Sgr A* and neighbors: Pulsars at the galactic center

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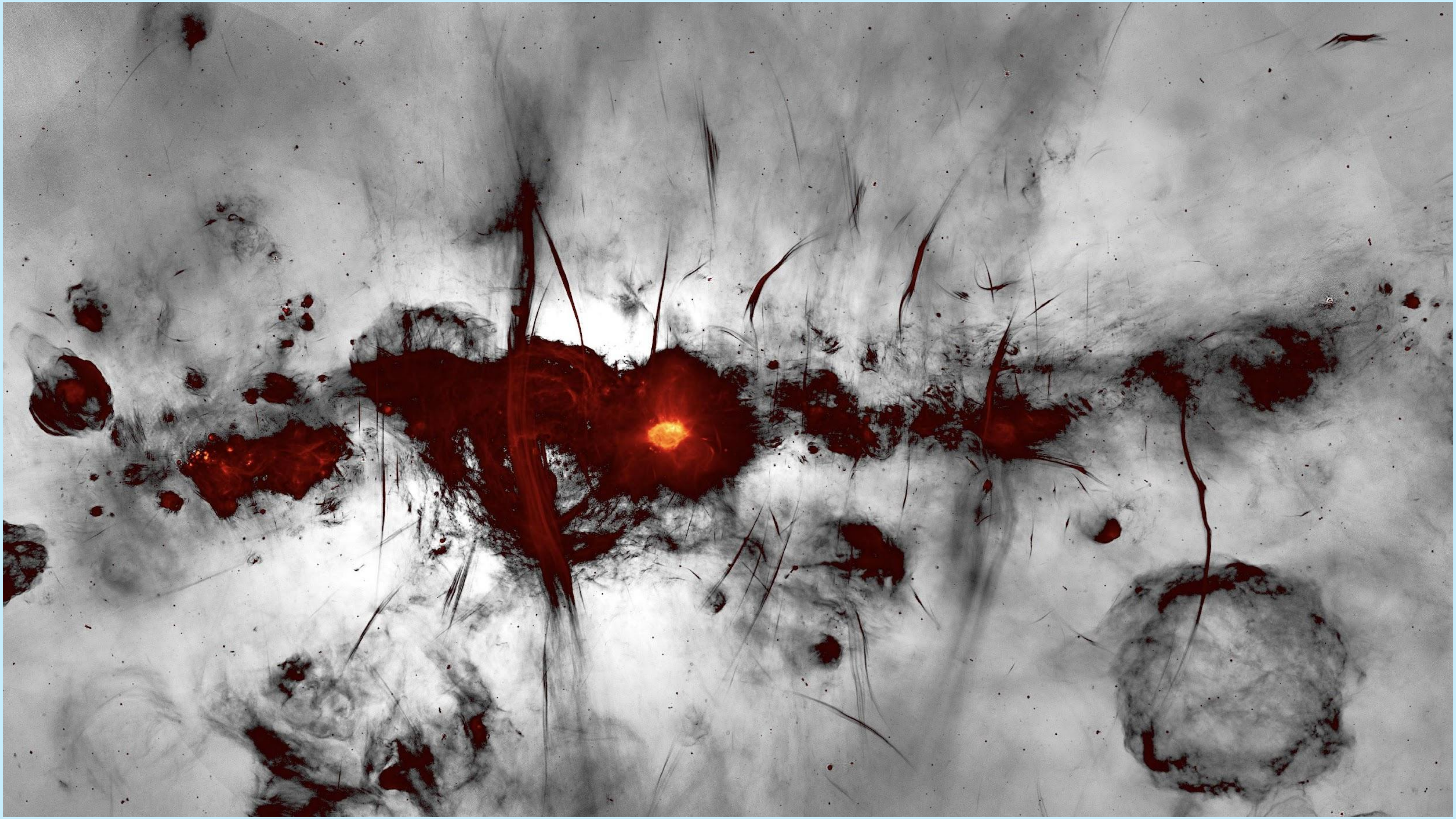
AAS 2025 Splinter session

Jan 15, 2025

Overview

- The galactic center and measurements of the supermassive black hole Sgr A*
- Pulsar-based measurements of gravity around Sgr A*
- The galactic center magnetar PSR J1745-2900
- The ngVLA and expectations for galactic center pulsar searches



Galactic center at 1.3 GHz from MeerKAT (I. Heywood,

VLBI imaging of Sgr A*

Early VLBA imaging show a compact source implying size less than few-AU (Backer et al 1993).

Bower & Backer 1998, using VLBA at 7 mm □

Apparent size affected by scattering at longer wavelengths. Suggests MBH of ~ 10^6 $M_\odot$

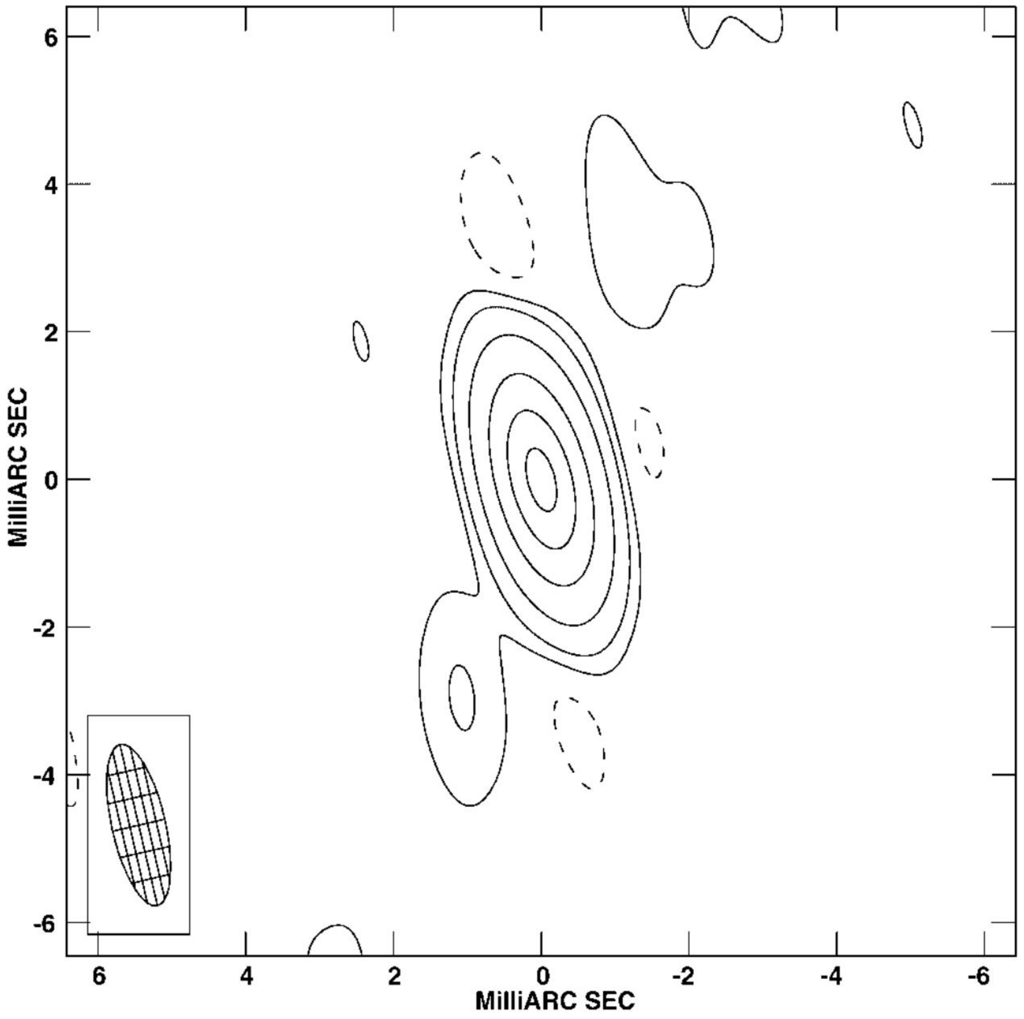
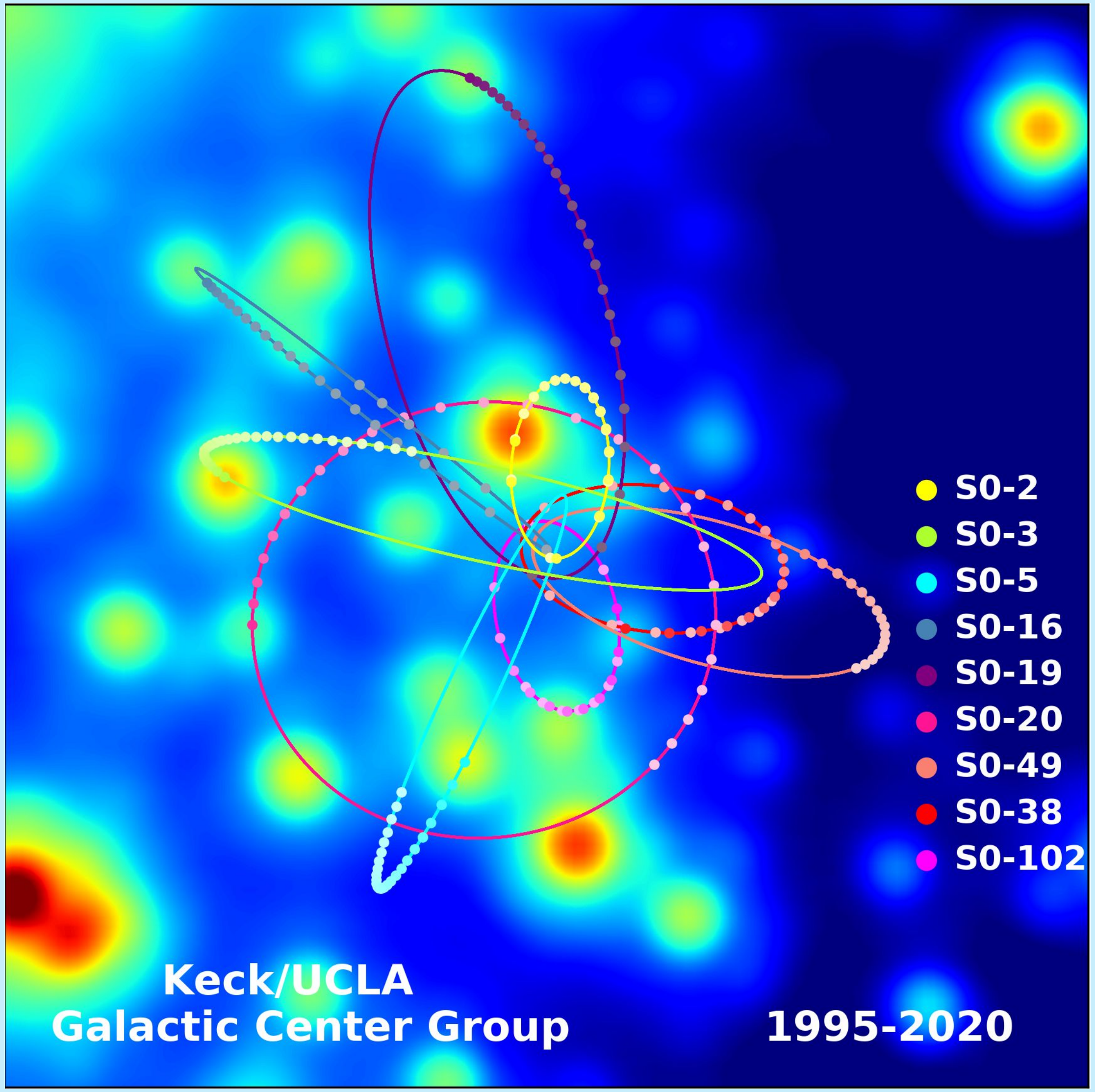


FIG. 1.—A uniformly weighted image of Sgr A*. The beam is shown in the lower left-hand corner. The contours are −0.01, 0.01, 0.03, 0.10, 0.30, 0.60, and 0.90 times the peak intensity of 0.87 Jy $beam^{-1}$.

Galactic center SMBH Sgr A*

Can track stellar orbits near Sgr A* via IR imaging over years (e.g., Ghez et al 1998, Do et al 2019, Gravity Collaboration 2022, etc).

Determines mass of central object to be 4 x 10^6 $M_\odot$

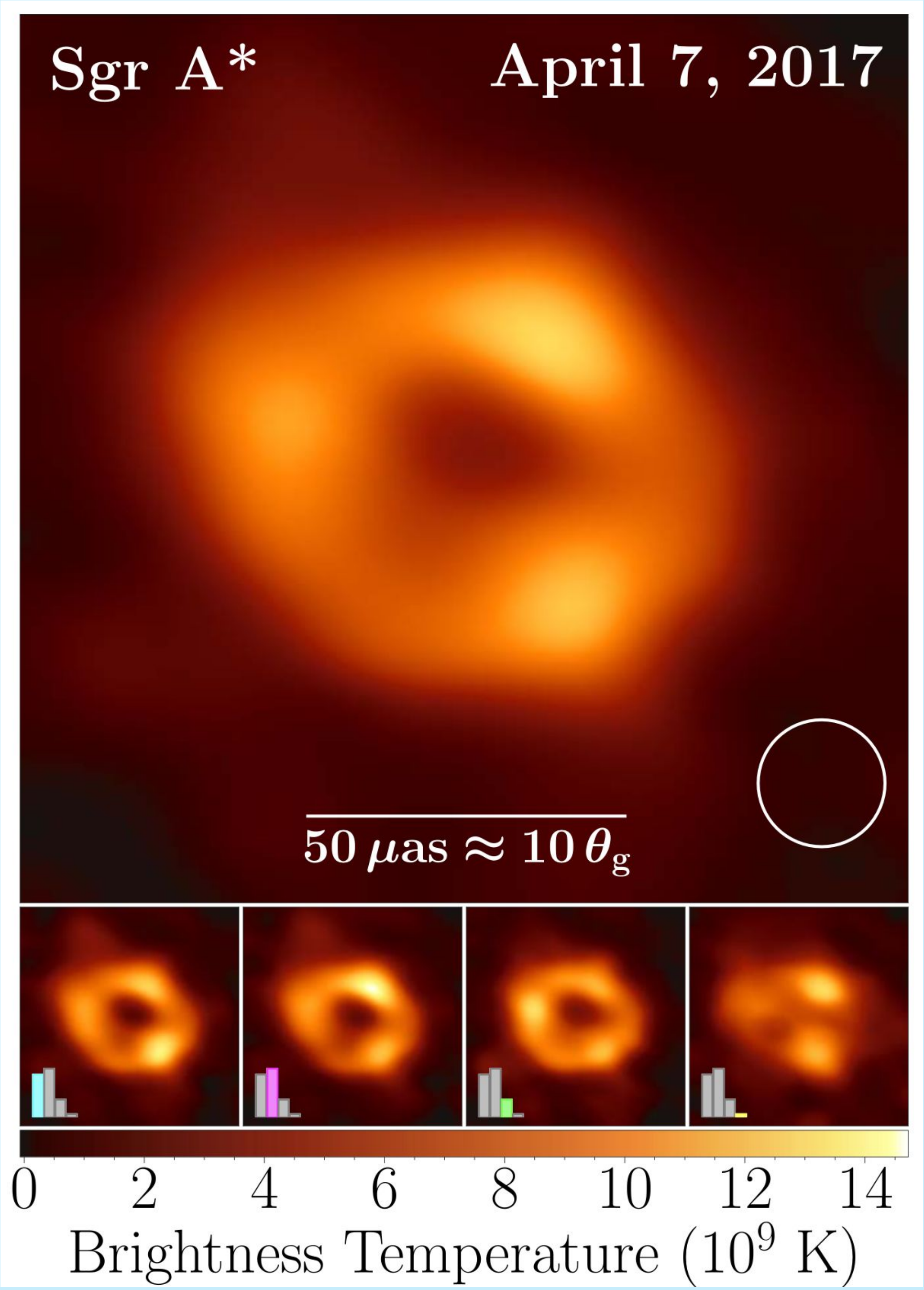


Galactic center SMBH Sgr A*

Event Horizon Telescope observed Sgr A* using global VLBI at 1.7 mm.

Direct image of BH shadow (EHT Collab., 2022)

Image consistent with GR and BH mass of $4.0^{+1.1}_{-0.6} \times 10^6 M_\odot$



Testing gravity with Sgr A* and pulsars

- Pulsar timing provides a direct measurement of changes in the light-travel time between the pulsar and Earth.
  - A pulsar orbiting Sgr A* thus can be used as a detailed probe of the spacetime around a supermassive BH.
- Some fundamental general relativity predictions:
  - "Cosmic censorship" – There is a maximum spin rate for a BH, as a function of its mass. Testable via measurement of M, S.
  - "No-hair theorem" – Spacetime around a BH is fully described by its mass and spin. Testable by measuring quadrupole or higher moments and checking for consistency.

Testing gravity with Sgr A* and pulsars

Liu et al (2012) presented results for timing a pulsar orbiting Sgr A* and detecting various relativistic effects □

Want orbits of ~years (or less!):

P~10y □ a~0.003pc □ 75mas

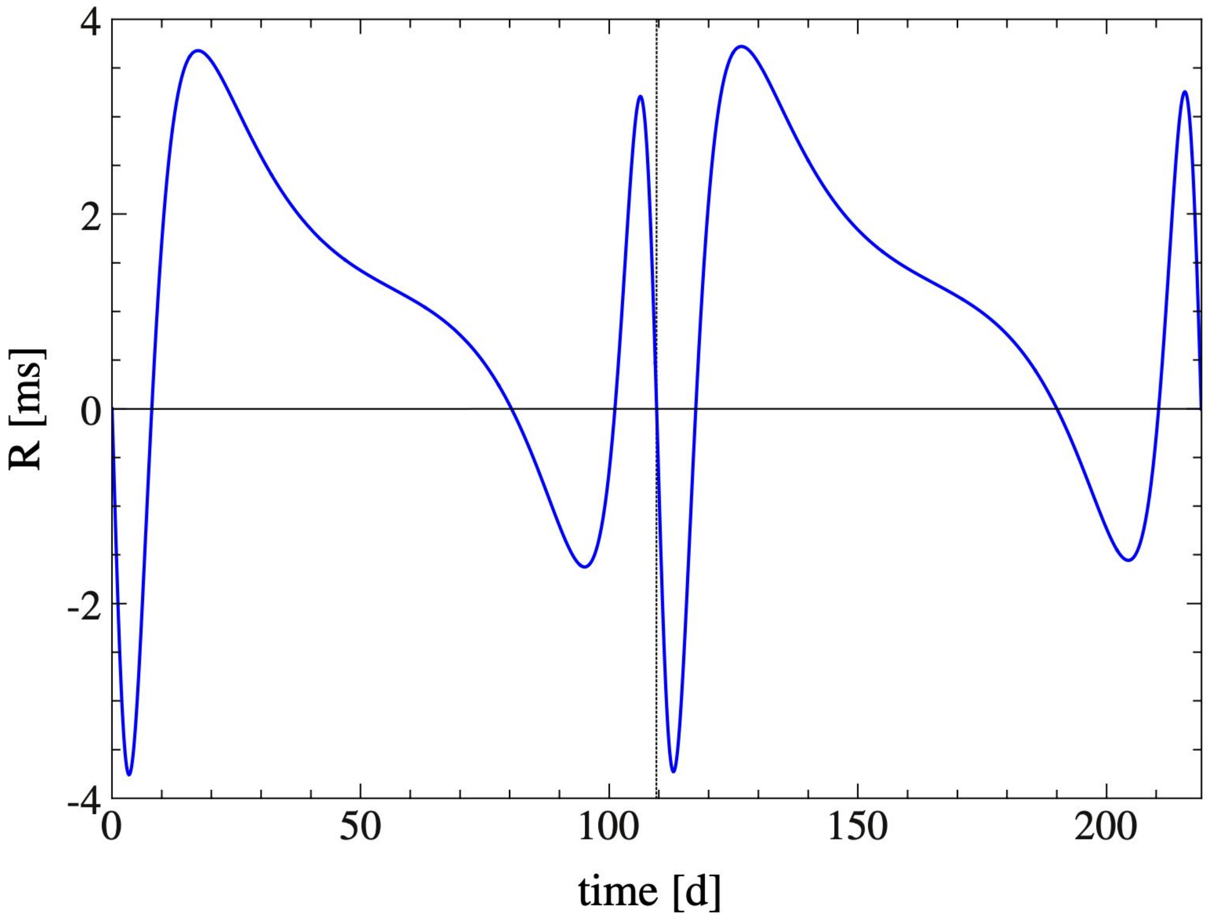
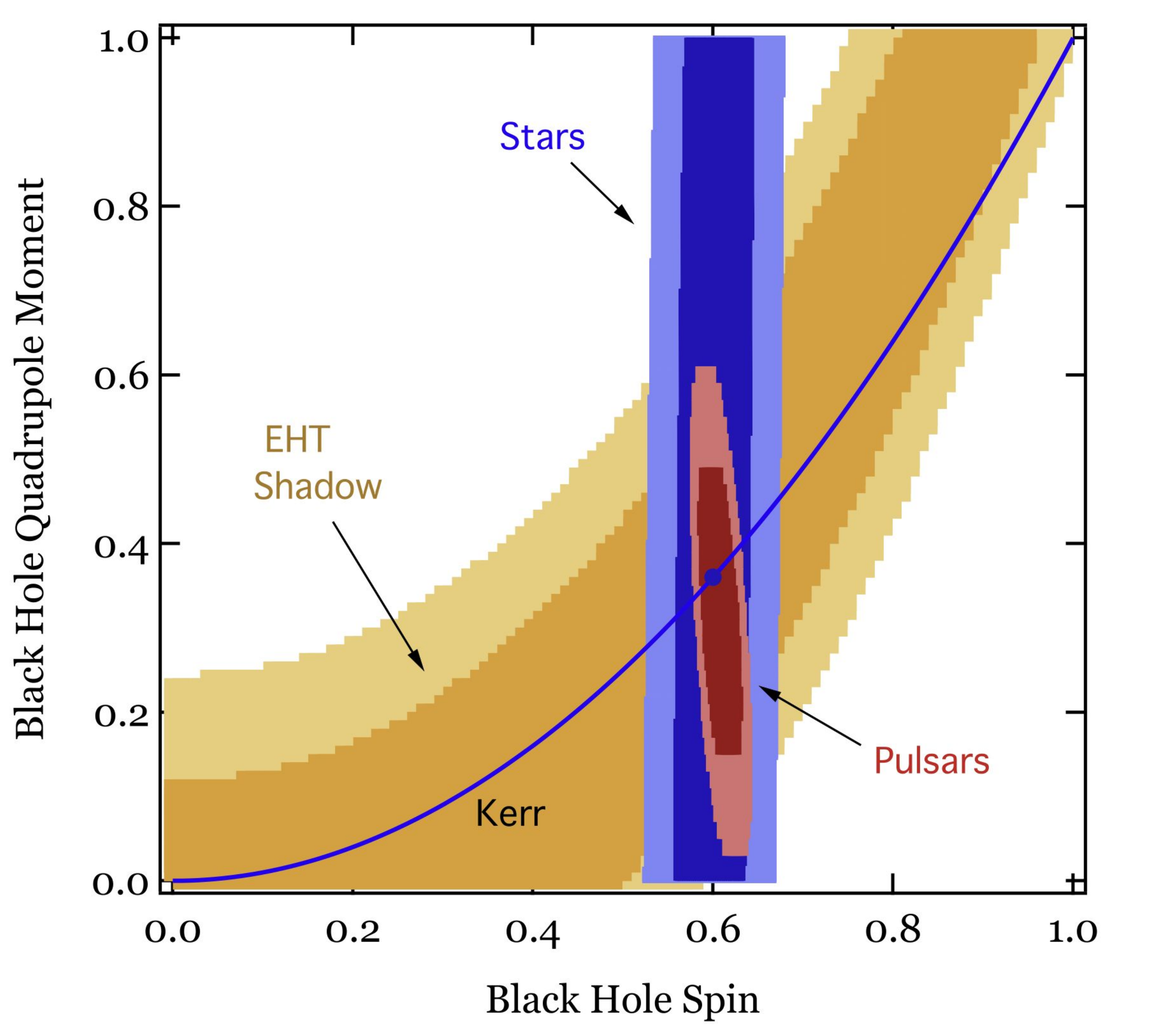


Figure 9. Residuals caused by the quadrupole moment of Sgr A* plotted for two orbital phases. We have used the same orbital and black hole parameters as in Figure 5.

Testing gravity with Sgr A* and pulsars

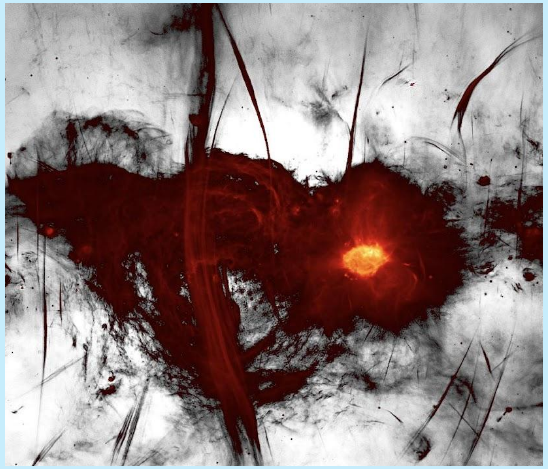
Psaltis et al (2016) compared predicted Sgr A* parameter measurements using EHT imaging, stellar orbits and pulsar timing

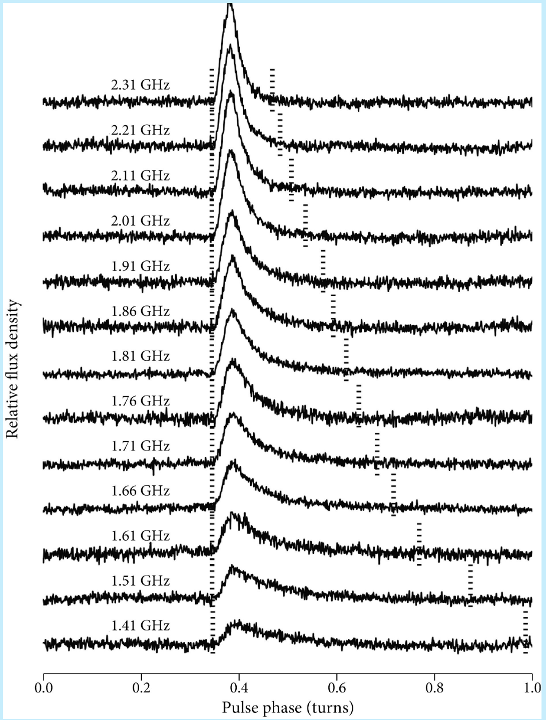
Multiple approaches increase robustness, help mitigate systematic effects.



Pulsars at the galactic center?

- Based on various observational constraints, expectation of up to ~1000 active pulsars near GC (e.g., Wharton et al 2012, ...)
  - Currently only 7 known within 0.5deg
- Problems with detecting them:
  - The GC is really really far away and pulsars are faint
  - There is lots of “junk” in the way excessive dispersion and scattering
  - Prediction of scattering times ~ 350s * f_{GHz}^{-4} (e.g., Lazio & Cordes 1998)

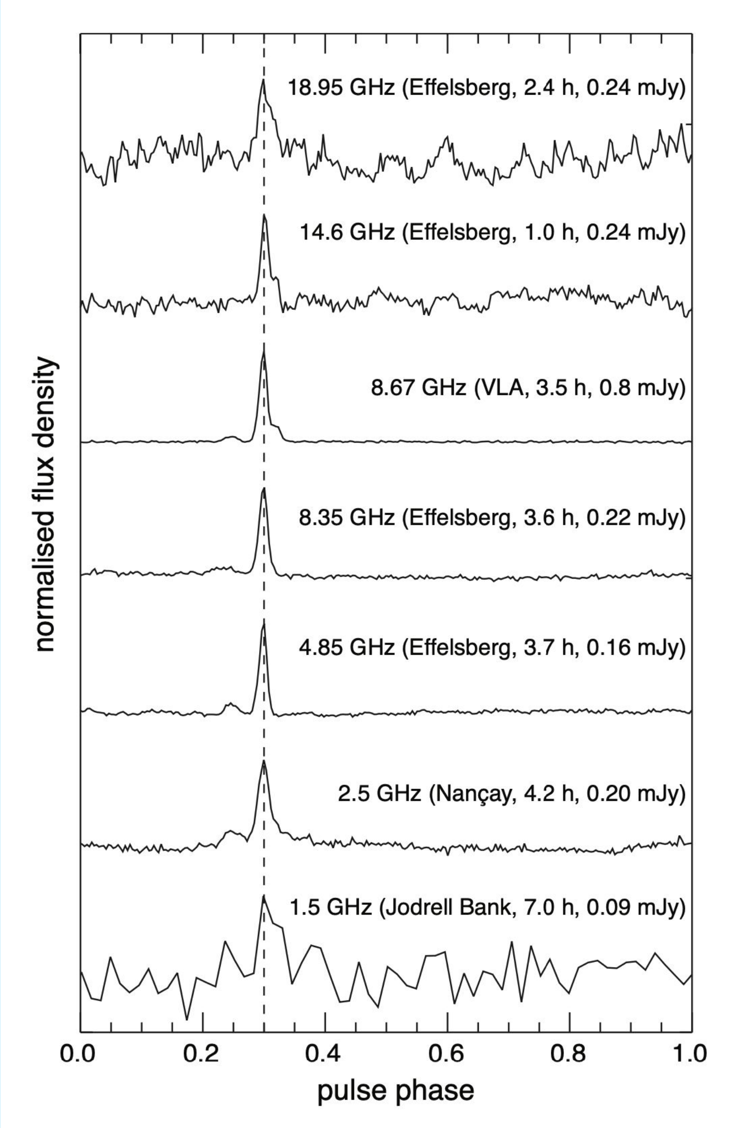




(Pennucci et al 2015)

The galactic center magnetar J1745-2900

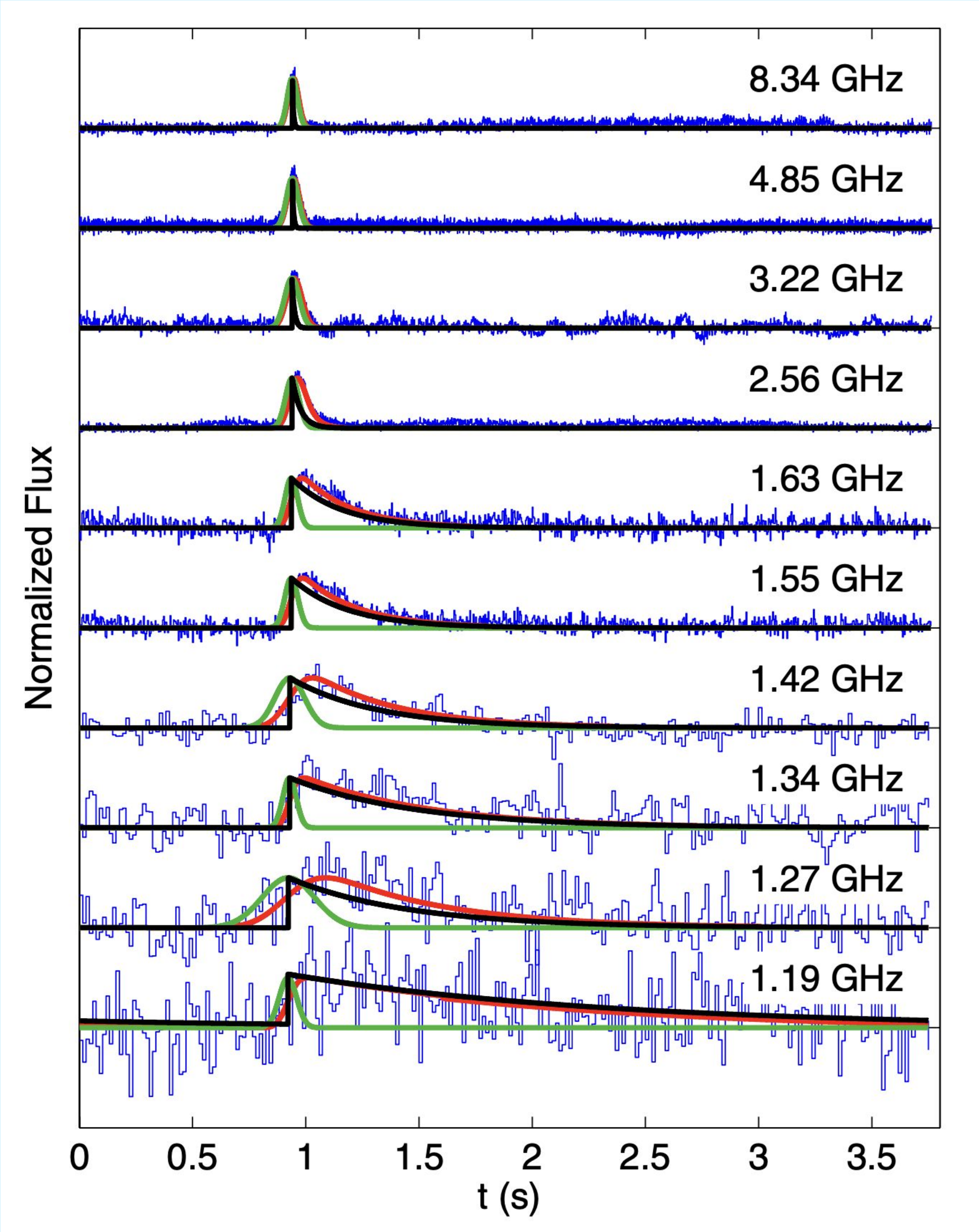
- Discovered in 2013 via X-ray outburst (Kennea+, Mori+, Rea+, 2013)
- Radio detections followed (Eatough+ 2013)
- Only 3” (0.1 pc) separation from Sgr A*
- P 3.7 s, DM 1750 pc/cm^3, RM 67000 rad/m^2 !!



PSR J1745-2900 Scattering

Temporal broadening shown to be “only” ~1.3s at 1 GHz (plot from Spitler et al 2014)!

Almost 3 orders of magnitude less than “hyper-strong” scattering predictions for GC.

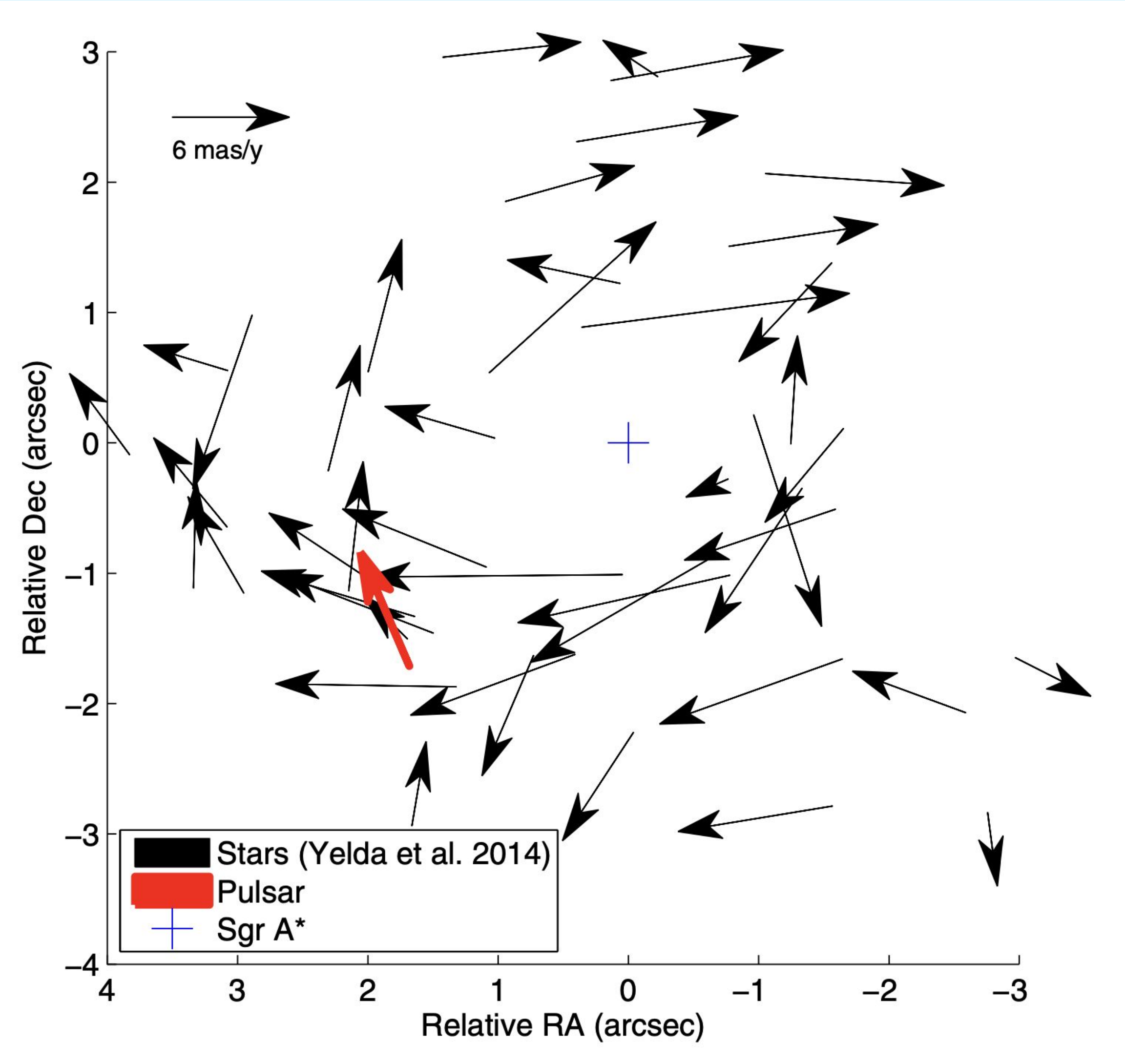


PSR J1745-2900
VLBI astrometry

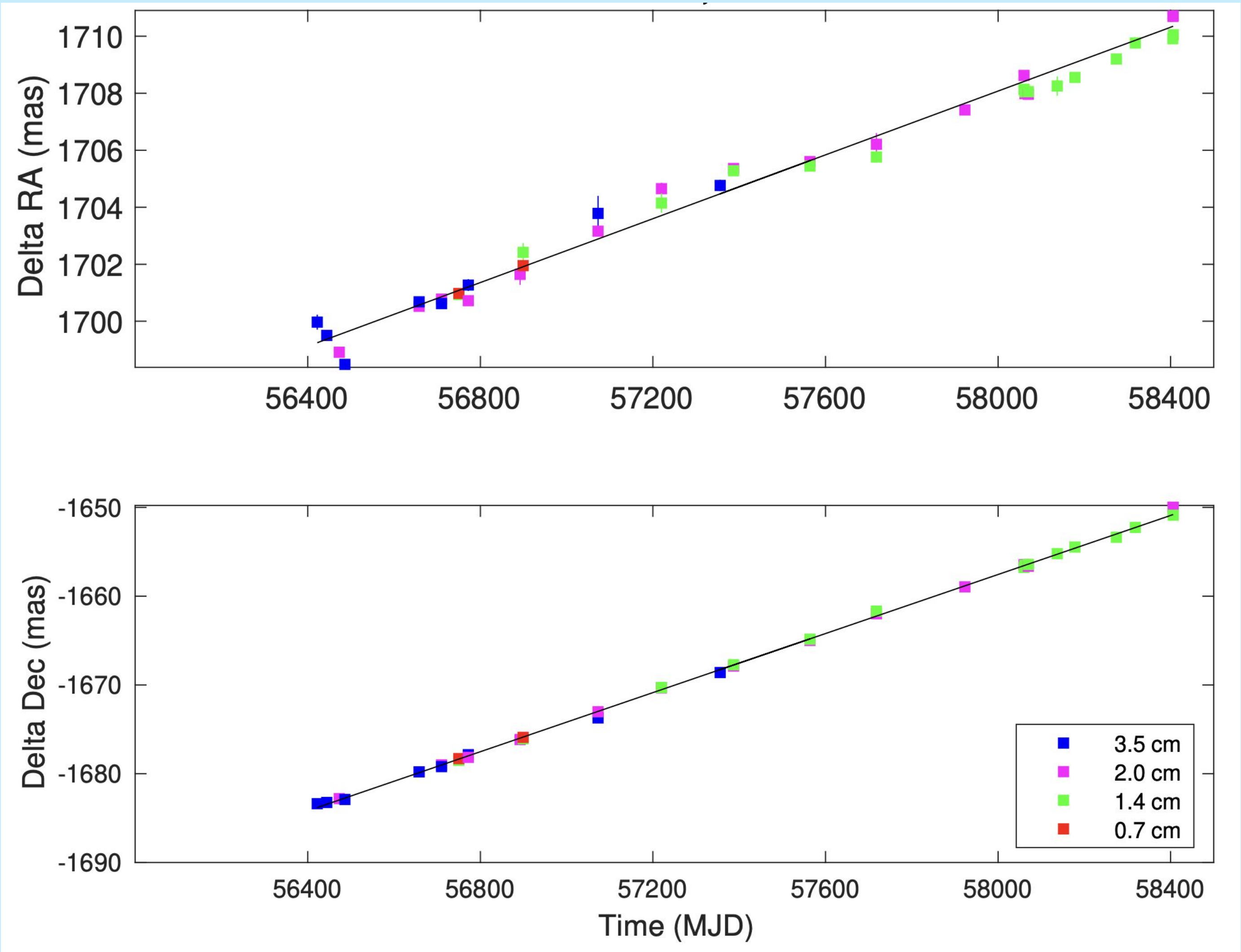
VLA+VLBA astrometry of pulsar (Bower et al 2014, 2015), key findings:

Pulsar and Sgr A* show *same* angular scatter-broadening; screen distance likely ~few kpc.

Proper motion likely associates pulsar with disk of massive stars orbiting Sgr A*



Longer-term astrometry update



Additional measurements (Bower et al 2025 in prep) show:

PM consistent with 2015 result.

Hint of acceleration consistent with orbit around Sgr A*.

Systematic “wiggle” in RA; likely refractive wander not an additional binary orbit (comparison with timing data).

ngVLA overview

Key design choice: Antennas in fixed locations

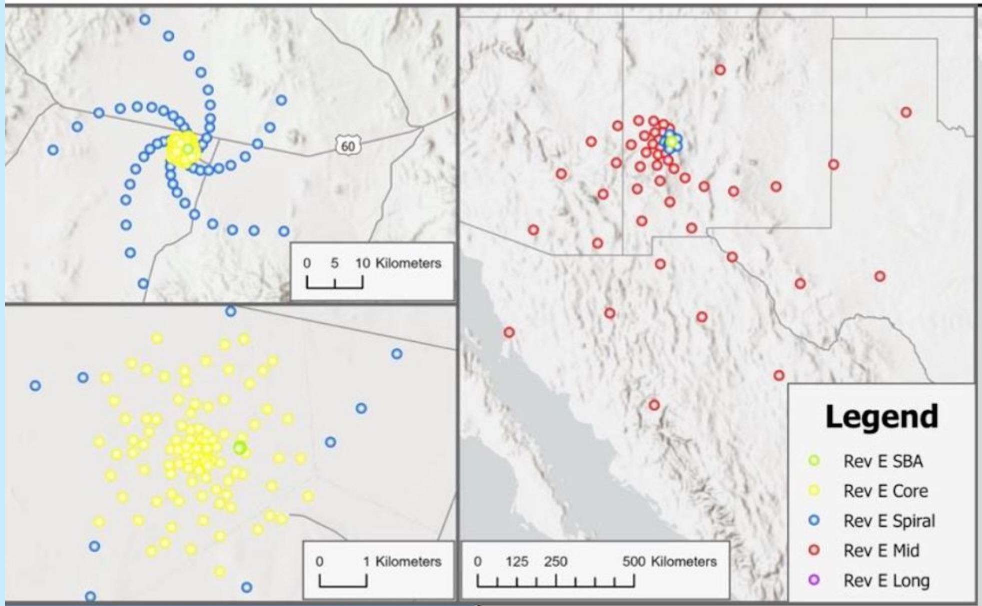
- ***Year-round access to all angular resolutions***
- ***PI-driven facility providing science subarrays***

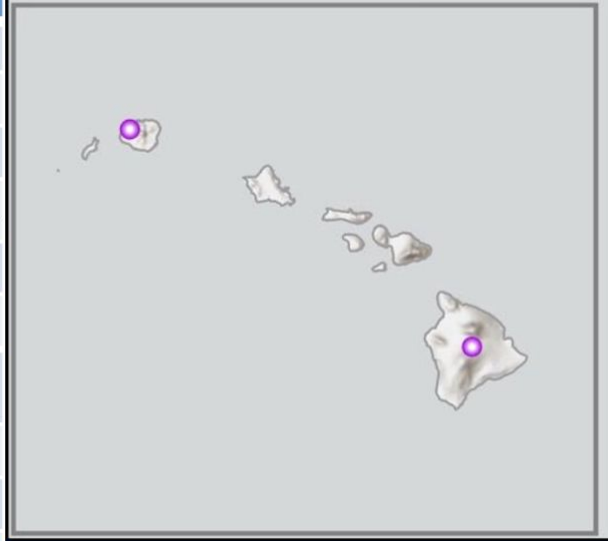
- **Frequency Range**: 1.2 - 116 GHz
- **Main Array**: 244 x 18m offset Gregorian Antennas
  - **Core**: 114 antennas; B_{max} = 4.3 km
  - **Spiral**: 54 antennas; B_{max} = 39 km
  - **Mid**: 46 antennas in NM, AZ, TX, MX; B_{max}=1070 km
  - **Long**: 30 antennas across continent; B_{max}= 8860 km
- **Short Baseline Array**: 19 x 6m offset Greg. Antennas
  - Use 4 x 18m in **Total Power mode** to fill (*u*,*v*) hole

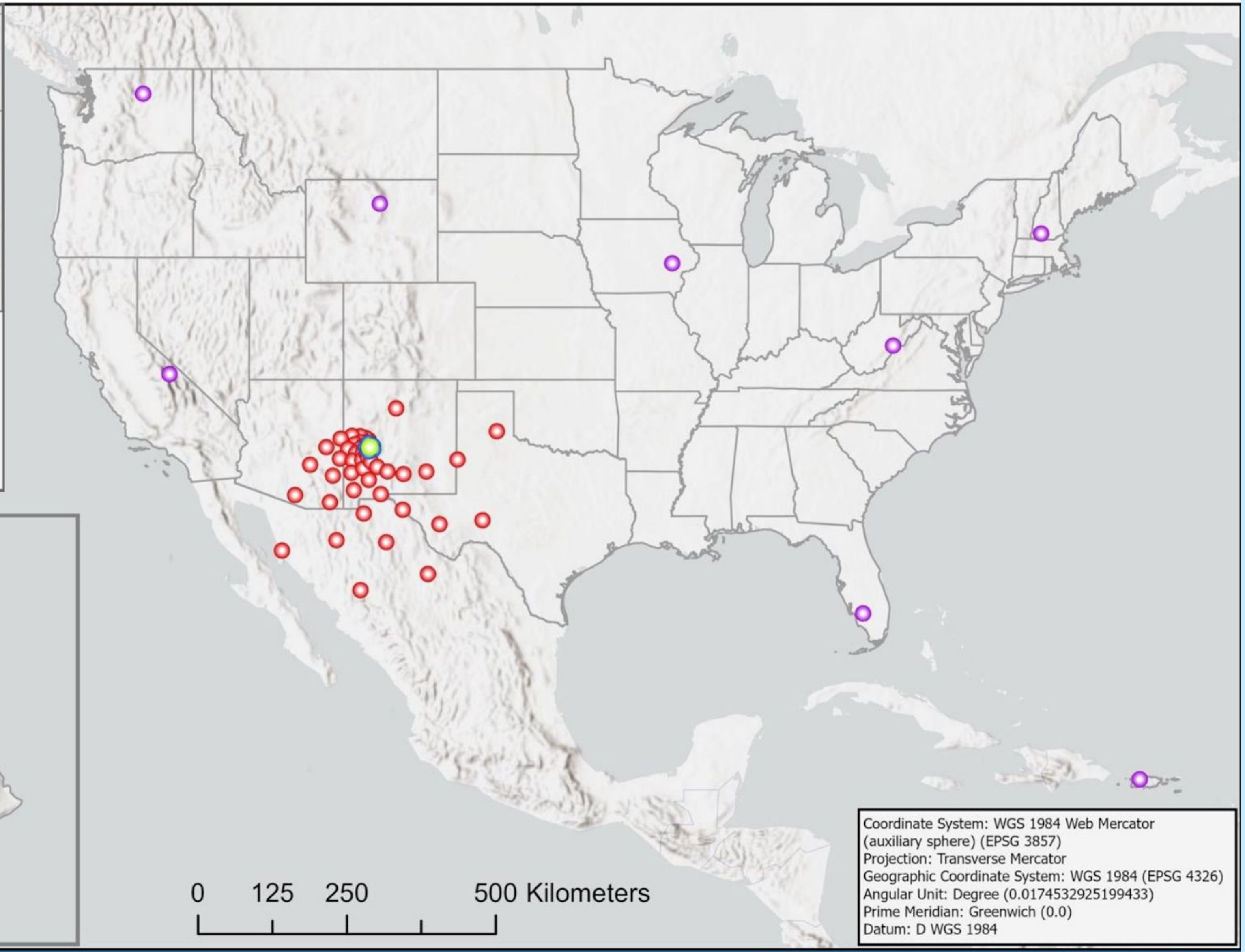
Band #	Freq. Range (GHz)
1	1.2 - 3.5
2	3.5 - 12.3
3	12.3 - 20.5
4	20.5 - 34
5	30.5 - 50.5
6	70 - 116

Correlator / Beamformer	Requirement (design)
digital efficiency	>95%
narrowest channel	<1 kHz
total # channels	>240,000
sub-band width	<250MHz (218.75)
total bandwidth	>14GHz/pol (20)
# formed beams	10

ngVLA will be ~10x more sensitive than the current VLA!



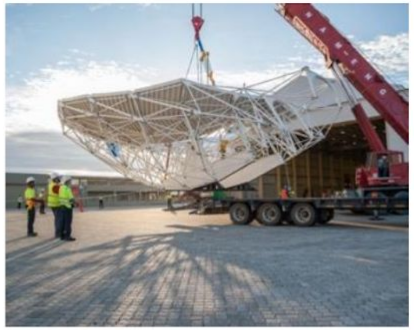


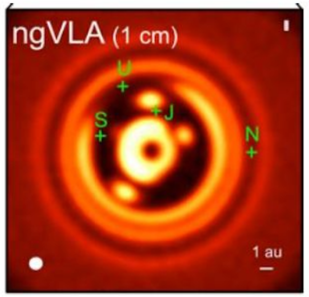


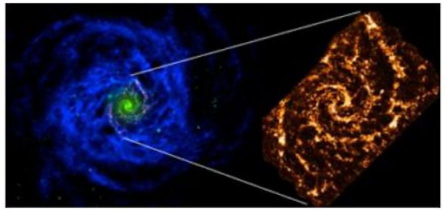
Long Antenna Sites

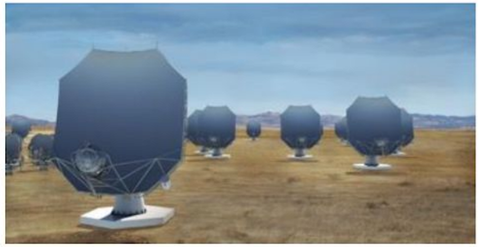
Qty	Location	Notes
3	Puerto Rico	Arecibo Site
3	Immokalee, FL	UF IFAS Site
3	Kauai, HI	Kokee Park Obs.
3	Hawaii, HI	Not MK Site
3	Hancock, NH	VLBA Site
3	Green Bank, WV	GBO
3	Brewster, WA	VLBA Site
3	High Park, WY	New Site
3	North Liberty, IA	VLBA site
3	Owens Valley, CA	VLBA site

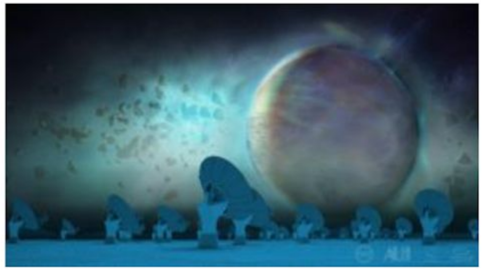
Big Picture - Timeline











2019 — ngVLA Submission to Astro2020

2021 — Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

2024 — Prototype Delivered to VLA Site

2028 — Complete NSF/MREFC FDR

ngVLA Construction →

2031 — Initiate ngVLA Early Science (> VLA capabilities)

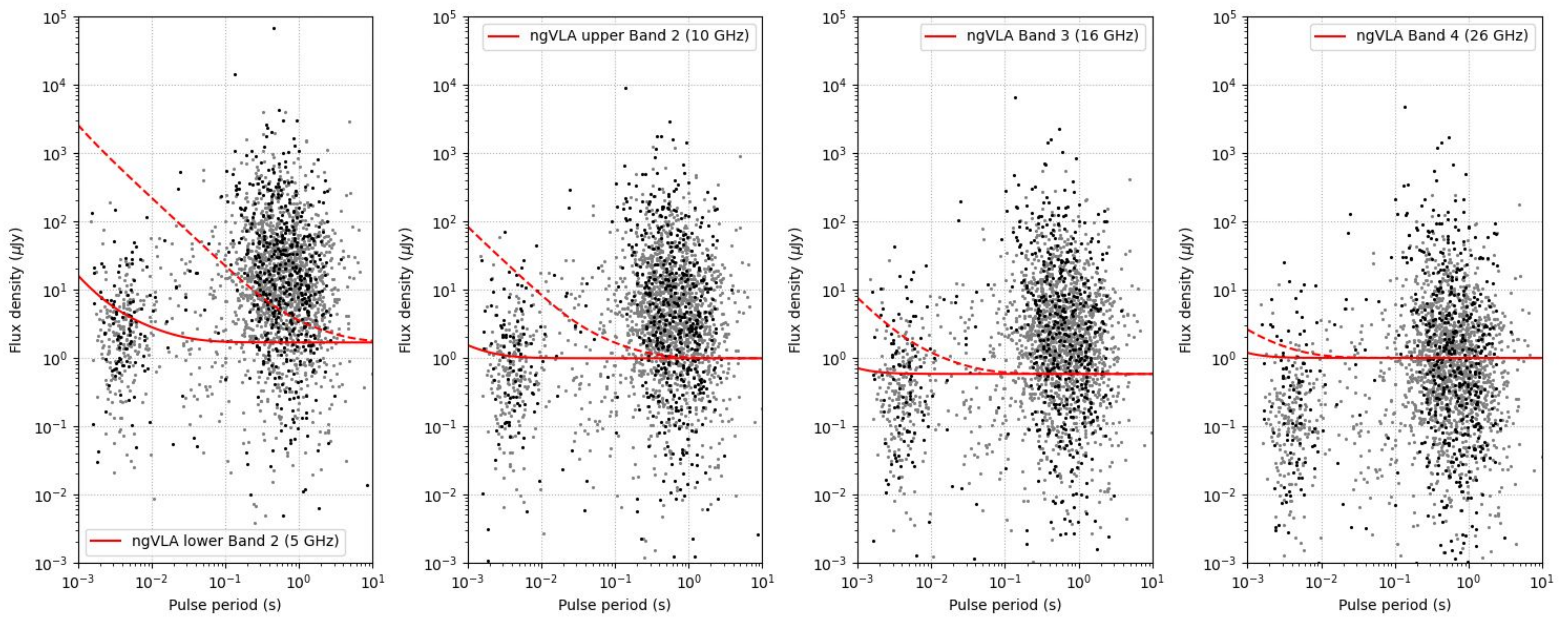
2037 — Achieve Full Science Operations

ngVLA prototype antenna!

https://public.nrao.edu/ngvla-webcam

ngVLA pulsar capabilities

- Pulsar capabilities are planned as a standard part of ngVLA – galactic center searches are a large part of KSG4.
- Correlator will include beamforming and pulsar processing:
  - At least 10 beams, either as subarrays or from a single array.
  - “Search mode” records power vs time (~100 us) and frequency (~MHz)
  - “Fold mode” records high-resolution pulse profiles at a known pulse period to be used for timing
  - Coherent dedispersion
  - At least 8 GHz total BW
- Pulse binning or gating for imaging/astrometry being considered.
- Wide-area “blind” pulsar search is *not* planned.



Assumptions: Pulsar data from ATNF catalog v2.5.1 and YMV16 DM-distance model; 6-h observation using central 168 ngVLA antennas (“core+spiral”) □ ~120mas beam at 16 GHz.

Caveat: This is not a “legit” population analysis; see e.g. Chennamangalam & Lorimer (2014) for example.

Summary

- Pulsars orbiting the galaxy's central BH Sgr A* would provide fundamental new tests of gravity around a supermassive black hole.
- Expectations of ~hundreds of pulsars in this area, but detection is challenging due to S/N and scattering.
- Observations in ~10—30 GHz with a large sensitive telescope like ngVLA are needed to find this population and perform these tests.
- ngVLA is being designed with pulsar capability and plans to search the galactic center are a key science goal.