Late-type Stars

with Perspective of Radio Observations

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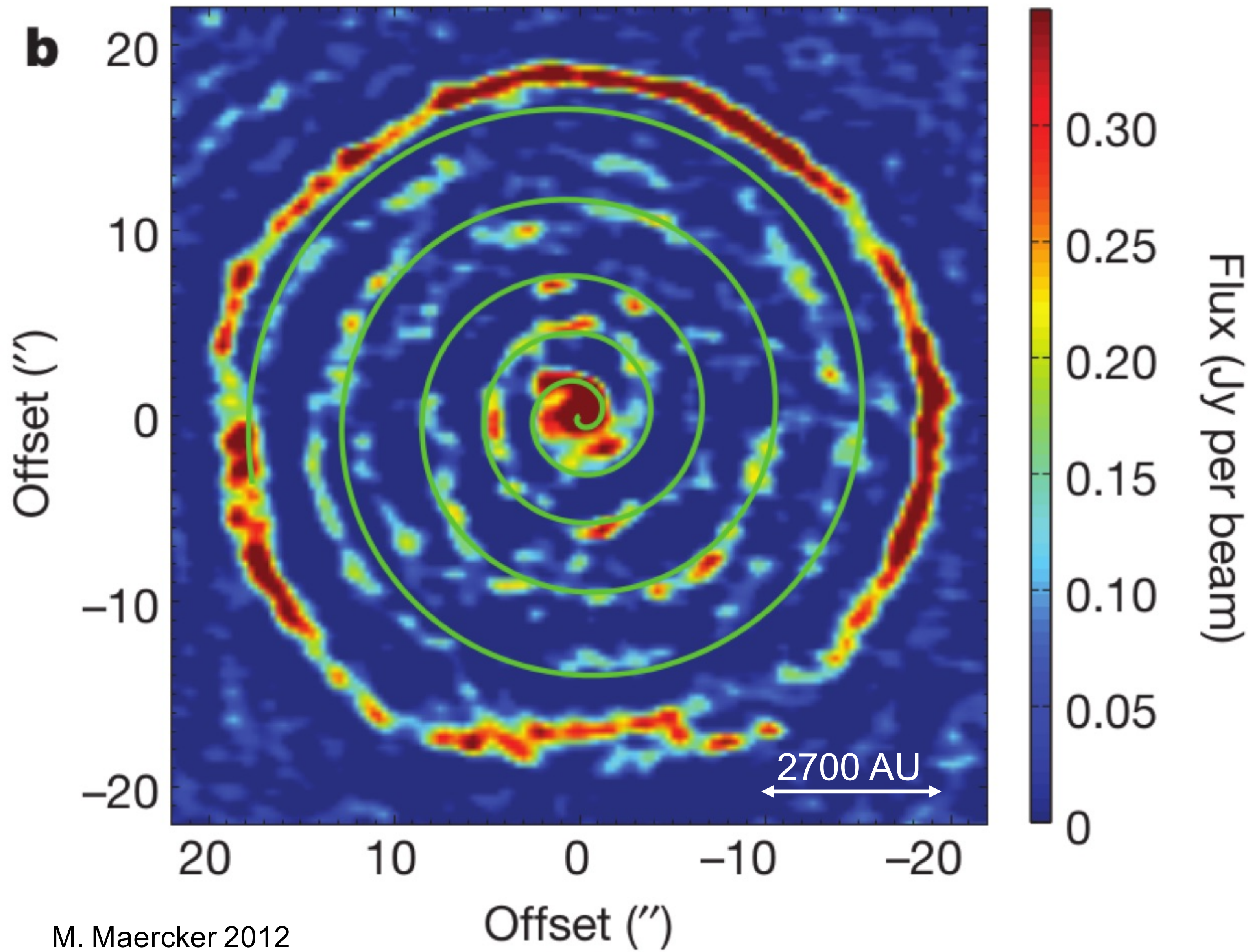
2018 Radio Winter School @University of Ulsan

Outline

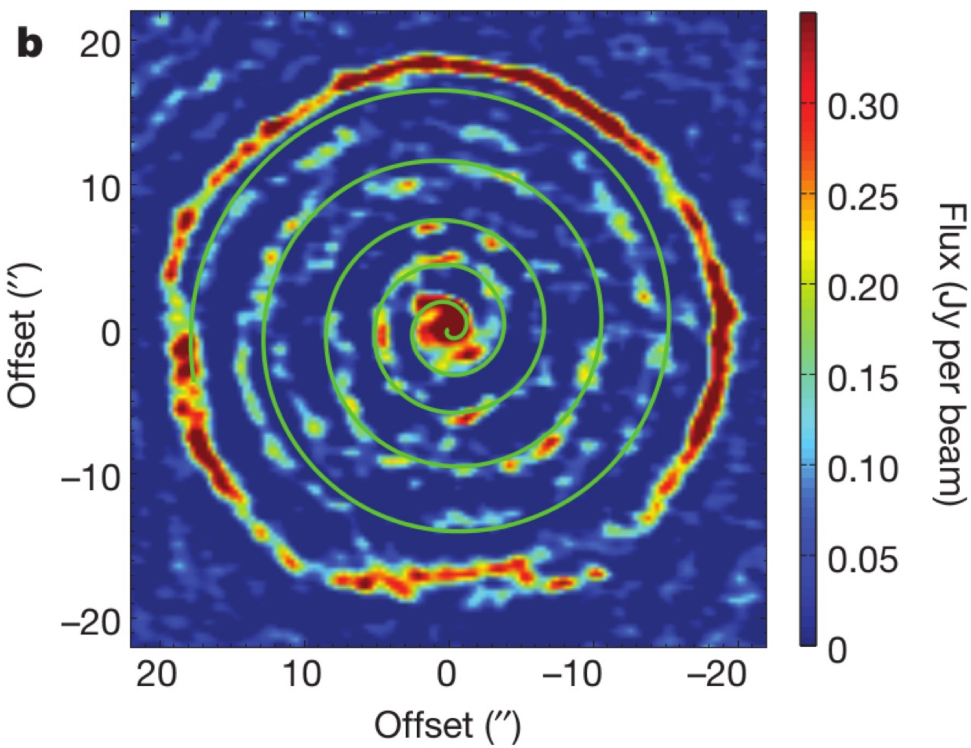
- Introduction to late-type stars with an example
- Brief description of stellar evolution
- Evolution of late-type stars (AGB to PN)
  - Physical characteristics of circumstellar envelopes of late-type stars
- Results of radio observations toward late-type stars
  - Masers around late-type stars
  - Multi-frequency observations
  - Polarization of late-type stars

Semi-major axis ~ 60 AU
Orbital period ~ 350 yr
System mass ~ 2 M_sun (1.3 and 0.7)

Mass-loss rate
At TP ~ 7×10^{-6} – 2.5×10^{-5} M_sun
At pre-TP ~ 10^{-6} M_sun
Shell expansion velocity ~ 14.3 km/sec

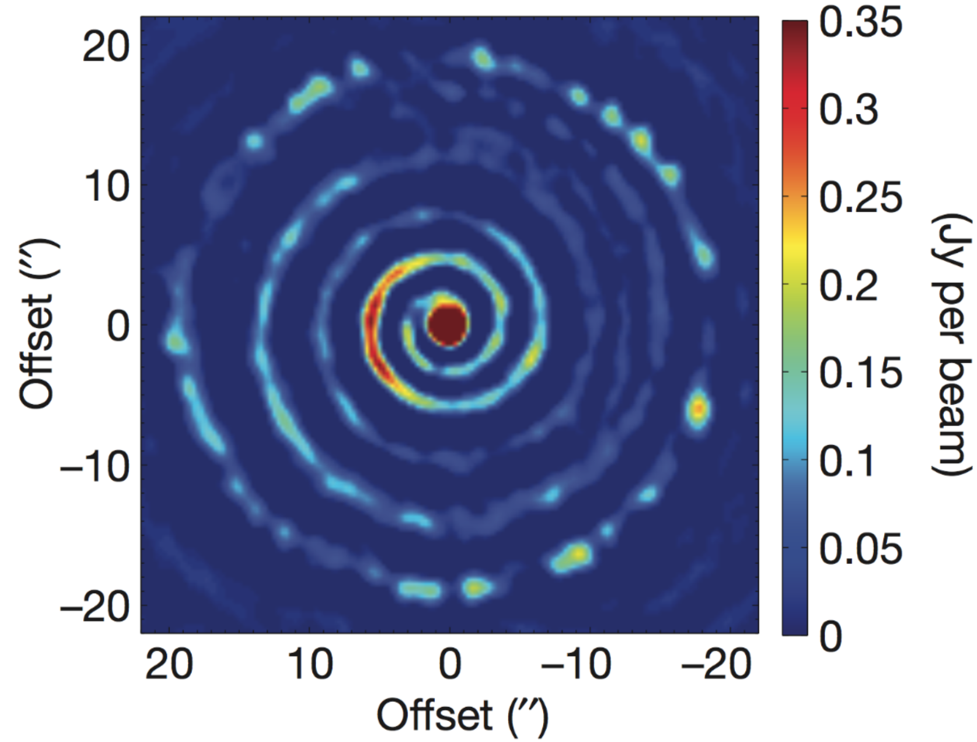


M. Maercker 2012



Observation

M. Maercker 2012



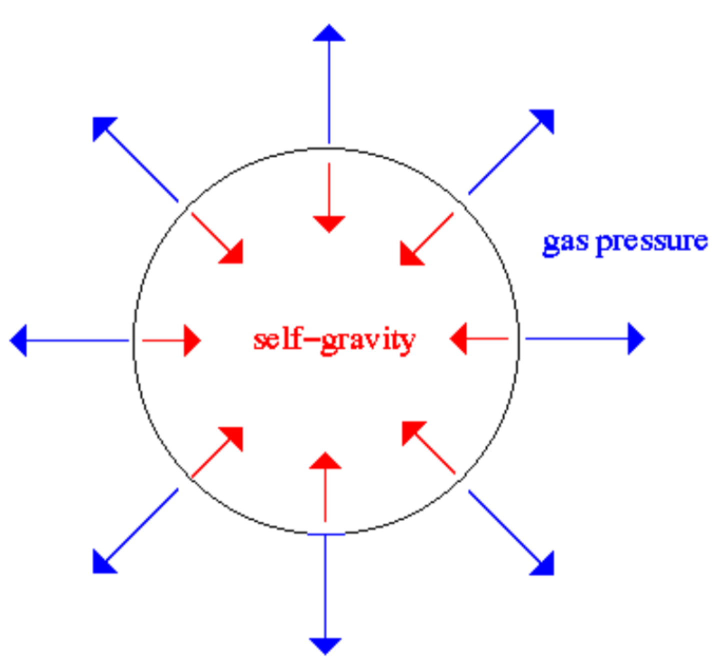
Model calculation

Shapes of CSE around binary AGB stars
~ physical parameters of binary system (separation, mass ratio)
~ density, temperature, chemistry
~ viewing angle

> temporal variation of the mass-loss rate
> expansion velocity
> supply new elements to the ISM → termination of AGB phase → stellar evolution models

Basic stellar physics

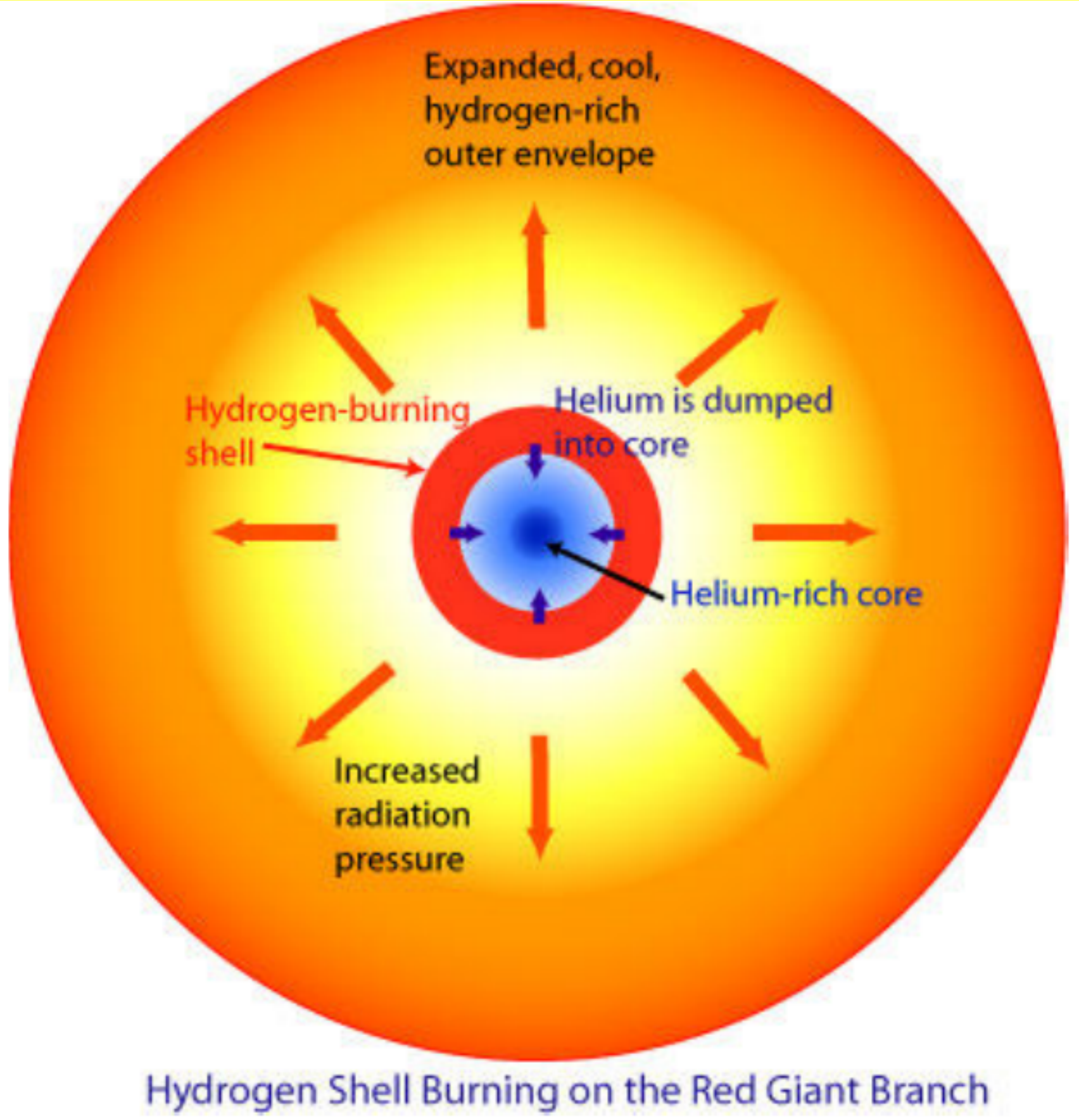
Hydrostatic equilibrium



$$\rho(r)dAdr\frac{d^2r}{dt^2} = -\frac{dP}{dr}drdA - \frac{GM_r\rho(r)dAdr}{r^2}$$

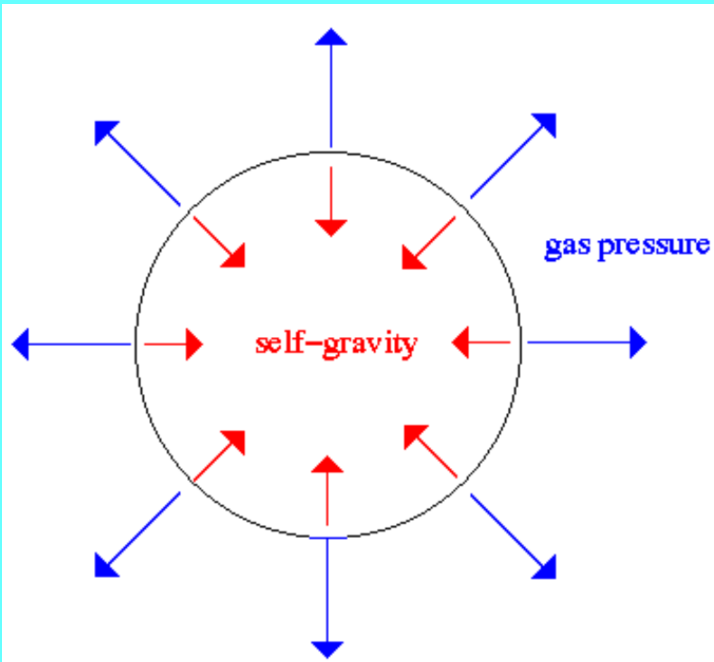
$$\frac{dP(r)}{dr} = -\frac{GM_r\rho(r)}{r^2}$$

Fusion reactions (hydrogen → helium)



Basic stellar physics

Hydrostatic equilibrium



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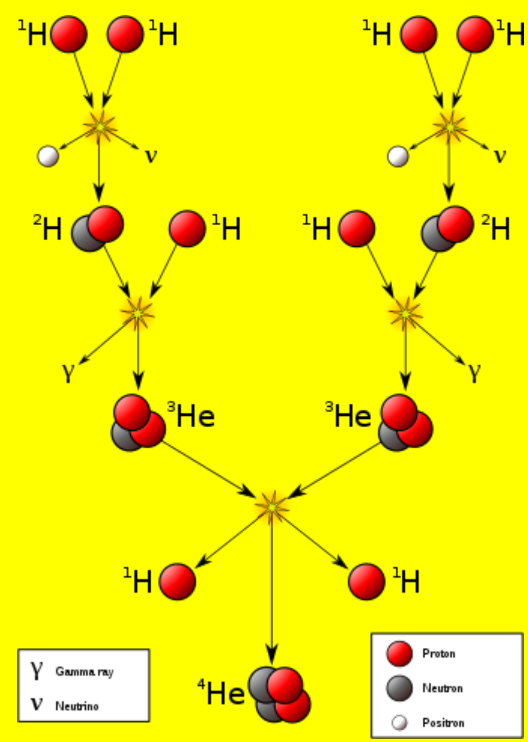
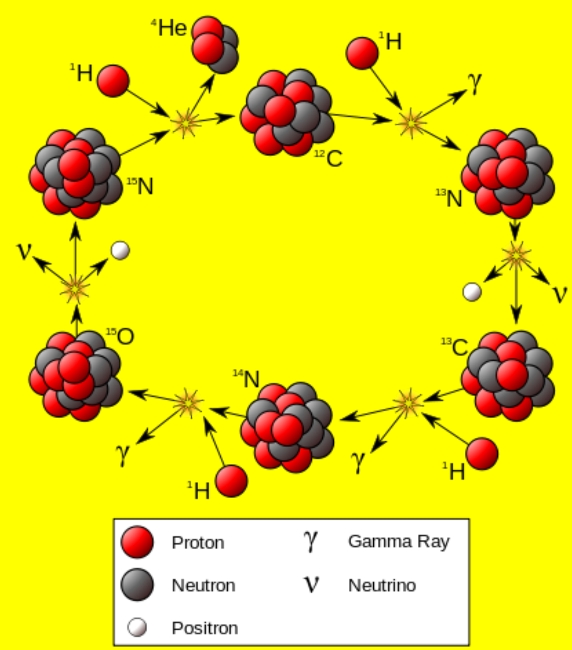
$$\frac{dP(r)}{dr} = -\frac{GM_r\rho(r)}{r^2}$$

Fusion reactions (hydrogen → helium)

P-P chain (< 1.3 M_sun)

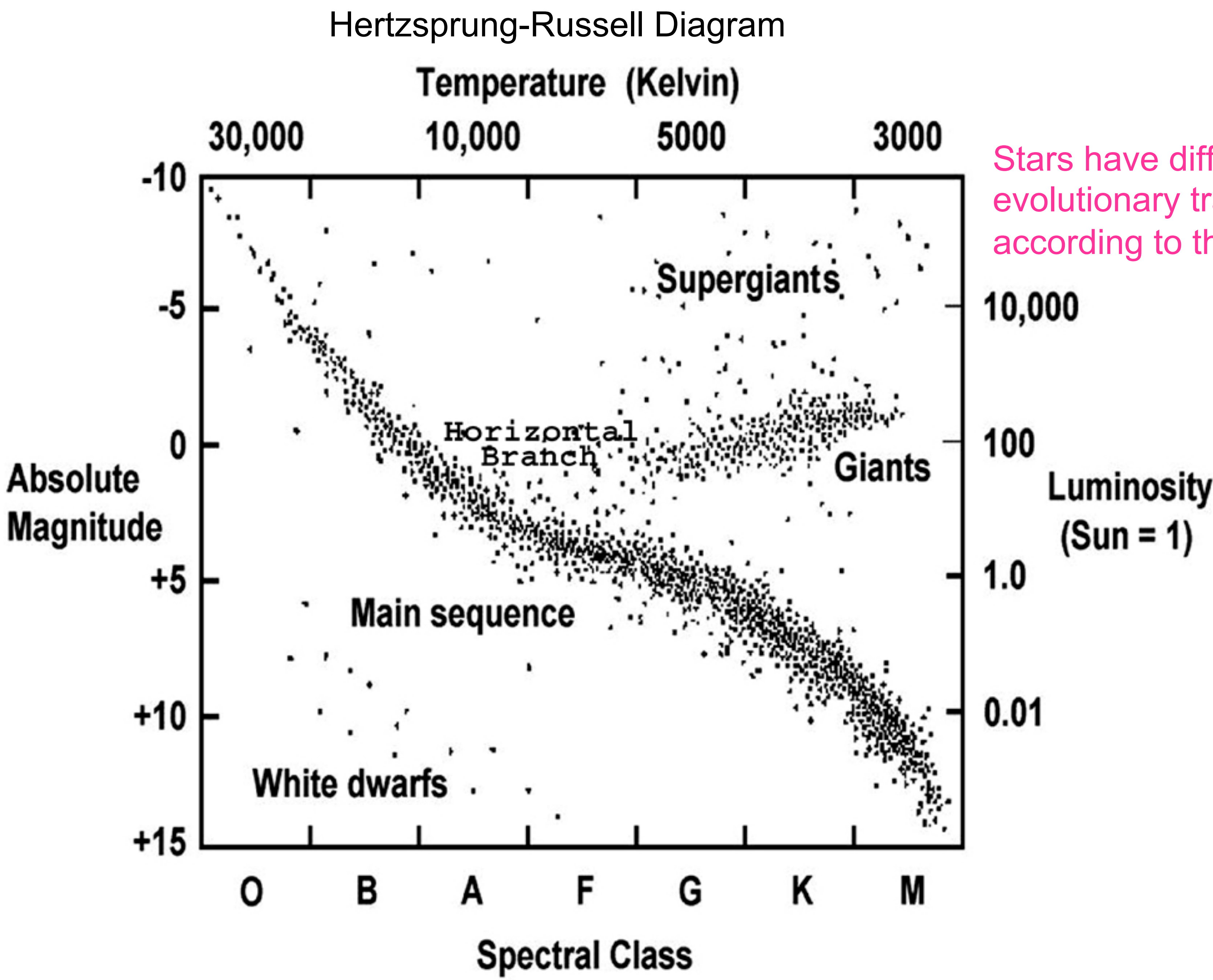
CNO cycle (> 1.3 M_sun)





Carl Friedrich von Weizsäcker 1938
Hans Bethe 1939

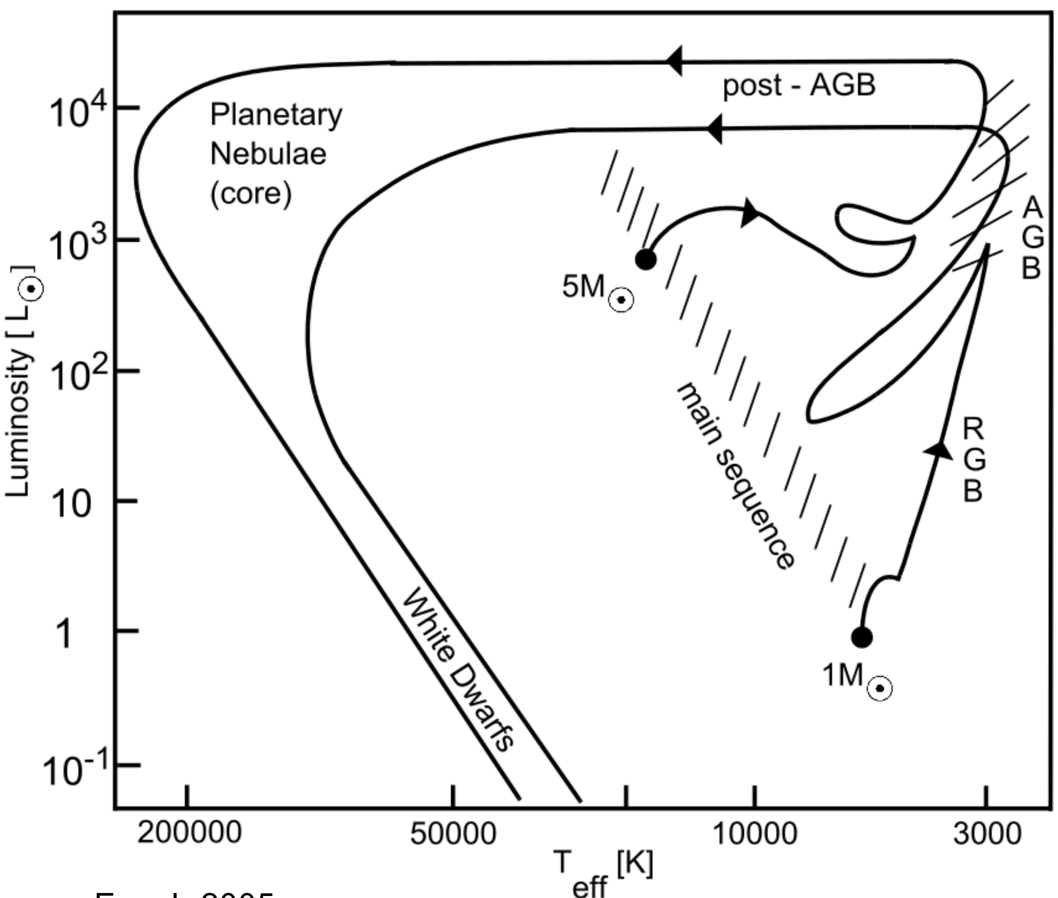
Stellar evolution



Stars have different evolutionary tracks according to their initial mass.

AGB to planetary nebula

Asymptotic Giant Branch



Engels 2005

Intermediate evolutionary phase
= Pre-Planetary Nebula (PPN) phase

- Dramatic change of morphology and outflow velocity (~100 km/s)
- Likely initiated during late-AGB phase

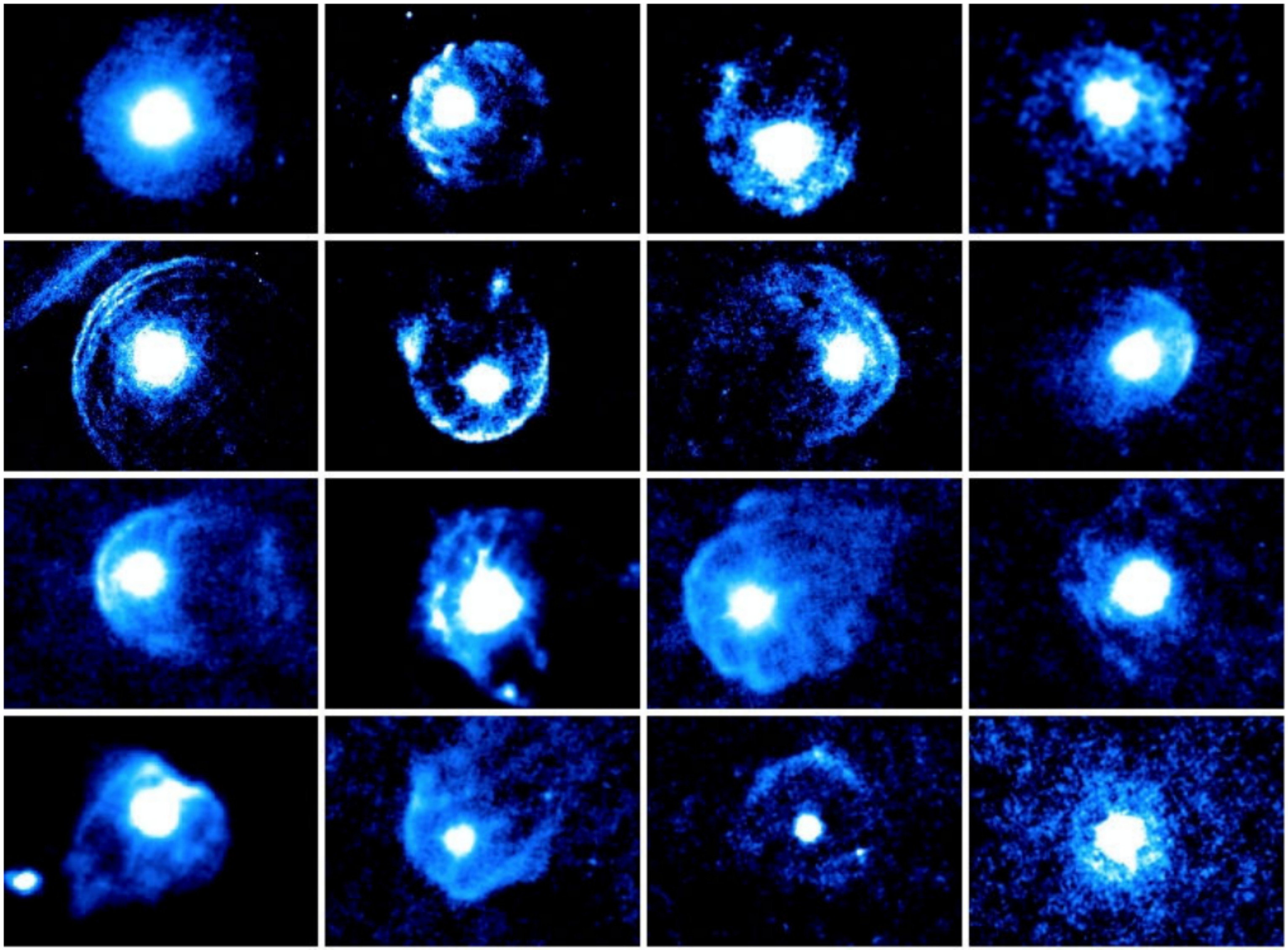
AGB phase

- Central degenerate core (C+O)
- He and H-shells (nuclear-burning)
- Very large H-rich stellar envelope
- Cool (Teff < 3000 K)
- Very luminous (~10^4 L_sun)
- Dusty, spherical expanding envelopes at low speeds(5- 20 km/s)
- Large mass-loss rate (~ 10^{-4} M_sun/yr)

Post-AGB and Planetary Nabula (PN) phase

- Mass-loss rate decreases
- Stars become hot → ionize CSE material
- Stellar envelope shrinks → Teff increases up to 30000 K → ionize detached circumstellar nebula
- End of stellar evolution for stars with mass of 0.8 – 8 M_sun

Expelled circumstellar matter (CSM) interacts with the ISM,
a bow shock can develop at the interface between the circumstellar envelope (CSE) and the ambient medium.



ate core (C+O)
(nuclear-burning)
stellar envelope
K)
10^4 L_sun)
expanding
speeds(5- 20 km/s)
rate (~ 10^{-4}

anetary Nabula

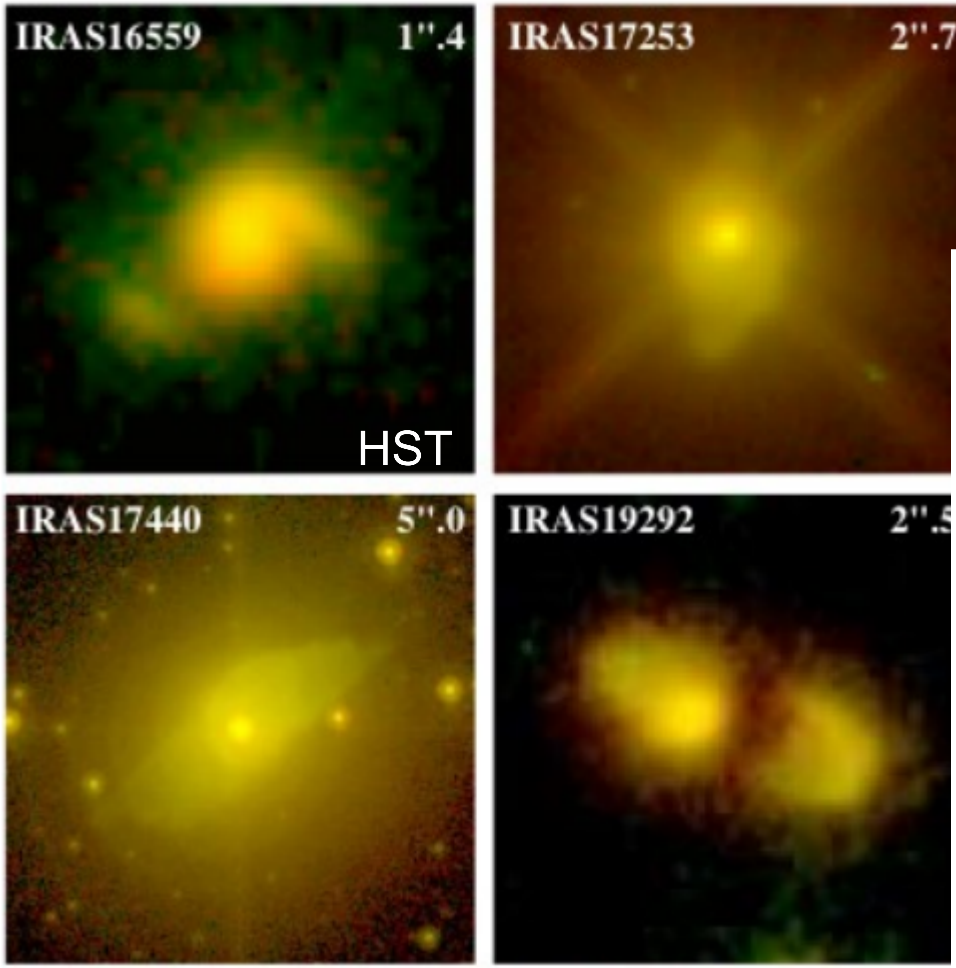
ecreases
t → ionize CSE

shrinks → Teff
000 K → ionize
ellar nebula
olution for stars
8 M_sun

HERSCHEL/PACS images of the ISM/CSM interaction seen around many mass-losing AGB and red supergiant stars (N. Cox 2012)

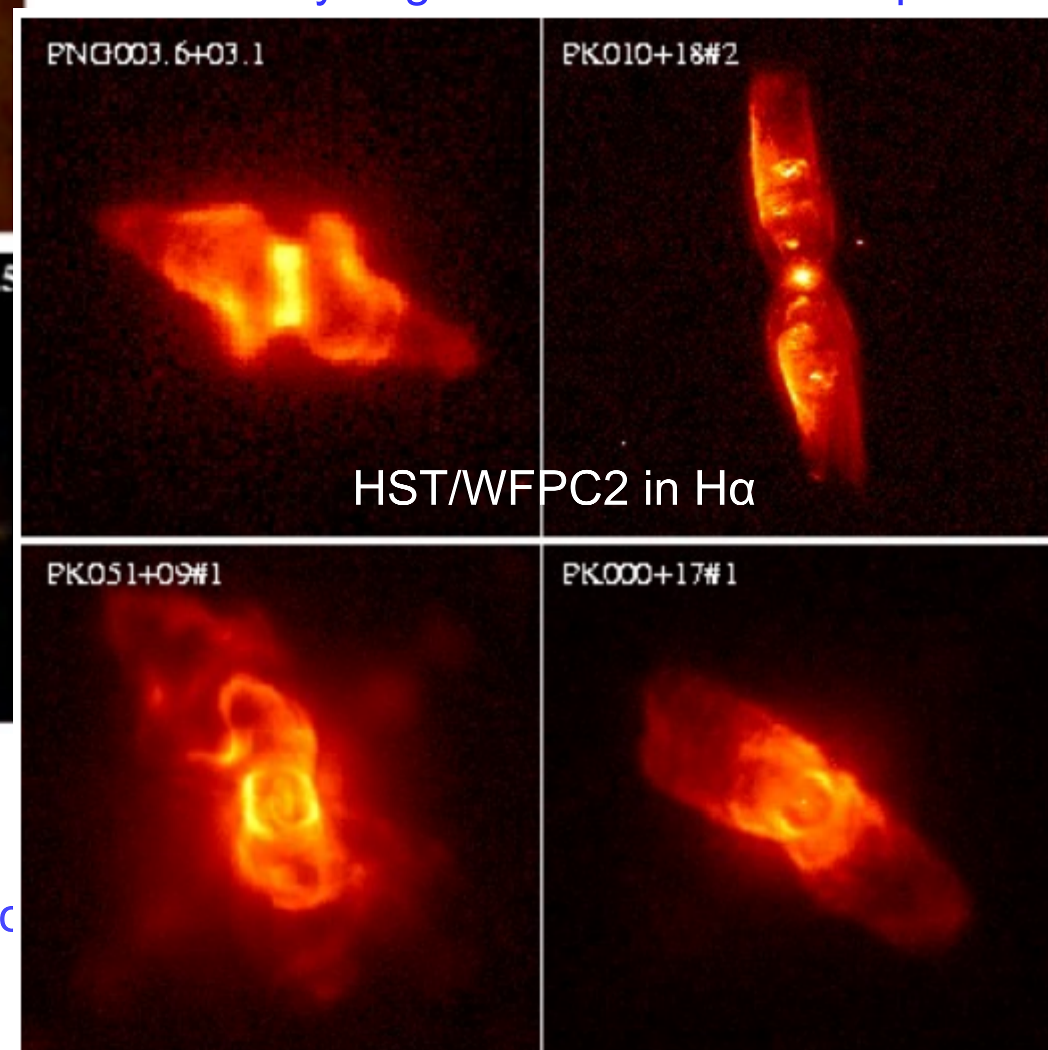
AGB to planetary nebula

Asymptotic Giant Branch



AGB phase

- Central degenerate core (C+O)
- He and H-shells (nuclear-burning)
- Very large H-rich stellar envelope



Intermediate evolutionary phase
= Pre-Planetary Nebula (PPN) phase

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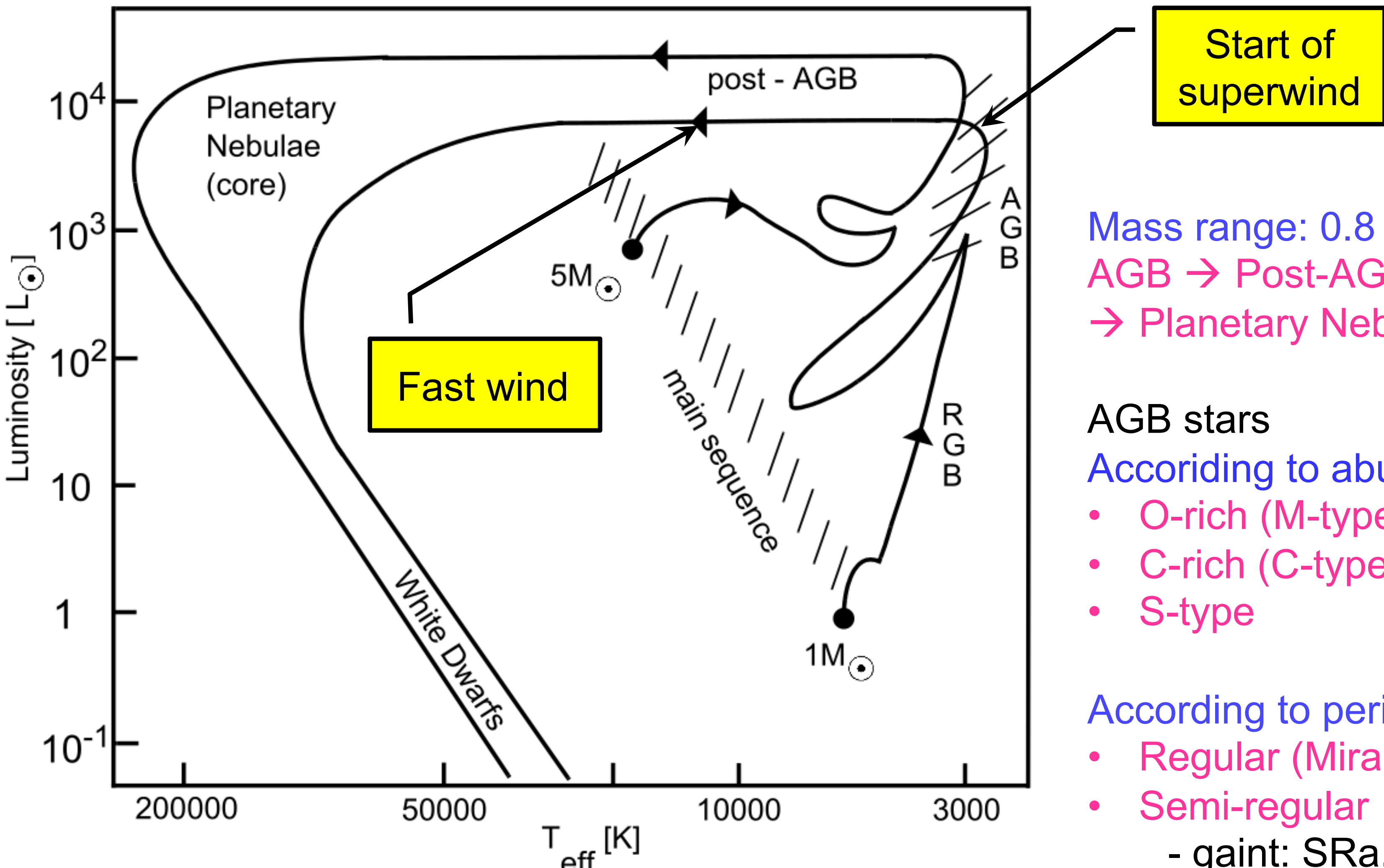
AGB to planetary nebula

Asymptotic Giant Branch



Engels 2005

Mass range: 0.8 - 8 M_sun

AGB → Post-AGB

→ Planetary Nebulae (PNe)

AGB stars

Accoriding to abundance

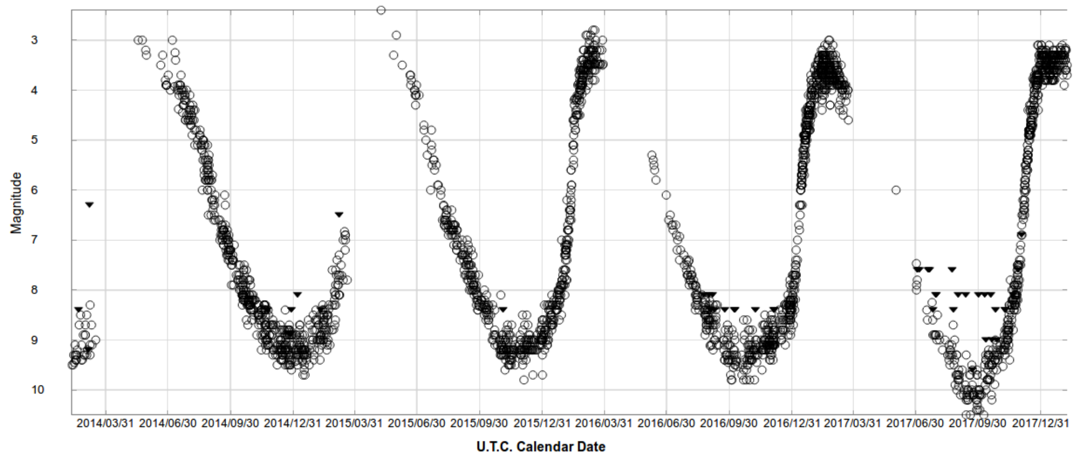
- O-rich (M-type)
- C-rich (C-type)
- S-type

According to period

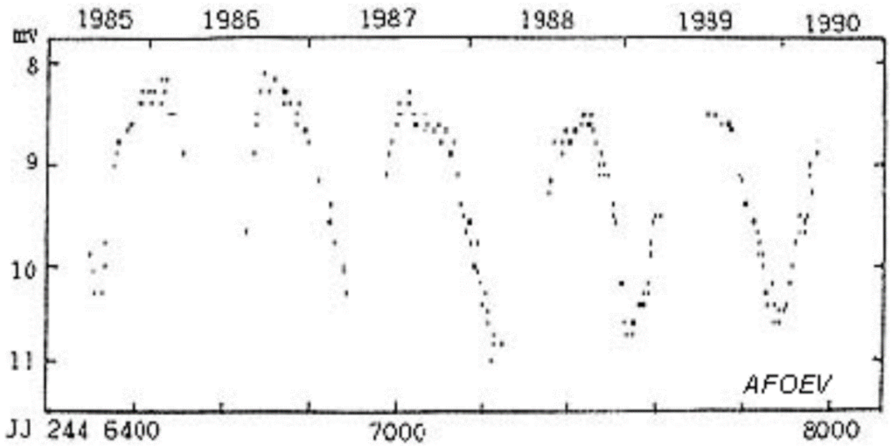
- Regular (Mira)
- Semi-regular
  - gaint: SRa, SRb
  - supergiant: SRc, SRd

Light curves of AGB

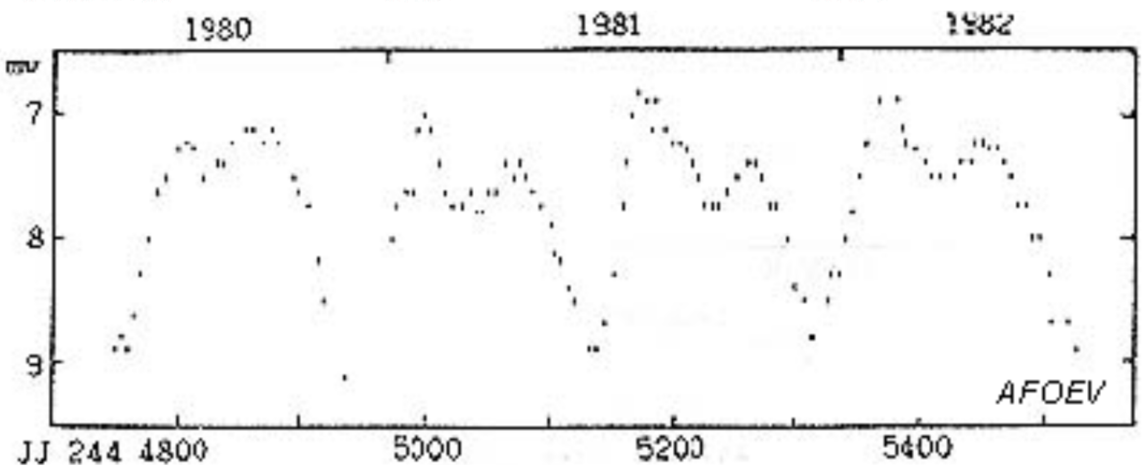
Mira



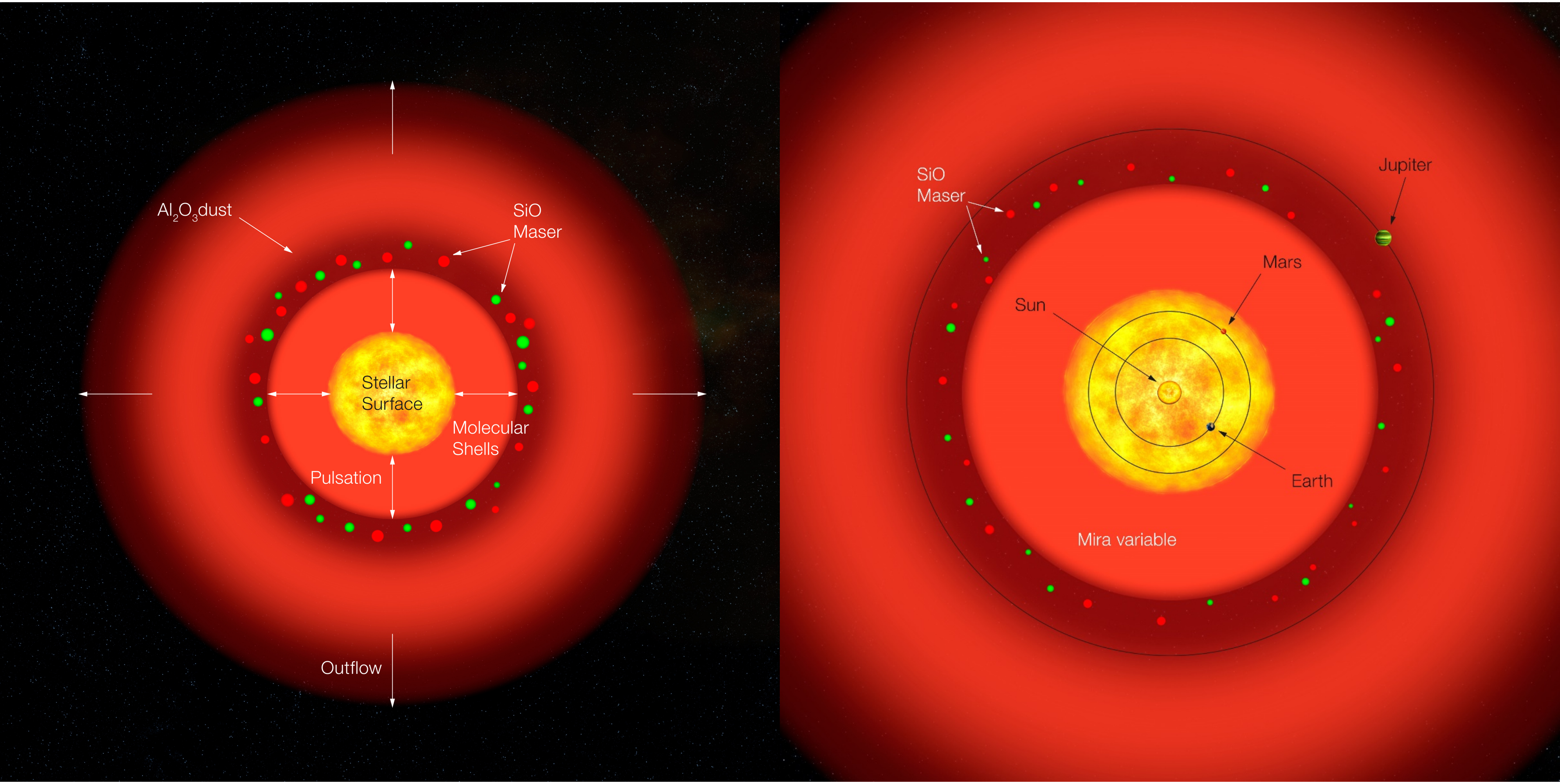
SRa



SRb



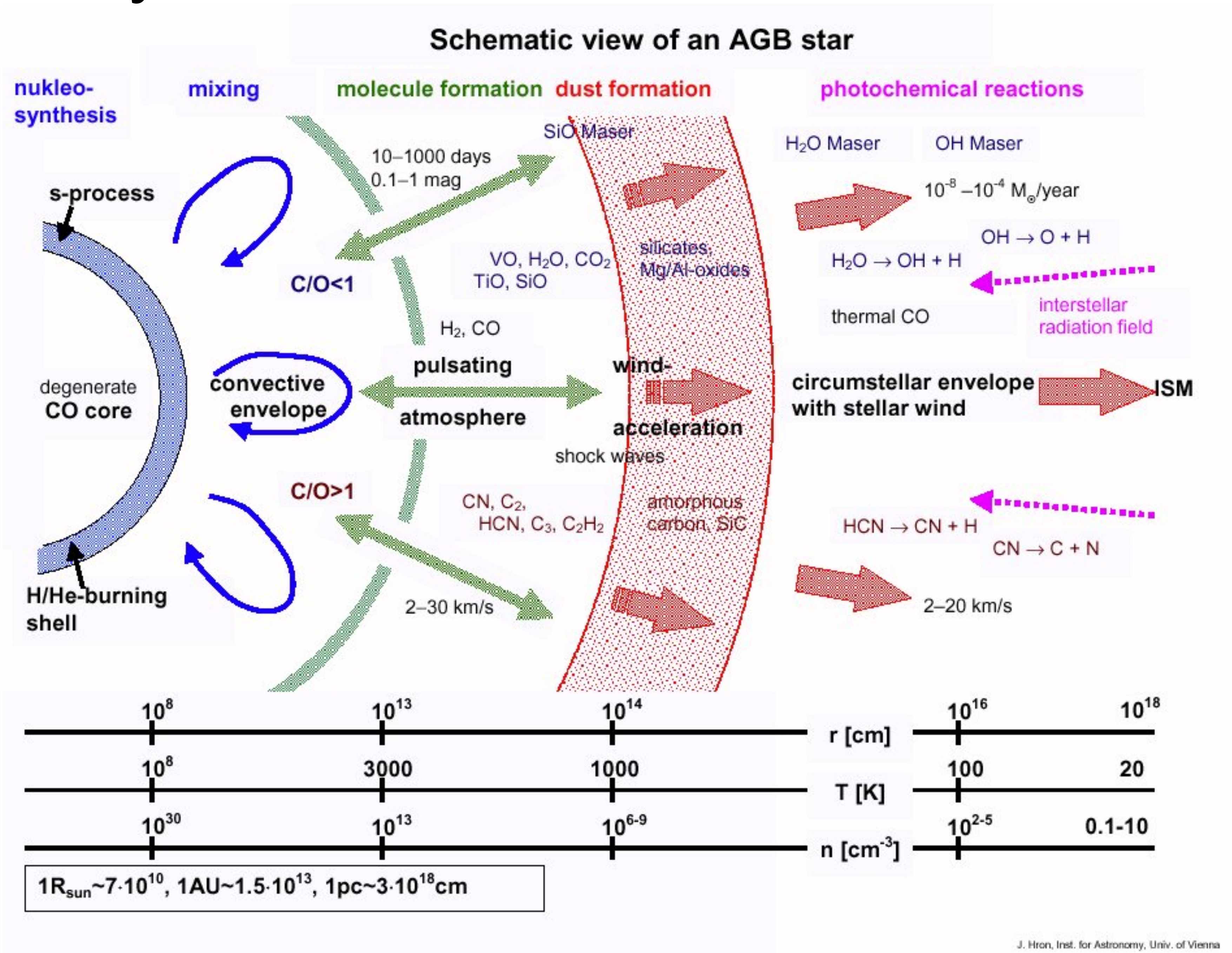
Physical environments of AGB stars



Credit: ESO

Structure of the pulsating red giant S Ori (artist's impression)

Physical environments of AGB stars



Credit: J. Hron

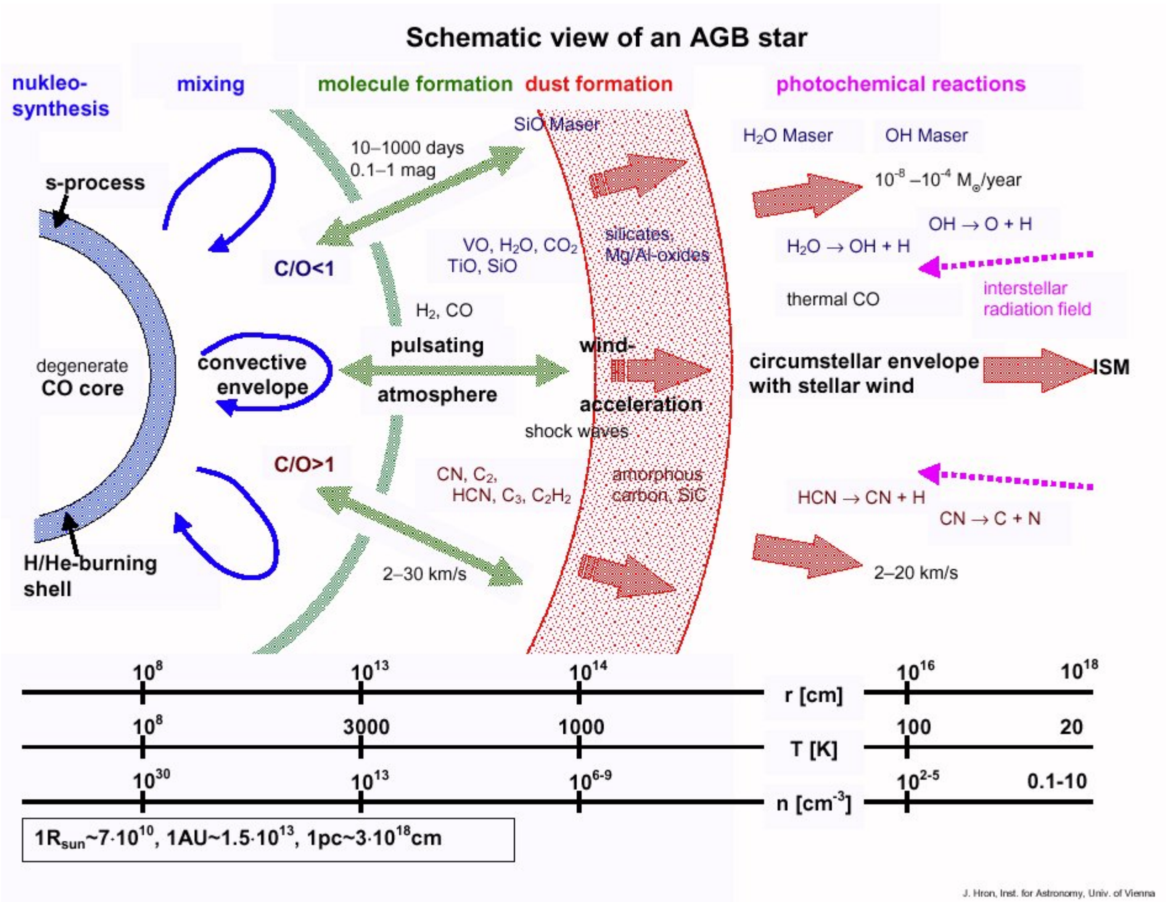
Physical environments of AGB stars

Mass-loss phenomena are crucial to study the AGB evolution.
How can we see the mass-loss during the period ABG to PN?

- **MASER** is an unique tool to study the physical environments of AGB stars
- So many AGBs show maser emission (statistical analysis can be done)
- Different characteristics of maser (distribution, variability, intensity) for each source
- Different masing regions according to the different molecules and transitions in the same source → enable us to trace the physical characteristics of CSEs along the distance from the central star
- The highest spatial resolution → enable us to get the dynamical information of the very local area → initiate-region of pulsation and outflow motion

Credit: J. Hron

Physical environments of AGB stars



Credit: J. Hron

Different species of maser can occur at the same source.
→ probe different regions

SiO maser v=1, J=1-0 (43 GHz)
T_k ~ 1500 K
n (H_2) ~ 10^9 – 10^{11} cm^{-3}

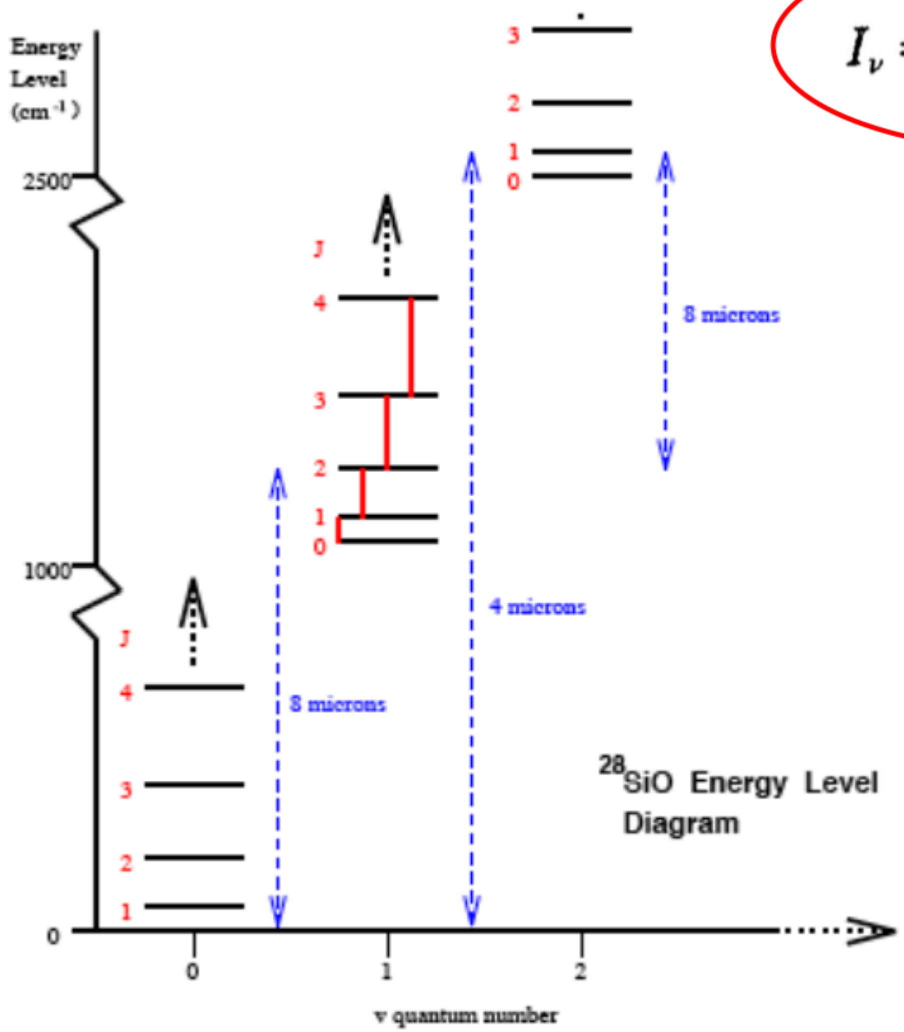
Water maser (22 GHz)
T_k ~ 400 – 1000 K
n (H_2) ~ 10^8 – 10^{10} cm^{-3}

OH maser (1665/7 MHz)
T_k ~ 100 K
n (H_2) ~ 10^5 cm^{-3}

Astrophysical masers

Microwave Amplification by Stimulated Emission of Radiation

$$I_\nu = I_\nu(0)\exp(-\tau_\nu) + \int_0^{\tau_\nu} \frac{j_\nu}{\kappa_\nu} \exp[-(\tau_\nu - \tau_\nu')]\,d\tau_\nu'$$

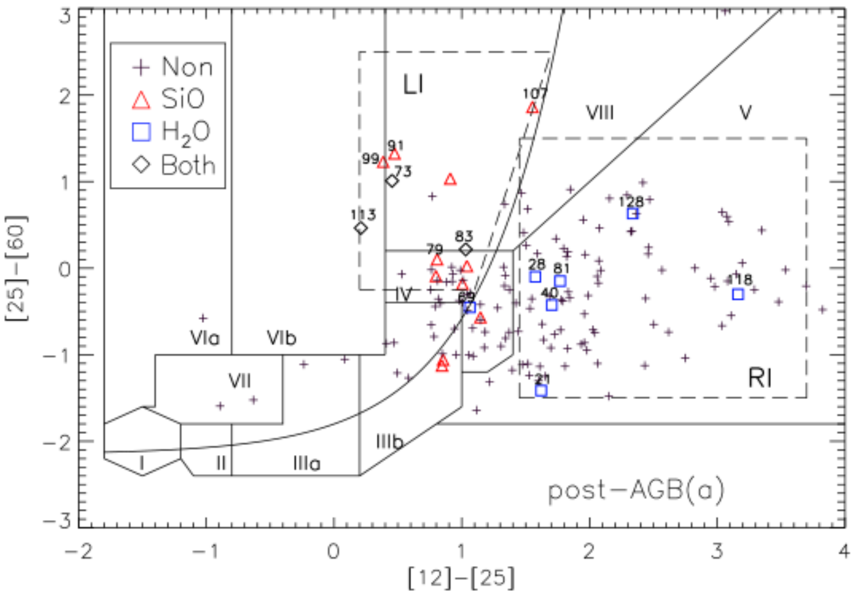


- Population inversion → exponential amplification along the path (unsaturated)
- Not in thermal equilibrium → difficult in Earth, occur frequently in space
- Pumping condition: collisional or radiative

- Highly beamed (not isotropic) and compact
- Narrow line width in spectra
- Temporal variability
- Can be polarized
- Can be resolved as a spot (depending on resolution)

Statistical analysis with masers

to study the evolutionary characteristics of late-type stars

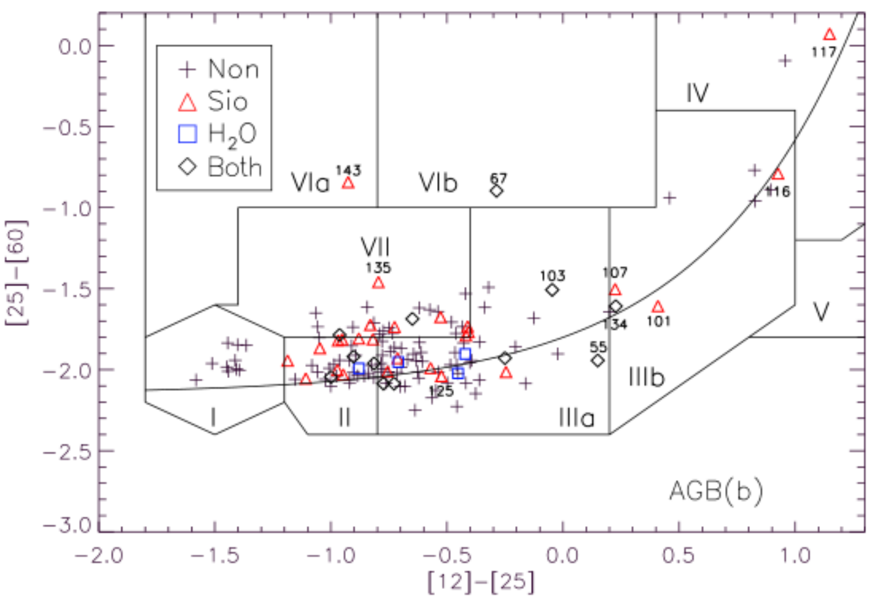


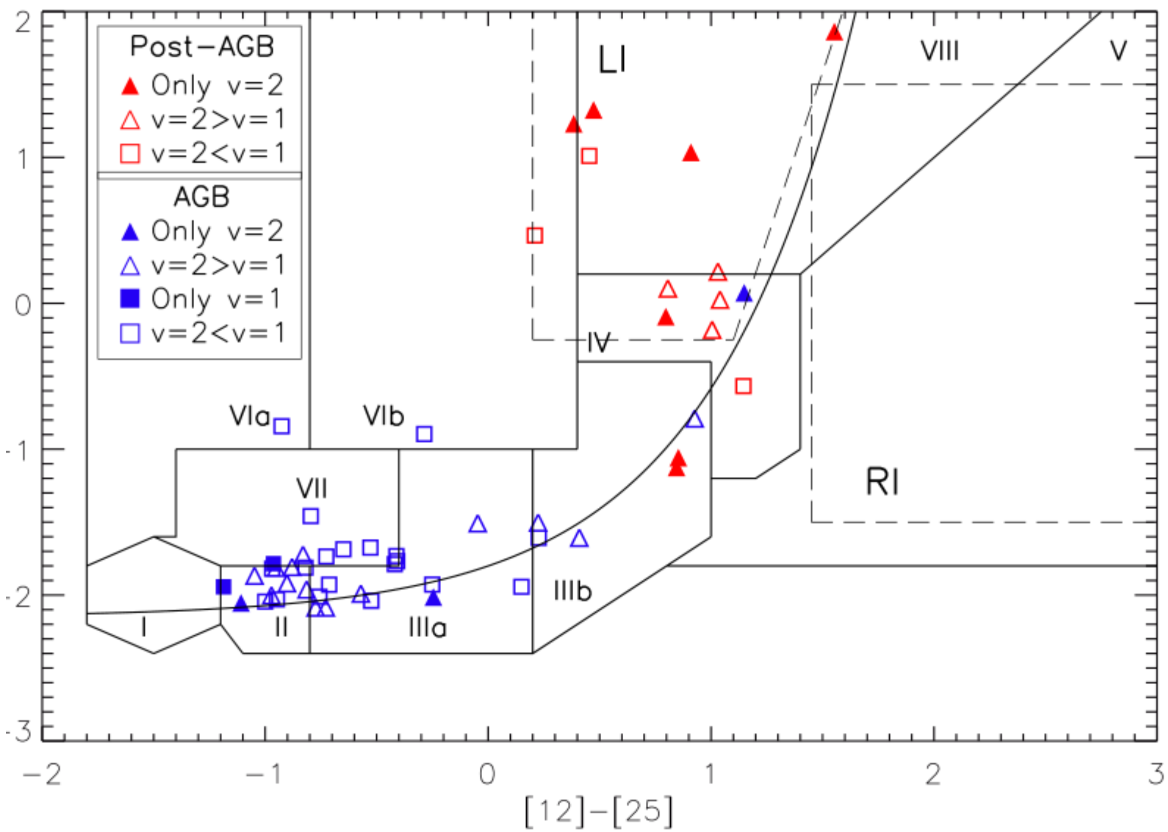
Post-AGB

- Both SiO and H2O masers: in the blue group (LI)
- Only H2O maser: in the red group (RI)

→ Different abundances of masing molecules in the CSEs due to the different mass and expansion velocity between LI and RI regions

→ Characteristics of evolutionary stage





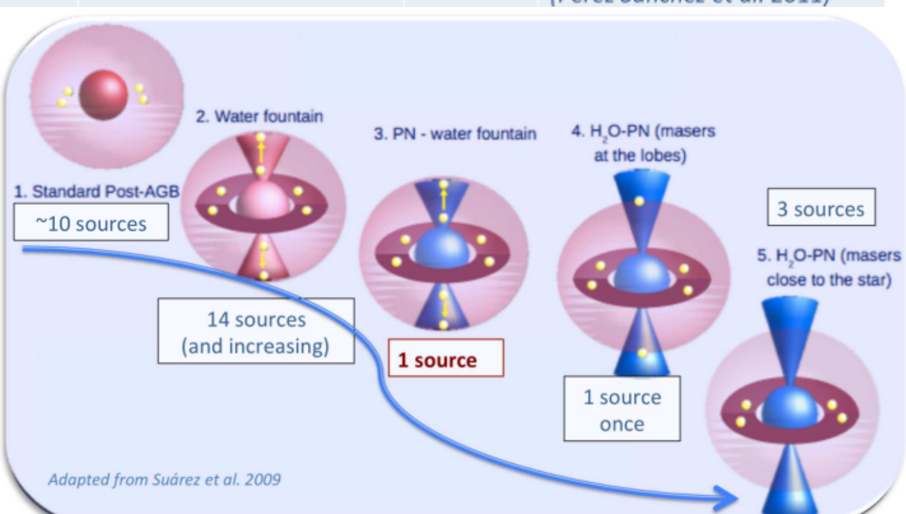
D. H. Yoon 2014

Water maser

as a tracer for the outflow motion of late-type stars

	Masers at the equatorial outflow	No masers at the equatorial outflow
Masers on the jet	 I15103 *(Suarez et al 2012+Bendjoya et al.-poster 17)* W43A *(Vlemmings et al.2006)* I18286 *(Yung et al. 2011)*	
Masers in bow-shocks	 I18460 *(Imai et al.2013)*	 OH12.8-0.9 *(Boboltz& Marvel 2005)* I19134 *(Imai et al 2007)* I19190 *(Day et al. 2010)* I16552 *(Suárez et al. 2008)* I16342 *(Sahai et al. 1999)* I18113 *(Gómez et al.2011)* I15445 *(Pérez Sanchez et al. 2011)* I18043 *(Pérez Sanchez et al. 2011)*

Credit: Suarez



Found in AGB, post-AGB, PN

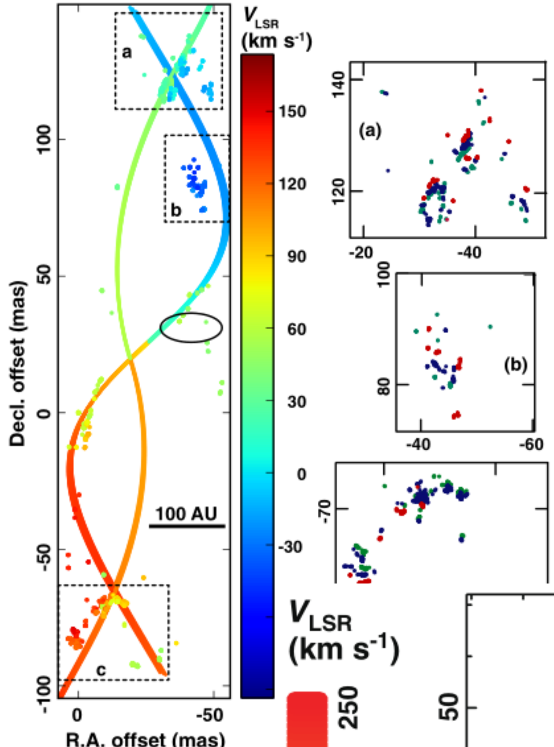
- Hyperfine transition (rotational): $6_{16} \rightarrow 5_{23}$
- Pumped mainly by shocks or by IR radiation
- Physical condition:
  - $T_k \sim 400 - 1000$ K
  - $n(H_2) \sim 10^8 - 10^{10}$ cm^{-3}
- Giving information for the position, velocity, proper motions

Water fountains

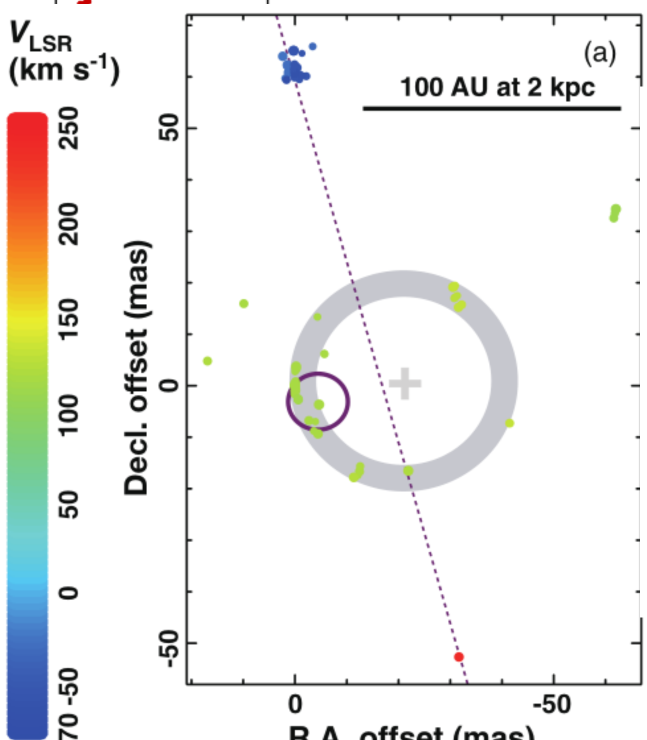
- Evolved stars with water masers (~ 100 km/s components) → jet tracer
- Late AGB, post-AGB, PN
- Bipolar outflow → axisymmetric jets
- Key objects to study the emission of jets that determine the shape of PNe

Water maser

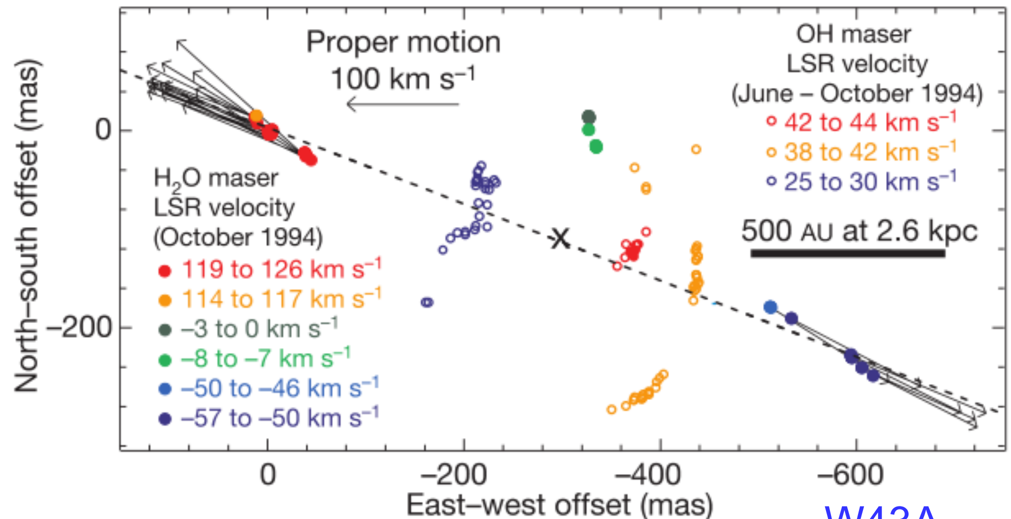
as a tracer for the outflow motion of late-type stars



18286-0959
Imai 2013

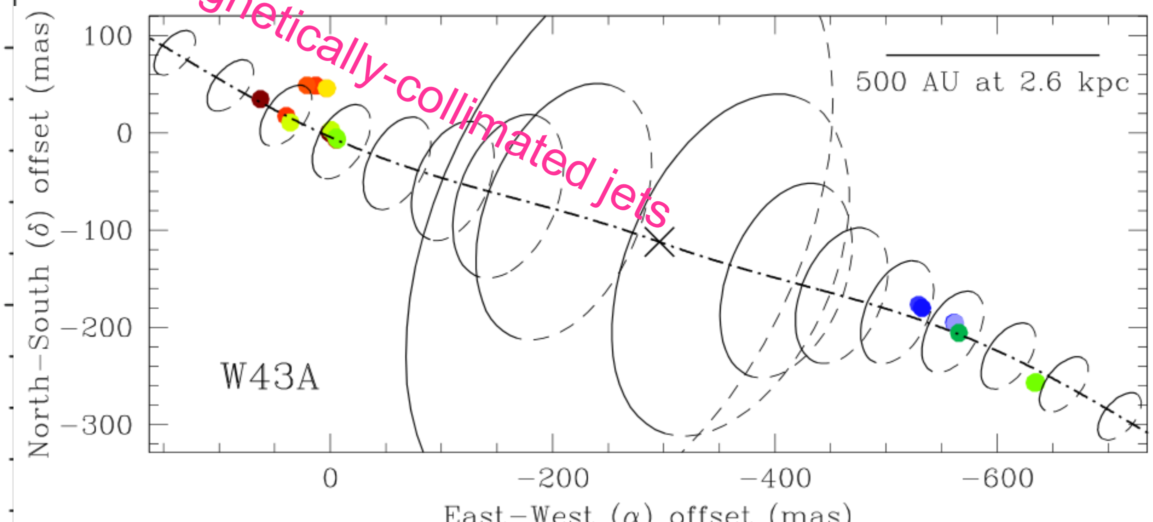


18460−0151
Imai 2013



W43A
Imai 2002

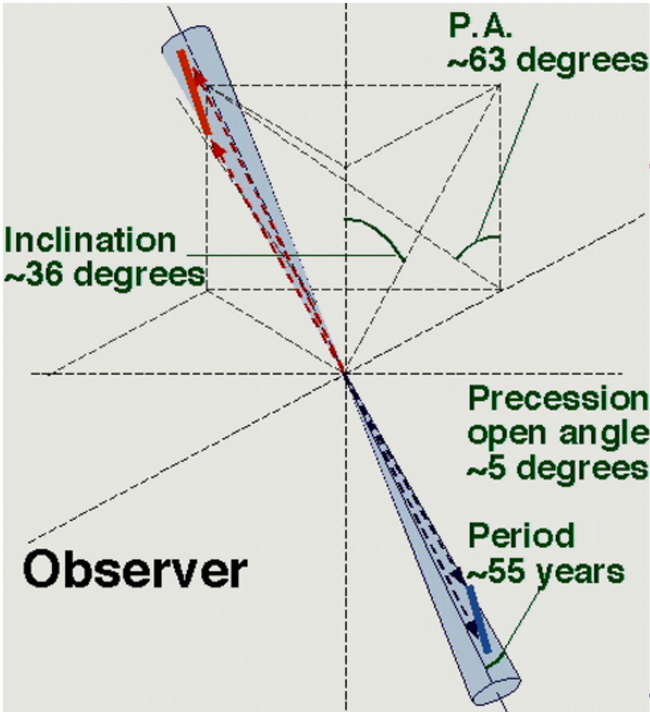
Magnetically-collimated jets

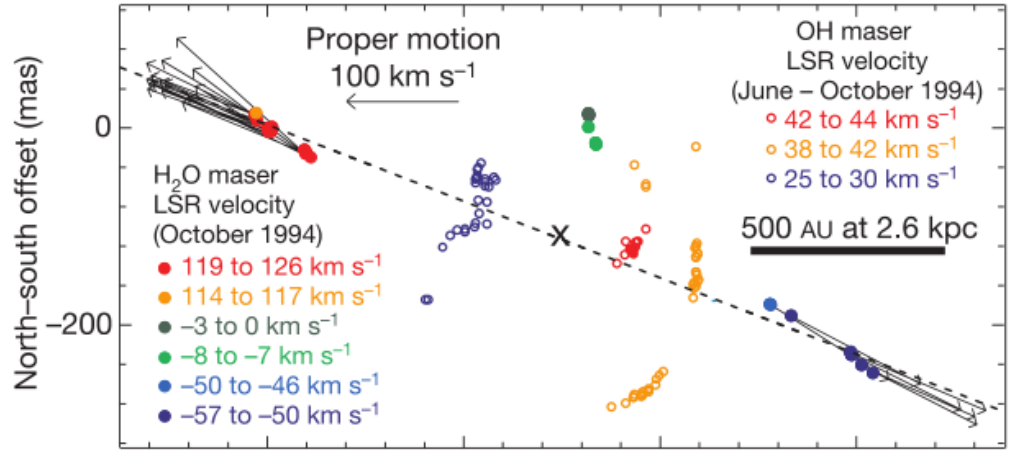


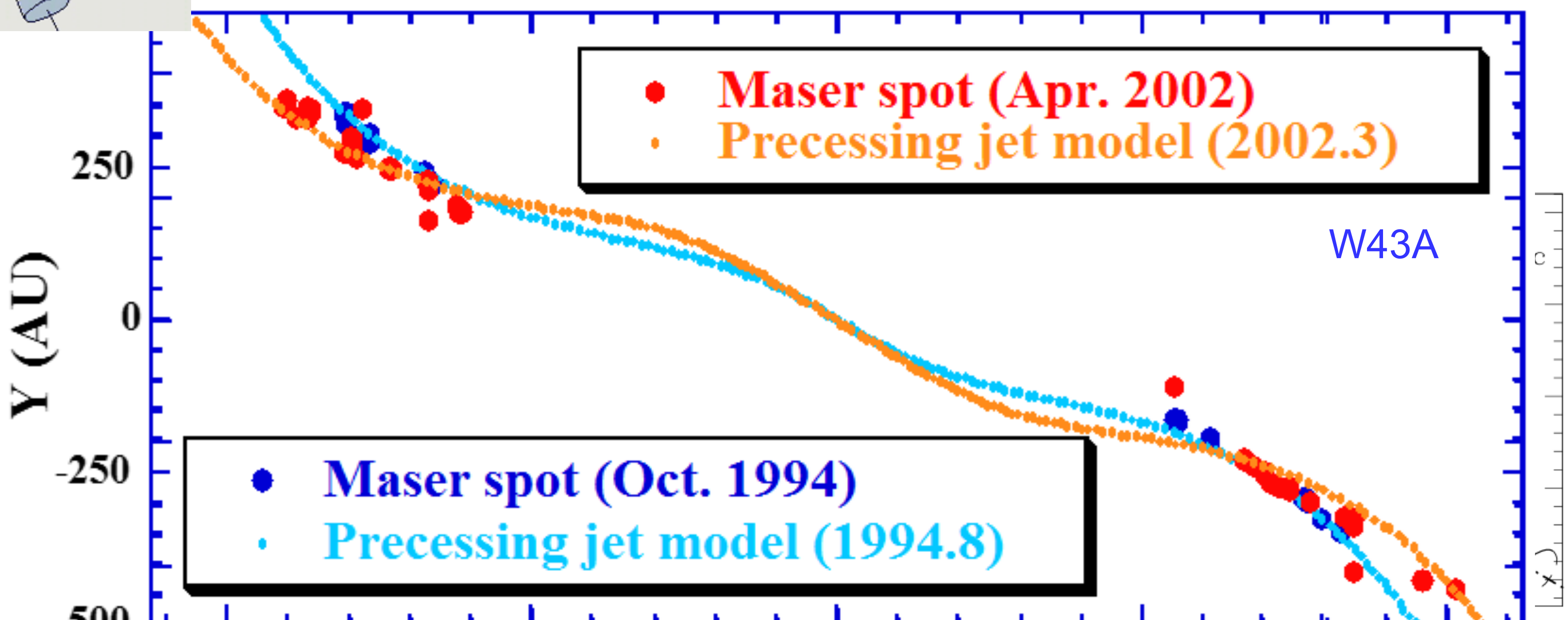
W43A
Vlemmings 2006

Water maser

racer for the outflow motion of late-type stars



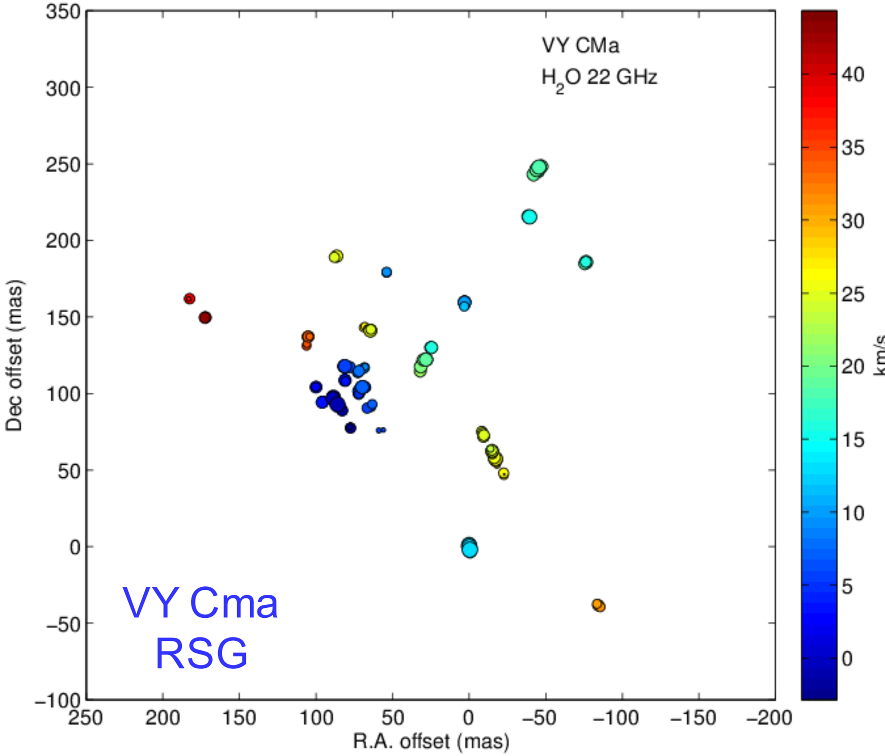




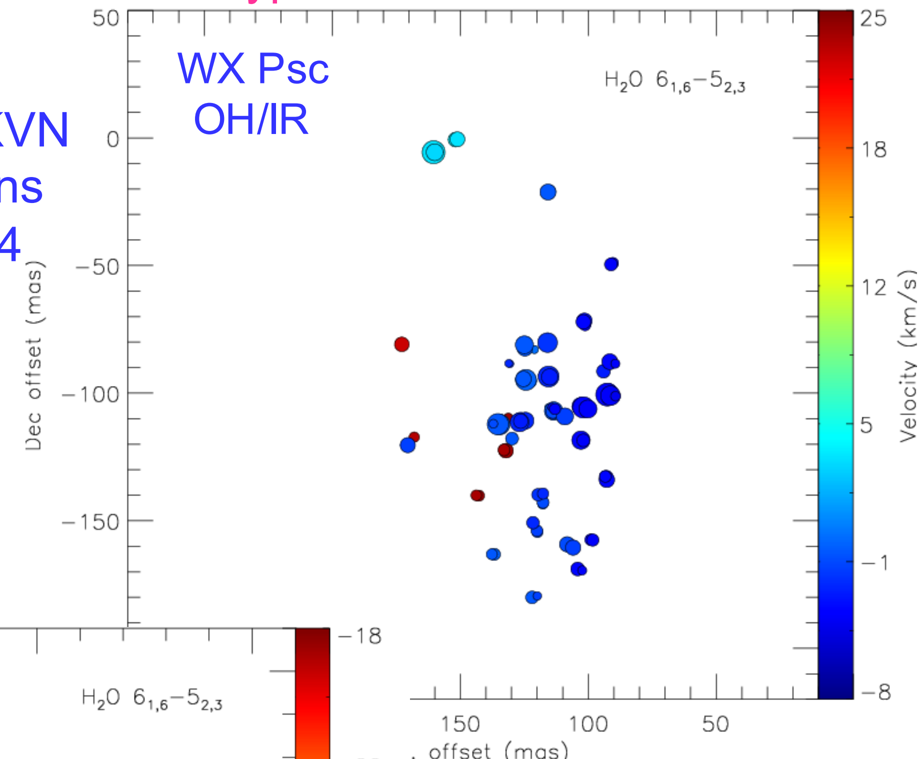
Found jet precession → imply the existence of a heavy planet or stellar companion

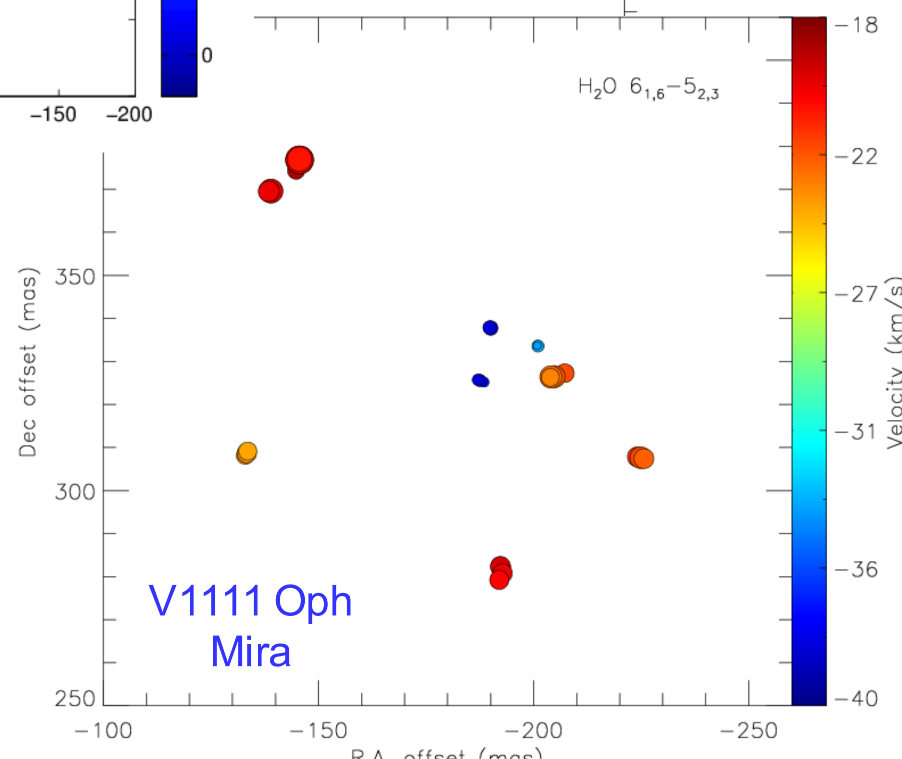
Water maser

as a tracer for the outflow motion of late-type stars



Results of KVN observations since 2014

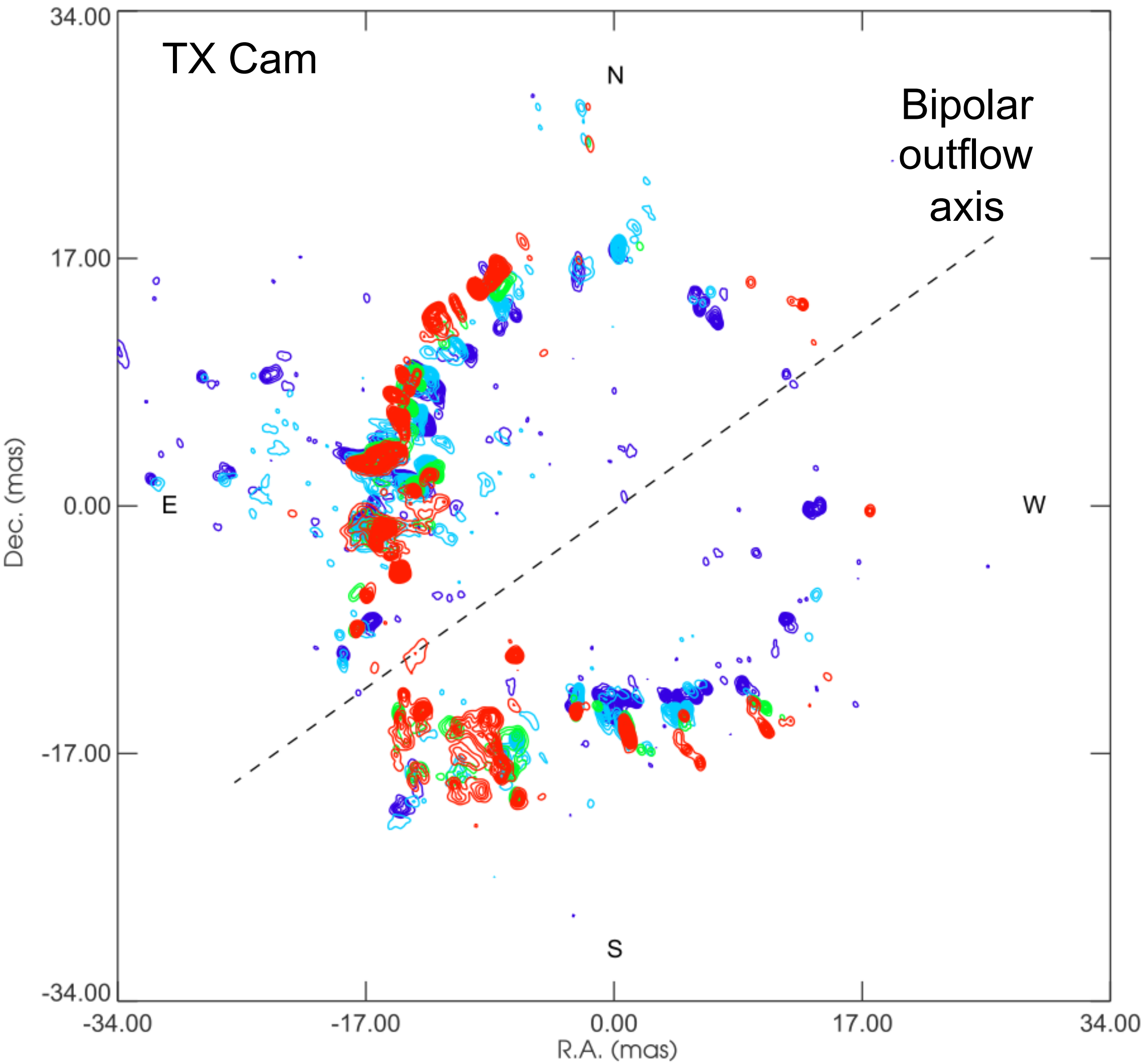




Position - velocity distributions show biopolarity of outflow, but much more irregular and asymmetric compared with WFs.

SiO maser

as a tracer for the physical environments of inner regions of CSEs



Gonidakis 2013

1997 May 24 (0.68): purple
1997 June 19 (0.78): blue
1997 October 9 (0.92): green
1997 December 17 (1.05): red

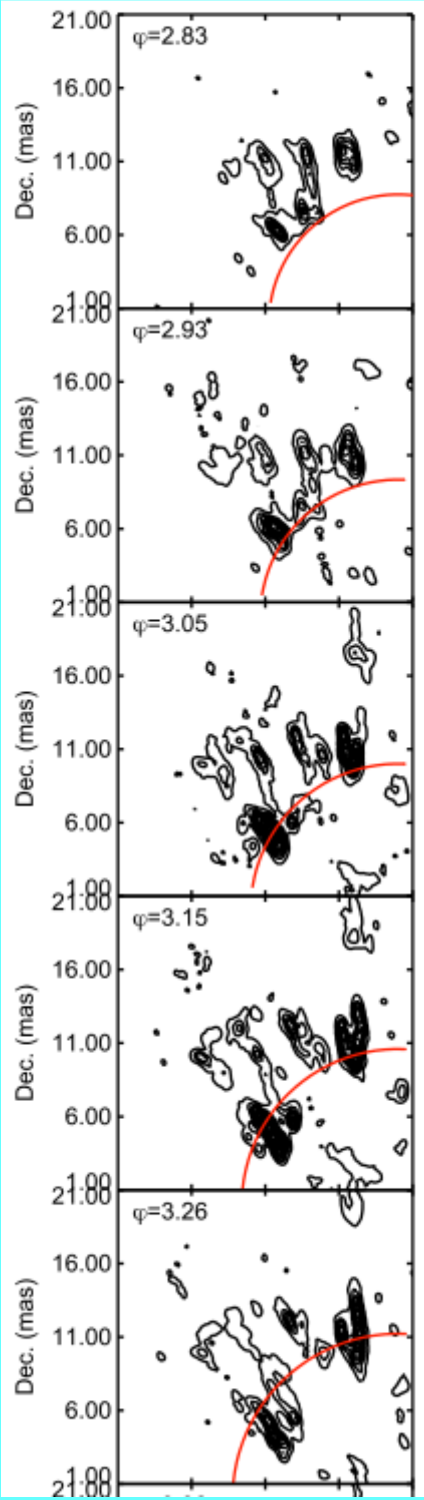
- **Shock wave**

A number of features dominated by **peculiar kinematics** (in movie) → **associate with the shock wave** permeating the extended atmosphere of TX Cam.

- **Bipolarity**

Showing **differences in expansion** along the NE–SW and SE–NW axes

Flow of material along the SE–NW axis is faster. → **bipolar outflow** around TX Cam



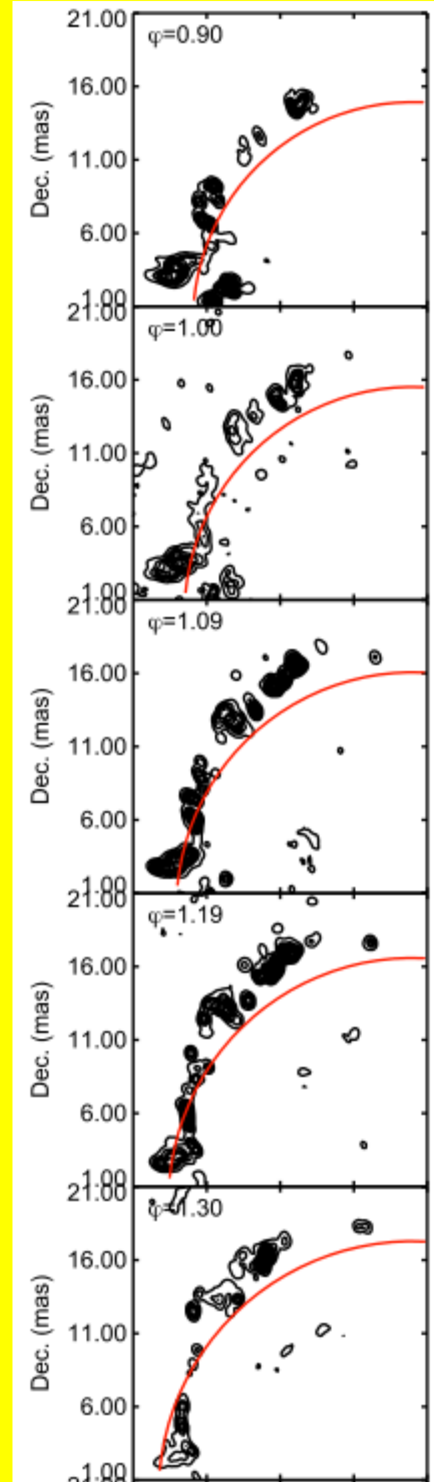
Shock permeates the masing region

→ **Increasing the collisional rate** in the passage of the shock

→ increasing the intensity of the maser spots

→ evidence of **collisional pumping**

Gonidakis 2013



Shock affects **only the kinematics of the ring**, just pushing the masing material to the outer region

→ **cannot conclude** the SiO masers are **purely collisional pumped**

Questions

- **How do AGB, RSG, and RG loose their mass ?**
- When and where do inhomogeneities and asymmetries form ?
- Which are the shaping mechanisms ?
- What is the role of binarity in AGB stars ?

Related issues

- Relationships between the photosphere, molecular layer, dust shell, and SiO maser shell
- Pulsation-driven extended atmospheres, dust formation, and radiative acceleration on dust grains dragging along the gas

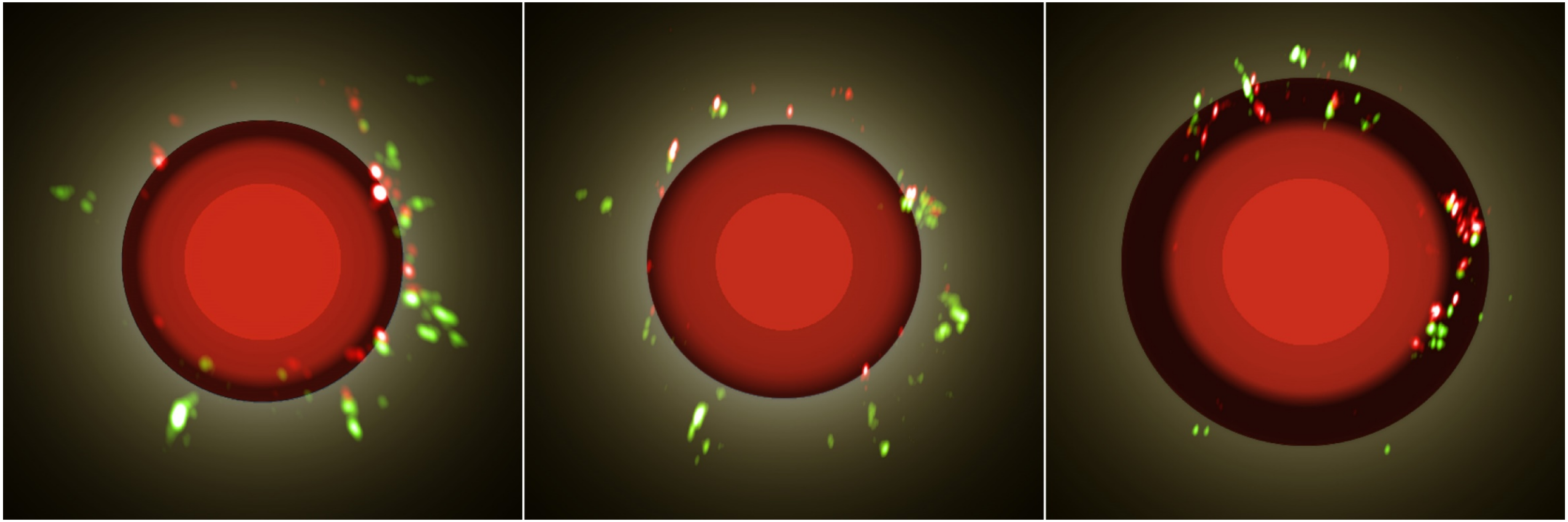
Strong needs for multi-epoch, multi-frequency (near-IR, mid-IR, sub mm, mm) observations with high resolution

- To observe different distances from the stellar photosphere
- To explore the extended stellar atmospheres
- To establish links between the spatial scales of molecular envelopes and of the dust shell
- To understand the process of dust formation and of mass loss
- Recent researches focus on the role of Al_2O_3 dust which can form at a relatively high temperature (~1700 K).
- Radial structure and kinematics of the stellar atmosphere and the CSE lead us to better understand the mass-loss process and its connection to stellar pulsation.

SiO maser

as a tracer for the physical environments of inner regions of CSEs

VLTI/MIDI and VLBA/SiO maser observations of S Ori

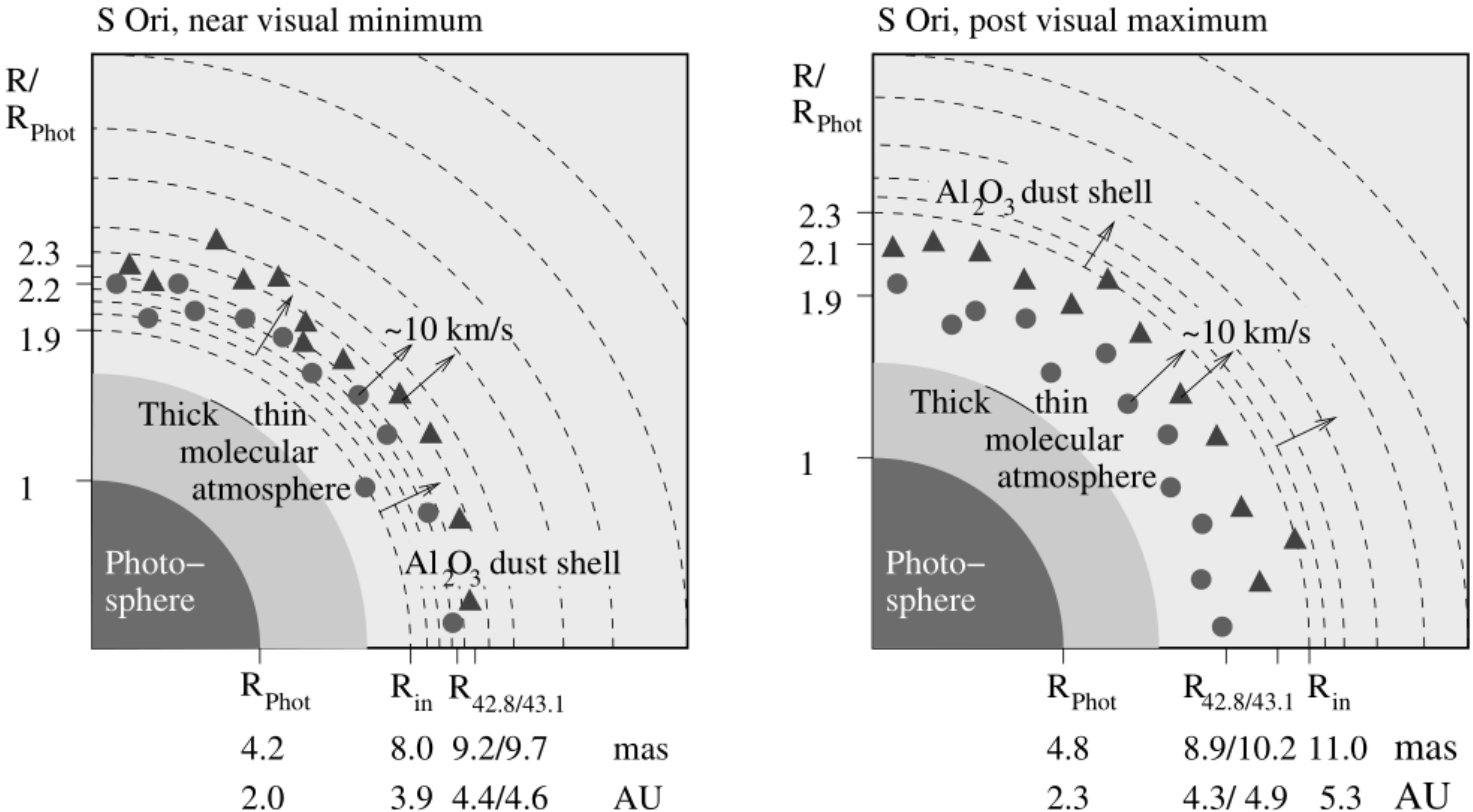


- (red) v=2, J=1-0, 42.8 GHz (green) v=1, J=1-0, 43.1 GHz SiO maser images on MIDI model with photosphere, molecular layer, Al_2O_3 dust
- Al_2O_3 dust has an inner radius of ~2 stellar radii, and may be co-located with the SiO maser region.
- The location of the SiO maser emission is consistent with earlier observations and with theoretical models by Gray et al. 2009
- The maser velocity structure indicates a radial gas expansion with velocity ~10 km/sec

SiO maser

as a tracer for the physical environments of inner regions of CSEs

VLTI/MIDI and VLBA/SiO maser observations of S Ori



Radial structure of the CSE of S Ori, Al_2O_3 dust shell (dashed arcs), 42.8GHz and 43.1GHz maser spots (circles/triangles)

Polarization observations

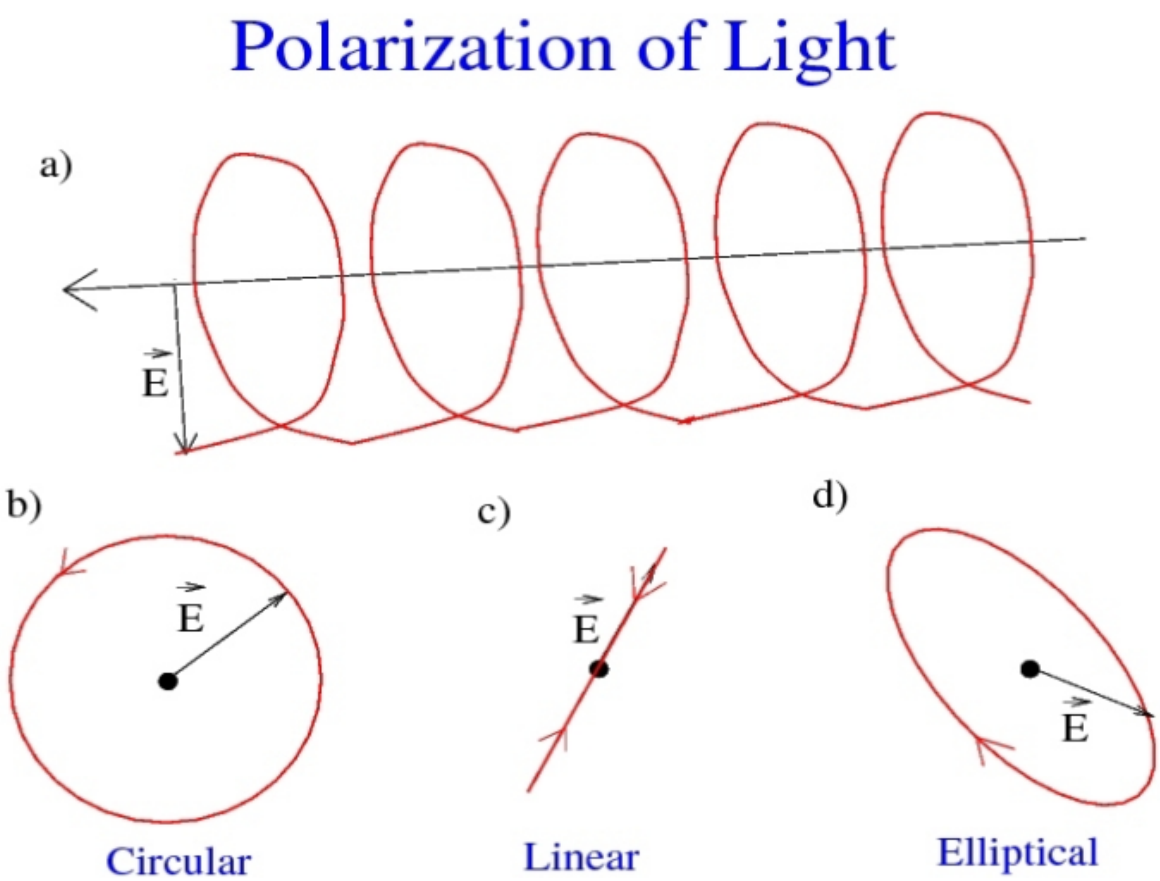
Role of polarization in mass-loss processes of late-type stars

- A study of mass-loss of late-type stars needs a lot of information about the physical processes of CSEs.
- Radiation pressure on dust grains → acceleration of the stellar wind → mass-loss of evolved stars
  - strongly related to the kinematics and morphology of pulsation-driven extended atmospheres

- Polarization observations of circumstellar dust and molecular lines give information about dust properties and magnetic fields in CSEs of evolved stars.
- Polarimetric continuum obs. → orientation of elongated dust grains due to a global magnetic field
- Polarized maser emission → strength and geometry of the magnetic field in the expanding envelopes
- Polarization affects a morphology of CSEs and outflow motions that are closely related to the mass-loss during the period from AGB to PN.

Polarization observations

What is polarization?



Light is oscillating E and B fields.

Polarization is how the wave oscillates.

Polarization observations

Basic of polarization: Stokes parameters

Light wave that propagates in the z direction:

$$\vec{E}_x(z,t) = E_{0x}\cos(kz - \omega t)\,\vec{x}$$

$$\vec{E}_y(z,t) = E_{0y}\cos(kz - \omega t + \varepsilon)\,\vec{y}$$

$$S_0 = I = E_{0x}^2 + E_{0y}^2$$

$$S_1 = Q = E_{0x}^2 - E_{0y}^2$$

$$S_2 = U = 2E_{0x}E_{0y}\cos\varepsilon$$

$$S_3 = V = 2E_{0x}E_{0y}\sin\varepsilon$$

- Linear polarization $Q \neq 0,\ U \neq 0,\ V = 0$
- Circular polarization $Q = 0,\ U = 0,\ V \neq 0$
- Fully polarized light $I^2 = Q^2 + U^2 + V^2$
- Partially polarized light $I^2 > Q^2 + U^2 + V^2$
- Unpolarized light $Q = U = V = 0$

Polarization observations

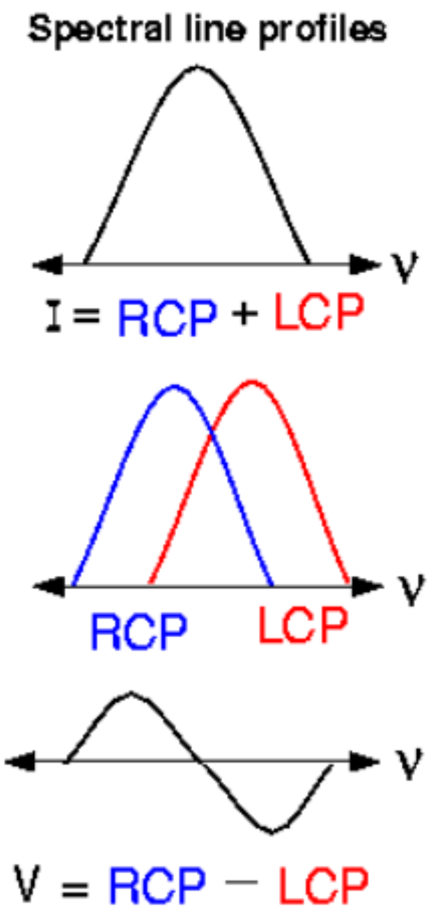
Astrophysical Polarization

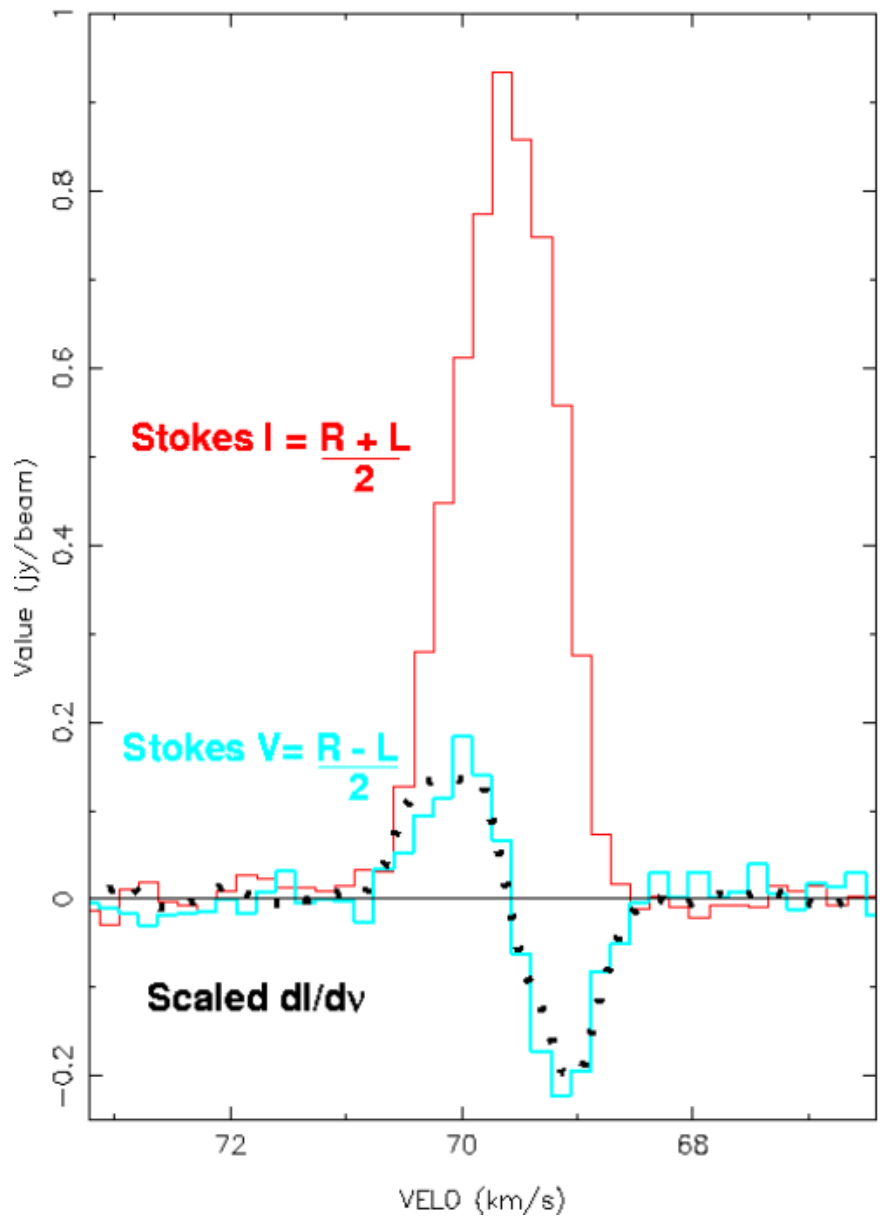
- **Processes which generate polarized radiation:**
  - Synchrotron emission: Up to ~80% linearly polarized, with no circular polarization. Measurement provides information on strength and orientation of magnetic fields, level of turbulence.
  - Dust Emission: Spinning aspherical dust grains in molecular clouds are aligned and this provides information about the direction of the plane of sky component of the magnetic field.
  - Zeeman line splitting: Presence of B-field splits RCP and LCP components of spectral lines by 2.8 Hz/μG. Measurement provides direct measure of B-field.

- **Processes which modify polarization state:**
  - Faraday rotation: Magnetoionic region rotates plane of linear polarization. Measurement of rotation gives B-field estimate.
  - Faraday conversion: Particles in magnetic fields can cause the polarization ellipticity to change, turning a fraction of the linear polarization into circular.

Polarization observations

Example: Zeeman effect





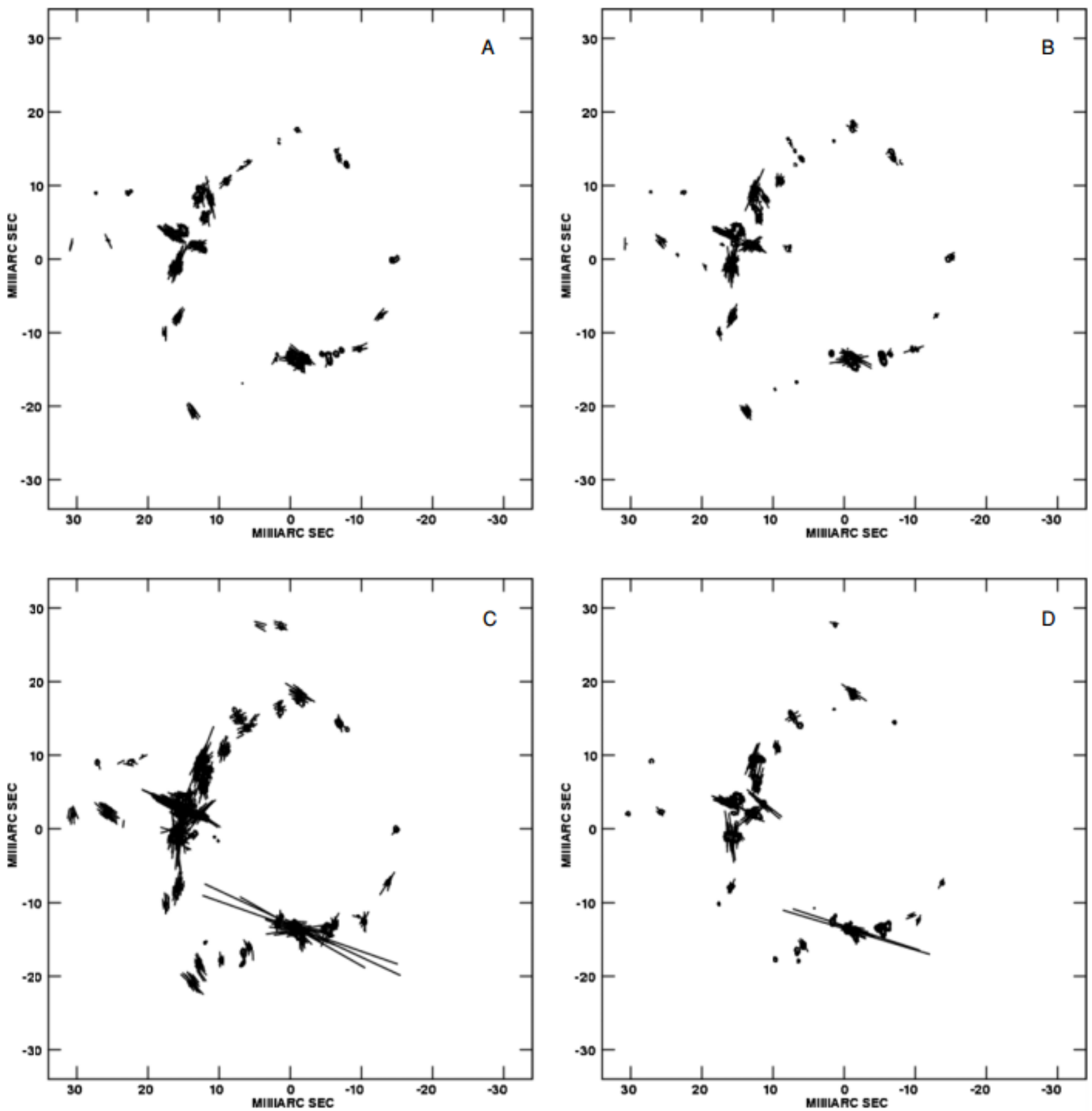
Atoms and molecules with a net magnetic moment will have their energy levels split in the presence of a magnetic field.

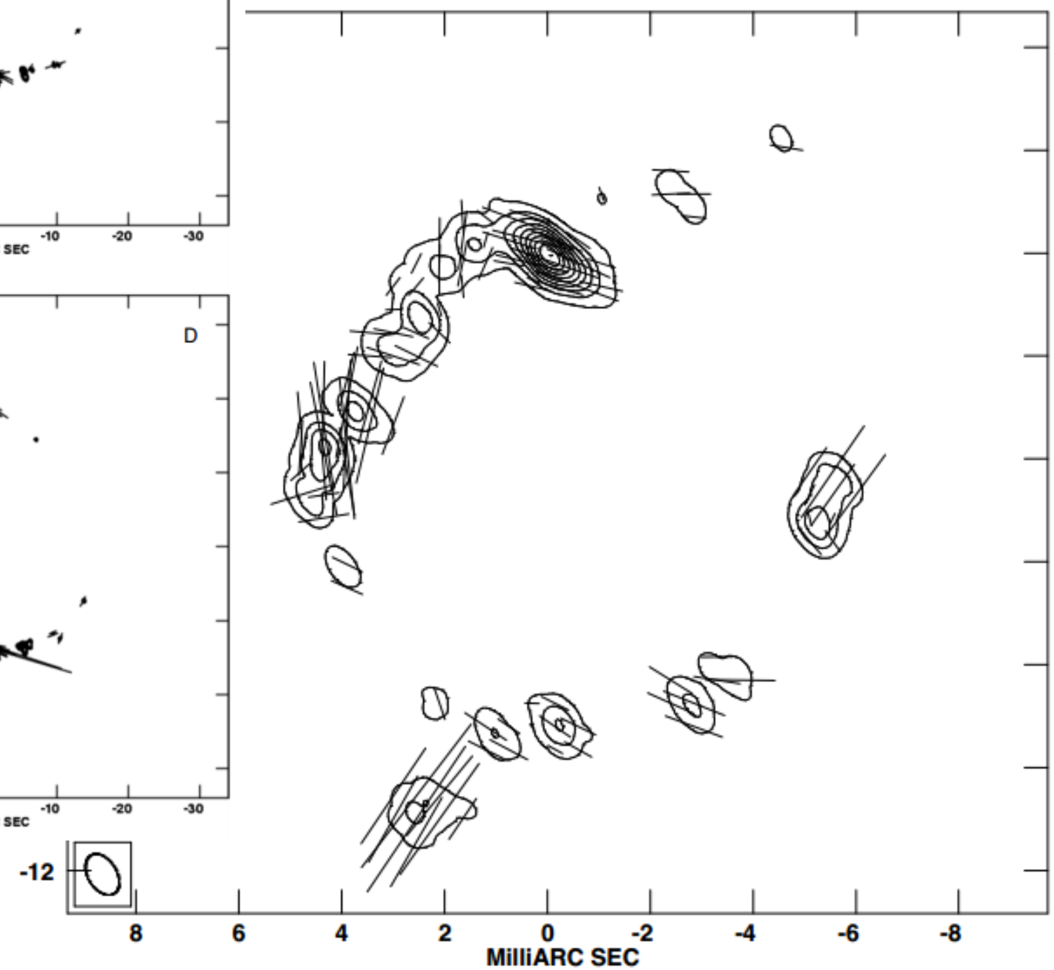
Detected by observing the frequency shift between right and left circularly polarized emission.

Polarization observations

SiO maser polarization

OH/IR star OH 44.8-2.3
SiO v=1 J=1-0 (43 GHz) maser
Amiri 2011

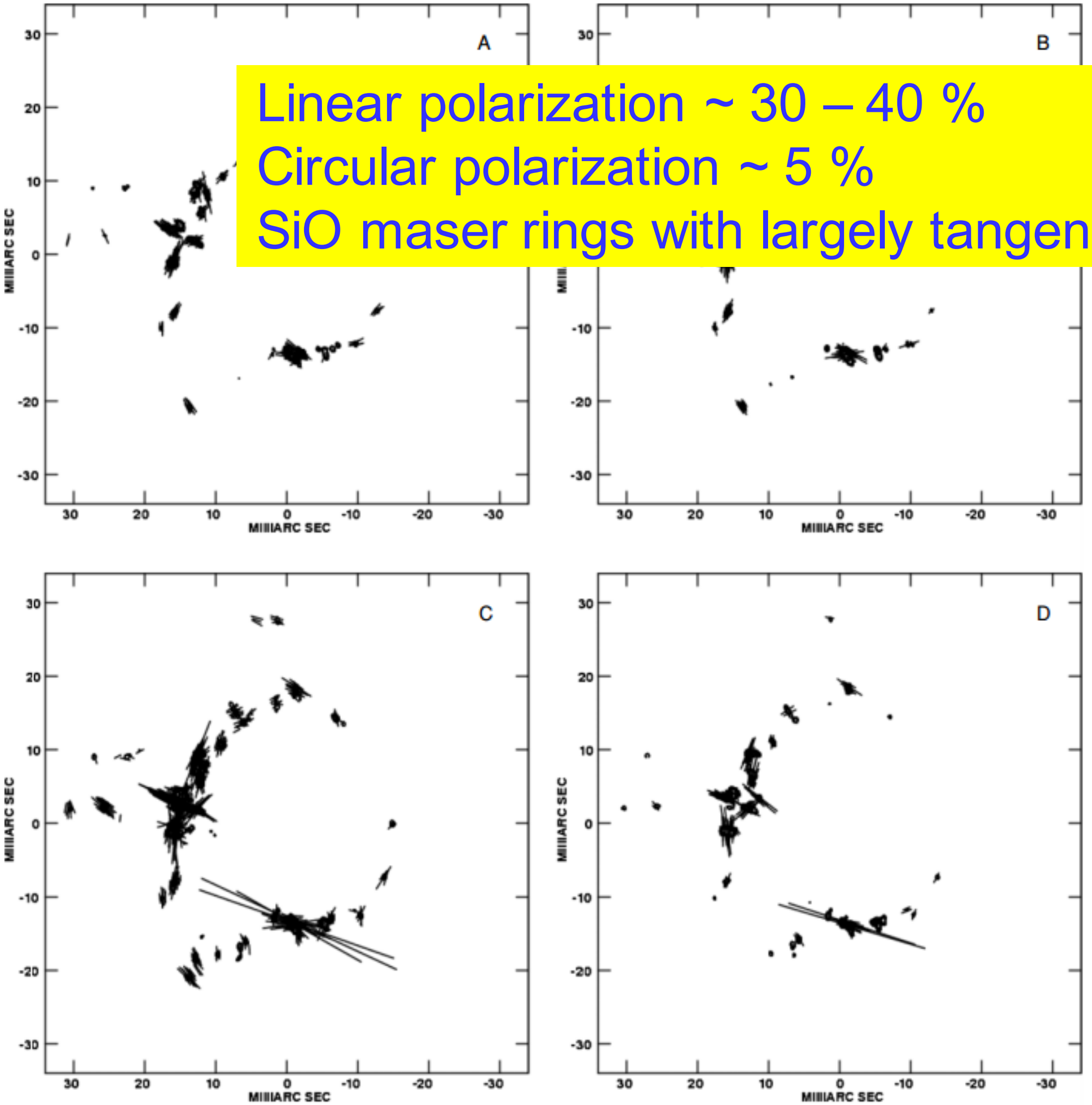




AGB star TX Cam
SiO v=1 J=1-0 (43 GHz) maser
Kemball 2009

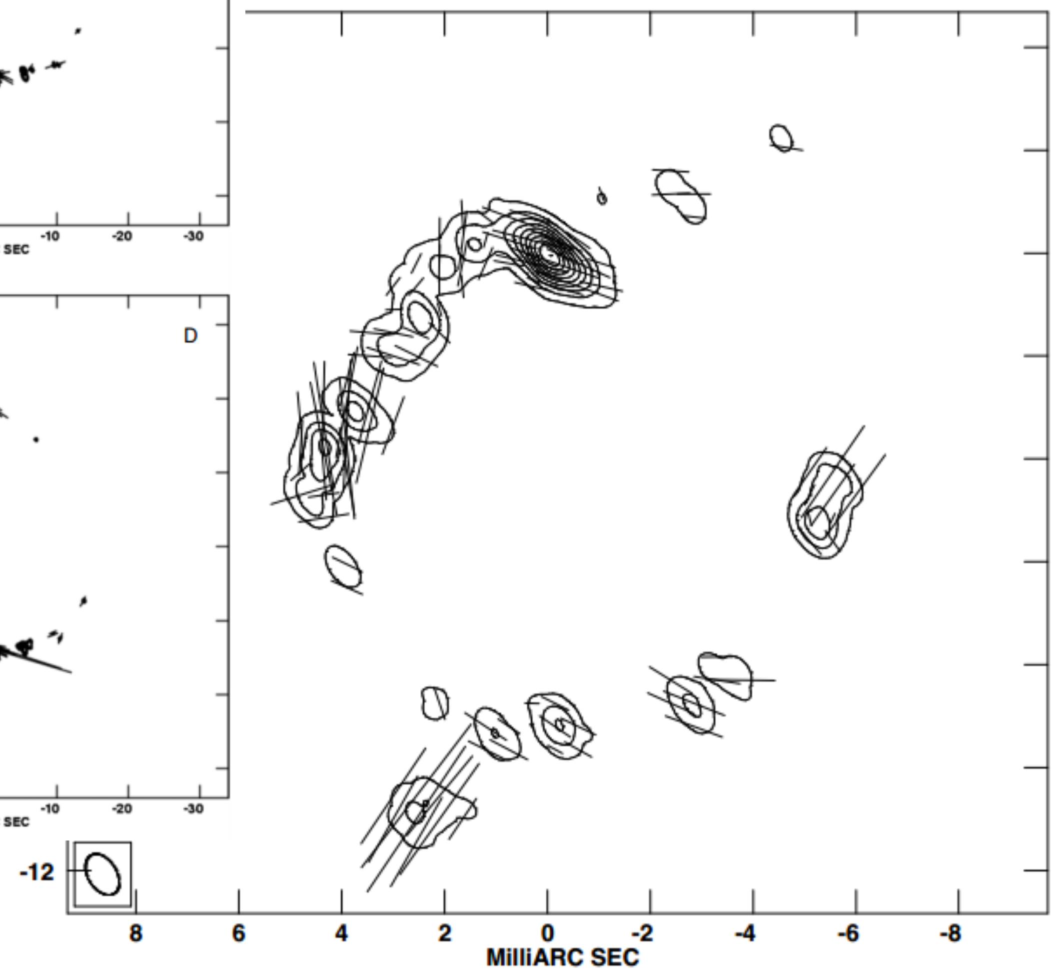
Polarization observations

SiO maser polarization



Linear polarization ~ 30 – 40 %
Circular polarization ~ 5 %
SiO maser rings with largely tangential linear polarization.

2.3
Hz) maser
Amiri 2011

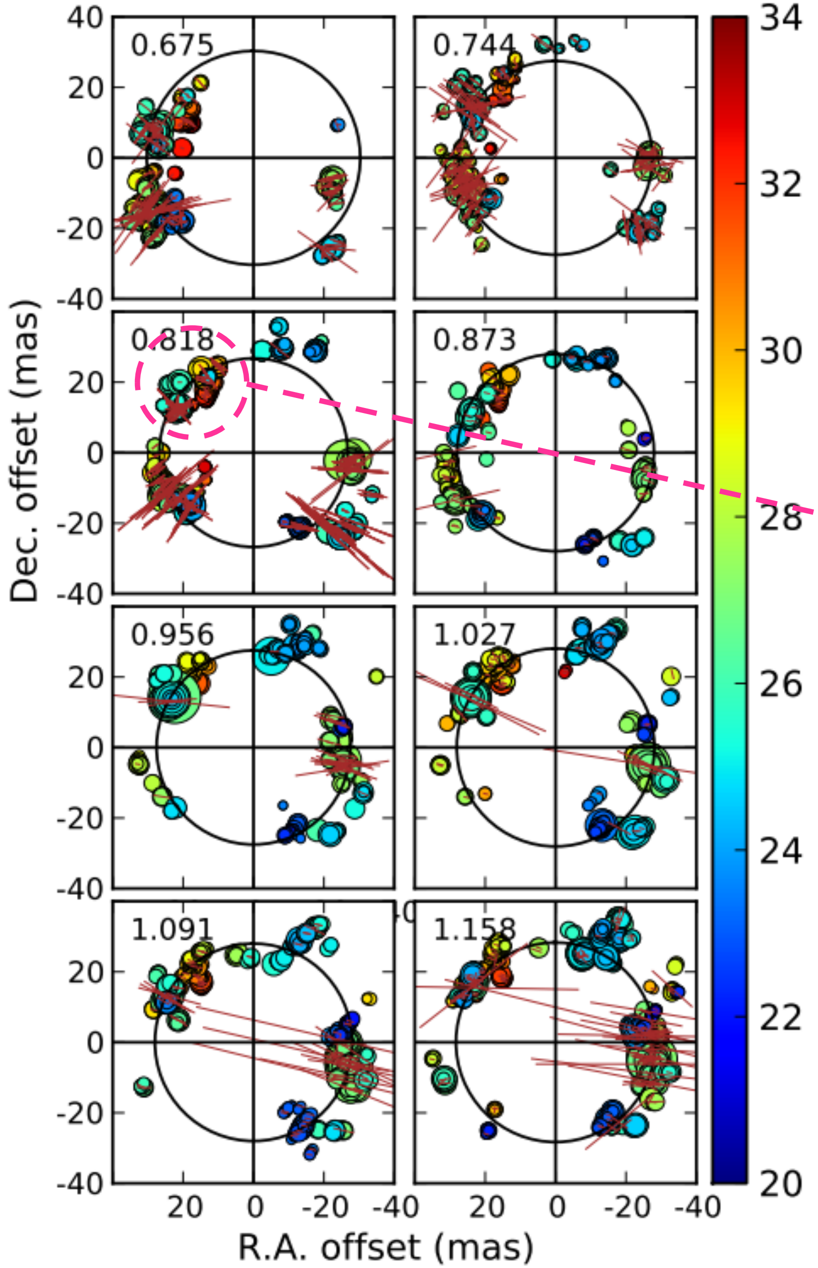


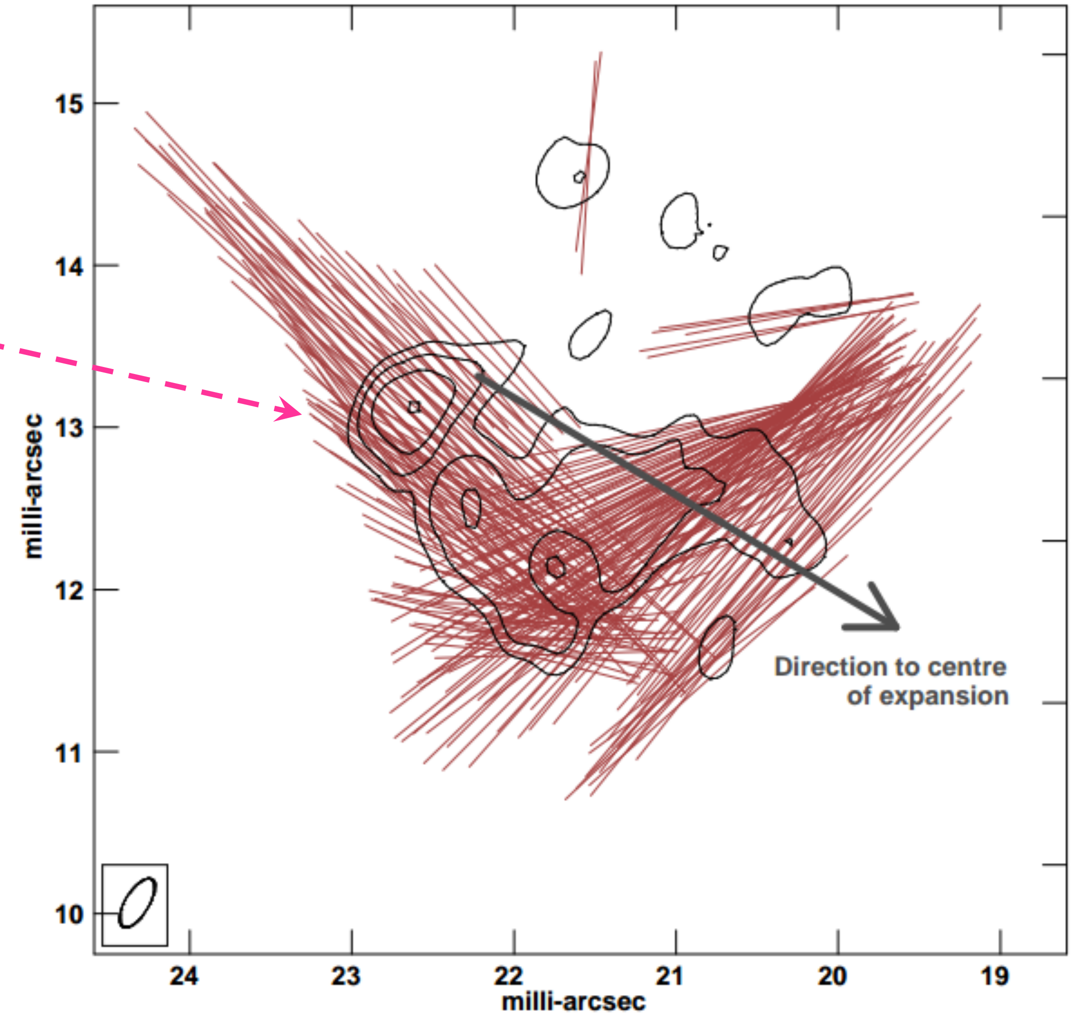
AGB star TX Cam
SiO v=1 J=1-0 (43 GHz) maser
Kemball 2009

Polarization observations

SiO maser polarization

AGB star R Cassiopeiae
SiO v=1 J=1-0 (43 GHz)

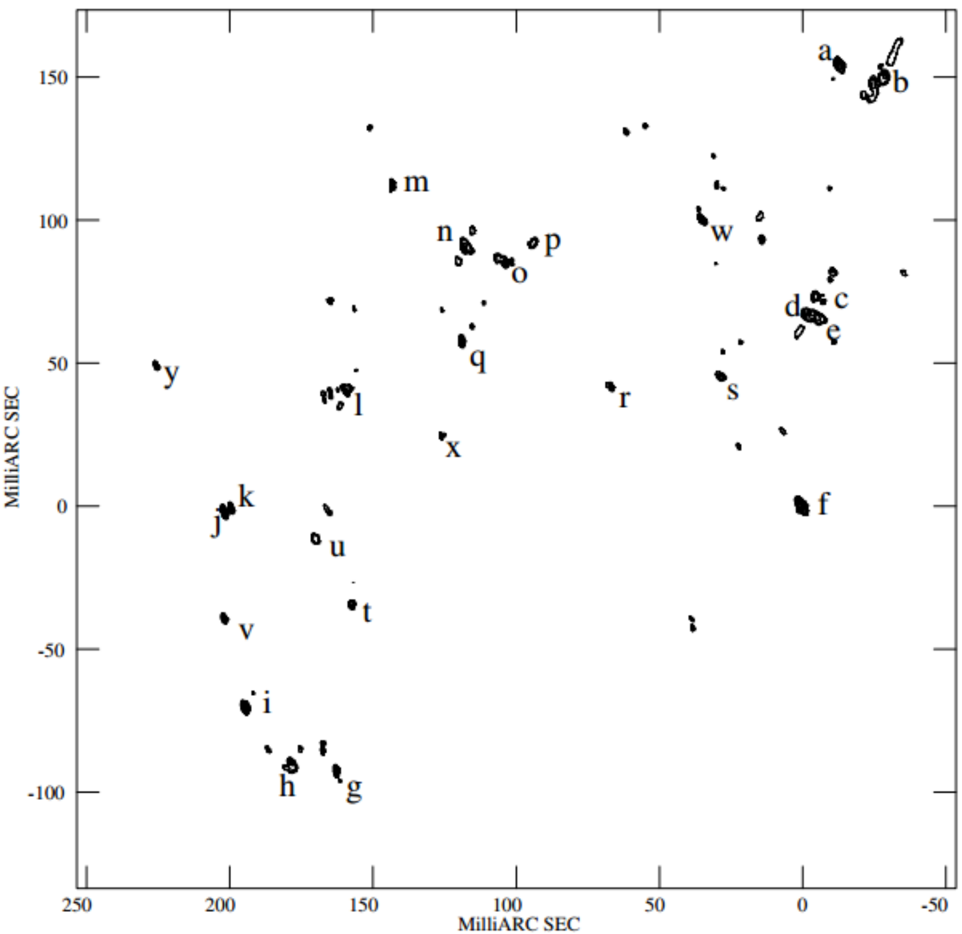




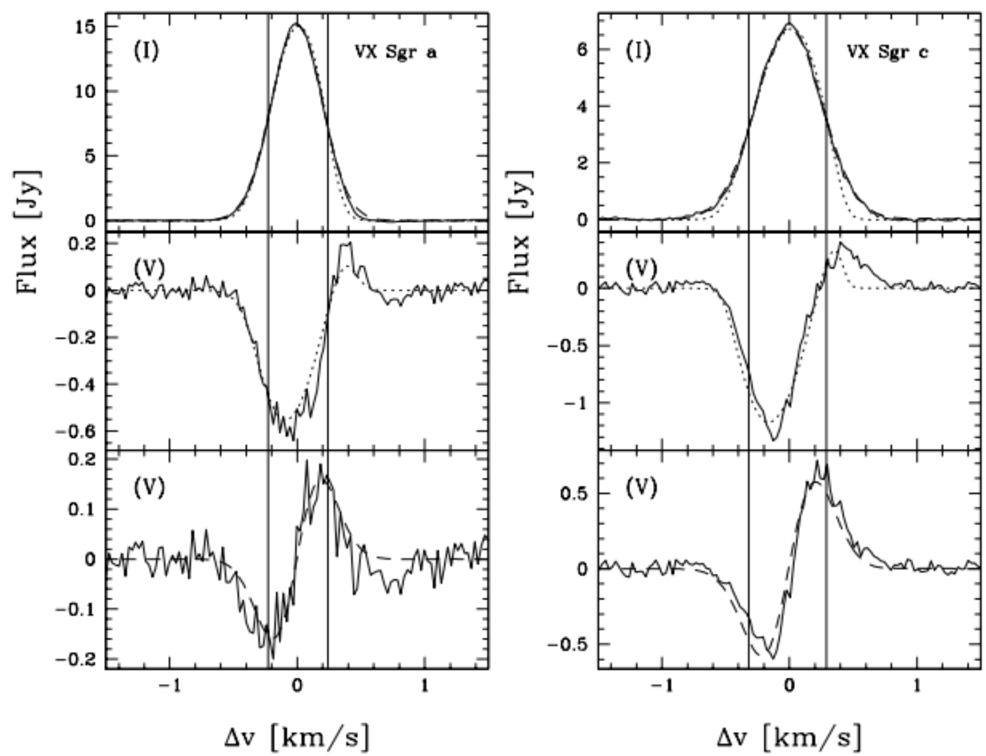
Assaf 2013

Polarization observations

Water maser polarization



VX Sgr
22 GHz H2O Maser



Vlemmings 2005

B field ~ few hundreds mG

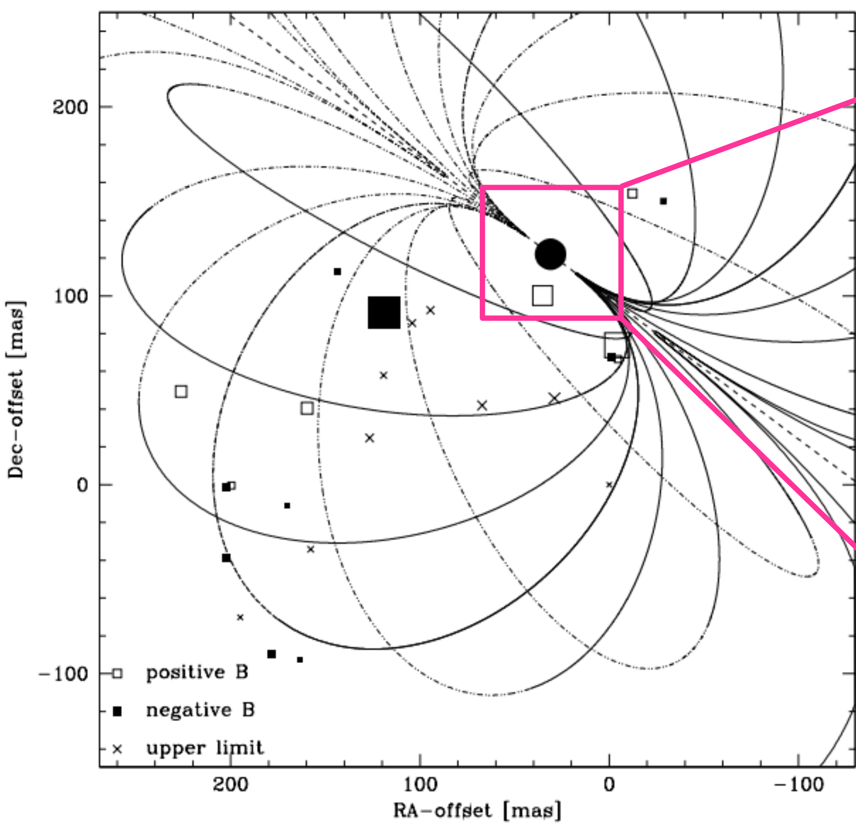
Linear polarization rare and weak (< 2 %)

Circular polarization 0.3 to 20%

Polarization observations

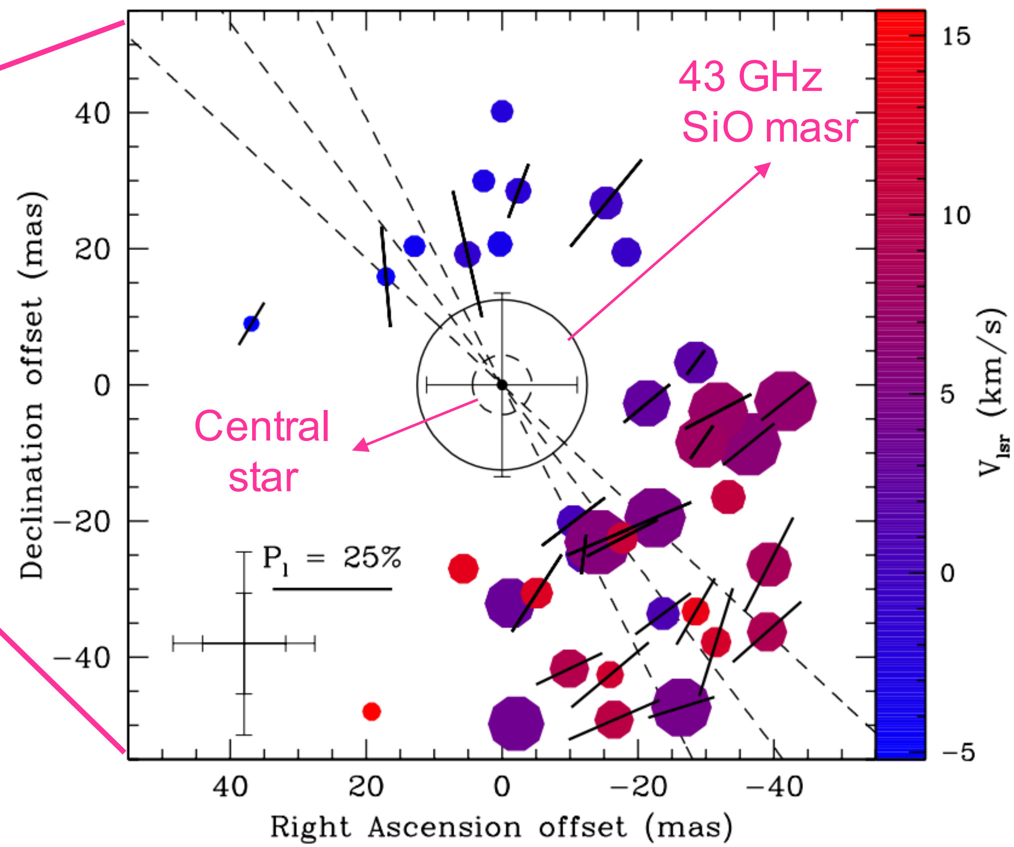
Magnetic field around red super giant VX Sgr

VX Sgr
22 GHz H2O Maser



Vlemmings 2005 (VLBA obs.)

VX Sgr
^{29}SiO v=0 J=5-4 (215 GHz) maser



Vlemmings 2011 (SMA obs.)

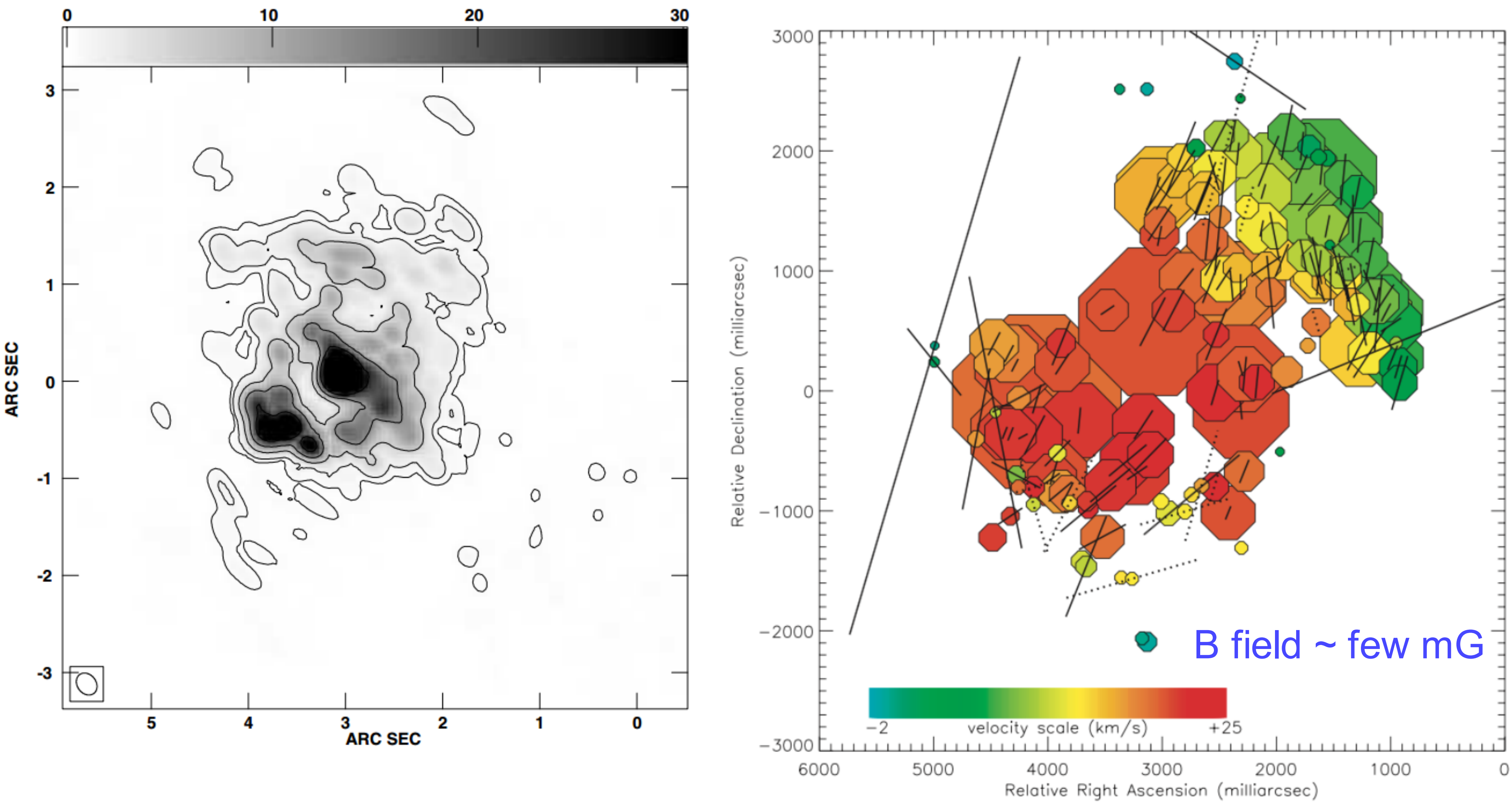
Best fitted dipole magnetic field for the H_2O maser around VX Sgr

Consistent with large-scale dipole magnetic field determined from H_2O

Polarization observations

OH maser polarization

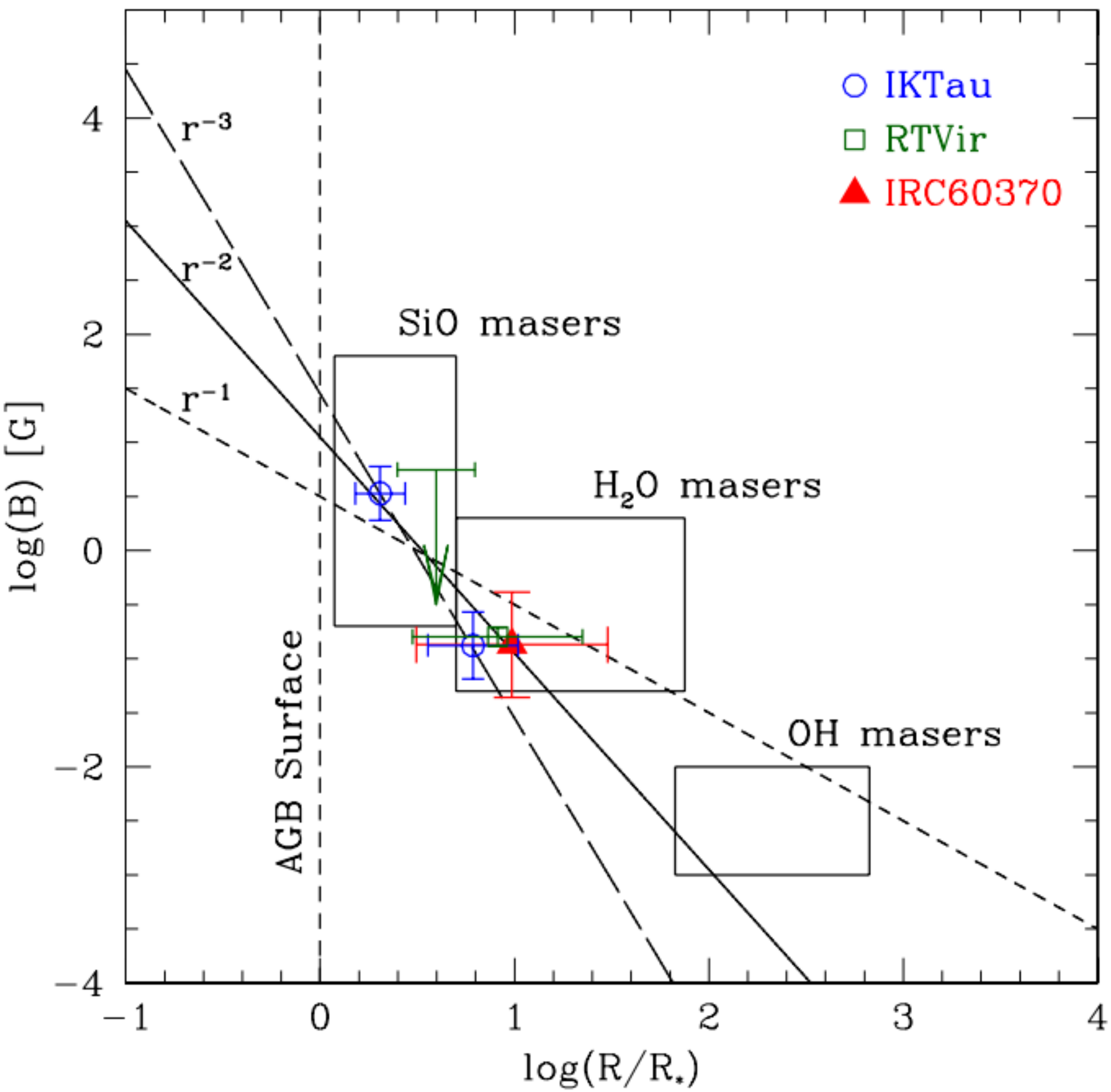
NML Cyg 1612 MHz OH Maser (MERLIN obs.)



Etoka & Diamond 2004

Polarization observations

Magnetic field strength from masers



Leal-Ferreira 2013

Magnetic field strength along the line of sight versus the radial distance of the masers to the star.

r^{-1}: toroidal

r^{-2}: solar type field

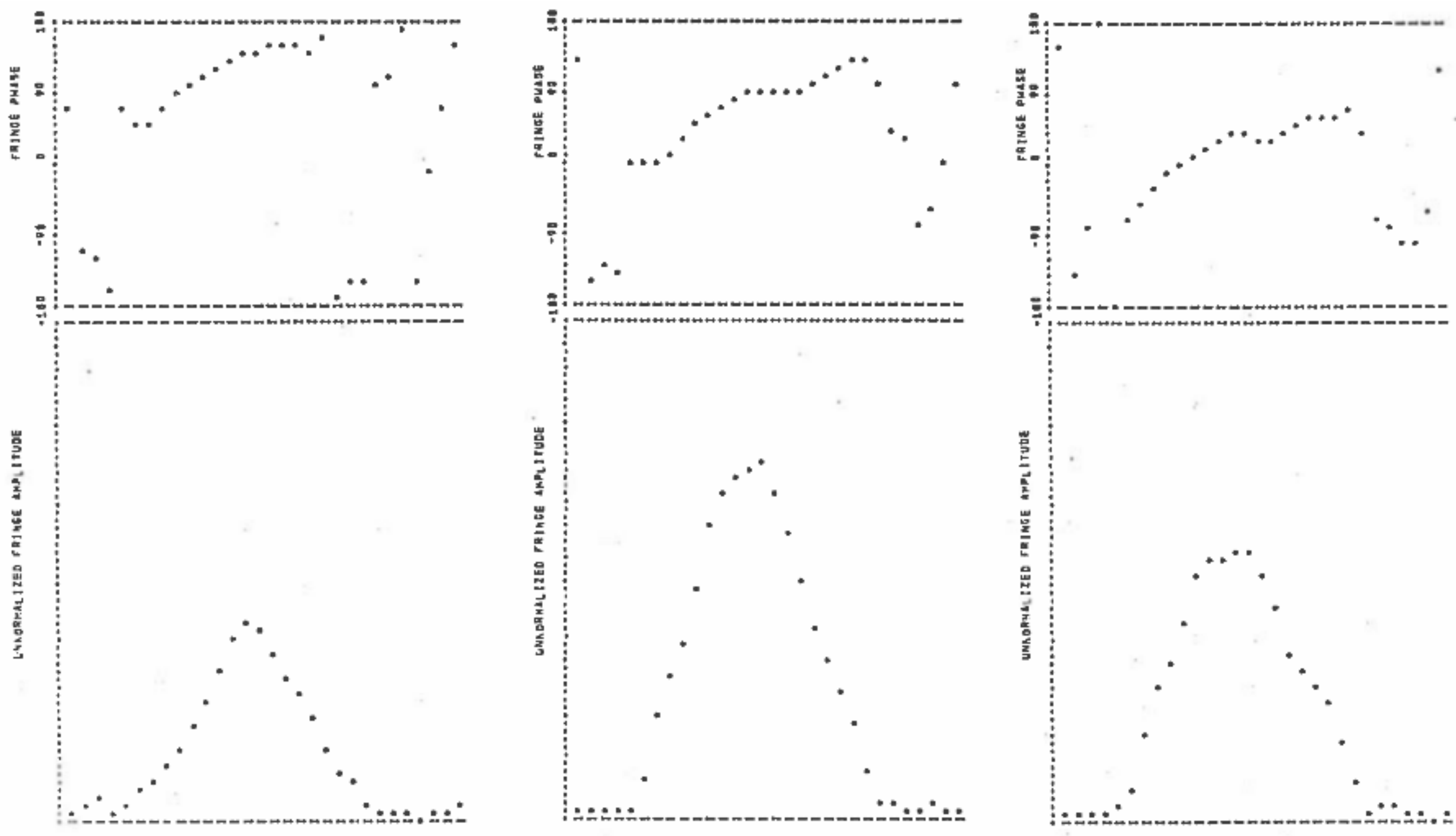
r^{-3}: dipole field

AGB Magnetic Fields

- Single stars: internal dynamo (Blackman et al. 2001) or interaction with circumstellar disk
- Binary/planet companion: common envelope dynamo (Nordhaus et al. 2006)

Summary with a historical plot

First VLBI spectrum



1665 MHz OH emission of W3 obtained from Haystack and Greenbank (June 8 - 10, 1967) by J. M. Moran