Constraining the dust physics in the innermost regions of protoplanetary disks

a radiative transfer modelling approach to large interferometric surveys

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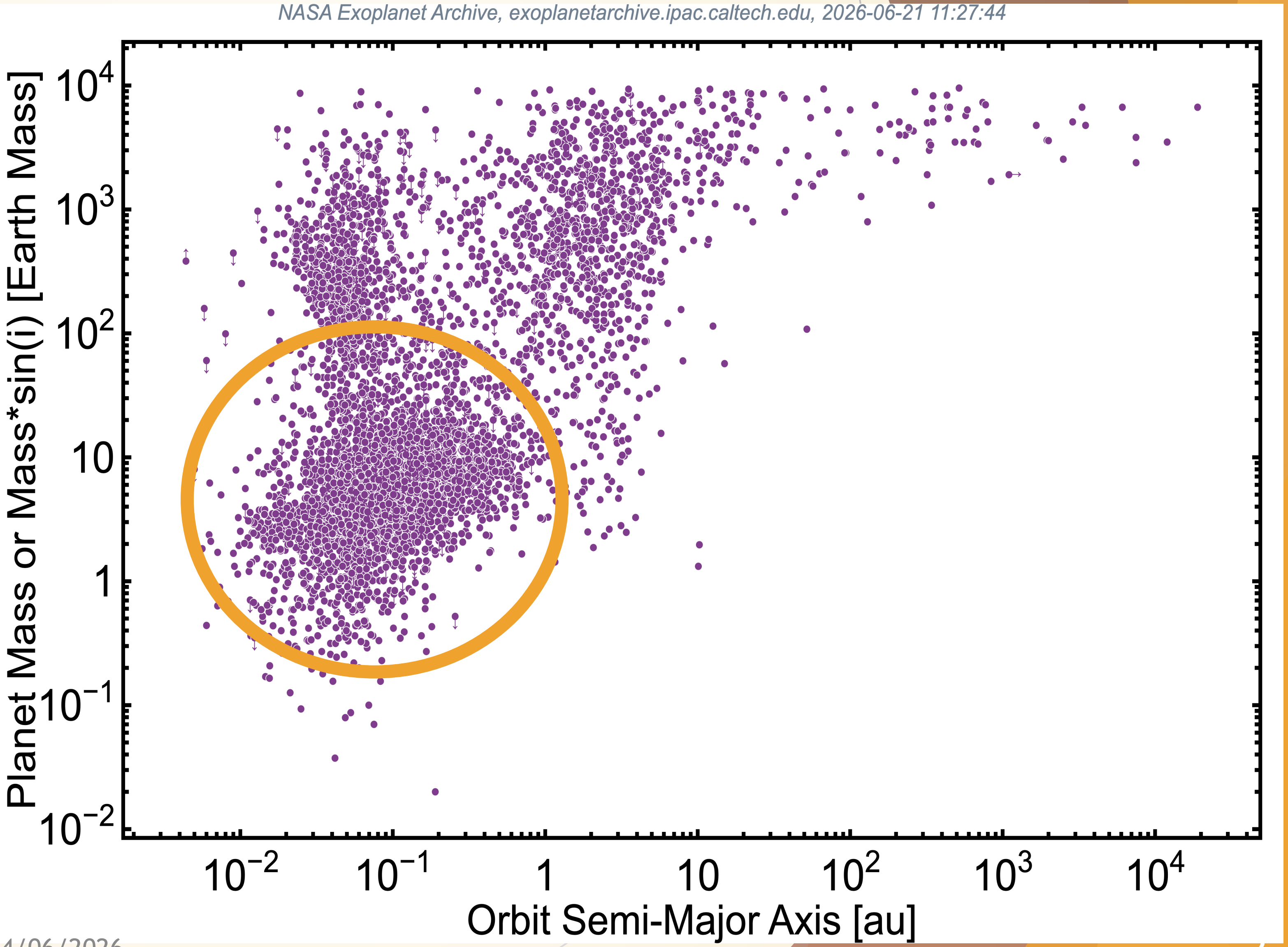
The innermost regions of protoplanetary disks

- Most commonly detected exoplanet population:
  super-Earths & mini-Neptunes between 0.01 and 1 au



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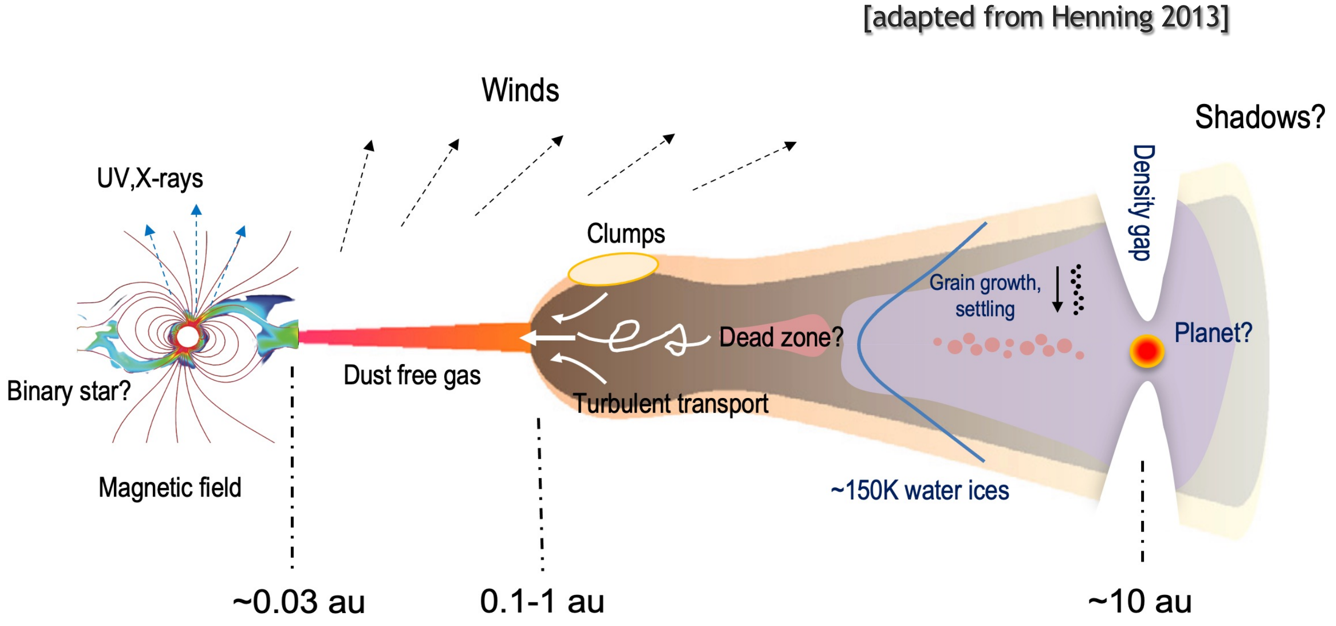
- Location of the **inner edge of the dusty disk**, truncated by **sublimation** (~1500 K)
  - peak dust density
  - complex processes: instabilities (MRI, turbulence)



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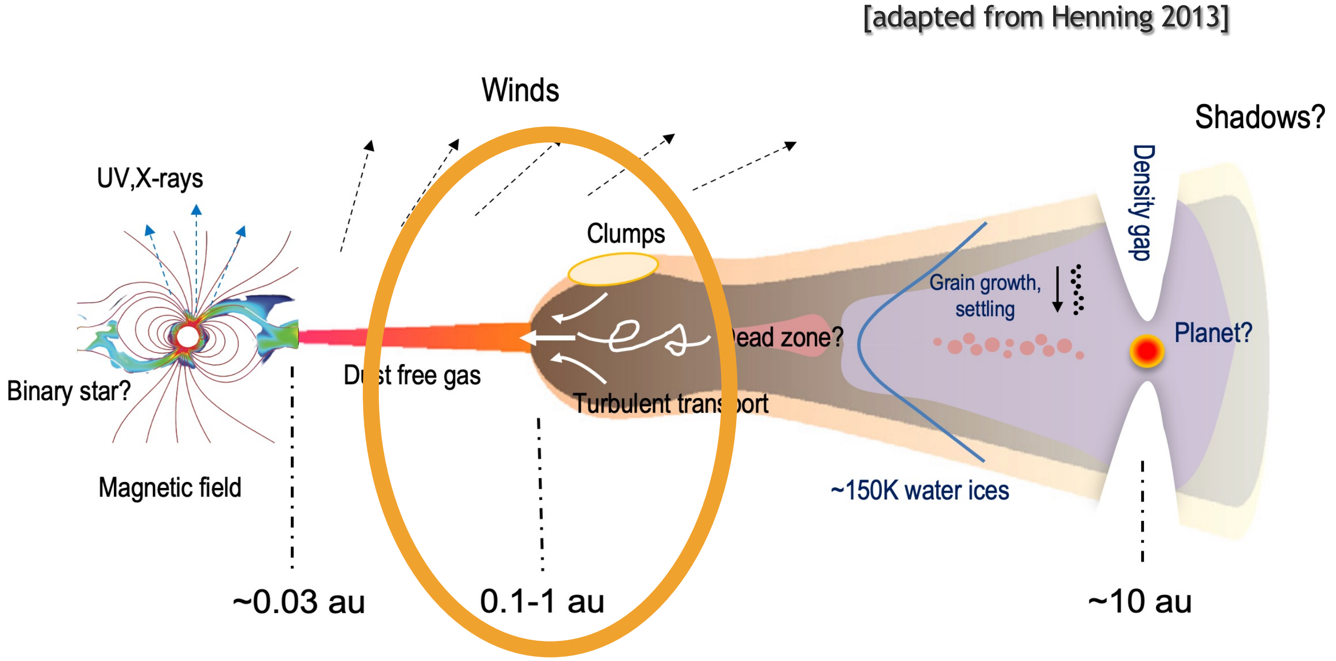

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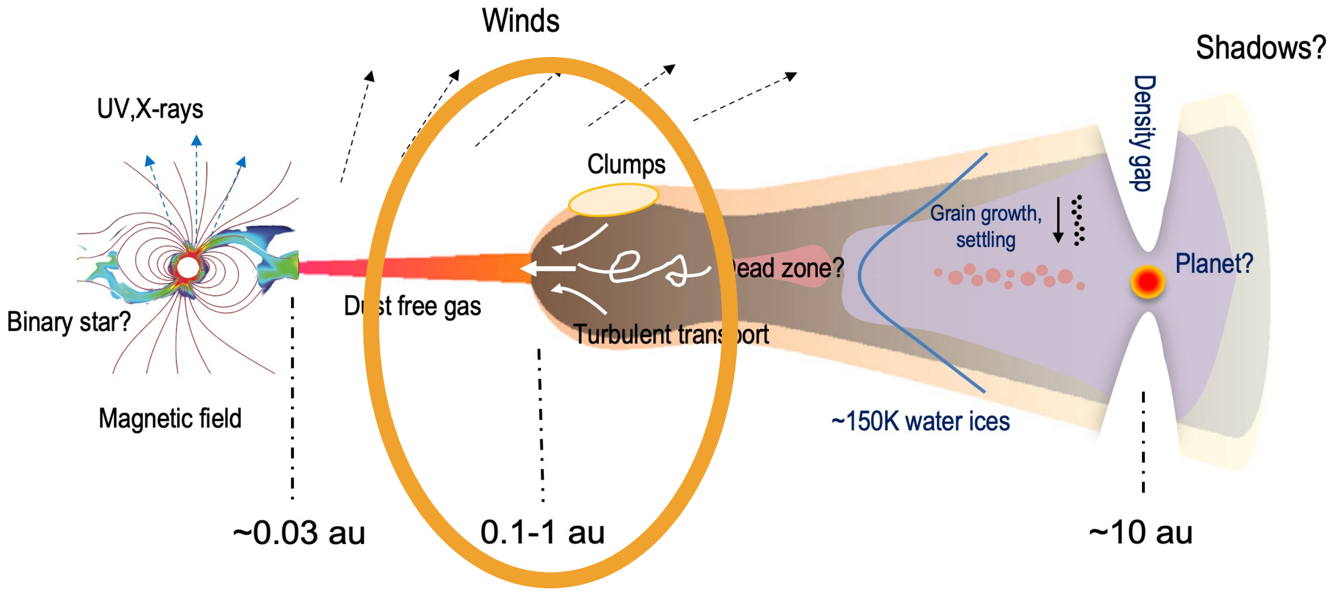
- Optical interferometry:
  - **sizes, widths, fluxes, asymmetries** of the inner rim region



1-10 mas @ 100 pc: only accessible to optical interferometry

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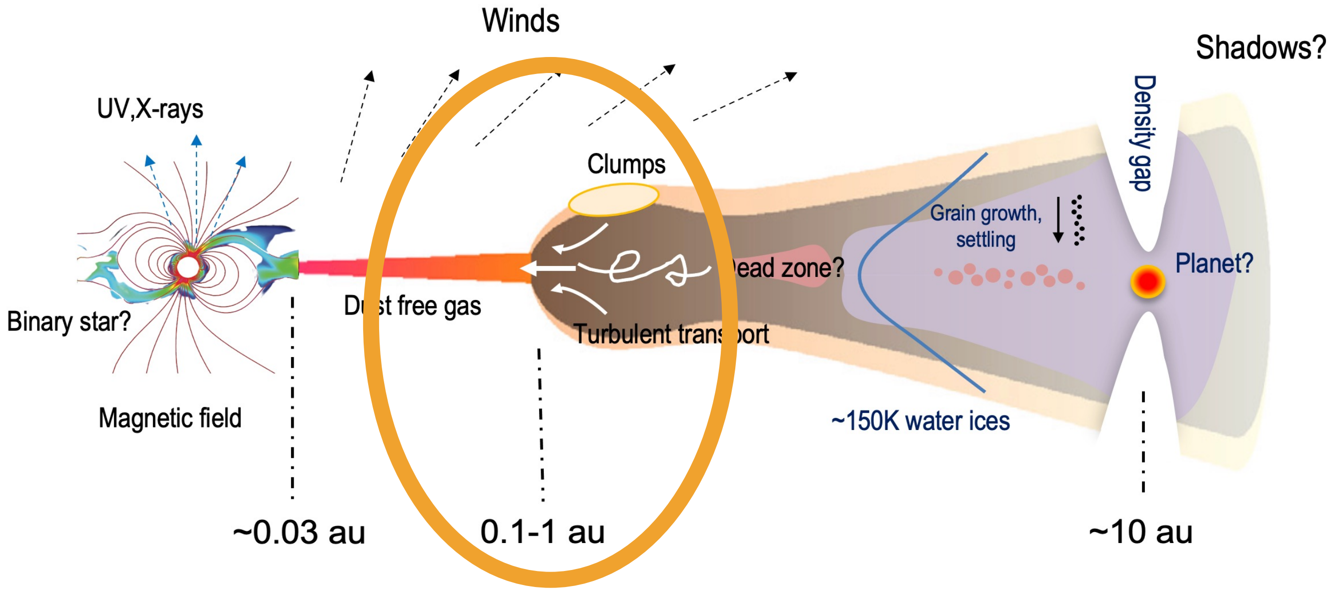
[adapted from Henning 2013]



Can we constrain dust composition from observations of the inner rim?

How common are dust sub-structures in the inner regions?

Observing and modeling the inner rim

- First observations: IOTA (Millan-Gabet+99)
- Sizes compared to theoretical approximations: passive irradiated disk, backwarming…

Passive irradiated disk

$$R(\epsilon) = \left(\frac{L_\star}{16\pi\epsilon\sigma T_{\rm g}^4} \right)^{1/2}$$

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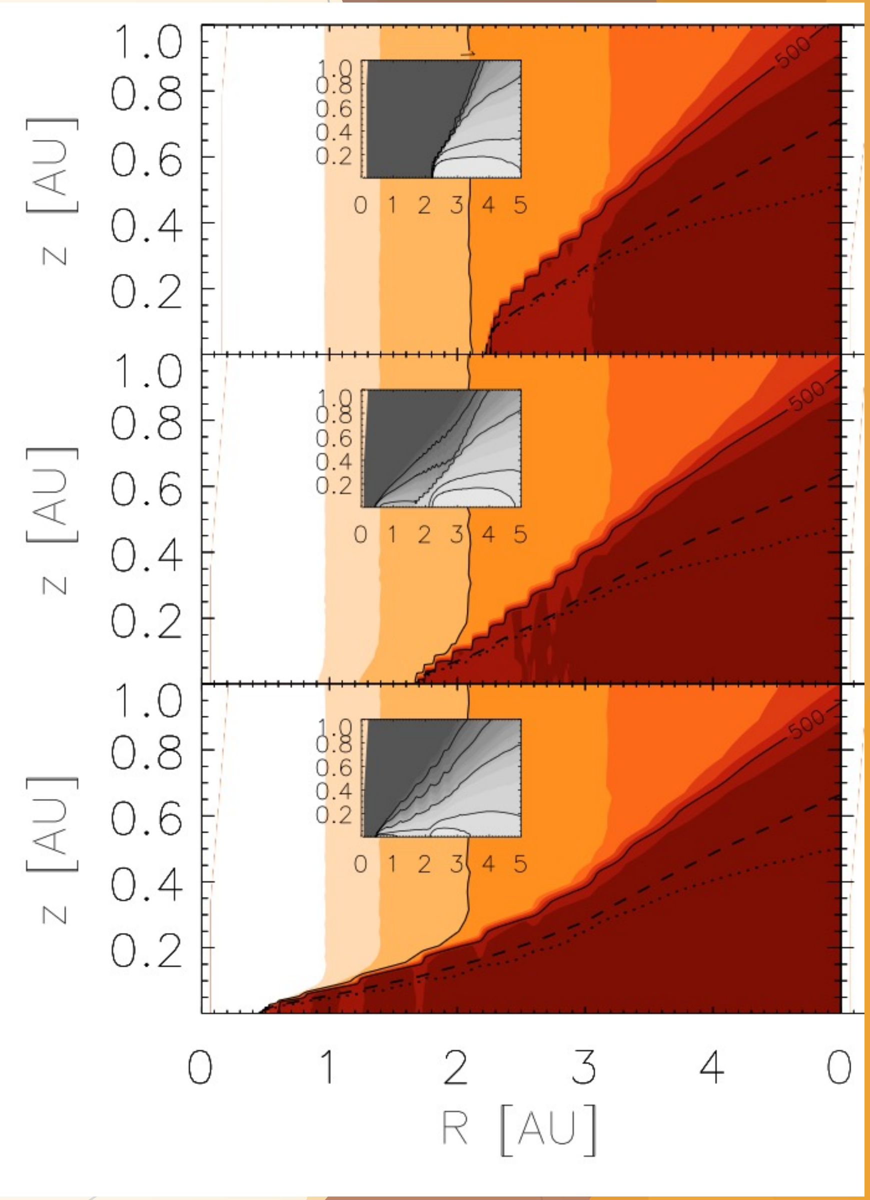
- *Kama+09, Klarmann+18*: 2D radiative transfer with self-consistent treatment of dust sublimation

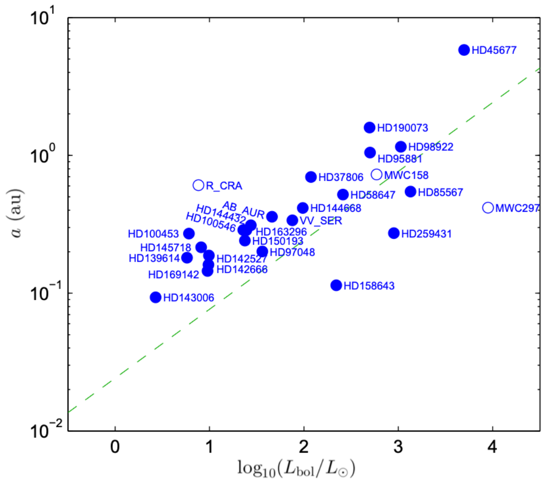


Kama+09

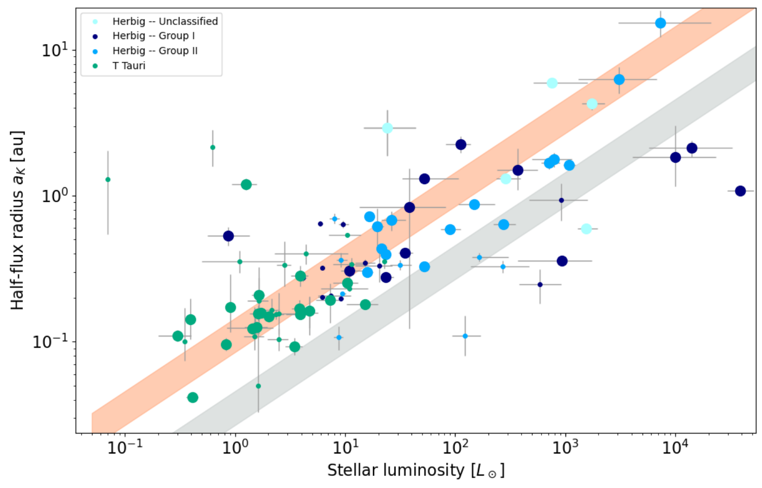
Observing and modeling the inner rim

- First observations: IOTA (Millan-Gabet+99)
- Sizes compared to theoretical approximations: passive irradiated disk, backwarming…
- *Kama+09, Klarmann+18*: 2D radiative transfer with self-consistent treatment of dust sublimation
- We now have large VLTI surveys of ~120 stars from 1 to 10 µm, partially overlapping
    - Need for a **grid of self-consistent models** with a large range of **stellar luminosities**, **spectral bands, dust compositions**, and **inclinations**

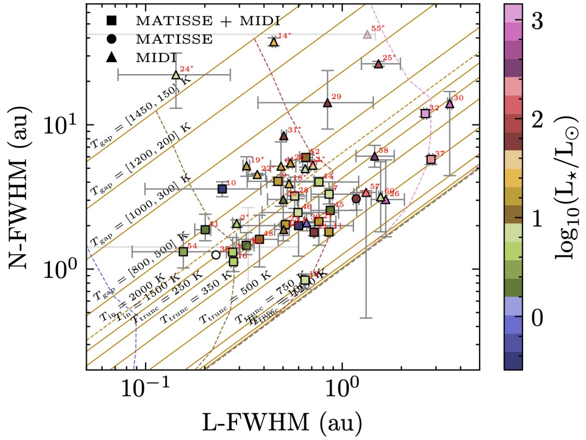
PIONIER, H band
51 Herbig stars
Lazareff+17



GRAVITY, K band
92 Herbig & T Tauri
GRAVITY Coll.+19,21
GRAVITY Coll. in prep.



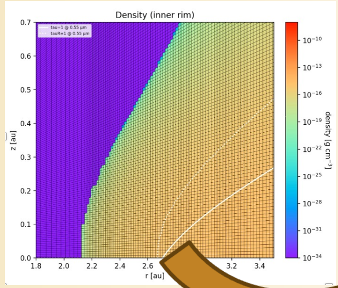
MATISSE, L & N bands
60 Herbig & T Tauri
Scheuck in prep.
van Hasteere in prep.



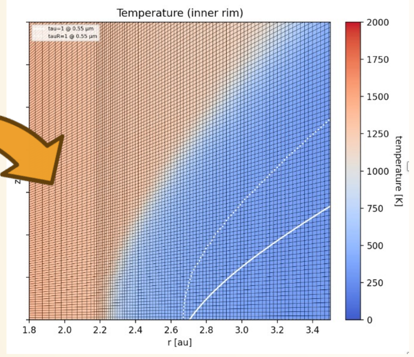
From self-consistent models to visibilities

Radiative transfer with MCMax
(Min+09, Kama+09, Klarmann+18)

initial density map



temperature map



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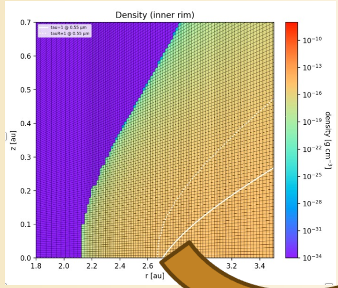

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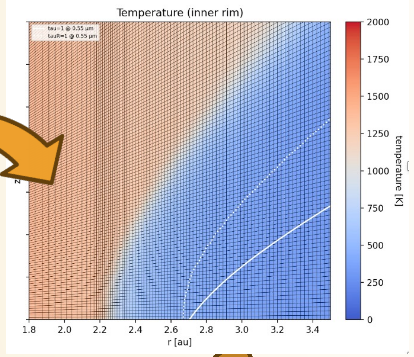

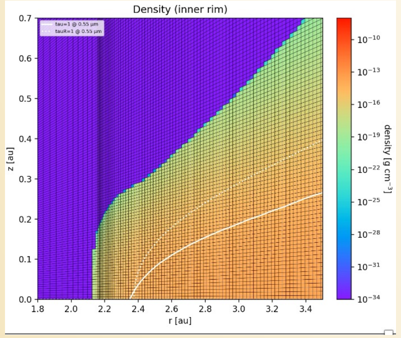

new density map

Dust sublimation
Vertical hydrostatic equilibrium
Grid refinement

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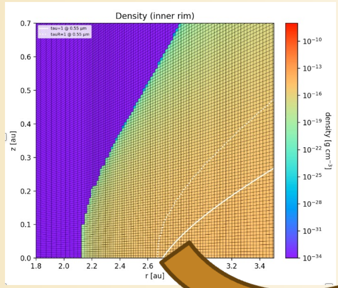

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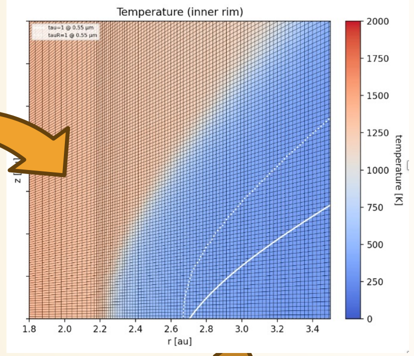
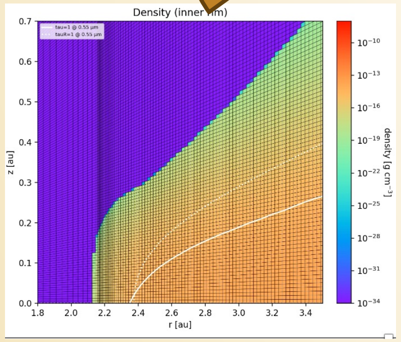


Radiative transfer



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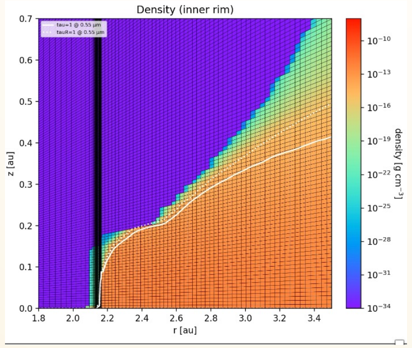
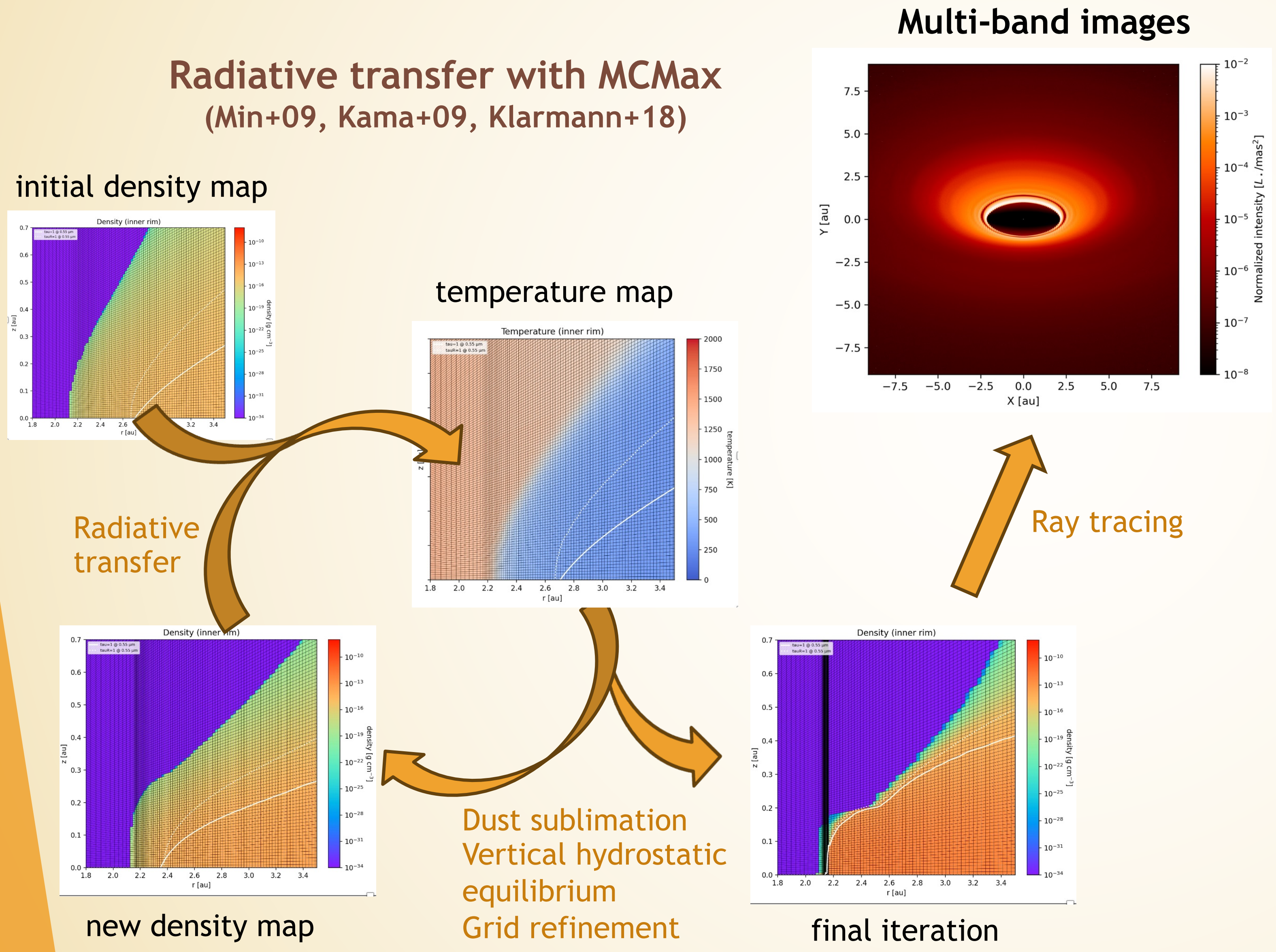


final iteration

From self-consistent models to visibilities



From self-consistent models to visibilities

Interferometric observables

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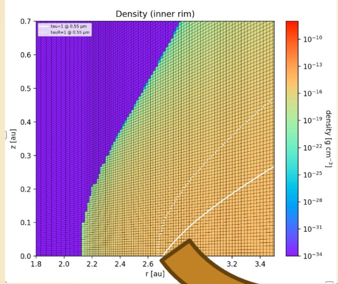
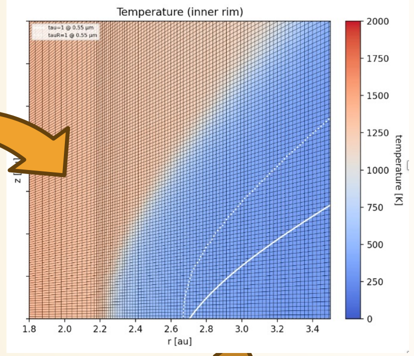
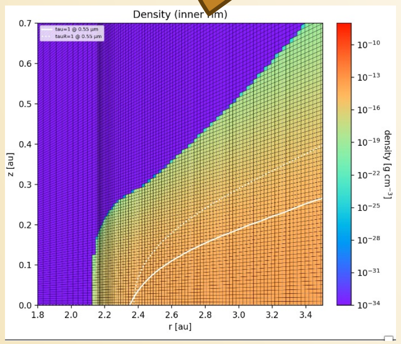


temperature map



Radiative transfer



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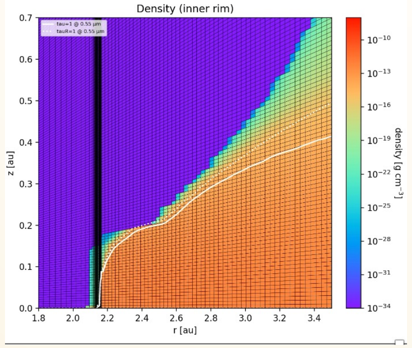
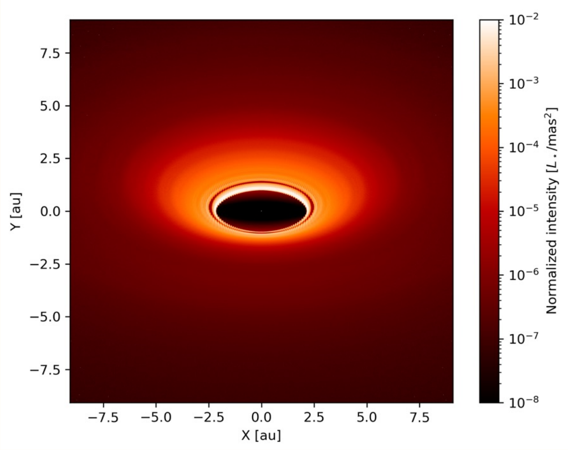


final iteration

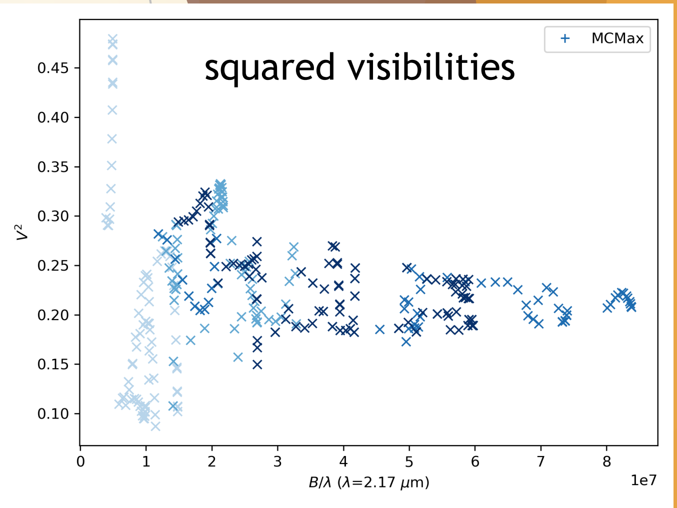
Ray tracing

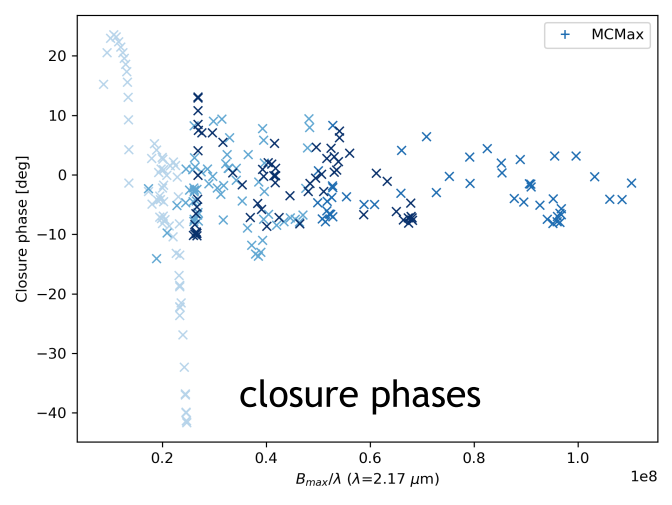
Multi-band images



Aspro2
(JMMC)

VLTI simulation





Available for: **Spectral bands:** H, K, L, N
Inclinations: 0 to 72°

Model grid

K-band, face-on disks

0.23 $L_\odot$ | **1.25 $L_\odot$** | **8 $L_\odot$** | **47 $L_\odot$** | **275 $L_\odot$** | **1550 $L_\odot$**

Olivine: 0.1 μm

0.1

Olivine: 0.1 μm (99%)
+ Iron: 0.1 μm (1%)

0.1 | 0.1

Olivine: 0.1 μm (80%)
+ 100 μm (20%)

0.1 | 100

Olivine: interstellar size distribution (MRN)

0.1 | 1 | 10 | 100 | 1000

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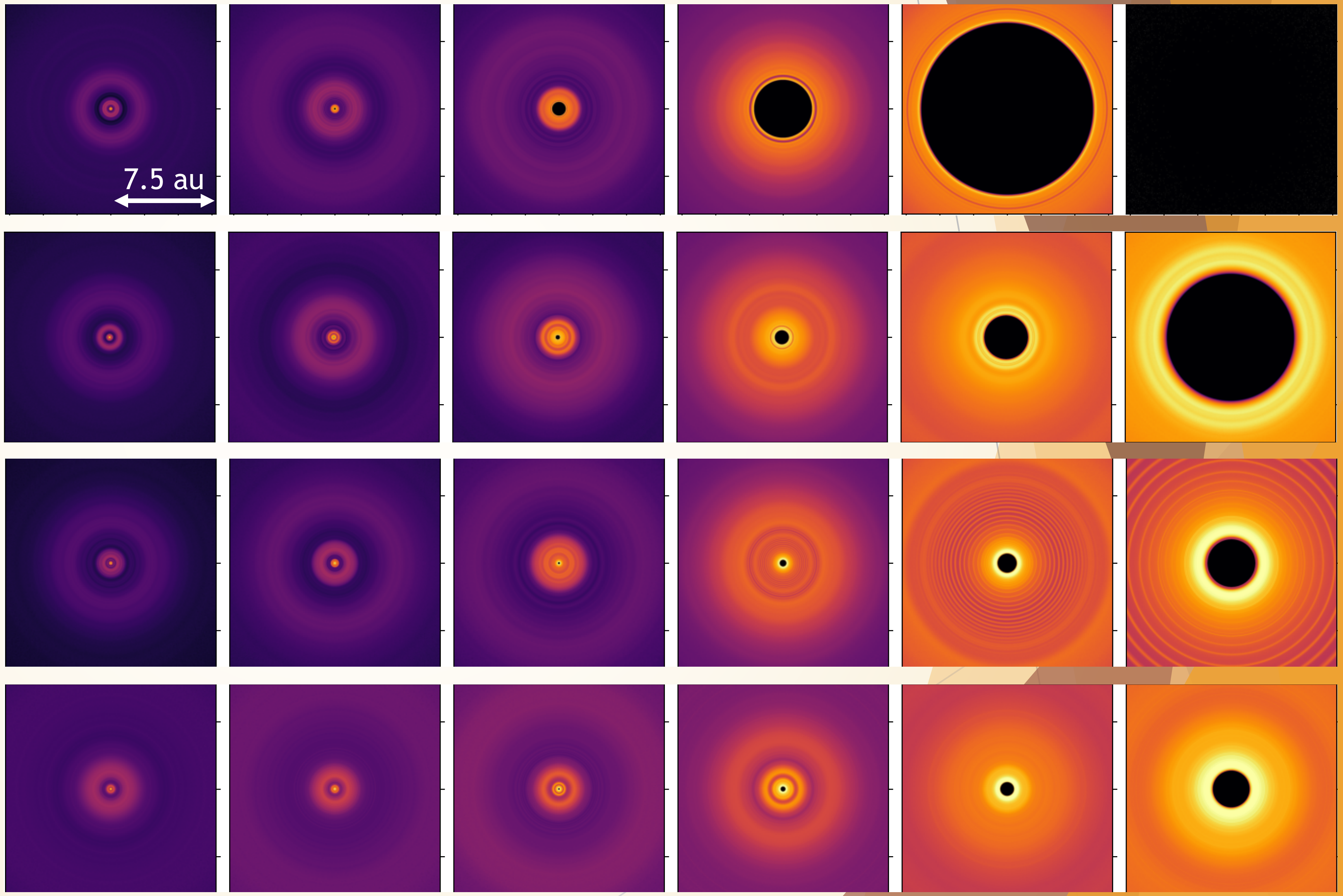

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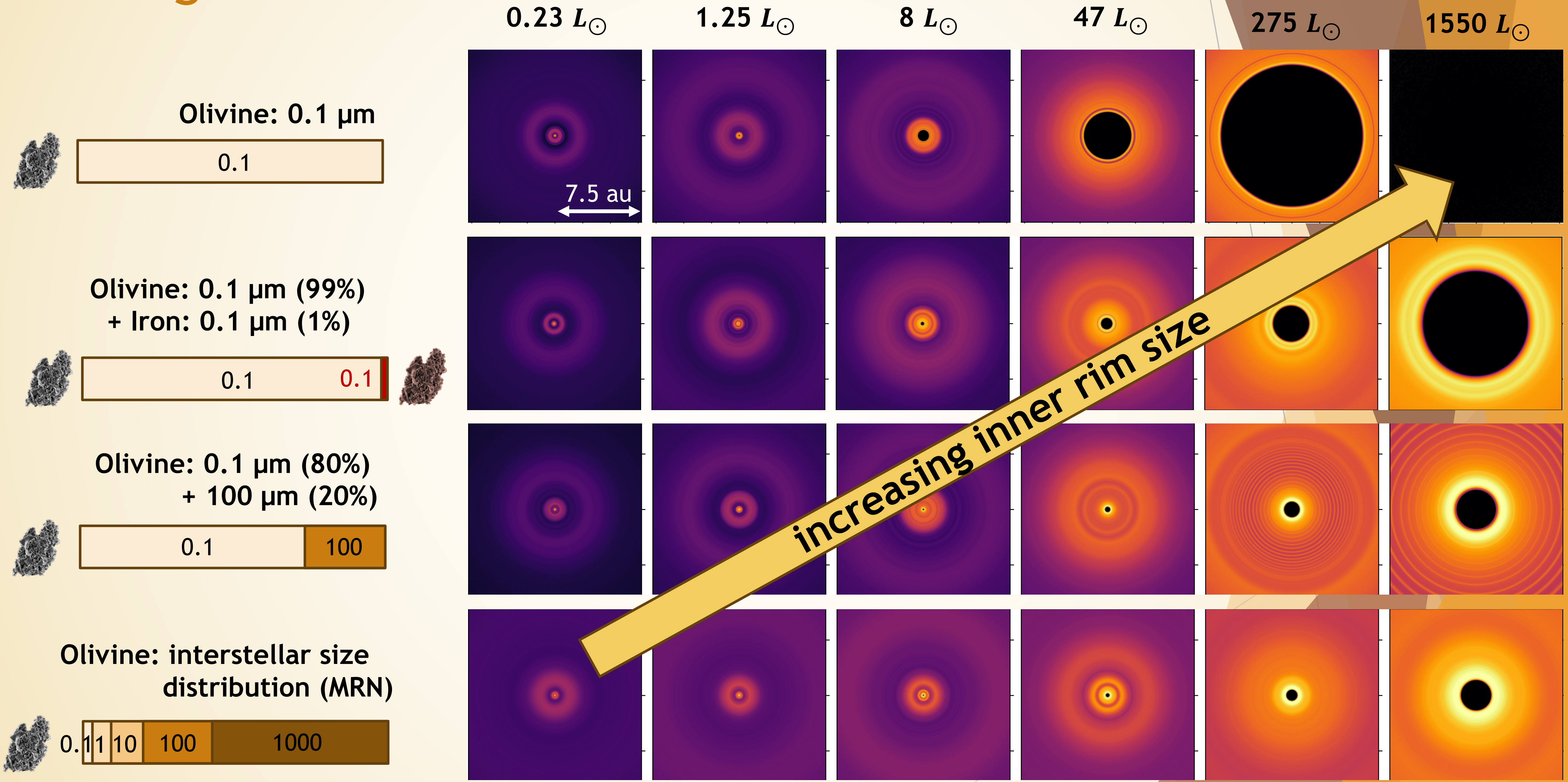
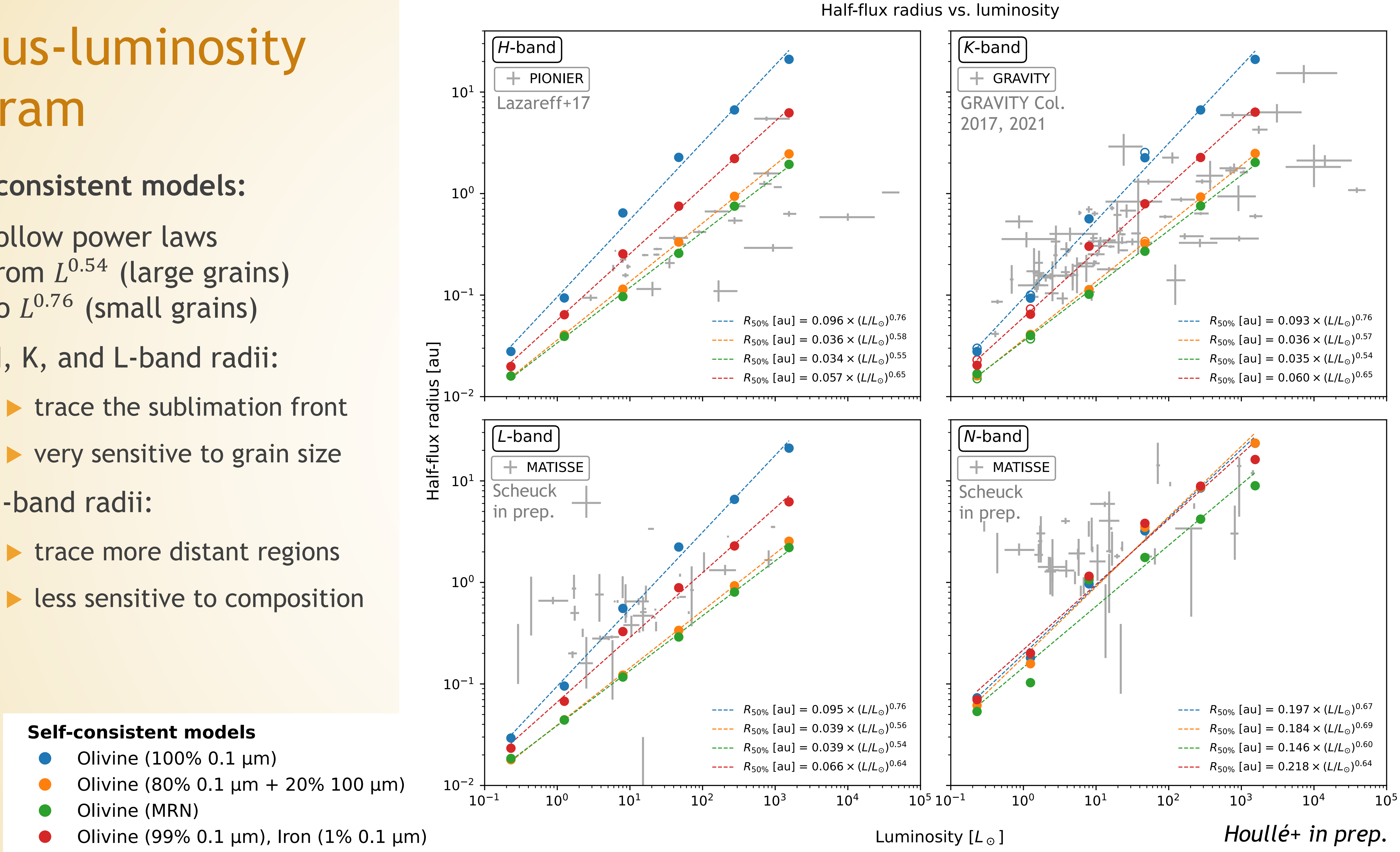


Radius-luminosity diagram

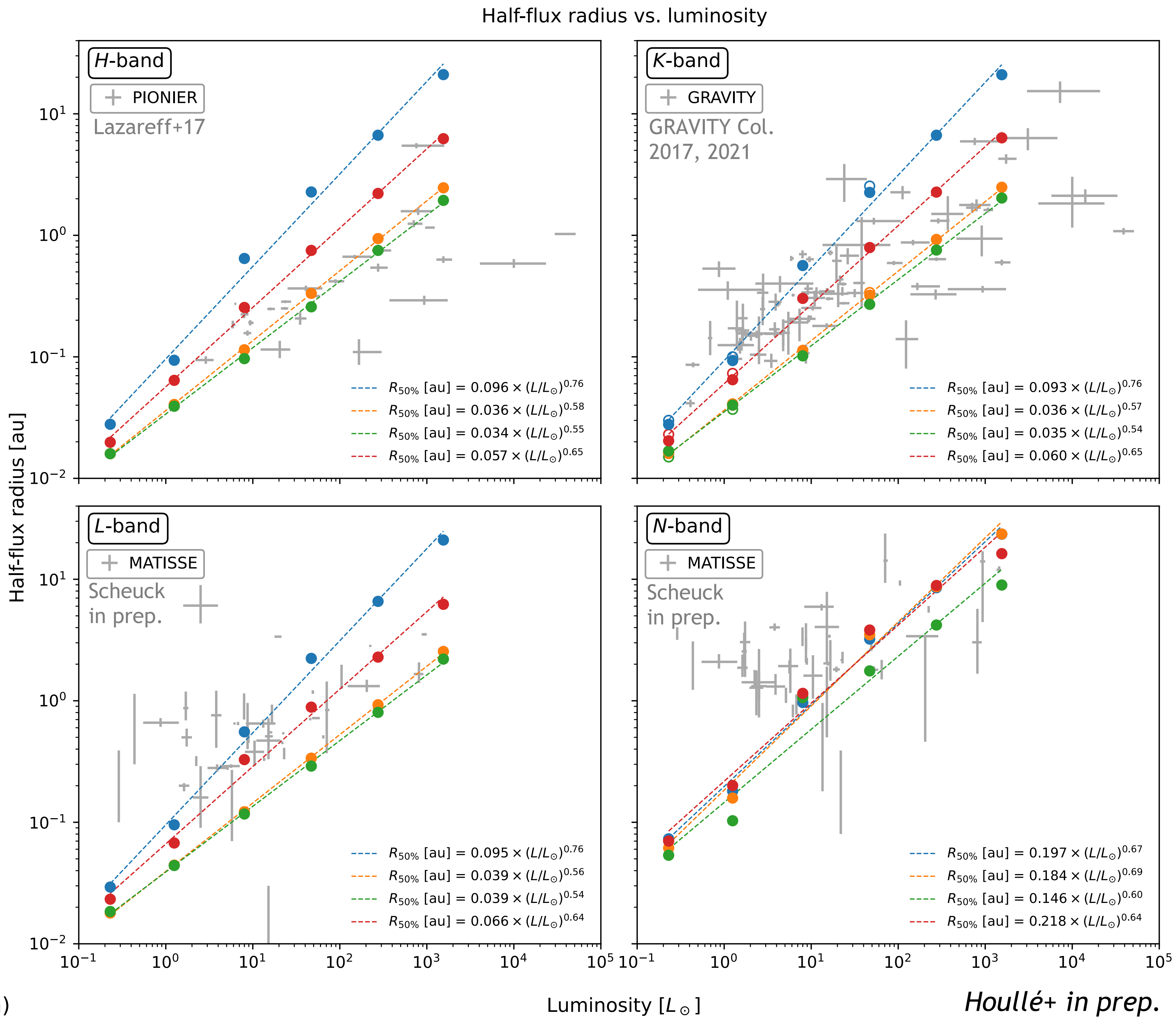
- **Self-consistent models:**
  - follow power laws from $L^{0.54}$ (large grains) to $L^{0.76}$ (small grains)
  - H, K, and L-band radii:
    - trace the sublimation front
    - very sensitive to grain size
  - N-band radii:
    - trace more distant regions
    - less sensitive to composition



Houllé+ in prep.

Radius-luminosity diagram

- **Data-model comparison:**
  - Dispersion of K-band radii well reproduced for intermediate-mass stars
  - Undersized outliers for massive Herbig stars (H, K)
  - Oversized outliers for T Tauri stars (K, L, N)



Self-consistent models

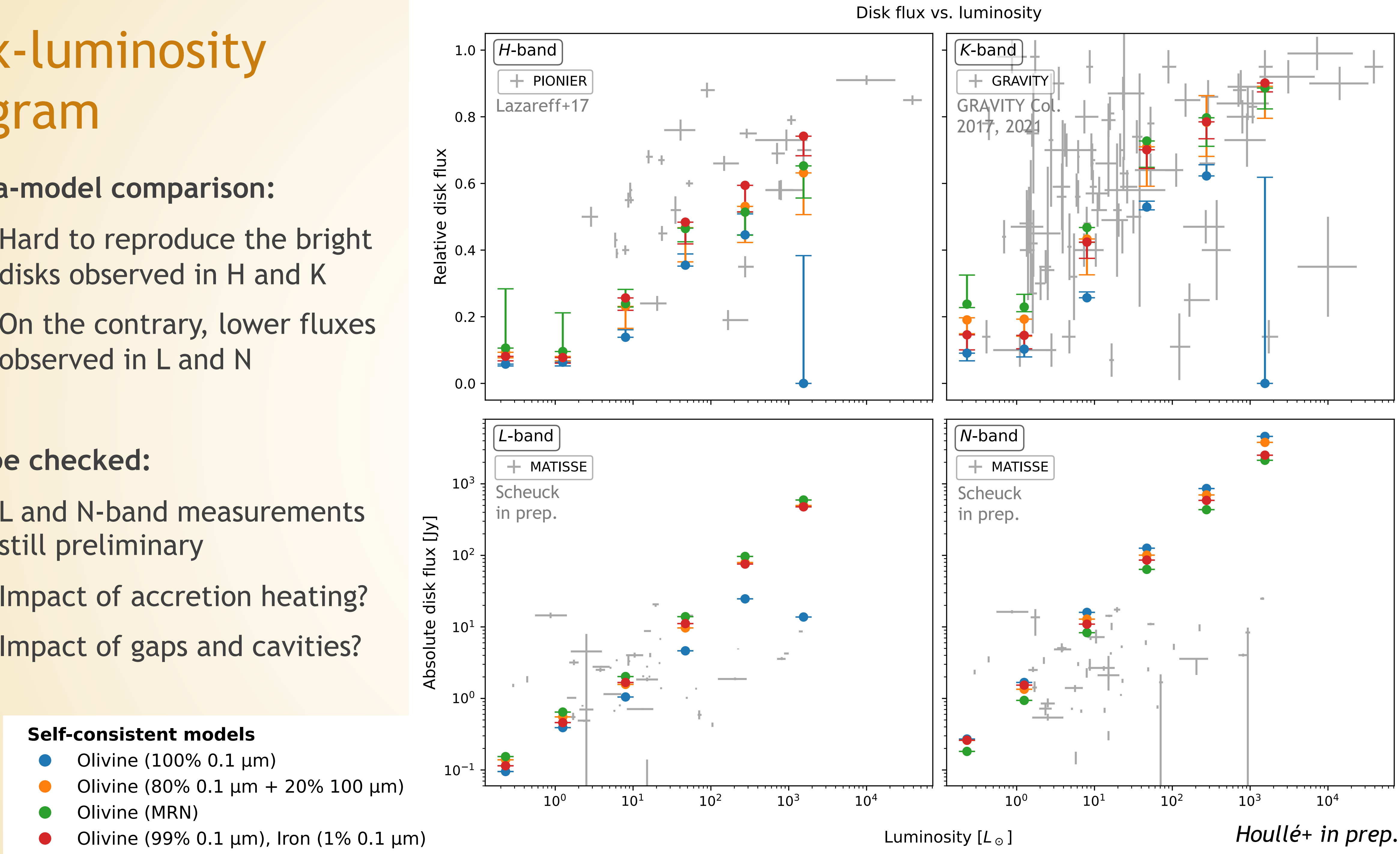
- Olivine (100% 0.1 μm)
- Olivine (80% 0.1 μm + 20% 100 μm)
- Olivine (MRN)
- Olivine (99% 0.1 μm), Iron (1% 0.1 μm)

Houllé+ in prep.

Flux-luminosity diagram

- **Data-model comparison:**
  - Hard to reproduce the bright disks observed in H and K
  - On the contrary, lower fluxes observed in L and N

- **To be checked:**
  - L and N-band measurements still preliminary
  - Impact of accretion heating?
  - Impact of gaps and cavities?



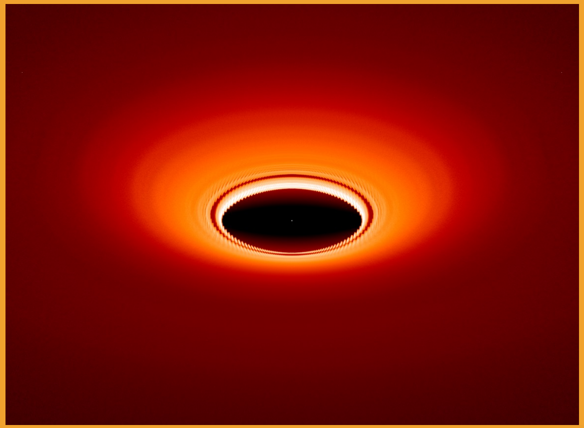
Houllé+ in prep.

Asymmetries in the inner disk

- Non-zero closure phases: non-axisymmetric source
- Can be obtained in two physical ways:

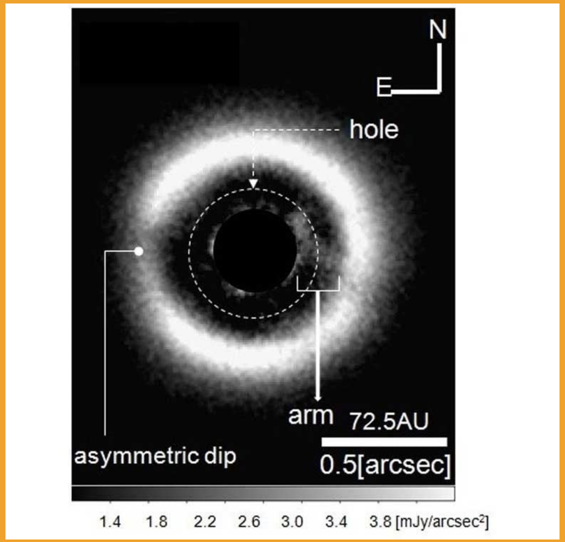
Radiative transfer simulations needed to reject a pure inclination effect

Axisymmetric inclined disk



MCMax model
47 $L_{\odot}$, 0.1 μm grains

Non-axisymmetric disk



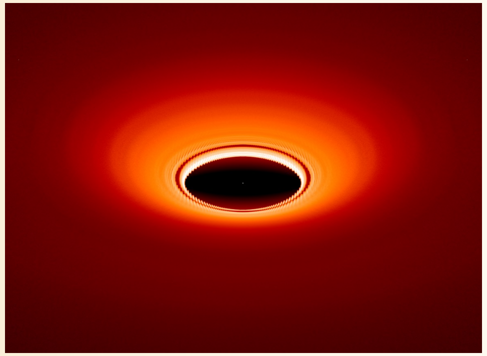
J1604, Mayama+ 2012

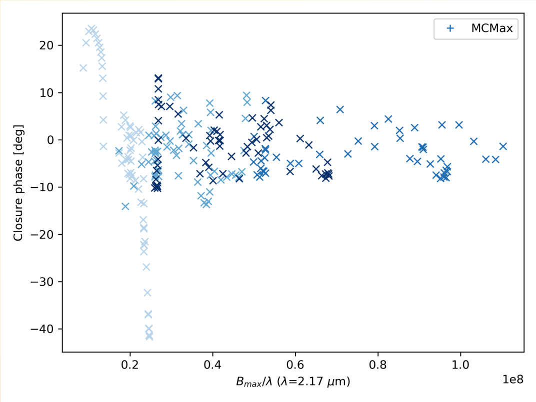
- **Talk by Antonia Drescher (S16):** rotating structures seen in GRAVITY data

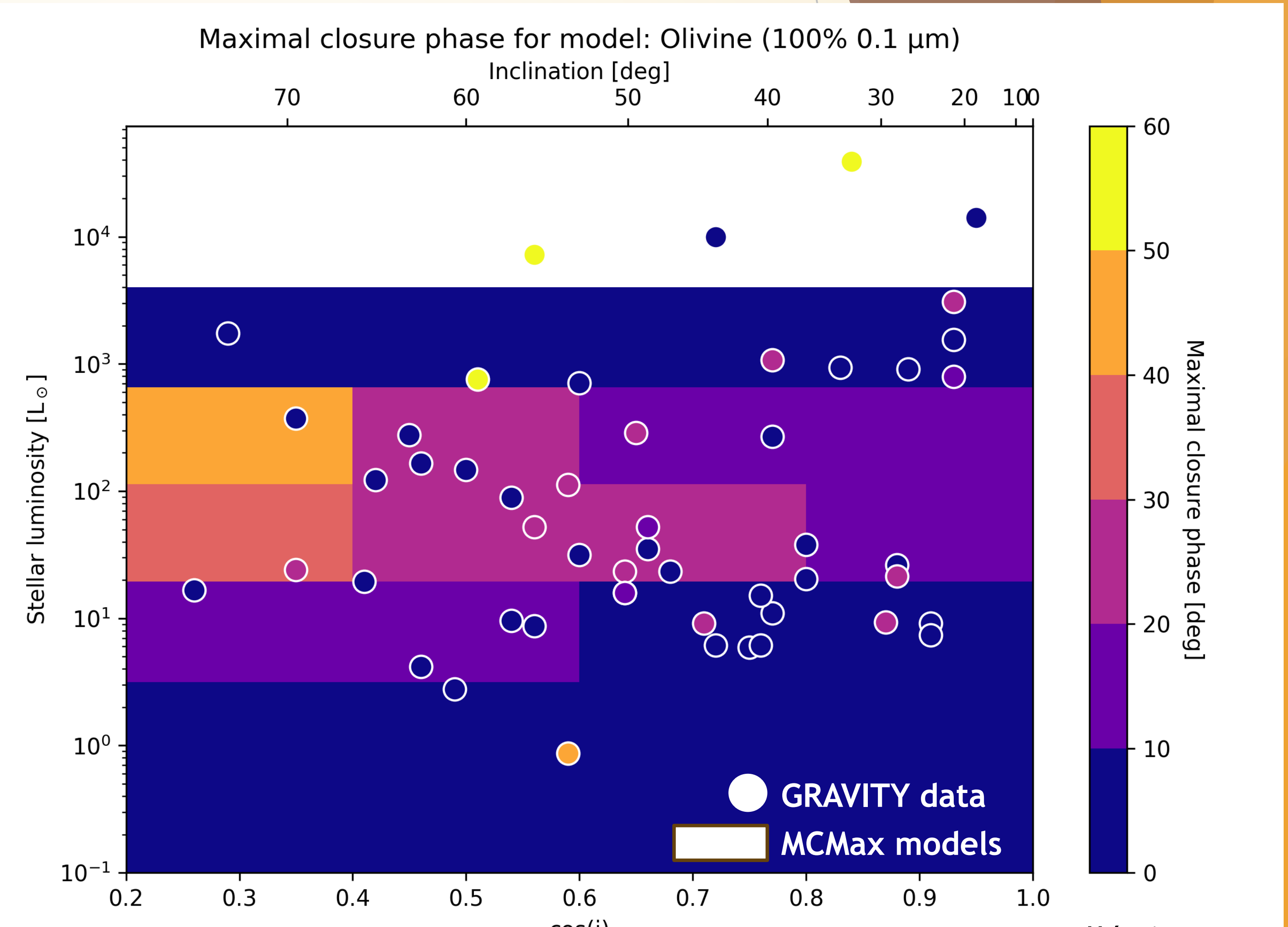
- **Talk by Siméo Evelain (S02):** synthetic interferometric observations of vortices

Maximal closure phase: data vs. model

- Maximal closure phase as function of inclination and stellar luminosity







Houllé+ in prep.

Summary & perspectives

- **Large interferometric surveys** of inner disks now available (1-10 µm: PIONIER, GRAVITY, MATISSE)
- We are creating a large grid of **self-consistent radiative transfer models** of the inner rim
  - Varying dust **grain size** and **species**, stellar **luminosities**, **inclinations**, **spectral bands**
- Explore the compatibility of these models with the available data and the **need for additional complexity: a**ccretion heating, cavities?
- Constraints on the **asymmetry created by inclined disks vs. dust sub-structures**

Fitting rings to simulated visibilities