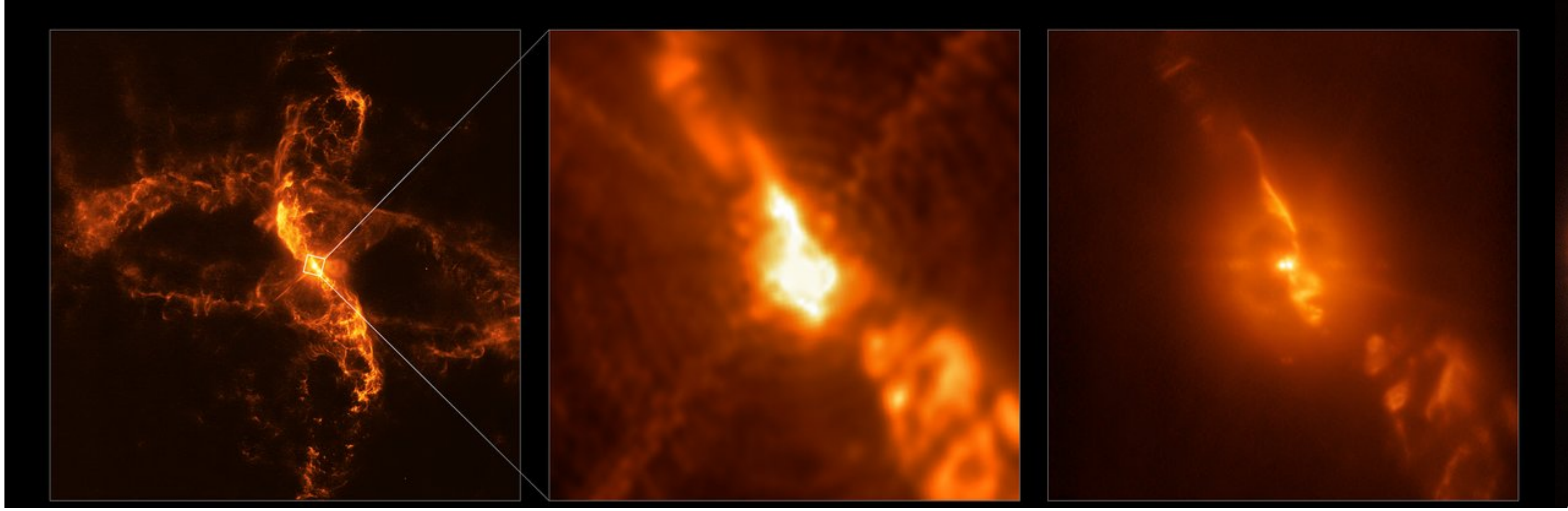
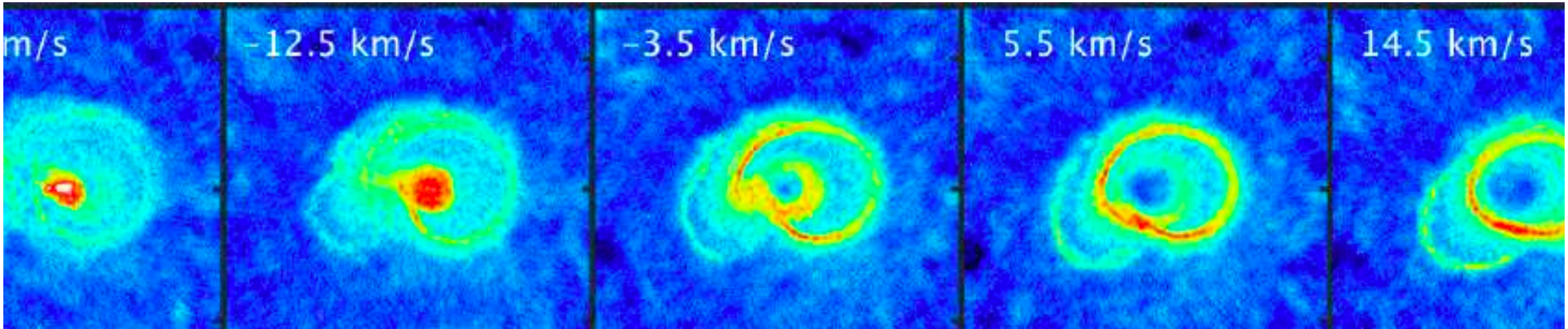


Evolved Stars

Regional VLBI Workshop 2019, Mexico City

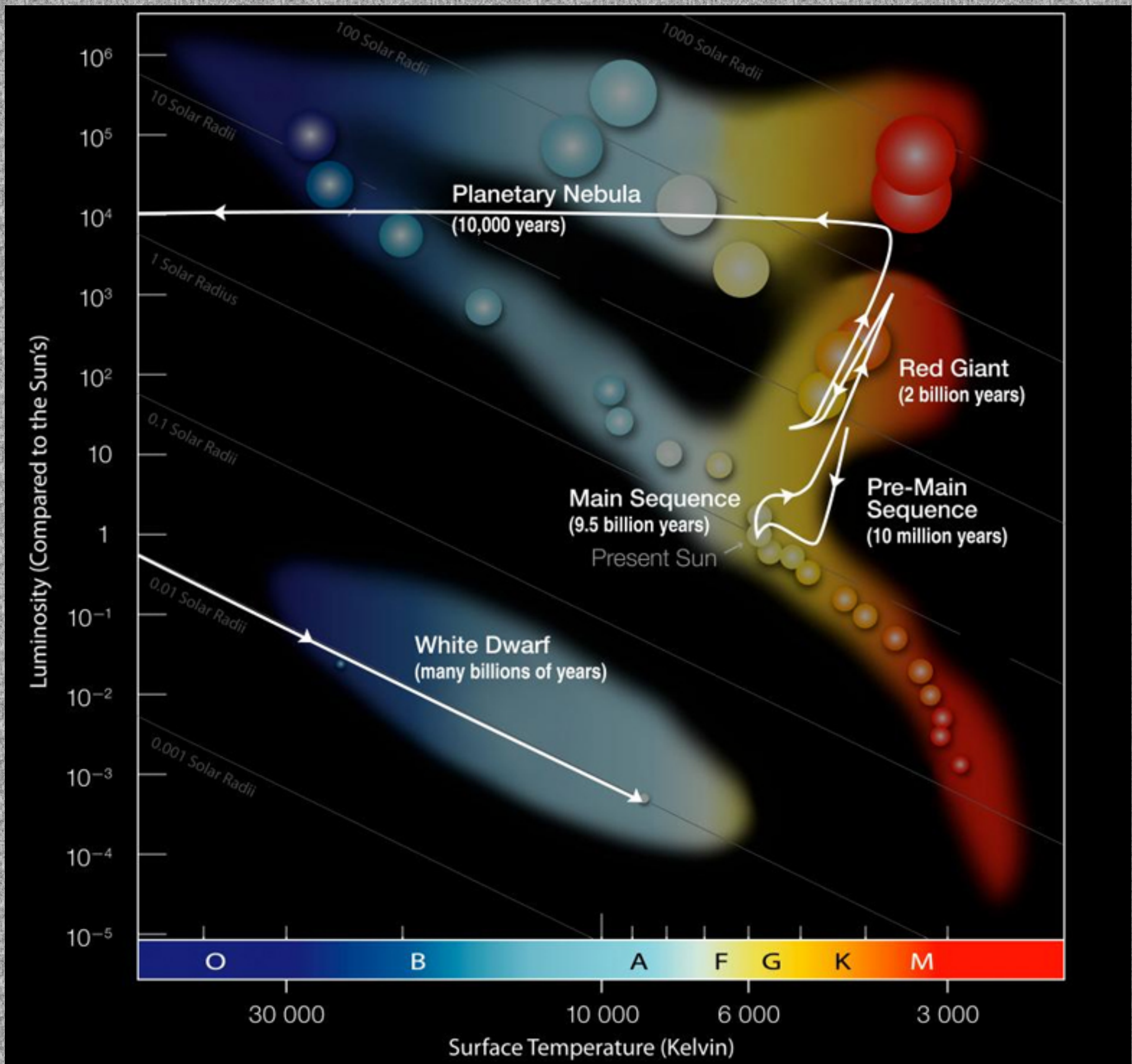
Liz Humphreys (ESO)

EUROPEAN ARC
ALMA Regional Centre

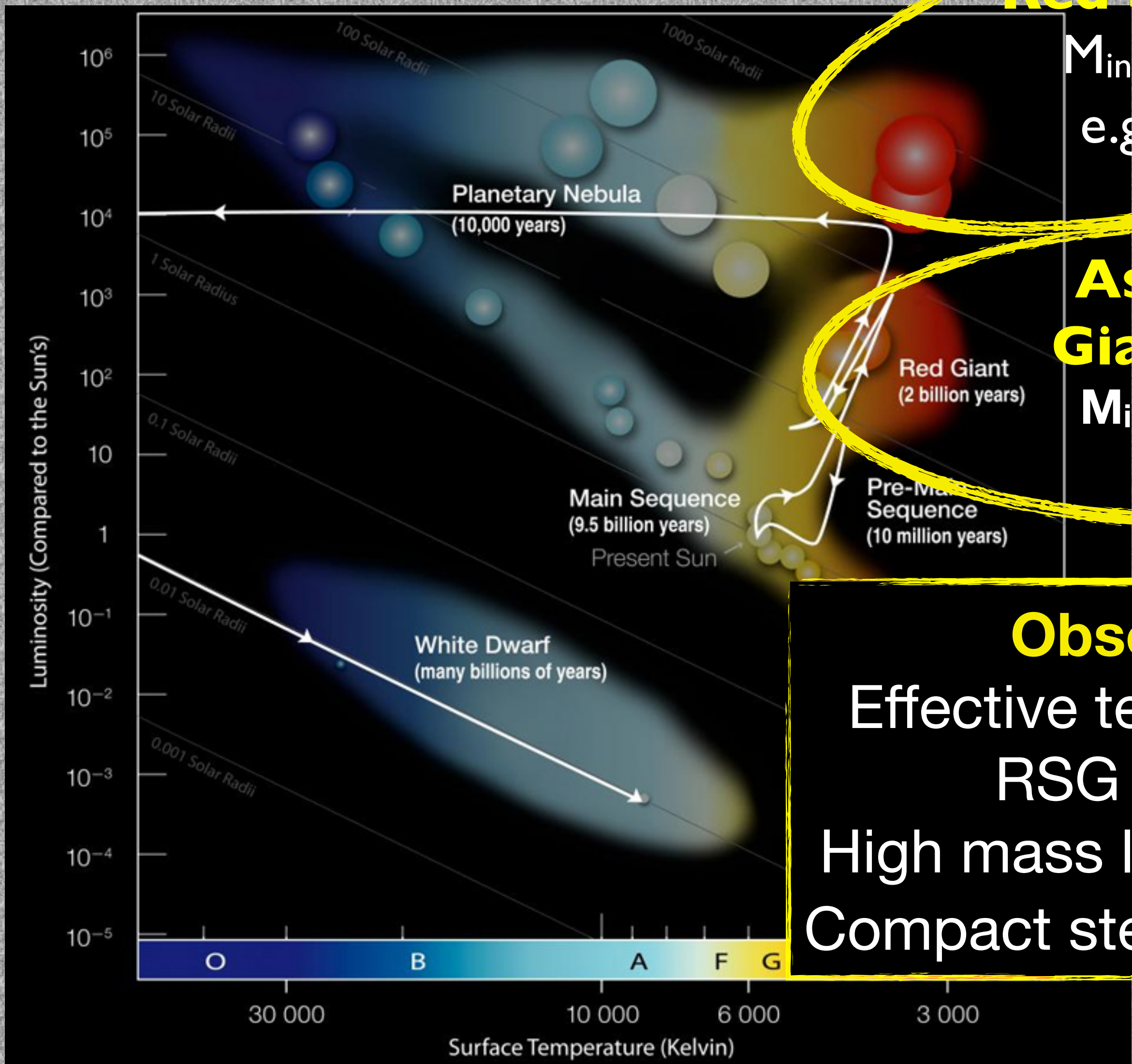


Credits: R Aqr - Schmid et al. 2017; R Scl - Maercker et al. 2012; HD 101584 - Olofsson et al. 2019

HR-Diagram


100 Solar Radii
1000 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radii
0.01 Solar Radii
0.001 Solar Radii
Planetary Nebula
(10,000 years)
Red Giant
(2 billion years)
Main Sequence
(9.5 billion years)
Pre-Main
Sequence
(10 million years)
Present Sun
White Dwarf
(many billions of years)
Luminosity (Compared to the Sun's)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30 000
10 000
6 000
3 000
Surface Temperature (Kelvin)

AGB and RSG Stars



Red Super Giants

$M_{initial}$: 8 - 35 $M_\odot$

e.g. Betelgeuse

Asymptotic Giant Branch

$M_{initial}$: 1- 8 $M_\odot$

e.g. Mira

Observational Similarities

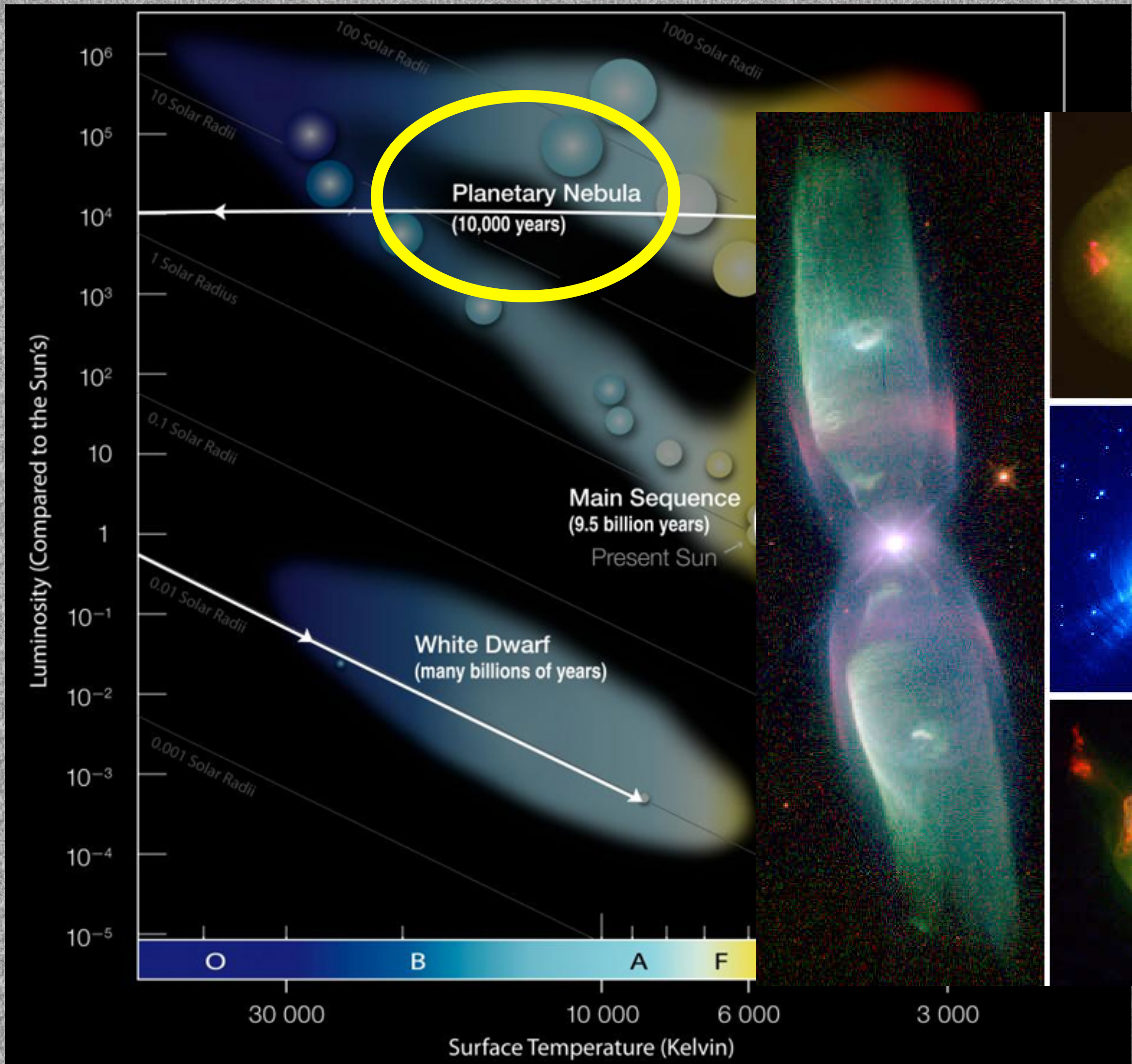
Effective temperatures ~ 2500 - 4000 K

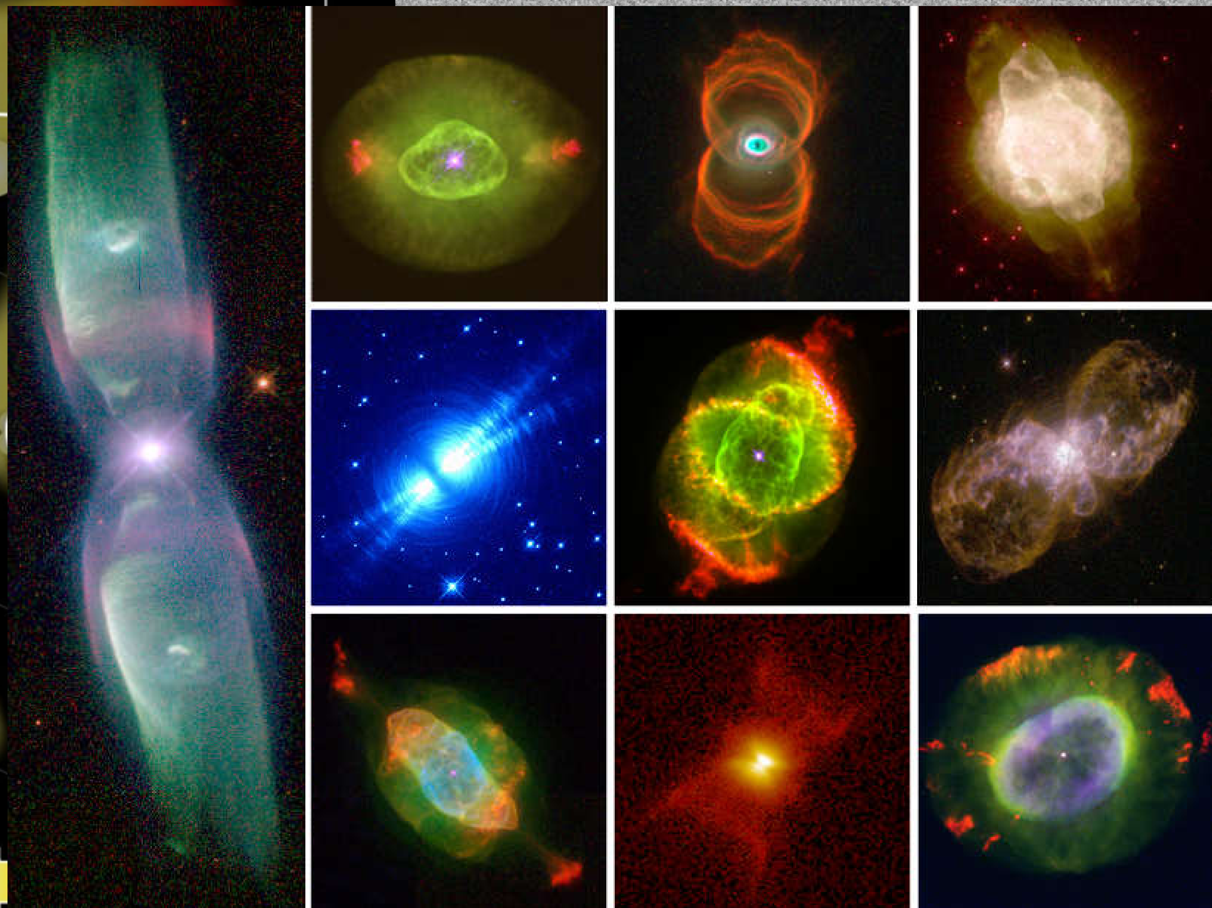
RSG + AGB stellar pulsation

High mass loss rates ~ 10^{-7} to 10^{-4} $M_\odot yr^{-1}$

Compact stellar core + extended envelope

Planetary Nebulae





HST

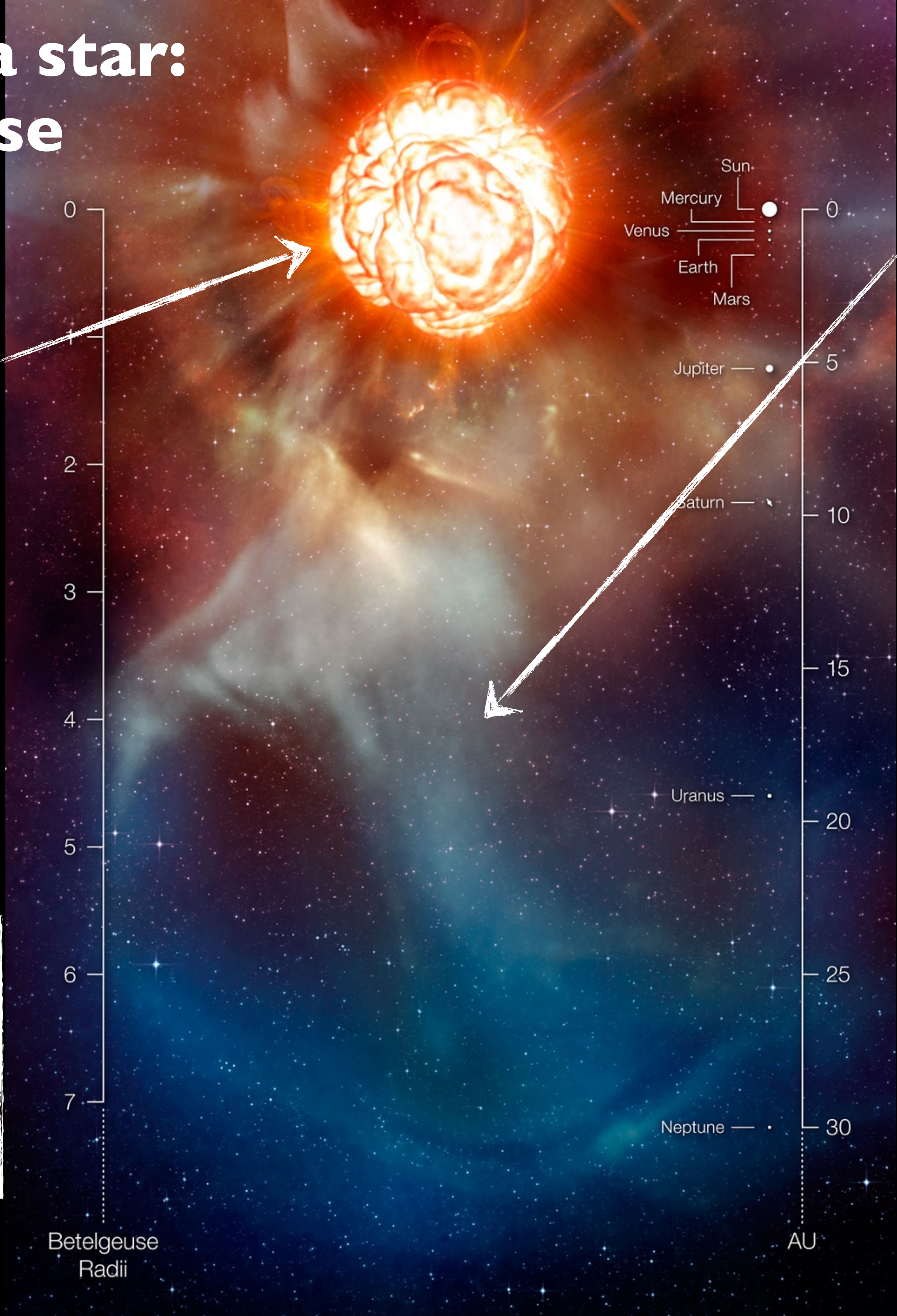
Anatomy of a star: e.g. Betelgeuse

Central star convective cells

Photosphere Angular Diameter: 43 mas

Effective temperature: 3700 K

VLTI/AMBER
Ohnaka et al. (2009)



Giant gas plume shows mass loss asymmetry

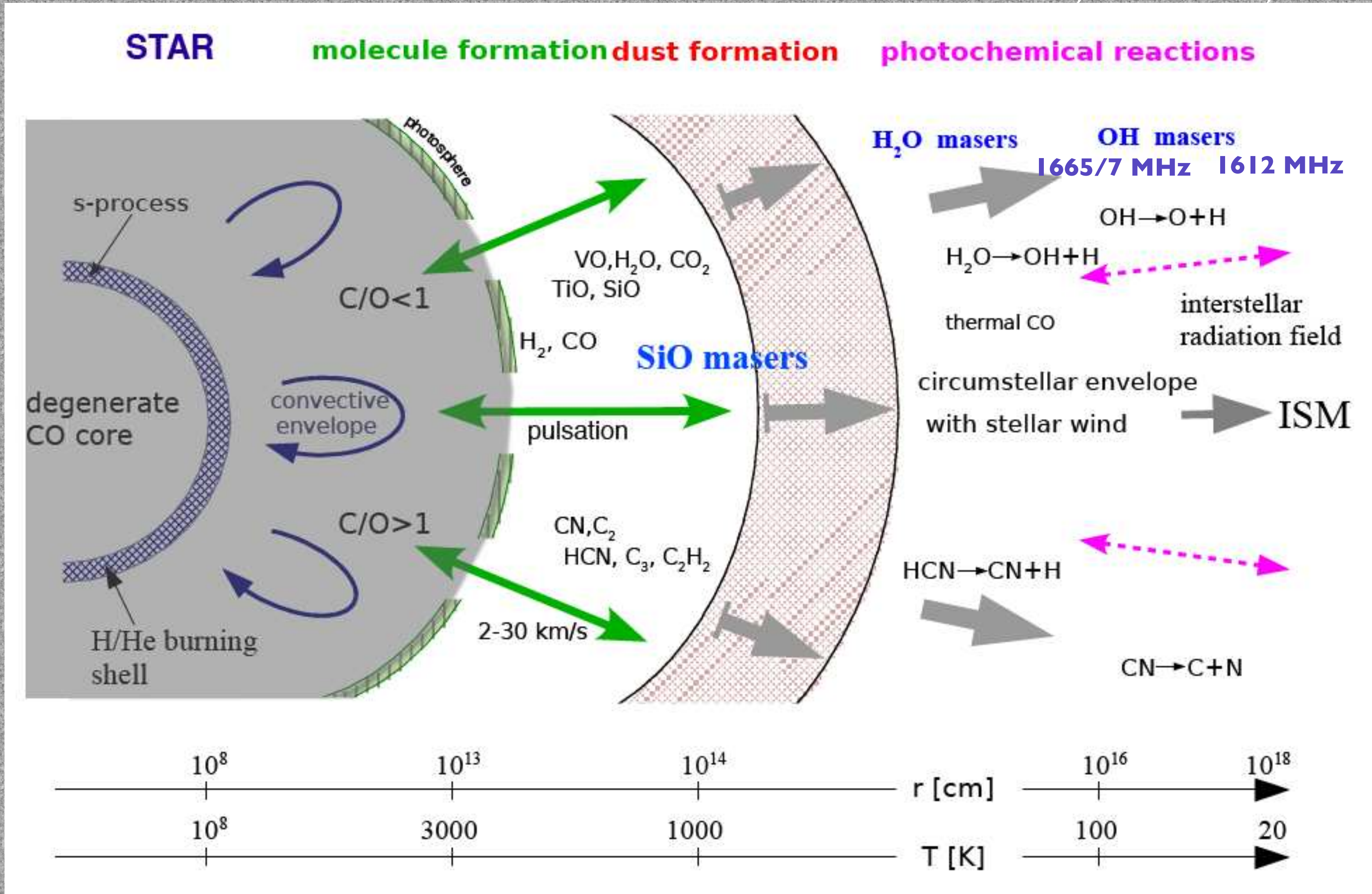
Circumstellar envelope (CSE) extends much further

Molecules + Dust

VLT/NACO
Kervella et al. (2009)

Mass-loss and masers

After Colomer, Le Bertre, et al.



Oxygen-rich AGB stars: SiO, H_2O and OH masers often observed towards the same star

Location in the CSE governed by factors including excitation, chemistry

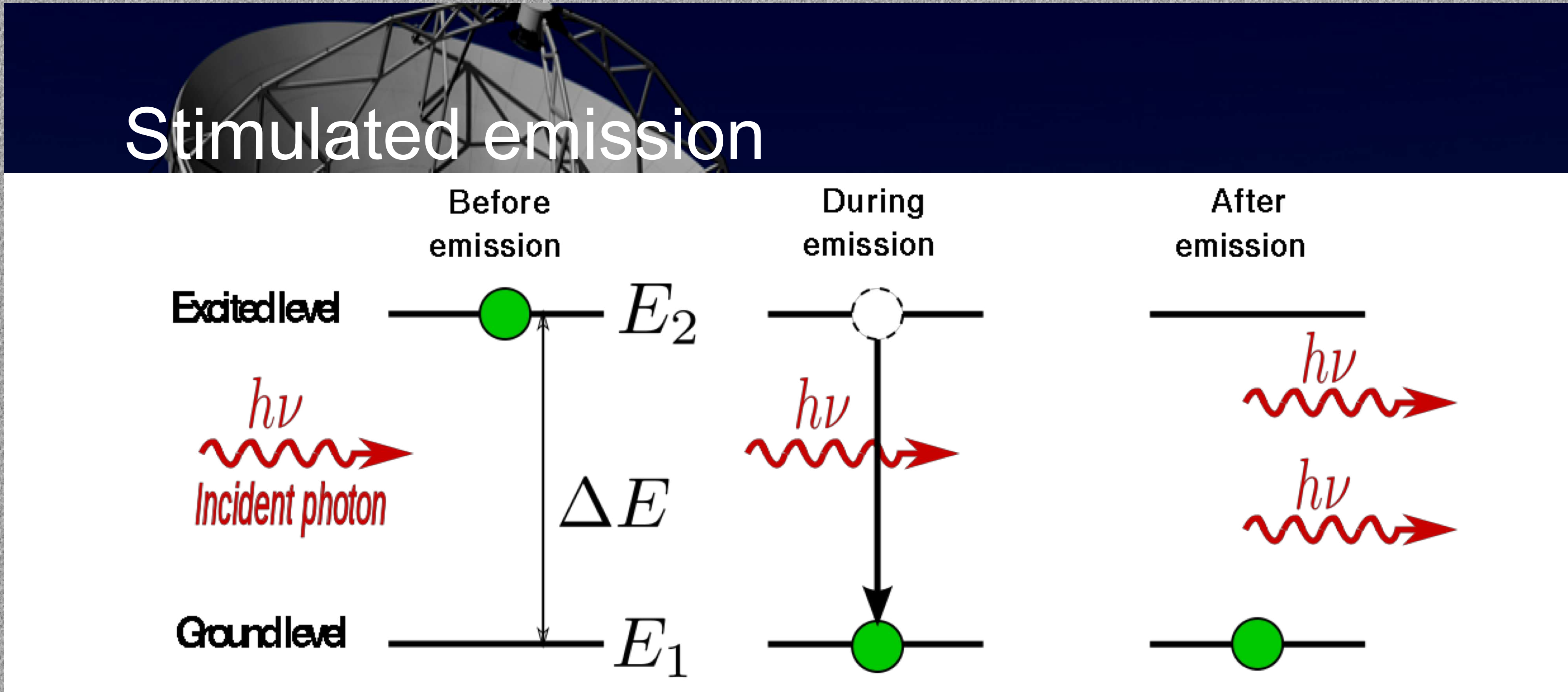
Aside: Masers

(Microwave Amplification by Stimulated Emission of Radiation)

- Compact, high brightness temperature masers enable study at high angular resolution (e.g. 1 milliarcsecond)
- **Found in:** Evolved stars, AGN, star formation, supernova remnants, comets and planetary atmospheres….
- **Species include:** SiO, H_2O, OH, HCN, CH_3OH, SiS, NH_3, hydrogen recombination masers
- **Uses include:**
    - Determine gas physical conditions
    - Dynamics (3D velocities from proper motions)
    - Magnetic field estimation
    - Distances, maser cosmology (talk by Jim Braatz)

Maser amplification

See e.g. Maser Sources in Astrophysics by Malcolm Gray

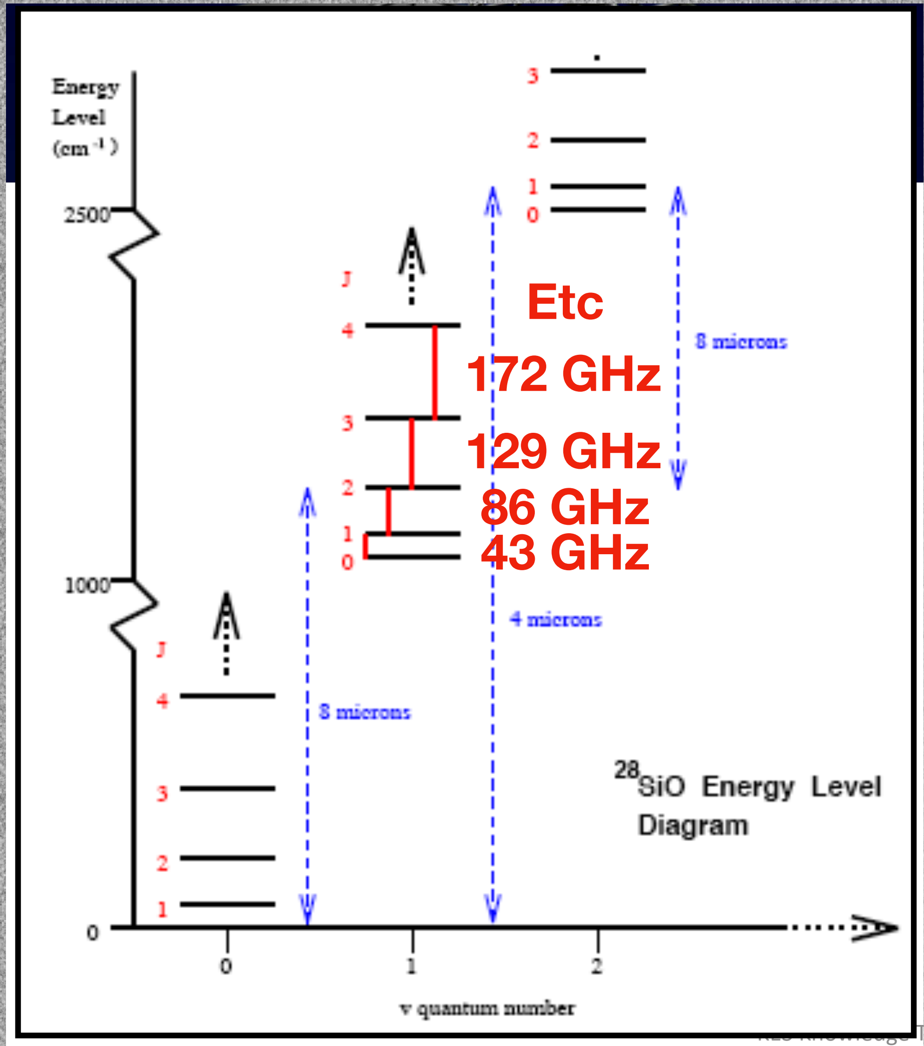


Emitted photons: same frequency, phase and direction as stimulating photon

Exponential amplification (in the unsaturated regime)

Population inversion is a pre-requisite for maser action
Maser pump e.g. radiative or collisional

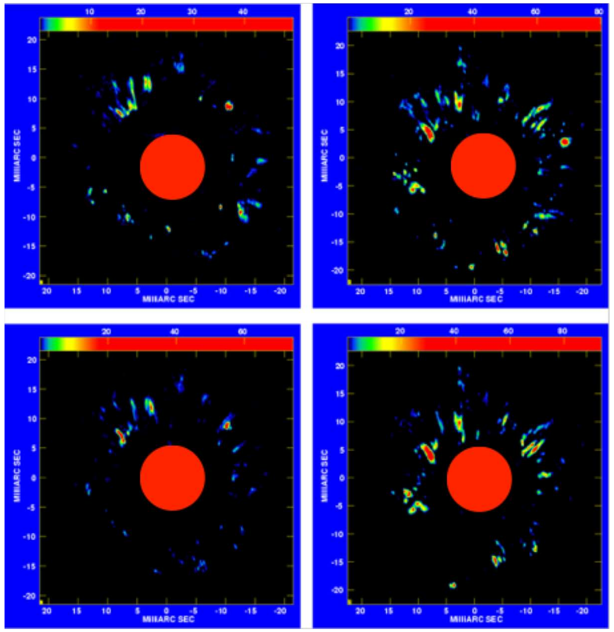
Maser transitions e.g. SiO



SiO emission from rotational transitions in v=0 is usually thermal not maser

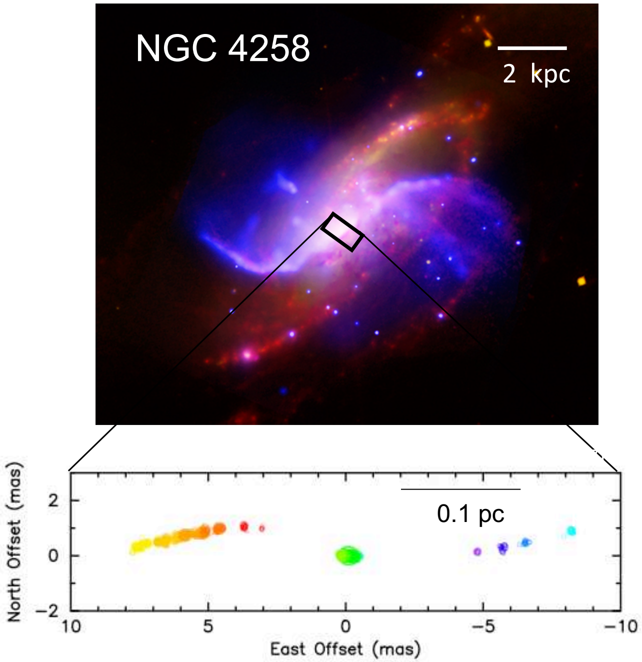
Masers:VLBI

Maser environments at high angular resolution



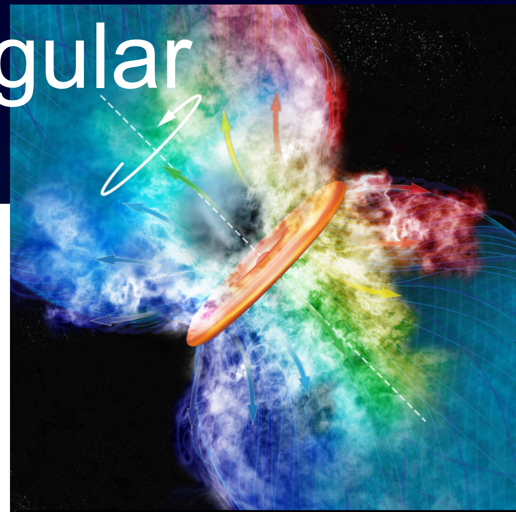
SiO Masers in AGB Stars

Yi et al.
Angular resolution ~ 1 mas

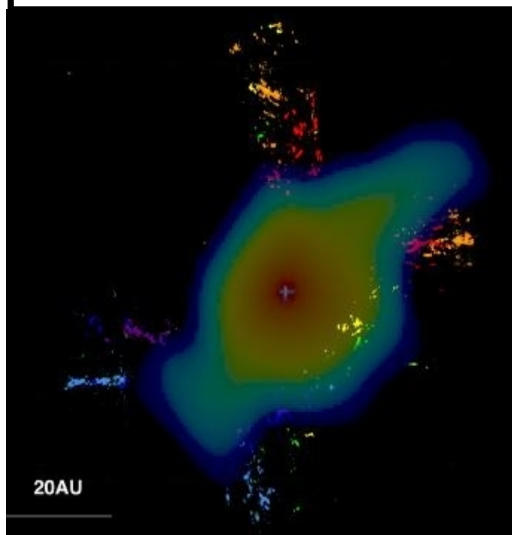


H_2O Megamasers in AGN

Argon et al. (2007)

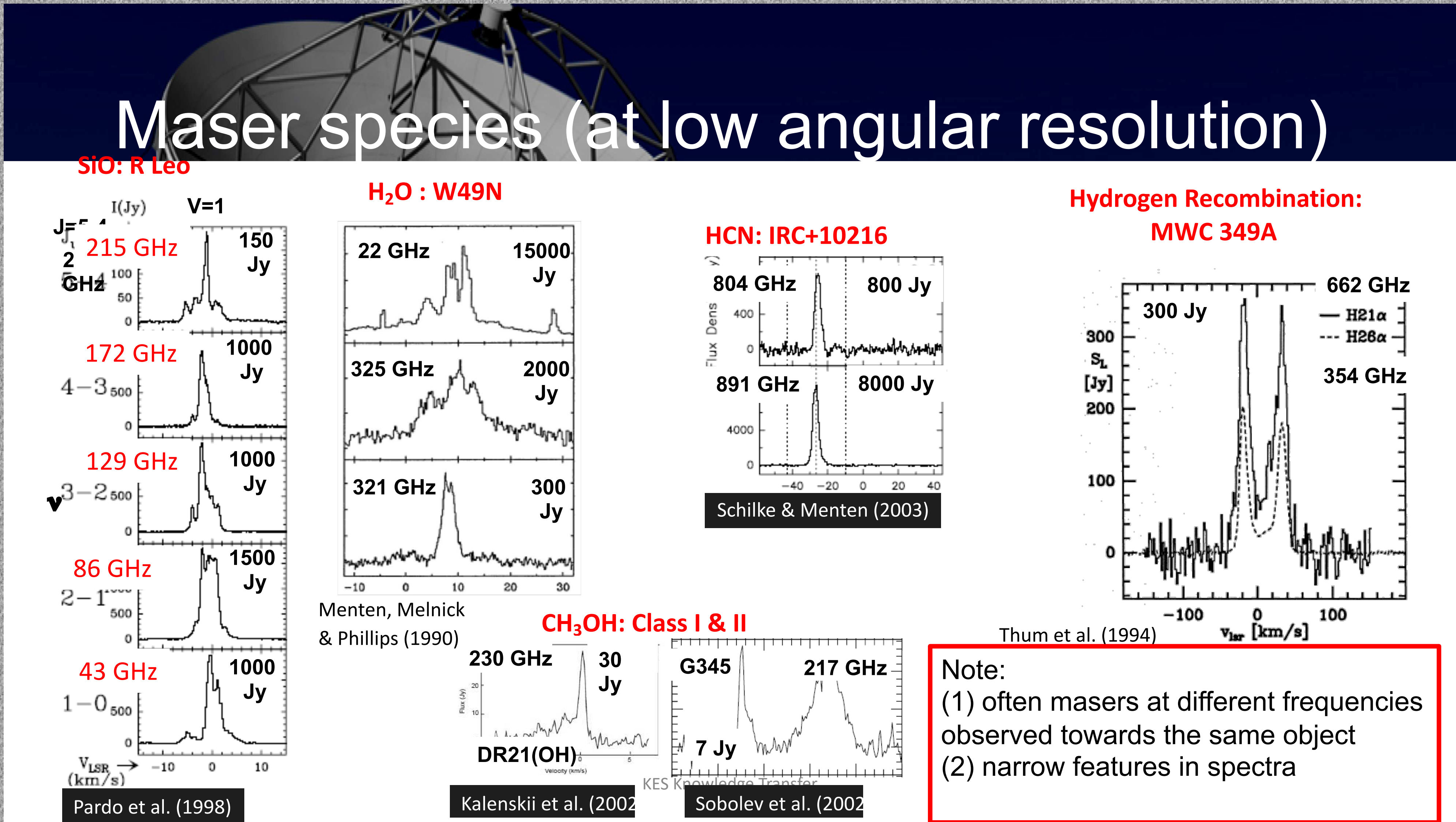


SiO masers in star formation



Maser amplification paths should have velocity coherence (velocity gradients along them should not be high)

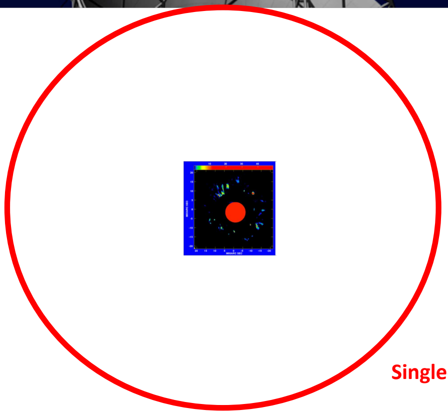
Masers: single-dish spectra

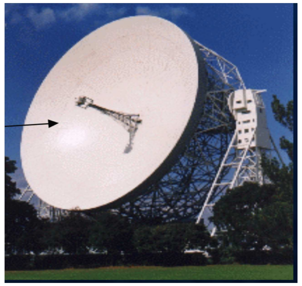


Observe galactic masers at high velocity resolution (ideally 0.1-0.2 km/s) to spectrally-resolve the narrow features

Narrow features in maser spectra

Sign of maser emission

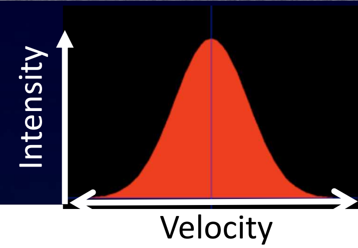


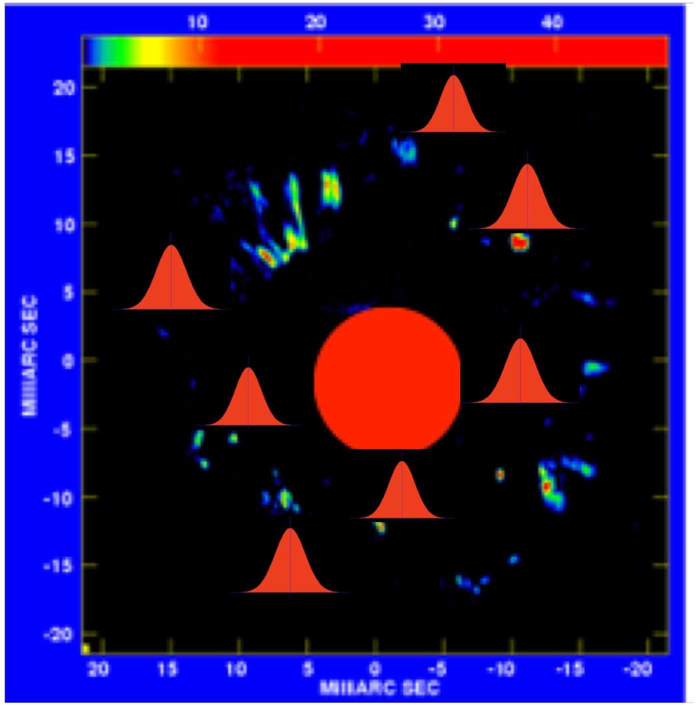


Single-dish telescope beam e.g. 15 arcseconds

Maser variability: individual features can vary or the whole single-dish spectrum

Narrow features in maser spectra





Individual maser clouds have narrow linewidths / spectra centered at their own velocities

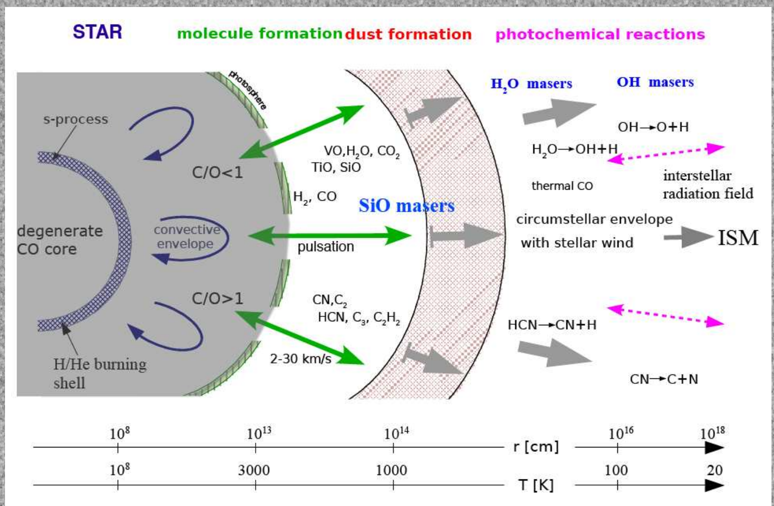
Given certain assumptions, and if no turbulence, the maximum line profile width of a cloud should be the thermal/Doppler linewidth (due to particle motions shifting the line frequency by the Doppler effect)

FWHM (km/s) $$\Delta v_{1/2} = 2(ln2)^{1/2}\Delta v_D = 0.2(T/A_m)^{1/2}$$

Where T is the gas kinetic temperture and Am is the molecular mass number. For SiO Am = 44 and T = 1500 K, so FWHM = 1.2 km/s

Single-dish spectra a blend of line profiles from the individual maser clouds

Stellar Surface / Photosphere

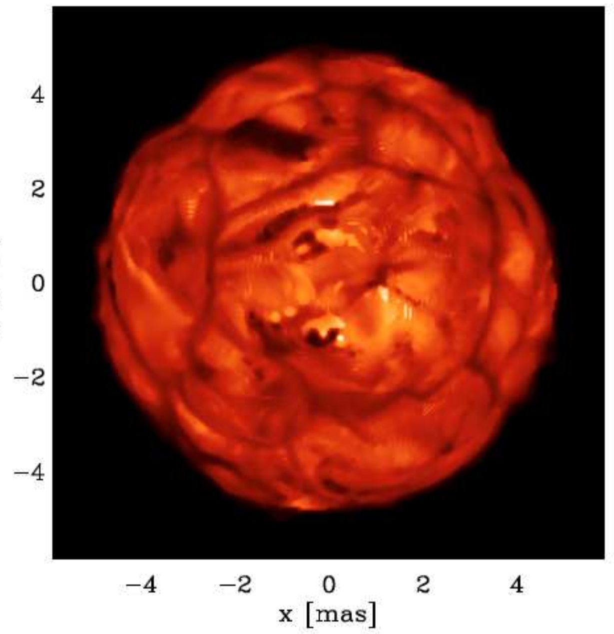


Stellar radii (from optical/infrared)

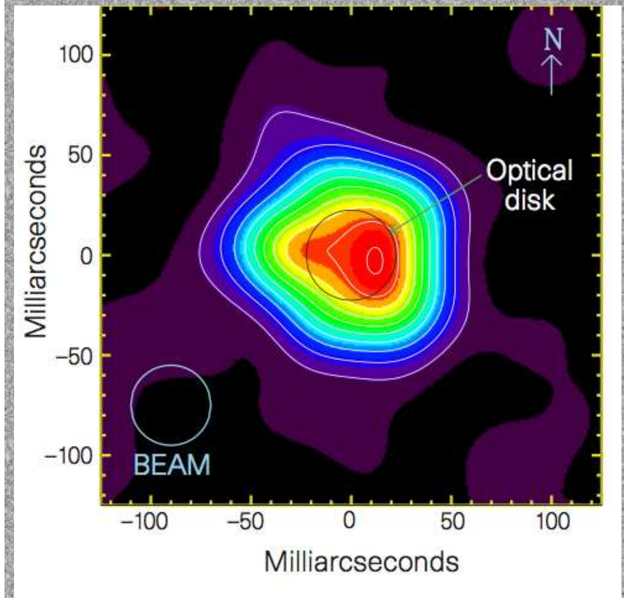
Stars	Diameter at 2.3 micron (mas)*	Distance (pc)	Stellar radius (AU)
Betelgeuse (RSG)	43	~200	4.3
Antares (RSG)	37	170	3.2
W Hya (AGB)	~40	98	2.0
R Dor (AGB)	47	59	1.4
Mira (AGB)	25	92	1.2

* **"Radio photosphere" is approximately twice this - Reid & Menten (1997, 2007)**

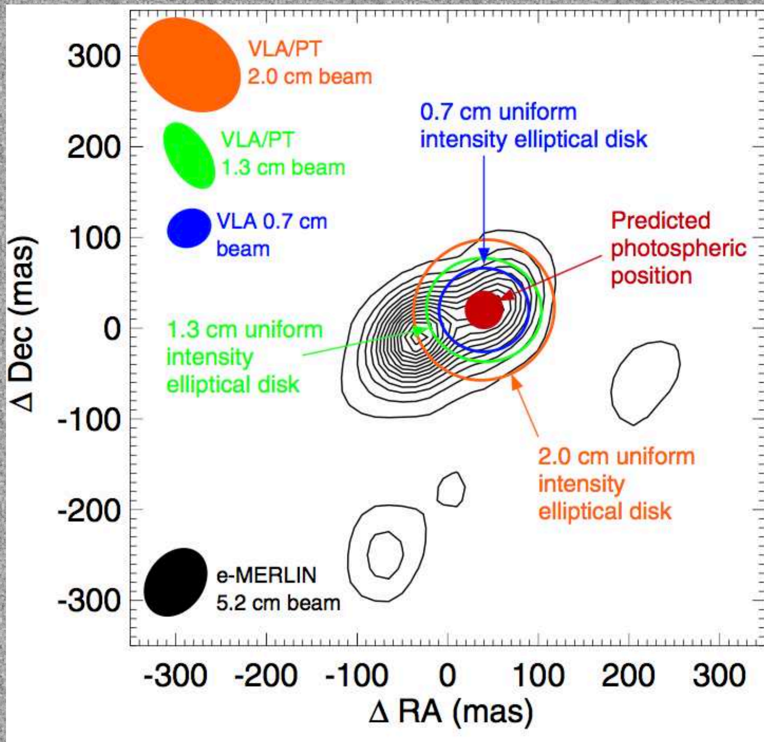
Stellar surface believed to be covered by convective cells



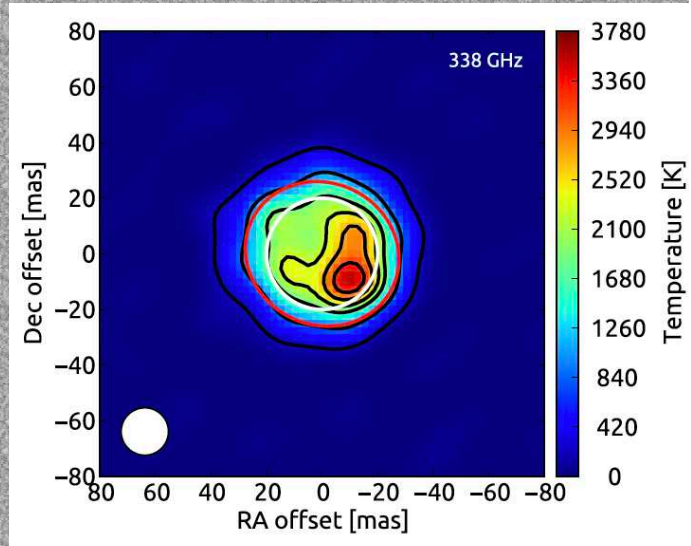
IR Simulations
Freytag & Hofner 2008



Betelgeuse
VLA 7mm
Lim et al. 1998 Nature



Betelgeuse
VLA & e-MERLIN 5 cm
Richards et al. 2012
O'Gorman et al. 2015

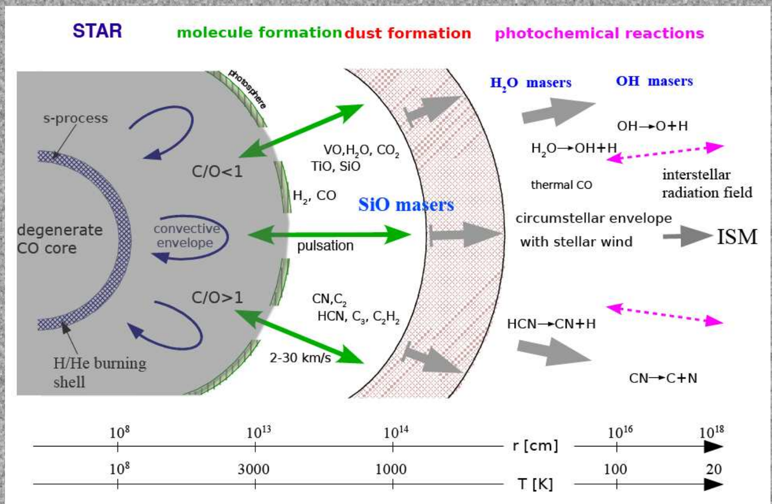


W Hya
ALMA 338 GHz/0.9 mm
Vlemmings et al. 2017

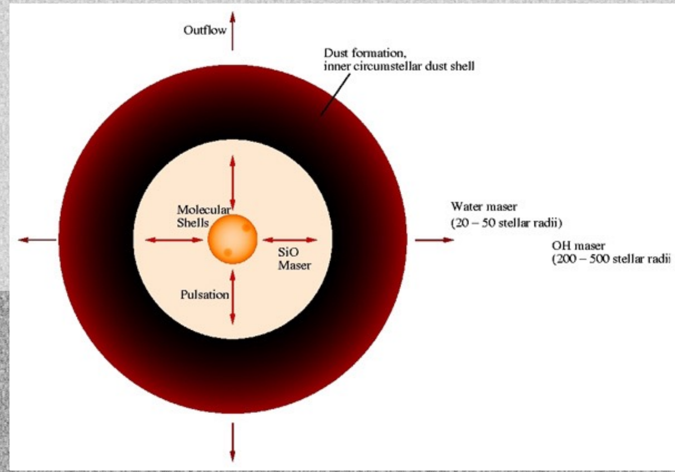
Convective cells can have a lifetime of many years (Freytag et al. 2017)

See also Matthews et al. 2018

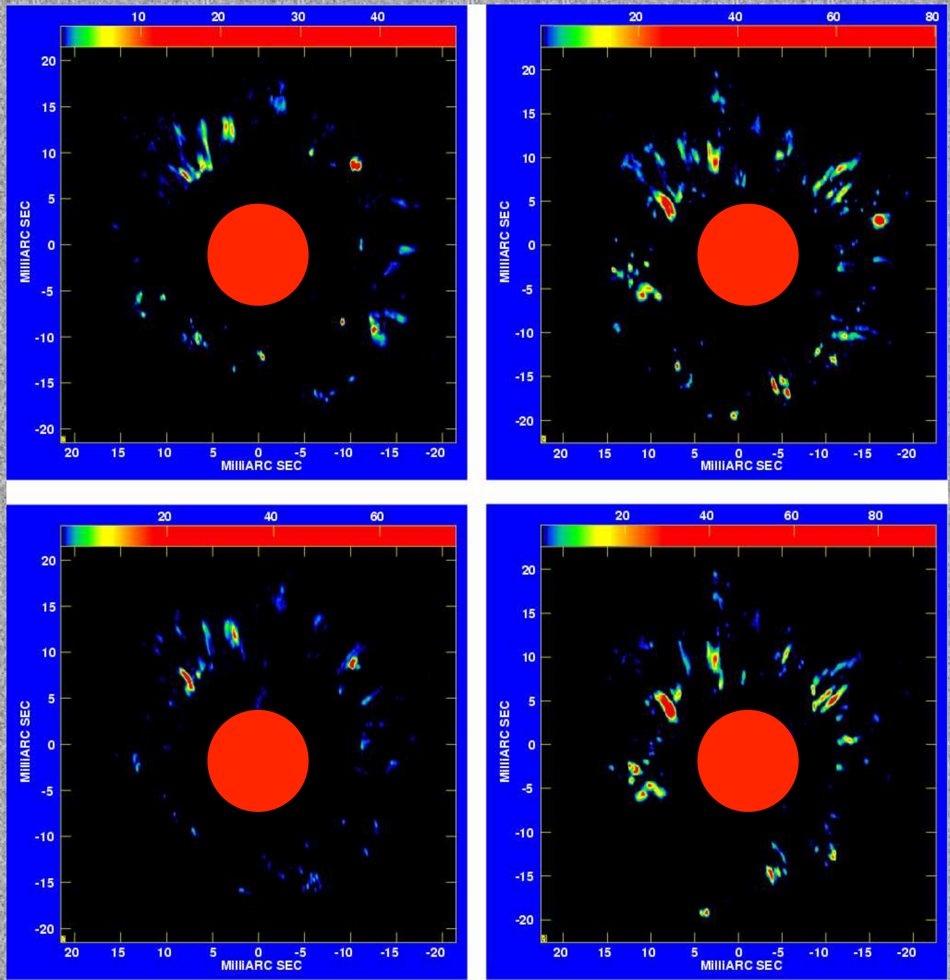
Inner circumstellar envelope (CSE)



SiO masers < 5 R*



TX Cam at 4 epochs

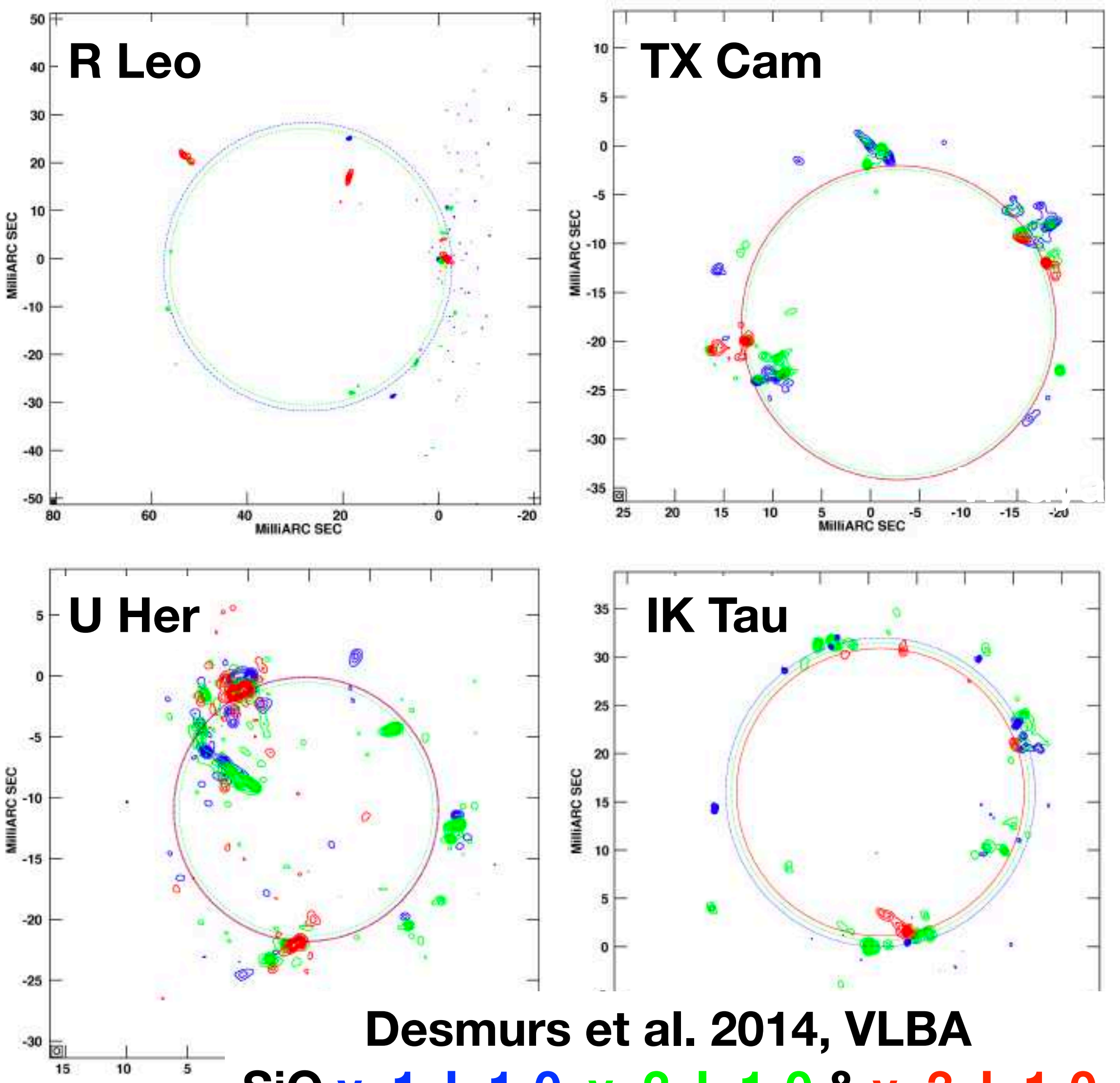


VLBA - 43 GHz

Yi et al. 2005

- Rings of maser features at ~2 - 4 R*
- Star is resolved out (marked on "by eye" here)
- Proper motions give 3D velocities
- Use to derive magnetic-field, physical conditions (T~1500 K; $n(H_2)\sim 10^9$ cm^{-3})
- Use e.g. VLBA at 43 and 86 GHz, KVN, …

Gallery of SiO maser rings

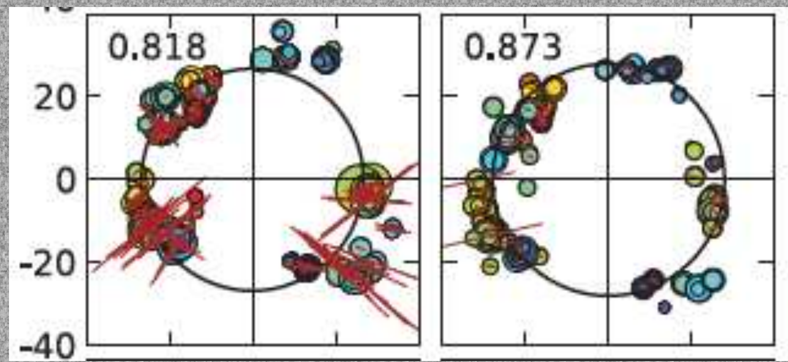


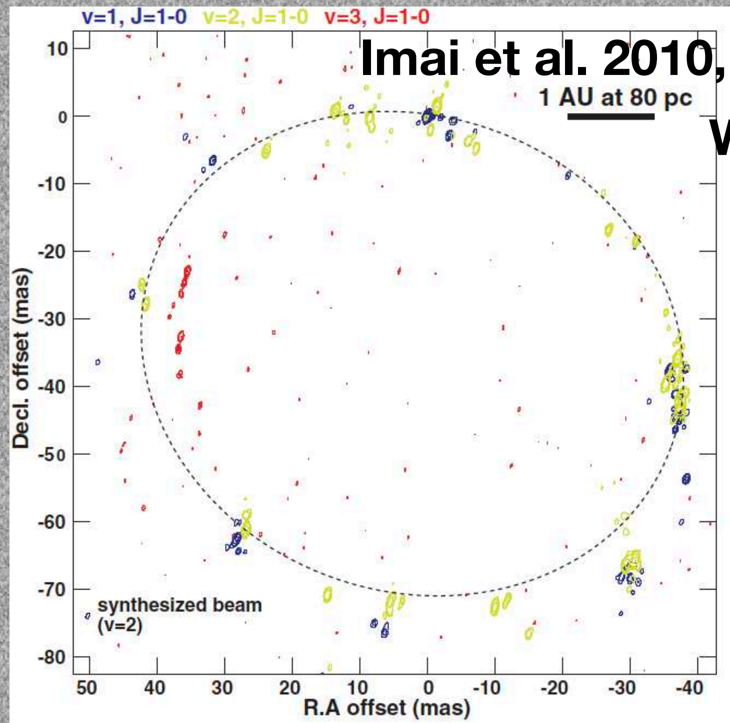
Desmurs et al. 2014, VLBA

SiO v=1 J=1-0, v=2 J=1-0 & v=3 J=1-0

R Cas - Assaf et al. 2013

Multiple VLBA epochs & polarization

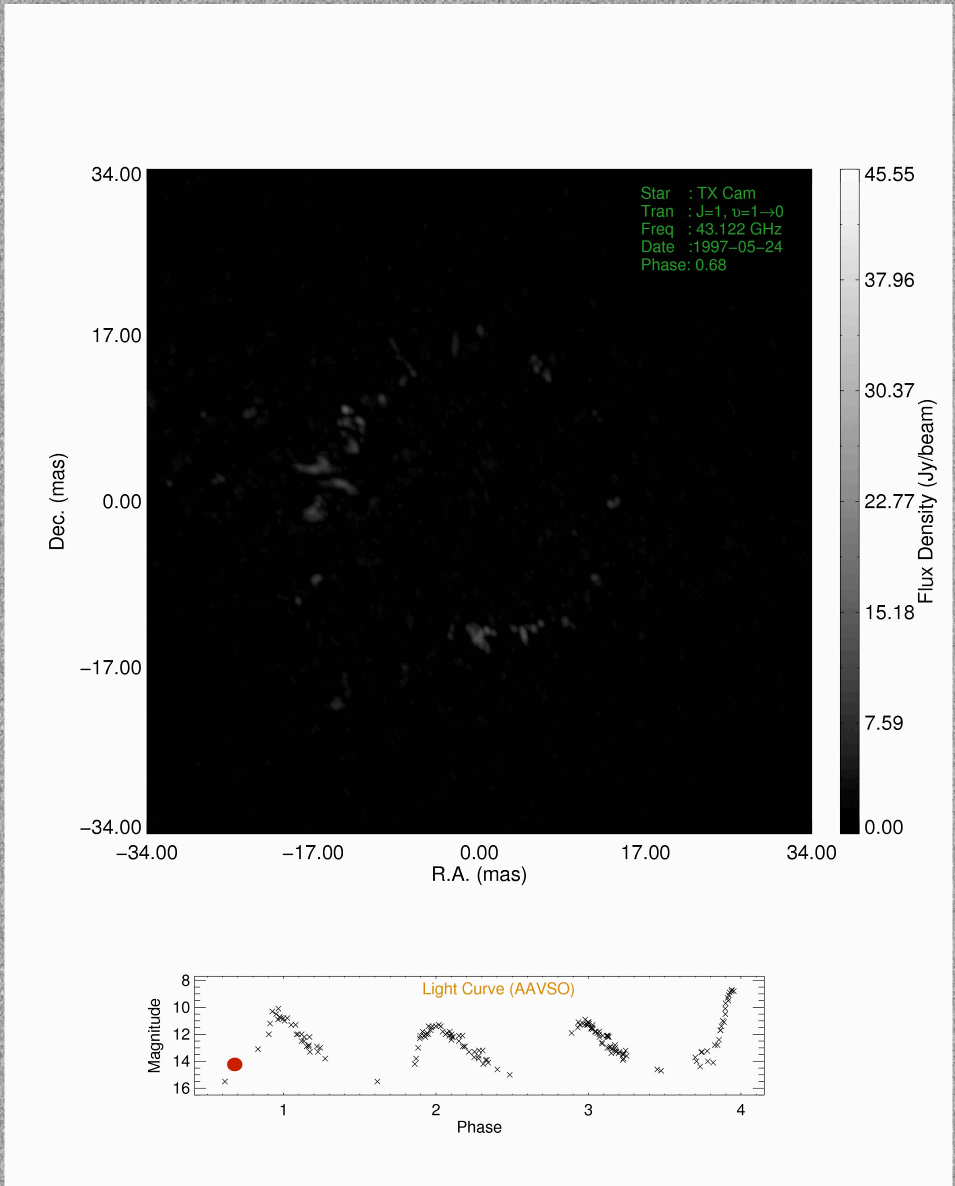




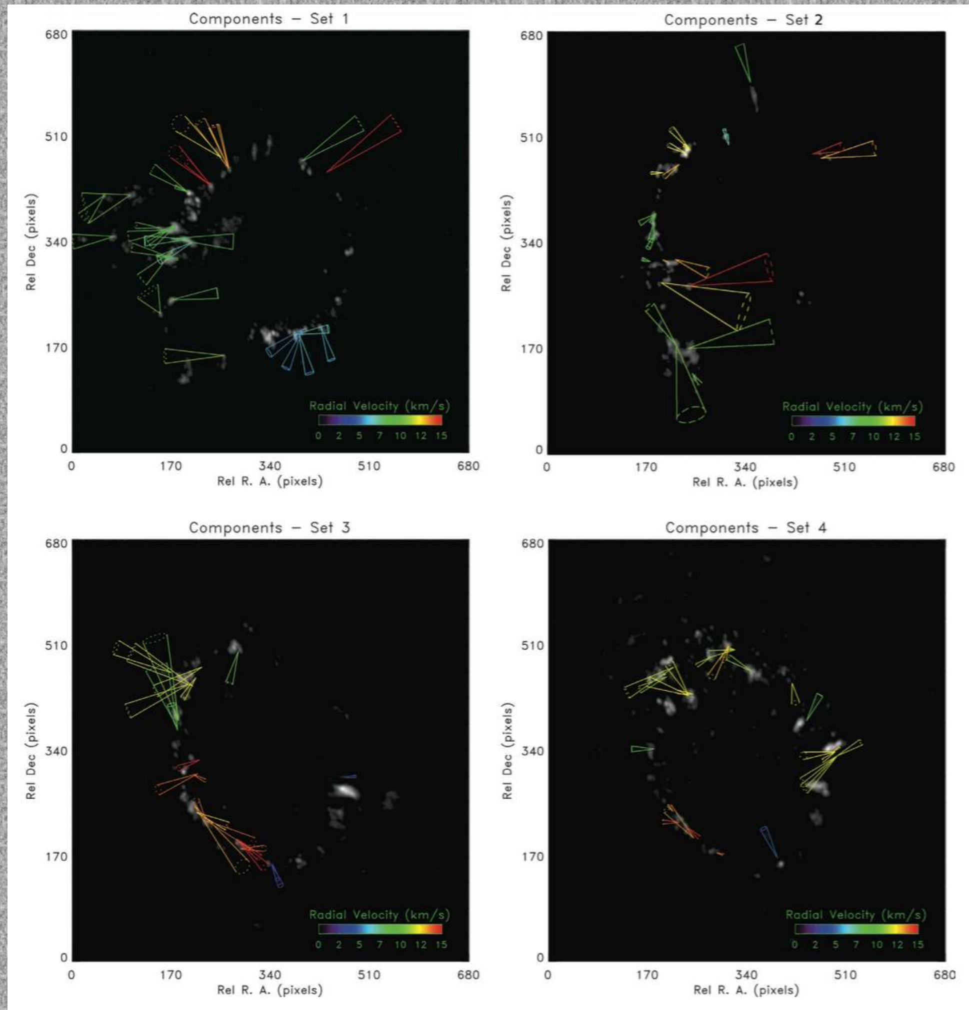
Imai et al. 2010, VERA

VLBI observations can resolve out large proportions of the SiO maser flux e.g. Desmurs et al. 2018

TX Cam: ~2 stellar cycles



3D Component Kinematics

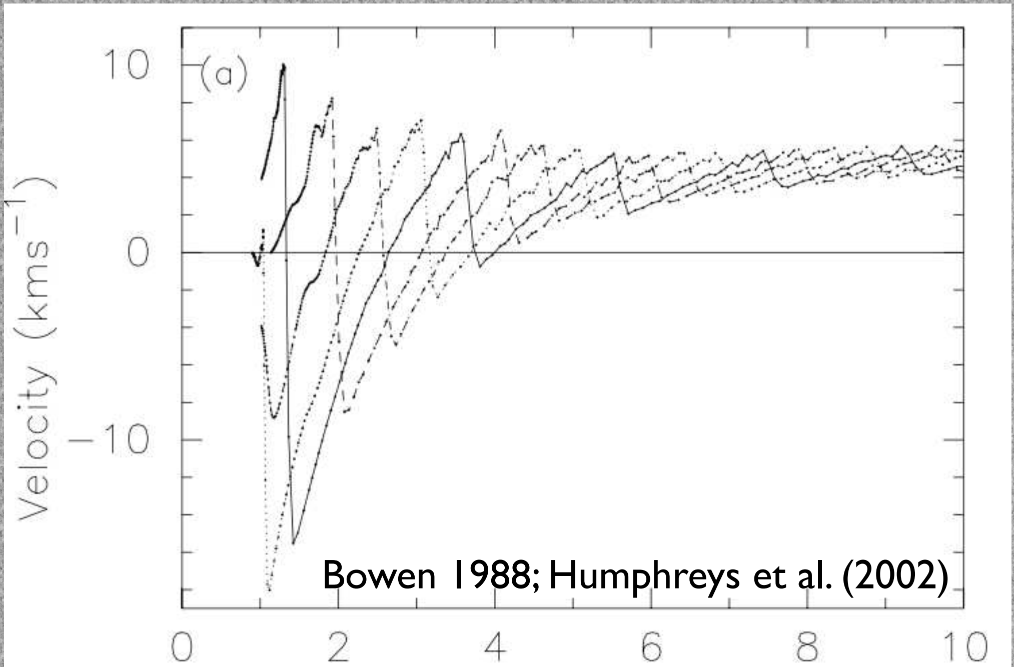


Gonidakis et al. 2013; VLBA 43 GHz

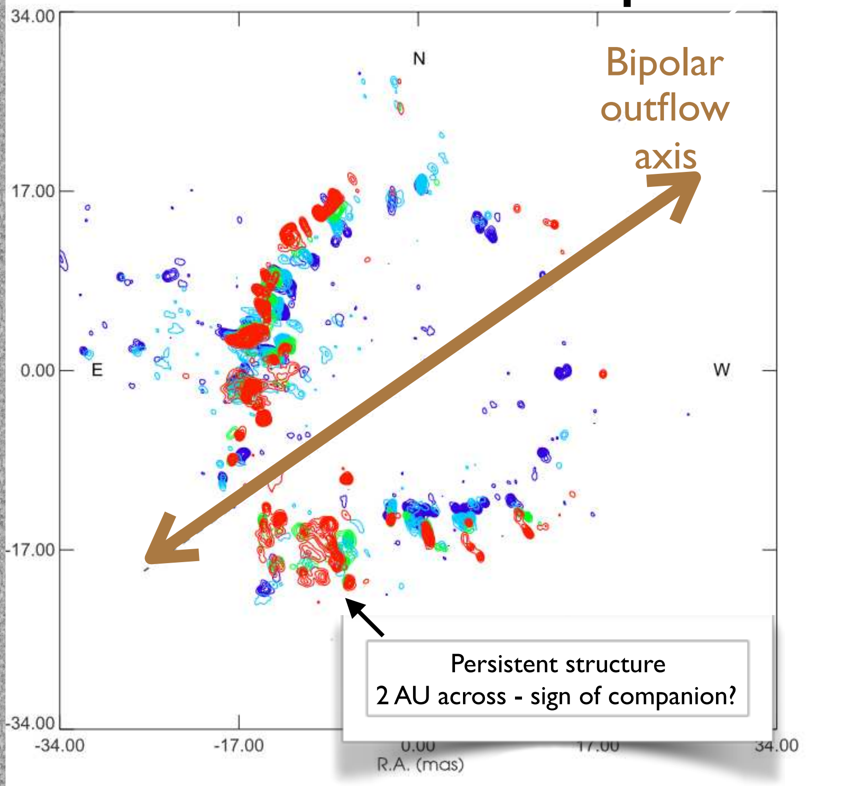
Outflow and infall detected, complex non-radial motions

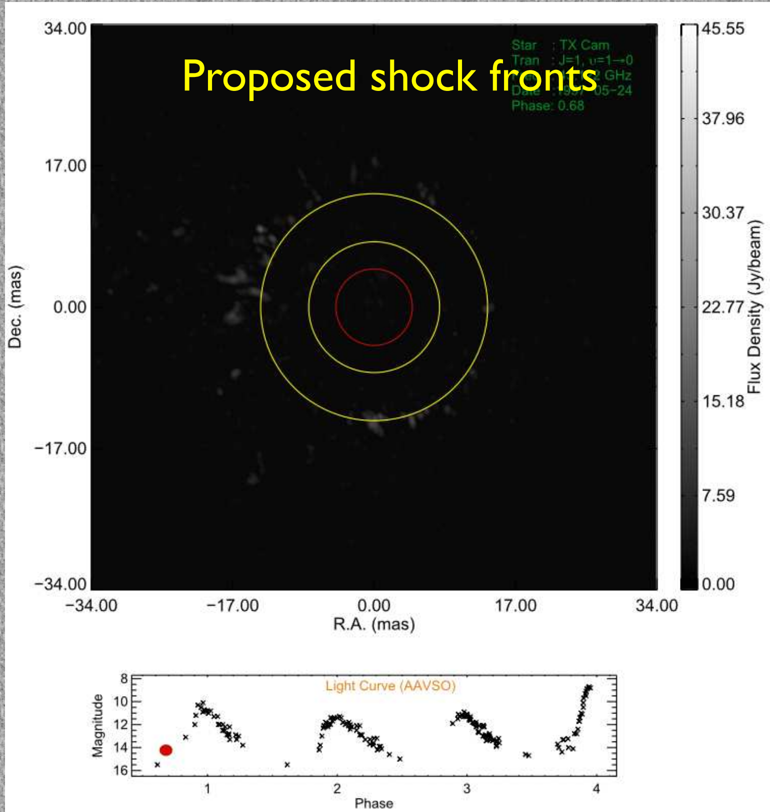
Shock velocity ~7 km/s, broadly consistent with radio photosphere constraints

Evidence for bipolar outflow



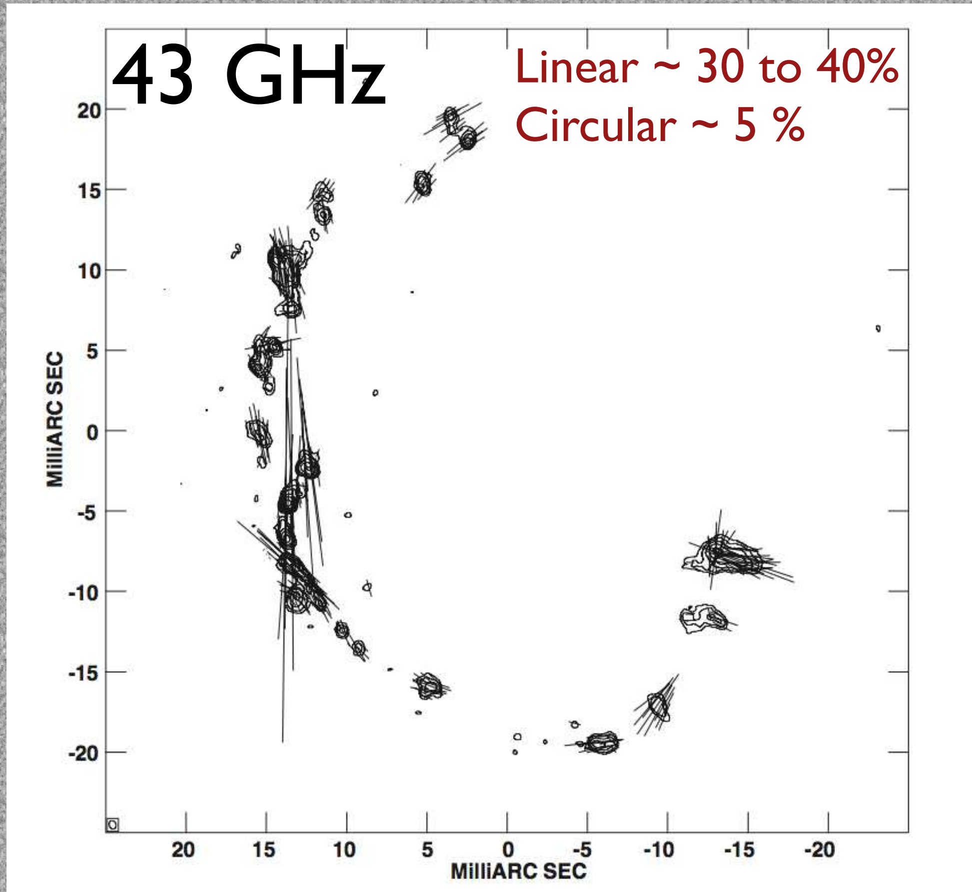
Colours are different epochs





SiO maser polarization

- Linear polarization —> magnetic field morphology
- Circular polarisation —> average l-o-s magnetic field strength
- Ordered magnetic fields of a few Gauss in AGB stars



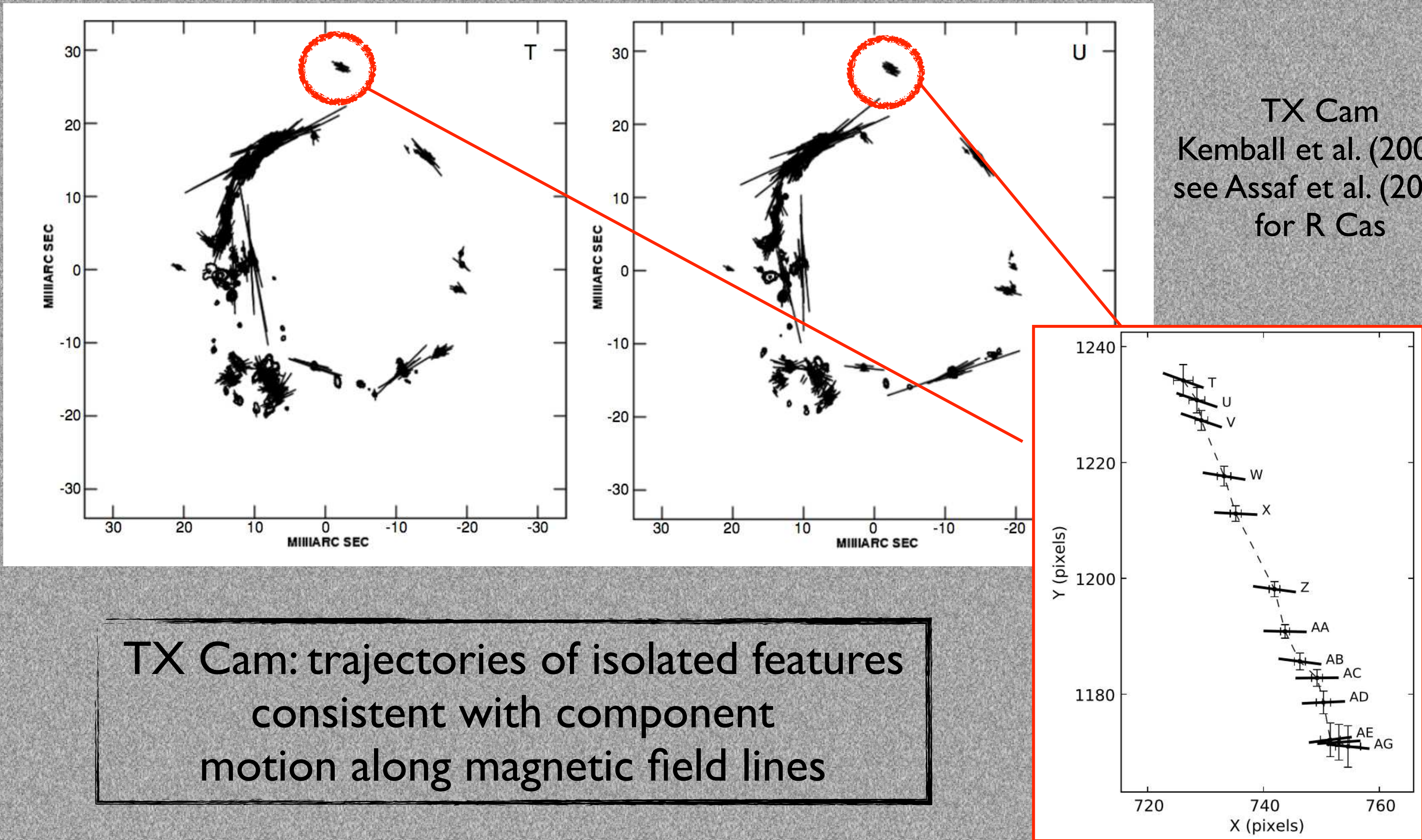
Kemball et al. (2009, 2011, VLBA)

Largely tangential linear polarization pattern

Assumed here as due to the Zeeman Effect

See also e.g. Assaf et al. 2013

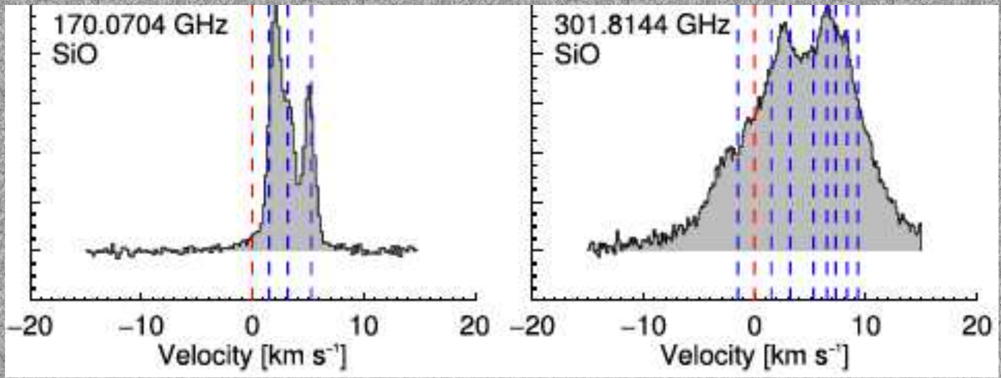
Is the magnetic field dynamically-significant in the TX Cam inner CSE?



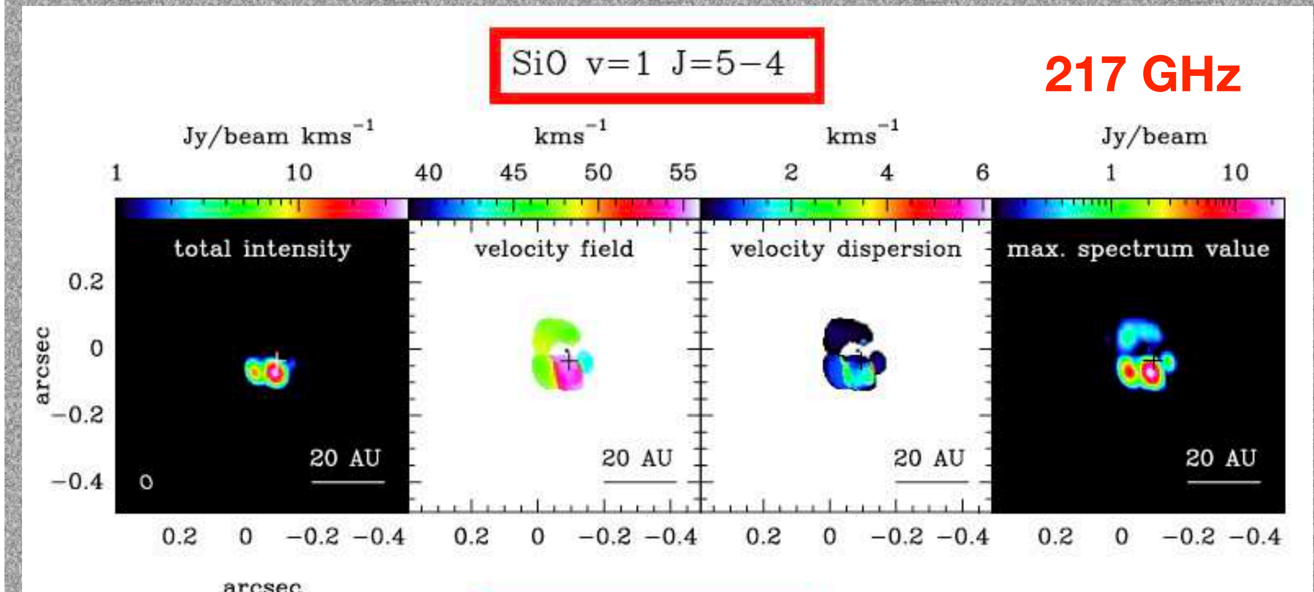
TX Cam
Kemball et al. (2009),
see Assaf et al. (2013)
for R Cas

TX Cam: trajectories of isolated features consistent with component motion along magnetic field lines

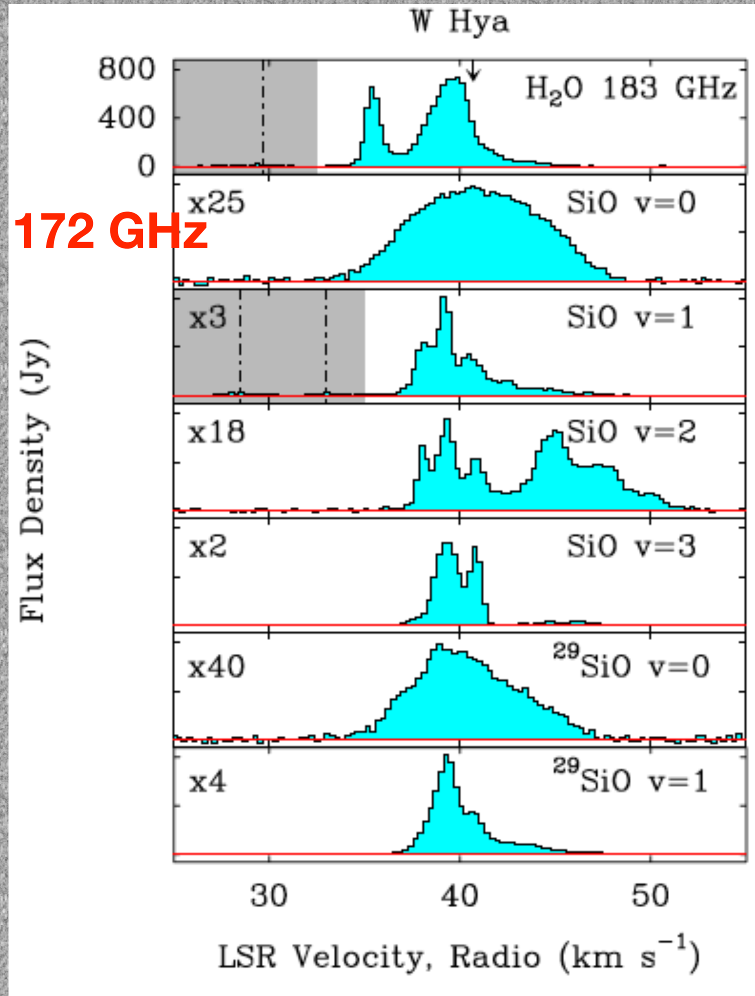
Evolved star mm/submm SiO masers



R Dor, APEX, De Beck & Olofsson 2018

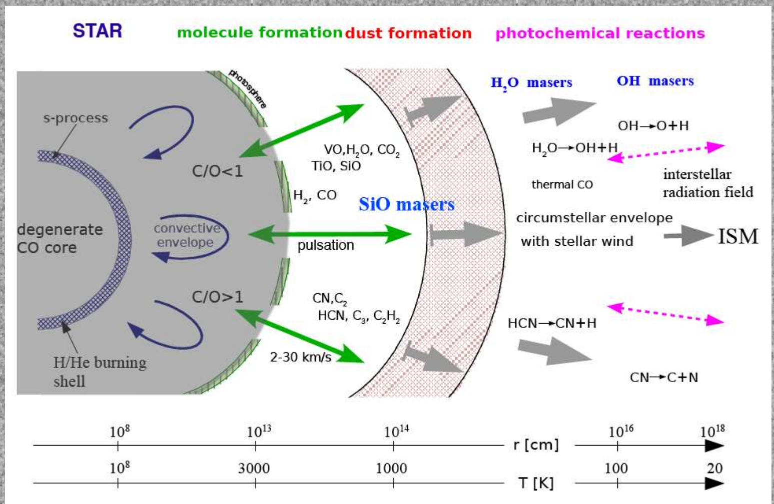


Mira, ALMA long baseline science verification data



SiO J=4-3 lines, APEX
Humphreys et al. 2017

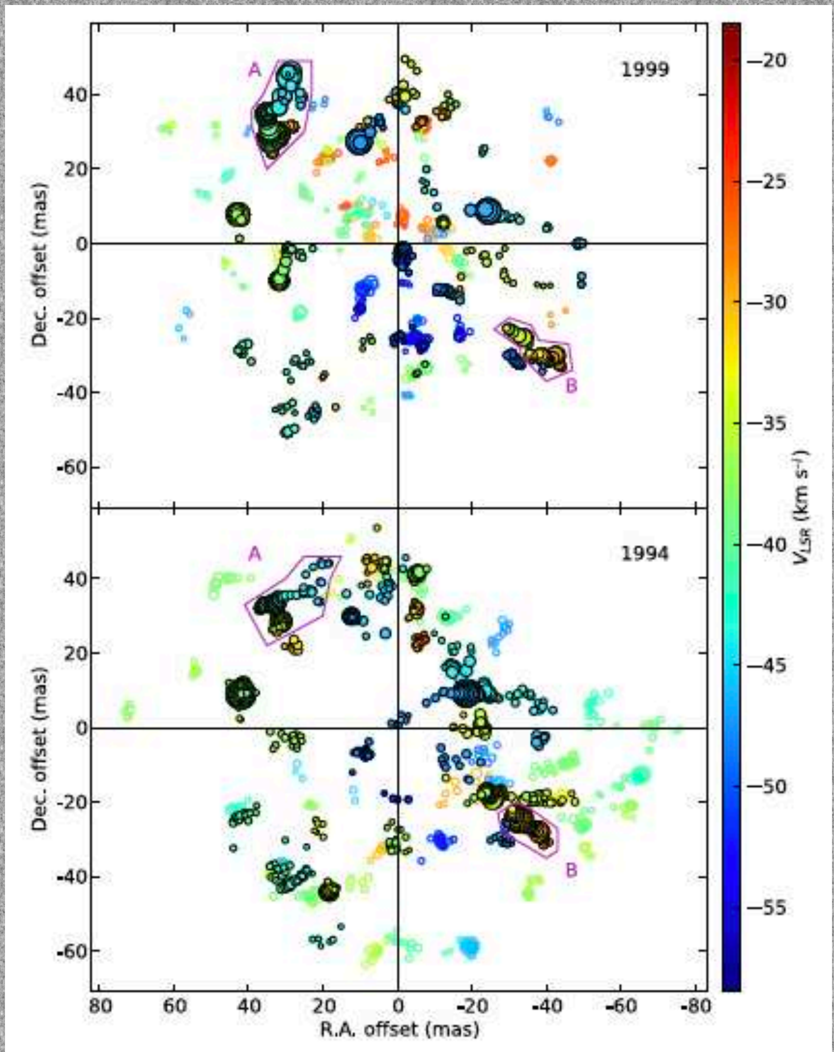
Wind Acceleration Zone / H_2O Masers

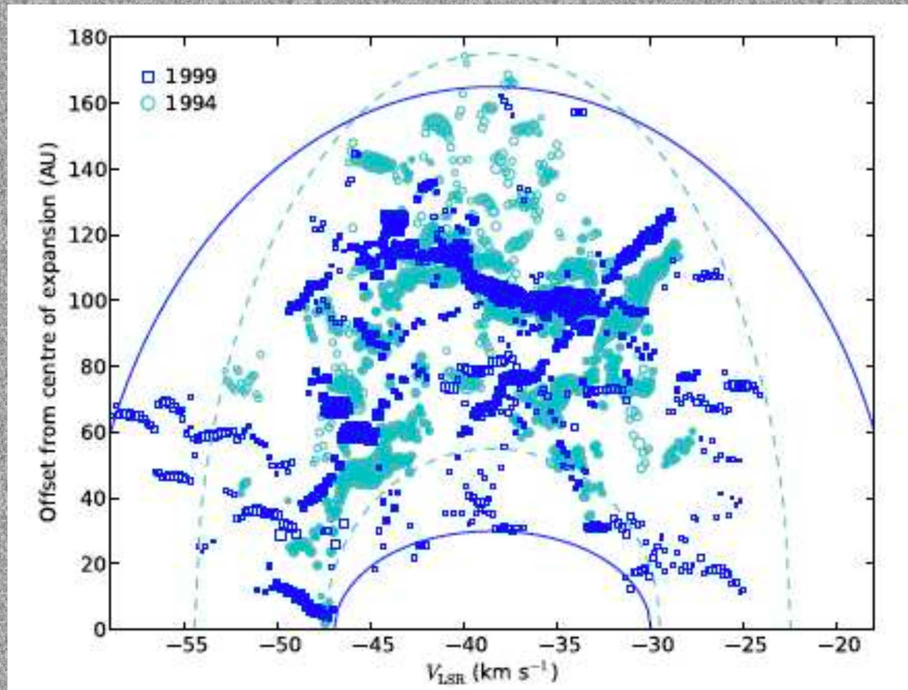


H_2O Masers at 22 GHz: 5 - 50 R_*

(very approximate radii)

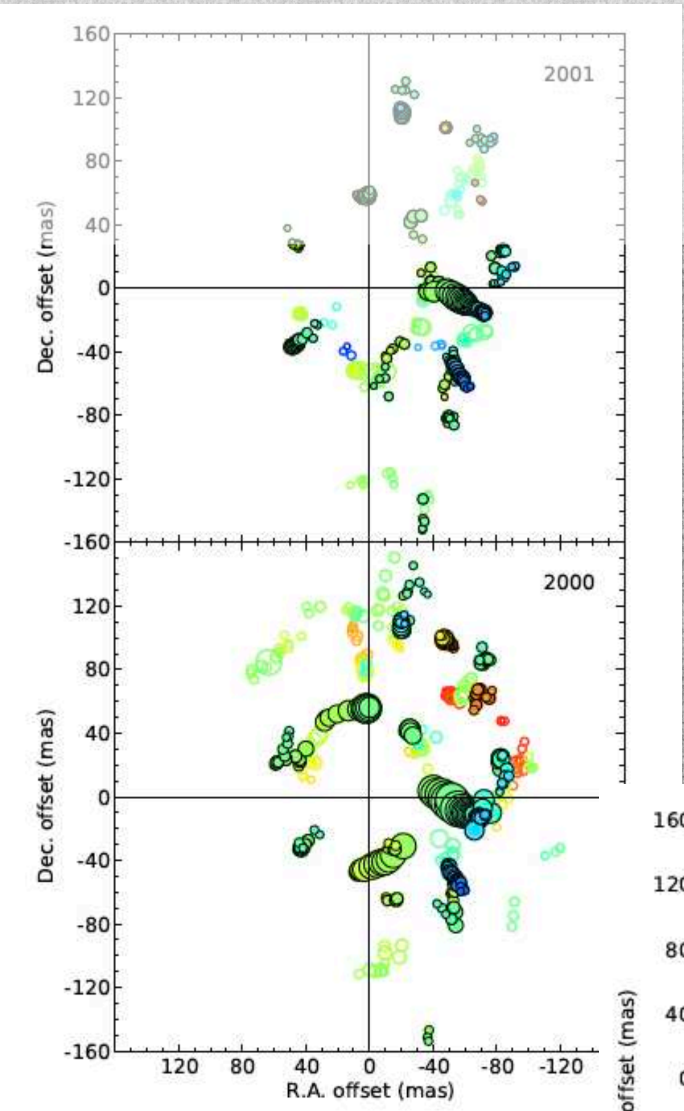
S Per - RSG

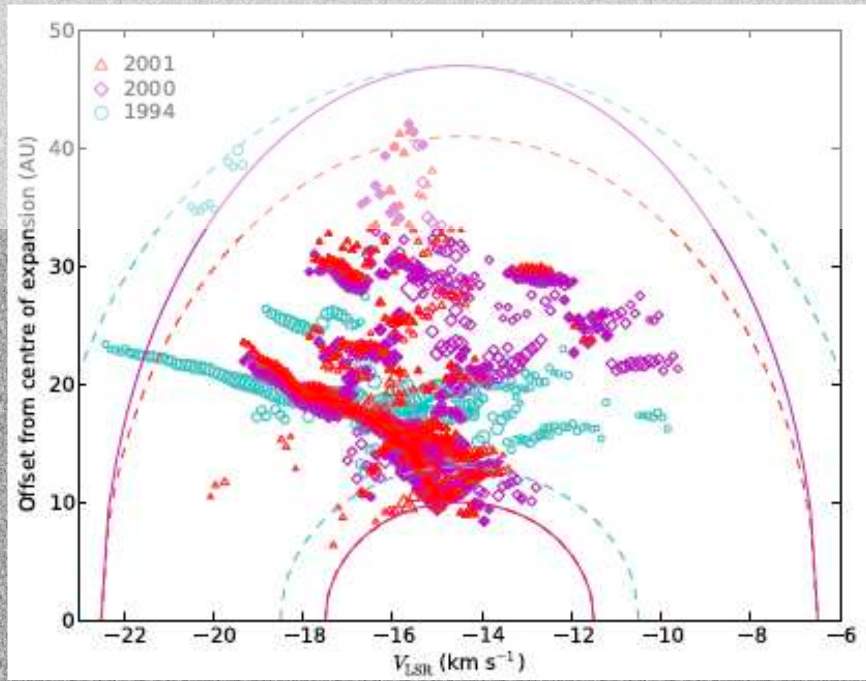




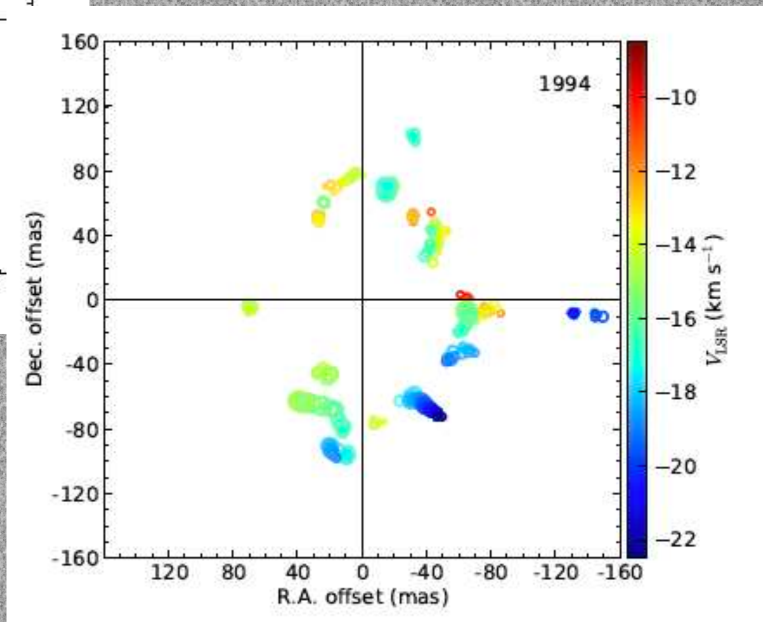
Projected distance of masers from expansion centre as a function of V_{LSR}

Richards et al. 2012, MERLIN; 10 to 50 mas resolution





Inner and outer shell radii and expansion velocities for spherical shells



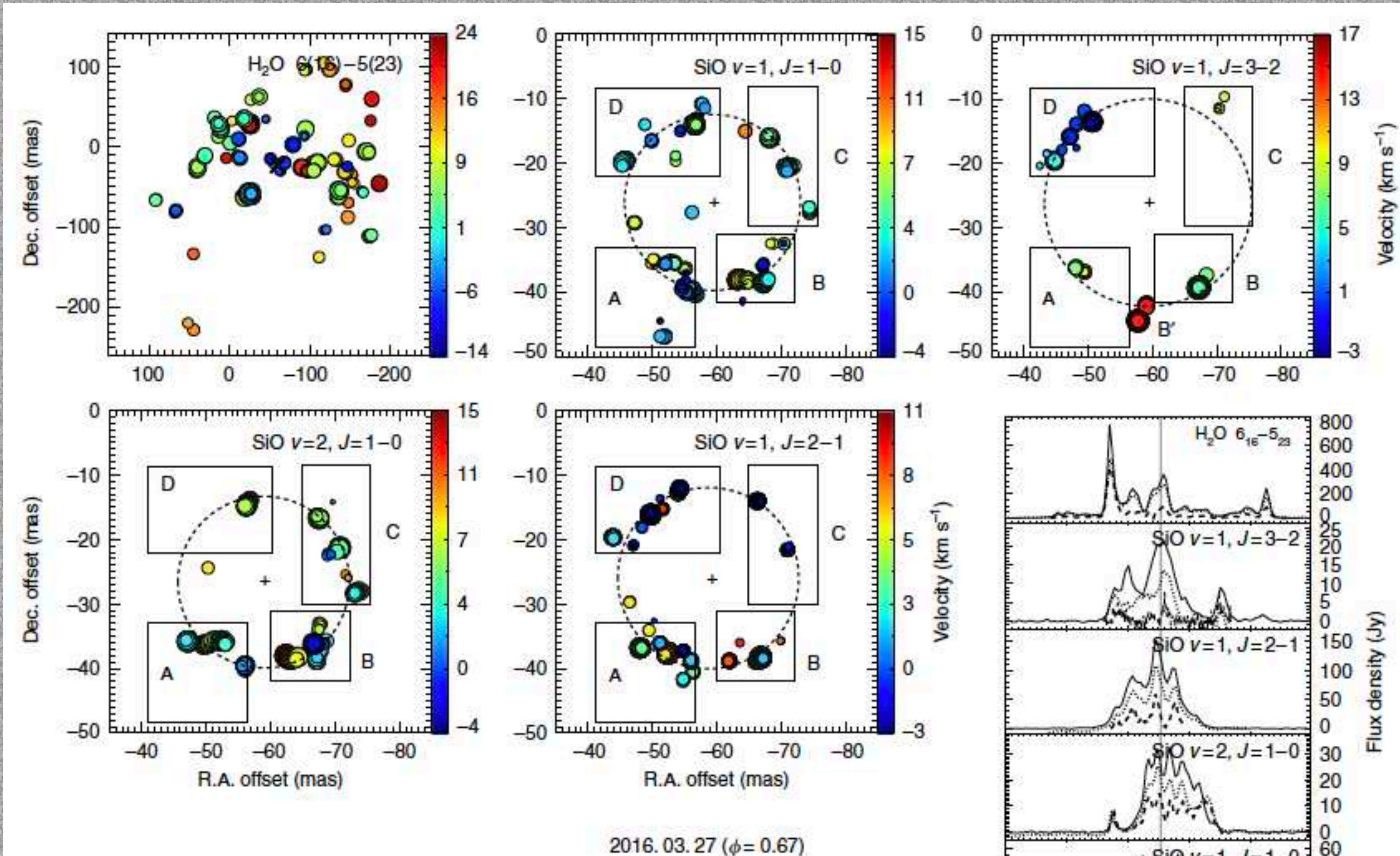
Expansion velocity increases by >= factor 2 between inner and outer shells

U Her - AGB

Richards et al. 2012, MERLIN; 10 to 50 mas resolution

Simultaneous SiO & H_2O Observations

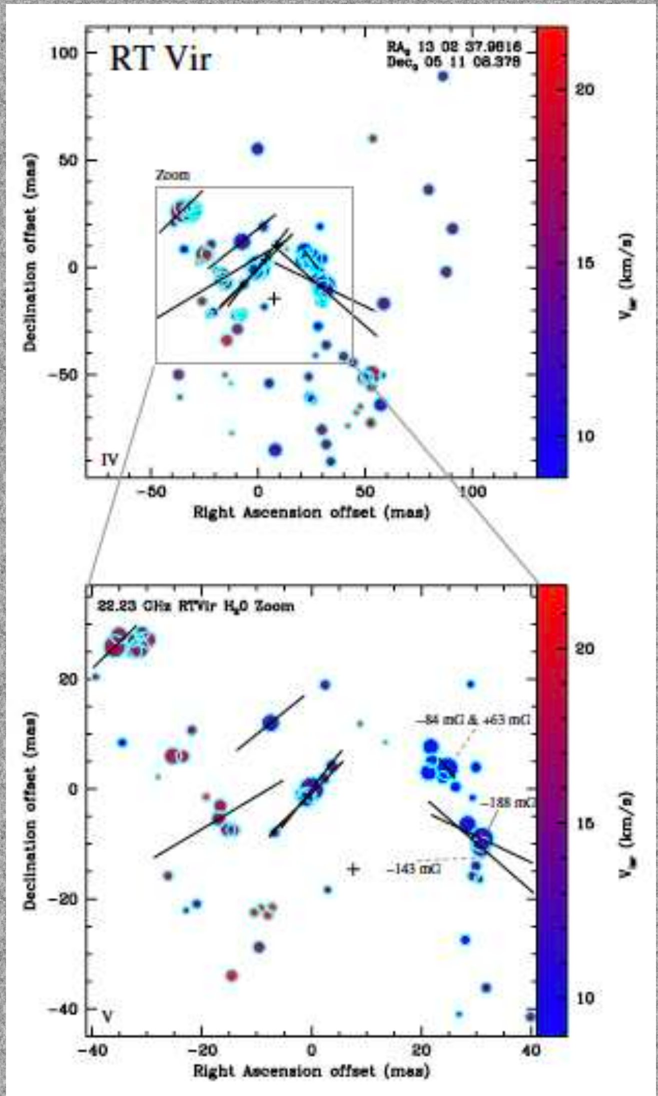
KVN - VX Sgr - Yoon et al. 2018: 22, 43, 86, 129 GHz



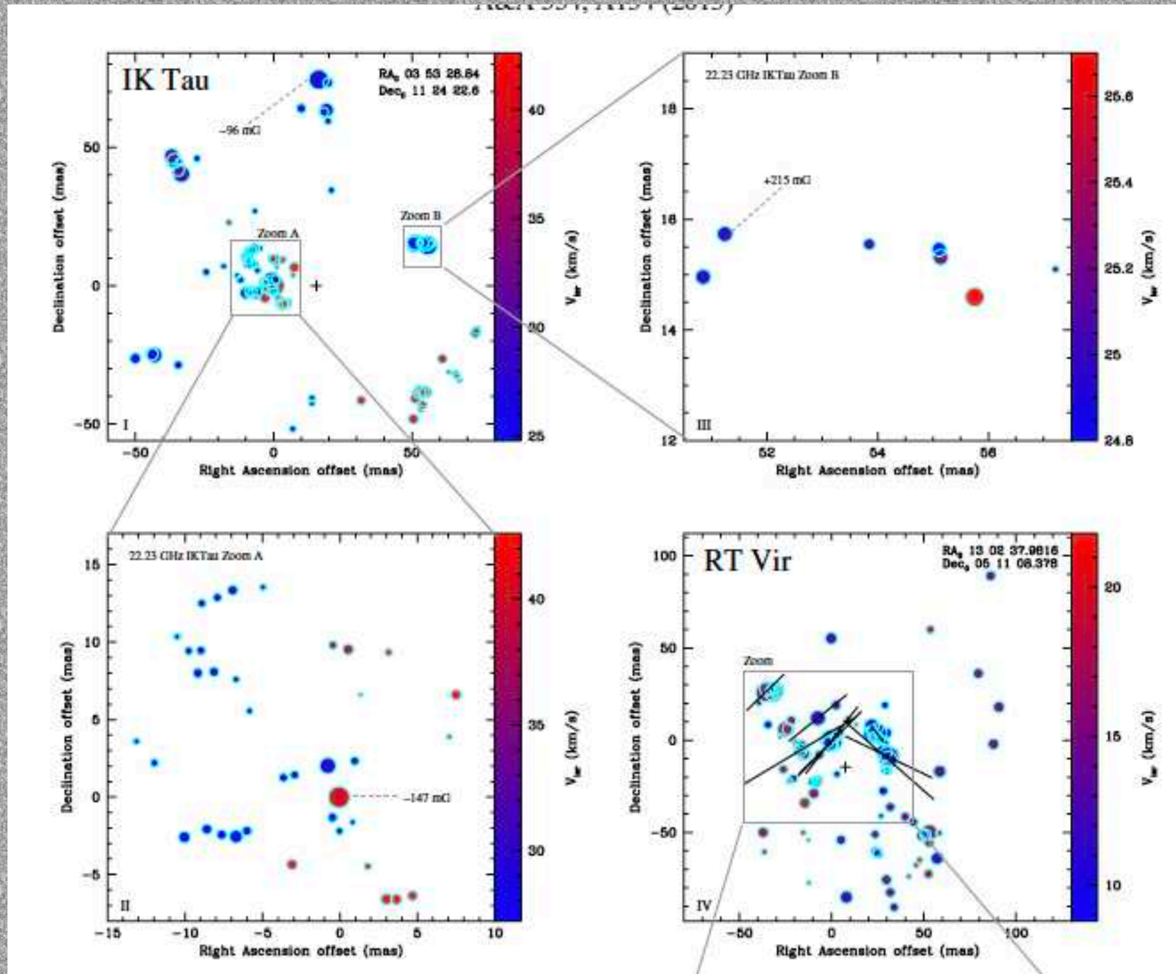
Simultaneously tracing gas both sides of the dust formation zone

H_2O maser polarization

~2 mas resolution



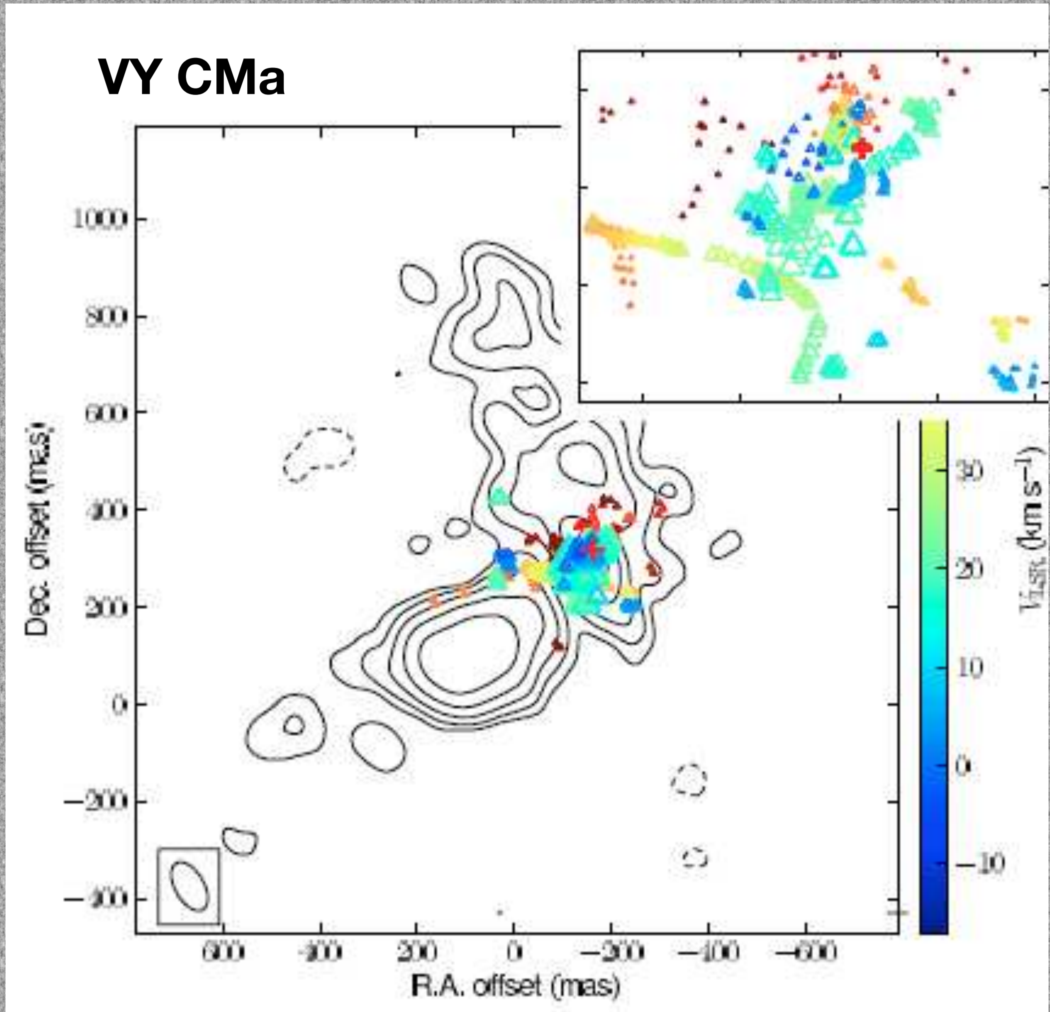
Magnetic fields few hundreds of mG



VLBA; Leal Ferreira et al. 2013

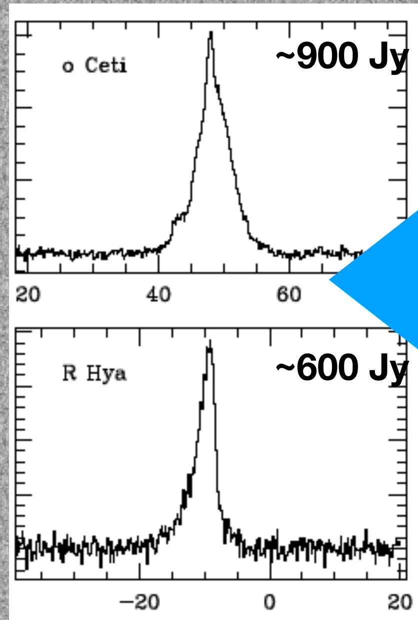
Linear polarisation rare and weak (< 2 %)
Circular polarisation 0.3 to 20%

Evolved star mm/submm H_2O masers



321, 325 and 658 GHz water masers
ALMA, Richards et al. 2014

Contours: submm continuum



658 GHz
Water
Masers

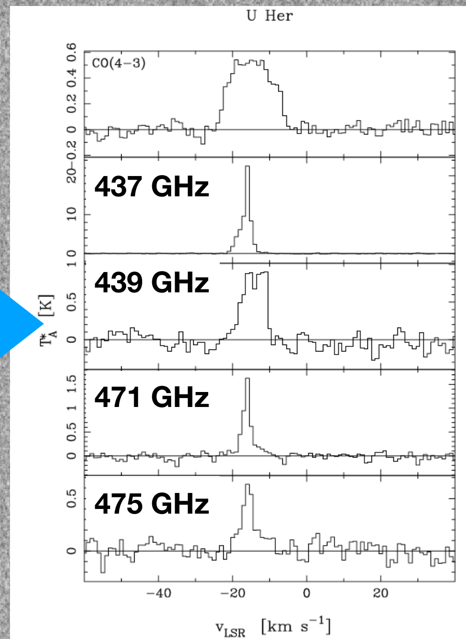
APEX

Baudry et al.
2018

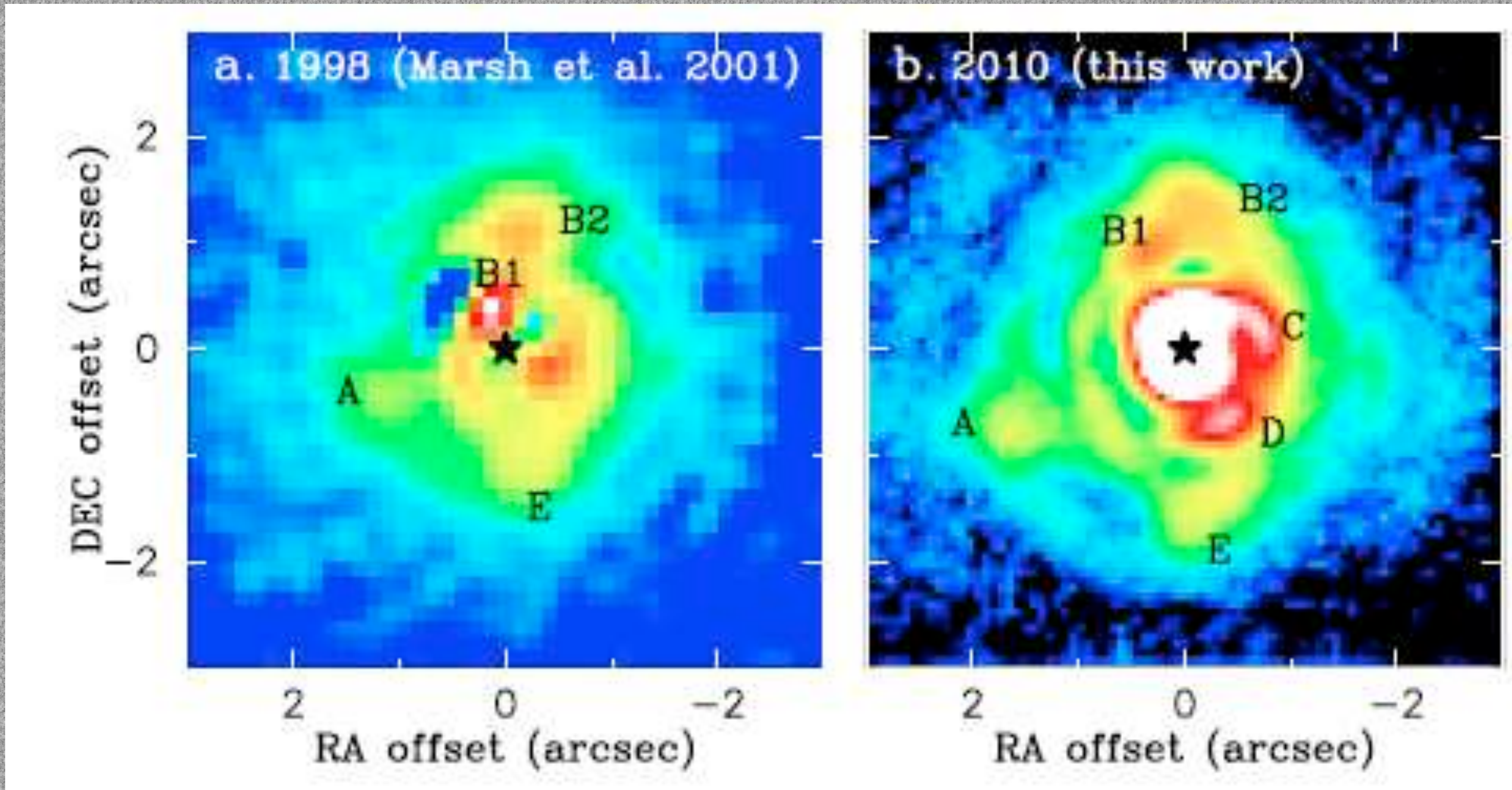
437, 439,
471, 475 GHz
Water
Masers

APEX

Humphreys et al.
in prep



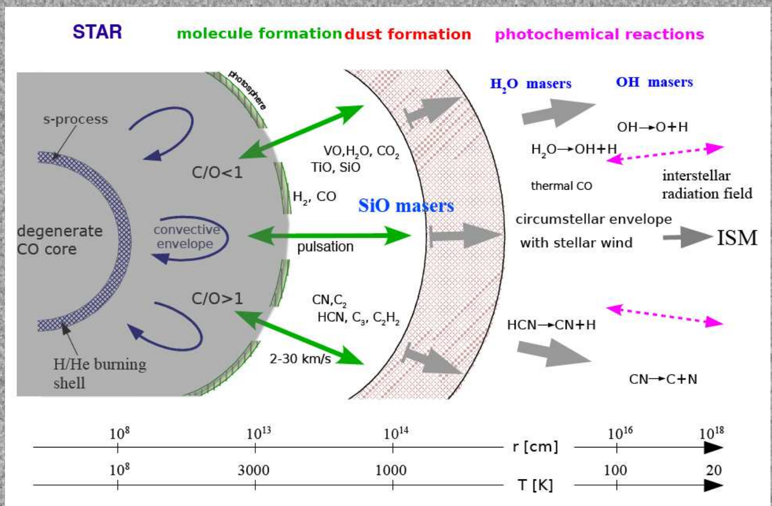
Clumpy dust motions



6 clumpy dust clouds at 43 - 96 R*
Derived expansion velocity ~ 34 km/s

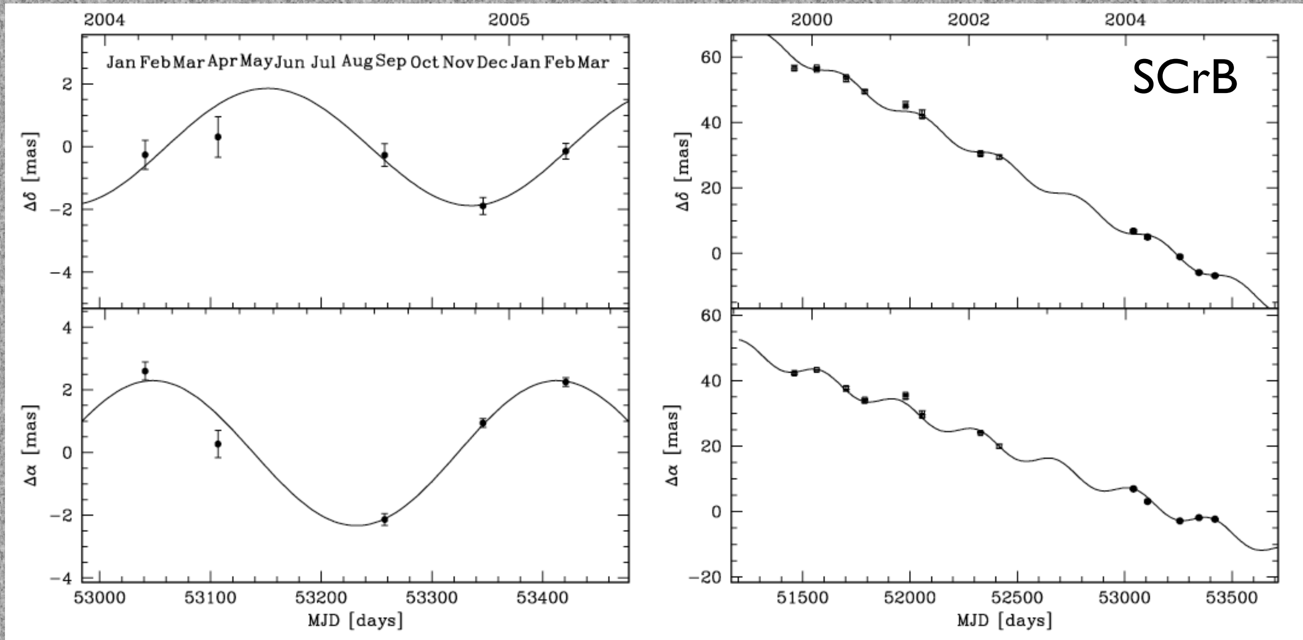
Antares (RSG)
VLT VISIR
17.7 micron; 0.5”
Ohnaka (2014)

Stellar Wind / OH Masers



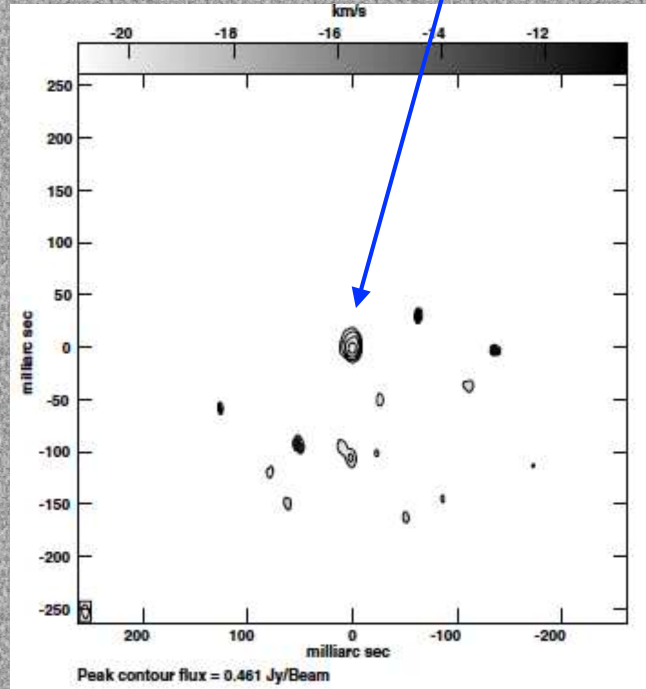
1665 and 1667 OH Masers ~100 - 1000 R*

[Caveat: can be at same distance as 22 GHz H2O masers]



Vlemmings et al. 2007:VLBA at 1665 & 1667 MHz

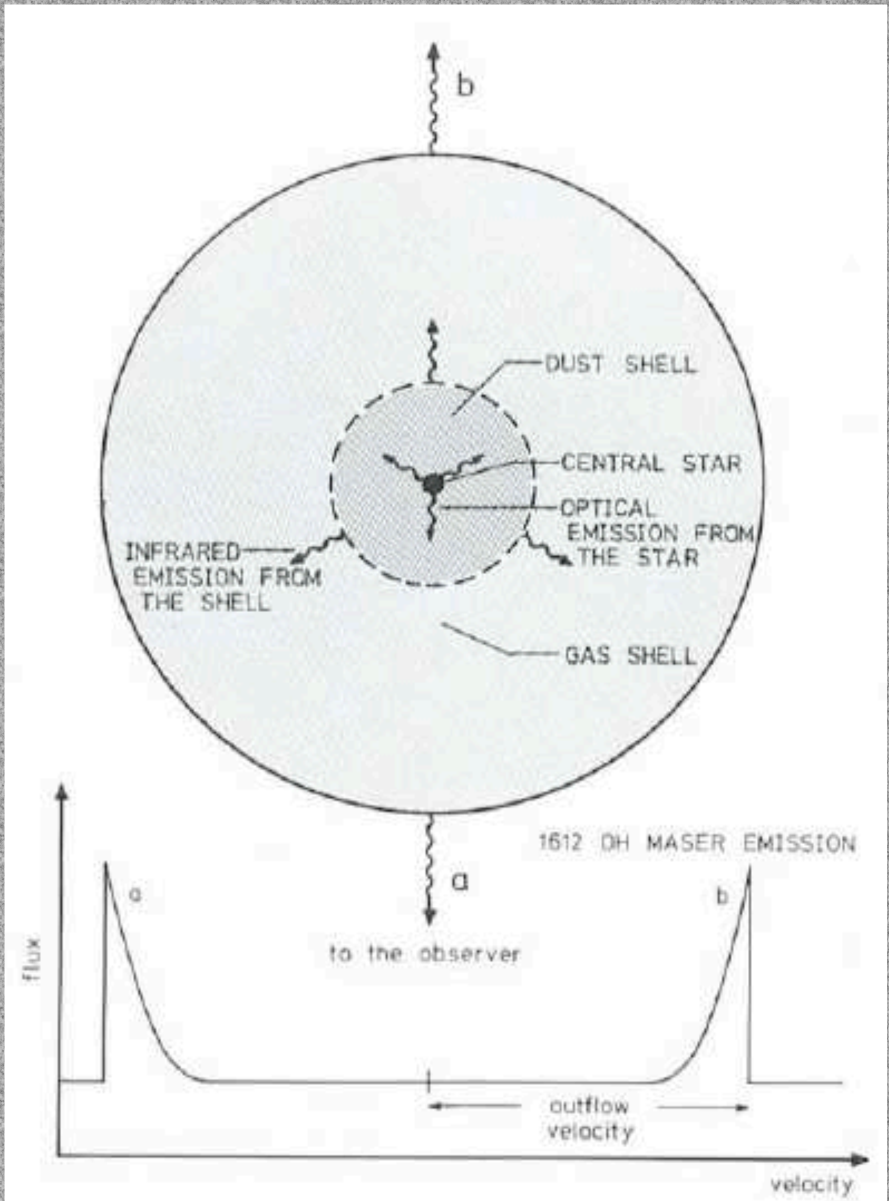
Amplified Stellar Image



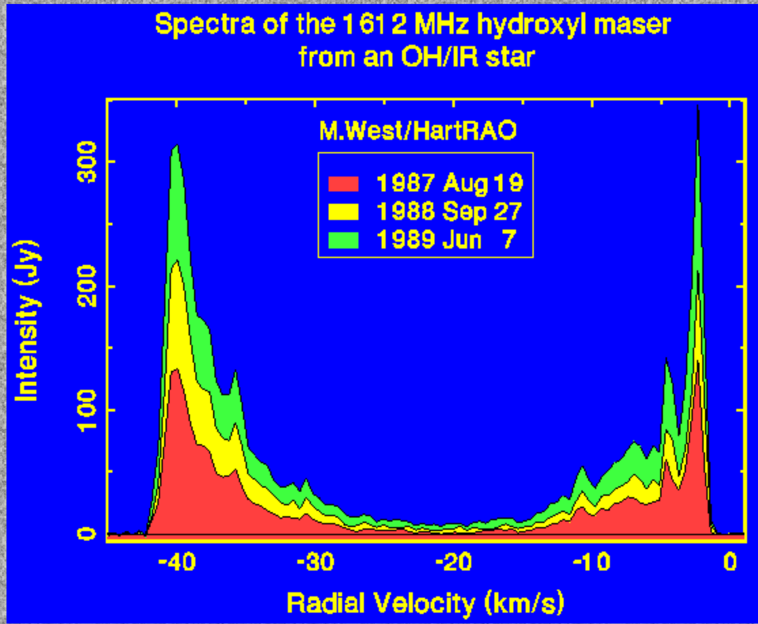
- VLBI astrometric observations of circumstellar OH masers can yield the proper motions and parallaxes of AGB stars
- Most blue-shifted circumstellar OH maser spot believed to be the *Amplified Stellar Image*

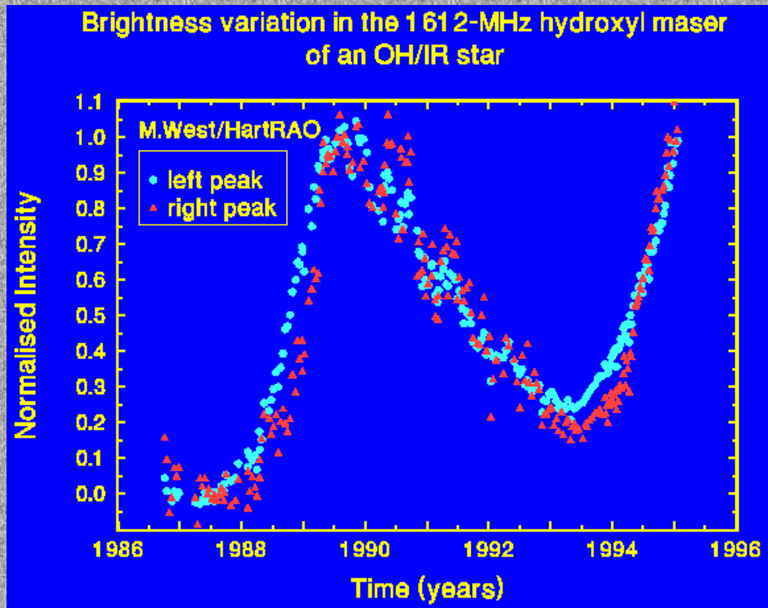
Adding in the SKA to VLBI networks —> very many objects within a few kpc accessible (Green et al. 2015)

OH 1612 MHz Masers ~ 1000 R*

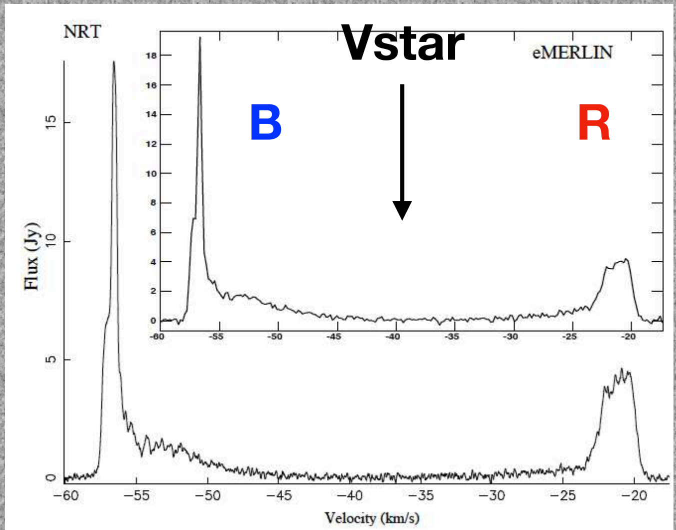


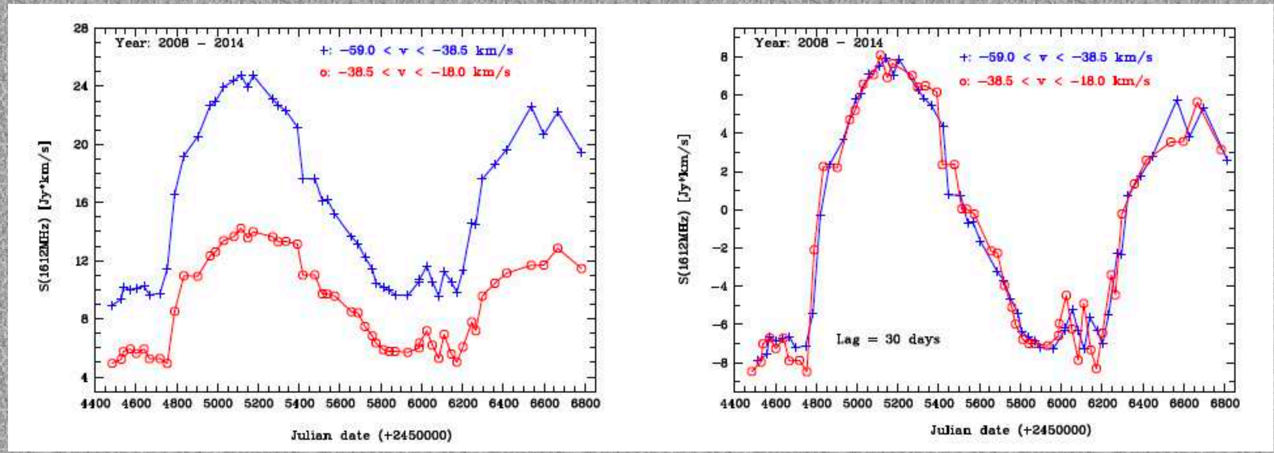
Engels



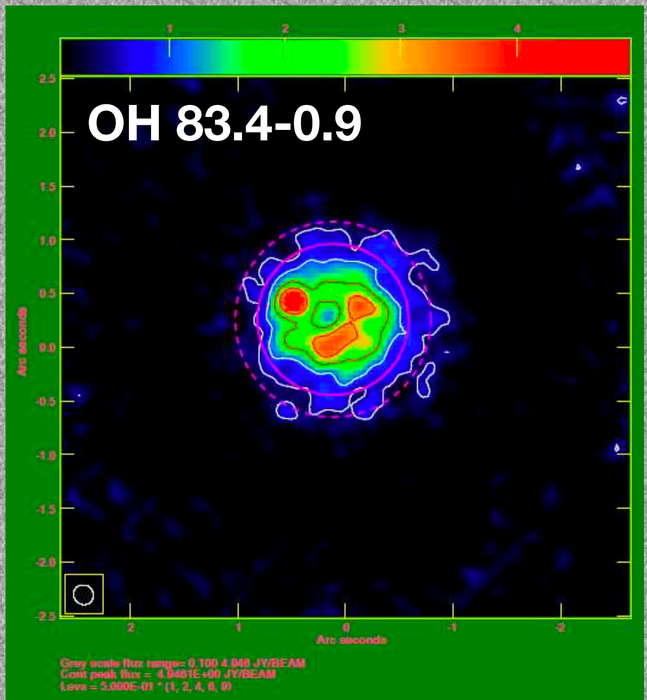


OH 1612 MHz Masers: Phase Lag Distance





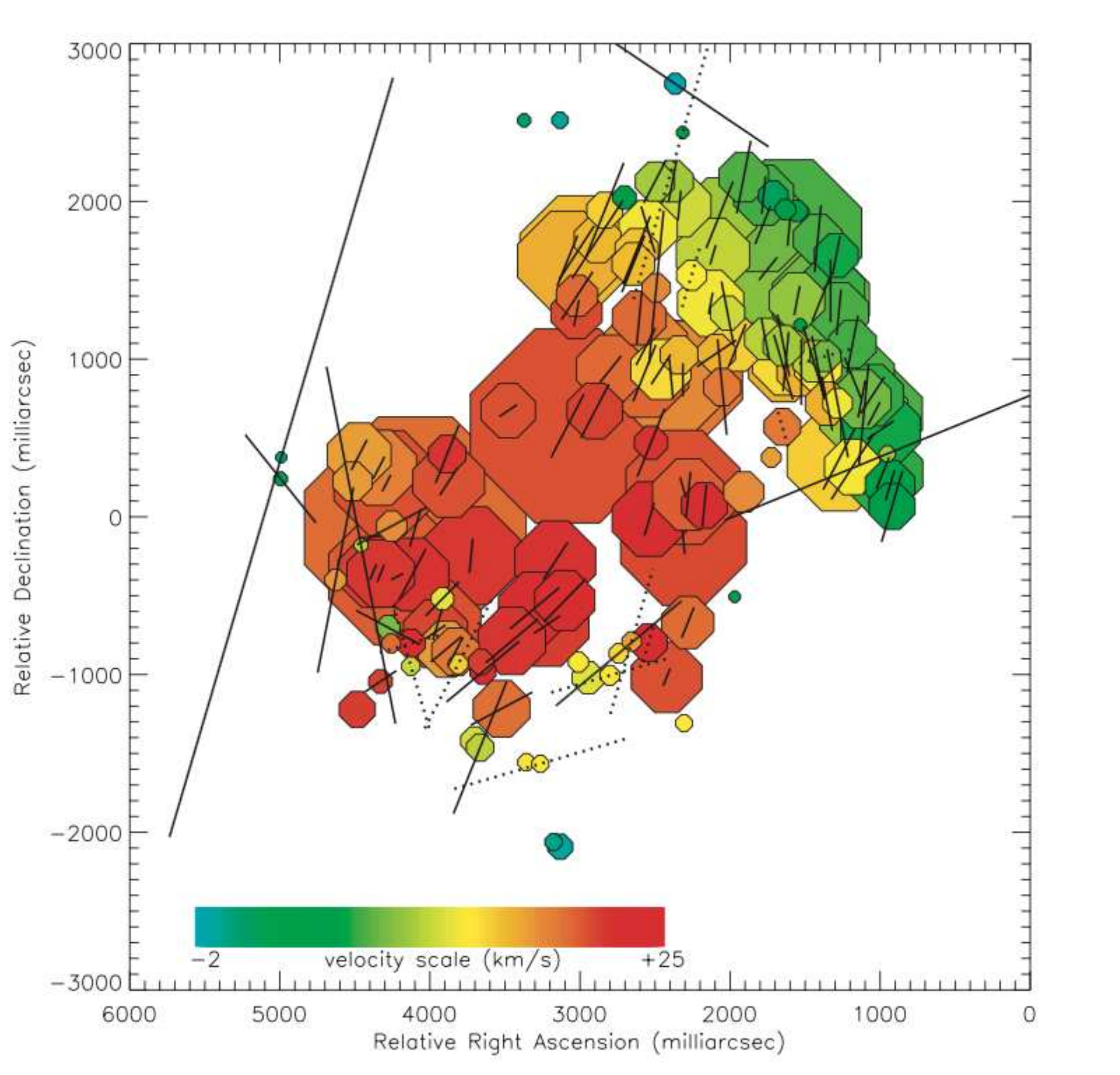
Etoka et al. 2014: Nancay Radio Telescope & e-MERLIN



- Distance determination via the phase lag method
- Measure of OH maser shell angular diameter (interferometer)
- Measure time lag of variability between peaks (single-dish) —> linear diameter

Distance = 3.3+/-0.6 kpc

OH 1612 MHz Masers: Polarization



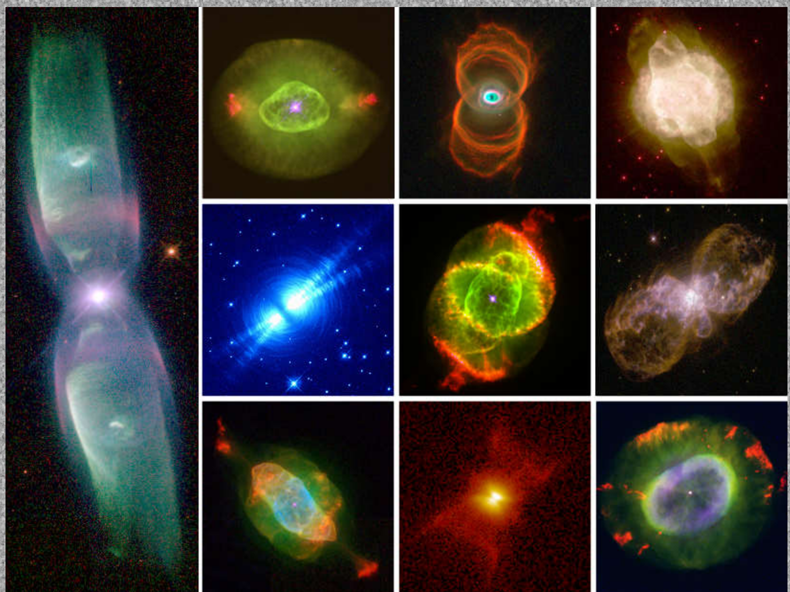
NML Cyg: Etoka & Diamond 2004

MERLIN, 0.17 arcsec resolution

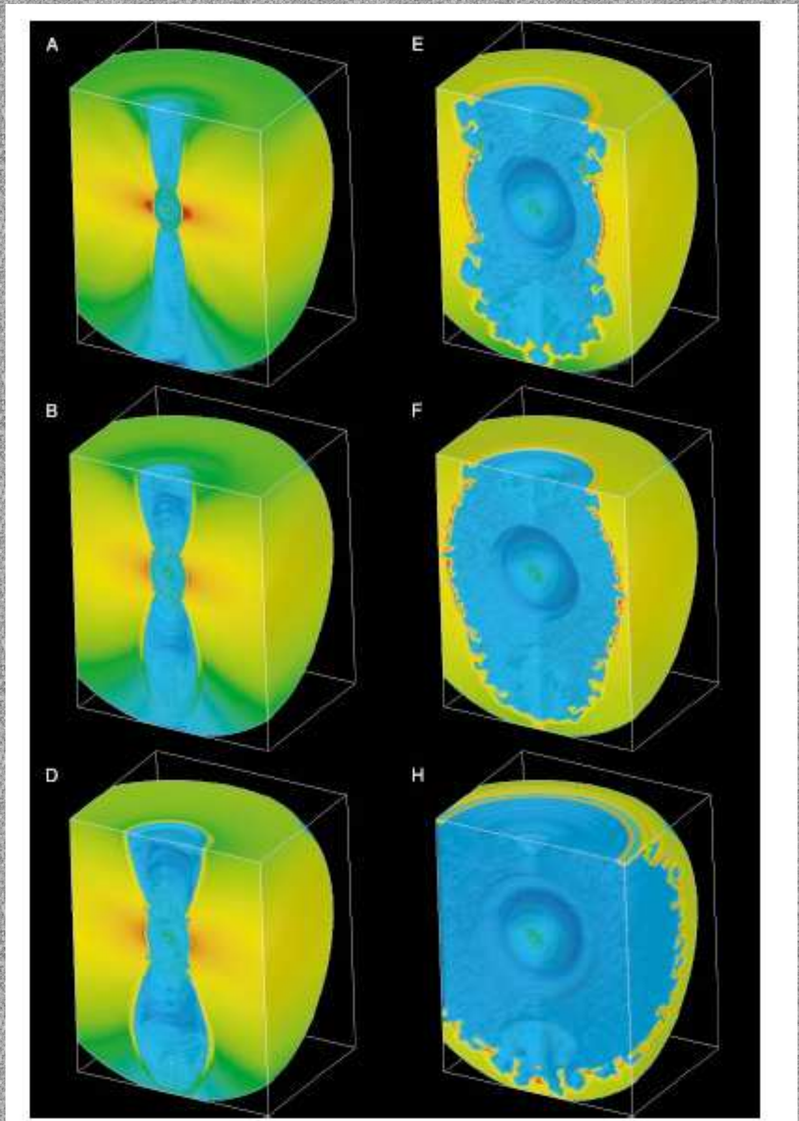
- Often strongly linearly polarised
- Masers reveal an ordered magnetic field several thousands of AU from the star
- Field strength at these distances is typically a few mG

Area of symbol proportional to maser spot intensity

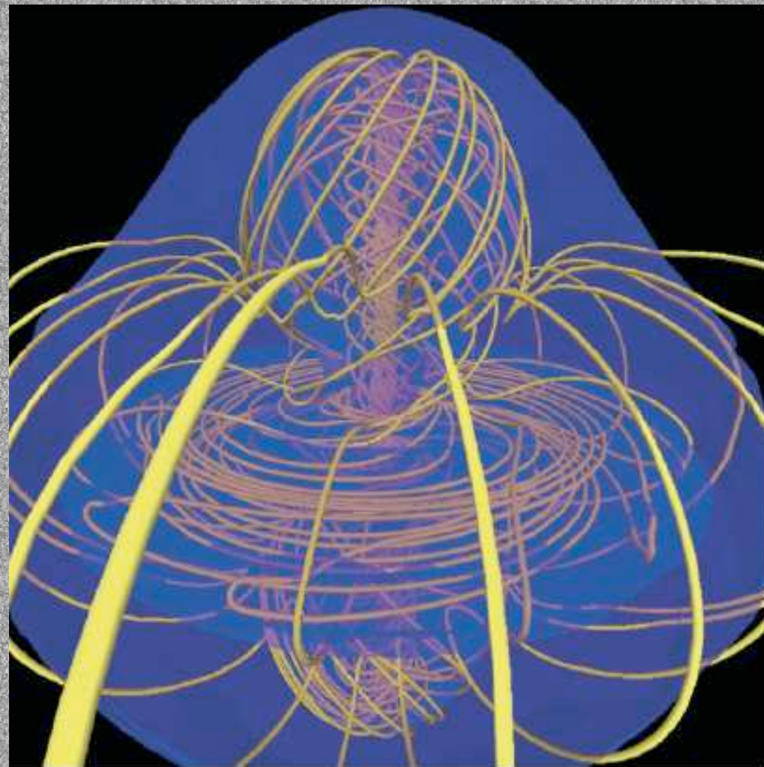
Shaping to Planetary Nebulae



Planetary Nebula Shaping



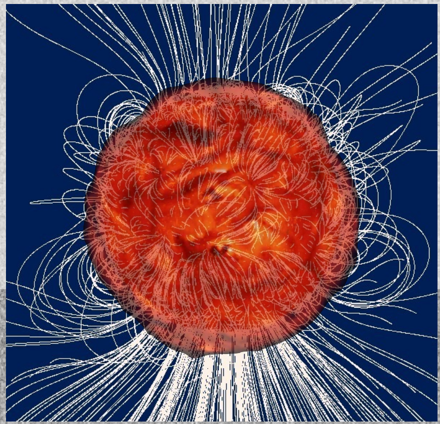
Gawryszczak et al. 2002

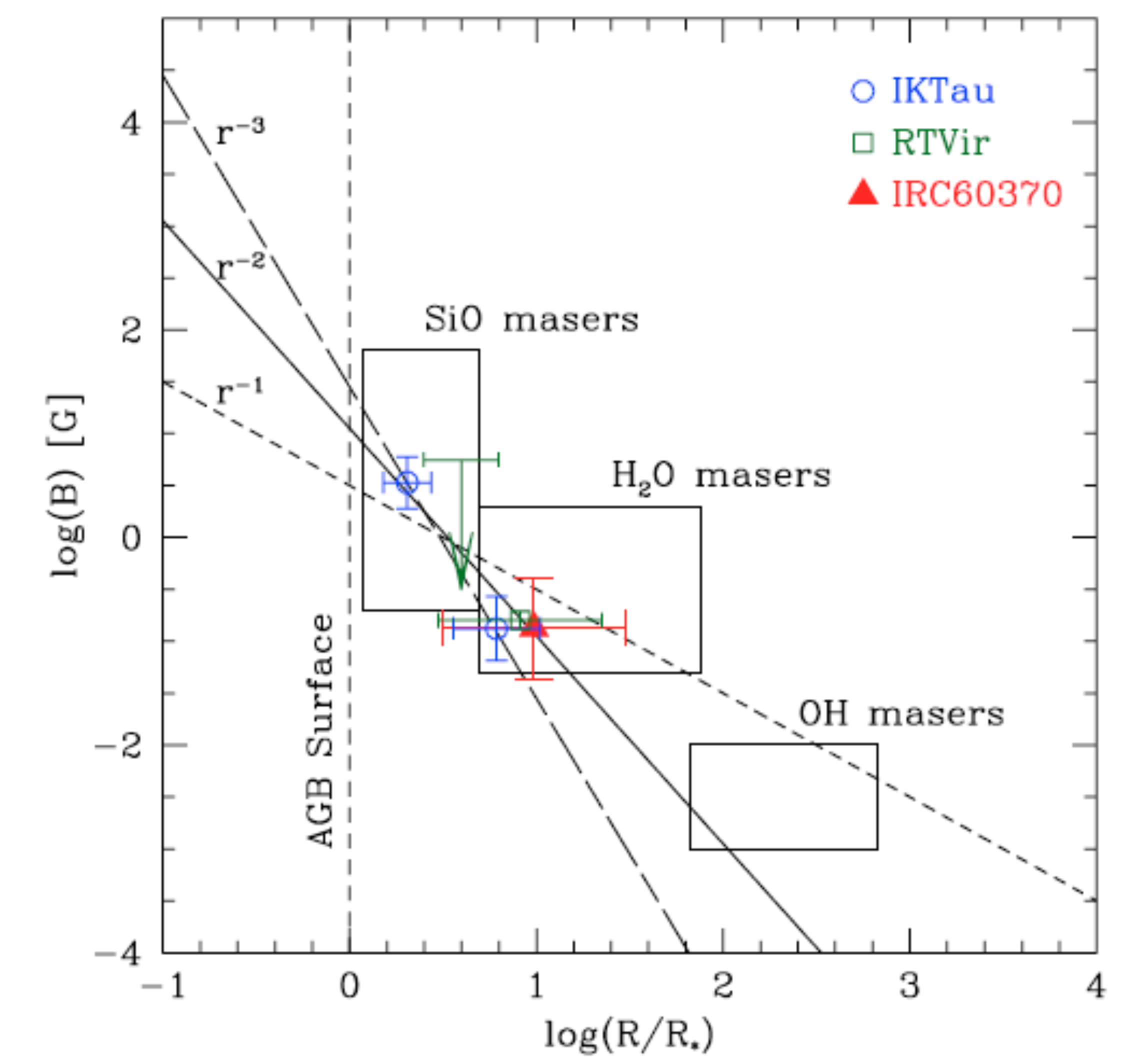


Matt, Frank & Blackman 2006

Companion vs. Magnetic Field?

Magnetic fields from maser measurements



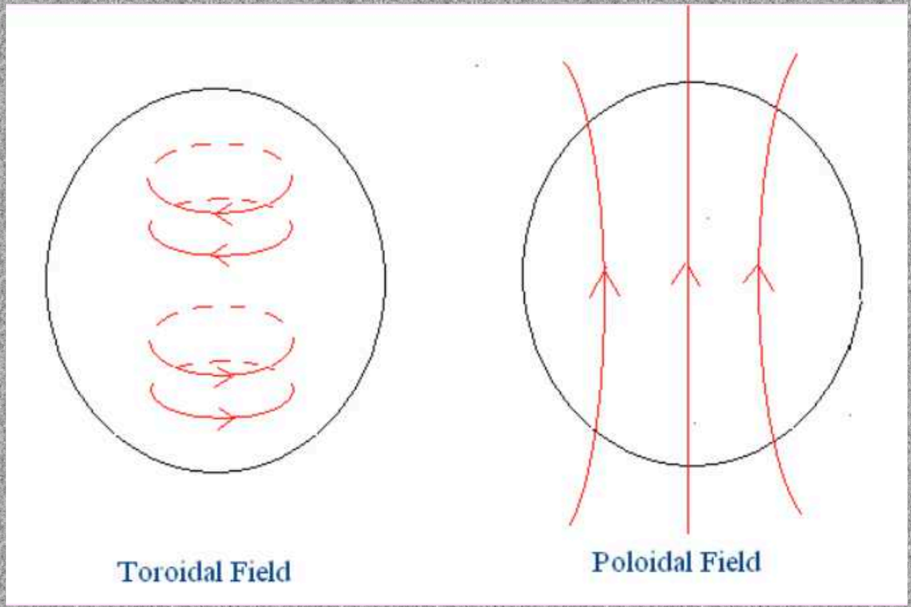


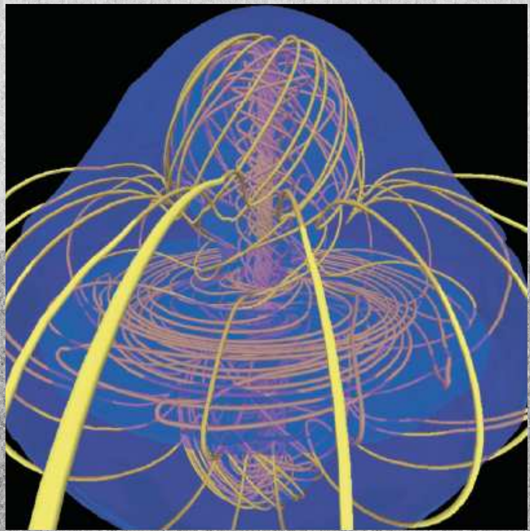
Leal-Ferreira et al. 2013

r^{-1}: toroidal *

r^{-2}: poloidal field *

r^{-3}: dipole field



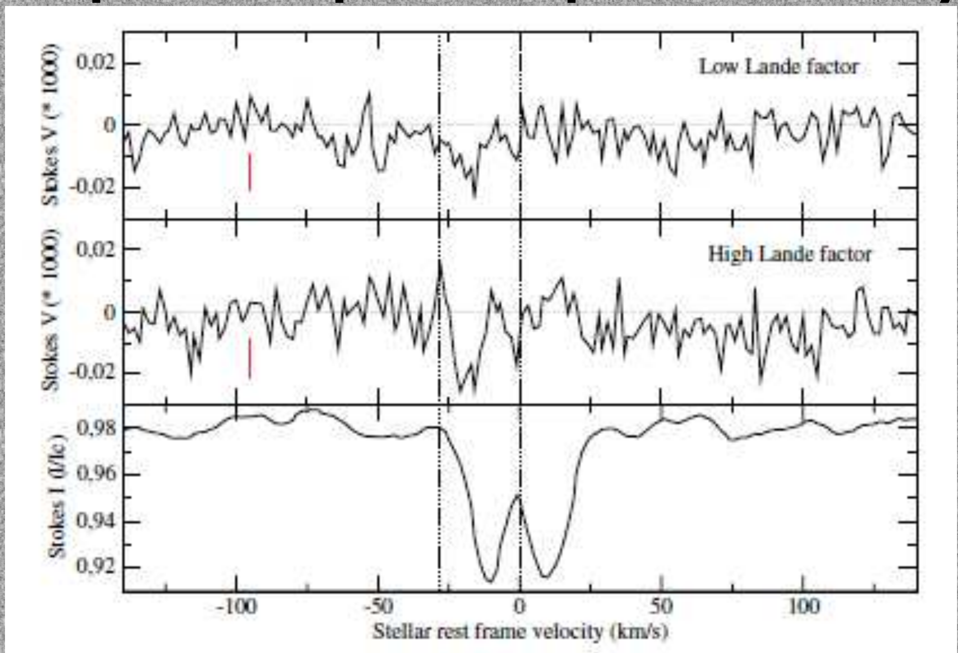


Matt, Frank & Blackman 2006

AGB Magnetic Fields

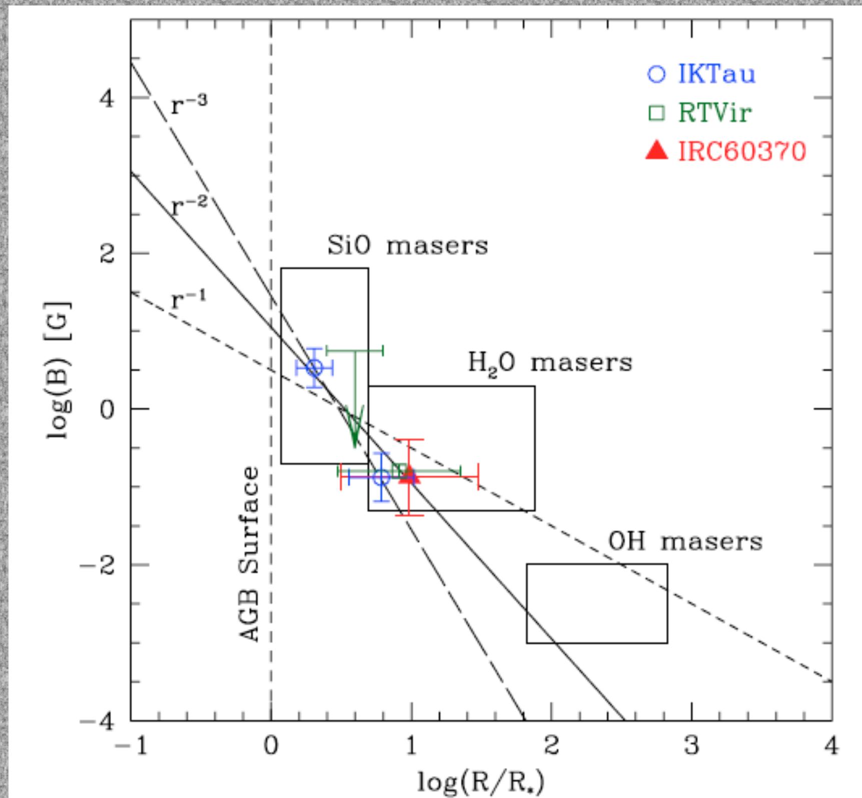
Magnetic dynamo models invoking the differential rotation between a rapidly rotating core and a more slowly rotating outer layer have been shown to produce sufficient magnetic fields (e.g. Blackman 2001).

Optical spectropolarimetry



2-3 Gauss, Lebre et al. 2014

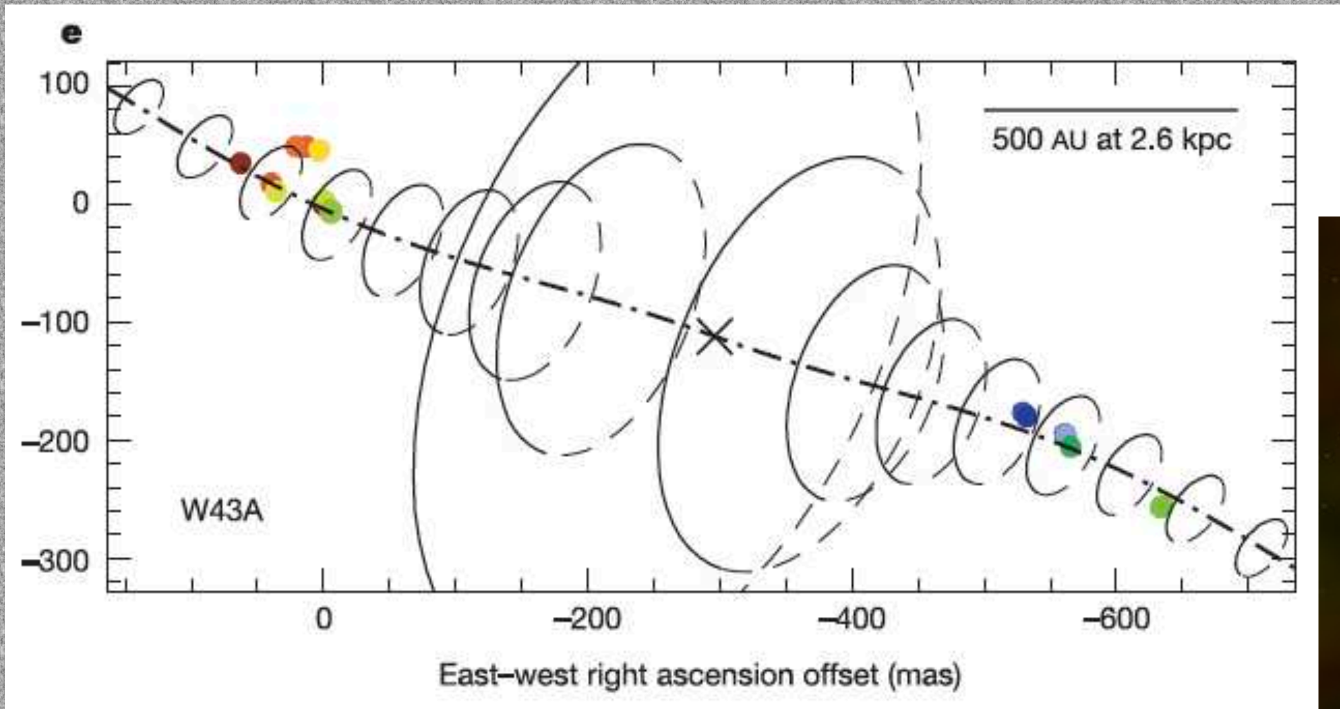
Masers



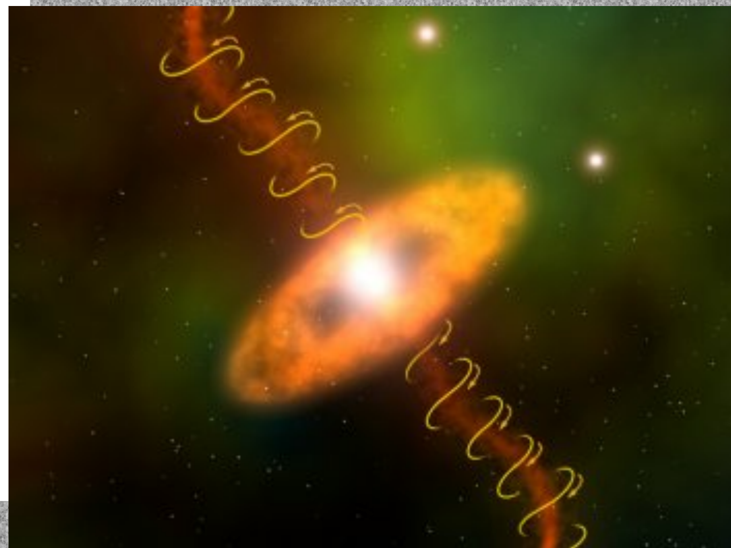
Leal-Ferreira et al. 2013

Proto-Planetary Nebulae

- Rarely, post-AGB/proto-Planetary Nebulae show highly-collimated water maser jets
- These “water fountains” are likely the progenitors of bi-polar Planetary Nebulae
- Magnetic collimation of the jet in W43A
-



Masers at ~1000 AU
From the star



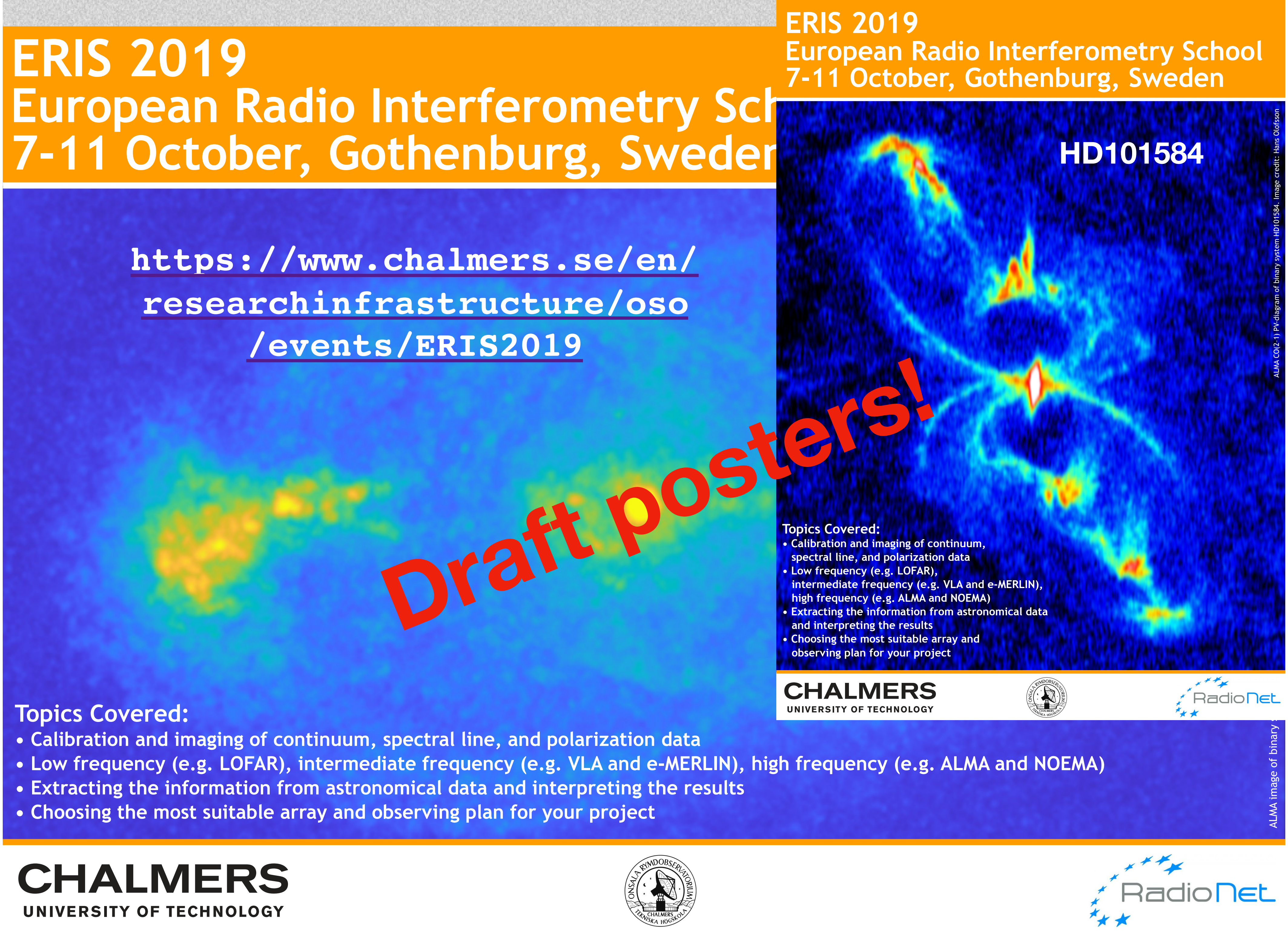
VLBA, Vlemmings et al. 2006
Toroidal component of B field along the jet
B= 200 +/- 75 mG in the jet

Imai et al. 2002

Polarization of 22 GHz H_2O masers that trace a precessing jet

Summary

- Evolved star mass-loss and shaping mechanisms still need to be understood
- Masers provide excellent tools for probing the mass-loss process
- Single-dish science is very relevant for evolved star masers:
  - variability monitoring (masers can flare)
  - surveys, new source detections
  - stellar systemic velocity determination (from SiO masers)
- VLBI observations of the masers can yield gas physical conditions, 3D velocities and magnetic field estimations. Also distances



ERIS 2019
European Radio Interferometry Sch
7-11 October, Gothenburg, Sweden
https://www.chalmers.se/en/researchinfrastructure/oso/events/ERIS2019
Draft posters!
Topics Covered:
• Calibration and imaging of continuum, spectral line, and polarization data
• Low frequency (e.g. LOFAR), intermediate frequency (e.g. VLA and e-MERLIN), high frequency (e.g. ALMA and NOEMA)
• Extracting the information from astronomical data and interpreting the results
• Choosing the most suitable array and observing plan for your project
ALMA image of binary
CHALMERS
UNIVERSITY OF TECHNOLOGY
RadioNet
ERIS 2019
European Radio Interferometry School
7-11 October, Gothenburg, Sweden
HD101584
ALMA CO(2-1) PV-diagram of binary system HD101584. Image credit: Hans Olofsson
Topics Covered:
• Calibration and imaging of continuum, spectral line, and polarization data
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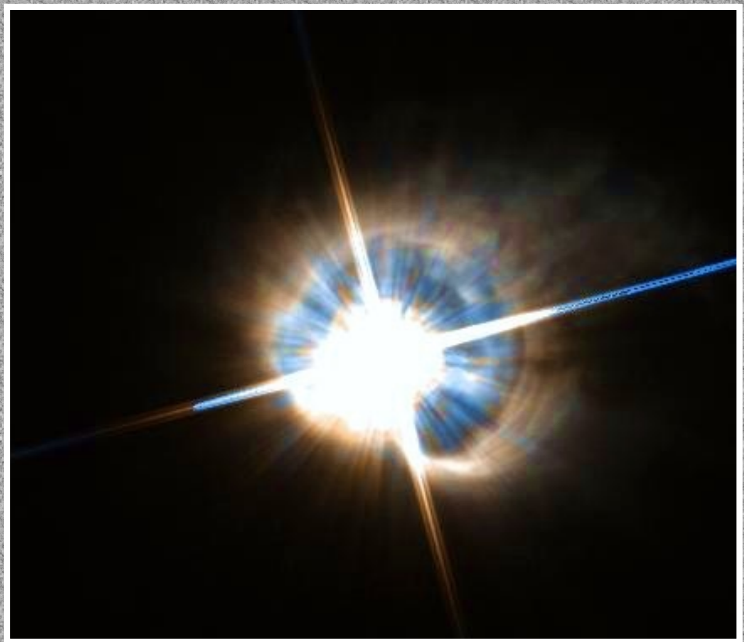
• Extracting the information from astronomical data and interpreting the results
• Choosing the most suitable array and observing plan for your project
CHALMERS
UNIVERSITY OF TECHNOLOGY
RadioNet

HD 101584: optical data

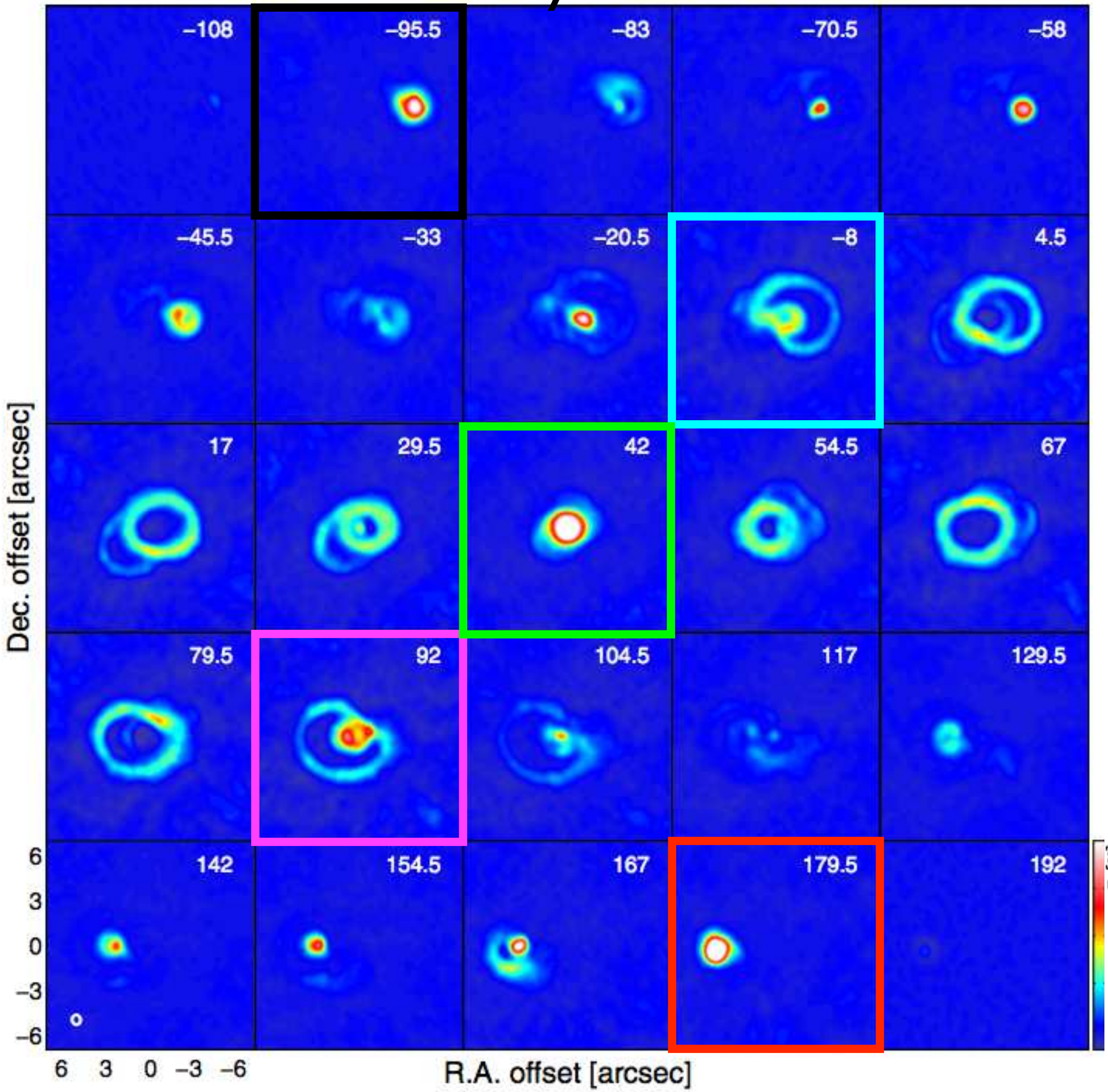


HST
Sahai+ 2007

- Most likely a post-AGB object*
- Central star 7th magnitude A6Ia star
- Mass estimate ~ 0.6 Msun
- Binary period 140 - 220 days
- System has undergone an evolution (possibly common envelope) where the companion spiralled in but survived

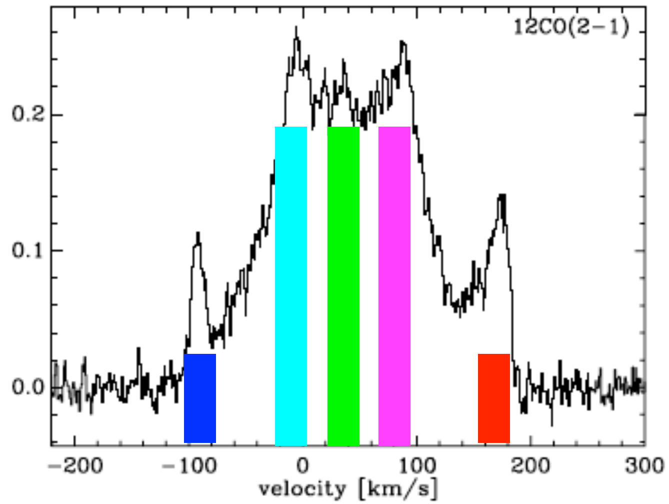
* Now under debate

Velocity channels



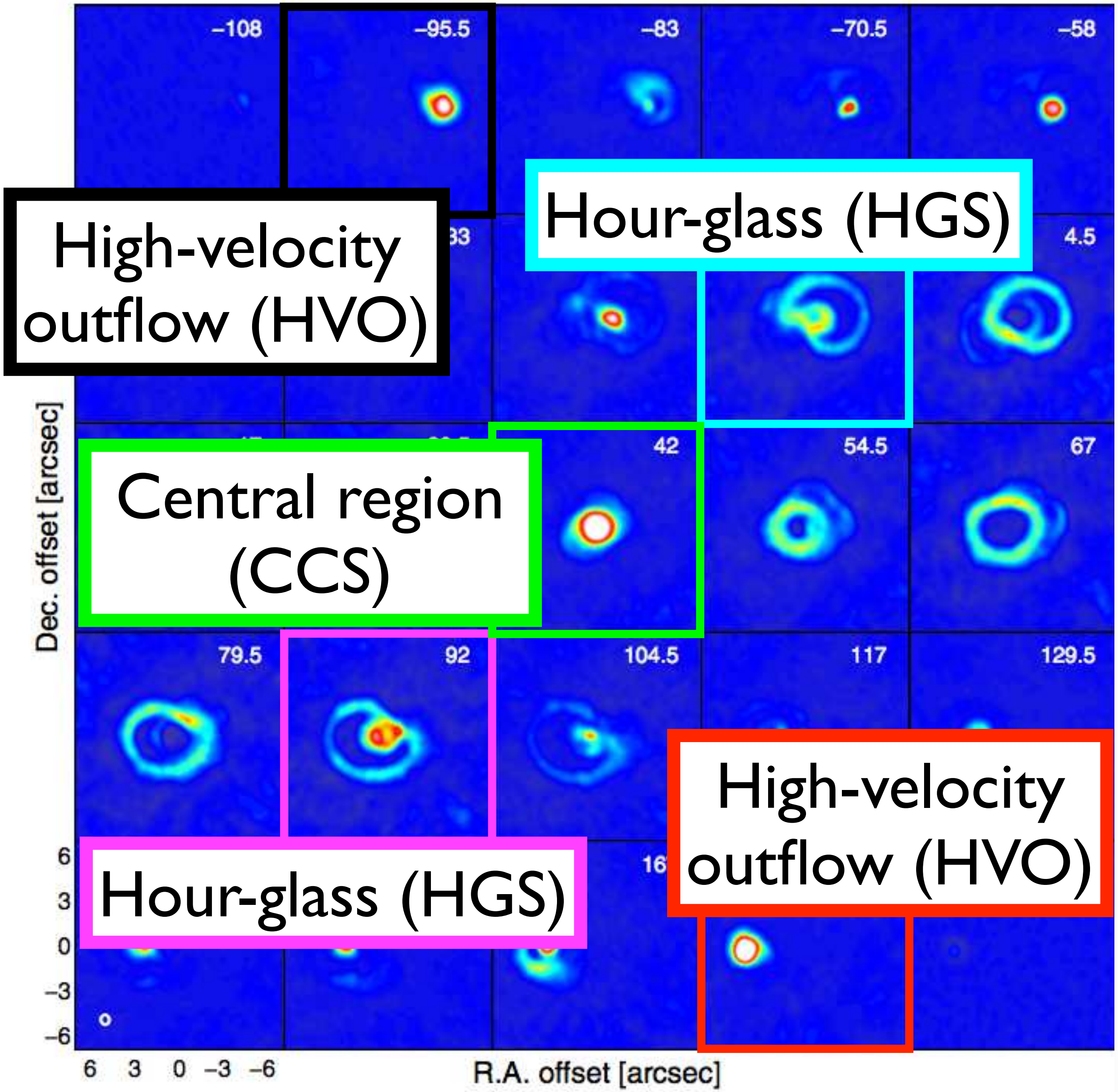
HD 101584
ALMA
CO (2-1)

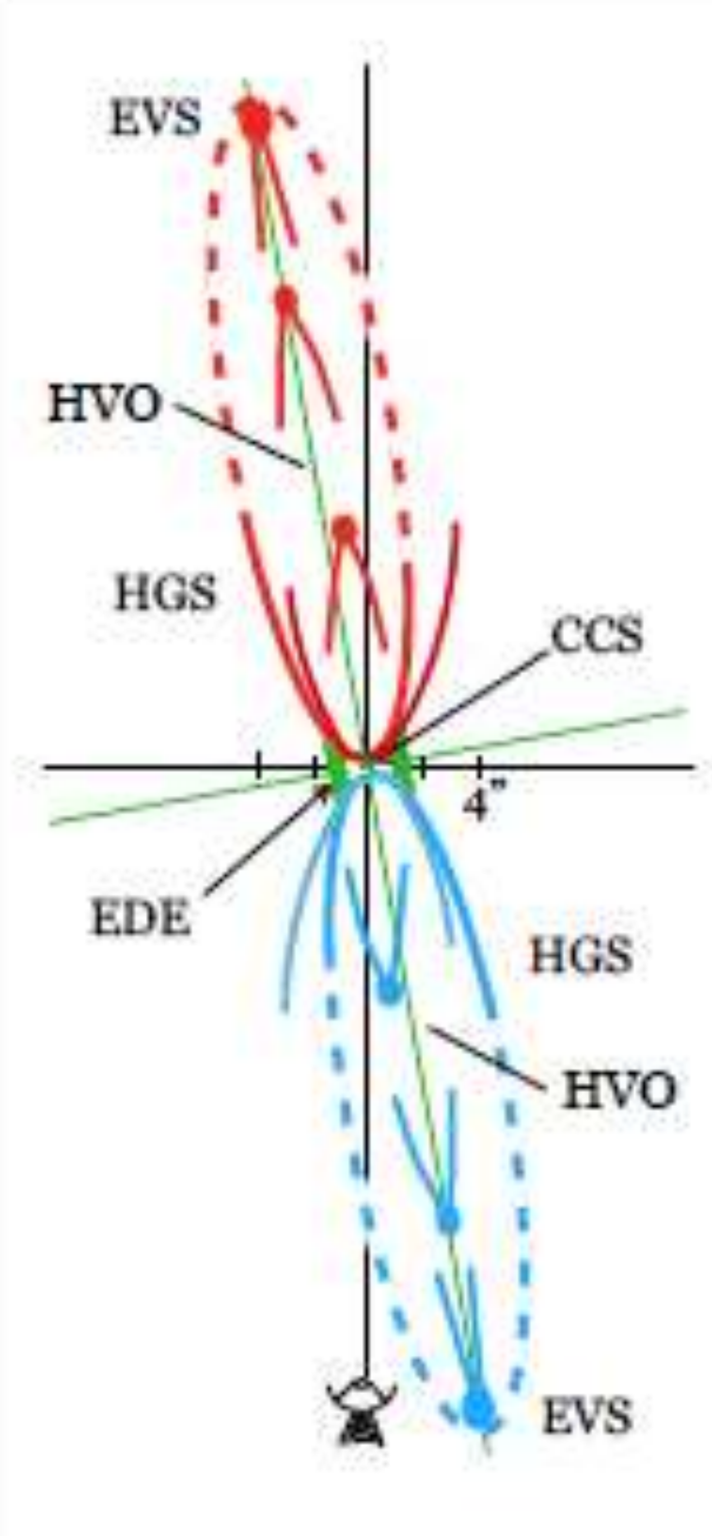
At least 3 kinematical components



OLOFSSON et al. 2015

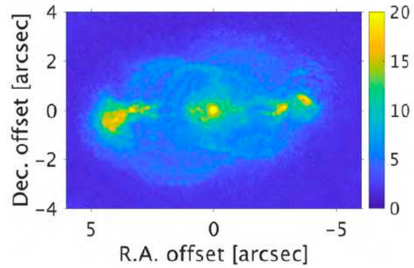
Almost pole-on hour-glass system

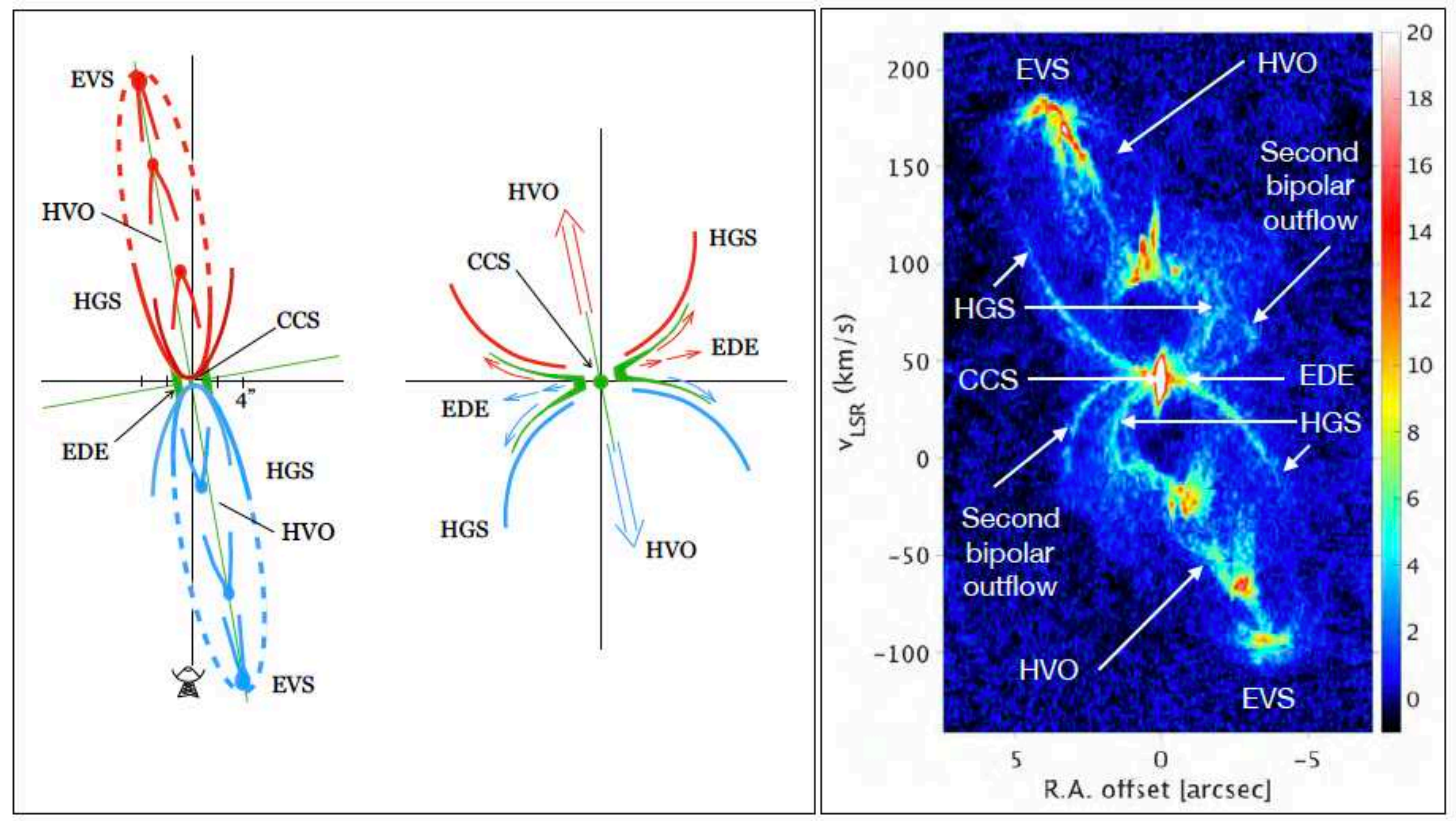




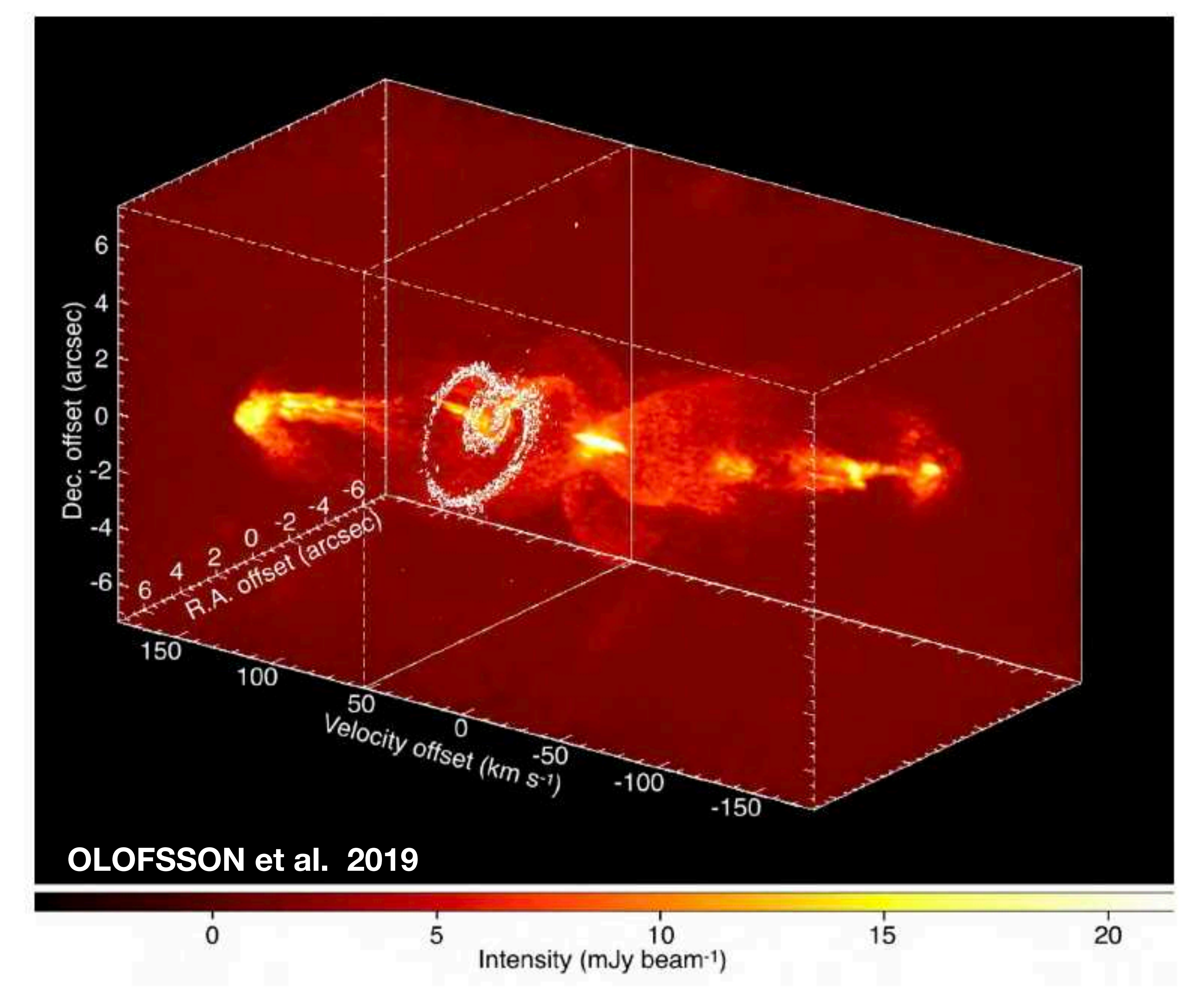
OLOFSSON et al. 2019

Morphology





OLOFSSON et al. 2019



Dec. offset (arcsec)
R.A. offset (arcsec)
Velocity offset (km s-1)
OLOFSSON et al. 2019
Intensity (mJy beam-1)