

# Time dependent synthetic observables of 3D models of AGB stars and dusty winds



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### Project EXWINGS:

- ▶ Explaining the WINds of cool Giant and Supergiant stars with global 3D models
- ▶ <https://www.astro.uu.se/exwings/index.html>

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**Astronomy  
&  
Astrophysics**

## Global 3D radiation-hydrodynamical models of AGB stars with dust-driven winds

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**Astronomy  
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Astrophysics**

## Asymmetries in asymptotic giant branch stars and their winds

### I. From 3D RHD models to synthetic observables

Joachim Wiegert<sup>✉</sup>, Bernd Freytag<sup>✉</sup>, and Susanne Höfner<sup>✉</sup>

## Asymmetries in asymptotic giant branch stars and their winds

### II. Observability of clumpy dust cloud formation

Joachim Wiegert<sup>1</sup>, Bernd Freytag<sup>1</sup>, and Susanne Höfner<sup>1</sup>

# Asymptotic Giant Branch (AGB)

Late evolutionary stage of  $0.8 - 8 M_{\odot}$  stars

## Structure

- ▶ Hot **core of carbon and oxygen**.
- ▶ Helium  $\rightarrow$  carbon fusion in **inner shell**.
- ▶ Hydrogen  $\rightarrow$  helium fusion in **outer shell**.
- ▶ Huge **convective layer**. Up to  $300-400 R_{\odot}$ .

## Properties

- ▶ Pulsations, convection, dredge-ups, massive outflows of gas.
- ▶ Dust formation and dust-driven winds cause mass losses of  $10^{-8}$  to  $10^{-4} M_{\odot}/\text{yr}$ .

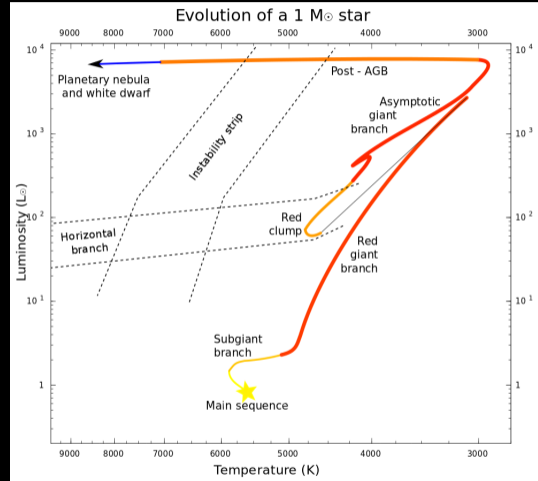


Figure: [https://commons.wikimedia.org/wiki/File:Evolutionary\\_track\\_1m.svg](https://commons.wikimedia.org/wiki/File:Evolutionary_track_1m.svg)

# Project

## Code summary and aims

### ▶ CO5BOLD

3D radiation-hydrodynamical (RHD) simulations of convection in AGB stars, dust and wind-formation, and outflow of material.

(Freytag et al. 2012, and Freytag & Höfner 2023)

### ▶ RADMC-3D

3D radiative transfer through dust (Dullemond et al. 2012).

## Aims

- ▶ Employ CO5BOLD models in RADMC-3D
  - Create large sets of time-dependent synthetic observations.
- ▶ Statistics and predictions on the formation and prevalence of observable dust clouds.  
**How often and for how long within region where winds start? (2 to 6  $R_*$ .)**
- ▶ Compare with observations.
  - Dust emission features.
  - Photocenter movements.
  - Synthetic Stokes parameters.

# Project

## Model data

### Stars

- ▶  $1 M_{\odot}$ , M-type. Period: 1.5 yrs
- ▶ Averages:  
 $7000 L_{\odot}$ , 2800 K,  $355 R_{\odot}$  (1.65 au)

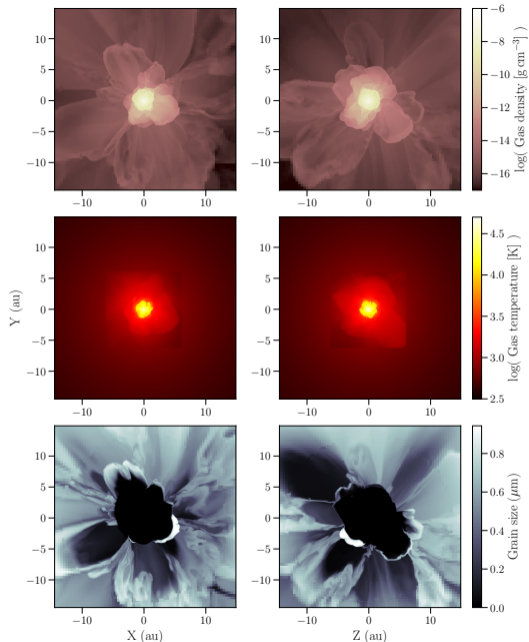
### Dust

- ▶  $\text{Mg}_2\text{SiO}_4$  (Forsterite-like)
- ▶ Grains  $< 1 \mu\text{m}$ .
- ▶ Distribution of hollow spheres.  
etc.

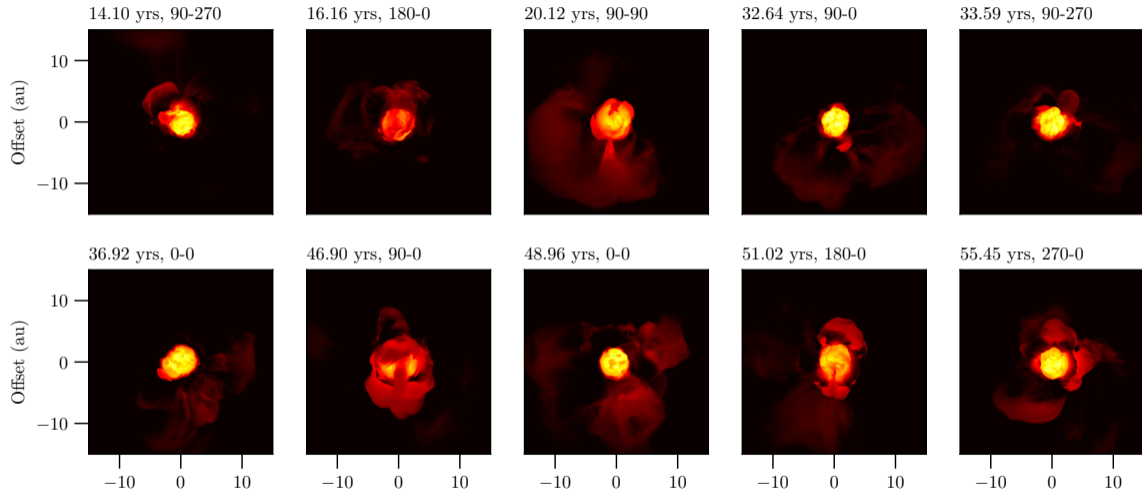
### 3 Models

Different sticking coefficient ( $\alpha_{\text{stick}}$ )

- ▶ **Model-A:** 1 ( $\sim 5 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ )
- ▶ **Model-B:** 0.1 ( $\sim 2 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ )
- ▶ **Model-C:** 0.01 ( $\sim 0.1 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ )

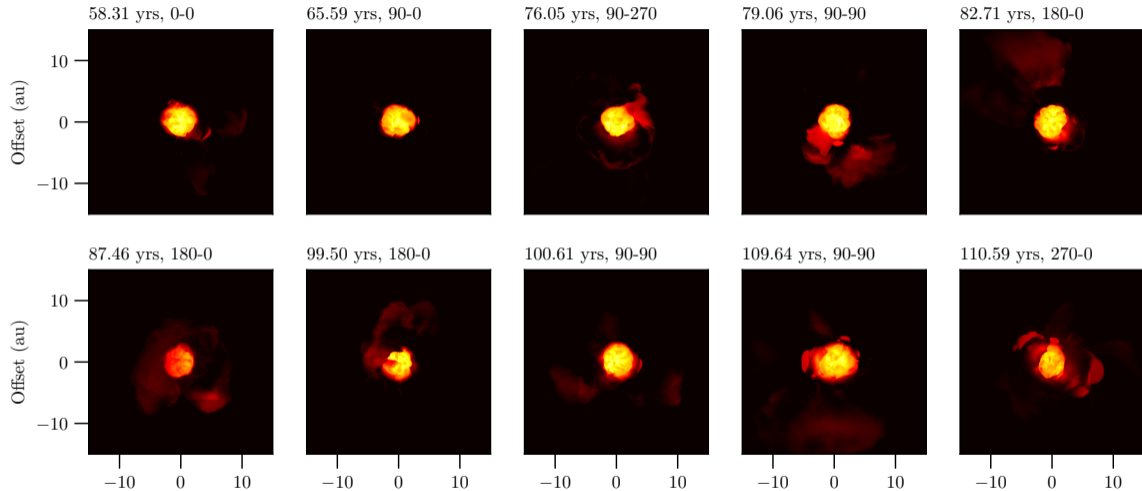


## Results: Model-A, sticking coefficient = 1



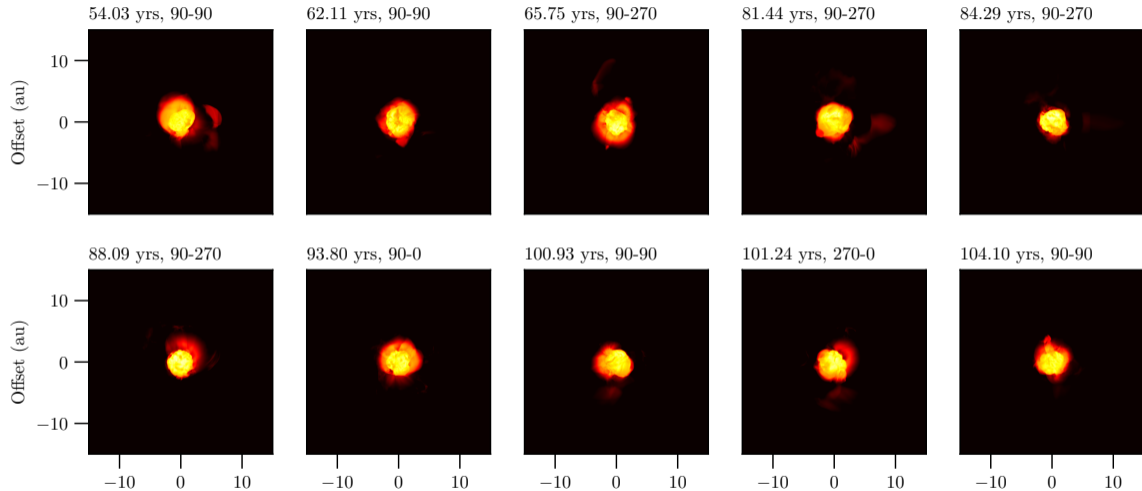
► Images at 10  $\mu\text{m}$  of random snapshots and LOS-angles (non-linear flux scale).

## Results: Model-B, sticking coefficient = 0.1



► Images at 10  $\mu\text{m}$  of random snapshots and LOS-angles (non-linear flux scale).

## Results: Model-C, sticking coefficient = 0.01

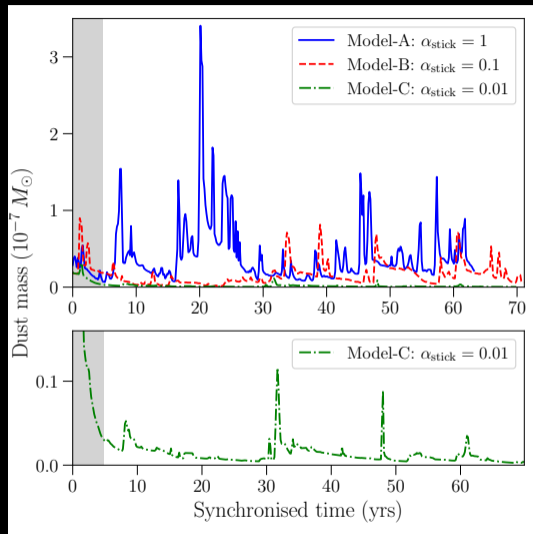


► Images at 10  $\mu\text{m}$  of random snapshots and LOS-angles (non-linear flux scale).

# Results

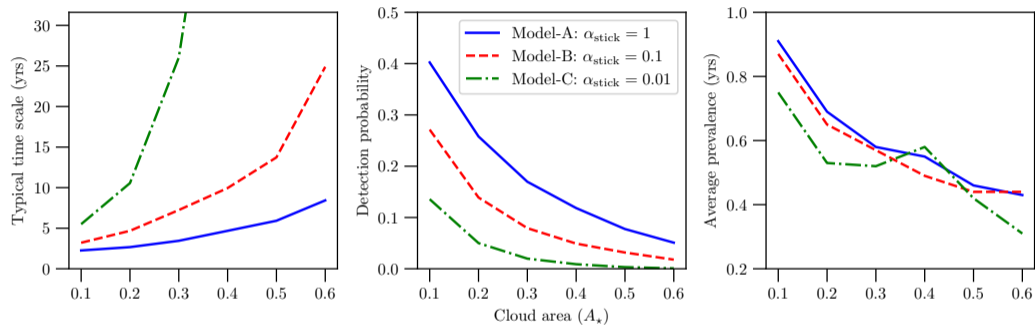
## Dust mass as function of time

- ▶ **Average dust mass:**
  - **A:**  $4.2 \times 10^{-8} M_{\odot}$
  - **B:**  $1.5 \times 10^{-8} M_{\odot}$
  - **C:**  $1.3 \times 10^{-9} M_{\odot}$
- ▶ **B** & **C** not relaxed for  $\sim 5$  years.
- ▶ Less than an order of magnitude difference between **Models A** and **B**.
- ▶ Dramatic local differences.
- ▶ Fast variations due to dust destruction.
- ▶ Long term removal connected to winds.
- ▶ **Model-C:** Normally produces too small amounts of dust for dust-driven winds except in bursts (or “puffs”).



# Results

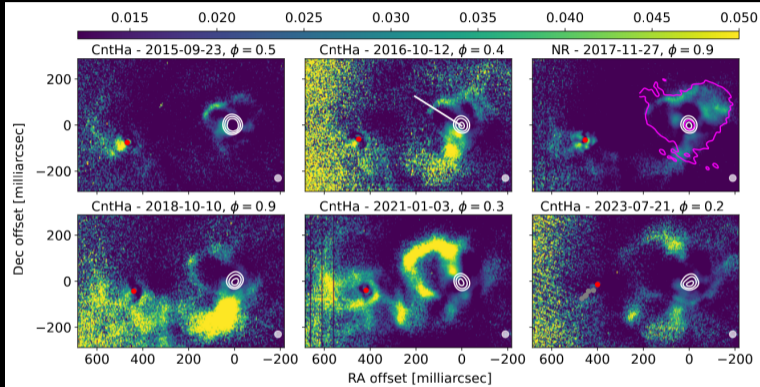
## Cloud statistics – Periods, probabilities



- ▶ Snapshots with at least one cloud that fulfils limits (flux & size in terms of stellar disc).
- ▶ Sporadic cloud formation should complicate observation planning.
- ▶ **Best case scenario:** 2-6 yrs periods, 0.8-0.9 yrs prevalence.
- ▶ **Worst case:** More than 70 yrs between events.

# Relevant observation

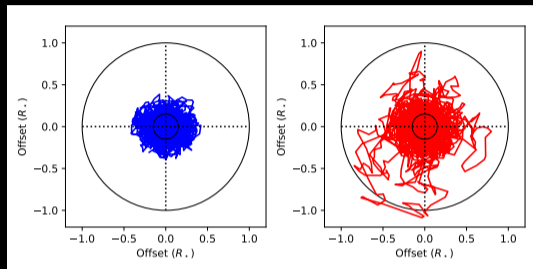
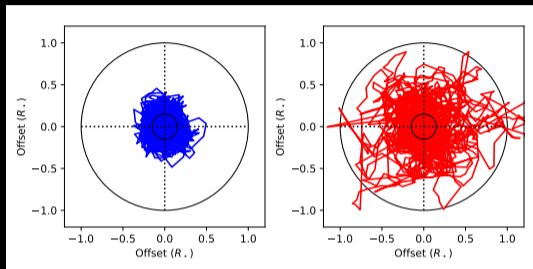
Khouri, T., Vlemmings, W. H. T., Raudales Oseguera D. A., et al. 2026, A&A



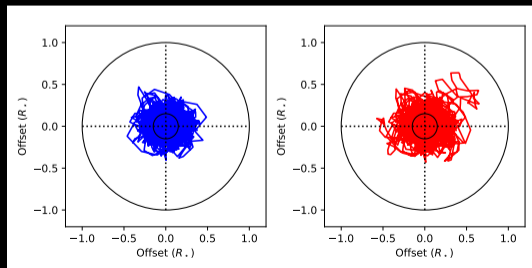
- ▶ Dust & gas emerging from Mira A. Polarized light at  $0.65$  and  $0.82 \mu\text{m}$  ( $100 \text{ mas} \sim 10 \text{ au}$ ).
- ▶ Massive gas ejecta. Should only form every 50-200 yrs to be the origin of Mira A's MLR
- ▶ **Model-C**:  $> 70$  yrs between dust-driven events with several "puffs" in a few years. (both with  $\text{MLR} \approx 10^{-7} M_{\odot} \text{ yr}^{-1}$ )

# Photocenter movements

Inspired by Béguin et al. (2024, A&A)

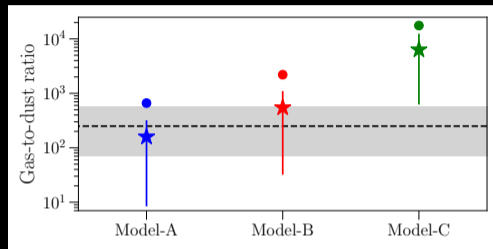


- ▶ About  $6 \times 70$  yrs of data combined.
- ▶ Blue (left panels): No dust.  $17\% \pm 9\%$  of  $R_*$ .
- ▶ **Model-A**: Top left.  $29\% \pm 22\%$
- ▶ **Model-B**: Top right.  $23\% \pm 16\%$
- ▶ **Model-C**: Bottom right.  $19\% \pm 11\%$
- ▶ At  $0.62 \mu\text{m}$  - Gaia's G-band.



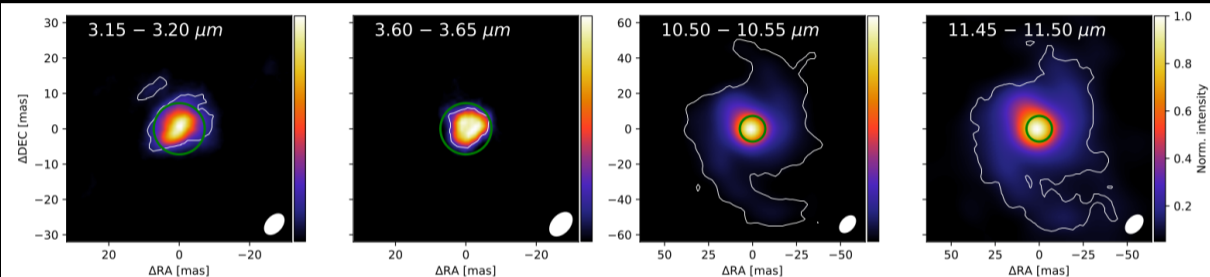
# Summary

- ▶ Large sets of synthetic images.
- ▶ Sporadic dust cloud formation complicates observational possibilities.
- ▶ **Best-case scenario:**
  - 2 to 6 yrs intervals
  - Clouds detectable for **0.8 to 0.9 yrs**.
- ▶ **A & B** very dramatic but overall similar to observed statistics. (right: Gas-to-dust ratio compared to NESS, Wallström et al, 2025, A&A).
- ▶ **Model-C** similar to Mira A?
- ▶ **Ongoing**
  - Photocenter data need to be compared with Gaia data.
  - Stokes parameters.



# Backup

Planquart, L., Paladini, C., Jorissen, A., et al. 2024, A&A, 687, A306

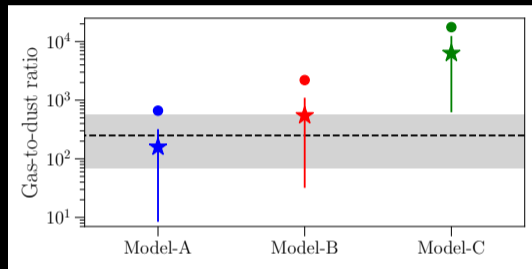
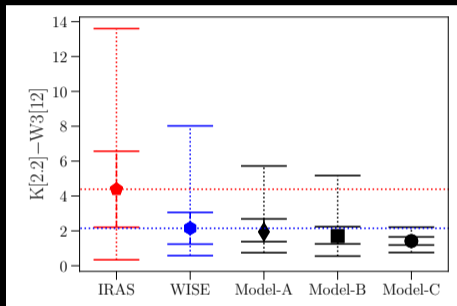


**Fig. 4.** MATISSE images of V Hya reconstructed with SQUEEZE at four different spectral ranges across the  $L$  and  $N$  bands. The green circle represents the expected star diameter of 14.5 mas as measured in the  $K$  band (Millan-Gabet et al. 2003). The white contour is drawn at  $3\sigma$  (as described in Appendix C). The white ellipse in the bottom right corner represents the mean synthesised primary beam.

- ▶ V Hya: Silicon and carbon-rich dust, compare our 10  $\mu\text{m}$  with their  $\gtrsim 10 \mu\text{m}$ .
- ▶ “[...] extension seen is likely to be related to the dust-forming region.”

# Backup

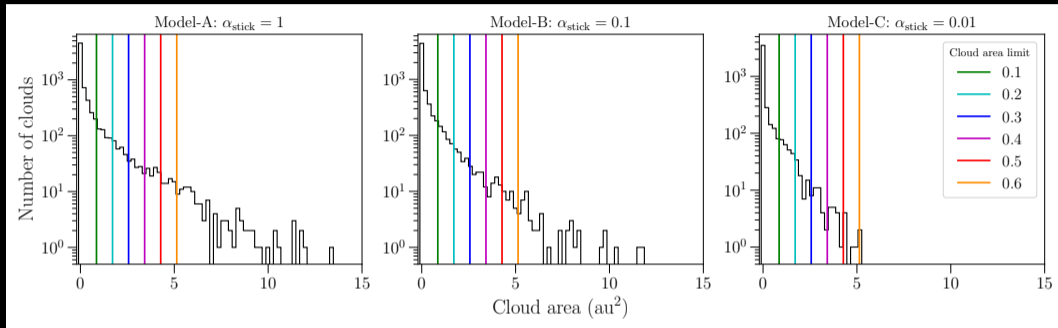
## Observed statistics comparison



- ▶ Models are within observed ranges of IR colours (Suh, K.-W. 2021, ApJS, 256, 43).
  - Caveat! No molecular lines in models so exact numbers may be different.
- ▶ And mostly for gas-to-dust ranges. (NESS from Wallström, S. H. J., et al. 2025, A&A, 704, A276).

# Backup

## Cloud statistics – numbers and sizes

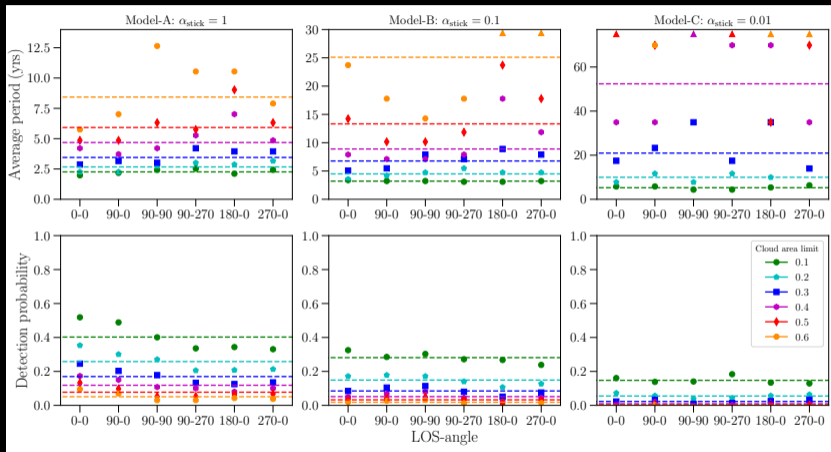


### Image cloud detection:

- ▶ Limited by flux density based on contrast to star and exposure time (i.e. roughly 30 min at 200 pc with VLTI) and within a 2 to 6  $R_*$  annulus.
- ▶ Cloud area limits are in order of average stellar disc area;  $A_*(R_* = 1.65 \text{ au})$ .
- ▶ General statistics on clouds  $> 0.1 A_*$ .

# Backup

## Cloud statistics – LOS dependence?



- ▶ Localised variation is large but spherically symmetric over large time scales. (Exception with low number statistics.)