Capabilities and Geometry of VLBI Mode in Millimetron Mission

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Millimetron Science

Millimetron will have six main scientific directions with ***breakthrough scientific tasks of Nobel prize level***. Science working groups were organized in 2019 to prepare corresponding scientific cases for both observational modes of the observatory:

1. **Relativistic Astrophysics and S-E VLBI**
2. **Cosmology**
3. **Compact Heavily Obscured Galaxy Nuclei**
4. **The Water Trail**
5. **Filaments and magnetic fields on various scales**
6. **Solar System**

Millimetron Space-VLBI

Scientific Tasks & Constraints

VLBI Scientific tasks:

- High resolution 1D/**2D imaging** of black hole vicinity (M87 & Sgr A*)
- Search for wormholes
- High resolution AGN&QSO survey

Constraints:

- Sensitivity of space telescope and space-ground baselines
- Onboard stable hydrogen clock
- Data downlink channel and onboard memory
- Tracking stations
- Space-ground VLBI geometry and space telescope orbit configuration
- Data processing and orbit accuracy
- Scheduling of observations

Onboard VLBI Instruments

Freq. band, (GHz)	$T_{rx,}$ (K)	Polarization	№ of Channels*	Channel Bandwidth, (GHz)	Comment
31 - 45	< 17	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
84 – 136	< 37	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
211 – 275	< 90	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
275 – 373	< 120	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Design
690	TBC	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	TBC

Multi-frequency capabilities in talk of Taehyun Jung

(*) - 2 channels (USB, LSB) for each circular polarization correspond to the bandwidth of 1.99 GHz, 4 channels of 0.97 GHz for 2 polarization channels is 4 GHz in total

Sensitivity

ALMA Band No.	Bandwidth (GHz)	Frequency* (GHz)	$SEFD_{MM}$ (Jy)	$SEFD_{ALMA}$** (Jy)	$SEFD_{MM\text{-}ALMA}$ (Jy)
1	31-45	40	1100	14	124
3	84-136	90	2760	42	340
6	211-275	240	5520	58	565
7	275-373	340	7180	70	710

RMS error of flux density measured at baseline between stations 1 and 2 can be estimated by known relation:

$$\delta S = 1.14 \cdot \frac{SEFD_{12} \cdot 10^3}{\sqrt{2 \Delta F \tau}}, \text{ (mJy)}$$

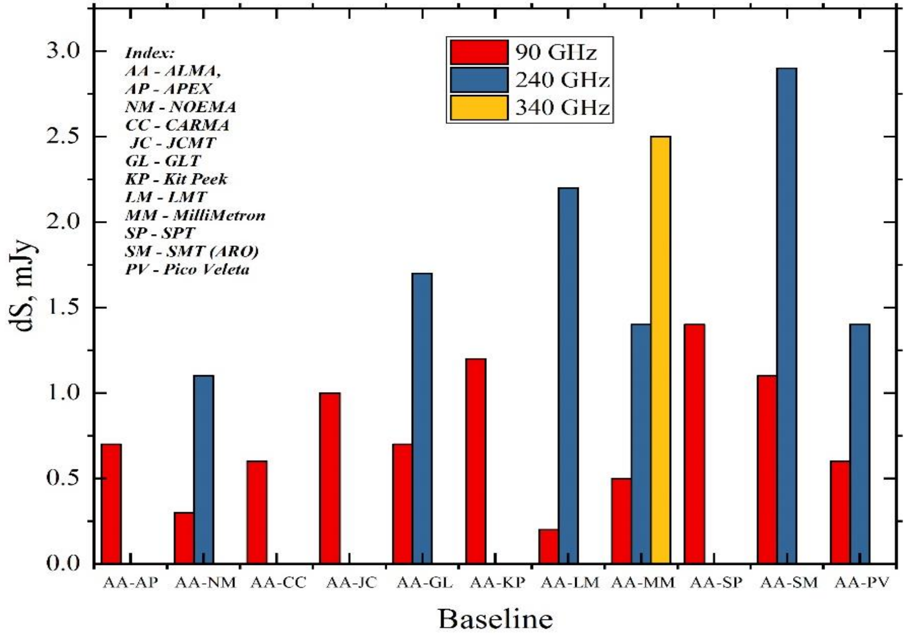
Where 1.14 coefficient is the correction coefficient due to a number of quantization bits per sample, ΔF - formatter input bandwidth (Hz) per specified frequency/ polarization channel and τ - integration time interval (sec).

(*) - Nominal observing frequency at MM bands; Note: assumption that Millimetron bandwidth is 4 GHz

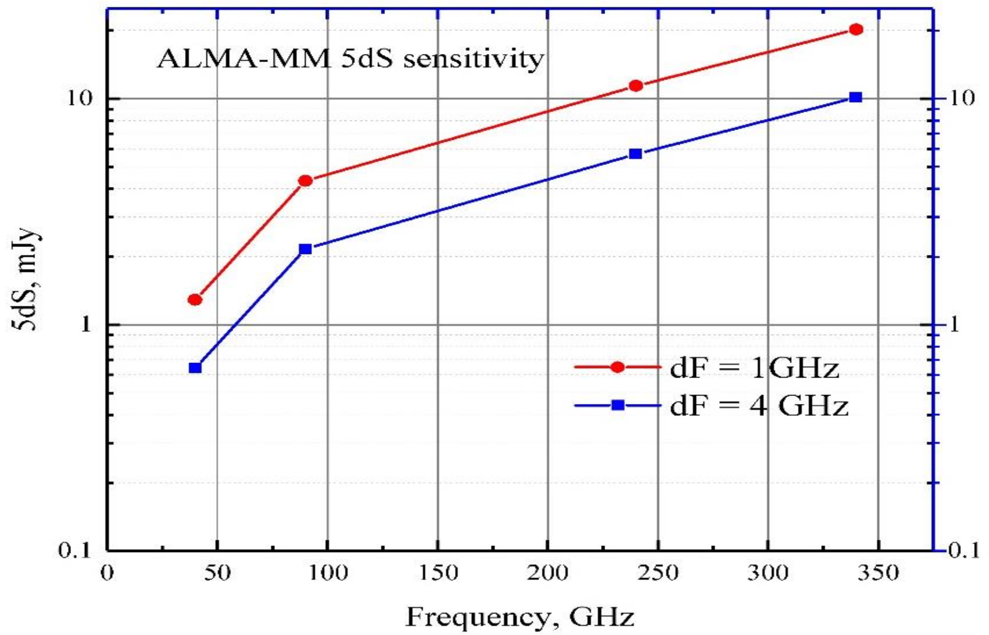
(**) - ALMA array: 50·12 m

Sensitivity

Frequency (GHz)	τ^* (sec)	$SEFD_{ALMA\text{-}MM}$ (Jy)	5dS, 1GHz (mJy)	5dS, 4GHz (mJy)
40	150	124	1.290	0.645
90	100	340	4.333	2.167
240	40	565	11.386	5.693
340	20	710	20.235	10.118



Sensitivity (1σ, dS mJy) at MM-ALMA-EHT baselines
Bandwidth is 4 GHz



ALMA-MM (5dS, mJy) sensitivity (table on top)
Bandwidth 1 & 4 GHz

(*) - Use atmosphere phase compensation at ALMA; Note: assumption, that data has 2 bits quantization

Angular Resolution

Orbit Type	Best Angular Resolution, (µas)				
	43 GHz	90 GHz	240 GHz	330 GHz	690 GHz
Circular Orbit (40000 km)	36	18	5.9	4.8	2.2
HEO Orbit (350 000 km)	4.5	2.1	0.8	0.6	0.27
L2 Orbit	0.8	0.4	0.14	0.1	0.05

*Rudnitskiy et al., in prep.

Onboard Hydrogen Clock

TRL 9

Frequency standard with high stability is very important for the space-ground VLBI frequencies. "Vremya-Ch" is developing onboard hydrogen clock for "Millimetron", the cur development – technological models developed for tests.

Onboard hydrogen frequency standards

Time interval, (s)	Frequency Instability, σ		
	AFT* System		"Millimetron" requirements
	Disabled	Enabled	
1	$6.00 \cdot 10^{-14}$	$4.90 \cdot 10^{-14}$	$\leq 7 \cdot 10^{-14}$
10	$1.05 \cdot 10^{-14}$	$8.30 \cdot 10^{-15}$	$\leq 1 \cdot 10^{-14}$
100	$2.73 \cdot 10^{-15}$	$1.83 \cdot 10^{-15}$	$\leq 2 \cdot 10^{-15}$
1000	$1.10 \cdot 10^{-15}$	$8.84 \cdot 10^{-16}$	$\leq 5 \cdot 10^{-16}$
3600	$7.10 \cdot 10^{-15}$	$4.86 \cdot 10^{-16}$	$\leq 5 \cdot 10^{-16}$

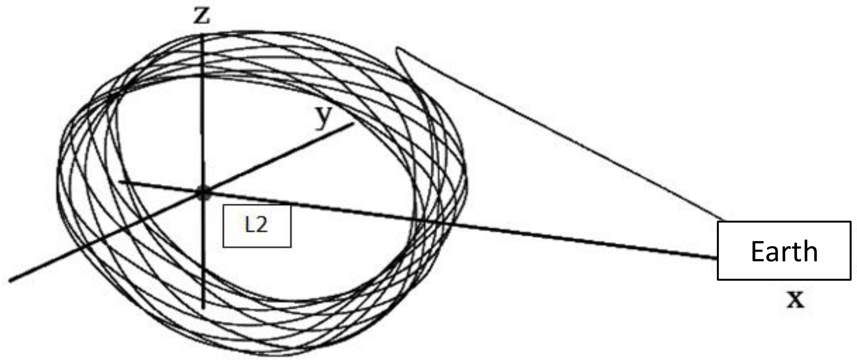
(*) - adiabatic fast transition of atoms

Demidov et. al., Izmeritelnaya technika, 8, 2018

Space-VLBI Geometry

L2 orbit

- Halo orbit around L2 point of Sun-Earth system, distance 1.5 million kilometers
- Orbit period – 178 days.
- Baseline – 1 500 000 km, max.
- Time of oscillation around L2 is about half of a year.
- Antenna view angle opening is ± 75° in ecliptic latitude and longitude.

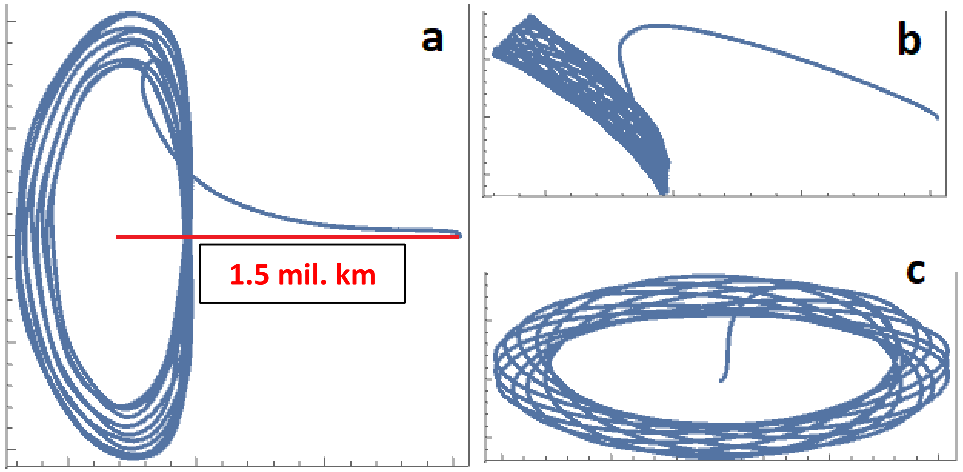


Halo orbit (coordinate system with respect to L2 point)

Combined orbit (L2+near-Earth orbit)

- High elliptical near-Earth orbit (HEO)
- Orbit period – 10 days.
- Baseline – up to 350 000 km, max.
- Possible transition from/to L2 point of Sun-Earth system using the gravitational maneuver near the Moon

Andrey Andrianov Talk

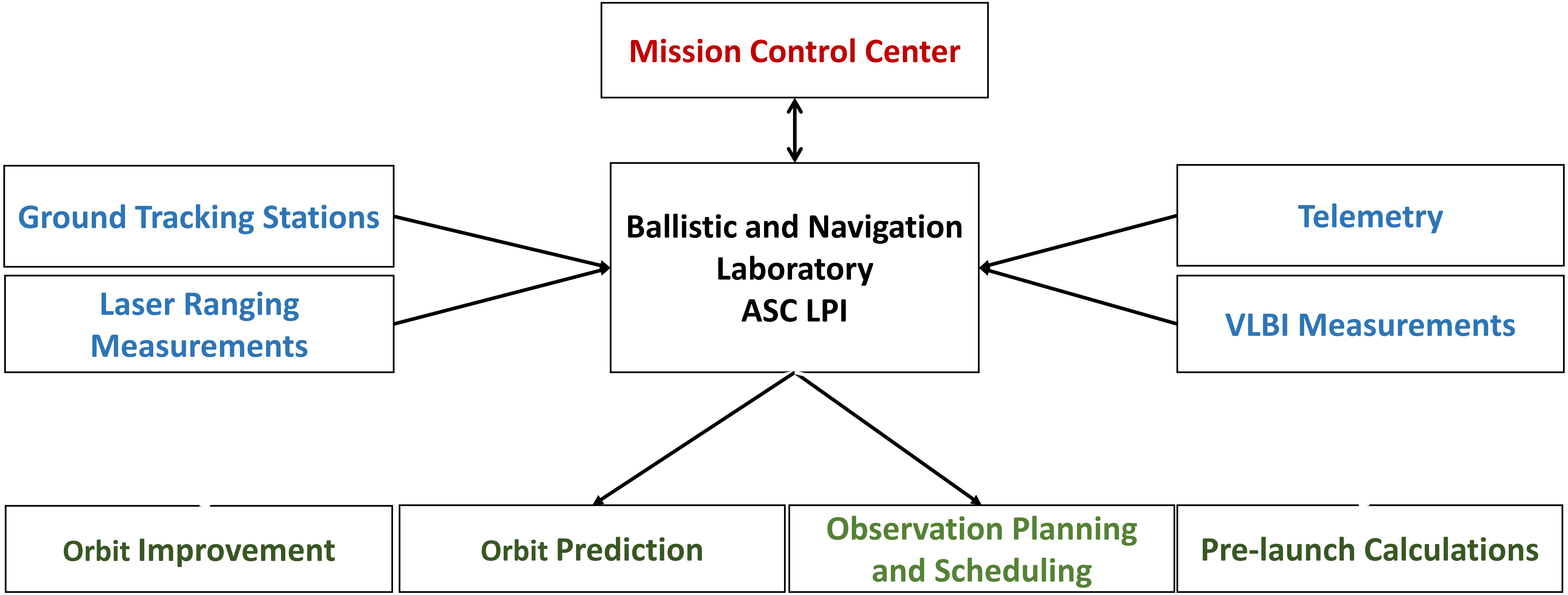


Halo orbit projections:
(a) – XY plane, (b) XZ plane, (c) – YZ plane

*Andrianov et al., MNRAS, 2021

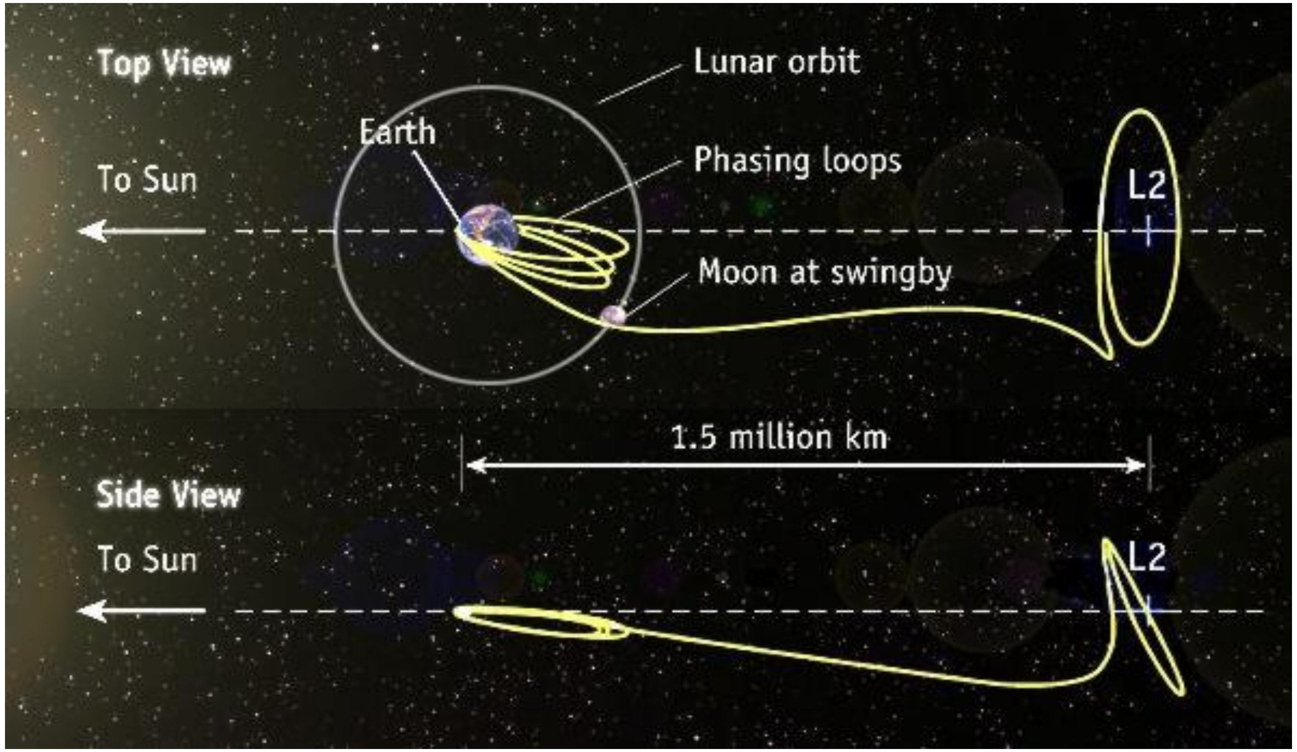
Ballistic and Navigation Support

Organized ballistic and navigation support laboratory to provide ballistic and navigation support for the Millimetron space mission: **pre-launch stage, during the launch, in orbit**



More information: http://millimetron.ru/

Ballistic and Navigation Support



Millimetron will operate in orbit around L2 point of the Sun-Earth system, located at 1.5 million km in anti-Sun direction.

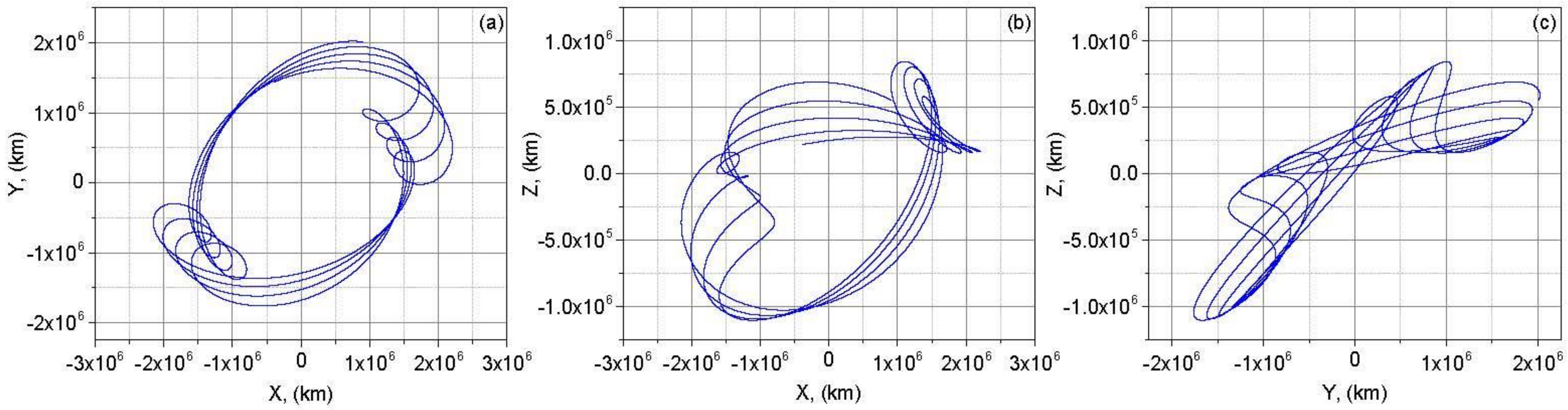
Flight stage	Velocity, m/s	Fuel, kg
Transfer correction to L2	90	320
Station-keeping in L2	15/year	
	45 (3 years)	154
	75 (5 years)	258
	105 (7 years)	364
	150 (10 years)	524
Deorbit	0-10	33
Transfer correction to Earth	45	150
HEO formation	100	330
Total (5 years in L2)	**320**	**1091**

Fuel estimations showed that it is not possible to perform a direct flight from point L2 to a highly elliptical orbit. Additional gravity assist maneuvers are needed to reduce these fuel costs.

Considered a new nominal orbital configuration around L2 point to meet the scientific requirements (especially for VLBI mode)

*Rudnitskiy et al., in prep.

New Nominal Orbit in L2 Point



Orbit around L2 point of Sun-Earth system
Exit from the ecliptic plane: 400000 km

*Rudnitskiy et al., in prep.

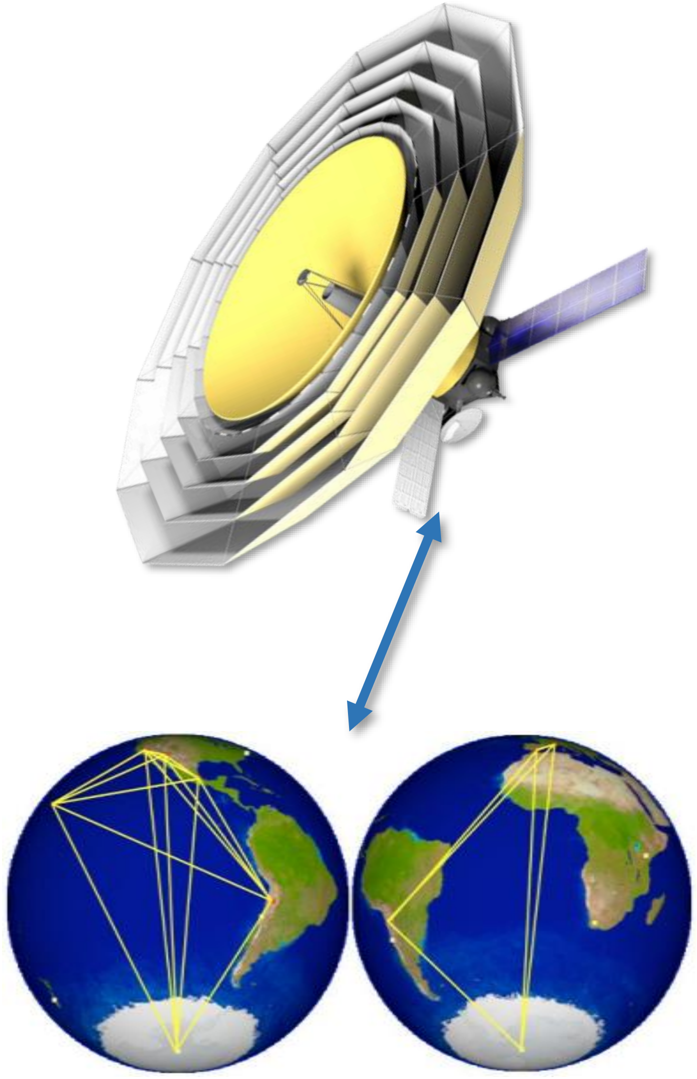
VLBI Simulations

Target sources: Sgr A* and M87
Ground telescopes: EHT global array
Observing frequency: 240 GHz
Bandwidth: 2 GHz
Integration time: 10 s

Total duration of observation: 900 minutes
(limited by onboard memory – 100 Tb)

Observation length: 24 hours (1 day) – 900 min/24 hrs

Millimetron sensitivity @ 240 GHz: ~5520 Jy

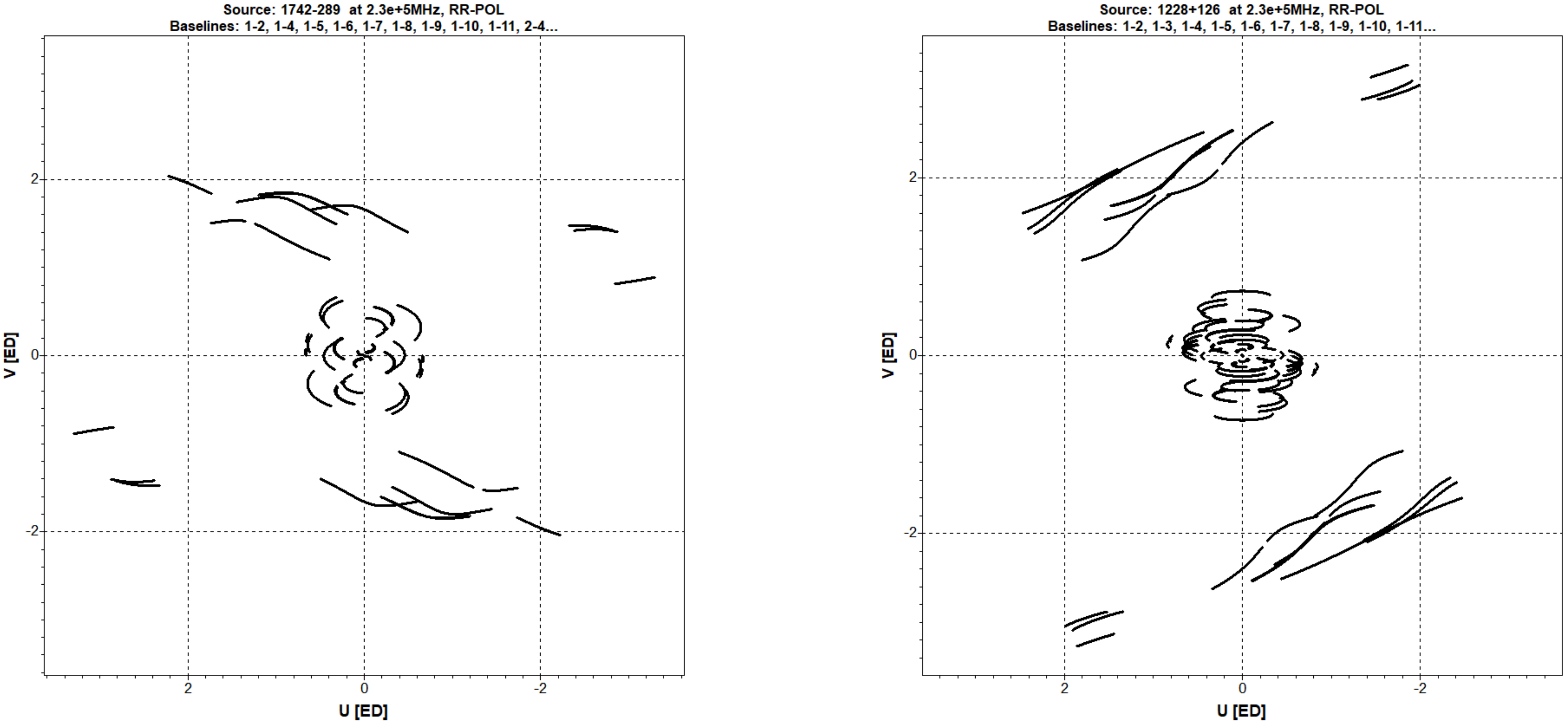


Ground Telescopes

Telescope	X, (m)	Y, (m)	Z, (m)	SEFD, (Jy)	D, (m)
IRAM 30	5088967.900	-301681.6000	3825015.8000	3500	30
SMT	-1828796.200	-5054406.800	3427865.200	15000	10
SMA	-5464523.400	-2493147.080	2150611.750	5000	16
LMT	-768713.9637	-5988541.7982	2063275.9472	4000	50
ALMA	2225061.164	-5440057.37	-2481681.15	80	70
APEX	2225039.53	-5441197.63	-2479303.36	5000	12
JCMT	-5464584.68	-2493001.17	2150653.98	10000	15
GLT	1500692.00	-1191735.0	6066409.0	4000	12
NOEMA	4523998.40	468045.240	4460309.760	1000	47
KP	-1995678.840	-5037317.697	3357328.025	13000	12

VLBI Simulations

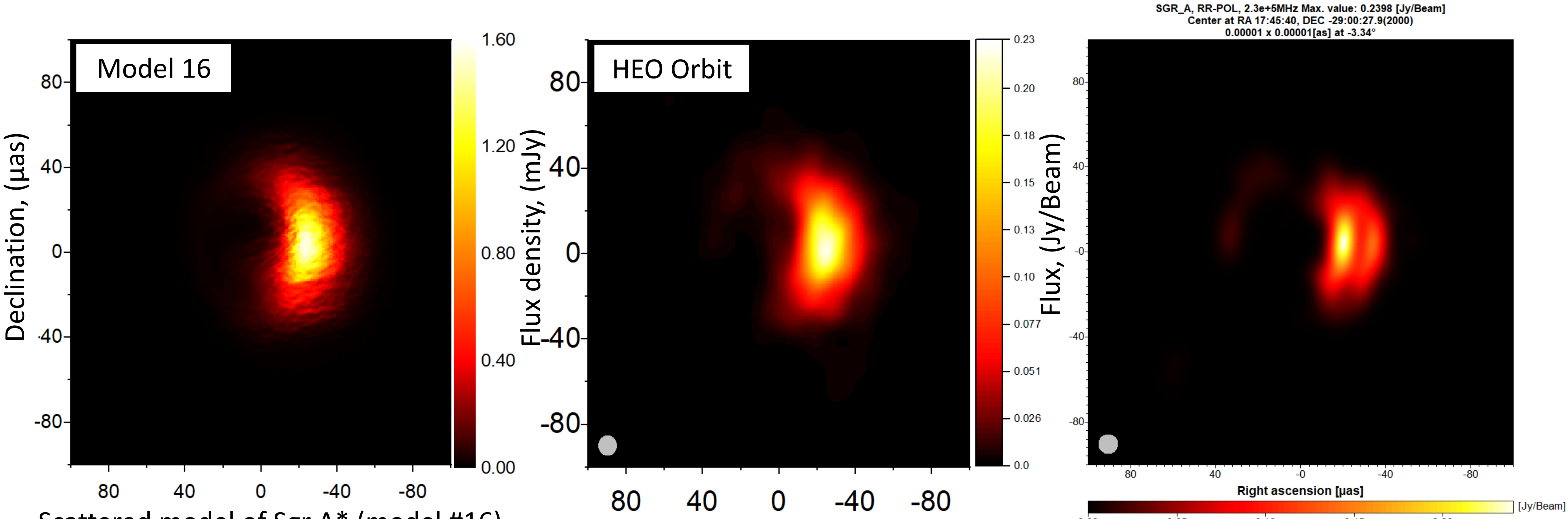
(u,v) coverage



(u,v) coverage for Sgr A* (left) and M87 (right)

VLBI Simulations

Simulations of Sgr A* VLBI imaging for L2 Orbit (comparison with HEO Orbit)

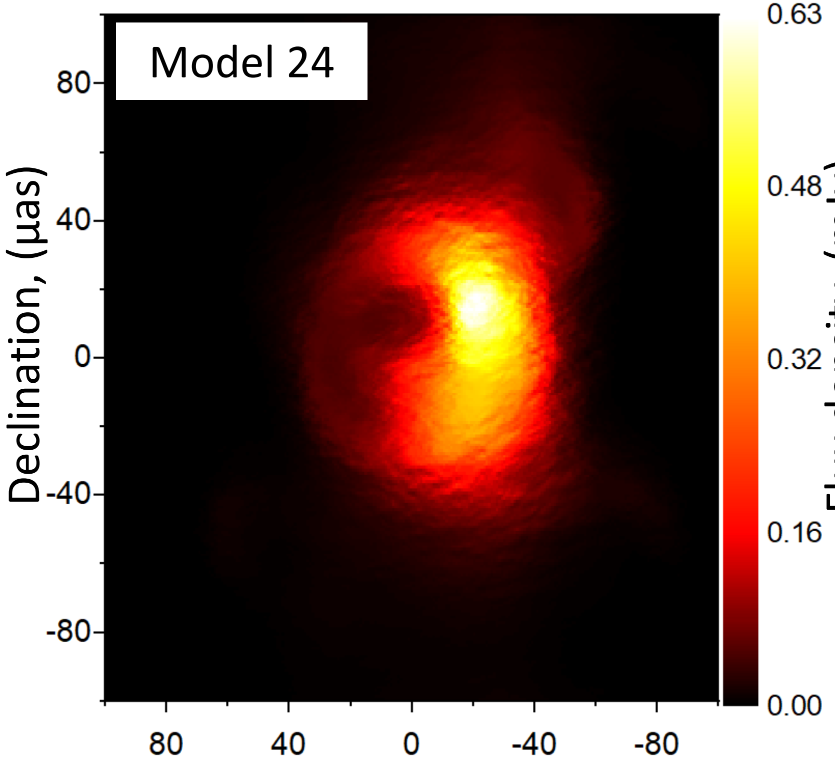


Scattered model of Sgr A* (model #16)
(Moscibrodzka et al. 2016)

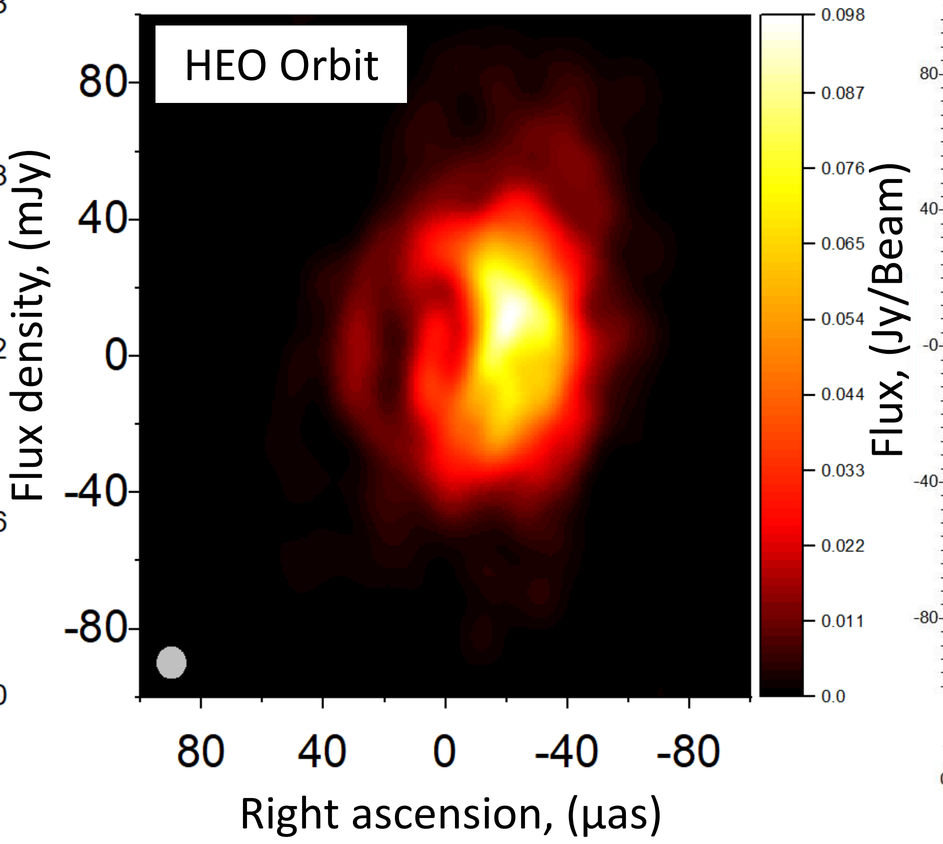
Simulated image of Sgr A* (model 16) for HEO orbit (center) and for L2 orbit (right)

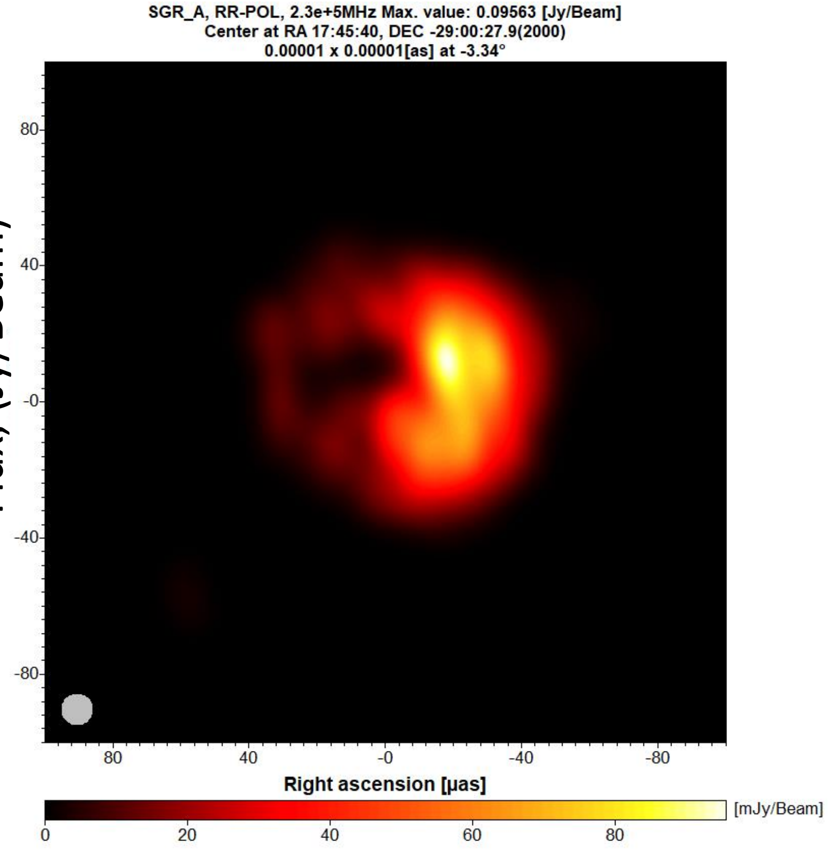
VLBI Simulations

Simulations of Sgr A* VLBI imaging for L2 Orbit (comparison with HEO Orbit)



Scattered model of Sgr A* (model #24)
(Moscibrodzka et al. 2016)

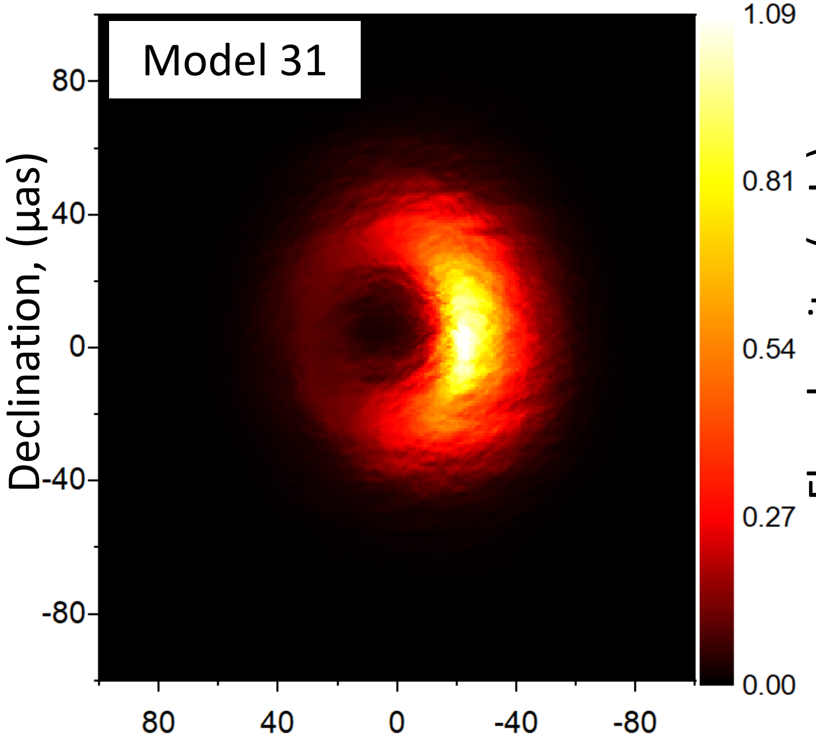




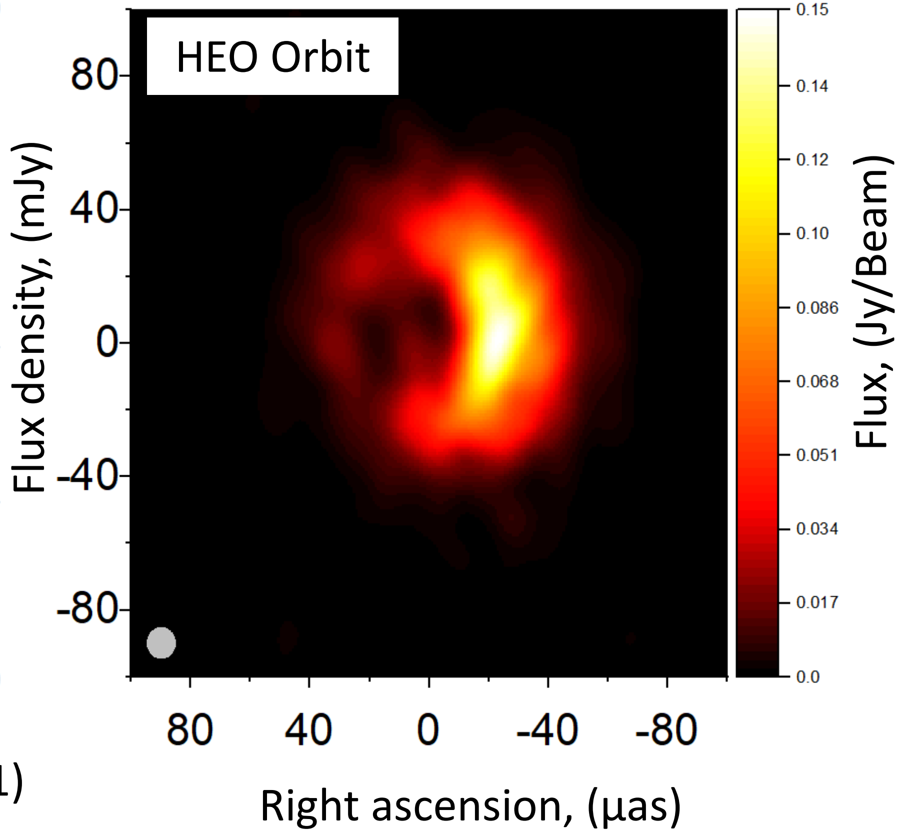
Simulated image of Sgr A* (model 24) for HEO orbit (center) and for L2 orbit (right)

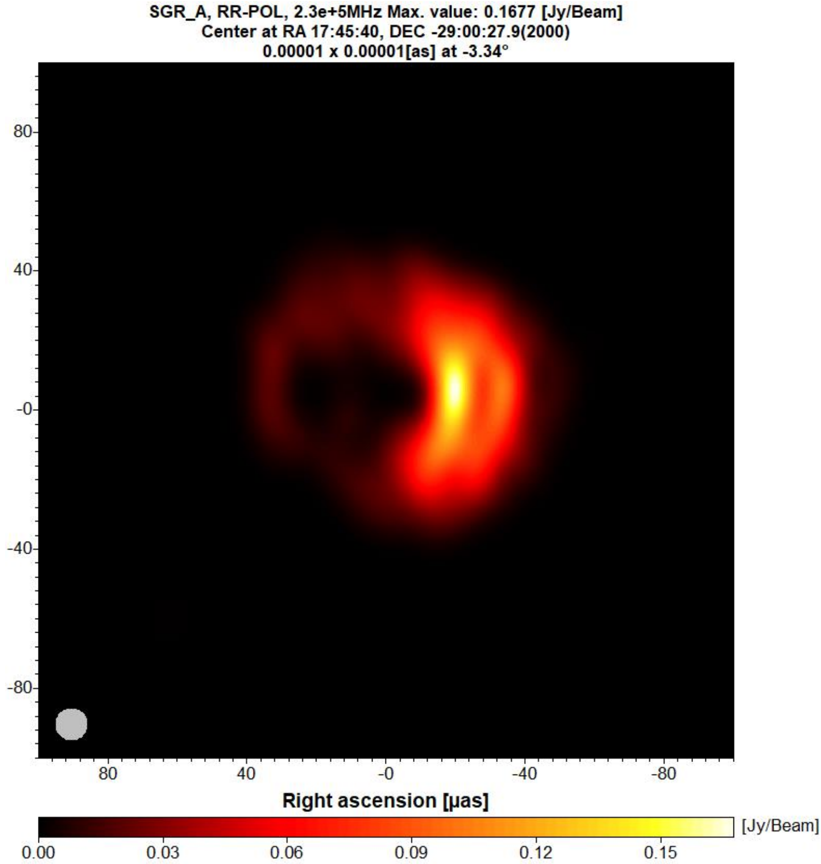
VLBI Simulations

Simulations of Sgr A* VLBI imaging for L2 Orbit (comparison with HEO Orbit)



Scattered model of Sgr A* (model #31)
(Moscibrodzka et al. 2016)

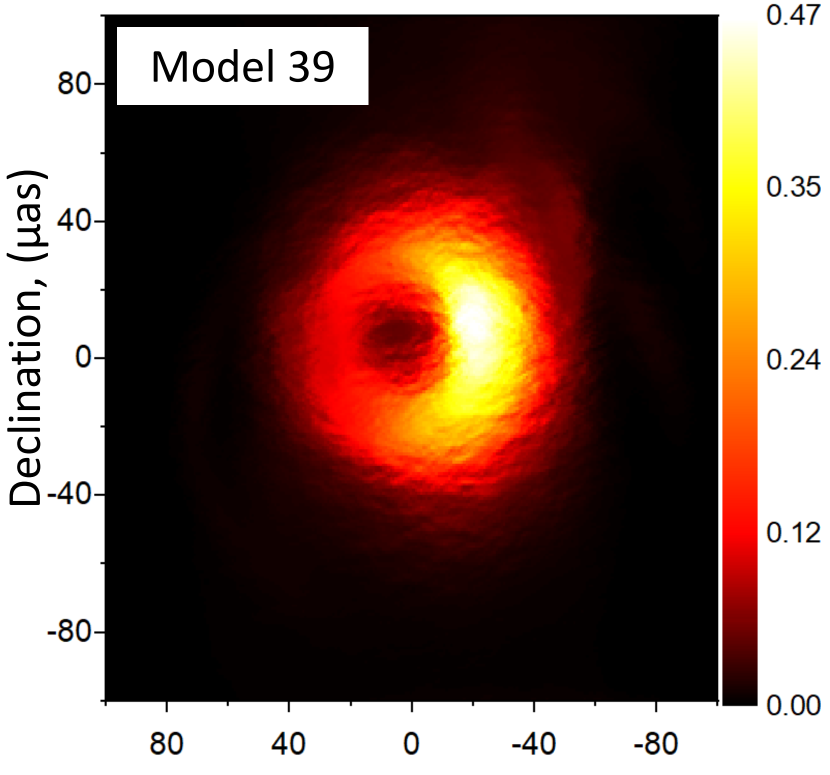




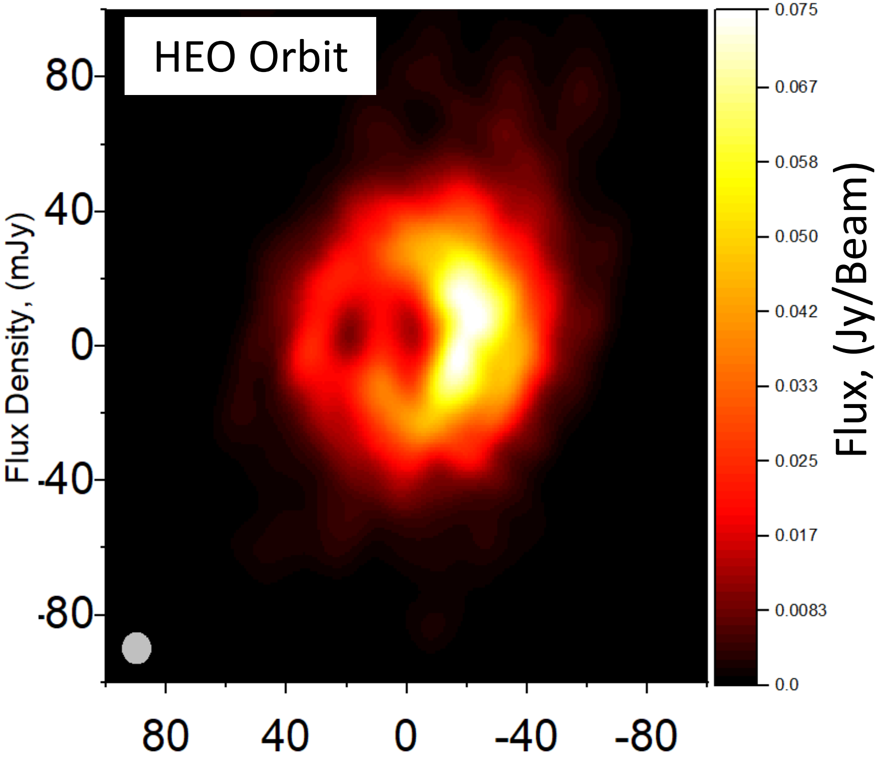
Simulated image of Sgr A* (model 31) for HEO orbit (center) and for L2 orbit (right)

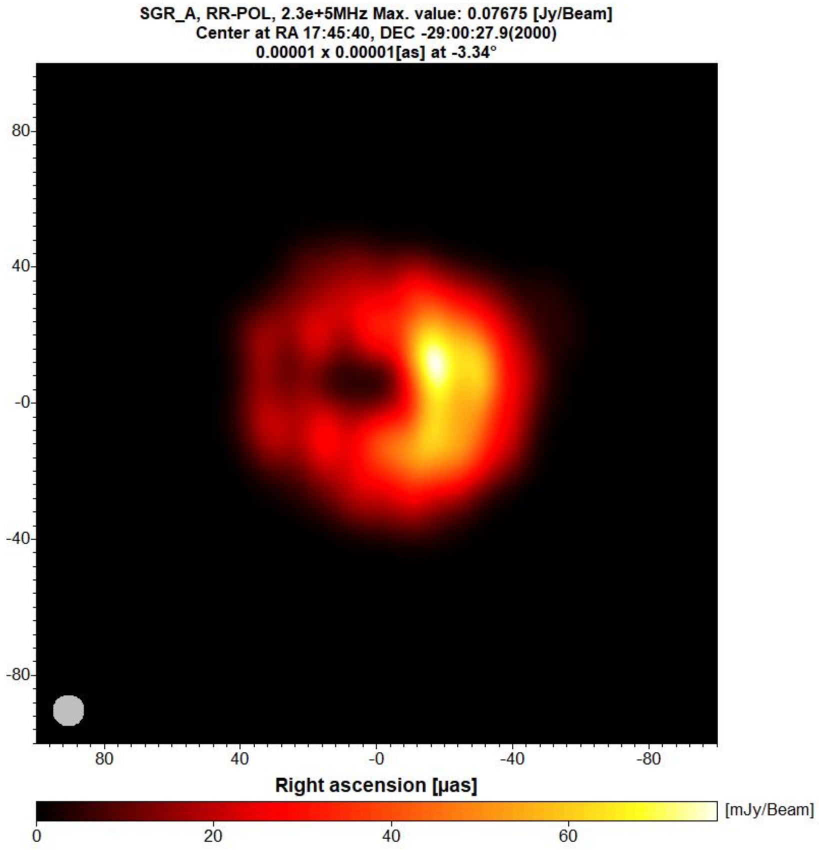
VLBI Simulations

Simulations of Sgr A* VLBI imaging for L2 Orbit (comparison with HEO Orbit)



Scattered model of Sgr A* (model #39)
(Moscibrodzka et al. 2016)

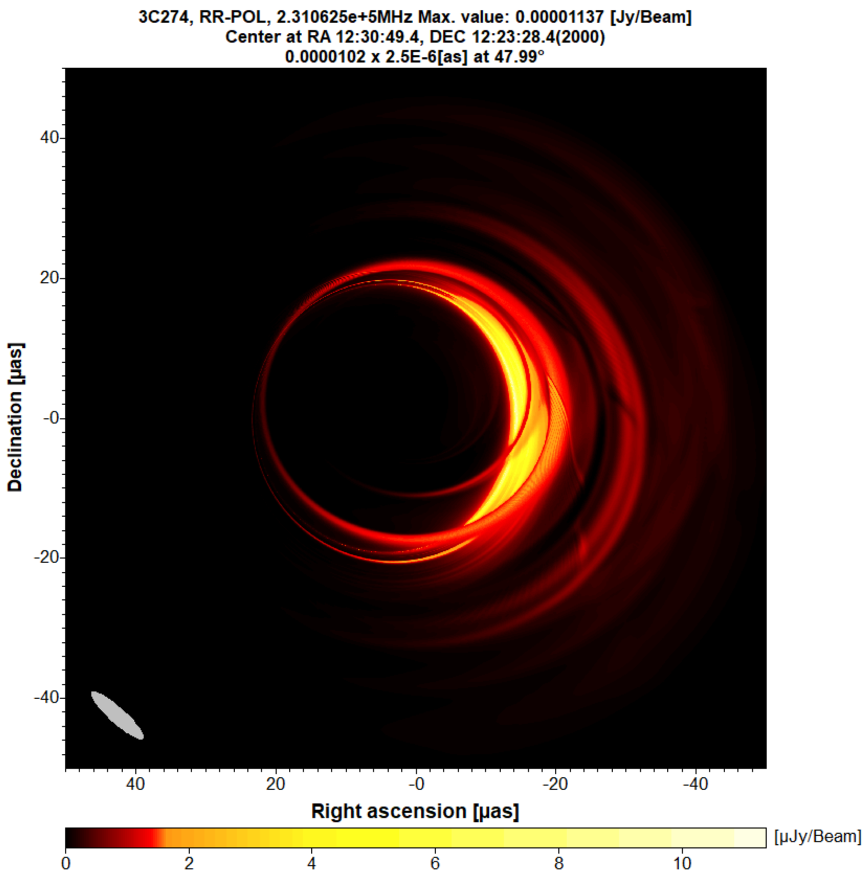




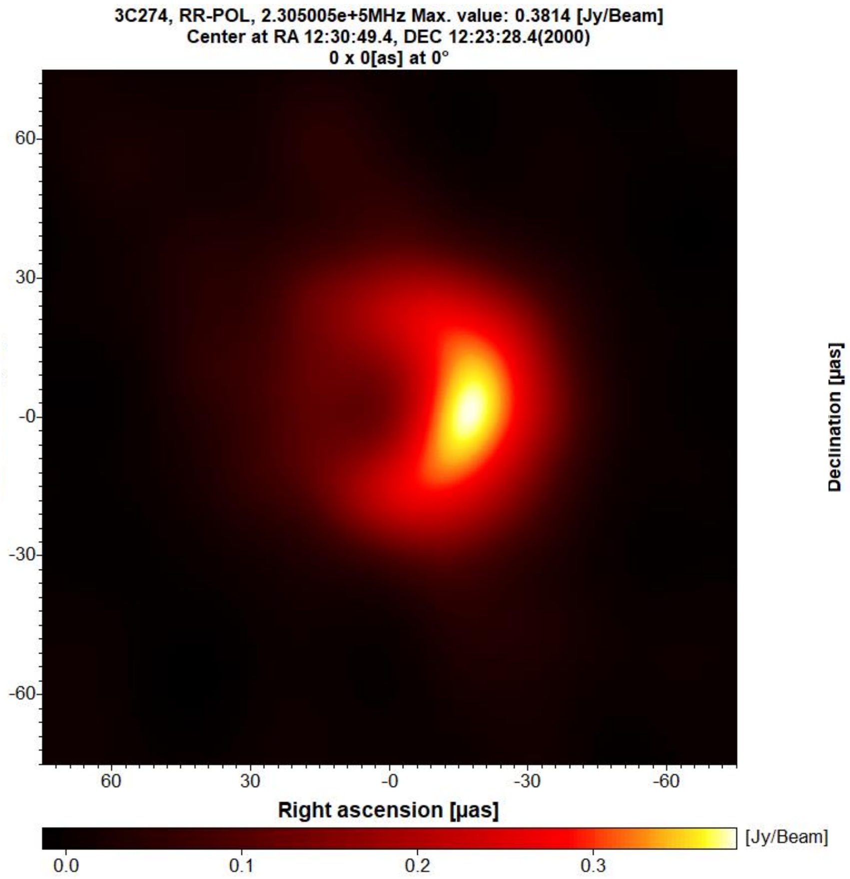
Simulated image of Sgr A* (model 39) for HEO orbit (center) and for L2 orbit (right)

VLBI Simulations

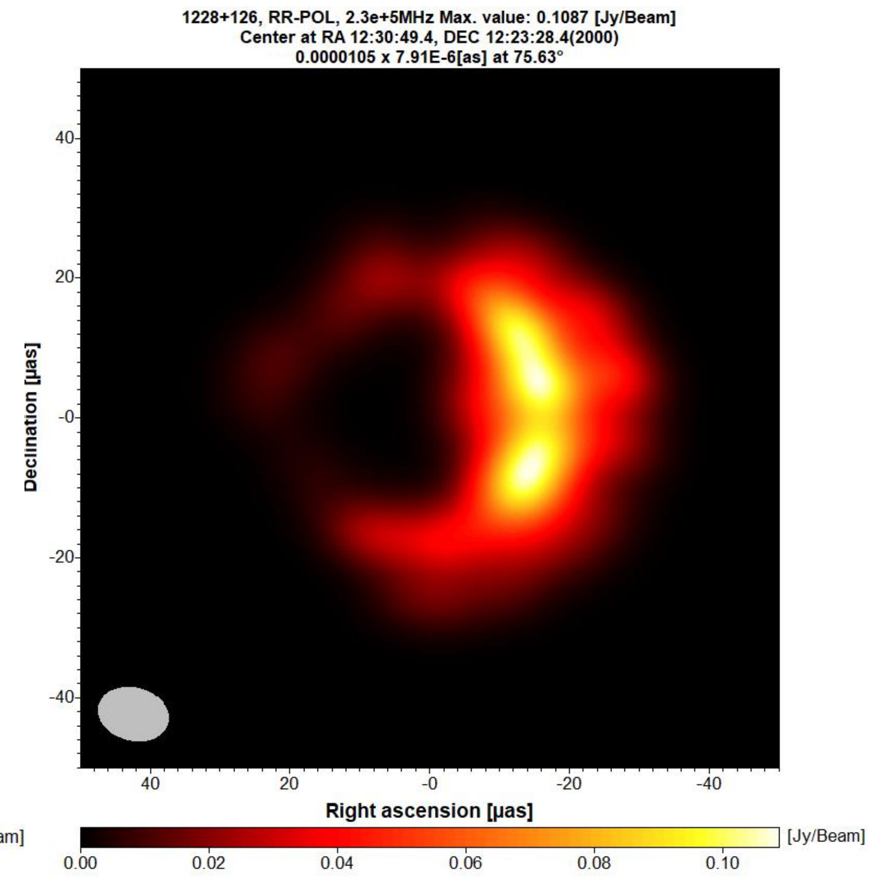
Simulations of M87 VLBI imaging for L2 Orbit



Model (S. Chernov)

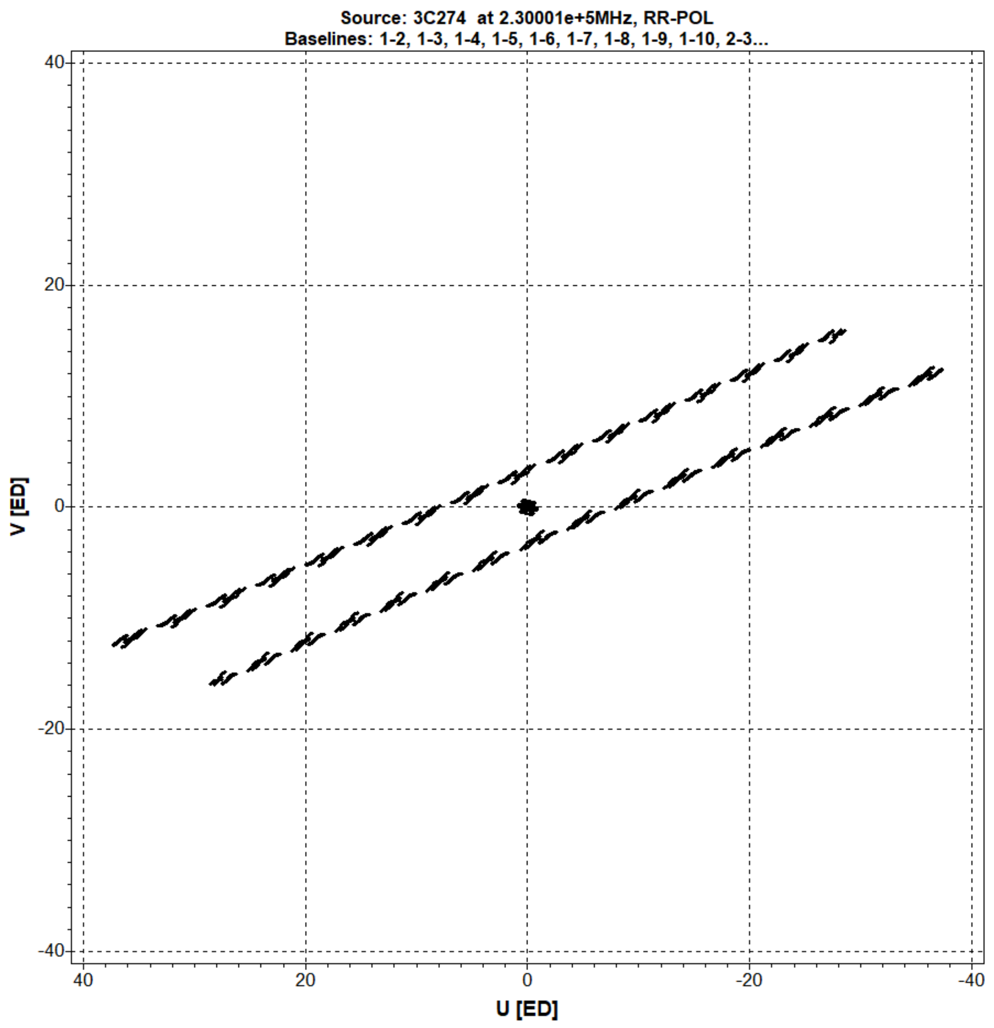


EHT Only

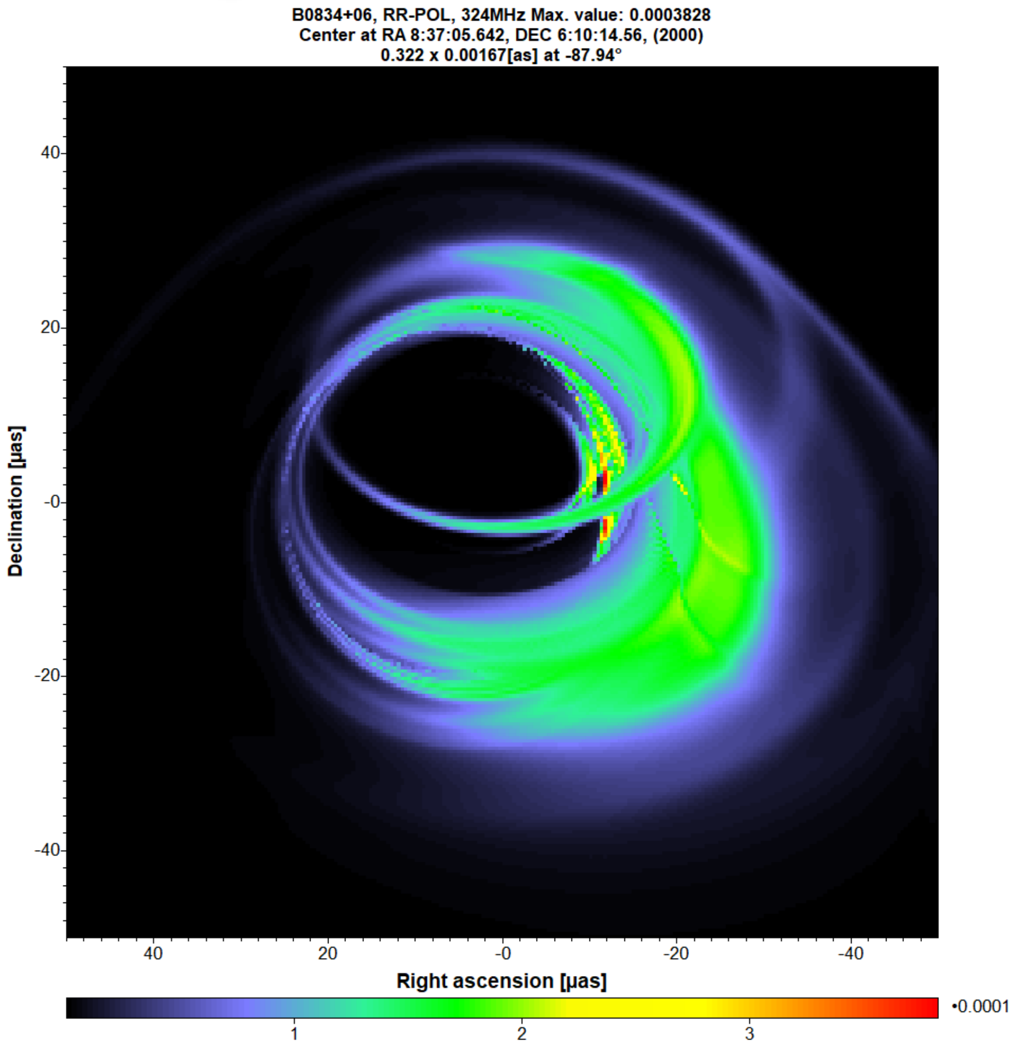


MM (L2) + EHT

VLBI Simulations
Photon Rings



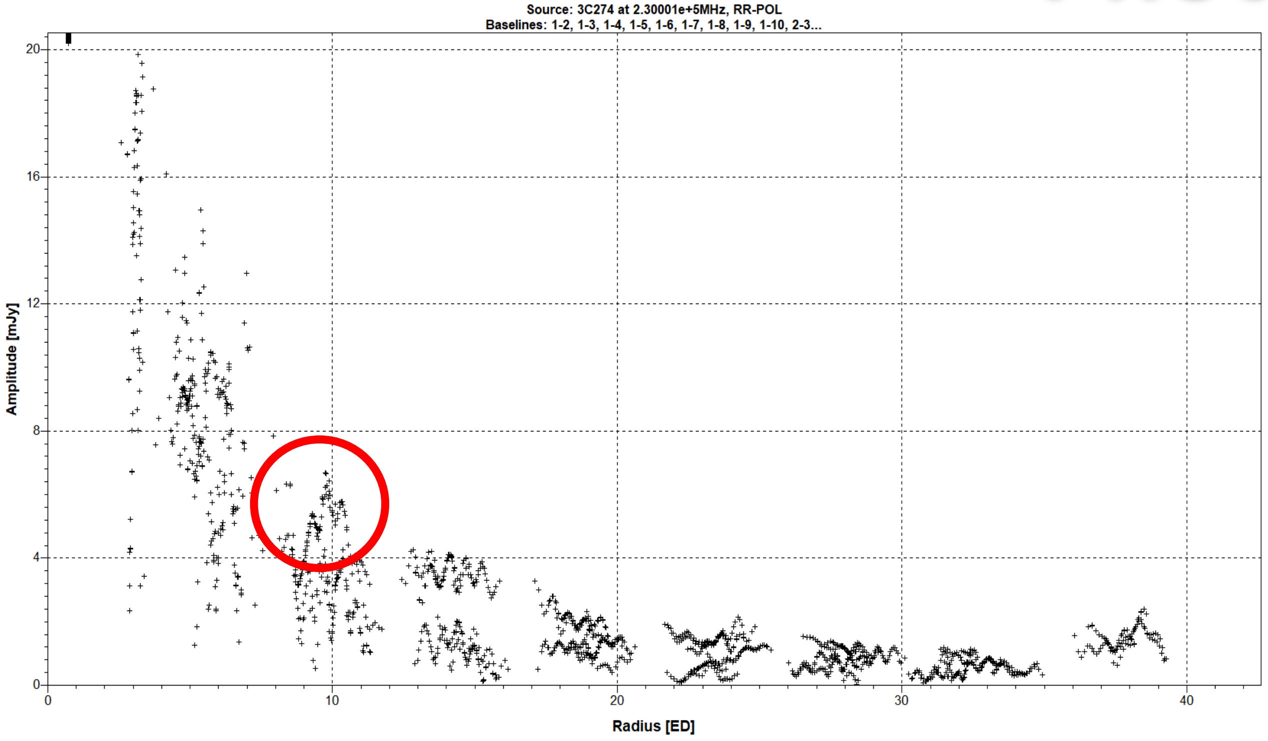
(u,v) coverage accumulated for 16 days

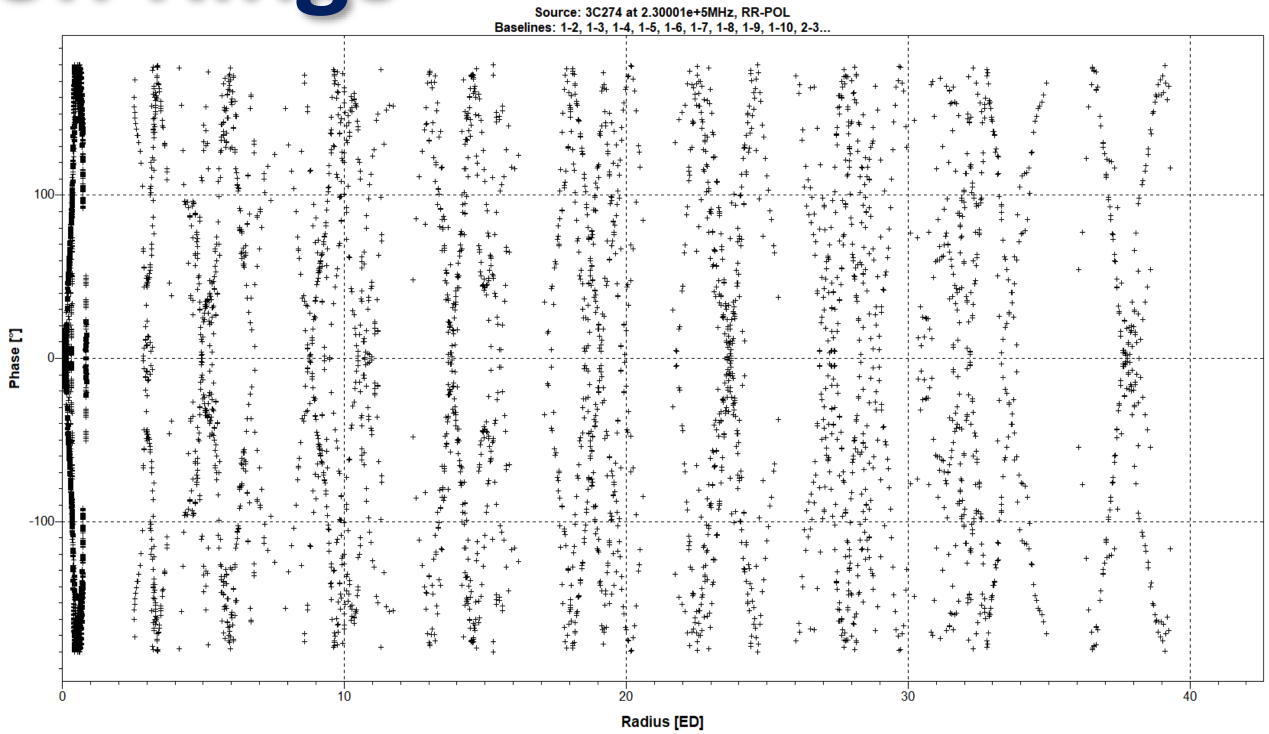


M87 model by S. Chernov

VLBI Simulations

Photon Rings



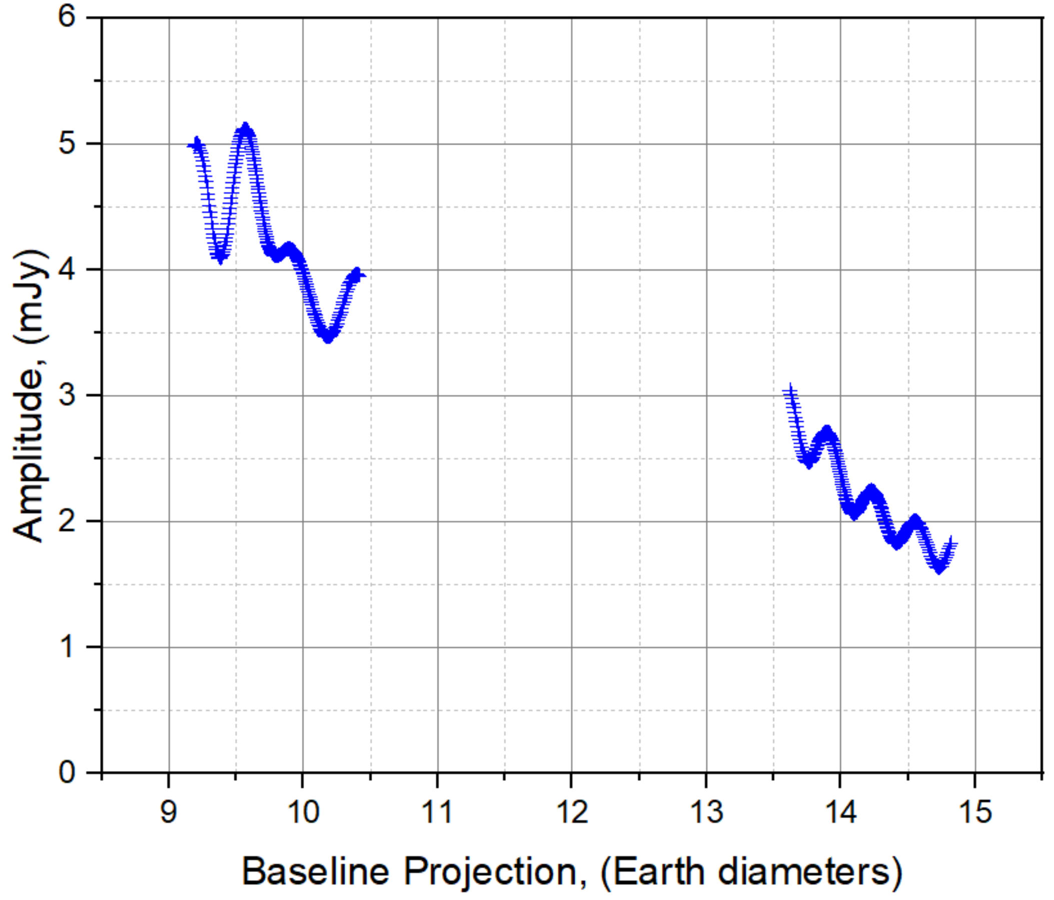


10 ED 20 ED 30 ED

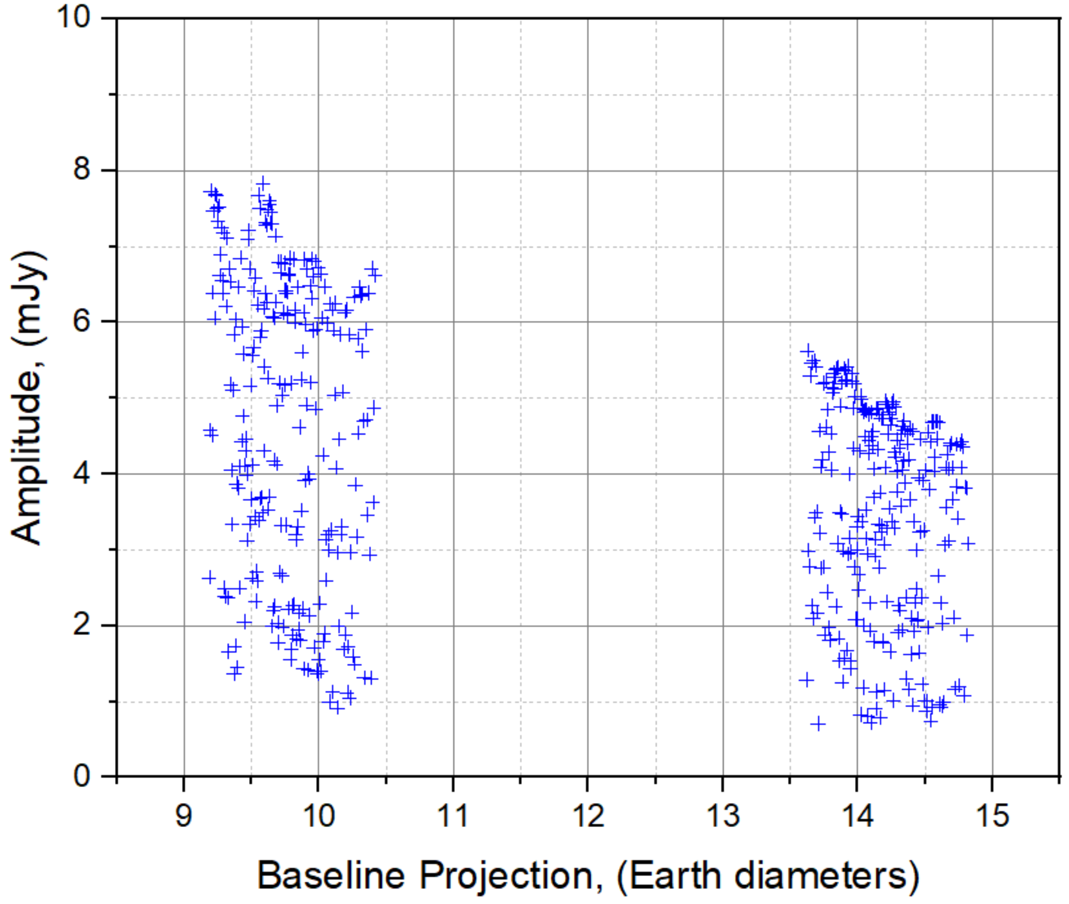
Detectable: first ring.

Need to improve sensitivity.

VLBI Simulations
Photon Rings



Ideal case



Applied sensitivity model

Conclusions

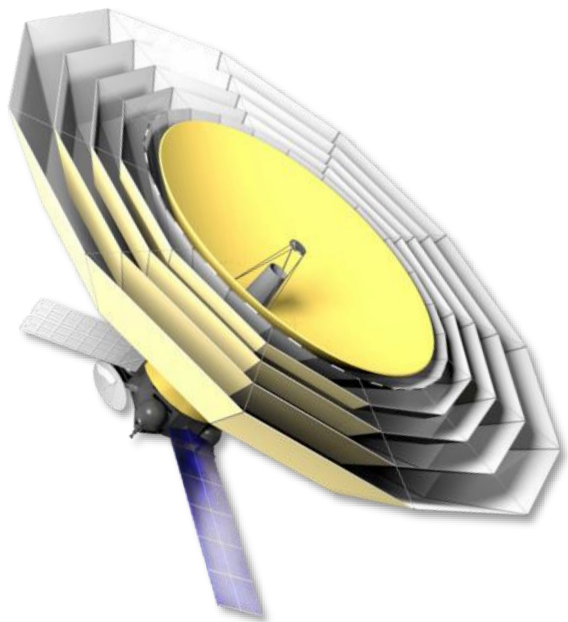
- Proposed ***new nominal orbit*** with smaller exit from the ecliptic plane (~400 000 km) + better satellite radio visibility

- Imaging observations for Sgr A * and M87 in L2 point **are possible!**
  Within 24 hours versus ~7 days for high elliptical orbit (HEO)

- ***Current senisitivity and L2 orbit are capable of observing photon rings*** (at least the first one). Improved senisitivity will lead to better results.

More information: http://millimetron.ru/

Thank you for your attention!



Millimetron Space Observatory Collaboration

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Millimetron project web-page: http://millimetron.ru/

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