The innermost regions of young stars as probed by GRAVITY

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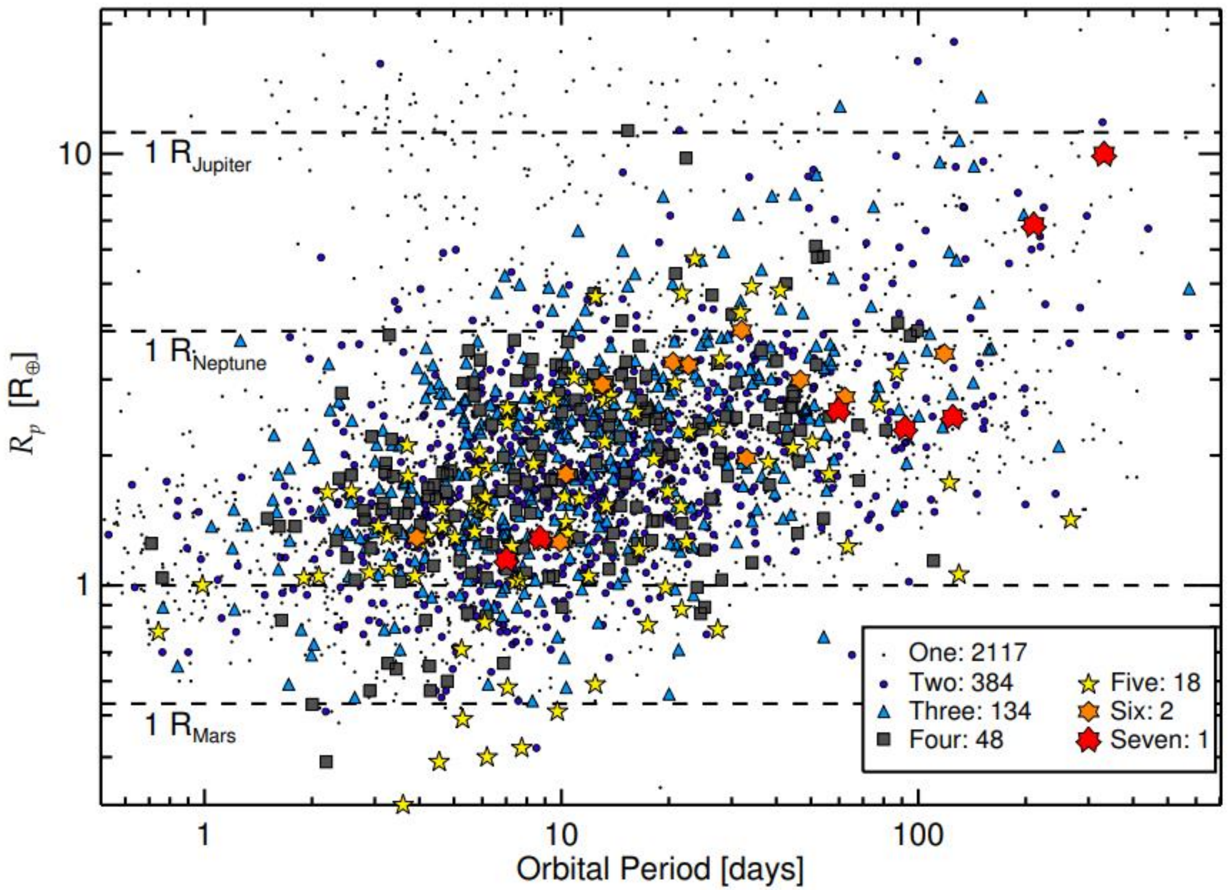
On behalf the GRAVITY collaboration

Outline

- Motivation
- Breakthrough from optical long-baseline interferometry
- Probing the inner edge of the dusty disk
- Probing the accretion-ejection processes
- The future with GRAVITY+

An extreme diversity of planetary systems

Current population of known exoplanets exhibit **a wide diversity in nature and architecture**



[Lissauer+2014]

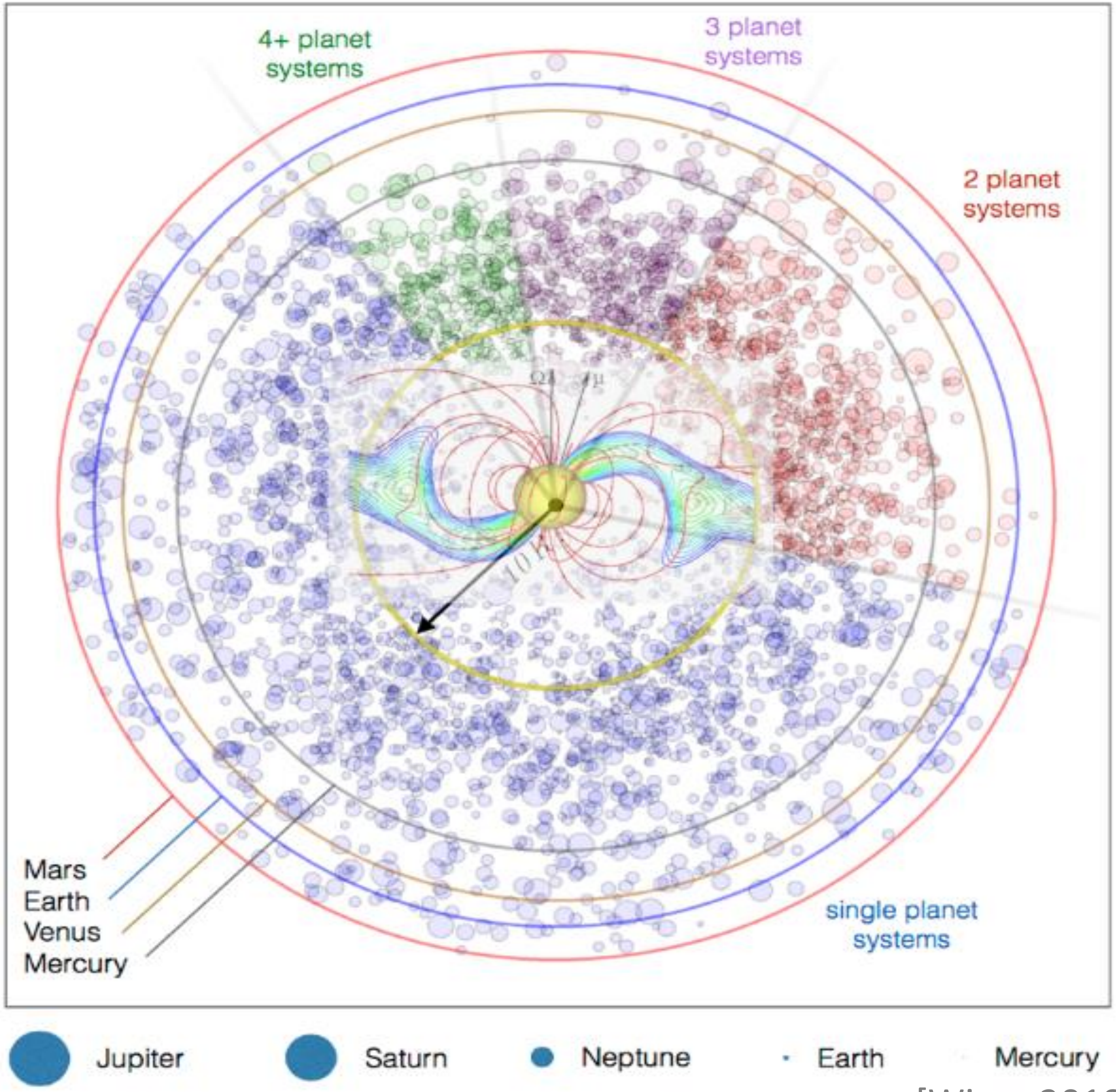
- Origin of diversity?
- Which processes determine the final outcome of planetary systems?

« Kepler » population: planets with sizes as small as and orbits as large as those of the Earth

Close-in low-mass planets

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?

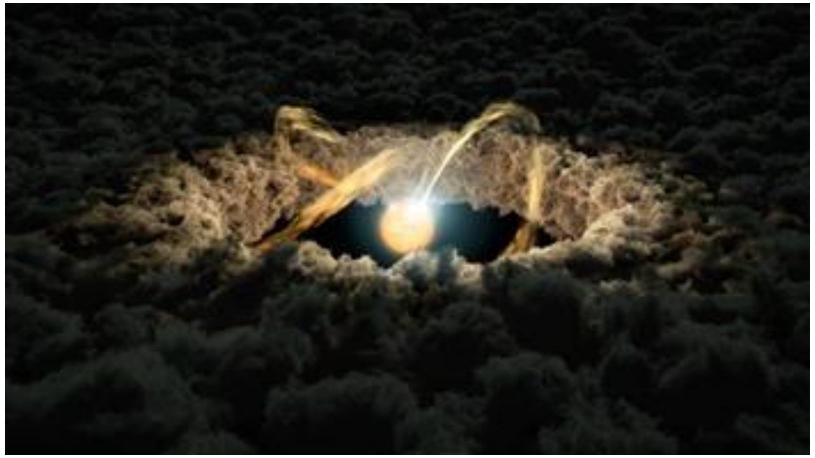
[Mishra+2023; Batygin & Morbidelli 2023]



[Winn+2018]
[Blinova+2016]

Structure and evolution of protoplanetary disks

- **Material reservoirs** from which star and planets are formed.
- Mostly constituted of **gas**, with a small fraction in **dust grains**
- Set the **initial conditions for planet formation**.
- **Interactions planet(s)/host disk**: brief (< 10 Myr) but foundational
    - Imprinted on the disk structures
    - Impact the evolution of the planet-star-disk system.

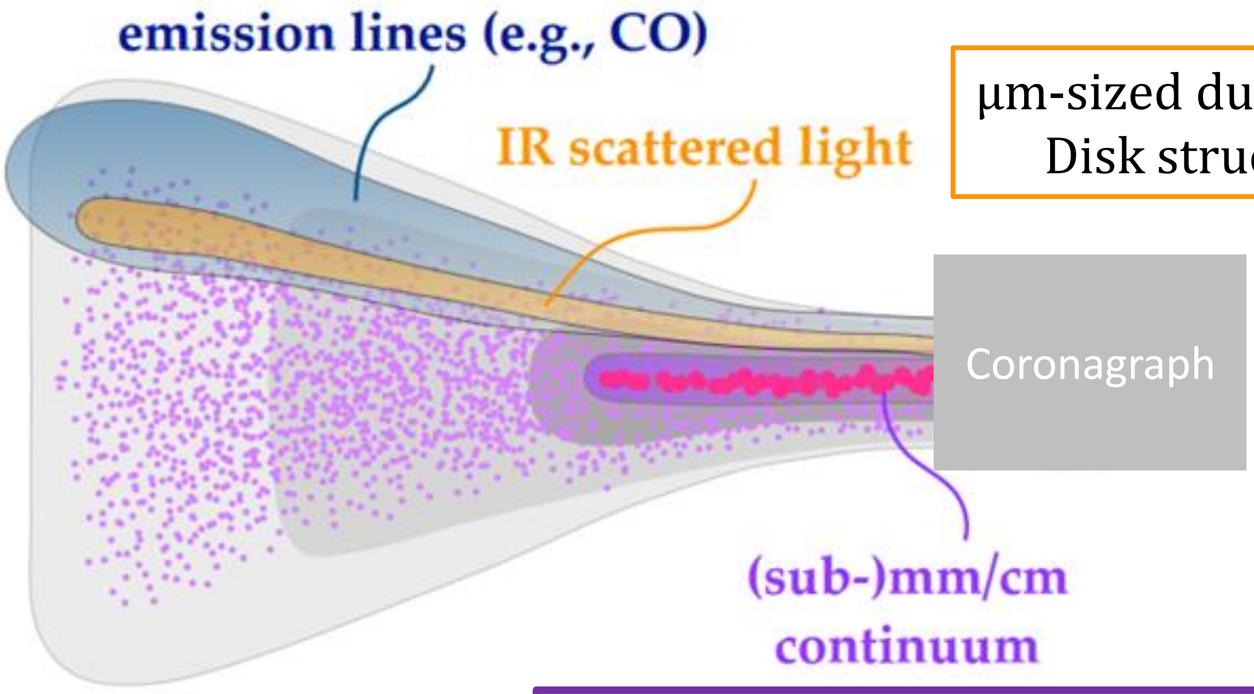


How do disks shape star and planet formation?

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

Motivation - Global view of the protoplanetary disk structure

100 au — 10 au — 1 au



μm-sized dust grains
Disk structures

5 au resolution

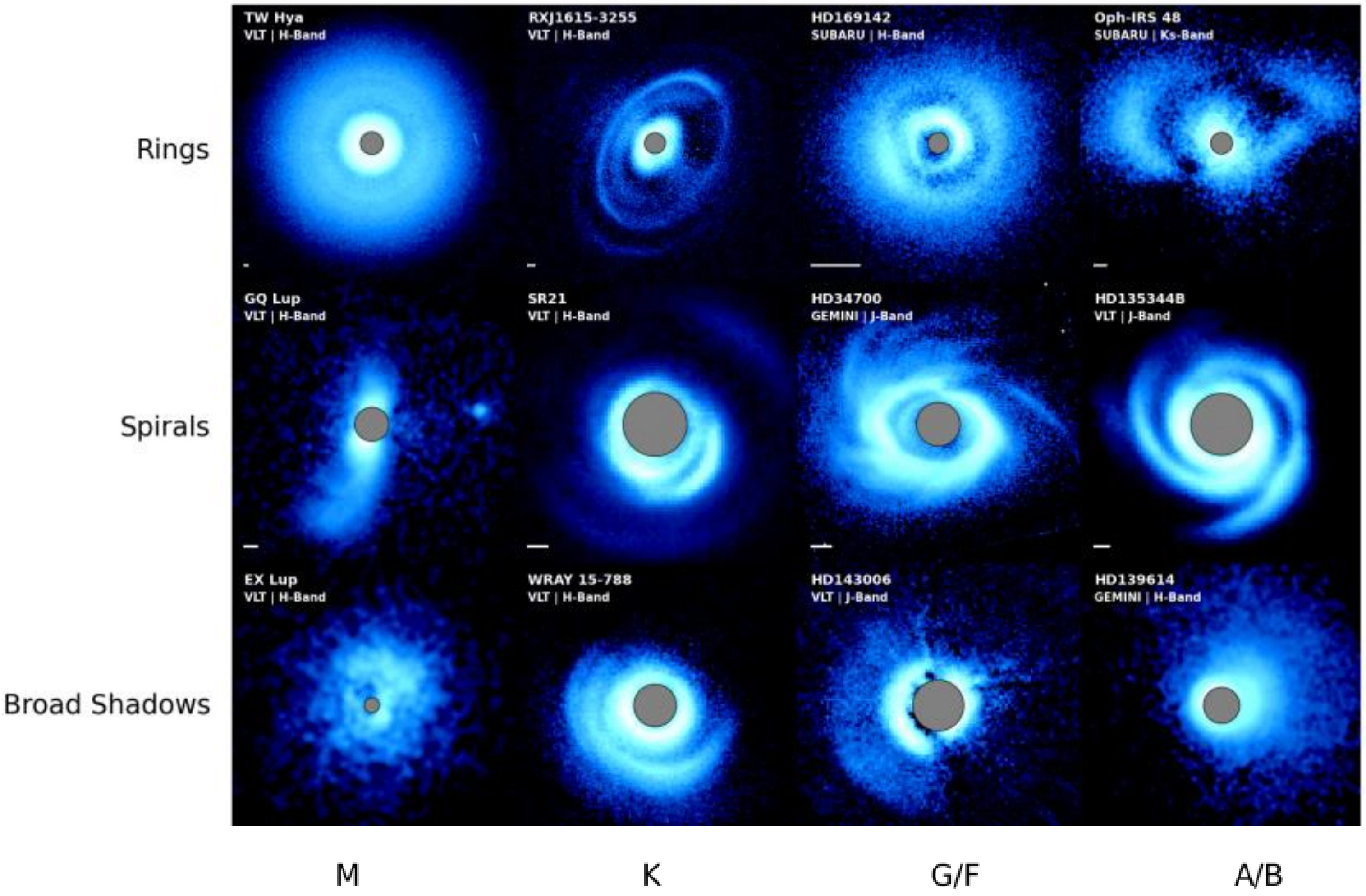
5-15 au resolution

Pebble-sized particles
Dust density and temperature

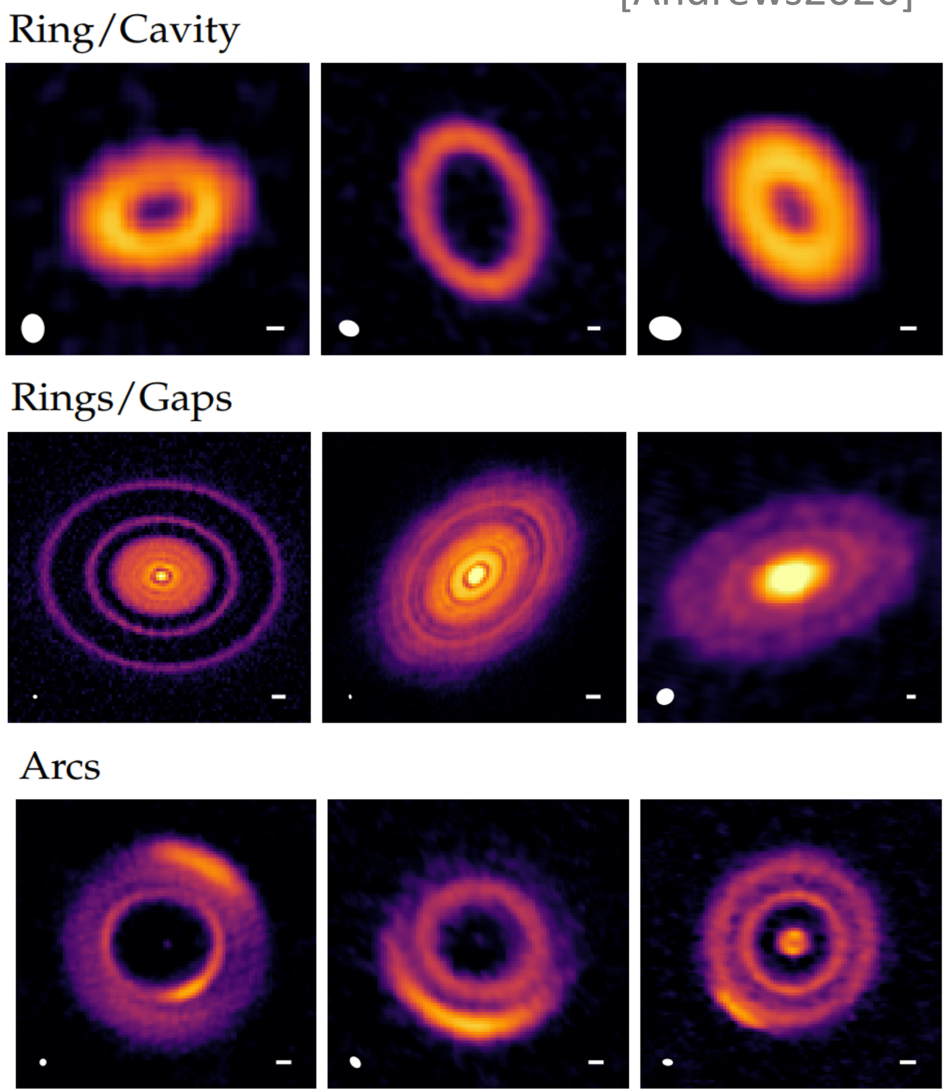
[Andrews2020]

Near-infrared and millimetric imaging of the outer disk

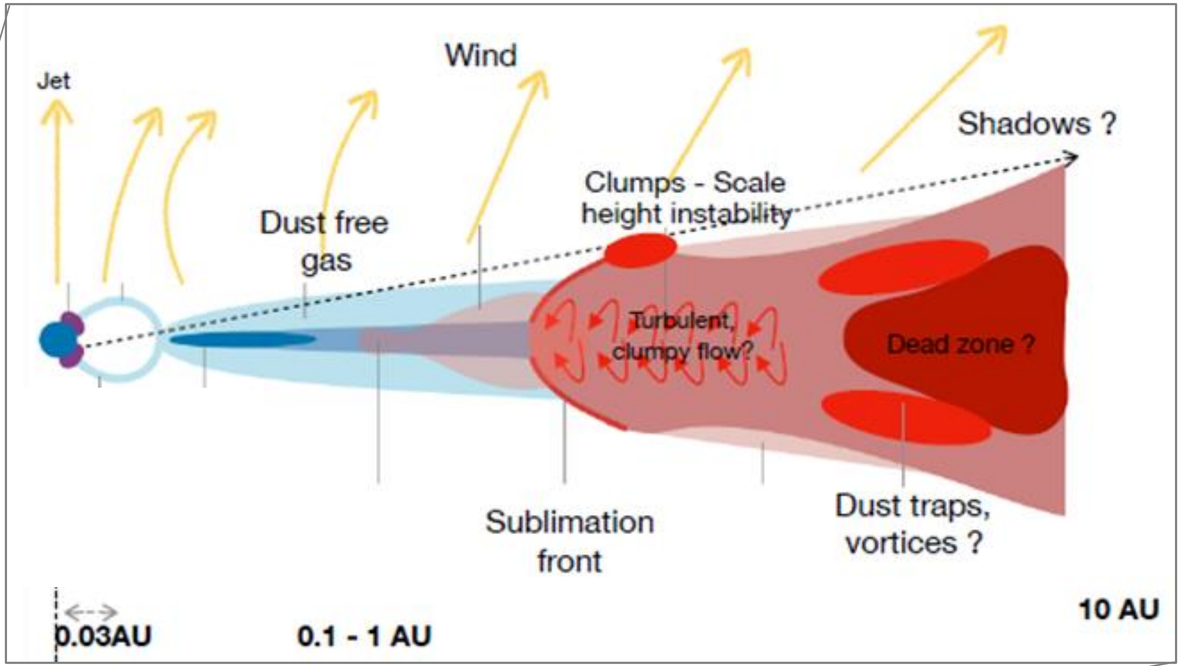
[Benisty+2022, PPVII]

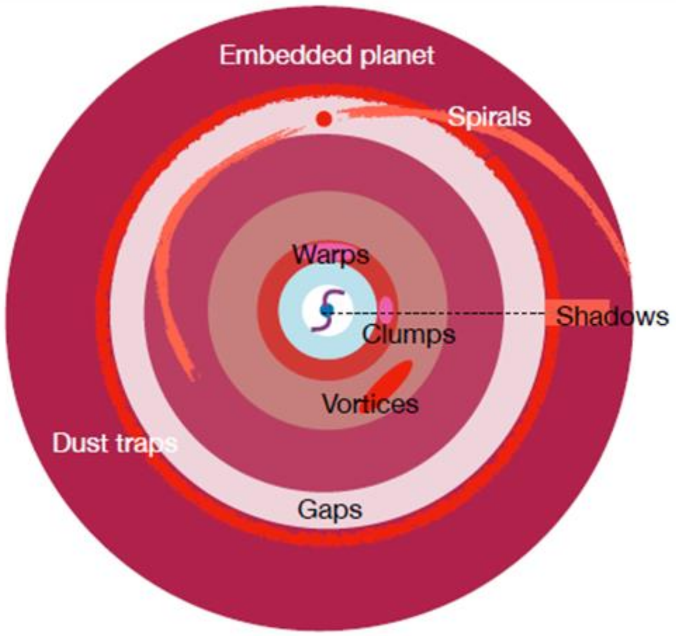


[Andrews2020]

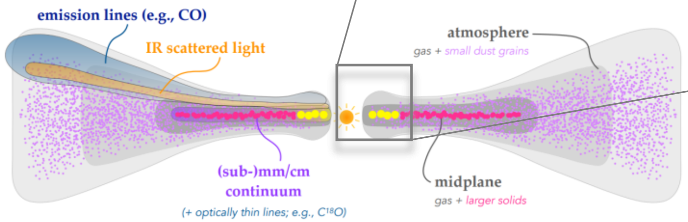


Global view of the protoplanetary disk structure: toward the star-disk interactions





[Adapted from Dullemond & Monnier 2010]



Optical long-baseline interferometry breakthrough

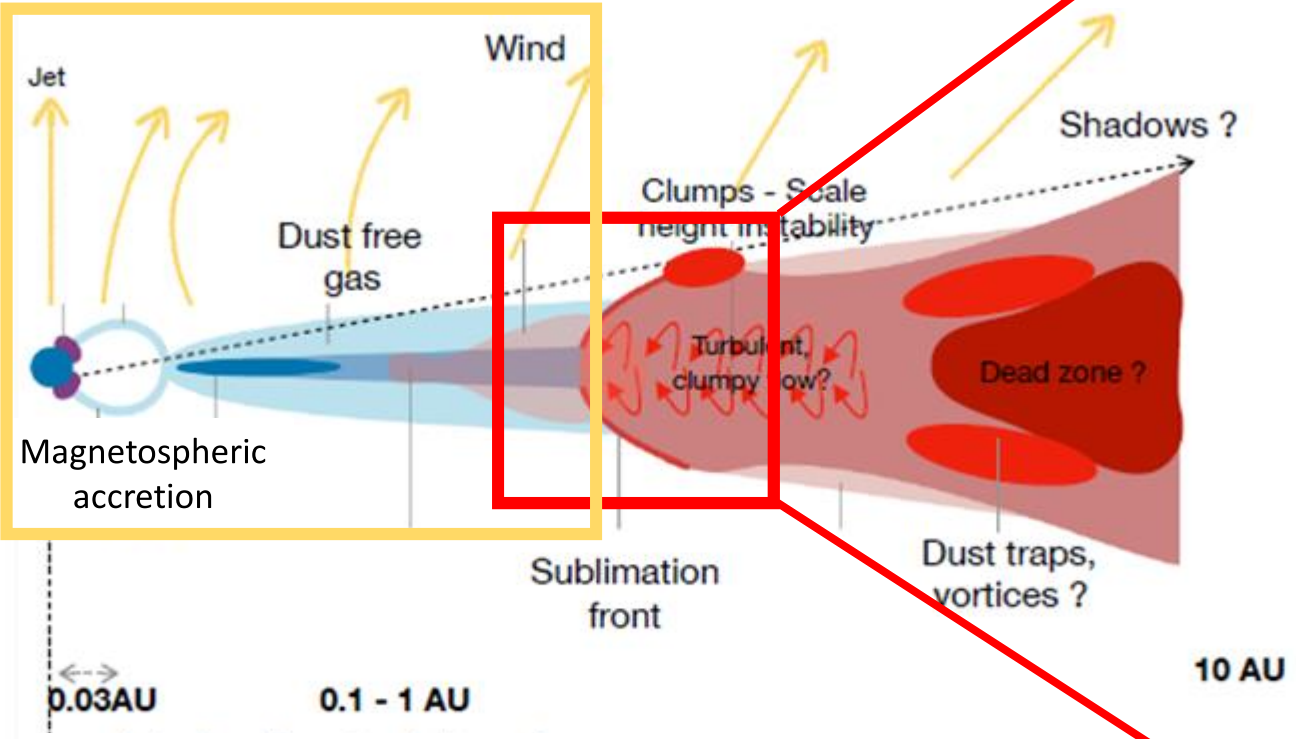
Spectro-astrometry

~a few 0.01 au

Photometry

Spectro-polarimetry

ESPaDOnS in visible
SPIRou in NIR



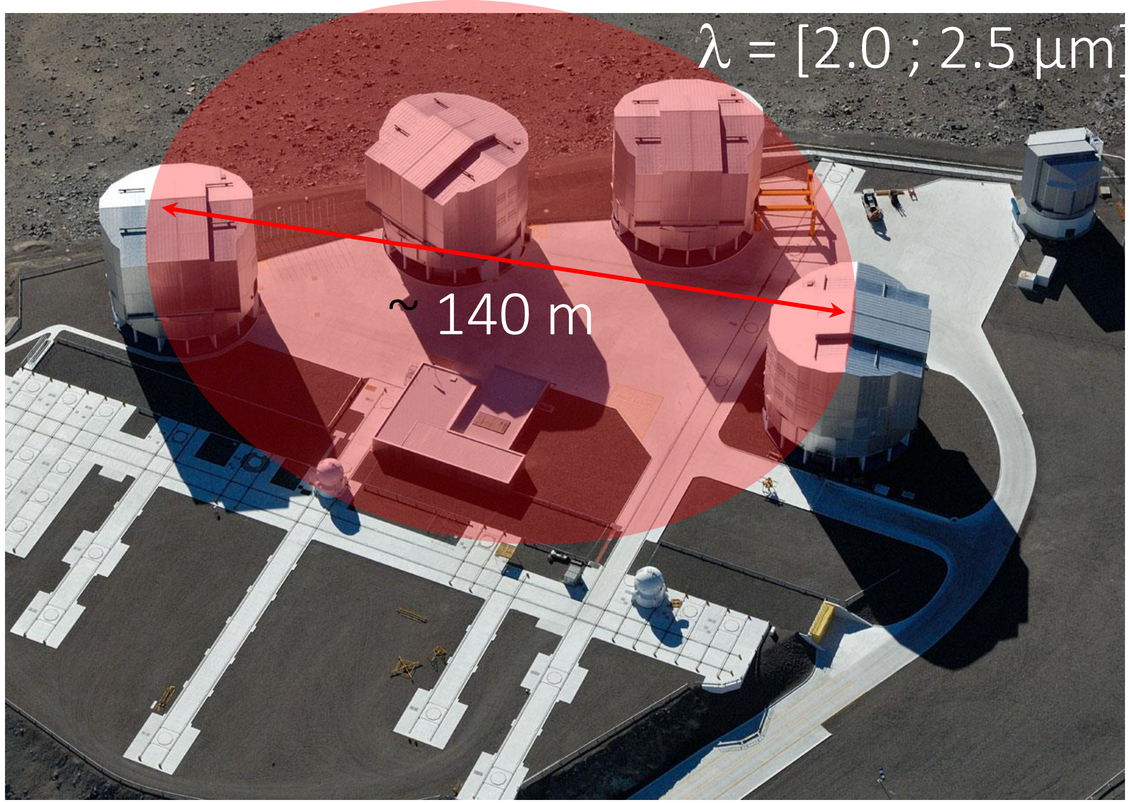
0.3-0.5 au in NIR
~2 au in MIR

~0.2 au in NIR

GRAVITY at VLTI

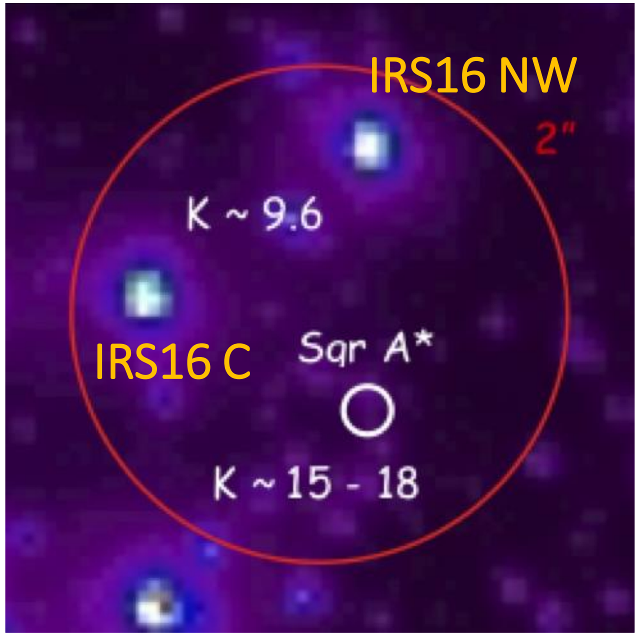
Number of combined telescopes: 4
Spectral range: K-band [2.0 µm; 2.4 µm]
Spectral resolutions: 4000, 500, 20
Start of operation: 2016

Interferometry
to synthetize a giant mirror of 140 m



Angular resolution of 3.5 mas @ 2.2 µm

Astrometry
with reference stars



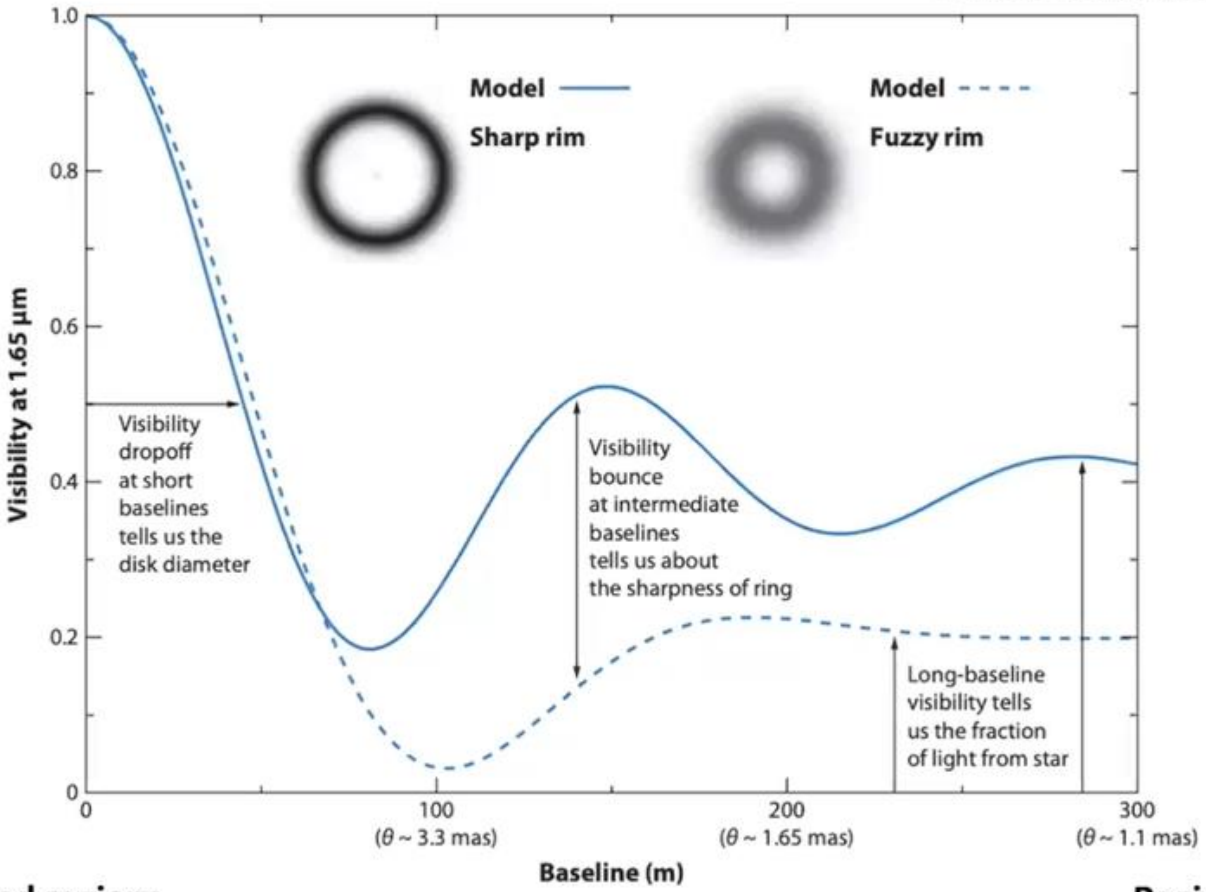
Accuracy ~ a few 10 µas


MPE
Max-Planck-Institut für
extraterrestrische Physik

Interferometric observables: visibilities

Dullemond & Monnier 2010

$\theta \sim \frac{\lambda}{B}$



Visibility V^2 ~ extent

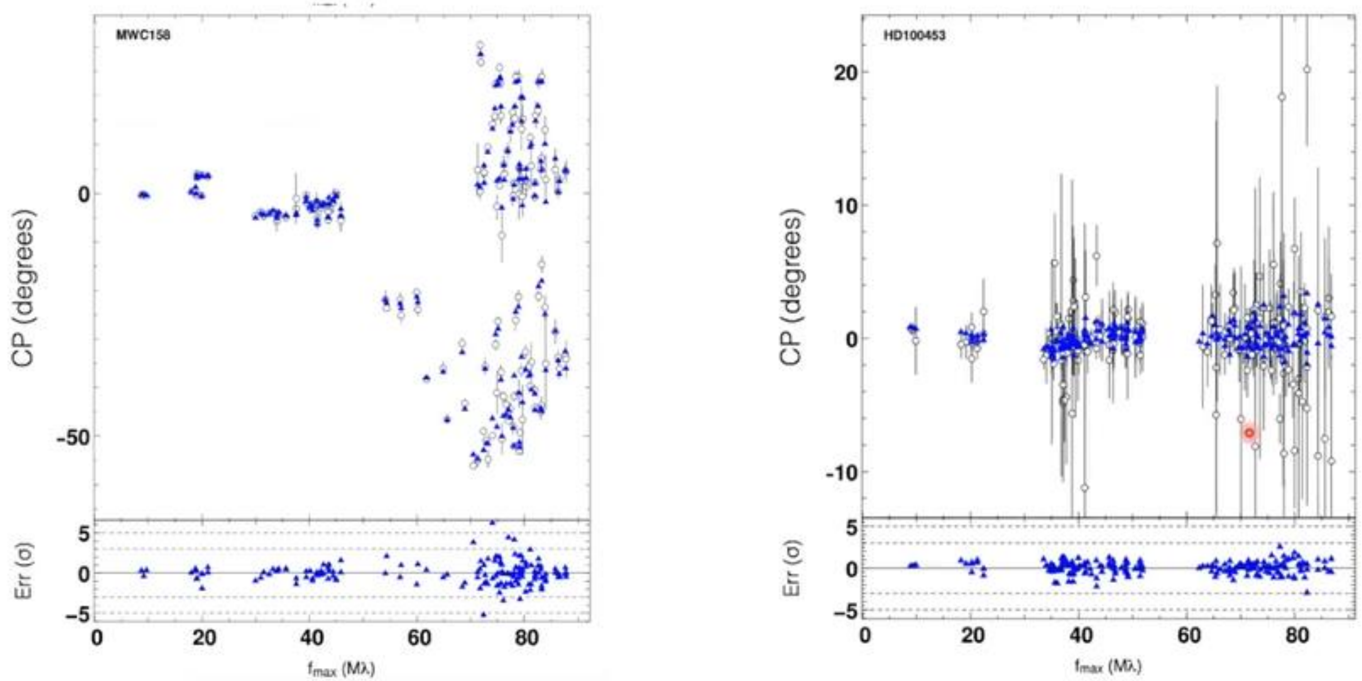
V^2 vs. λ = dust temperature

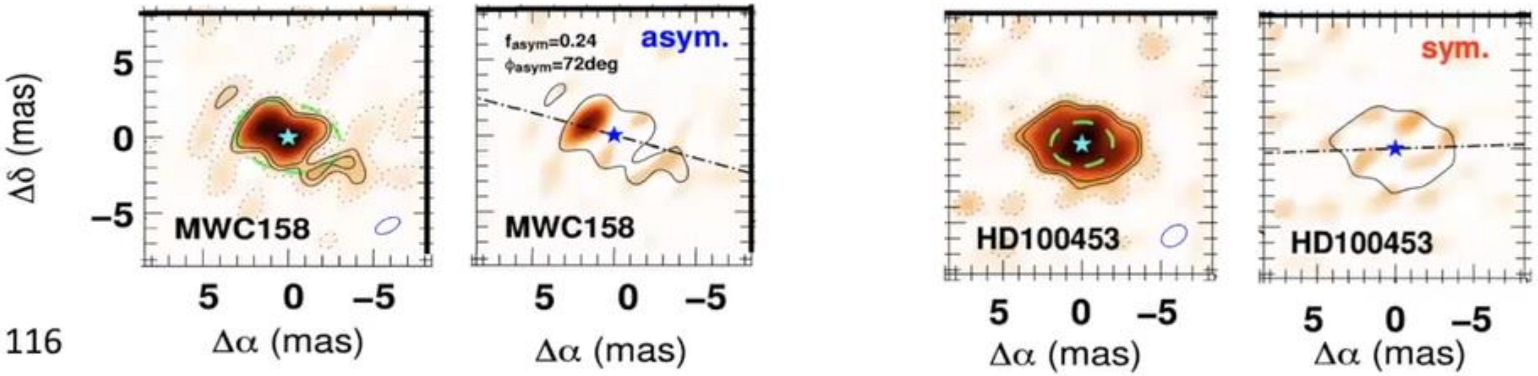
More extended regions of underlying brightness distribution

Regions closer to the centre of the underlying brightness distribution

Interferometric observables: closure phases

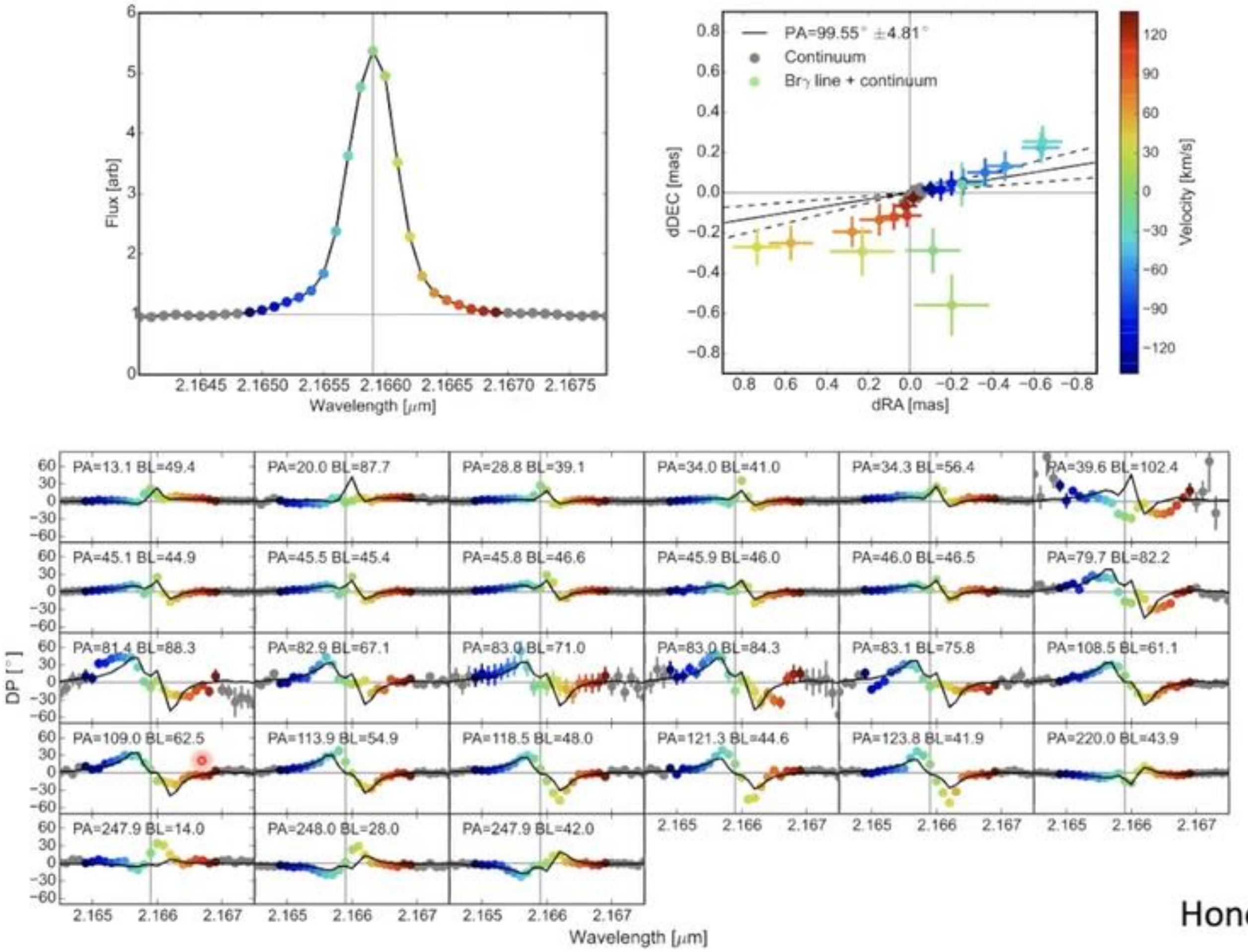
Closure Phase CP = asymmetry





Kluska+ (2020) A&A 636, 116

Interferometric observables: spectro-differential visibilities and phases



Differential visibility = relative extent
Differential phase = relative photocenter shift

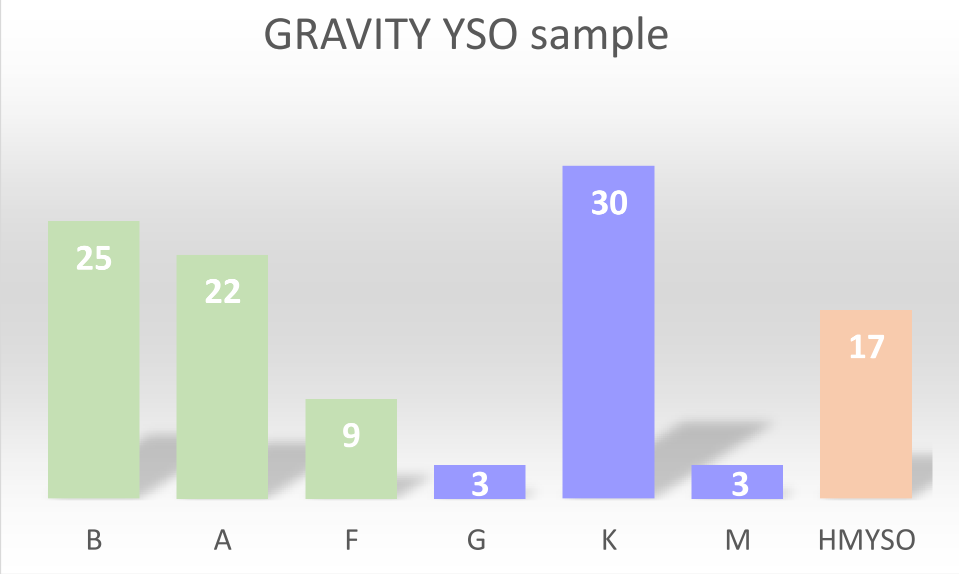
Hone+ (2017) A&A 607, 17

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, in press

Aims.

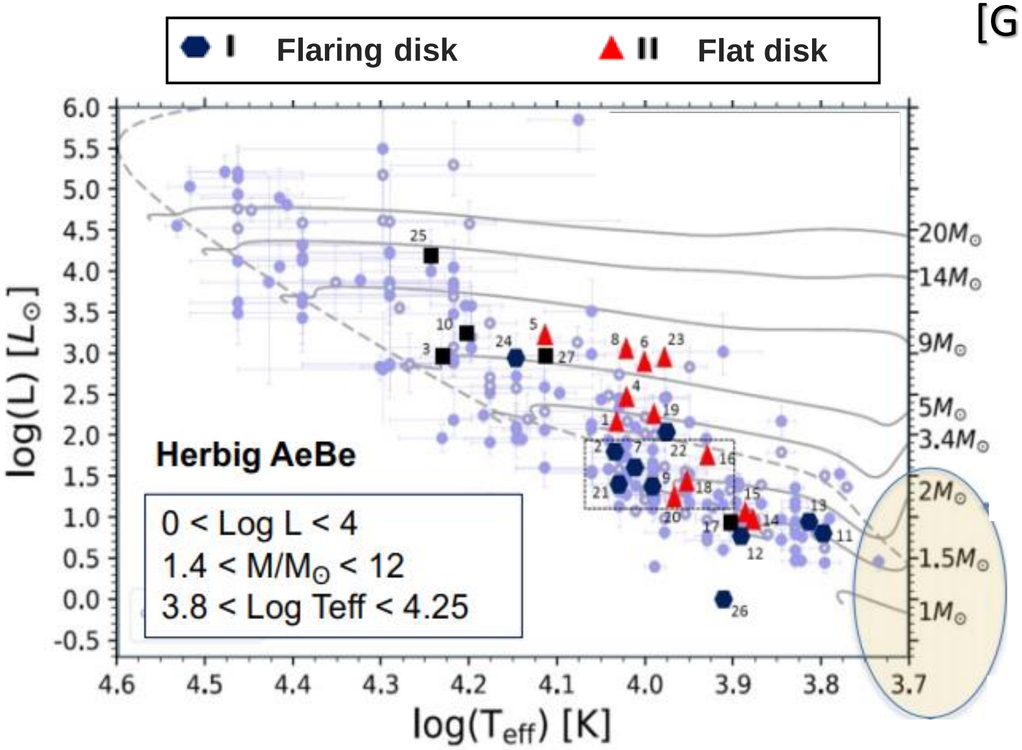
- Use the 4 telescopes, the sensitivity and accuracy of GRAVITY to investigate the findings of the pioniering works [Millan-Gabet+2001; Eisner+2005; 2007; 2014; Monnier & Dullemond 2010; Kraus 2015] within a statistical approach.
- Use the spectral resolution (R ~4000) and the full K-band to simultaneously study the dust emission and the hot (Brγ) and warm (CO) gas.



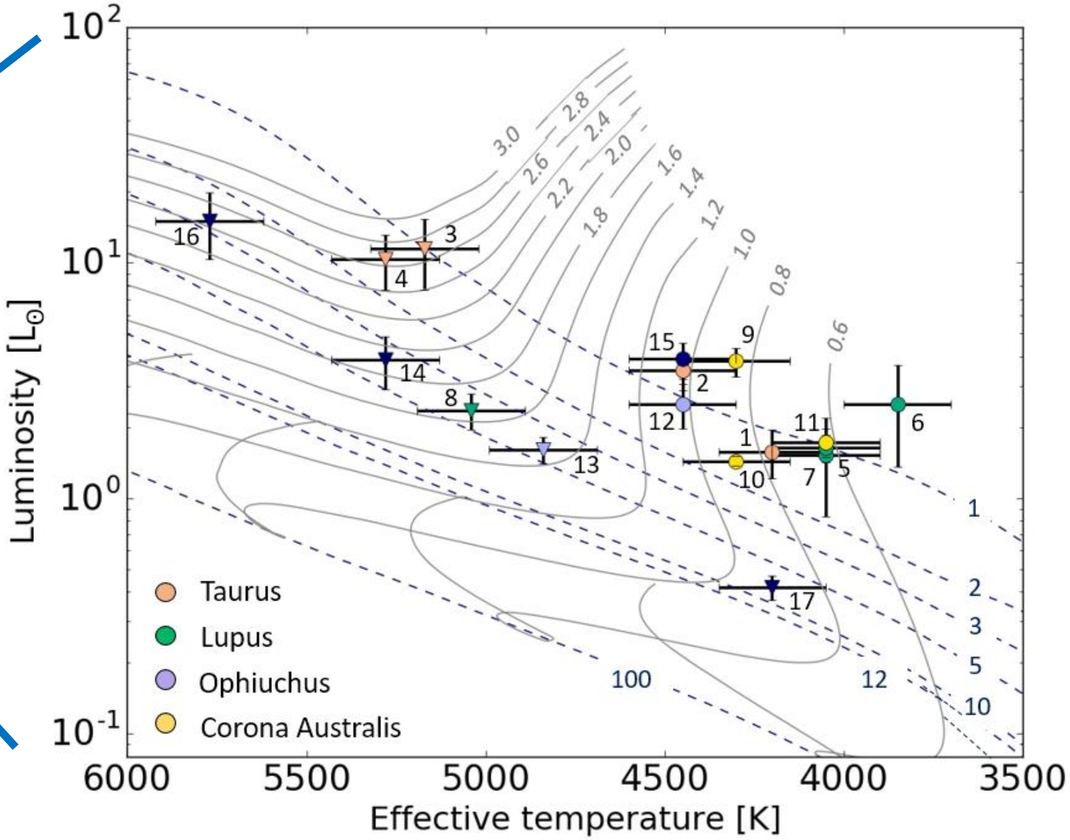
Probing the inner edge of the dusty disk

Statistical study of YSOs dusty disks

[GRAVITY Coll.: Perraut+2019] (27 Herbig stars)



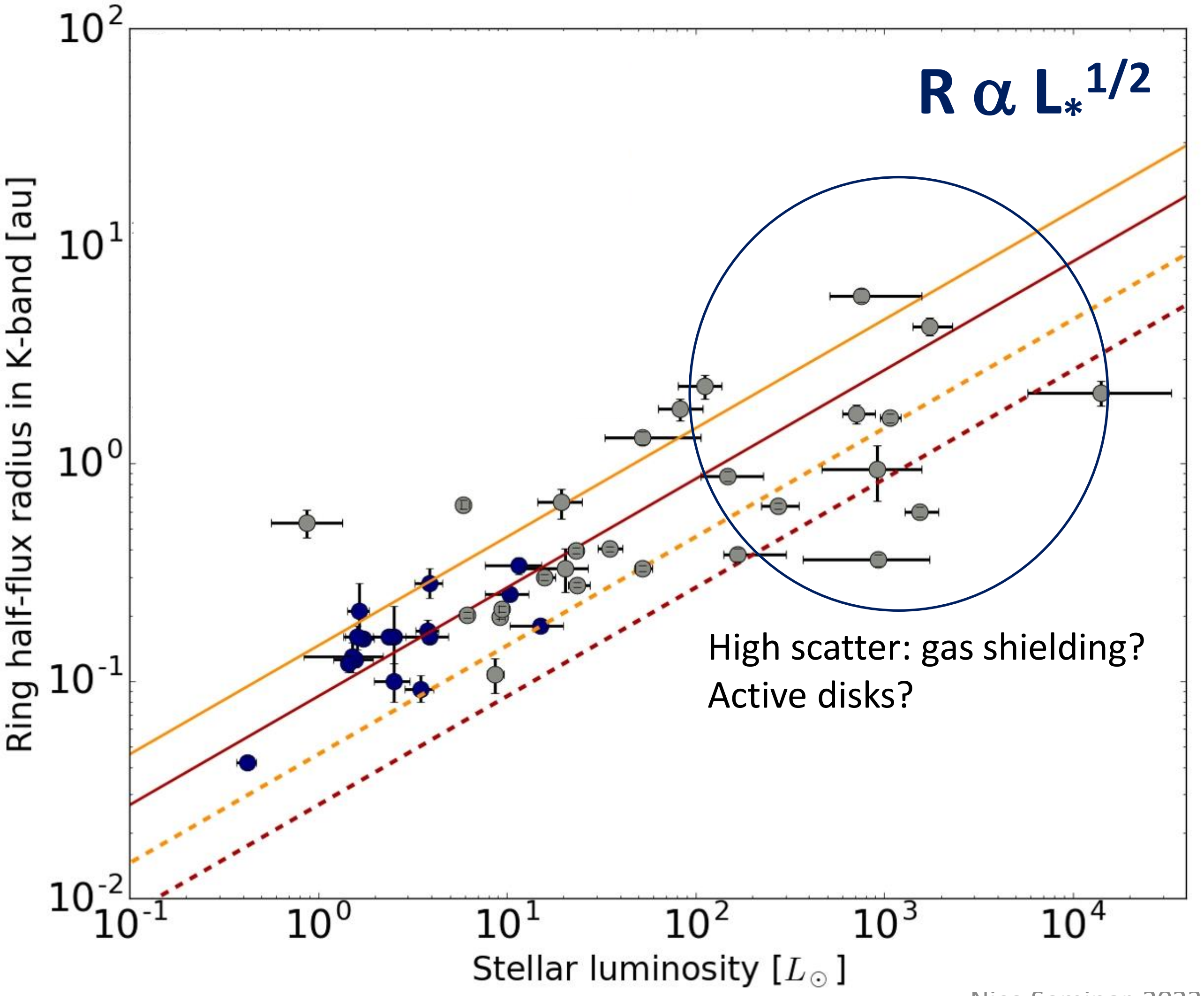
[GRAVITY Coll.: Perraut+2021] (17 T Tauri stars)



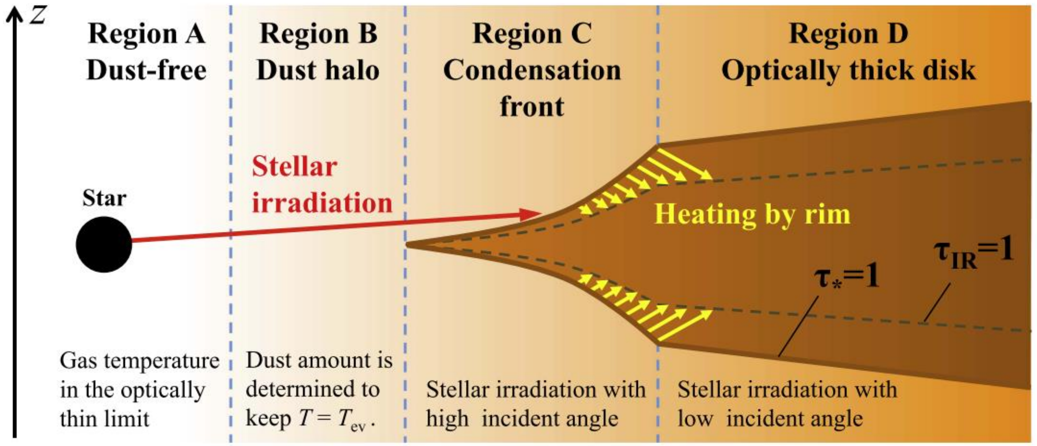
- Fully convective
- With a radiative core

[GRAVITY Coll.: Perraut+2019]

Revisit the Radius-Luminosity relation

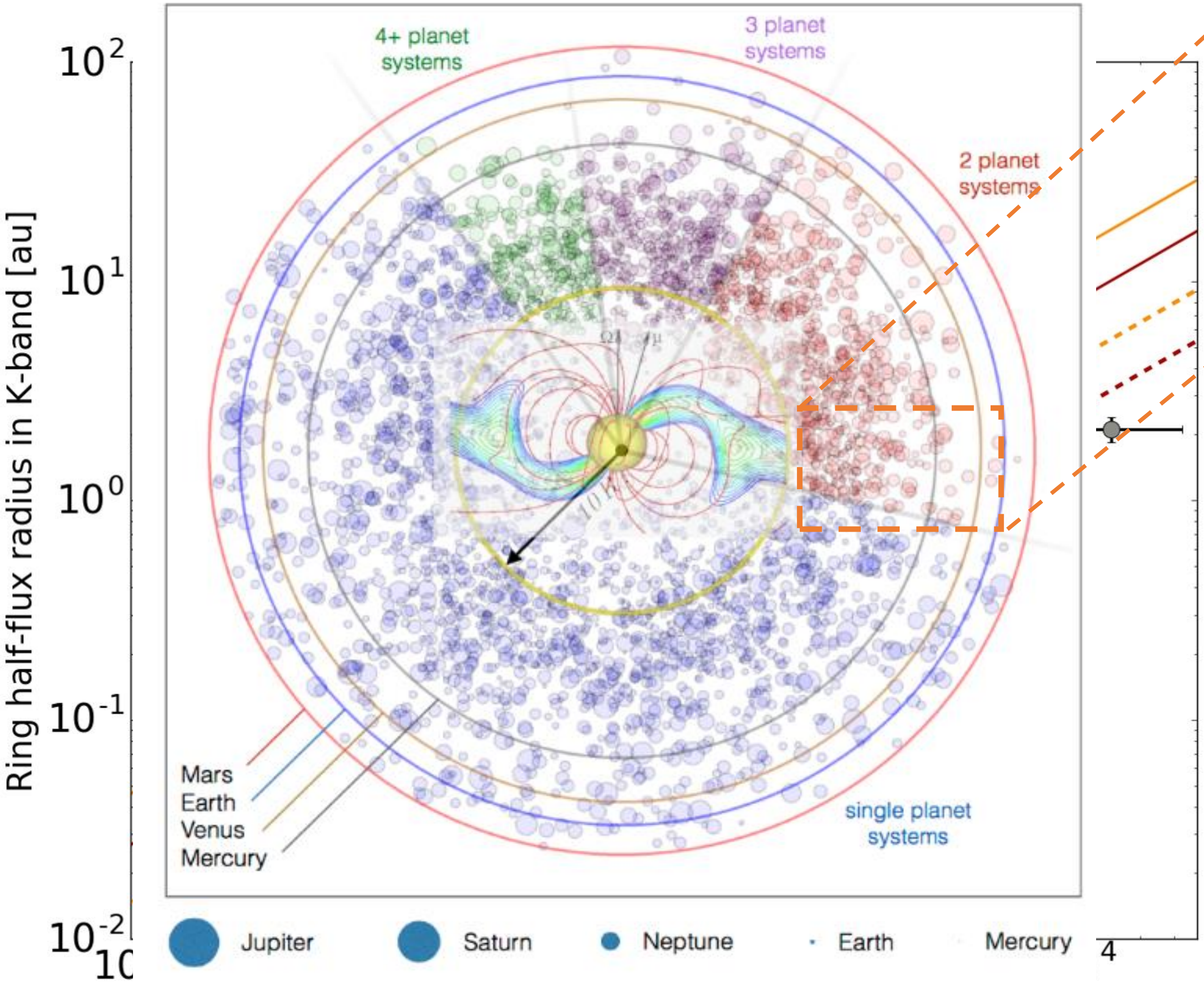


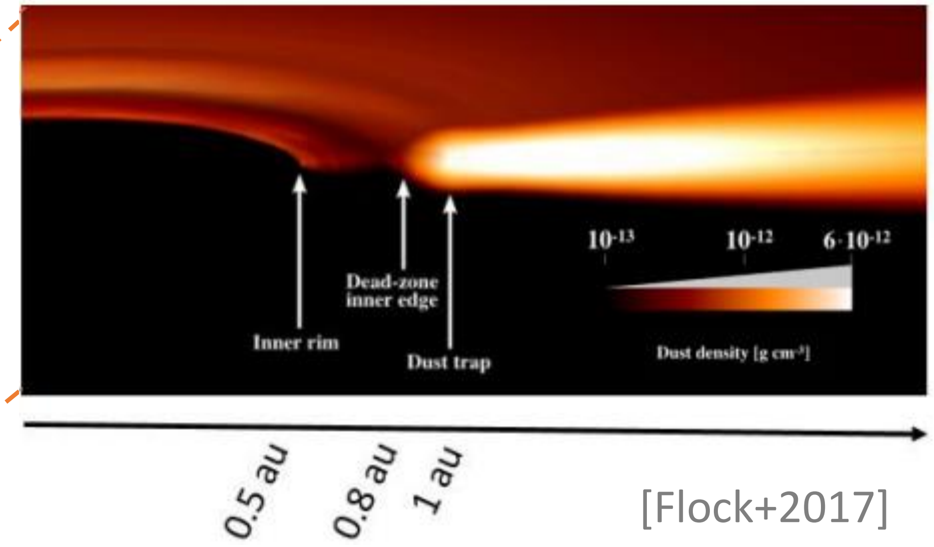
Consistent with an optically thin, passive disk, where starlight absorbed at the sublimation front heats the rim, making it vertically extended.



[Ueda+2017]

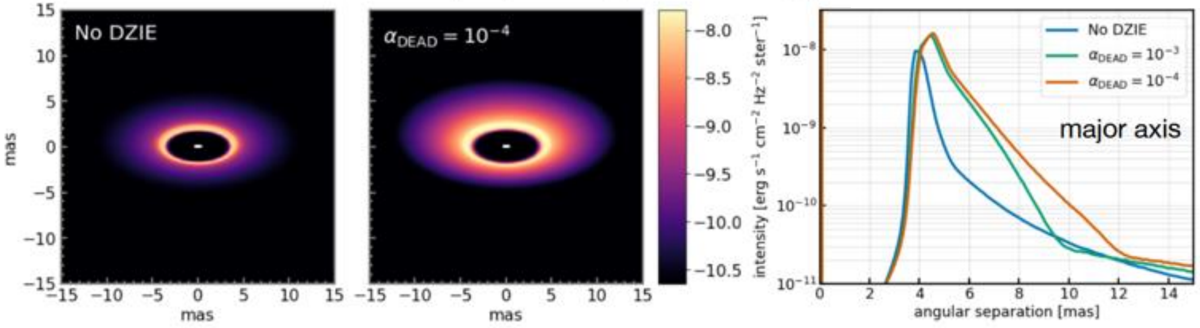
Advanced modeling of the inner rim



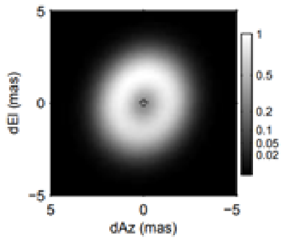


[Flock+2017]

$\lambda = 2.20$ μm, $i = 60^\circ$, $\dot{M} = 10^{-8} M_\odot$ yr⁻ [Ueda+, in prep]

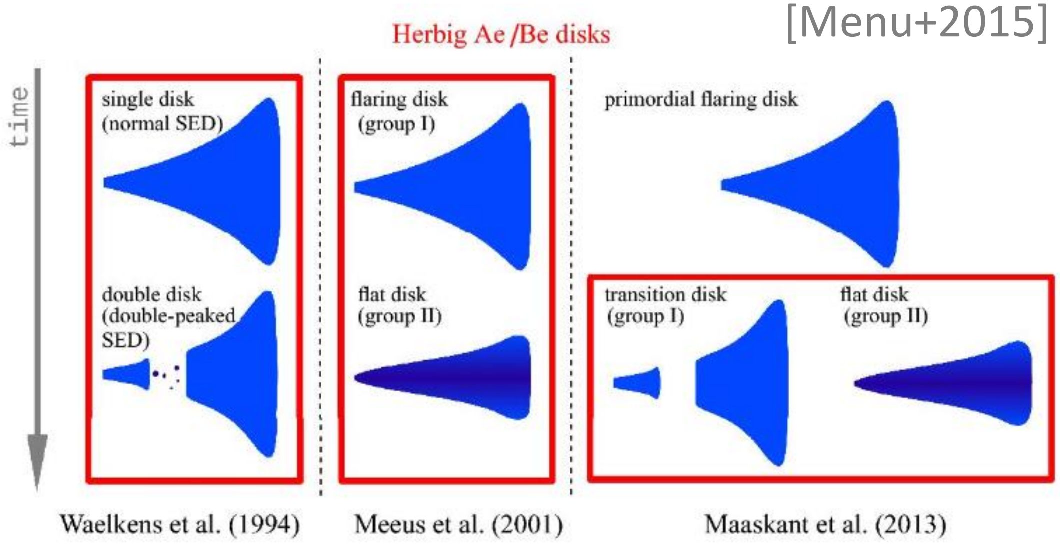


[Lazareff+2017]

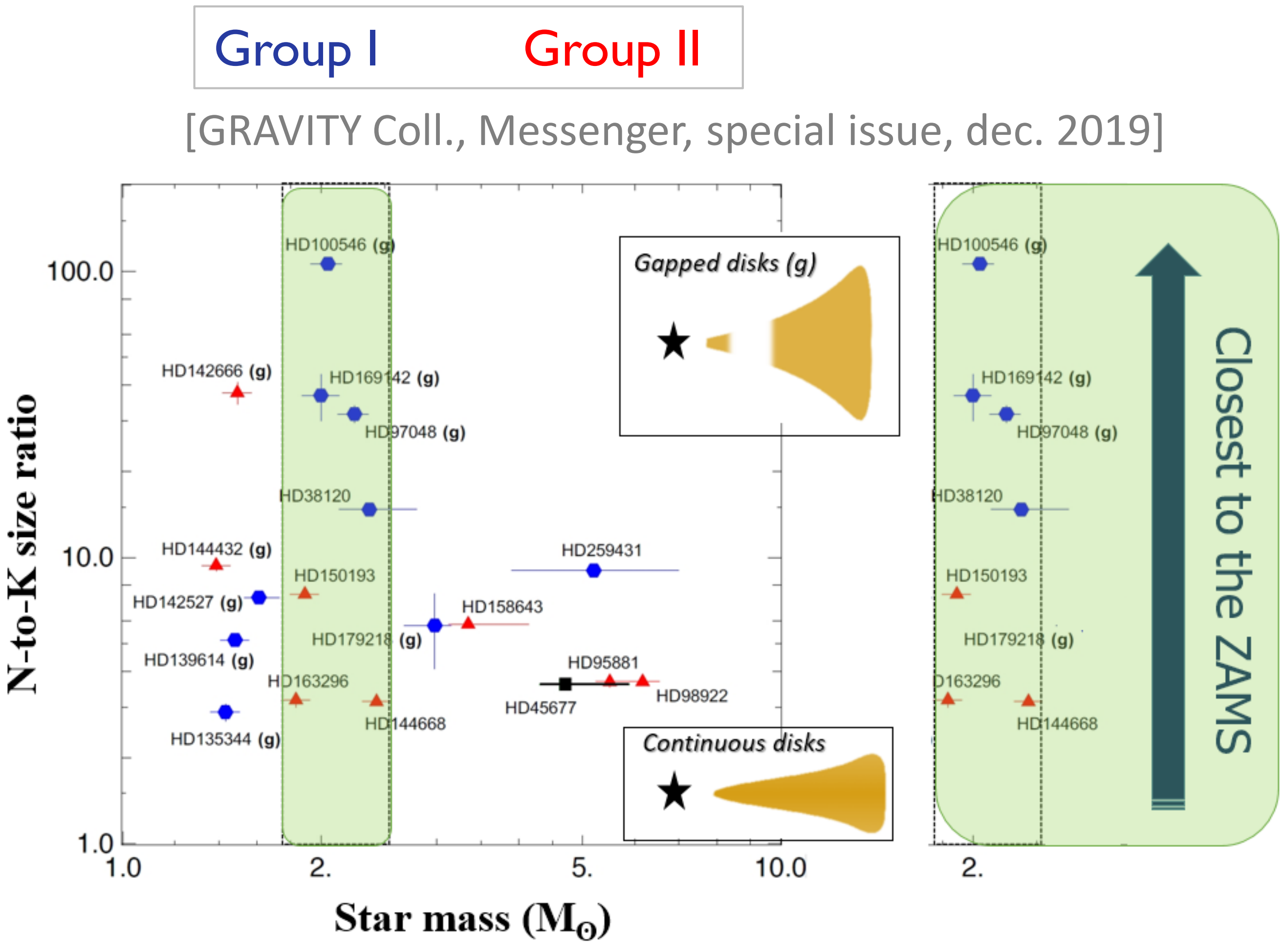


Toward an evolutionary scenario?

[Menu+2015]



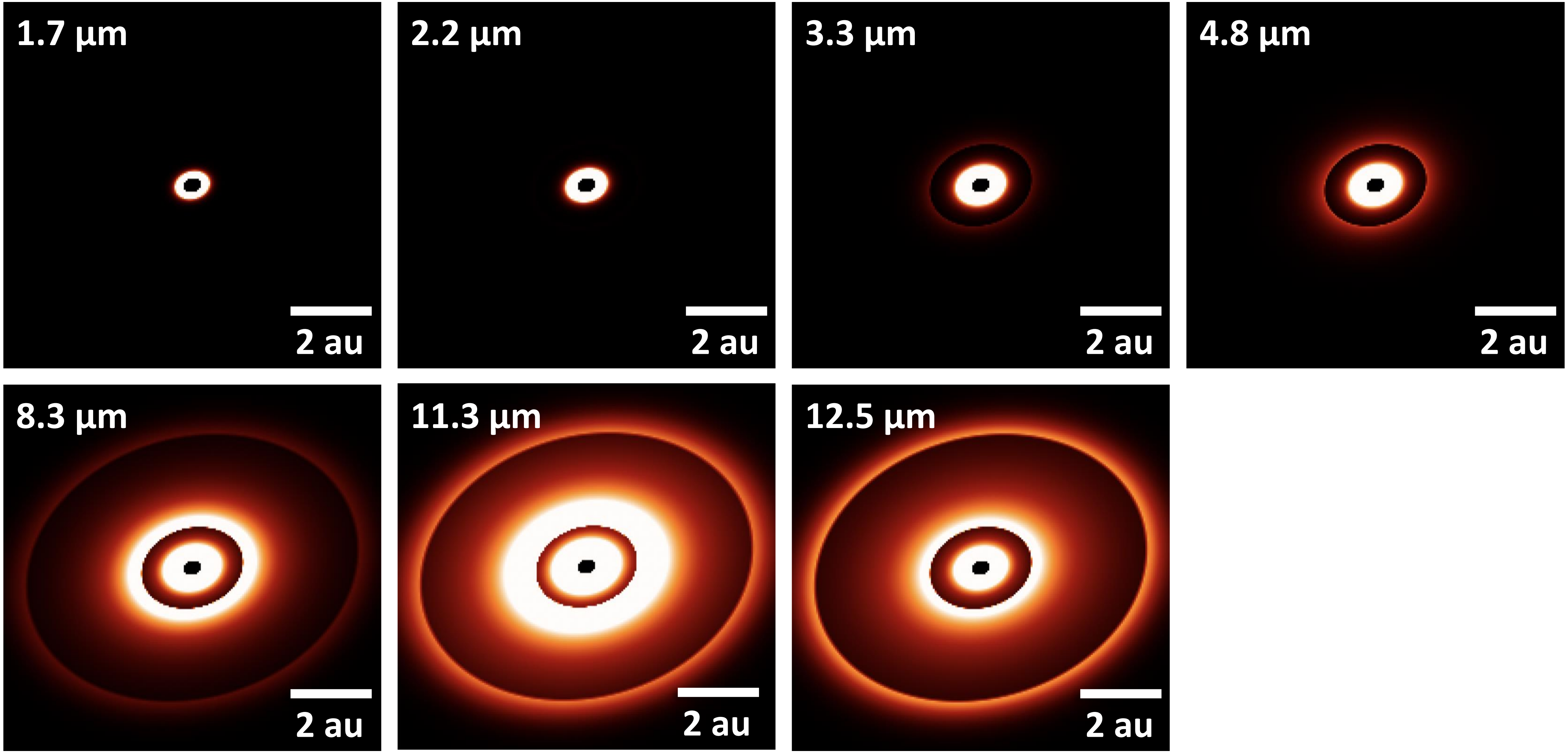
[GRAVITY Coll., Messenger, special issue, dec. 2019]



Need to populate this diagram with MATISSE and GRAVITY+

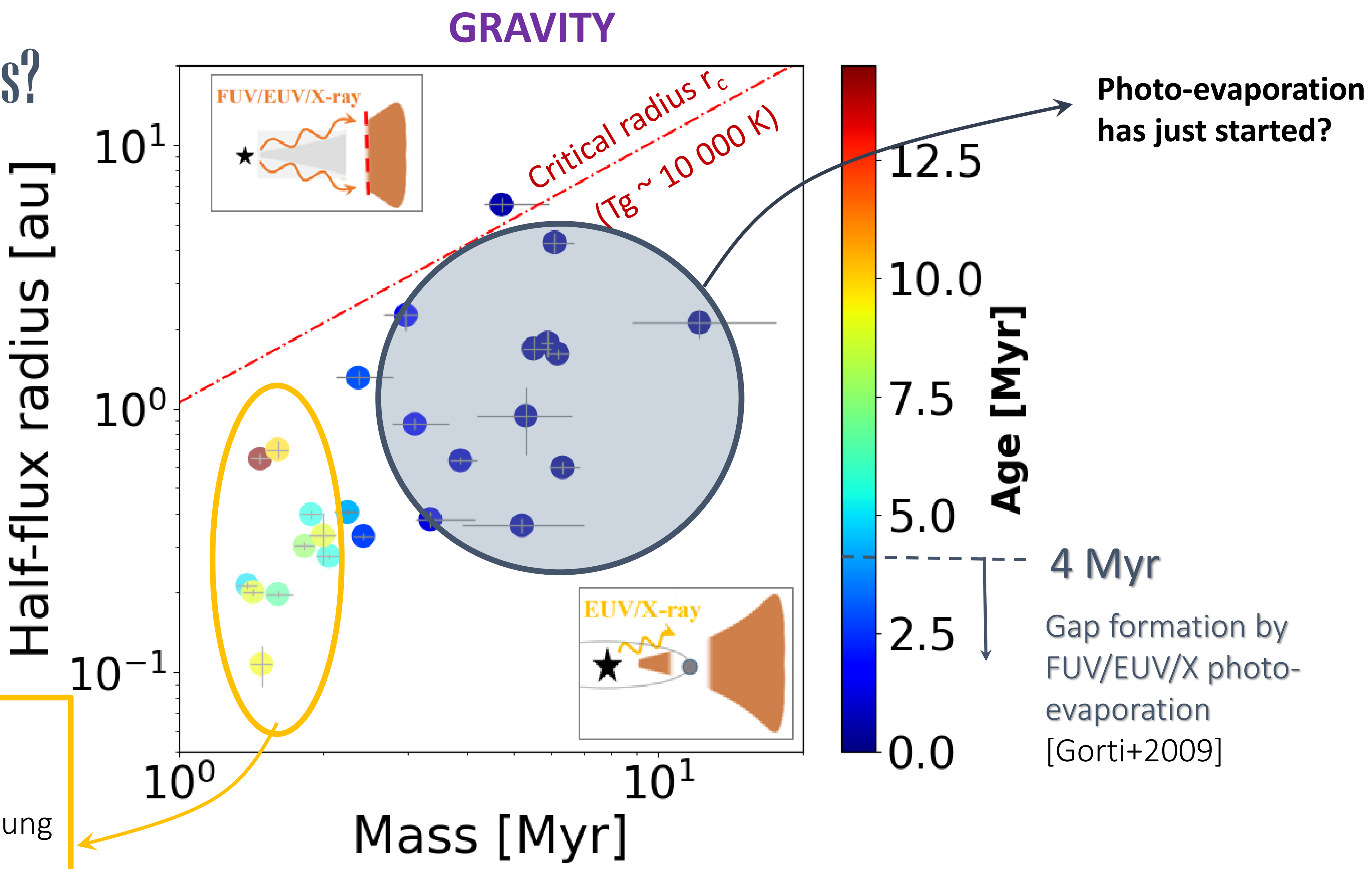
Combining GRAVITY and MATISSE data

[Varga et al. in prep]



[From GRAVITY Coll.: Perraut+2019]

Origin of the gaps?



Gapped, 5-10 Myr objects:

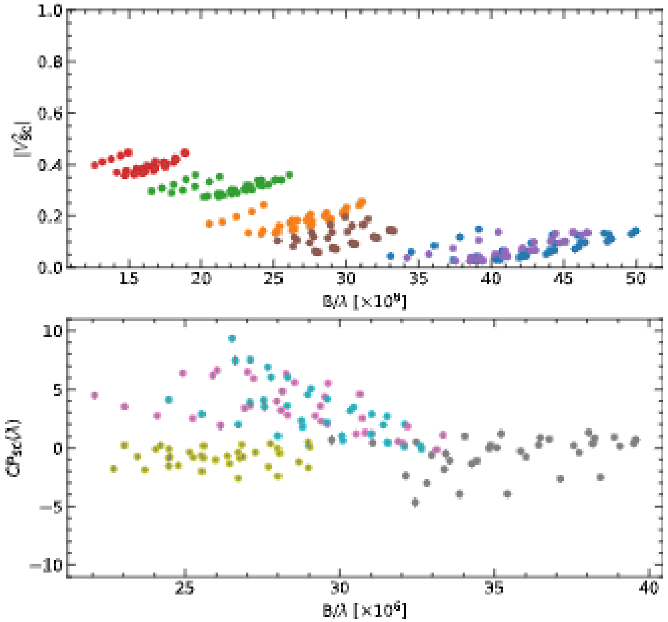
- EUV-photoevaporation?
- Dynamical clearing of young planets?

Connecting the inner and outer disks - Survey on 20 transitional disks

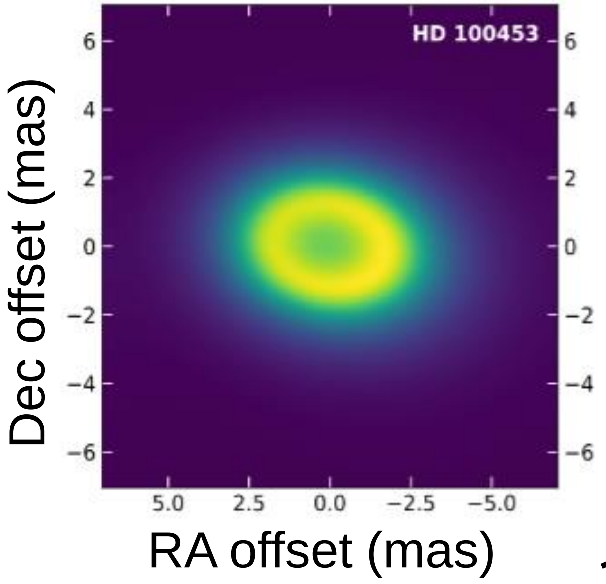
GRAVITY

(i, PA) for the inner disks
(i, PA) for the outer disks

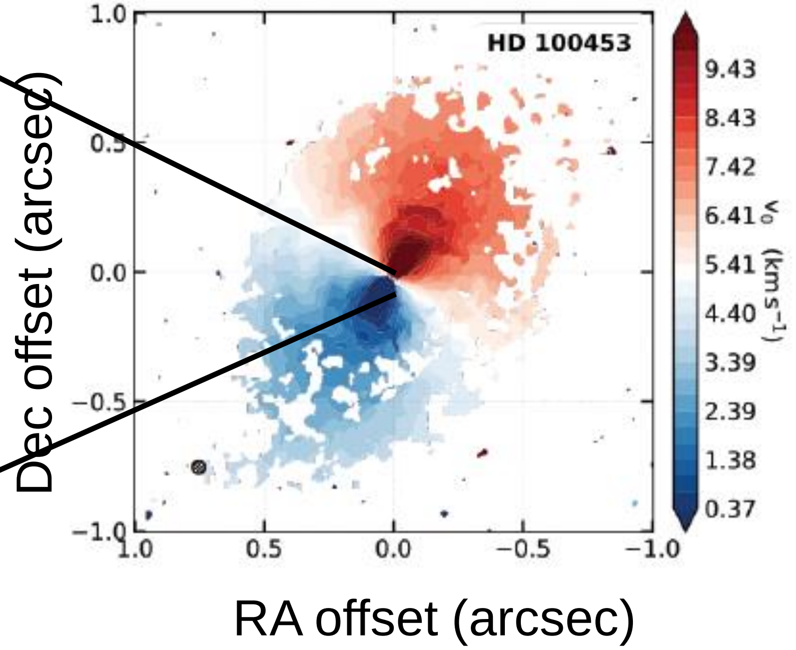
ALMA



K-band INNER DISK

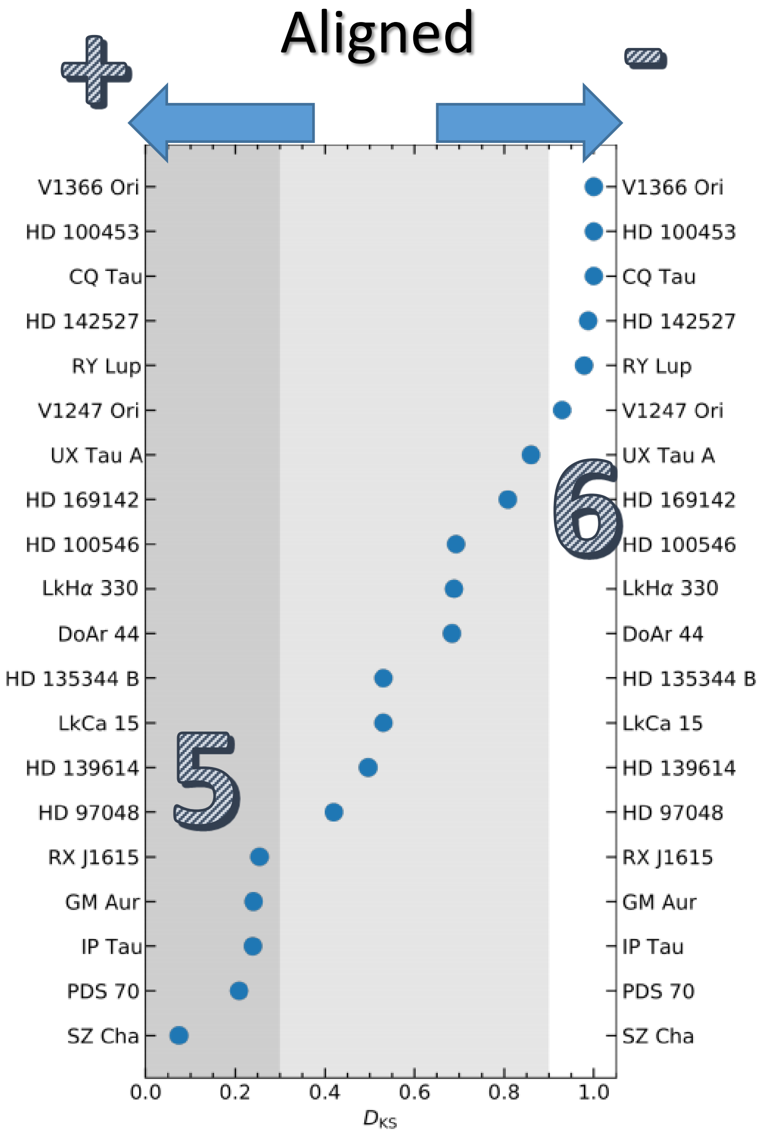


CO - OUTER DISK

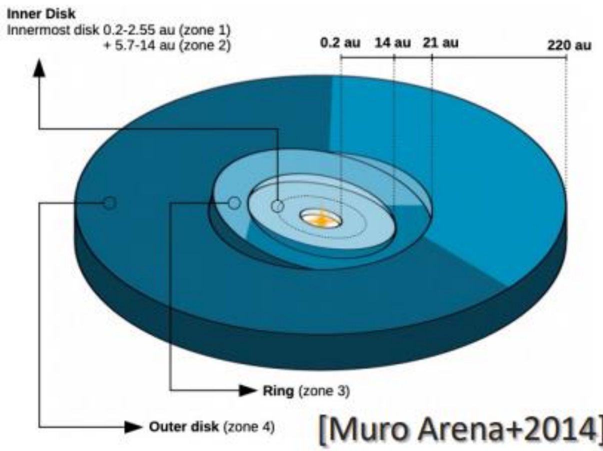


[Bohn, Benisty, Perraut+2022]

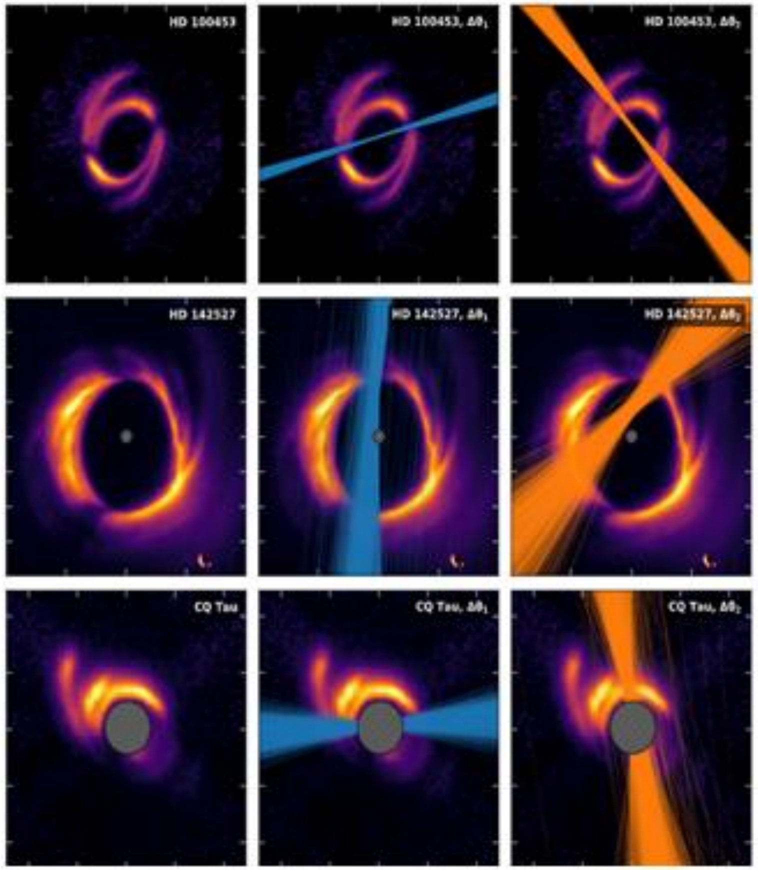
Connecting the inner and outer disks - look for misalignments



Measured misalignment ➔ predictions of the shadows' positions



[Muro Arena+2014]



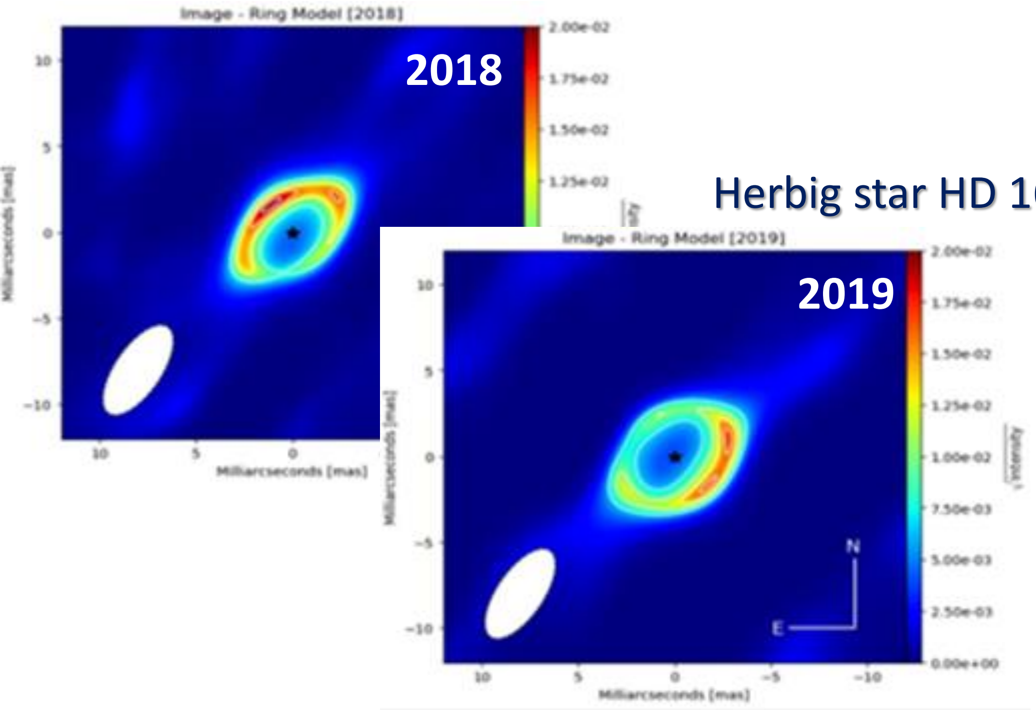
Warps?
Massive companion?
Outcome of earlier stages?

Imaging the innermost regions of Herbig stars and variability

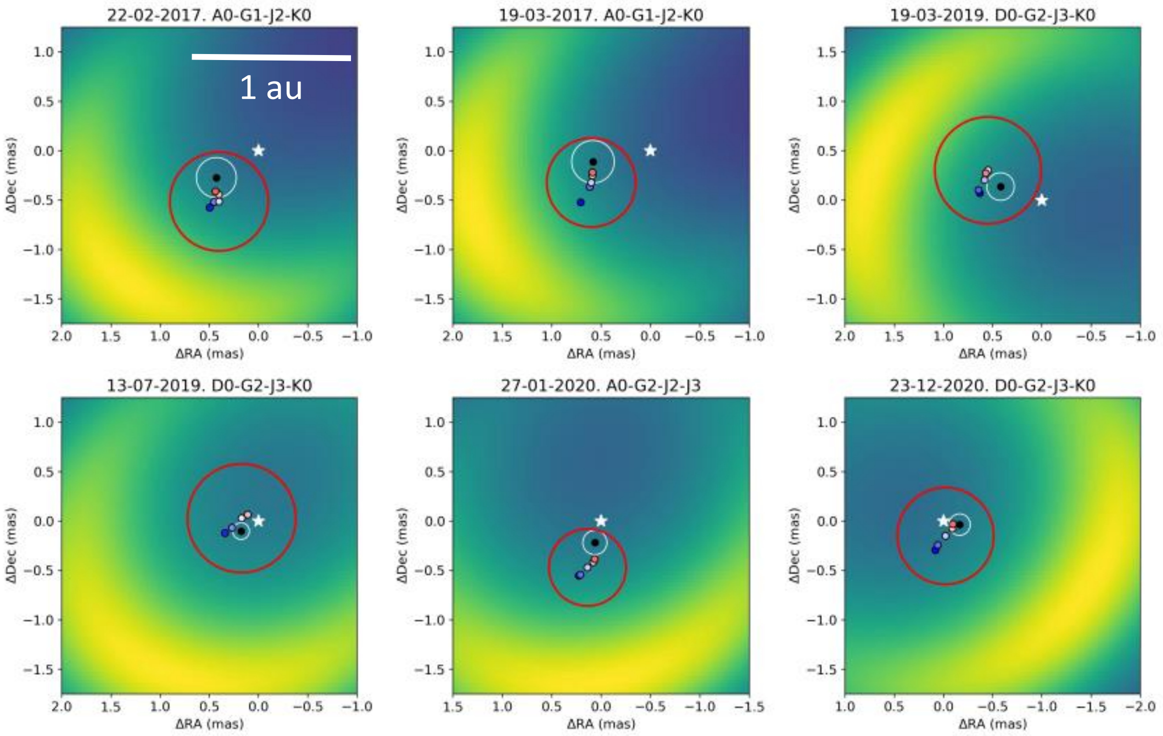
Very challenging due to **compactness** and **variability** at short timescales

[GRAVITY Coll.: Sanchez-Bermudez+2021]

[GRAVITY Coll.: Ganci+, subm.]



Herbig star HD 163296



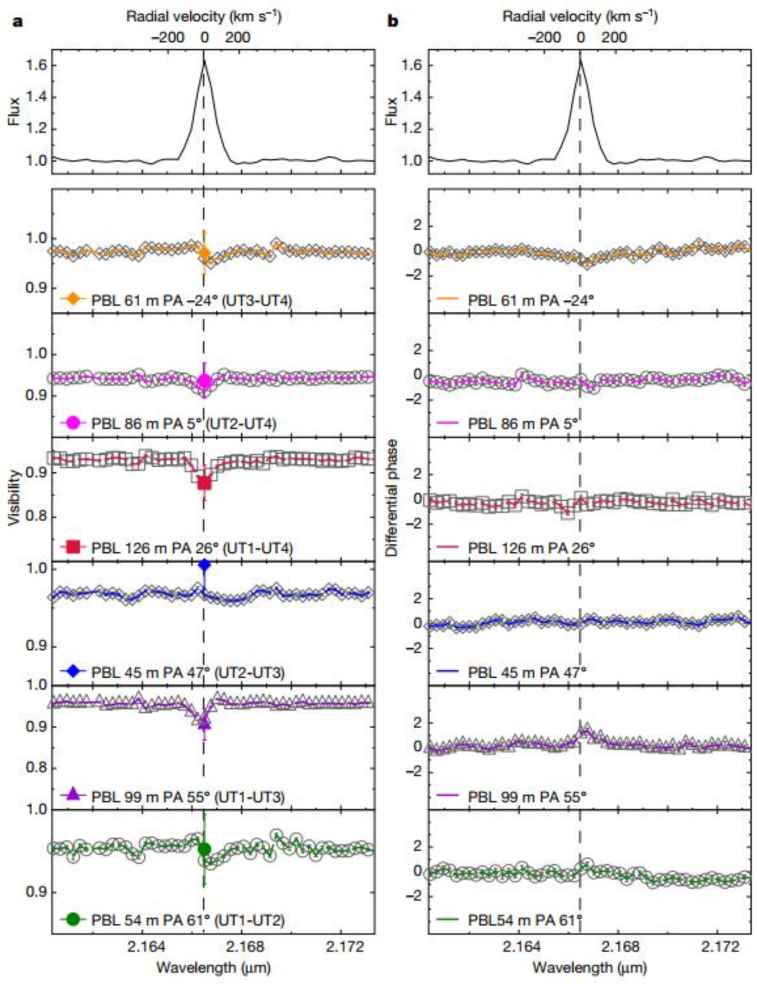
Large vortex at ~1 au triggered by hydrodynamical instabilities
Asymmetric disk wind or sub-stellar/planetary accreting companion?

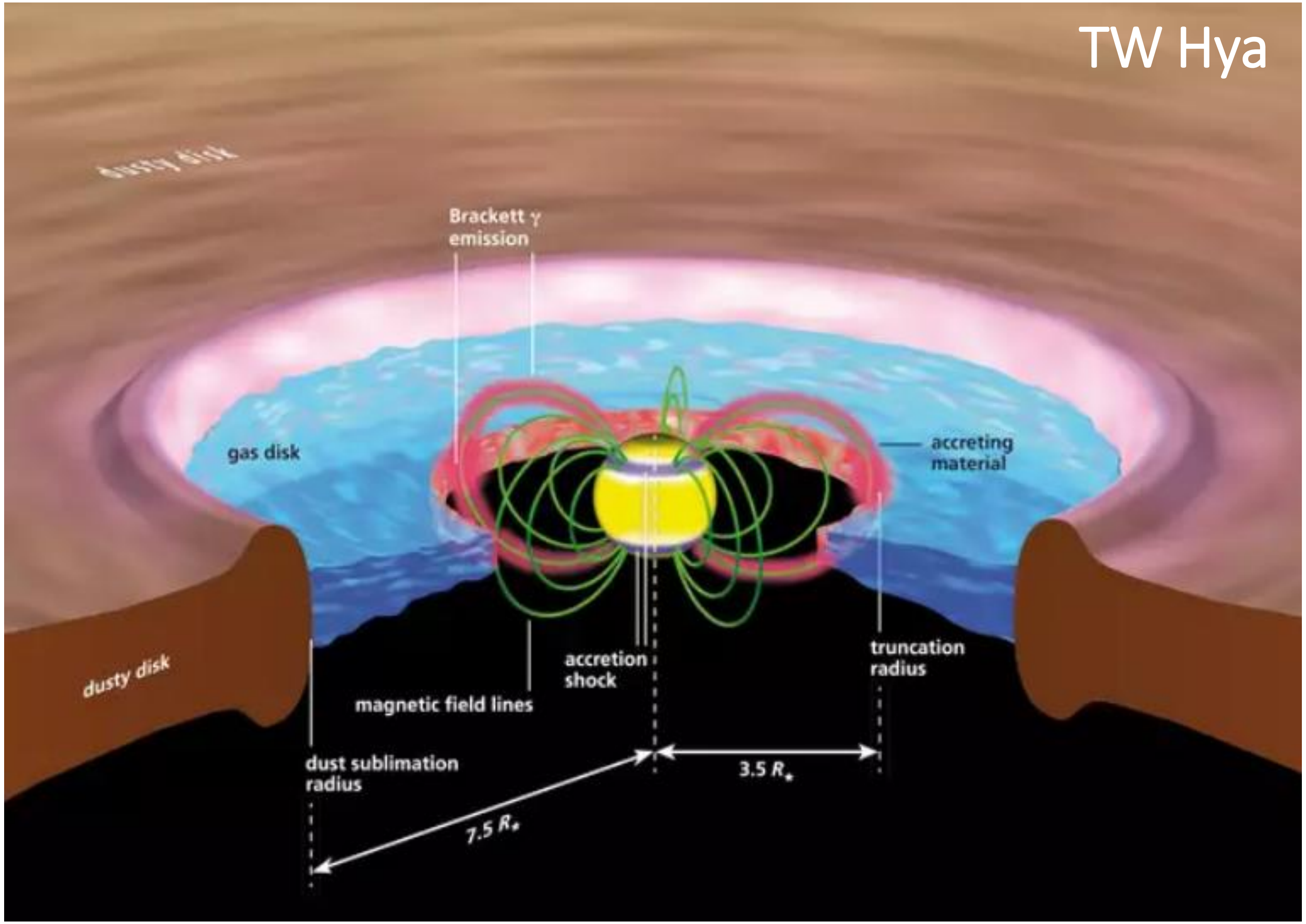
Probing the accretion-ejection processes

[GRAVITY Coll.: Garcia-Lopez+2020, Nature]

Probing the magnetospheric accretion on TW Hya

GRAVITY



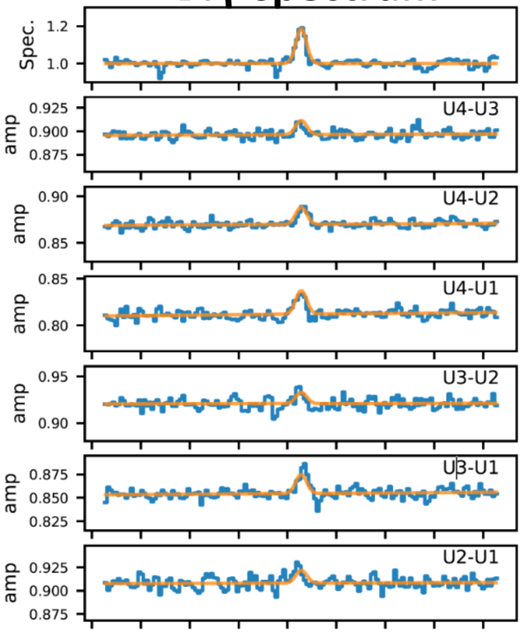


[Bouvier, Perraut, Le Bouquin+2020]
[Bouvier, Alecian, Alencar+2020]

Probing the accretion flows on DoAr44

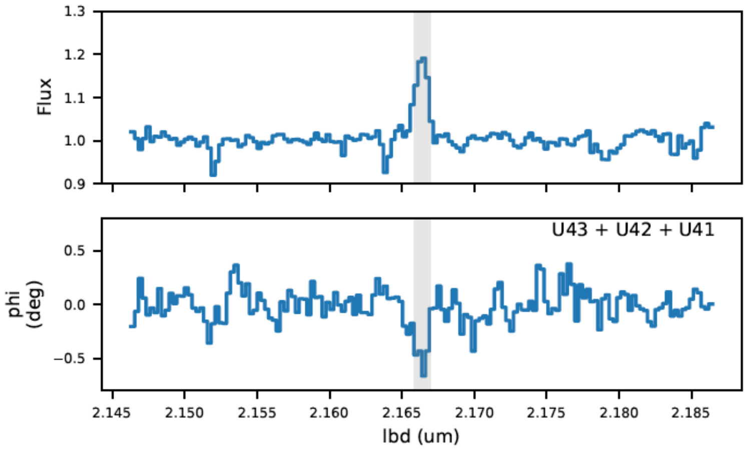
GRAVITY

Brγ spectrum

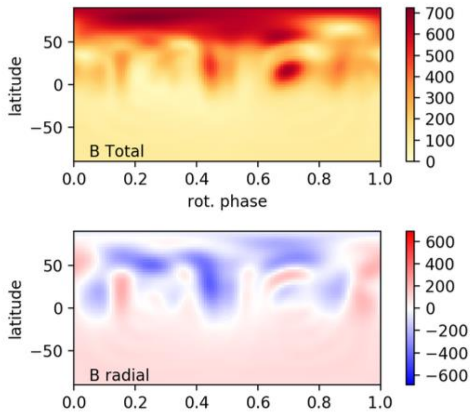


Brγ visibilities

Brγ spectrum



Brγ spectro-astrometry



ESPaDOnS

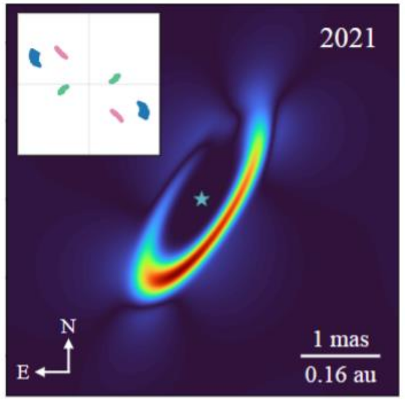
B ≈ 2.0 +/- 0.8 kG
Rmag ≈ 4.6 R_*

- ➢ Inner-outer disk misalignment confirmed
- ➢ Size of the magnetosphere < 5 R*
- ➢ Slightly offset from the star (~1 R*)

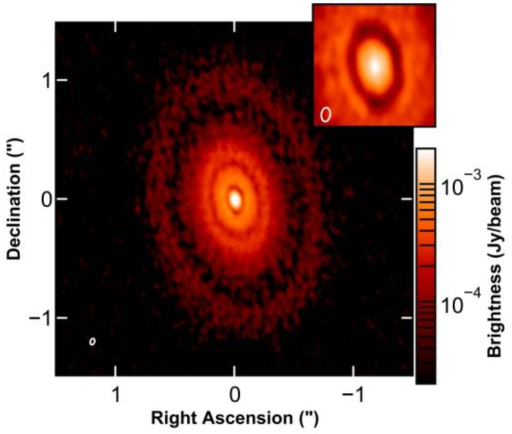
Observations fully compatible with magnetospheric accretion scenario

Probing the innermost regions of CI Tau

Best-model of GRAVITY K-band continuum

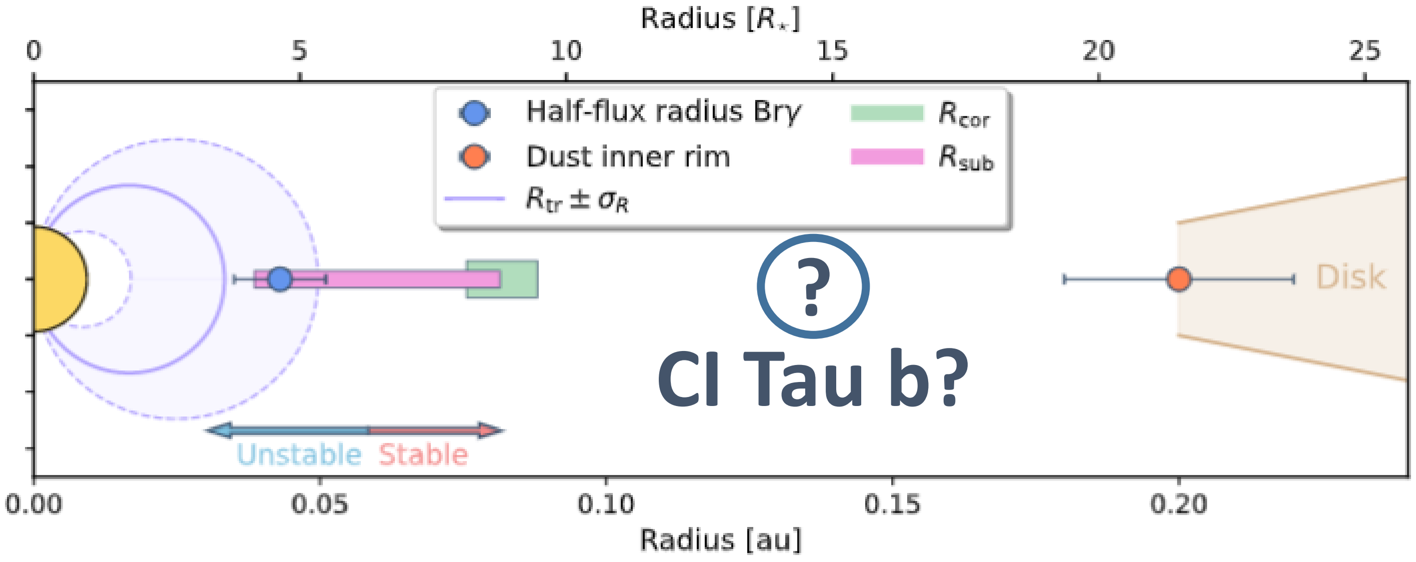


ALMA



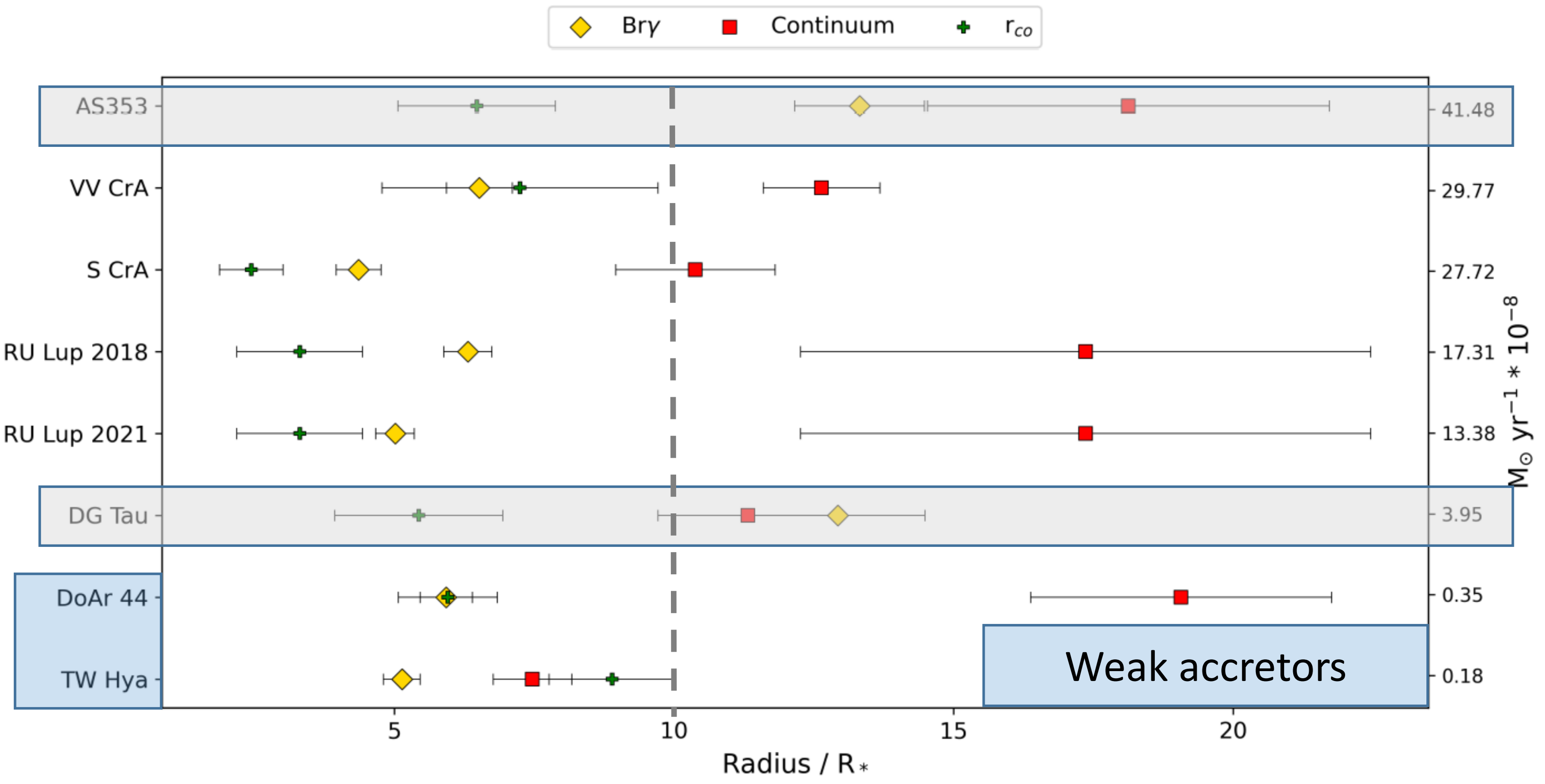
[Clarke+2018]

- Strongly inclined inner disk (i ~70°) and inner-outer disk misalignment
- Inner edge of the dusty disk significantly larger than R_{sub}
- Size of Brγ emitting region ~ 5 R*



[GRAVITY Coll.: Wojtczak+2023, A&A, 669, 59]

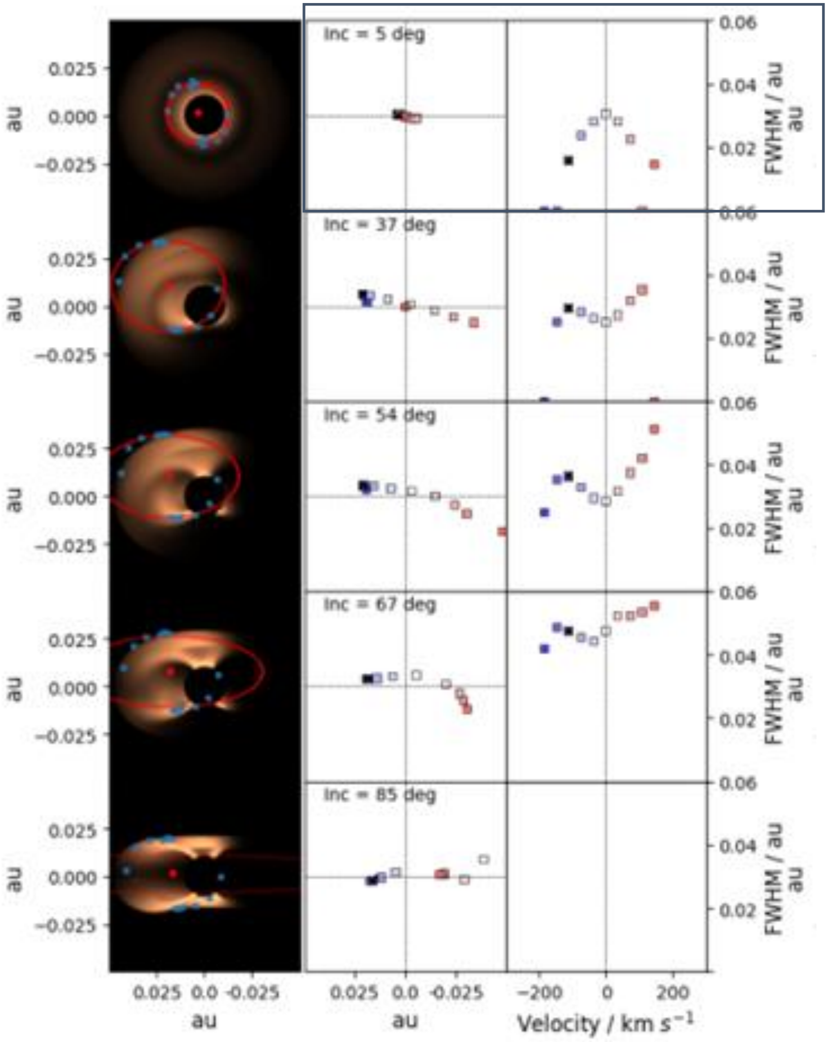
Hot hydrogen Brγ line of a sample of T Tauri stars

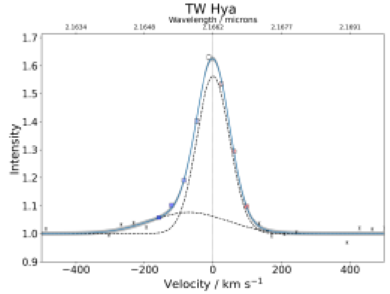


Magnetospheric accretion is not always the dominant contribution in the Brγ line emission

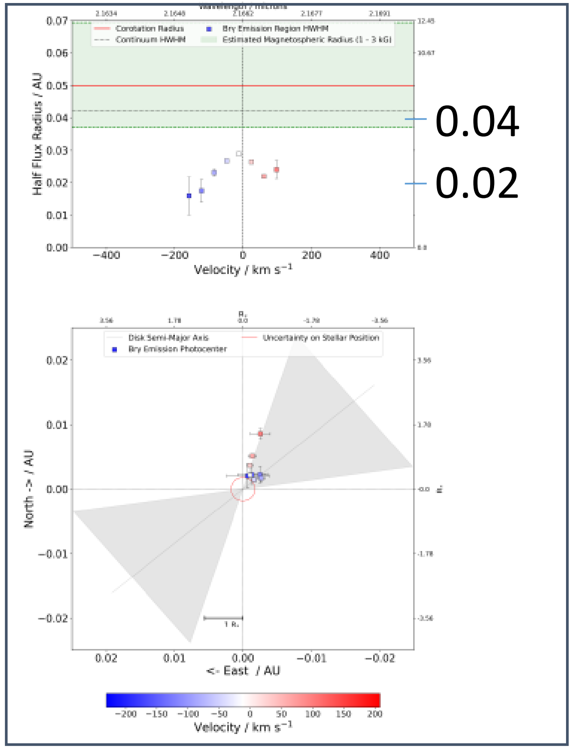
Testing the magnetospheric accretion models

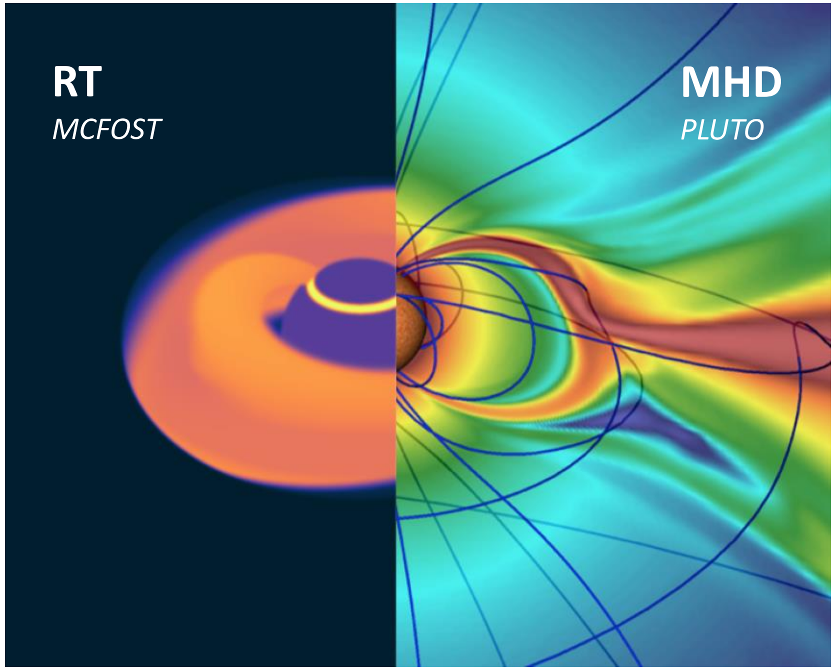
spidi-eu.org





TW Hya



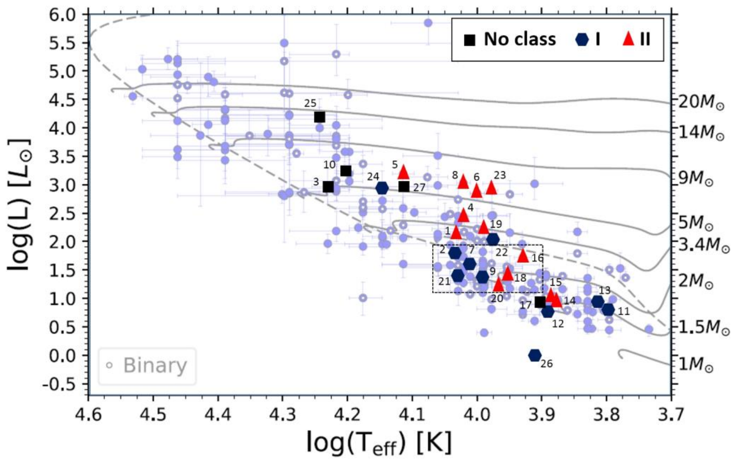


[Tessore+2023]

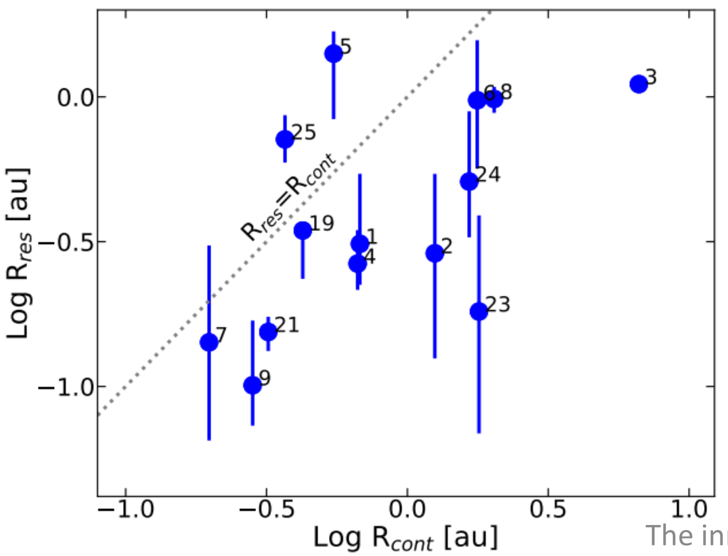
[GRAVITY Coll.: Wojtczak+2022, A&A, 669, 59]

[GRAVITY Coll.: Garcia-Lopez+2023, in revision]

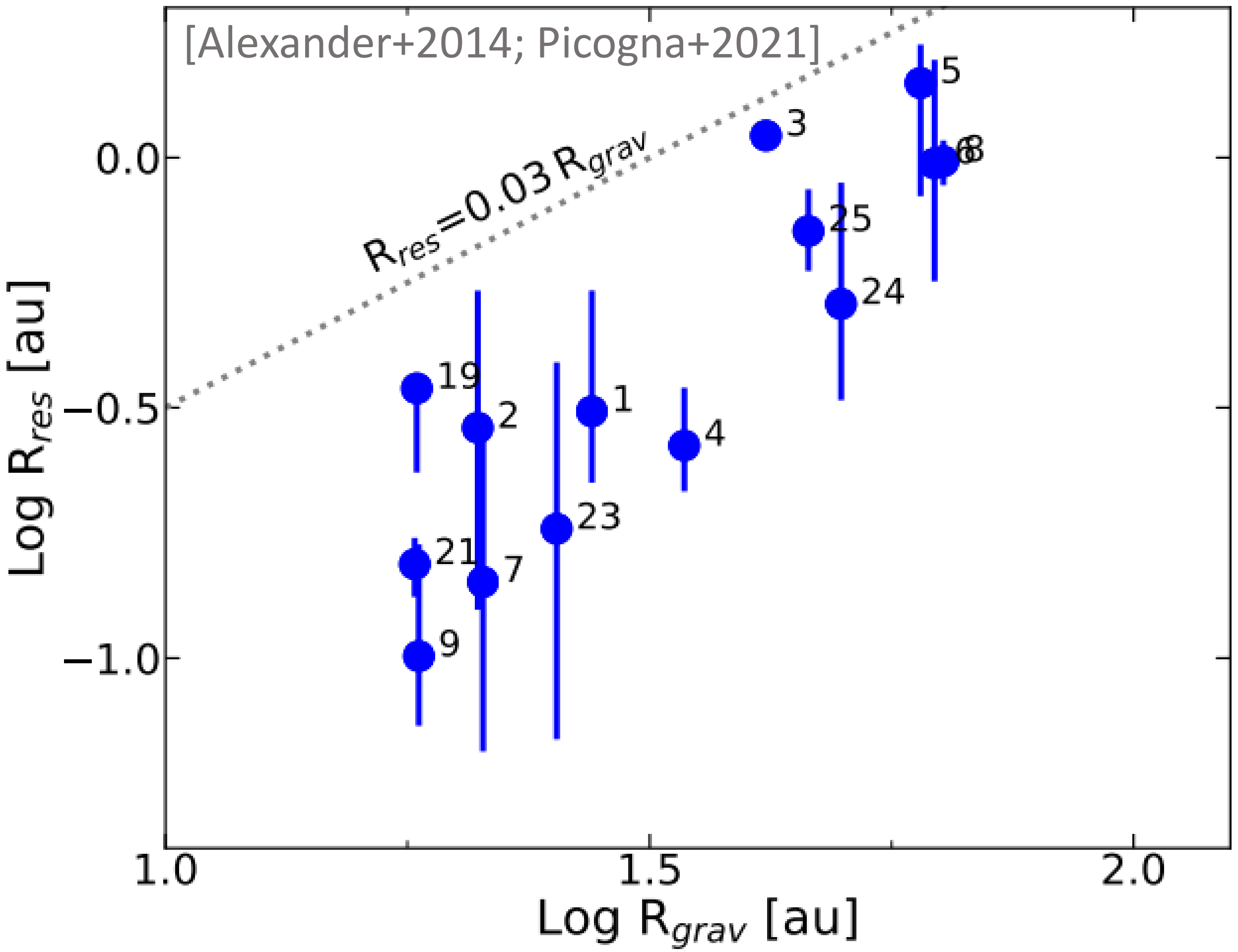
Hot hydrogen Brγ line of a sample of Herbig stars



Brγ more compact than continuum

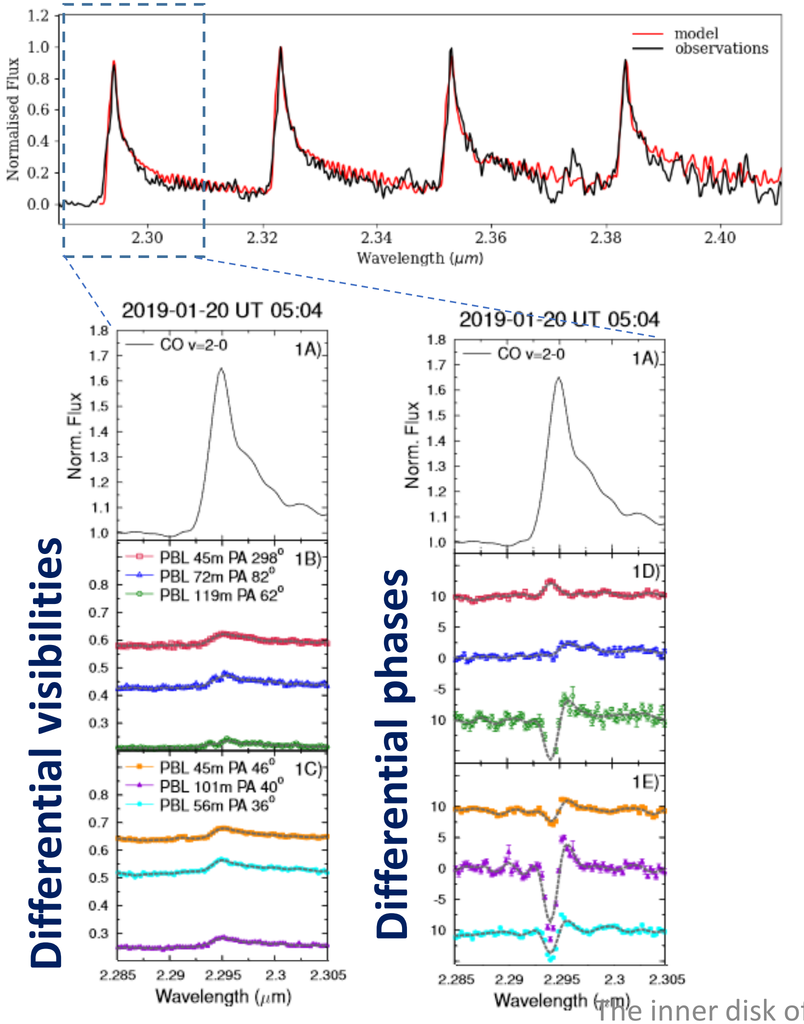


Brγ much smaller than peak of photoevaporative winds

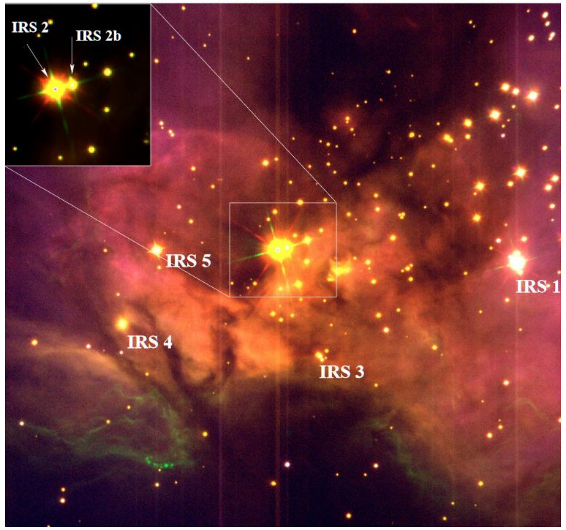


The GRAVITY observations across the CO bandheads

GRAVITY CO bandheads (R ~ 4000)



Continuum	diameter [mas]	diameter [au]	i [°]	PA [°]
	$3.99\pm^{0.08}_{0.1}$	$1.69\pm^{0.03}_{0.04}$	34 ± 1	166 ± 1
Bandhead				
All	$2.74\pm^{0.08}_{0.07}$	1.16 ± 0.03	32 ± 3	$168\pm^{5}_{4}$
$v = 2–0$	$2.9\pm^{0.1}_{0.2}$	$1.21\pm^{0.04}_{0.08}$	$33\pm^{5}_{8}$	$159\pm^{8}_{5}$
$v = 3–1$	2.6 ± 0.1	1.10 ± 0.04	$28\pm^{6}_{7}$	$177\pm^{14}_{12}$
$v = 4–2$	2.8 ± 0.1	1.18 ± 0.04	$32\pm^{4}_{5}$	$169\pm^{11}_{7}$
$v = 5–3$	2.5 ± 0.1	1.06 ± 0.04	$33\pm^{4}_{6}$	$187\pm^{9}_{12}$



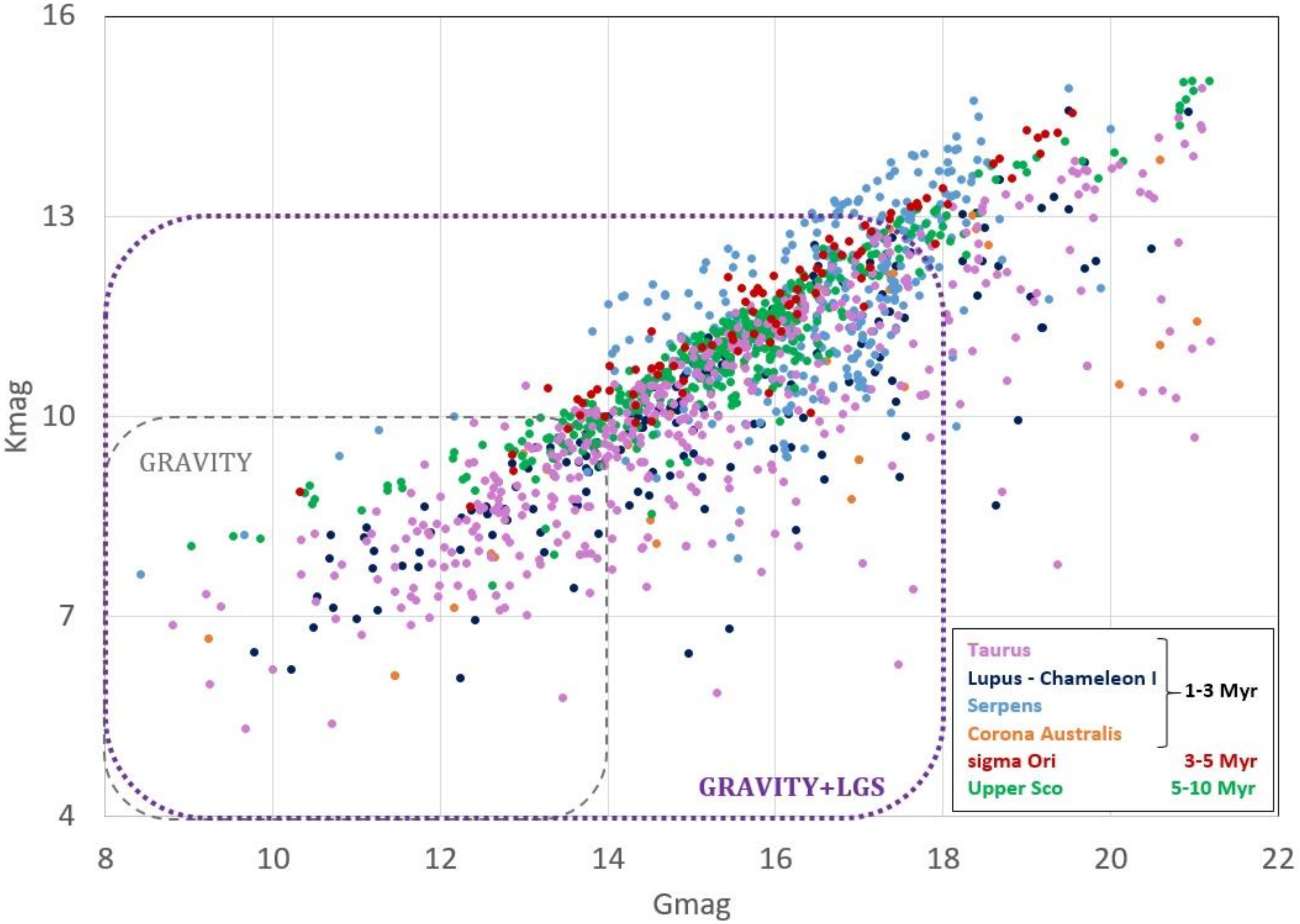
NGC 2024 IRS2

- CO emitting region more compact than continuum
- Radial extent (ΔR) of the CO-emitting region relatively small
- CO emission above the mid-plane (T ~ 2800 K)
- M* ~15 $M_{\odot}$ (gas shielding)

The future with GRAVITY+

The future with GRAVITY+

G+ increases sensitivity and sky coverage

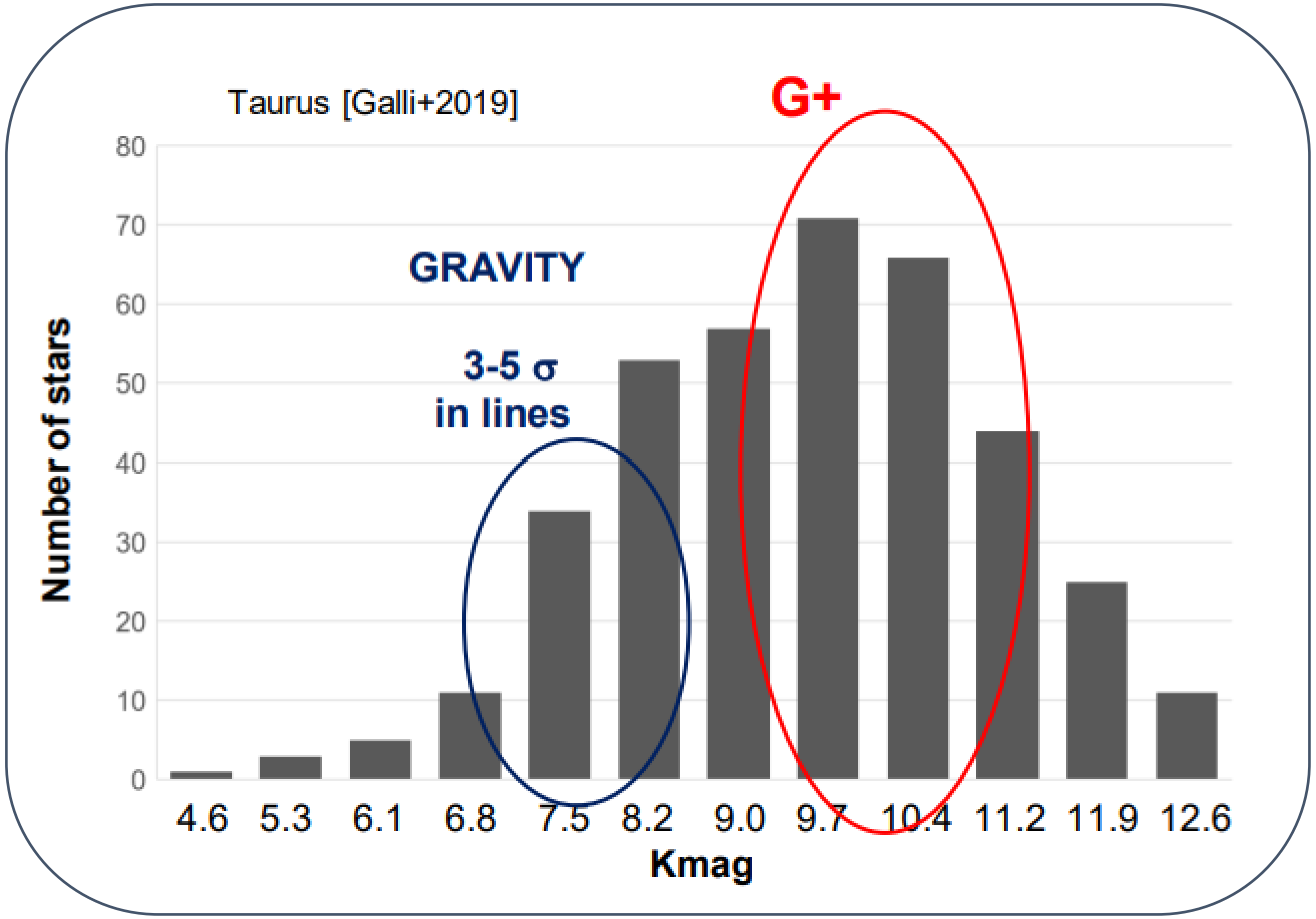


- access to a large number of stars in several Star Forming Regions
- cover a large parameter space in terms of mass, luminosity, age

⇒ **More representative samples**

⇒ **Trends** with central star properties

The future with GRAVITY+



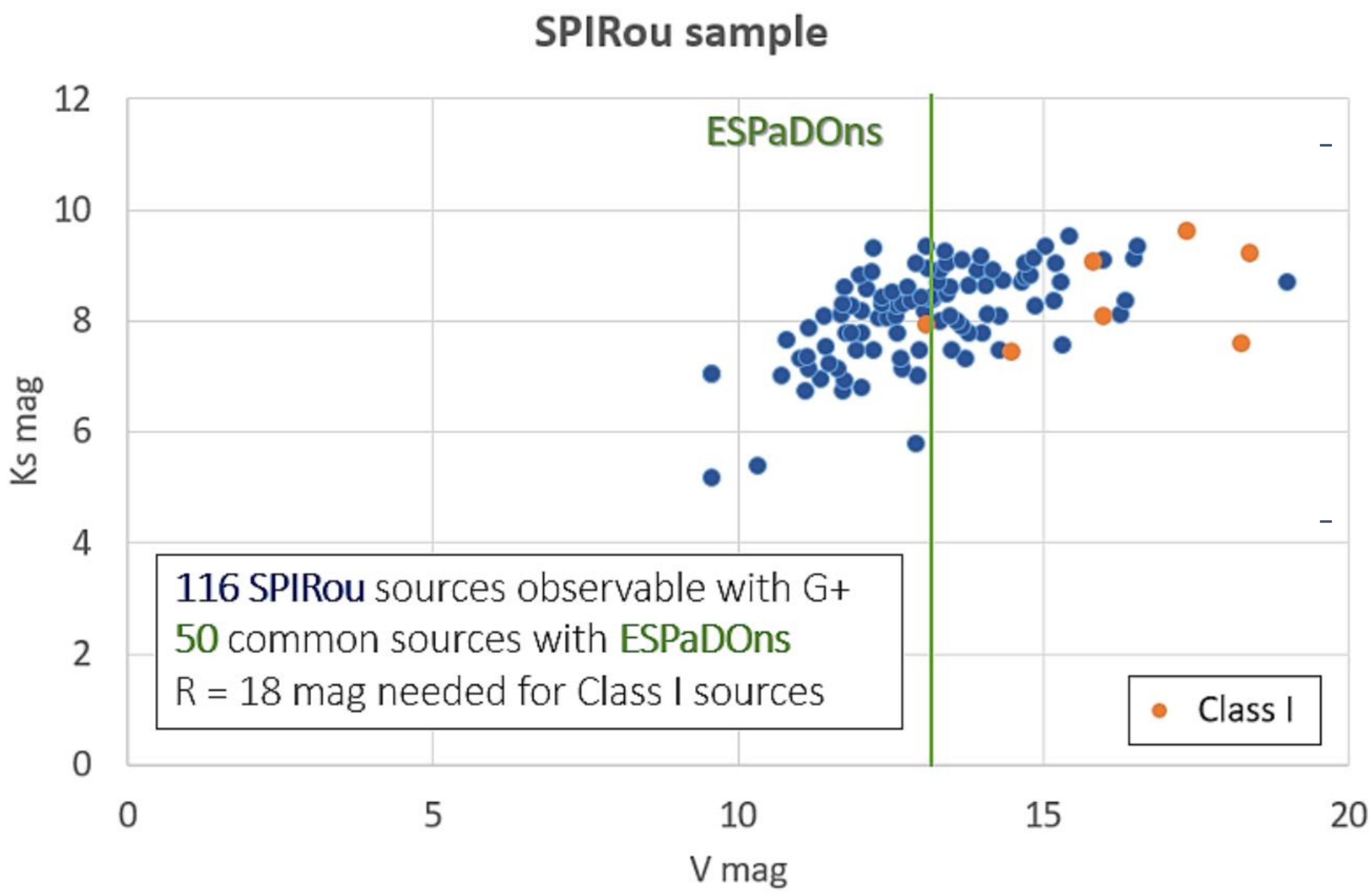
G+ makes spectro-astrometry possible:

- on **fainter T Tauri stars** with a few hours of integration (as today with GRAVITY on stars with Kmag ~ 7-8)
- on brighter targets with shorter integration

⇒ **better time monitoring** of size of the Brγ line emitting region and its temporal on-sky displacement

⇒ **Strong synergies with spectro-polarimetry** for monitoring the magnetic field topology

The future with GRAVITY+



- Better overlap with spectro-polarimetry for monitoring the magnetic field topology, studying accretion phenomena, inner disk shaping by magnetic field, …

- Access to Class I sources: probing a different regime of accretion, stronger magnetic fields

Conclusion

GRAVITY YSO LP provides an invaluable **homogeneous data set**

√ Looking for trends with the central stars' properties

√ Demographic studies (Herbig, T Tauri, HMYSO)

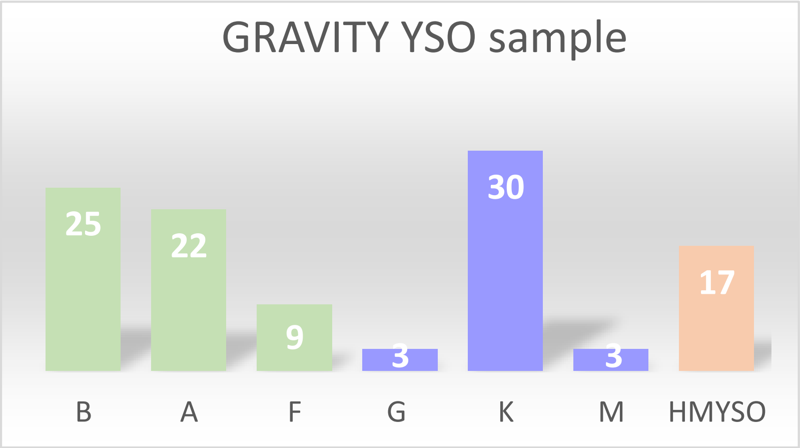
√ Variability follow-up, …

√ Test advanced models

Increasing interest of the YSO **non-interferometrist community**

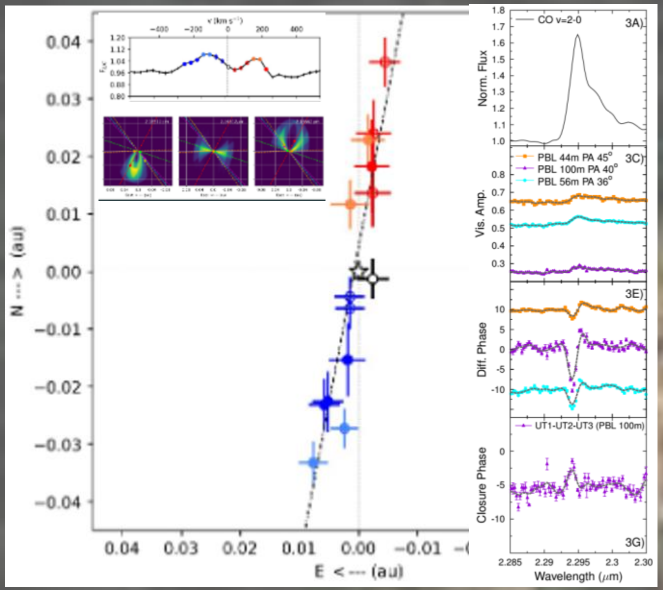
Interest of **multi-technique** and **multi-wavelength** campaigns to probe different scales and ingredients and address the open questions on planet formation

- *Do planets or substructures form first?*
- *How do substructures evolve with time?*
- *How do disk substructures affect disk evolution?*
- *What is the impact of environmental effects on substructure formation?*

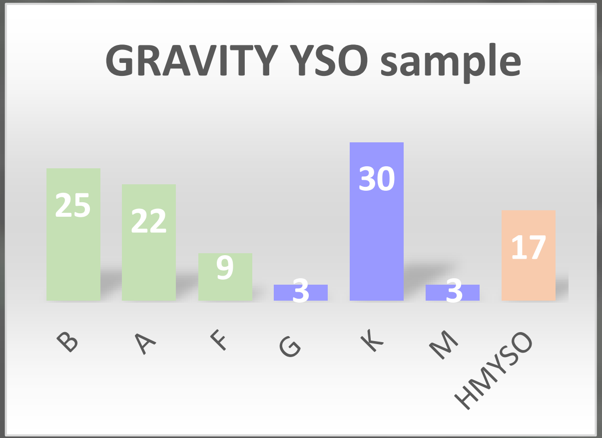


The innermost regions of young stars at sub-astronomical unit scale as probed by GRAVITY

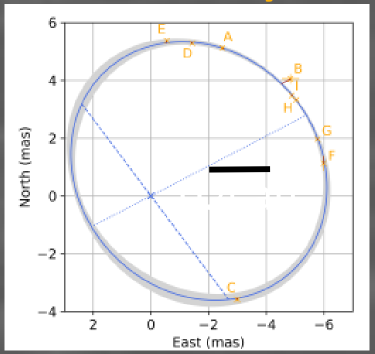
Rotation curves and stellar masses



HD 141569: GRAVITY Coll. Ganci+ 2021
NGC 2024 IRS 2: GRAVITY Coll. Caratti+ 2020
51 Oph: GRAVITY Coll. Koutoulaki+ 2020

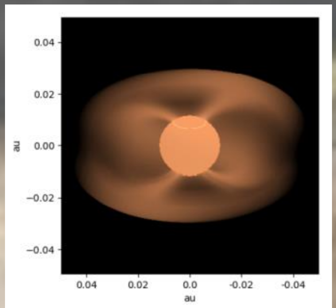


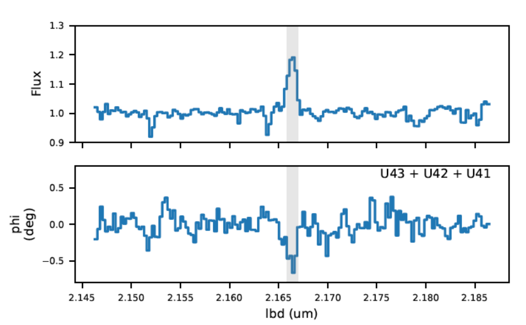
Binarity



WW Cha: GRAVITY Coll. Eupen+2020

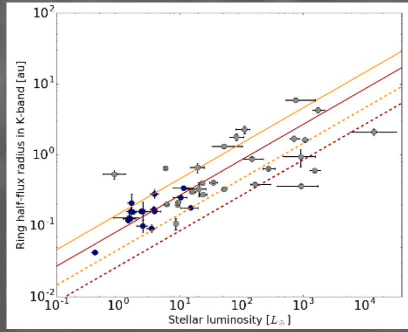
Star-disk interaction and magnetospheric accretion



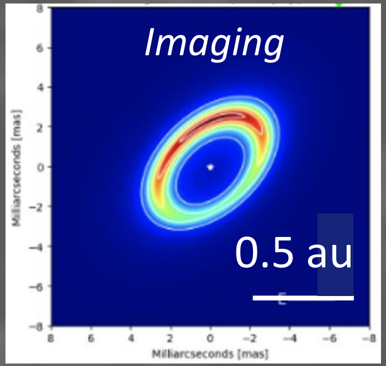


TWHya: GRAVITY Coll. Garcia-Lopez+2020
DoAr44: Bouvier, Perraut+2020
S CrA N: GRAVITY Coll. Garcia-Lopez+2017
T Tauri: GRAVITY Coll. Wojtczak+2022

The inner dusty disk morphology and variability

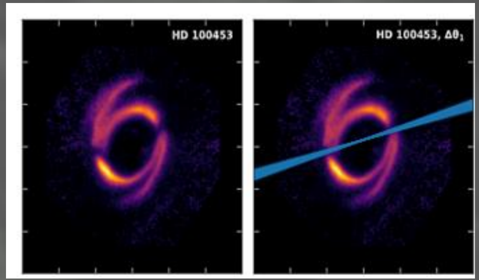


Statistical study of 27 Herbig and 17 T Tauri stars
GRAVITY Coll. Perraut+ 2019, 2021



HD 163296:
GRAVITY Coll. Sanchez+ 2021

Connecting inner and outer disks and looking for (mis-)alignment



Statistical study of 20 transitional disks
Bohn, Benisty, Perraut+ 2022