The Event Horizon Telescope: New Results and Future Plans

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EHT Collaboration

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SUMMARY

- EHT is a network of λ (sub)mm antennas to make a Global VLBI array.
- At λ 1.3mm and 0.8mm, angular resolution $\sim$ 20 micro μas
- SgrA* and M87 have the largest apparent BH Event Horizons.

  General Relativity in the strong-field regime.

  Accretion and outflow at the edge of a BH.
- SgrA* $\sim$ 4 $10^6 M_0$ BH at Galactic Center.

  We resolve structures on scale of Event Horizon.
- M87 giant elliptical galaxy with $\sim$ 7 $10^9 M_0$ BH in nucleus.

  We detect structure at the base of relativistic jet.
- EHT Roadmap 2010 - 2015; critical contribution of CARMA.

SgrA* Evidence for a Black Hole

- *Evidence suggests SgrA* is a* 4 10^6 *solar mass black hole at the galactic center:*
- *Mass estimates from orbitting stars (Gillessen et.al 2008, Ghez. et el. 2008),*
- *Proper motion limits on SgrA* itself (Backer & Sramek 1999, Reid & Brunthaler 2004).*
- *Size limits on SgrA* from VLBI (Bower et al. 2004, Shen et al. 2005, Doeleman et al. 2008).*
- *The observations imply a mass density for SgrA** $> \ 9\ 10^{22} M_0$ *per cubic parsec.*
- *Close observational correlation between the mass of our galaxy and it's velocity dispersion suggest strong connection between formation of the black hole and the galaxy itself.*
- *The best evidence thus far is from studying the proper motion of stars near SgrA*.*
- *EHT will increase our understanding and add to the mounting evidence for a Massive Black Hole at the Galactic center.*

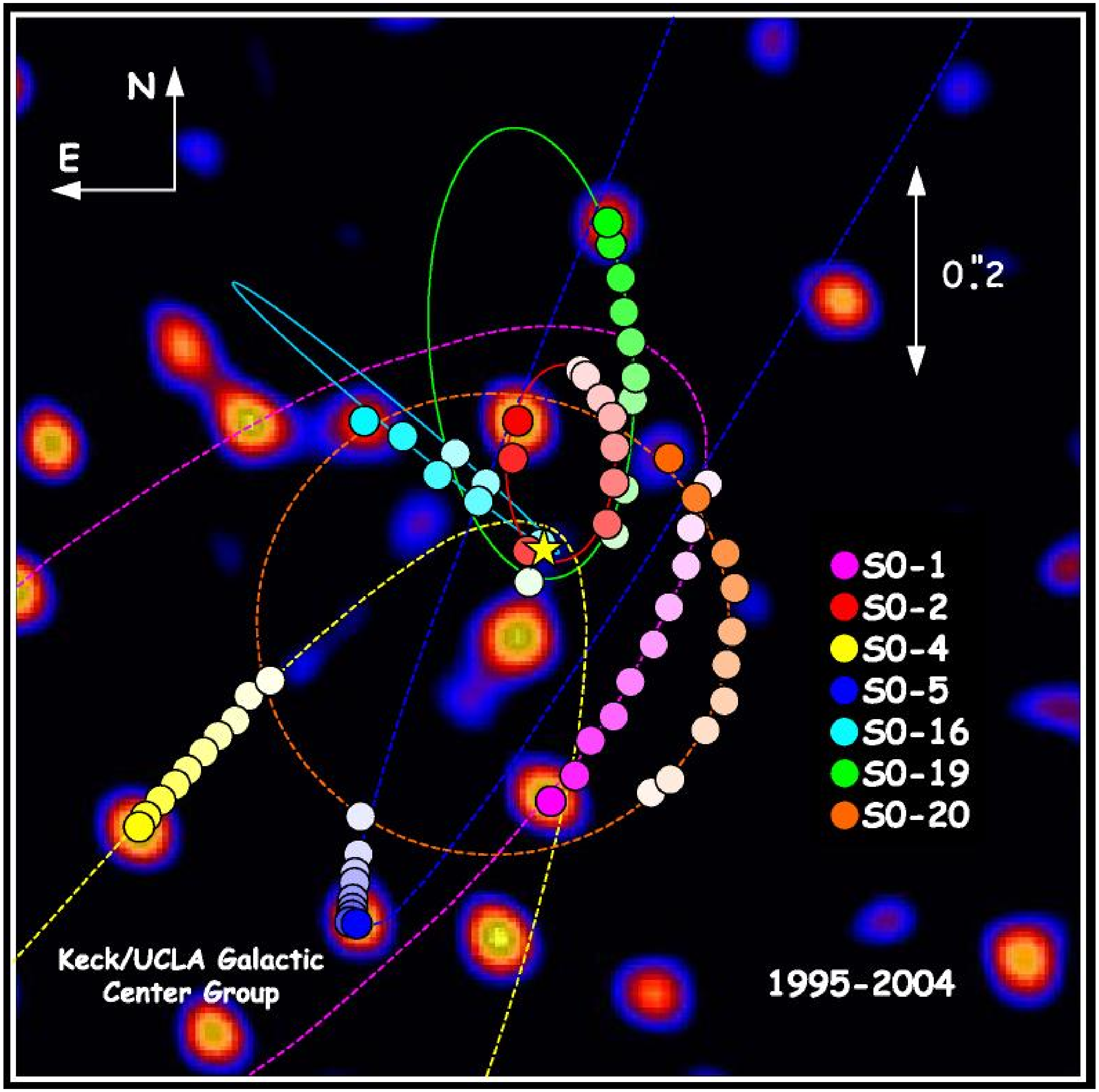


Figure 1: Star orbits

The Event Horizon Telescope

- *The EHT is a network of (sub)mm wavelength antennas that are linked together to function as a Global VLBI array.*
- *At* $\lambda 1.3mm$*, the angular resolution of the EHT* $\sim$ *20 micro arcseconds.*
- *Need* λmm *observations to minimize dispersion by the Inter-Stellar Medium which goes as* λ^2*.*
- *For SgrA*, the* $4\ 10^6 M_0$ *black hole at the Galactic Center, the EHT has resolved structures on scale of the Event Horizon.*
- *Similar scale structures have also been detected at the base of the relativistic jet in M87, a giant elliptical galaxy harboring a* $\sim 10^9 M_0$ *black hole.*
- *Currently IBOB and BEE2 boards and CASPER firmware are used to phase up and process the signals from the antennas, then pass the data to the Mark VB data recorder.*
- *Closure phase* $(O = \phi_1 + \phi_2 - \phi_3)$ *is used for calibration as phase errors are subtracted out.*
- *2007-2010 SgrA* observations with ARO/SMT, CARMA, and JCMT estimated Schwarzschild radius* $0.37 AU$*.*

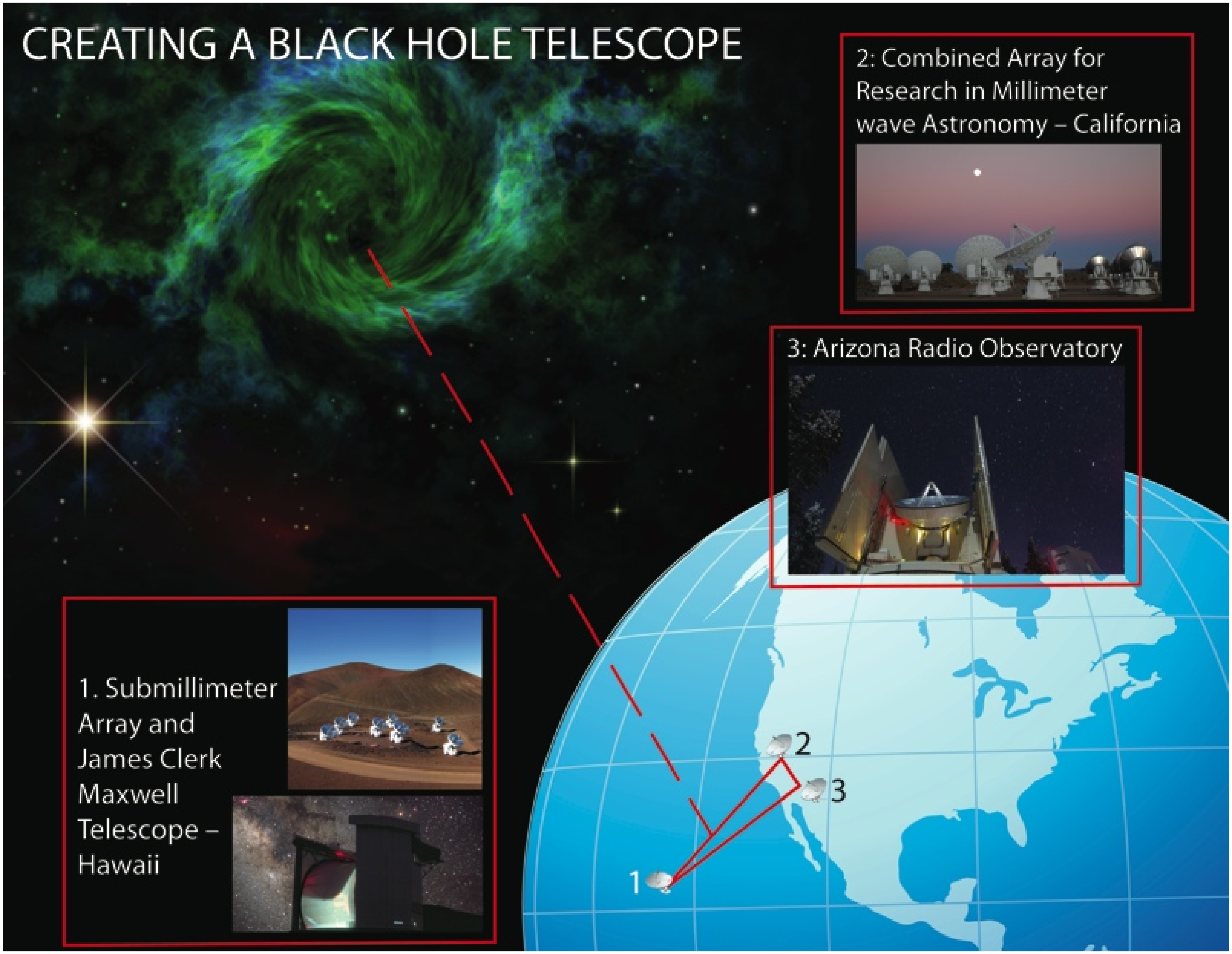


Figure 2: VLBI overview

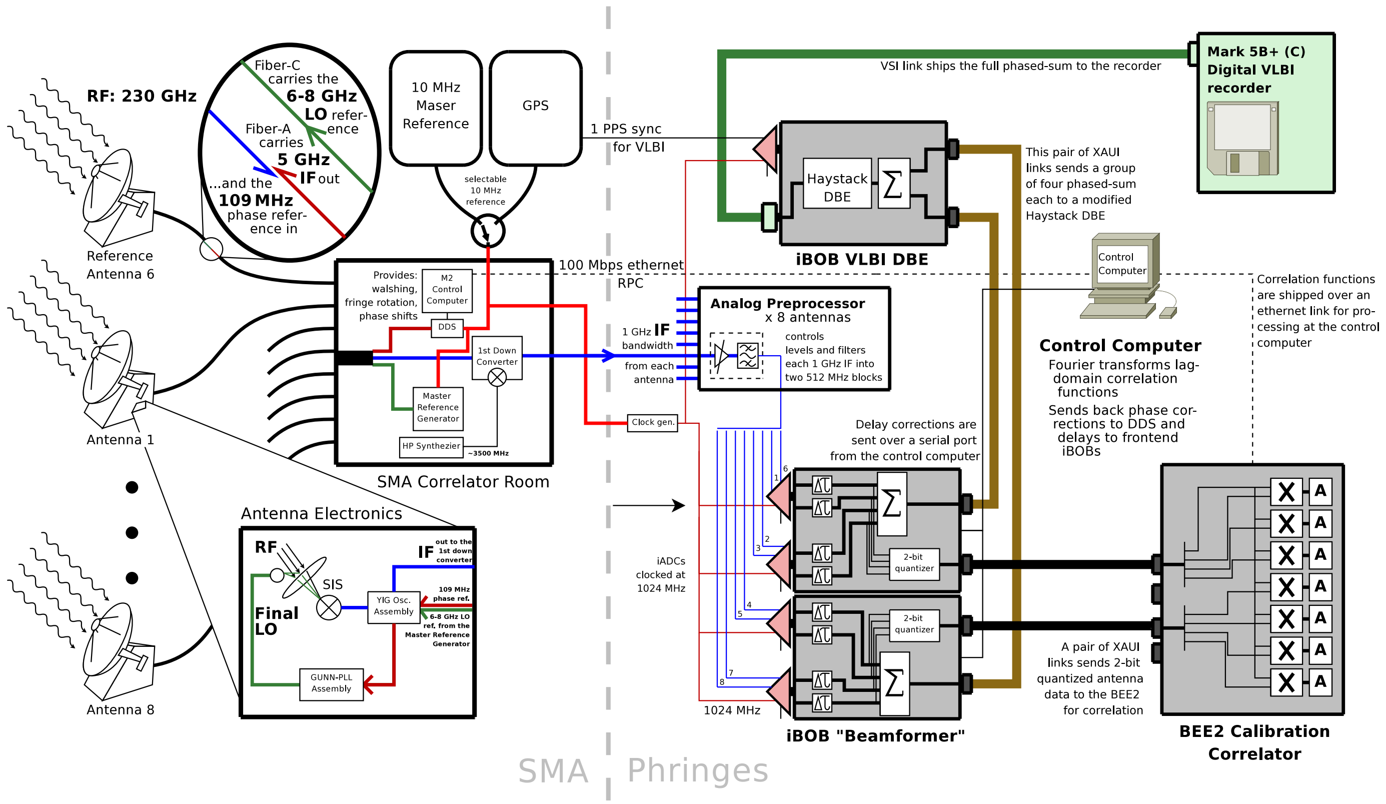
Figure 3: CARMA MOON

Figure 4: JCMT and SMA telescopes on Mauna Kea

Figure 5: VLBI maser

CASPER Libraries and Hardware

- *CASPER (Collaboration for Astronomical Signal Processing and Engineering Research.)*
- *FPGA based hardware is now used in phasing up the antennas with 1 GHz Bandwidth*
- *The system design uses modular DSP boards with a flexible interconnect architecture which allows reconfiguration of the computing resources for multiple applications.*
- *The programming model uses a system generation library with hardware abstractions which allow the application programmer to focus on the application rather than the details of the hardware.*
- *The system design and programming model together allow the application software to survive by using a technology independent design flow. .*
- *Scalable CASPER technology allows for the phased arrays that improve sensitivty .*
- *Next generation architecture of the broadband phased array processor upgrade based on the ROACH Virtex-5, is targeted for deployment in 2012.*
- *This will allow double the bandwidth and increased sensitivity.*



RF: 230 GHz
Reference Antenna 6
Antenna 1
Antenna 8
Fiber-C carries the 6-8 GHz LO reference
Fiber-A carries 5 GHz IF out
...and the 109 MHz phase reference in
10 MHz Maser Reference
GPS
selectable 10 MHz reference
1 PPS sync for VLBI
100 Mbps ethernet RPC
Provides: walshing, fringe rotation, phase shifts
M2 Control Computer
DDS
1st Down Converter
Master Reference Generator
HP Synthezier
~3500 MHz
SMA Correlator Room
Antenna Electronics
RF
IF
out to the 1st down converter
SIS
Final LO
YIG Osc. Assembly
109 MHz phase ref.
6-8 GHz LO ref. from the Master Reference Generator
GUNN-PLL Assembly
VSI link ships the full phased-sum to the recorder
Mark 5B+ (C) Digital VLBI recorder
Haystack DBE
iBOB VLBI DBE
This pair of XAUI links sends a group of four phased-sum each to a modified Haystack DBE
Control Computer
Analog Preprocessor x 8 antennas
1 GHz IF bandwidth from each antenna
controls levels and filters each 1 GHz IF into two 512 MHz blocks
Clock gen.
Control Computer
Fourier transforms lag-domain correlation functions
Sends back phase corrections to DDS and delays to frontend iBOBs
Correlation functions are shipped over an ethernet link for processing at the control computer
Delay corrections are sent over a serial port from the control computer
iADCs clocked at 1024 MHz
2-bit quantizer
1024 MHz
iBOB "Beamformer"
A pair of XAUI links sends 2-bit quantized antenna data to the BEE2 for correlation
BEE2 Calibration Correlator
SMA
Phringes

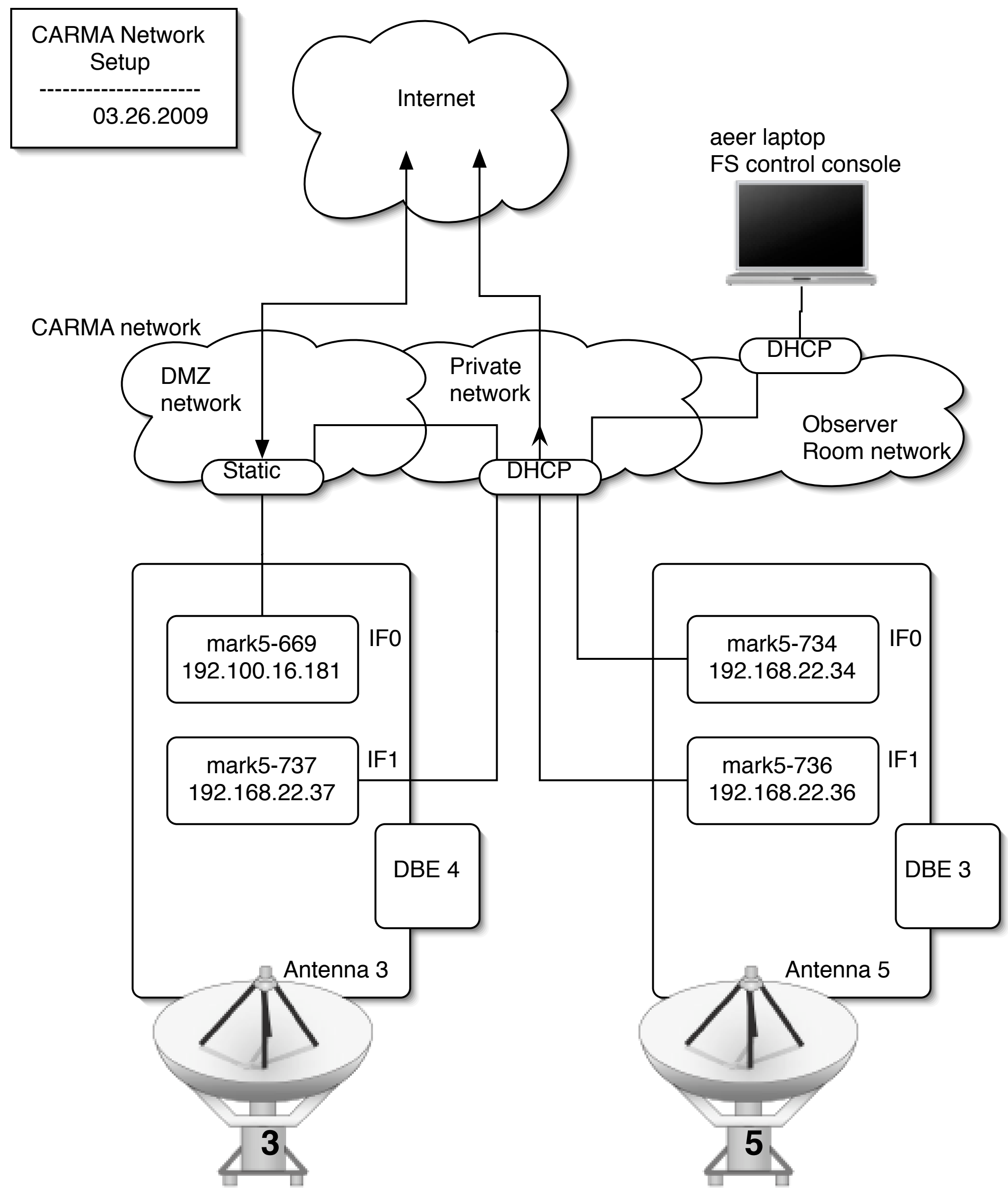


Figure 1. CARMA network layout for the Mark5B systems

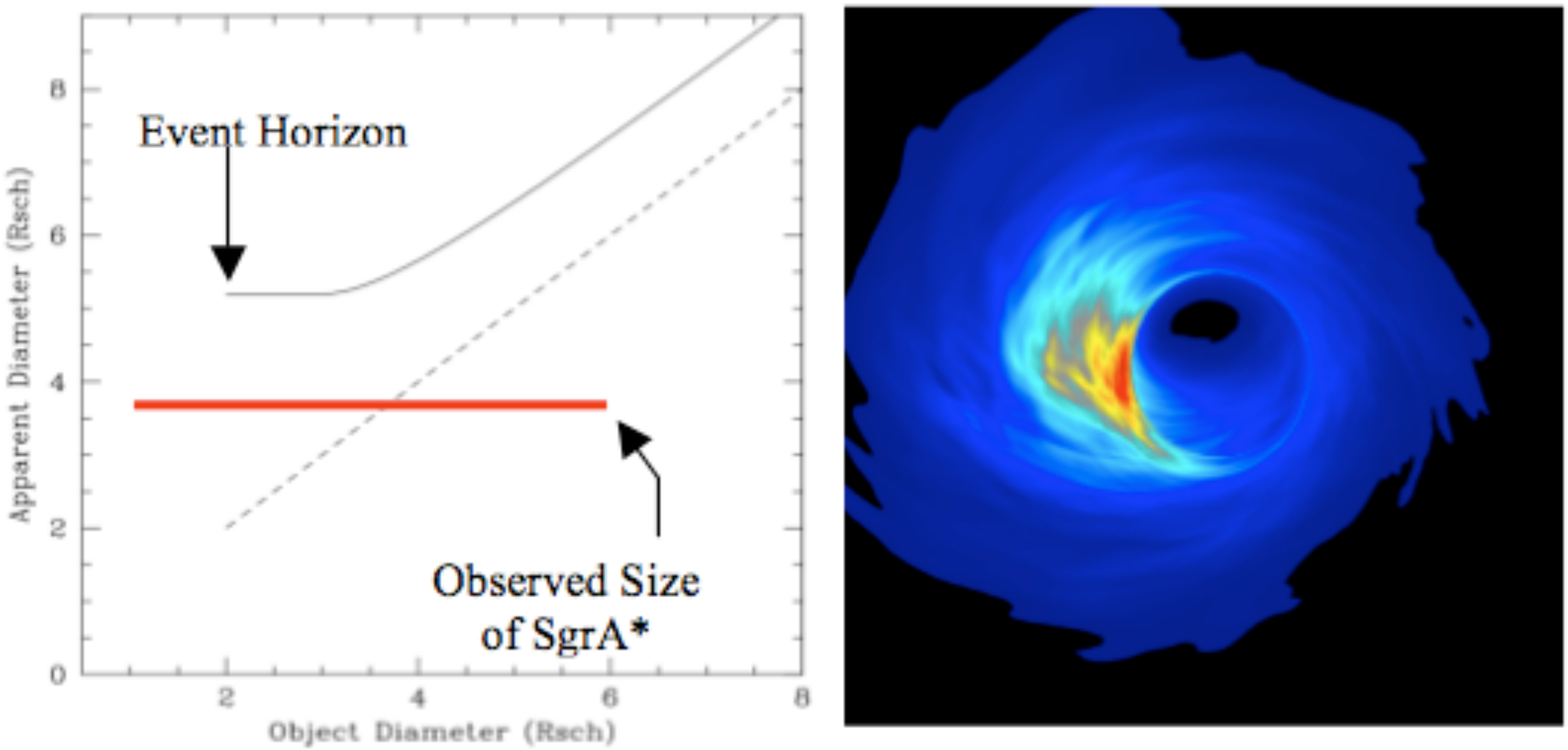
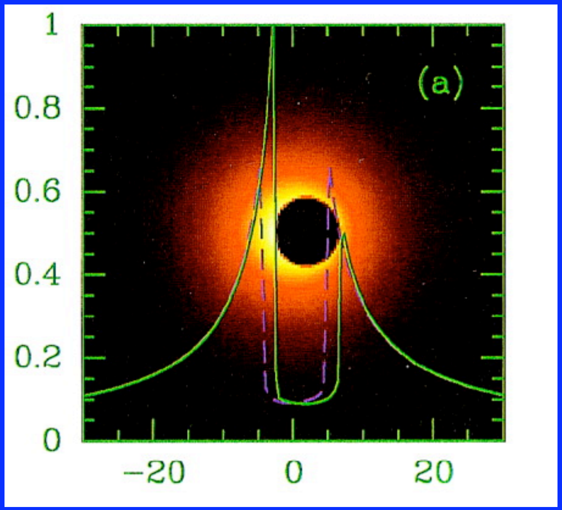


Figure 7: SgrA Results and Black Hole models: Solid black line is apparent diameter with lensing by a black hole. Dashed line with no lensing. The intrinsic size of SgrA* observed with $\lambda 1.3mm$ VLBI (red line) is smaller than the minimum apparent size of the black hole event horizon suggesting that the submm emission of SgrA* must be offset from the black hole position. This can be understood in the context of General relativistic MHD accretion disk simulations (right), which exhibit compact regions of emissions due to Doppler enhancement of the approaching side of an accretion disk.

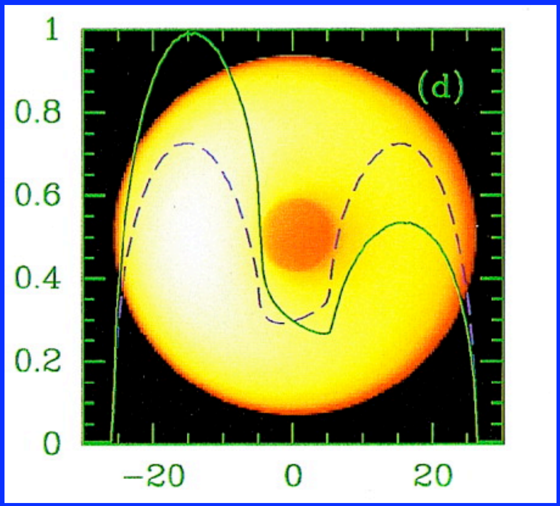
What did we see?

- *A symmetric emitting surface surrounding a black hole is gravitationally lensed to appear larger than its true diameter.*
- *The intrinsic size of SgrA* observed with $\lambda 1.3mm$ VLBI is smaller than the minimum apparent size of the black hole event horizon suggesting that the submm emission of SgrA* must be offset from the black hole position.*
- *This can be understood in the context of General relativistic MHD accretion disk simulations, which exhibit compact regions of emissions due to Doppler enhancement of the approaching side of an accretion disk.*

Resolving Rsch-scale structures



Spinning (a=1)



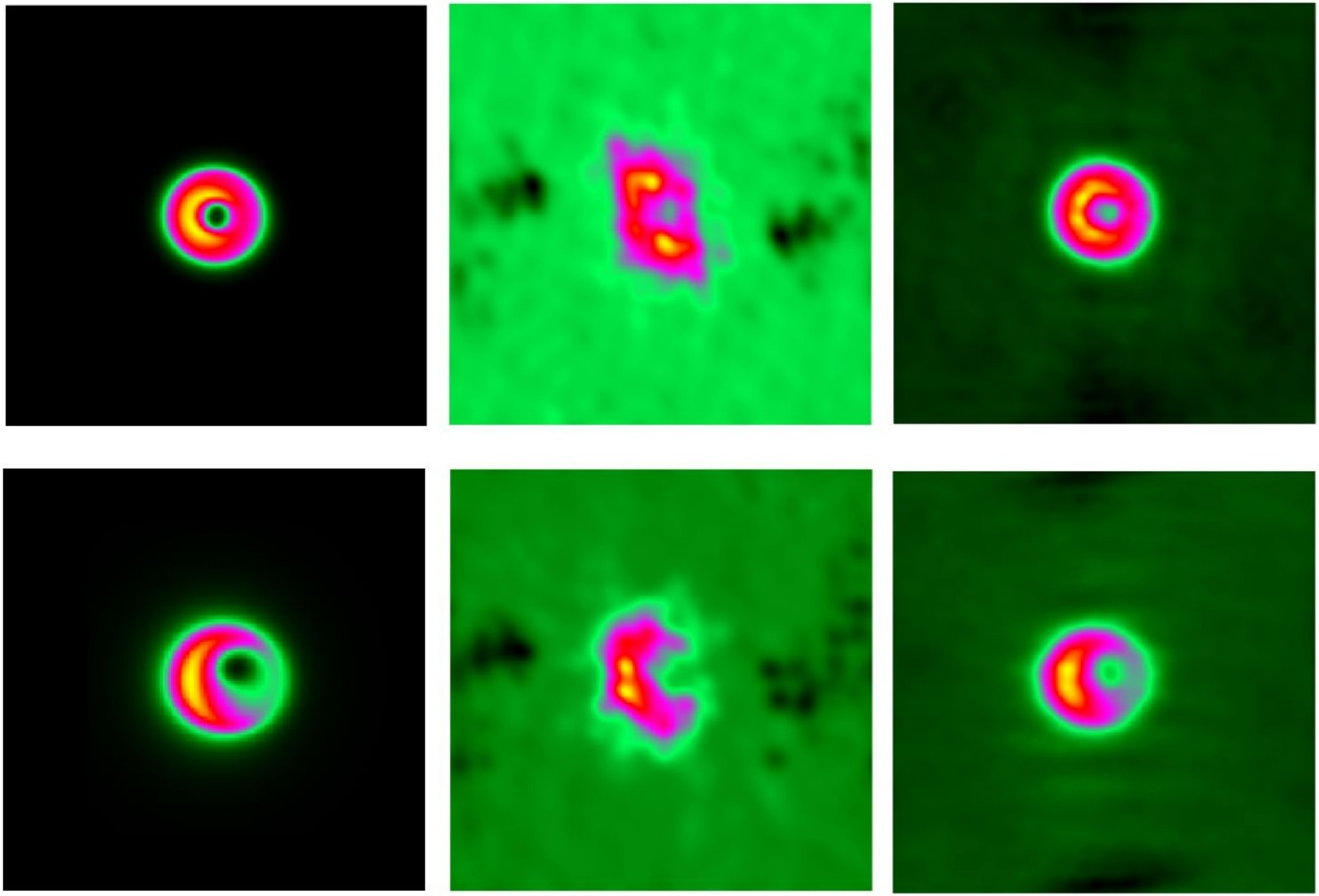
Non-spinning (a=0)

Falcke
Melia
Agol

- SgrA* has the largest apparent Schwarzschild radius of any BH candidate.
- Rsch = 10µas
- Shadow = 5.2 Rsch (non-spinning)
  = 4.5 Rsch (maximally spinning)

What should we see?

- *VLBI simulations of SgrA* have given us a good idea of what to expect from imaging.*
- *Left: models that have been scatter broadened by the Inter Stellar Medium.*
- *Middle: images reconstructed using a 7-station* $\lambda = 0.8mm$ *wavelength array that could reasonably scheduled within the next 3-5 years.*
- *Right: images reconstructed using 13-station array that could be assembled this decade.*



M87

- *MMVLBI of the galaxy M87 (Virgo A), reveal a size for the jet base of 40 microarcsec, ~ 5 Schwarzschild radius for the central black hole.*
- *This size is signicantly smaller than the Innermost Stable Circular Orbit (ISCO) for a non-spinning black hole, suggesting that the Virgo A jet must originate through extraction of energy from the region immediately surrounding a spinning black hole.*
- *Detailed study of the region where the jet is launched requires angular resolution corresponding to a few Schwarzschild radii (R Sch = 2GM/c)*
- *At a distance of 16Mpc, M87 BH mass $\sim 6.6\ 10^9 M_{sun}$. Schwarzschild radius of the M87 black hole (6.3 10^{-4} parsecs or 2 10^{15} cm, an angle of 8 microarcsec .*
- *Global MMVLBI can study the formation of relativistic jets on scales of a black hole and accretion disk.*

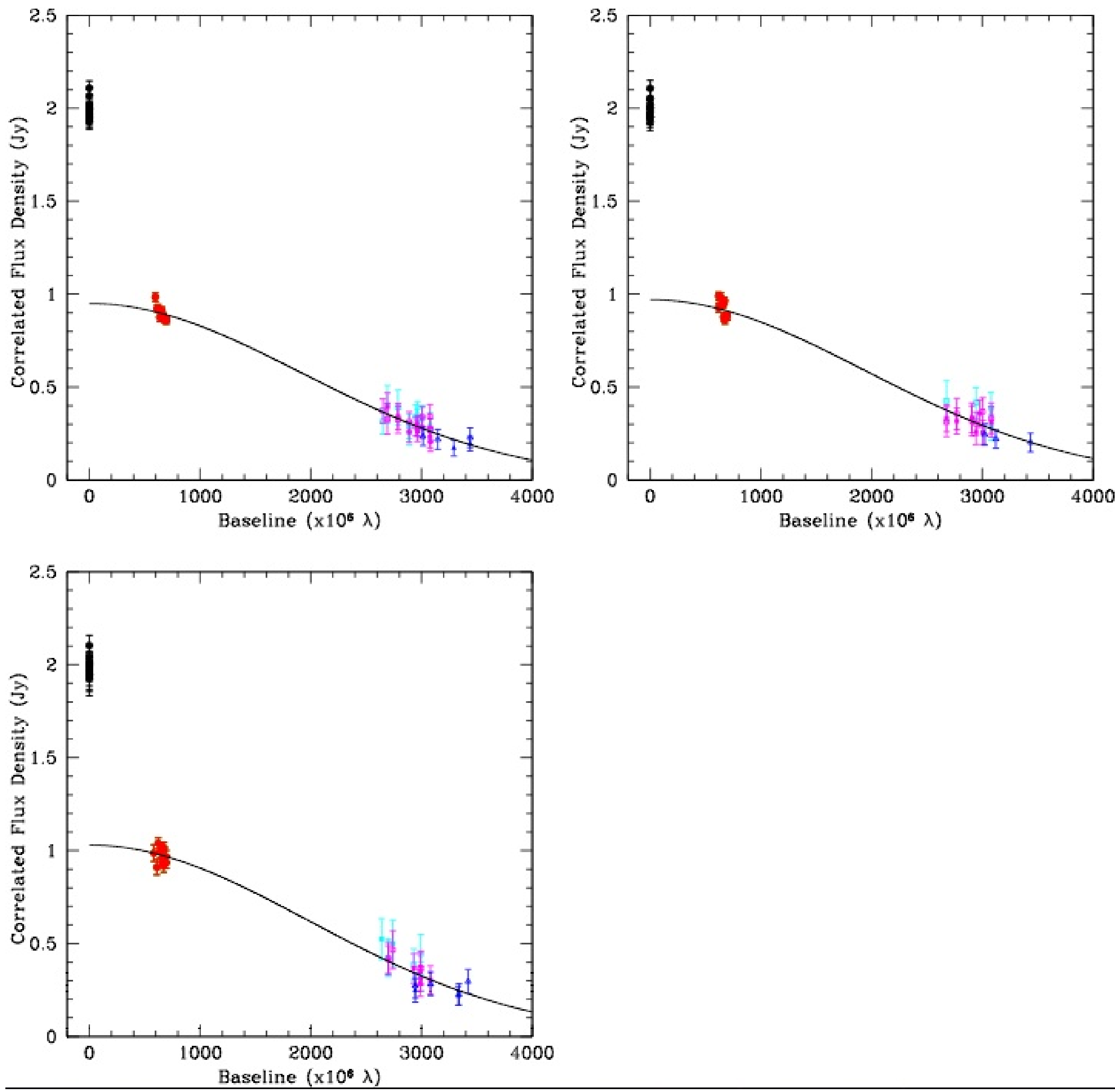


Figure 9: M87 2009 April 5, 6, 7. CARMA-CARMA (black); CARMA-SMT (red); CARMA-JCMT (magenta and teal); SMT-JCMT (blue). Solid black curves show least squares circular Gaussian models.

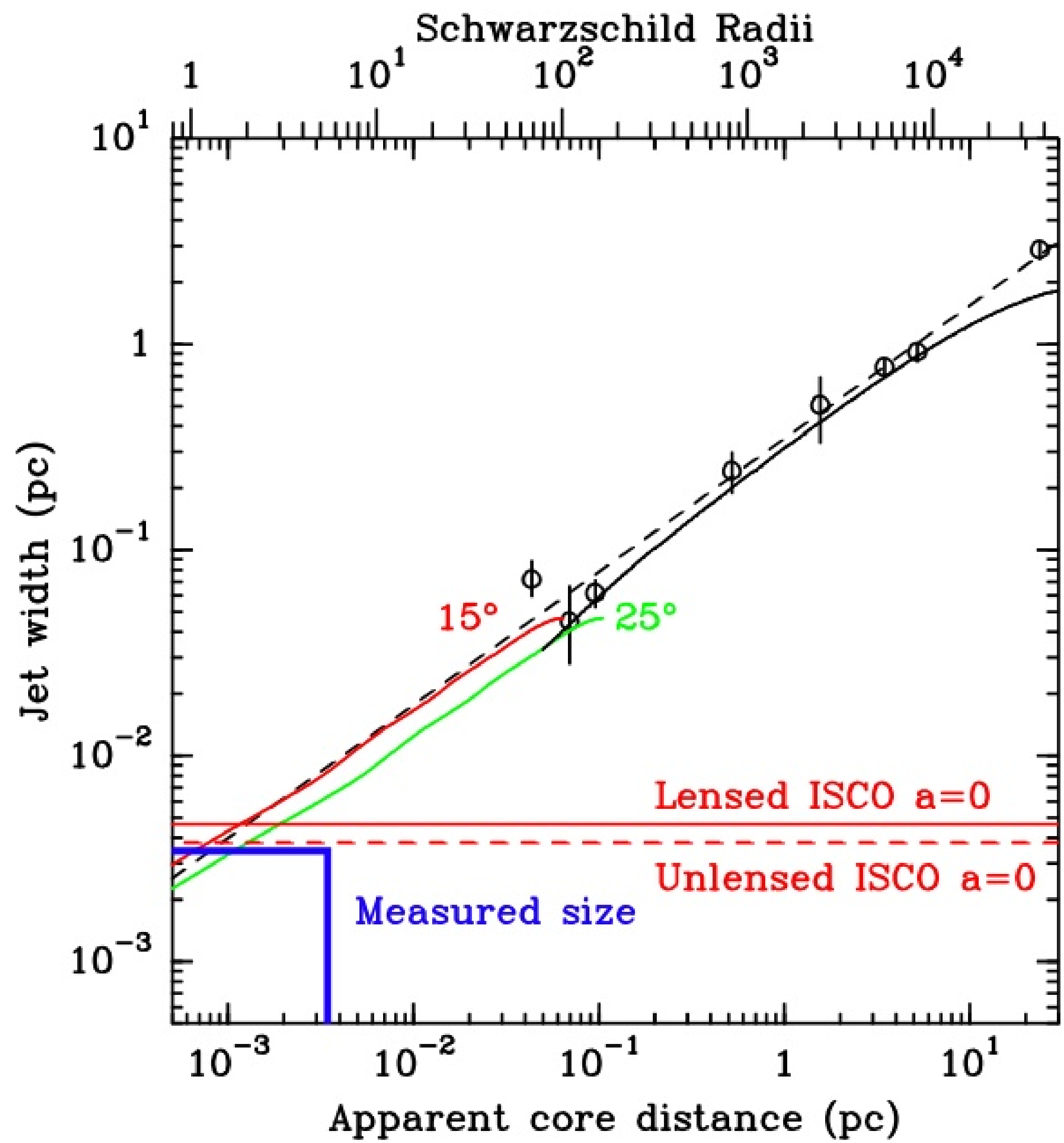


Figure 10: M87 April 2009 jet width versus radius. The red horizontal line indicates the apparent size of the Innermost Stable Circular Orbit (for a non-spinning black hole). Dashed red ISCO without gravitational lensing.

Improving Sensitivity

- *Enhancing EHT sensitivity: dual polarization, phased arrays, wideband VLBI backends, and high-speed VLBI recorders.*
- *Time-variable changes can be resolved and monitored on 10-second time scales.*
- *Simulations model flares in SgrA* as orbiting hot-spots in the accretion flow, EHT can potentially time these orbits and provide new estimates of the black hole spin.*
- *Planned upgrade to SMA and CARMA this year will allow us to form beams at these locations, improving the image and sensitivity from the 2007-2009 observations.*
- *ALMA will be phased up and contributing to the EHT within a few years.*

Figure 11: E-configuration

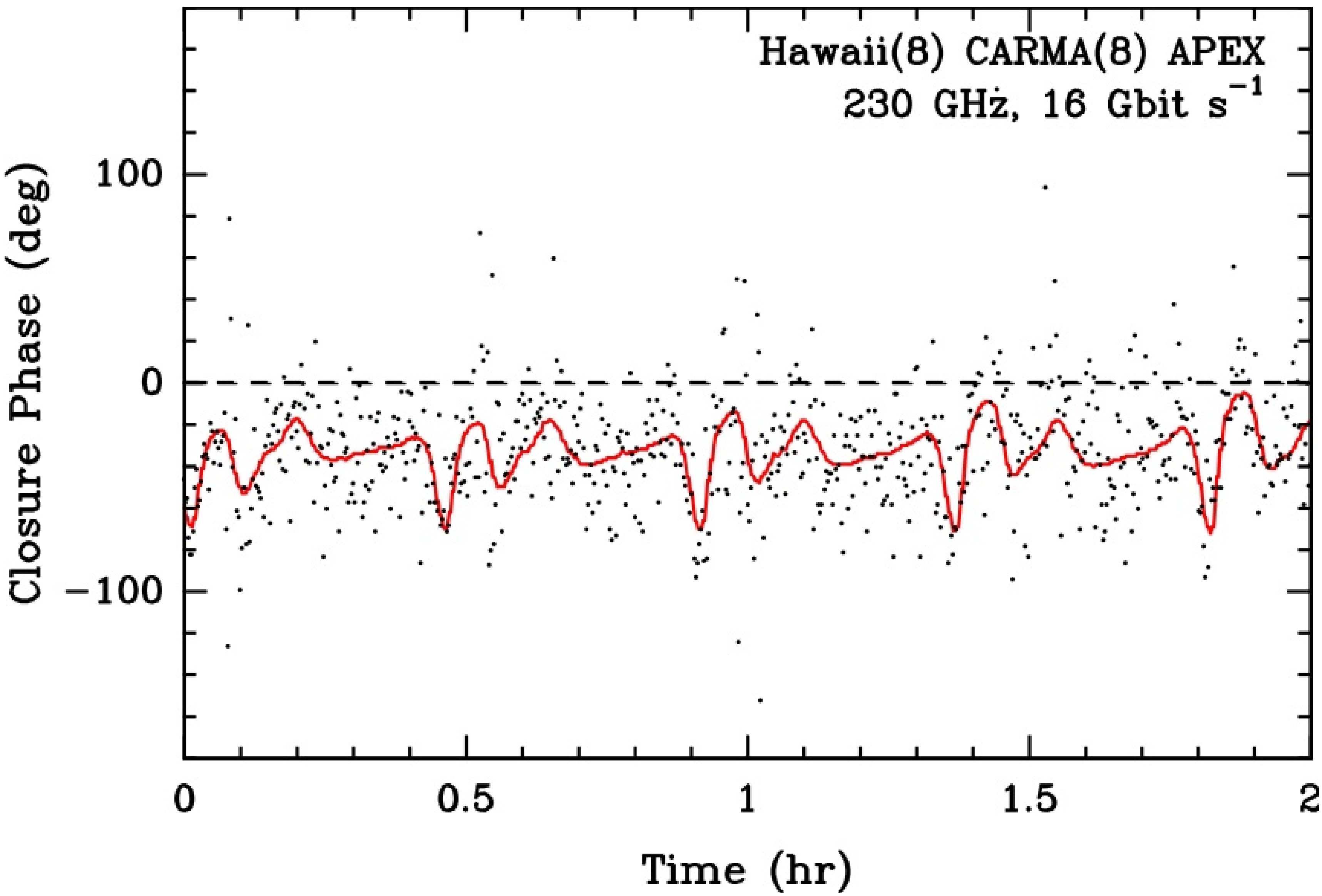


Figure 12: Closure Phase with APEX

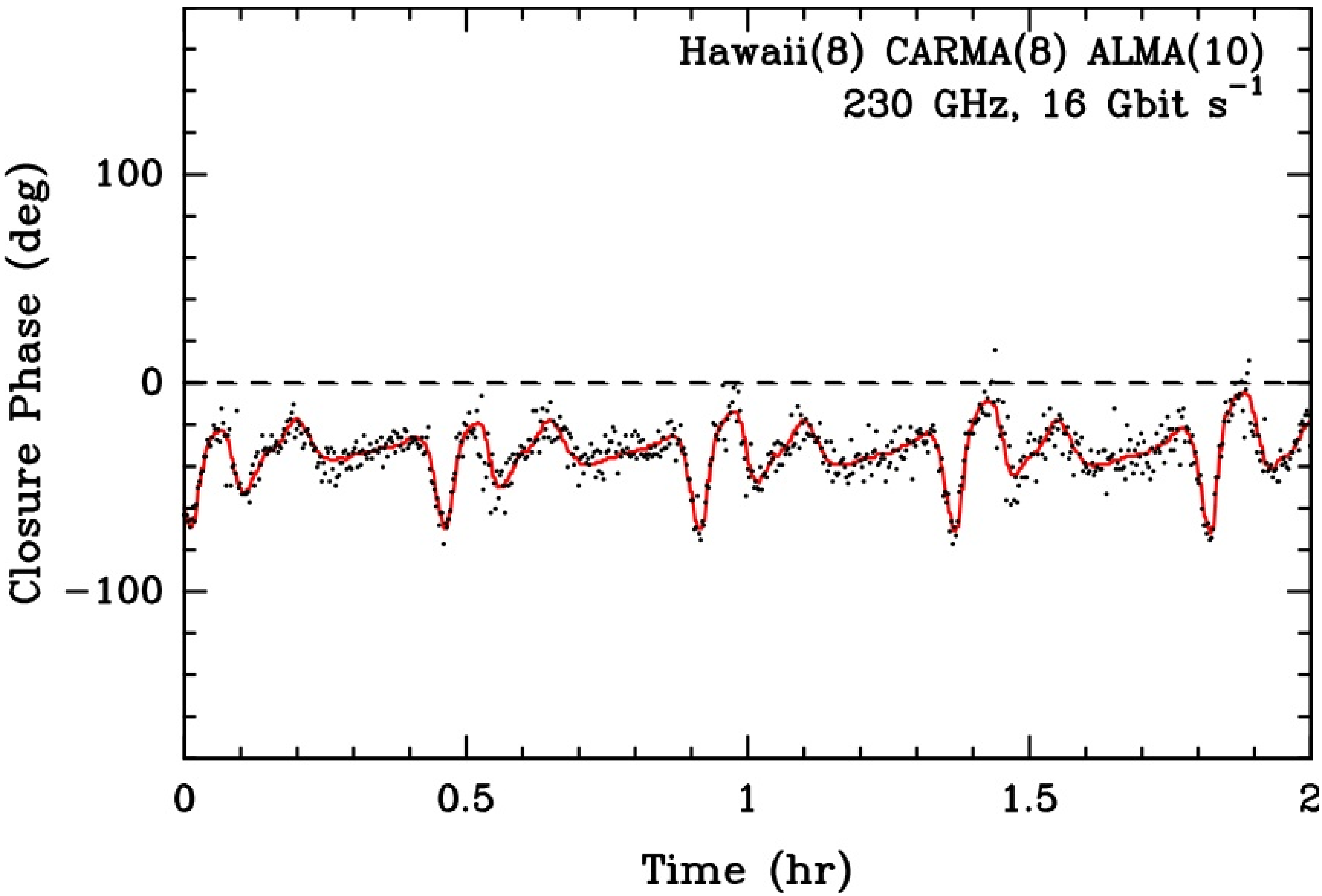


Figure 13: Closure Phase with ALMA10

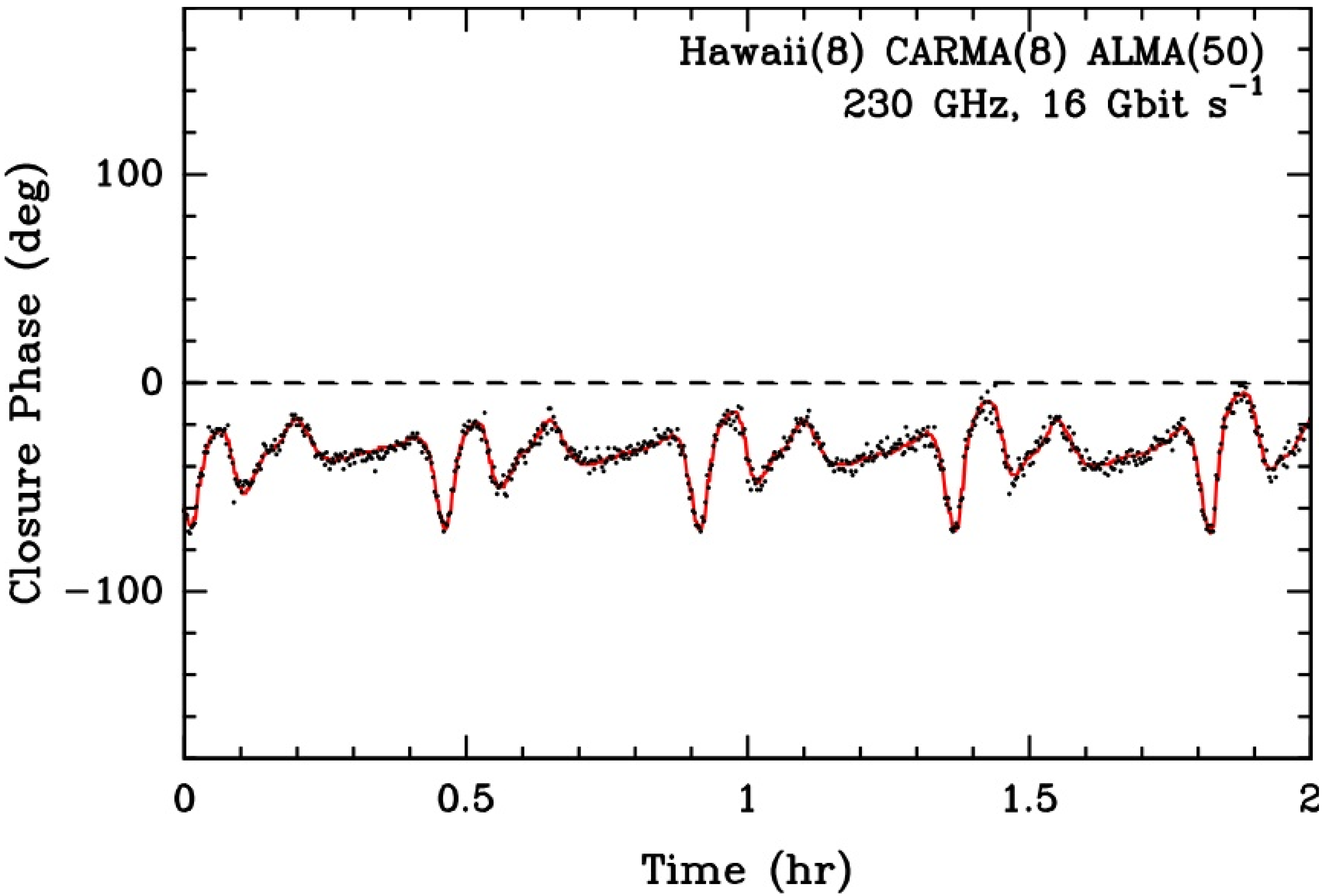


Figure 14: Closure Phase with ALMA50

STATION CALIBRATION

- *Correlated flux on VLBI target source =*

  correlation coeficient x sqrt(Ta/Tsys(i) Ta/Tsys(j)) x phasing efficiency

- T_a *on target source: SgrA* in complex FoV.*

  phasing efficiency: atmospheric phase; pointing errors; wind.

- *Real time calibration of array stations using station correlator.*

  Need good station uvcoverage to isolate and calibrate target source.

  Use extended array configurations to spatially filter out large scale structure if atmospheric phase correction is good enough.

- *High instantaneous bandwidth. (Maximum atmospheric correlation time* $\sim 10s$*)*

ROADMAP FOR MMVLBI

- *2008-2010: 500 MHz band on 1-2 antennas at CARMA.*

  Analog input into ADC for each antenna in VLBI station.

  Custom formatting into VLBI recorder.

- *2011-2012 Two 500 MHz bands.*

  digital beamforming at single phase center.

  use CARMA correlator for beamformer calibration.

  Custom formatting into VLBI recorder.

  (e.g. CARMA 4-8 antennas x 2 pols x 4 500 MHz bands)

- *2015+ High speed digitized data for each antenna in VLBI station.*

  frequency domain delay and fringe rate correction.

  digital beamforming at multiple phase centers.

  use station correlators for beamformer calibration.

  industry standard data to disk. (e.g. 10GbE)

  (e.g. CARMA 15 antennas x 2 pols x 8 GHz)

MMVLBI with ALMA

- *2010-2012 Limited station commitment to VLBI .*

  Typical 1 week/year.

  No ALMA participation.

- *2015+ Major station committtment to VLBI with ALMA*

  VLBI as a science motivation for maintaining university facilities.

  2 sessions (e.g. Spring and Fall)

  1-2 week gap to reduce data and mitigate bad weather.

- *Heterogeneous VLBI stations*

  Long Term Plan to align station capabilities.

- *Frequency, Pols x Bandwidth.*

  CARMA 230 GHz x 2 pols. Analog data from antennas.

  SMA 230 GHz x 1 pol; 345 GHz x 2 pols. Analog data from antennas.

  ALMA 230 GHz and 345 GHz dual polarization. 2 Ghz digital data from antennas.

CONCLUSION

- *VLBI using CARMA, JCMT and ARO/SMT on Mt. Graham in Arizona at 1.3mm.*

  We resolve structures on scale of Event Horizon.

  SgrA emission varies over a few hours on scales of several Schwarzschild radii.*

- *Simulations model flares in SgrA* as orbiting hot-spots in the accretion flow.*
- *EHT adds DSP to existing (sub)mm facilities for VLBI*
- *Phased arrays, wideband backends, and high-speed recorders can monitor 10-s time scales.*
- *EHT can time these orbits and provide estimates of black hole spin.*
- *M87: Size constrains jet formation and production of TeV photons observed with Fermi Gamma-ray satellite.*
- *EHT bring us as close to the edge of BH as we are likely to come for decades.*