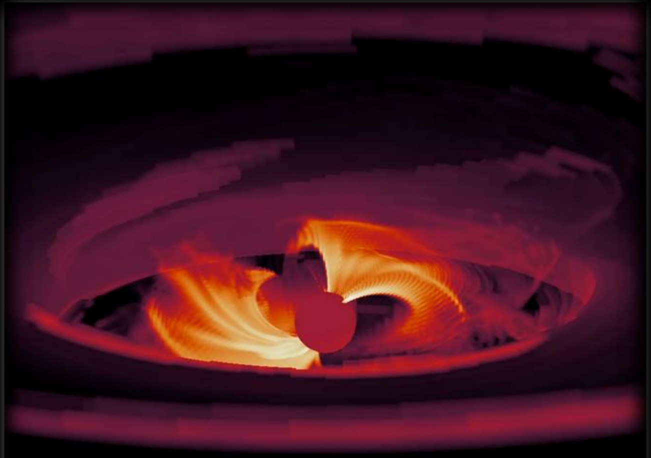
Star-disk interaction region of Young Stellar Objects as probed with VLTI/GRAVITY



Karine Perraut

Institut de Planétologie et d'Astrophysique de Grenoble

Université Grenoble Alpes / CNRS, France

and the GRAVITY and GRAVITY+ collaborations

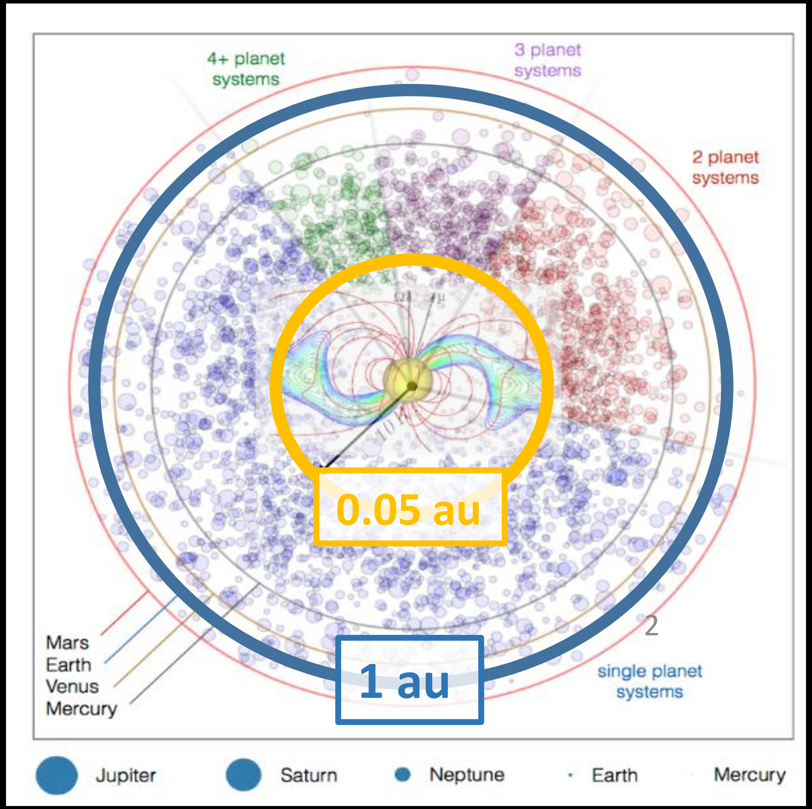
An extreme diversity of planetary systems

« Kepler » population

Current population of known exoplanets exhibits **a wide diversity in nature (mass, radius) and architecture**

Most common outcome of planet formation seem to be **super-Earth and mini-Neptune planets**, none of which exist in our own solar system

Large number of small planets detected within 1 AU of their central star, with a significant fraction of them in multiple-planet systems, all in all very different from our Solar System



[Batygin&Laughlin 2015]
[Blinova+2016]

Origin of planetary systems diversity?

Physical conditions favoring the observed (close-in) planets demographics?

Exploring the birthplace of these planets

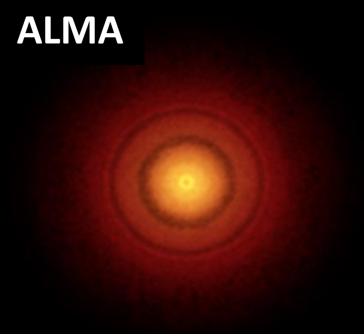
The protoplanetary disks:

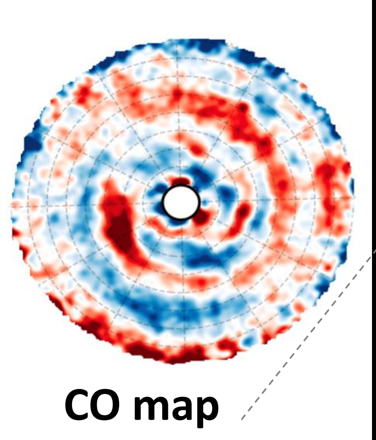
- **Material reservoirs** from which matter is accreted onto the star and from which planets are built.
- Mostly constituted of **gas**, with a small fraction in **dust grains**
- Star formation, planet formation, and disk evolution **influence each other**.
- **Interactions star-planet(s)/host disk**:
    - Brief (a few Myr) but foundational
    - Set stellar and planetary properties persisting for billions of years
    - Impact the evolution of the planet-star-disk system.

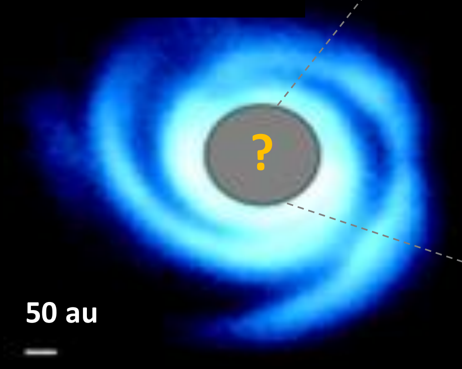
Observe **structures** and **evolution** of protoplanetary disks ***while*** planet formation is happening

Toward a global view of th … disks

[DSHARP, Rosotti+2019, Teague+ 2020, 2021]

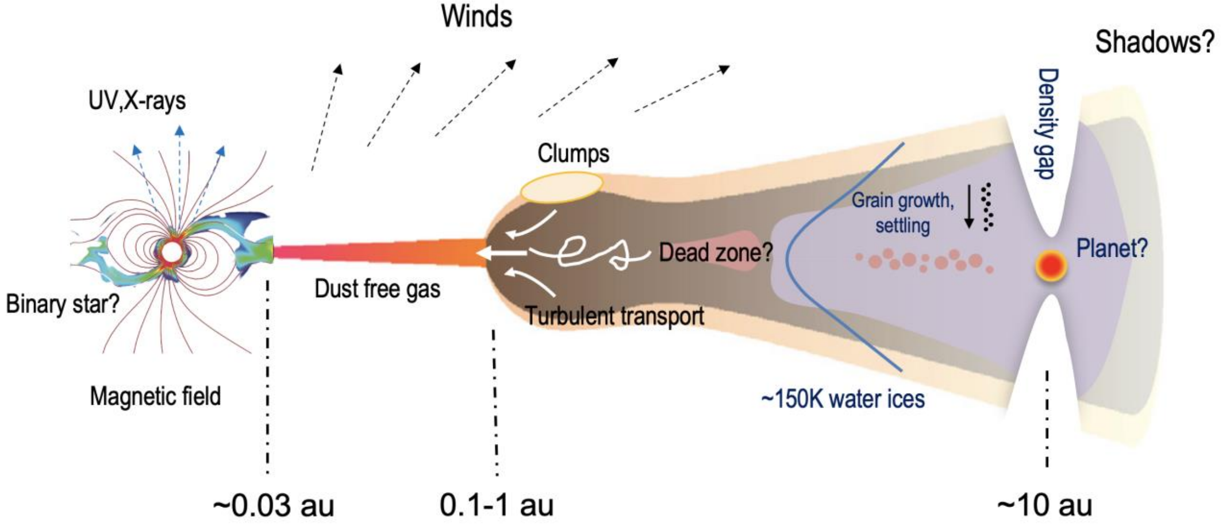






[Benisty+2023, PPVII]

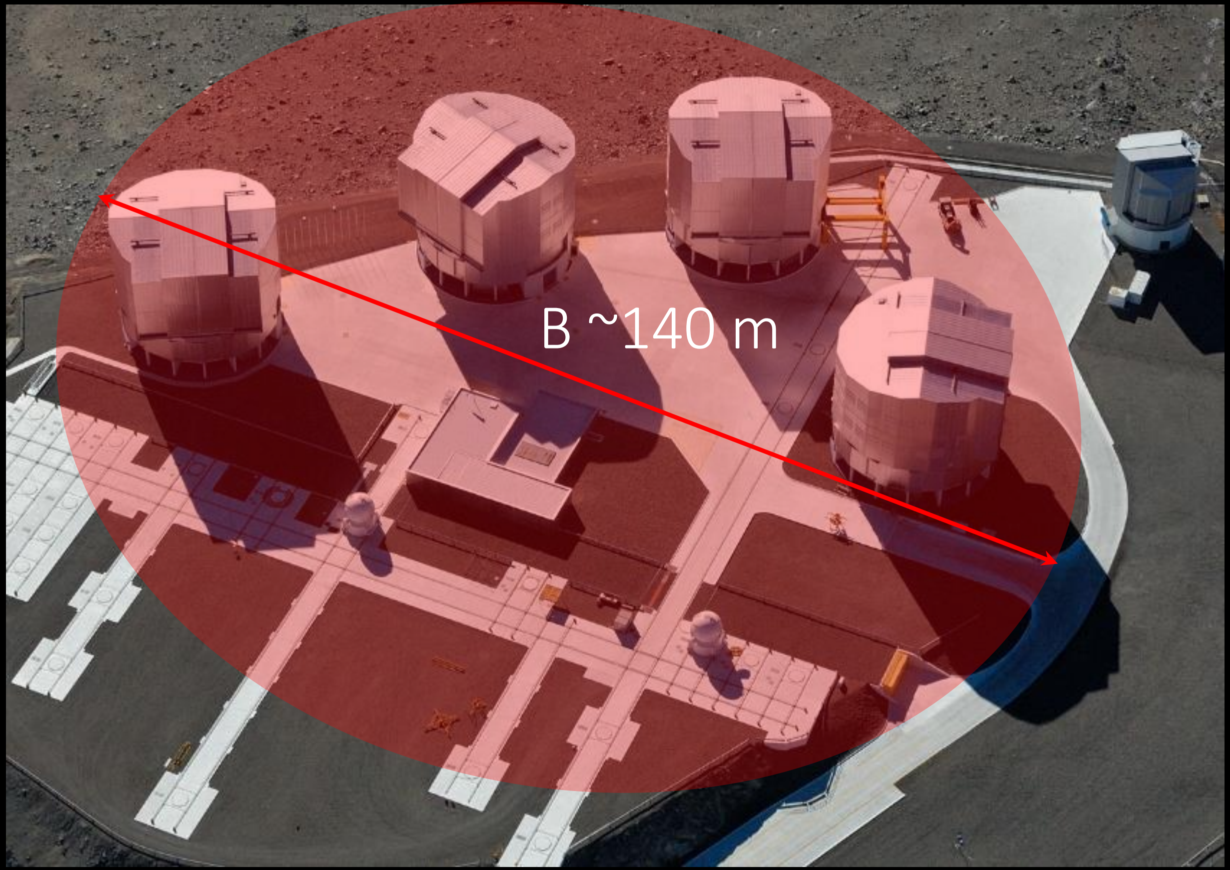
Within **multi-technique** and **multi-λ** approaches (visible/NIR/MIR, interferometry/spectroscopy/spectro-polarimetry, …)

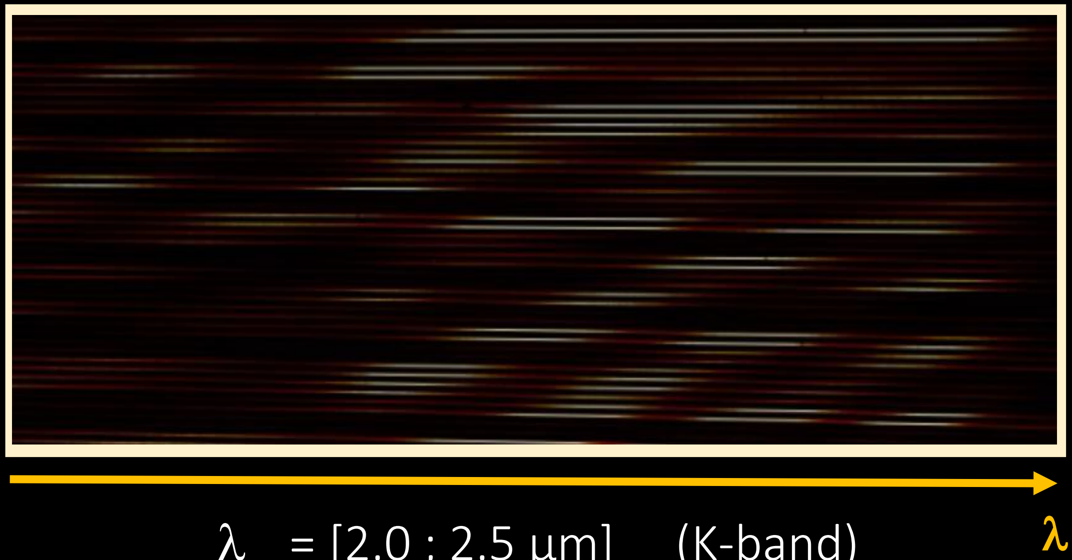


At 140 pc, such spatial scales require an angular resolution better than 1 mas ⇒ **optical long-baseline interferometry**

The GRAVITY instrument at the combined focus of the VLTI

GRAVITY at VLT Interferometer synthetizes a giant mirror of 140 m





λ = [2.0 ; 2.5 μm] (K-band)

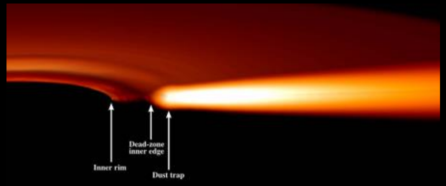
ℛ Up to 4000

Angular resolution
λ/2B ~ 0.5 au @ 140 pc

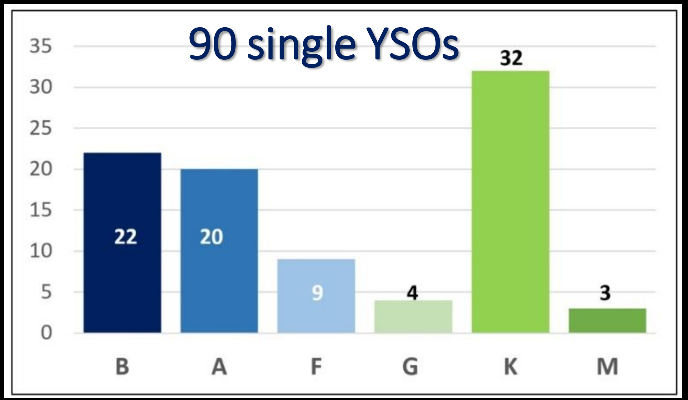
16 articles (GRAVITY YSO Large Program serie)
~230 citations

The GRAVITY YSO Large Program

- Started end of 2017
- Use the 4 telescopes, the sensitivity and accuracy of GRAVITY in K-band to investigate the findings of the pioniering works [Millan-Gabet+2001; Eisner+2005; 2007; 2014; Monnier & Dullemond 2010; Kraus 2015] **within a statistical approach**.
- **Spatial structure of the inner ~1 au disk**
  - ✓ Properties of the inner dust rim
  - ✓ Gap formation
  - ✓ Asymmetries and temporal variability at short orbital timescales
  - ✓ Inner/outer disks misalignment

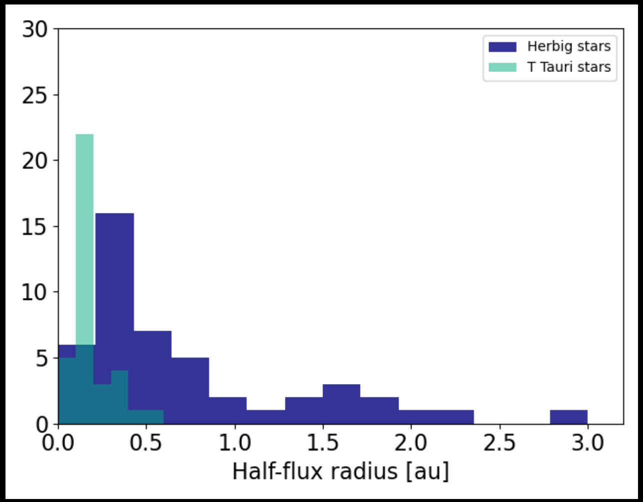


- **Study of hot H and warm CO**
  - ✓ Spatial location of line-emitting region, excitation mechanism (accretion, winds), kinematics



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

Location of GRAVITY K-band emission



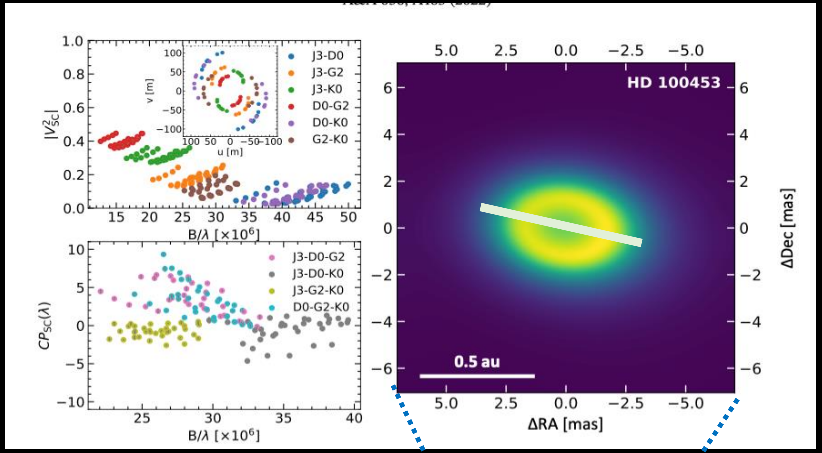
[GRAVITY Coll. Perraut+ 2019, 2021, in prep]

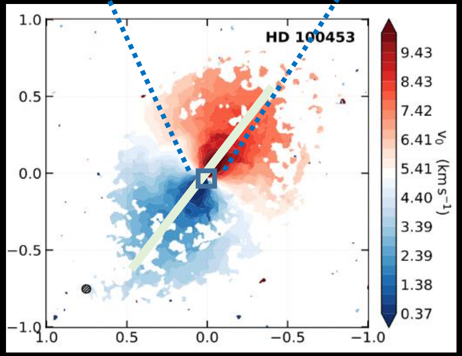
[Bohn, Benisty, Perraut+2022]

The link between inner and outer disk

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

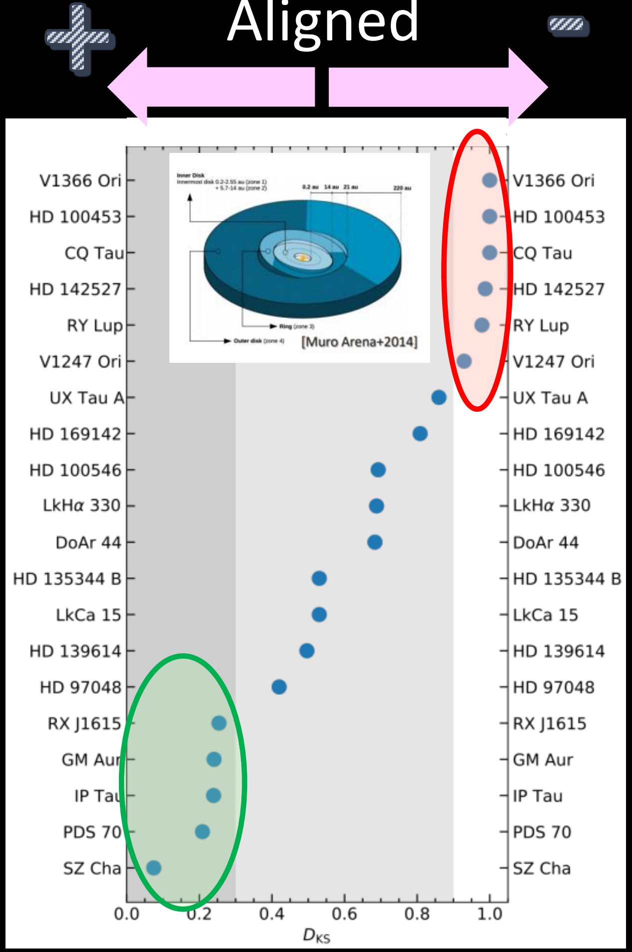
GRAVITY K-band inner disk



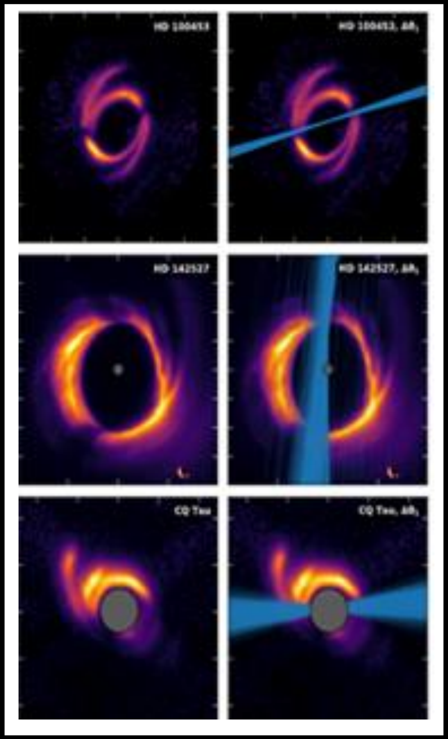


ALMA CO outer disk

Aligned



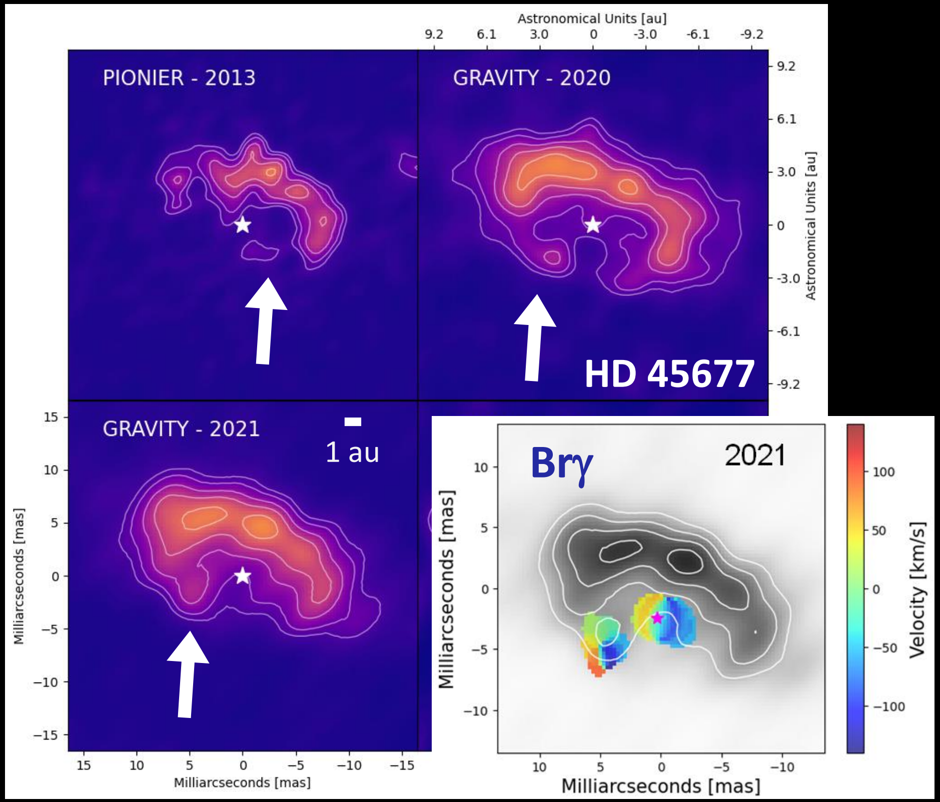
SPHERE shadows



Warps?
Massive companion?
Outcome of earlier stages?

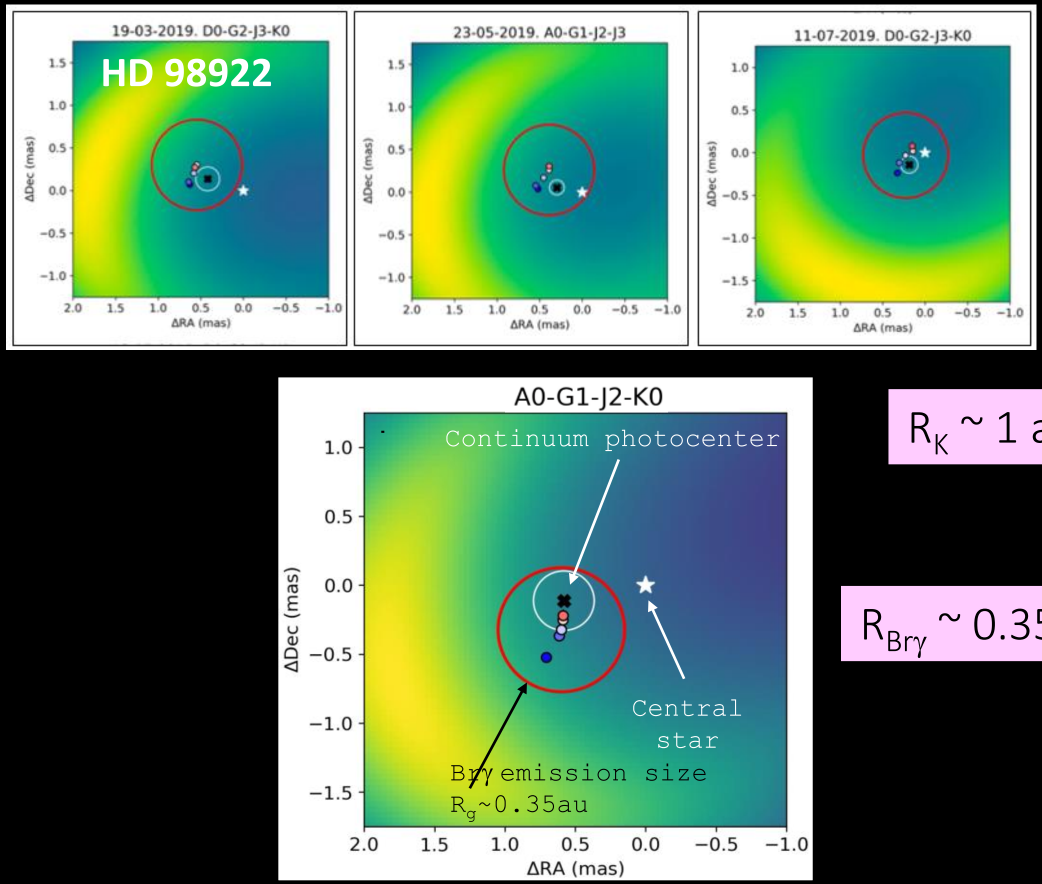
Morphology and temporal variability in the innermost regions

GRAVITY image reconstruction in the K-band continuum and in Brγ line



[GRAVITY Coll. Sanchez-Bermudez+, in prep]

Model fitting of GRAVITY data in the K-band continuum and in Brγ line

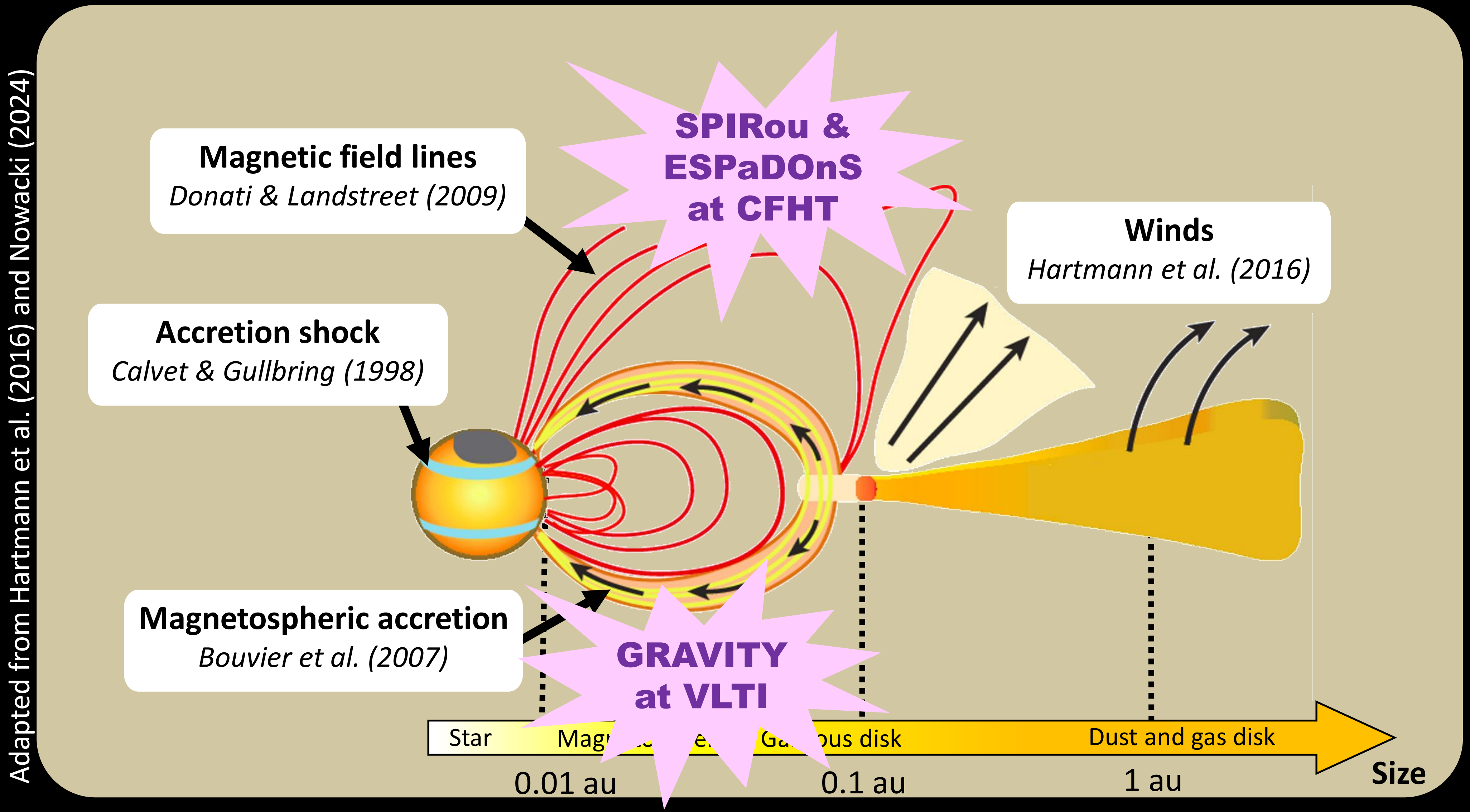


R_K ~ 1 au

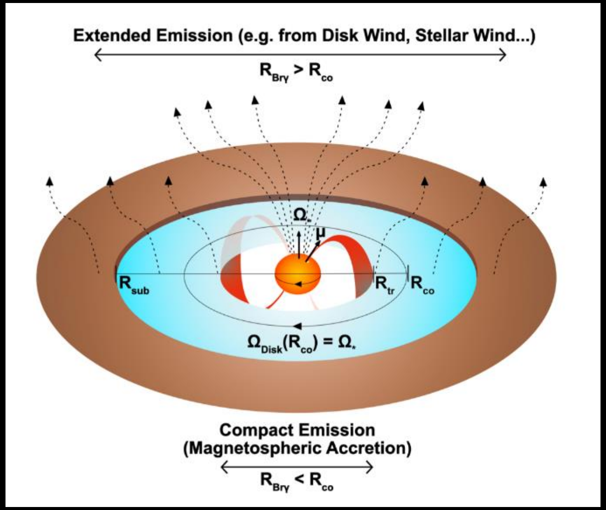
$R_{Br\gamma}$ ~ 0.35 au

[GRAVITY Coll. Ganci+2024]

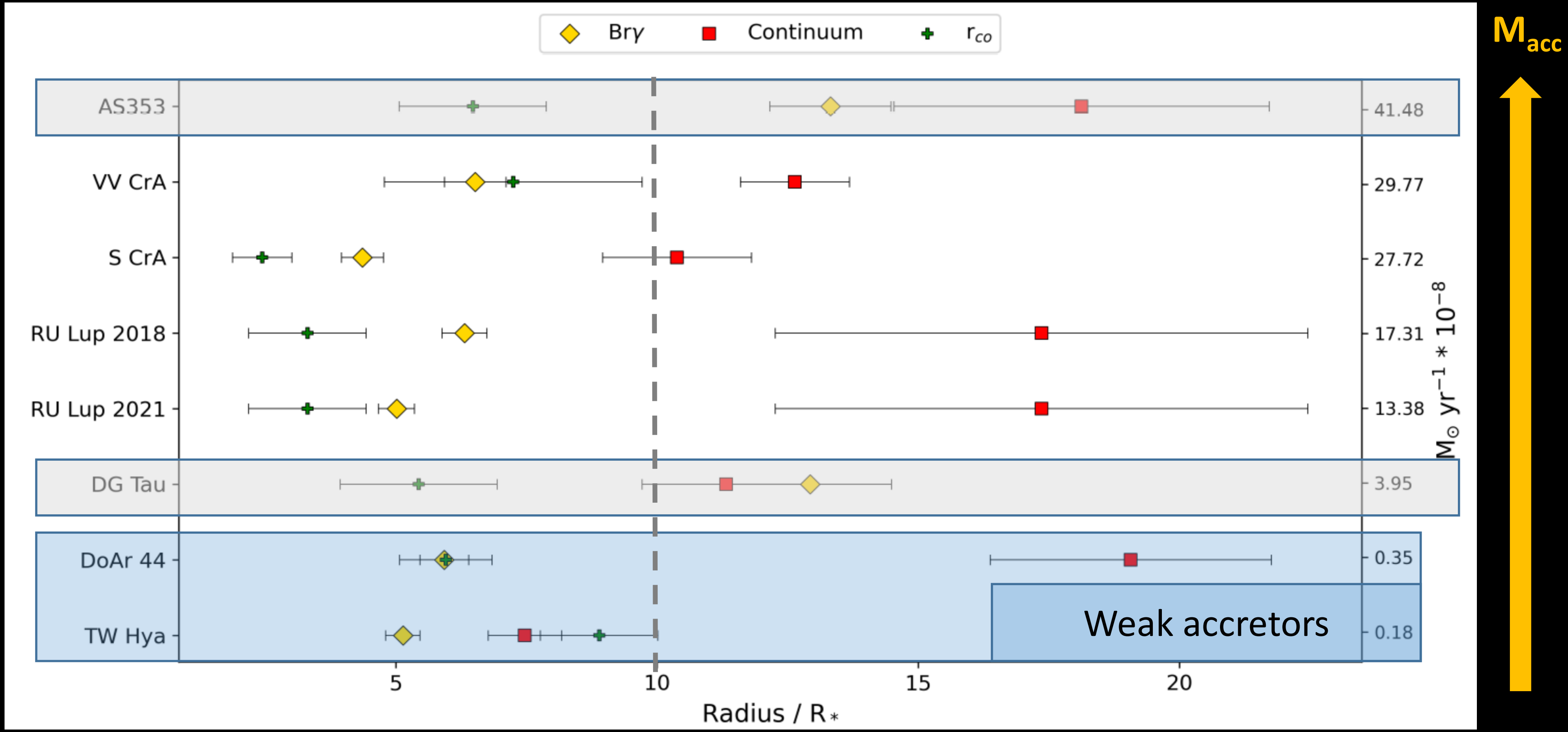
Accretion-ejection processes in T Tauri stars



Disentangling the spatial location of inflow/outflow with GRAVITY



GRAVITY K-band continuum and Brγ sizes

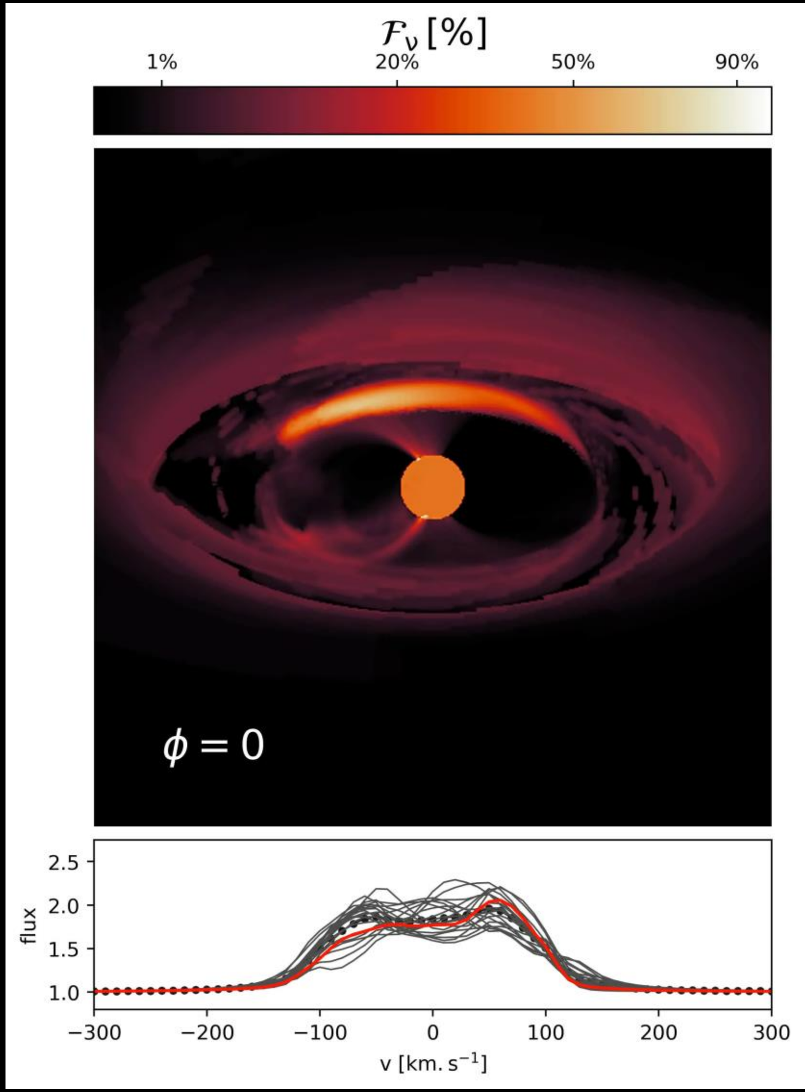


[GRAVITY Coll. Wojtczak+2023]

Dedicated radiative transfer models

spidi-eu.org

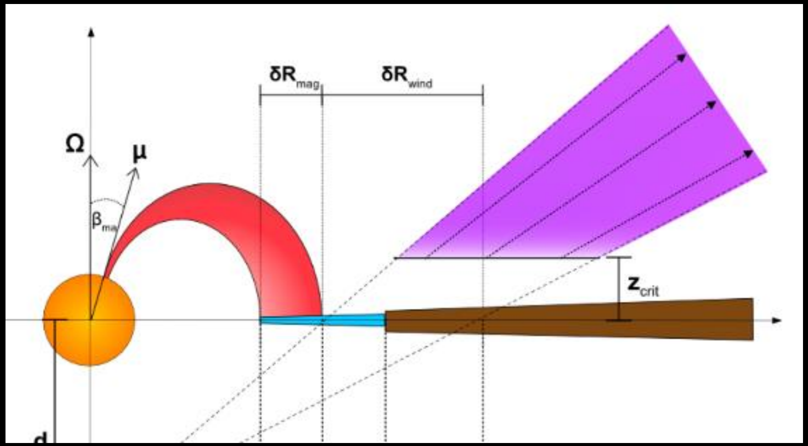
Pure magnetospheric accretion model



[Tessore+2021, 2023]

Synthetic images, whose sizes could be compared with GRAVITY measurements

Magnetospheric accretion + wind model



Non- axisymmetric accretion flow

R_{mag} = 6-7 R_* ; T_{mag} = 7000-8600 K

Conical Disk Wind

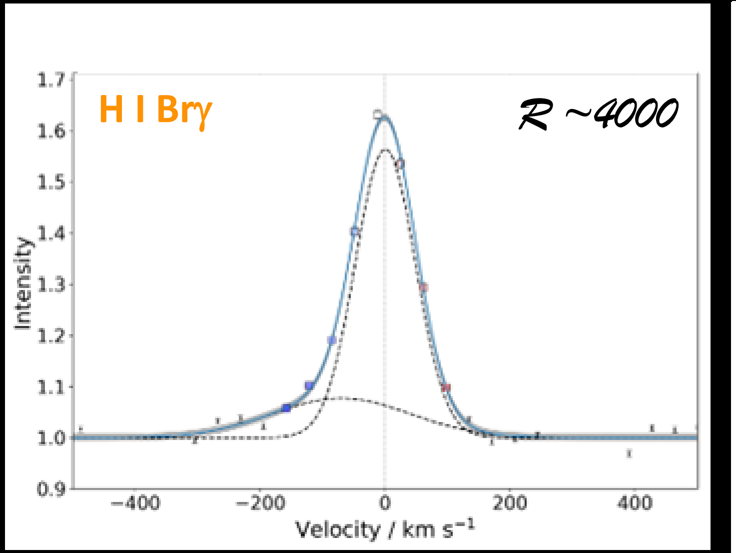
*Rwind = 7-15 R**

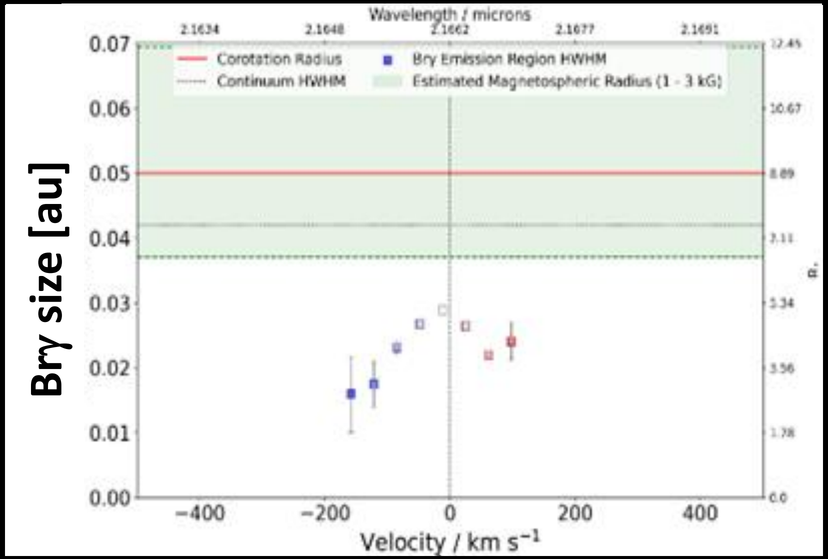
[Tessore+2021, Wojtczak+2024]

The case of weak accretors – TW Hya

GRAVITY spectrum and Brγ sizes

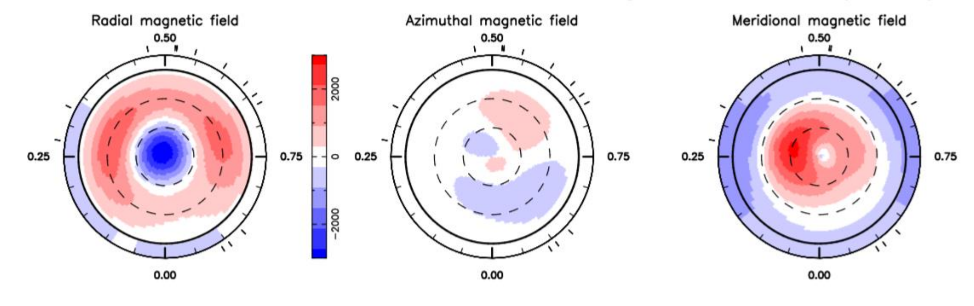
TW Hya





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

ESPaDOnS magnetic field topology



[Donati+2011]

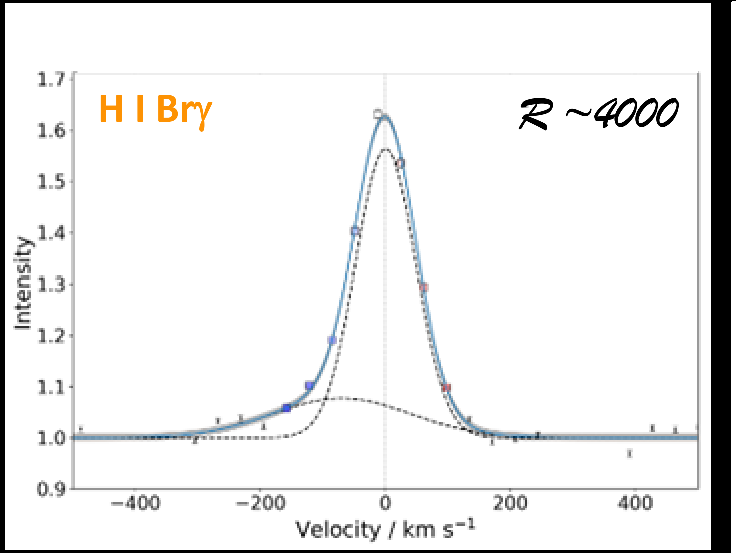
$R_{mag} \sim 3.6\text{-}4.8\ R_{\odot}$

[Bessolaz+2008]

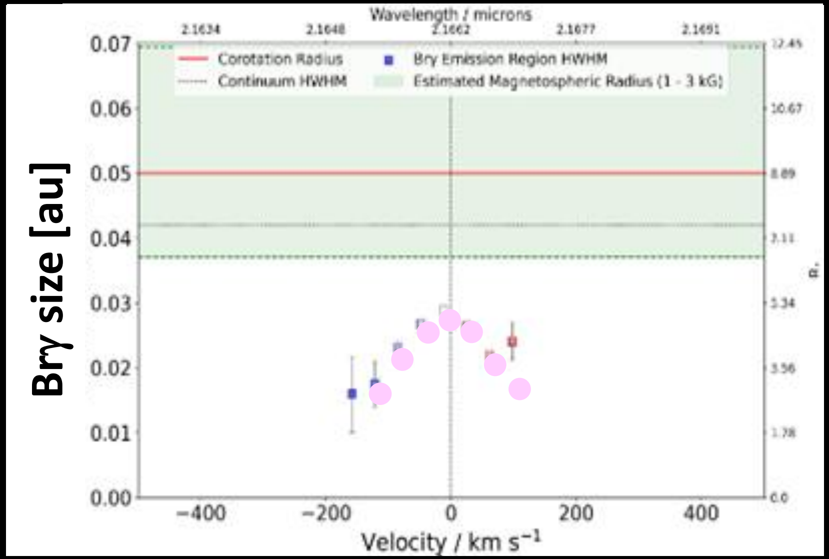
[GRAVITY Coll. Garcia-Lopez+2020]
[GRAVITY Coll. Wojtczak+2023]

The case of weak accretors – TW Hya

GRAVITY spectrum and Brγ sizes



TW Hya

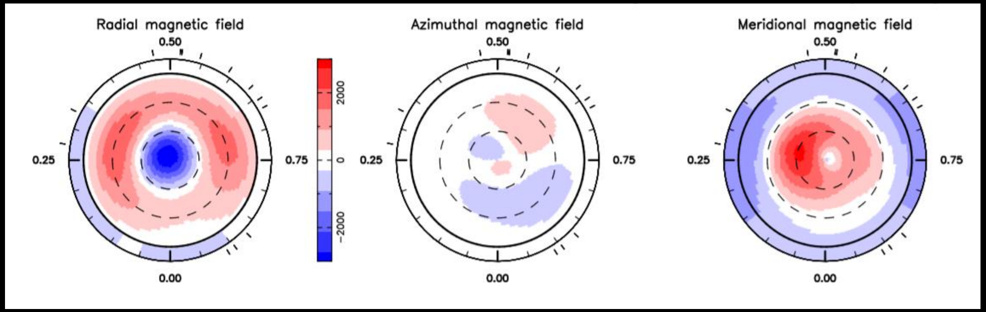


$R_{Br\gamma} \sim 4.5\ R_{\odot}$

- Radiative Transfer accretion model

Our measurements are in agreement with the magnetospheric accretion scenario, where the stellar magnetic field truncates the inner disk.

ESPaDOnS magnetic field topology



$R_{mag} \sim 3.6\text{-}4.8\ R_{\odot}$

[Bessolaz+2008]

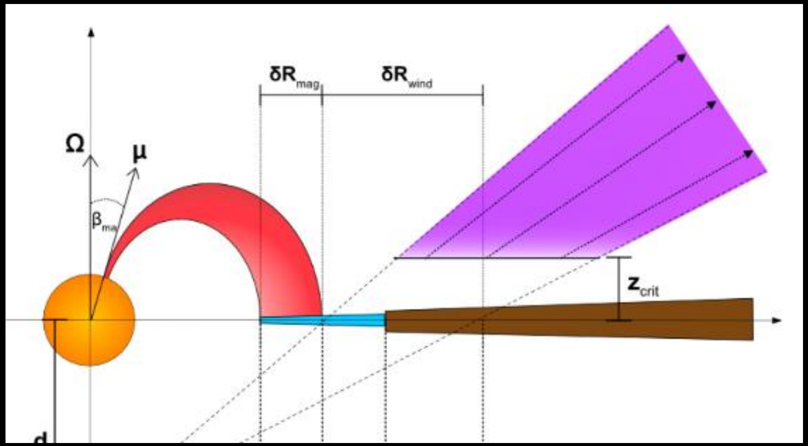
[Donati+2011]

[GRAVITY Coll. Garcia-Lopez+2020]
[GRAVITY Coll. Wojtczak+2023]

The case of the strong accretors – RU Lup

[Wojtczak+2024]

Magnetospheric accretion + wind model



Non- axisymmetric accretion flow

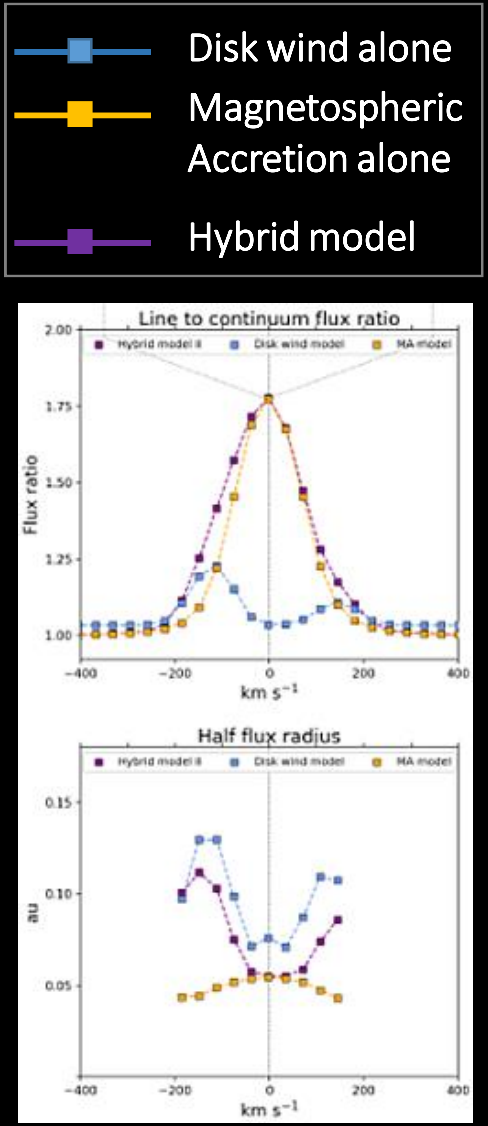
R_{mag} = 6-7 R_* ; T_{mag} = 7000-8600 K

Conical Disk Wind

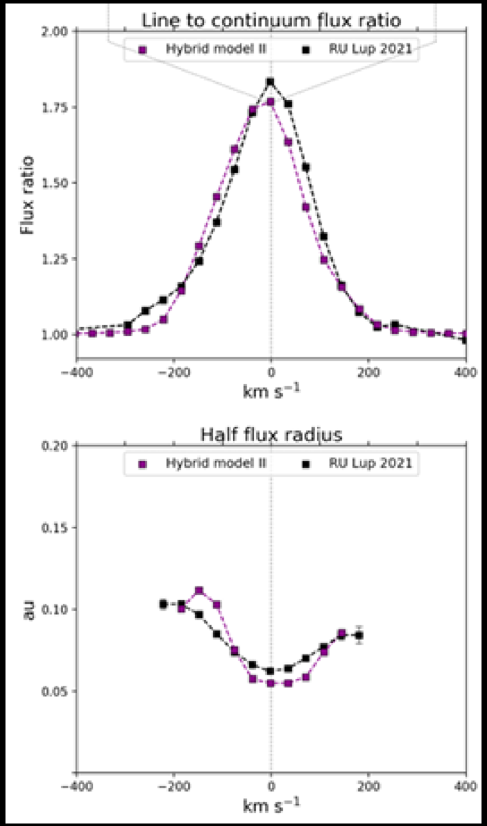
*Rwind = 7-15 R**

H I Brγ line

Size of the Brγ emitting region

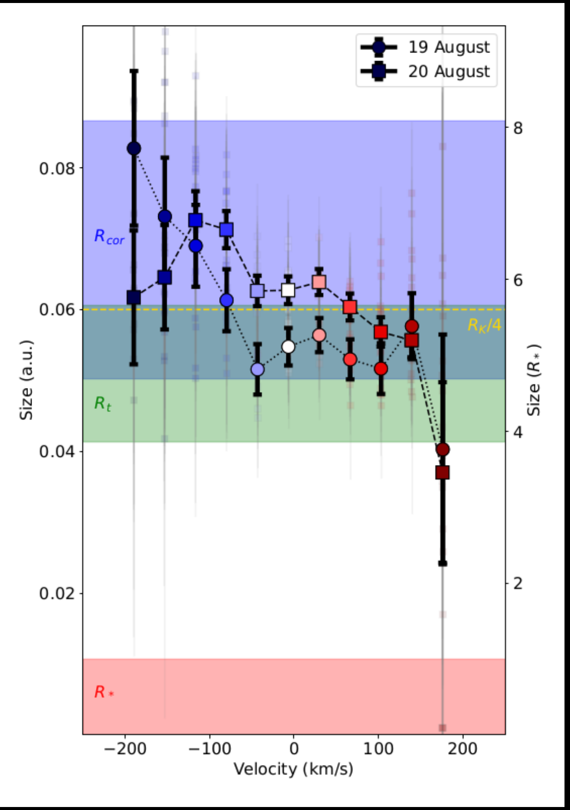


● RU Lup GRAVITY data
● Hybrid model



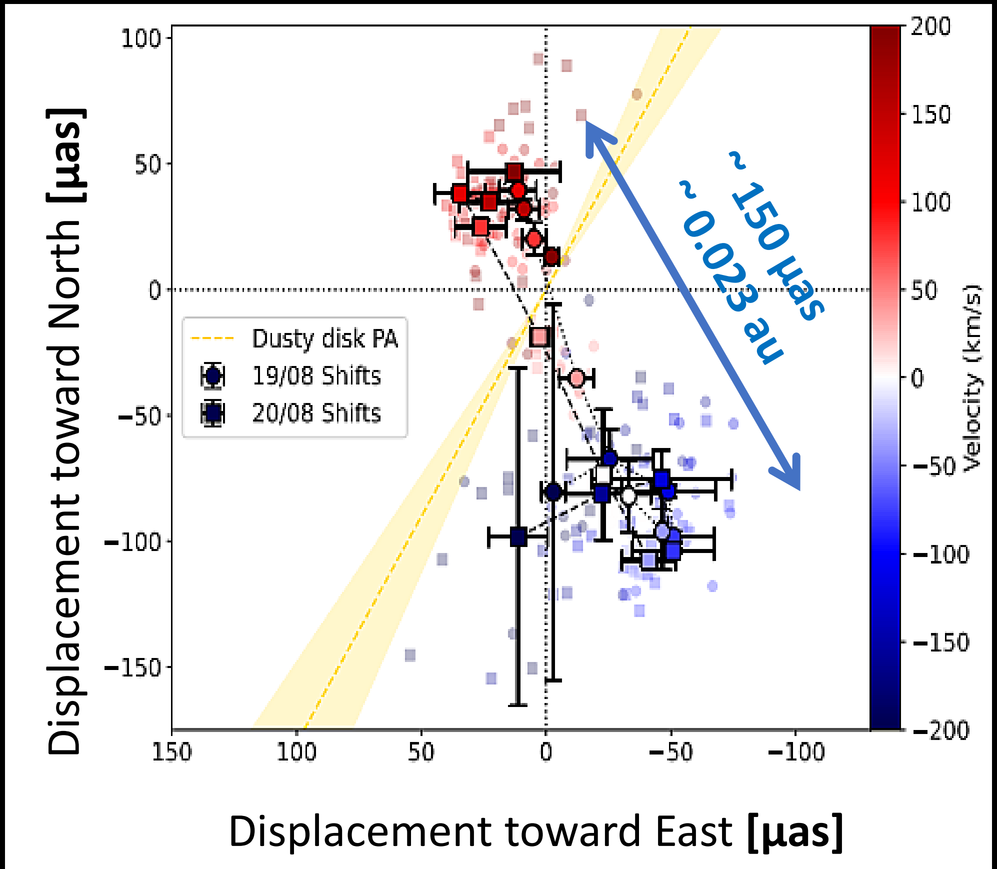
Monitoring accretion-ejection in T Tauri stars – S CrA N

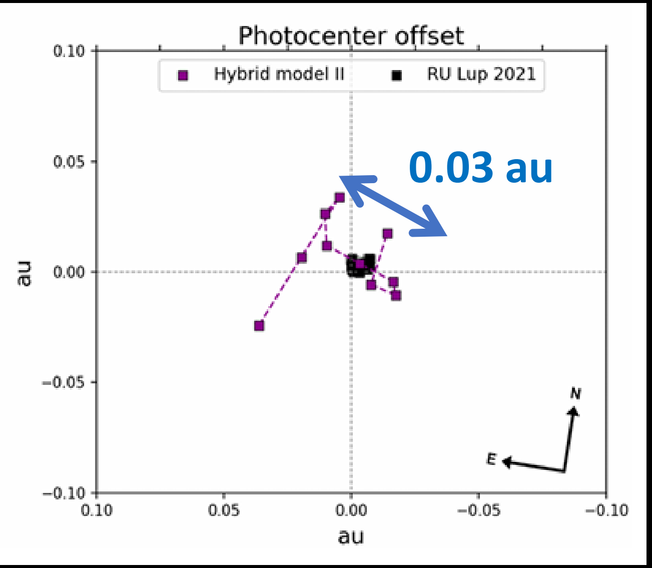
Sizes of the Brγ line emitting region with GRAVITY



[GRAVITY Coll. Nowacki+2024]

Sub-au astrometry of the Brγ line emitting region with GRAVITY

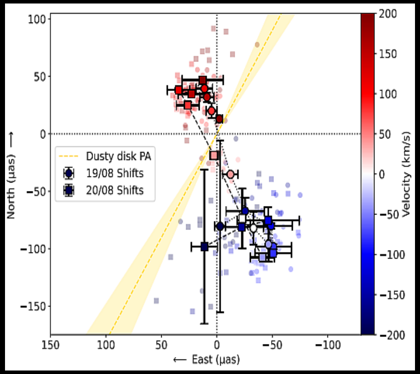


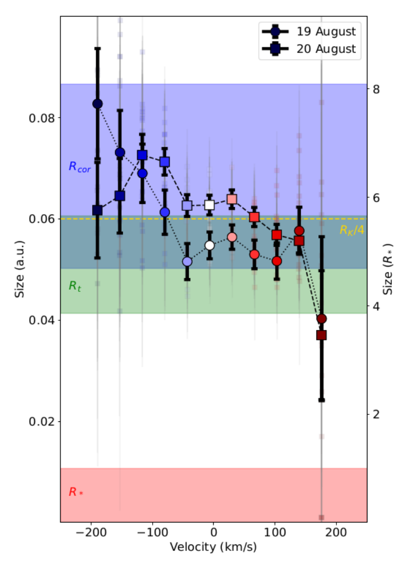


- $R_{Br\gamma}$ ~ R_{mag} in the core of the line, and **larger in the blue wing**
- On-sky displacement perpendicular to the inner disk PA ⇒ **polar process**
- Similar displacements on 2 consecutive nights ⇒ **not pure magnetospheric accretion only**
- In agreement with the hybrid radiative transfer model

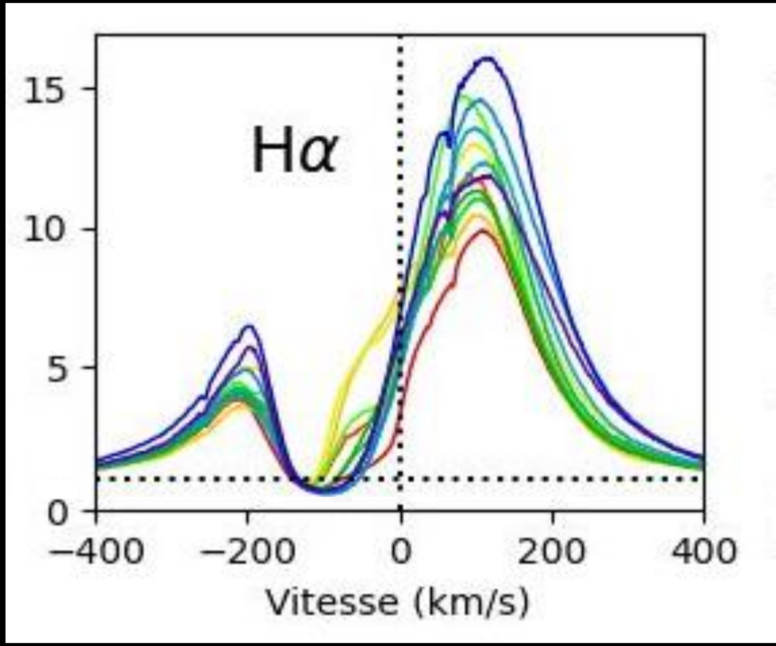
Monitoring accretion-ejection in T Tauri stars – S CrA N

- Combining different techniques to draw a coherent picture



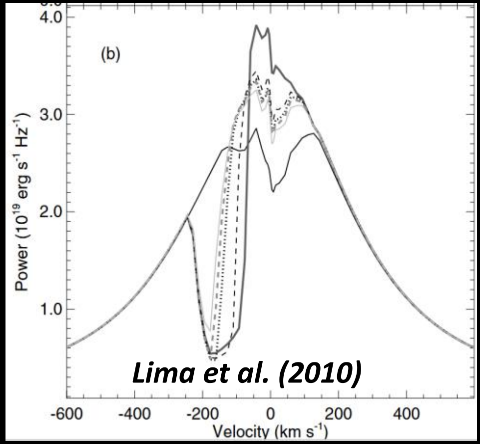


ESPaDOnS Hα profiles over 2 stellar periods



[Nowacki+2023]

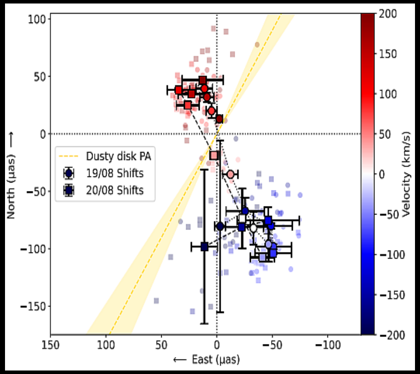
- **Variable** profile
- Large blue absorption in agreement with:
  - **strong accretion** ***(10^{-7} $M_\odot$/yr)***
  - **disk wind**: intense ***(≥10^{-8} $M_\odot$/an),*** dense ***(5.10 $^{-9}$ kg/m^3),*** *and* compact ***(R_{do} ≈ 10-20 R_*)***

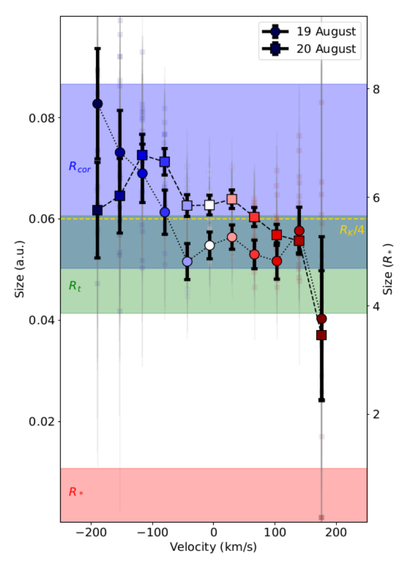


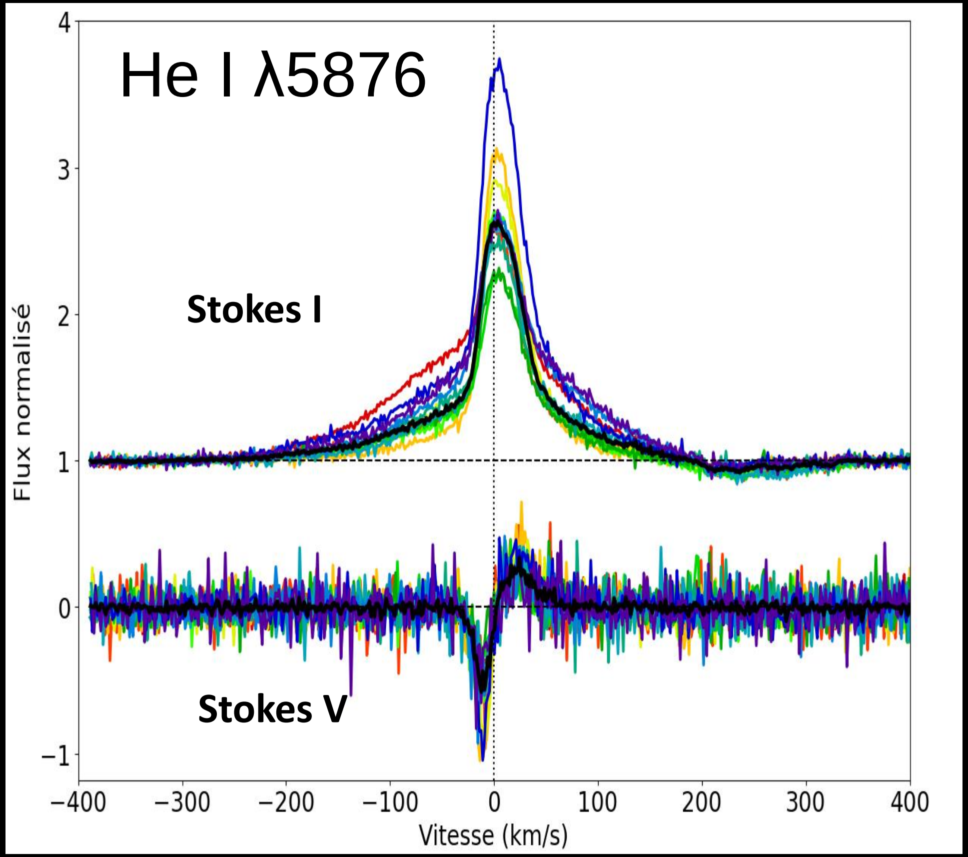
Lima et al. (2010)

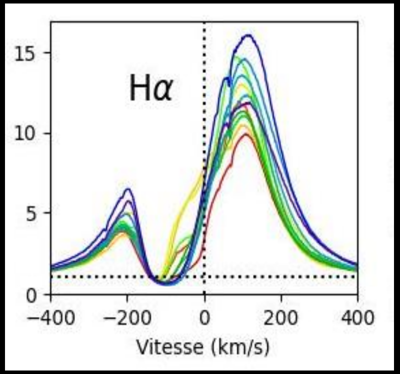
Monitoring accretion-ejection in T Tauri stars – S CrA N

- Combining different techniques to draw a coherent picture





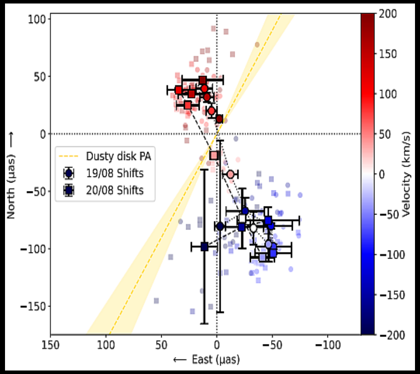


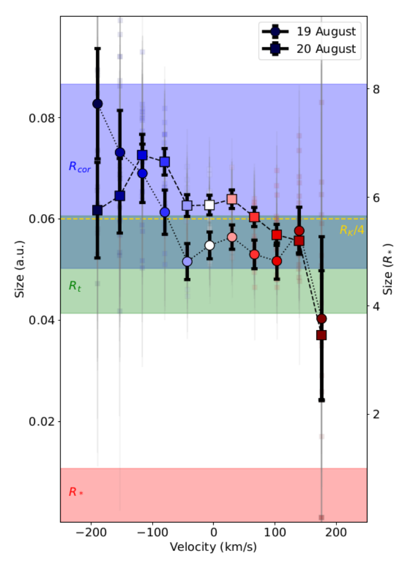


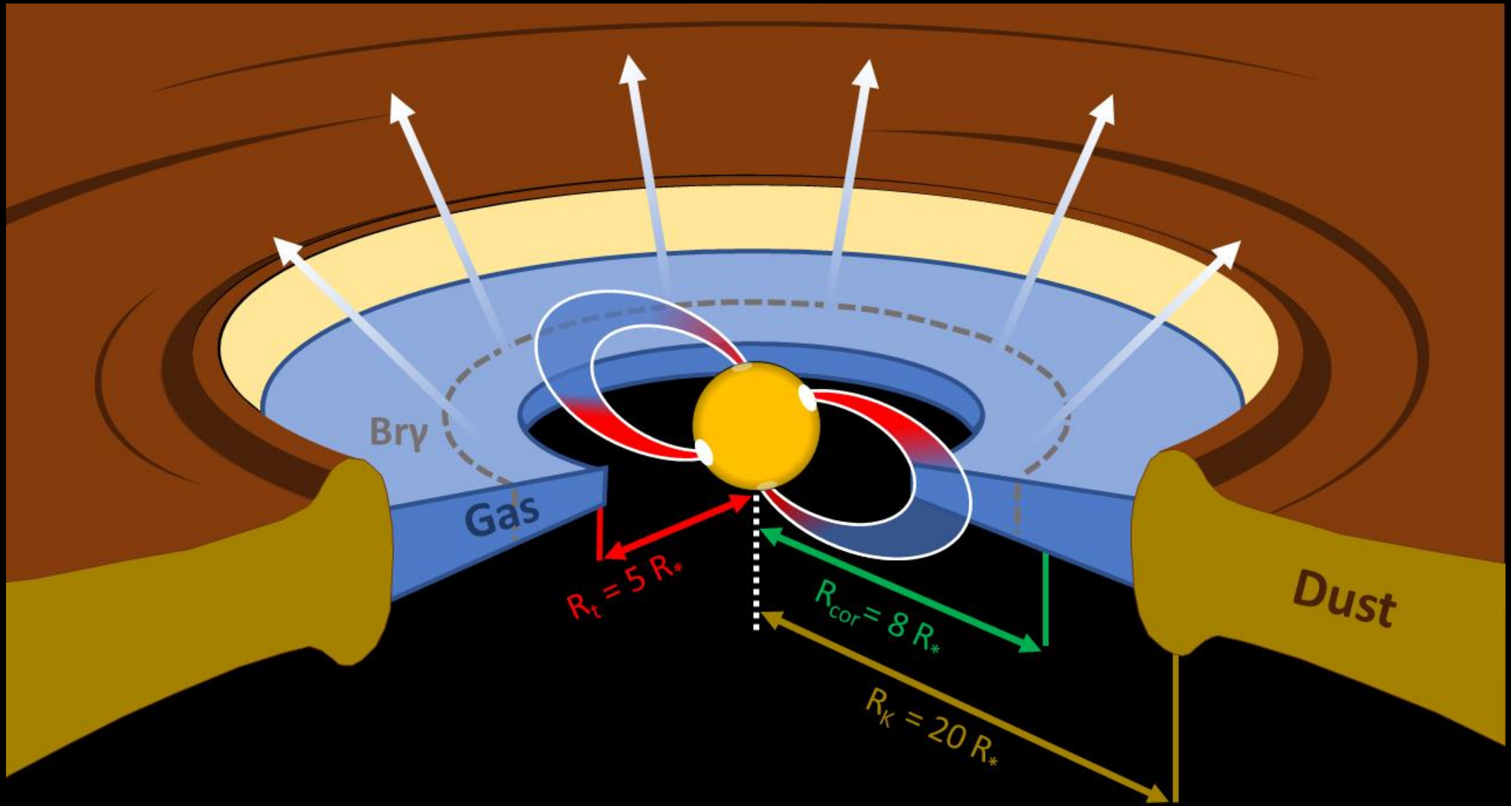
- Asymmetric Stokes V signal traces the **magnetic field at the footprint of the accretion columns**
- **Axisymmetric large-scale magnetic field** (70% of the total energy) that is primarily located in the dipolar component

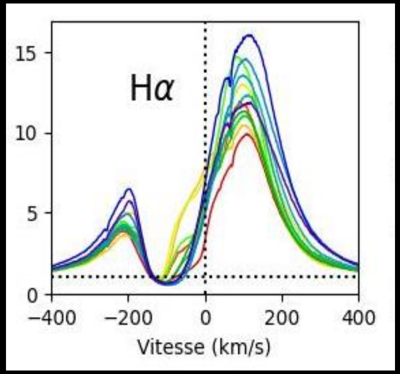
Monitoring accretion-ejection in T Tauri stars – S CrA N

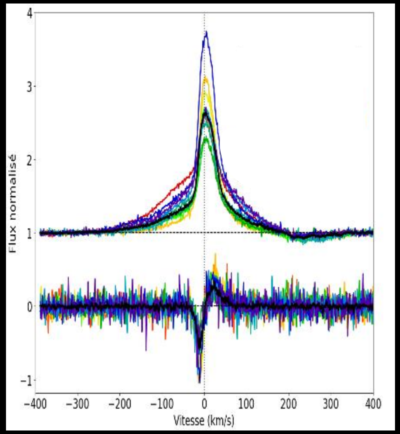
Combining different techniques to draw a coherent picture





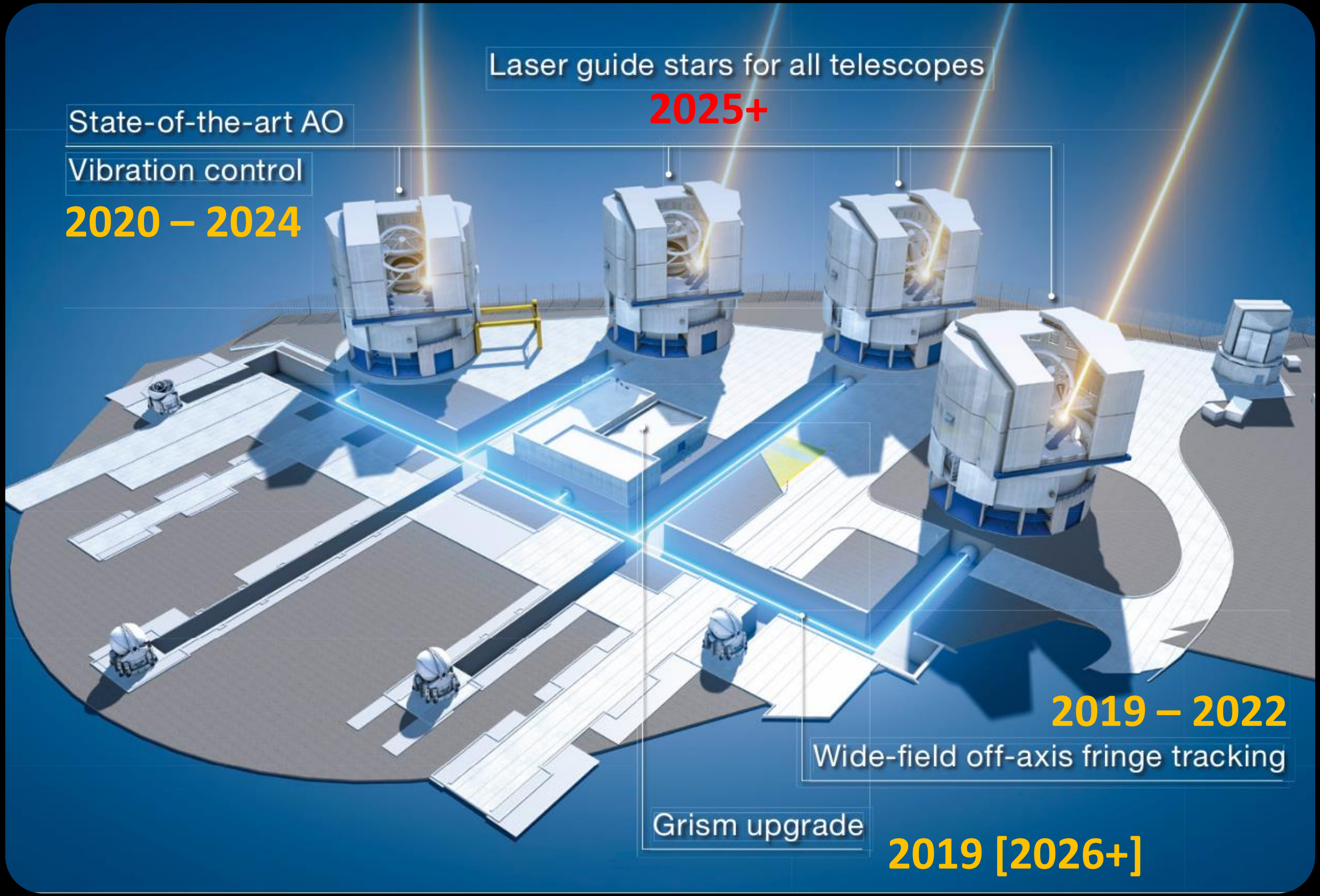


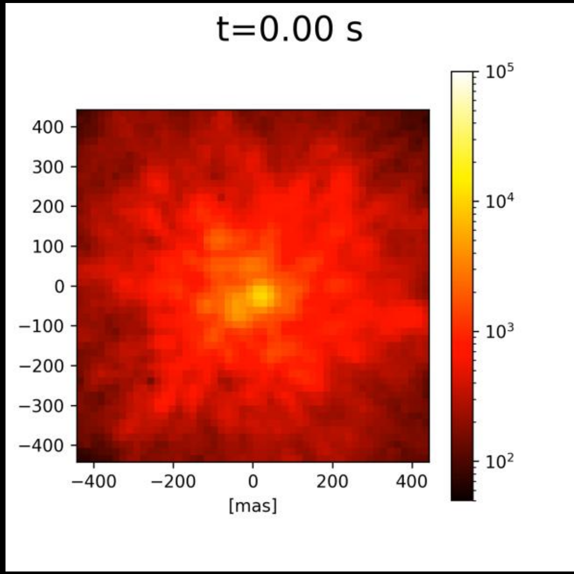


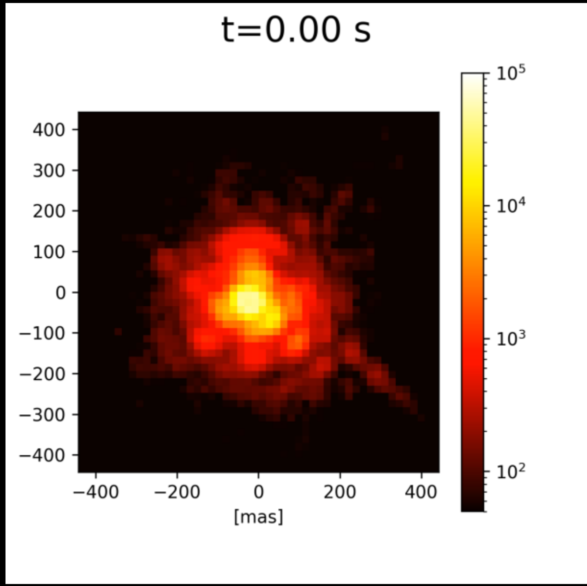


[GRAVITY Coll. Nowacki+2024]

Opportunities of GRAVITY+ for YSOs







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

Different Star Forming Regions and access to new classes

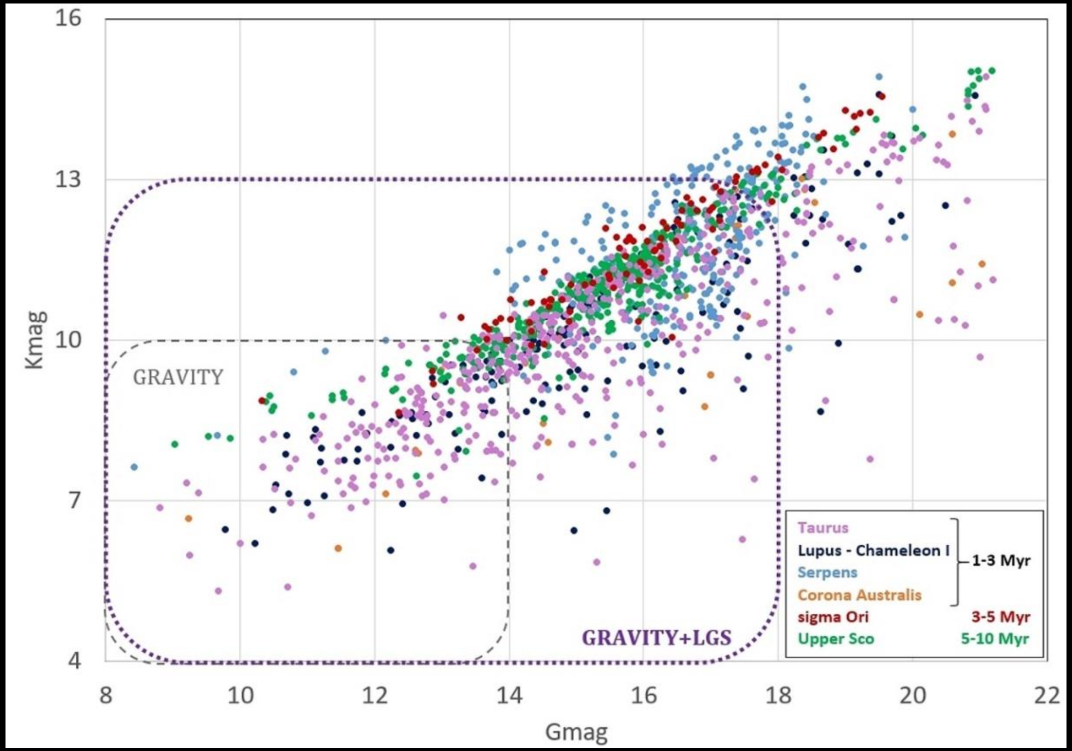
Thanks to LGS and off-axis fringe tracking:

- Less biaised samples
- Demographic studies
- Test advanced models

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

Access to **Class-I sources**:

- Younger sources
- Different regime of accretion
- Stronger and more complex magnetic fields



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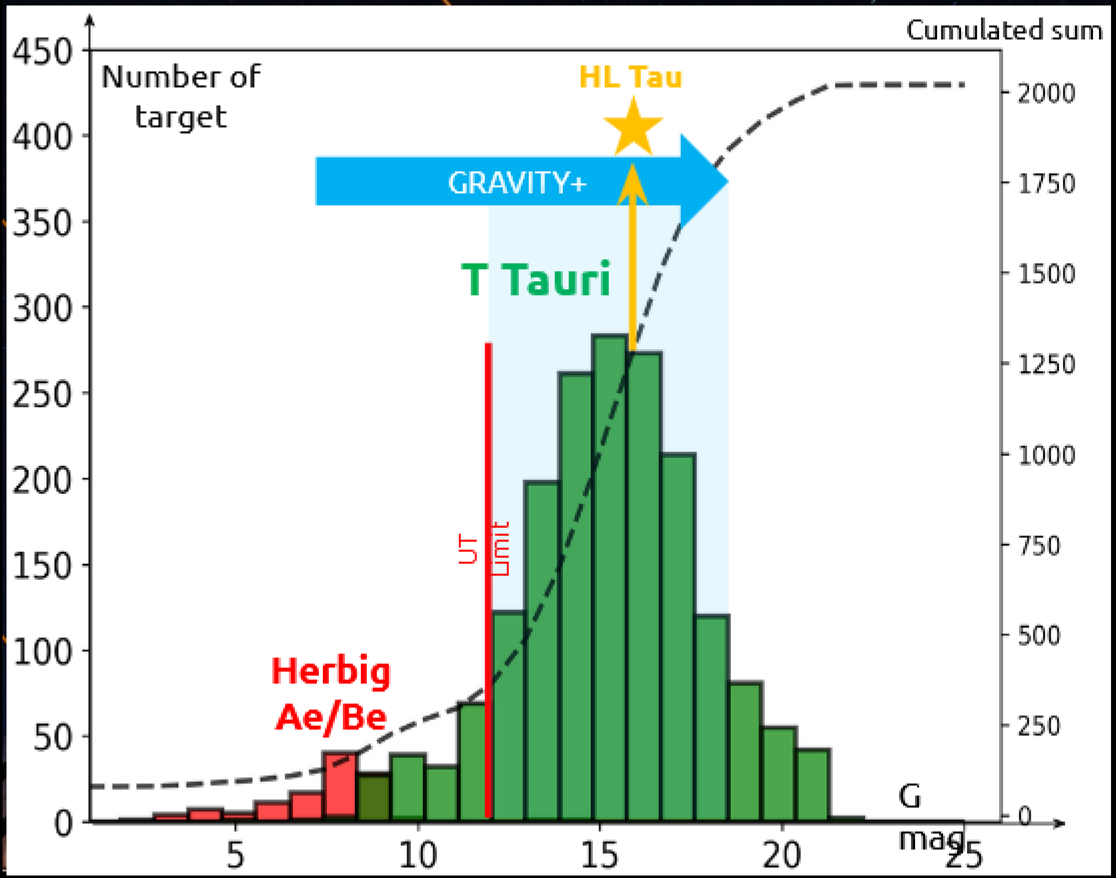
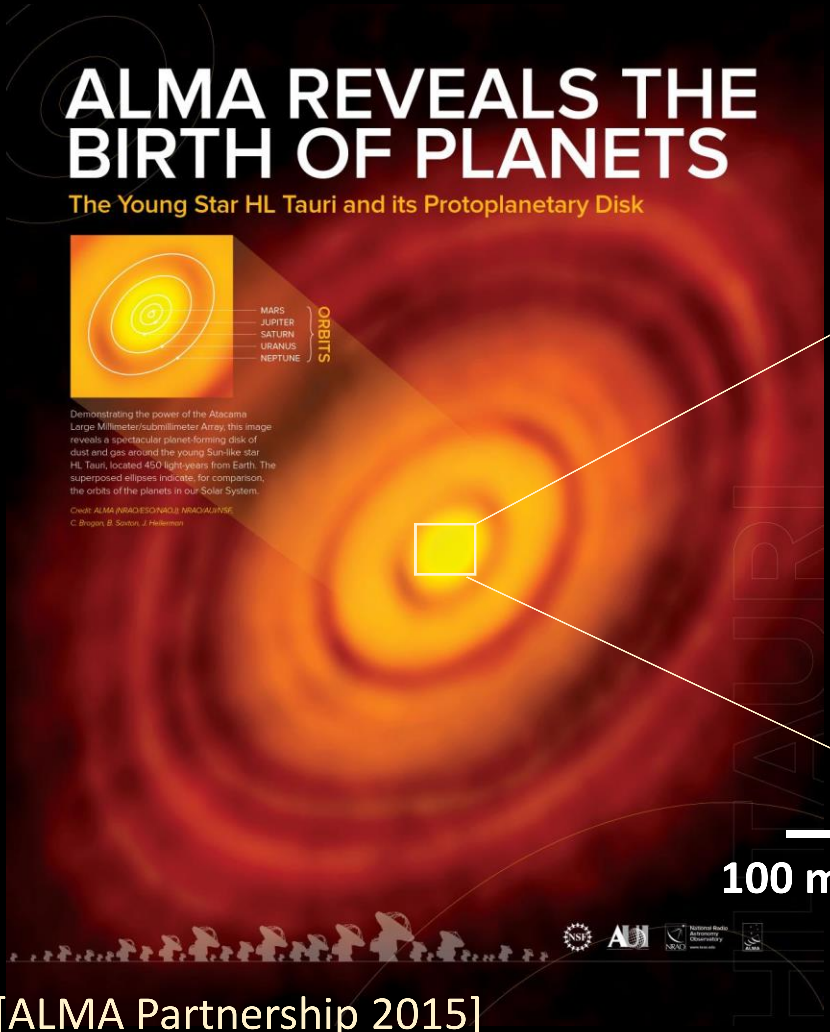
Up Sco [Luhman+2020]



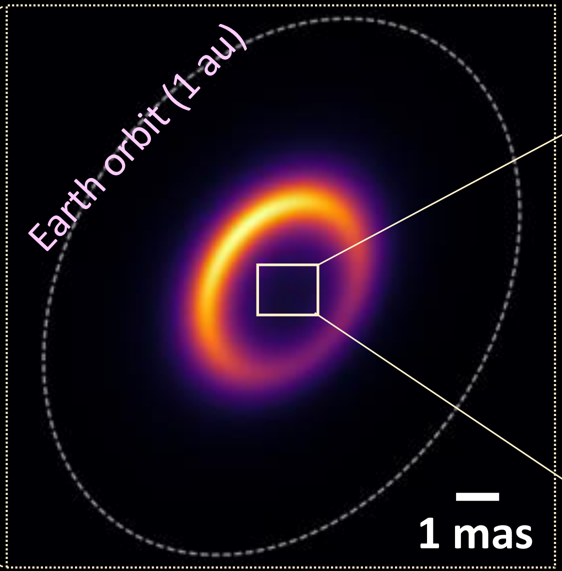
[Crédit: G. Bourdarot]

The inner au of HL Tau revealed by GRAVITY+



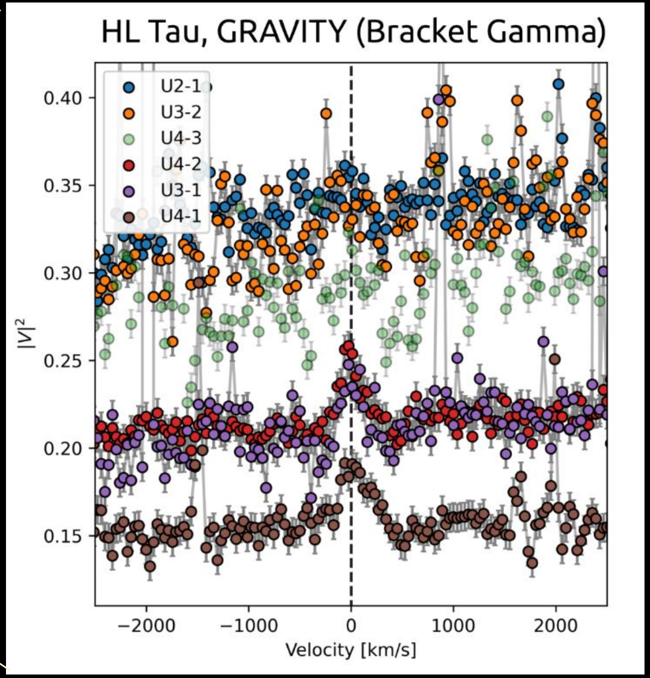
[ALMA Partnership 2015]

GRAVITY+



Inner/outer disk alignment

GRAVITY+ kinematic

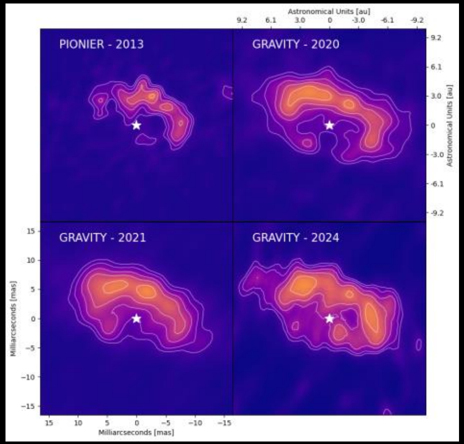


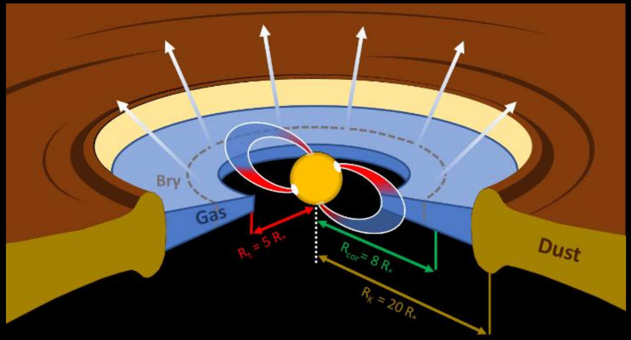
Resolution of the magnetospheric accretion region

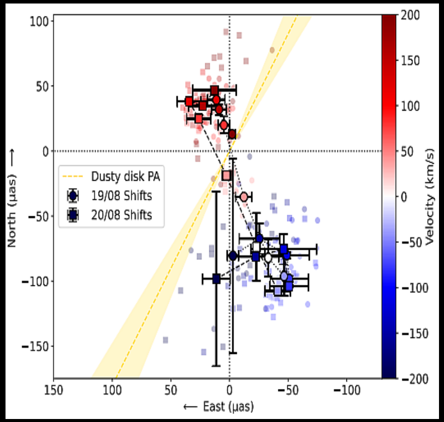
[GRAVITY+ Coll. submitted]
[GRAVITY+ Coll. Bourdarot+ in prep]

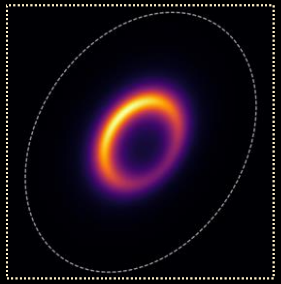
Take away messages

- **Near-infrared interferometry** provides invaluable constraints to study
  - <u>**Asymmetry and variability**</u> of the inner disk's morphology
  - <u>**Accretion-ejection processes**</u> in the star-disk interaction region
- Interest of <u>**simultaneous**</u> **multi-technique and multi-wavelength campaigns**
- **Exciting times to come with GRAVITY+** to extend the study to Class I objects and **monitoring the accretion flows at <u>high-cadence</u> (< 1 h)**









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