# The VLBI Space Observatory Programme VSOP-2

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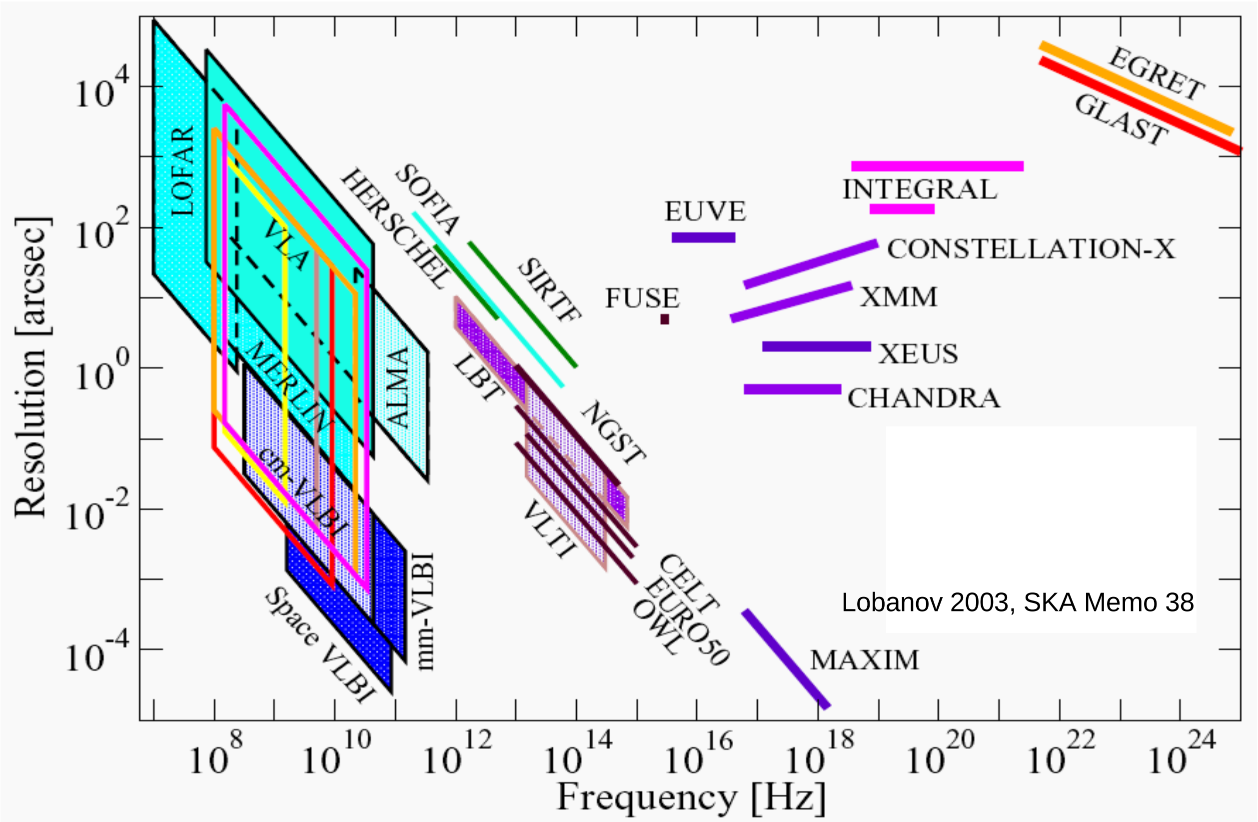
# Astronomical Drivers



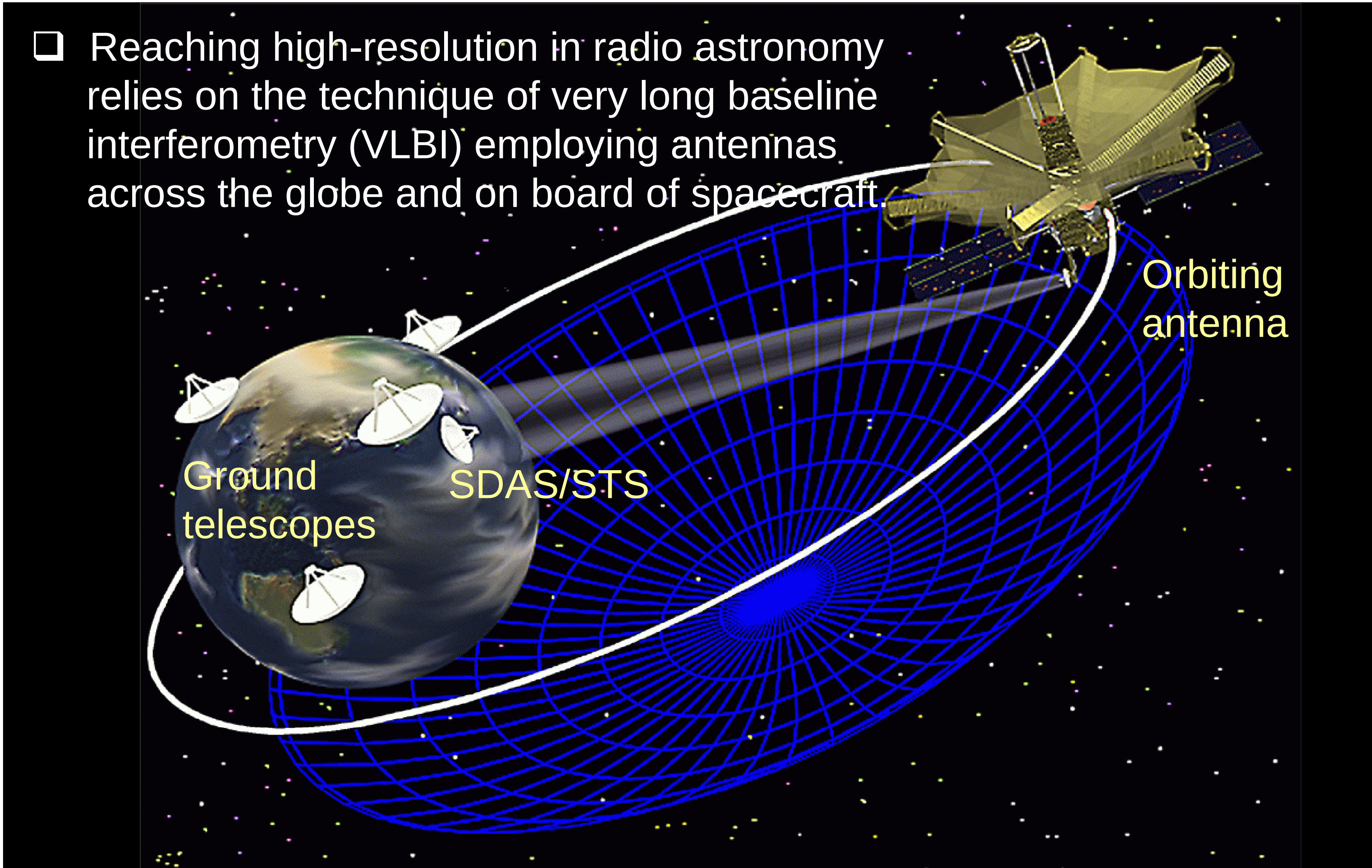
- Increasing the spectral range available for atronomical observations.
- Reaching higher sensitivity and resolution of astronomical instruments.
- Interferometer: Sensitivity ∝ sum of the areas of individual elements.
  Resolution ∝ largest separation between the elements.
- Interferometry offers an effective way to expand the capabilities of astronomical instruments.



# Quest for Resolution



- Reaching high-resolution in radio astronomy relies on the technique of very long baseline interferometry (VLBI) employing antennas across the globe and on board of spacecraft.



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# Space VLBI Timeline

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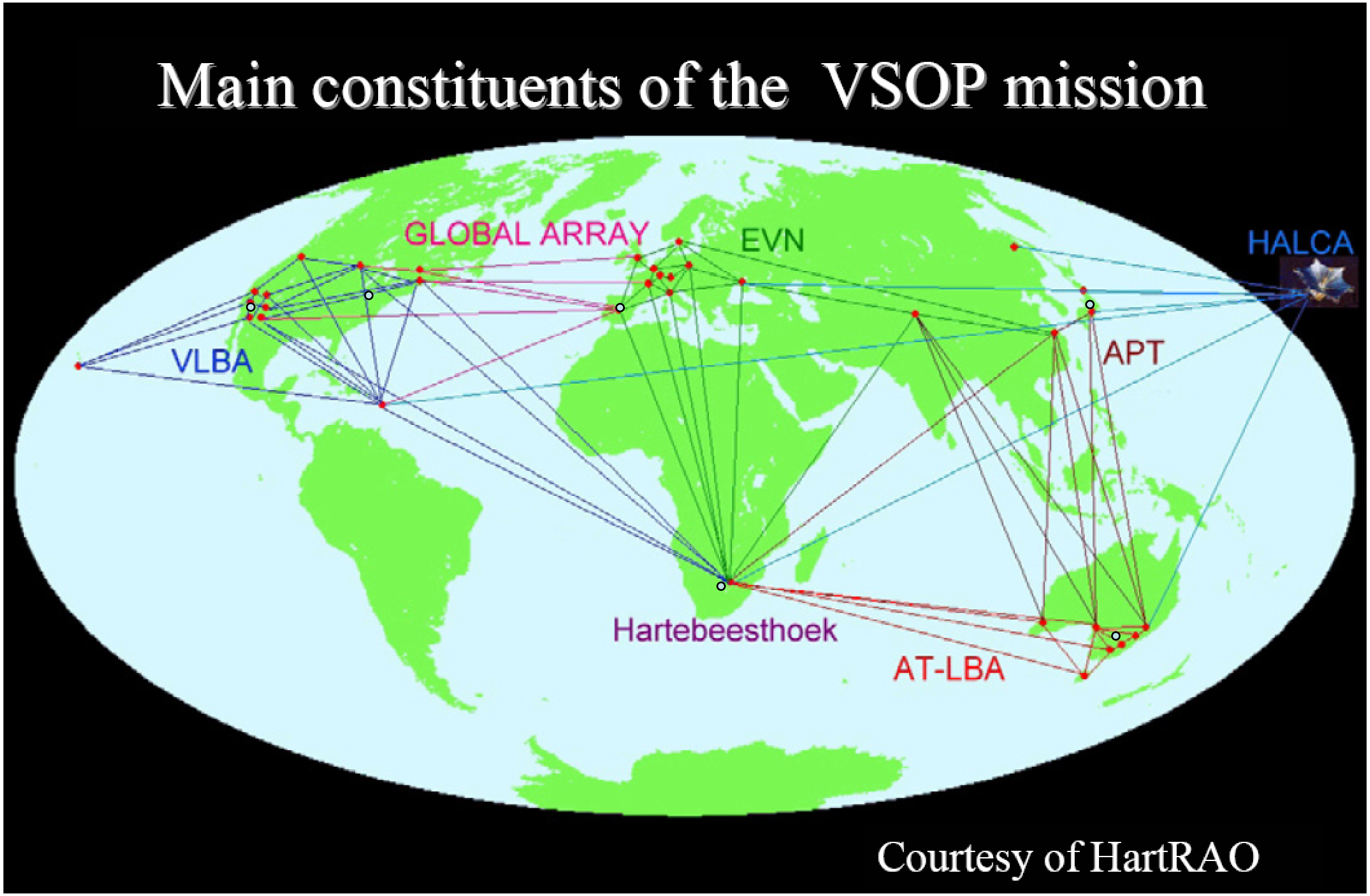
- Early discussions (beginning of 1980-s).
- **QUASAT**, **IVS**, **KRT-30**, **ARISE**: proposals, phase-A studies.
- **TDRSS**: successful detections at 2.3 and 15GHz, on space-ground baselines (1986).
- **RadioAstron**: started in mid 1980-s; under preparation.
- **VSOP** (VLBI Space Observatory Programme):proposed in 1987, launched in 1997; operated until 2006 at 1.6 ad 5 GHz.
  - led by ISAS/JAXA, with substantial contributions from JPL/NASA, NRAO, DRAO/CSA, ATNF, and EVN (tracking stations, observing, correlator facilities).
  - was approved and operated as a technology demonstrator.

# VSOP Mission



- VSOP used global array of radio telescopes and tracking stations



# HALCA Satellite



- Basic parameters of HALCA: satellite orbit and observing bands and sensitivities

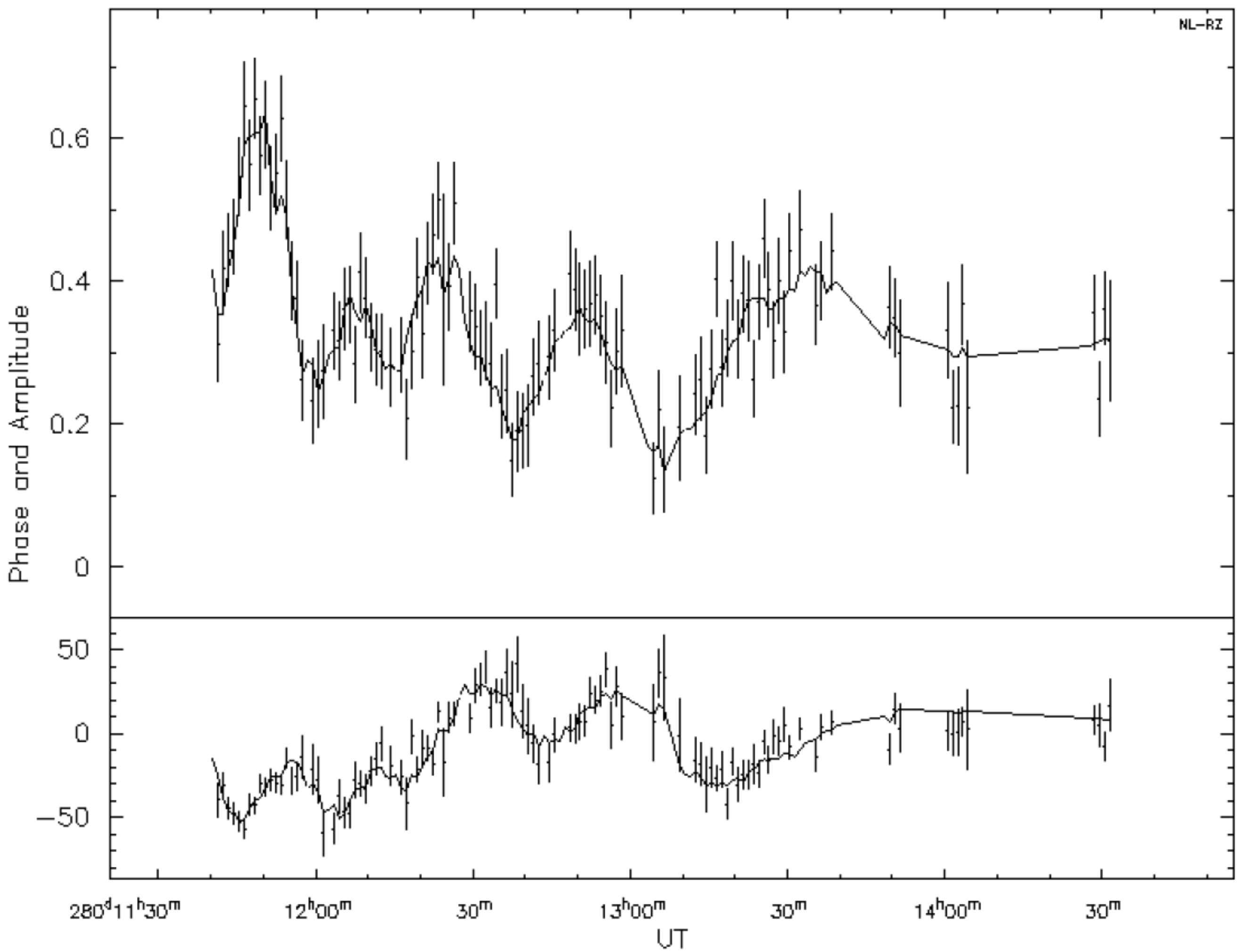
| Element | Value |
|---|---|
| Period | 6.3 hours |
| Inclination | 31 degrees |
| Apogee altitude | 21,400 km |
| Perigee altitude | 560 km |

| Band | 1.6 GHz | 5 GHz |
|---|---|---|
| Frequency | 1.60–1.73 GHz | 4.7–5.0 GHz |
| Polarization | LCP only | LCP only |
| $T_{\rm sys}$ | 75 K | 95 K |
| Aperture Efficiency | 24% | 34% |
| System gain | 4.3 mK Jy$^{-1}$ | 6.2 mK Jy$^{-1}$ |
| $T_{\rm sys}$ (Equivalent Flux Density) | 17,400 Jy | 15,300 Jy |
| Typical Coherence Time ($\tau_c$) | 600 s | 400 s |
| $7\sigma$ Sensitivity to VLBA Antenna: | | |
| Continuum source (1) | 131 mJy | 147 mJy |
| Line source (2) | 4.2 Jy/ch | 4.7 Jy/ch |

# Data on space baselines

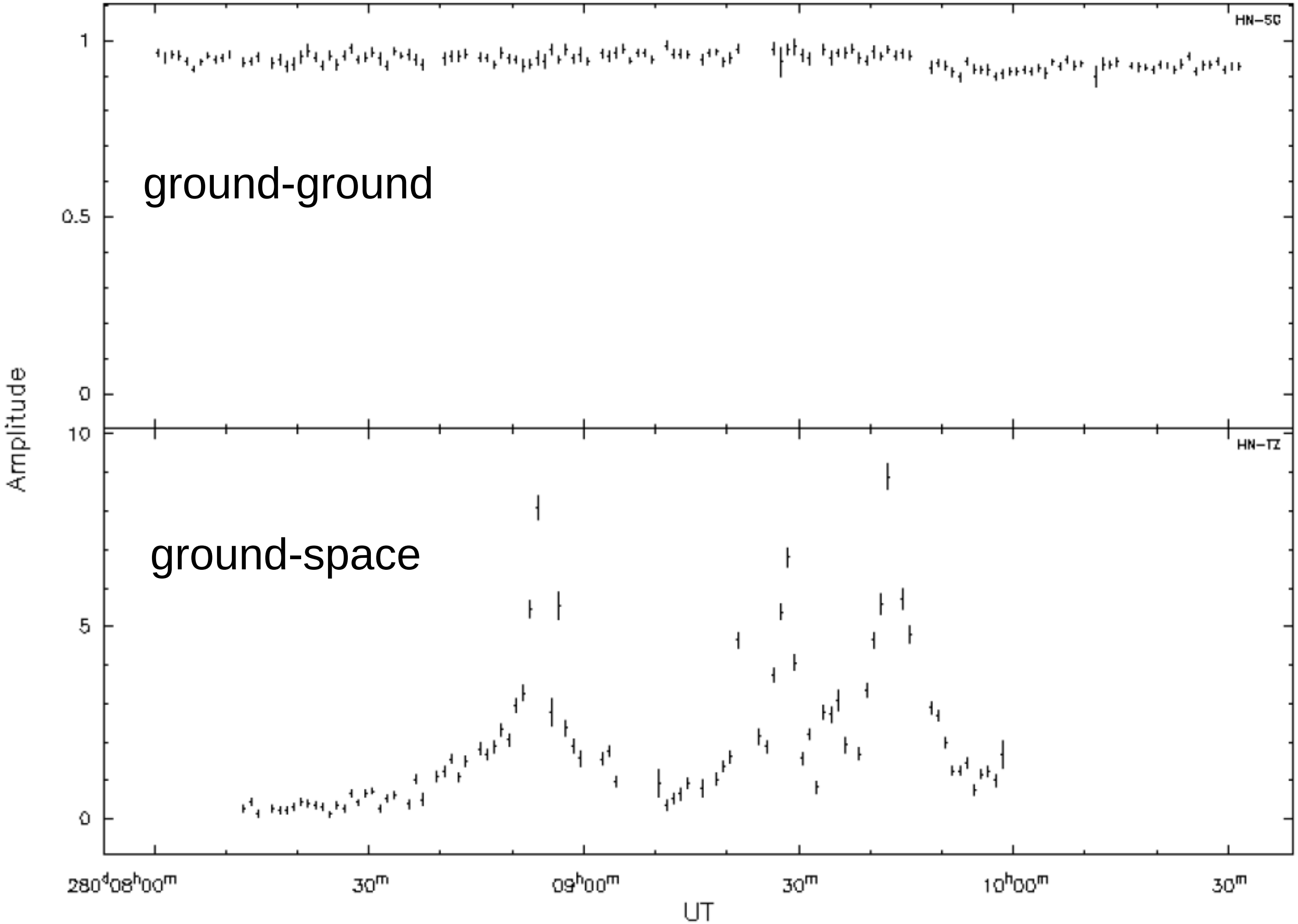


- Ground-space baselines of VSOP provided good quality data



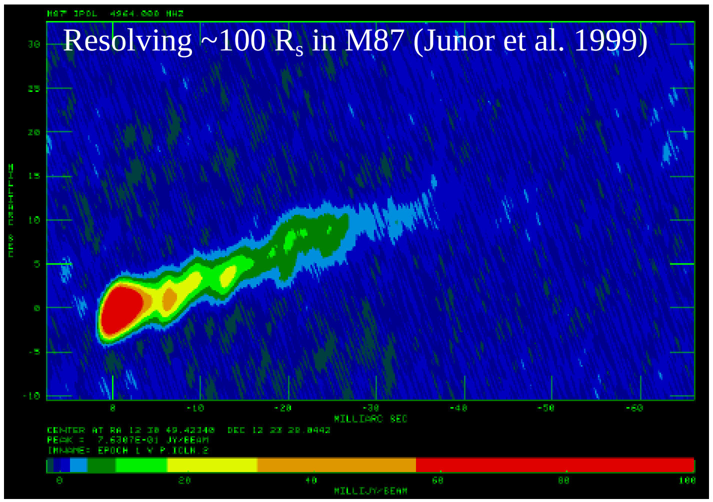
# Structure on space baselines

- Information from ground-space baselines was unique and could not be obtained from ground-ground baseline data.

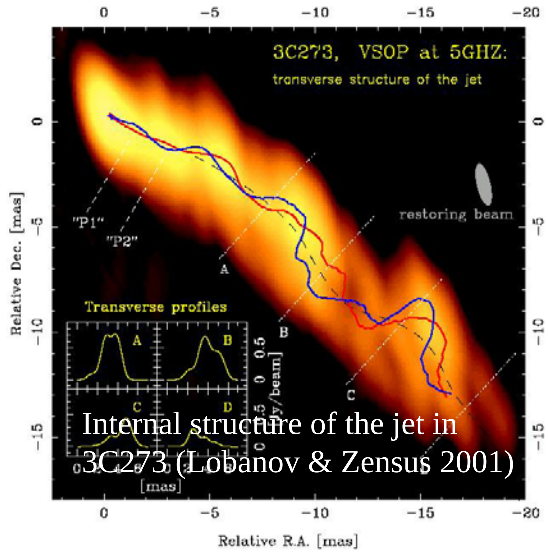


# Results from VSOP

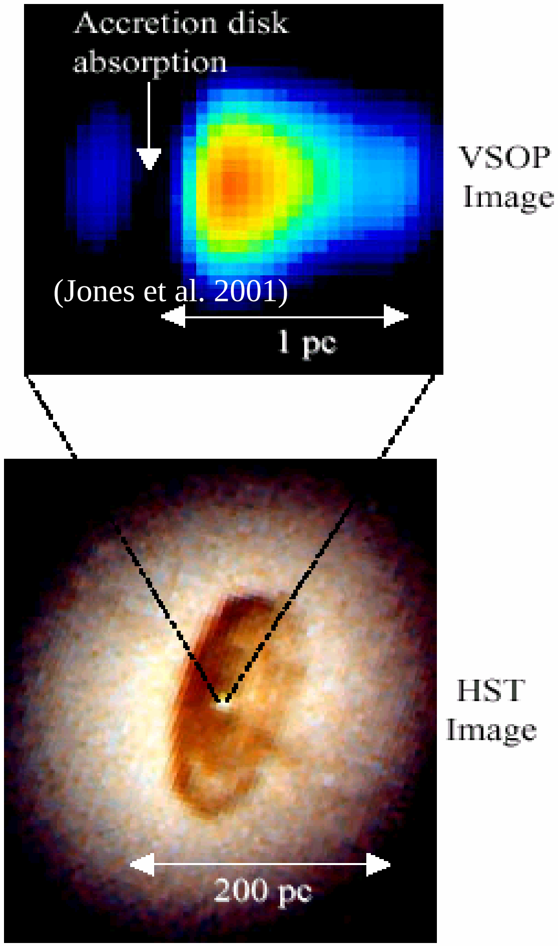
- ❑ VSOP was a powerful tool for AGN studies on sub-pc and pc scales.



Resolving ~100 $R_s$ in M87 (Junor et al. 1999)

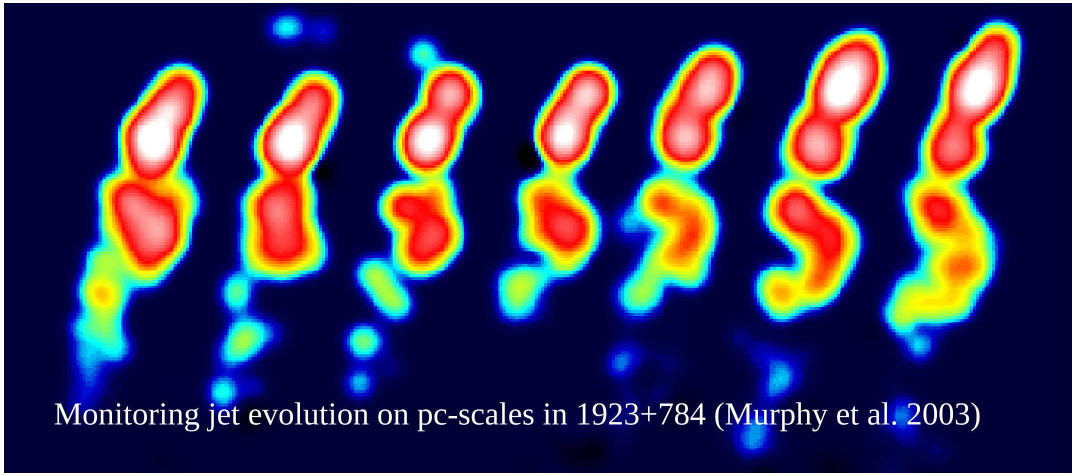


Internal structure of the jet in 3C273 (Lobanov & Zensus 2001)



(Jones et al. 2001)

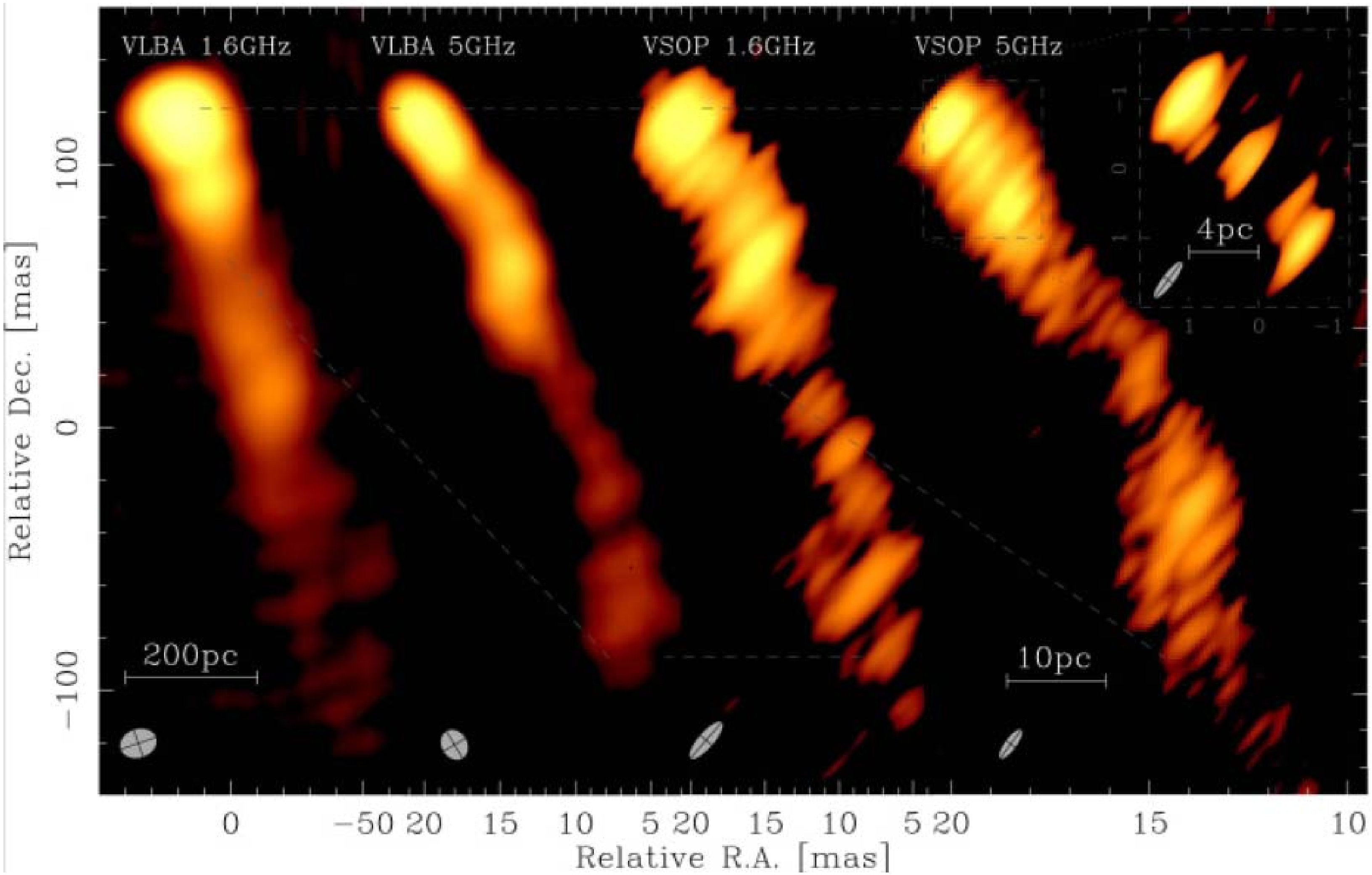
Accretion Disk in NGC 4261


Monitoring jet evolution on pc-scales in 1923+784 (Murphy et al. 2003)

# VSOP Results II



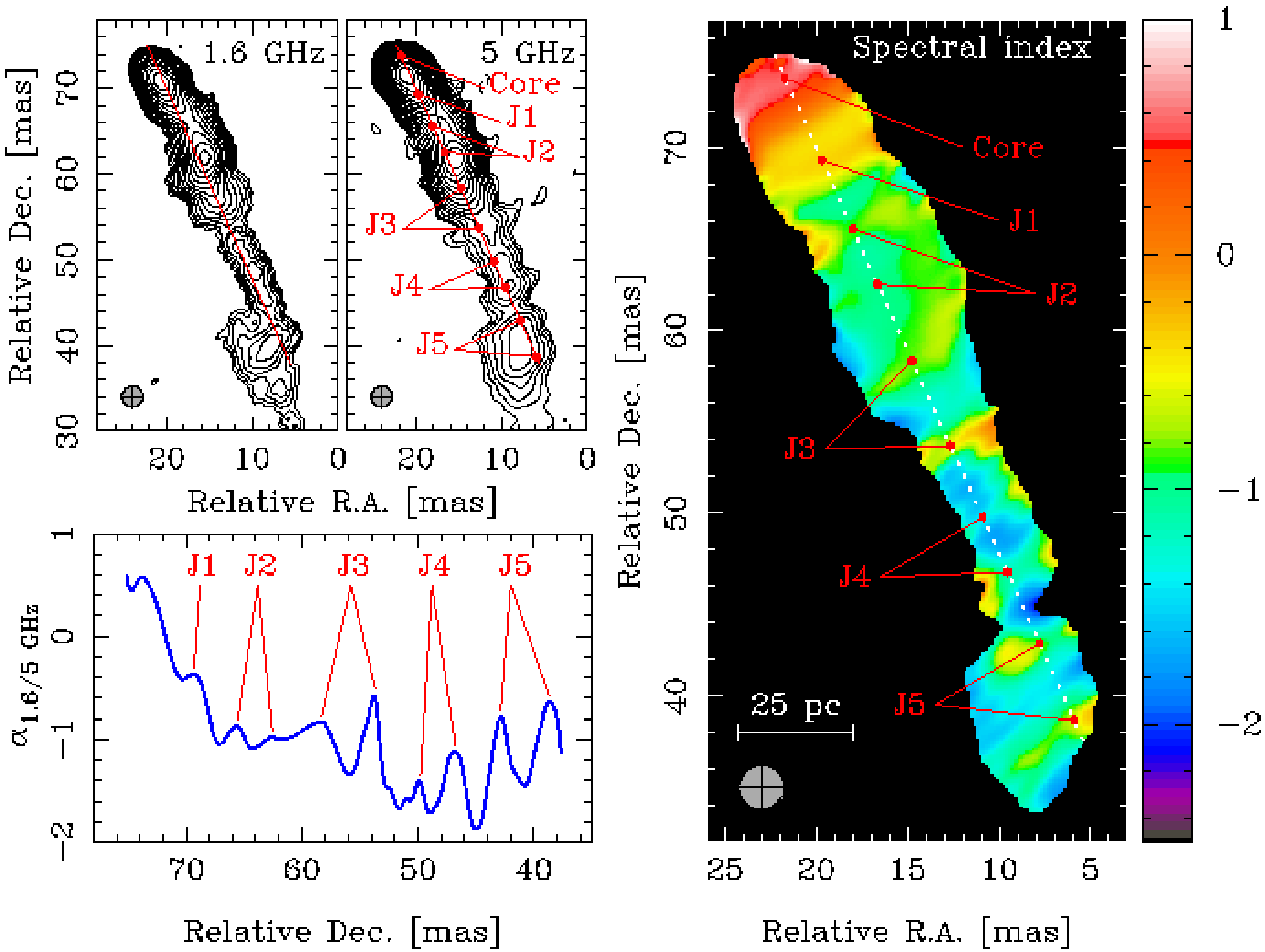
- VSOP observations probed a range of angular scales and provided matched resolution images for ground VLBI observations at shorter wavelegnths



# VSOP Results III



- Spectral index image from matched resolution VSOP/VLBI observations



# VSOP in Space Science



- The IAA Annual Award in 2005 was given to the VSOP, putting it into the distinguished company of other award recipients: MIR Space Station (2001), Space Shuttle (2002), SOHO (2003), and HST (2004)

# From VSOP to VSOP-2



- **VSOP-2**: approved in April 2006 by JAXA as a science mission.
  Total mission budget ~200M$.
  Will operate at 8, 22, and 43 GHz.
  Launch planned for February 2012. Operational until 2017+.

| ***Mission*** | **VSOP (1997)** | **VSOP-2 (2012)** |
|---|---|---|
| ***Mission Type*** | Engineering | Science |
| ***Aperture*** | 8m | 9m |
| ***Frequencies*** | 1.6, 5 GHz | 8,22,43 GHz |
| ***Polarization*** | LCP | Dual |
| ***Data Rate*** | 128 Mbps | 1 Gbps |
| ***Apogee Ht.*** | 20,000 km | 25,000 km |
| ***Phase Referencing*** | No | Yes (8 GHz) |
| ***Best Resolution*** | ~400 µas | ~40 µas |

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# VSOP-2: Resolution

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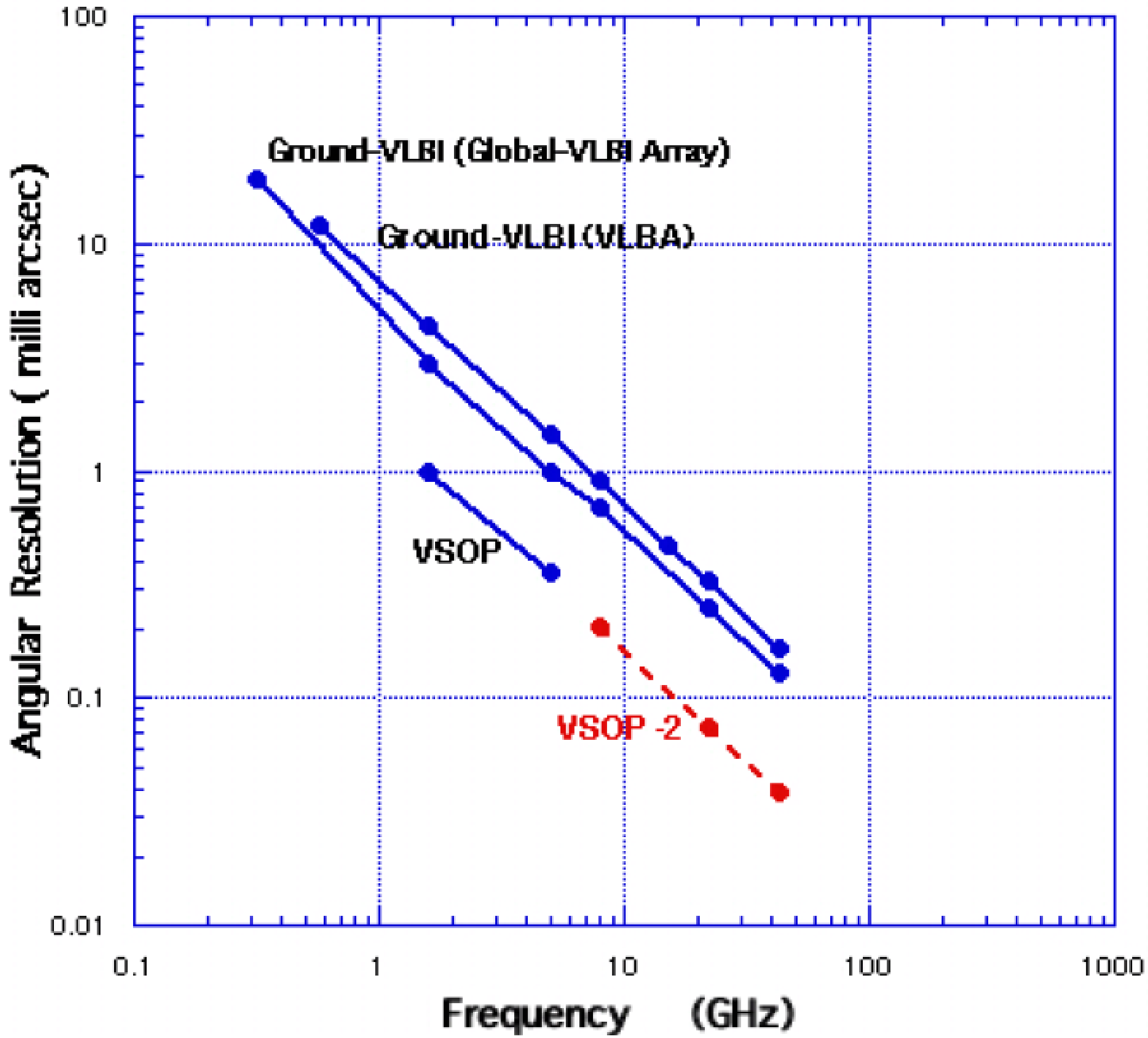
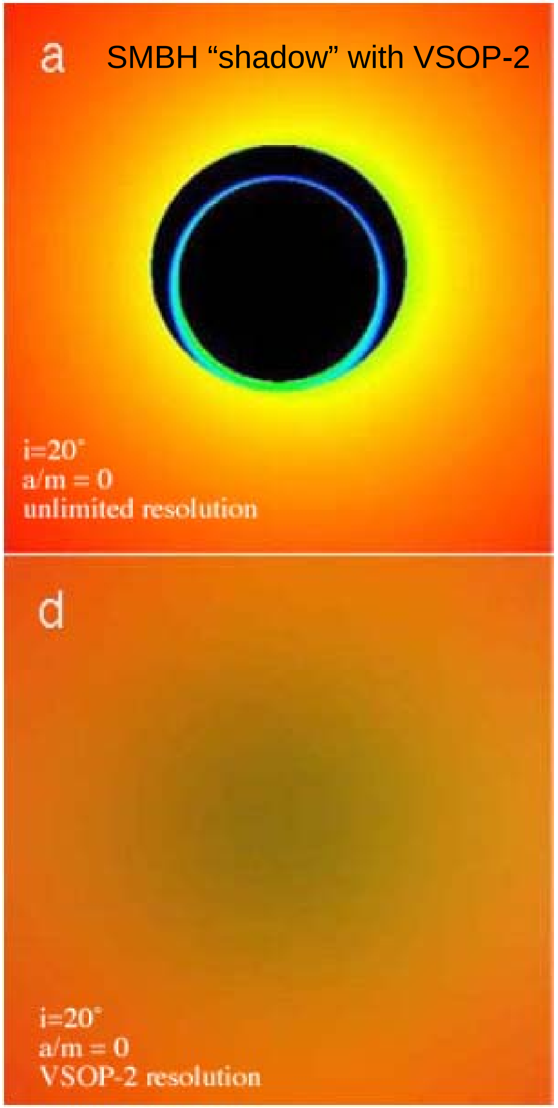


# Science with VSOP-2



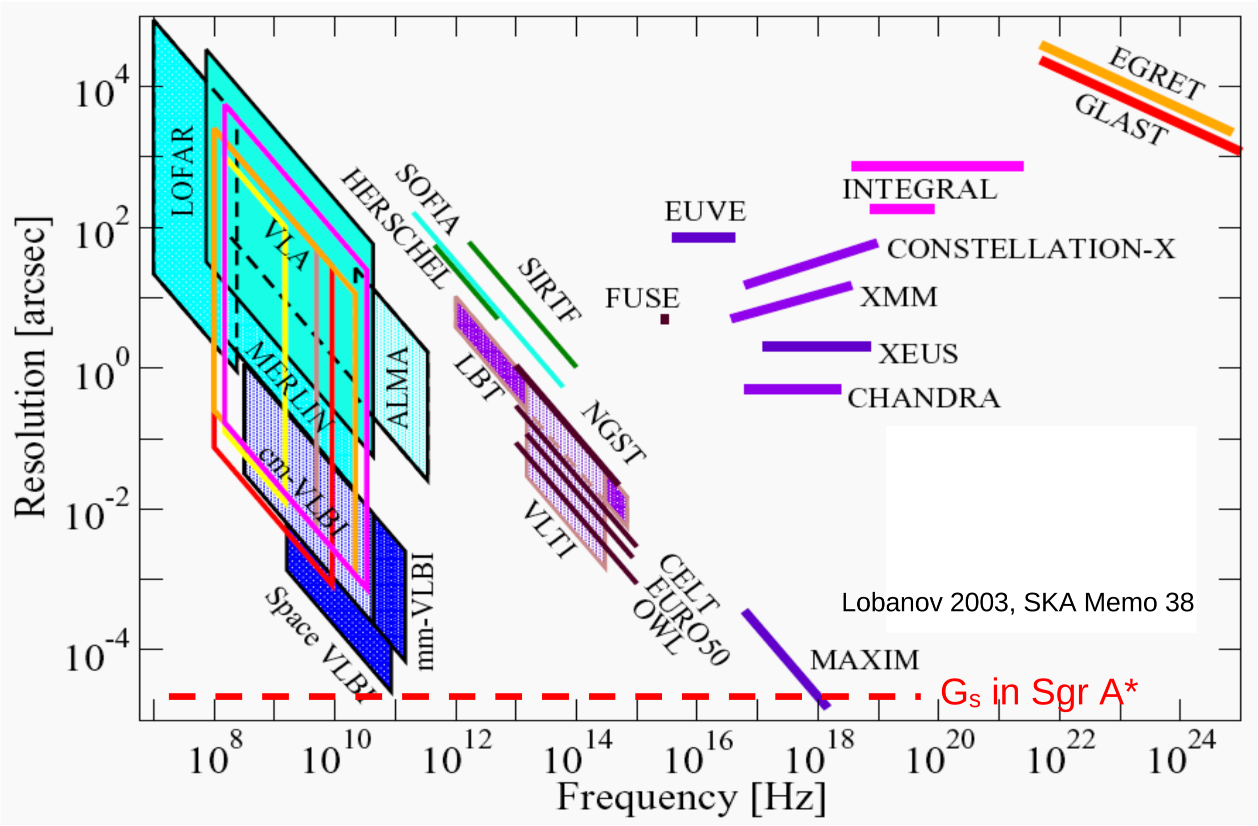
- VSOP-2 will have a 10 times better sensitivity (0.3 mJy/beam at 8 GHz) and resolution (~40 µas at 43GHz) compared to VSOP.
- Main science themes will be expanded to include:
  - direct imaging of hot ($10^9$–$10^{10}$ K) material in AGN accretion disks.
  - a imaging of the vicinity of SMBH (M87: a BH "shadow" is ~26 μas).
  - acceleration, collimation and internal structure of relativistic jets.
  - imaging magnetospheres and non-thermal radio continuum in protostars.
  - $H_2O$ masers in protoplanetary disks and accretion disks in AGN.
  - SiO masers in Asymptotic Giant Branch (AGB) stars.



# Studying the BH Vicinity

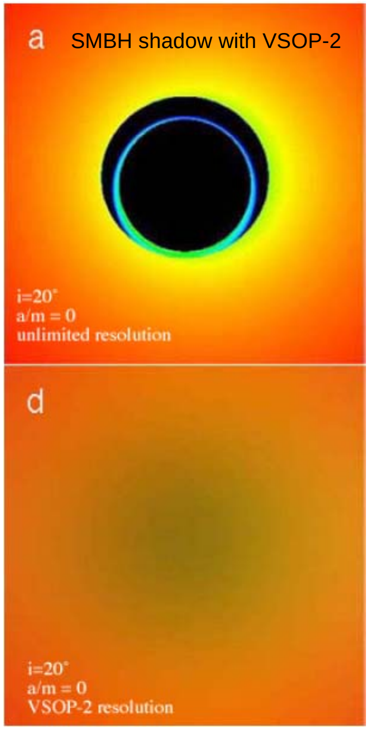


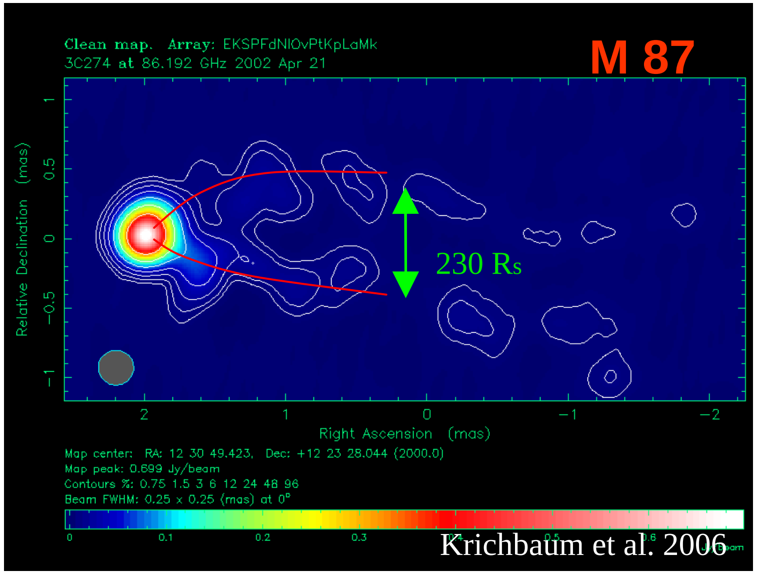
- **X-ray:** spectroscopy (1D, model dependent); interferometry (not available)
- **Optical, IR:** interferometry (need good uv-coverage, phase closures)
- **GWave:** interferometry (detection depends on pre-calculated templates)
- **Radio:** GVLBI (2D, calibration), SVLBI (2D, orbit determination)

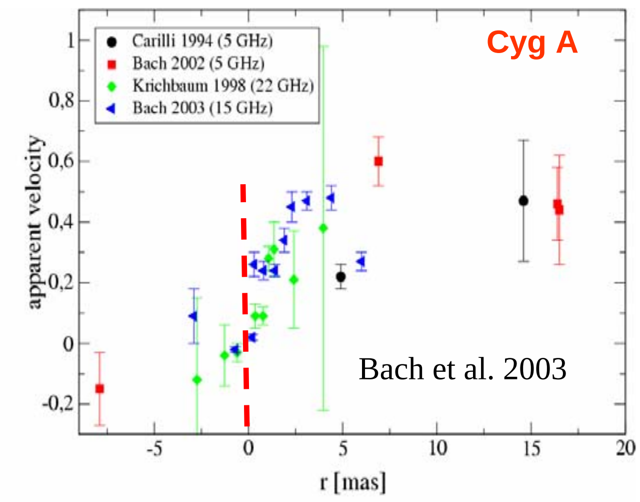


# VLBI on BH Vicinity

- Direct imaging of hot ($10^9$–$10^{10}$ K) material in AGN accretion disks in the vicinity of SMBH (M87: a BH "shadow" size ~26 µas, space VLBI: ~40 µas; mm-VLBI: 20 µas @ 215 GHz).
- Formation, acceleration, collimation and internal structure of relativistic jets.



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# How black is black hole?

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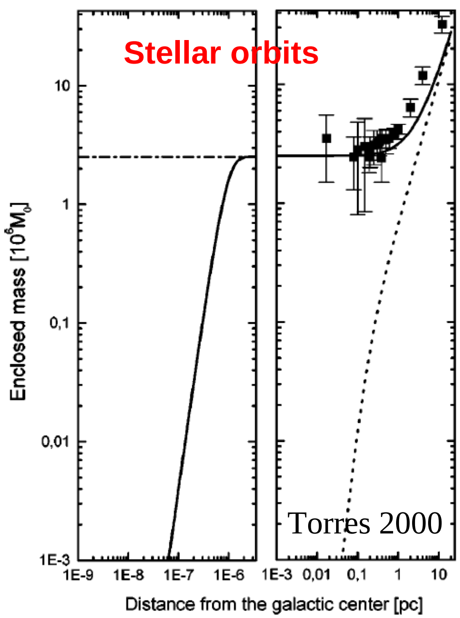
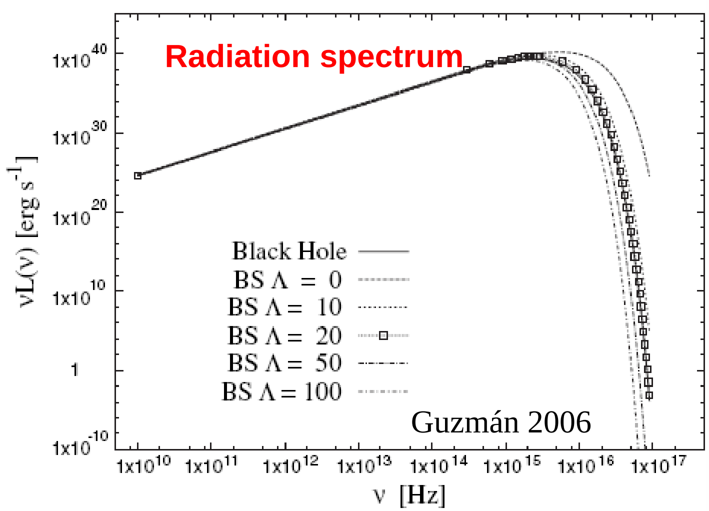
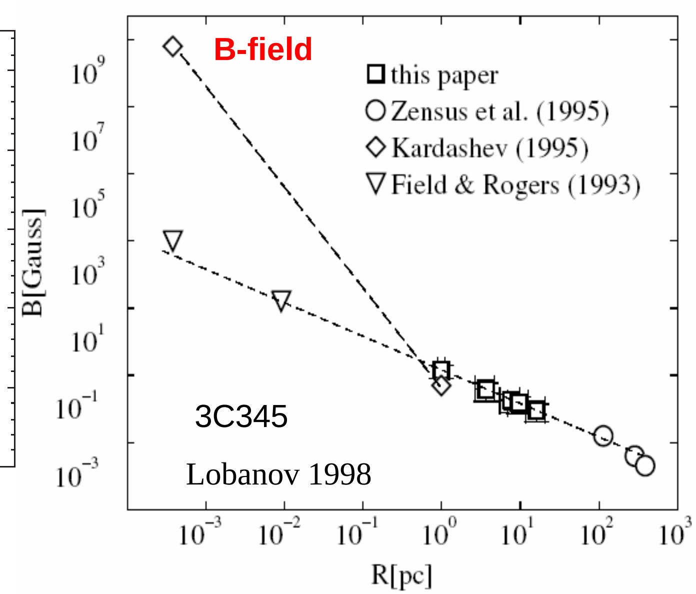
- Present evidence does not strictly prove existence of BH.
- Need to devise instruments and experiments to distinguish effectively between BH and their alternatives:
  - **stellar orbits:** (S1, Sgr A*) good enough for BH vs. ν condensate tests
  - **radiation spectrum:** high energies (BH vs. BS), ELF (BH vs. MECO)
  - **gravitation waves:** BH vs. anything (but need accurate templates)
  - **VLBI:** 2D imaging (BH vs. BS/MECO?), B-field (BH vs MECO)



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# Observational requirements

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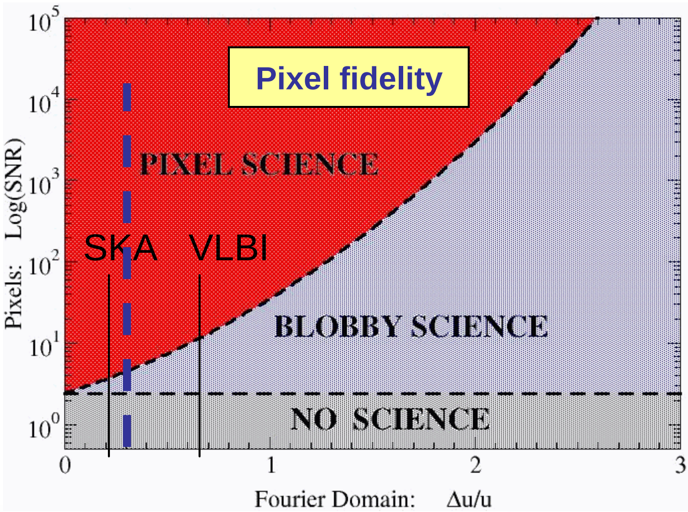
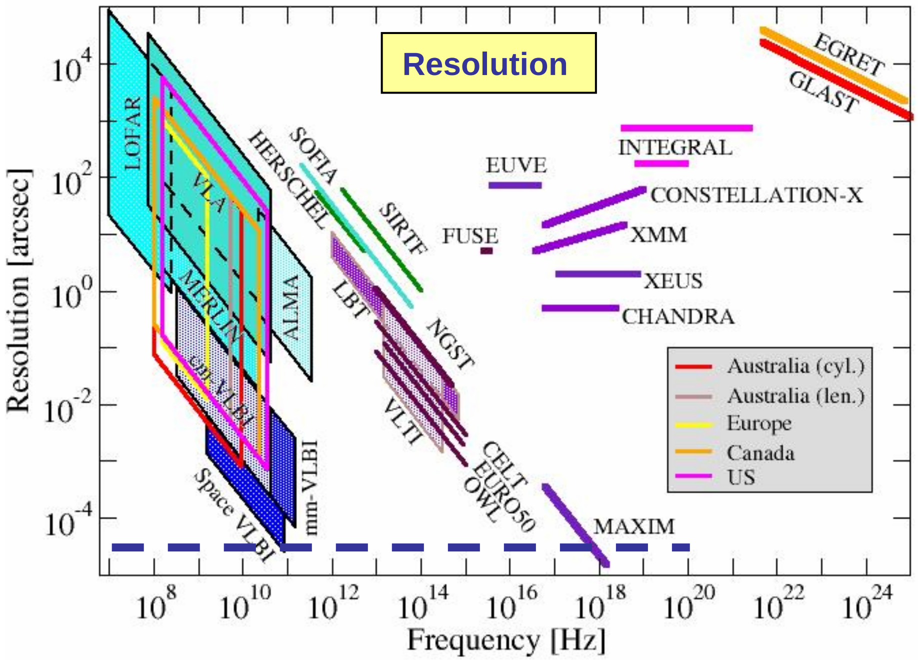
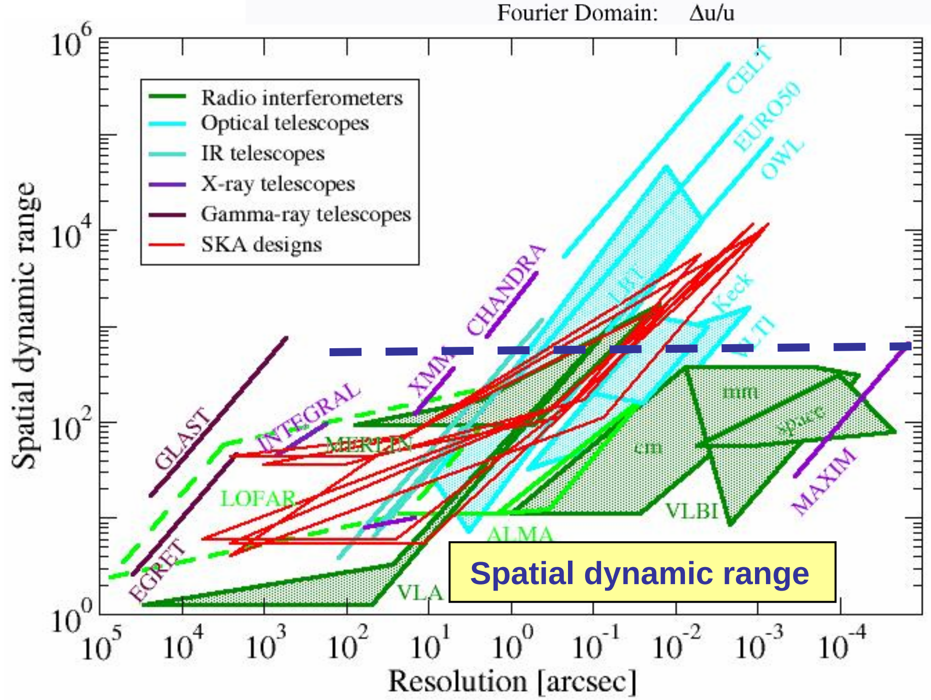
- Effective studies of SMBH and their vicinity will require imaging with:
  - ~10 μas resolution;
  - spatial dynamic range of >500
  - pixel fidelity down to SNR~5



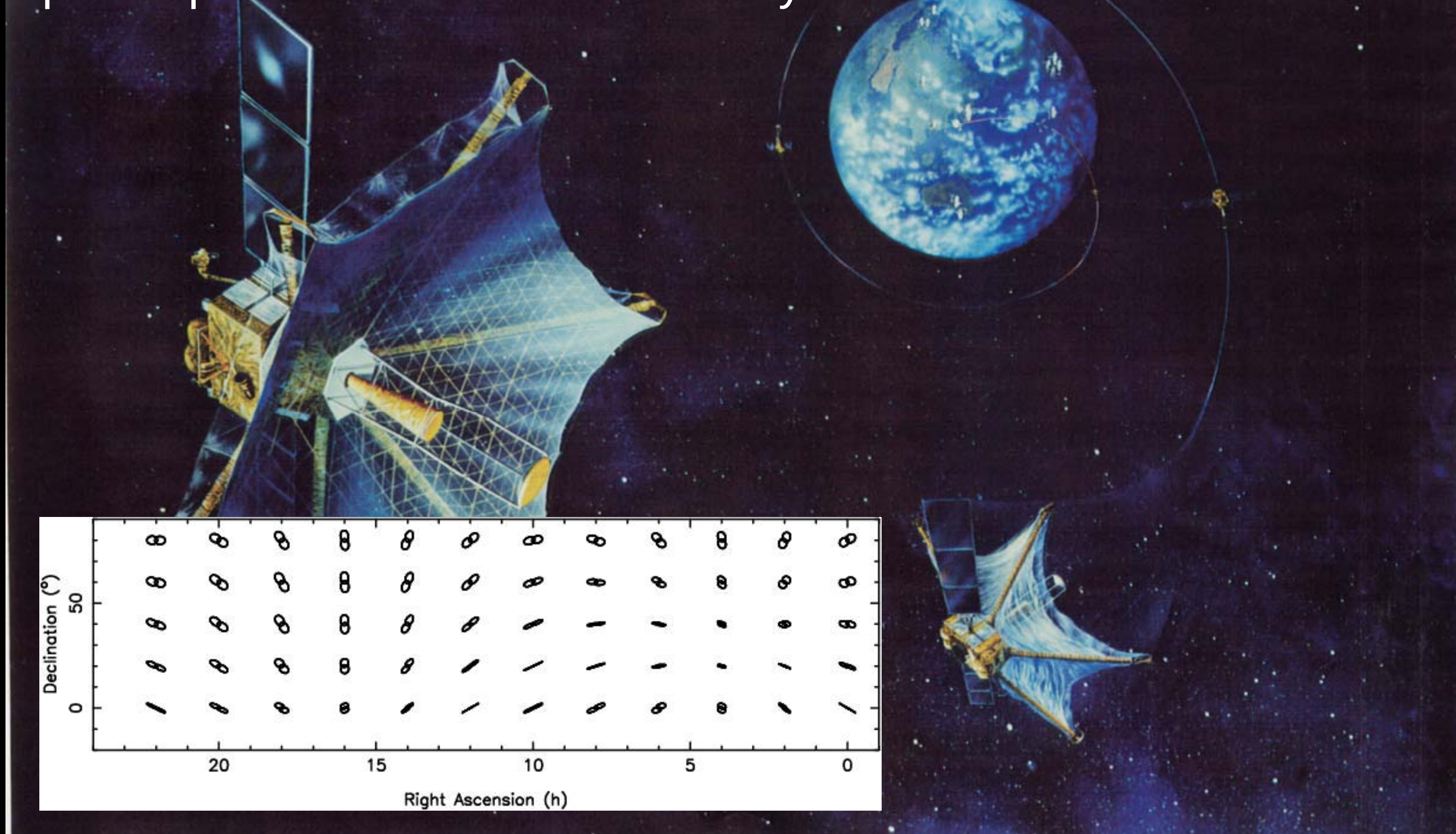



# VSOP-2 Squared?



- Bringing a second radio telescope in orbit will enhance dramatically observing capabilities of space VLBI observations, pioneering the space-space baseline interferometry.



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# Future Prospects

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- Space radio astronomy is a vibrant and rapidly growing field of science and technology opening up new areas of fundamental research.

- High-sensitivity space VLBI (VSOP-2 and beyond) is one of the primary (and affordable) tools for addressing a range of fundamental physical problems related to black holes.

- VSOP-2 is highly complementary to other major future astrophysical facilities such as LOFAR, ALMA, SKA, GLAST, JWST, and ELTs).

- Space VLBI technology paves the way to future space interferometry instruments.

- Opting for a future two-spacecraft space VLBI mission would be a significant milestone in the development of space interferometry.