Lecture outline

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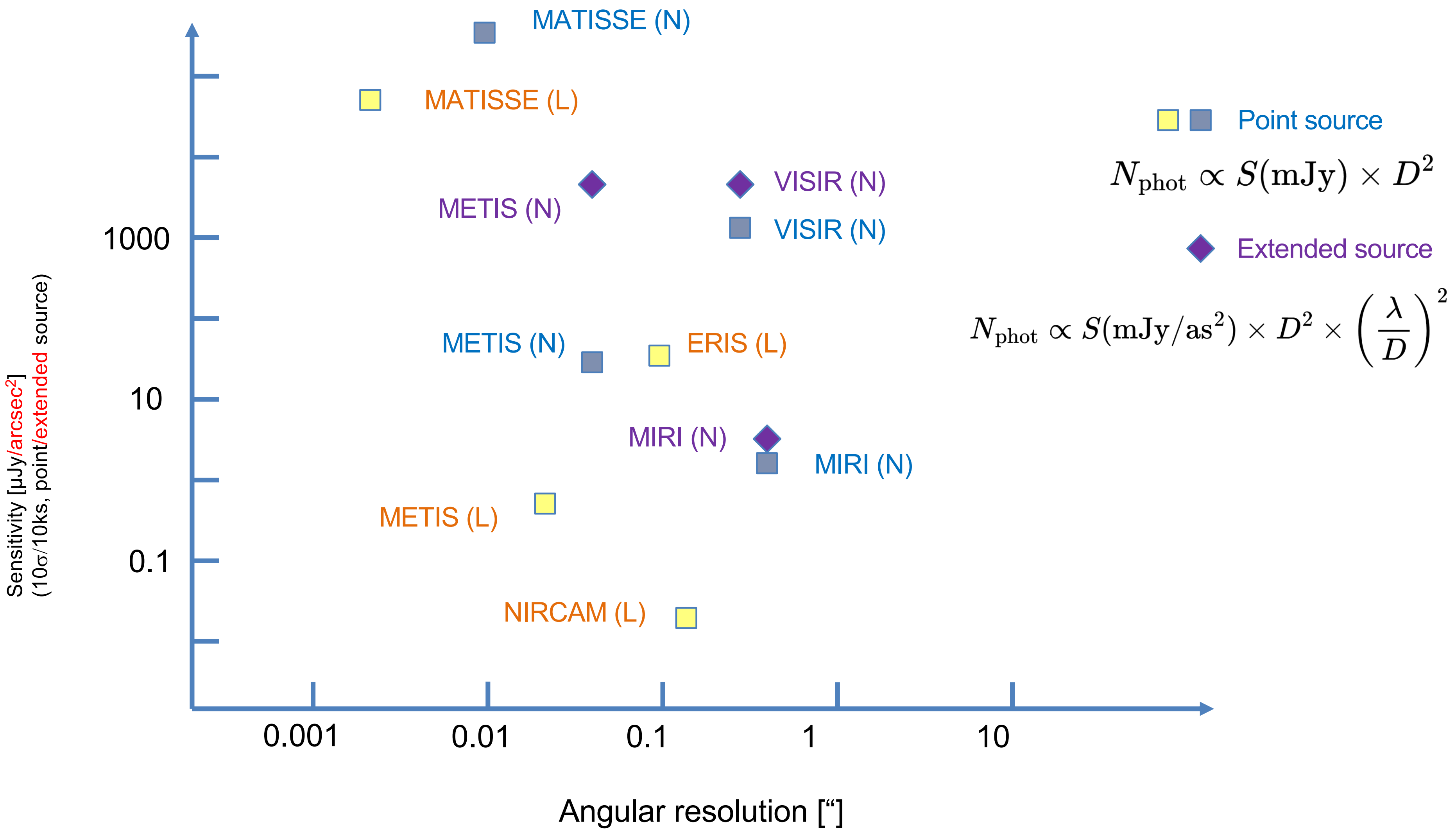
Sensitivity figures (mid-infrared)

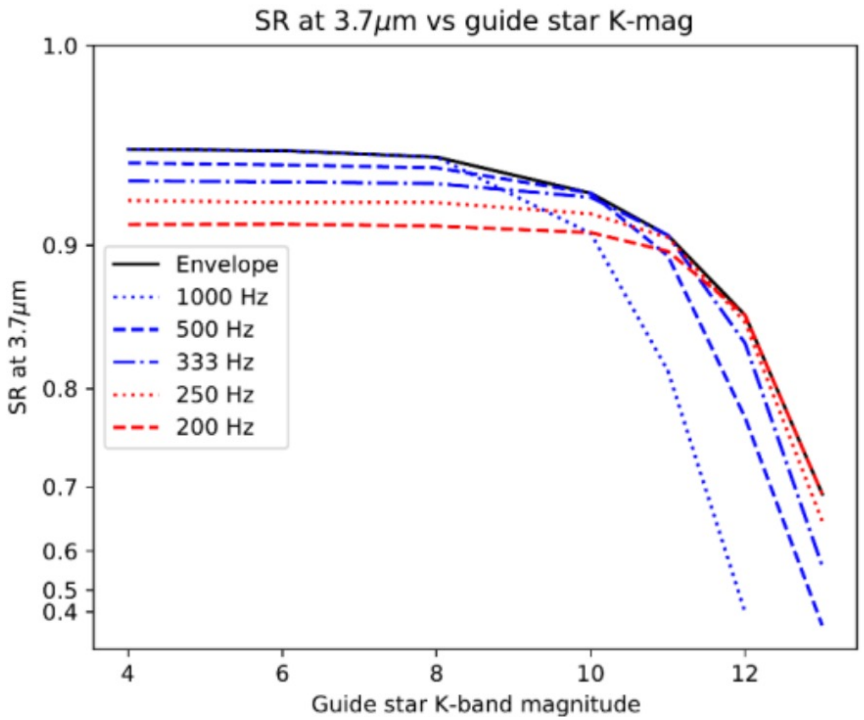


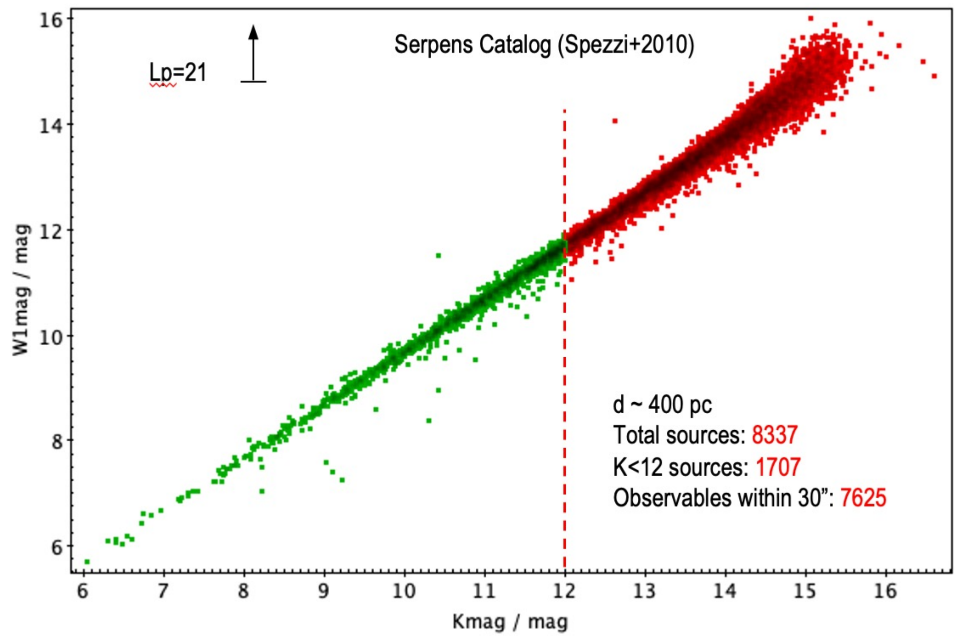
Observing constraints

- Spatial resolution

HARMONI/MICADO [H]	METIS [L]	METIS [N]
10 mas (1.5 au @ 140pc)	20 mas (3 au)	50 mas (8 au)

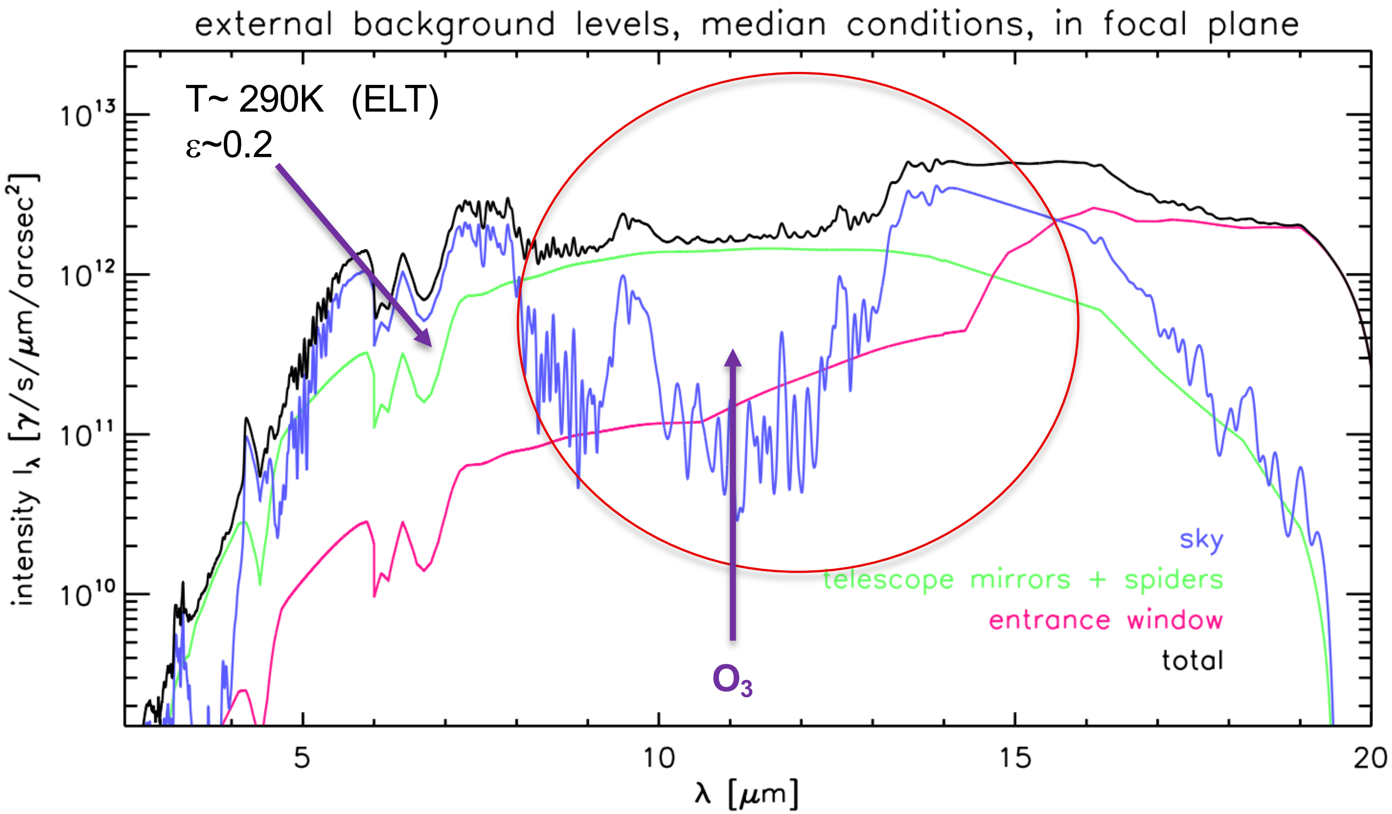
- Sky coverage (but no laser guide star)





Sensitivity figures (mid-infrared)

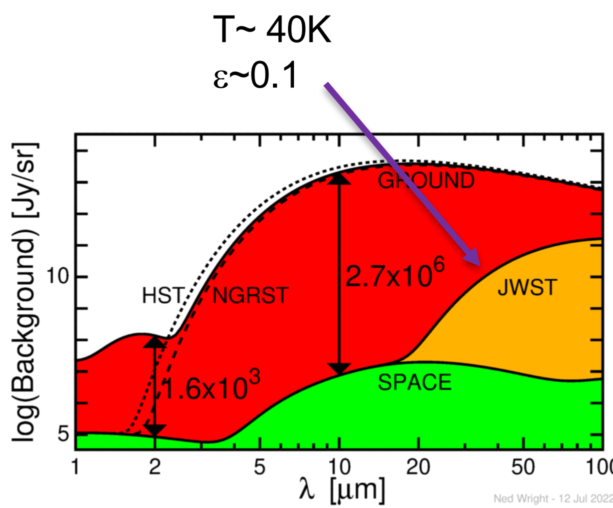
- Point source sensitivity vs extended source sensitivity = telescope size “matters” vs. “does not matter”
- Contributions: photon noise/thermal background, detector noise → **huge** difference between ground and space



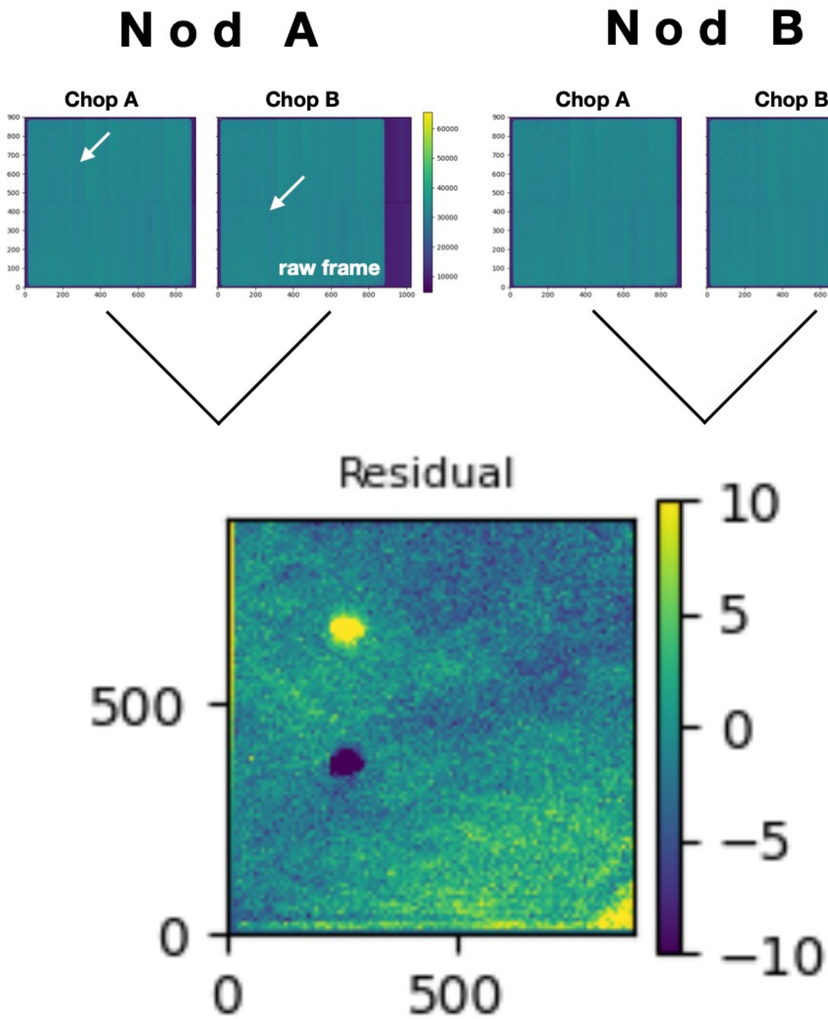
METIS Consortium

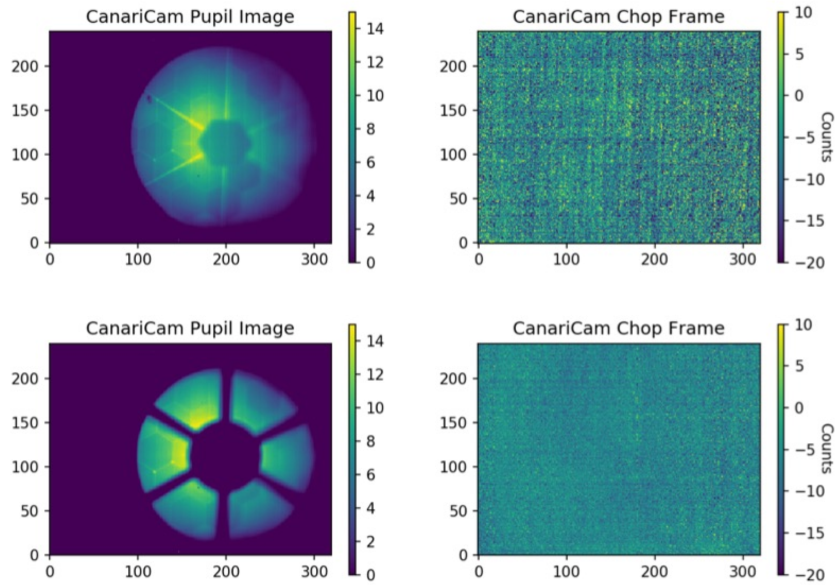
$$SNR_{/\mathrm{pix}} = \frac{S \times NDIT \times t_e}{\sqrt{NDIT \times (S + B + \mathrm{Dark}) \times t_e + NIDT \times \mathrm{RON}^2}}$$

Goal is to be background limited (BLIP)



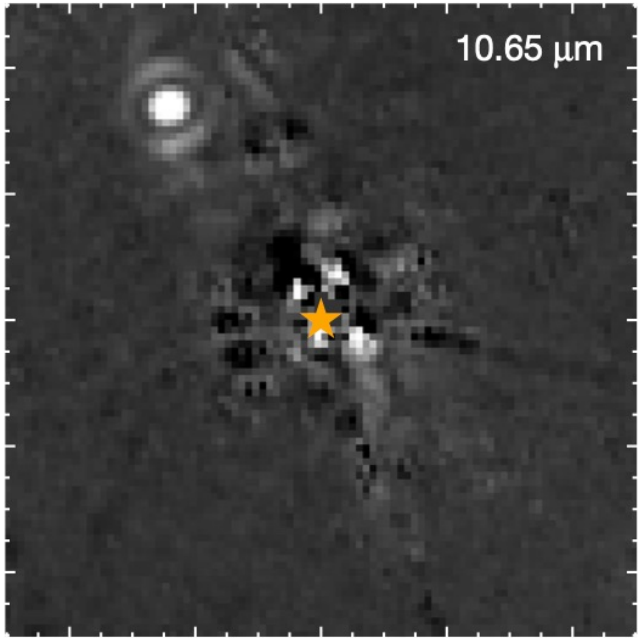
Sensitivity figures (mid-infrared)

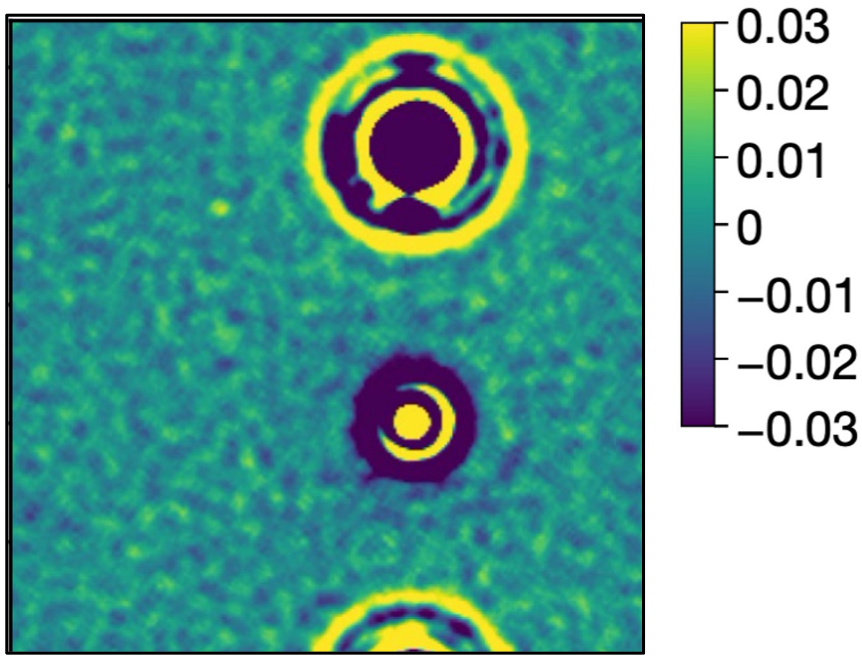




[Butscher 2020, METIS Consortium]

Eps Indi Ab

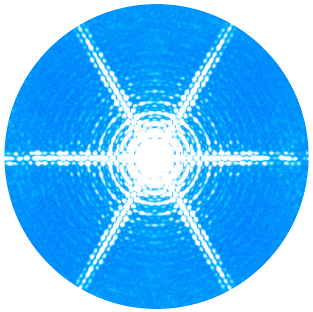




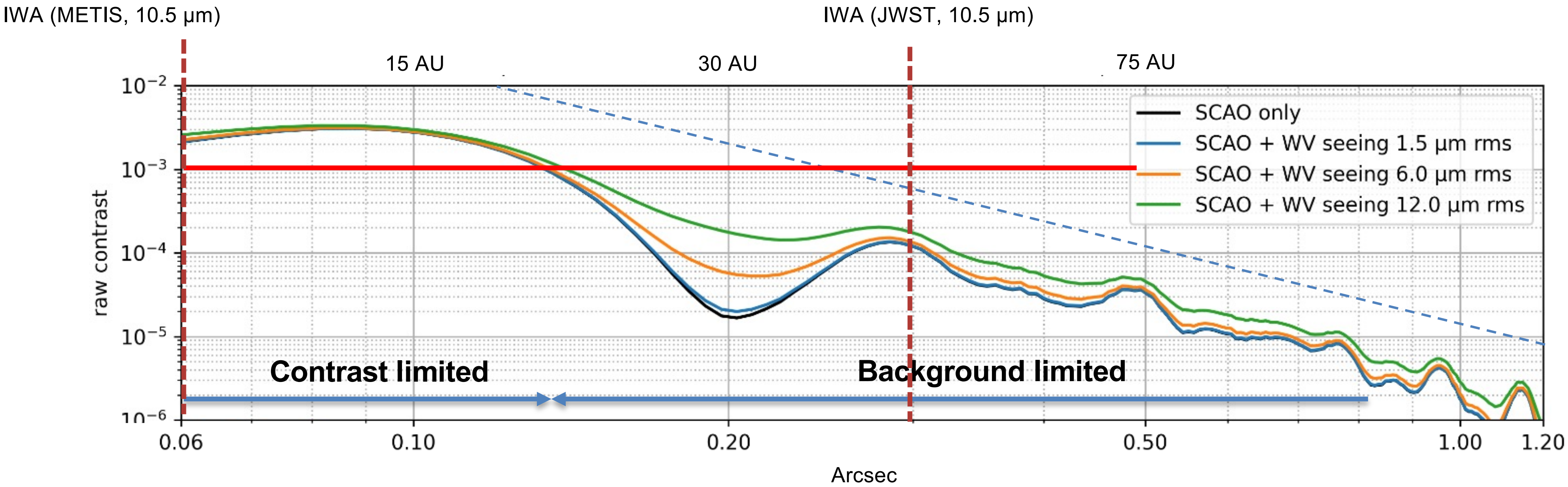
[Matthews 2024]

- VISIR/NEAR experiment (+AO), Kasper et al. 2017

High contrast imaging



N-band contrast curve



[Quanz 2018, Absil 2024]

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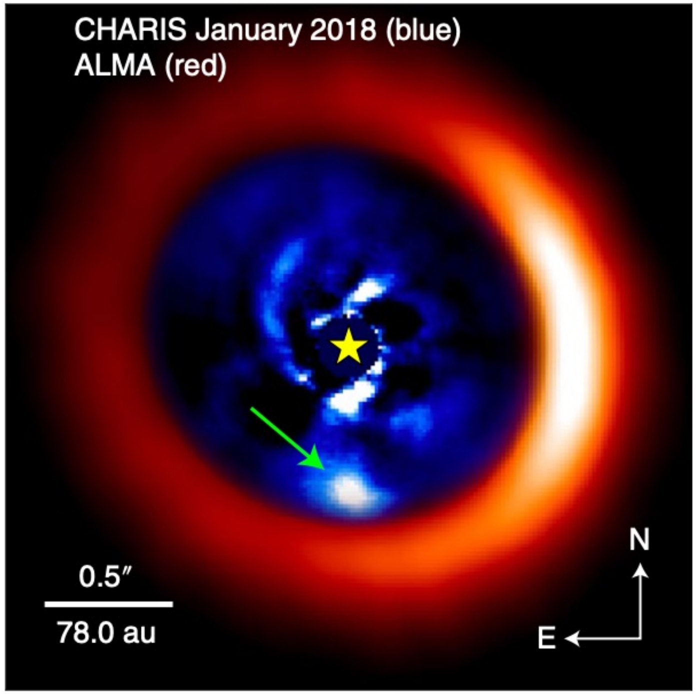
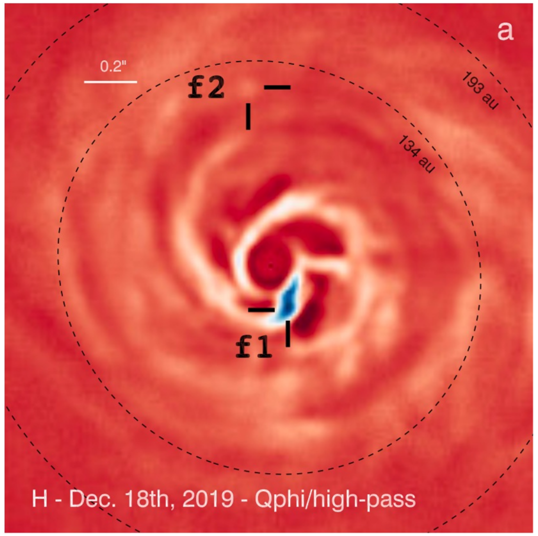
The AB Aur case



[Currie 2022]



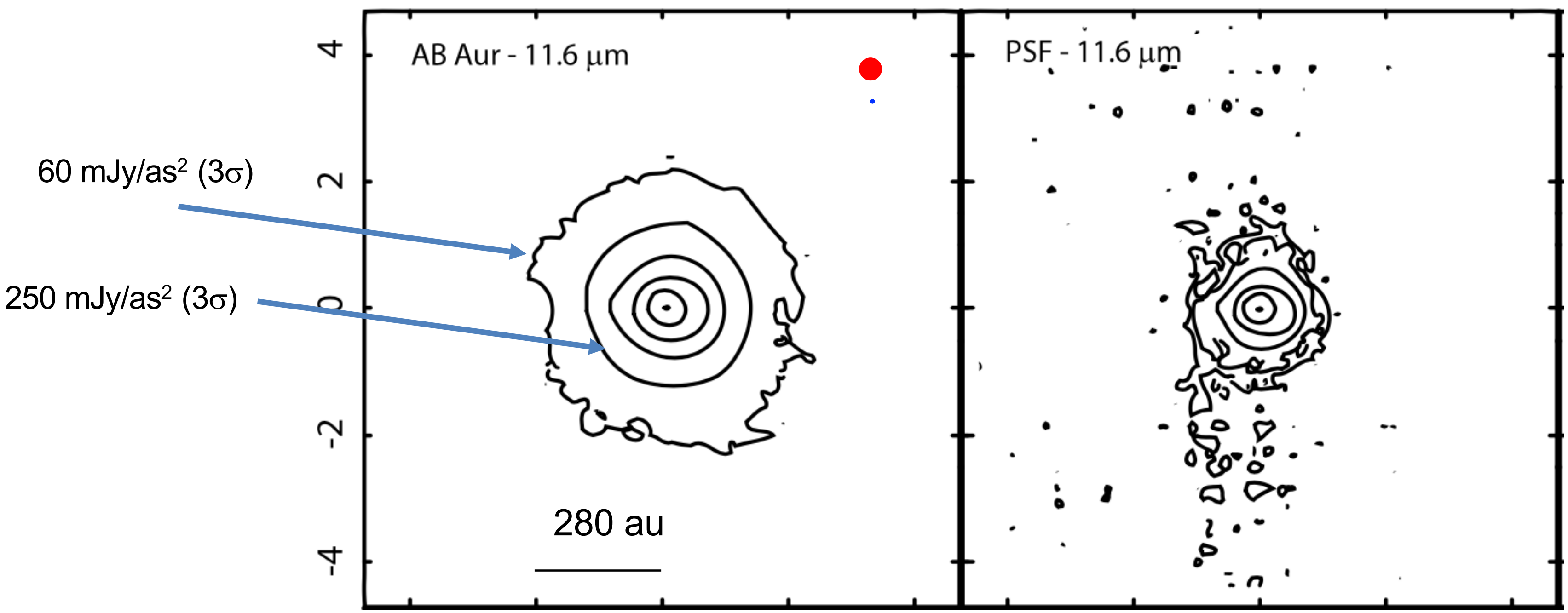
[Boccaletti 2020]

near-IR | mid-IR | Sub-mm

AB Aur's disk in the mid-IR

GEMINI-North (8.2m)
METIS/ELT (39m)

[Marinas 2011, 2006]



- Bulk of N band compact emission located within ~15 AU
- Faint emission detected out to **280 AU** and **350 AU** in N and Q bands, respectively → **Thermal emission ?**

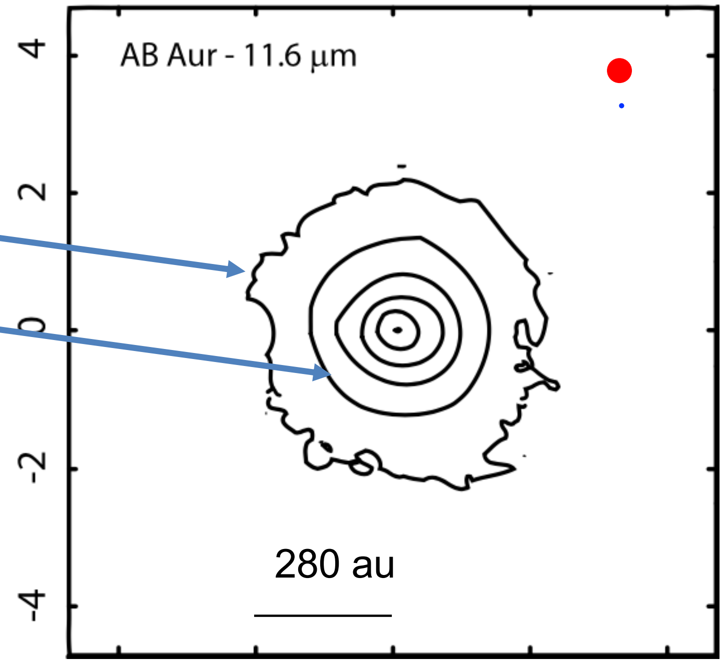
AB Aur's disk in the mid-IR

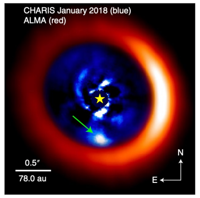
GEMINI-North (8.2m)
METIS/ELT (39m)

[Marinas 2011, 2006]

60 mJy/as^2 (3σ)

250 mJy/as^2 (3σ)





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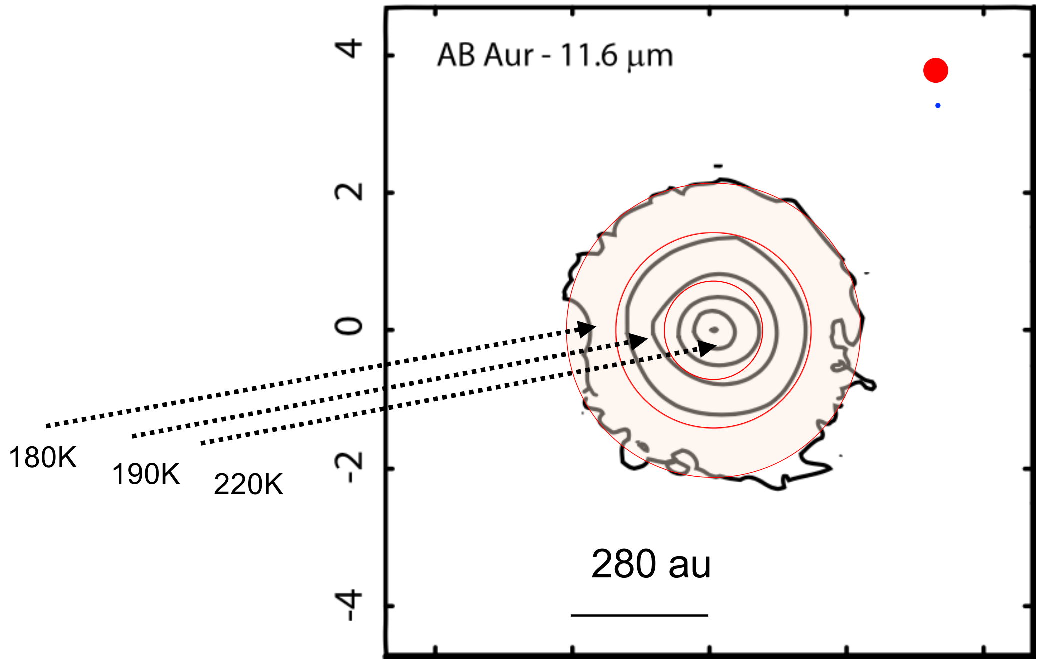
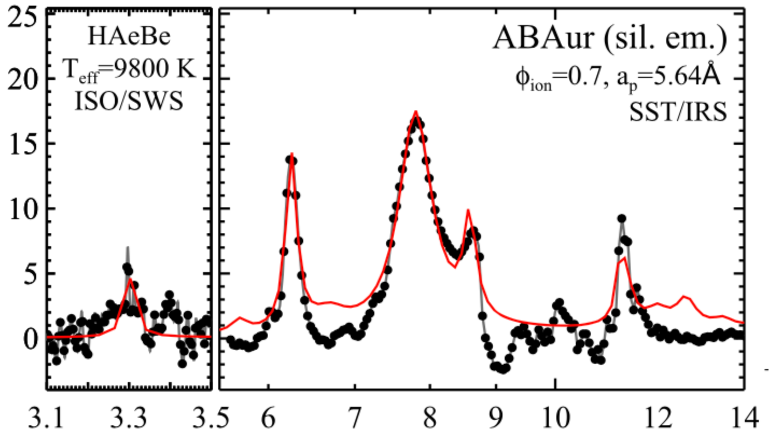
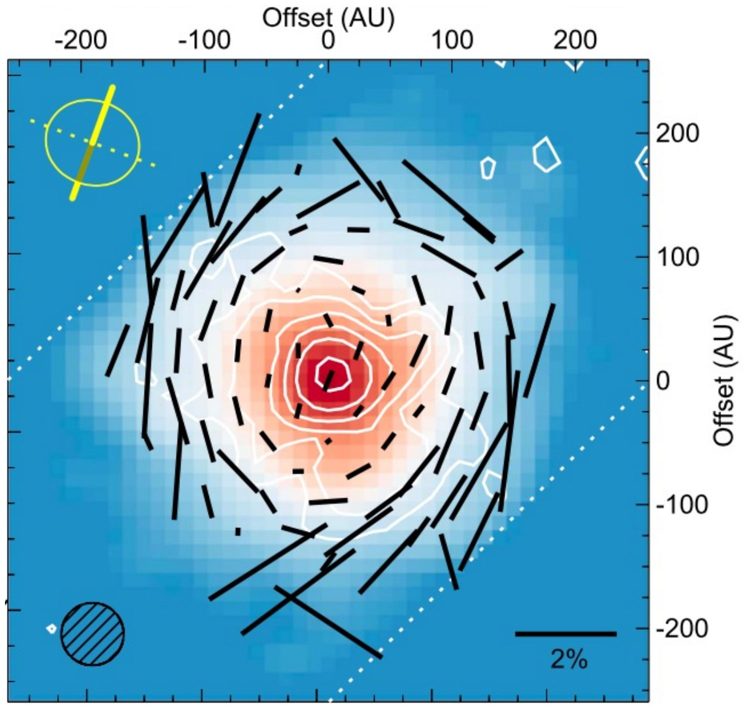




- Predicted color temperature (obs/model): 220 K / 103 K , 190 K / 59 K , 220 K / 46 K
- Invoke small (~0.1µm) grains or mixture with PAHs

Polarization map at 10μm

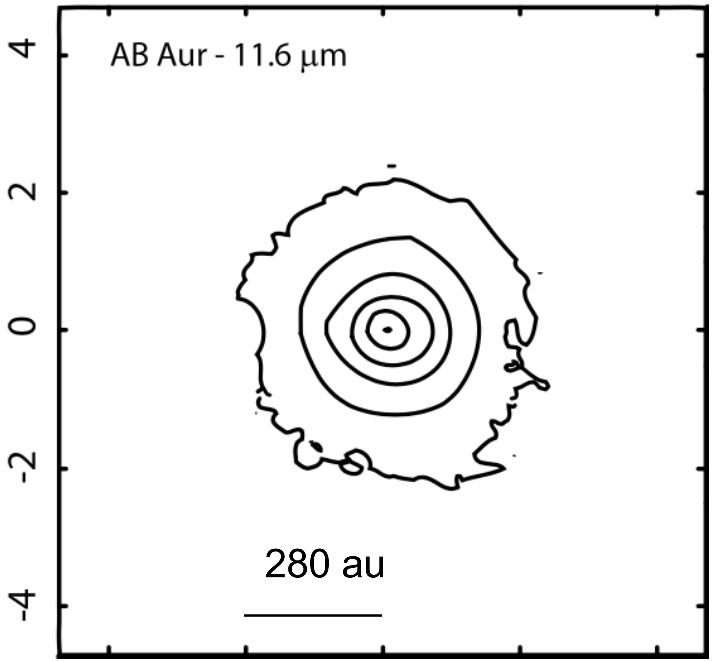
[Li 2016]

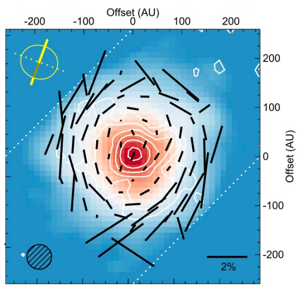


- CanariCam with Dual Beam Polarization mode on 10.4-m **segmented** GranTeCan telescope
- Two components in the polarization map: magnetized region vs. scattered light region

Polarization map at 10μm

[Marinas 2011, 2006]



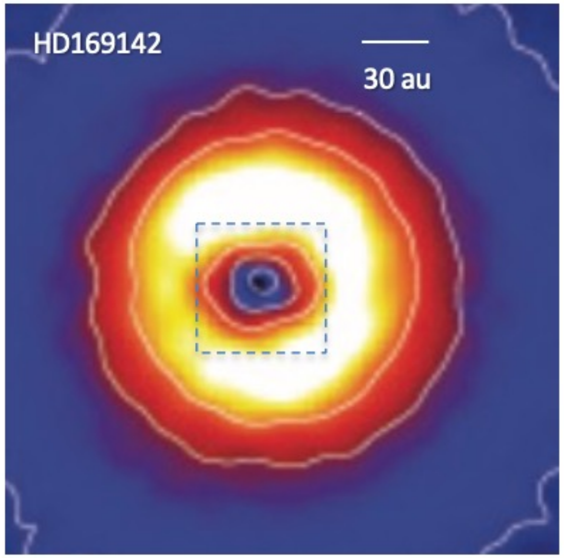


- CanariCam with Dual Beam Polarization mode on 10.4-m **segmented** GranTeCan telescope
- Two components in the polarization map: magnetized region vs. scattered light region

Towards ELT resolution

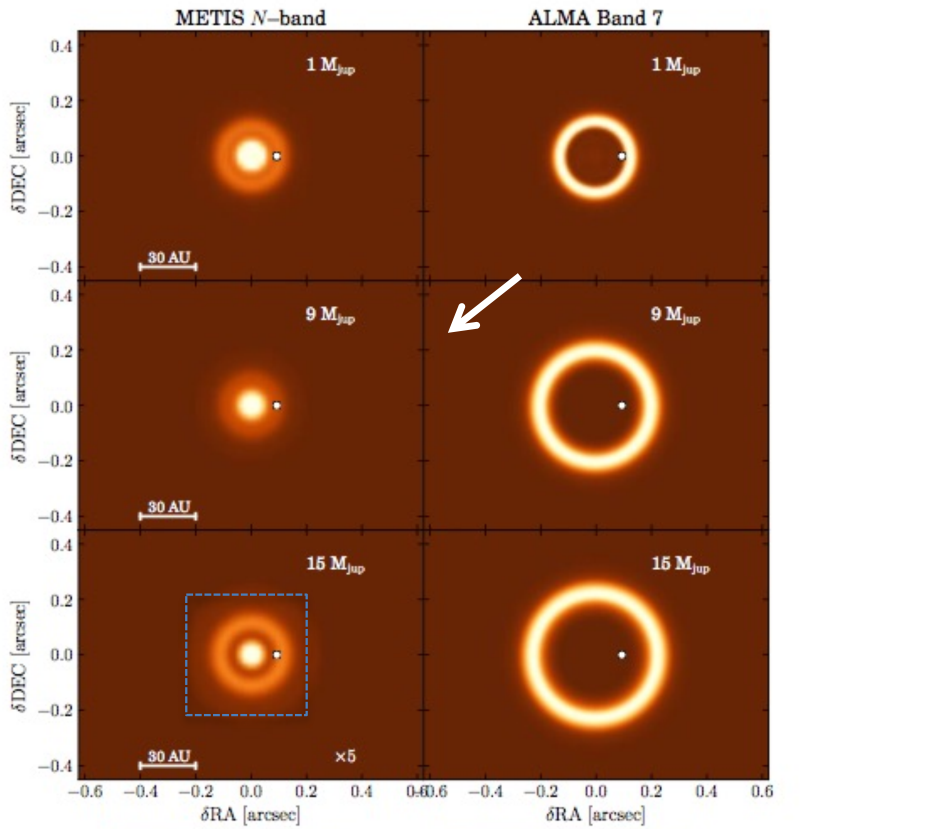
- Resolving gaps with METIS in the N band
- Complementarity of near-IR, mid-IR and sub-mm imaging
- Mapping the distribution of grains with different sizes

[Marinas 2011, GEMINI]



Resolution 0.3" at 10μm. Imaging the PAH distribution only at large radii >50 au

[MST 2022]



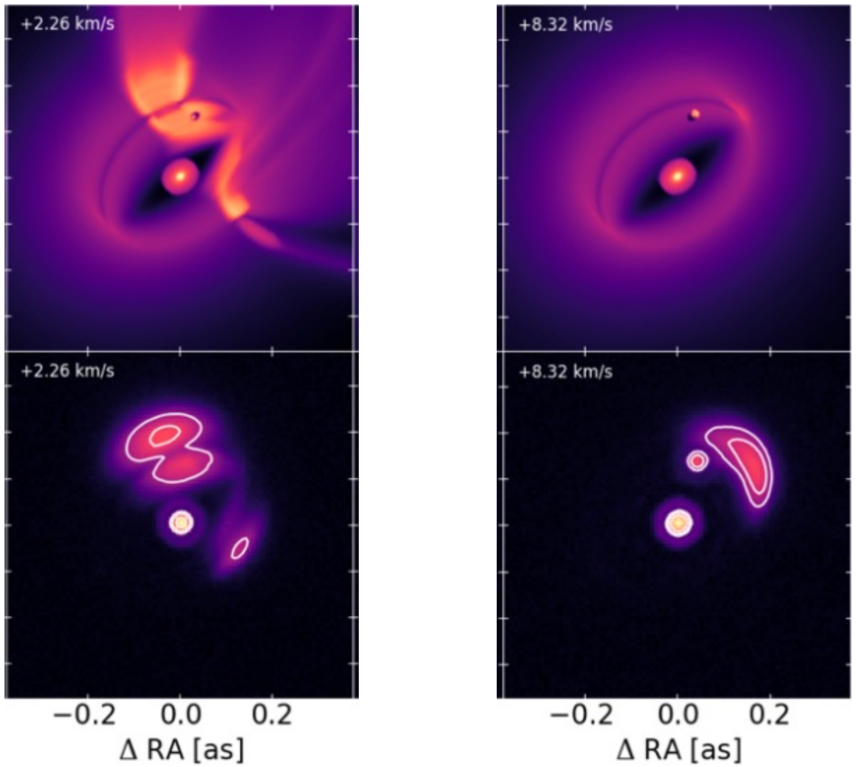
Simulation of METIS 10μm imaging of a disk at 150pc around a solar-type star with an embedded planet at ~20 au. The linear scale is 30au. Comparison to ALMA imaging in Band 7

Gas dynamics in the inner disk

- Kinematic signatures of circumplanetary disks with METIS in CO at 4.7µm

HD100546 model, CO, 4.7µm

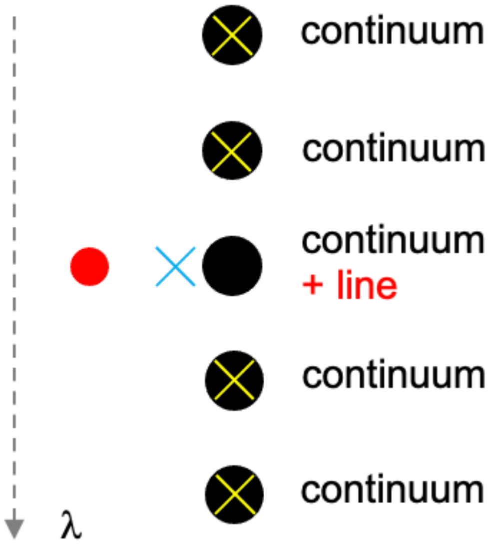
HD100546 simulation, IFU METIS



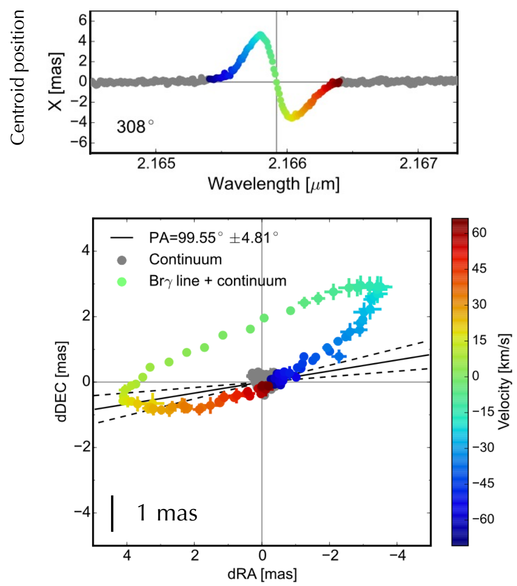
[Oberg, Kamp 2023]

Gas dynamics in the inner disk

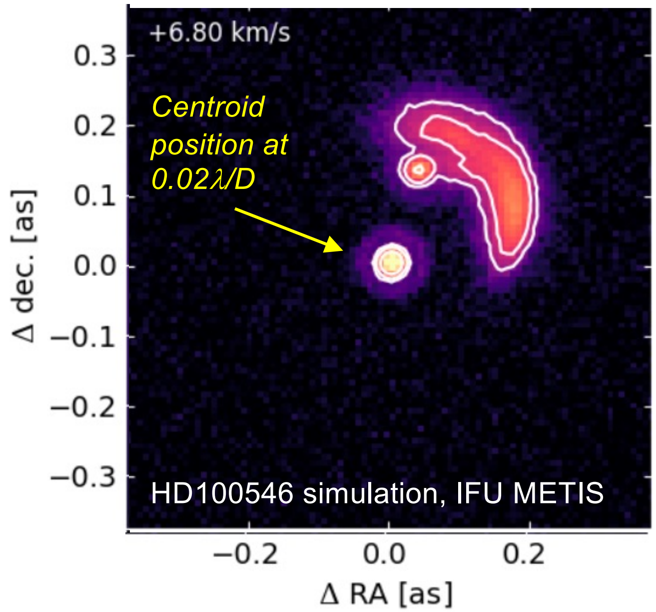
- Kinematic signatures of protoplanets at ~10 au --> ~ PSF scale
- Dynamics of the (atomic, molecular) gas at <1 au scale with *spectro-astrometry* --> *~0.02xPSF*



CRIRES (+)

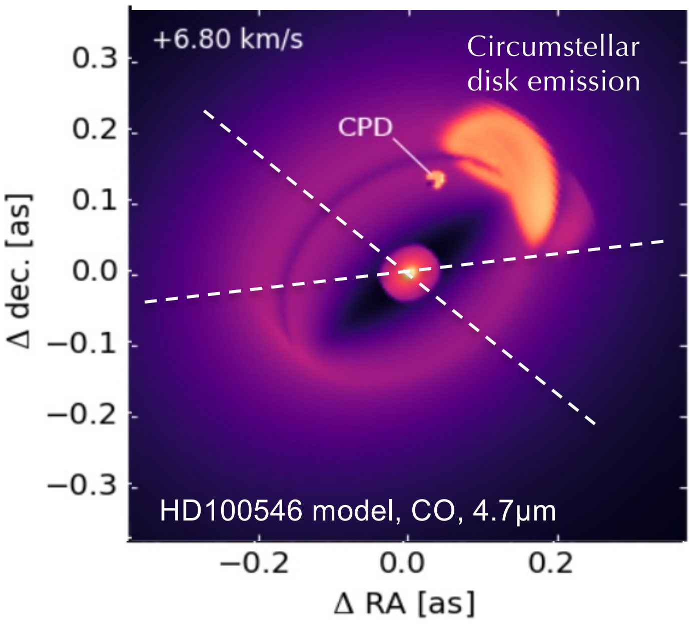


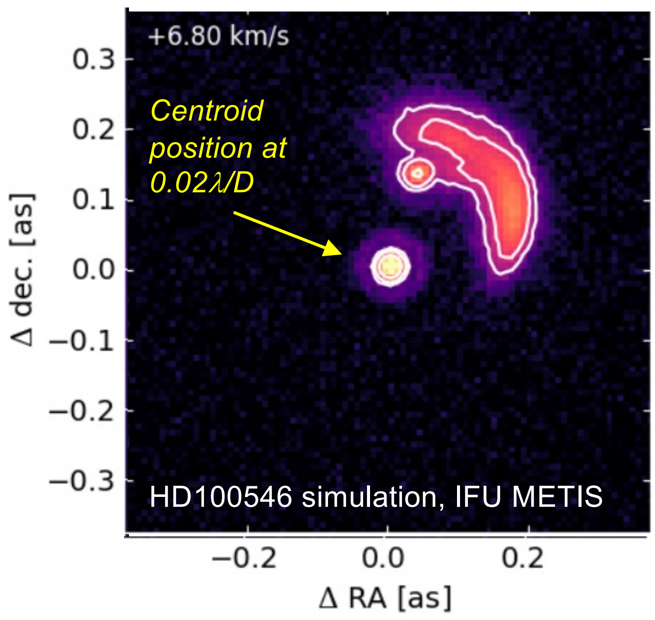
[Hone 2017]



Gas dynamics in the inner disk

- Kinematic signatures of protoplanets at ~10 au --> ~ PSF scale
- Dynamics of the (atomic, molecular) gas at <1 au scale with *spectro-astrometry* --> *~0.02xPSF*
- High-spectral resolution is critical for resolving low-, high-velocity components in line profiles





[Oberg, Kamp 2023]

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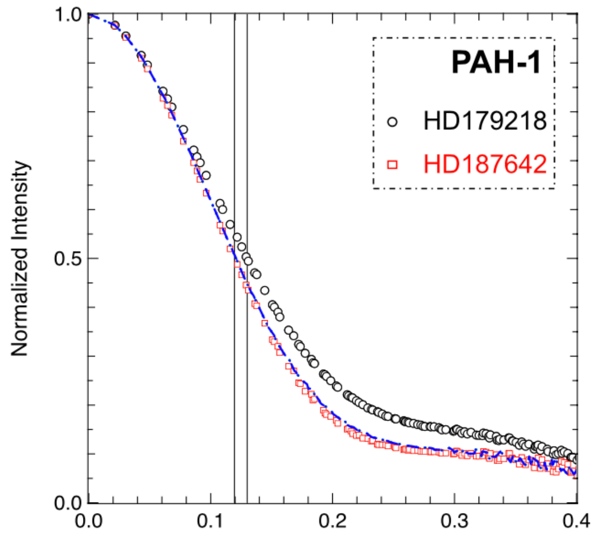
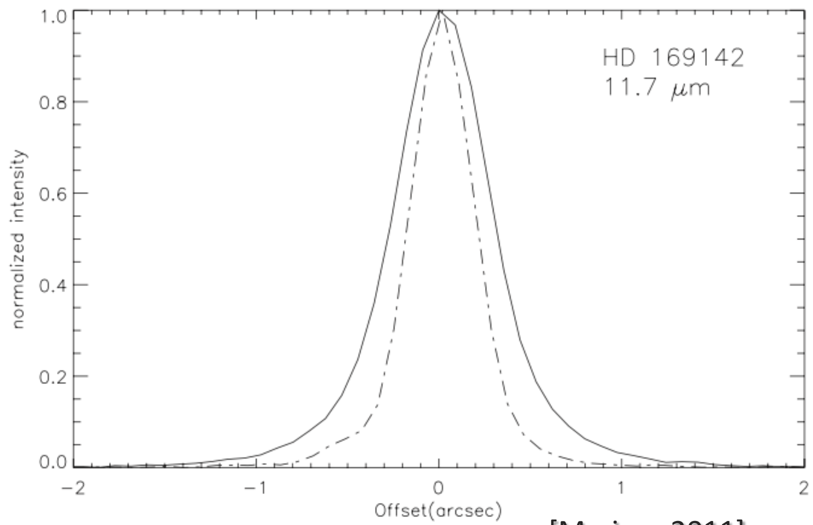
The reservoir of carbonaceous grains

- 8-m class telescope at 10 μm deliver a **characteristic size** measurement



[Taha, Labadie 2018]



[Marinas 2011]

$$\Phi_d = \sqrt{\Phi^2 - \Phi_p^2}$$

Deconvolved diameter

Measured profile

PSF

Calibrator	Filter	$D_{d,L}$ [″]	$D_{d,PSF}$ [″]
HD 169414	PAH-1	0.092 ± 0.004	0.103 ± 0.003
HD 187642	PAH-1	0.082 ± 0.005	0.101 ± 0.003
HD 169414	PAH-2	0.084 ± 0.003	0.096 ± 0.002
HD 187642	PAH-2	0.081 ± 0.002	0.087 ± 0.002
HD 187642	Si-6	≤0.024 ± 0.009	≤0.035 ± 0.011

CanariCam -- > 0.3” resolution

--> Minimum deconvolved diameter is ~0.03”

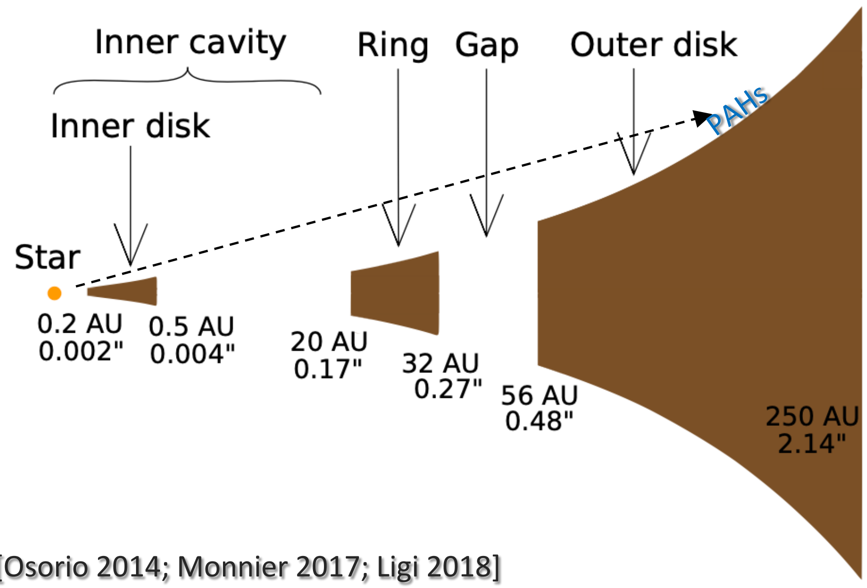
METIS --> 0.06” resolution

--> Minimum deconvolved diameter as small as ~0.006”

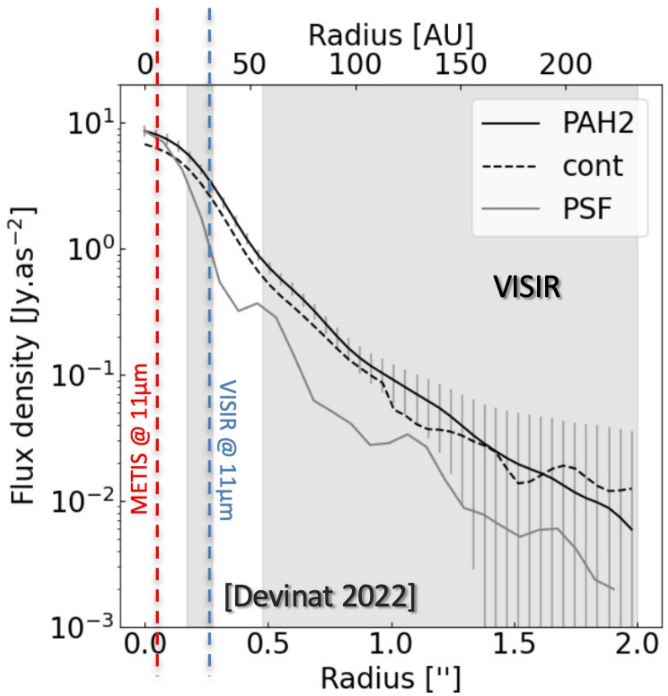
For partially resolved source, deconvolution techniques are implemented

The reservoir of carbonaceous grains

- Disk content in carbonaceous nanograins in inner region (Yoffe 2023; Kokoulina 2021; Devinat 2022)



[Osorio 2014; Monnier 2017; Ligi 2018]



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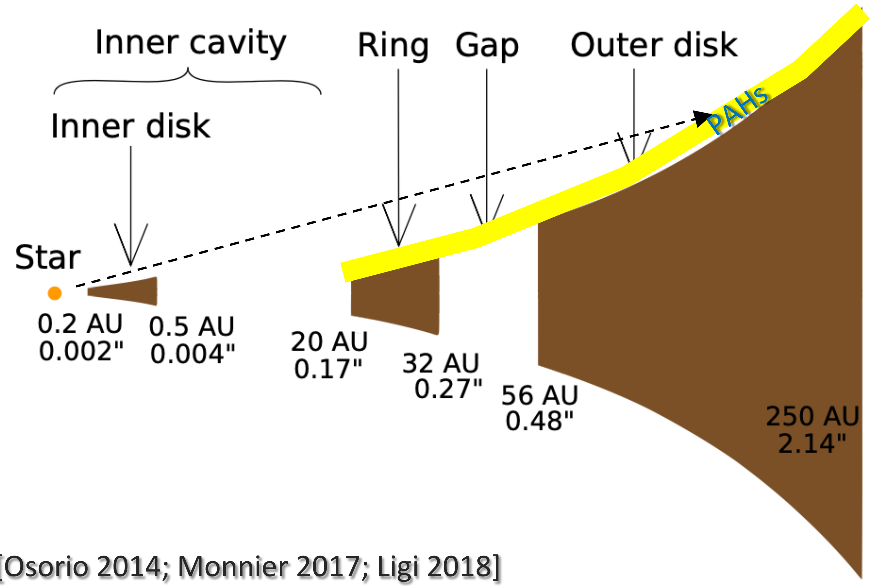
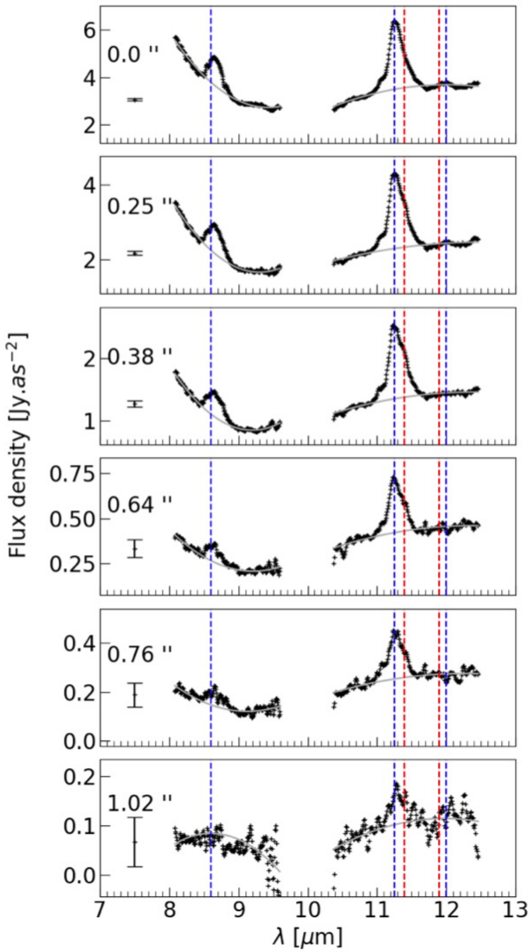


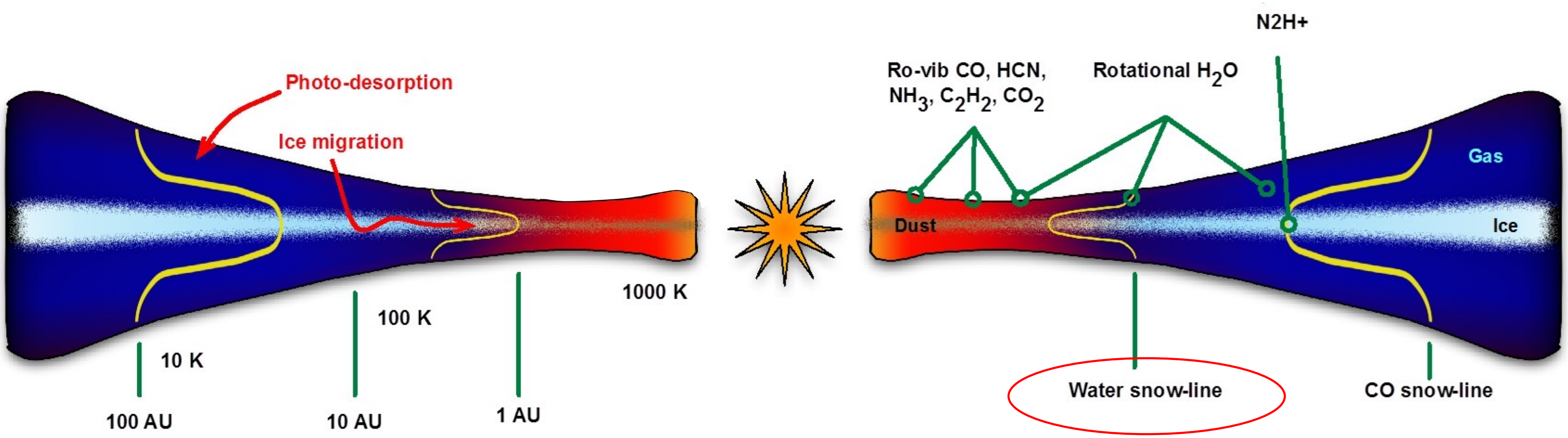
[Osorio 2014; Monnier 2017; Ligi 2018]

0.3” resolution (VISIR) → 0.06” resolution (METIS)



The water snowline in disks

- Ice species as efficient site for chemical reactions (Tazaki+2021)
- Role of ices in favoring grain growth?
- Planetesimal formation at the snow line (Drazkowska+2017) → *location depends on sublimation temperature*

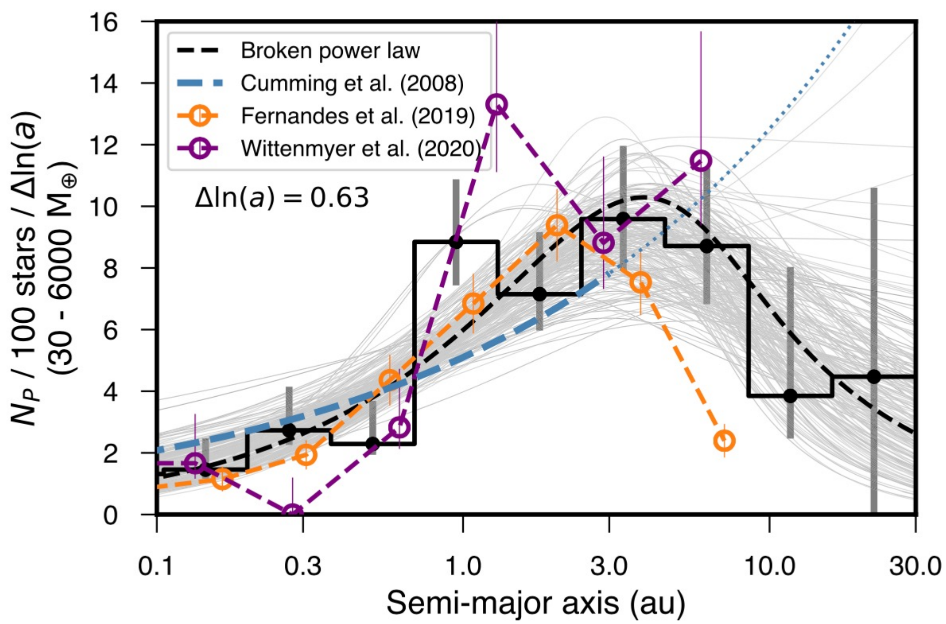


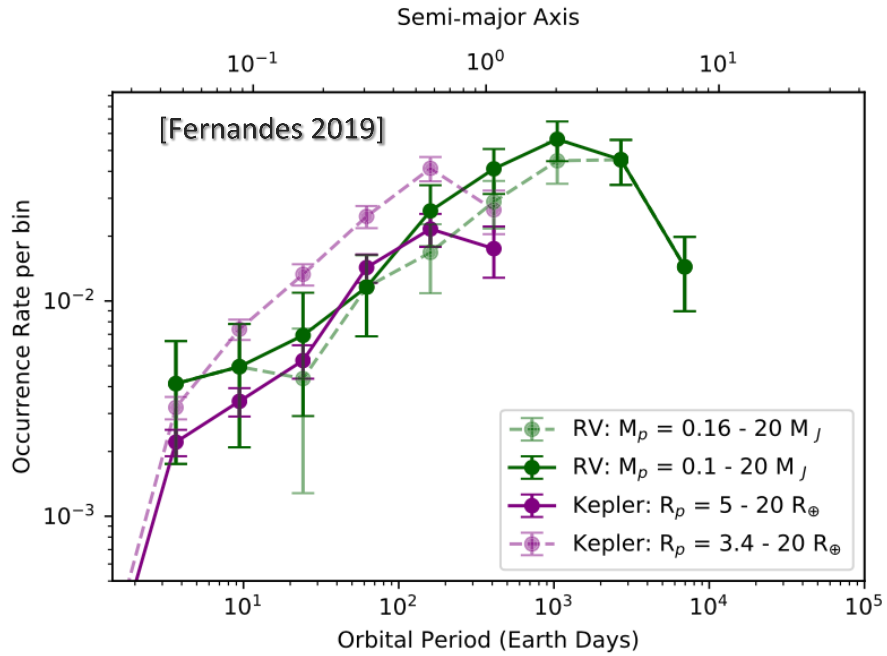
age-dependent

The water snowline in disks

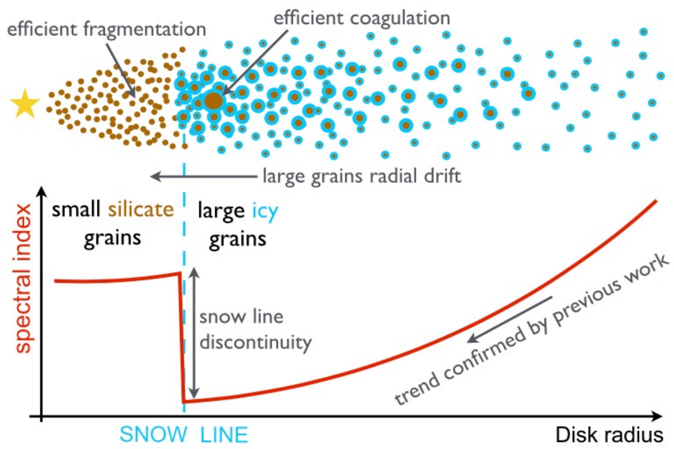
- Possible higher occurrence of Jupiter and sub-Jupiter planets close to the water-ice line
- F,G,K,M-type central star

[Fulton 2021]



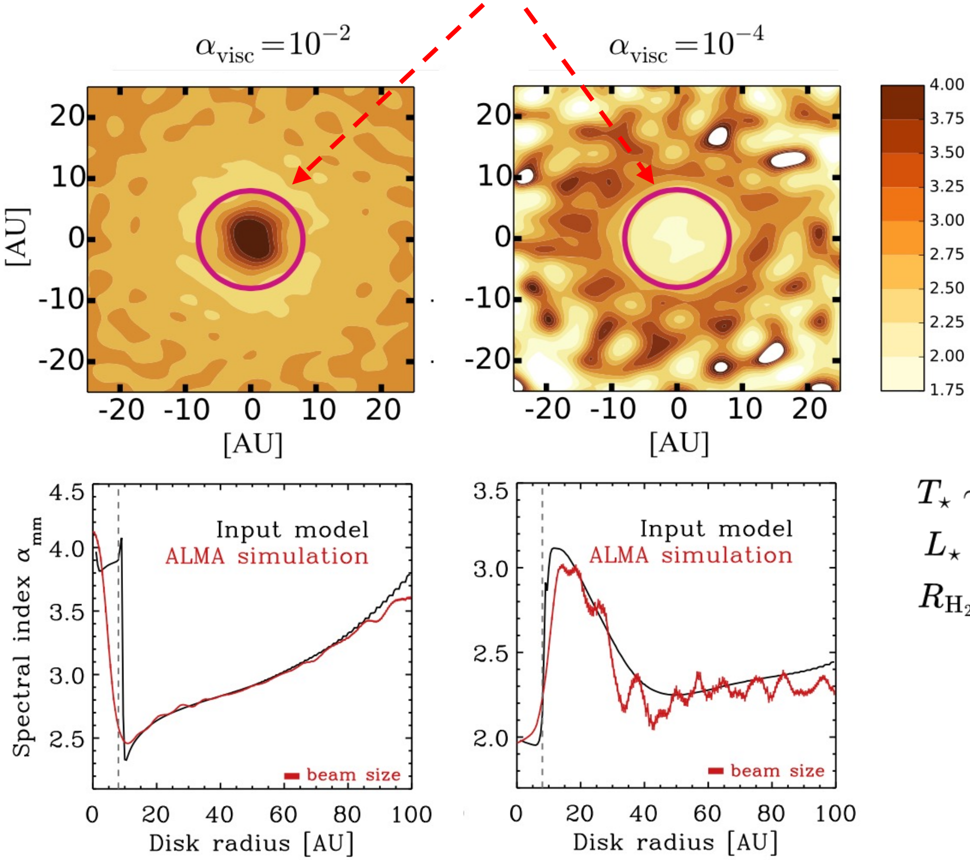


H_2O snowline in continuum's spectral indices: principle



$$\alpha_{mm} = \ln\left(\text{image}_{1.3mm}/\text{image}_{3.0mm}\right)/\ln\left(\lambda_{3.0}/\lambda_{1.3}\right)$$

Spectral index break



$T_\star \sim 9000\,\mathrm{K}$

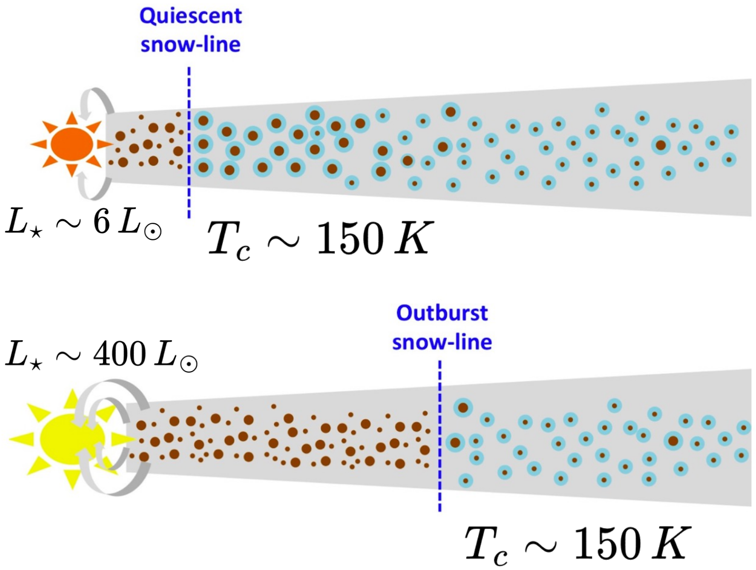
$L_\star \sim 30\,L_\odot$

$R_{H_2O} \sim 8\,\mathrm{au}$

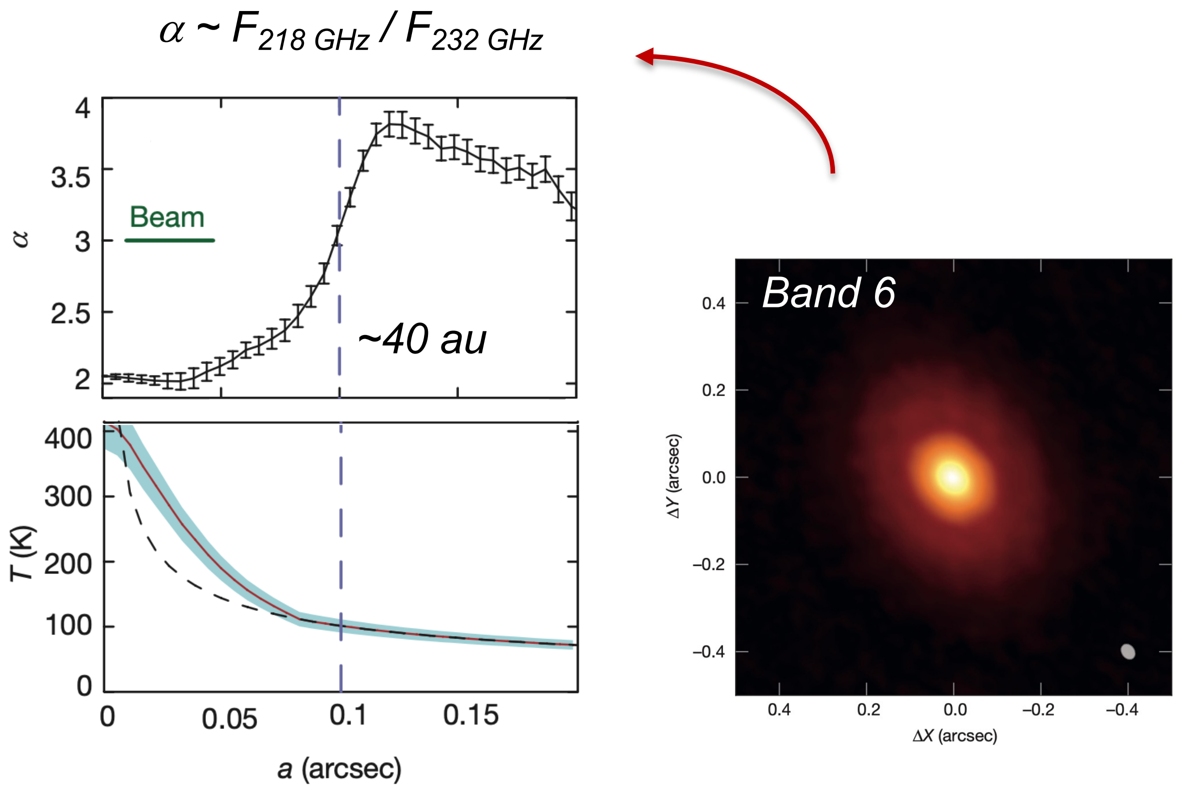
[Banzatti 2015]

H_2O snowline in continuum's spectral indices: V883 Ori

- FU Ori-type outburst moves **H_2O snow line** outwards

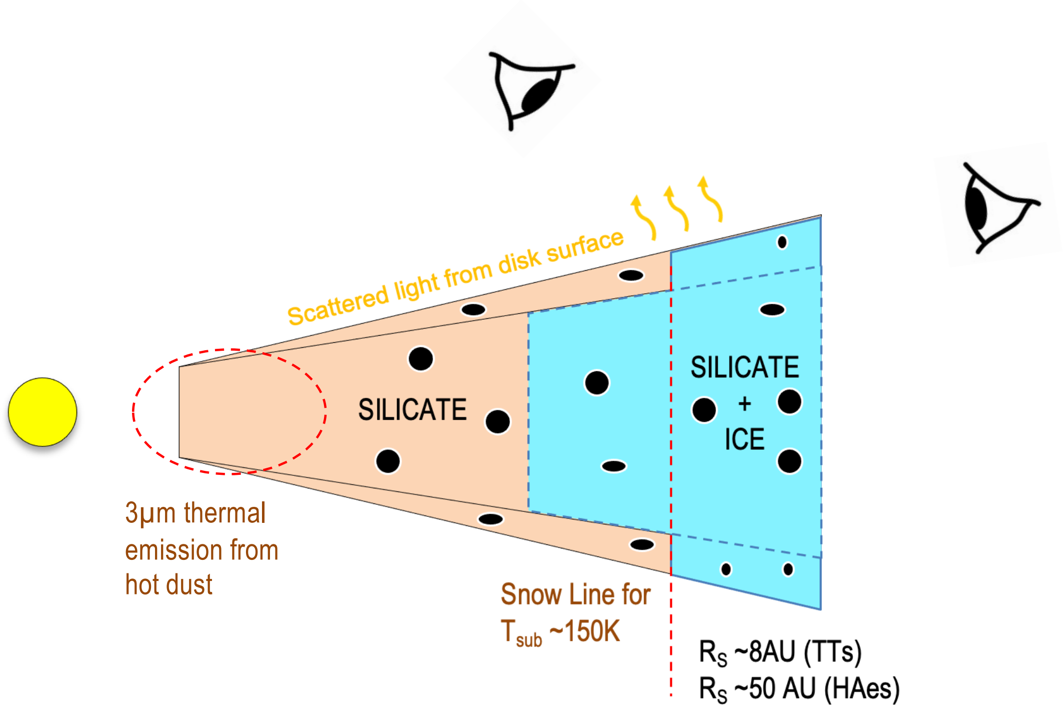


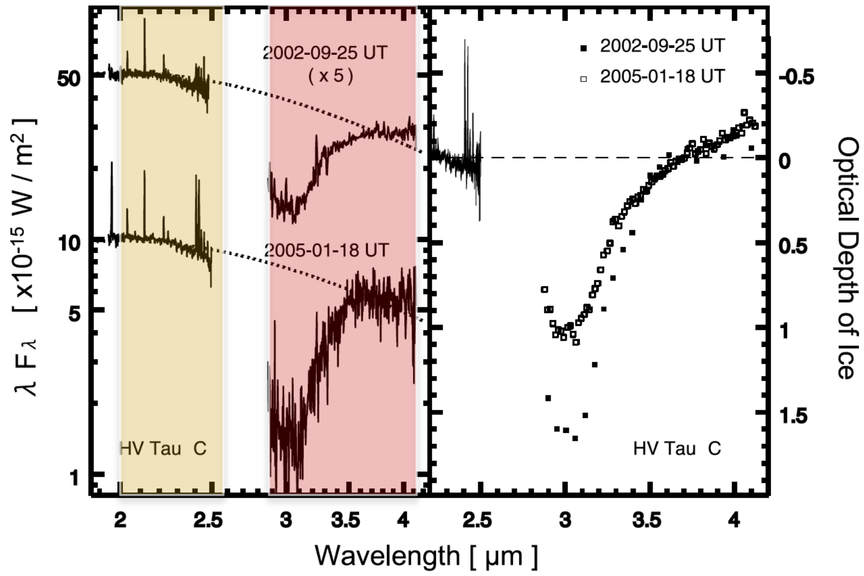
[Cieza 2016]



The water snowline in disks

- 3.1 μm broadband feature observed in *absorption*
- Search for differences in the IR colors of light scattered at the disk surface

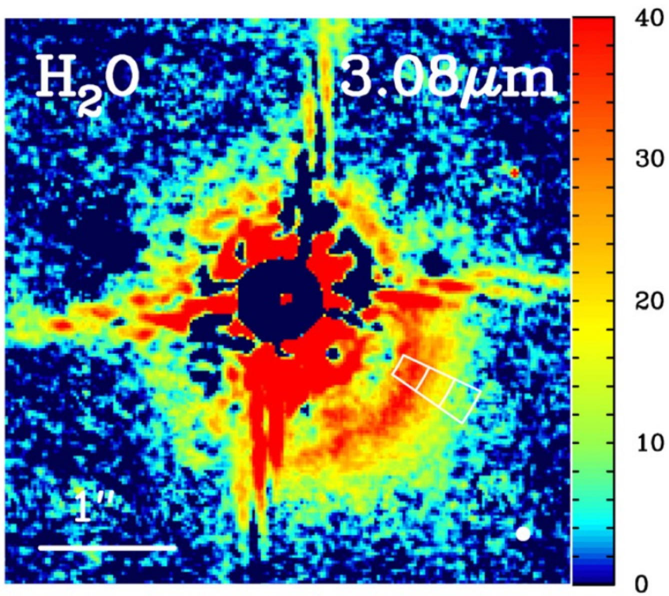


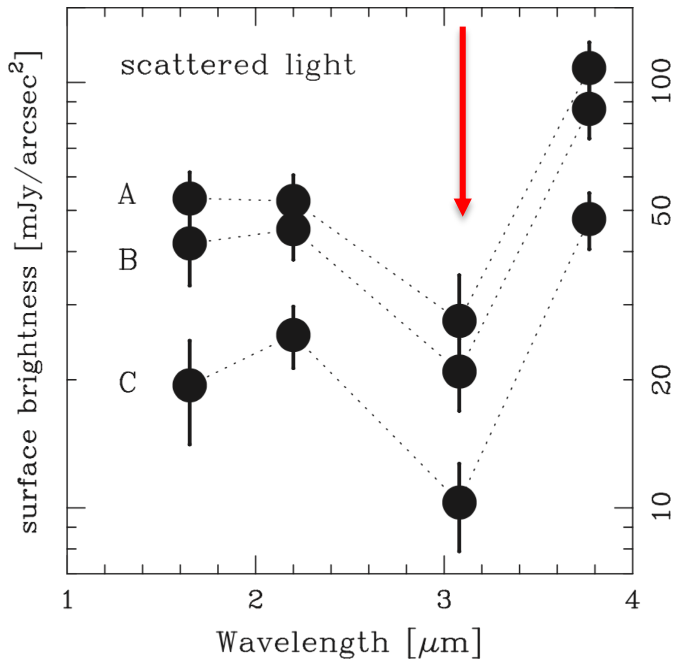


[Terada 2007; Pontoppidan 2005]

Resolving the snow line at 3.1 µm

- H (1.65µm) to L’ (3.8µm) beneficial for water ices detection in disks atmospheres
- Pioneered by Inoue+2008, Honda+2009 with CIAO/SUBARU in HD142527

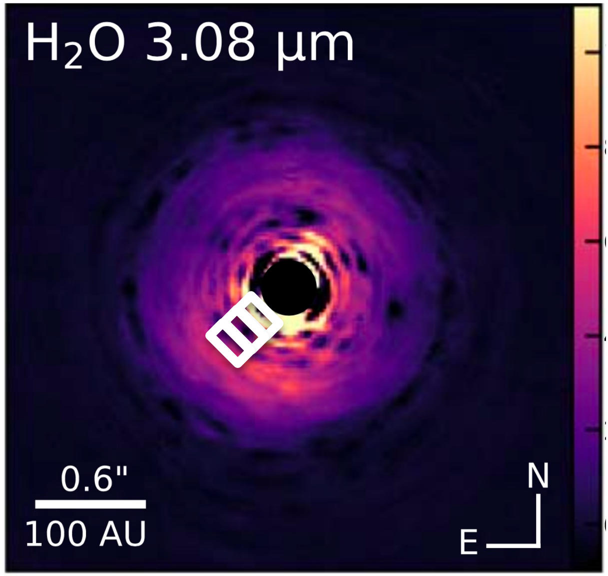




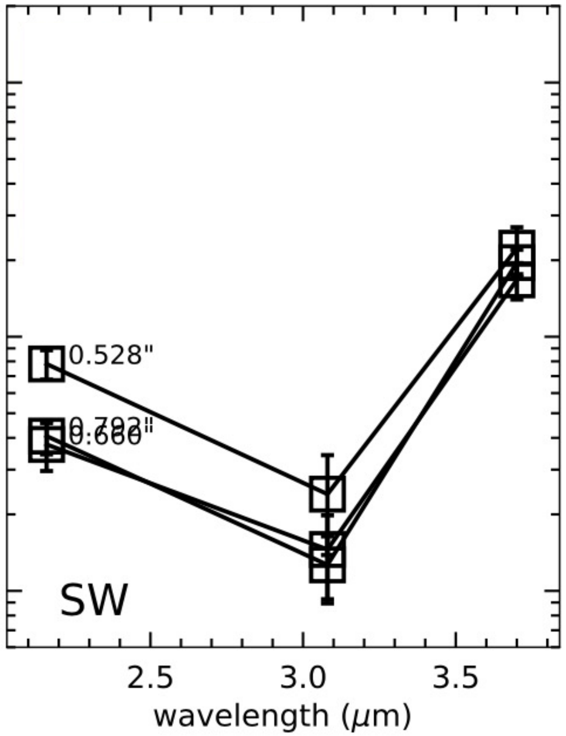
[Honda 2009]

Resolving the snow line at 3.1 µm

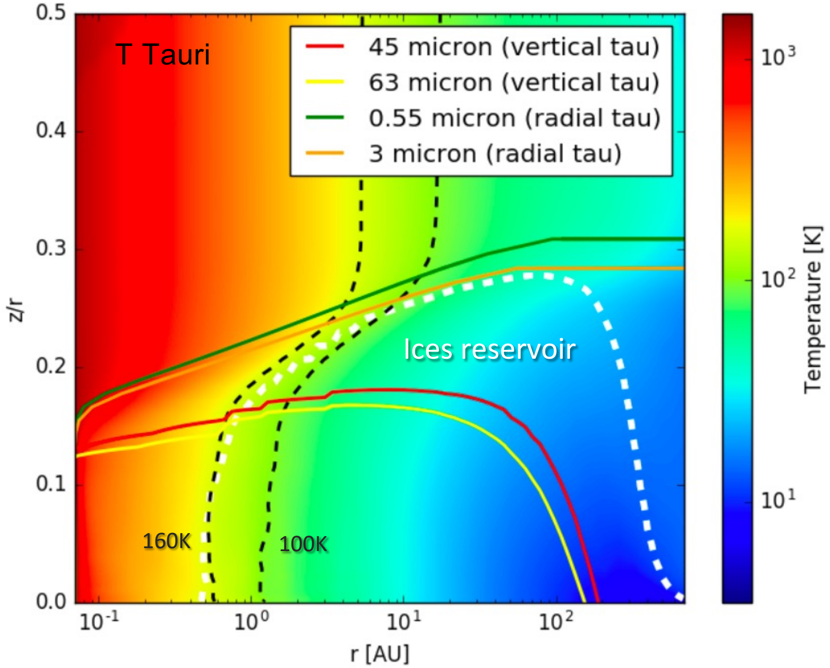
- H (1.65µm) to L' (3.8µm) beneficial for water ices detection in disks atmospheres
- Observed in HD142527, HD100546, AB Aur



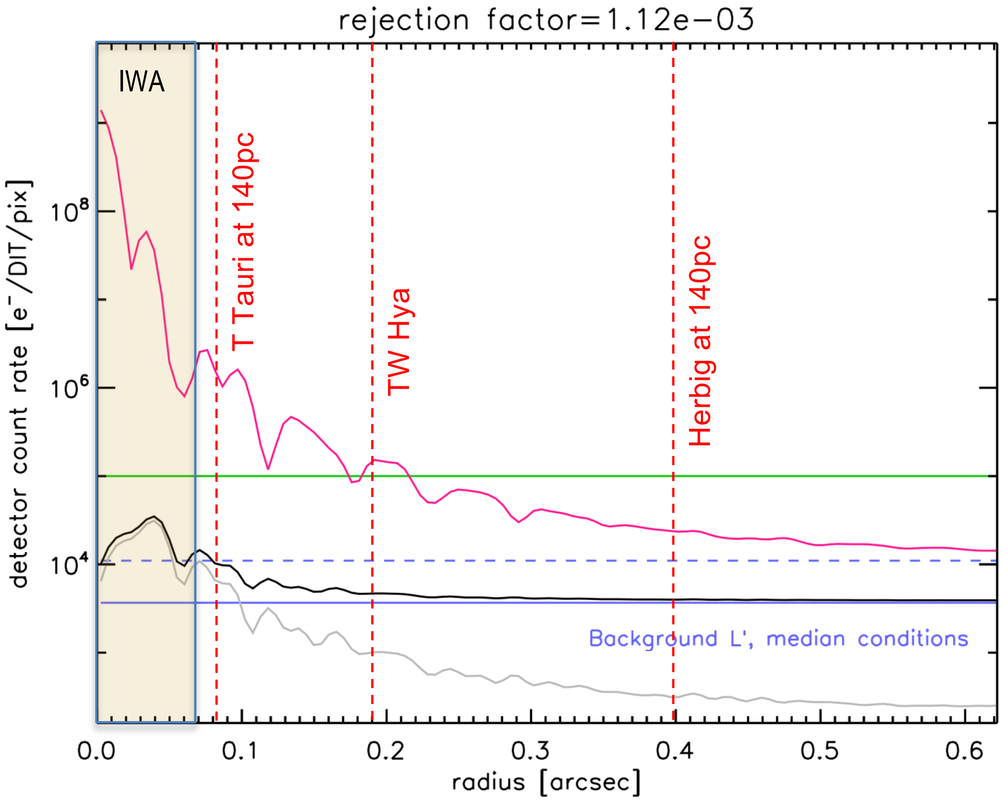
[Betti+2022, AB Aur]



ELT Simulations



[Kamp 2018]

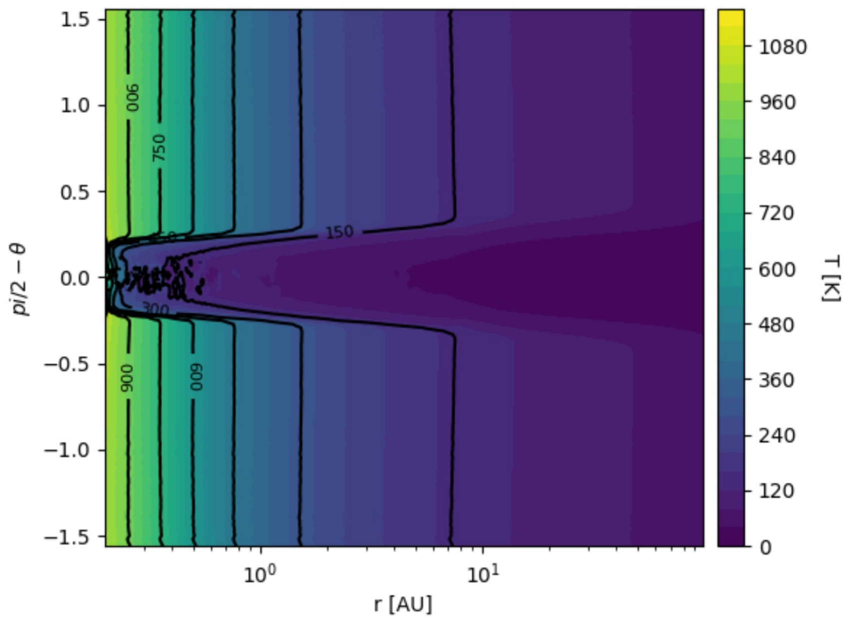


[Carlomagno 2018]

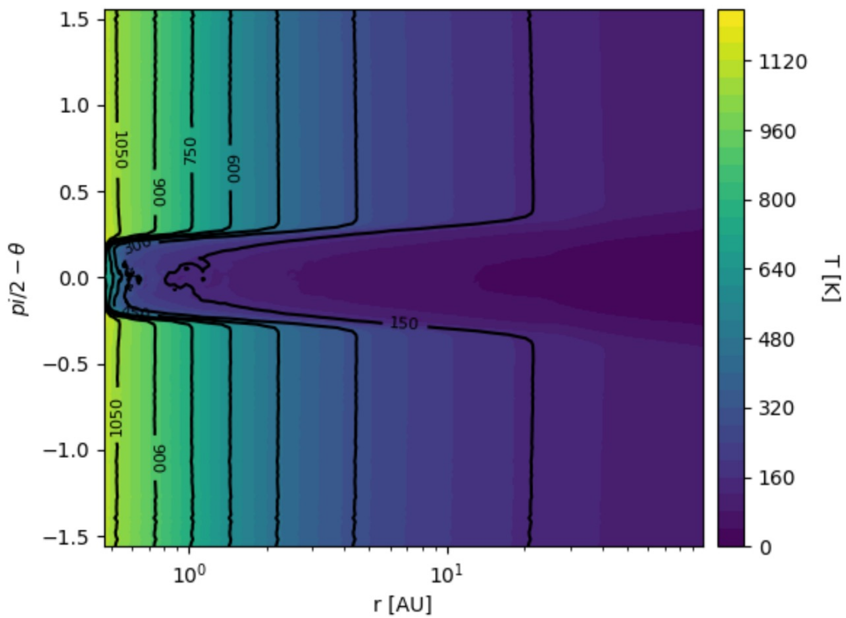
ELT Simulations

- Canonical T Tauri and Herbig AeBe models (based on Kamp 2018)

- Ms = 0.7 Msun



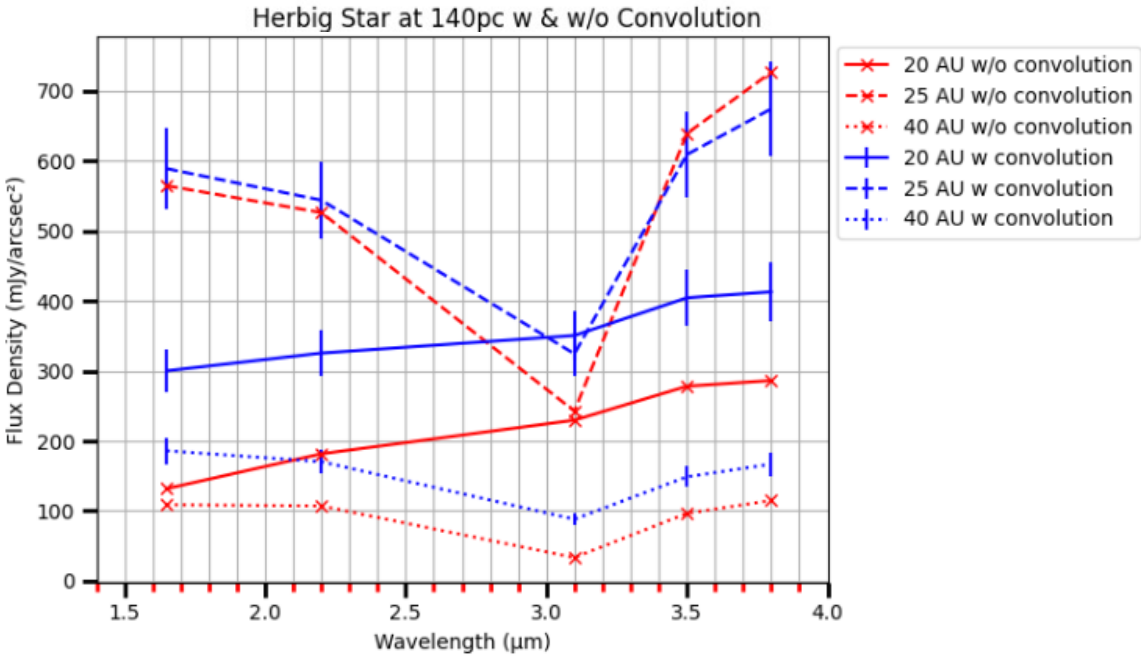
- Ms = 1.6 Msun



[Kaufhold 2024]

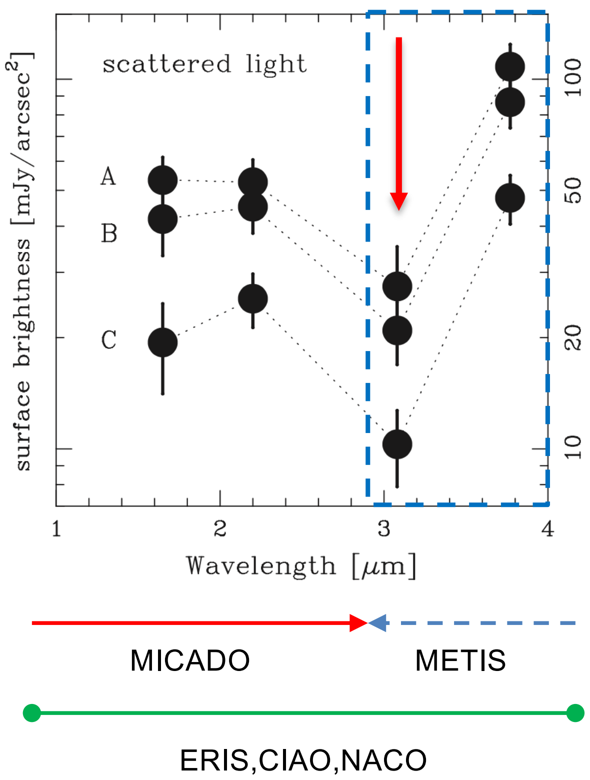
ELT Simulations

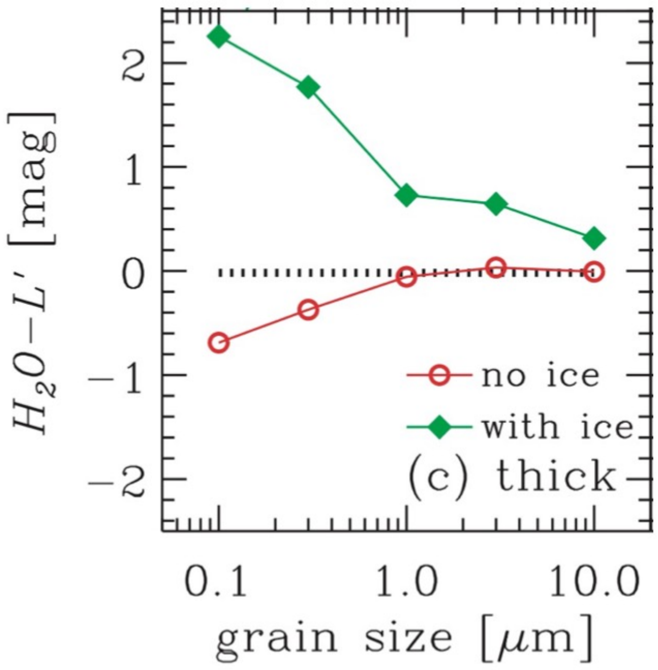
- Water snow line set at 25 AU
- Simple test with after convolution with the ELT point spread function



[Kaufhold 2024]

Applicability with the ELT





[Inoue 2018]

- Unique complementarity with NIRCAM IFU for H_2O ices

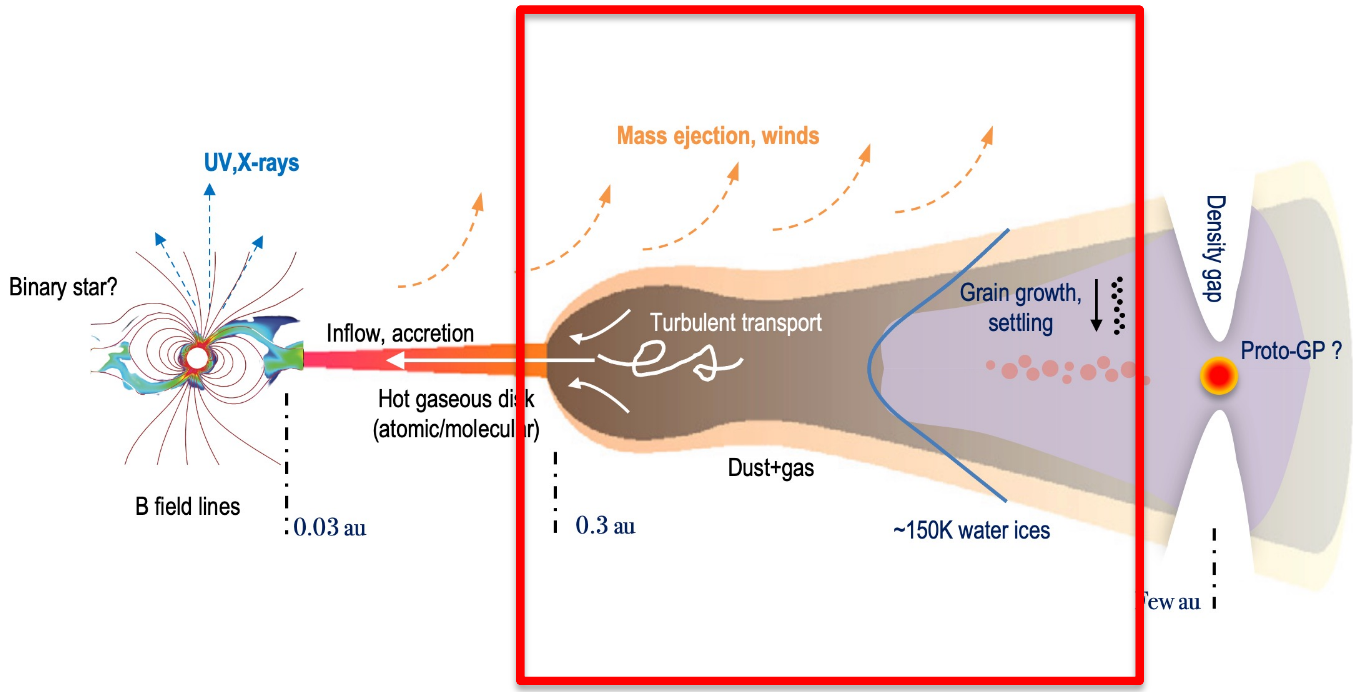
Lecture outline

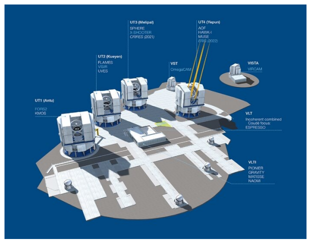
I. Description and specificities of the ELT and VLT(I)

- Observing techniques
- Performances
- Observational challenges

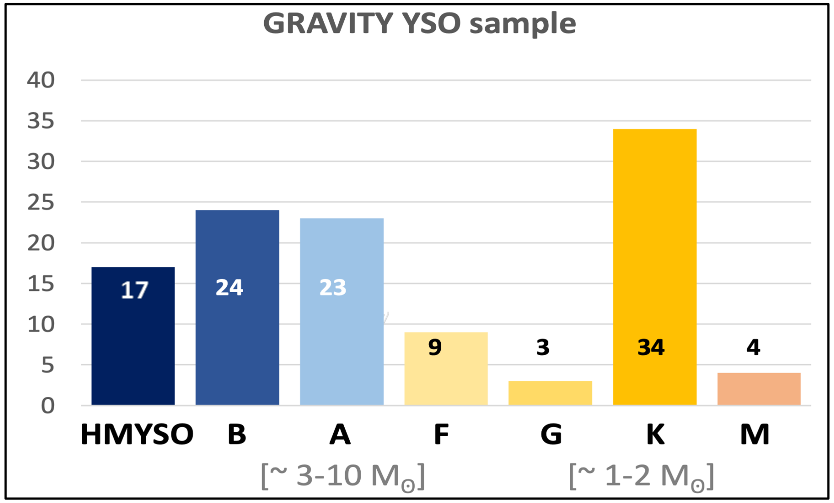
- II. Complementary science with the ELT/VLT(I)
  - Structure of protoplanetary disks
  - Composition of planet forming material
  - The inner regions of protoplanetary disks

The inner 1 AU region





The GRAVITY YSO Survey

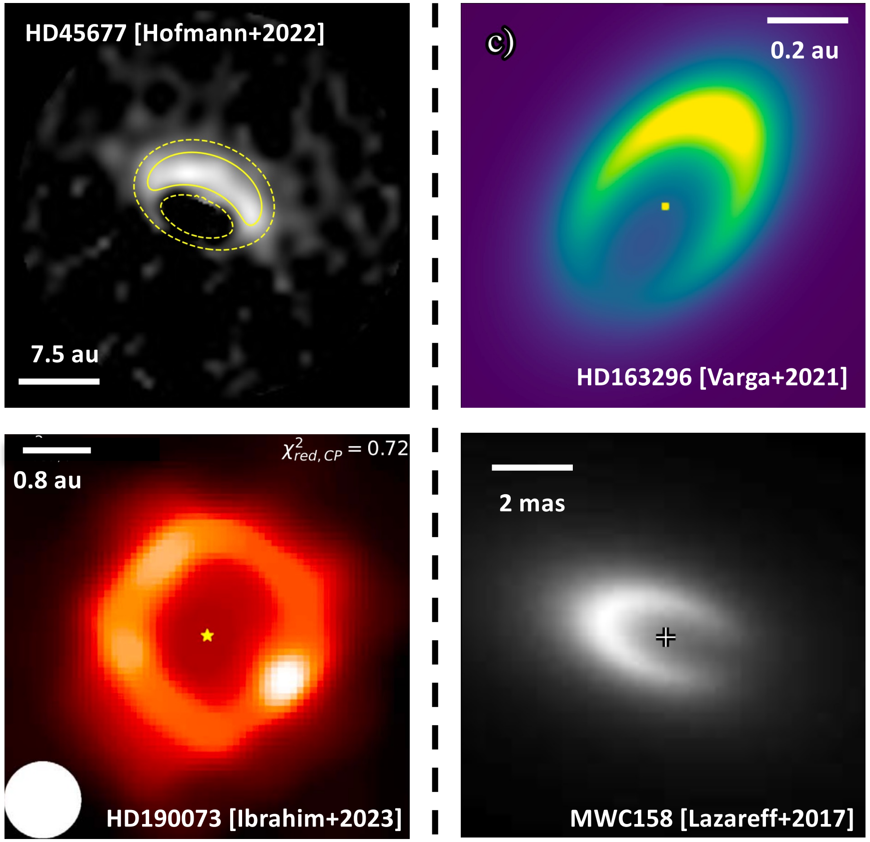


- Spatial structure of the inner ~1 au disk
  - ✓ Properties of the inner dust rim
  - ✓ Asymmetries and their temporal variability at short orbital timescales
  - ✓ Inner/outer disks misalignment
- Study of hot H and warm CO
  - ✓ Spatial location of line-emitting region, excitation mechanism (accretion, winds), kinematics
- Focuses on individual objects with peculiar properties

Asymmetric Features in YSOs

Image reconstruction

Model fitting

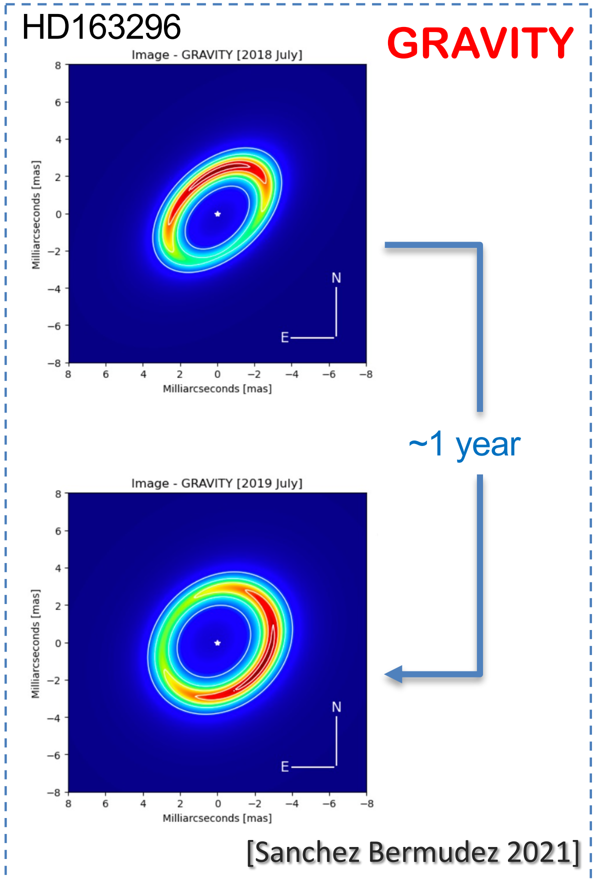


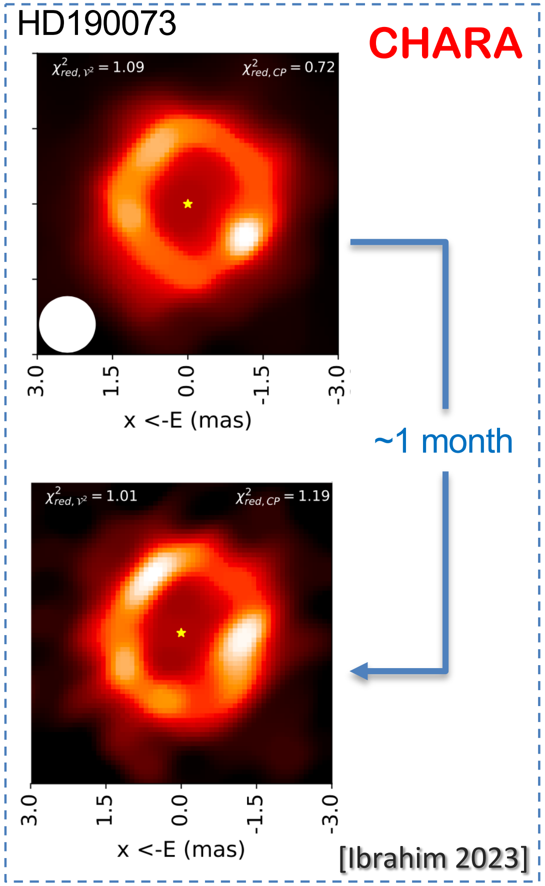
Time variable structures in the inner disk

- Following disk dynamics at short orbital time scales (e.g., disk-induced variability)

$$T_{\rm orb} = 2\pi\sqrt{\frac{R^3}{GM_*}}$$

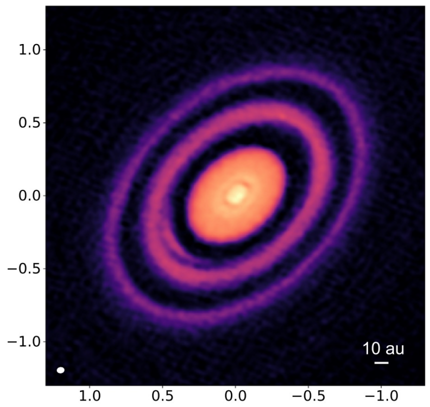
$$T_{\rm orb} \sim 0.5\,{\rm yr}$$





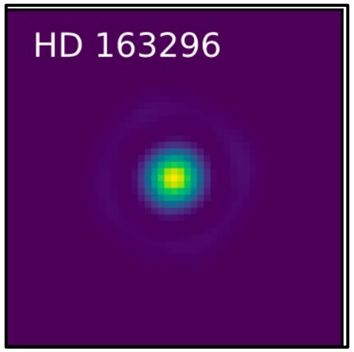
HD163296's portrait

Large scale sub-mm



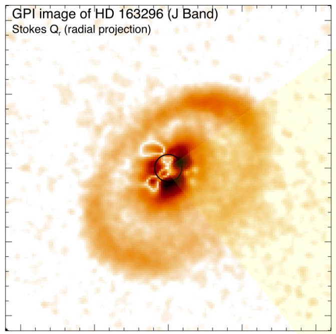
[Isella 2018]

Unresolved mid-IR emission



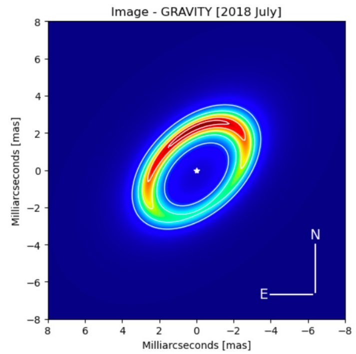
[Petit dit de la Roche 2021]

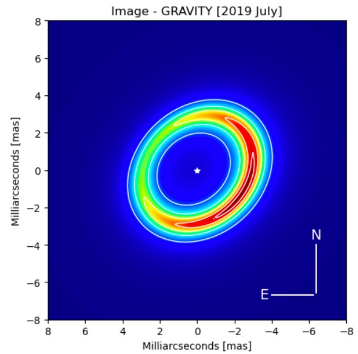
Large scale IR scattered light



[Monnier 2018]

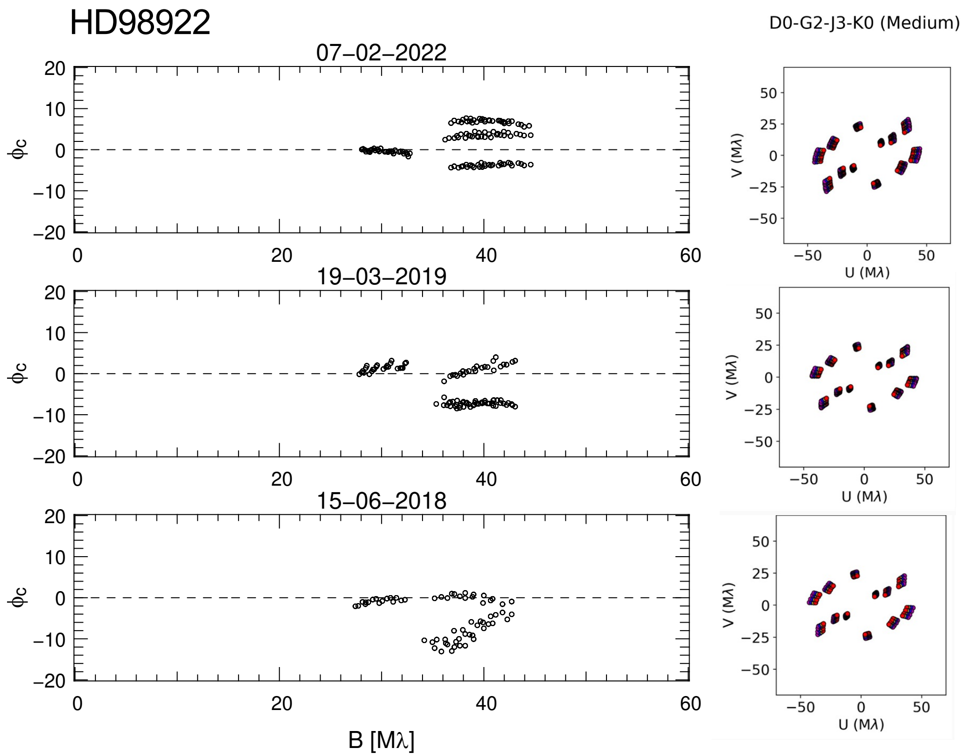
Near-IR thermal emission





Time variable structures in the inner disk

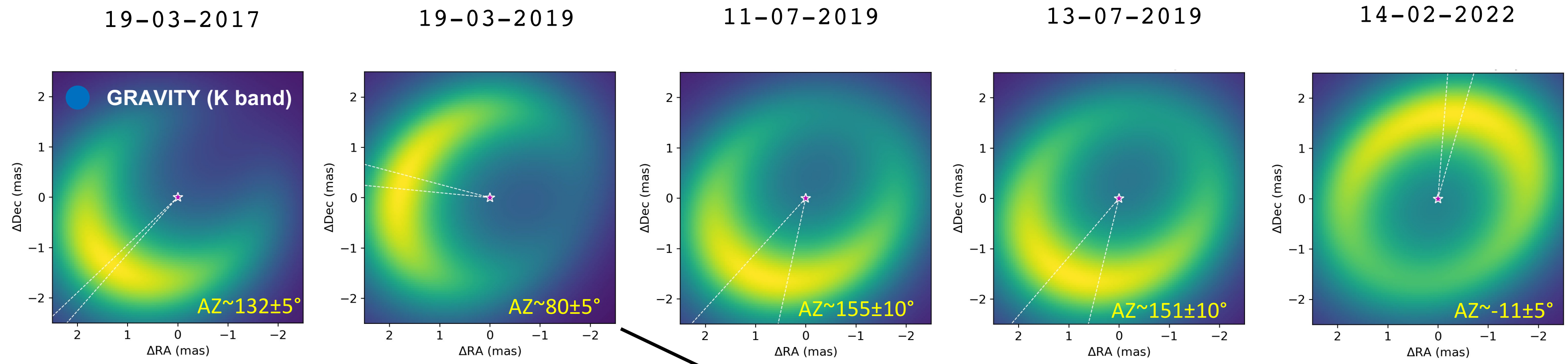
- Signature in the **closure phase** signal



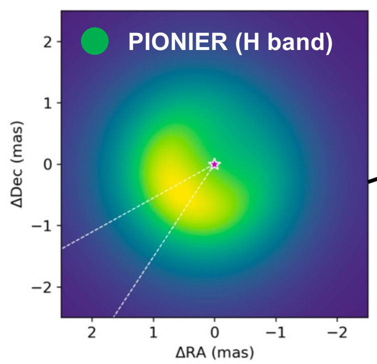
[Gravity Coll.: Ganci, Labadie+2024]

Orbital motion in the inner disk

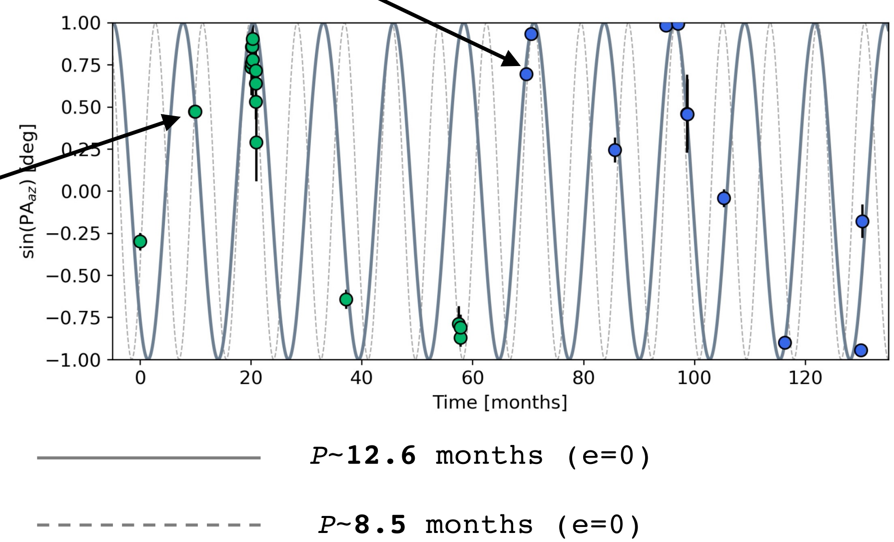
11-year PIONIER+GRAVITY campaign on the ~0.2 Myr Herbig Be star HD98922



R_{dust} ~ 1.4 au



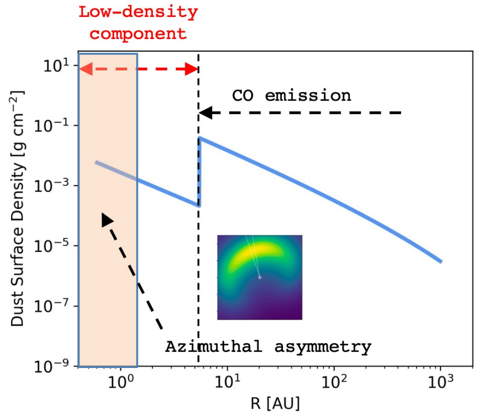
R_{dust} ~ 0.7 au



- With M_{*} = 6 $M_{\odot}$, $T_{Kepl.}$(1.4 au) ~8.5 months and $T_{Kepl.}$(0.7au) ~ 3 months
- **Sub-Keplerian** orbital motion?
- Motion in **HD190073** twice as slow as Keplerian rotation (Ibrahim+2023)

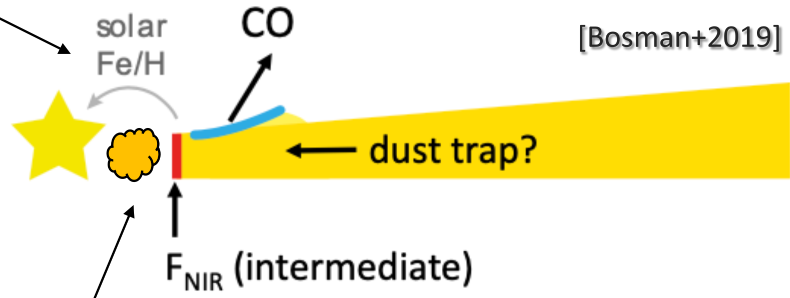
[Gravity Coll.: Ganci, Labadie+2024]

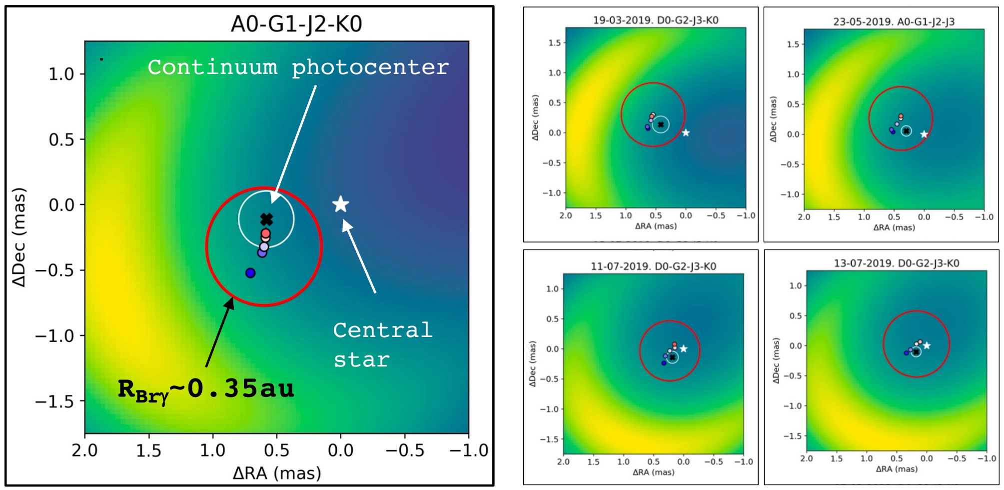
A near-IR view of HD98922's inner disk

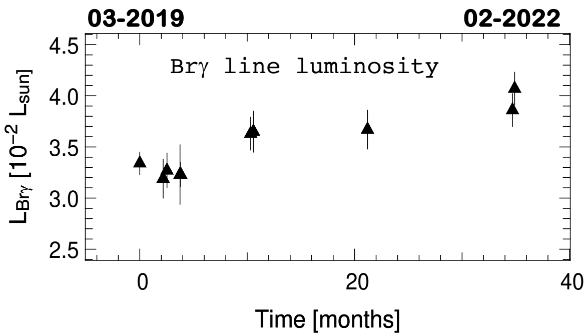


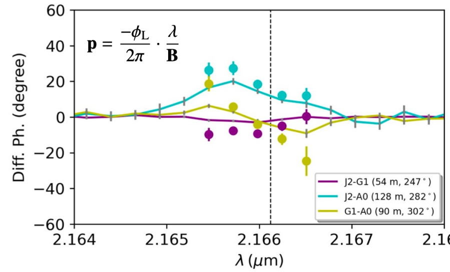
group II disks:

no/small cavities
flat + substructures (common)







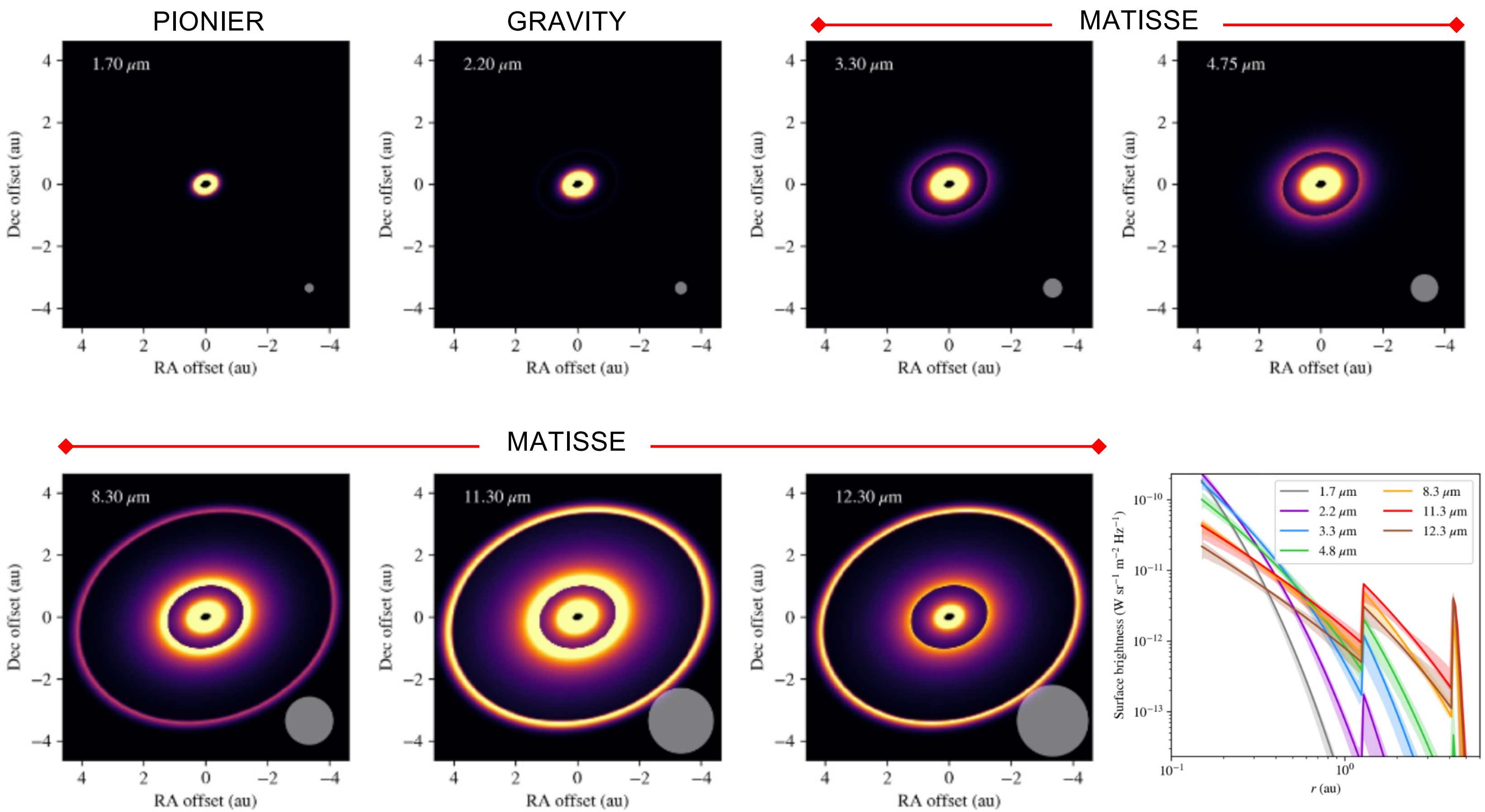


- **Very low-mass companion to explain the Brγ-line properties?**
- **Assymetric disk wind extending from ~0.1 to ~1au?**

[Gravity Coll.: Ganci, Labadie+2024]

Multi-ring inner disk in HD144432

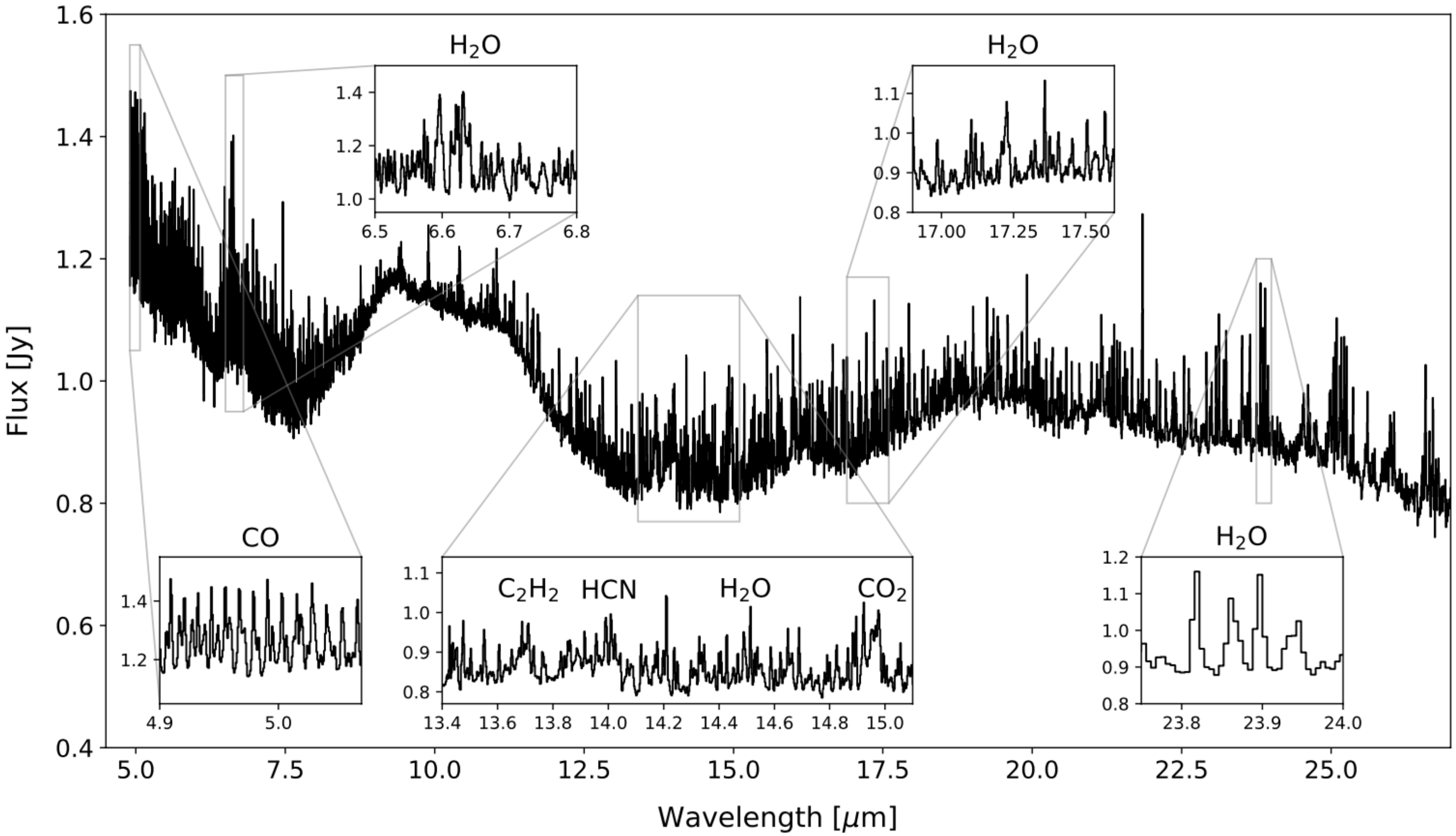
- ***A multi-ring iron-rich disk in HD144432 revealed by PIONIER, GRAVITY and MATISSE***



[Varga, MATISSE/GRAVITY coll. +2024]

Multi-instrument campaigns

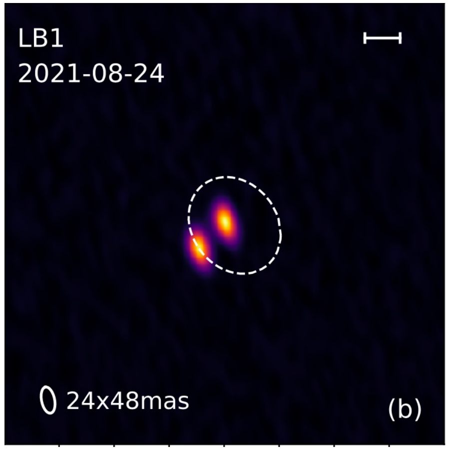
- ***Disks properties in the DF Tau close binary system with JWST/MIRI, ALMA, GRAVITY and IRTF-iSHELL***

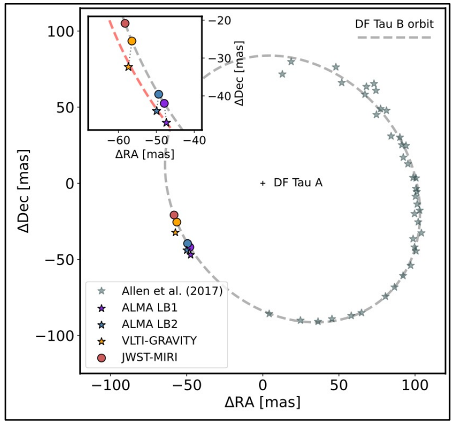


[Grant+2024]

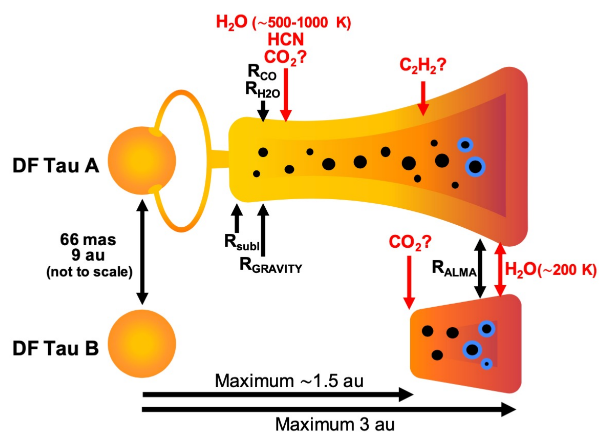
Multi-instrument campaigns

- ***Disks properties in the DF Tau close binary system with JWST/MIRI, ALMA, GRAVITY and IRTF-iSHELL***





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^2_r	8.38	5.05



[Grant+2024]

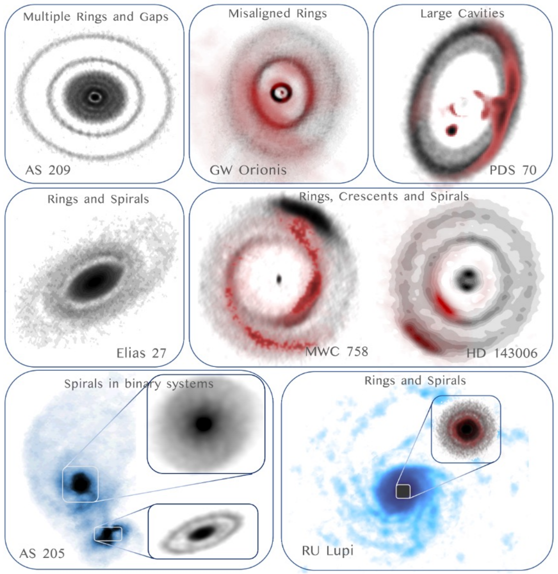
Final word

Witnessing planet formation in disks

Disk mineralogy and chemistry

Star/disk interactions

Disk structures "at all scales" and variability



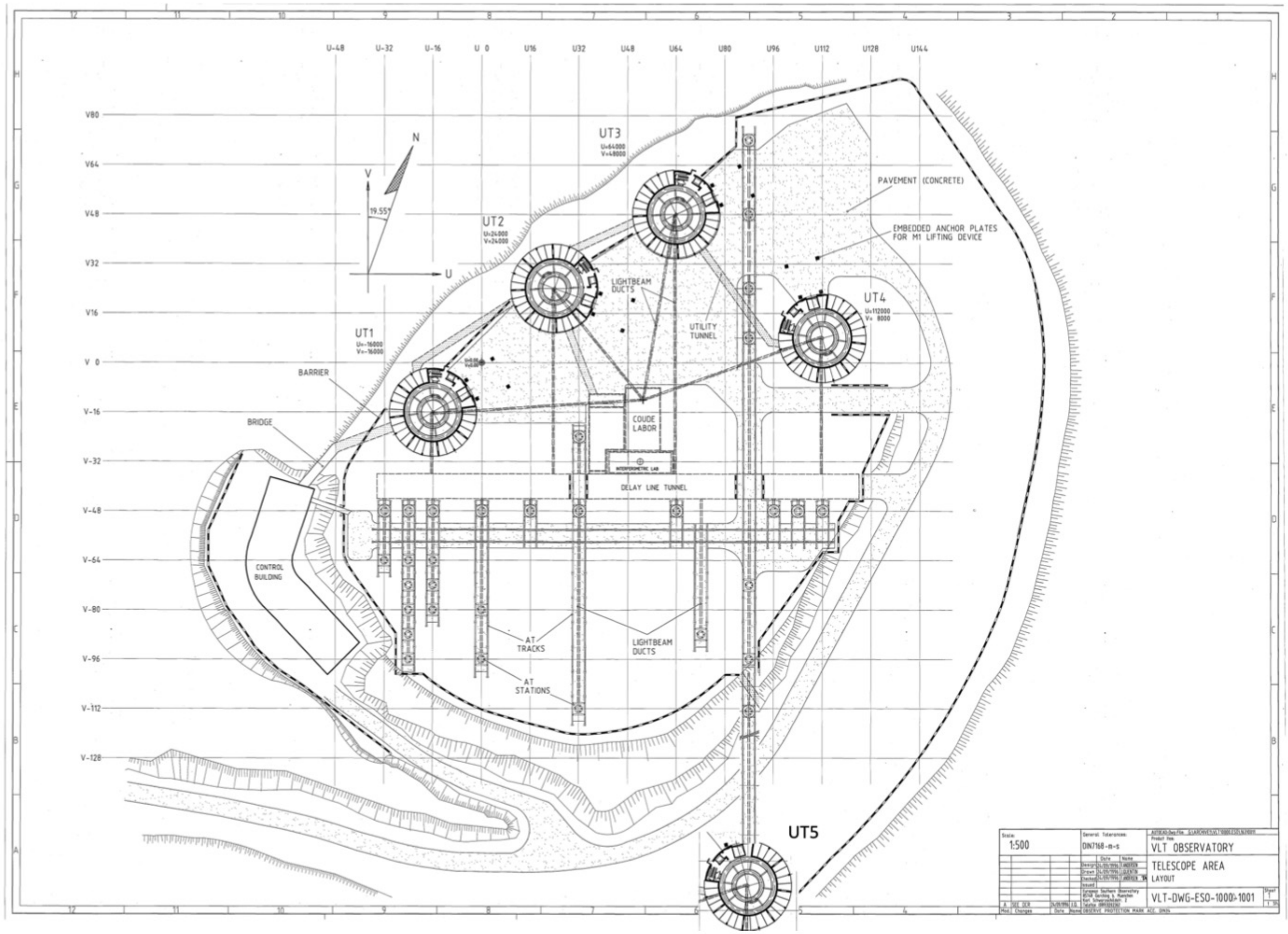
[Bae+2023]

Influence of the environment

Disk evolutionary phases

Disks identification and classification

Towards km-baselines



[Lacour+2024]