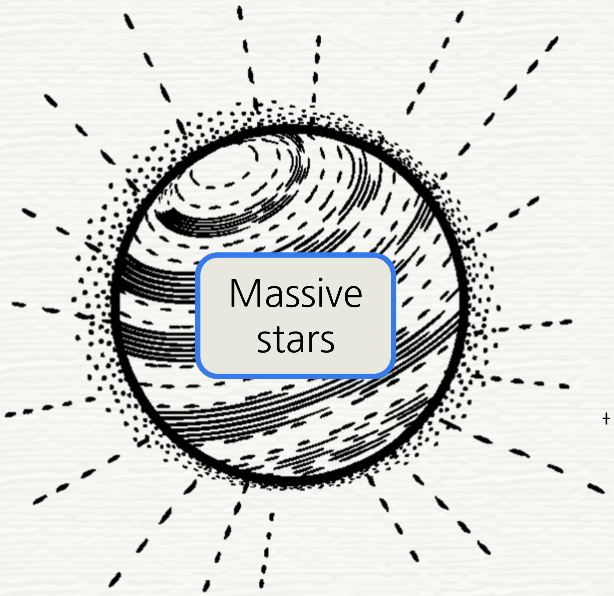
High-angular resolution insights into massive stars

Emma Bordier - bordier@ph1.uni-koeln.de
I. Physikalisches Institut, University of Cologne

<u>In collaboration with</u>: A. Frost, H. Sana, W.J de Wit, A. Mérand, F. Peissker, L. Labadie, L. Woglo, A. Matter

Why are they important?

- First Stars and Galaxy formation and evolution
- Nucleosynthesis and feedback
- Supernova and compact objects
- Gravitational waves sources



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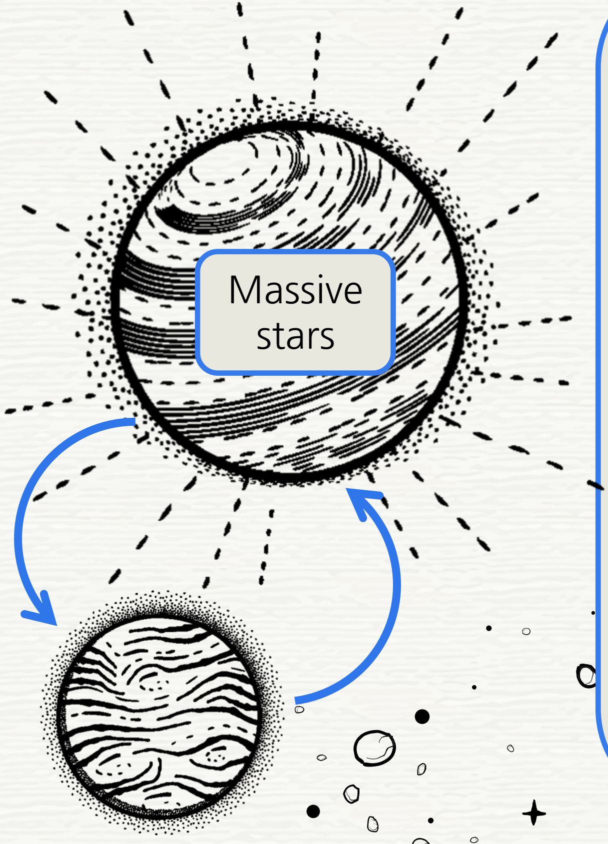


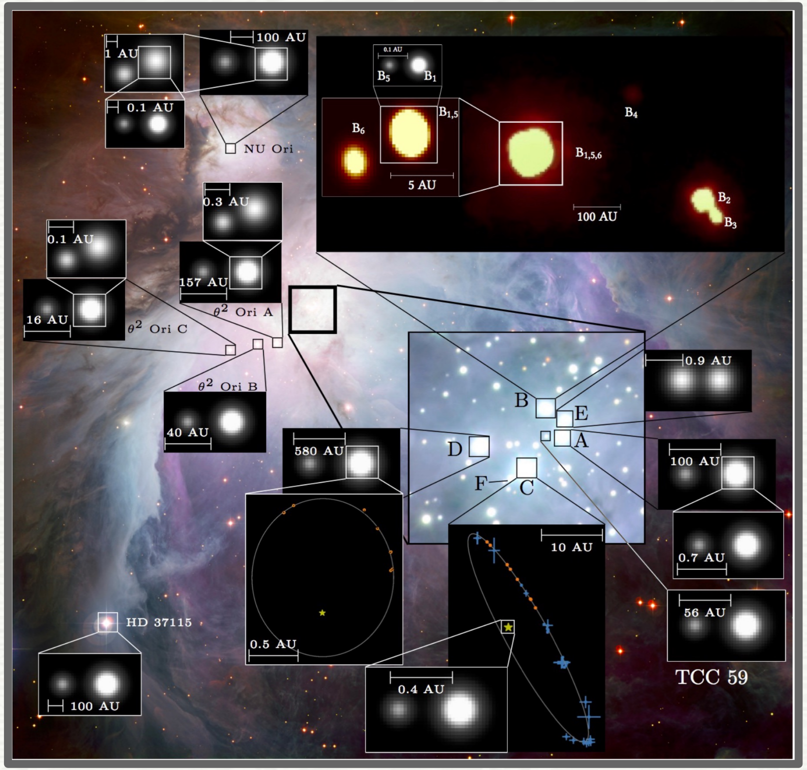
Characteristics

- $M_{init.} \gtrsim 8\ M_{\odot}$
- $\tau_{form} \sim 10^5 years$ (Tan et al. 2014)
- $\tau_{life} \sim 10^6 years$

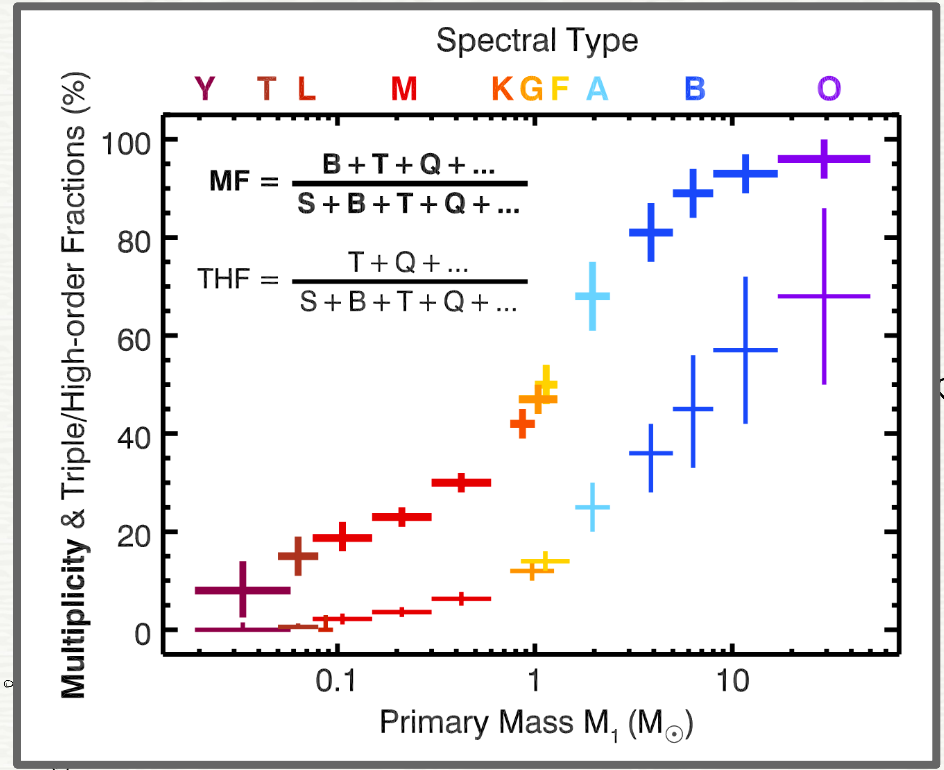
- **>90%** are found in a multiple system while on the main sequence
- **>30-40%** are short-period close-in systems

(e.g. Sana et al. 2012, 2014, Moe & Di Stefano 2017, Offner et al. 2022)

Multiplicity is a common feature for **most massive stars**



Gravity Collaboration et al. 2018



Offner et al. 2022 (PP7 review)

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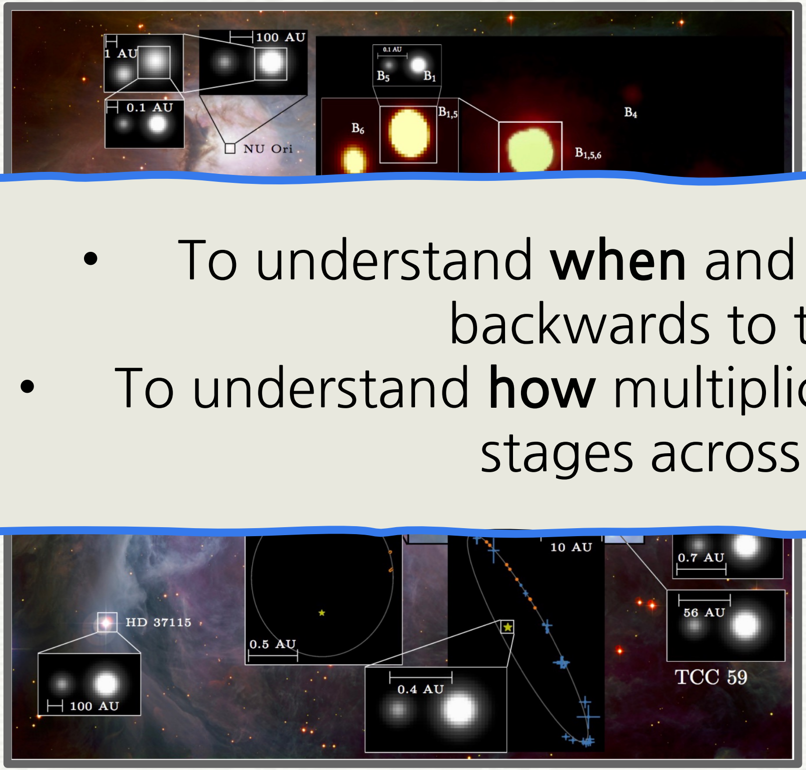

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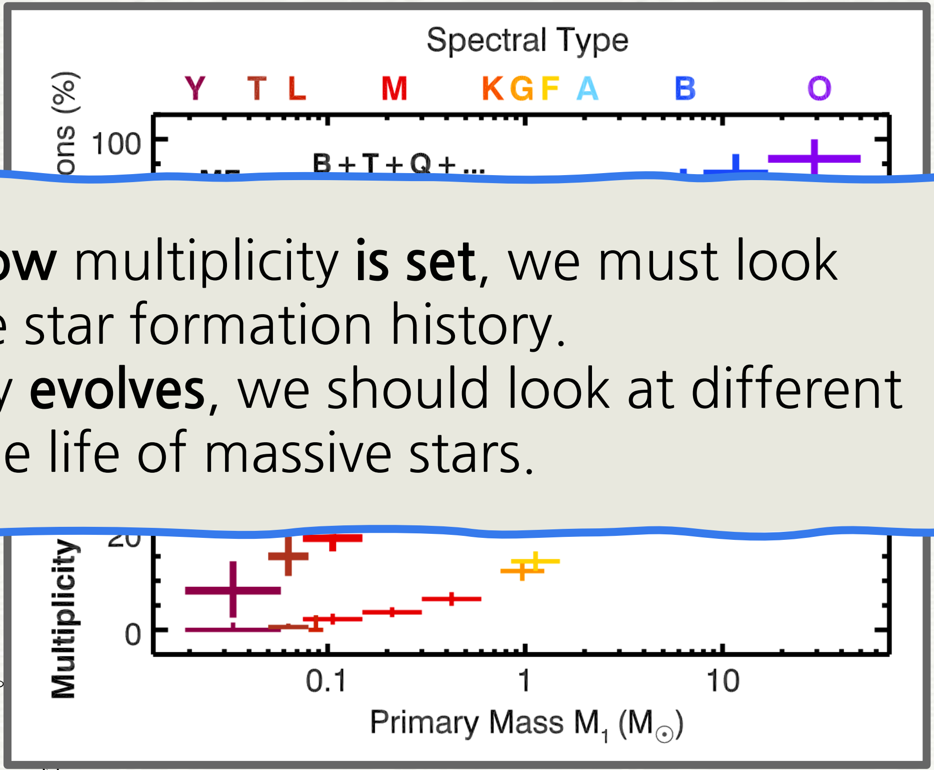
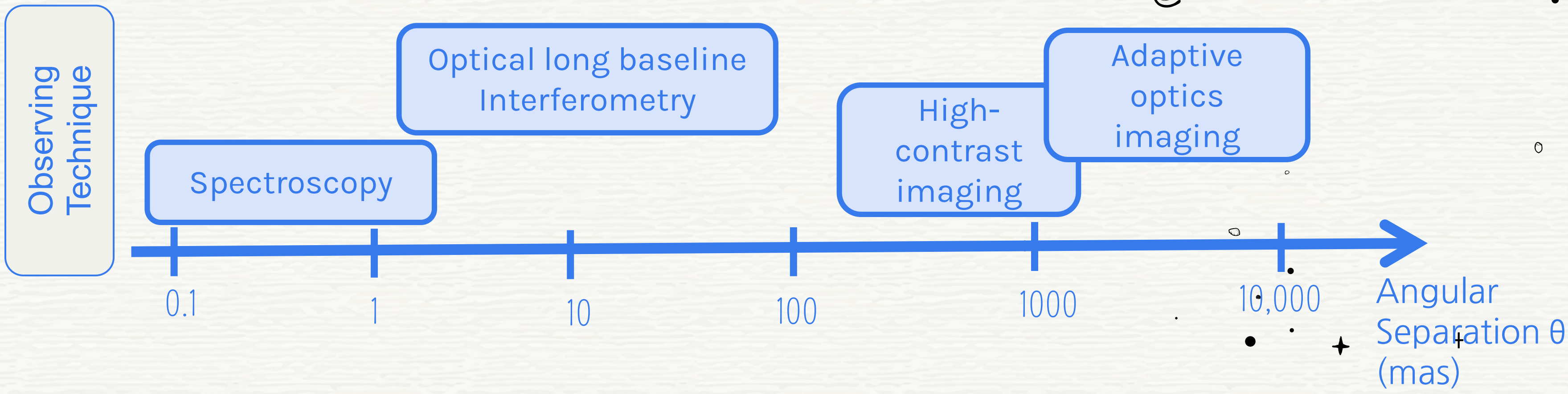


Offner et al. 2022 (PP7 review)

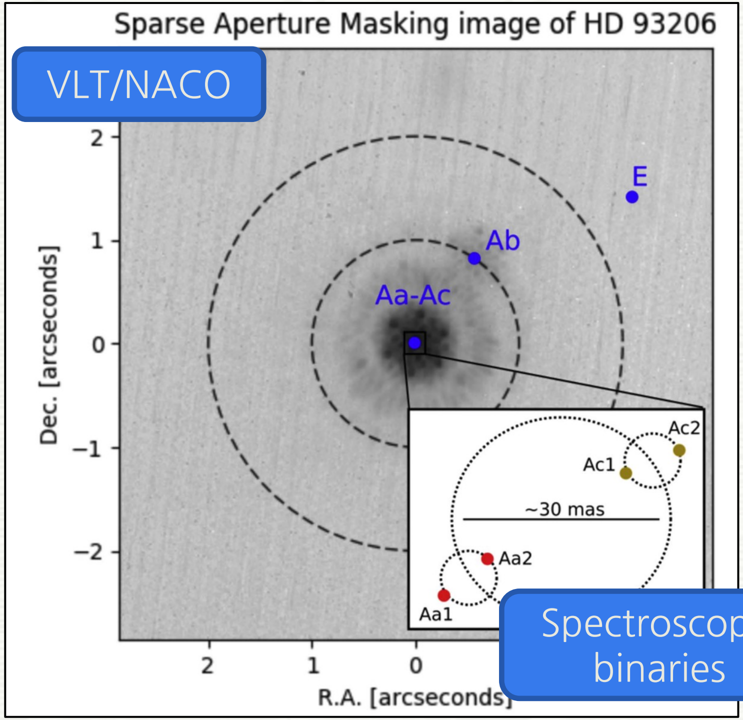
- To understand **when** and **how** multiplicity **is set**, we must look backwards to the star formation history.
- To understand **how** multiplicity **evolves**, we should look at different stages across the life of massive stars.

Multiplicity from an observational point of view



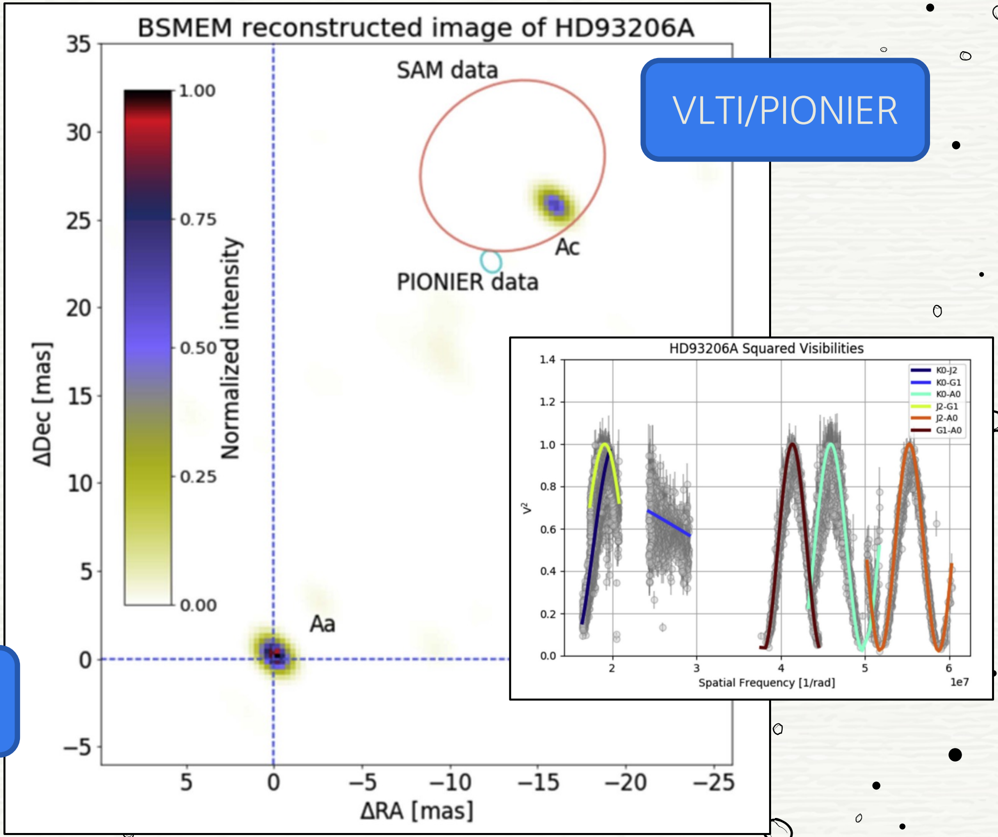
Adapted from Sana et al. 2016

Example of QZ Car (HD 93206)



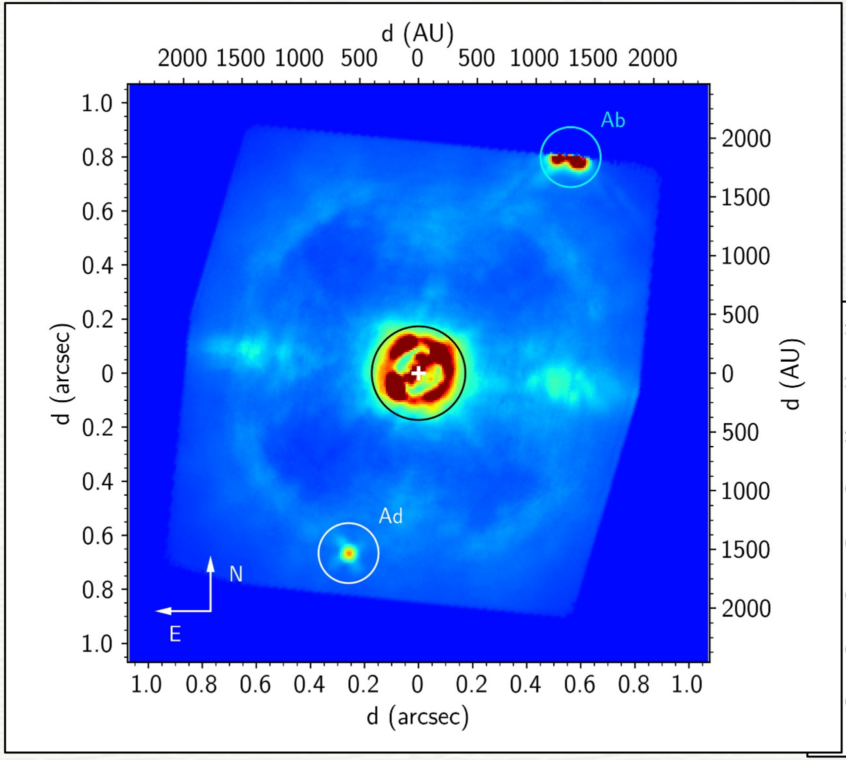
VLT/NACO

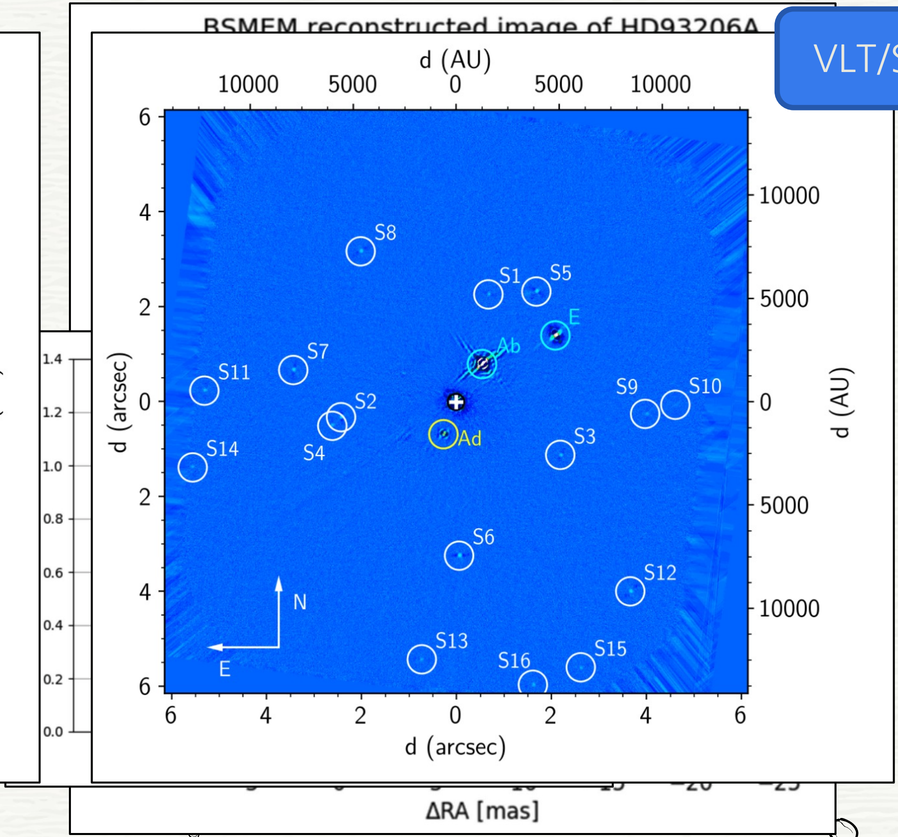
Spectroscopic binaries



VLTI/PIONIER

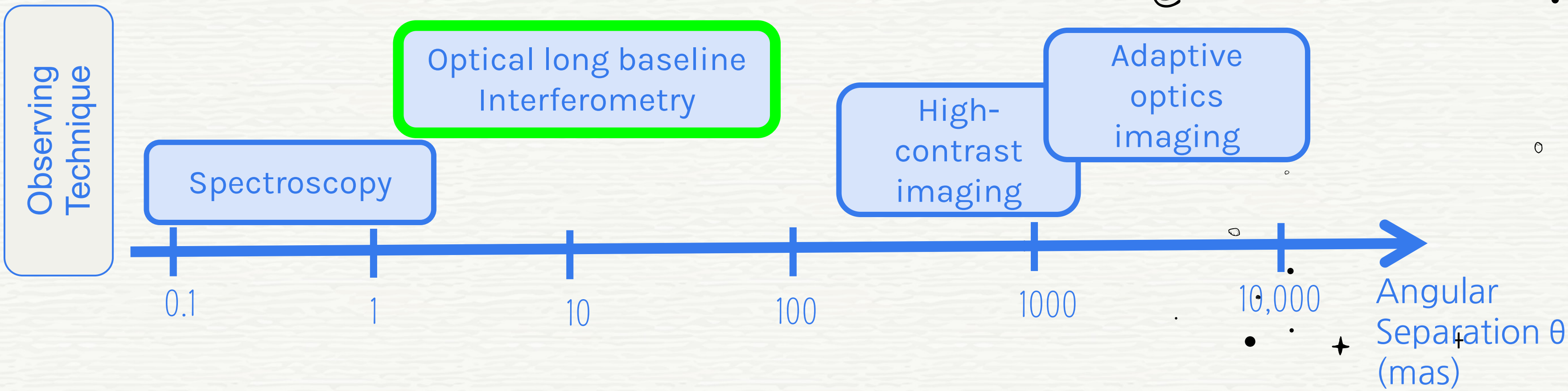
Example of QZ Car (HD 93206)





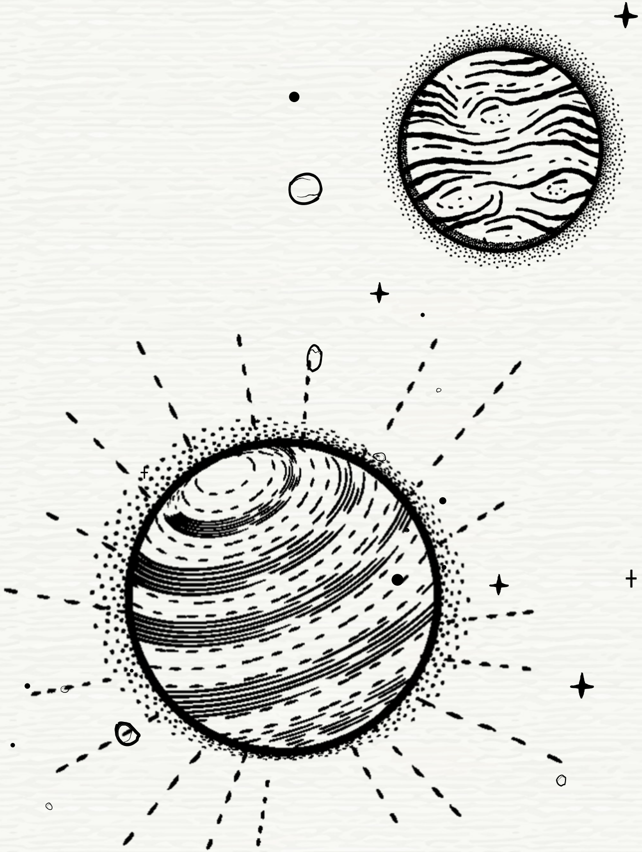
VLT/SPHERE

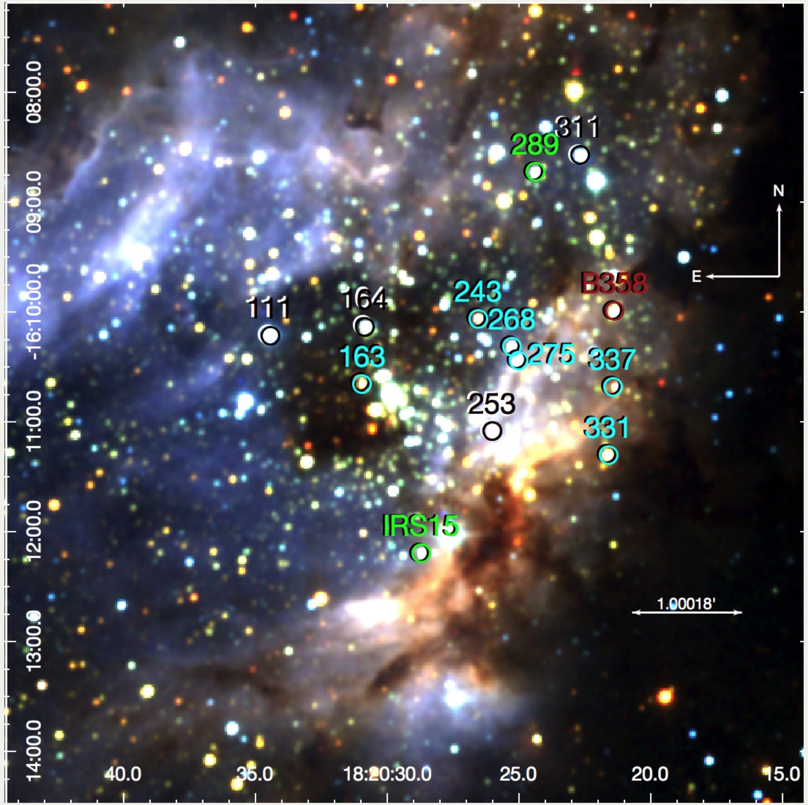
Multiplicity from an observational point of view



Adapted from Sana et al. 2016

Multiplicity of young O stars in M17 with VLTI/GRAVITY





M17 Star-forming region

- In the Carina-Sagittarius spiral arm
- One of the :
  - Closest: $1.68^{+0.13}_{-0.11}$ kpc — Kuhn+2019
  - Most luminous: $3.6\times10^{6}L_{\odot}$ — Povich+2007
  - Youngest: ~1 Myr — Hanson+1997

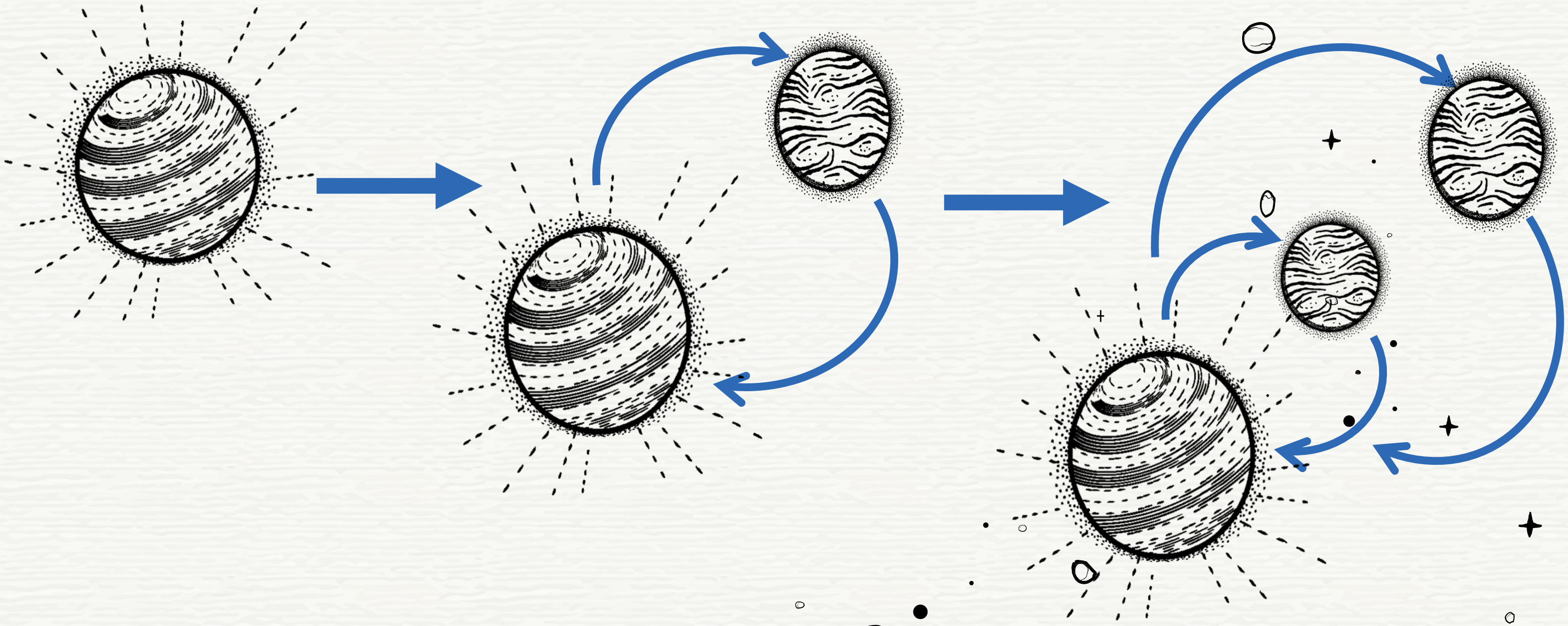
  Star-forming region in our Galaxy

- Low radial velocity dispersion

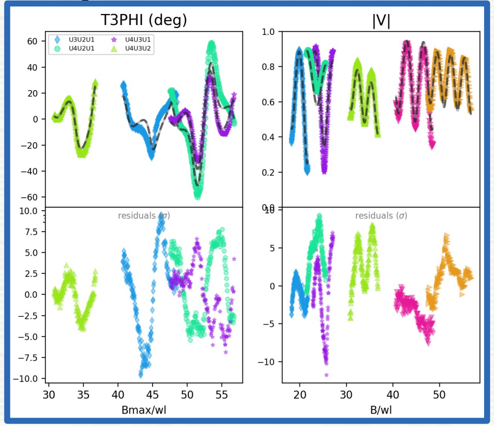
→ lack of short period binaries — Sana et al. 2017

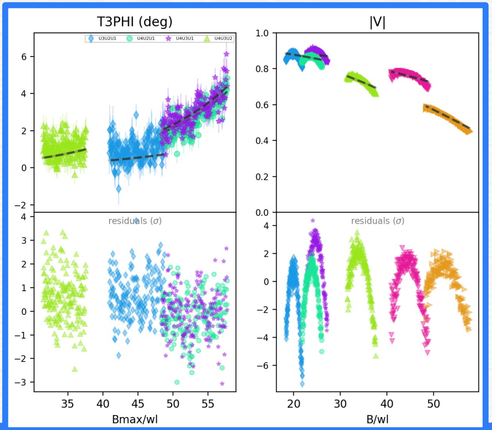
→ good test for the migration scenario

What's the multiplicity of massive stars younger than <1Myr?



What's the multiplicity of massive stars younger than <1Myr?





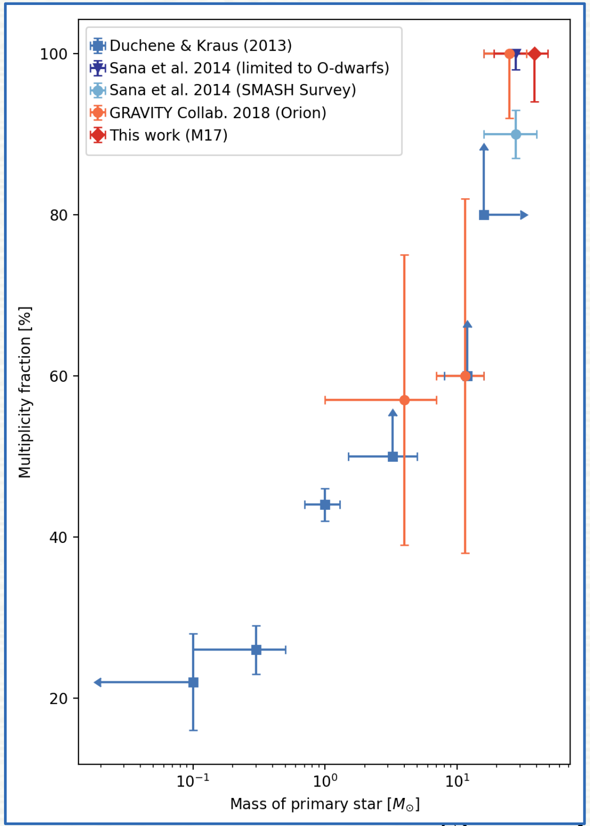
- Position of the companion(s) $(\Delta \mathbf{x_i}, \Delta \mathbf{y_i})$
- Flux ratio $(\mathbf{f_r})$

PMOIRED

By Antoine Mérand (ESO)

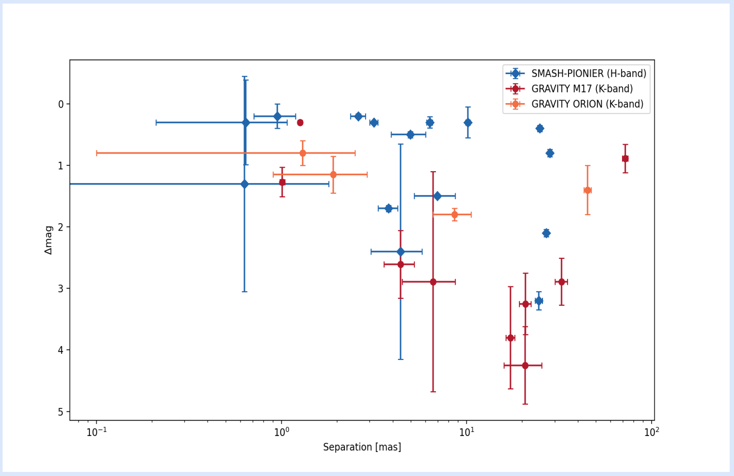
Out of 6 systems:

- 3 binaries
- 3 triples



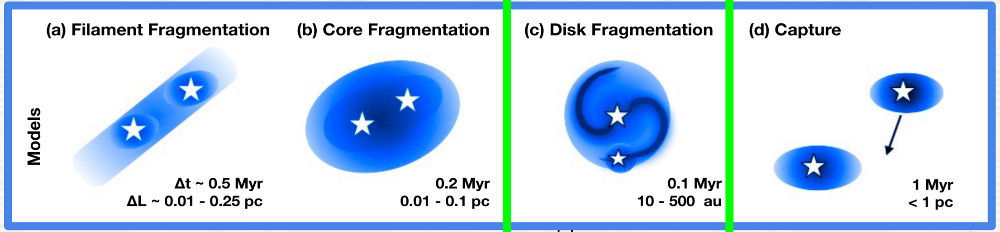
Companion properties → Formation mechanisms ?

NOT short-period
Separations range from
1.2 to 120 au



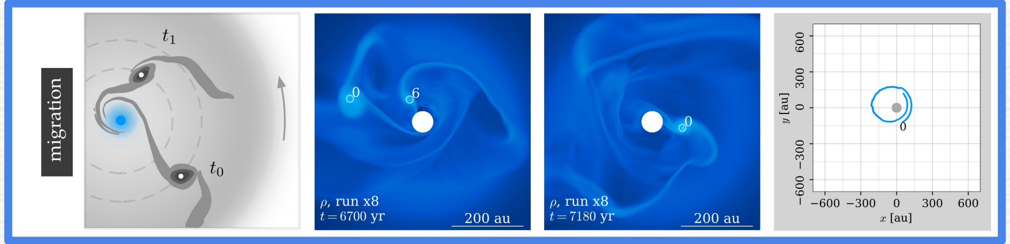
Results and discussions in Bordier et al. 2022, 2024

1. Mechanisms for multiple formation



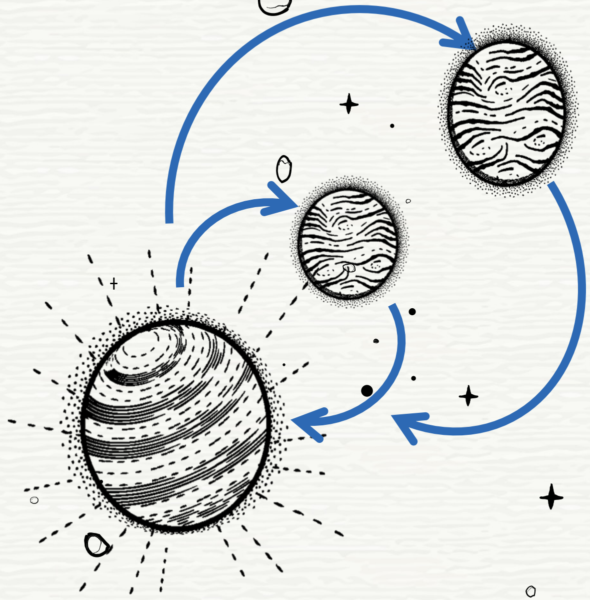
Offner et al. 2022

Migration through interactions with the disk



Oliva et al. 2020

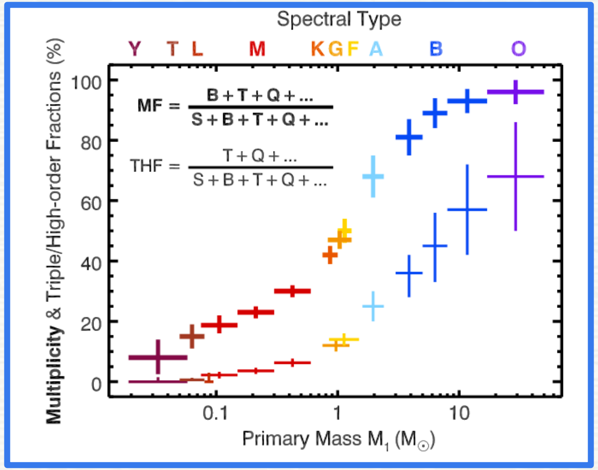
Orbital parameters of massive hierarchical triples with VLTI/PIONIER



Why hierarchical triple systems?

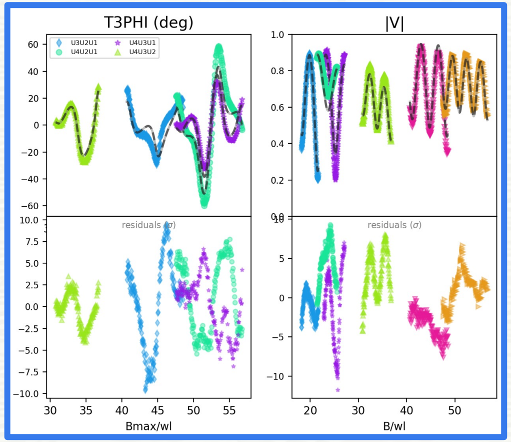
Large fraction of O stars are found in triples (or higher-order multiples)

Sana+2014, Offner+2022



M17 : young massive stars

Bordier+2022



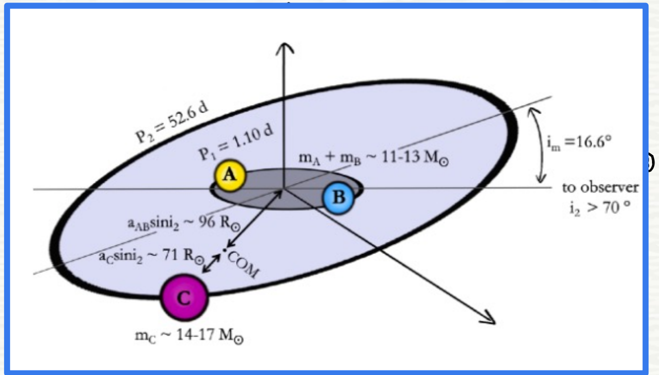
TIC 470710327

A-B: 1.10d eclipsing binary

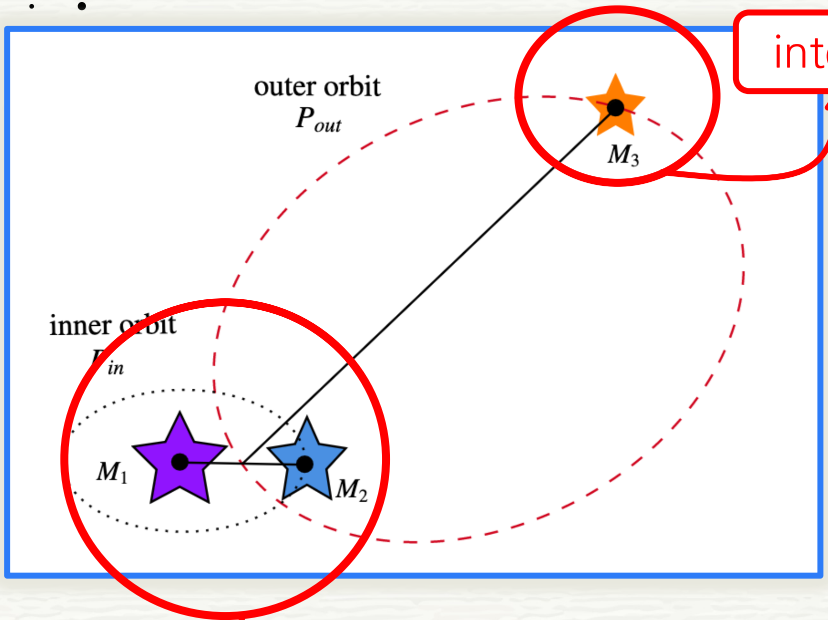
C: 52.04d

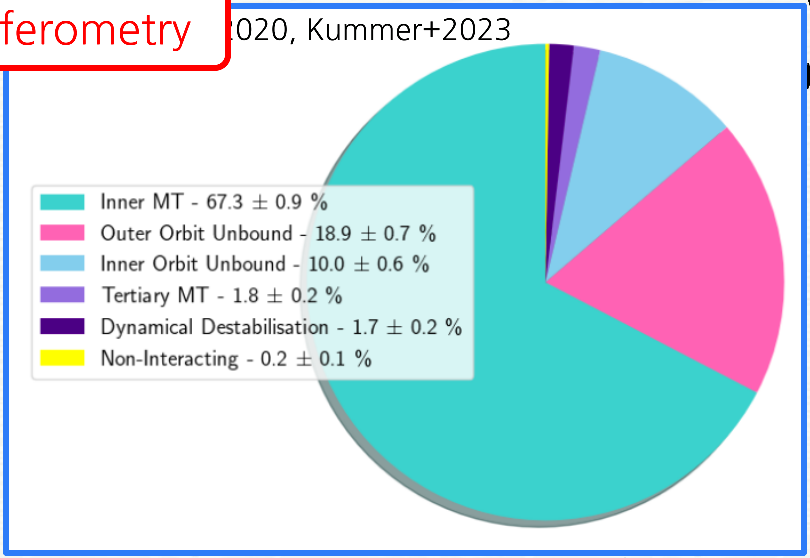
$M_C > M_{A+B}$

Eisner+2022



- Discriminate between different **formation** and **evolution** scenarios
- Place constraints on theoretical models
- Understand the interactions and effects of multiple stars



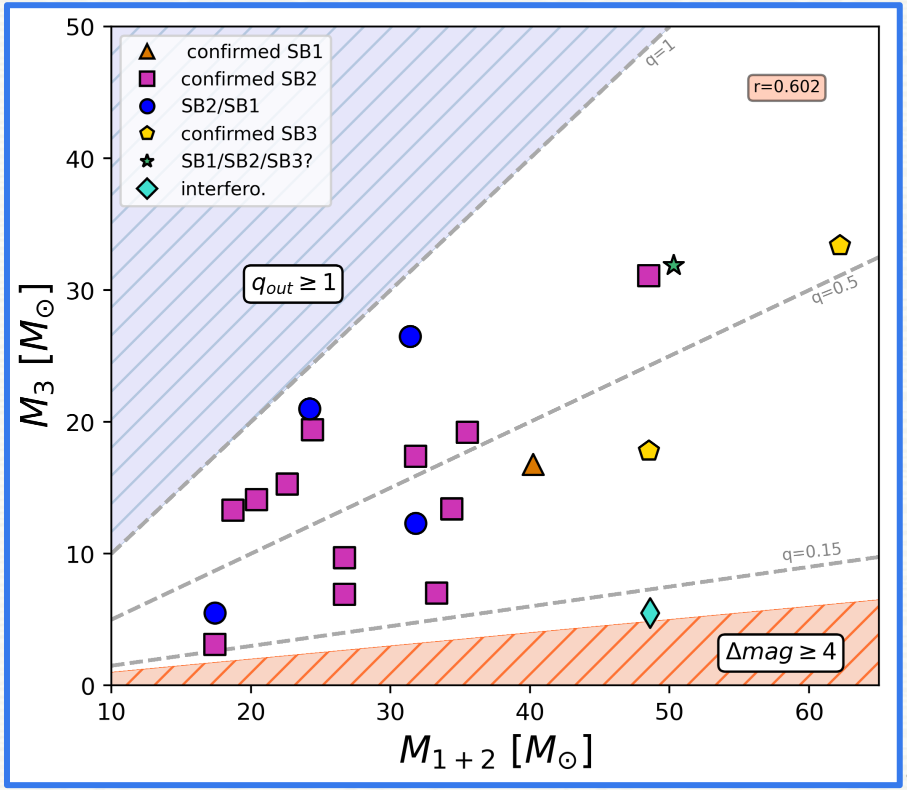


Spectroscopy

VZKL cycles: mutual t … er and outer binary orbit
→ angular momentum is exchanged between the orbits.
→ e_{in} and i_{rel} vary periodically
→ acts on a timescale mostly dependent on P^2_{out}/P_{in} and e_{out}

$P_{out} \sim 5P_{in}$: stable hierarchy and new evolutionary pathways open up compared to binary evolution

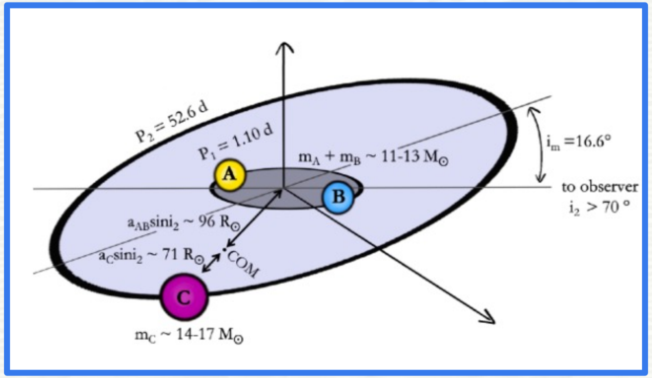
The following results are submitted - Bordier et al. 2025 subm.

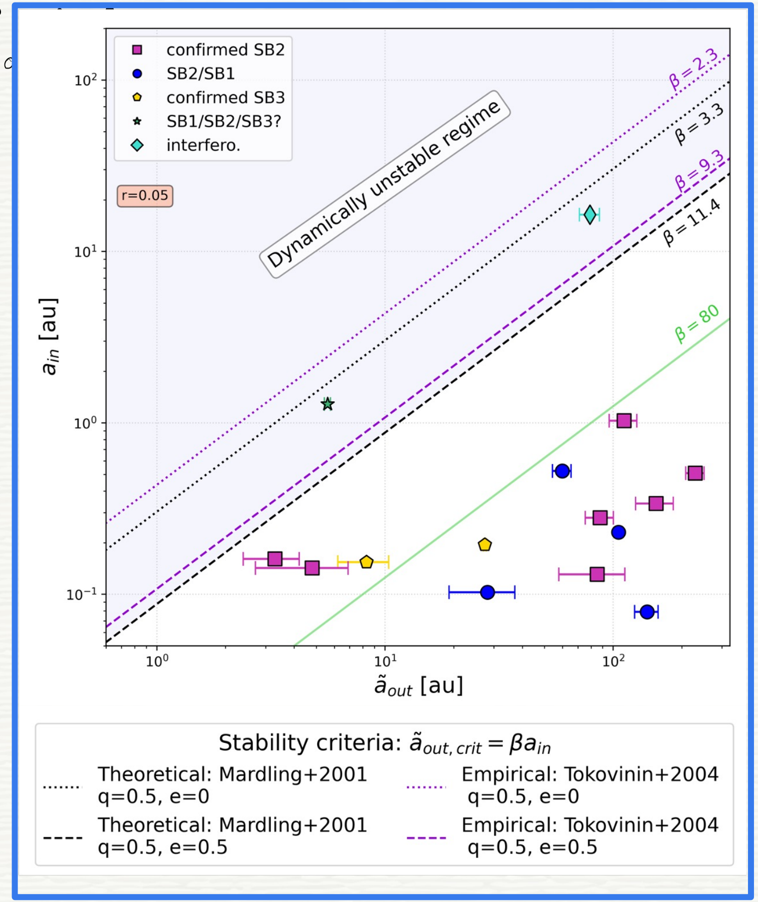


- >50% of the triples have $q_{out} > 0.5$

→ **the outer companion is more massive than one of the inner components**

→ More mass transfer initiated by the tertiary ?

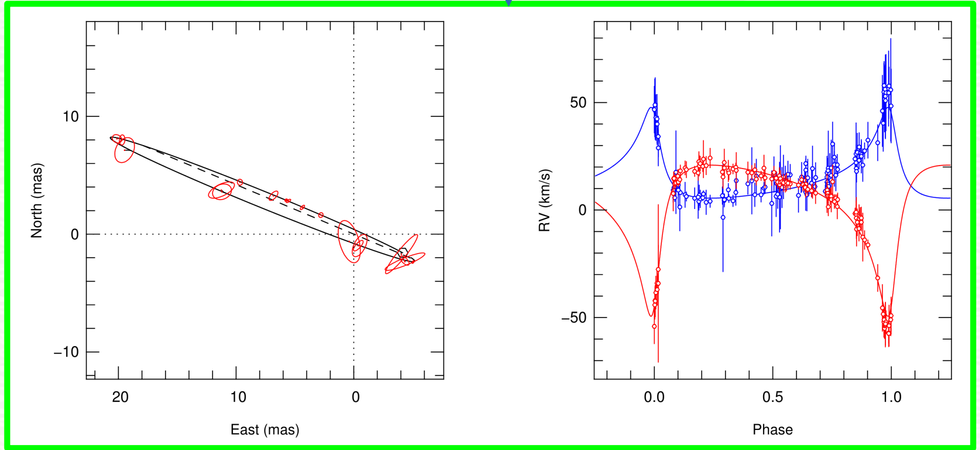




Bordier et al. 2025 subm.

- ONLY ONE massive triple is fully “interferometric”
- Lack of triples with wide inner periods

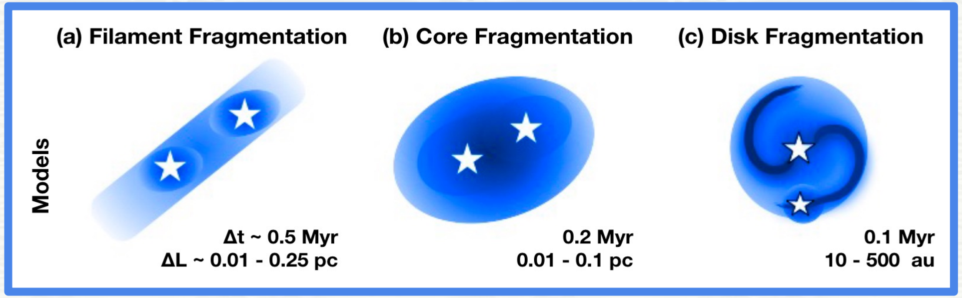
- Full orbits need to be determined, to have the relative inclinations



Le Bouquin et al. 2017

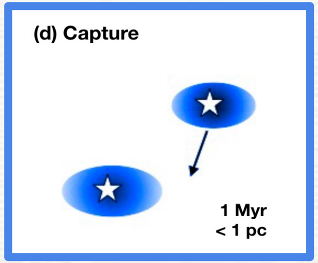
The formation of companions

- 1. Companions can form at different scales through fragmentation



Offner et al. 2022

2. Dynamical evolution affecting the binary statistics and evolution.



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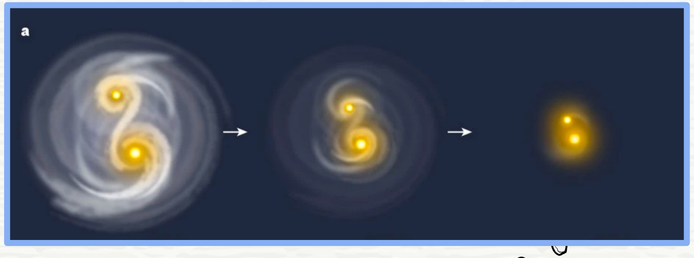
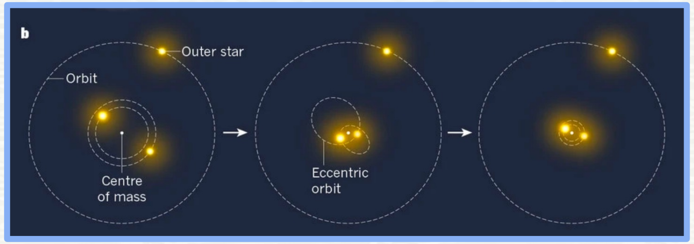
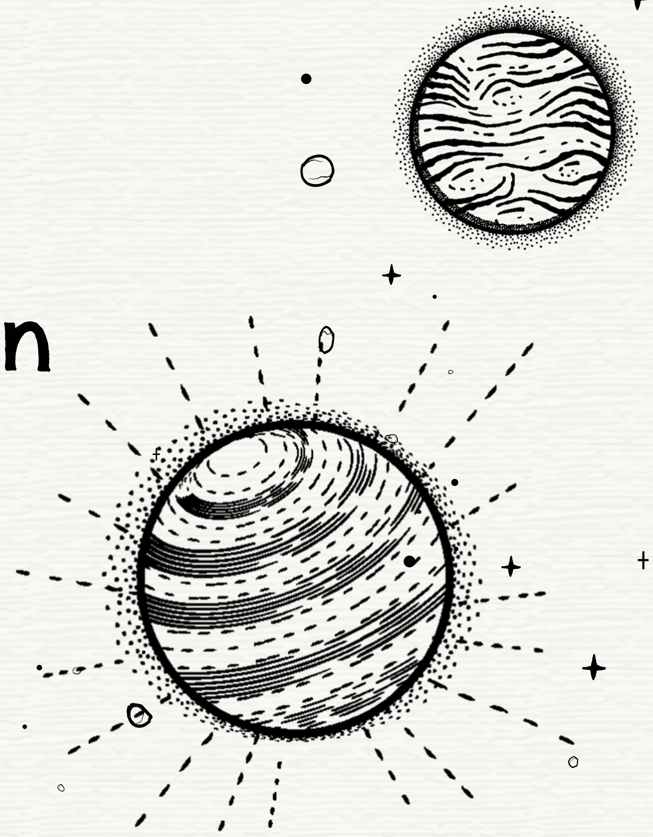


Von Zeipel-Kozai-Lidov (ZKL) cycles in the case of triples

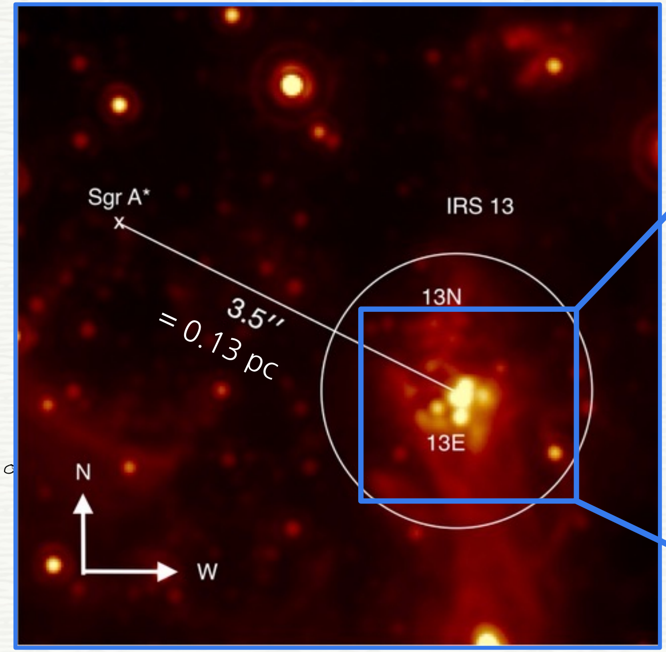


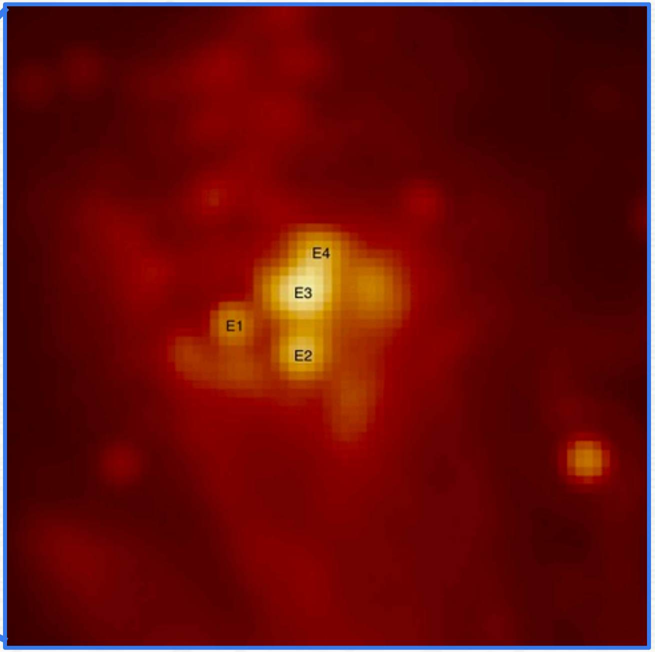
Geller et al. 2017

First VLTI/MATISSE observations of the core region of IRS 13 in the vicinity of SgrA*



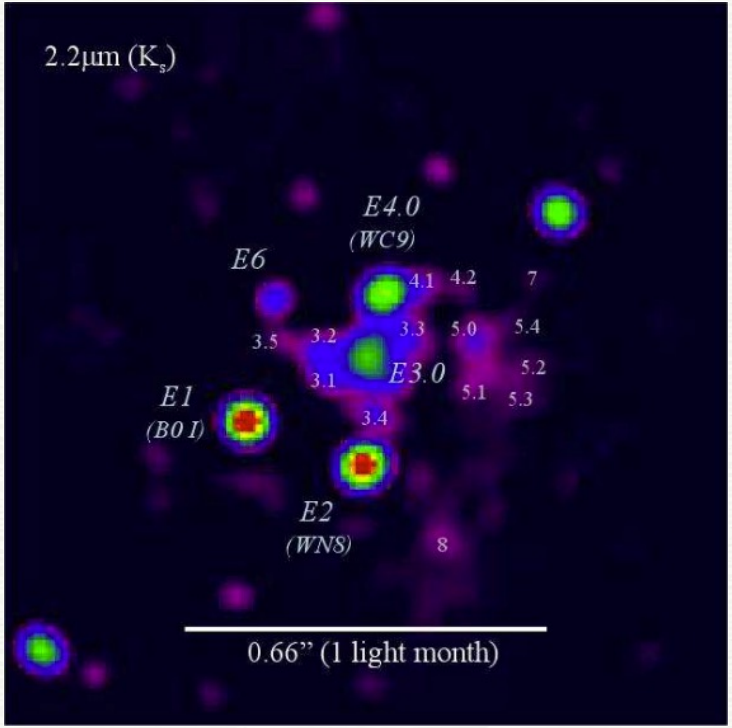
The IRS 13 cluster





2004 NACO L-band

IRS 13 stellar content



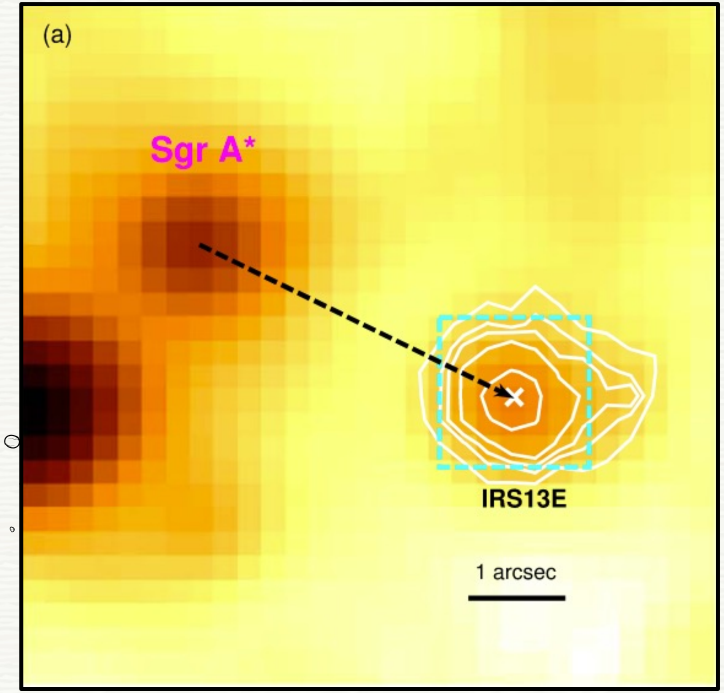
NACO K-band Fritz et al. 2010

- At least 12 stars in the core region of IRS13 (Paumard et al. 2006)
- Many early type stars (young stars):

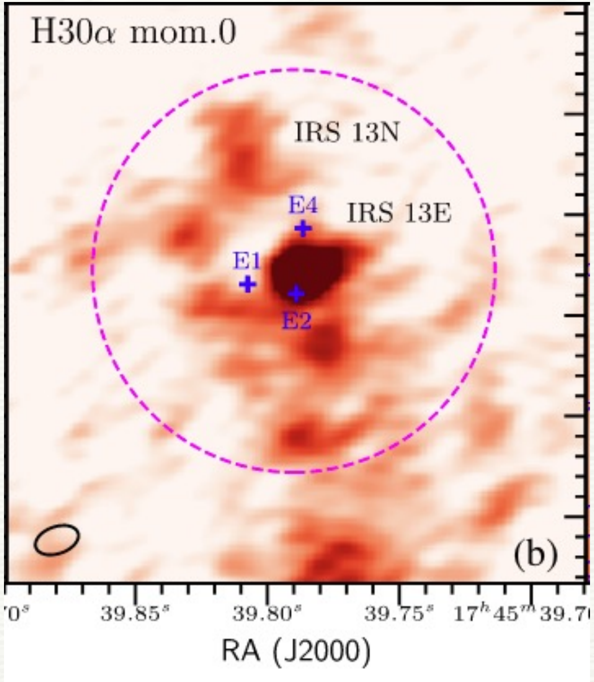
E1: OB supergiant (O5I)
E2: WN8
E4: WC9
Maillard et al. 2004

- IMBH of $10^{3-4} M_{\odot}$? (Schodel et al. 2005)
- Strong dust emission whose origin is still under debate

Nature of E3: an IMBH or colliding winds?

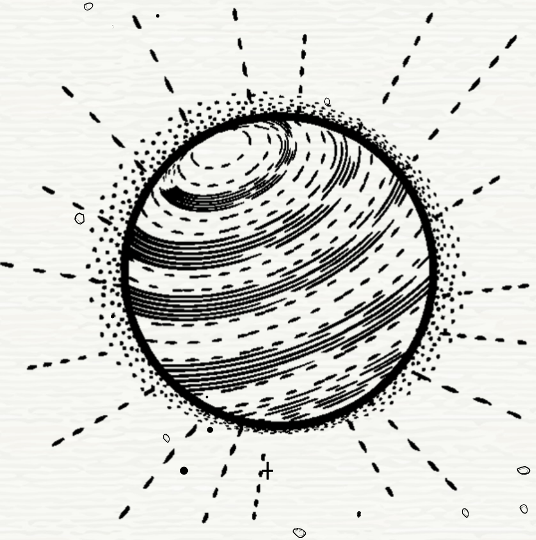


Chandra 2-8 keV Zhu et al. 2020



ALMA H30α Wang et al. 2020

- Concentration of warm dust and gas? (Fritz et al. 2010)
- THE IMBH of IRS 13? (Tsuboi et al. 2019)
- Colliding winds from E2 and E4? (Wang et al. 2020, Zhu et al. 2020)



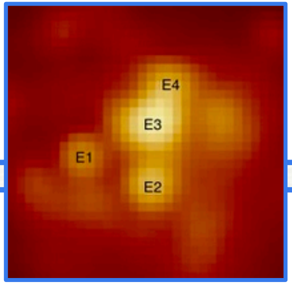
⚠ This section contains unpublished, preliminary results

VLTI/MATISSE Observations

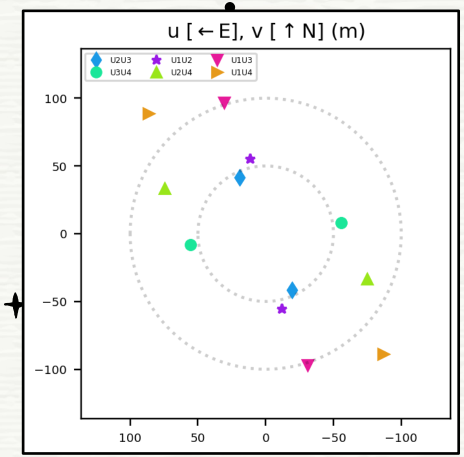
Quick overview of the data

- Observed during MATISSE technical time in 2023
- UT3 problem
- E3 not observed → E1 & E2

→ Only 3 visibilities and 1 closure phase



- Unstable weather conditions:
  Seeing ~1.5-2”
  Coherence time ~2ms.

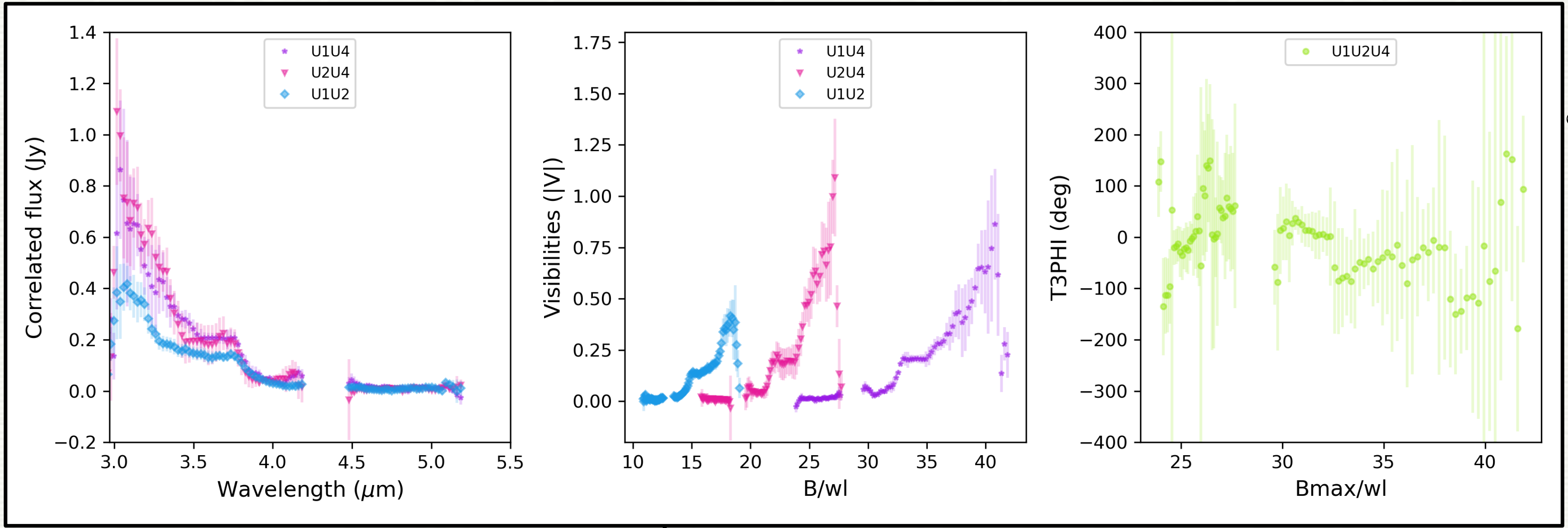


UV-plane

UT4: photometry issues

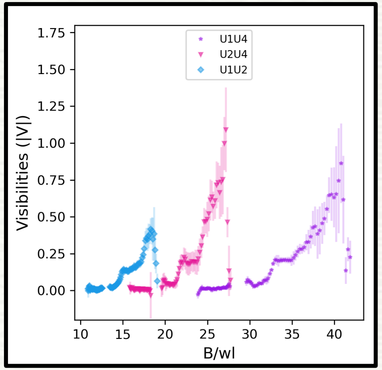
VISIBILITY and CLOSURE PHASES

E1

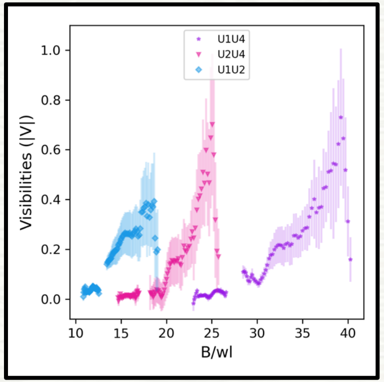


What can we tell from these observables?

E1



E2



- |V| ≠1 → the object is resolved

Stellar emission + Cold Dust/gas

Stellar emission	Cold Dust/gas
Massive stars (O/WR) T>25,000K	Surrounding disk/envelope T~500K
Seen in the L band	Dominates in the M band

Modelling with LITPro and PMOIRED

Two parametric tools to fit geometric models to the interferometric observables

JMMC

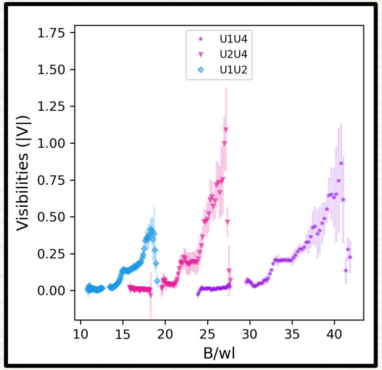
LITpro

PMOIRED

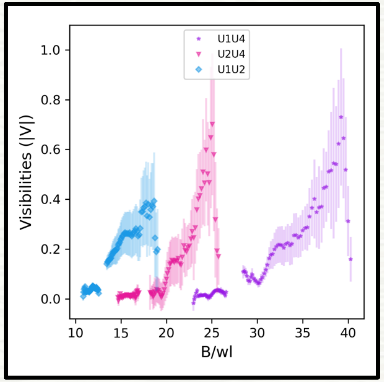
Mérand et al. 2022

What can we tell from these observables?

E1



E2



Physical components

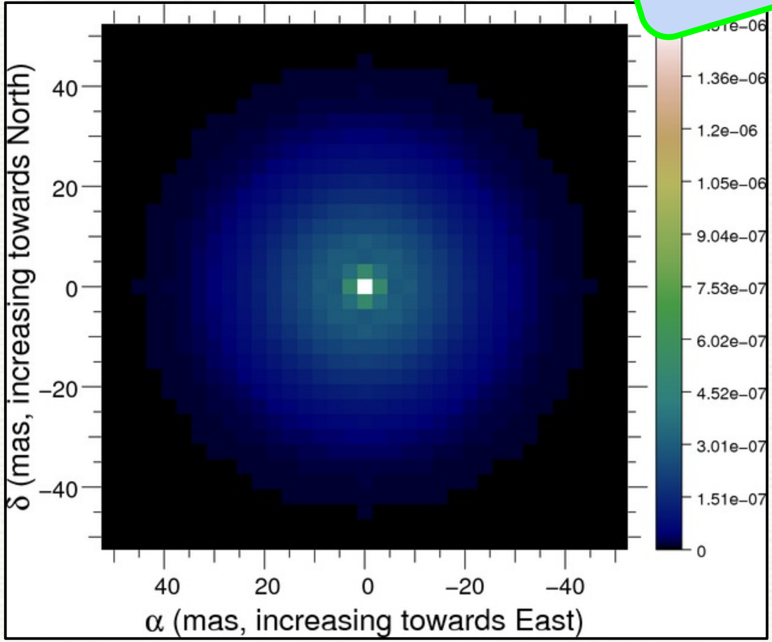
Stellar emission	+	Cold Dust/gas
Massive stars (O/WR) T>25,000K		Surrounding disk/envelope T~500K

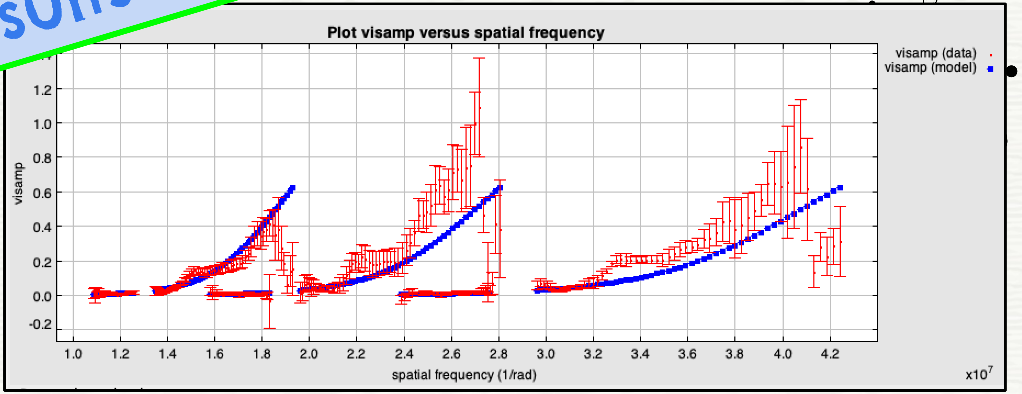
Model

Unresolved punct (x,y)=(0,0) BB: T>25 kK Flux?	Gaussian/ Uniform disk BB: T~500K FWHM/diam? Position? Flux?

E1 LITPro

⚠️Preliminary results⚠️





Geometric model:

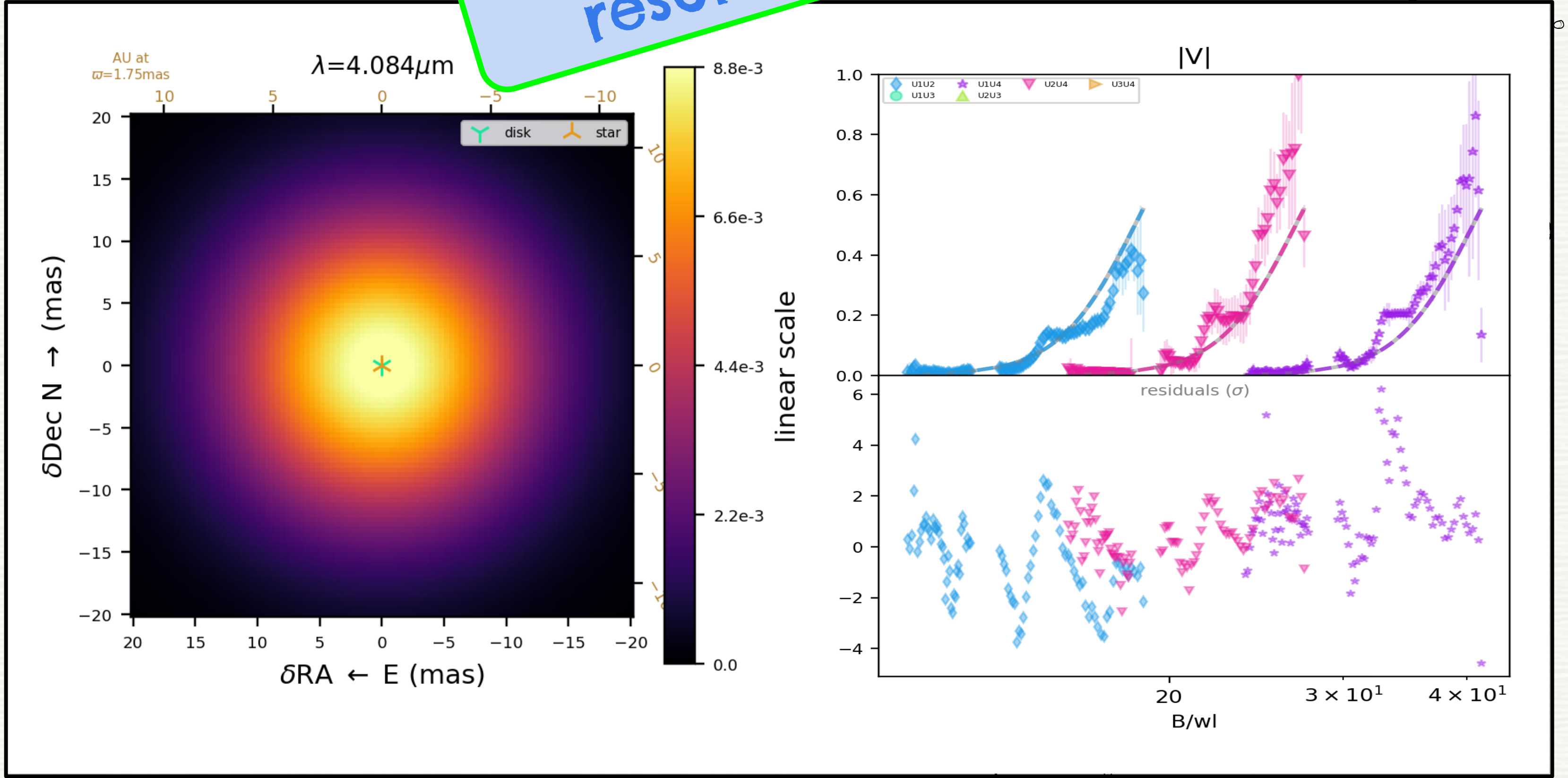
Unresolved central star
(x,y)=(0,0)
T > 25,000K

Surrounded by a Gaussian disk:
FWHM > 25 mas
T ~ 350 K

Work done by Lionel Woglo
Bachelor thesis

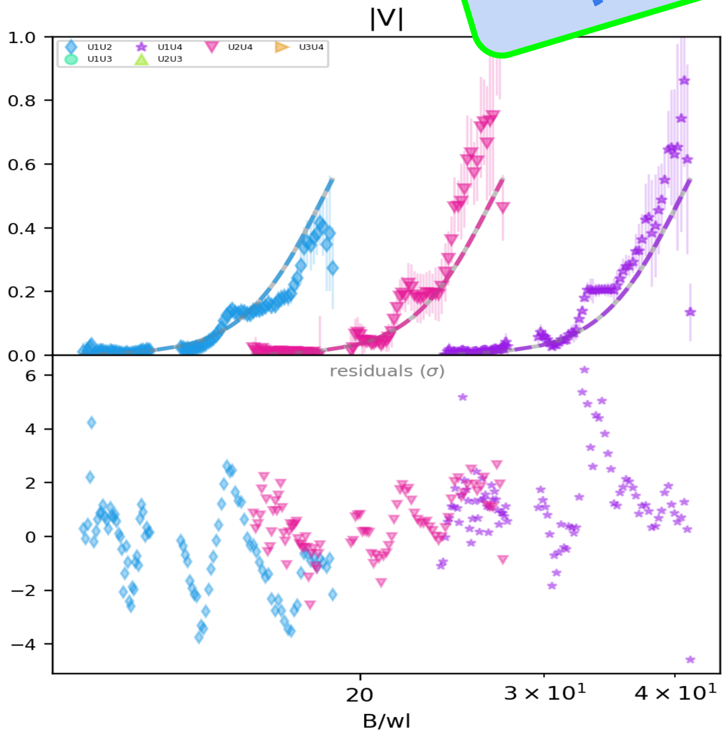
E1 PMOIRED

⚠️Preliminary results⚠️



E1 PMOIRED

⚠️Preliminary results⚠️



Geometric model: $\chi^2 = 2.12$

Unresolved central star
(x,y)=(0,0)
T > 25,000K

Surrounded by a Gaussian disk (>90% of the emission)
FWHM ~ 30 mas
T ~ 550 K

Fully resolved feature that extends above 240 au around the central star

- Dust from an envelope?
- Effects of a stellar disk?

E1 SED

Work done by Lionel Woglo
Bachelor thesis

From NACO observations HKLM bands

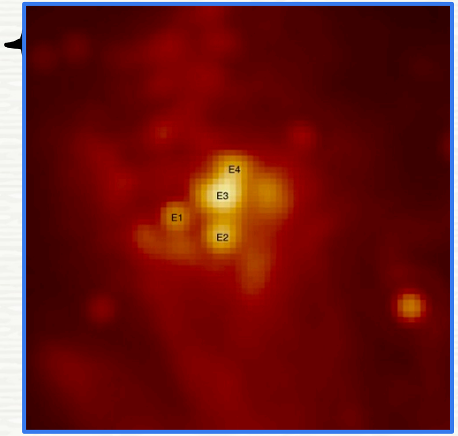
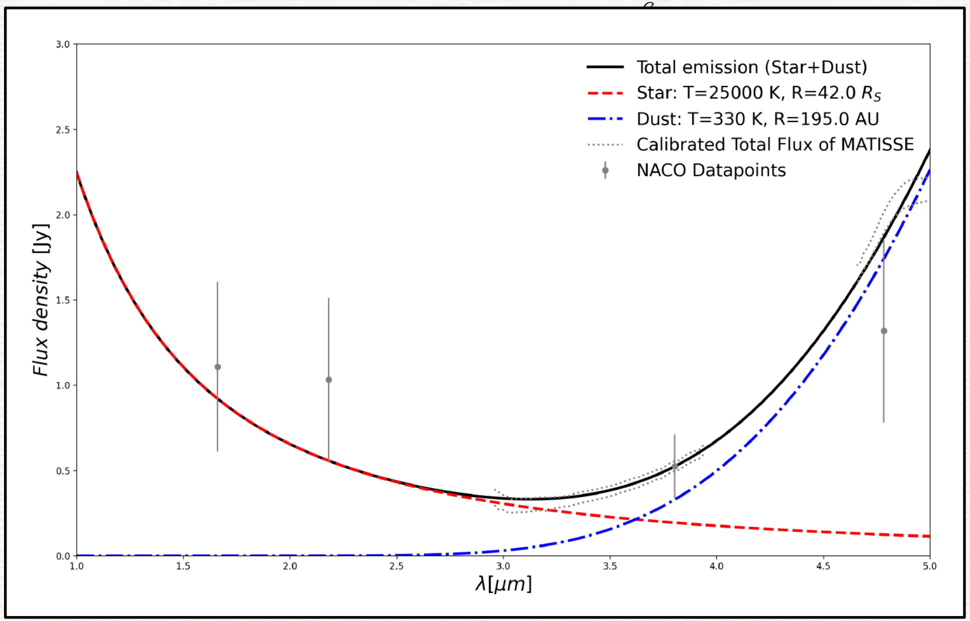


Table 3: Magnitudes and flux densities

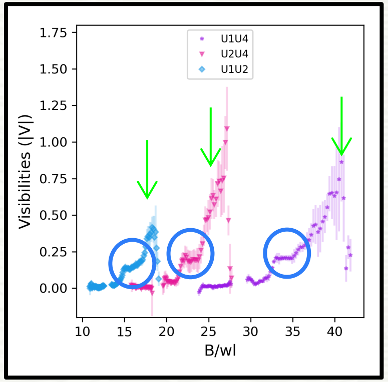
	E1		E2	
Band	Magnitude	Flux [Jy]	Magnitude	Flux [Jy]
H	12.23 ± 0.52	1.11 ± 0.50	12.38 ± 0.55	0.98 ± 0.46
K	9.97 ± 0.60	1.03 ± 0.48	9.96 ± 0.60	1.05 ± 0.49
L	8.60 ± 0.57	0.53 ± 0.19	8.05 ± 0.56	0.88 ± 0.31
M	6.99 ± 0.67	1.32 ± 0.54	6.40 ± 0.67	2.06 ± 0.86

SED reconstructed with HYPERION

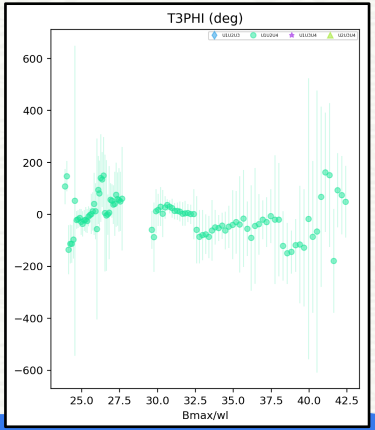


What can we tell from these observables?

E1



±180deg



Stellar emission + **Cold Dust/gas**

+ asym. Disk?
+ companions?

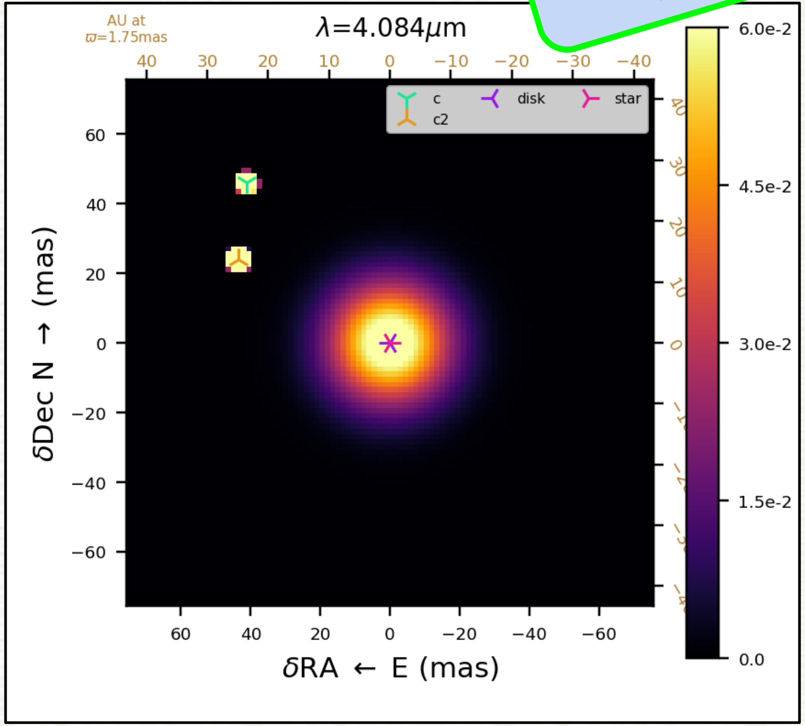
Stellar emission	Cold Dust/gas
Massive stars (O/WR) T>25,000K	Surrouding disk/envelope T~500K
Unresolved punct (x,y)=(0,0) BB: T>25 kK Flux?	Gaussian/ Uniform disk BB: T~500K FWHM/diam? Position? Flux?

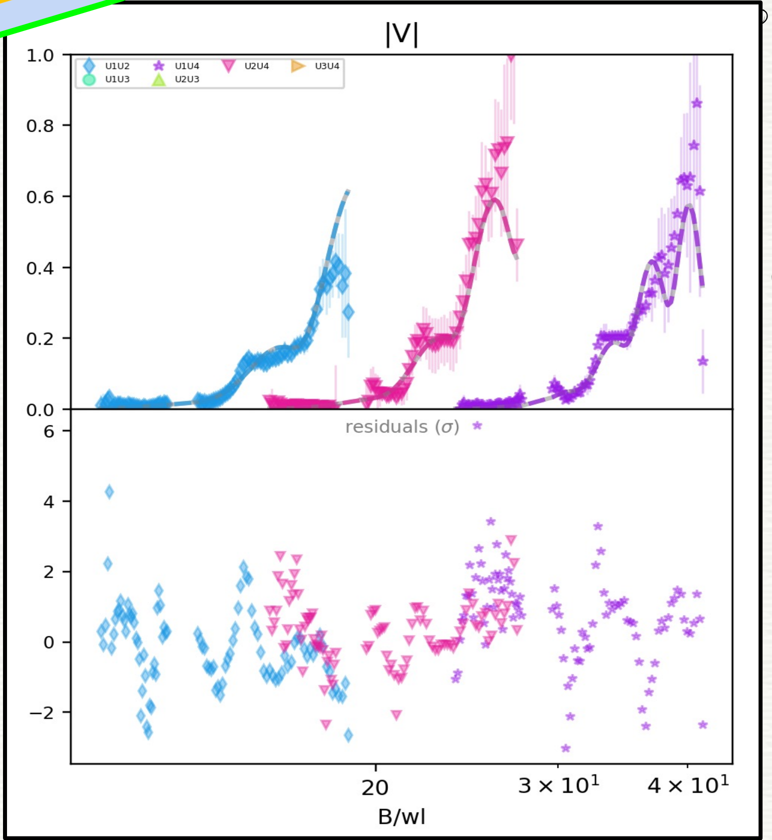
Physical nature

Model

E1 PMOIRED

⚠Preliminary results⚠





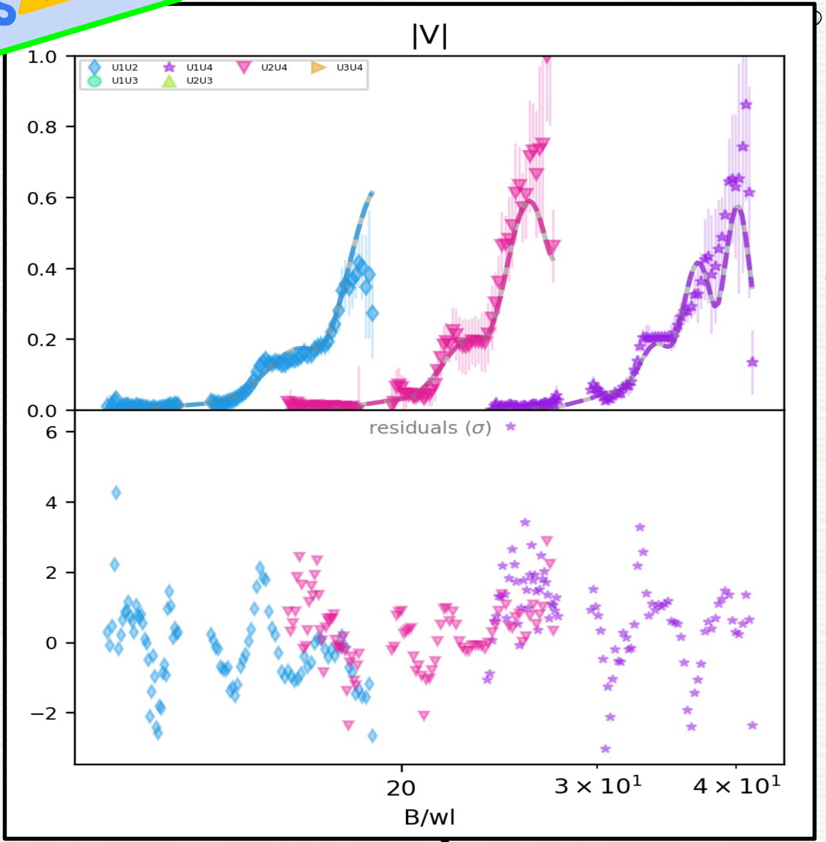
Bordier, Woglo et al. 2025 in prep.

E1 PMOIRED

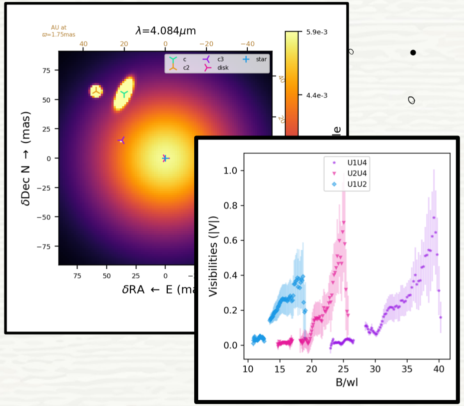
⚠️Preliminary results⚠️

Geometric model: $\chi^2 = 1.22$

- Star (unresolved punct)
- + Envelope/ Disk:
  Gaussian : FWHM = 33 ± 12 mas
  90% of the flux
- 2nd star (unresolved punct):
  T~20,000K
  diam~ 8±1 mas
  $\rho \sim 60$ mas → $\tilde{a} \sim 480 \pm 37$ au
- 3rd star (unresolved punct):
  T~20,000K
  diam~ 7±1 mas
  $\rho \sim 48$ mas → $\tilde{a} \sim 370 \pm 38$ au



What does it tell us about E1 and IRS13?



- VLTI/MATISSE observations: it is possible to resolve objects in this region
- Nature of the close environments of E1 & E2 in the larger context of the GC environment

- E1 is an O5I star: >90 % are in multiple systems
- IRS 13 behaves as other massive clusters?
- Are we finally detecting massive binaries in the GC? (Peissker 2024 in press).

- Success of these observations motivates further investigations: ERIS/GRAVITY(+)
- And request observations of E3

University of Cologne

ph1 Universität zu Köln

SFB 1601

Thanks for your attention!

Emma Bordier
bordier@ph1.uni-koeln.de

I. Physikalisches Institut, University of Cologne