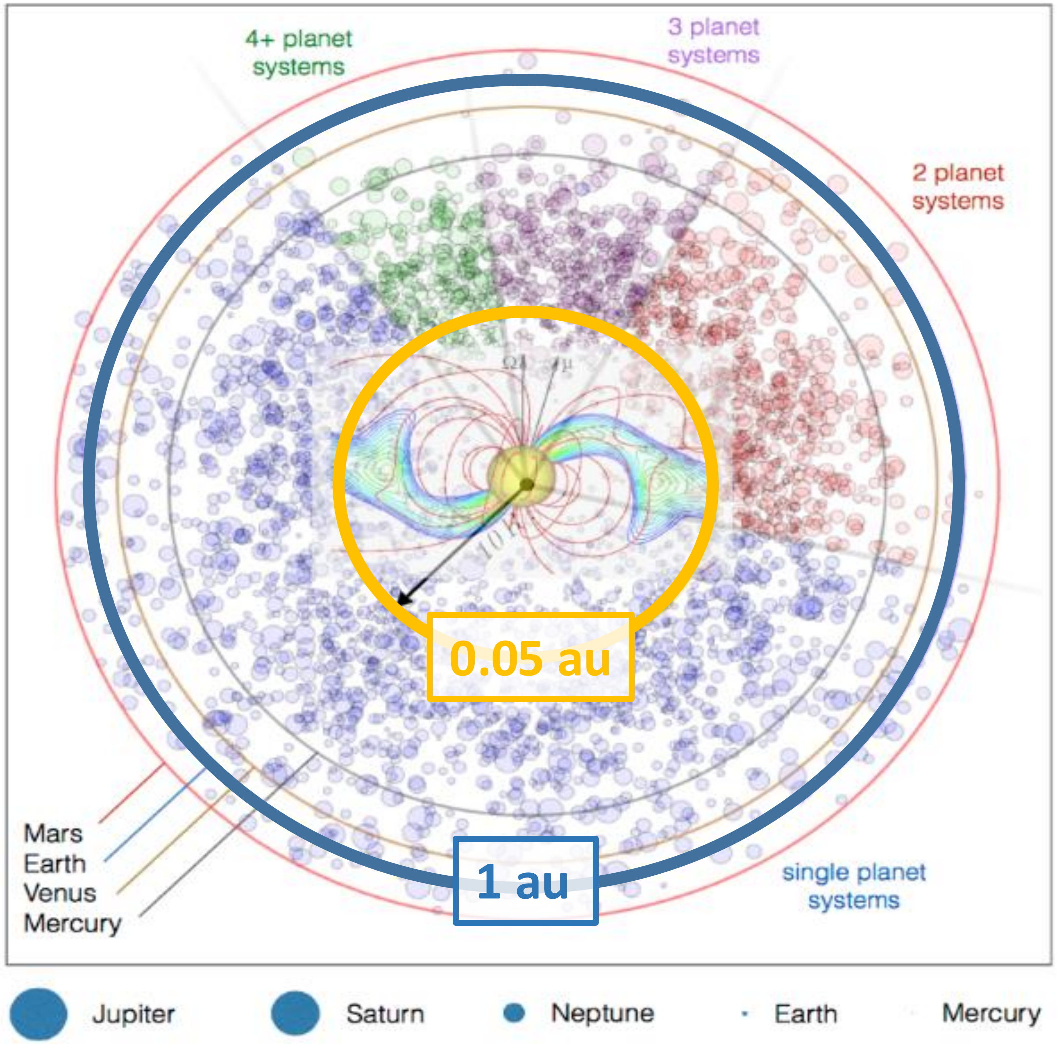
Young Stellar Object with GRAVITY and perspective of GRAVITY+

Karine PERRAUT
on behalf the GRAVITY Collaboration

Université Grenoble Alpes

IPAG

Close-in low-mass planets



[Blinova+2016]

[Batygin&Laughlin 2015]

Current population of known exoplanets:

- **Wide diversity in nature and architecture**
- **Many close-in low-mass planets revealed by Kepler**

⇒ Origin of diversity? Which processes determine the final outcome of planetary systems?

⇒ Which initial conditions would favor compact, short-period multi-planet systems in the inner disk, at a distance ranging from 0.1 au to a few au from the central star?

[Mishra+2023; Batygin & Morbidelli 2023]

Exploring the birthplace of the close-in planets: The protoplanetary disks

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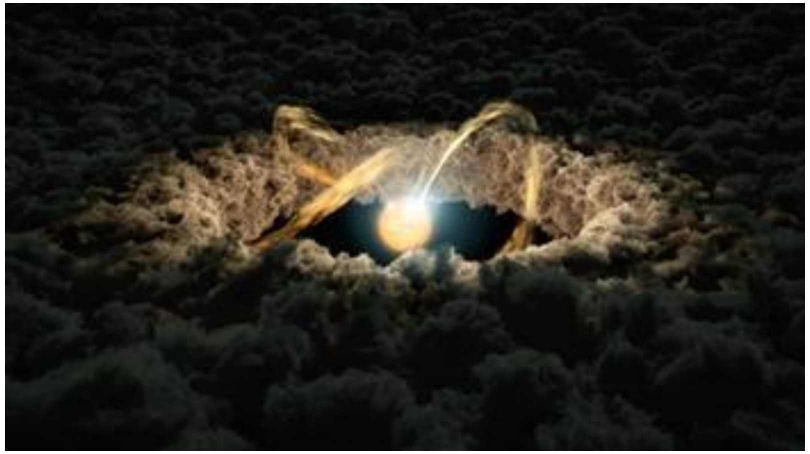
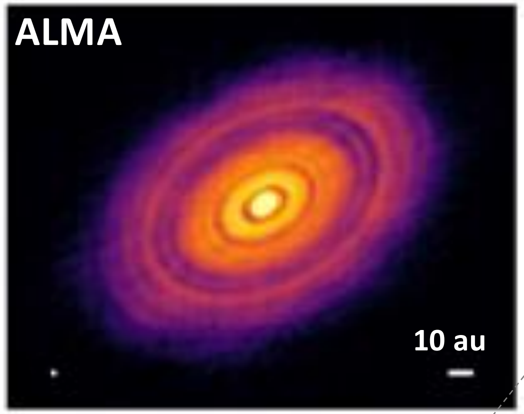
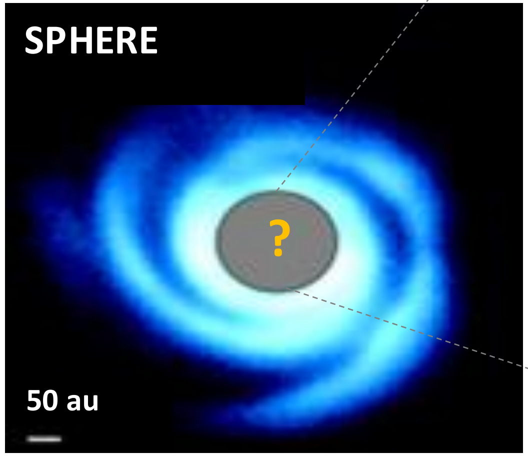
- Material reservoir from which star and planets are formed.
- Planet formation when the YSO still actively accreting from its circumstellar disk.
- Accretion of disk material impacts star's properties and evolution
- High-energy radiation drastically affects physical and chemical evolution of the proto-atmosphere of nascent planets
- Star formation, planet formation and disk evolution processes occur simultaneously and influence each other
- Brief (a few Myr) but foundational mutual influences



Observe **structures** and **evolution** of protoplanetary disks ***while*** planet formation is happening

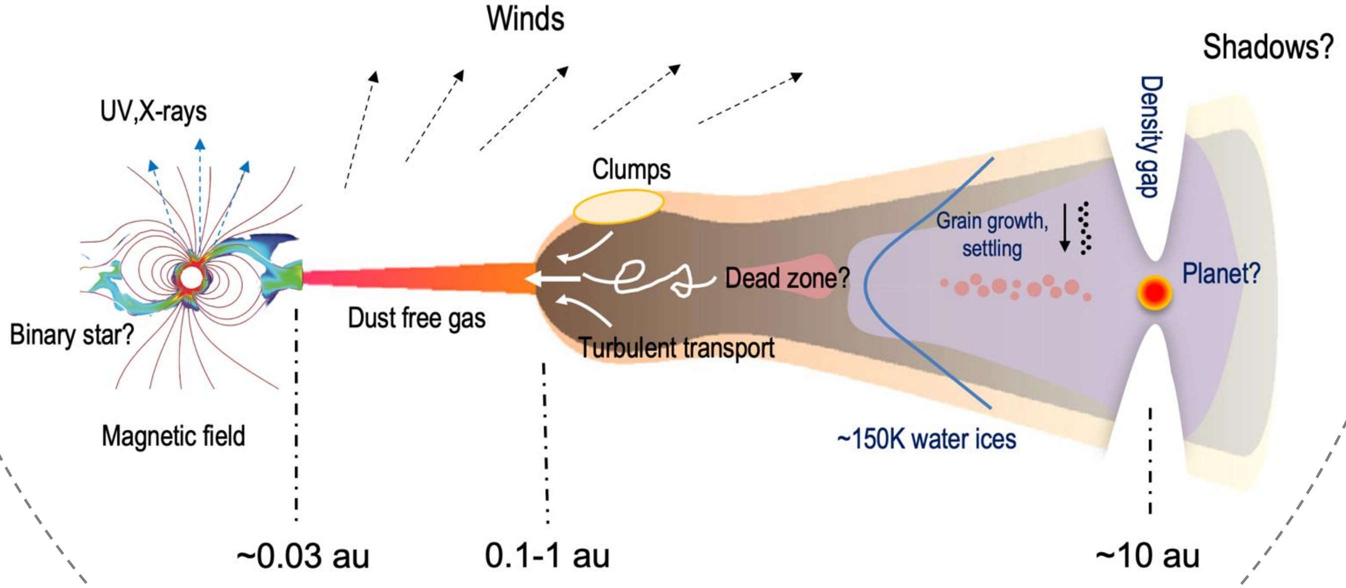
Probing the first au with GRAVITY





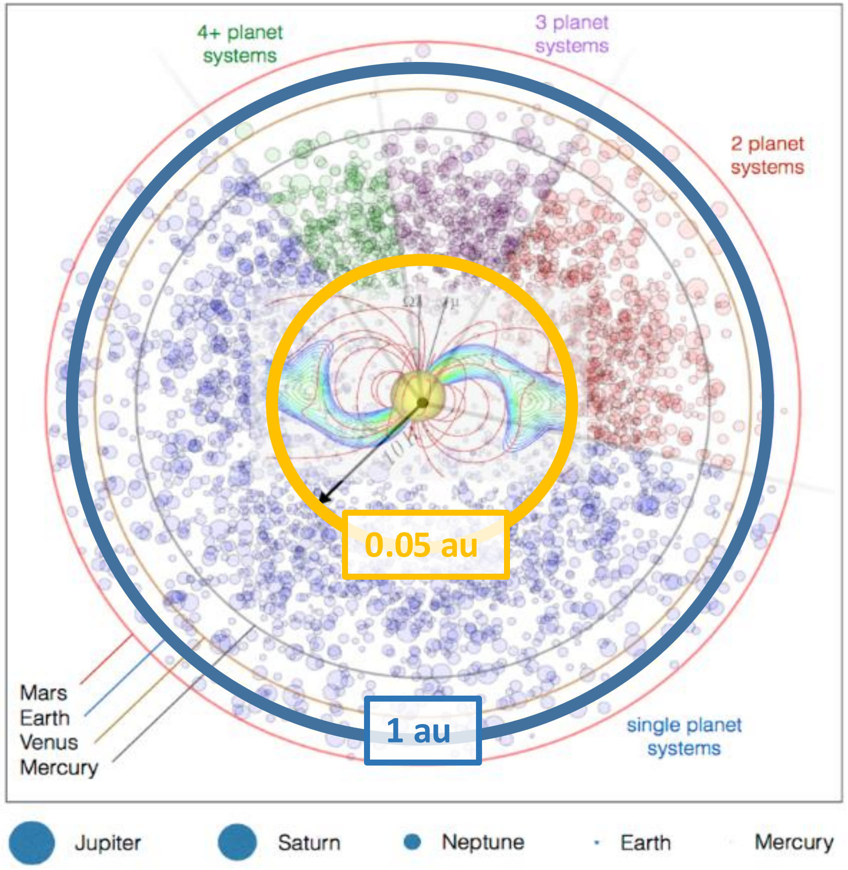
Zooming-in to study:

- Inner rim of the dusty disk
- Star-disk interaction region



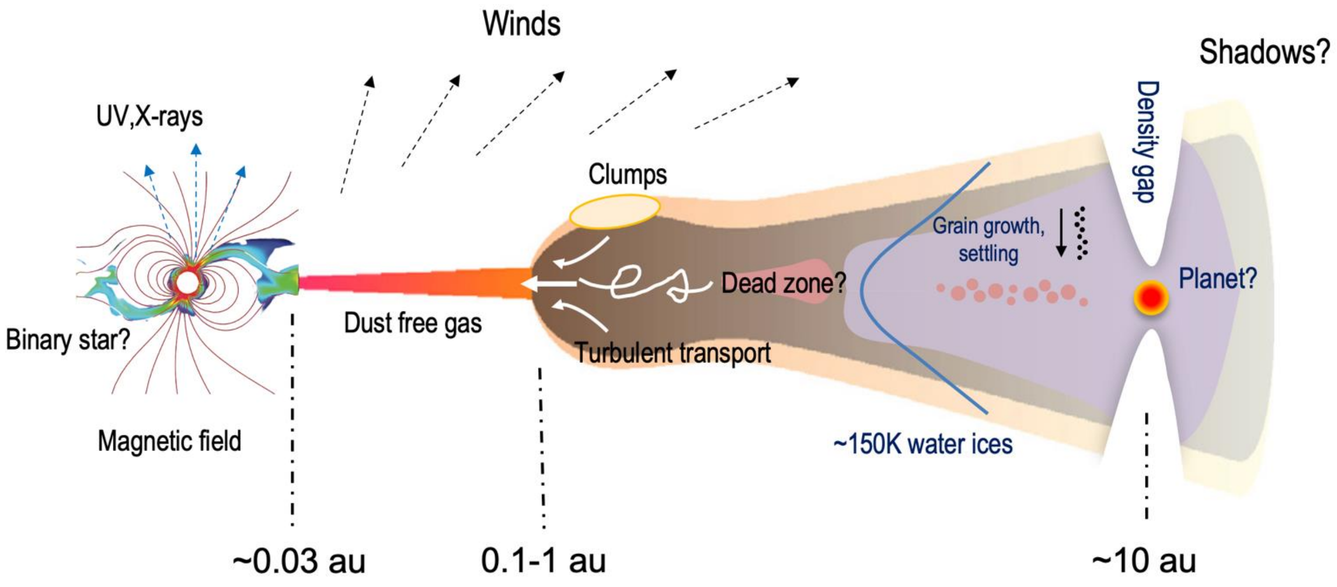
[adapted from Henning 2013]

Probing the first au with GRAVITY...



... within a multi-technique and multi-λ approach

(visible/NIR/MIR, interferometry/spectroscopy/spectro-polarimetry, ...)

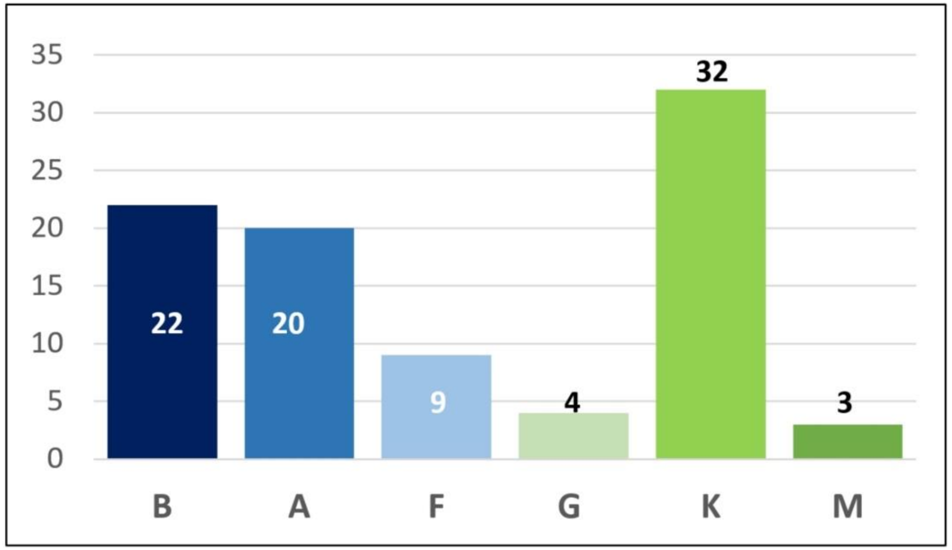


The GRAVITY YSO Large Program

GRAVITY Coll., 2017, A&A, 608, 78
GRAVITY Coll., 2019, A&A, 632, 53
GRAVITY Coll., 2020, A&A, 635, 12
GRAVITY Coll., 2020, Nature, 584, 546
GRAVITY Coll., 2020, A&A, 642, 162
GRAVITY Coll., 2021, A&A, 645, 50
GRAVITY Coll., 2021, A&A, 648, 37
GRAVITY Coll., 2021, A&A, 654, 97
GRAVITY Coll., 2021, A&A, 655, 73
GRAVITY Coll., 2021, A&A, 655, 112
GRAVITY Coll., 2023, A&A, 669, 59
GRAVITY Coll., 2023, A&A, 674, 203
GRAVITY Coll., 2024, A&A, 682, 165
GRAVITY Coll., 2024, A&A, 684, 43
GRAVITY Coll., 2024, A&A, 684, 200
GRAVITY Coll., 2024, A&A, 690, 123
GRAVITY Coll., 2024, A&A, 684, 200

Aims.

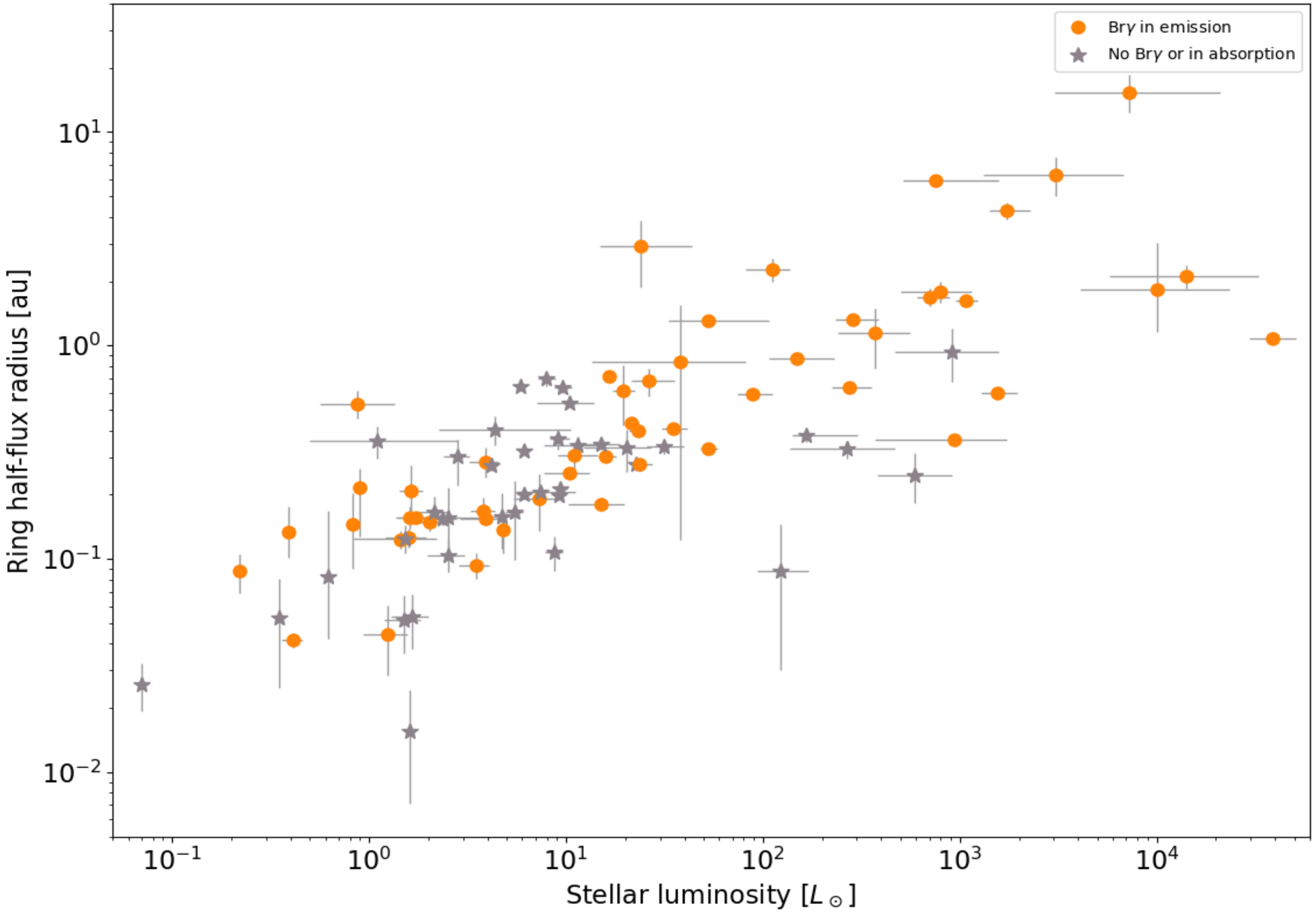
- Use the 4 telescopes, the sensitivity and accuracy of GRAVITY to investigate the findings of the pioniering works [Millan-Gabet+2001; Eisner+2005; 2007; 2014; Monnier & Dullemond 2010; Kraus 2015] within a statistical approach.
- Spatially resolve the dust emission and the morphology of the innermost regions of the disk (dust sublimation front, asymmetries, …)
- Connect the inner disk's morphology and structures to those of the outer disk
- Use the spectral resolution (R ~4000) to study the emitting regions and the kinematics of the hot (HI Brγ) and warm (CO) gas



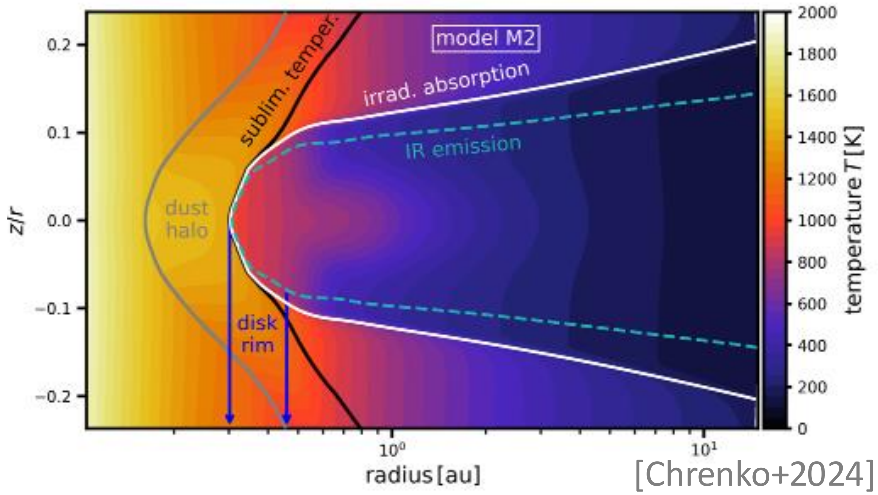
[~ 3-10 $M_\odot$] [~ 1-2 $M_\odot$]

Revisiting the Radius-Luminosity relation

$R \alpha L_*^{1/2}$



Consistent with passively irradiated disk with optically thin cavity (dust sublimation)



[Chrenko+2024]

Light scattering at low L*? [Pinte+2008]
Scatter at large luminosities: backwarming, accretion, self-shielding?

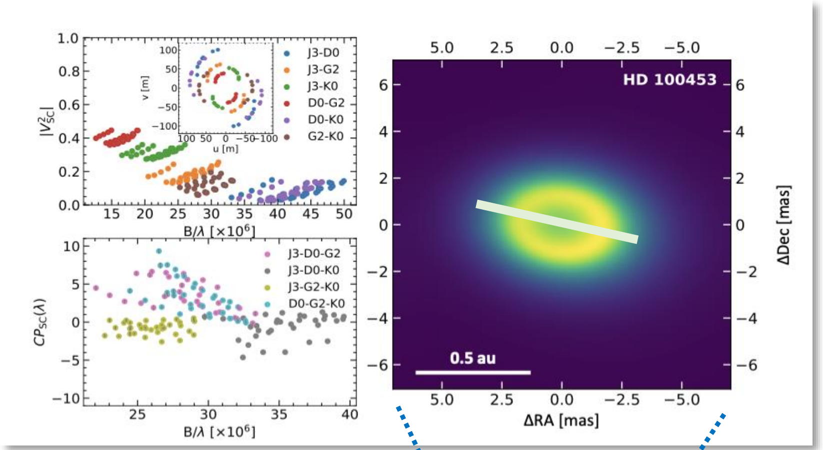
GRAVITY Coll. Perraut+2019, 2021, in prep

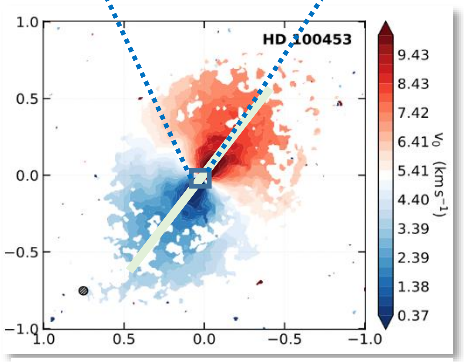
The link between inner and outer disk

Statistical study on 20 disks with dust-depleted cavities: 6 with inner/outer disk misalignment

Bohn+2022

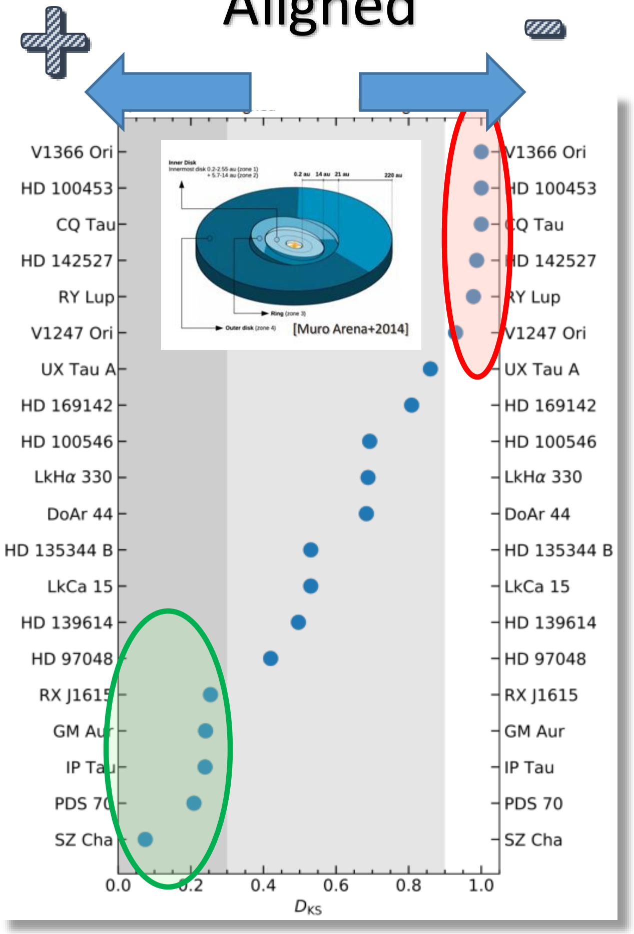
GRAVITY K-band inner disk



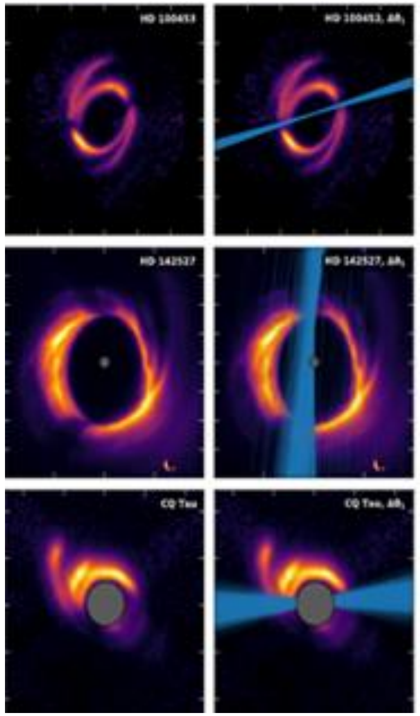


ALMA CO outer disk

Aligned



SPHERE shadows



Warps?
Massive companion?
Outcome of earlier stages?

Imaging sub-structures in the inner regions

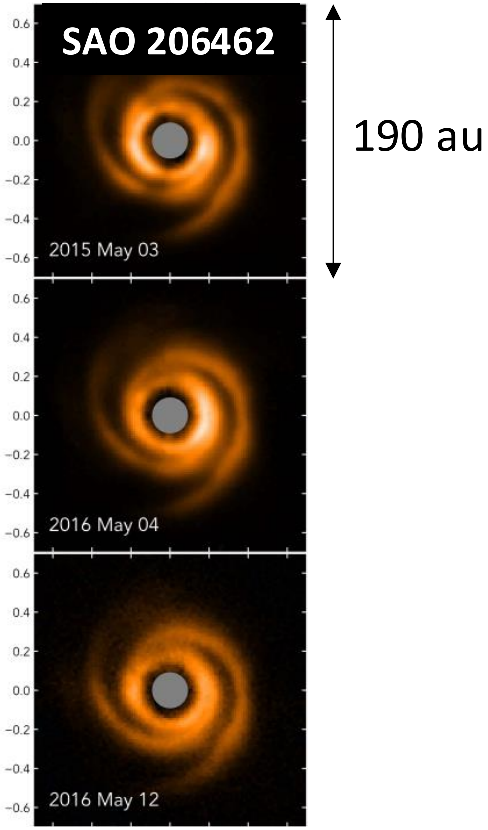
Outer disk:
- Lots of substructures
- Temporally variable

Indirectly map the innermost regions that are as diverse and as variable as the outer ones

SPHERE (J-band)

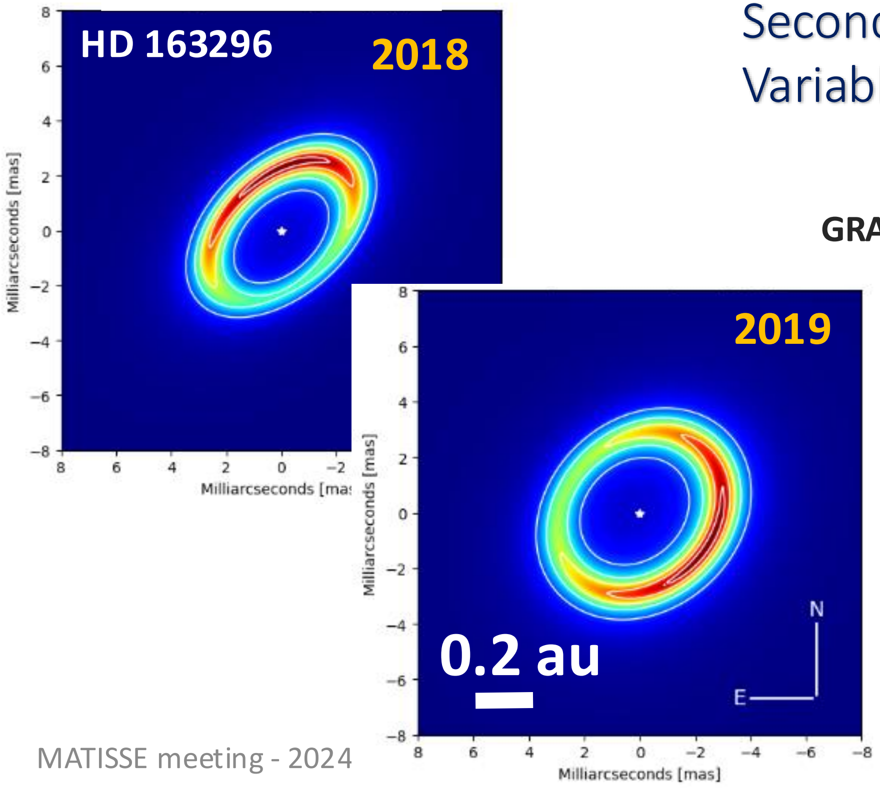
+1 year

+1 week



[Stolker+2017]

GRAVITY (K-band)



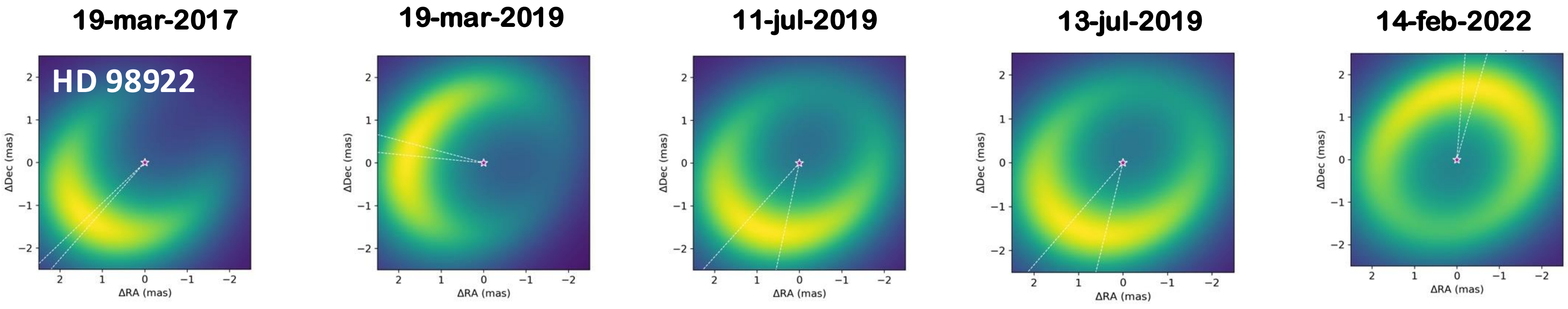
Vortex? [Varga+2021]
Second generation dust? [Chen+2019]
Variable shadowing? [Kobus+2020]

GRAVITY Coll.: Sanchez-Bermudez+2021

Temporal variability in the innermost regions

GRAVITY (K-band)

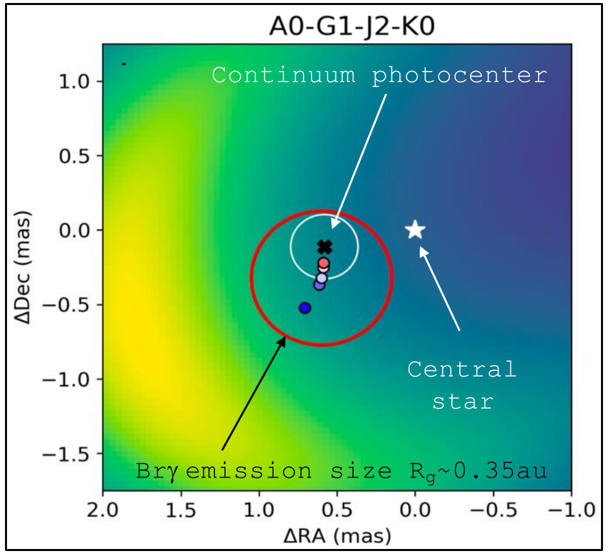
GRAVITY Coll.: Ganci+2024



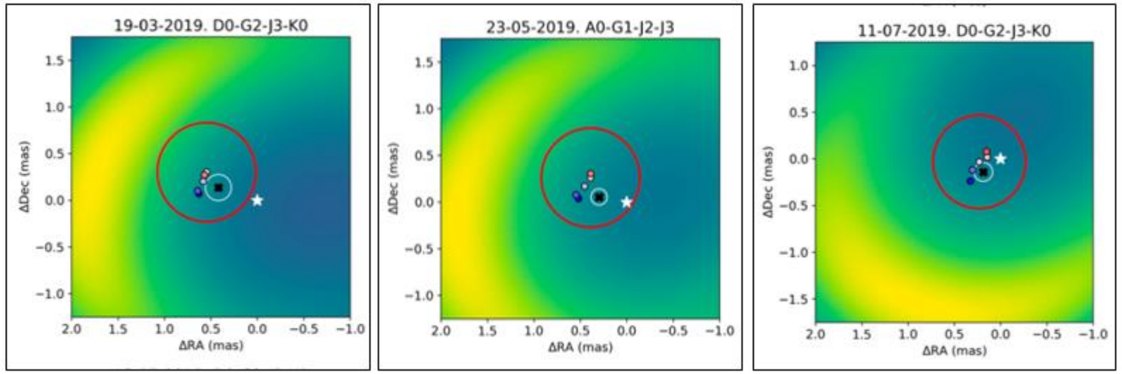
$R_{Dusty\ ring}$ ~ 1.3 au

Large vortex at ~1 au triggered by hydrodynamical instabilities

GRAVITY (Brγ)



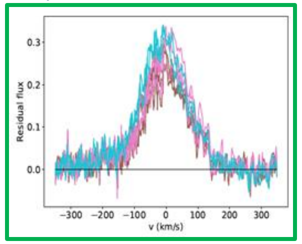
$R_{Br\gamma}$ ~ 0.35 au



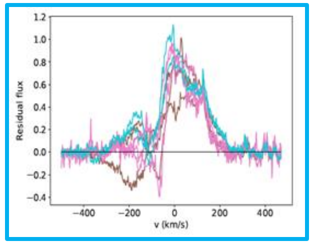
Asymmetric disk wind?
Sub-stellar/planetary accreting companion?

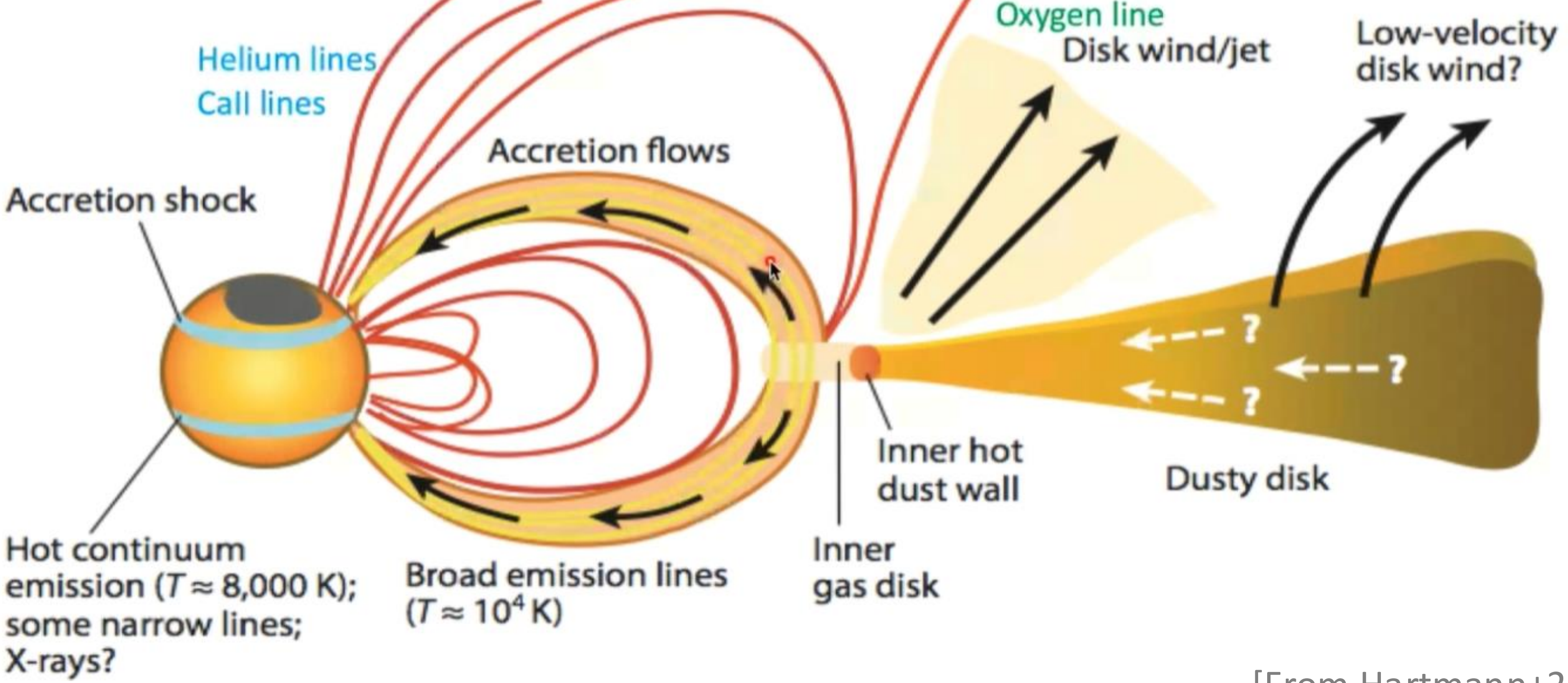
Accretion-ejection in the star-disk interaction region

Brγ – 2166 nm



HeI – 1083 nm



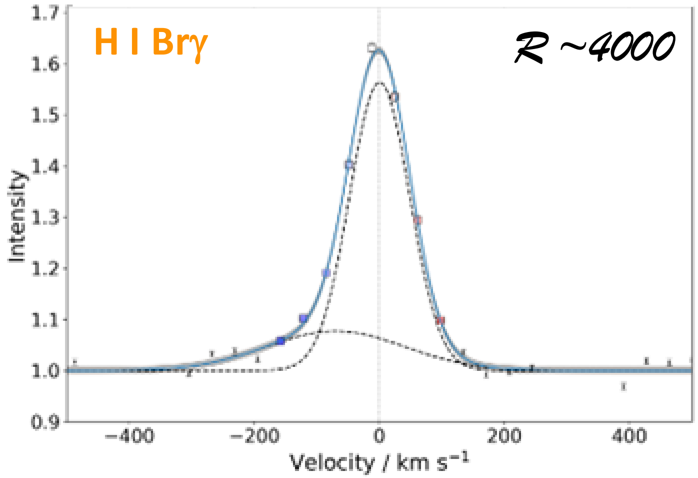


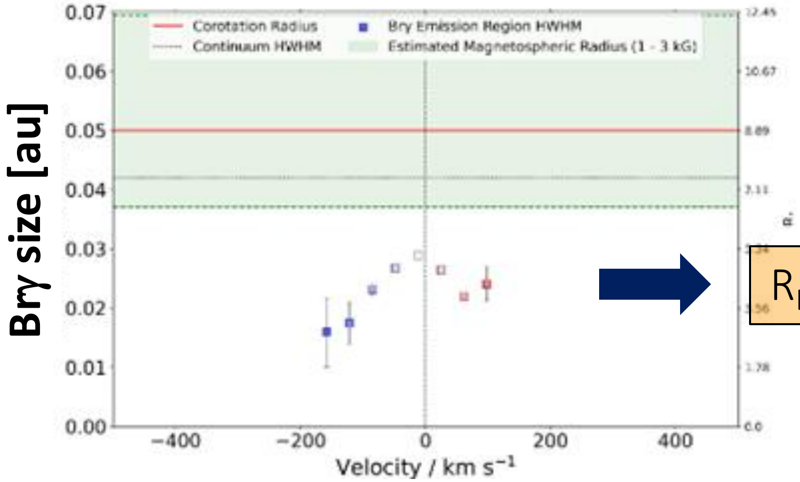
[From Hartmann+2016]

Probing the magnetospheric accretion in TW Hya

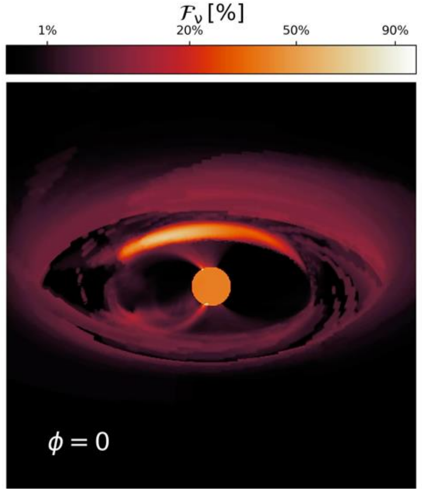
spidi-eu.org

GRAVITY interferometry



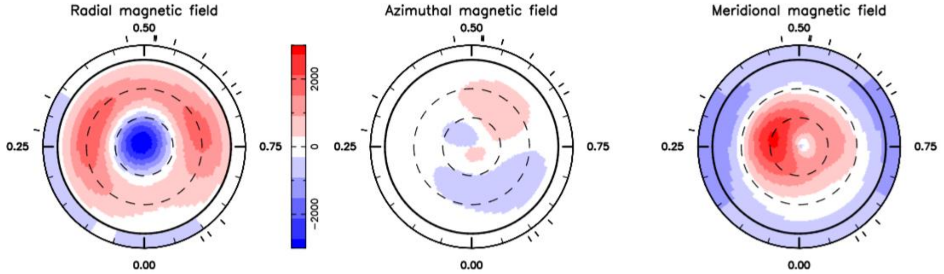


$R_{Br\gamma}$ ~ 4.5 $R_{\odot}$



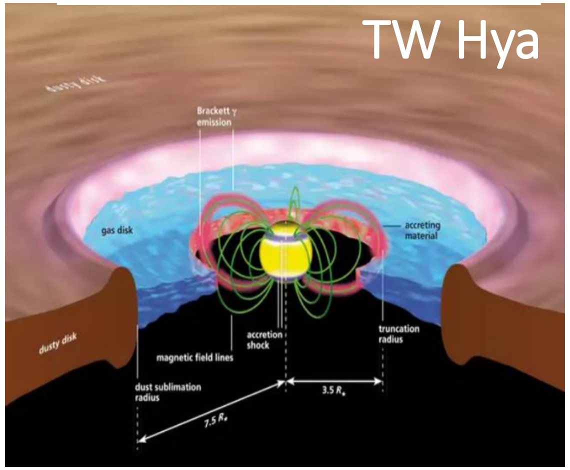
GRAVITY Coll.: Garcia-Lopez+2020

ESPaDOnS spectro-polarimetry



R_{mag} ~ 3.6-4.8 $R_{\odot}$

[Bessolaz+2008]

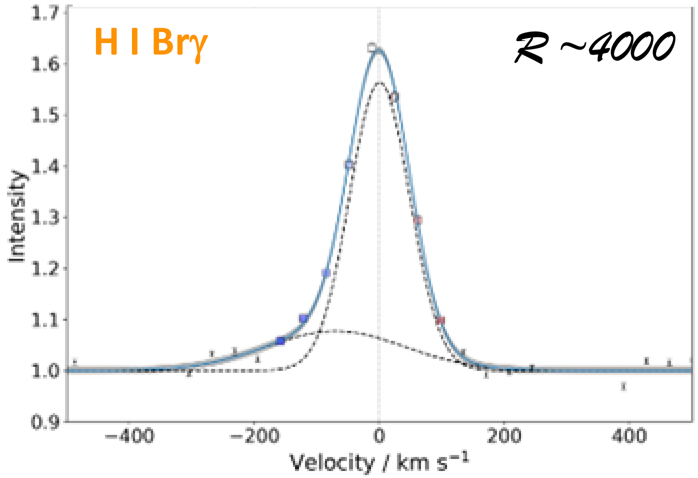


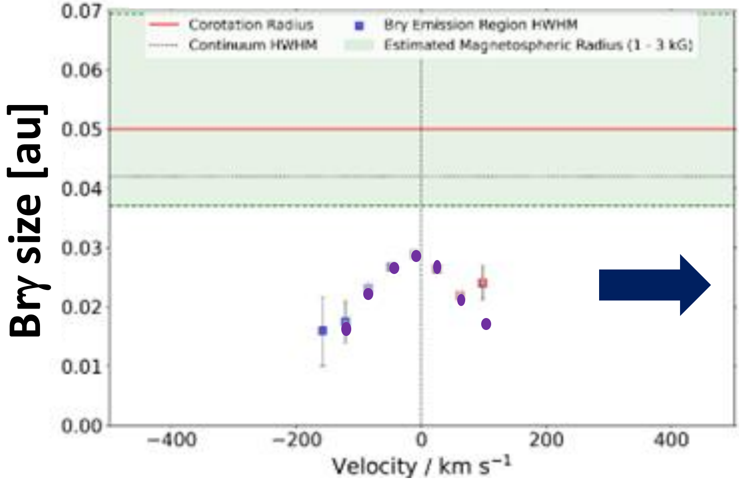
[Donati+2011]

Probing the magnetospheric accretion in TW Hya

spidi-eu.org

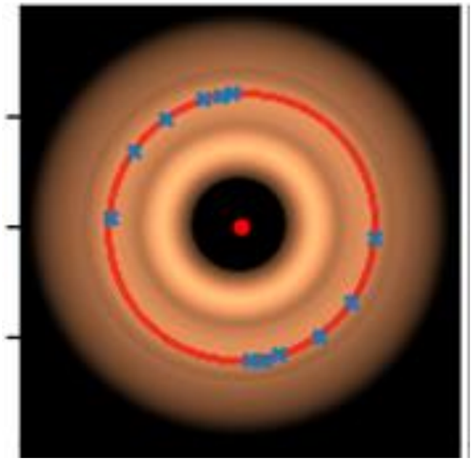
GRAVITY interferometry





Radiative Transfer accretion model

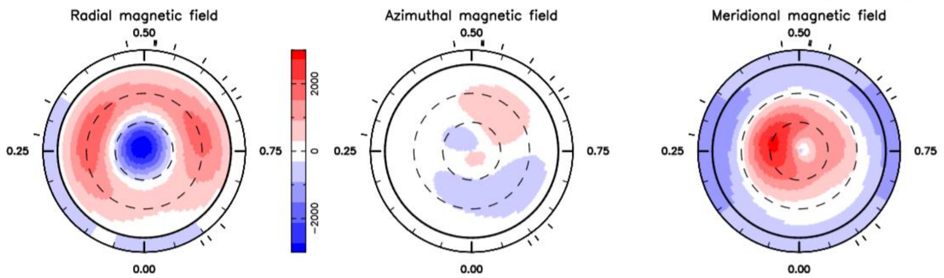
• Model



$R_{Br\gamma}$ ~ 4.5 $R_{\odot}$

GRAVITY Coll.: Garcia-Lopez+2020

ESPaDOnS spectro-polarimetry



[Donati+2011]

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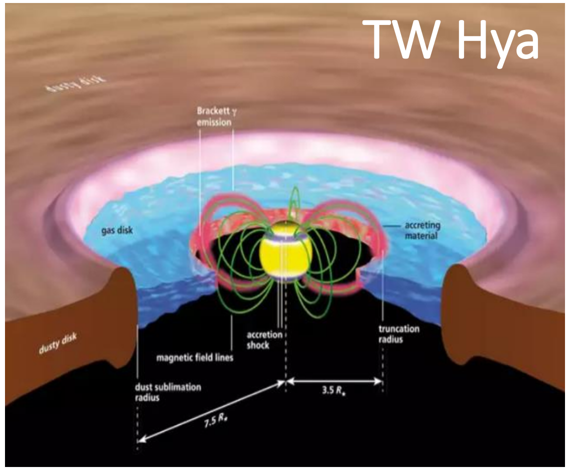
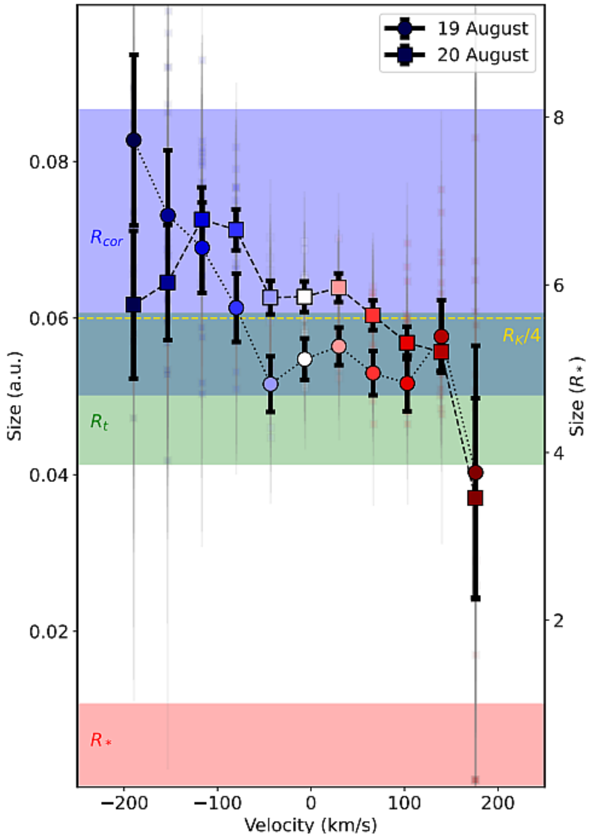
[Bessolaz+2008]

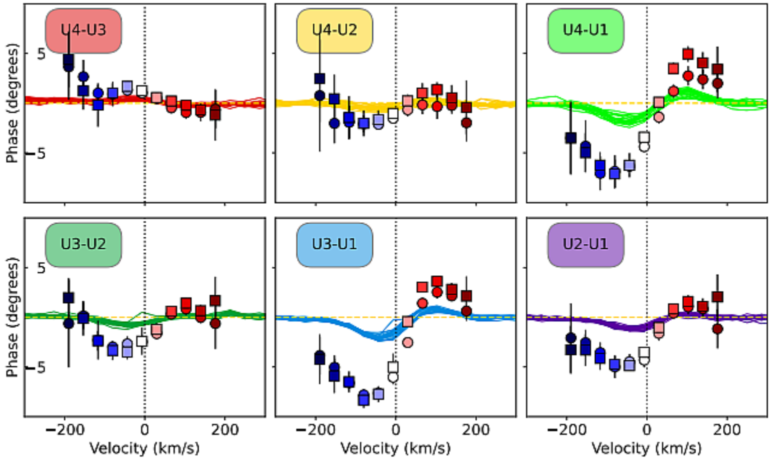


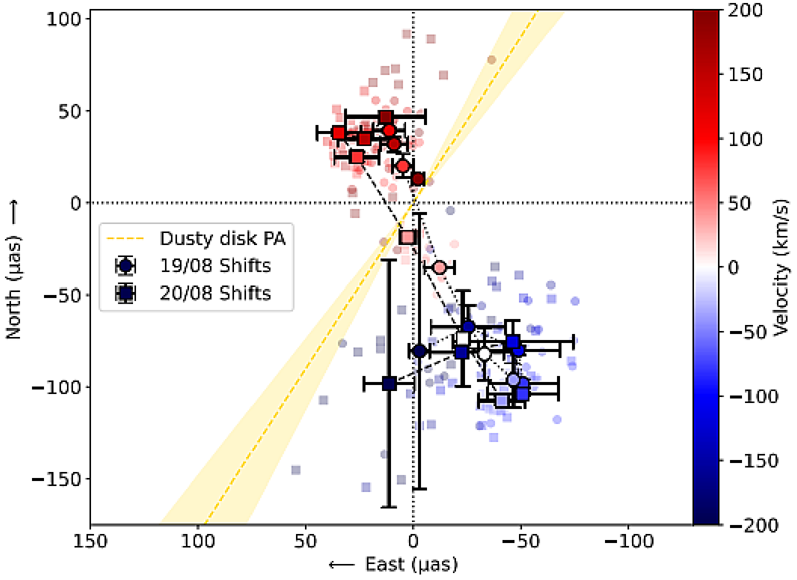
Accretion-ejection processes in strong accretors

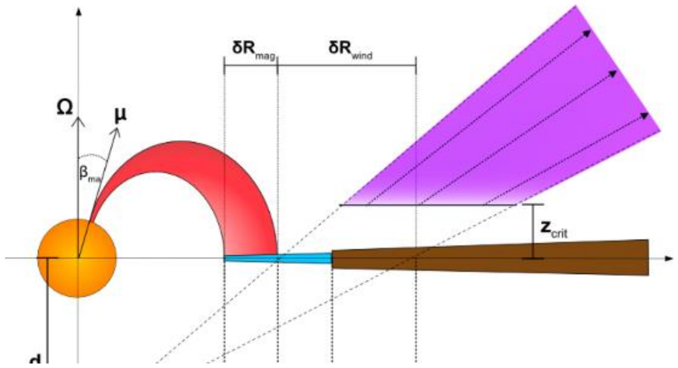
S CrA N



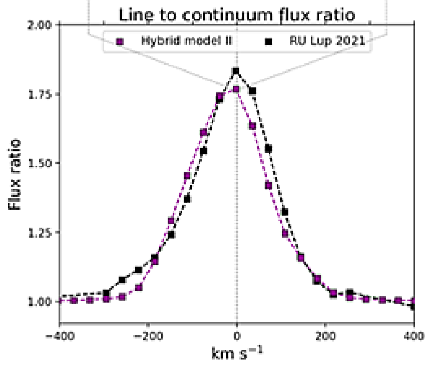
GRAVITY Coll.: Nowacki+2024

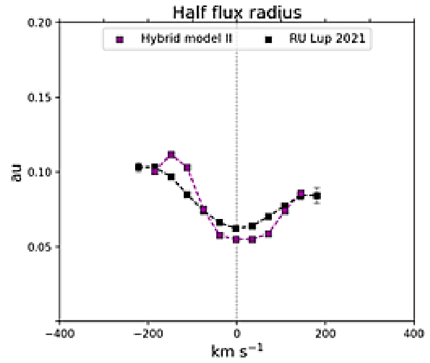






RU Lup

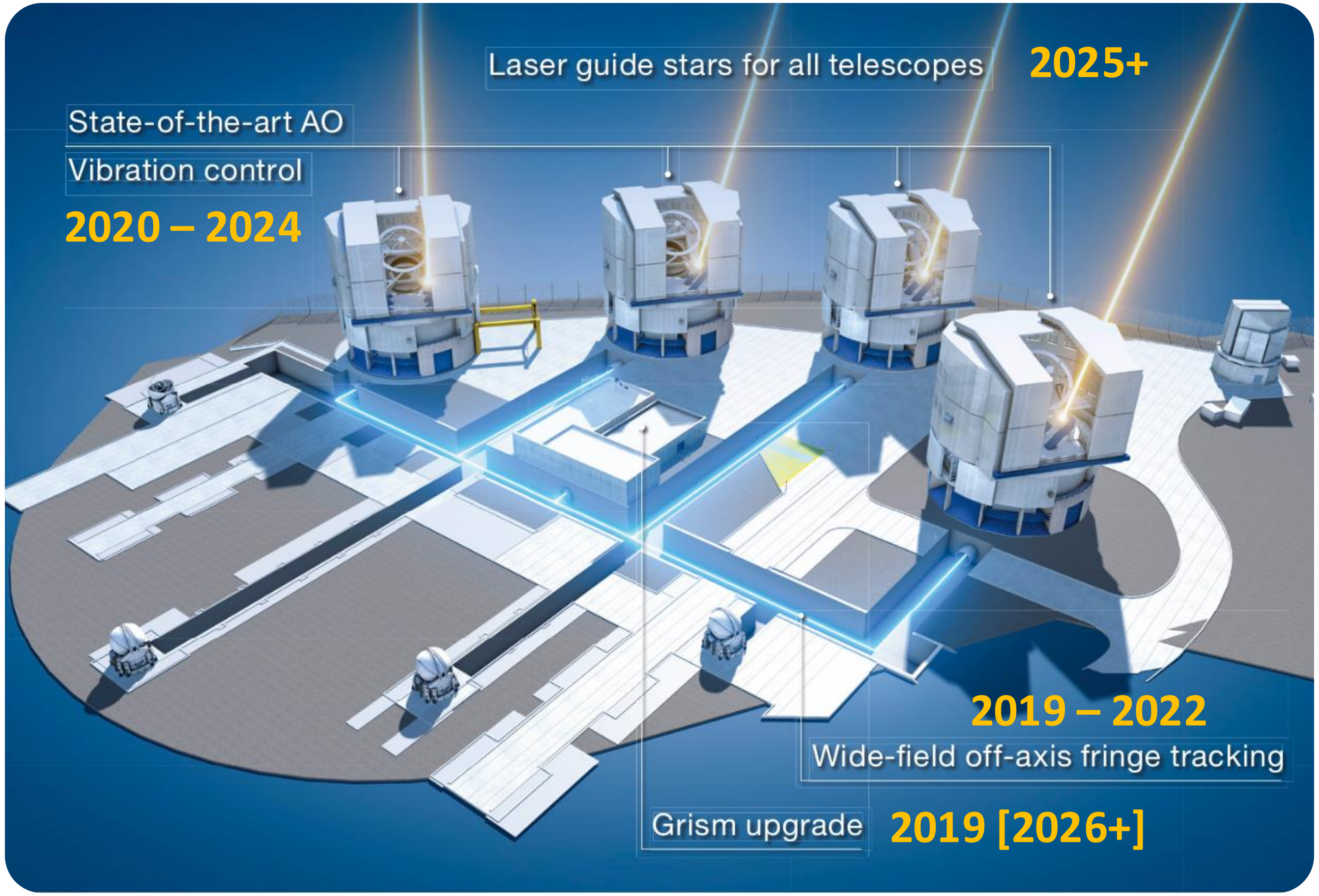




Tessore+2021
Tessore+2023
Wojtczak+2024

GRAVITY data
Modelling

Opportunities of GRAVITY+ for YSOs



[The Messenger 189, dec. 2022; GRAVITY+Coll, 2022; Abuter+2024] [Nowak+2024; Berdeu+2024]

SOC: J. Bouvier – P. Caselli – M. Flock – L. Labadie (co-chair) – K. Perraut (chair) – T. Ray – P. Schilke – S. Spezzano – R. van Boekel

Invited speakers: G. Bourdarot – C. Dougados – S. Grant
L. Perez – S. Takasao – R. Teague

From GRAVITY to GRAVITY+

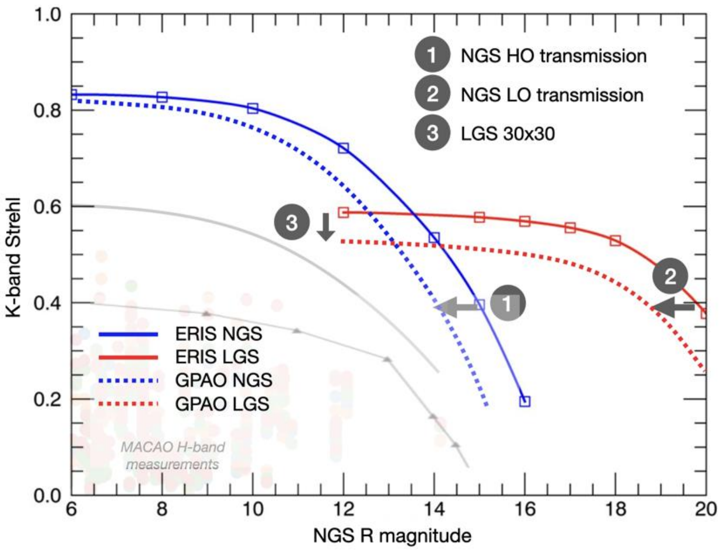
What will not change:
- Number of combined telescopes [4]
- Baselines' length and orientation [(u,v) plane]
- Spectral range [K band]

What will change:
- Sensitivity
  - FT limiting magnitude: K = 10 ⇒ 13
  - AO limiting magnitude: G = 12 ⇒ 18

- Sky coverage
  All Galactic Plane region observable

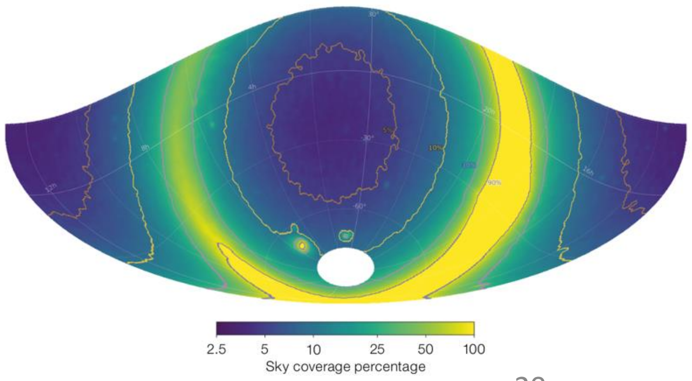
- Accuracy

State-of-the-art adaptive optics



- *New wavefront sensors*
- *NGS and LGS modules*
- *New deformable mirrors*

Off-axis (30") fringe tracking

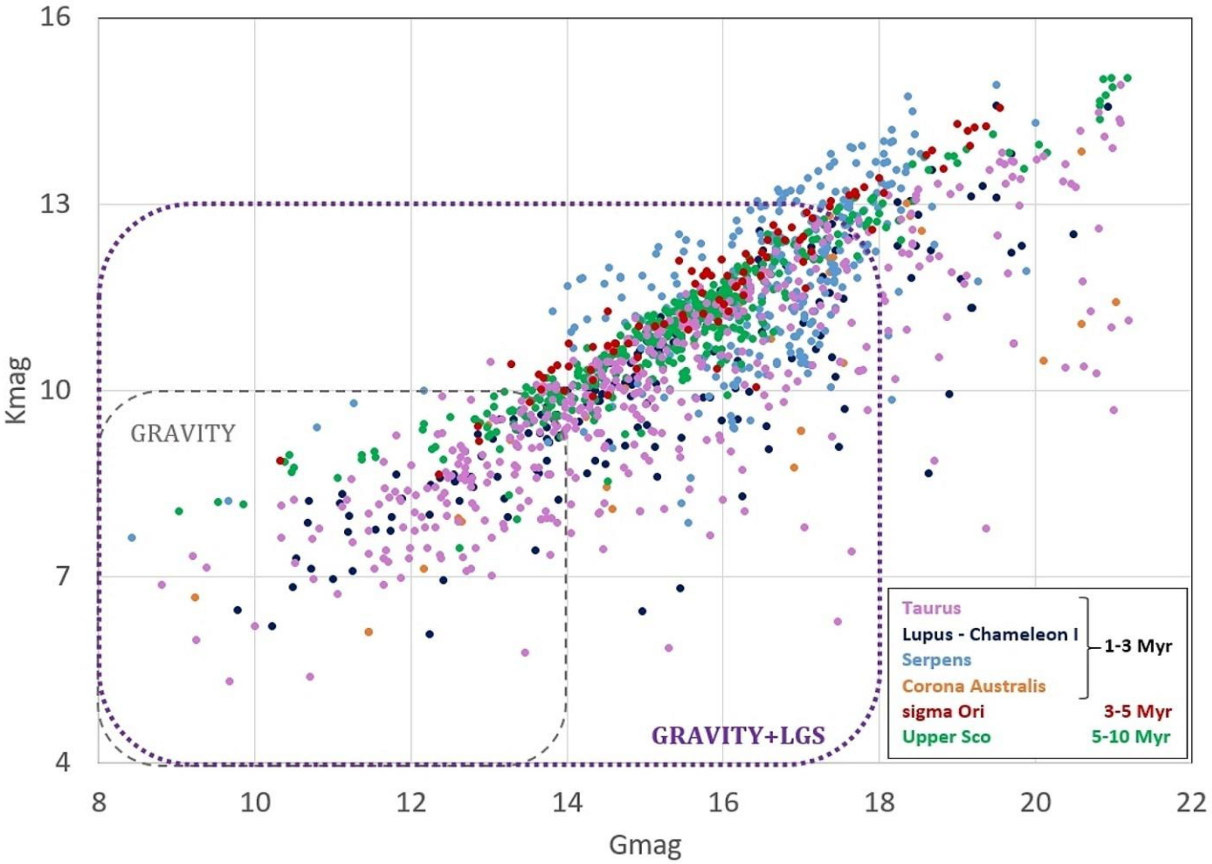


Different Star Forming Regions

Thanks to LGS and off-axis fringe tracking:

- Less biaised samples
- Demographic studies
- Test advanced models

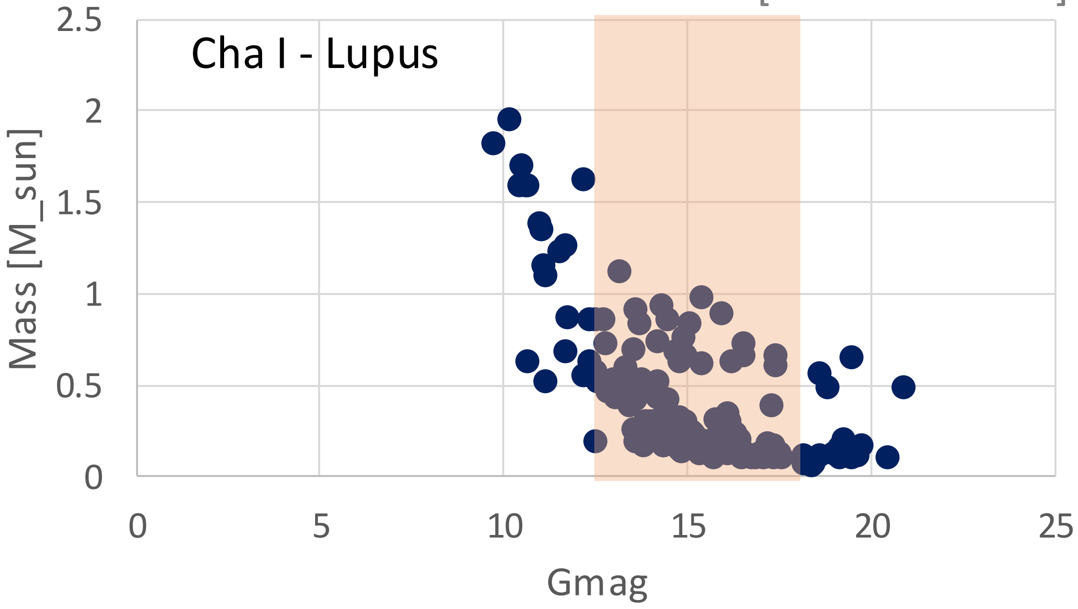
SFR	Nb of sources [catalog]	GRAVITY	GRAVITY+ NGS	GRAVITY+ LGS
Cr A	35 [Cazzoletti+2019]	8	8	26 (74%)
Ser	291 [Erickson+2015]	5	7	231 (79%)
Up. Sco	567 [Luhman+2020]	67	77	399 (70%)
Tau	435 [Galli+2019]	151	157	381 (87%)
Cha + Lup	168 [Mulders+2017]	56	57	146 (87%)
TOTAL	**1496**	**287**	**306**	**1183 (79%)**



Reaching new classes of objects

- Access to lower mass stars and to a larger sample of high-mass YSOs, including extra-galactic as e.g. in the magellanic clouds

[Mulders+2017]



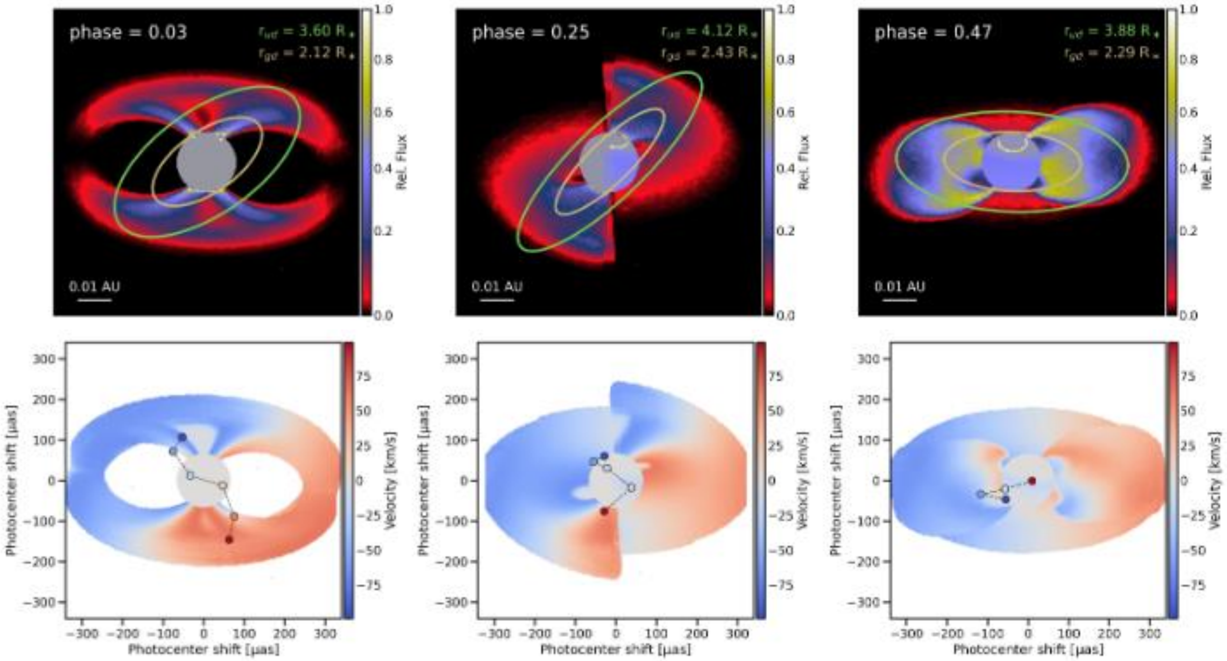
- Class-I sources will be observable for the first time by optical interferometry:
  - Younger sources
  - Different regime of accretion
  - Stronger and more complex magnetic fields

Total	53
GRAVITY	7
GRAVITY+	7
GRAVITY+_LGS	28 (53%)

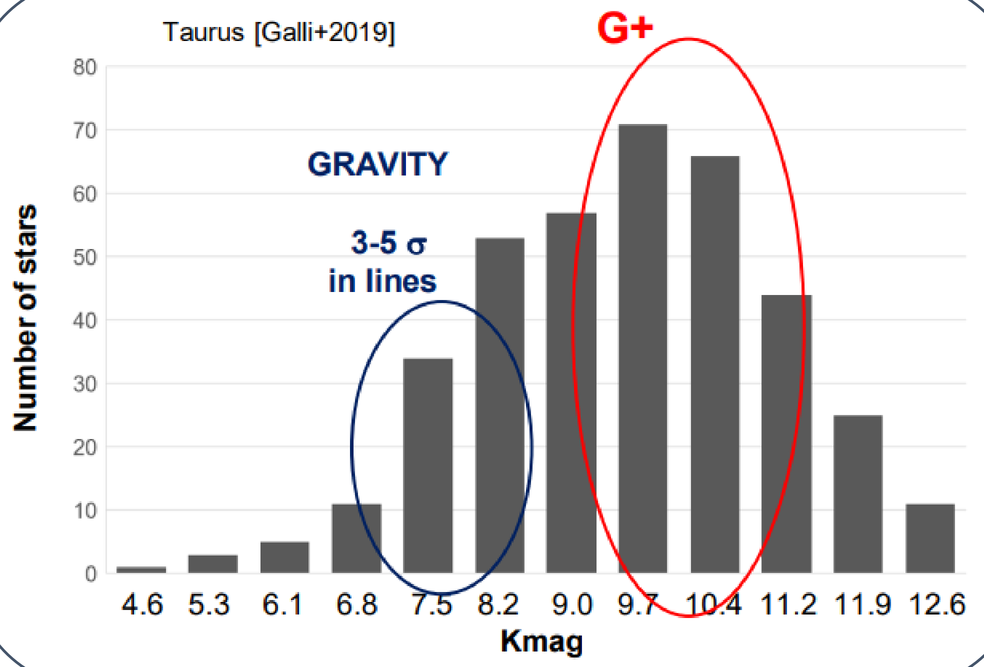
[Connelley+2010]

Monitor accretion-ejection in T Tauris

Monitoring over rotation periods to better probe the origin of the accretion flows



[Tessore+2023]



- « FAINT » mode to probe other tracers than Brγ (He I, Na, ...)
- Better overlap with other instruments (SPIRou, JWST/MIRI, ...)

Take away messages

GRAVITY YSO Large Program – an invaluable **homogeneous data set**

√ Demographic studies

√ Variability follow-up

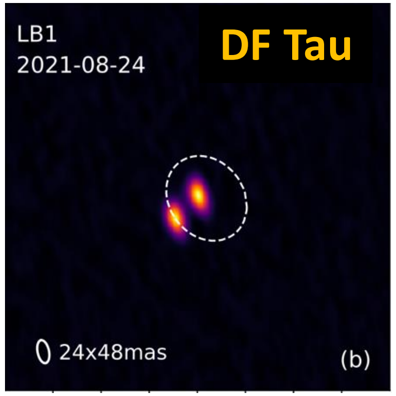
√ Test advanced disk structure and accretion/ejection models

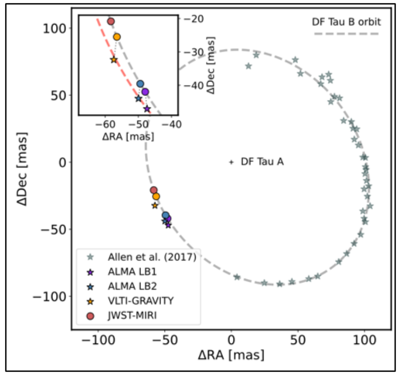
Exciting times to come with **GRAVITY+ and LGS**

Interest of **multi-technique** and **multi-wavelength** campaigns to probe different scales

VLTI suite, JWST, ALMA, IR spectroscopy, spectro-polarimetry (SPIRou + ESPaDOnS in VISION), ELT

To be developed in the ANR IRYSS project (2024-2028)





[Grant,.., Nowacki, Perraut+2024]

Parameter	VLTI-GRAVITY Models	
	Binary only	Binary + disk around A
ΔRA [mas]	$57.39^{+0.18}_{-0.17}$	57.38 ± 0.22
ΔDec [mas]	-32.35 ± 0.34	$-32.38^{+0.41}_{-0.42}$
ρ [mas]	65.9 ± 0.5	65.9 ± 0.6
F_A	0.66 ± 0.03	$0.61^{+0.04}_{-0.06}$
F_B	0.34 ± 0.03	0.28 ± 0.04
F_{disk}	-	0.11 ± 0.07
HWHM [mas]	-	1.0 ± 0.6
HWHM [au]	-	0.14 ± 0.09
χ_r^2	8.38	5.05