School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

UNIVERSITY OF LEEDS

On the Binarity of Massive Stars in the HR Diagram

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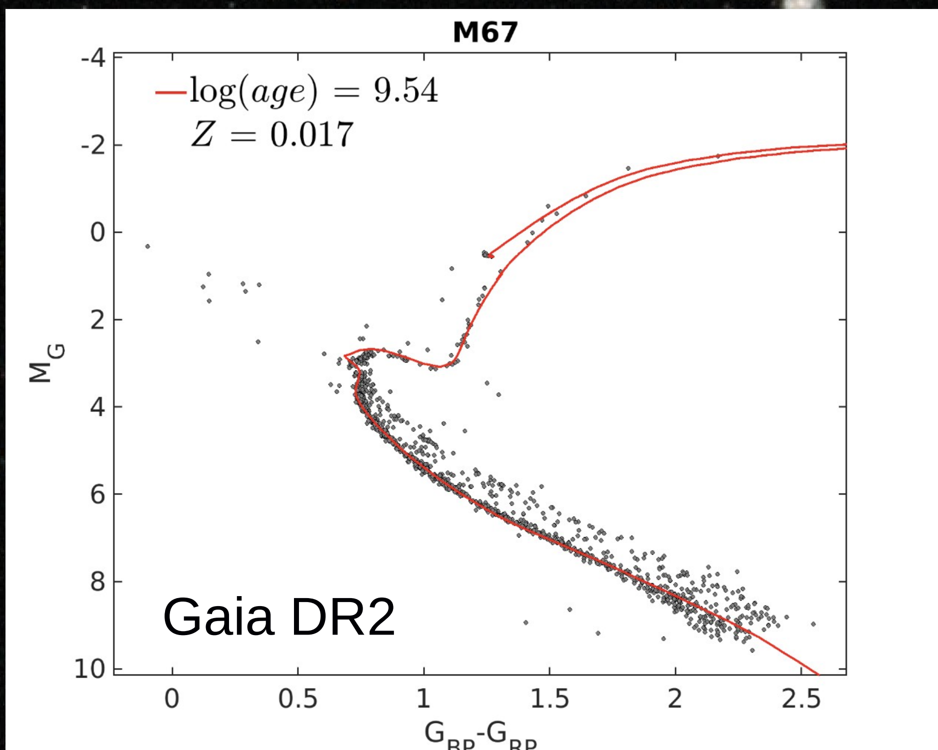
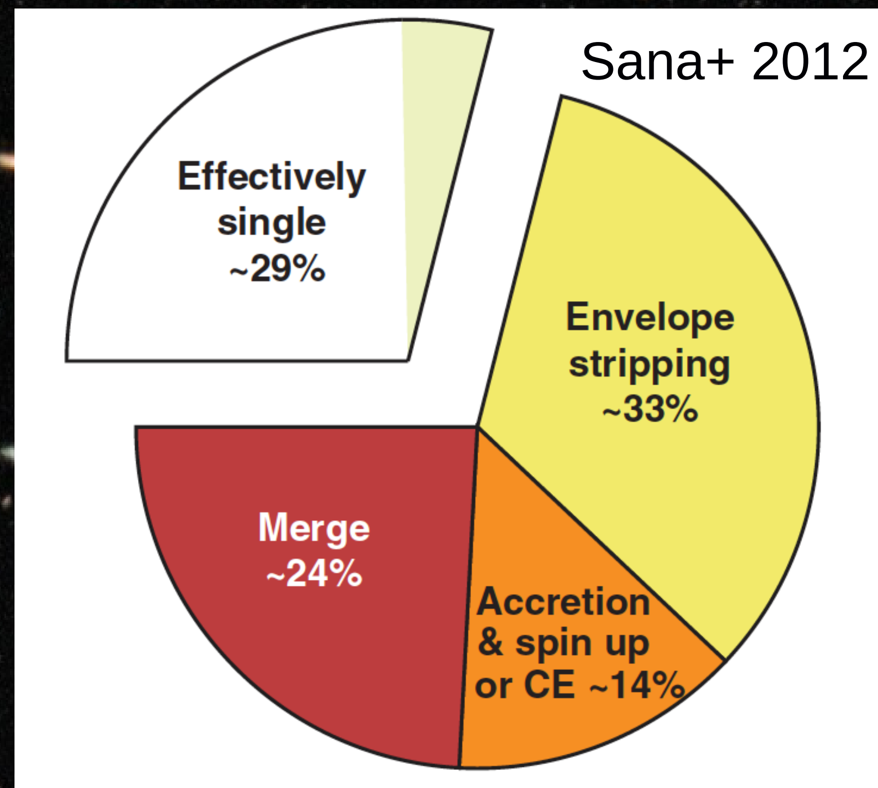
POEMS

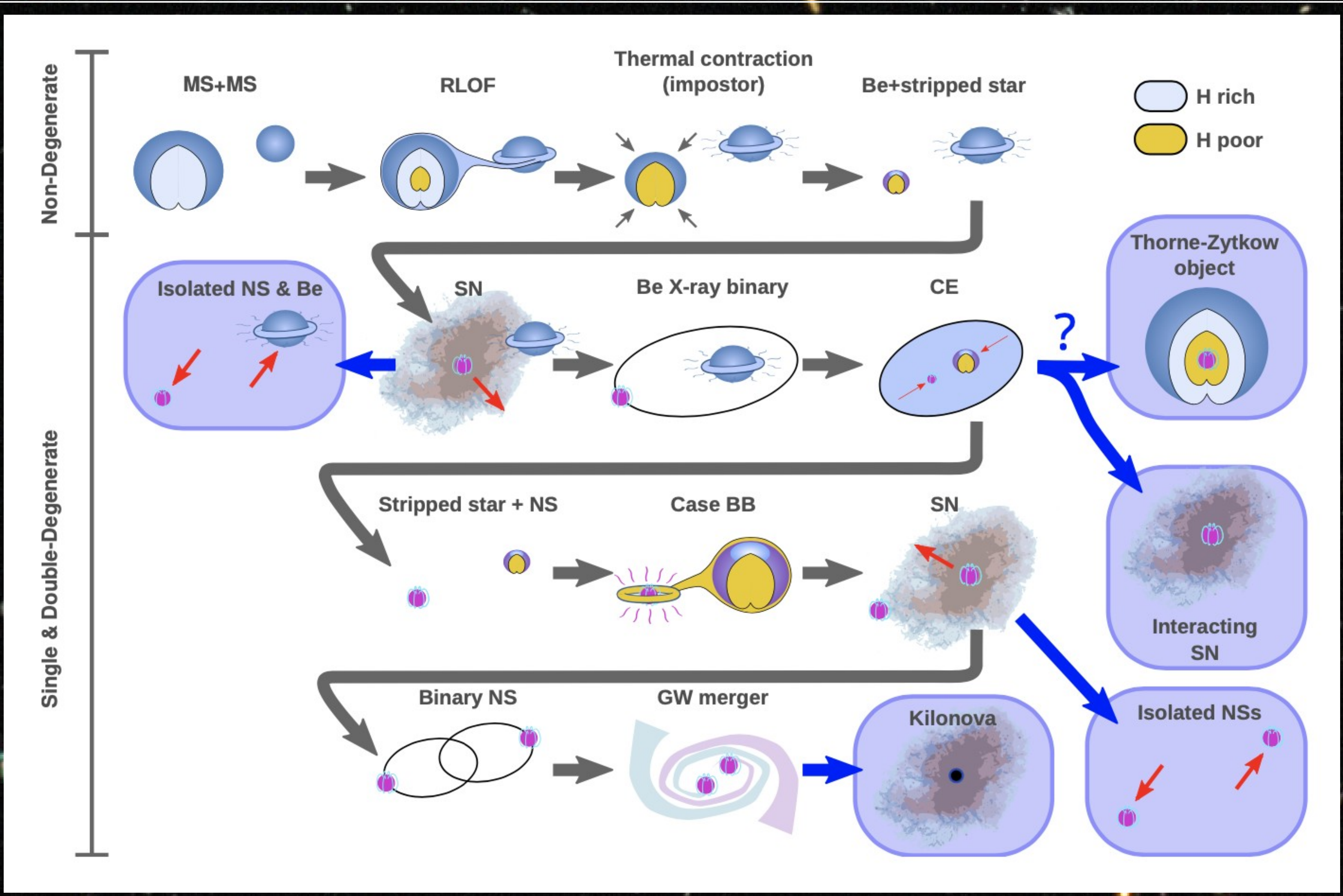
Why study (massive) binary stars?

- Multiplicity of massive Main Sequence stars close to 100%
- 70% of all massive stars will interact with their companions at some stage in their evolution.





Why study (massive) binary stars?



See talks by Lucas de Sa, Koushik Sen

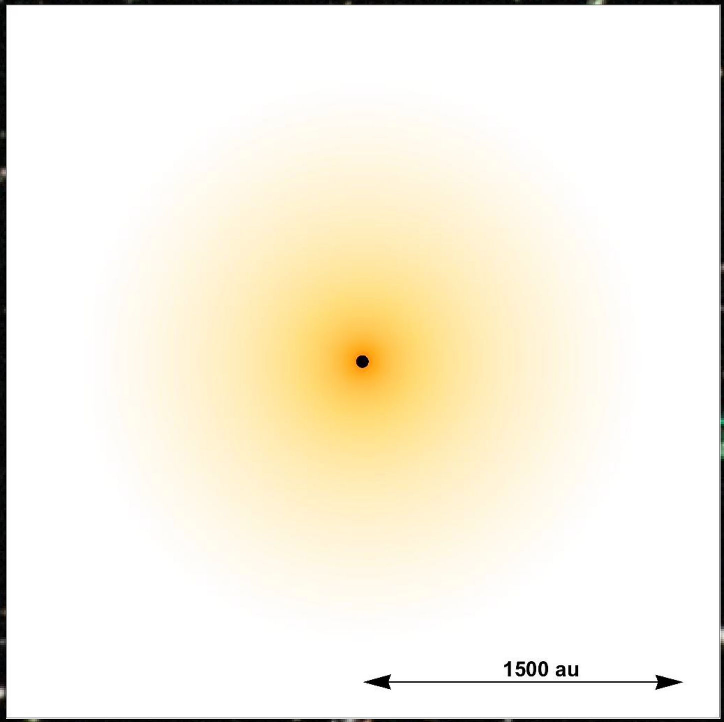
Marchant & Bodensteiner 2024

Their formation

- Formation mechanism & its details largely unknown :
    - capture,
    - (disk) fragmentation
    - (with added migration)

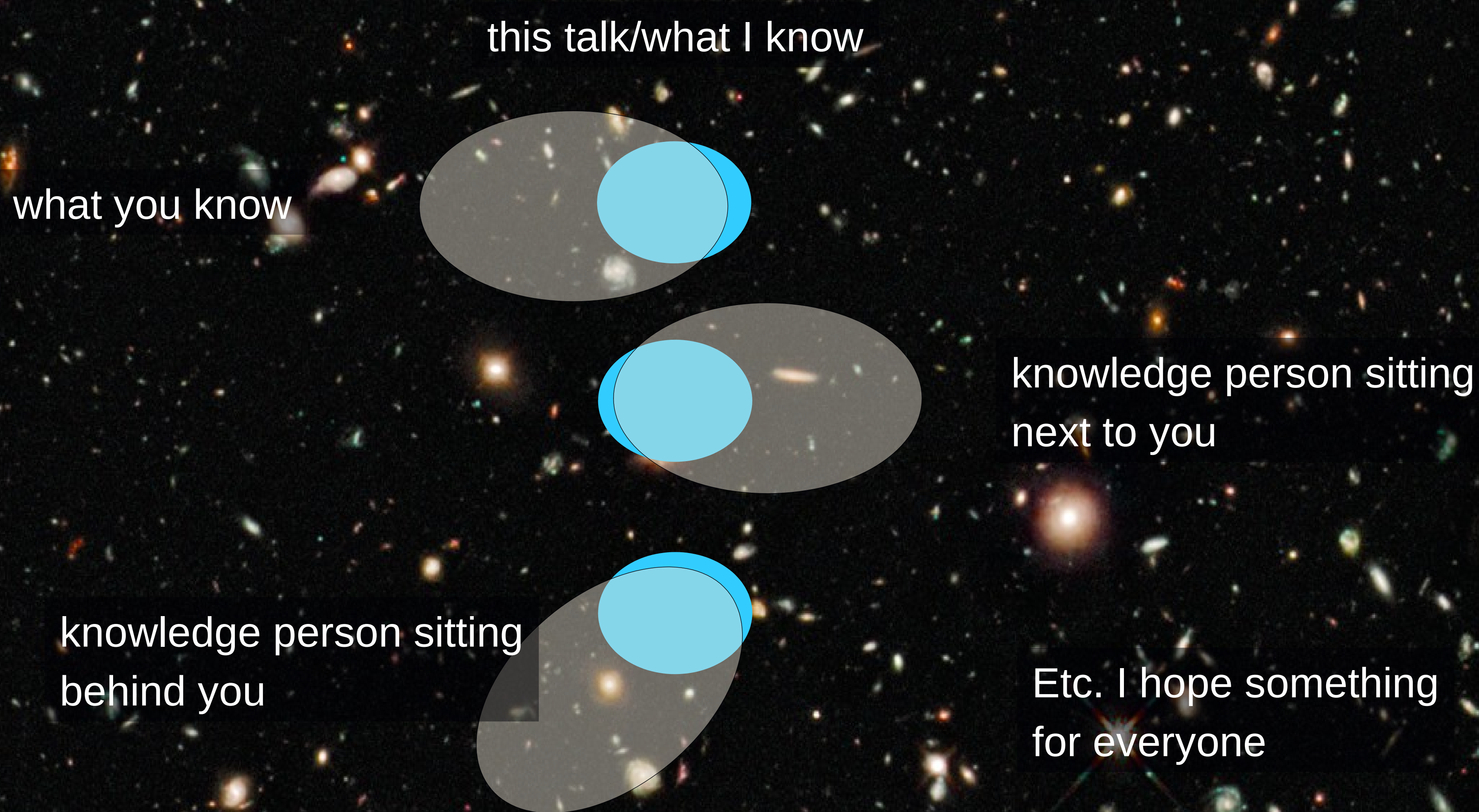
  (Krumholz+ 2009; Rosen+ 2016; Lund & Bonnell 2018; Meyer+2018)

- Latest simulations form binaries at large range of separations, down to smallest scales



Meyer+ 2018

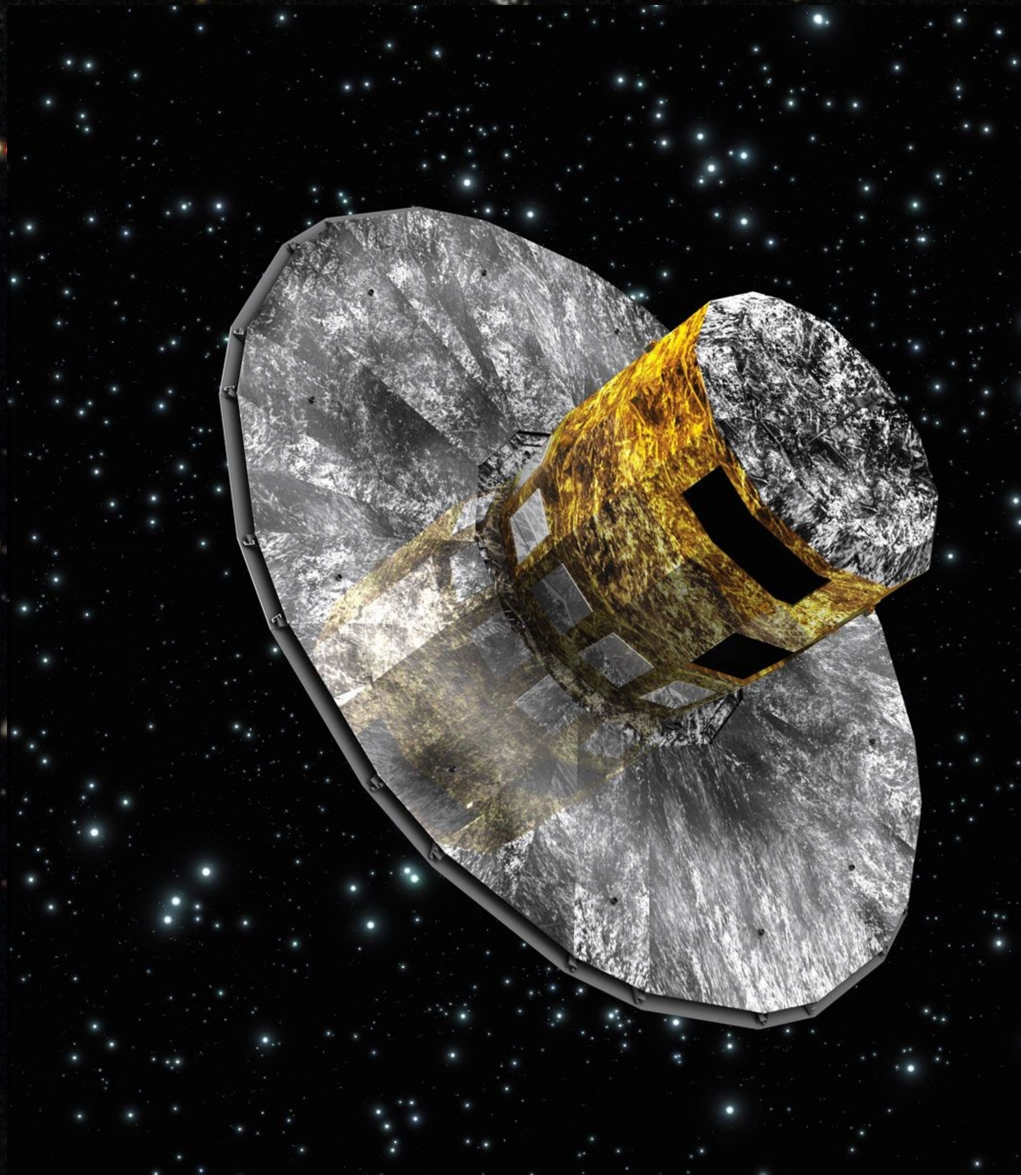
Topics covered in this talk



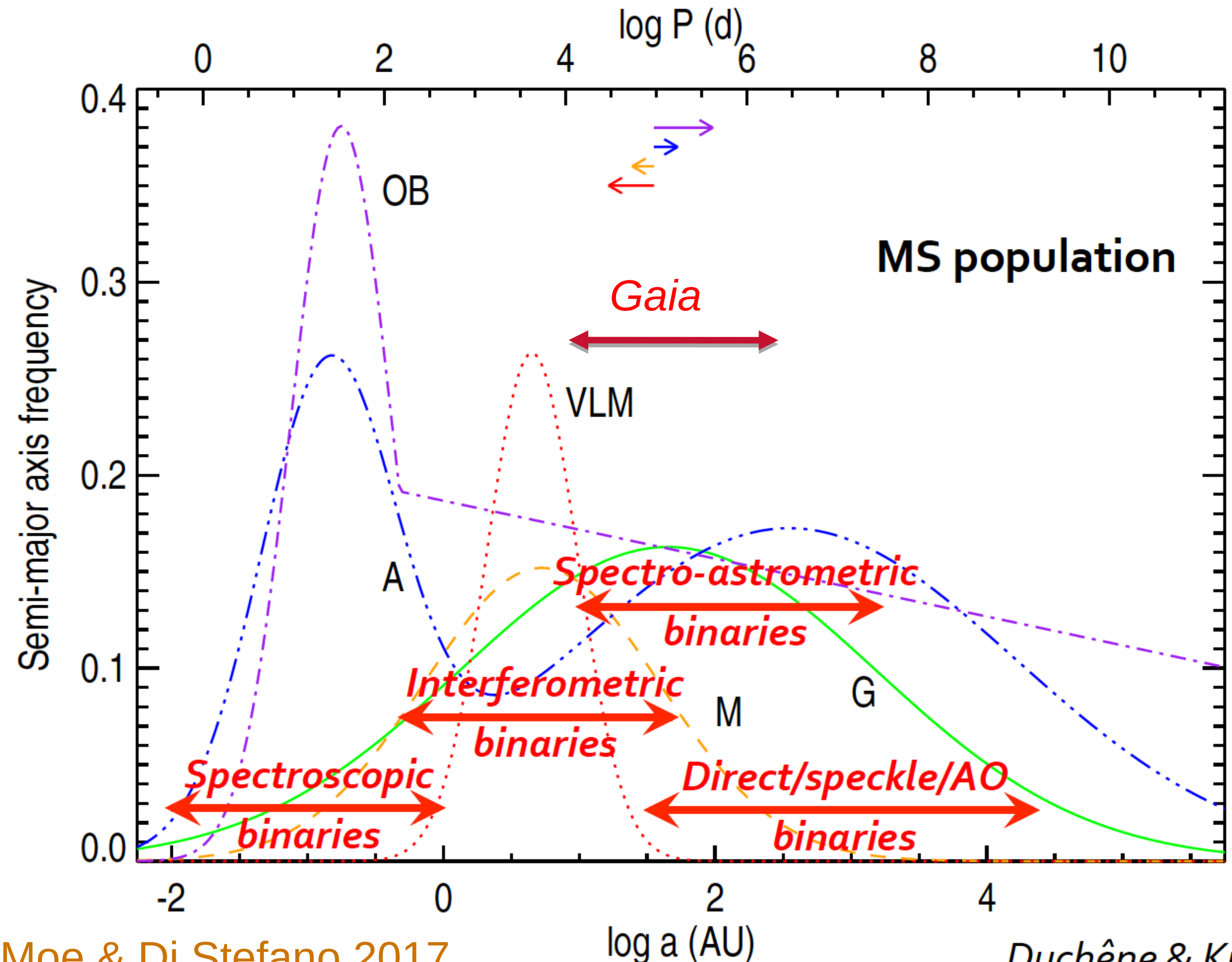
Outline

- Intro
- Evolutionary connections
- Binary fractions
- Digression to Gaia
- Formation

- Outro



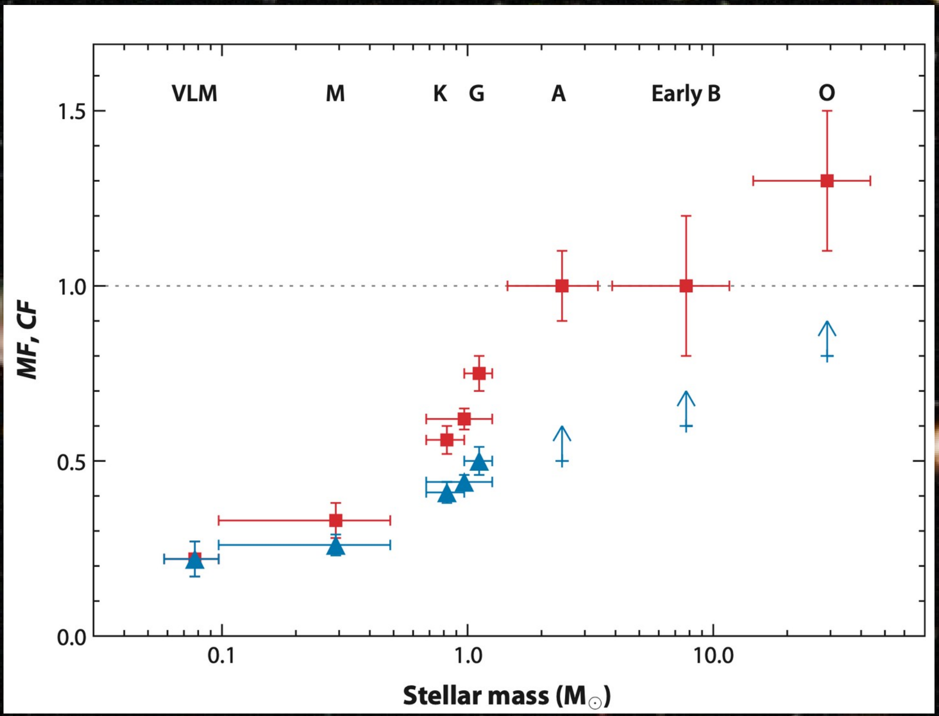
Need many complementary techniques to sample all separations



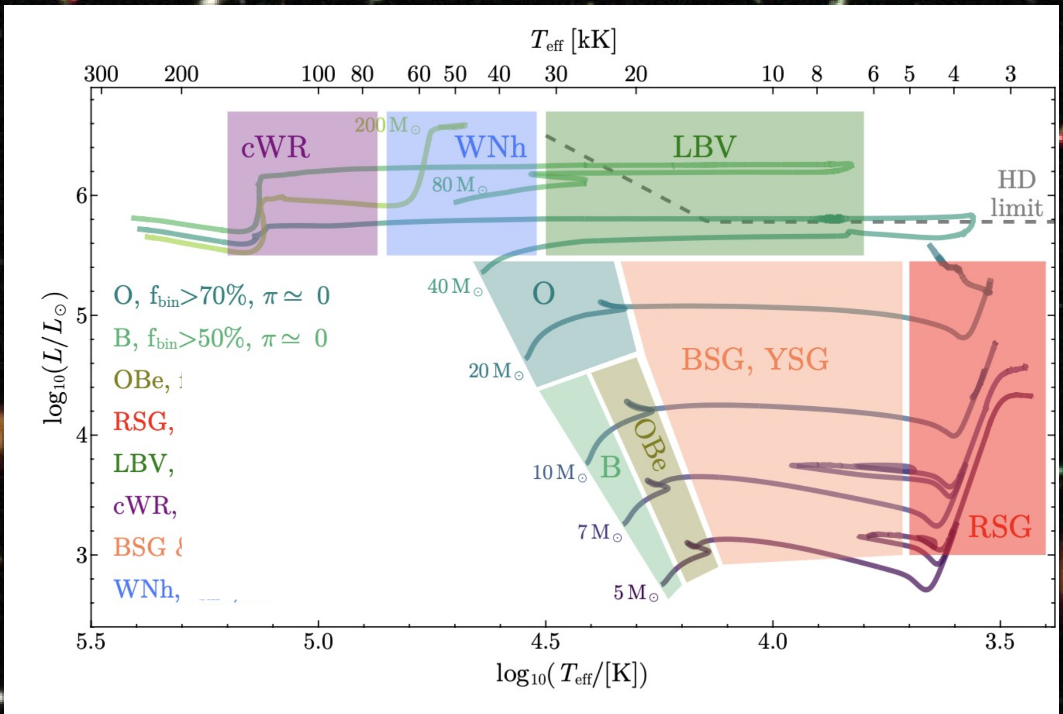
See also Moe & Di Stefano 2017

Duchêne & Kraus (2013)

Massive Star Binarity across the HR Diagram



Duchêne & Kraus 2013



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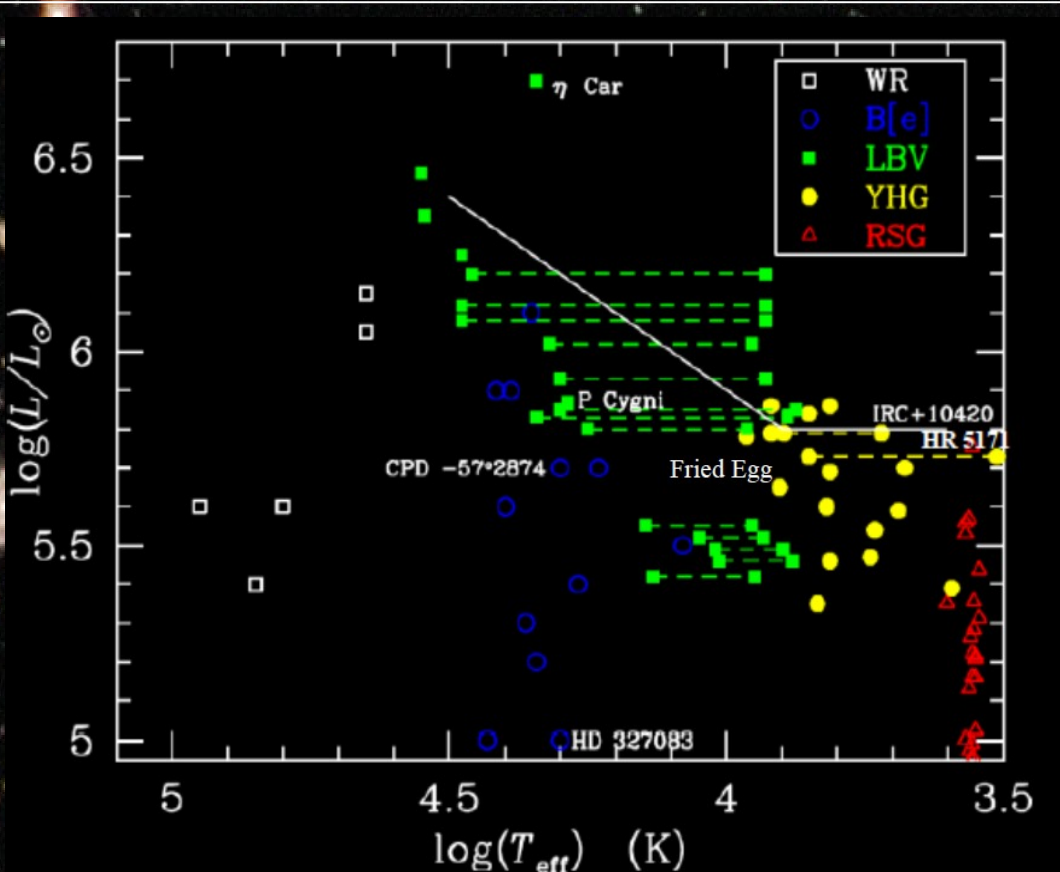
Evolutionary connections



Based on HR diagram from Oudmaijer+ 2009 (pre-Gaia, see Smith+2019, Rate+ 2020)

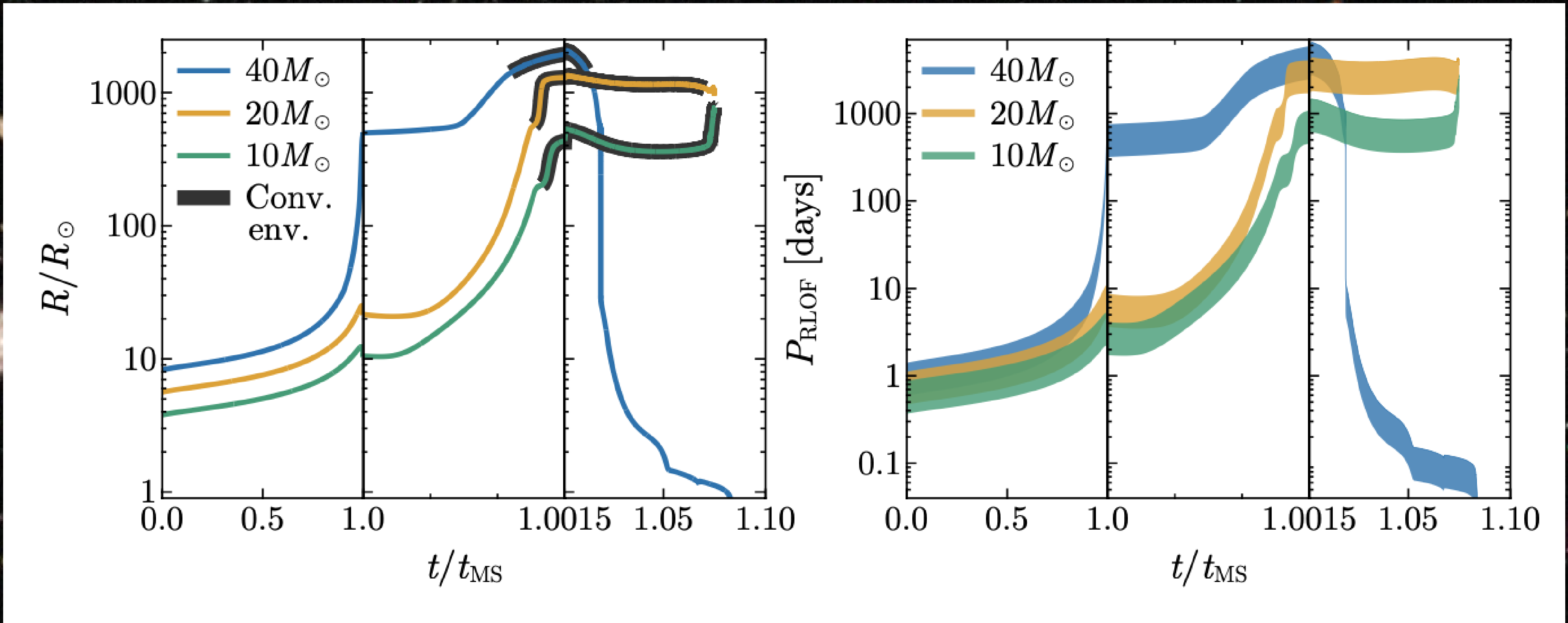
Two of the various evolutionary paths :

RSG
↓
Post-RSG/
ellow Hypergiant
↓
B[e]/LBV
↓
WR
↓
SN

O/WNh
↓
LBV
↓
WN
↓
WR
↓
WO

(Conti)

Expectations regarding close binaries



Stars get larger – hence Roche Lobe gets larger…

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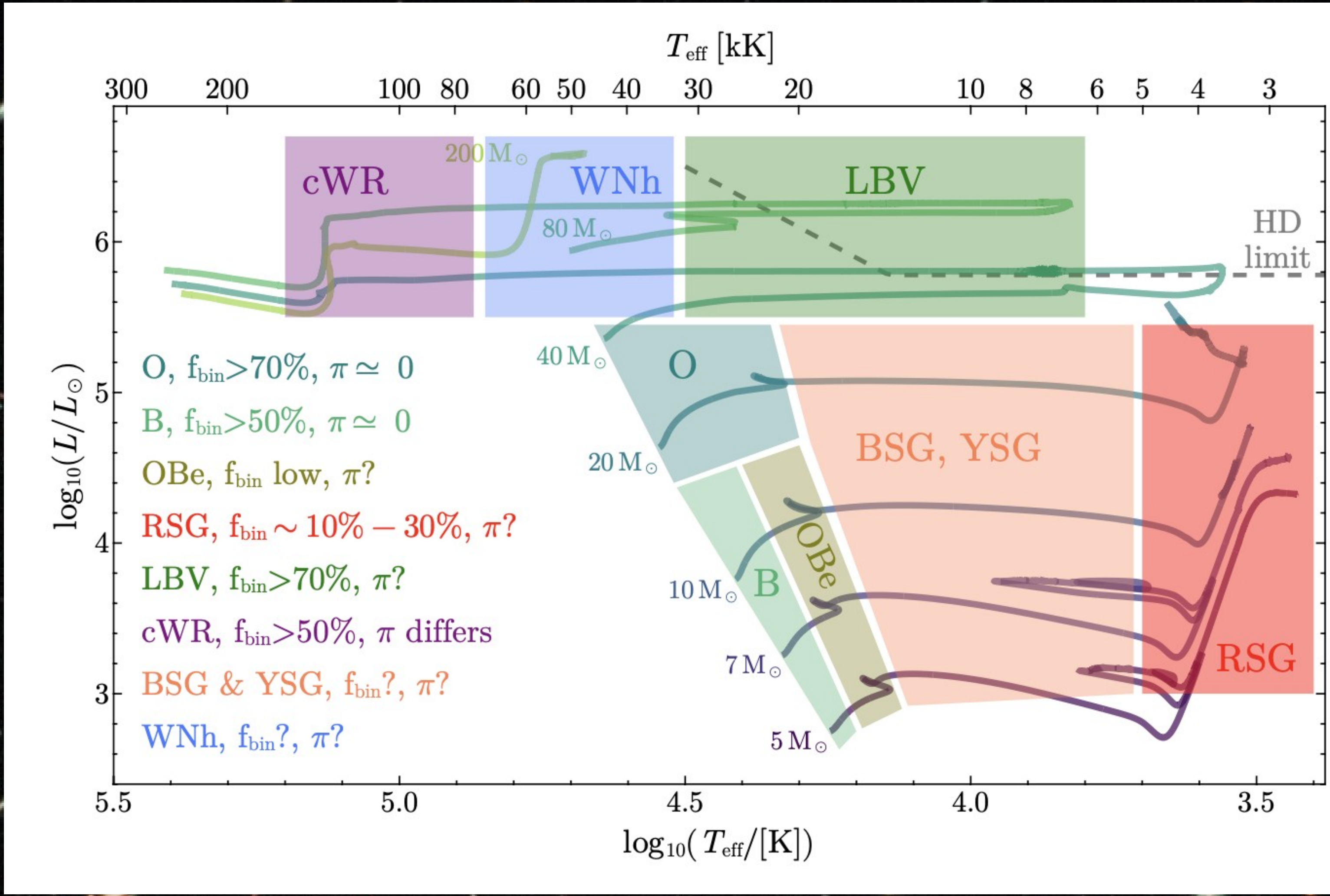
Massive Star Binarity across the HR Diagram



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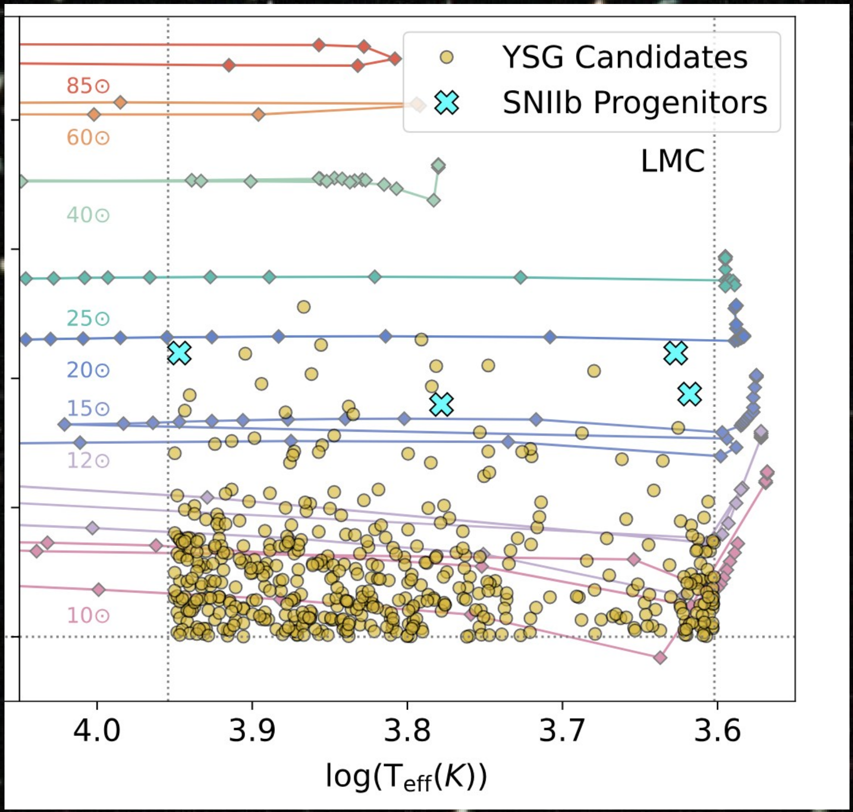
Further parts of HR diagram: Yellow HG/SG

Yellow Supergiants: 20-60% Photometry. O'Grady+ Astro-ph, yesterday

Trend with location in HR diagram?

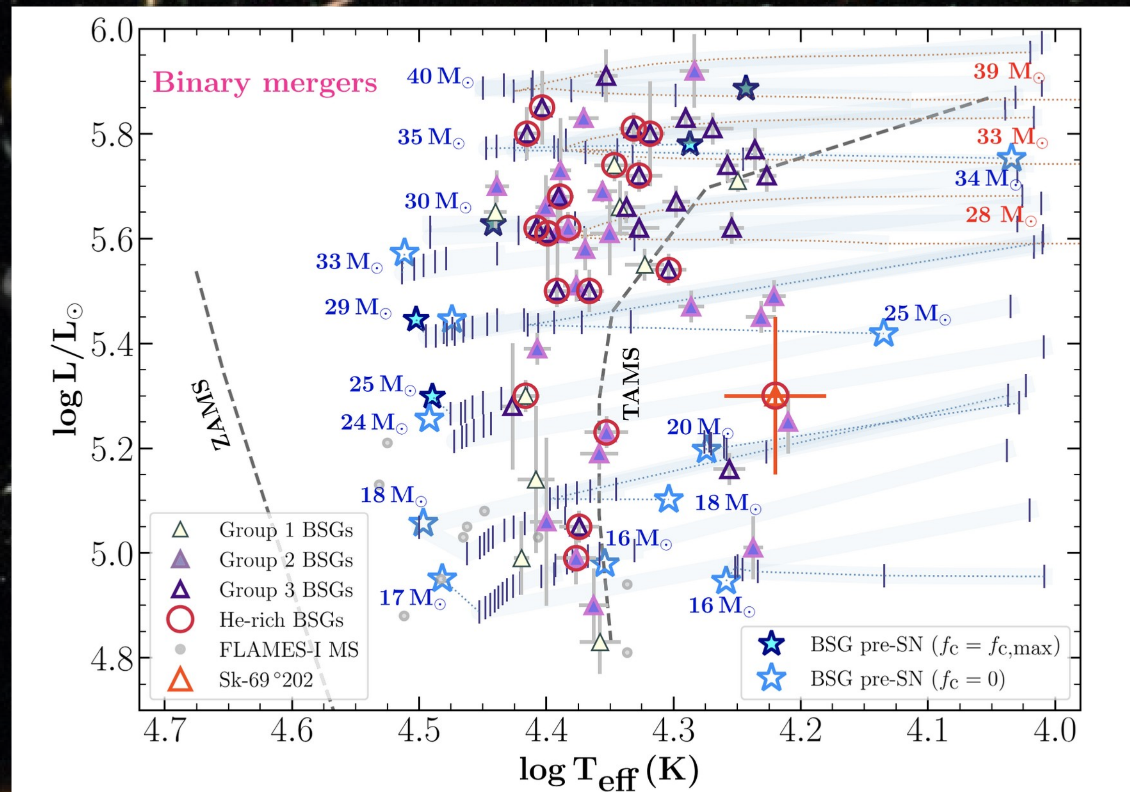


Further parts of HR diagram: Blue Supergiants

Blue Supergiants: 20-50%
Dunstall+ 2015,
Ritchie+ 2022

Trend with cluster environment?

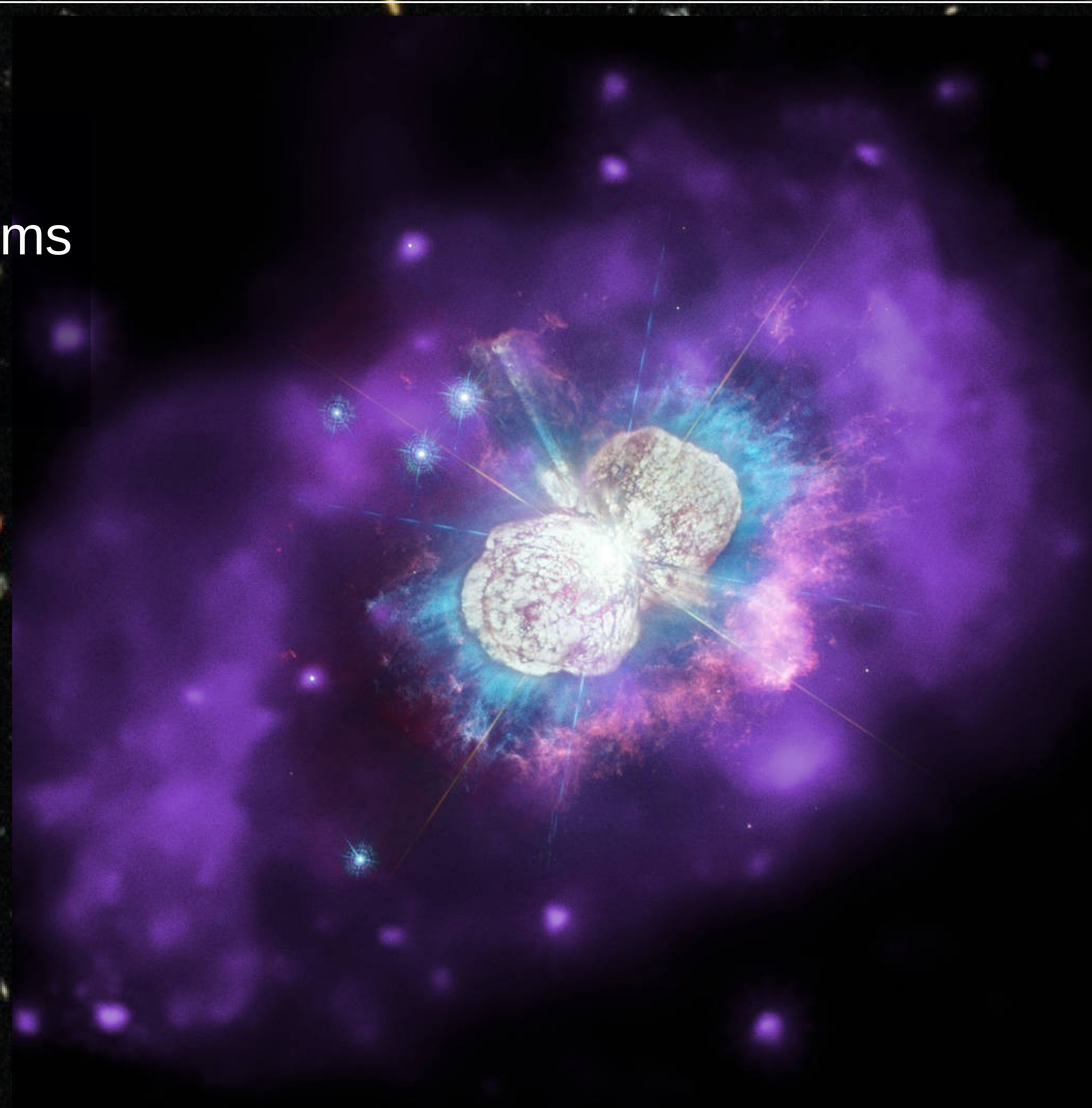
Trend with location in HR diagram?



Menon+ 2024

Further parts of HR diagram: Very Massive Stars

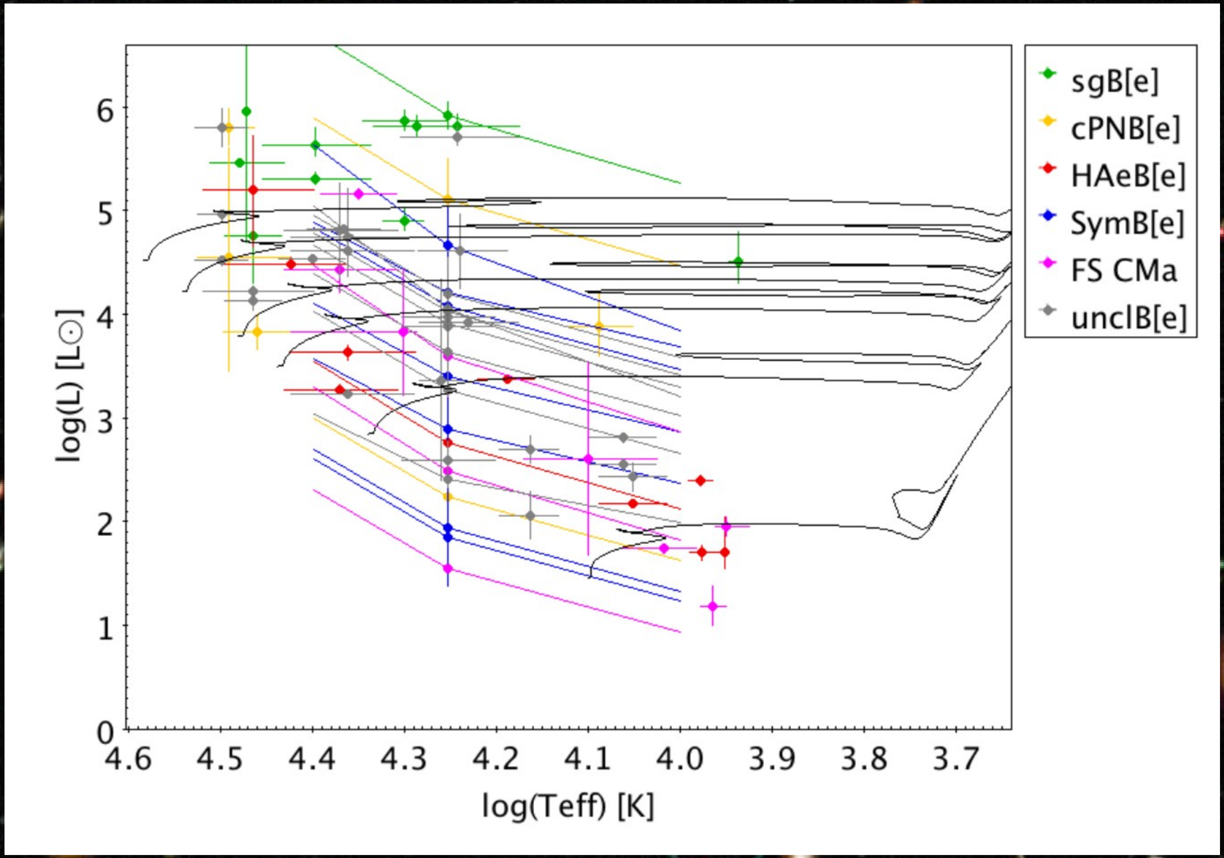
Mostly identified based on luminosity, few binary systems found to host VMS (Martins 2015)



Eta Car
Credit: NASA

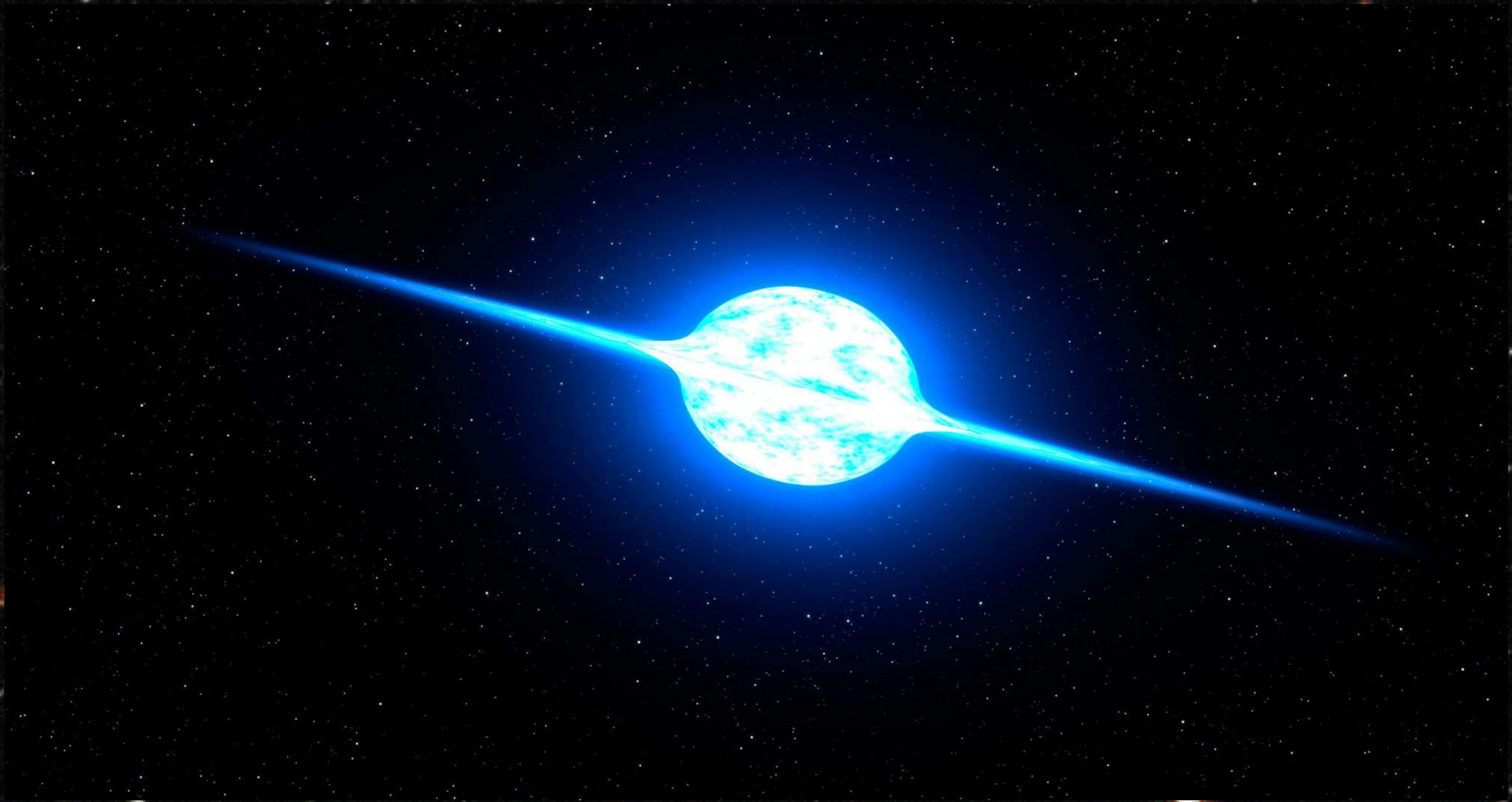
Further parts of HR diagram: B[e] stars

- 74 Galactic B[e] objects in Gaia (preliminary)
- Few unambiguous supergiants among unclassified B[e] objects
- Binarity (literature) 30%
- No trend with position in HR diagram



Tate, Woodley, Oudmaijer in prep.
Sample from Miroshnichenko+ 2007

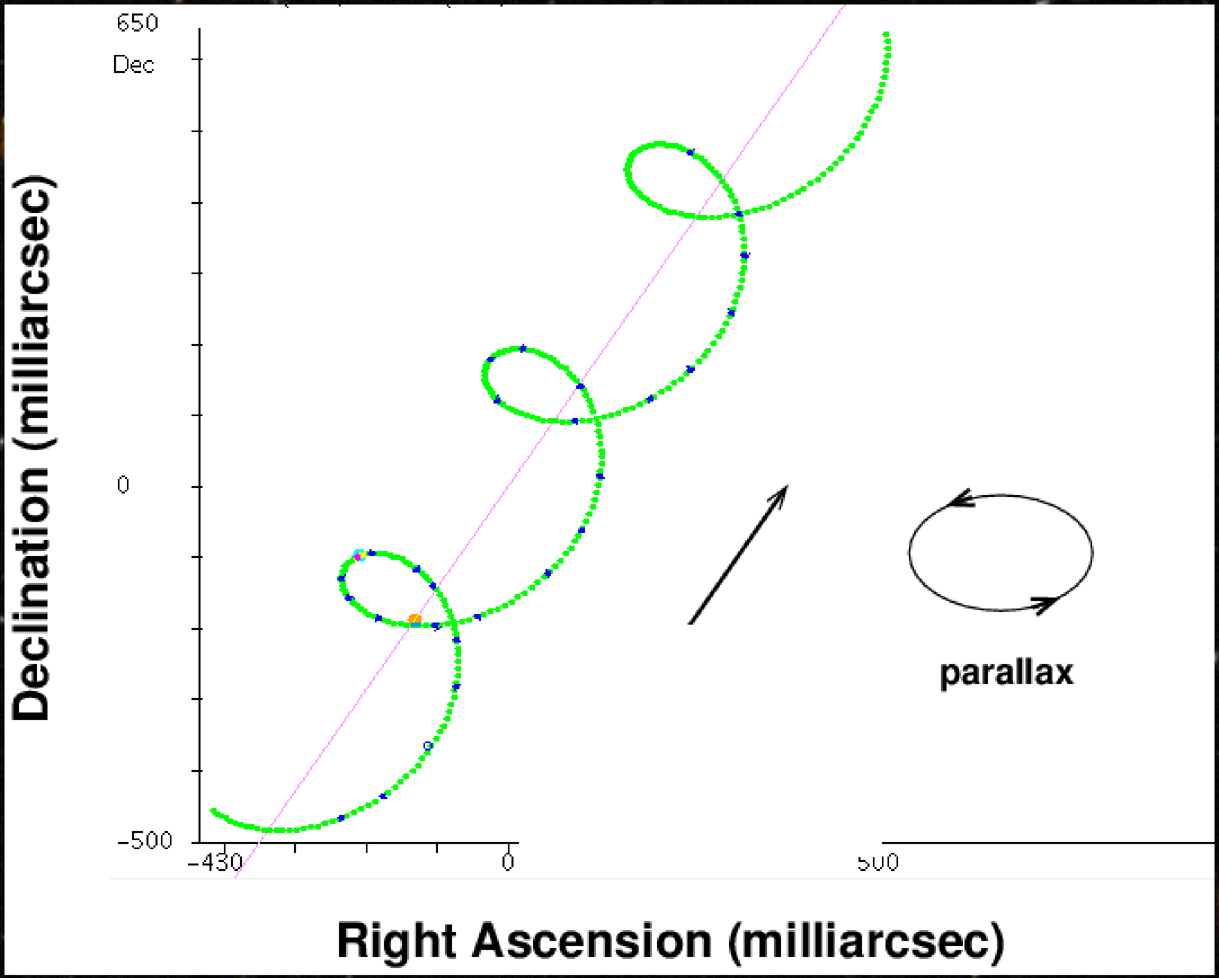
Further parts of HR diagram : Be stars



See also talk by Robert Klement

Credit: Bacon StSci

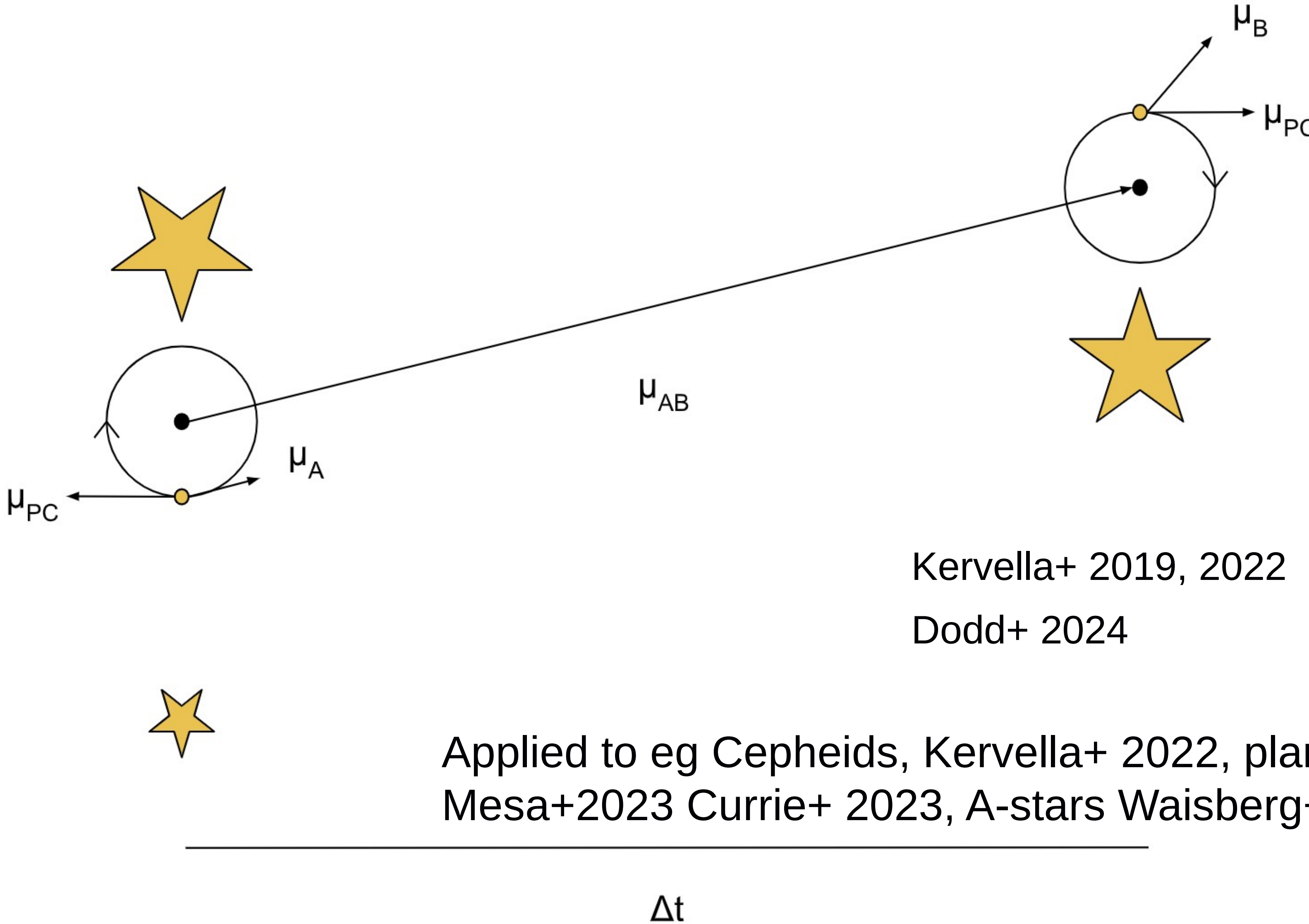
Intermezzo: parallaxes from Gaia



- Gaia has observed about 2 billion objects with <0.05 mas precision.
- Good binary detection instrument

http://sci.esa.int/gaia-stellar-family-portrait/

Proper Motion Anomaly (PMA)



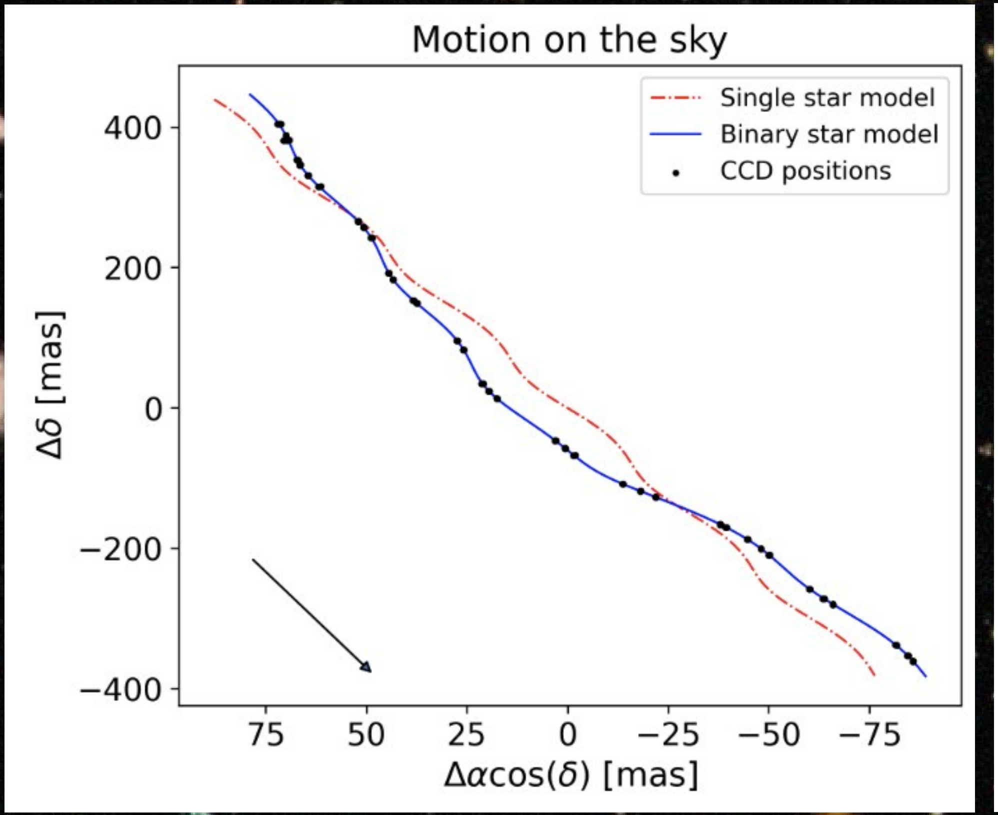
Kervella+ 2019, 2022

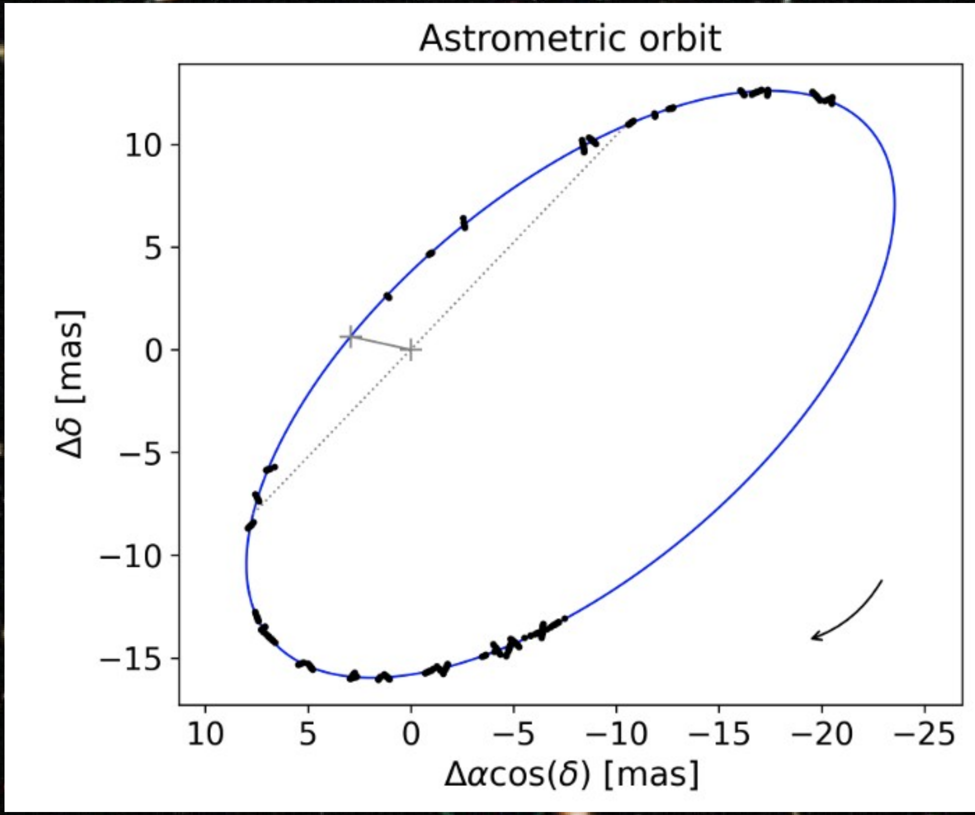
Dodd+ 2024

Applied to eg Cepheids, Kervella+ 2022, planets, Mesa+2023 Currie+ 2023, A-stars Waisberg+2023

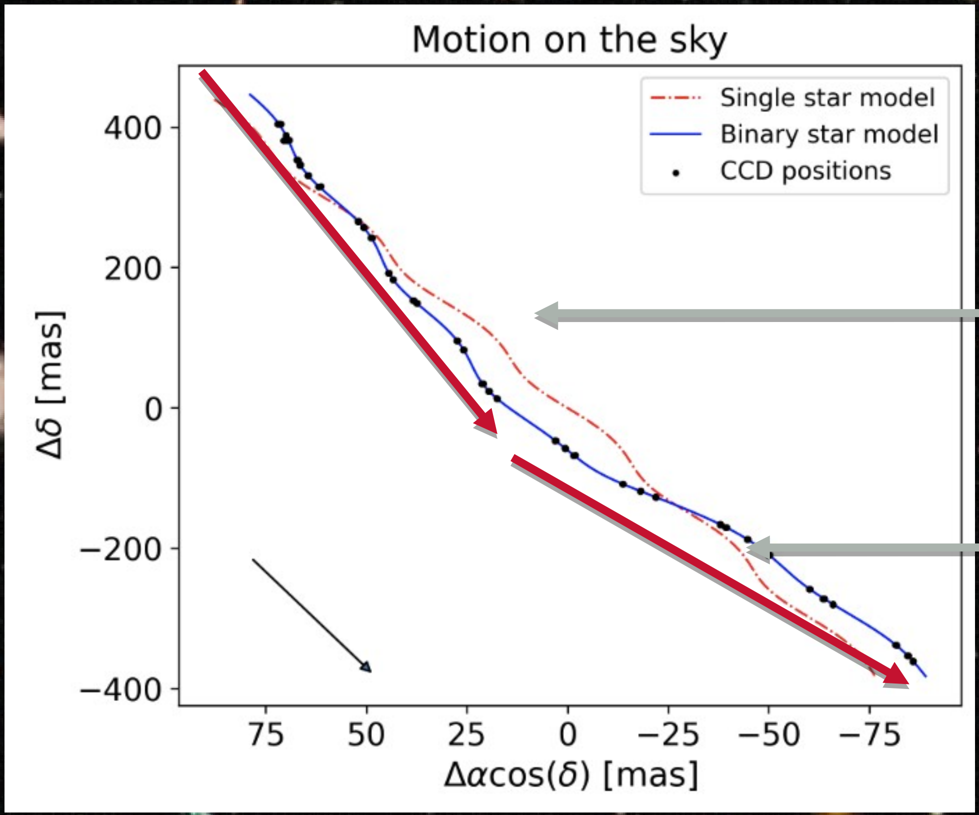
Gaia DR4 preview - Gaia BH3

(Gaia Collaboration, Panuzzo+ 2024)





Gaia as binary detector



Can also use Gaia data to find "Proper Motion Anomaly"

Early Gaia data

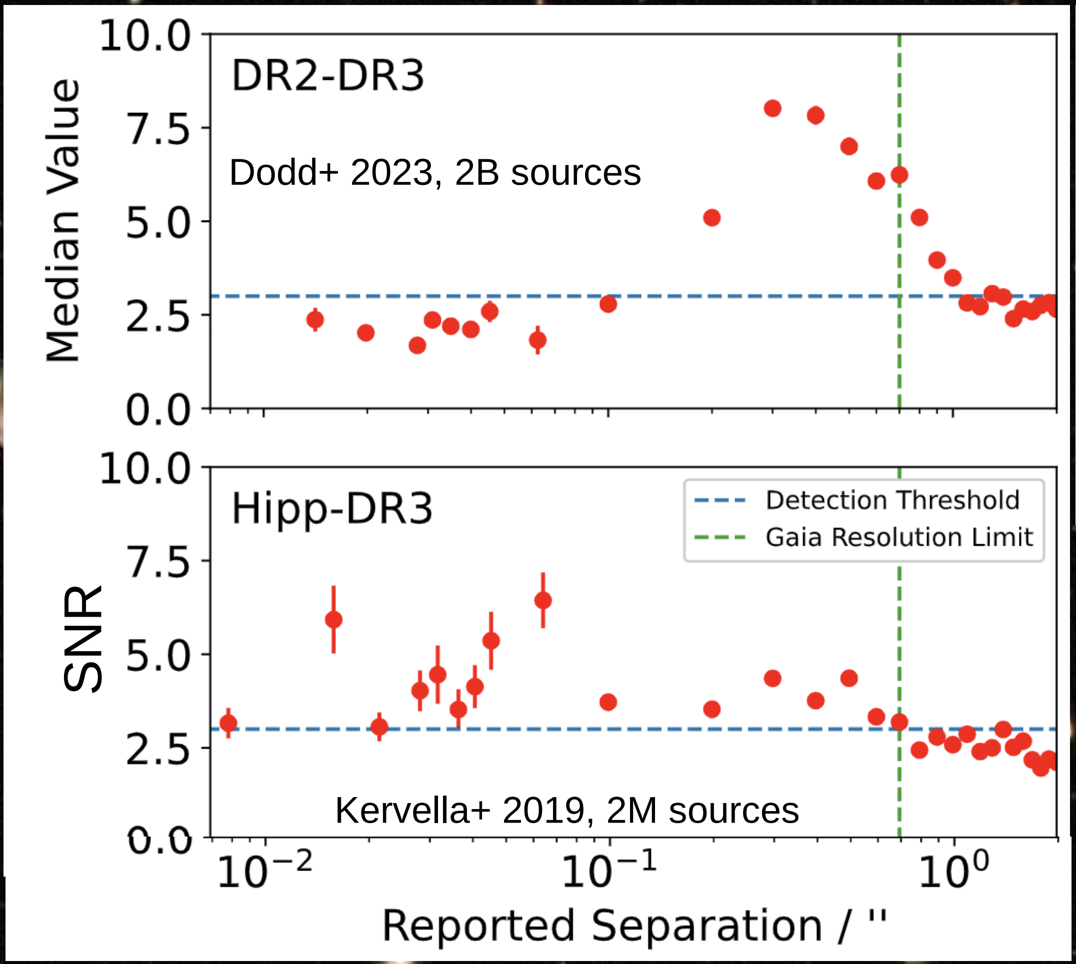
Recent Gaia data

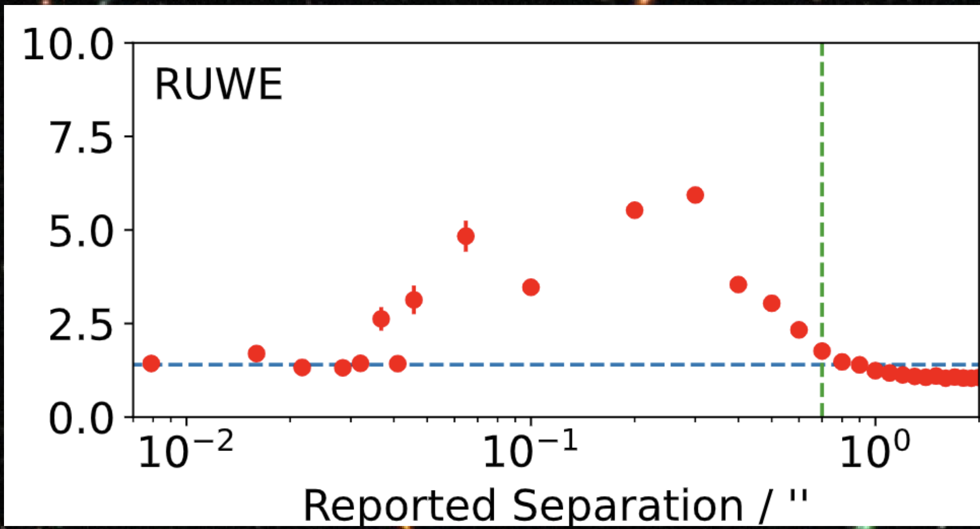
Difference between two vectors gives PMa, can be applied to 2 billion Gaia objects

Here we use DR2 vs DR3

Dodd+ 2024

Proper Motion Anomaly – empirical separation limits





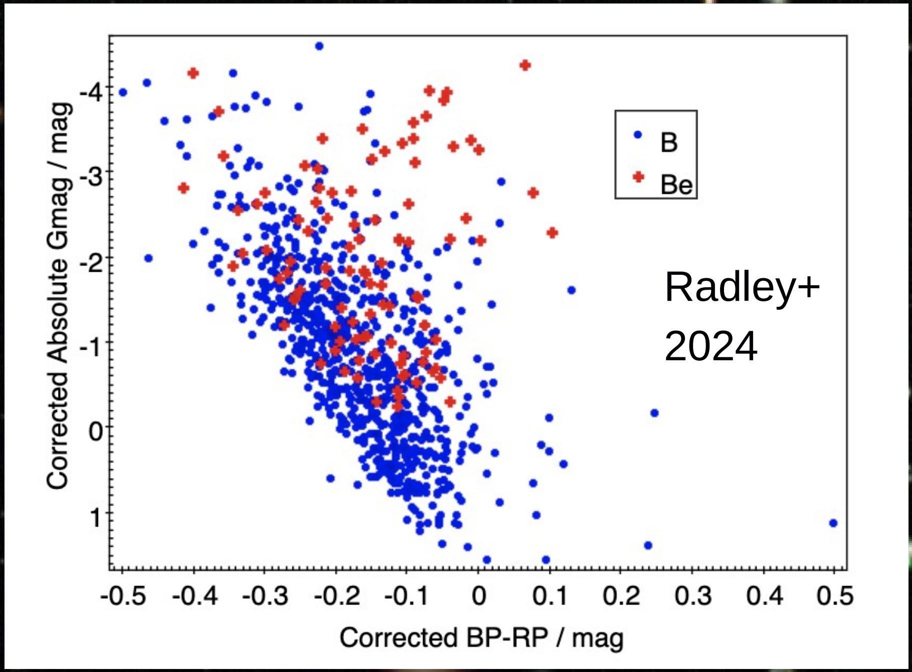
>11000 Binaries taken from Washington Double Star Catalog (Mason+2022)

Dodd+ (2024).

A comparative study into binarity of B & Be stars

The sample

- Drawn from Bright Star Catalog
- Complete to V = 7
- 900 B stars, 120 Be stars
- Typical distance 200 pc



- Almost exactly same observational biases as comparable distances, brightnesses, point sources etc
- Point sources at Gaia resolution

Dodd+ 2024

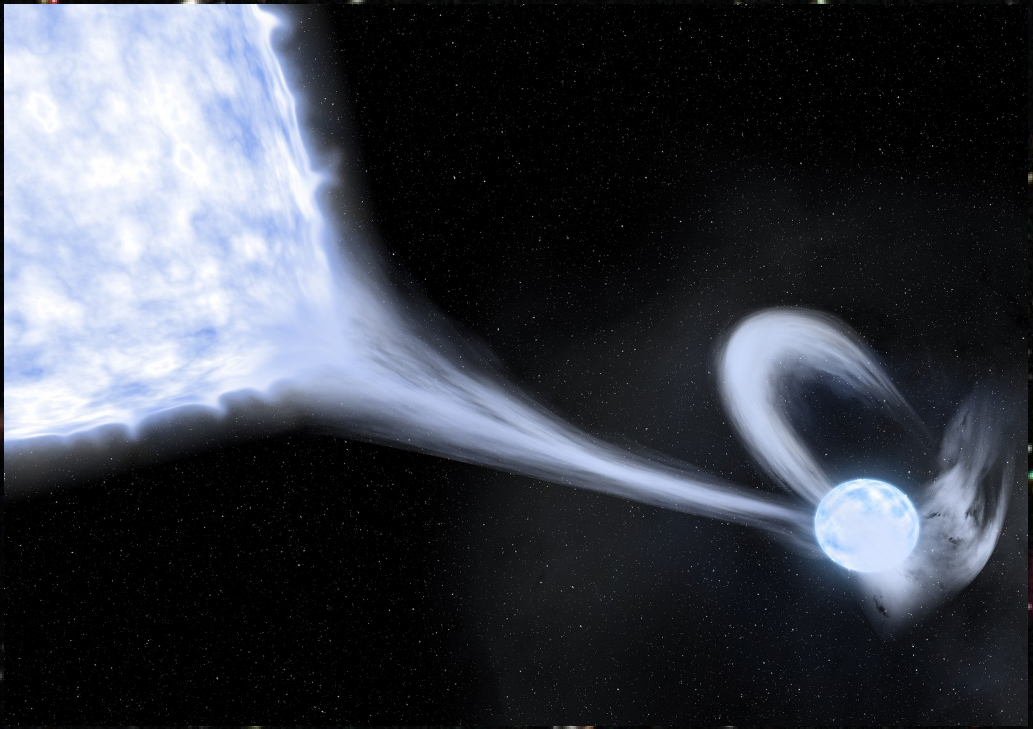
A comparative study into binarity of B & Be stars

Separation Range / $''$	B	Be	Detection Method
$0.02 \leq x \leq 0.2$	$28 \pm 1\%$	$17 \pm 3\%$	Detected by the Hipparcos-DR3 PMa but not the DR2-DR3 PMa.
$0.02 \leq x \leq 0.7$	$42 \pm 2\%$	$28 \pm 4\%$	Detected by the Hipparcos-DR3 PMa.
$0.2 \leq x \leq 1.1$	$27 \pm 1\%$	$29 \pm 4\%$	Detected by the Gaia DR2-DR3 PMa.
$0.04 \leq x \leq 0.7$	$27 \pm 1\%$	$20 \pm 4\%$	Detected by the RUWE.
$0.1 \leq x \leq 8$	$29 \pm 8\%$	$30 \pm 8\%$	Detected by Oudmaijer & Parr (2010)
$0.7 \leq x \leq 10$	$6 \pm 1\%$	$10 \pm 3\%$	Resolved as binary by Gaia.

A dearth of Be binaries at the smallest separations

A dearth of Be binaries at smallest separations

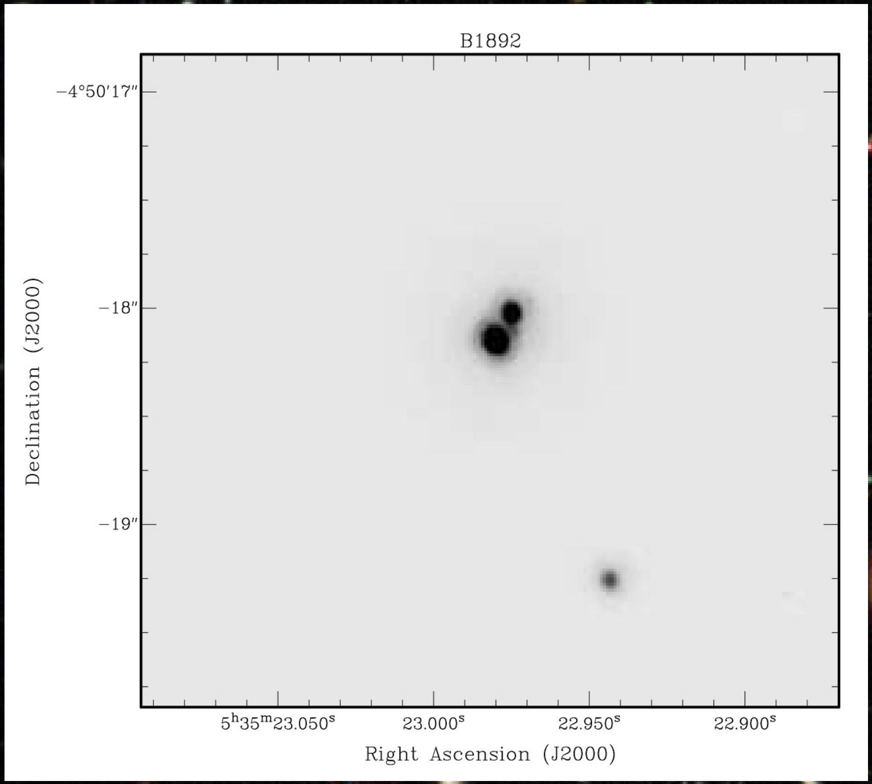
- Either they are single or have undetectable companions
- Stripped companions expected to be too faint to be traced by PMA
- So, problem solved?



Credit: Ylva Gotberg

A dearth of Be binaries at smallest separations

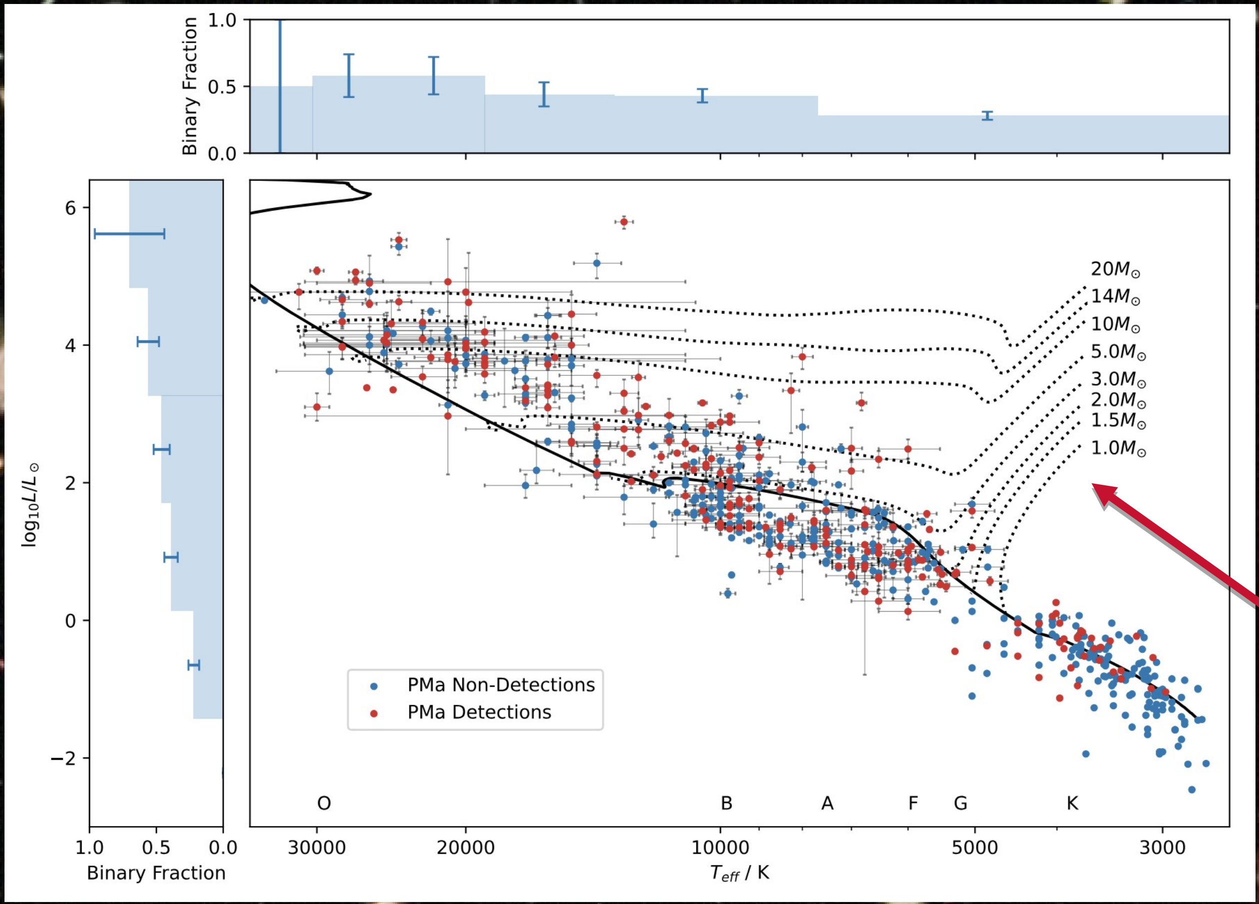
- Typical separations probed are 5 – 20 au
- Too wide for interaction to occur
- Migration?
- Third companion would facilitate migration and enhanced formation Be stars (Toomen+ 2022, Preece+2022, Kummer+ 2024)



- Some known stripped companions in triple system (Naze+ 2022)

Oudmaijer & Parr 2010

Further parts of HR diagram :
Herbig Ae/Be pre-Main Sequence stars



- Proper-Motion Anomaly applied to Herbig stars
- Large binary fractions, no evidence for evolution in these data
- (RUWE not suitable as
- presence disks/etended emission affects PSF solution)

Pre-Main Sequence Tracks!

Preliminary
Dodd+ 2025

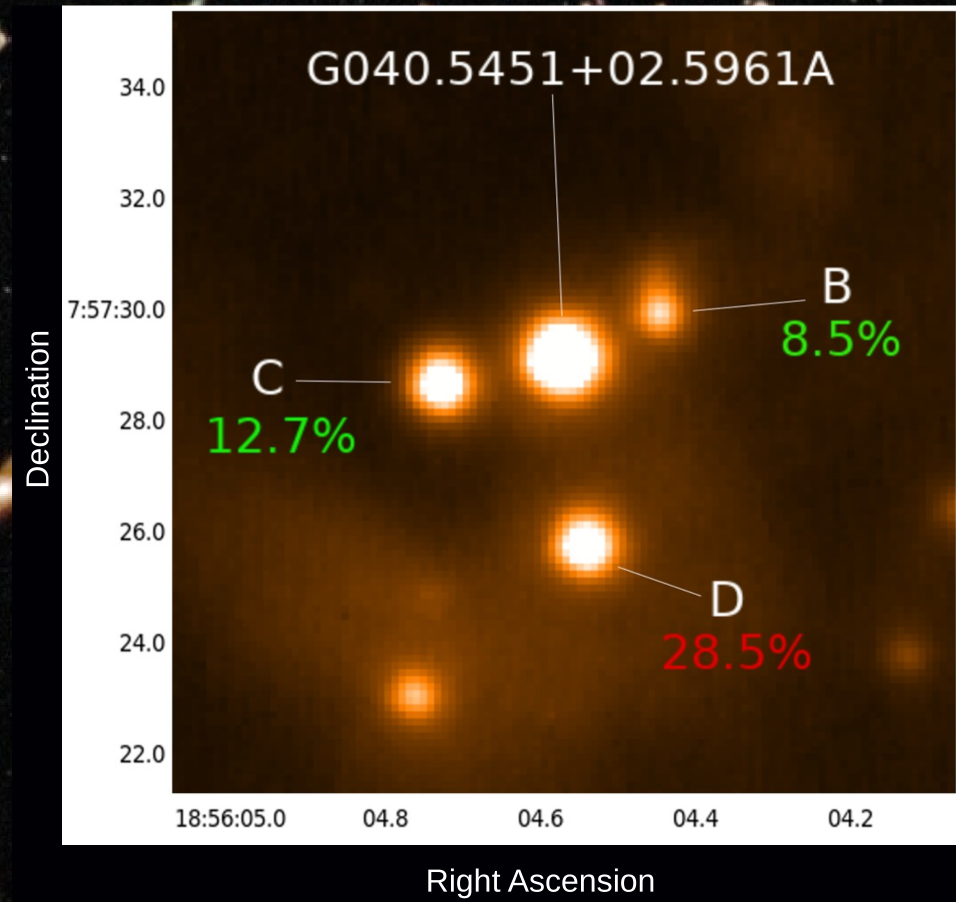
Further parts of HR diagram :
Massive Young Stellar Objects

Used UKIDSS and VVV infrared surveys to study hundreds of MYSOs (and low-mass YSOs)

- Follow-up to Pomohaci + 2019 NaCo MYSO multiplicity study

Statistical method – companion probability depends on separation and stellar background density

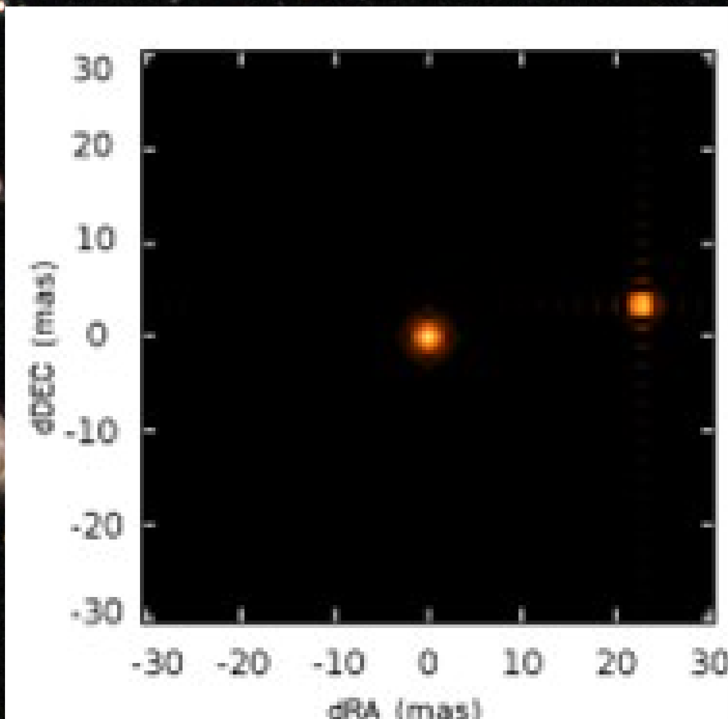
Large MYSO multiplicity fraction



Shenton+ 2024

See talk
By Emma Bordier

Near-infrared Interferometry



Model fit to PIONIER data of PDS 37
Koumpia+ 2019

Probes 2-300 au scales

PIONIER : 2/2 50 au scale binaries – Koumpia+ 2019

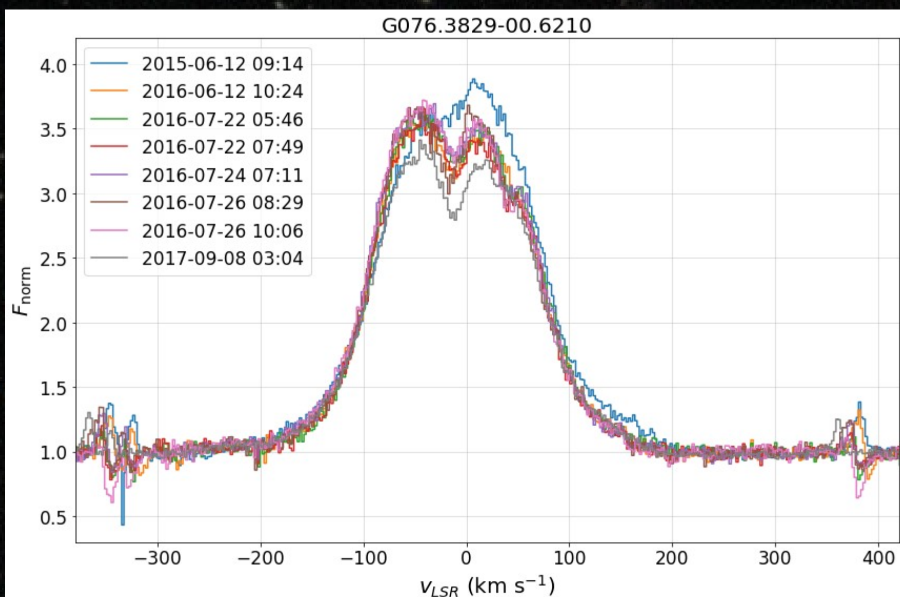
GRAVITY/AMBER mini-survey – 1/6 Koumpa+ 2021

ESO Large Programme VLTI/GRAVITY of 24 objects (led by Koutoulaki, Oudmaijer)

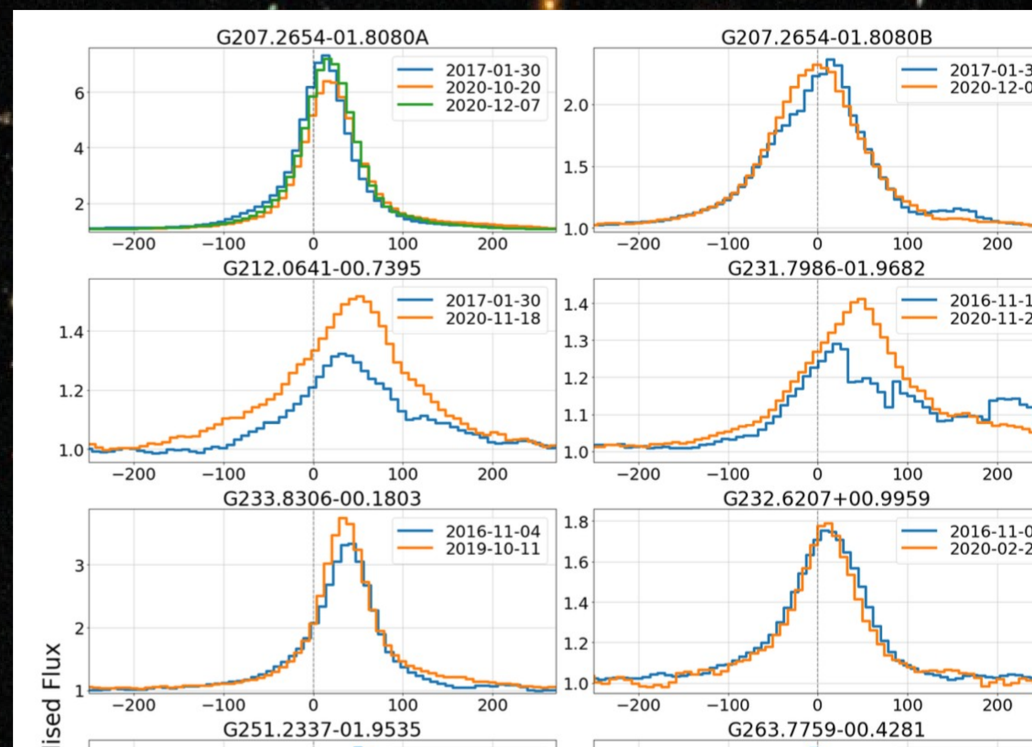
Currently data being taken

Radial velocity variations

- 2 MYSOs observed with high-resolution K-band IGRINS spectroscopy
  - 6-8 epochs each
- 40 objects observed with
  - X-shooter, project completed this week
  - 2 epochs each



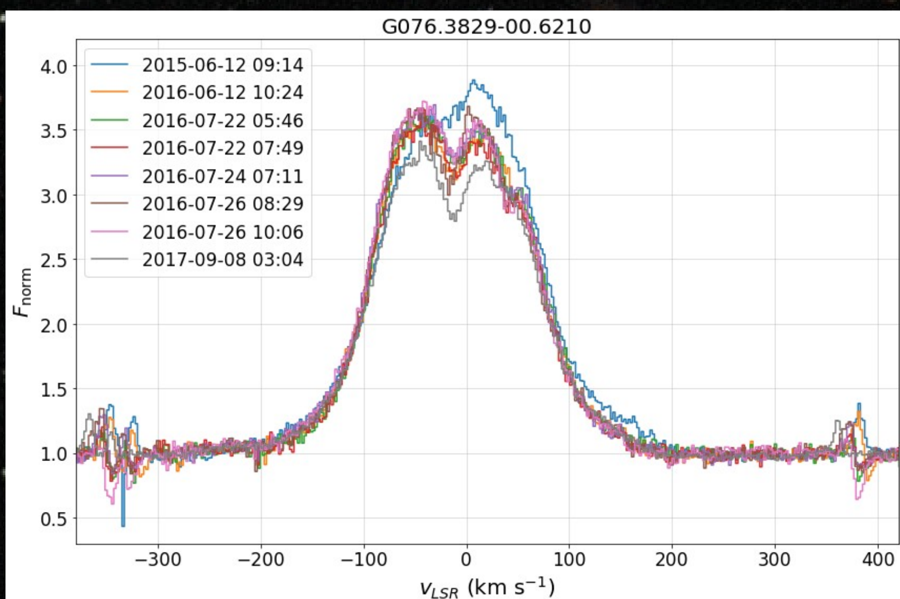
Brγ (2.166 µm) – bright tracer of MYSOs

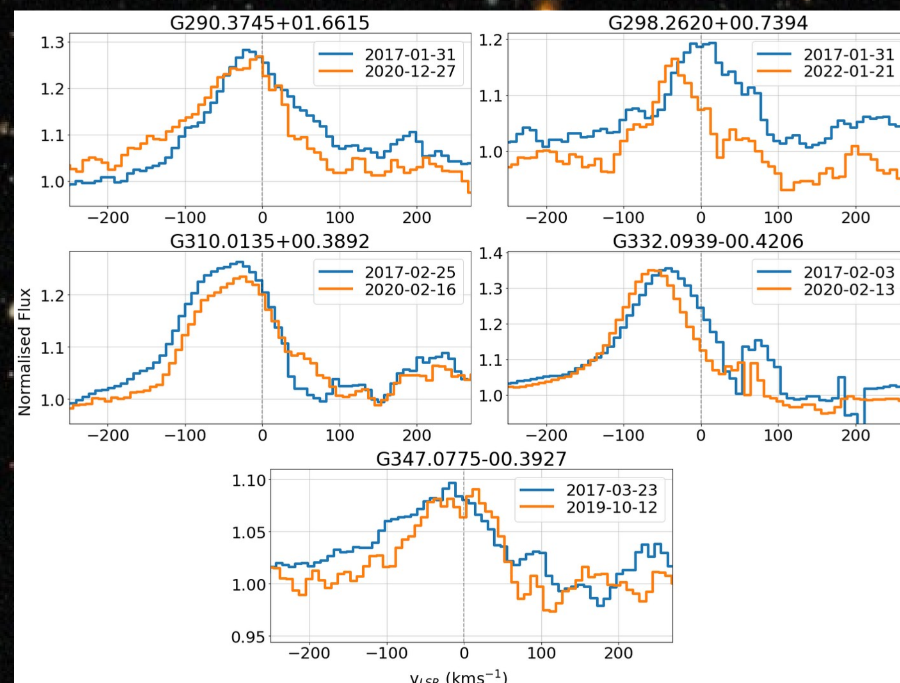


Radial velocity variations

Multiple fraction low, 20%. When taking into typical RV cuts (20-50 km/s), close to zero%

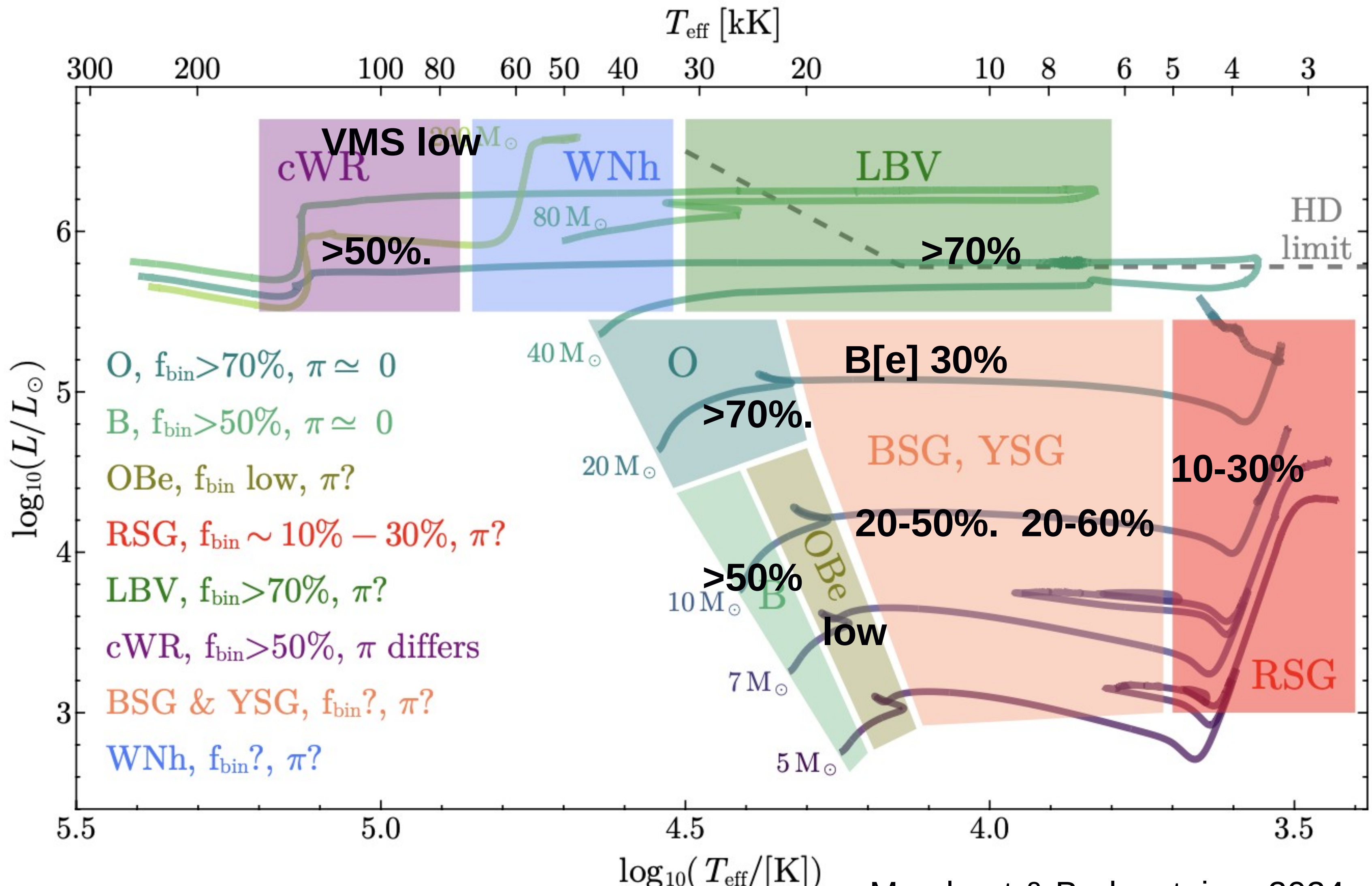
Hardening of binaries after formation on the way to Main Sequence? (cf. Ramirez-Tannus+ 2021, Bordier+ 2022)





Brγ (2.166 µm) – bright tracer of MYSOs

Final slides I/III Round-up



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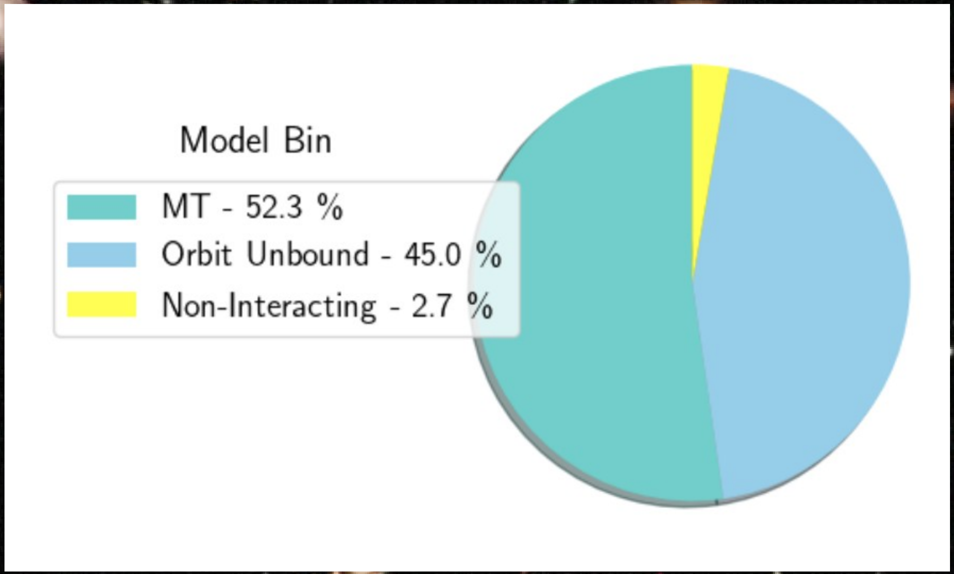
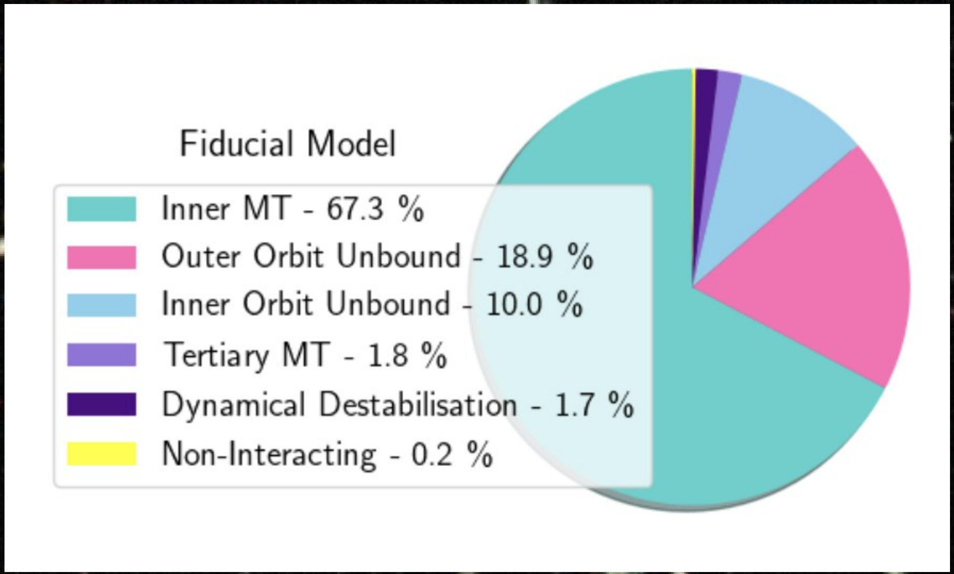
Final slides II/III– triples are the new binaries

- More and more observed and inferred
- Speed up interactions of inner binary

Kummer+ 2024





Final slides III/III Conclusions

- Binarity of massive stars: large!

  * Varies across HR diagram → evolution

  * Probability of interacting with companions: large!

- Important for understanding stellar evolution & end products
- Origin close binaries due to migration, not in situ formation
- Next step : Understanding triple systems
- Future is bright: detailed studies of small samples and statistical studies of larger samples

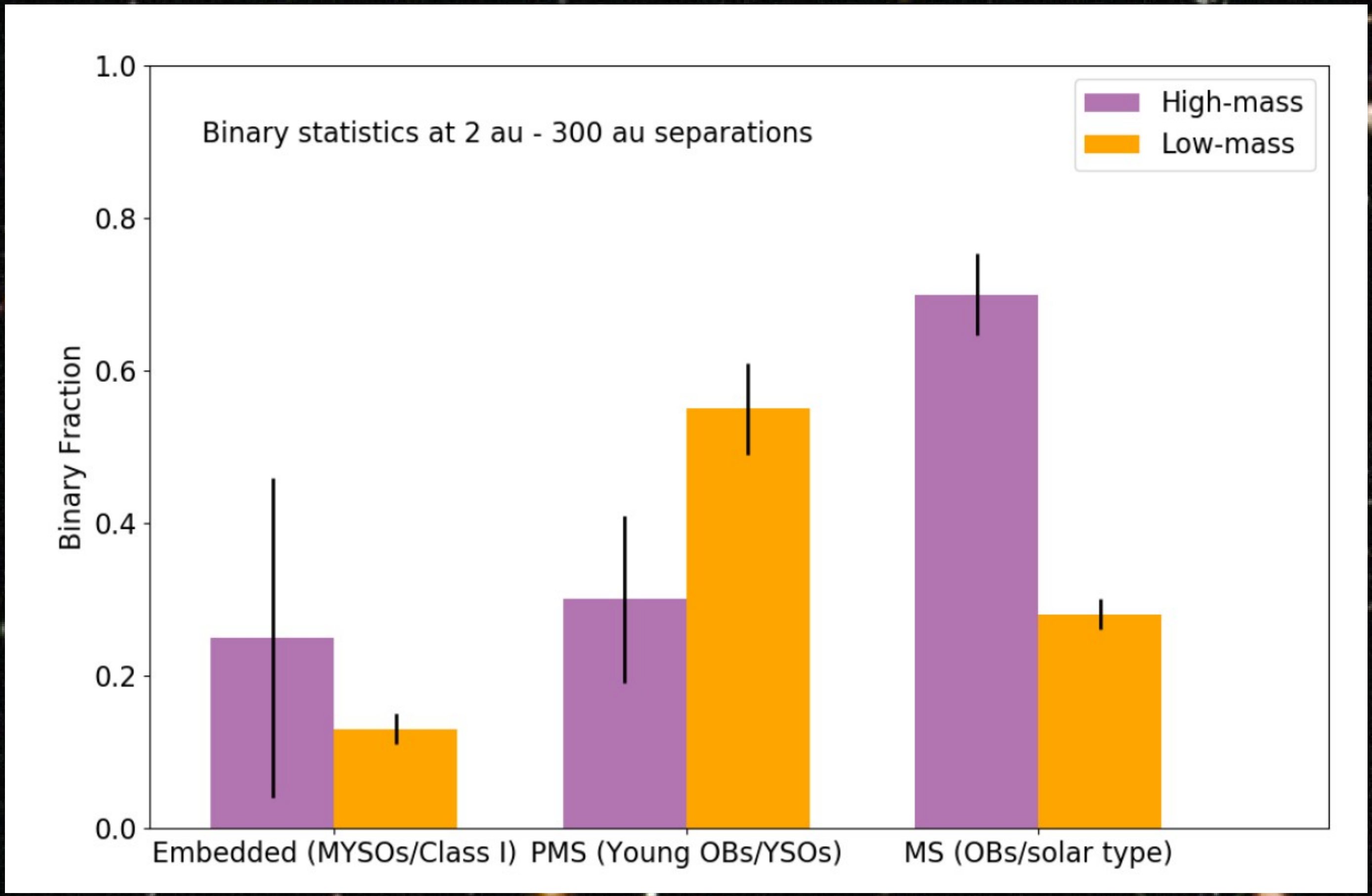
  * Gaia DR4, ELTs, SKA, Next generation interferometers,

  All-sky surveys, Long term monitoring

Summary: Triples are the new binaries

- Carried out largest comparative study into binarity of B and Be stars
- Binarity similar > 0.04”, but dearth of Be binaries in 0.02-0.04” range
- Consistent with stripped companions
- However, these need to have migrated inwards for interaction to occur
- Third companion enhances migration process and potentially plays integral part in Be formation
- Gaia PMA proves excellent tool for statistical studies into binarity.

Binarity



- Hints that binarity over the probed separation range increases as function of time (cf disk fragmentation + migration Meyer+ 2019)