The Asgard/BIFROST visitor instrument for VLTI: Science cases for low-noise, large-format detector arrays

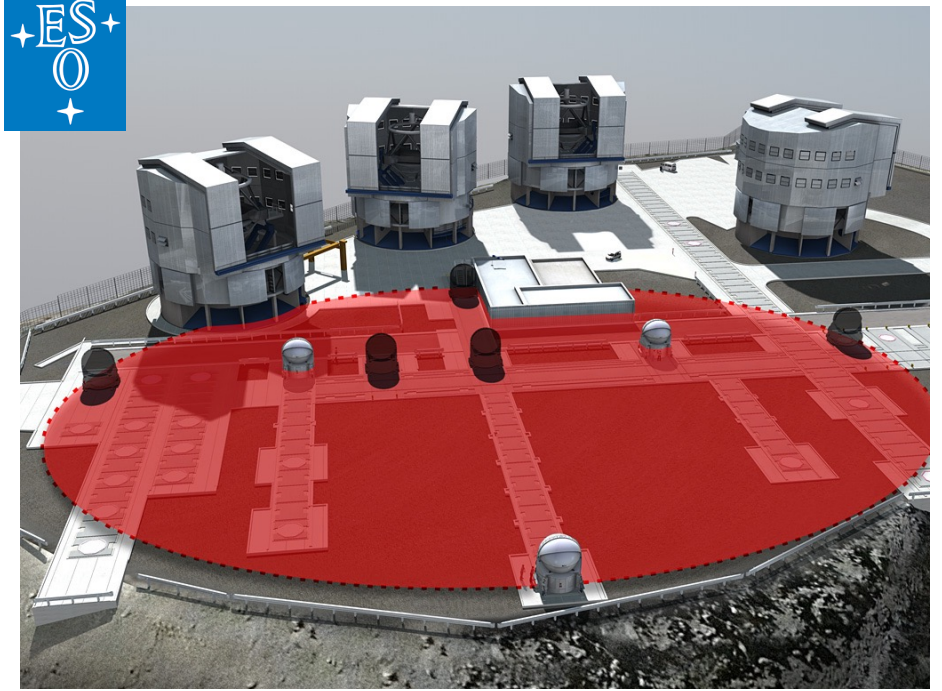
Stefan Kraus

BIFROST team: S. Chhabra, D. Mortimer, T. Gardner, I. Codron, Y. Lu, O. Snaith (Exeter), N. Anugu (CHARA), J. Monnier (Michigan), Andrea Bianco, Michele Frangiamore (INAF), Philipp Huke (Emden)

Asgard partners: M. Ireland, B Courtney-Barrer, D. Brodrick (ANU), B. Norris, P. Tuthill (Sydney), S. Gross (Macquarie U.), F. Martinache, M. N'Diaye, N. Cvetojevic (OCA), D. Defrere, M.-A. Martinod, R. Laurier, M. Salman, K. Missaen, G. Garreau, A. Bigioli, S. Verlinden, G. Raskin (Leuven), J. Loicq, C. Dandumont, A. Mazzoli (CSL), L. Labadie, A. Sanny (Cologne)

"What future for European large-format IR detectors" workshop
Paris, 2022 December 7

VLT Interferometer



VLT Interferometer, Chile

4x8.2m ➜ sensitivity
4x1.8m ➜ imaging

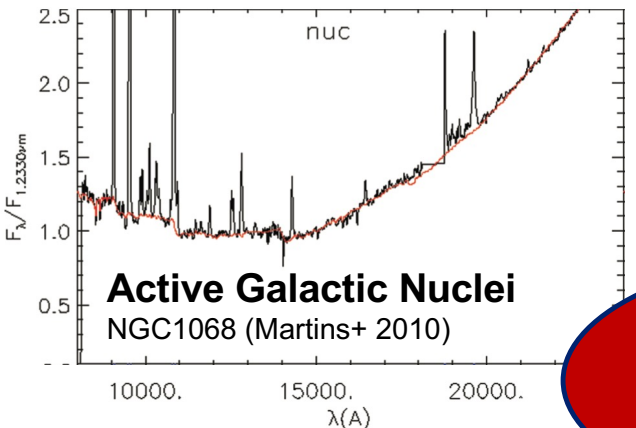
Angular resolution:

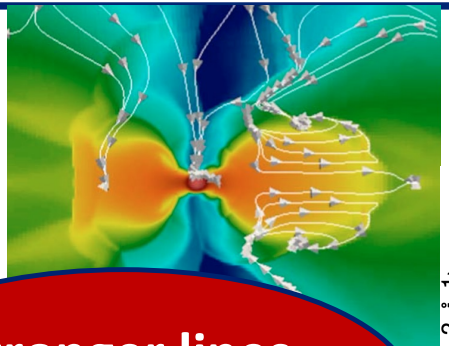
λ/B ≳ 2 milli-arcsecond

2nd-gen instruments:

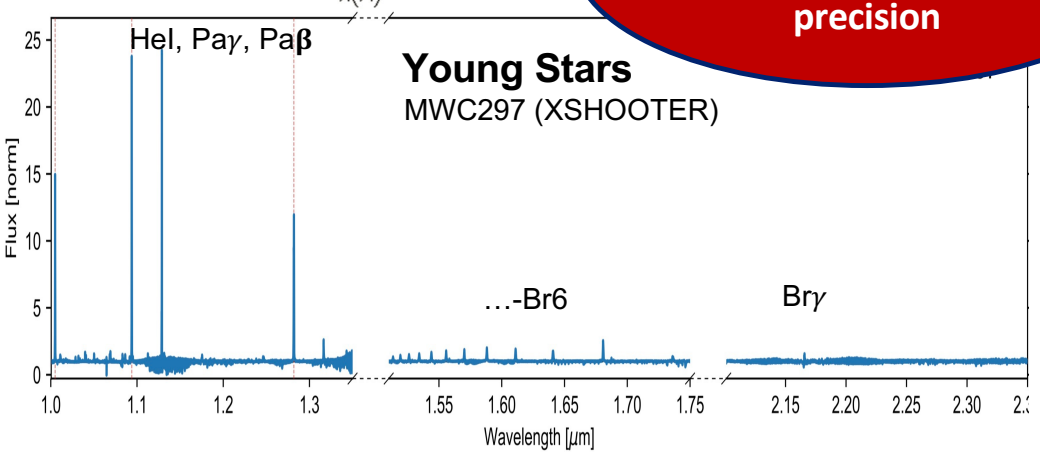
GRAVITY:	2-2.5 μm	R ≦ 4000
MATISSE:	3-13 μm	R ≦ 3300

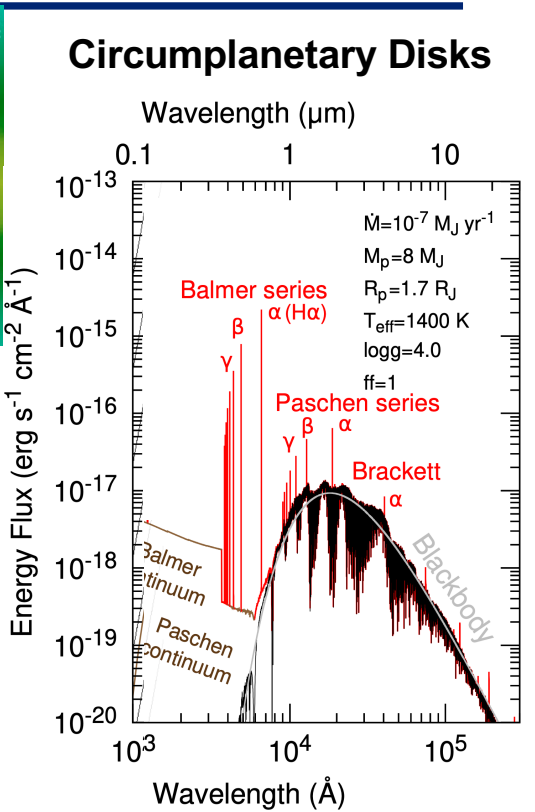
Why shorter wavelengths at VLTI?





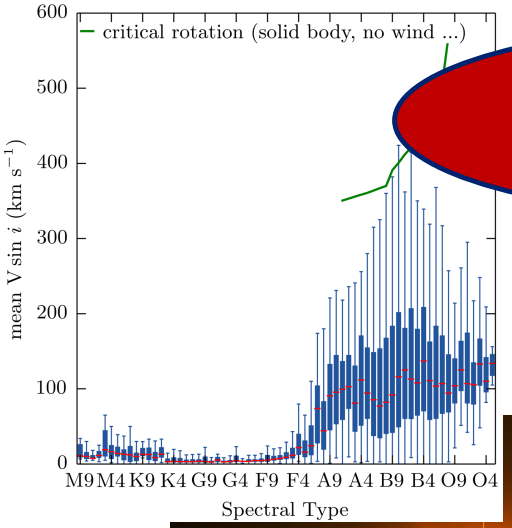
Stronger lines
➜ **sensitivity / SNR / precision**



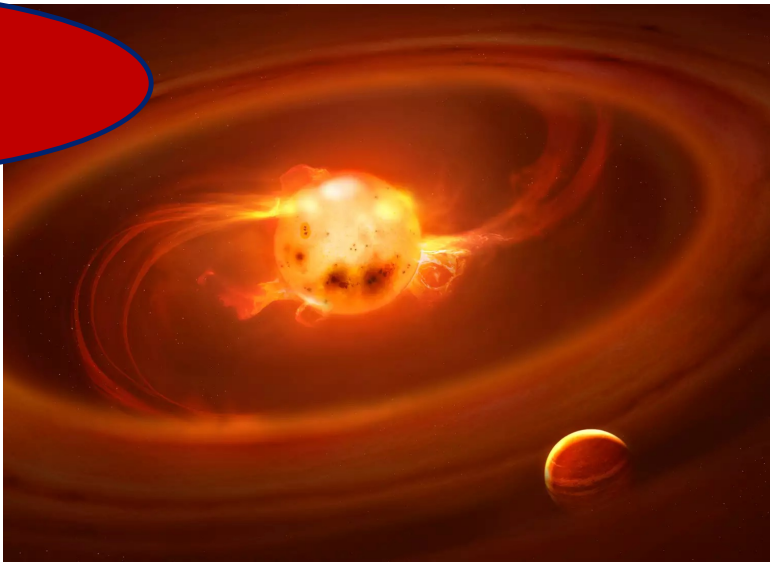


Marleau+ 2022; Szulágyi 2020; Aoyama+ 2020

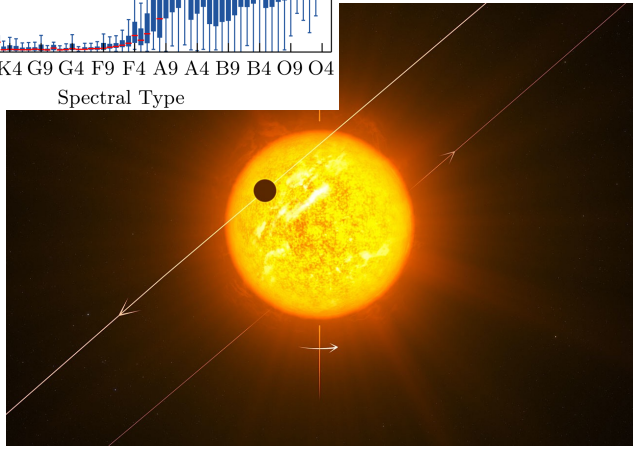
Why spectral resolution R=25,000?



Gas kinematics



Spin-orbit alignment
of slower-rotating stars



Disk kinematics,
accretion,
outflows,
…

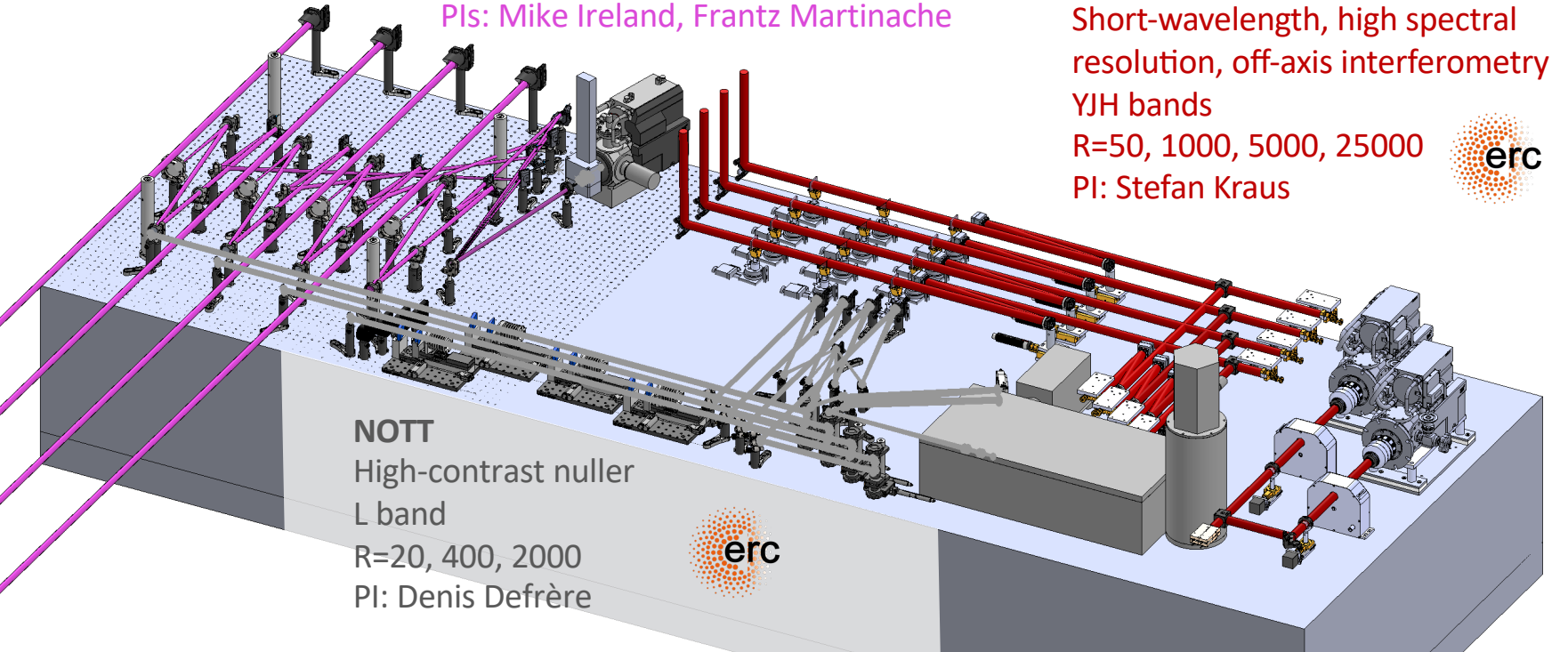
ESO PR; Mark Garlick; Fremat

Asgard Suite of VLTI Instruments

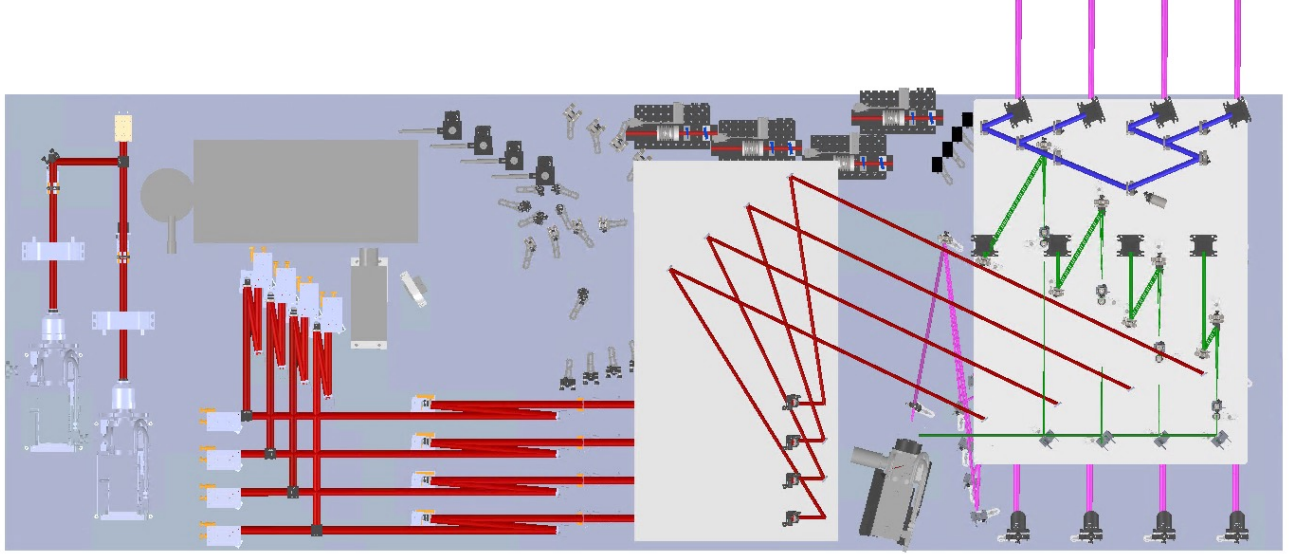
HEIMDALLR
Fringe tracker
Dual K band
PIs: Mike Ireland, Frantz Martinache

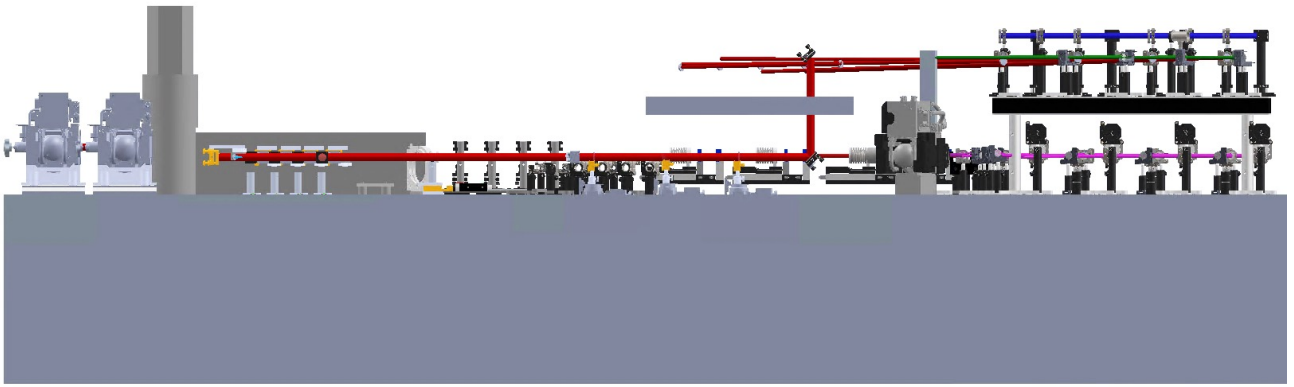
Baldr
Lab-AO system
J or H band

BIFROST
Short-wavelength, high spectral resolution, off-axis interferometry
YJH bands
R=50, 1000, 5000, 25000
PI: Stefan Kraus

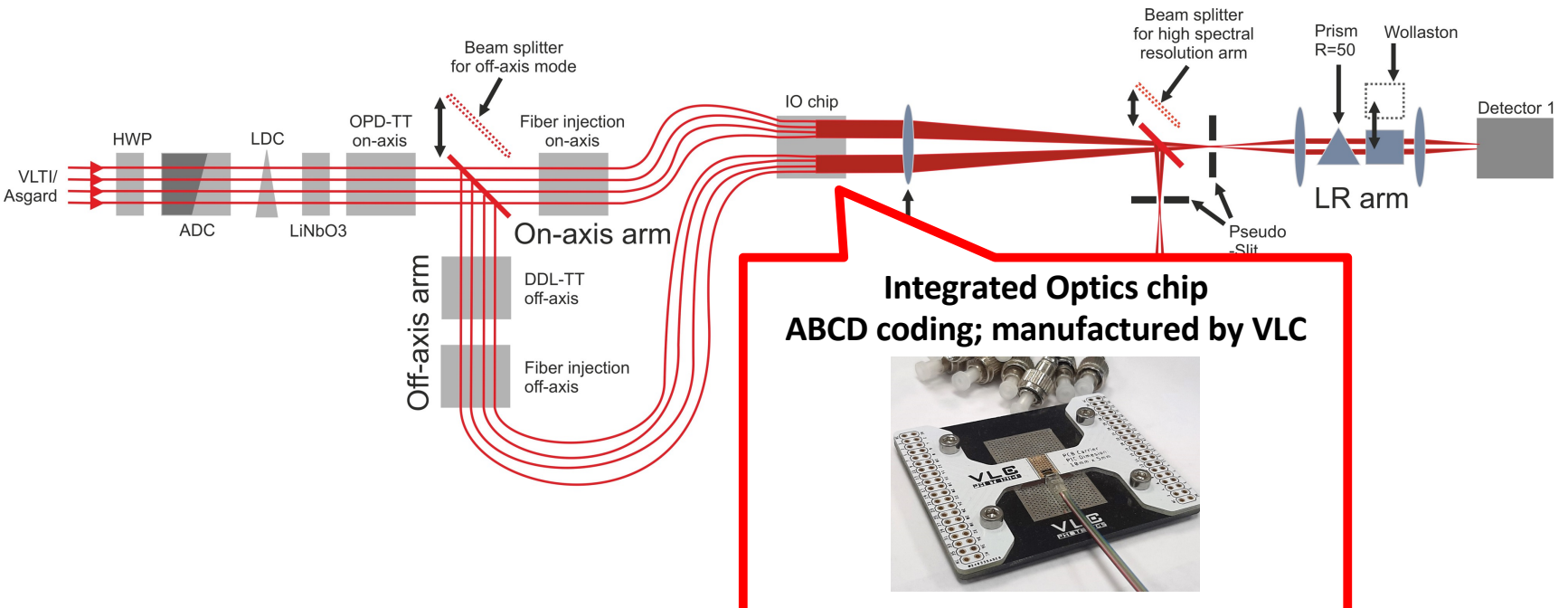


NOTT
High-contrast nuller
L band
R=20, 400, 2000
PI: Denis Defrère



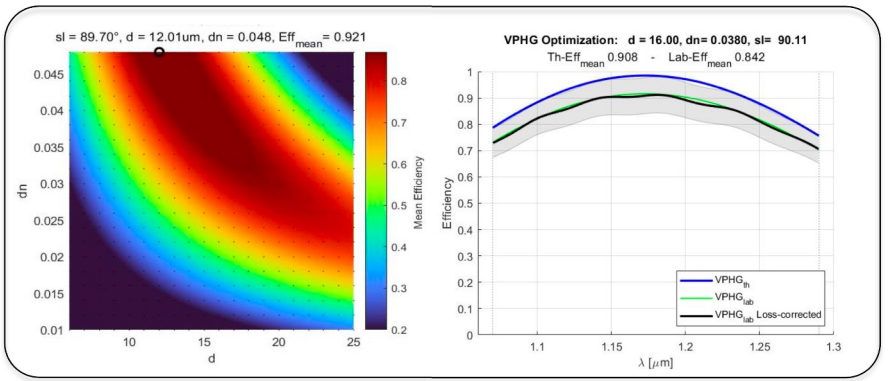


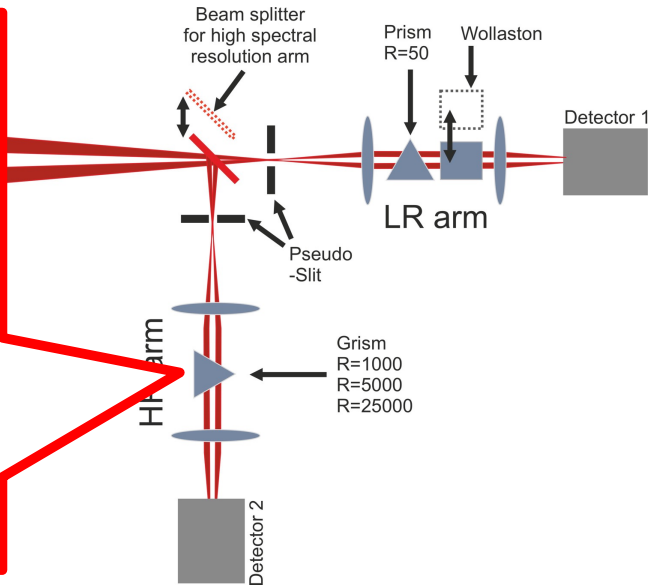
BIFROST Optical Design



Volume Phase Holographic Gratings

manufactured by INAF, Bianco/Frangiamore





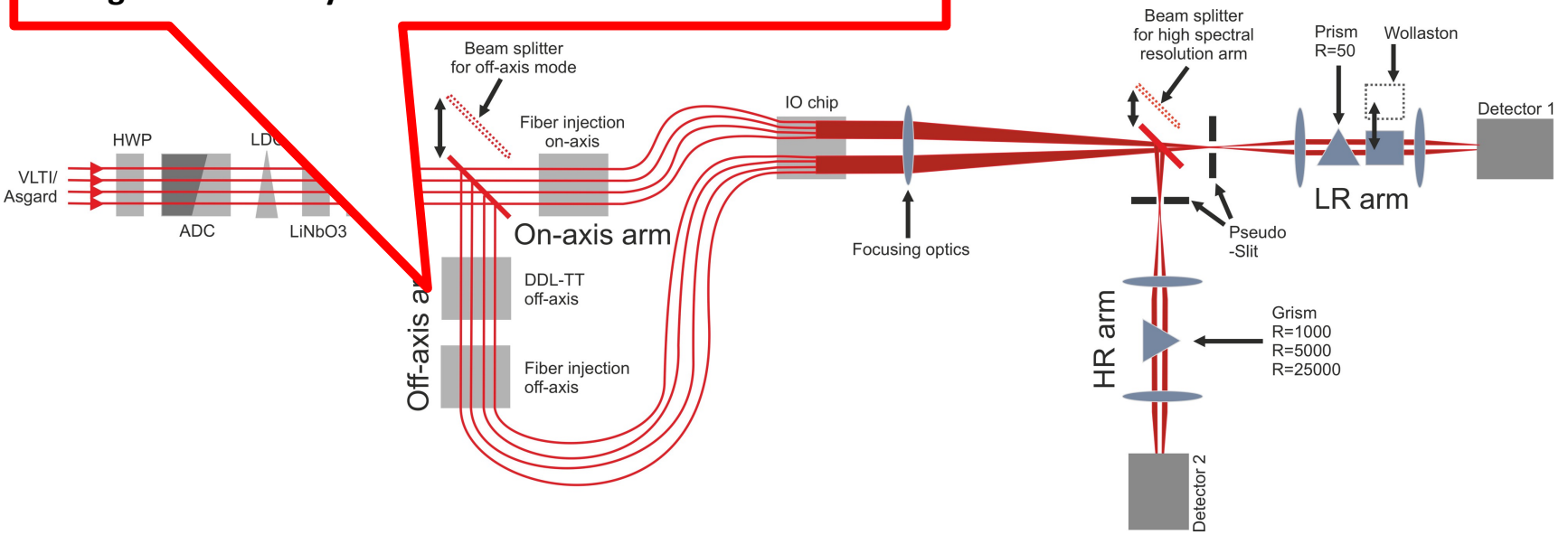
On-axis/off-axis arm (equiv. GRAVITY dual-field):

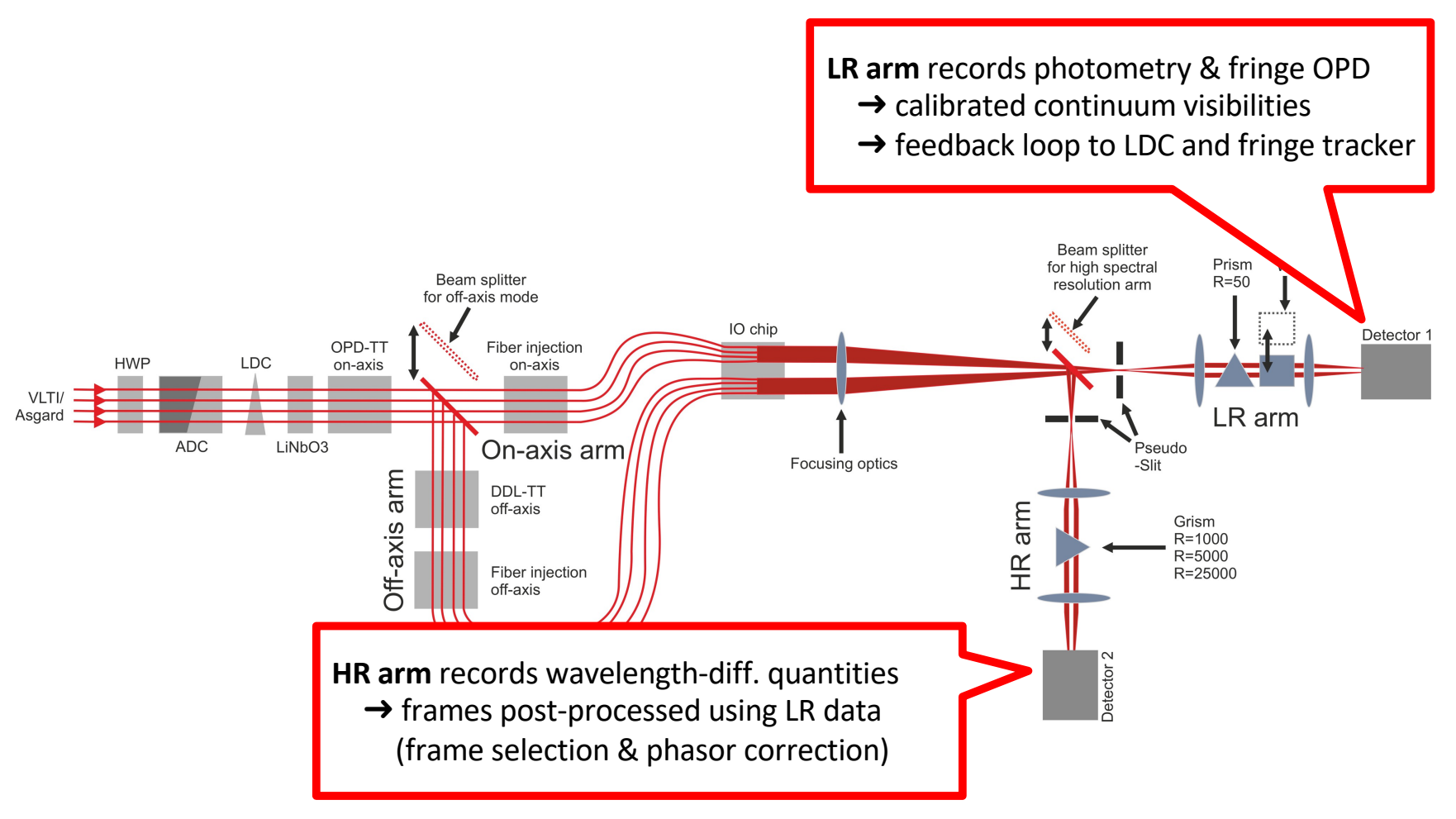
On-axis and off-axis light

…combined in same IO device,

…passing through same spectrograph,

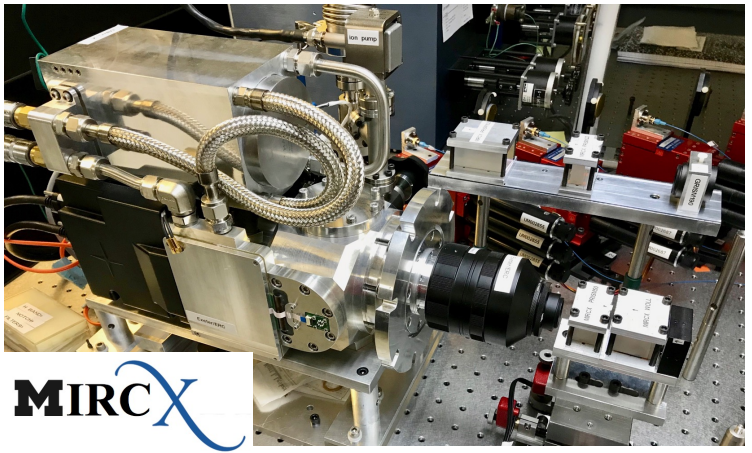
…registered side-by-side on same detectors

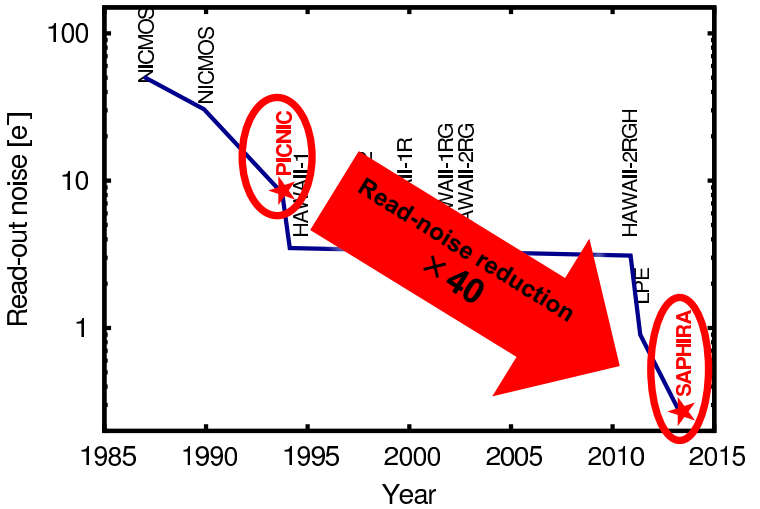



LR arm records photometry & fringe OPD
→ calibrated continuum visibilities
→ feedback loop to LDC and fringe tracker
VLTI/
Asgard
HWP
ADC
LDC
LiNbO3
OPD-TT
on-axis
Beam splitter
for off-axis mode
Fiber injection
on-axis
On-axis arm
Off-axis arm
DDL-TT
off-axis
Fiber injection
off-axis
IO chip
Focusing optics
Beam splitter
for high spectral
resolution arm
Pseudo
-Slit
Prism
R=50
LR arm
Detector 1
HR arm
Grism
R=1000
R=5000
R=25000
Detector 2
HR arm records wavelength-diff. quantities
→ frames post-processed using LR data
(frame selection & phasor correction)

BIFROST Detector #1

Detector #1 (LR-arm, R=50):
optimized for low read-noise, 50-1000 frames/s

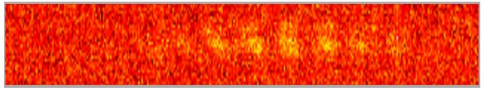




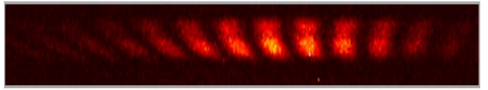
Avalanche photodiode (APD)-based detector

- → based on Leonardo/SAPHIRA e-APD array
- → sub-electron noise at 3500 Hz, Fowler sampling
- → CRED One from First Light Imaging

Conventional detector:



eAPD (gain 30):

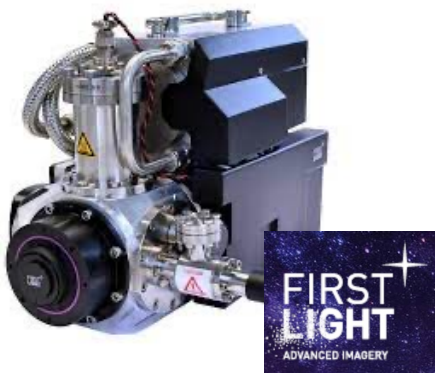


BIFROST Detector #2

Detector #2 (HR-arm, R=1000, 5000, 25000):
optimized for low background, few frames/s

Option #1:
Saphira APD 320x256
(CRED One)

LEONARDO



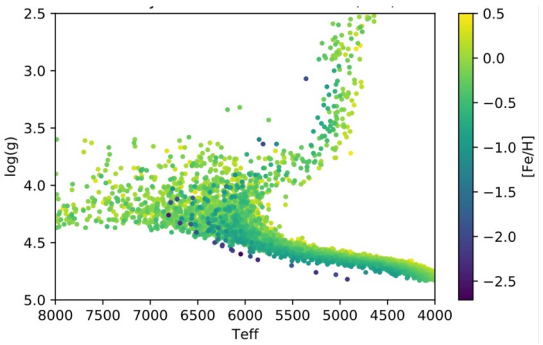
Option #2:
Large-format APD

512x512	ESO/MPE/NRC
1024x1024 Ike Pono	NASA
2048x2048 IBEX	ESA

Option #3:
HgCdTe
(ALFA, Teledyne/Hawaii2RG)

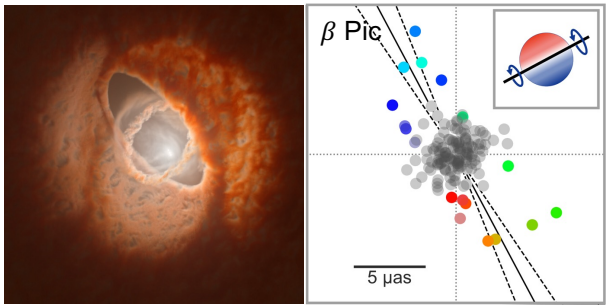
BIFROST Key Science Cases

(1) GAIA binary survey



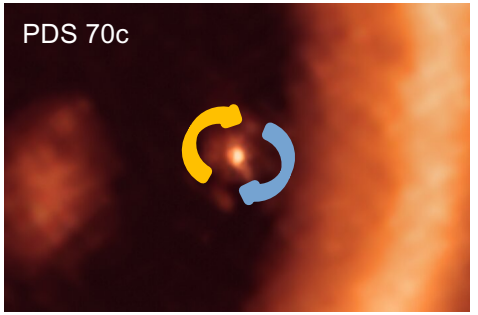
What are the fundamental properties of stars?

(2) Architecture of binary & planetary systems



What determines star & planetary system architectures?

(3) Exoplanet Spectroscopy & Circumplanetary Disk kinematics



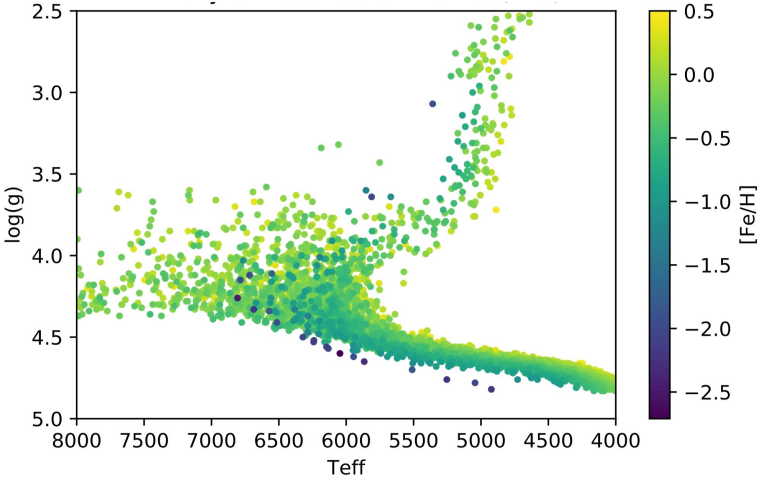
How are planets forming?

Science case #1: Fundamental Stellar Astrophysics

GAIA-BIFROST survey:
Accessible with 1.8m VLTI telescopes: **~6000 binaries**
within range of 1 kpc

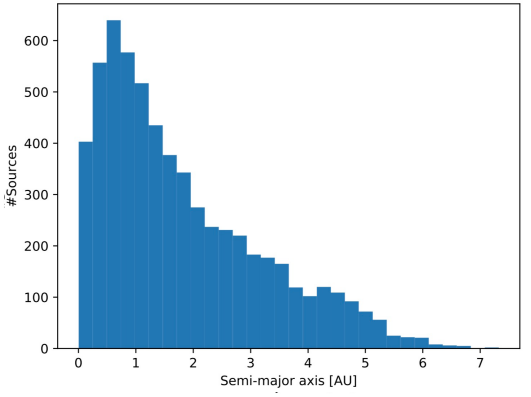
Flux-ratio measurement at **single epoch (20 min) yields:**

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

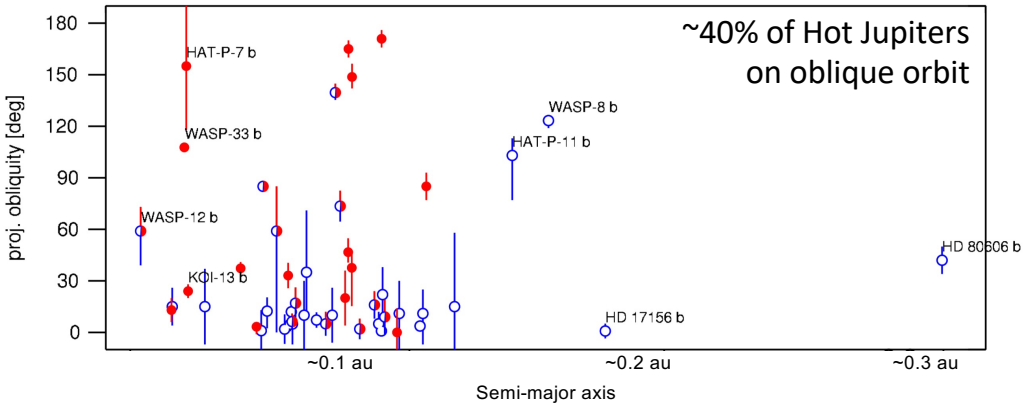


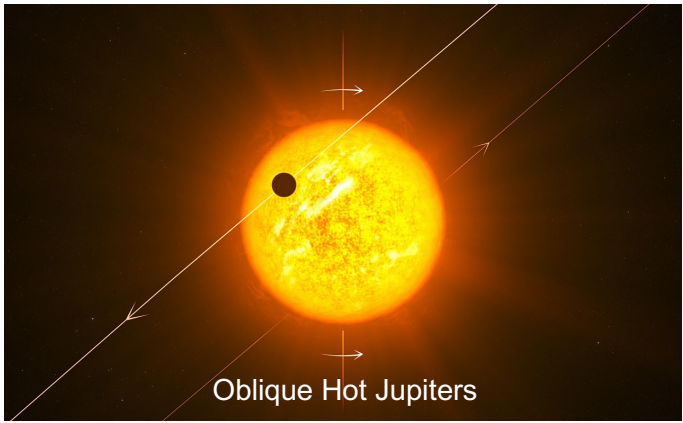
Select **rare stellar populations** most valuable for improving evolutionary models, e.g.:

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



Science case #2: Dynamical History of Stellar/Planetary Systems



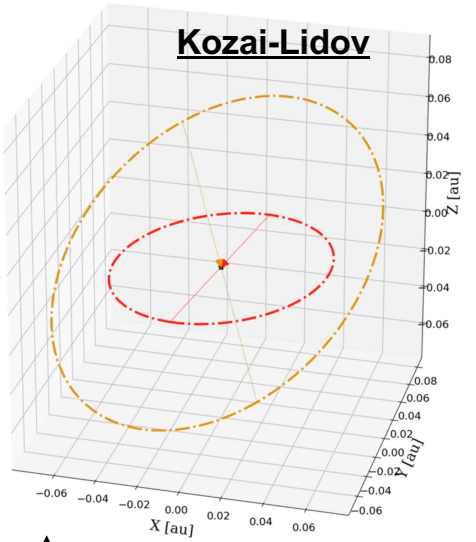


Rossiter-McLaughlin effect allows measuring spin-orbit alignment ("obliquity") for **transiting systems**

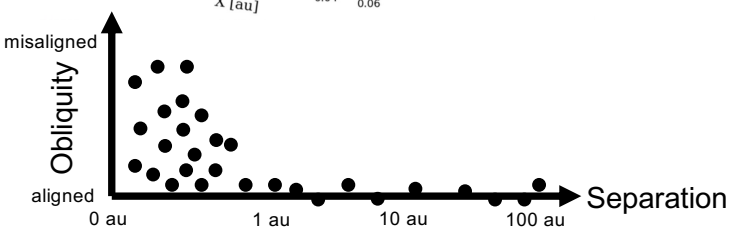
Albrecht+ 2012; Romanova+ 2013

Science case #2: Dynamical History of Stellar/Planetary Systems

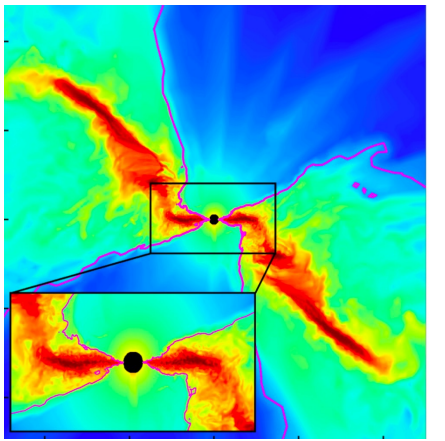
Kozai-Lidov



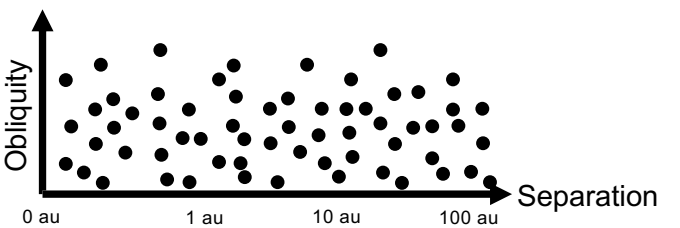
Migration accompanied by orbital tightening



Primordial misalignment



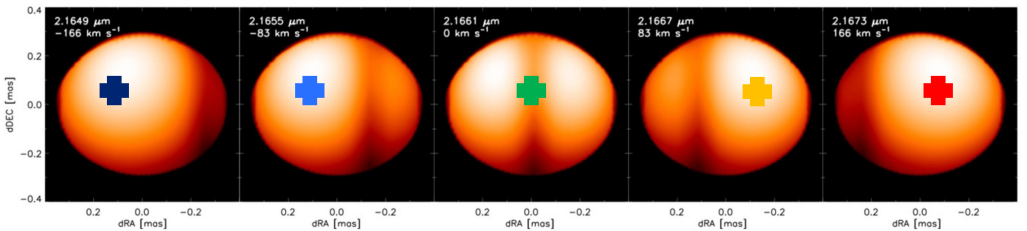
Disk warping, Star-disk capture, 'titled' accretion …



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

Liska+ 2019; Livingston

Science case #2: Dynamical History of Stellar/Planetary Systems

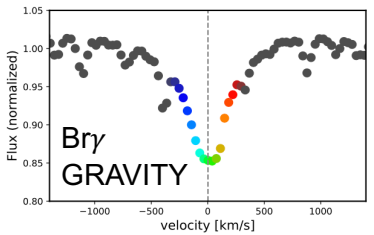


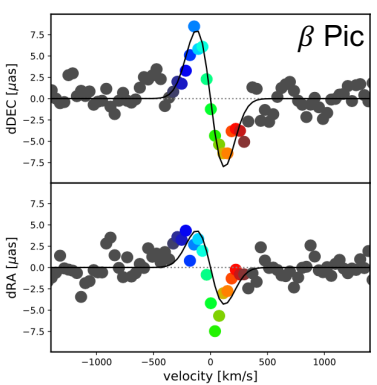
Measure photocenter displacement in photospheric absorption line

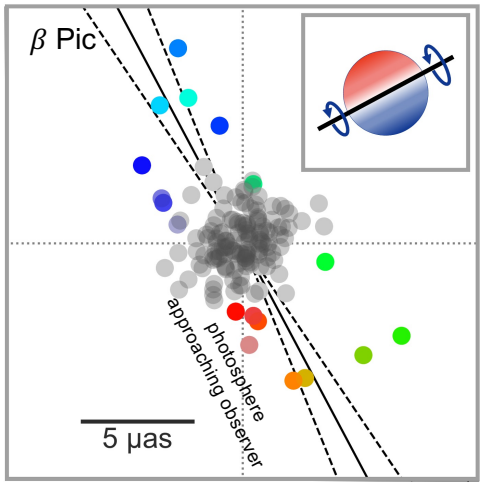
➜ **Tight constraints on sky-projected spin-axis orientation**

Survey:

Spin-orbit alignments for large sample of binaries and planet host stars





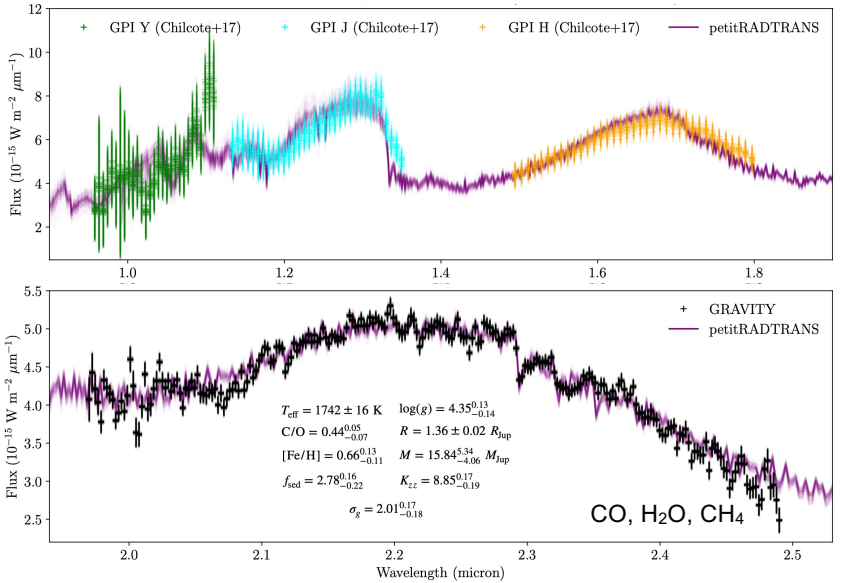


***β* Pic**: 3-D obliquity angle 3±5°

➜ **Spin / planet orbit / debris disk well aligned**

Kraus+ 2012, 2020b

Science case #3: Exoplanets & Circumplanetary Disks



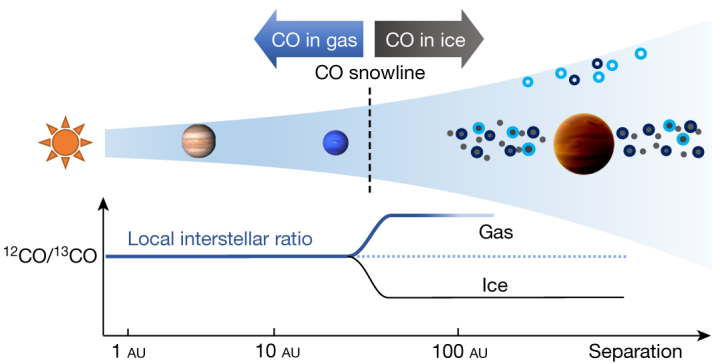
β Pic b retrieval (GRAVITY collab. 2020)

Fit performed	T (K)	$\log(g/g_0)$	Metallicity [Fe/H]	C/O ratio	Mass ($M_{\rm Jup}$)
GRAVITY data only	1847 ± 55	$3.3^{+0.54}_{-0.42}$	$-0.53^{+0.28}_{-0.34}$	$0.35^{+0.07}_{-0.09}$	$1.4^{+3.94}_{-0.87}$
GRAVITY + GPI YJH band data	1742 ± 10	$4.34^{+0.08}_{-0.09}$	$0.68^{+0.11}_{-0.08}$	$0.43^{+0.04}_{-0.03}$	$15.43^{+2.91}_{-2.79}$

Chilcote+ 2017; Zhang+ 2021

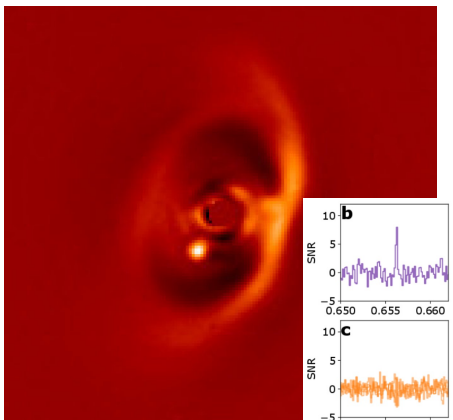
BIFROST wavelength range (1-1.7 μm) complements GRAVITY+:

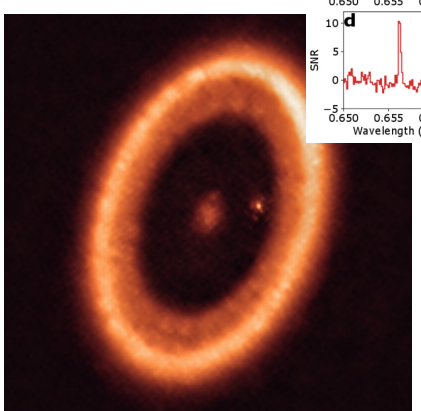
- **surface gravity**
- **cloud particle sizes**
- **new molecules**



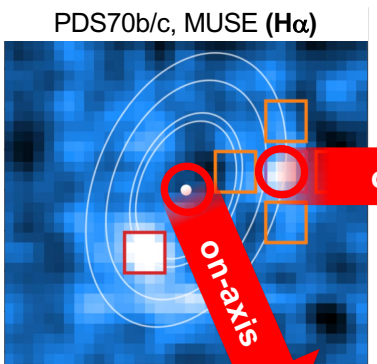
→ **Formation location**
from volatile abundances / isotopologues
(C/O, ^{12}CO/^{13}CO, …)

Science case #3: Exoplanets & Circumplanetary Disks

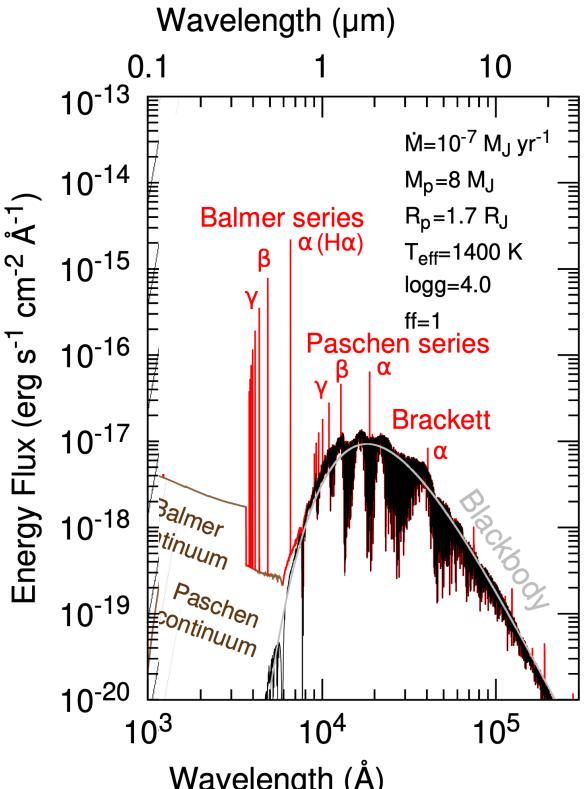




Resolve kinematics in circumplanetary disk with BIFROST (Pa**γ**, Pa**β**, HeI 1.083 μm)



Fringe tracker



0.3”

Keppler+ 2018; Müller+ 2018; Haffert+ 2019; Benisty+ 2021; Aoyama+ 2020

Asgard/BIFROST: Application for fast/low-noise detectors

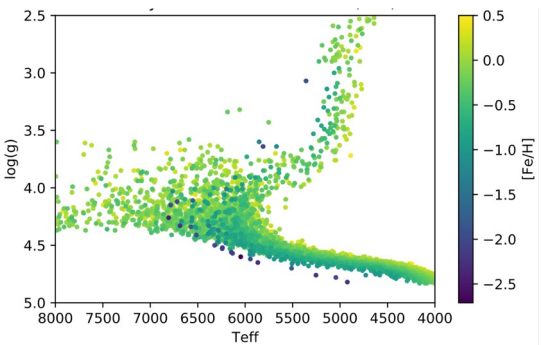
Asgard Suite proposed for VLTI visitor focus
BIFROST opens short-wavelength/high-spectral resolution window for VLTI

Detectors will be key limiting factor for achieving sensitivity goal

LR arm: APD detector needed for ultra-low read noise

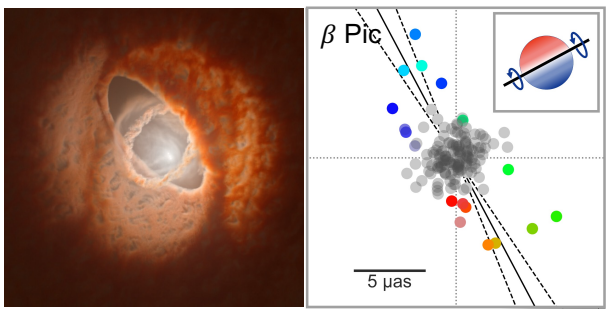
HR arm: large-format APD or HgCdTe

(1) GAIA Binaries Survey



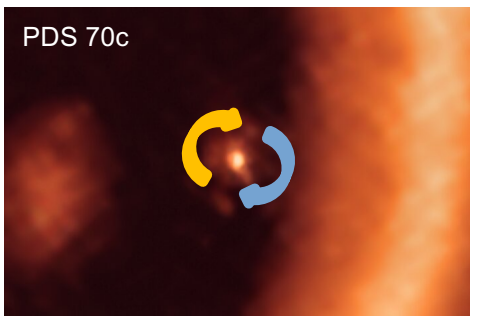
What are the fundamental properties of stars?

(2) Orbit Obliquities



What determines architecture of star & planetary systems?

(3) Exoplanet Spectroscopy & Circumplanetary Disks



How are planets forming?