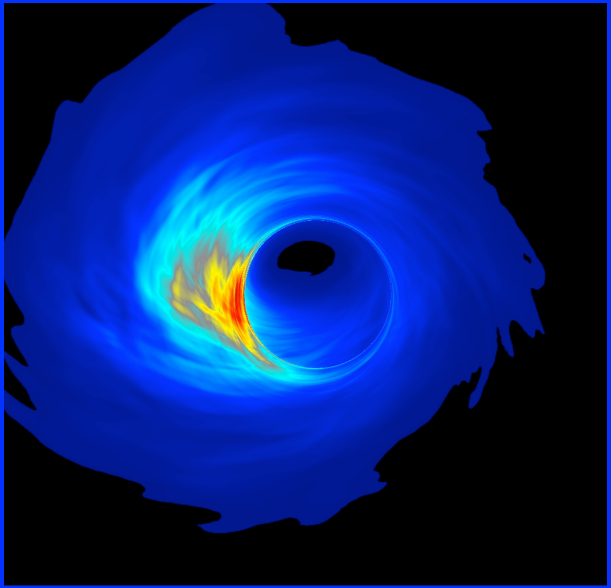
The Event Horizon Telescope: Results on SgrA* & M87



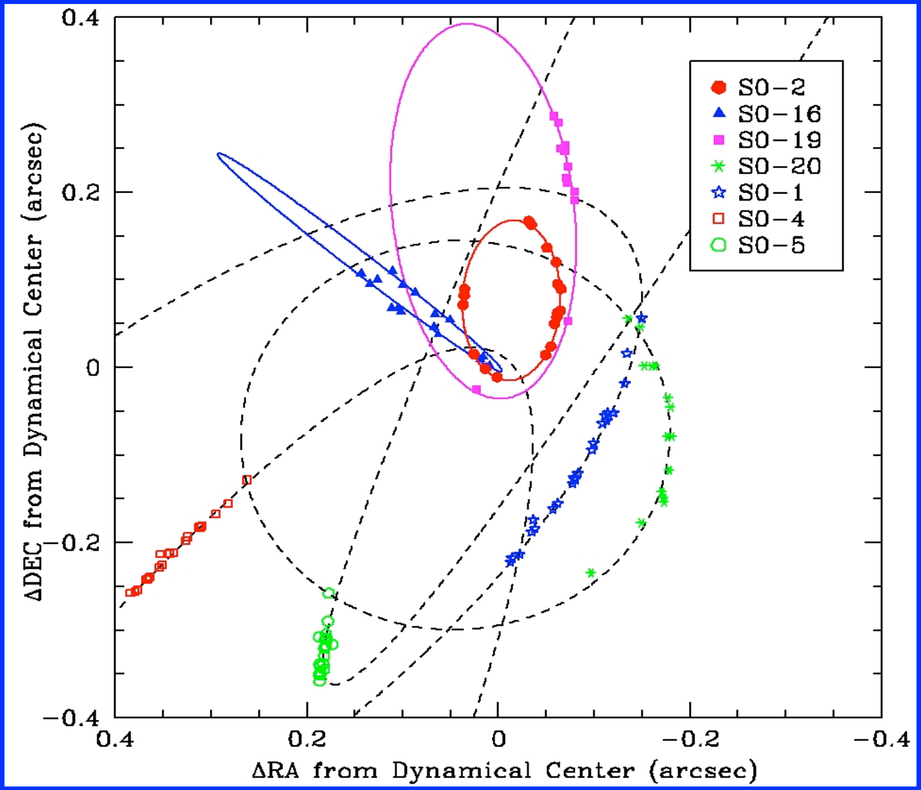
"Assembling a telescope that can observe and image a black hole with event horizon scale resolution."

Sheperd Doeleman
MIT Haystack Observatory

SgrA*: Best Case for a SMBH

SgrA*: Best Case for a SMBH

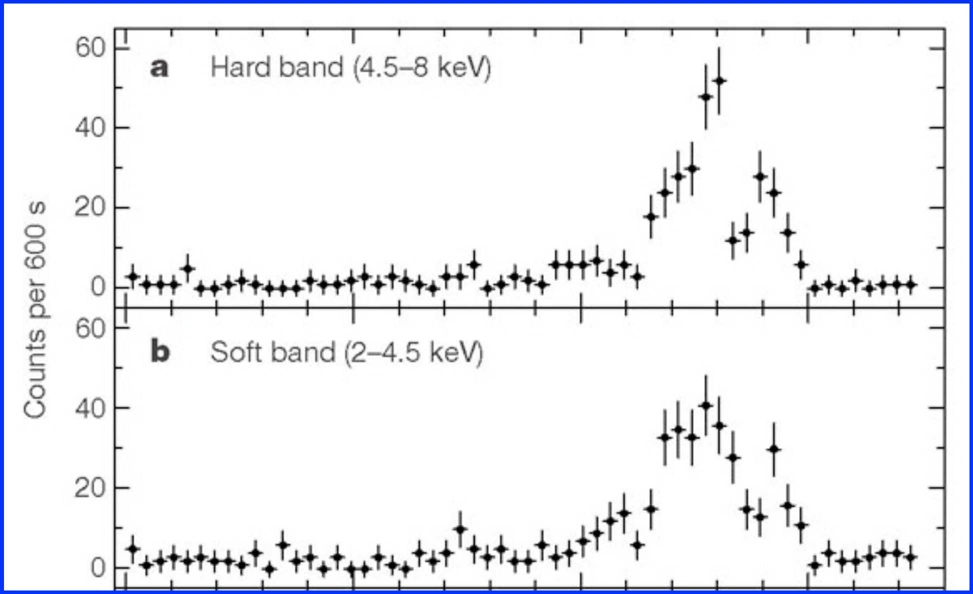
- Stellar orbits approaching within 45 AU.



Ghez et al 2005

SgrA*: Best Case for a SMBH

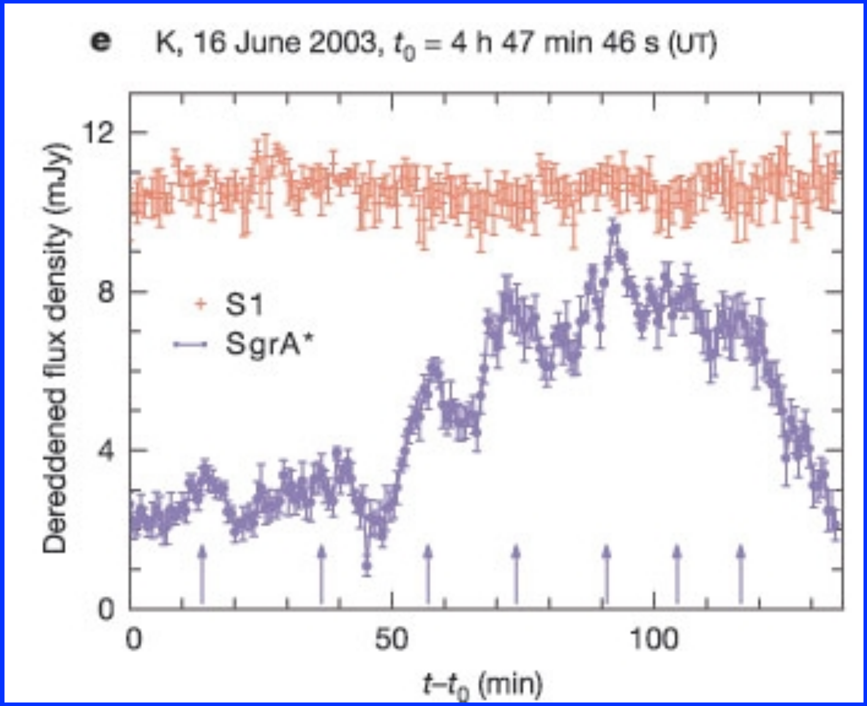
- Stellar orbits approaching within 45 AU.
- Short time scale X-ray flares (300 sec rise).



Baganoff et al 2001

SgrA*: Best Case for a SMBH

- Stellar orbits approaching within 45 AU.
- Short time scale X-ray flares (300 sec rise).
- IF flares with modulation (a>0).



VLT: Genzel et al 2003

VLBA Movie of M87 @ 43 GHz (7 mm)

Craig Walker et al. 2008

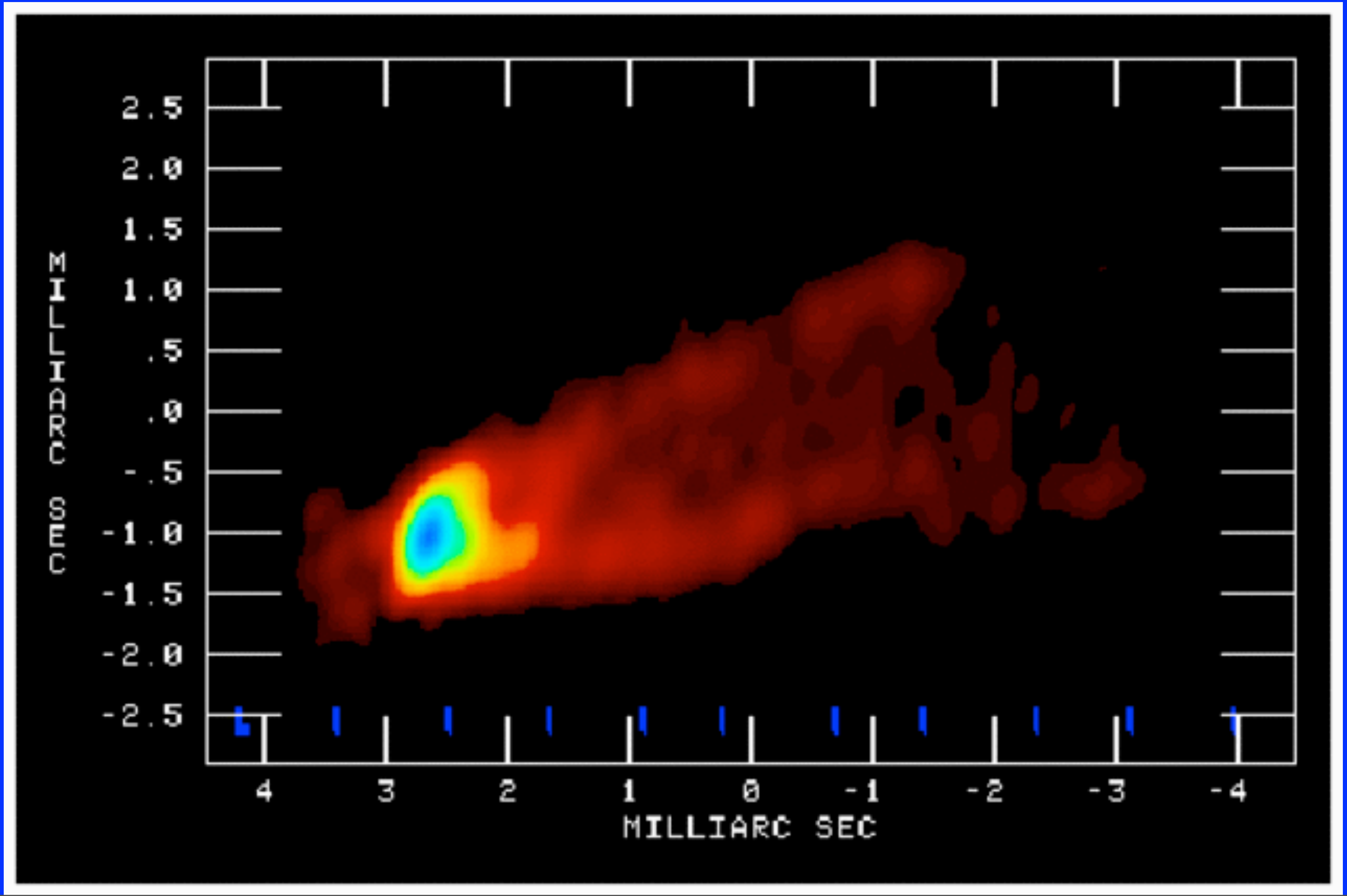
6.6×10^9 Solar Mass BH at 16 Mpc

Beam: 0.43x0.21 mas   0.2mas = 0.016pc = $60R_s$ 1mas/yr = 0.25c

VLBA Movie of M87 @ 43 GHz (7 mm)

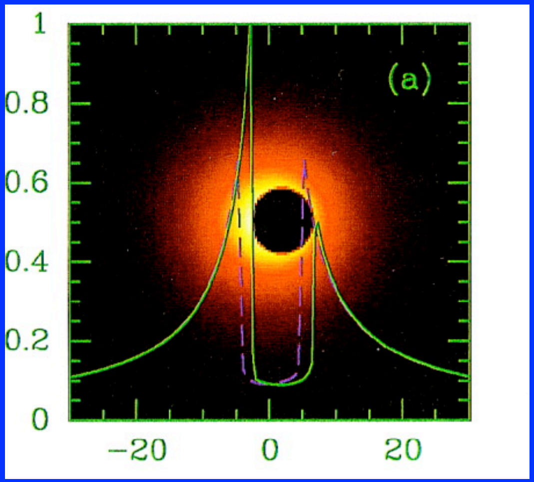
Craig Walker et al. 2008

6.6×10^9 Solar Mass BH at 16 Mpc



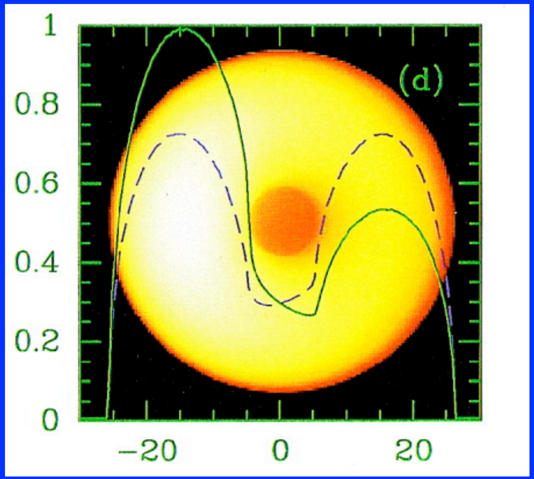
Strong GR Effects:

- The black hole 'shadow' (Bardeen 1973; Falcke, Agol, Melia 2000; Johannsen & Psaltis 2010)



Spinning (a=1)

Dsh = 9/2 * Rsch



Non-spinning (a=0)

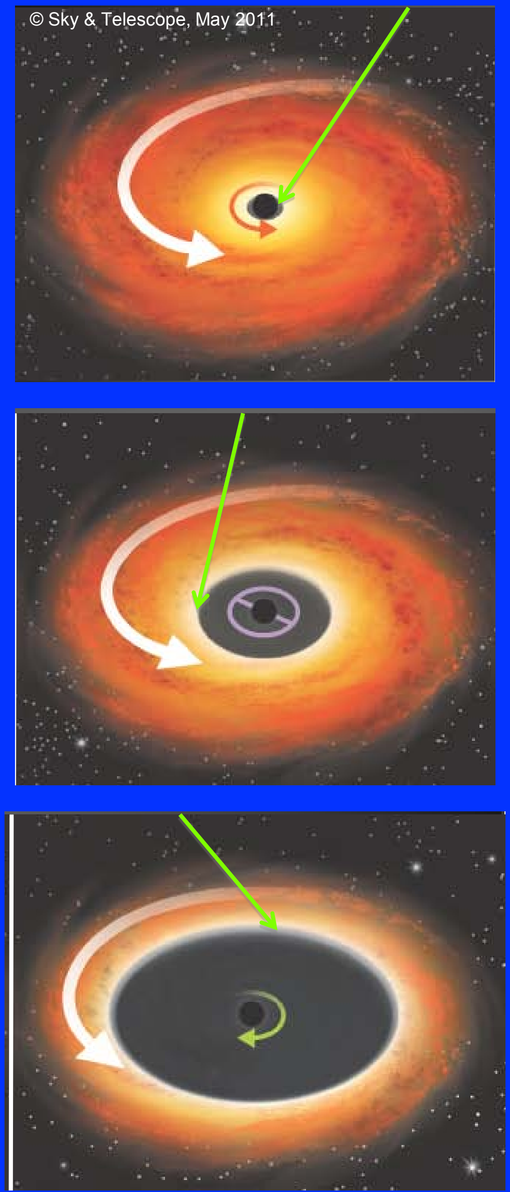
Dsh = sqrt(27) * Rsch

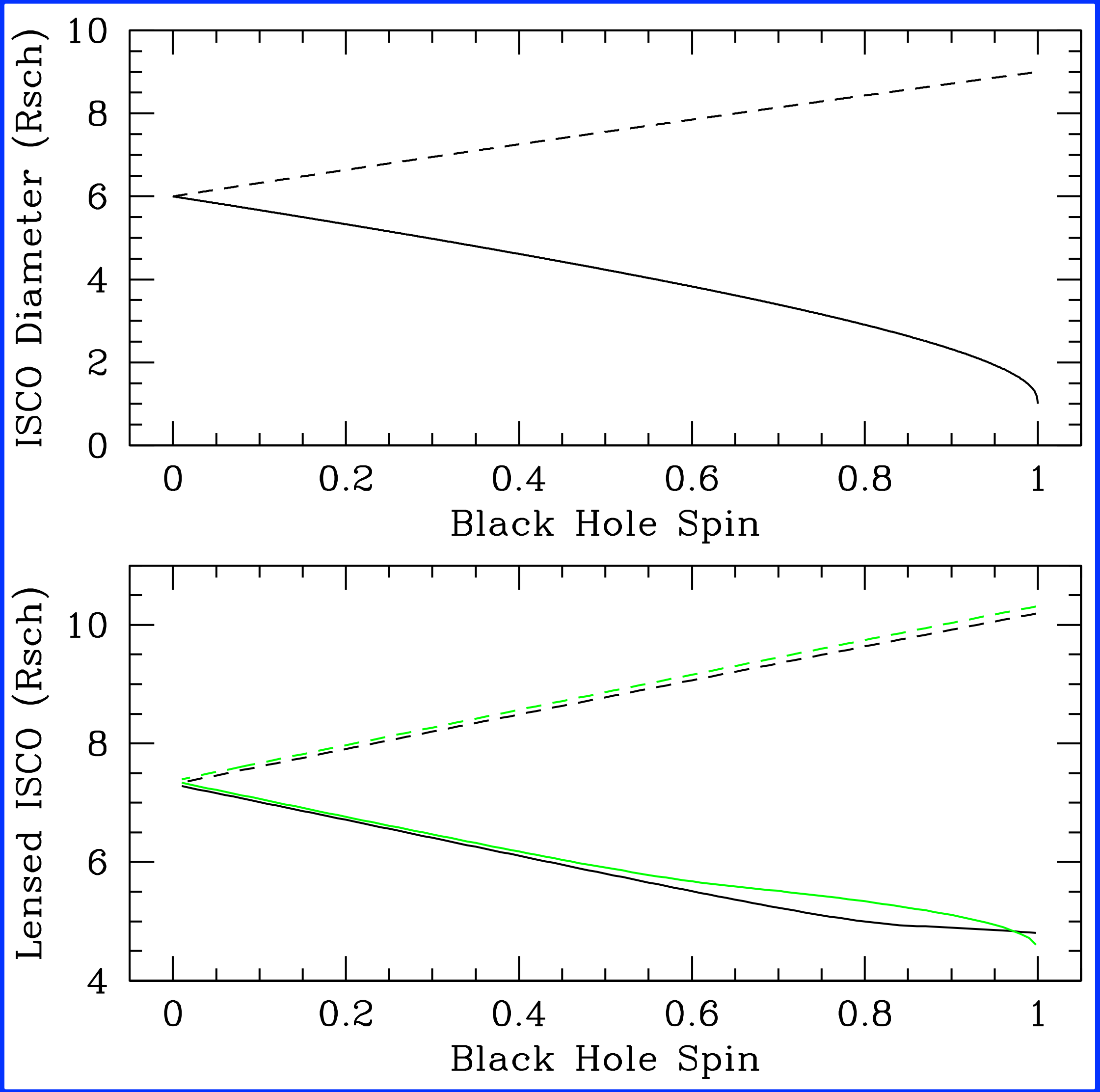
- Measuring the shadow gives Mass.

(Johannsen, Psaltis et al 2012).

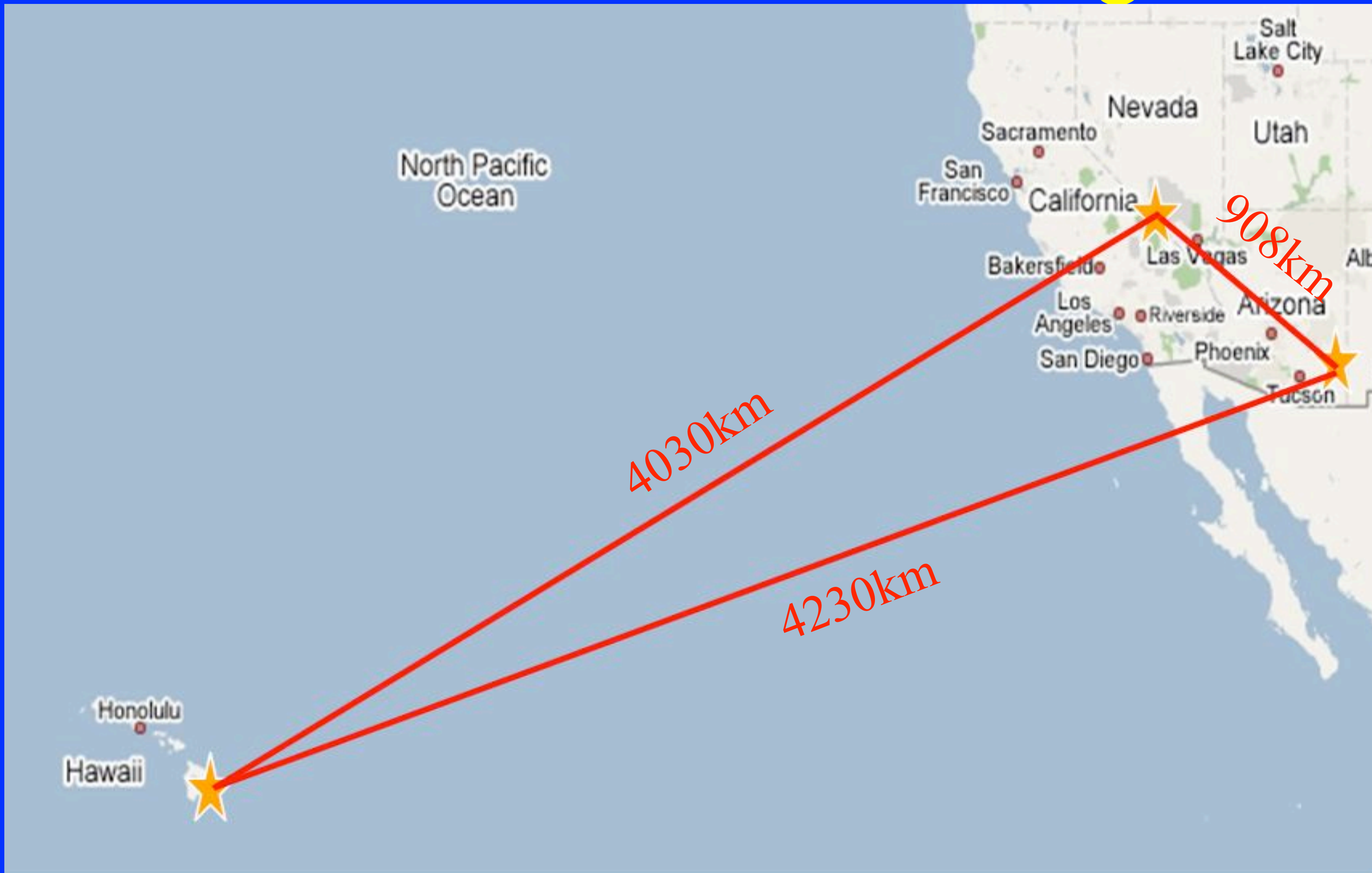
Strong GR Effects:

- Innermost Stable Circular Orbit Size.



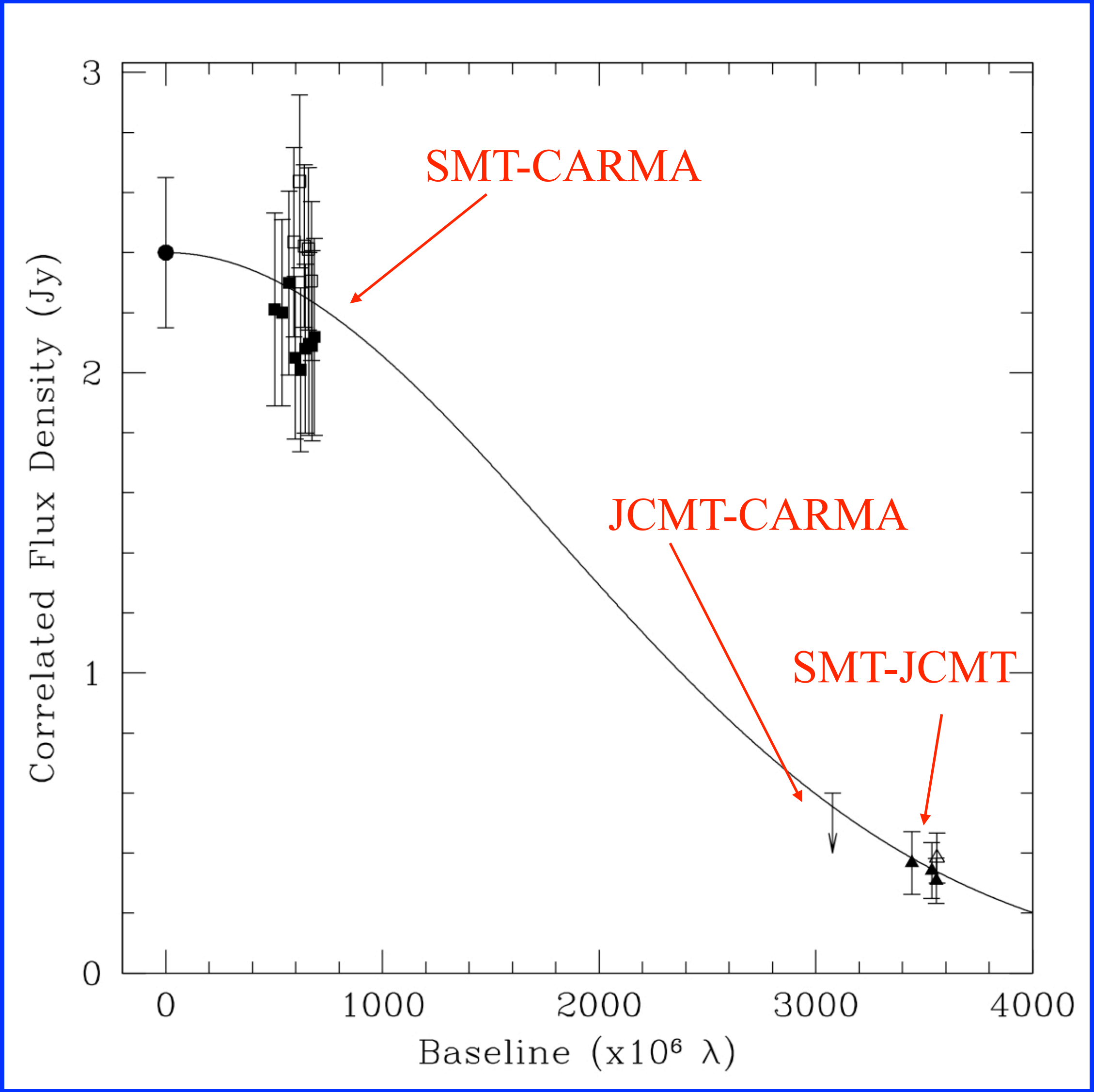


1.3mmλ Observations of SgrA*



Successful SgrA* detections: 2007, 2009, 2011, 2012

Determining the size of SgrA*

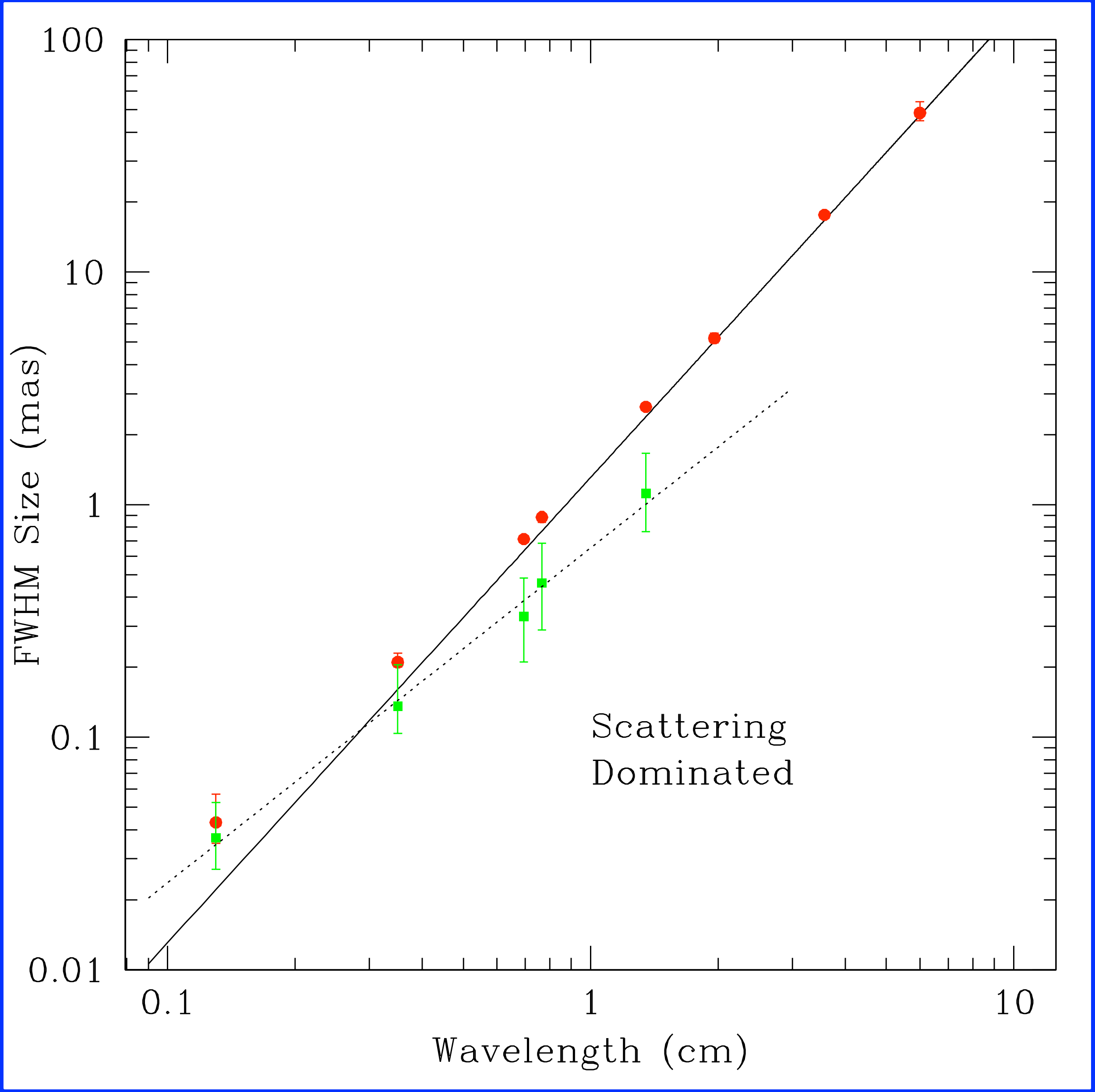


About 4 Schwarzschild radii across.

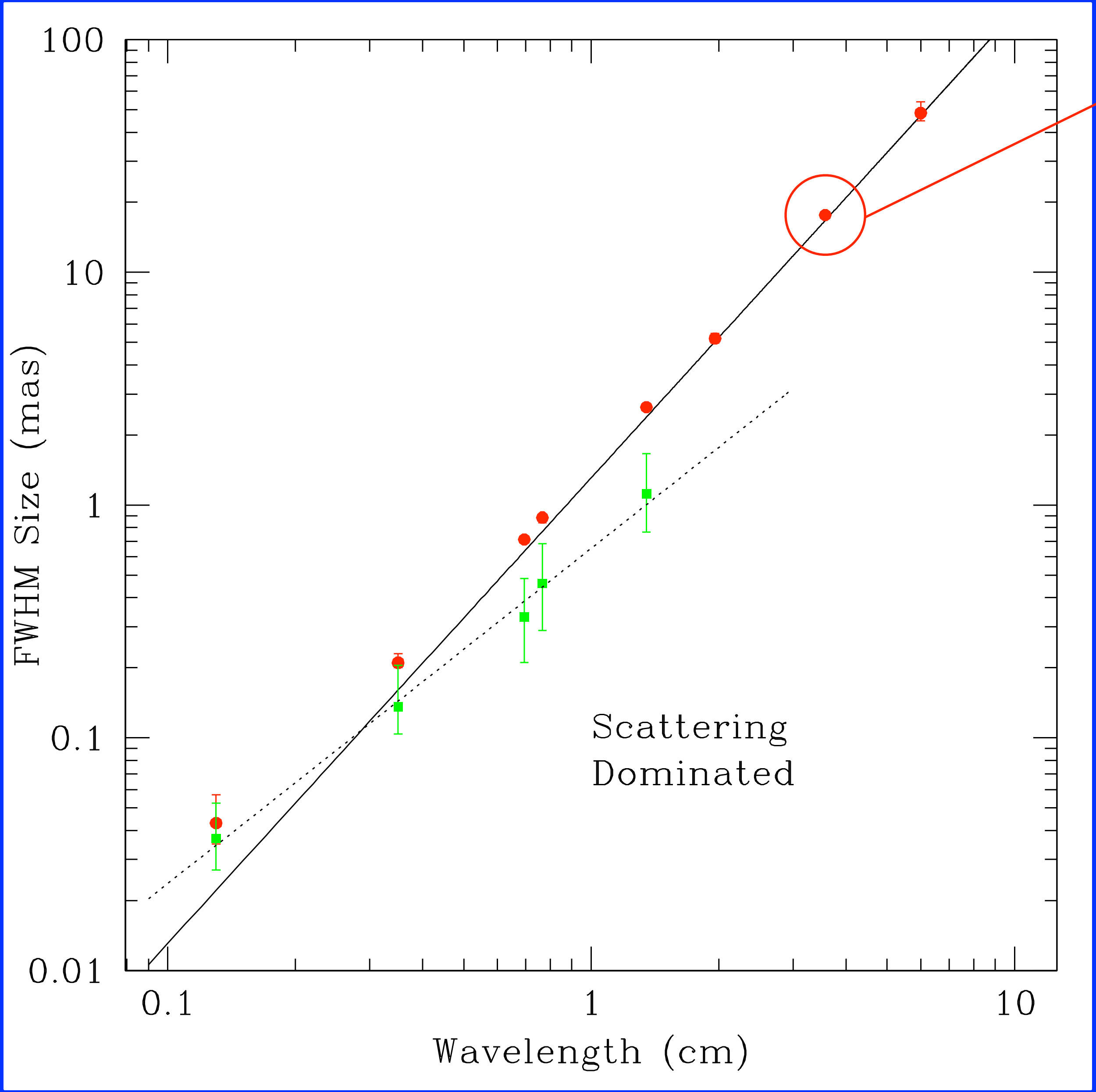
SgrA* has the largest apparent event horizon of any black hole in the Universe.

$$\rho = 10^{23} M_{\odot} pc^{-3}$$

Piercing the Scattering Screen

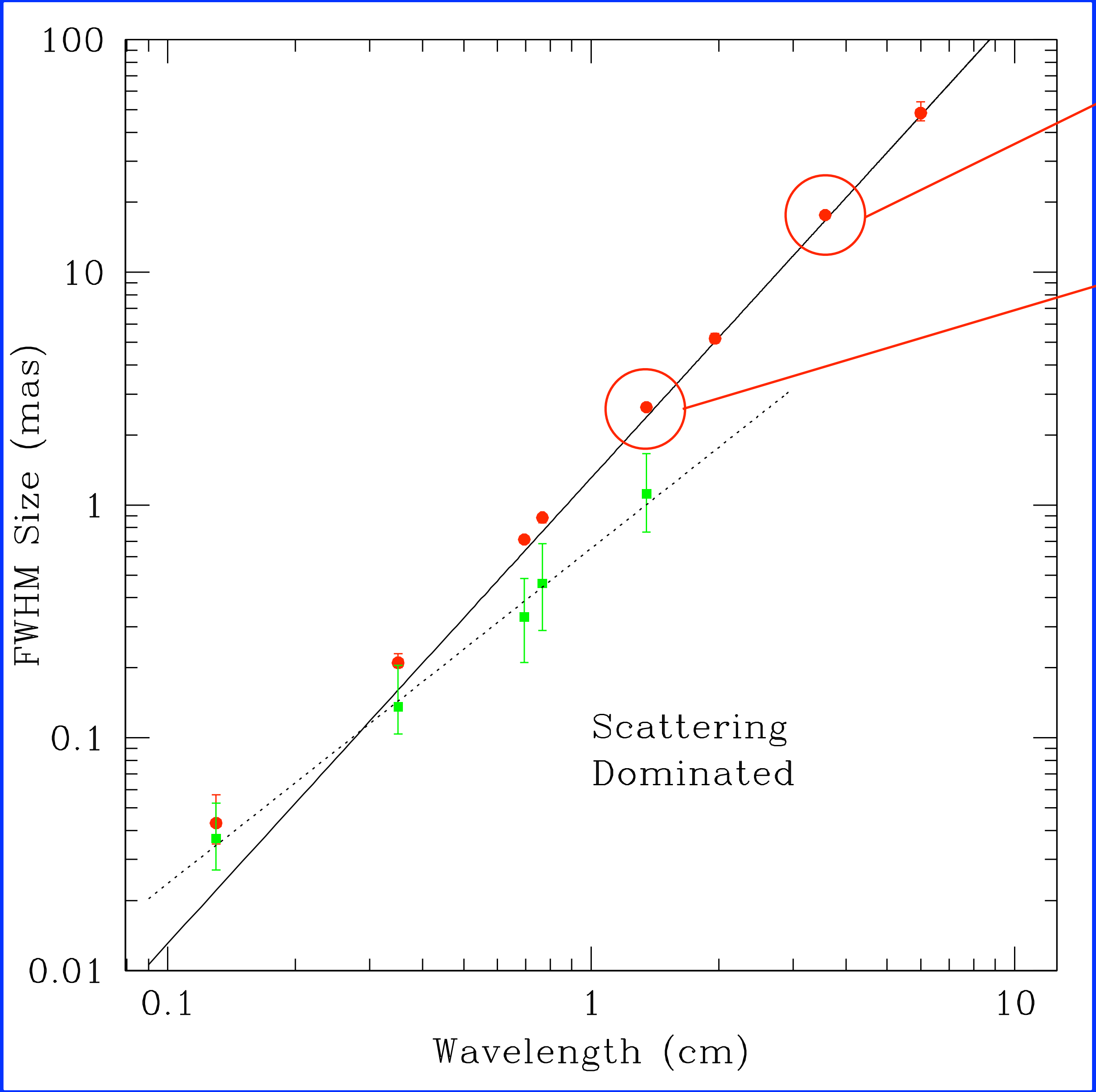


Piercing the Scattering Screen



Lo 1975
Jauncy 1989

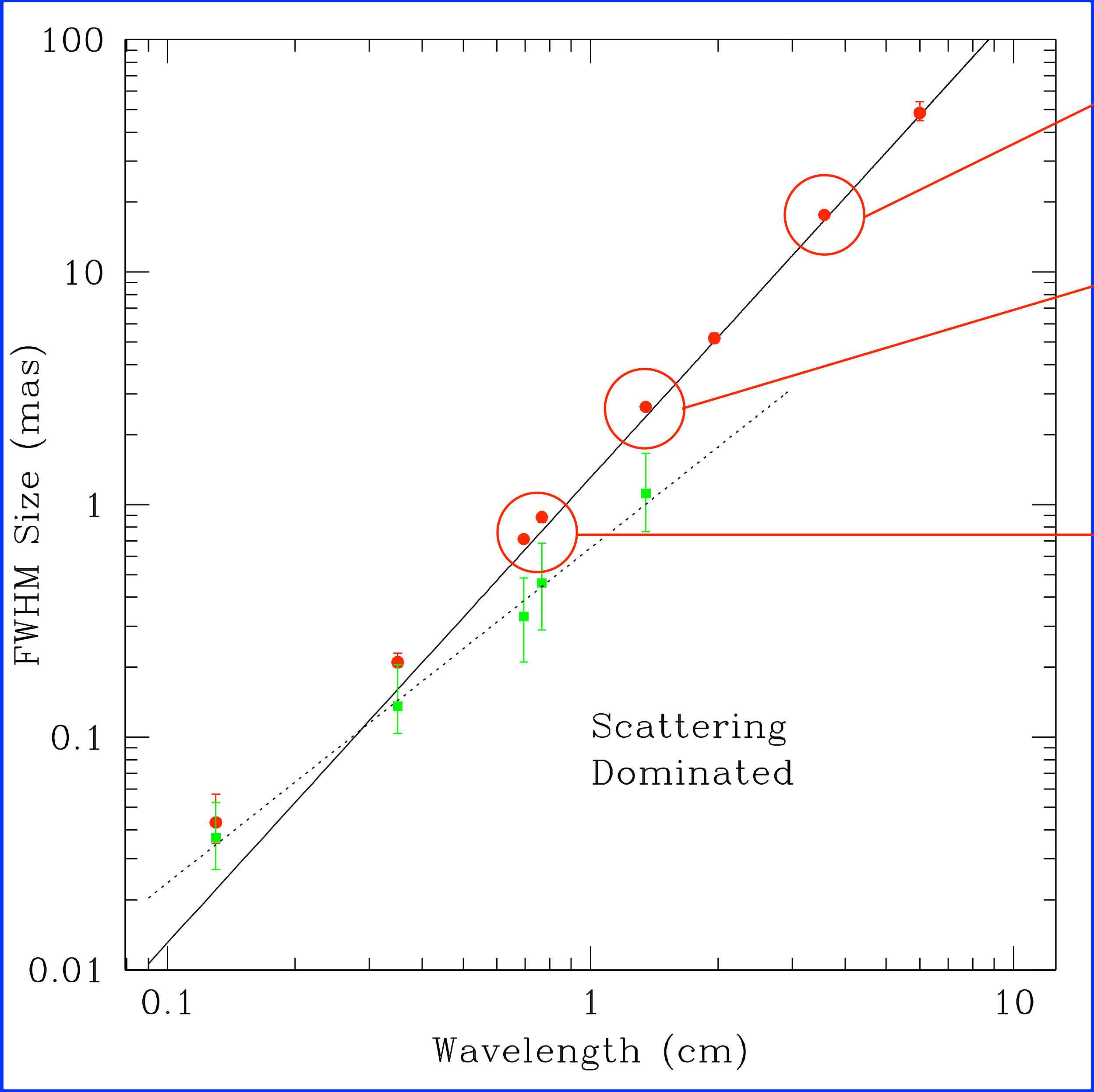
Piercing the Scattering Screen



Lo 1975
Jauncy 1989

Lo 1985
Marcaide 1999

Piercing the Scattering Screen

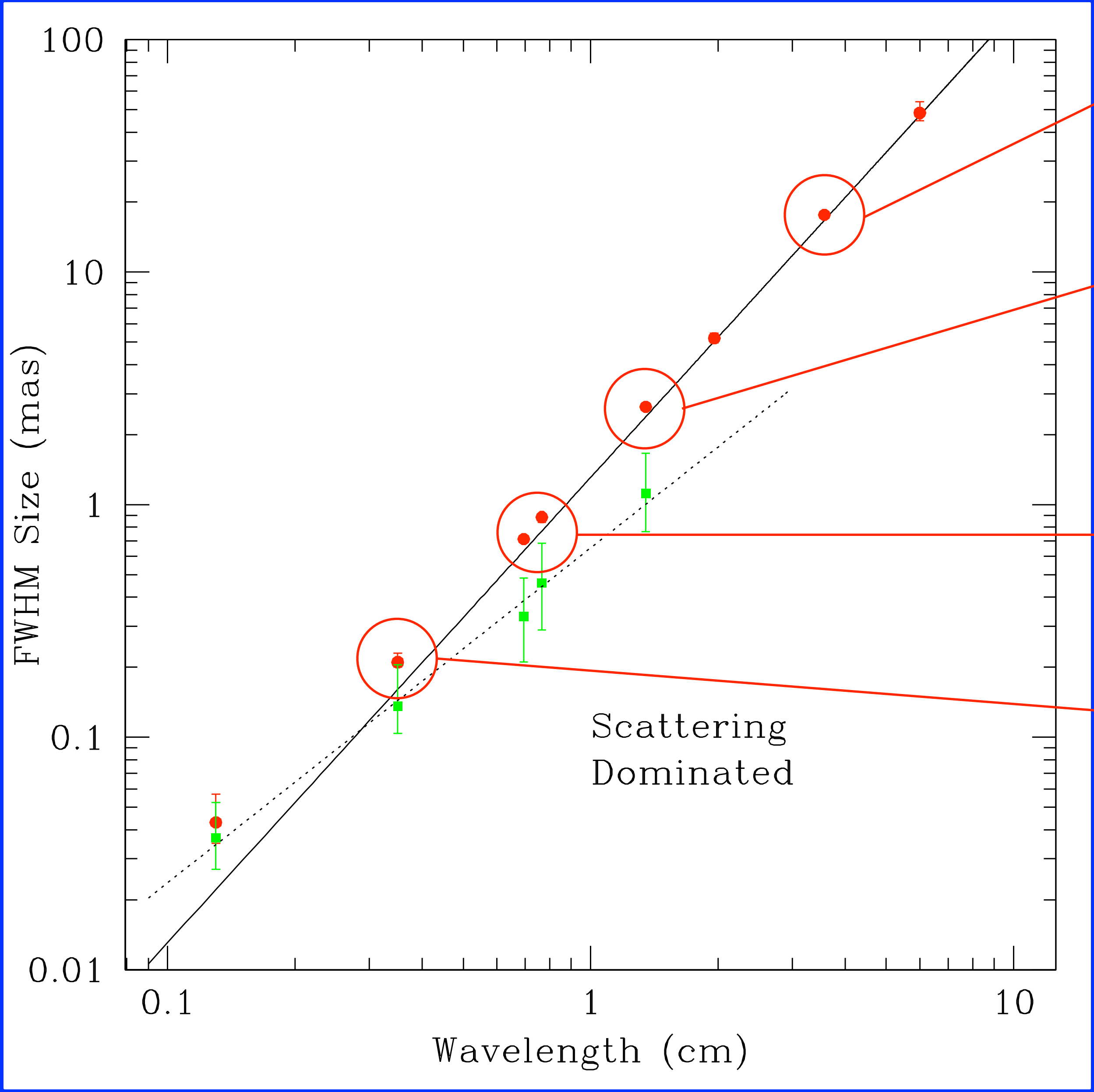


Lo 1975
Jauncy 1989

Lo 1985
Marcaide 1999

Backer 1993
Krichbaum 1993
Bower 2004

Piercing the Scattering Screen



Lo 1975
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Bower 2004

Rogers 1994
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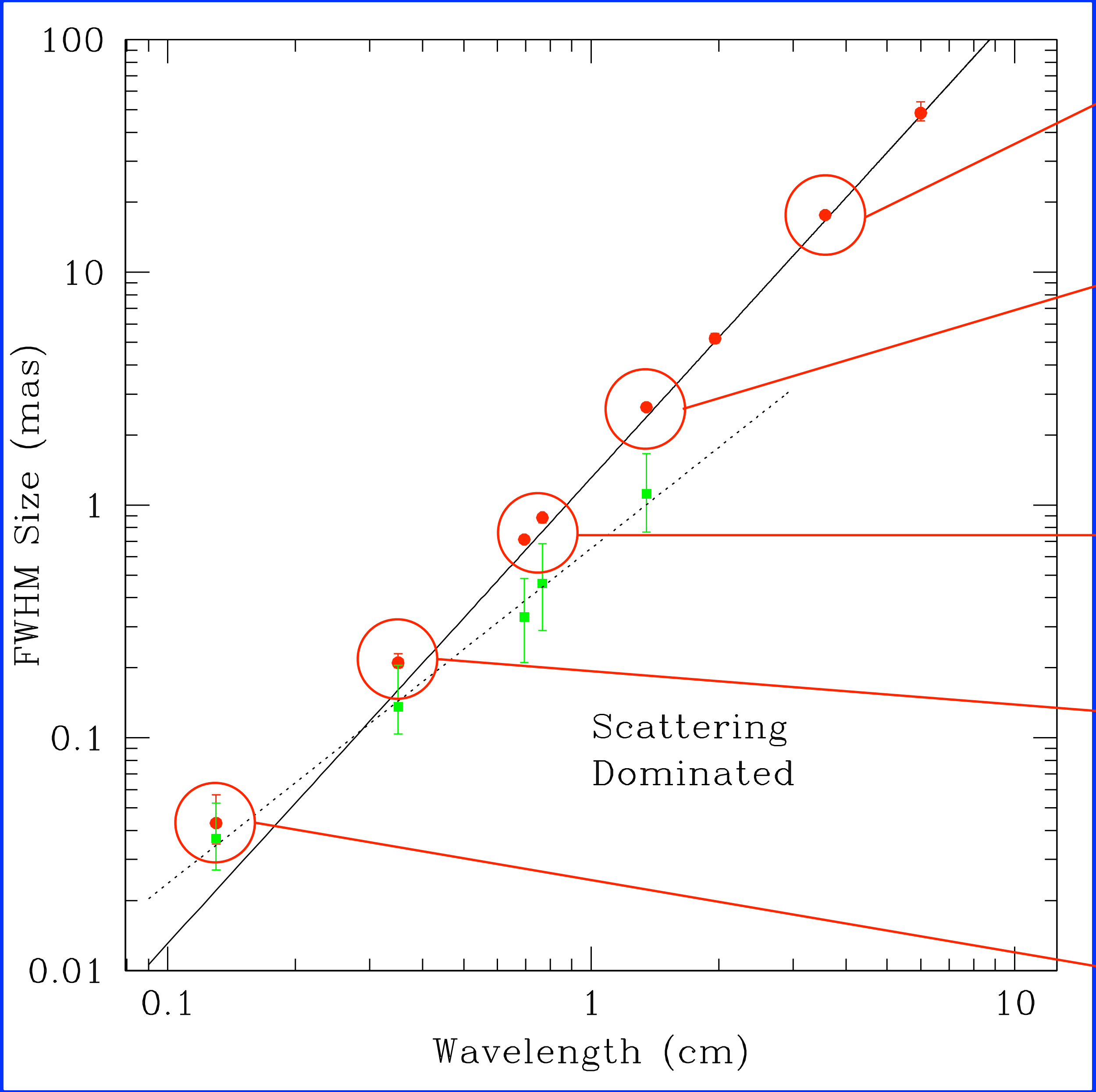
Shen 2005

Piercing the Scattering Screen



Lo 1975
Jauncy 1989

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Marcaide 1999

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Krichbaum 1993
Bower 2004

Rogers 1994
Krichbaum 1998
Shen 2005

Doeleman 2008
Fish 2011

The minimum apparent size.

$$R_a = \begin{cases} 3\sqrt{3}\left(R_{sch}/2\right) & R \le 1.5 R_{sch} \\ R / \sqrt{1 - R_{sch} / R} & R > 1.5 R_{sch} \end{cases}$$

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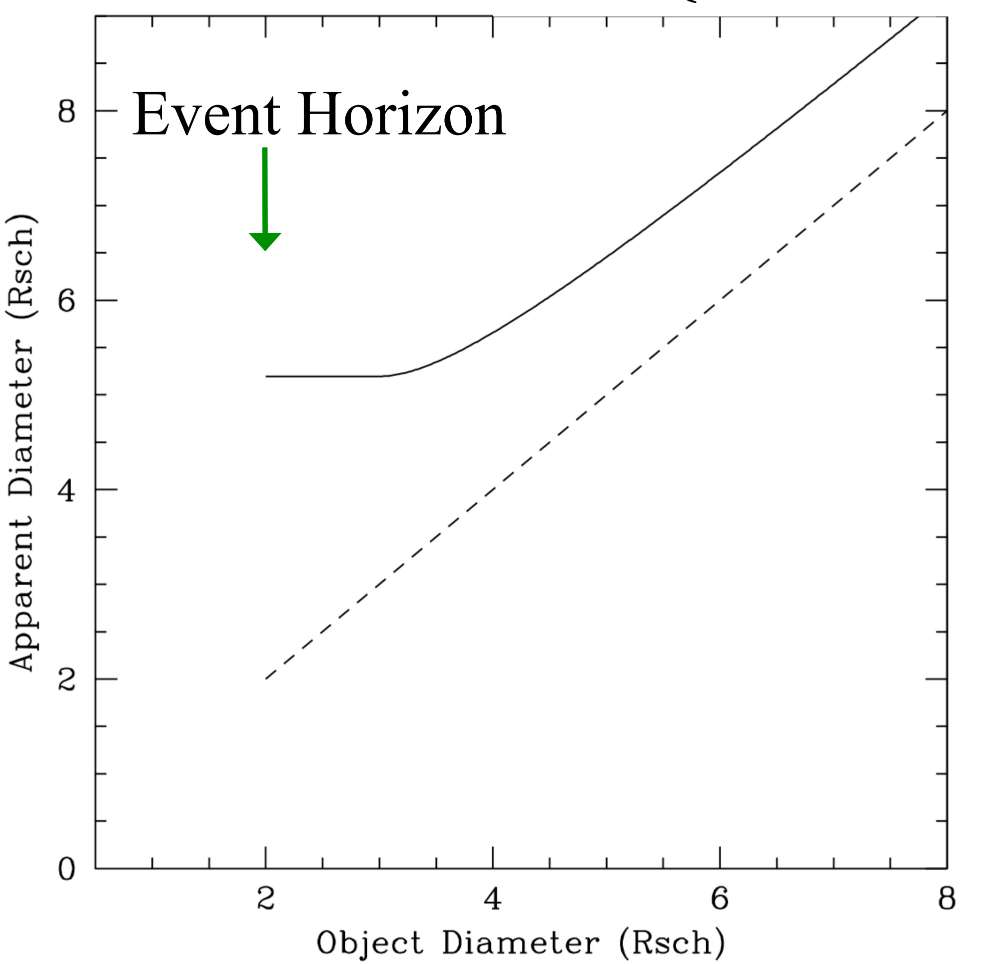

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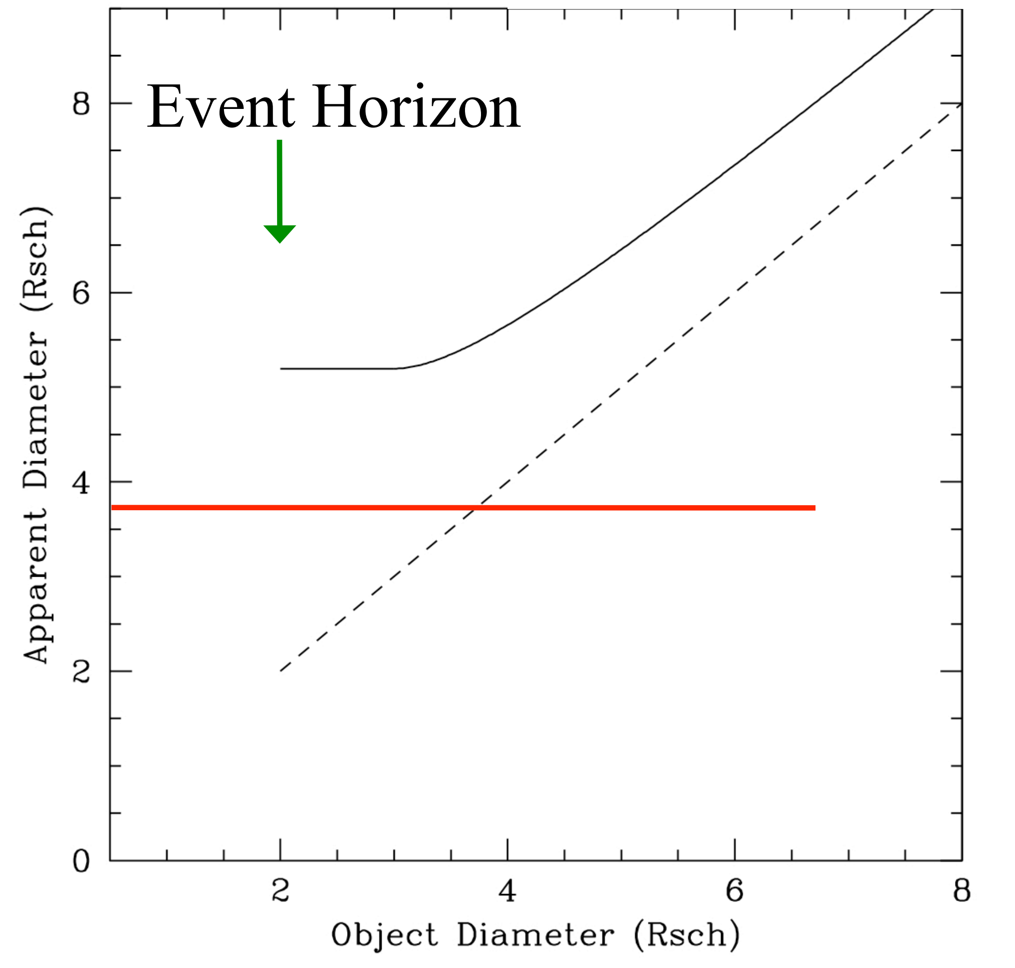
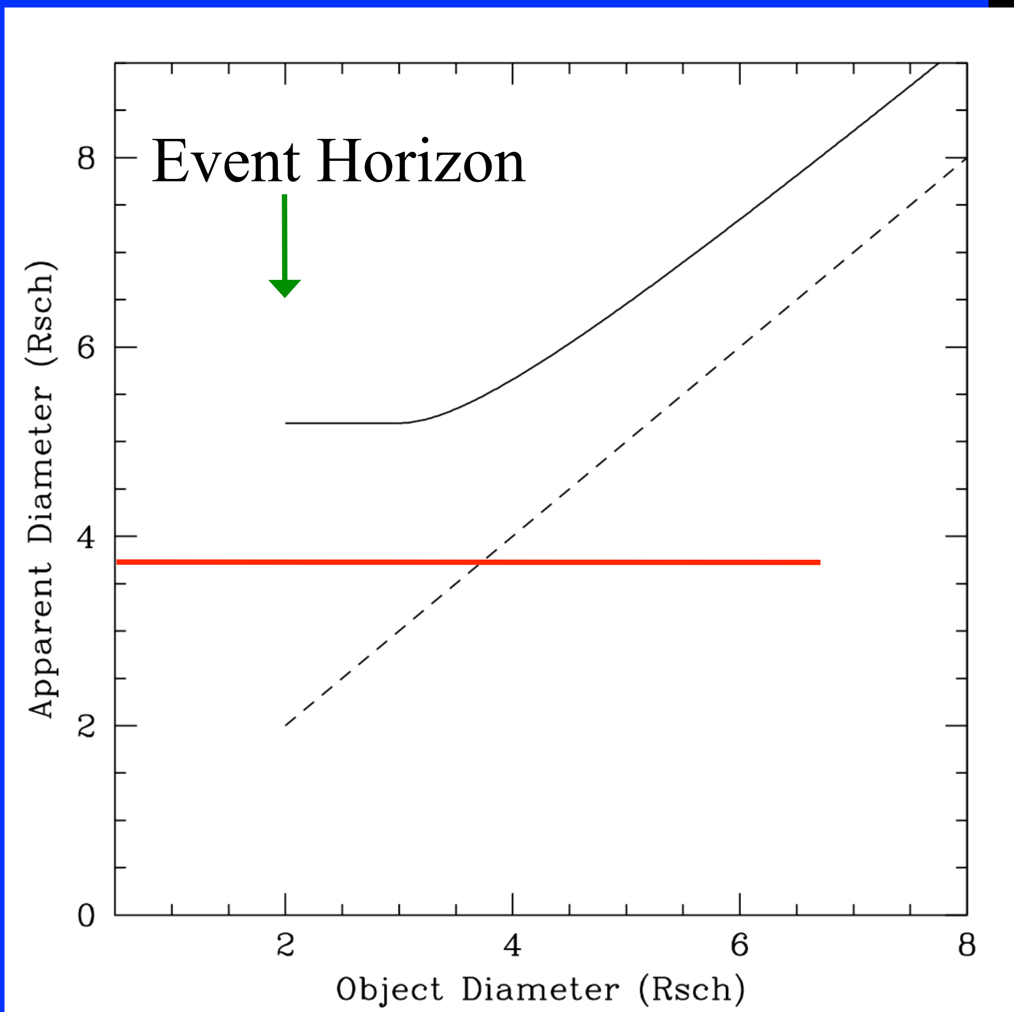
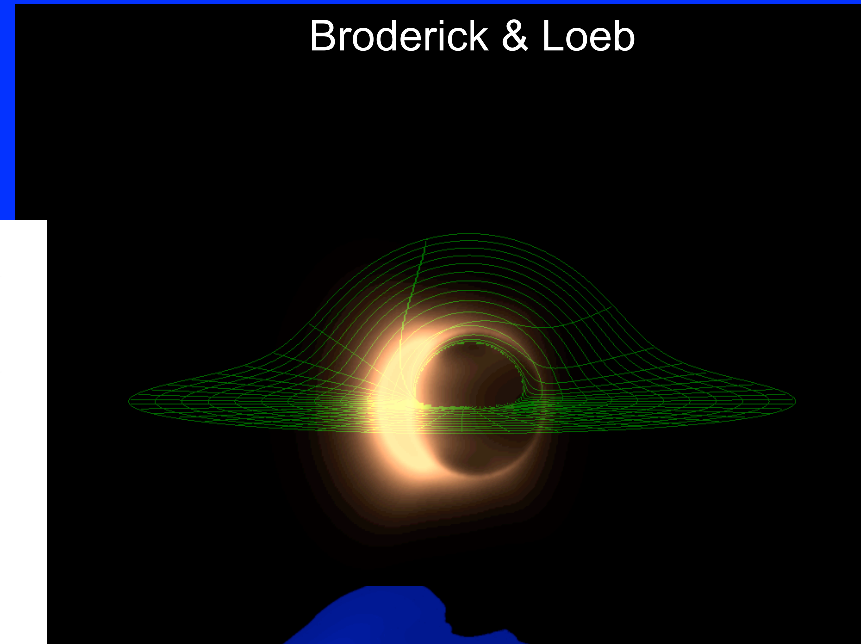
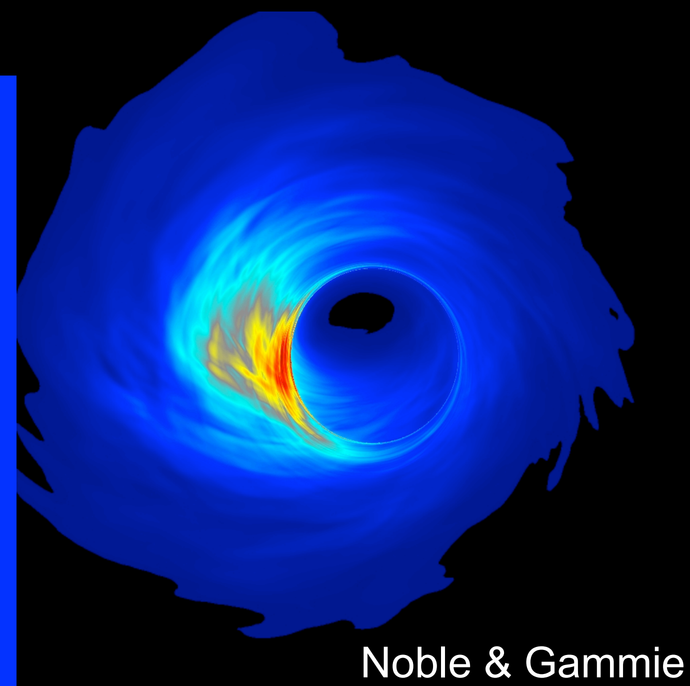


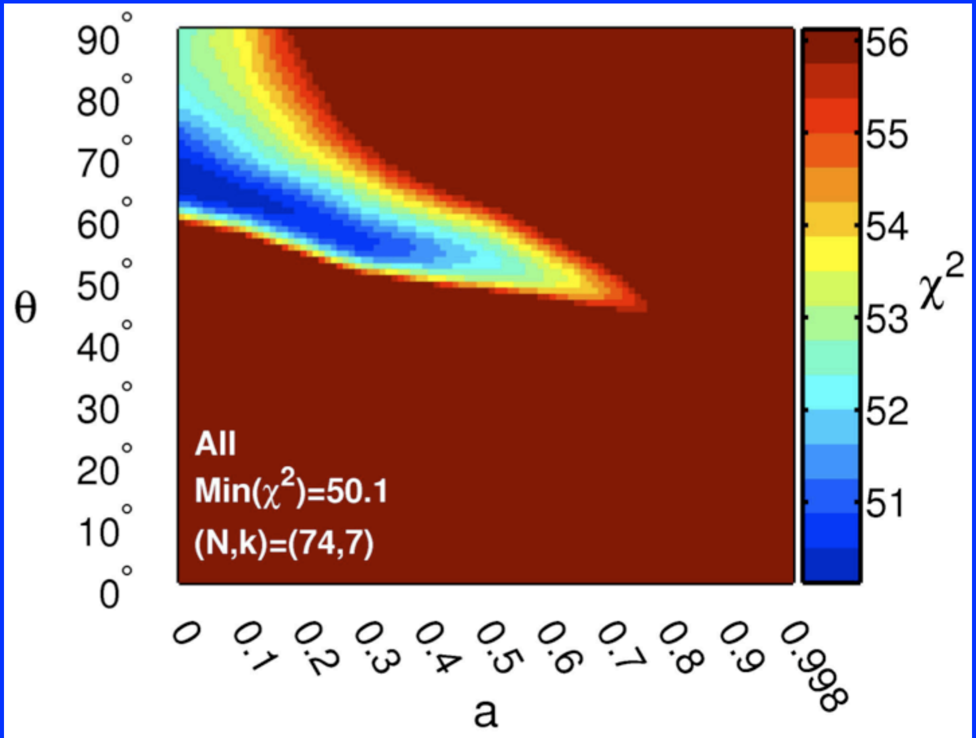
The minimum apparent size.

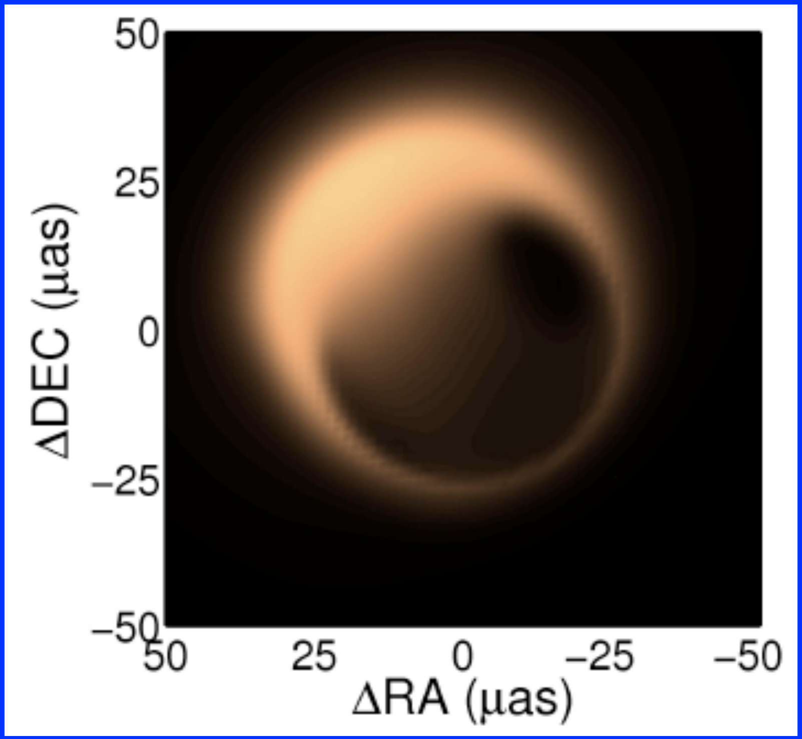






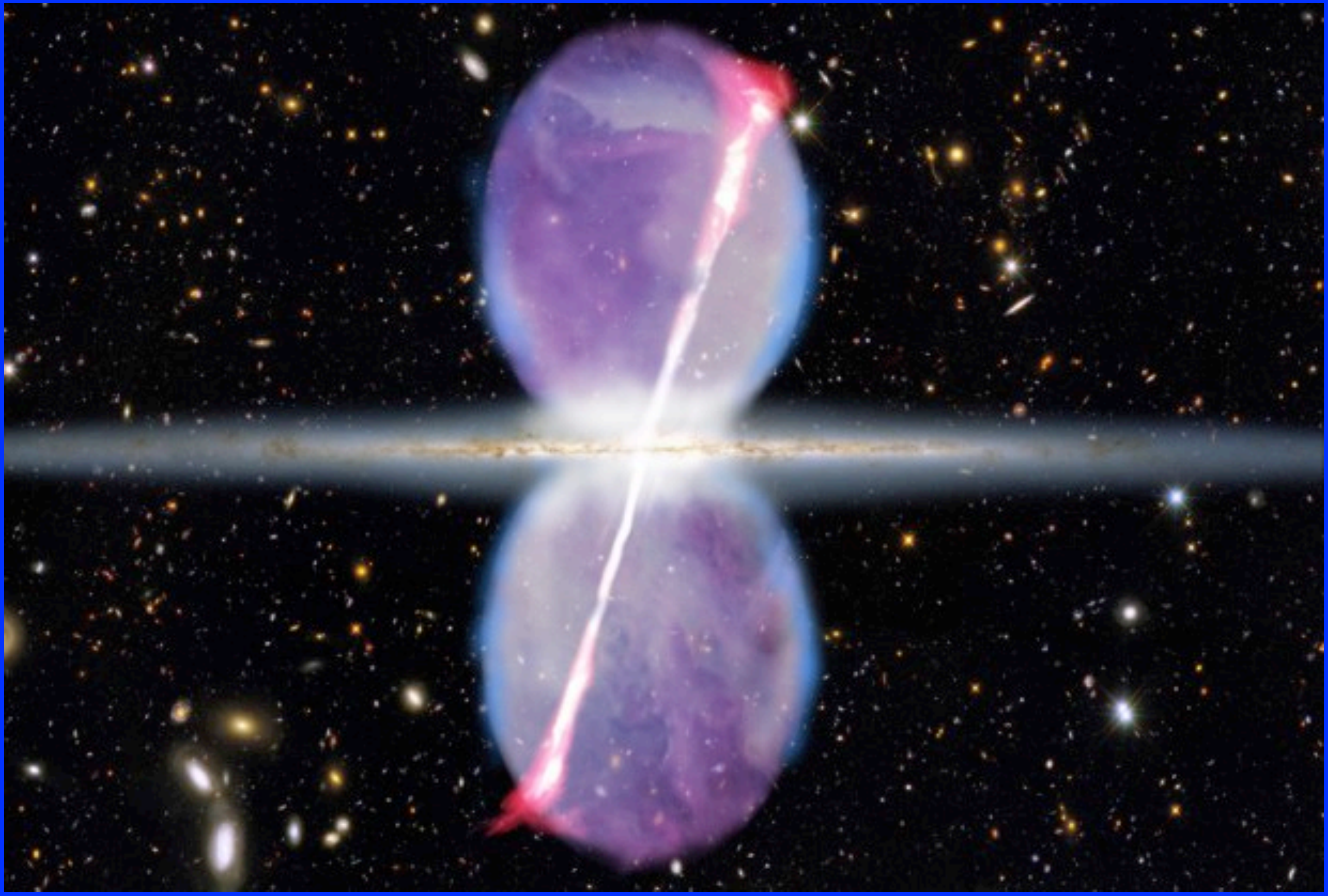
Tighter Constraints on BH using RIAF models of SgrA*.





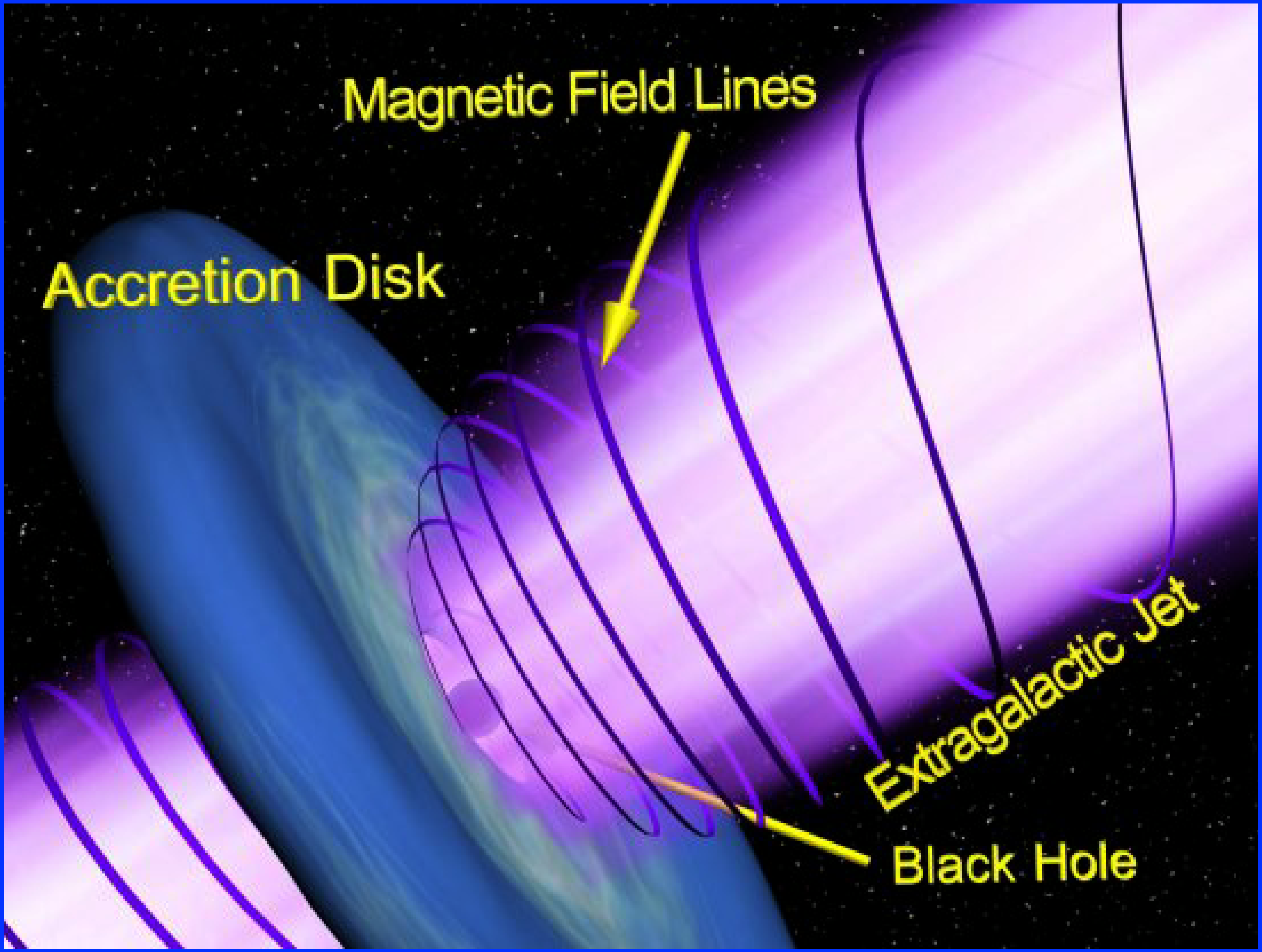
Broderick, Fish, Doeleman & Loeb 2011

Tighter Constraints on BH using RIAF models of SgrA*.

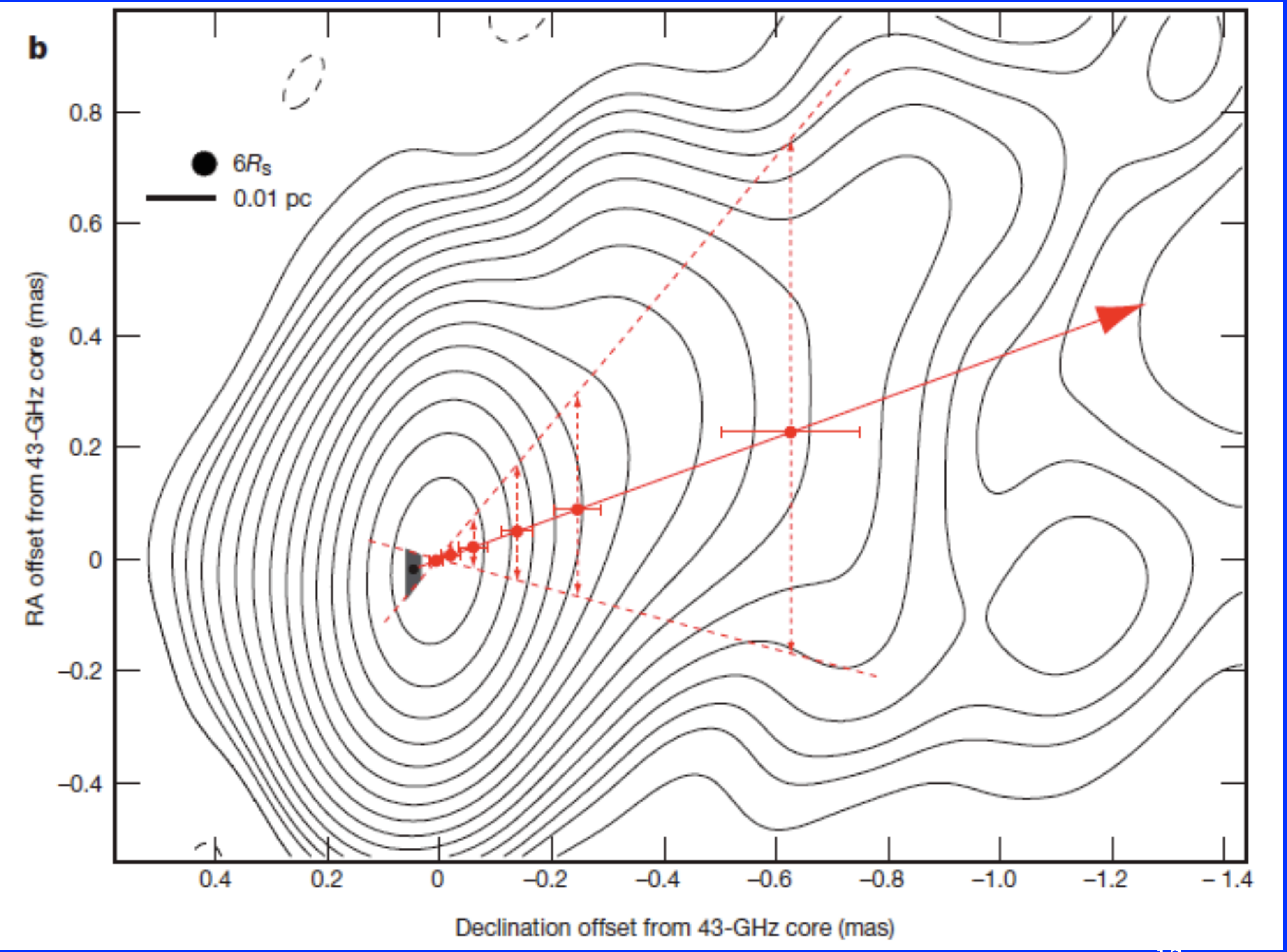


Su & Finkbeiner 2011

Relativistic Jets

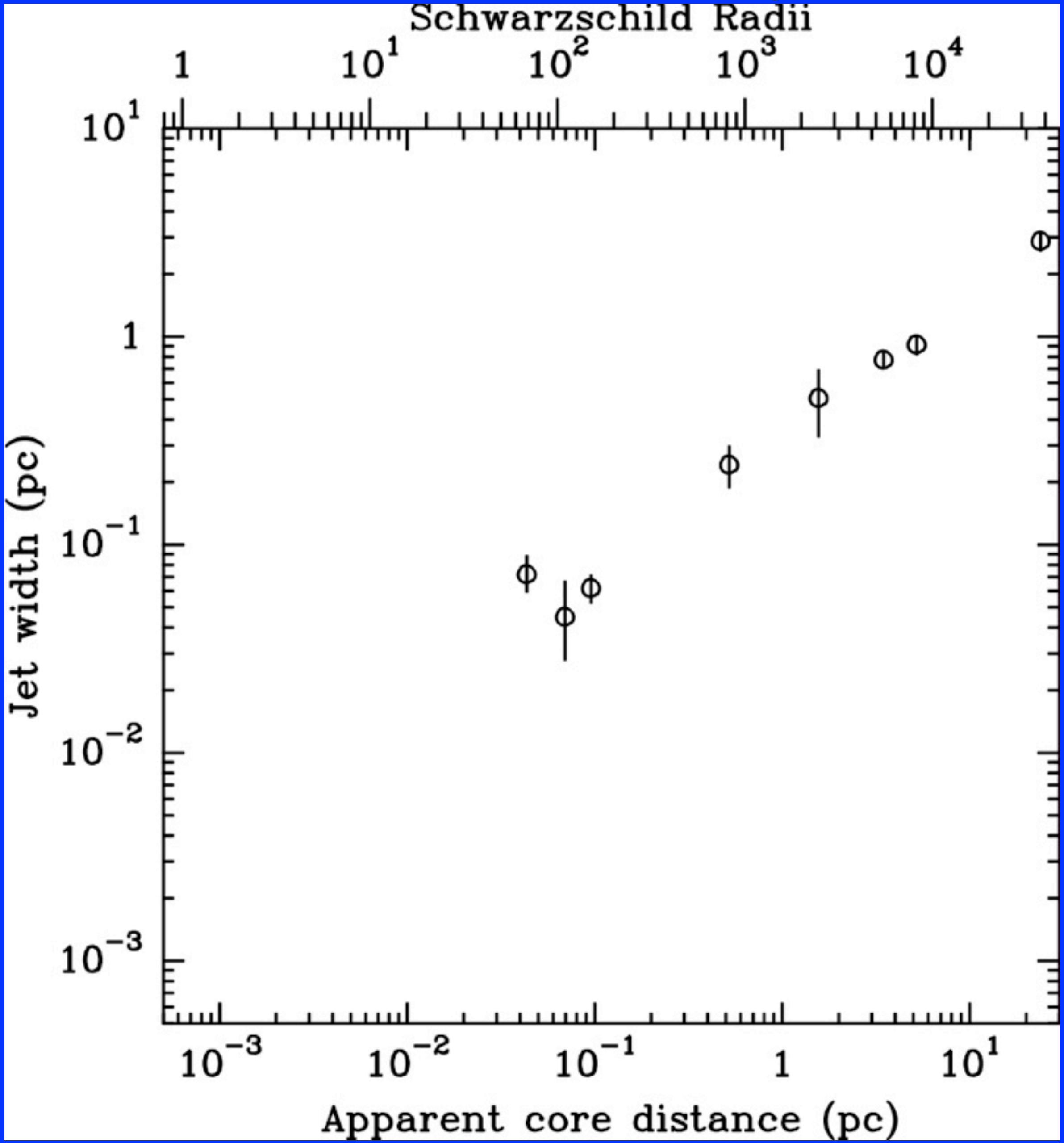


Location of M87's SMBH

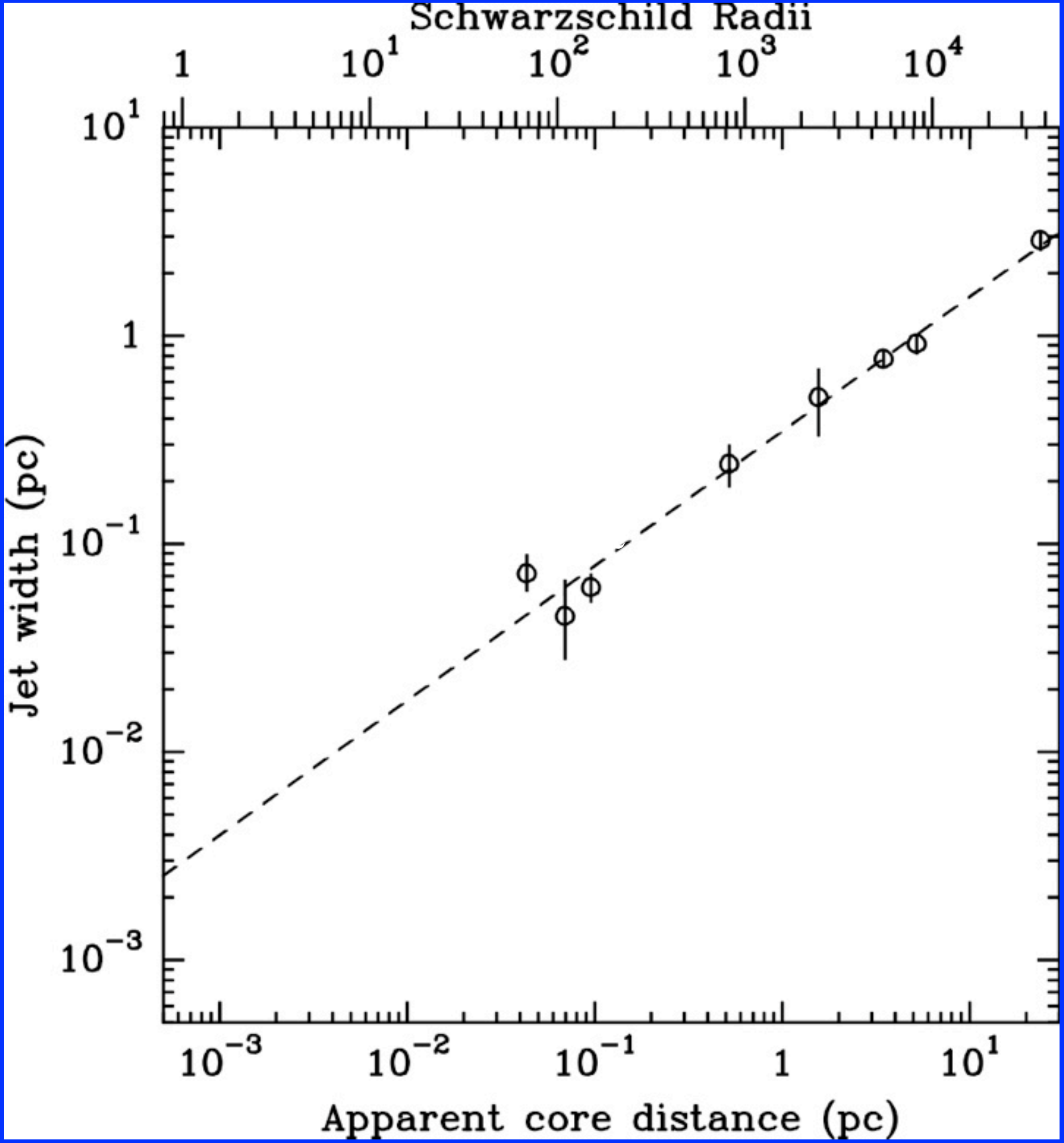


Hada et al, Nature, 2011

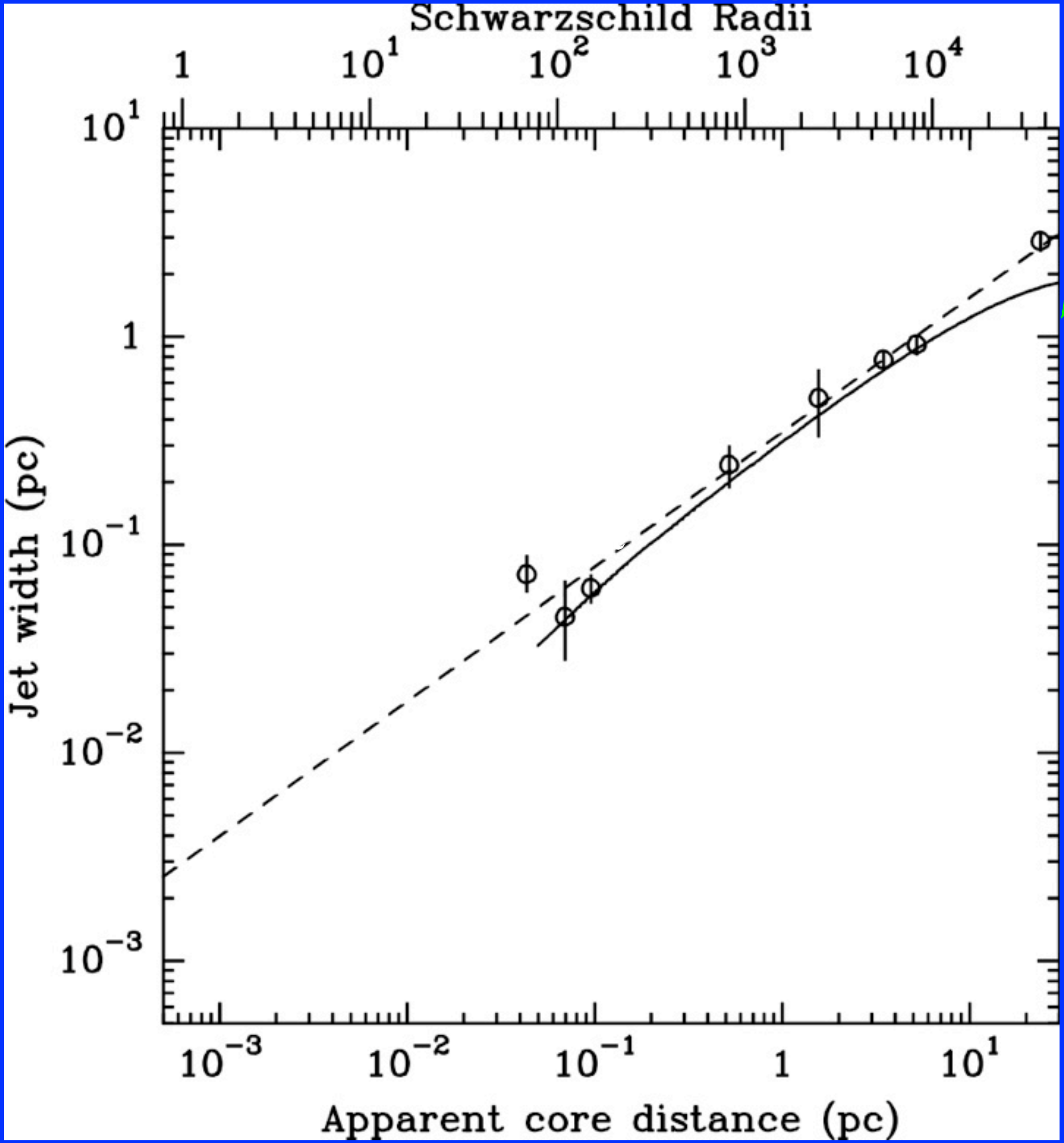
M87: Jet Origins



M87: Jet Origins

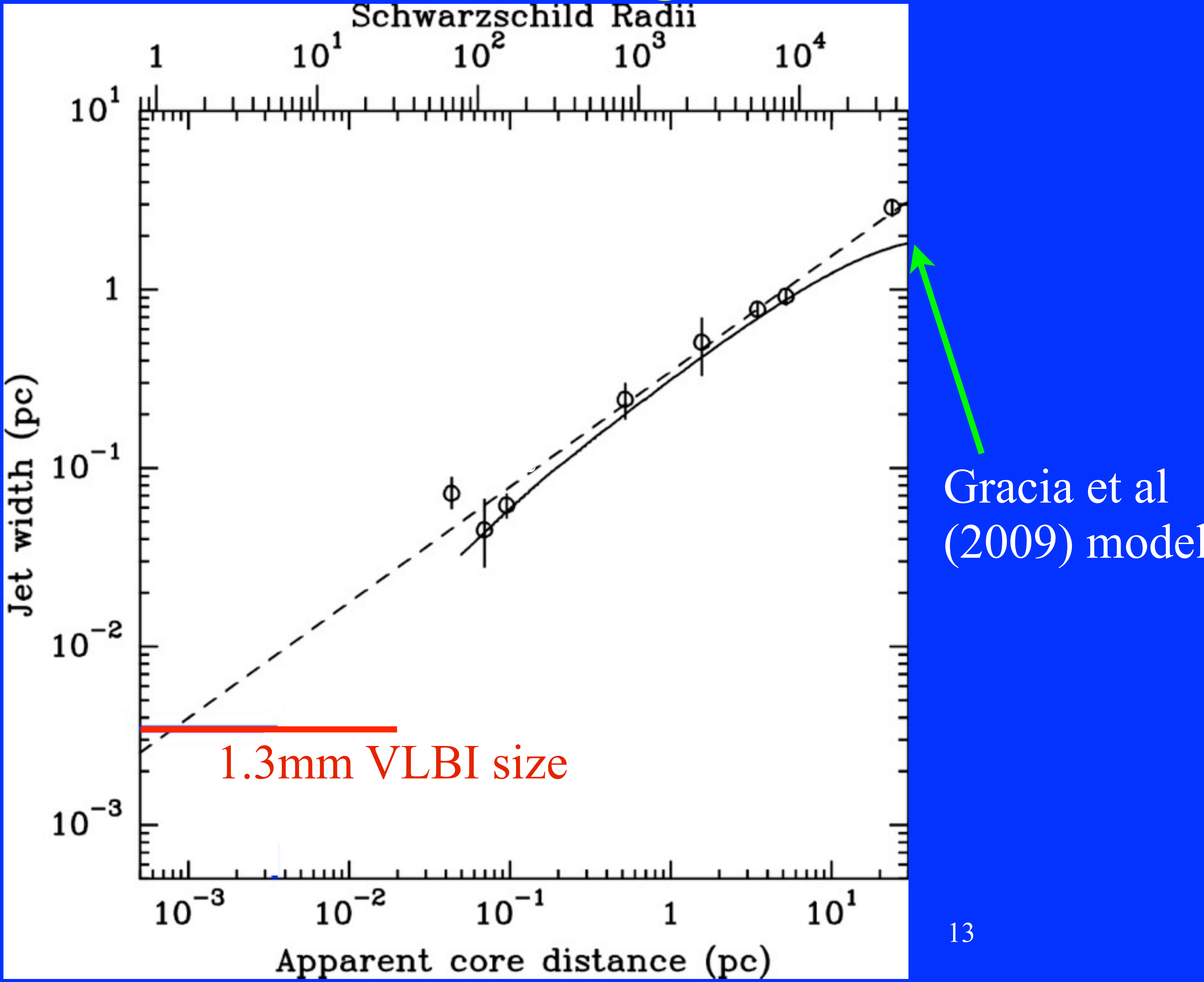


M87: Jet Origins

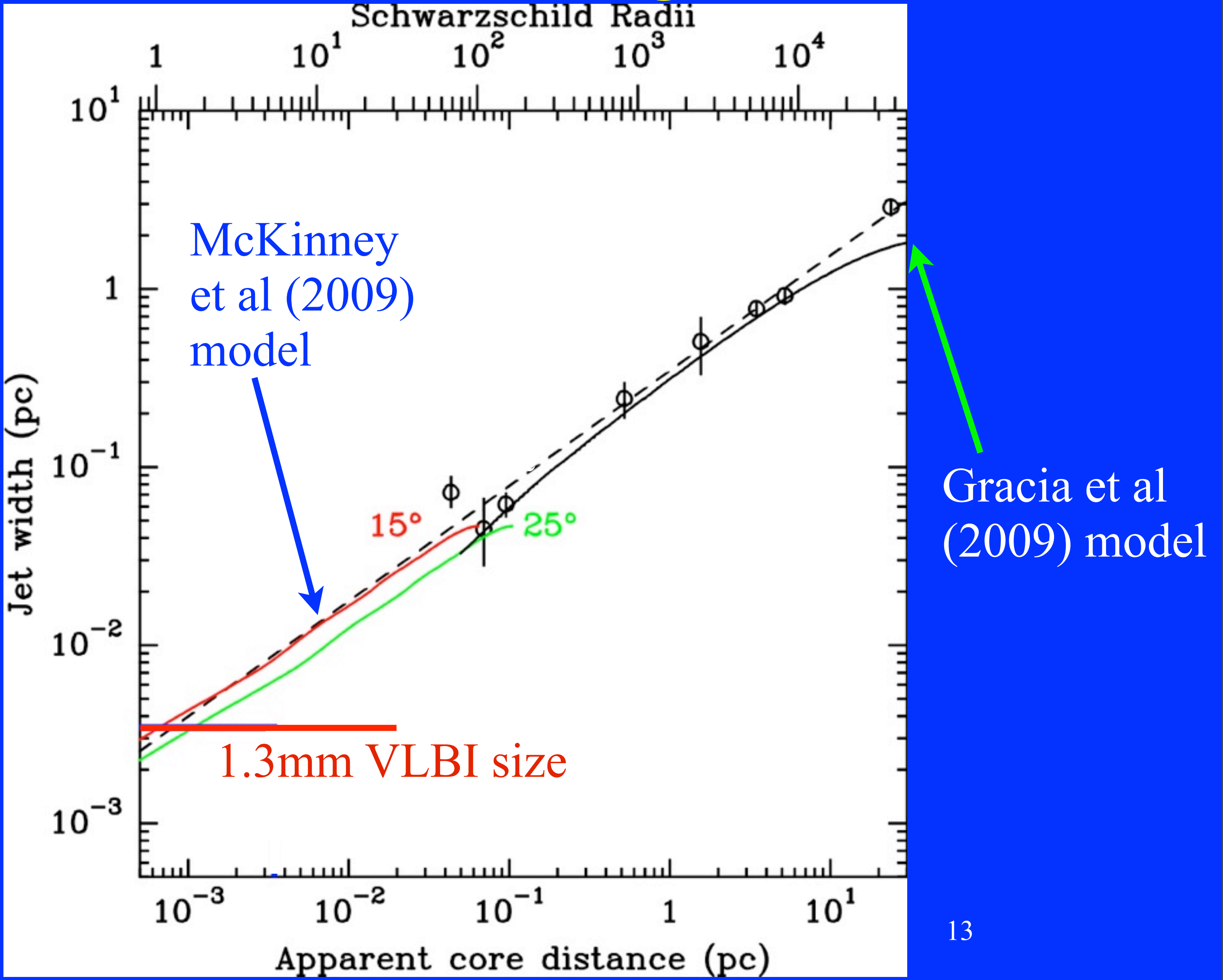


Gracia et al (2009) model

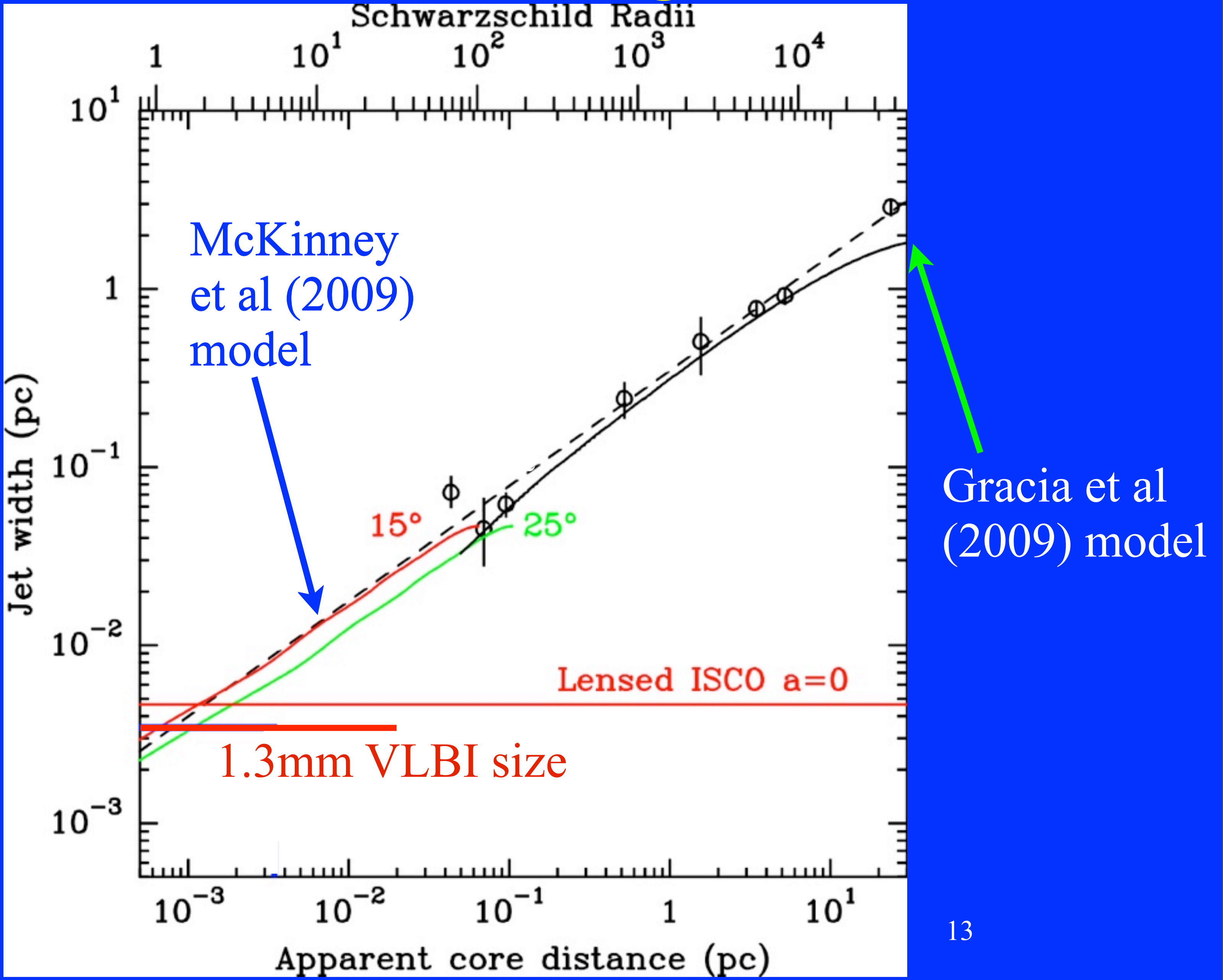
M87: Jet Origins



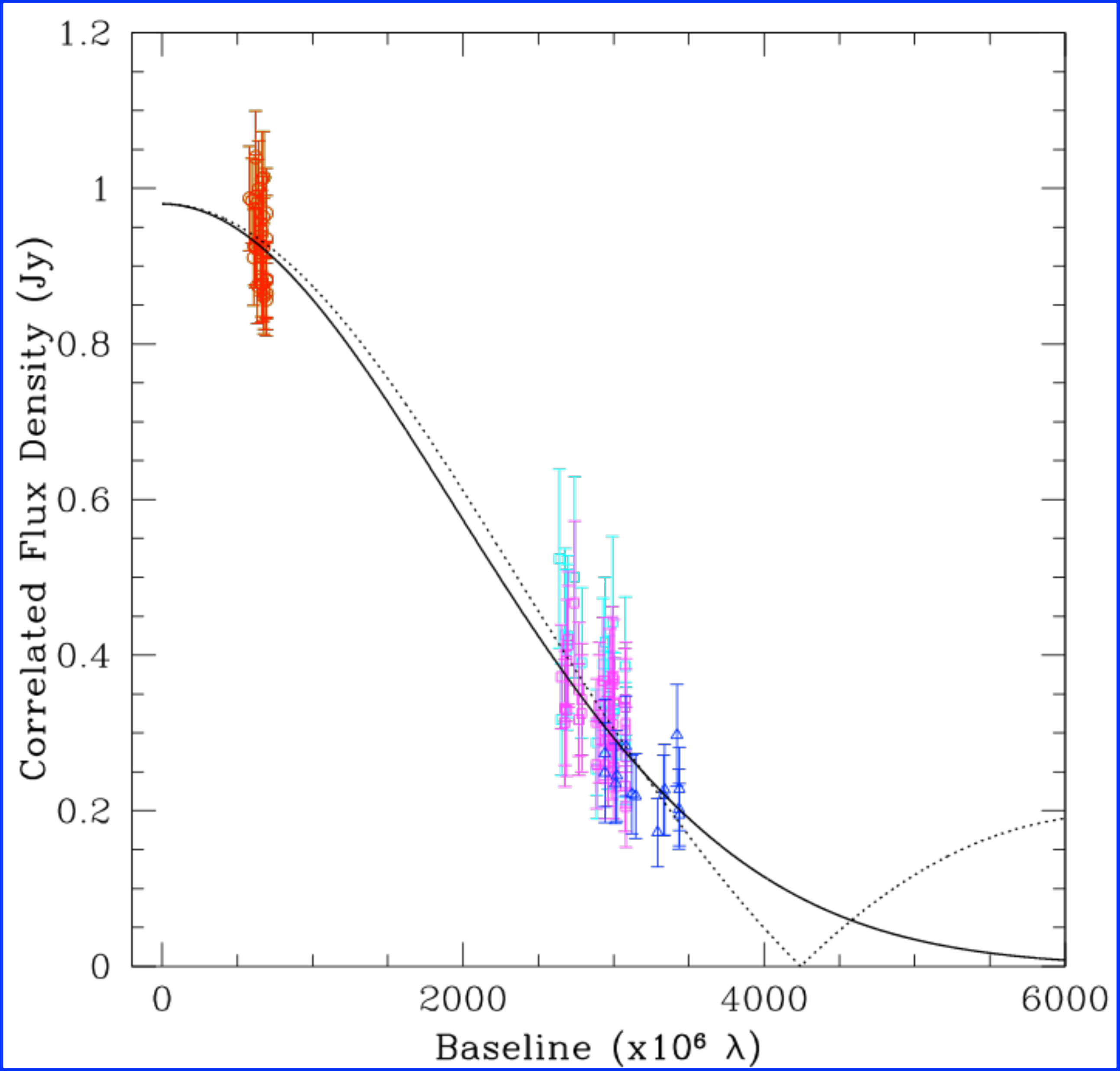
M87: Jet Origins



M87: Jet Origins

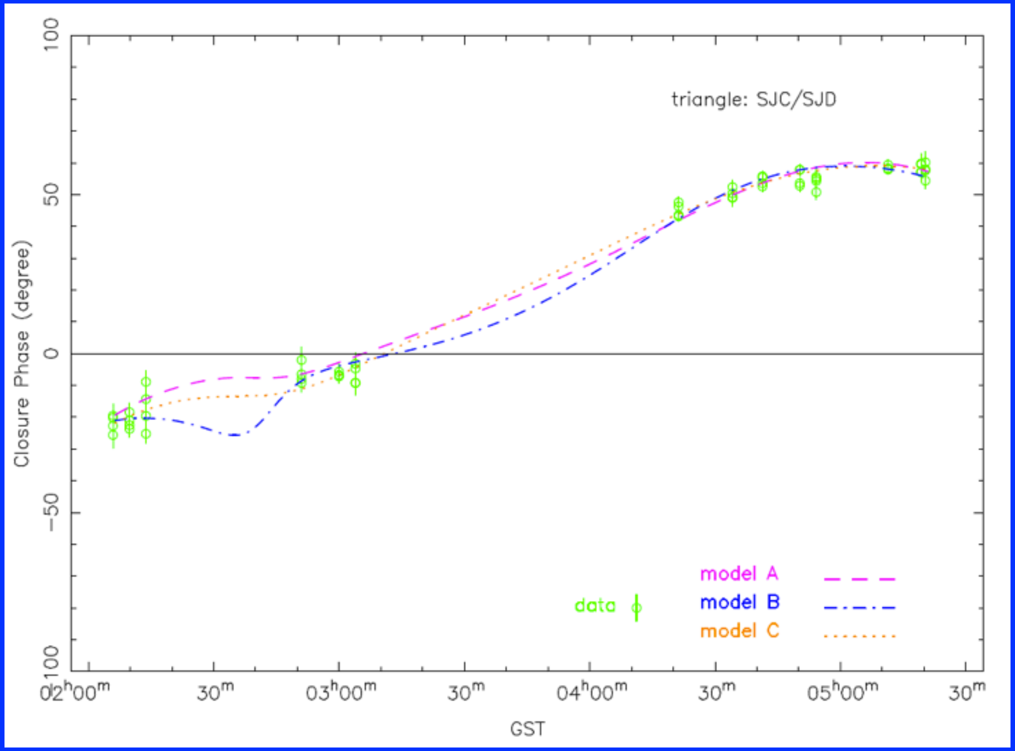


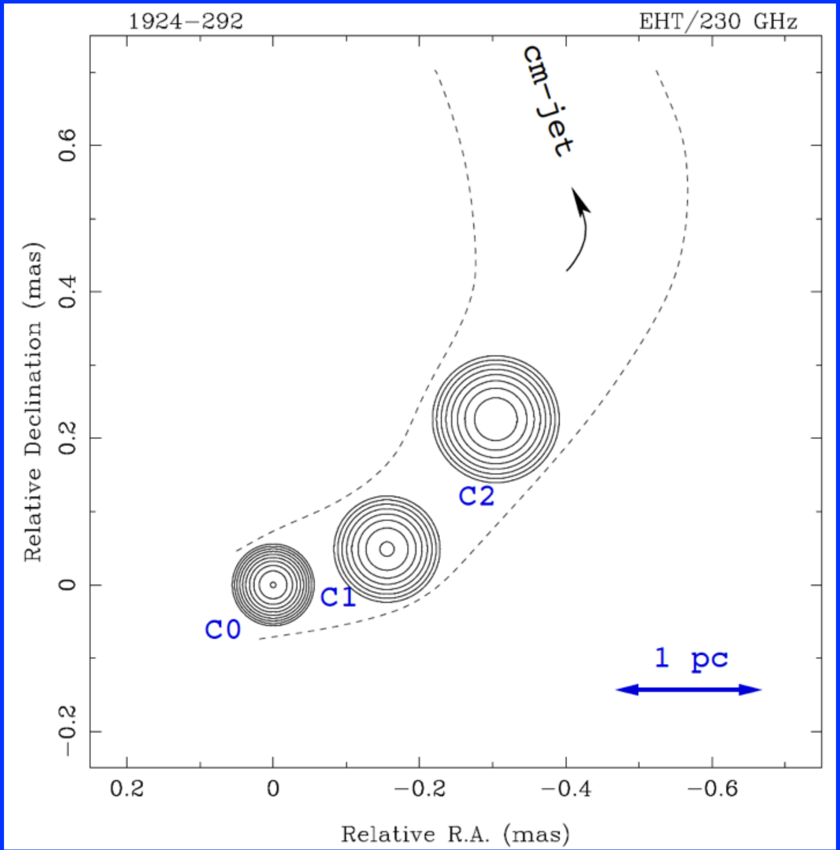
Size of the M87 Jet Base



Robust 1.3mm VLBI Closure Phases

Quasar 1921-293





Rusen Lu et al 2012

SgrA*'s view of the EHT

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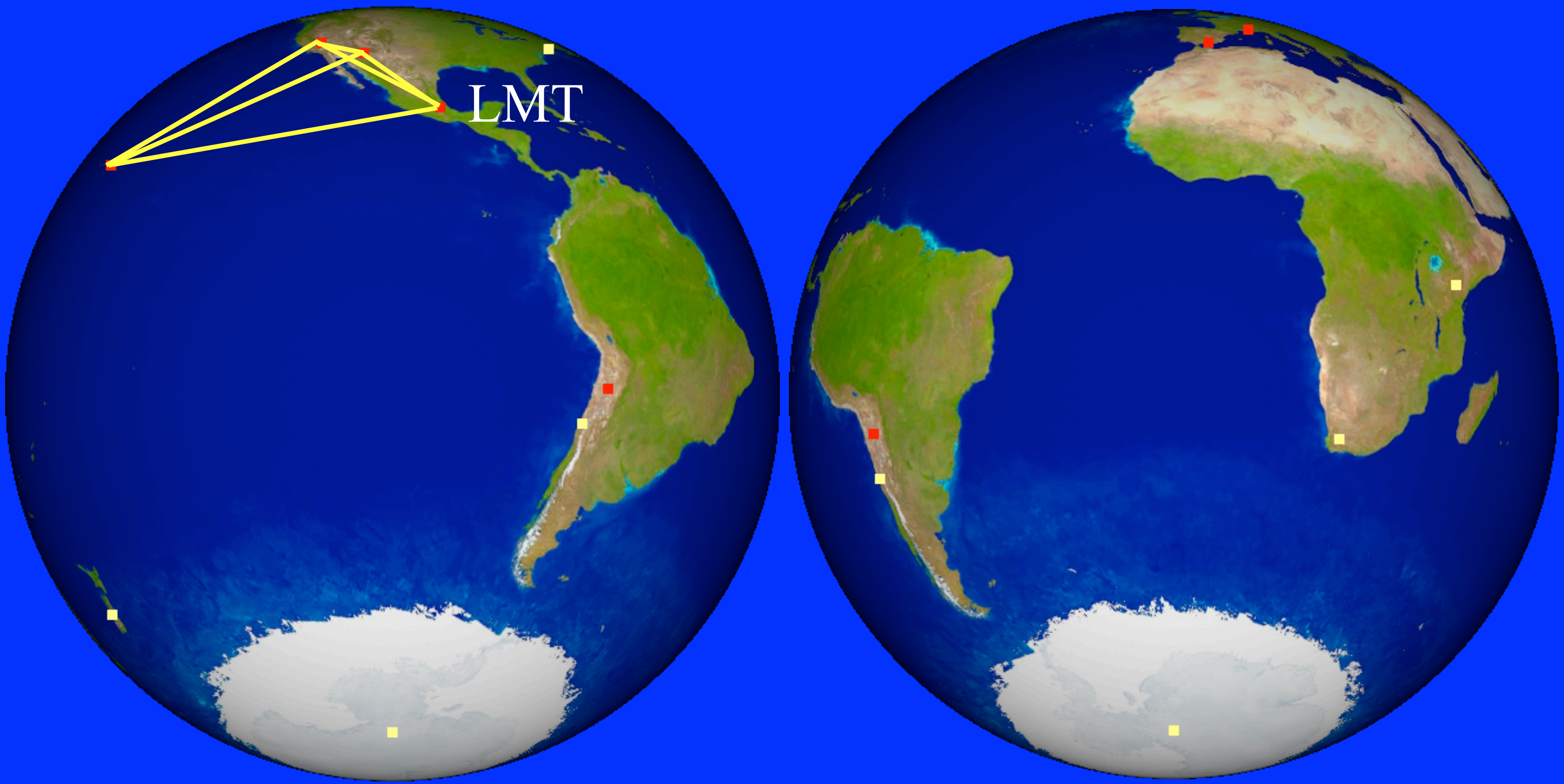
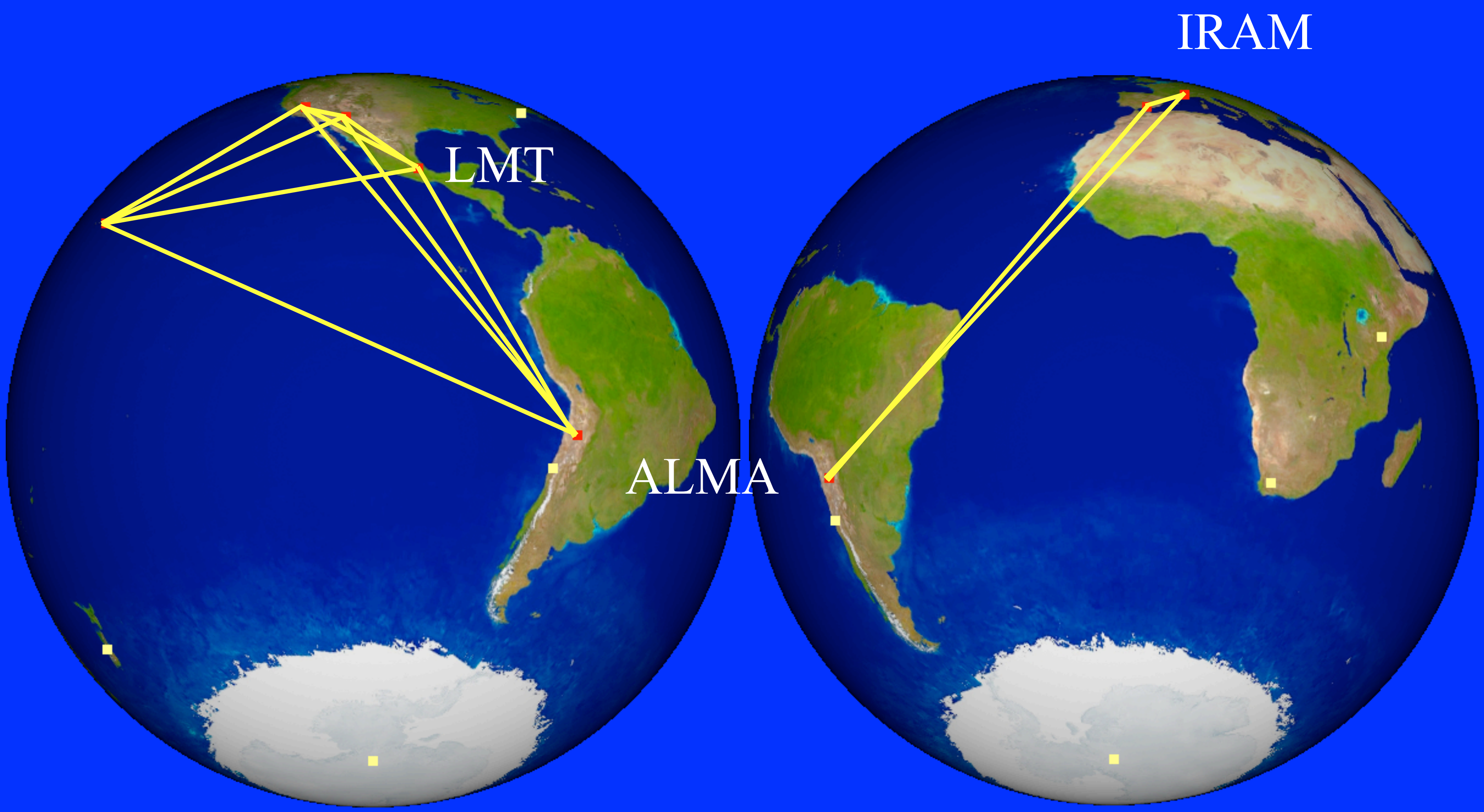
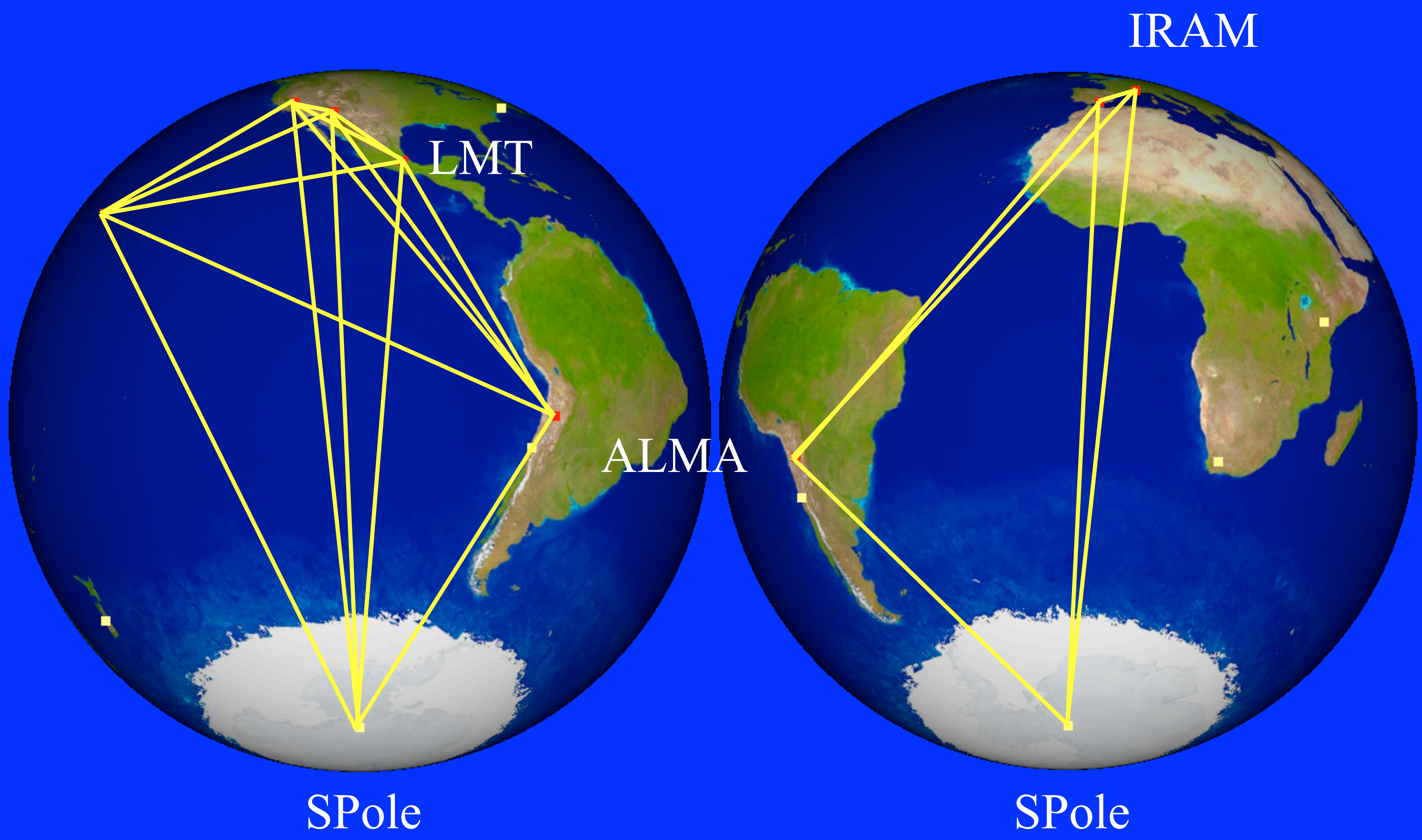


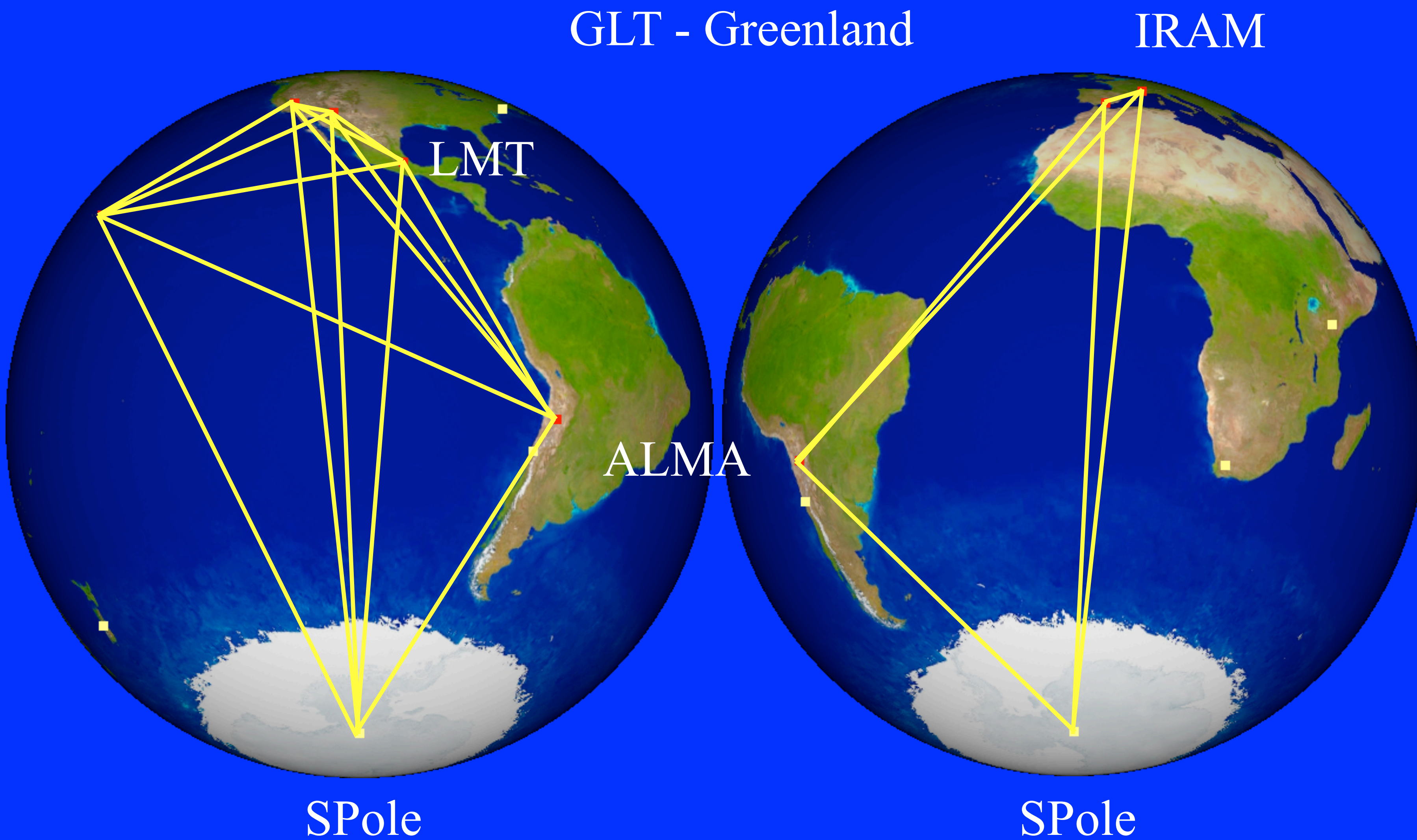
SgrA*'s view of the EHT



SgrA*'s view of the EHT



SgrA*'s view of the EHT

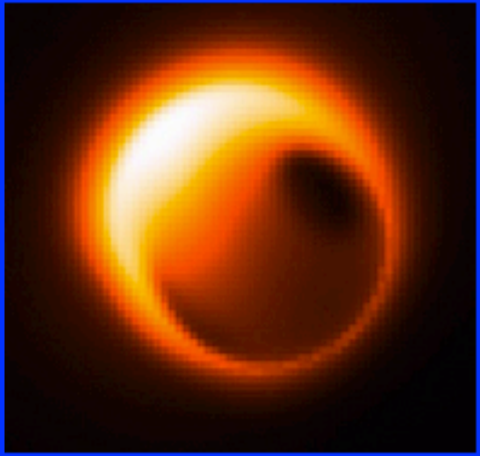


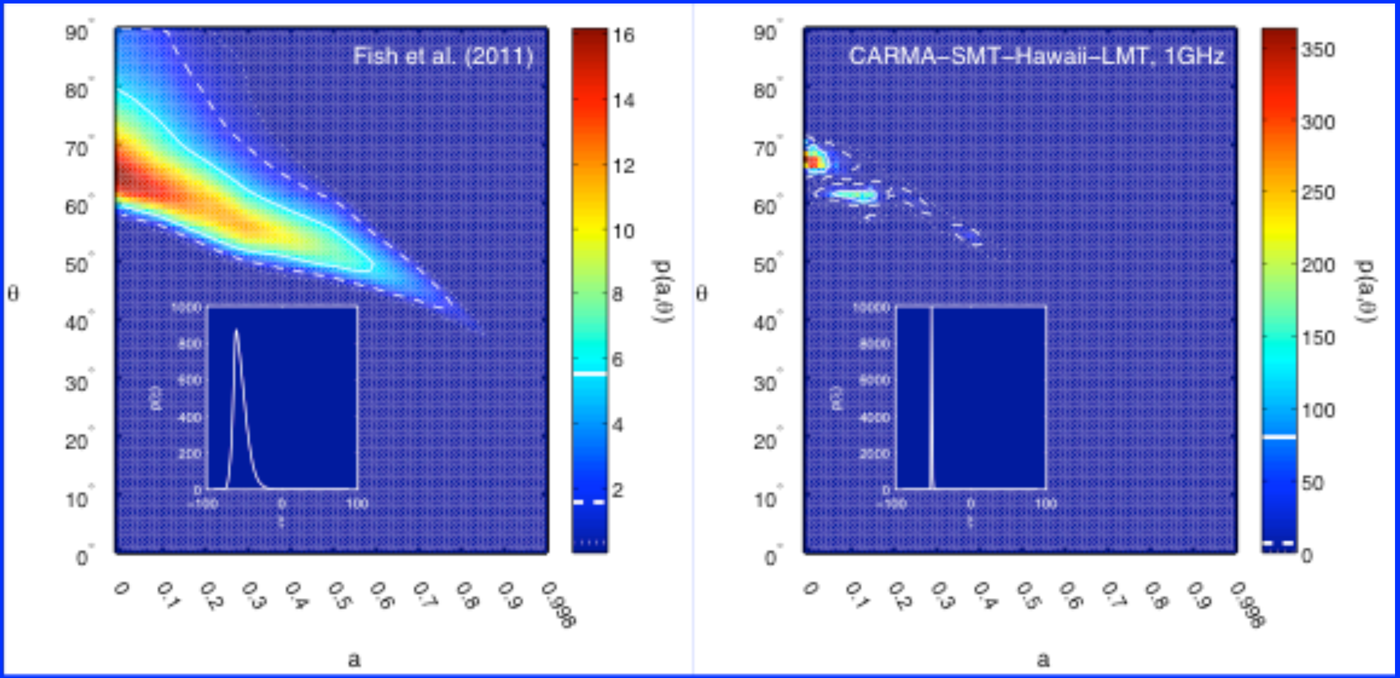
EHT Sites:

- CARMA, SMT, (CSO, JCMT, SMA)
- IRAM 30m, P. de Bure

- LMT : planning for 3mm and 1.3mm
- ALMA : phasing underway (funded).
- Greenland Telescope : planning for telescope.
- South Pole : planning for VLBI system (funded).
- Haystack Observatory : New Dish

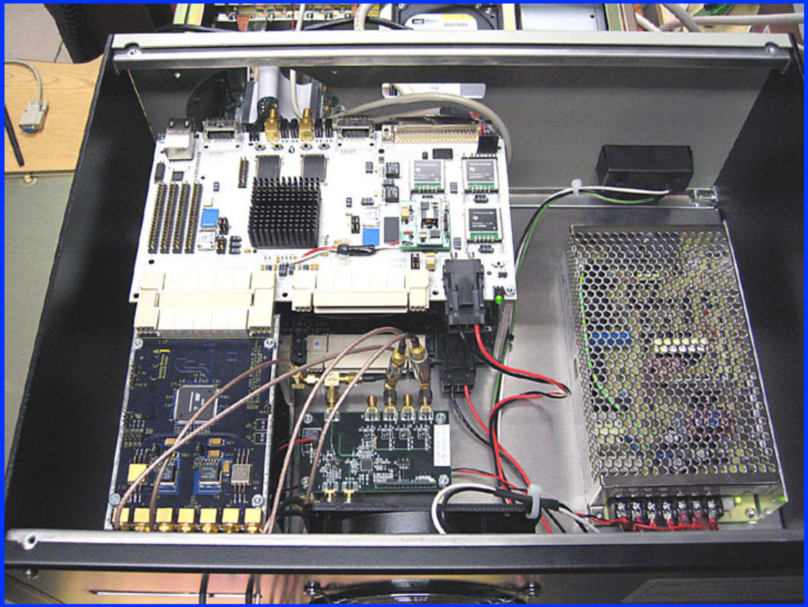
LMT: Improving RIAF models through closure phases.



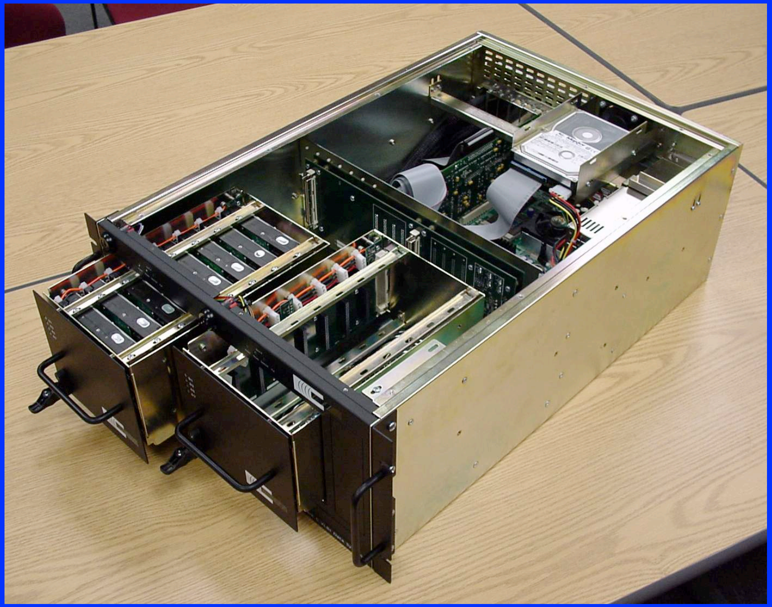


4Gb/s VLBI System
UC Berkeley/Haystack

CASPER iBOB Digital Backend (DBE)



Digital Recorder (Mark5)



- Total cost $75K per station.
- X8 improvement in BW: factor of x2.8 in sensitivity.
- Key to breaking through mm sensitivity barrier.

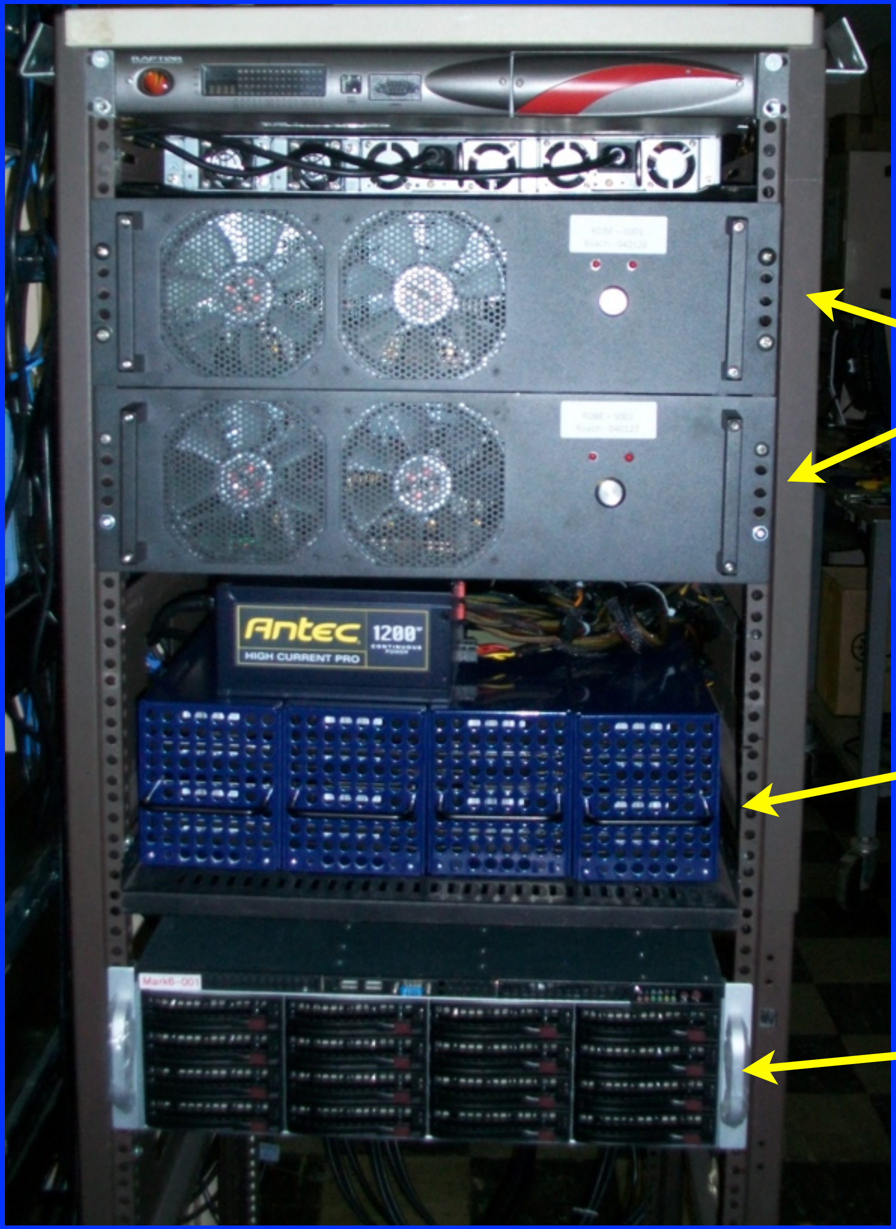
ROACH1 DBE

NRAO, Haystack, CASPER, S Africa (KAT)

DBBC (8 Gb/s)

INAF + MPIfR

Mk6 + RDBE-S System Tests



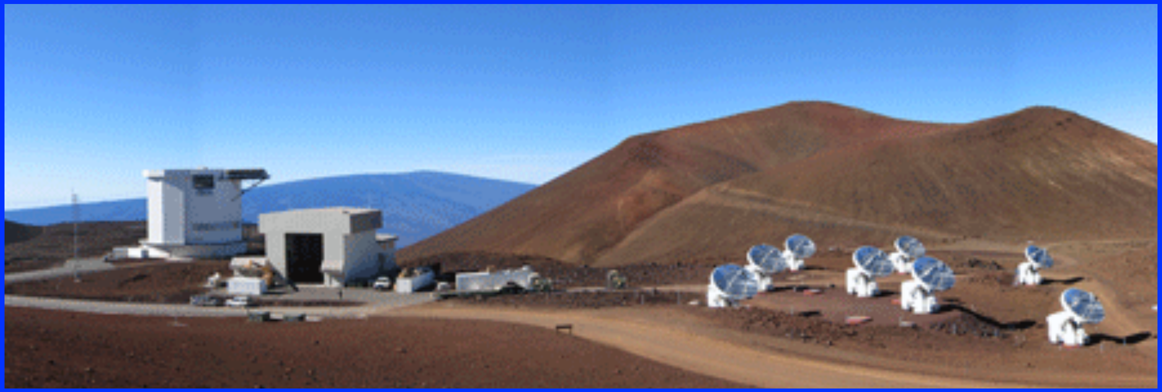
16 Gb/s

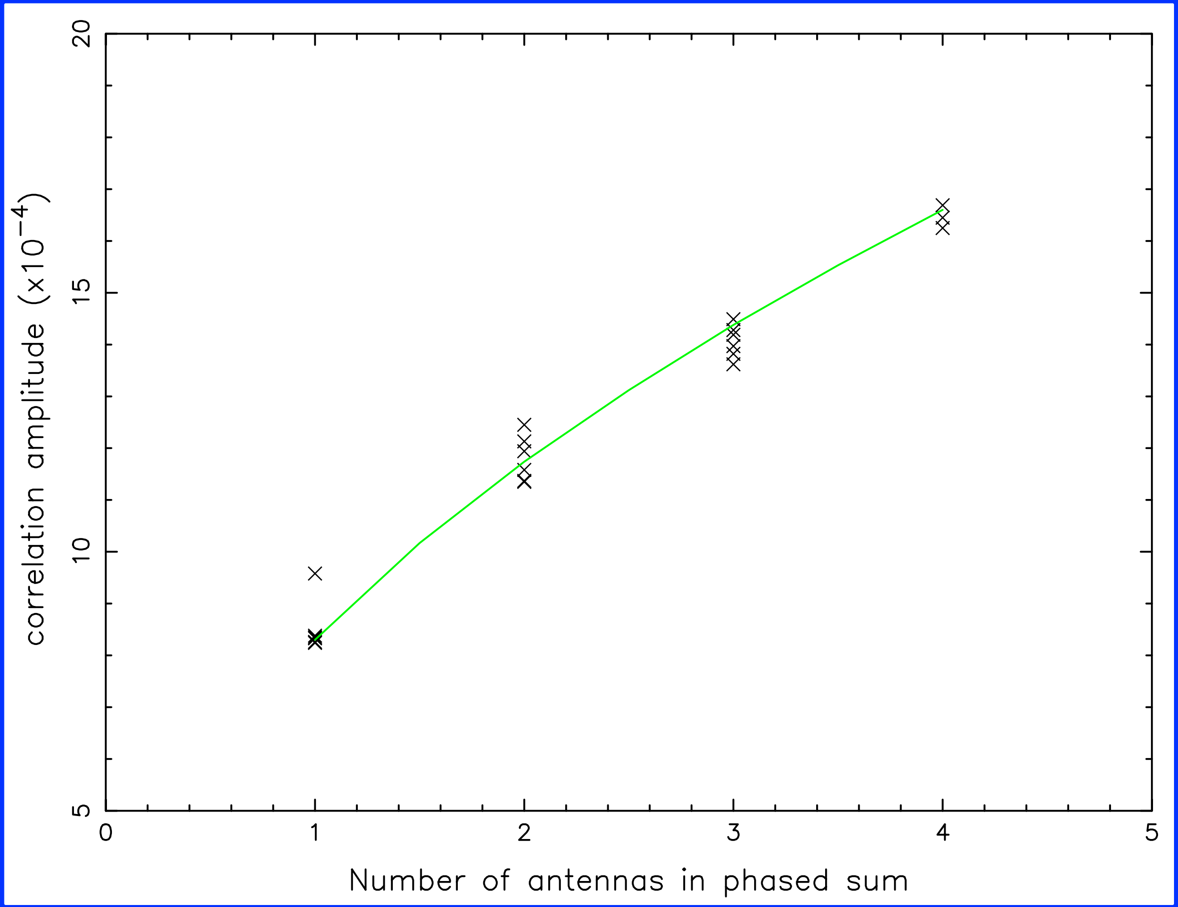
RDBE-S units

Mk6 Disk Storage:
4 x 8 1TB disks

Mk6 System

Phasing Arrays: SMA, CARMA, ALMA





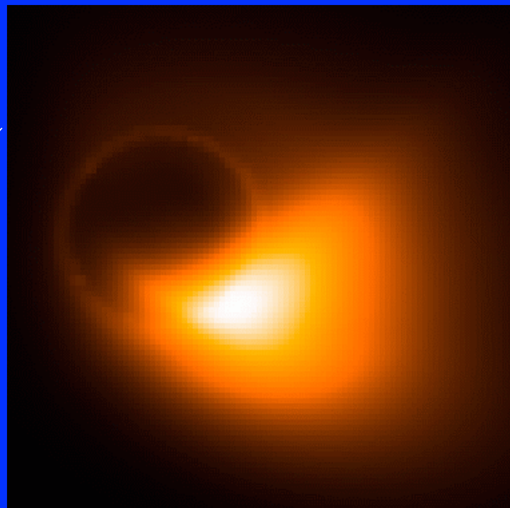
SMA: Weintroub, Primiani, Young, Blundell, et al

CARMA: Wright, Plambeck, Bower, McMahon, Dexter, et al

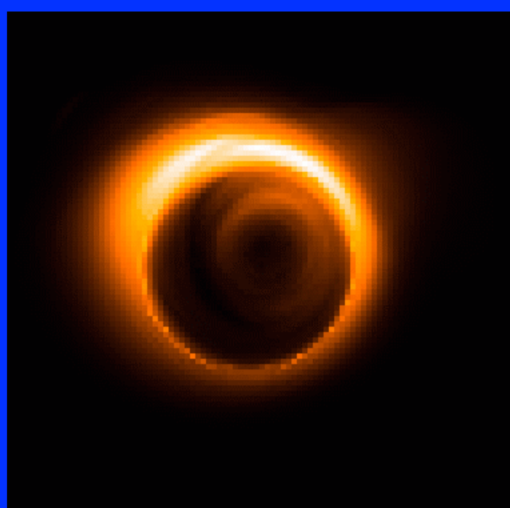
ALMA: Internationally Funded and Advanced Design and Fabrication underway.

Progression to an Image: M87
Baron & Monnier (U. Michigan)

Broderick et al

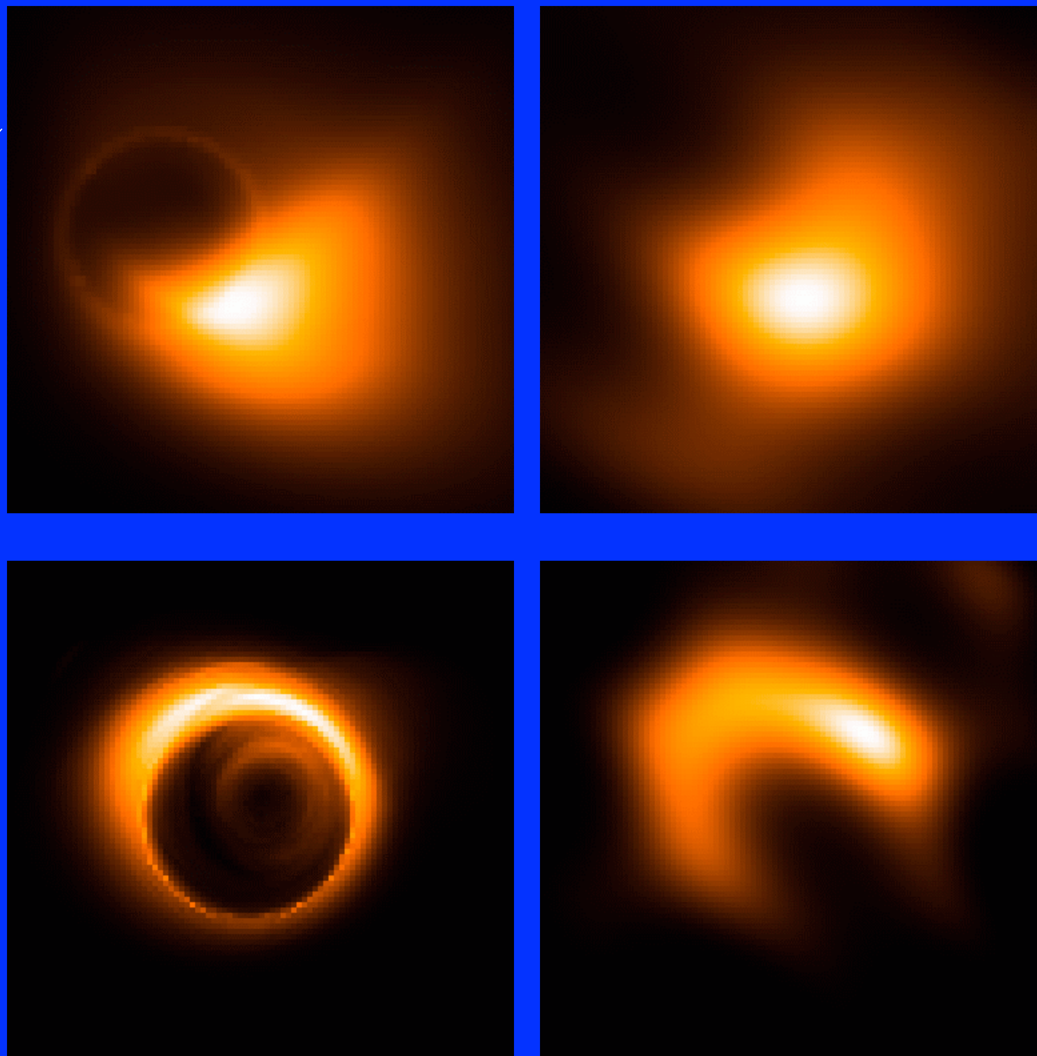


Dexter et al

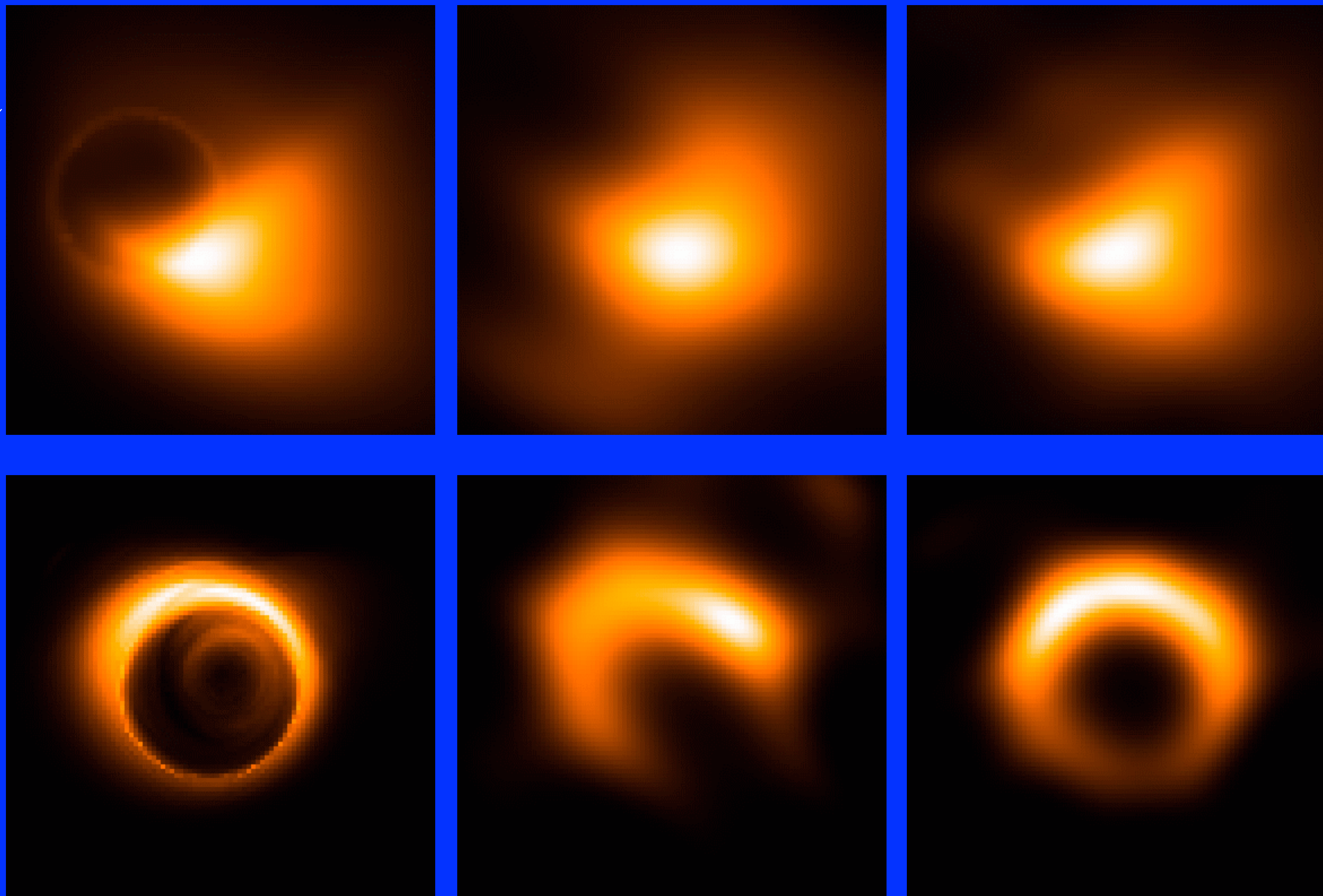


GR Model

Progression to an Image: M87
Baron & Monnier (U. Michigan)



Progression to an Image: M87
Baron & Monnier (U. Michigan)



EHT Conference: 18-20 Jan

- ~70 theorists, observers, instrumentalists.
- Goal: to create a coherent EHT science case.
    - Review state-of-the-art in BH theory/simulation.
    - Explore ties between EHT and other wavebands.
    - Next steps in computational and theoretical development.
    - Link science direction and technical plans.
    - <u>Conclusions: "Image Critical", "Focus now on Time Domain"</u>
- Goal: to set out an EHT Technical Roadmap.
    - Review current status of EHT sites.
    - Describe ongoing technical developments.
    - Explore additional technical possibilities.
    - Prioritize by scientific impact.
    - <u>Conclusions: "Critical List Identified", "Technical Roadmap"</u>

The Event Horizon Telescope: Bringing Black Holes into Focus

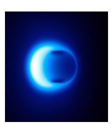
EPO: EHT website

www.eventhorizontelescope.org

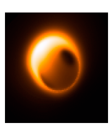
| Science | Technology | Array | Collaborators | News | Publications | Meetings

Science

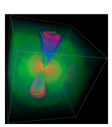
Key science objectives



Testing general relativity - Einstein's theory of general relativity predicts that there will be a roughly circular "shadow" around a black hole. The EHT aims to image the shadow to test this prediction and determine the mass of black holes



Understanding accretion around a black hole - Black holes exert a strong gravitational pull on nearby matter. Some of this matter ultimately falls into the black hole in a process called accretion. One of the objectives of the EHT is to improve our understanding of the physics of accretion.



Understanding jet genesis and collimation - Most galaxies show large scale jets of very fast moving plasma that are launched from the central black hole. One possibility is that these jets are launched very close to the rapidly-rotating central black hole. Most of these jets remain tightly confined to a narrow opening angle even far from the black hole. The EHT will improve our understanding of the process of generation and collimation of these jets.

Event Horizon Telescope Collaboration

MIT Haystack: Shep Doeleman, Alan Rogers, Vincent Fish, et al
NAOJ: Mareki Honma, Tomoaki Oyama, Kazunori Akiyama
U. Arizona Steward Obs: Lucy Ziurys, Robert Freund, Dan Marrone
Harvard CfA: Jonathan Weintroub, Jim Moran, Ray Blundell, et al
CARMA: Dick Plambeck, Mel Wright, David Woody, Geoff Bower
NRAO: John Webber, Ray Escoffier, Rich Lacasse
Caltech Submillimeter Observatory: Richard Chamberlin
UC Berkeley SSL: Dan Werthimer
MPIfR: Thomas Krichbaum, Anton Zensus, Alan Roy, et al
IRAM: Michael Bremer, Karl Schuster
APEX: Karl Menten, Michael Lindqvist
James Clerk Maxwell Telescope: Remo Tilanus, Per Friberg
ASIAA: Paul Ho, Makoto Inoue, Keiichi Asada
U. Concepcion: Neil Nagar

EHT Organization

- Goal: Establish plan for EHT organization.
    - The scope of EHT activities is growing.
    - Interest from many groups.
    - Data quality will soon sharply increase; so will data quantity.
    - EHT has ‘finite window’ for critical observations.
    - Logistics for observations ad-hoc.
    - Increasing need for structured EPO for the EHT.
- Need for Structure (MOU)
    - Organizational Meeting with most facilities represented.
    - General consensus: Science Document, Technical Roadmap, MOU (resources, allocation, publications).
    - EHT Organization Committee to be formed to draft documents - Spring 2012.

Summary

- Resolving SMBHs on Rsch scales has been done and resolution in time possible.
- Imaging with the EHT possible by 2015.
- High precision VLBI measurements are linking strong GR on small scales to BH impact on galactic scales.
- Very exciting time for the project.