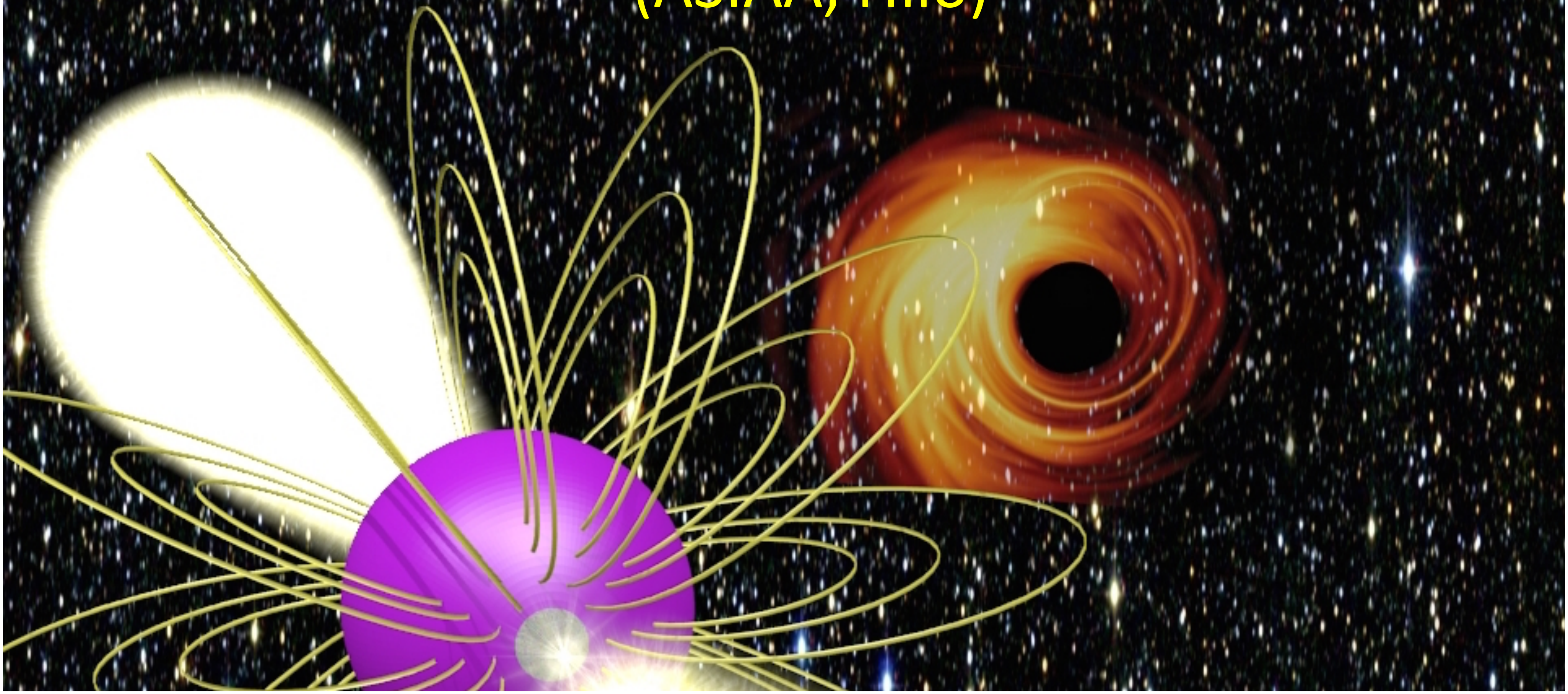
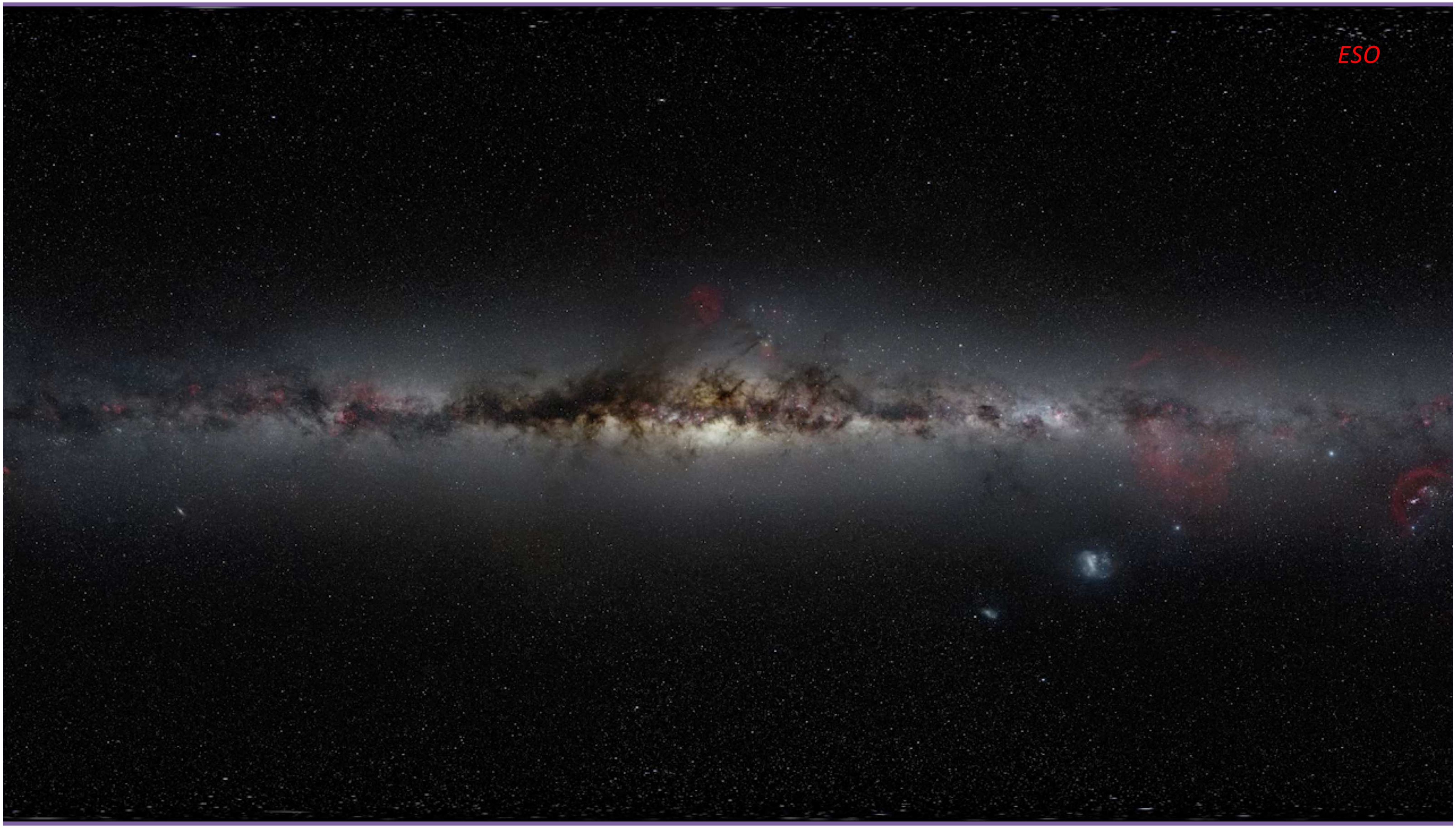
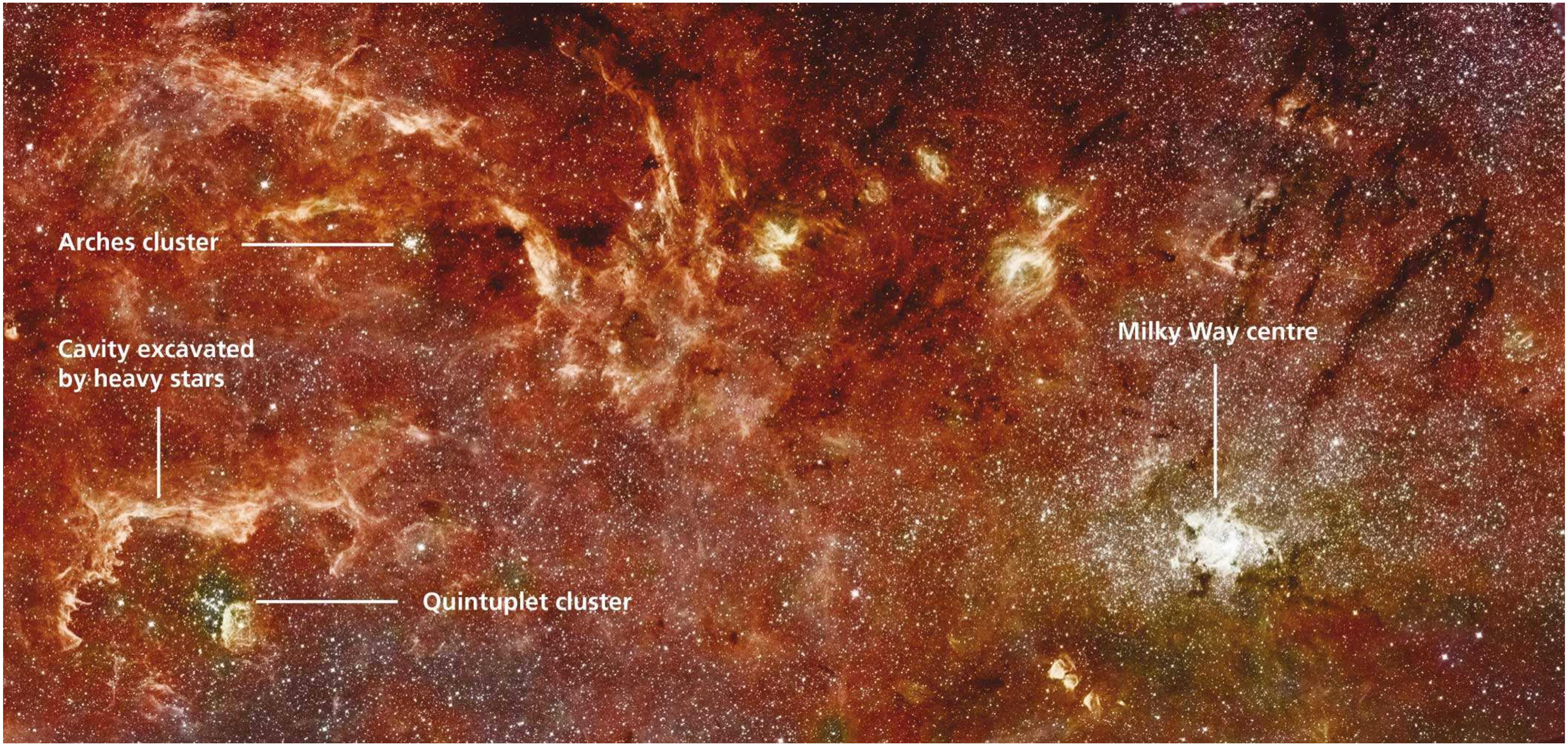
Galactic Center VLBI: Sagittarius A* and the Galactic Center Pulsar

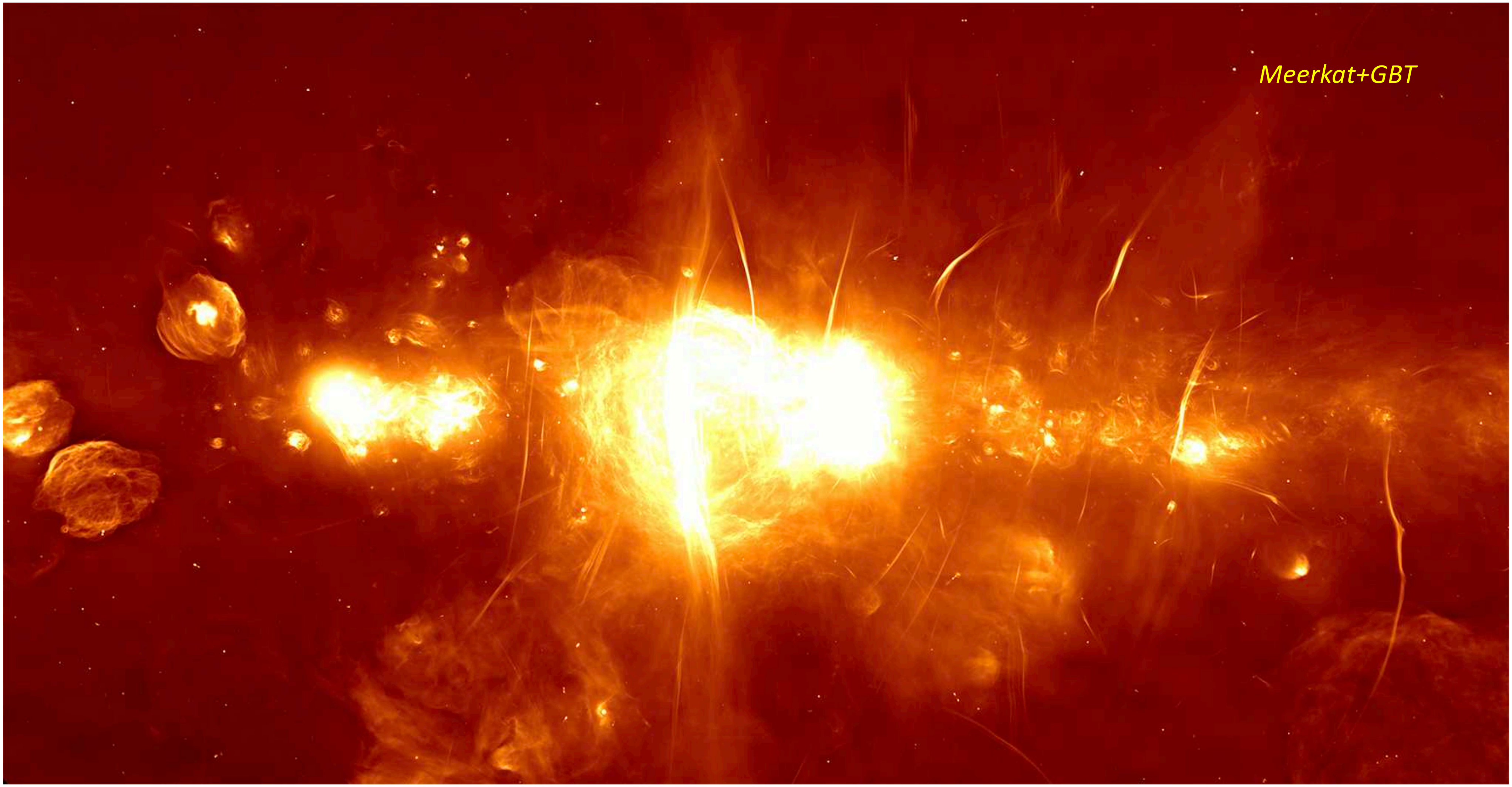
Geoffrey C. Bower
(ASIAA, Hilo)

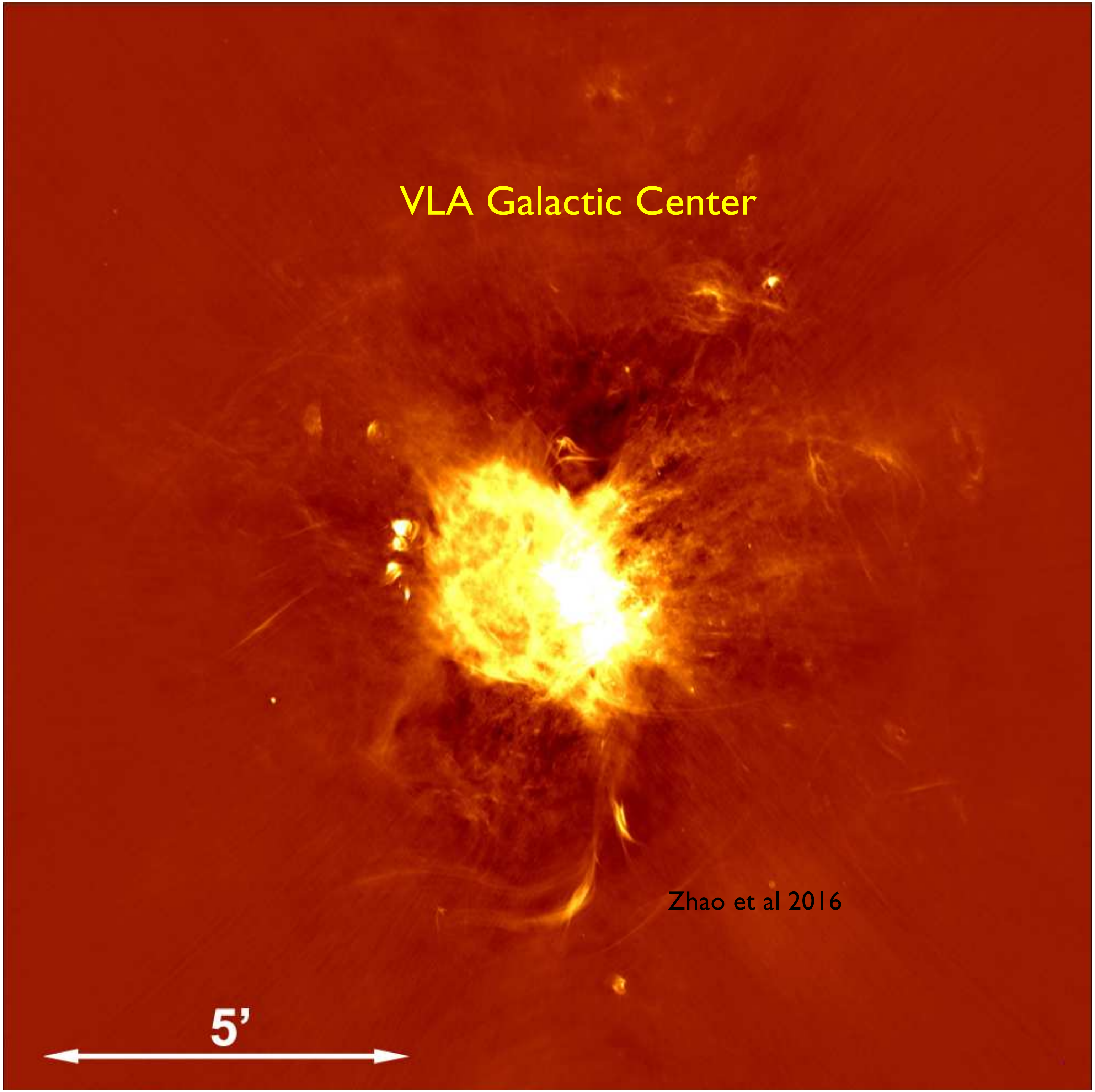


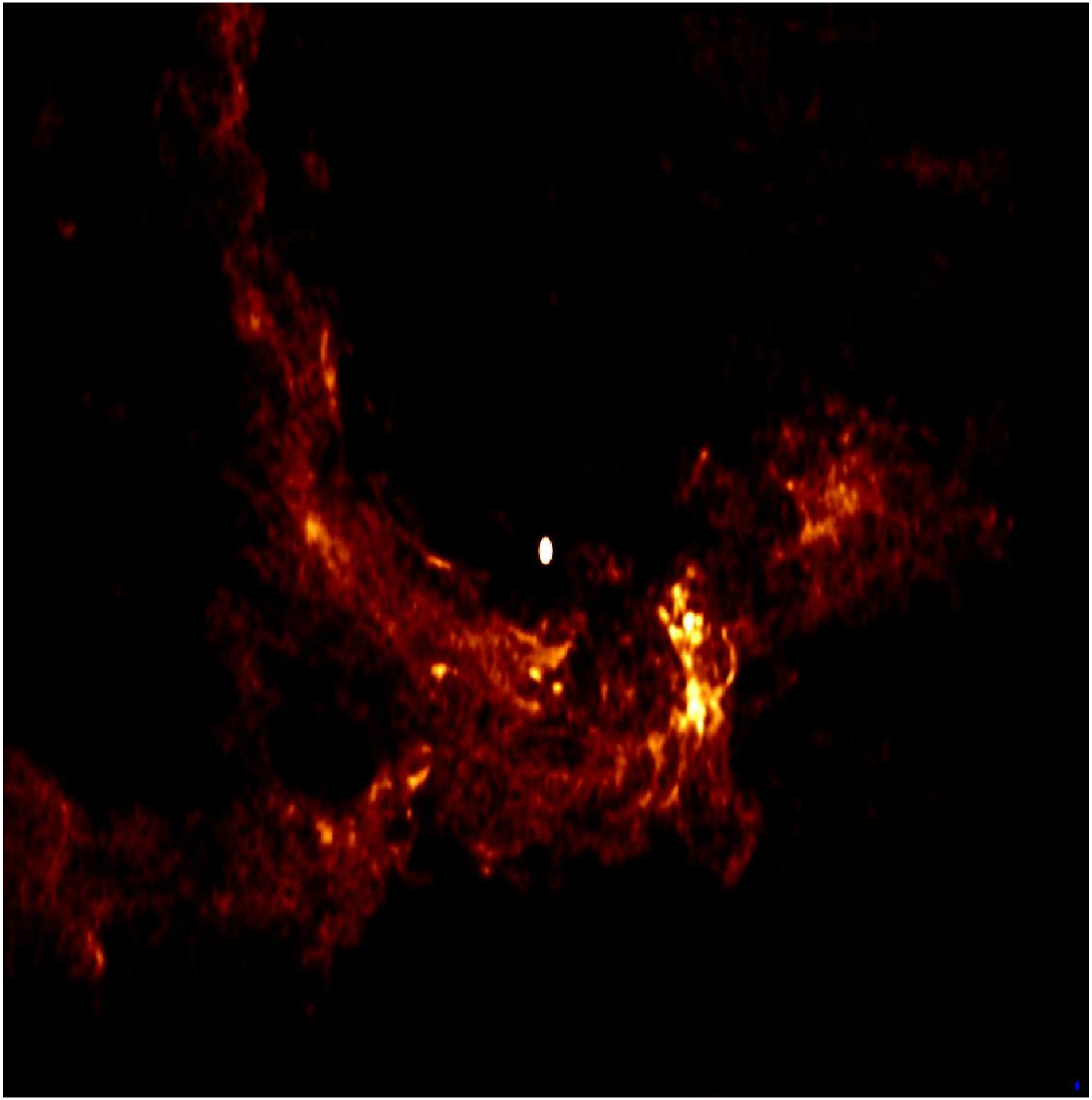

ESO



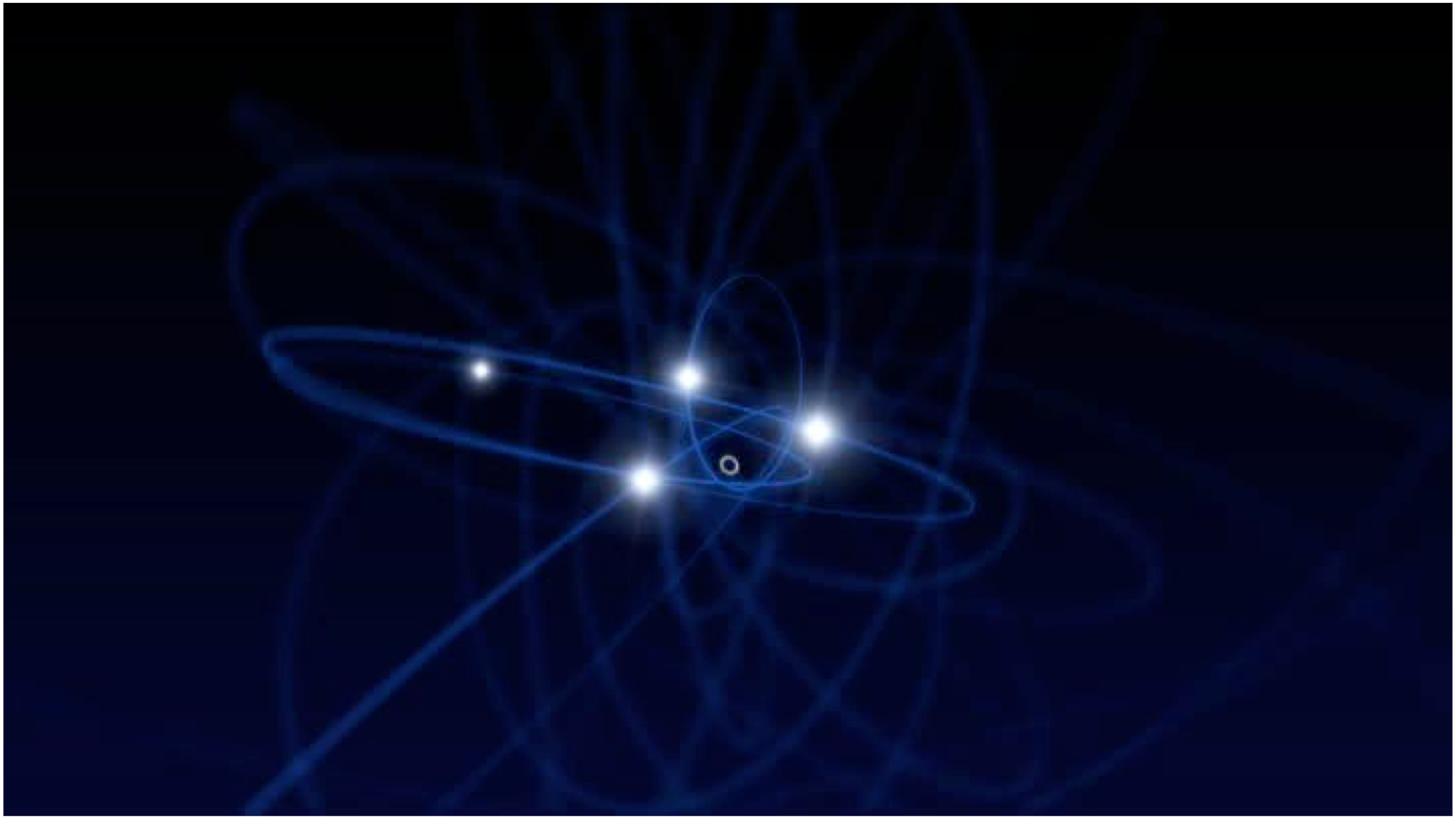
HST & Spitzer: Wang, Stolovy et al 2015


Meerkat+GBT


VLA Galactic Center
Zhao et al 2016
5'

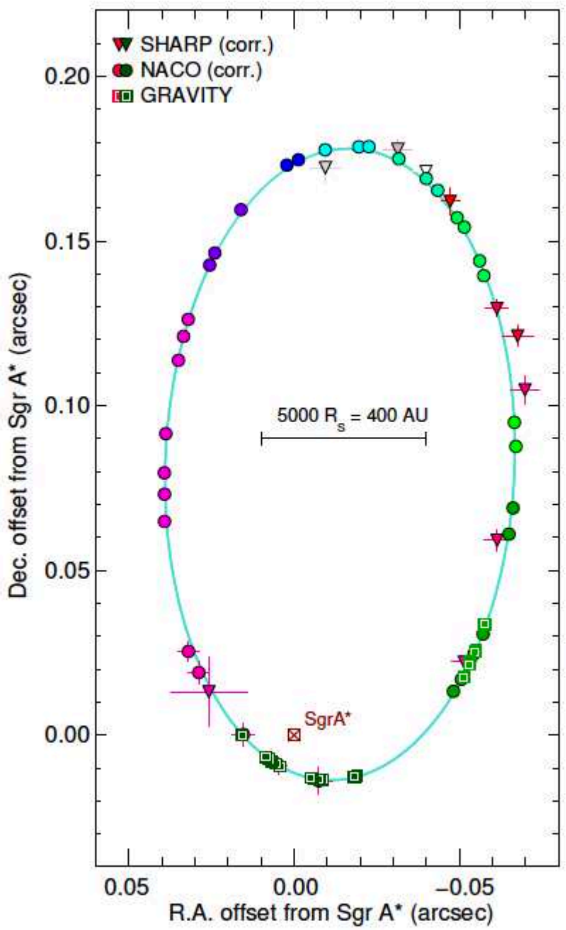


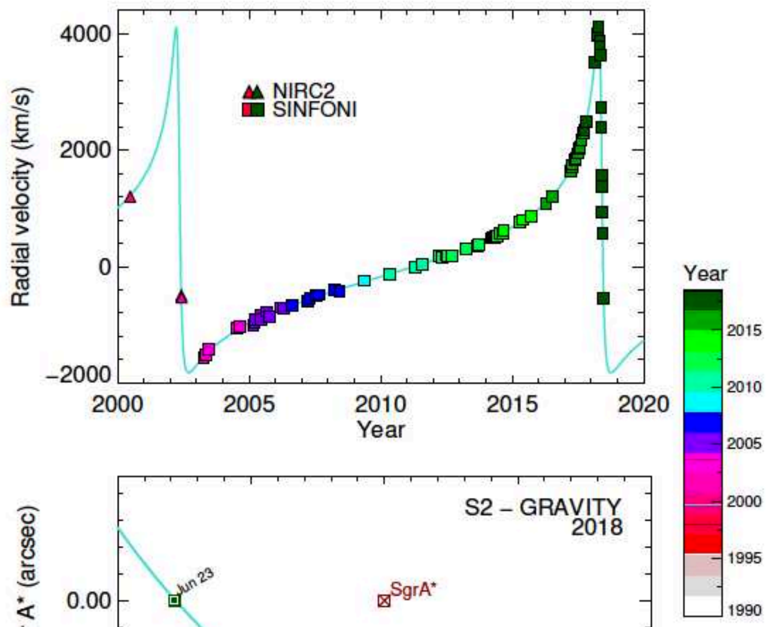
Stellar Orbits Around Sgr A*

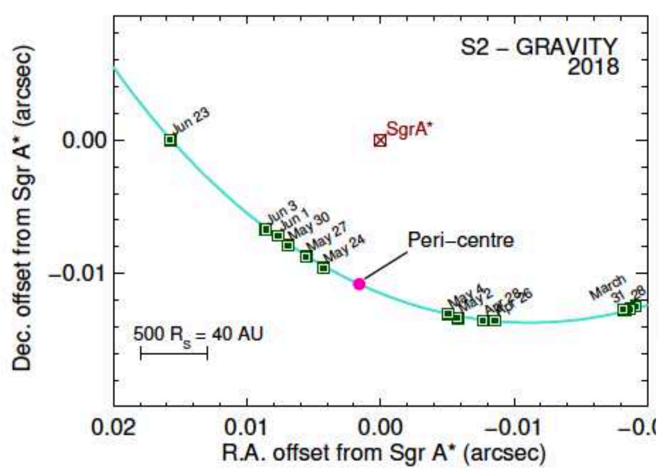


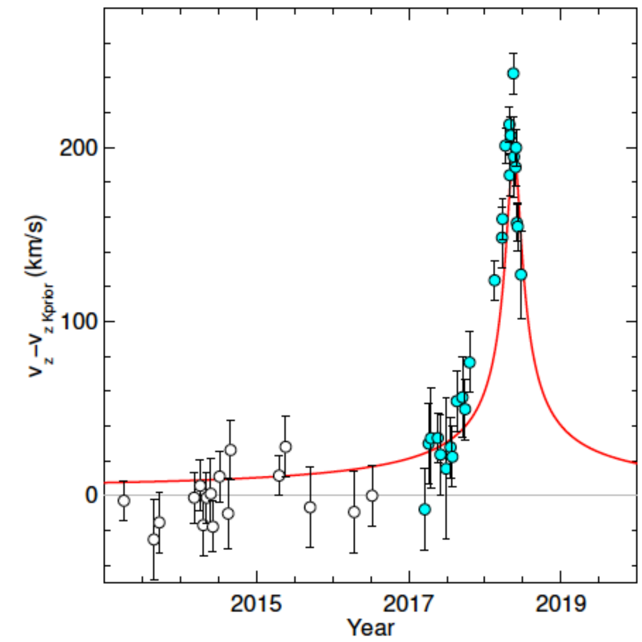
Genzel, Gillessen et al

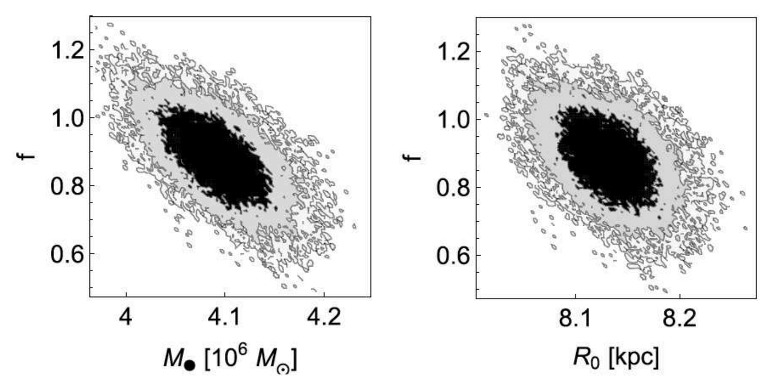
Strong Evidence for a Black Hole





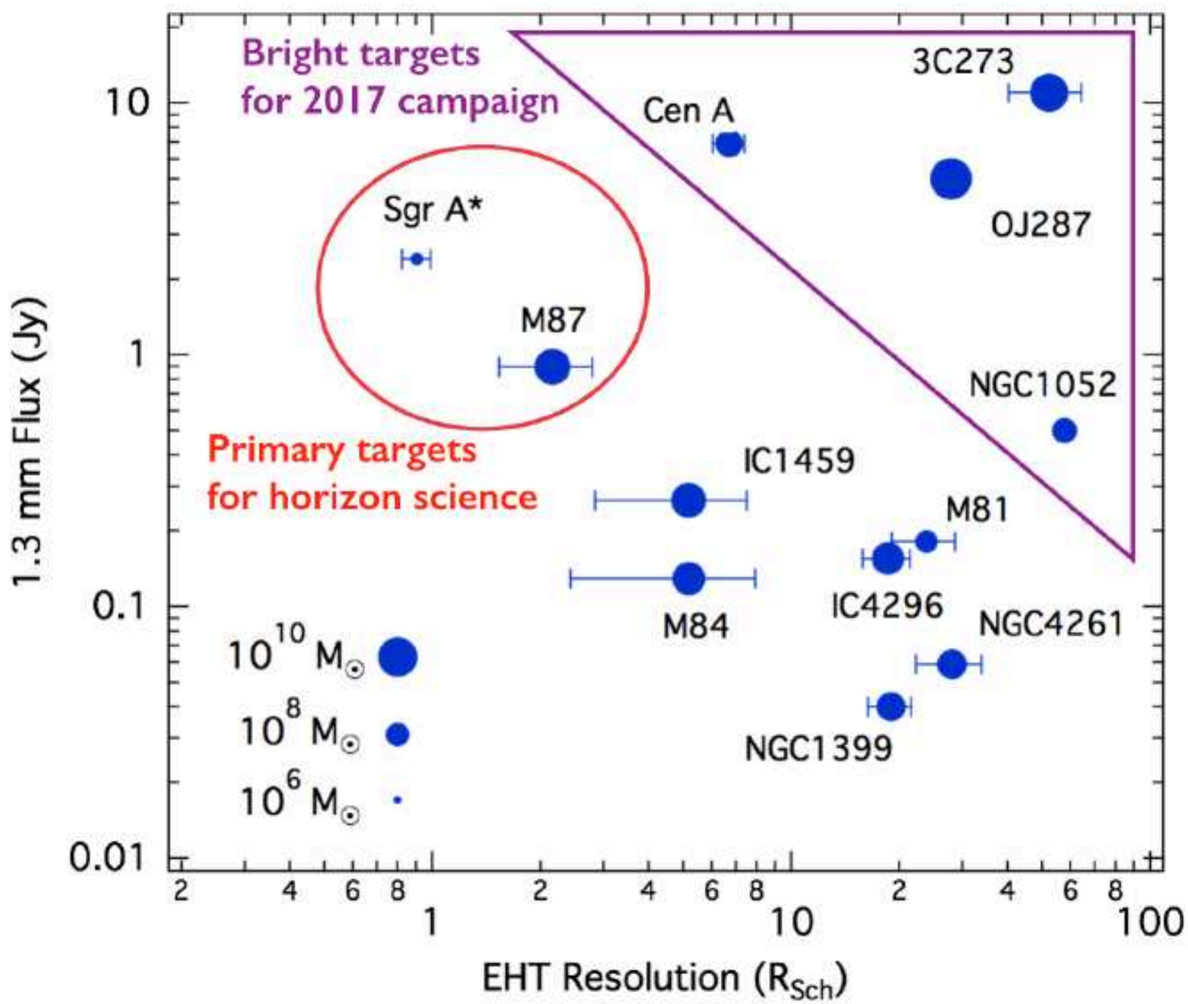


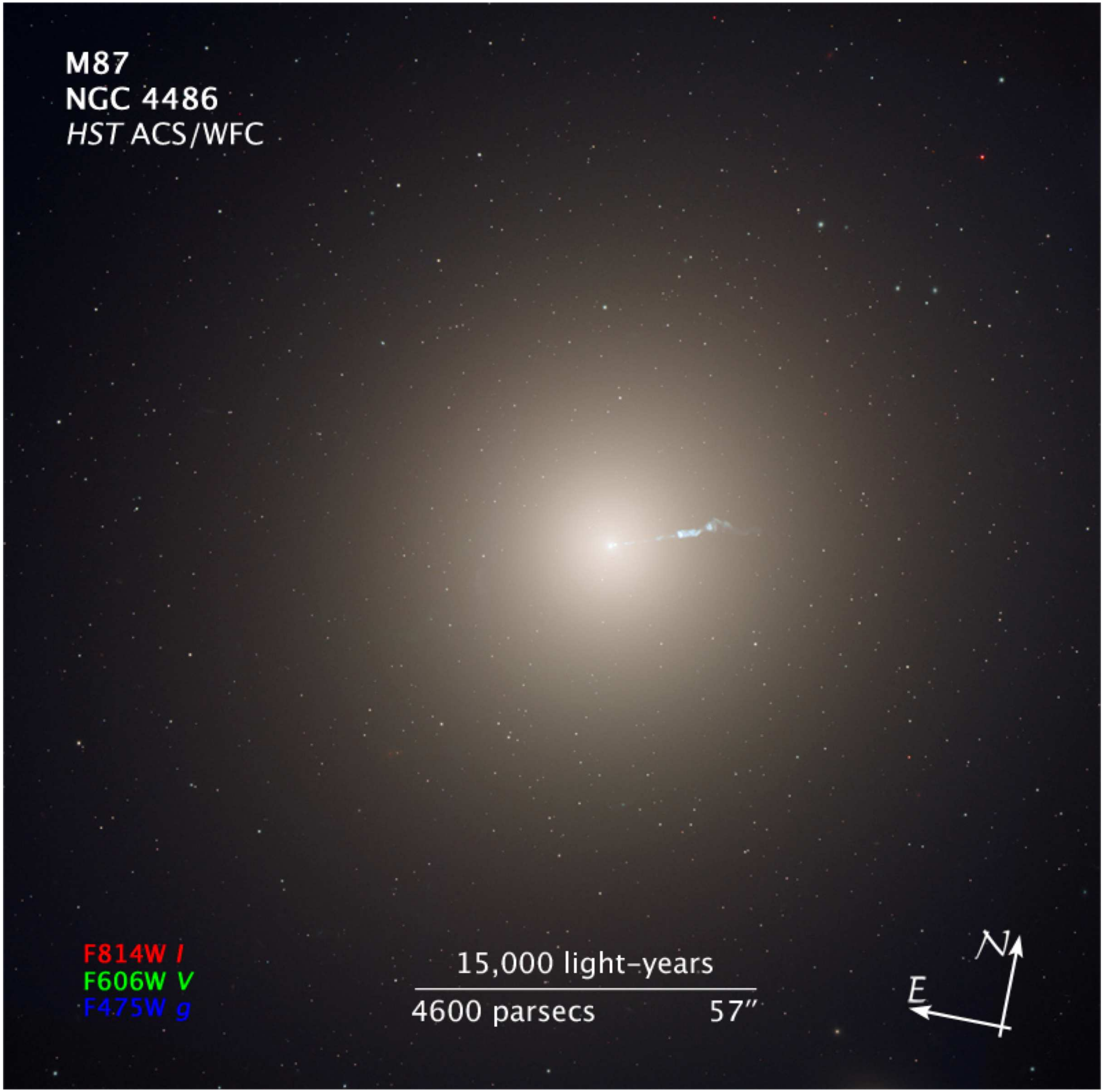


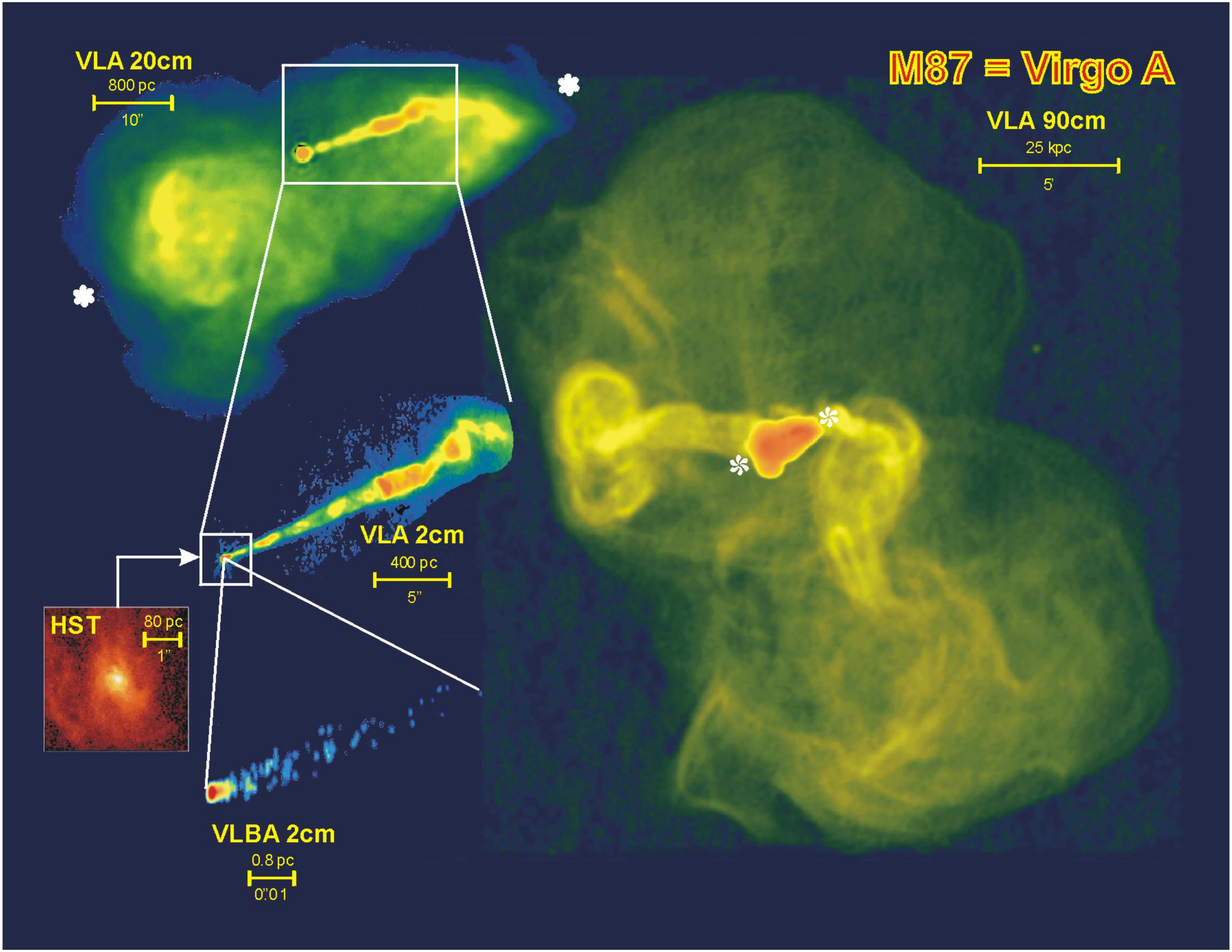


GRAVITY Collaboration 2018

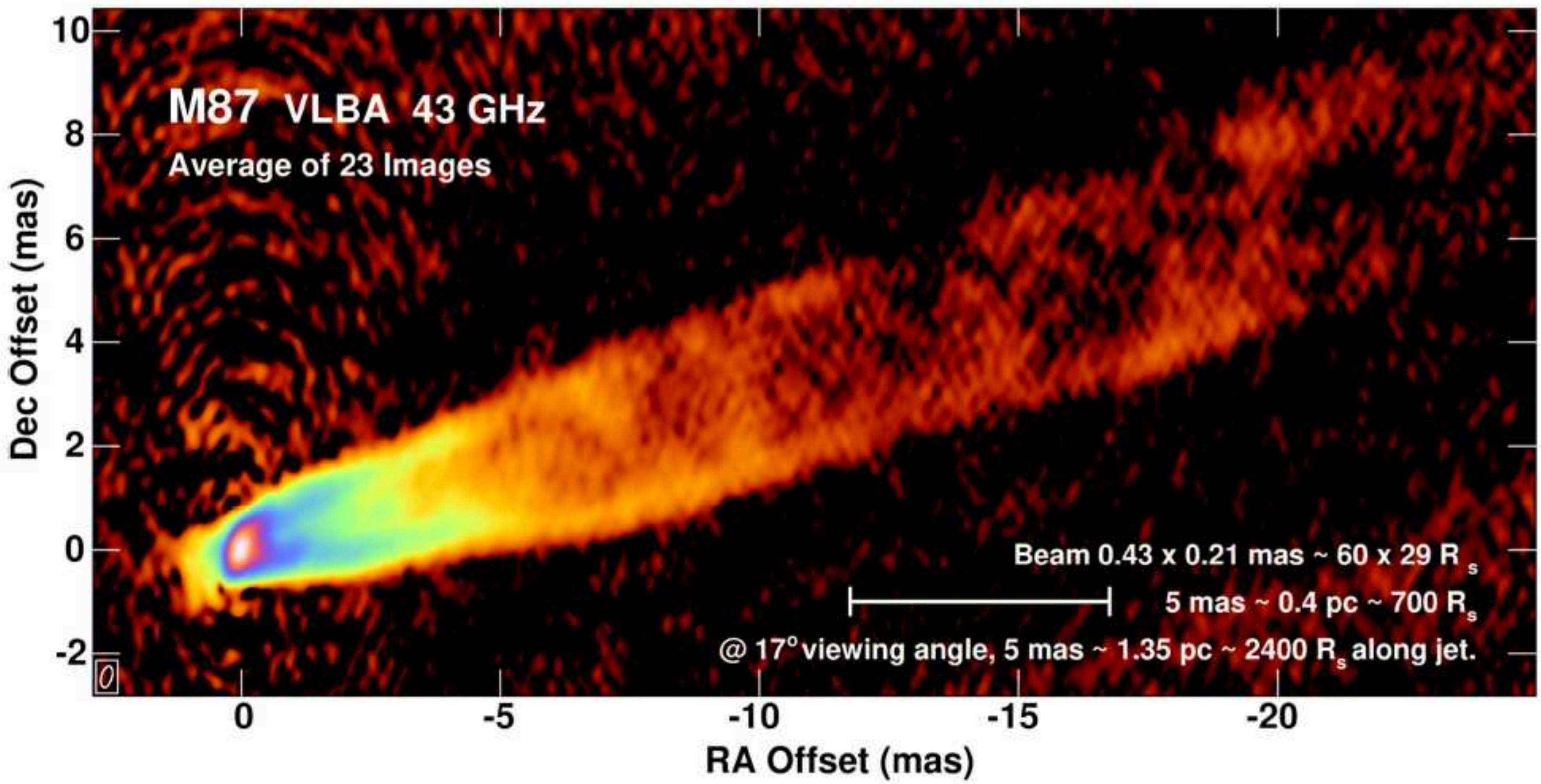
The Largest Black Holes on the Sky




M87
NGC 4486
HST ACS/WFC
F814W I
F606W V
F475W g
15,000 light-years
4600 parsecs
57″
N
E



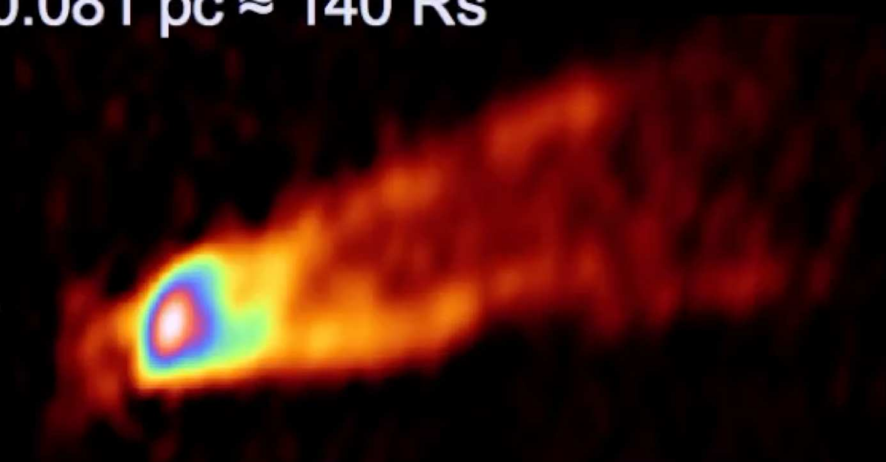
M87 = Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0."01



Walker et al 2018

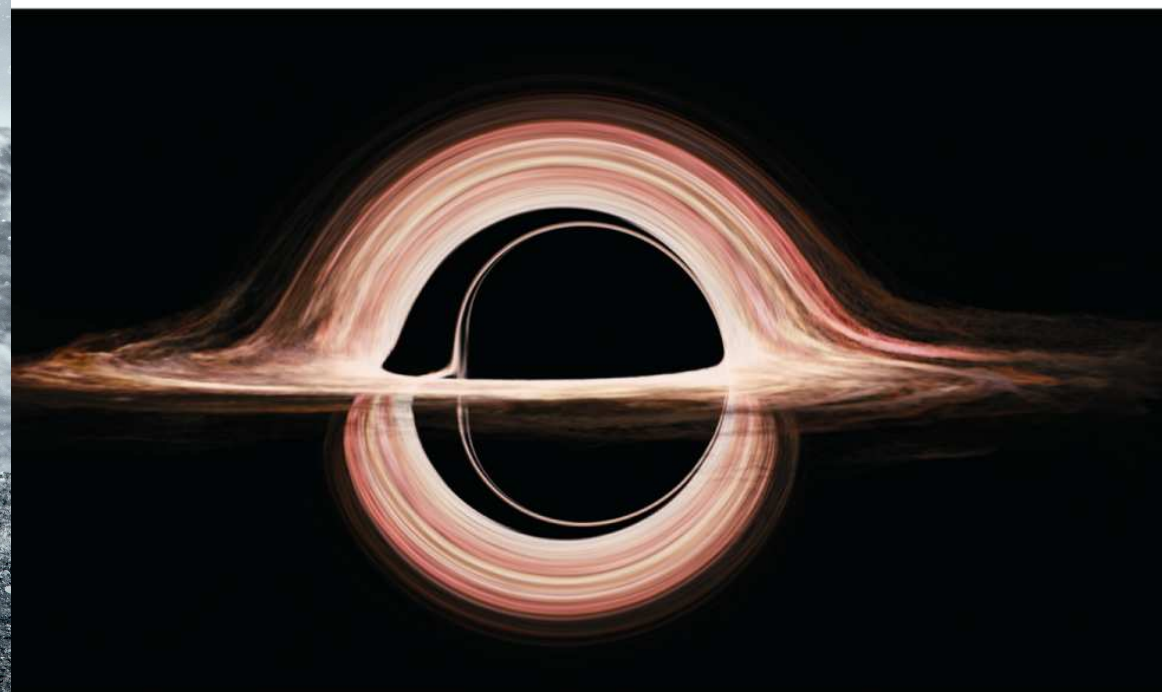
M87 INNER JET

2007: Interval three weeks
VLBA at 43 GHz
Resolution 0.21 X 0.43 mas
Scale: 1 mas = 0.081 pc ≈ 140 Rs

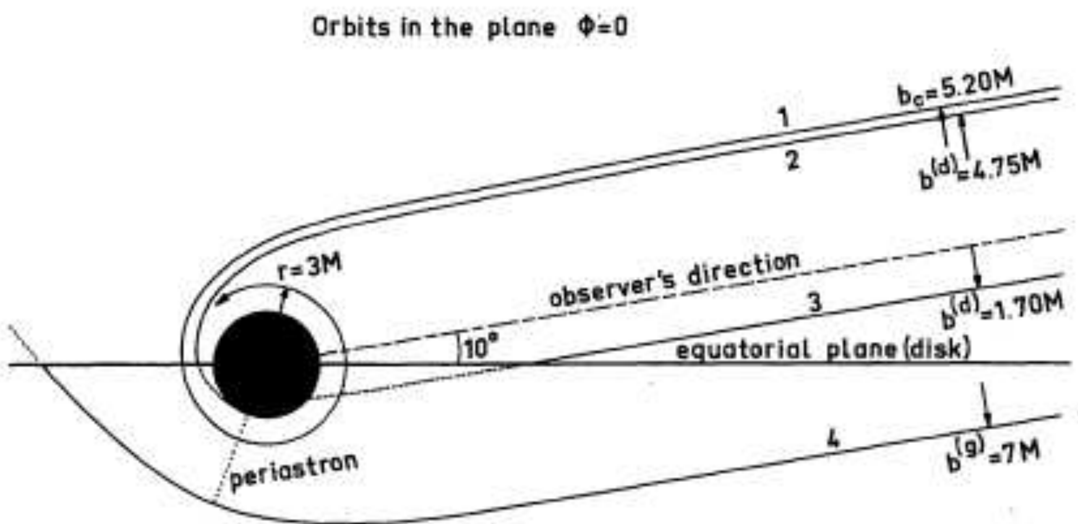


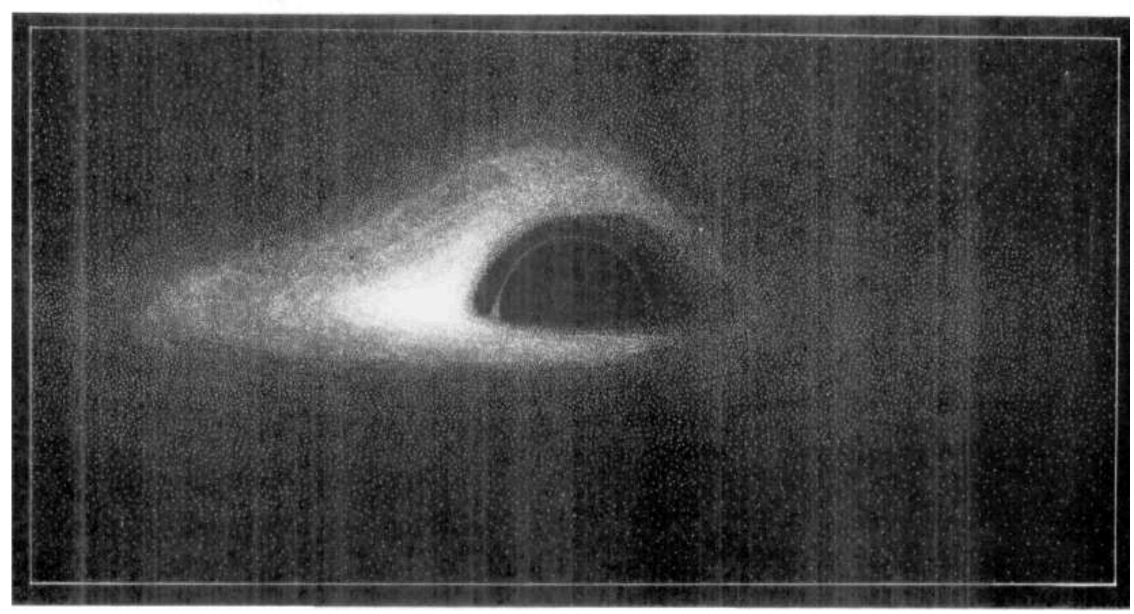
Walker, Hardee, Davies,
Ly, & Junor Ap. J. 2018


MATTHEW McCONAUGHEY
ANNE HATHAWAY
JESSICA CHASTAIN
AND MICHAEL CAINE
THE END OF EARTH WILL NOT BE THE END OF US.
A FILM BY CHRISTOPHER NOLAN
INTERSTELLAR
IN 70MM IMAX, 70MM FILM AND 35MM FILM
ON NOVEMBER 5
EVERYWHERE
NOVEMBER 7



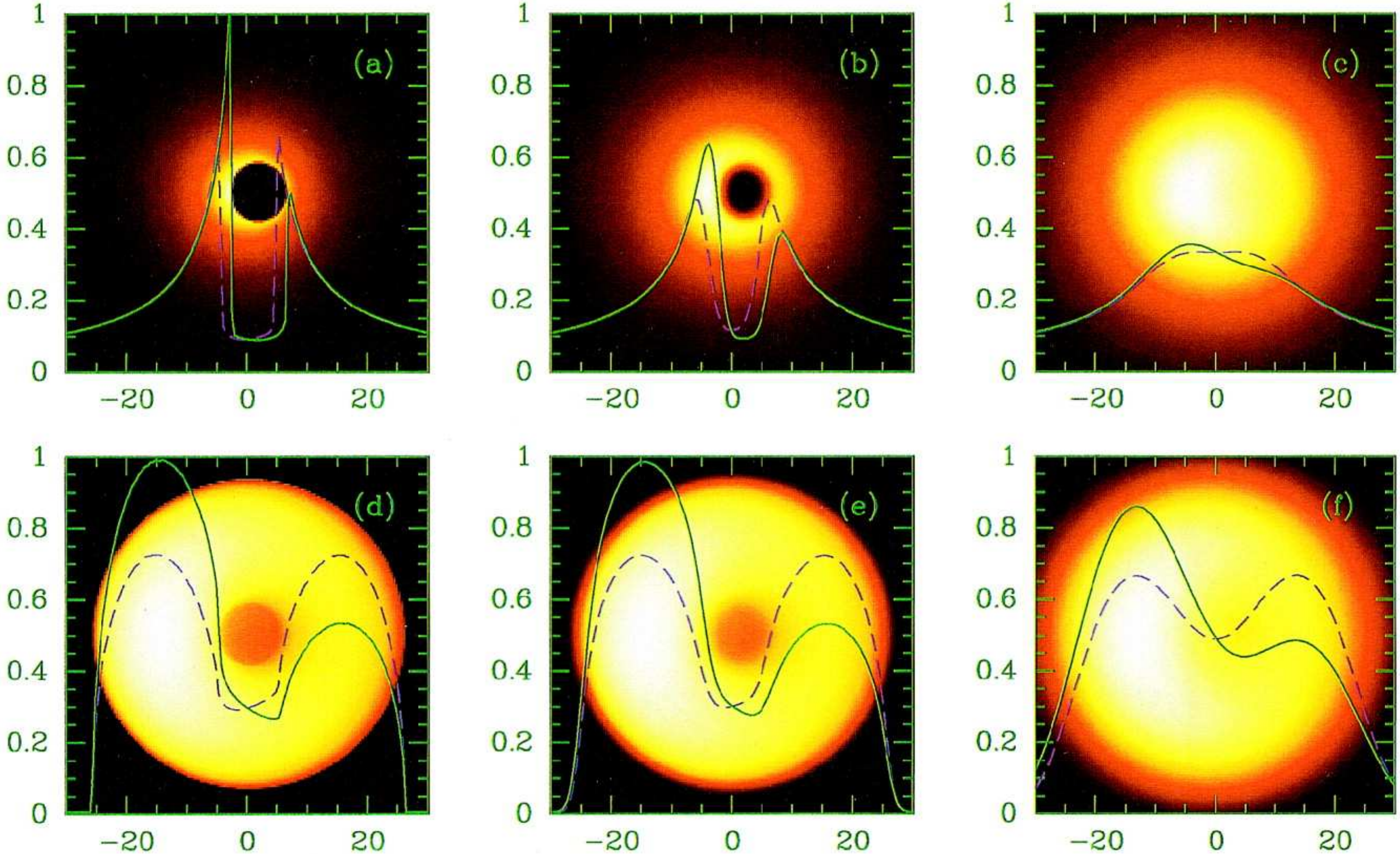
Light Bent by the Black Hole



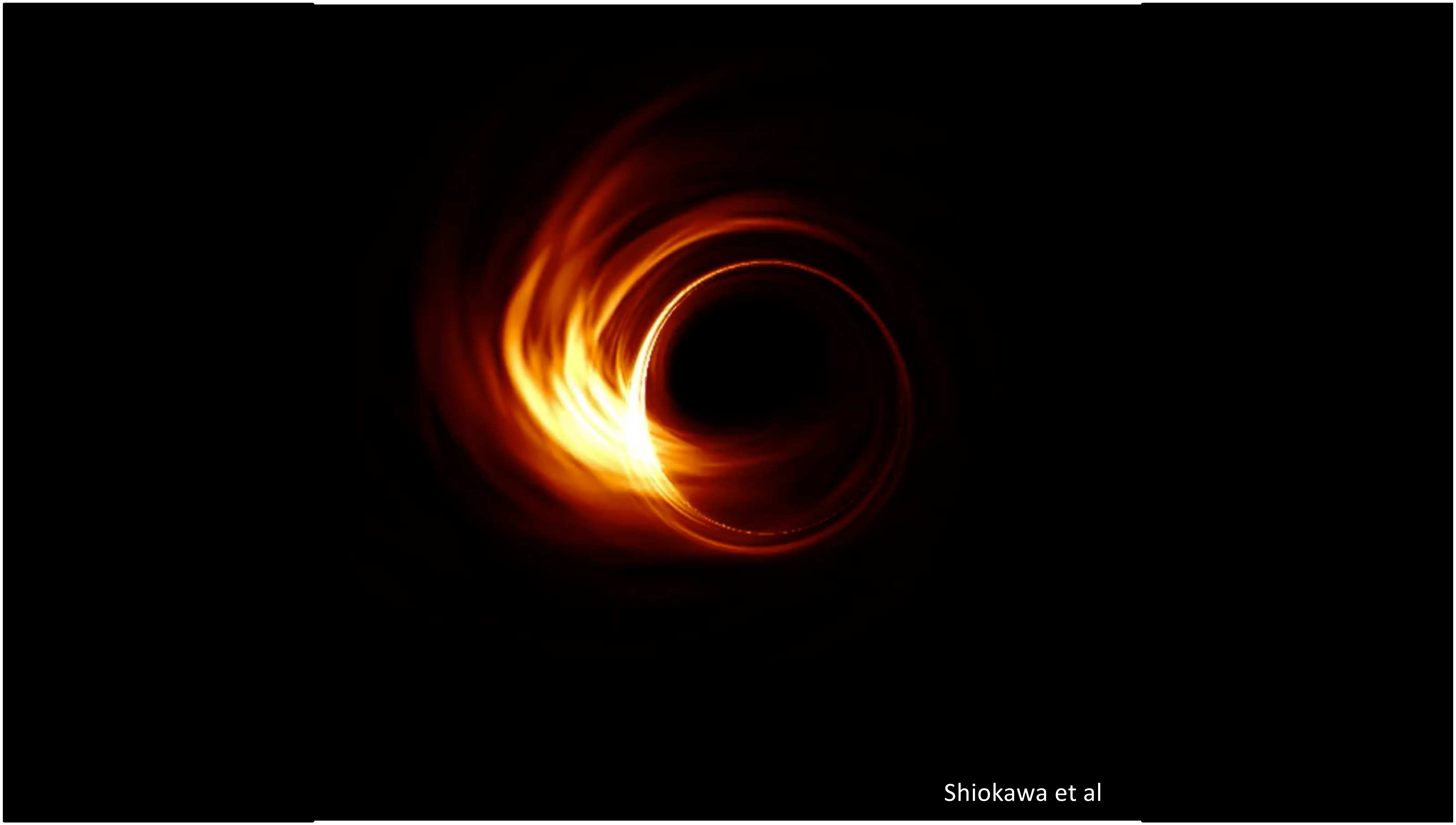


Bardeen 1973
Luminet 1979

The Black Hole Shadow

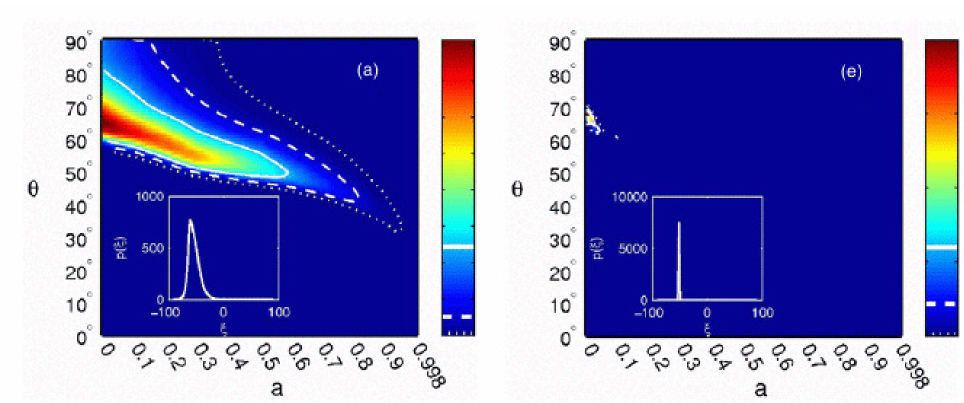


Falcke, Melia, Agol 2000

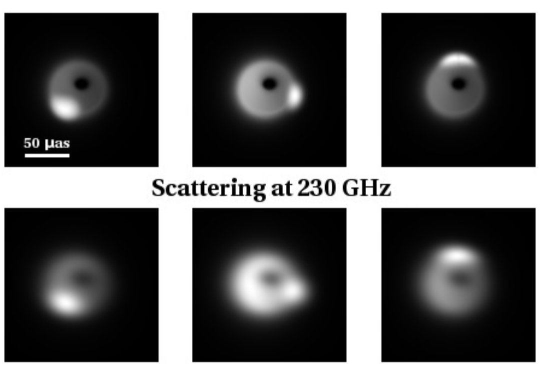

Shiokawa et al

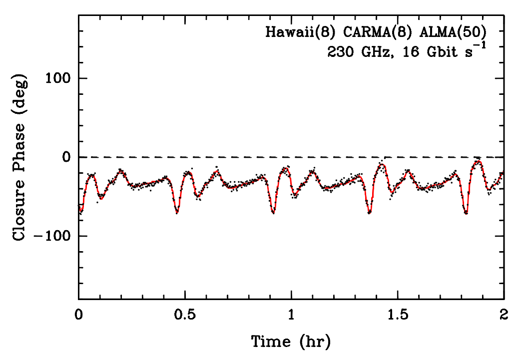
Fundamental Physics with Sgr A*

Constraints on Black Hole Spin from images
Broderick et al 2011

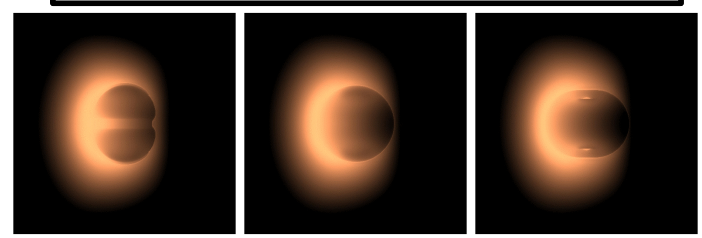


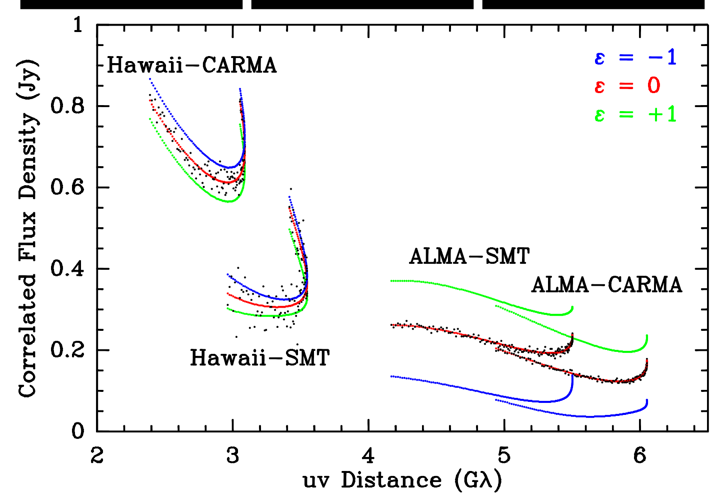
Constraints on Geometry/Mass from Orbiting Hot Spots
Doeleman et al 2009

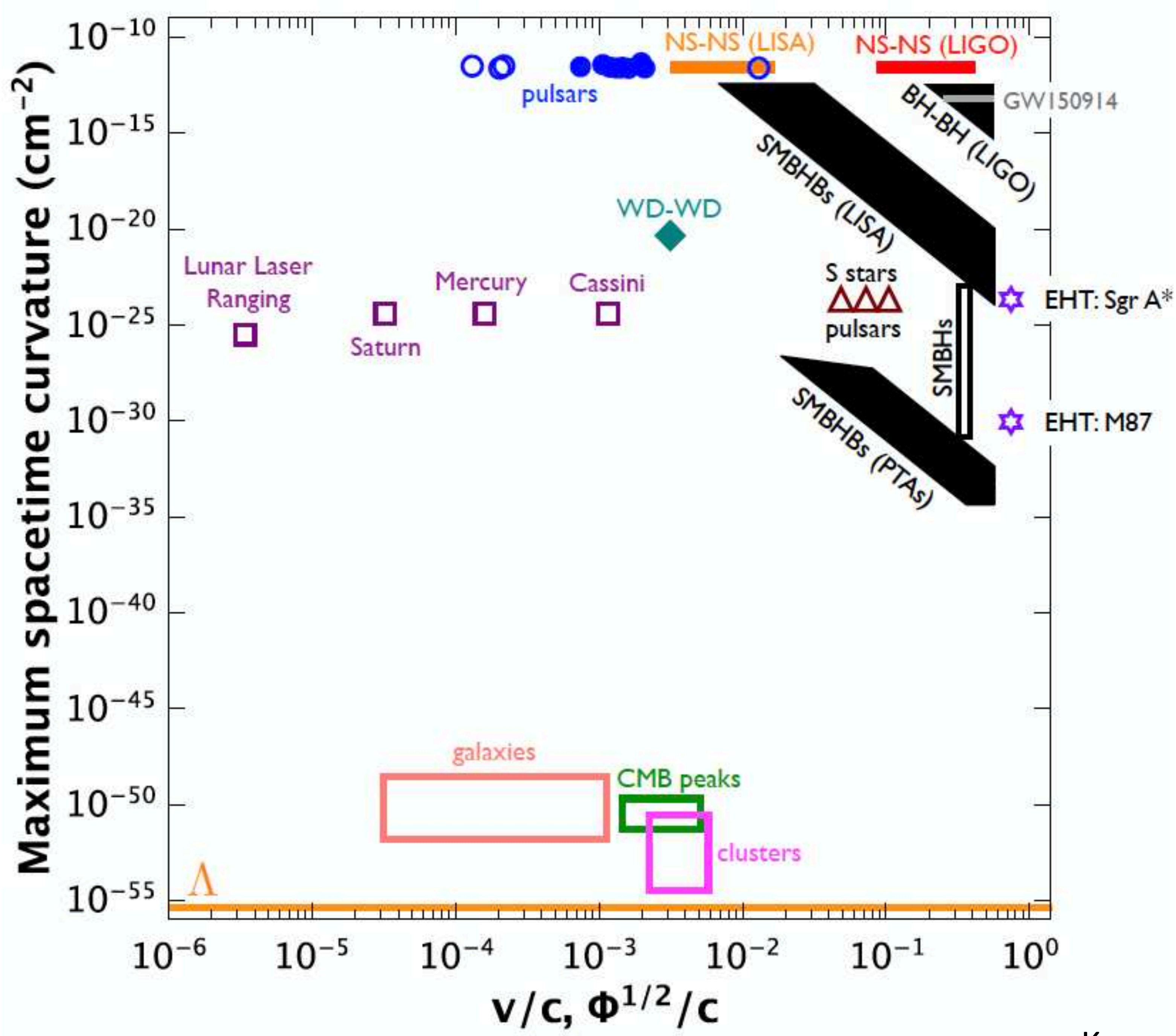




Violations of the No-Hair Theorem
Introduction of Quadrupole Moment
Psaltis and Broderick





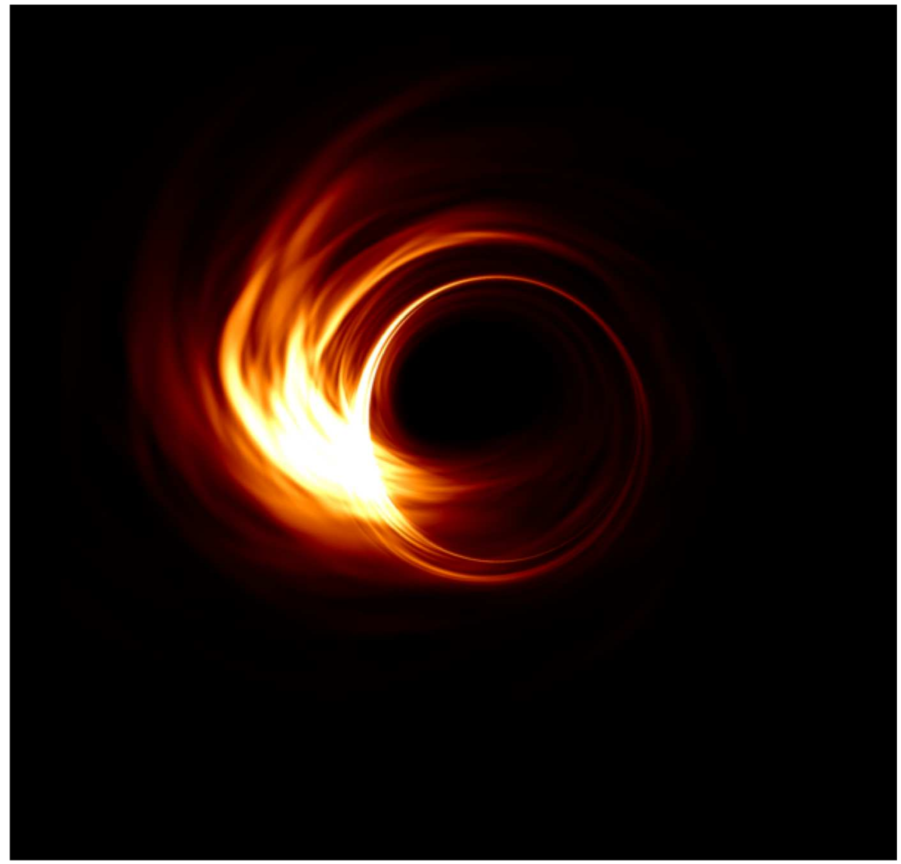


Maximum spacetime curvature (cm^{-2})
v/c, $\Phi^{1/2}$/c
pulsars
NS-NS (LISA)
NS-NS (LIGO)
GW150914
BH-BH (LIGO)
SMBHBs (LISA)
WD-WD
Lunar Laser Ranging
Saturn
Mercury
Cassini
S stars
pulsars
SMBHs
EHT: Sgr A*
EHT: M87
SMBHBs (PTAs)
galaxies
CMB peaks
clusters
Λ

Kramer et al

Event Horizon Telescope

- Global collaboration to observe BHs with resolution comparable to the event horizon
  - >200 members
  - Dozens of institutions
- Ad hoc array operated ~10 days per year
- Technology development



Event Horizon Telescope

Funding Support

RadioNet

NWO Netherlands Organisation for Scientific Research

John Templeton Foundation

日本学術振興会 Japan Society for the Promotion of Science

Max-Planck-Gesellschaft

NASA

dgapa Dirección General de Asuntos del Personal Académico

MOST 科技部 Ministry of Science and Technology

中国科学院 Chinese Academy of Sciences

Instituto Geográfico Nacional

National Research Foundation of Korea

Gordon and Betty Moore Foundation

CONACYT Consejo Nacional de Ciencia y Tecnología

NSFC

Academia Sinica

erc European Research Council

NSF

Ministry of Science, ICT and Future Planning

NAOJ National Astronomical Observatory of Japan

nst 국가과학기술연구회

中华人民共和国科学技术部 Ministry of Science and Technology of the People's Republic of China

Gobierno de España Ministerio de Economía y Competitividad

cnrs Centre National de la Recherche Scientifique

Academy of Finland

KASI 한국천문연구원 Korea Astronomy & Space Science Institute

NOVA

Event Horizon Telescope

Institutions on the EHT Board

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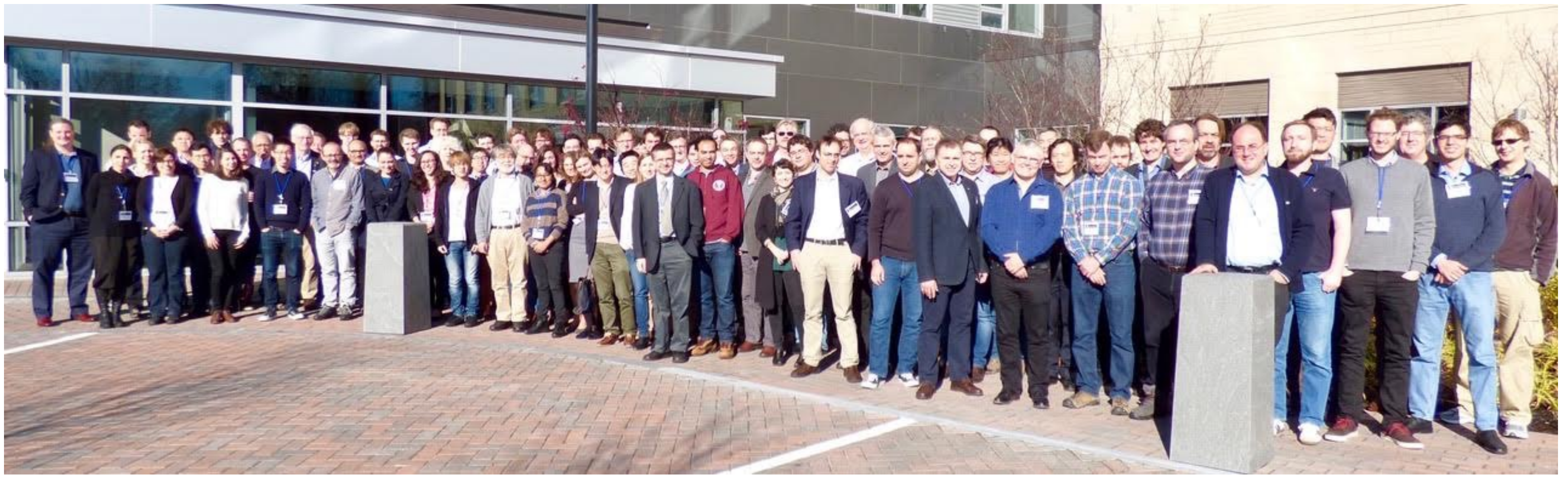
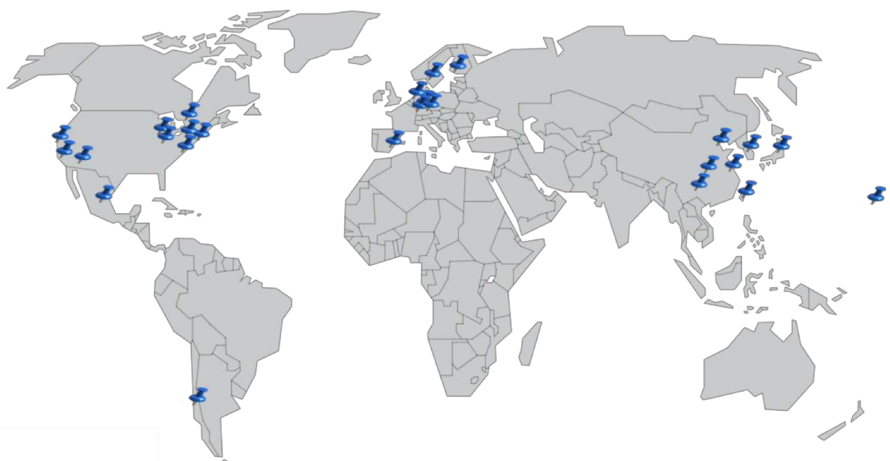
Shanghai Astronomical Observatory
Institute of Statistical Mathematics
University of Waterloo
Yunnan Observatory

Event Horizon Telescope

Global Team at the EHT2016 Conference

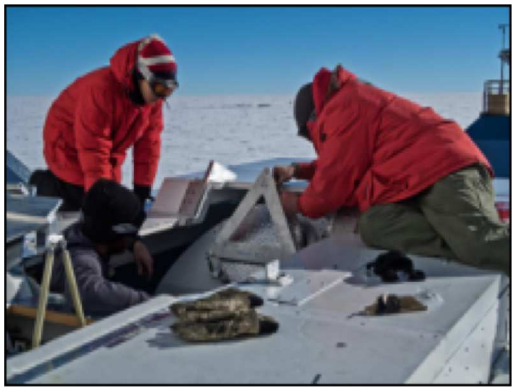


11/2016; Cambridge, MA



Event Horizon Telescope

Members of the EHT team at Telescopes

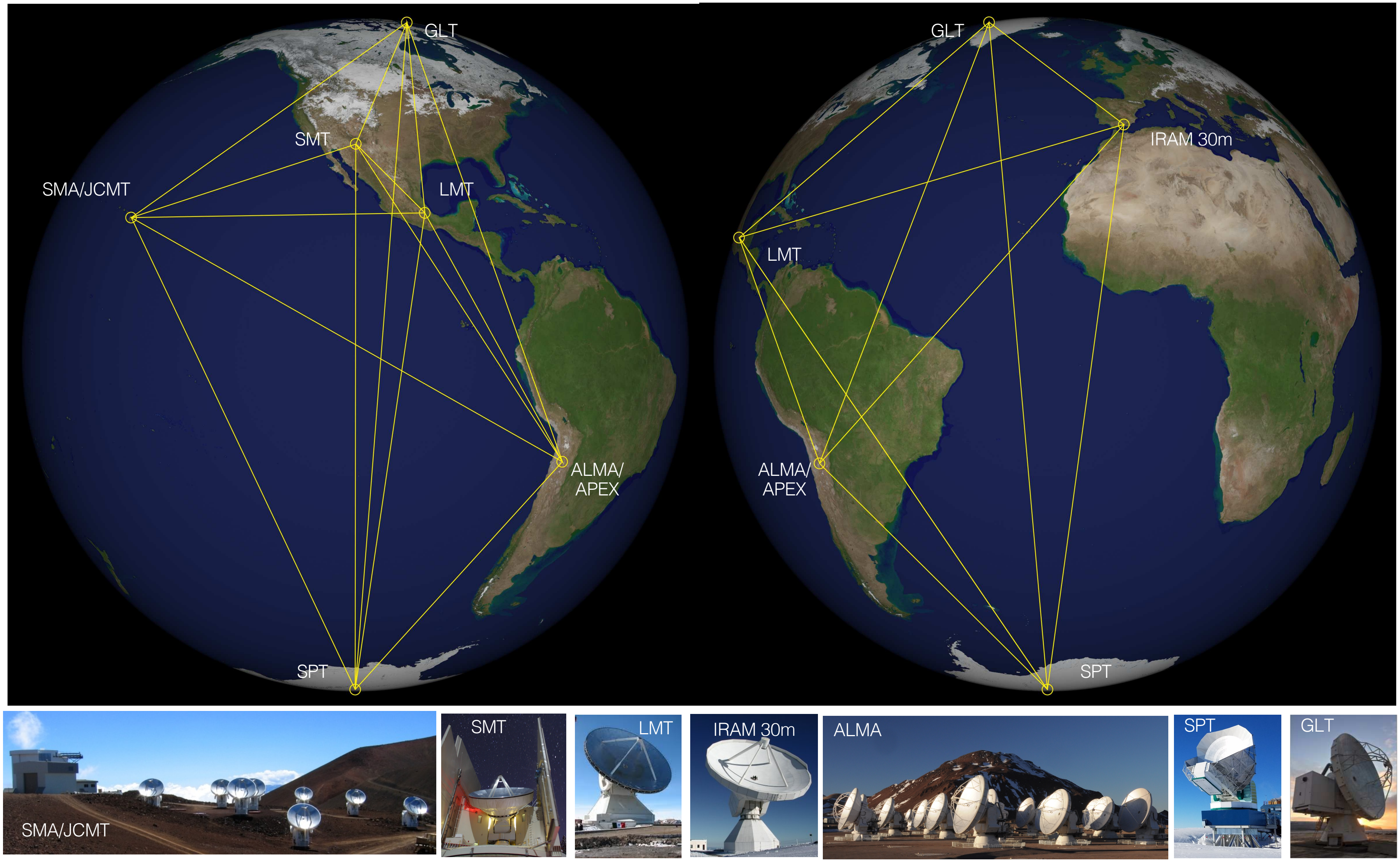






Practical Challenges of BH Shadow Imaging

- Shadow is very small
  - θ_g = GM/Dc^2 ~ 5 μas
  - θ_{shadow} ~ 10 GM/Dc^2 ~ 50 μas
- Need a global mm VLBI array
  - θ_{array} = ƛ/D = 1.3mm/11000 km ~ 20 μas
- But no such network exists!
  - Need to use an ad hoc network

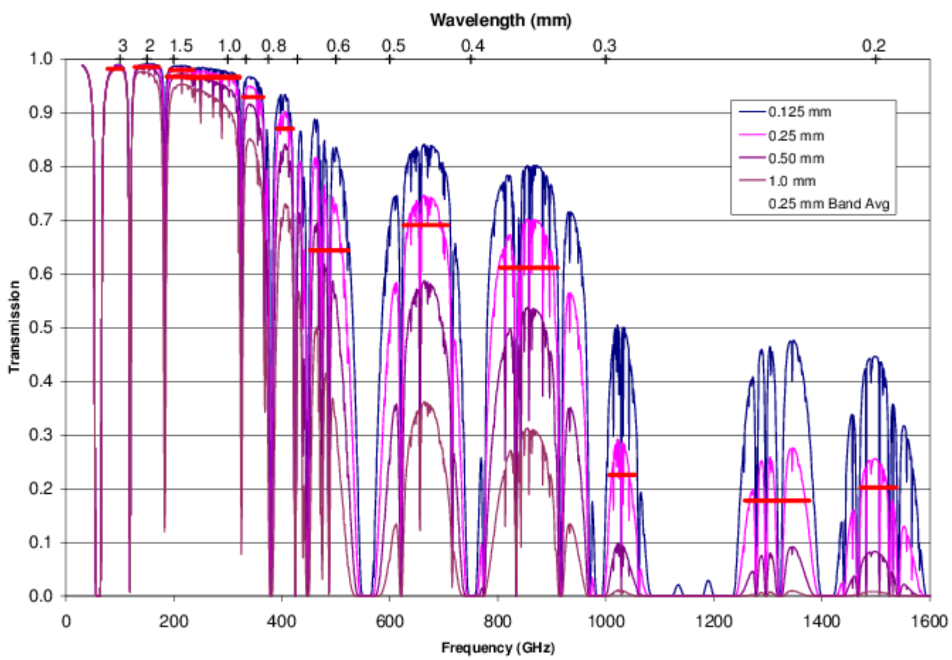
Event Horizon Telescope in 2018



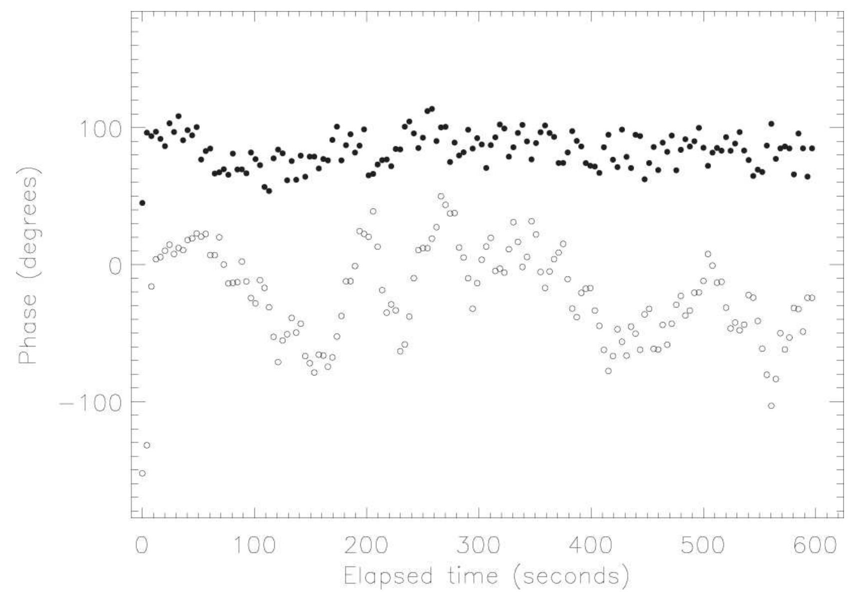
D. Marrone/UofA

Practical Challenges of BH Shadow Imaging

- Atmosphere at mm wavelengths is difficult



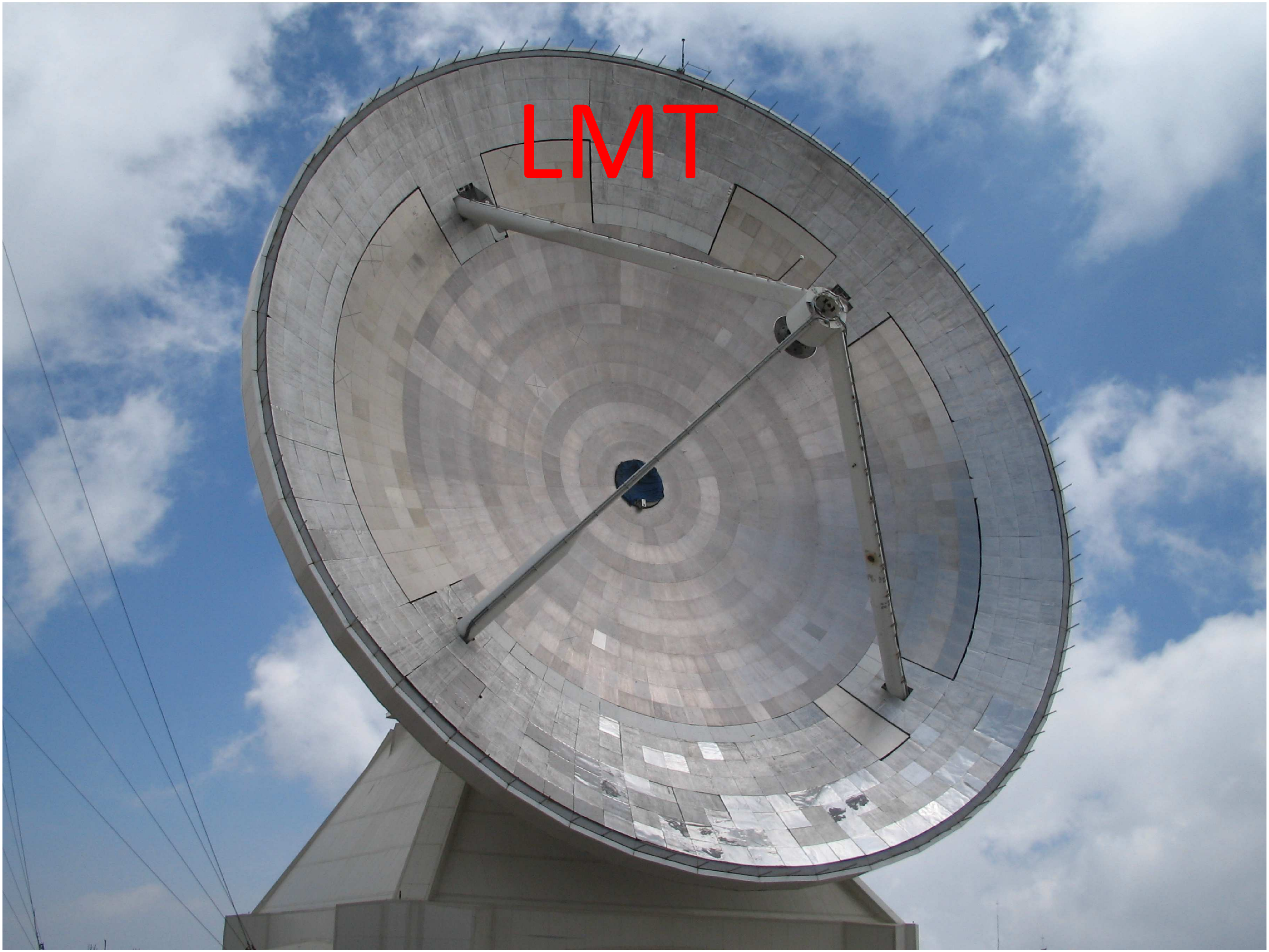
Goldsmith et al



Matthews et al 2018

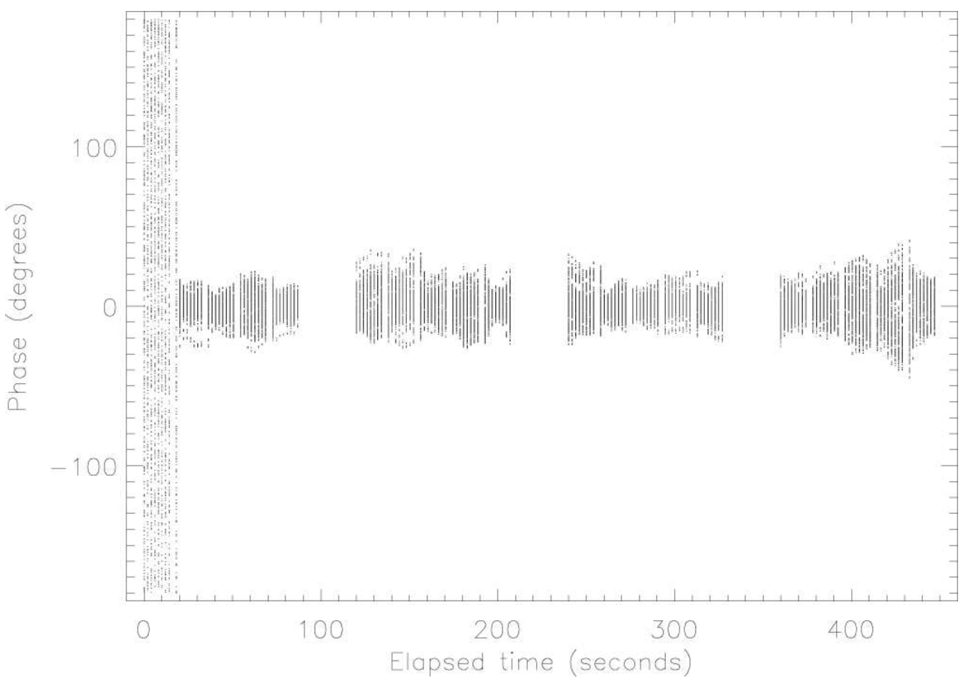
Practical Challenges of BH Shadow Imaging

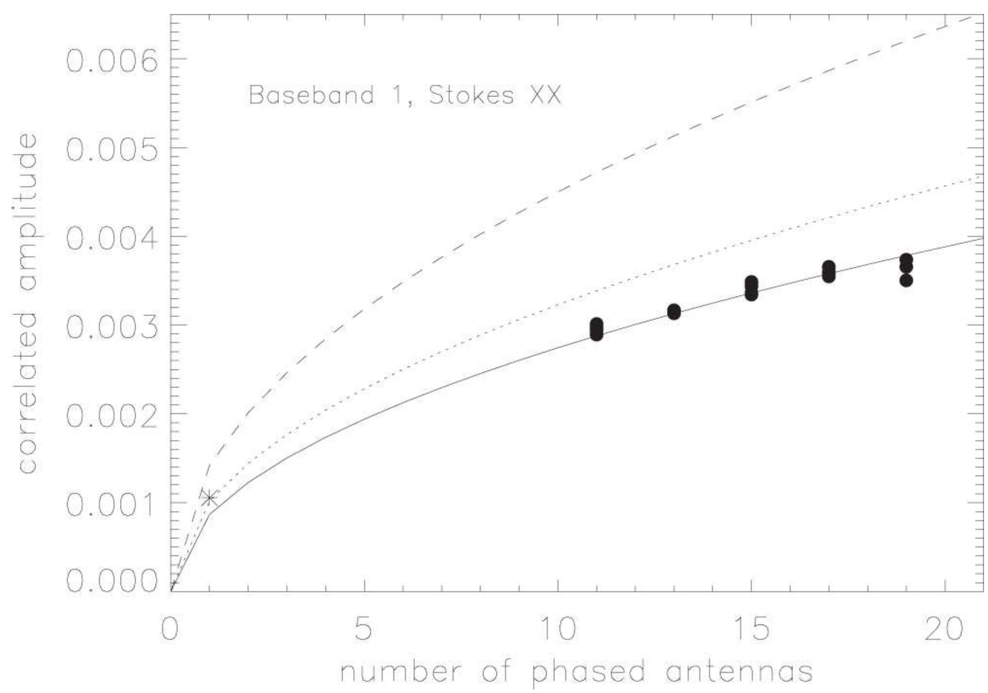
- Sources are faint and resolved on long baselines
  - S~1 Jy
- Millimeter telescopes are not very sensitive
  - SEFD~10^4 Jy
  - dS = SEFD/sqrt(2*BW* τ) ~ 50 mJy
    - BW=2 GHz, τ=10 s
- → New Telescopes
- → Increase BW


LMT


ALMA

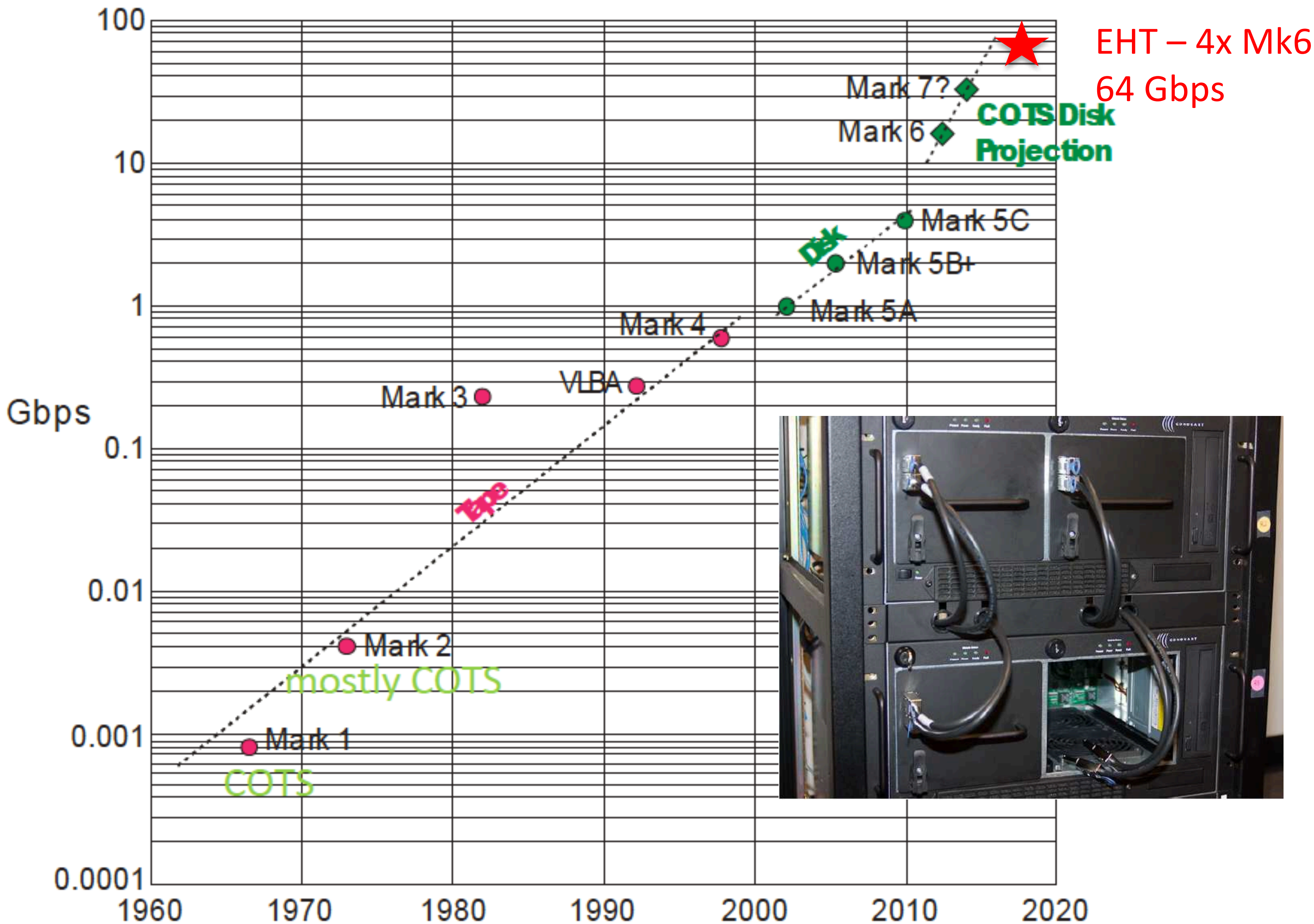
ALMA Phasing





Matthews et al 2018

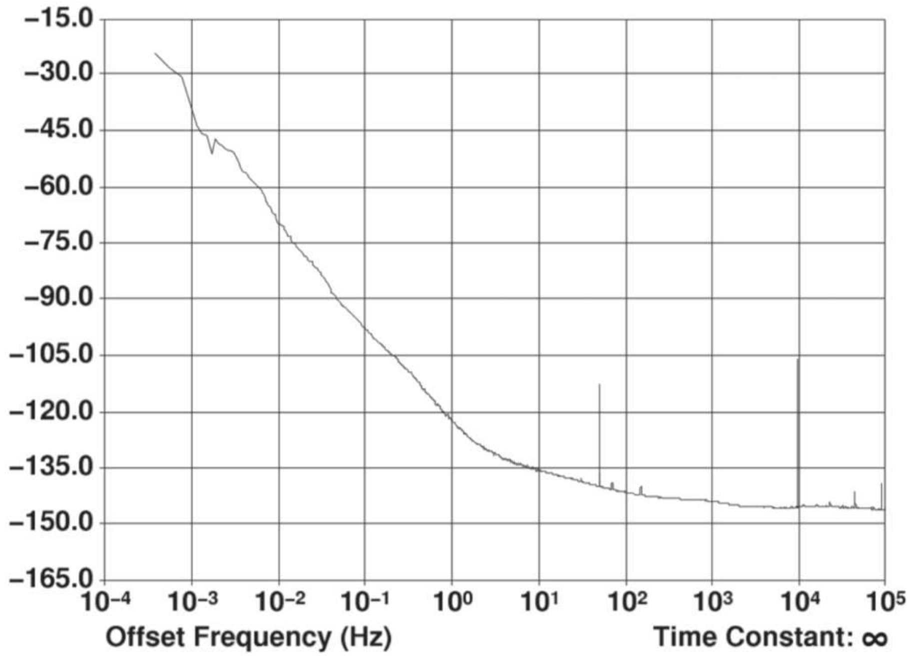
Recording rate capability vs. time

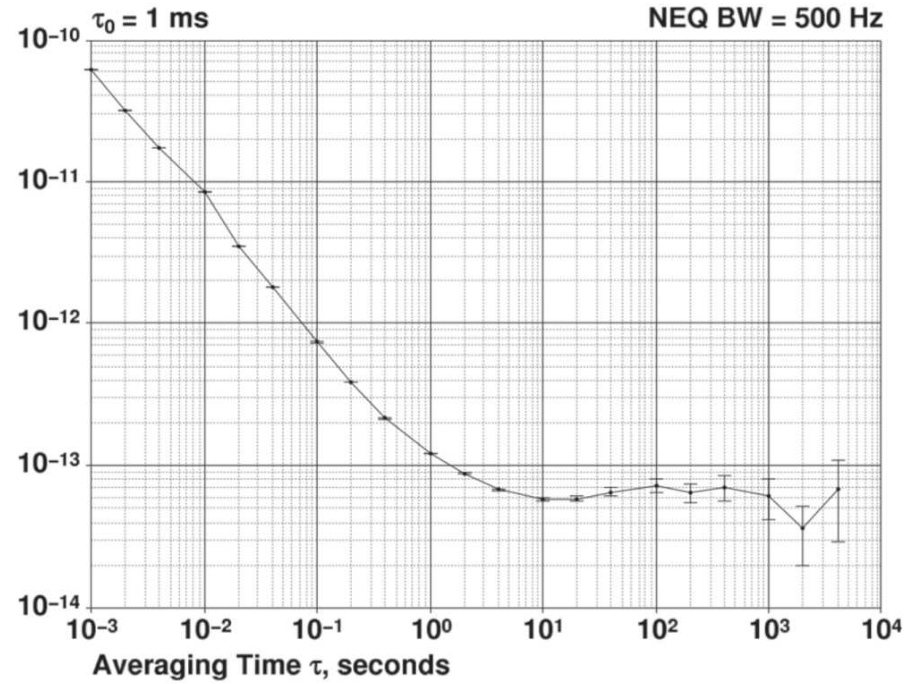


Whitney et al 2012

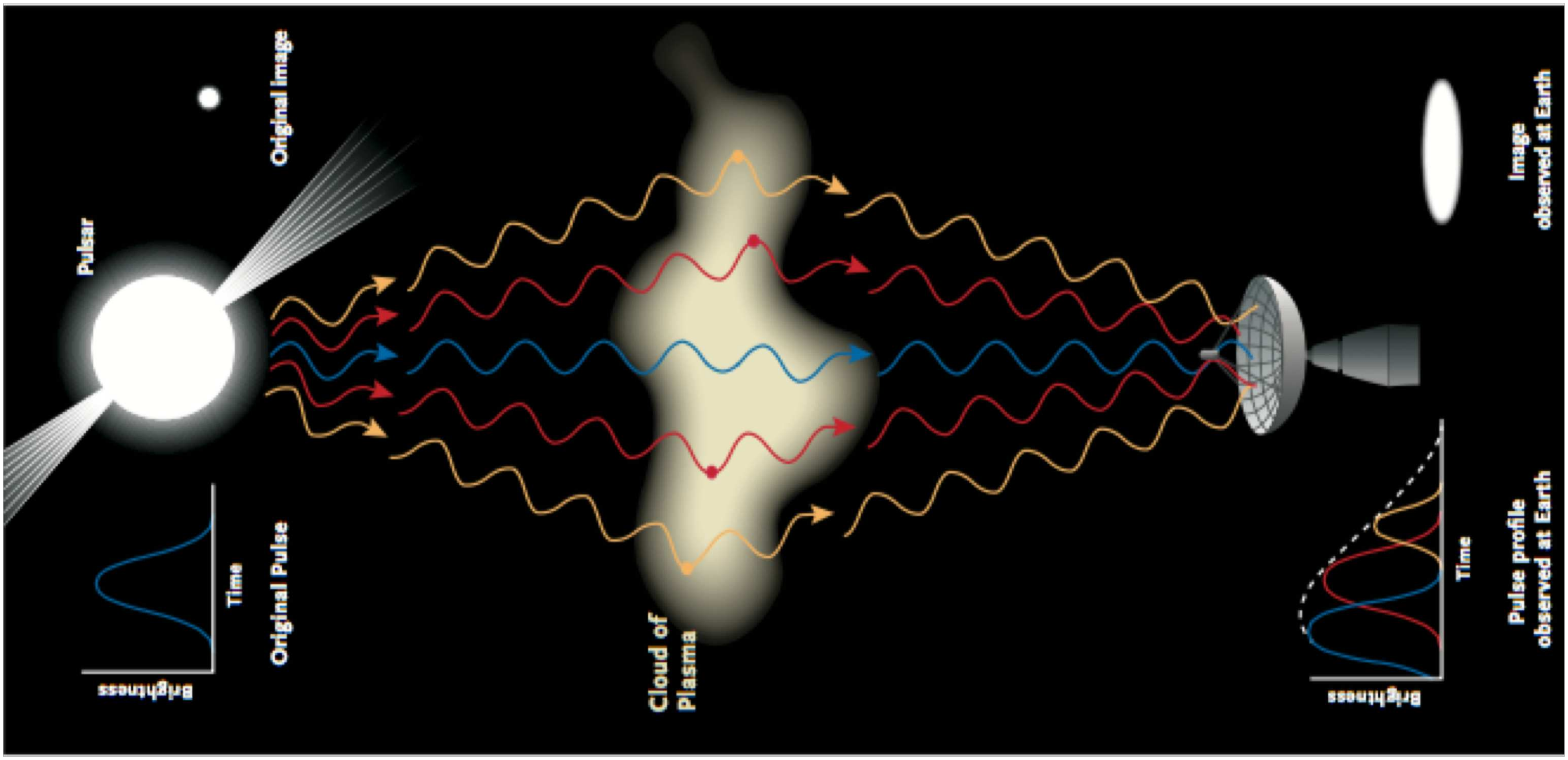
High Frequency Requires High Precision

ALMA Maser Performance
Matthews et al 2018

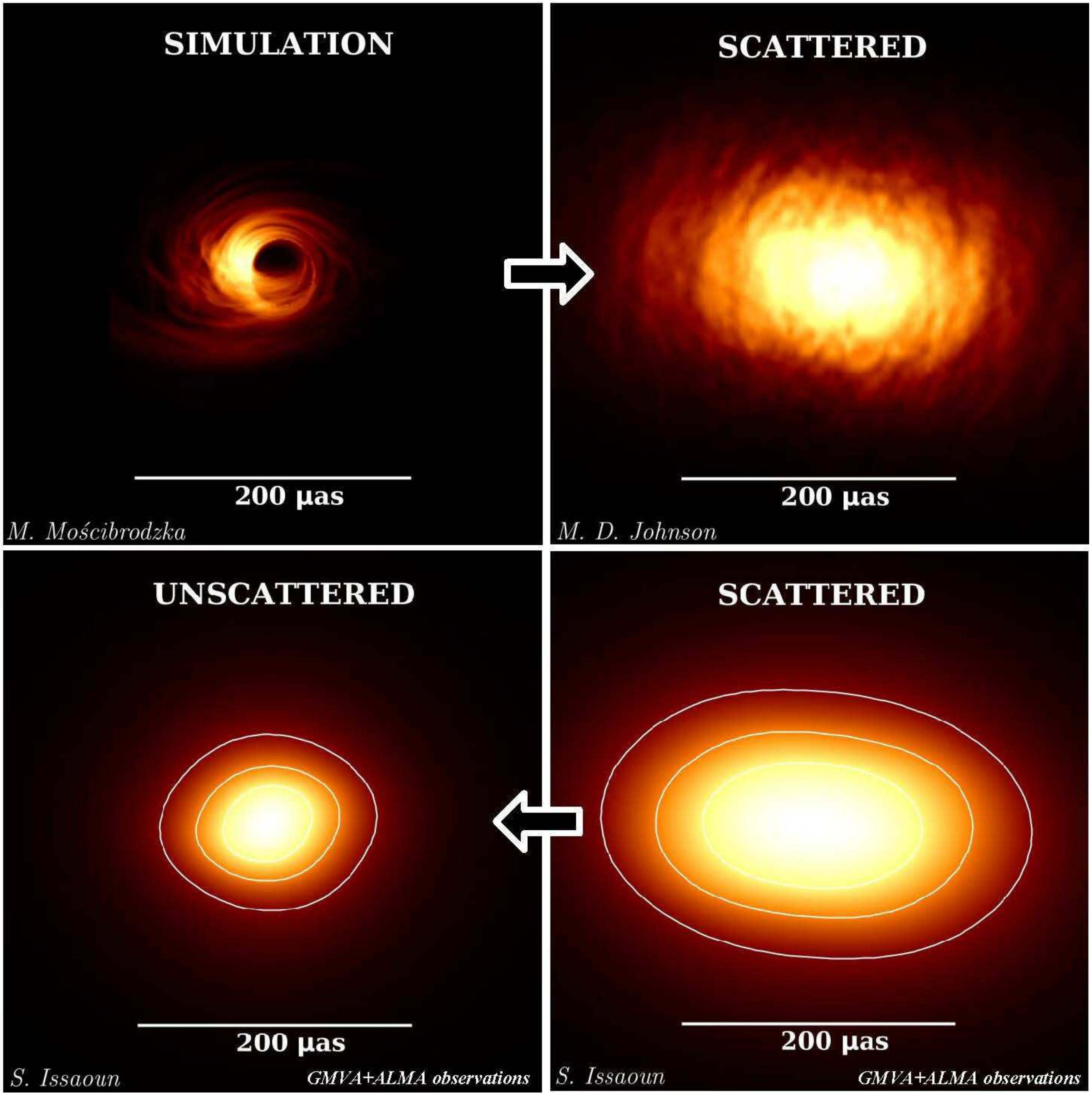




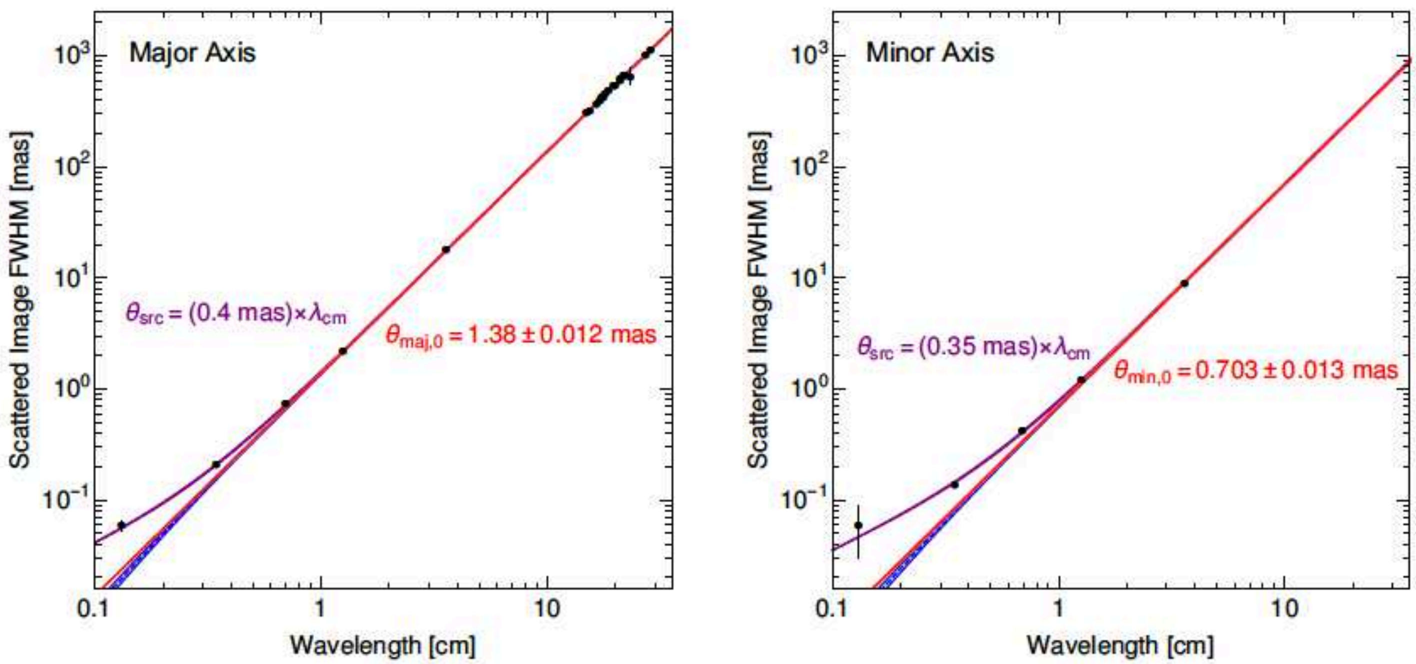
Scattering Blurs Imaging



Haggard & Bower, Sky & Tel, 2016


SIMULATION
200 μas
M. Mościbrodzka
SCATTERED
200 μas
M. D. Johnson
UNSCATTERED
200 μas
S. Issaoun
GMVA+ALMA observations
SCATTERED
200 μas
S. Issaoun
GMVA+ALMA observations

The Intrinsic Size of Sgr A*

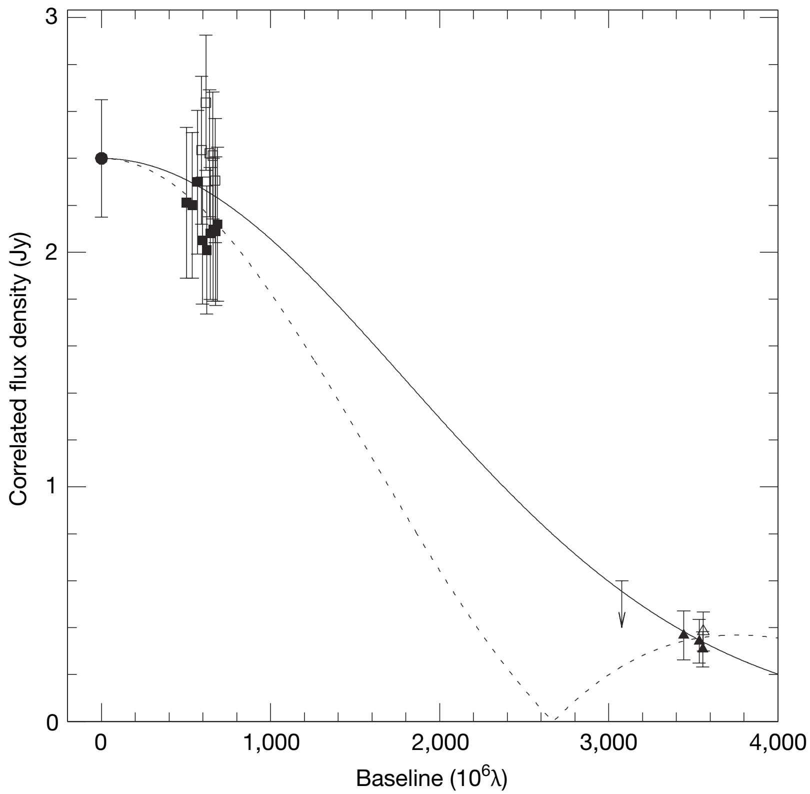


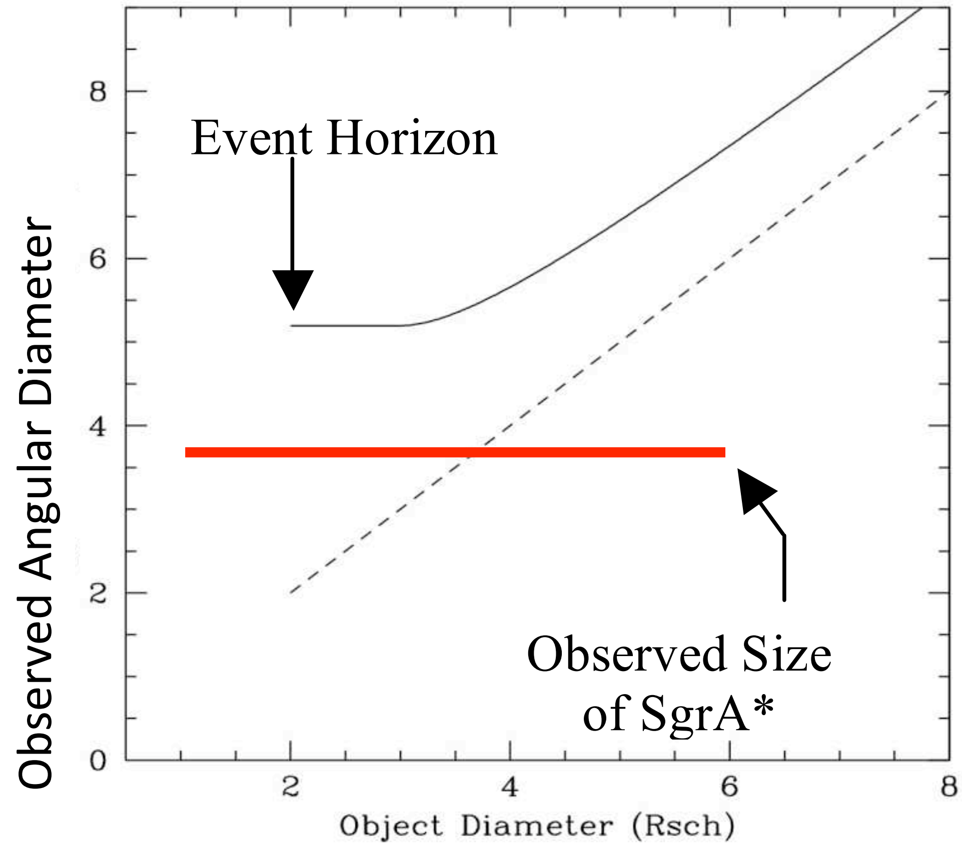
$10^5 R_s$

$\sim 5\ R_s$

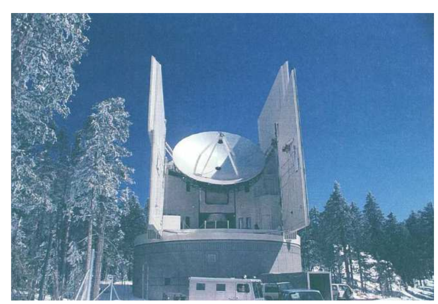
Johnson et al 2018

MM VLBI Imaging of Sgr A*

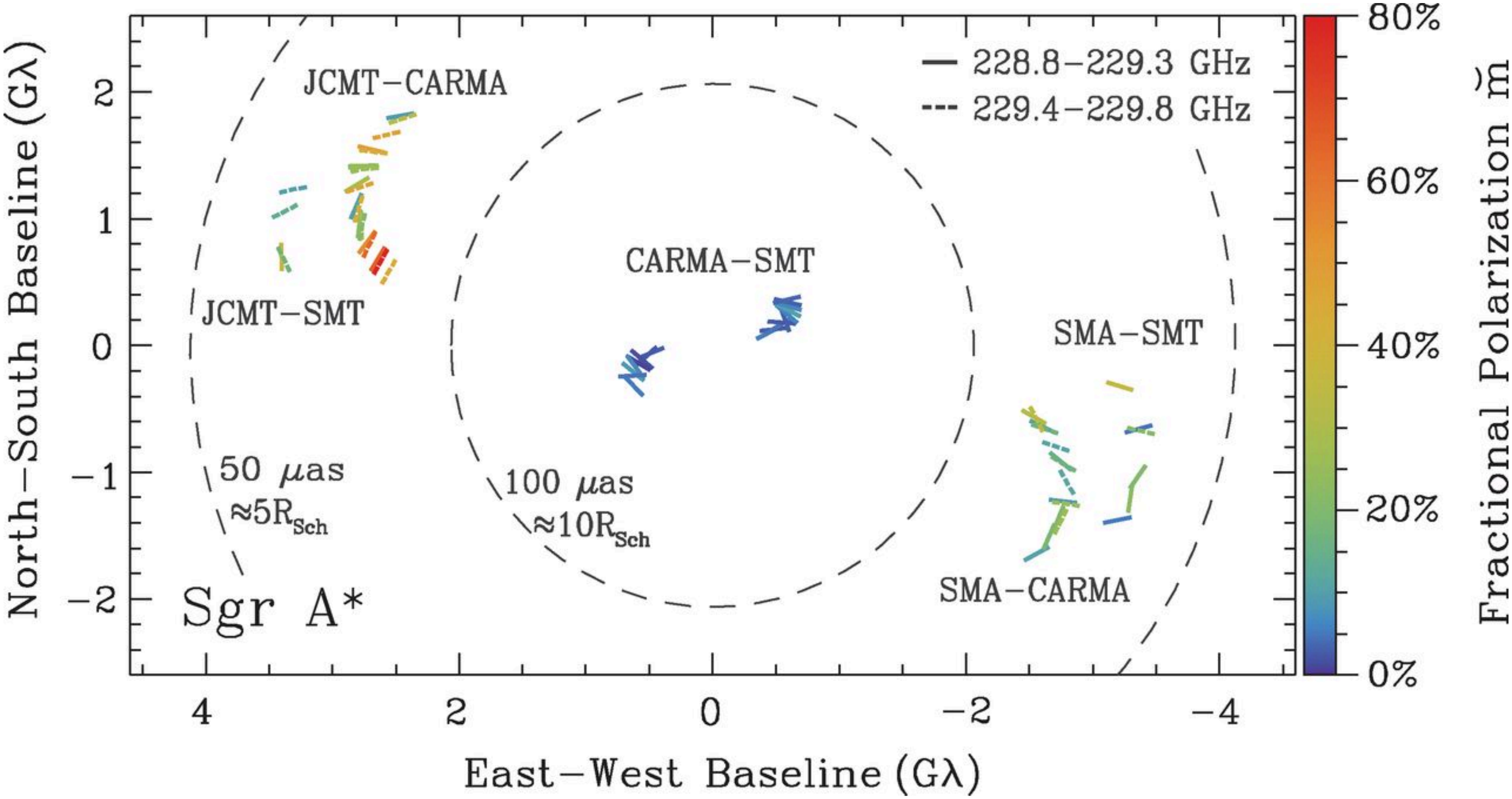




Doeleman et al 2008

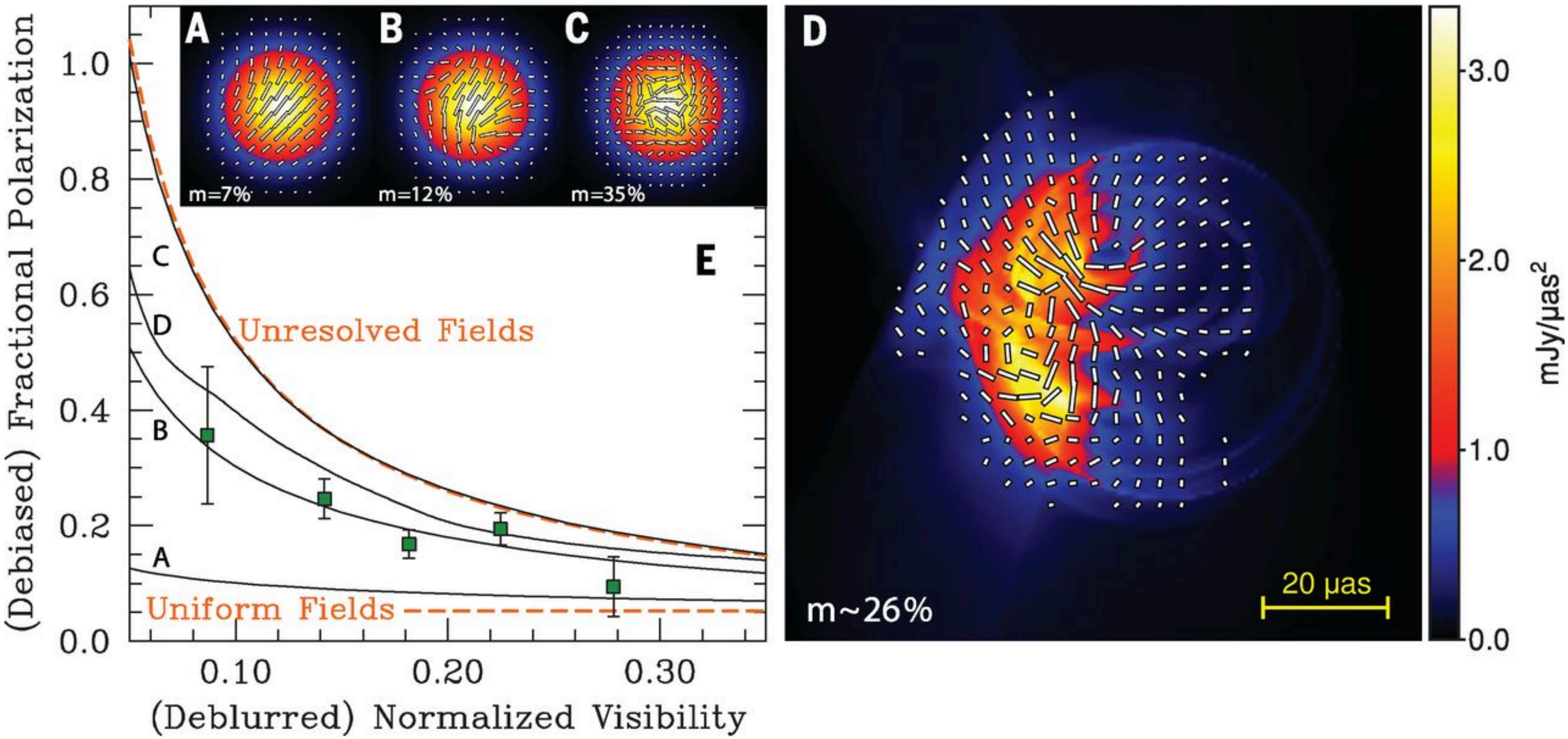


EHT Polarization of Sgr A*



Johnson et al 2015

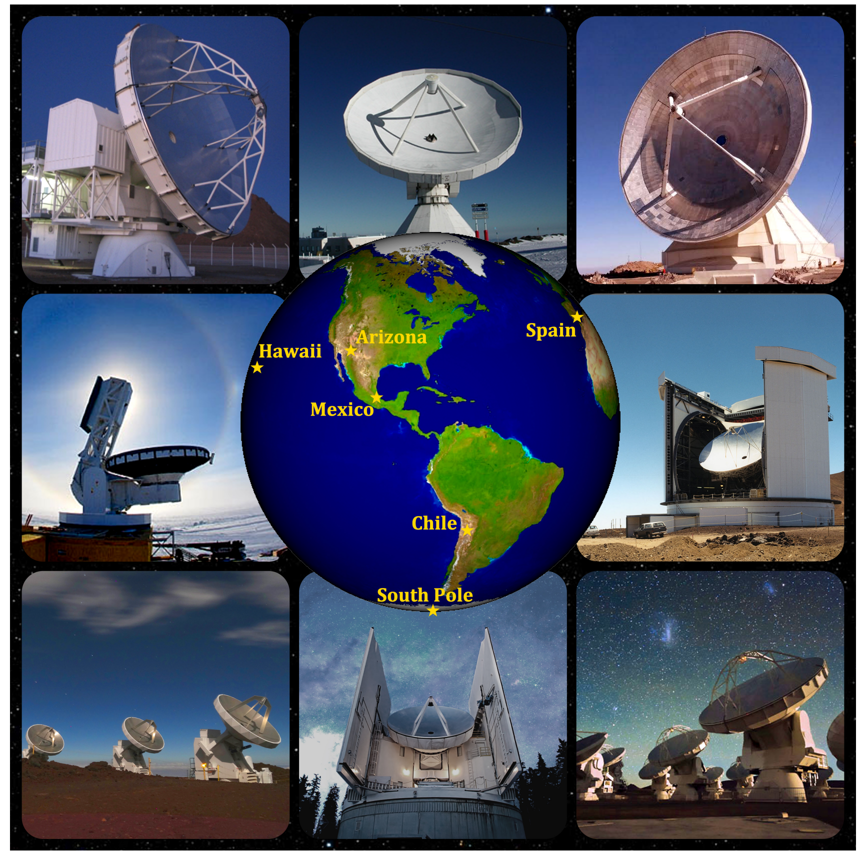
EHT Polarization of Sgr A*



Johnson et al 2015

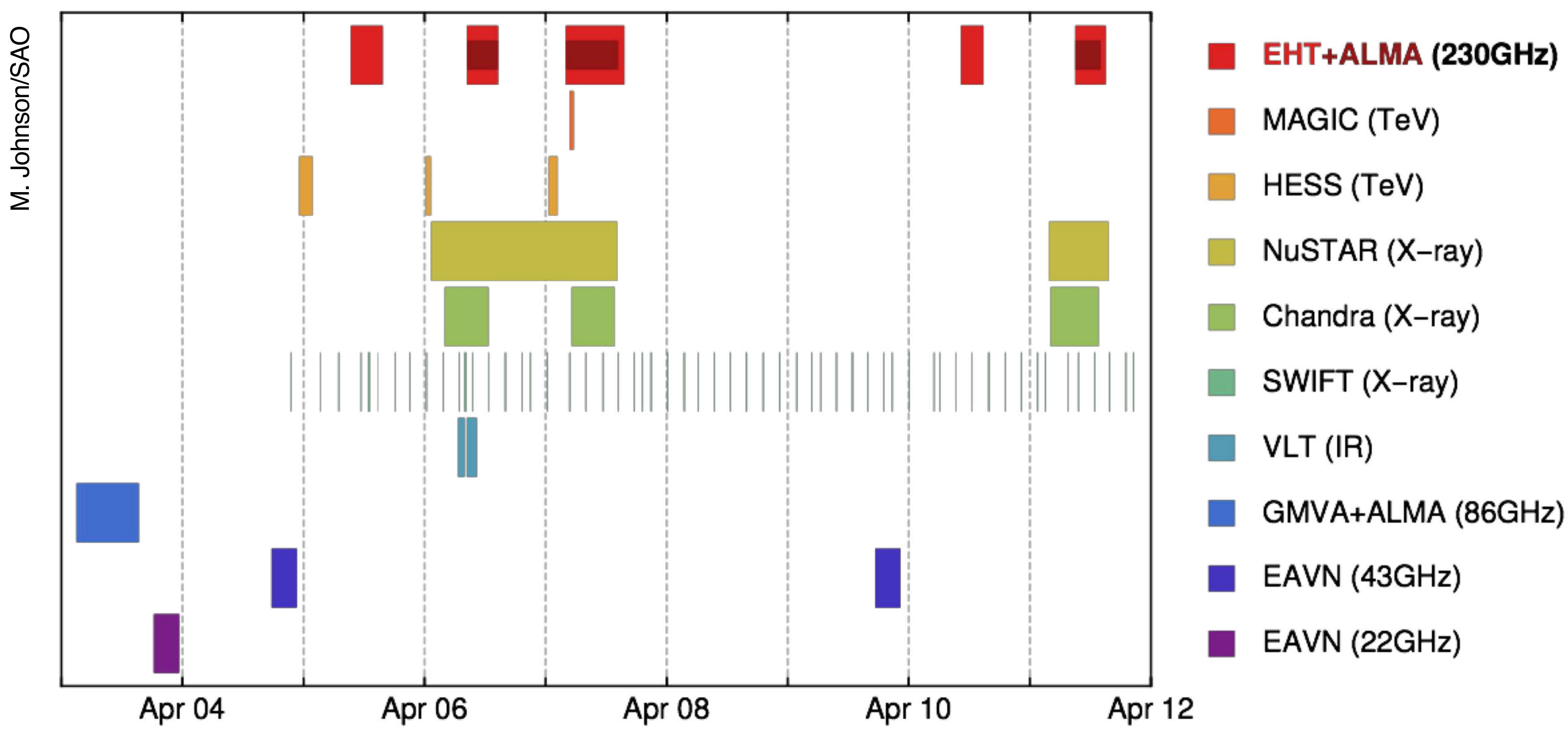
Event Horizon Telescope in 2017

- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter Telescope (SMT), Arizona

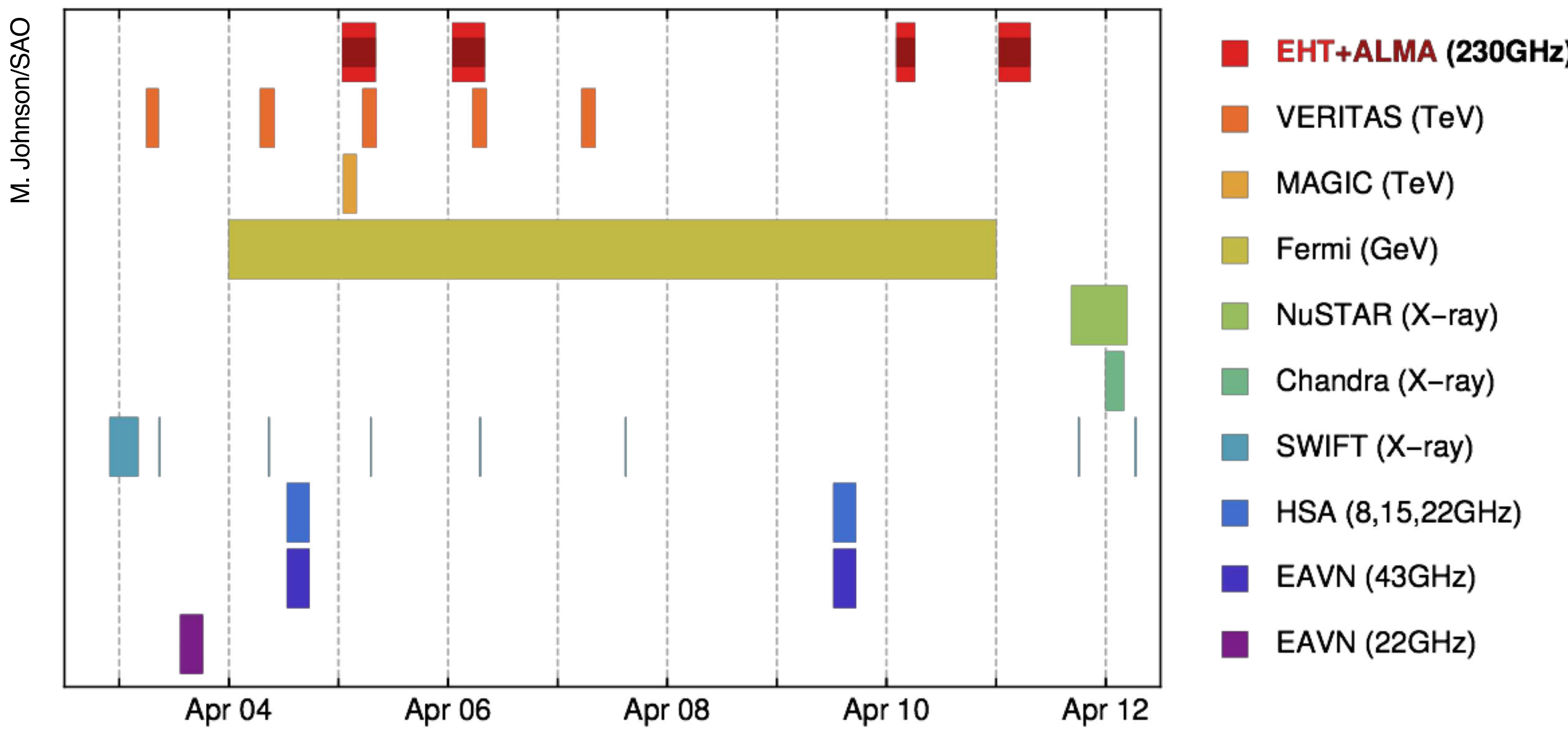


M. Johnson/SAO

Multi-Wavelength Coverage: Sgr A* in April 2017

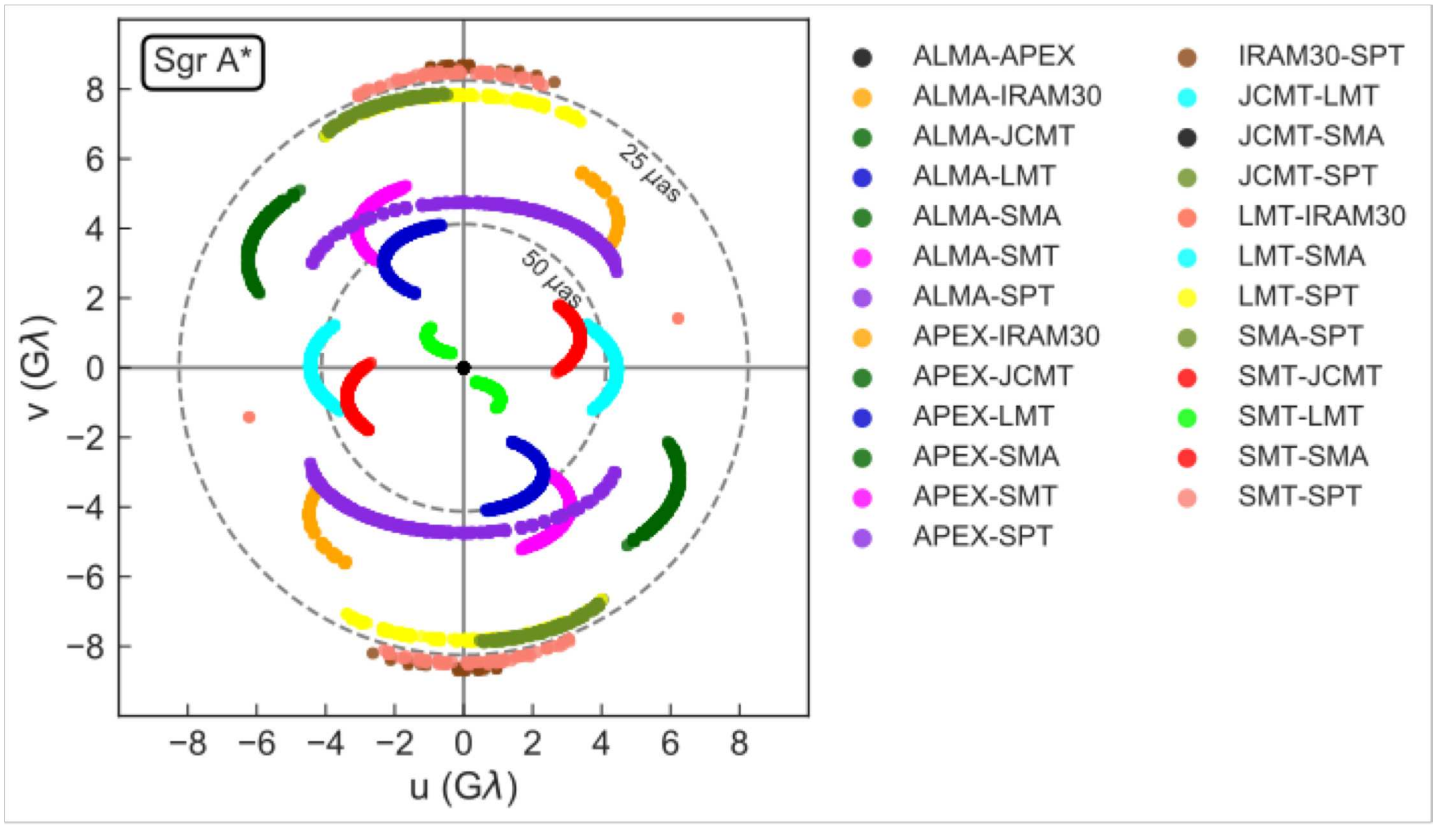


Multi-Wavelength Coverage: M87 in April 2017



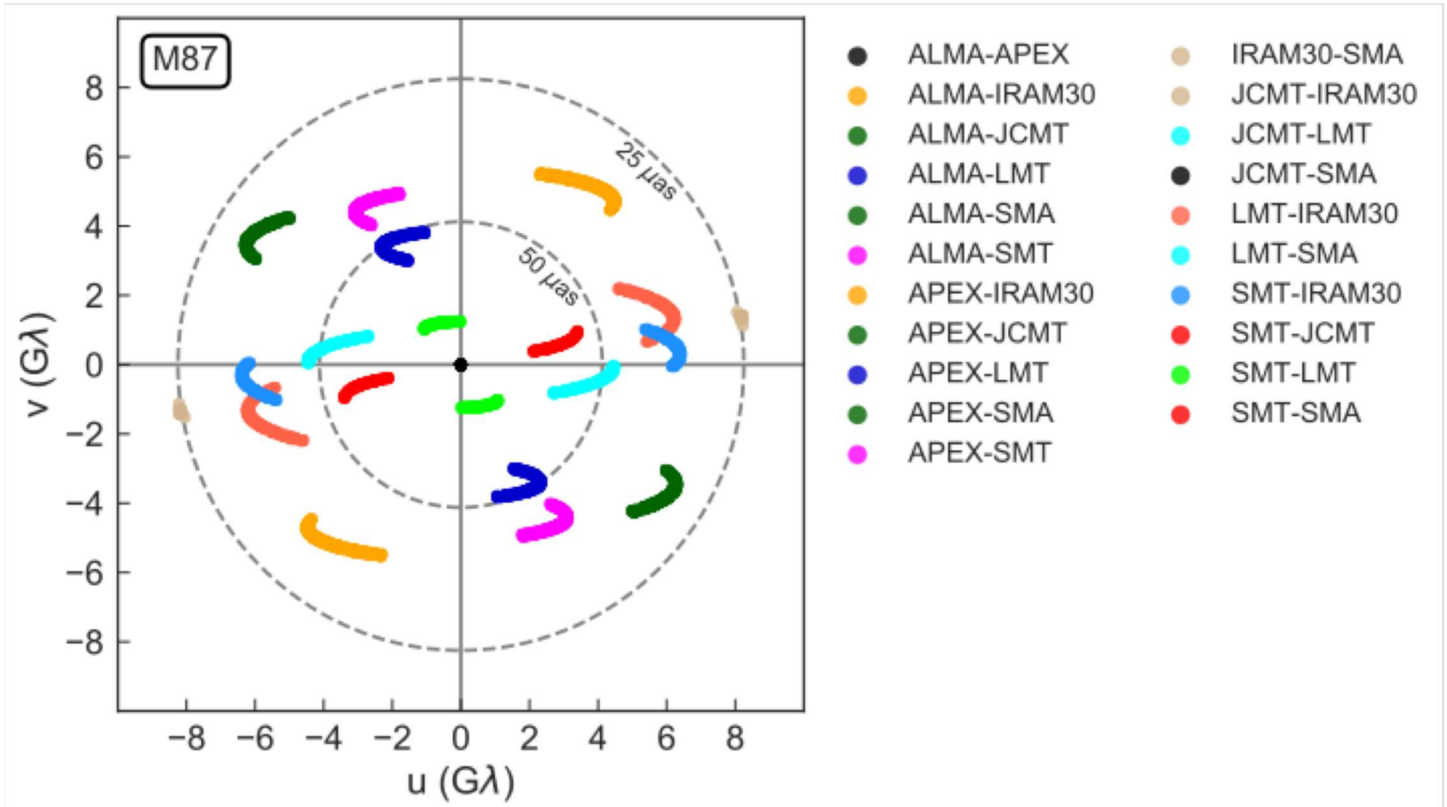
u-v Coverage with EHT 2017: Sgr A*

Calibration & Error Analysis WG

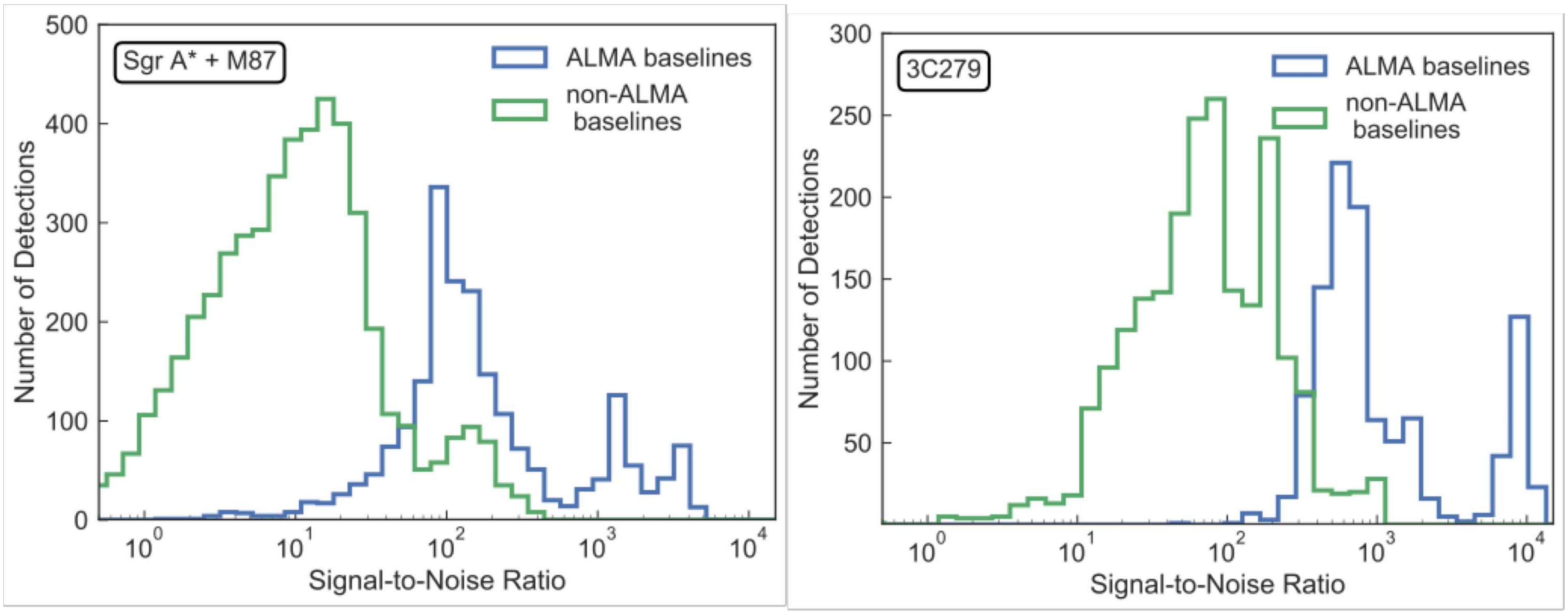


u-v Coverage with EHT 2017: M87

Calibration & Error Analysis WG

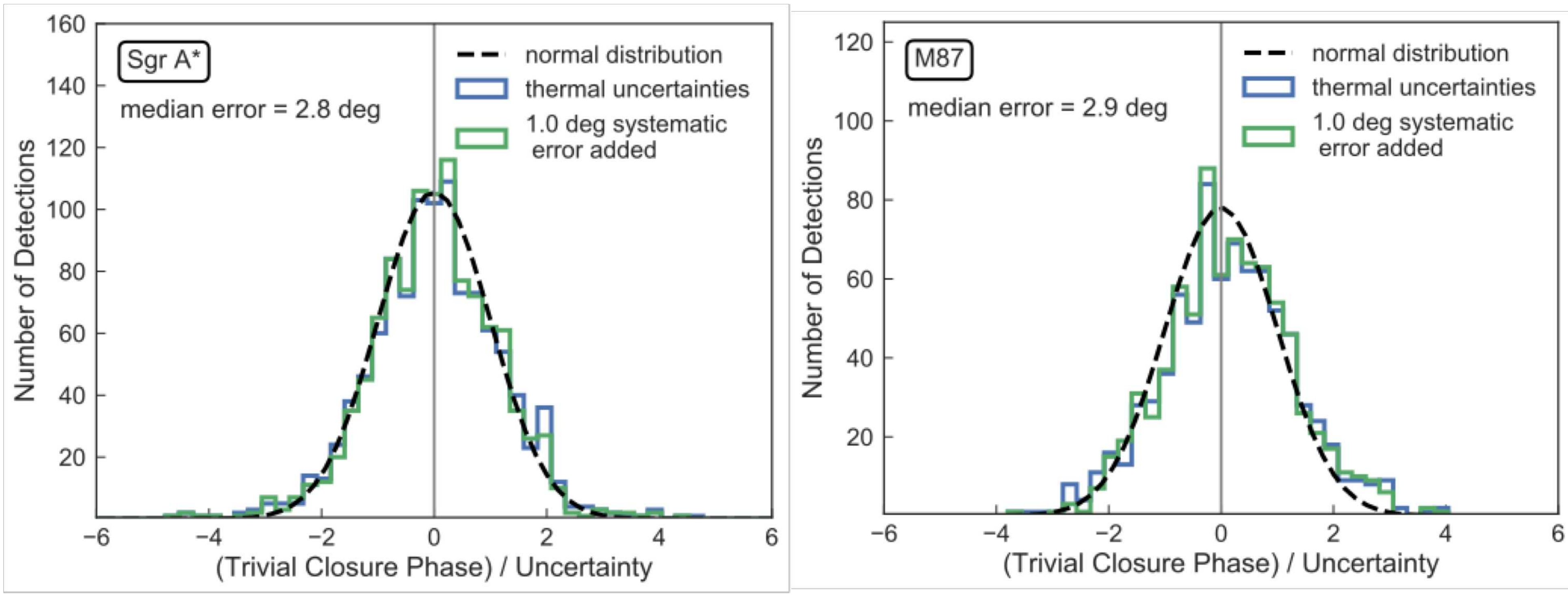


EHT2017: A Large Number of Highly Significant Detections



Calibration & Error Analysis WG

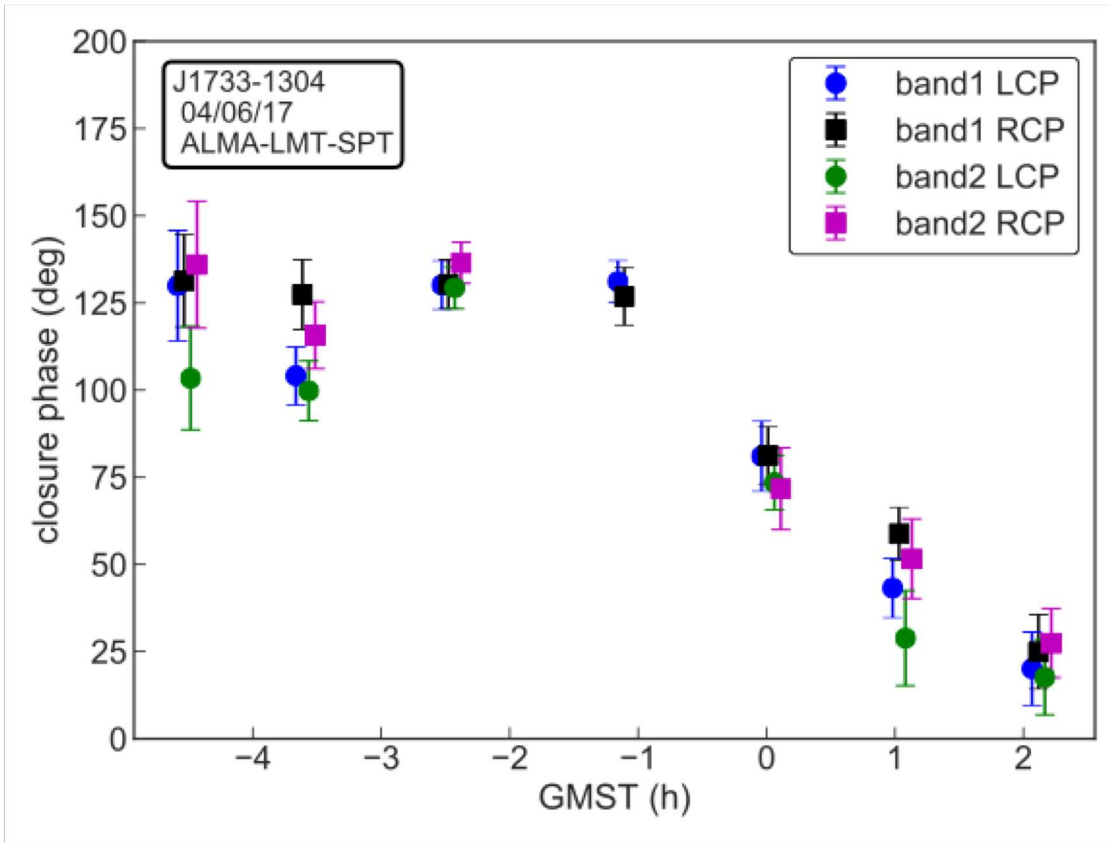
EHT2017: Quantifying and Understanding Measurement Uncertainties



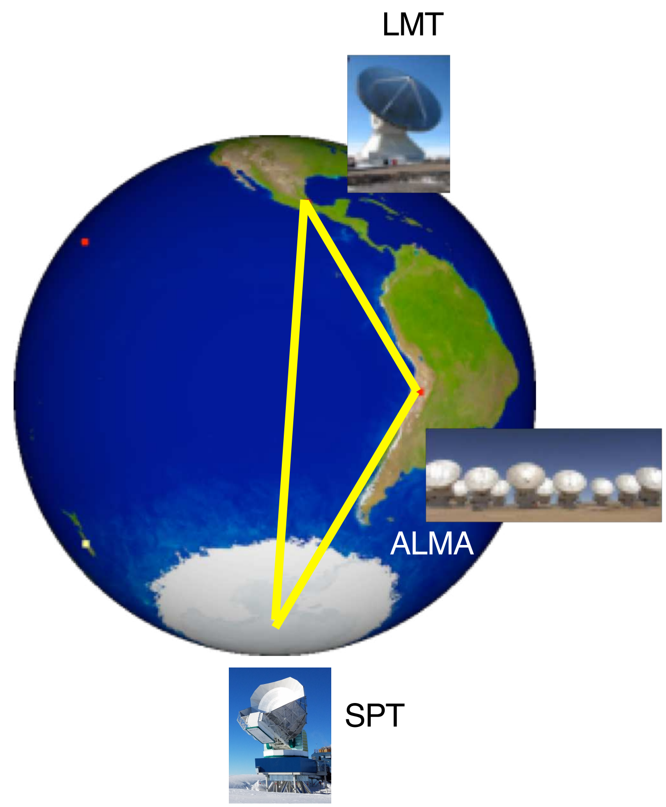
Closure phases along trivial triangles are consistent with zero, within thermal uncertainties

Calibration & Error Analysis WG

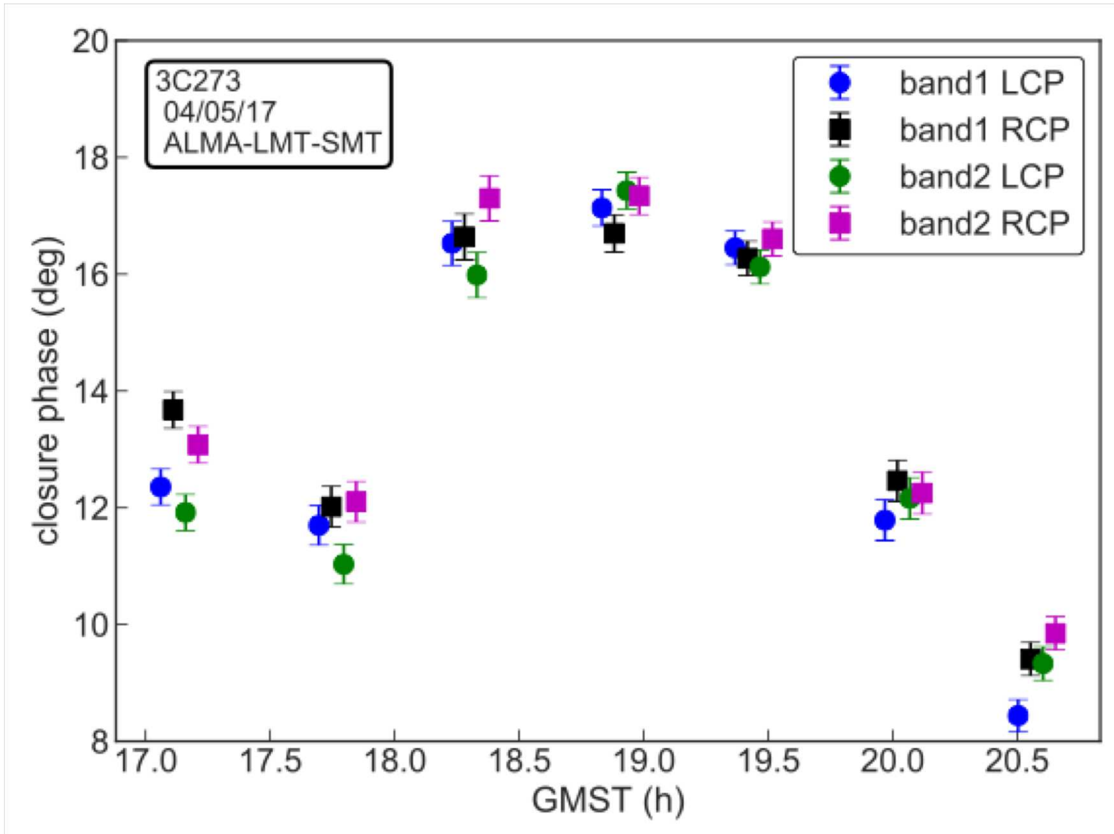
EHT2017: J1733-1304



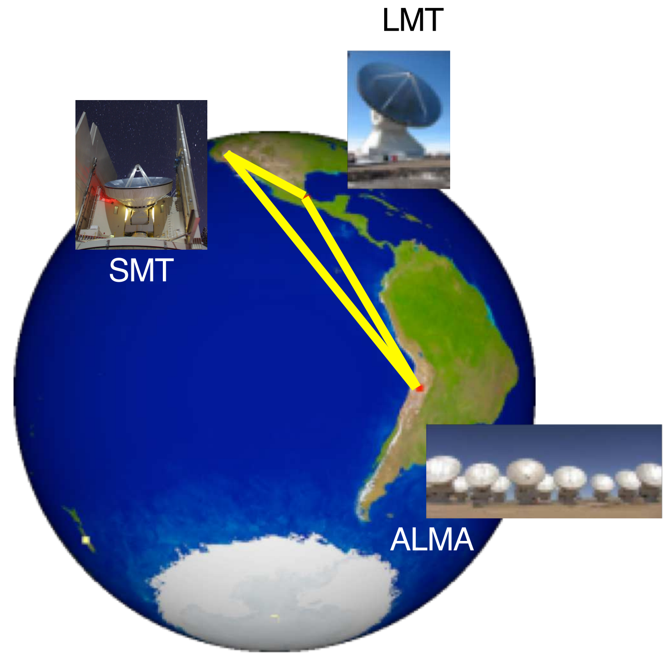
Calibration & Error Analysis WG



EHT2017: 3C273



Calibration & Error Analysis WG



The Event Horizon Telescope

- The highest resolution images of black holes
- Inclusion of ALMA and LMT is a leap in sensitivity and imaging quality
- 2017 data are excellent
- Extreme care is being taken in analysis and imaging
- *Big things to come in 2019 and beyond!*

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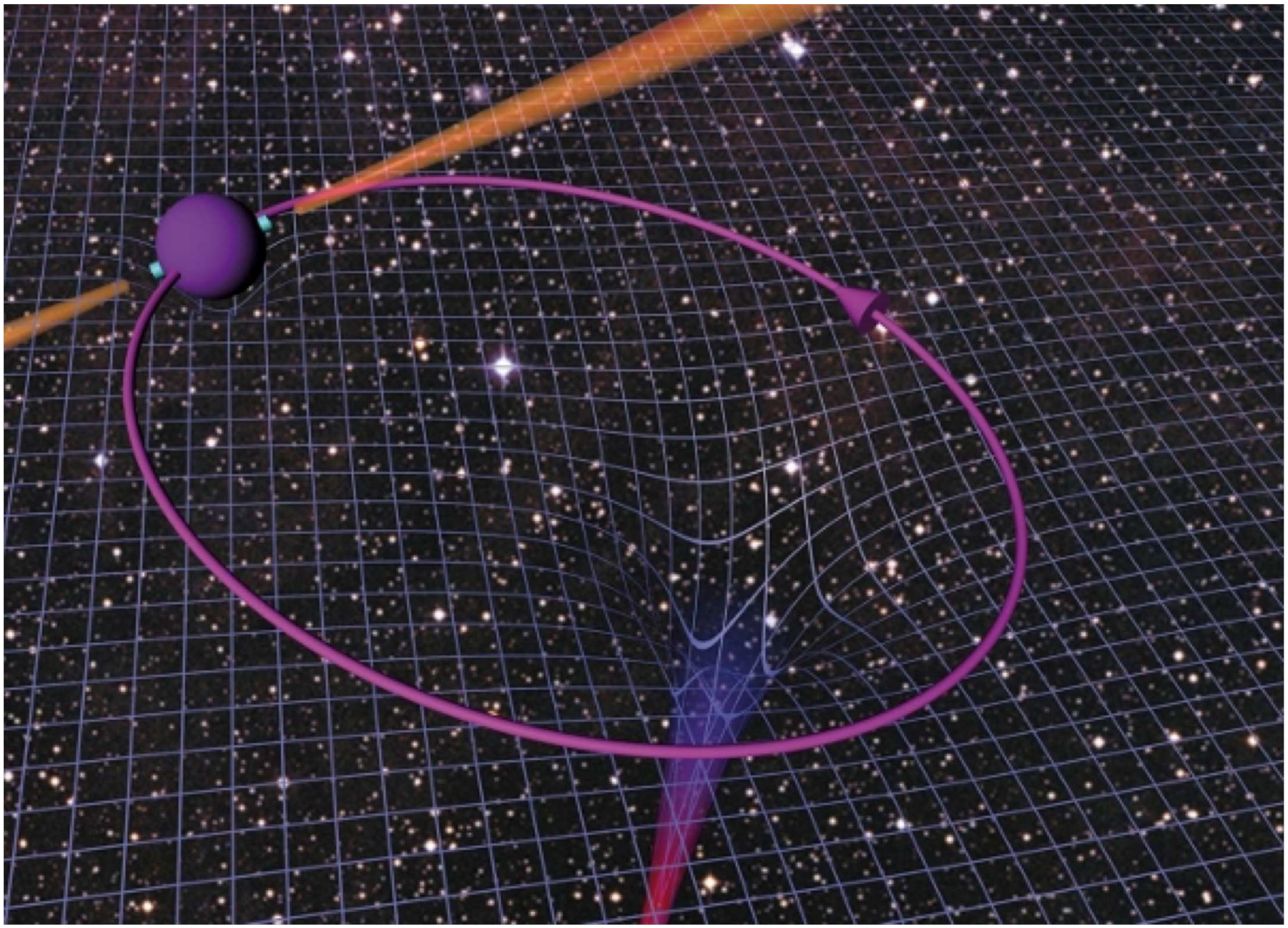
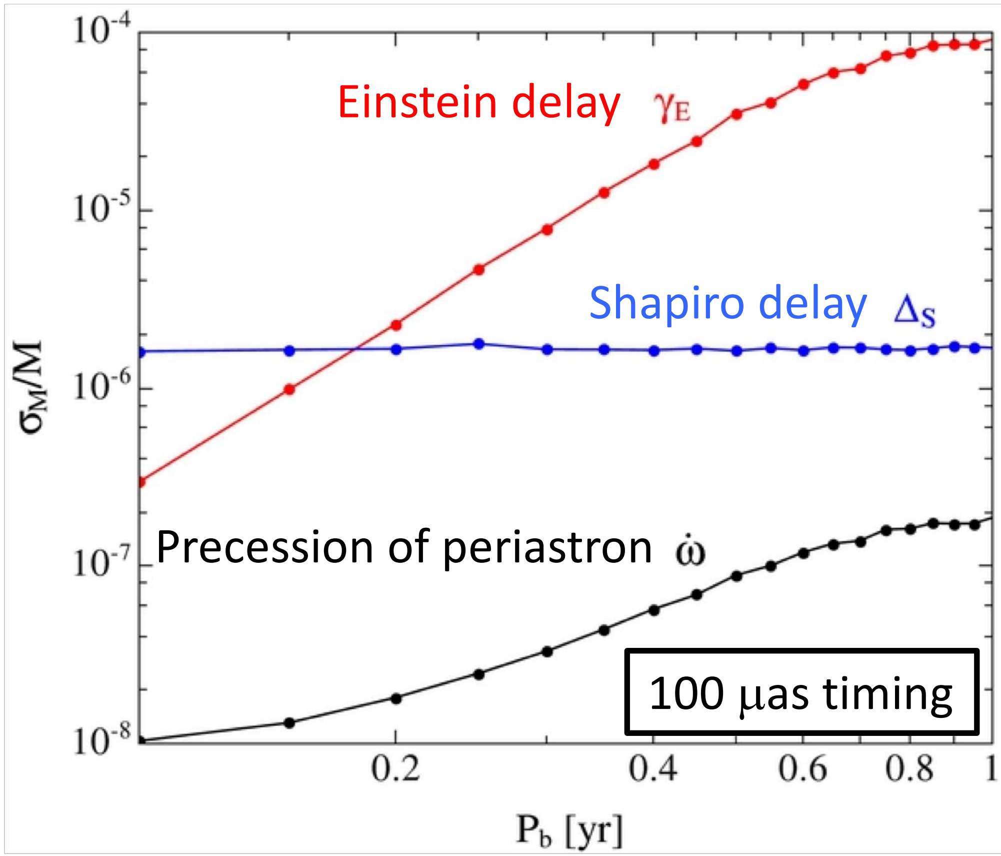
A Pulsar in Orbit Around a BH



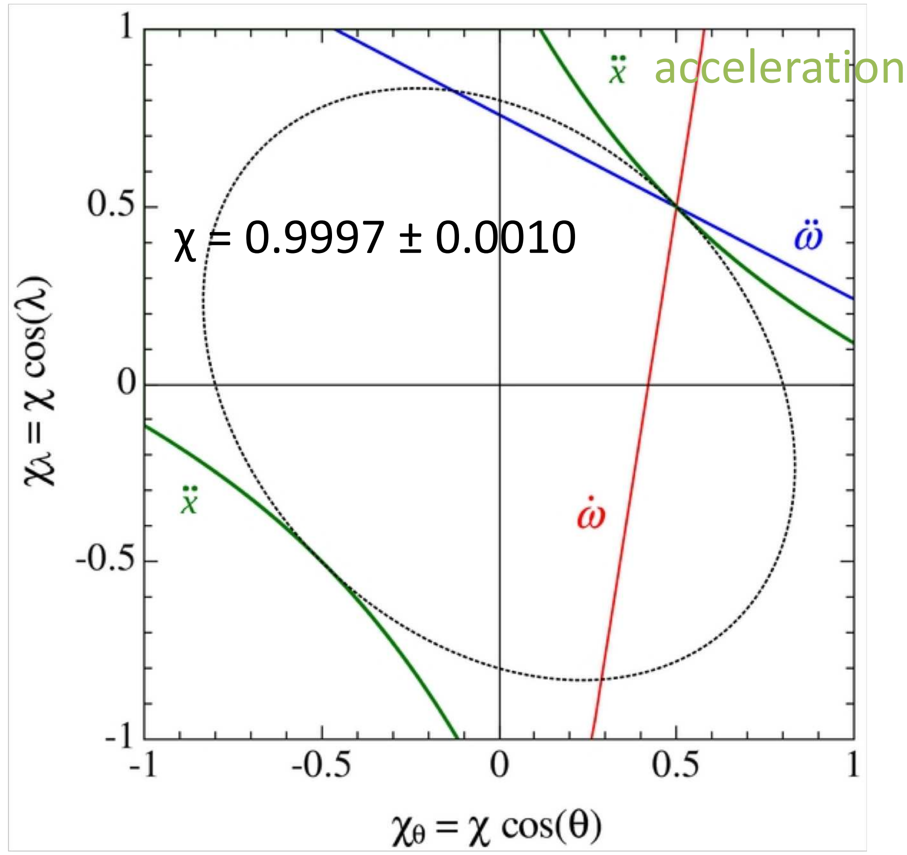
Kramer et al

Using Pulsars to Measure Spacetime Around Sgr A*

Black Hole Mass



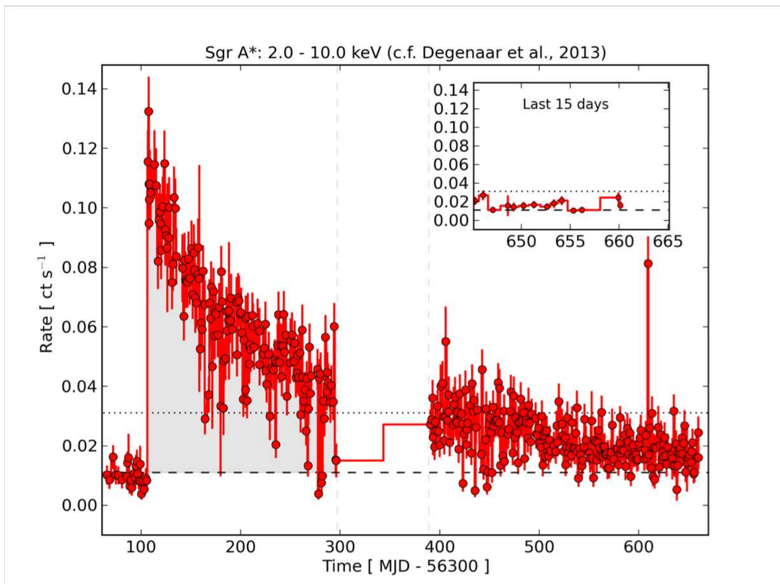
Black Hole Spin



Liu et al 2012

Galactic Center Magnetar Discovery

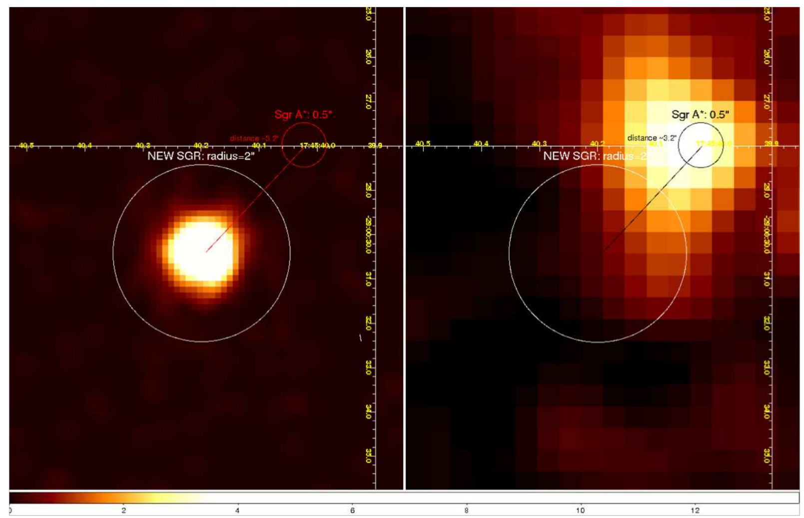
X-Ray Burst



Degenaar et al. 2013
Kennea et al. 2013

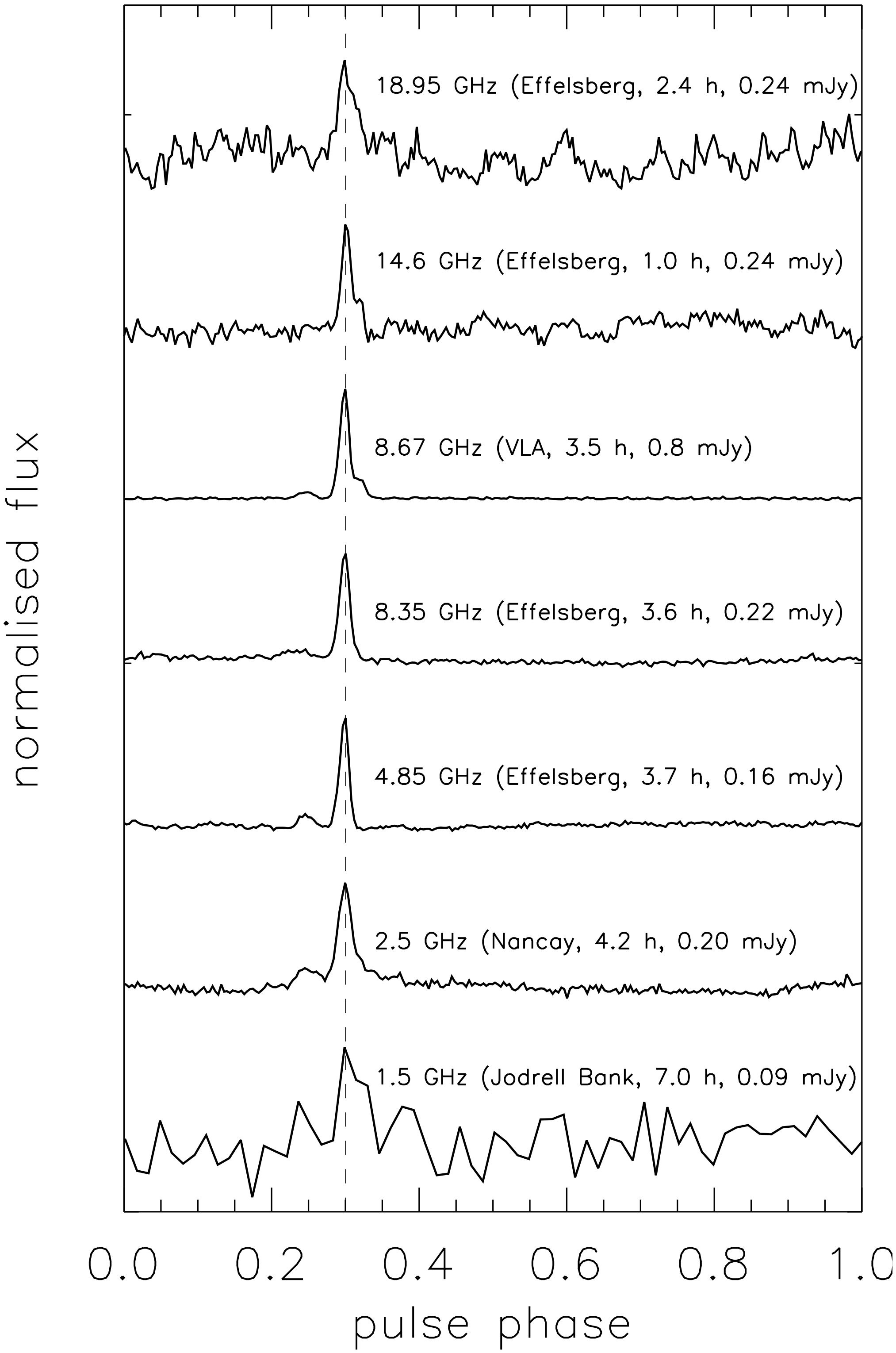
SGR J1745-29

X-ray Localization: ~2" to Sgr A*



Rea et al. 2013

2" ~ 0.1 pc

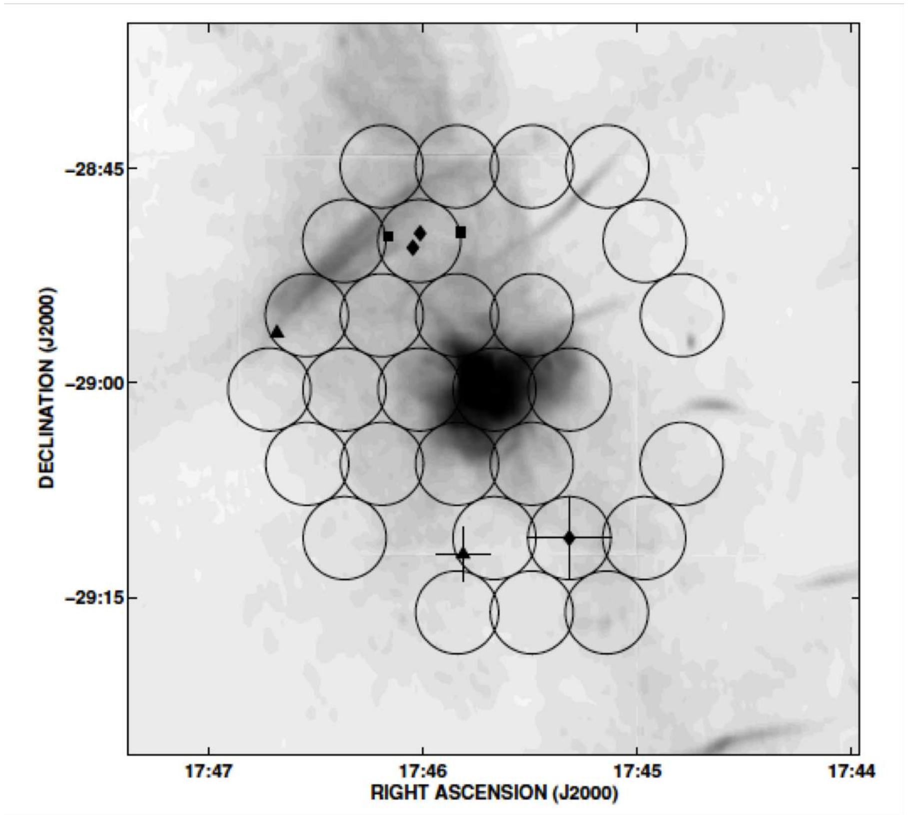


Radio Detection

- P = 3.76354676(2) s
- P/Pdot → B ~ 10^{14} G
- $T_{spindown}$ ~ 9000 yrs
- DM = 1778 +/- 3 cm^{-3} pc
- RM = -7 x 10^4 rad m^{-2}
- Flux ~0.2 - 1 mJy
- spectrum ~flat
- Only 4 radio magnetars known – chance alignment is 10^{-8}

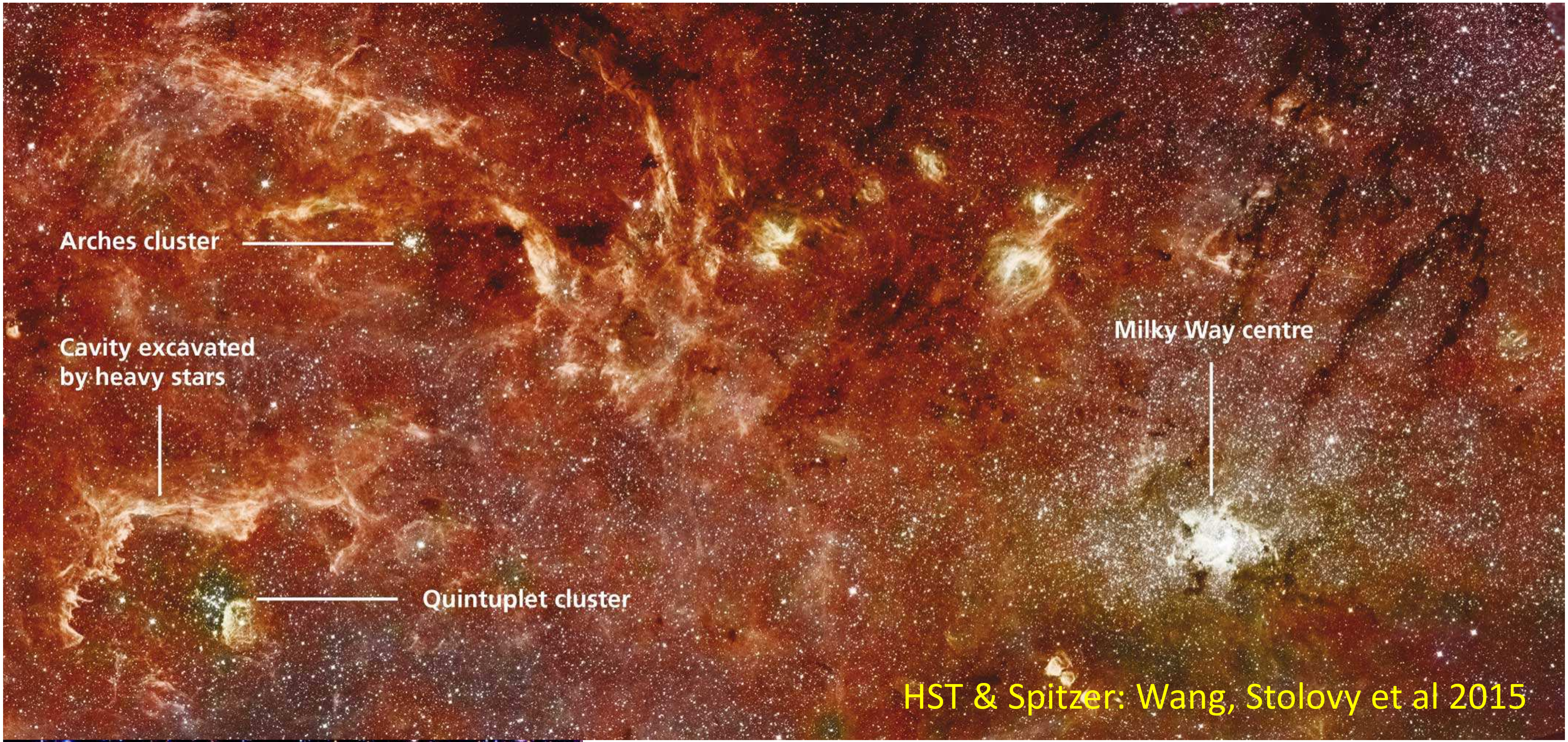
Eatough et al. 2013
Shannon and Johnston 2013

Known GC Pulsars



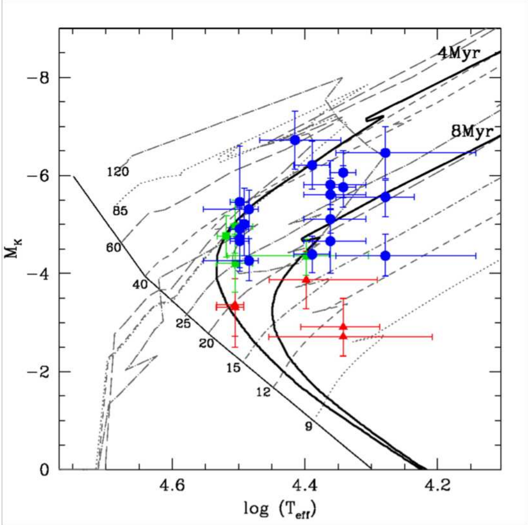
PSR	P (ms)	B (10^{12} G)	DM (pc cm^{-3})	τ_{sc} (2 GHz; ms)
1746-2850I	1077	38	962	100
1746-2850II	1478	3	1456	145
1745-2910	982	---	1088	---
1746–2856	945	4	1168	---
1745–2912	187	---	1130	144

Johnston et al. 2006
Deneva et al. 2009



- WR+OB Stars
- T~2.5 – 5.8 Myr
- $M \sim 10^4\ M_{sun}$

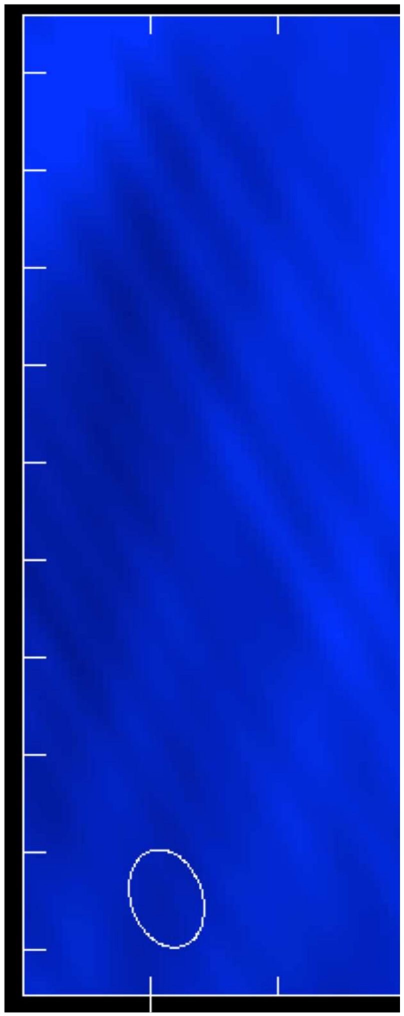
Paumard et al 2006, Lu et al 2013

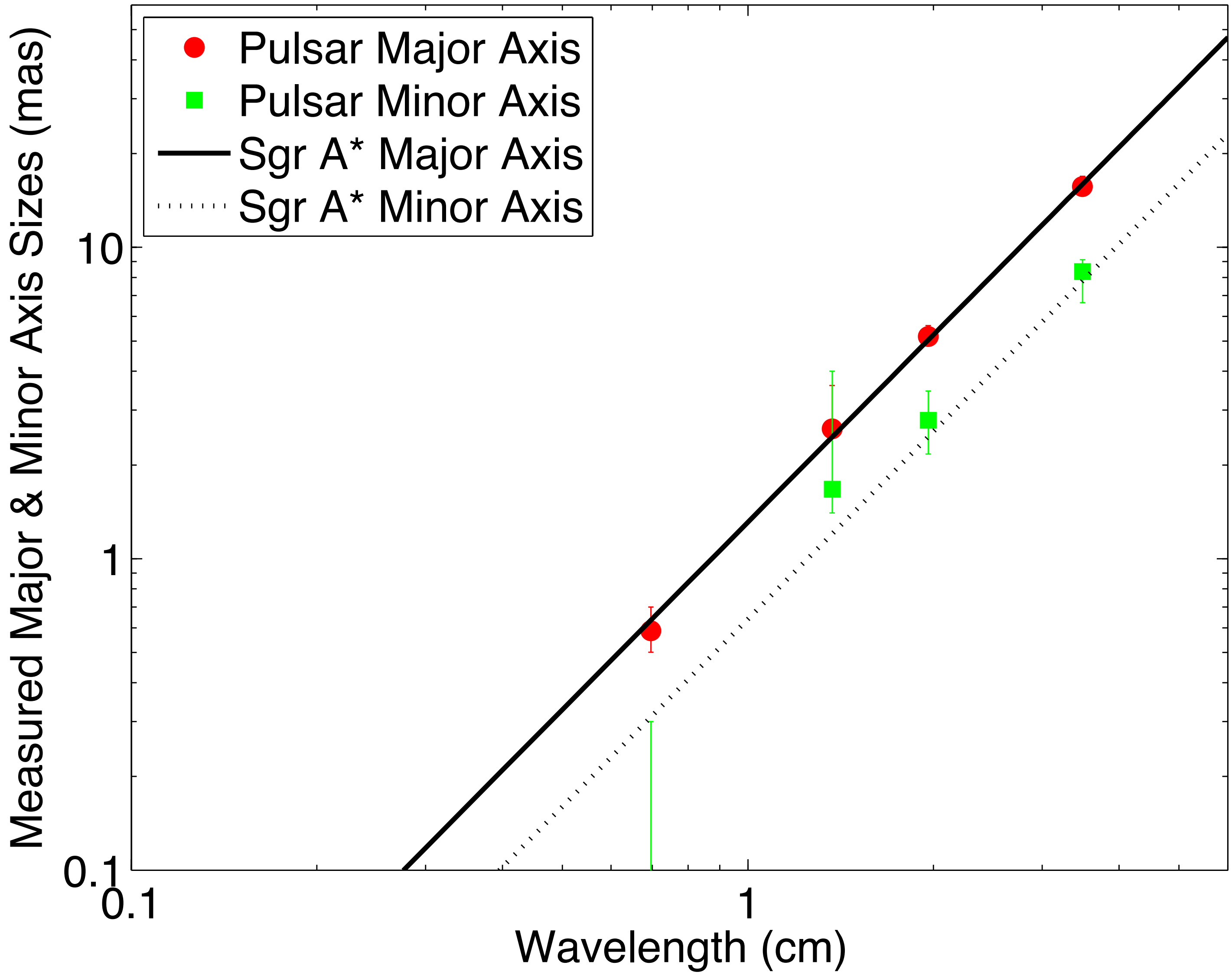


- 10^3 pulsars with P < 100 y

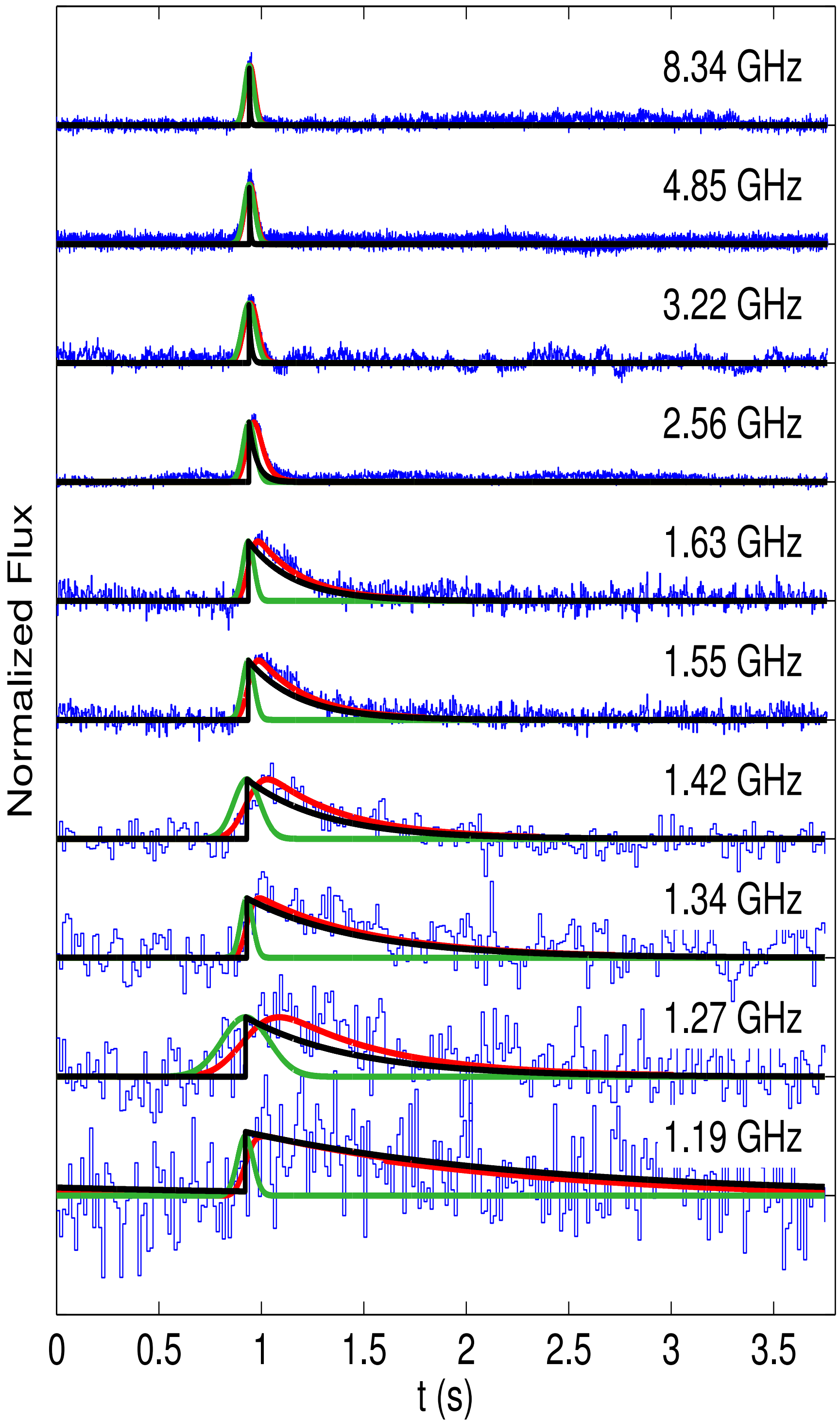
Pfahl & Loeb 2004

Angular Broadening of the Pulsar

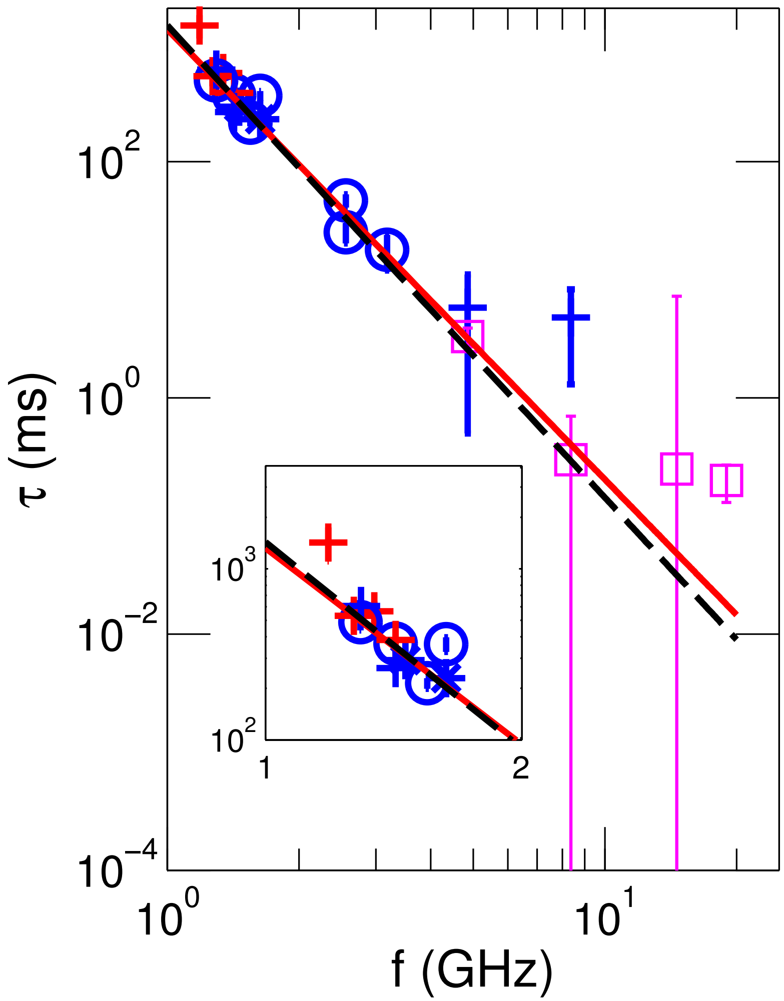




Bower et al. 2014

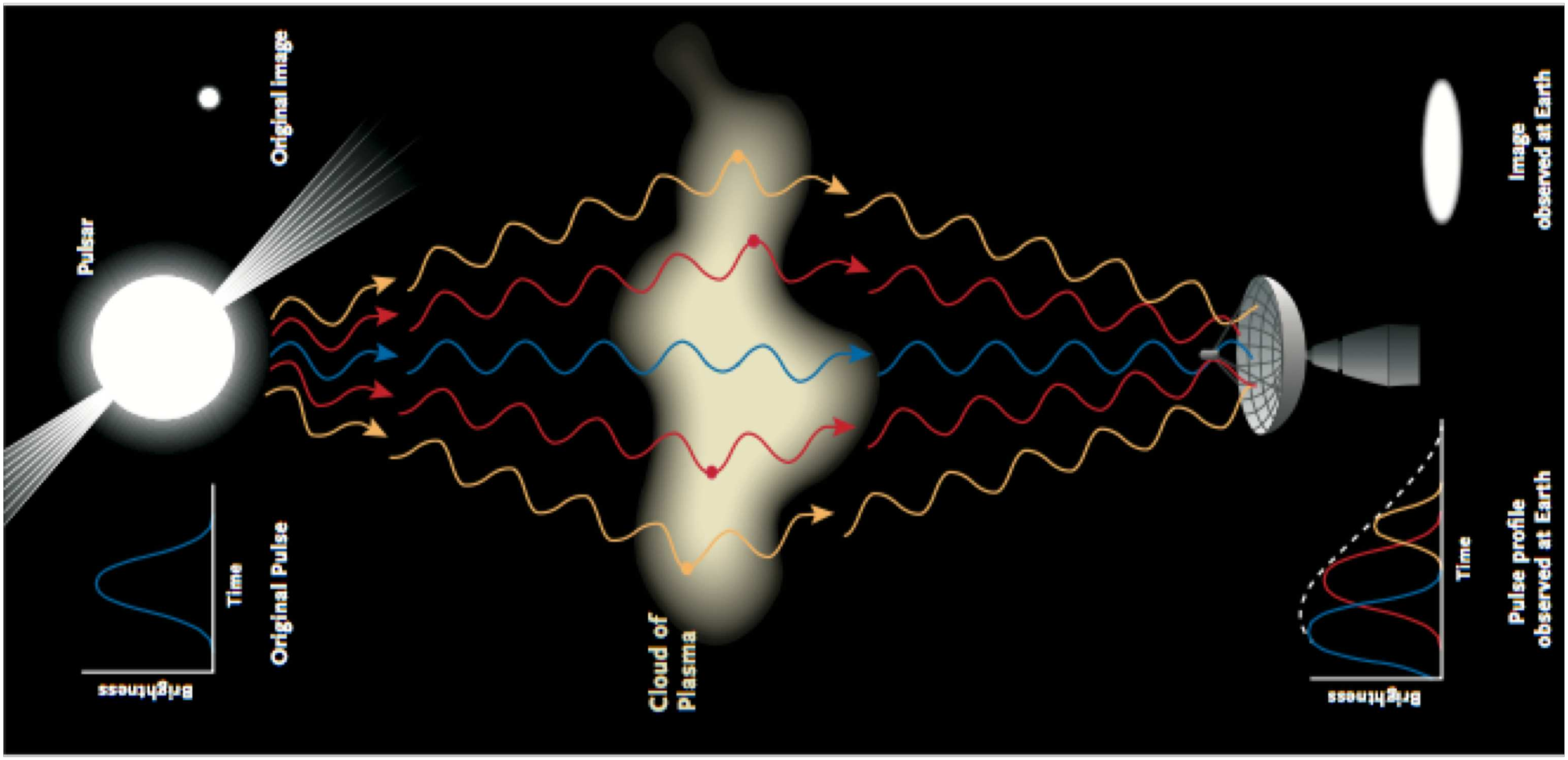


Temporal Scattering



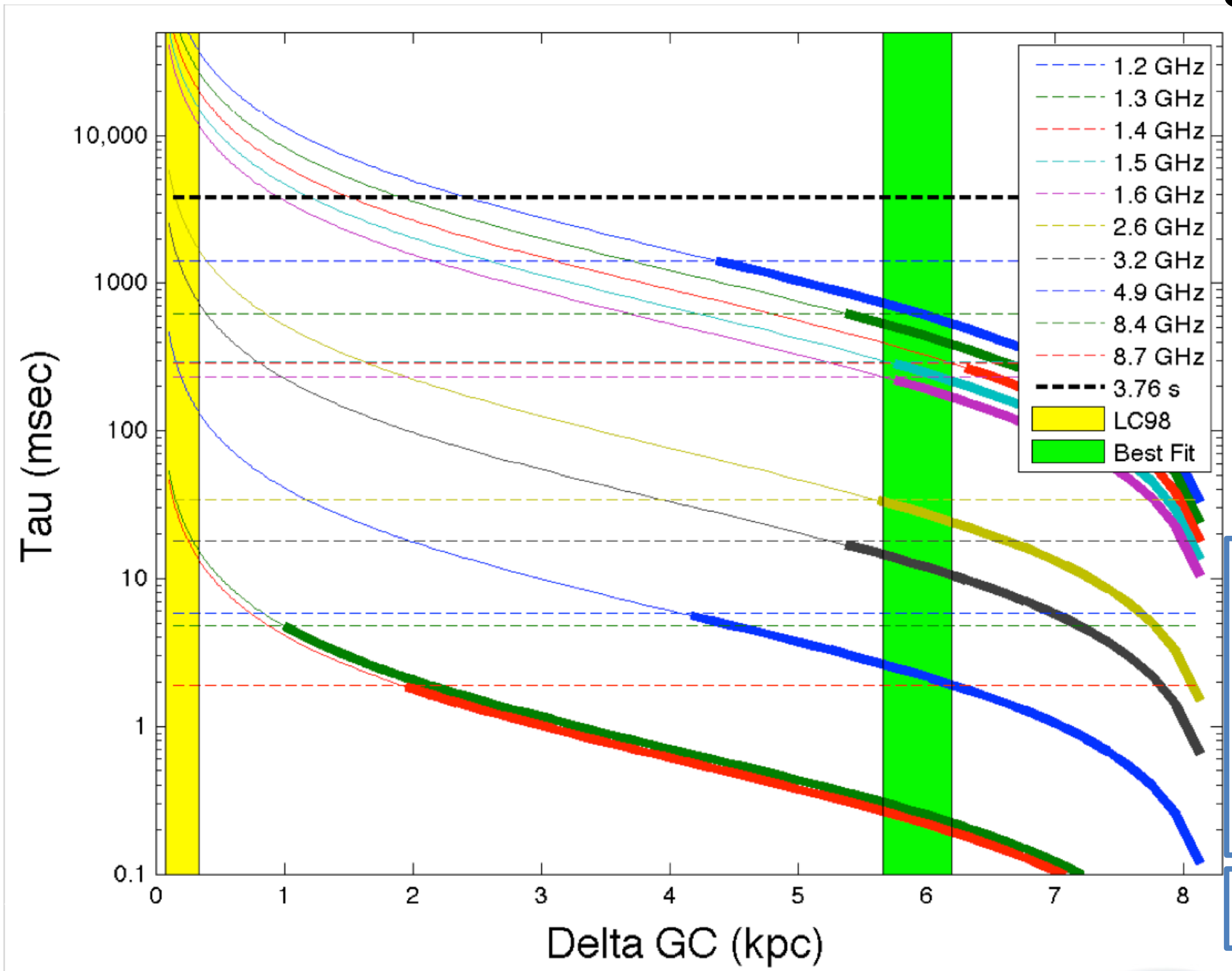
Spitler et al. 2014

Scattering Inhibits Imaging



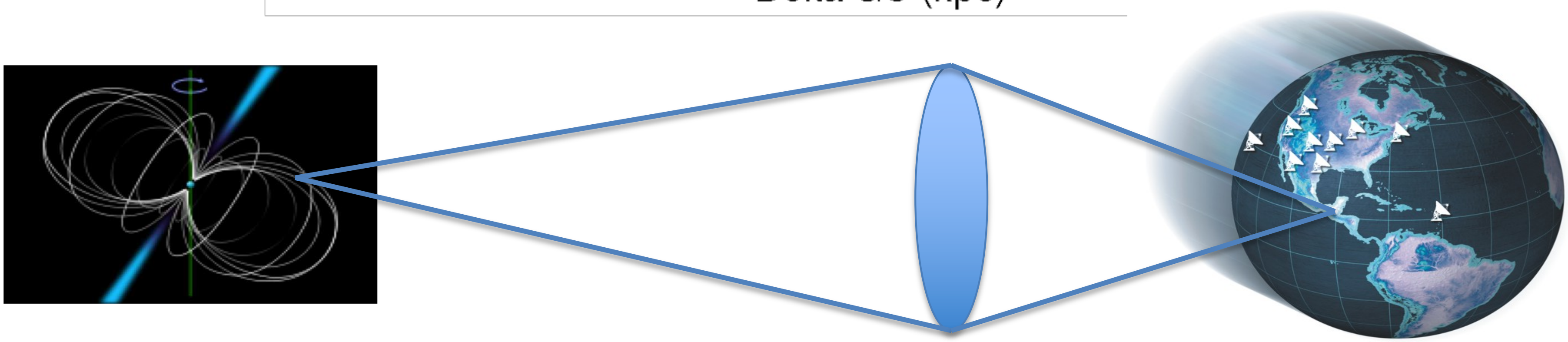
Haggard & Bower, Sky & Tel, 2016

A New Distance for the GC Scattering Screen

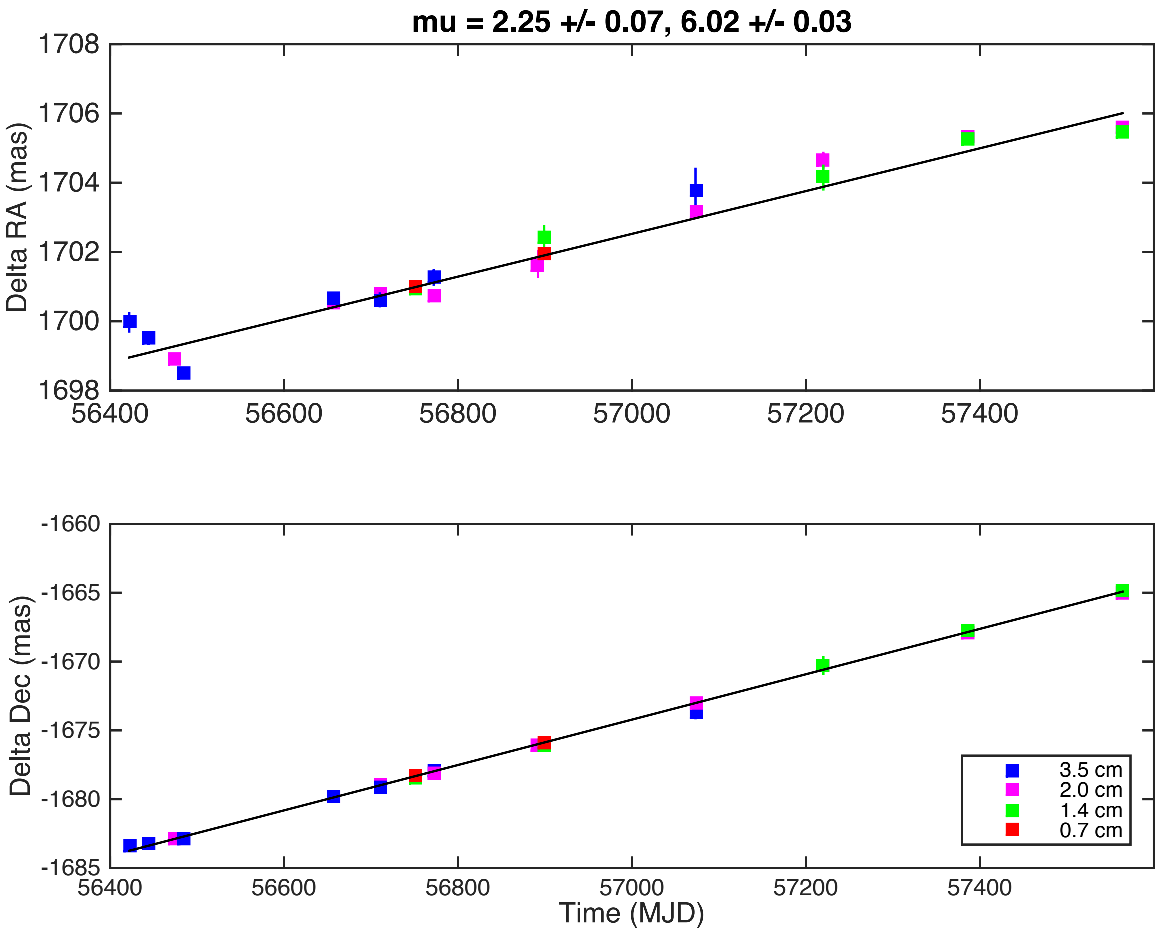


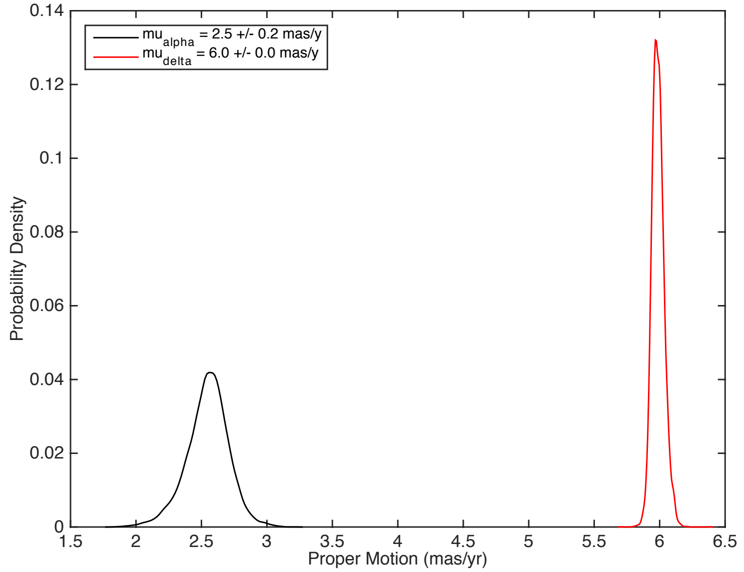
Alternate Solution: Uniform Distribution of scatterers between GC & Sun

Bower et al. 2014

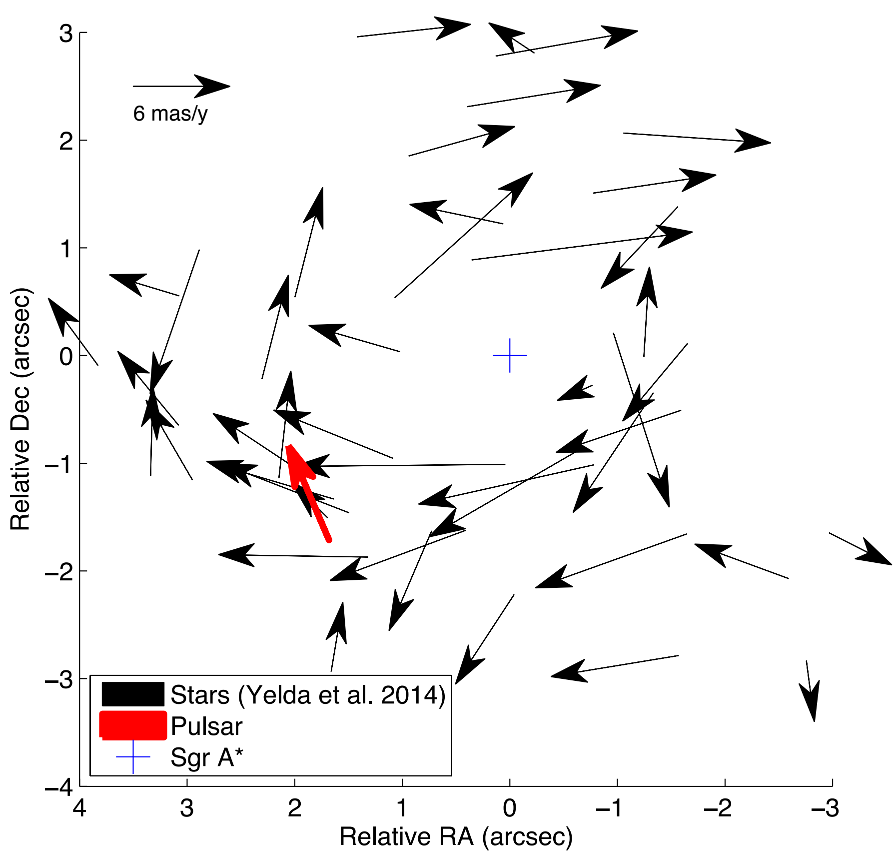


Astrometry of SGR J1745-29





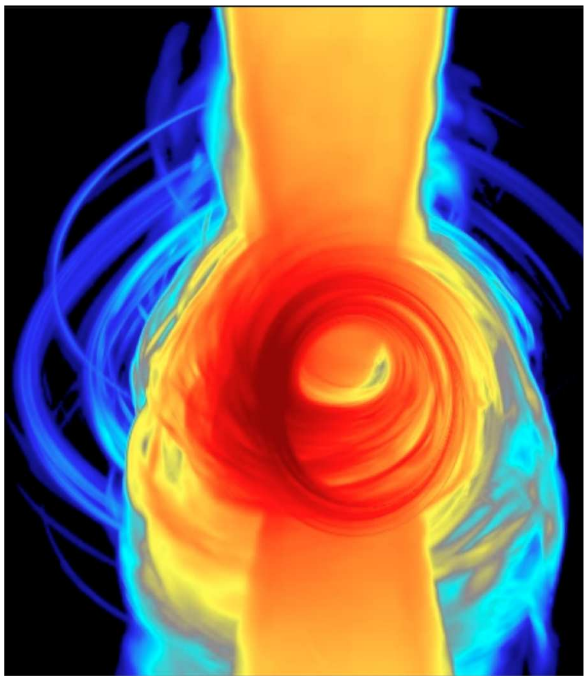
The GC Pulsar Likely Originates in the Clockwise Stellar Disk



- V_{proj}=240 +/- 3 km s^{-1}
- R_{proj}=0.097 pc
- P>700 y

- Acceleration measures |z| and would conclusively demonstrate that the PSR is bound to Sgr A*

Exciting Times in the Galactic Center



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