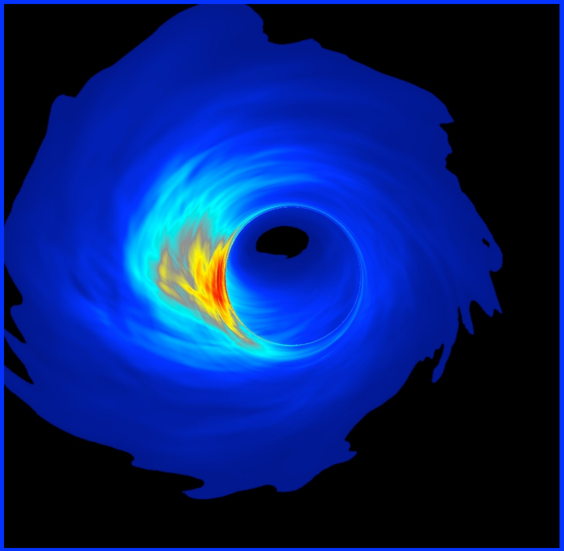
Imaging and Time Resolving Black Holes



Sheperd Doeleman (MIT & SAO)

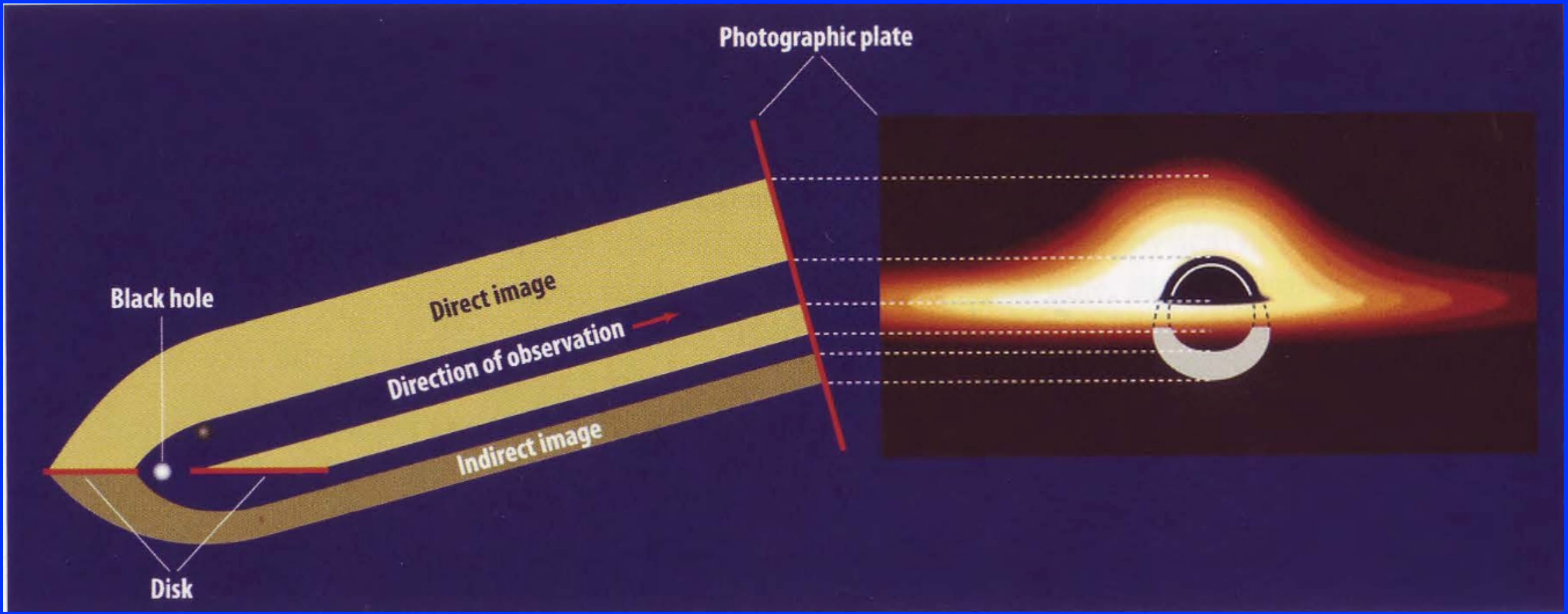
Centaurus A: Optical

Centaurus A: Radio

EHT Science Themes

- Is there an Event Horizon?
- Does GR hold near Black Holes?
- How do Black Holes grow and launch jets?

Strong GR: The Black Hole Shadow



Bardeen 1973
Luminet 1979

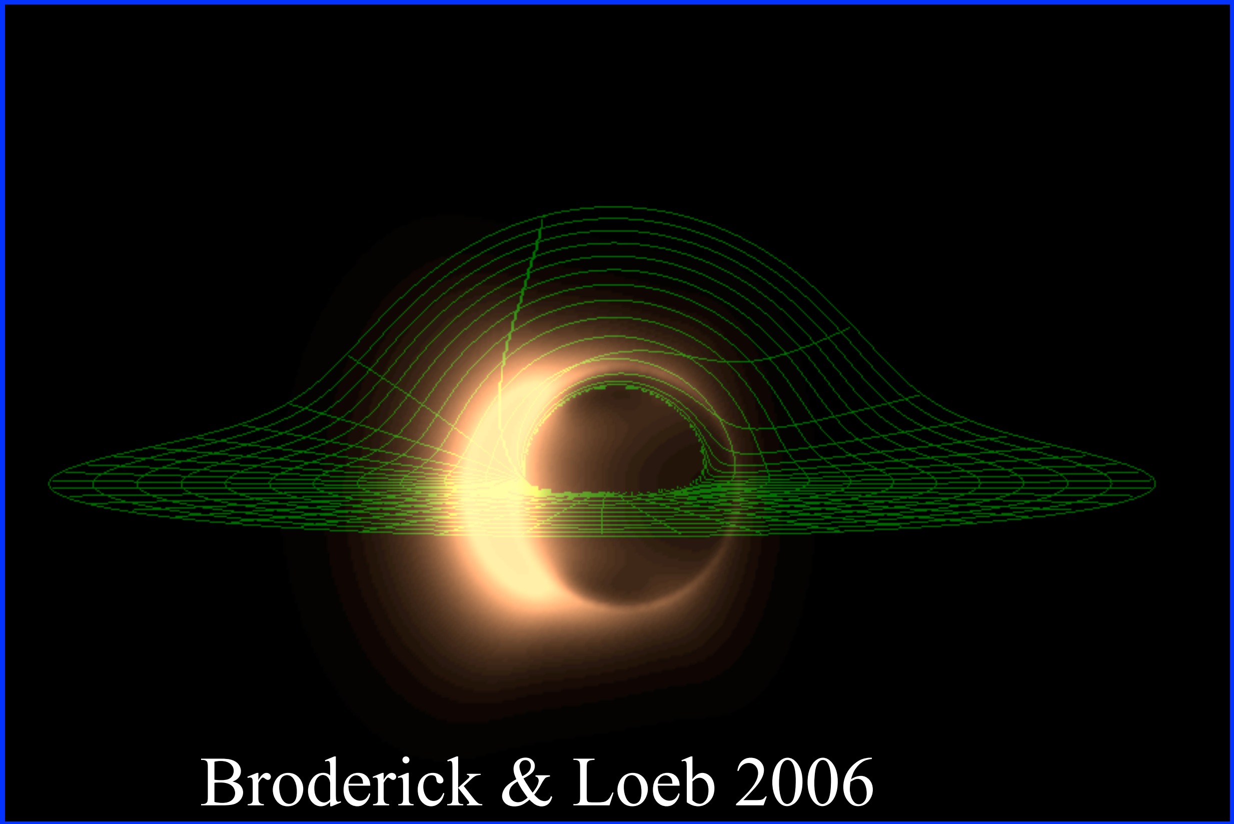
Shadow Diameter:

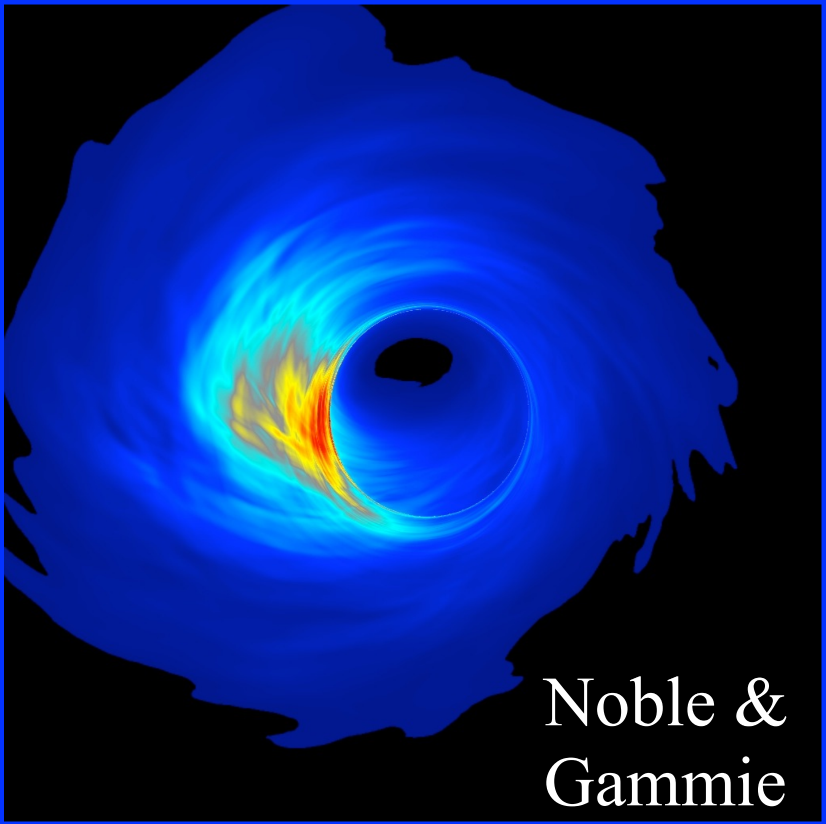
Non-spinning (a=0)
Dsh = sqrt(27) * Rsch

Spinning (a=1)
Dsh = 9/2 * Rsch

Shadow size and shape encodes GR (e.g., Johannsen & Psaltis 2010).

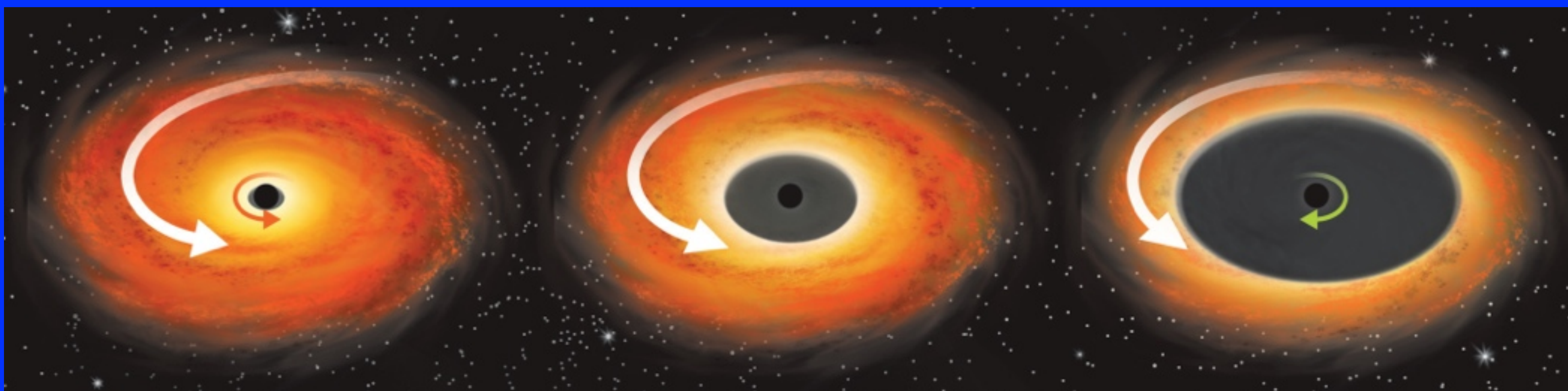
Theoretical Views





Strong GR Effects: the ISCO

- Innermost Stable Circular Orbit Size.



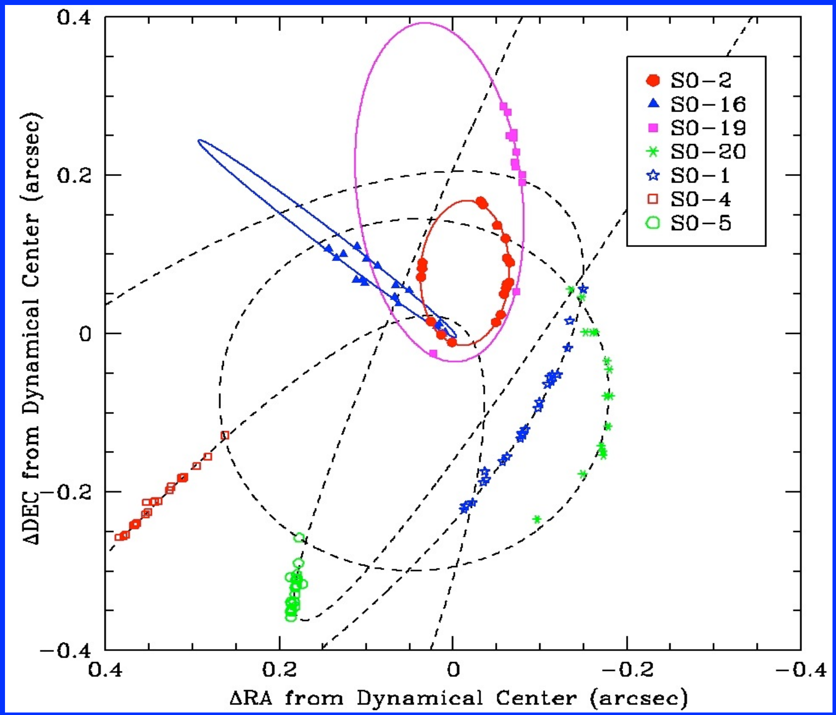
Sky & Telescope

Max. Prograde
ISCO_d = 1 Rsch

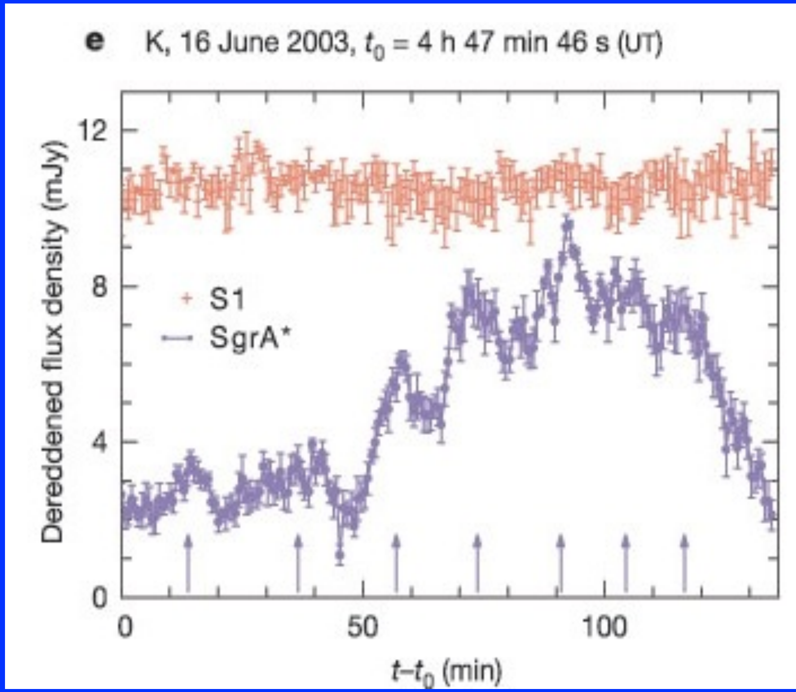
No Spin
ISCO_d = 6 Rsch

Max Retrograde
ISCO_d = 9 Rsch

SgrA*: Best Case for a SMBH

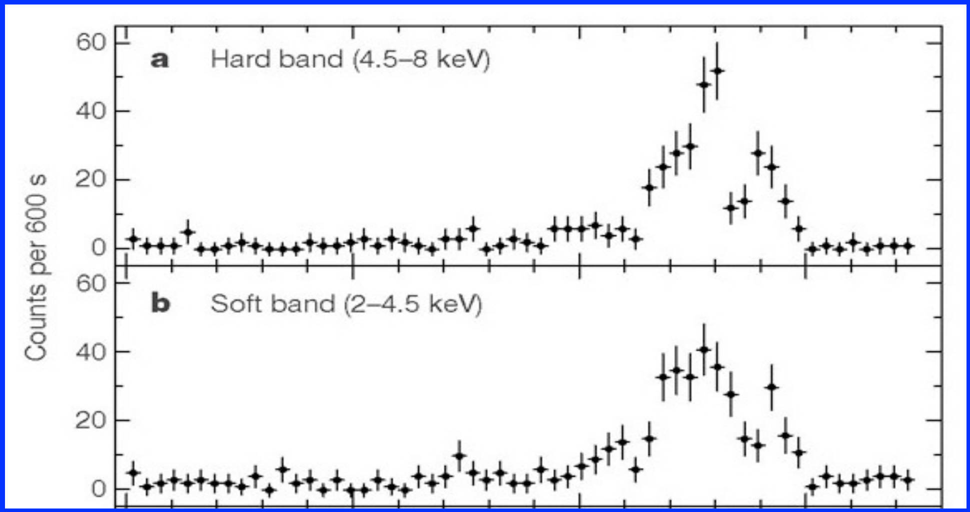


Ghez et al 2005



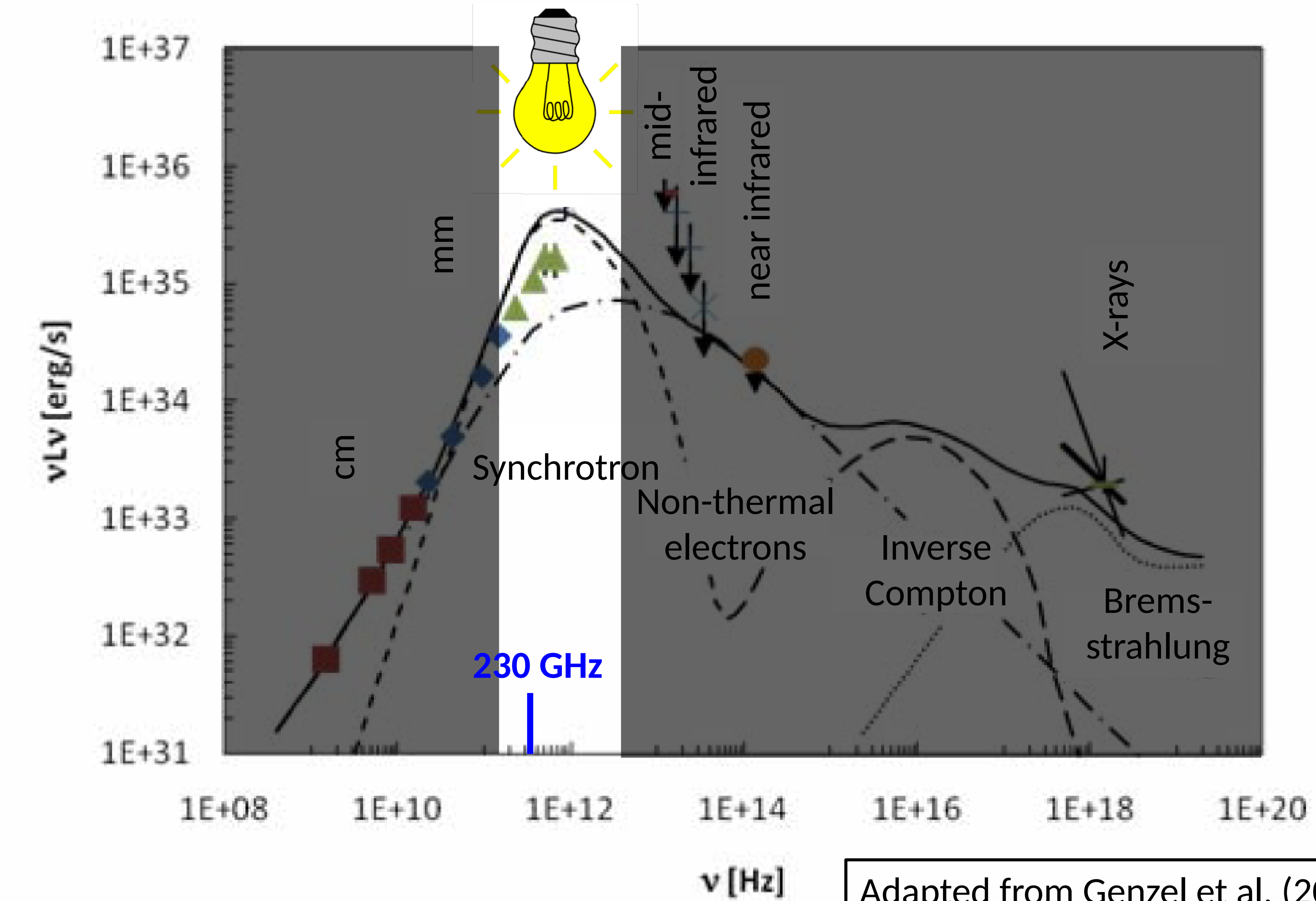
VLT: Genzel et al 2003

Shadow diameter = 52 micro arcsec



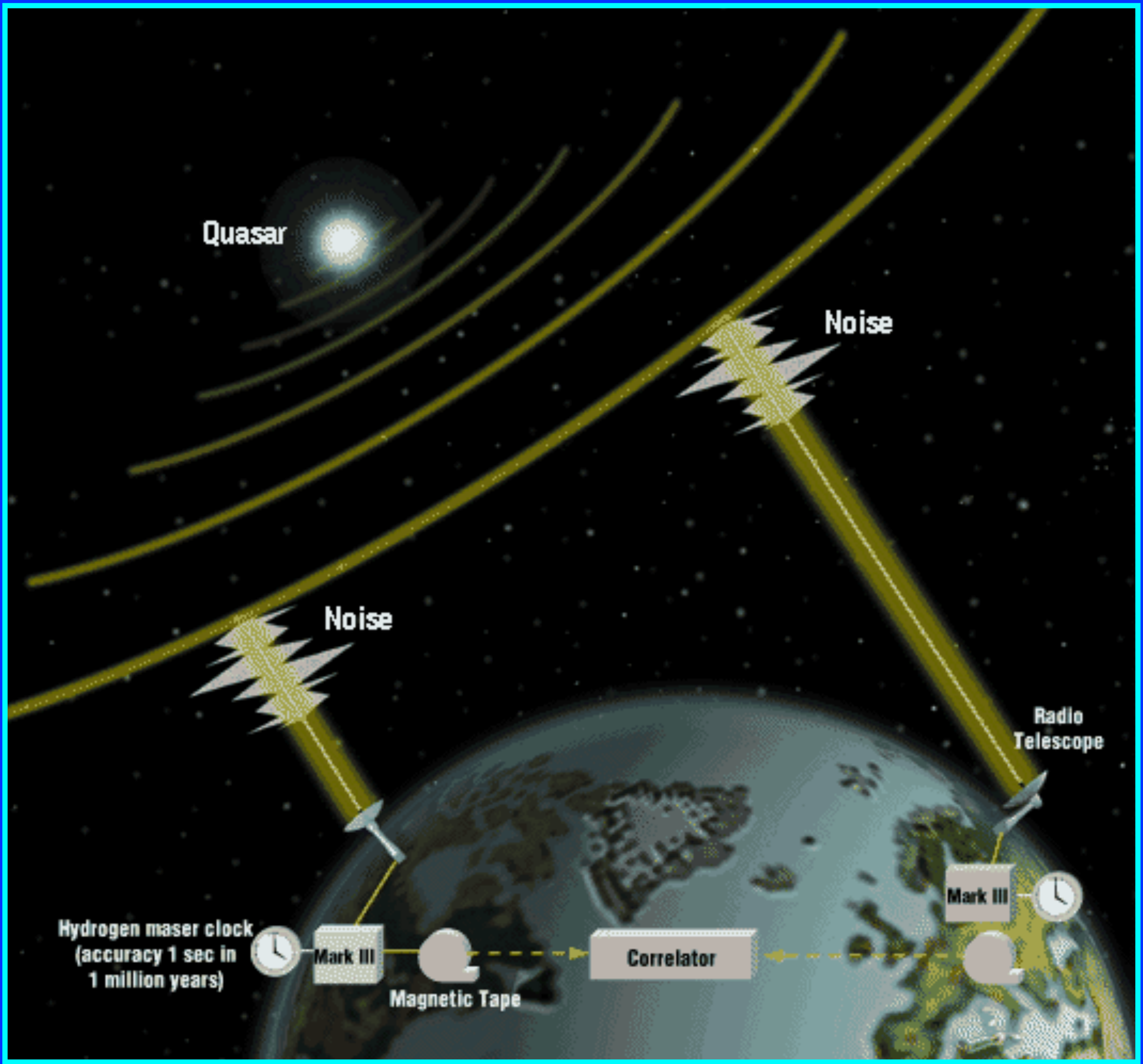
Baganoff et al 2001

Sgr A* Spectrum



Adapted from Genzel et al. (2010)

Short Wavelength VLBI



Resolution:

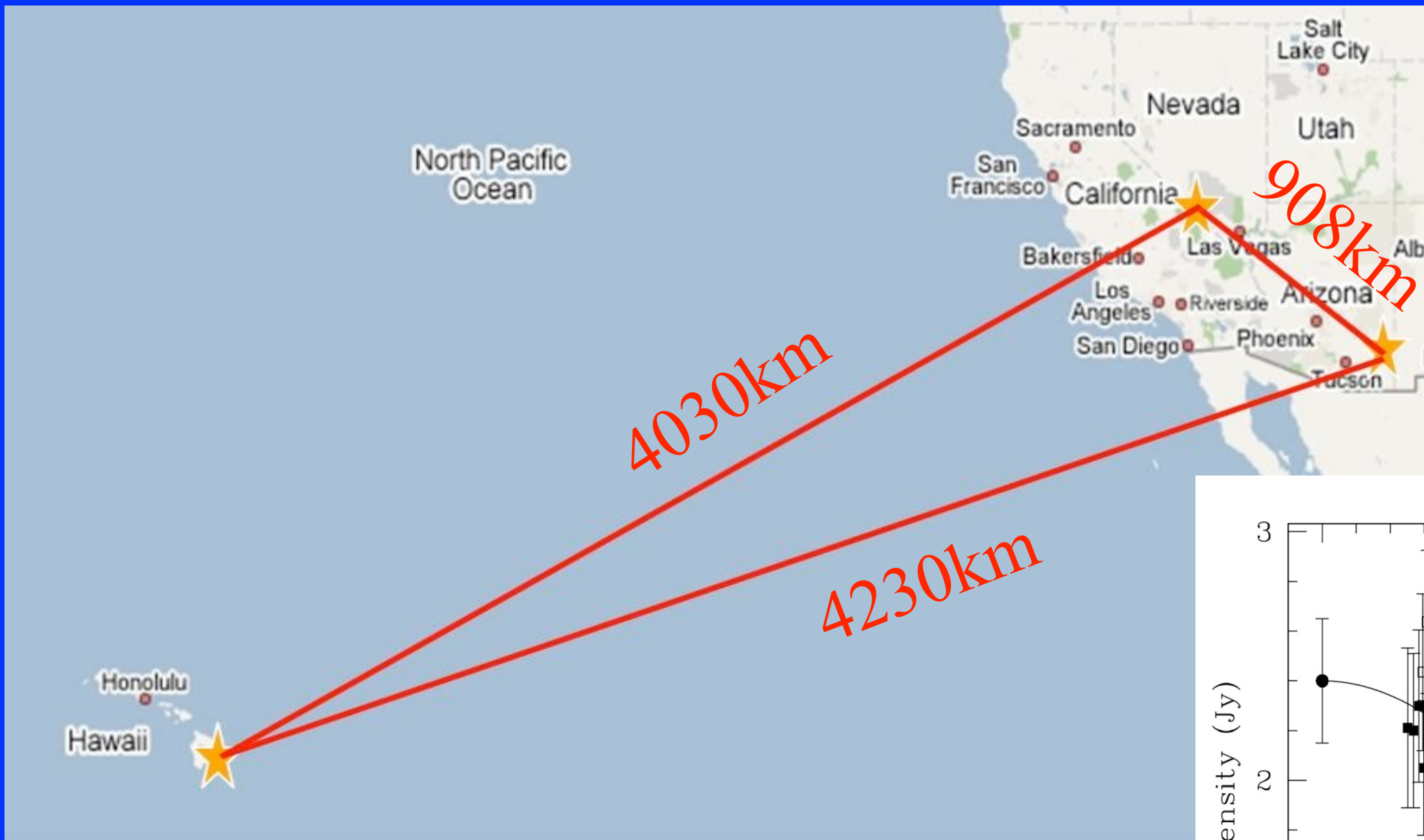
λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

ISM Scattering:

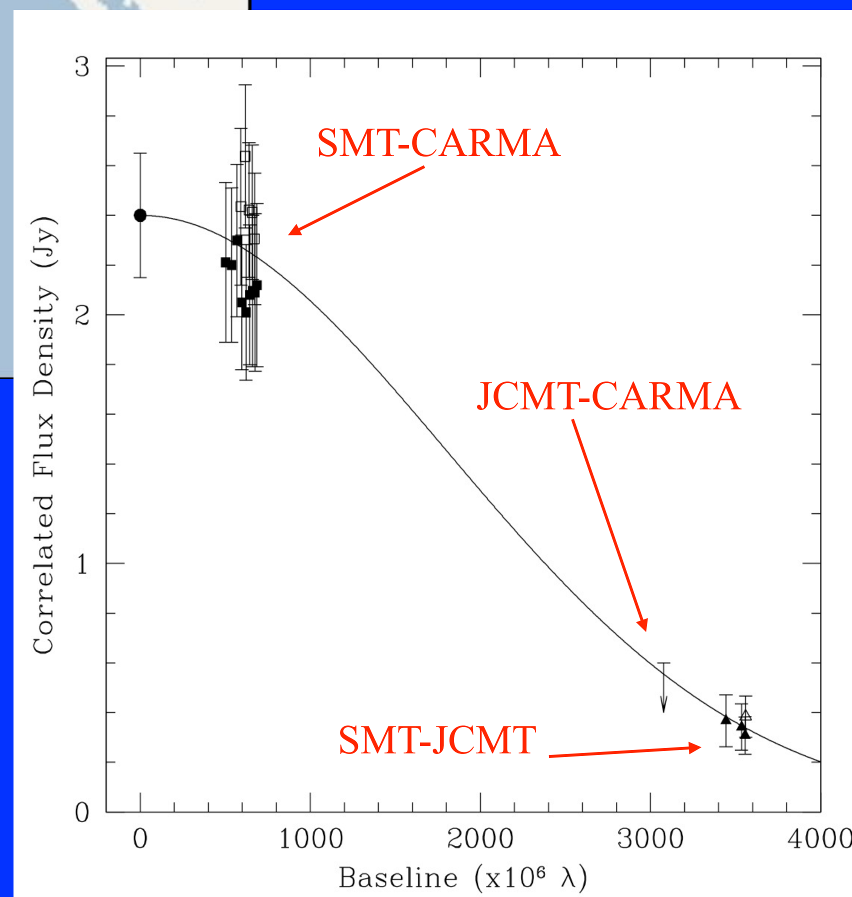
Θscat ~ λ^2

Shadow size (SgrA*):
50 μas

SgrA*: Event Horizon Structure Confirmed



Doeleman et al 2008

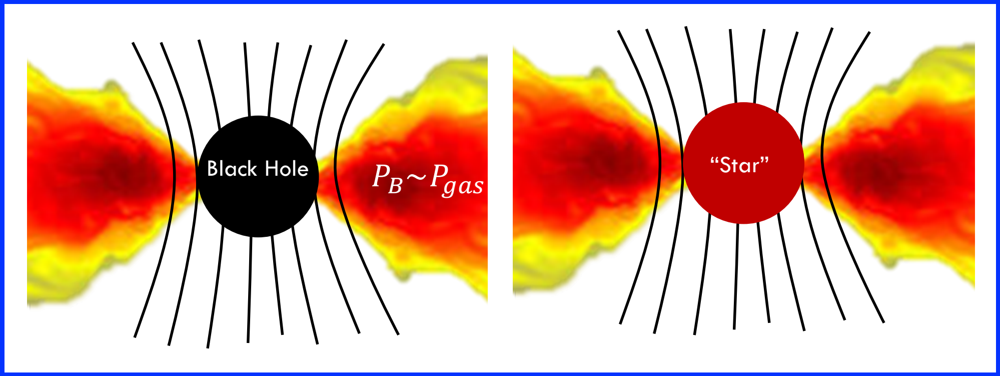


About 4 Schwarzschild radii across.

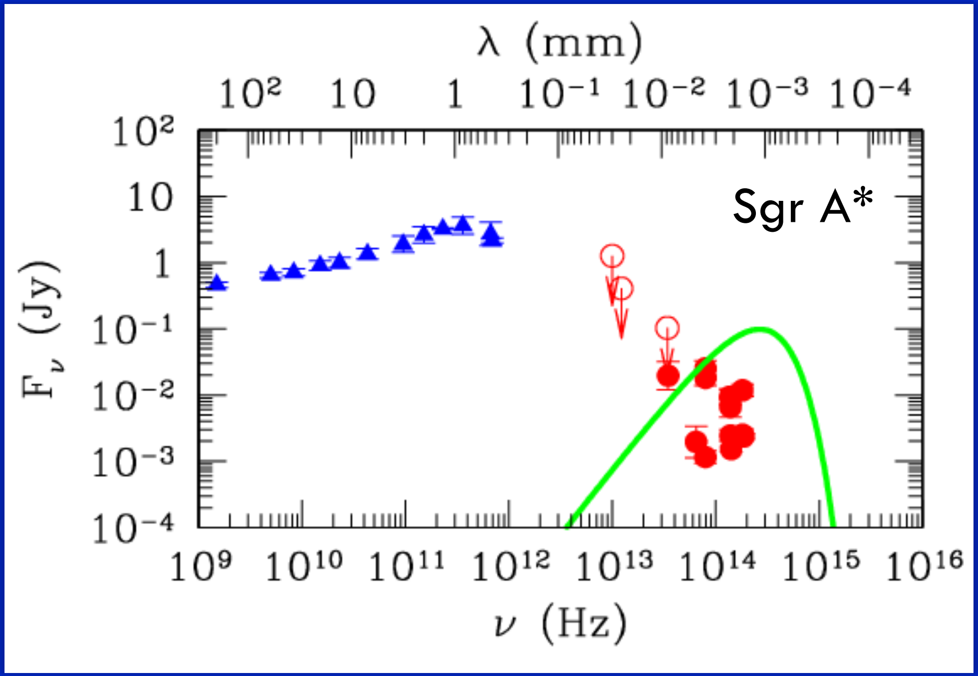
$$\rho = 10^{23} M_{\odot} pc^{-3}$$

4 million suns within the orbit of Mercury.

Existence of an Event Horizon



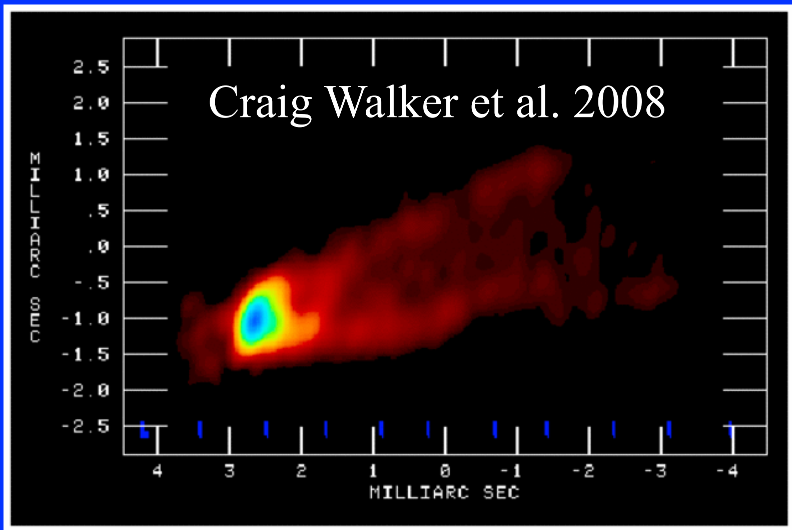
Lack of Horizon implies additional radiative signature.

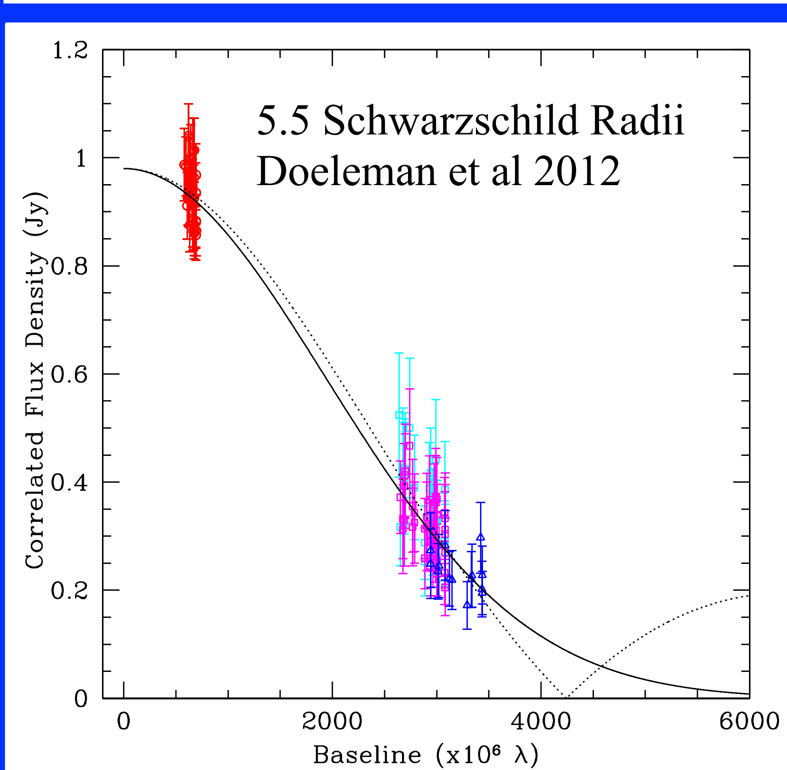


Evidence of expected blackbody not observed.

Broderick, Loeb & Narayan 2009

M87: BH Origins of a Relativistic Jet

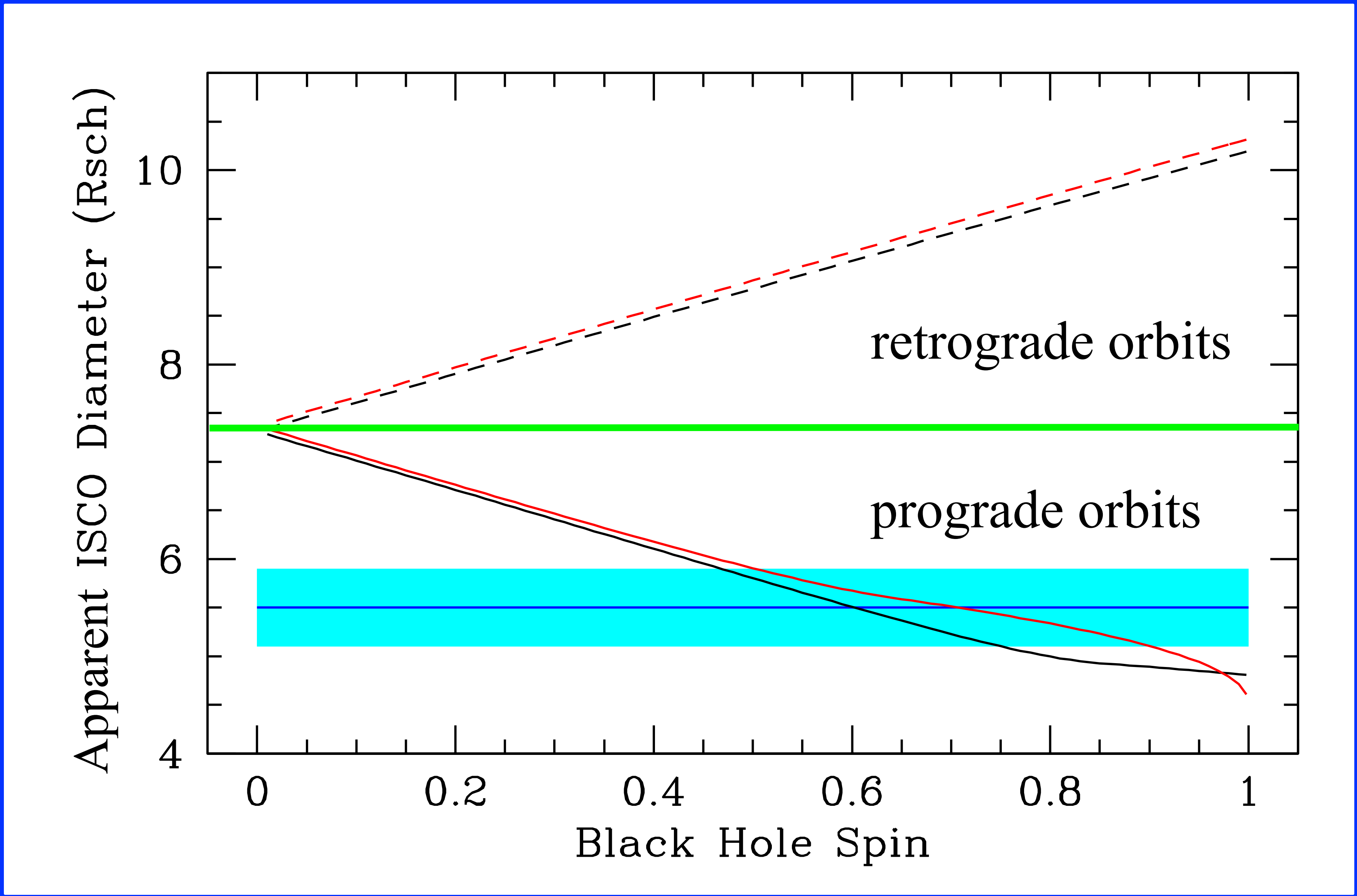




Graphic: Broderick

Strong GR Effects:

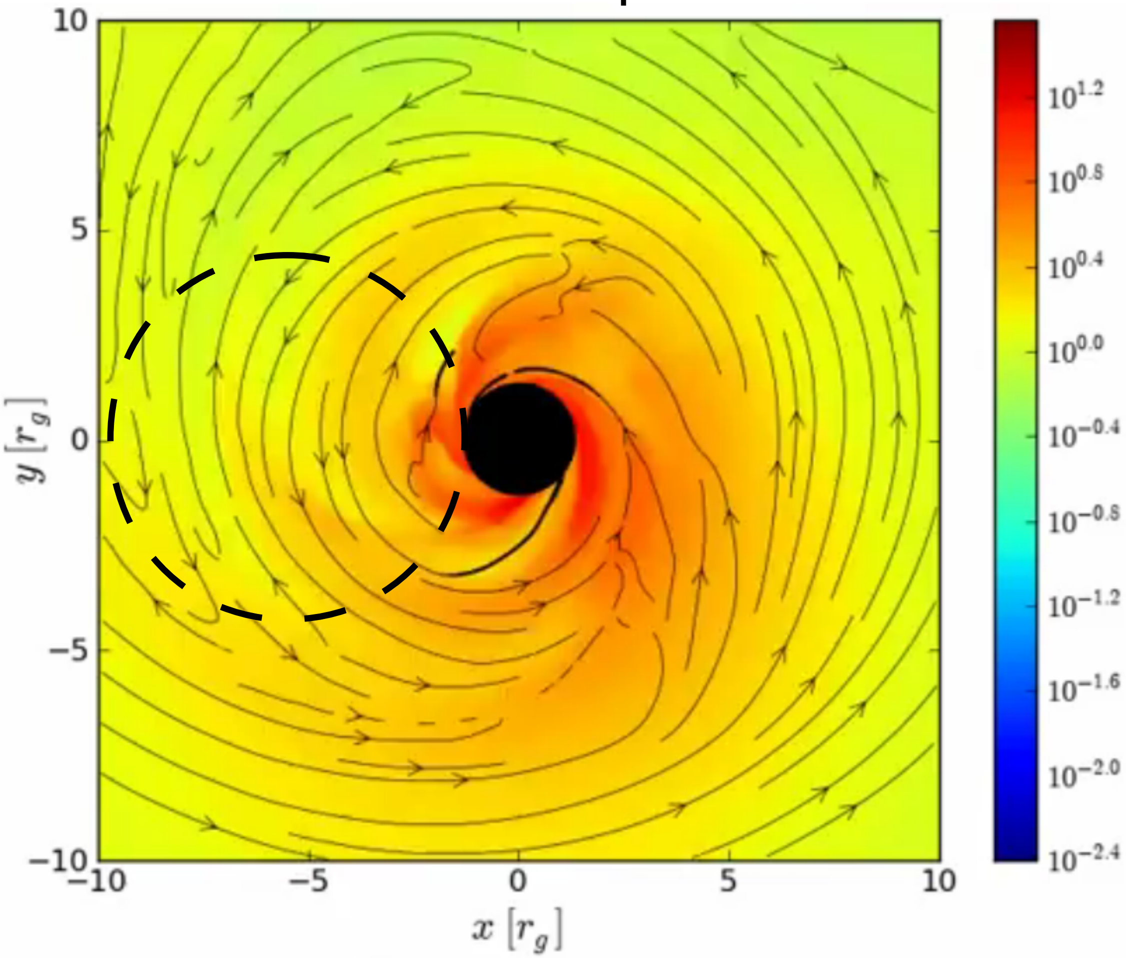
- Smaller than the expected ISCO: prograde disk.



Doeleman et al 2012

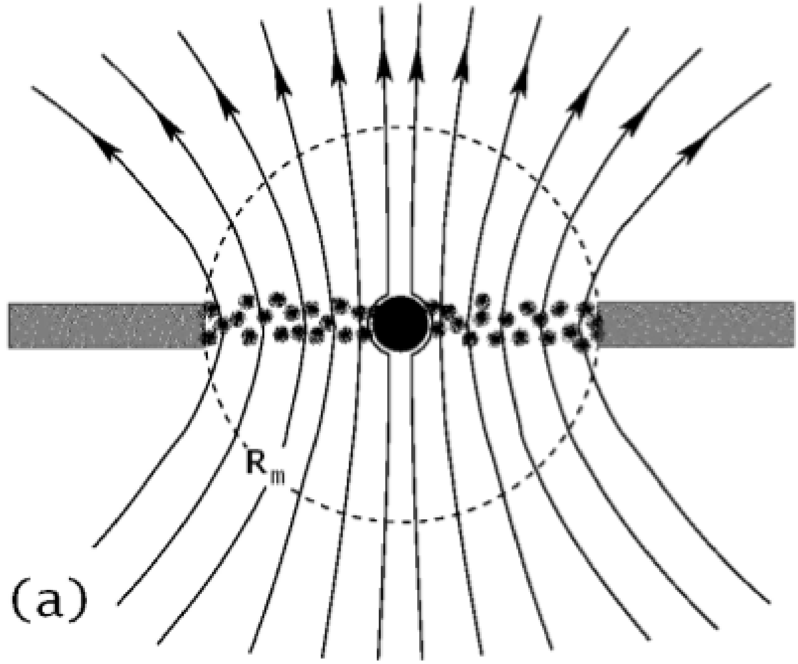
Ordered Fields?

Sheared Fields in Keplerian Flow



McKinney et al. (2012)

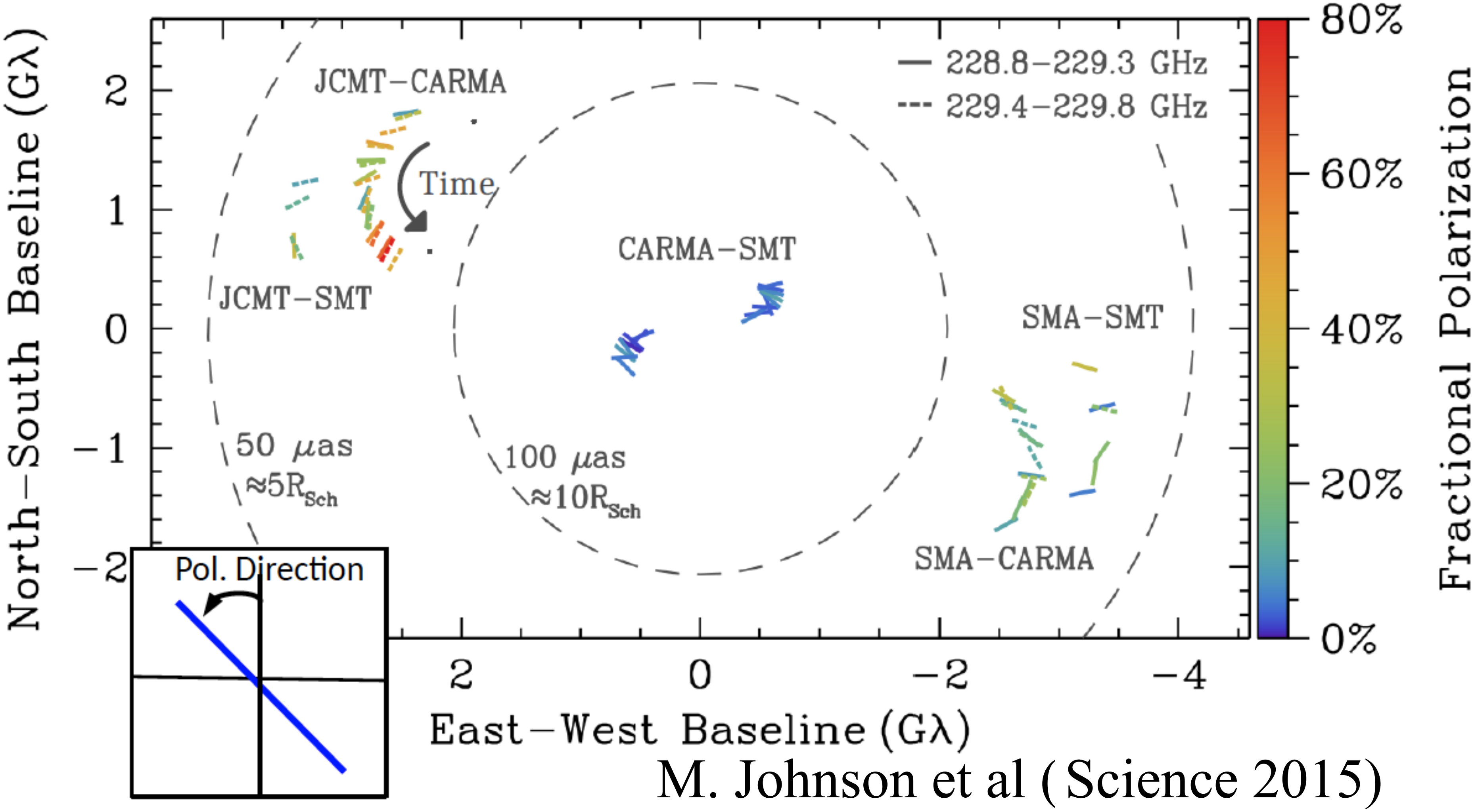
Magnetically-Arrested Disk



Narayan et al. (2003)

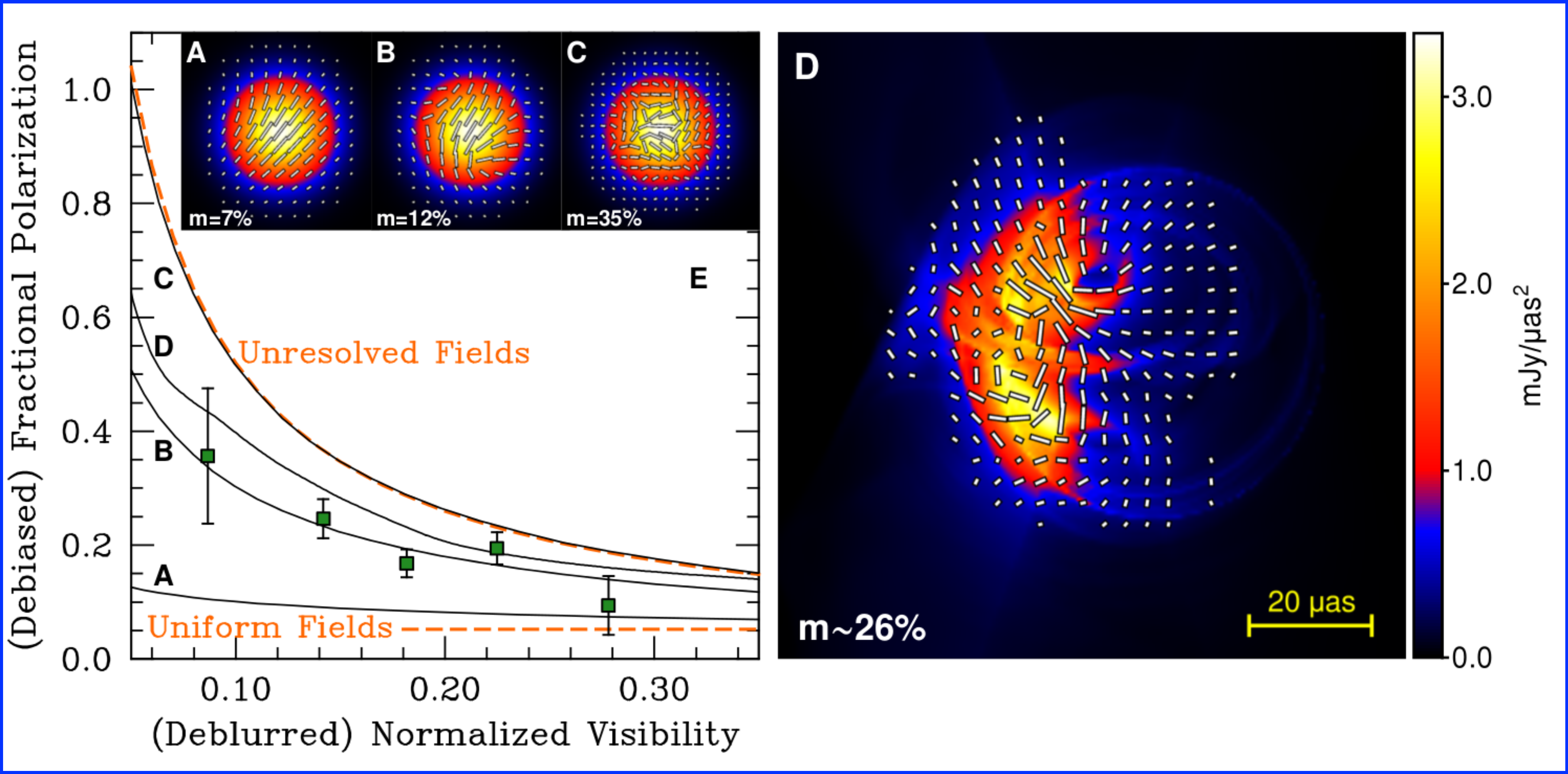
Sgr A* with the EHT

2013 EHT Data



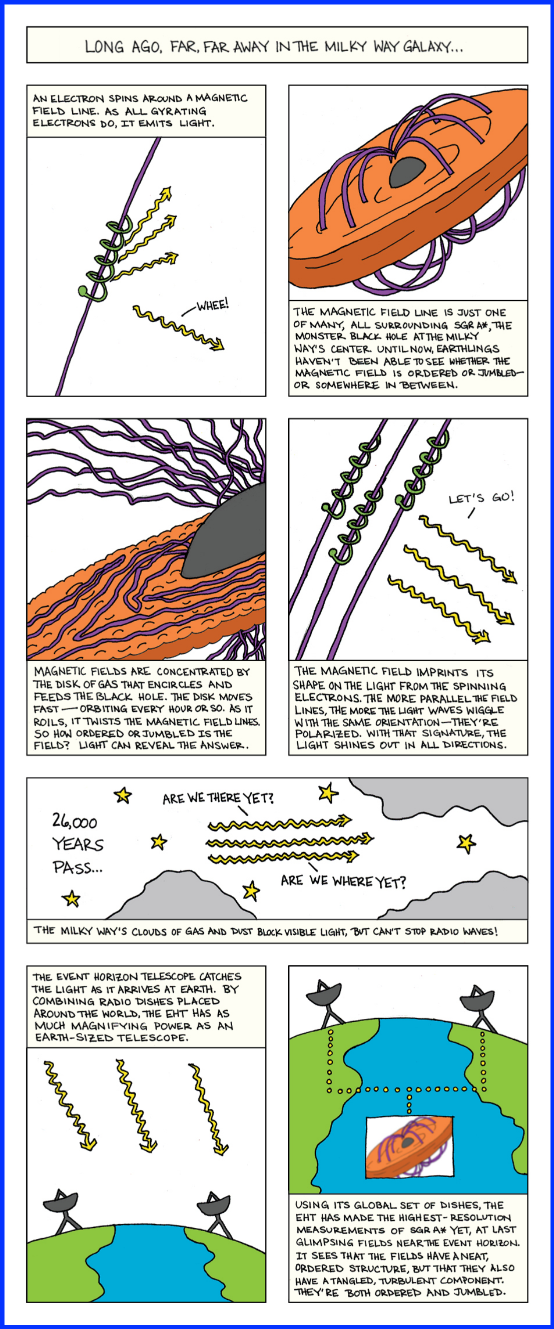
M. Johnson et al (Science 2015)

Ordered Fields at the Event Horizon



Johnson et al 2015

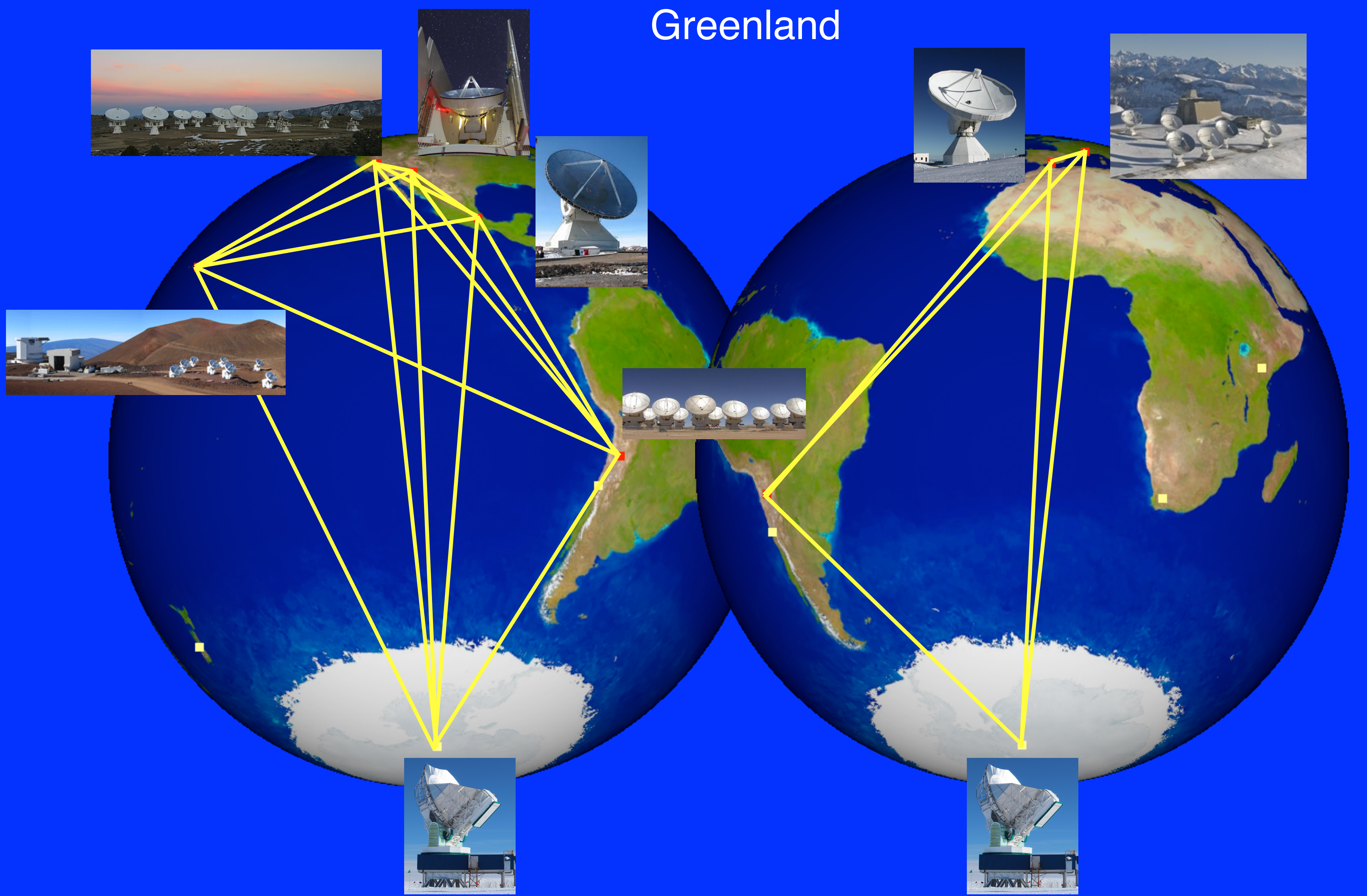
Getting the 13-yr old demographic



EHT Specifications: The Next 2-3 Years

- Increase stations from 3 to 8: baseline number grows from 3 to 28 (n*(n-1)/2).
- Bandwidth increase from 1 GHz to 16 GHz.
- Collecting area increase by x10.
- Impact:
  - Sensitivity increase by x40: Long baselines.
  - Full closure phase information: modeling/imaging.
  - Full polarization information: magnetic fields.
  - Time domain: time resolving BH/jet dynamics.
- Hardware build-out supported through MSIP.

SgrA*'s view of the EHT



EHT Expansion: 2014/15

1.3mm VLBI Detections:

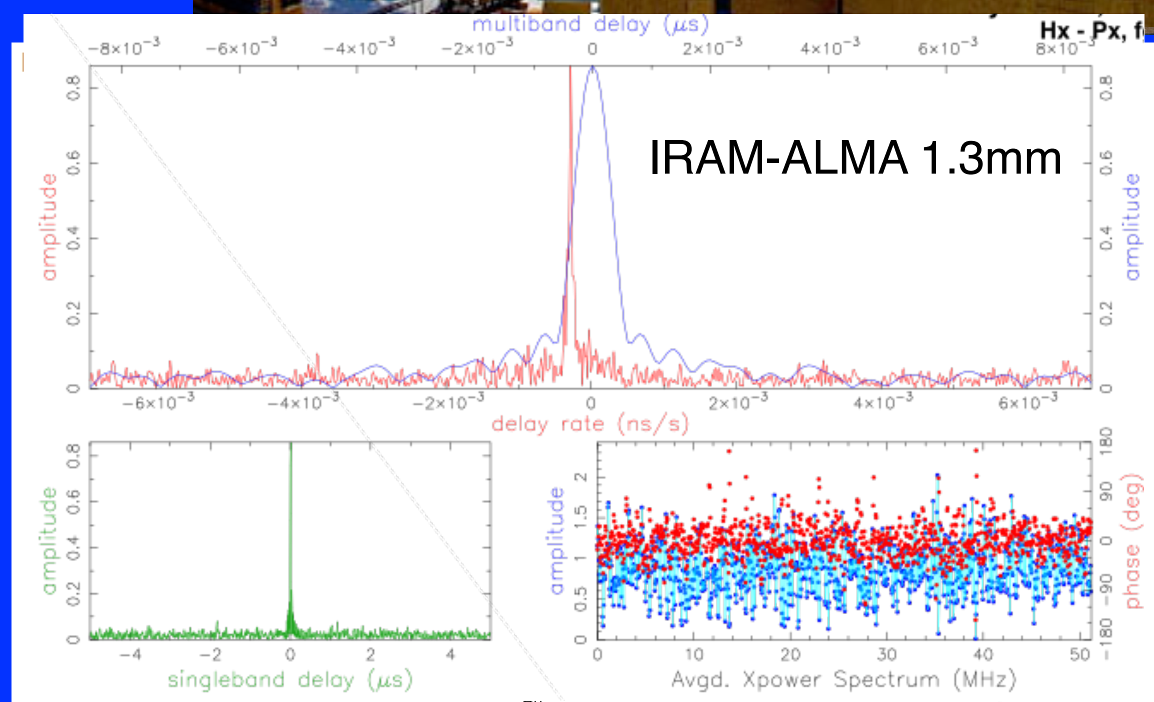
Large Millimeter Telescope

APEX Telescope

South Pole Telescope

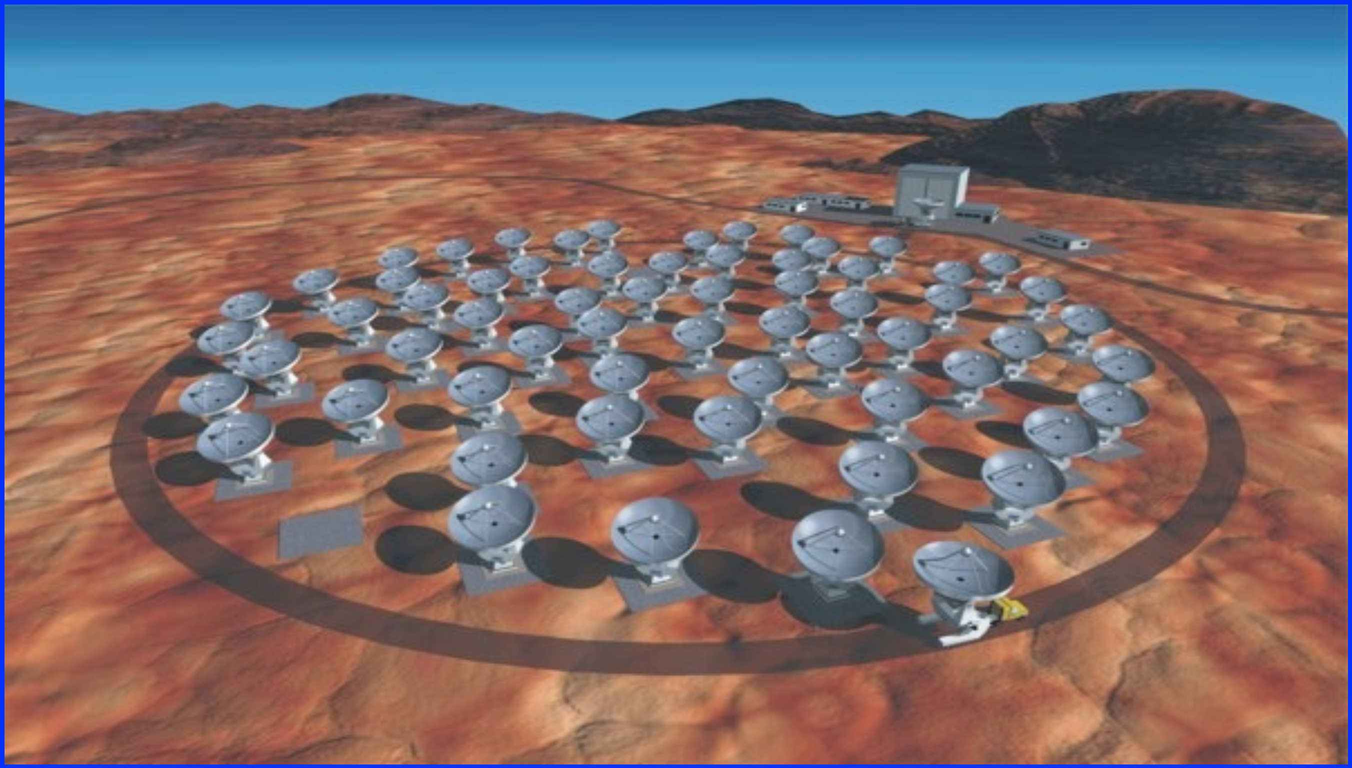
IRAM 30m

ALMA

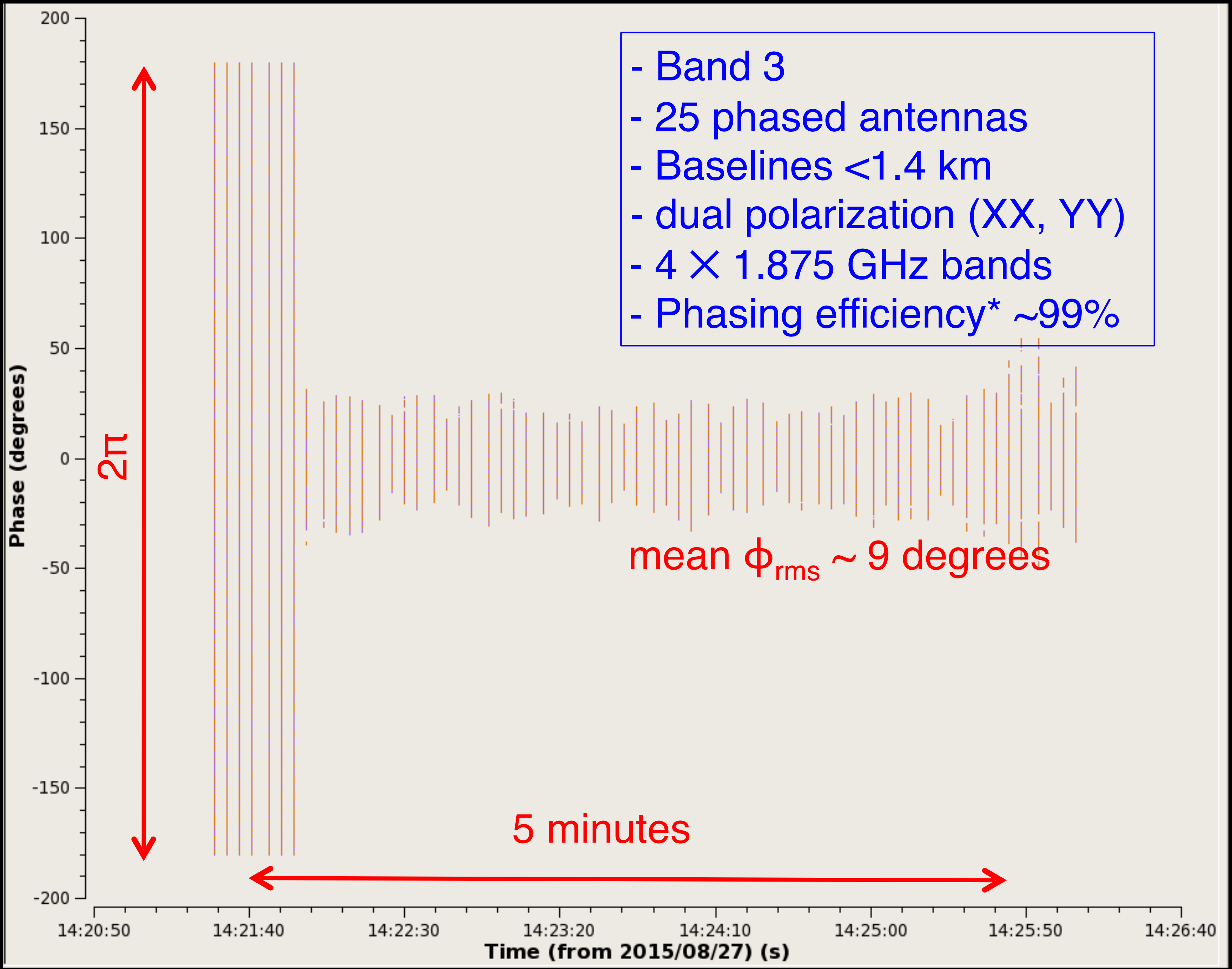


Phasing ALMA

- Increase resolution by x2, sensitivity by x10.
- Maser, recorders, correlator hardware, fiber.
- Complete - now commissioning.



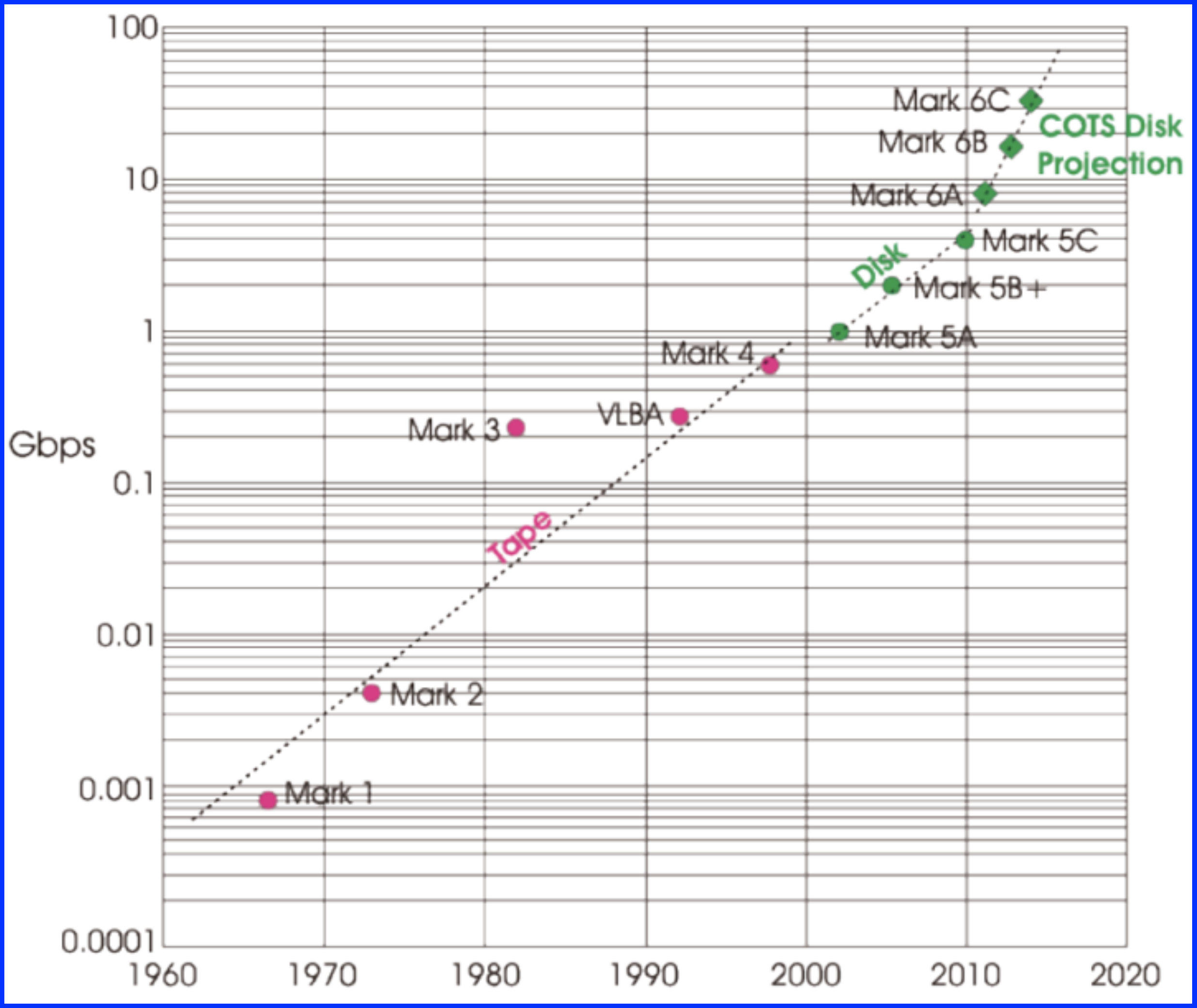
ALMA Phasing System observation from August 2015:



Next Gen VLBI Technology: Keeping up with Moore

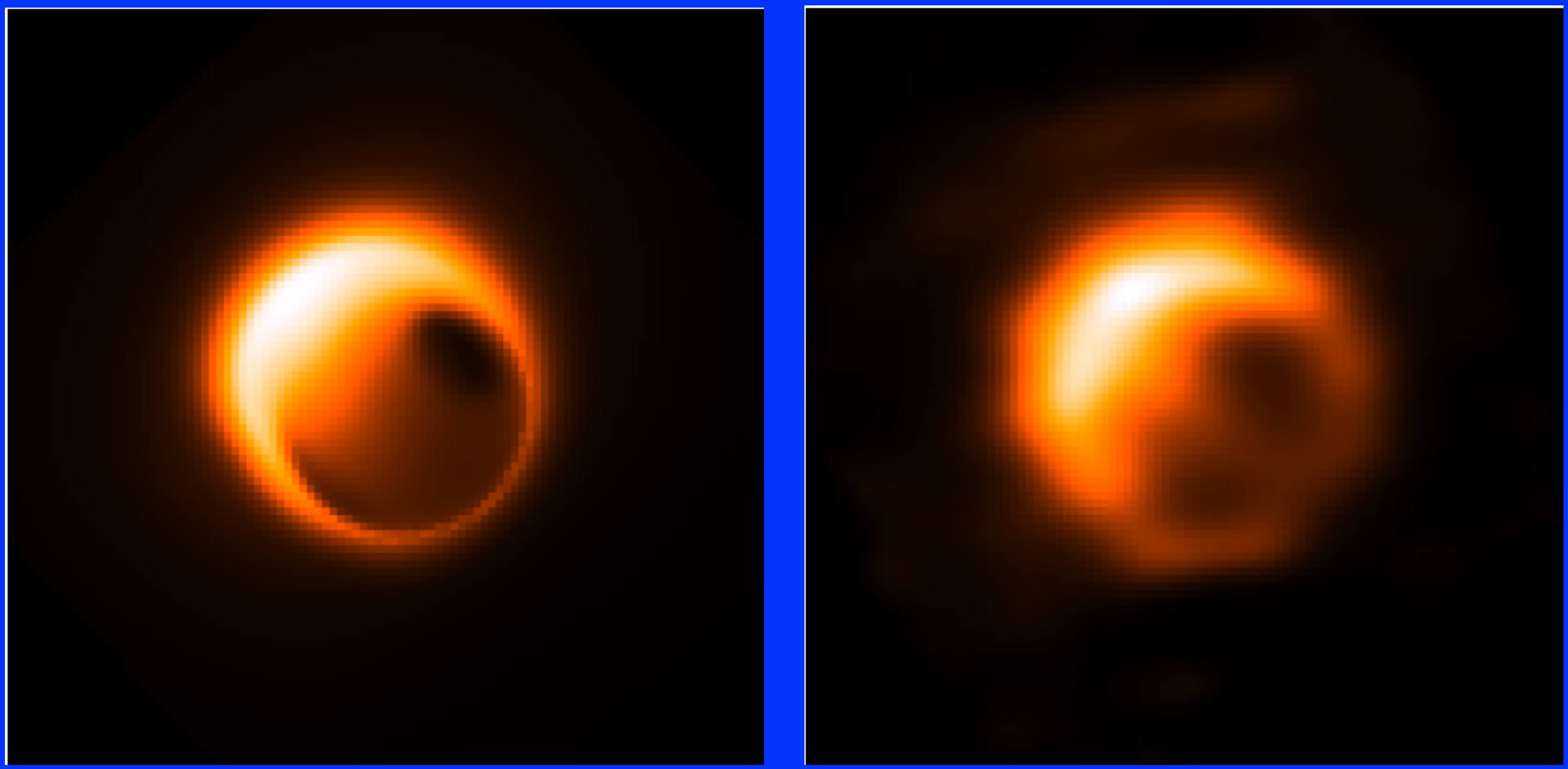
Roach Digital Backend (RDBE2)

Digital Recorder (Mark6)



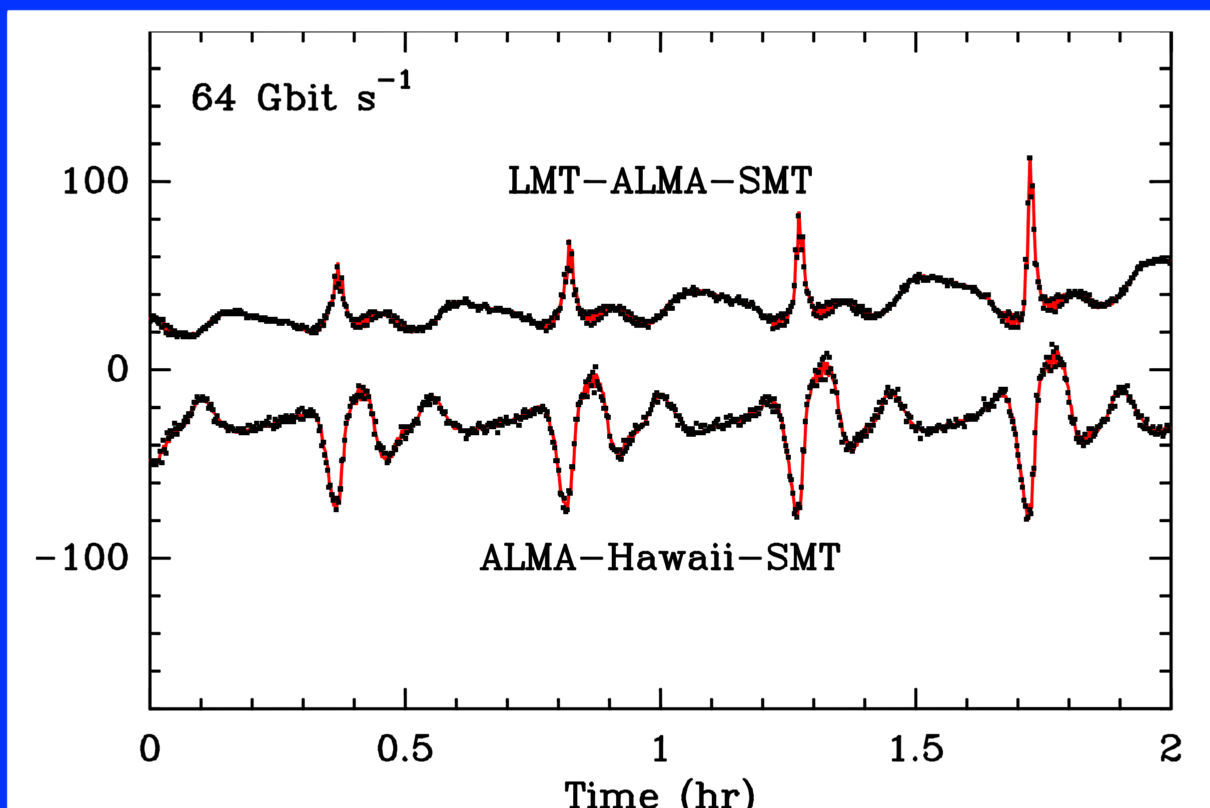
Expand from 16 Gb/s to 64Gb/s.
Data per session: ~7 PetaBytes.

Imaging:
Optical Interferometry & De-blurring

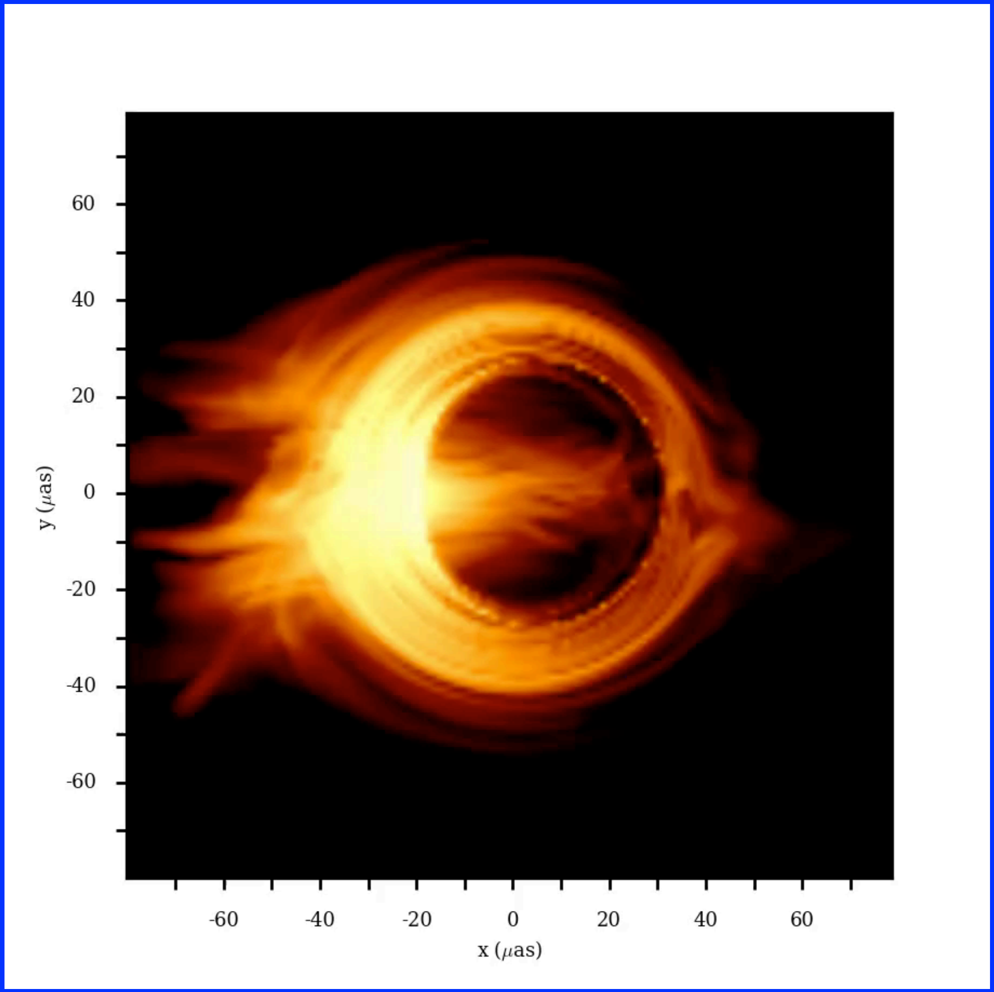


Fish et al, ApJ, v.795, p.134, 2014.

Time Resolving BH Orbits

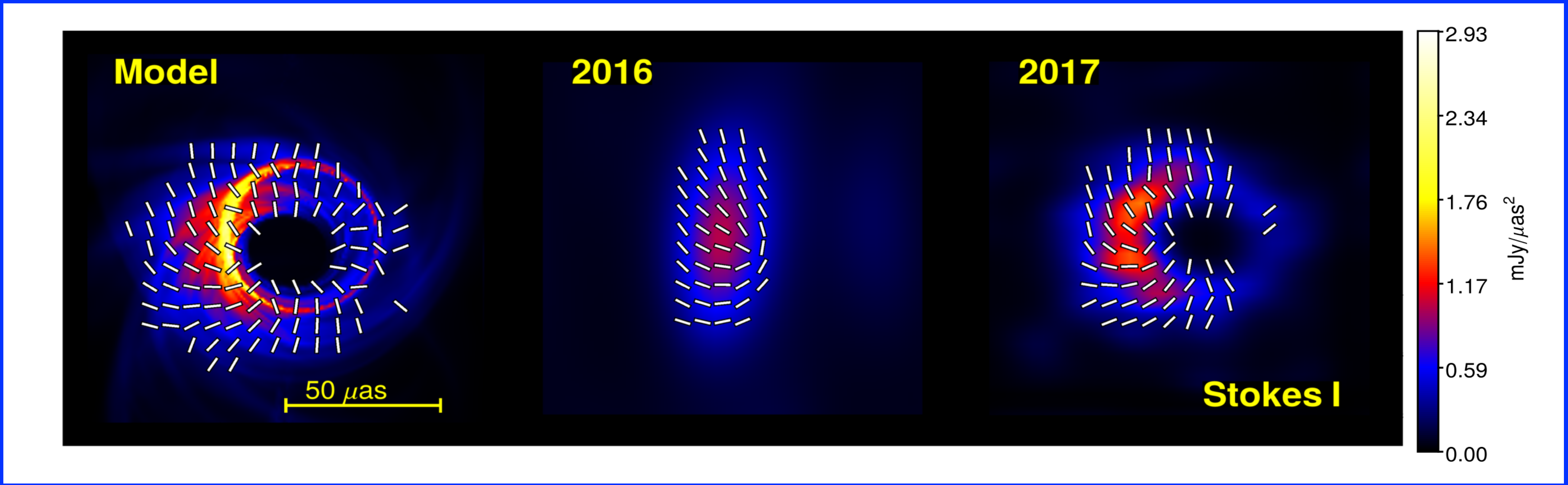


Closure phases as probes of Turbulence



Hotaka Shiokawa

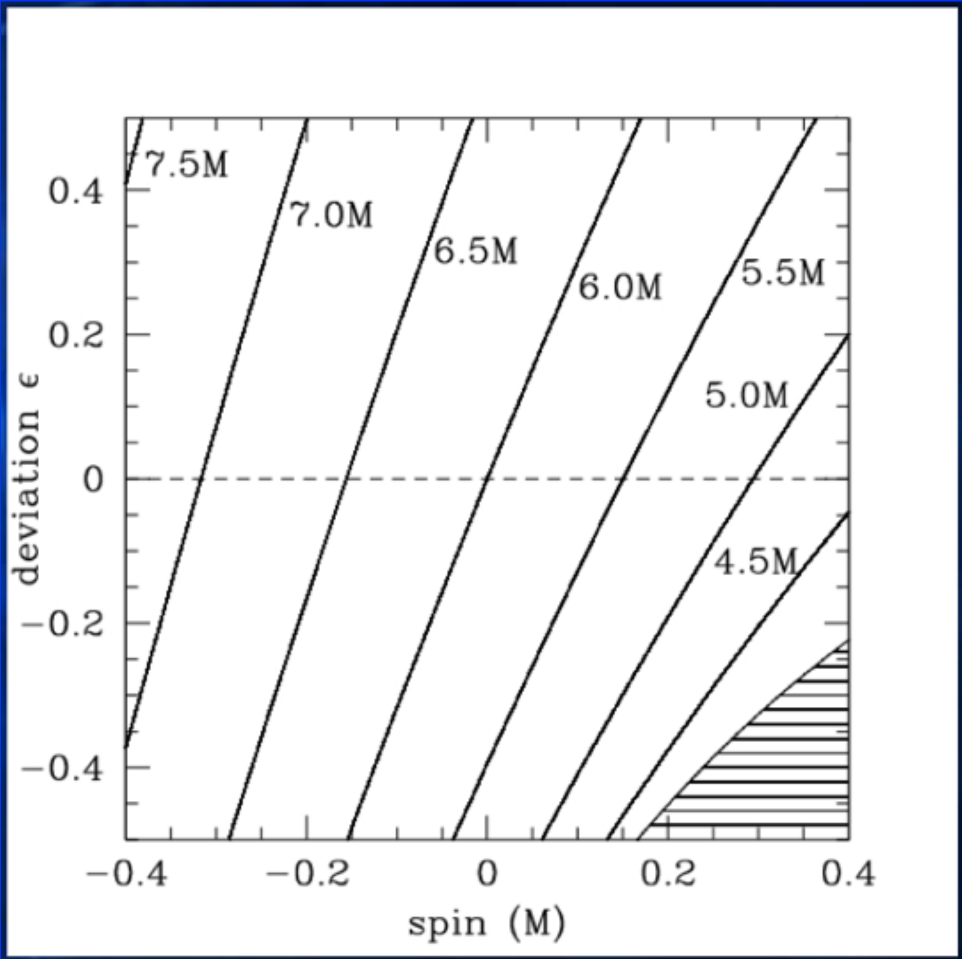
Polarimetric Imaging: Maximum Entropy Approaches

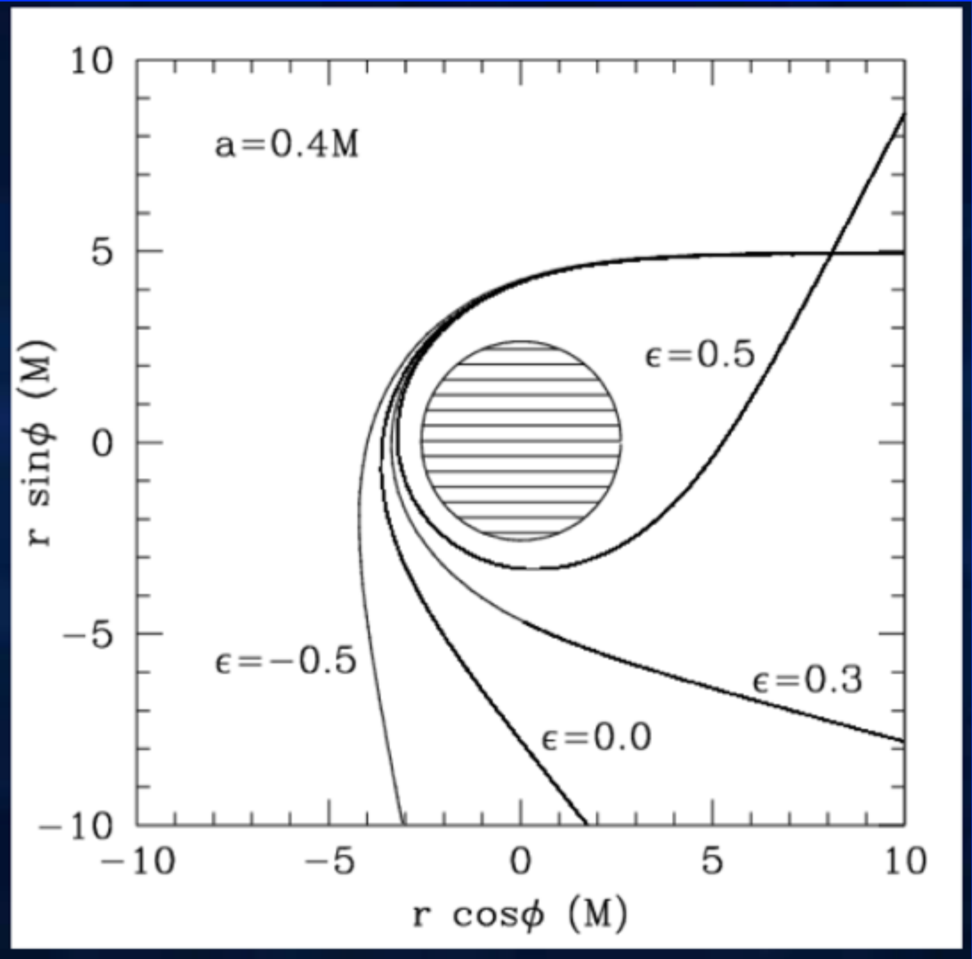


Chael et al, submitted to ApJ.

Perturbing the Kerr Metric: Quasi-Kerr

$Q' = -a^2/M^2 + \varepsilon$



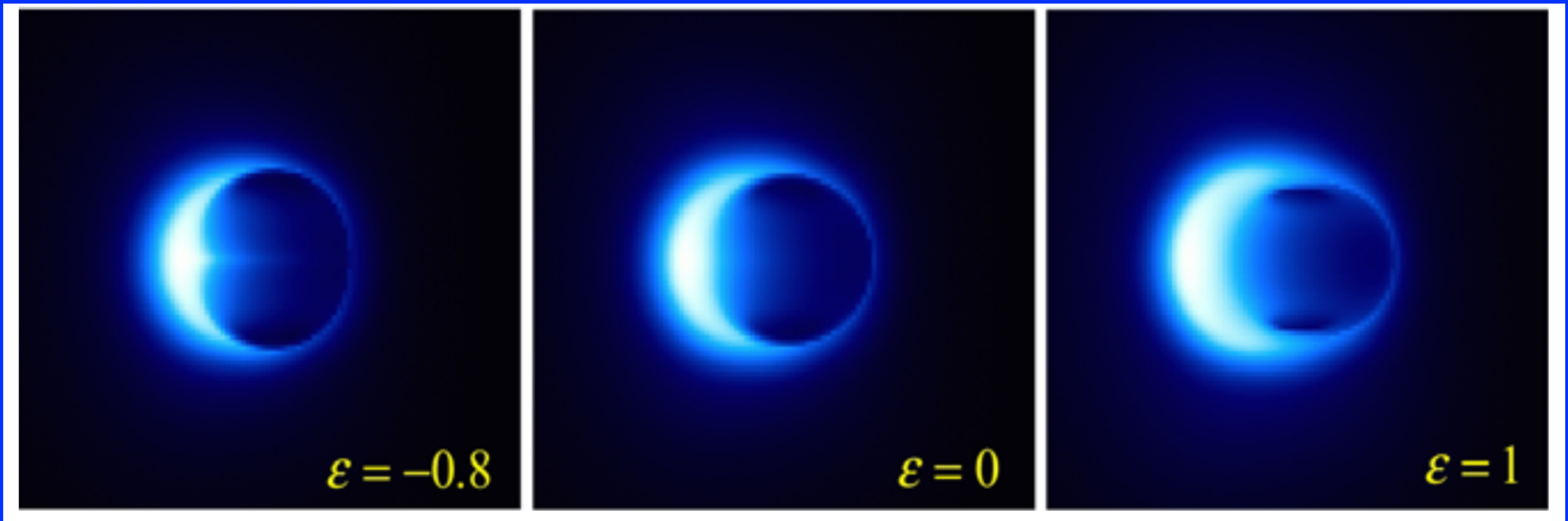


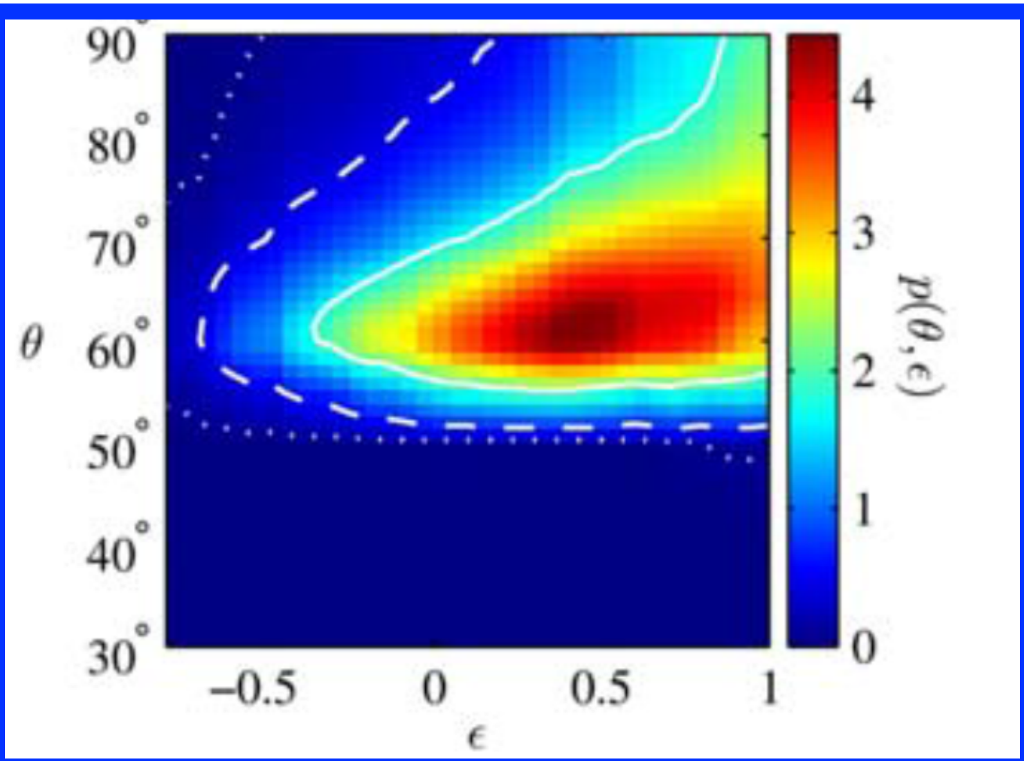
Location of the ISCO

Lightbending

Johannsen & Psaltis: (2010), (2011)

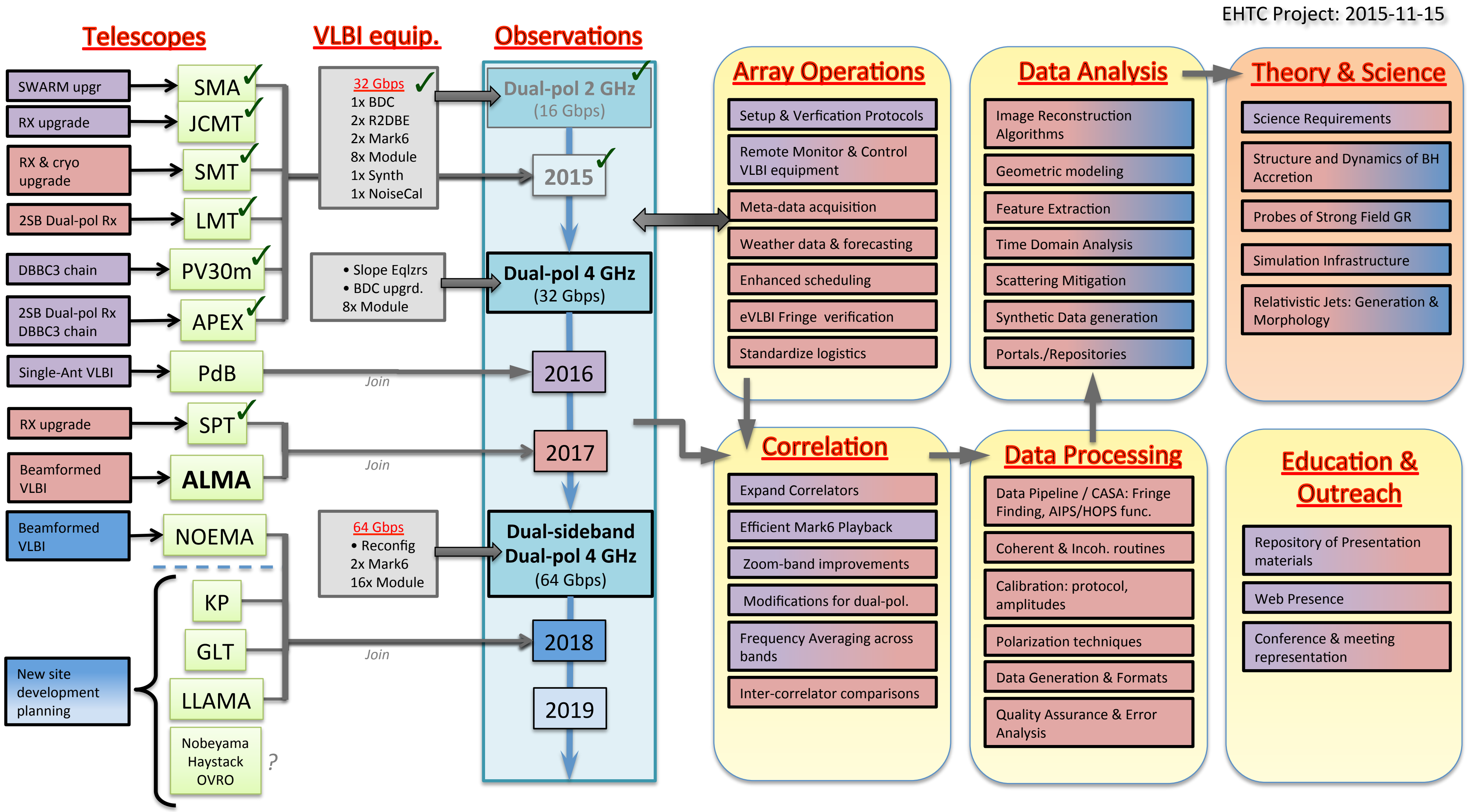
Tests of GR





Broderick, Johannsen, Loeb & Psaltis, ApJ, v784, 7B, 2014

EHT Roadmap



EHTC Project: 2015-11-15
Telescopes
VLBI equip.
Observations
SWARM upgr
SMA
RX upgrade
JCMT
RX & cryo upgrade
SMT
2SB Dual-pol Rx
LMT
DBBC3 chain
PV30m
2SB Dual-pol Rx DBBC3 chain
APEX
Single-Ant VLBI
PdB
RX upgrade
SPT
Beamformed VLBI
ALMA
Beamformed VLBI
NOEMA
New site development planning
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
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

The EHT Vitals

- Careful staging of precursor science.
- Matched by advanced technical development
- Impact across radio astronomy:
  - VLBA upgrade uses EHT recorders and backends.
  - Phasing system for ALMA from EHT program.
  - New SMA correlator/phasing system.
  - ALMA Dev program for next gen ALMA correlator.
- High degree of leverage: > $1.5B in telescopes.
- EHT Collaboration in advanced organization.
- EHT on-track for full (ALMA) observations in 2017.

The Future

- Series of observations and enhancements over the next 3-5 years.
- More BW: 256 Gb/s
- ALMA Dev innovation: SMA as testbed
- Next Gen VLBI instrumentation
- Move to 345GHz
- University based mmVLBI array for community
  - Broad Science Case (Fish et al 2014)
  - Specialized data reduction, instrumentation dev.
  - Student/Postdoc training: black belt interferometry.
- Interdisciplinary black hole studies.

EHT Collaboration

MPIfR - Bonn
ASIAA
SAO/CfA
MIT Haystack
CARMA
NAOJ
U. Arizona
BHC

NRAO
UC Berkeley
IRAM
APEX
JCMT
U. Concepcion
UNAM

Perimeter Institute
U. Illinois UC
UMD
Onsala Space Obs.
U. Mass Amherst
LMT
INAOE

Interstellar: