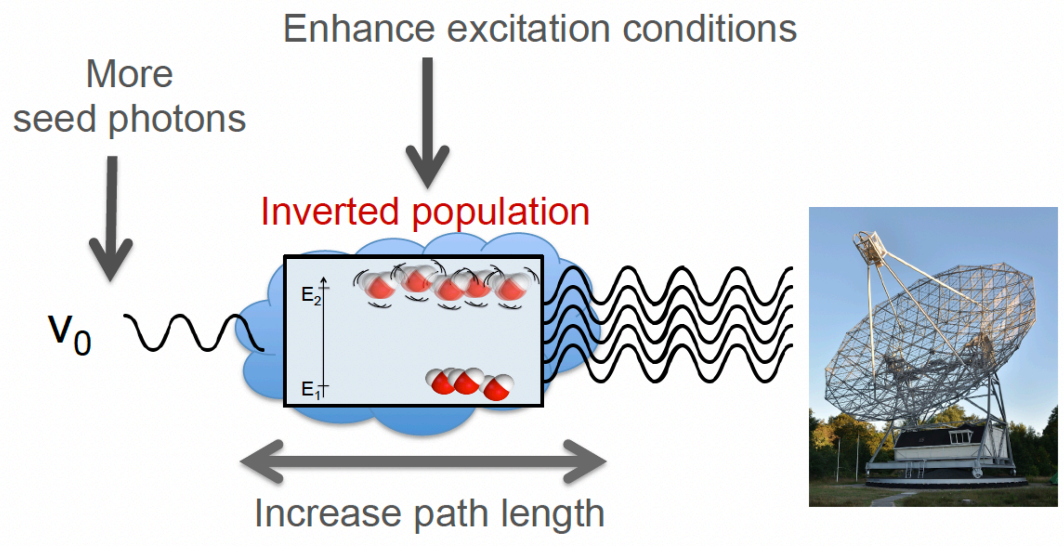
Stellar Evolution Studies Using Masers

Liz Humphreys (ESO/ALMA)

EVN Symposium,11 July 2022, Cork

Masers

Microwave Amplification by Stimulated Emission of Radiation



Burns et al. 2018

Compact, high brightness temperature masers enable study at high-angular resolution

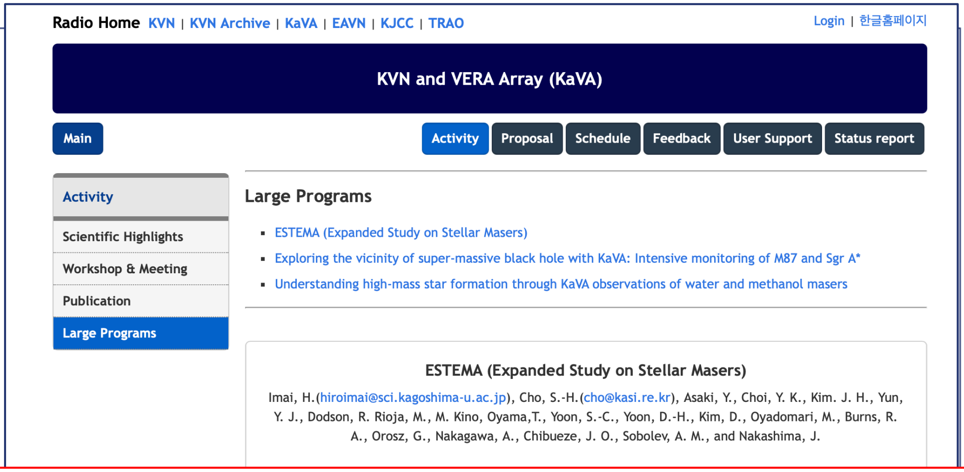
- **Found in:** evolved stars, star-formation, AGN, supernova remnants, comets and planetary atmospheres, …

- **Species include:** SiO, H_2O, OH, CH_3OH, HCN, SiS, NH_3, formaldehyde, H recombination masers

ALMA

Masers

- Uses include:
  - Determine gas physical conditions
  - Gas kinematics (3D velocities from proper motions)
  - Magnetic field estimation
  - Distances and accurate stellar l-o-s velocities

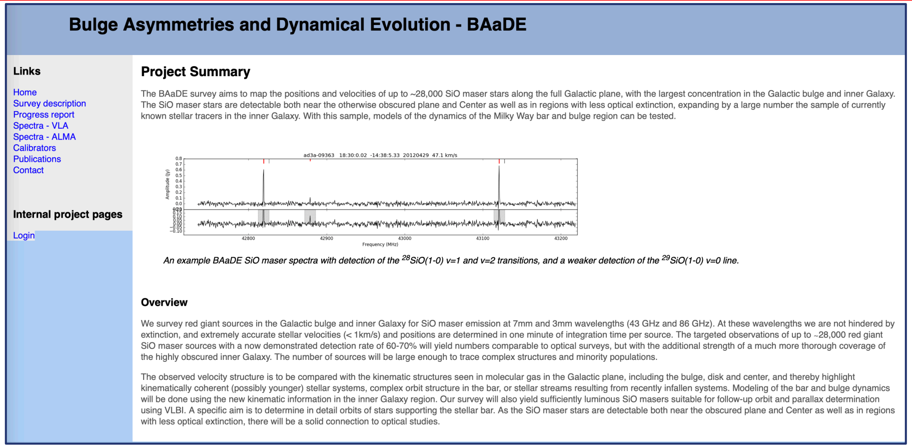


ESTEMA: Expanded Study of Stellar Masers

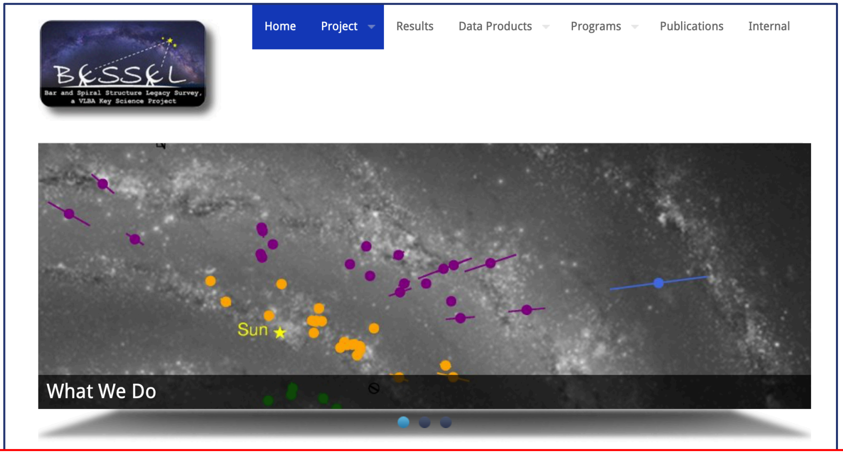
Imai, Cho et al.

Sjouwerman, Pihlstroem et al.

BAaDE: Bulge Asymmetries and Dynamical Evolution



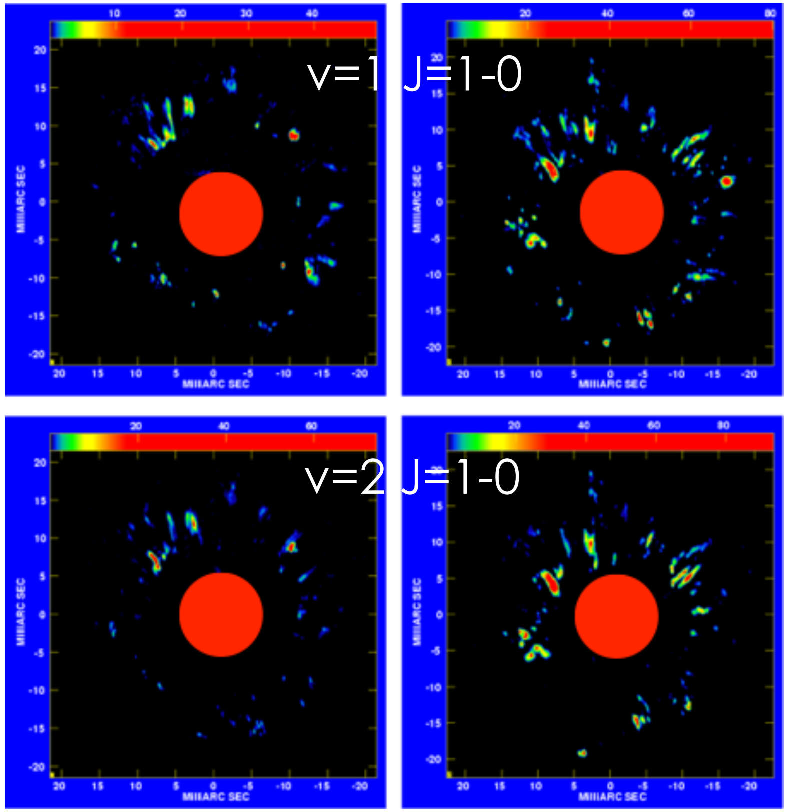
Reid, Sakai et al.



BeSSeL: Bar and Spiral Structure Legacy Survey

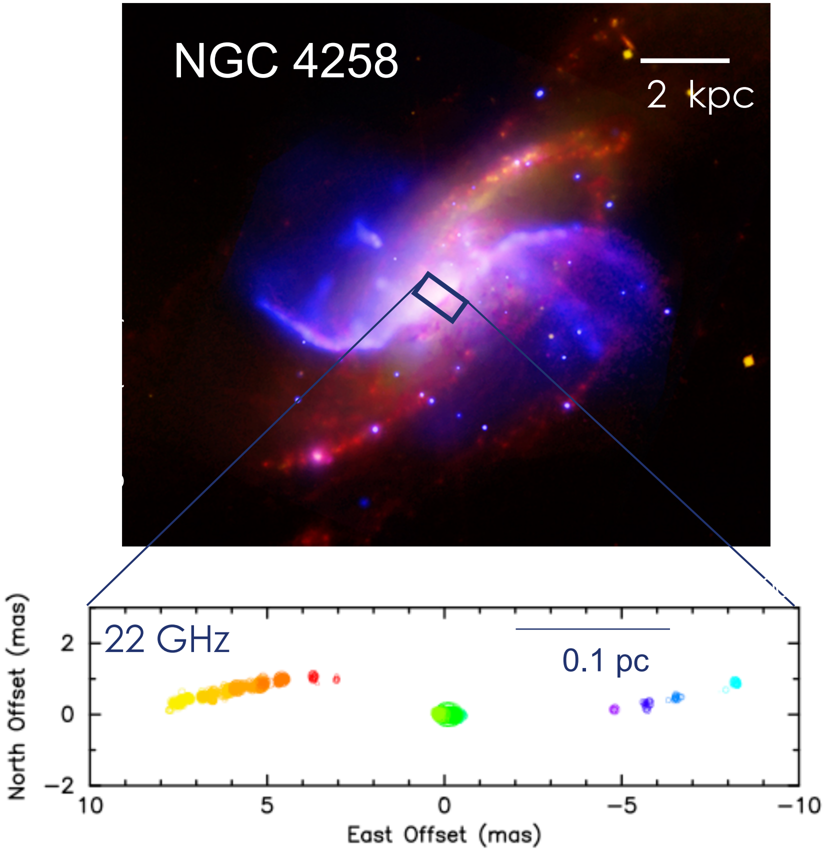
Maser environments at high angular resolution

TX Cam 43 GHz



SiO Masers in AGB Stars

Yi et al. (2005)
Angular resolution ~ 1 mas



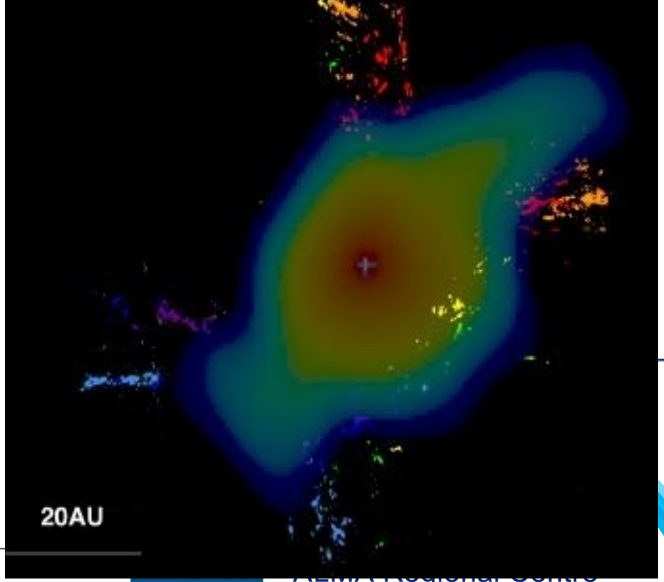
H_2O Megamasers in AGN

Argon et al. (2007)

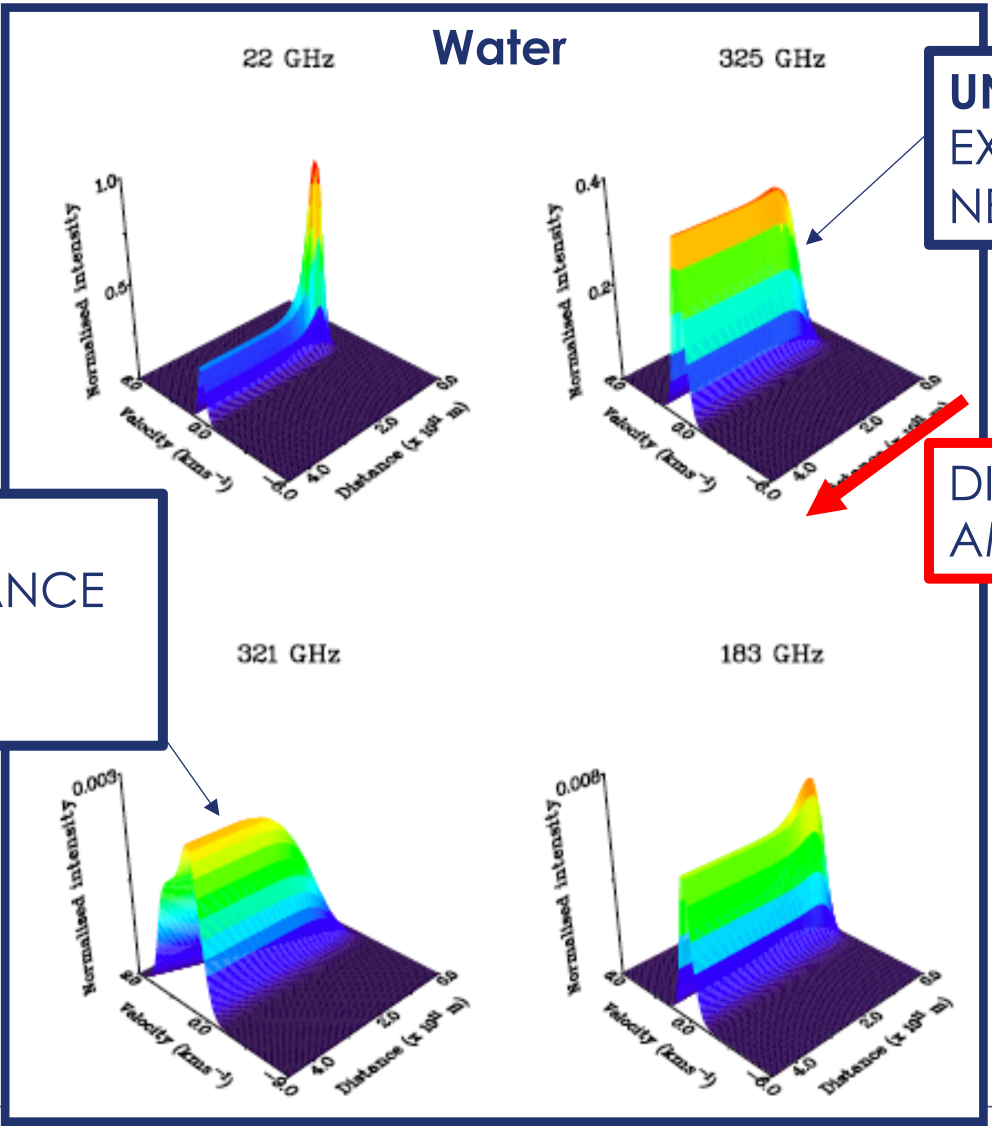
Orion Source I
Bill Saxton

SiO masers in star formation

Matthews et al. 2010,
Goddi et al. 2011, Greenhill et al 2013



Individual maser clouds



UNSATURATED REGIME
EXPONENTIAL GROWTH WITH DISTANCE
NEGLIGIBLE EFFECT ON POPULATIONS

DISTANCE ALONG MASER
AMPLIFICATION PATH/GAIN LENGTH

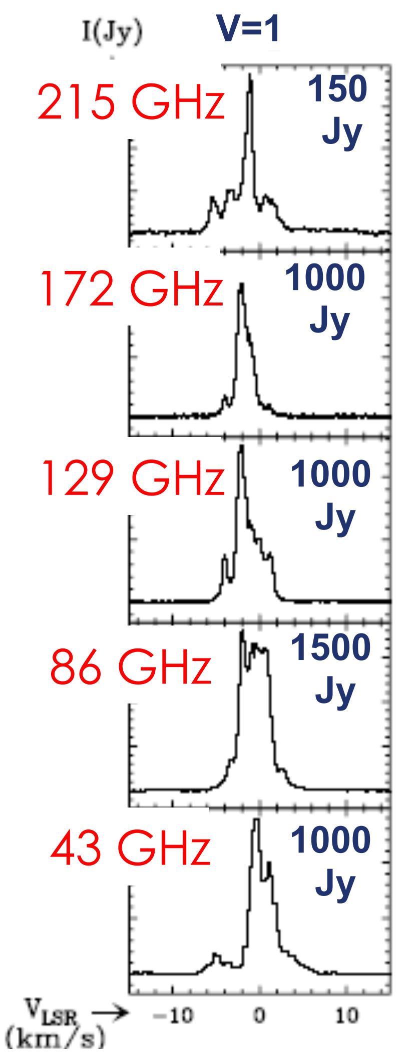
SATURATED REGIME
LINEAR GROWTH WITH DISTANCE
POPULATIONS AFFECTED →
COMPETITIVE GAIN

Size:
0.5 – 2 AU in AGB stars
5 – 10 AU Red Supergiants
Richards et al. (2012)
Linewidth:
Several factors but for water in Evolved Stars thermal linewidth FWHM ~ 1.5 kms^{-1}

Humphreys et al. (2001)

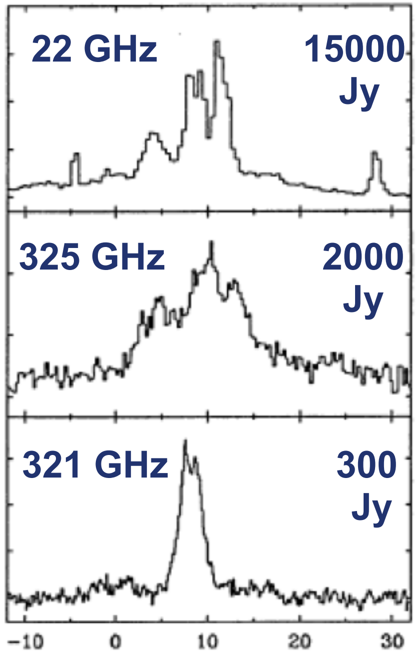
Masers: single-dish observations

SiO: R Leo



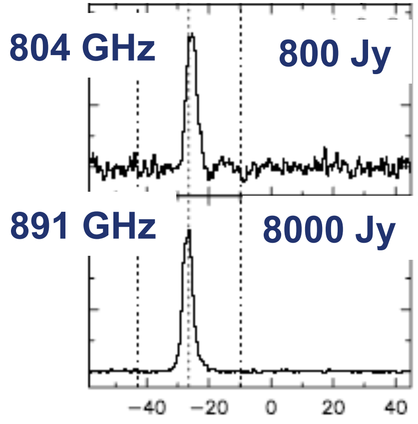
Pardo et al. (1998)

H_2O : W49N



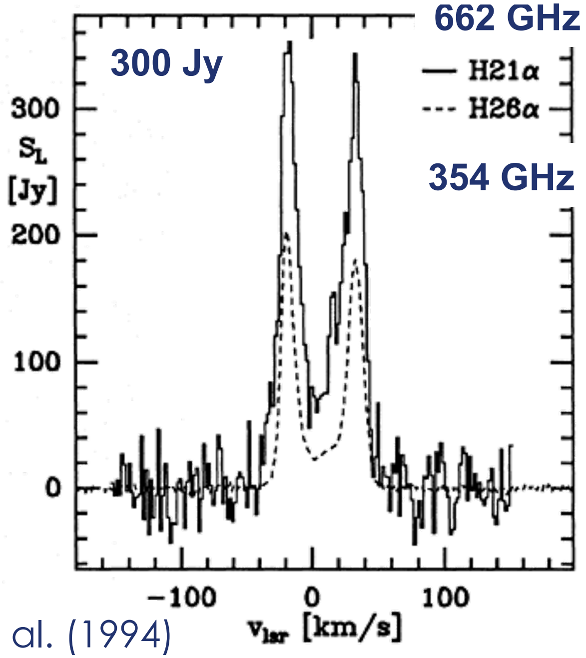
Menten, Melnick & Phillips (1990)

HCN: IRC+10216



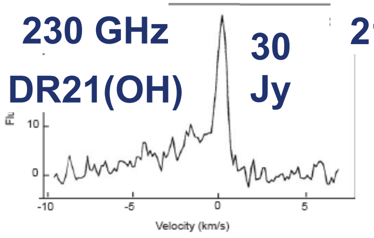
Schilke & Menten (2003)

Hydrogen Recombination: MWC 349A

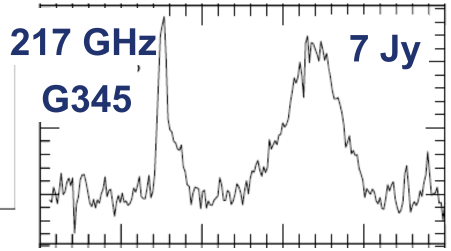


Thum et al. (1994)

CH_3OH: Class I & II



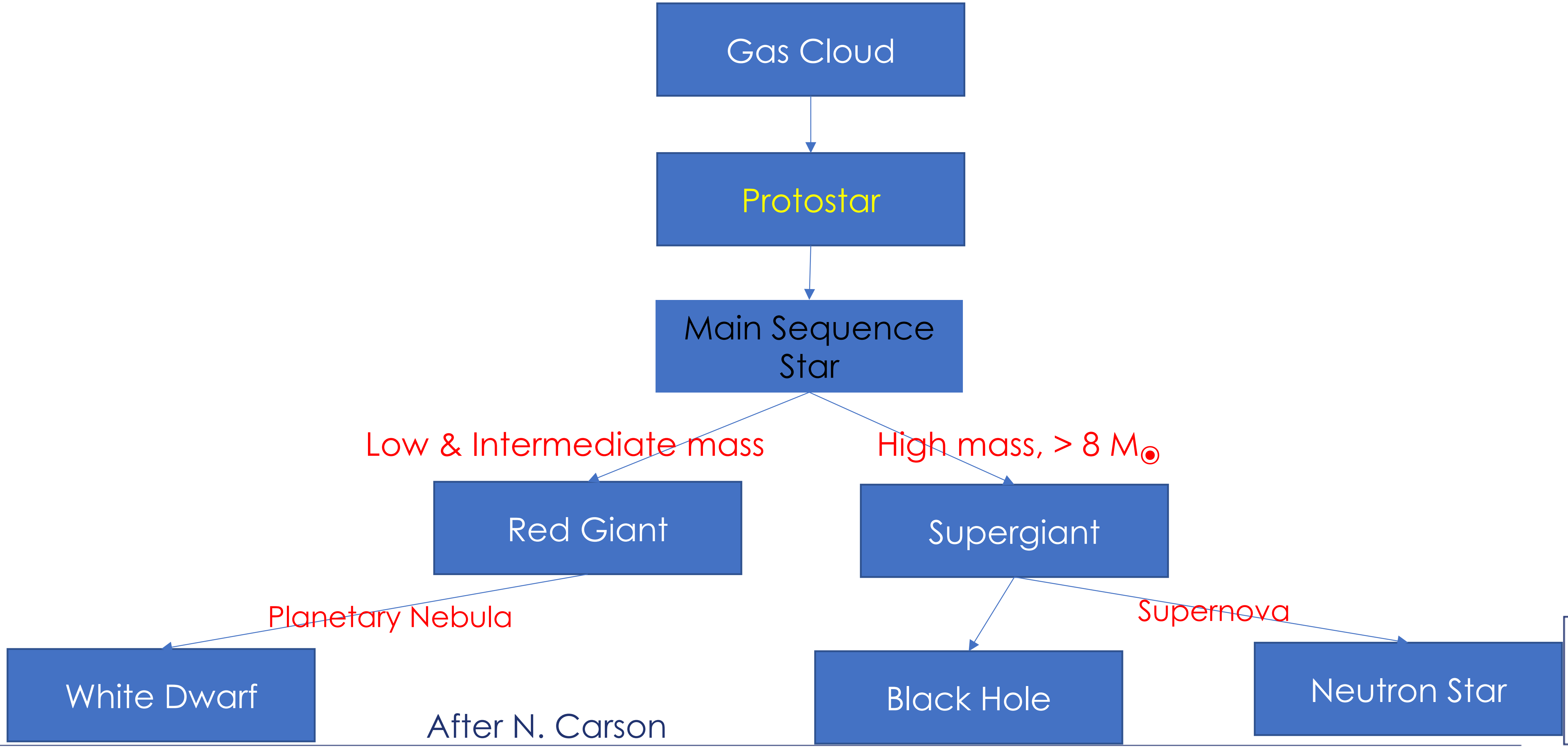
Kalenskii et al. (2002)



Sobolev et al. (2002)

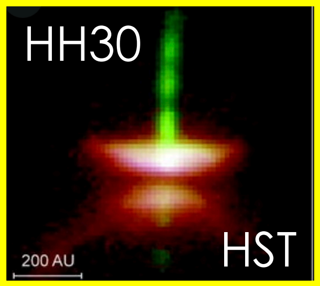
Note:
(1) often masers at different frequencies observed towards the same object
(2) usually blend of multiple maser clouds
(3) narrow features in spectra
(4) variability

Stellar Evolution in a Nutshell

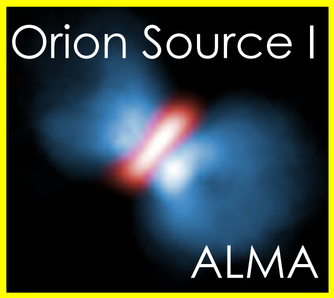


After N. Carson

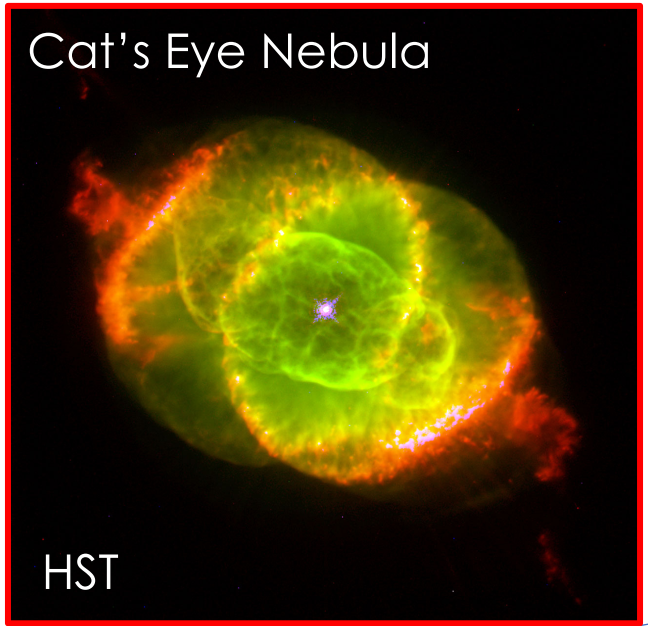
Stellar Evolution in a Nutshell

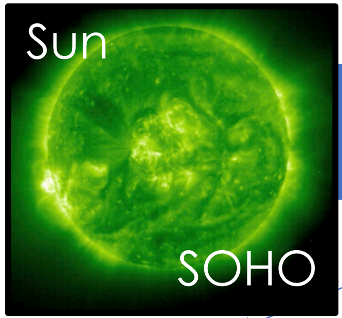


Gas Cloud

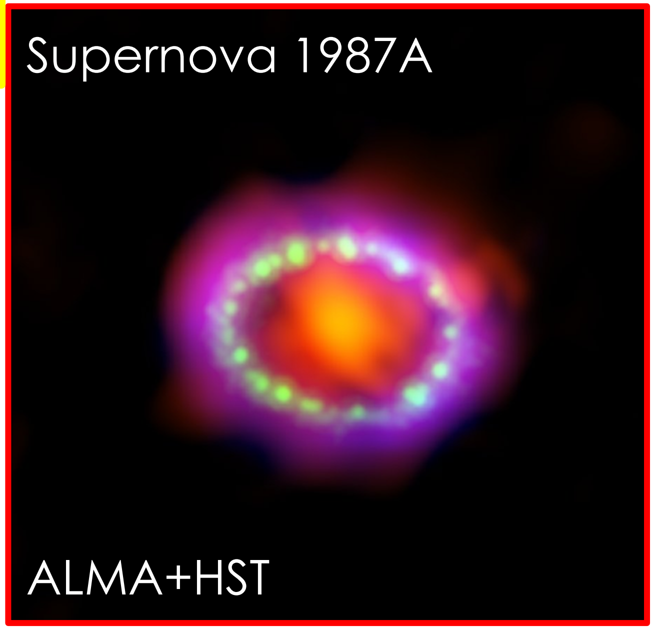


Protostar





Main Sequence Star



Red Giant

Supergiant

Planetary Nebula

Supernova

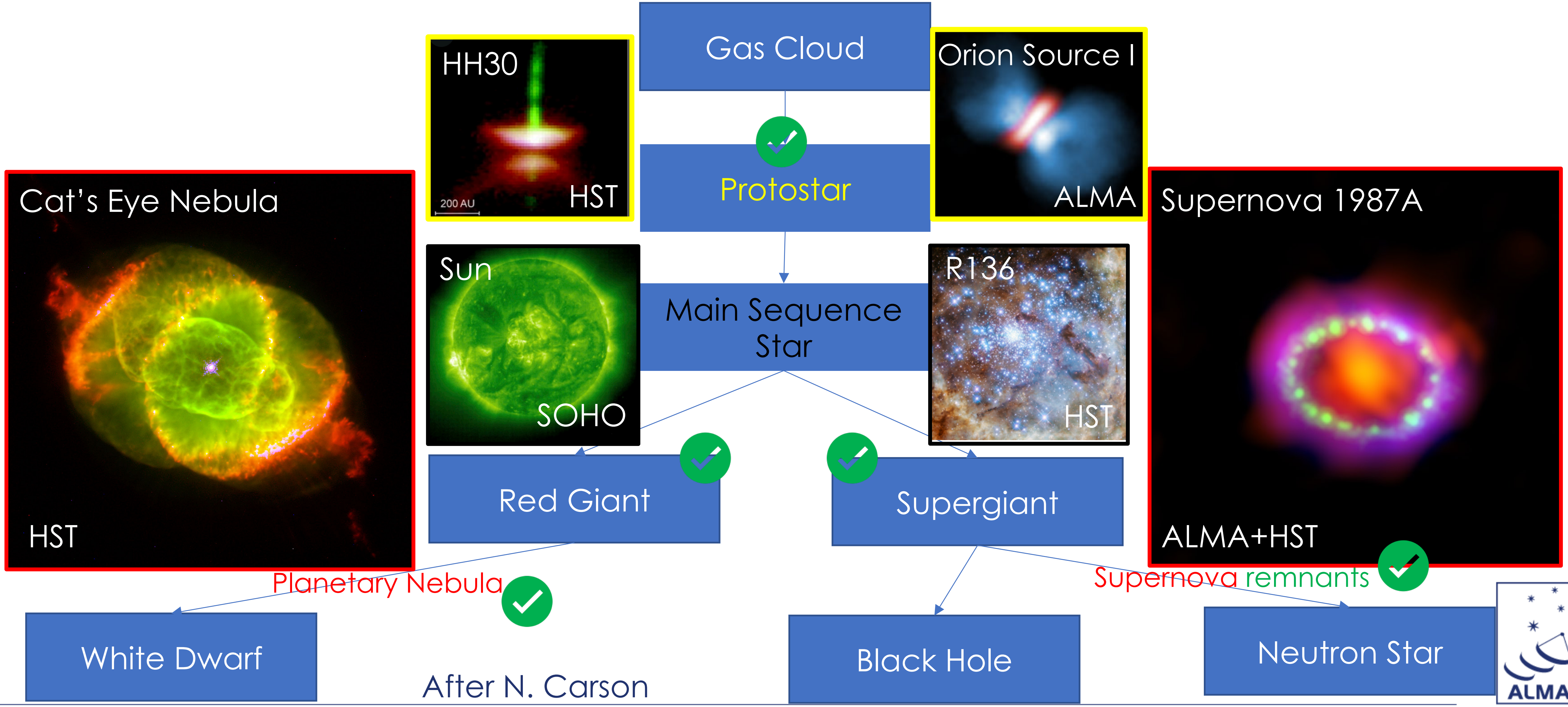
White Dwarf

Black Hole

Neutron Star

After N. Carson

Stellar Evolution and Masers



After N. Carson

Stellar Evolution Maser Talks

- **Michal Durjasz** - Yet another 6.7 GHz imaging of the high-mass star-forming region Cep A HW2
- **Gabriele Surcis** - 6.7 GHz CH_3OH masers polarization in massive star-forming regions: the Flux-Limited Sample
- **Malcolm Gray** - 3D Models of Astrophysical Masers with Polarization
- **Agnieszka Kobak** - The first look at the coincidence of methanol and excited OH masers around HMYSOs
- **Artis Aberfelds** - Cloudlet evolution in IRAS 20126+4104 during last15 years and its periodic variability

ALMA

Posters

- **16. Bartkiewicz et al.** - Methanol and excited OH masers in HMYSOs at a milliarcsecond scale
- **17. Shmeld et al.** - VLBI observation results of two variable sources from Irbene CH_3OH maser monitoring programme
- **18. Rygl** - Proper motions along the Sagittarius spiral arm
- **24. Algaba** – VLBI in Malaysia: current status and future plans

Masers in Star-Formation

High-mass star formation

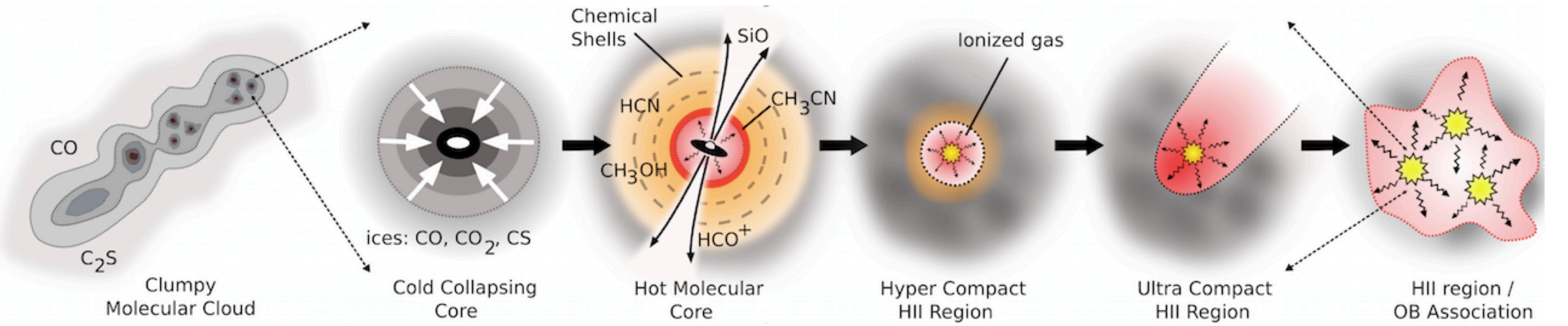


Image credit: Cormac Purcell

Masers in star-formation:

- H_2O
- CH_3OH
- OH
- SiO
- NH_3
- H_2CO

More common

- Masers are generally more prevalent in regions surrounding massive protostars, due to their higher luminosities and more energetic outflows
- Generally the masers trace hot, dense molecular gas, revealing the kinematics of star-forming material within a few 1000 AU of very young stars, including:
  - accretion disks and their associated jets
  - shocks where the jets impact ambient gas in the outflow lobes

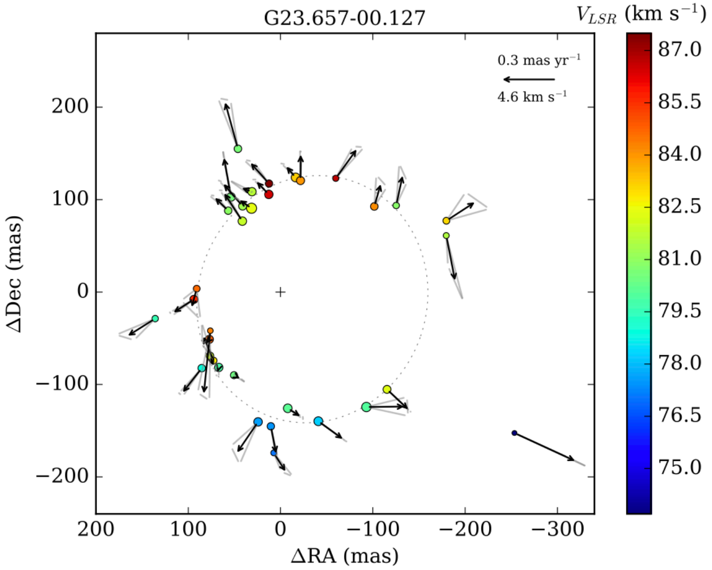
Hunter et al. 2020

See talks by Durjasz, Surcis (today) and Kobak, Aberfelds (Thursday)

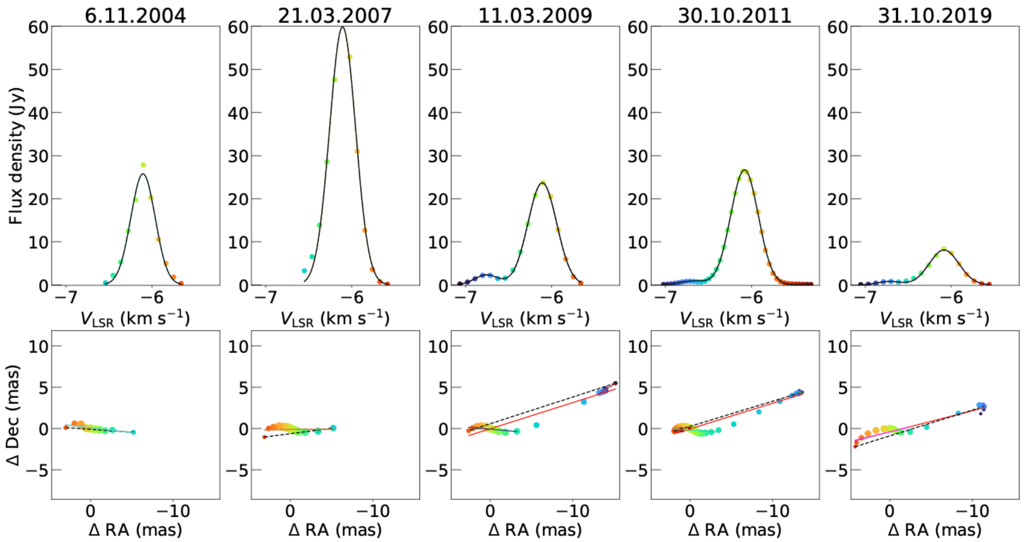
6.7 GHz Methanol Masers

- Methanol masers at 6.7 GHz are uniquely associated with high-mass star-formation
- Maser cloud(let)s ~10 AU in size, found within 1000 AU of HMYSOs
- EVN has been critical to their study, e.g.,

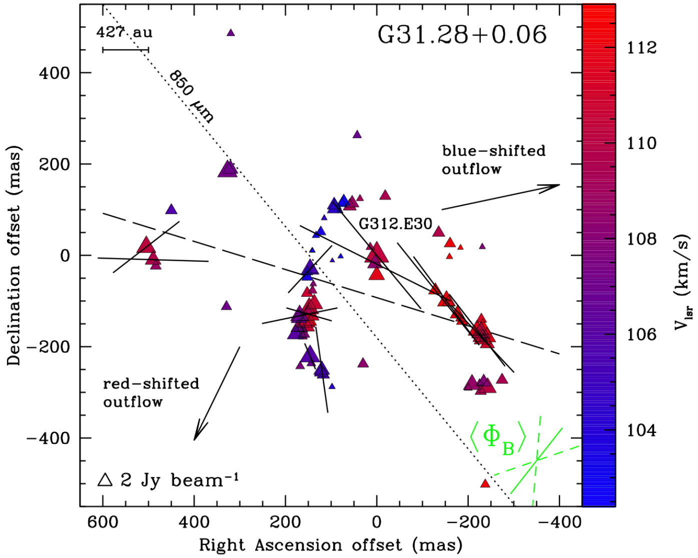
Bartkiewicz et al. 2020



Aberfelds et al. 2021

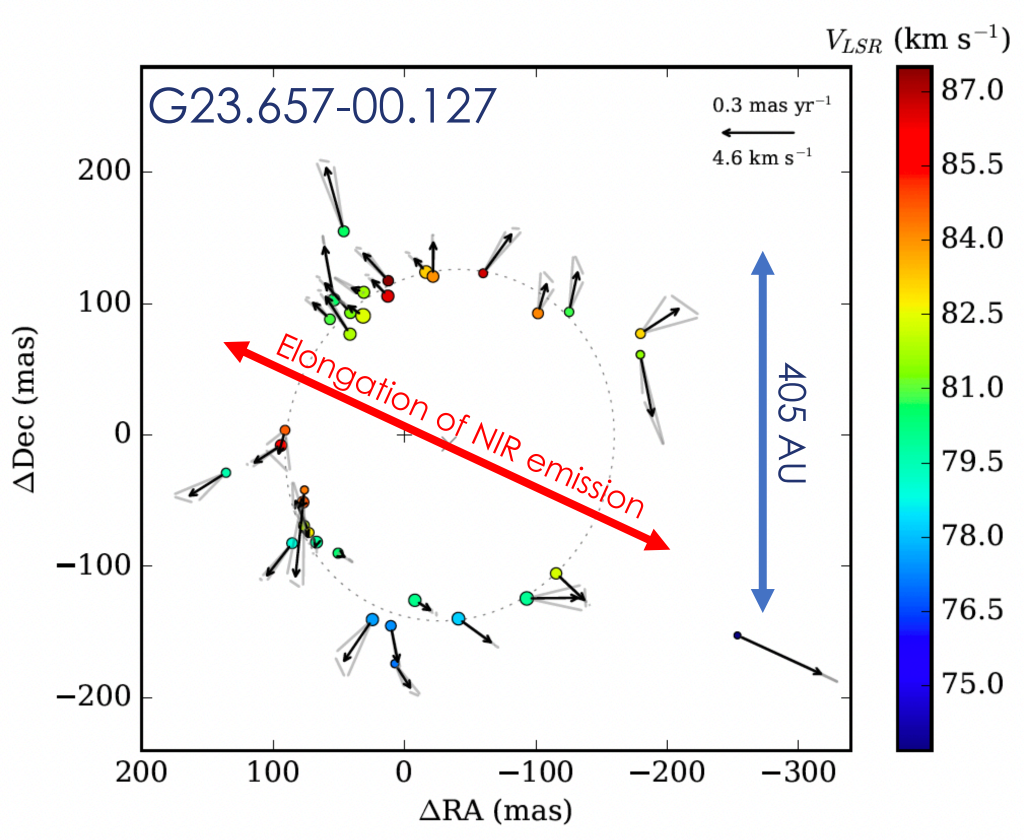


Surcis et al. 2022



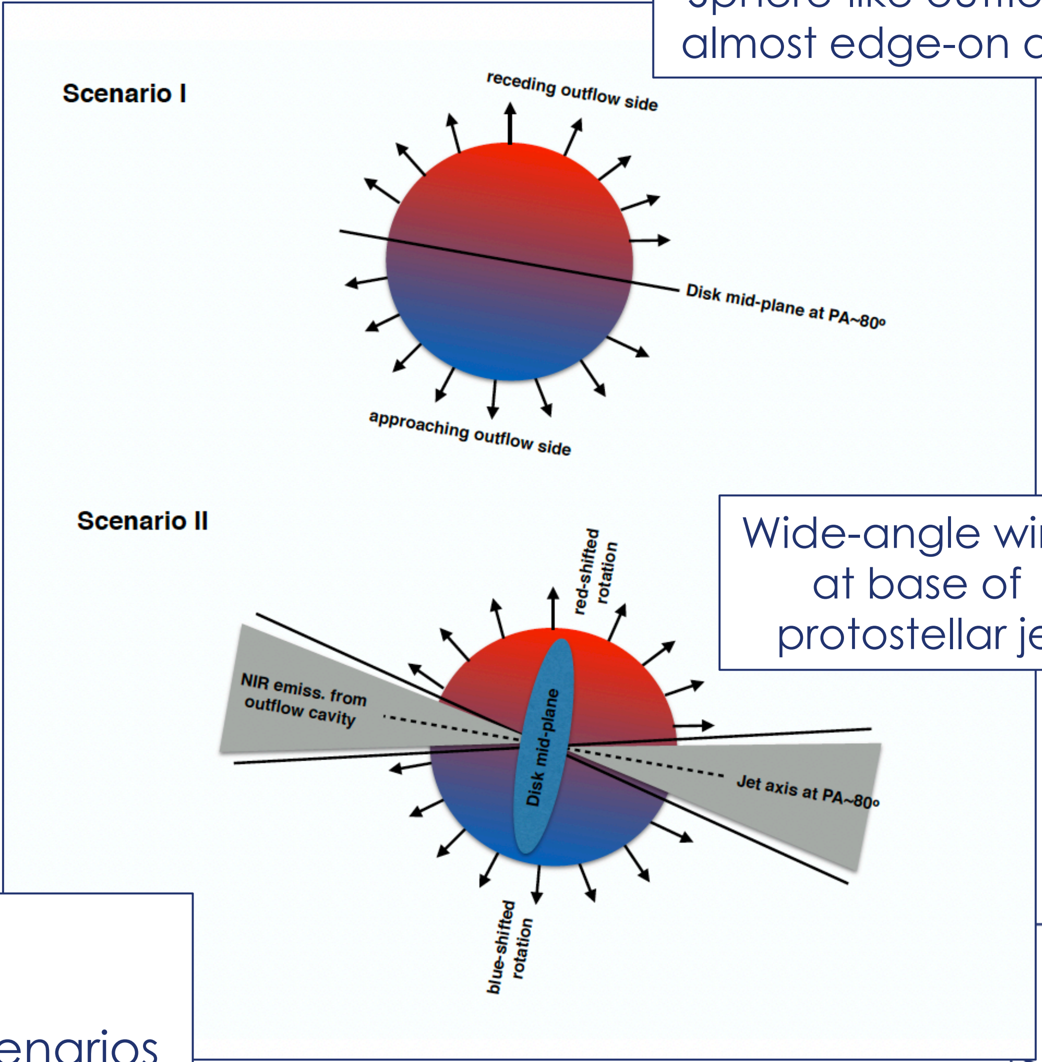
Range of morphologies but ~20-30% targets are ring-type

What is the origin of the rings?



Bartkiewicz et al. 2020 EVN 6.7 GHz

Sphere-like outflow, almost edge-on disk



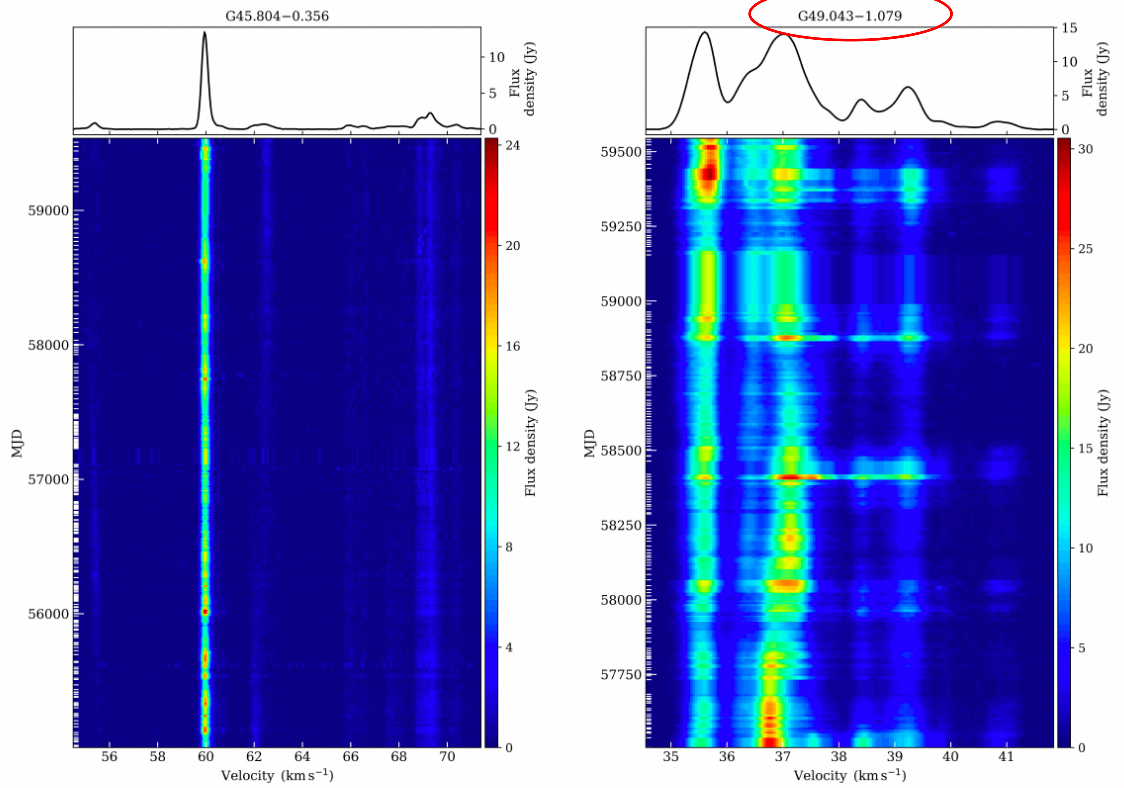
Wide-angle wind at base of protostellar jet

- 3 epochs over 10.3 years
- Mostly radial expansion, mean velocity ~ 3 kms^{-1}
- VLA observations can discriminate between the scenarios

See also Bartkiewicz et al. 2009, 2016

6.7 GHz Methanol Maser Periodic Variability

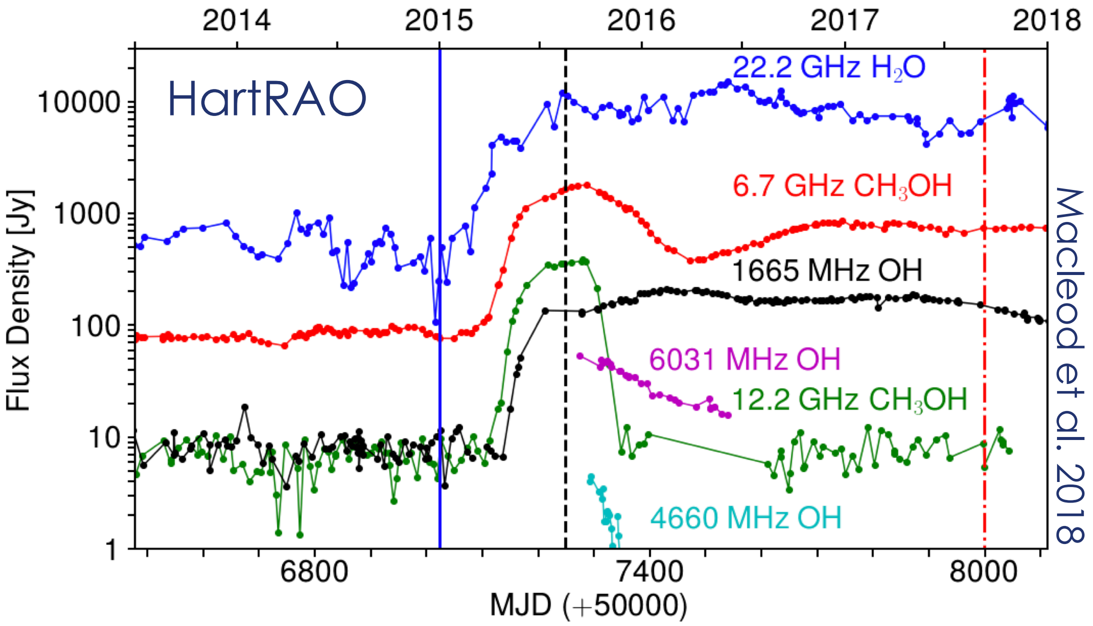
- 26 targets display periodic behaviour with periods ranging between 24 to 670 days (usually between 100 and 300 days)
- Synchronicity of infrared and methanol flares in some sources is evidence for pumping mechanism modulation being a leading cause (Szymczak et al. 2015, Olech et al. 2020)
- Discovery of anti-correlation between 22 GHz H_2O and methanol towards G107.298+5.639 (Olech et al. 2020)



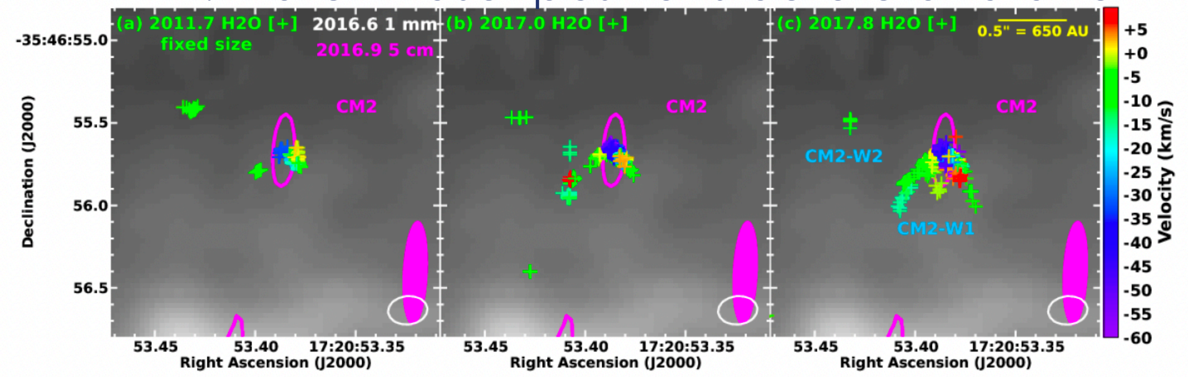
Olech et al. 2022, Torun 32m

Accretion Bursts

Masers tracing an accretion burst in NGC 6334I



VLA: water maser positions before and after

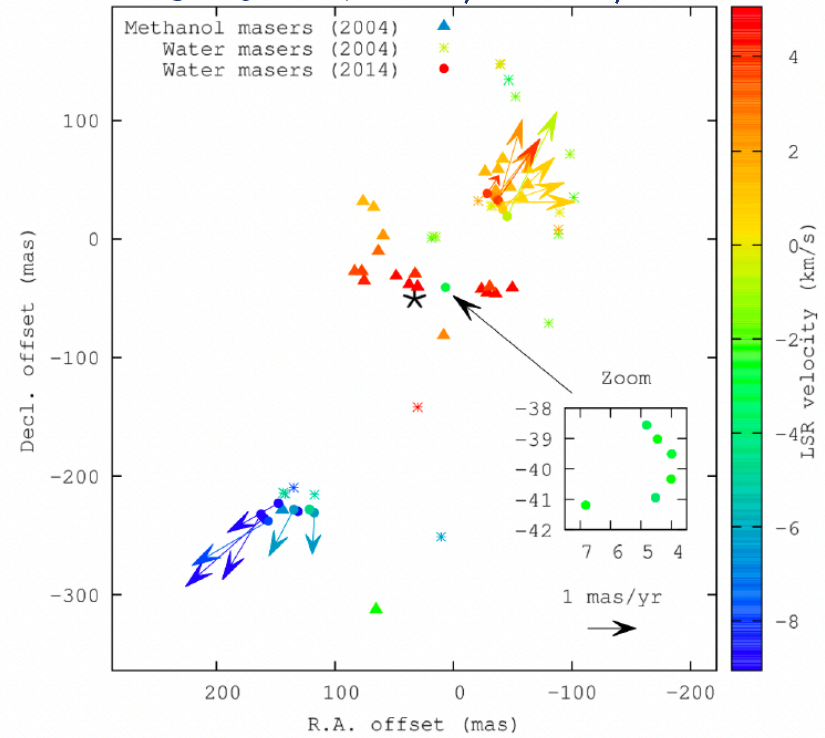


Brogan et al. 2018. See also Bayandina et al. 2022.

Maser flares in lines that are radiatively pumped by infrared photons can be directly associated with bursts of accretion onto the central protostars – Hunter et al. 2020

Maser Monitoring Organisation (M2O) formed to perform single-dish monitoring and trigger interferometry observations during events: https://www.masermonitoring.com

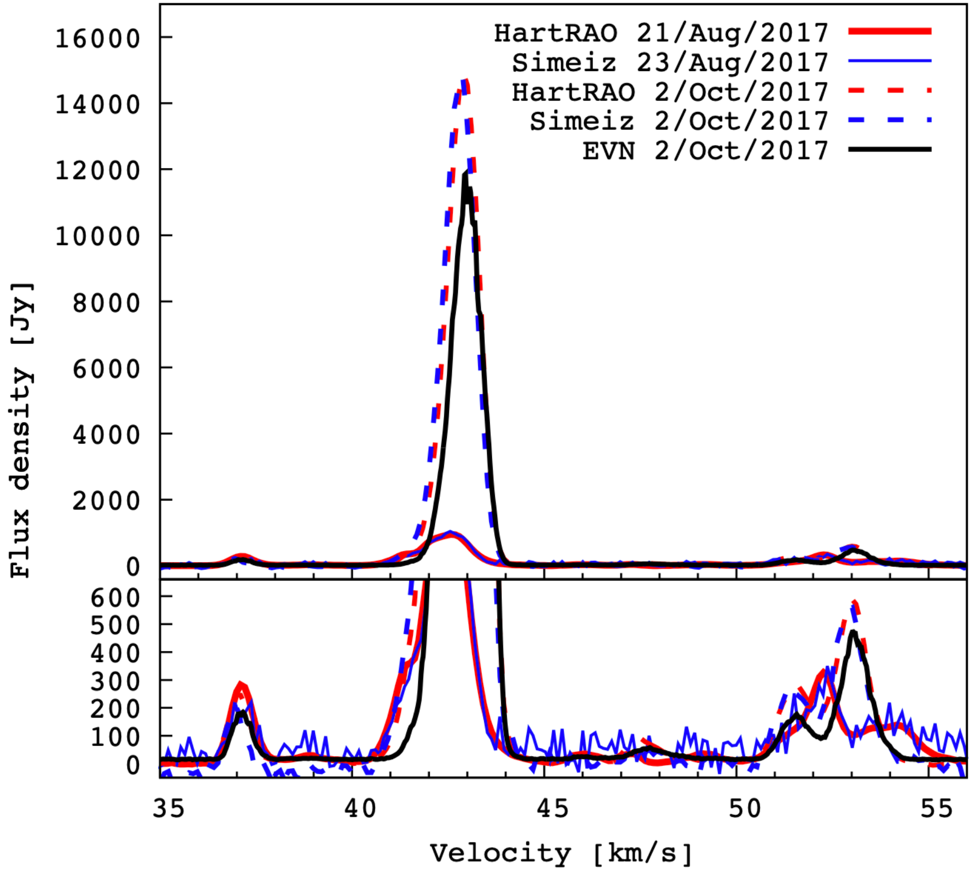
AFGL 5142: EVN, VERA, VLBA

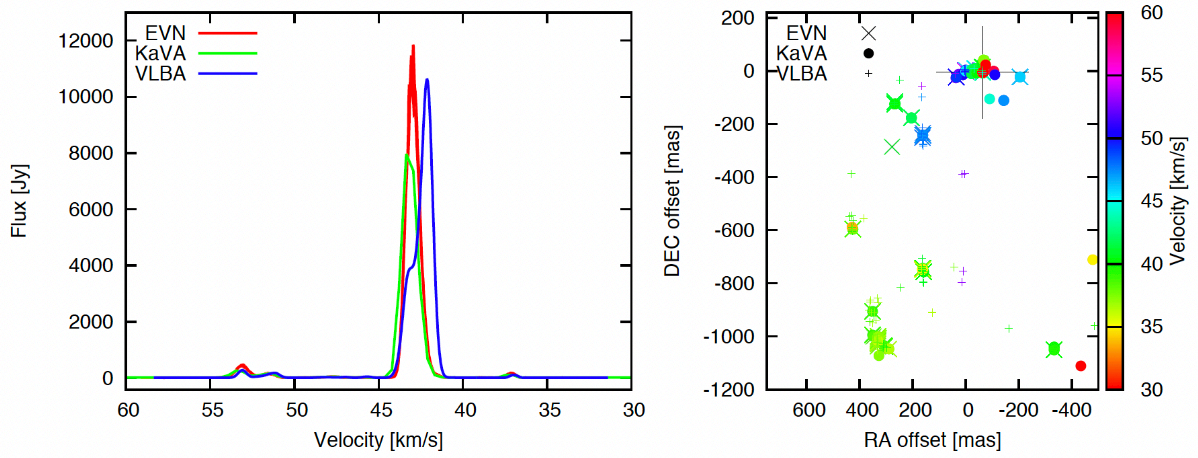


Goddi & Moscadelli 2006
Goddi et al. 2007
Burns et al. 2017
Hunter et al. 2020

Maser Superbursts

G25.65+1.05 Water Maser Superburst





- Superburst refers to a particularly extreme class of maser bursts, where a maser emitting region exhibits a sudden increase in flux density of several orders of magnitude

- There are 3 recognised water maser superburst star forming regions (SFRs): Orion KL, W49N and G25.65+1.05

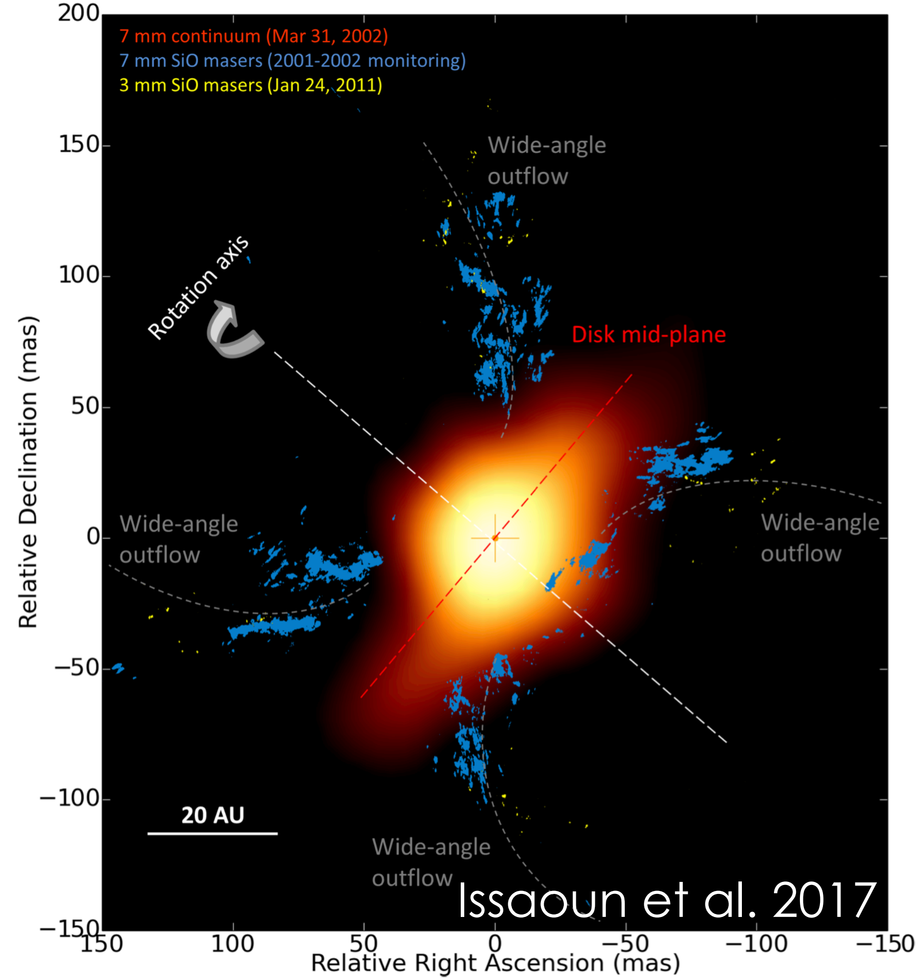
- In this case, its cause was determined to be an increase in maser path length generated by the superposition of multiple maser emitting regions aligning in the line of sight to the observer

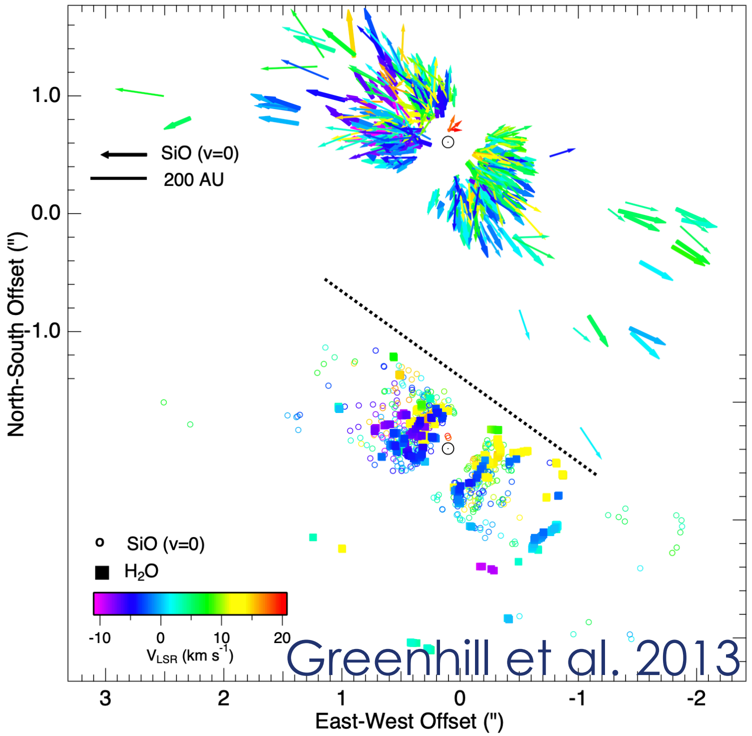
Extreme maser burst not associated with an accretion burst e.g. Burns et al. 2020

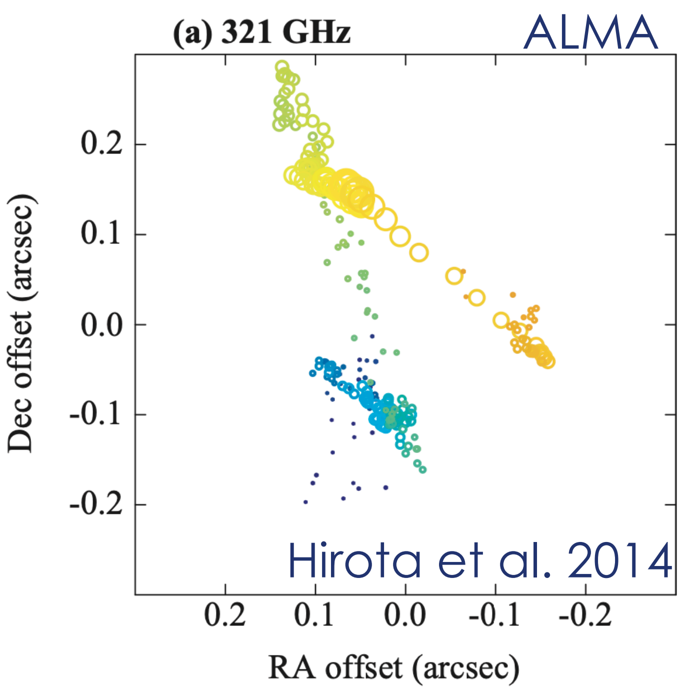
ALMA

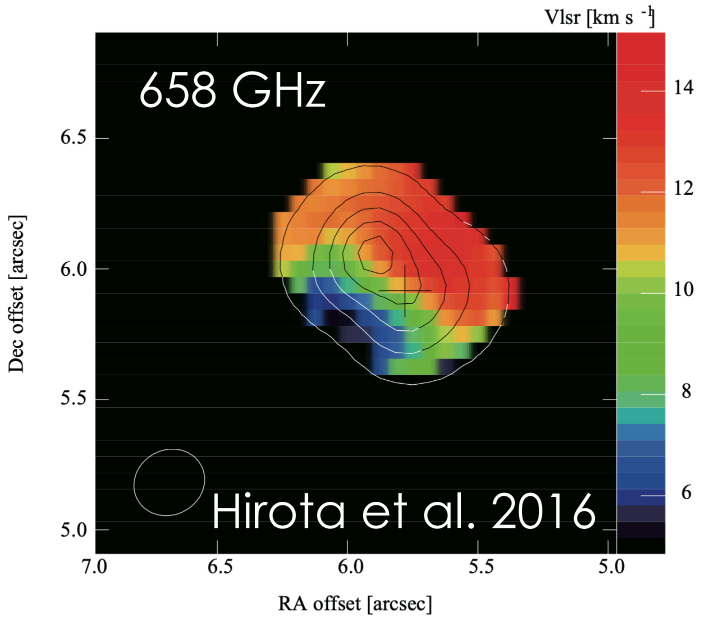
Orion Source I

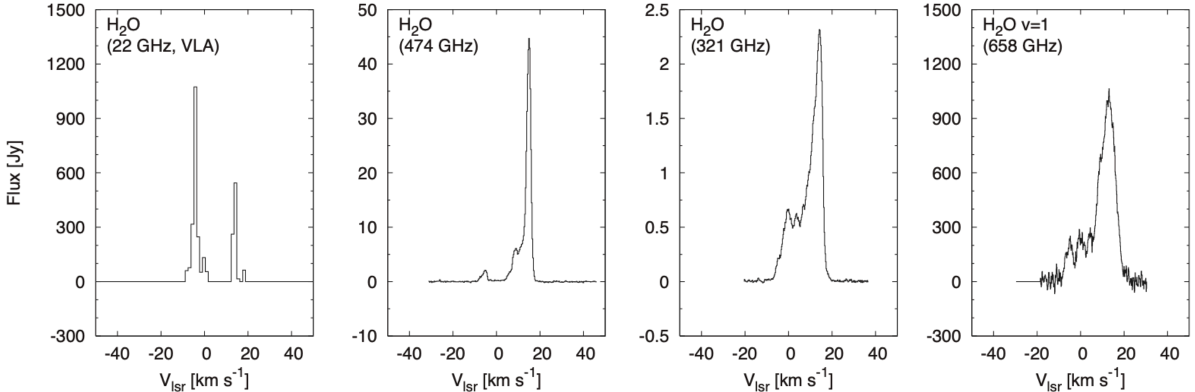
Masers at higher frequency











Hirota et al. 2018

So many more publications e.g.

EVN:
- Sanna et al. (2017) - Planar infall of CH_3OH gas around Cepheus A HW2
- Moscadelli et al. (2017) - Extended CH_3OH maser flare excited by a bursting massive YSO

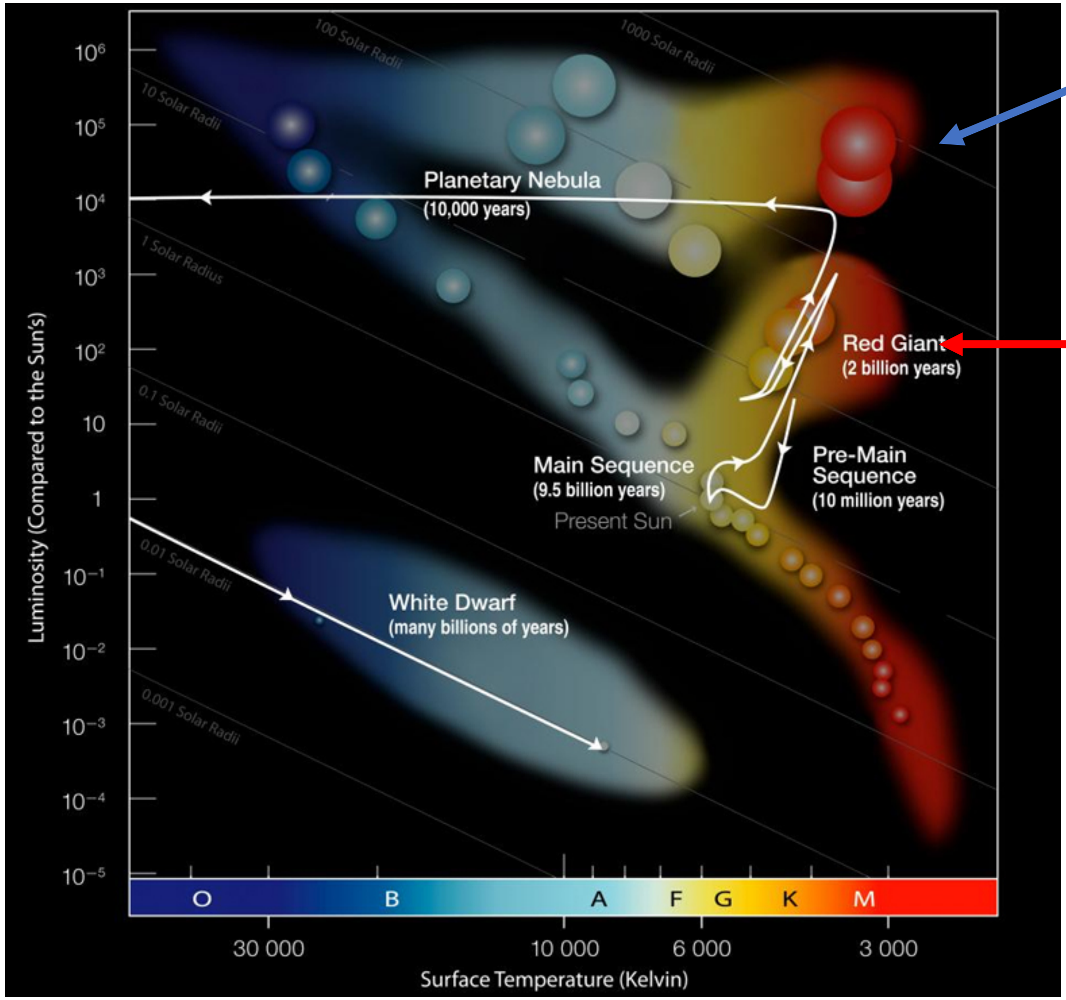
VLBA:
- Goddi et al. (2017) - Measuring magnetic fields from water masers in the synchrotron protostellar jet in W3(H_2O)

VERA & ALMA:
- Hirota et al. (2021) - Water maser variability in a high-mass YSO outburst. VERA and ALMA observations of S255 NIRS 3

MERLIN:
- Darwish et al. (2020)- OH maser towards IRAS 06056+2131: polarization parameters and evolution status
- Darwish et al. (2020) - Methanol and water maser observations separate disc and outflow sources in IRAS 19410+2336

Modelling:
- Gray, Etoka & Pimpanuwat (2020) - Analysis of methanol maser flares in G107.298+5.63 and S255-NIRS3

Evolved Stars



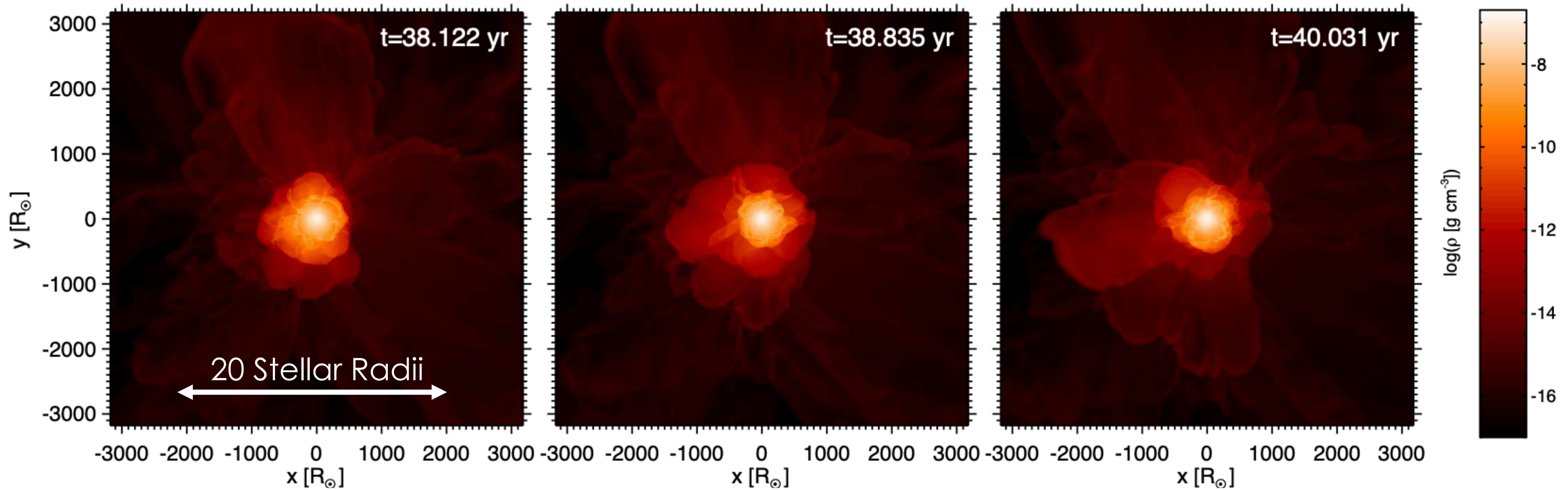
Red Super Giants
$M_{initial}$: 8 - 35 $M_\odot$
e.g. Betelgeuse

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

Mass-loss and Masers

After Colomer, Le Bertre, et al.

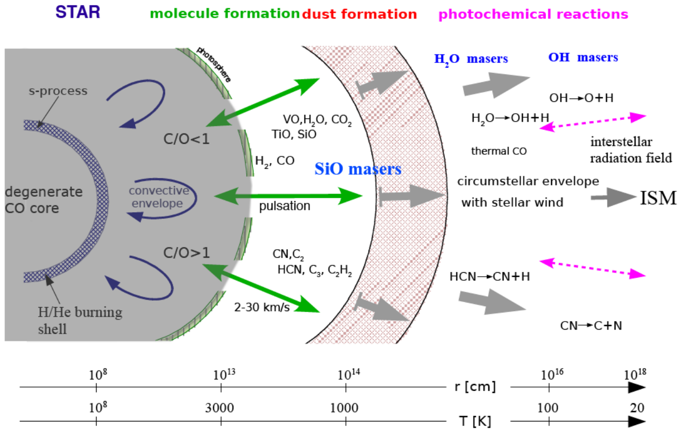


Hoefner & Freytag 2022:

1000 R$_\odot$ = 5 AU

Time-dependent structure of a 3D radiation-hydrodynamical model of an AGB star, including interior dynamics (convection, pulsation), dust formation and wind acceleration, computed with the CO5BOLD code

Stellar Surface / Photosphere

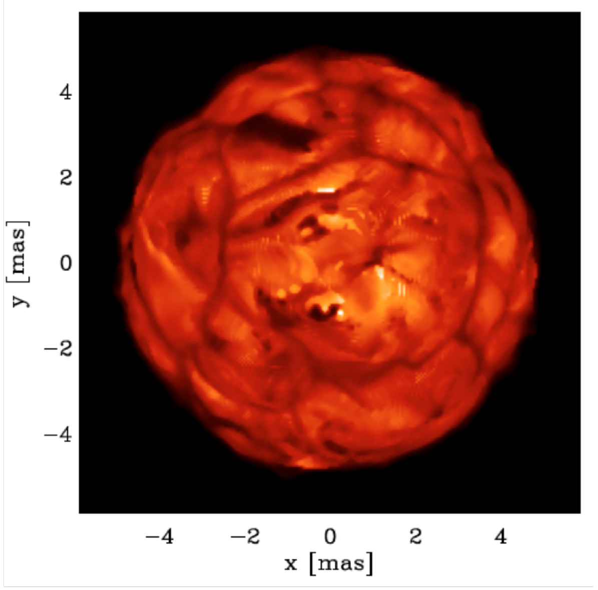


Stellar radii (from optical/IR)

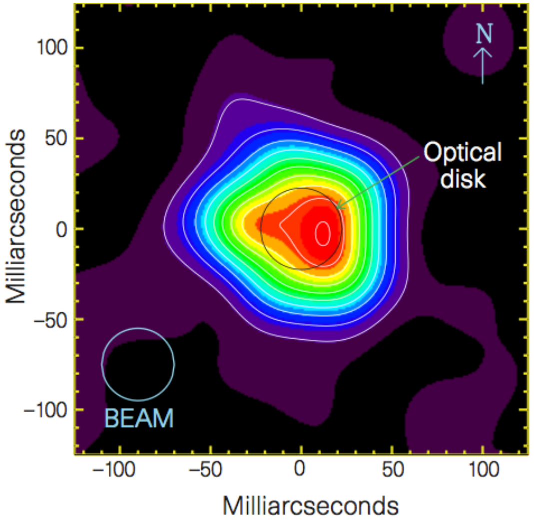
Stars	Diameter at 2.3 micron (mas) *	Distance (pc)	Stellar radius (AU)
Betelgeuse (RSG)	43	~200	4.3
Antares (RSG)	37	170	3.2
W Hya (AGB)	~40	98	2.0
R Dor (AGB)	47	59	1.4
Mira (AGB)	25	92	1.2

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

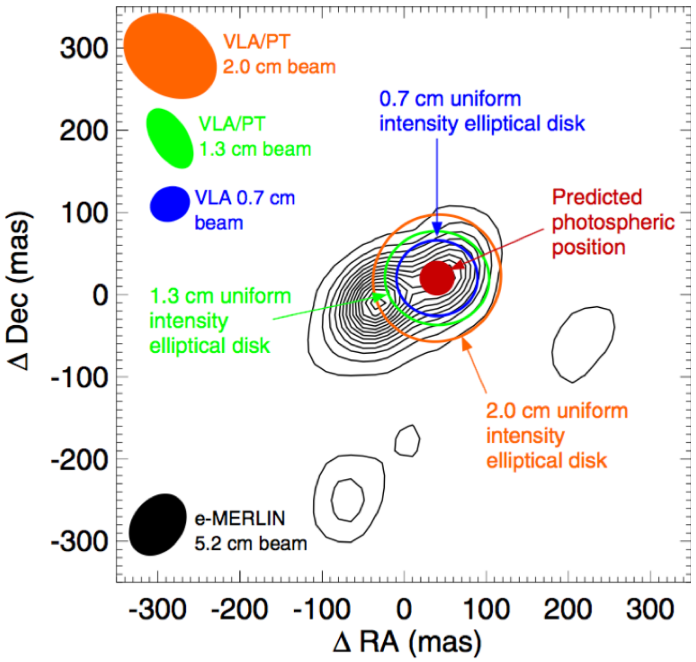
Stellar surface believed to be covered by convective cells



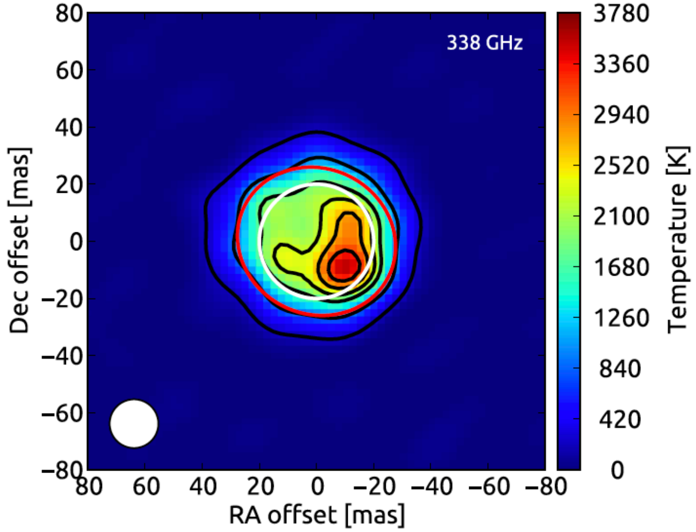
IR Simulations
Freytag & Hofner 2008



Betelgeuse, VLA 7mm
Lim et al. 1998 Nature



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

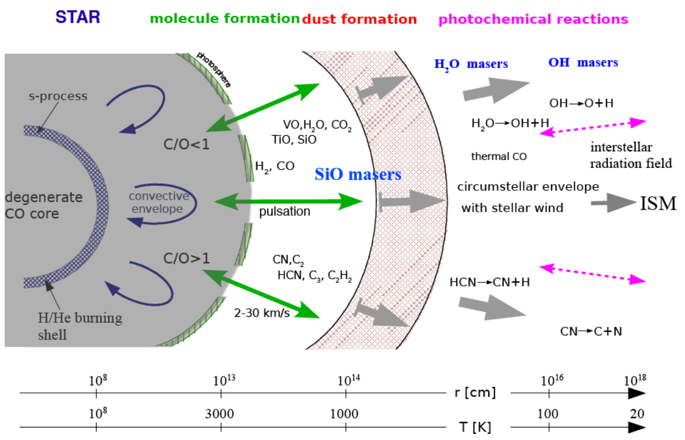


W Hya
ALMA 338 GHz/0.9 mm
Vlemmings et al. 2017

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

See also Matthews et al. 2018, **Hoefner & Freytag 2022**

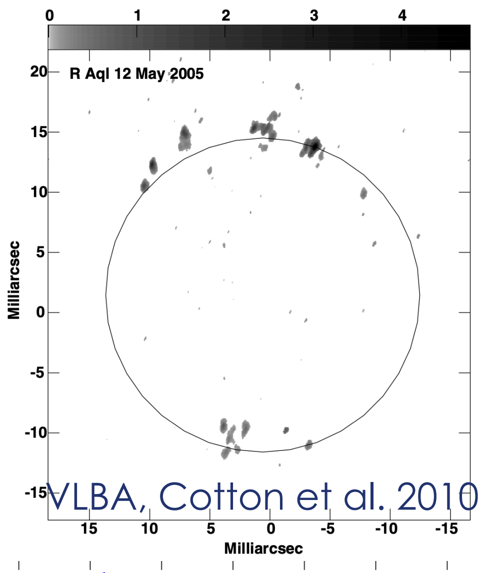
Inner Circumstellar Envelope: < 5 R_{star}



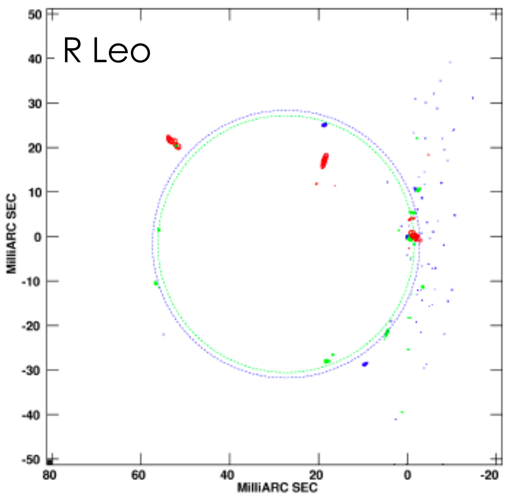
SiO Masers

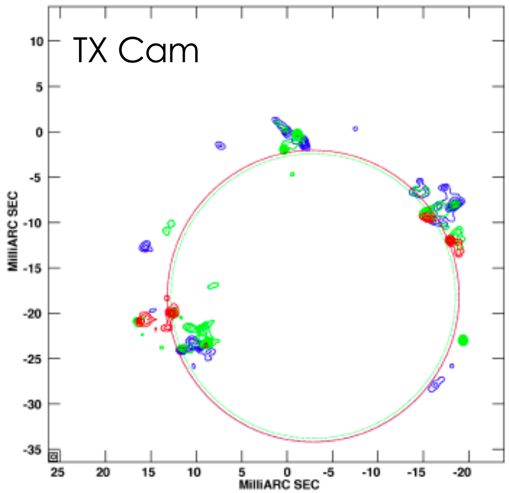
See talk by Gray on 3D maser modelling with polarization

Gallery of SiO maser rings

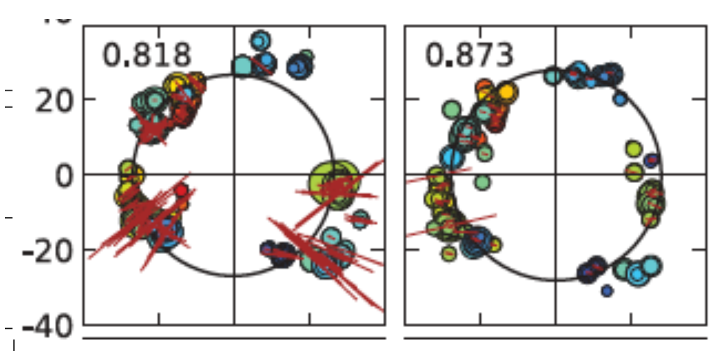


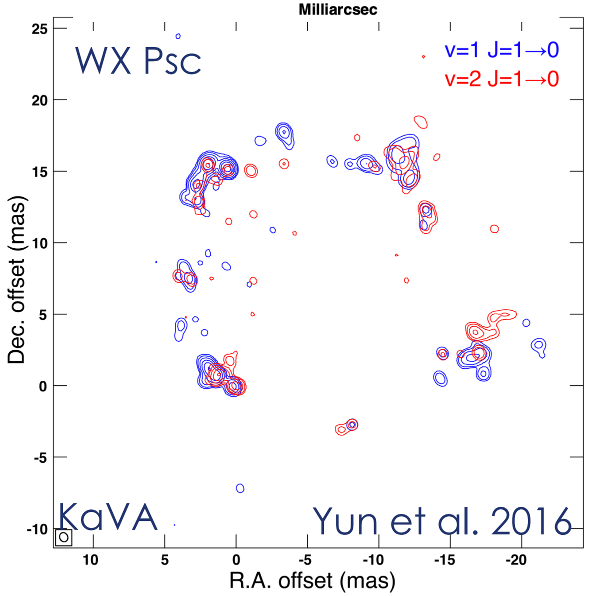
VLBA, Cotton et al. 2010



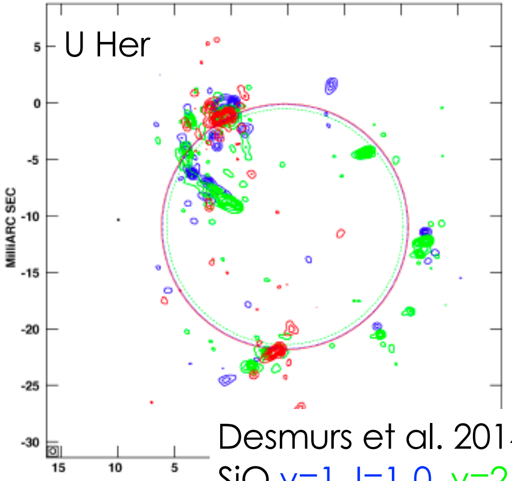


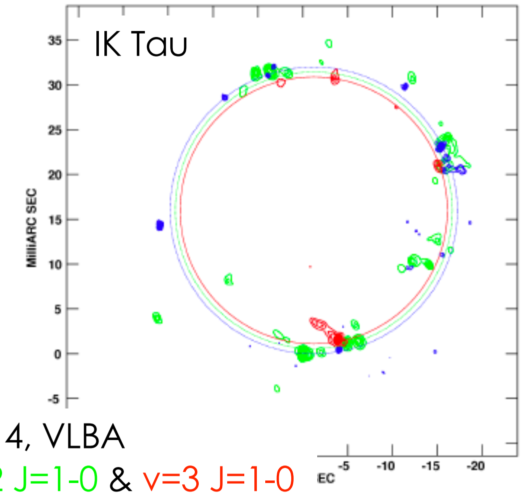
R Cas - Assaf et al. 2013
Multiple VLBA epochs & polarization





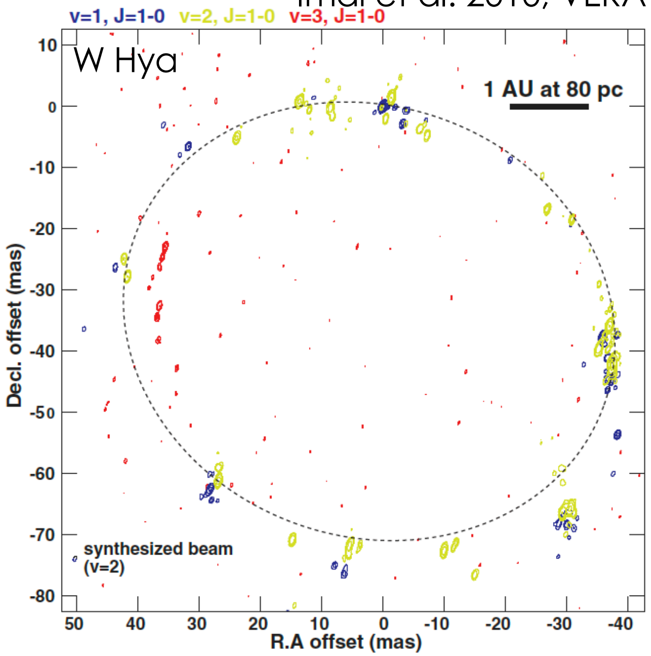
Yun et al. 2016





Desmurs et al. 2014, VLBA
SiO v=1 J=1-0, v=2 J=1-0 & v=3 J=1-0

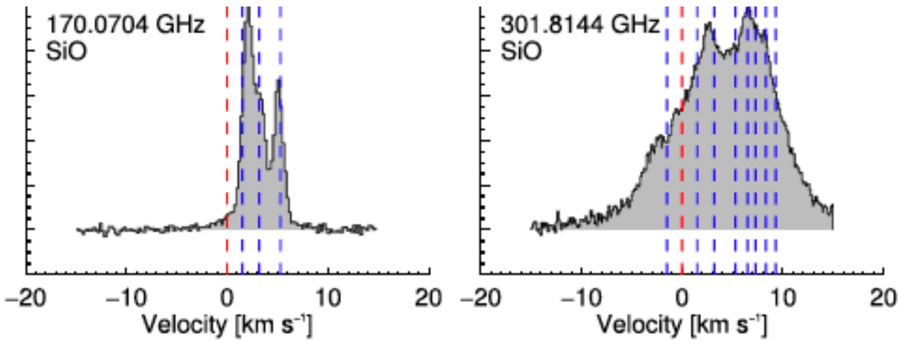
Imai et al. 2010, VERA



Outflow and infall detected, complex non-radial motions – Gonidakis et al. 2013

ALMA

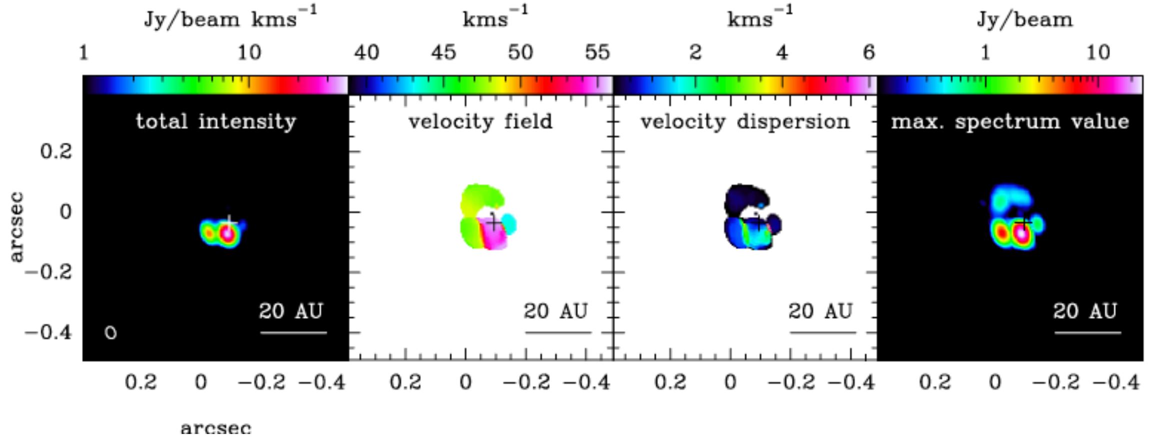
Evolved star mm/submm SiO masers



R Dor, APEX, De Beck & Olofsson 2018

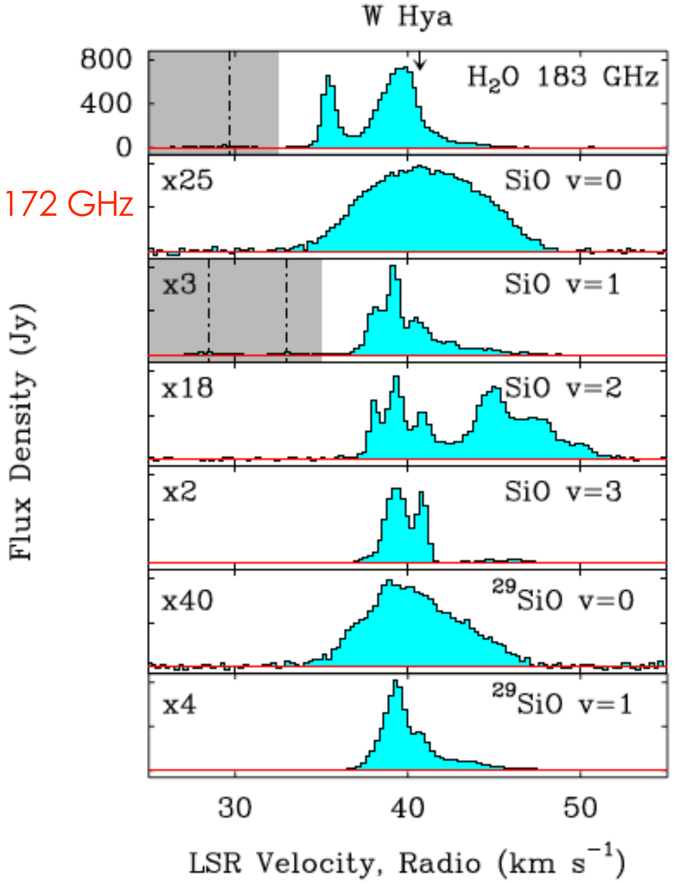
SiO v=1 J=5−4

217 GHz



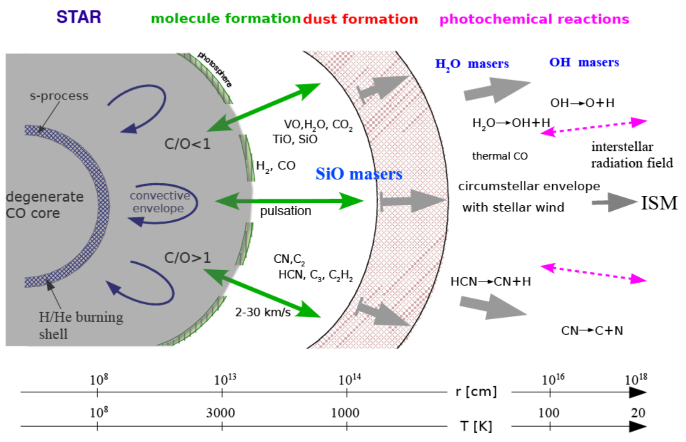
Mira, ALMA long baseline science verification data

172 GHz



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

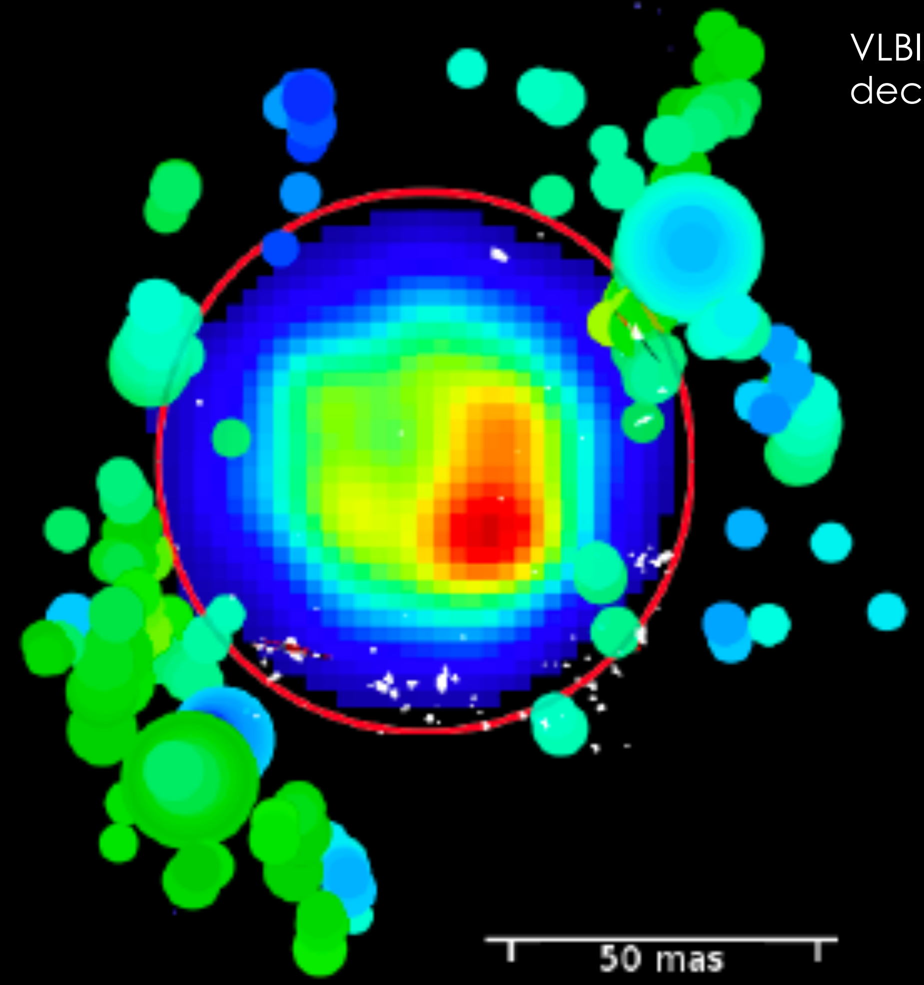
Wind acceleration zone / H_2O masers



Stellar Surface, Hotspot	Coloured disk	ALMA 338 GHz continuum	Vlemmings et al. 2017
Radio Photosphere	Red circle	VLA 22 GHz continuum	Reid & Menten 1990
SiO masers	White spots	VLBA 43 Gz	Cotton et al. 2008
Water masers	Coloured spots	MERLIN 22 GHz	Richards et al. 2012

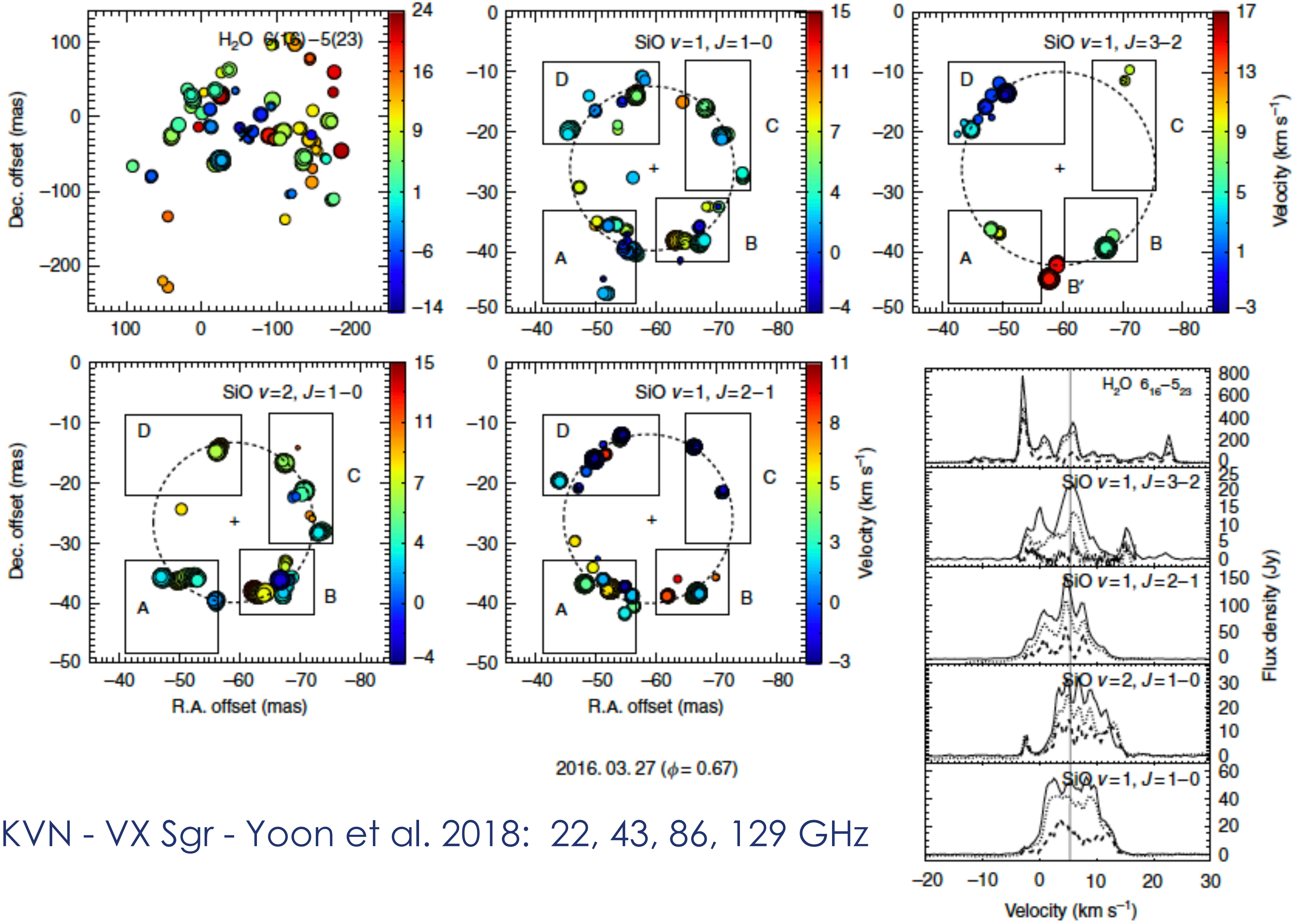
W Hya – AGB Star

VLBI20-30: a scientific roadmap for the next decade Eds: Venturi, Paragi & Lindqvist



Simultaneous SiO & H_2O Observations

Simultaneously tracing gas both sides of the dust formation zone

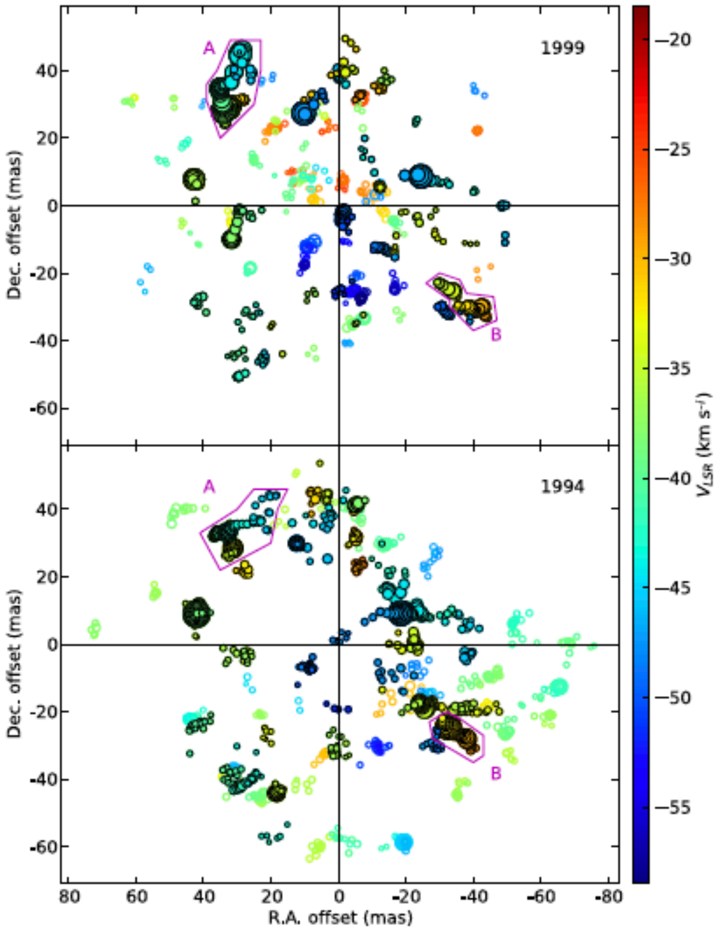


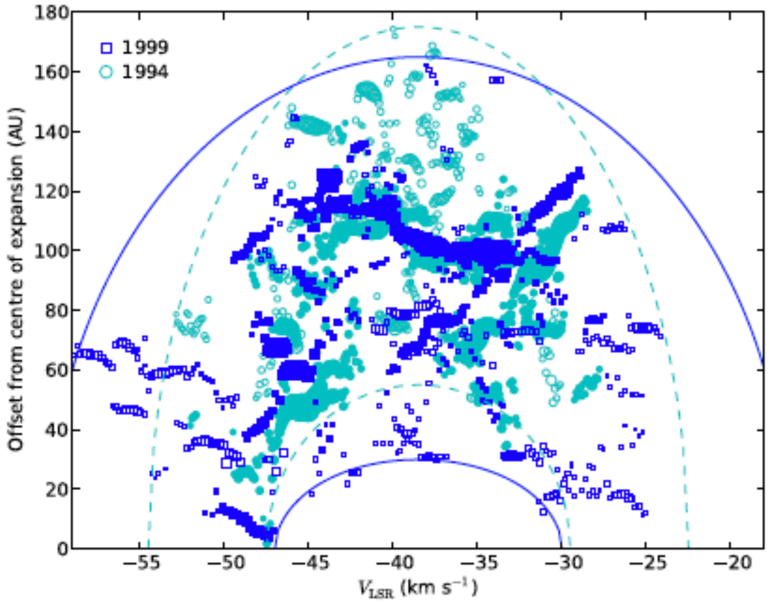
KVN - VX Sgr - Yoon et al. 2018: 22, 43, 86, 129 GHz

H_2O Masers at 22 GHz: 5 - 50 R_*

(very approximate radii)

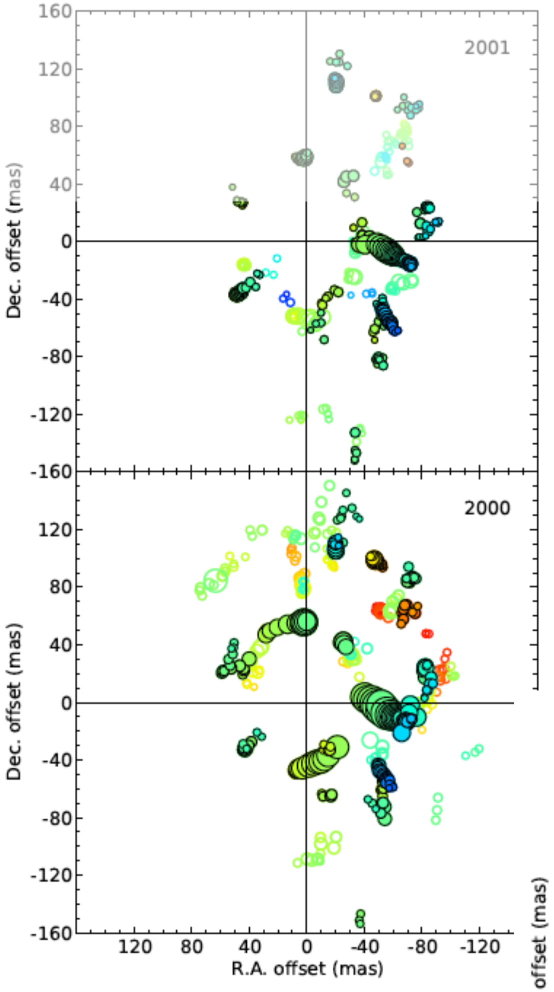
S Per - RSG

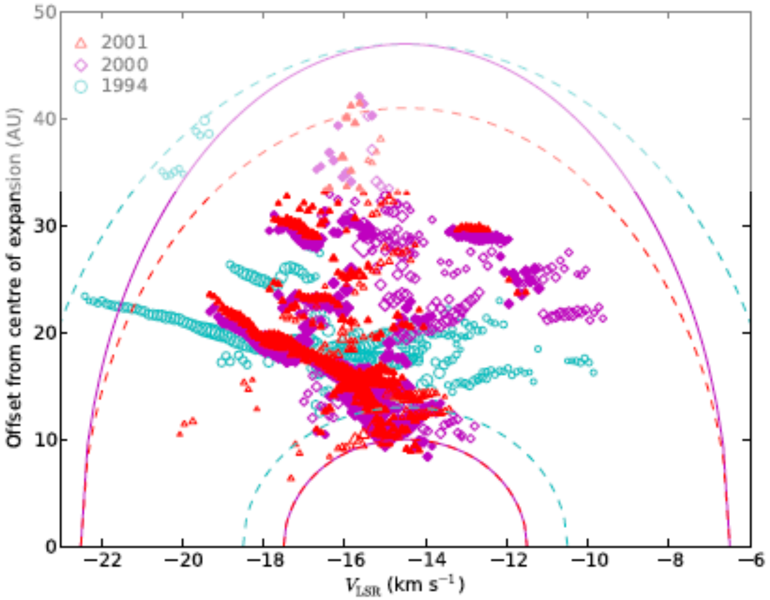


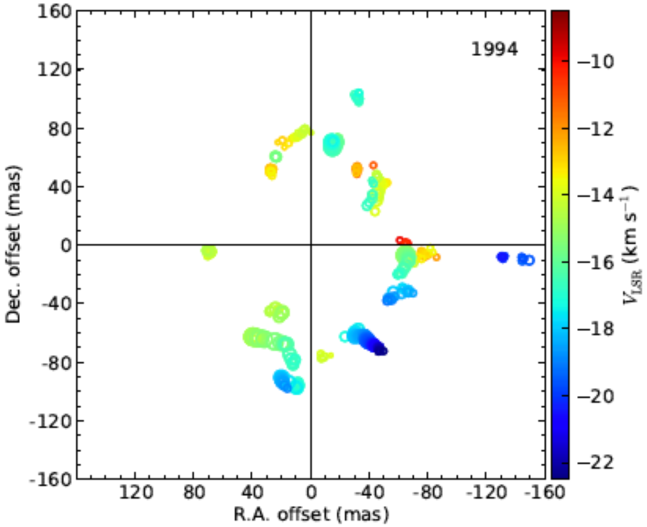


Projected distance of masers from expansion centre as a function of V_{LSR}

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







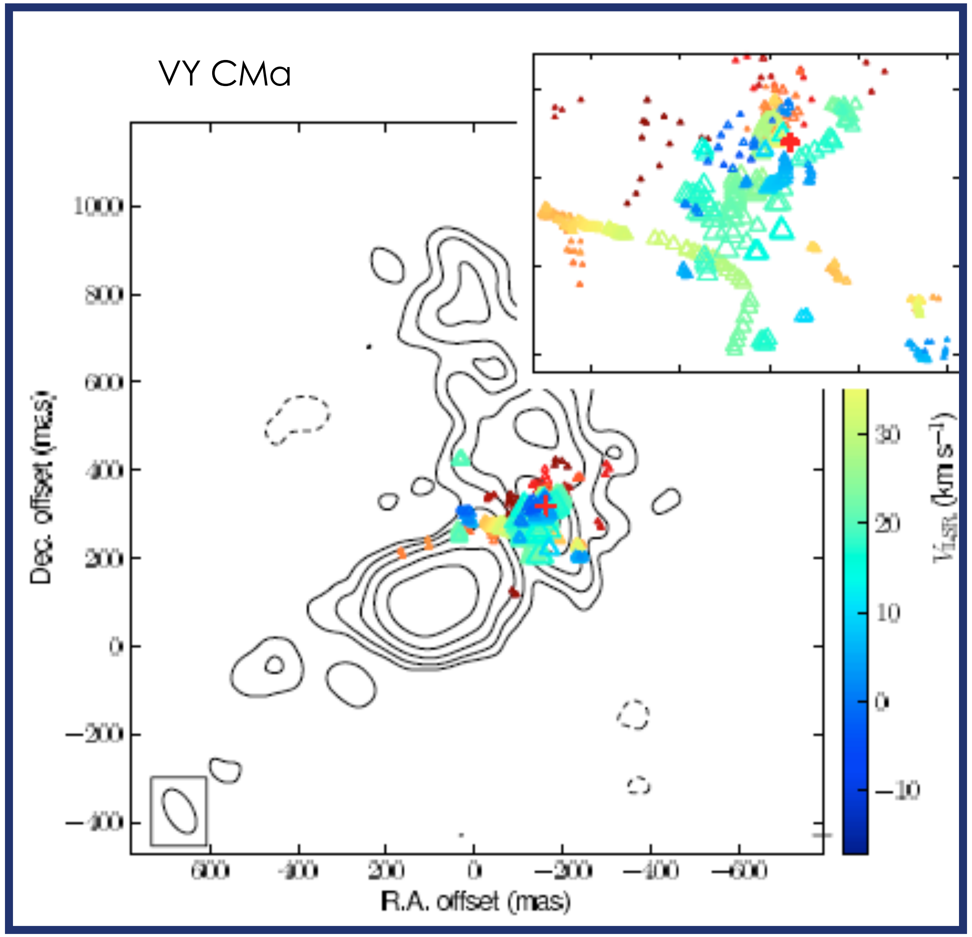
Inner and outer shell radii and expansion velocities for spherical shells

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

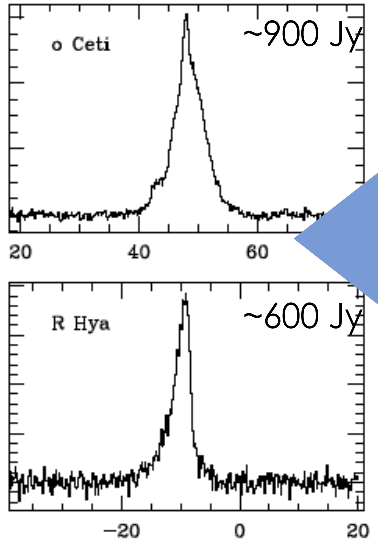
U Her - AGB

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

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

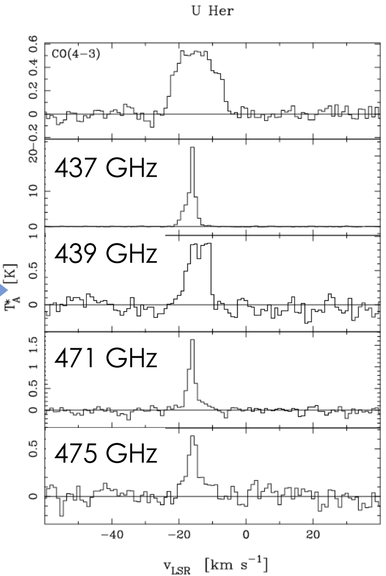
APEX

Baudry et al. 2018

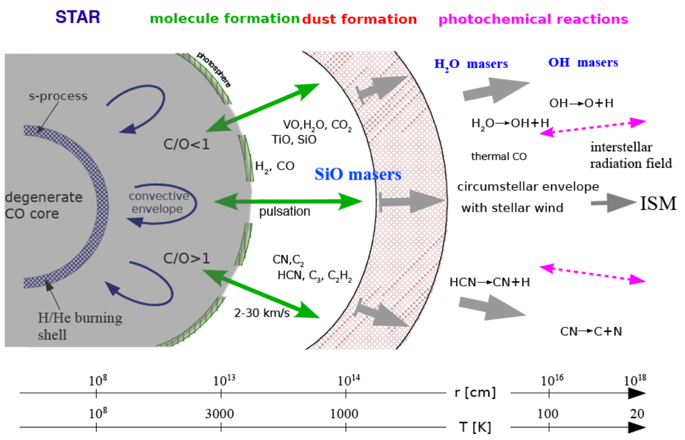
437, 439, 471, 475 GHz Water Masers

APEX

Bergman & Humphreys 2020



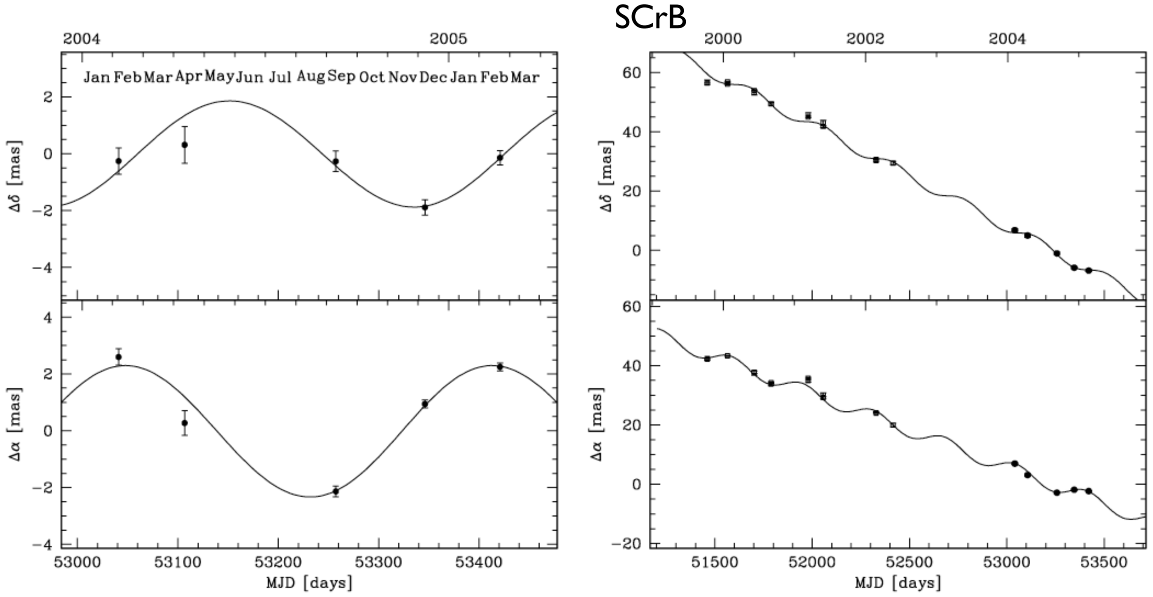
Stellar Wind / OH Masers

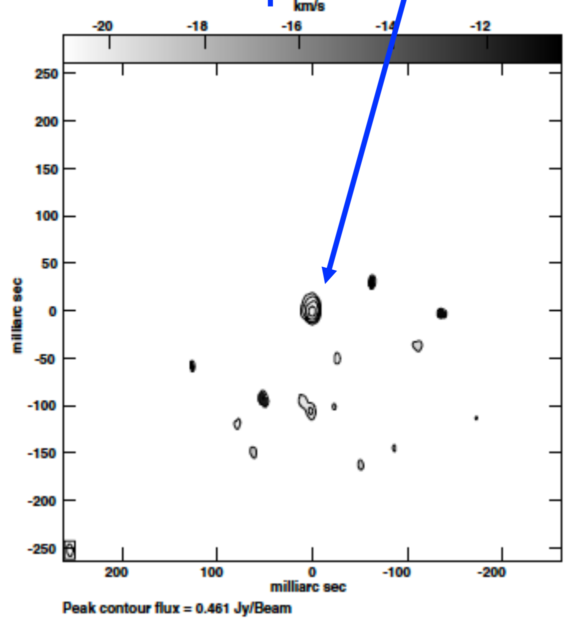


1665 and 1667 OH Masers ~100 - 1000 R*

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

Amplified Stellar Image



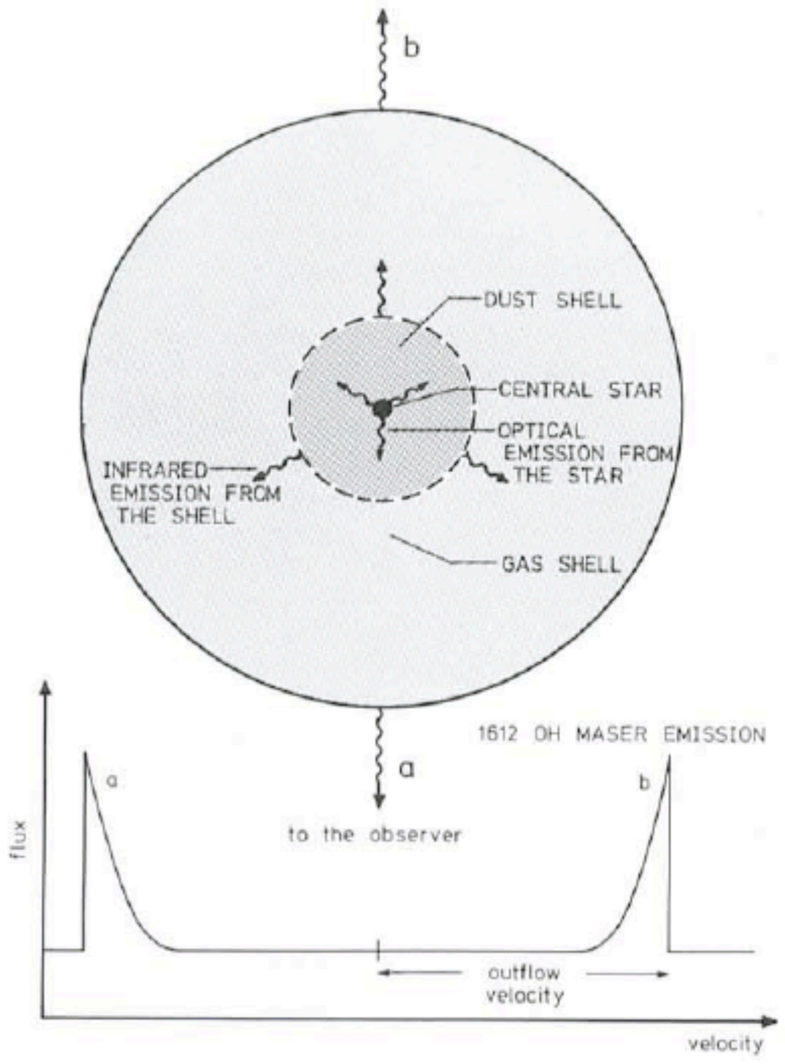


Vlemmings et al. 2007: VLBA at 1665 & 1667 MHz

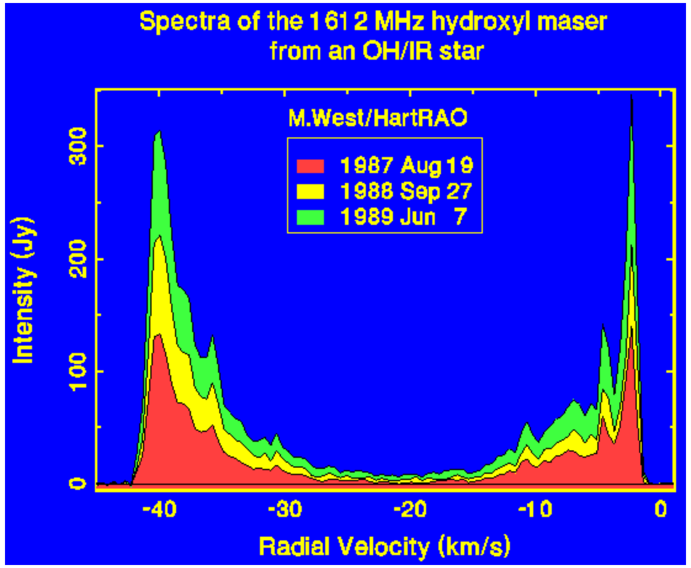
- VLBI astrometric observations of circumstellar OH masers can yield the proper motions and parallaxes of AGB stars
- Most blue-shifted circumstellar OH maser spot believed to be the *Amplified Stellar Image*

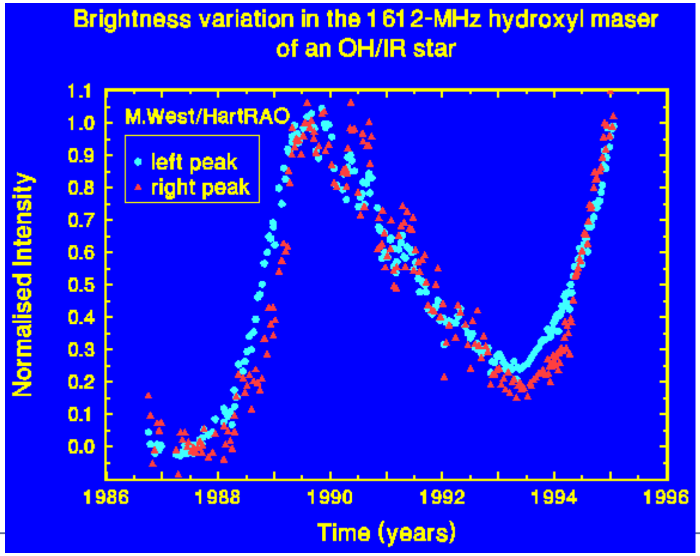
Adding in the SKA to VLBI networks —> very many objects within a few kpc accessible (Green et al. 2015)

OH 1612 MHz Masers ~ 1000 R*

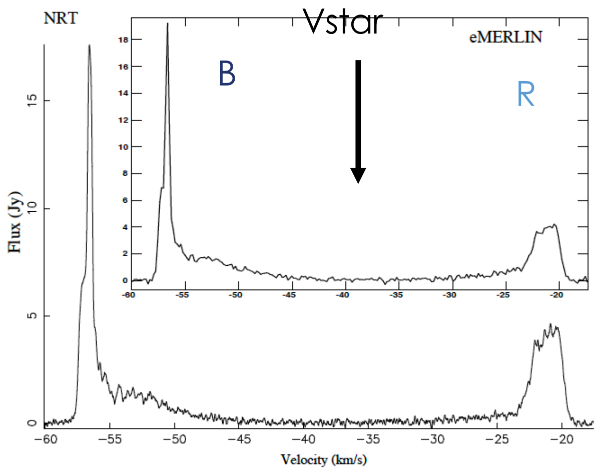


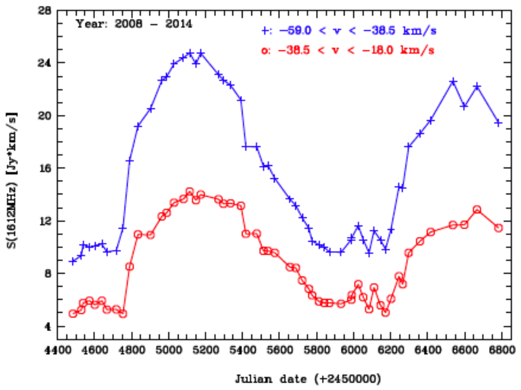
Engels

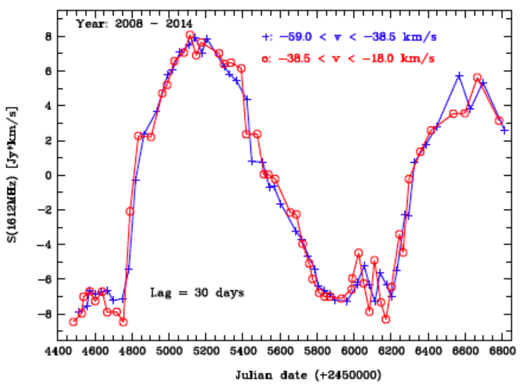




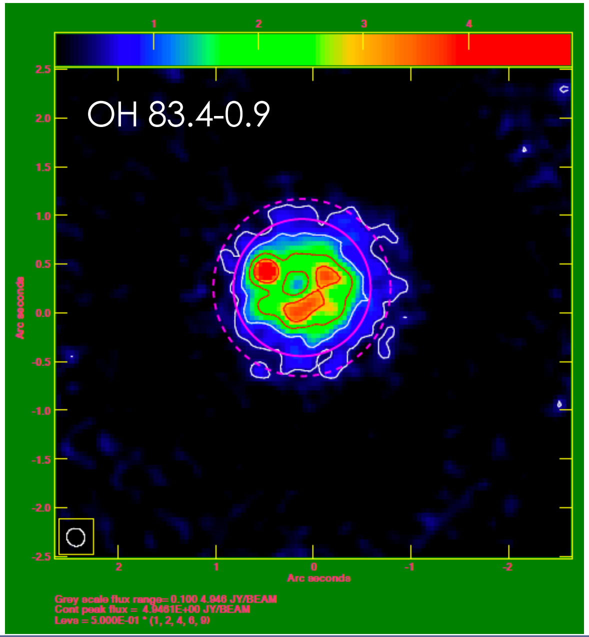
OH 1612 MHz Masers: Phase Lag Distance







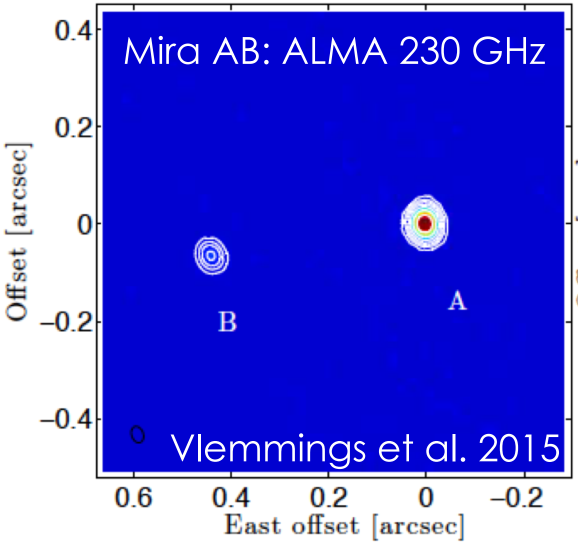
Etoka et al. 2014: Nancay Radio Telescope & e-MERLIN

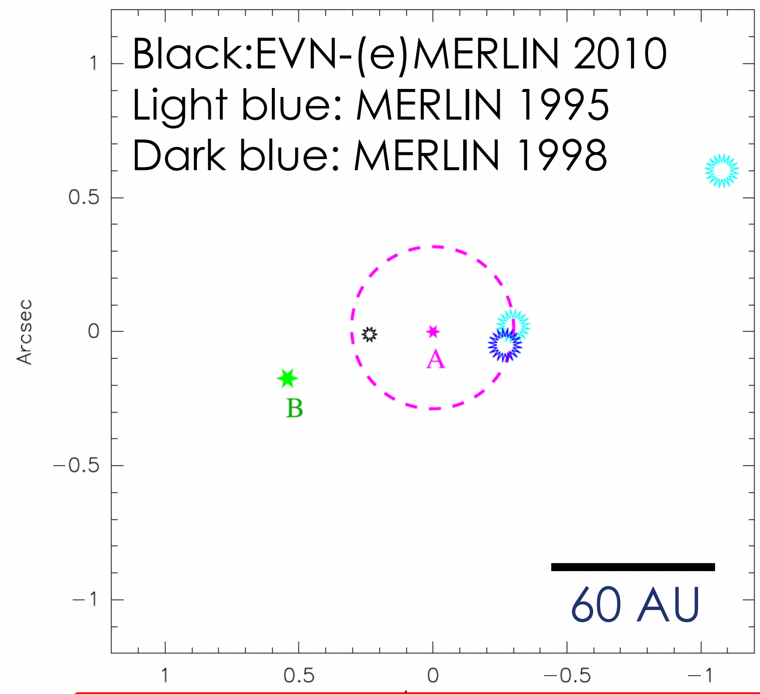


- Distance determination via the phase lag method
- Measure of OH maser shell angular diameter (interferometer)
- Measure time lag of variability between peaks (single-dish) —> linear diameter

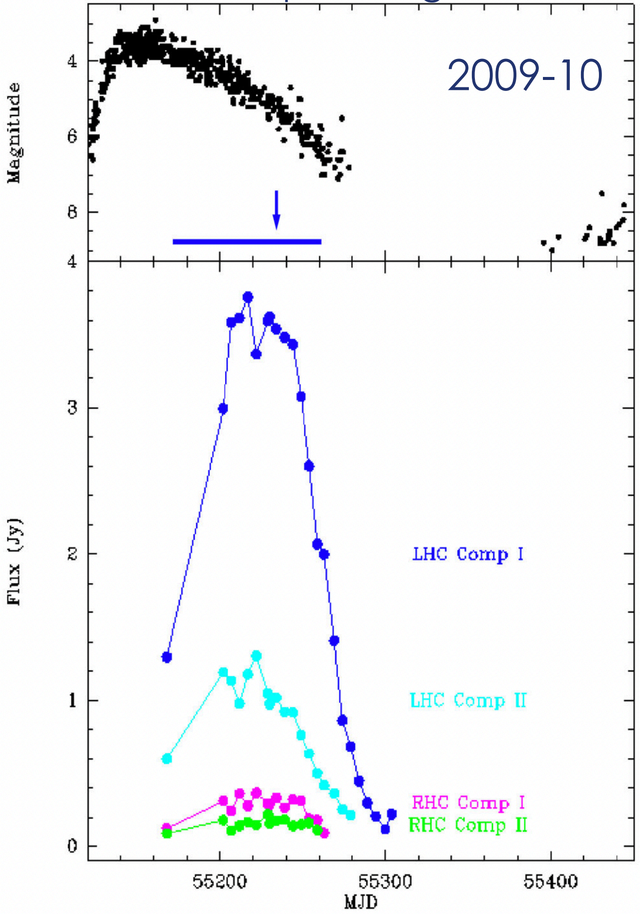
Distance = 3.3+/-0.6 kpc

Recurring OH flares towards Mira



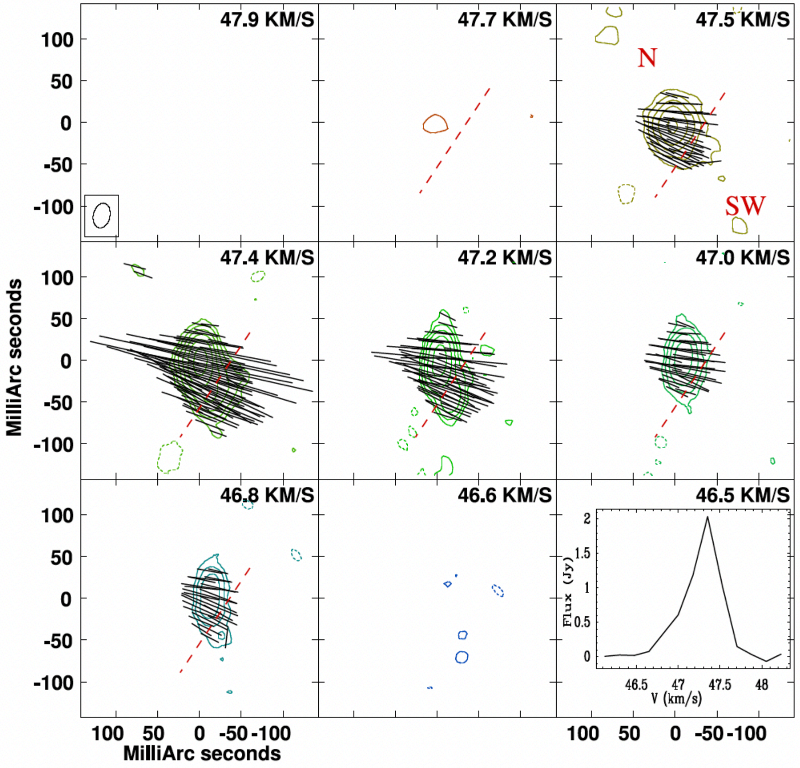


AAVSO Optical Light Curve



Flaring of different components in the NRT spectrum

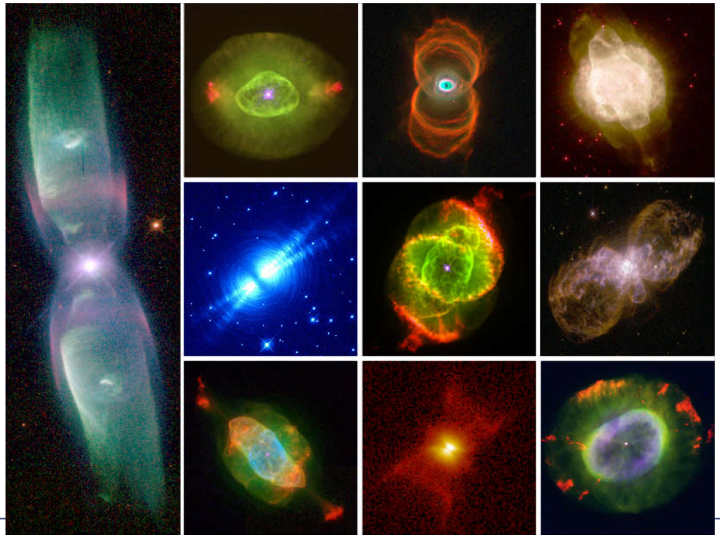
Etoka et al. 2017



EVN-(e)MERLIN 1665 MHz Stokes I with polarization Information overlaid

Regions where the transient OH maser emission occurs are different from the standard OH maser zone

Shaping to Planetary Nebulae



ATOMIUM

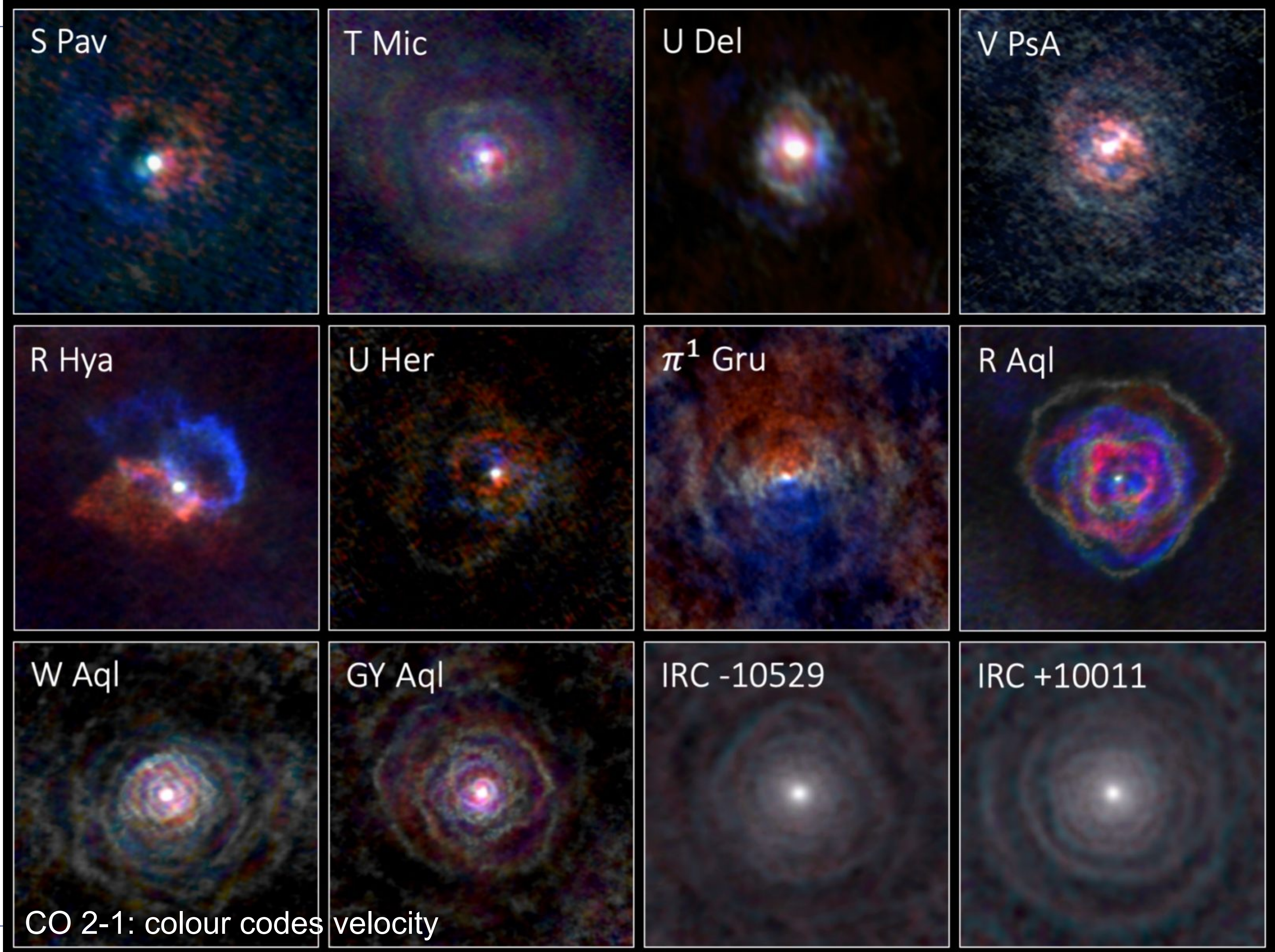
ALMA Large Program
PI: Decin

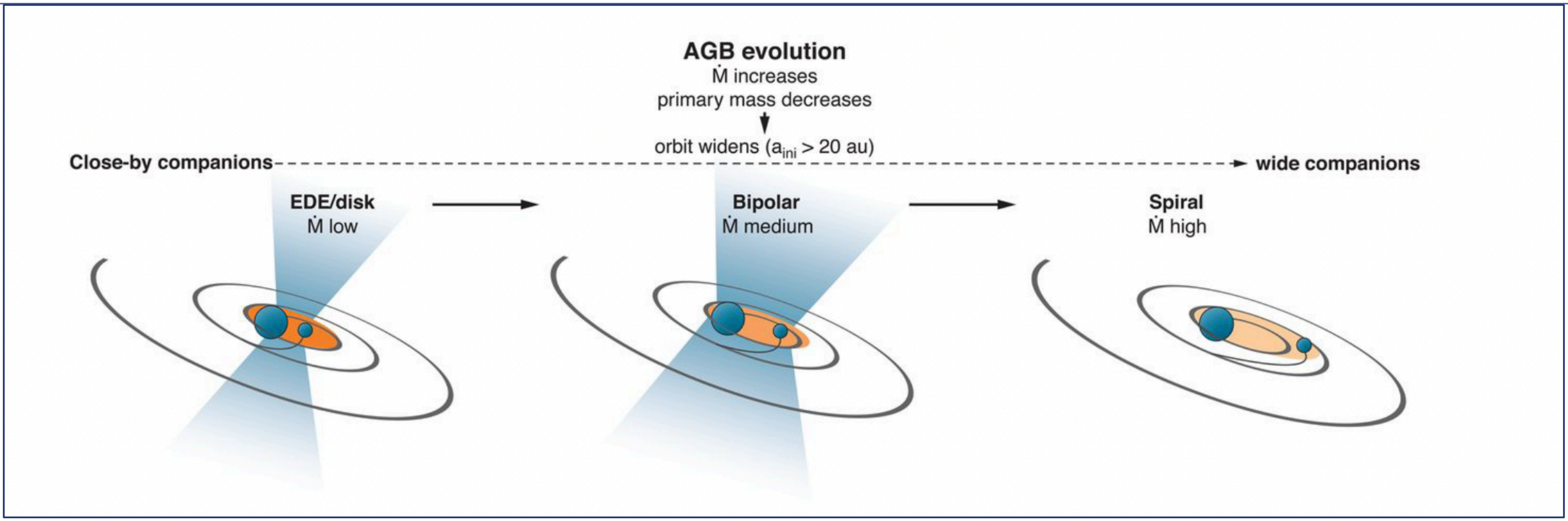
ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars

Implications for Shaping to Planetary Nebulae

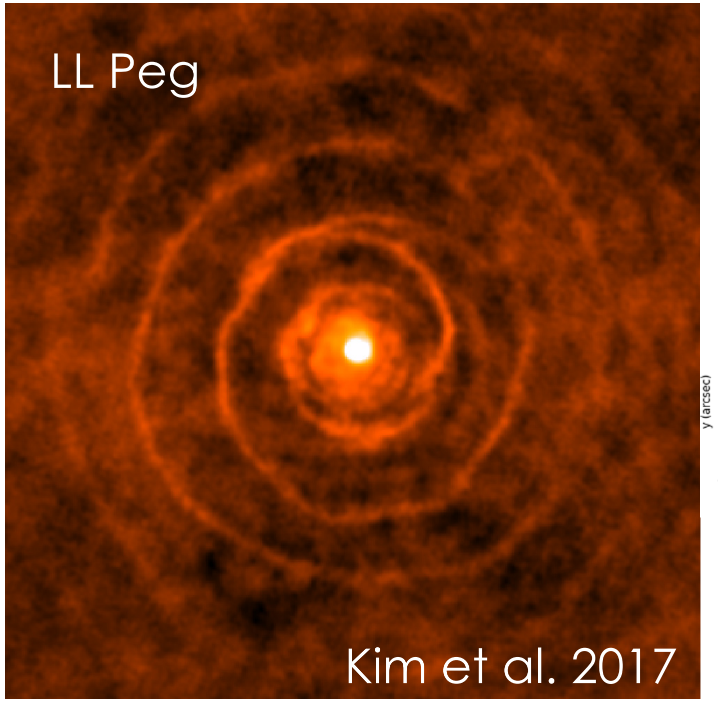
Decin et al. 2020

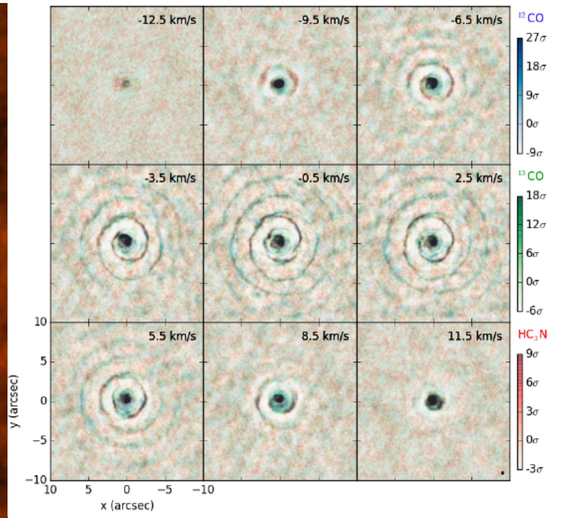
CO 2-1, SiO 5-4 & 6-5
0.24” & 1” resolution

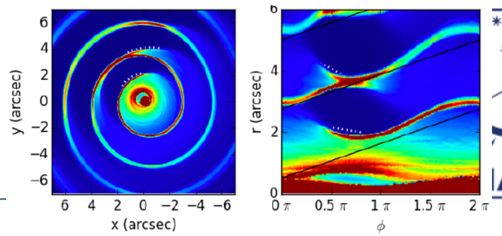




- Evolution of a spherical wind from an AGB star into an aspherical Planetary Nebula could be due to binary interactions
- Same physics shapes both AGB winds and PN
- Morphology and mass-loss rate are correlated
- Evolutionary scenario proposed

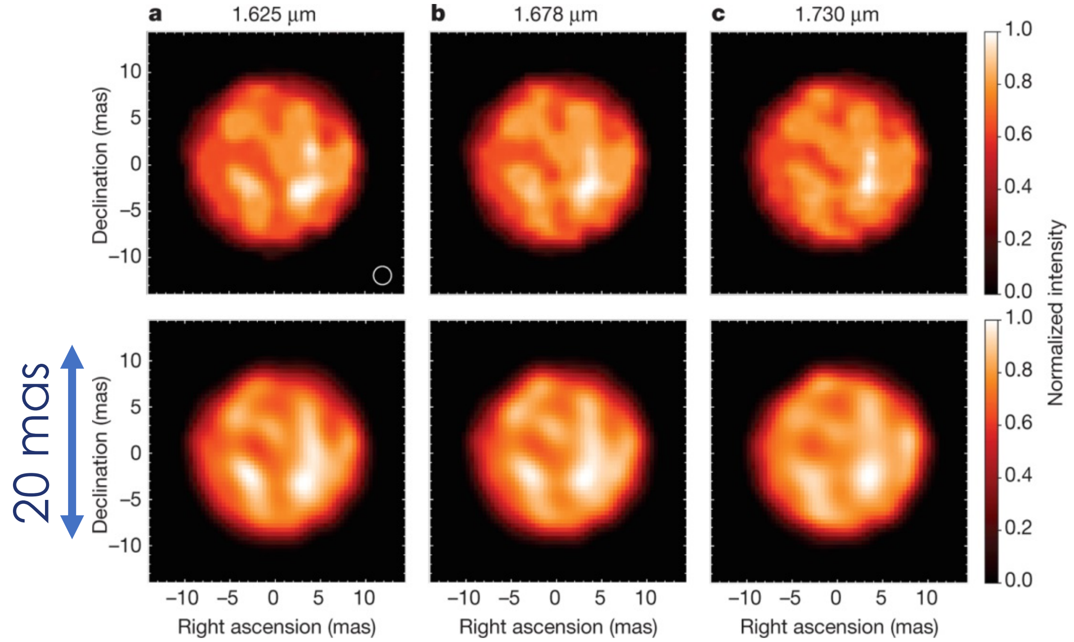




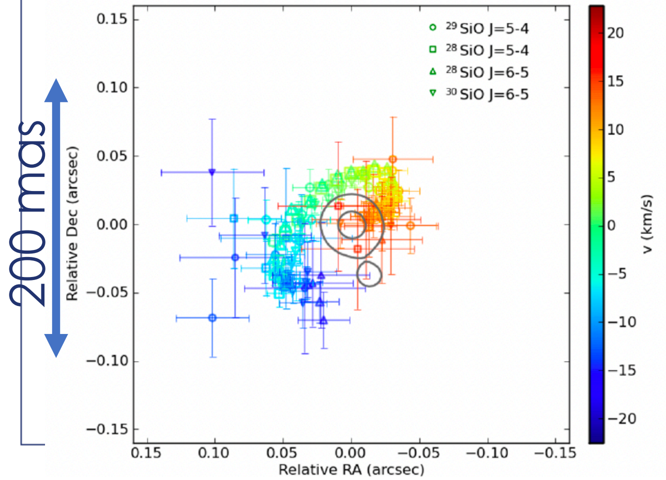


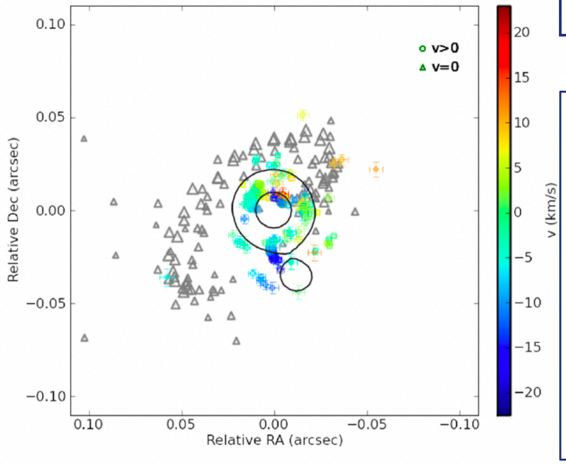
π^1 Gru

Stellar Surface: VLTI
Paladini et al. 2018

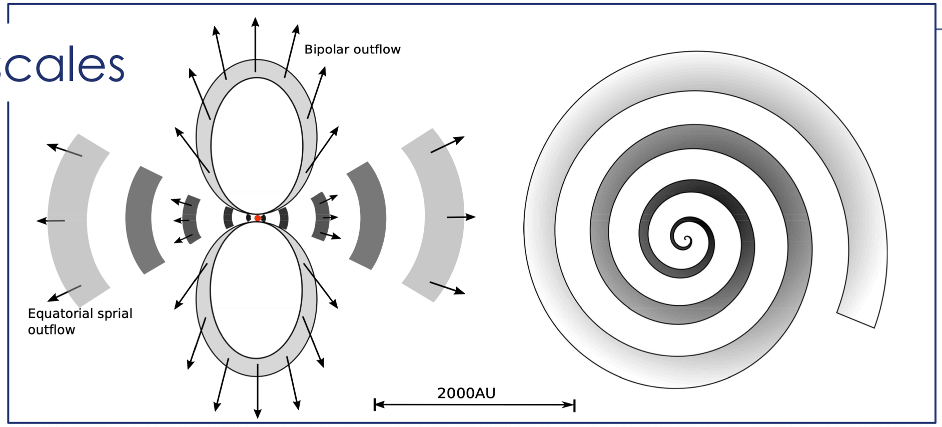


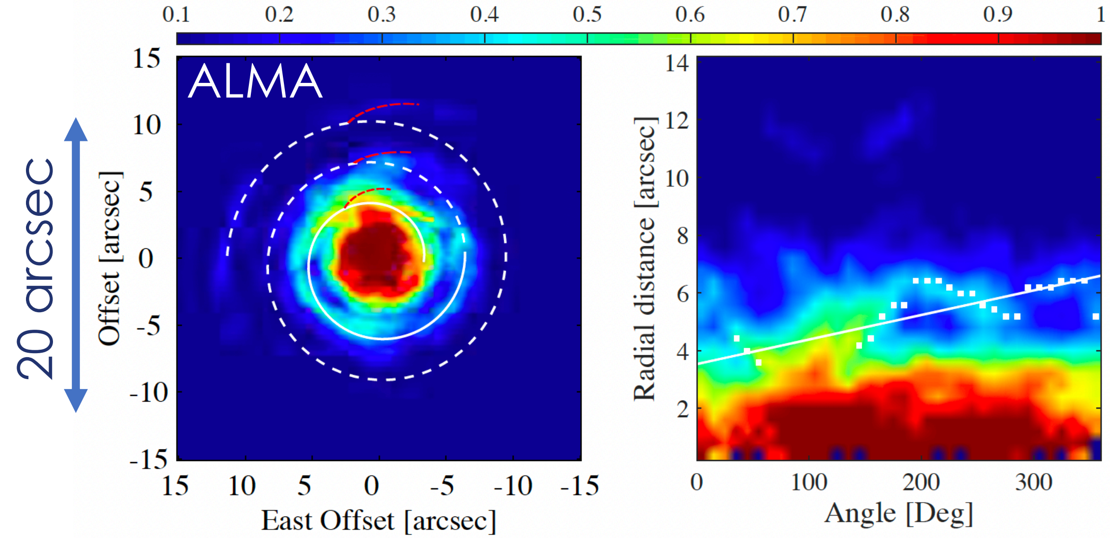
Homan et al. 2020, ALMA





Large-scales



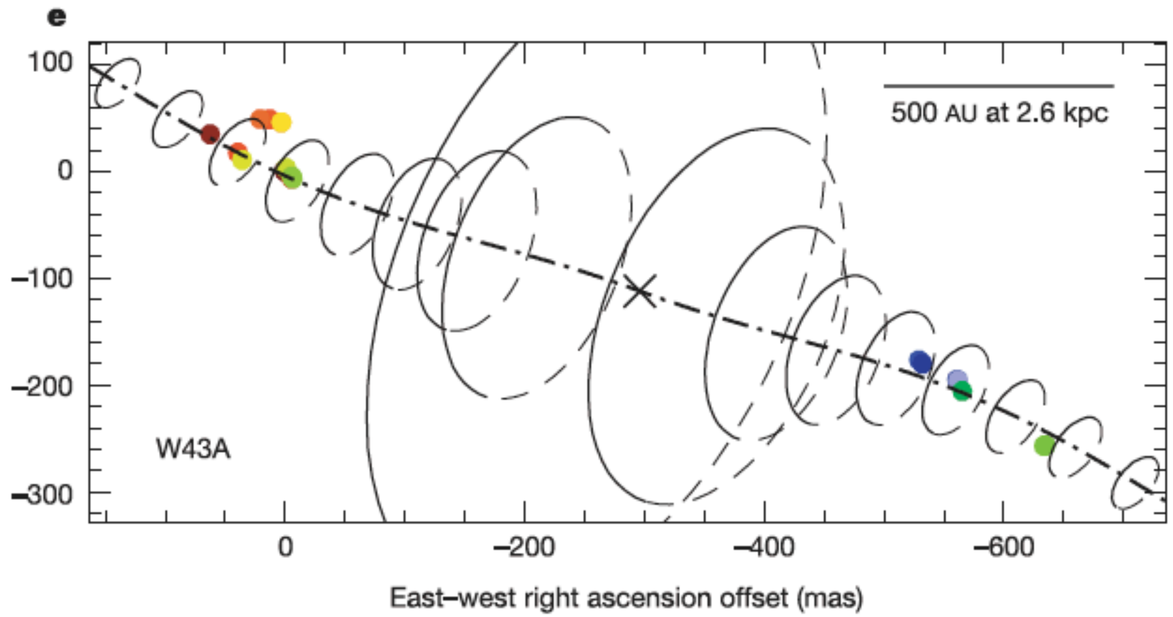


Doan et al. 2020

- SiO emission at scales smaller than 0.5” exhibits signatures of gas in rotation, expected for gas in the wind-companion interaction zone
- An investigation of SiO maser emission reveals what could be a stream of gas accelerating from the surface of the AGB star to the companion

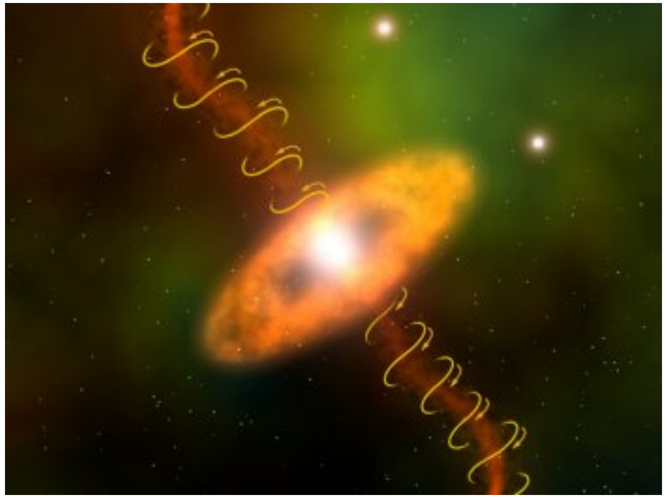
Masers in pre-Planetary Nebulae

- 15 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



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

Masers at ~1000 AU
From the star



Imai et al. 2002

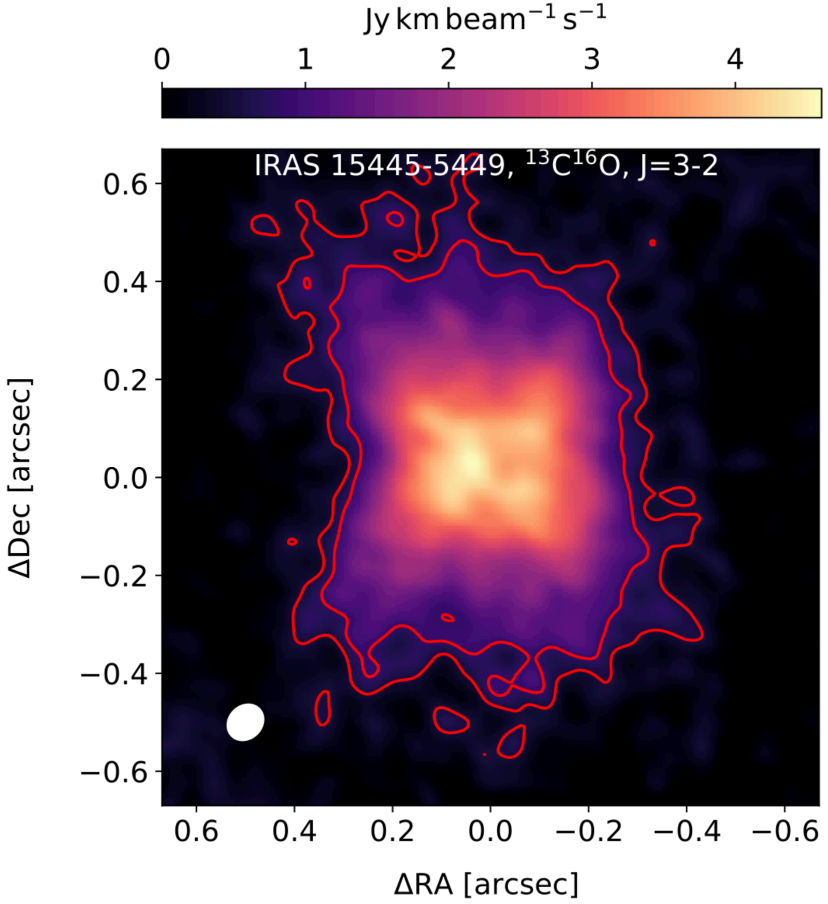
Polarization of 22 GHz H_2O masers that trace a precessing jet

ALMA Water Fountain Observations

- ALMA CO isotopologue observations towards water fountains reveal they had low initial masses (< 4 M⊙) and ejected a significant fraction of it over less than a few hundred years

- The only mechanism able to explain such rapid mass ejection is **common-envelope evolution**

- Water fountain sources show characteristic fast bipolar outflows, outflows and jets likely play an important role right before, during or immediately after the common-envelope phase



Khouri et al. 2022

ALMA

Common Envelope Evolution

- Low-mass companion enters the atmosphere of an AGB or red giant star
- Companion spirals in and transfers orbital energy and angular momentum into the envelope
- Part or all of the envelope is removed
- The companion either stops in a tight orbit or merges into the core

REICHARDT
Phantom Code
t=0.83 yrs
The more massive star has expanded to become a red giant...
t=2.82 yrs
This process is known as Roche-lobe overflow
t=6.35 yrs
Tidal dissipation between the two stars causes the separation to slowly decrease
t=7.86 yrs
The disk around the companion continues to grow
t=8.93 yrs
Gas is also thrown out into space, forming two wakes around the orbiting stars
t=9.82 yrs
The orbital separation decreases more rapidly now...
t=11.7 yrs
A common gaseous envelope begins to engulf the companion
t=12.9 yrs
As the companion enters the giant's atmosphere...
t=13.3 yrs
As the companion enters the giant's atmosphere...
t=13.8 yrs
...gravitational drag causes the companion to plunge towards the giant's core
t=14.8 yrs
The companion may eventually merge with the giant's core...
t=16 yrs
...or it might expell the common envelope and survive as a compact binary

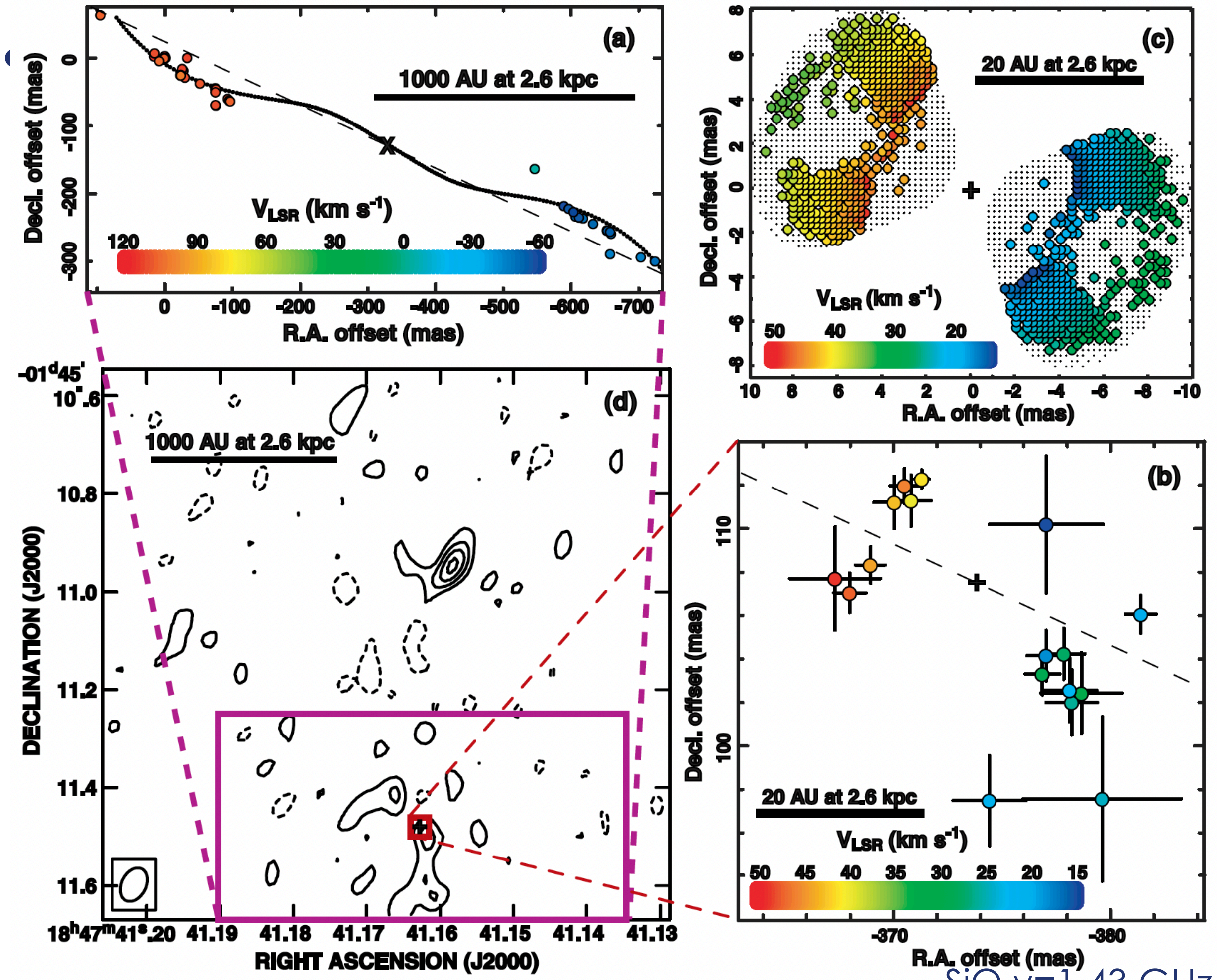
Also submm H_2O masers – Tafoya et al. 2014

Water Fountains: SiO masers

W43A

H_2O – 22 GHz

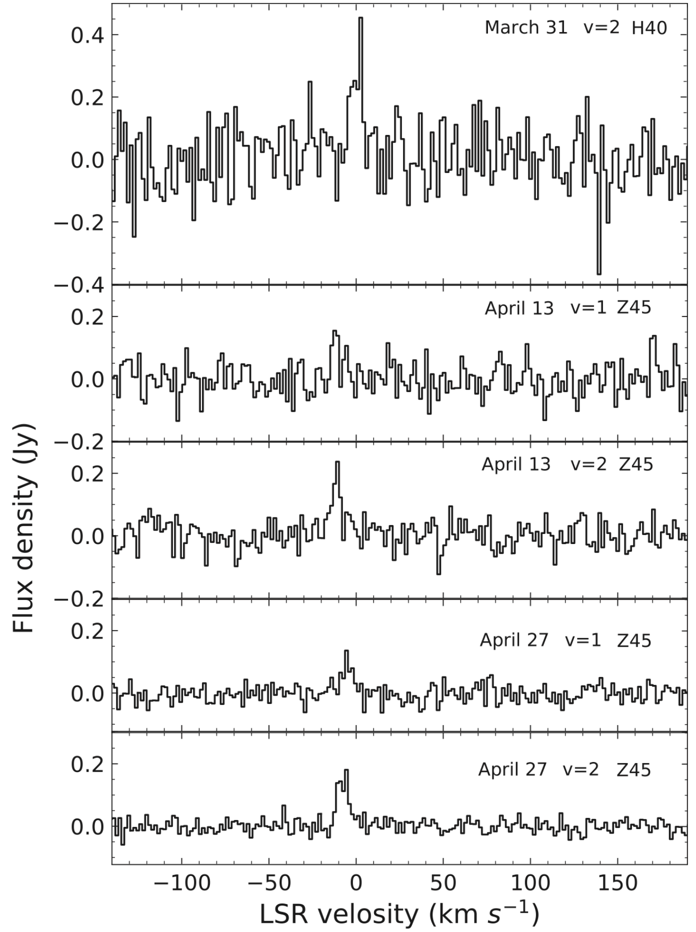
Model for SiO



SiO v=1 43 GHz

Imai et al. 2005, VLBA

IRAS 16552−3050



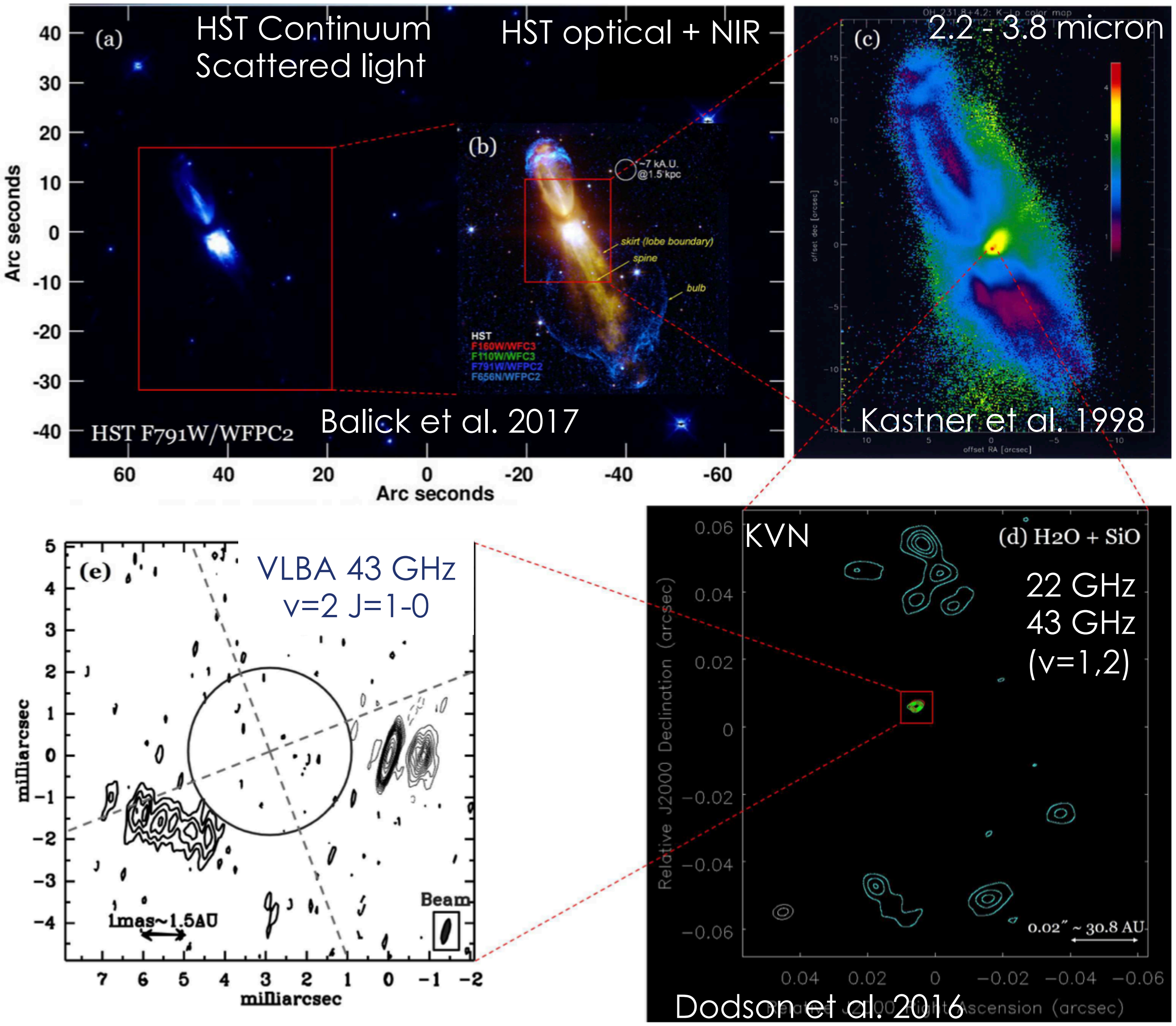
v=1&2
J=1-0

Amada et al. 2022, Nobeyama

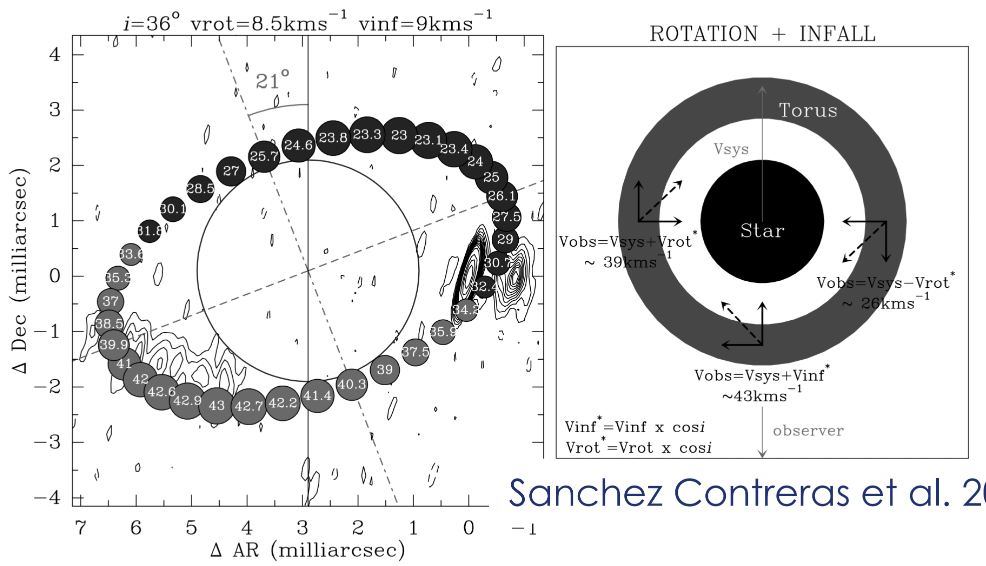
Pre-planetary nebula OH 231.8+4.2

Kim et al. 2019, SiO & water masers, KVN & VLBA

Other Pre-PN and PN



Sanchez Contreras et al. 2002



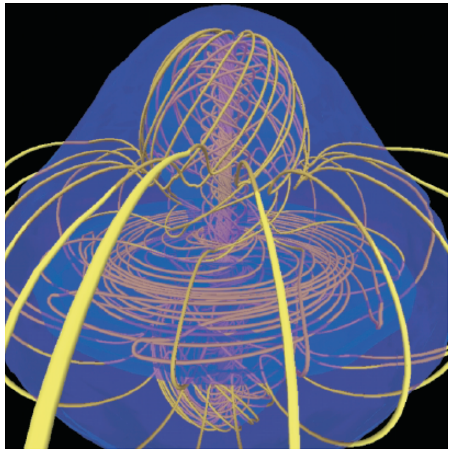
Sanchez Contreras et al. 2002

Other pre-PN can display maser emission (not only the water fountain targets)

In addition, maser emission (H_2O and/or OH) is known towards at least 8 Planetary Nebulae

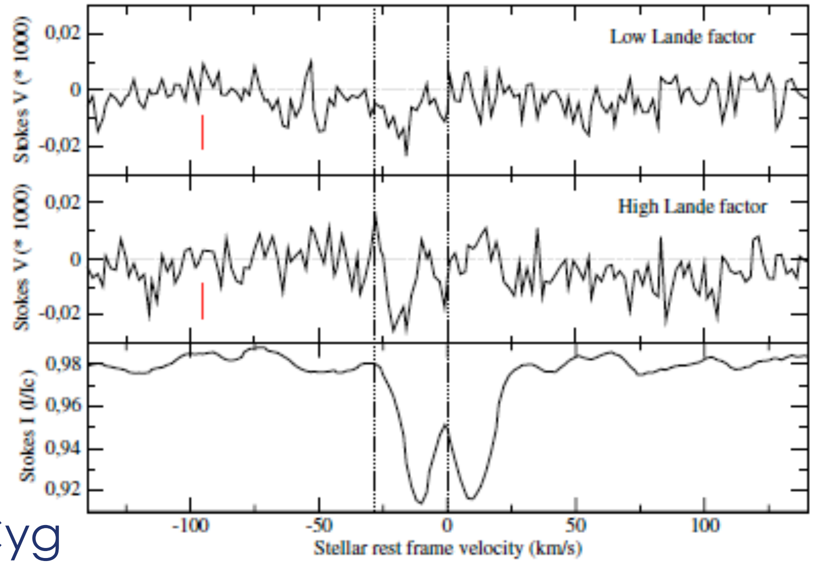
Planetary Nebulae that host maser emission are believed to be at a very young stage (Uscanga et al. 2022)

What is the role of magnetic fields?


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).

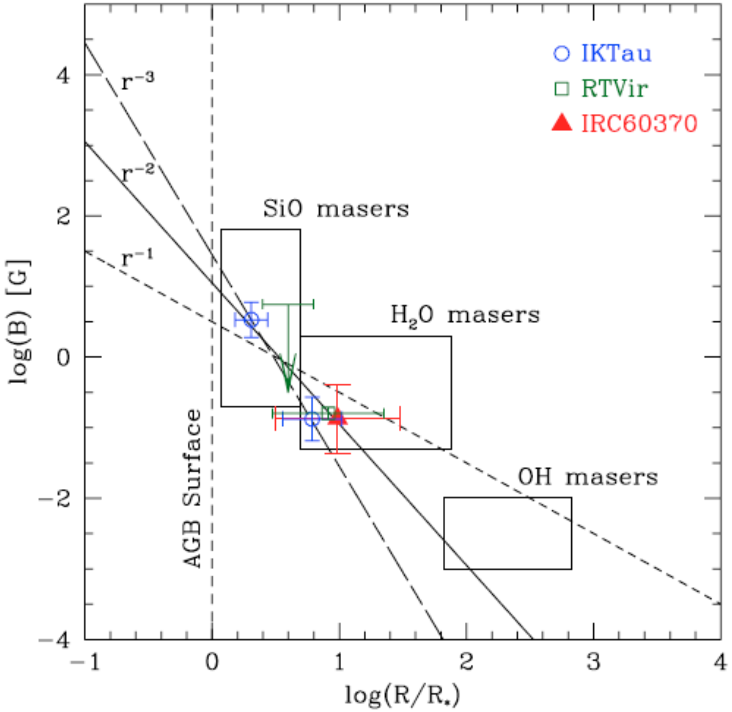
Optical spectropolarimetry



Chi Cyg

2-3 Gauss, Lebre et al. 2014

Masers



r^{-1}: toroidal
r^{-2}: solar-type

Leal-Ferreira et al. 2013
Duthu et al. 2017
Vlemmings et al. 2019

ALMA

Summary

- High-angular resolution observations of masers are making critical contributions to the understanding of stellar evolution e.g.,
  - EVN observations of methanol masers in high-mass star formation
  - VLBI and VLA maser observations, in conjunction with single-dish monitoring observations, are constraining accretion bursts and maser superbursts
  - Large maser programs such as BeSSeL, BAaDE and ESTEMA probe stellar evolution and galactic structure/dynamics
  - VLBI and ALMA observations are yielding new information on the shaping process to Planetary Nebulae

ALMA