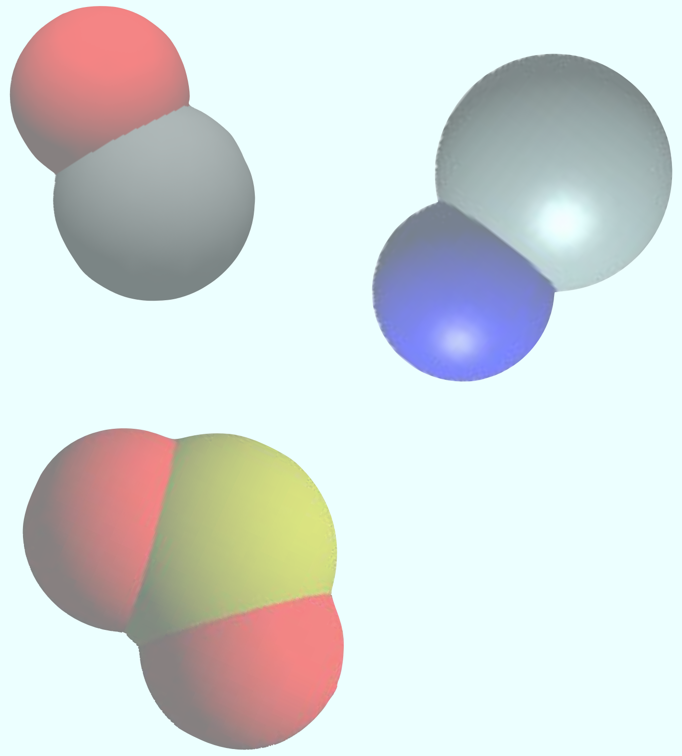
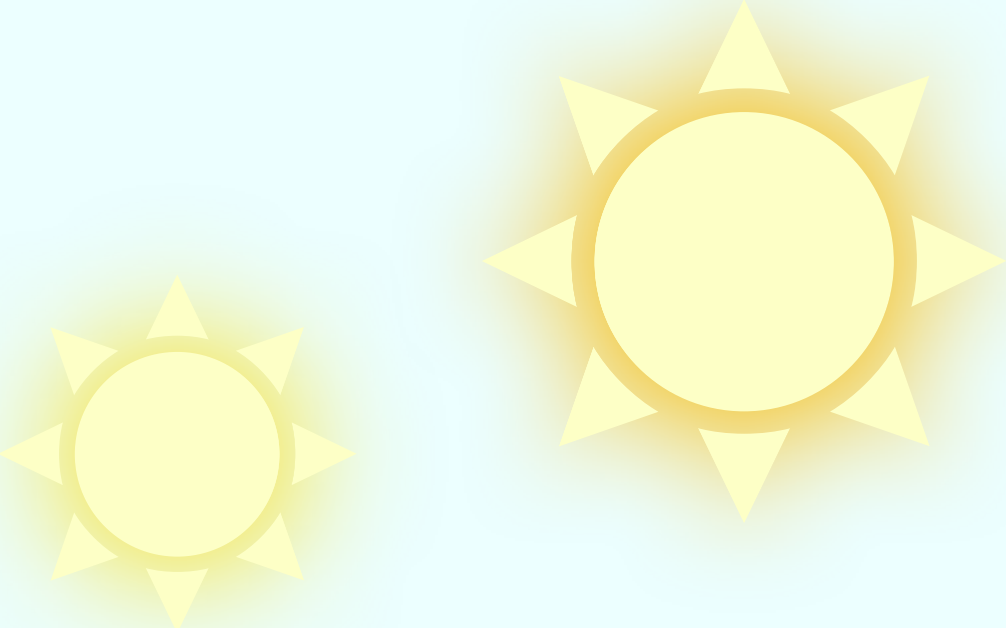




Beyond gravity: What can Phantom and MCFOST models tell us about observables in binary AGB systems

Dr Taïssa Danilovich

Australian Research Council DECRA Fellow

MONASH University

Joint Franco-Australian Phantom and MCFOST Users Workshop, February 2024

The evolutionary journey of stars like our Sun

Red giant branch

AGB star
(Asymptotic Giant Branch)

Planetary nebula

← Main sequence star (initially ~0.8 to 8 times the mass of the Sun)

Image credit: ESO/S. Steinhöfel

The dust-driven winds of AGB stars

1. Stellar pulsations (periods of ~1 year) push material outwards
2. Some material cools and forms dust before it falls back down
3. Radiation pressure from high luminosity of the star accelerates dust away
4. Dust grains collide with gas and drag gas outwards as well
5. Hence, material is lost from the star through this stellar wind
6. …
7. Profit (i.e. the enrichment of the ISM and an increasingly metal-rich galaxy)

How do we go from this

↓

(e.g. the Sun)

To this? →

(The diversity and asymmetry of planetary nebulae)

© Judy Schmidt

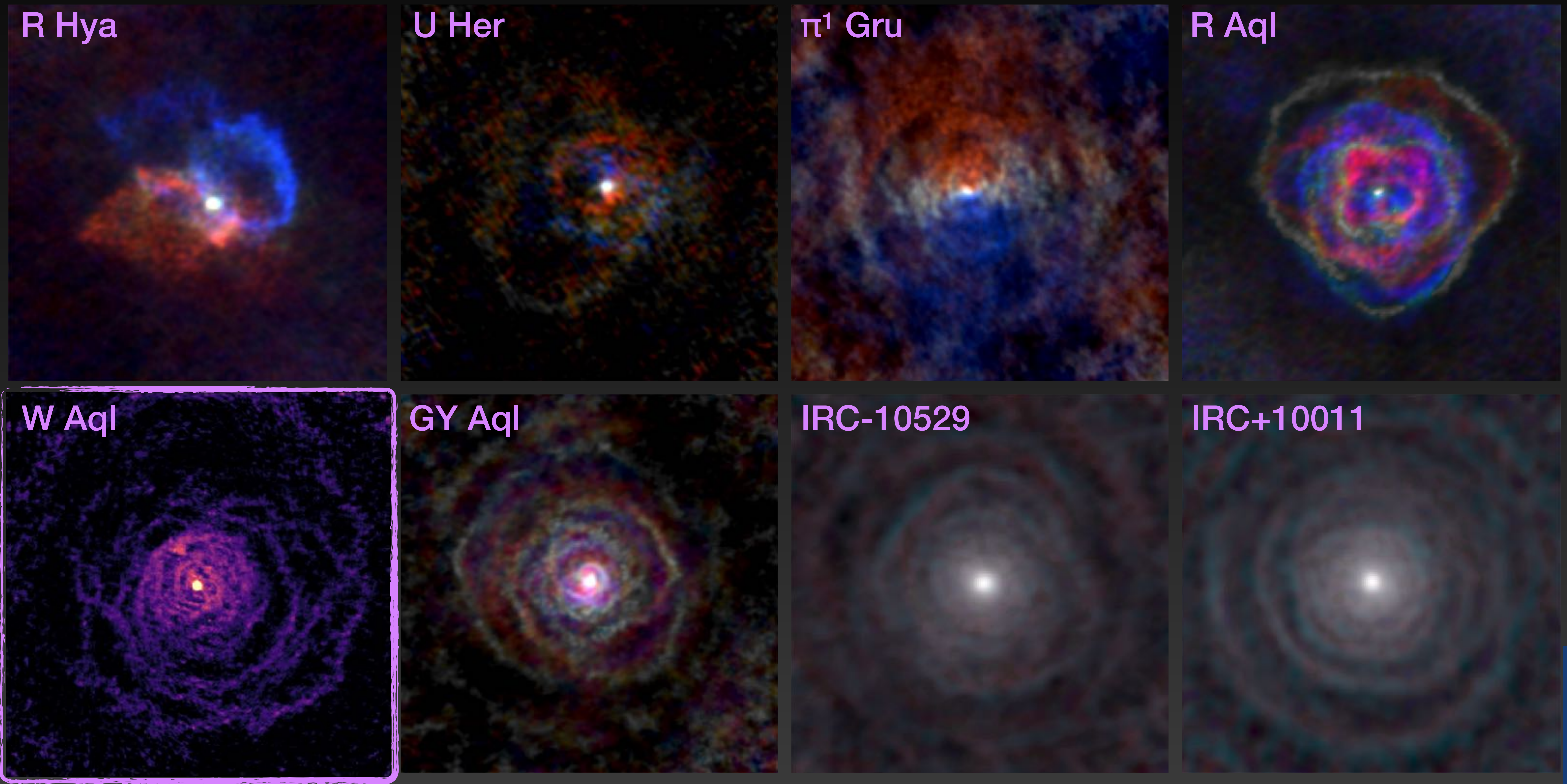
Binaries?

Magnetic fields?

ALMA reveals a plethora of binary AGB stars

(Every star a special snowflake)

CO composite images



Images from ATOMIUM, an ALMA Large Programme (Decin et al 2020)

W Aquilae

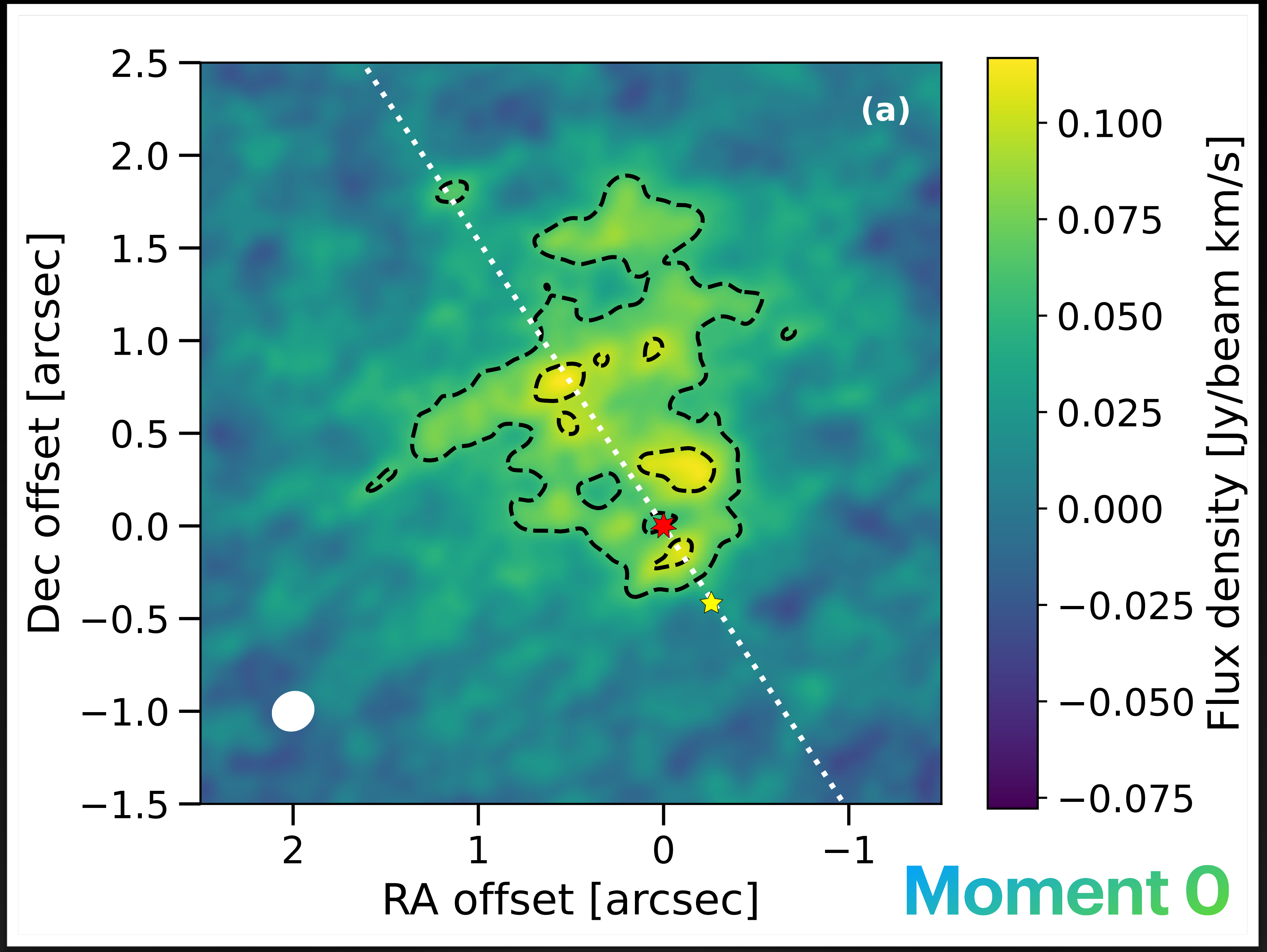
S-type AGB star

- S-type AGB star: carbon/oxygen ~ 1
- Close by (~395 pc)
- Moderately high mass-loss rate ($3 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$)
- Has a known main sequence (F9) companion
  - Current separation ~200 au
  - Long period (~1100 years)
  - Found (by us) to have a highly eccentric orbit ($e \approx 0.93$)

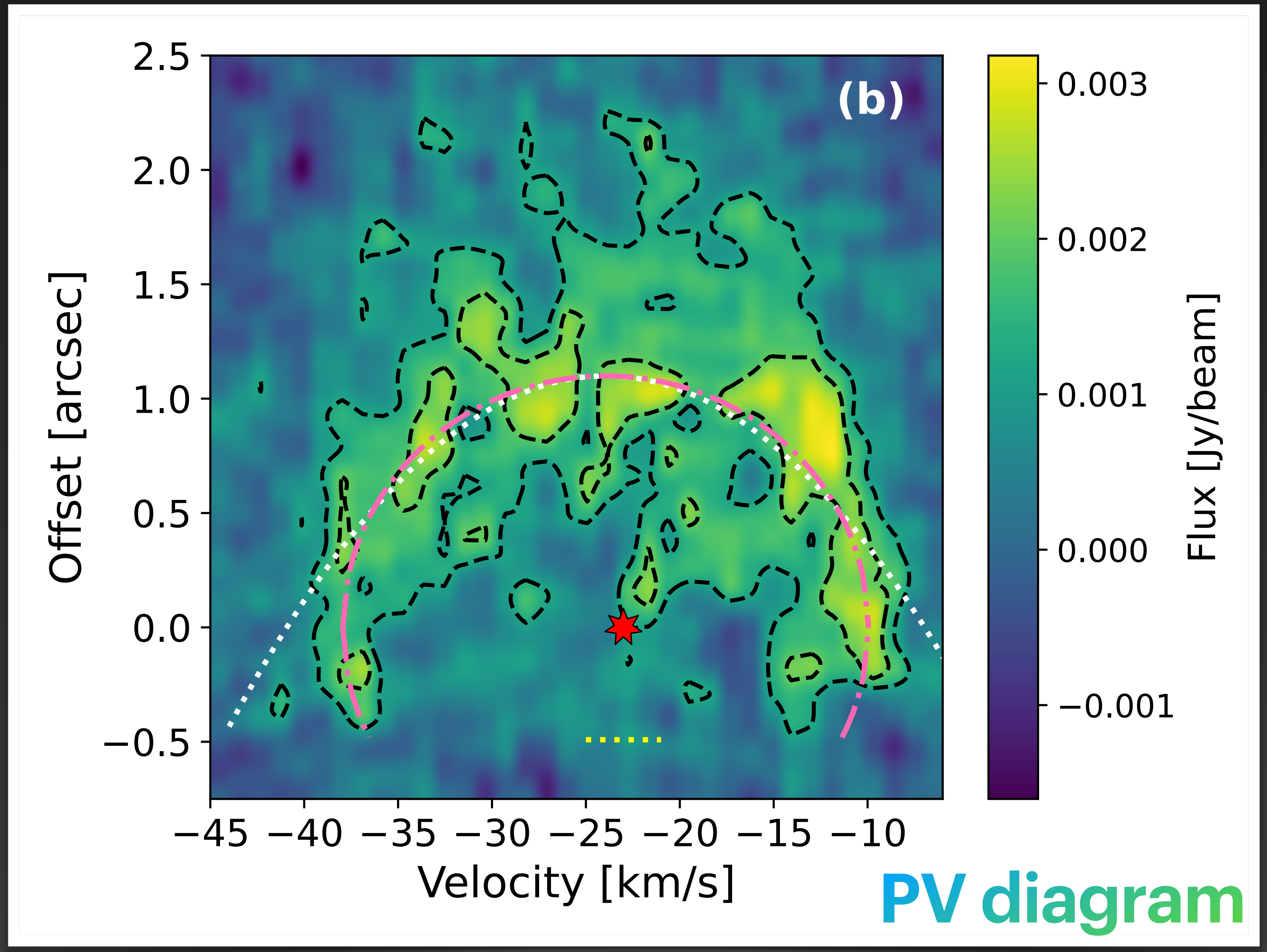
It all started with SiN

(Danilovich et al, *Nature Astronomy*, 2024)

- Highly asymmetric emission
- Arc in PV diagram
- SiN formation favoured in the presence of a (main sequence) companion (see Van de Sande & Millar, 2021)
- **Hypothesis:** SiN formed around periastron from irradiation by F9 companion with highly eccentric orbit



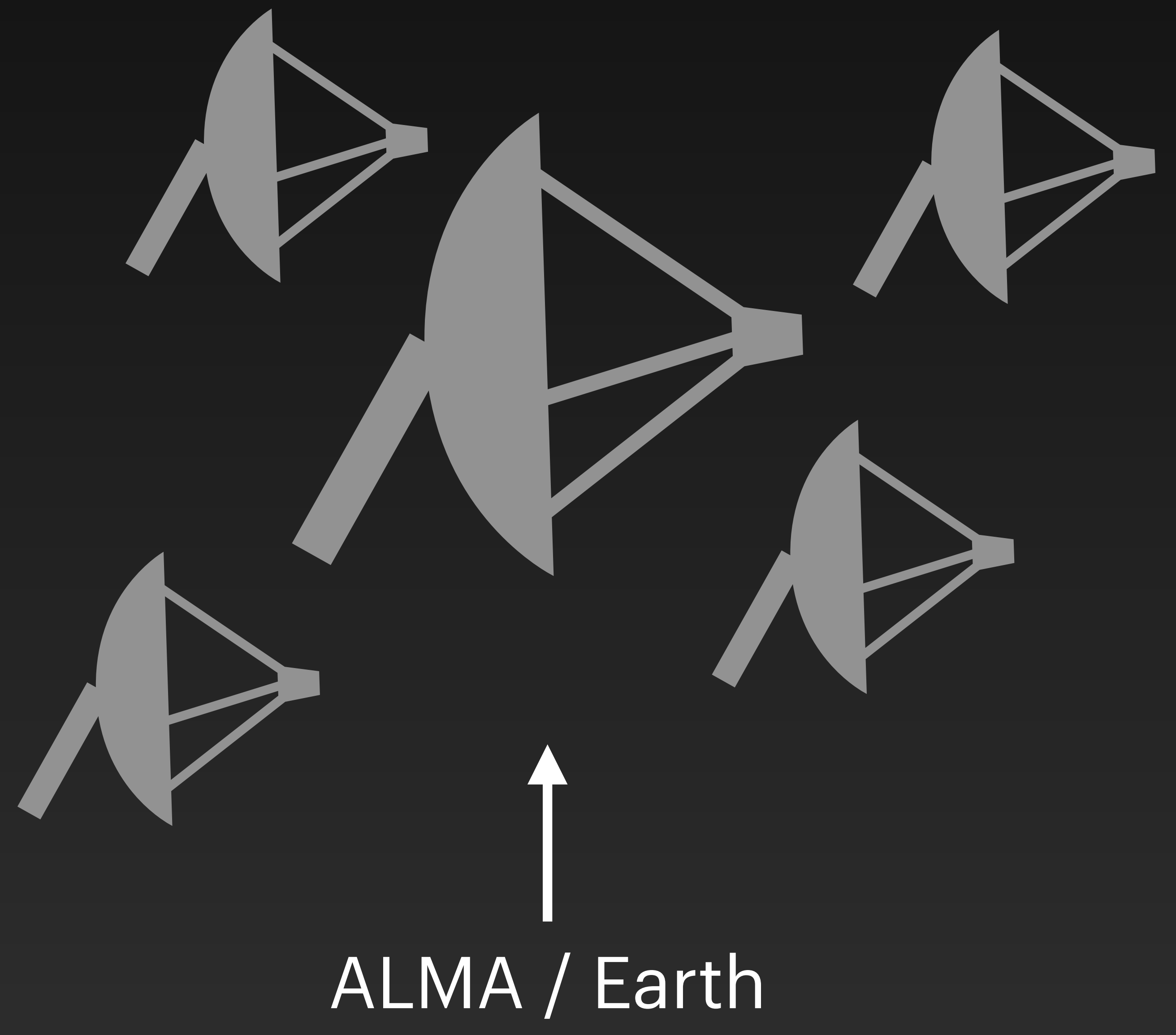
Moment 0

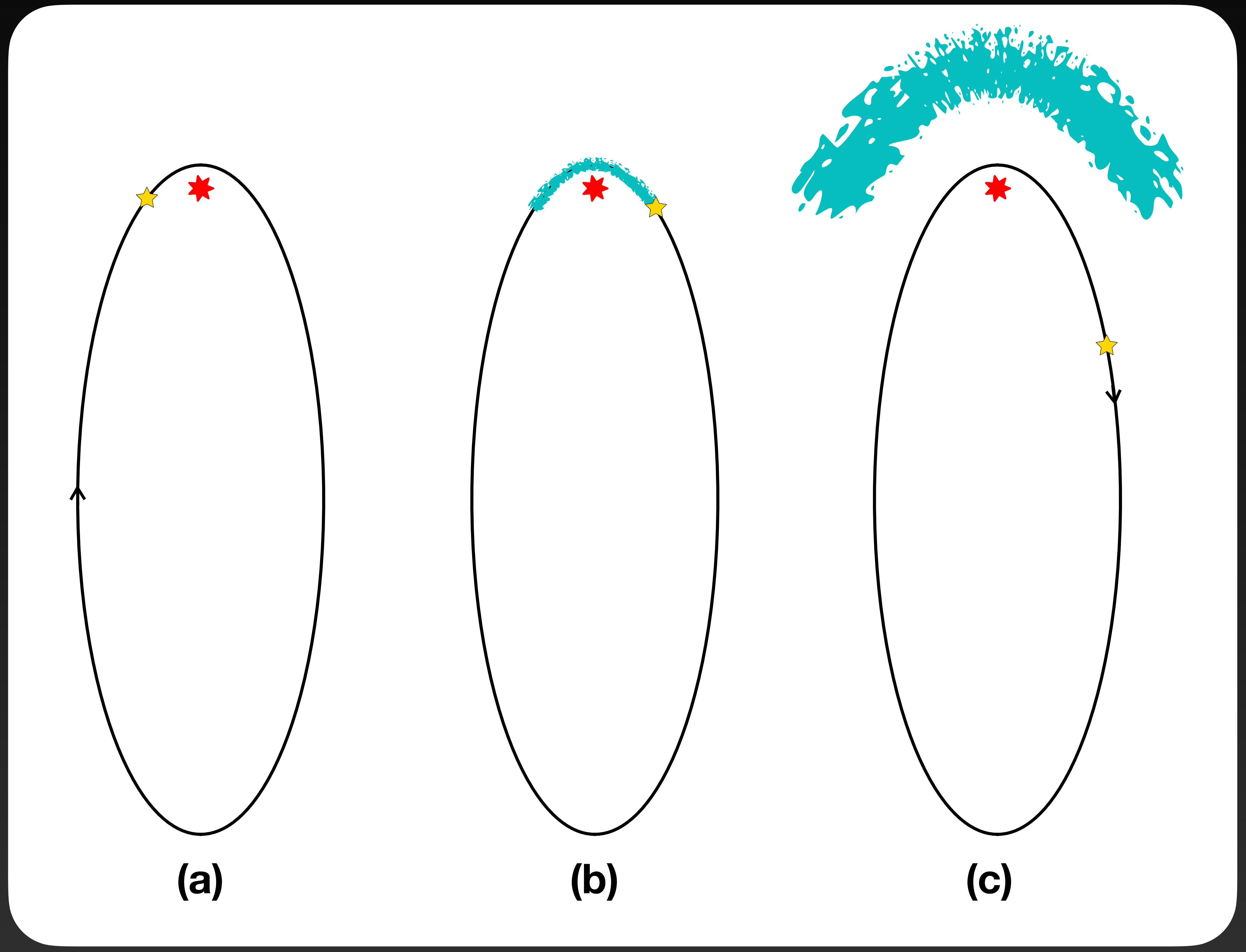


PV diagram

SiN formation scenario

A face-on view of the orbit
(in the frame of the AGB star)





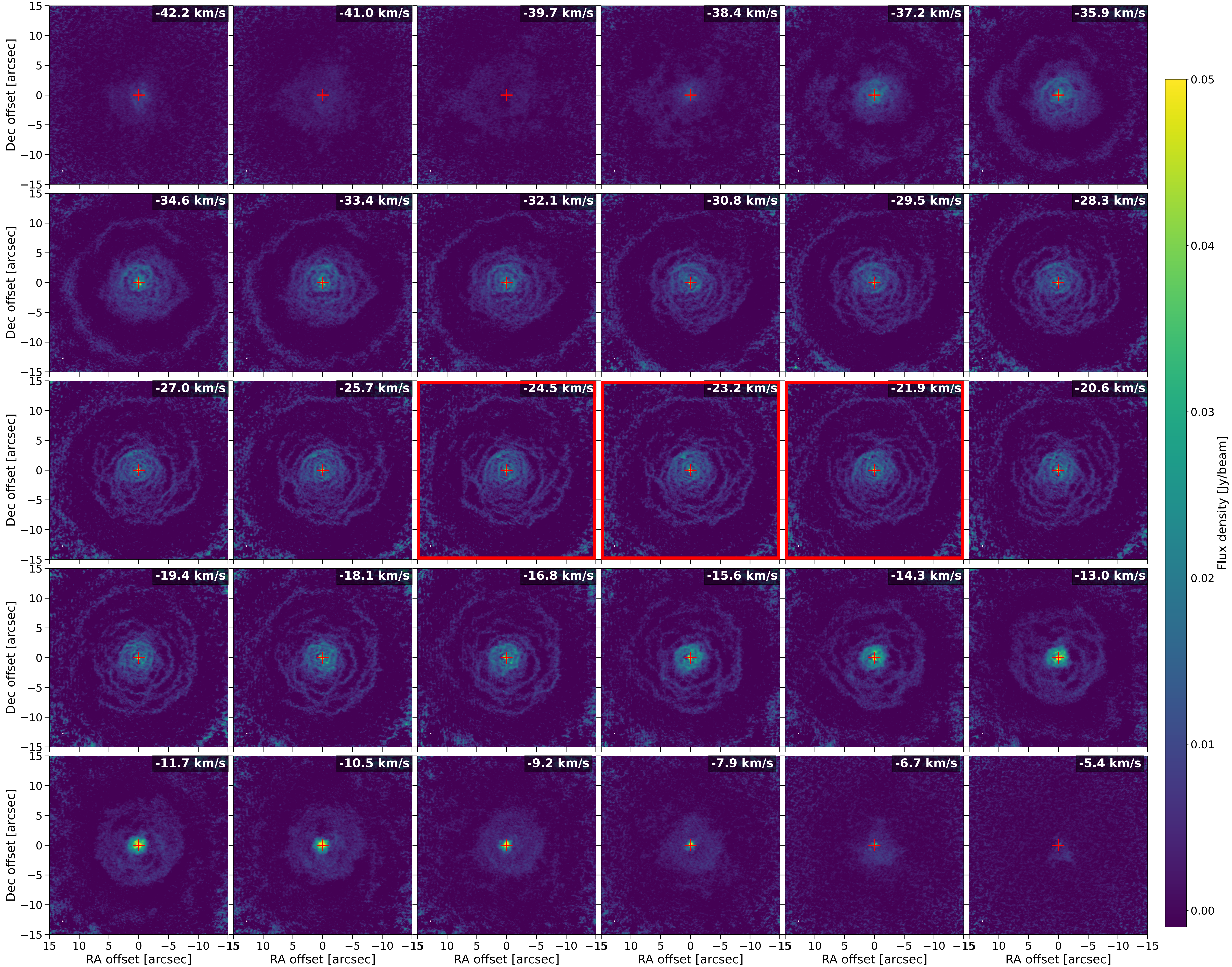
The asymmetric formation of SiN:

F9 approaches AGB star & enters dense inner wind.

Periastron passage has occurred and SiN has formed in the wake of the F9 star.

The F9 star has moved along its orbit and arc of SiN has expanded with the AGB wind.

CO (2-1) channels towards W Aquilae



CO traces density.

How does this match the eccentric orbit picture?

Resolution: 132 x 123 milliarcsec

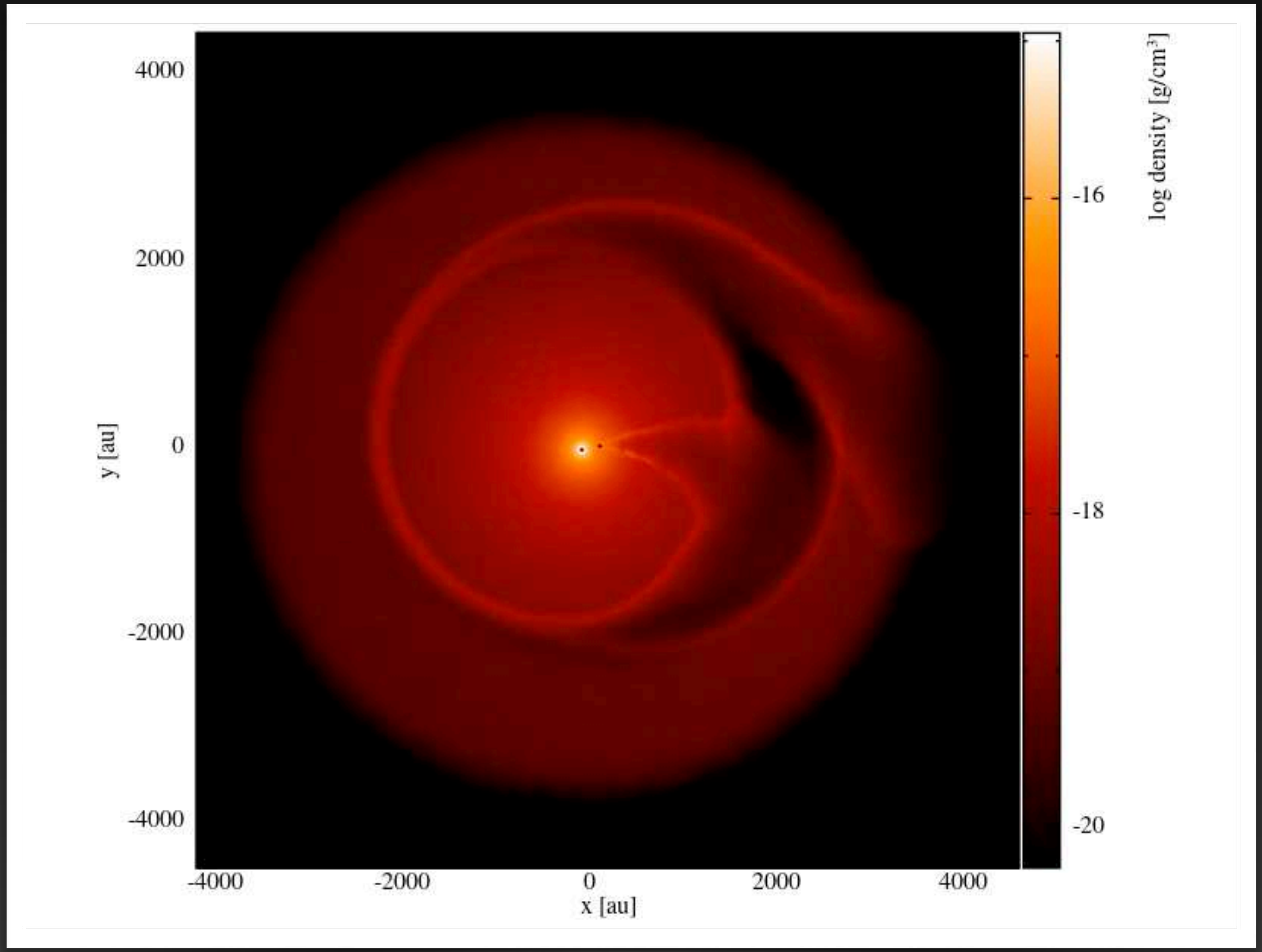
Hydrodynamic models

Thanks to Jolien Malfait

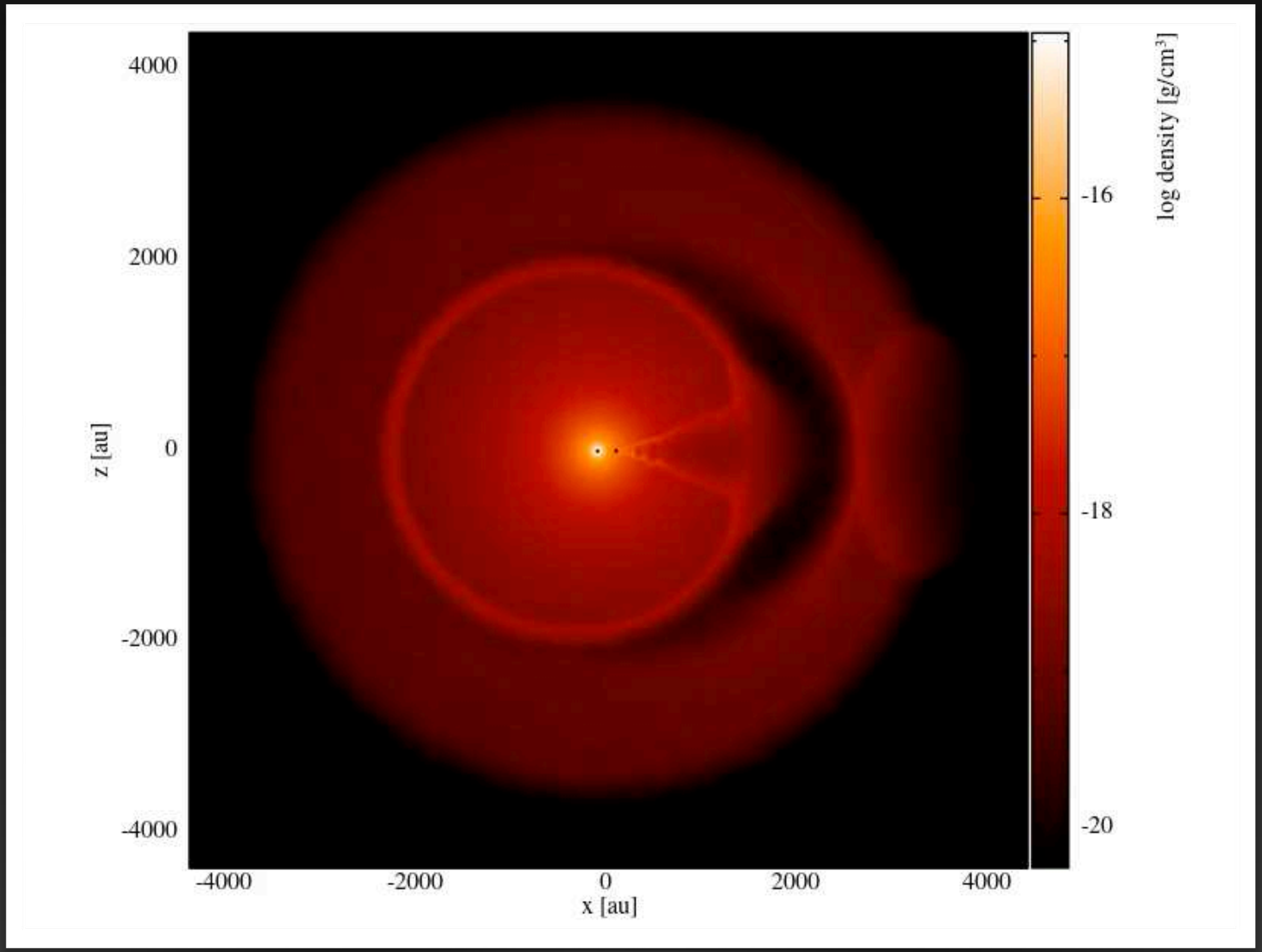
e = 0.92, a = 125 au,

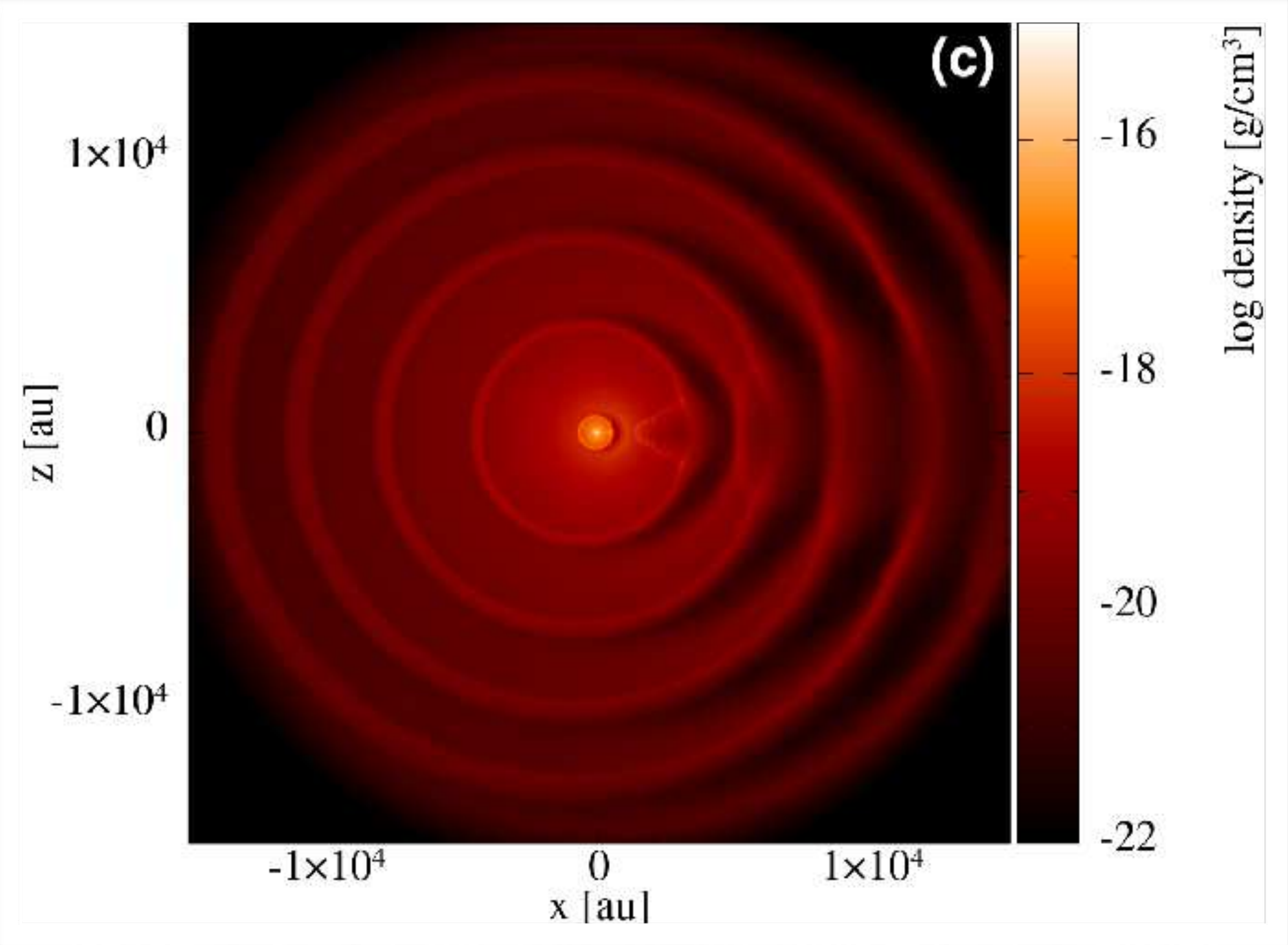
M_{AGB} = 1.6 $M_\odot$, M_{F9} = 1.06 $M_\odot$

Face on



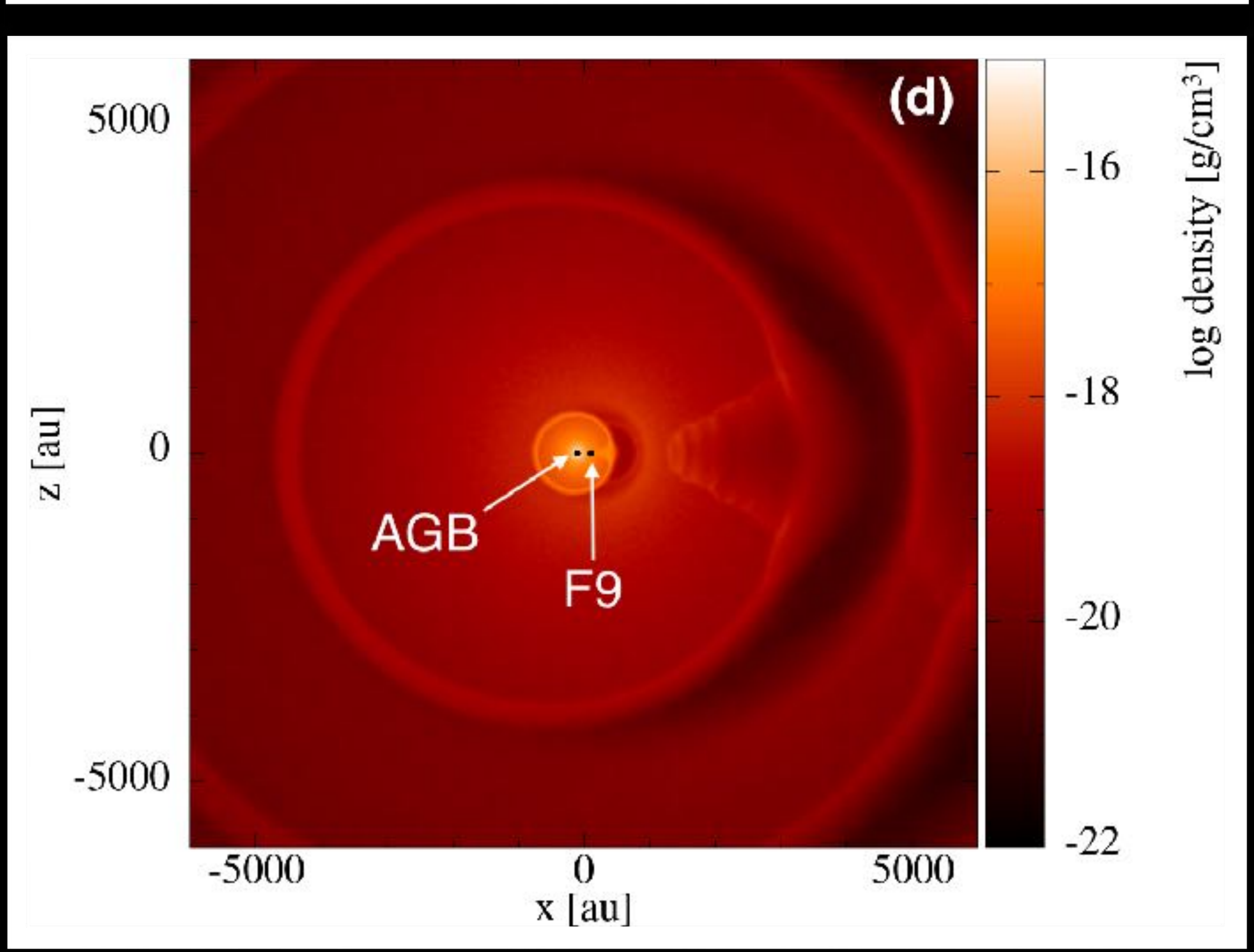
Edge on

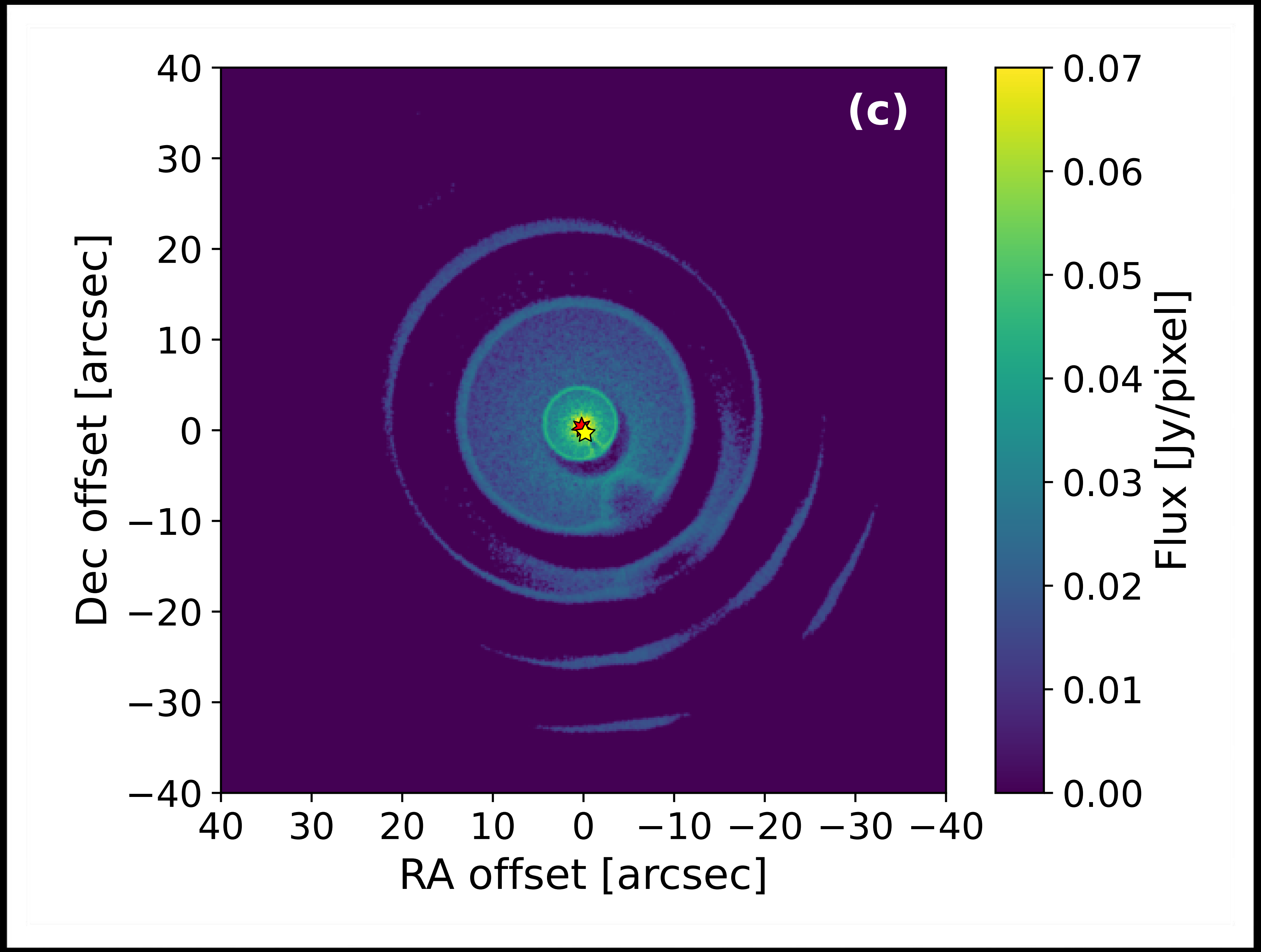




Use MCFOST to process SPH

- Process Phantom model with MCFOST
- Get channel maps
  - Includes photodissociation 👍

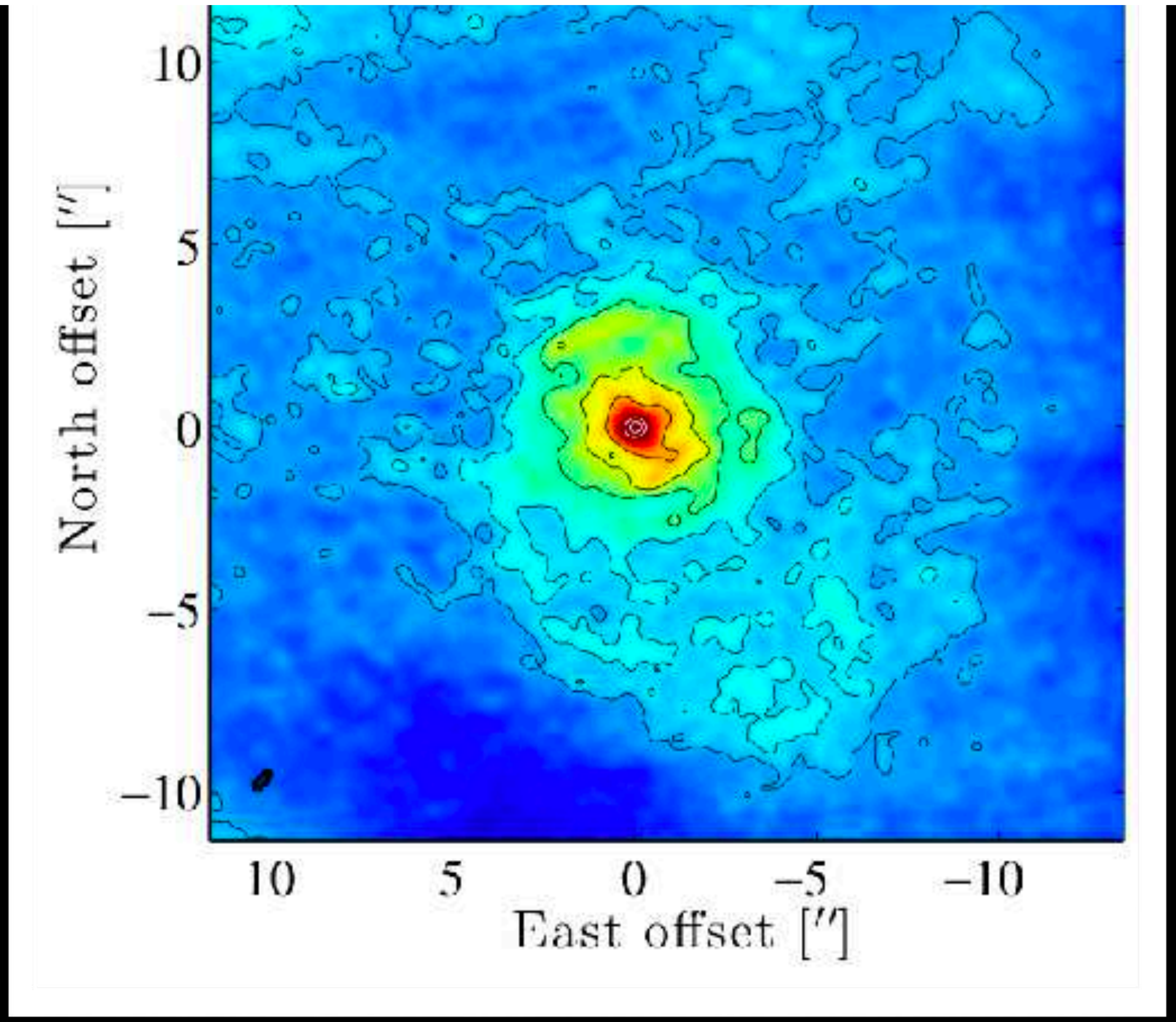




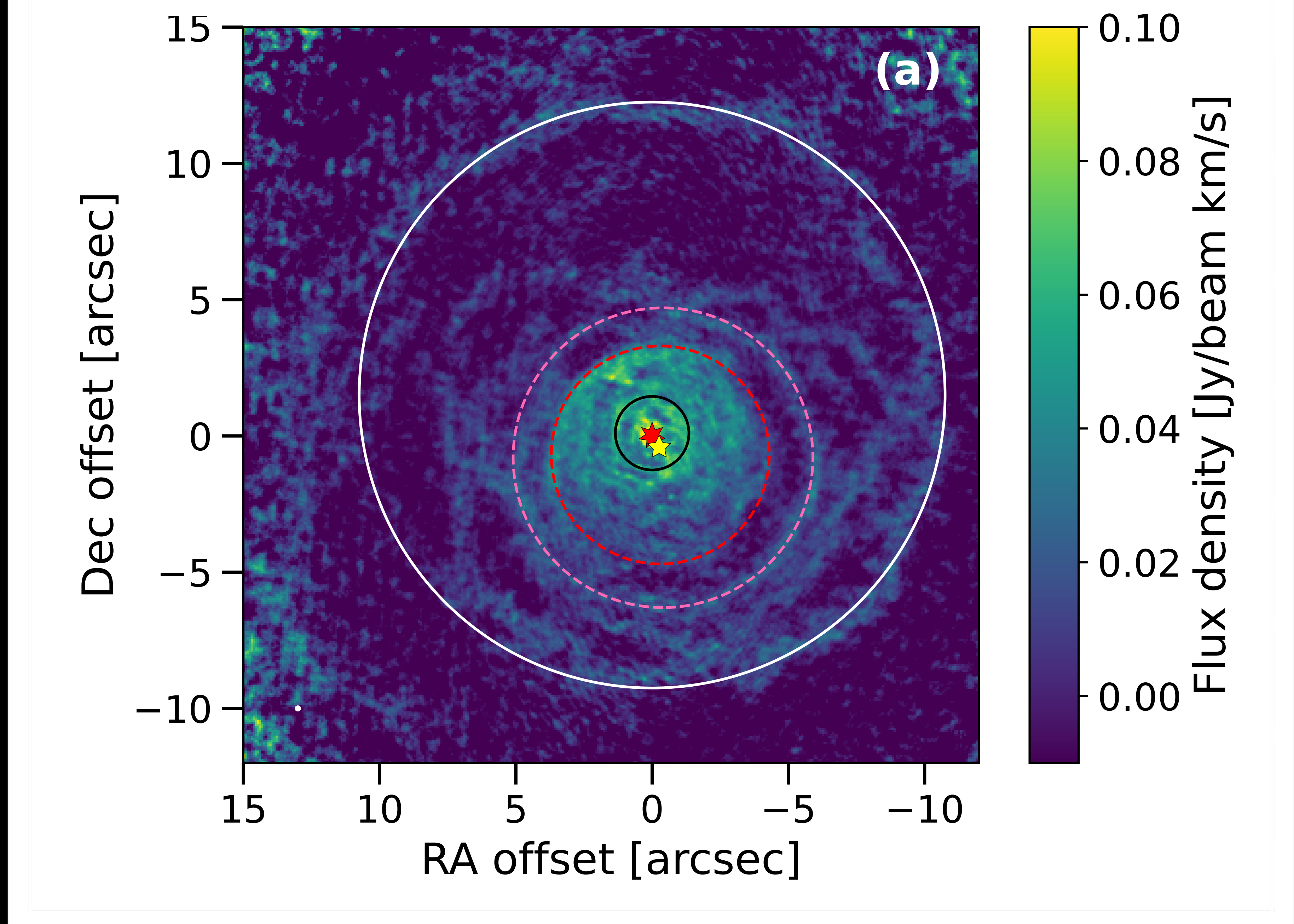
Use MCFOST to process SPH

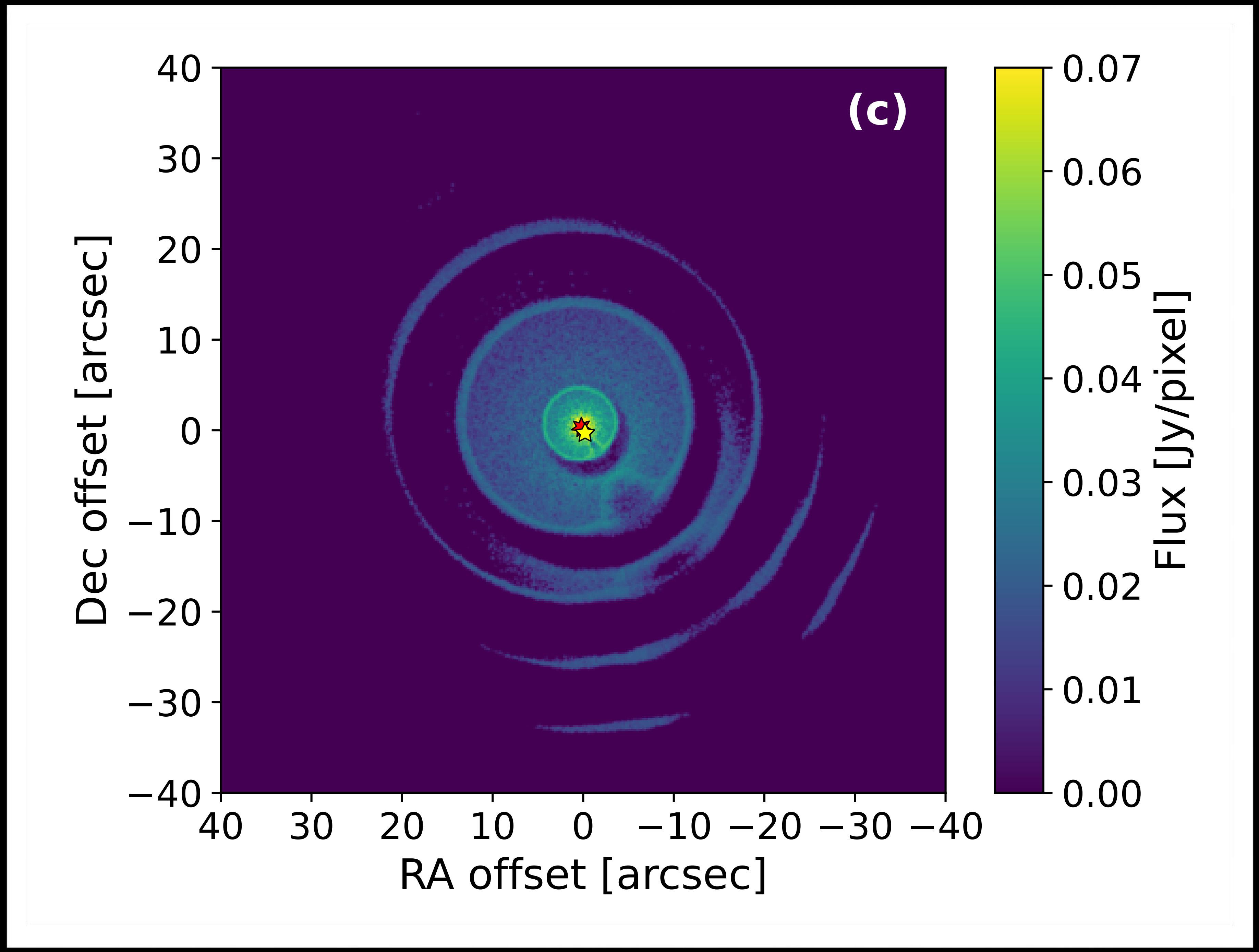
- Process Phantom model with MCFOST
- Get channel maps
  - Includes photodissociation 👍

CO (3-2) Ramstedt et al 2017

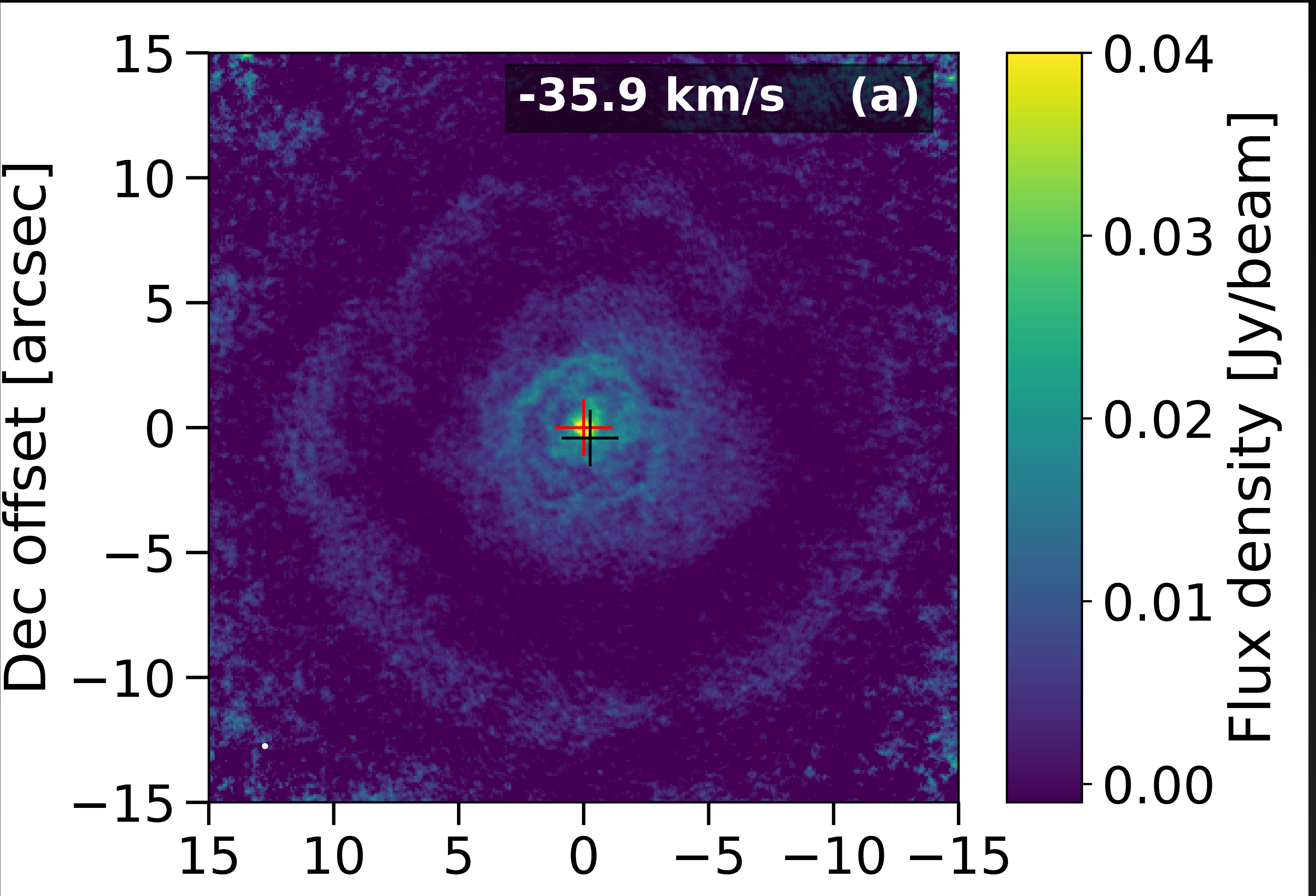


CO central 3 channels

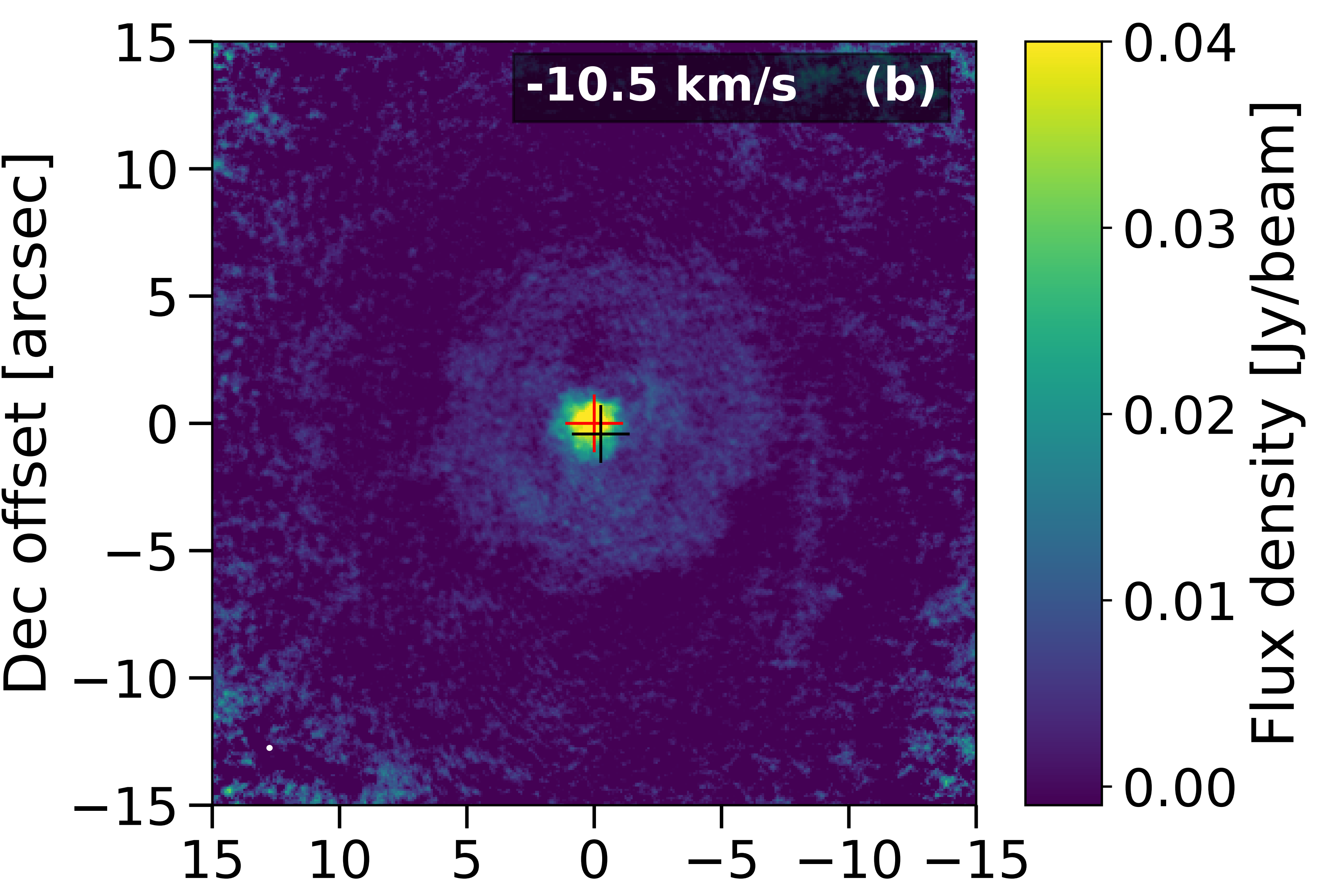




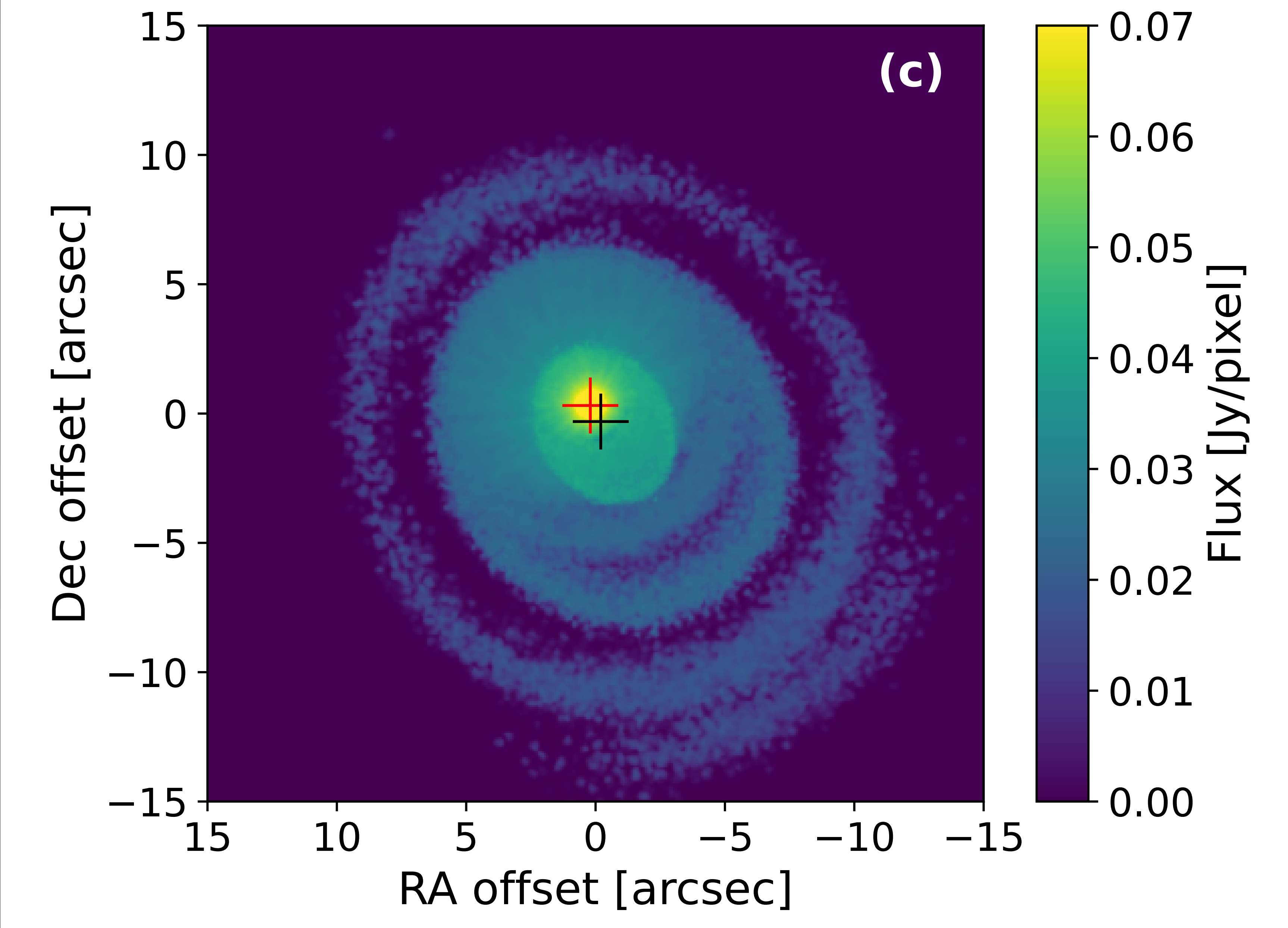
High and low velocity channels



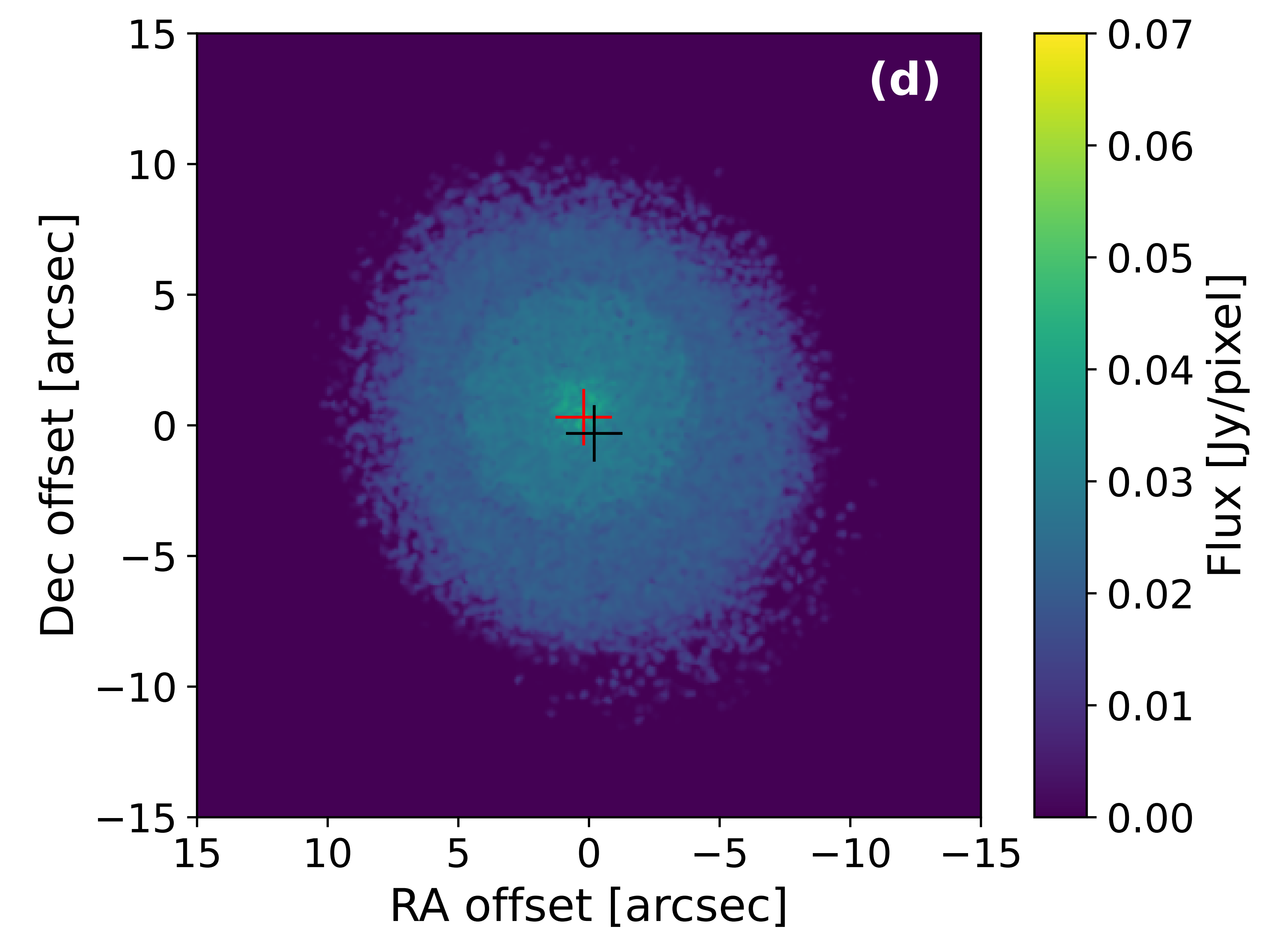
ALMA



Asymmetry between high/low velocity velocity channels solves another long-standing W Aql mystery



Phantom + MCFOST



“Blue Blob”

In spectral line profiles

- Explained using the SPH model
- Asymmetric red/blue channels
- Manifests on blue side (coming towards us) if companion moves into the sky (away from us) during periastron
- Therefore, we were able to constrain direction of orbital motion
  - Can’t measure any other way except during periastron in ~900 years!

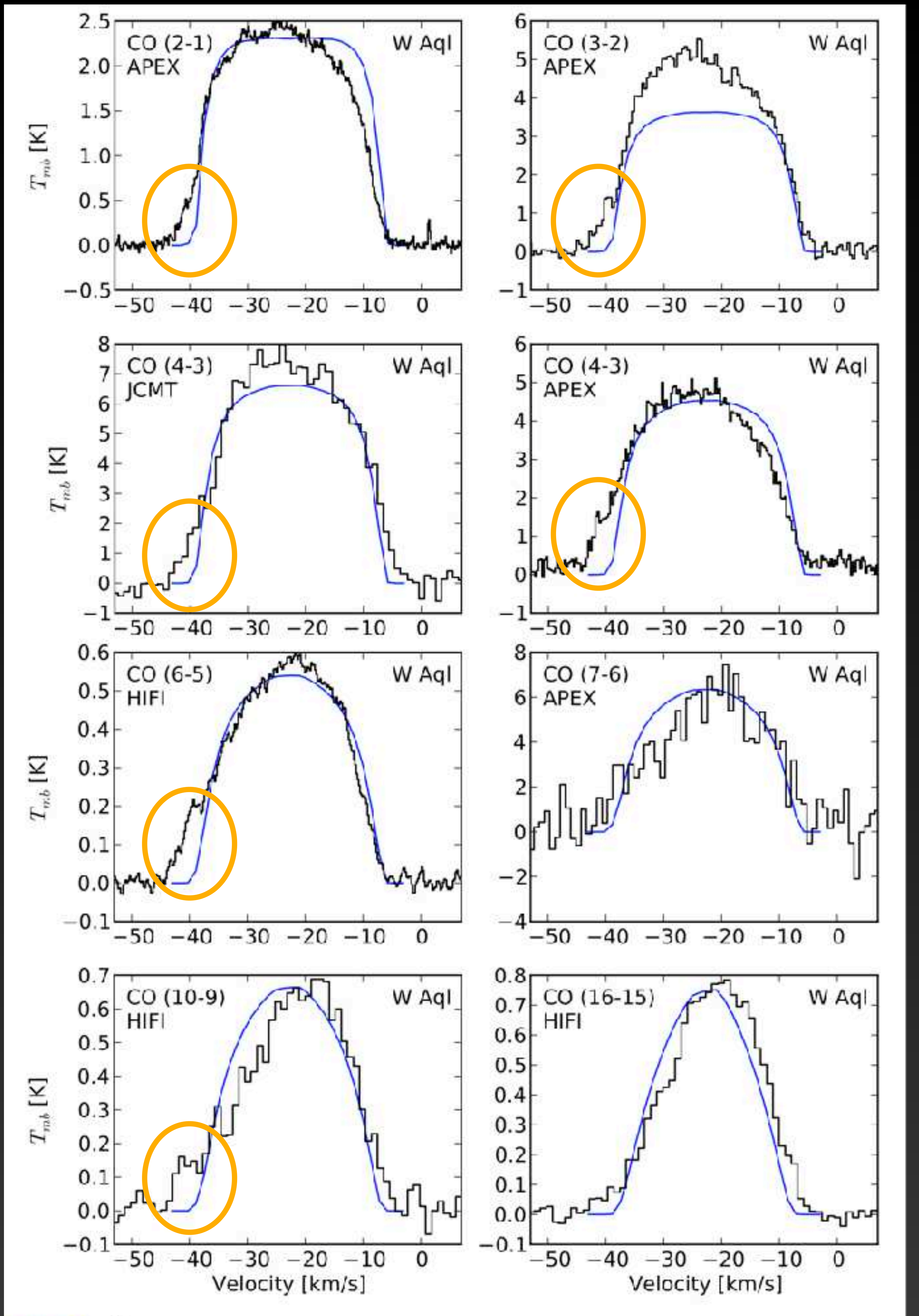


Fig. 6. ^{12}CO model line profiles (solid blue lines) and observed data (black histograms). Model parameters are listed in Table 6.

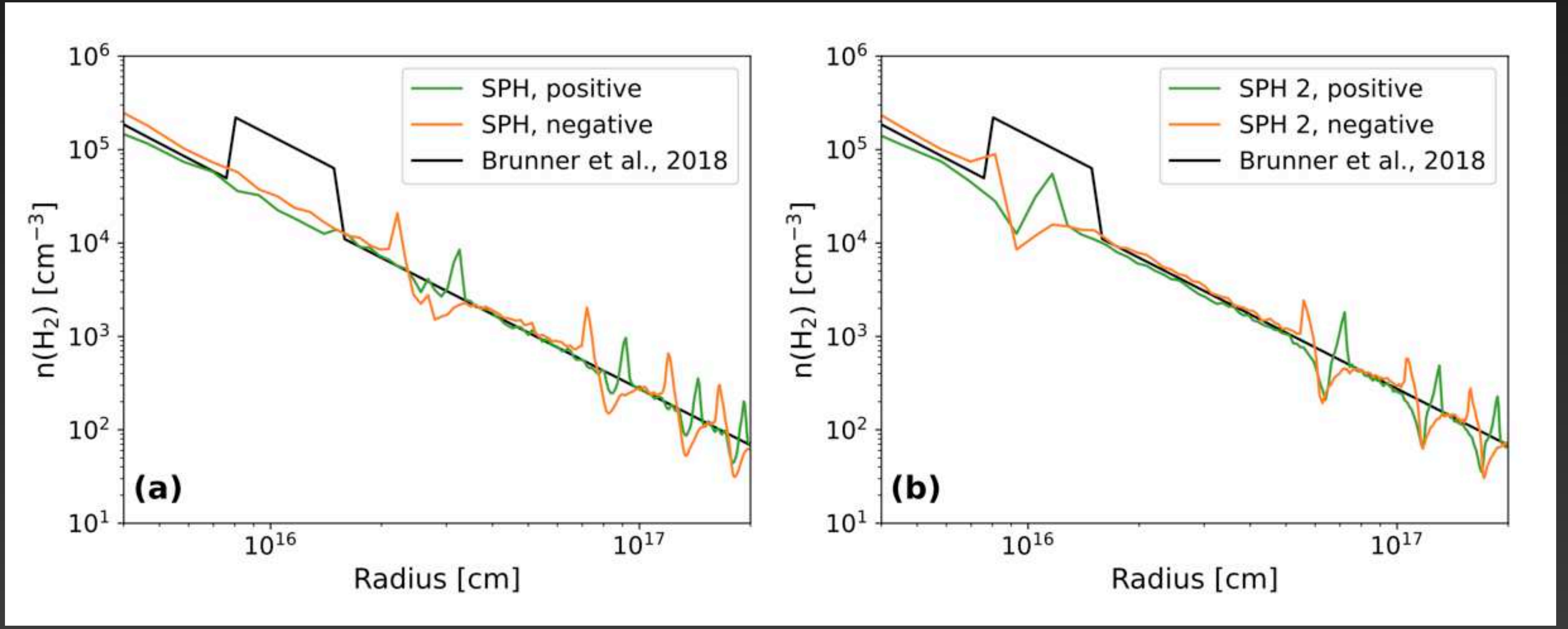
Plot from Danilovich et al (2014)

Analysing the density distribution

- Earlier radiative transfer modelling of lower-res ALMA data found a need for a radial overdensity (Brunner, Danilovich, et al 2018)
- People have assumed that periastron causes enhanced mass loss
- Phantom model just rearranges material
- Small accretion radius enhances asymmetry

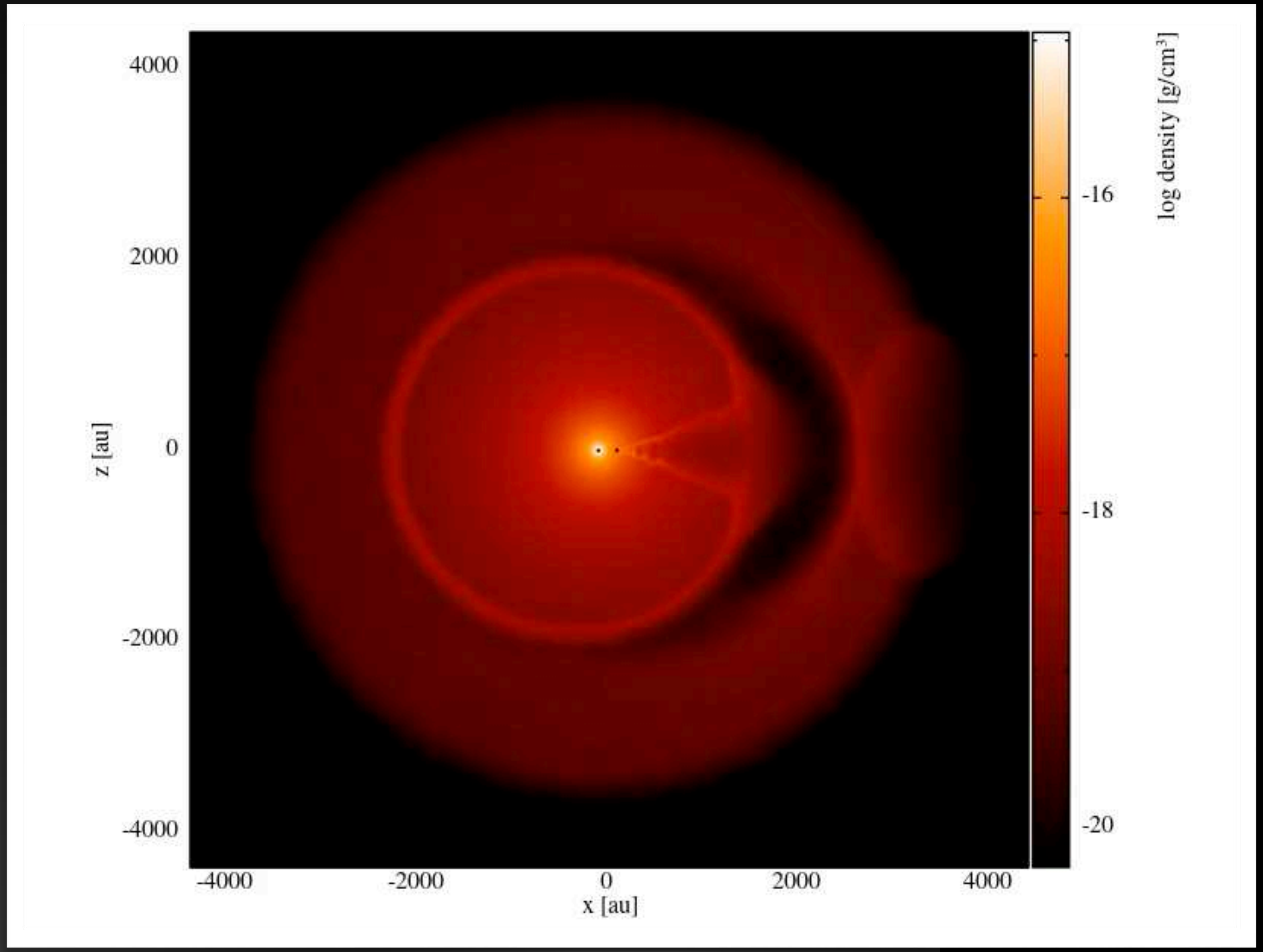
Jolien's model

Supplementary test model

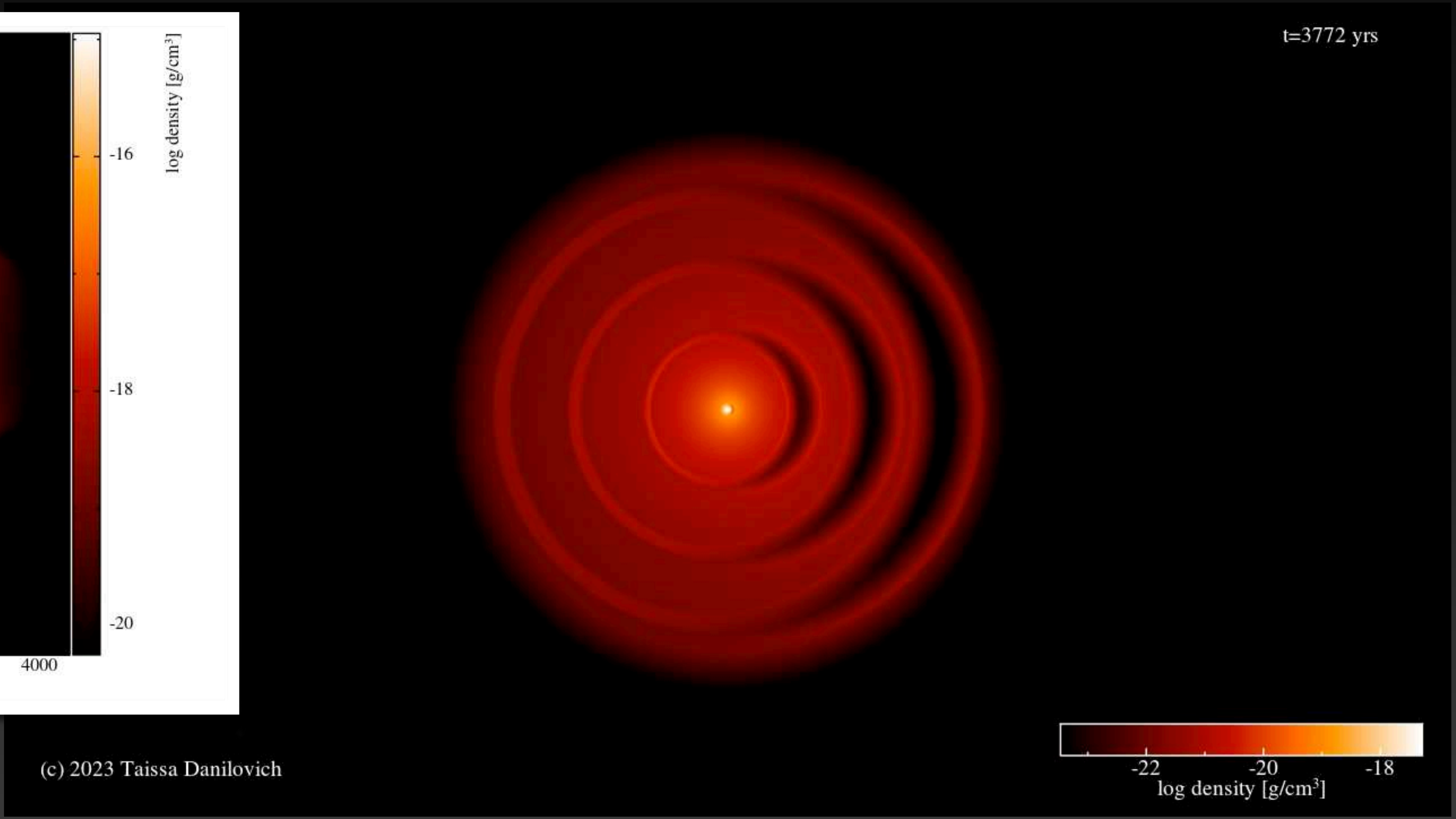


Small vs large accretion radii

$r_{acc} = 0.05$ au



$r_{acc} = 1$ au

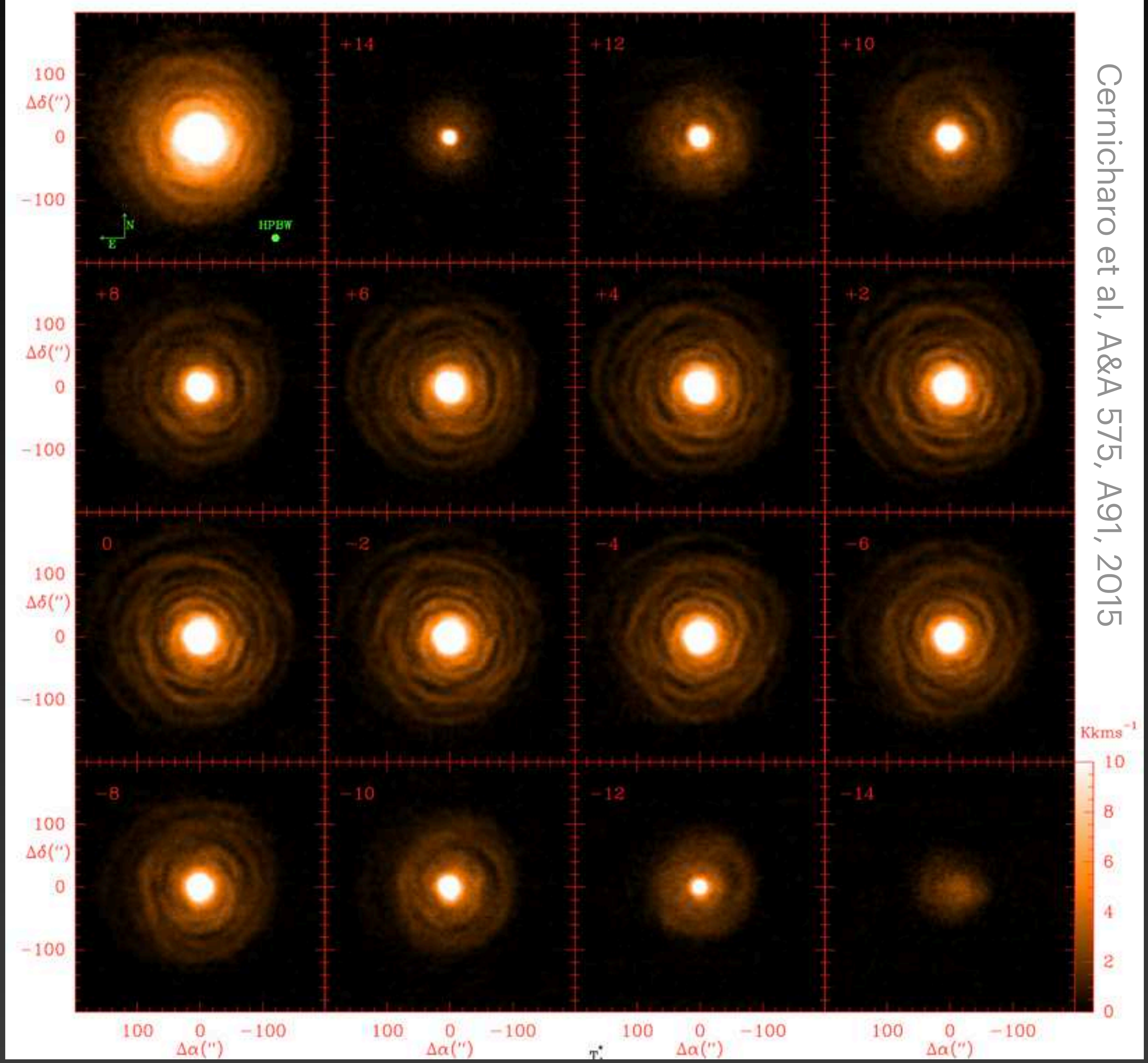


(c) 2023 Taissa Danilovich

Compare with CW Leo / IRC +10216

(aka, the Peanut Nebula 🥜)

- CW Leo is the closest (120 pc) carbon star and the most-studied AGB star
- Lots of shells very clearly seen in dust, CO, various other molecules
- Cernicharo et al predict a 800 yr eccentric orbit, where periastron increases mass-loss rate
- But! We don’t need variable mass-loss to explain shells

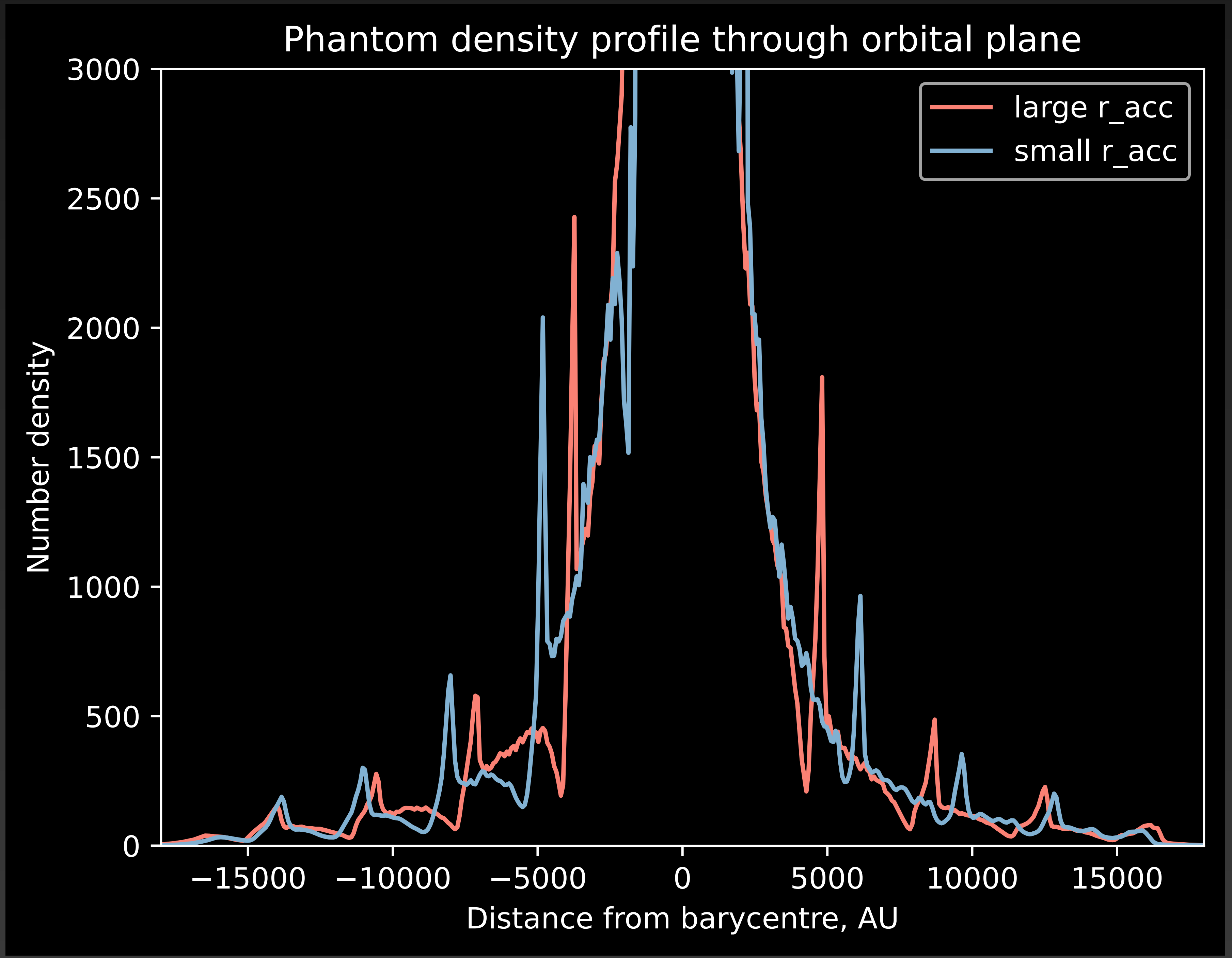


Cernicharo et al, A&A 575, A91, 2015

CW Leo intensity distribution

(Still Cernicharo et al 2015)

- The observed radial intensity distribution for CW Leo (east to west) is similar to W Aql Phantom (number density) distribution.



CW Leo intensity

W Aql density

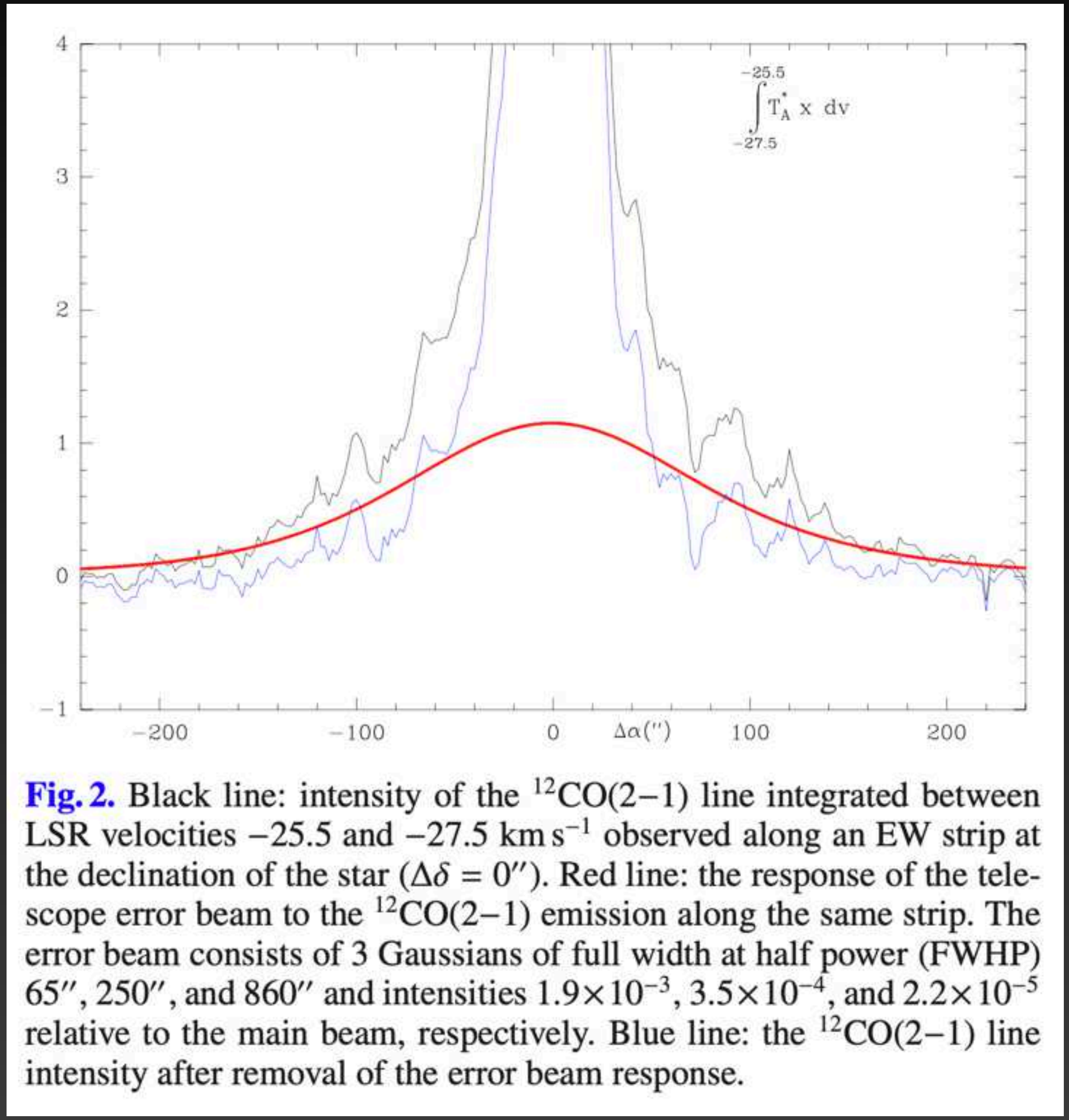


Fig. 2. Black line: intensity of the $^{12}CO(2-1)$ line integrated between LSR velocities −25.5 and −27.5 km s^{-1} observed along an EW strip at the declination of the star ($\Delta\delta = 0''$). Red line: the response of the telescope error beam to the $^{12}CO(2-1)$ emission along the same strip. The error beam consists of 3 Gaussians of full width at half power (FWHP) 65'', 250'', and 860'' and intensities 1.9×10^{-3}, 3.5×10^{-4}, and 2.2×10^{-5} relative to the main beam, respectively. Blue line: the $^{12}CO(2-1)$ line intensity after removal of the error beam response.

CW Leo intensity distribution

(Still Cernicharo et al 2015)

- The observed radial intensity distribution for CW Leo (east to west) is similar to W Aql Phantom (number density) distribution.
- Cernicharo et al used a toy model to reproduce the shells:
    - AGB star wobbles
    - Mass-loss increases during “periastron”
    - (No physical companion in the model)
- However! We can do better now.

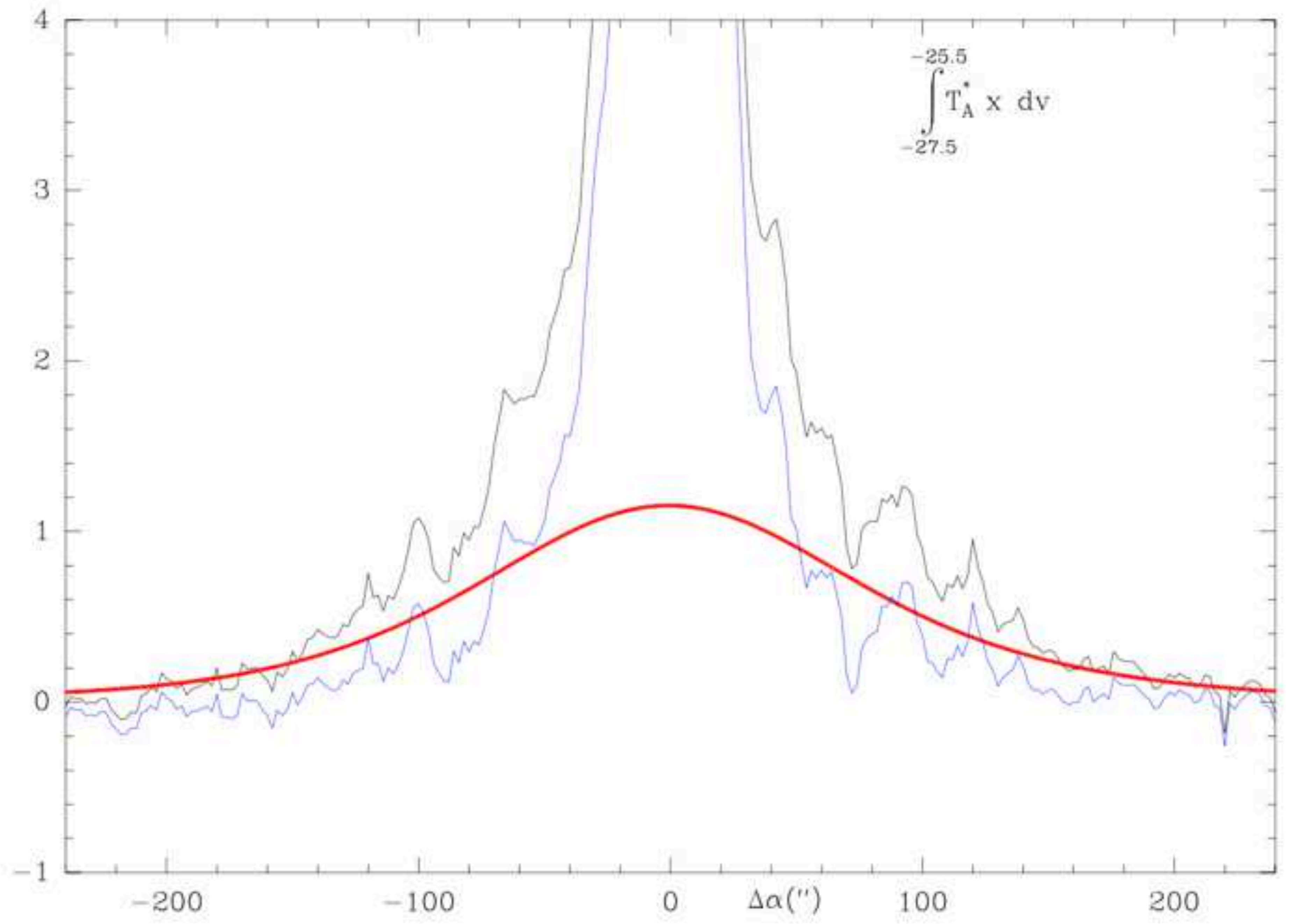


Fig. 2. Black line: intensity of the ^{12}CO(2−1) line integrated between LSR velocities −25.5 and −27.5 km s^{-1} observed along an EW strip at the declination of the star ($\Delta\delta = 0''$). Red line: the response of the telescope error beam to the ^{12}CO(2−1) emission along the same strip. The error beam consists of 3 Gaussians of full width at half power (FWHP) 65″, 250″, and 860″ and intensities 1.9×10^{-3}, 3.5×10^{-4}, and 2.2×10^{-5} relative to the main beam, respectively. Blue line: the ^{12}CO(2−1) line intensity after removal of the error beam response.

A Phantom + MCFOST model for CW Leo

Coming later this year from Nimantha

- Carbonaceous dust formation implemented in Phantom (see Luis's talk earlier on common envelope model)
- Going to test dust formation induced by shocks from companion motion
- (Other models do find dust forms in the wake of shocks – Freytag & Höfner, 2023)
- Can the companion account for CW Leo's dustiness?

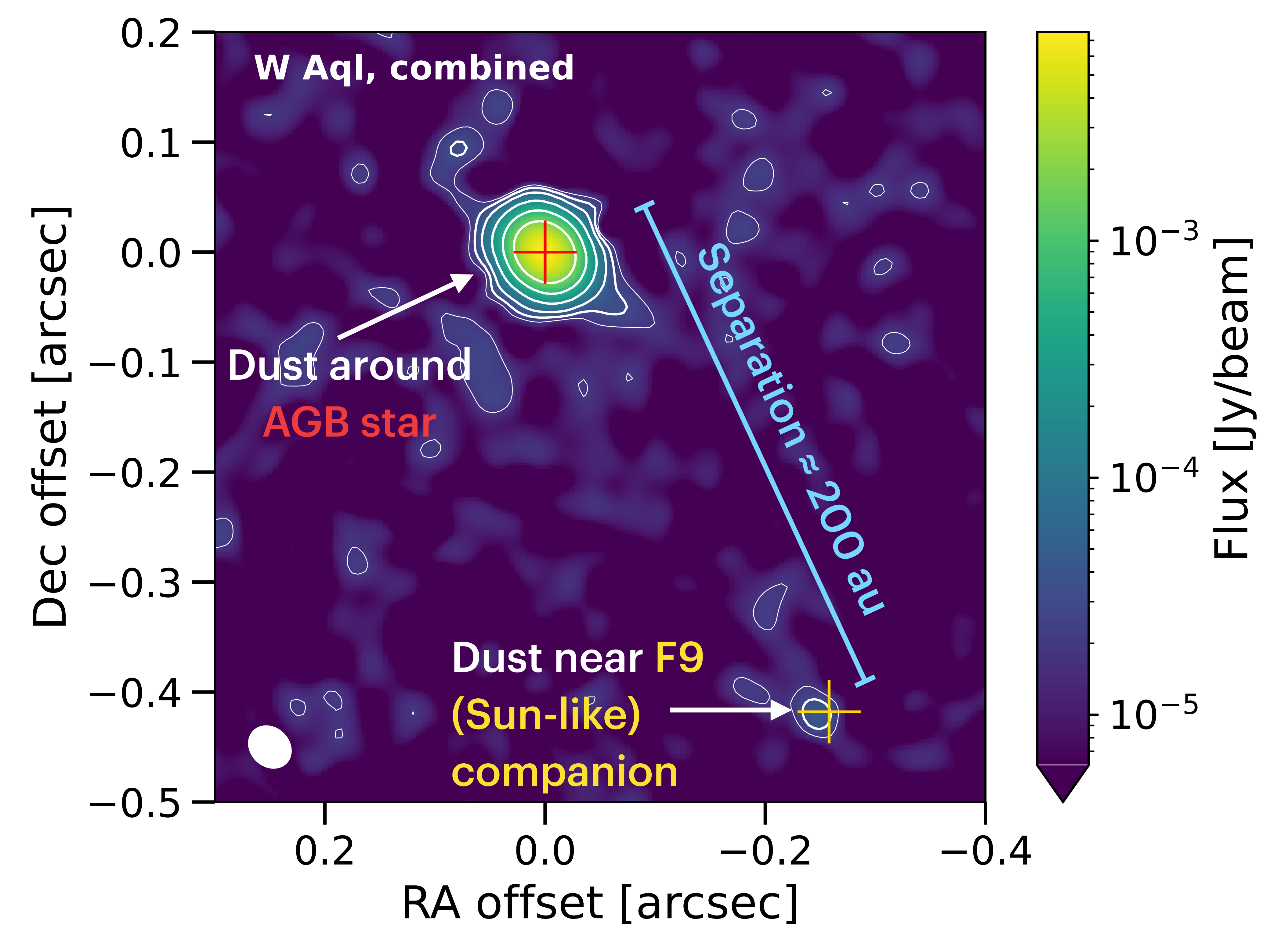
NASA/STScI

Peanut? 🥜

Dust and companions

- W Aql model did not include any dust
- We know W Aql is a dusty star, 2 mag of extinction for F9 companion
- But CW Leo is dustier
- Even for W Aql we see some dust forming near the companion, even though it's 200 au from the AGB star!
- CW Leo + closer companion = more dust? Nimantha will find out

ALMA continuum



Some caveats for CW Leo

- It's the most-studied AGB star but we only have indirect evidence for a companion
- (Also true of many other AGB stars)
- Dust obscuring optical, etc starlight?
- Small & faint companion?
- But there is evidence of UV-driven chemistry
- Delicate balance between observational evidence and model parameters


NASA/STScI
Peanut? 🥜

Broader implications?

- If companions in the wind cause shocks
- And (additional) dust forms in the wake of shocks
- And more dust leads to more mass-loss…
- Does having a companion lead to a higher mass-loss rate?

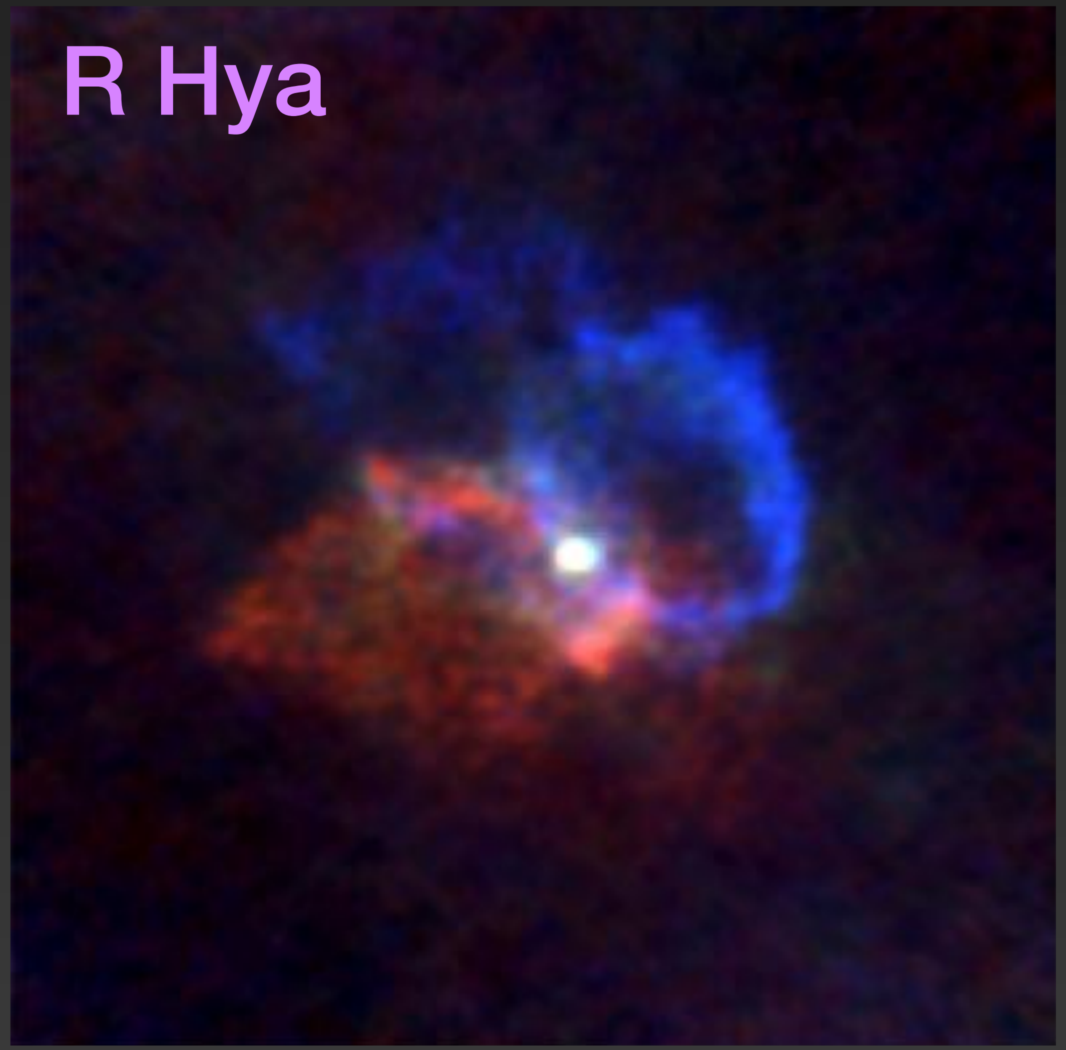
- If most AGB stars observed at high enough resolution with ALMA have companions…
- Are we just not seeing the single stars because they have less dust and hence lower mass-loss rates?

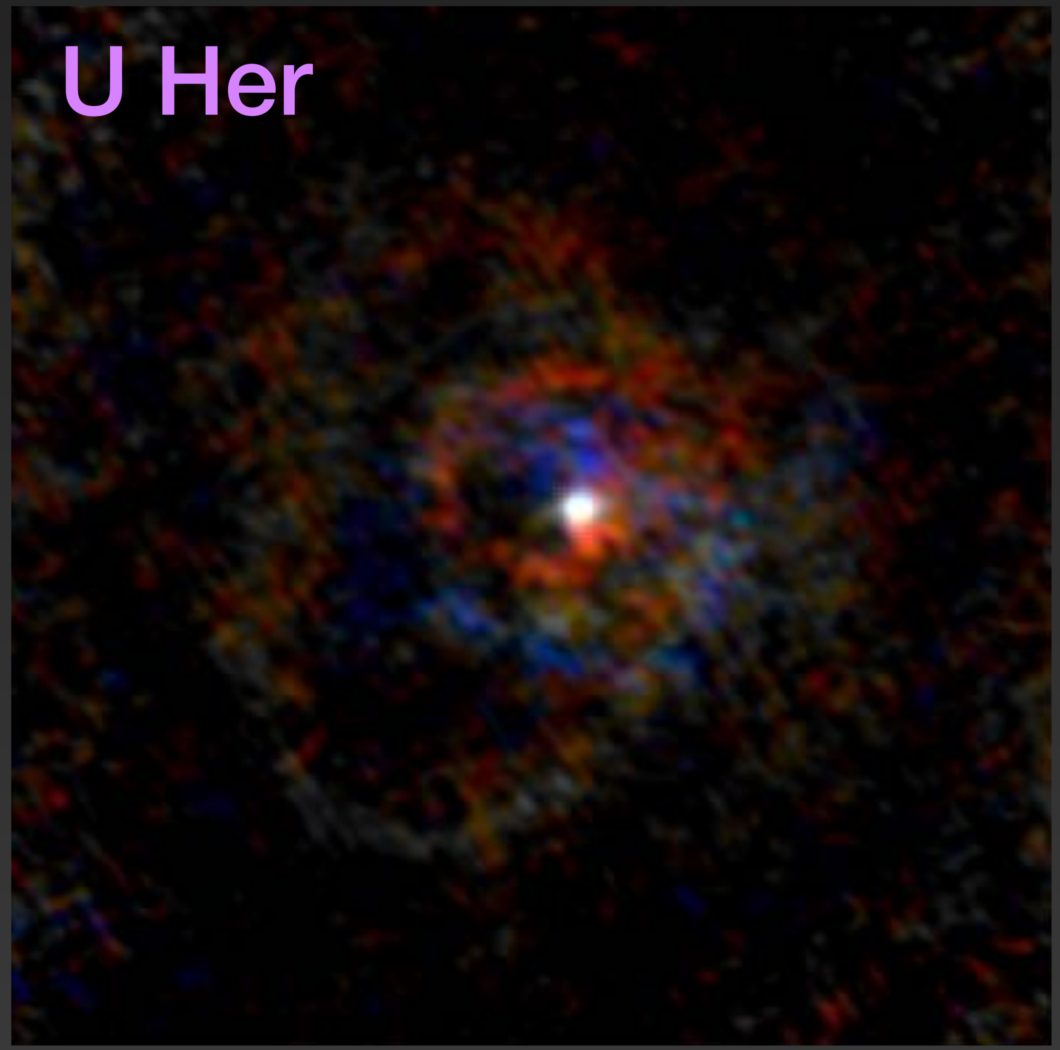
Watch this space...

Luckily, there is still a lot of ALMA data to analyse...

Summary

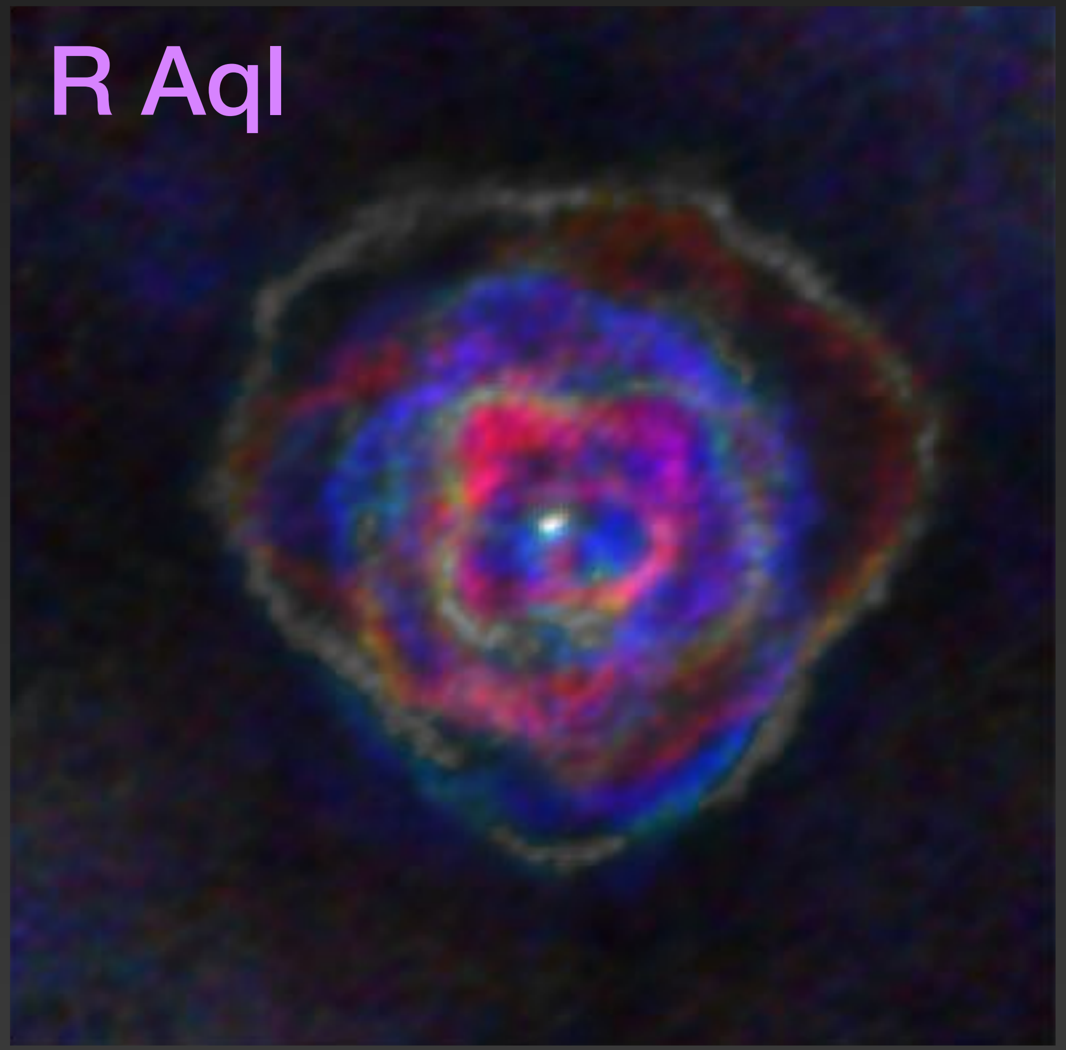
- Phantom + MCFOST + ALMA + chemistry = characterise binary orbits
- Next, checking dust formation in binary wake (Nimantha)
- And dust distributions in ALMA
- Also, lots of weird stars left to try to understand…


R Hya


U Her


π^1 Gru

Montarges et al (in prep)


R Aql

Advances in Cool Evolved Stars

8–12 July, 2024 in Melbourne, Australia

The ACES conference will be held at Monash University in Melbourne, Australia over 8–12 July, 2024.

The goal of ACES is to bring together researchers working on all aspects of cool evolved stars — especially AGB and post-AGB stars and red supergiants.

Registration and abstract submission are now open.

The abstract submission deadline is 15 March 2024.

URL: https://sites.google.com/monash.edu/aces/home