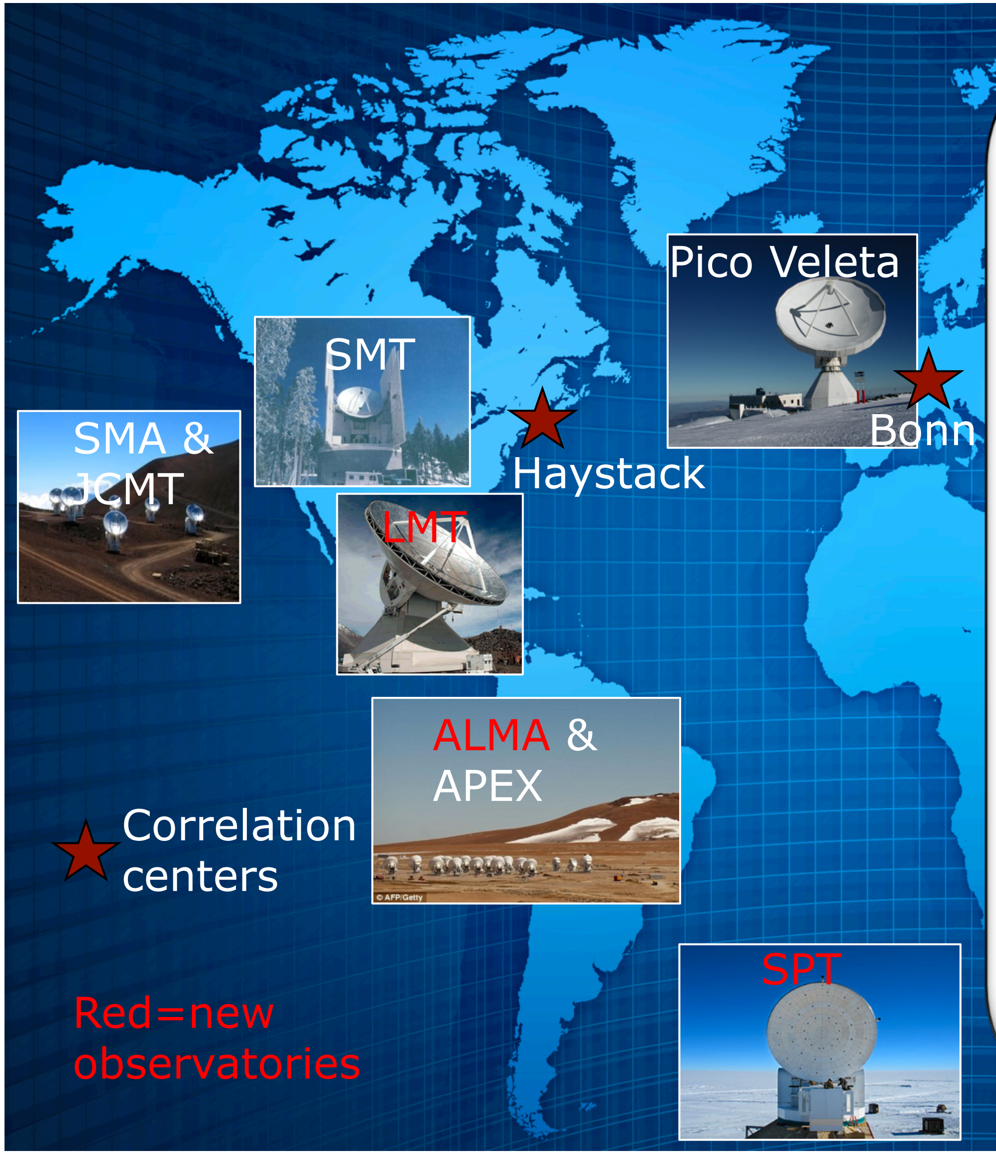
Event Horizon Telescope



Note: not all columns are the same price ...

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

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

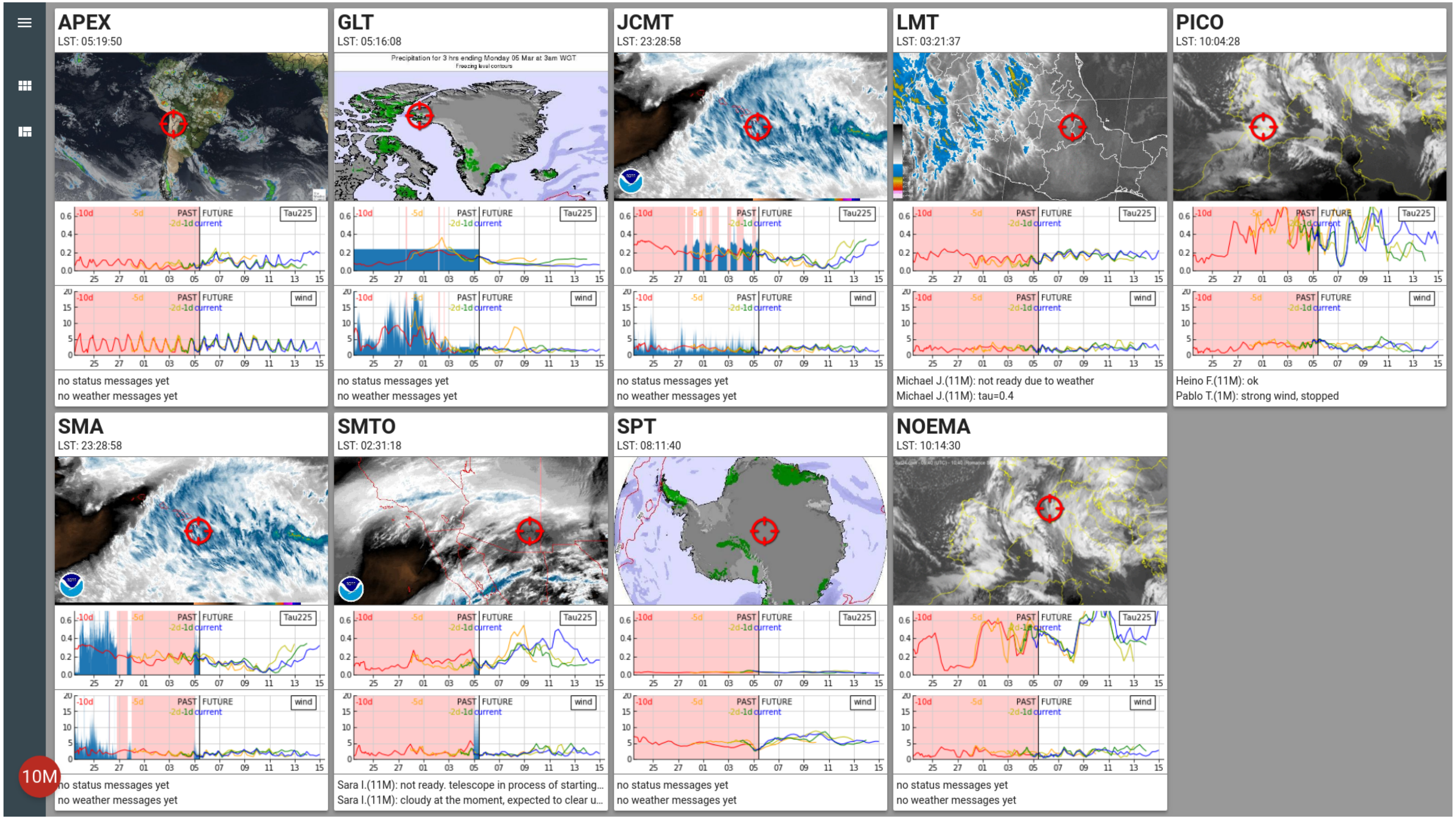
2019: Automatic
upload of schedules


1
3
4
BHC%0007/48000/4
BHC%0008/48000/4

VLBI Real Time Monitor

Radboud University Nijmegen

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

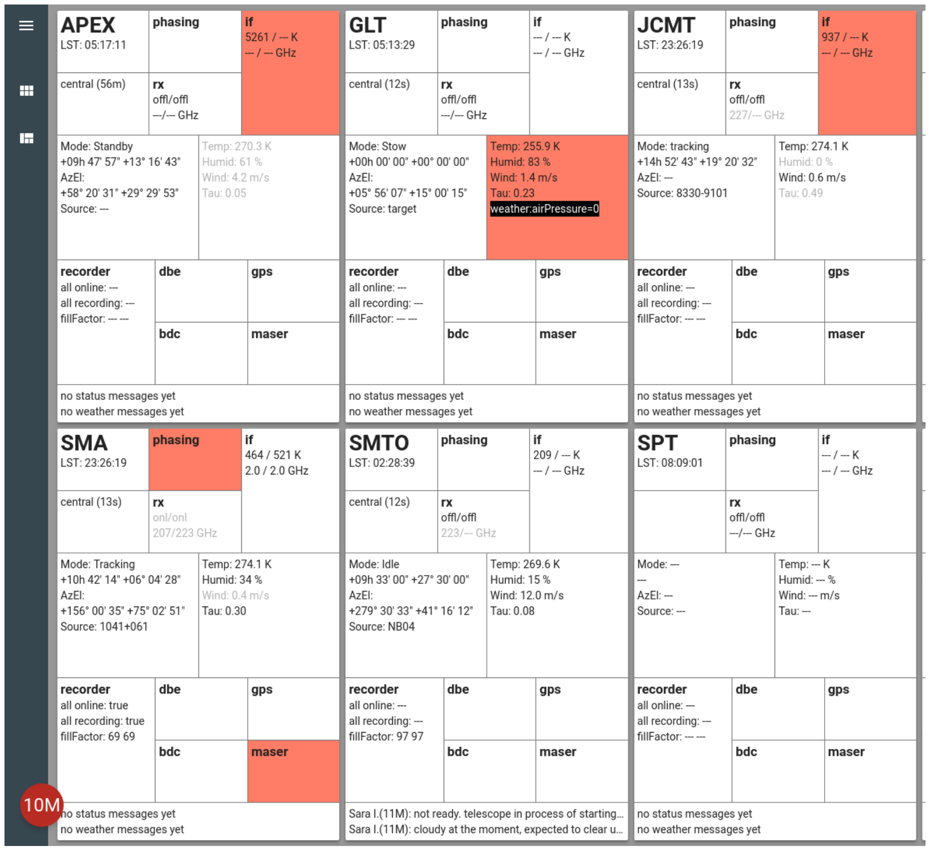


VLBI Monitor Realtime Display

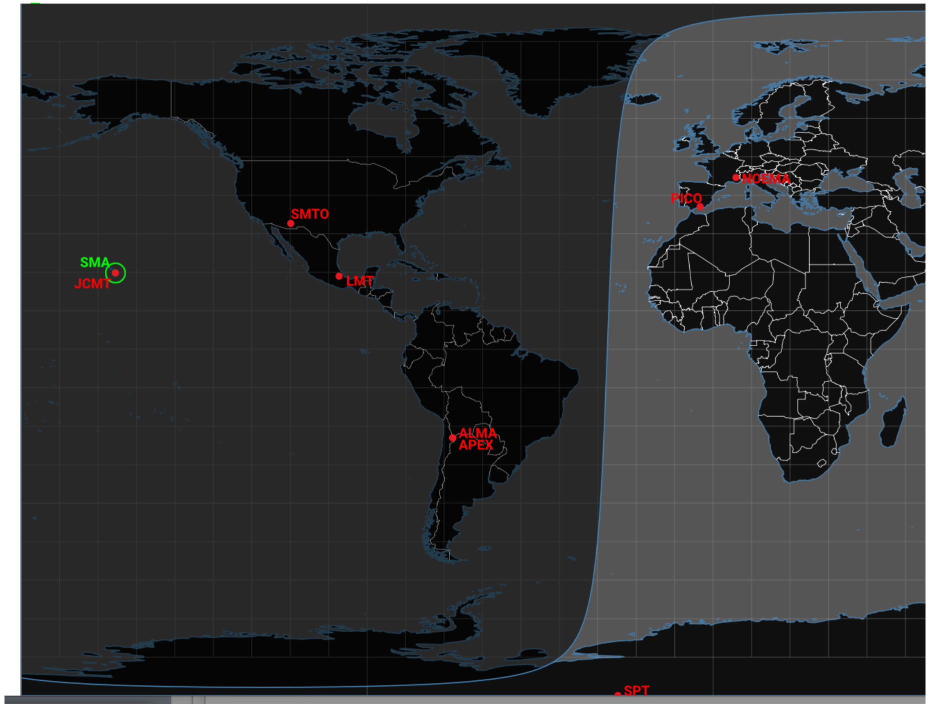
Radboud University Nijmegen

2019: logging of all metadata in one database

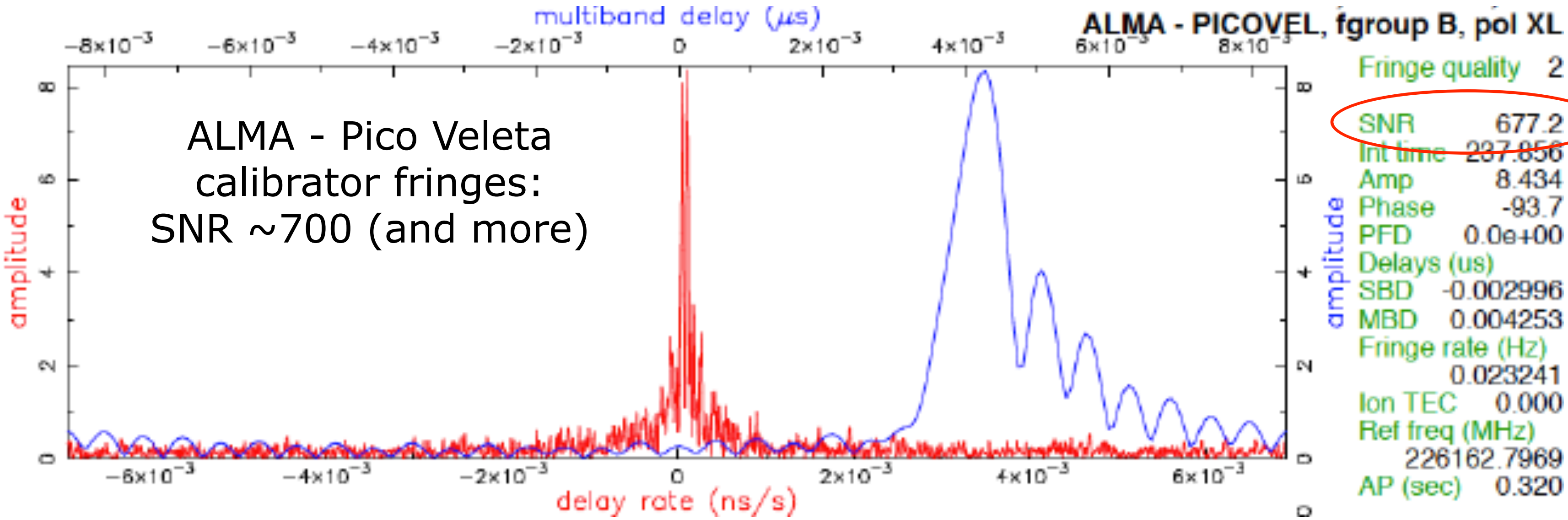
- Weather (tau, Temp, Wind, ..)
- Telescope: Tsys, Pointing, …
- VLBI equip: memory, recording, gain control, maser parameters



EHT VLBI live world map

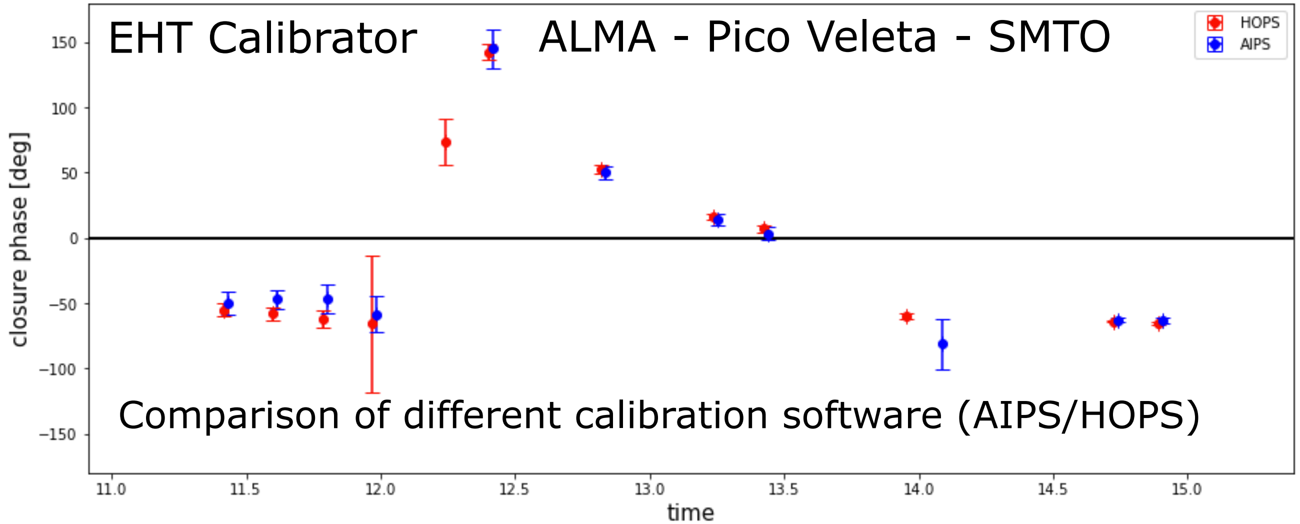


EHT 2017 – Data Quality



1mm closure phases

Multiple imaging &
calibration teams
(AIPS/HOPS/CASA)



EHT Data Analysis

Radboud University Nijmegen

- 01/2017: EHT Dress Rehearsal
- 03/2017: Operation Readiness Review
- 04/2017: observing run 6/10 days
- 06-07/2017: 1st Correlation pass
- 10/2017: 1st Engineering data release (Calibrators only) & Data issues review
- 12/2017: SPT data arrives
- 01-02/2018: 2nd Engineering data release (Calibrators only) & Data issues review
- 04/2018: Engineering data release 3: calibrators only for imaging and science analysis
- 05/2018: Earliest time to start imaging of Sgr A* and M87 with 2017 data

VLBI Software Developments

- Broad-band (AIPS/HOPS)
- New CASA VLBI (JIVE/BlackHoleCam)
  - fringe fitter
  - various scripts
- CASA/HOPS/AIPS cross-comparison
- Multiple …
  - imaging algorithms
  - imaging challenges
  - imaging teams

Picard: CASA VLBI Pipeline

Radboud University Nijmegen

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

Measurement Set

Load FITS-IDI files

<u>Features</u>
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

<u>Diagnostics</u>
print input parameters

plots of calibration solution tables

metedata overview

flag tables

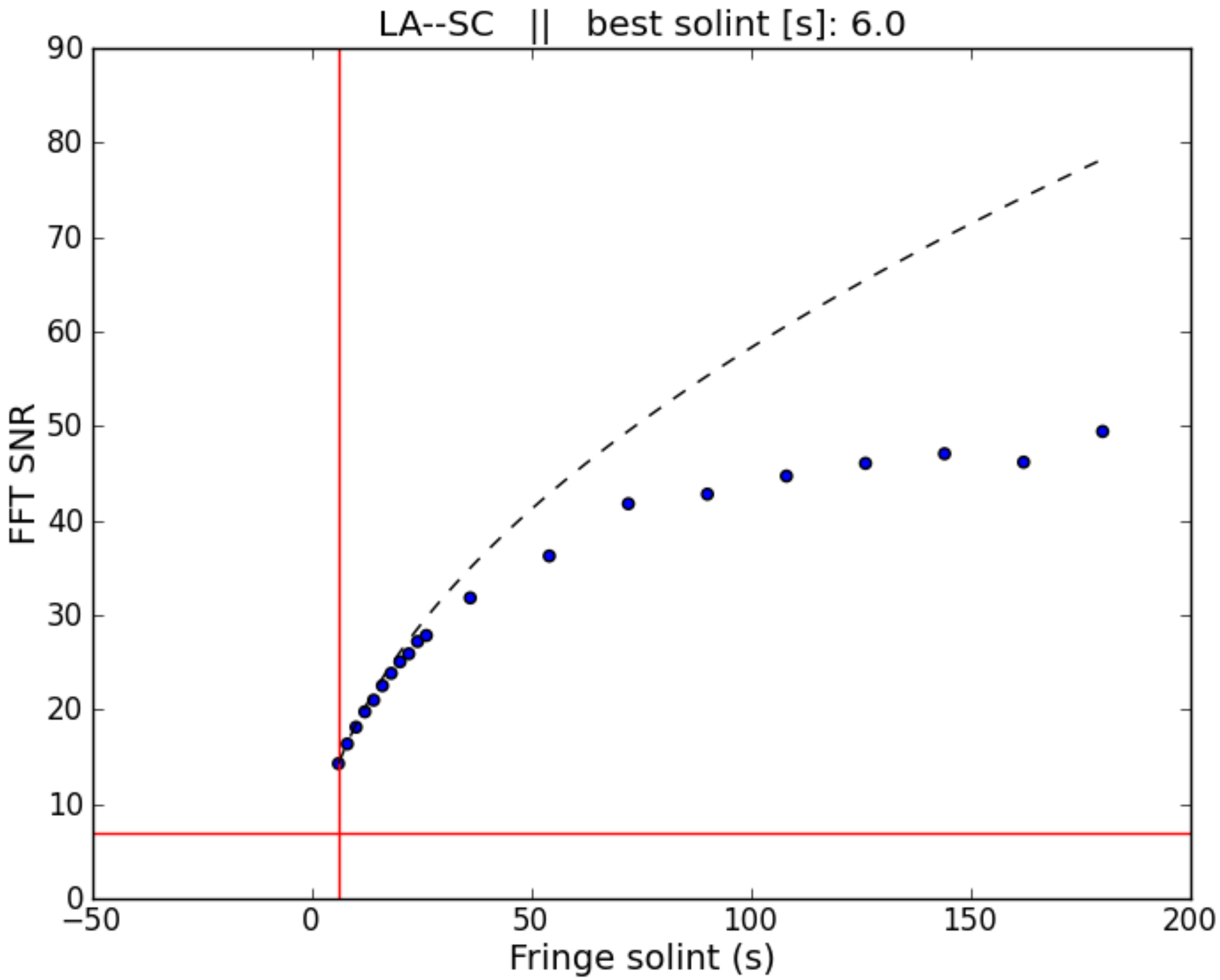
summary file of observation

plots of calibrated visibilities

M. Janssen (Radboud Univ)

Heuristic parameters

Radboud University Nijmegen



M. Janssen (Radboud Univ)

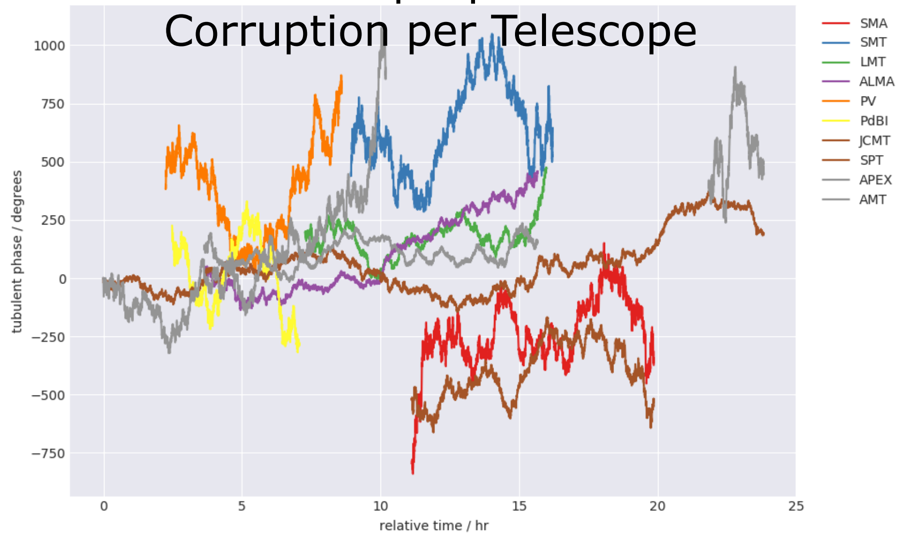
MeqSilhouette + CASA Pipeline

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

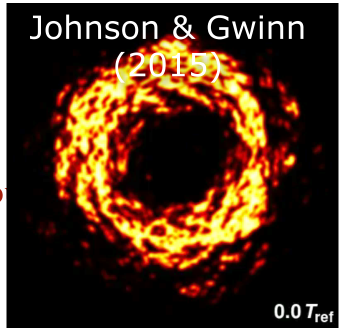


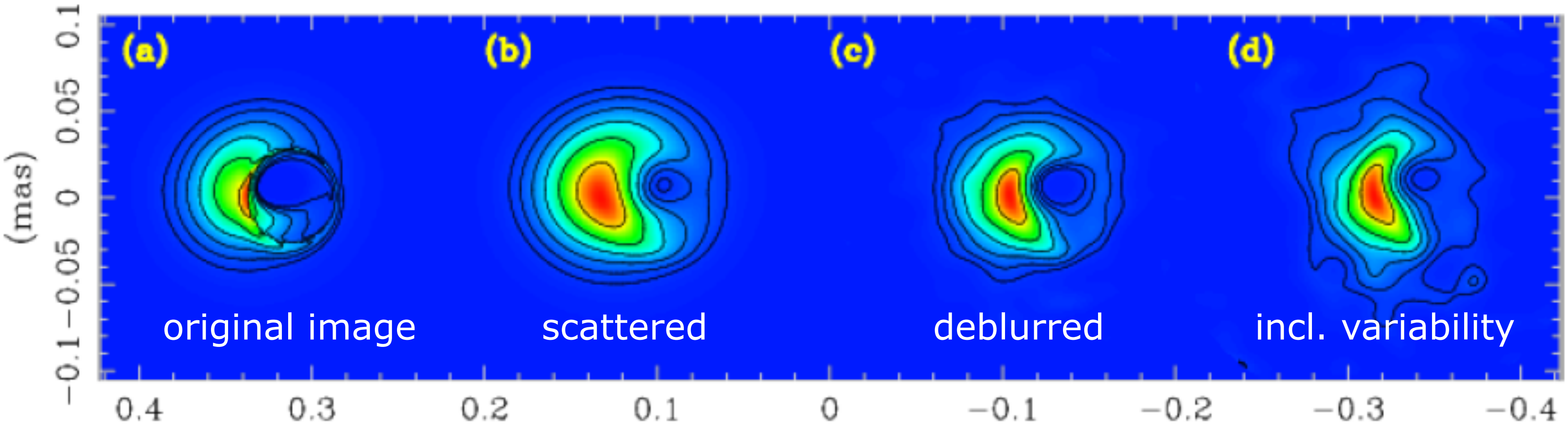
Current development

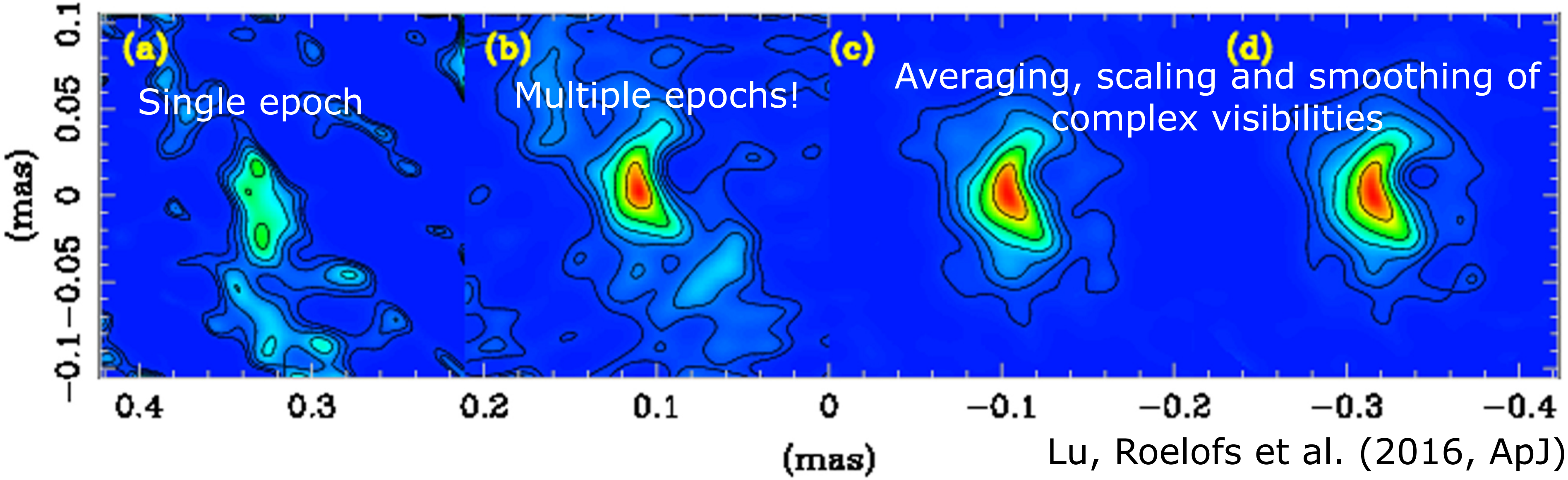
- MeqSilhouette + CASA Pipeline + Metadata from VLBI Monitor (**F. Roelofs**)
- Compare synthetic data to actual EHT data ⇒ quantify black hole parameter uncertainties

What we **might** see

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





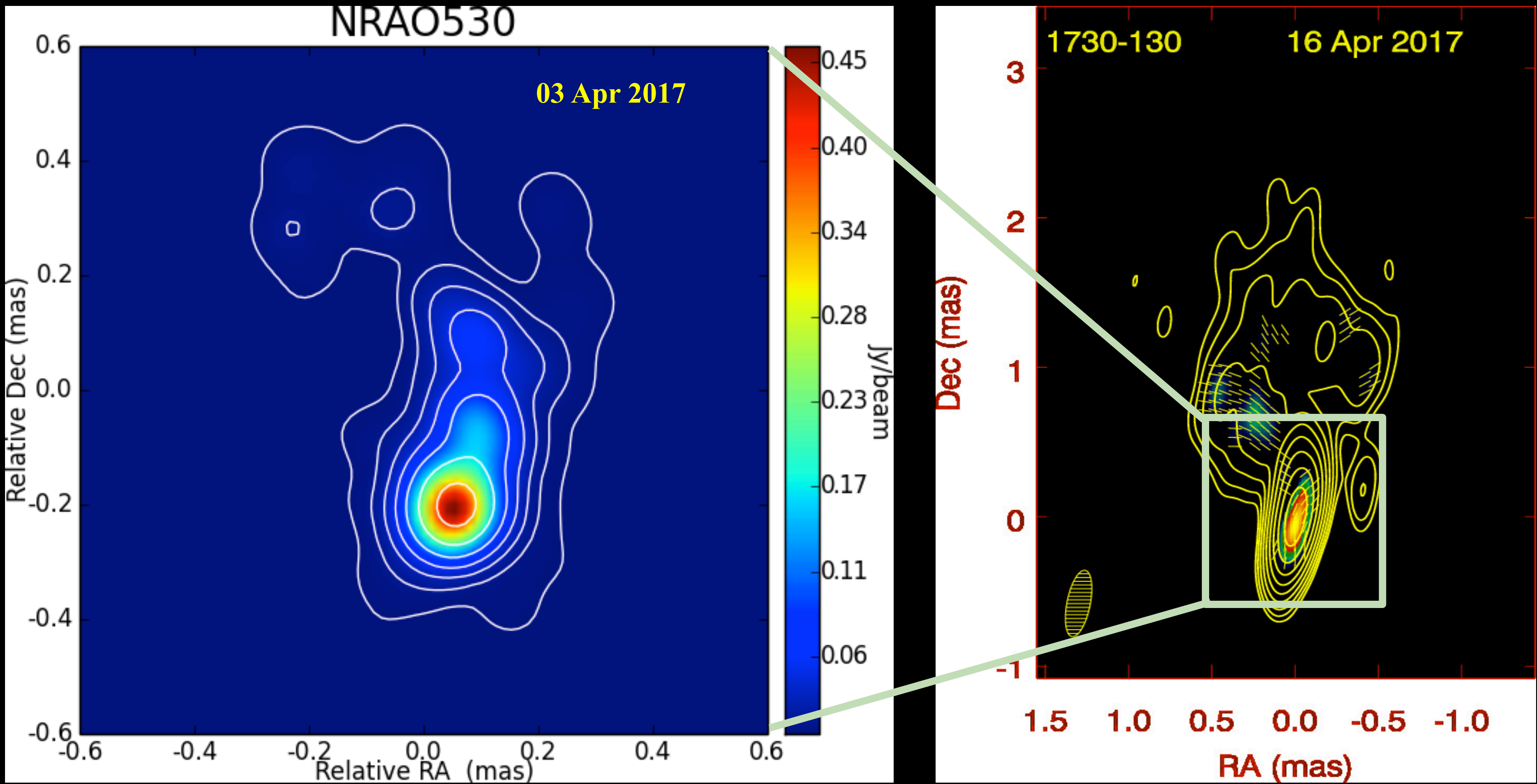


Lu, Roelofs et al. (2016, ApJ)

First VLBI with ALMA in April 2017

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

The first image from VLBI with ALMA



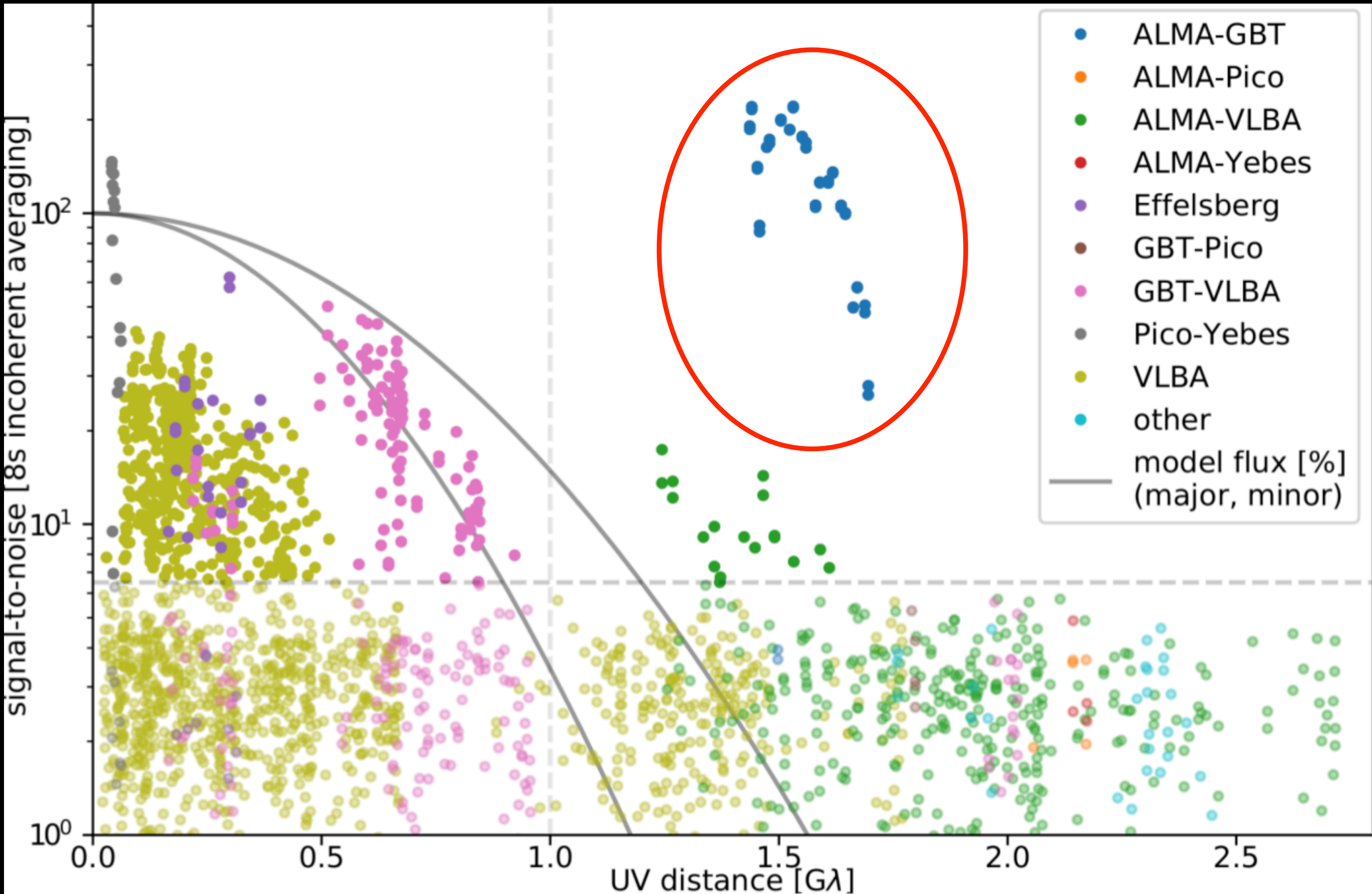
Closure imaging using MEM with the *EHT-imaging* library (Chael et al. 2018)

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

Radboud University

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

Current solid detections of Sgr A*

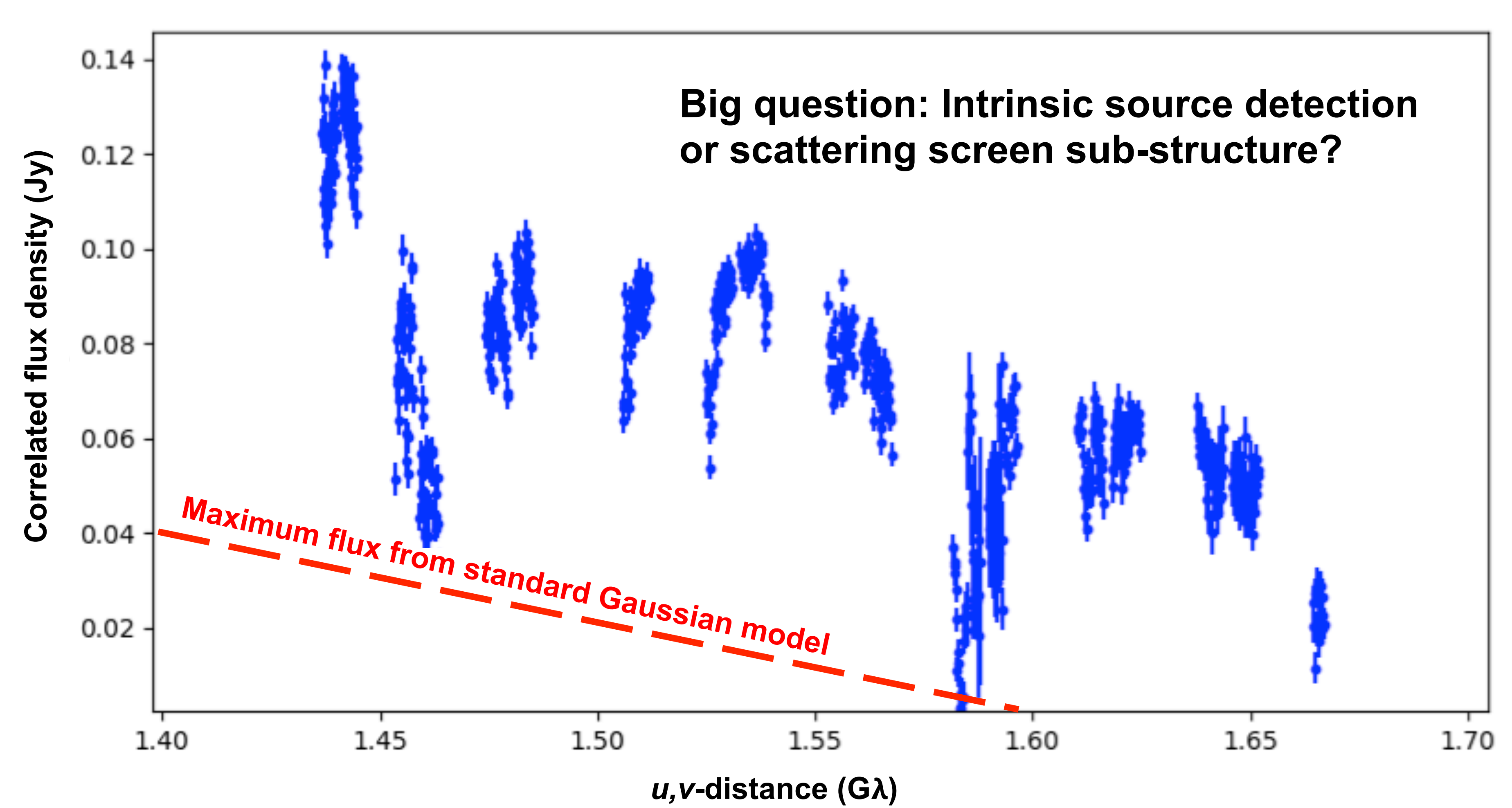


BLACK HOLE CAM | CfA | erc | Radboud University

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

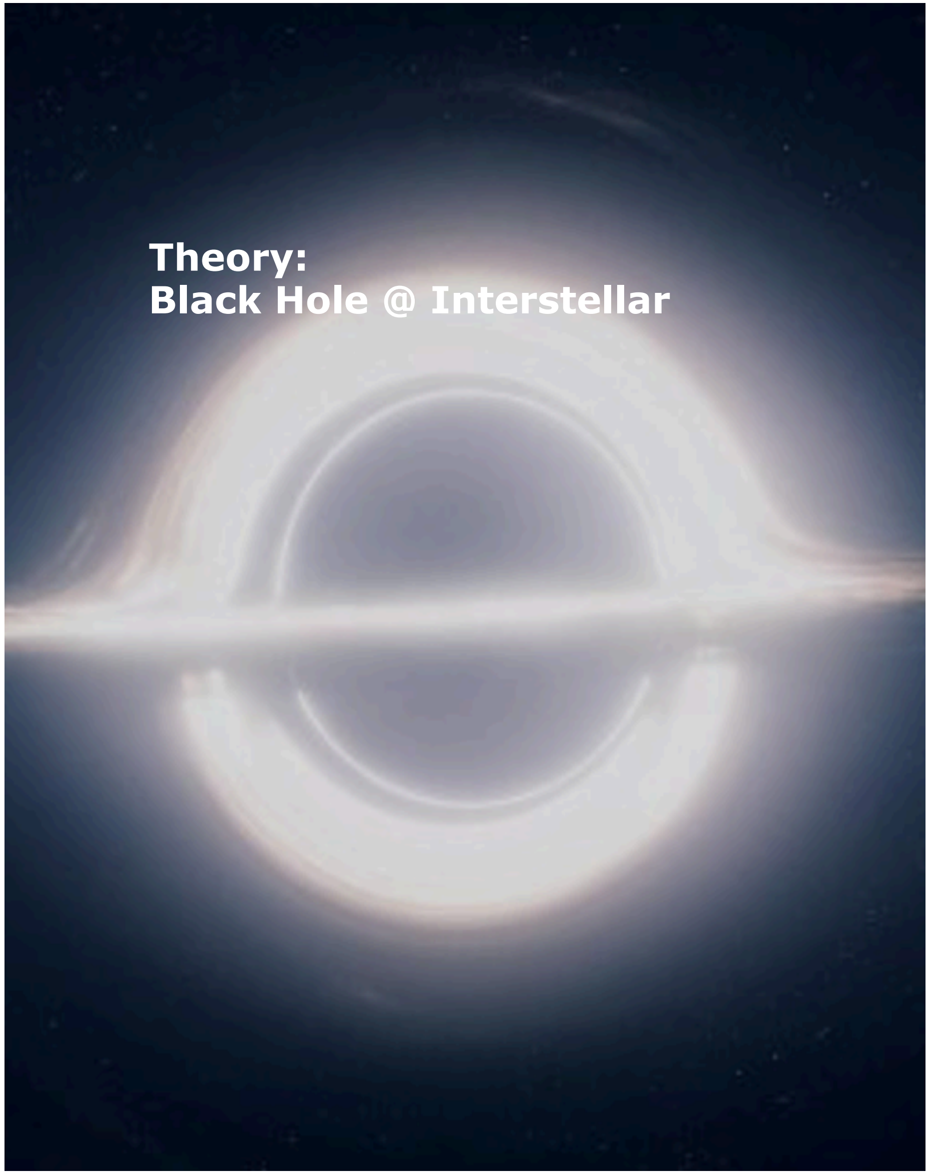
Significant non-Gaussian flux detected

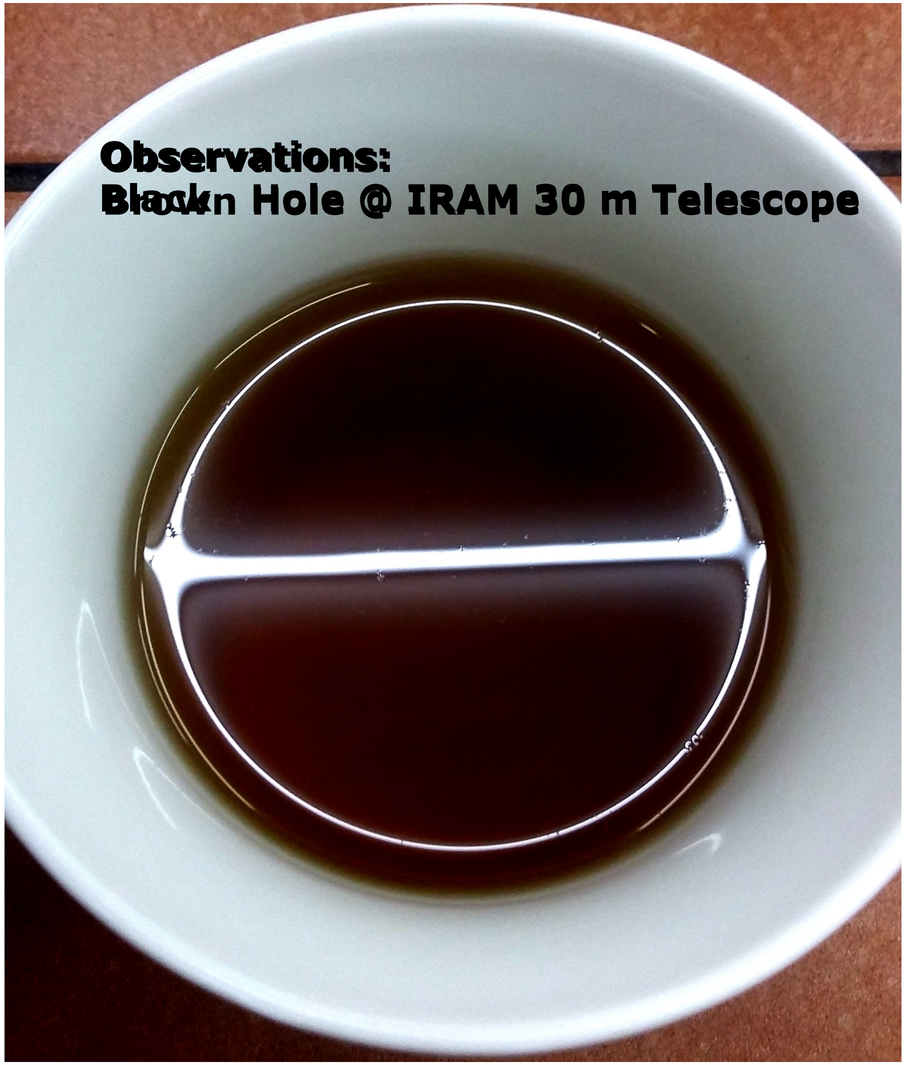
ALMA - GBT baseline on Sagittarius A*



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

Scientists stunned by first image of black hole

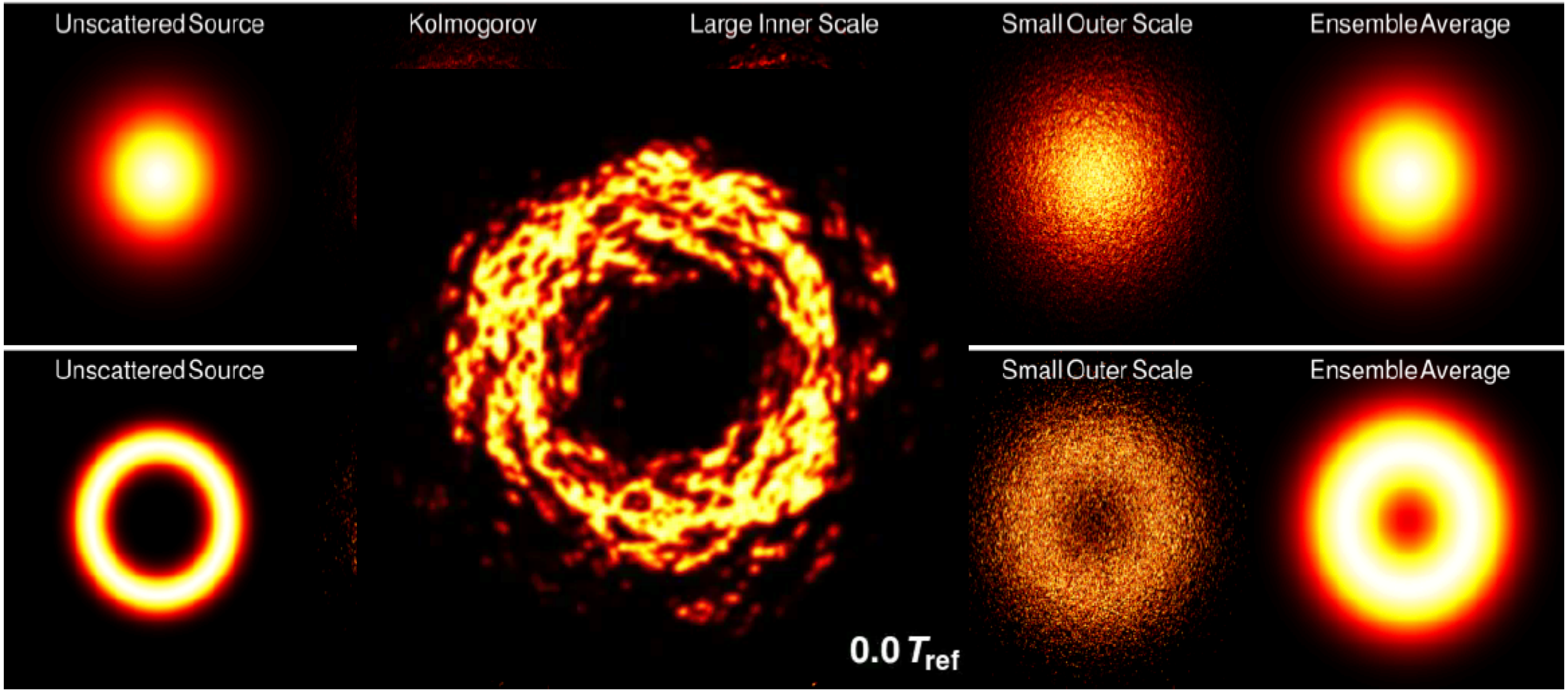




Ignacio Ruiz

Scattering

Radboud University Nijmegen

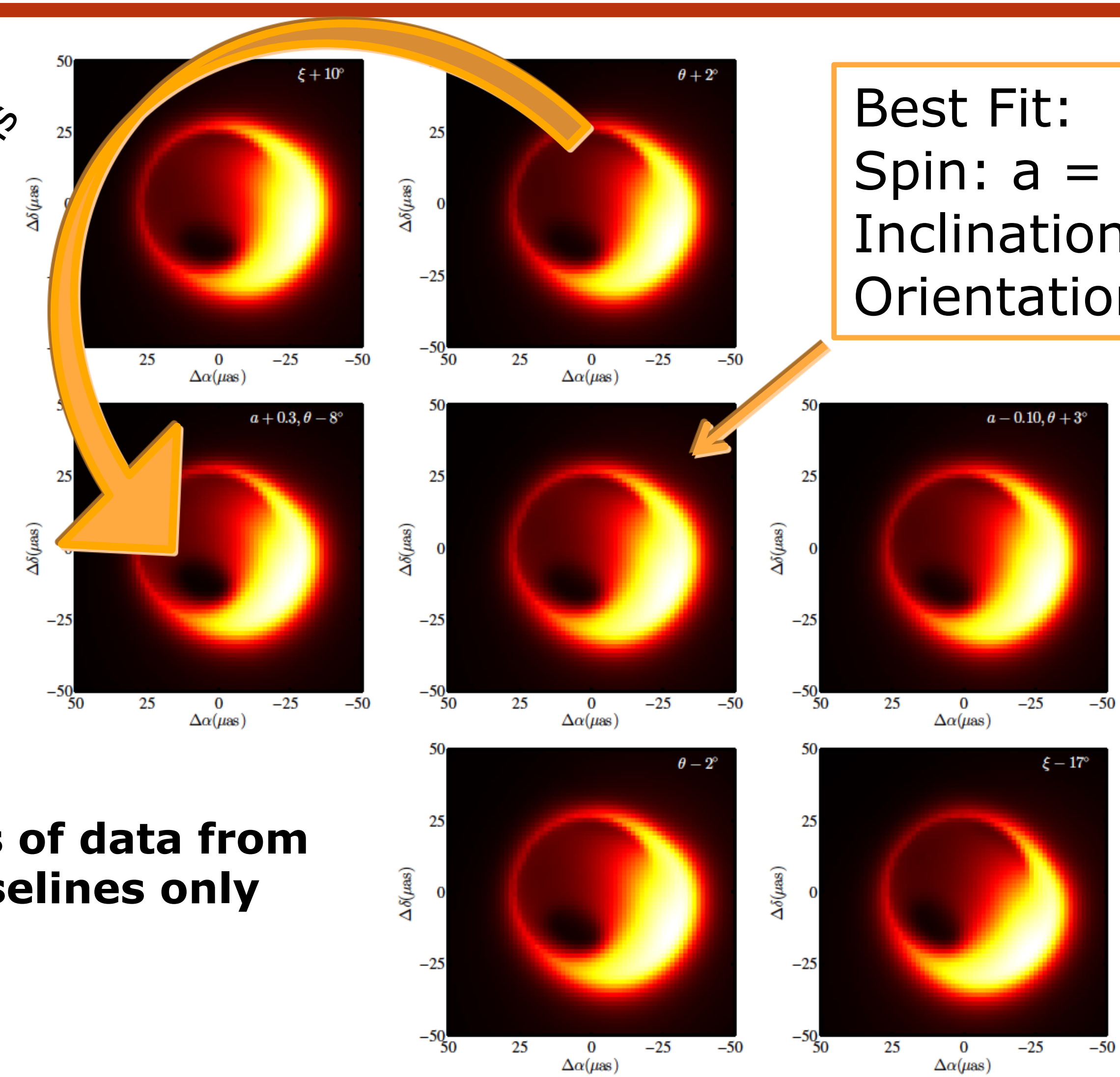


Johnson & Gwinn (2015)

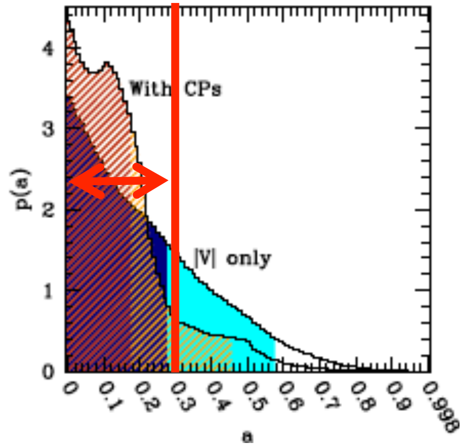
Fitting optimal shadow model to get BH parameters

Radboud University Nijmegen

1 σ variations



Best Fit:
Spin: a = $0.10_{-0.1}^{+0.3}$
Inclination θ = 60º±3º
Orientation: ξ= 156º±15º



Spin

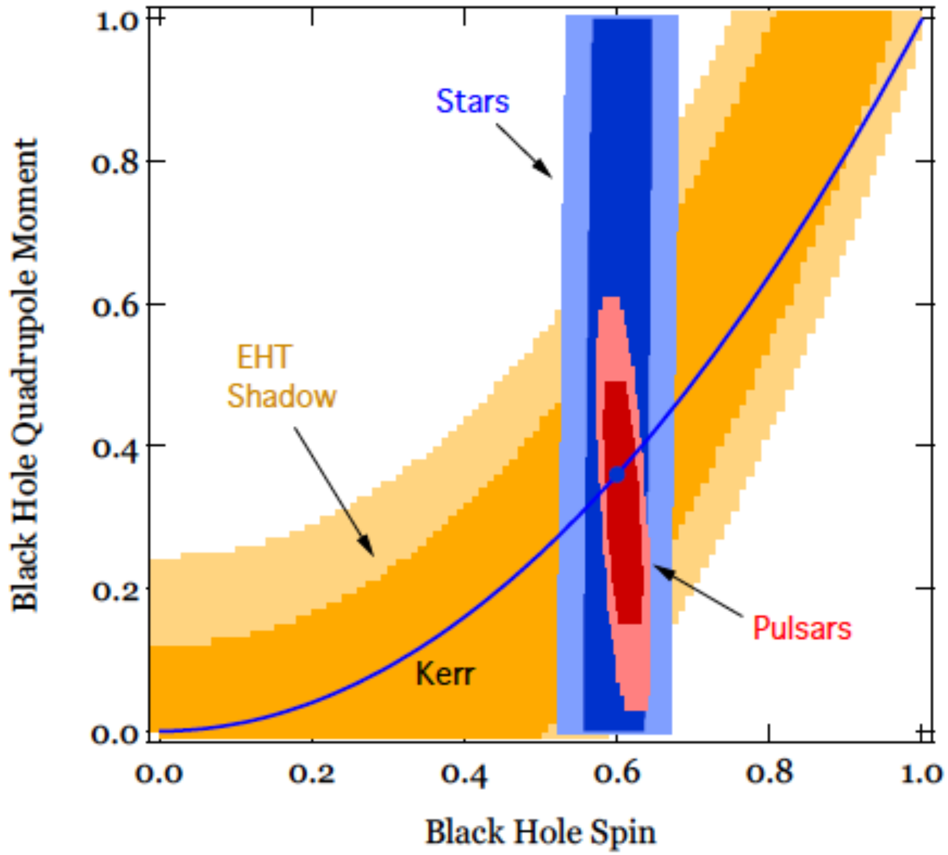
7 years of data from 3 baselines only

Broderick et al. (2016)

Multimessengers: Stars, Pulsars, EHT

Radboud University Nijmegen

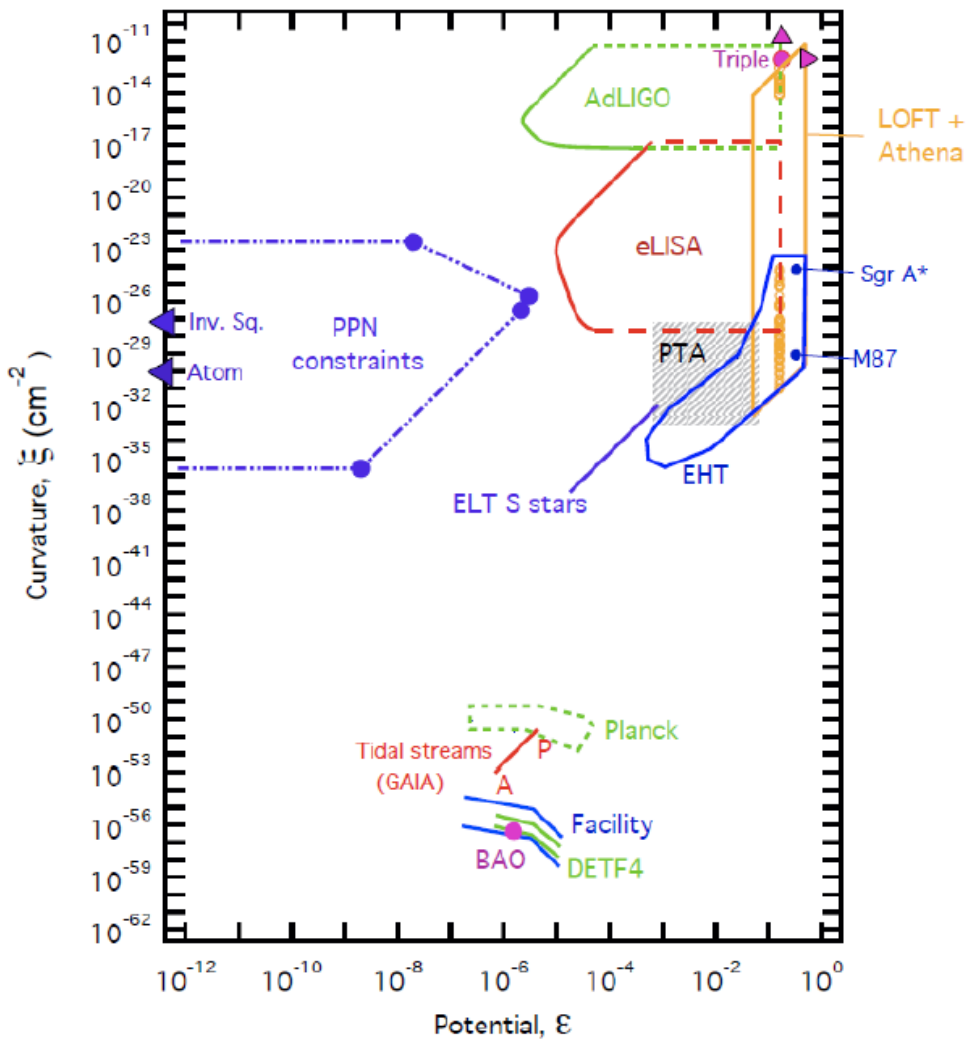
- Shadow alone may not be enough
- Black-hole spin and quadrupole moment are ambiguous
- Add orthogonal constraint from orbits of stars and pulsars
- May allow tests of GR in strongly curved static space time.



Psaltis, Wex, Kramer (2016)

EHT and LIGO

Radboud University Nijmegen

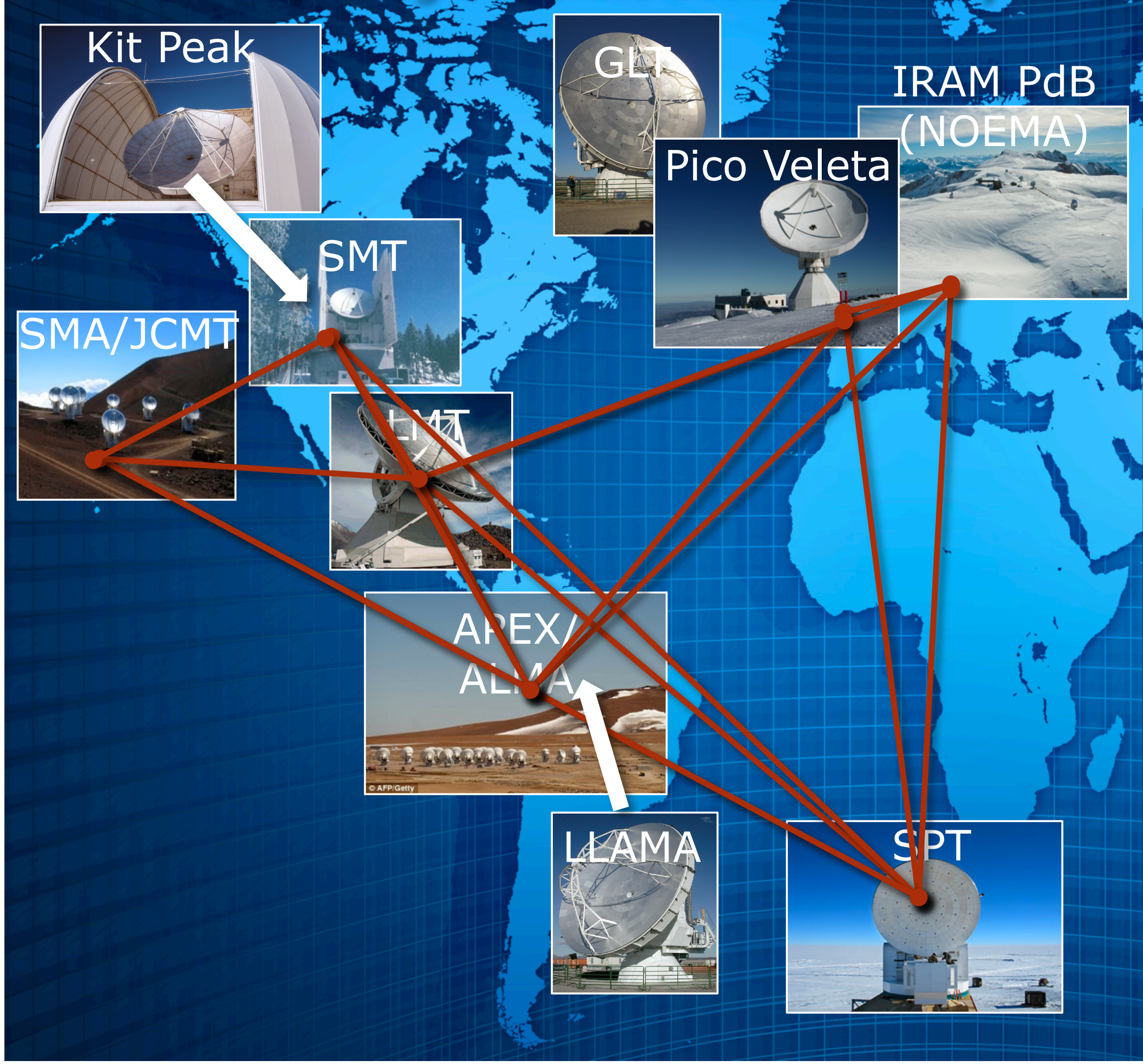


Baker, Psaltis, Skordis (2015)

Event Horizon Telescope Upgrades

Event Horizon Telescope

Very Long Baseline Intereremetry at mm-waves (mmVLBI)



Next run:

- April 16-30
- Double Bandwidth
- (8 GHz, 2 pol)

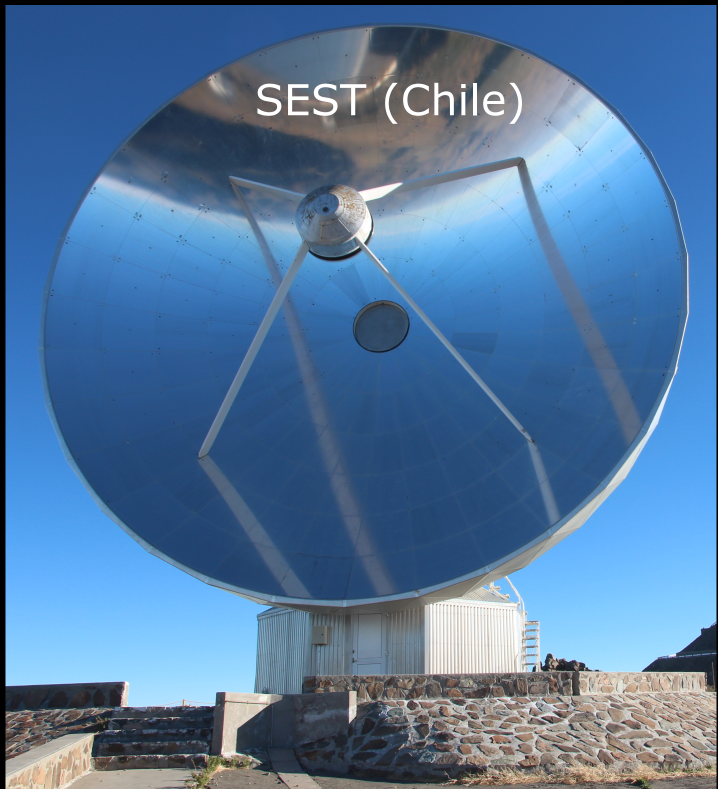
New Telescopes:

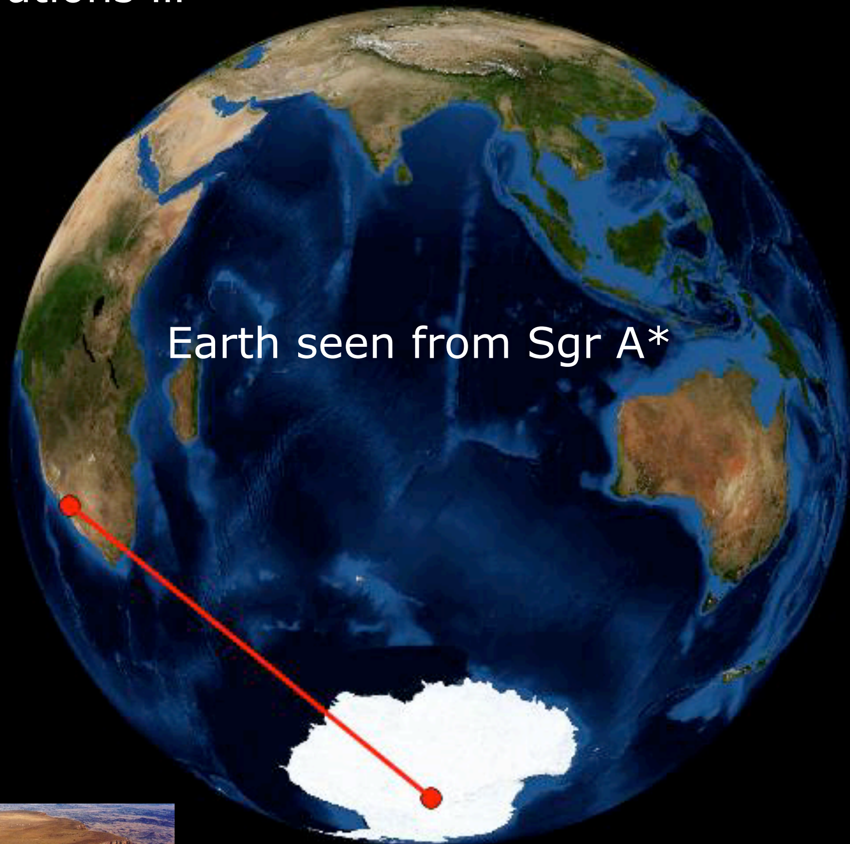
- Greenland Telescope (2018)
- Kit Peak (2019)
- NOEMA (2020) 10x15m dishes!

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 …





Gamsberg
(Namibia)

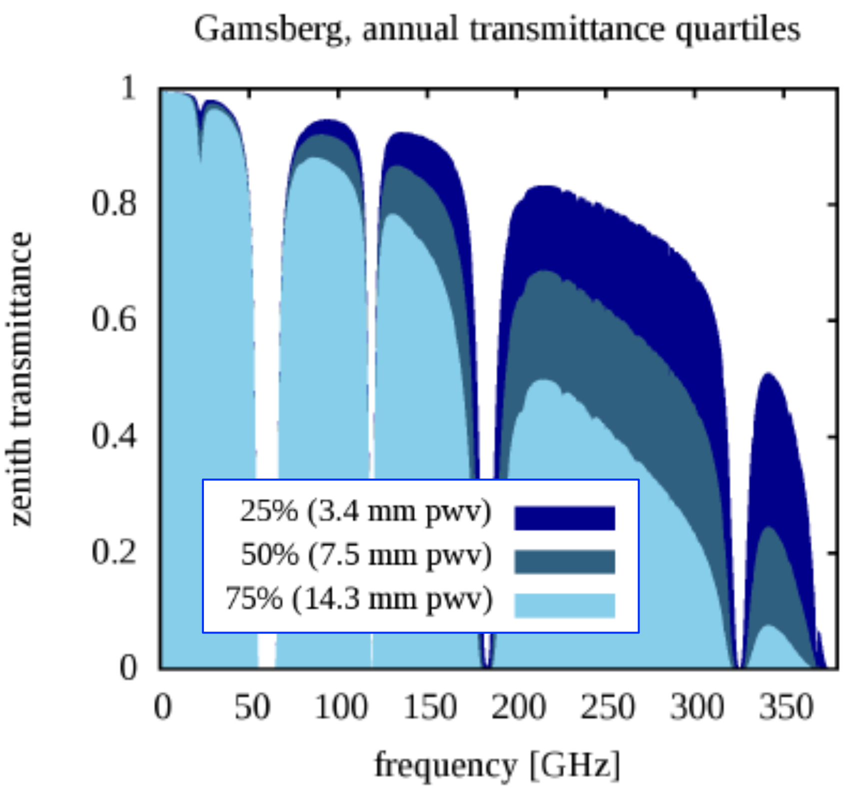
Gamsberg – 2347 m

Radboud University Nijmegen

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

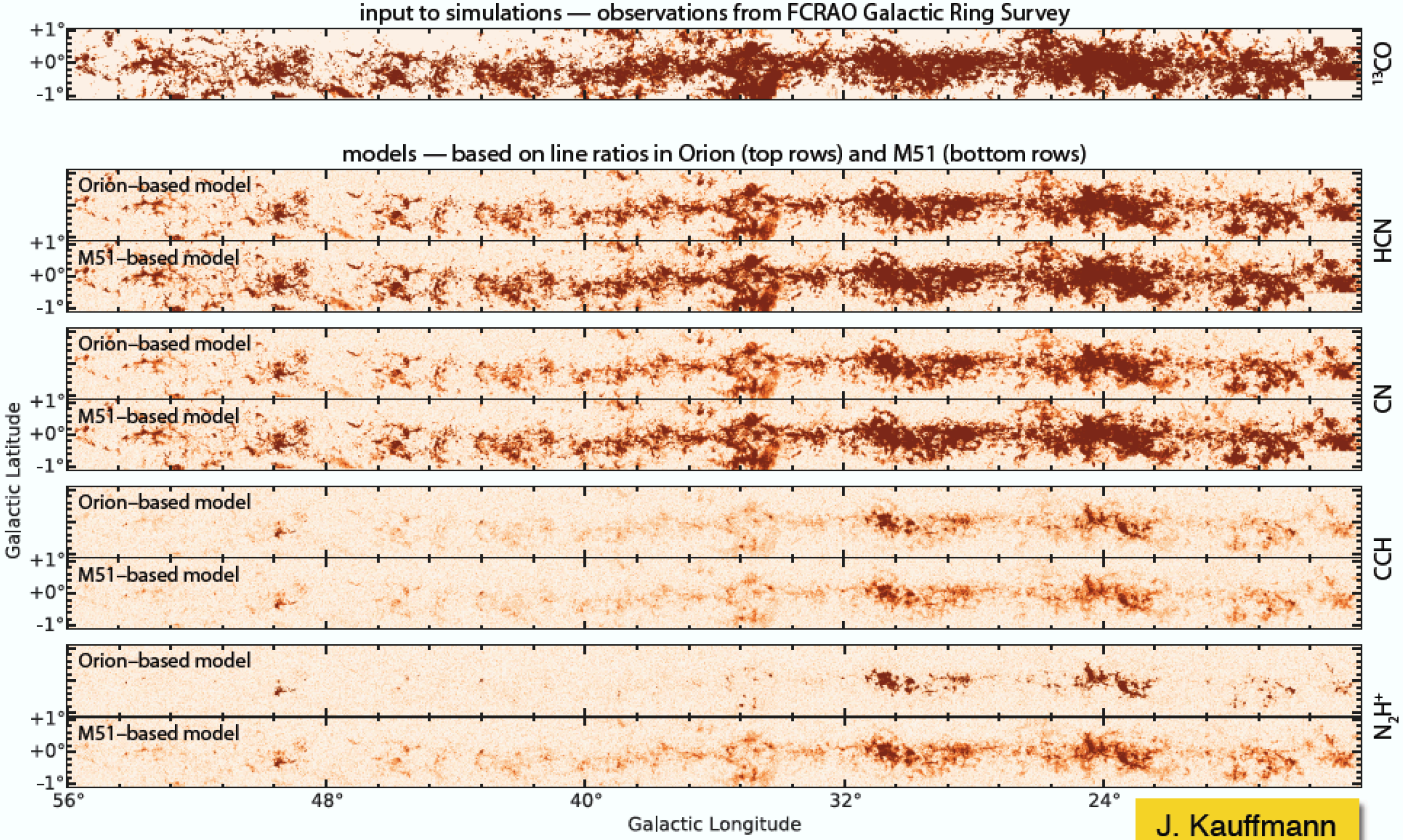
Sarazin (1994)


Dorob
National Park
Karibib
Henties Bay
Namibia
Windhuk
Witvlei
B1
B6
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:

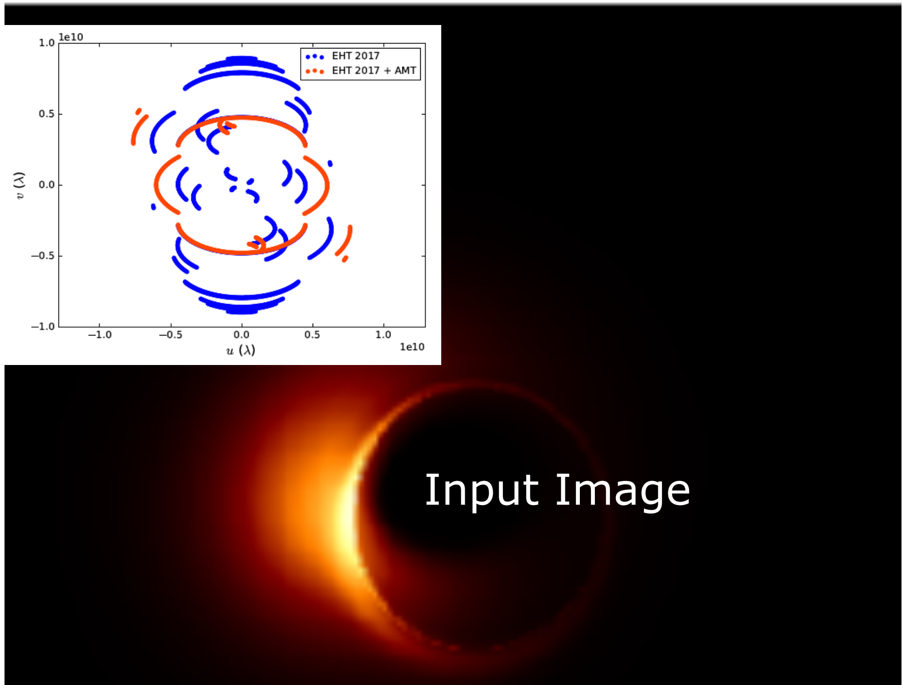
could do $|\ell| < 60$ deg, $|b| < 1$ deg to reasonable depth in 3,000 h

“Infrastructure”

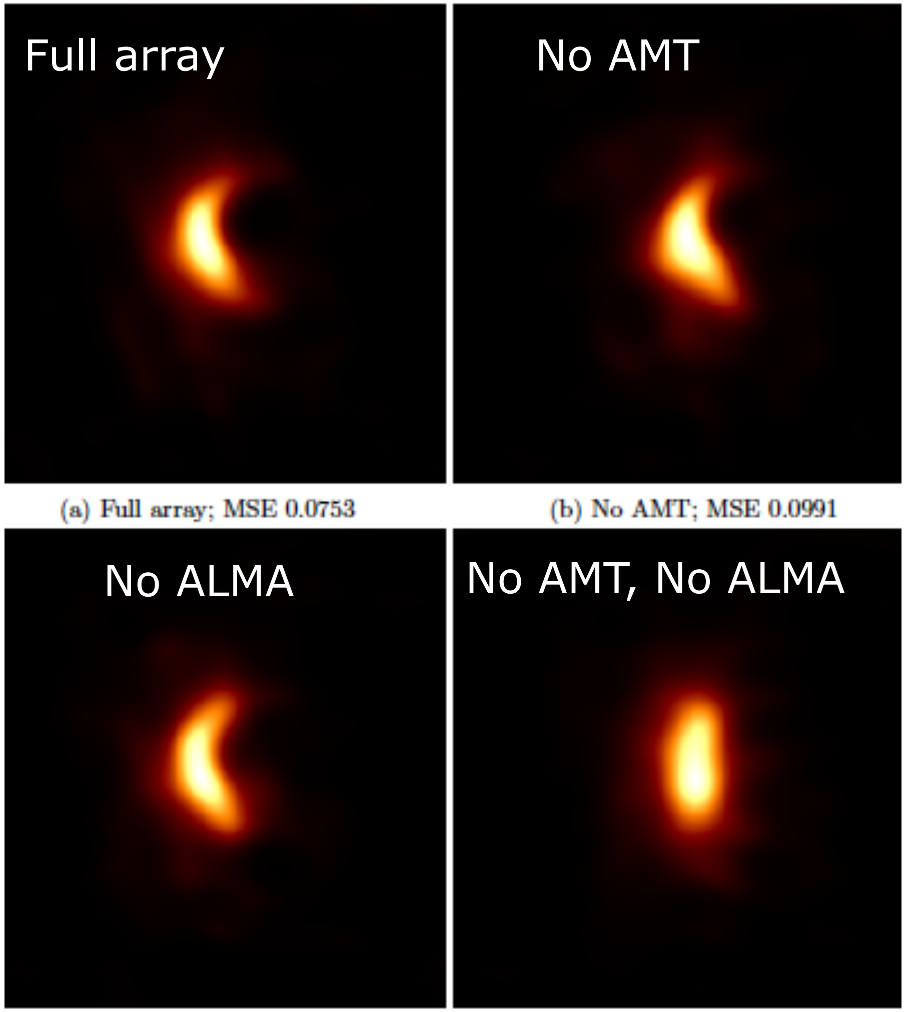
Radboud University Nijmegen

Image reconstruction

Radboud University Nijmegen



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

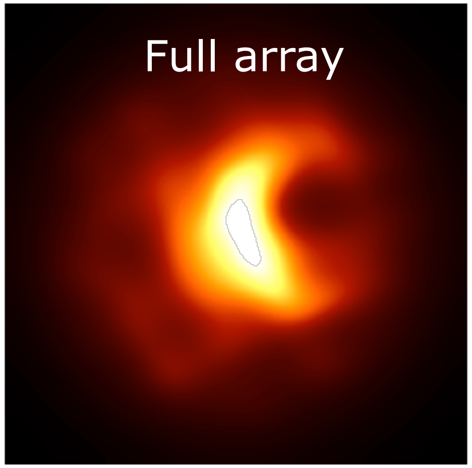


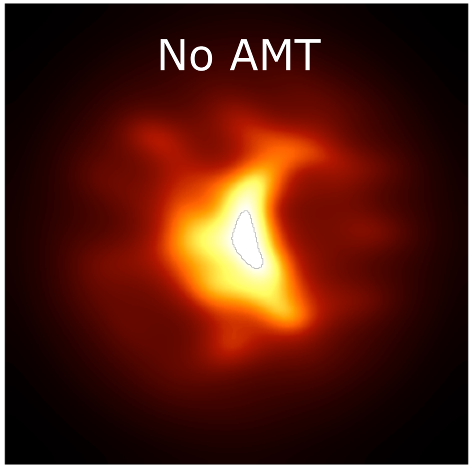
(a) Full array; MSE 0.0753
(b) No AMT; MSE 0.0991
(c) No ALMA; MSE 0.0887
(d) No ALMA, AMT; MSE 0.1130

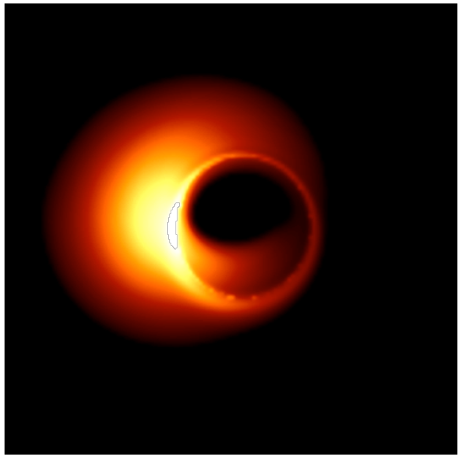
Freek Roelofs (based on Lu, Roelofs et al. 2015, ApJ)

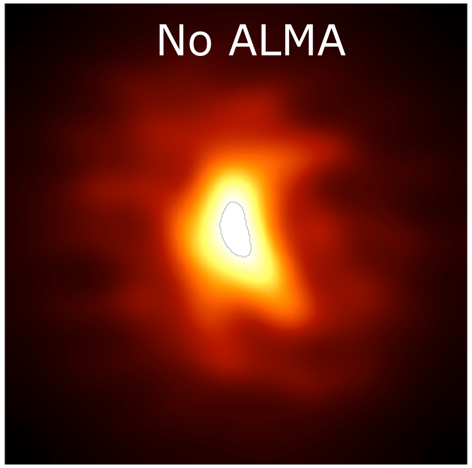
Imaging with the AMT

Radboud University Nijmegen









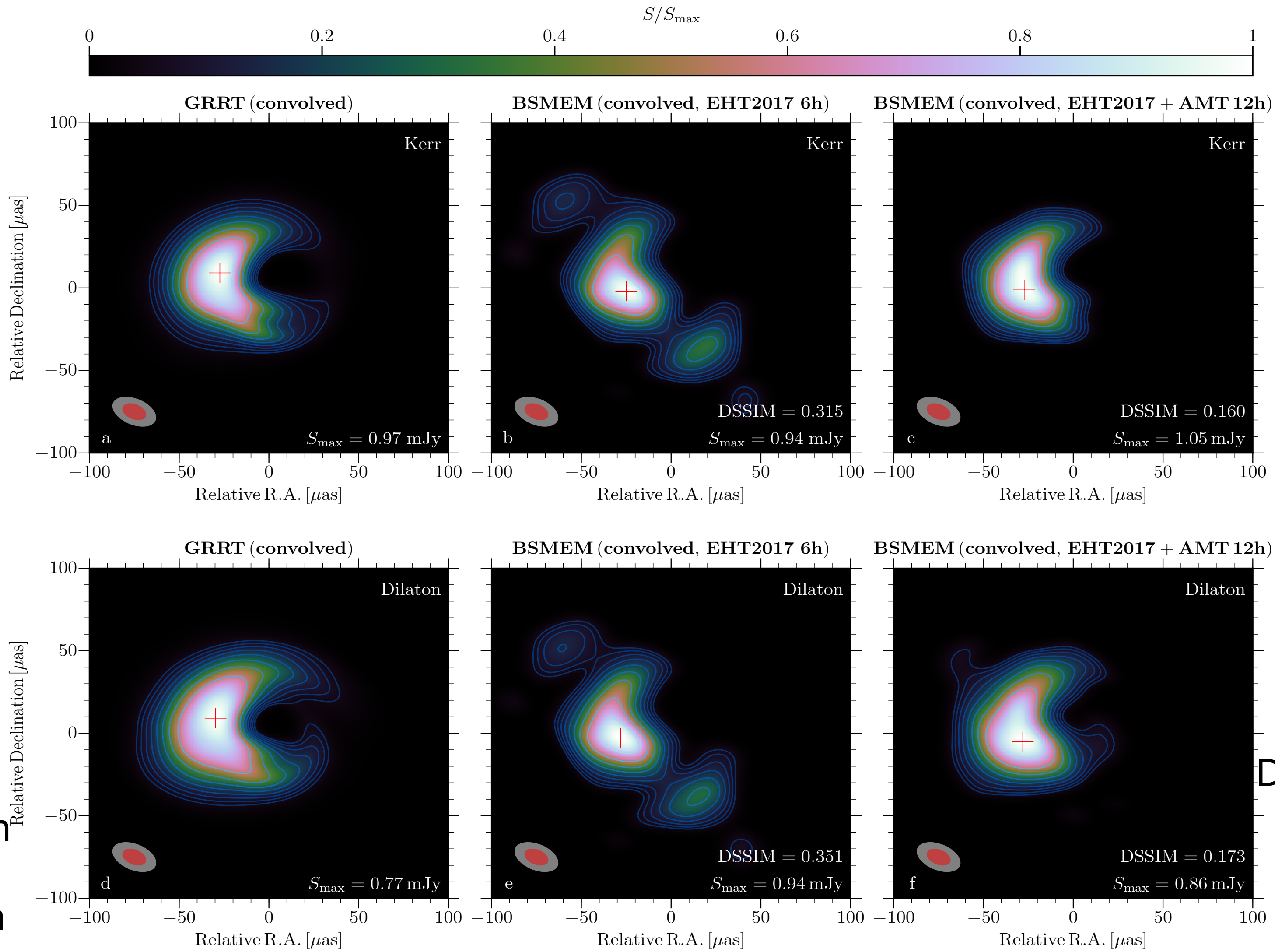
- Includes source variability
- 8 epochs
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering
- EHT imaging library

F. Roelofs

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 ≥100 pc in galaxies
- straightforward and compelling to map large nearby clouds
- technically feasible and compelling to map Milky Way in many lines

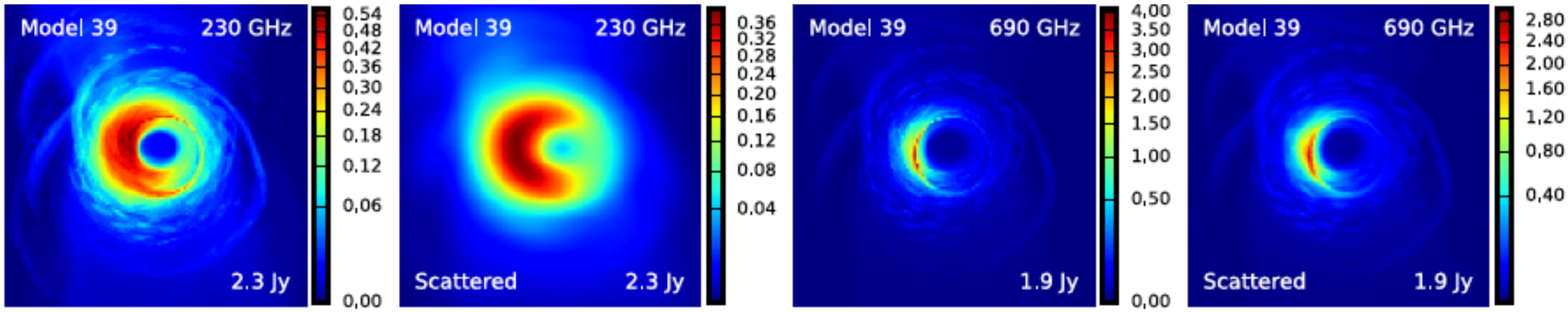
general science themes:

- 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?)

Black Hole Shadow Simulations at 690 GHz (!)

Radboud University Nijmegen

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



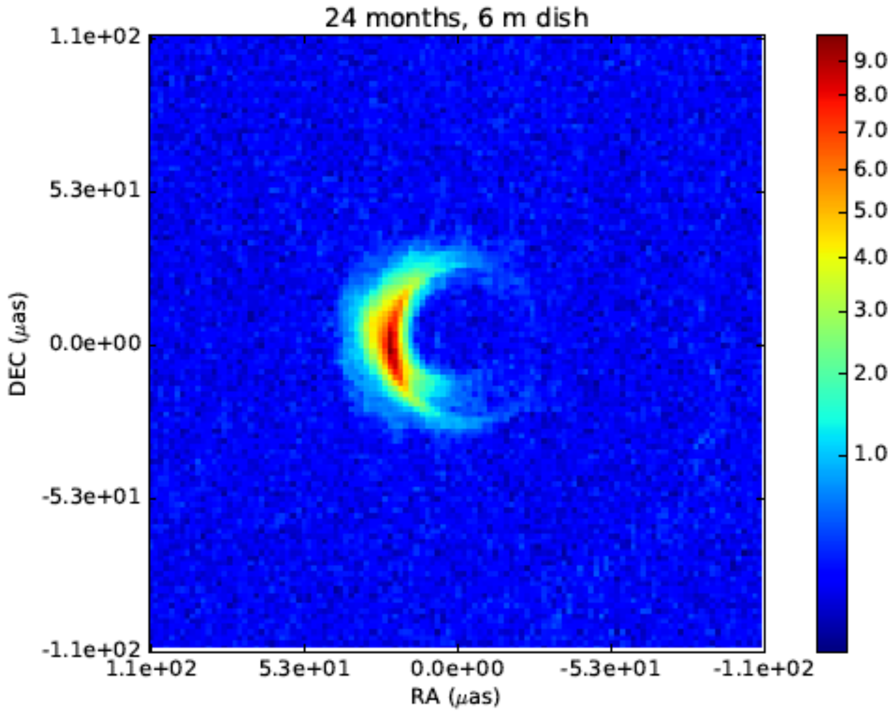
Moscibrodzka et al. (Radoud Univ)

ESA-Radboud study: Event Horizon Imager (EHI)

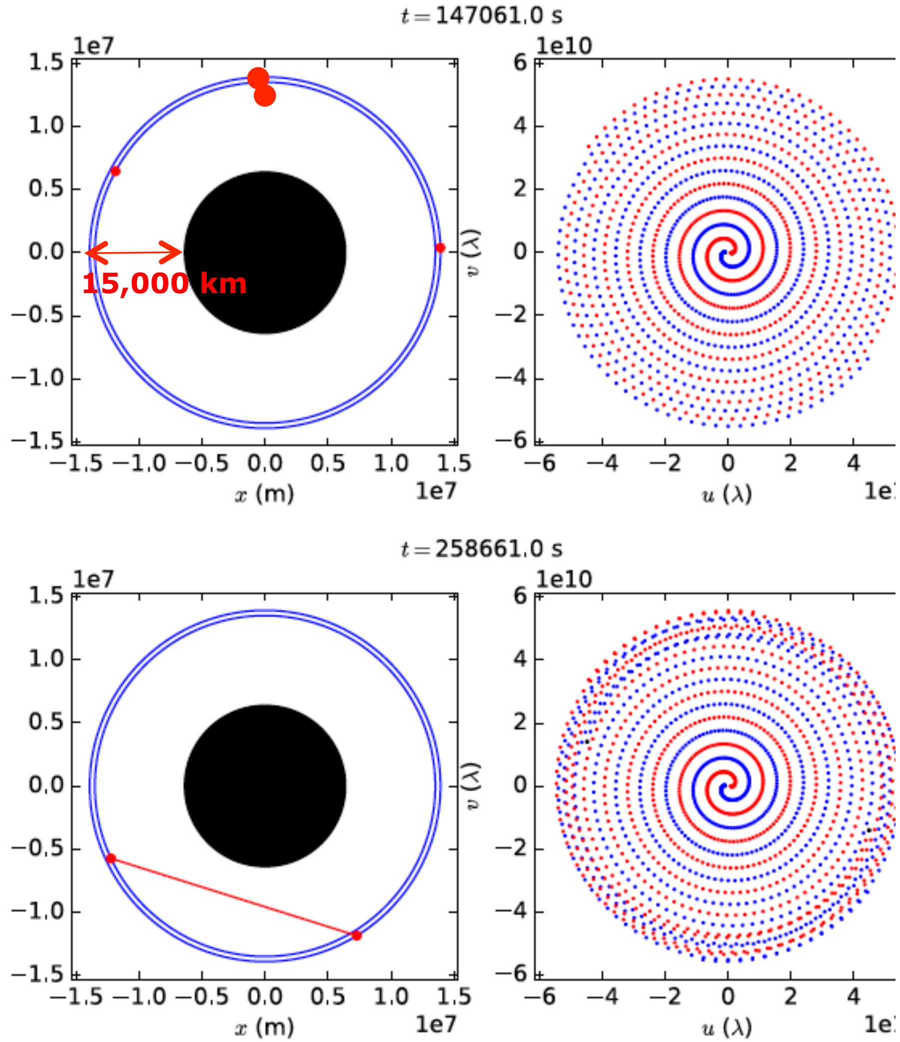
Radboud University Nijmegen

Reconstructed Space-VLBI image

Includes variability due to scattering and source variations



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



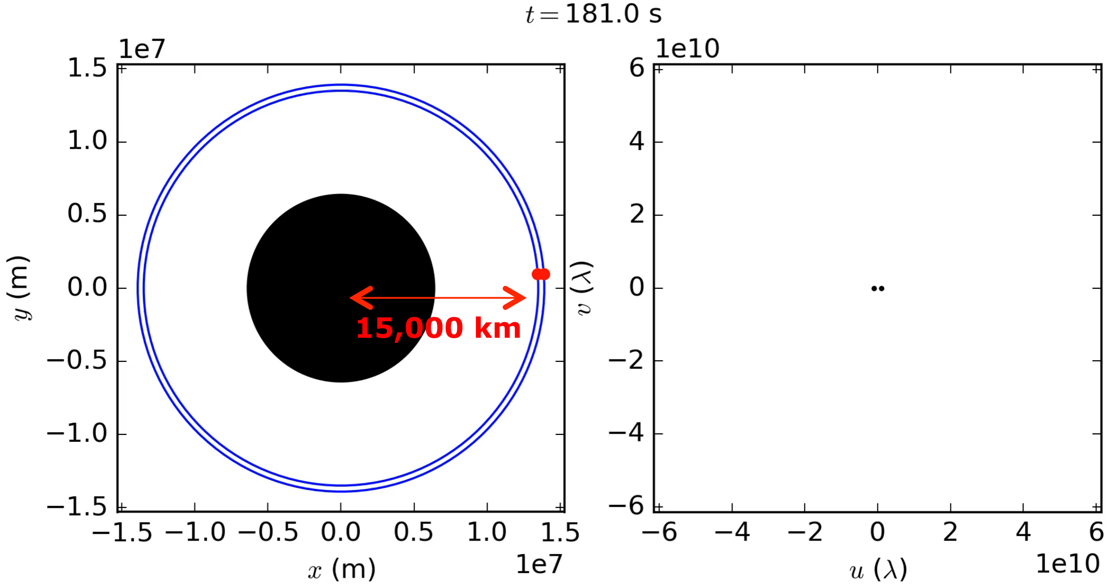
Martin-Neira, V.Kudriashov (ESA)

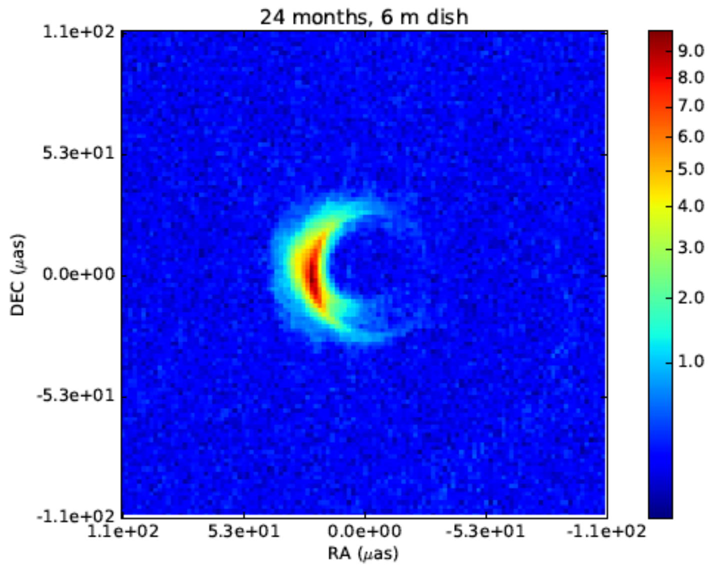
ESA-Radboud study: Event Horizon Imager (EHI)

Radboud University Nijmegen

Reconstructed Space-VLBI image

Includes variability due to scattering and source variations

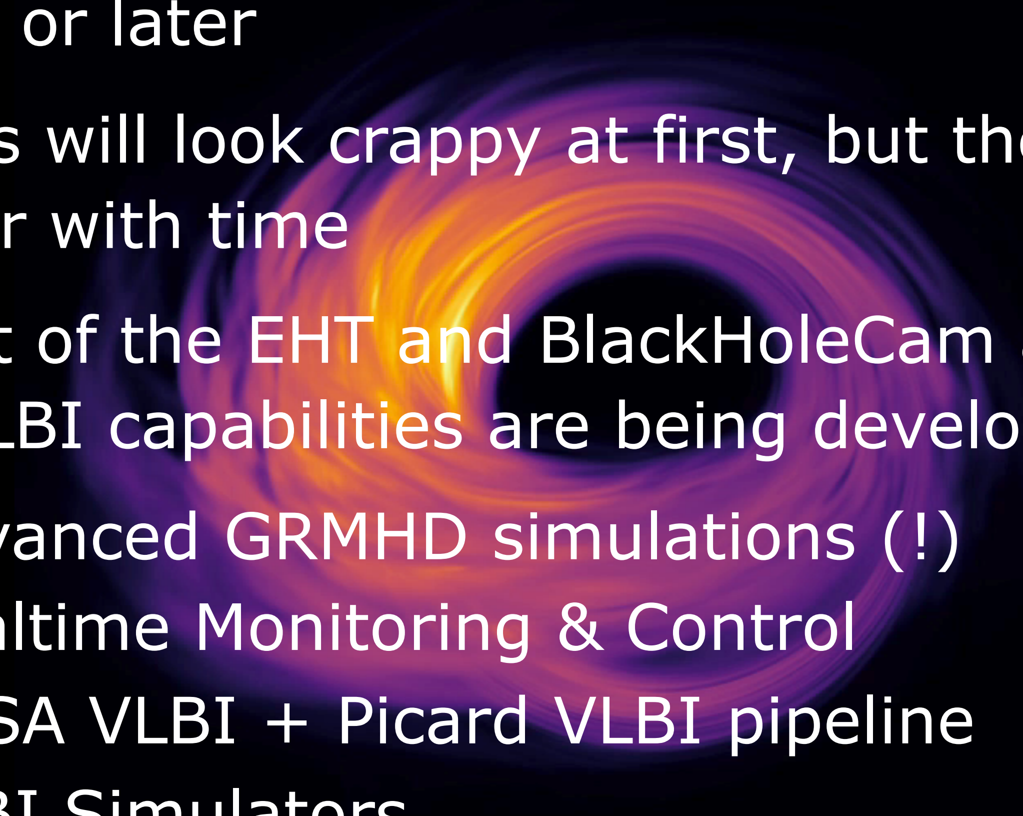




Martin-Neira, V.Kudriashov (ESA)

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

Conclusion

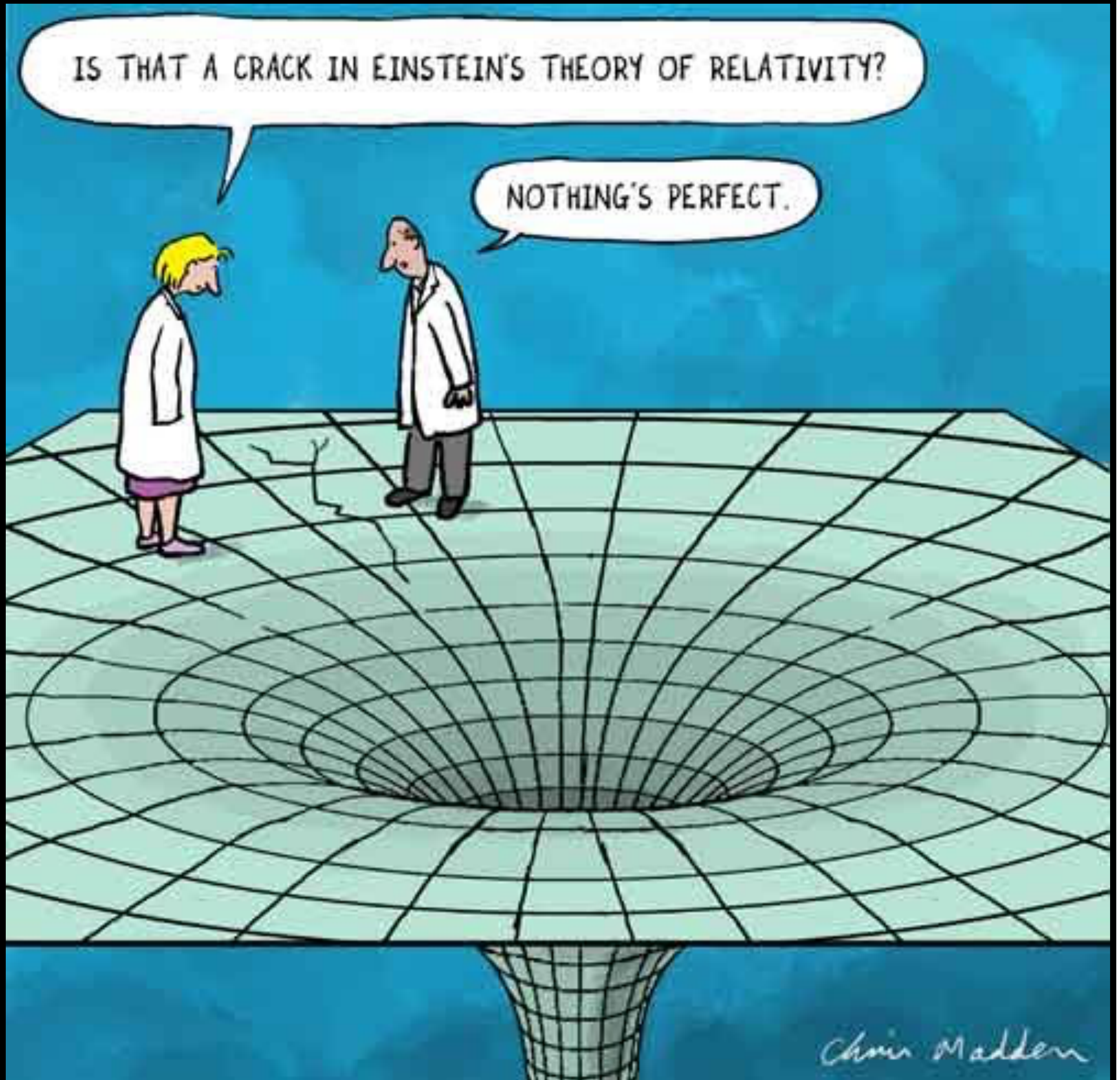


- Images of the shadow of black holes will come sooner or later
- Images will look crappy at first, but they will become sharper with time
- As part of the EHT and BlackHoleCam a number of new VLBI capabilities are being developed:
  - Advanced GRMHD simulations (!)
  - Realtime Monitoring & Control
  - CASA VLBI + Picard VLBI pipeline
  - VLBI Simulators
  - Imaging
- Future: more sites, space VLBI

Use and improve!

h.falcke@astro.ru.nl

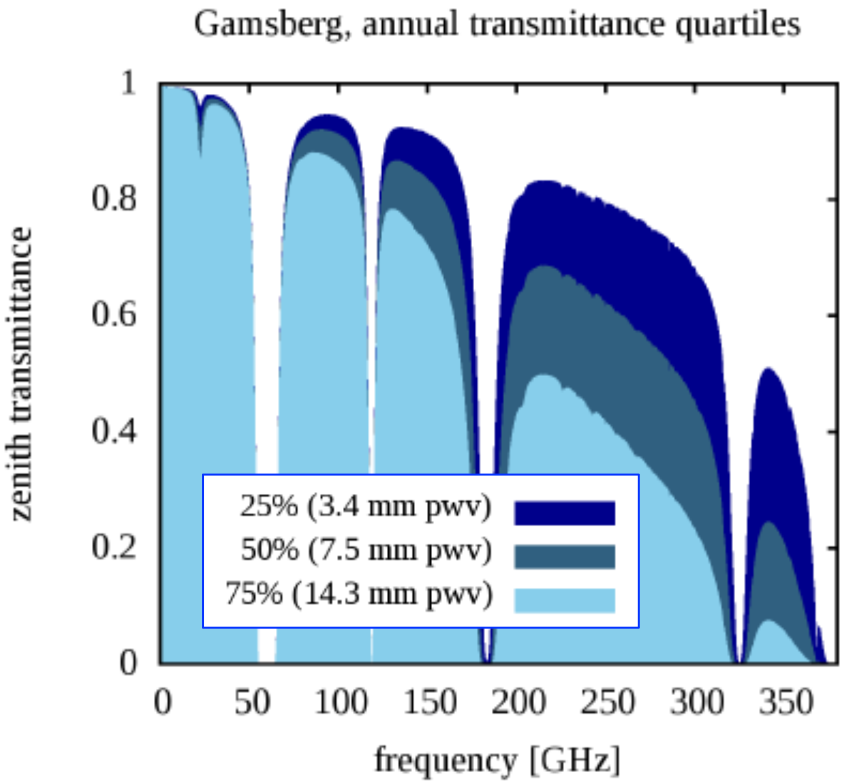
@hfalcke



Gamsberg – Weather

African mm-Wave Telescope

1mm VLBI weather ~ 50% of the year



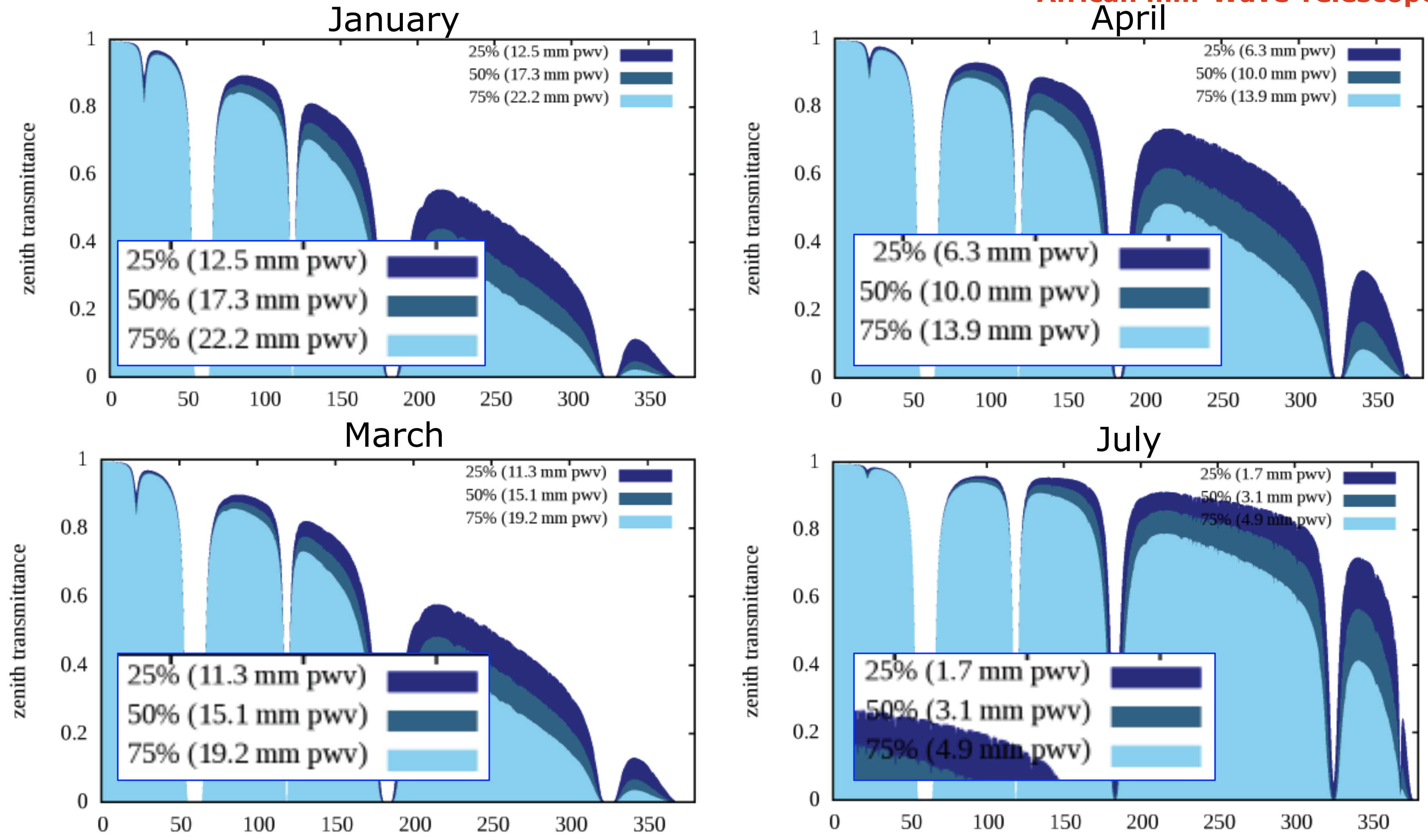
F. Roeolfs based on model from S. Paine

- 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)

Gamsberg – Annual Variation

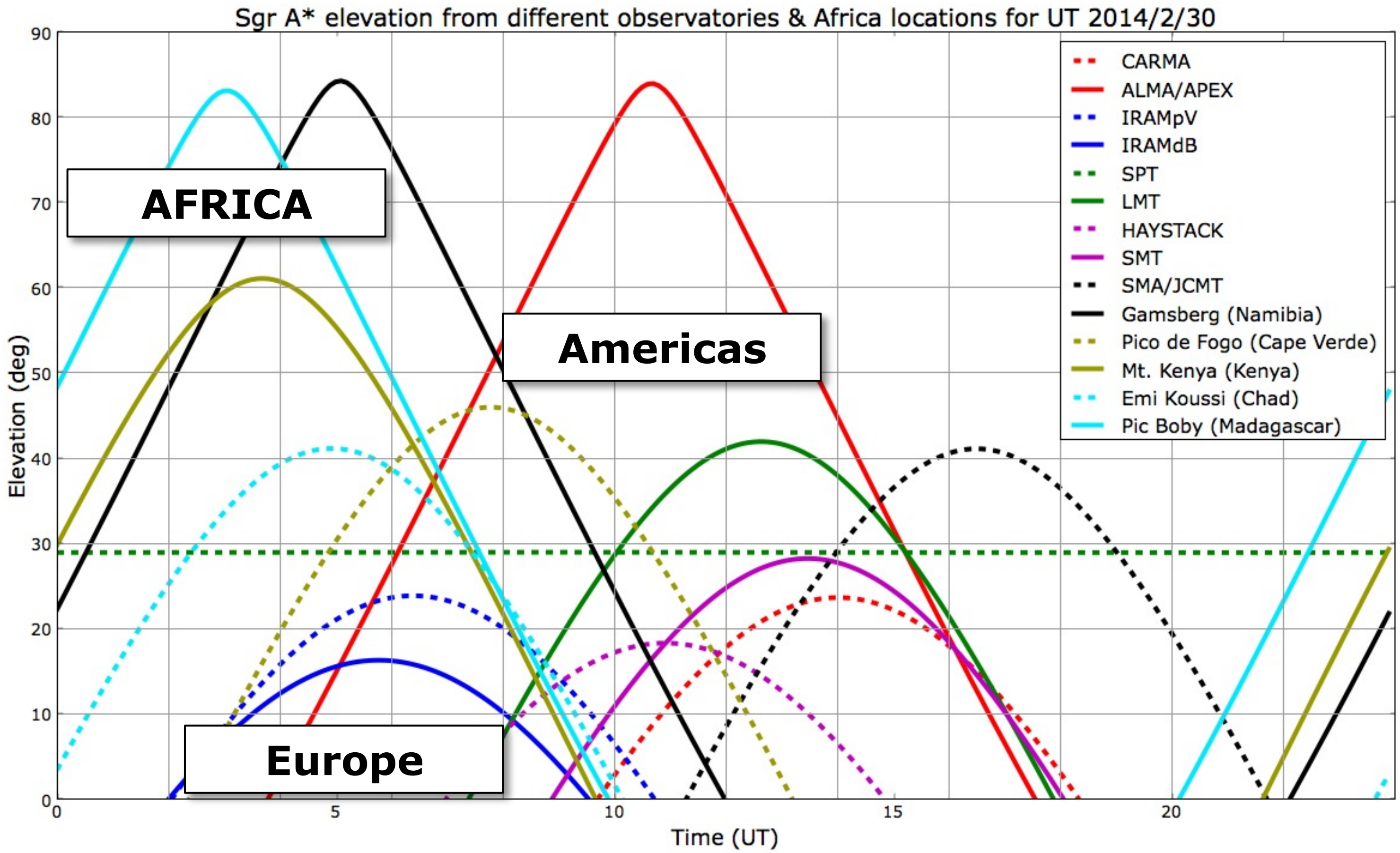
African mm-Wave Telescope



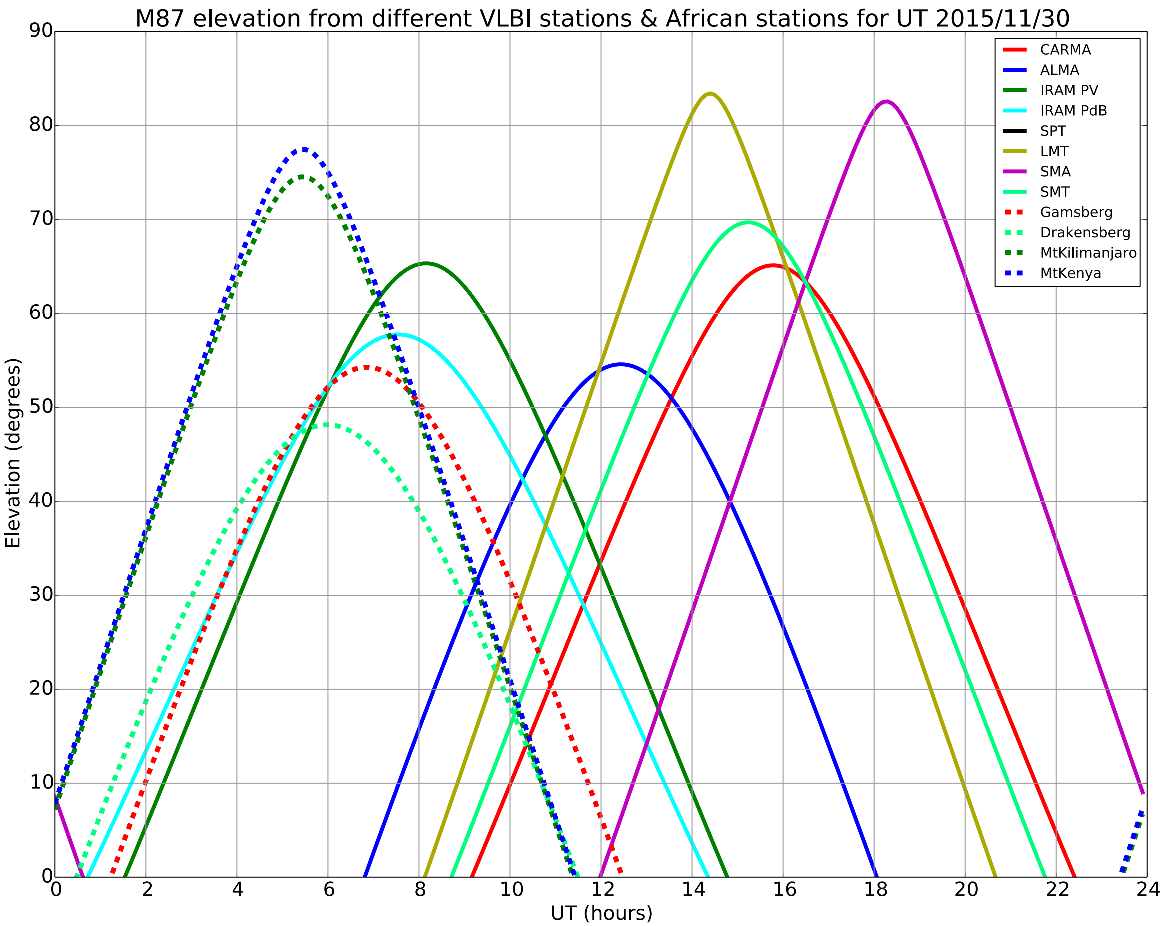
F. Roeolfs based on model from S. Paine

*Visibility for African sites: Sgr A**

African mm-Wave Telescope



M87 visibility for African sites



Gamsberg in-situ measurement

African mm-Wave Telescope

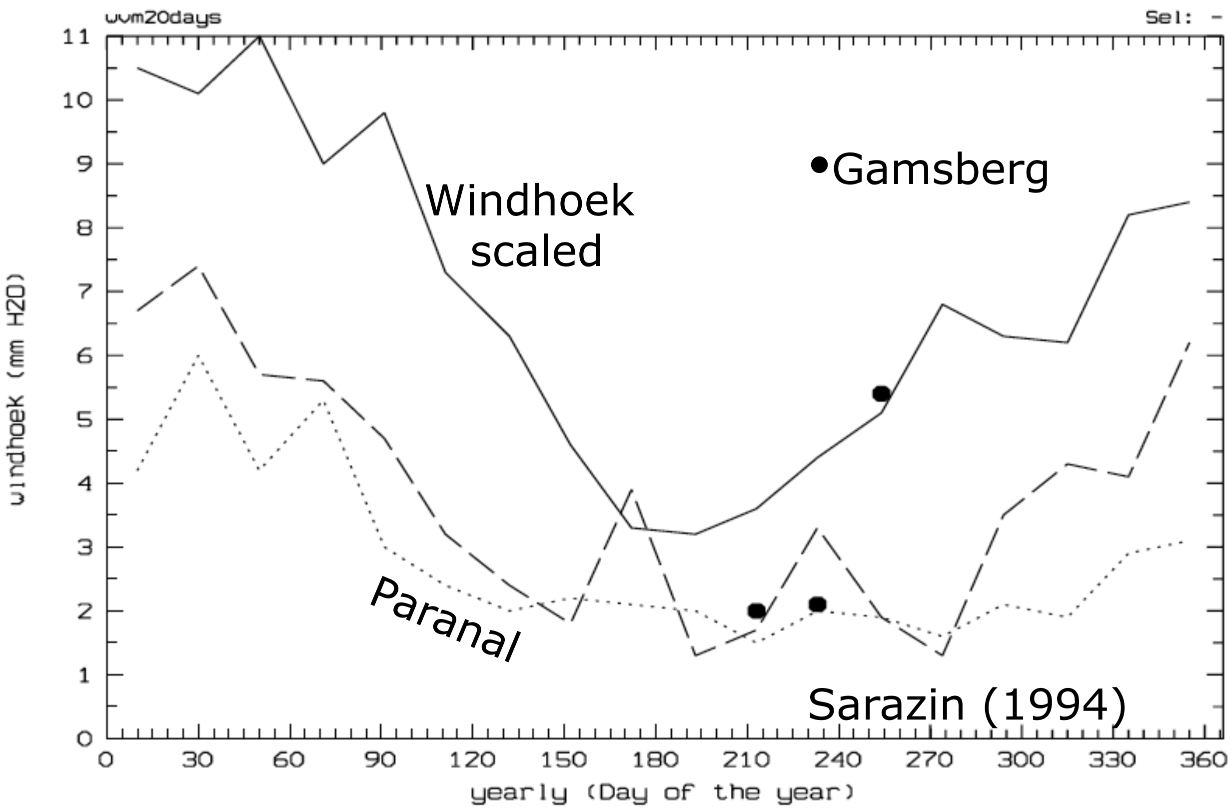


Figure 1: Seasonal variation of precipitable H_2O computed on the basis of 20 days median from 1985-1993 Windhoek radiosonde night flights (full line) from the altitude of Gamsberg compared to 1983-1989 in situ Paranal (dotted line) and La Silla (dashed line) nighttime statistics. The Gamsberg in situ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