Physics of Extreme Massive Stars
24-28 June 2024

A high-angular resolution insight into the onset of stellar multiplicity in massive star formation

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MASSIVE STARS ALSO...

HIGH-DEGREE OF MULTIPLICITY
(on the main sequence)

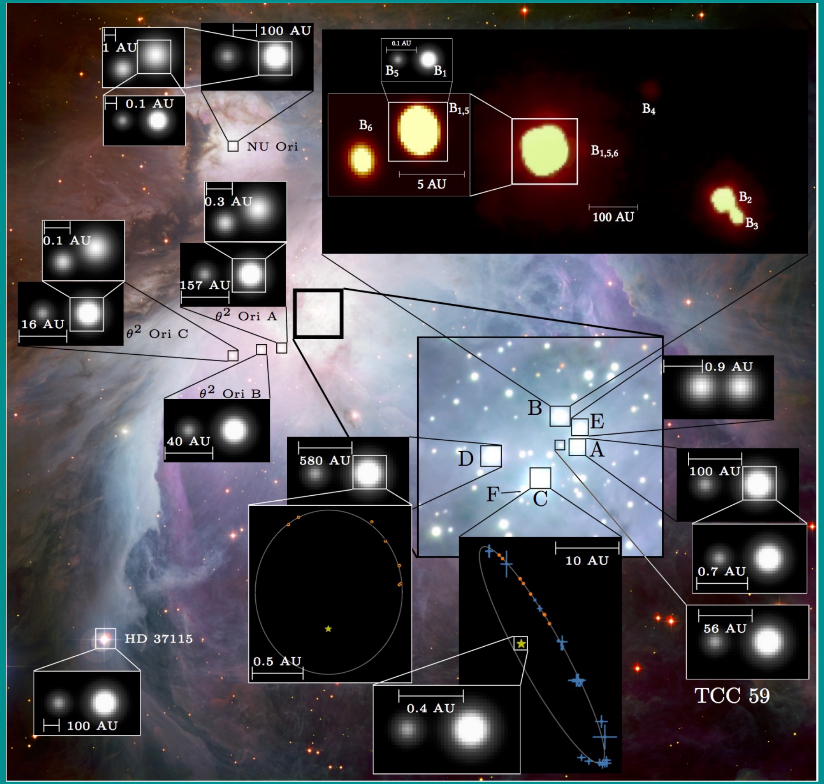
Sana. Et al. 2012, 2014
Moe & Di Stefano 2017

- 90% have at least one companion on the main sequence

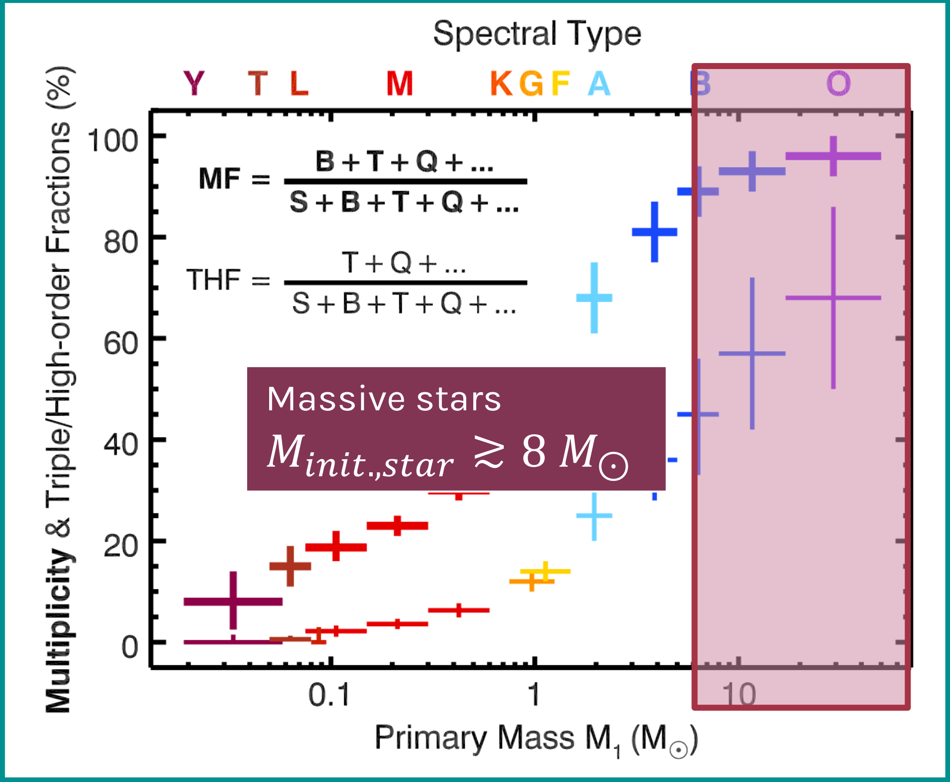
- 30-50% have periods of less than a month
  > strong implications for their evolution (mass transfer, common envelope evolution, mergers etc...)

Multiplicity is a common feature for stars

Main-sequence phase



Gravity Collaboration et al. 2018



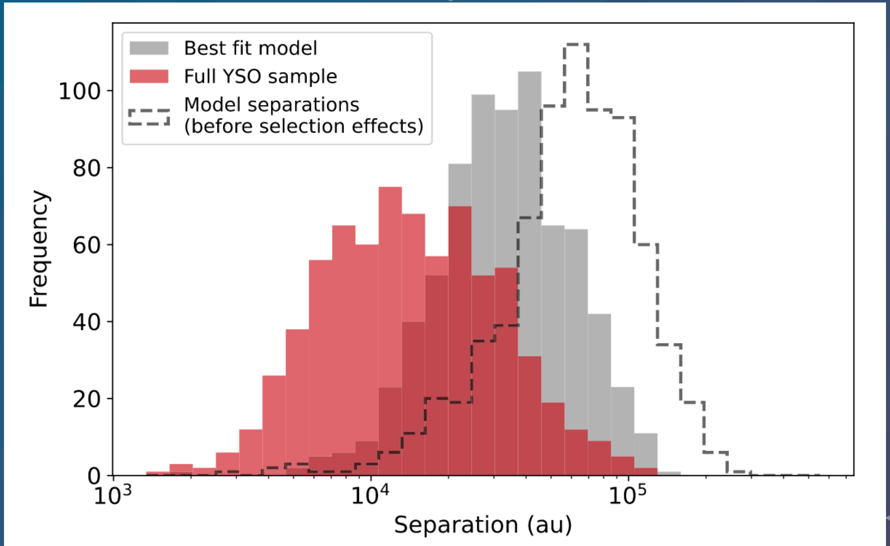
Offner et al. 2022 (PPVII review)

MASSIVE STARS ALSO...

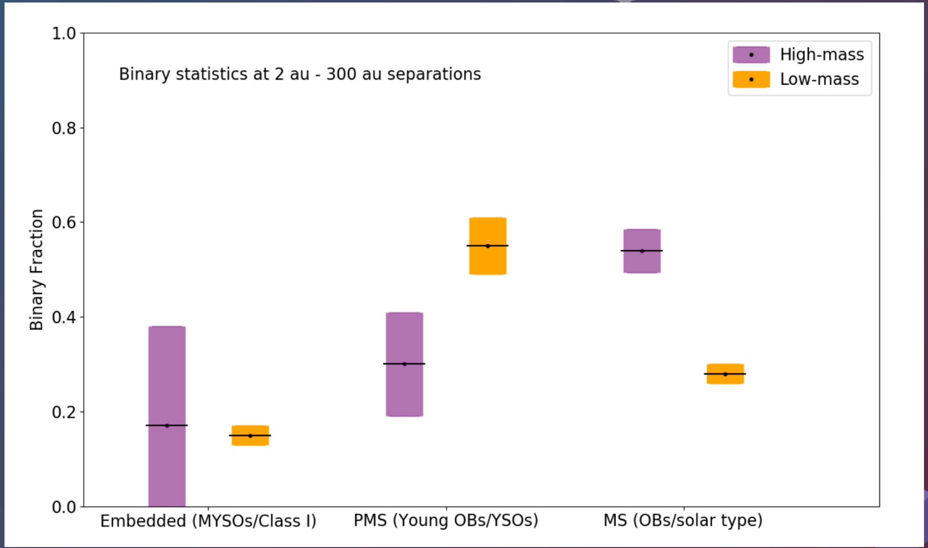
HIGH-DEGREE OF MULTIPLICITY
(at earlier stages?)

- ~ 60-70% of MYSOs — Shenton et al. 2024
- For separations from 100 to 10,000au
- Spectroscopic binaries?

At earlier stages?

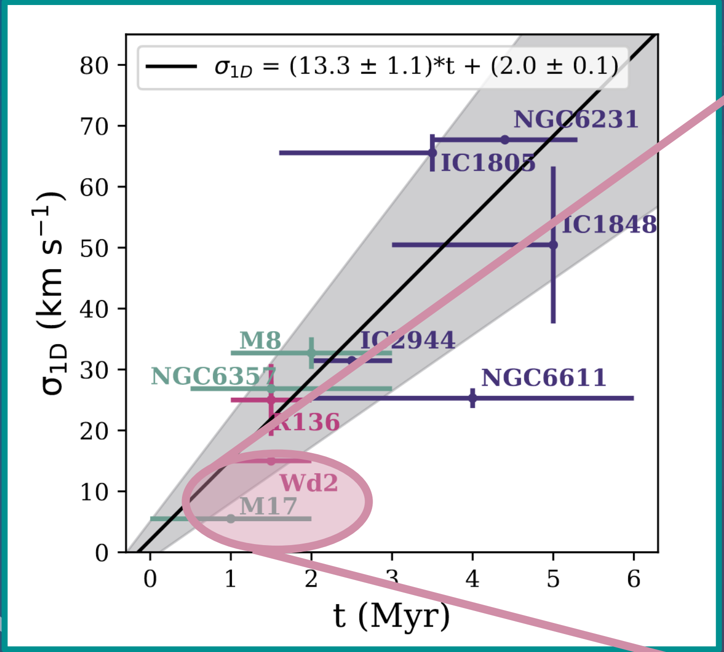


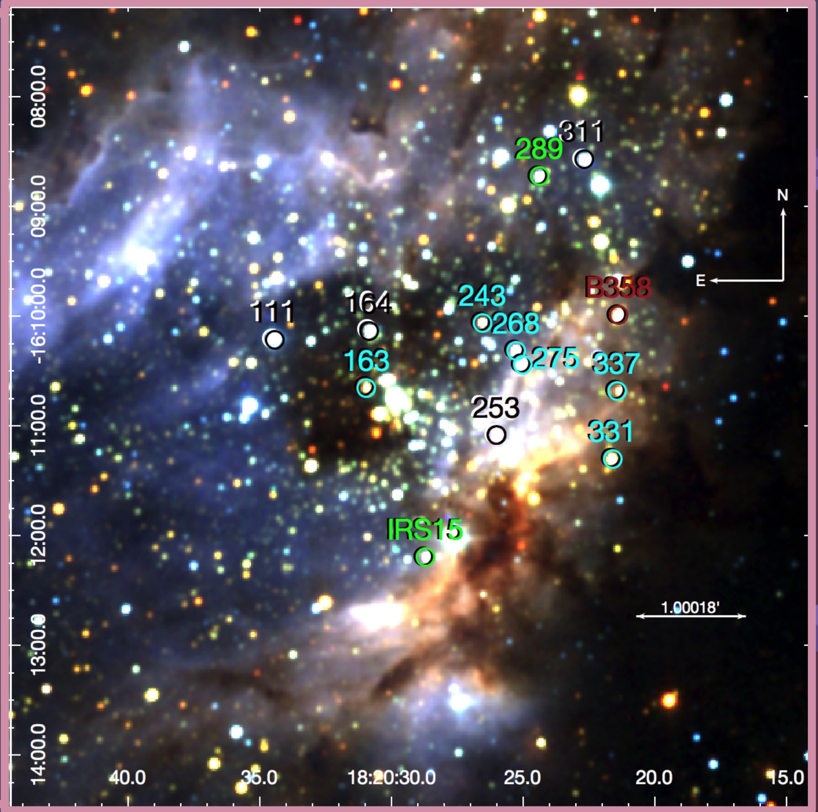
Shenton et al. 2024
UKIRT, UKIDSS, VVV
Separations: ~1000 to 100,000 au



Koumpia et al. 2021
VLTI/GRAVITY
Separations: ~2 to 300 au

Lack of short period binaries?





Ramirez-Tannus et al. 2021,2017
Sana et al. 2017
Ramirez-Tannus & Derkink, subm.

MASSIVE STARS ALSO...

HIGH-DEGREE OF MULTIPLICITY (at earlier stages?)

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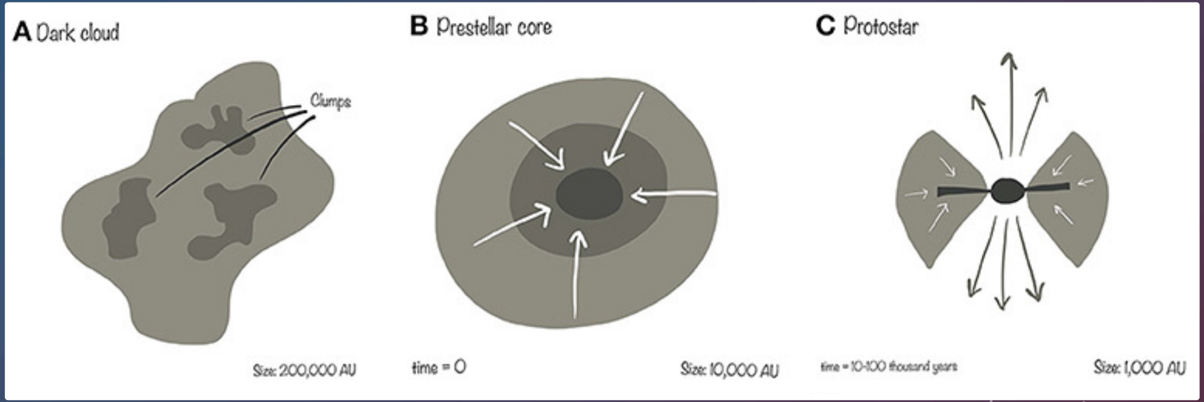
FORMATION TIMESCALE

- $\sim 10^5$years — Tan et al. 2014
- via monolithic collapse /competitive accretion
  Zinnecker et al. 2007
- formation of companions?

The formation of companions

1. Companions can form at different scales through fragmentation



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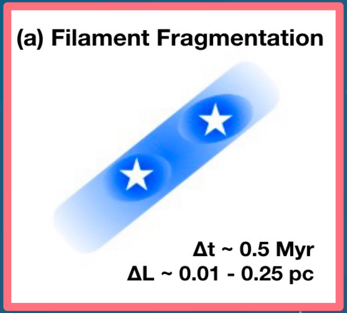

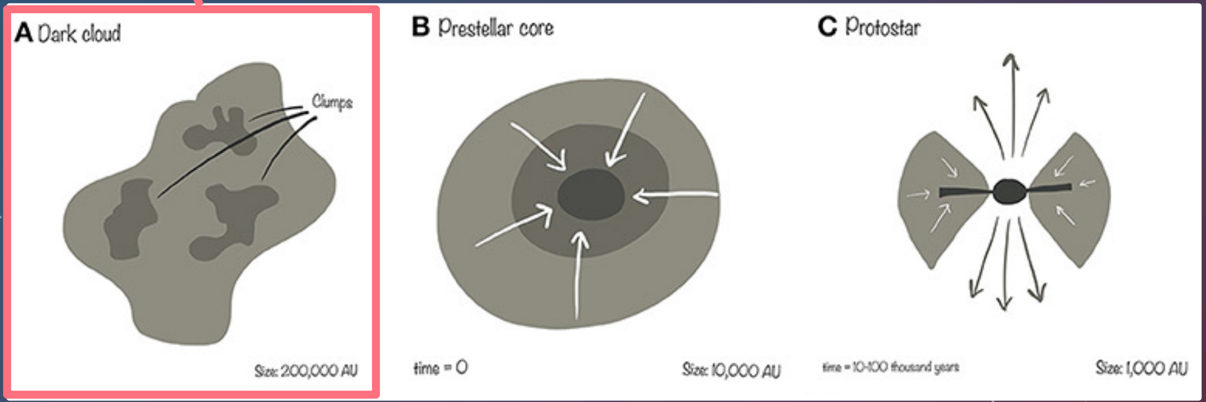

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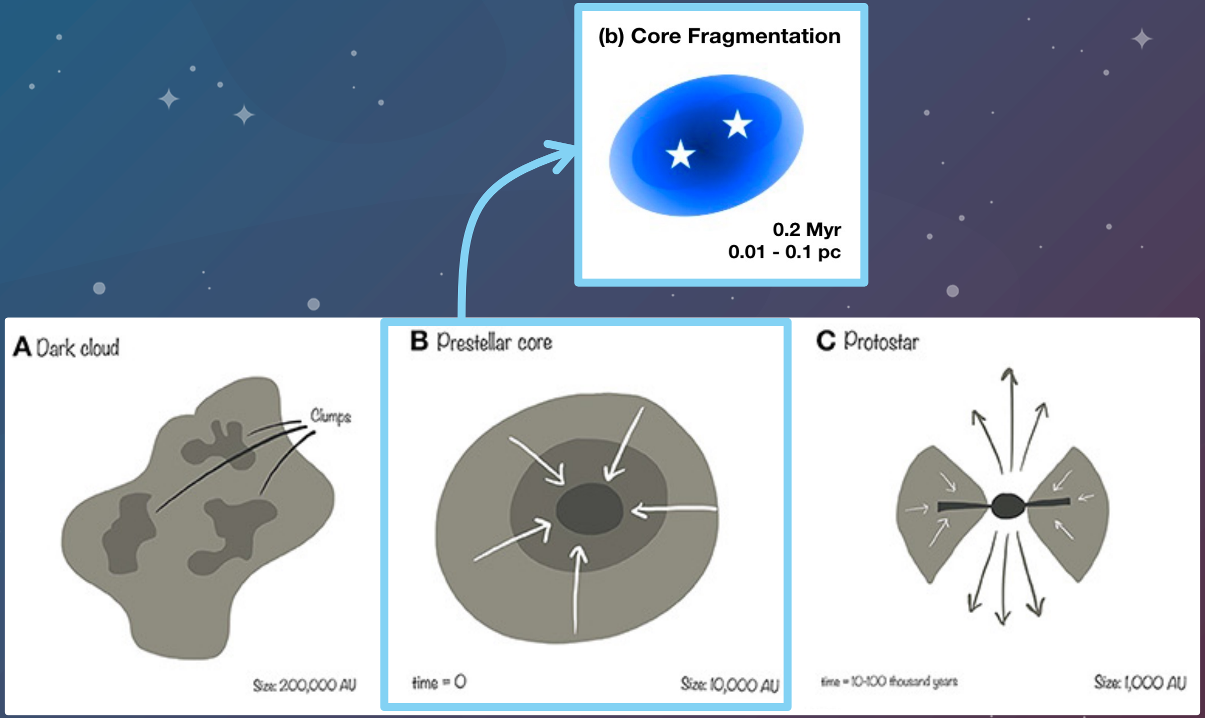

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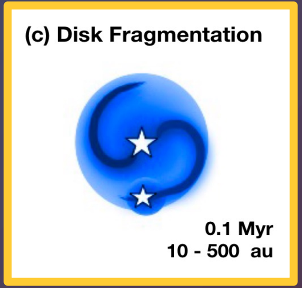

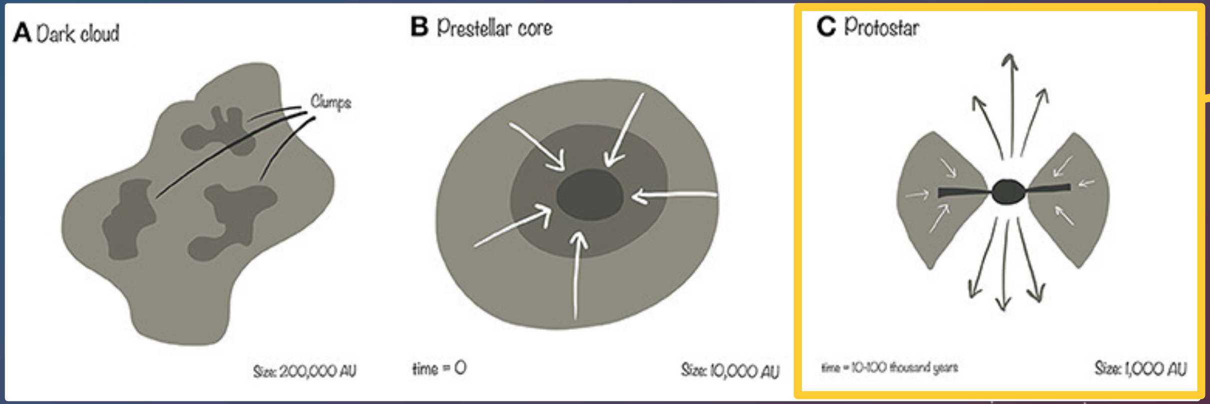

The formation of companions – in theory

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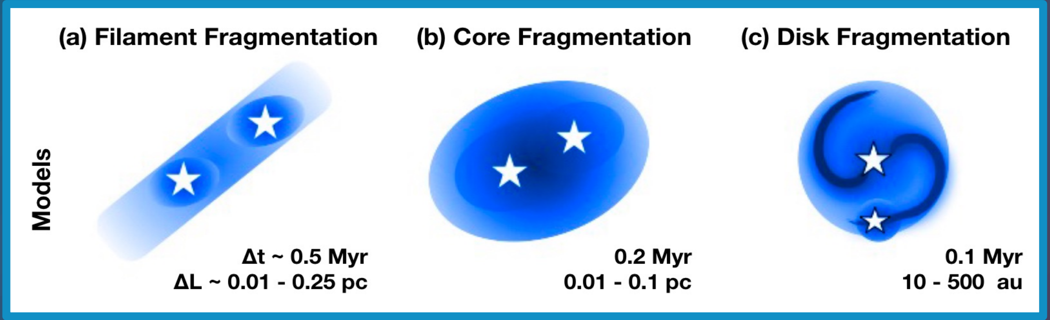
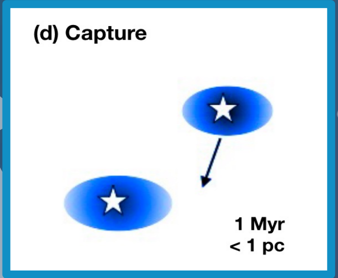


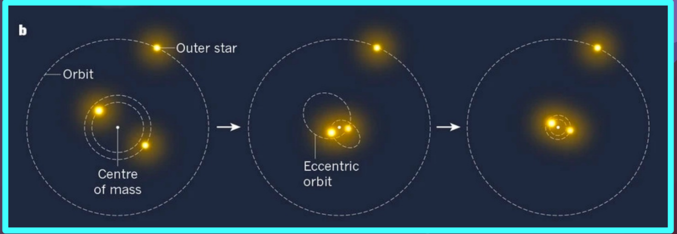
Offner et al. 2022

2. Dynamical evolution affecting the binary statistics and evolution



Migration through interactions with the disk

Migrated assisted by Kozai-Lidov cycles



Geller et al. 2017

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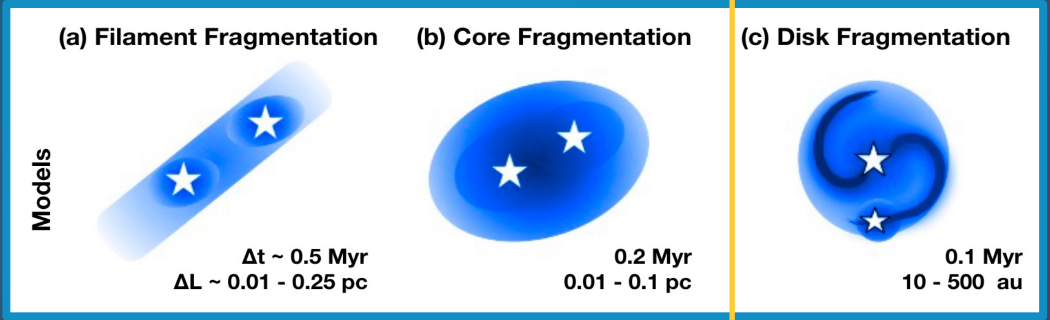

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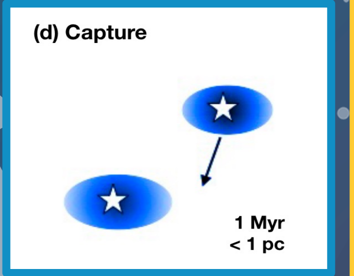

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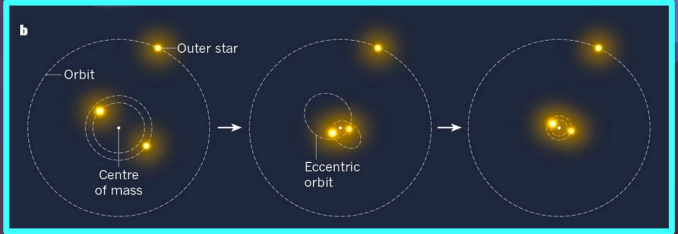
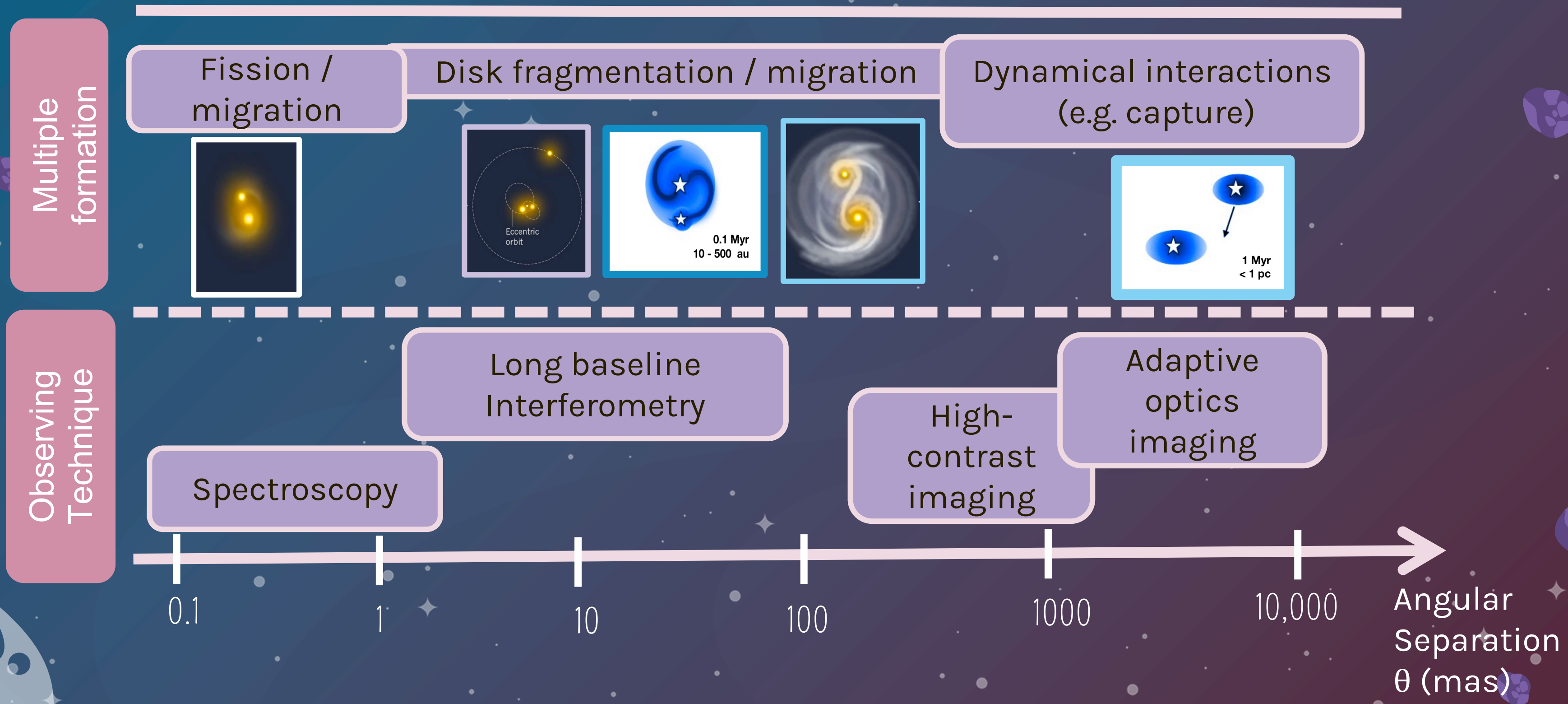
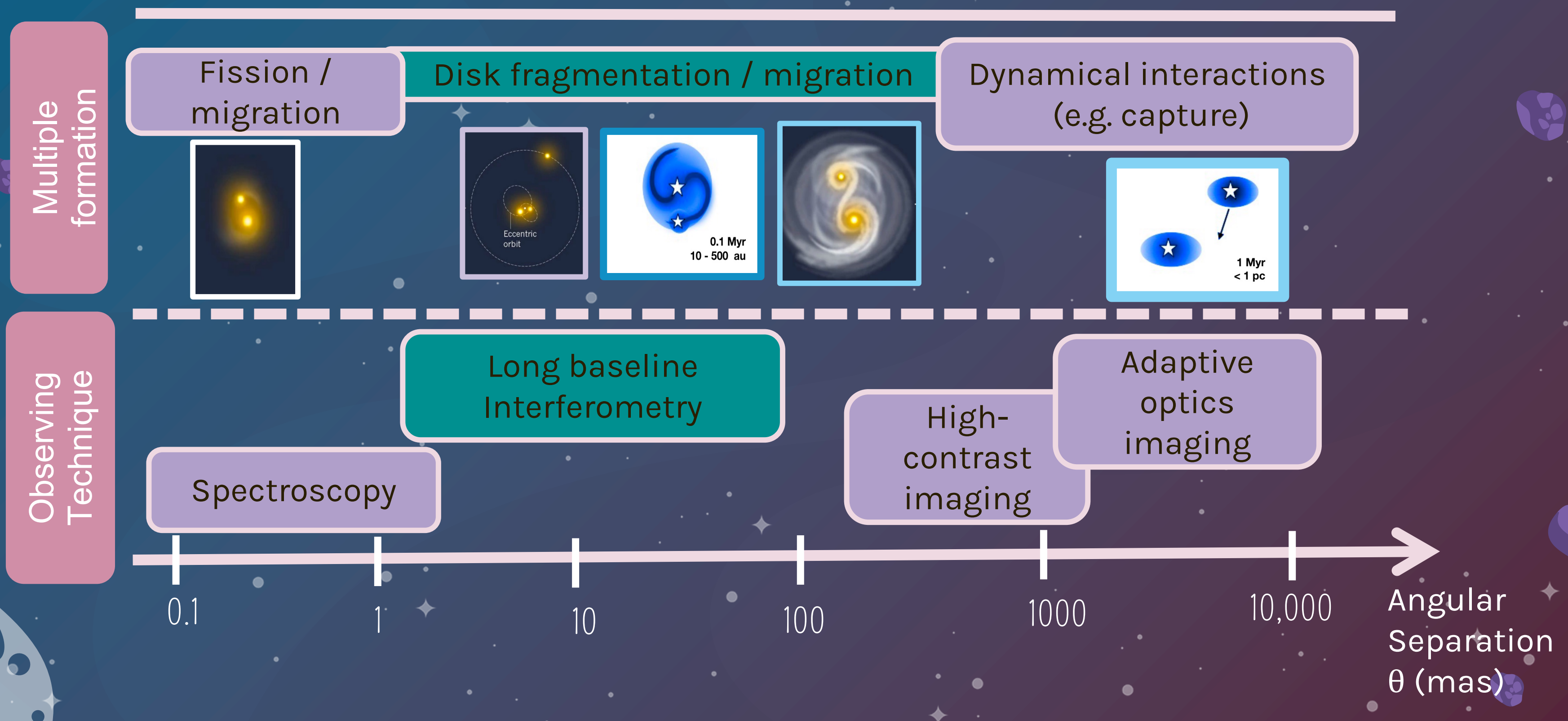


Geller et al. 2017

The formation of companions - observationally



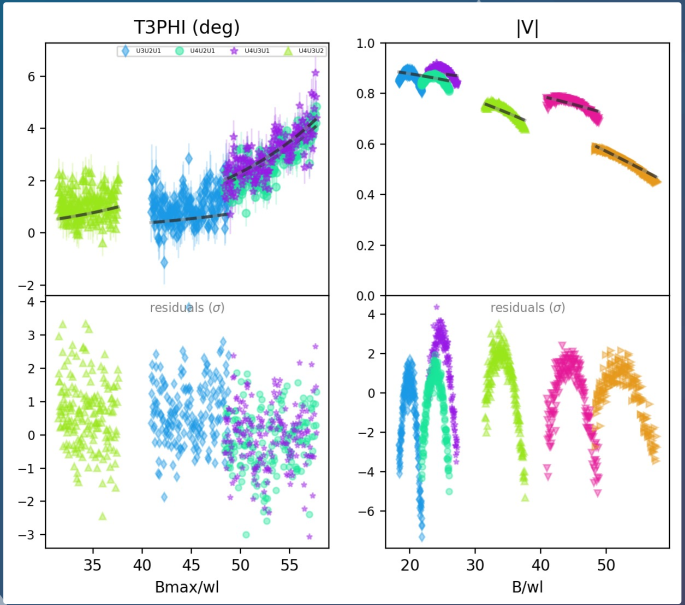
The formation of companions - observationally



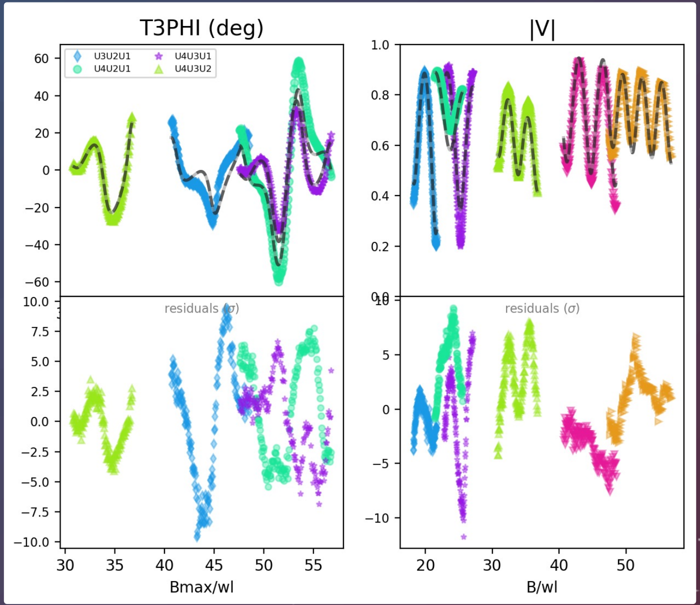
1-120 au range: the case of M17

Optical Interferometry: VLTI/GRAVITY

3 binaries: B189NE, B98 ,B111



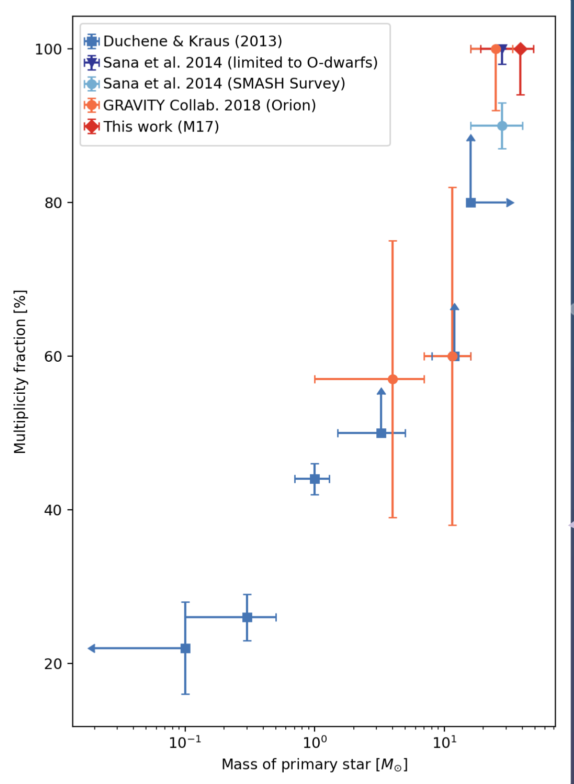
3 triples: B189SW, B0, B260



Modelling of the interferometric observables: **LITPro / PMOIRED** (Mérand et al. 2022)

1-120 au range: the case of M17

Optical Interferometry: VLTI/GRAVITY



Multiplicity fraction:

$$MF = \frac{N_{multiple}}{N_{multiple} + N_{single}}$$

$$= \mathbf{100^{+0}_{-6}}\ \%$$

Bordier et al. 2022

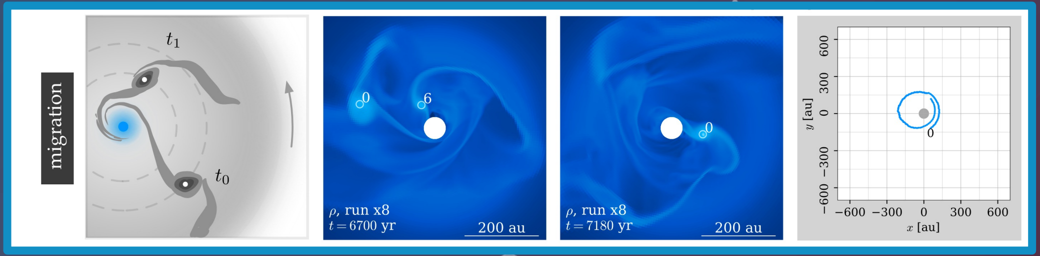
1-120 au range: the case of M17

Optical Interferometry: VLTI/GRAVITY

- The detections of companions within the expected size of massive accretion **disk and down to 1au are consistent with disk fragmentation theories** and **inward (ongoing) migration**. Given the young age of M17, dynamical interactions might be ongoing and the final binary parameters are still to be modified.

Bordier et al. 2022

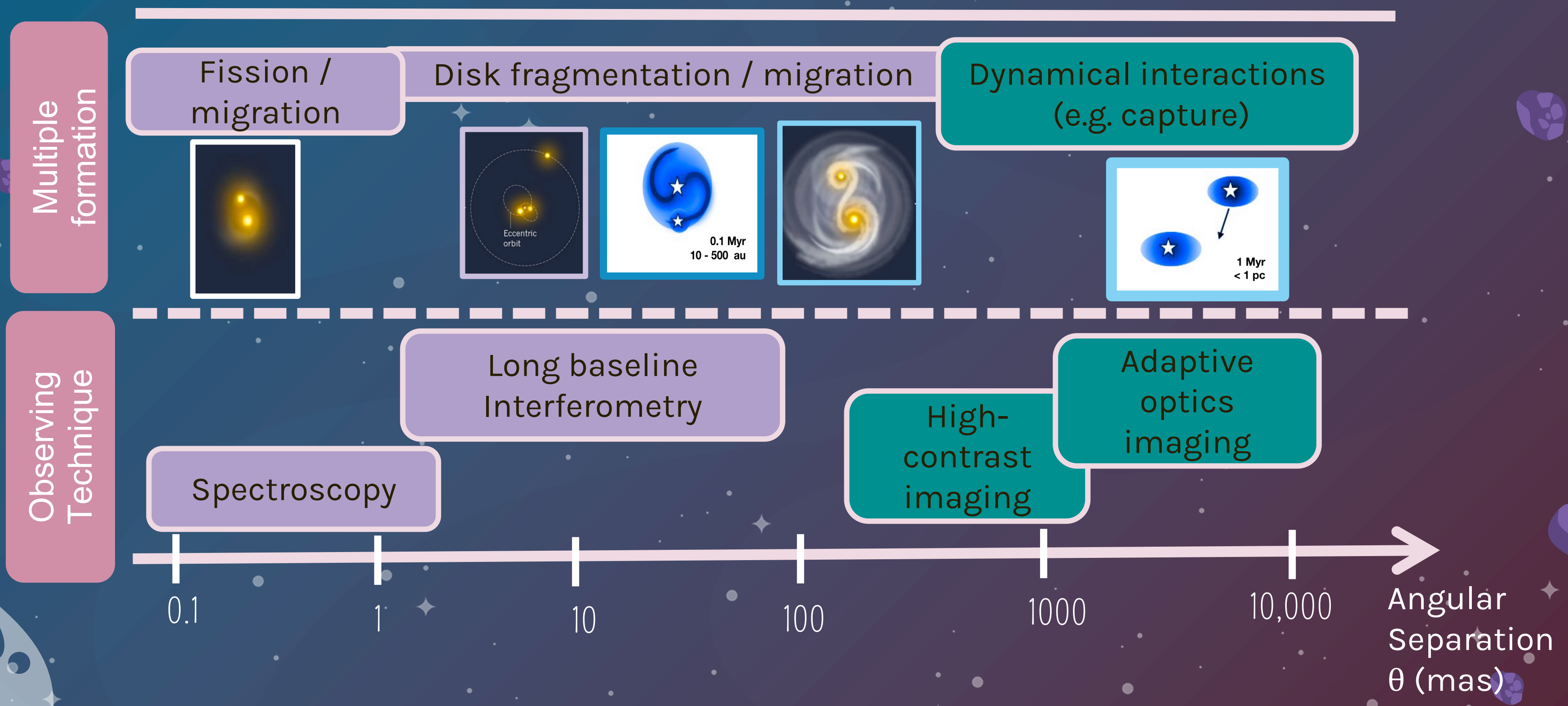
Migration through interactions with the disk



Oliva et al. 2020

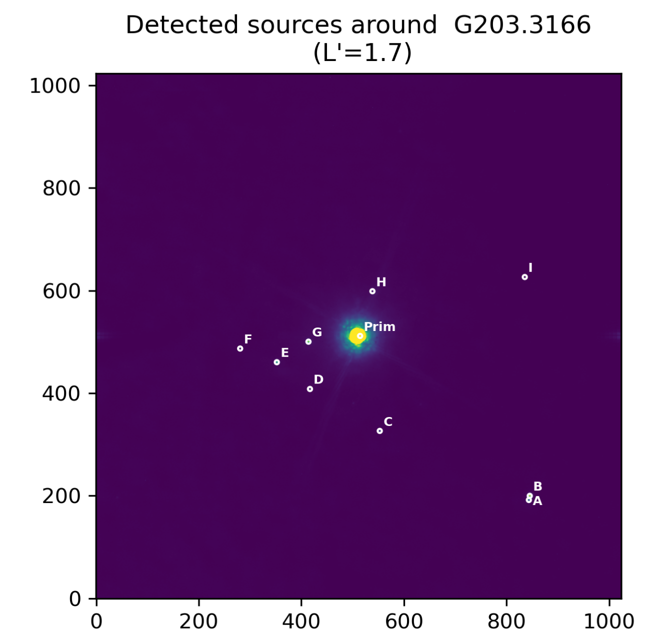
⚠️ GRAVITY observations:
- No signature of accretion disks
- Spin-orbit alignments cannot be checked

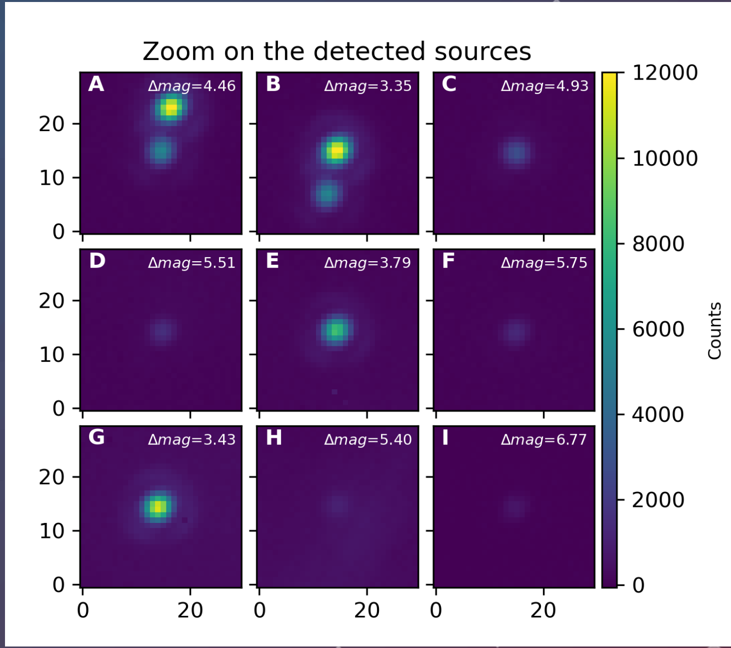
The formation of companions - observationally



600-50,000 au range: 13 MYSOs from RMS catalogue

High—contrast imaging: VLT/NACO

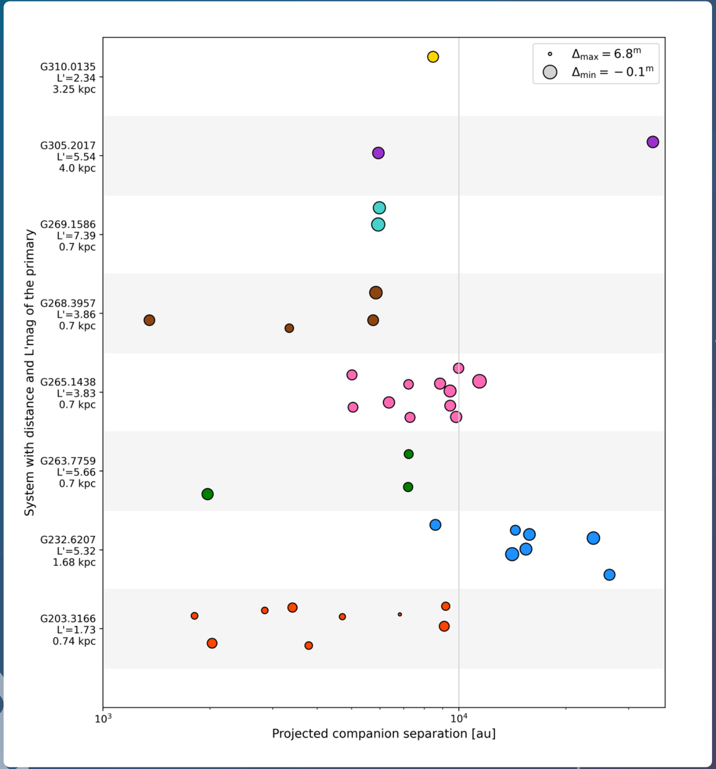




Analysis: **Source detection and PSF fitting (DAOPHOT) + chance projection**

600-50,000 au range: 13 MYSOs from RMS catalogue

High—contrast imaging: VLT/NACO



- We derive the following parameters, from which we can also compute the MF and CF:

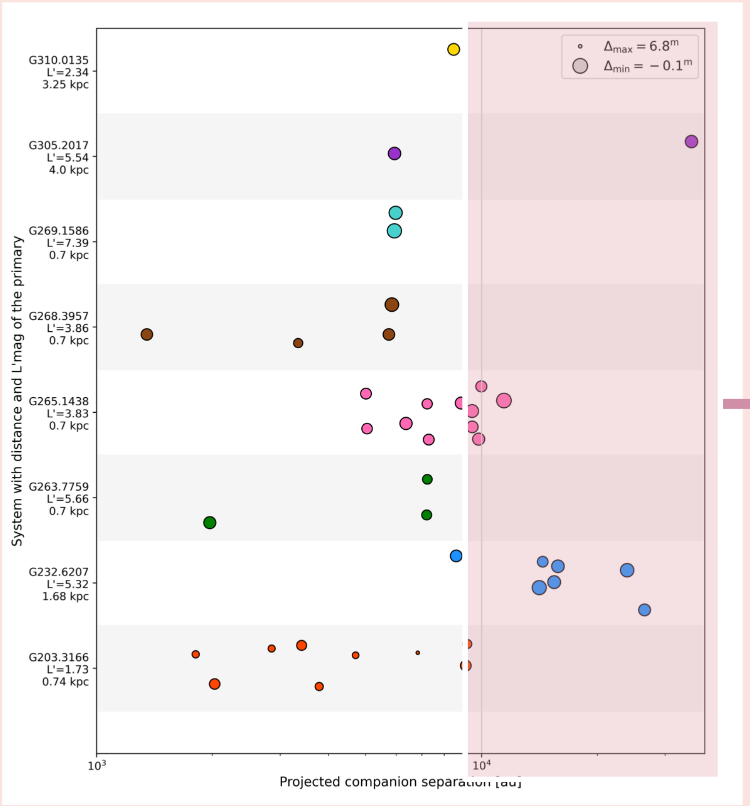
$$\mathbf{MF = 62\% \pm 13\%}$$
$$\mathbf{CF_{600-10000} = 2.46 \pm 0.12}$$

- The separation at which companions are found can tell us about the formation paths involved in the formation of massive multiples.

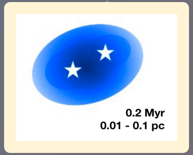
Bordier et al. 2024

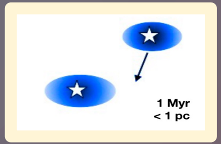
600-50,000 au range: 13 MYSOs from RMS catalogue

High—contrast imaging: VLT/NACO



Most likely formed via **core fragmentation capture** or other dynamical interactions (e.g. **outward migration**)

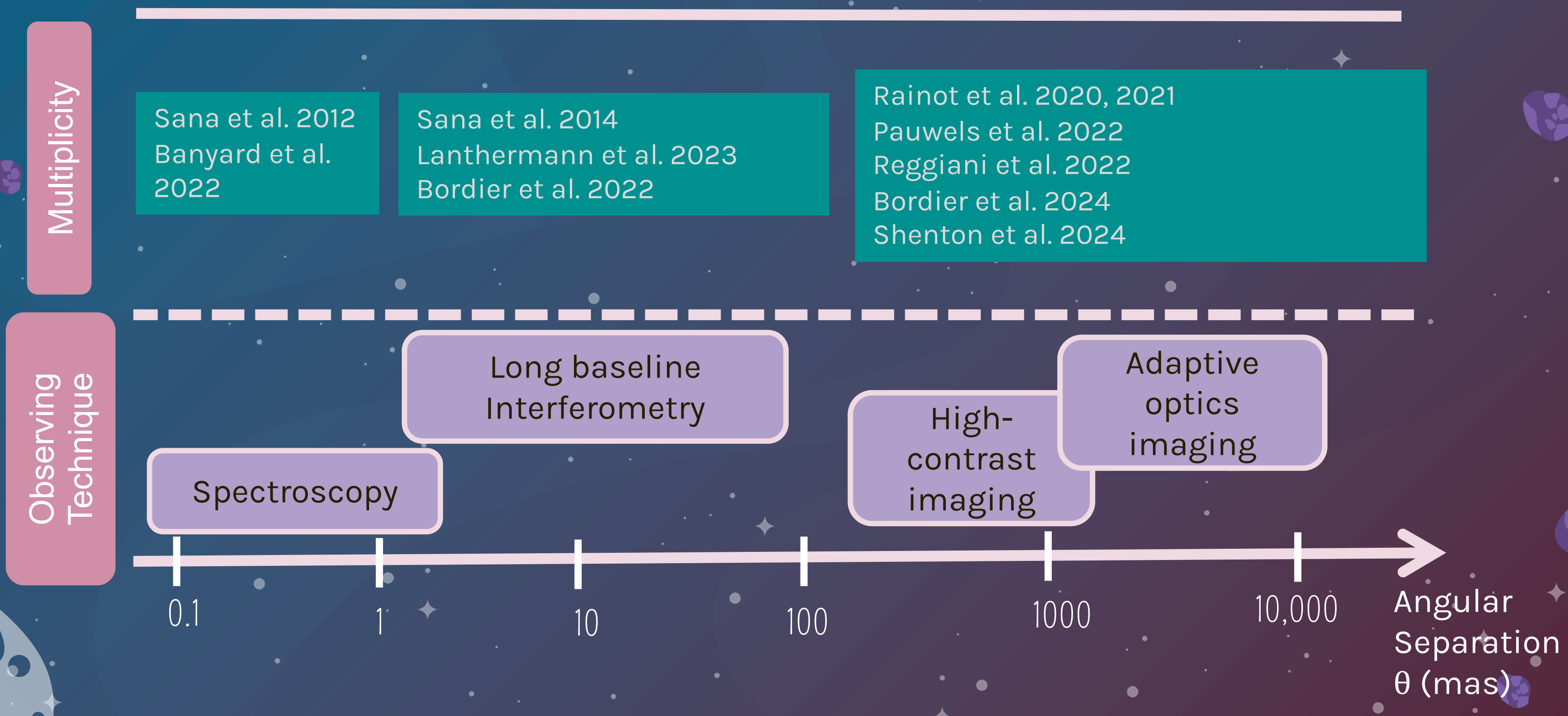




- interactions between multiple systems (Leigh et al. 2016)
- Partner exchange and shifting hierarchies in gas-rich environments (Bate et al. 2012)

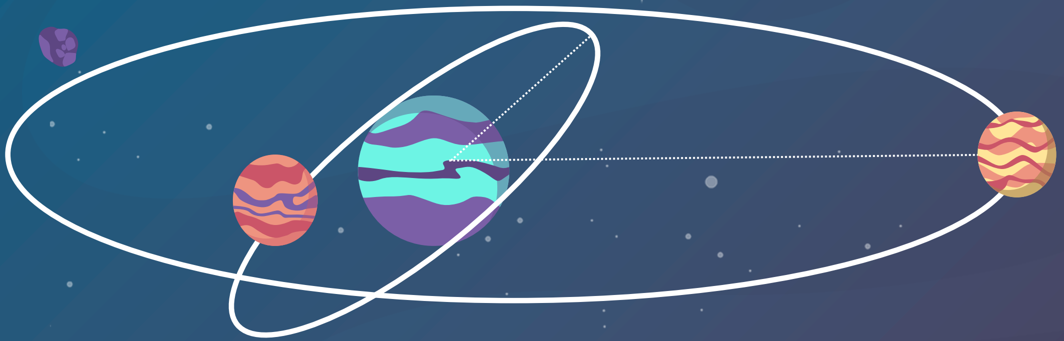
Bordier et al. 2024

“Triple” is the new “binary”

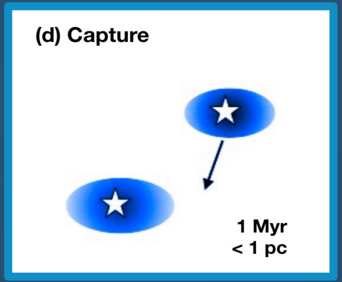


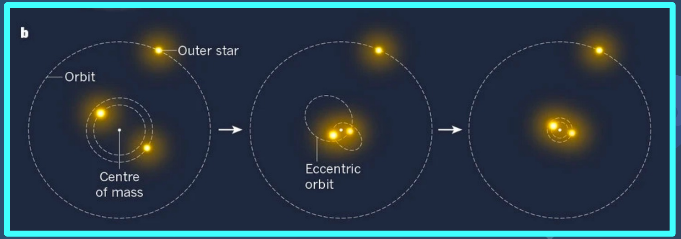
Monitoring main sequence massive triples

Combining spectroscopy and optical interferometry



Formation mechanisms of the inner and outer binary





Offner et al, 2022
Geller et al. 2017

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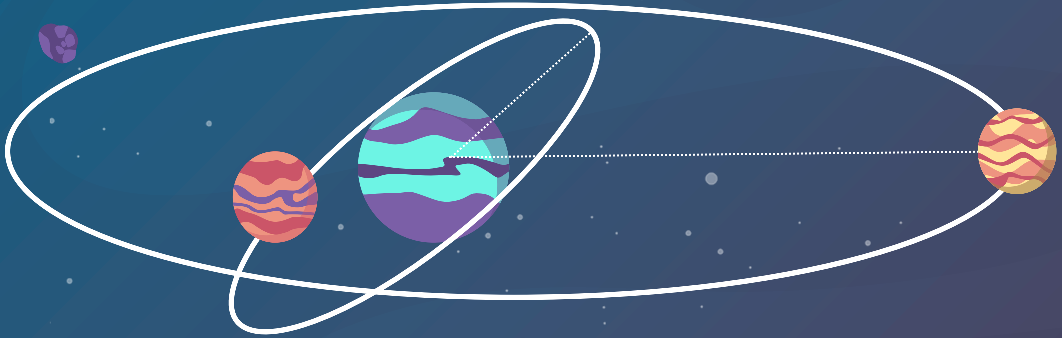
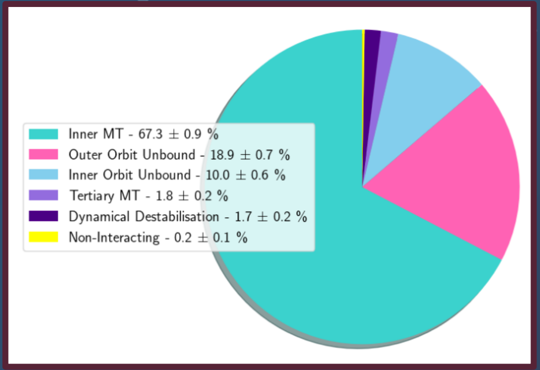


Evolution pathways and predictions for the final fate of the system:

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

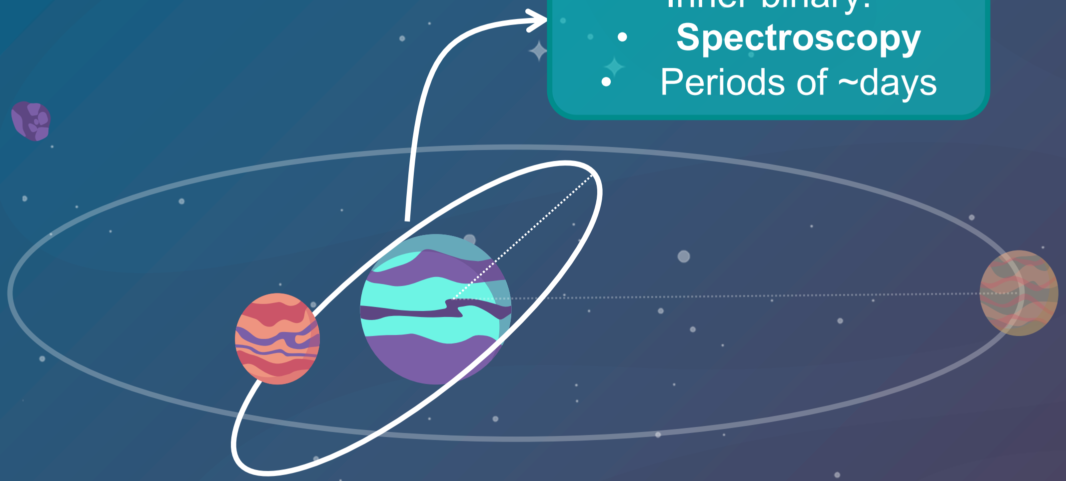


Toonen et al, 2016
Kummer et al. 2023

Monitoring main sequence massive triples

Combining spectroscopy and optical interferometry

Inner binary:
- **Spectroscopy**
- Periods of ~days



Monitoring main sequence massive triples

Combining spectroscopy and optical interferometry

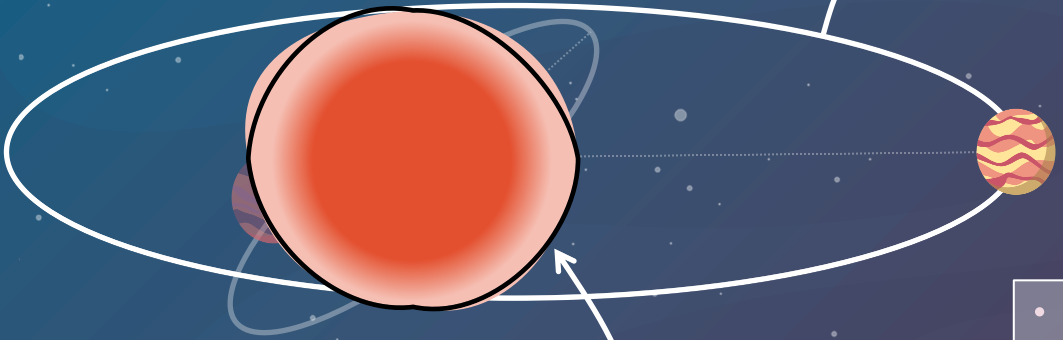
Outer binary:

- **Interferometry**
- Periods of ~years

Monitoring main sequence massive triples

Combining spectroscopy and optical interferometry

Outer binary:
- **Interferometry**
- Periods of ~years

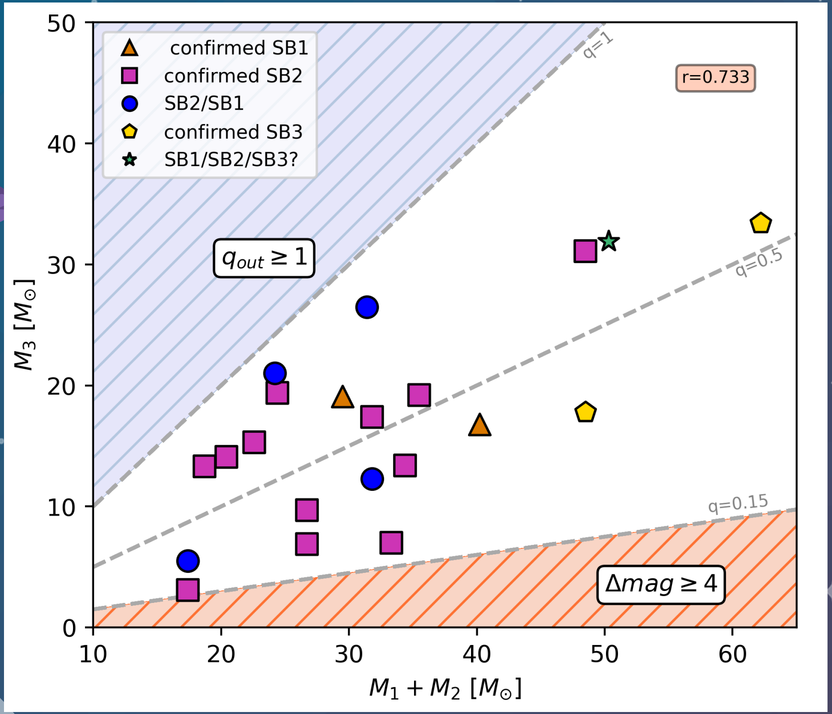


Inner binary unresolved with interferometry

- 21 massive hierarchical triples

→ **Look for correlations between the orbital and binary parameters**
→ **Check the stability of the systems**
→ **Study their architectures**

Triple systems: Von Zeipel Kozai Lidov effects



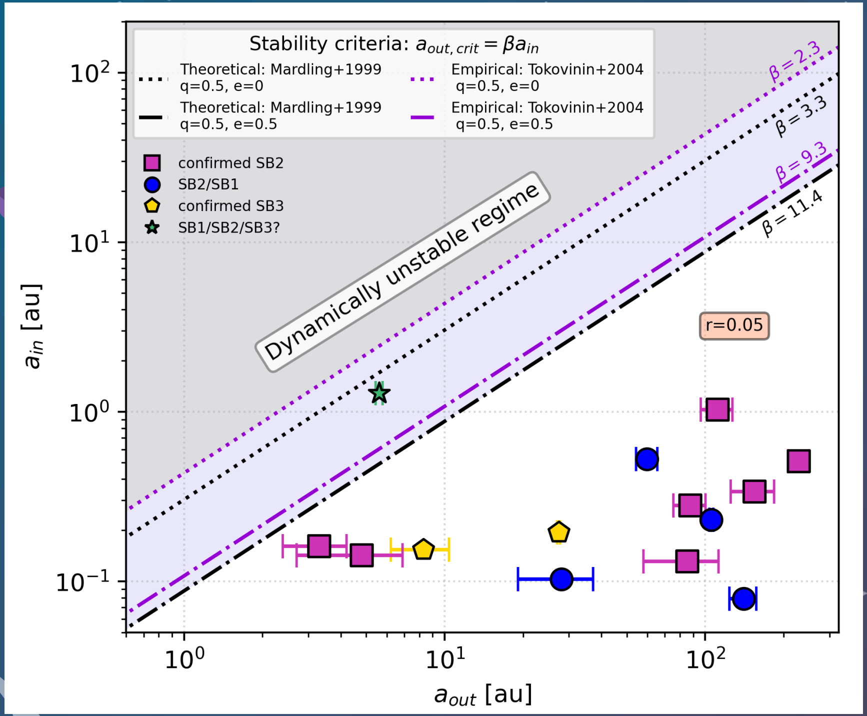
Bordier et al. subm.

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

Formation:
→ Challenging with disk-fragmentation-only theories (spin-orbit do no longer stands)
→ Increased cross-section
→ Dynamical effects: capture? Partner exchange? Hierarchy shifts?

Evolution:
→ More mass transfer initiated by the tertiary ?
→ Stronger tidal effects while at periastron?

Triples systems: stability criterion



Bordier et al. subm.

- All systems are found in the stable regime but one (CPD-47-2963)

→ Empirical stability criterion needs to be refined for the high-mass regime?

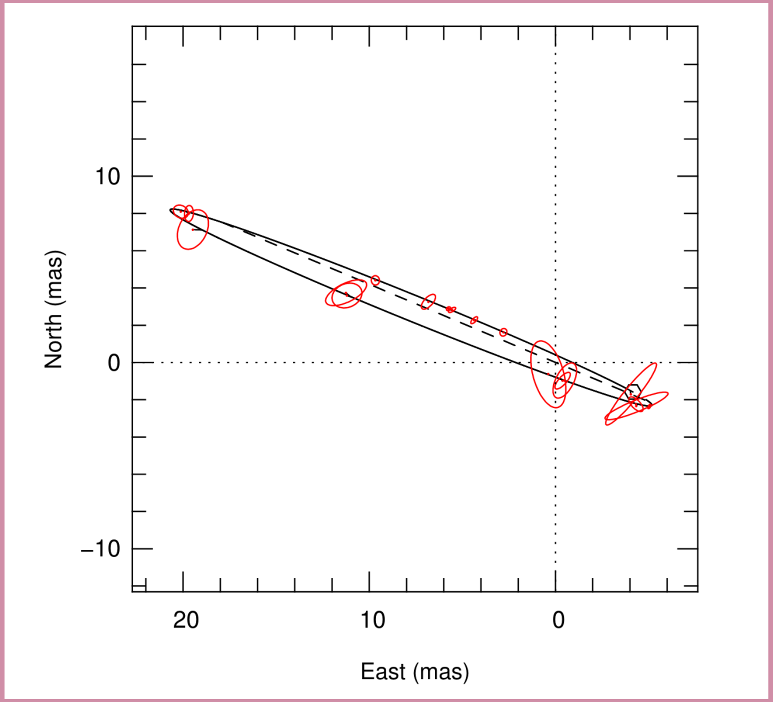
- Based on a single snapshot for $\tilde{a}_{out}$

→ Need to reconstruct the orbit to get interferometric orbital solutions

Triples systems: reconstructing the orbits

Ongoing work – resolved astrometric orbits

- Case of HD 164794 -



Element	Unit	Value	Uncertainty
T	MJD	46 613	21
P	days	33 10.4	7.0
a	mas	14.78	0.13
e		0.6508	0.0039
Ω	deg	67.21	0.51
ω	deg	210.4	1.3
i	deg	86.64	0.53
f_H		0.62	0.02
K_a	km s^{-1}	21.1	1.0
K_b	km s^{-1}	35.14	0.74
g	km s^{-1}	14.79	0.29
From apparent orbit and distance			
d	pc	1250	100
M_t	$M_\odot$	77	18
From apparent orbit and radial velocities			
d	pc	881	22
M_a	$M_\odot$	16.77	0.99
M_b	$M_\odot$	10.07	0.89

Le Bouquin et al. 2017

Triples systems: reconstructing the orbits

Ongoing work – resolved astrometric orbits

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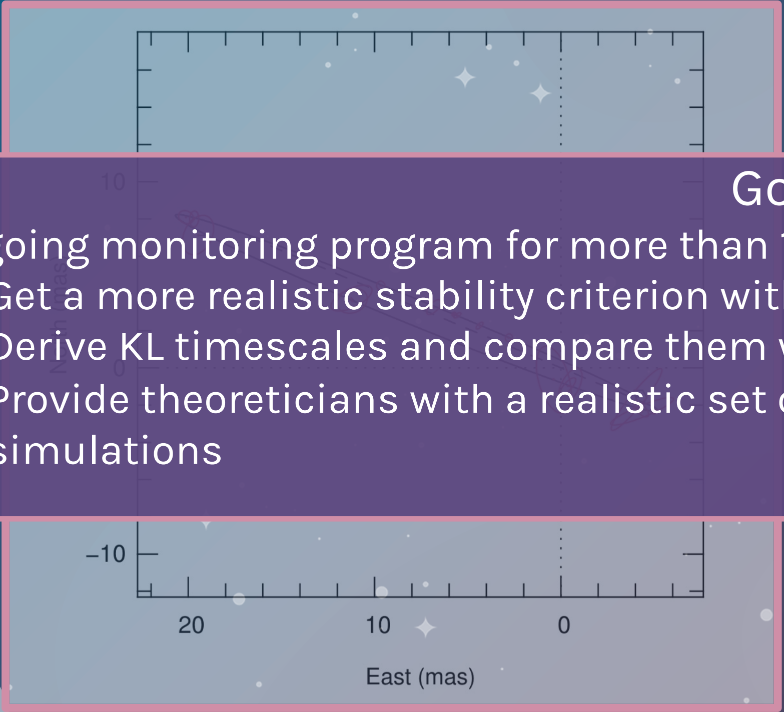

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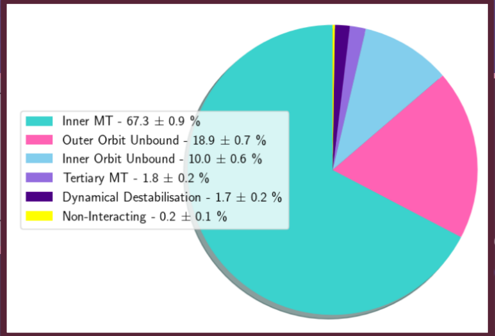
Goals:

Ongoing monitoring program for more than 10 years, following 16 massive triples with LBI:

- Get a more realistic stability criterion with measured eout and I rel
- Derive KL timescales and compare them with tidal effects
- Provide theoreticians with a realistic set of distributions for their evolution simulations



Conclusions

- ~50 young massive systems were characterized by means of high-angular resolution techniques
- The high-degree of multiplicity is observed early in massive star evolution.
- A massive **triple system** seems to be the outcome of massive star formation, for separations ranging up to 50,000 au.
- However, confirming or discarding one or the other formation pathway is not straightforward.
  - Disk fragmentation + dynamical evolution (migration or ZKL): formation of close binaries
  - Wide companions : core fragmentation or capture
- Full orbital solutions of triples will help constraining the formation and evolution of such systems