The Future of the Event Horizon Telescope

Heino Falcke

Radboud University, Nijmegen

& ASTRON, Dwingeloo

Event Horizon Telescope Consortium

Lynden-Bell & Rees 1971

Radboud University Nijmegen

Mon. Not. R. astr. Soc. (1971) **152**, 461–475.

ON QUASARS, DUST AND THE GALACTIC CENTRE

D. Lynden-Bell and M. J. Rees

2. Very long baseline interferometry may soon be possible with a broad enough bandwidth to measure sources as weak as 0·5 f.u. to diameters of 10^{-3}″. If so, it may be possible to determine the size of any central black hole that there may be in our galaxy. However H II may render the central source opaque with a greater angular size.

This suggests that discs which cannot radiate efficiently enough at 10^4–10^5 °K will blow up into spheres.

First Detection of Sgr A(*)

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INTENSE SUB-ARCSECOND STRUCTURE IN THE GALACTIC CENTER

Bruce Balick
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
AND
Robert L. Brown
National Radio Astronomy Observatory*
Received 1974 June 3

ABSTRACT

The detection of strong radio emission in the direction of the inner 1-pc core of the galactic nucleus is reported. The structure is bright (brightness temperature $\gtrsim 10^7$ °K), unresolved ($\theta \lesssim 0\overset{''}{.}1$), and distributed within a few seconds of the brightest infrared and radio emission seen previously.

Subject headings: galactic nuclei — radio sources

NRAO
Green Bank
Interferometer
(GBI)

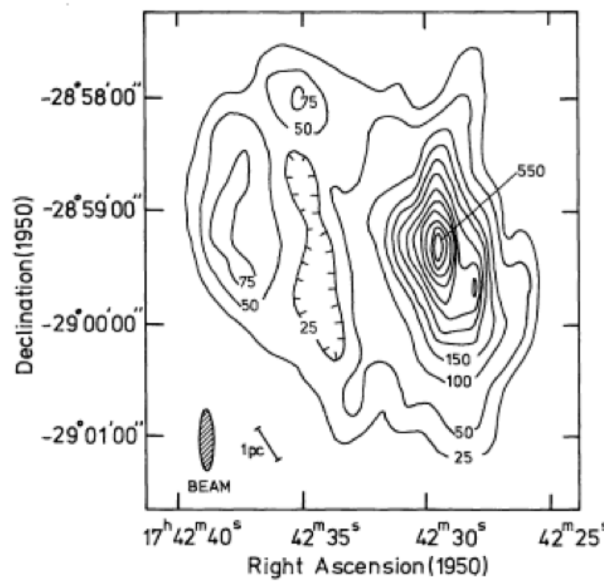
A Full Synthesis Map of Sgr A at 5 GHz

R. D. Ekers, W. M. Goss and U. J. Schwarz
Kapteyn Astronomical Institute, University of Groningen

D. Downes
Max-Planck-Institut für Radioastronomie, Bonn

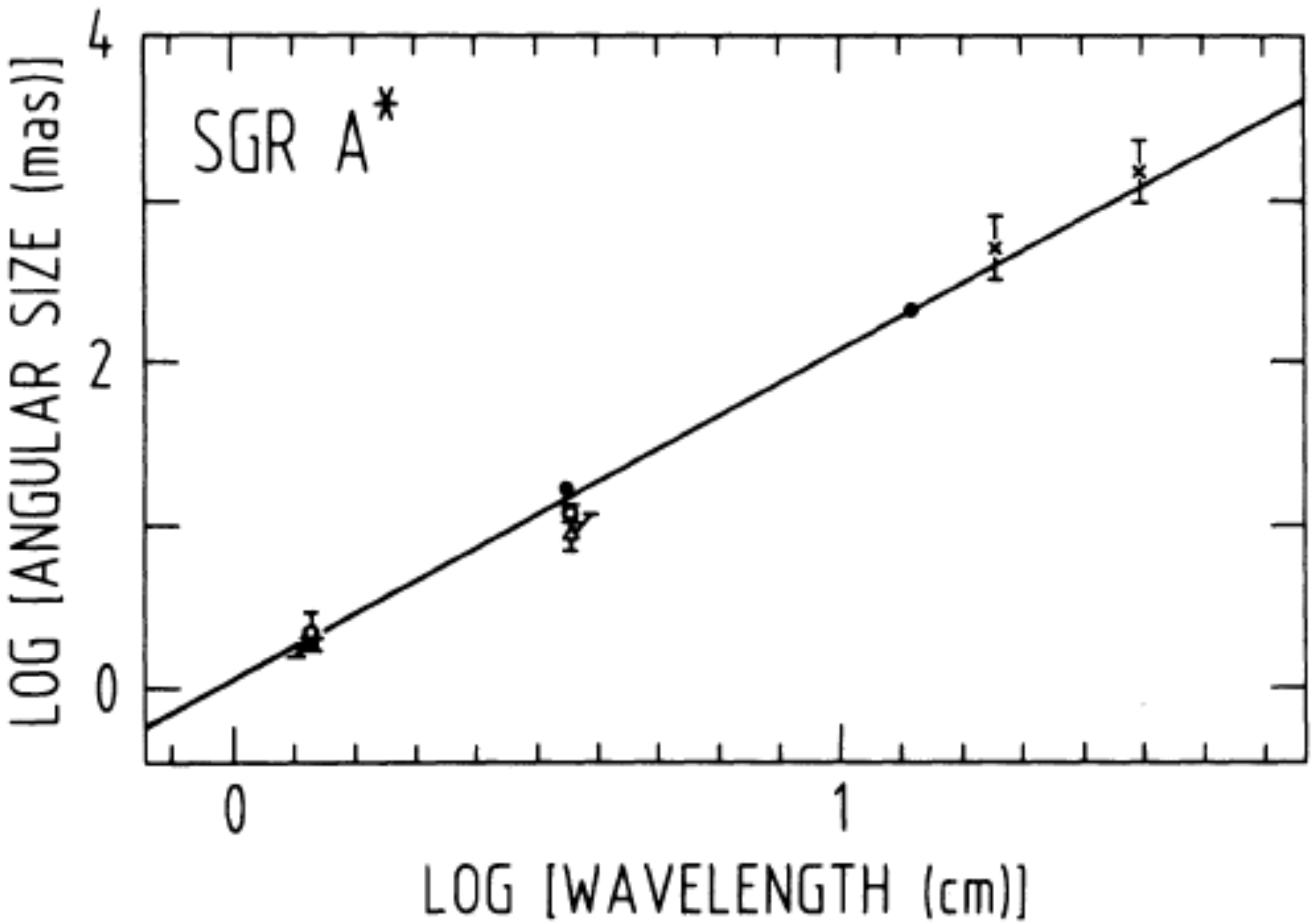
D. H. Rogstad
Owens Valley Radio Observatory, California Institute of Technology, Pasadena, Ca

Received April 21, 1975



Westerbork
Synthesis
Radio
Telescope
(WSRT)

VLBI of Sgr A*: Scattering



Kellerman et al. (1977), Lo et al. (1981 & 1985), Jauncey et al. (1989), van Langevelde et al. (1992), Marcaide et al. (1992)

From first 7mm VLBI observations to the shadow

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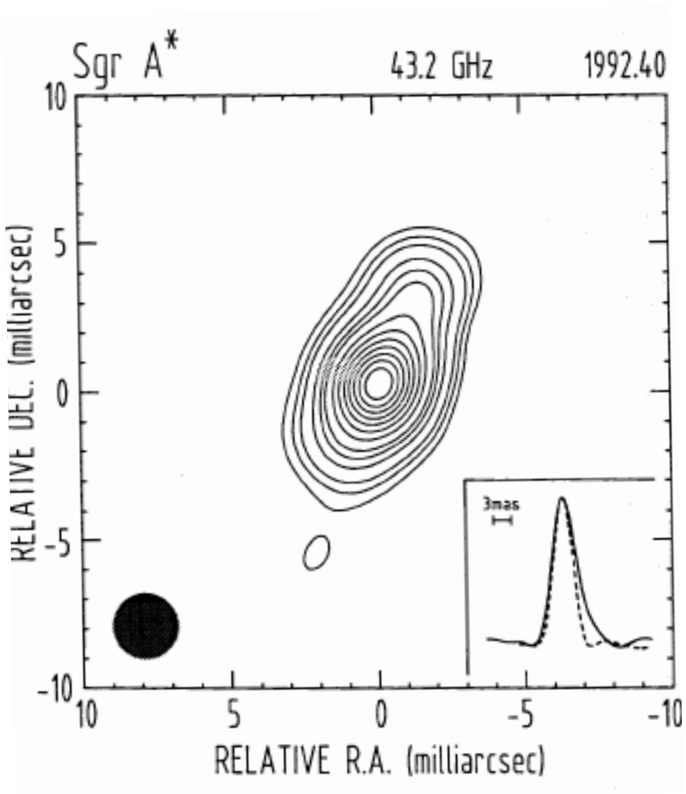
First 7mm VLBI



Krichbaum et al. (1993)

(see also Backer et al. (1993))

Jet Model for Sgr A*:

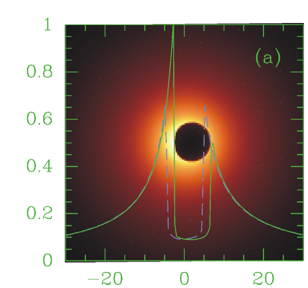
wavelength-dependent size & low accretion rate

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

We see that even at high frequencies the size of the jet is smaller than current VLBI resolution. If we go even further, i.e. to submm wavelengths, the size of the emitting region approaches the minimal size, which is the size of a Black Hole of mass $\sim 10^6 M_\odot$. This scale then should correspond to the

Falcke, Mannheim, Biermann (1993)
see also Falcke & Markoff (2000)

⇒ **Black Hole Shadow**
Falcke, Melia, Agol (2000)



Intrinsic Radio Size of Sgr A*

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

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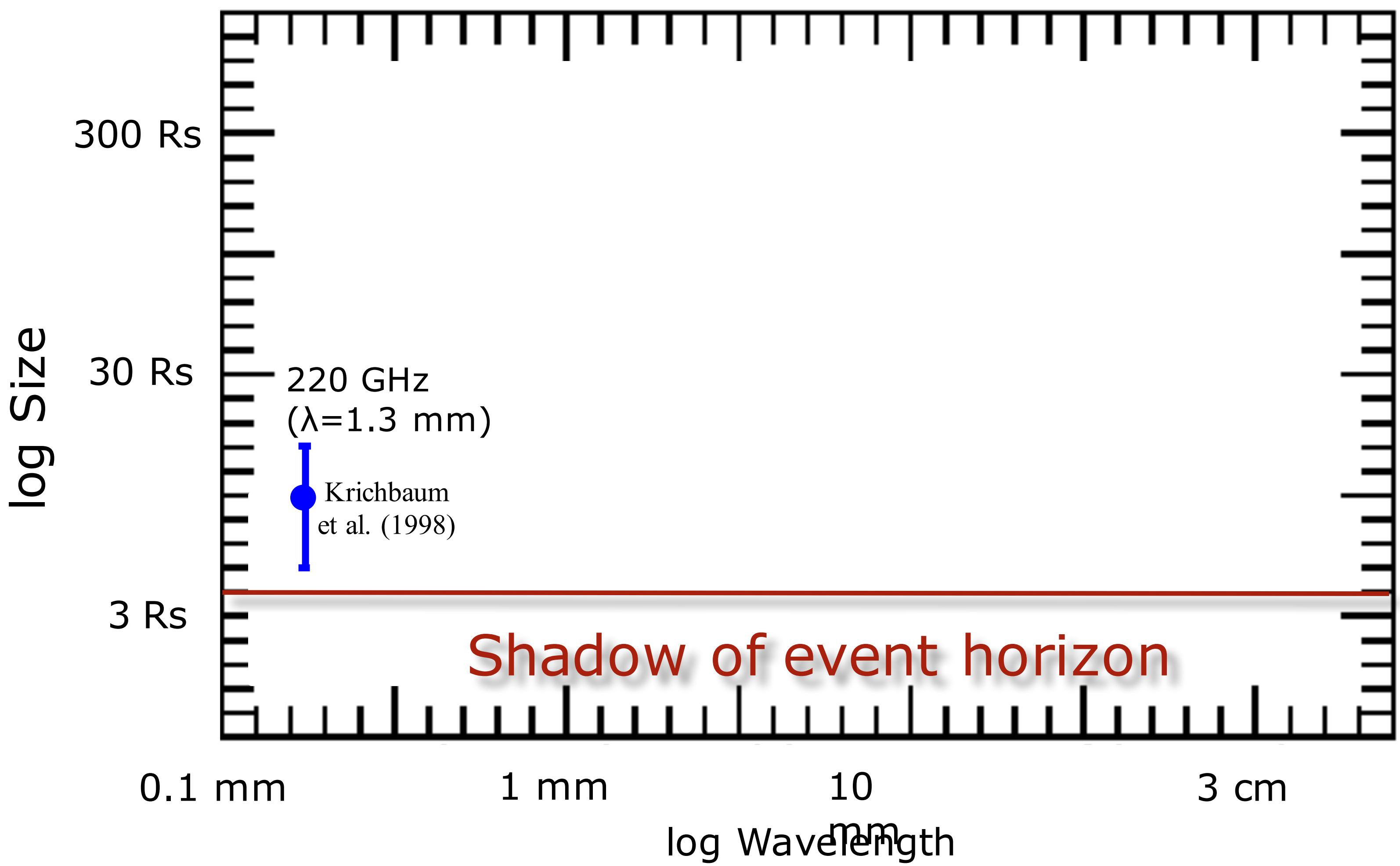

Falcke & Markoff, Class. & Quant. Gravity (2013)

Radio Lags measured with ALMA & VLA

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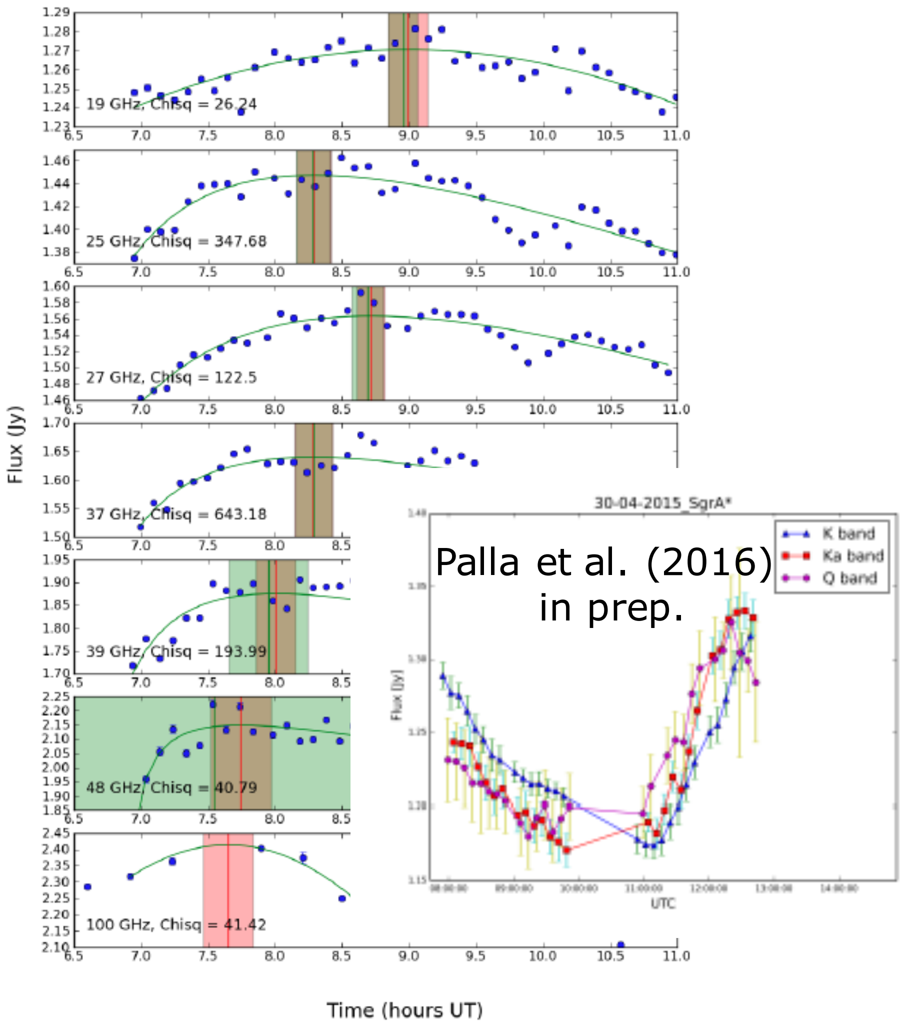
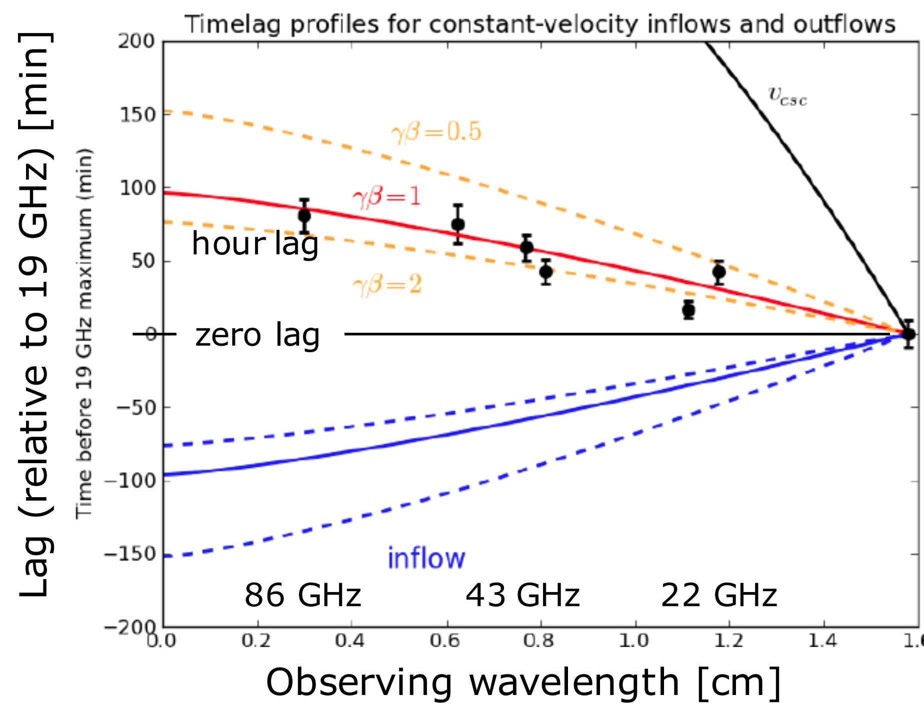
Flux evolution at different frequencies



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)

Two-dimensional structure of Sgr A: fairly elongated*

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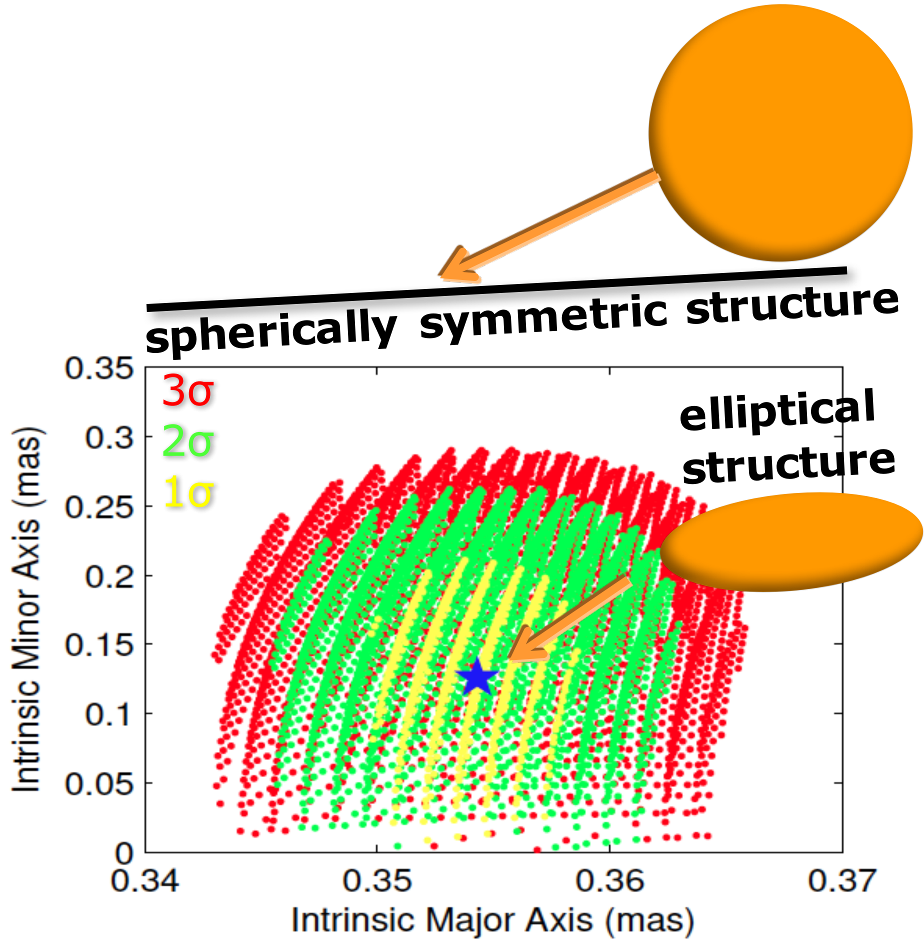
- Accurate closure amplitude measurements of 2D-size of Sgr A* with the VLBA.
- Size at 43 GHz: (35.4 ±0.4) Rs × (12.6±5.5) Rs at PA (95±4)°



Bower et al. (2014, ApJ)

Intrinsic asymmetries in Sgr A (or scattering after all?)*

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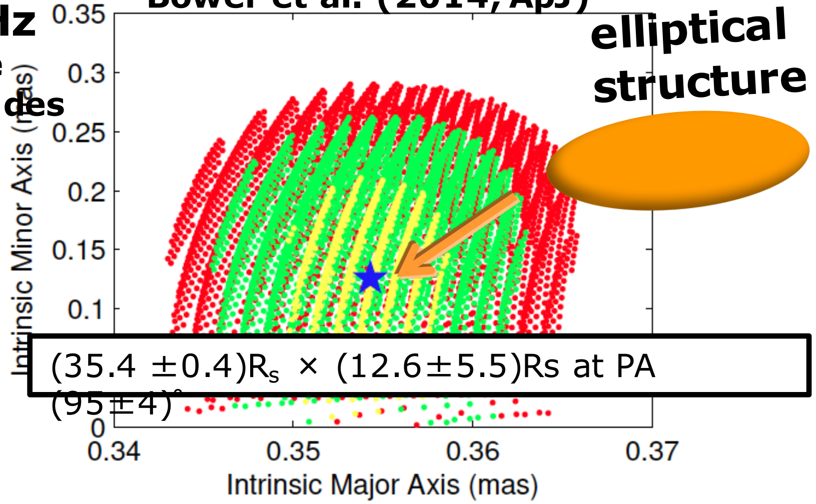
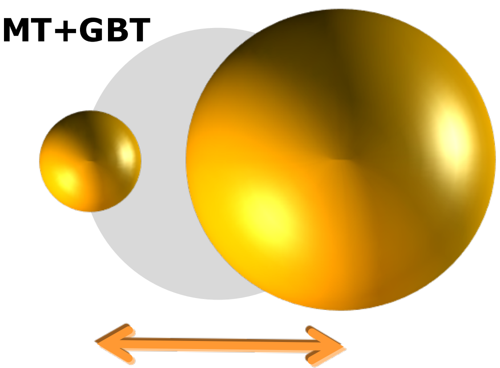
43 GHz
Closure amplitudes

Bower et al. (2014, ApJ)



Brinkerink et al. (2016)

86 GHz
VLBA+LMT+GBT



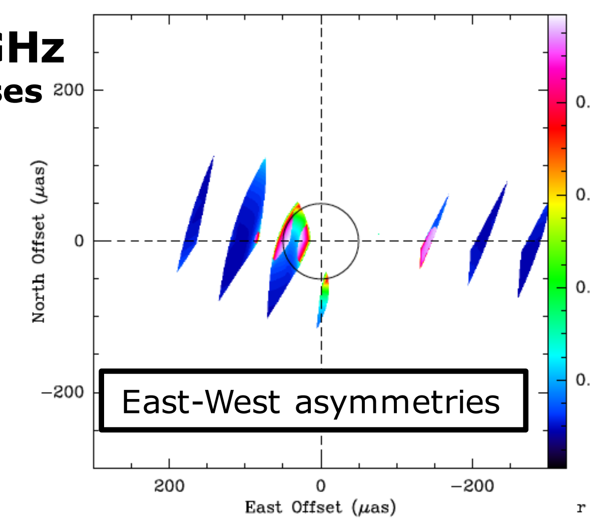
~50 μarcsecond (5 R_s)

86 GHz
VLBA+LMT+GBT

	BD183C	
	Closure Amp.	Self Calibration
Maj. Axis	145 ± 9 μas	142 ± 7 μas
Min. Axis	114^{+14}_{-19} μas	113^{+11}_{-17} μas
P. A.	$88°^{+9}_{-4}$	$89°^{+10}_{-4}$
Axial ratio	$1.27^{+0.26}_{-0.15}$	$1.25^{+0.22}_{-0.12}$

Ortiz et al. (2016)

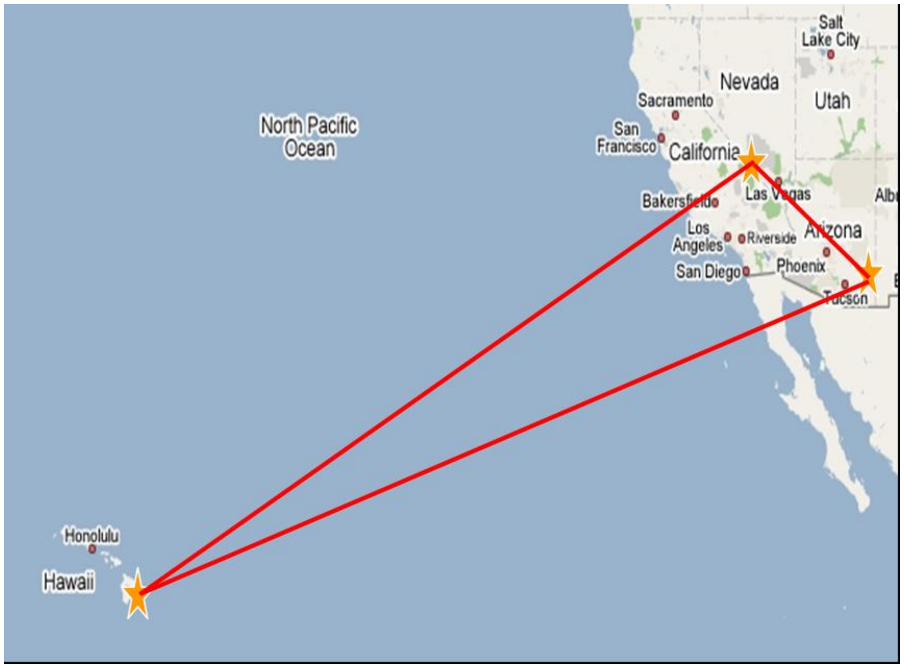
230 GHz
cl. phases



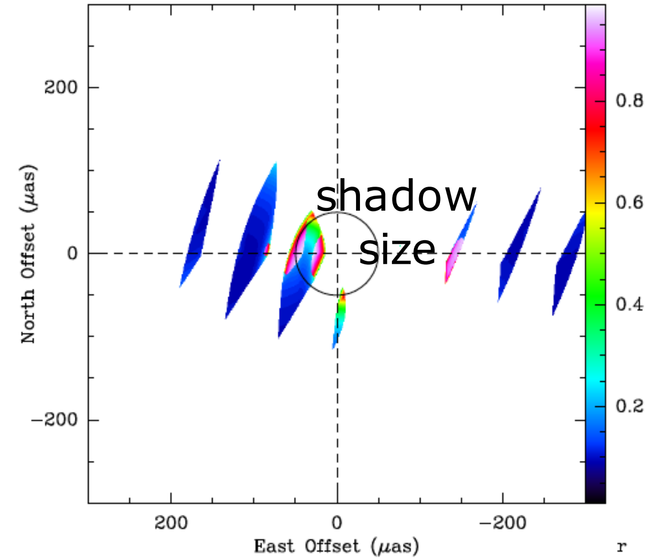
Fish et al. (2016)

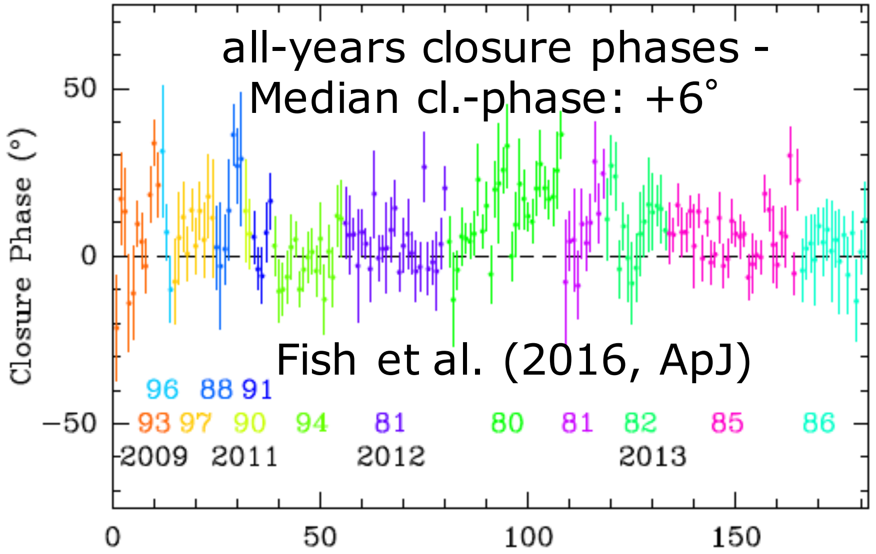
Closure phases at 1.3 mm

Hawaii-California-Arizona triangle



allowed point source offsets





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

VLBA+LMT+GBT: Shadow-sized substructure @ λ3mm

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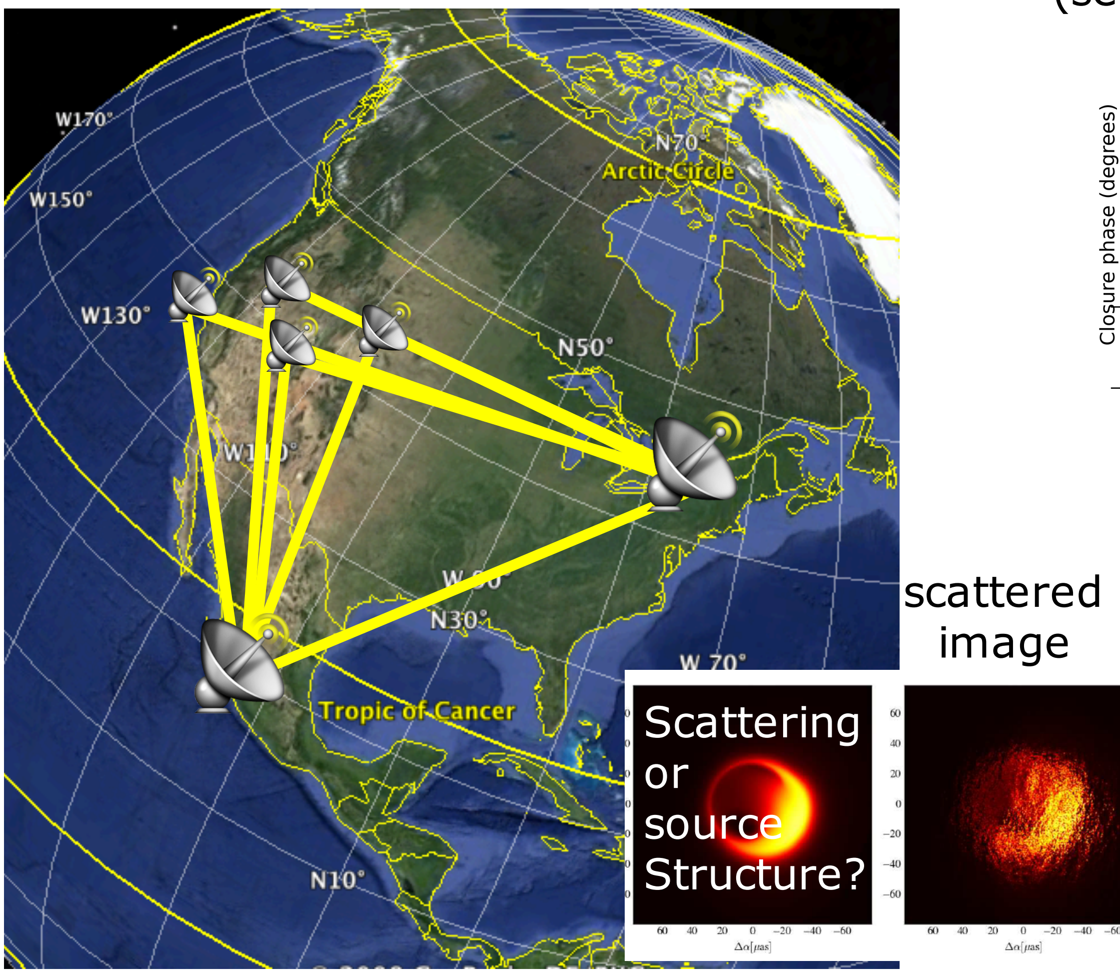
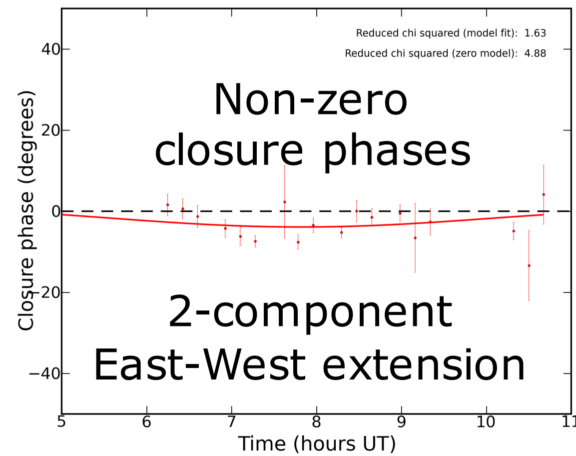
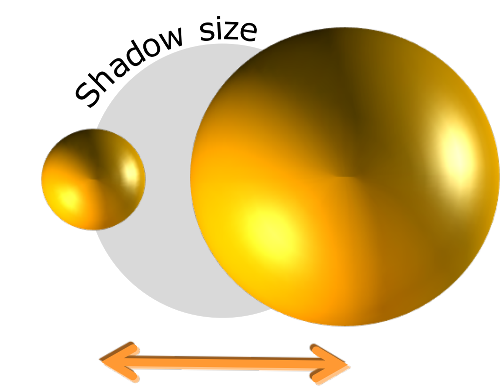
Brinkerink et al. (2016, MNRAS, in press)
(see also Ortiz et al. 2016)

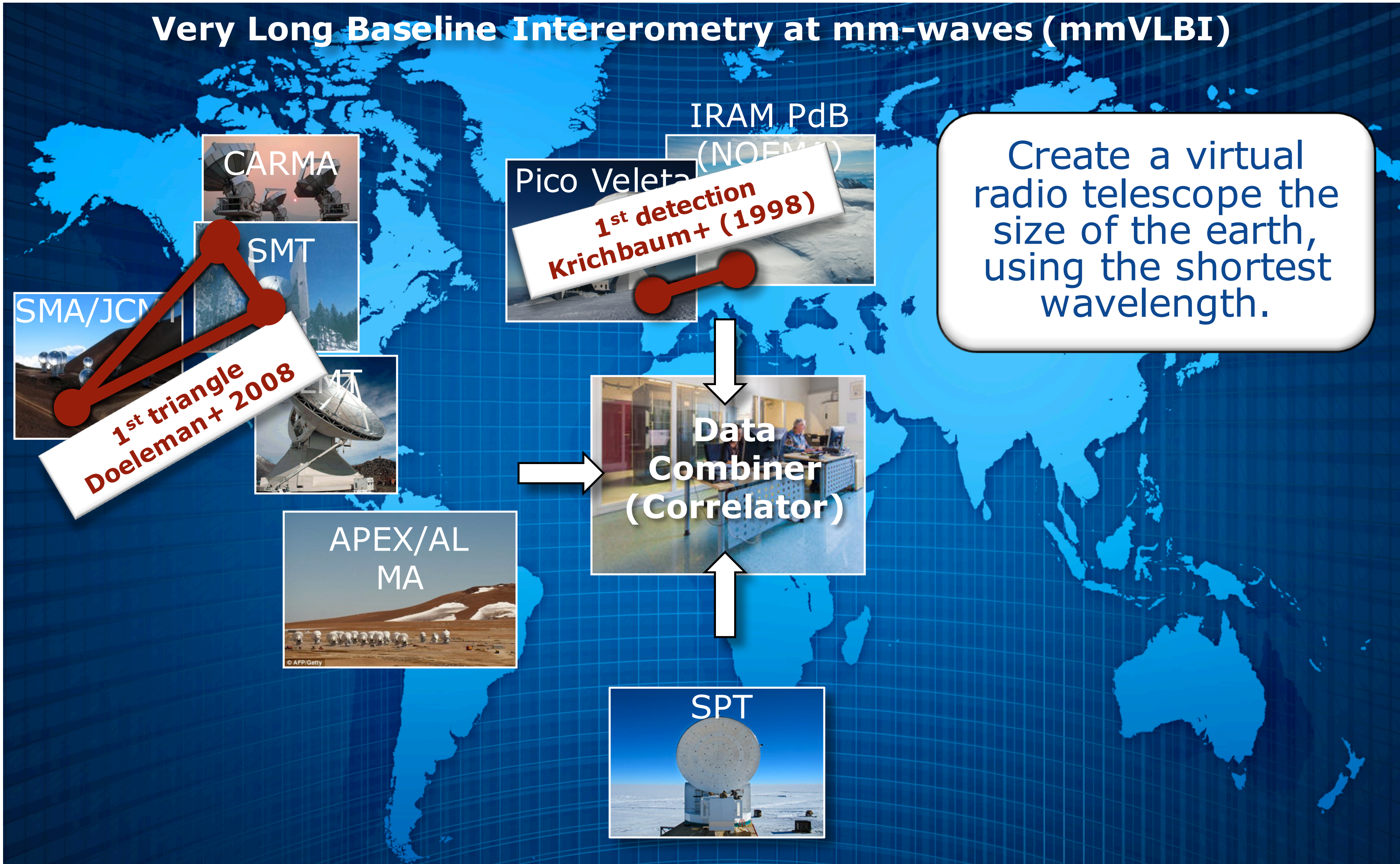




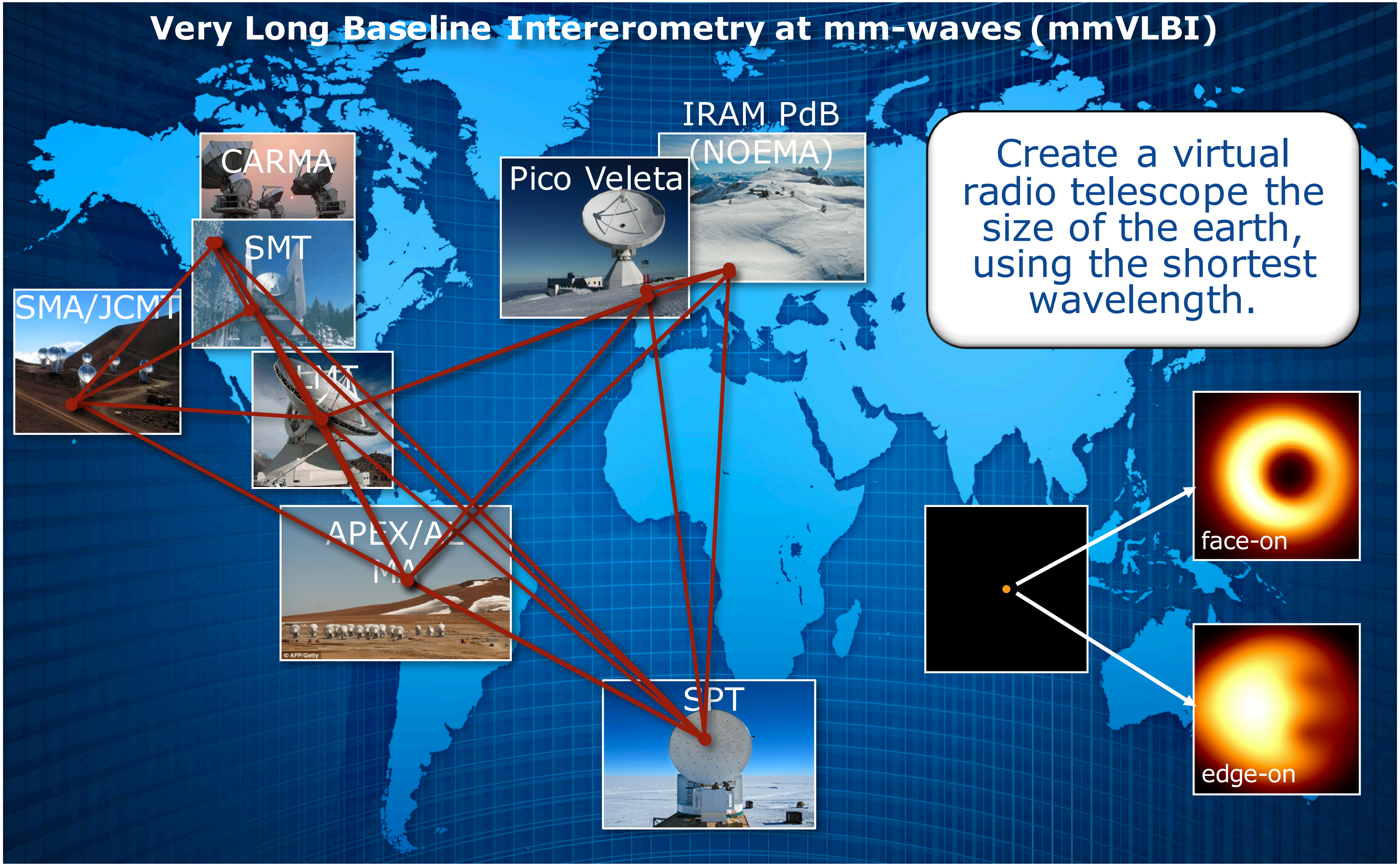


~50 μarcsecond (5 R_s)

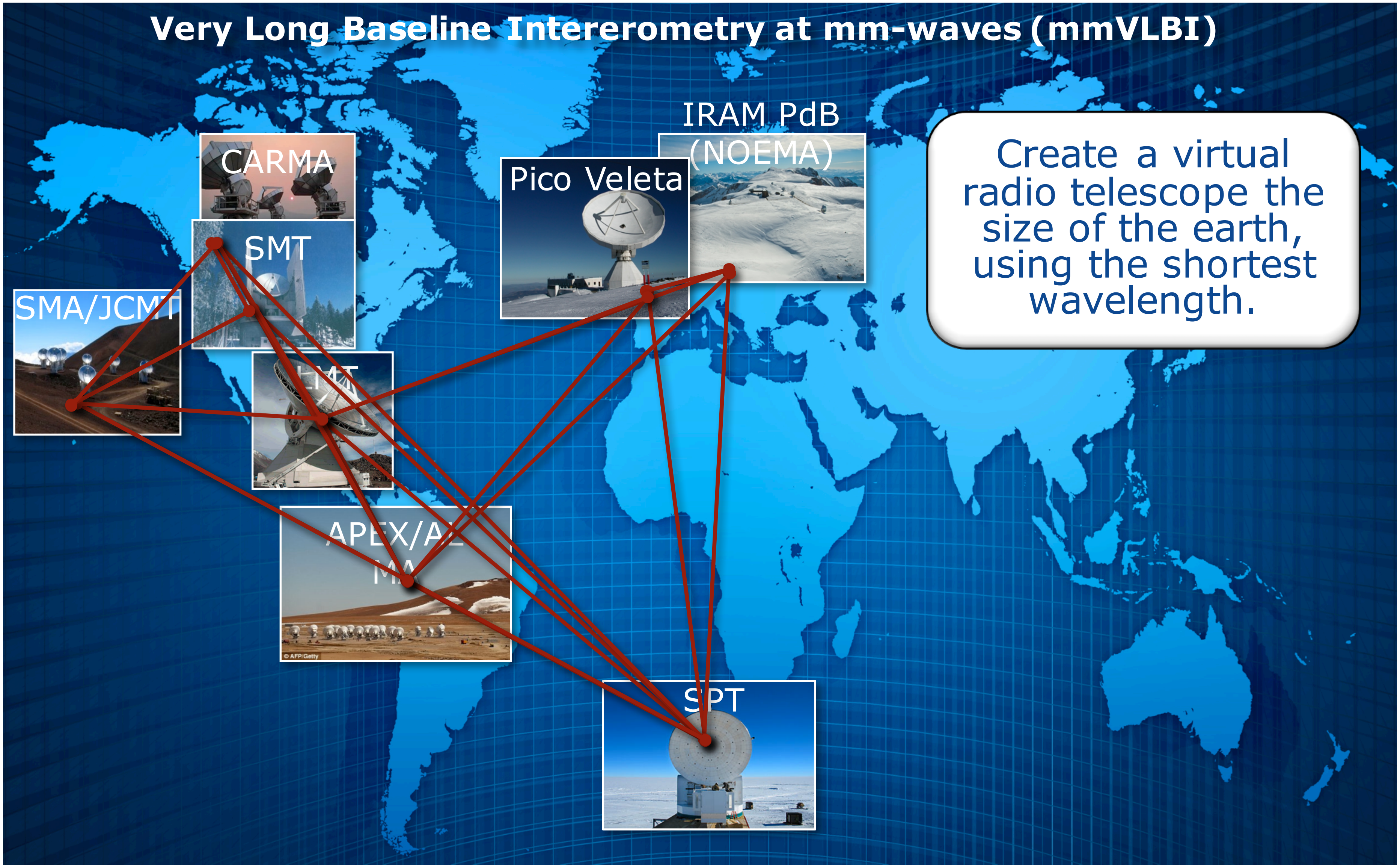
Event Horizon Telescope



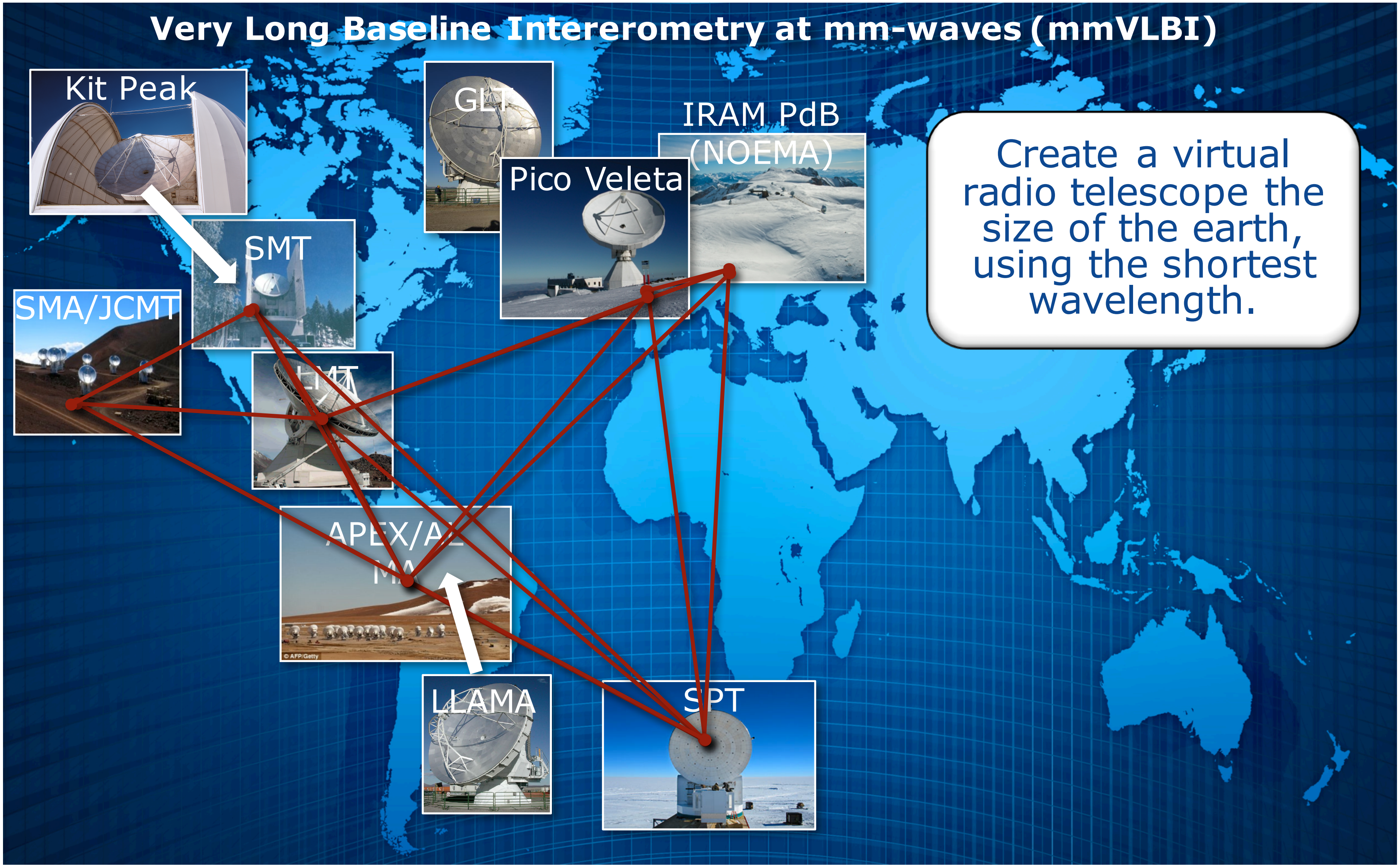
Event Horizon Telescope



Event Horizon Telescope



Event Horizon Telescope



VLBI with Africa mm-telescope?

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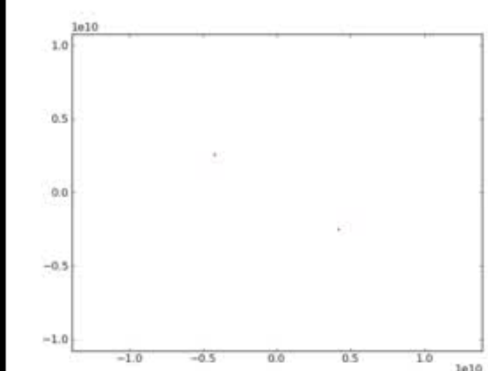
A dedicated African cm and mm-VLBI telescope for EHT, EVN, & SKA. investment cost: ~8 M€ + operations …

Earth seen from Sgr A*



Gamsberg – 2347 m

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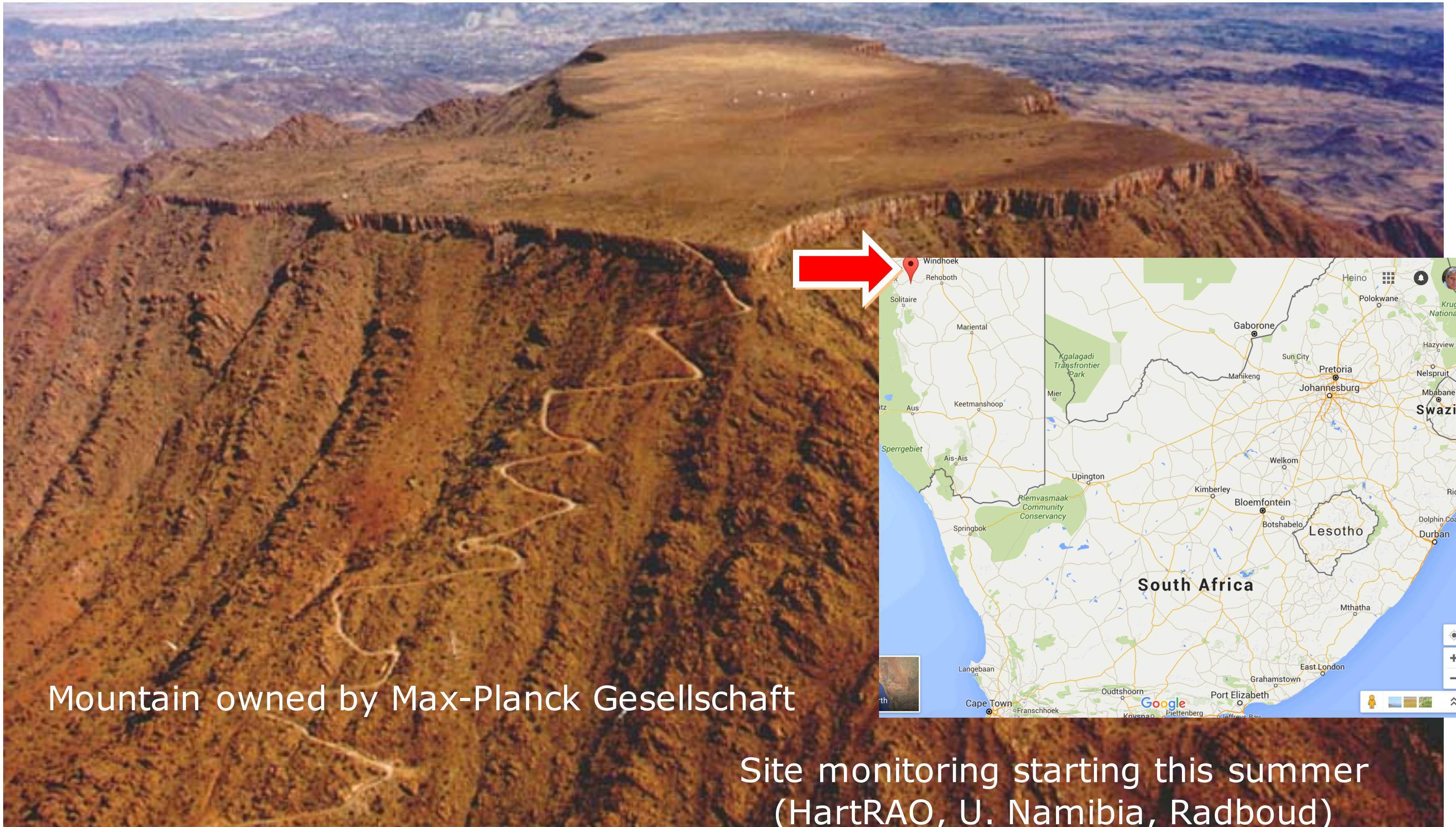
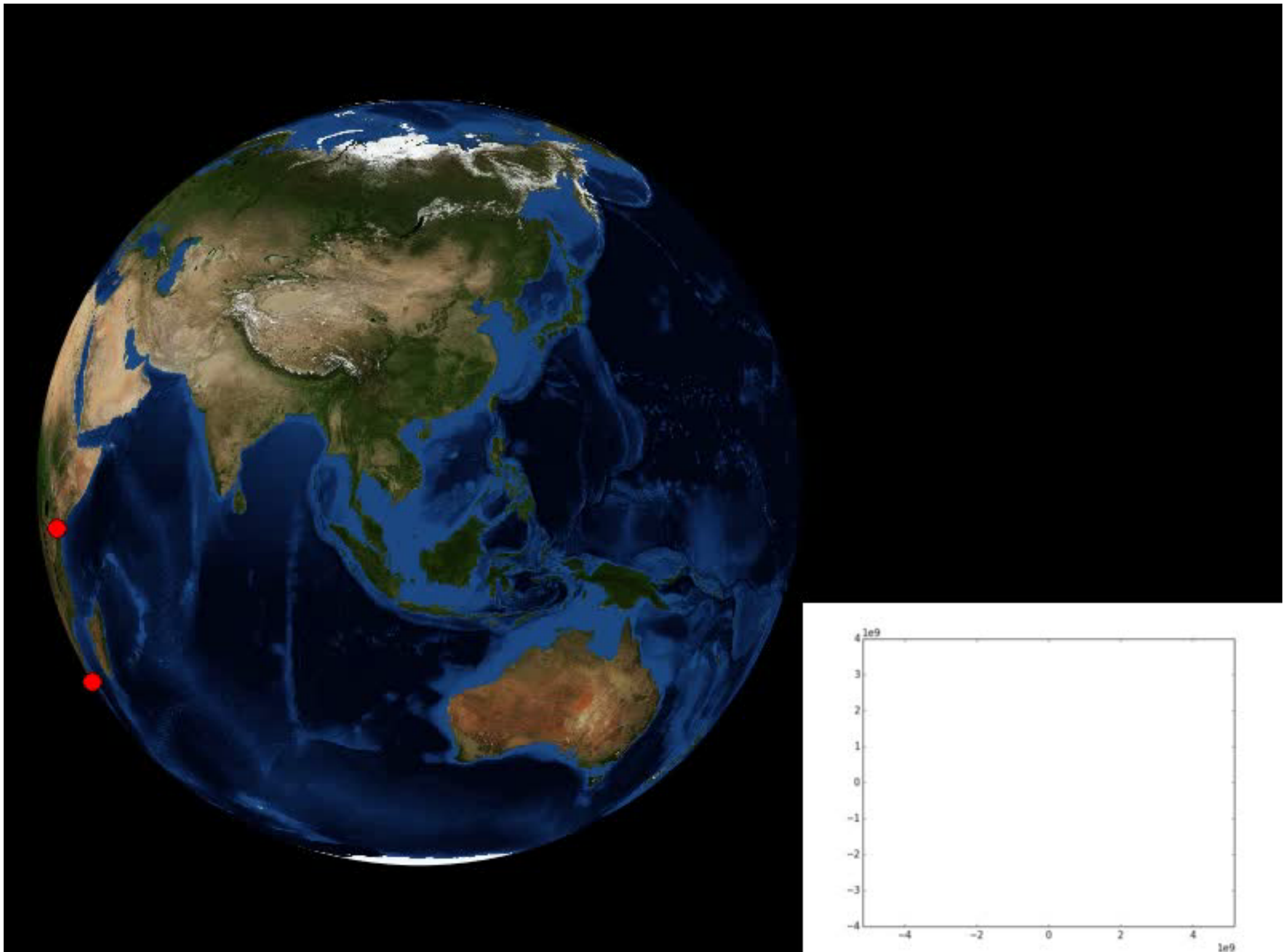


Mountain owned by Max-Planck Gesellschaft

Site monitoring starting this summer
(HartRAO, U. Namibia, Radboud)

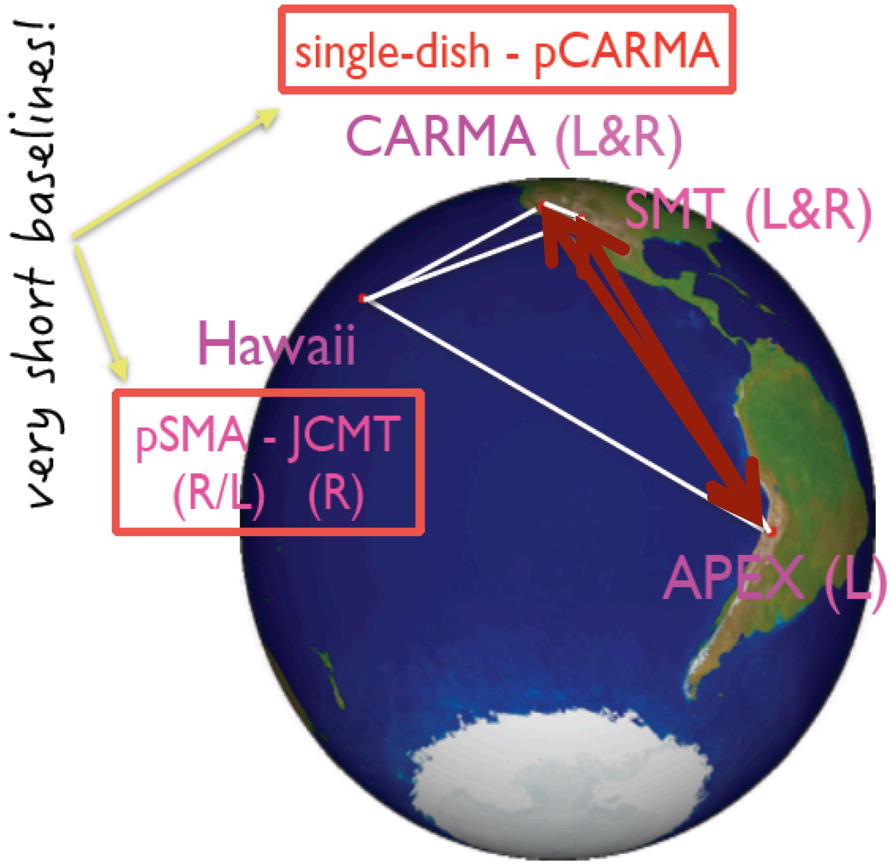
An African Dream:
A future EHT Array for M87

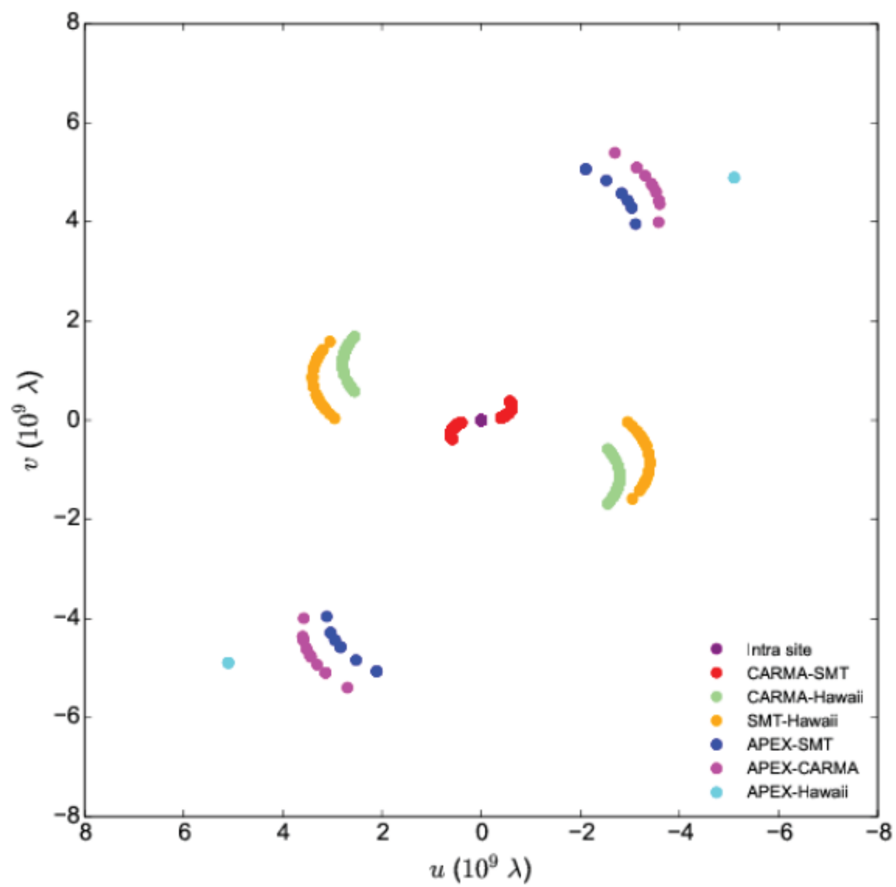
Radboud University Nijmegen



1.3 mm EHT with APEX

Arizona/California - Chile





Lu, Krichbaum et al., in prep.

South Pole – APEX fringes

South Pole - Chile

National Science Foundation
WHERE DISCOVERIES BEGIN

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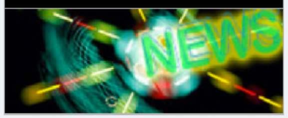

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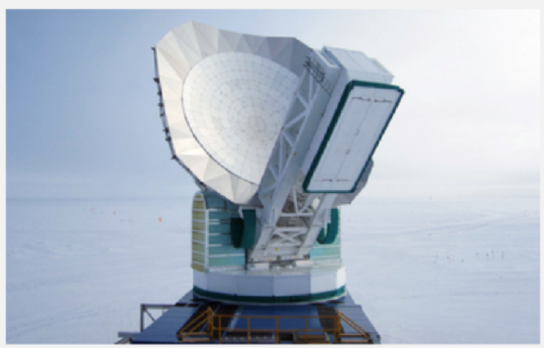
Press Release 15-041

Planet-sized 'virtual telescope' expands to the South Pole to observe black holes in detail

NSF-supported South Pole Telescope incorporated as part of global network

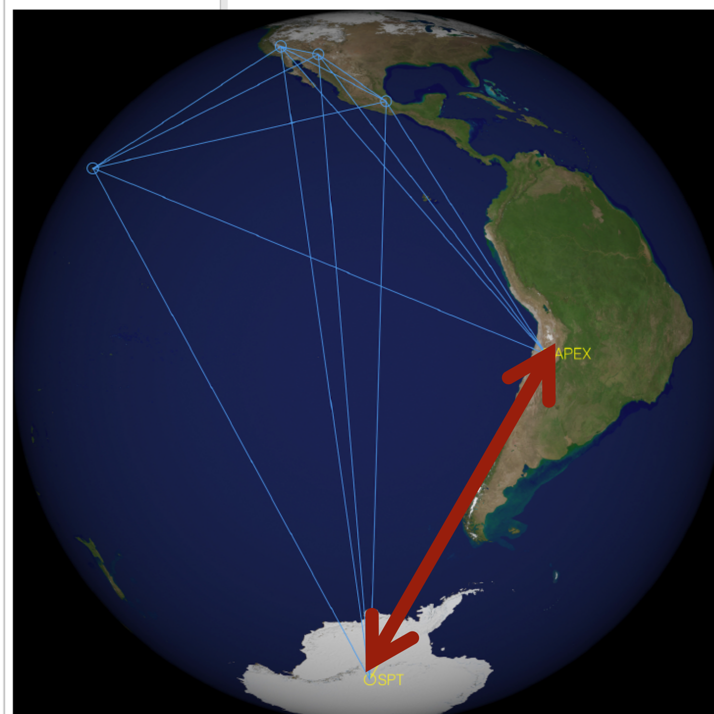


The South Pole Telescope.
Credit and Larger Version

April 21, 2015

B-roll of the South Pole Telescope is available from NSF's Dena Headlee, dheadlee@nsf.gov / (703) 292-7739.

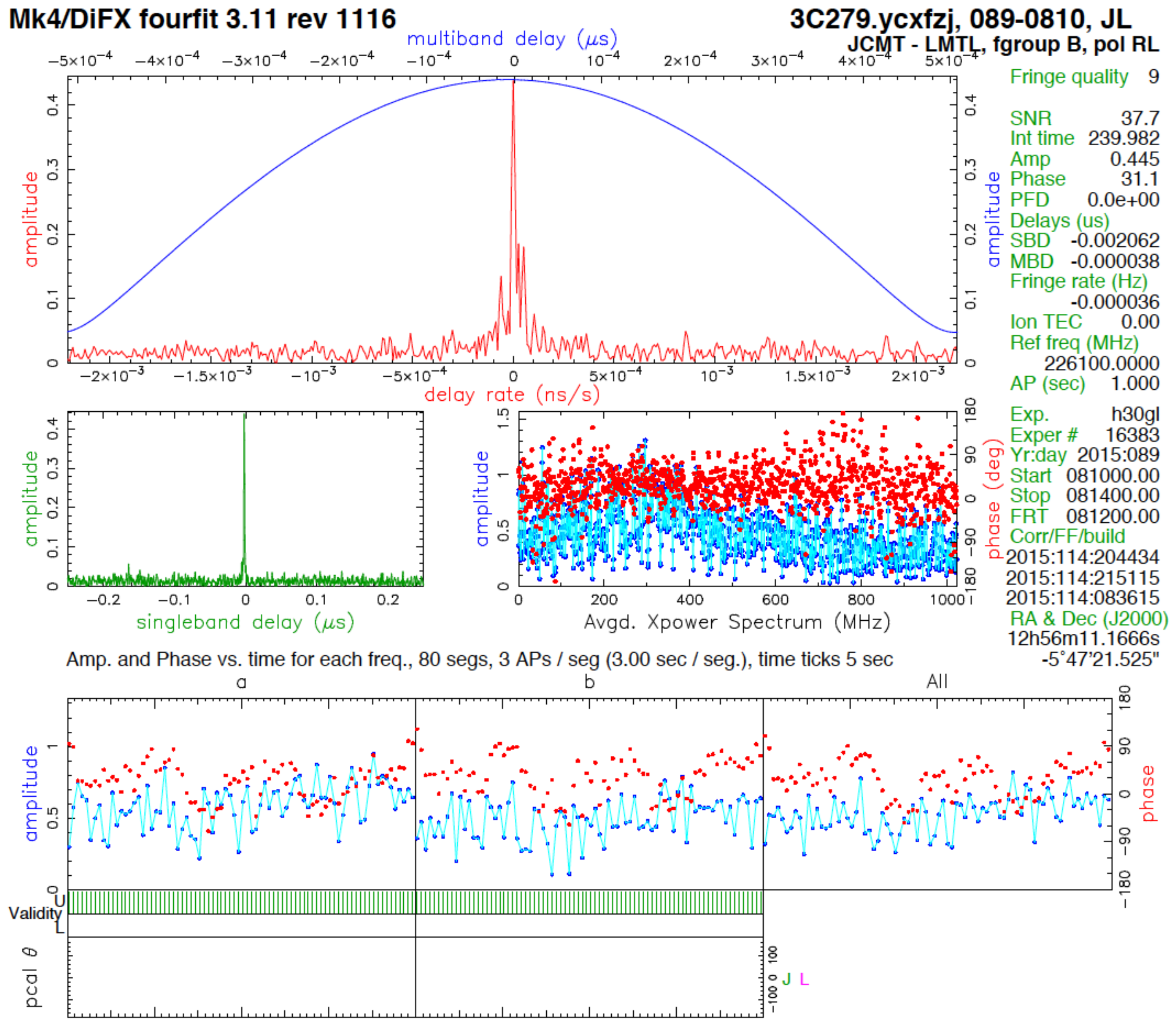
Astronomers building a globe-spanning virtual telescope capable of photographing the "event horizon" of the black hole at the center of our Milky Way have extended their instrument to



led by Dan Marrone (Arizona)

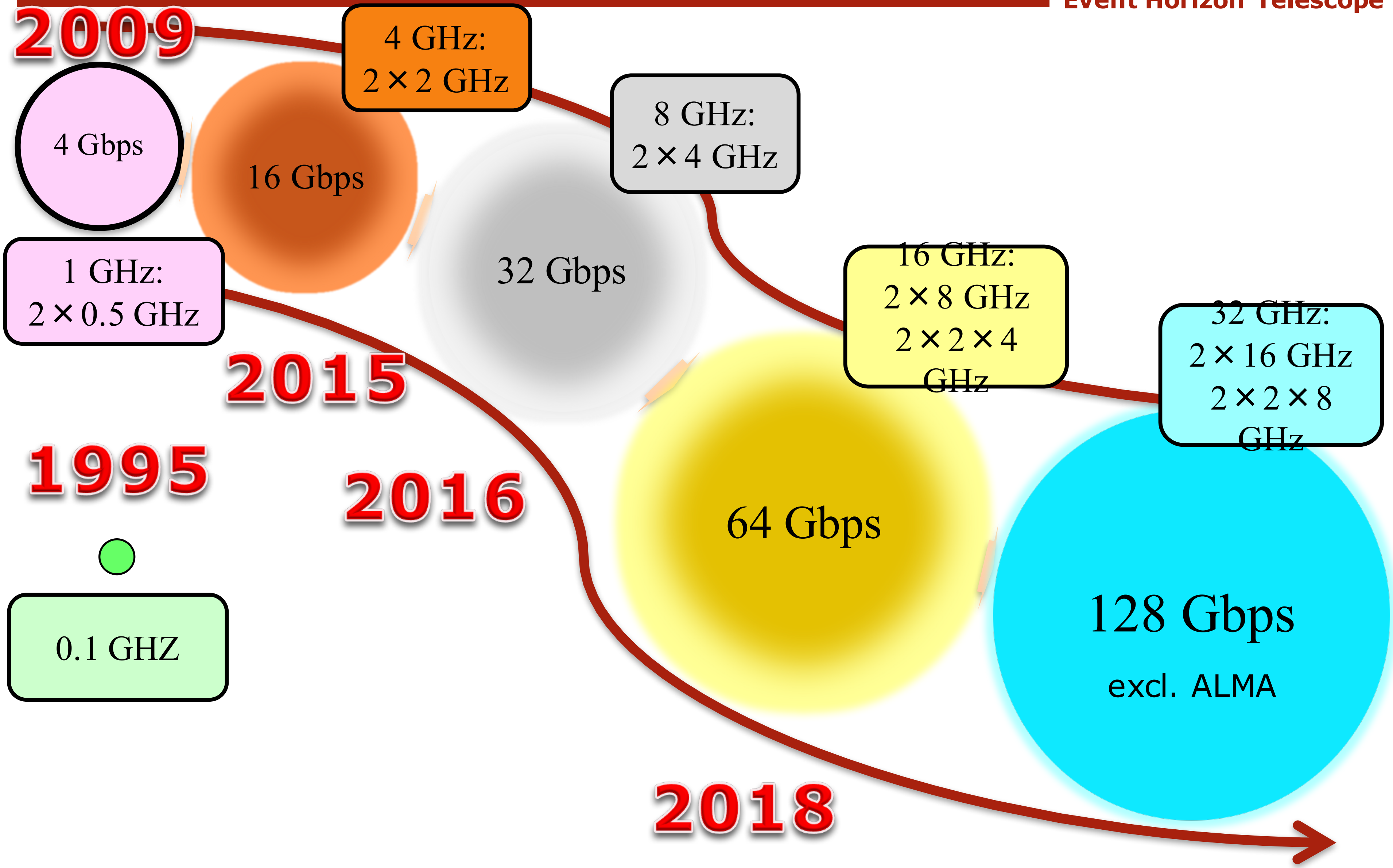
LMT – JCMT fringes

Mexico-Hawaii



Future mmVLBI bandwidths

Event Horizon Telescope



R. Tilanus

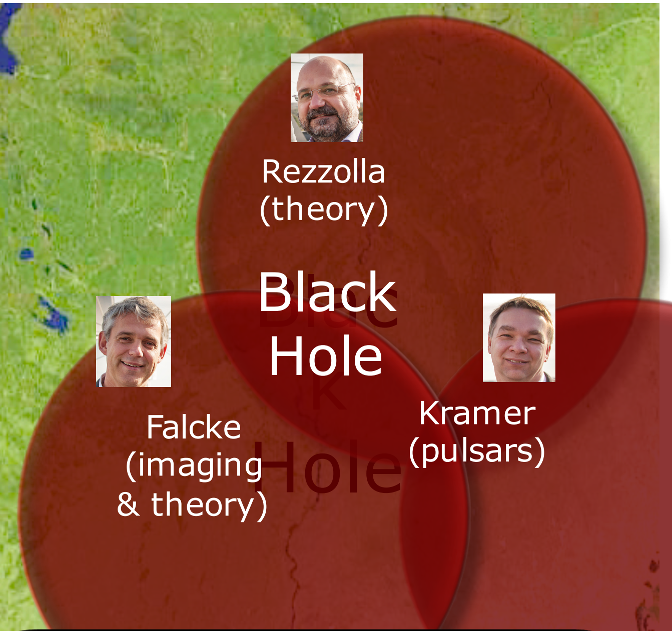
Road towards the EHT

- 1995 IRAM 1.3 mm experiment (PI Krichbaum)
- 2004 Green Bank Sgr A*@40 conference joint declaration
  - 2005 informal telecons towards mmVLBI consortium
- 2005 Haystack-led 1.3 mm three-station experiments (PI Doeleman), EHT precursor
  - ALMA phasing project (PI Doeleman)
- 2009 EHT named at AAS coffee break
  - mm-VLBI of Sgr A* listed in US & EU decadal
  - 2012 1st EHT meeting, Tucson & "mm-VLBI with ALMA", ESO
  - 2014 Waterloo EHT meeting, f2f negotiations
- 2013 & 2014 ERC BlackHoleCam, NSF MSIP grant, & institutional grants at: ASIAA, MPIfR, NOAJ, …
- 2015 EHT interim board formed, telco negotiations
- 2016 Consortium Agreement accepted, legal review

ERC Synergy project: BlackHoleCam

To avoid confusion: BHC is a European funded project, which is a partner in EHT not a separate network!

Matching grant from NSF MSIP: 6.5 M$ for EHT (PI Doeleman)



14M€ funding to:

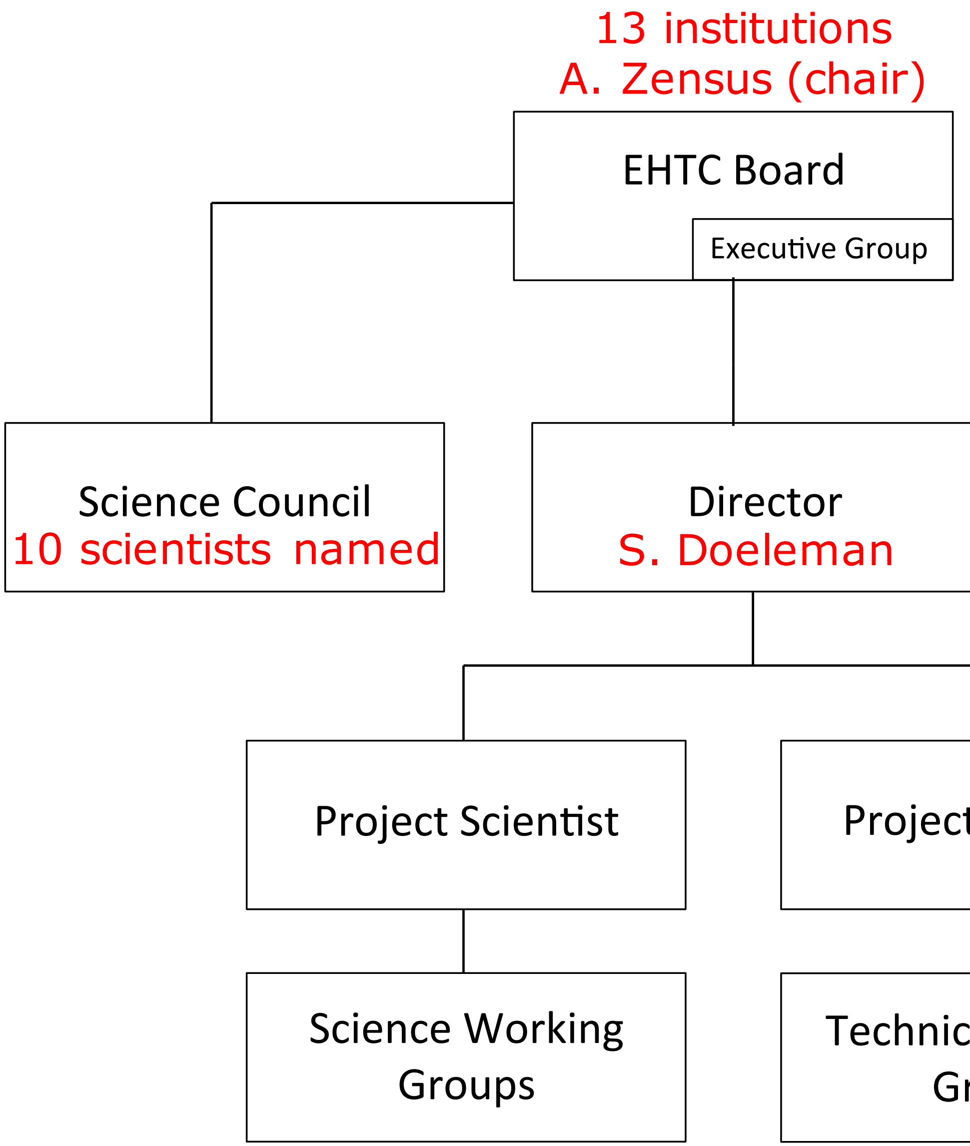
- image black hole
- model black hole
- map spacetime around black holes with stars & pulsars

EHT Science

Global EHT Investments

- Arizona: SMTO, South Pole VLBI equipment, receiver, theory
- ASIAA: Greenland Telescope, Maser cost-sharing, SouthPole maser, Alma phasing
- BlackHoleCam (Radboud, Frankfurt, Bonn): Phasing PdeB (NOEMA), data pipelining (in CASA), monitoring & control, VLBI backend hardware & disks, theory
- Harvard/SAO: SMA, NSF-MSIP management, VLBI equipment, theory
- IRAM, LMT (INAOE), JCMT (EACOA), SPT (Chicago): telescope time.
- MPIfR: Apex, VLBI instrumentation for Pico Veleta and PdeBure, VLBI correlation, Alma phasing
- MIT Haystack: Alma phasing, correlation, analysis software, management
- NAOJ: ASTE experiment (2010), Alma phasing, software
- Perimeter: theory

EHT structure



Individual EHT membership still to be defined (and possible)!

EHT Stakeholders & board

- Harvard/SAO (USA)
  - R. Brissenden
- MIT Haystack (USA)
  - C. Lonsdale
- Univ. Arizona (USA)
  - B. Jannuzzi
- Univ. Chicago (USA)
  - J. Carlstrom
- Perimeter (Canada)
  - A. Broderick
- MPIFR Bonn (Germany)
  - A. Zenus
- IRAM (D/F/E)
  - K. Schuster
- Radboud Univ. (Netherlands)
  - H. Falcke
- Univ. Frankfurt (Germany)
  - L. Rezzolla
- INAOE (Mexico)
  - D. Hughes
- EACOA (East Aisa)
  - P. Ho
- NOAJ (Japan)
  - M. Honma
- ASIAA (Taiwan)
  - M. Inoue

ALMA & VLBI

- GMVA operates as 3mm VLBI operator
- EHT operates as experiment and 1.3 mm VLBI operator (trial)
  - can support limited number of external proposals
- ALMA makes some fraction of time available for VLBI at 1.3 and 3 mm
- NRAO receives proposals and distributes to EHT and partner telescopes
  - EHT provides technical and scientific assessment
  - Proposals are reviewed by individual telescopes
- ALMA receives, reviews & ranks proposals
- EHT + ALMA jointly schedule successful proposals
- First session: April 5-14, 2017

EHT Interim Board formed

MIT HAYSTACK OBSERVATORY

ARIZONA

USA

HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS (CfA)

SOUTH POLE TELESCOPE (SPT)

Radboud Universiteit Nijmegen

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

BLACK HOLE CAM

Max-Planck-Institut für Radioastronomie

Europe

iram
Institut de Radioastronomie Millimétrique

中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

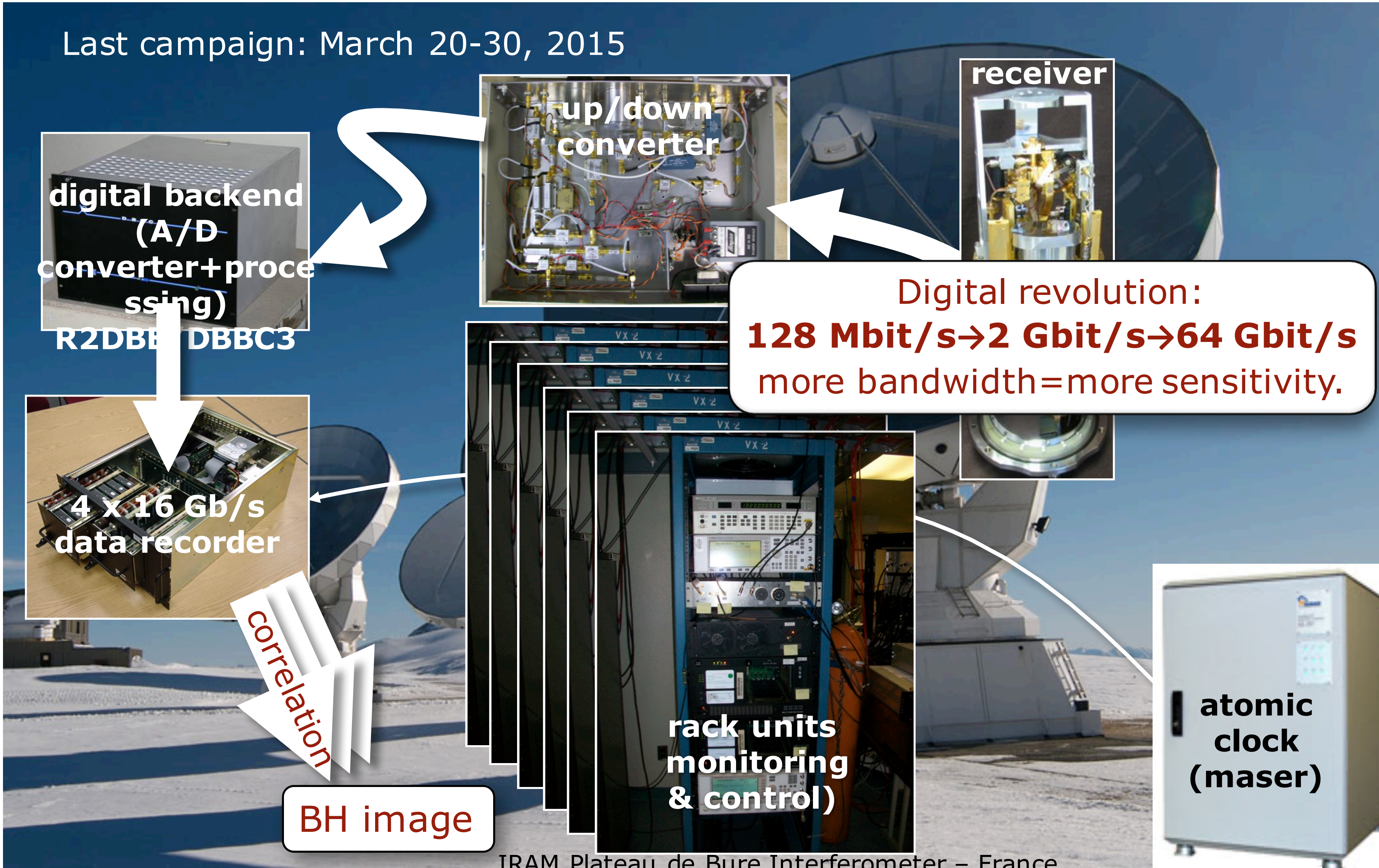
ASIA

国立天文台 NAOJ

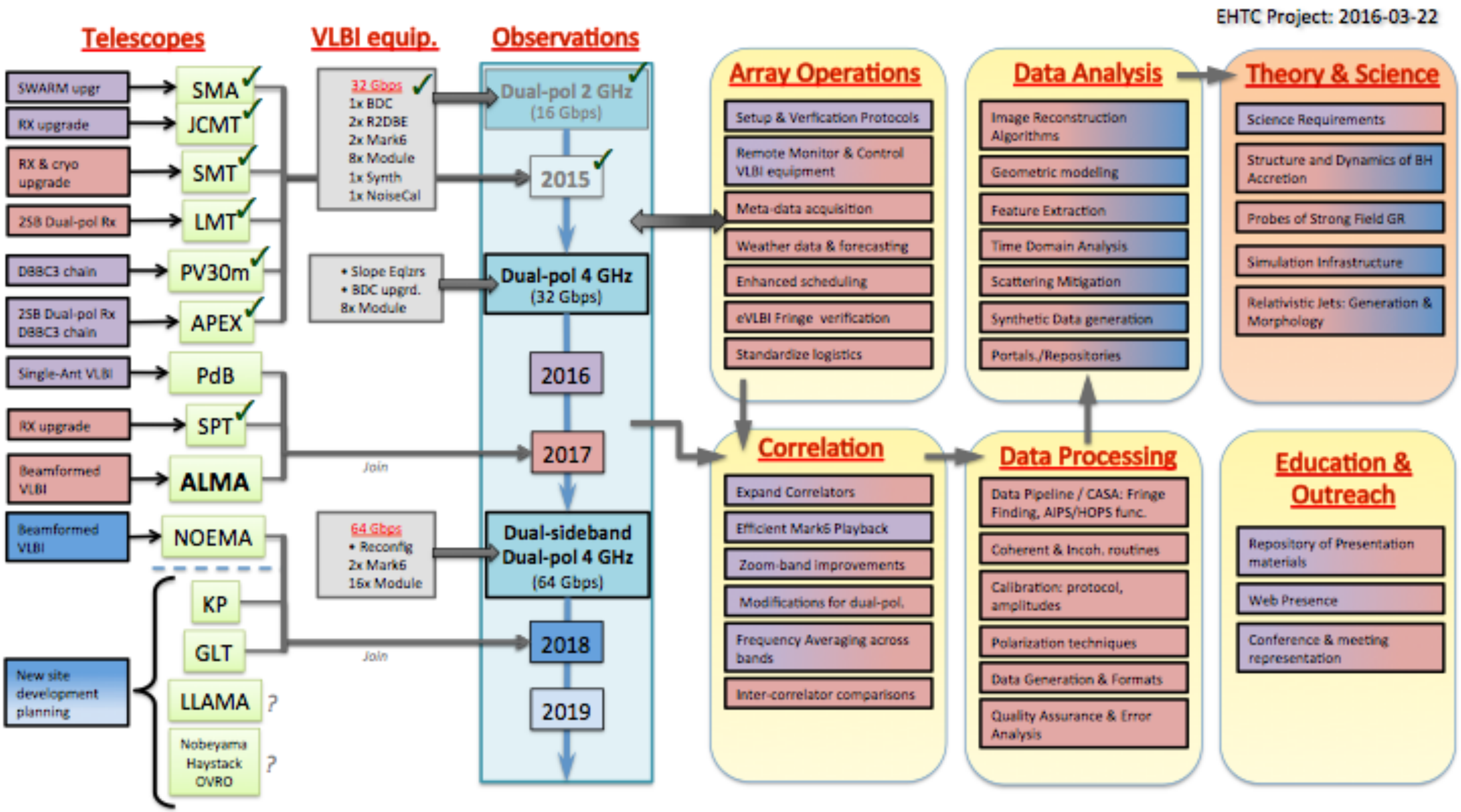
EAObservatory

Mexico

The VLBI System



EHT Roadmap


EHTC Project: 2016-03-22
Telescopes
VLBI equip.
Observations
SWARM upgr
RX upgrade
RX & cryo upgrade
258 Dual-pol Rx
DBBC3 chain
258 Dual-pol Rx DBBC3 chain
Single-Ant VLBI
RX upgrade
Beamformed VLBI
Beamformed VLBI
New site development planning
SMA
JCMT
SMT
LMT
PV30m
APEX
PdB
SPT
ALMA
NOEMA
KP
GLT
LLAMA ?
Nobeyama Haystack OVRO ?
32 Gbps
1x BDC
2x R2DBE
2x Mark6
8x Module
1x Synth
1x NoiseCal
• Slope Eqlzrs
• BDC upgrd.
8x Module
64 Gbps
• Reconfig
2x Mark6
16x Module
Join
Join
Dual-pol 2 GHz (16 Gbps)
2015
Dual-pol 4 GHz (32 Gbps)
2016
2017
Dual-sideband Dual-pol 4 GHz (64 Gbps)
2018
2019
Array Operations
Setup & Verfication Protocols
Remote Monitor & Control VLBI equipment
Meta-data acquisition
Weather data & forecasting
Enhanced scheduling
eVLBI Fringe verification
Standardize logistics
Data Analysis
Image Reconstruction Algorithms
Geometric modeling
Feature Extraction
Time Domain Analysis
Scattering Mitigation
Synthetic Data generation
Portals./Repositories
Theory & Science
Science Requirements
Structure and Dynamics of BH Accretion
Probes of Strong Field GR
Simulation Infrastructure
Relativistic Jets: Generation & Morphology
Correlation
Expand Correlators
Efficient Mark6 Playback
Zoom-band improvements
Modifications for dual-pol.
Frequency Averaging across bands
Inter-correlator comparisons
Data Processing
Data Pipeline / CASA: Fringe Finding, AIPS/HOPS func.
Coherent & Incoh. routines
Calibration: protocol, amplitudes
Polarization techniques
Data Generation & Formats
Quality Assurance & Error Analysis
Education & Outreach
Repository of Presentation materials
Web Presence
Conference & meeting representation

Scattering & Variability

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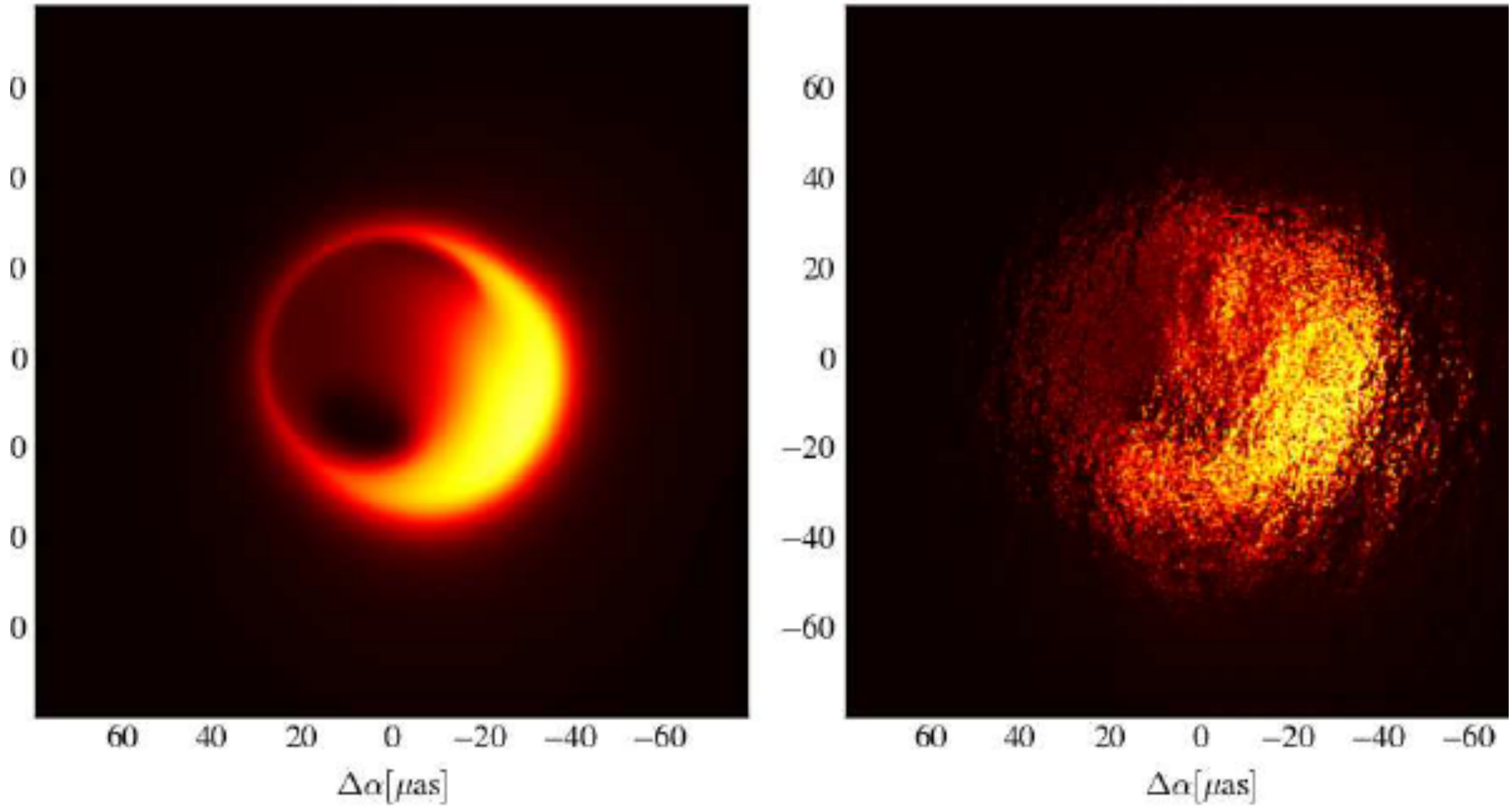

Broderick, Johnson et al. (2016)

Scattering

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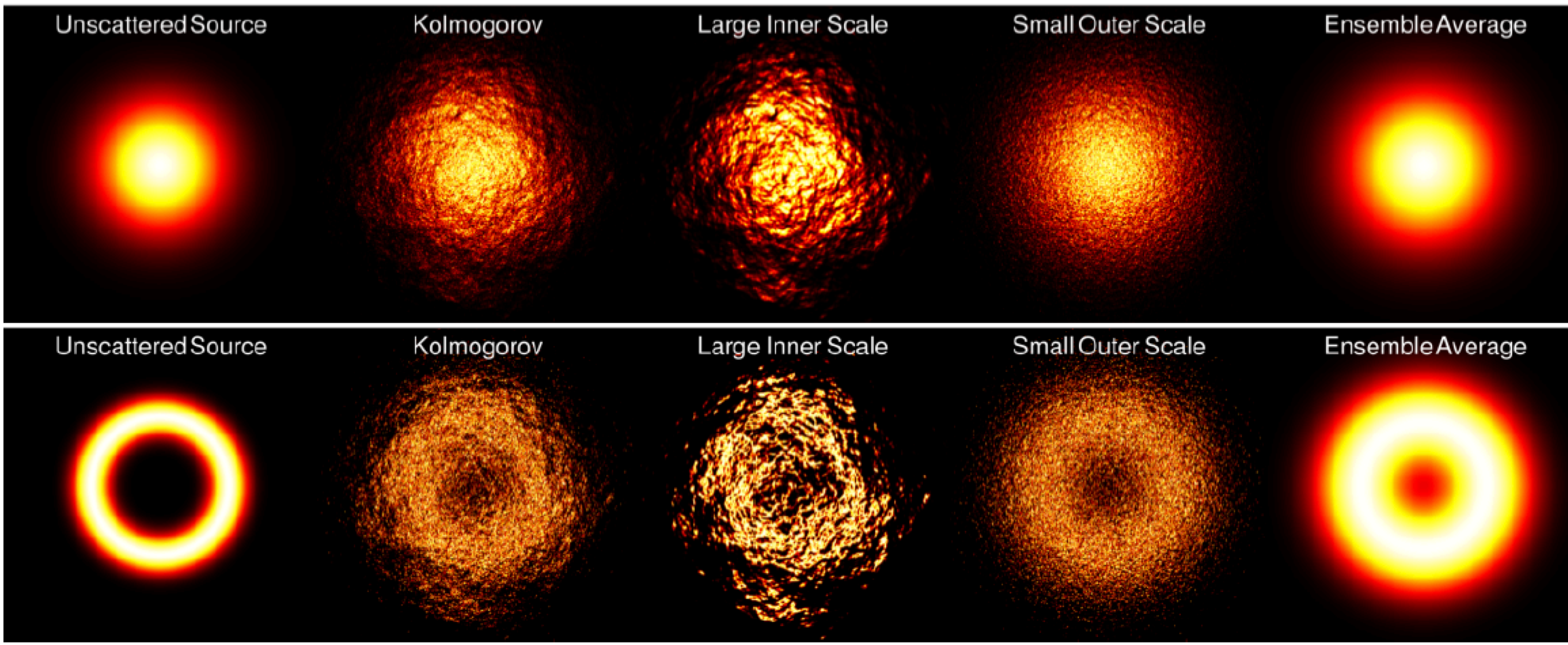
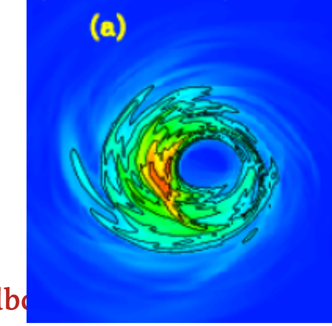
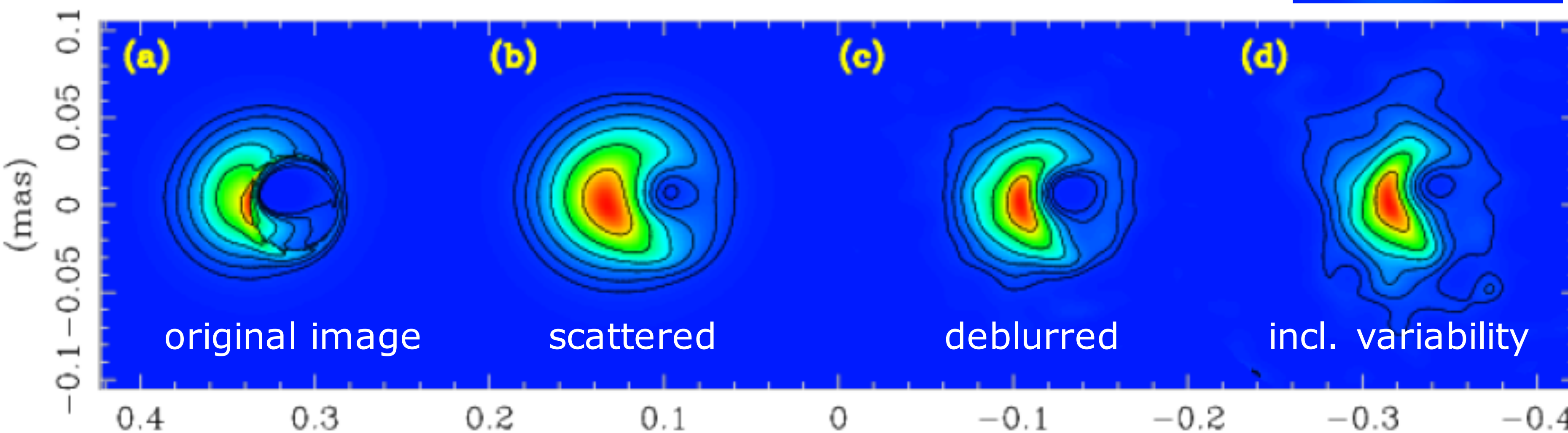
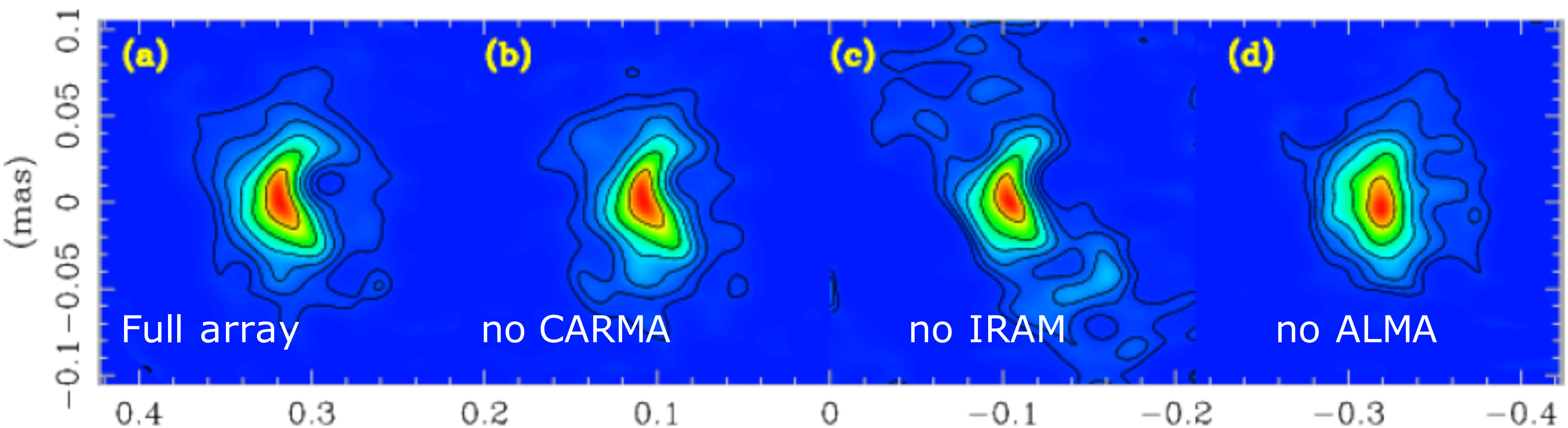


Johnson & Gwinn (2015)

Image reconstruction







Lu, Roelofs et al. (2016, APJ)

Future: 350 GHz VLBI images of 2D GRMHD

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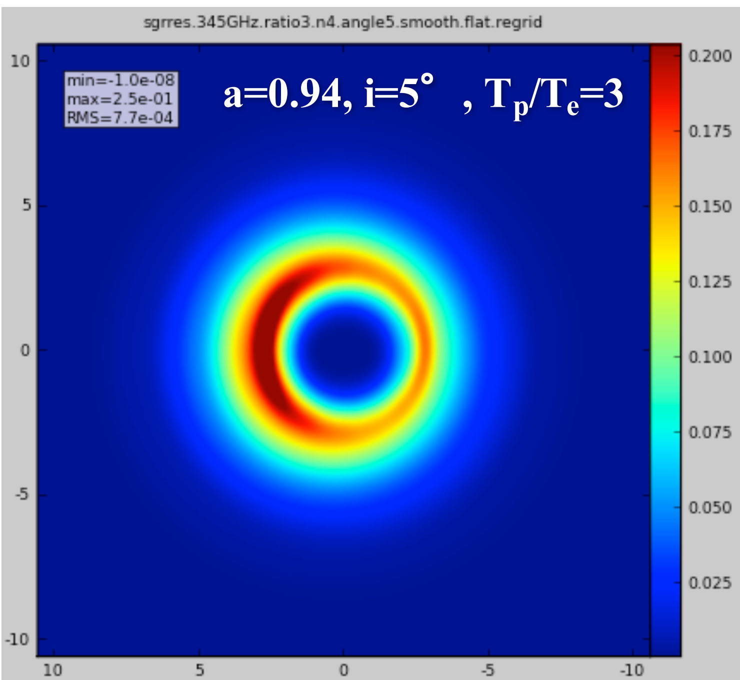
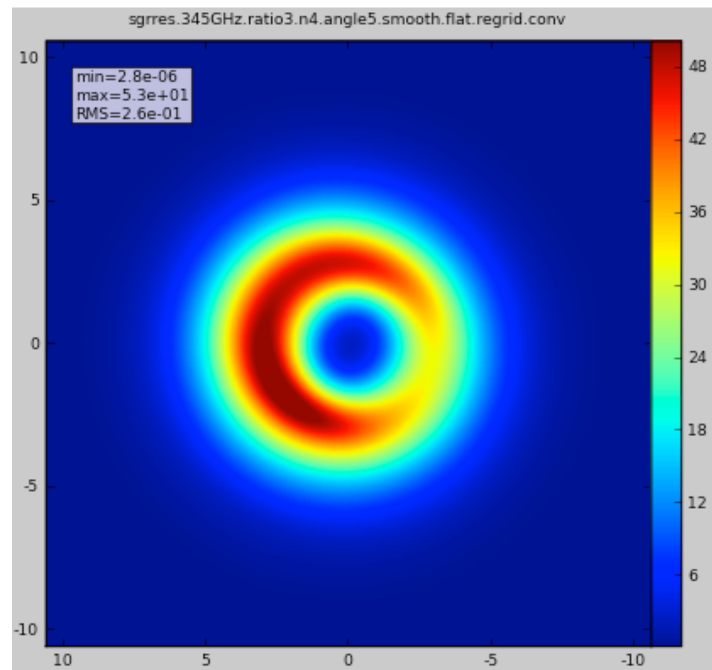
face-on orientation

"disk-only" model from Mościbrodzka et al. (2009)

model



reconstructed VLBI Image



Falcke et al. (2011)

Future: 350 GHz VLBI images of 2D GRMHD

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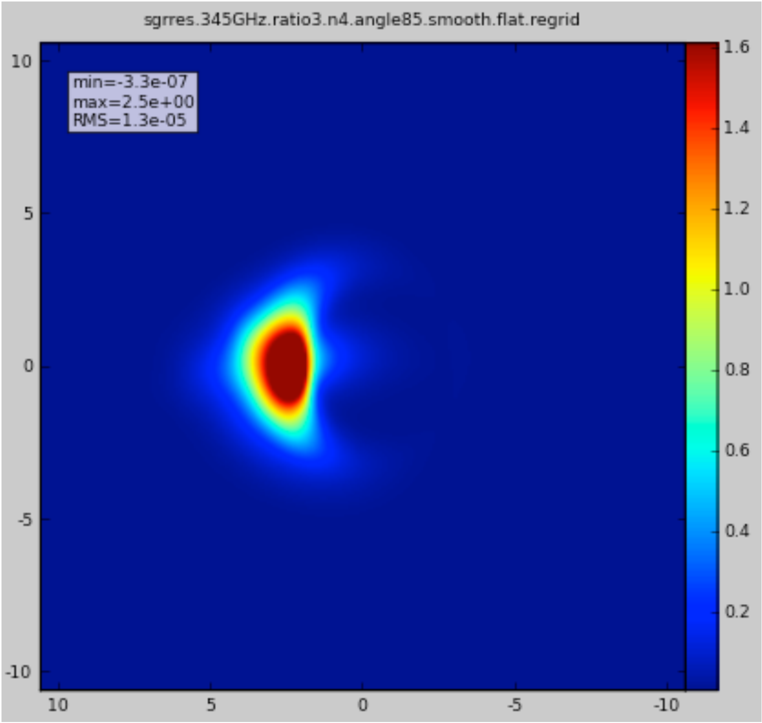
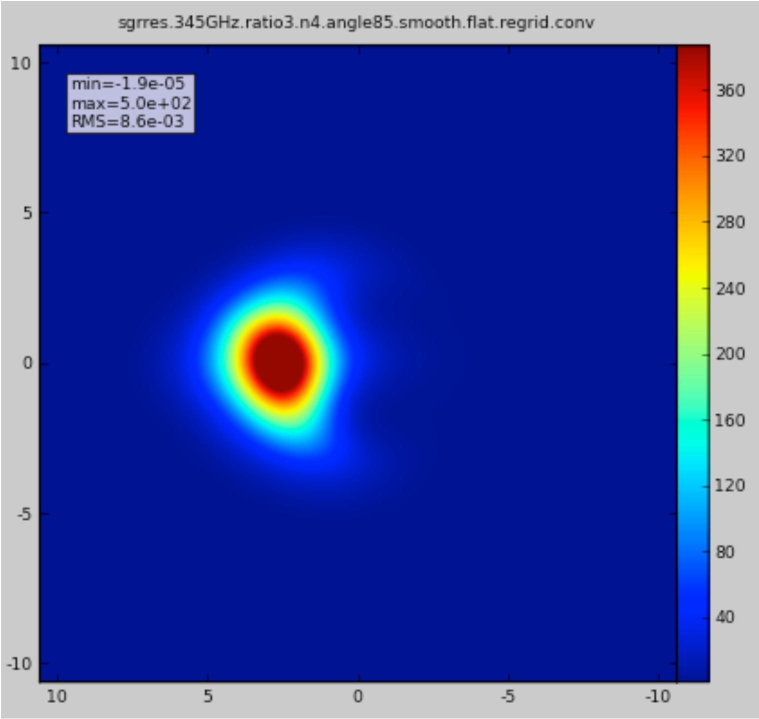
edge-on orientation

scatter-broadened model

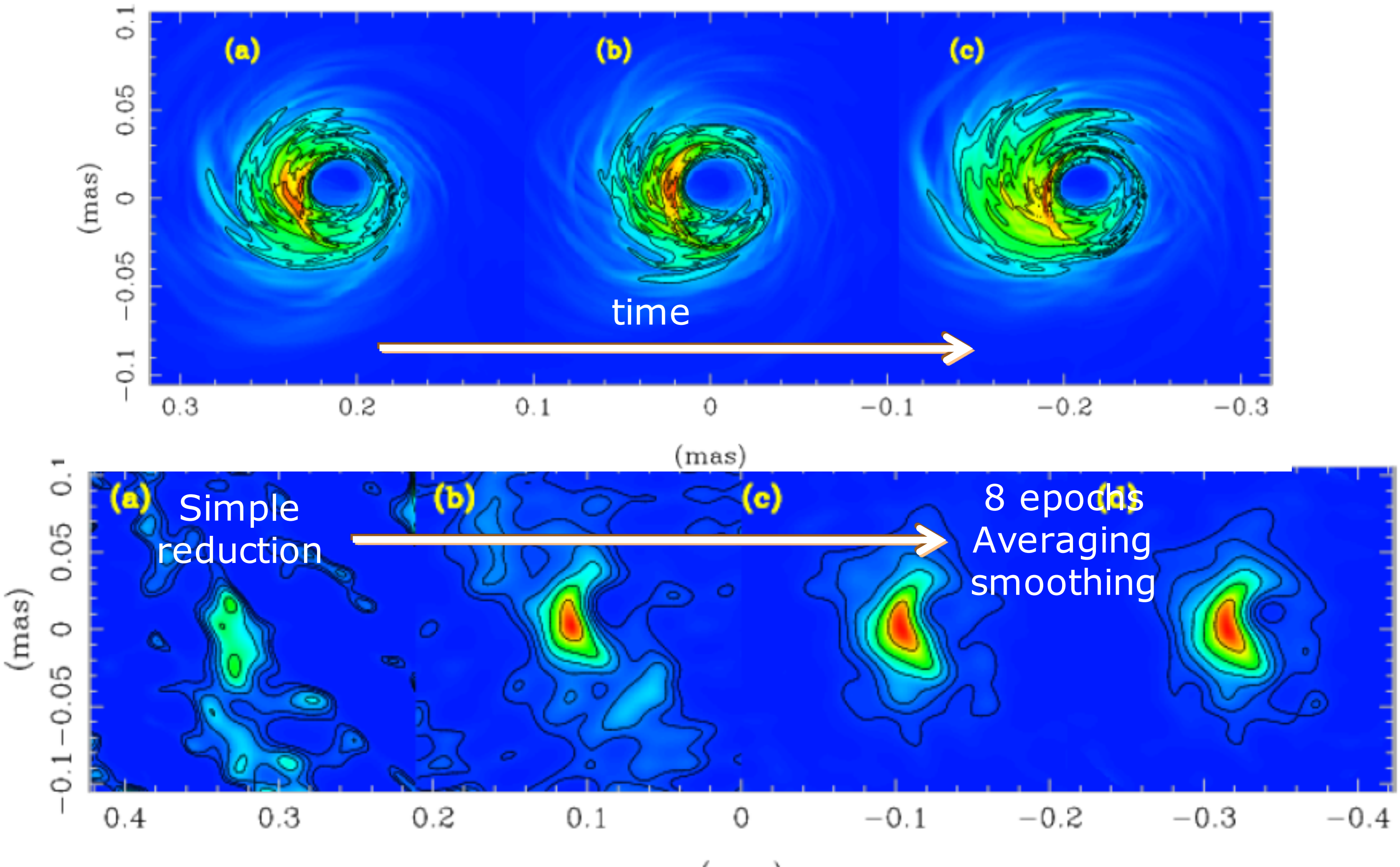


reconstructed Image



Falcke et al. (2011)

Source Variability



Lu, Roelofs et al. (2016, APJ)

Fitting optimal shadow model to get BH parameters

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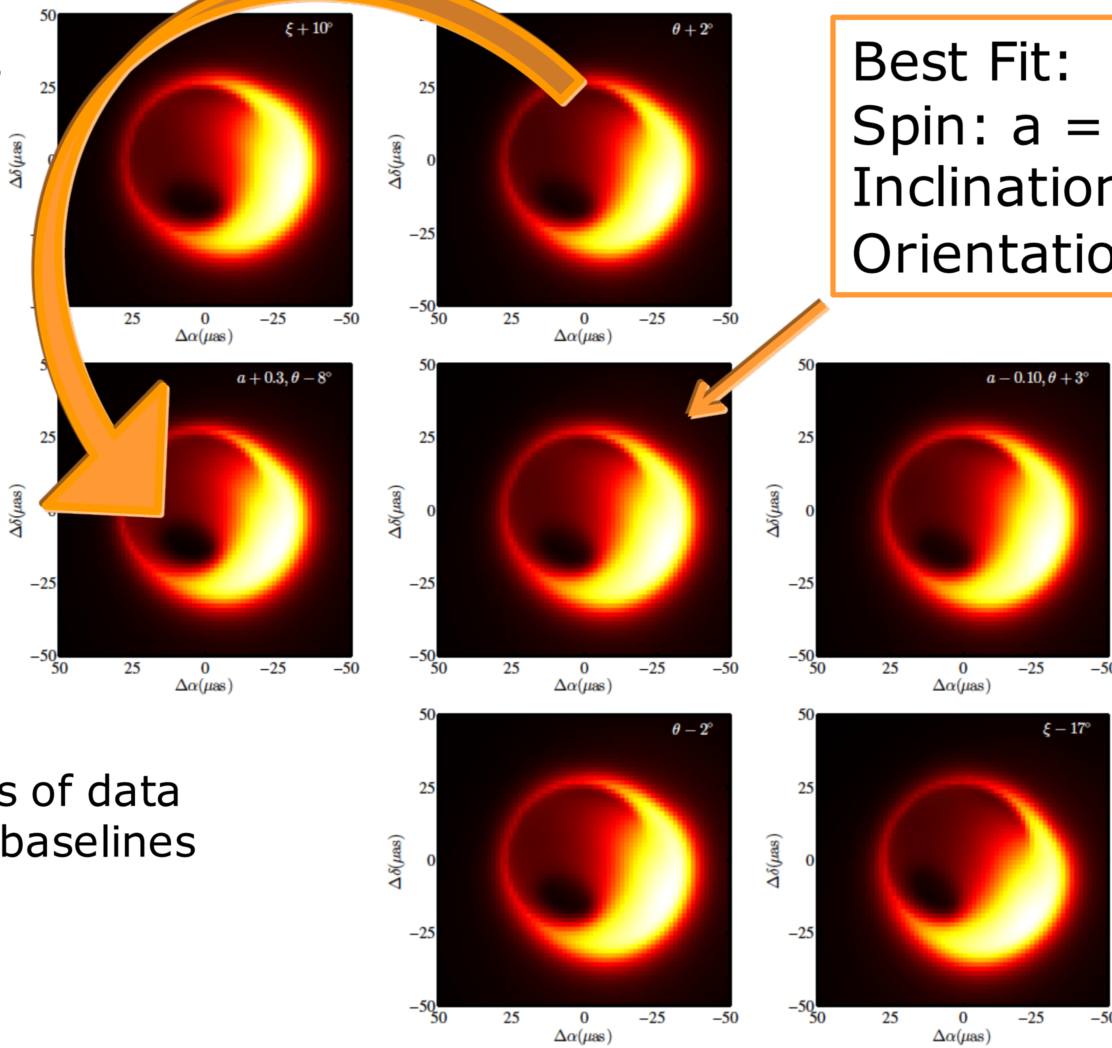
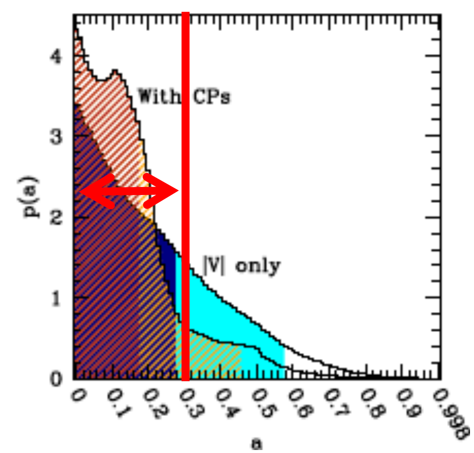
1 σ variations



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

Broderick et al. (2016)

Fitting optimal shadow model

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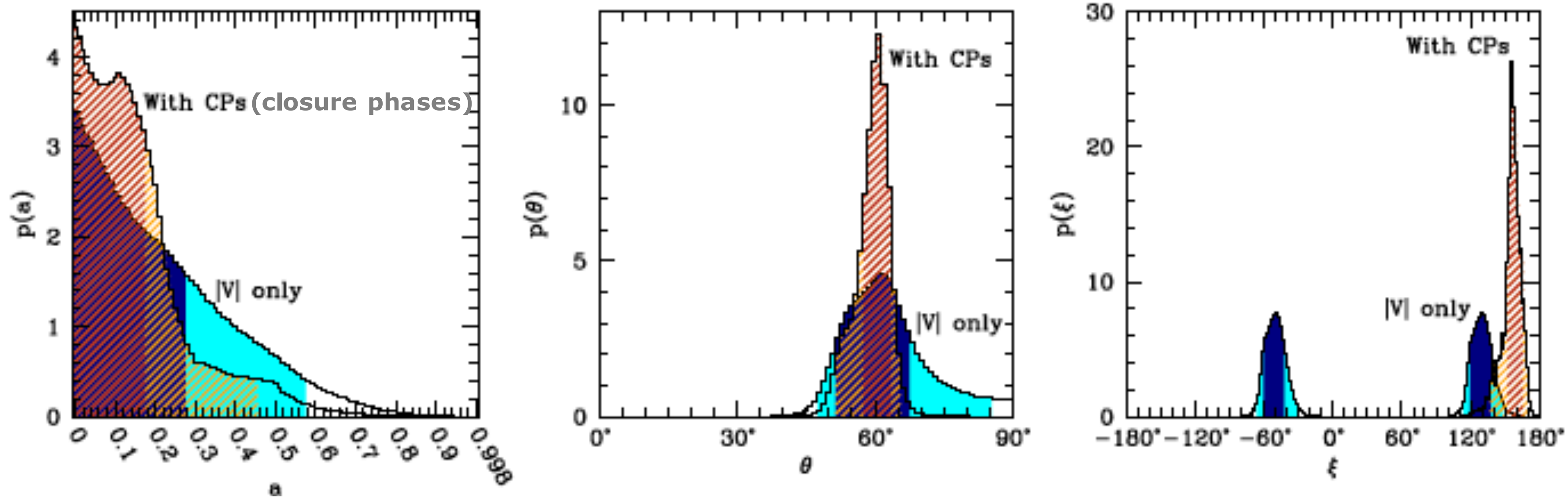
Spin



Broderick et al. (2016)

Models with jet emission give slightly different results

Moscibrodzka et al. (2014)

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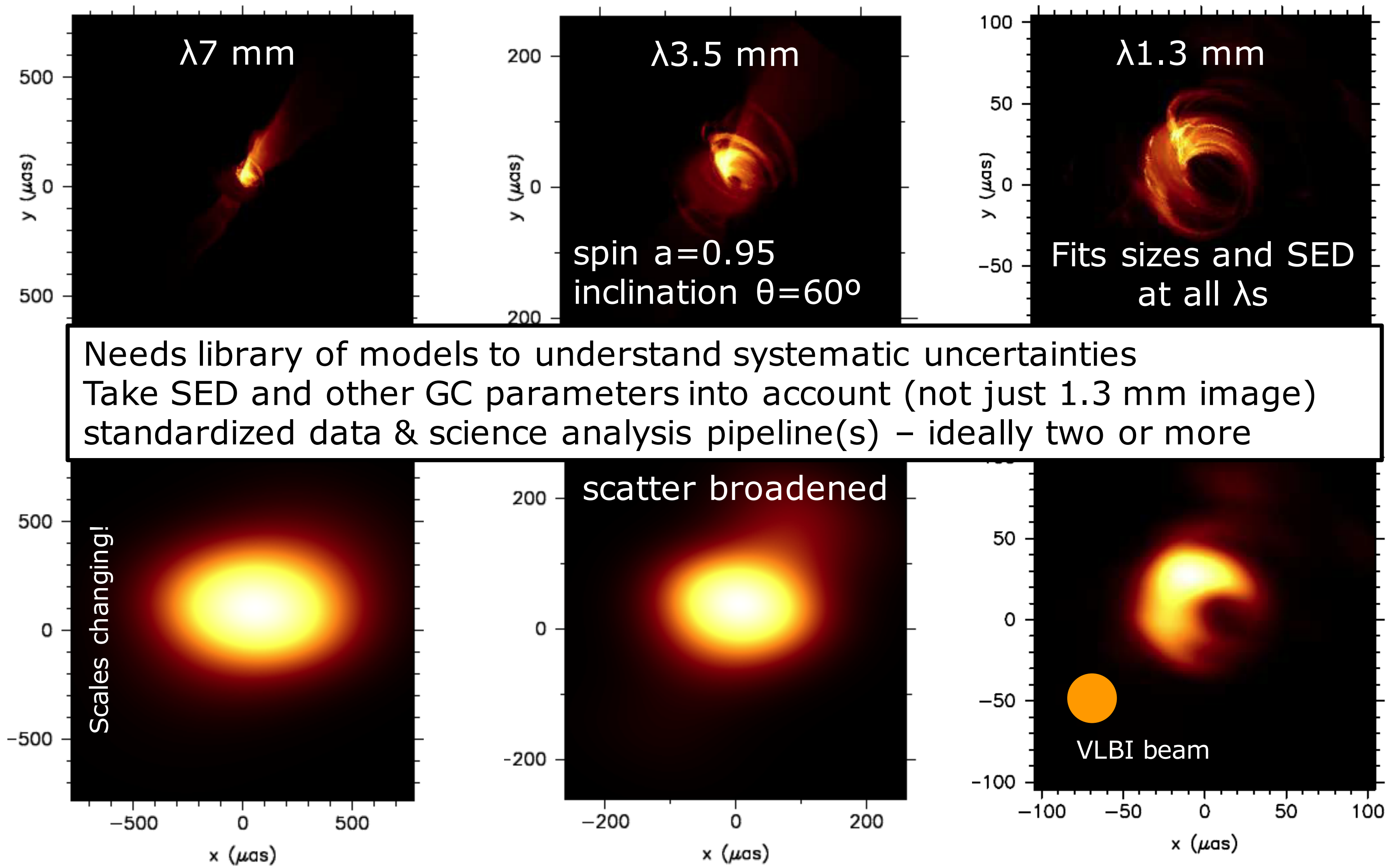

Needs library of models to understand systematic uncertainties
Take SED and other GC parameters into account (not just 1.3 mm image)
standardized data & science analysis pipeline(s) – ideally two or more

Shadow Industry: Different Spacetimes

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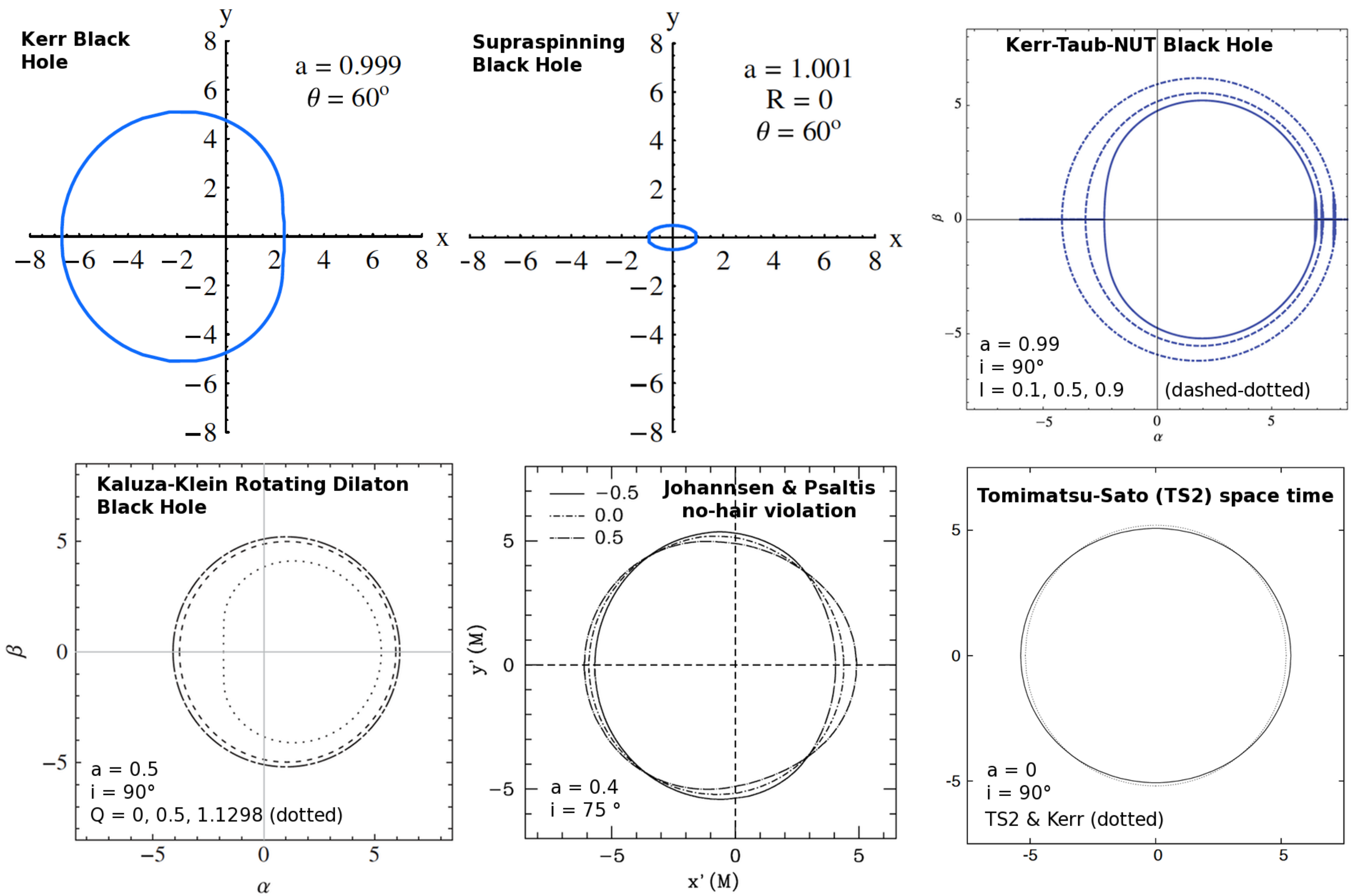

Falcke & Markoff, Class. & Quant. Gravity (2013)
See also Johansen (2016), Class. & Quant. Gravity

Deviations from GR

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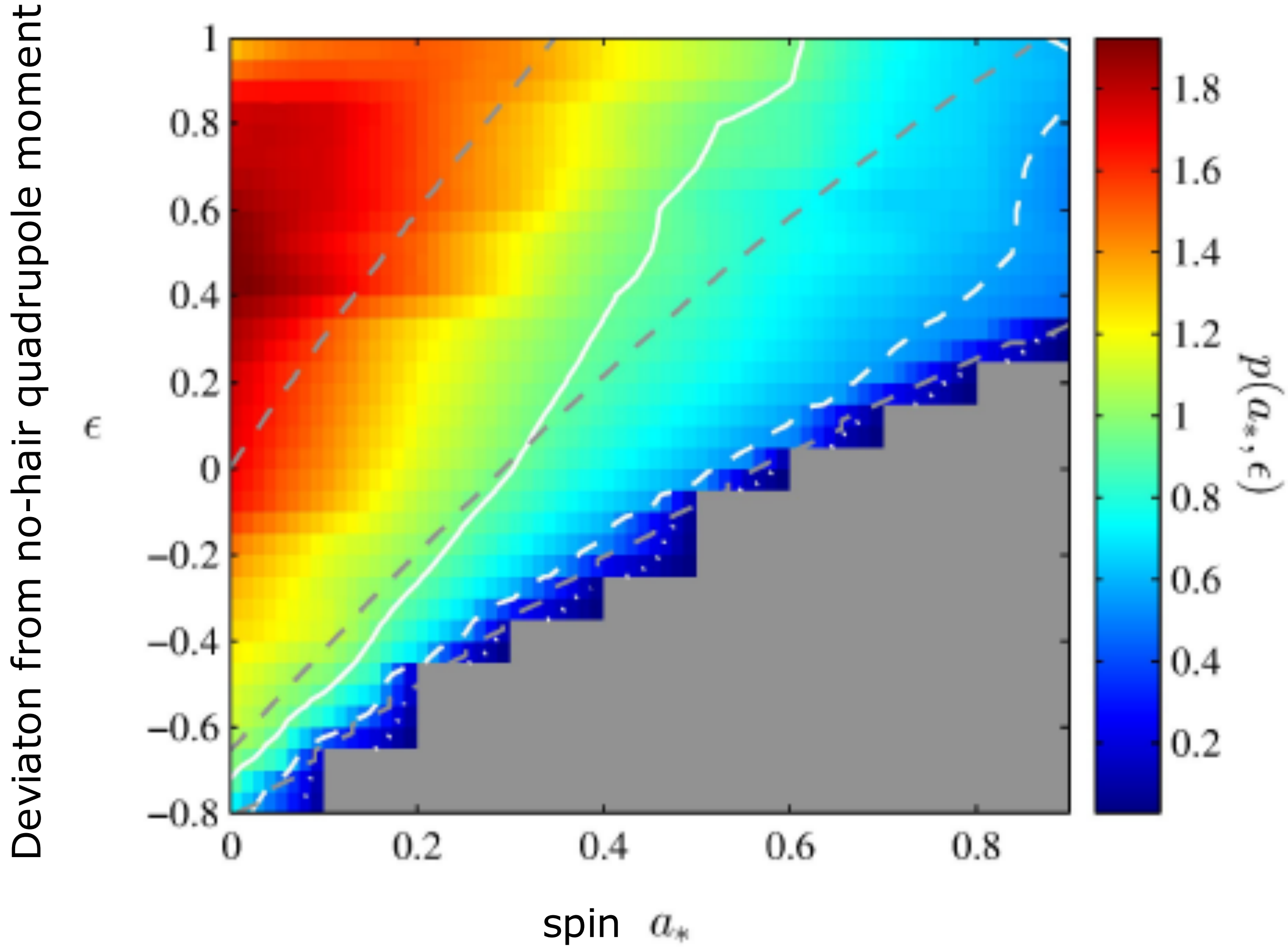

Broderick et al. (2014), Johannsen (2016)

Simulating and quantifying non-Einstein gravity

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

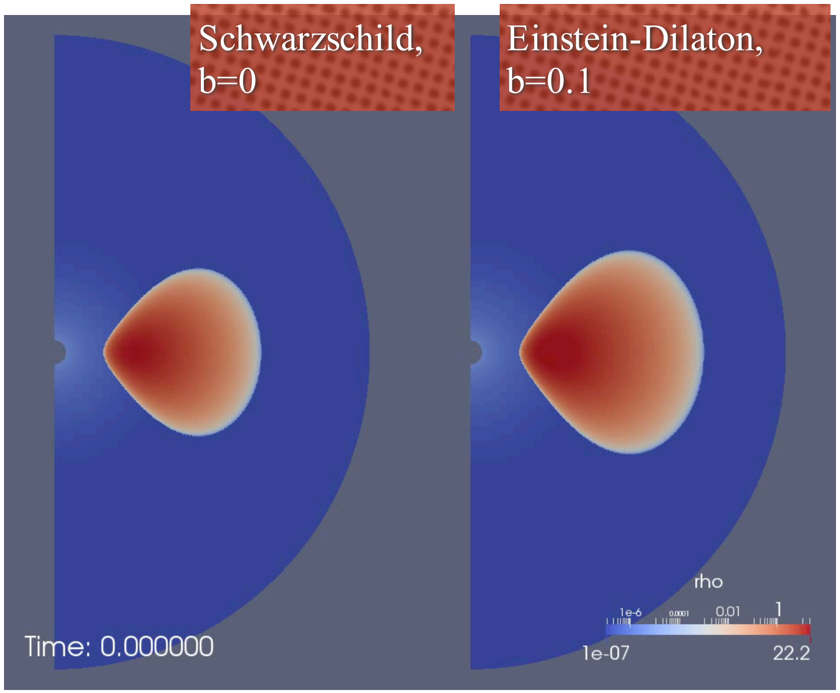
$$ds^2 = -\left(\frac{\rho - 2\mu}{\rho + 2b}\right)dt^2 + \left(\frac{\rho + 2b}{\rho - 2\mu}\right)d\rho^2 + (\rho^2 + 2b\rho)d\Omega^2 \qquad r^2 = \rho^2 + 2b\rho, \qquad M = \mu + b.$$

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

Multi.messengers: Stars, Pulsars, EHT

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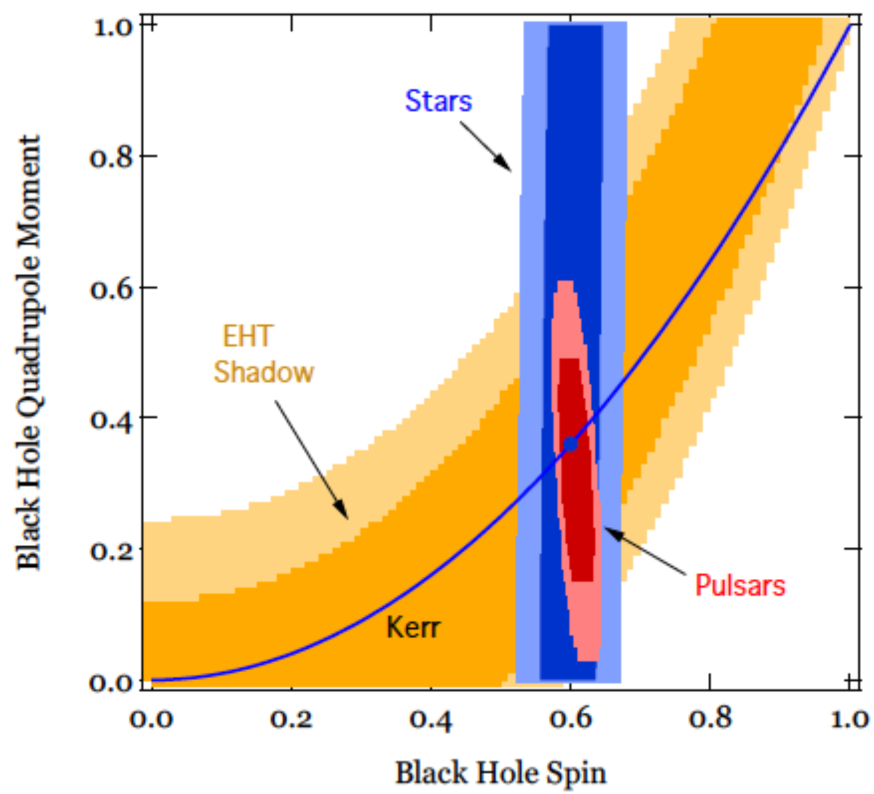
- Uncertainties in measurements of the black-hole spin and quadrupole moment using orbits of stars and pulsars are nearly orthogonal to those obtained from measuring of the black hole
- Tests validity of GR in strongly curved static space time.



Psaltis, Wex, Kramer (2016)

EHT and LIGO

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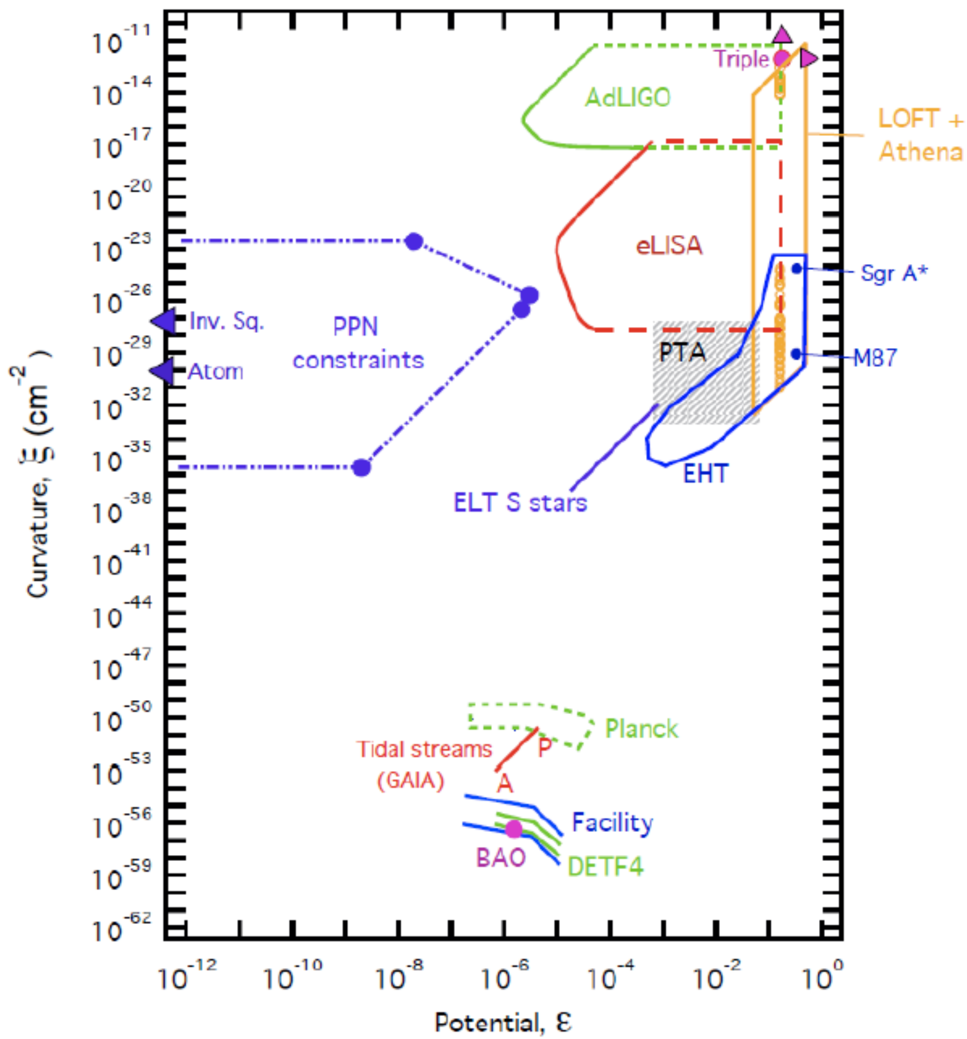

Baker, Psaltis, Skordis (2015)

Conclusions

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- Future of EHT is bright
  - Global consortium is forming
  - More & bigger telescopes: ALMA, LMT, IRAM NOEMA, SPT, GLT, Africa? (… but CARMA is gone☹□)
  - More bandwidth: (0.1 GHz) 1 GHz → 16 GHz (32 GHz)
  - Better analysis tools (CASA VLBI, imaging, de-blurring, variability, polarization)
- Science analysis:
  - Library of GRMHD simulations and images from different codes & groups
  - Independent analysis pipelines to cross-check results
  - End-to-end detector/array simulations
  - Multi-wavelength input needed to constrain fitting