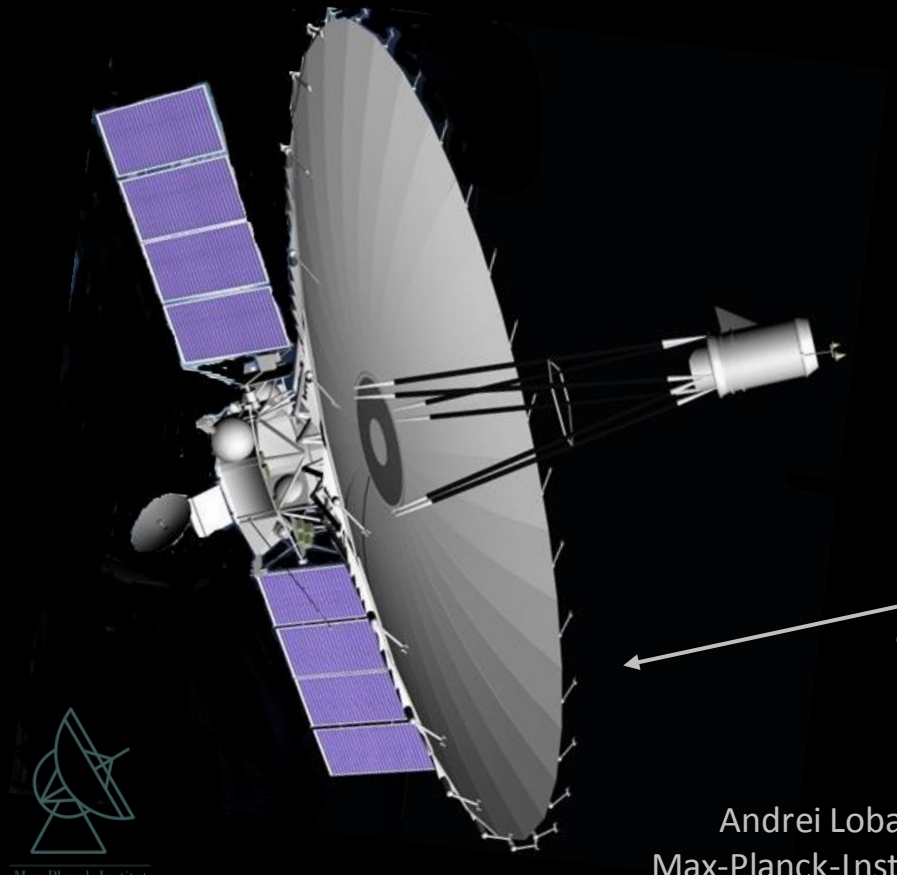
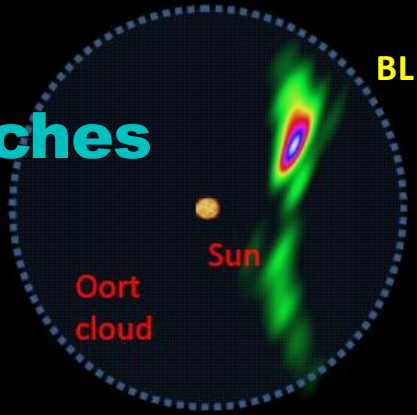
Space VLBI Imaging:
Multi-scale and multi-directional approaches





900 000 000 light years

Alpha
Centauri

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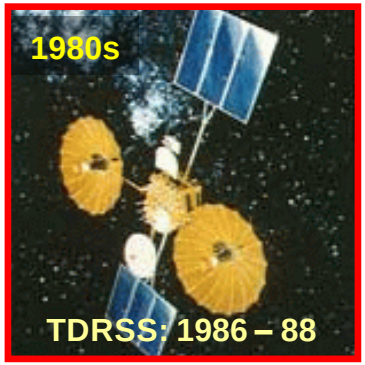
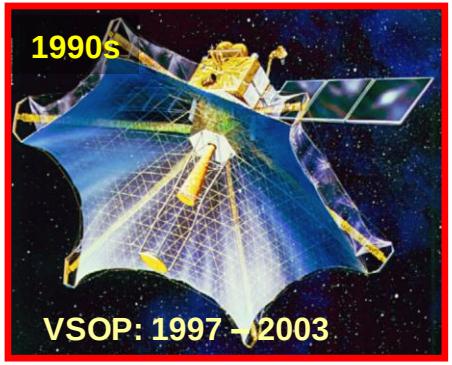
Max-Planck-Institut für Radioastronomie

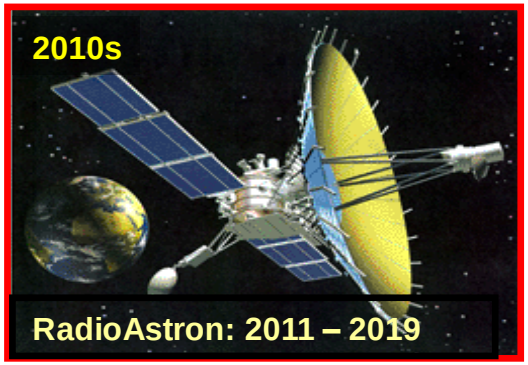
Max-Planck-Institut
für Radioastronomie

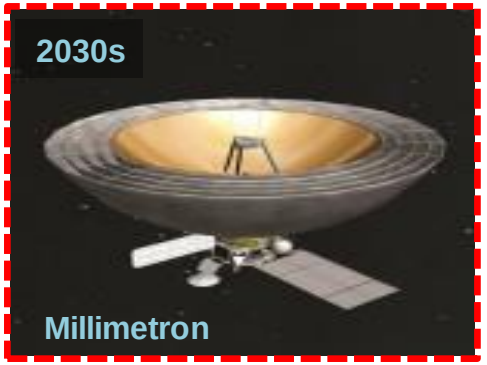
Space VLBI

- **First proposed already in 1970-s**, space VLBI has counted so far three instruments and only one dedicated mission. MPIfR has been a key partner for VSOP and RadioAstron, and actively contributes to further SVLBI efforts.









Other space VLBI Initiatives (incomplete list):

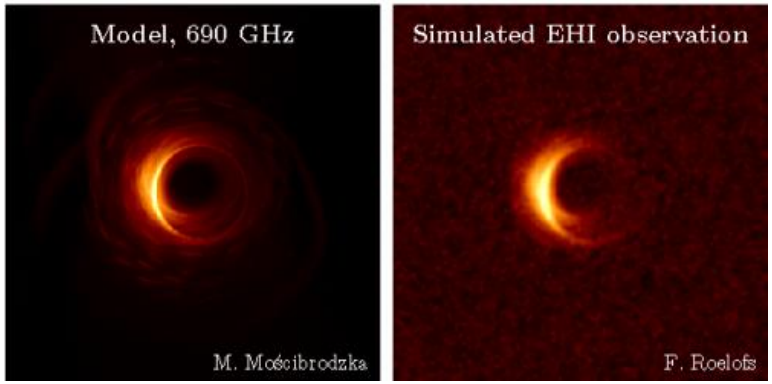
KRT-30 (1978-82)	QUASAT (1980s)	IVS (1987-91)	ALFA (1990s)
ARISE (2000s)	VSOP-2 (2000s)	SURO (2010s)	N-SVLBI (2012 –)

EHI: Event Horizon Imager (2018 –) BHI: Black Hole Imager (2019 –)
+ more ideas and proposals

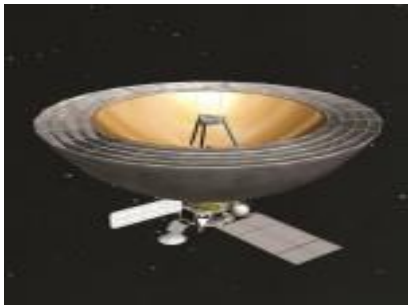
SVLBI:
- **Maximum detectable brightness temperature ∝ baseline length.**
- **Factor of N increase in baseline length can only matched by a factor of ~N sensitivity improvement of GVLBI with a matching angular resolution.**

Next Decade(s) of Space VLBI

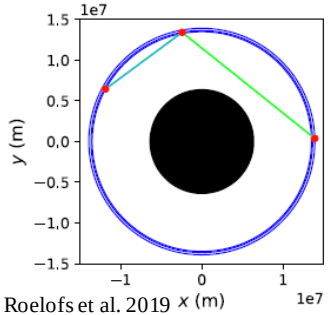
- Black hole and event horizon science dominate the present scope of SVLBI science.
- Millimetron: VLBI science is essentially an add on to the single dish operations in L2. Visibility detection/tracking in L2 (photon ring science). Imaging in quasi RA mode before/after L2 operations.
- EHI: Free-flyer concept: 3 SRT on close orbits, observing at 650 GHz. Targeting Sgr A* and M87.
- BHI: 2+ SRT on LEO, fast uv-filling, moderate increase of baseline length. Multiple targets.



Millimetron

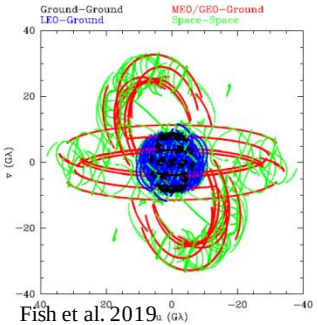


EHI

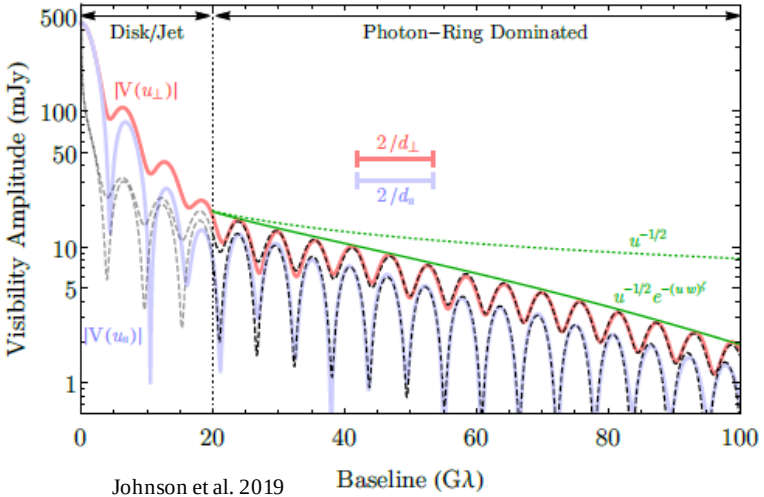


Roelofs et al. 2019

BHI



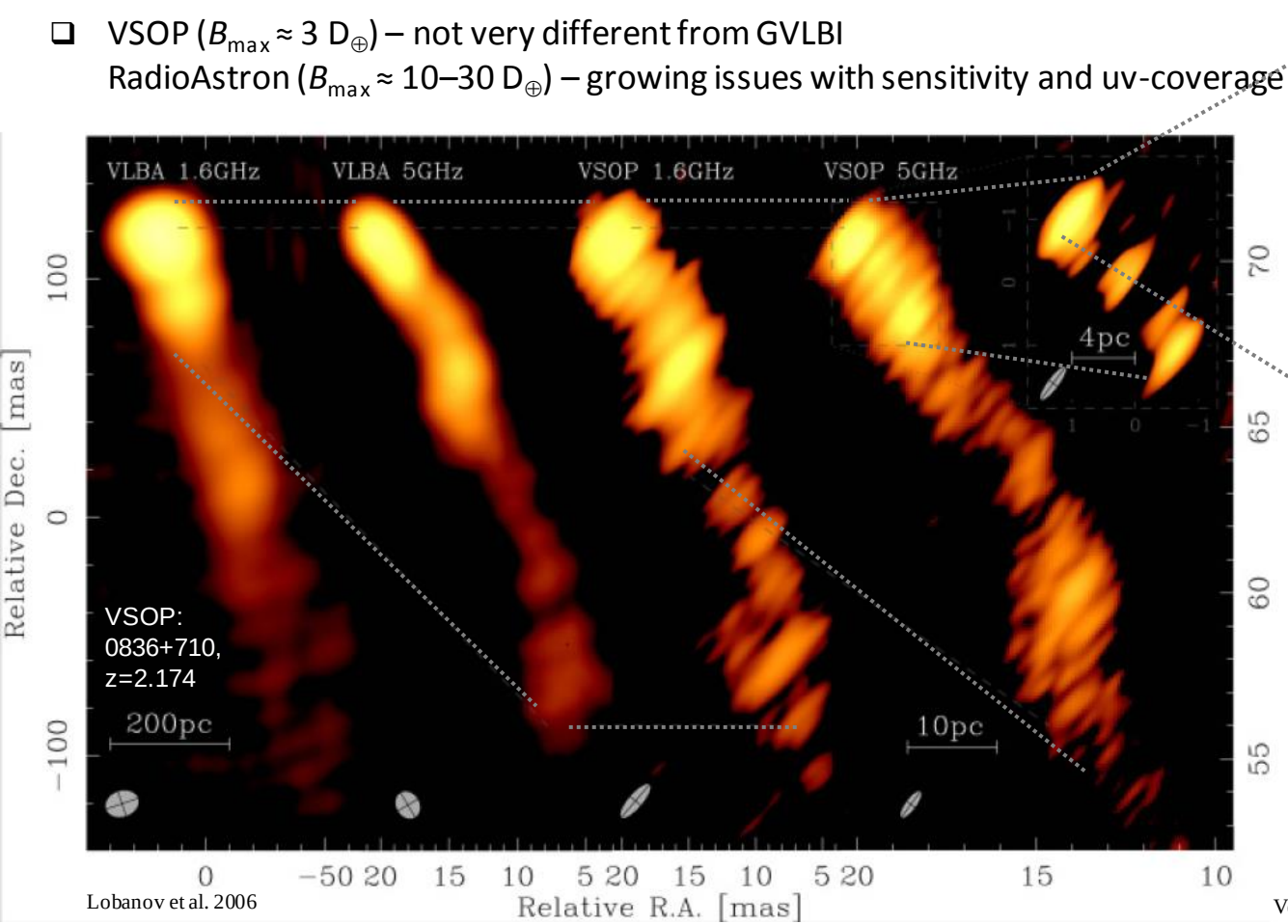
Fish et al. 2019



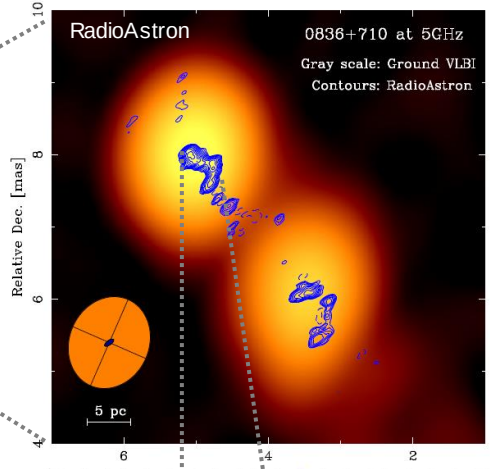
Johnson et al. 2019

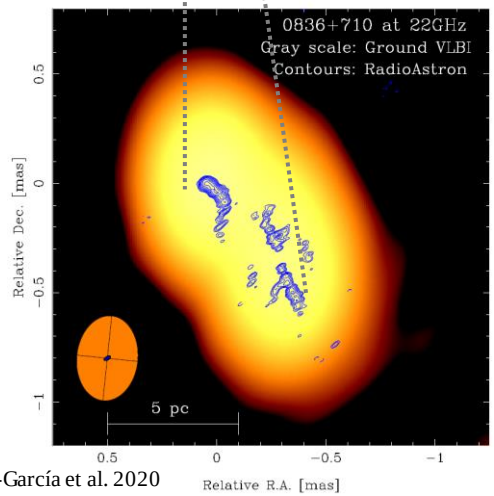
Imaging with SVLBI

- VSOP ($B_{max} \approx 3\ D_{\oplus}$) – not very different from GVLBI
  RadioAstron ($B_{max} \approx 10–30\ D_{\oplus}$) – growing issues with sensitivity and uv-coverage



Lobanov et al. 2006

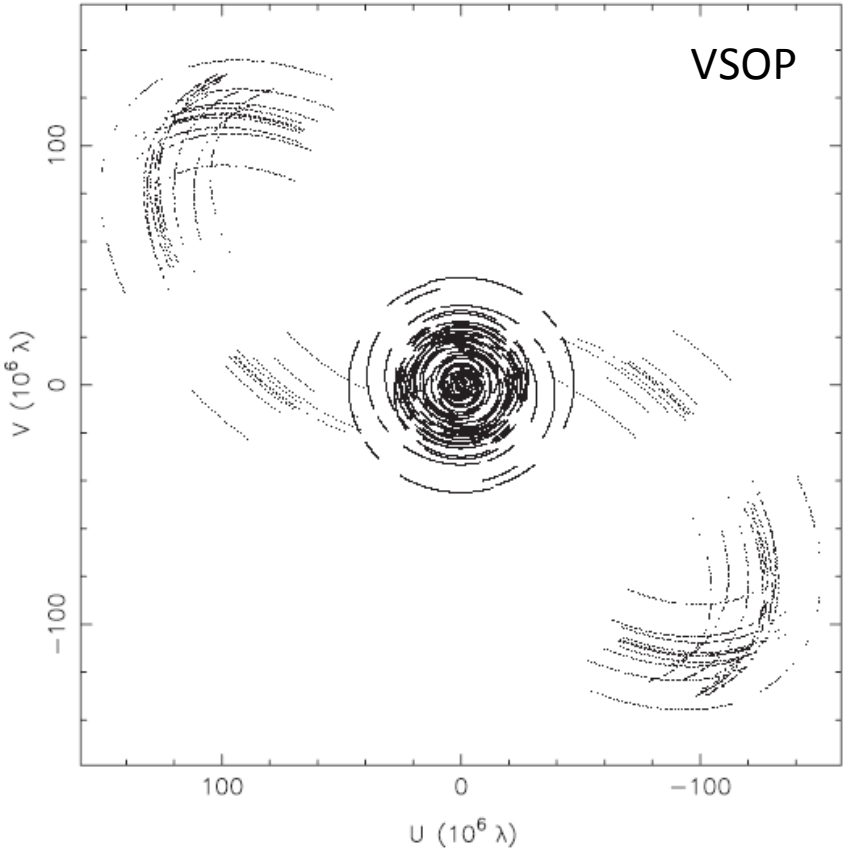


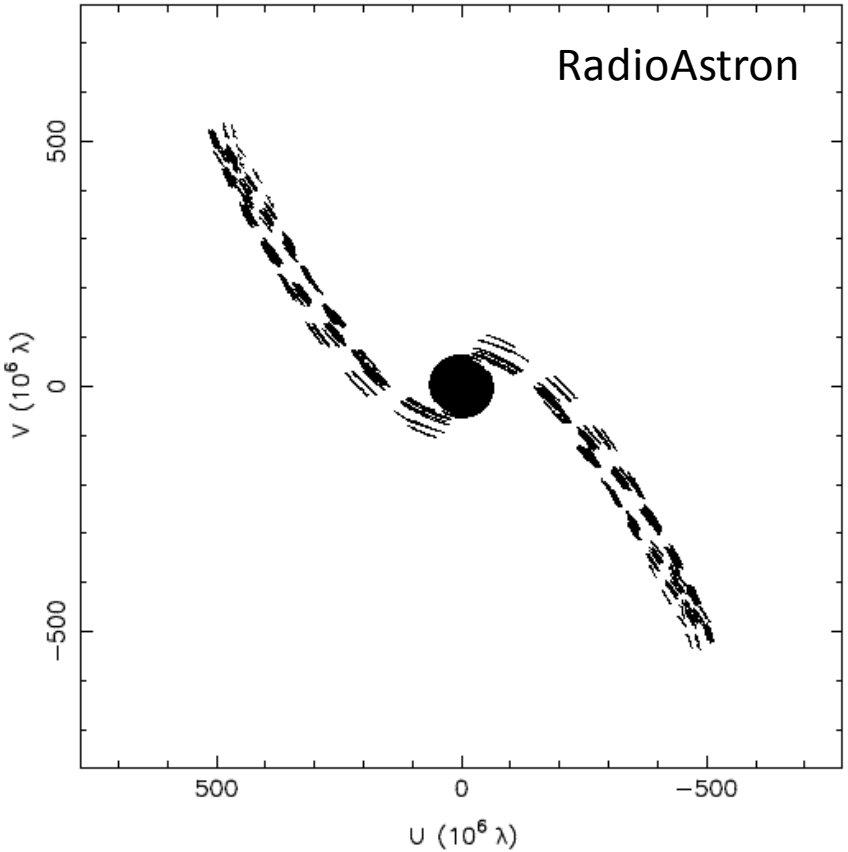


Vega-García et al. 2020

SVLBI Imaging: uv-coverages

- Main issues with SVLBI uv-coverages: gaps and limited P.A. coverages on space baselines.





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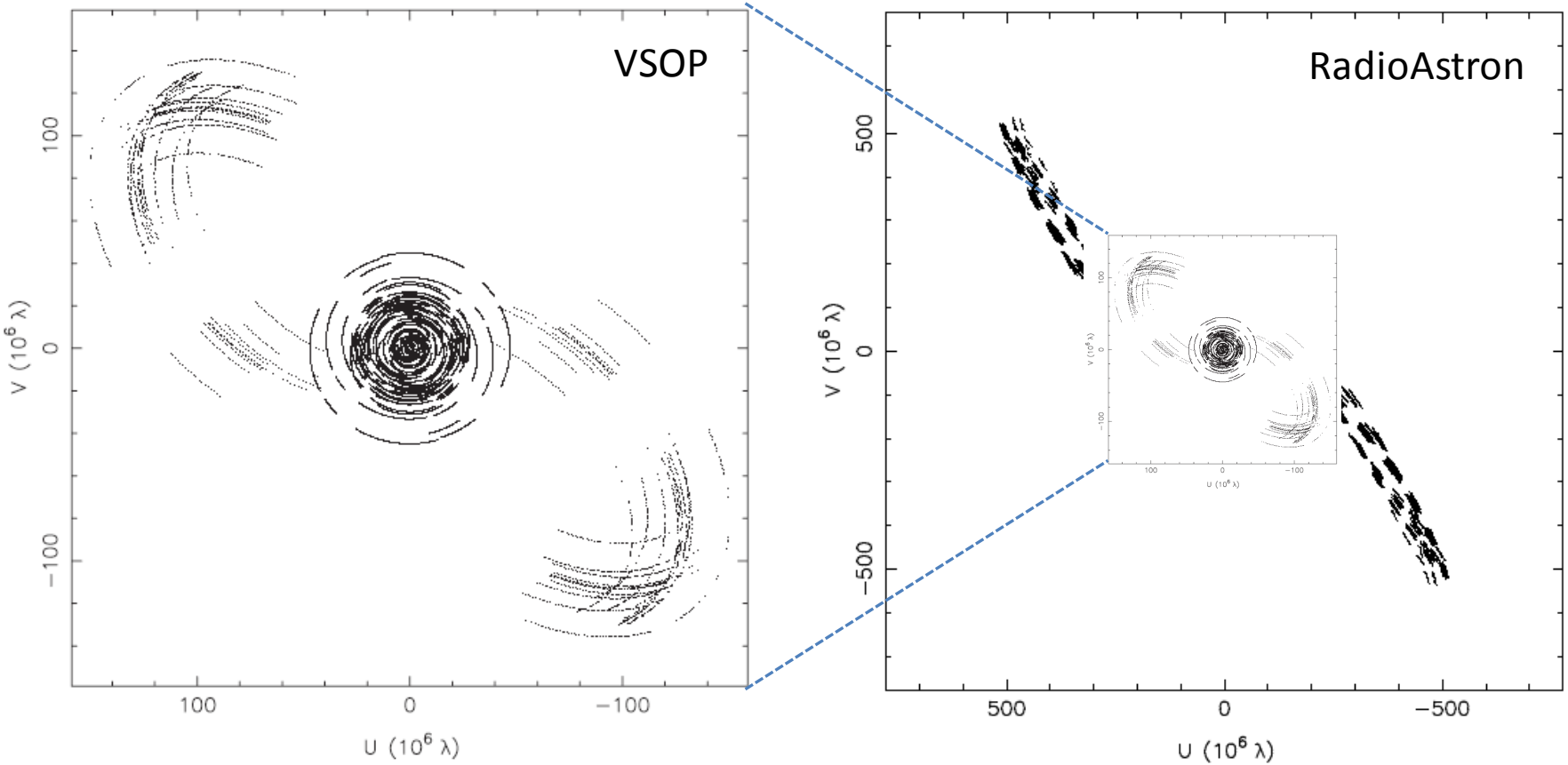
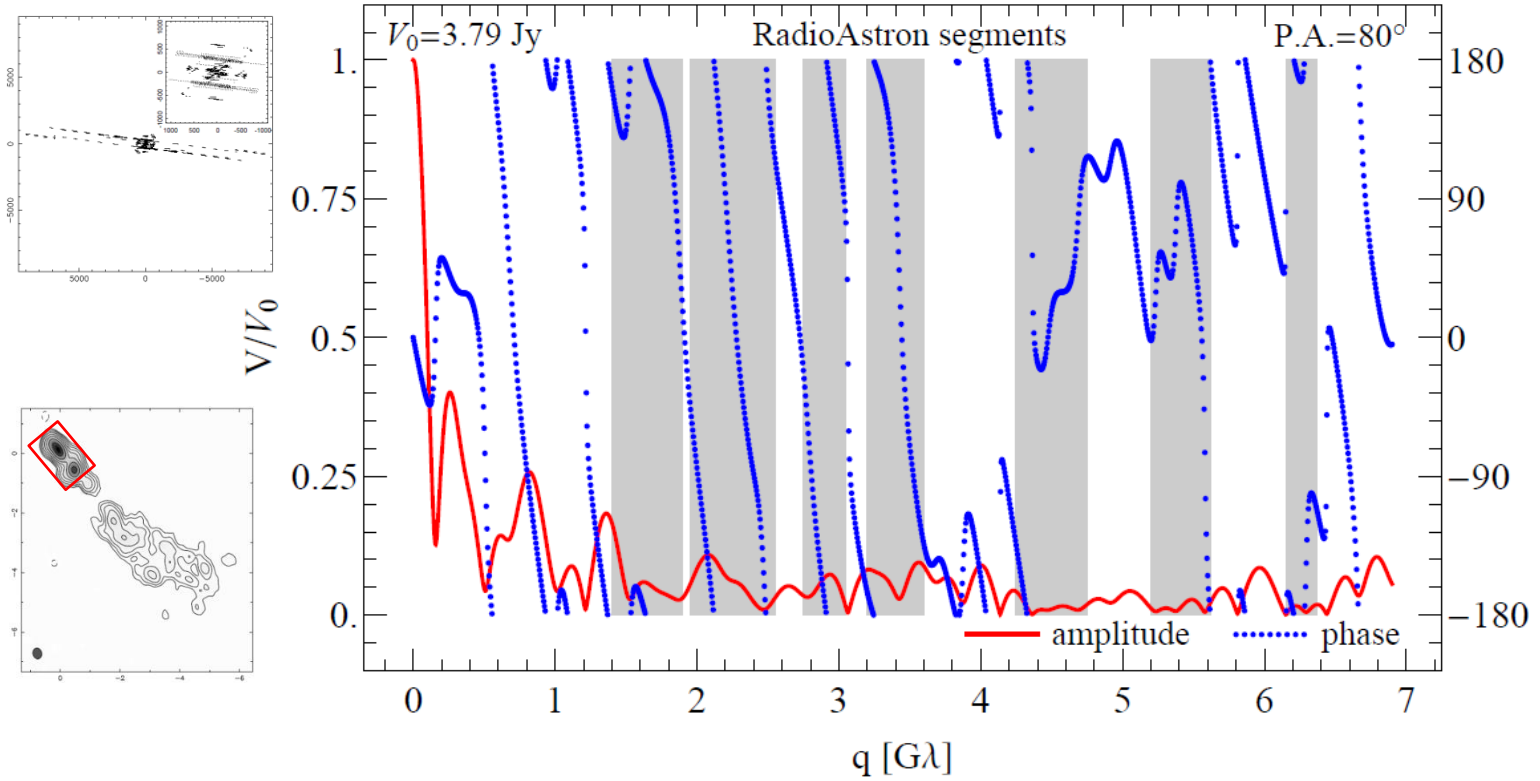


Scales and Nulls

- Visibility response of RadioAstron's space baselines to inner 1.5 mas structure of 3C273



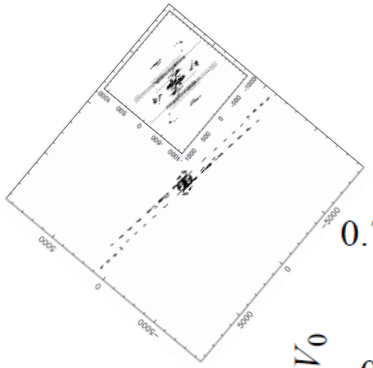
Gaps:
not properly interpolated over

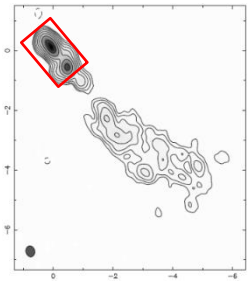
Nulls:
non-detections are normally not included into imaging;

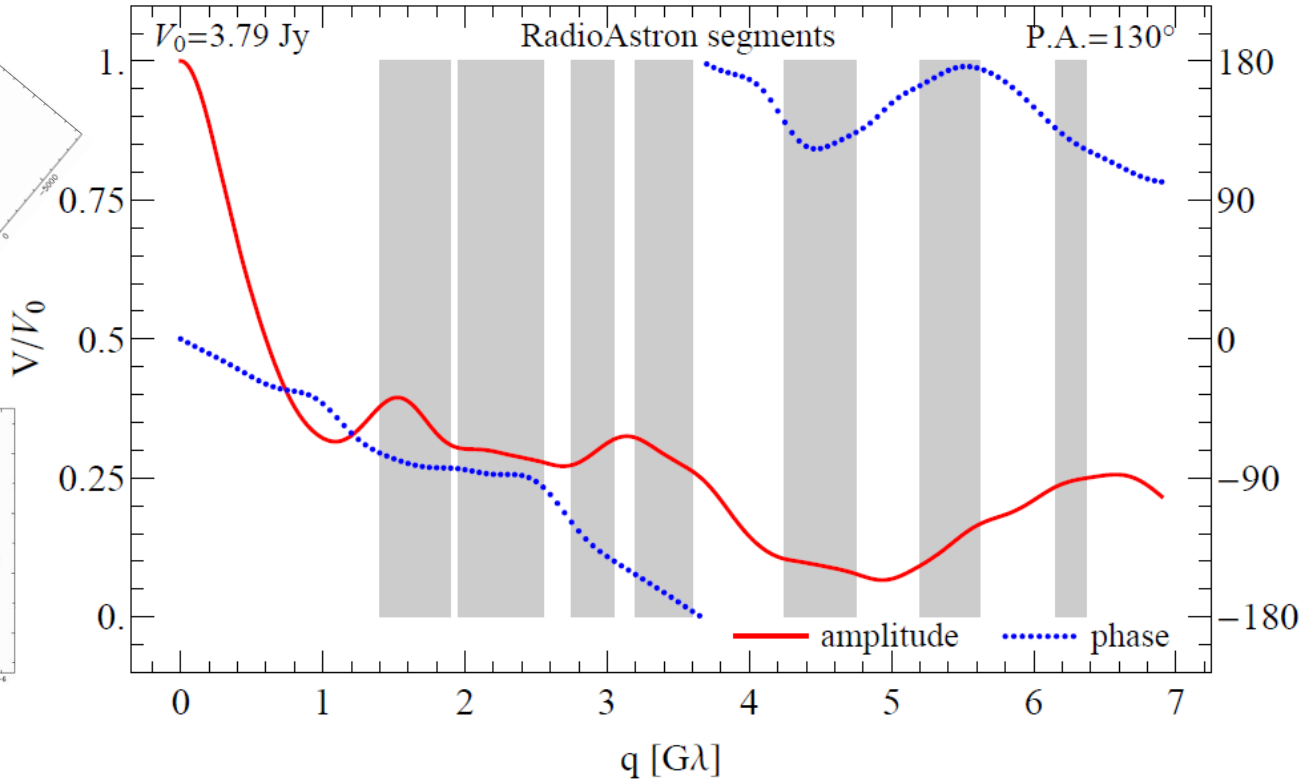
or (worse still) often edited out on the pretext of being "noisy data"

Scales and Nulls

- Space VLBI for imaging: either hope to get lucky or try to invent imaging methods dealing with scales and nulls.





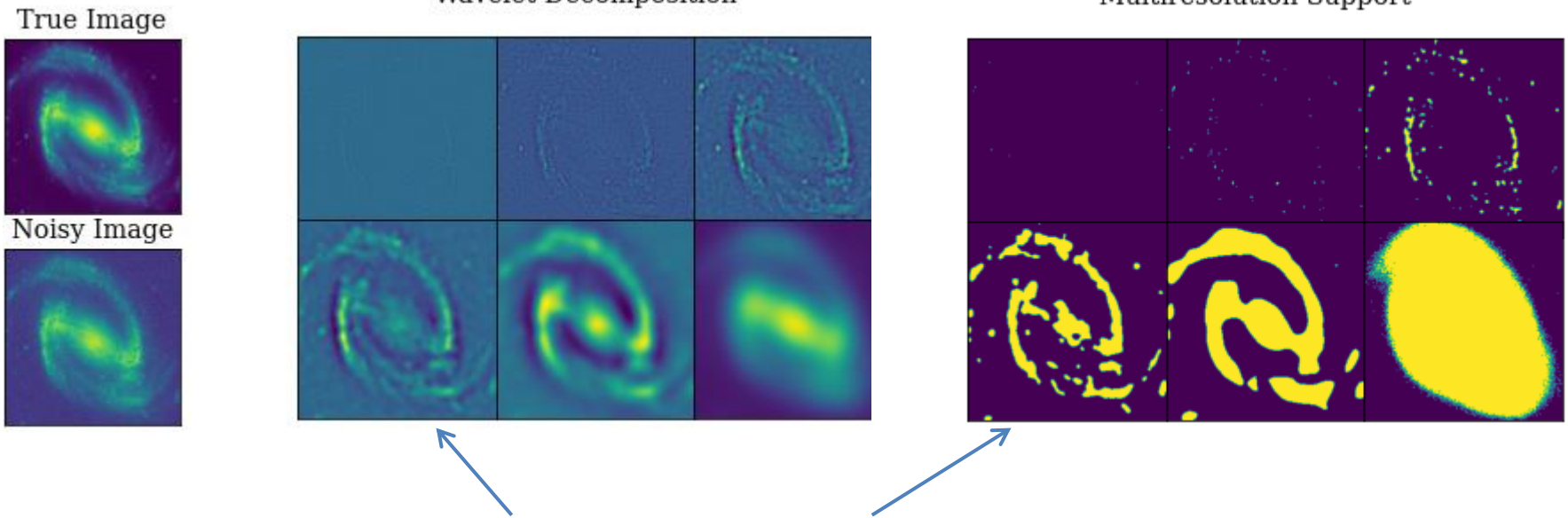


Needed:

-- dealing with missing scales
-- dealing with structural phase
-- dealing with rapid changes of structural phase

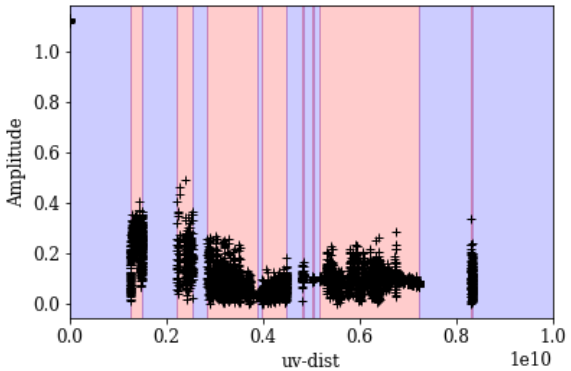
Wavelet Deconvolution

- Typically applied to image domain for multiresolution support and denoising.
- Can also be applied in uv-domain for suppressing sidelobes and minimizing the signal from non-covered scales.

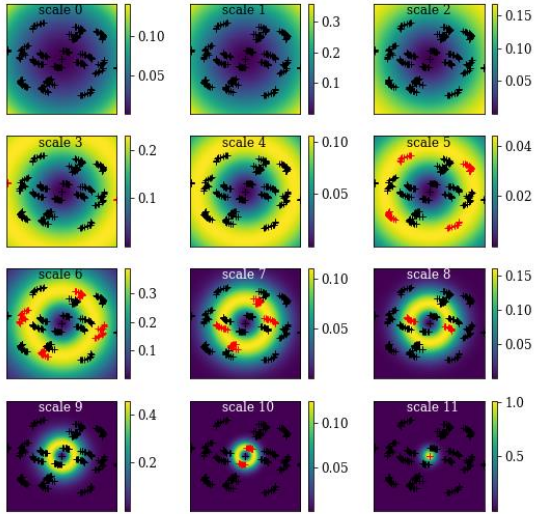


Multiscale imaging: DoG-HIT

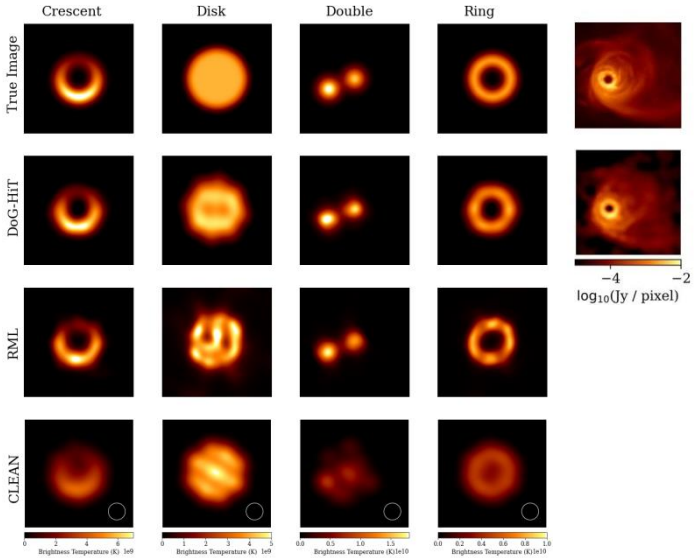
- Difference of Gaussians (DoG) wavelets and hard image thresholding (HIT) are applied for effectively promoting Fourier scales covered by data and suppressing input from non-covered scales
- DoG-HIT performs similarly or sloghtly better than other RML methods on the market, but does not require large „parameter surveys“ to localize the best reconstruction.



Radial scales
covered by uv-coverage



Scales fitted to uv-coverage

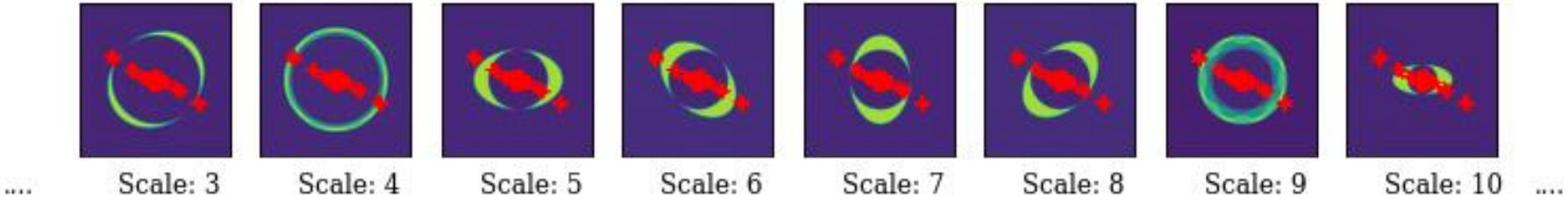


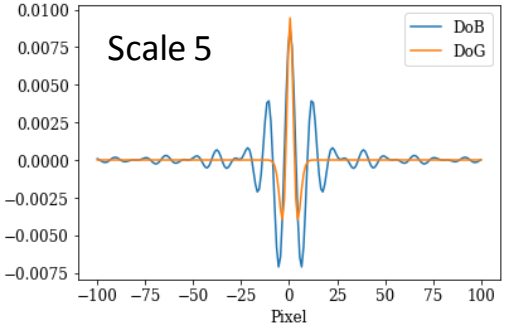
Comparisons of image reconstruction

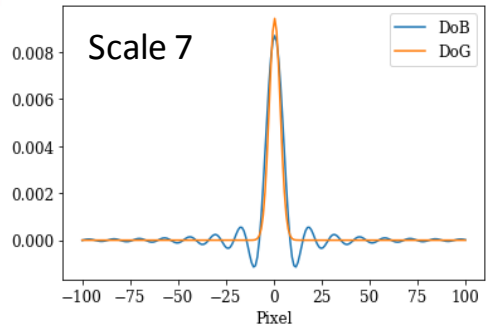
Müller & Lobanov 2022a, A&A, in press, arXiv:2206.09501

Multidirectional Imaging

- Difference of elliptical Bessel functions (DoB) dictionaries, maintaining orthogonality while allowing for further sidelobe reduction and directional sensitivity.







Fourier domain:

- Heaviside masks
- orthogonal

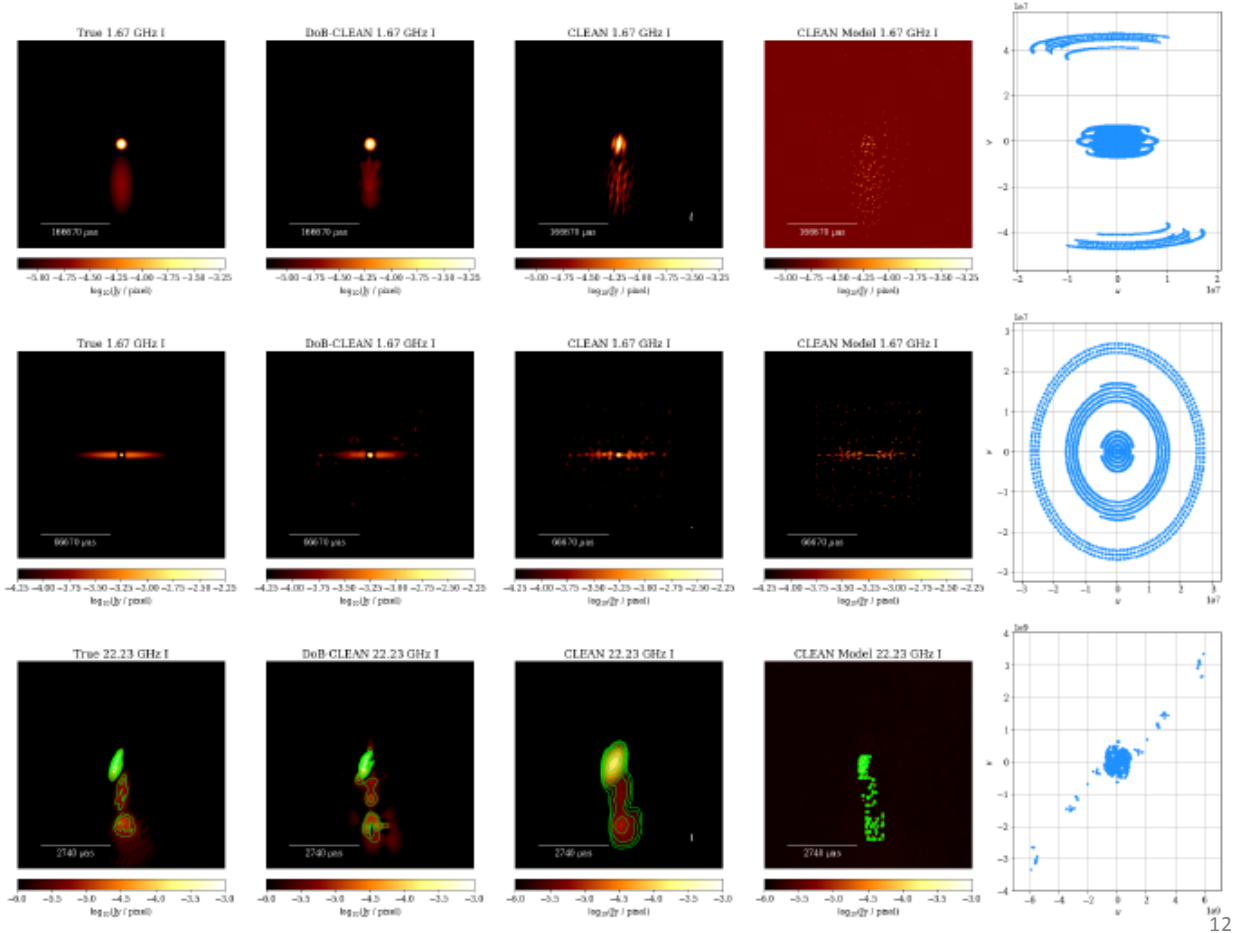
Image domain:

- No sidelobes
- Positive flux

DoB-CLEAN

- Combining DoB directionality with iterative and interactive capacities of CLEAN.

  Known problems of CLEAN (lack of regularization, representation of extended emission) are effectively dealt with by multi scale fitting to uv-coverage.



Müller & Lobanov 2022b, A&A, subm.

Summary

- Space VLBI studies break new grounds in astronomy by pushing the limits of angular resolution.
- Imaging with space VLBI instruments will get progressively more challenging with increasing length of space baselines.
- Critical issues for space VLBI imaging:
  - radial gaps and azimuthal directivity of uv-coverages
  - dealing with (near) nulls in the visibility distribution
- Wavelet deconvolution can be applied effectively to image reconstruction from visibility data while taking into account scale-dependent and direction-dependent effects of the observing uv-coverage:
  - DoG wavelets for dealing with radial effects (gaps)
  - DoB dictionaries for dealing with directional effects
- Further work is needed for dealing with the nulls (advanced interpolation? Bayesian approaches?)