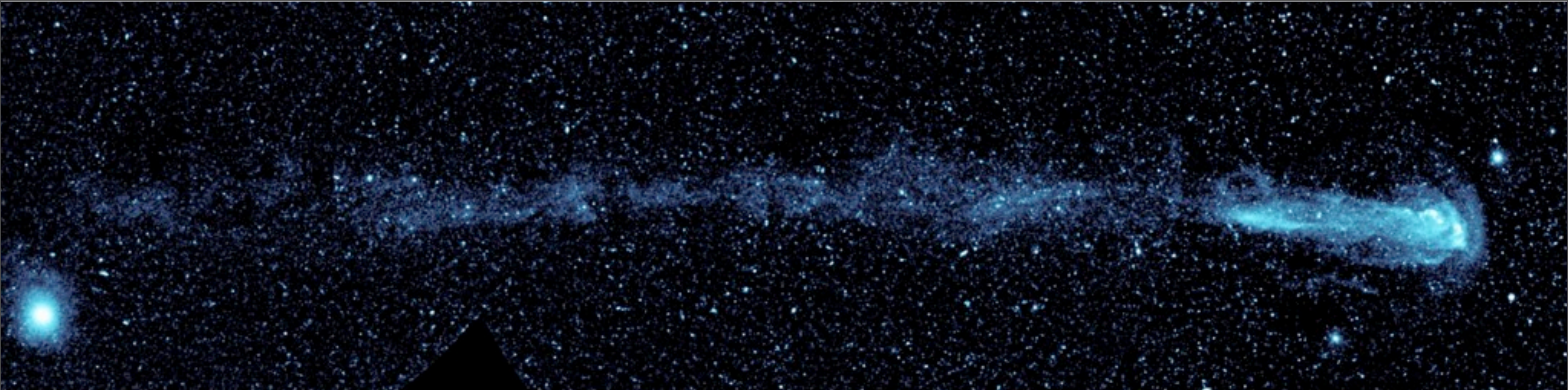
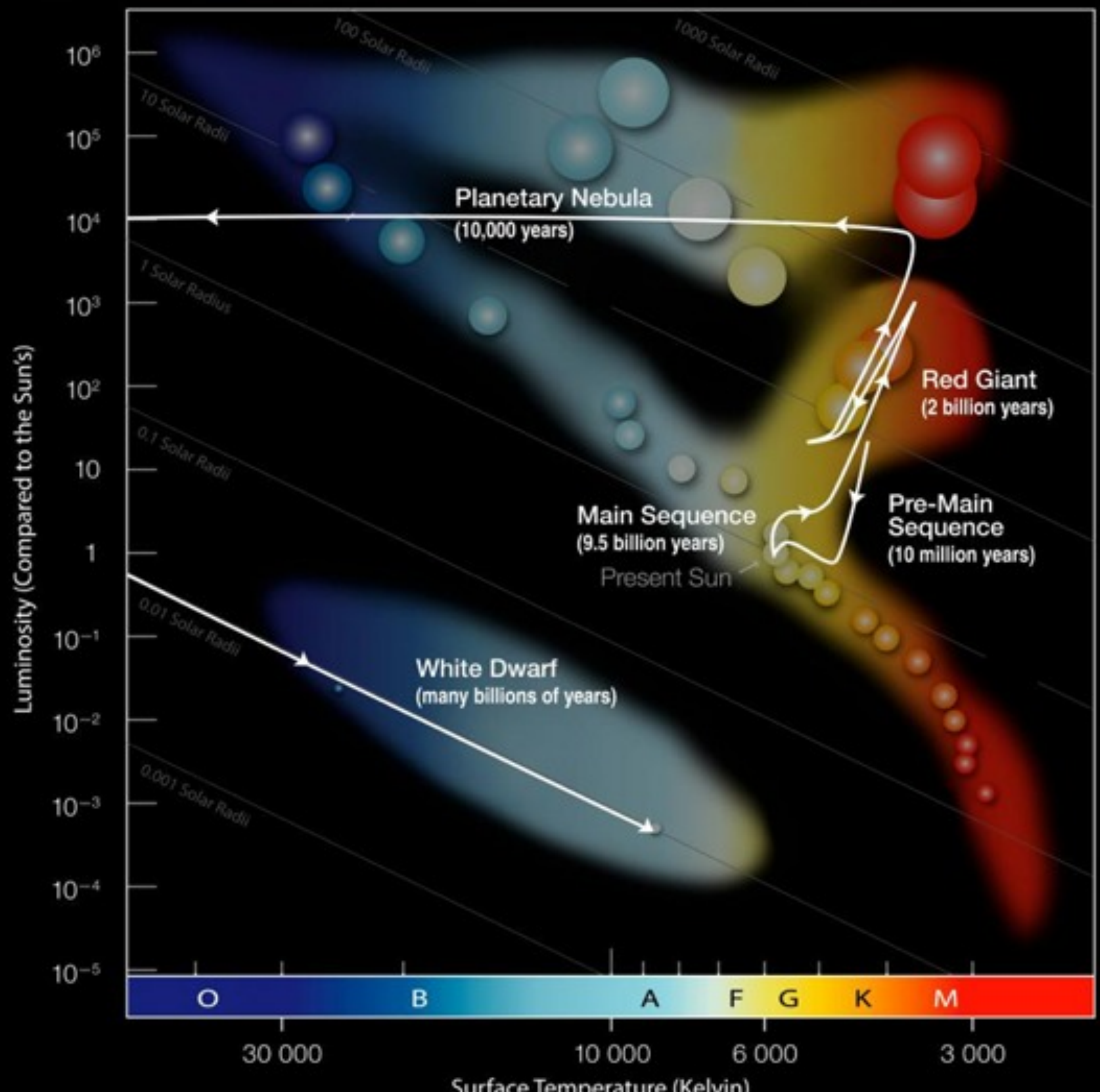


Late-Type Stars

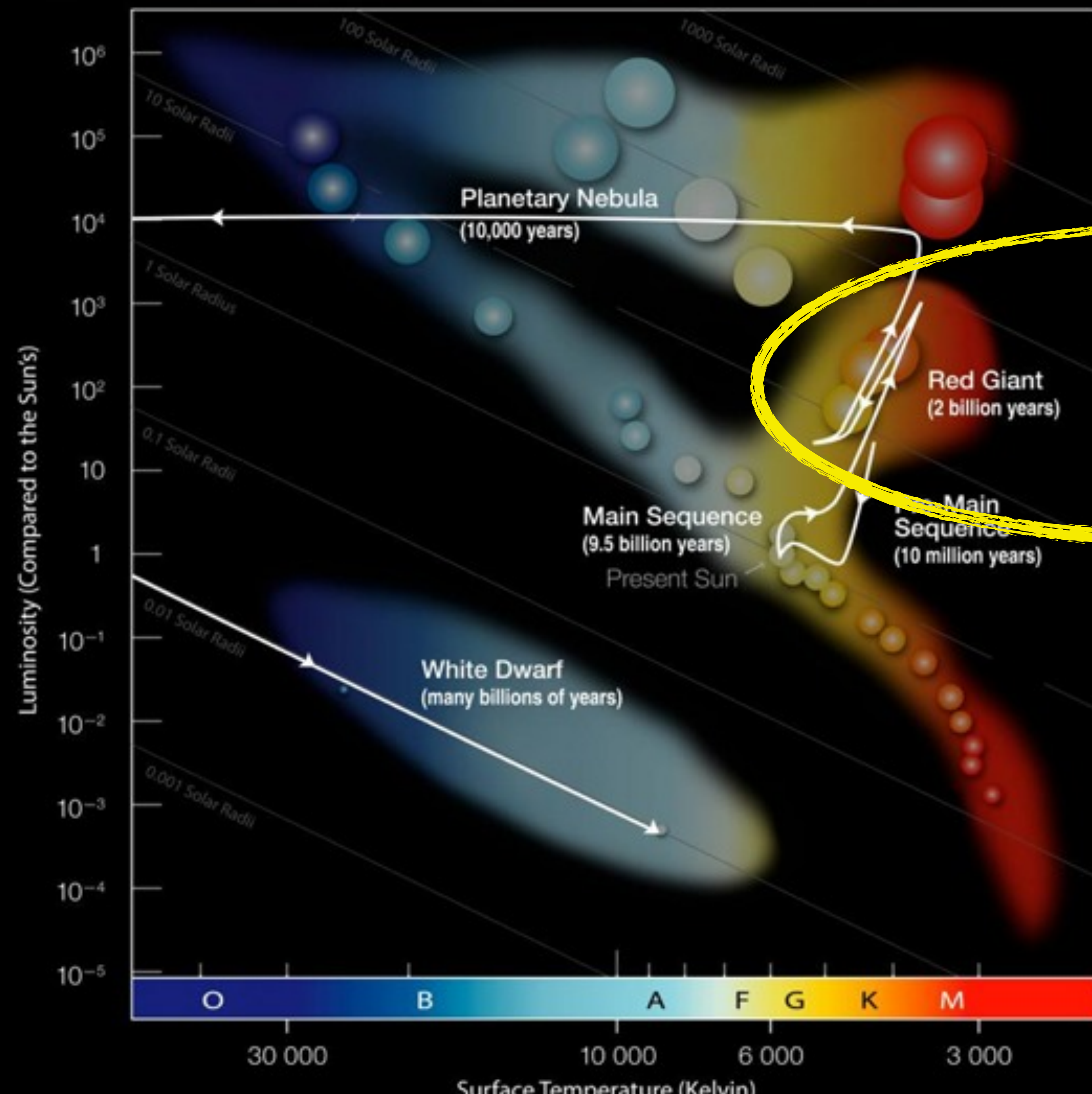
Liz Humphreys (ESO)

Markus Wittkowski, Alain Baudry, Eric Blackman, Jason Grunhut, Susanne Hoefner, Franz Kerschbaum, Pierre Kervella, Mikako Matsuura, Iain Mcdonald, Claudia Paladini, Anita Richards, Albert Zijlstra

H-R 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)

H-R Diagram

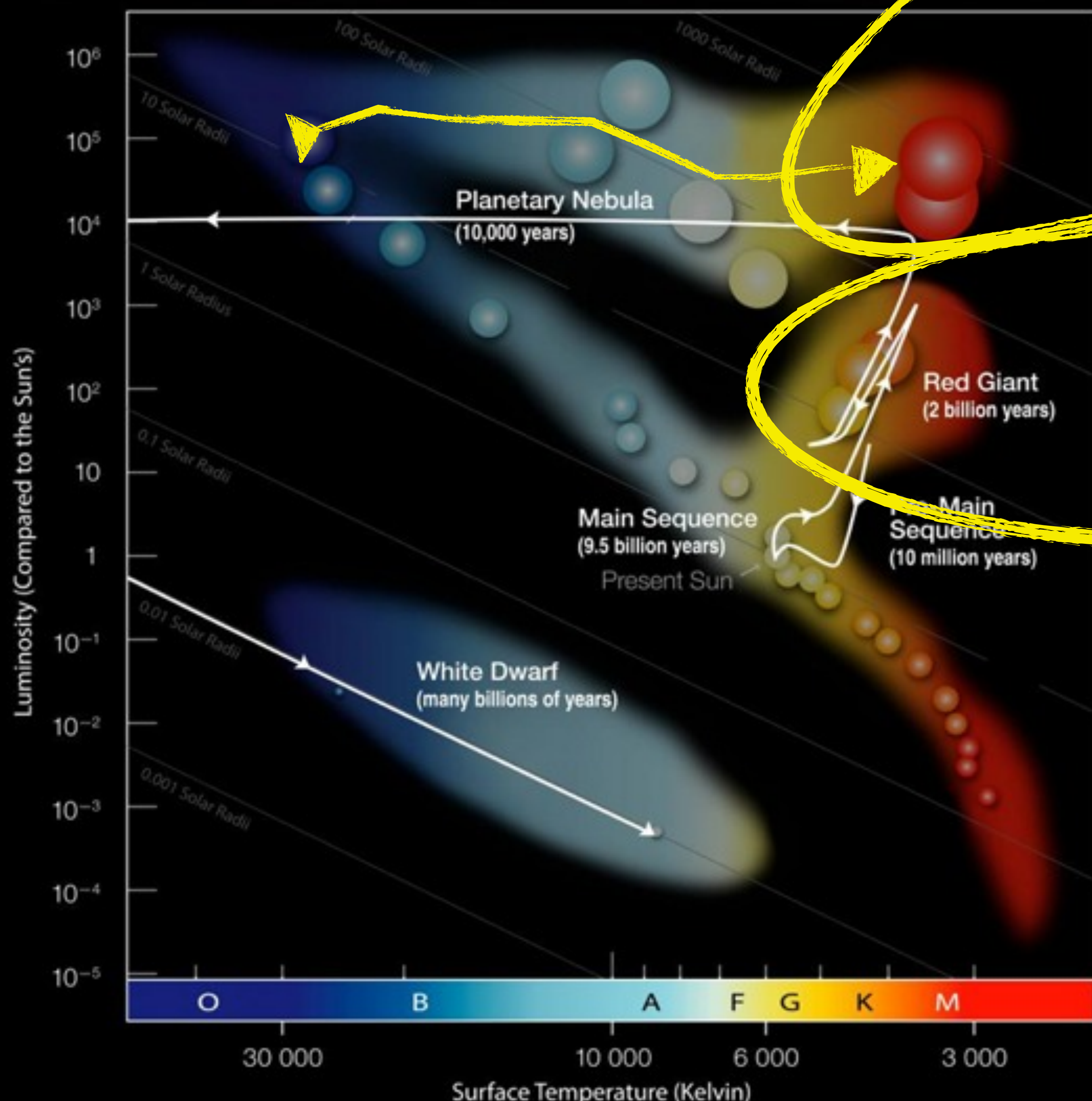


Asymptotic
Giant **B**ranch
$M_{initial}$: 1- 8 $M_{\odot}$
e.g. Mira

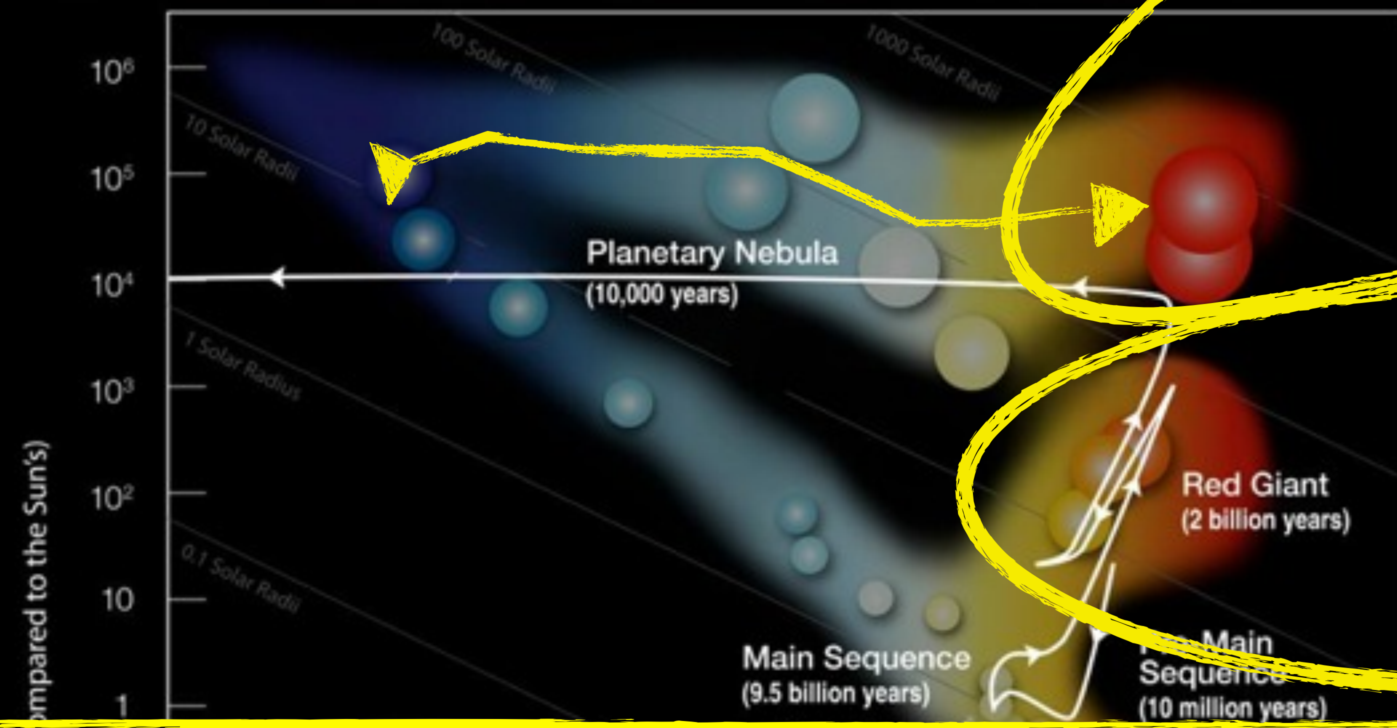
H-R Diagram

Red **S**uper **G**iants
$M_{initial}$: 8 - 35 $M_\odot$
e.g. Betelgeuse, Antares

Asymptotic **G**iant **B**ranch
$M_{initial}$: 1- 8 $M_\odot$
e.g. Mira



H-R Diagram



Red **S**uper **G**iants
$M_{initial}$: 8 - 35 $M_{\odot}$
e.g. Betelgeuse, Antares

Asymptotic **G**iant **B**ranch
$M_{initial}$: 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

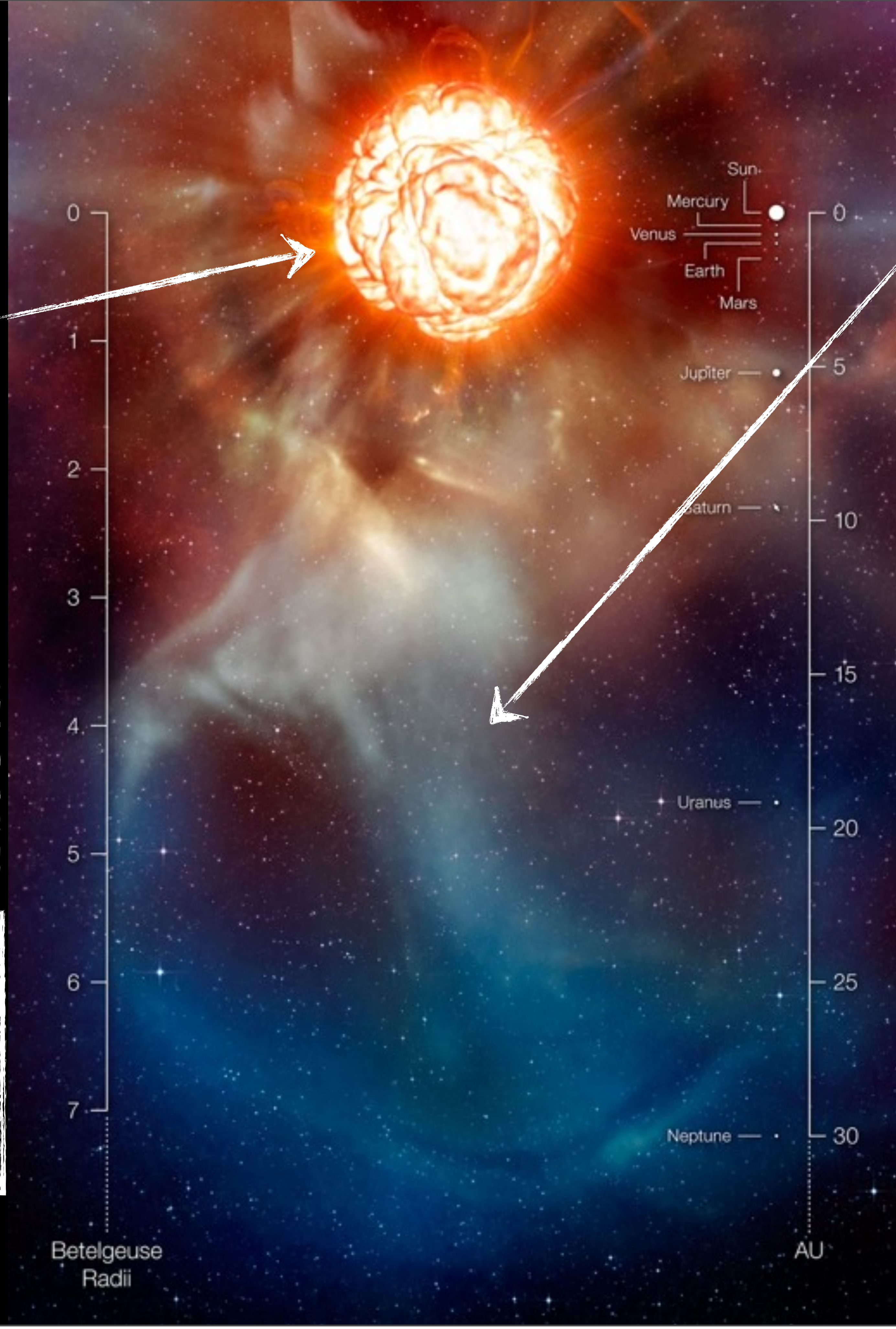
Betelgeuse

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

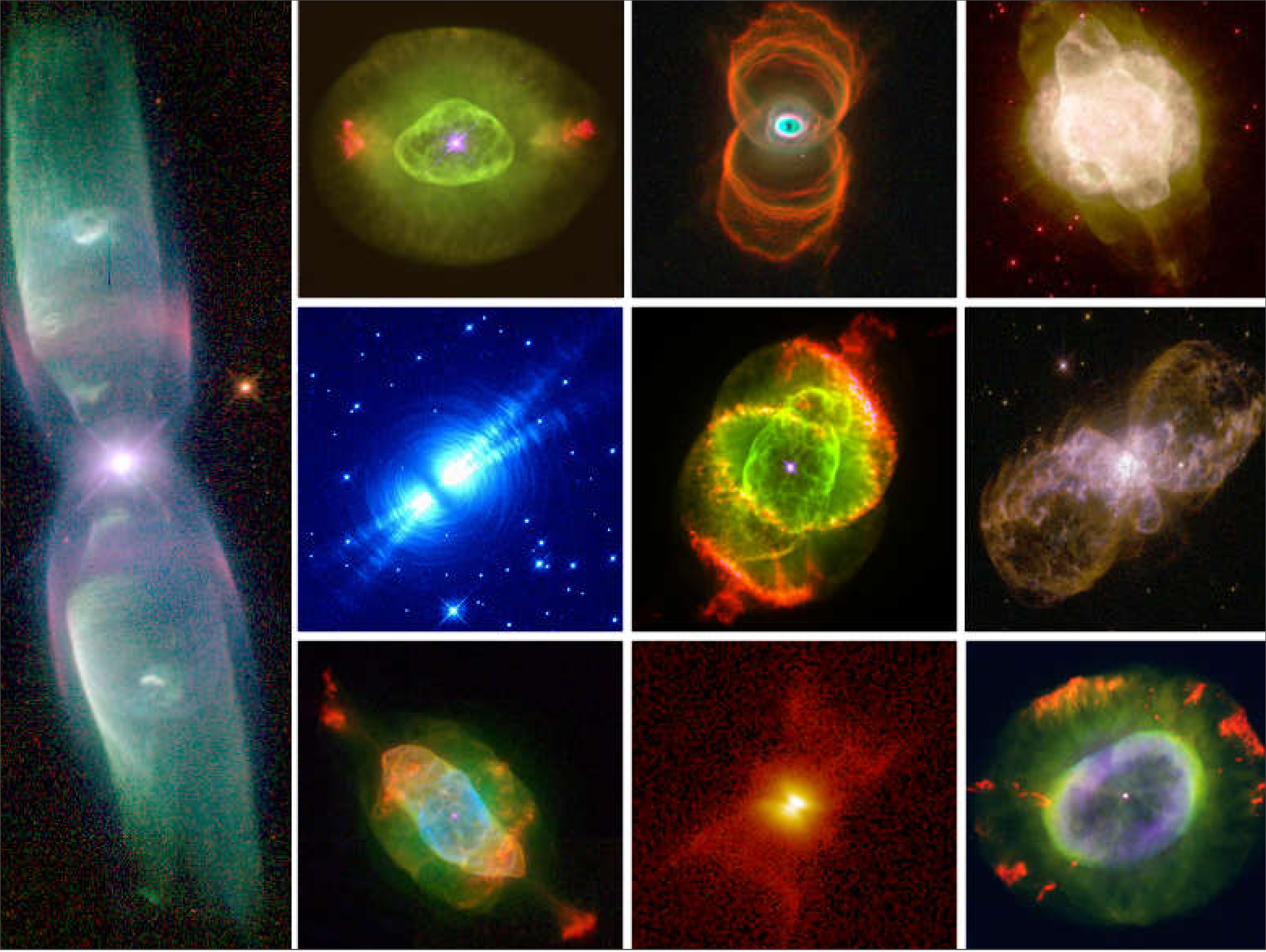
Circumstellar envelope extends much further

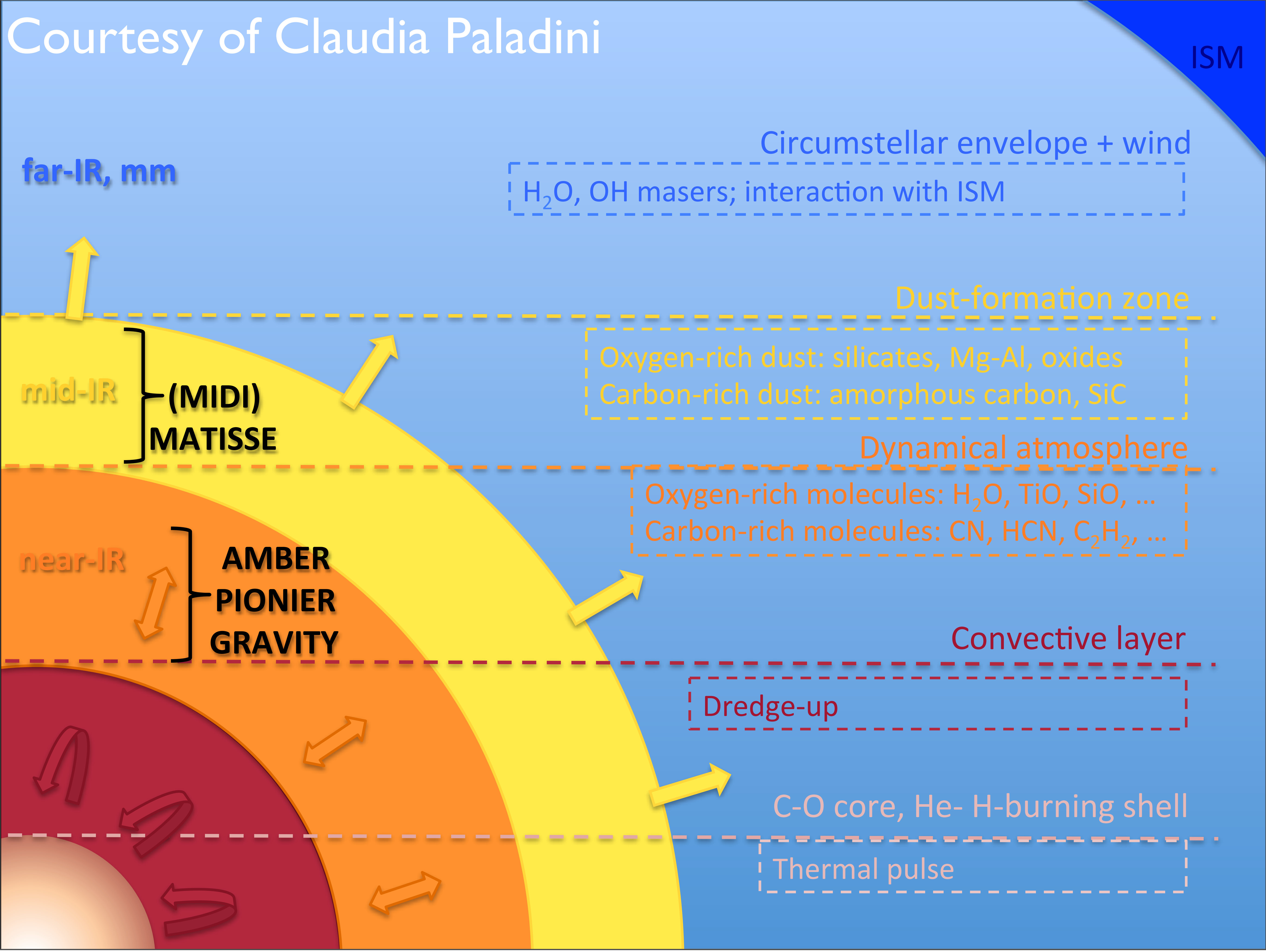
Molecules + Dust

VLT/NACO
Kervella et al. (2009)

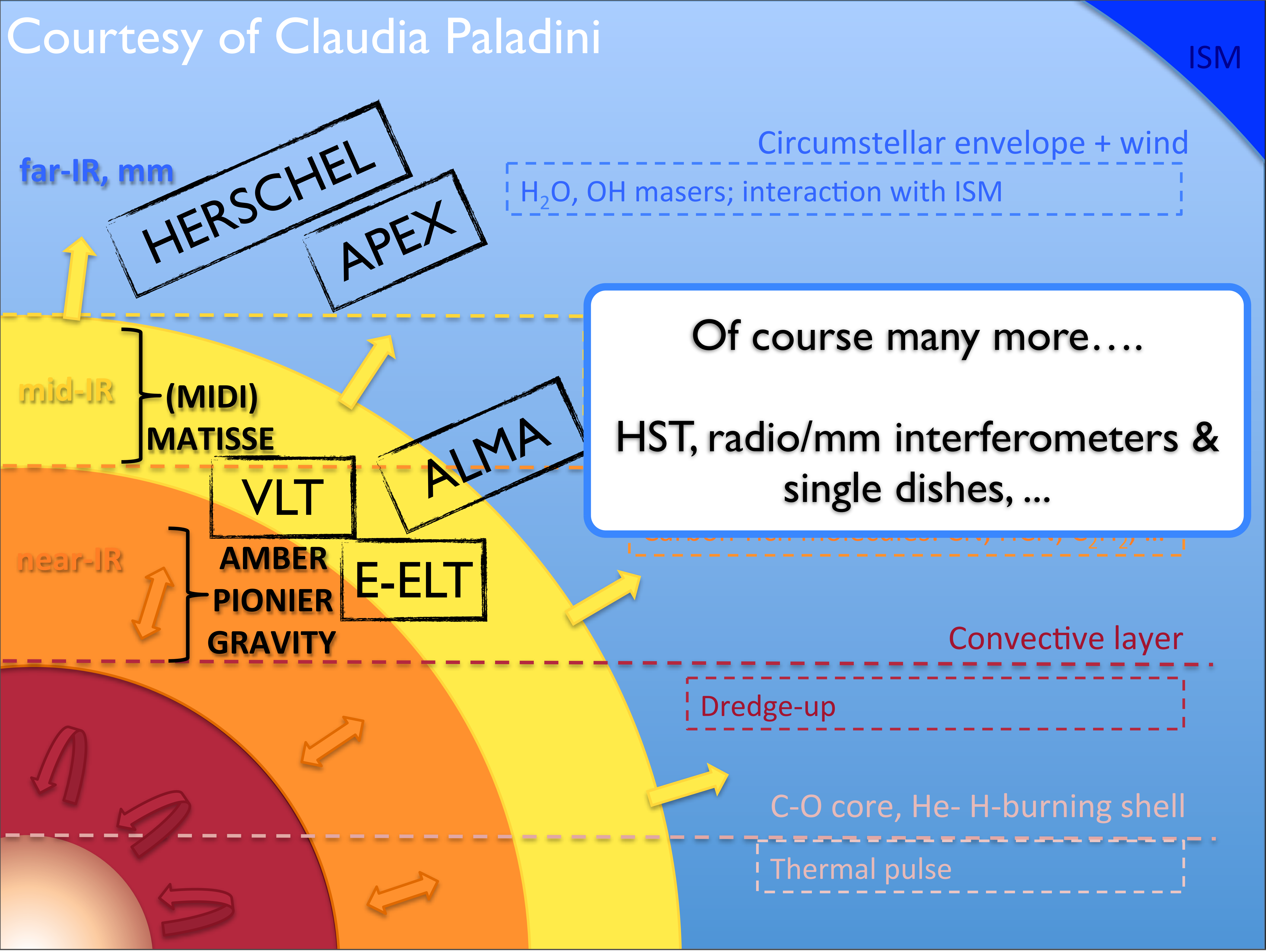
Why?

- Role in stellar evolution
  - Shaping of AGB stars to Planetary Nebulae
  - RSG -> Supernova
- Chemical evolution of galaxies
  - Understanding the mass loss process
- Contribution to the light of stellar populations
  - Effect of metallicity





Courtesy of Claudia Paladini
ISM
Circumstellar envelope + wind
far-IR, mm
H2O, OH masers; interaction with ISM
Dust-formation zone
Oxygen-rich dust: silicates, Mg-Al, oxides
Carbon-rich dust: amorphous carbon, SiC
mid-IR
(MIDI)
MATISSE
Dynamical atmosphere
Oxygen-rich molecules: H2O, TiO, SiO, …
Carbon-rich molecules: CN, HCN, C2H2, …
near-IR
AMBER
PIONIER
GRAVITY
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse


Courtesy of Claudia Paladini
ISM
Circumstellar envelope + wind
H$_2$O, OH masers; interaction with ISM
far-IR, mm
HERSCHEL
APEX
mid-IR
(MIDI)
MATISSE
ALMA
VLT
near-IR
AMBER
PIONIER
GRAVITY
E-ELT
Of course many more….
HST, radio/mm interferometers & single dishes, ...
Convective layer
Dredge-up
C-O core, He- H-burning shell
Thermal pulse

I. Stellar Surface & Dynamical Atmosphere

II. Dust Formation Zone & Dust

III. Outer Wind & ISM Interaction

IV. Chemistry

V. Binarity

V1. Magnetic Fields

VII. Metallicity & Extragalactic

I. Stellar Surface & Dynamical Atmosphere

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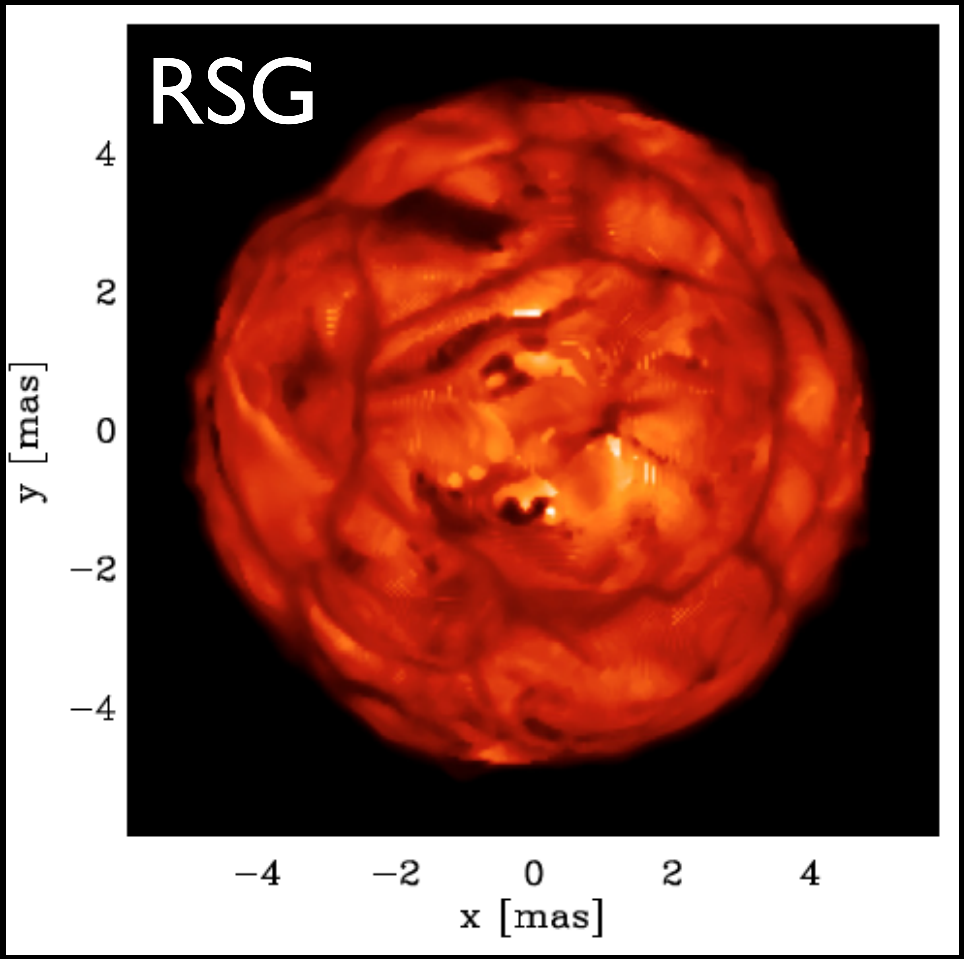
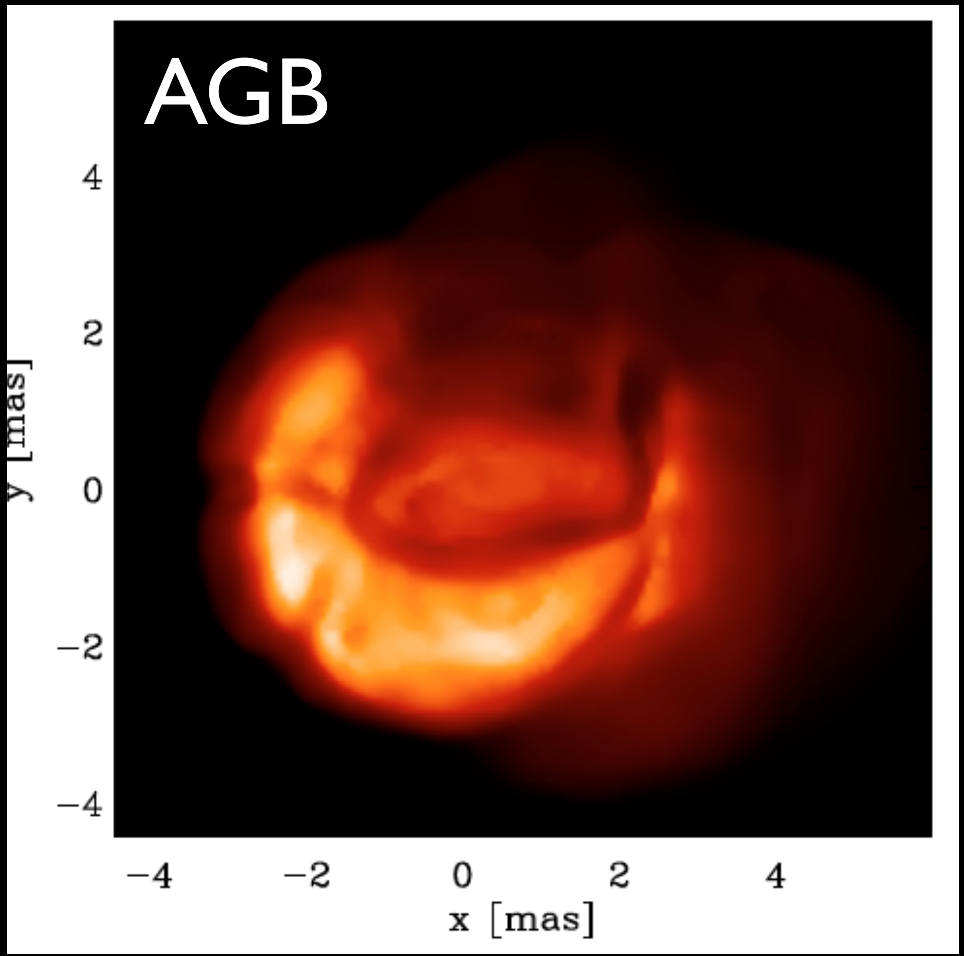




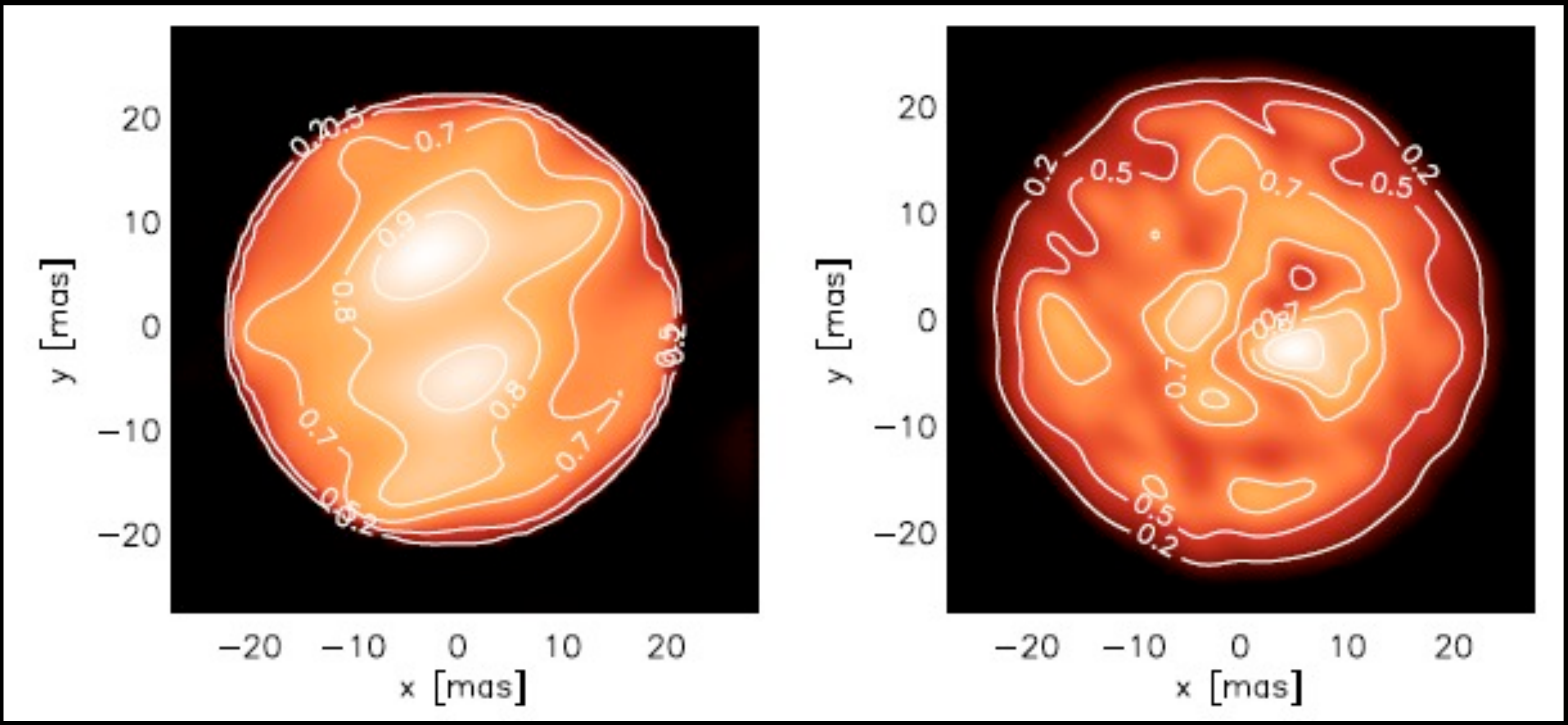
Surface Convection Simulations

- Surface of RSGs covered by a few convective cells with a size of ~60 % of stellar surface
- Evolve on timescales of years
- Visible in the infrared, particularly in the H-band
- In the optical, short-lived (weeks to months) structures, small-scale (<10 % of stellar radius)

Freytag & Hoefner 2008; Chiavassa et al. 2013

Betelgeuse

Observations | Simulations

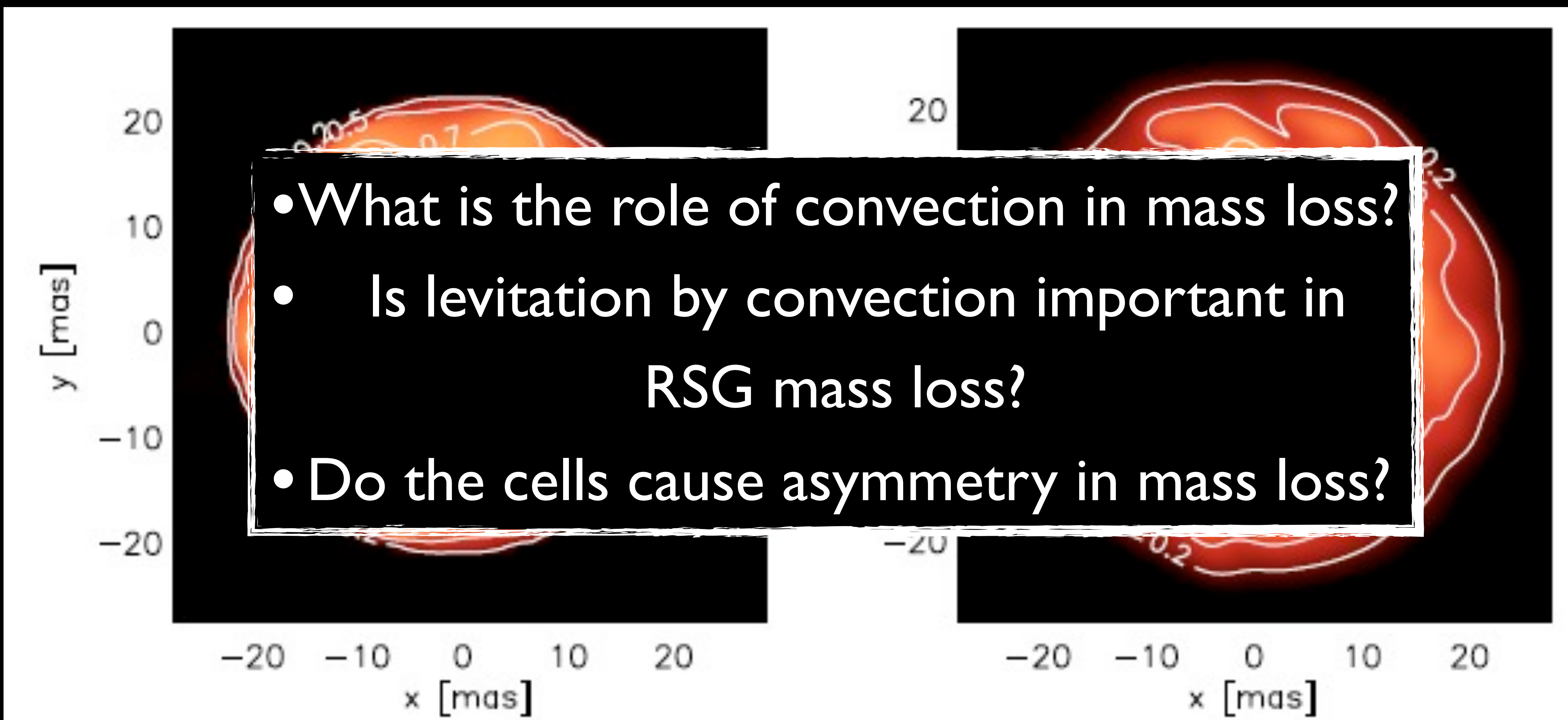


IOTA H-band, Haubois et al. 2009, Chiavassa et al. 2010

Betelgeuse

Observations

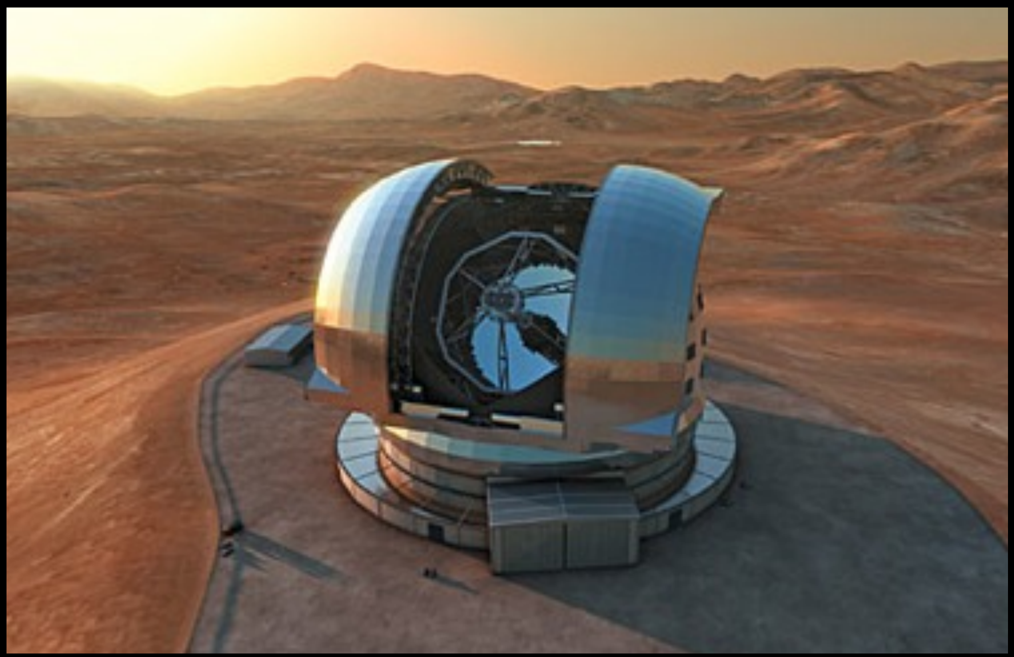
Simulations



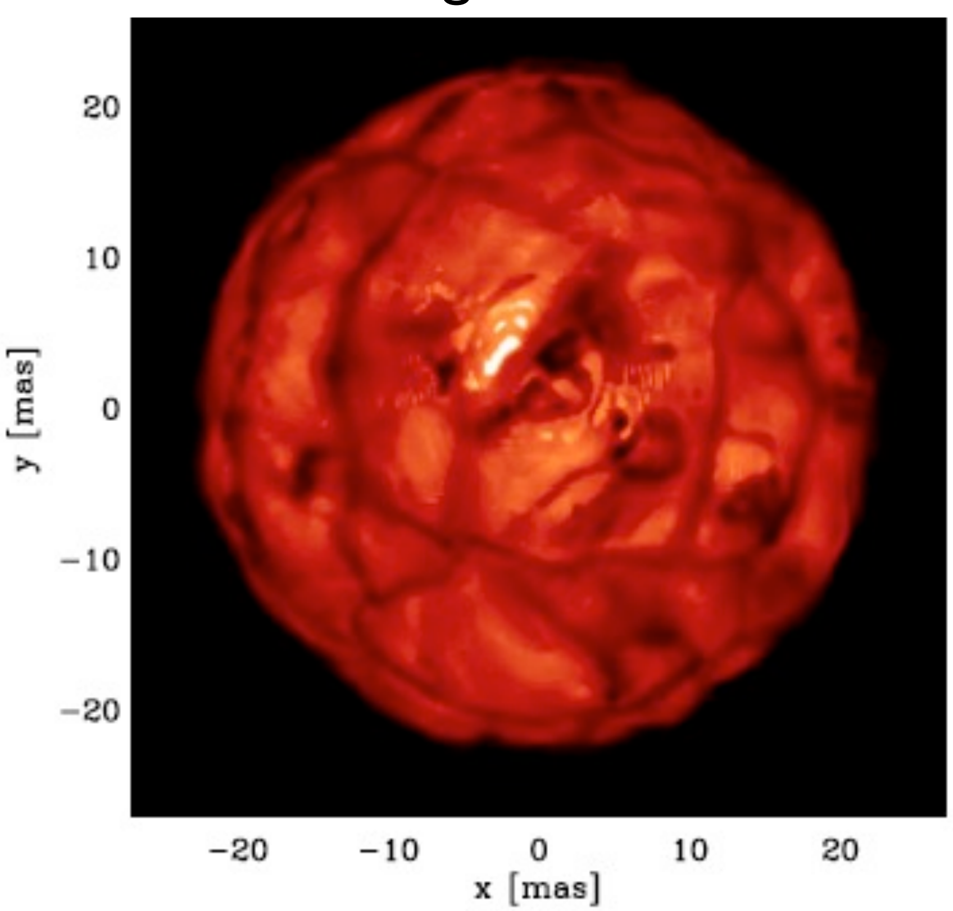
- What is the role of convection in mass loss?
- Is levitation by convection important in RSG mass loss?
- Do the cells cause asymmetry in mass loss?

IOTA H-band, Haubois et al. 2009, Chiavassa et al. 2010

Study with optical/IR interferometry & E-ELT



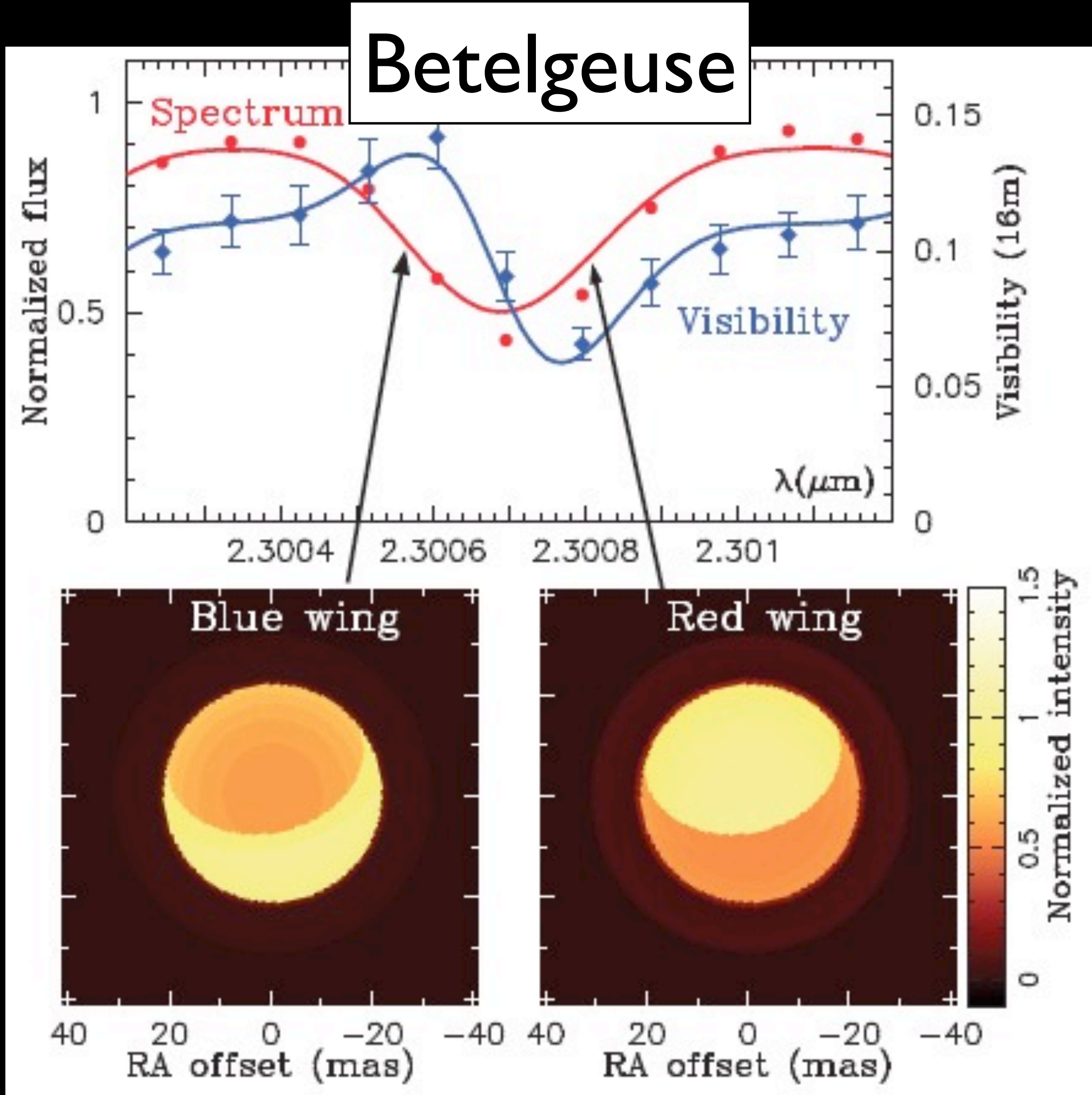
H-band Betelgeuse Simulations

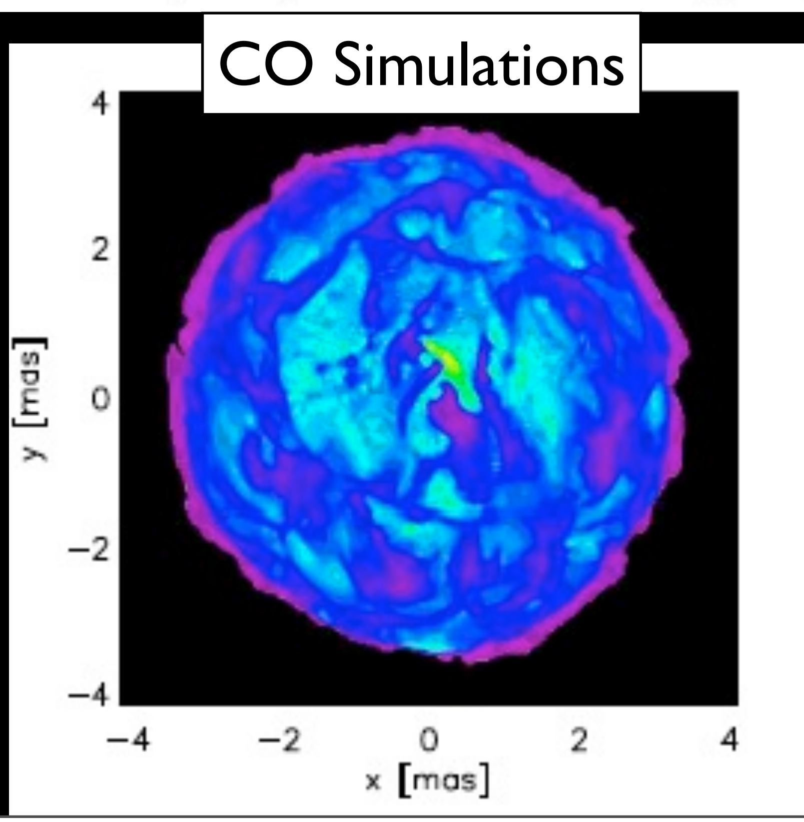


Stars	Size at 2.3 micron
Betelgeuse (RSG)	43 mas
R Dor (AGB)	47 mas
Antares (RSG)	37 mas

E-ELT H-band PSF: 9 mas

Chiavassa, Freytag & Plez (2013)



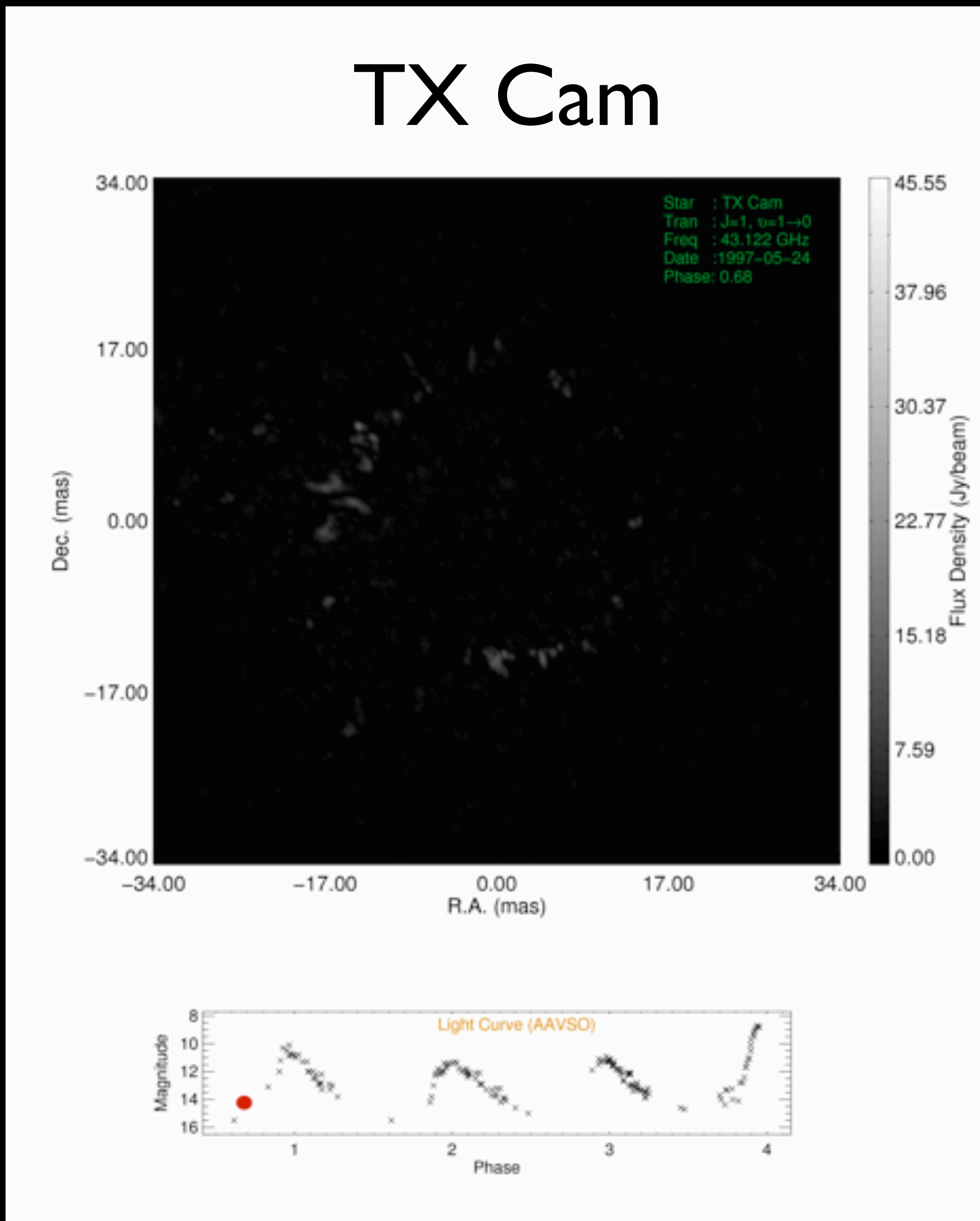


CO Motions in the Dynamical Atmosphere

- CO first overtone red and blue wings from different regions of stellar disk
- Patch of CO gas moving outward/inward at 10-15 km/s
- CO gas in remaining region moving in the opposite direction at same velocities
- Emission from ~1.5 R*, likely related to convective surface

VLTI/AMBER Ohnaka et al. 2009; Arroyo-Torres et al. 2015

SiO Masers in the Extended Dynamical Atmosphere



- SiO masers typically~2 - 4 R*
- Multi-epoch observations of TX Cam trace outflow at 7 km/s, infall, complex motions
- Use to derive B-field, physical conditions (T~1500 K; n(H_2)~ 10^9 cm^{-3})
- Throughout the ALMA Bands
- Targets for mmVLBI with phased ALMA

Gonidakis et al. 2013; VLBA 43 GHz

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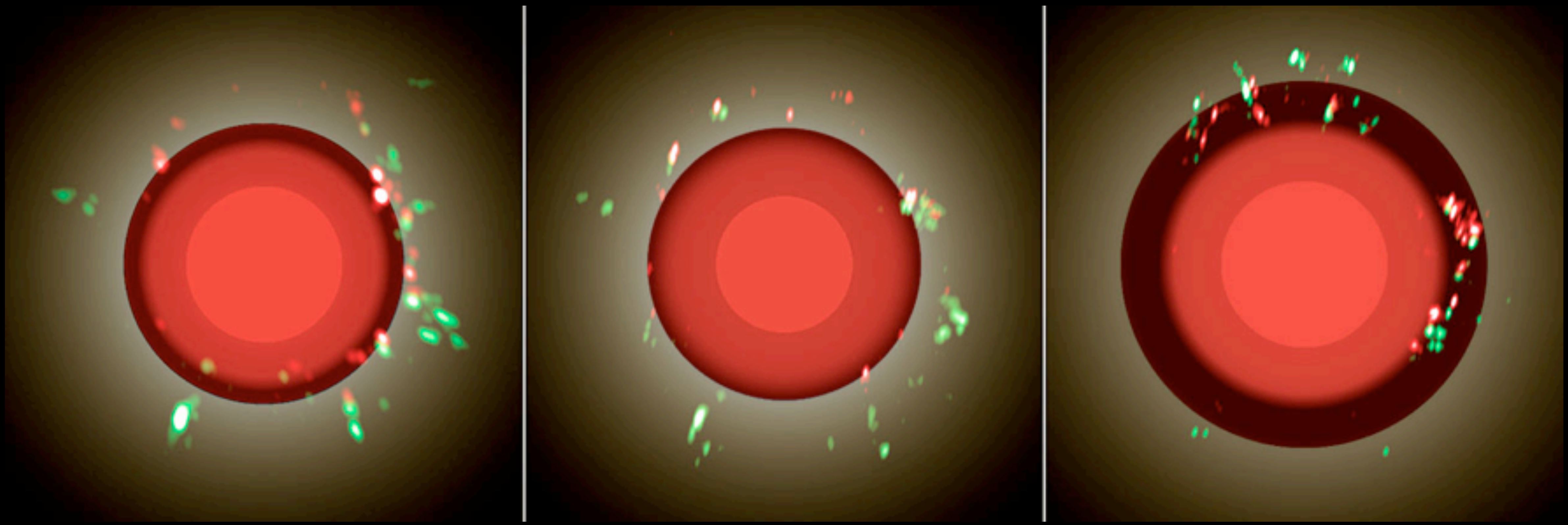
VII. Metallicity & Extragalactic

Dust Formation

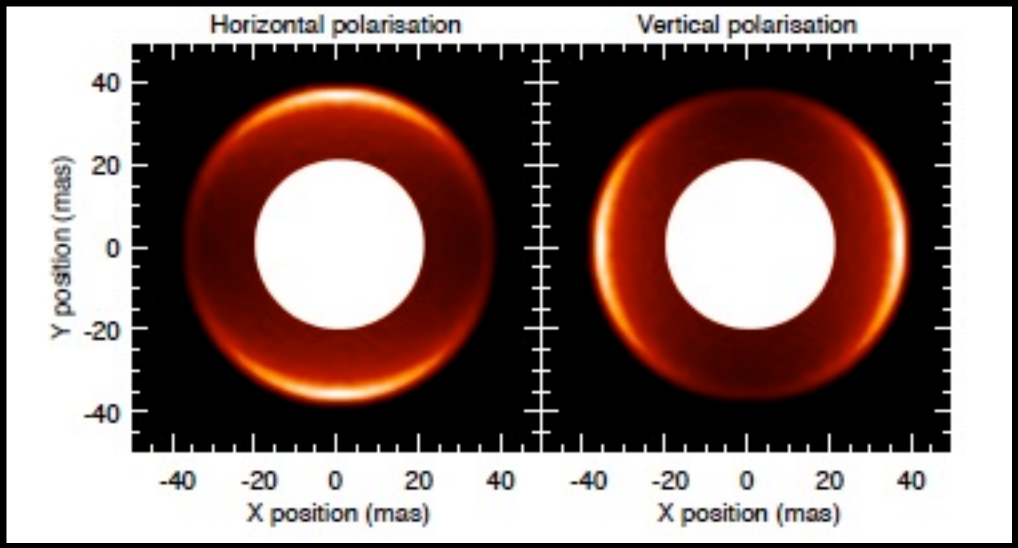
- How does dust form in O-rich stars?
  - Gas phase chemistry & nucleation
- Dust condensation, size, composition
  - Al_2O_3, forsterite, pyroxine, olivine
- Role of dust in mass loss
- All as a function of metallicity….

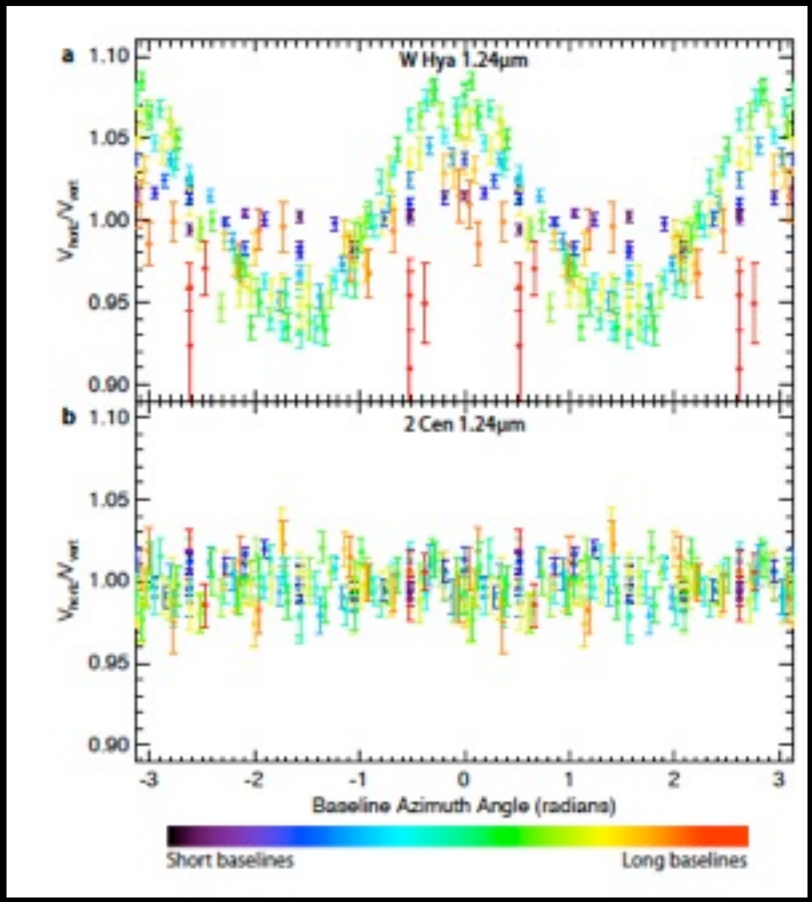


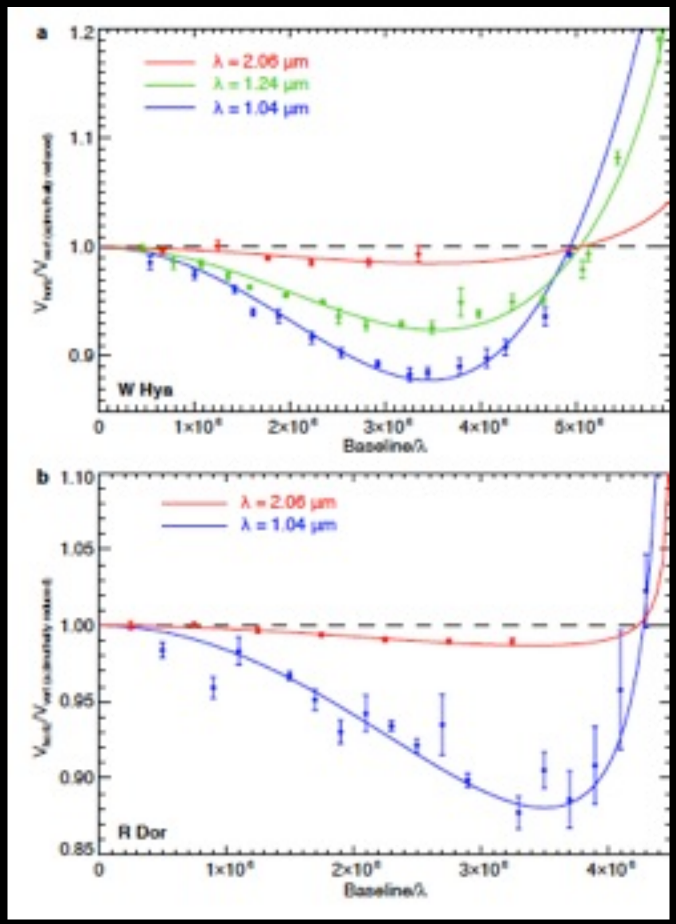
Wittkowski et al. (2007) VLTI/MIDI; Karovicova et al. (2013)

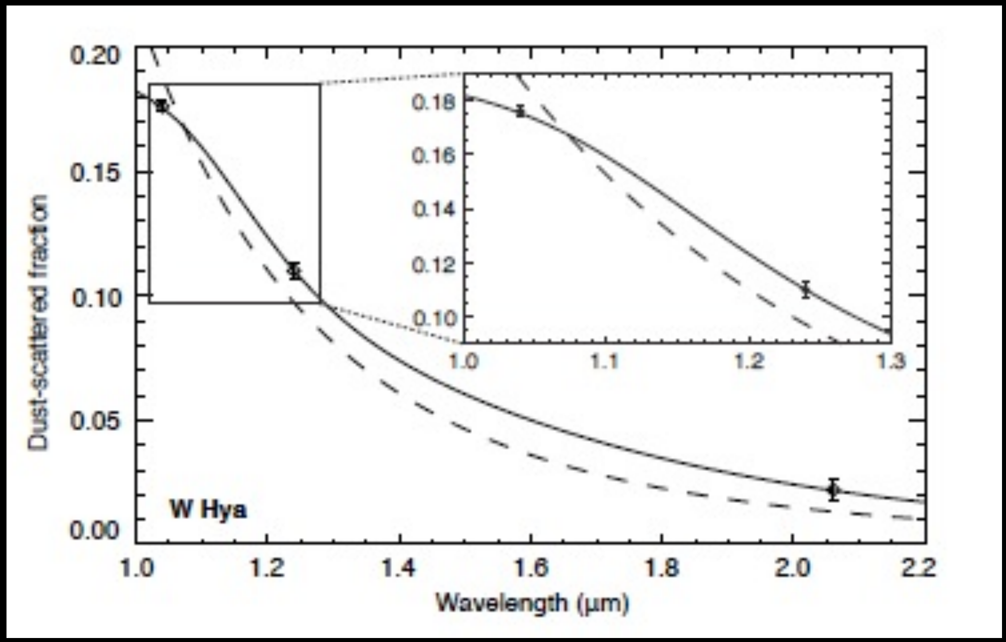
Large, transparent grains around the star

Aperture-masked, polarimetric IR interferometry: VLT/NACO
10 mas spatial scales



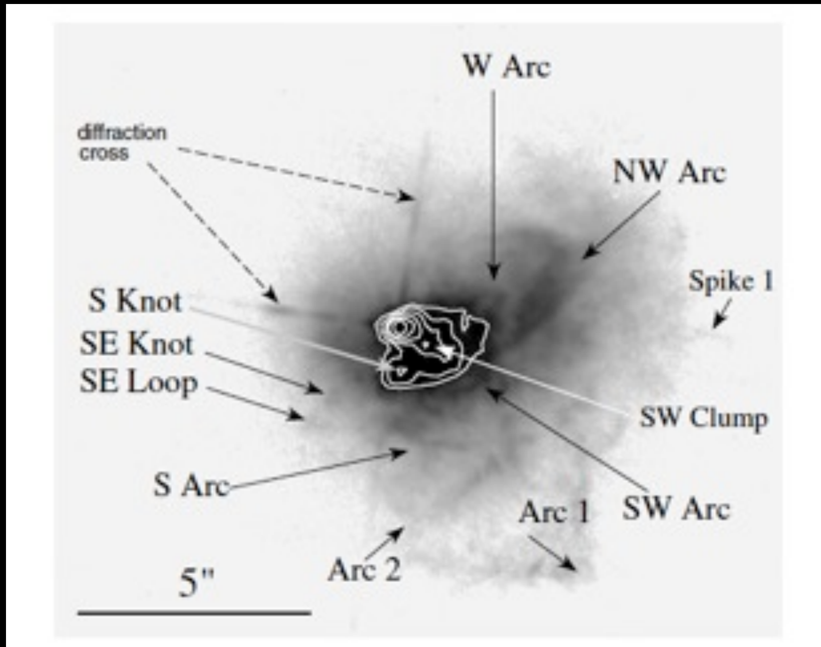






Norris et al. (2012)

Wind acceleration: H_2O Masers

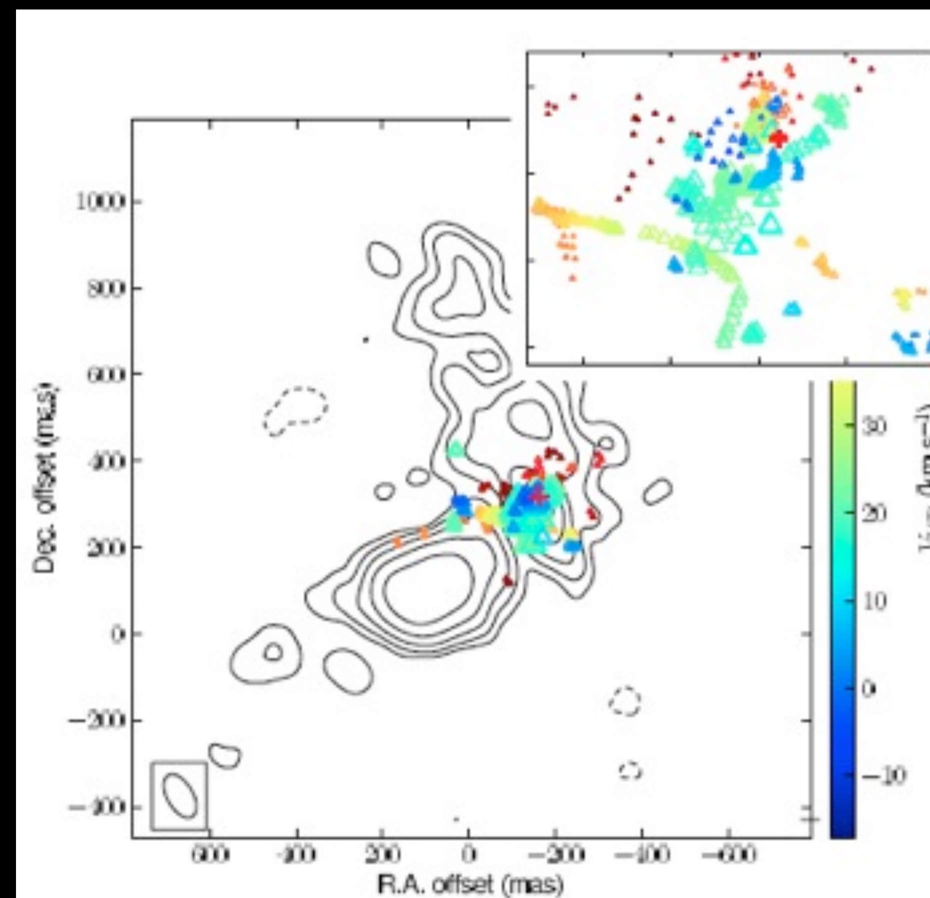


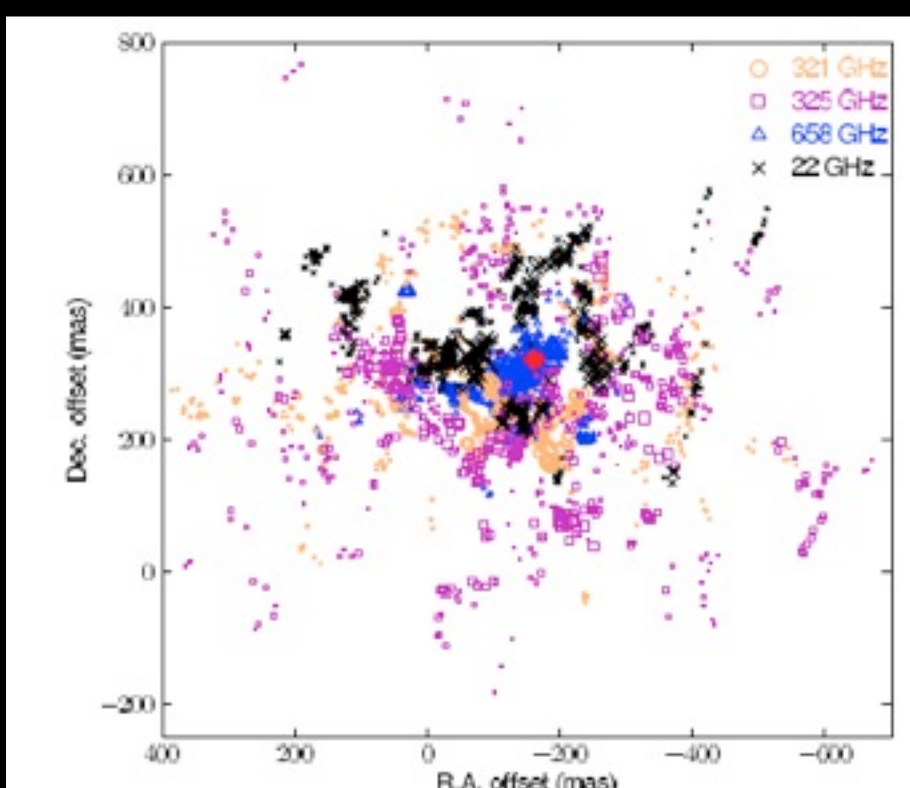
VY CMa (RSG)

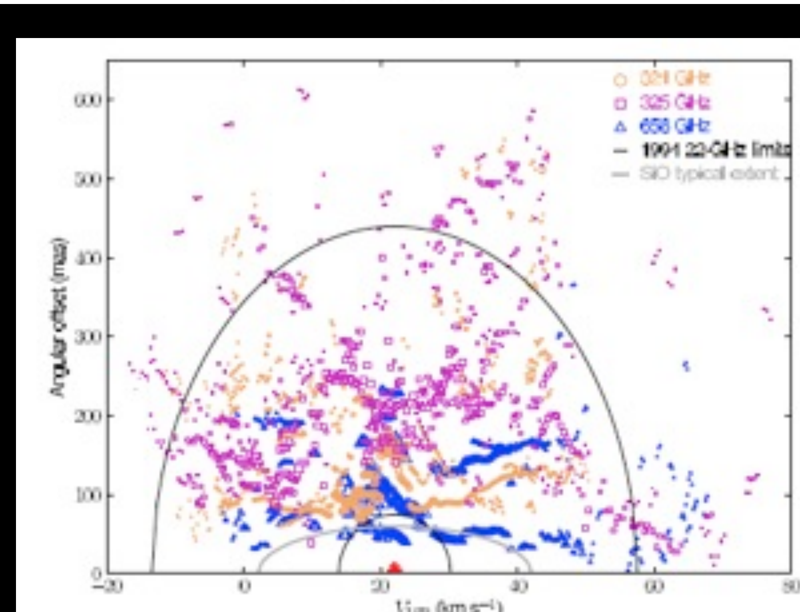
Richards et al. (2014)

ALMA 2.7 km baseline, 0.1 to 0.2”

Relative position uncertainties B9 maser spots: << 0.1”





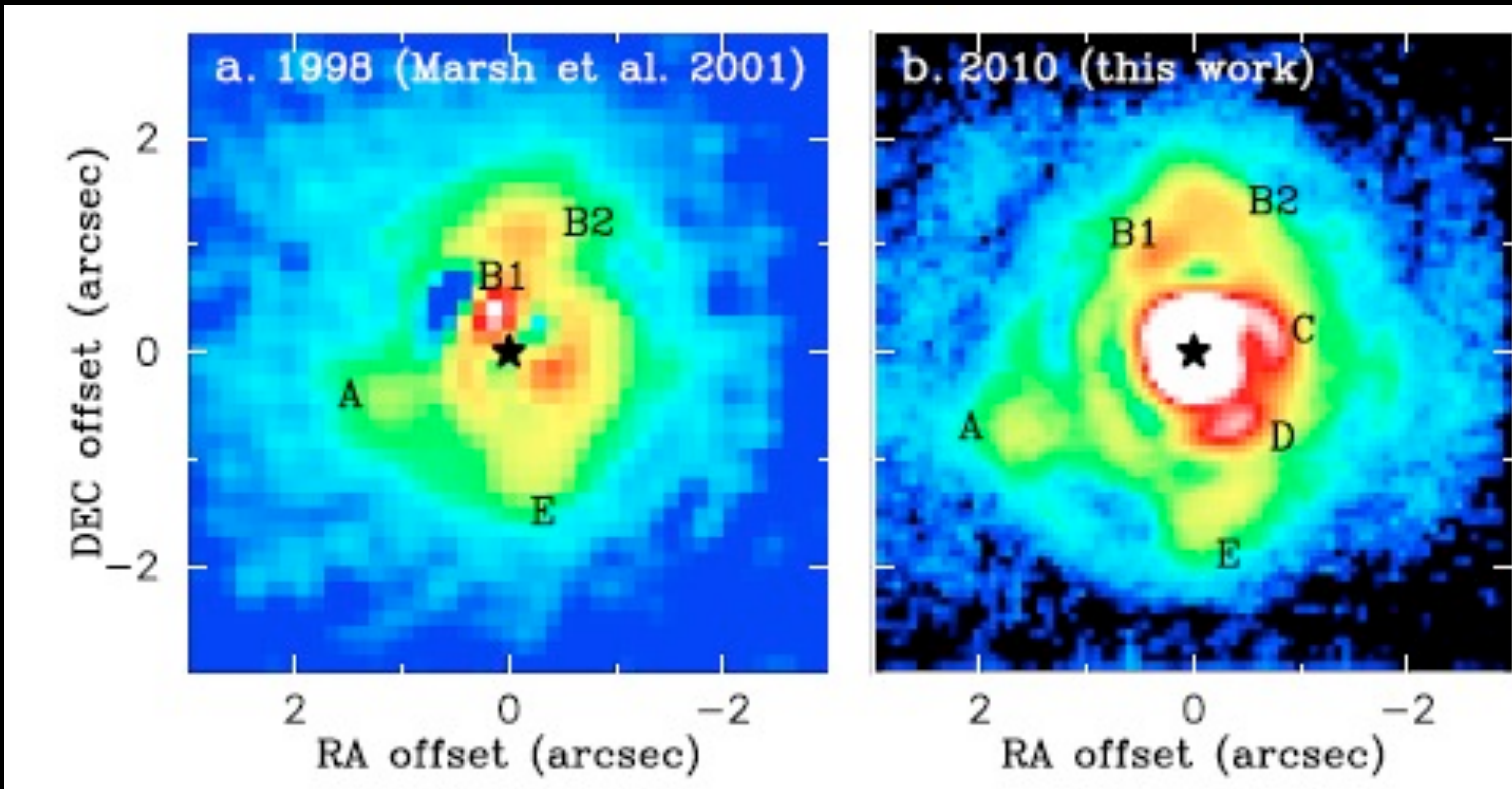


H_2O masers straddle the dust formation zone

Proper motions, physical conditions, B-field

Throughout the ALMA Bands

Clumpy Dust Motions

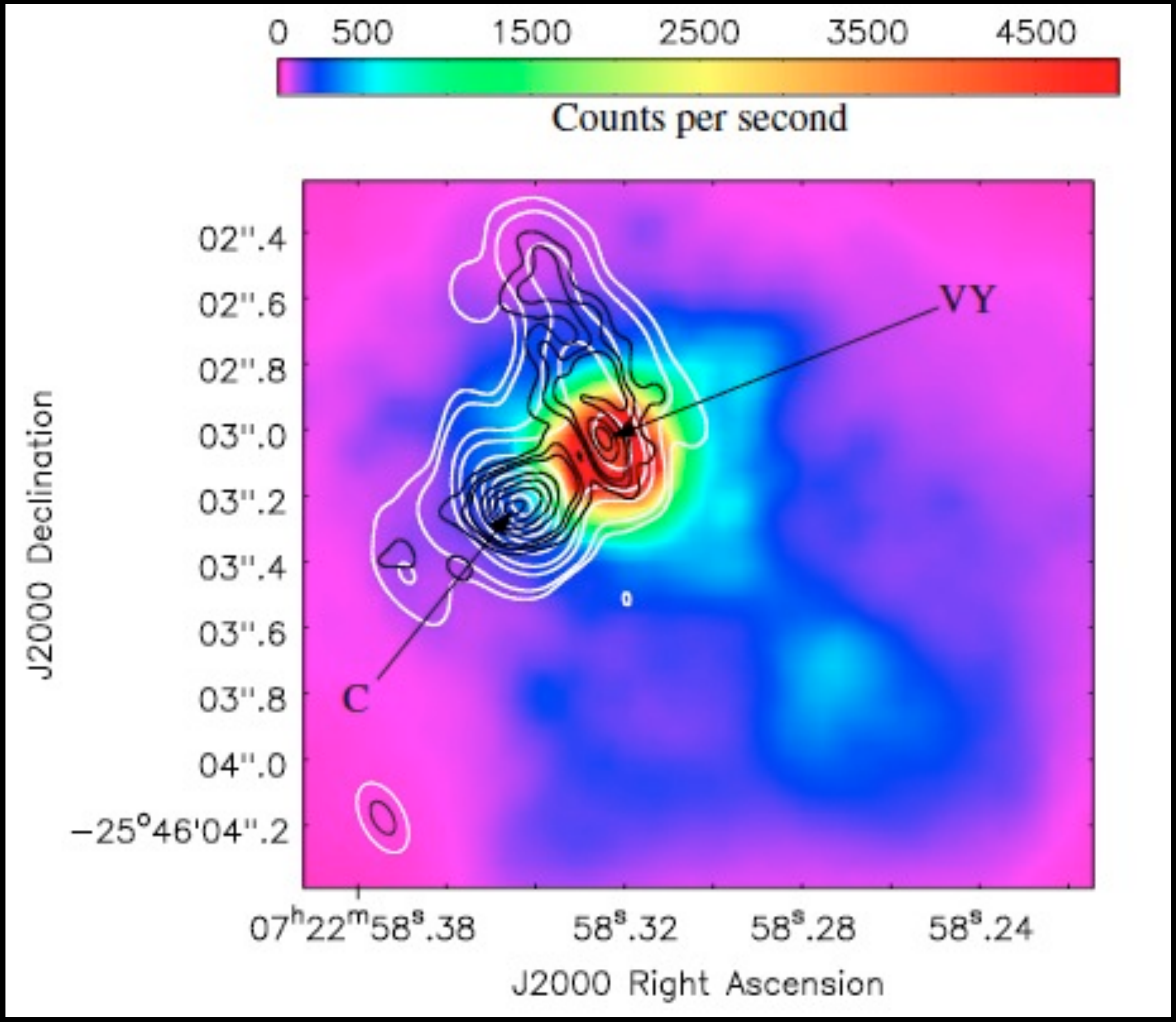


6 clumpy dust clouds at 43 - 96 R*
Derived expansion velocity ~ 34 km/s

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

Dust Asymmetries, Blob(s)

VY CMa (RSG)



Asymmetric dust in "preferred" directions

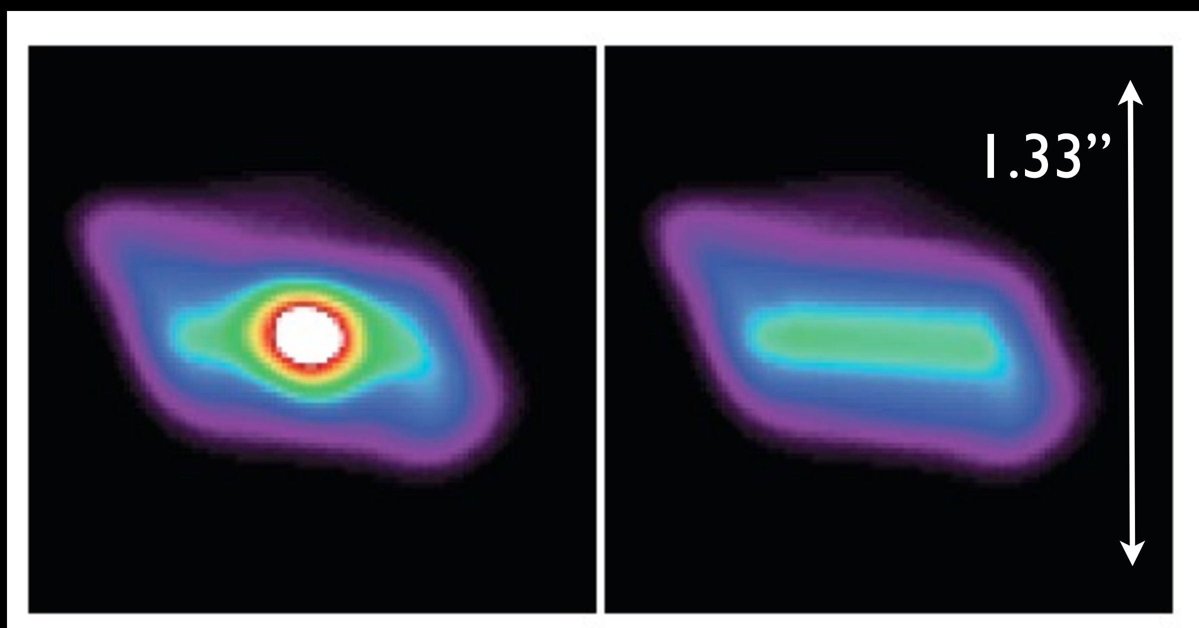
Long-lived compared with convection cell timescale, sign of B-field?

Dust emission not strongest over stellar position

O'Gormann et al. (2015); ALMA continuum, 345 & 690 GHz Bands

Many new results on structures & asymmetry (dust and molecules) in dynamical atmosphere, dust formation zone & further out….

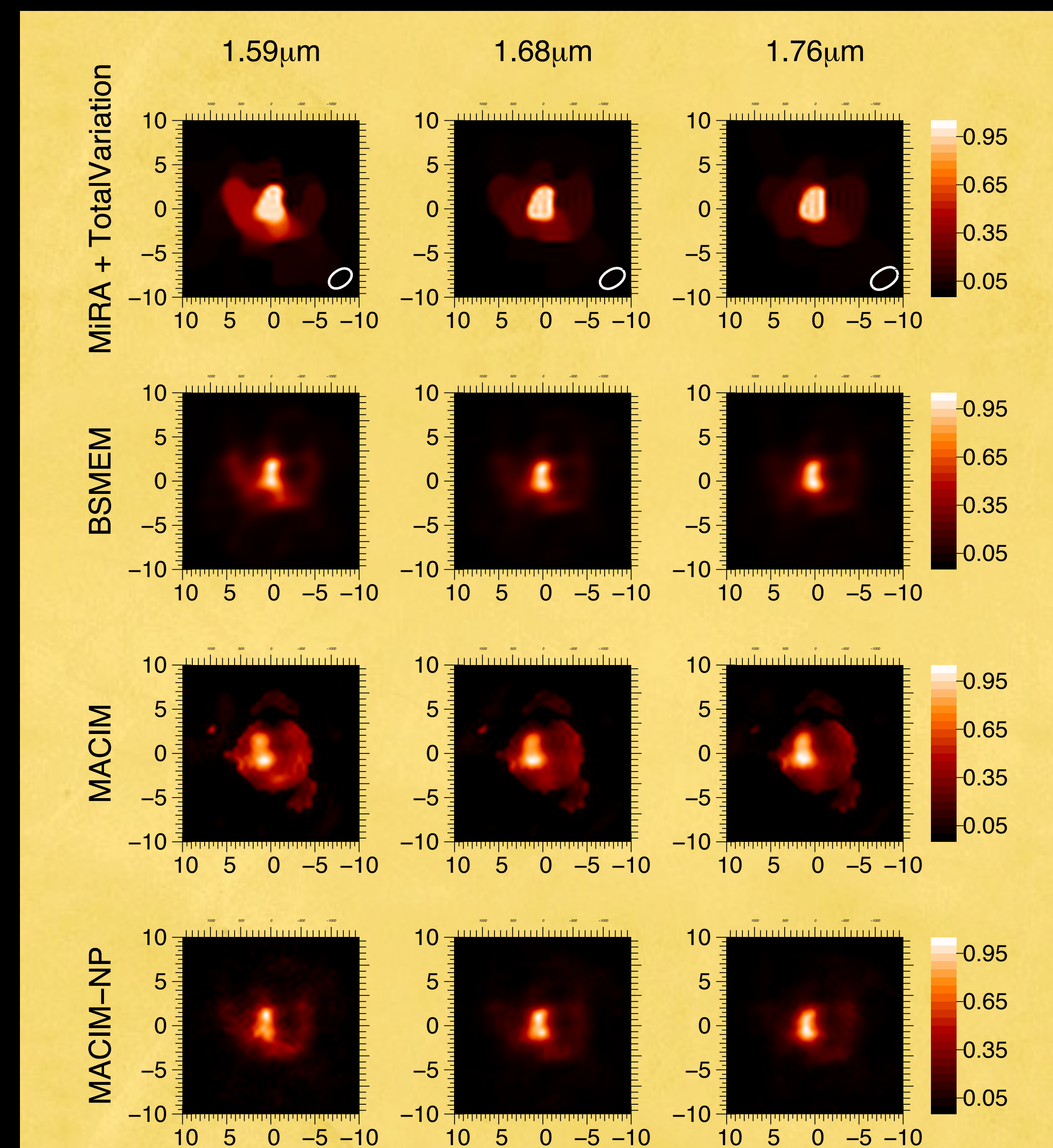
VLT/NACO



L2 Pup (AGB) Disk
Kervella et al. (2014)

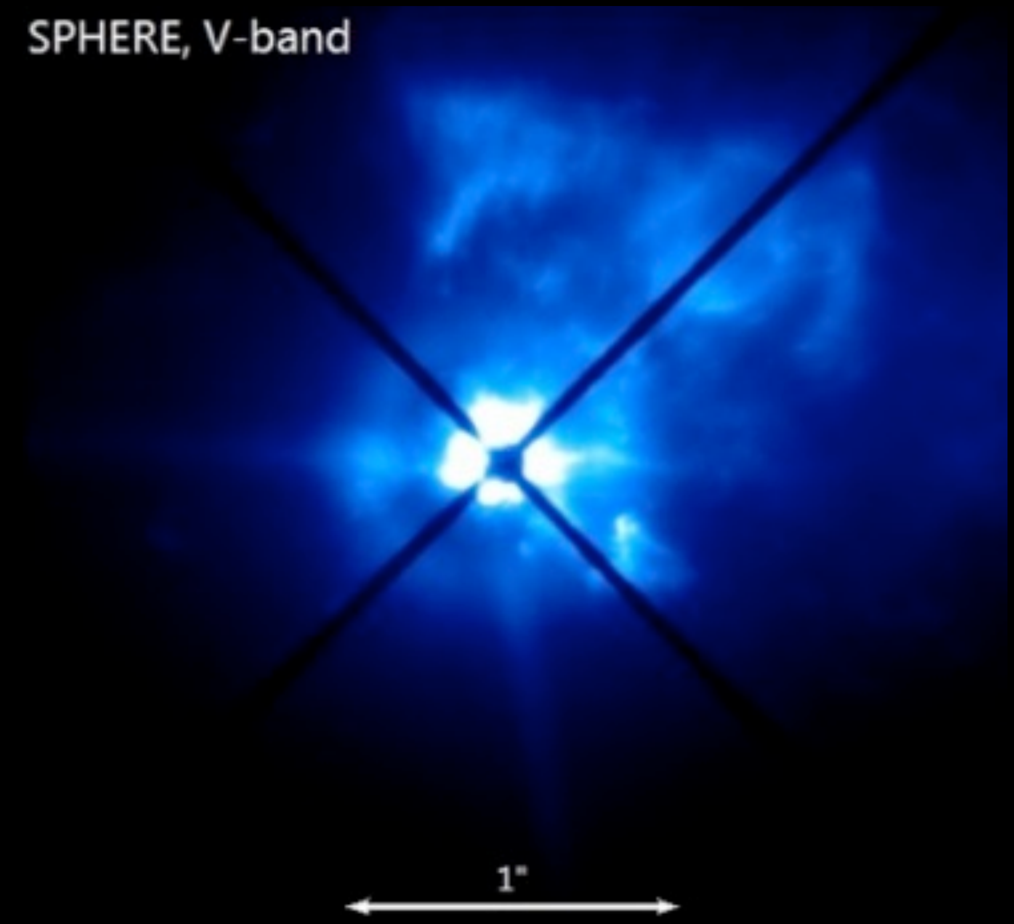
Timescales of the features need to be studied

VLTI PIONIER

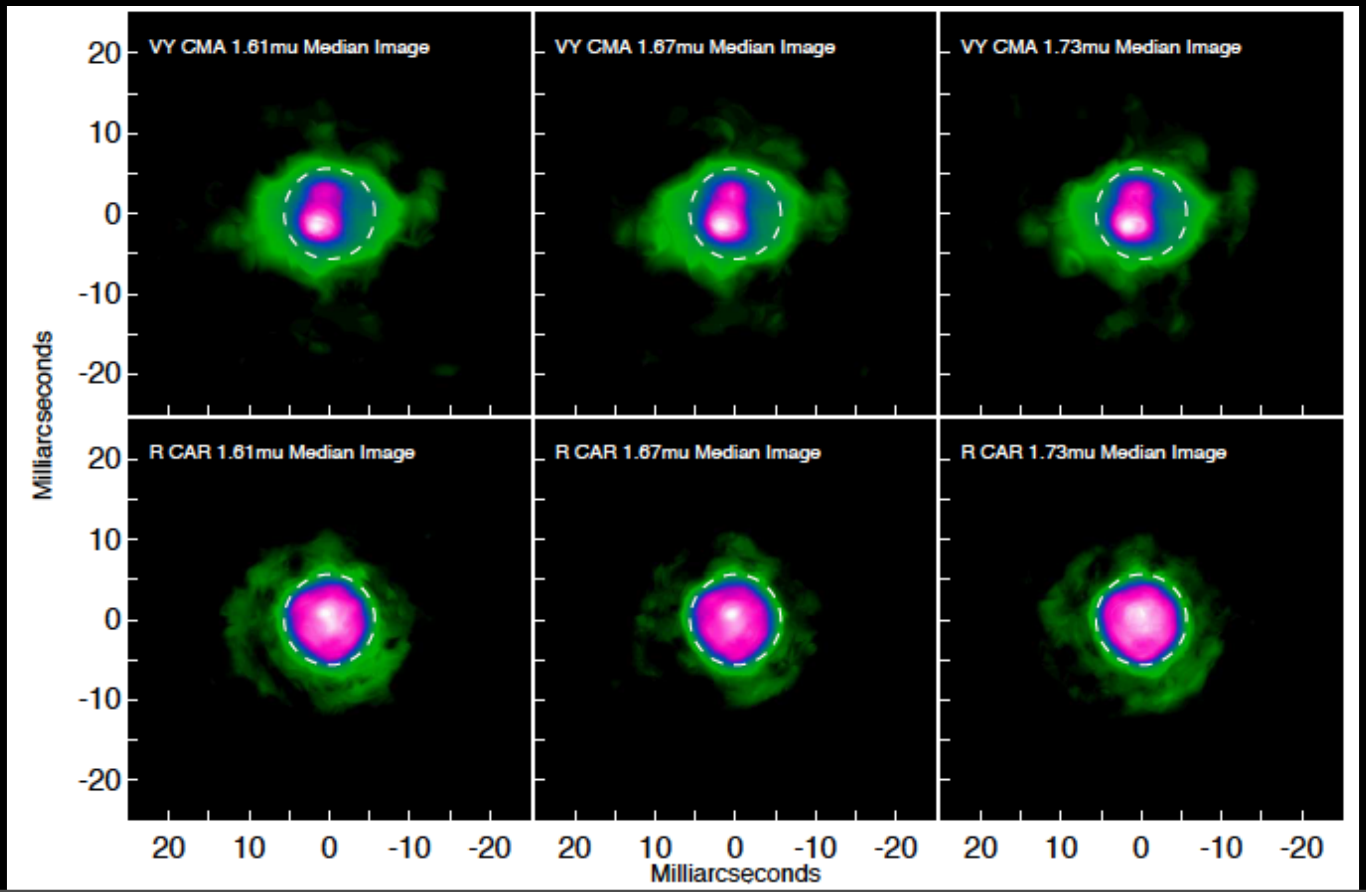


R For (C-rich AGB); Paladini et al. in prep

VY CMa VLT/SPHERE Commissioning Data



Siebenmorgen, Vlemmings



VLTI/PIONIER
Imaging Contest
Wittkowski, Monnier
10 teams

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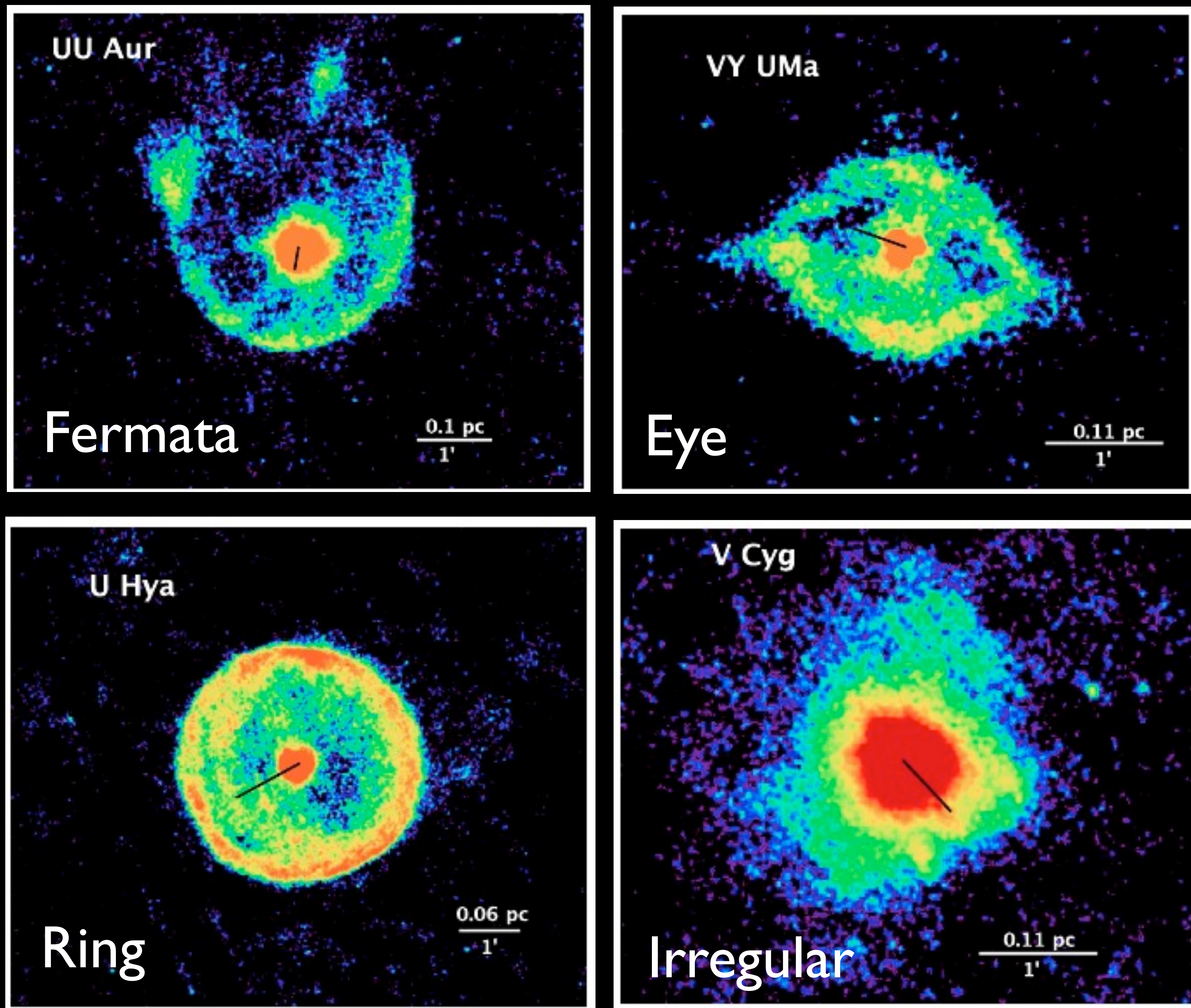
Circumstellar Envelope - ISM Interaction

Cox et al. 2012; Herschel PACS 70 micron

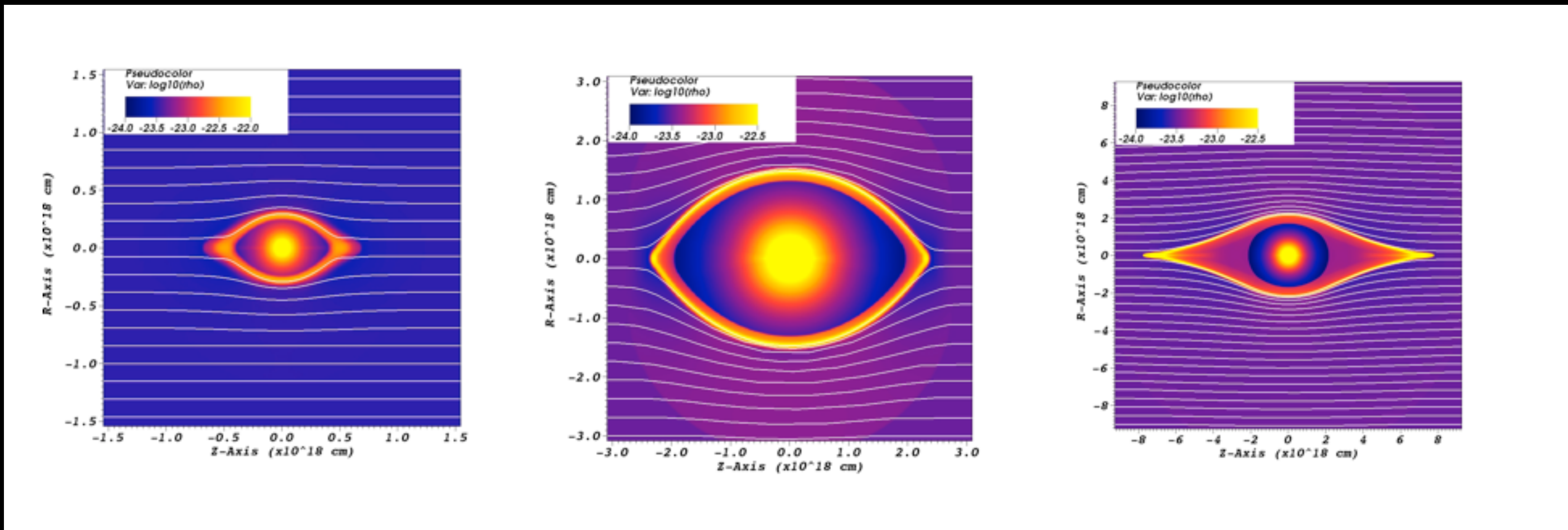
Bow shocks

Galactic B Field

Thermal Pulses



Eye Formation



- Galactic magnetic fields of 5 to 10 microgauss
- Eye structures are transient
- An explosion of a Planetary Nebula at the centre forms asymmetric nebula

van Marle et al. (2014)

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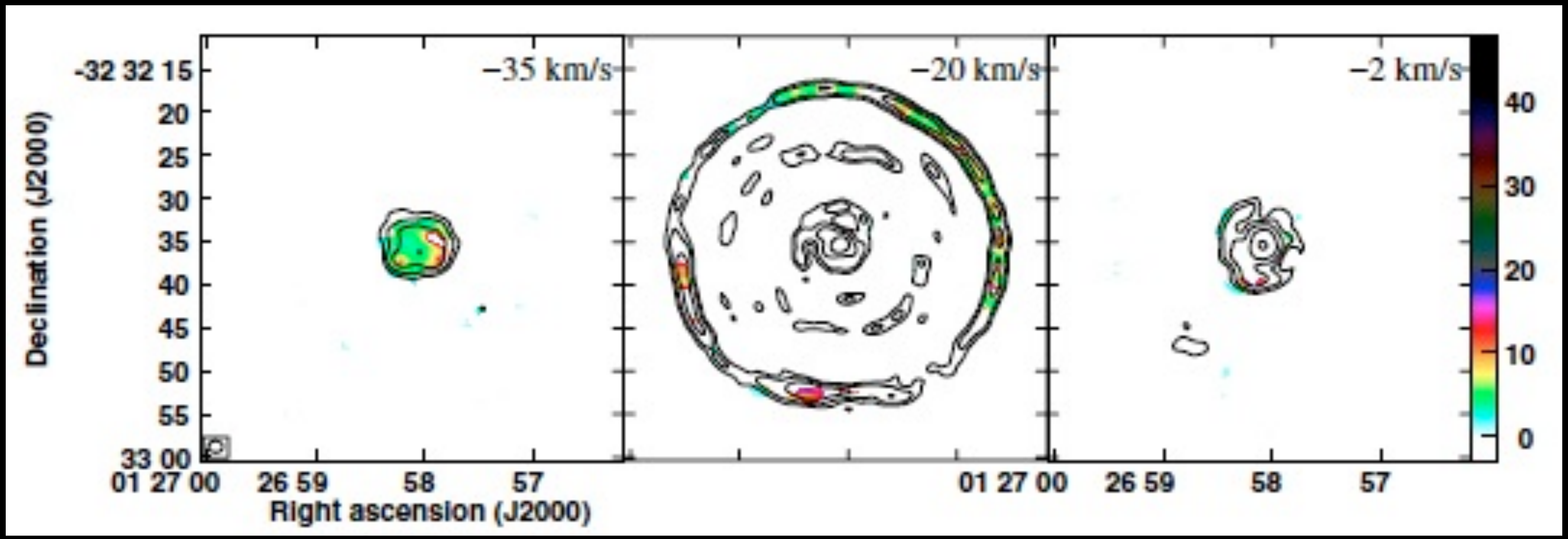
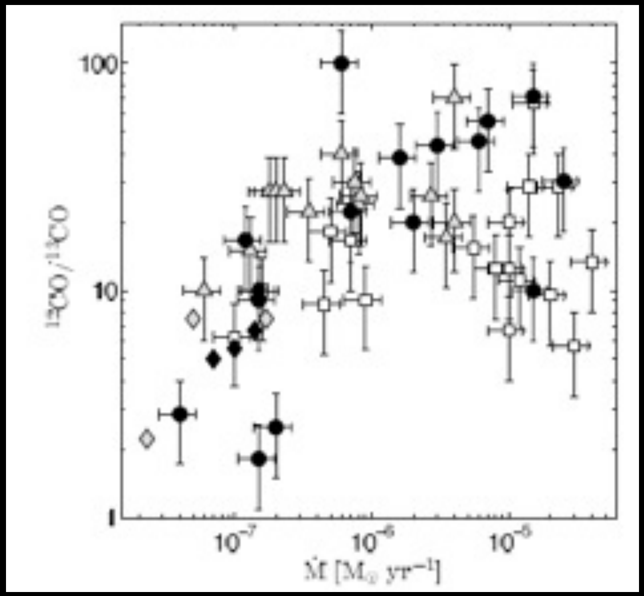
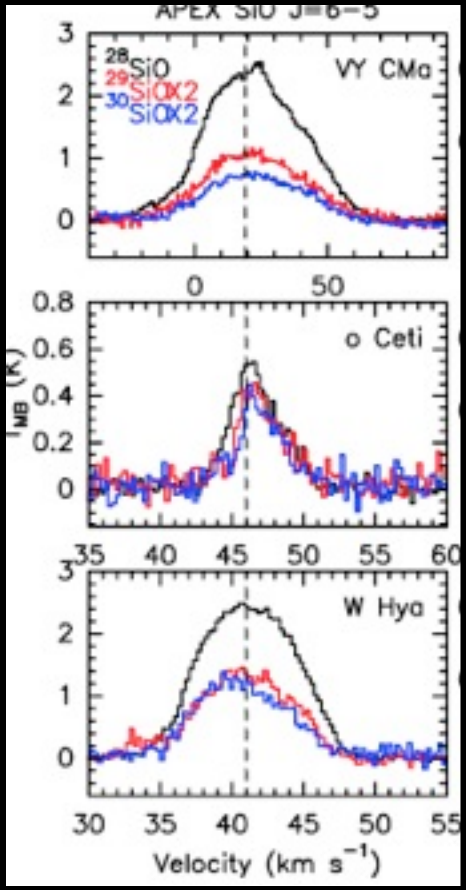
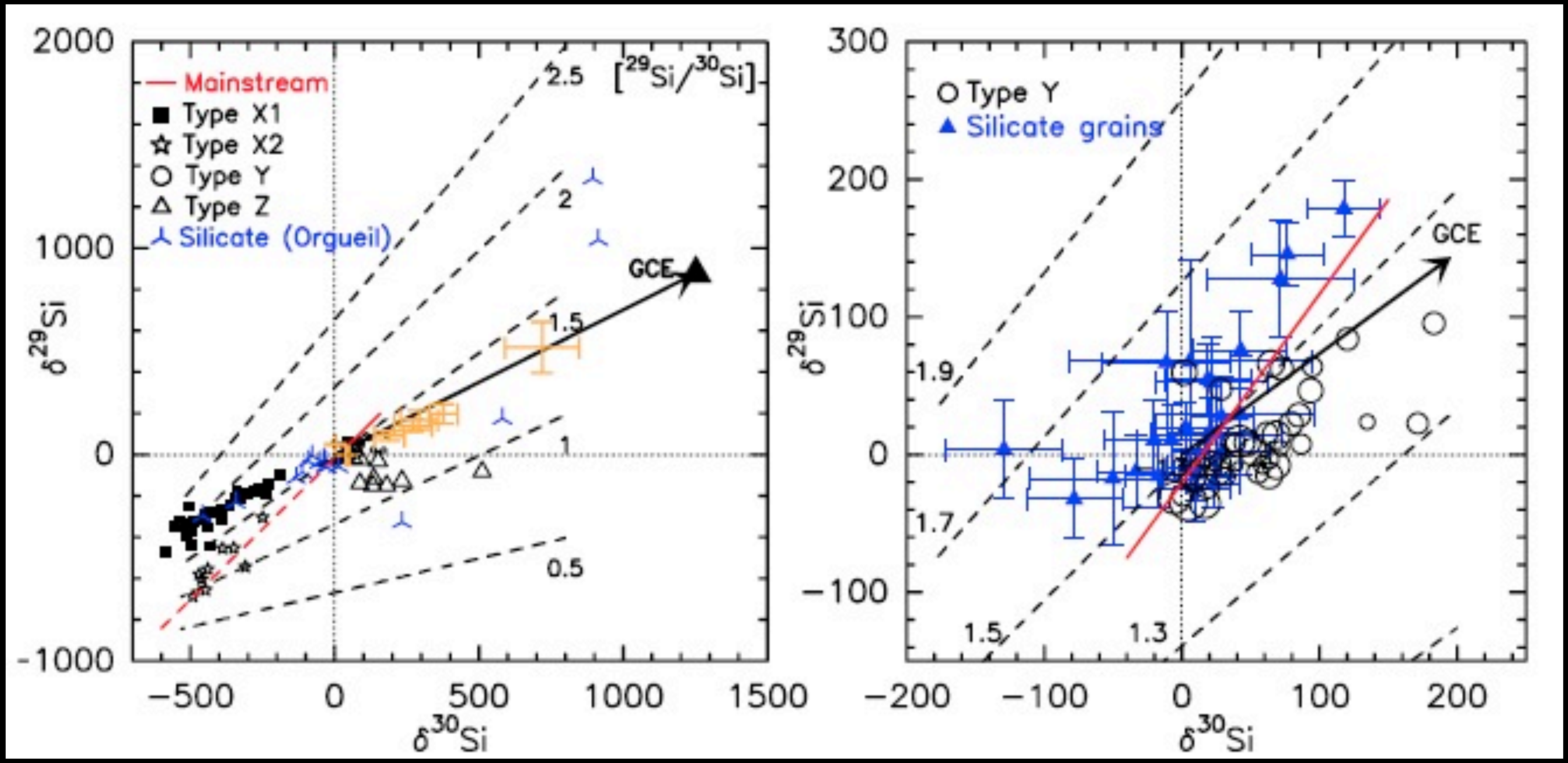
Nucleosynthesis & Isotopes

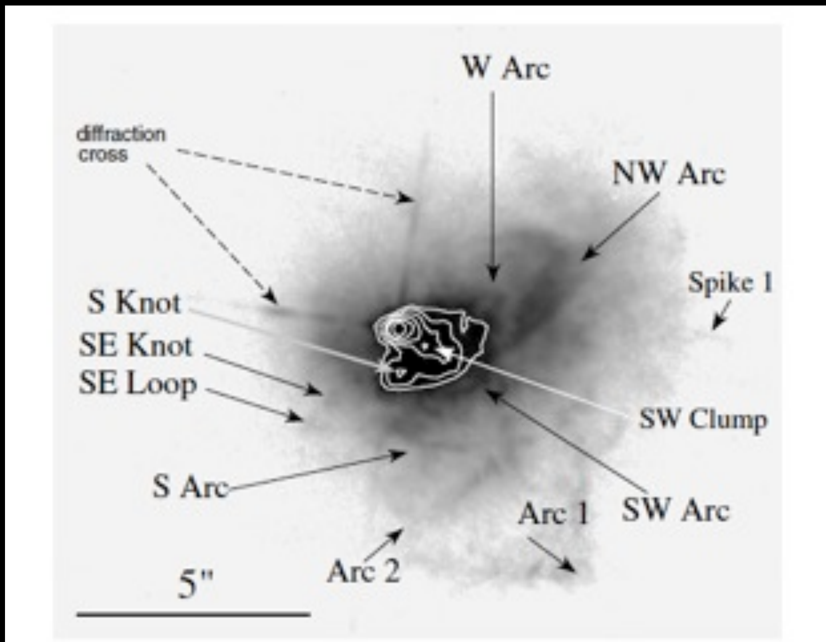








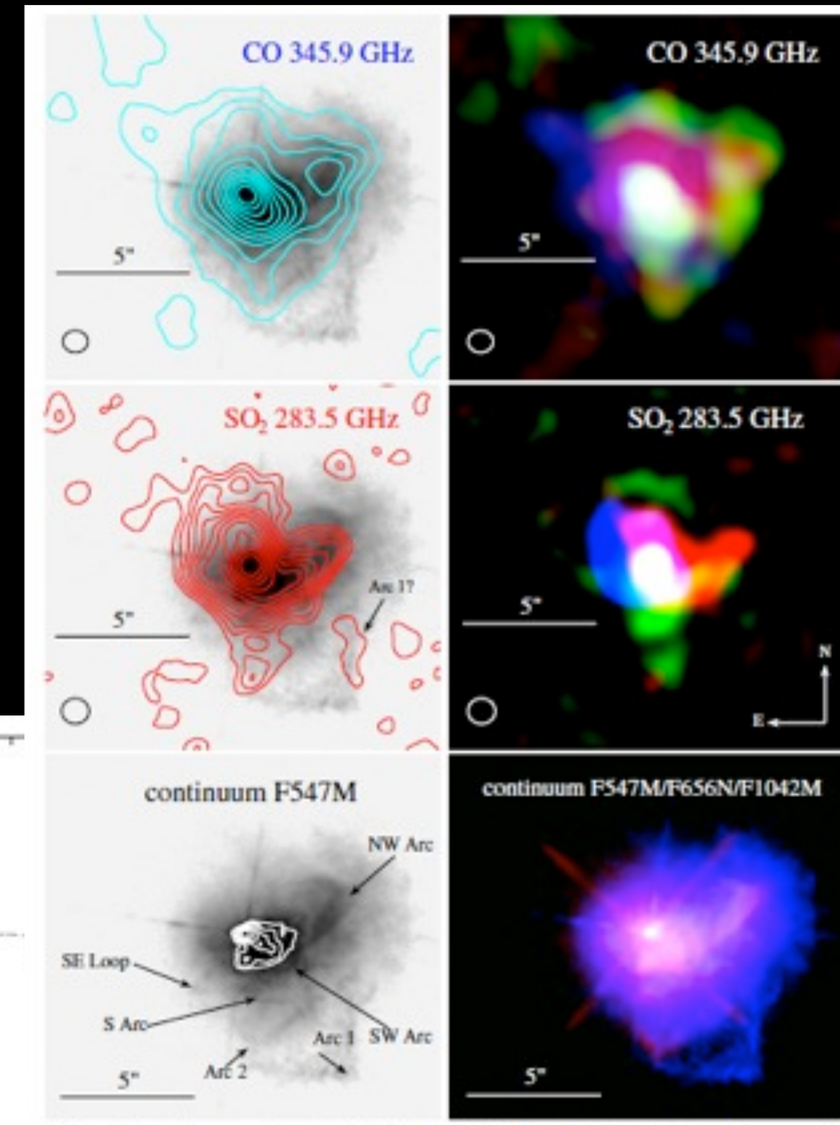
Peng et al. 2013, APEX; Vlemmings et al. 2013, ALMA; Ramstedt & Olofsson (2014)

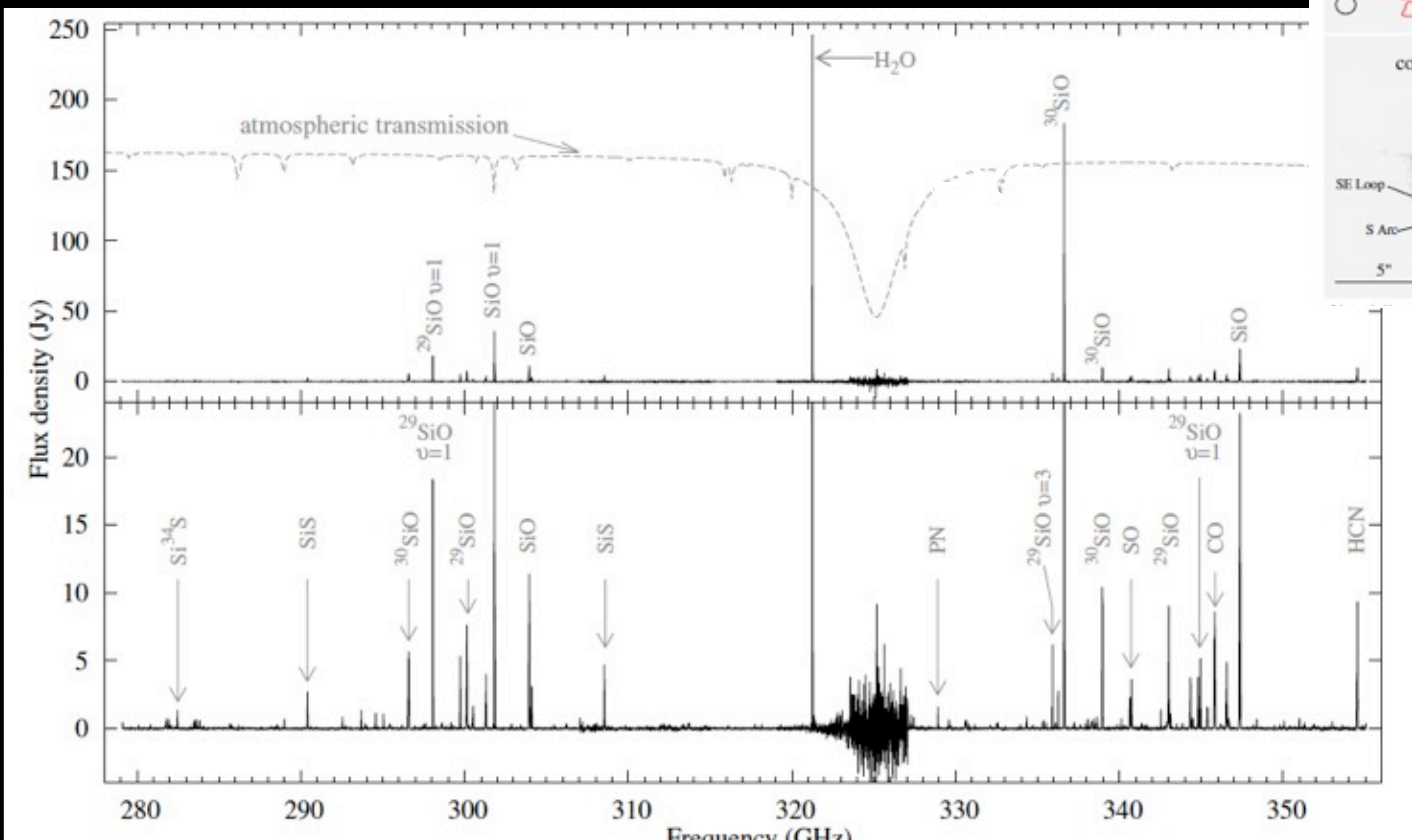


Chemistry

VY CMa

Diverse in molecular species:
Oxygen-rich: VY CMa
Carbon-rich: IRC+10216

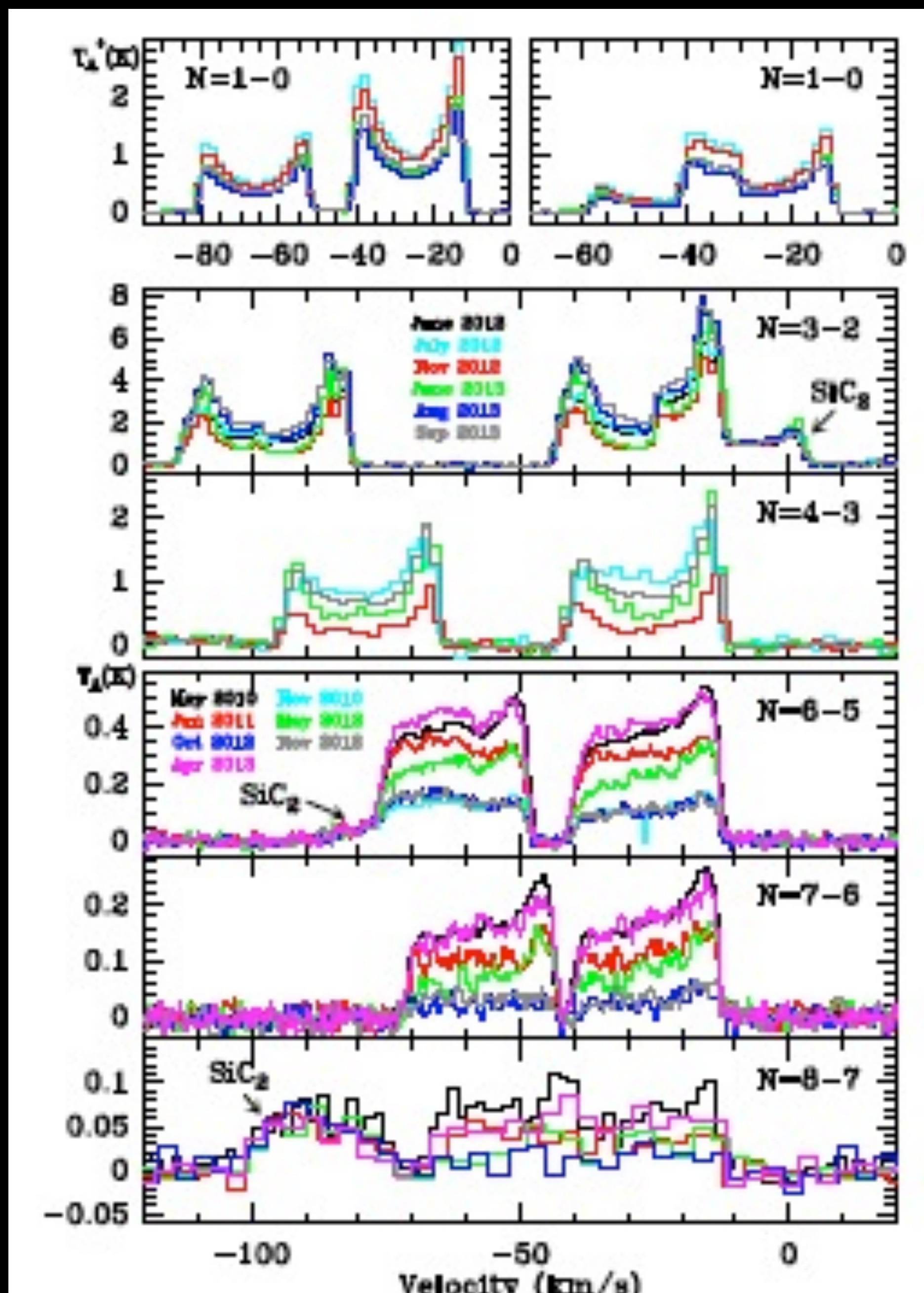


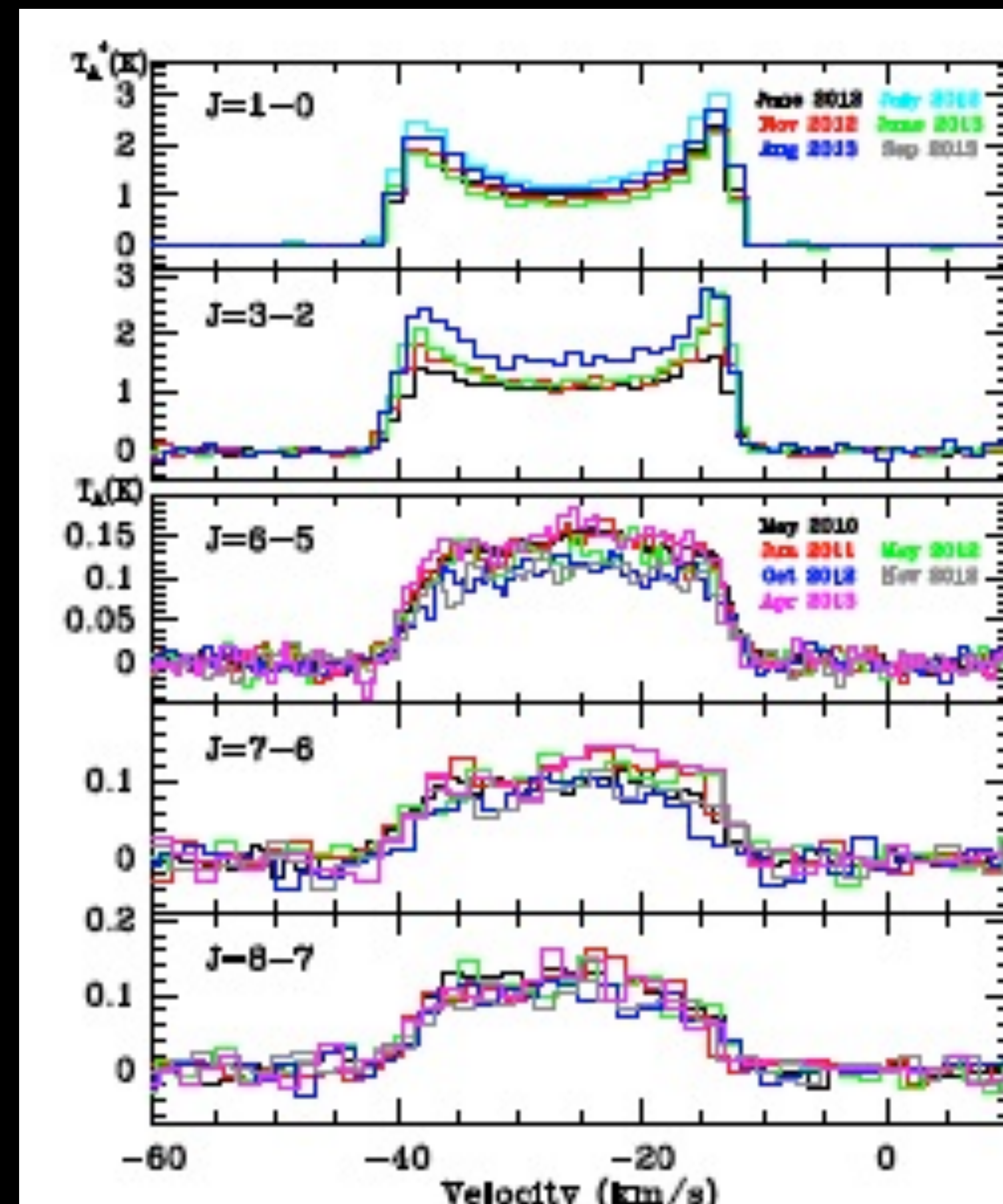


SMA
Line Survey

Kaminski
et al. 2013

Time variations in molecular line intensities





IRAM 30m; Cernicharo et al. 2014

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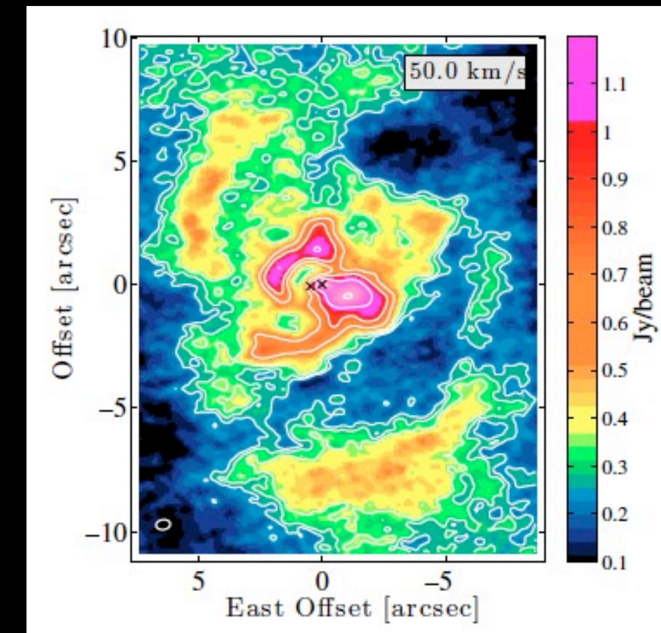
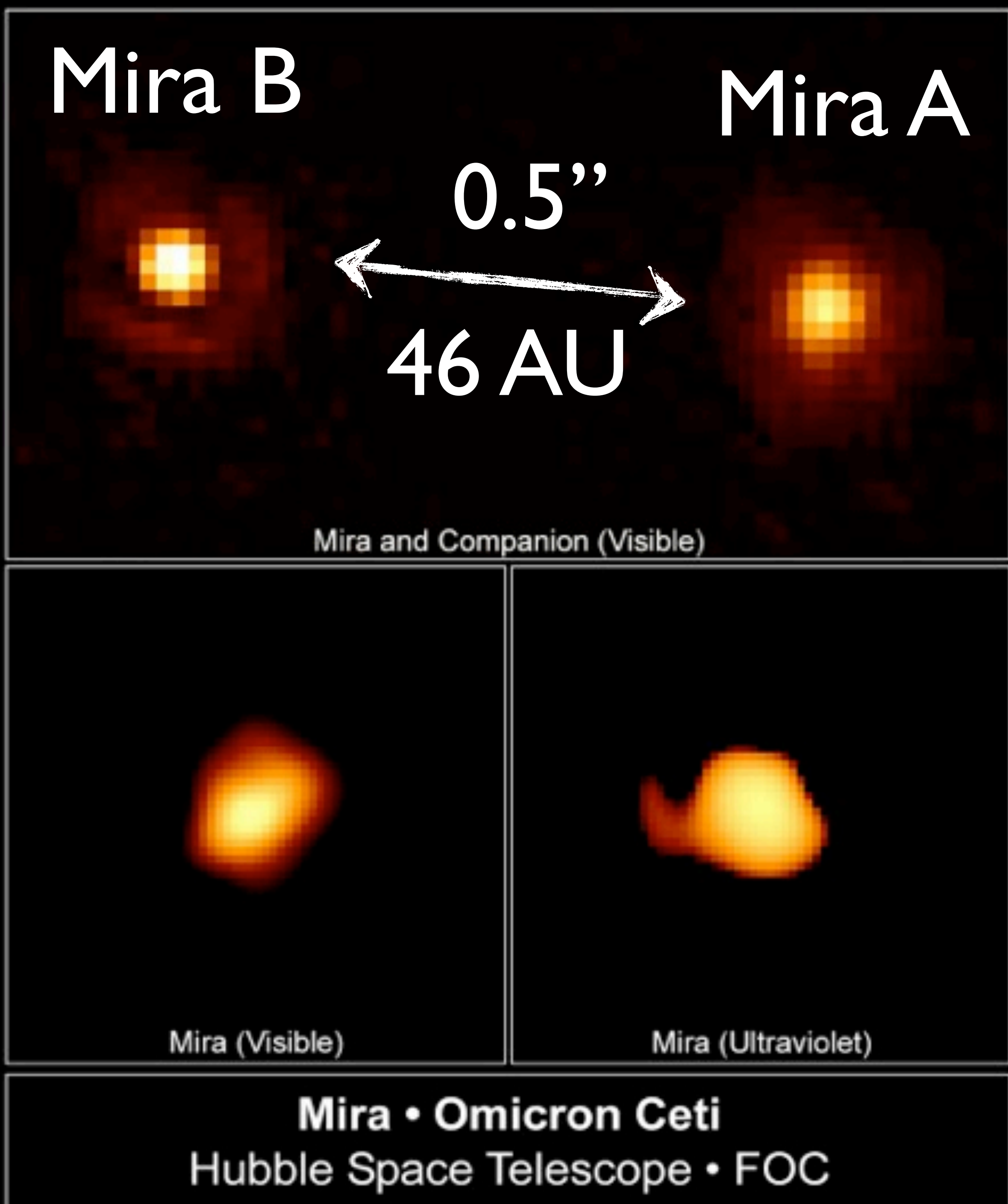
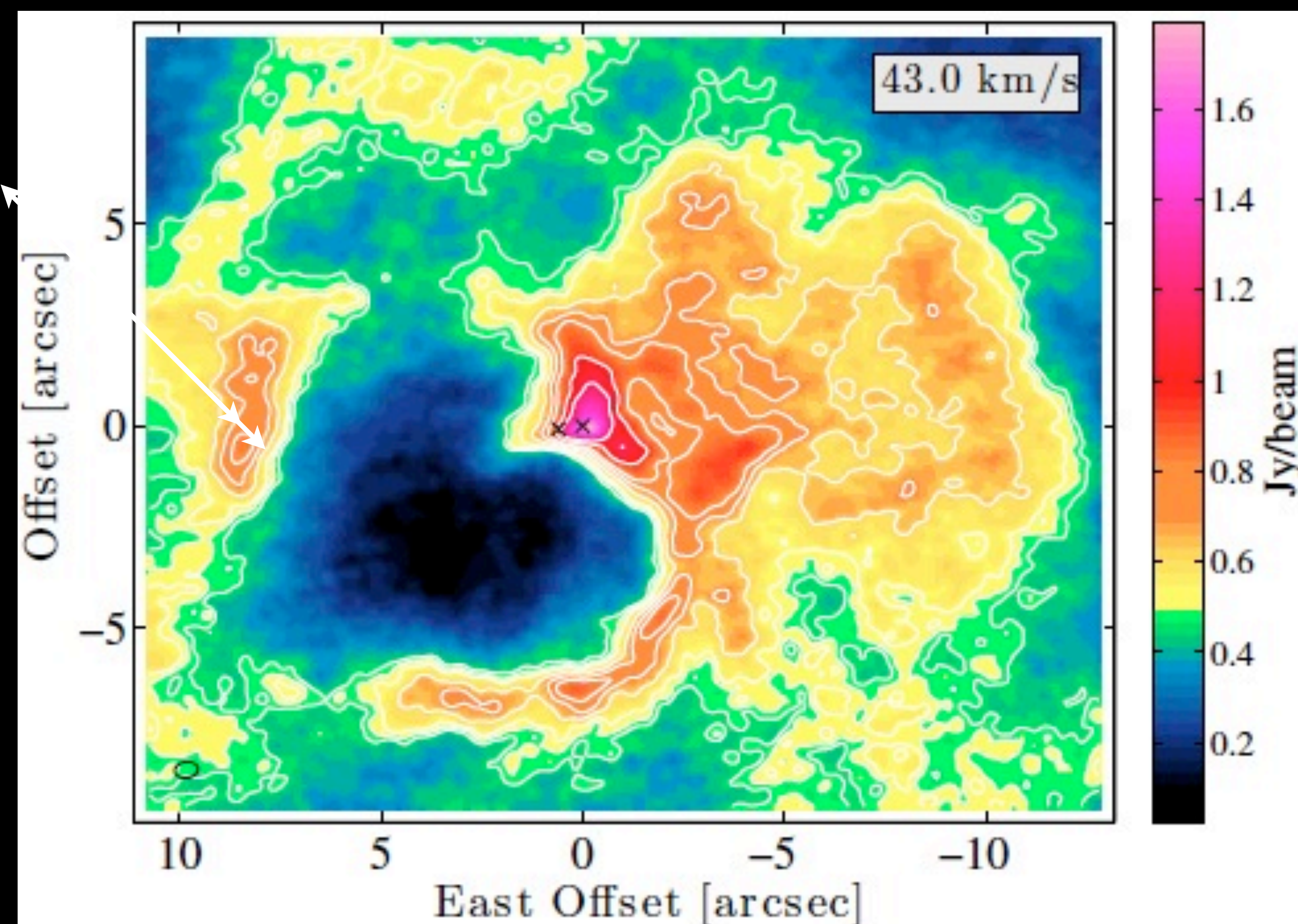
Binarity

- What is the effect on mass loss?
- Role in Shaping Process to PN



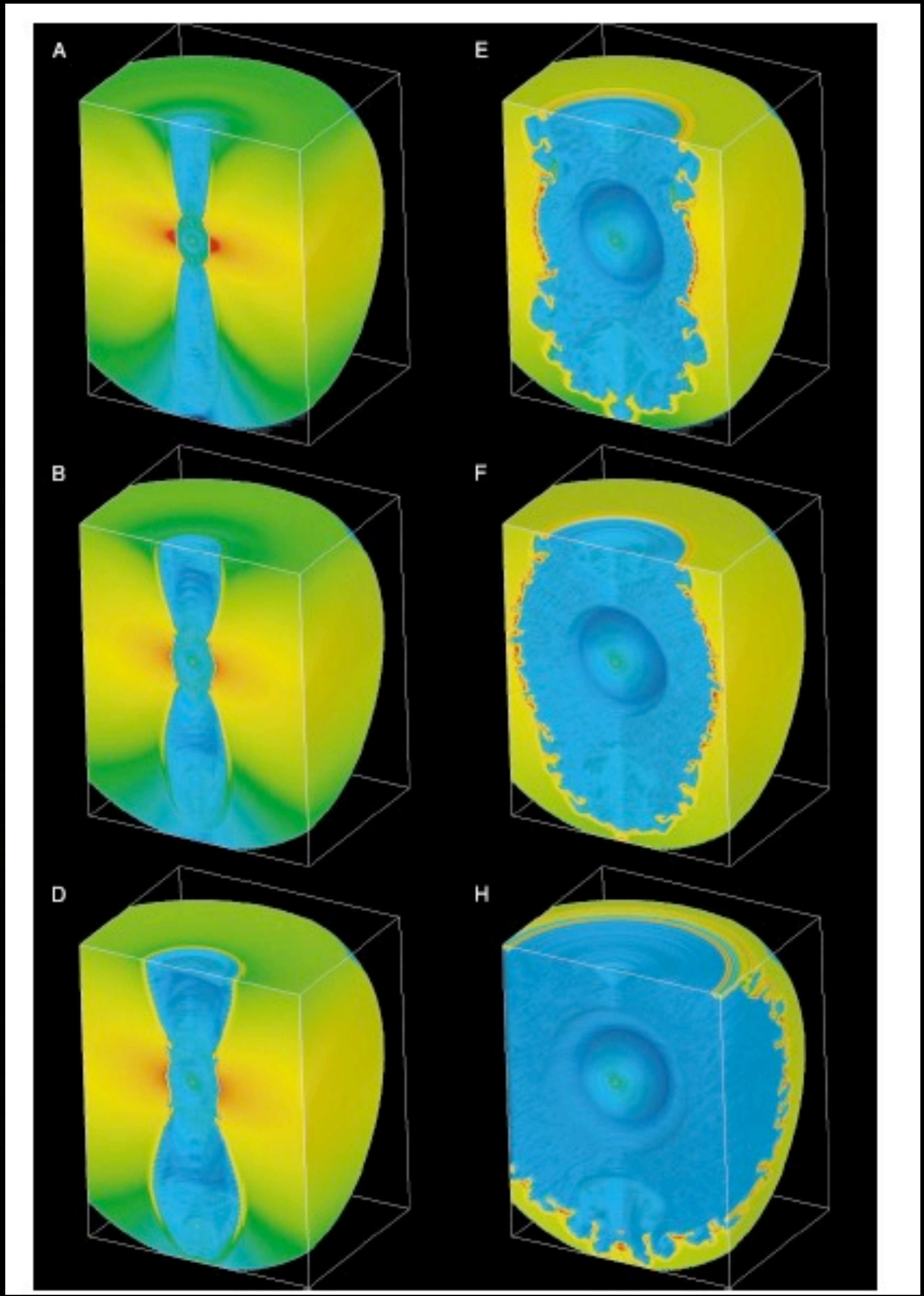




Ramstedt et al. 2014, ALMA

Binarity: envelope structures
Spirals, Arcs & Bubbles

R Sculptoris
Maercker et al. 2012, ALMA
Also IRC+10216 Cernicharo et al., Decin et al.



Gawryszczak et al. 2002

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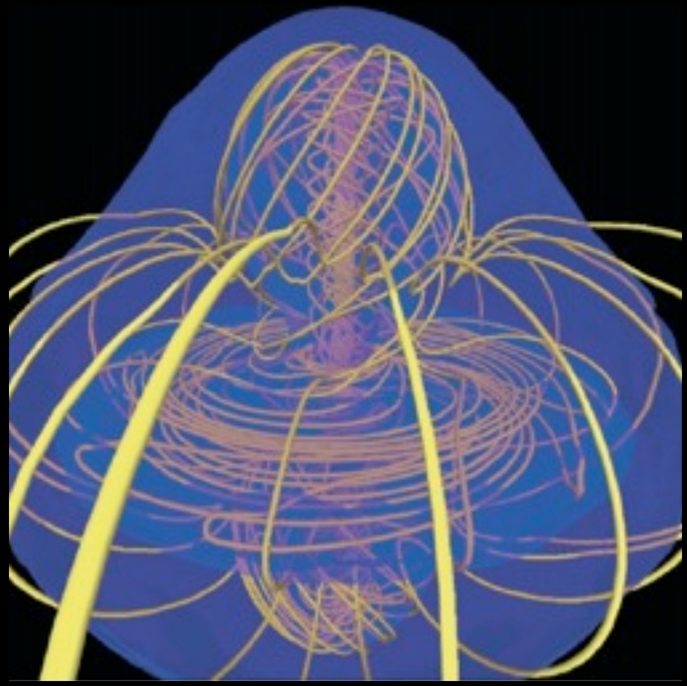
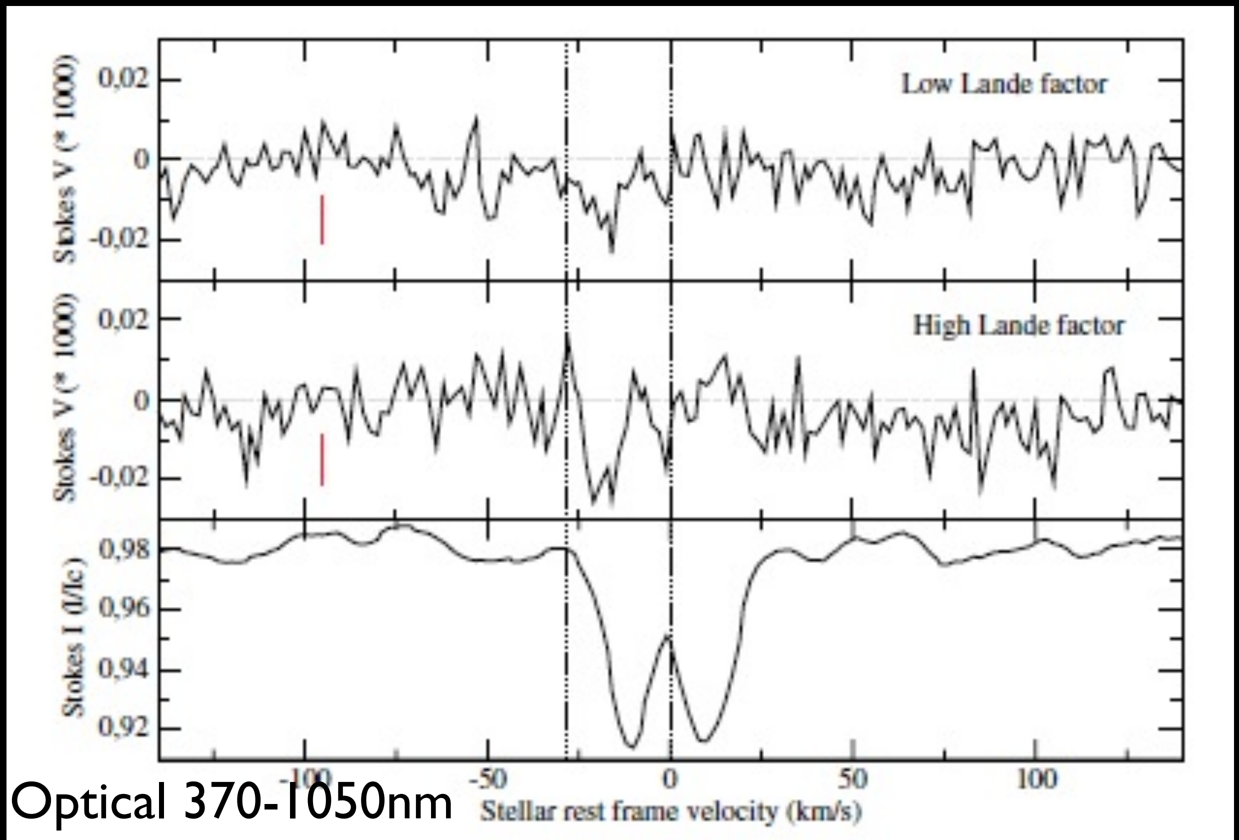


Matt, Frank & Blackman 2006

AGB Magnetic Fields

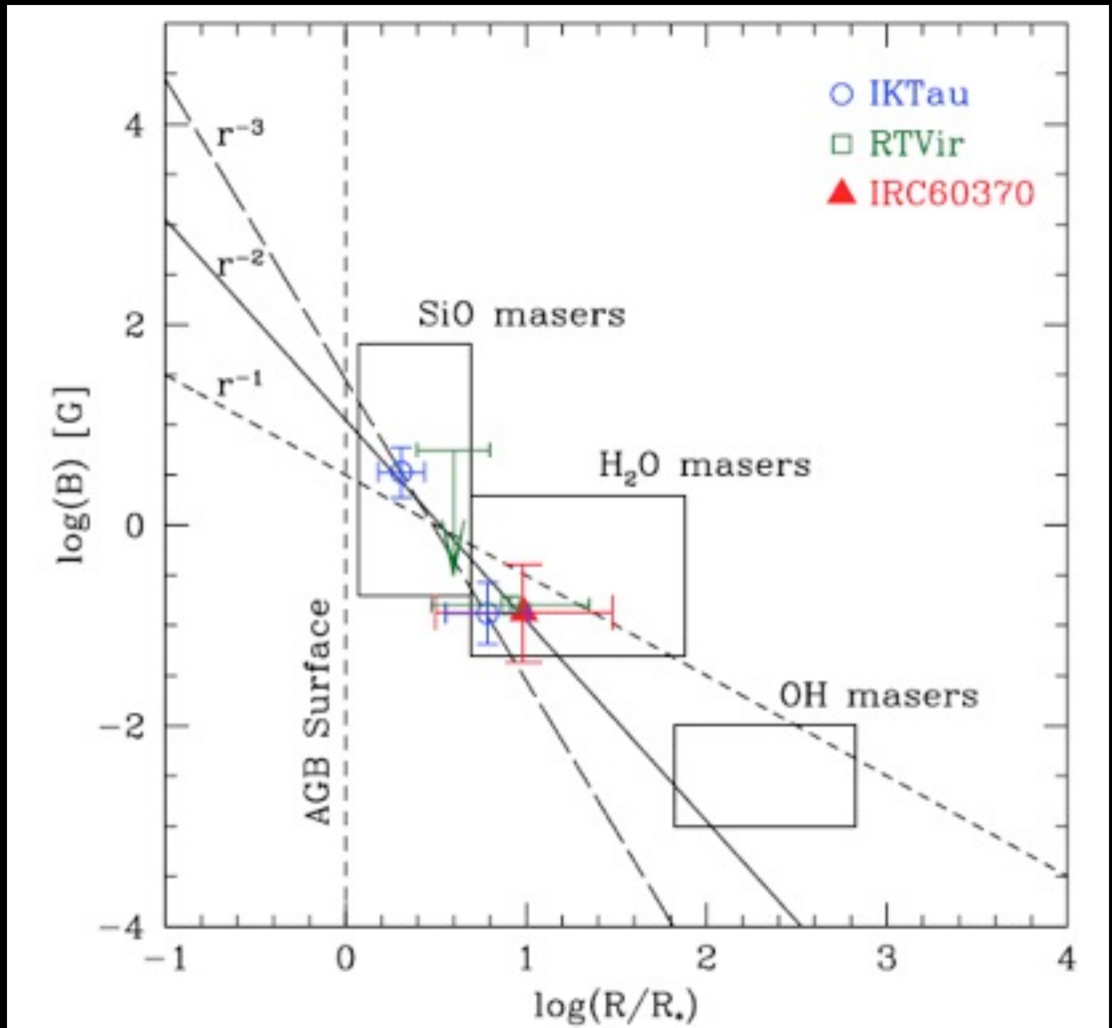
- Single stars: internal dynamo (Blackman et al. 2001) or interaction with circumstellar disk
- Binary/planet companion: common envelope dynamo (Nordhaus et al. 2006)

Central Star - Chi Cyg



2-3 Gauss, Lebre et al. 2014

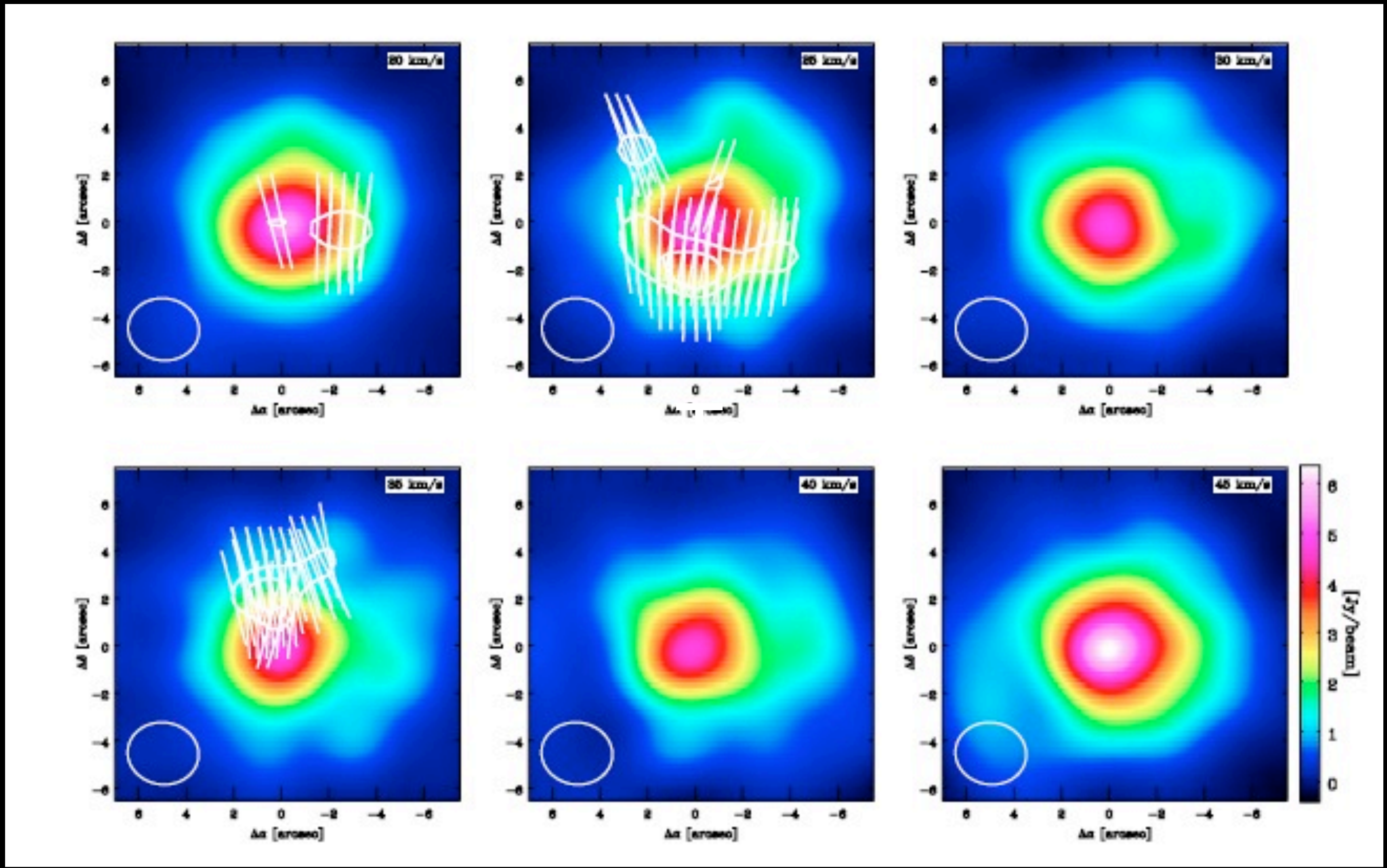
Envelope



Leal-Ferreira et al. 2013

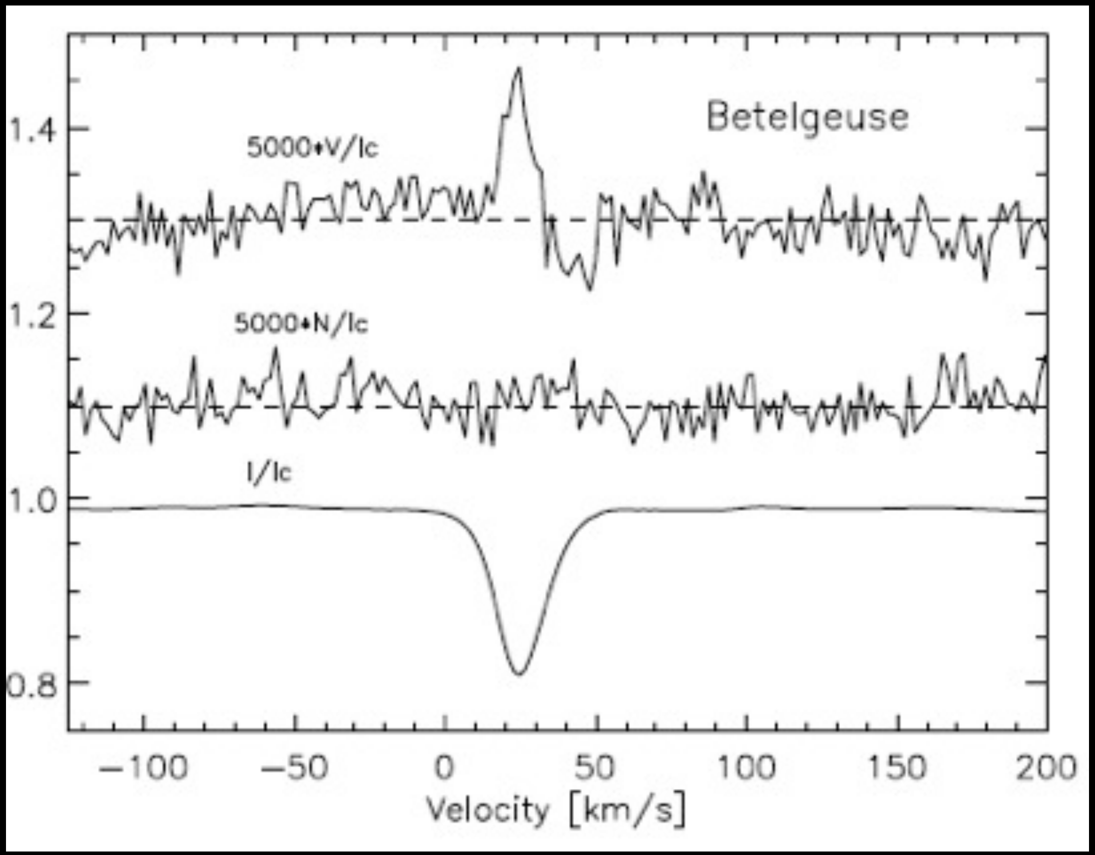
CO Polarization

SMA
Vlemmings
et al.
(2012)



ALMA high spectral resolution full polarization capability will be transformational (low spectral resolution full polarization at Cycle 3)

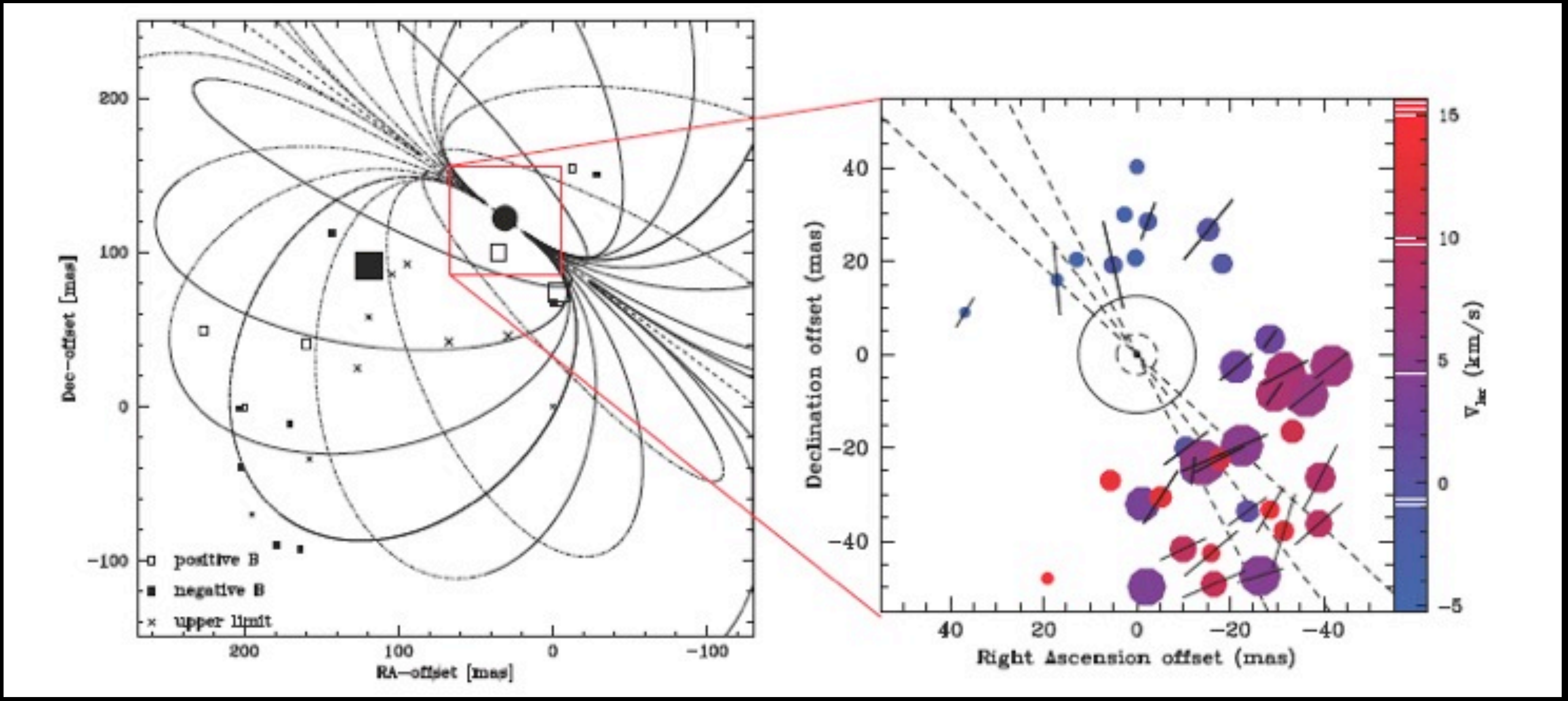
Central Star



RSG Magnetic Fields

1 Gauss
Auriere et al. 2010

Envelope



Vlemmings et al. 2005, 2011

I. Stellar Surface & Dynamical Atmosphere

II. Dust Formation Zone & Dust

III. Outer Wind & ISM Interaction

IV. Chemistry

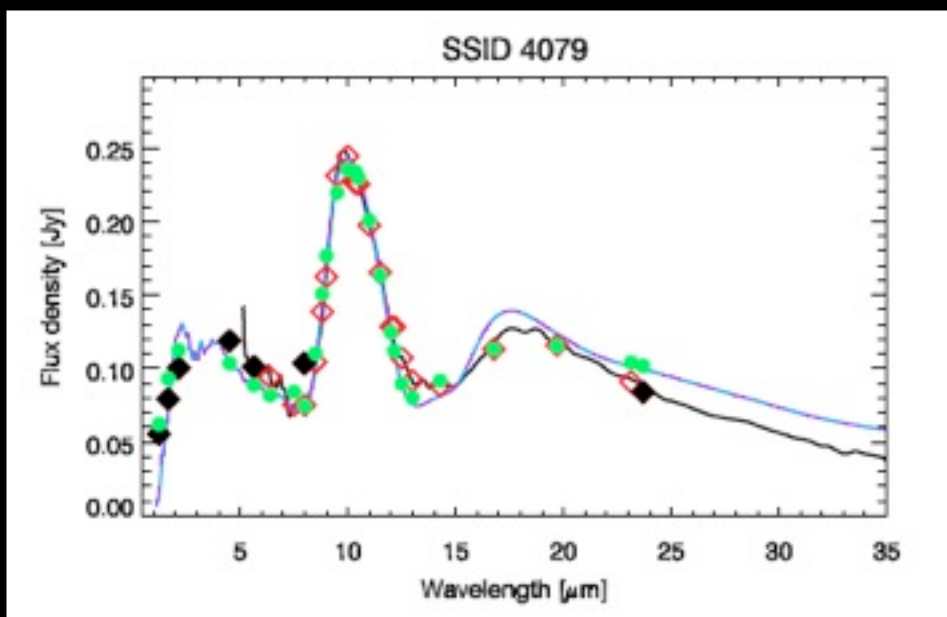
V. Binarity

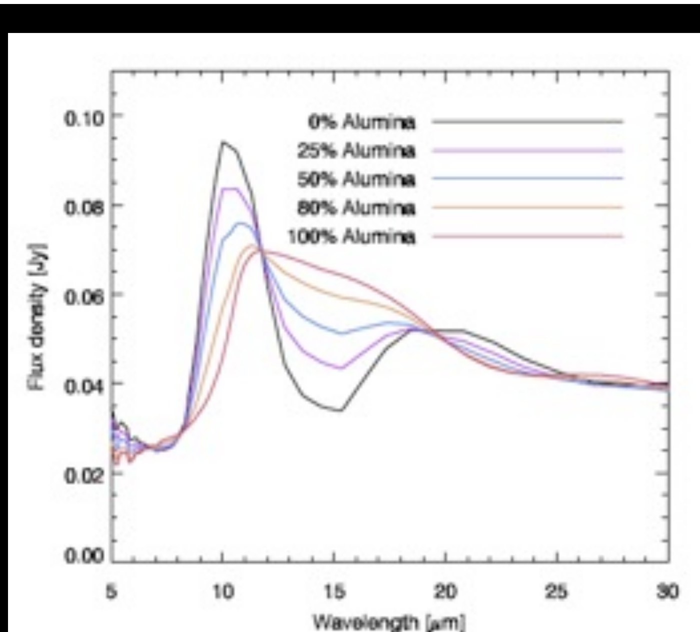
VI. Magnetic Fields

VII. Metallicity & Extragalactic

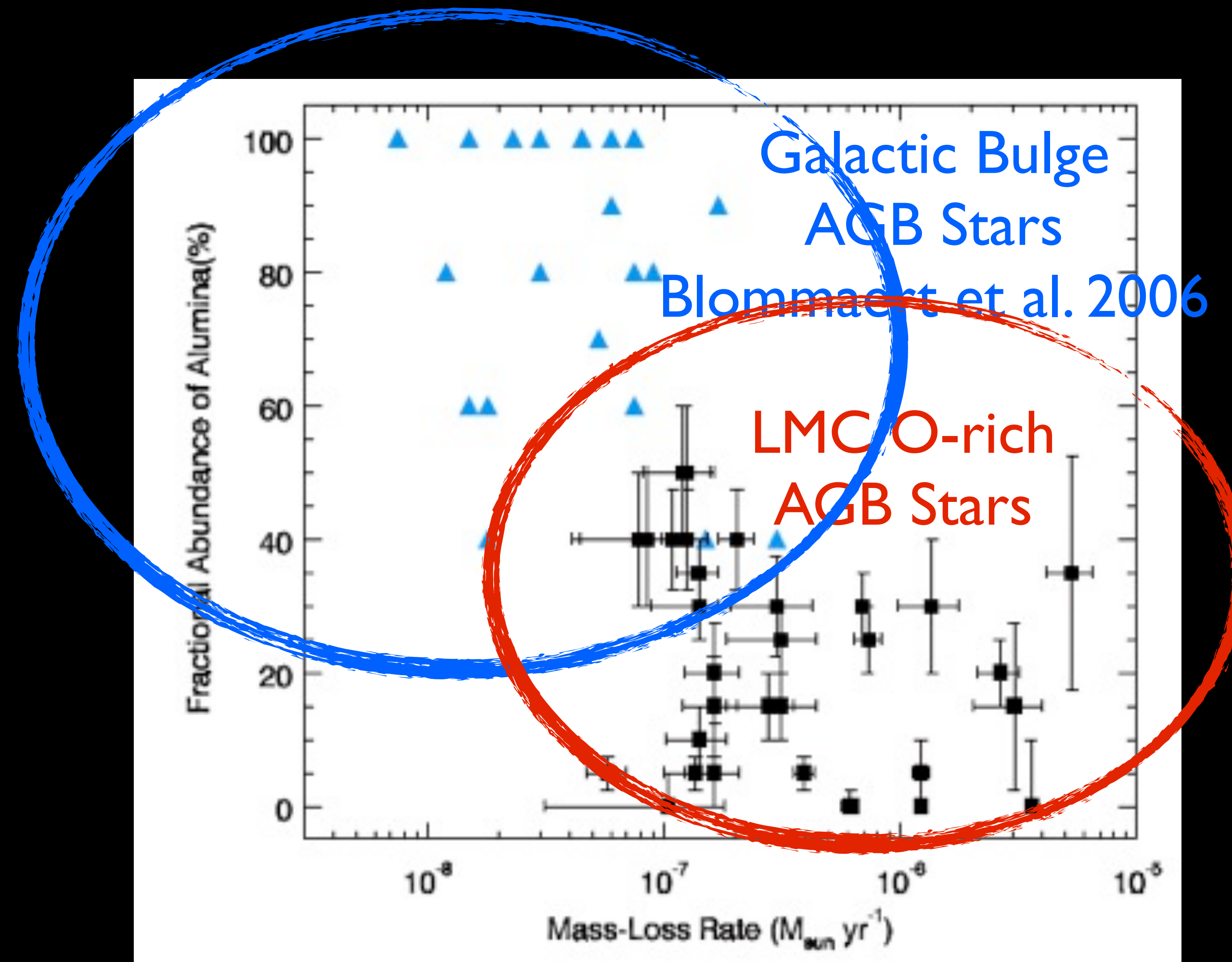
Metallicity/Extragalactic

- Dust and wind formation at low metallicity
- Implications for stellar populations
- Dust budget





Dust composition varies with metallicity



Alumina abundance

Spitzer 5-35 micron; Jones et al. 2014

Key Science for the 2020s

- Link surface features, dust, mass loss, circumstellar envelope
    - use complementarity of VLTI, E-ELT, ALMA and other radio facilities to track molecules & dust as they move away from the star
- Understand dust formation as a function of metallicity
    - dust return to the ISM
- Characterise magnetic fields
- Determine shaping process of Planetary Nebulae
    - binarity vs magnetic fields
- Characterise circumstellar structures e.g. disks
- Episodic events & time monitoring (for everything!)

ESO 2020s Wish List

VLTI

- First goal should be to have GRAVITY and MATISSE

- Combine instruments for simultaneous multi-wavelength observations
  - Enable probe of stellar surface where spots are observed, geometry of envelope and dust formation zone in a single-shot i.e. from photosphere up to 10-20 R*
  - simultaneity important e.g. because of stellar pulsation

- Extend to shorter wavelengths e.g. J-Band to create an i-shooter interferometer.

- High spectral resolution needed R=100,000

- Add optical instrument e.g. V-band

- Time-monitoring observations, coordination with ALMA for multi-wavelength monitoring

ESO 2020s Wish List

ALMA

- ALMA full spectral resolution, full polarization capability needed as soon as possible
- Large programmes to enable study of statistical samples of e.g. post-AGB CO outflow power and momenta

mm VLBI with phased ALMA

- mmVLBI with phased ALMA (masers)
- mmVLBI with phased ALMA (continuum)
  - relatively short 200 to 300 km baselines to image photospheres

APEX

- Facility Band 9 Receiver on APEX

ESO 2020s Wish List

ELT

- High spectral resolution R=100,000 and high spectral resolution spectro-polarimeter
- High spectral resolution throughout near and mid IR for understanding dust composition

VLT

- Importance of CRIRES and CRIRES+, high spectral resolution spectro-polarimetry
- VISIR upgrade important

STEPS 2015

Stellar End Products: the low mass - high mass connection

http://www.eso.org/sci/meetings/2015/STEPS2015.html

- ESO Garching, 6-10 July 2015
- Confirmed Invited Speakers: Jean-Phillipe Berger, Henri Boffin, Graham Harper, Susanne Hoefner, Roberta Humphreys, Joel Kastner, Franz Kerschbaum, Agnes Lebre, Orsola de Marco, Mikako Matsuura, Iain Mcdonald, Georges Meynet, Benoit Mosser, Hans Olofsson, Claudia Paladini, Sofia Ramstedt, Anita Richards, Laurence Sabin, Nathan Smith, Leonardo Testi, Albert Zijlstra