GAIA-BIFROST survey:

GAIA BInaries: Formation & fundamental pRoperties Of Stars and planeTary systems

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UNIVERSITY OF EXETER

EAS meeting
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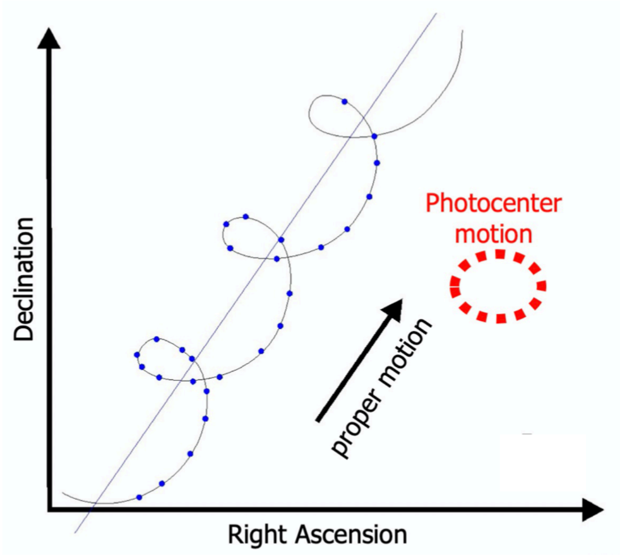
erc

The *real* revolution: GAIA binaries

GAIA will provide a census of stellar multiplicity in solar neighborhood:

>0.1″: resolved

<0.1″: photocenter (5-16 µas accuracy)

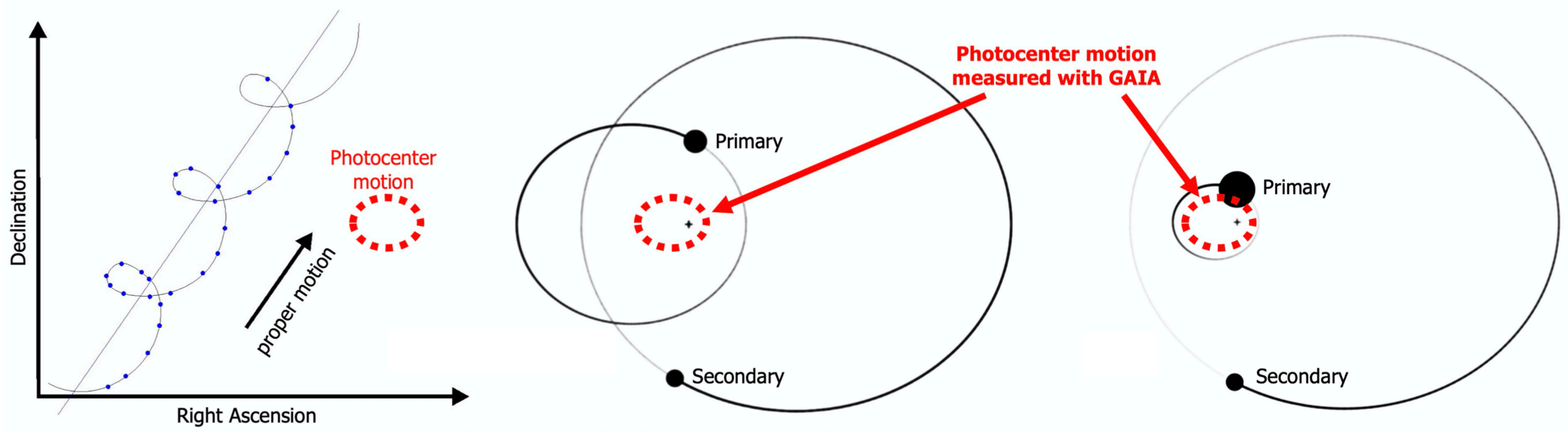


Data Release 3:

Radial Velocity SB2 orbit + photocenter motion for ∽**28 million non-single stars** (Robin+ 2012; Eyer+ 2013)

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

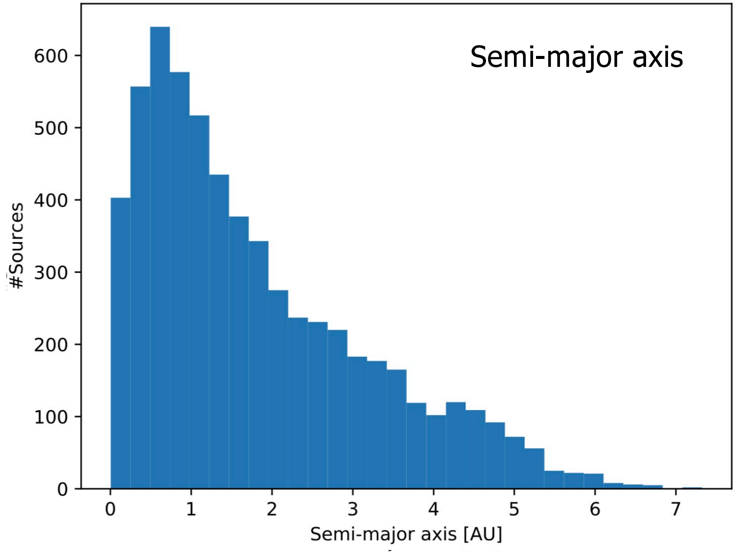
GAIA binaries: Dynamical masses

For GAIA short-period ≲ 10 yrs binaries, flux-ratio measurement at **single epoch (20 min pointing) yields:**

- Fully characterized 3-D orbits
- Dynamical masses for all components
- Precision ages (for evolved objects, with complementary spectroscopy)

GAIA-BIFROST survey:
Sample size: ~6000 stars (with 1.8m VLTI telescopes)

Separations of few AUs
➜ fills gap between RV/eclipsing systems and wide AO binaries
➜ very **pristine, non-interacting systems!**



Galactic Population Model
of observable sample (Casagrande)

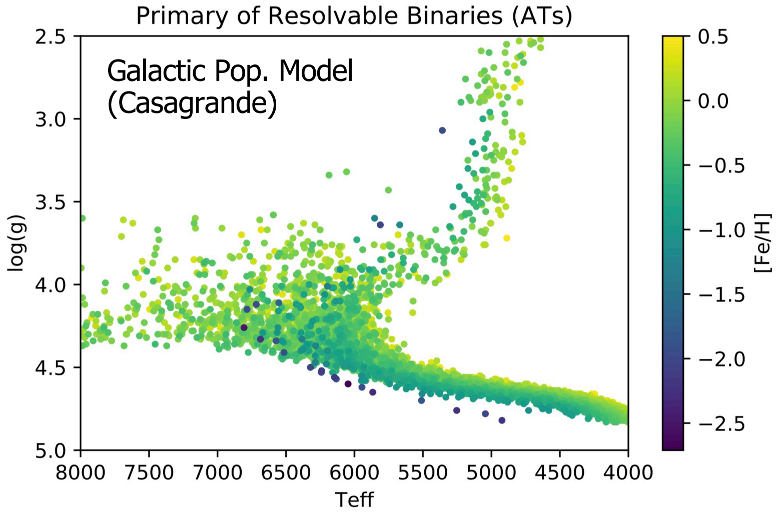
Fundamental Stellar Astrophysics

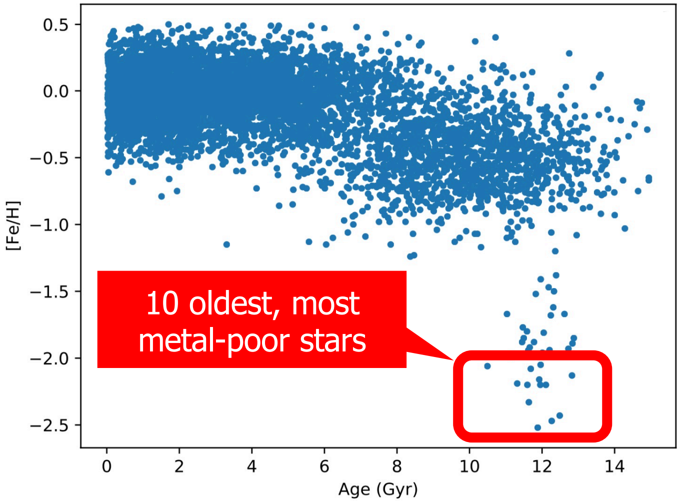
Dynamical masses:

Gold standard for calibrating evolutionary models

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

- Low-mass stars (Baraffe+ 2014)
- Pre-main-sequence stars (Gallart+ 2005)
- Massive stars: overshooting, mass loss (Constantino+ 2018)
- Very-low metallicity stars
- …





Galactic Archaeology

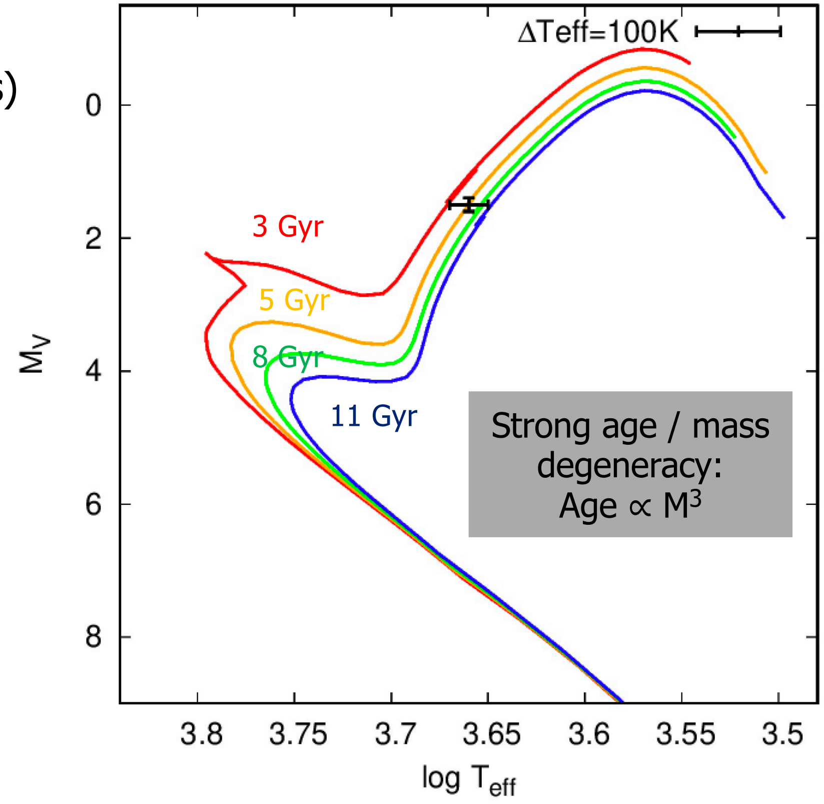
Determine ages with isochrone+BIFROST mass method
(with complementary elemental abundances from other surveys)

Select Red Giant Branch objects with [M/H]<-0.5
(ages metallicity insensitive:
Δ[M/H]=0.1 ➜ <2% age uncertainty)

- **➜ <3% mass uncertainty**
- **➜ <10% age uncertainty**
  (more accurate & direct than competing methods)
- **➜ calibrate asteroseismology relation**
  (essential for TESS & PLATO!)

Astroseismology provides mass + radii estimates, but requires calibration to improve beyond current
9% mass accuracy, 45% age uncertainty

(even with accurate parallaxes (2%), T_{eff} (1%) & fluxes (2%);
e.g. Epstein+ 2014, Gaulme+2016)



Soderblom+ 2010

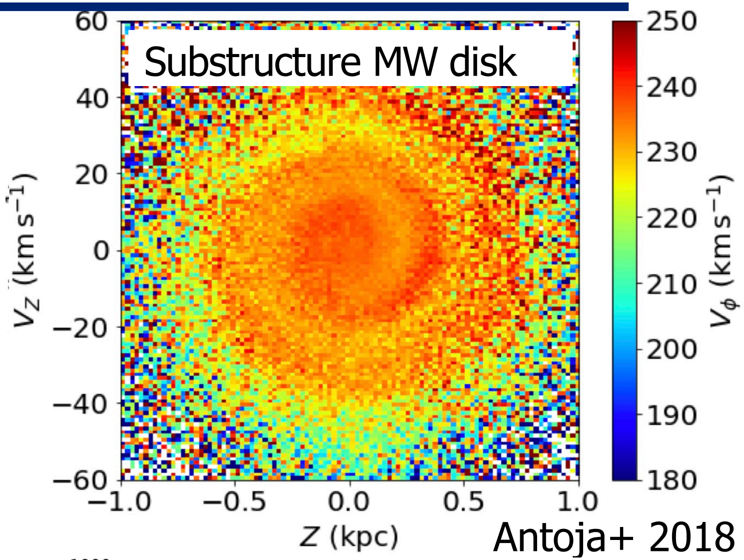
Galactic Archaeology

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

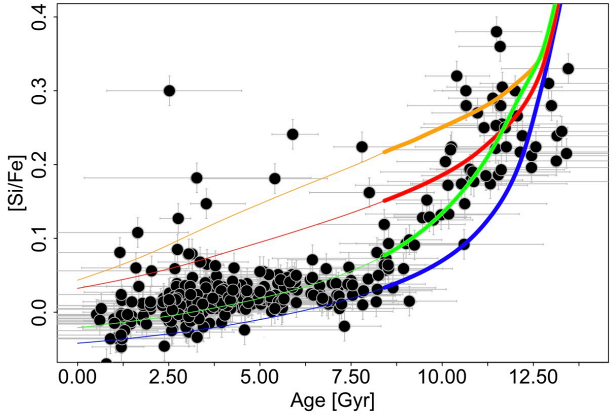
- Separate different age populations
  ➜ MW substructures, minor mergers
  (e.g. Freeman & Bland-Hawthorn 2002)

- Episodic star formation
  ➜ quick changes in abundance, followed by plateaus

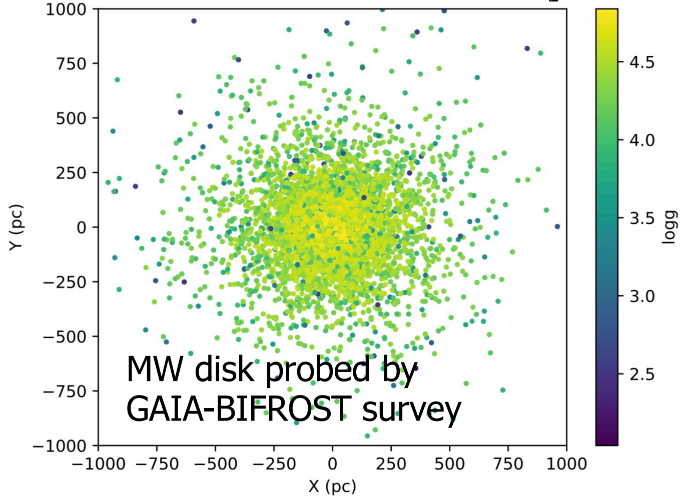
- Observe sudden transition 8 Gyrs ago
  from forming metal-rich stars to metal-poor stars



Antoja+ 2018



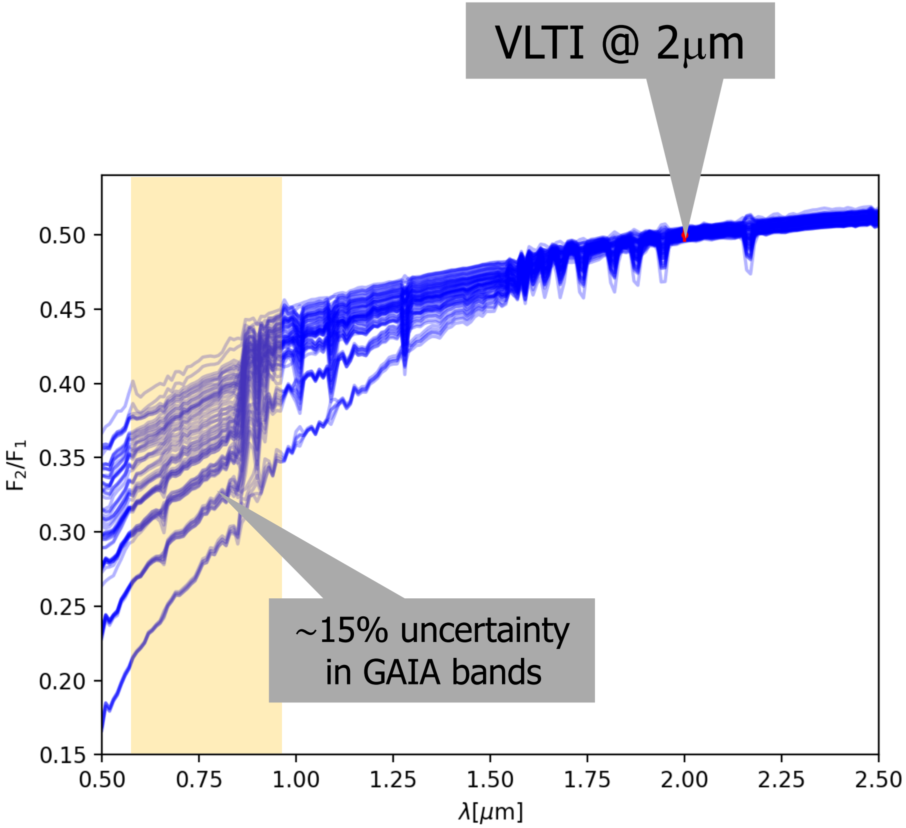
Haywood+ 2015



Why “BIFROST” VLTI visitor instrument?

Resolving GAIA binaries with existing VLTI instruments requires extrapolating flux ratio to GAIA wavebands

➜ introduces unacceptably large error



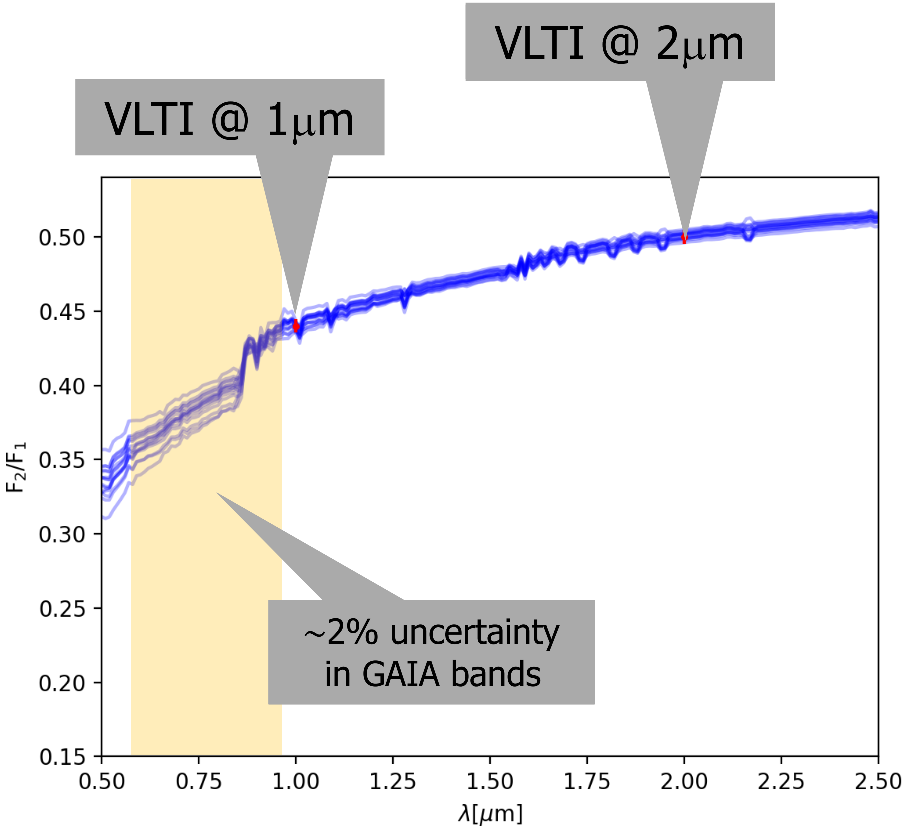
Why "BIFROST" VLTI visitor instrument?

Short wavelength
(1-1.4 µm):

- Measure binary flux ratio close to GAIA bandpass
  ➜ **2% (3%) accuracy** on flux ratio (dyn. masses)
- **Nearly doubles VLTI resolution!**
  ➜ $\lambda/2B$ = 0.5 mas

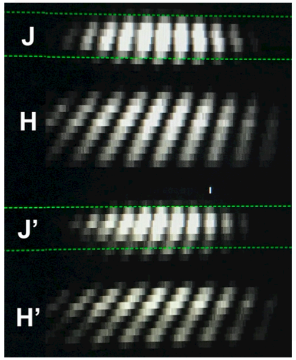
Infrastructure readiness:

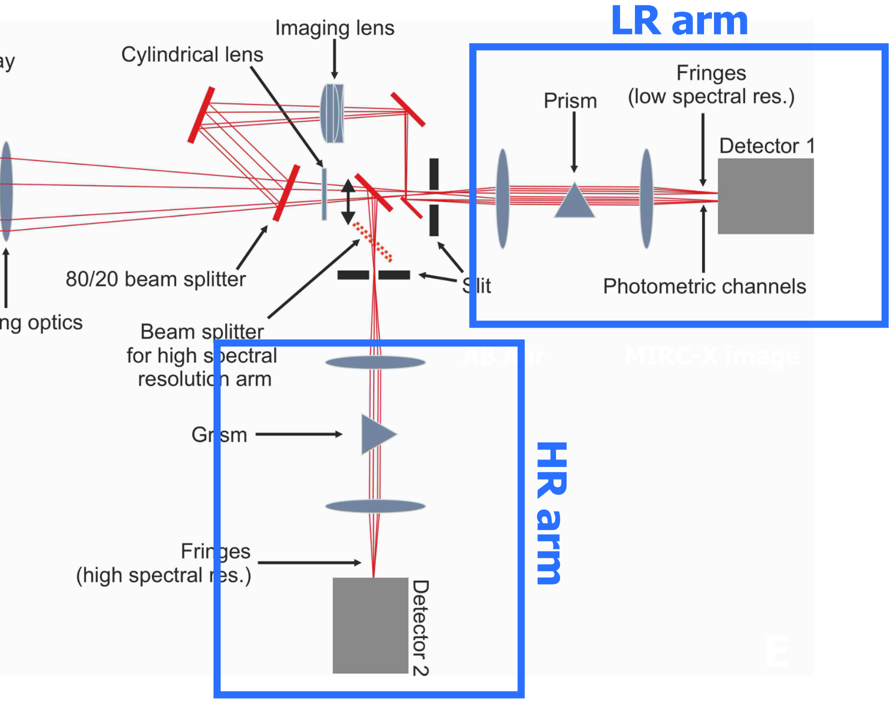
- Fringe tracking from GRAVITY
- 1.8m ATs just equipped with state-of-art AO
- 8.2m UTs extreme-AO coming soon



"BIFROST" VLTI visitor instrument

- Proposed visitor instrument: contingent on funding! ➜ could be operational from early 2024
- Records **continuum (1-1.4 μm)** + **high spectral data (up to R=25,000)** simultaneously
- Design based on MIRC-X instrument (Kraus+ 2018, Anugu+ subm.)





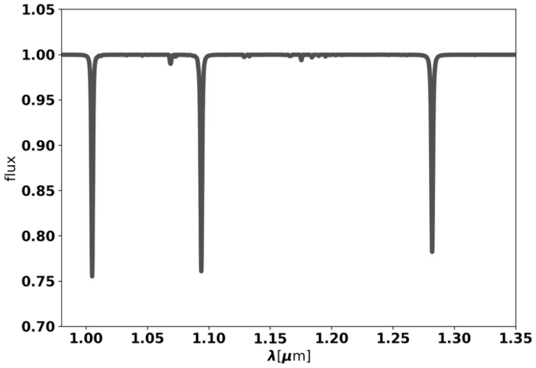
MIRC-X:
6-tel. imager
at CHARA,
high sensitivity,
build as part of
ERC project
"ImagePlanetFormDiscs"

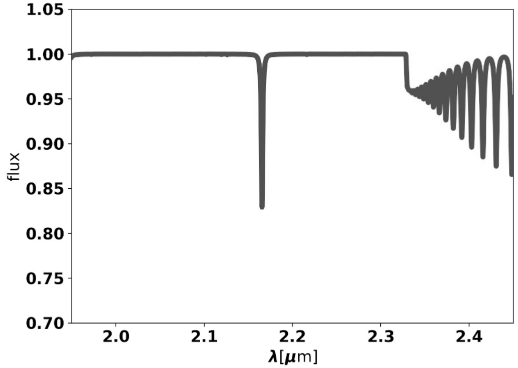
Why “BIFROST” VLTI visitor instrument?

➜ **Velocity-resolved studies at extreme angular resolution**
imaging λ/B <0.5 mas
photocenter <1 µas

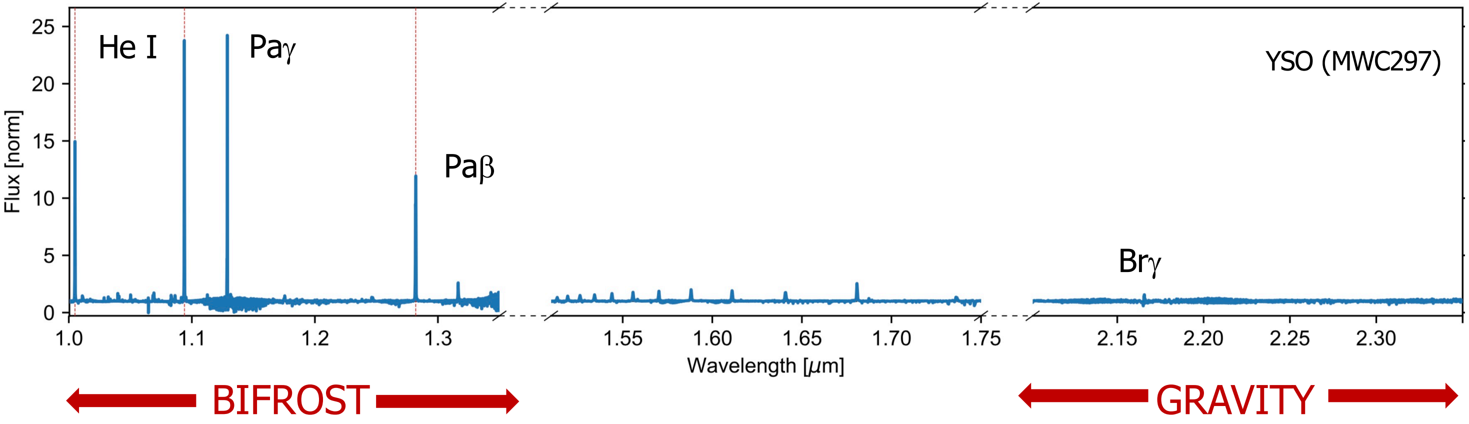
High spectral resolution
(R=1000, 6000, 25000):

Photospheric absorption lines

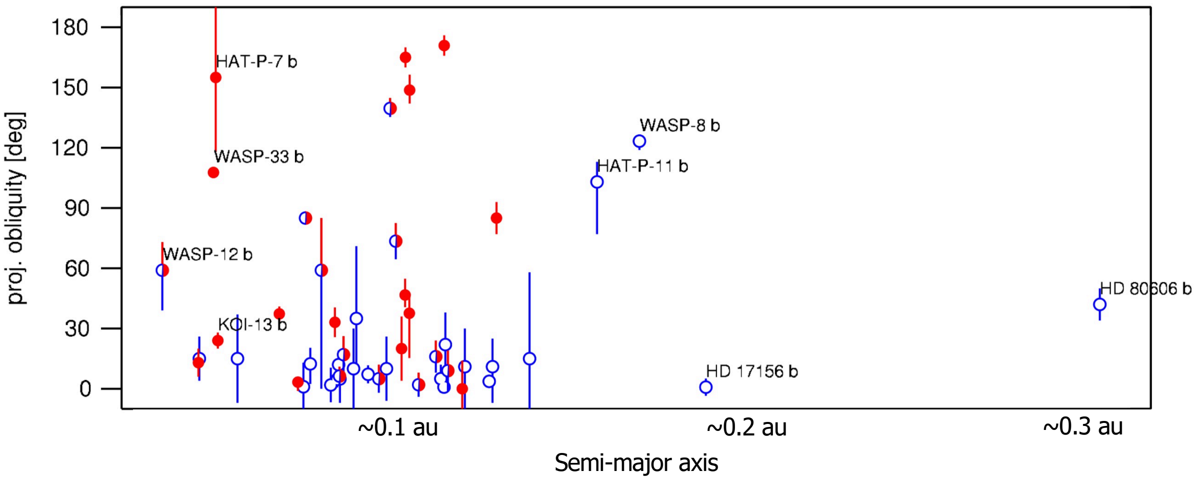


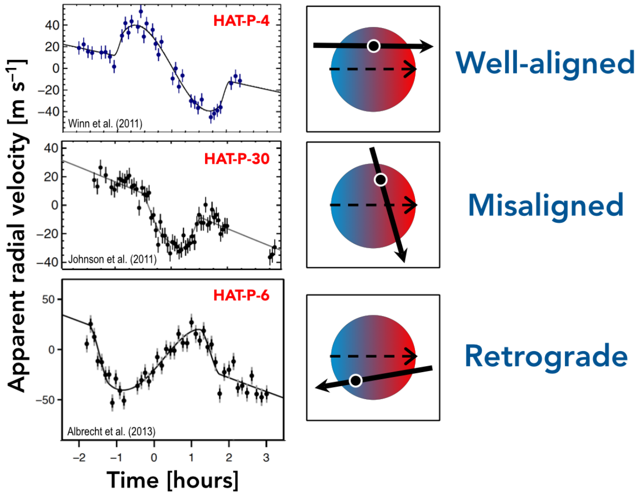


Emission lines



Spin-orbit alignment: Rossiter-McLaughlin effect





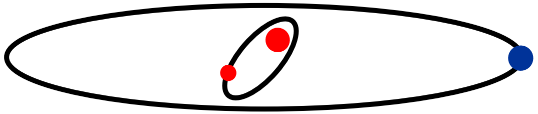
~40% of Hot Jupiters orbit host star on oblique orbit (Campante+ 2016)

Rossiter-McLaughlin effect enables measuring spin-orbit alignment for transiting systems.
Obliquity of non-transiting planets on wide (>0.3 au) orbits is largely unexplored

Albrecht+ 2012; Romanova+ 2013

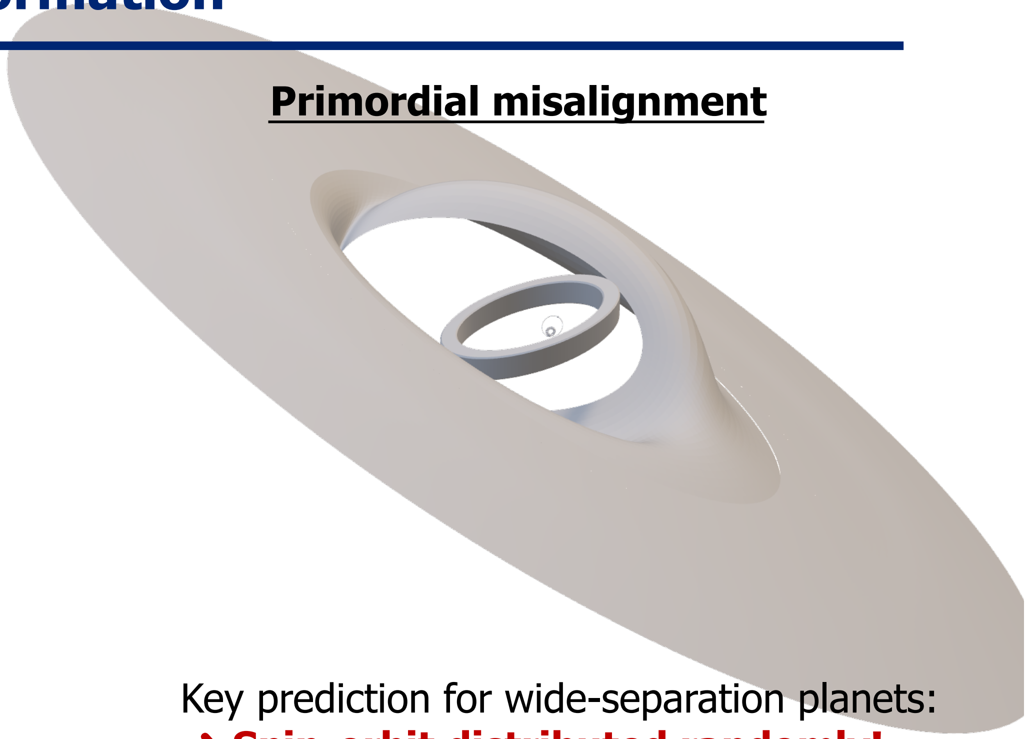
Planet Formation

Dynamical scattering / Kozai-Lidov



Key prediction for wide-separation planets:
➜ Spin-orbit predominately aligned!

Primordial misalignment



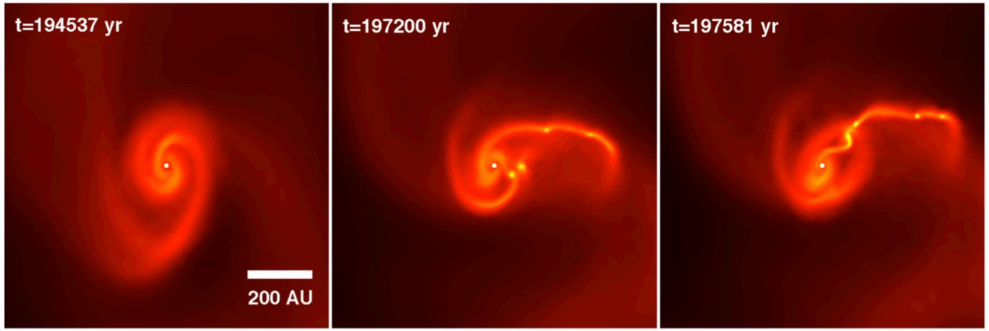
Key prediction for wide-separation planets:
➜ Spin-orbit distributed randomly!

Measuring spin-orbit alignment for wide-separation systems decisive test on formation theories

Kraus+ 2020a

Binary Formation

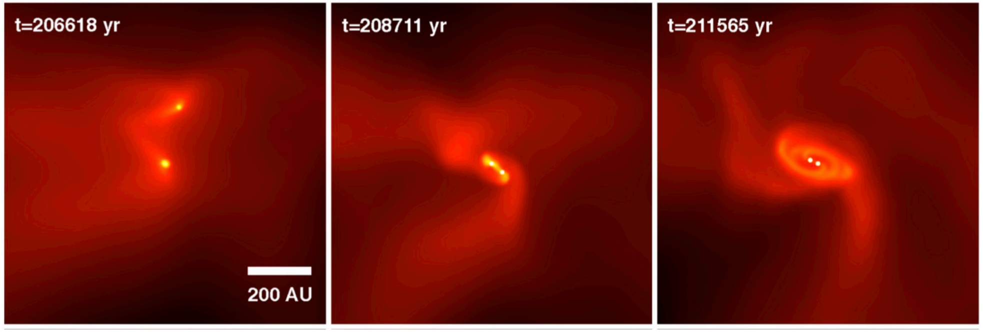
DISK fragmentation



Companions form in circumstellar disk through fragmentation / merging

Key prediction:
➜ Spin-orbit predominately aligned!

CLOUD fragmentation



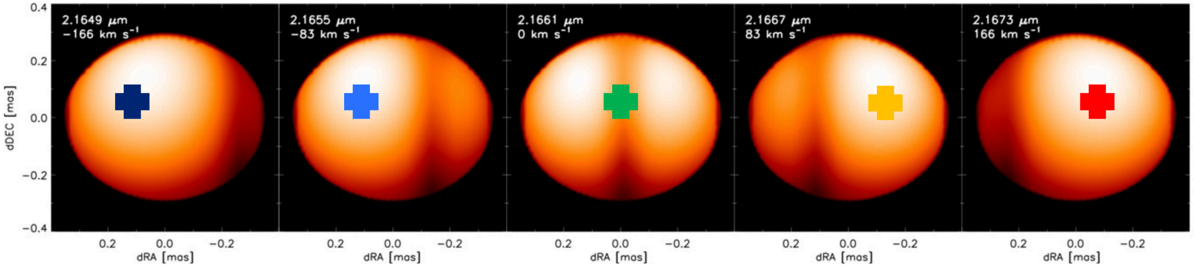
Protostars form separately and undergo star-disk encounter to form tight binary

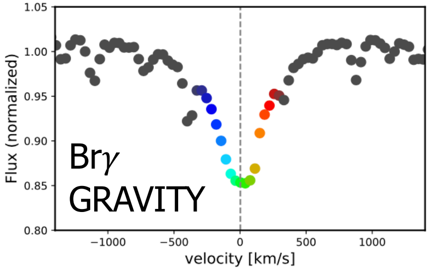
Key prediction:
➜ Spin-orbit distributed randomly!

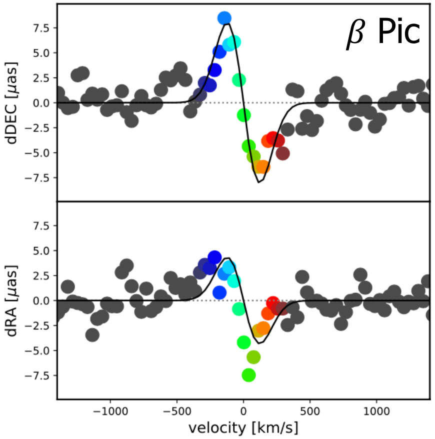
Measuring spin-orbit alignment for wide-separation systems decisive test on formation theories

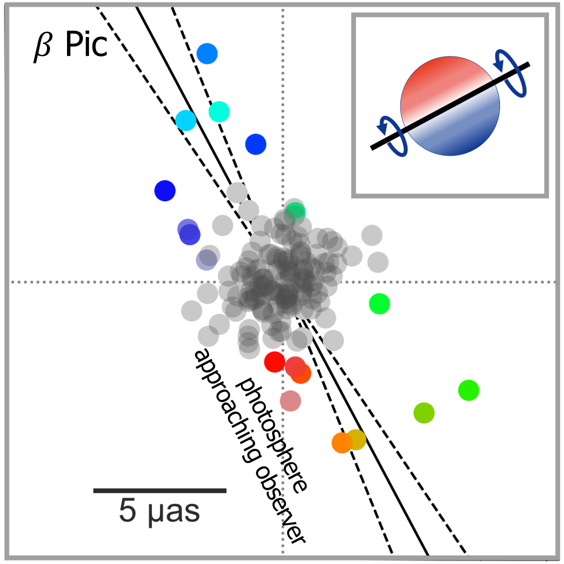
Bate 2018

Spin-orbit alignment: Interferometry









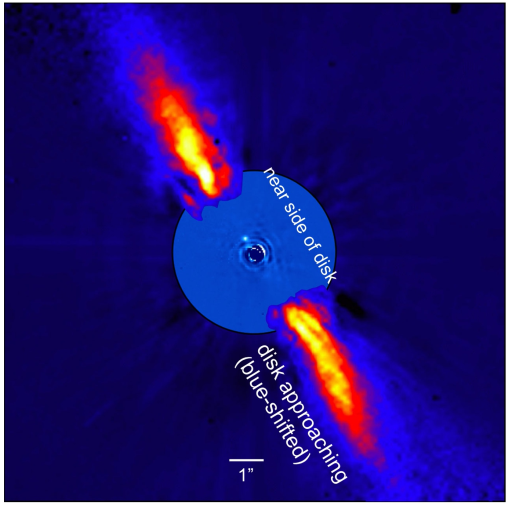
Measure photocenter displacement
in photospheric absorption line

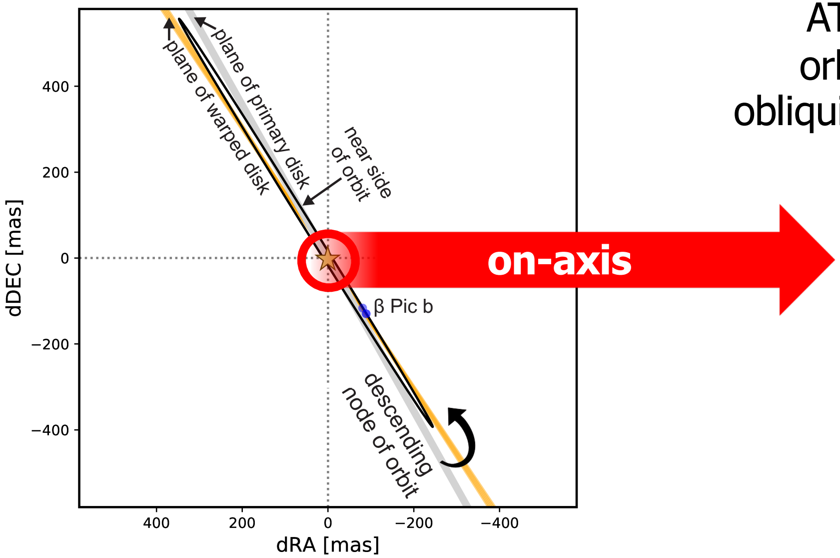
➜ Tight constraints on sky-projected spin-axis orientation

➜ moderate constraints on inclination
(can be improved w/ astroseismology)

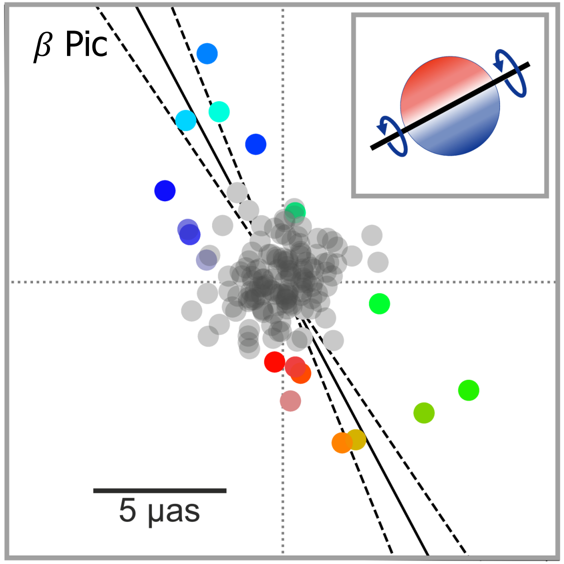
Kraus+ 2012, 2020b

Spin-orbit alignment: Interferometry





ATs: orbit obliquity



BIFROST will achieve 10× higher astrometric accuracy

➜ Spin-orbit alignments for smaller stars & slow rotators

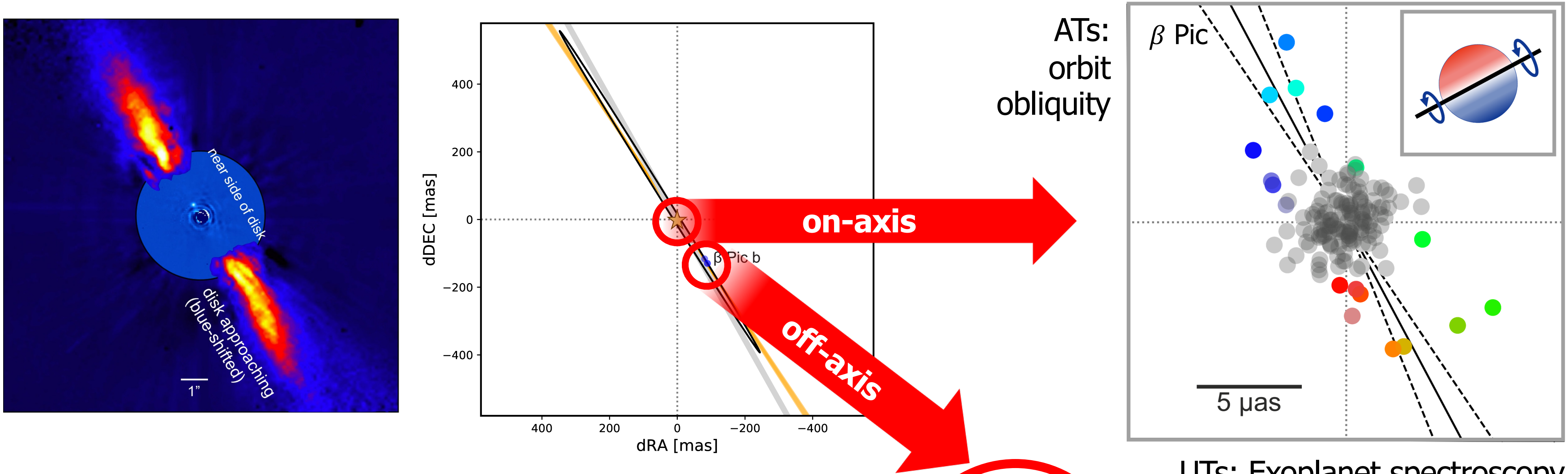
➜ Survey on hundreds of GAIA binaries + planets

***β* Pic:** 3-D obliquity angle 3±5°

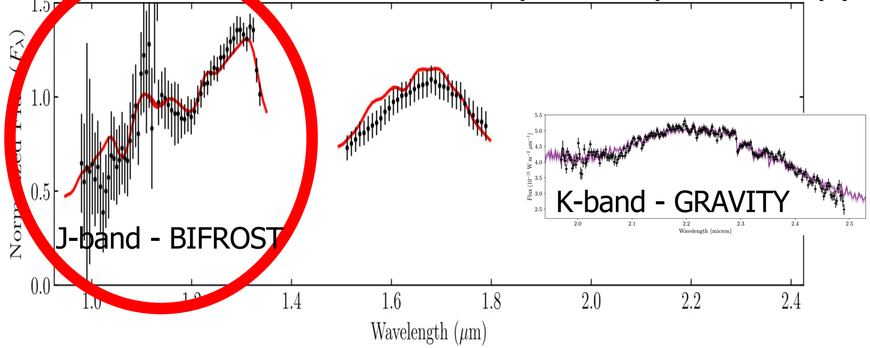
➜ Spin / planet orbit / debris disk well aligned

Kraus+ 2020b; ESO/Lagrange/SPHERE

Exoplanet Spectroscopy



UTs: Exoplanet spectroscopy



BIFROST off-axis spectroscopy of GAIA planets (with UTs)

➜ Combines star-light suppression from extreme-AO + correlated flux from interferometry

➜ High-resolution spectroscopy for exoplanets down to 0.02″ separation

Kraus+ 2020b; GRAVITY collab. 2020; ESO/Lagrange/SPHERE

Summary

GAIA DR3 offers vast potential

…to unveil **dynamical processes that govern architecture of Star & Planetary systems**

…to measure **fundamental stellar parameters** with unprecedented precision & efficiency

- "BIFROST": VLTI visitor instrument concept with unique characteristics:
  - **short-wavelength:** ➜ close to GAIA bandpass, good spectral tracers
  - **high spectral resolution:** ➜ spin orientation & kinematical studies
  - **use of VLTI infrastructure:** ➜ 0.001" resolution, sensitivity (1.8m+8.2m)

- "GAIA-BIFROST": Proposed survey on **GAIA binaries + planets** to measure
  - **precision dynamical masses:** ➜ up to ~6000 stars
  - **precision ages:** ➜ up to ~2000 stars, out to 1 kpc
  - **spin-orbit alignment:** ➜ up to ~1300 stars

- Community engagement