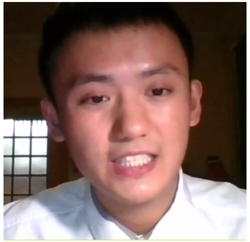
GAIA binaries with CHARA & VLTI

Stefan Kraus, Tyler Gardner, Yi Lu



Sorabh Chhabra, Dan Mortimer, Isabelle Codron, Owain Snaith (Exeter),
Narsi Anugu (CHARA), John Monnier (Michigan), Michael Ireland, Luca Casagrande (ANU),
MIRCX/MYSTIC team, CHARA team

2023 May 31
SPICA workshop

University of Exeter

The GAIA opportunity: Astrometric binaries/planets

GAIA DR3 provides census of stellar multiplicity in solar neighborhood (Robin+ 2012, Eyer+ 2013):

>0.1″: resolved, only 157 binaries w/direct meas. M_1 and M_2

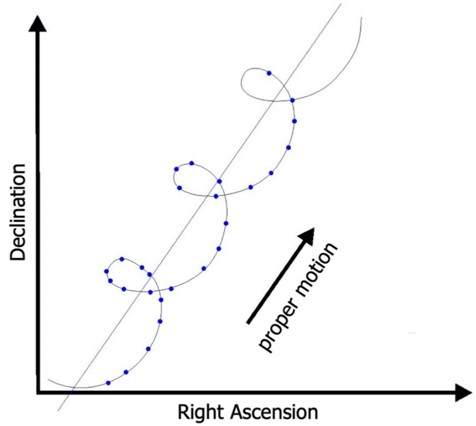
<0.1″: photocenter (~10 μas accuracy)

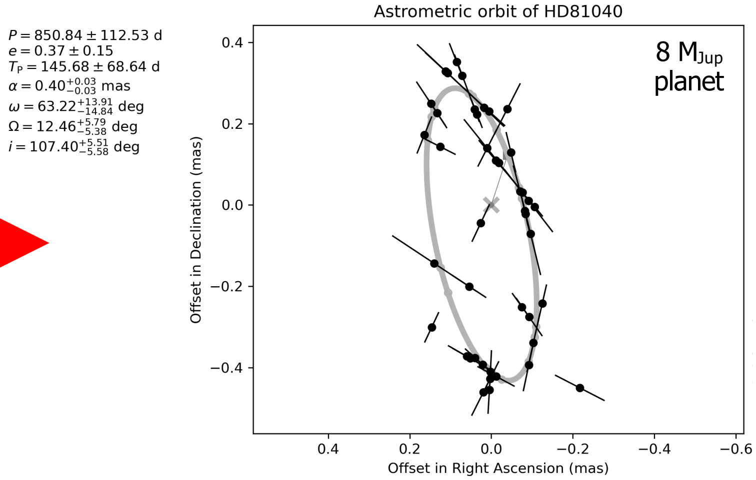
Unresolved binaries:

~28,000,000 non-single stars, RVs + photocenter orbits

Giant planets:

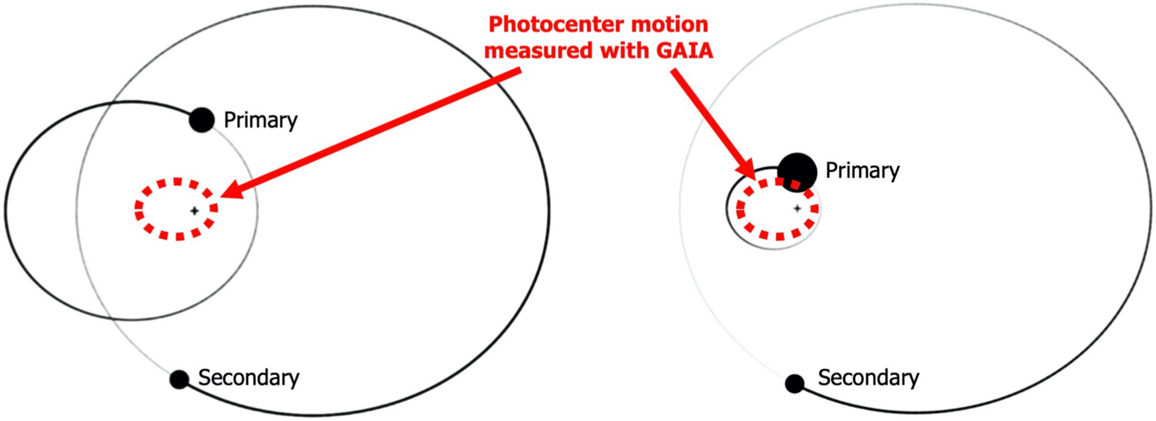
~100,000 astrometric orbits





GAIA binaries: Flux-ratio/separation degeneracy

GAIA's photocenter 'orbits' face stellar flux ratio / separation degeneracy
➜ No dynamical masses for non-eclipsing systems



low-flux-ratio / wide separation

high-flux-ratio / small separation

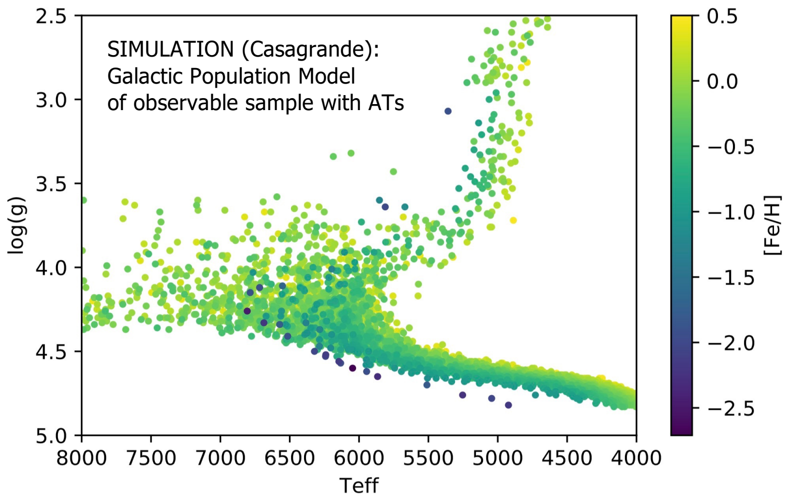
GAIA-BIFROST survey @ CHARA+VLTI

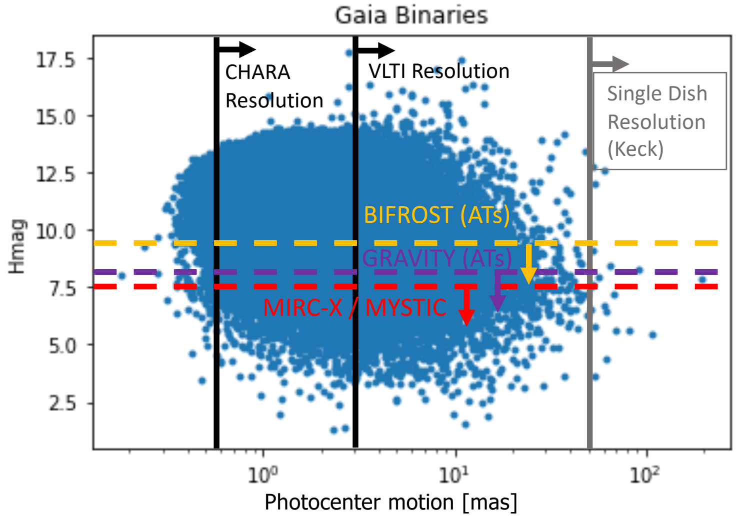
Flux-ratio measurement at **single epoch** yields:

- **Fully characterized 3-D orbits**
- **Dynamical masses**
- **Precision ages (for evolved objects)**

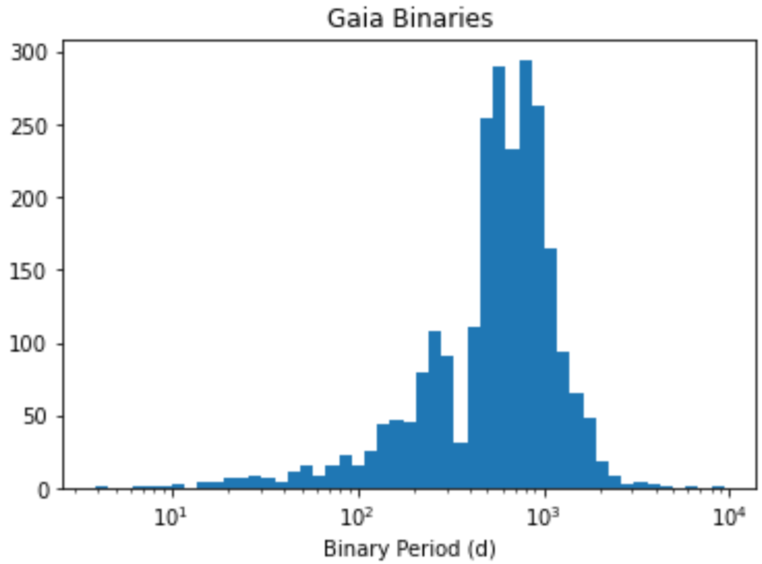
GAIA-BIFROST survey ("GAIA-BInaries: Formation & fund. paRameters of Stars + planeTs"), funded by ERC Consolidator grant

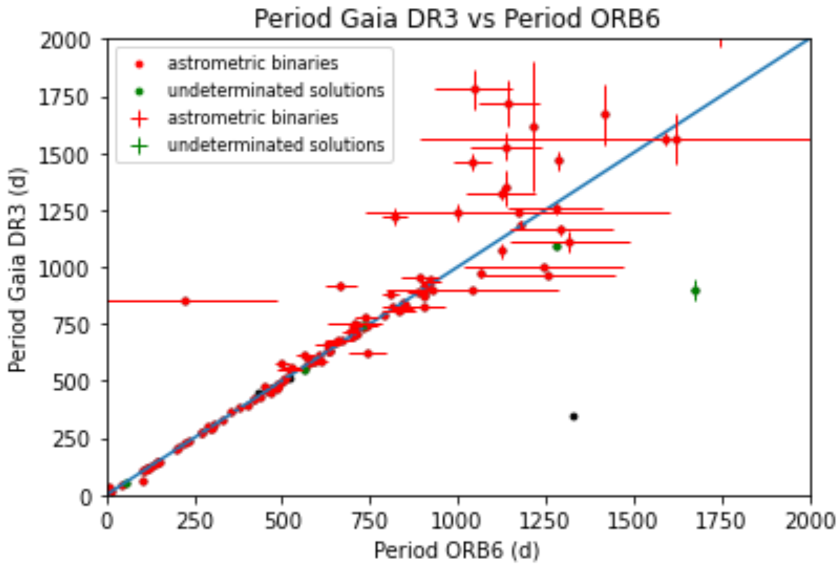
Accessible with MIRCX + BIFROST: **~6000 binaries** (d<1 kpc)





Analysis of DR3 sample





Yi Lu+ in prep

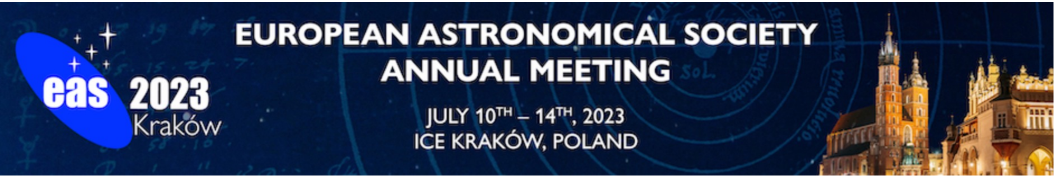
Target selection

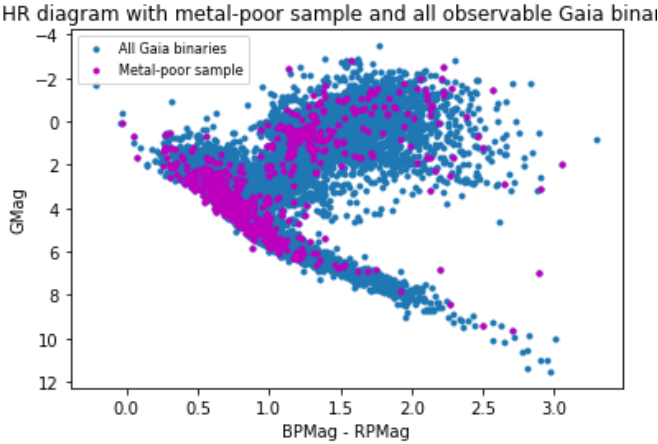
Select **rare stellar populations** most valuable for improving evolutionary models, e.g.:

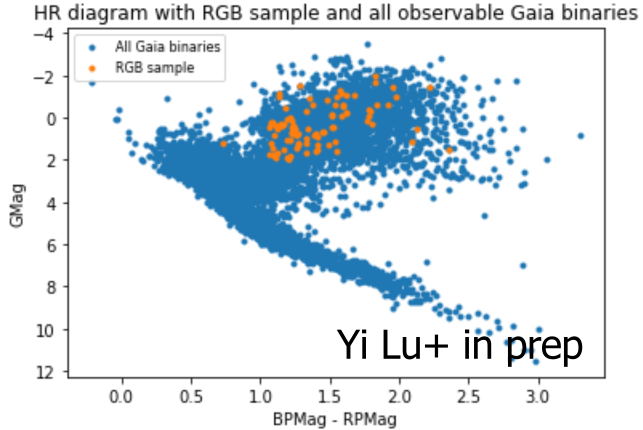
- Massive stars: overshooting, mass loss
- Low-mass stars
- Pre-main-sequence stars
- Very-low metallicity stars
- Cepheids
- Evolved stars
- …

Dedicated lunch session at EAS 2023, Krakow, Poland to discuss target selection/prioritization & synergies:

LS8, Monday July 10, 12:30-14:15







Yi Lu+ in prep

Galactic Archaeology

Red Giant Branch stars good age indicator
(especially for [M/H]<-0.5, where ages largely metallicity insensitive).

Problem: strong age/mass degeneracy

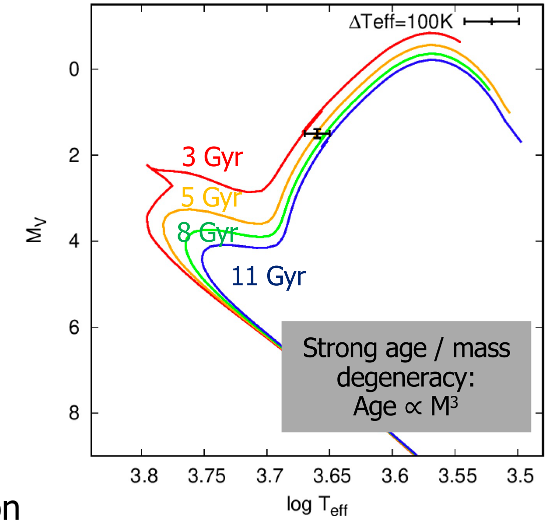
Interferometry dynamical mass + isochrones:
mass uncertainty 3% ➜ **age uncertainty 10%**

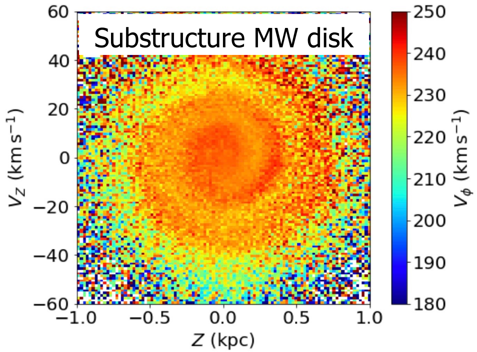
Astroseismology (best competing method):
mass/radius uncertainty 9% ➜ **age uncertainty 45%**

Use dynamical masses to calibrate asteroseismology scaling relation
(essential for TESS & PLATO!)

Ages crucial to **uncover the history of Milky Way**, e.g.:

- Separate diff. age populations ➜ MW substructures, minor mergers
- Episodic star formation ➜ quick change in abundance, followed by plateau





Soderblom+ 2010
Antoja+ 2018

Star Formation through the Cosmic Ages

Star Formation at low metallicity might proceed differently:

➜ Lower dust opacities

➜ Greater cooling rates at high gas densities

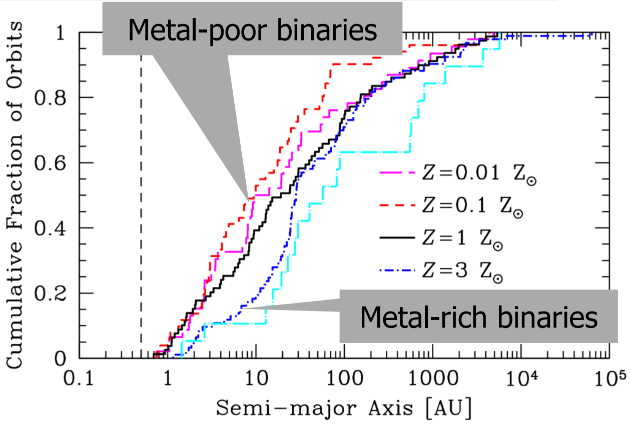
➜ Increased fragmentation in disks/cores

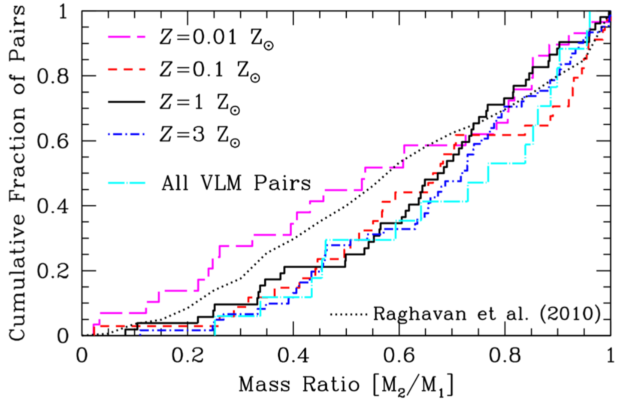
Prediction for binary properties:

Metal-poor binaries preferentially
tighter & with more unequal mass ratio
(Machida+ 2009, Bate 2019)

GAIA-BIFROST:

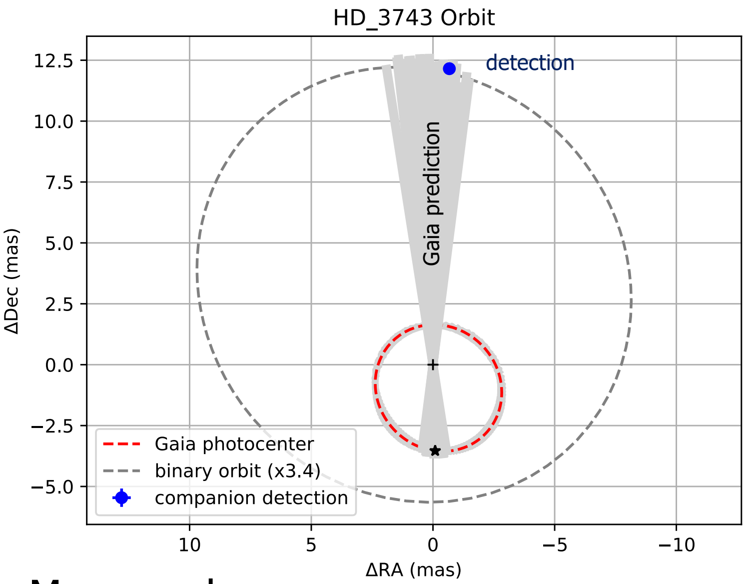
- compare separation & mass ratio distribution for metal-poor and metal-rich subsample
- use dynamical masses to improve evolutionary models for metal-poor stars





Bate 2019

Preliminary results



- Orbital elements from Gaia
- Scale between Gaia orbit and our data point gives semi major axis → **dynamical mass** of system
- Flux ratio and photocenter orbit → **individual masses**

$$(M_1+M_2)^{1/3} P^{2/3} [M_2 / (M_1+M_2) - f/(1+f)] = a_{photo} / plx$$

For all binaries:

$M_1 + M_2 = a_{semi}^3 / P^2$

With SB1:

$K_1 = 2pi\, a_1 \sin(i) / [P (1-e^2)^{1/2}]$

$a_{semi} = a_1 + a_2$

$a_1 / a_2 = M_2 / M_1$

With SB2:

$K_1 / K_2 = M_2 / M_1$

Measured masses:

$M_1 = 2.19 \pm 0.44\ M_{sun}$ *($2.23 \pm 0.2\ M_{sun}$ from isochrone fit)*

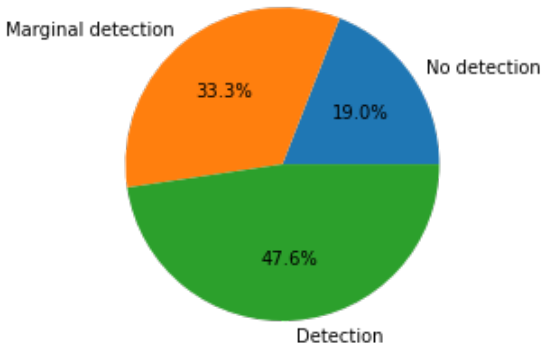
$M_2 = 1.43 \pm 0.22\ M_{sun}$ *(0.9 – 2.1 estimated from M1 + orbit)*

Gardner+ in prep

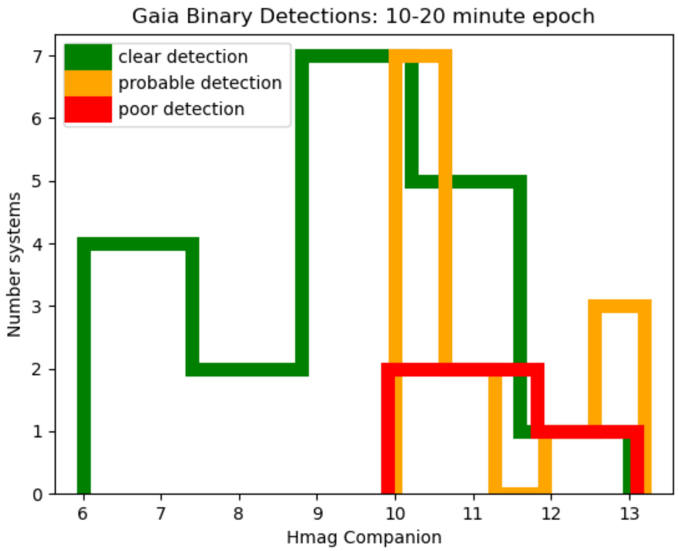
Preliminary results

Sample observed in CHARA pilot study so far

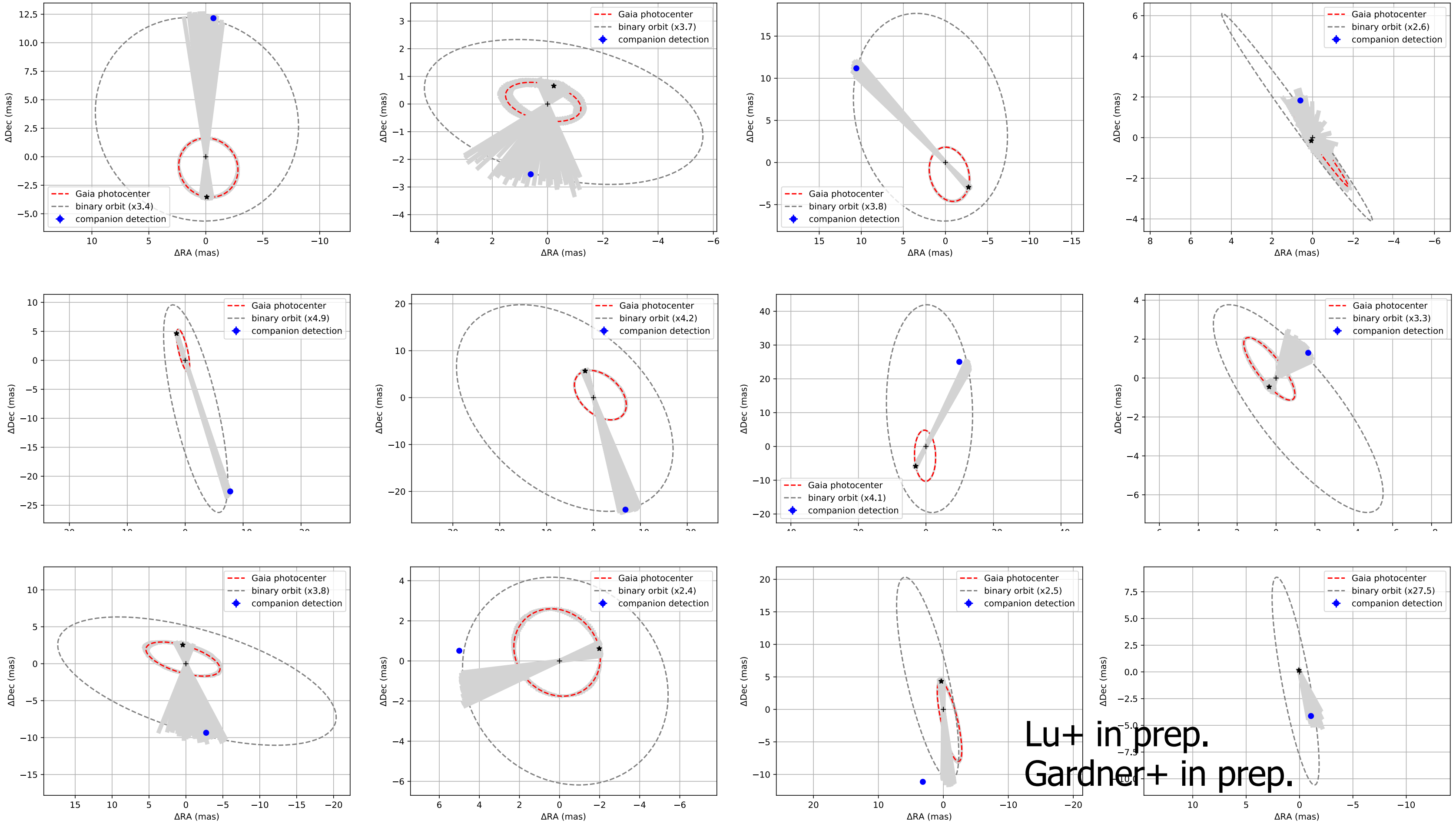
	2022	2023
Intermediate-mass stars	28	10
Giant Branch stars	15	10



2022 data



Yi Lu+ in prep

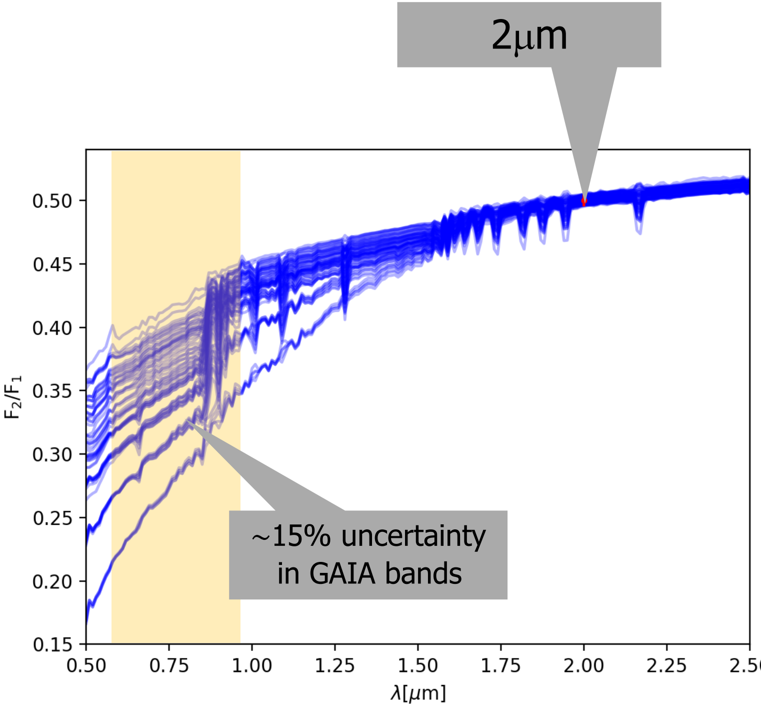


Lu+ in prep.
Gardner+ in prep.

Measuring flux ratio close to GAIA bands

With DR3: achievable dynamical mass precision limited by GAIA orbital elements

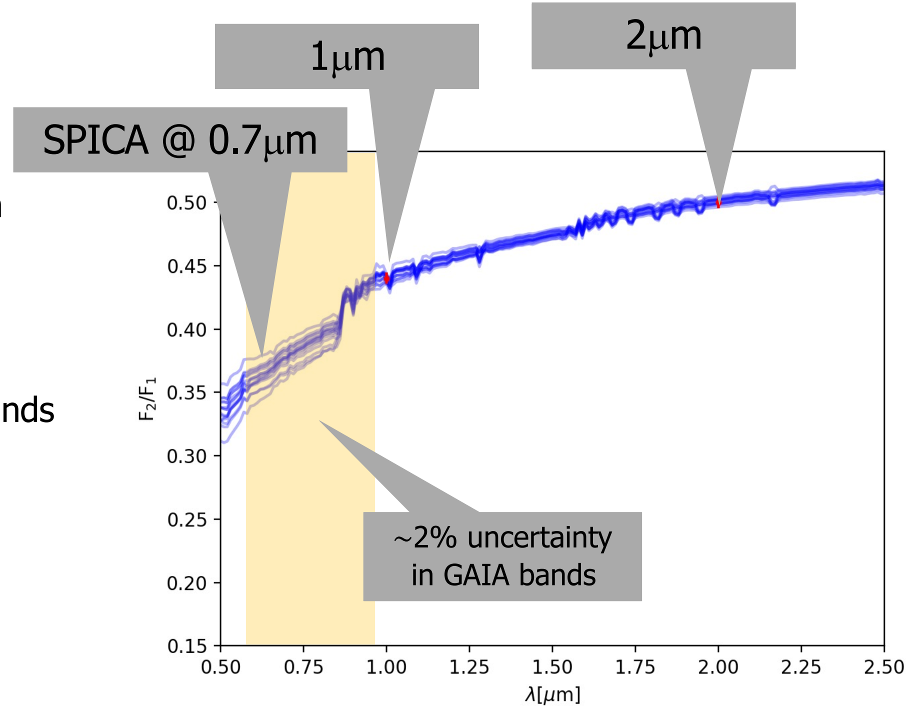
Future: Wavelength-dependence of flux ratio could become a limiting factor



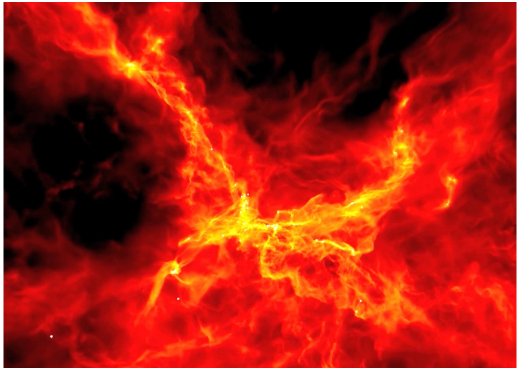
Measuring flux ratio close to GAIA bands

With DR3: achievable dynamical mass precision limited by GAIA orbital elements

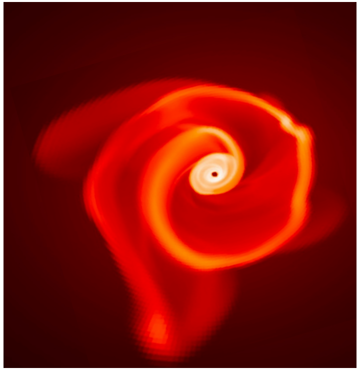
Future: Wavelength-dependence of flux ratio could become a limiting factor
➜ measure in multiple bands & close to GAIA bands



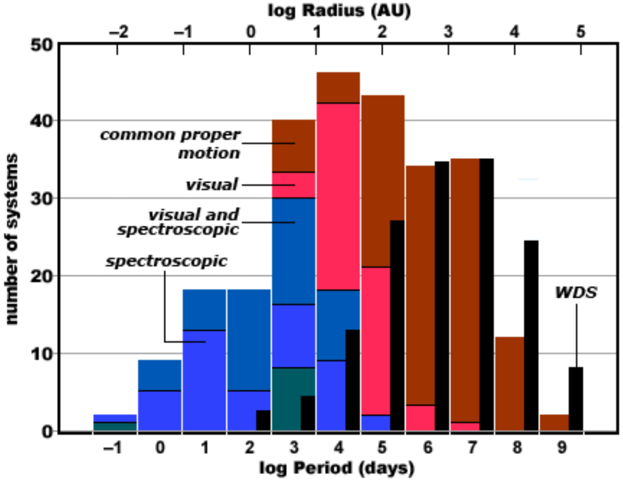
BINARY FORMATION



CLOUD fragmentation
1000…10,000 AU

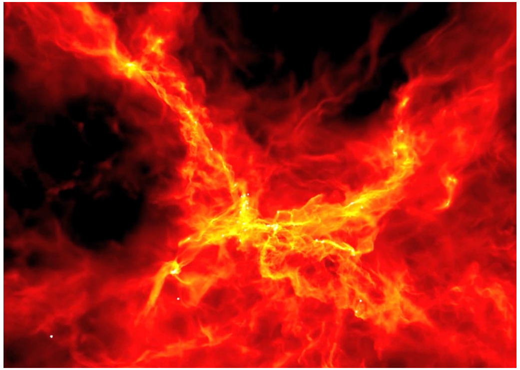


DISK fragmentation
30…300 AU



Raghavan+ 2010

BINARY FORMATION



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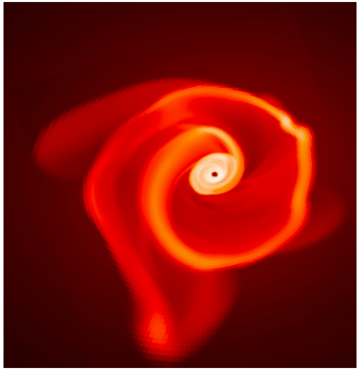

DISK fragmentation
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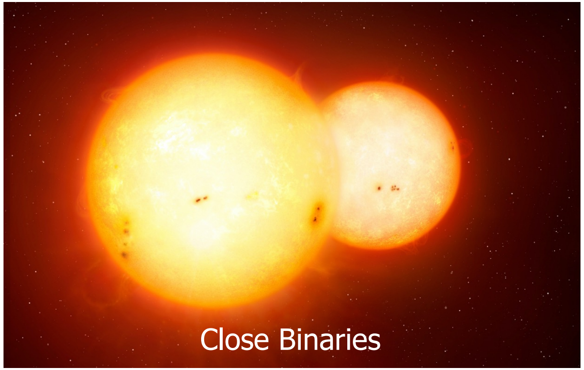
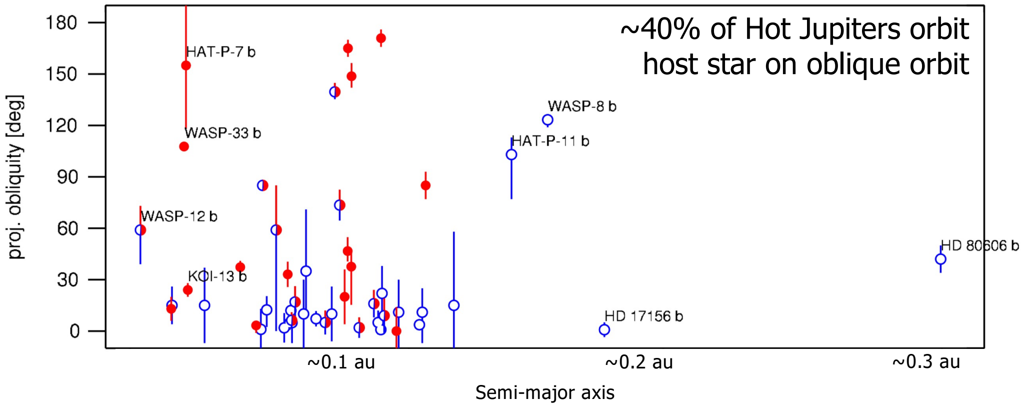
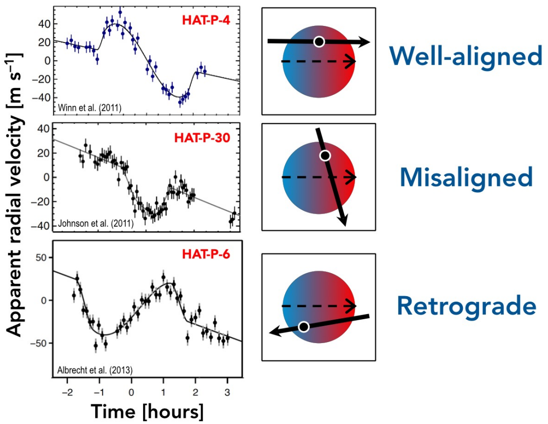
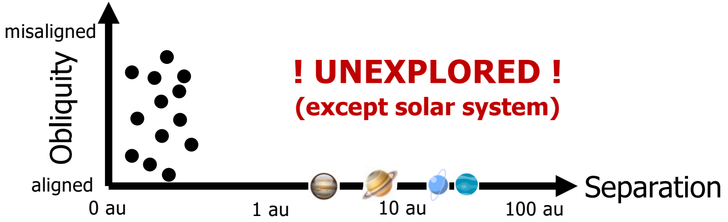


???

Spin-orbit alignment: Rossiter-McLaughlin effect





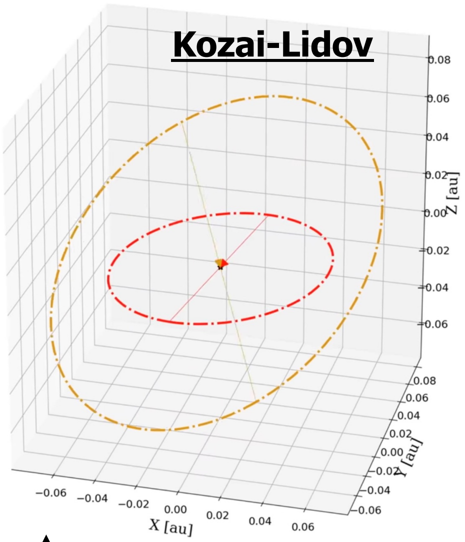


Rossiter-McLaughlin effect allows measuring spin-orbit alignment ("obliquity") for **transiting systems**

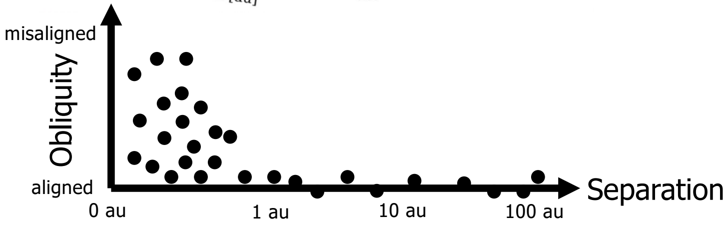
Albrecht+ 2012; Romanova+ 2013

Planet Formation

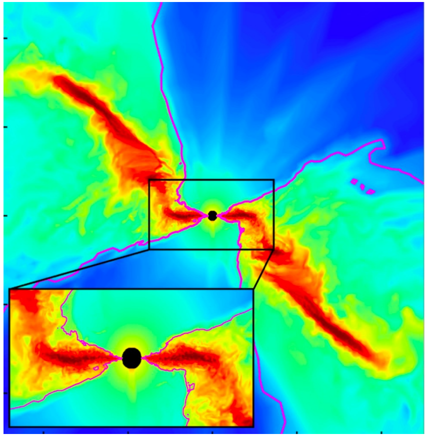
Kozai-Lidov



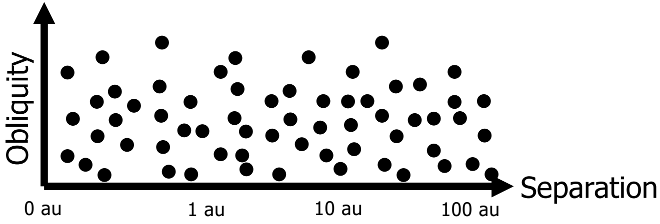
Migration accompanied by orbital tightening



Primordial misalignment



Disk warping,
Star-disk capture,
'titled' accretion
…

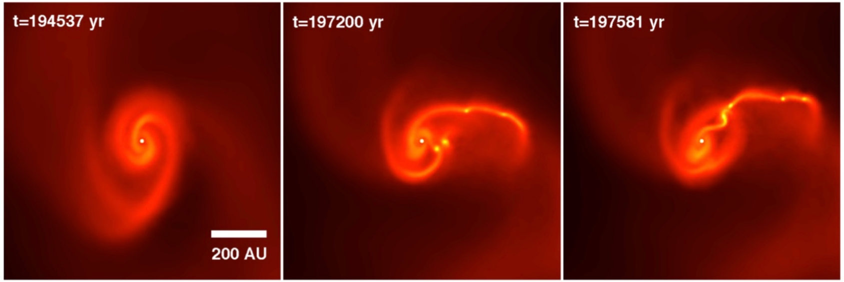


Measuring spin-orbit alignment for wide-separation systems decisive test on formation + dynamical evolution

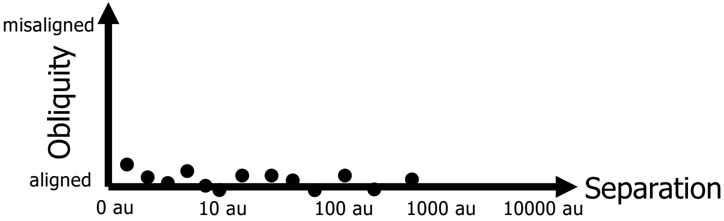
Liska+ 2019; Livingston

Binary Formation

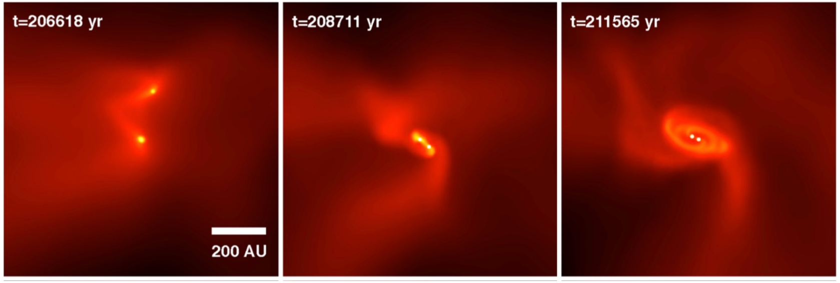
DISK fragmentation



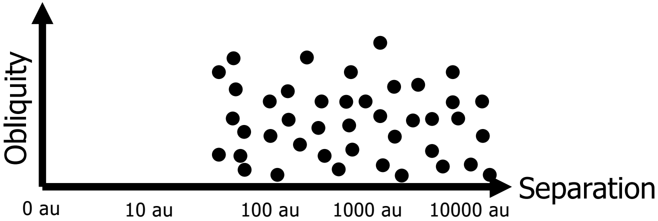
Companions form in coplanar circumstellar disk through fragmentation



CLOUD fragmentation



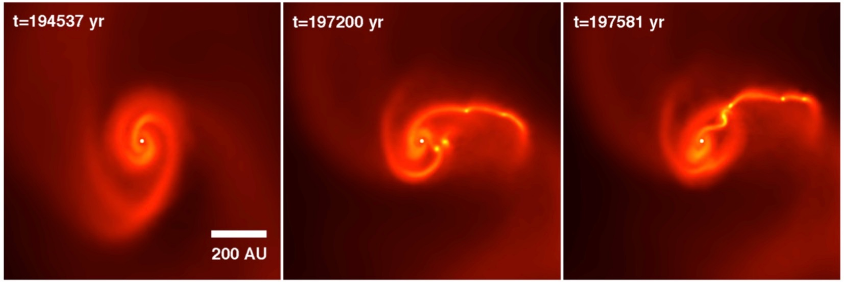
Protostars form separately and undergo star-disk encounter to form tight binary



Bate 2018

Binary Formation

DISK fragmentation



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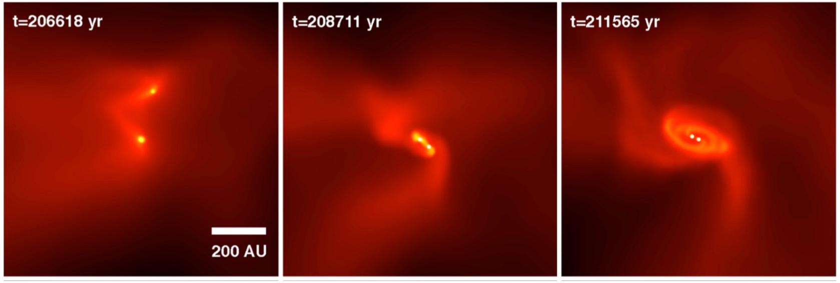
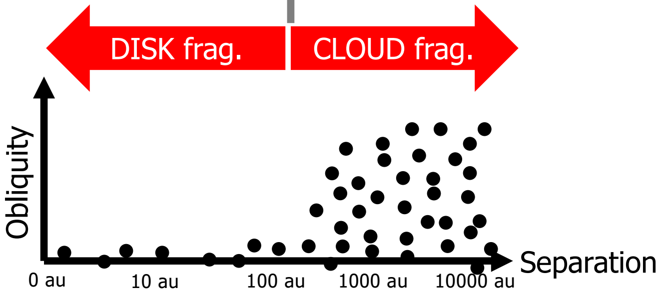
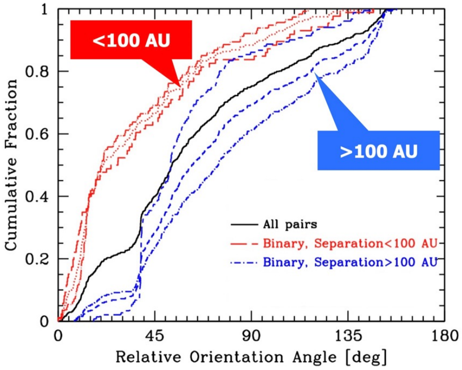


Disentangle contributing processes:

- Compare obliquity distrib. for systems with and without wide companion
- Spin-spin alignment
- ...





Spin-spin alignment from Bate 2018 cloud-collapse SPH simulation

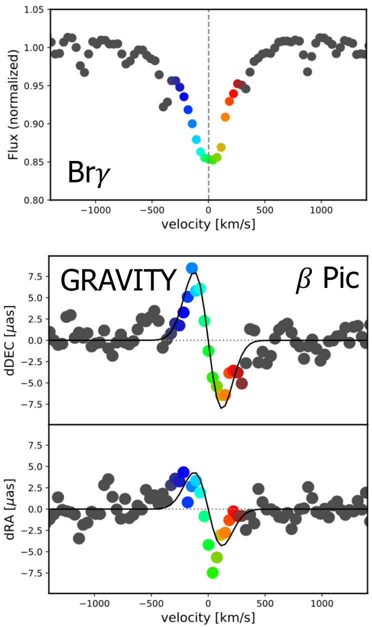
Measuring spin-orbit alignments with interferometry

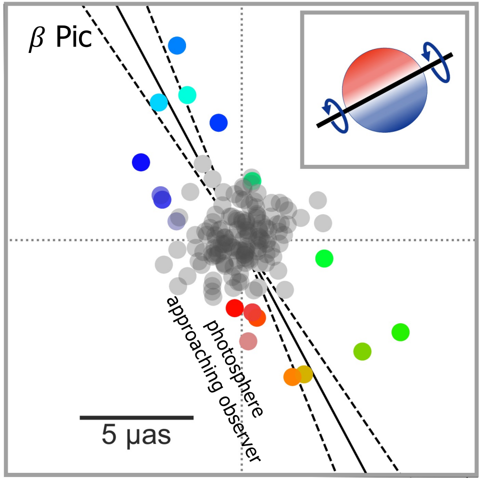
Photocenter displacement in photospheric absorption line constrains sky-projected orientation of stellar spin-axis

+ Inclination from v sin(i) + astroseismology

➜ 3D orientation of stellar spin axis

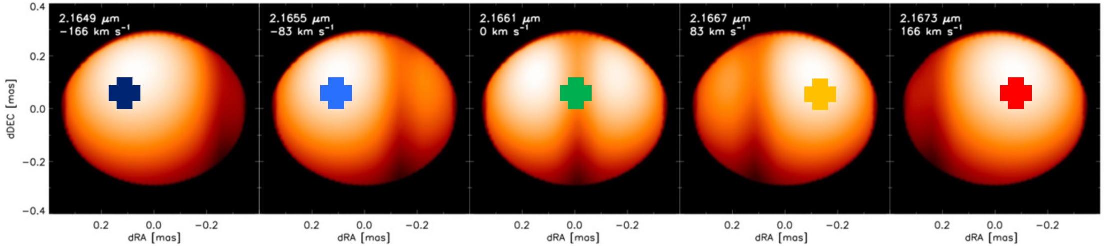
High spectral interferometry with SPICA or BIFROST needed to measure spin-orbit alignment for smaller stars & slow rotators





β Pic: 3-D obliquity angle 3±5°

➜ Spin / planet orbit / debris disk well aligned

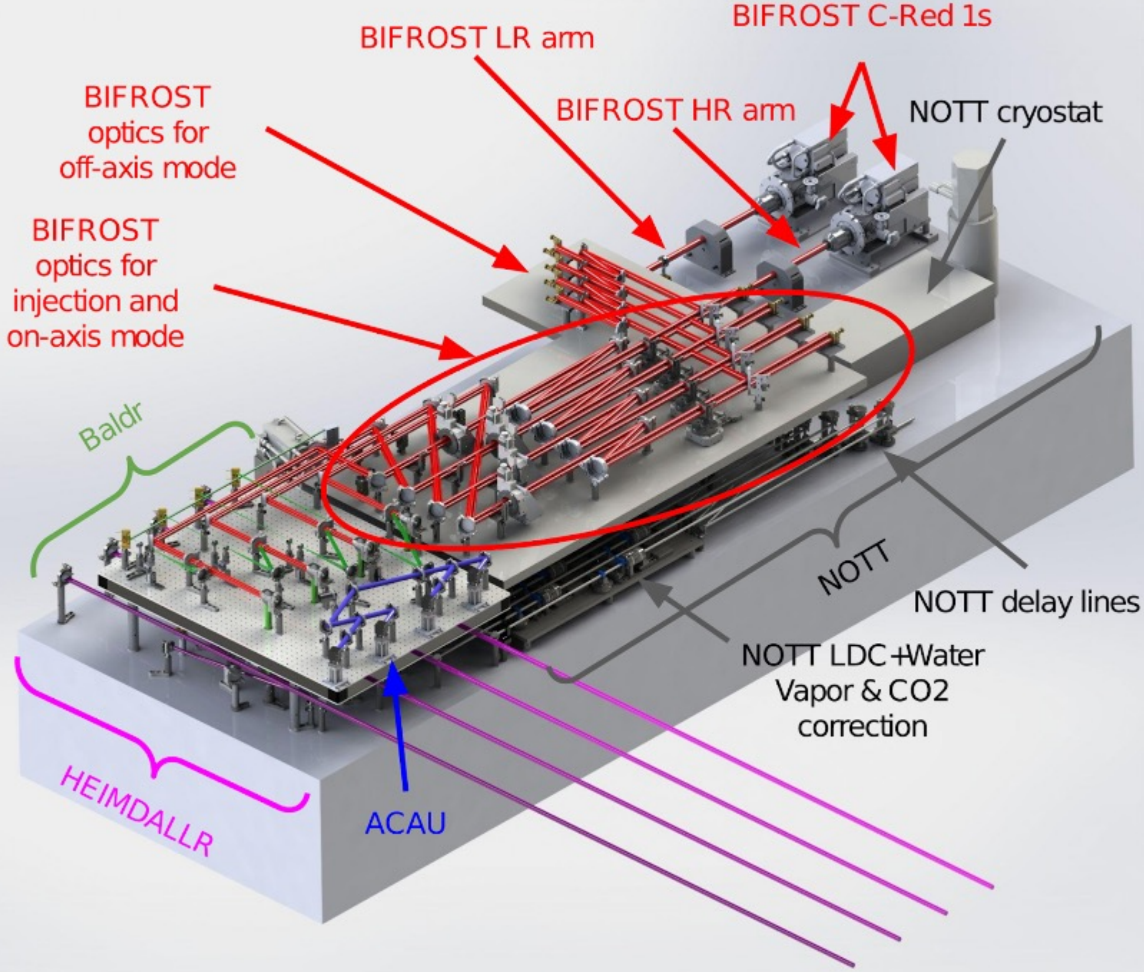


Kraus+ 2012, 2020b

Southern Hemisphere Survey with Asgard/BIFROST

VLTI visitor instrument optimised for:

- short wavelengths (1-1.8 μm)
- high spectral resolution

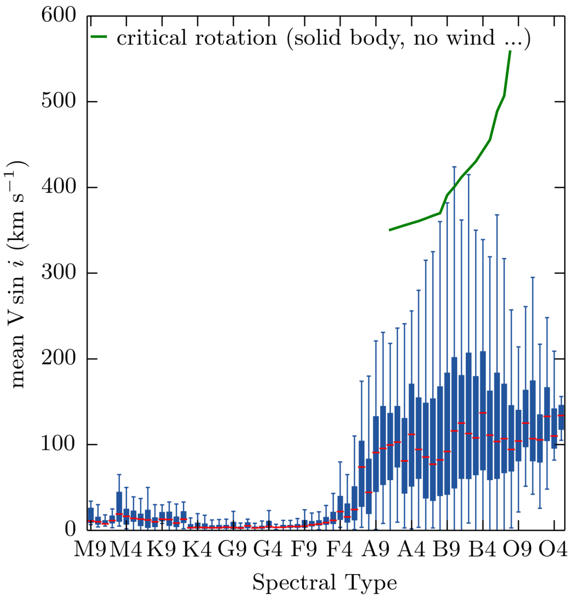


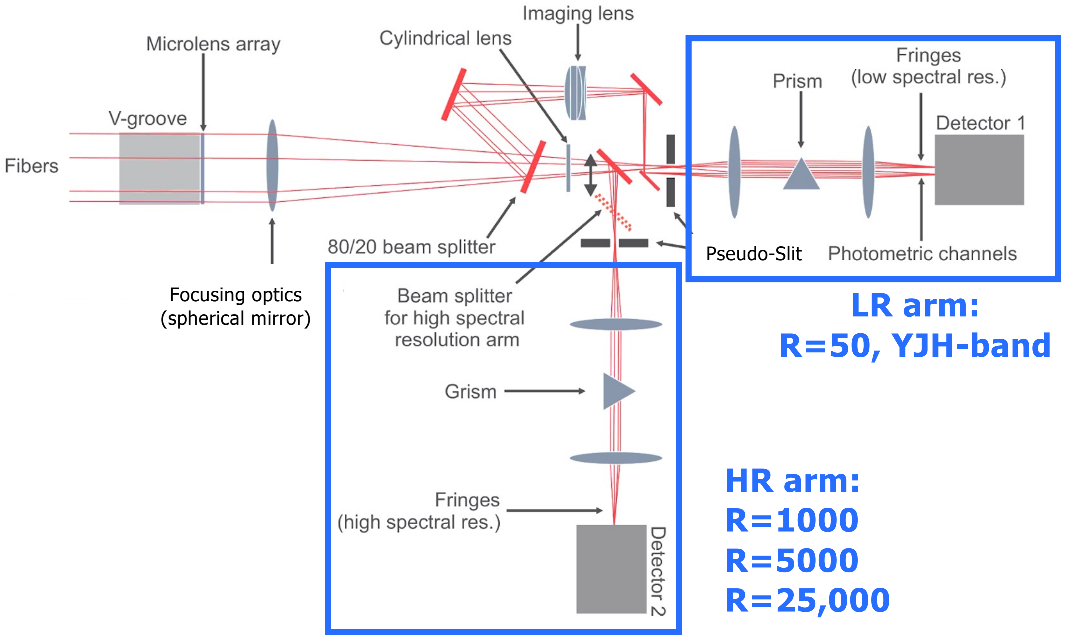
ASGARD

BIFROST

BIFROST: VLTI visitor instrument

- Part of 'Asgard Suite': NOTT L-band nuller + Heimdallr fringe tracker
- formal ESO approval process started in March 2022





Summary & Synergies with SPICA

GAIA-BIFROST survey @ CHARA+VLTI to provide…

- **Dynamical masses**
  - Survey started with MIRC-X (H) + MYSTIC (K)
  - Adding shorter wavelengths will increase precision: MIRC-X (J) + SPICA (R)
- **Spin-orbit alignment**
  - R=6000 VPHG to be manufactured for MIRC-X (J band)
  - R=10,000 with SPICA (R band) could add slower rotators

- We should coordinate SPICA and GAIA-BIFROST efforts!
- Asgard/BIFROST instrument proposed to ESO (survey could start 2026)

BIFROST

- Join us for lunch session at **EAS meeting in Krakow** to discuss target selection & synergies:
  LS8: Monday, July 10th, 12:30 … 14:15