RY Tau and HD 142666: insights from the CHARA/CLIMB YSO survey

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CHARA meeting 2018 – Paris, France – March 13th 2018

Talk Outline

- **Introduction to young stellar objects**
- **CHARA/CLIMB YSO survey**
- **RY Tau and HD 142666**
- **Methodology**
- **Insights from radiative transfer analysis**

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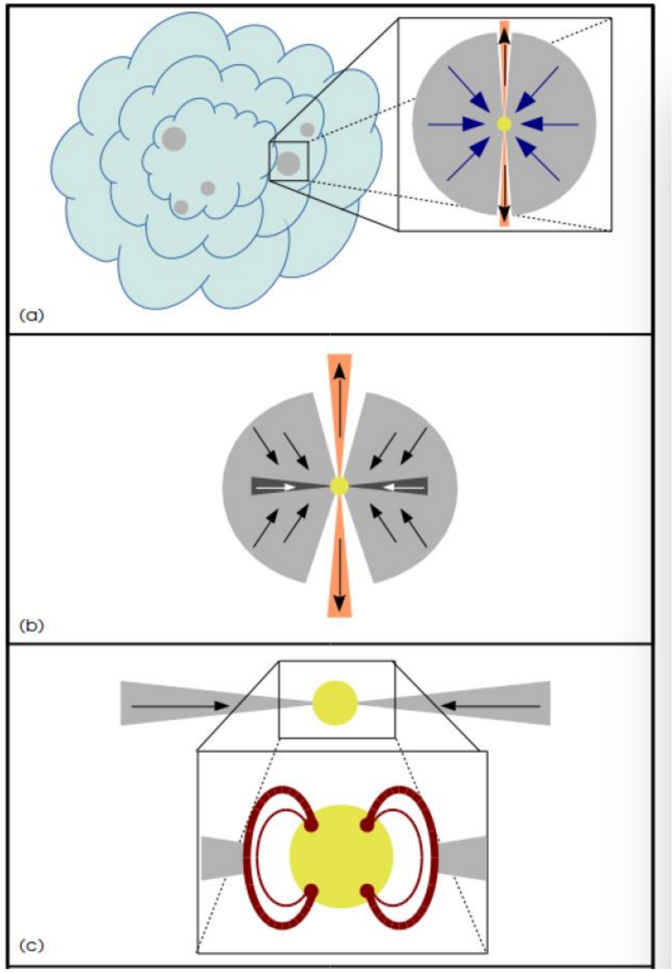
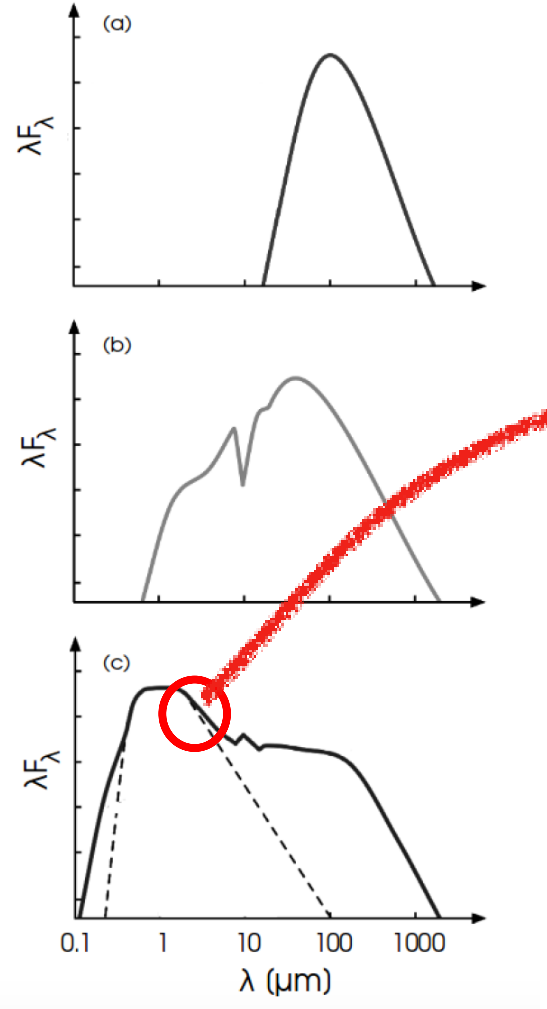
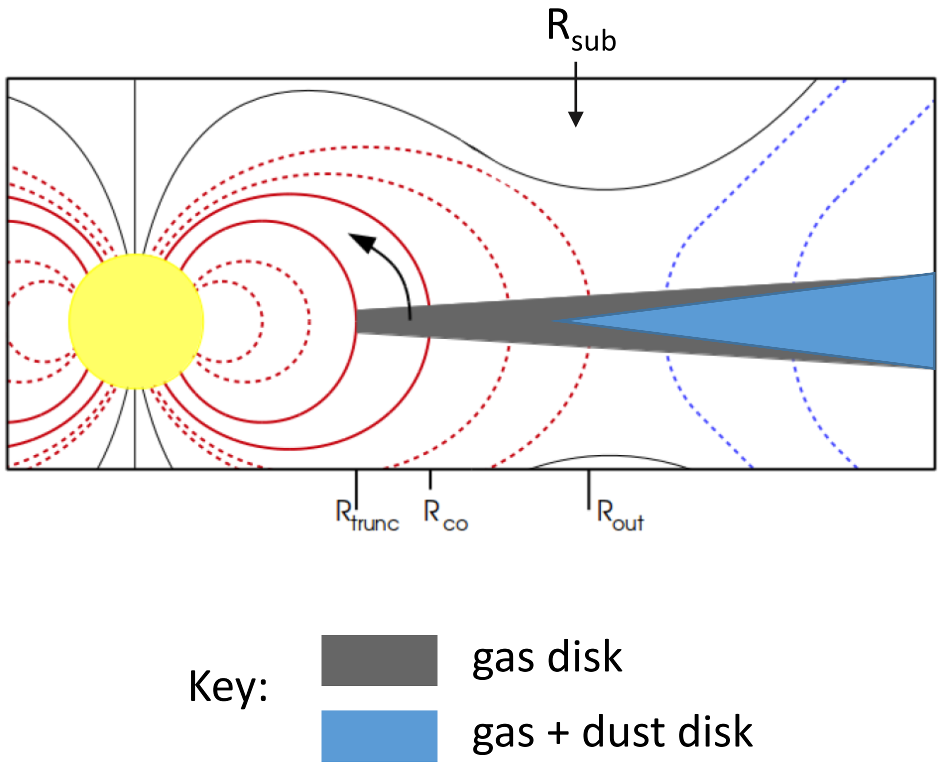
Introduction: Young Stellar Objects



Davies. C 2015 PhD Thesis





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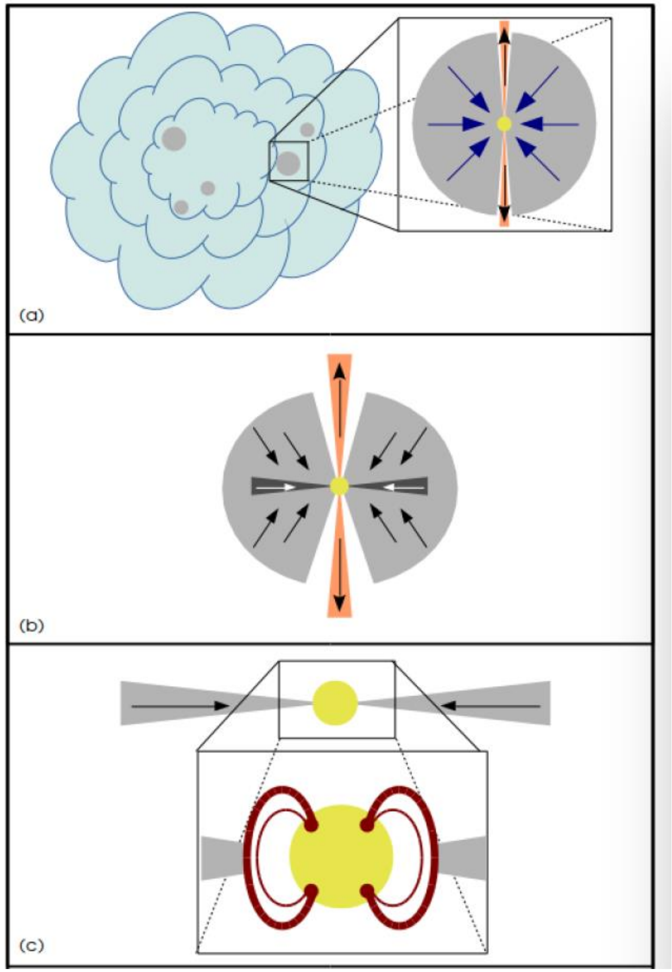

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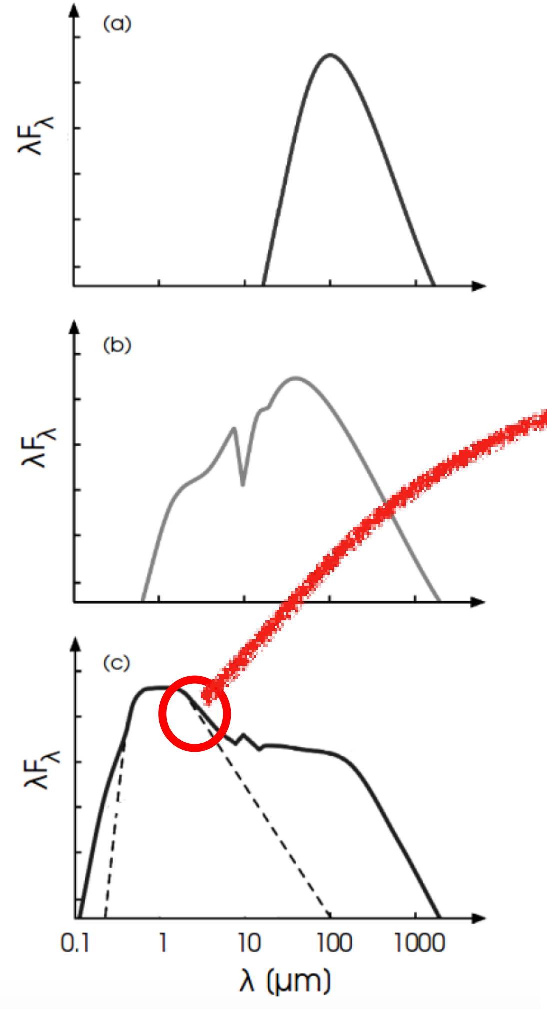
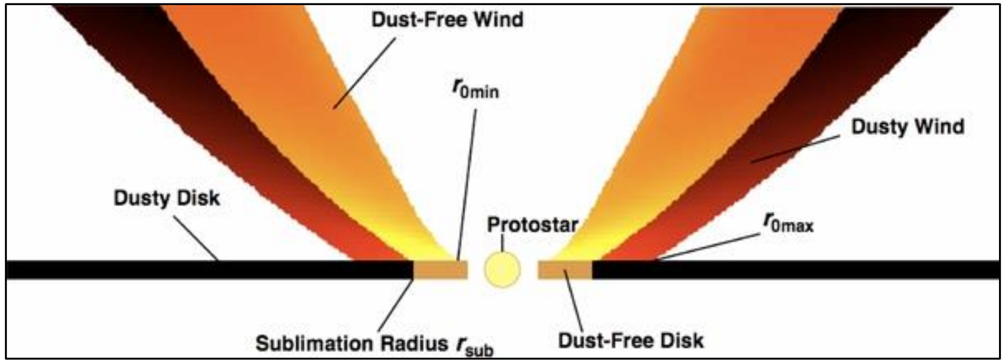
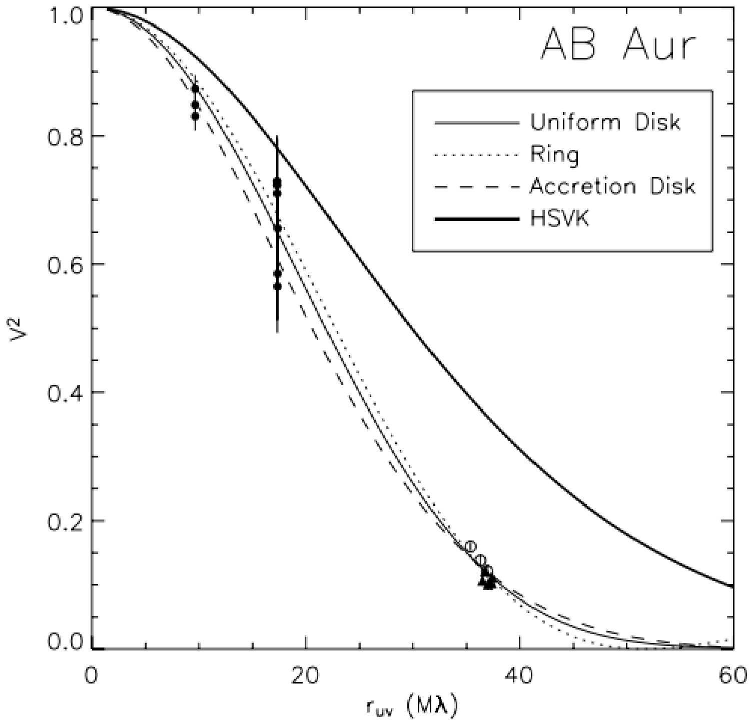




Bans & Konigl (2012)

Introduction: Young Stellar Objects

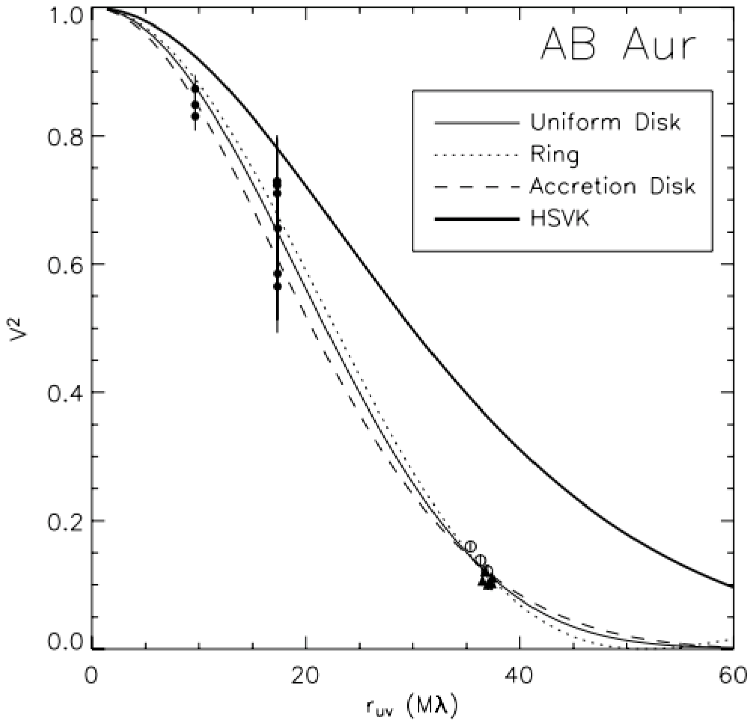
- Early, short baseline interferometric observations were fit well with ring models.



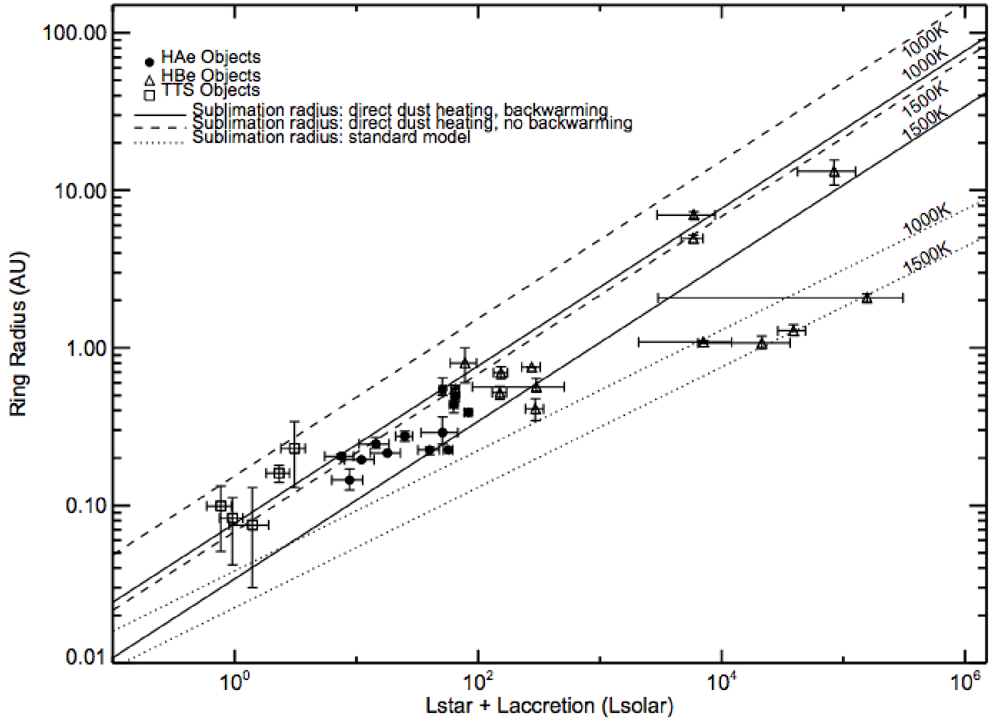
Eisner et al. (2003) – PTI data

Introduction: Young Stellar Objects

- Early, short baseline interferometric observations were fit well with ring models.
- The characteristic size of these rings scaled with stellar luminosity → near-constant temperature across sample.
- Emission likely associated with the dust sublimation front (vertical rim).



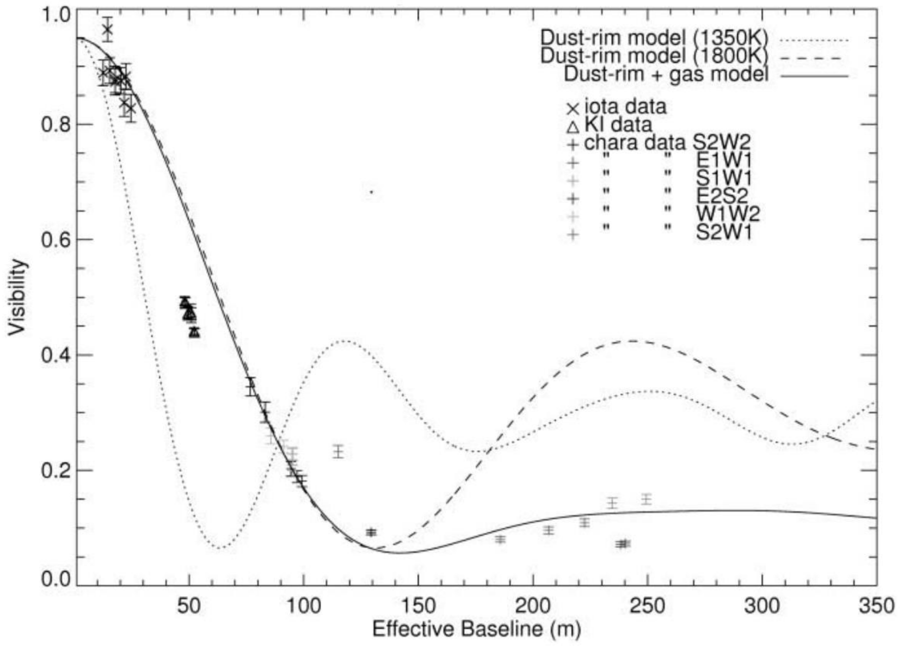
Eisner et al. (2003) – PTI data



Millan-Gabet et al. (2007)

Introduction: Young Stellar Objects

- Addition of longer baseline observations, provided by CHARA/CLASSIC indicated that the "bounces" in the visibilities predicted by the simple ring models did not adequately fit the data.
- More detailed modelling of Herbig AeBe stars revealed curved disk rims provided visibilities more consistent with observations.
- Some observations also indicated that hotter material could also exist interior to the silicate dust sublimation radius.
    - optically thick gas?
    - more refractory grain species (e.g. iron)



Tannirkulam et al. (2008)

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- RY Tau and HD 142666
- Methodology
- Insights from radiative transfer analysis

CHARA NIRO survey

- Observed **36** Near-IR Objects (NIRO) in H and K bands using CLASSIC & CLIMB between 2004 and 2014

- All the data has been reduced using a pipeline developed at UM.
  - CLASSIC data reduced (in the main) by Brian Kloppenborg
  - I reduced the full CLIMB data set:
    1. Bad scans (drifting etc) are flagged and removed.
    2. Fluxes are inspected for drop out due to cloud or instrumental effects.
    3. Power spectrum inspected and the "background level" selected manually.
    4. Transfer function inspected.

- Provides single estimate of closure phase (CLIMB) and three estimates of the visibility for each baseline pair (one from each CLIMB "output": B1B2_P0, B1B2_P1, B1B2_P3 etc).

- Here, the three estimates of the visibility were inspected for consistency with one another and a weighted average computed for use in the remaining analysis.

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Fact file: HD 142666 & RY Tau

HD 142666

SpT	$T_{\rm eff}$ (K)	$\log g$	$\log Z$	d (pc)	$L_\star/L_\odot$	$A_{\rm V}$	$R_\star/R_\odot$	$M_\star/M_\odot$	$F_{\star,{\rm H}}$	$F_{\star,{\rm K}}$	$R_{\rm out}$ (au)
A8	7500	4.3	0.2	150	19.3	1.63	2.42	1.97	0.61	0.35	60

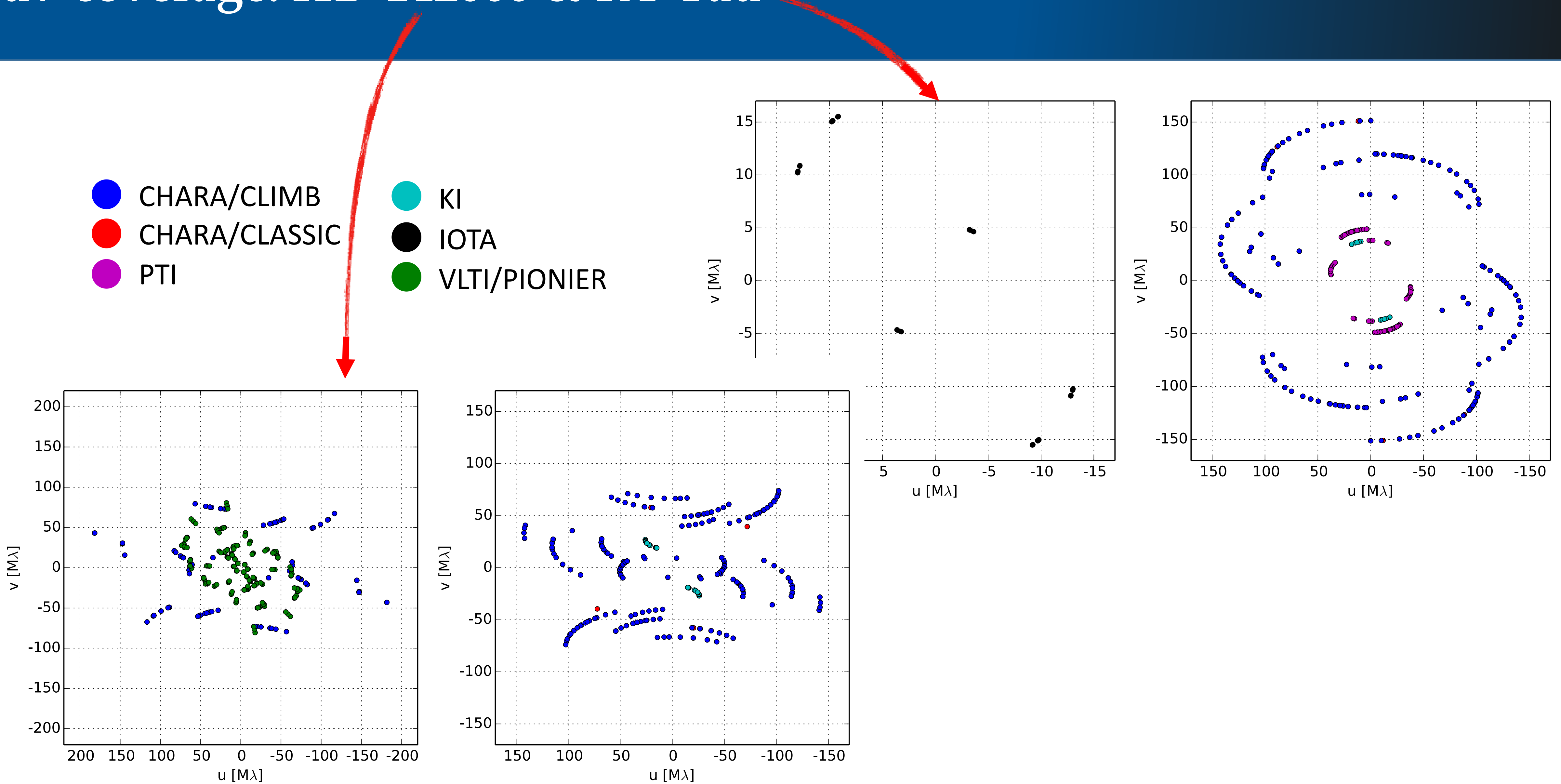
Meeus et al. (1998), Dent et al. (2005), Garufi et al. (2017), Guimarães et al. (2006), McDonald et al. (2017), Lindegren et al. (2016)

RY Tau

SpT	$T_{\rm eff}$ (K)	$\log g$	$\log Z$	d (pc)	$L_\star$ ($L_\odot$)	$A_{\rm V}$	$R_\star$ ($R_\odot$)	$M_\star$ ($M_\odot$)	$F_{\star,{\rm H}}$ (%)	$F_{\star,{\rm K}}$ (%)	$R_{\rm out}$ (au)
G1	5945	1.8	0.0	140	21.3	2.92	4.26	2.44	71	45	80

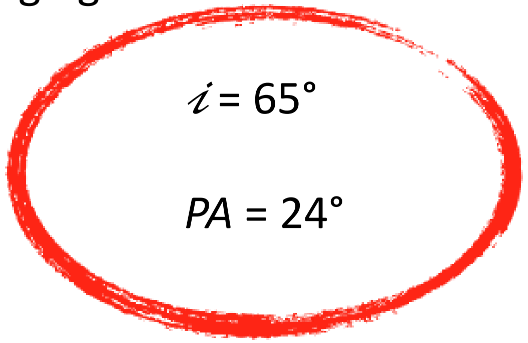
Calvet et al. (2004); Elias (1978); Isella et al. (2010); Takami et al. (2013)

uv-coverage: HD 142666 & RY Tau

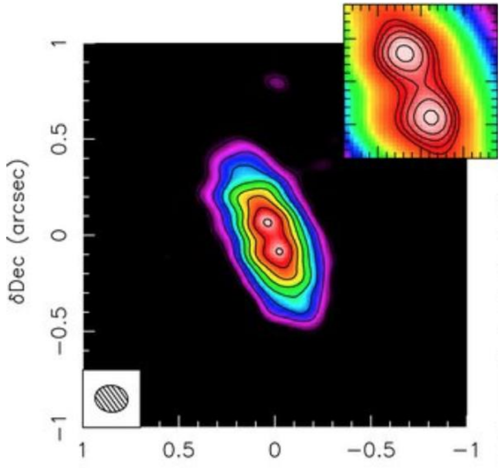


System geometry: RY Tau

- Viewing geometry of RY Tau well-constrained from CARMA submm/mm interferometry and HST imaging.



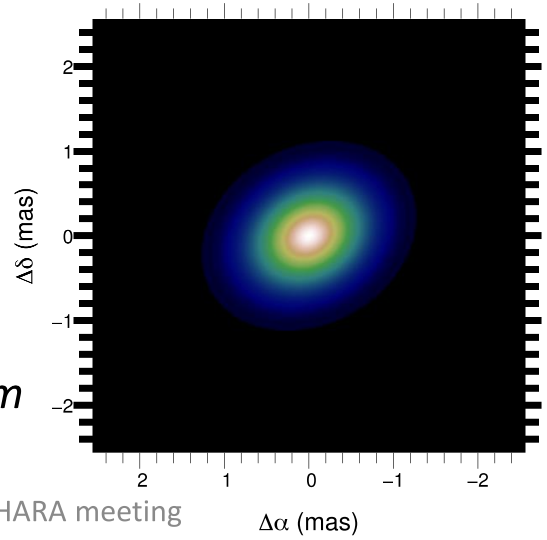
Agra-Amboage et al. (2009)

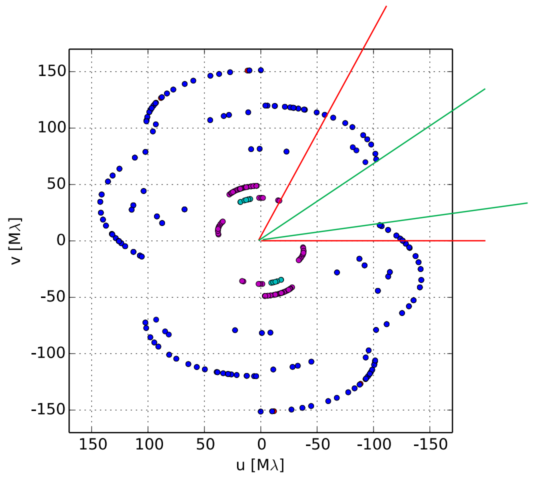


Isella et al. (2010)

- Our CHARA/CLIMB uv coverage has insufficient sensitivity along the apparent disk minor axis to be able to recover this geometry:

"clean" K-band beam

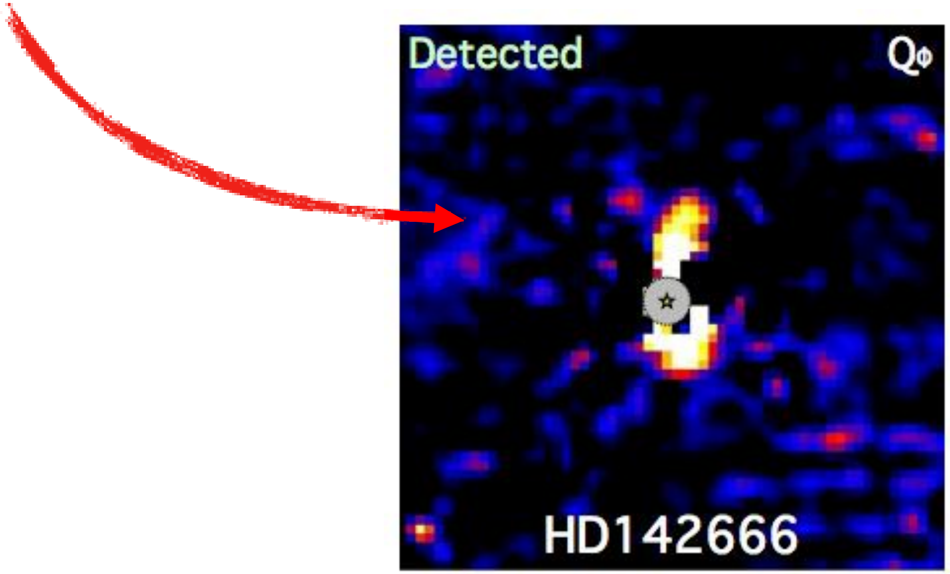




System geometry: HD 142666

- Viewing geometry of HD 142666 not very well constrained from previous observations: moderate inclinations (40-60°; Vural et al. 2014; Lazareff et al. 2016) indicated while prior constraints on position angle comes from VLT/NACO.

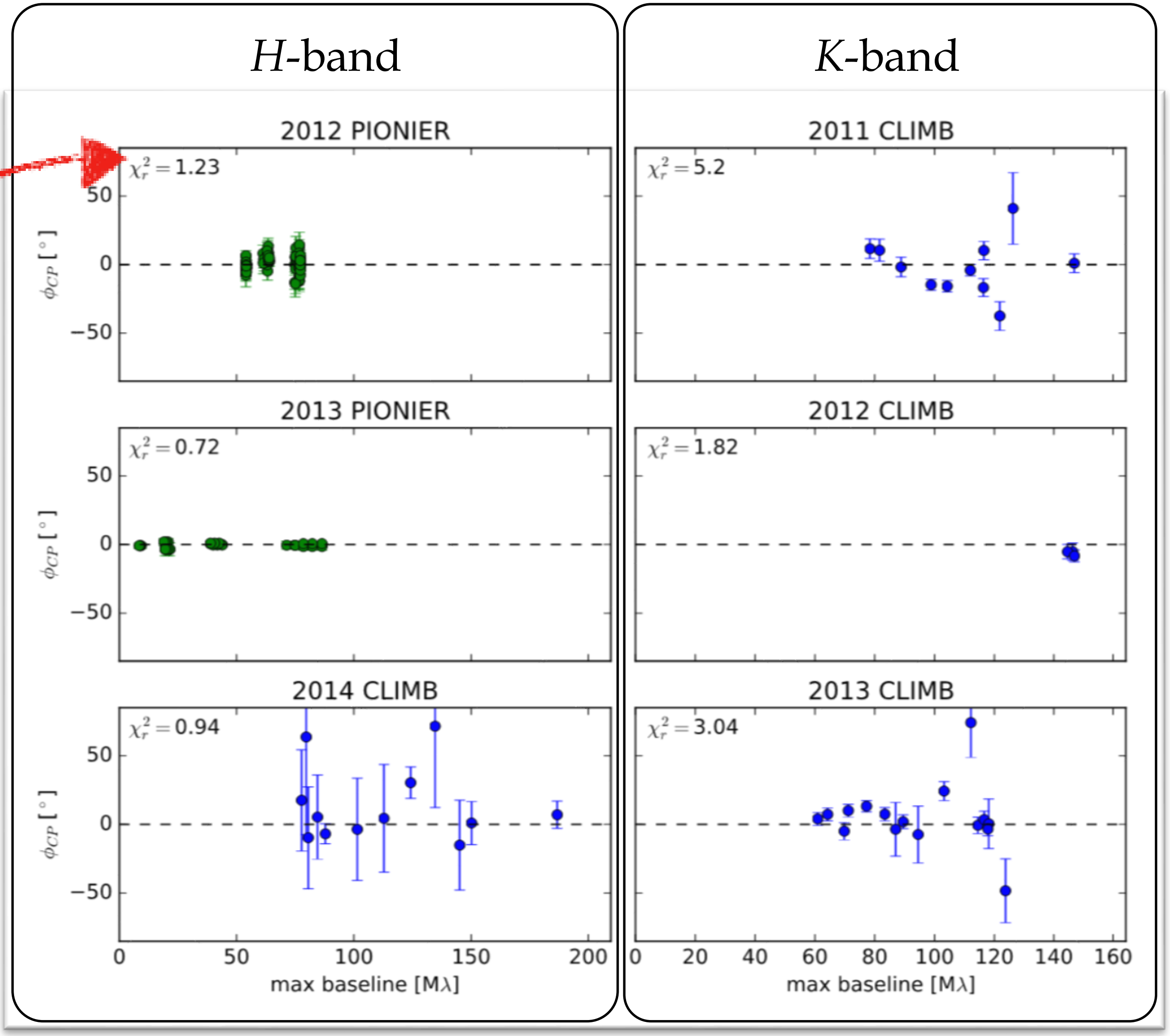
- Use geometric models for this.



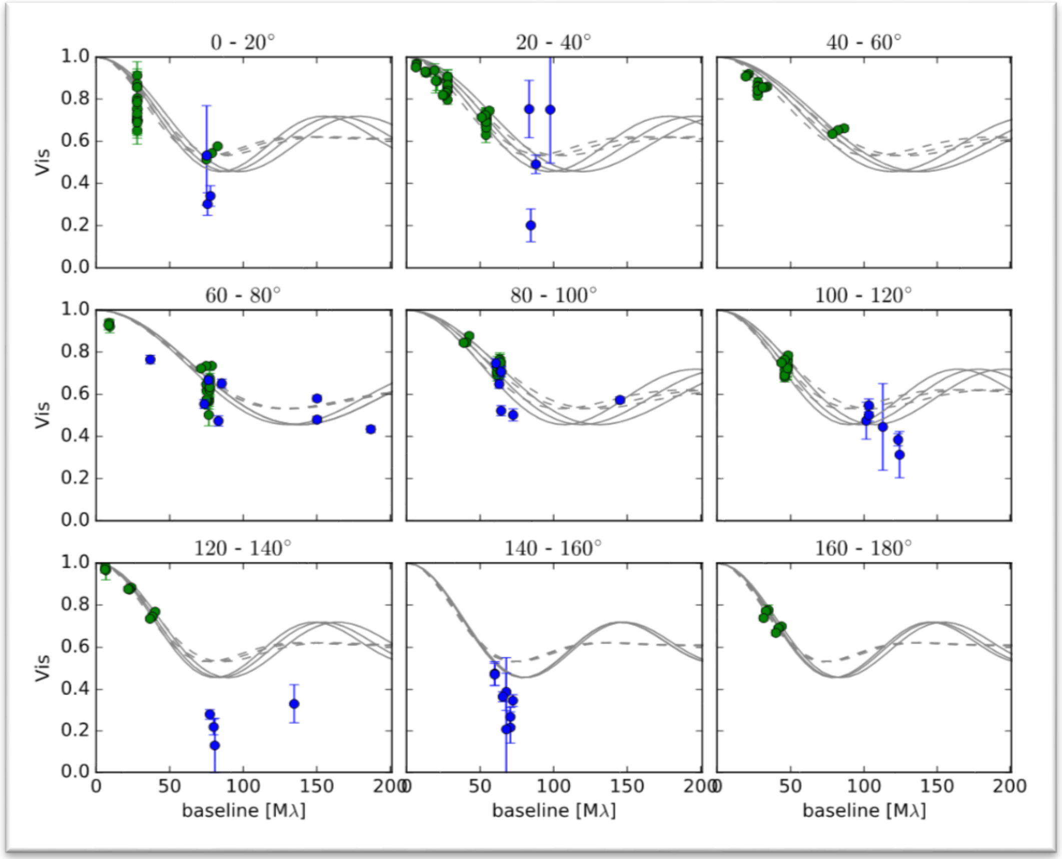
Garufi et al. (2017)

System geometry: HD 142666

chi-square for centro-symmetric (zero CP) model.

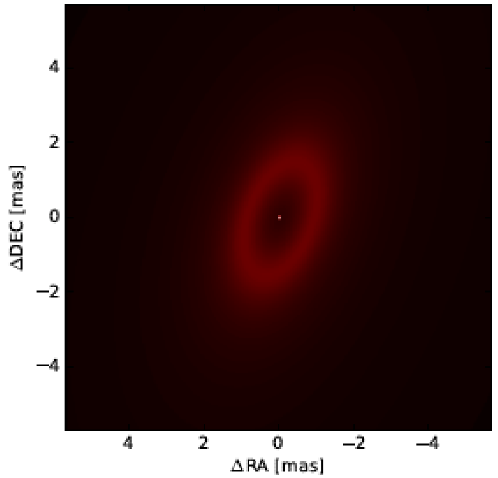


System geometry: HD 142666



PS + ring

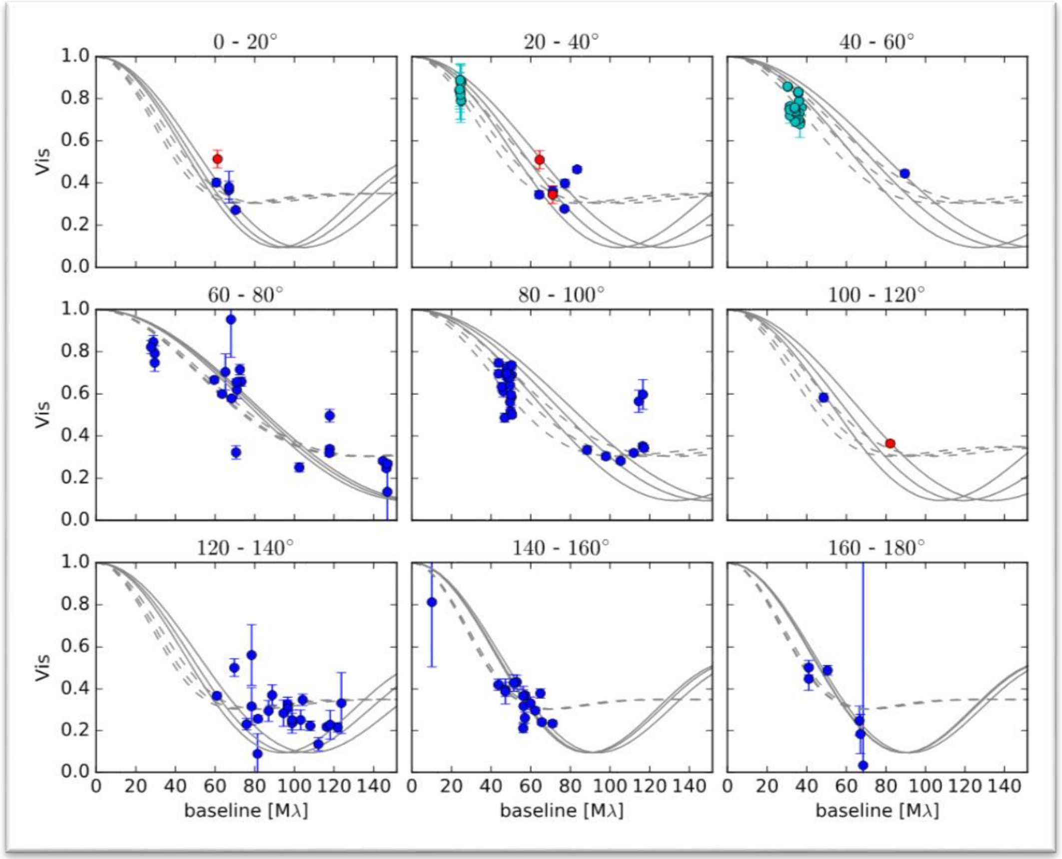
PS + smoothed ring



***H*-band**:

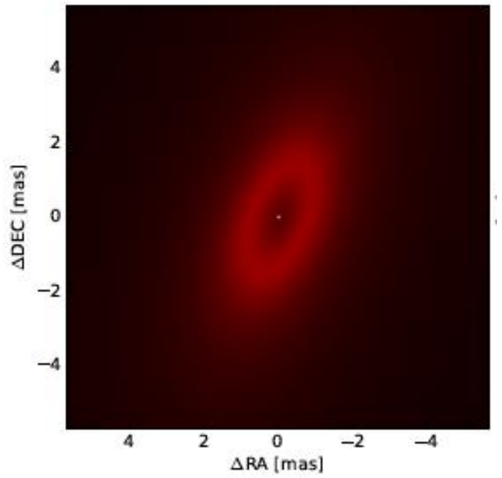
PS + ring	PS + smoothed ring
$\chi_r^2 = 10.87$	$\chi_r^2 = 8.94$
i = 55.6±2.2°	i = 56.7±1.7°
PA = 155±2°	*PA* = 160±2°
R = 1.44±0.05 mas	R = 1.58±0.04 mas

System geometry: HD 142666



PS + ring

PS + smoothed ring



***K*-band**:

$\chi_r^2 = 31.07$	$\chi_r^2 = 13.16$
i = 57.6±3.1°	i = 60.6±4.0°
PA = 162±4°	*PA* = 159±3°
R = 1.28±0.04 mas	R = 1.50±0.09 mas

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Methodology: Radiative transfer analysis

- Using TORUS (Harries 2000) to iteratively solve for radiative equilibrium in the disk

- Adopt 3 different prescriptions for dust sublimation (Draine 2003 silicates):

  1. Single-grain model; small grains (0.1μm)
  2. Single-grain model; large grains (1.2μm)

  } *gas-density dependent dust sublimation temperature*

  $$T_{sub} = G\rho^{\gamma}(r, z)$$

  3. Two-grain mixture: 0.1μm and 1.2μm grains in mass ratio of 9:1 with $T_{sub} = 1800$ K (Pollack et al. 1994).

     ↳ *rim curvature comes from grain size-dependent cooling efficiency*

- Vary scale height, h_0, and flaring parameter, β, where $h(r) = h_0 \left(\frac{r}{100au}\right)^{\beta}$.

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"**IN05**" models based on Isella & Natta (2005)

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"**THM07**" models based on Tannirkulam et al. (2007)

- Vary scale height, h_0, and flaring parameter, β, where $h(r) = h_0 \left(\frac{r}{100au}\right)^{\beta}$.

Methodology: Radiative transfer analysis

- Produce broadband model SEDs (optical to mm) at set disk inclination.
- Compute images at a set disk inclination at both 1.67 (H-band) and 2.13 μm (K band).
- Use python to rotate the images to disk PA and extract visibilities and closure phases at baseline lengths and position angles corresponding to u,v coverage.

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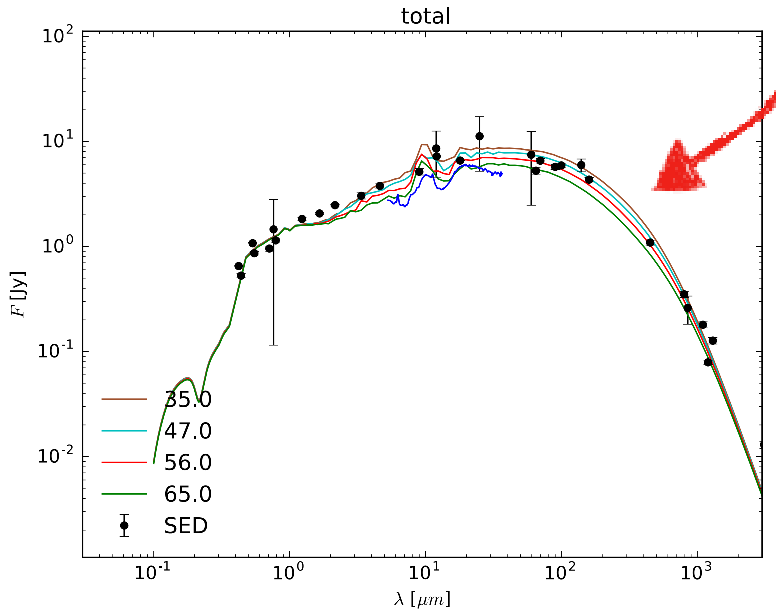
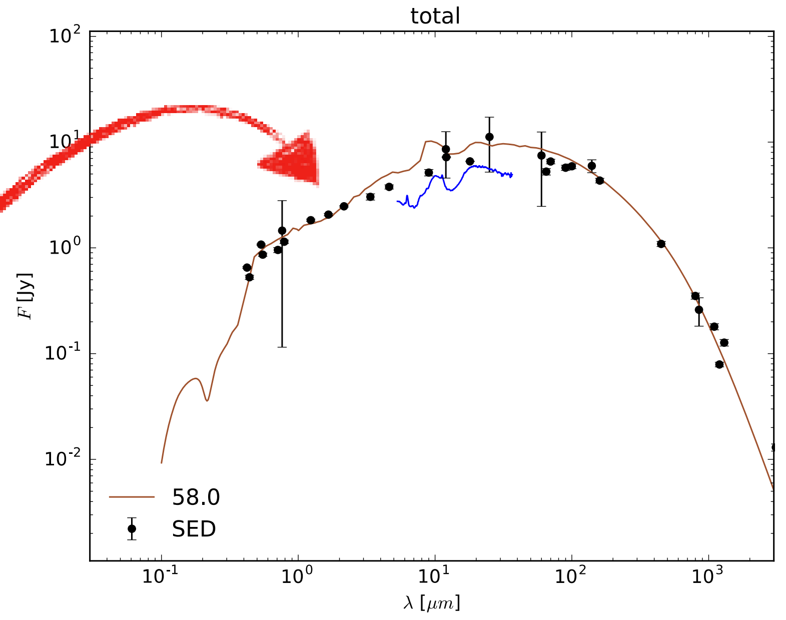
HD 142666: Large grains required

IN05 0.1μm (small) grain models



$h_0 = 7$au and $\beta = 1.09$ required to fit FIR portion of SED

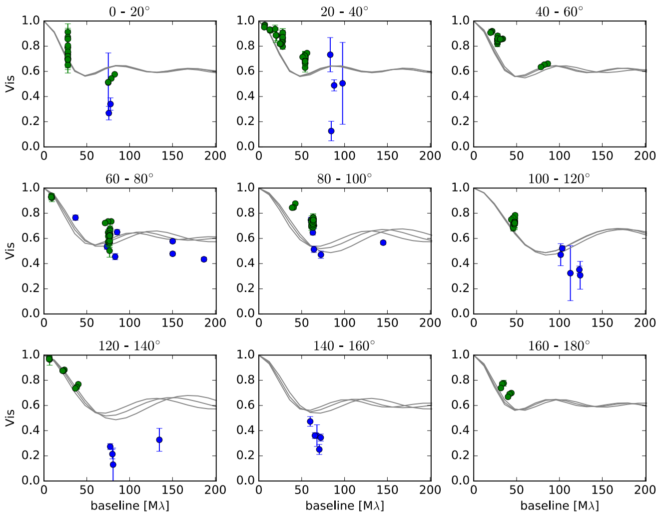
$h_0 = 10$au and $\beta = 1.06$ required to fit NIR portion of SED

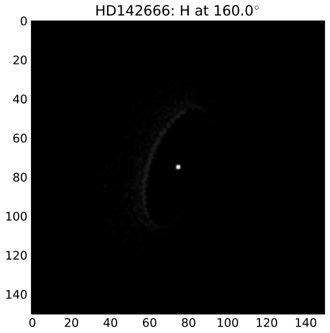


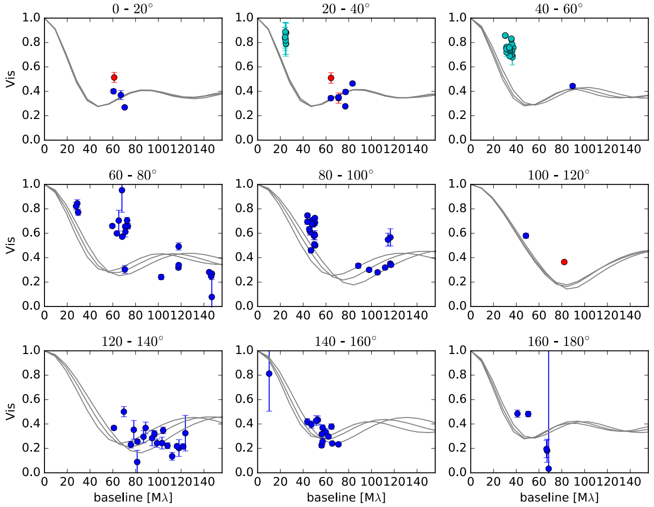
HD 142666: Large grains required

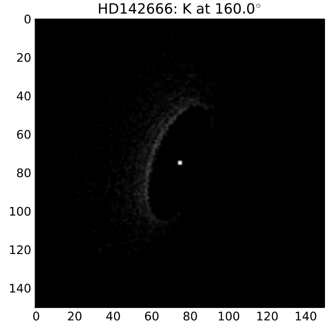
<u>IN05 0.1μm (small) grain models</u>

$(\textit{with}\ h_0 = 10au, \beta = 1.06\ \textit{and}\ i = 58^\circ)$





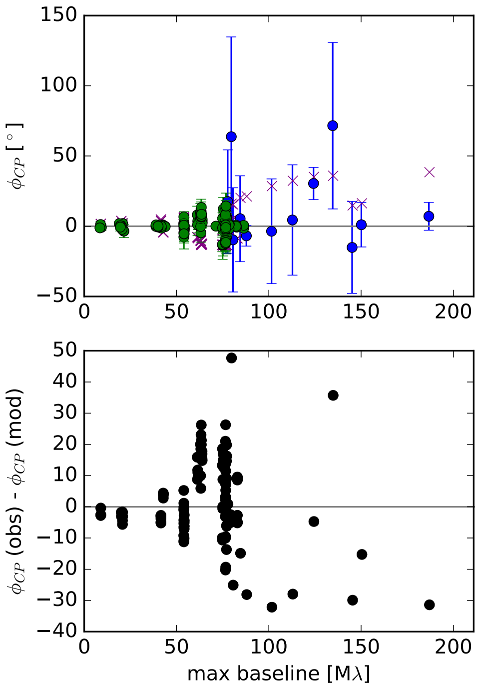


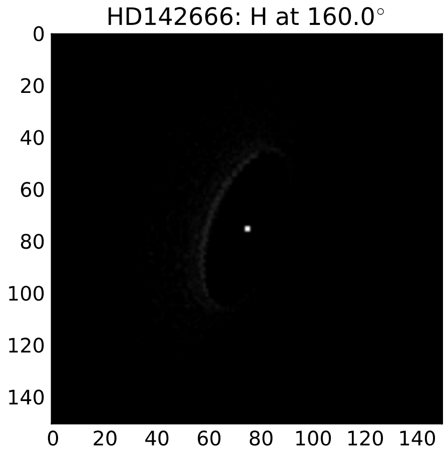


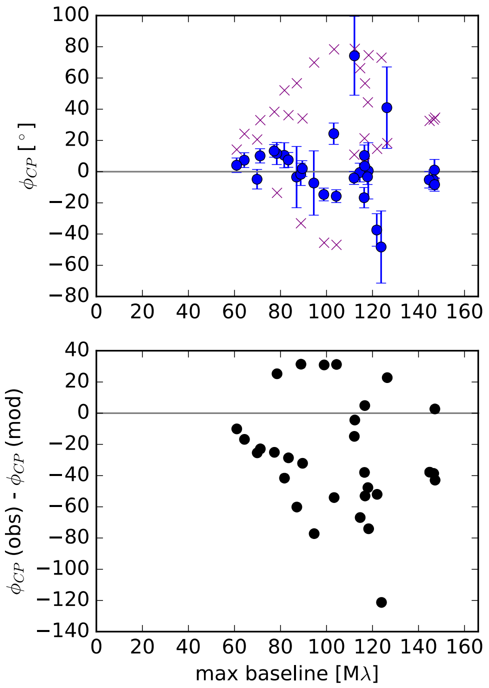
HD 142666: Large grains required

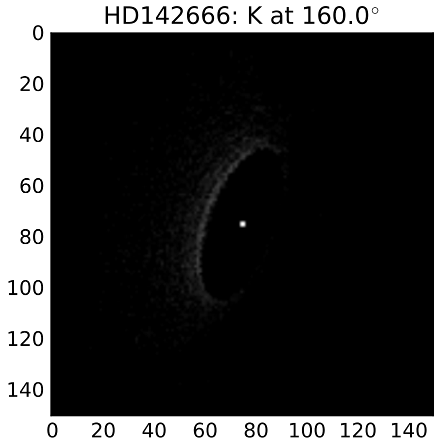
IN05 0.1μm (small) grain models

(with $h_0 = 10au, \beta = 1.06$ and $i = 58°$)





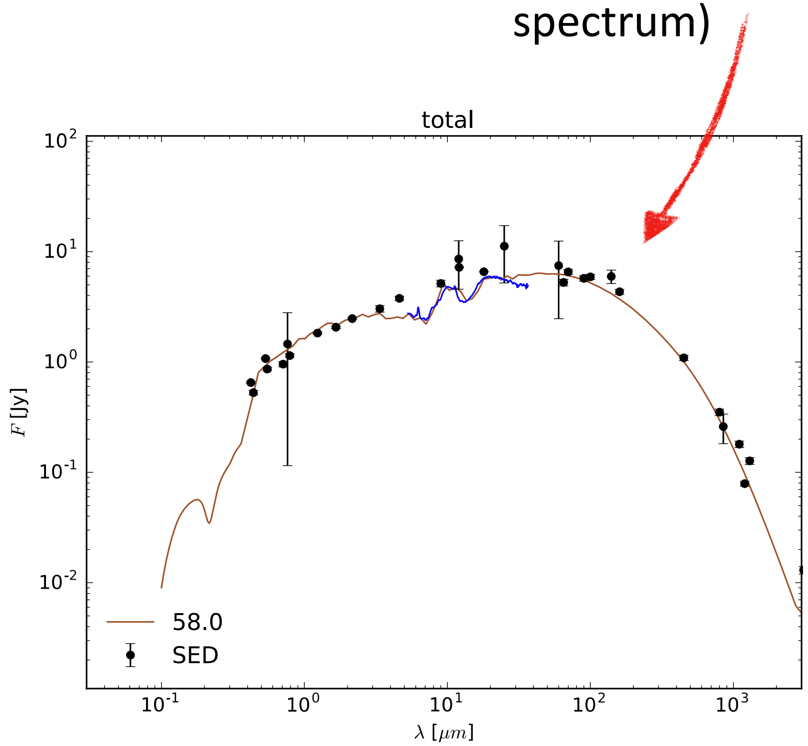




HD 142666: Large grains required

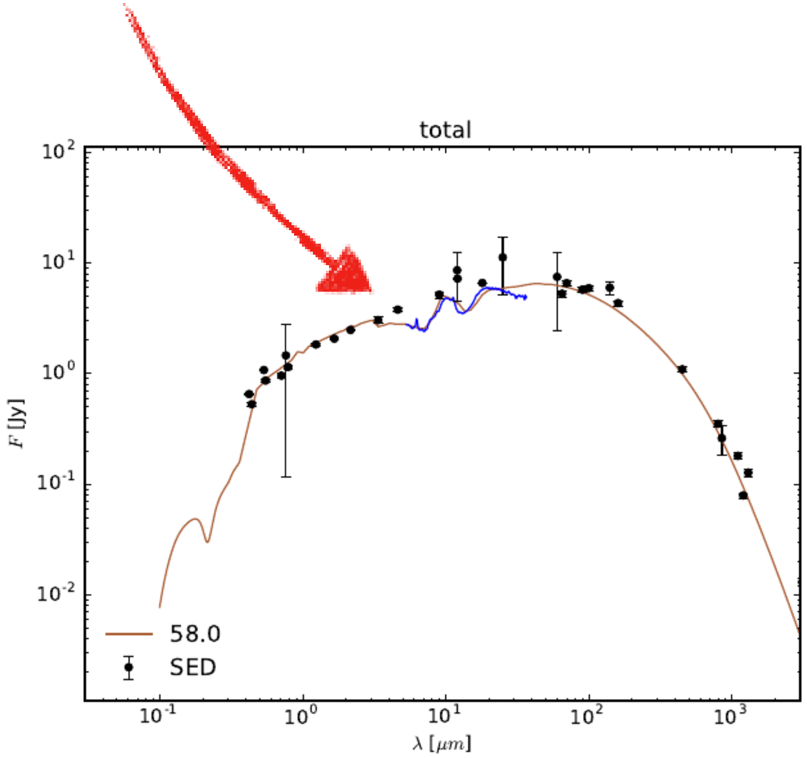
THM07 models (9:1 mass ratio of 0.1:0.6μm sized grains)

$h_0 = 8$au and $\beta = 1.08$ provides good fit across full SED (including Spitzer spectrum)



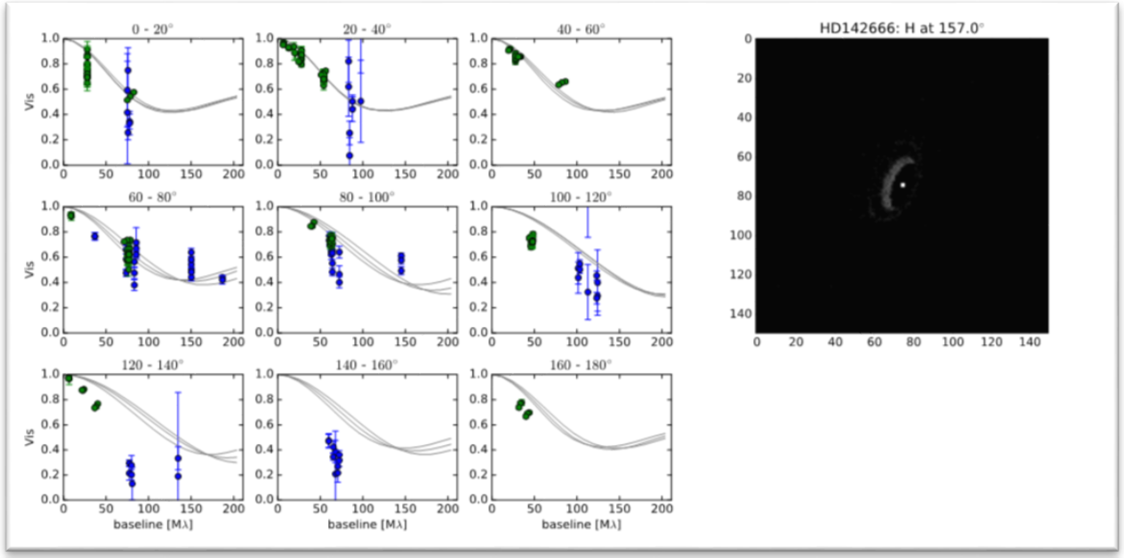
IN05 1.2μm (large) grain models

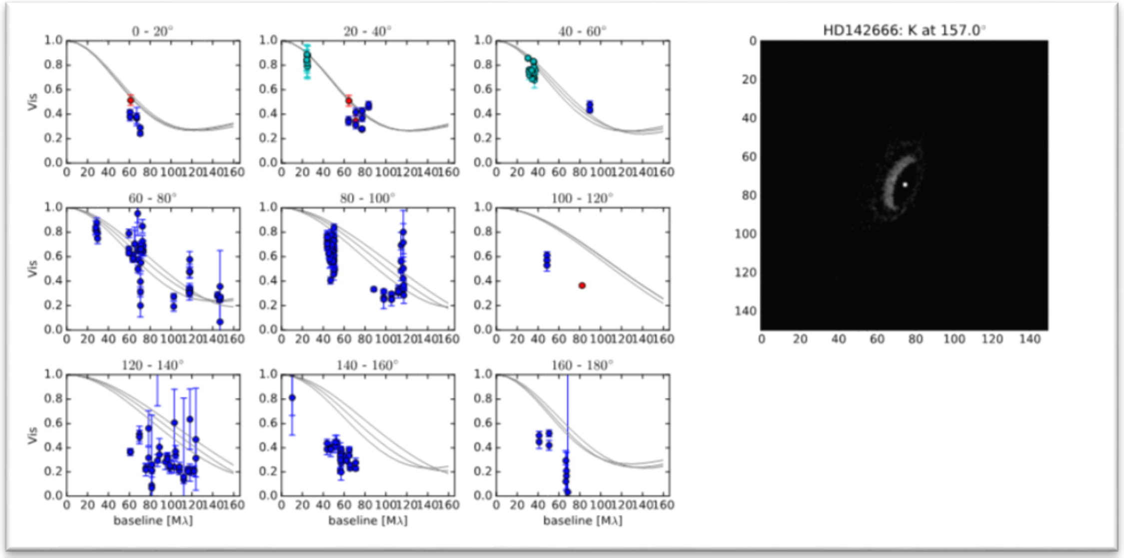
$h_0 = 7$au and $\beta = 1.09$ provides similarly good fit



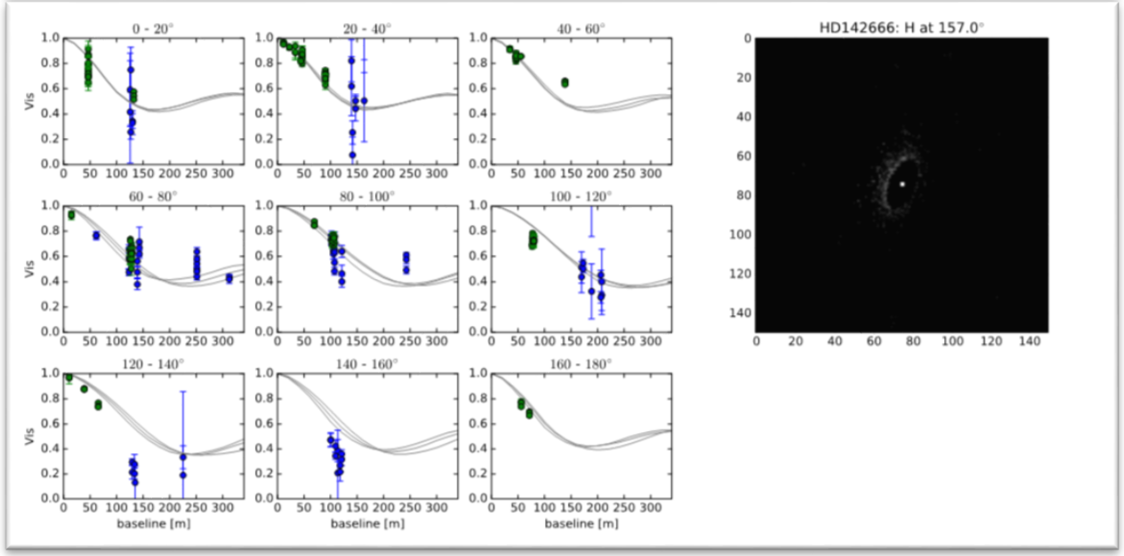
HD 142666: Large grains required

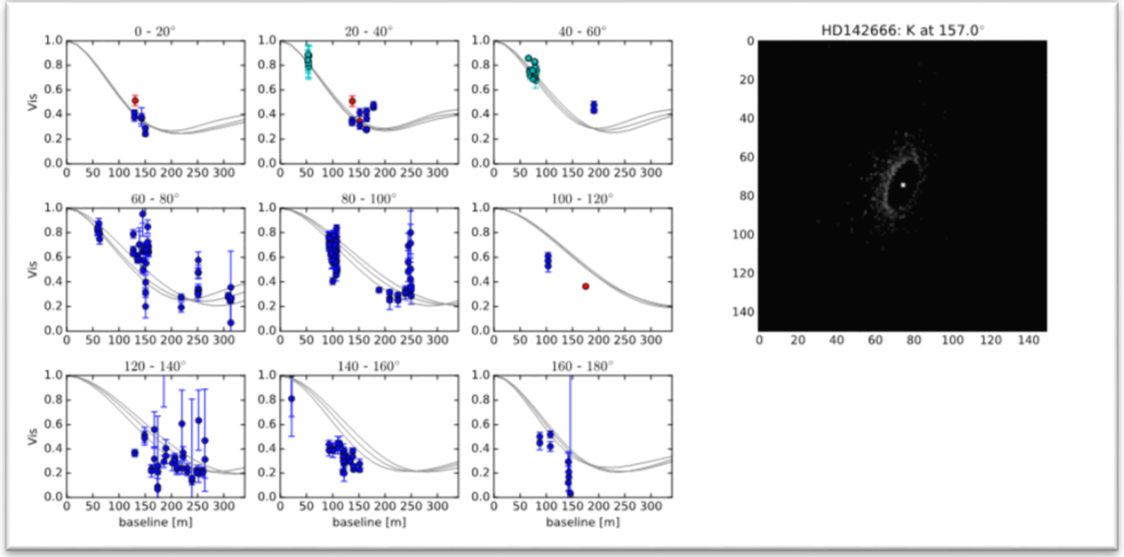
THM07 grain mixture





IN05 "large" grains





HD 142666: Large grains required

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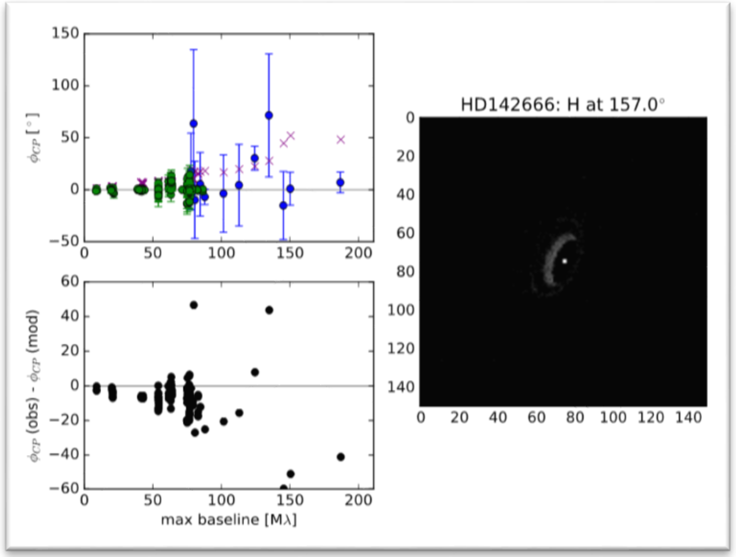

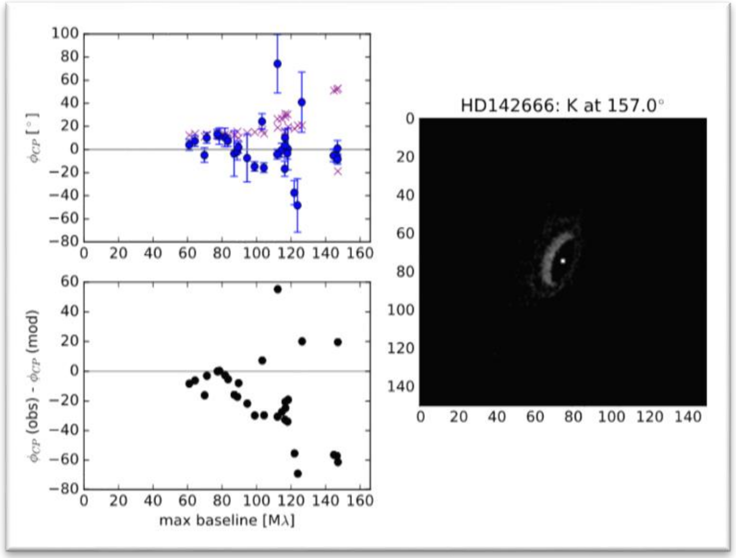

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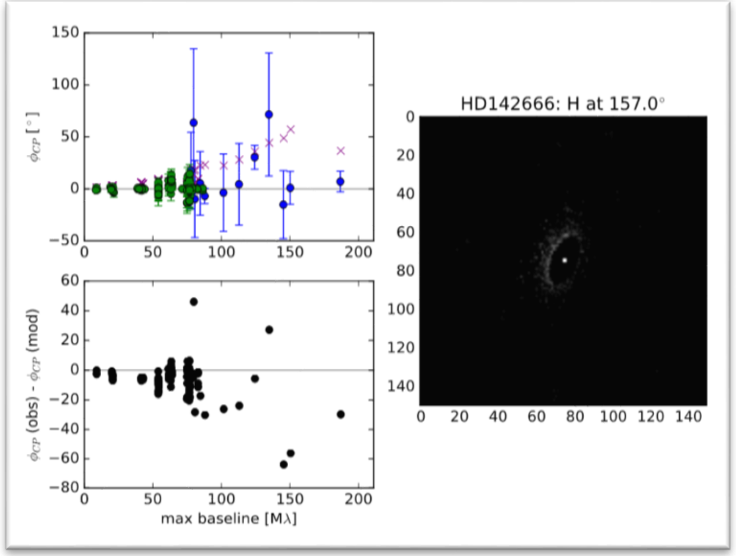
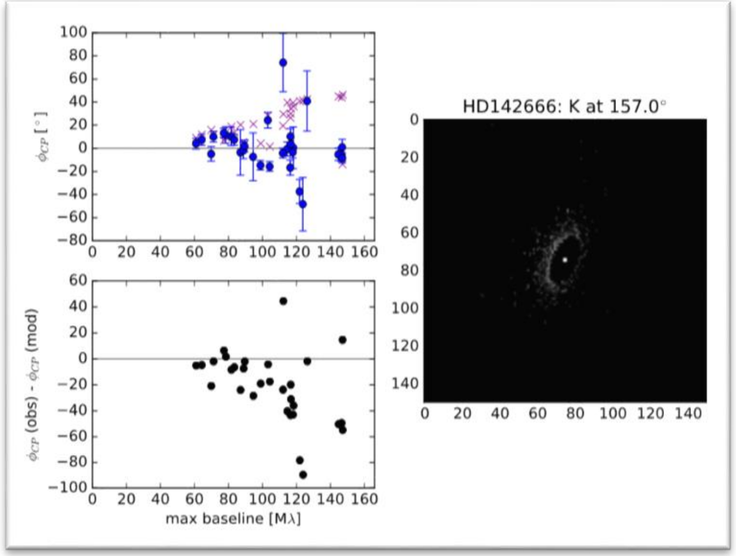
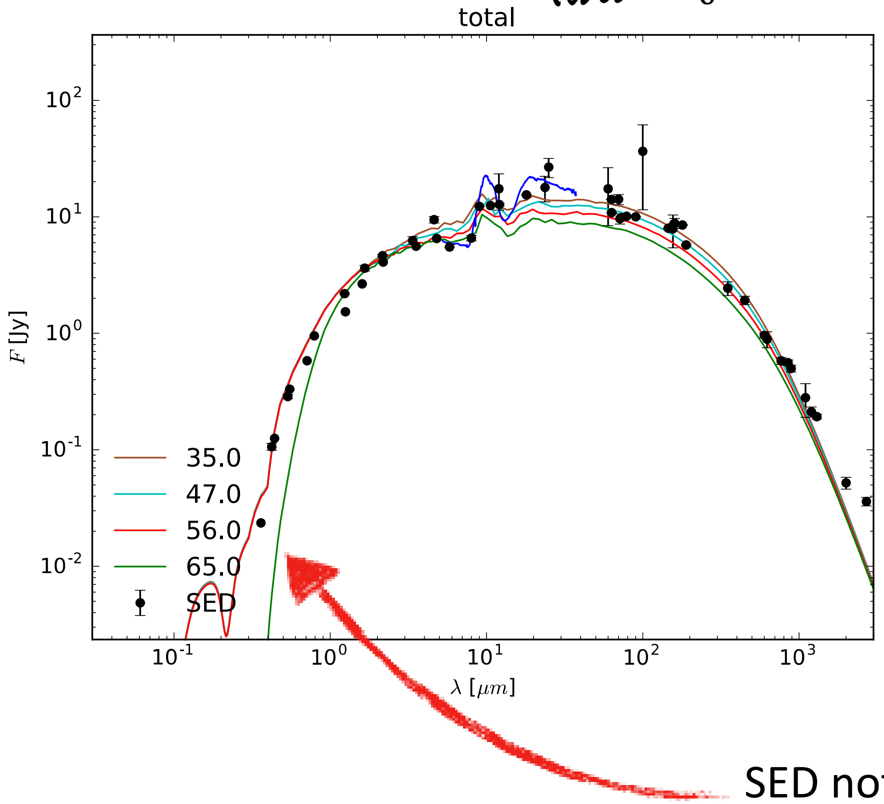


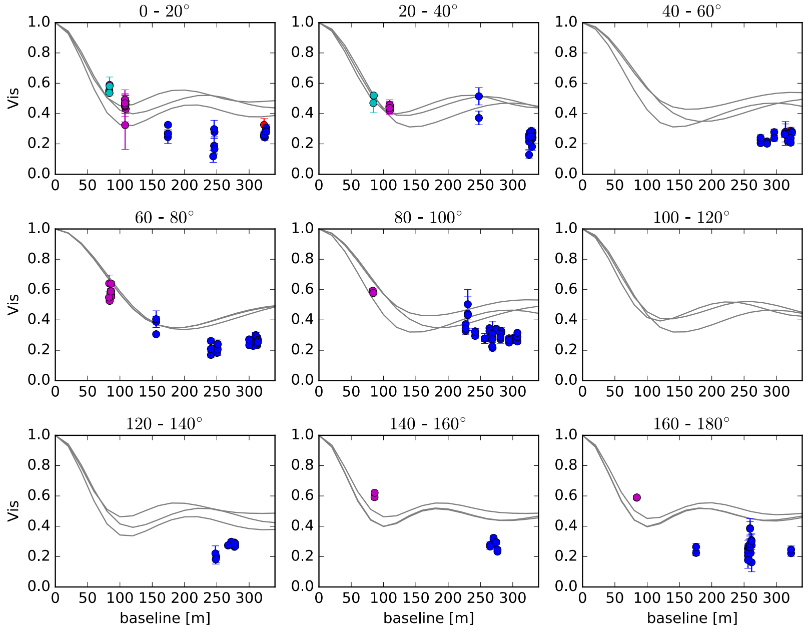


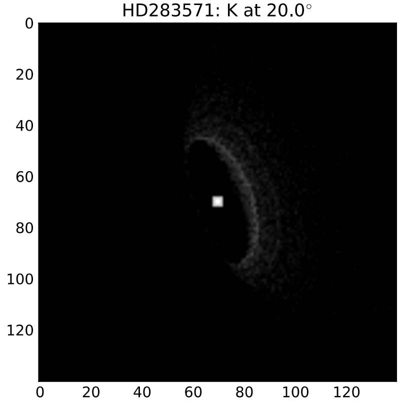
RY Tau: “full-disk” models insufficient

IN05 0.1μm (small) grain models

(with $h_0 = 10au, \beta = 1.05$ and $i = 60^\circ$)







SED not complicit with higher inclinations as inferred from longer wavelength observations.

RY Tau: "full-disk" models insufficient

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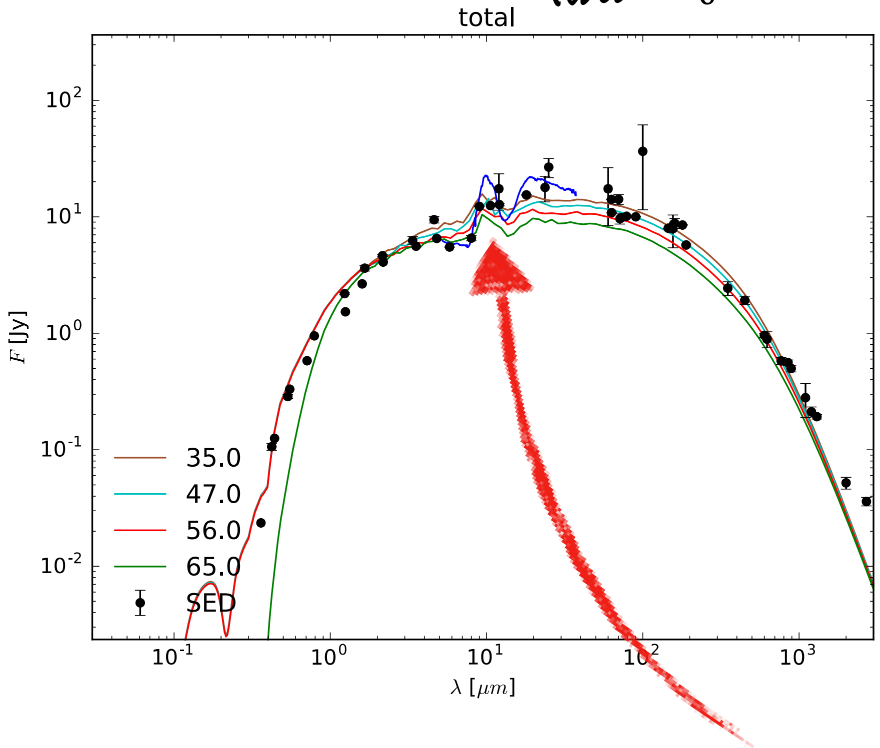
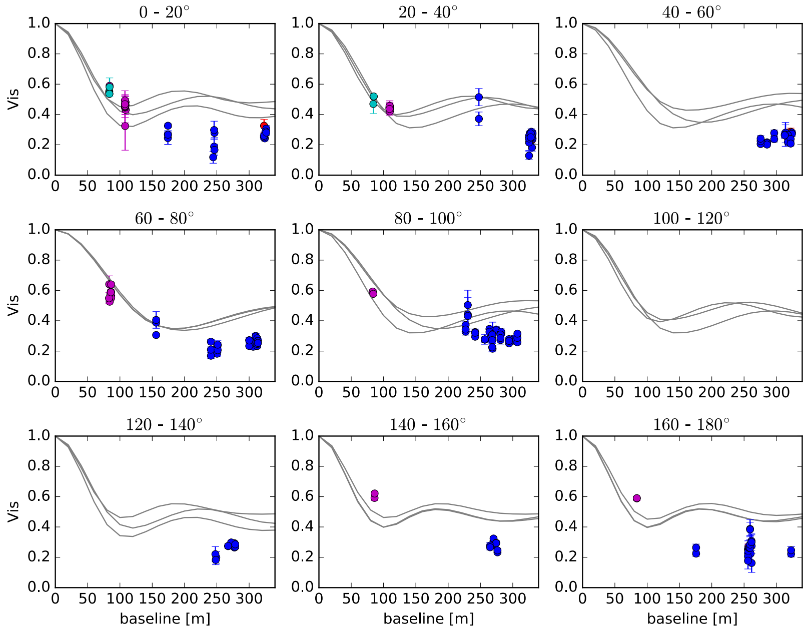
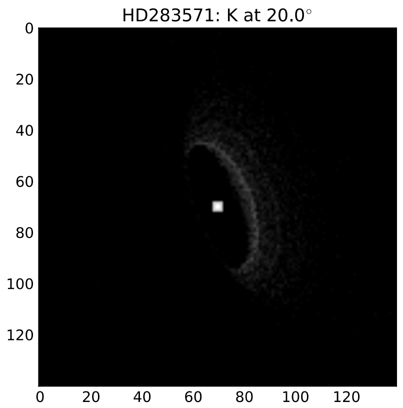
(with $h_0 = 10au, \beta = 1.05$ and $i = 60^\circ$)







Much stronger silicate emission is expected

RY Tau: "full-disk" models insufficient

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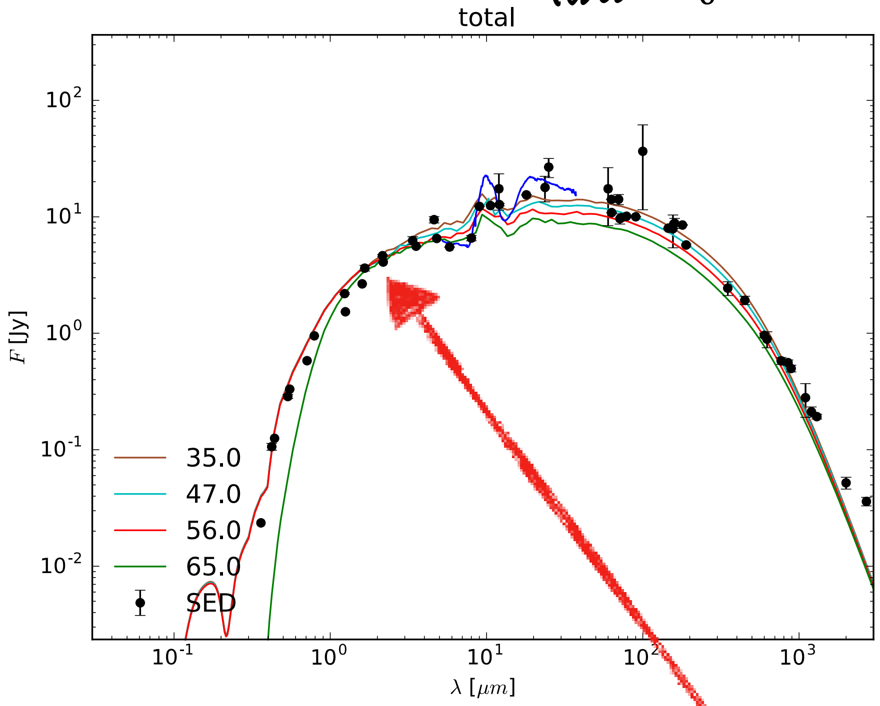
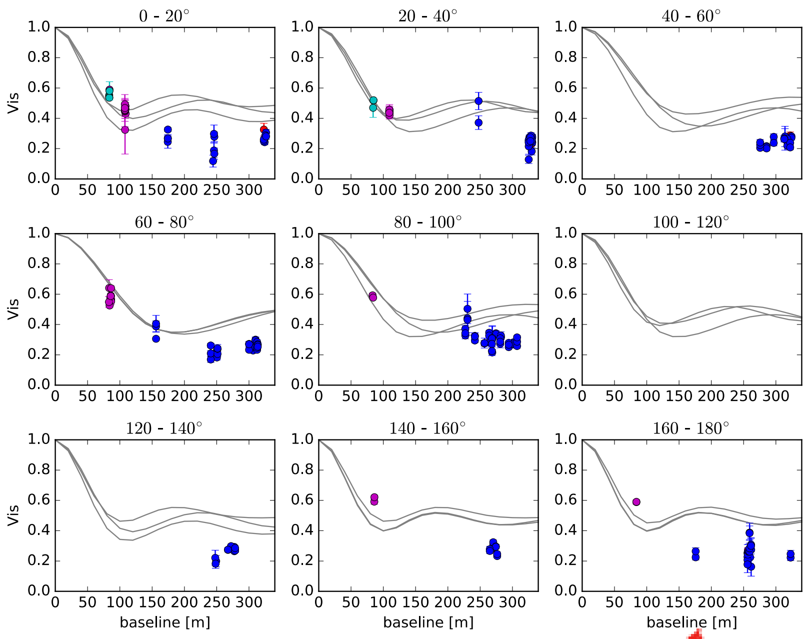
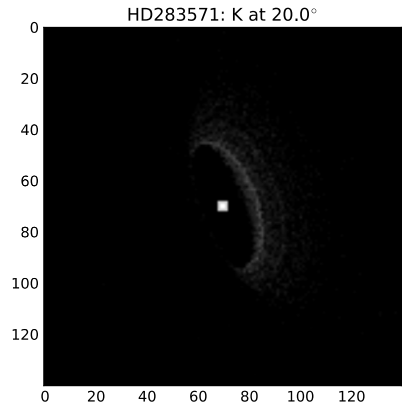
$(with\ h_0 = 10au, \beta = 1.05\ and\ i = 60°)$





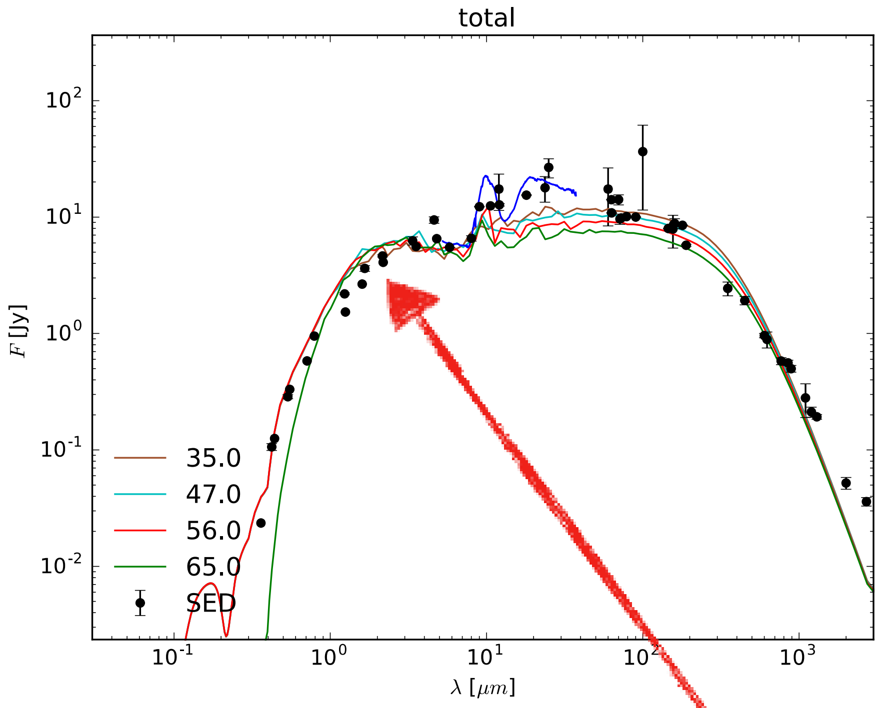


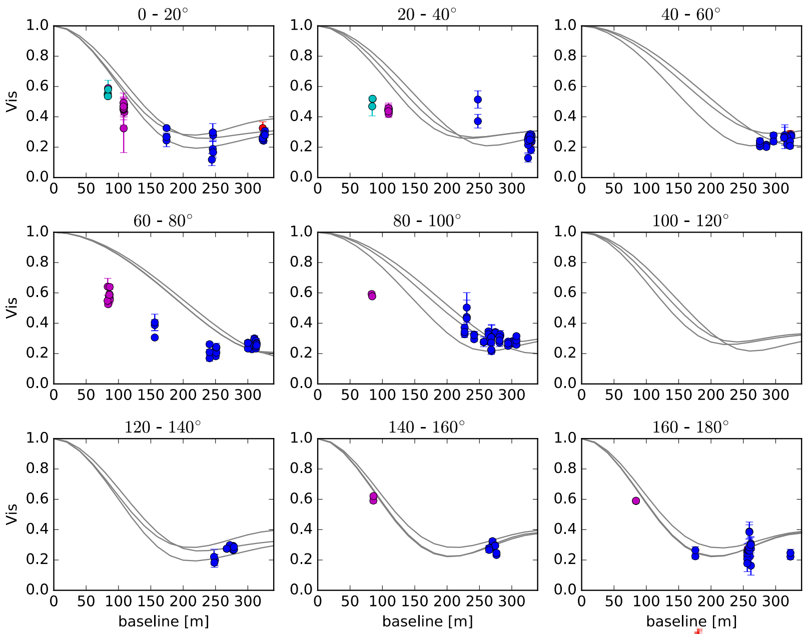
Stellar flux contribution from SED appears inconsistent with minimum visibility level.

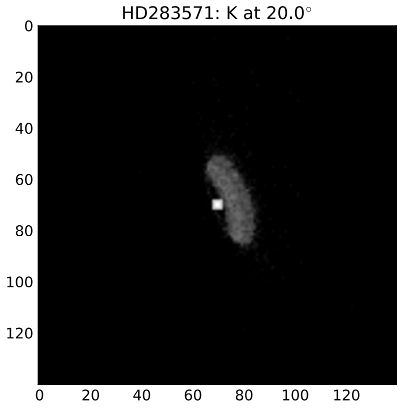
RY Tau: “full-disk” models insufficient

THM07 models (9:1 mass ratio of 0.1:1.2μm sized grains)

(still with $h_0 = 10au, \beta = 1.05$ and $i = 60^\circ$)







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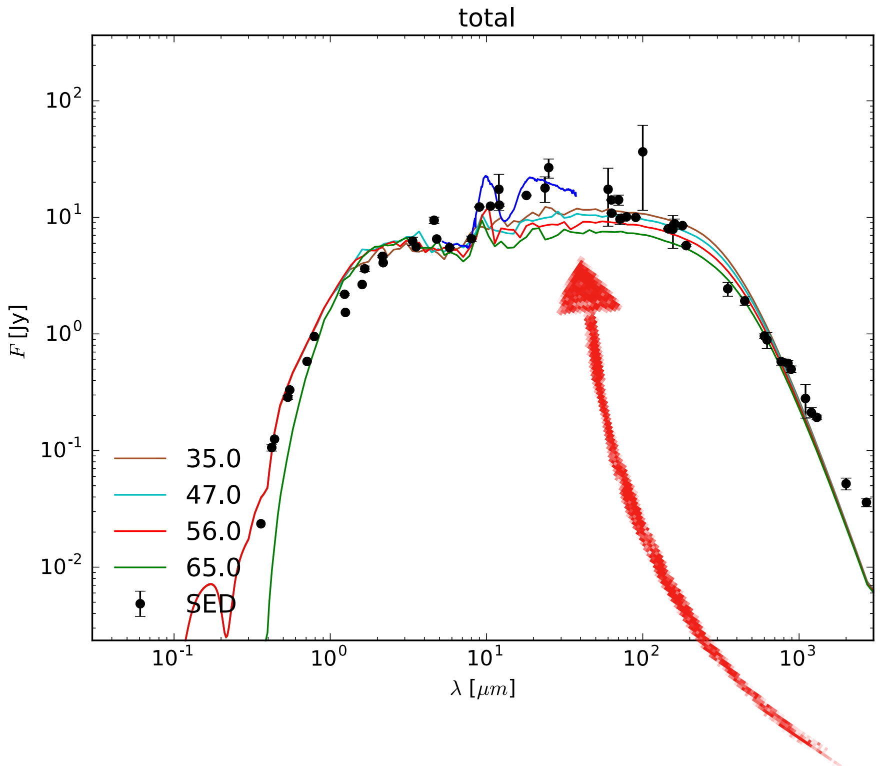
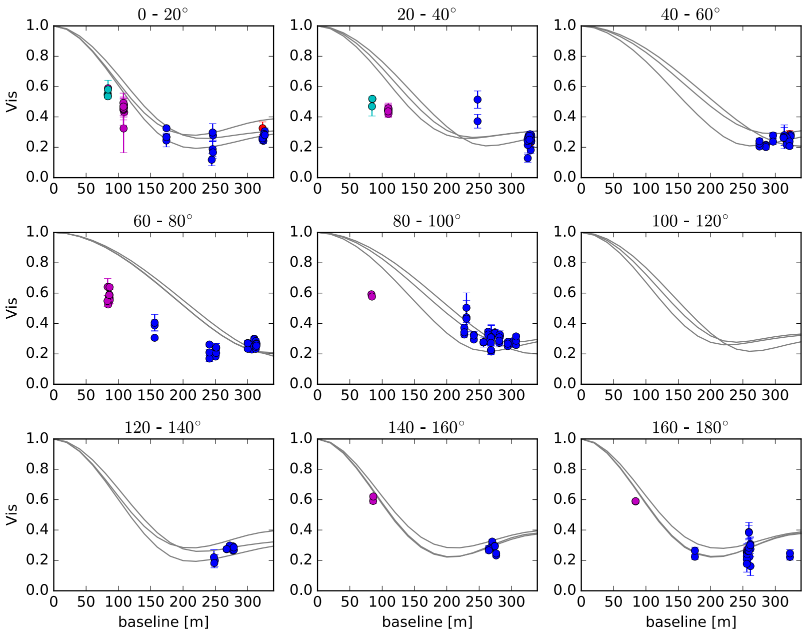
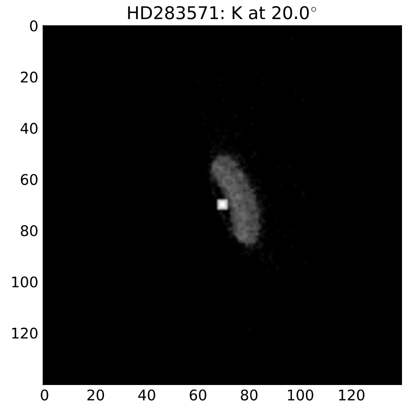






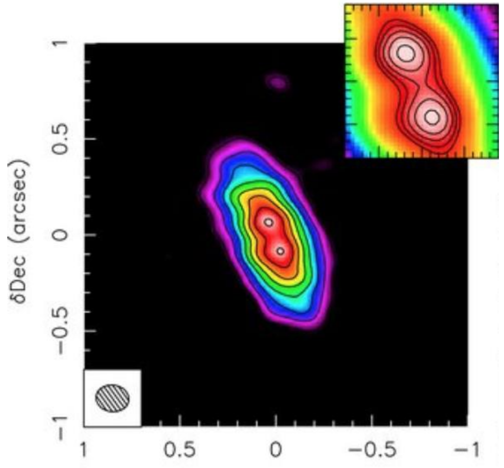
Much worse fit across MIR wavelengths

RY Tau: “full-disk” models insufficient

Previous work on SED modelling for RY Tau has suggested its disk may be pre-transitional (i.e. significant grain growth or clearing at certain disk annuli, producing gaps in the disk).

Introduced a “modular” structure into TORUS which:

- Iteratively solves for a radiative equilibrium temperature structure.
- Handles dust sublimation via an iterative process ***at all disk annuli***.
- Can populate different disk regions with different grain sizes/species/densities.
- Can settle grains of different sizes by different amounts.



Isella et al. (2010)

Summary

- CHARA NIRO surveyed 36 objects including several dozen YSOs.
- The data are all reduced: look out for publications led by Kluska, Labdon, Setterholm, Davies.
- Focused on the inner rim shape and structure in two YSOs: RY Tau and HD 142666.
- HD 142666's SED and visibilities are inconsistent with a small grain rim model: grain growth invoked.
- Smaller grain models provide a better fit to the SED and visibilities of RY Tau but so-far-explored "full disk" models appear insufficient.
- Final TORUS development tests are scheduled post HD 142666-publication.