Chromatic Imaging and Modeling of l Puppis: Unveiling Disc Asymmetries in B[e] Stars with VLTI/MATISSE

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B[e] phenomenon in a nutshell

B[e] designation [Allen & Swings 1976]

Peculiar class of objects defined by physical & spectral characteristics

→ **NOT** a stellar evolutionary stage

B [e]

- **B** → Massive star spectral type O9–A2
- **e** → Permitted emission lines; Large Near/Mid-IR excess (1-25 µm) + Strong Balmer (2µm) & low excitation of metals (visual)
- **[ ]** → Optical narrow forbidden lines in emission & absorption

⟺ Edge-on cut of a B[e] system

Total ~120 objects [Chen+2021]

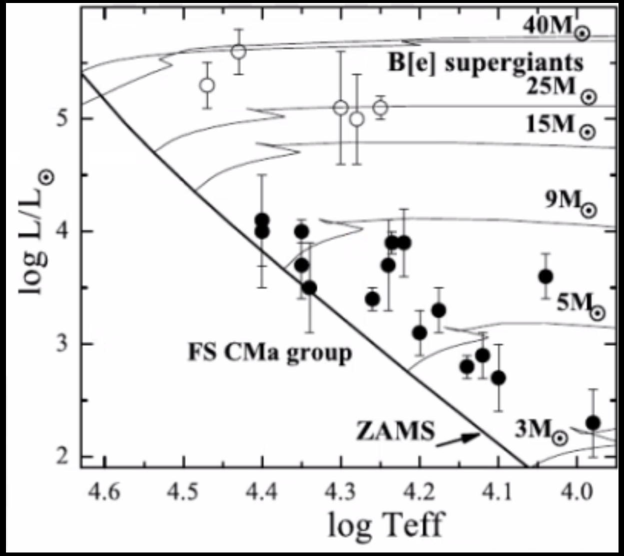
50% of B[e] class consists of FS CMa type & 30% are binary systems [Varga+2019]

Open questions

How & where do these discs form? How long are their lifetimes? What is its connection with the stellar evolution of massive stars & the impact on the galaxy scale? Which interaction between gas & dust?

Study framework

Groups with mass-loss rate & dust formation mechanisms + evolutionary stage still obscure



Science case

From B[e] heterogenous population [Lamers+1998], focus on SG & FS CMa

Circumstellar rings

can result from decretion/ejection/outbursts mechanism or binary interaction

Scope

Understand and constrain the overall geometry + dynamic + properties that generate & sustain their circumstellar material

How to shed light on B[e] discs?

Density, chemical composition & velocity structure of equatorial disc → high spectral resolution

Stellar distance & bolometric luminosity → accurate astrometric solutions

Size, relative flux & structures' position of stellar surface/disc components → high spatial angular resolution

Methodology

PI: A. Meilland

For the sake of the global context, aim at constraining CSE physical parameters from a specific B[e] star, l Puppis

→ Conduct VLTI/MATISSE observation campaigns

→ Constrain circumstellar environment geometry parameters with toymodels

→ Produce image reconstruction with MiRA

Collaborators:

J. Drevon, F. Millour, A. Meilland, A. Domiciano de Souza, C. Paladini, J. H. Leftley, P. Stee

l Puppis system

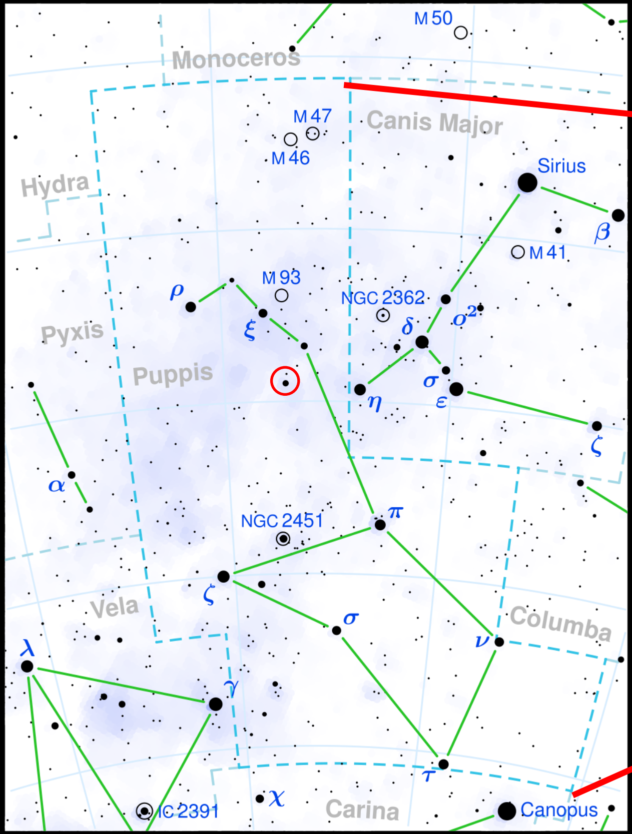
Other appellations: 3 Pup = HD 62623
= HR 2996

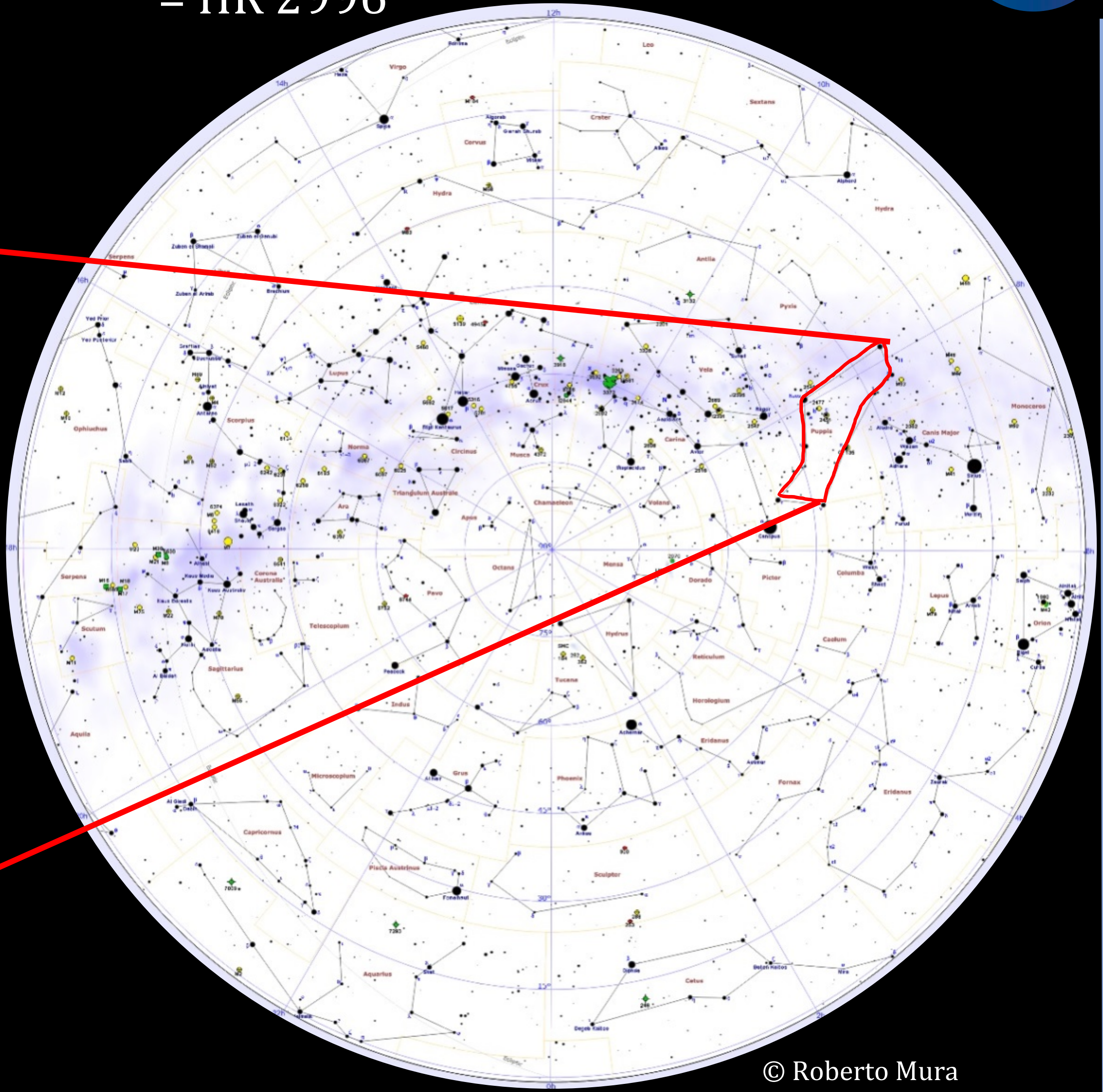
Observability

RA 07^{h}:43^{m}:48.5s

DEC -28°:57’:17.4”

Southern Hemisphere
Between November – April





l Puppis system

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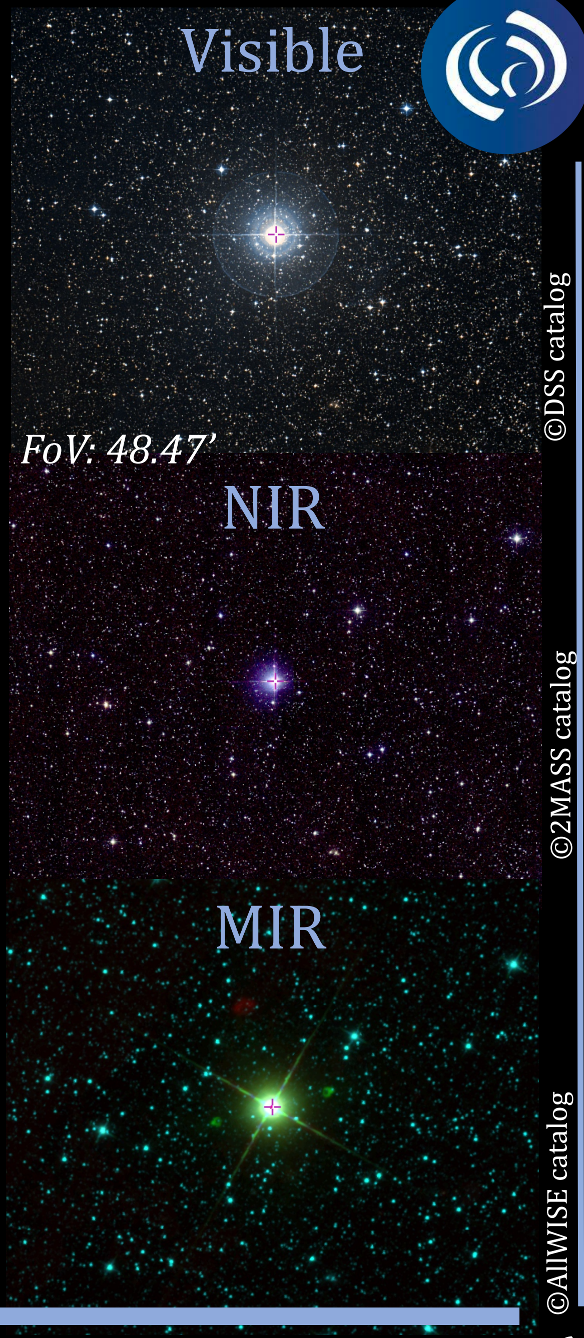


ID card

Brightest B[e] star known → 4 mag
d ~631 pc [GAIA DR2]
Binary system
Keplerian motion for dust & gas discs

Stellar composition

Primary → A[e]-type @ pre-RSG stage [Miroshnichenko+2020]
Secondary → Dwarf companion based on Radial Velocity [Plets+ 1995]

Might have undergone a mass transfer exchange according to Rensbergen+2008 model

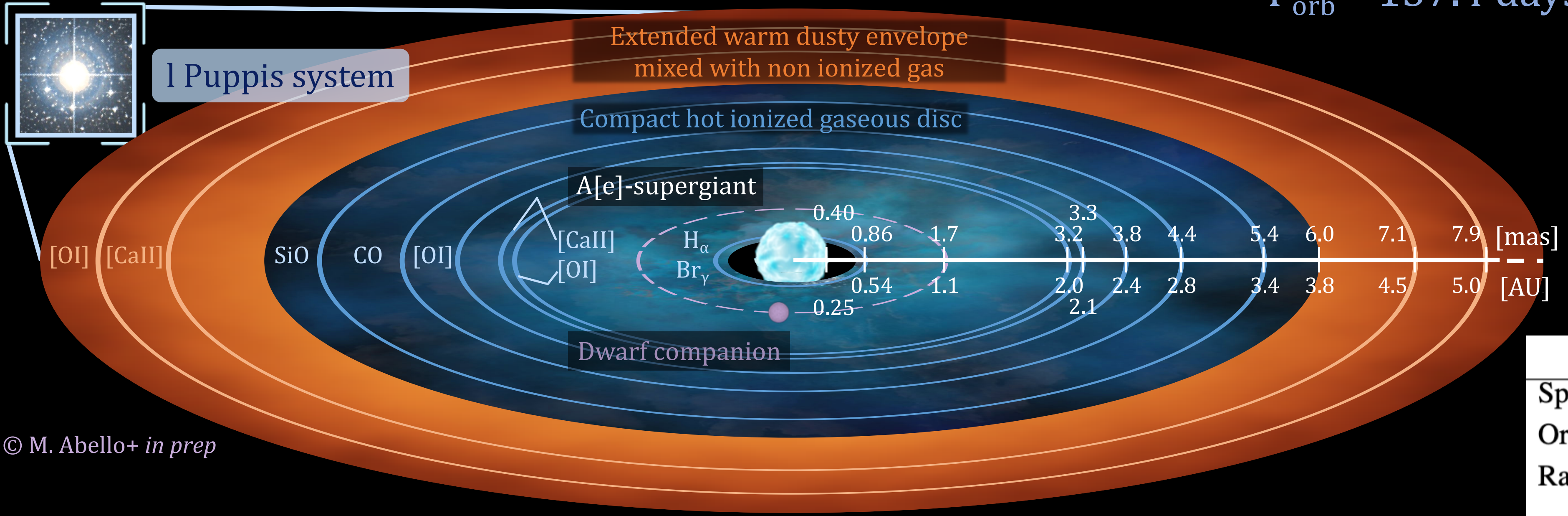
Uncertain nature of the host star

Suggests to move from sgB[e] group to FS CMa group [Miroshnichenko+2020]

l Puppis illustrative sketch

P_{orb} = 137.4 days → ~4.5 months
→ ~2.66 orbits/year

©DSS colored - STScI/NASA



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Spectroscopy results summarized from:
Millour+2011, Kraus+2015, Aret+2016, Maravelias+2018, Miroshnichenko+2020, Aidelman+2023

/!\ Spectroscopic binary → not resolved by IR interferometers

Supergiant star	
Spectral type	A2.7Ib
Orbital period P_{orb}	137.4 ± 0.1 days
Radius R_*	0.25 ± 0.03 A.U. 0.40± mas
Temperature $T_{eff,*}$	8500 ± 500 K
Mass M_*	8.8 ± 0.5 $M_\odot$
Luminosity $log(L_*/L_\odot)$	4.1 ± 0.1
Companion star	
Separation	1.11 ± 0.03 A.U. 1.7± mas
Radius R_c	~ 0.0014 A.U.
Temperature $T_{eff,c}$	~ 50 000 K
Mass M_c	0.75 ± 0.25 $M_\odot$

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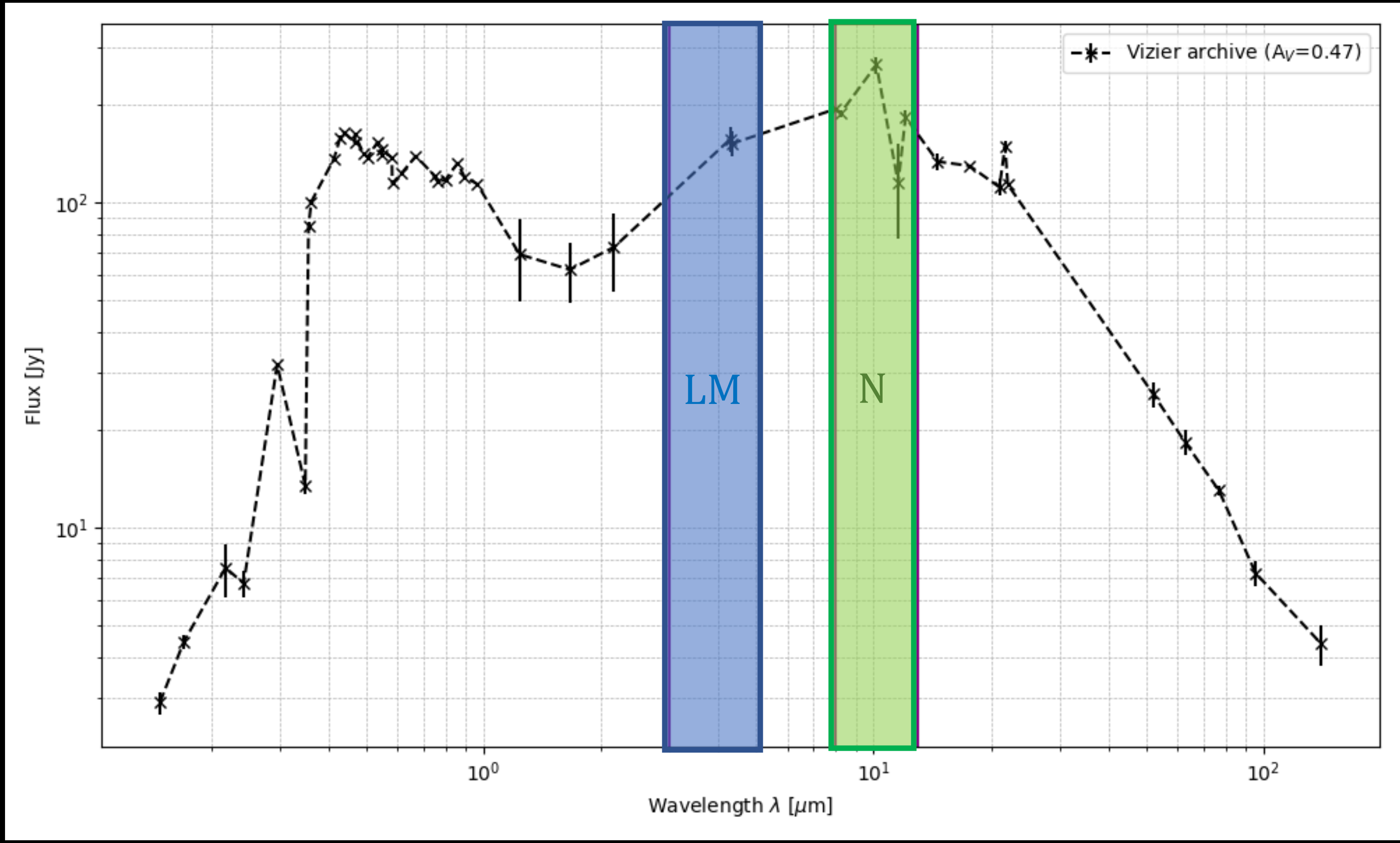
VLTI/MATISSE observations

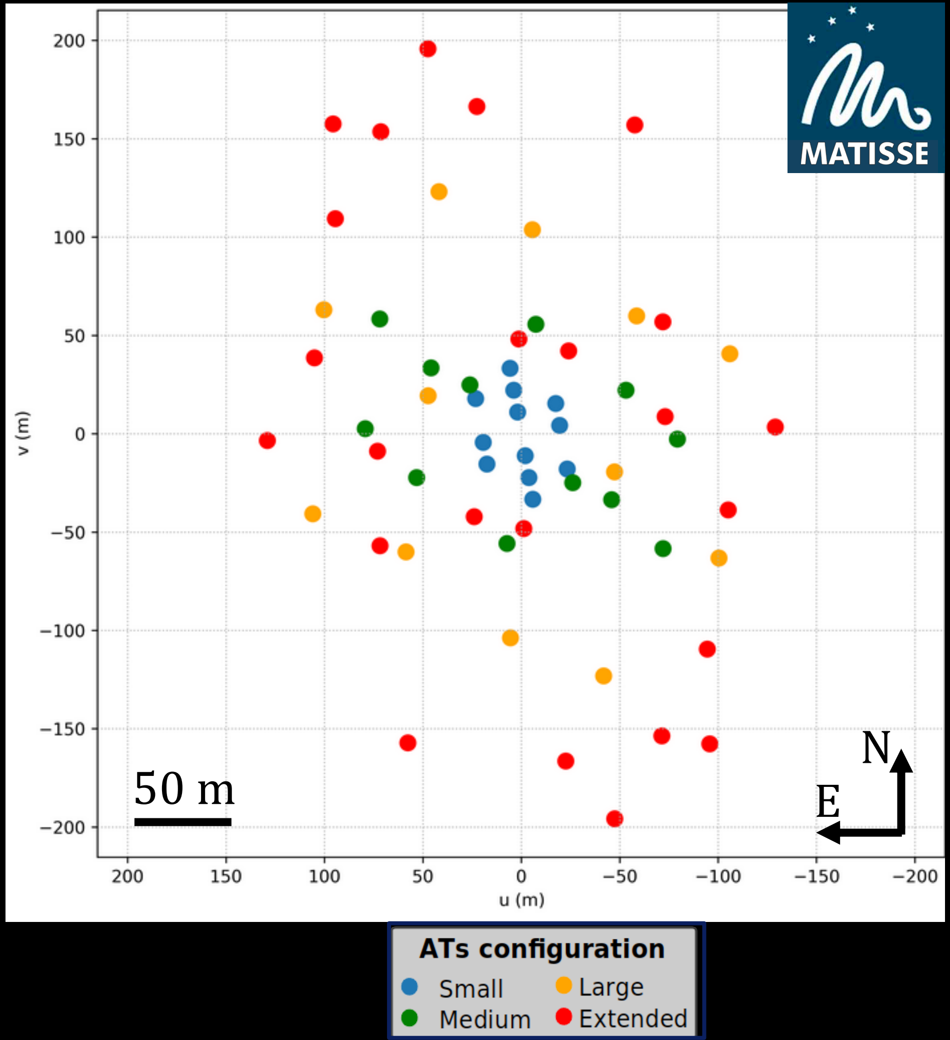
l Puppis SED



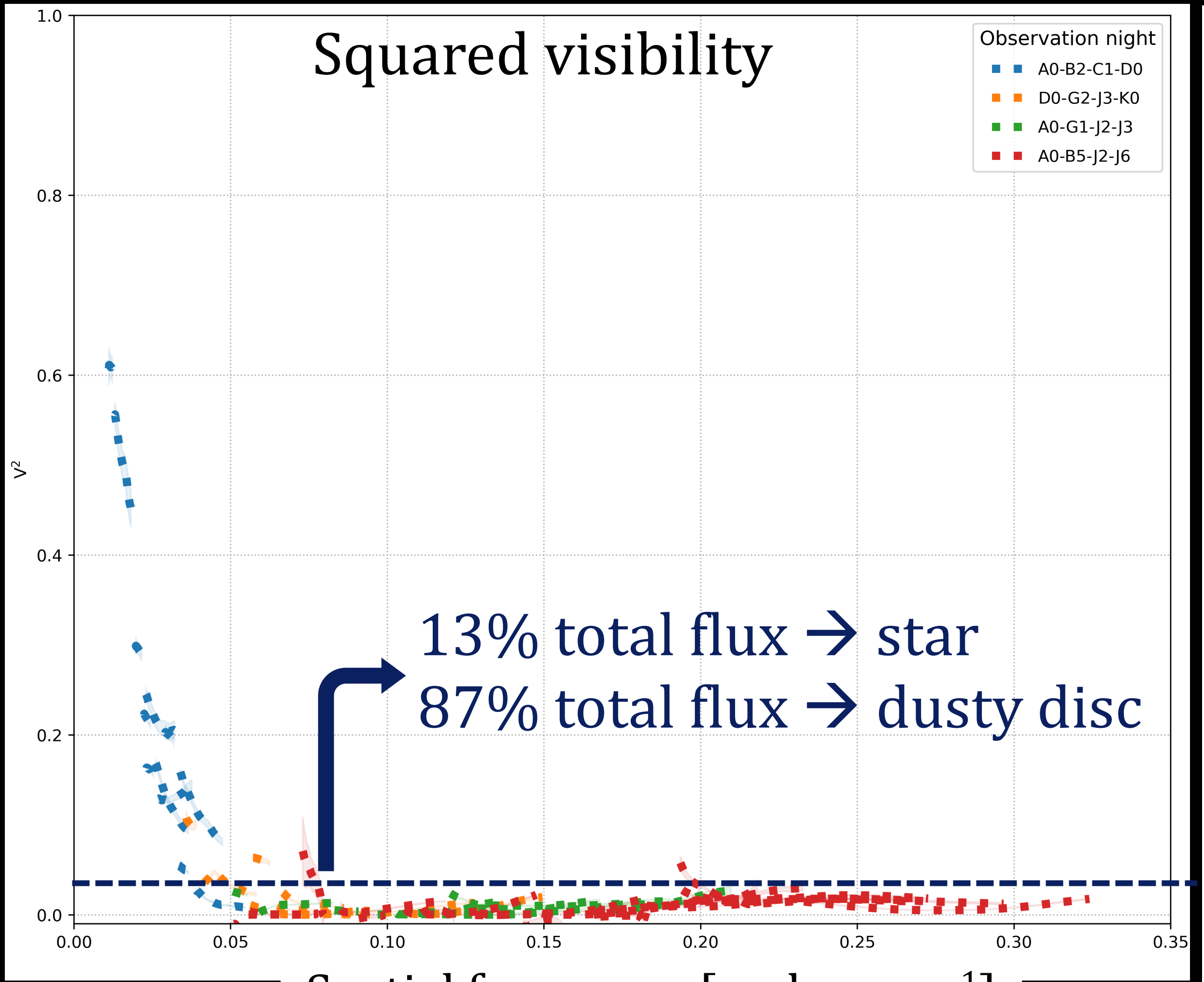
VO SED Analyzer

[Bayo+2008]

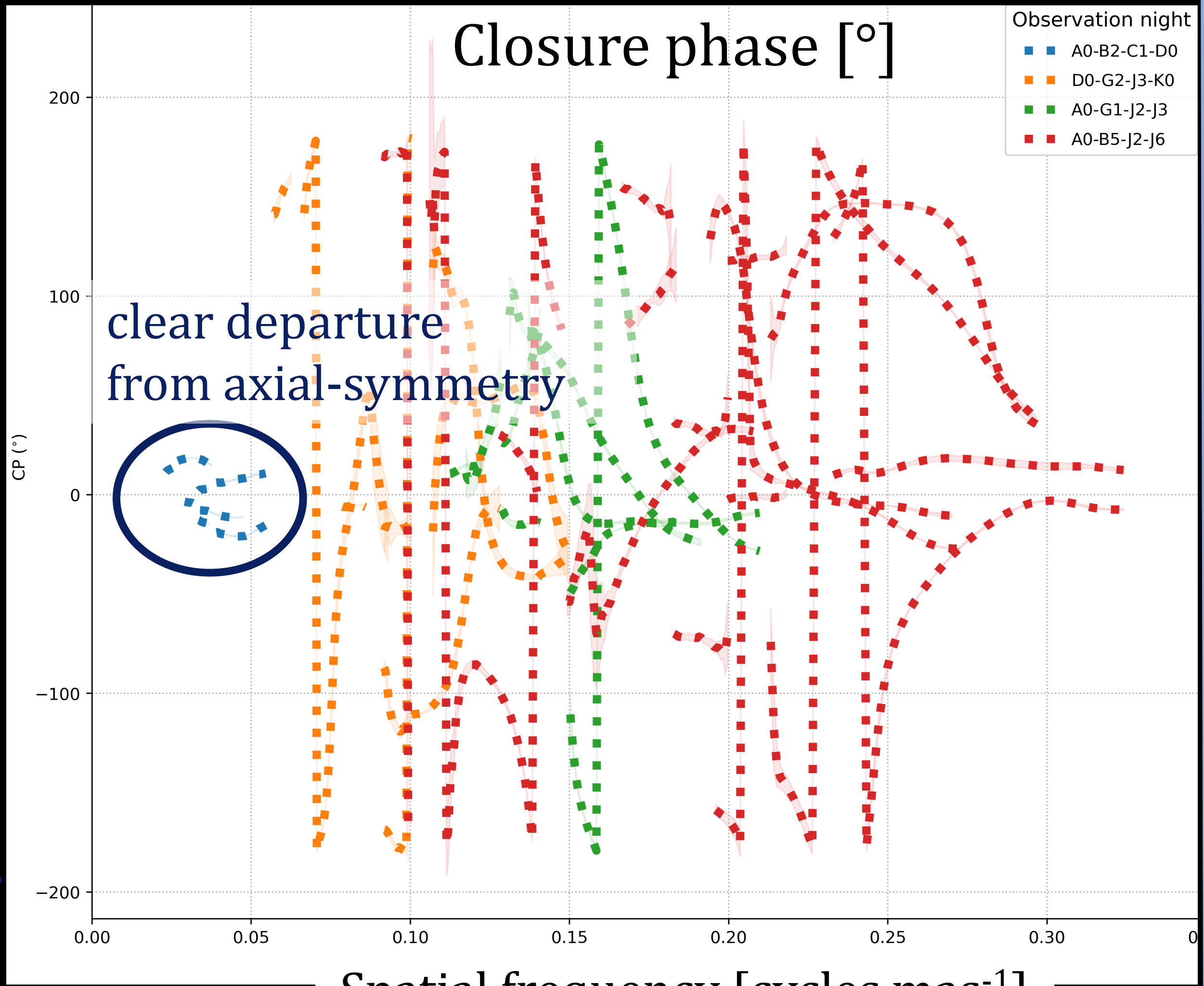
(*u*,*v*)-plane coverage



Step 0: MATISSE LM-data in low-spectral resolution



Spatial frequency [cycles.mas^{-1}]

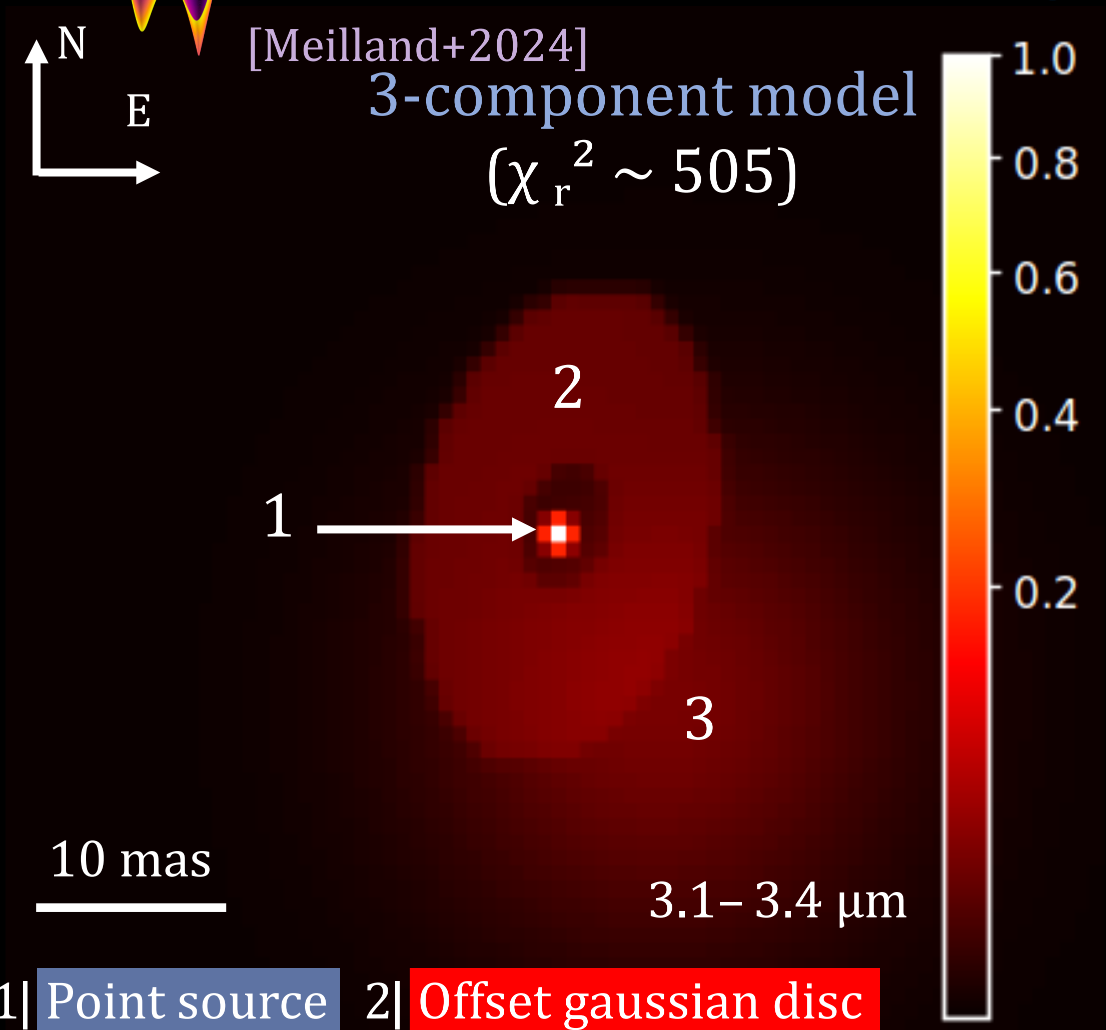


Spatial frequency [cycles.mas^{-1}]

Step 1: Geometric model fitting

Preliminary results

Disc geometrical parameters	Best fitted values MCMC sampling
Flux ratio [%]	star + gas disc ~ 7.9 Inner dust ring ~ 36.2 hot dust blob ~ 55.9
Dust ring major axis [mas]	r_{inner} ~ 6.77 | r_{outer} ~ 24.4
Dust ring position angle [°]	14.9°
Ring axis ratio | Inclination angle [°]	e ~1.52 i ~ 48.9
Skewness	0.11
Skewness position angle	-40.7°
Hot blob position [mas]	α ~ 7.04 | δ ~ -8.7
Hot blob size [mas]	FWHM ~16



1| Point source 2| Offset gaussian disc
3| Elliptical skewed gaussian ring

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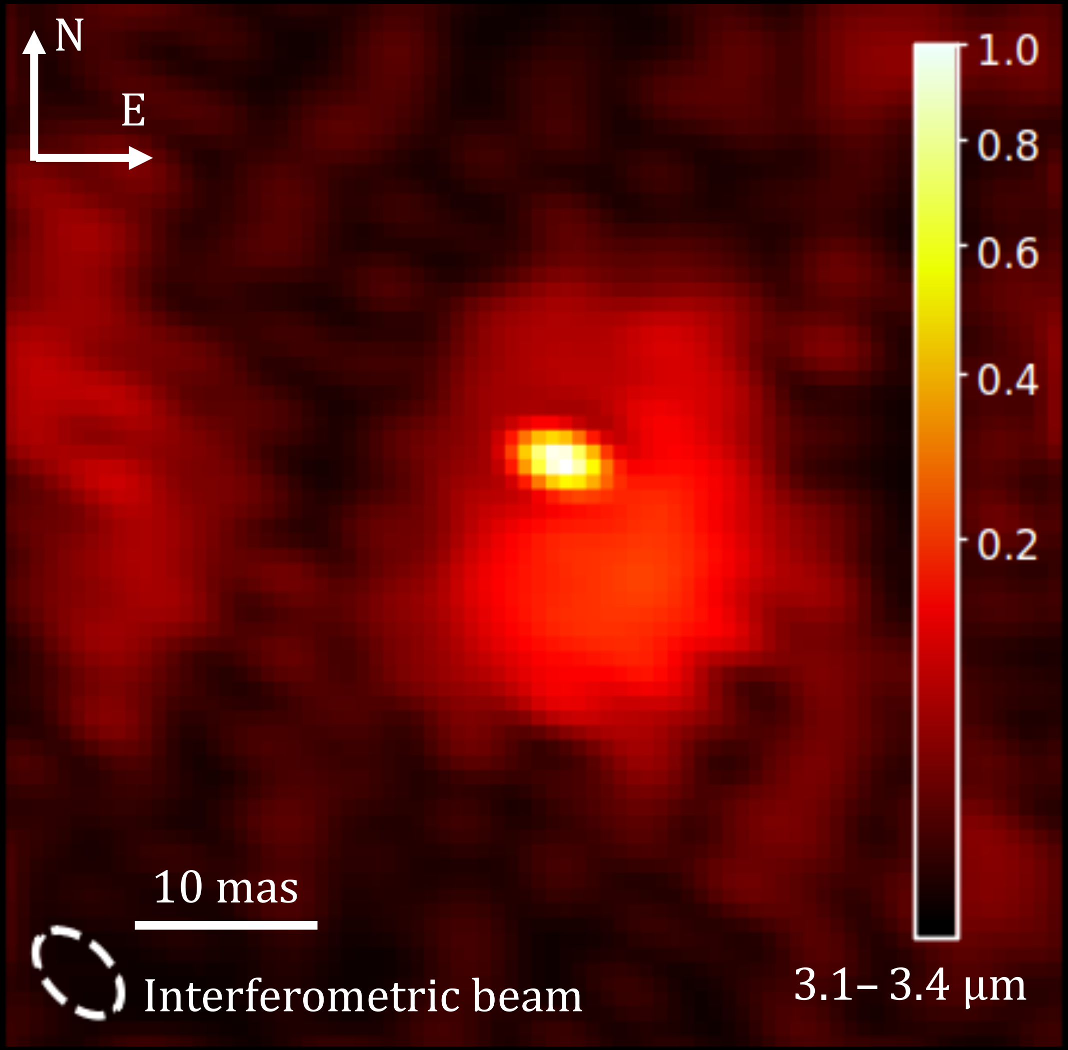
Step 2: Synthetic image from MiRA software

Preliminary results



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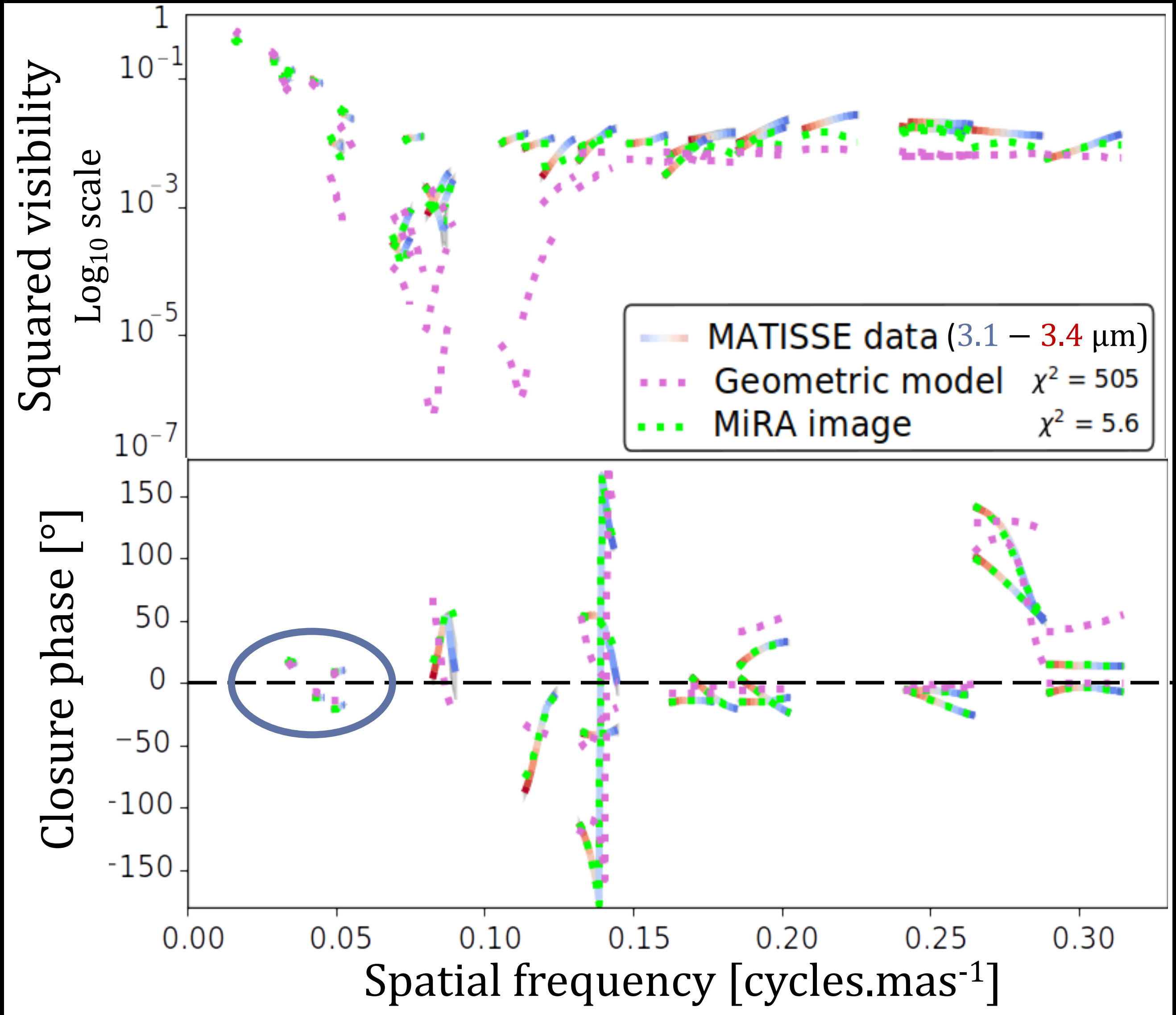
MiRA [Thiébaut 2018] convolved image

$(\chi_r^2 \sim 5.6)$

Identical image using either:

- geometric 3-component model or Dirac distribution as the starting image
- Using either the hyperbolic or the compactness regularization function

Step 3: Comparison l Puppis data *vs* simulated data



Chromatic multi-component model fitting → oimodeler/MCMC sampling

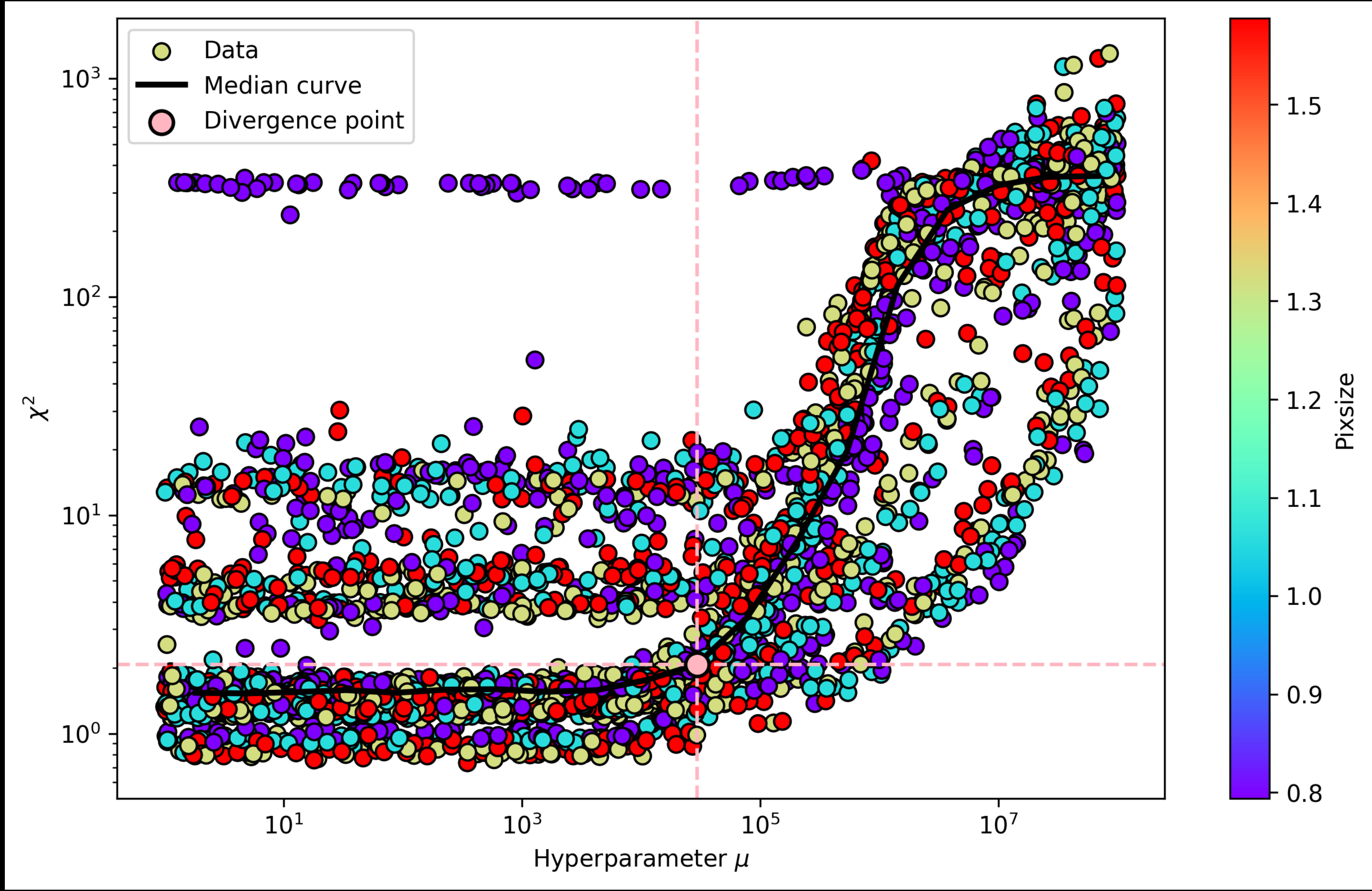
Image reconstruction techniques
→ MiRA algorithm

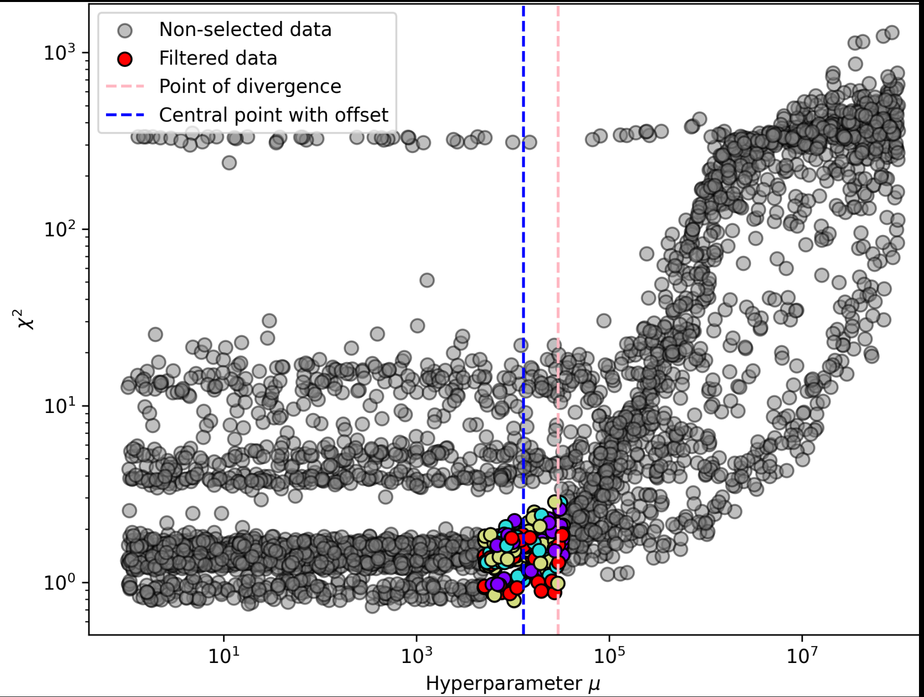
Consistency between two different fitting methods

→ Intriguing asymmetry at short spatial frequencies can be described in the direct space as a shifted and extended component in the dusty inner rim

→ Strong evidence for inhomogeneous dust shell

Step 4: L-curve inferred from the 3360 image grid

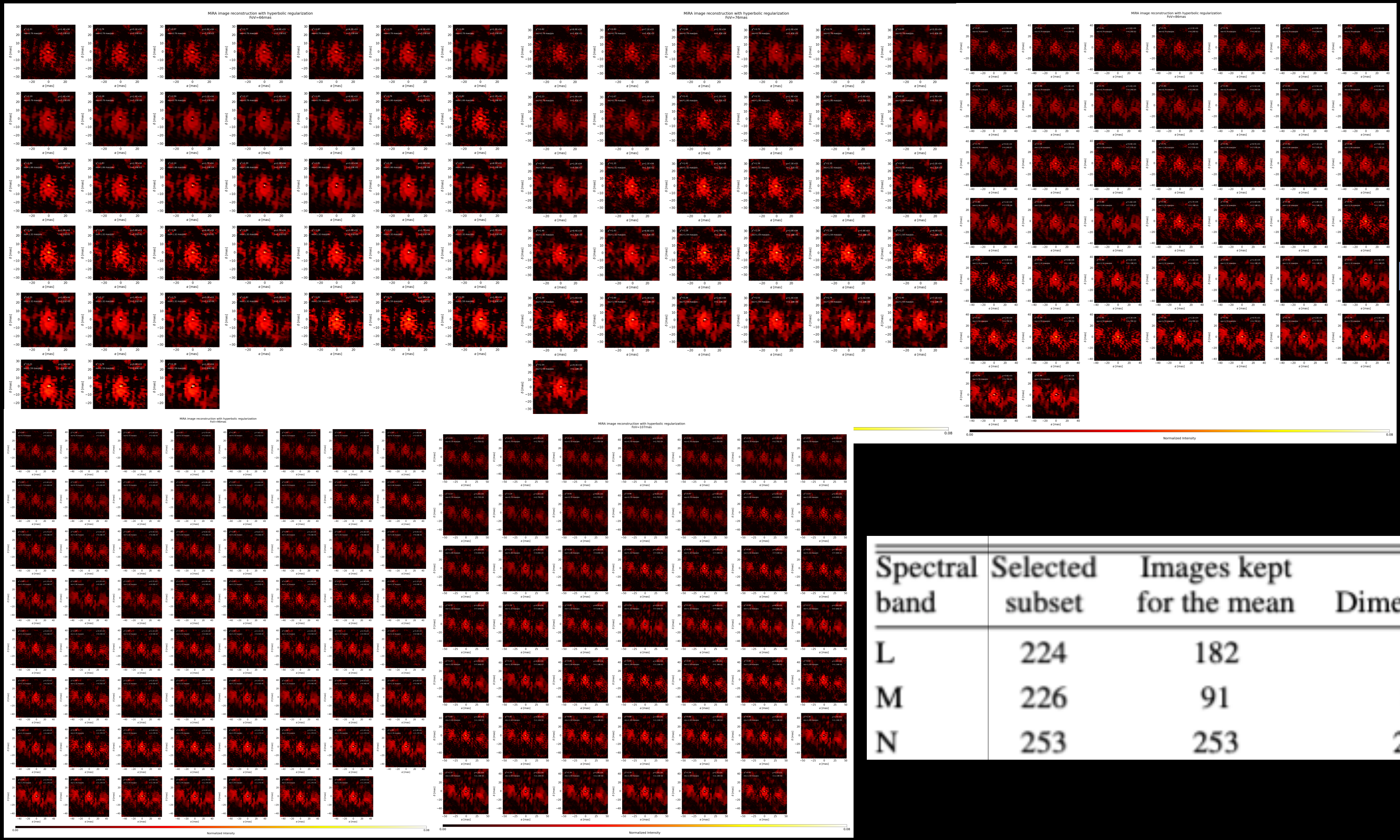




Identify the optimal weight μ

→ Define a statistically robust sample of reconstructed images

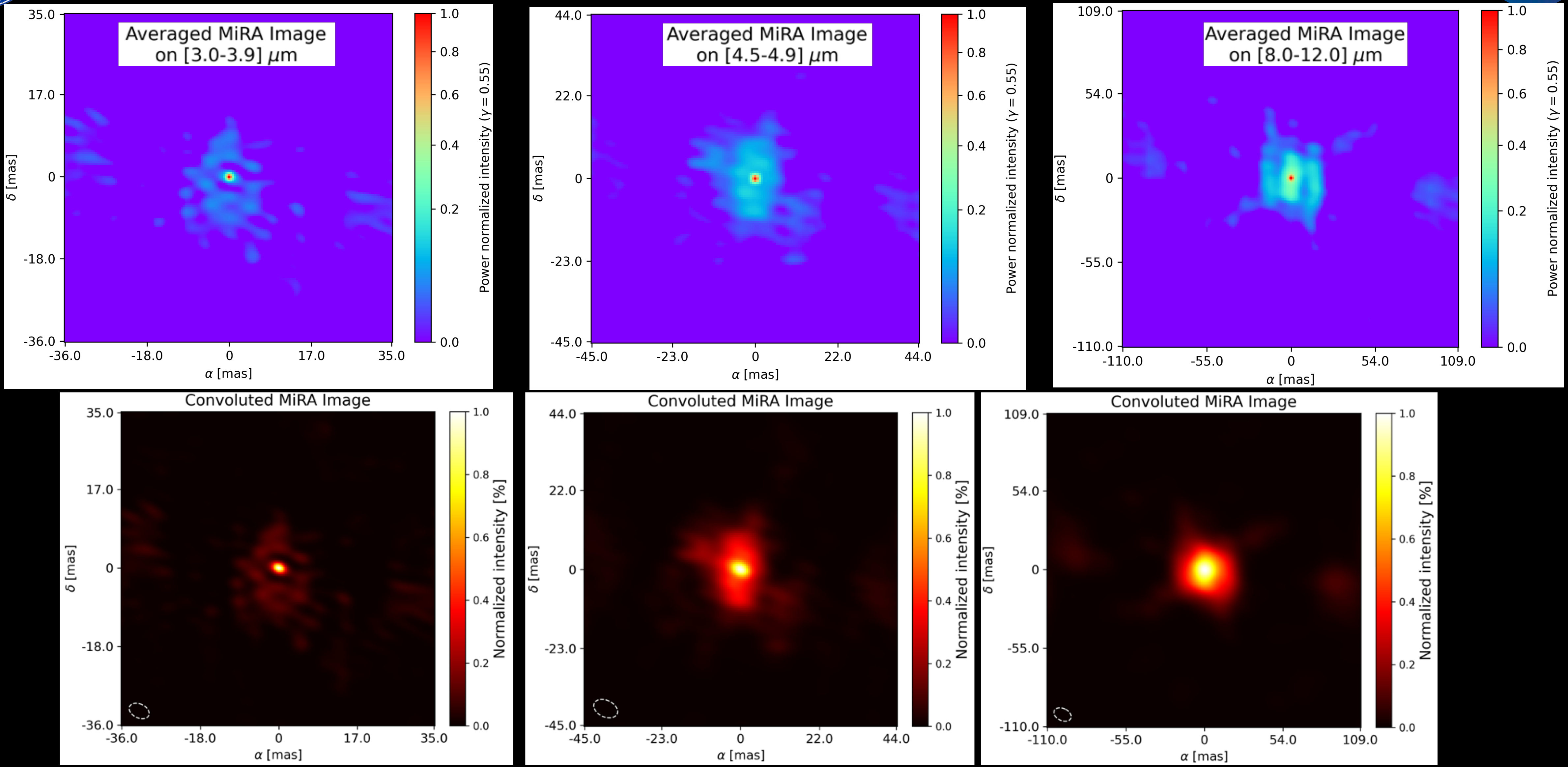
Step 5: Resampling the selected robust subset



Resample to the same resolution

Spectral band	Selected subset	Images kept for the mean	Average image characteristics Dimension [mas]	Pixel size [mas/pixel]
L	224	182	71.46	0.397
M	226	91	89.694	0.594
N	253	253	219.752	1.0565

Step 6: Averaged images



Step 7: Comparison with data

Spectral band	Comparison image/data χ^2_{global}	χ^2_{vis}	χ^2_{clos}
L	7.6	8.4	6.5
M	5.6	6.9	3.5
N	2.2	3.3	0.6

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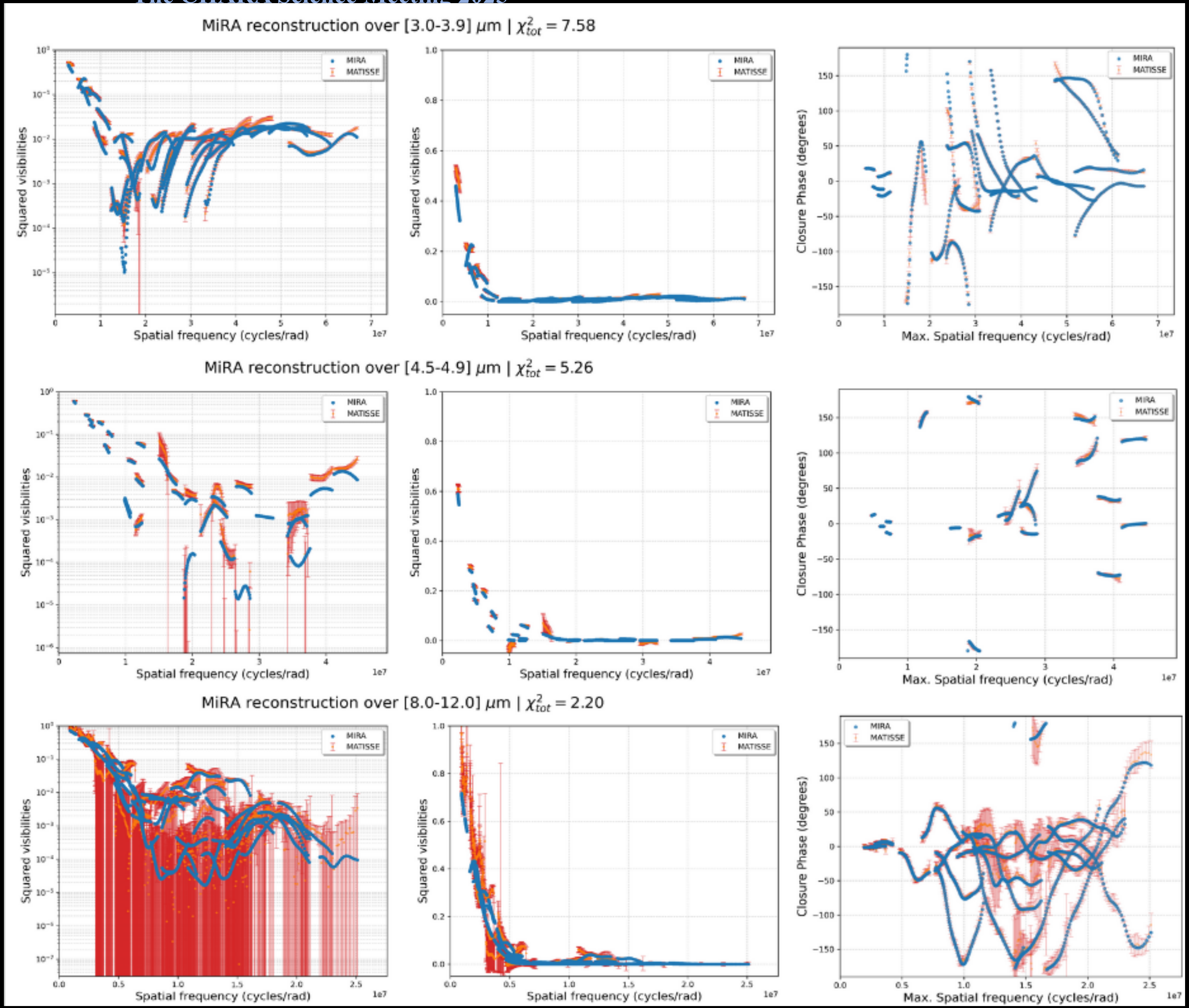
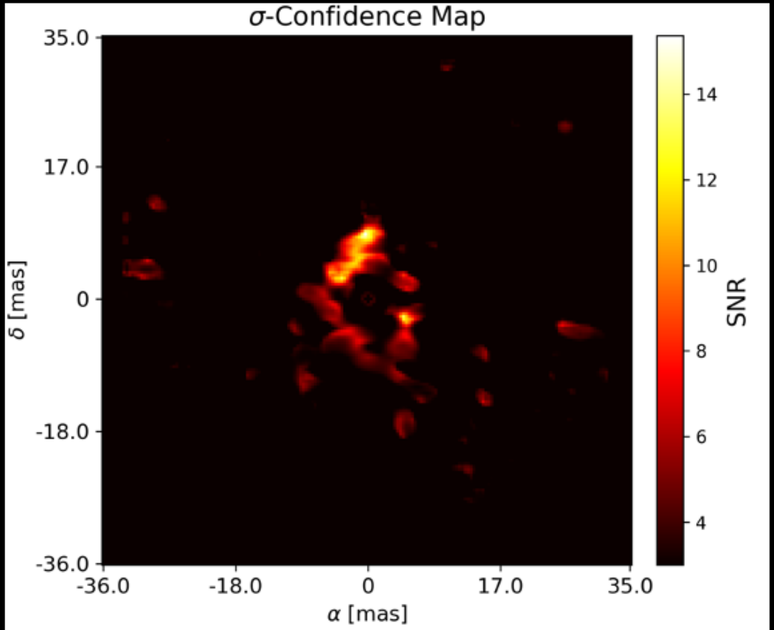
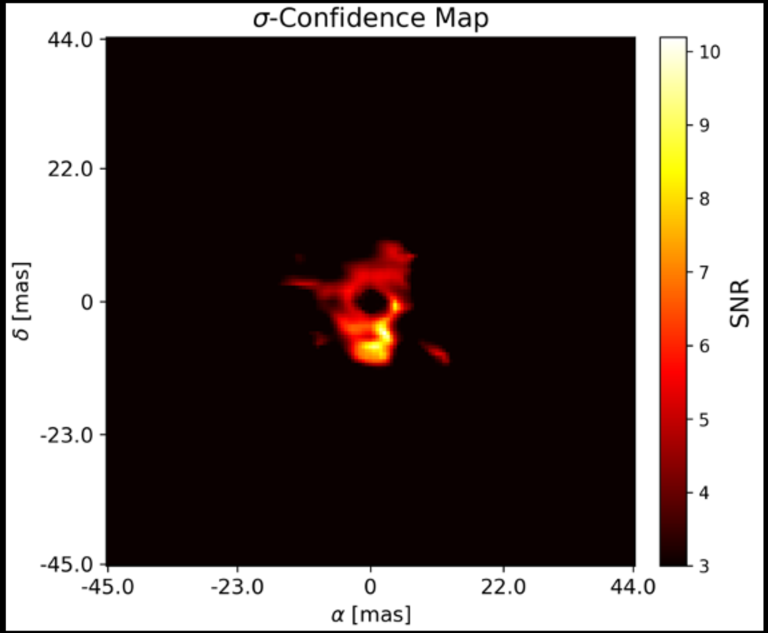
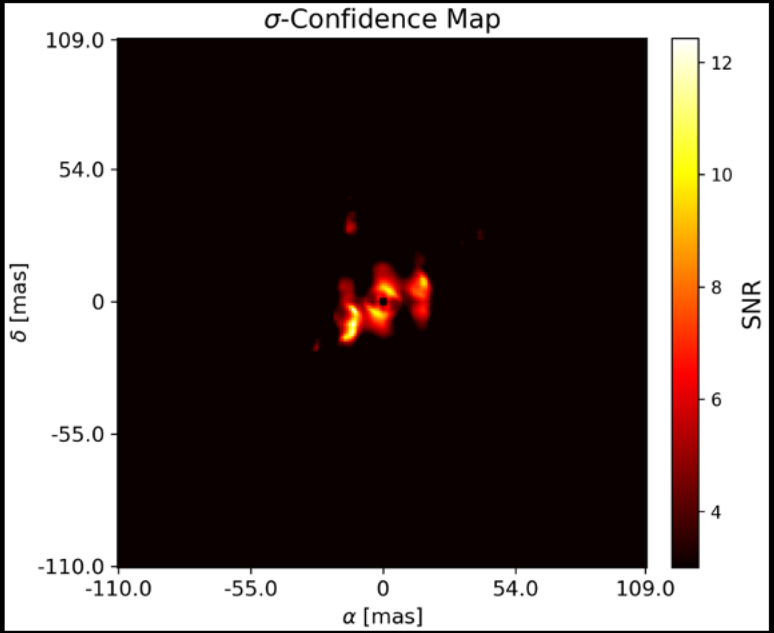


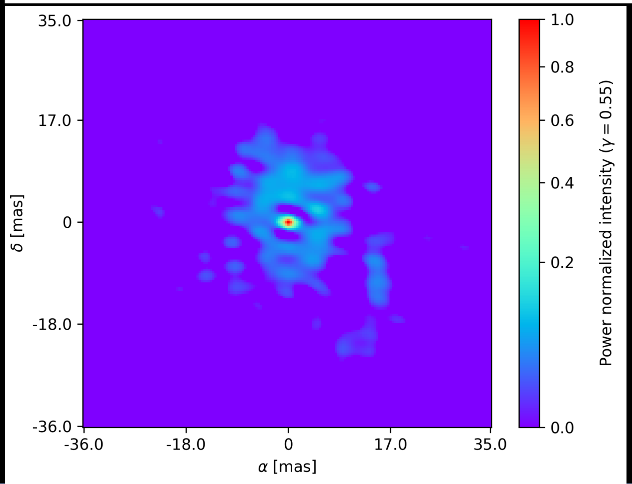
Step 8: Verification artefacts *VS* physical structures





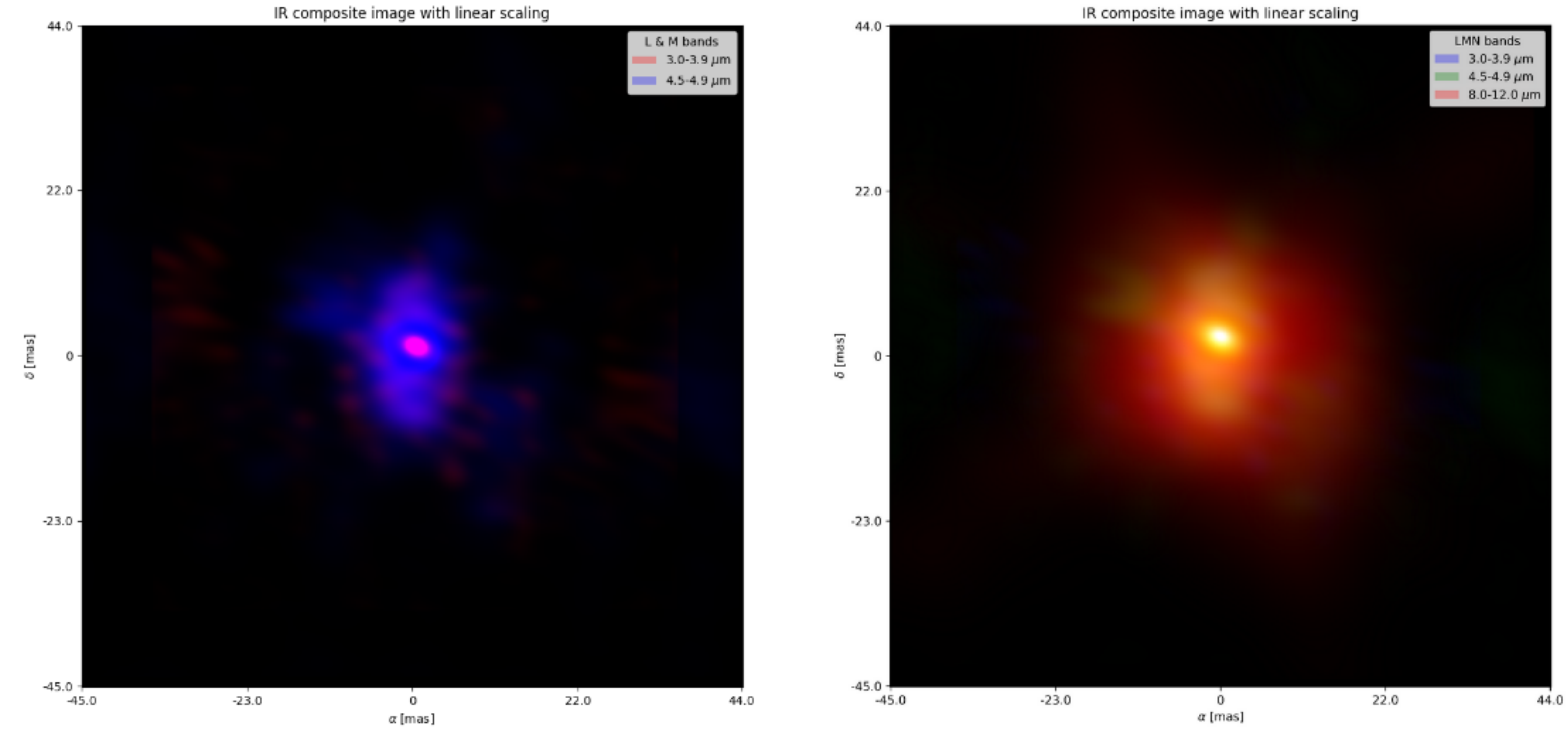


Sigma based confidence map



Low Frequency Filter [Millour+ 2012]

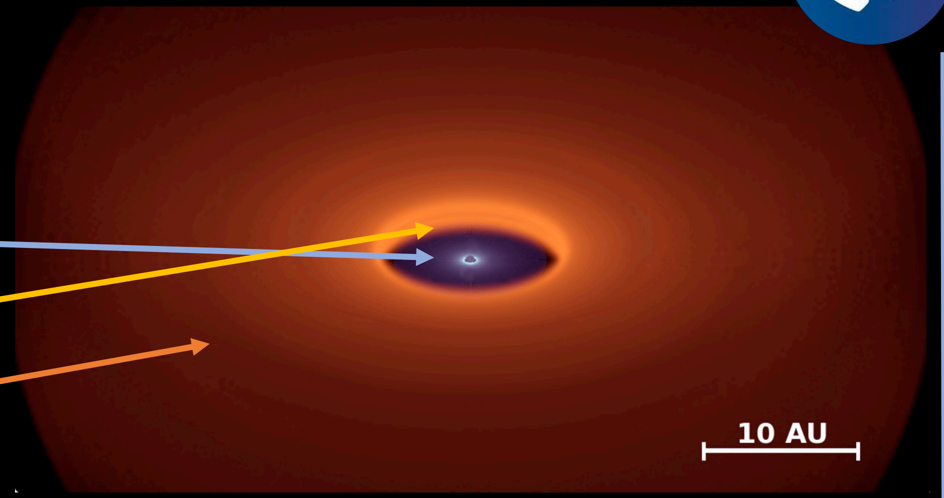
Colour-composite image LMN bands



VLTI 1st Gen results

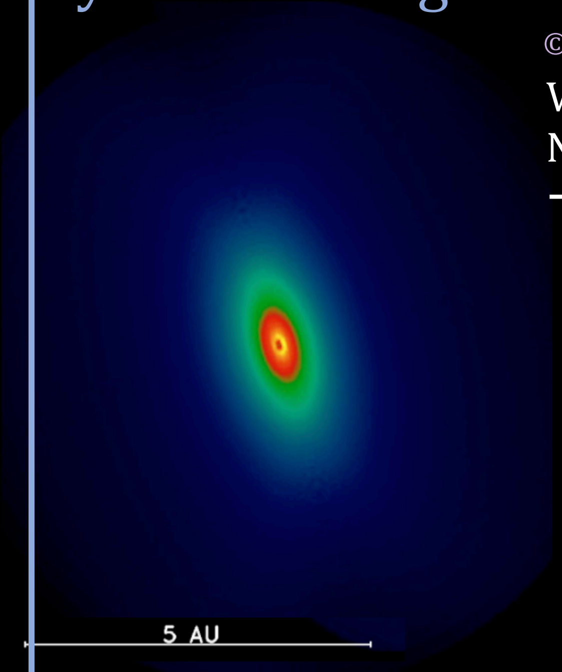
l Pup described by a 3-component model

Physical component	Relative flux	Geometric model	Resolved
Star + Gas disc	1%	Point source	—
Inner ring	40%	Elliptical skewed ring	X
Dust disc	59%	Extended centred background	X



Radiative transfer MC3D code + SIMECA modelisation
©Meilland+ 2010

Synthetic images

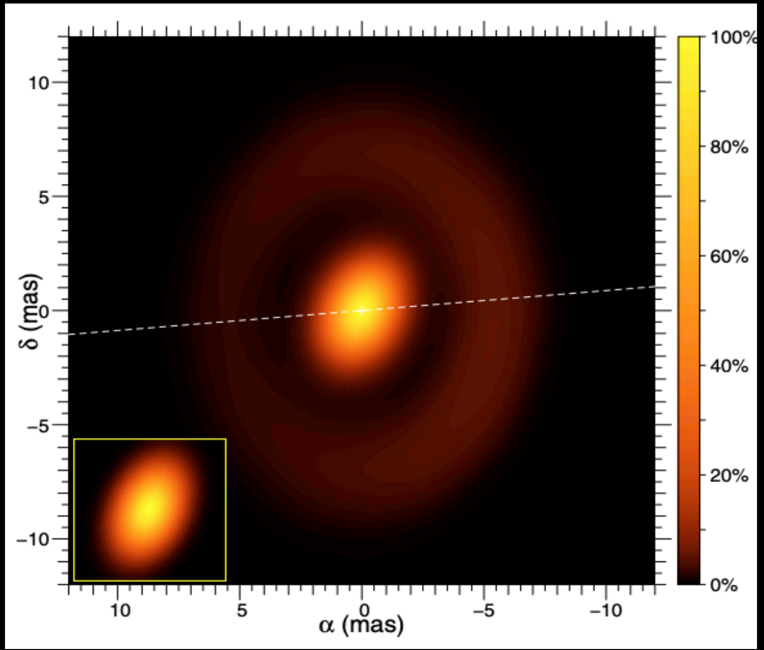


© Meilland+ 2010

VLTI/MIDI data
N band model (12µm)
→ Dust thermal emission

VLTI/AMBER data
K & H bands model
→ Gas emission

© Millour+ 2011



— Conclusion —

stars surrounded by a dense axi-symmetric dusty and gaseous disc

Discussions

- Ring inhomogeneity noticed in 2014 by Maravelias+2018 via spectroscopy &in McDonald spectrum taken in 2008.
- Are there jets/outflowing material from the companion? Or rather be the result of dust trapping (vortex)?
- Origin/nature of the blob: may result from clump formation due to the condensation of dust grains OR from binary interaction where the companion evaporates some of the dust located in the inner ring inhomogeneously.

Work perspectives

- Check if there is any temporal variability in the circumstellar material → binary effects or not? periodicity?
- Geometric modelling to finish to publish the paper.
- Submit ESO proposal wishing for GRAVITY & PIONIER data of l Pup → access to gas dynamic (K,H-bands).
- Interested in the CHARA fast snapshot imaging program →extend to northern B[e] stars + HK imaging

Thanks for your attention

If you want to collaborate, reach me at margaux.abello@oca.eu