Synergy IR / radio interferometers

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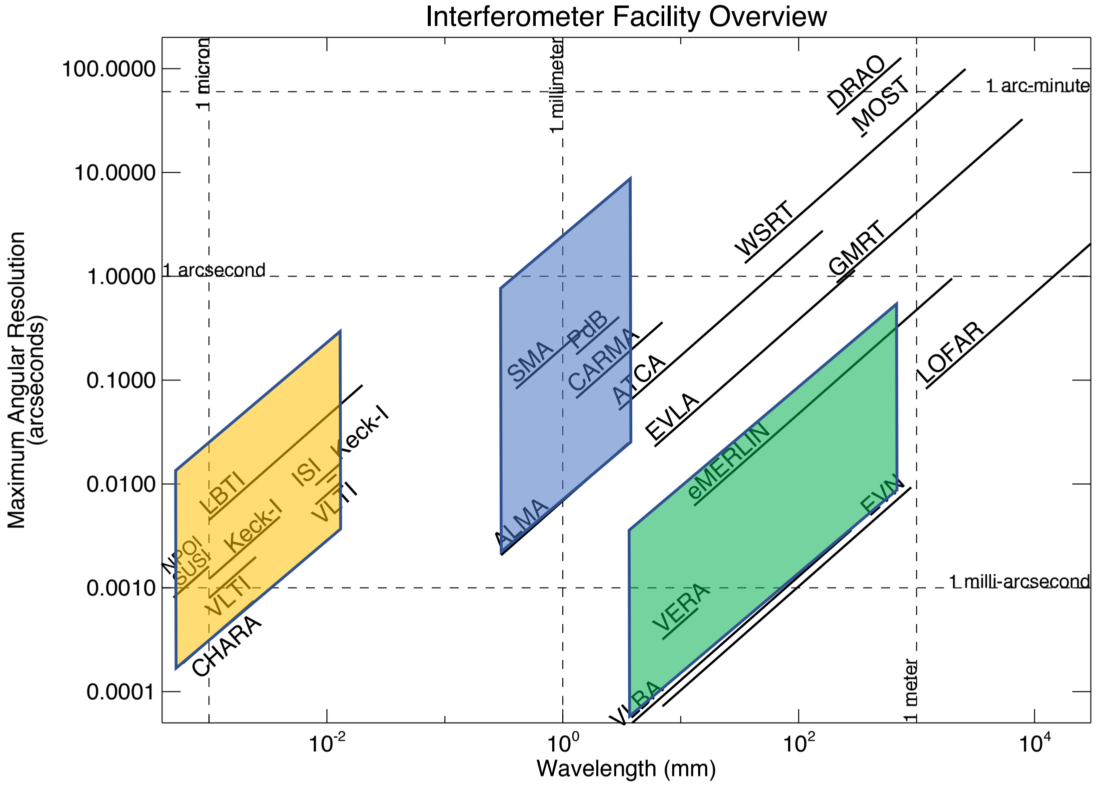
14th EVN Symposium & Users Meeting
8-11 Octorber 2018 - Granada

Why synergies?



- VLTI, VLBA, and ALMA can observe the same targets in terms of angular resolution and sensitivity.

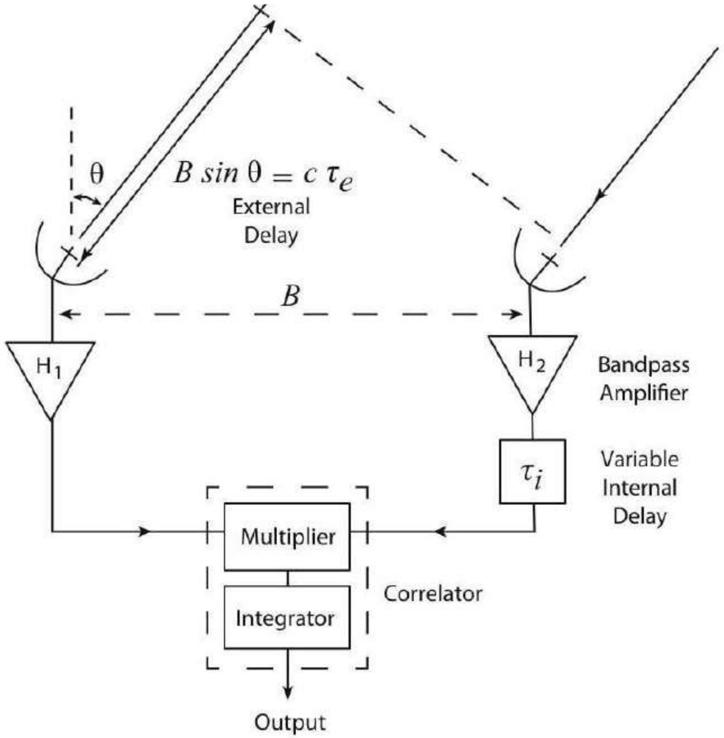
- They provide complementary information on different components and regions.

<u>Telescopes</u>:
CHARA: 6 x 1m
VLTI : 4 x 8m + 4 x 1.8 m
VLBA : 10 x 25 m
ALMA : 64 x 12 m
VLA : 27 x 25 m

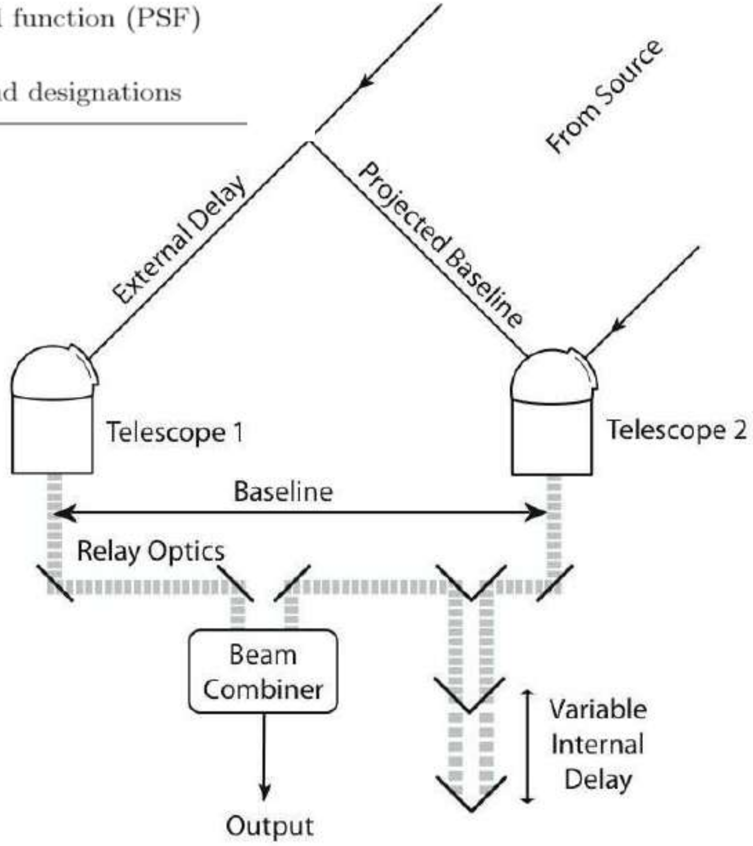
TABLE 2. Translation Guide for Interferometric Jargon

Radio	Optical/IR
Delay, lag	Optical path difference (OPD)
Delay residual	Differential piston
Correlator	Beam Combiner
Antenna gain	Strehl ratio
System temperature	Background level
Phase referencing	Fringe tracking
Antenna	Telescope
Feed	Detector
Dirty (or CLEAN) beam	Point spread function (PSF)
Log (flux density)	Magnitudes
Confusing band designations[1]	Obscure band designations

Cotton 2006



Radio



Optical / IR

Monnier 2003

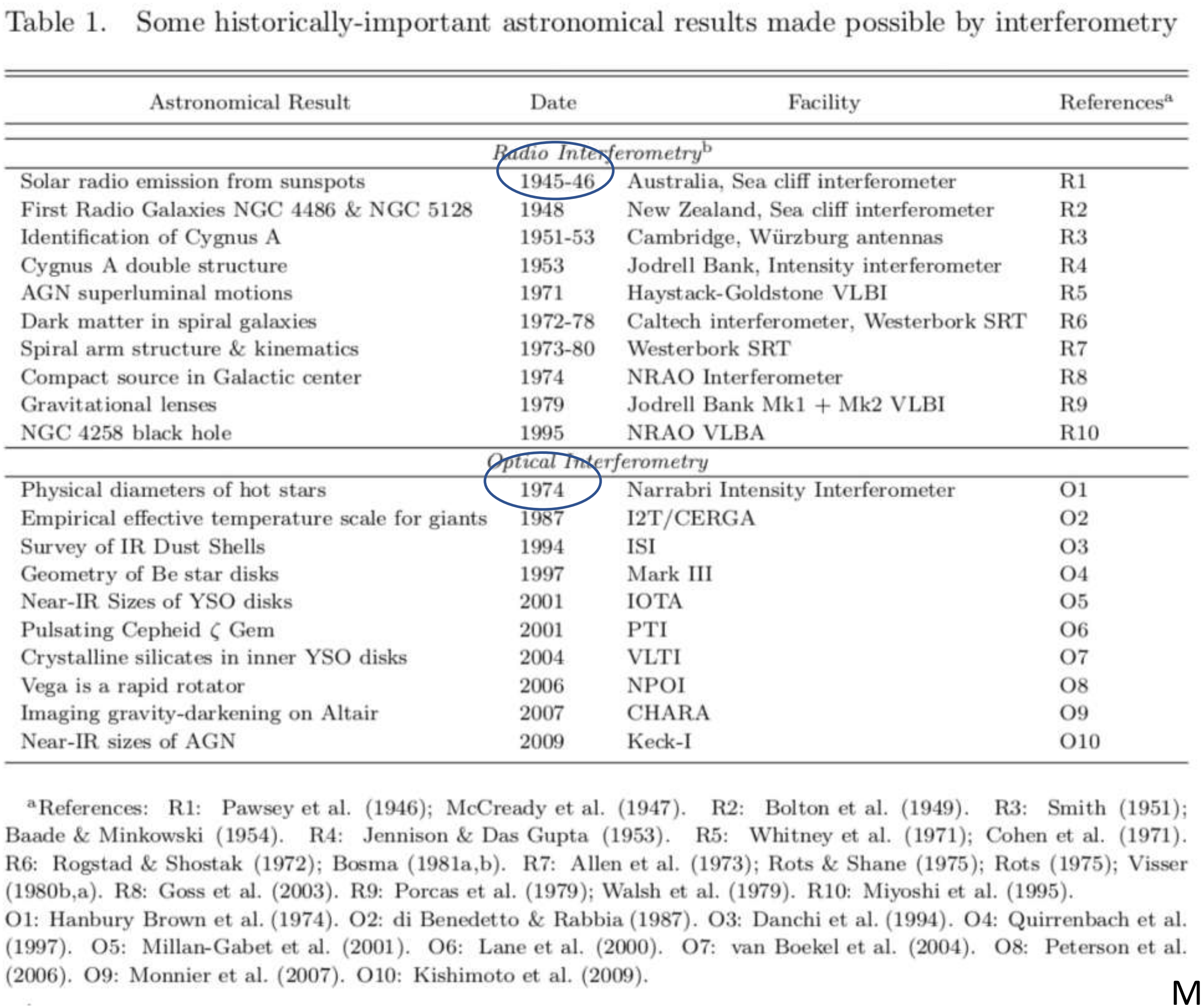


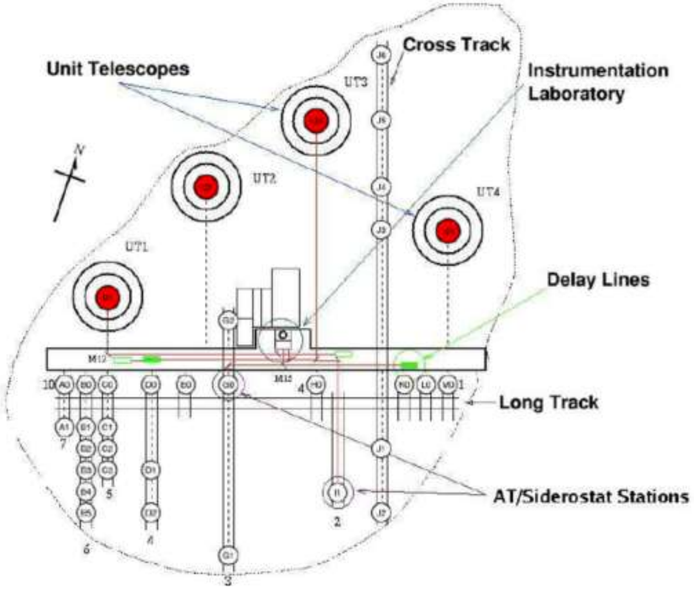
Table 1. Some historically-important astronomical results made possible by interferometry

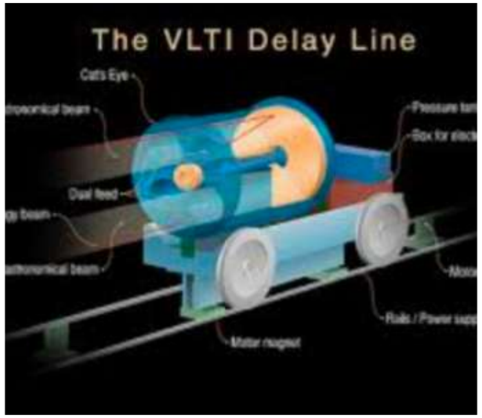
Astronomical Result	Date	Facility	References[a]
		Radio Interferometry[b]	
Solar radio emission from sunspots	1945-46	Australia, Sea cliff interferometer	R1
First Radio Galaxies NGC 4486 & NGC 5128	1948	New Zealand, Sea cliff interferometer	R2
Identification of Cygnus A	1951-53	Cambridge, Würzburg antennas	R3
Cygnus A double structure	1953	Jodrell Bank, Intensity interferometer	R4
AGN superluminal motions	1971	Haystack-Goldstone VLBI	R5
Dark matter in spiral galaxies	1972-78	Caltech interferometer, Westerbork SRT	R6
Spiral arm structure & kinematics	1973-80	Westerbork SRT	R7
Compact source in Galactic center	1974	NRAO Interferometer	R8
Gravitational lenses	1979	Jodrell Bank Mk1 + Mk2 VLBI	R9
NGC 4258 black hole	1995	NRAO VLBA	R10
		Optical Interferometry	
Physical diameters of hot stars	1974	Narrabri Intensity Interferometer	O1
Empirical effective temperature scale for giants	1987	I2T/CERGA	O2
Survey of IR Dust Shells	1994	ISI	O3
Geometry of Be star disks	1997	Mark III	O4
Near-IR Sizes of YSO disks	2001	IOTA	O5
Pulsating Cepheid ζ Gem	2001	PTI	O6
Crystalline silicates in inner YSO disks	2004	VLTI	O7
Vega is a rapid rotator	2006	NPOI	O8
Imaging gravity-darkening on Altair	2007	CHARA	O9
Near-IR sizes of AGN	2009	Keck-I	O10

[a] References: R1: Pawsey et al. (1946); McCready et al. (1947). R2: Bolton et al. (1949). R3: Smith (1951); Baade & Minkowski (1954). R4: Jennison & Das Gupta (1953). R5: Whitney et al. (1971); Cohen et al. (1971). R6: Rogstad & Shostak (1972); Bosma (1981a,b). R7: Allen et al. (1973); Rots & Shane (1975); Rots (1975); Visser (1980b,a). R8: Goss et al. (2003). R9: Porcas et al. (1979); Walsh et al. (1979). R10: Miyoshi et al. (1995). O1: Hanbury Brown et al. (1974). O2: di Benedetto & Rabbia (1987). O3: Danchi et al. (1994). O4: Quirrenbach et al. (1997). O5: Millan-Gabet et al. (2001). O6: Lane et al. (2000). O7: van Boekel et al. (2004). O8: Peterson et al. (2006). O9: Monnier et al. (2007). O10: Kishimoto et al. (2009).

Monnier 2012

VLTI

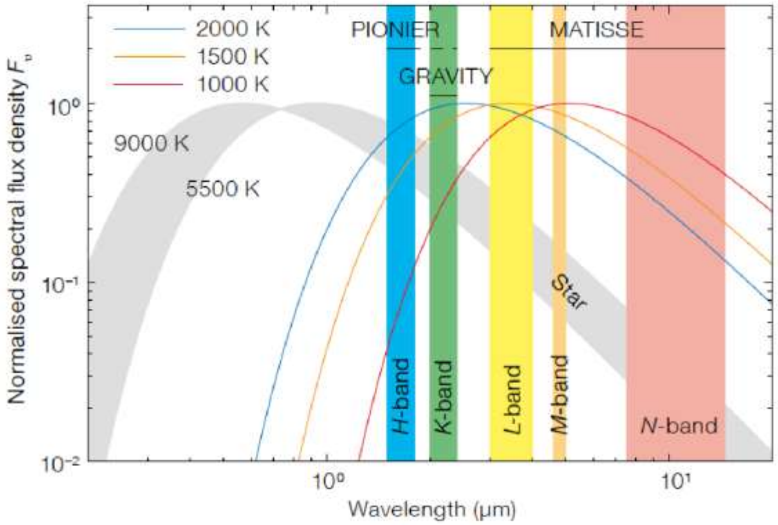

Unit Telescopes
Cross Track
Instrumentation Laboratory
UT1
UT2
UT3
UT4
N
Delay Lines
M12
Long Track
AT/Siderostat Stations


The VLTI Delay Line
Cat's Eye
Dual feed
Motor magnet

Instruments

	AMBER	PIONIER	GRAVITY	MATISSE
Status	decomm. late 2018	offered	offered	in commissioning
N tel.	3	4	4	4
bands / spectral resolution	H+K 35,1500,12000	H R=5,30	K R=22,500,4000	L+M+N R=30,5000
Mag. Lim AT/UT	6.5 / 9.0	8.0 / 8.0	8.5 / 10.5	
Fringe Tracker	FINITO (H)	-	GRAVITY (K)	GRAVITY (K)

- Previous: MIDI, VINCI
- PRIMA also discontinued

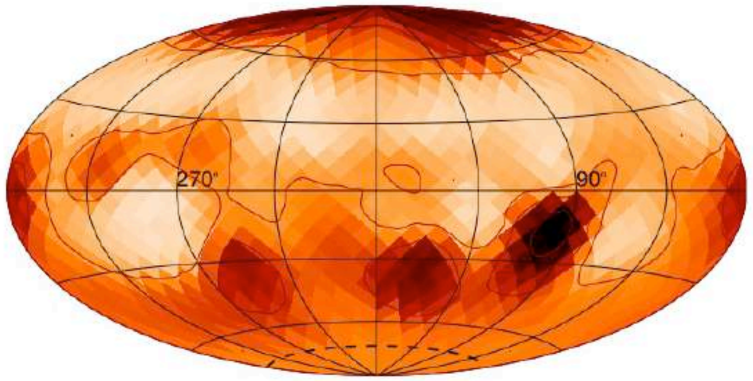


Ertel et al. 2012

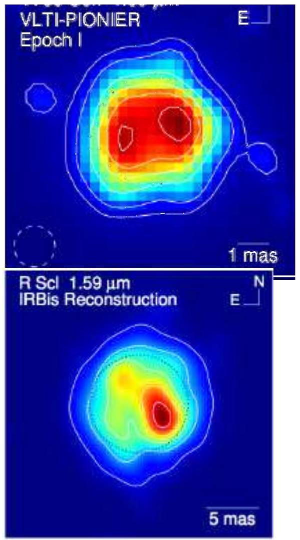
a few, perhaps biased,
SCIENCE CASES

IR-interferometry from snapshot to imaging

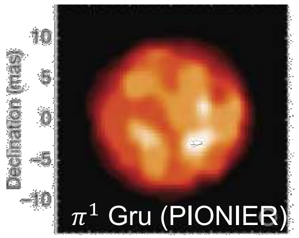
Stellar surfaces



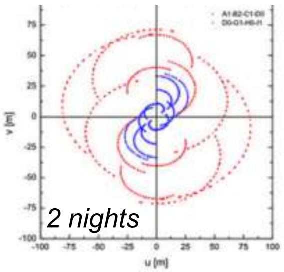
Zeta And (CHARA) (Roettenbacher et al. 2016)



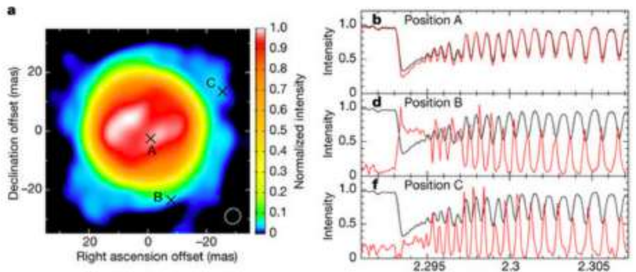
Wittkowski+ 2017a
Wittkowski+ 2017b



π^1 Gru (PIONIER)
Paladini+ 2018



2 nights



Antares (AMBER) Ohnaka+ 2017

Stellar spots: RS Sculptoris (PIONIER)

A&A 601, A3 (2017)

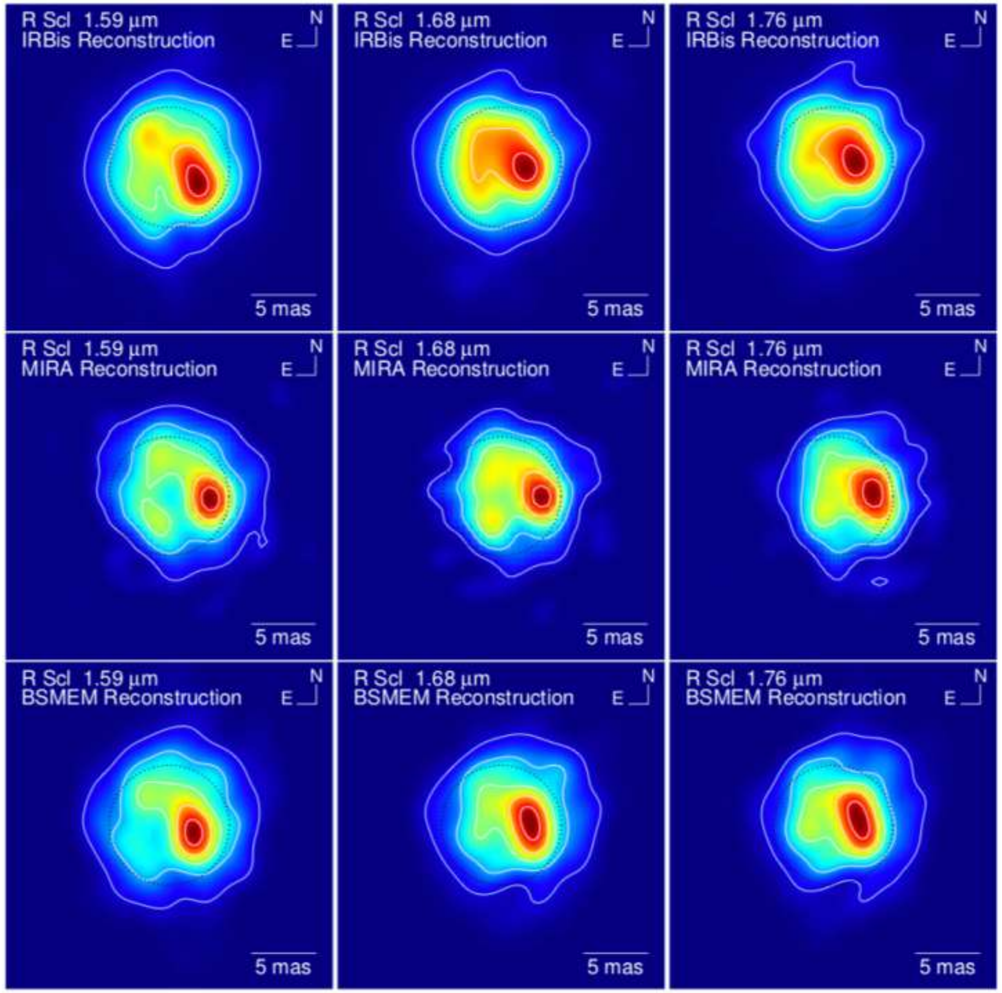


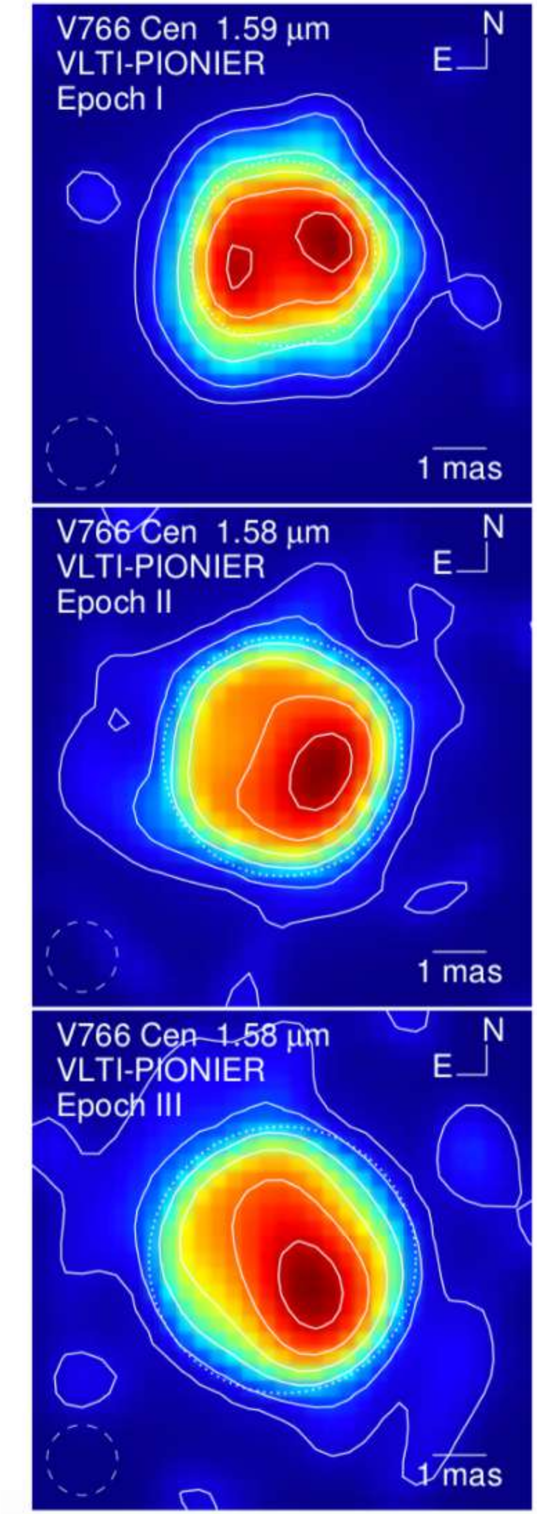
Fig. B.2. R Scl image reconstructions based on different image reconstruction packages. For comparison, the *top row* shows the reconstructions based on `IRBis` (Hofmann et al. 2014) that we adopted as the final result (as shown in Fig. 9), followed by reconstructions based on (*middle row*) `MiRA` (Thiébaut 2008) and (*bottom row*) `BSMEM` (Buscher 1994). The `MiRA` reconstruction uses a UD fit as a start image, smoothness as regularization function, and does not use a prior. The `BSMEM` reconstruction uses the model atmosphere images as first start images and priors and is based on maximum entropy as regularization function. The MiRA reconstructions use double the pixel size compared to the other two reconstructions.

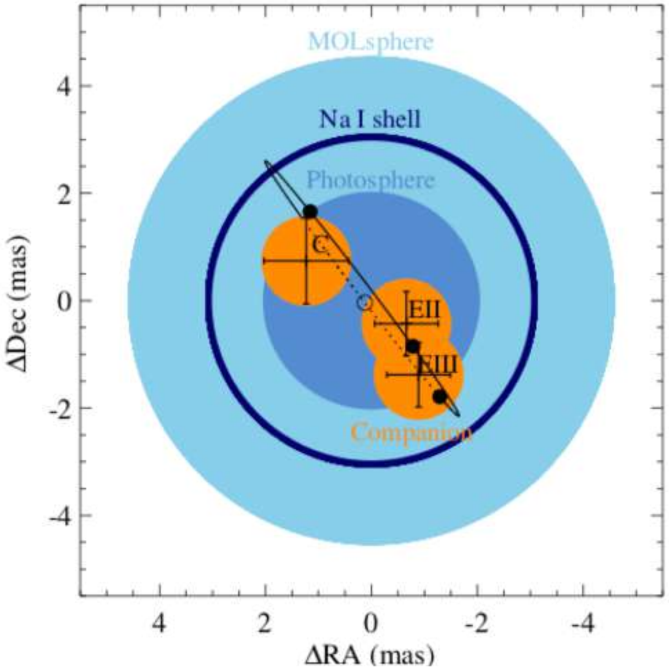
Wittkowski et al. 2017

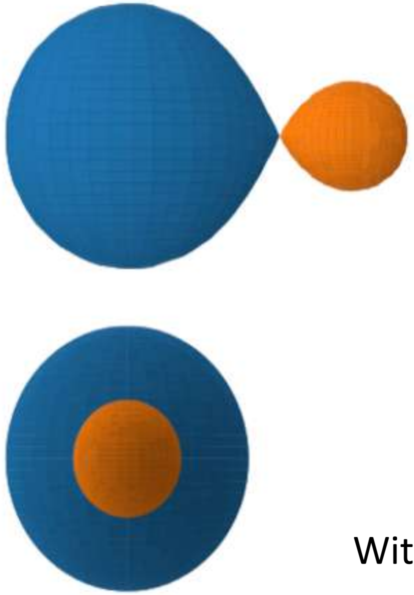
Synergies with VLA, eMERLIN, EVN

Imaging stellar surfaces

Companion to RSG V766 Cen

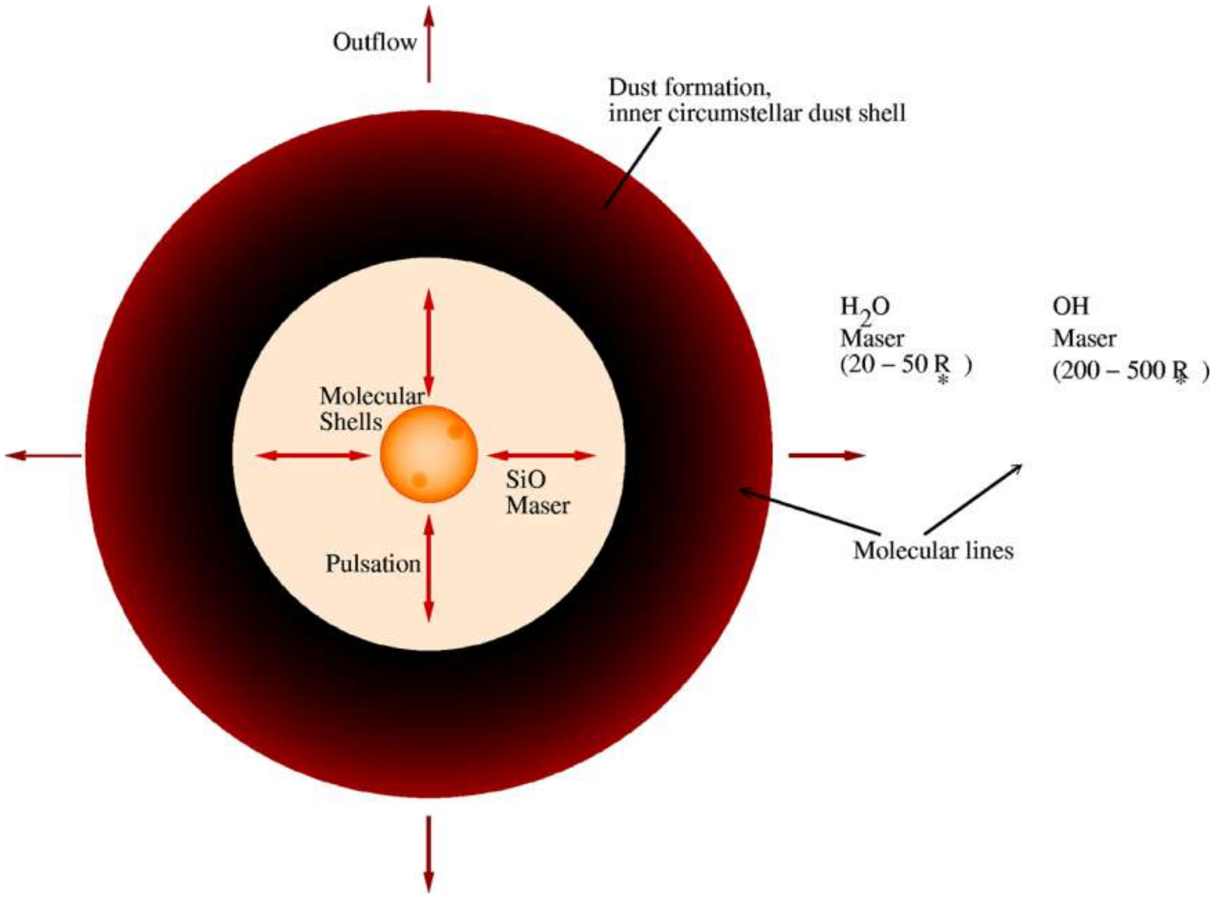






Wittkowski et al. 2017

Masers: joint VLBA/VLTI observations of Mira S Ori



VLTI (AMBER & MIDI):

- Size and shape of IR and MIR photosphere.
- CLV, effects by molecular layers, inhomogeneities.
- Size, chemistry, shape of the warm dust shell.

VLBA:

- SiO maser zone: size, shape, kinematics.
- Radio photosphere.
- Water and OH maser at larger distances.

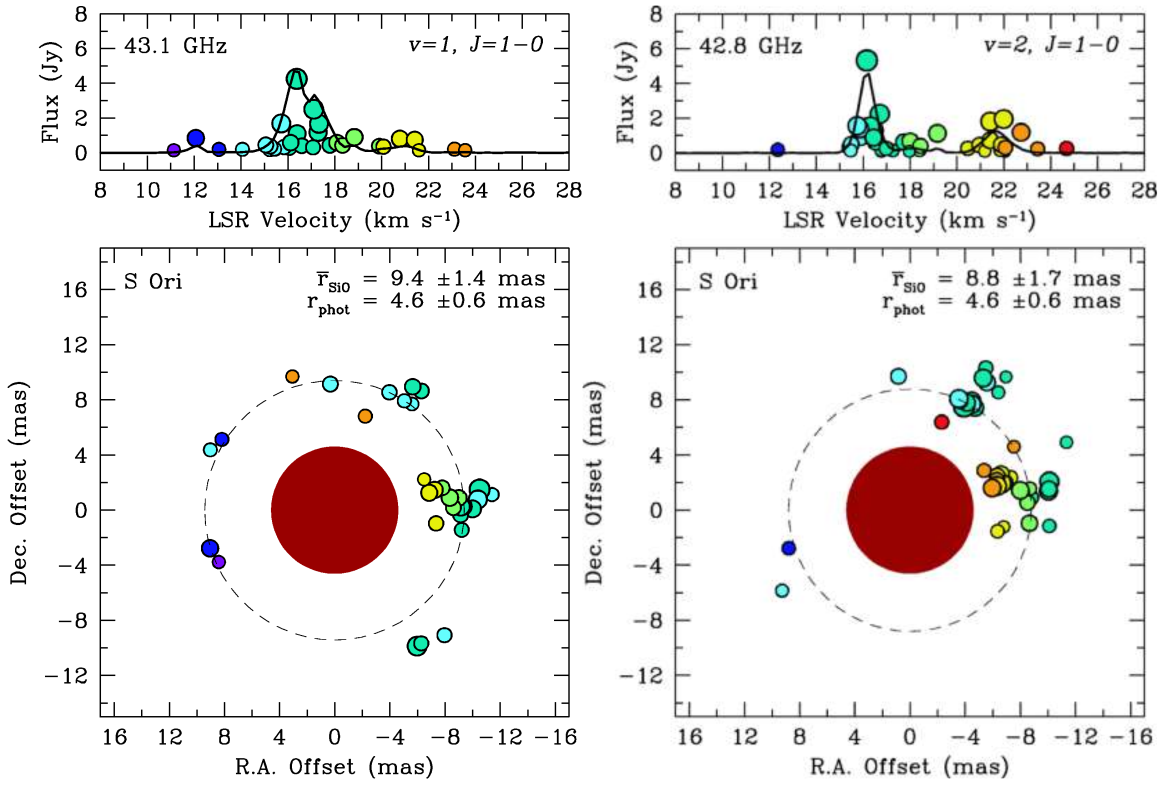
ALMA:

- mm Photosphere.
- Cool dust.
- High-fidelity images.
- Molecular bands / maser.

Detailed structure of atmosphere and circumstellar envelope
Detailed physics of the mass-loss process

Boboltz & Wittkowski 2005

Masers: joint VLBA/VLTI observations of Mira S Ori



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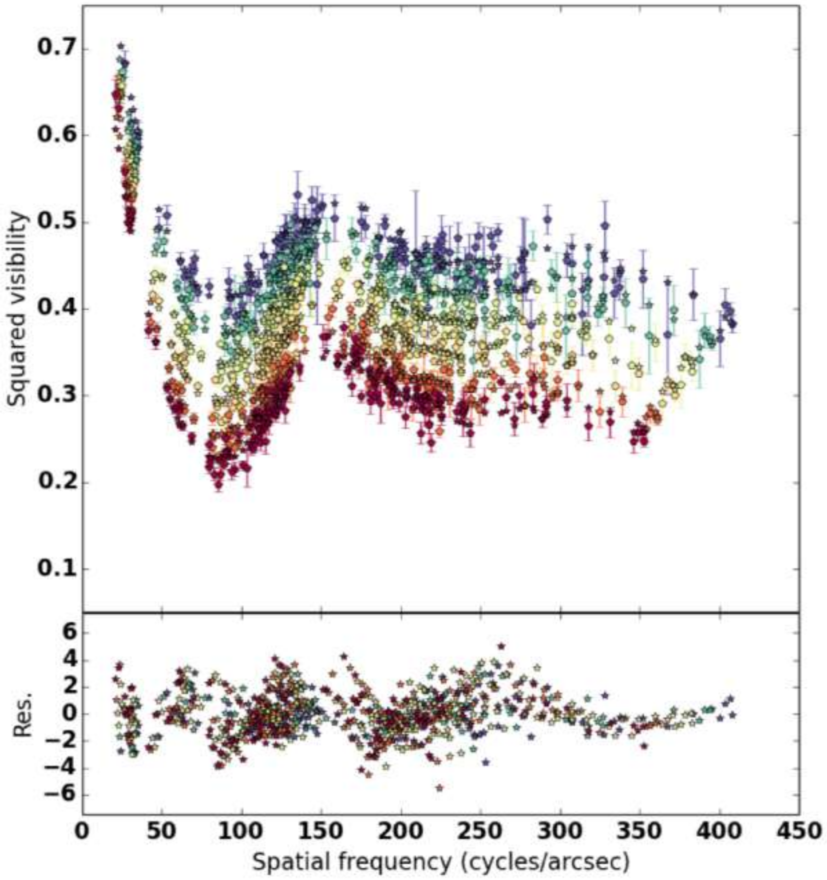
More about imaging:

VLTI/PIONIER: Image of the inner rim dust disk around a post-AGB binary



Kluska et al. 2018

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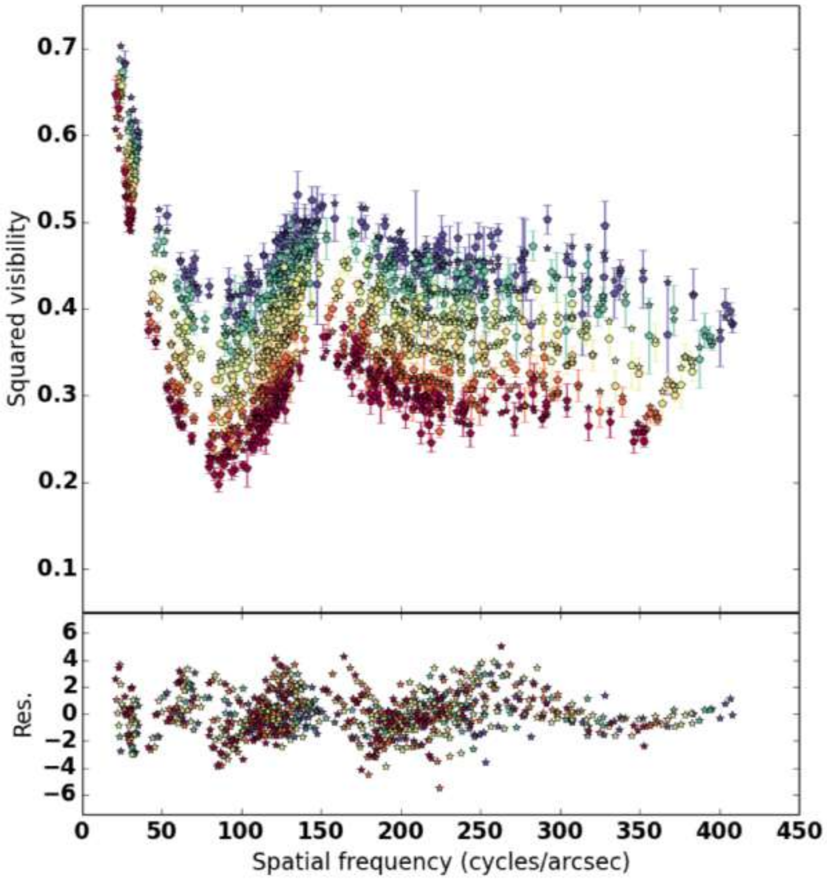
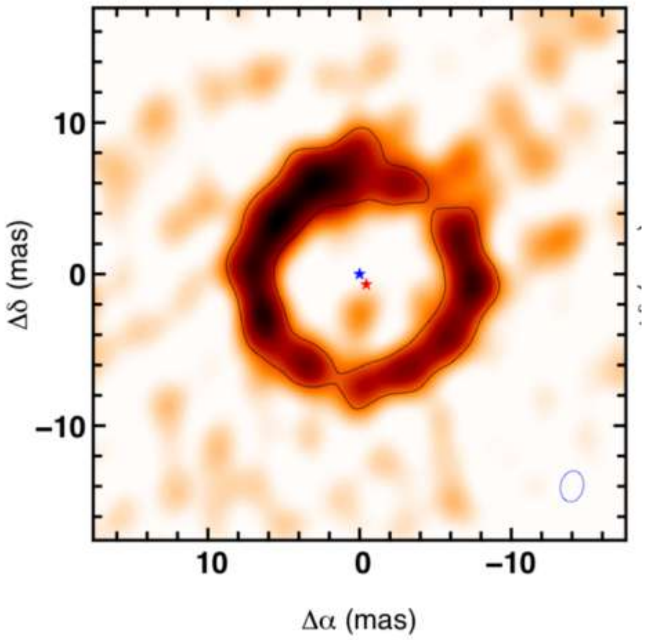
VLTI/PIONIER: Image of the inner rim dust disk around a post-AGB binary



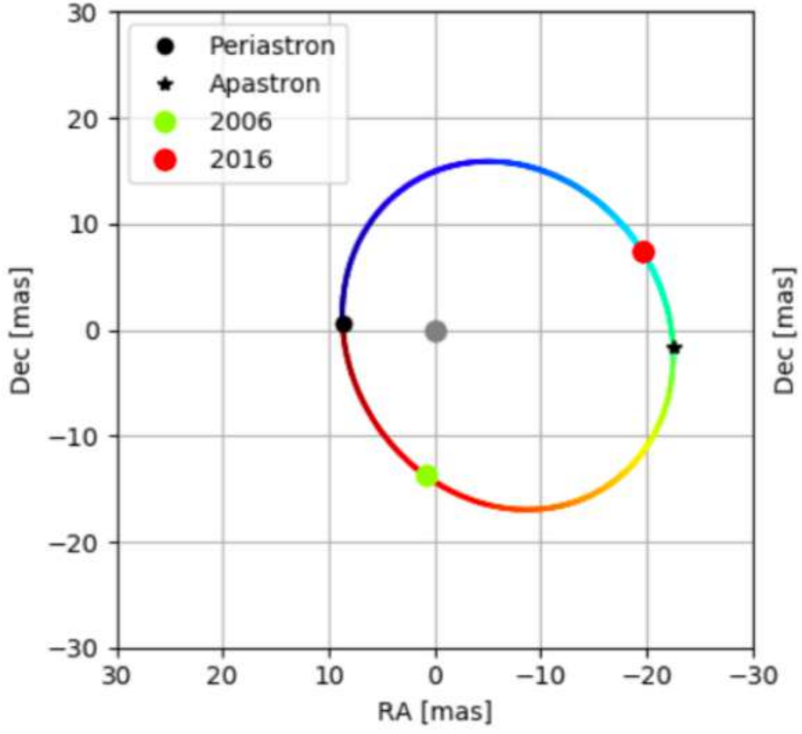
Kluska et al. 2018



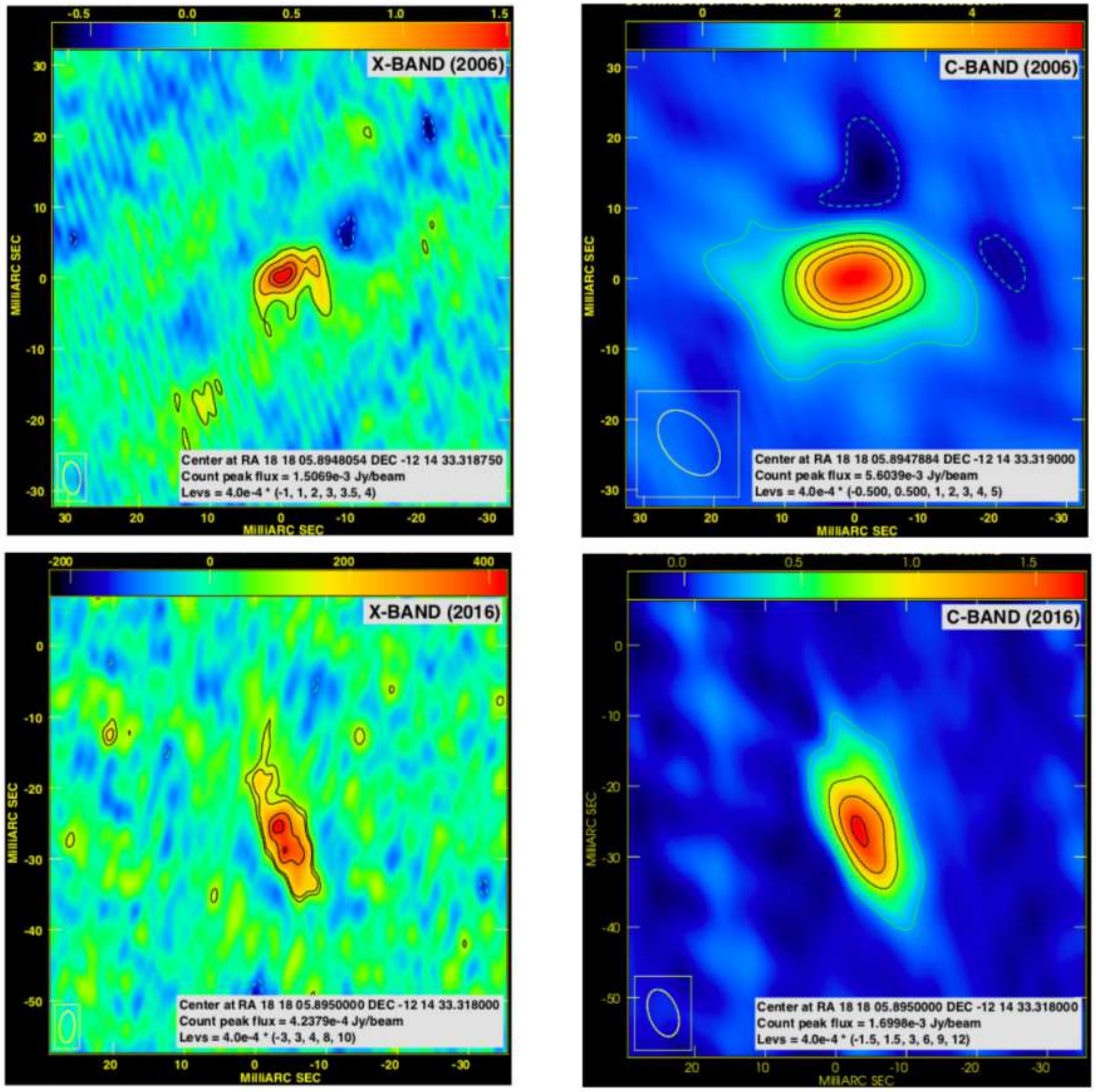
- Complement to a larger gaseous disk as observed by ALMA (Bujarrabal et al. 2018)
- Disks around luminous post-AGB binaries are scaled-up, more irradiated versions of protoplanetary disks around YSOs.

Wind-wind collision. The triple system HD167971

Orbit from VLTI/AMBER/PIONIER/GRAVITY



Sánchez-Bernúdez+ 2018. (VLBA)



Center at RA 18 18 05.8948054 DEC -12 14 33.318750
Count peak flux = 1.5069e-3 Jy/beam
Levs = 4.0e-4 * (-1, 1, 2, 3, 3.5, 4)

Center at RA 18 18 05.8947884 DEC -12 14 33.319000
Count peak flux = 5.6039e-3 Jy/beam
Levs = 4.0e-4 * (-0.500, 0.500, 1, 2, 3, 4, 5)

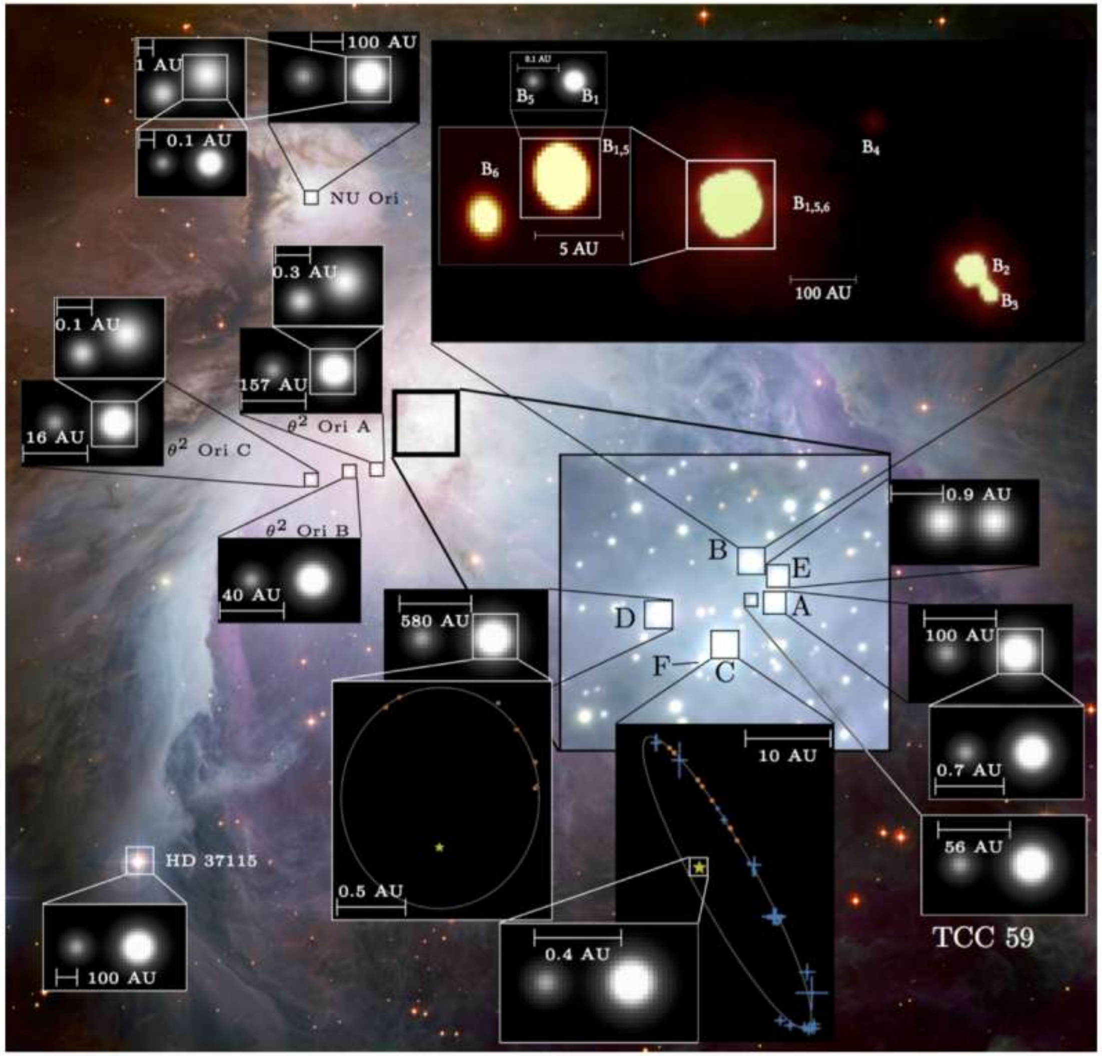
Center at RA 18 18 05.8950000 DEC -12 14 33.318000
Count peak flux = 4.2379e-4 Jy/beam
Levs = 4.0e-4 * (-3, 3, 4, 8, 10)

Center at RA 18 18 05.8950000 DEC -12 14 33.318000
Count peak flux = 1.6998e-3 Jy/beam
Levs = 4.0e-4 * (-1.5, 1.5, 3, 6, 9, 12)

VLTI/GRAVITY

Massive binary fraction: Multiple Star Systems in the Orion Nebula

Imaging and astrometric capabilities of GRAVITY



Karl et al. 2018

VLTI/GRAVITY

Massive binary fraction: Multiple Star Systems in the Orion Nebula

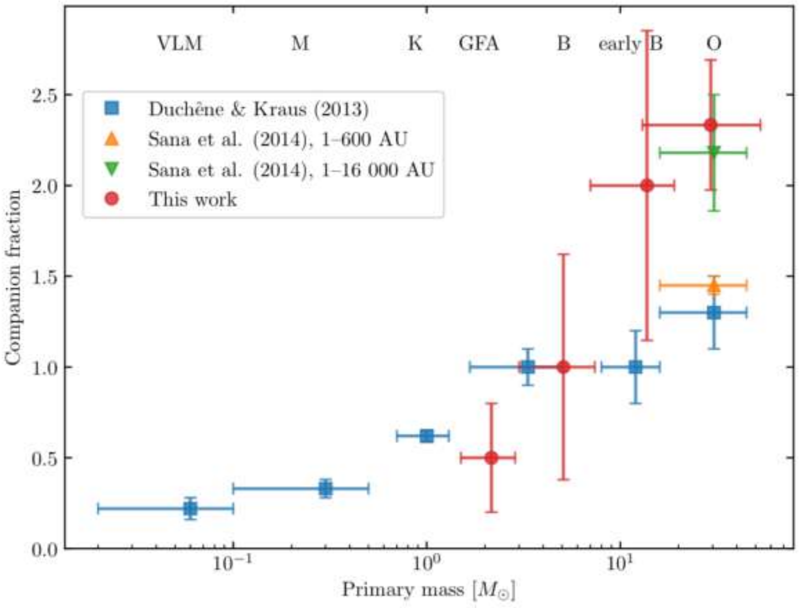
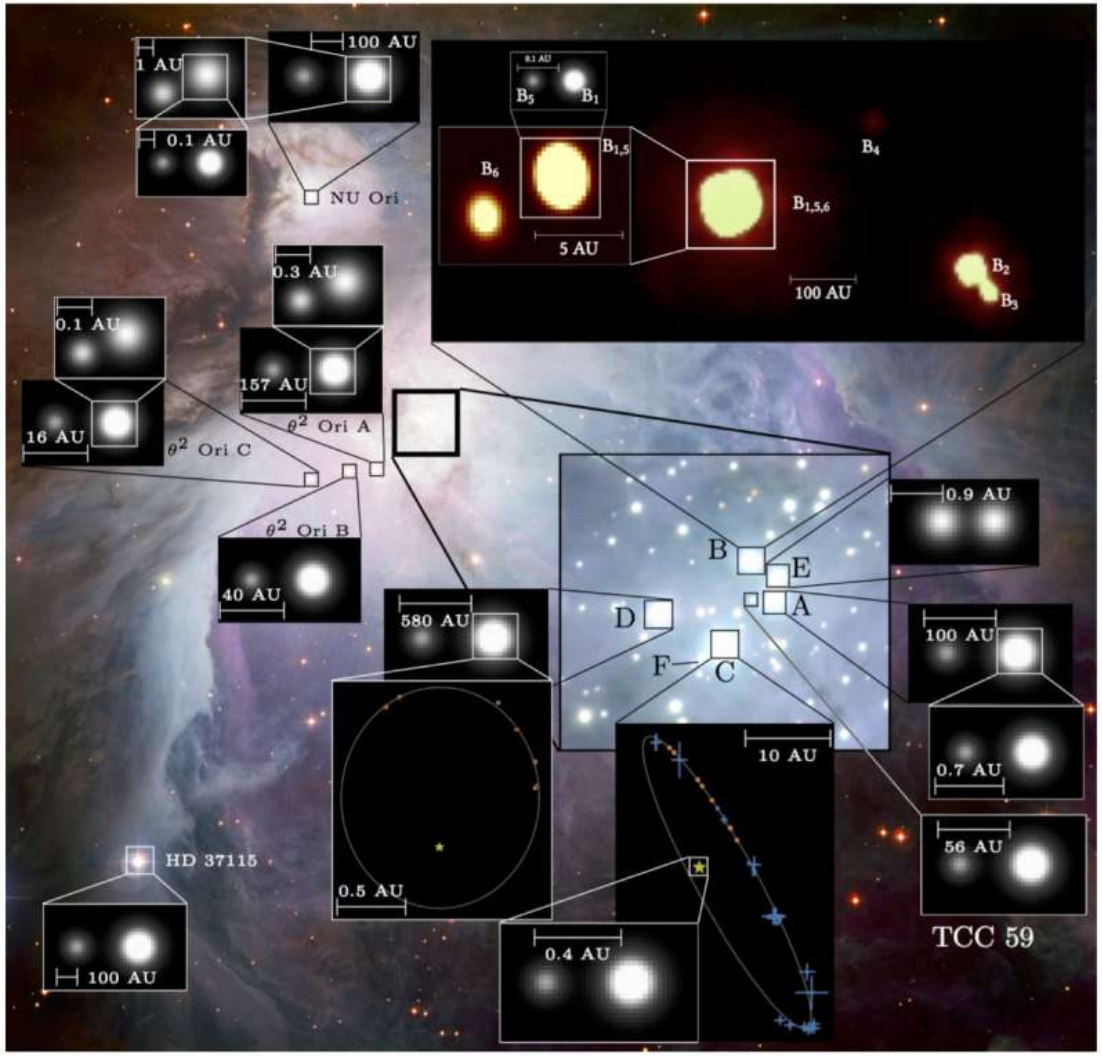


Fig. 14. The companion fraction CF as measured with GRAVITY for mass ranges $< 3\ M_\odot$, 3 –7 $M_\odot$, 7 –16 $M_\odot$, $> 16\ M_\odot$ (red circles). The values from Duchêne & Kraus (2013) for very low mass stars (VLM), spectral types M, K, G, F, A, B, early B and O (from left to right), and the values from Sana et al. (2014) for O stars are plotted for reference. The companion fraction of Sana et al. (2014) depends on the considered separation range for companions. A range $\lesssim 600$ AU is similar to the separations in our sample.

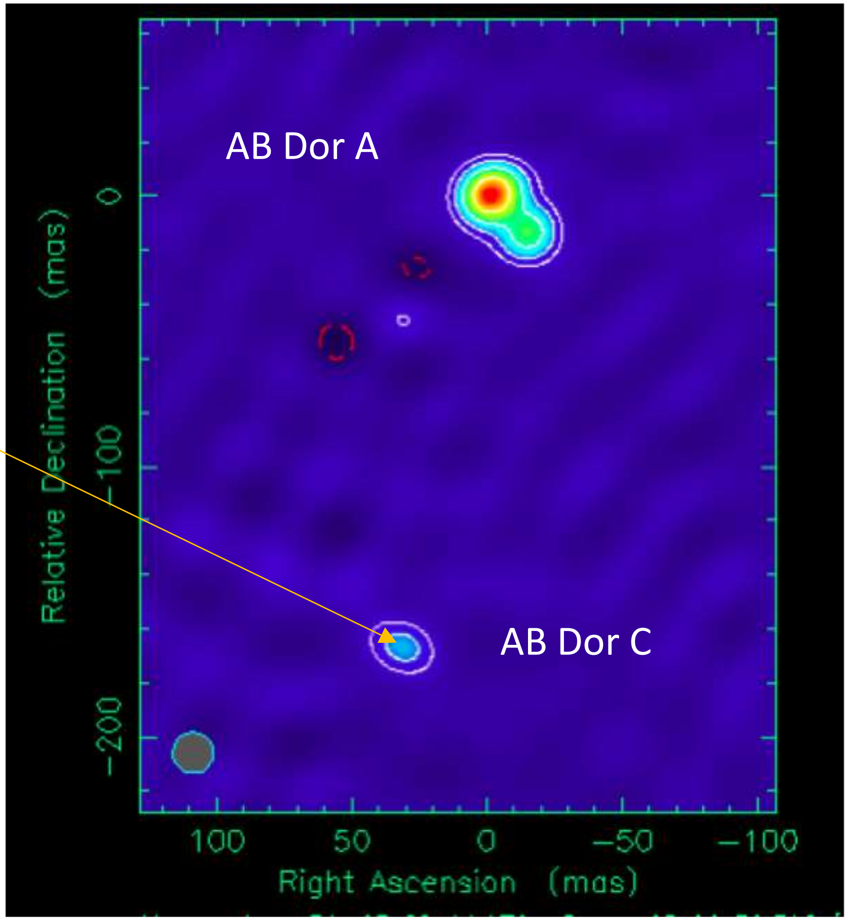


Karl et al. 2018

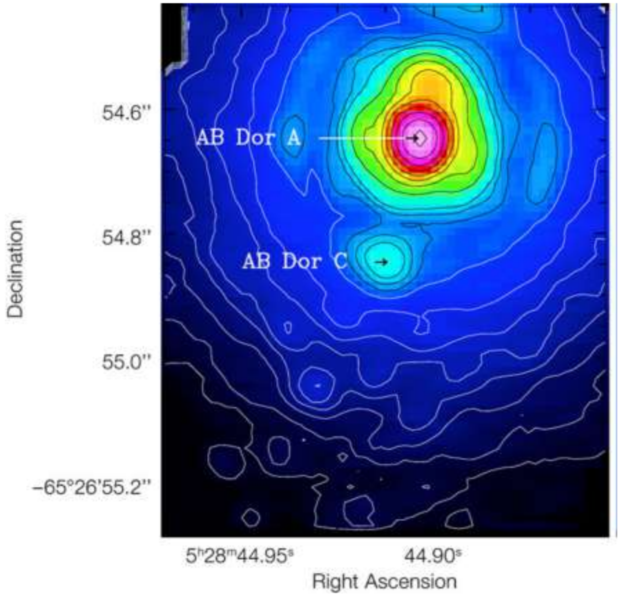
Low mass stars. AB Dor: LBA / VLTI

1. ABDorA strong radio emitter
2. ABDorC discovered by astrometric VLBI + dynamical mass
3. ABDorC difficult to image in NIR (high constrast) –10yr later
4. Important to calibrate stellar models
5. Radioemission discovered in ABDorC

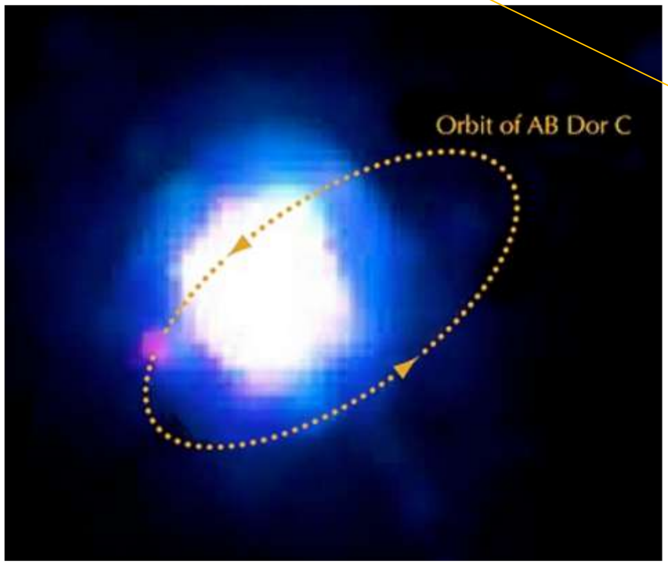
LBA 1.4GHz



SINFONI / VLT

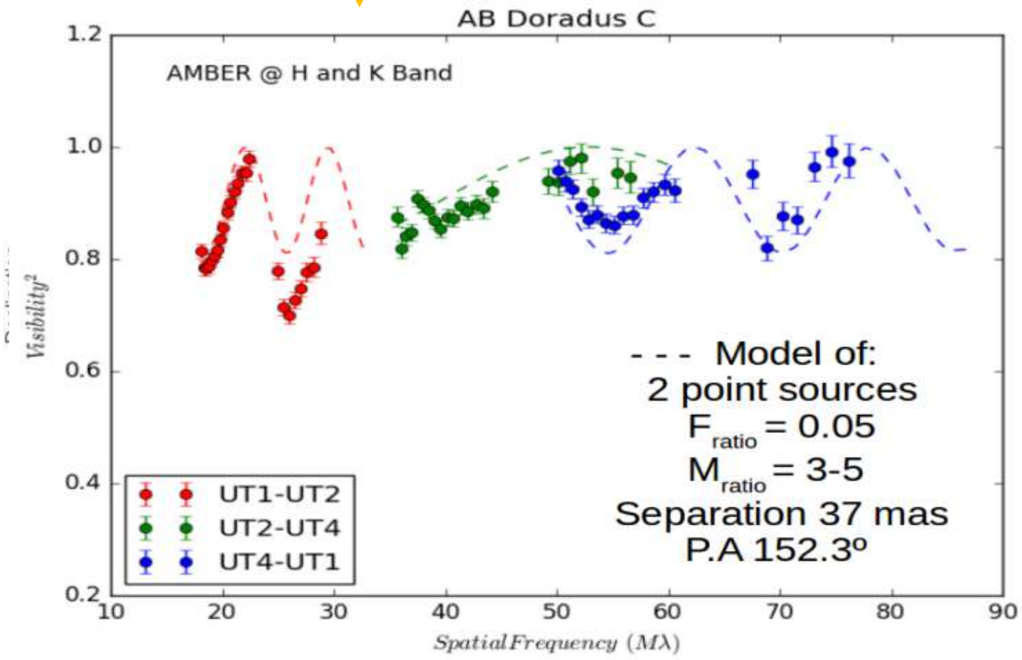


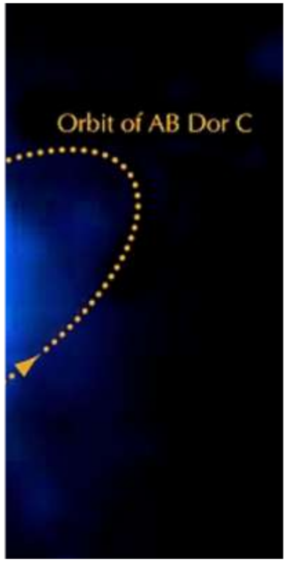
SDI / VLT



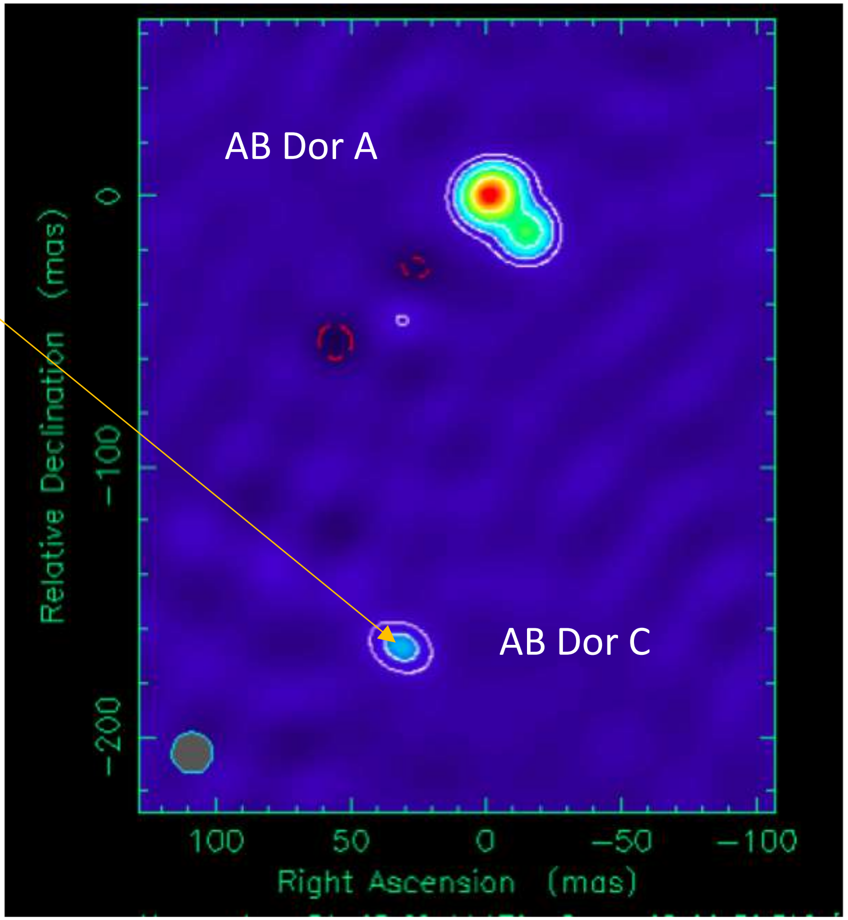
Low mass stars. AB Dor: LBA / VLTI

1. ABDorA strong radio emitter
2. ABDorC discovered by astrometric VLBI + dynamical mass
3. ABDorC difficult to image in NIR (high constrast) –10yr later
4. Important to calibrate stellar models
5. ABDorC found to be also radioemitter (see talk by Climent)
6. Non-standard VLTI/AMBER shows ABDorC could be binary

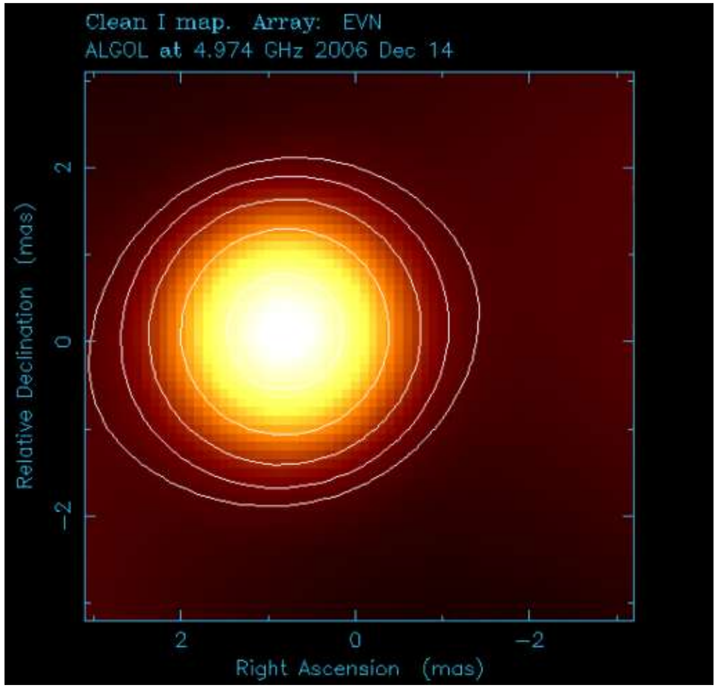


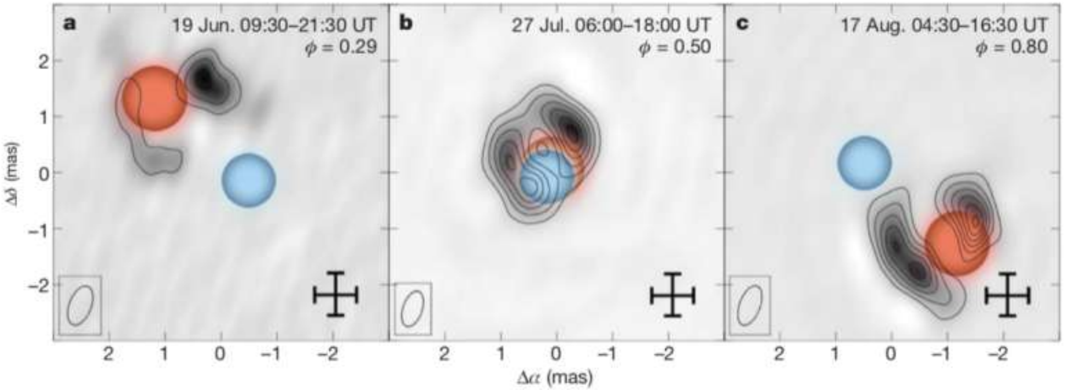


LBA 1.4GHz

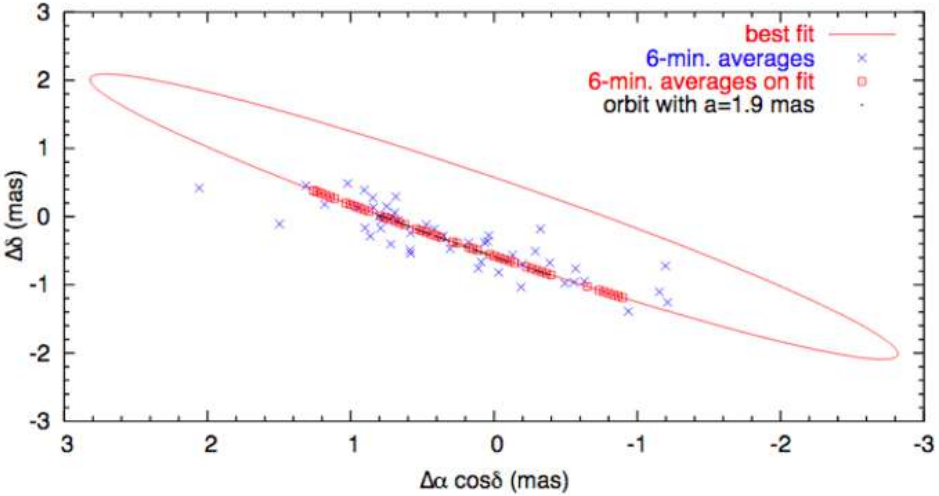


eEVN + CHARA observations of Algol (coronal studies + astrometry)



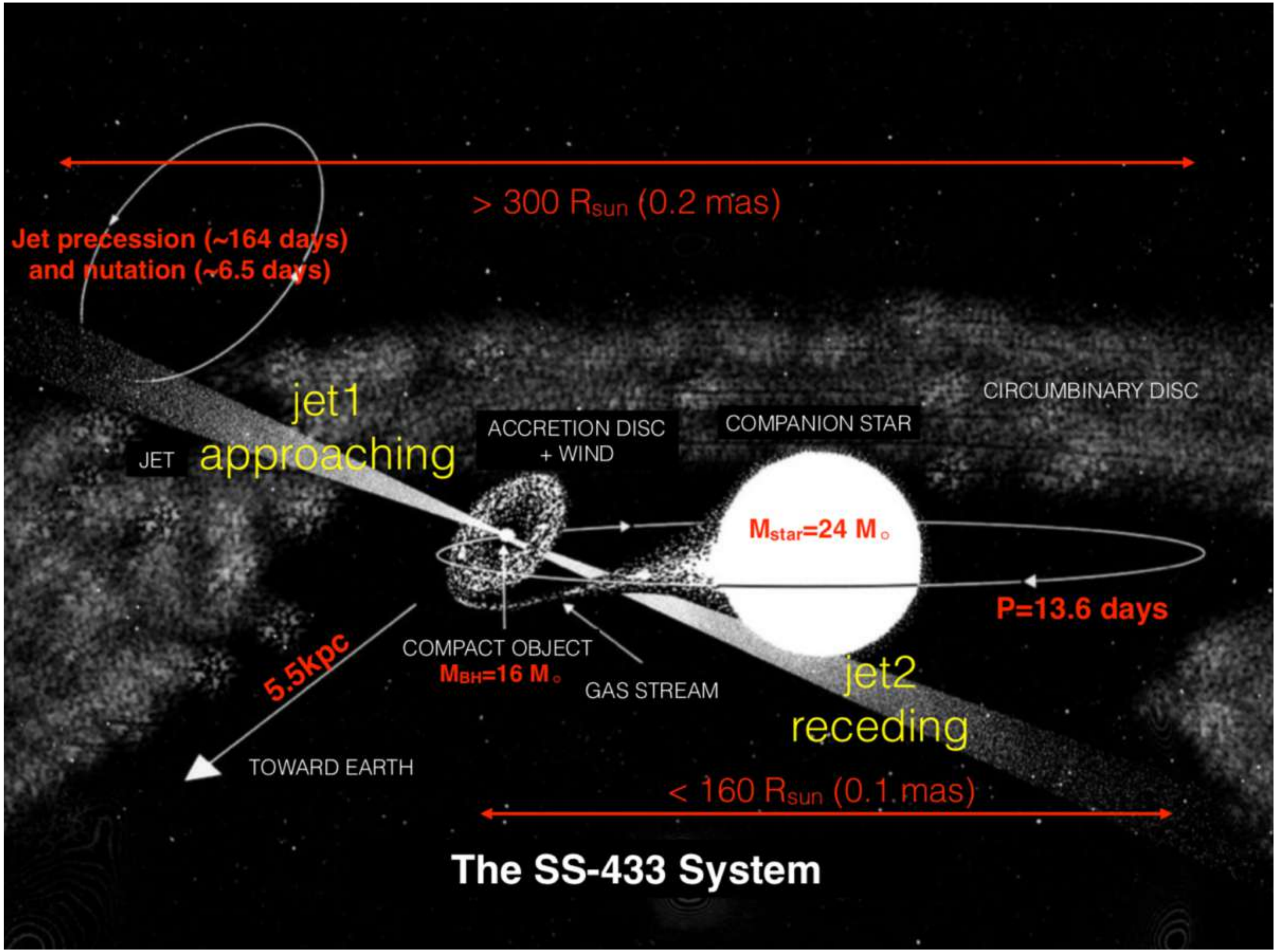


Peterson+ 2010. (VLBA)



Csizmadia+ 2006

VLTI / GRAVITY: Microquasar SS433

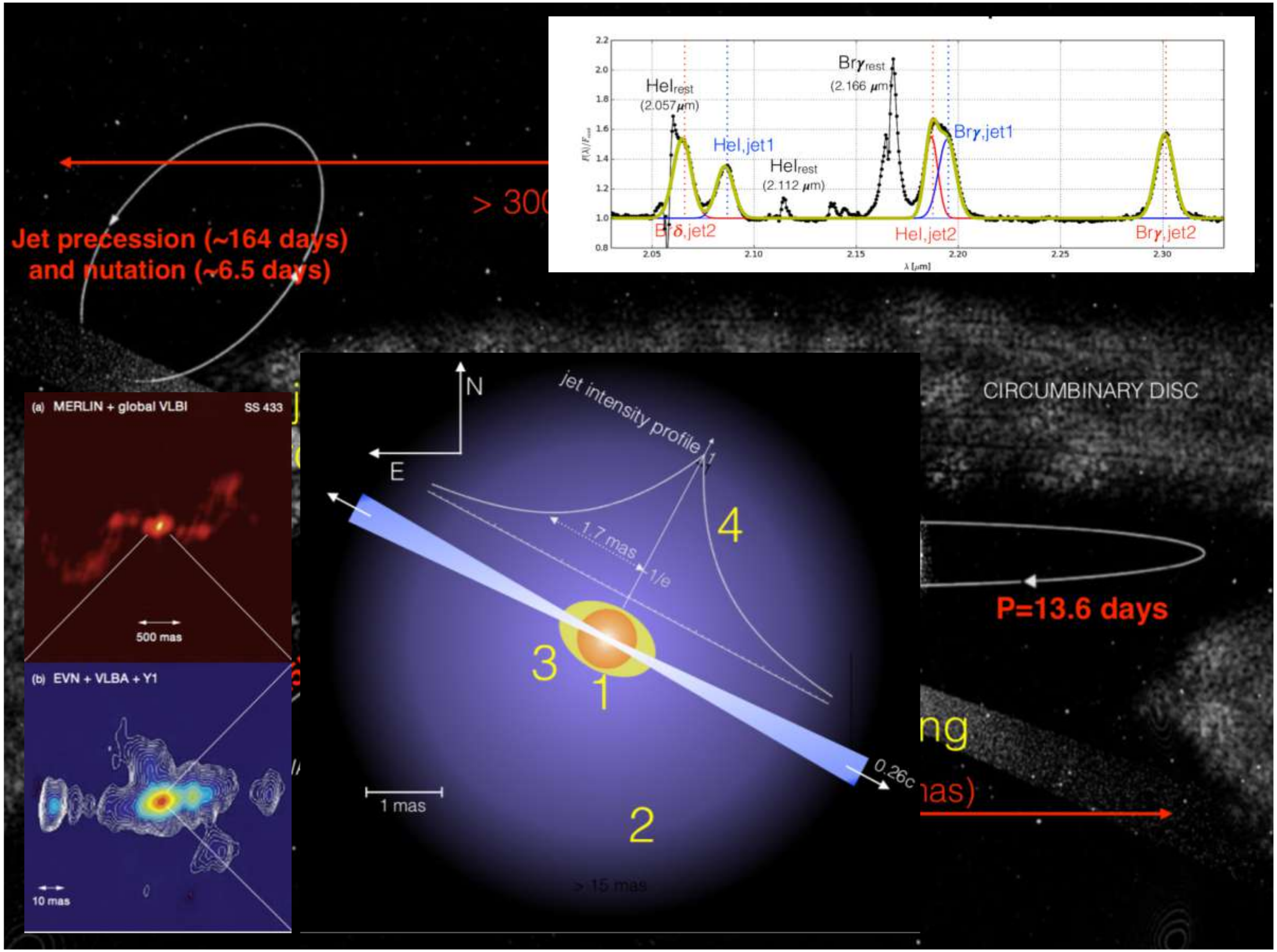


Petrucci et al. 2017

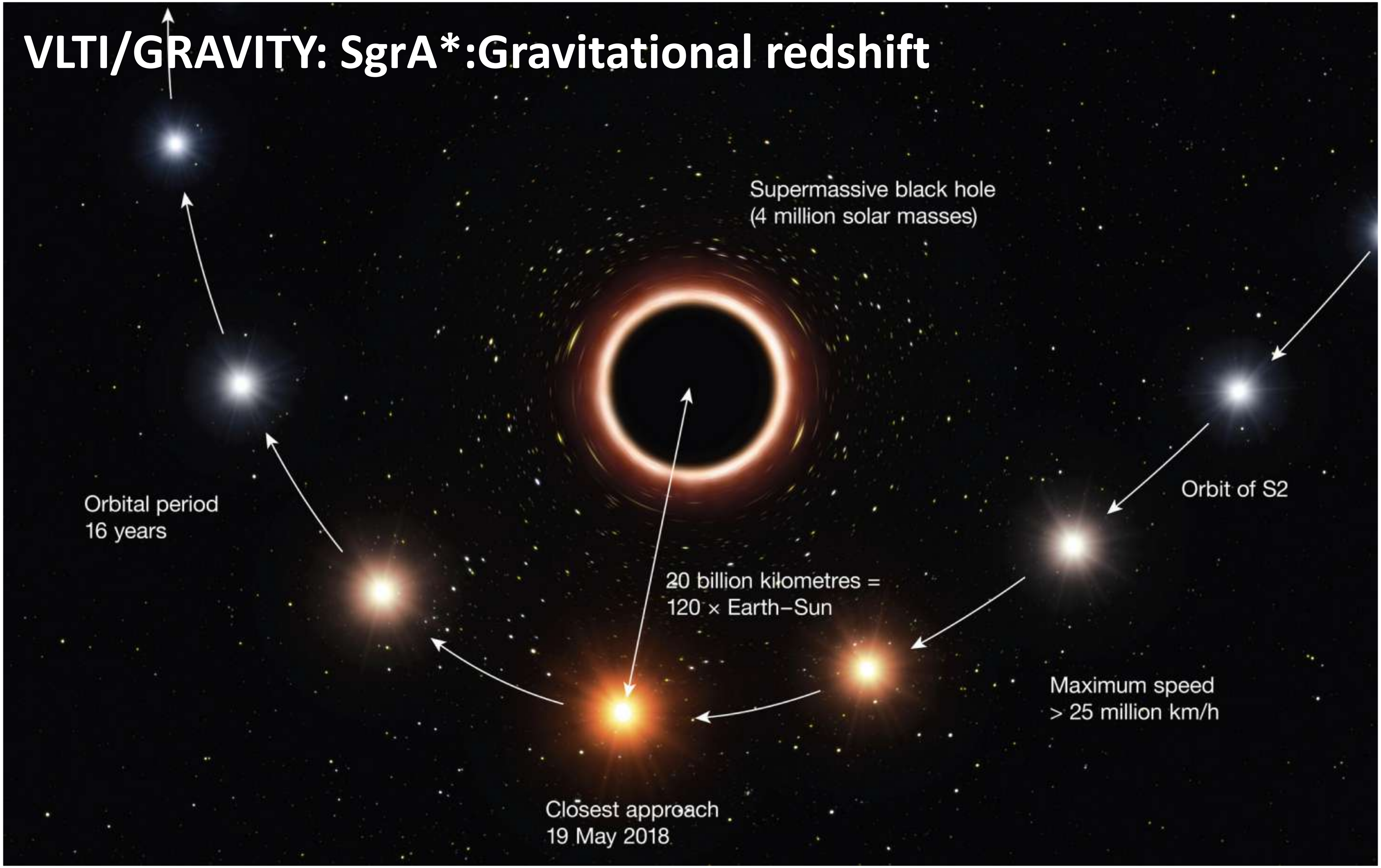
VLTI / GRAVITY:
Microquasar SS433

1. 90% of the infrared continuum comes a central source of ~0.8 mas
2. 10% IR from extended 15mas structure
3. Brγ line 1mas along the jet

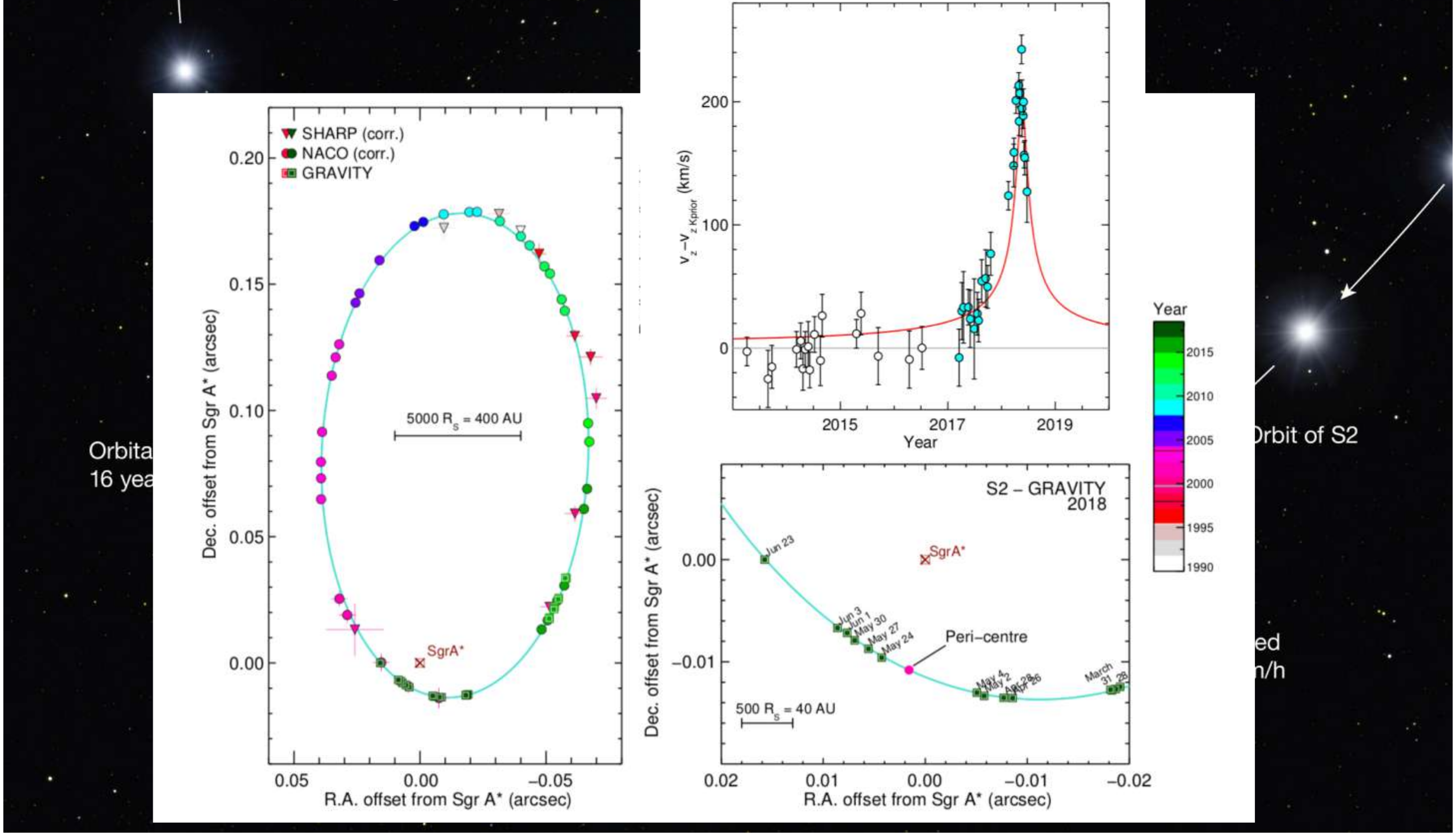
Petrucci et al. 2017



VLTI/GRAVITY: SgrA*:Gravitational redshift

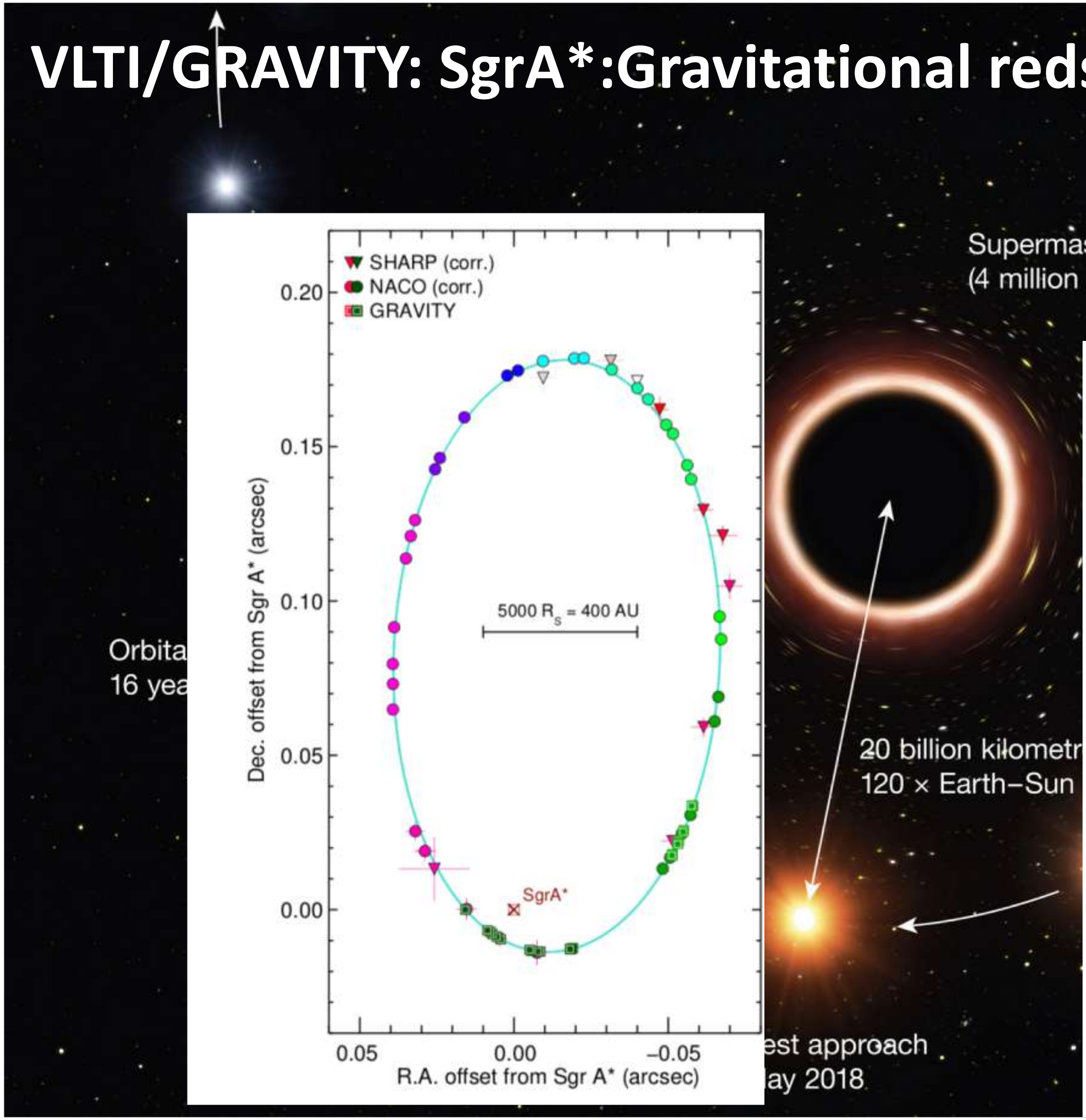


VLTI/GRAVITY: SgrA* Gravitational redshift



Abuter et al. 2018

VLTI/GRAVITY: SgrA*:Gravitational redshift



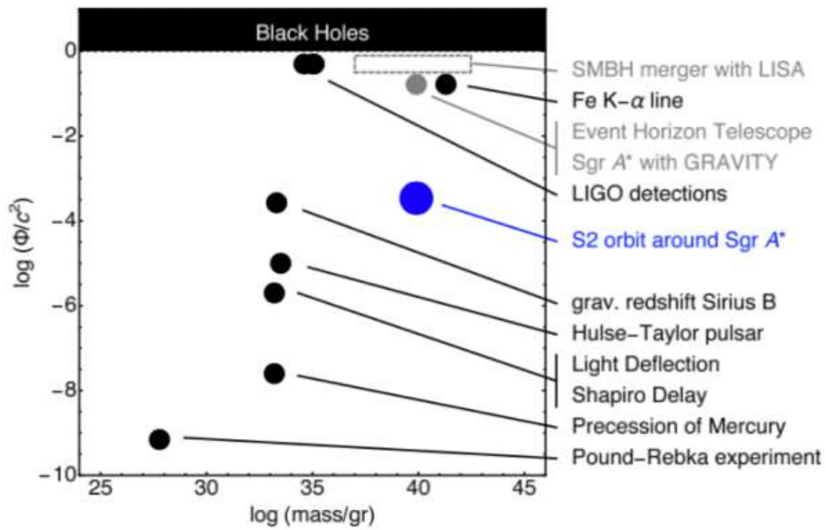


Fig. A.2. Comparison of tests of General Relativity, inspired by Psaltis (2004). Shown in black are well-established tests: the Pound & Rebka (1959) experiment, the precession of Mercury (Einstein 1916), light deflection and the Shapiro delay in the solar system, the Hulse-Taylor pulsar (Taylor & Weisberg 1982), the gravitational redshift of Sirius B (Greenstein et al. 1971; Barstow et al. 2005), the LIGO detections (Abbott et al. 2016a,c,b), and the relativistic Fe Kα line (Tanaka et al. 1995; Fabian et al. 2000). Future tests are shown in grey, and this work, which uses the S2 orbit around Sgr A*, is shown in blue.

Abuter et al. 2018

The future of (NIR) interferometry

- Extending to the visible
- Polarimetry
- Wide field astrometry
- More sensitivity
- Higher spectral resolution
- Imaging capabilities

But wait to ELT/SKA era..

Thanks!