Disks, Planets, and Planetary System Architectures with Asgard/BIFROST @ VLTI

University of Exeter

Stefan Kraus

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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)

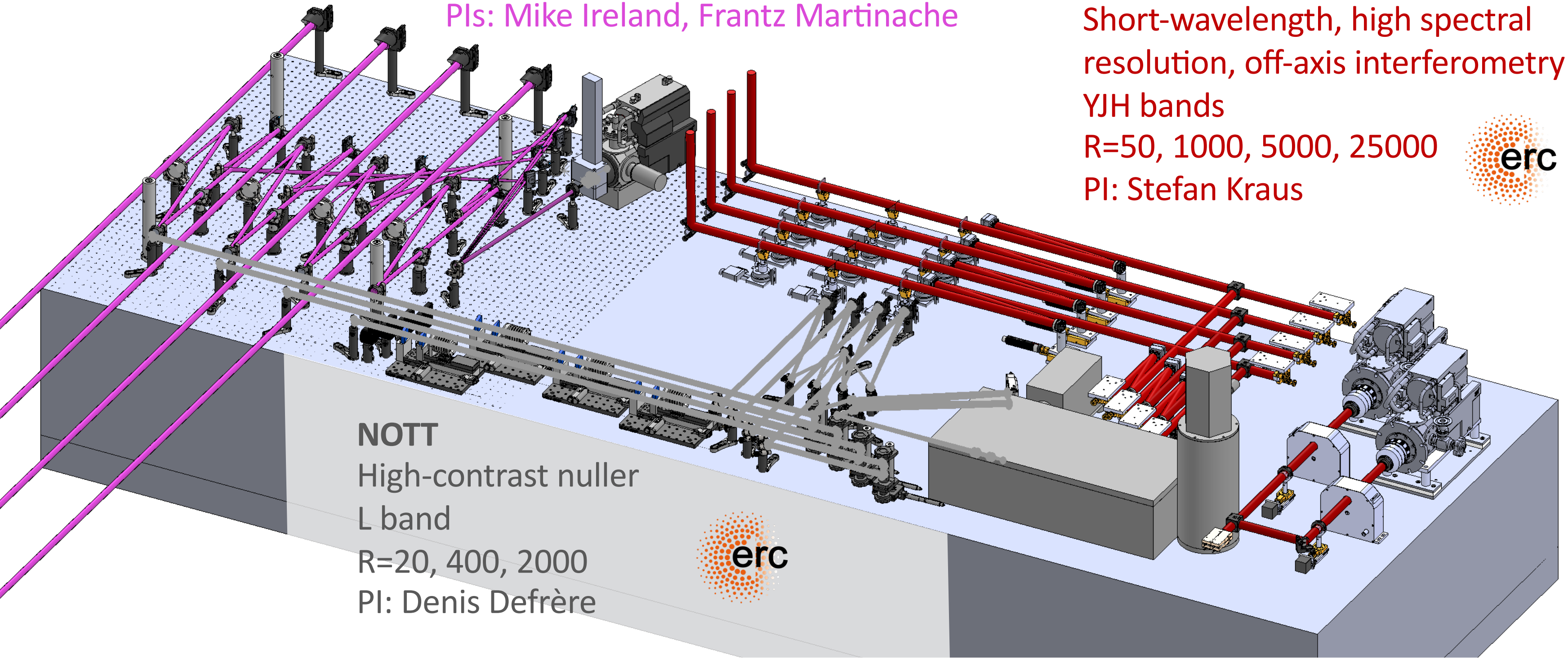
Disks and Planets workshop
ESO Garching, 2022 December 2

Asgard Suite of VLTI Instruments

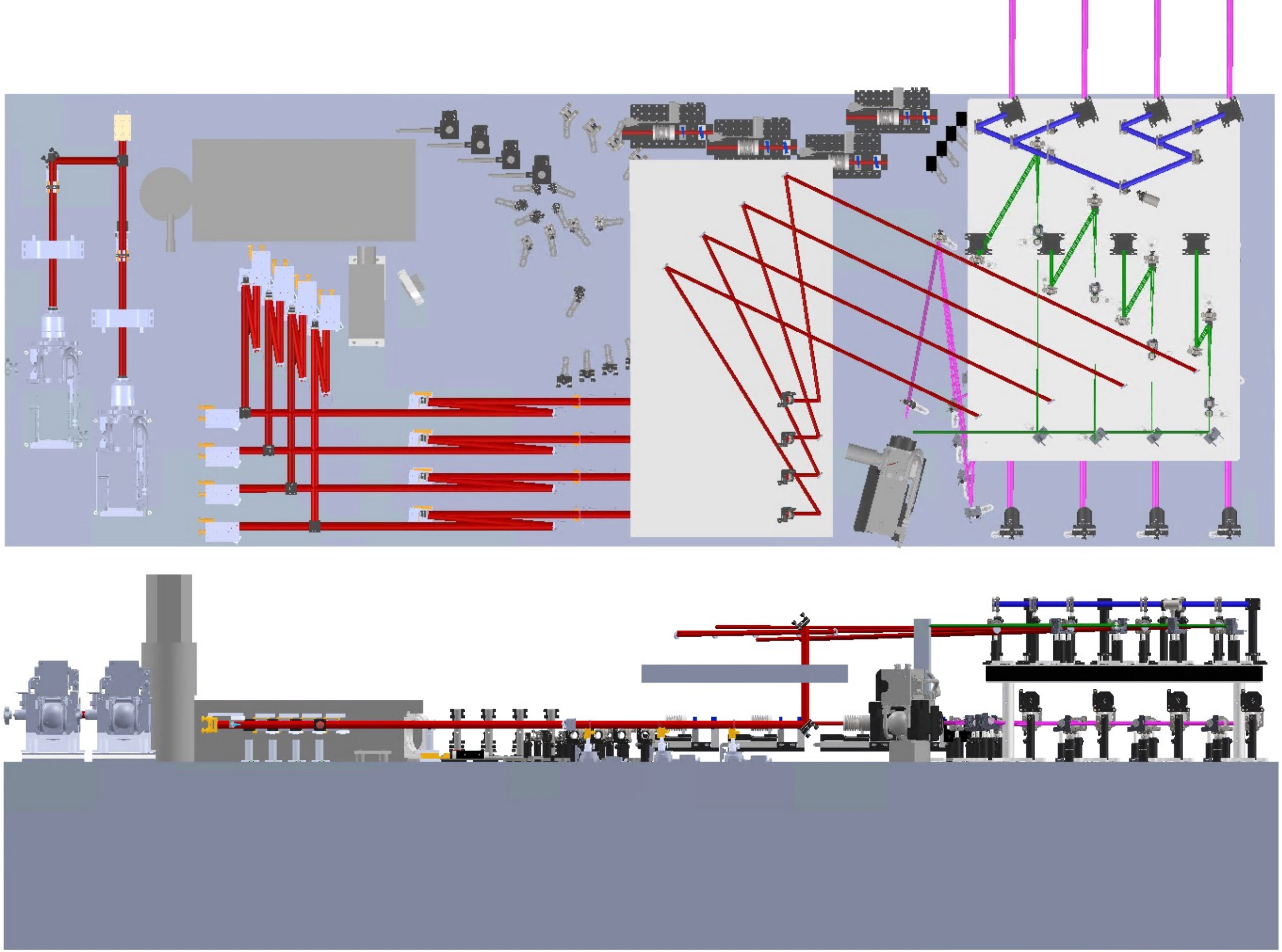
HEIMDALLR
Fringe tracker
Dual K band
PIs: Mike Ireland, Frantz Martinache

Baldr
Lab-AO system
J or H band

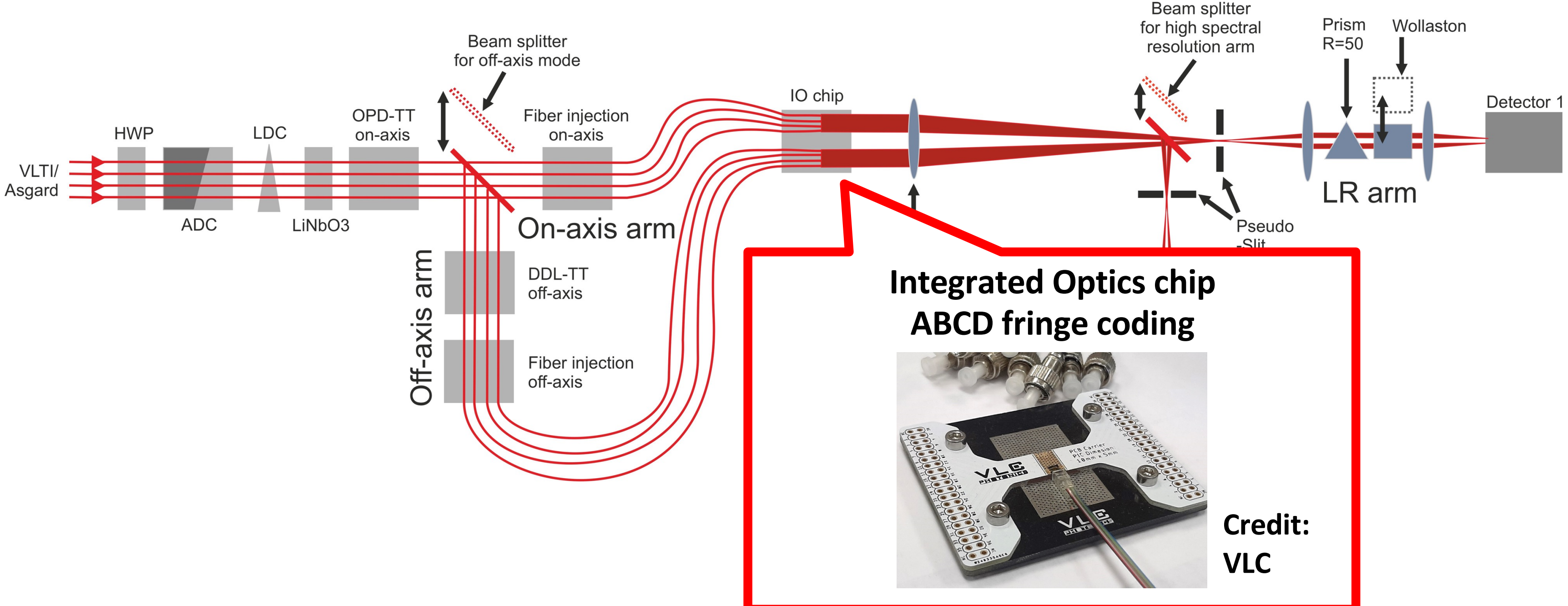
BIFROST
Short-wavelength, high spectral resolution, off-axis interferometry
YJH bands
R=50, 1000, 5000, 25000
PI: Stefan Kraus



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

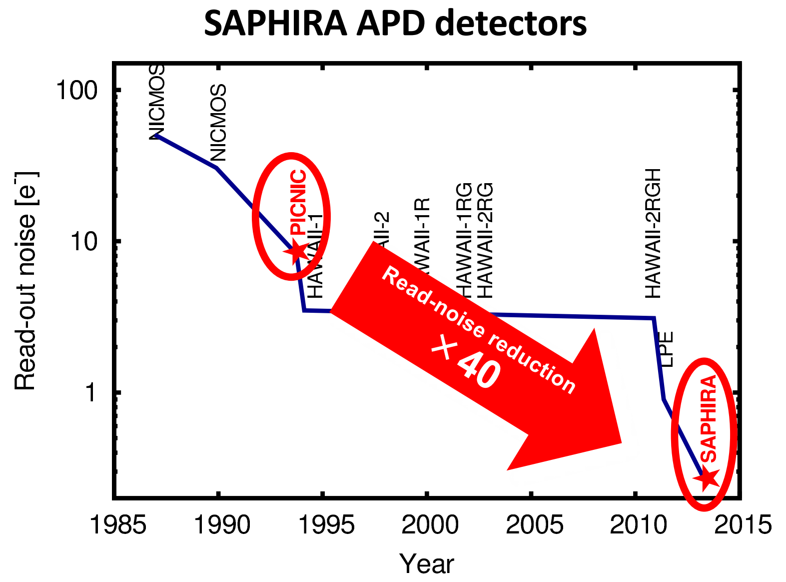


BIFROST Optical Design

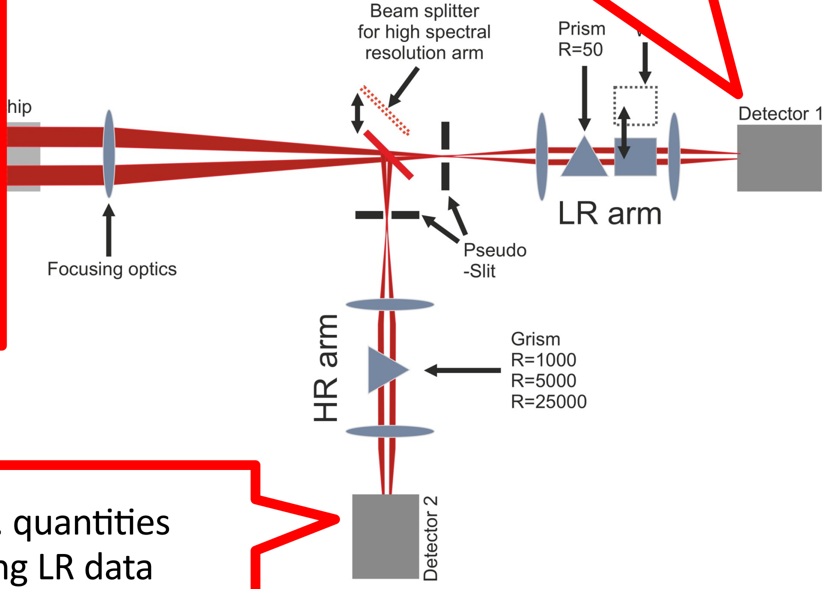


Integrated Optics chip
ABCD fringe coding

Credit: VLC

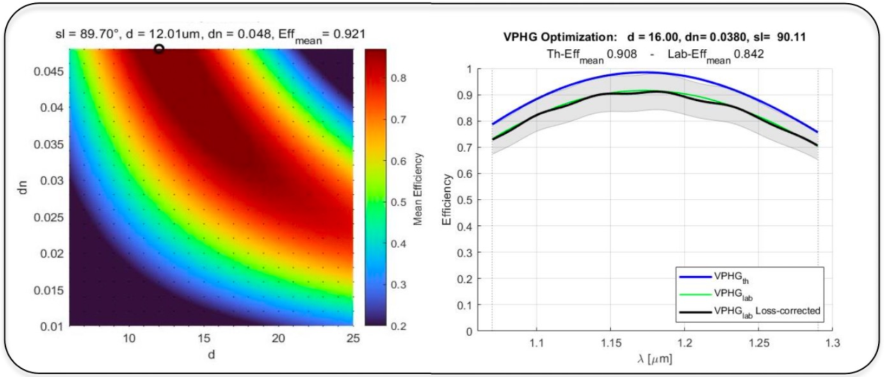


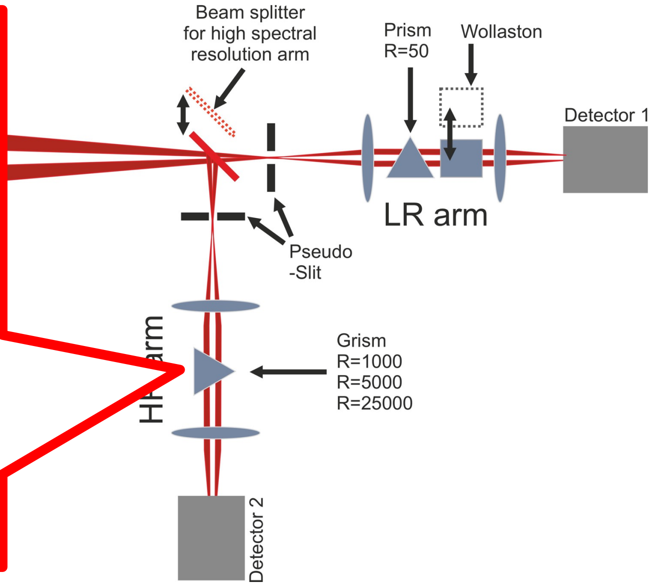
LR arm records photometry & fringe OPD
→ calibrated continuum visibilities
→ feedback loop to LDC and fringe tracker



HR arm records wavelength-diff. quantities
→ frames post-processed using LR data
(frame selection & phasor correction)

Volume Phase Holographic Gratings
manufactured by INAF, Bianco/Frangiamore





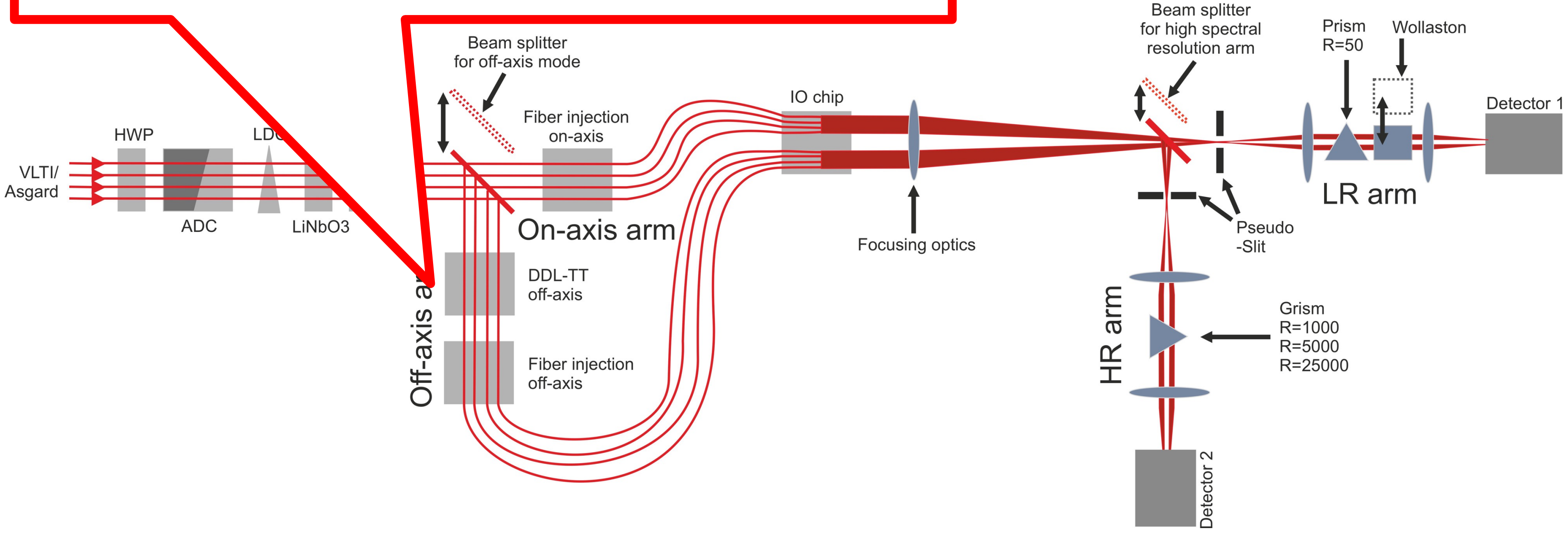
On-axis/off-axis arm (equiv. GRAVITY dual-field):

On-axis and off-axis light

...combined in same IO device,

...passing through same spectrograph,

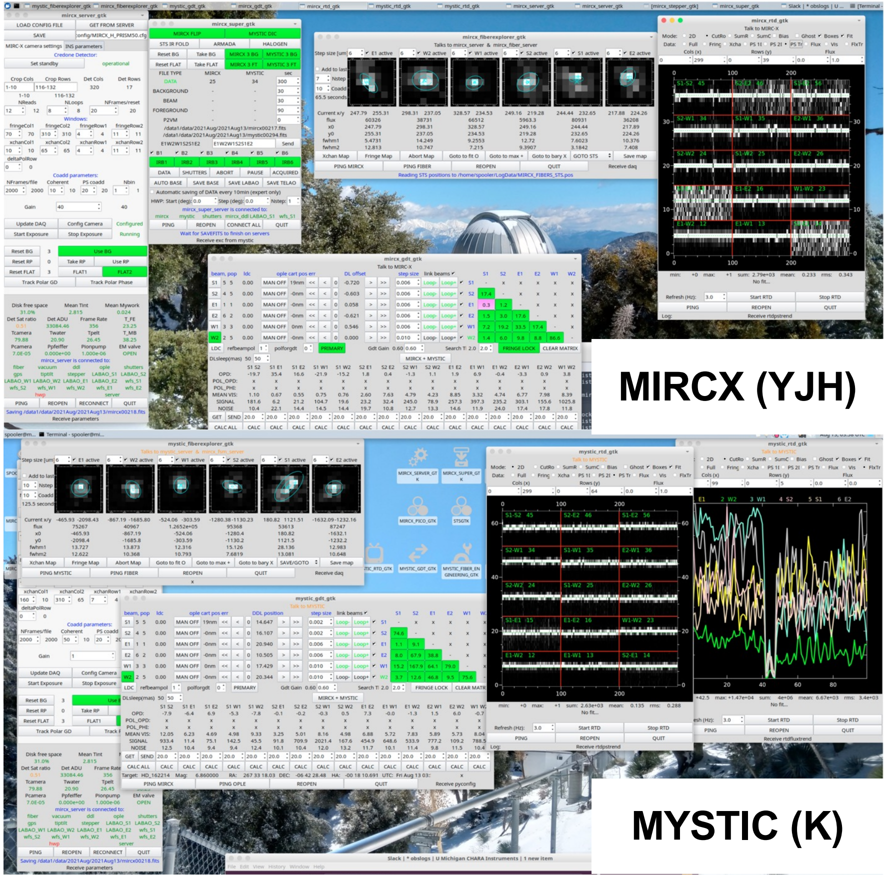
...registered side-by-side on same detectors



BIFROST Operations: Legacy from CHARA

Established framework from MIRCX+MYSTIC:

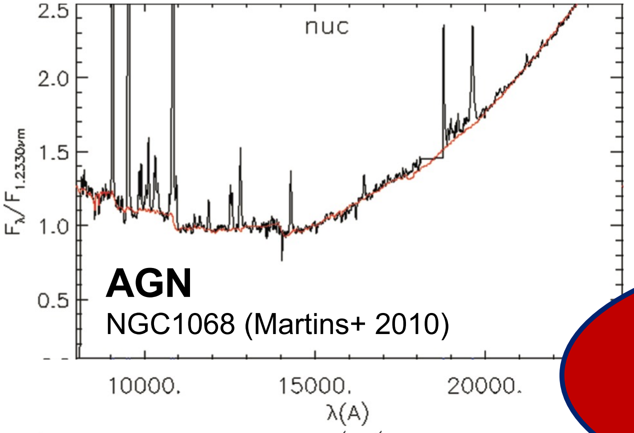
- Optical Design
- Sync. Dual-Arm Operation
- Operational Software
- Data Reduction Software

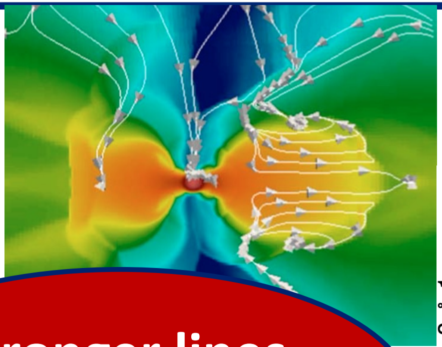


MIRCX (YJH)

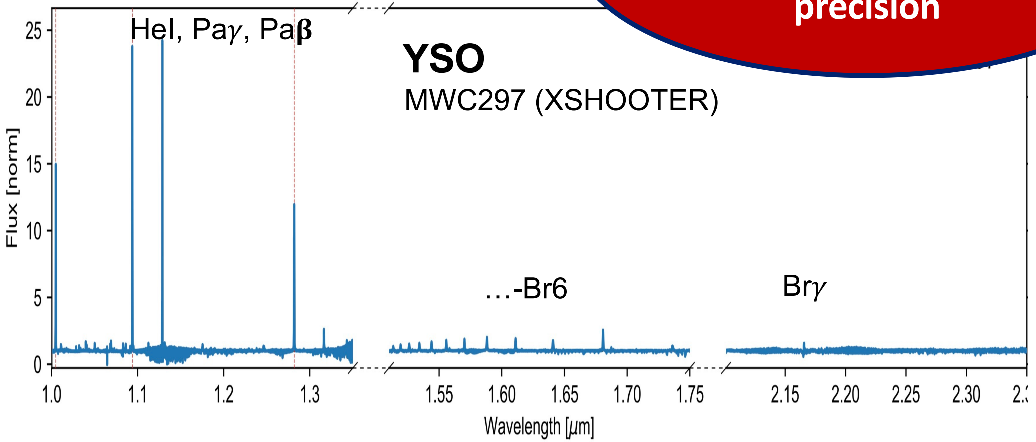
MYSTIC (K)

Why shorter wavelengths at VLTI?

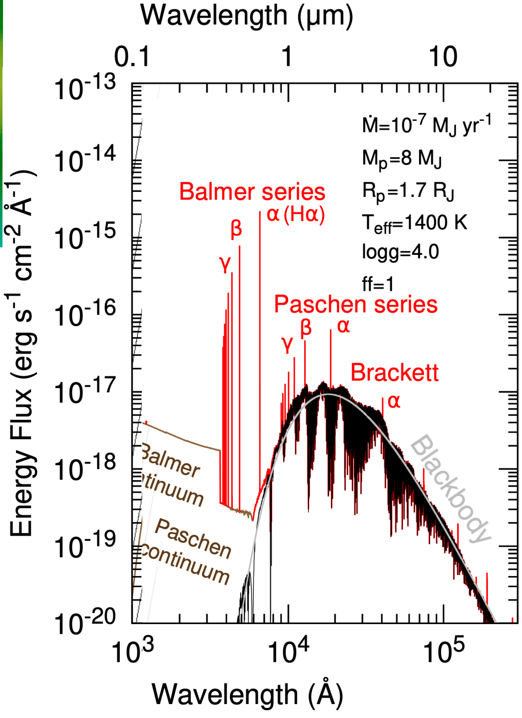




Stronger lines
➜ **sensitivity / SNR / precision**



Circumplanetary Disks

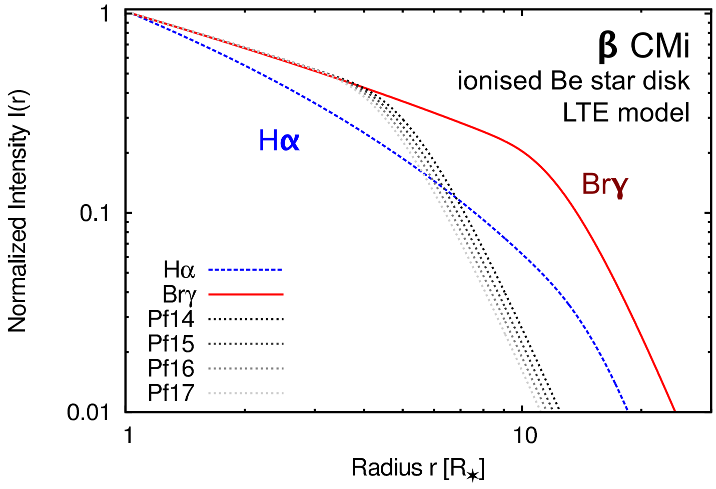


Marleau+ 2022; Szulágyi 2020; Aoyama+ 2020

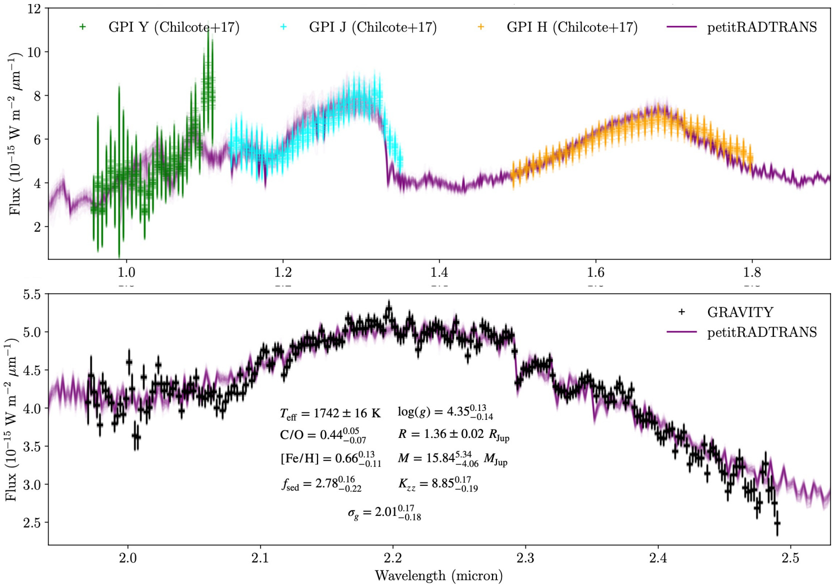
Why shorter wavelengths at VLTI?

Multi-line Transitions
➜ Gas density, Temp., …

New Molecules
➜ Atmosphere composition, Vertical Structure, Clouds, …



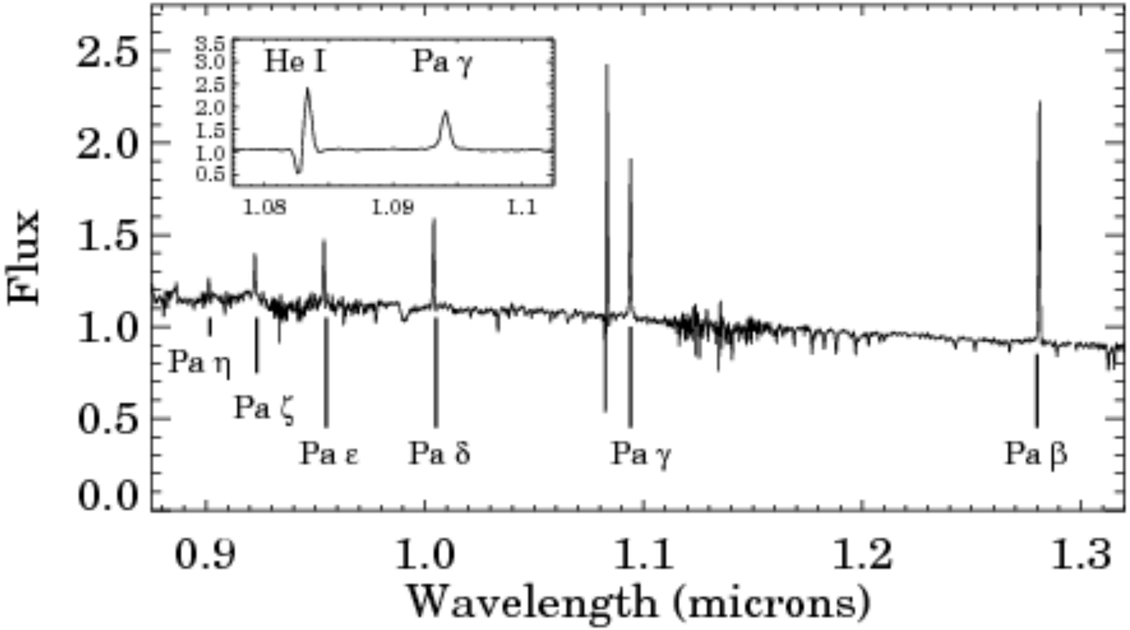
Kraus+ 2012a



Gravity coll. 2020

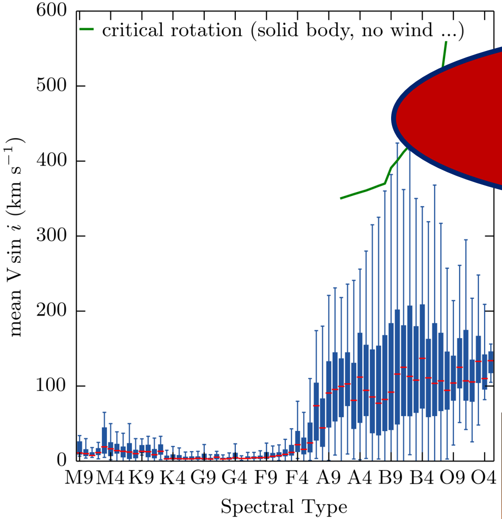
Why shorter wavelengths at VLTI?

New Processes



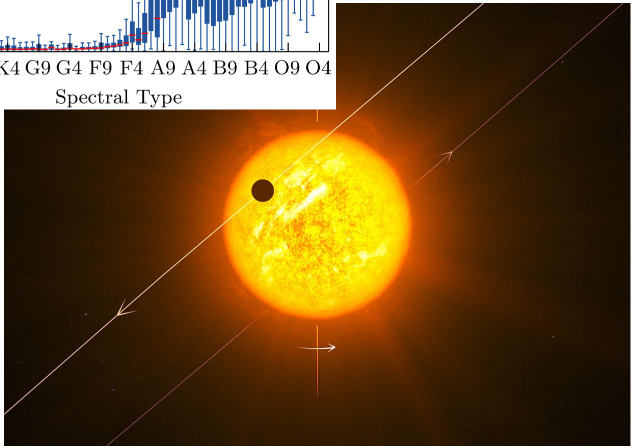
HeI	1.08 μm	(Accretion)
Pa**γ**	1.09 μm	
[Fe II]	1.26 μm	(Jets)
Paβ	1.28 μm	

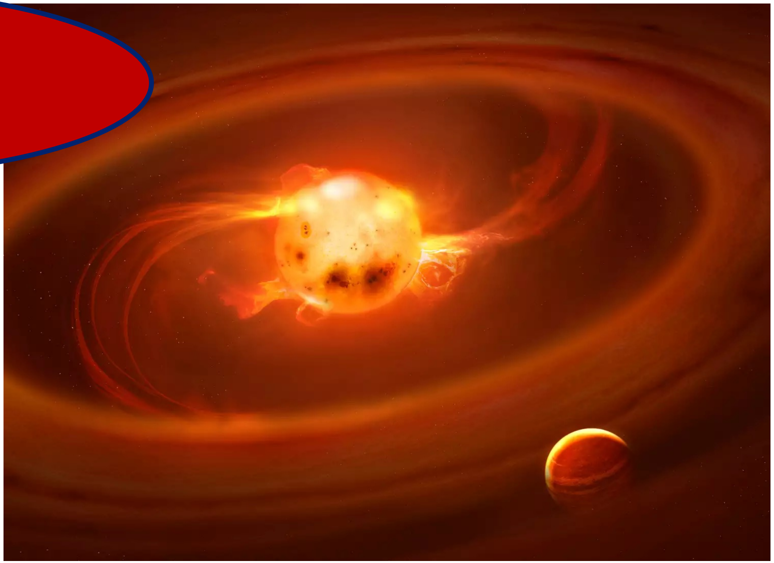
Why spectral resolution R=25,000?



Gas kinematics

Spin-orbit alignment
of slower-rotating stars





Disk kinematics,
accretion,
outflows,
...

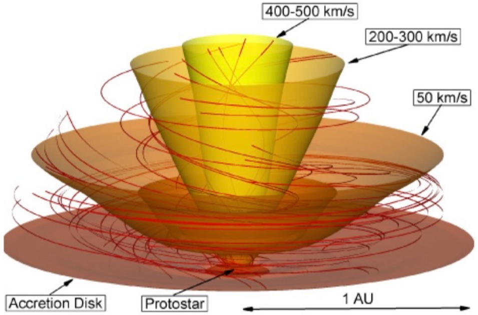
ESO PR; Mark Garlick; Fremat

BIFROST: Science cases on DISKS + EXOPLANETS

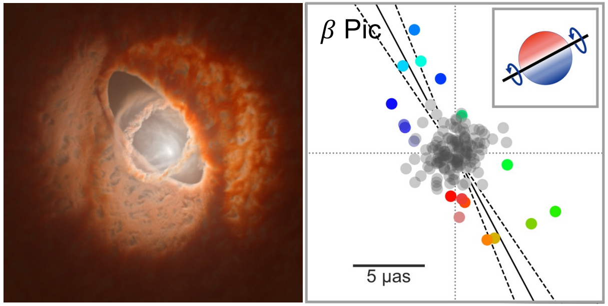
(1) Accretion & Ejection

(2) Orbit Obliquities

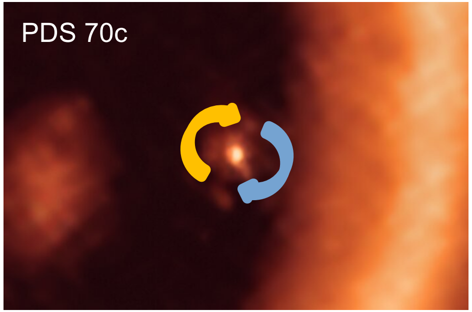
(3) Exoplanet Spectroscopy & Circumplanetary Disk kinematics



How are stars forming?



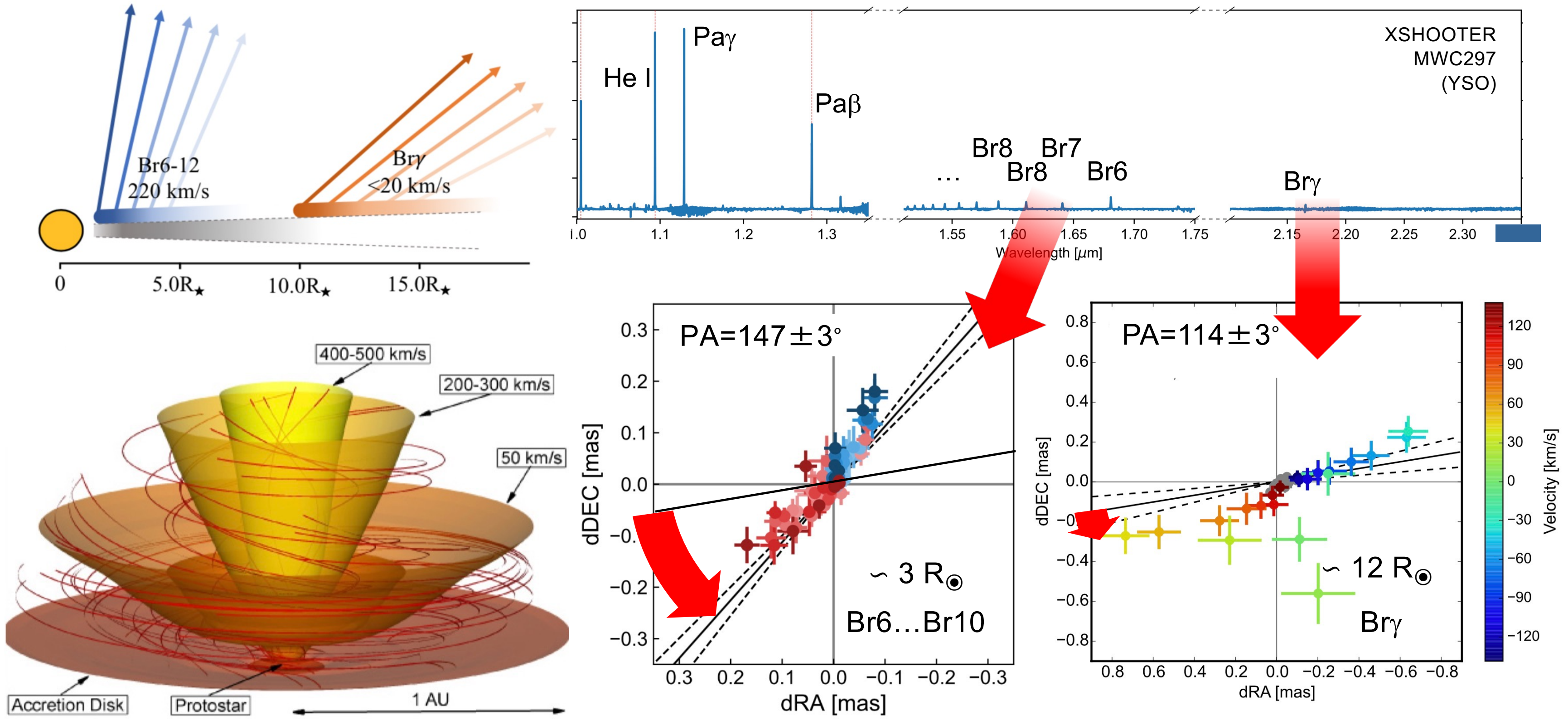
What determines architecture of star & planetary systems?



How are planets forming?

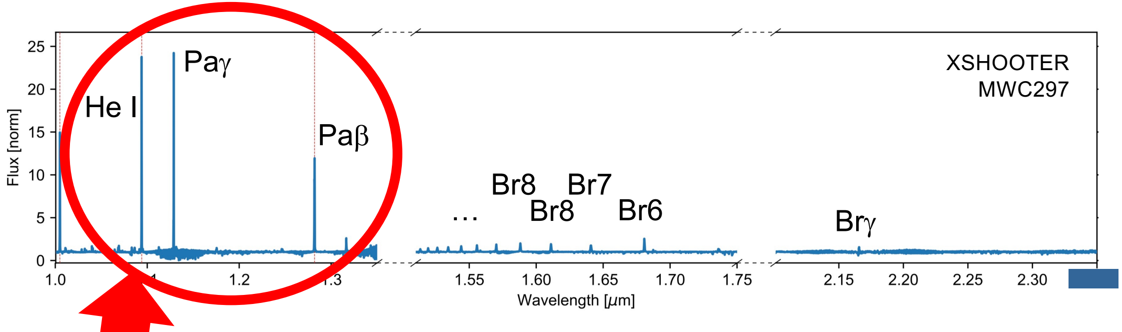
Kraus+ 2020a+b, Romanova+ 2016, Chilcote+ 2007

Science case #1: Accretion & Ejection



Hone+ 2017; Hone+, in prep.; Romanova+ 2016

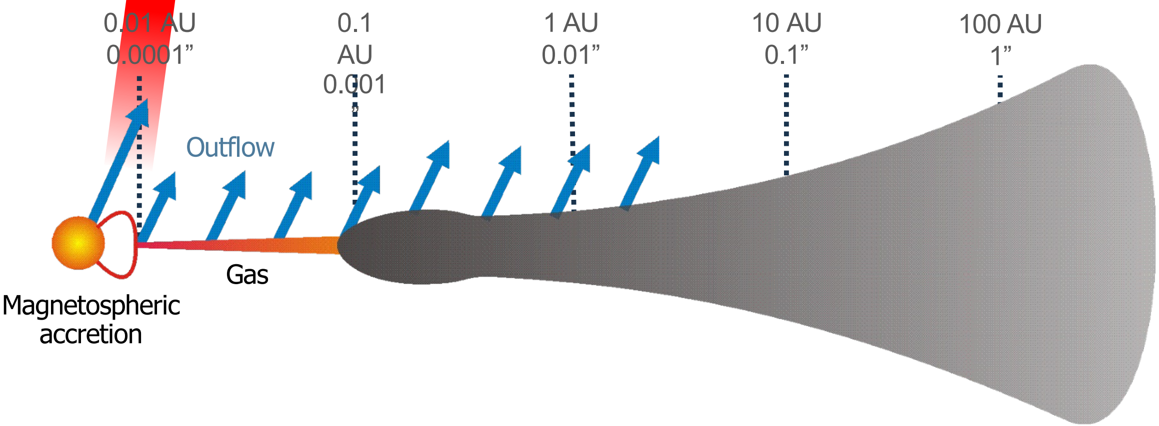
Science case #1: Accretion & Ejection



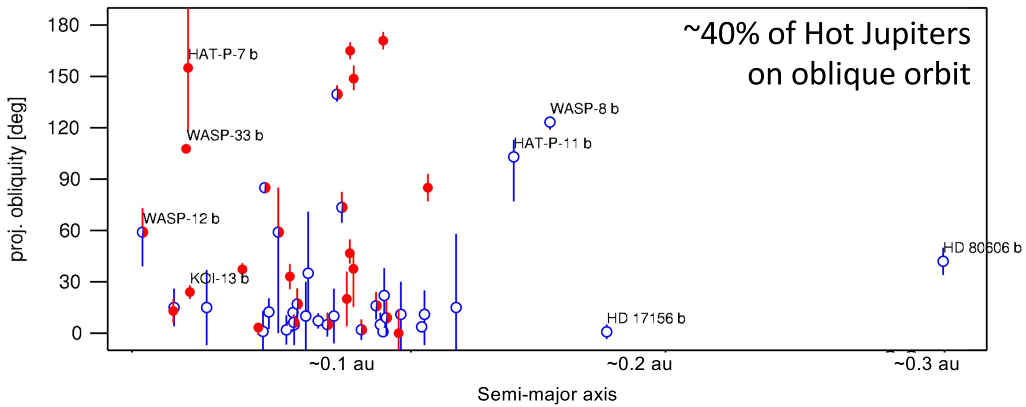
How is angular momentum transport facilitated in disks?

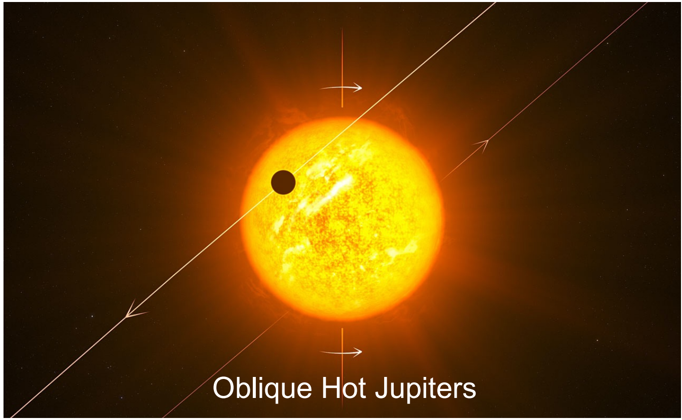
➜ Launching of MHD winds/jets

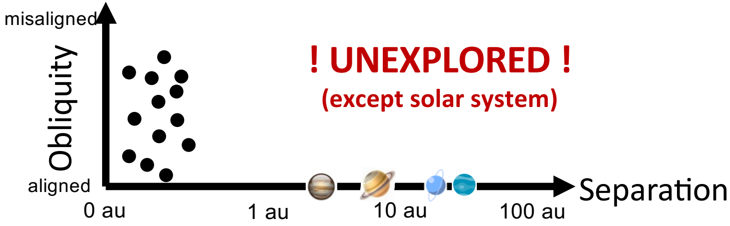
➜ Accretion geometry



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





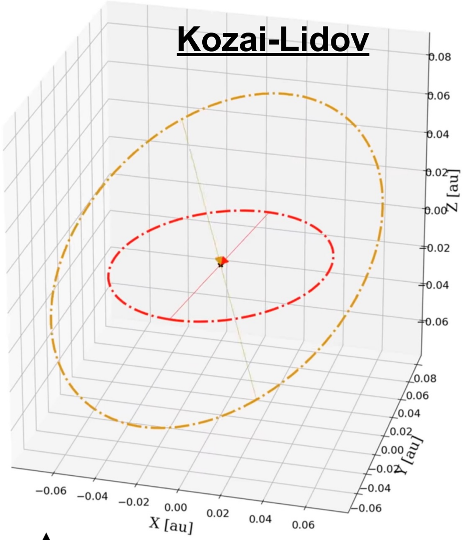


Rossiter-McLaughlin effect allows measuring spin-orbit alignment ("obliquity") for **transiting systems**

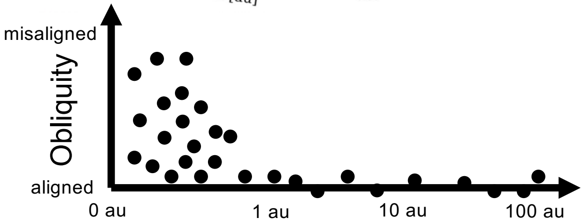
Albrecht+ 2012; Romanova+ 2013

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

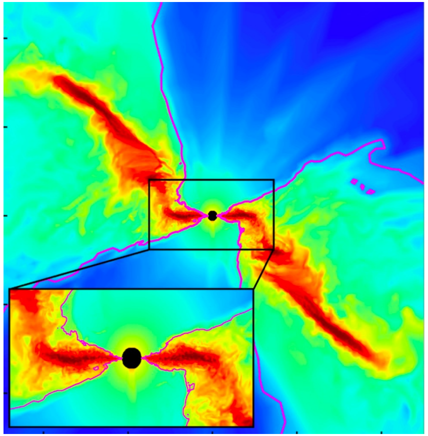
Kozai-Lidov



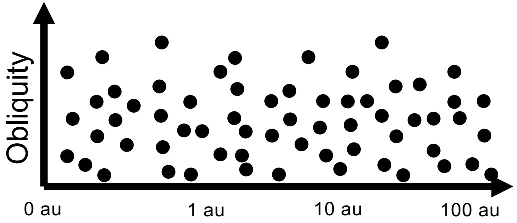
Migration accompanied by orbital tightening



Primordial misalignment



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

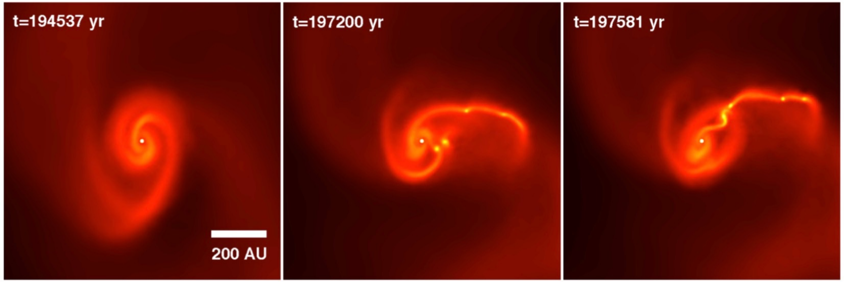


Measuring spin-orbit alignment for wide-separation systems decisive test on formation + dynamical evolution

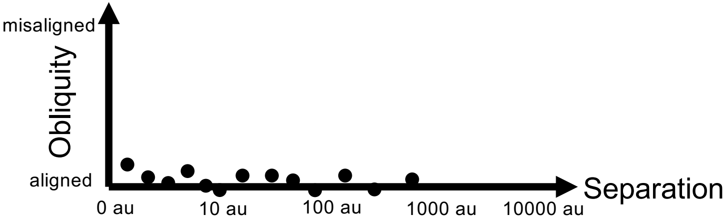
Liska+ 2019; Livingston

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

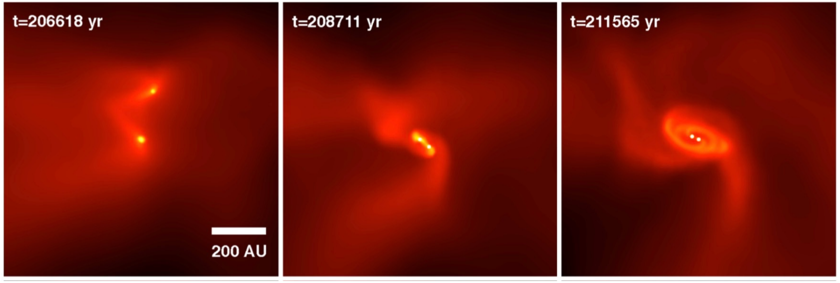
DISK fragmentation



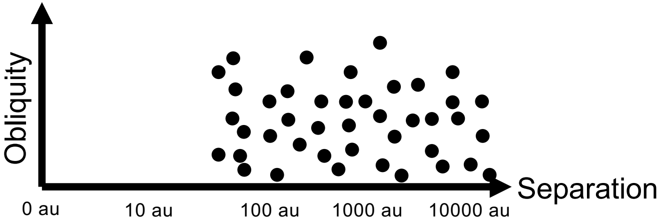
Companions form in coplanar circumstellar disk through fragmentation



CLOUD fragmentation



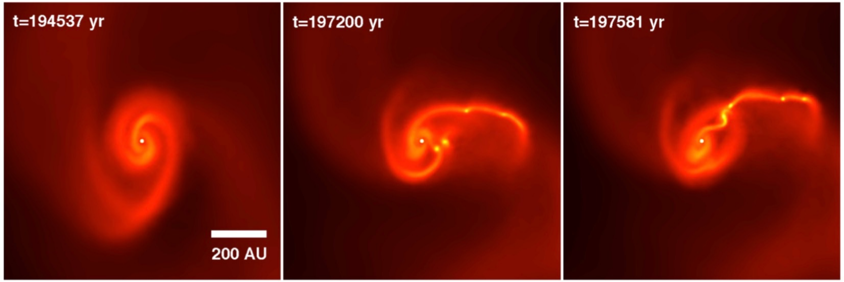
Stars form separately and undergo star-disk encounter to form tight binary



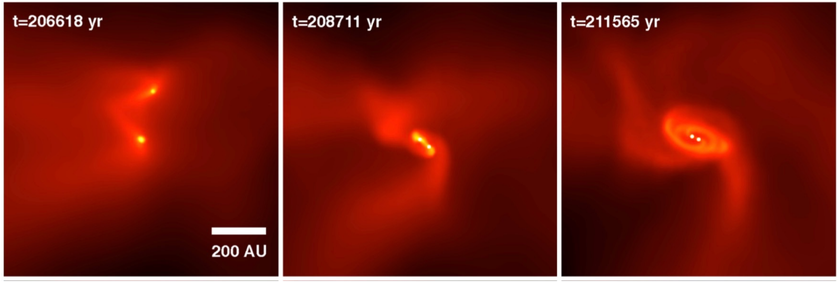
Bate 2018

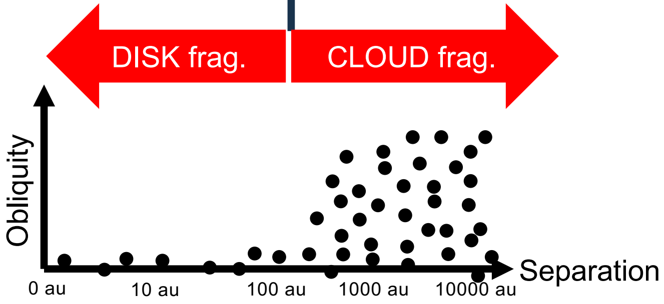
Science case #2: Dynamical History of Stellar/Planetary Systems

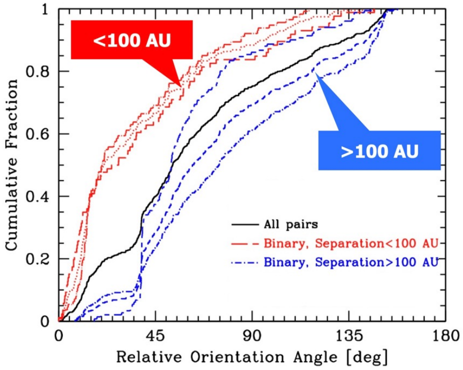
DISK fragmentation



CLOUD fragmentation

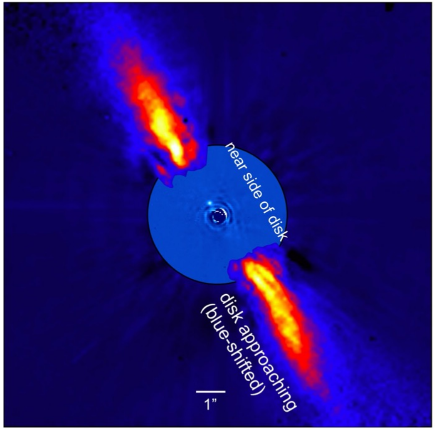


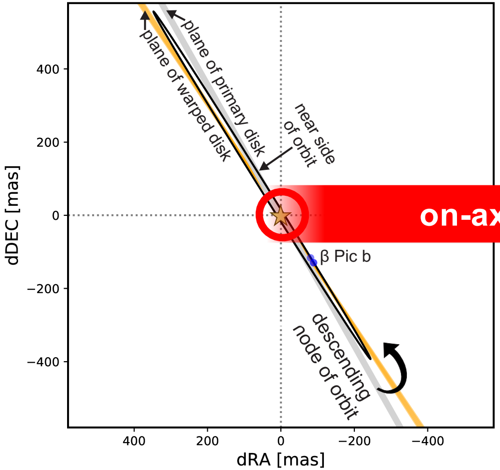




Spin-spin alignment from Bate 2018 cloud-collapse SPH simulation

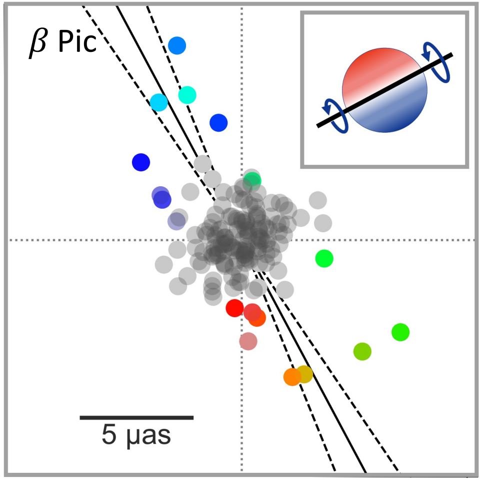
Science case #2: Dynamical History of Stellar/Planetary Systems





on-axis

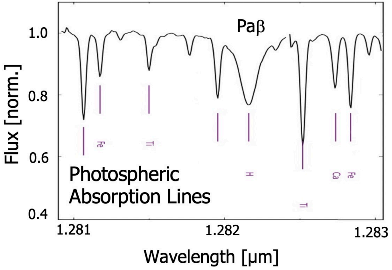
ATs:
orbit
obliquity



BIFROST's R=25000 mode

➜ Spin-orbit alignments for smaller stars & slow rotators

➜ Higher astrometric precision from accessing atomic lines

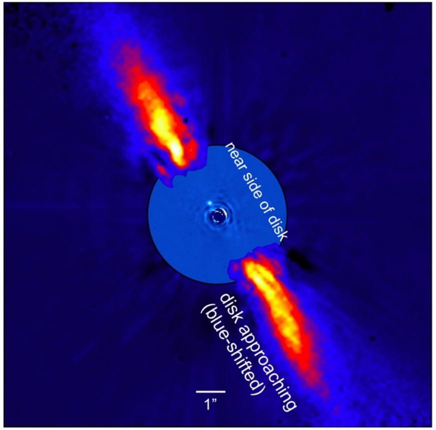


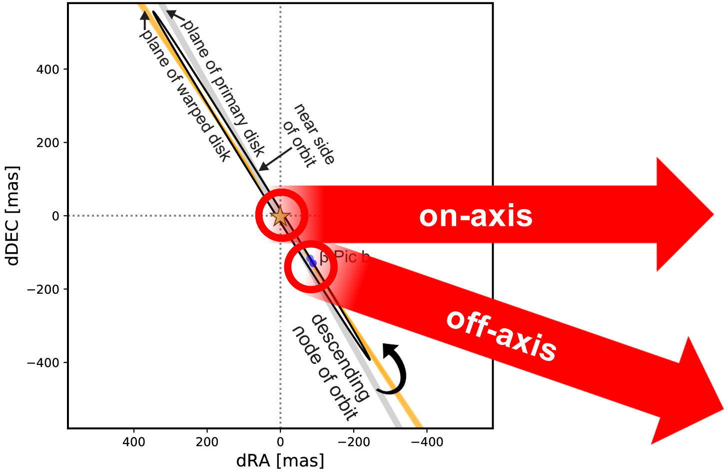
β Pic: 3-D obliquity angle 3±5º

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

Kraus+ 2020b; ESO/Lagrange/SPHERE; Nicholls+ 2017

Science case #3: Exoplanets & Circumplanetary Disks





Fringe tracker Heimdallr

K band

BIFROST

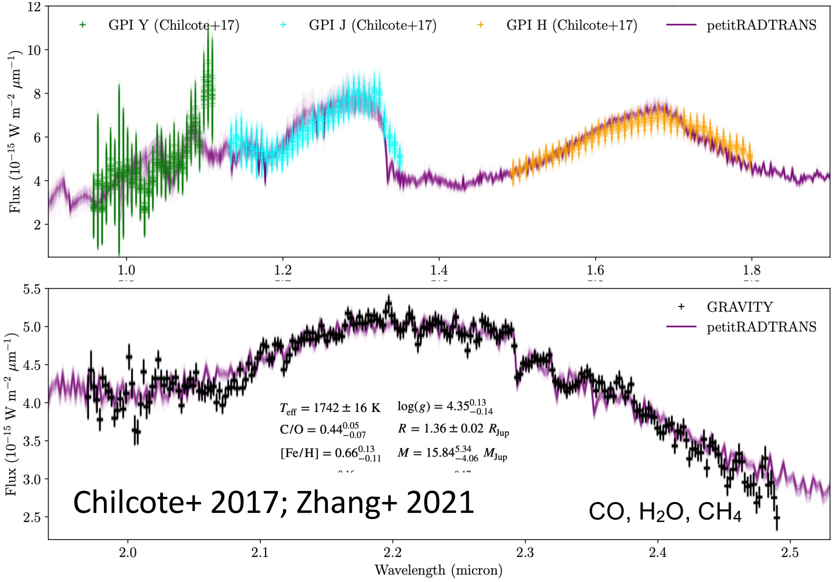
YJ or H band, R=50

BIFROST

YJ or H band,

R=1000, R=5000, R=25000

Science case #3: Exoplanets & Circumplanetary Disks

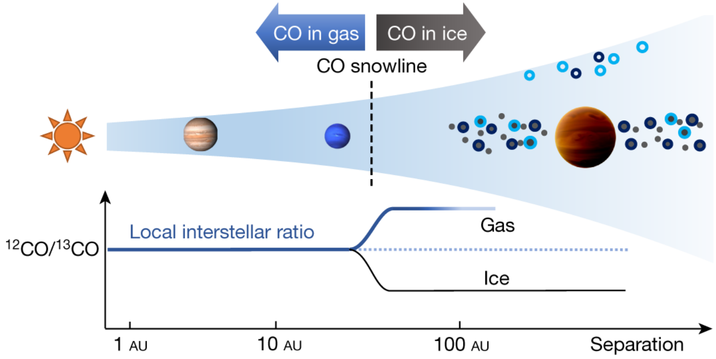


β Pic b retrieval (GRAVITY collab. 2020)

Fit performed	T (K)	$\log(g/g_0)$	Metallicity [Fe/H]	C/O ratio	Mass (M_{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	$4.34^{+0.08}_{-0.09}$	$0.68^{+0.11}_{-0.08}$	$0.43^{+0.04}_{-0.03}$	$15.43^{+2.91}_{-2.79}$

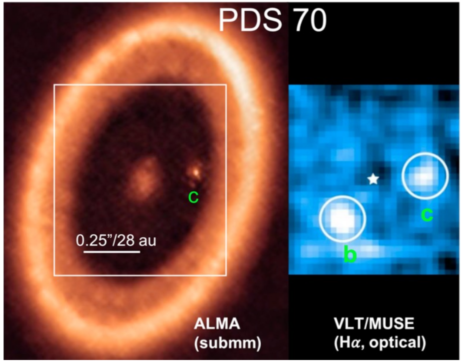
BIFROST wavelength range (1-1.7 µm) complements GRAVITY+:

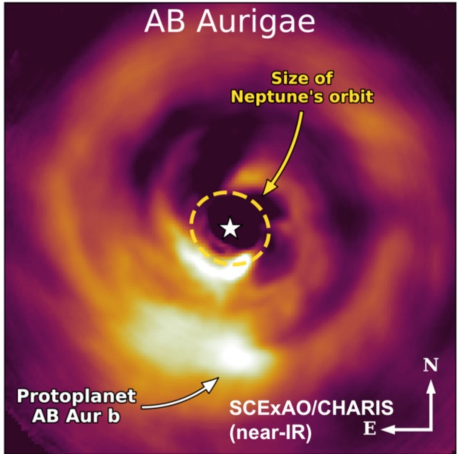
- **surface gravity**
- **cloud particle sizes**
- **new molecules**



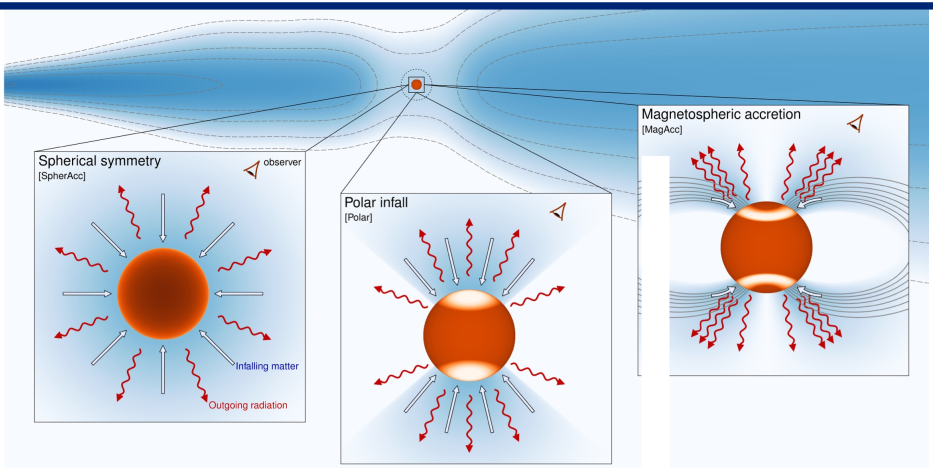
→ **Formation location**
from volatile abundances / isotopologues
(C/O, ^{12}CO/^{13}CO, …)

Science case #3: Exoplanets & Circumplanetary Disks





Currie+ 2022



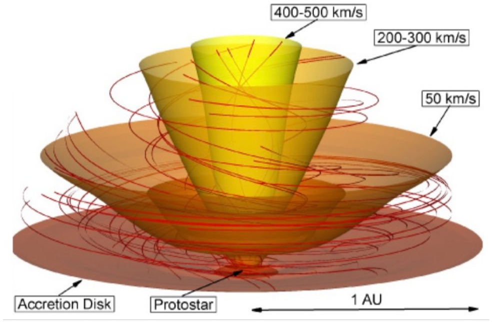
Observability of PDS70b CPD with BIFROST:

planet mass:	$<10\ M_J$
separation from star:	19 au = 0.19”
$L_{Pa\beta}$ / $L_{\odot}$:	2.7×10^{-8} (Aoyama+ 2021 model prediction)
Line width:	100 km/s FWHM
Integration time:	5.9 hrs for 3σ detection

Asgard Suite of VLTI visitor instruments

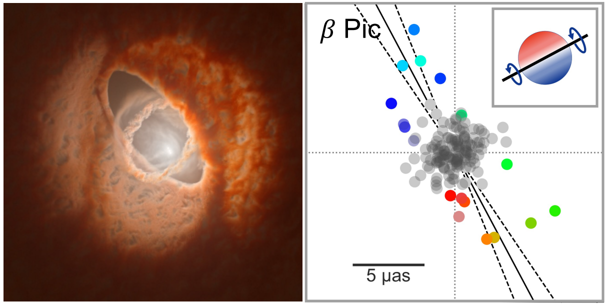
YJ/H band:	*BIFROST*	high spectral resolution + off-axis
H band:	*Balldr*	adaptive optics
K band:	*Heimdallr*	fringe tracker
L band:	*NOTT*	nuller

(1) Mass accretion & Ejection



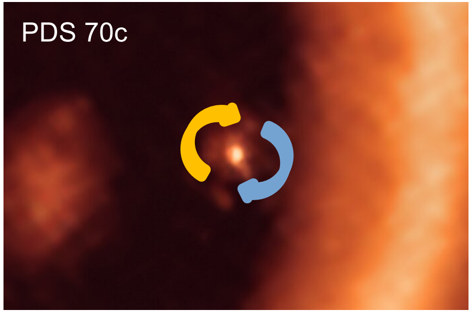
How are stars forming?

(2) Orbit Obliquities



What determines architecture of star & planetary systems?

(3) Exoplanet Spectroscopy & Circumplanetary Disks



How are planets forming?