ngSVLBI Workshop 2022

Orbital Configurations for Photon Ring Detection

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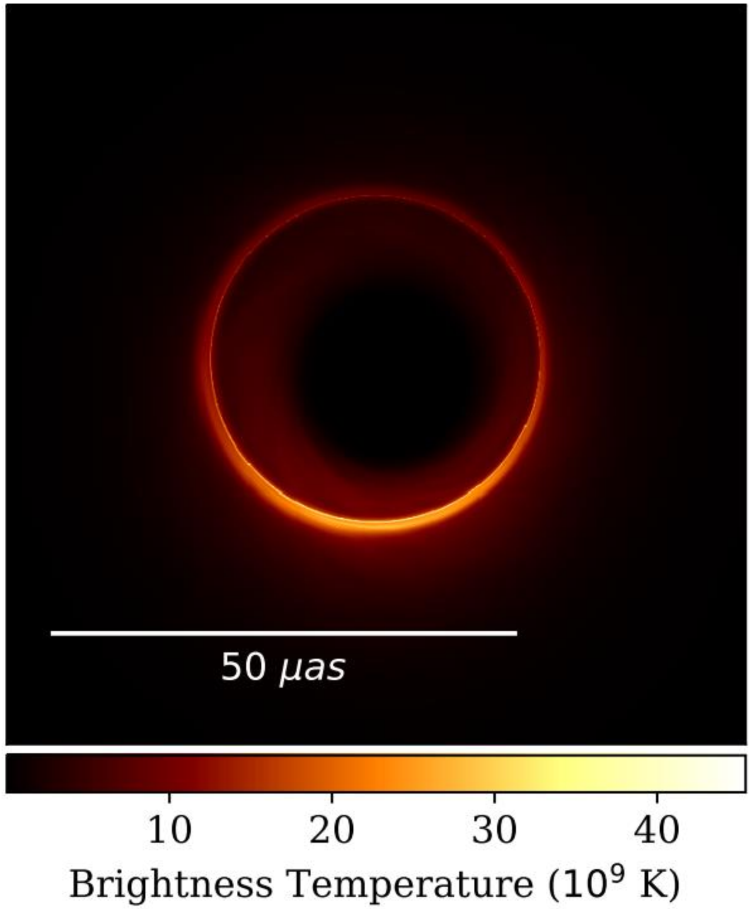
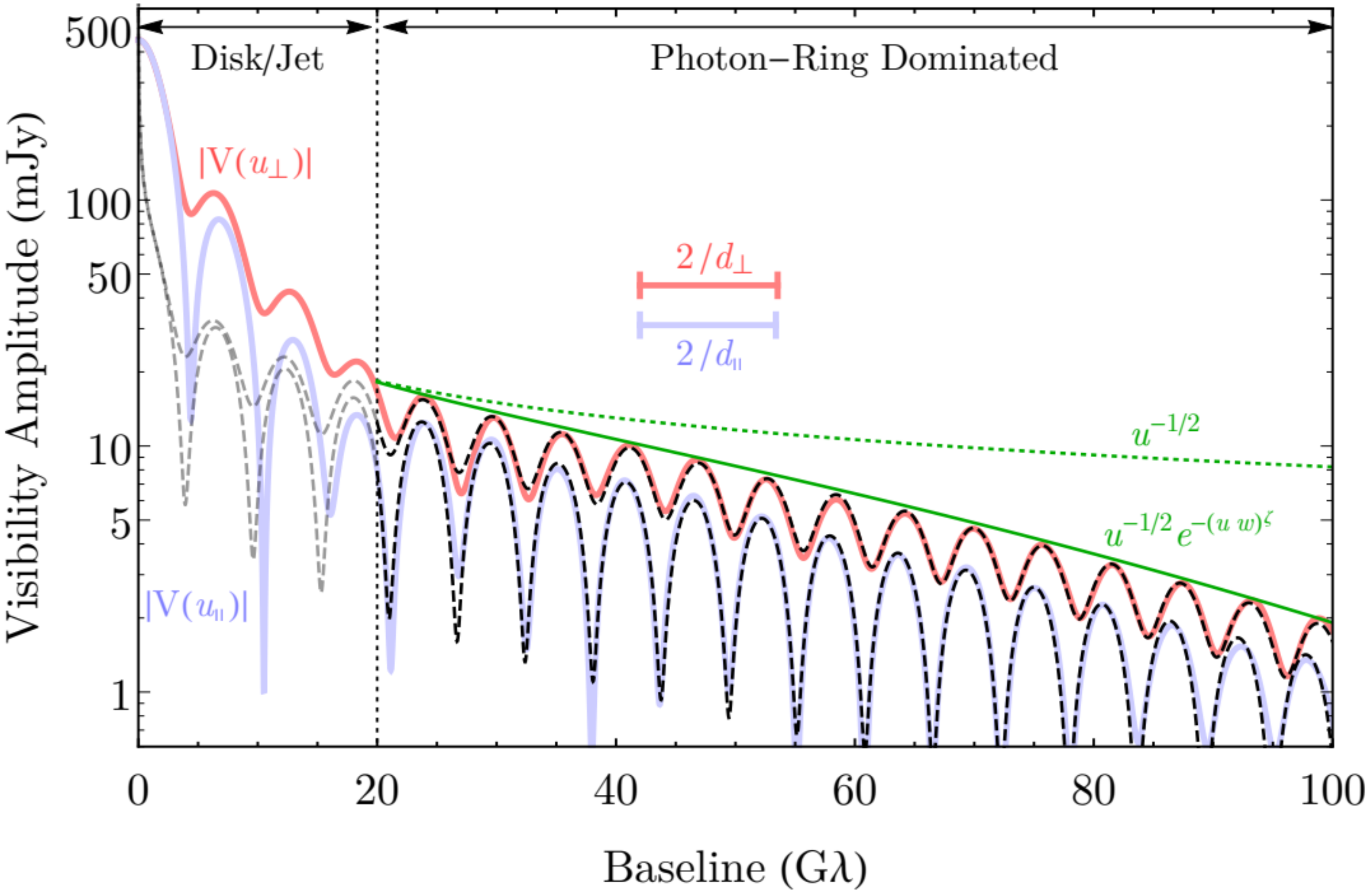
Interferometric Signature of Photon Rings

Credit: Michael D. Johnson, et al. 2020





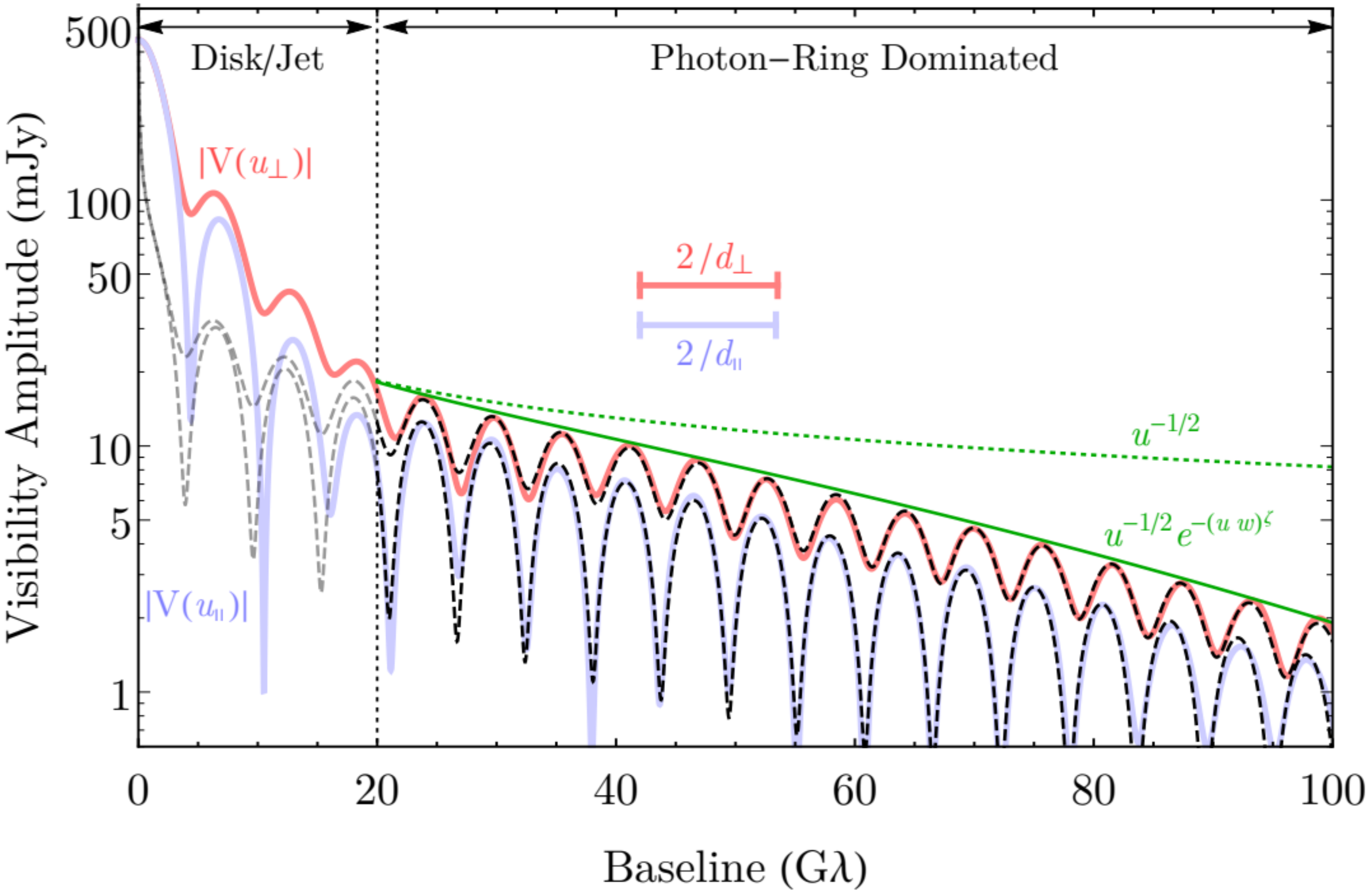
Interferometric Signature of Photon Rings

Broderick, Tiede, Pesce, Gold. 2022 – *Measuring Spin from Relative Photon-Ring Sizes*

Wielgus. 2021 – *Photon rings of spherically symmetric black holes and robust tests of non-Kerr metrics*

Gralla, Lupsasca, Marrone. 2020 – *The shape of the black hole photon ring: A precise test of strong-field general relativity*

Credit: Michael D. Johnson, et al. 2020



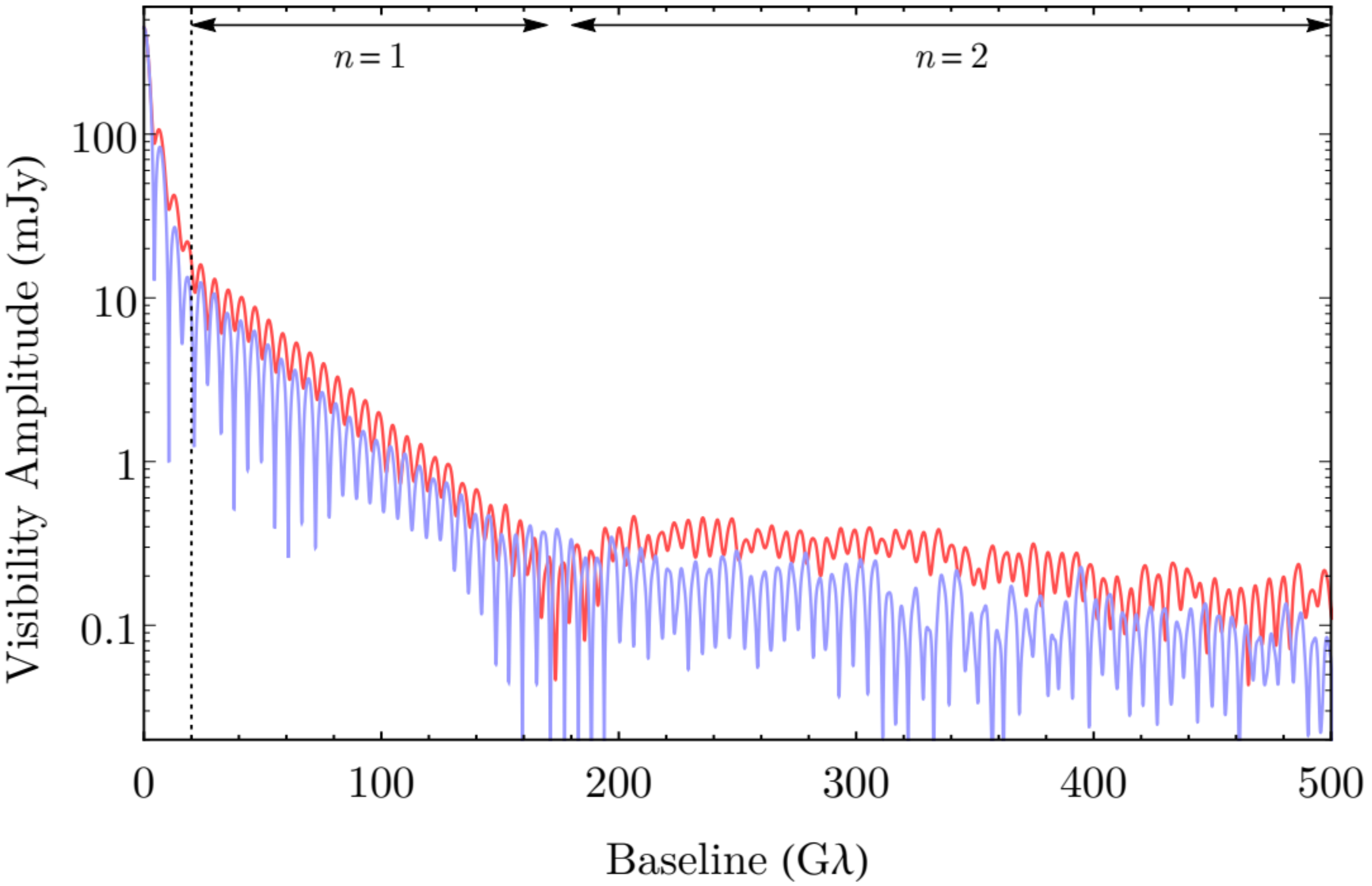
Performance Requirements

Credit: Michael D. Johnson, et al. 2020

1. Absolute baseline variation between 20 Gλ and 200 Gλ

2. Sample *(u,v)* plane at the Nyquist rate

3. Achieve the required baseline variation for any position on the celestial sphere



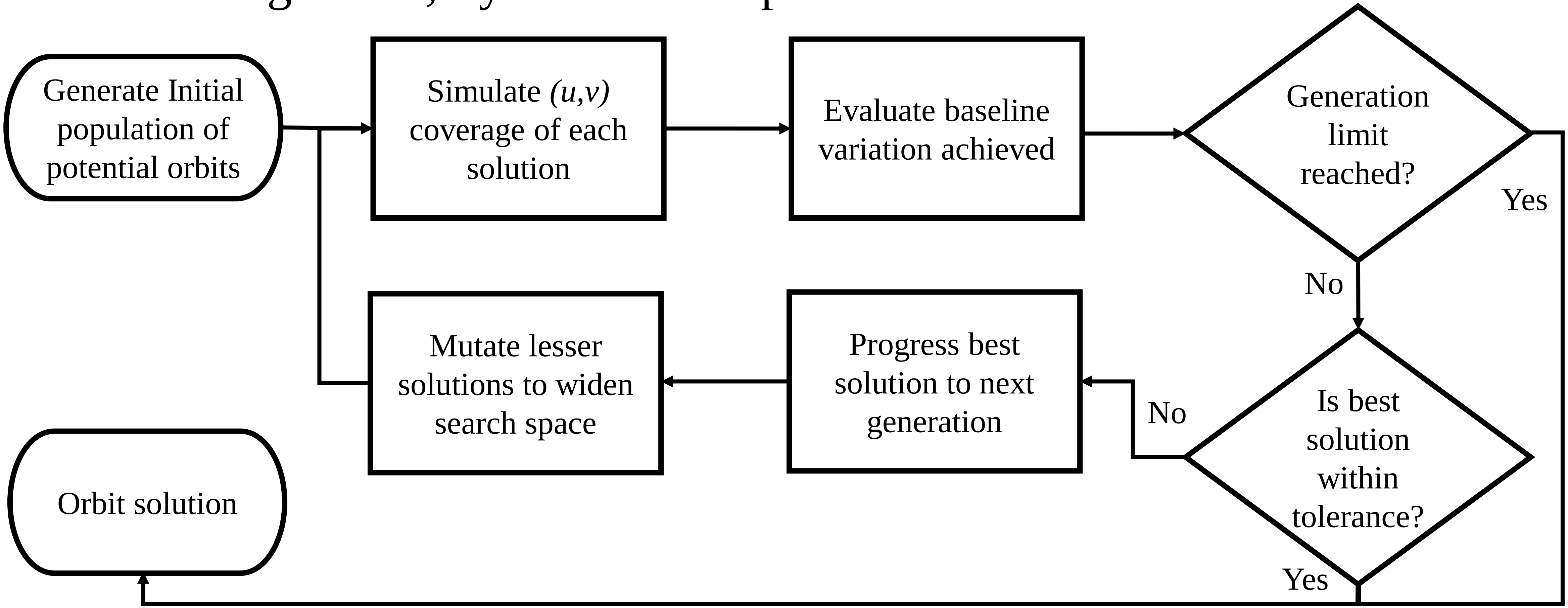
System Overview

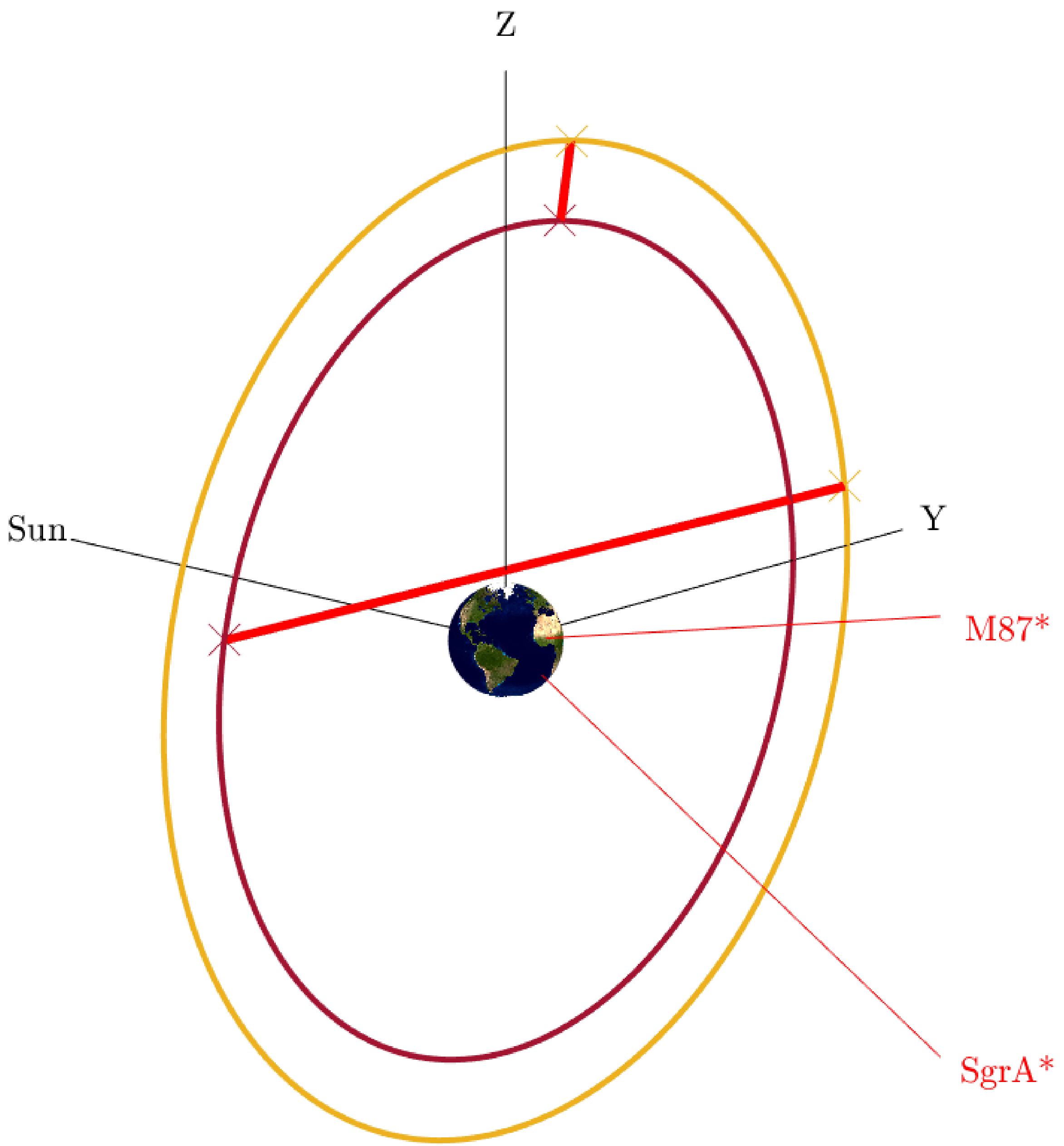
- Two radio telescopes forming an interferometer
- Primary frequency of 690 GHz (EHI Mission Concept)
- Range of alternative frequencies considered
- Onboard frequency standard

		~10 μas	~1 μas
Frequency [GHz]	Wavelength [mm]	20 Gλ [x10^4 km]	200 Gλ [x10^5 km]
230	1.30	2.61	2.61
345	0.87	1.74	1.74
590	0.51	1.02	1.02
690	0.43	0.87	0.87
1200	0.25	0.50	0.50

Orbit Optimisation

- Genetic Algorithm, Python-based optimisation method

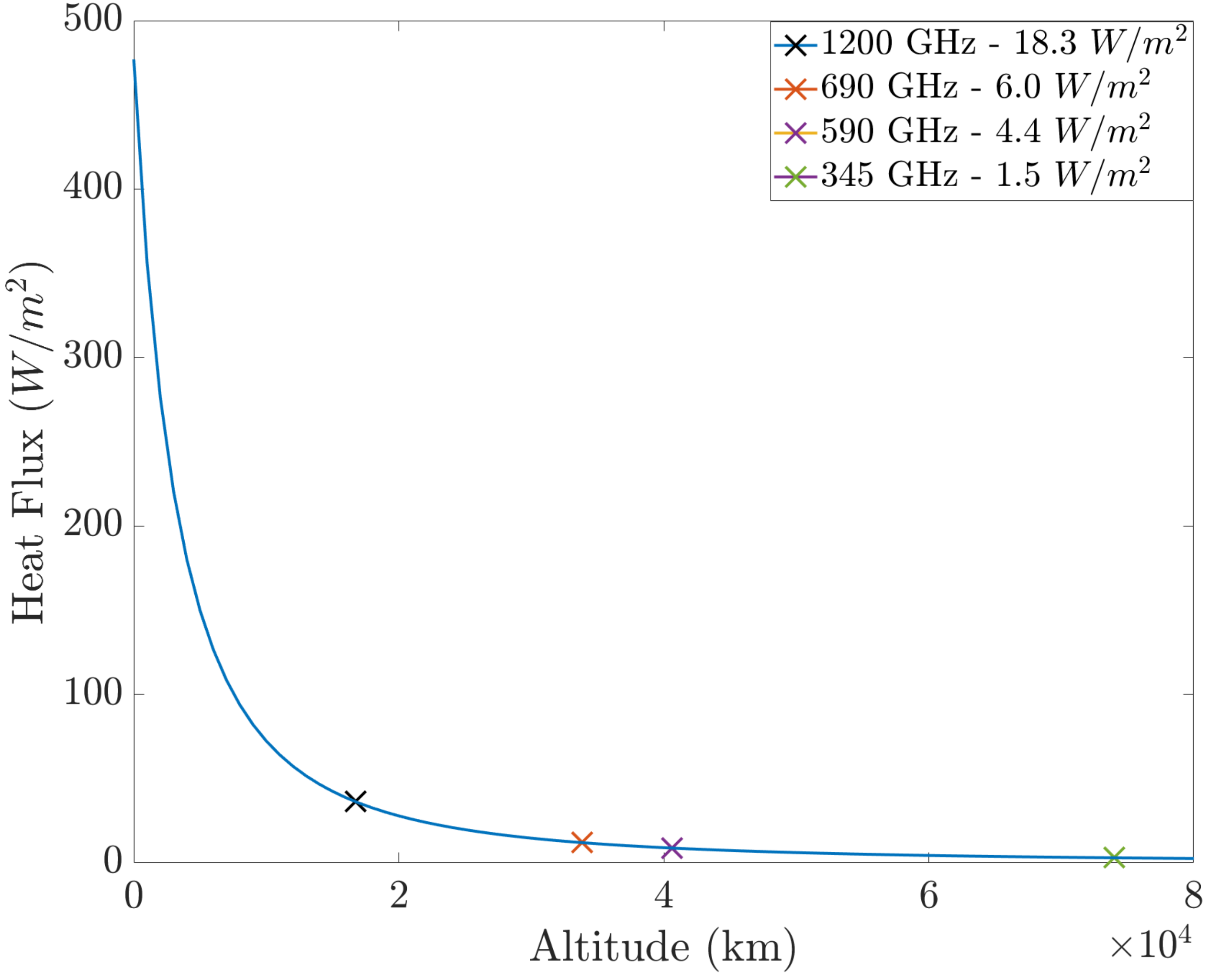




Earth Orbit

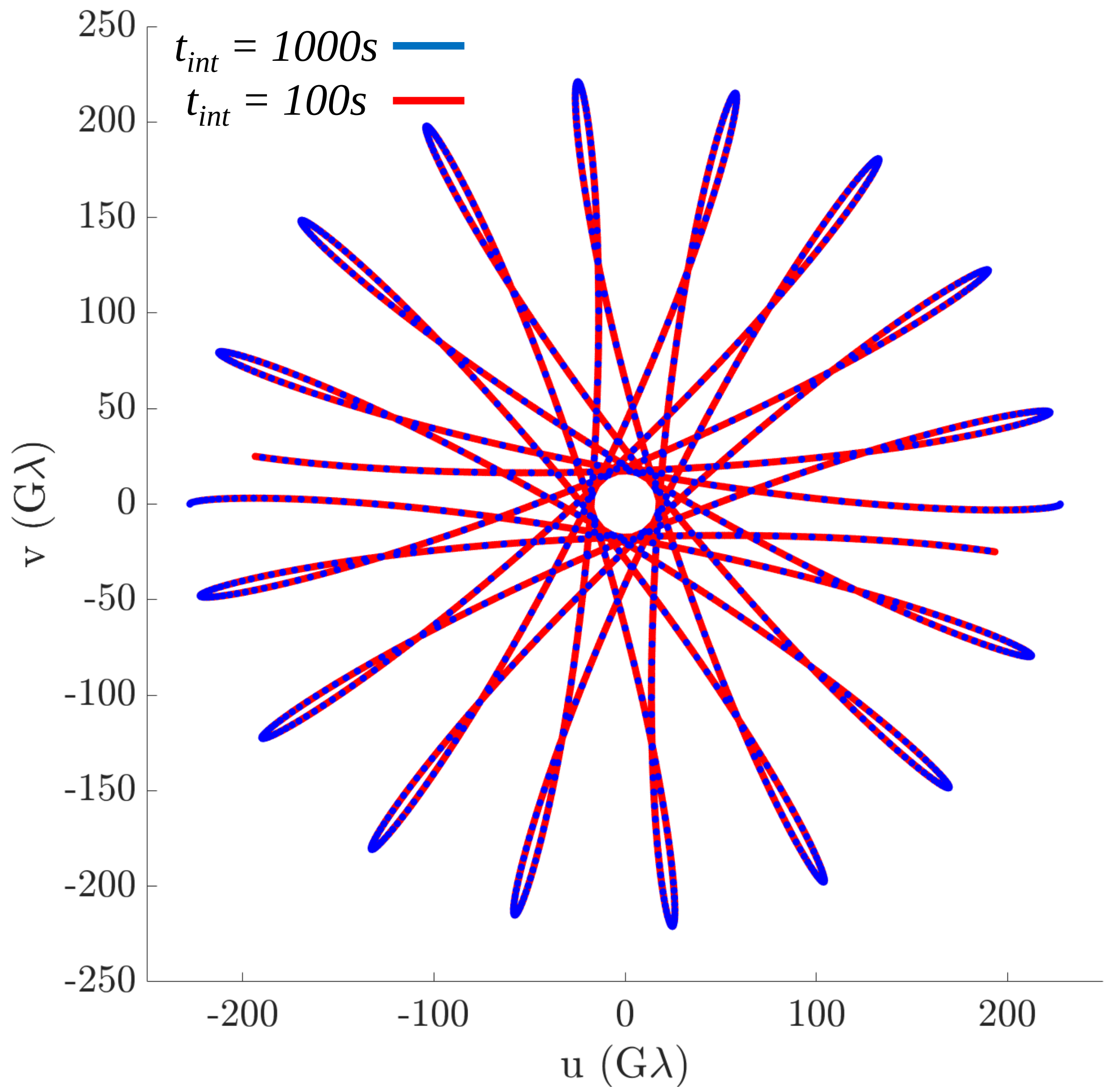
- Two circular, coplanar orbits
- Right ascension separated by 180° to achieve counter-rotating orbits
- Propagation with J2 harmonic perturbation

Frequency [GHz]	THEZA 1 Radius [km]	THEZA 2 Radius [km]
230	144000	121000
345	95800	80400
590	56000	47000
690	47900	40200
1200	27500	23100



Earth Orbit

- Demanding thermal control
  - < 4 K receiver temperature depending on mixer used
- Solar heat flux of ~1371 W/m^2
  - JWST-like sun shield
  - Observe away from the Sun
  - Sources visible for two, 60 day periods/yr
- Significant emission from the Earth

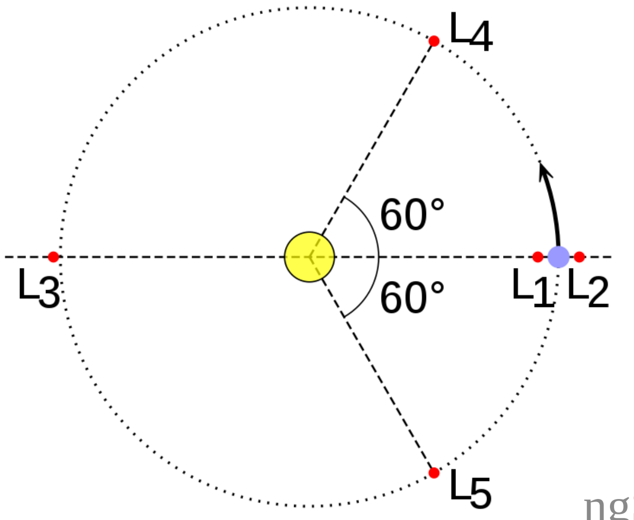


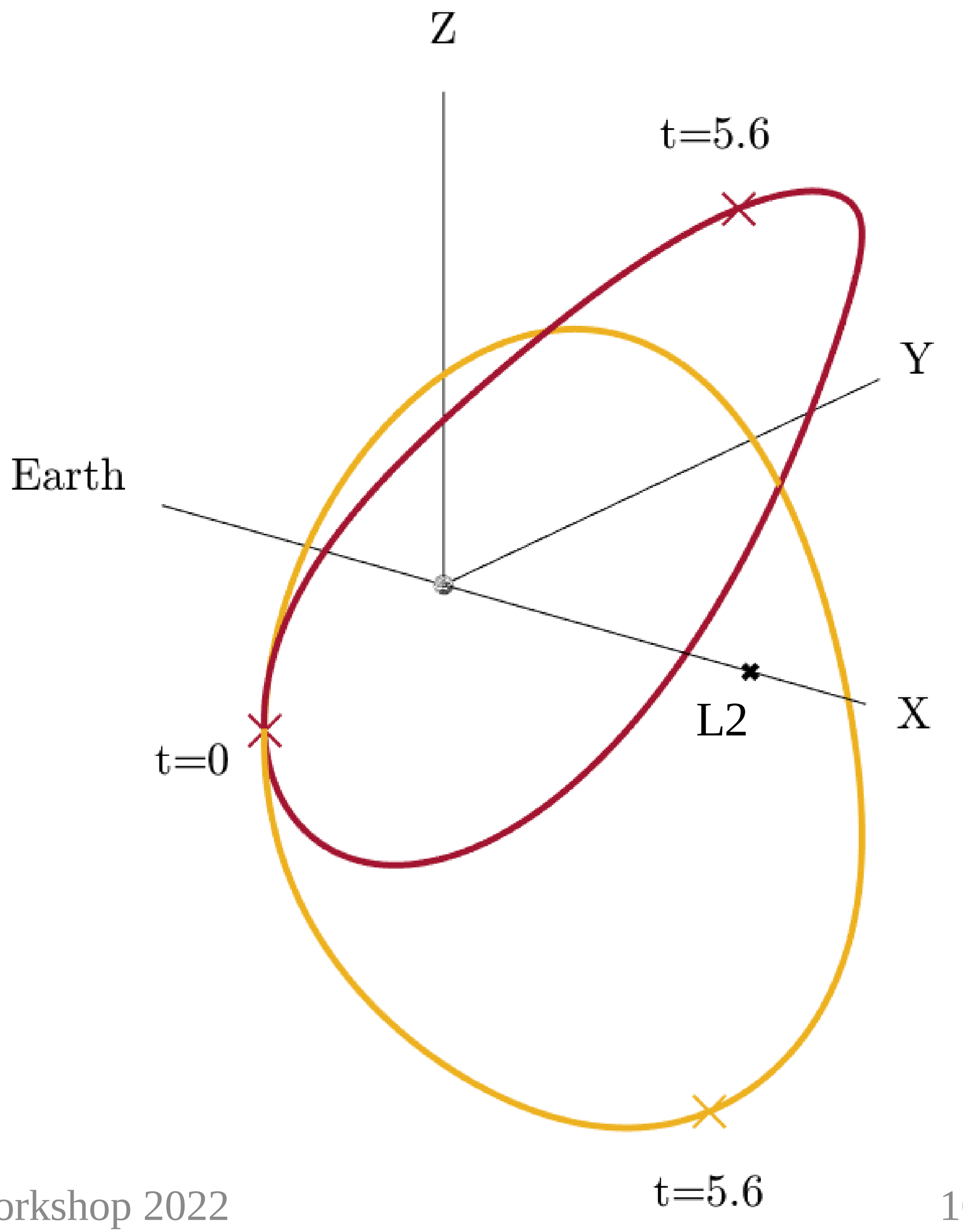
Earth Orbit

- Best case *(u,v)* coverage of M87* for 7-day observation
- 20 - 200 Gλ achieved regardless of date/time or position of source
- Baseline length variation achieved in 10hr period
  - *(u,v)* plane sampled ~3.3 Gλ in 10 hr
  - Rate increases to 0.15 Gλ for 7-day observation

Earth-Moon L2

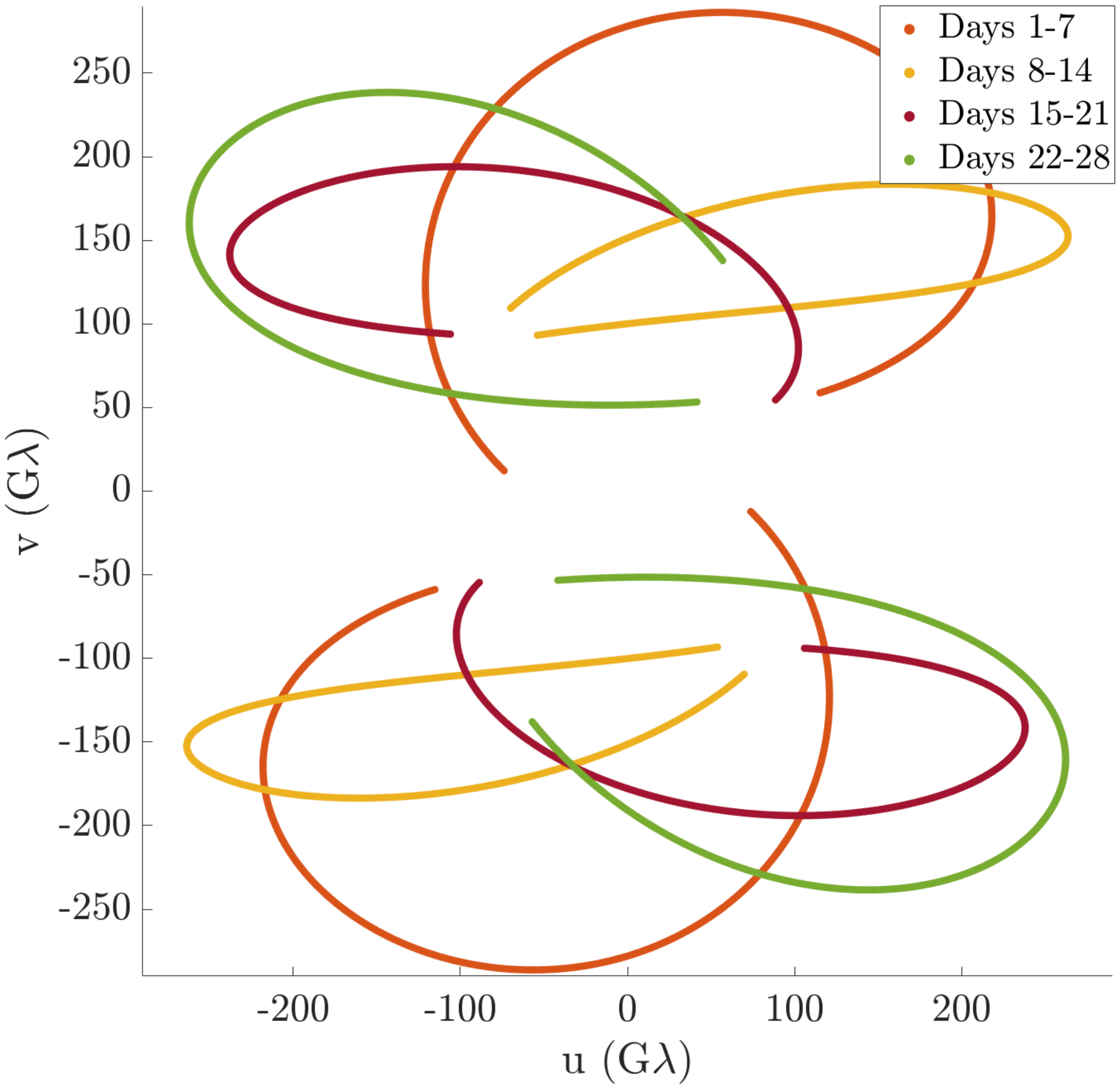
- Two halo orbits with z-excursion 60000 km
  - Perilune of ~18000 km
- Richardson's 3rd order analytical approximation
  - Numerical solution of 3-body problem for more accurate solution





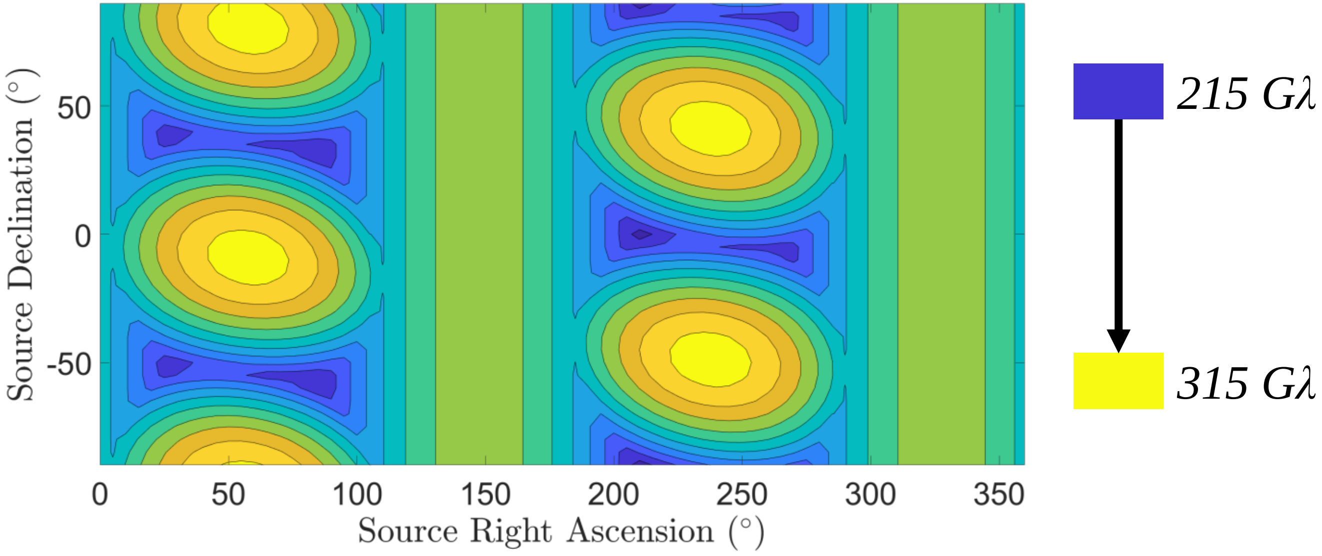
Earth-Moon L2

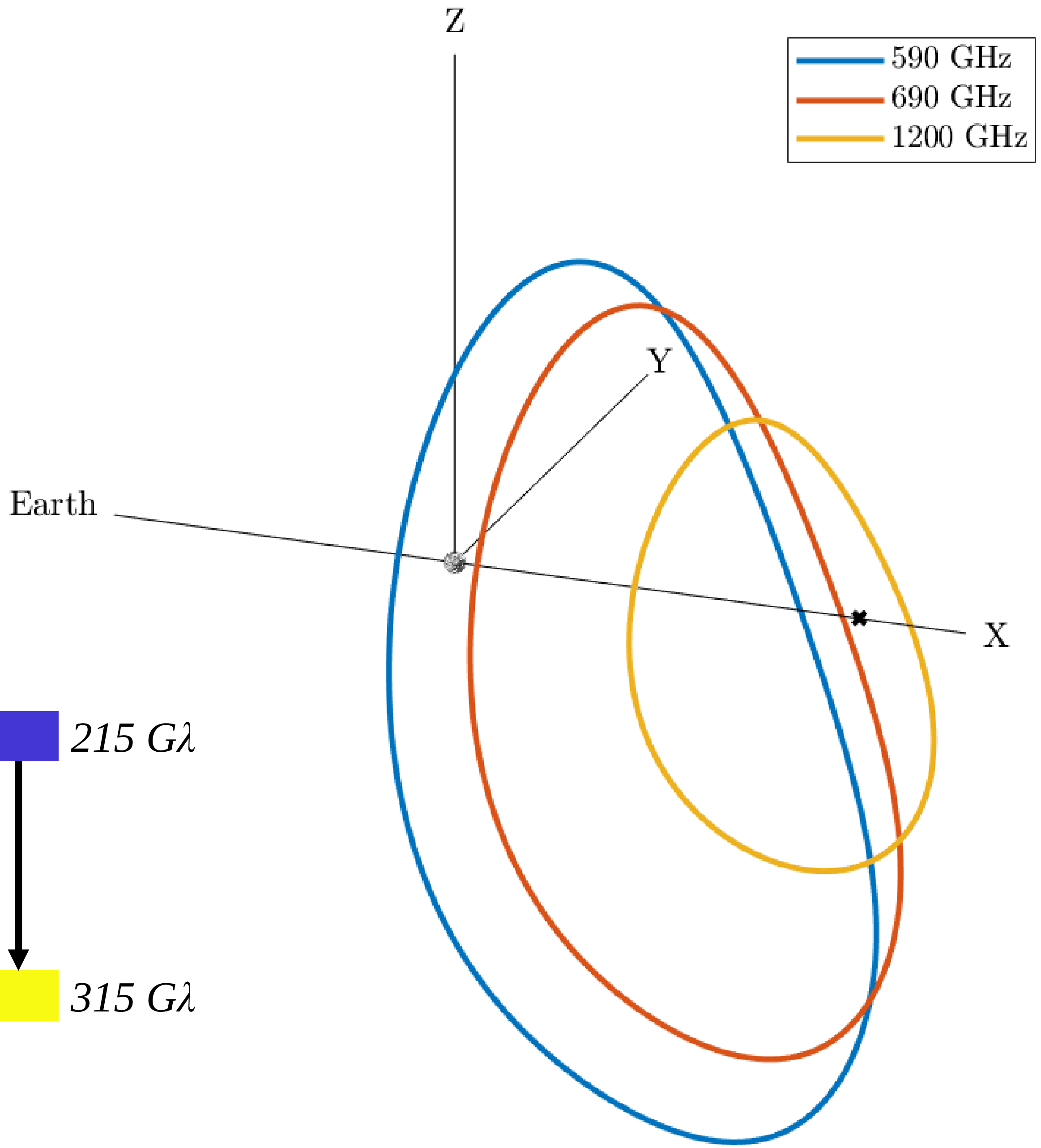
- 20 – 200 Gλ baseline variation achieved in 7 days
- Low Moon thermal emission and albedo creates more stable thermal environment
- At t_{int} = 1000s, signal sampled ~0.1 Gλ
  - Each oscillation sampled 50 times

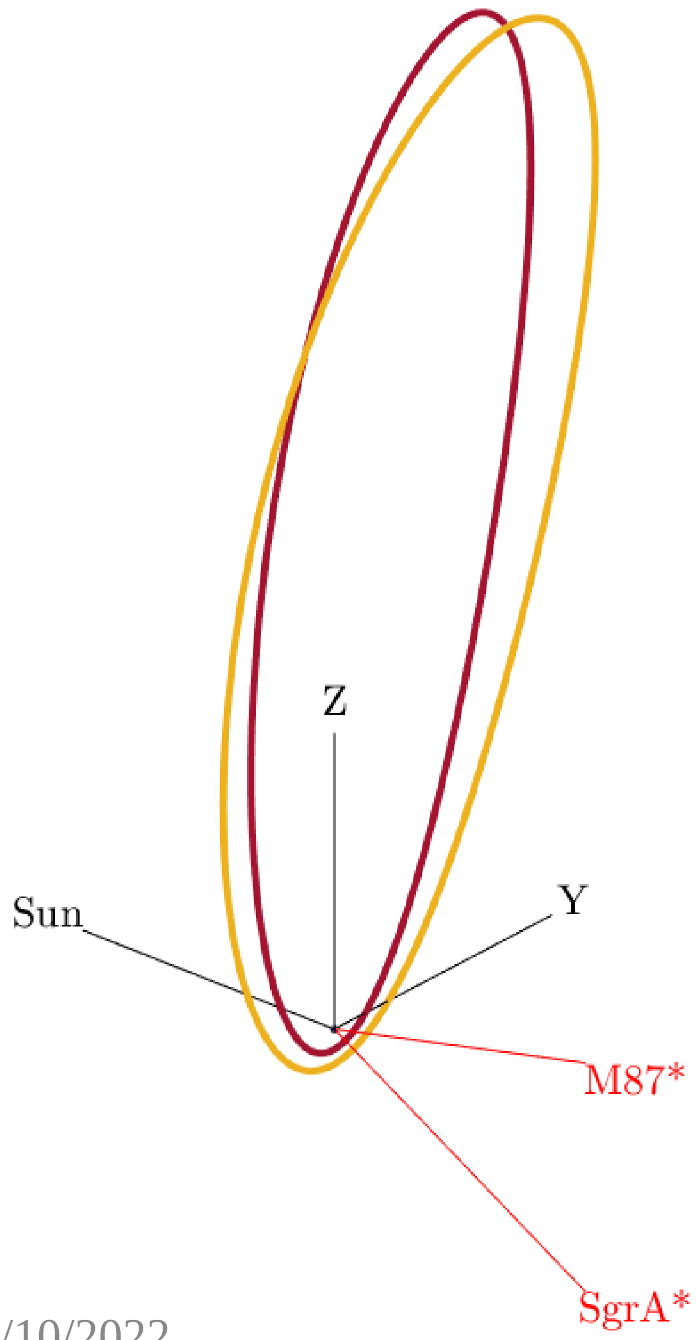


Earth-Moon L2

Frequency [GHz]	Z-Excursion [km]	X-Excursion [km]	Period [days]
590	60000	25600	11.2
690	51300	22700	13.1
1200	29500	16100	14.8



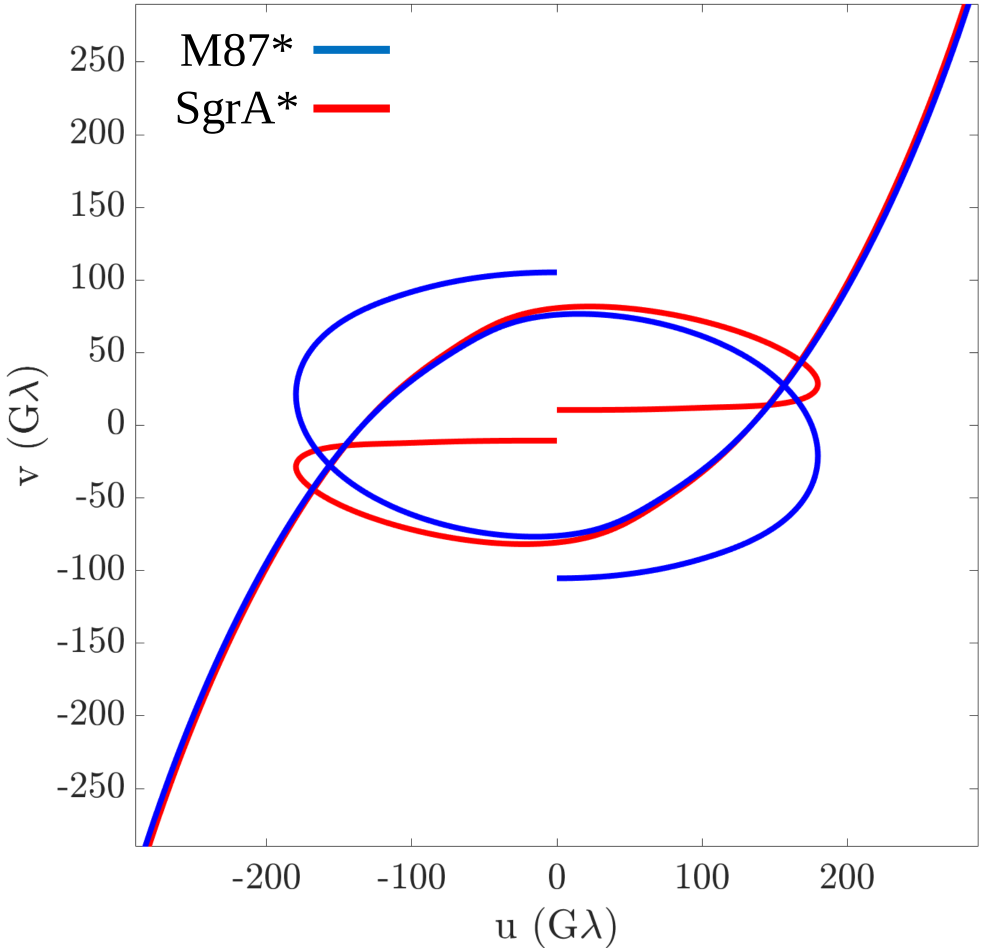


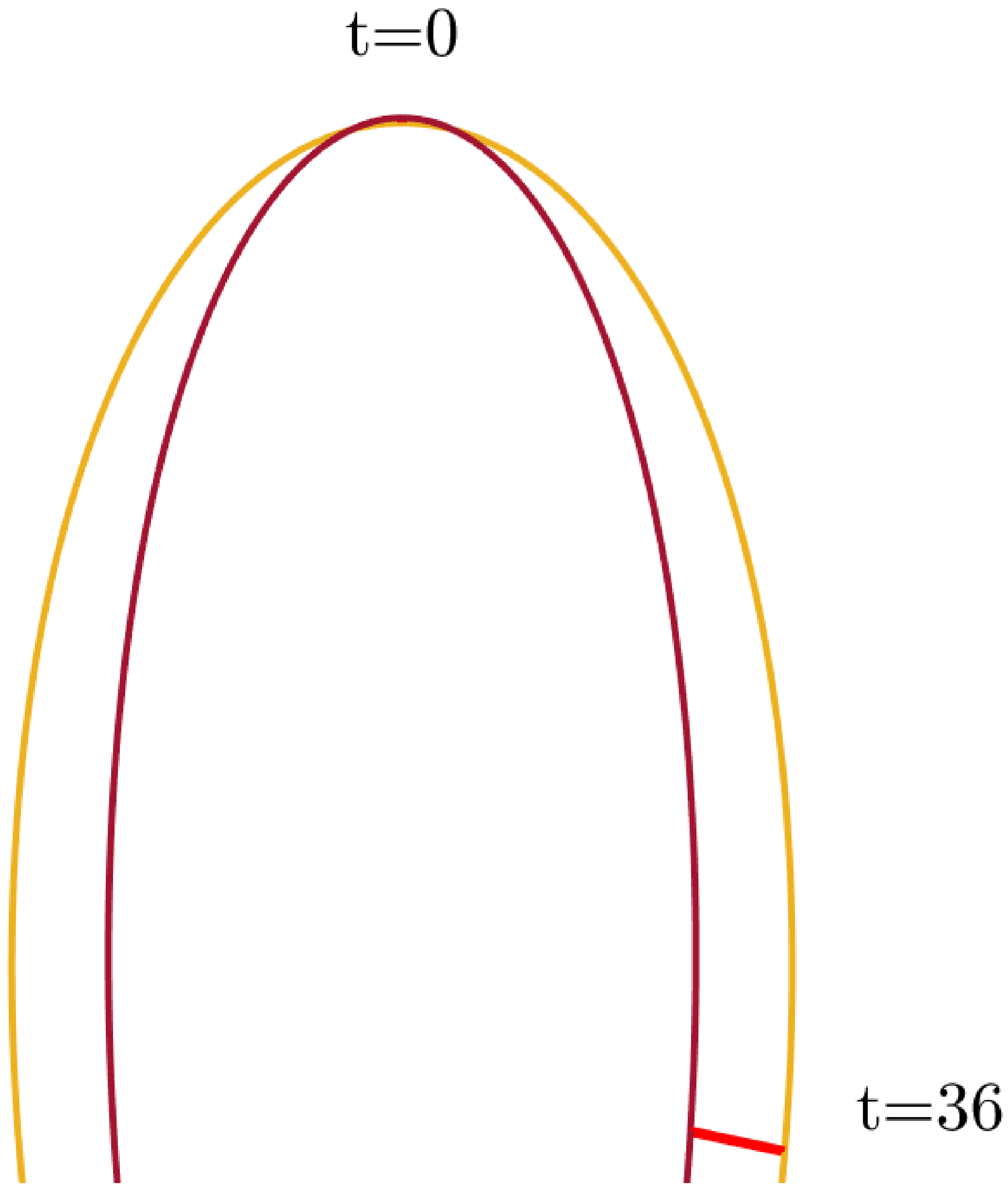


Sun-Earth L2

- Near-Rectilinear Halo Orbits (NRHO)
- Perigee radii of 36,000 and 46,000 km
- Apogee of ~1.8 million km
- Primary benefits:
  - Thermal stability
  - Improved downlink data rate at perigee
- Challenges:
  - 80 day period: Drastic reduction in availability

Sun-Earth L2


M87*
SgrA*
250
200
150
100
50
0
-50
-100
-150
-200
-250
v (Gλ)
-200
-100
0
100
200
u (Gλ)


t=0
t=36

Challenges

- Baseline determination
  - Combination of inter-satellite ranging (E.g. LISA Mission), ground-based observations and post processing

- Thermal control
  - Sun shield and observation away from solar direction
  - Active thermal control (E.g. Cryogenics)

- Data handling & Comms
  - Data rates > 1 Gbps achievable in Earth orbit below GEO, progressing to > 100 Gbps in near-future (NASA's TBIRD System, Robinson, et al. 2018)
  - Optical ISL introduces possibility of in-orbit correlation
  - Optical comms up to 622 Mbps demonstrated in Lunar orbit

- Onboard frequency standard

SNR & Thermal Noise

$$\sigma = \frac{1}{0.88}\sqrt{\frac{SEFD_1 SEFD_2}{2\Delta\nu t_{int}}}$$

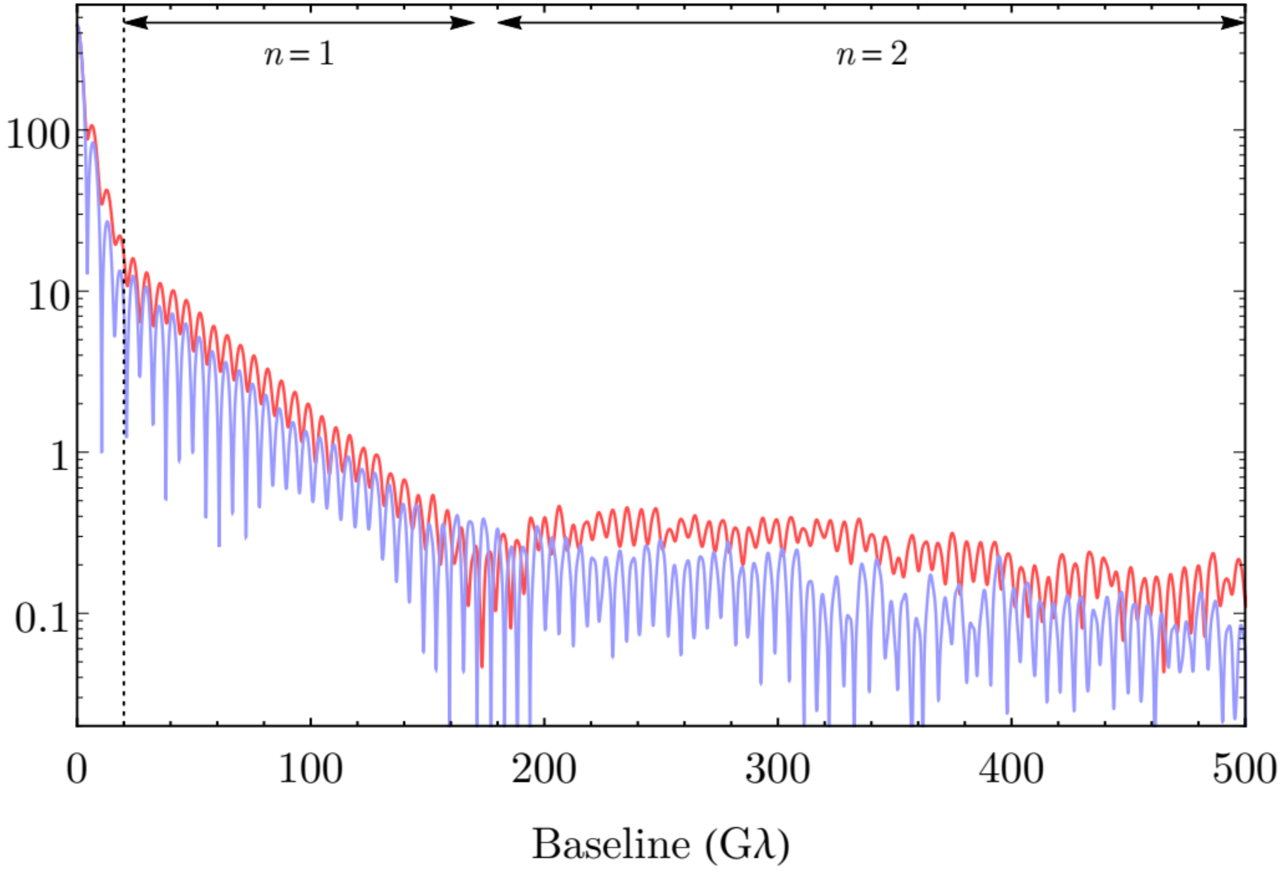
$$SEFD = \frac{2k_B T_{sys}}{\eta A}$$

Parameter	Value
f	690 GHz
D	15 m
T_{sys}	150 K
η (= η_{ap} η_{cor} η_{clock})	0.5

$\sigma_{thermal}$ [mJy]		Bandwidth [GHz] 4	16	32	64
t_{int} [s]	1	29.8 (33.6)	14.9 (67.2)	10.5 (95.0)	7.44 (134)
	10	9.42 (106)	4.71 (212)	3.33 (300)	2.35 (425)
	100	2.98 (336)	1.49 (672)	1.05 (950)	0.74 (1343)
	1000	0.94 (1062)	0.47 (2124)	0.33 (3004)	0.24 (4248)

SNR & Thermal Noise

Credit: Michael D. Johnson, et al. 2020



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Conclusion

- Range of potential orbit designs suitable for photon ring detection
  - All achieve required baseline variation for sources at all positions on the celestial sphere

- Scientific outputs:
  - Potential to improve mass and spin estimations of M87*
  - Consistency tests of GR
  - Measure deviations from the Kerr metric and general GR predictions

- General imaging: order of magnitude improvement on EHT to ~1 μas

- Starting point for more detailed mission concept design and feasibility analysis