Imaging and Filming Black Holes with the Event Horizon Telescope

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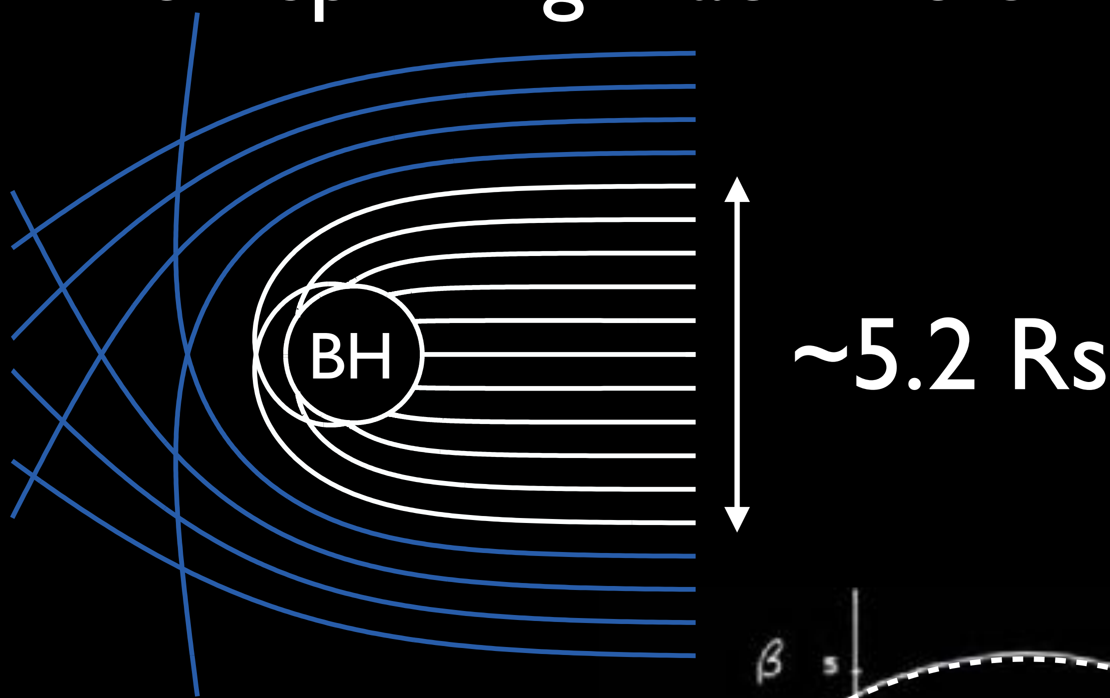
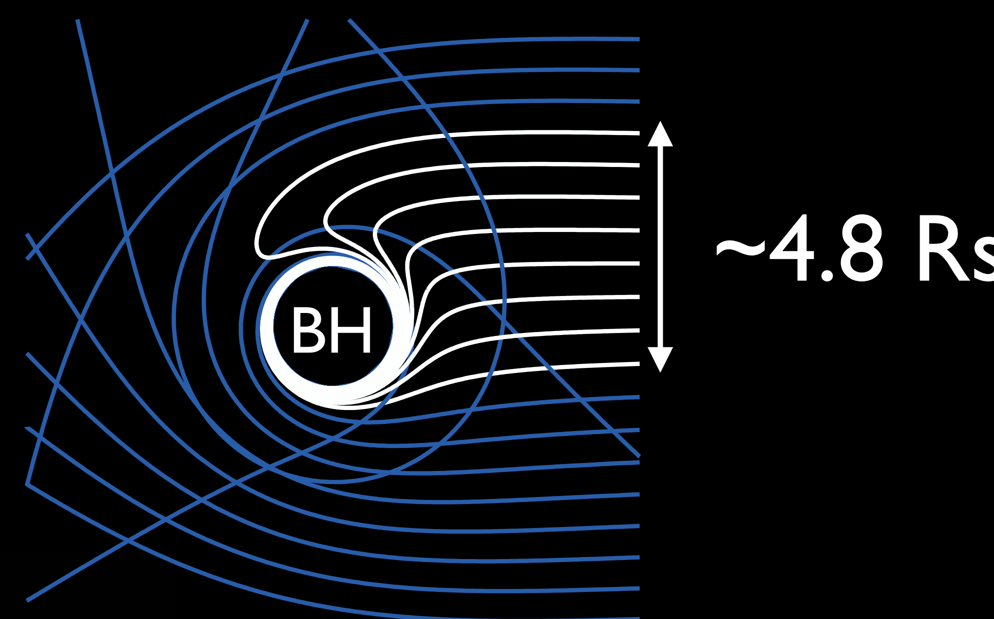
The Event Horizon Telescope Consortium

The Shadow of the Black Hole

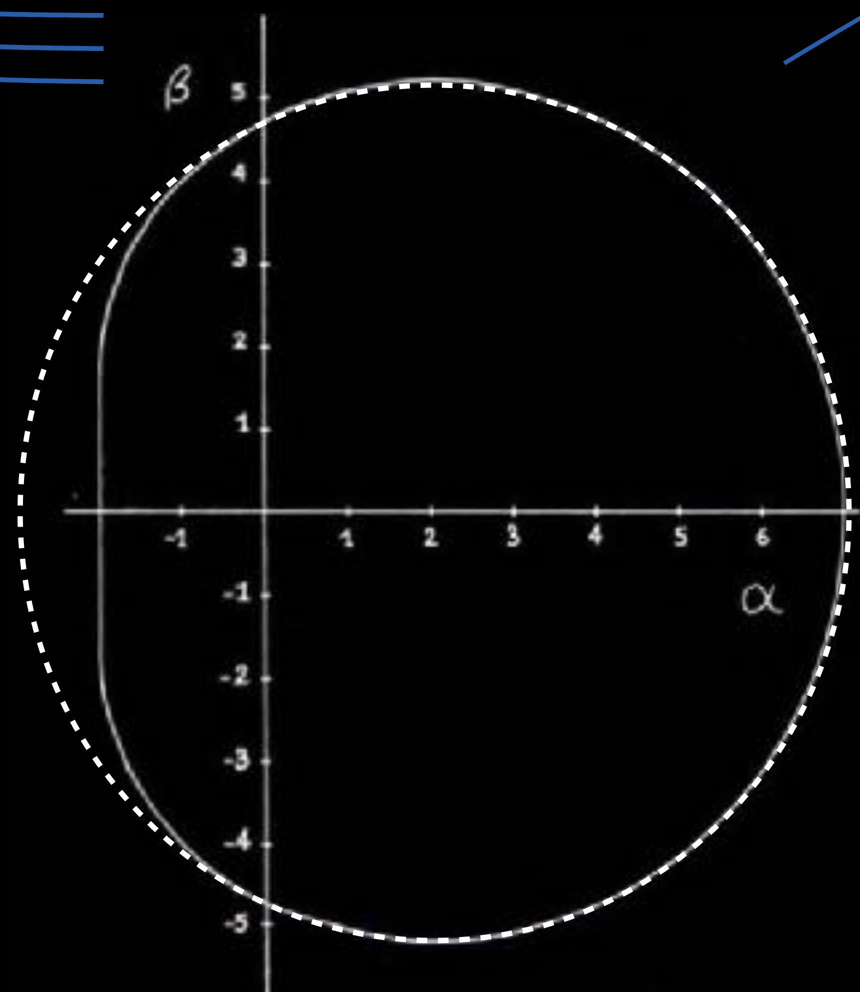
Non-spinning Black Hole



Maximumly spinning BH



(Courtesy of Hung-Yi Pu)



Black Holes cast shadows
(Bardeen 1973; Falcke et al. 2000)
with a radius that changes
only by 4% with the spin
(Johannsen & Psaltis 2010)

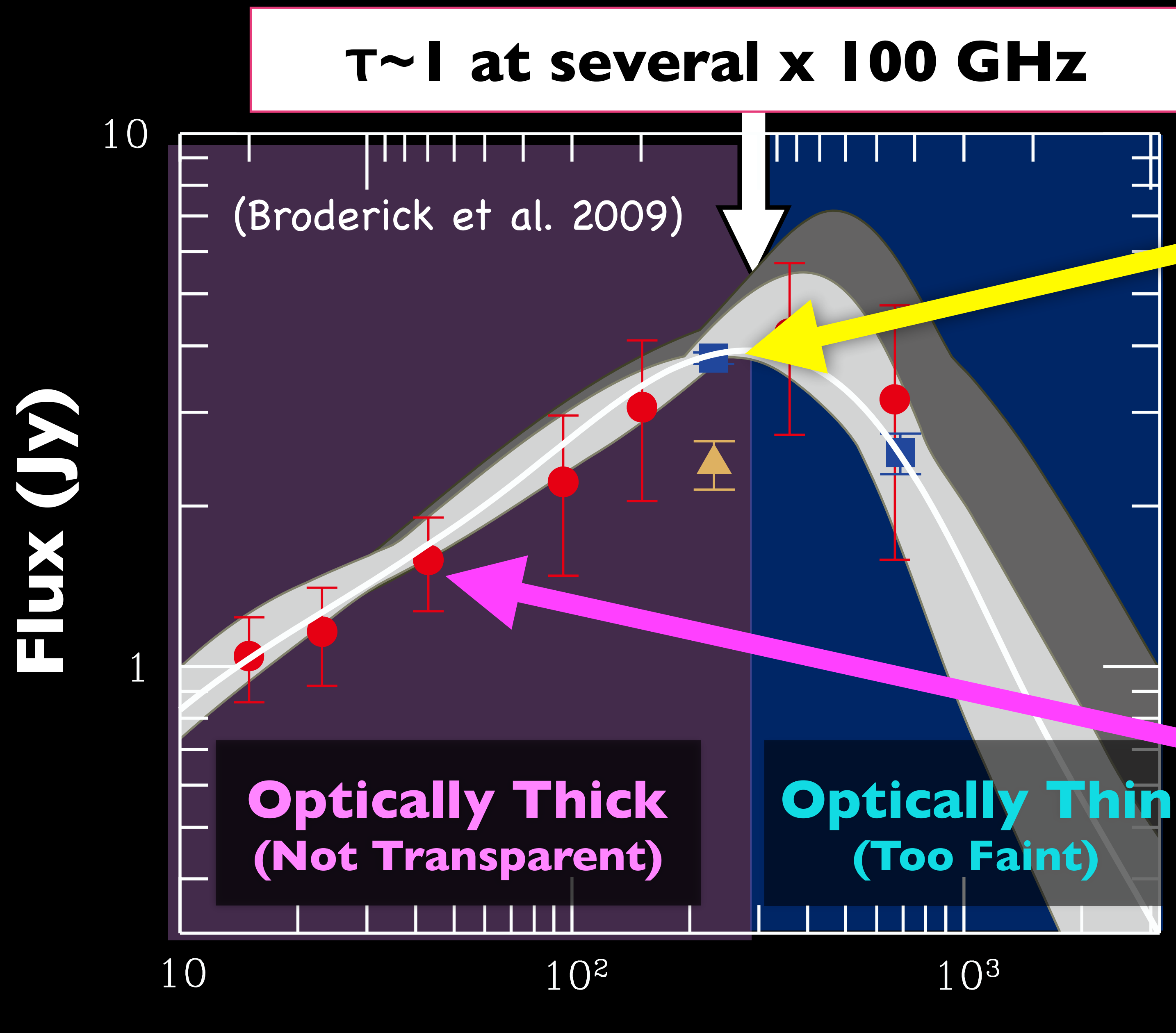
Event Horizon Telescope

Black Holes with the Largest Angular Sizes

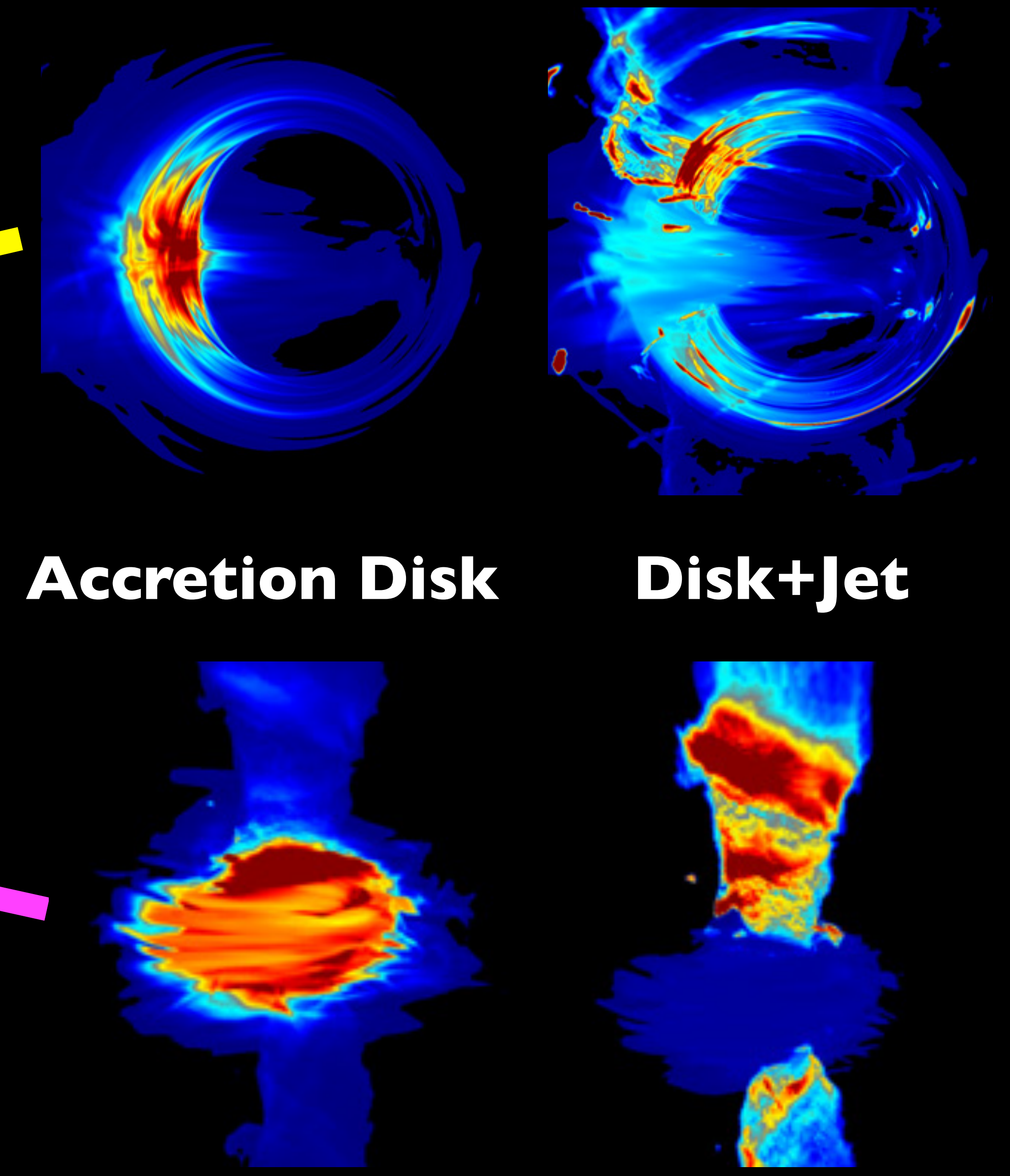
Source	BH Mass (M_{solar})	Distance (Mpc)	Angular radius of R_s (µas)
Sgr A* Galactic Center	4×10^6	0.008	10
M87 Virgo A	$3 - 6 \times 10^9$	16.5	3.6 - 7.3
M104 Sombrero Galaxy	1×10^9	10	2
Cen A	5×10^7	4	0.25

Event Horizon Telescope

The best frequency to see black holes

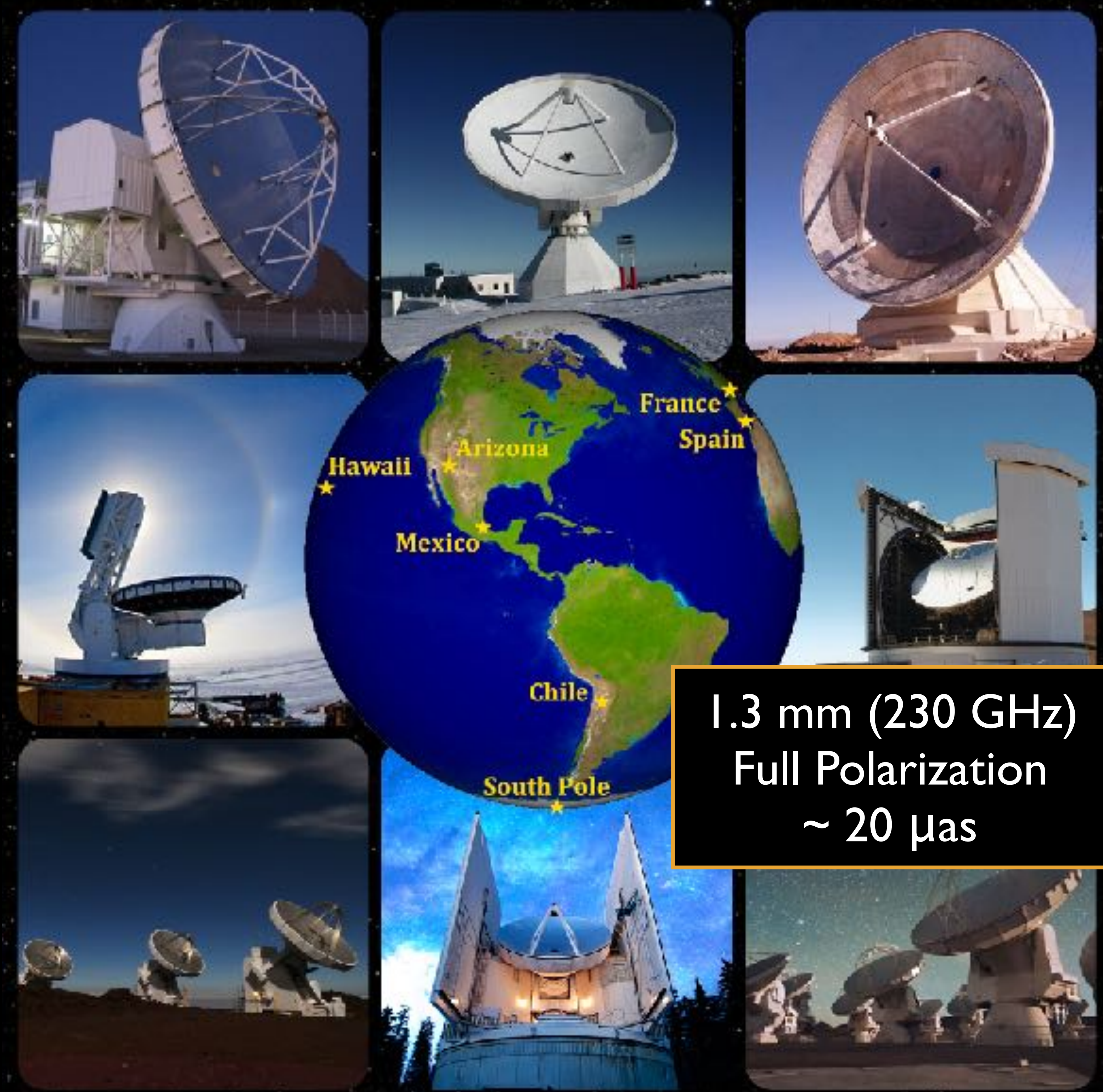


(Adapted from Broderick et al. 2009, ApJ)



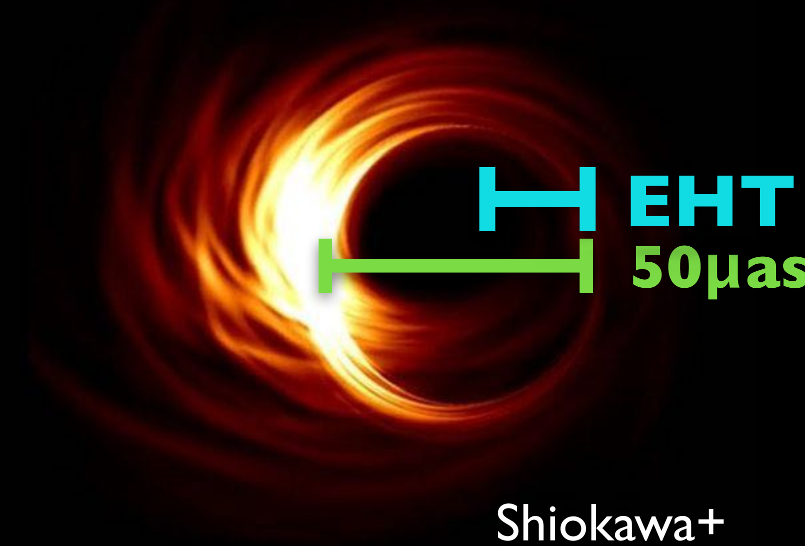
Moscibrodzka et al. 2014, A&A

Event Horizon Telescope



1.3 mm (230 GHz)
Full Polarization
~ 20 μas

Sgr A*

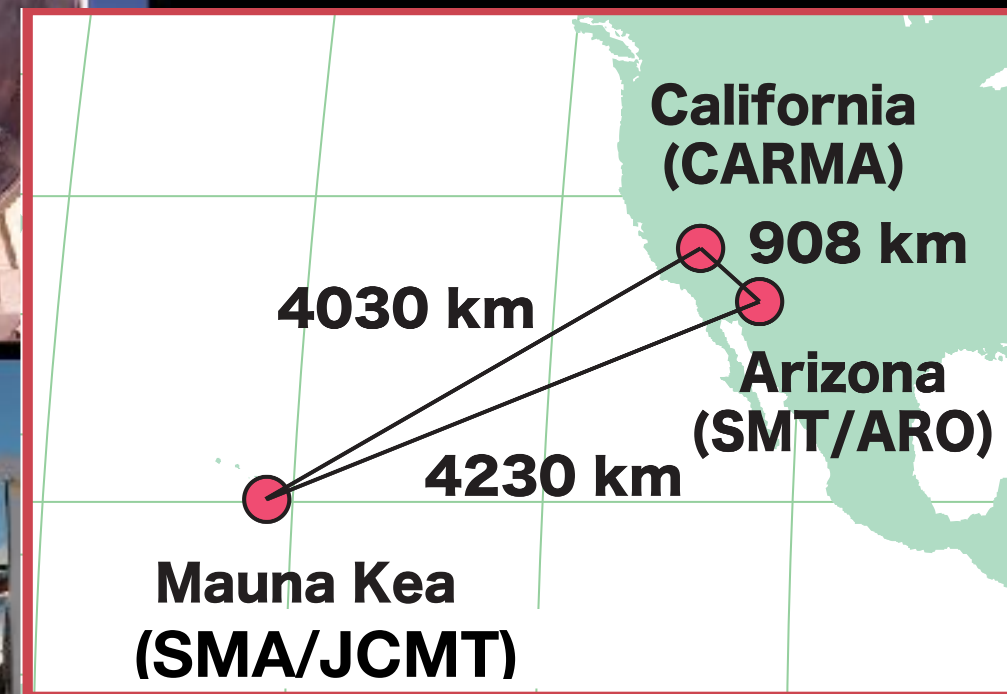


Shiokawa+

M87

Moscibrodkza, Dexter+17

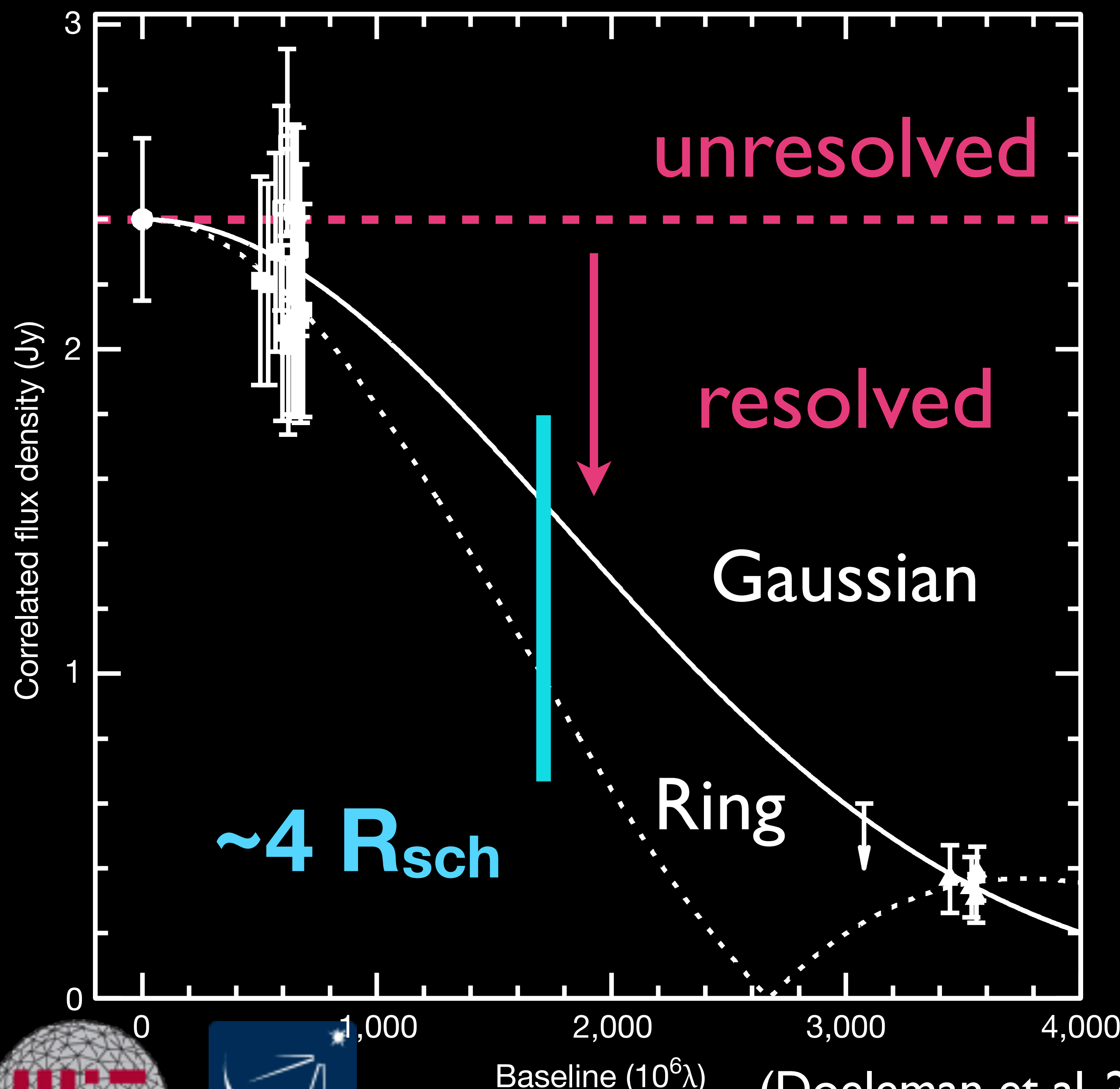
‘Early’ Event Horizon Telescope



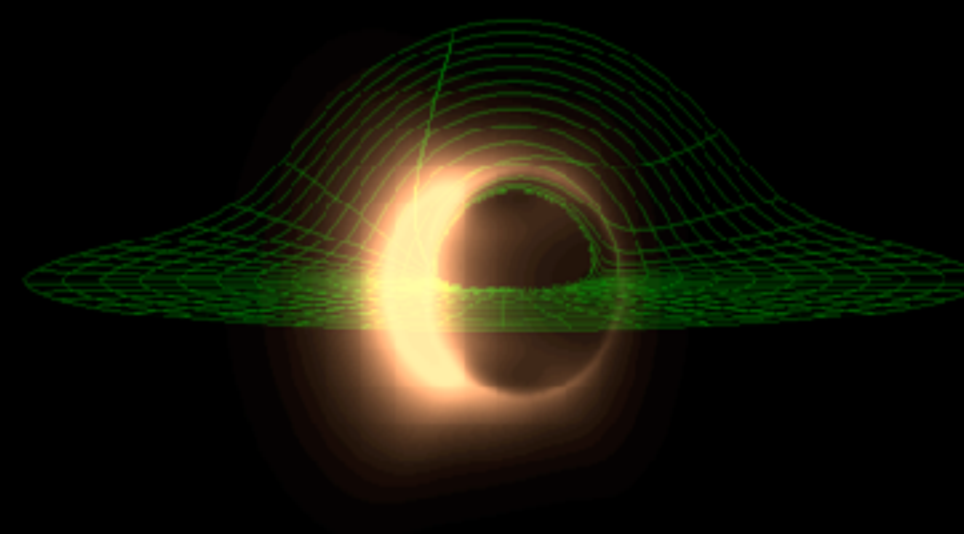
Event Horizon Telescope

Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)
   The emission is offset from the black hole



(Doeleman et al. 2008, Nature)

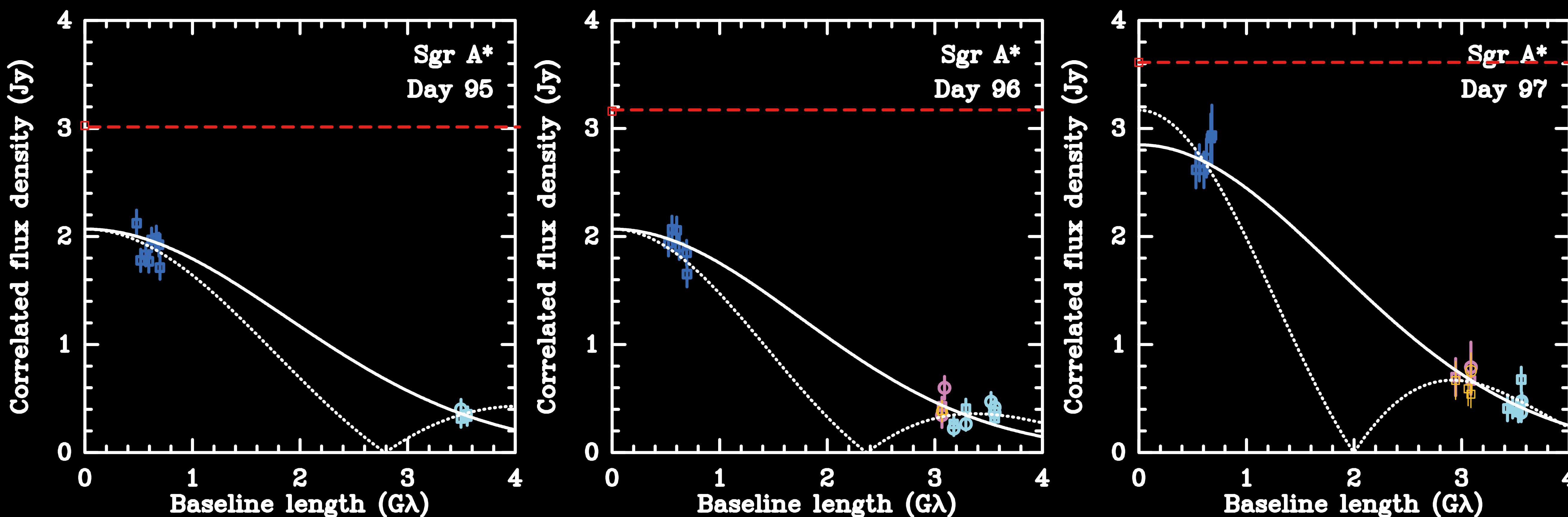


Broderick & Loeb 2006

Event Horizon Telescope

Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)
   The emission is offset from the black hole
2. Variability occurs on small (ISCO) scales (2009)

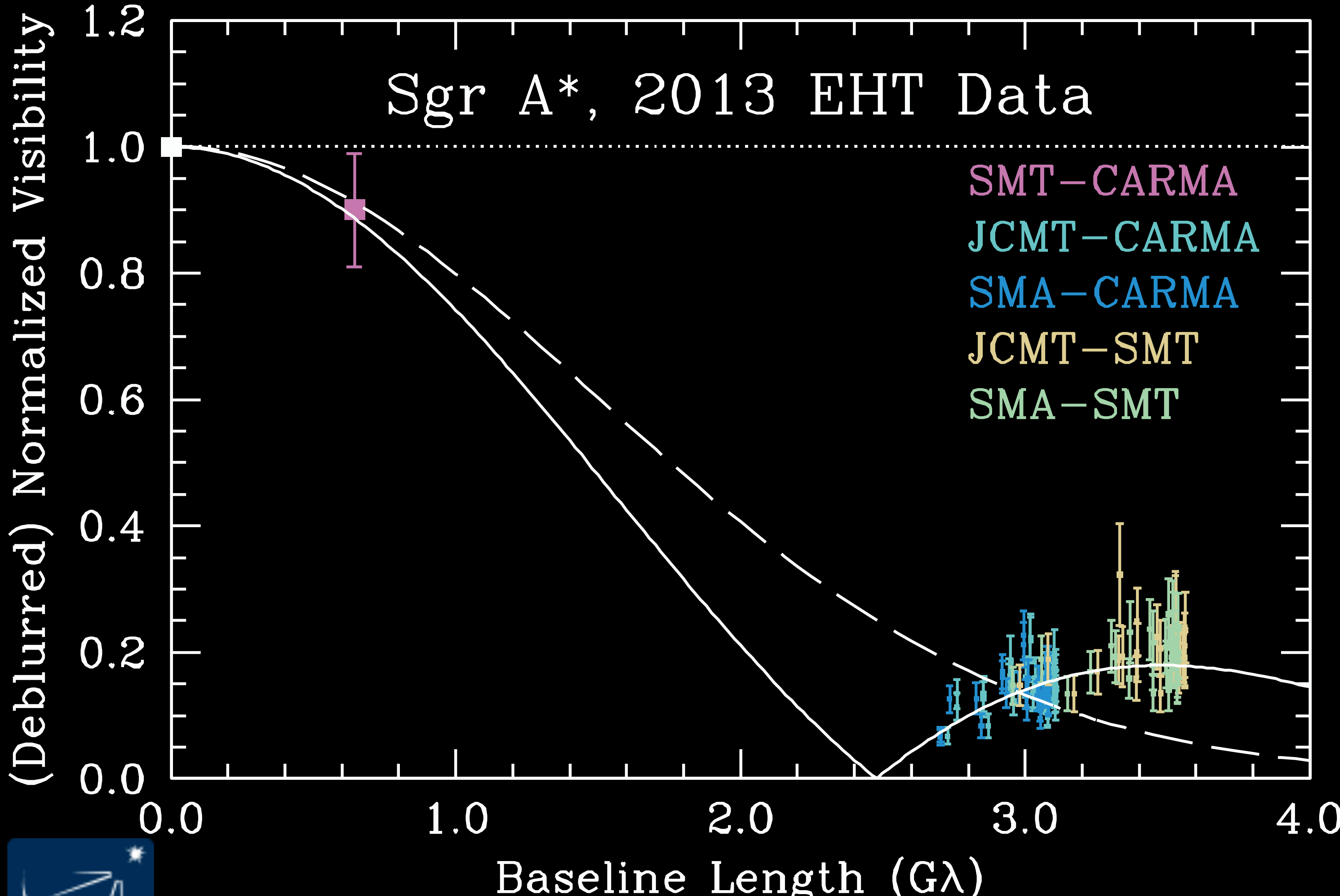


Fish et al. 2011, ApJL

Event Horizon Telescope

Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)
   The emission is offset from the black hole
2. Variability occurs on small (ISCO) scales (2009)
3. Discovery of the non-Gaussian-shape in the structure (2013)



Johnson+2015, Science
Lu+2018, ApJ

Event Horizon Telescope

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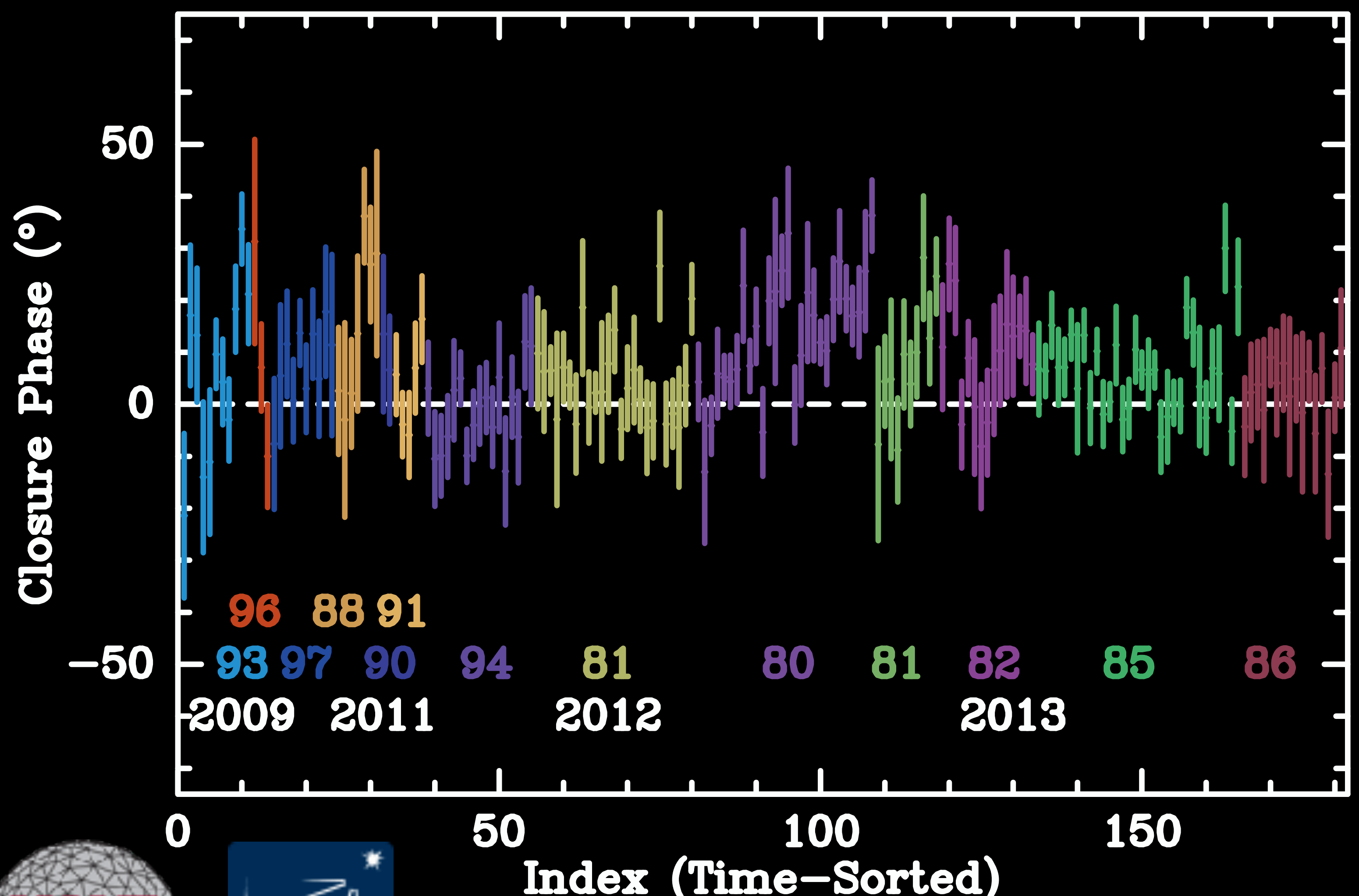
4. Discovery of the asymmetry in the structure (2007 - 2013)



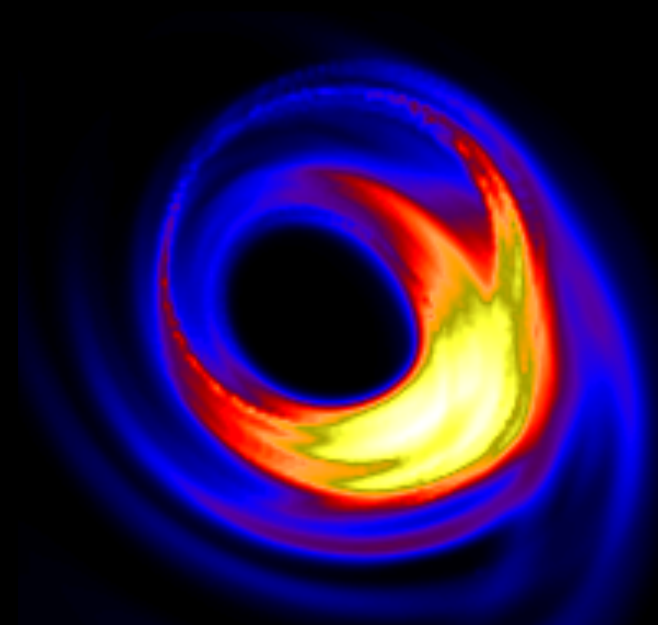
Broderick et al. 2016, ApJ
Fish et al. 2016, ApJ

Event Horizon Telescope

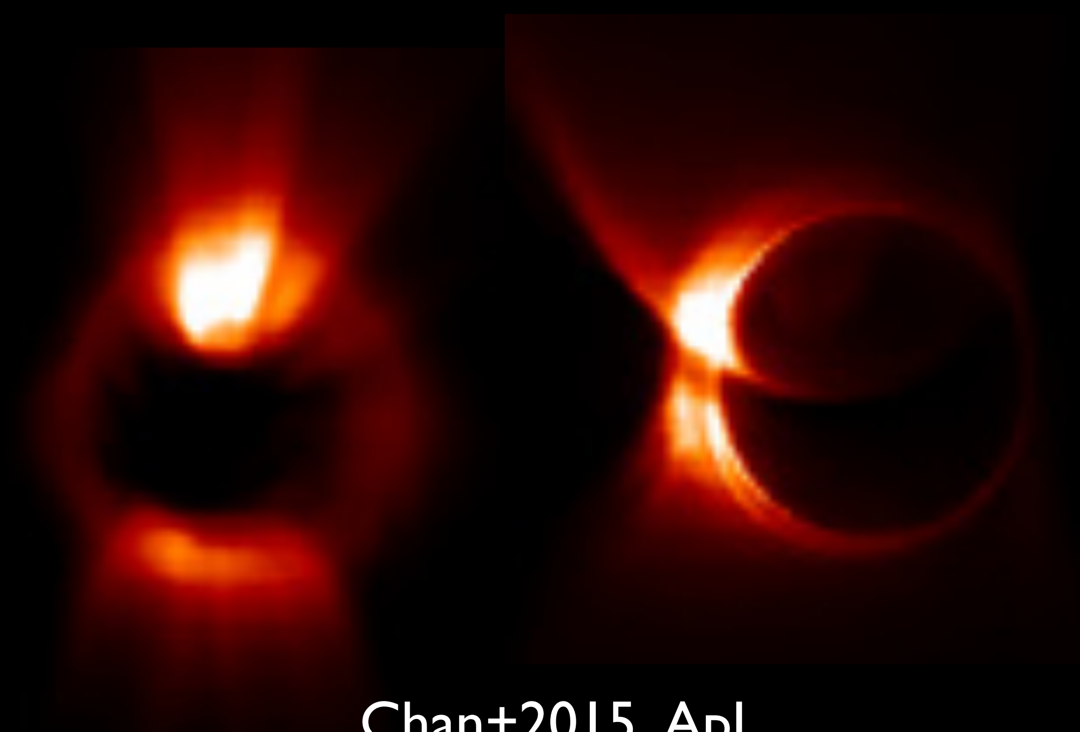
Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)
   The emission is offset from the black hole
2. Variability occurs on small (ISCO) scales (2009)
3. Discovery of the non-Gaussian-shape in the structure (2013)
4. Discovery of the asymmetry in the structure (2007 - 2013)
5. Analytic RIAF models/GRMHD models disfavor face-on disk

Broderick+2016, ApJ



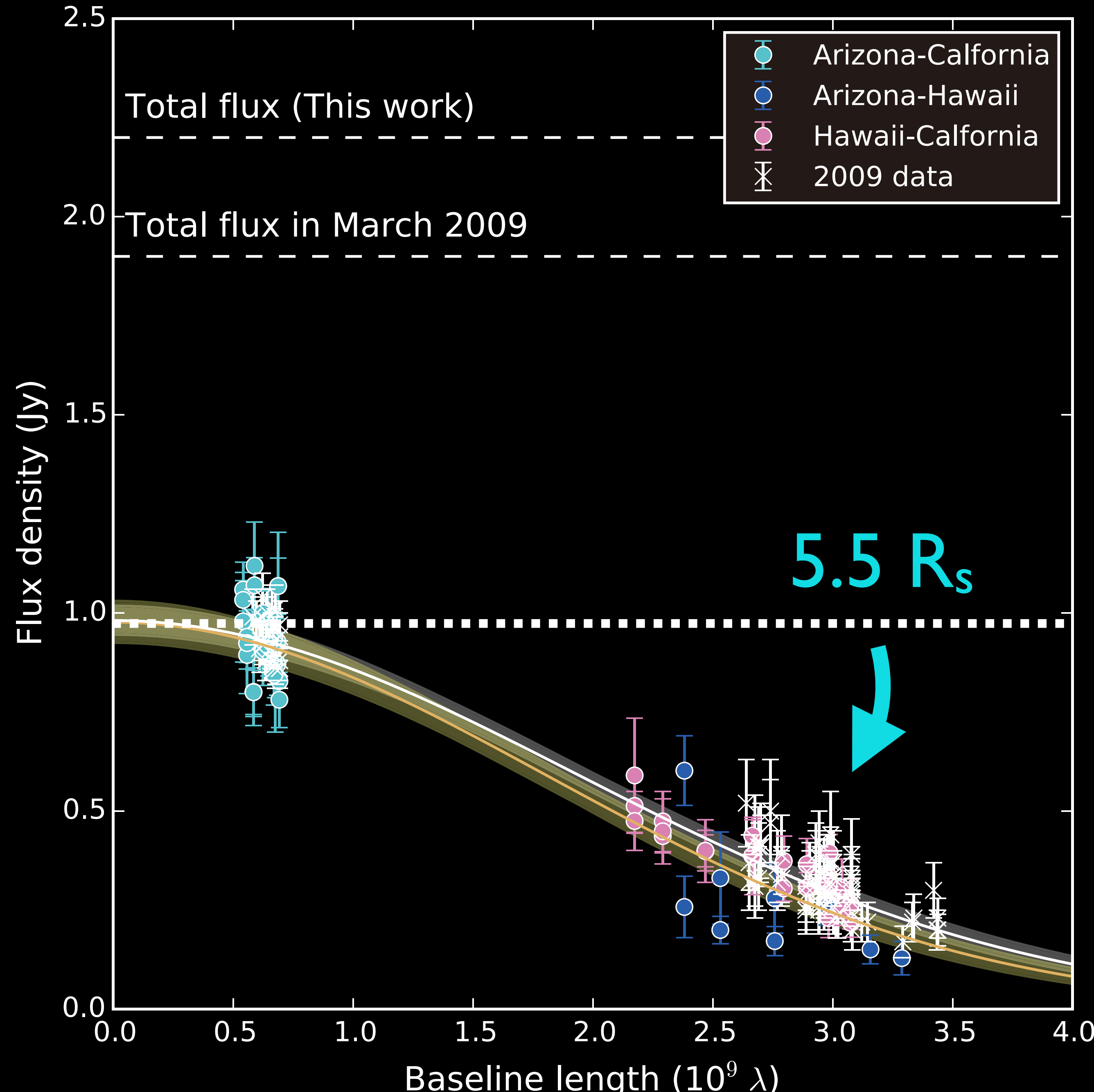
Dexter+2010 ApJ
(180deg flipped)



Chan+2015 ApJ

Early M87 observations

1. 1.3 mm emission is very compact (2009, 2012)

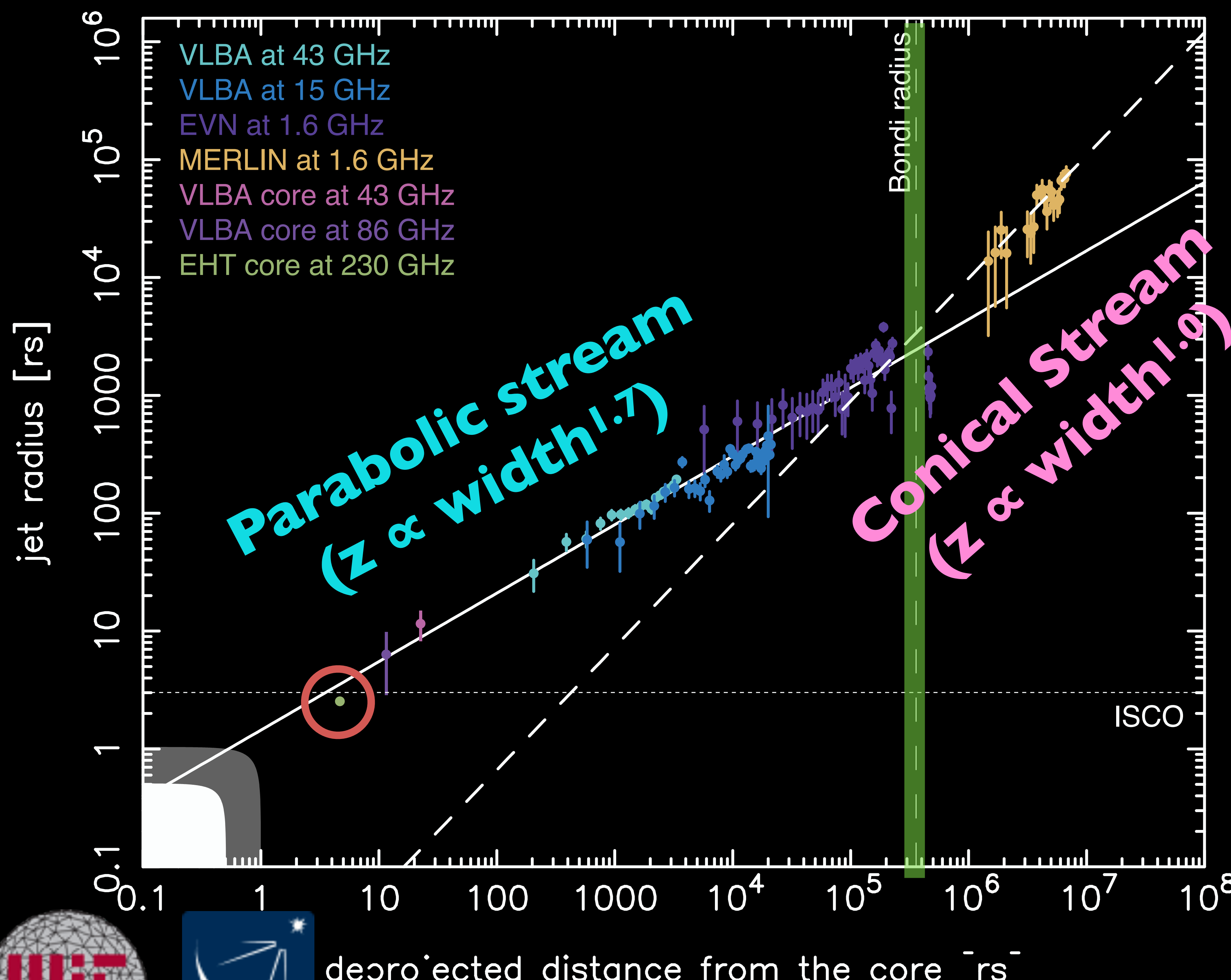


(Doeleman et al. 2012, Science, *Akiyama* et al. 2015, ApJ)

Event Horizon Telescope

Early M87 observations

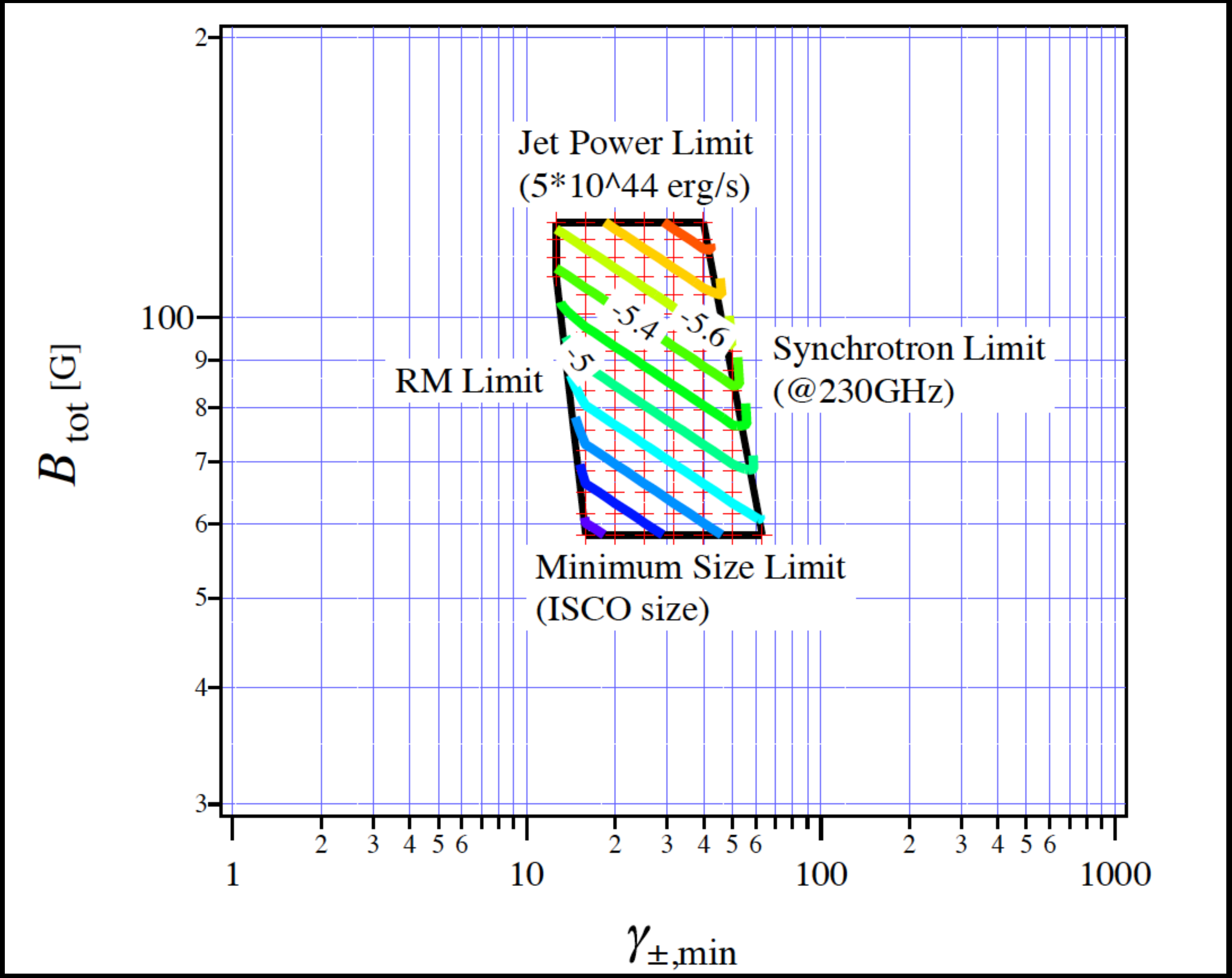
1. 1.3 mm emission is very compact (2009, 2012)
   Consistent with the parabolic collimation profile of the jet



Asada & Nakamura 2012
Doeleman et al. 2012
Nakamura & Asada 2013
Hada et al. 2013, 2016
Asada et al. 2016

Early M87 observations

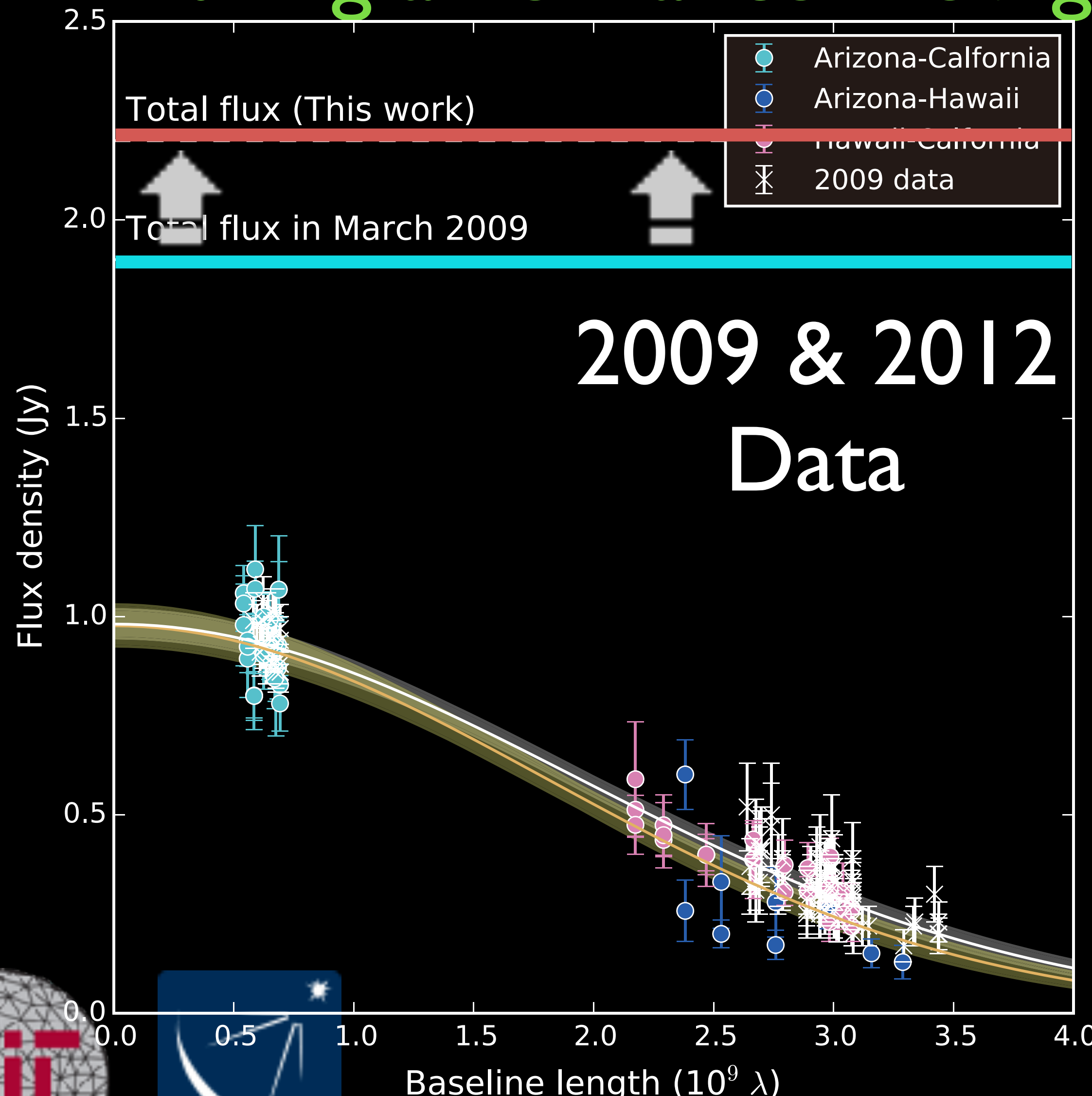
1. 1.3 mm emission is very compact (2009, 2012)
   Consistent with the parabolic collimation profile of the jet
   The jet base is magnetically dominated

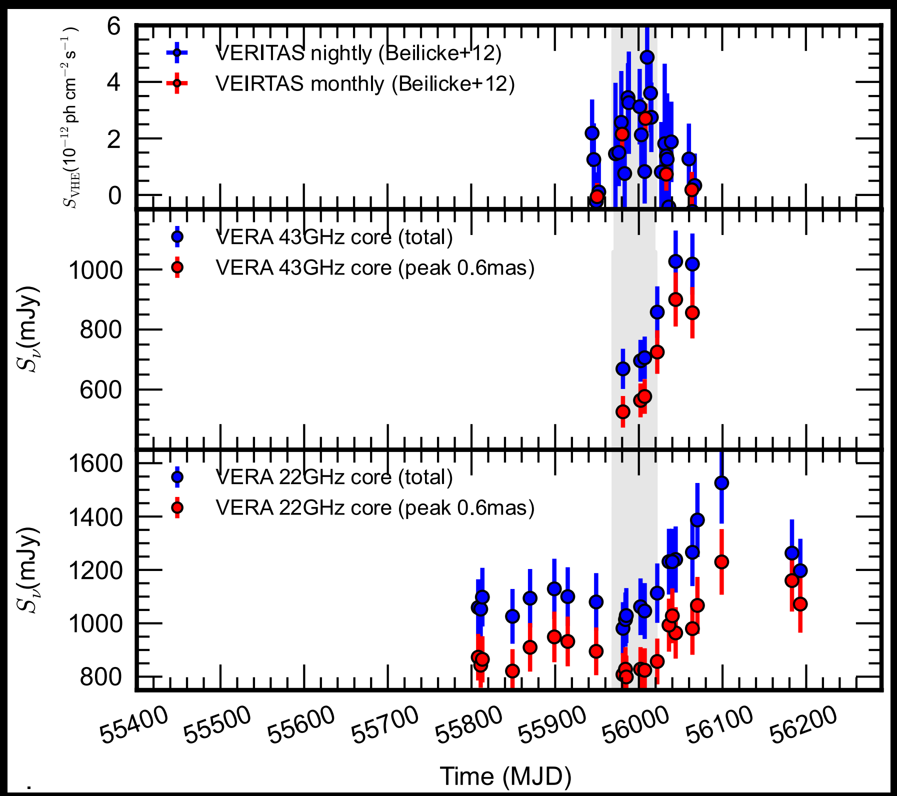


Kino et al. 2015, ApJ

Early M87 observations

1. 1.3 mm emission is very compact (2009, 2012)
   Consistent with the parabolic collimation profile of the jet
   The jet base is magnetically dominated
2. Event Horizon Scale structure is stable
   during an enhanced TeV gamma-ray state (2012)





TeV γ-ray

43 GHz

22 GHz

TeV emission region ~ 20 - 60 R_s

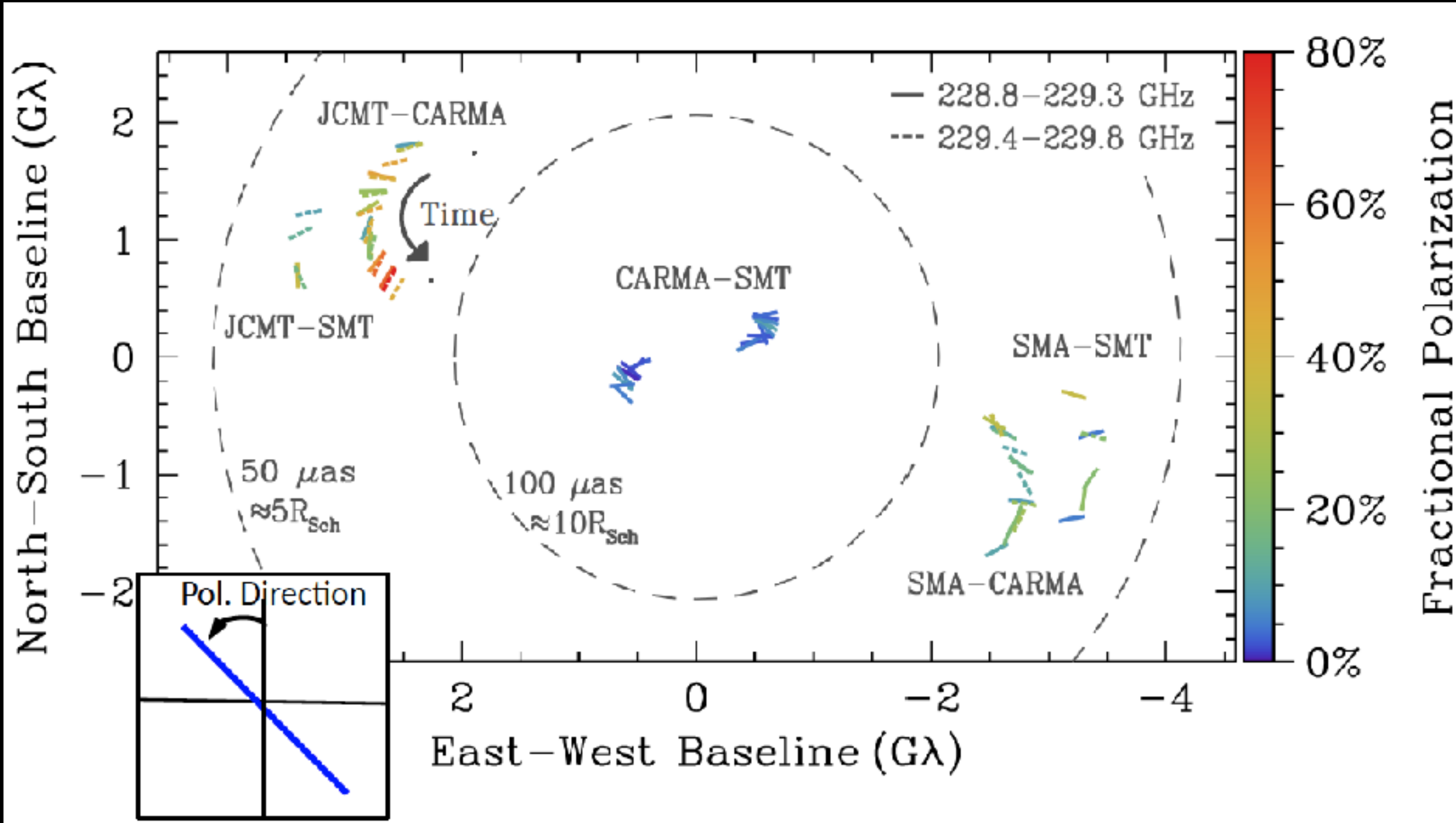
Akiyama et al. 2015, ApJ

Event Horizon Telescope

HAYSTACK OBSERVATORY

NRAO

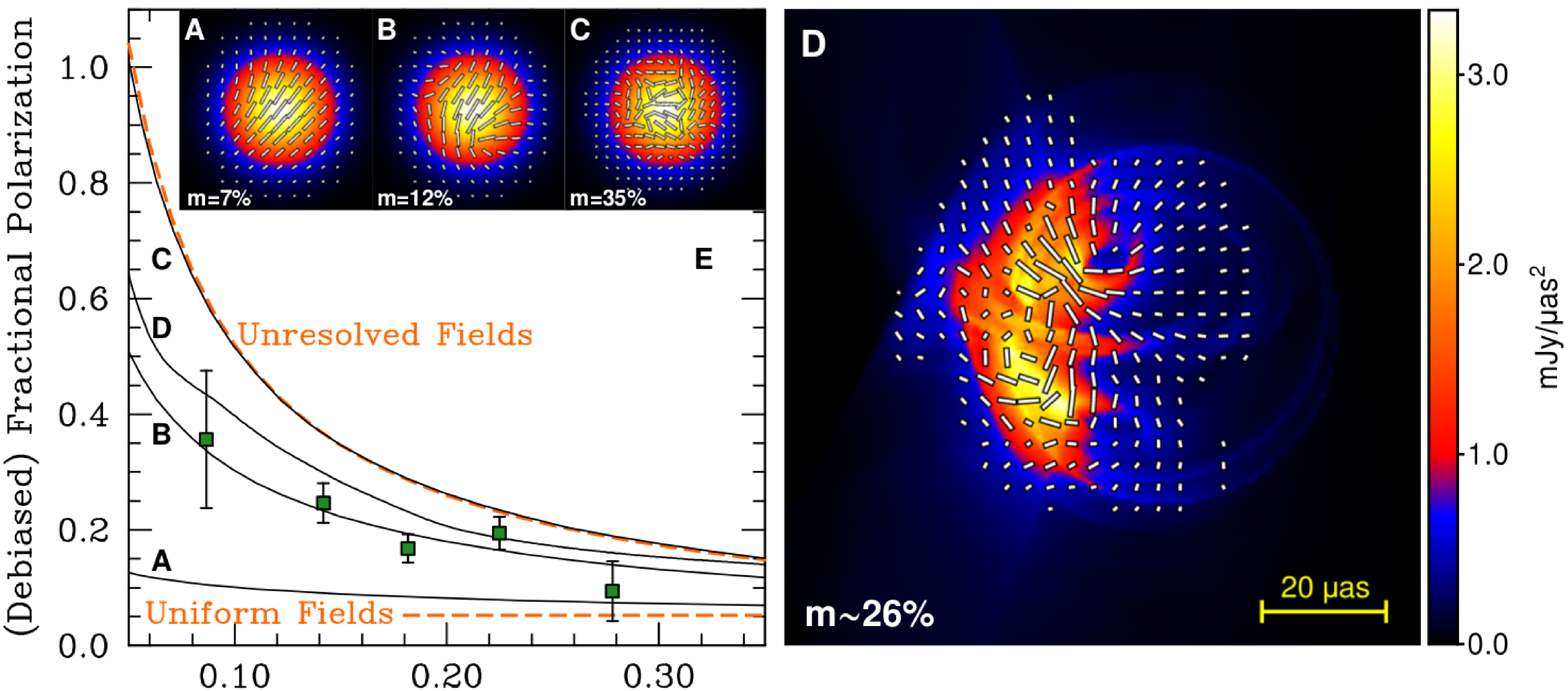
Rs-scale Polarization of Sgr A*



Johnson et al. 2015, Science

Event Horizon Telescope

Ordered Fields at the Event Horizon



More Compact ⟷ Larger Scale

Johnson et al. 2015, Science

EHT Collaboration

2012

2014

2016

Event Horizon Telescope

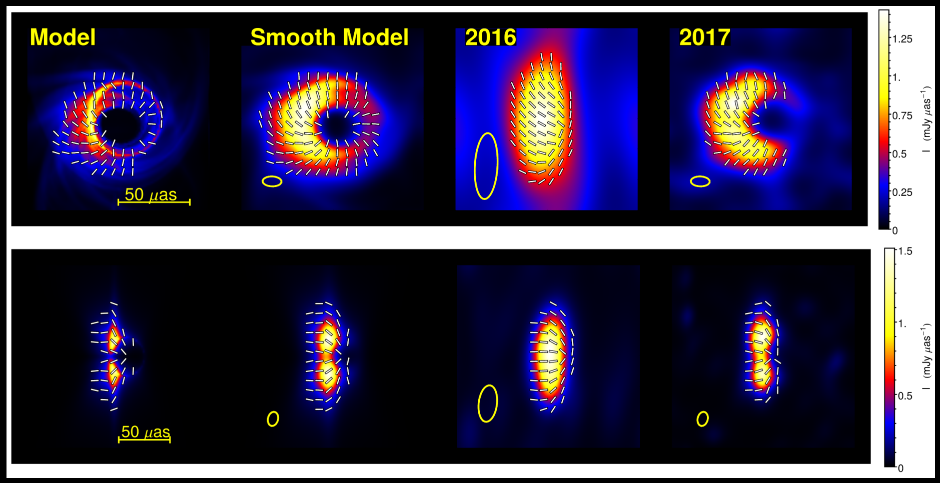
Event Horizon Telescope 2017/2018

Data reduction is on-going !!

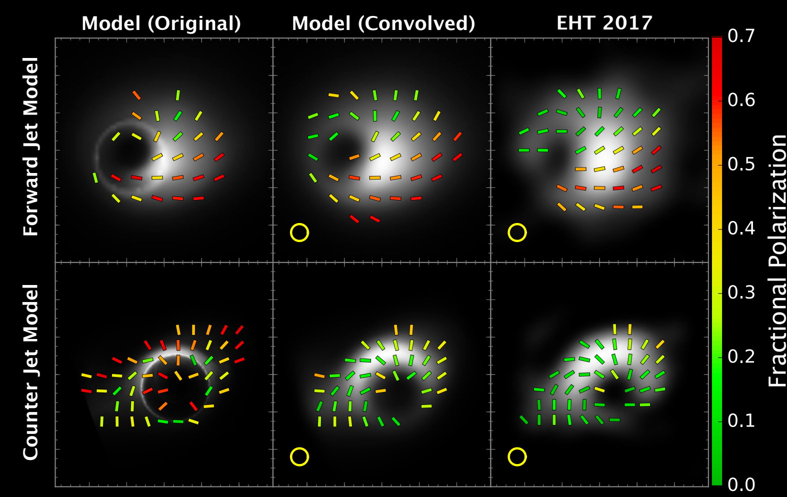
Event Horizon Telescope

New VLBI Imaging Techniques

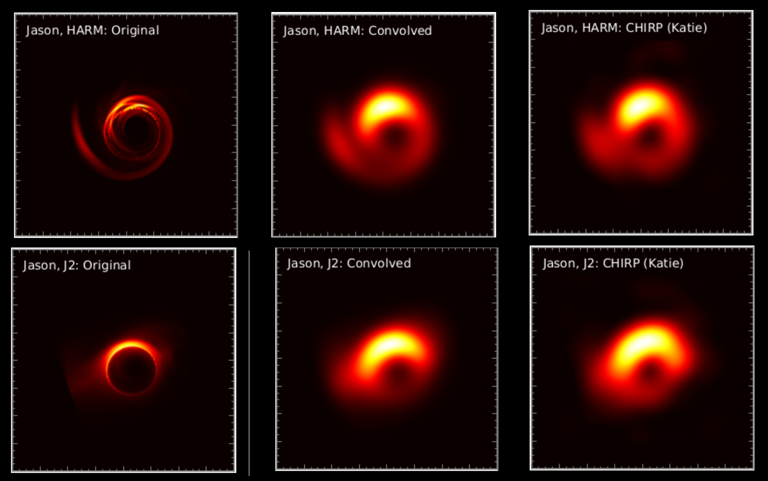
Maximum Entropy Method (MEM)
Chael et al. 2016, Fish et al. 2014,
Lu et al. 2014, 2016



Sparse Modeling
Akiyama et al. 2017a, 2017b
Ikeda et al. 2016, Honma et al. 2014



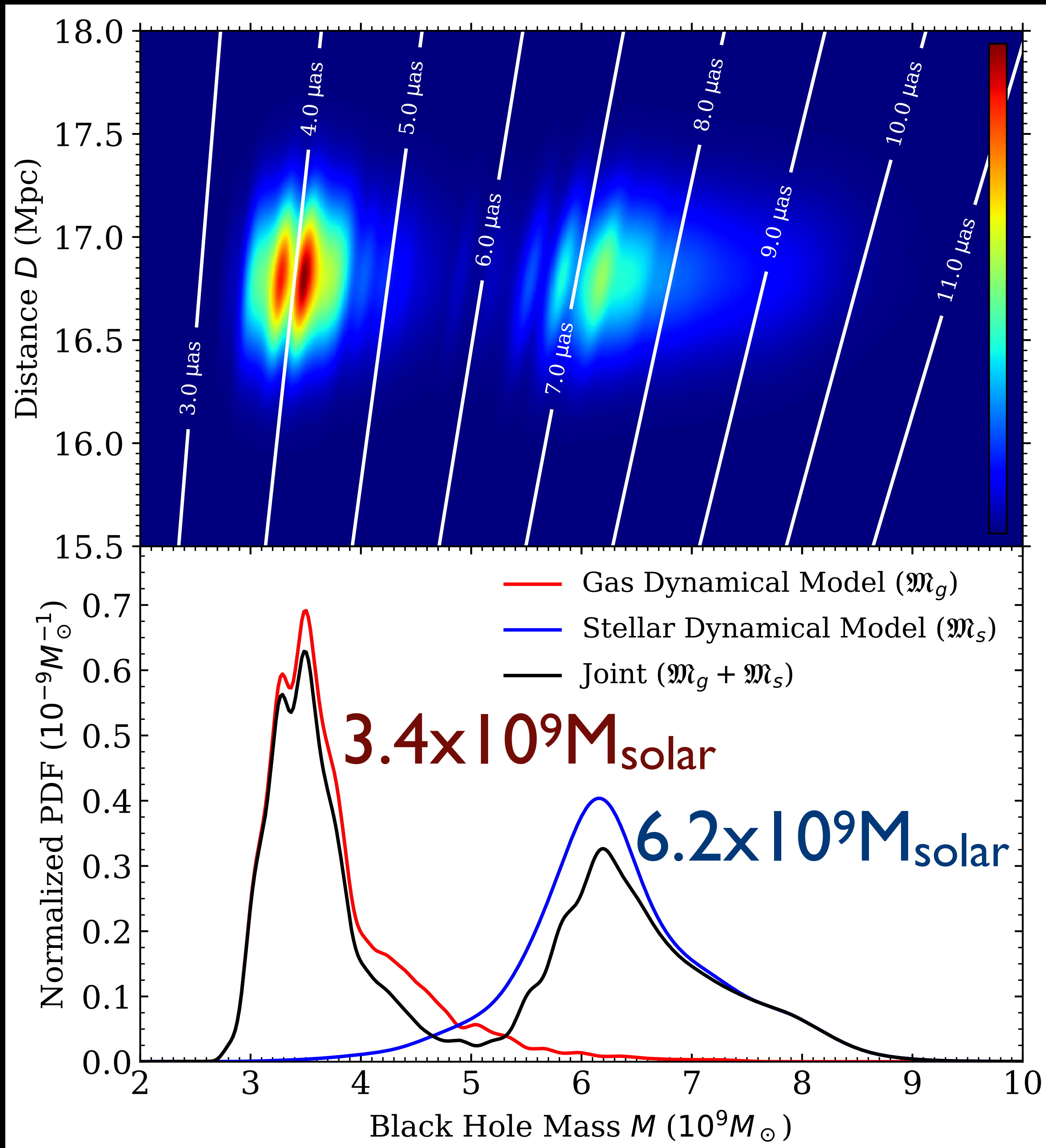
CHIRP (Machine-learning)
Bouman et al. 2016

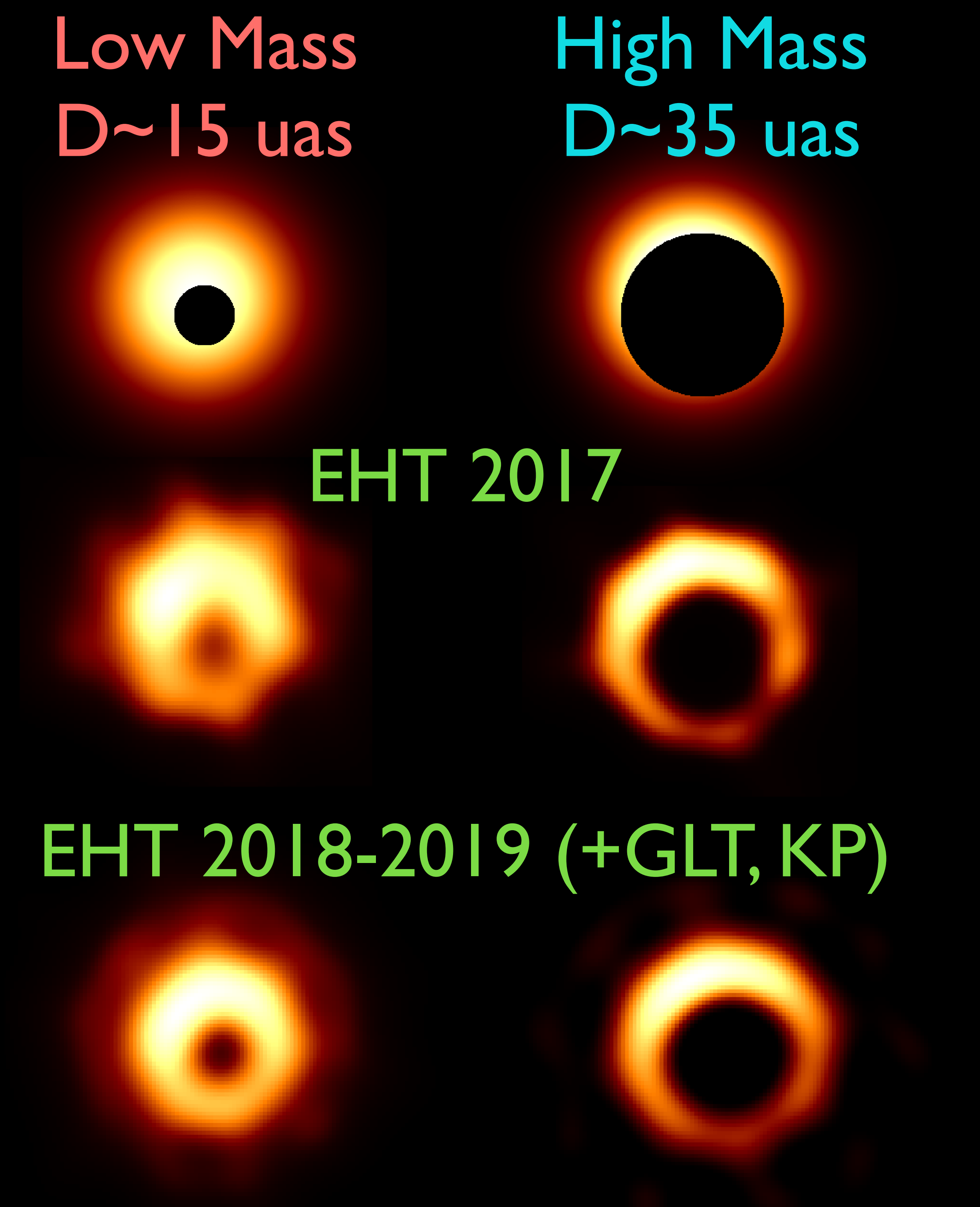


- All techniques can reconstruct images from closure quantities (closure phase, closure amplitude, …,)
- All techniques outperform CLEAN even when using closure phases particularly in super-resolution regimes

Event Horizon Telescope

The case of M87: Low Mass vs High Mass



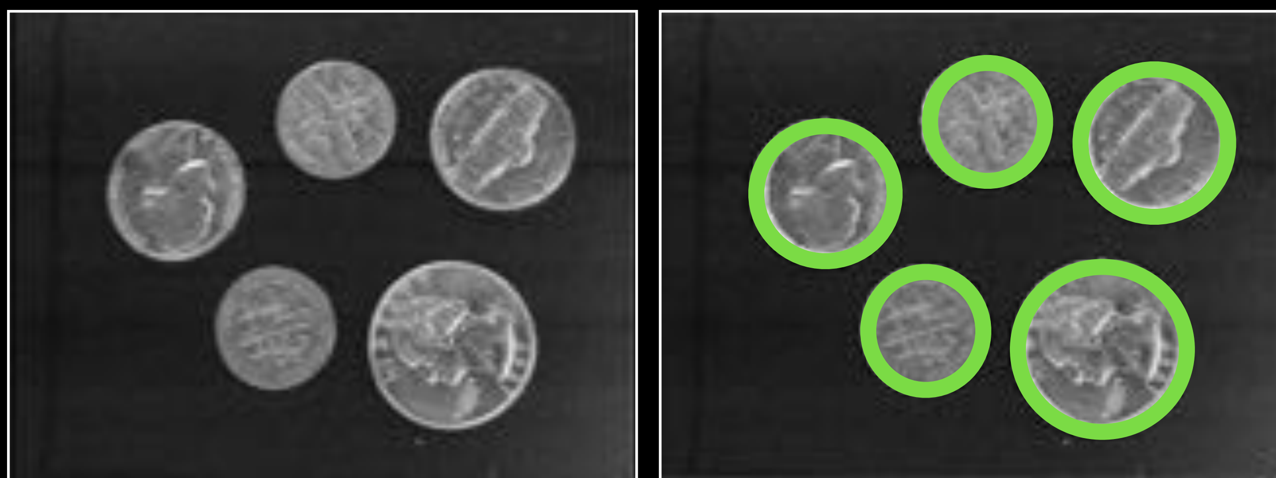


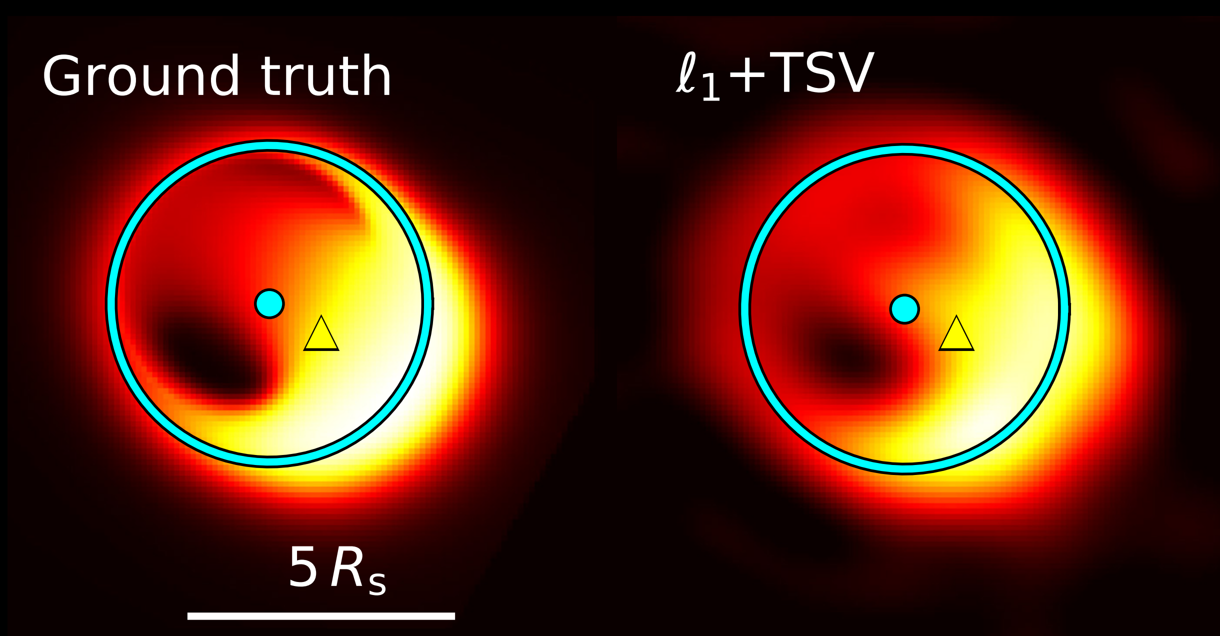
Akiyama et al. 2018 in prep

Event Horizon Telescope

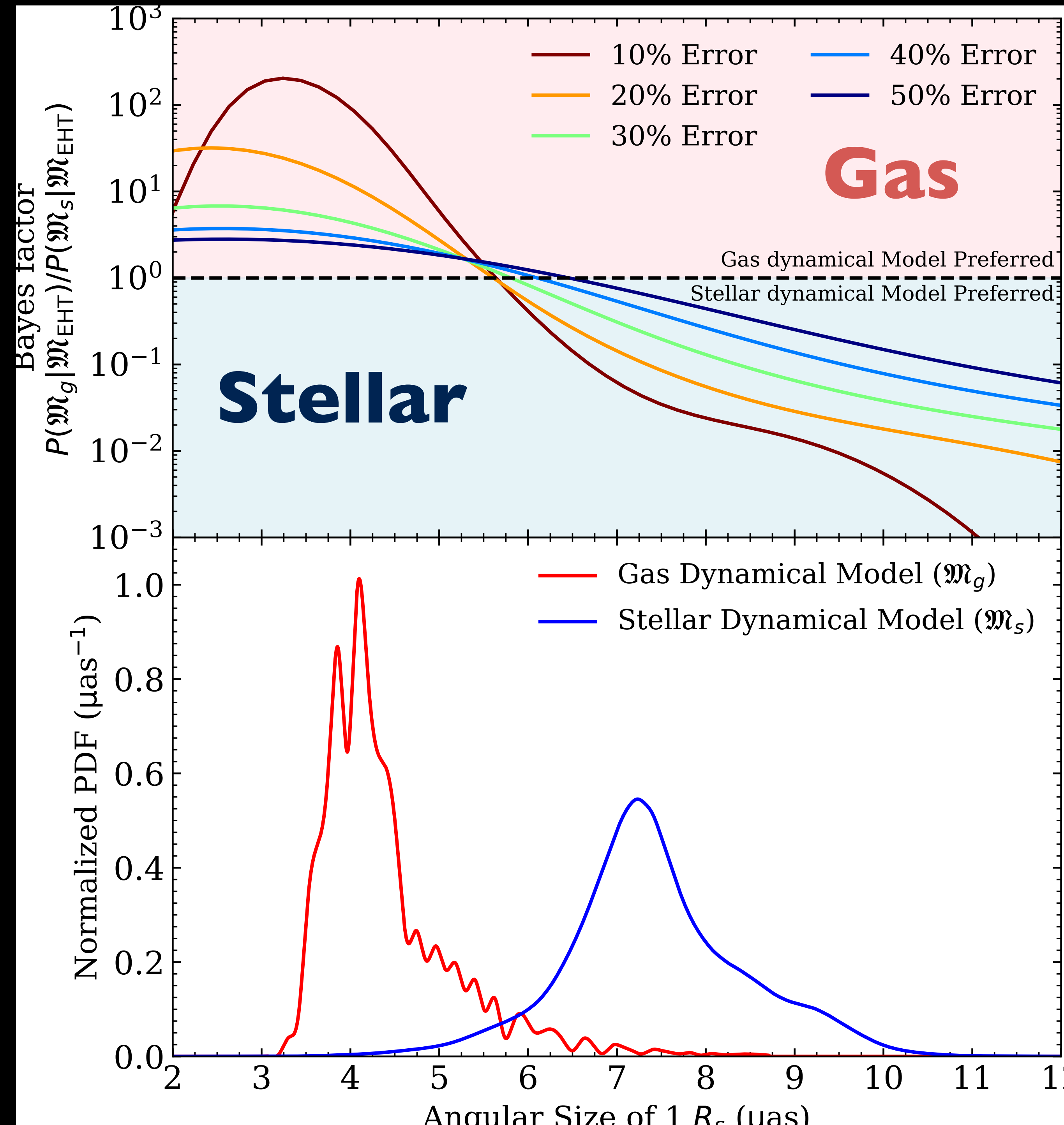
The case of M87: Low Mass vs High Mass

Circle/Elliptical Hough Transform





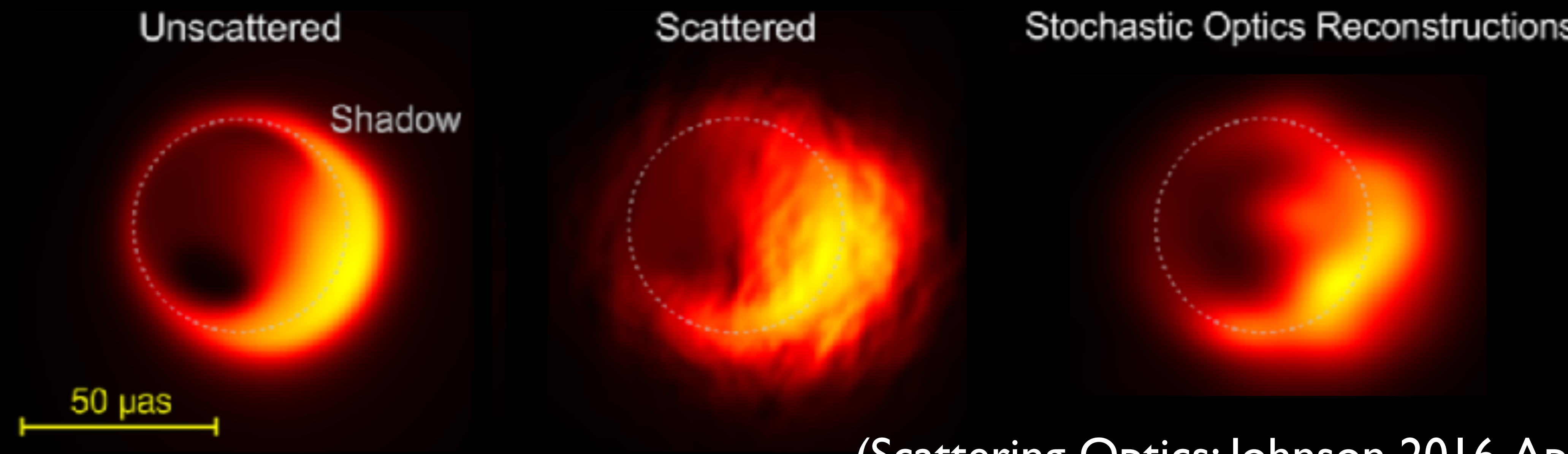
Kuramochi & ***Akiyama*** et al. 2018, ApJ
Psaltis et al. 2015, ApJ



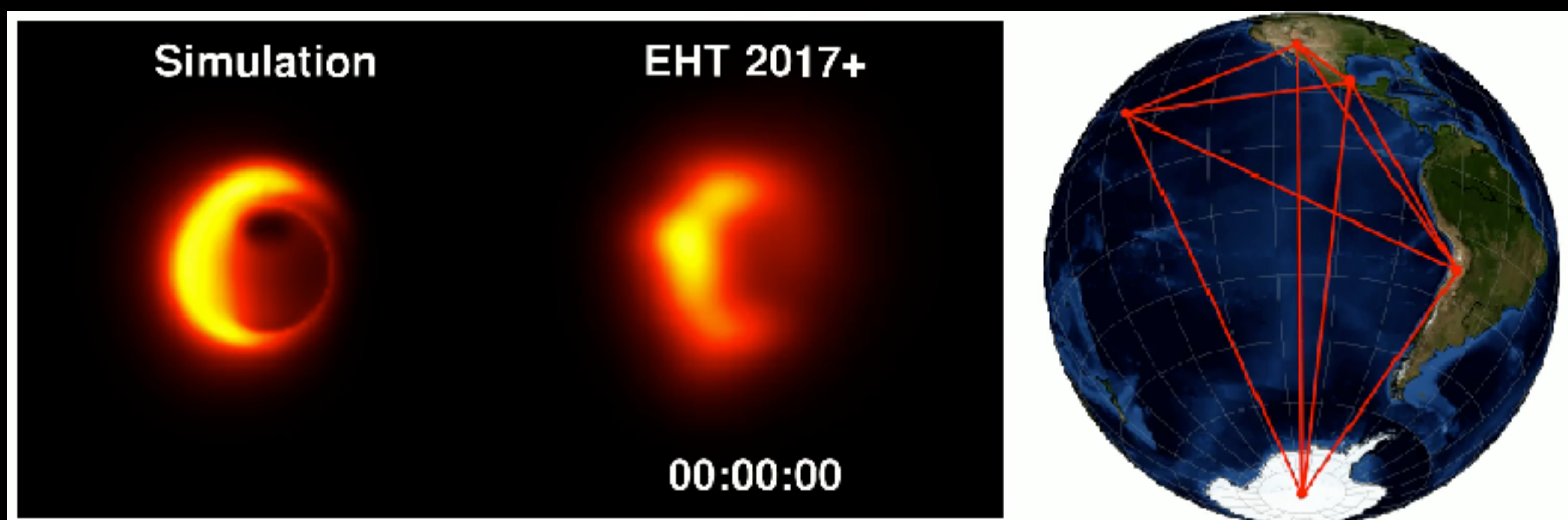
Akiyama et al. 2018 in prep

Event Horizon Telescope

The case of Sgr A*: Scattering / Variation



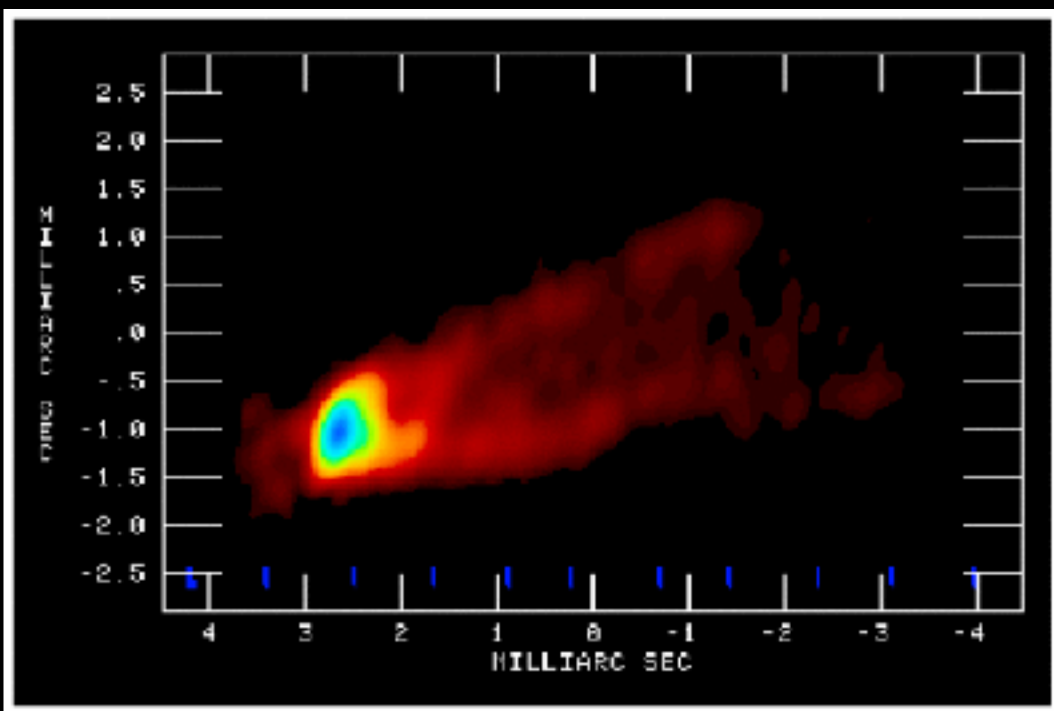
(Scattering Optics: Johnson 2016, ApJ)

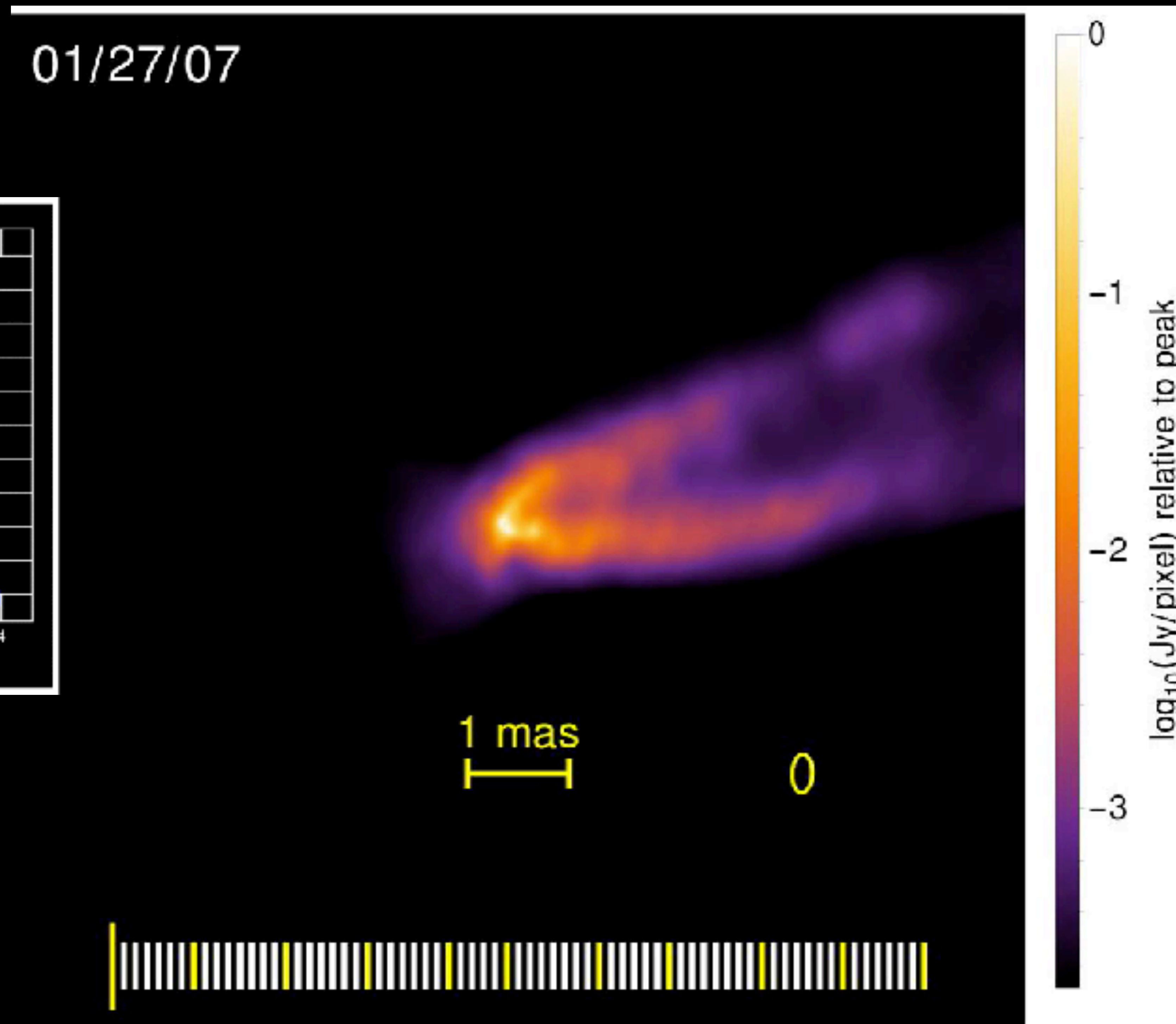


(Dynamical Imaging: Johnson et al. 2017, ApJ, Bouman et al. 2017, submitted)

Applications of Dynamical Imaging to M87 data

Revision of the Walker+08 movie





Conclusion

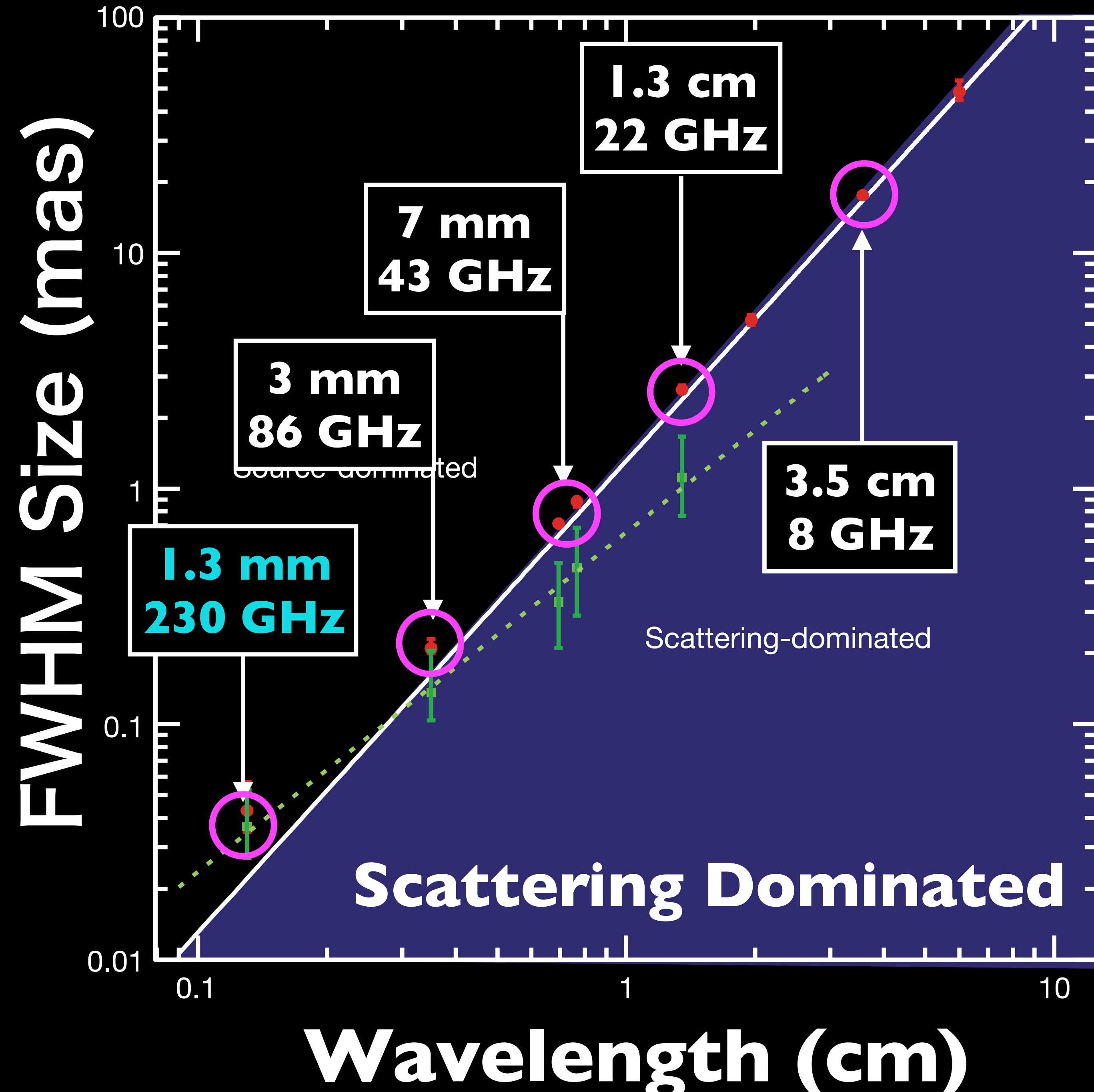
1.3mm VLBI has resolved ~few R_s structure for SgrA* & M87

Imaging an Event Horizon and observing BH orbits are within reach in < 2 years.

Event Horizon Telescope has been fully on-line since 2017.

Team and Support

Another issue for Sgr A*: Scattering



Doeleman et al. 2008, Nature

λ= 0.75 mm
ν= 400 GHz

Johnson & Narayan 2016
Johnson & Gwinn 2015

Event Horizon Telescope

Early M87 observations

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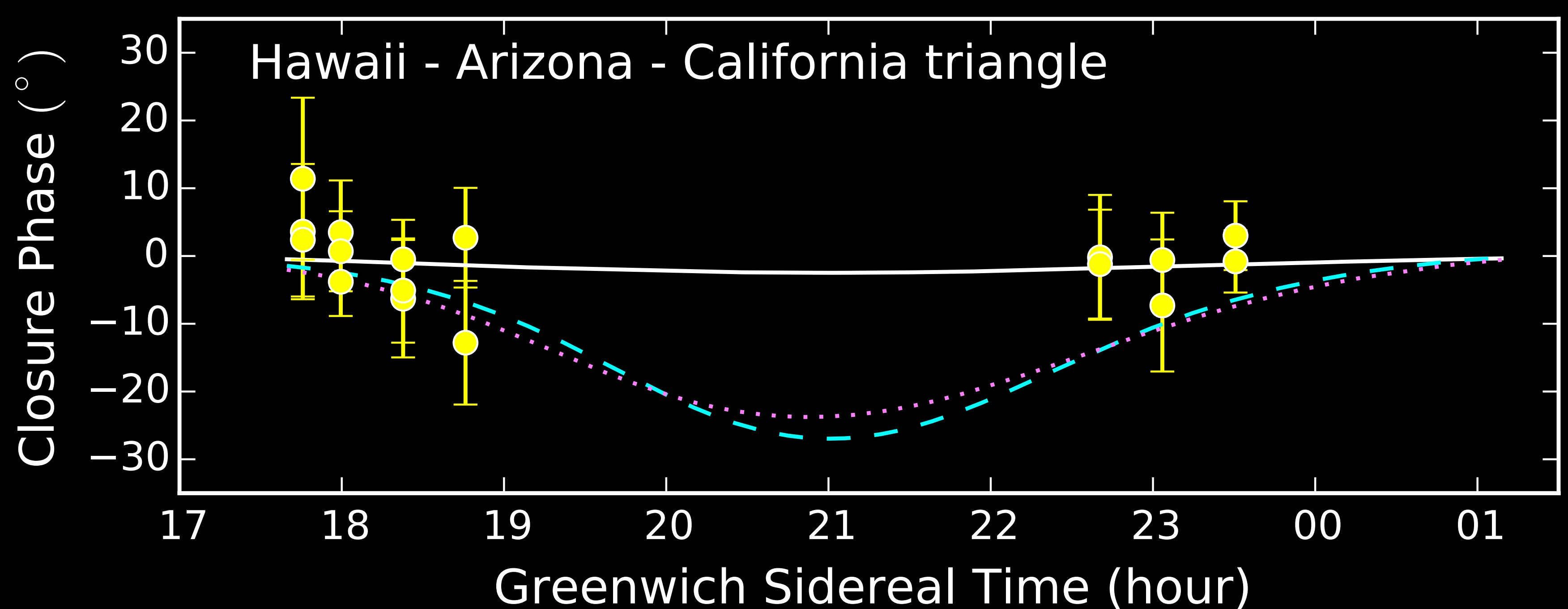
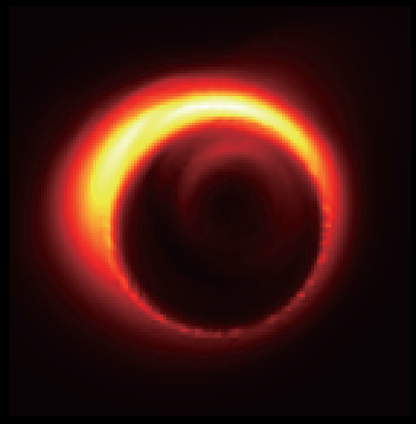
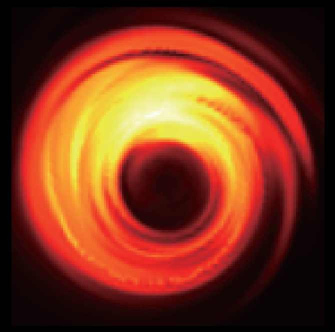
   Consistent with the parabolic collimation profile of the jet
   The jet base is magnetically dominated
2. Event Horizon Scale structure is stable
   during an enhanced TeV gamma-ray state (2012)
3. Closure Phase is consistent with zero (2012)
   Consistent with the compact emission models







Akiyama et al. 2015, ApJ

Event Horizon Telescope