End of First year Workshop, 10th October, Milan

SUBSTRUCTURES IN PROTOPLANETARY DISCS: HOW MUCH COUPLED ARE DUST AND GAS?

A PROXY FOR THE GAS DISC MASS

Benedetta Veronesi

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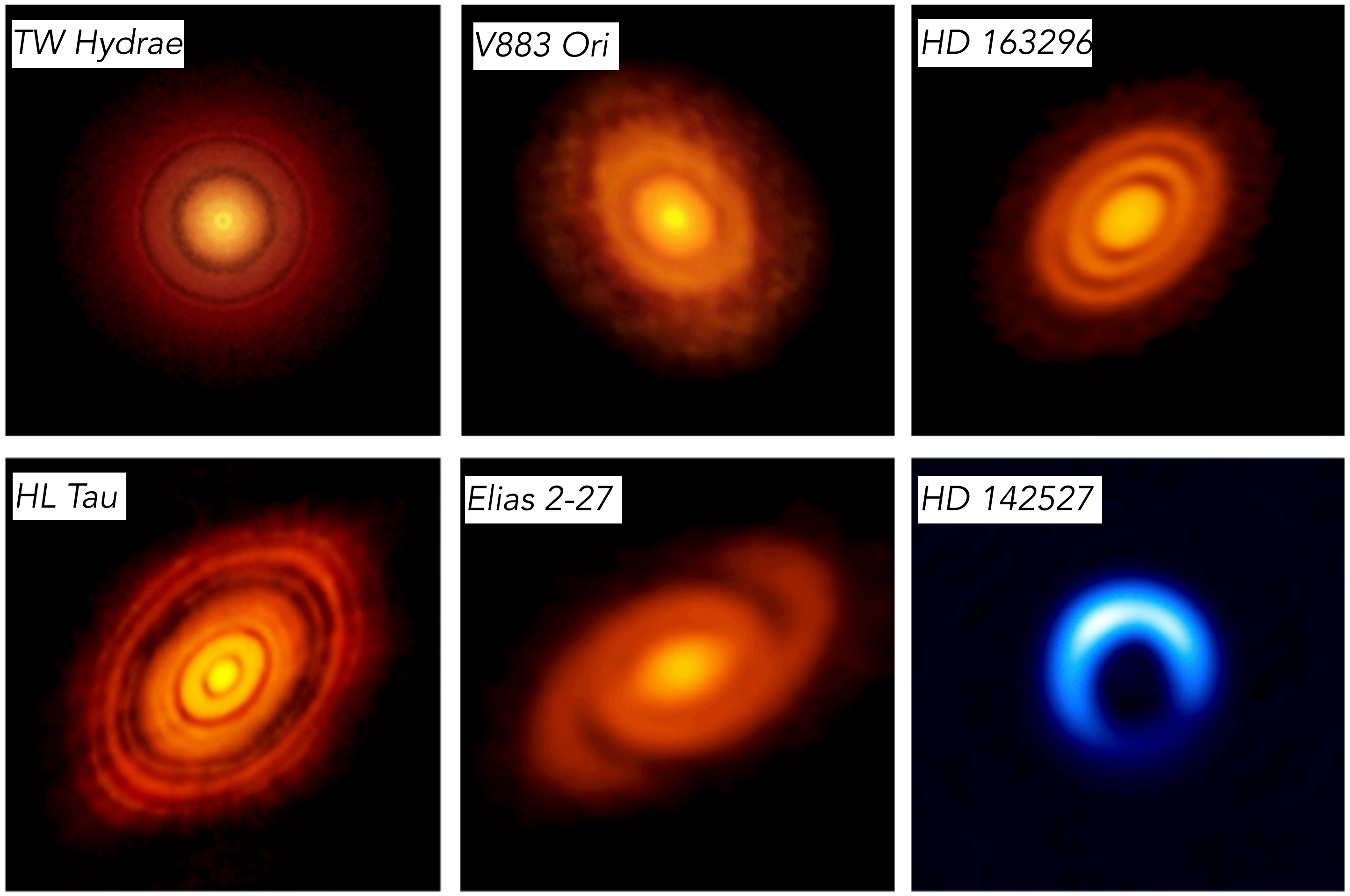
Enrico Ragusa (UniMi, Italy)

Daniel Price (Monash University, Australia)

Monash Centre for Astrophysics

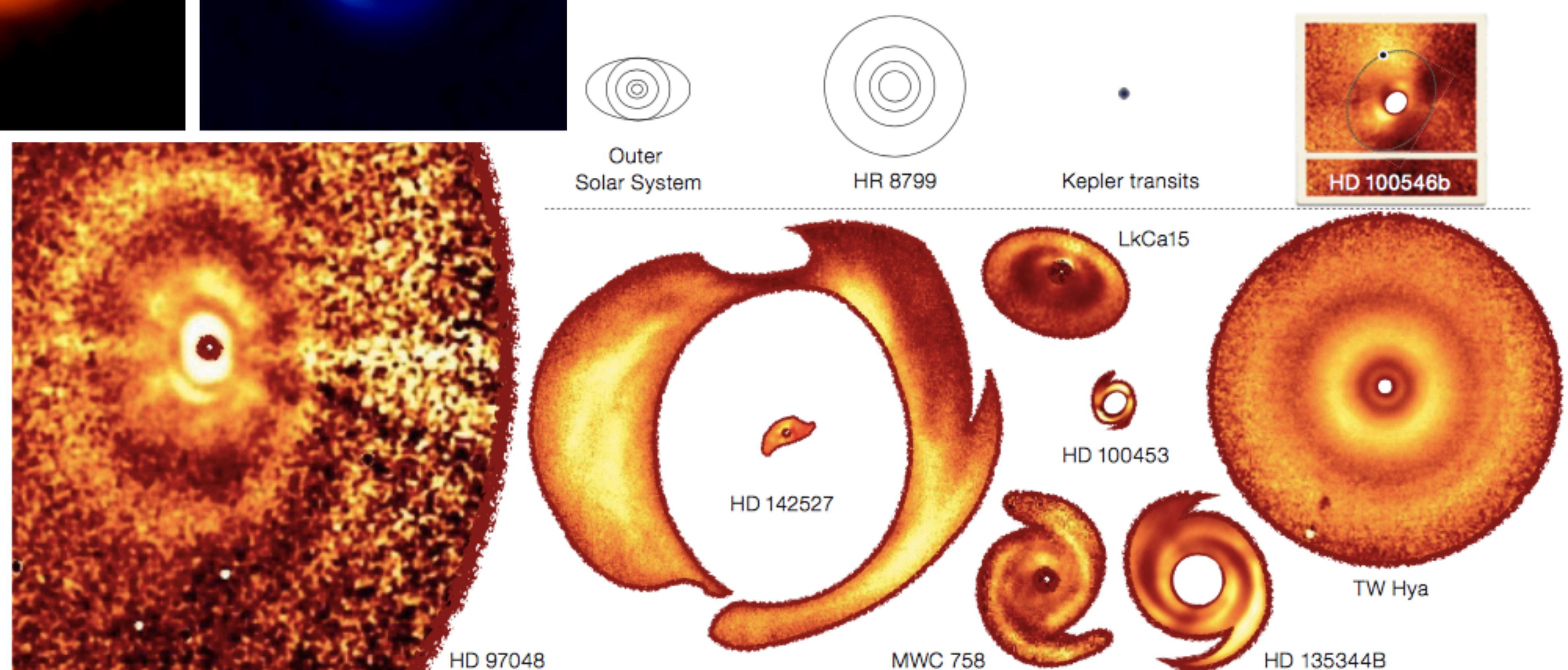
WHAT WE HAVE AND WHAT WE NEED:



- Micrometric dust grains (i.e. scattered light) on the disc SURFACE: **SPHERE**
- Millimetric/sub-millimetric dust grains on the disc MIDPLANE: **ALMA**

Garufi et al. ESO Messenger; **SPHERE**

Andrews; **ALMA** (ESO/NAOJ/NRAO)



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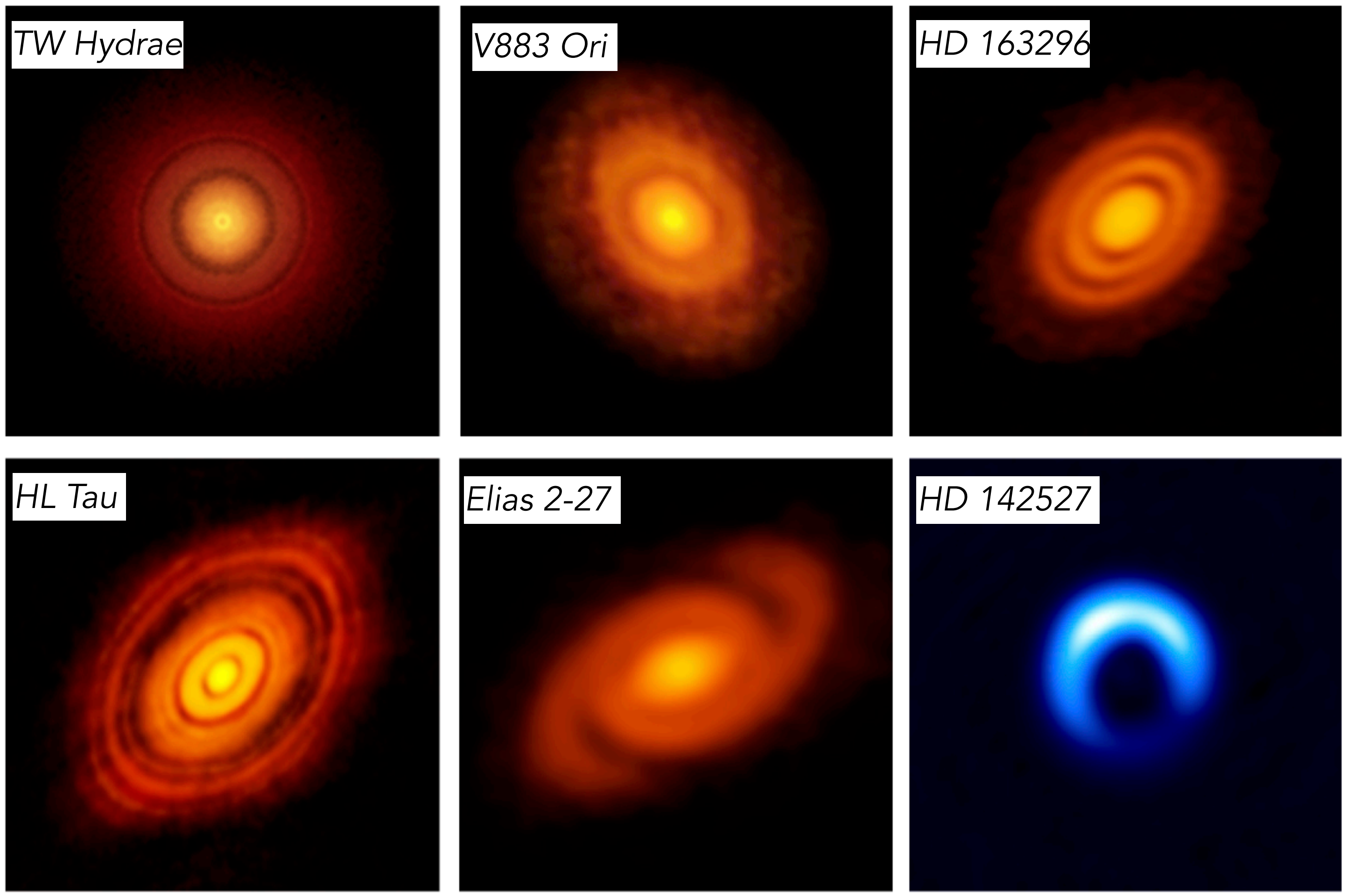
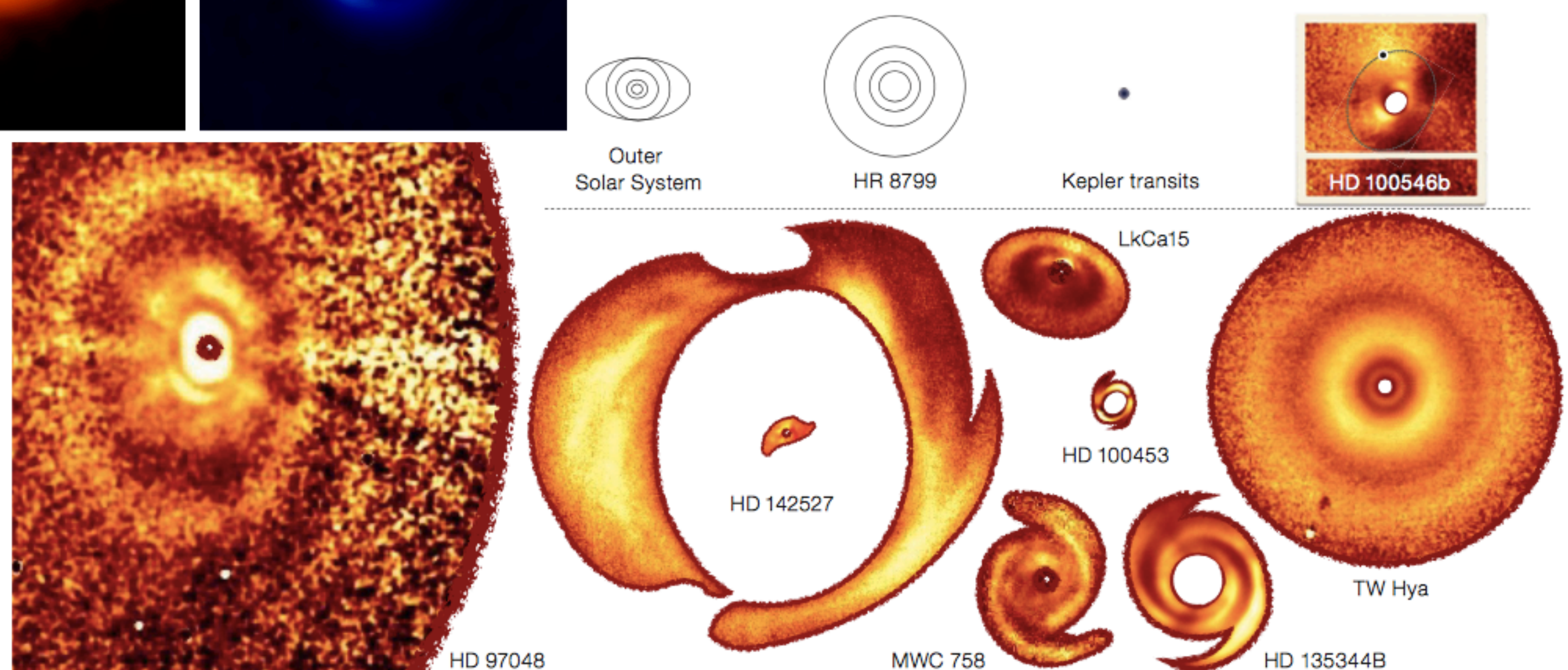


Andrews; **ALMA** (ESO/NAOJ/NRAO)

dust and gas interaction +
planet and disc interaction +
?
= Spirals, gaps, horseshoes…

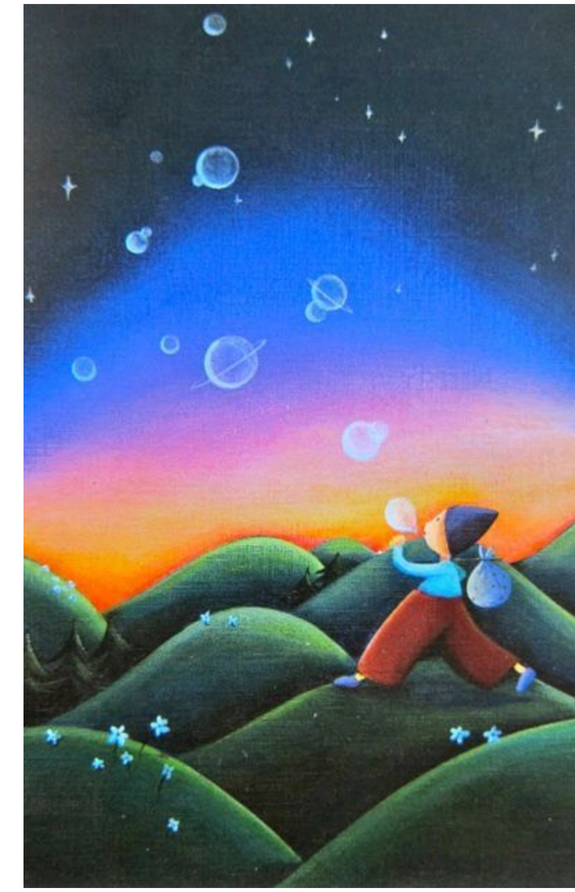
Garufi et al. ESO Messenger; **SPHERE**

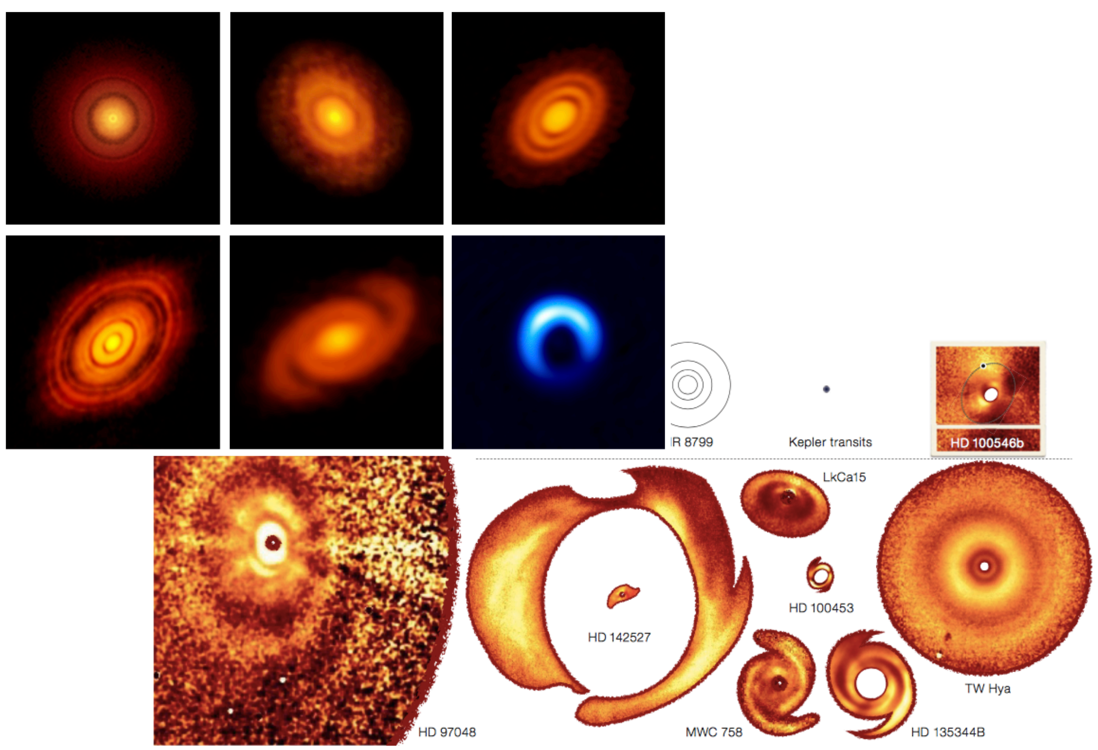


WHAT WE HAVE AND WHAT WE NEED:

Telescopes and instruments: **ALMA** (RADIO) and **SPHERE-VLT** (near-IR) are giving us high resolution images of protoplanetary discs

THEORY OF PLANET FORMATION





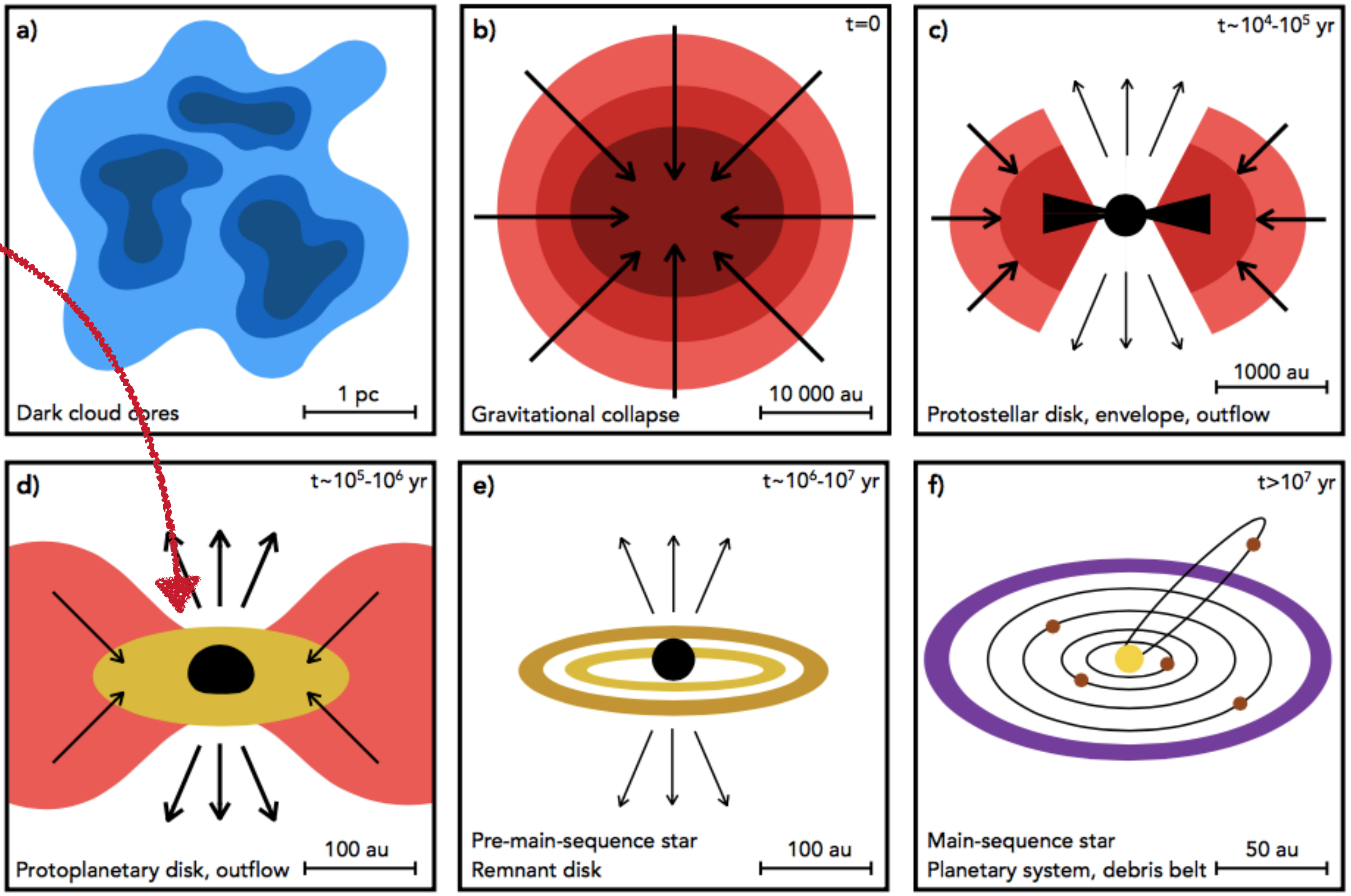
New powerful and fast computational tools:

1. **S**moothed **P**article **H**ydrodynamics codes (**PHANTOM** - Price et al, 2017);
2. MonteCarlo Radiative transport codes (**RADMC-3D** - Dullemond et al, 2012; **MCFOST** - Pinte et al, 2006).

WHERE ARE WE LOOKING AT?

Star formation process:
angular momentum conservation

Disc mass composition:
Gas 99% + dust 1%



Dullemond PhD Thesis

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Star formation process:
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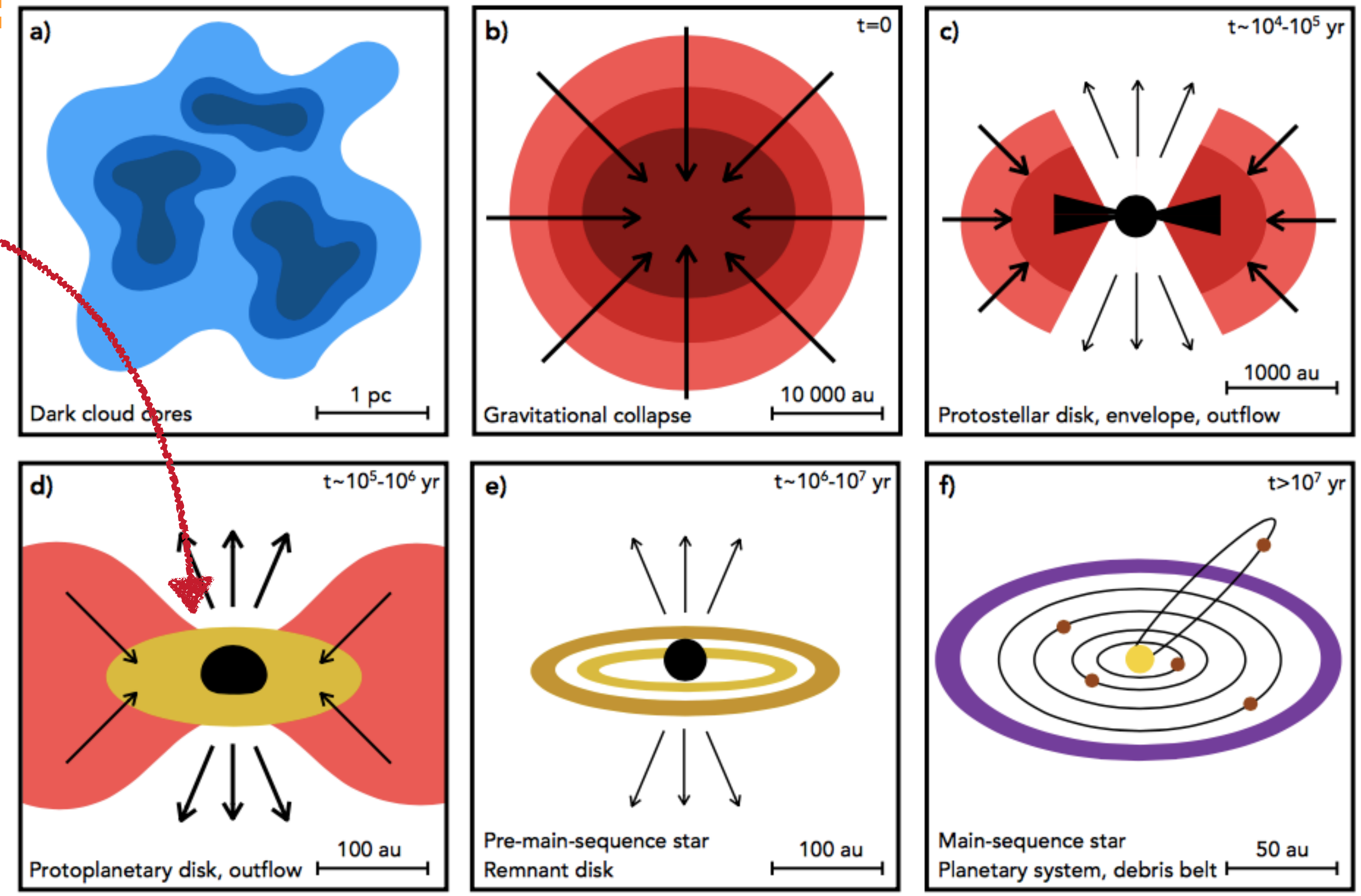
Disc dynamics and
accretion processes



Dullemond PhD Thesis

Gas dynamics: Navier-Stokes equations

- Radial structure: centrifugal equilibrium, $\Omega_k^2 = \mathcal{G} M_\star R^{-3}$
- Vertical structure: hydrostatic equilibrium, $H = c_s / \Omega_k$
- Viscous accretion process: $\nu = \alpha c_s H$

(*Shakura & Sunyaev 1973*)

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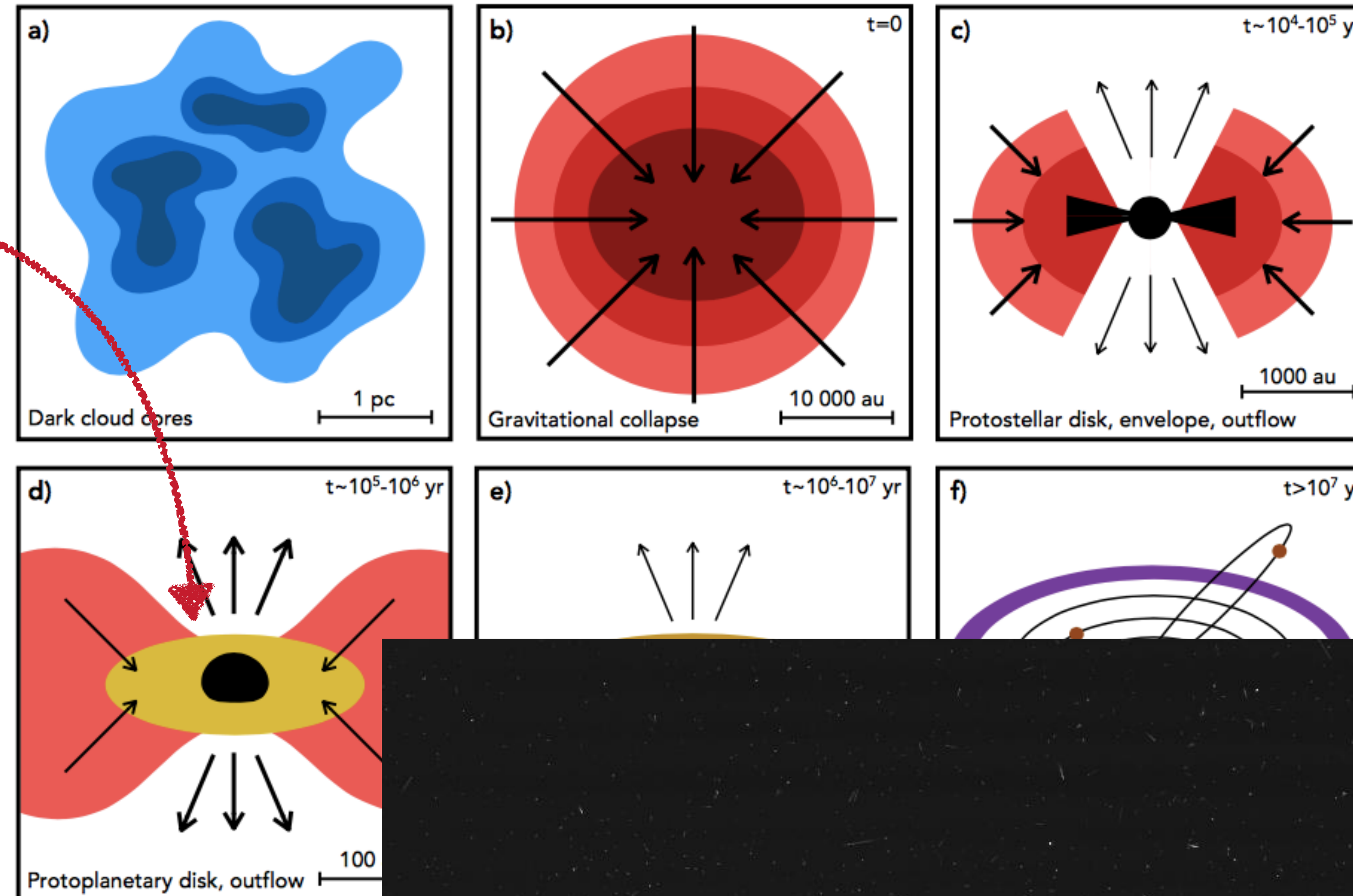

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  (*Shakura & Sunyaev 1973*)

“Disc” shape also on smaller scale: Saturn Satellite’s Pan with a Raviolo shape

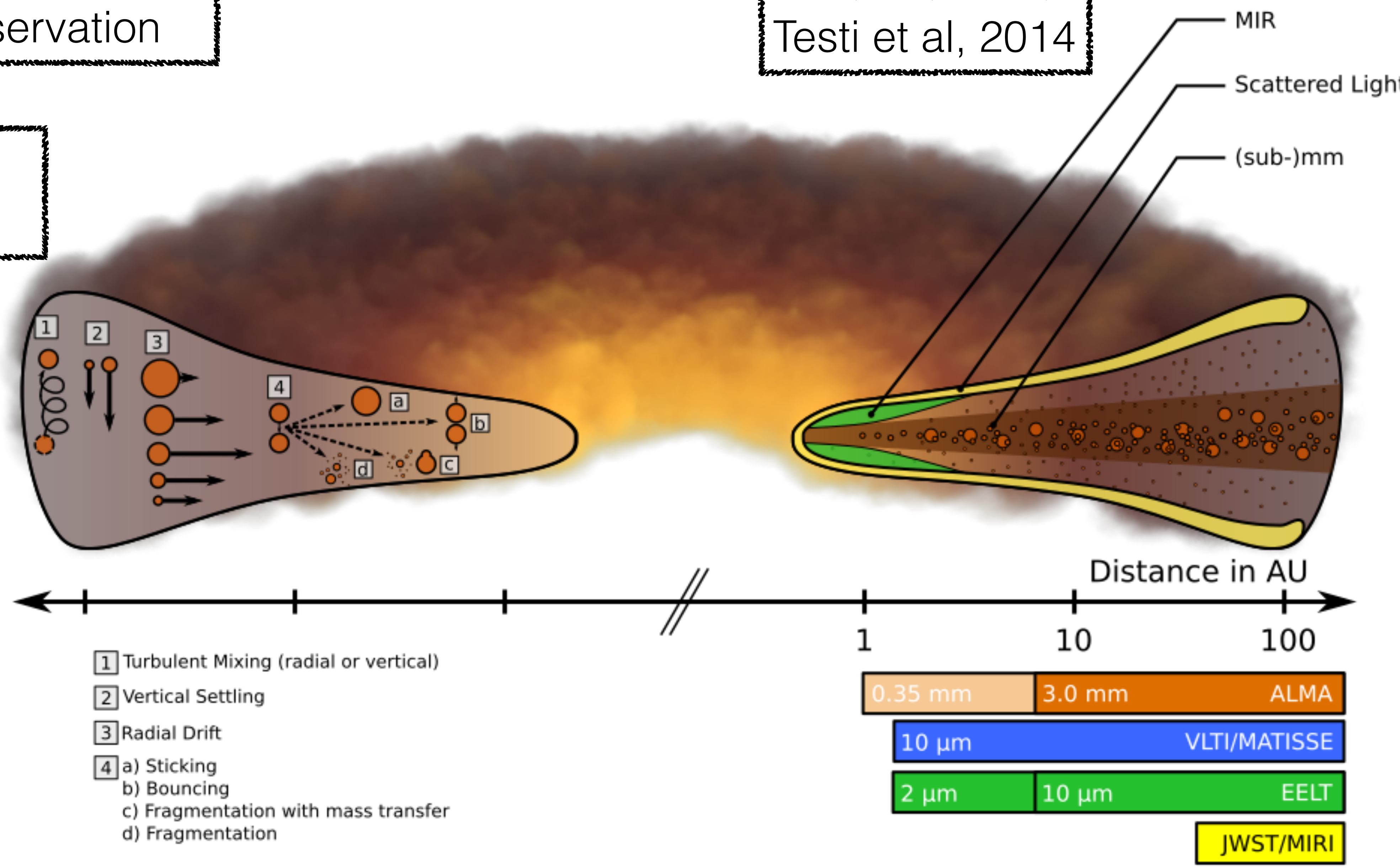
WHERE ARE WE LOOKING AT?

Star formation process:
angular momentum conservation

Disc mass composition:
Gas 99% + dust 1%

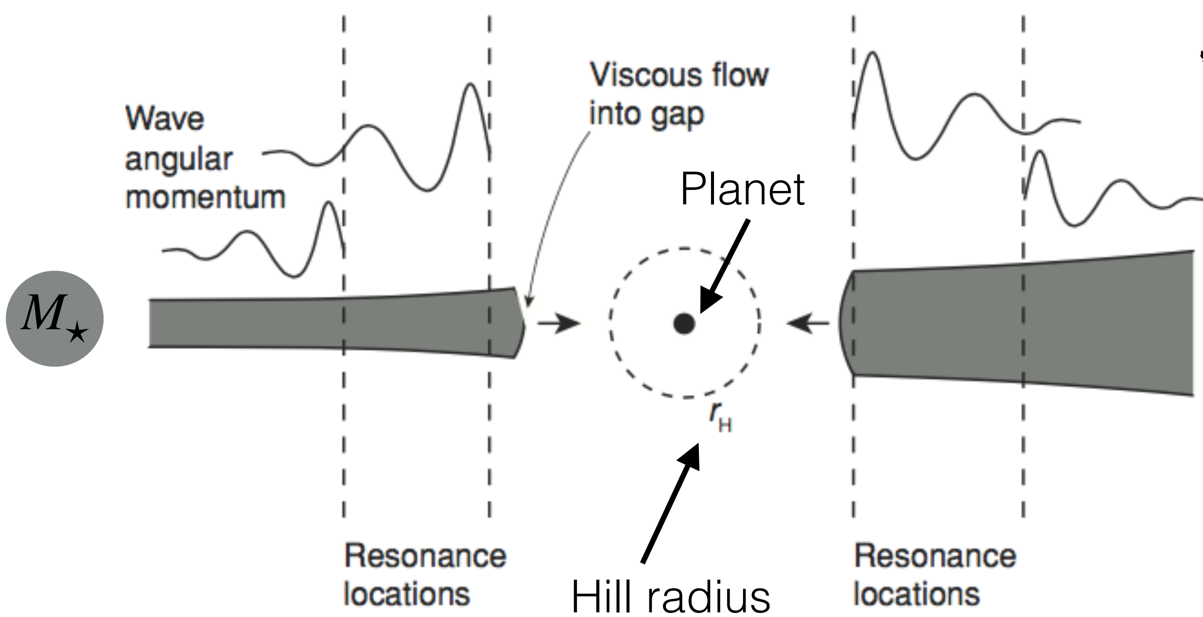
- **Disc opacity**: observations are dominated by dust
- **Grain growth**: first stage of planet formation
- **Chemical reactions**

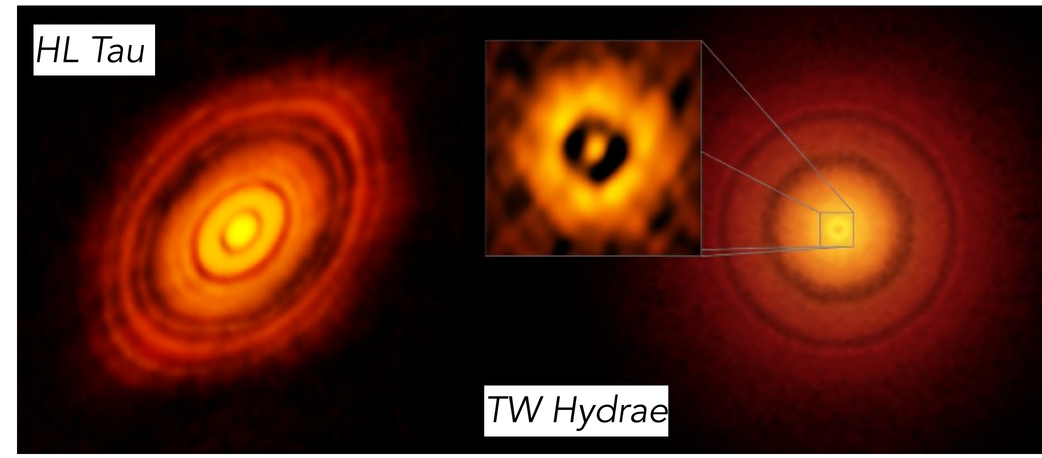
Testi et al, 2014

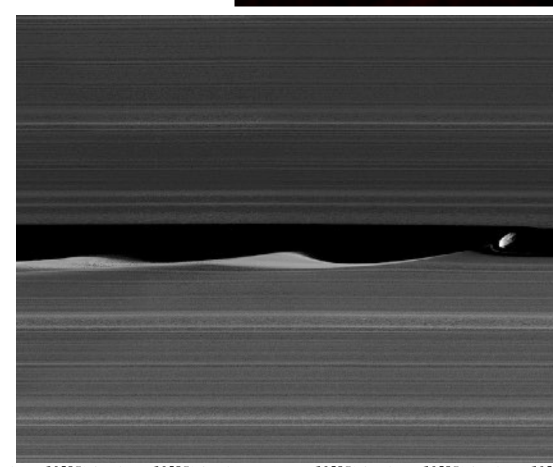


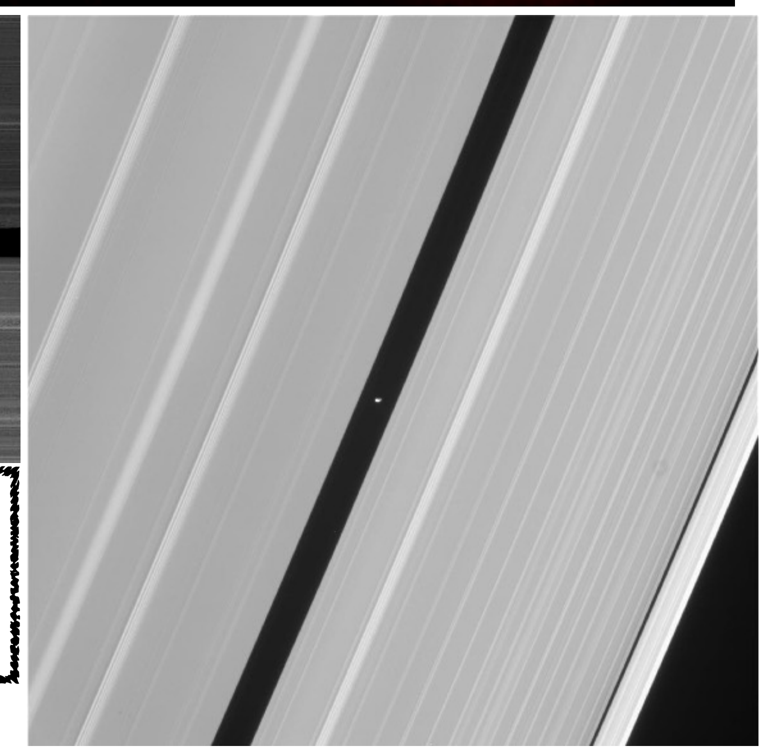
SPIRALS, RINGS, HORSESHOES…

Tidal torques+viscous torques = GAP formation



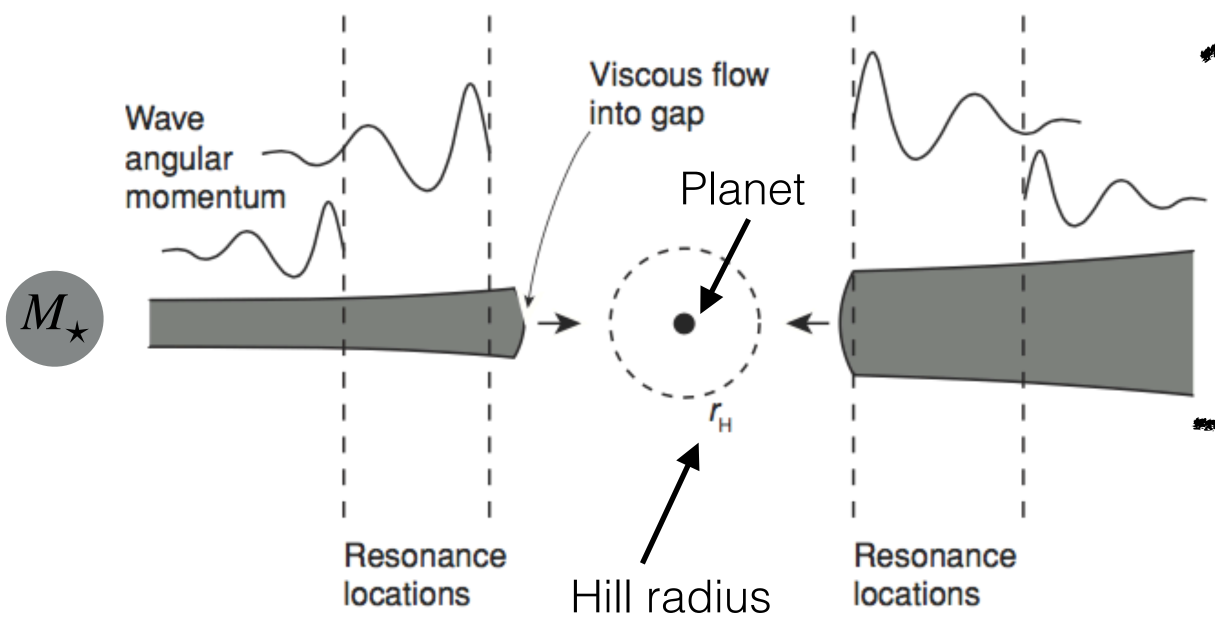






Gaps created by satellites inside Saturn's rings (Cassini's images)

SPIRALS, RINGS, HORSESHOES…



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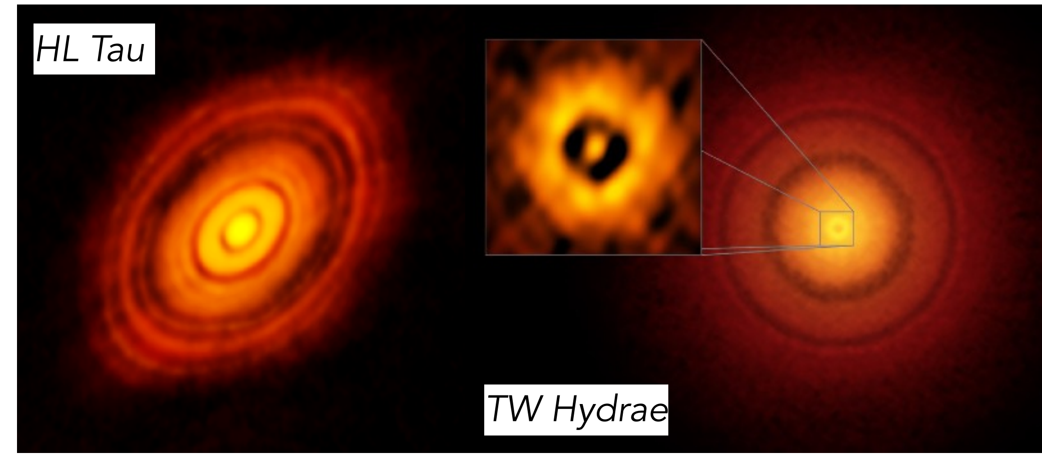
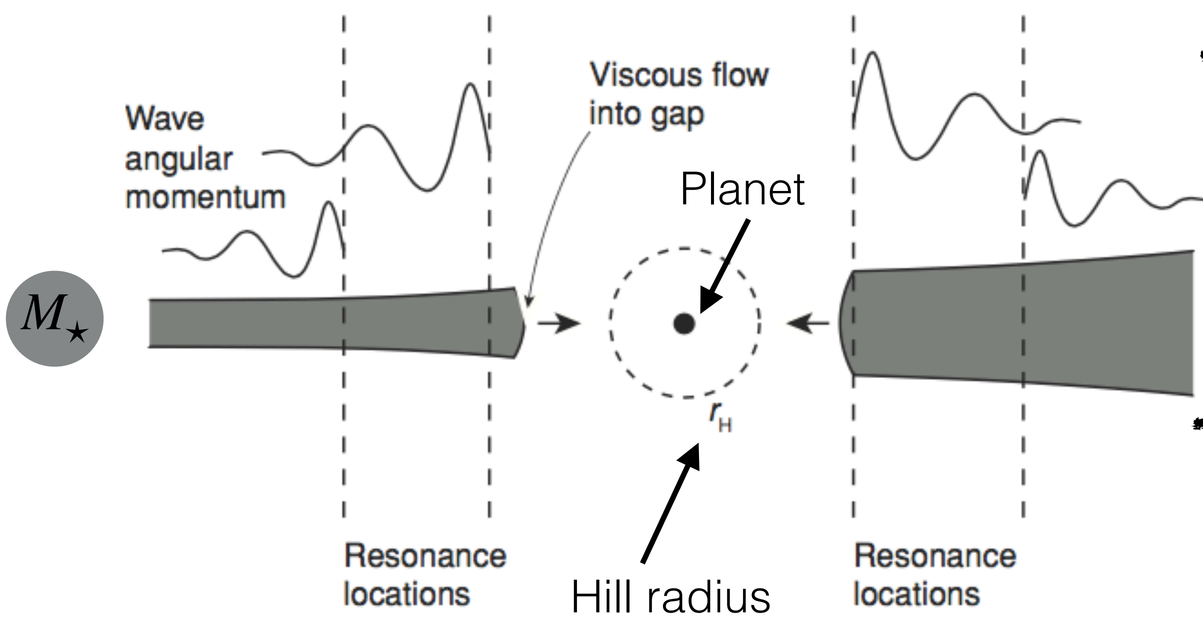


Constructive interference of density waves: planet driven SPIRAL ARMS

SPIRALS, RINGS, HORSESHOES…



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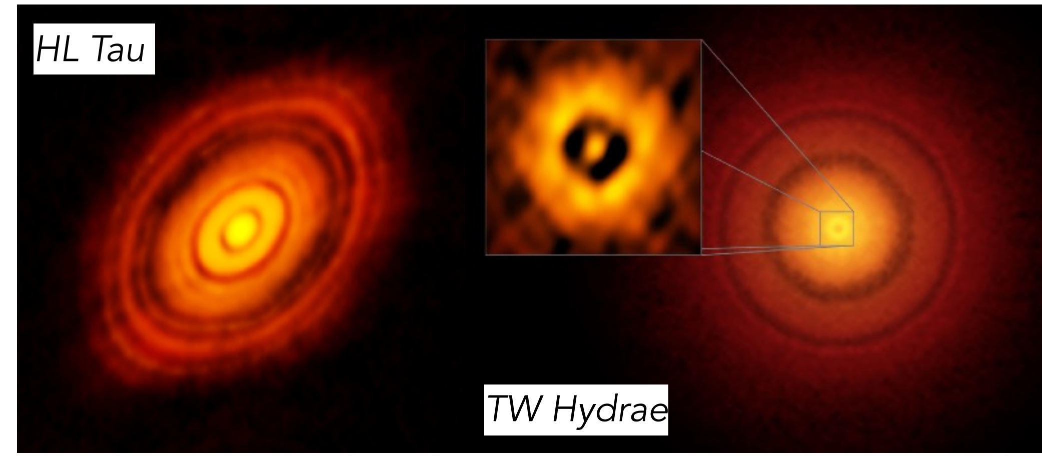

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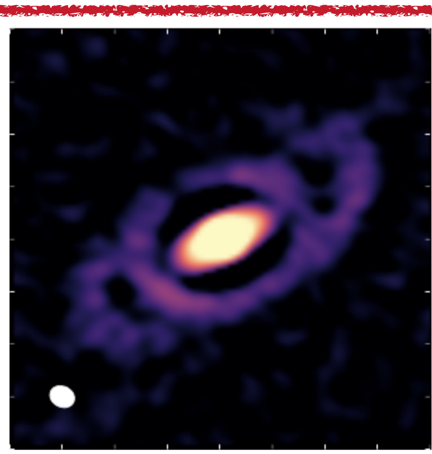
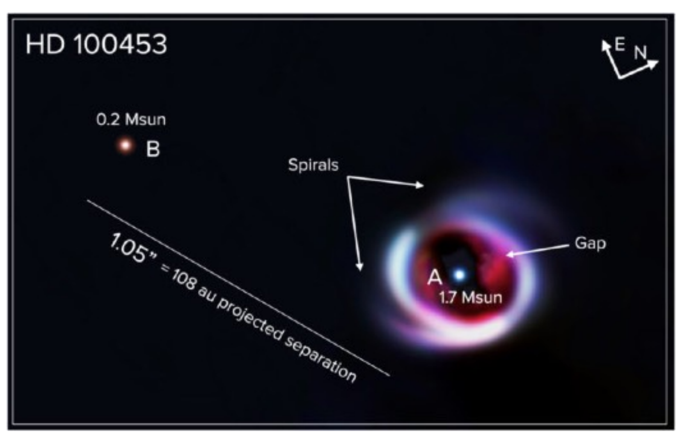
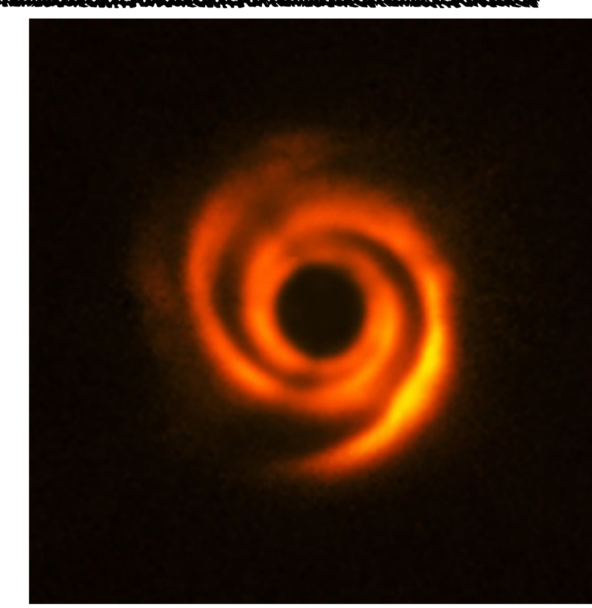




Others processes can form spiral arms:

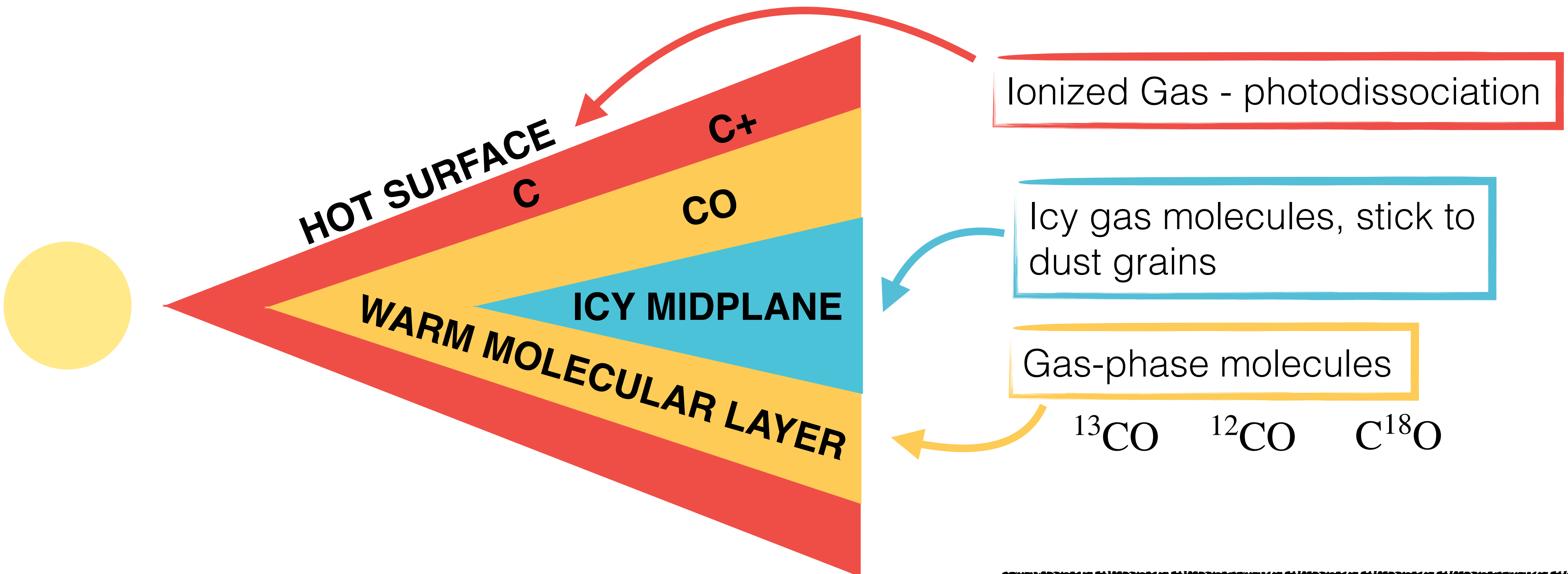


Self-gravitating discs
Dipierro et al (2014) , Kratter & Lodato (2016), Hall et al (2018), Cossins et al (2009), Rice et al (2005)

Possible close encounters (binary)?
Wagner et al (2018)

Dust vortices?
Cazzoletti et al (2018), van der Marel et al (2016)

A PUZZLING PROBLEM: (GAS) MASS IN DISCS



dust: bulk of dust mass comes from large (mm-sized) grains, settled in disc **midplane**, with **thermal emission**

- **Continuum** observations at **(sub-)mm** wavelengths

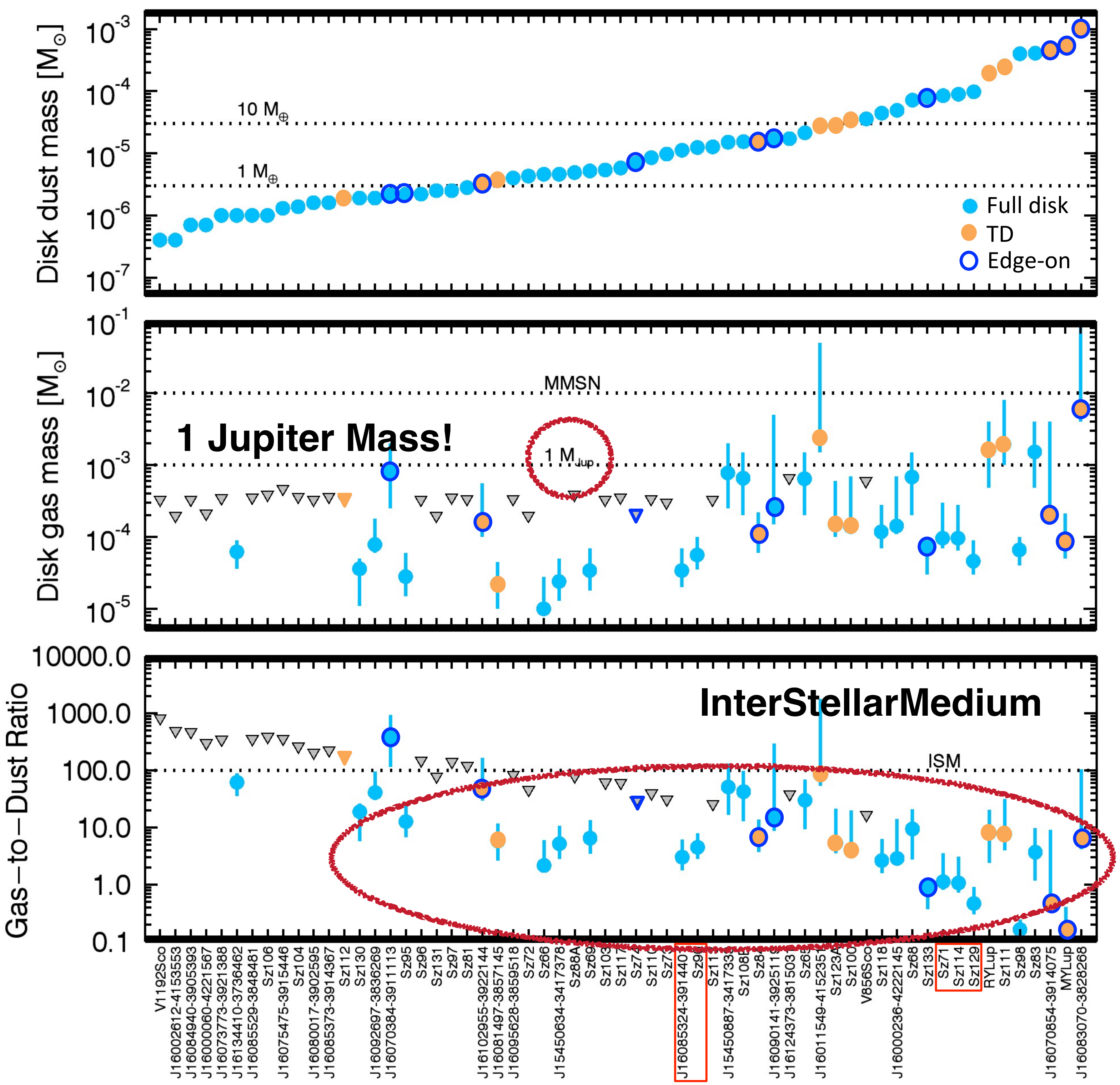
$$M_{\mathrm{dust}} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\mathrm{dust}})}$$

optically thin emission + Rayleigh-Jeans regime

gas: H_2 is the most abundant species.

- Symmetry of H_2: rotational lines emission too weak!
- Tracers: **CO-isotopologues** in the molecular layer

A PUZZLING PROBLEM: (GAS) MASS IN DISCS



Problem: low CO-based gas masses and gas-to-dust ratios

Why?

- Gas loss:
  - **Evolved discs population**: gas physically dissipated
- Low CO abundance:
  - due to **sequestering of carbon from CO to more complex molecules**;
  - or because it is **locked up into larger bodies**

Solutions?

Miotello et al. 2017

Veronesi et al in prep.

A PUZZLING PROBLEM: (GAS) MASS IN DISCS

Possible solution: matching information from different methods

CO-isotopologues emission & dust and gas interaction & …?

$$St = t_s \Omega \approx \frac{\rho_d a}{\Sigma_g}$$

Stopping time of a dust grain by gas

Dynamical timescale = $1/\Omega_k$

COUPLED $St \ll 1$

NOT COUPLED $St \gg 1$

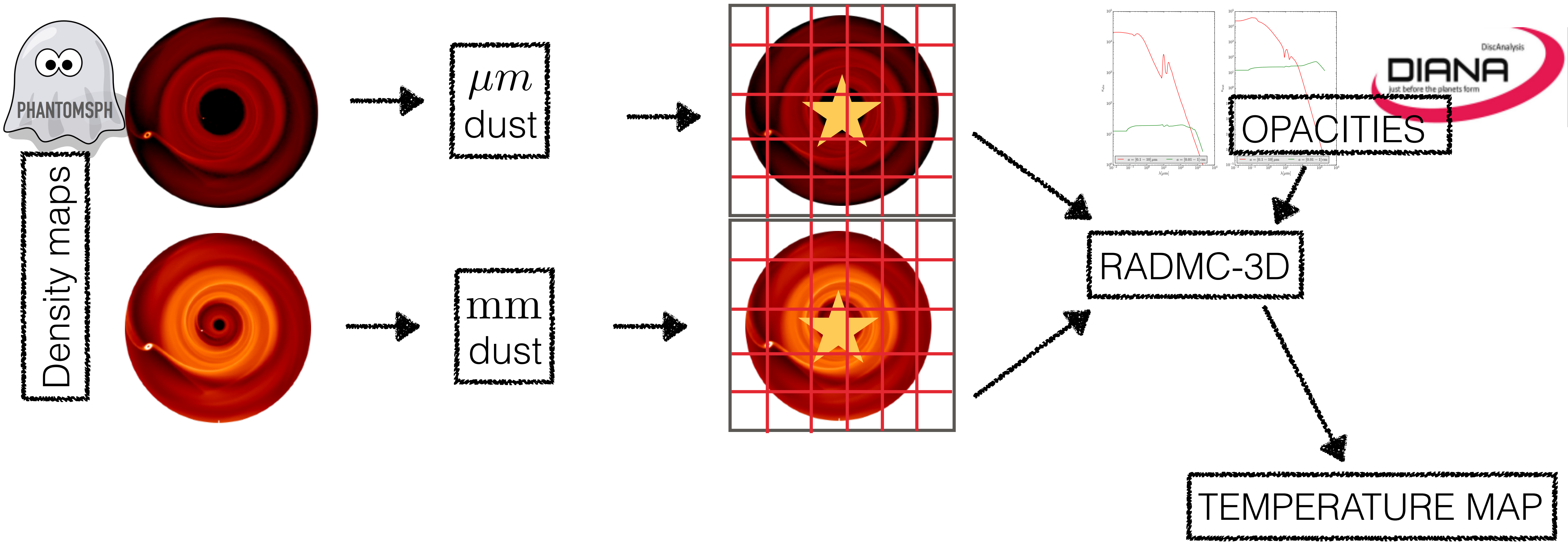
If the dust grain size is known, depending on the sub-structures we see (spirals, rings…) both in gas and dust, we can **infer information on the gas disc mass**

HOW?

Hydrodynamical and *radiative transfer* simulations of protoplanetary discs with different **Stokes number** values → **disc mass** values

WORKFLOW: FROM PHANTOM TO RADMC-3D

Veronesi et al in prep.



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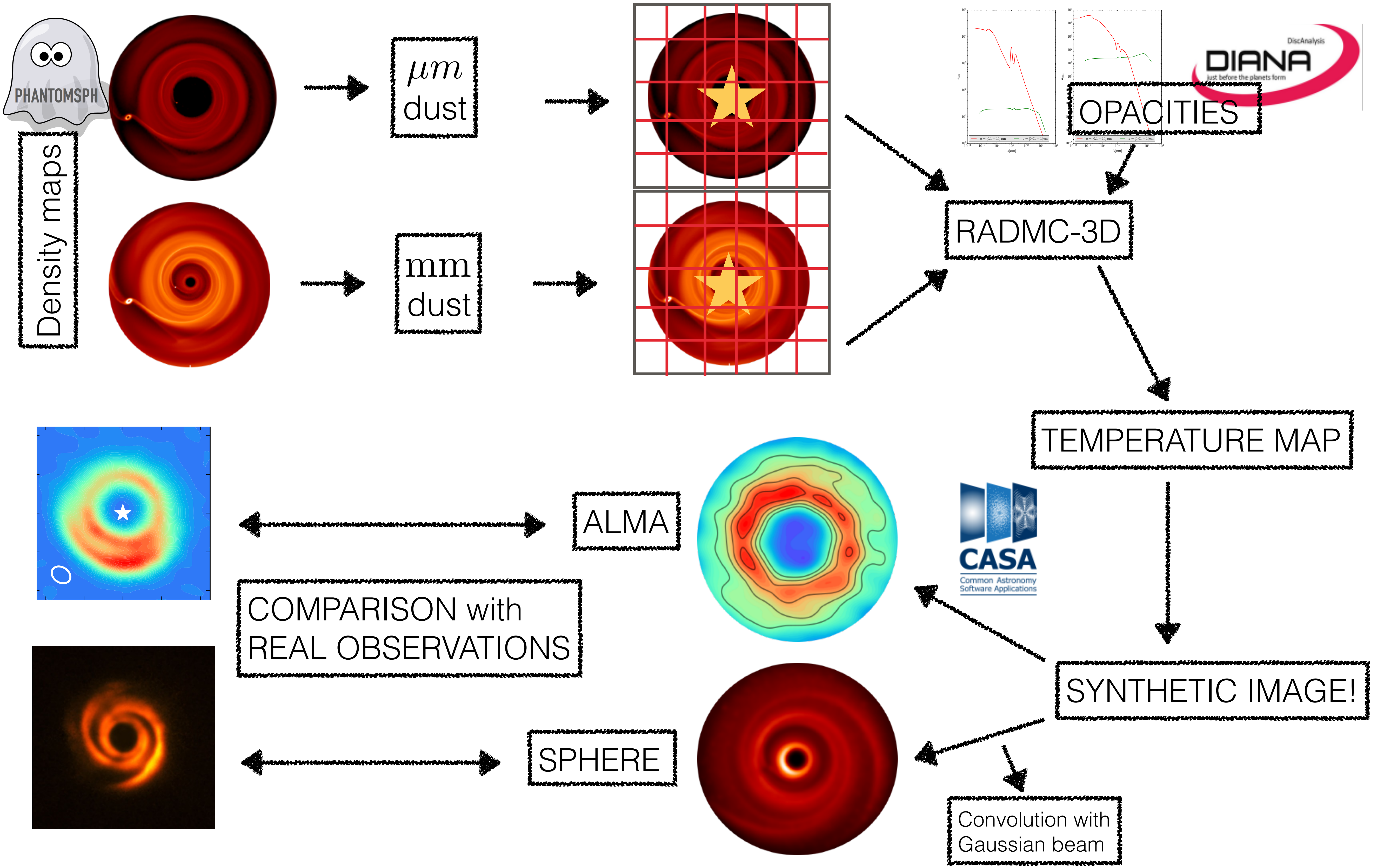
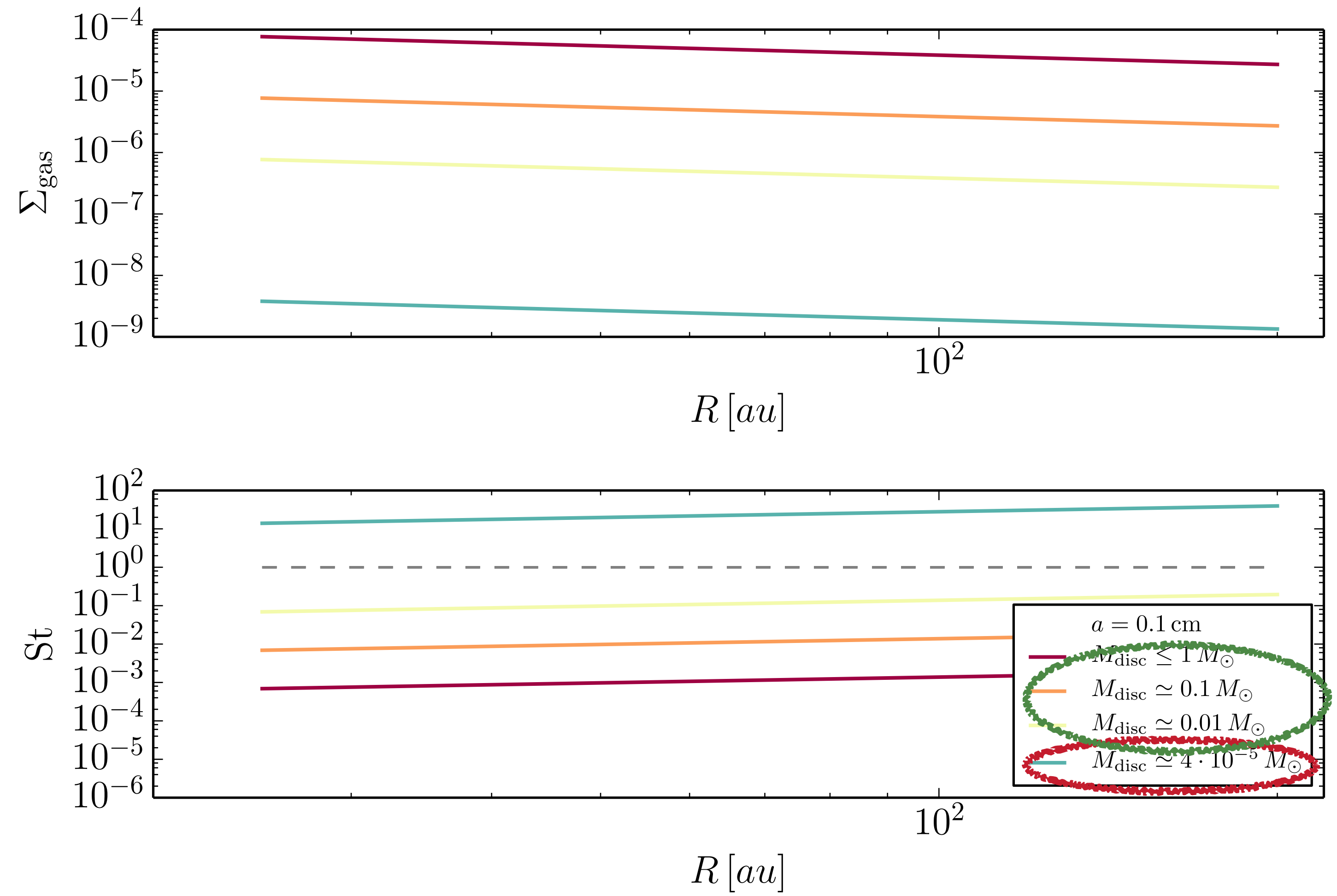


Veronesi et al in prep.

DUSTYDISC SETUPS

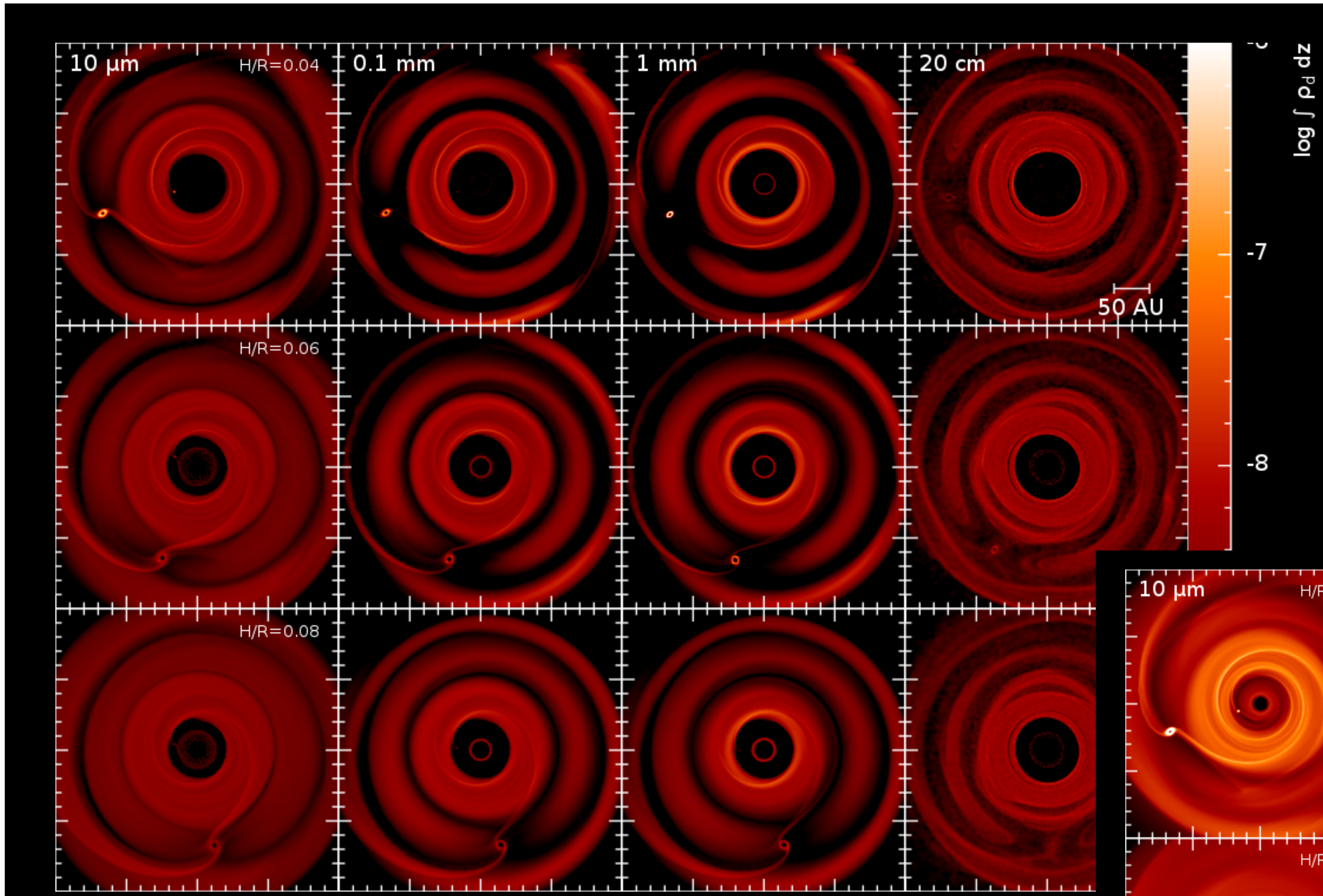
- Different gas disc masses in SPH can be modeled with different grain sizes ⟶ St !!
- One fluid (coupled gas and dust) + Two fluids (decoupled gas and dust) simulations
- 2 planets: $M_p \simeq 3 - 5\, M_j$ to reproduce an inner cavity, and an outer substructure (spirals or ring/horseshoe)
- Power-law surface density profile (both dust and gas)

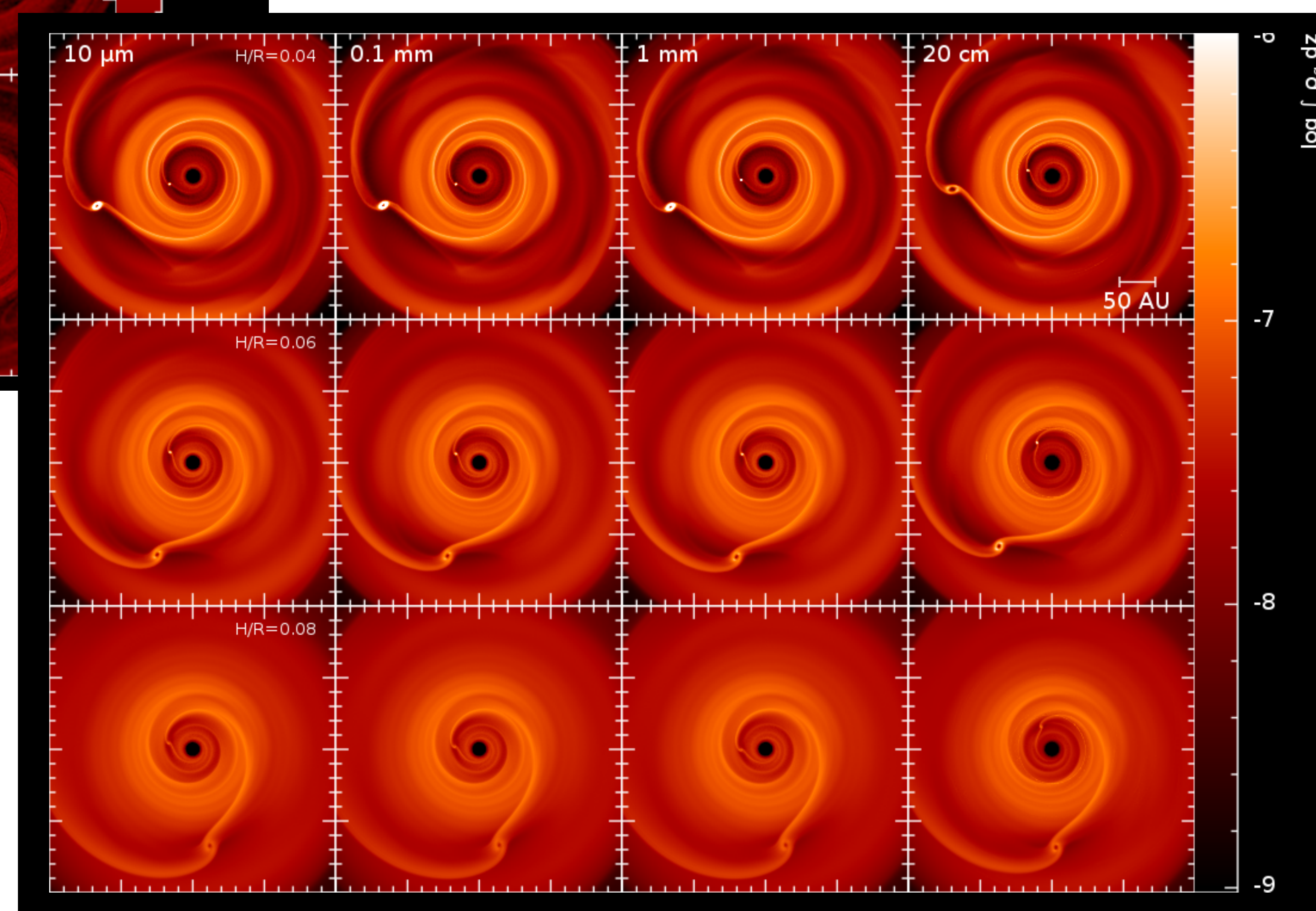


Initial conditions for surface density and Stokes number

***Veronesi et al* in prep.**

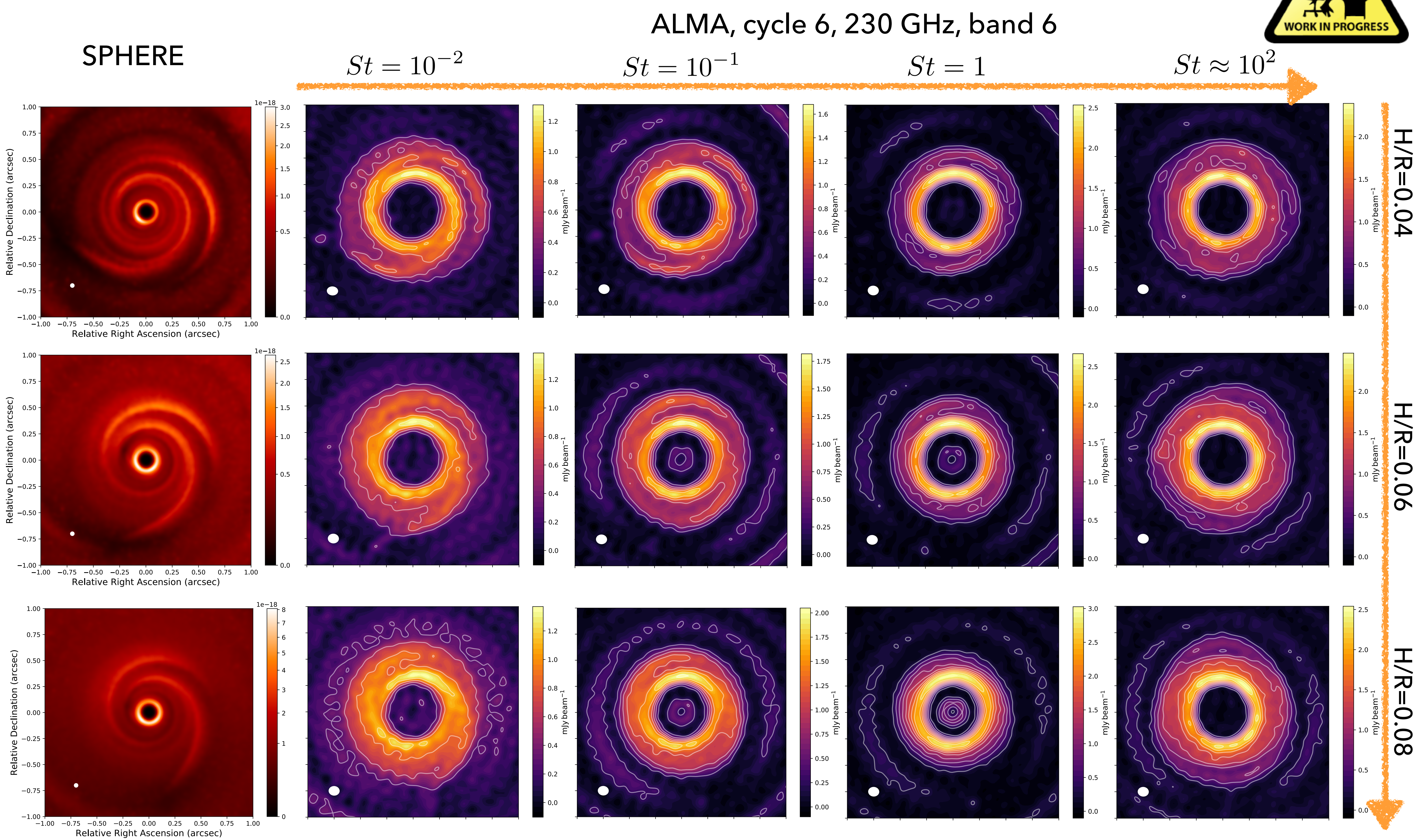
GAS & DUST SURFACE DENSITY MAPS





Veronesi et al in prep.

MOCK IMAGES RESULTS



Veronesi et al in prep.

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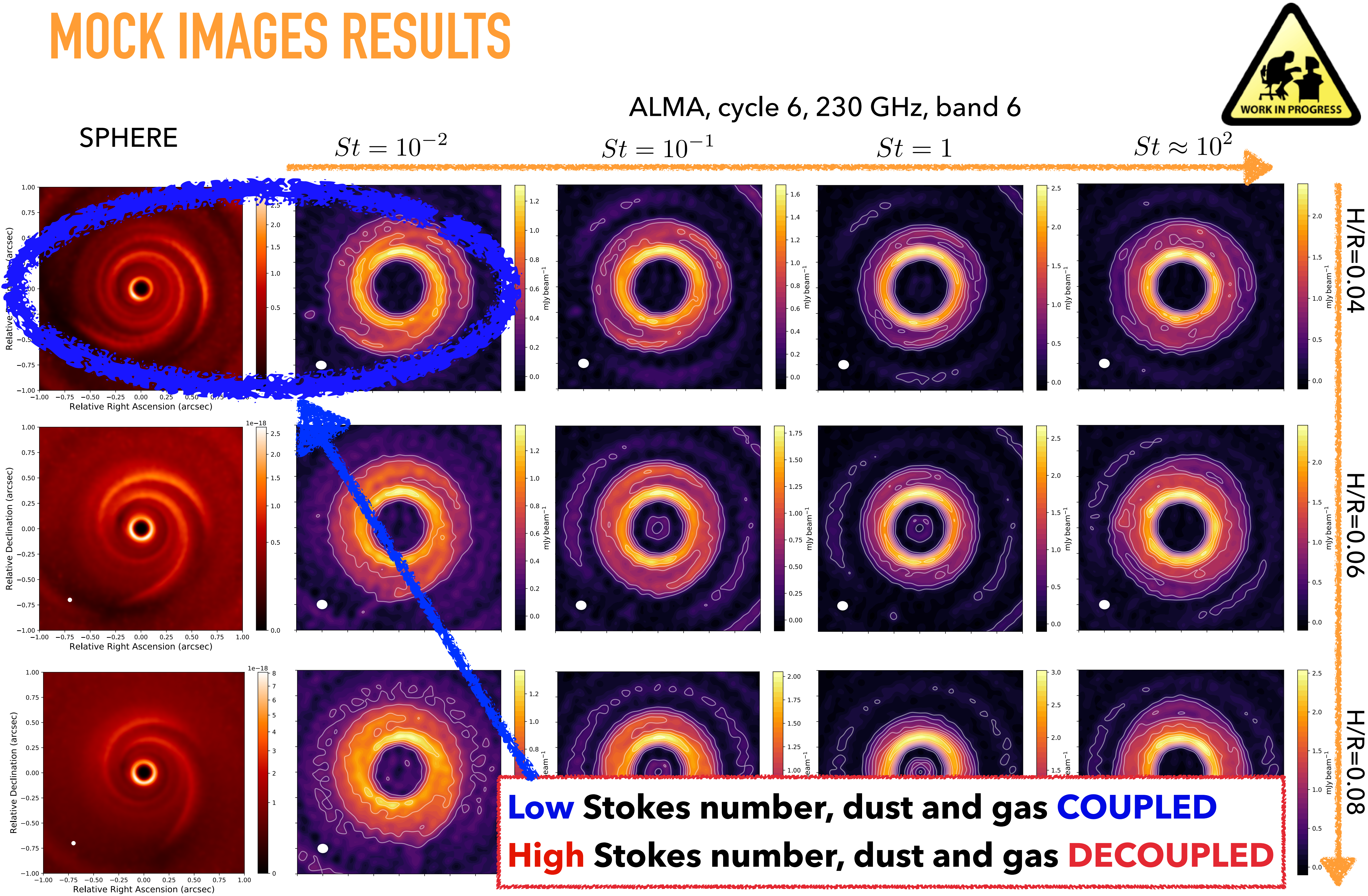
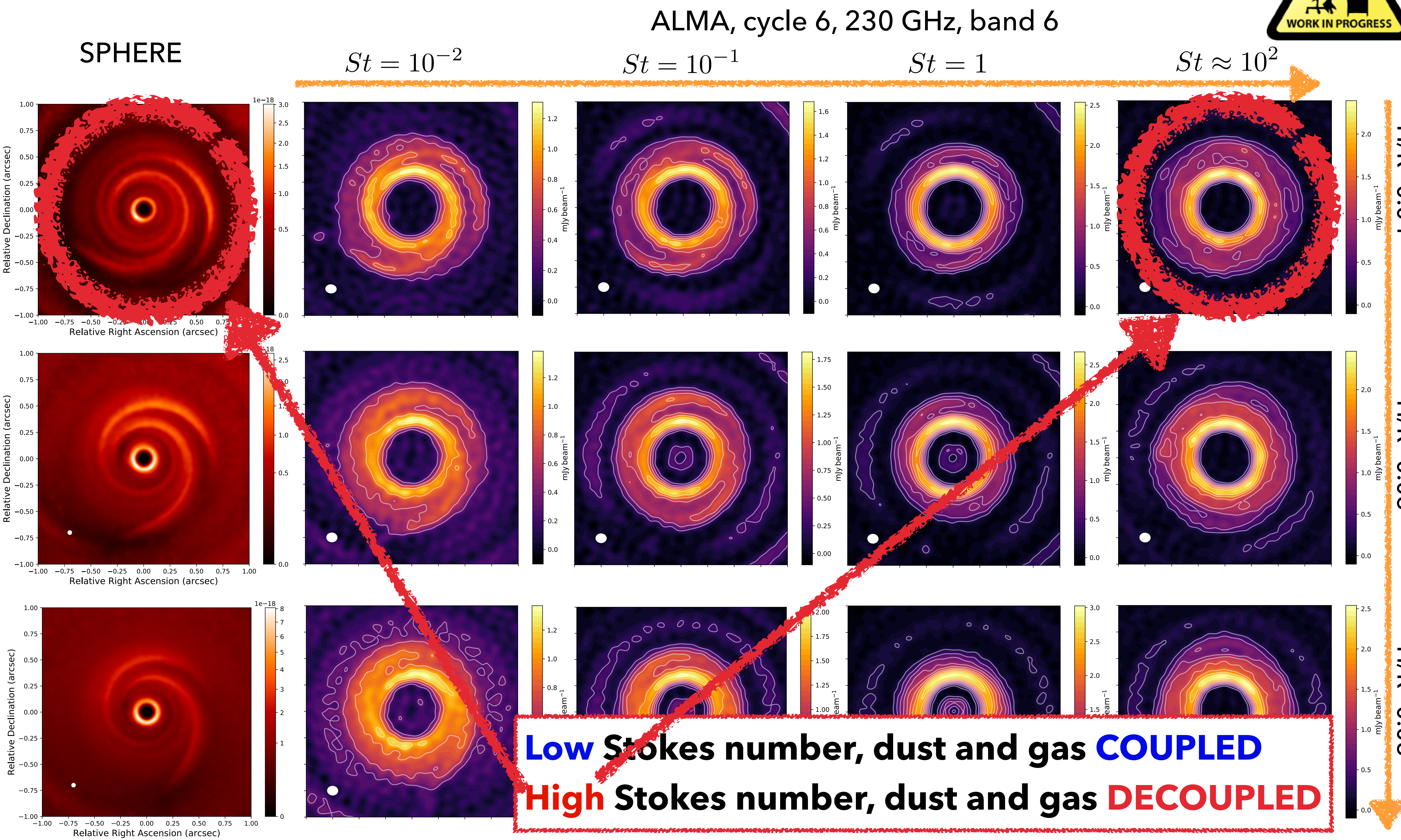


Low **Stokes number, dust and gas** **COUPLED**

High **Stokes number, dust and gas** **DECOUPLED**

Veronesi et al in prep.

MOCK IMAGES RESULTS



Low Stokes number, dust and gas **COUPLED**

High Stokes number, dust and gas **DECOUPLED**

TAKE HOME MESSAGES

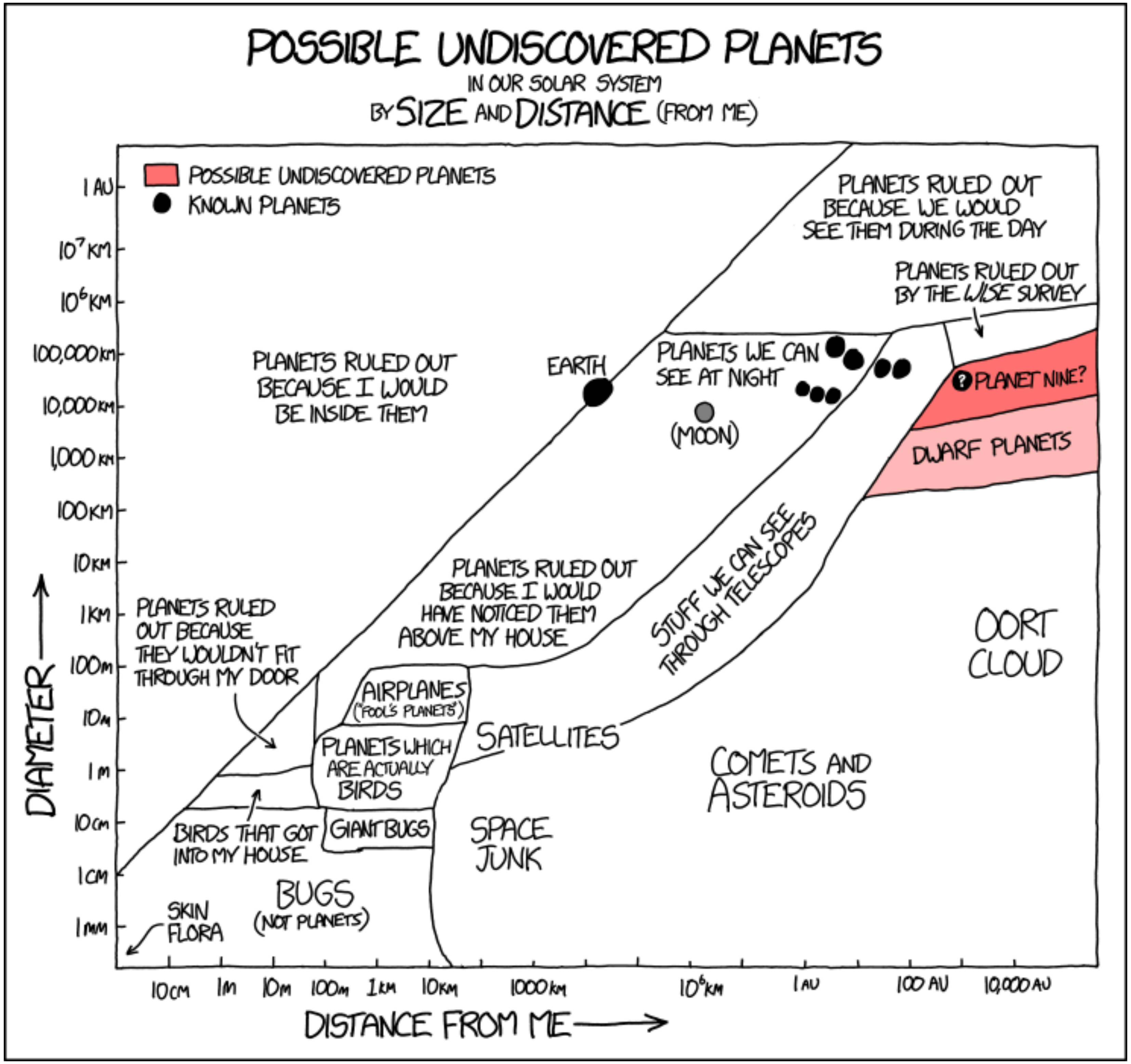
- Ballabio, Dipierro, **Veronesi** et al (2018): fixed a problem of dust mass non conservation in the SPH code (not in this talk).
- Different Stokes number are observable through ALMA and SPHERE images;
- The more coupled the dust and the gas are, the more non-axisymmetric are the structures → **spirals** both in ALMA and SPHERE images;

- If the observed grain size is known, the observed sub-structures in the ALMA/SPHERE image can give us an **hint on the gas disc mass** (see Stokes parameter definition).

IN PROGRESS + TO DO

- ***Veronesi et al***: paper in preparation!
- ***Work in progress***:
  - ☐ to find a quantitative relation between the Stokes number/disc masses and the ALMA-SPHERE images: **criterion for gas mass**
  - ☐ to model a disc taking into account regions with different Stokes number (i.e. grain growth process, dust segregation)
- ***Next years***:
  - Collaboration with research group in **California** to model protoplanetary discs collected by the **ALMA Large Program**.
  - Study of self-gravitating protoplanetary discs: collaborations with many research groups inside the RISE project "**Dustbusters**"

THANKS FOR THE ATTENTION!
QUESTIONS?



ONE-FLUID VS TWO-FLUID

Mixture of gas particles + fraction of gas particle taking into account the dust properties $\epsilon \equiv \rho_d/\rho$ + evolution equation for the dust fraction

$$\rho_g = (1-\epsilon)\rho \qquad \rho_d = \epsilon\rho \qquad \rho = \rho_d + \rho_g \qquad \mathbf{v} = \frac{\rho_g \mathbf{v}_g + \rho_d \mathbf{v}_d}{\rho_g + \rho_d}$$

- Gas & Dust fluid equations in the barycentric reference frame of the mixture (Laibe & Price, 2014a)

Two SEPARATED fluids, gas + dust, coupled by a DRAG term

ρ_g

ρ_d

- Gas properties are only defined on gas particles and dust properties are defined only on dust particles

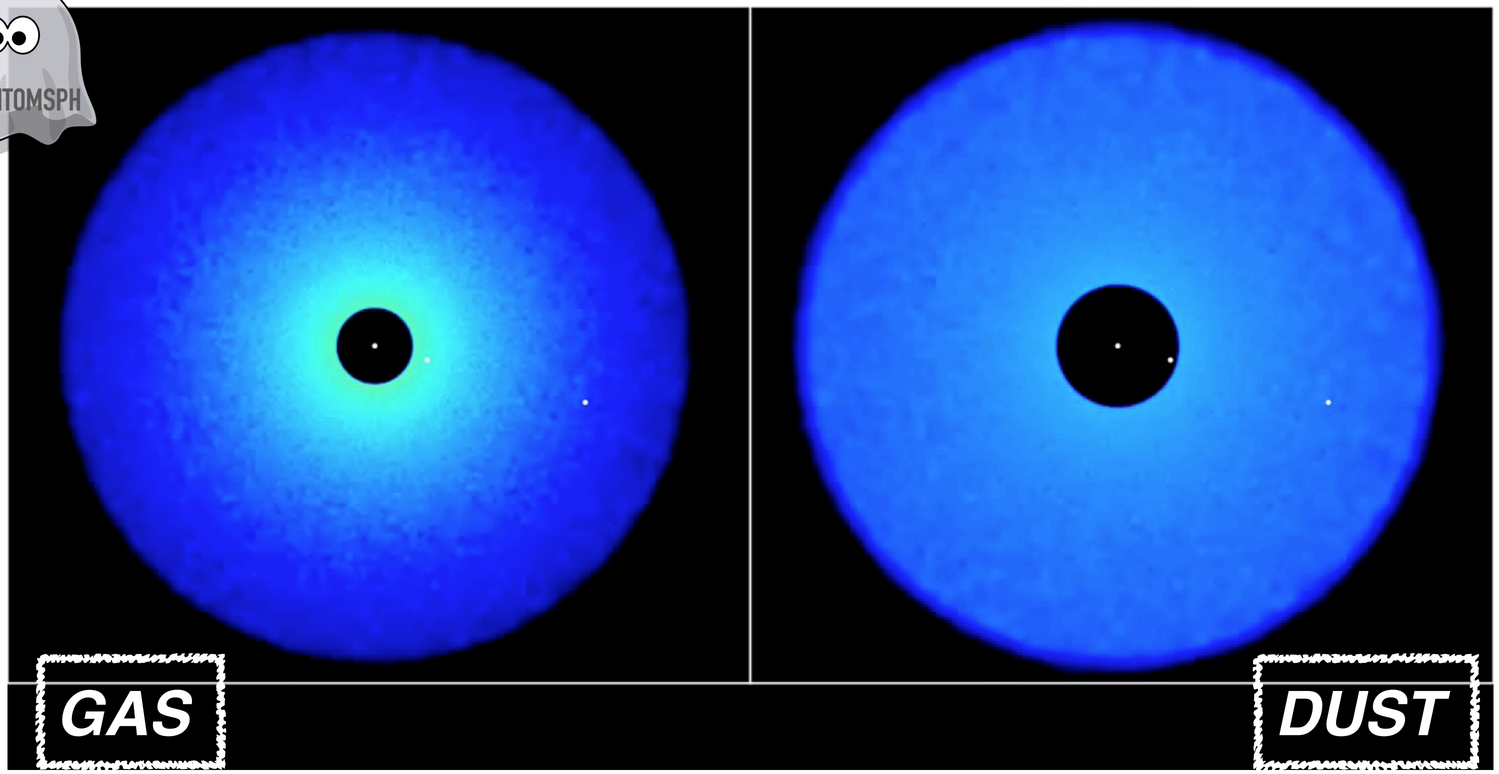
Terminal velocity approximation: $t_s < h/c_s$

stopping time << typical hydrodynamic timescale = time required for a sound wave to propagate over a characteristic distance (Youdin & Goodman 2005)

$\Delta\mathbf{v} = \mathbf{v}_d - \mathbf{v}_g$ reach a terminal velocity due to the balancing of the drag and pressure forces.

- No need of prohibitive temporal and spatial resolution requirements at high drag;
- No artificial trapping of dust under the resolution length of the gas;
- Multiple dust species coupled to the same gas phase are taken into account (Hutchison et al 2018).

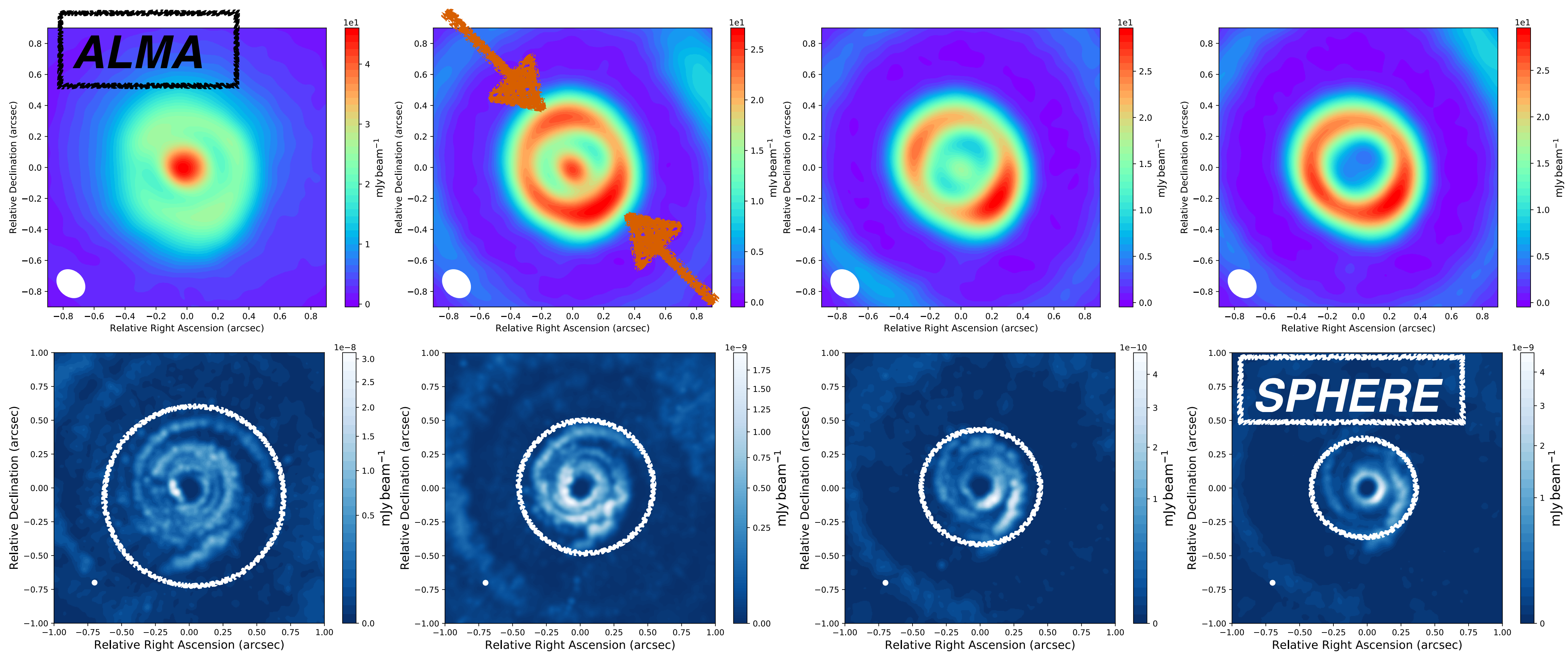
THE BEGINNING: HD135344B



$$R_{\rm out,gas} = R_{\rm out,dust} = 200 \text{ au}$$

Parameter	Value
$R_{\rm in,gas}$ [au]	25
$R_{\rm in,dust}$ [au]	40
$M_{\rm gas,disc}$ [$M_\odot$]	0.1
dust/gas	0.01
$(H/R)_0$ [$R_0 = 25$ au]	0.048
$M_{p,(\rm in,out)}$ [M_j]	(4,6)

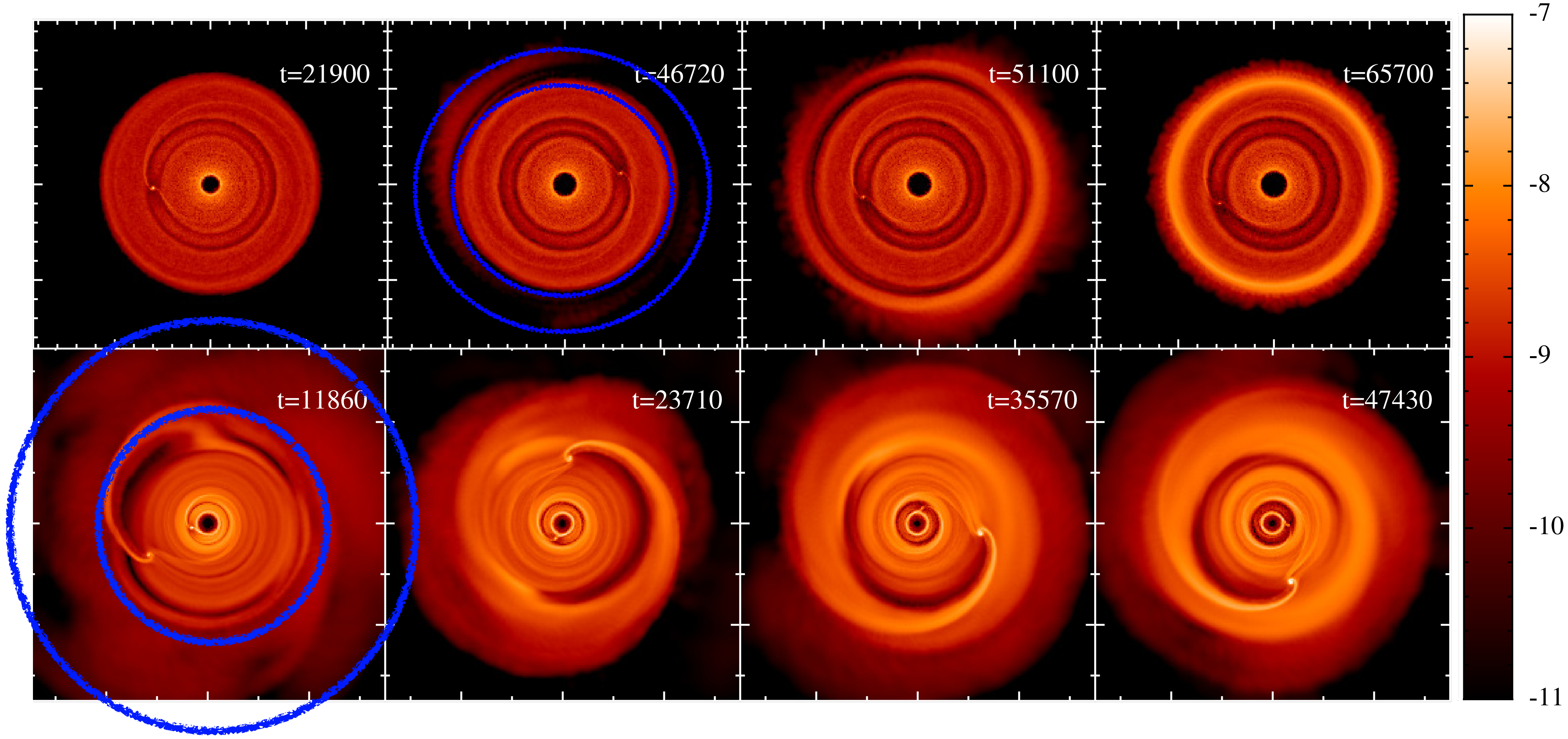
MASTER THESIS RESULT



EXCURSUS: BALLABIO, DIPIERRO, VERONESI ET AL

DO YOU HAVE A PROBLEM OF DUST?

One-fluid method:
Price et al 2017
Laibe & Price, 2014a
Price & Laibe, 2015a
Youdin & Goodman, 2005
(*terminal velocity approximation*)

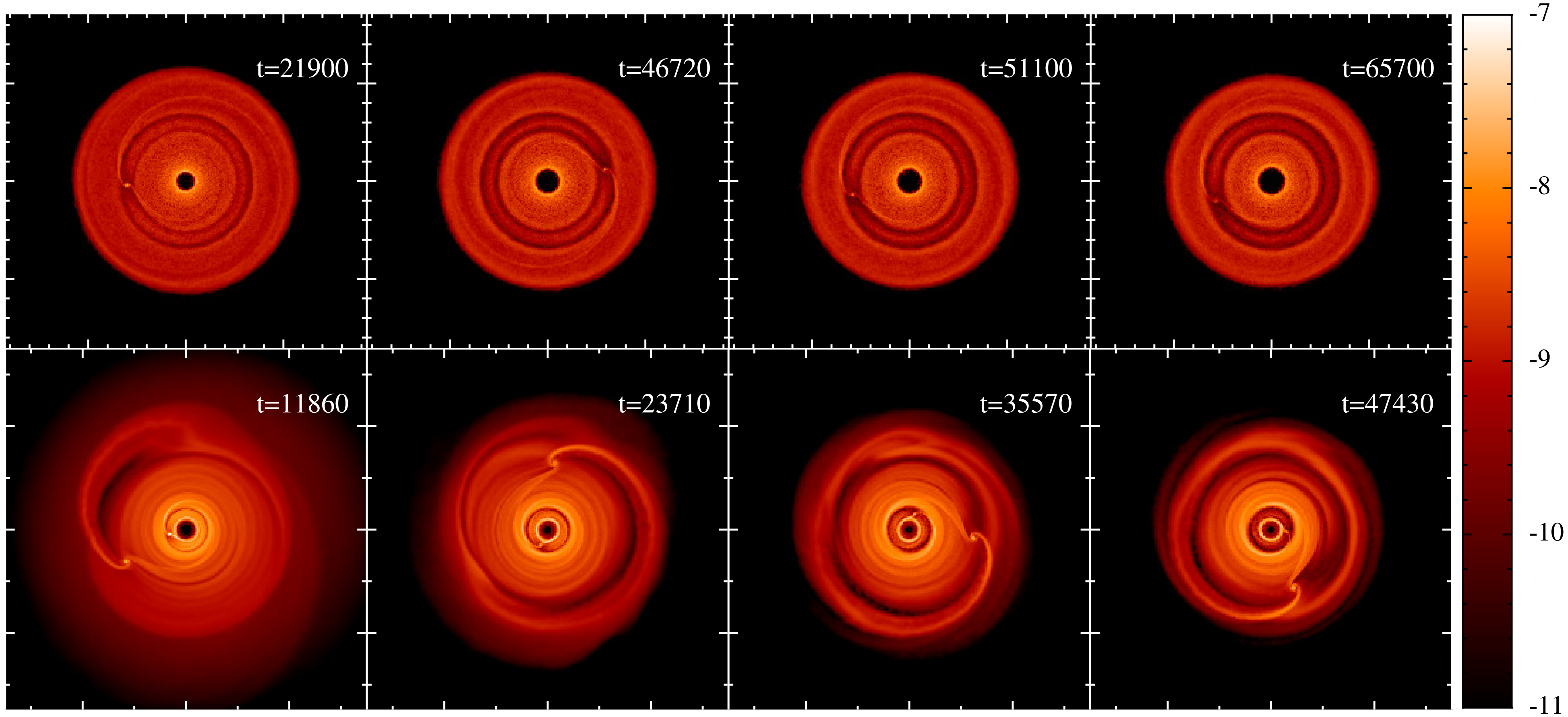


Dust mass non conservation:

1) **Strong dust diffusion**: steep gradients in the pressure, particles with **large stopping time:** $\epsilon t_s \nabla P$
It affects particles in the **upper/outer regions of discs** with
- high aspect ratio, H/R;
- low (in absolute value) radial power-law index for the temperature, q

2) **No constraint on the positivity of the dust fraction** ϵ

DO YOU HAVE A PROBLEM OF DUST?



DUSTBUSTERS IN ACTION!

PROBLEM SOLVED!

1) Limiting the rapid dust diffusion for problematic particles by means of a time stopping limiter:

$$\tilde{t}_s = \min\left(t_s, h/c_s\right)$$ → Limiting the Stokes number, OK where dust mass is negligible

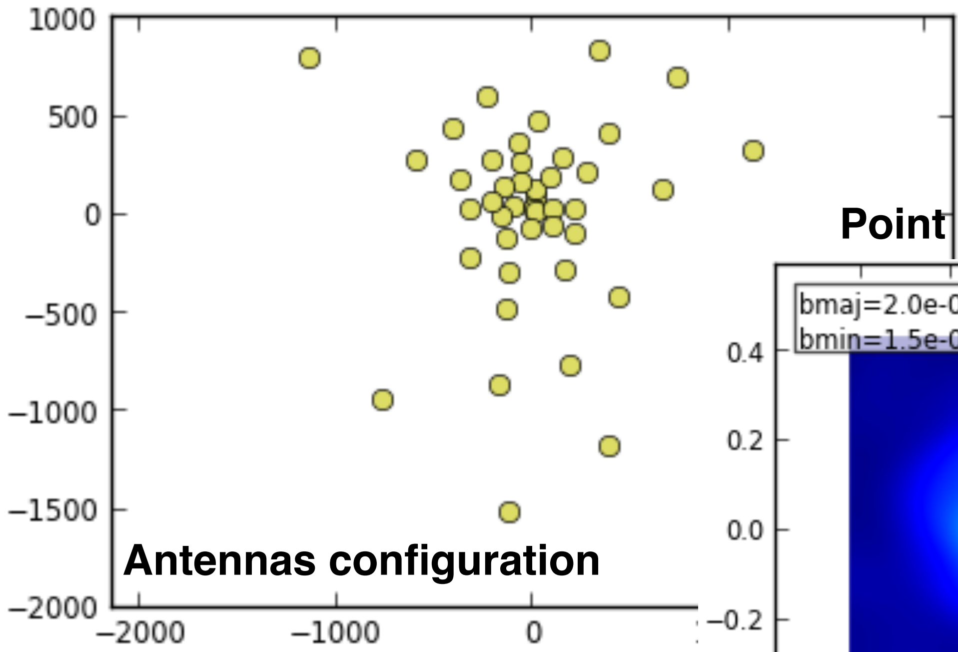
Solution localized strictly to particles that violate the terminal velocity approximation: $t_s < h/c_s$

2) Enforcing constraint on $0 < \epsilon < 1$ (no unphysical values):

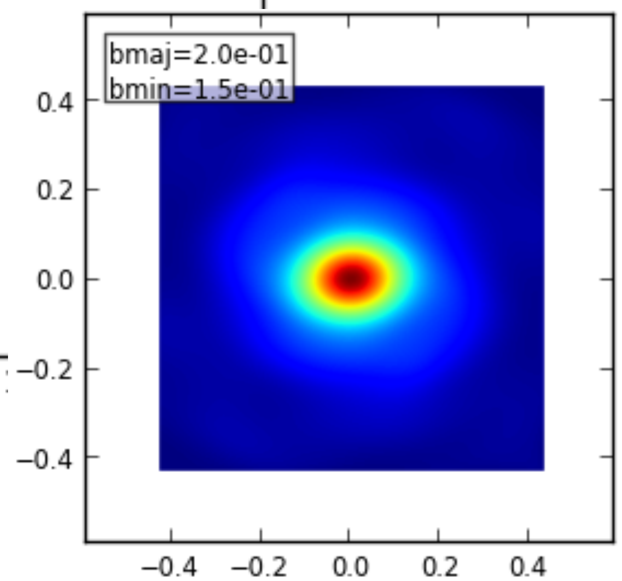
$$\epsilon = \frac{s^2}{1+s^2} \quad s = \sqrt{\frac{\rho_d}{\rho_g}}$$

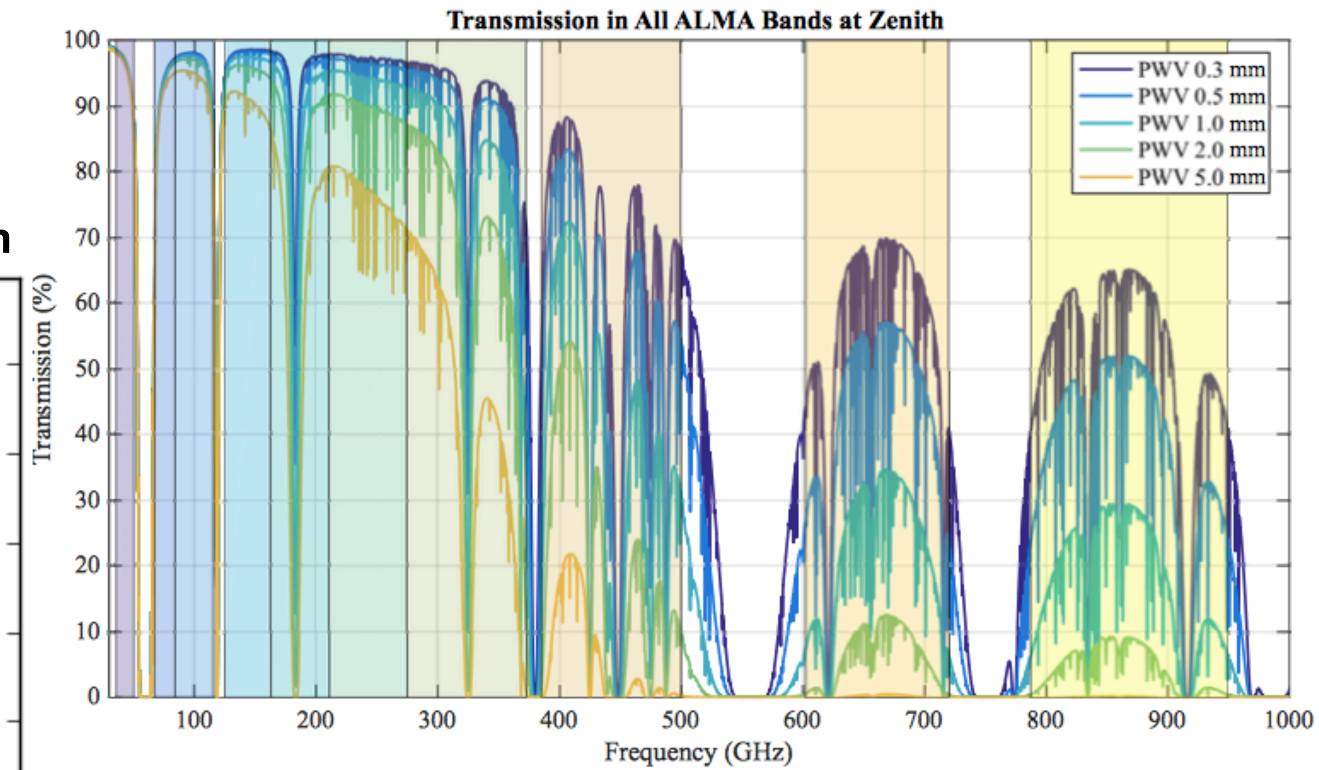
Veronesi et al in prep.

ALMA CYCLE 6: CASA - ALMA SIMULATOR

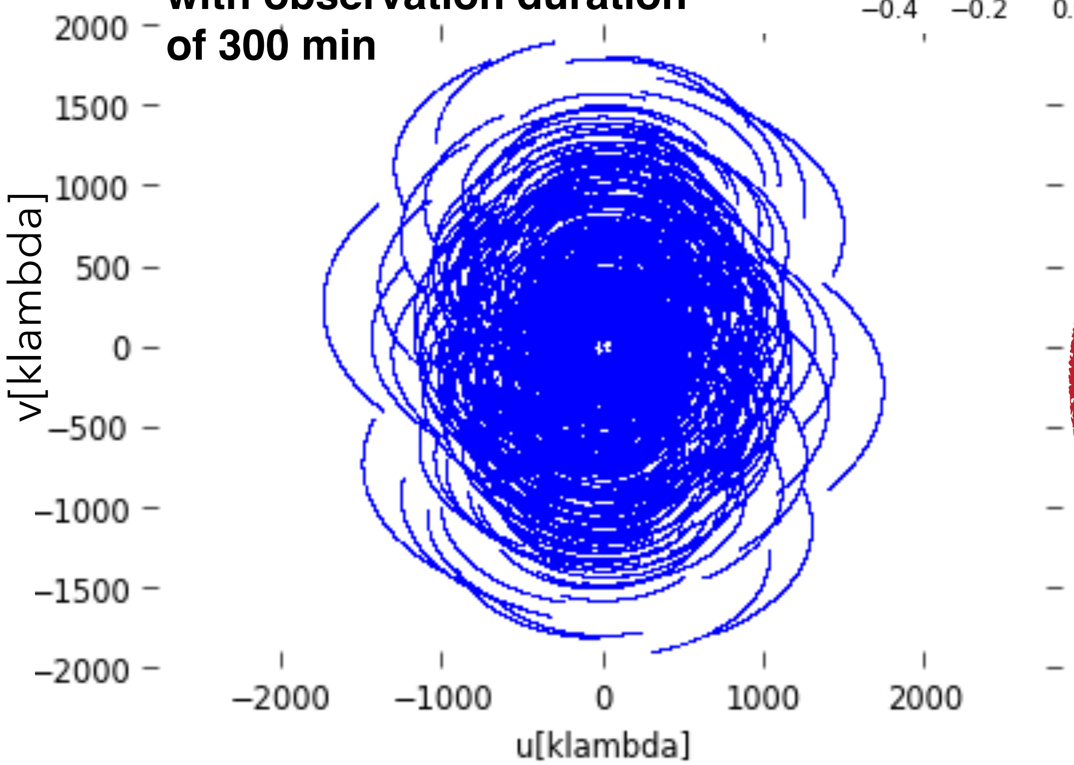


Point Spread Function

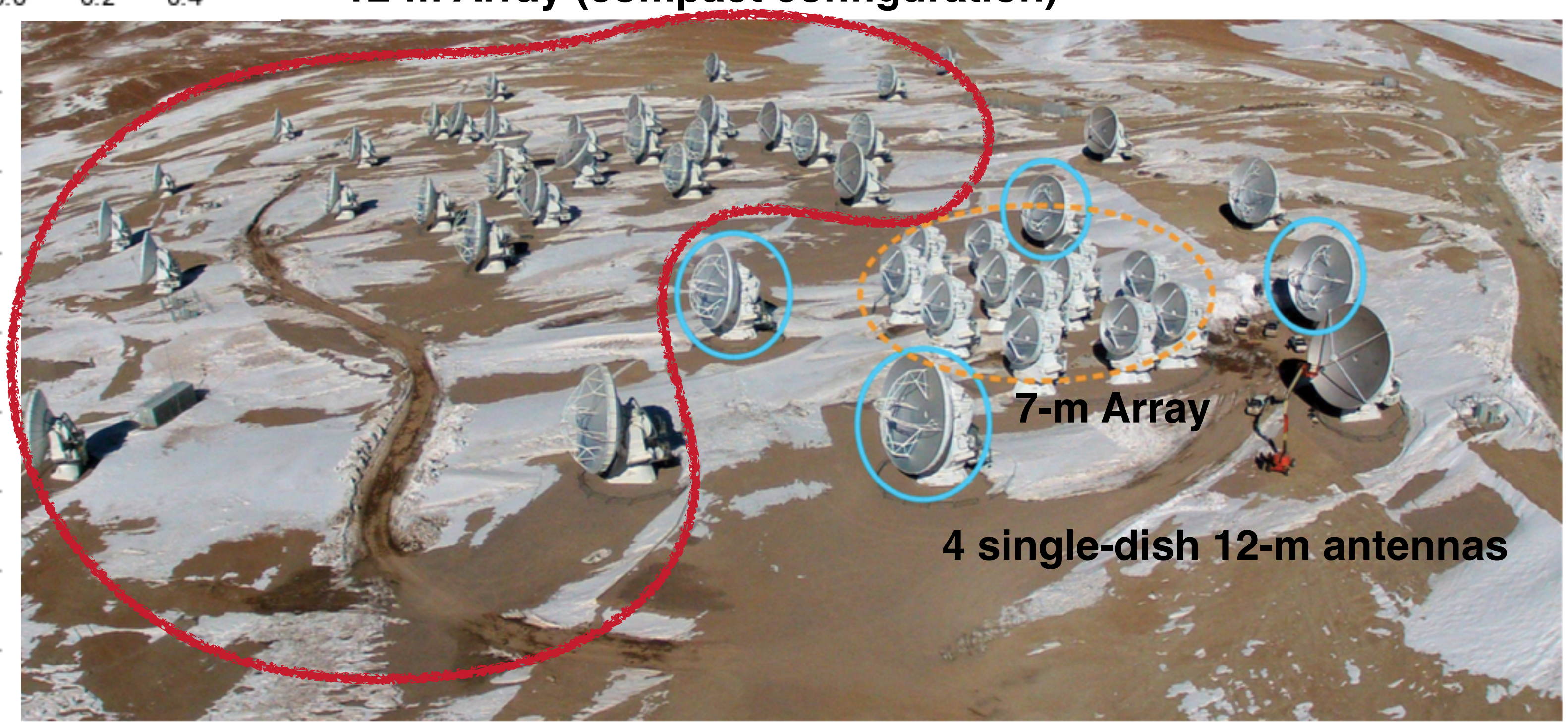


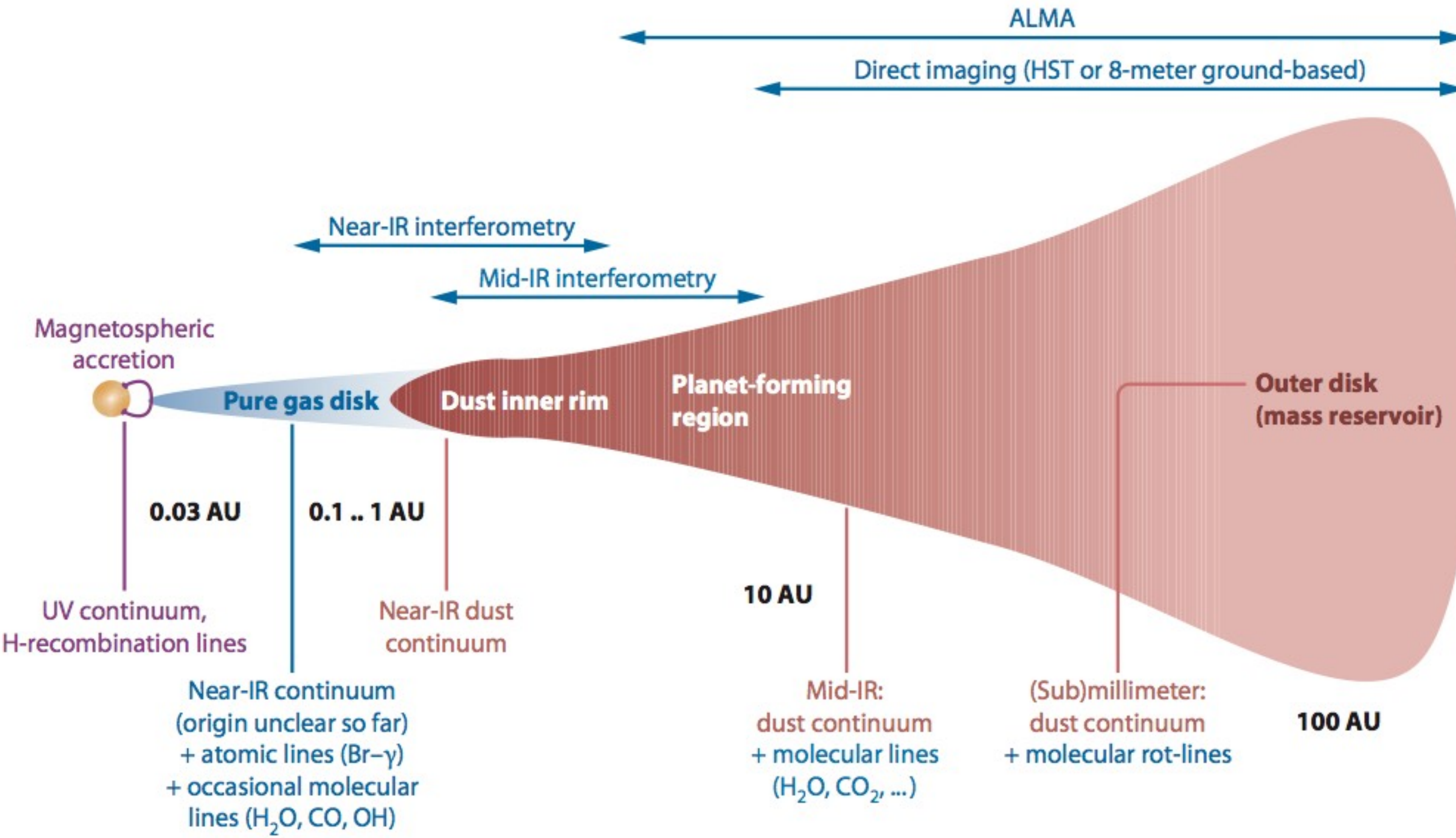


Spatial frequency coverage with observation duration of 300 min



12-m Array (compact configuration)




ALMA
Direct imaging (HST or 8-meter ground-based)
Near-IR interferometry
Mid-IR interferometry
Magnetospheric accretion
Pure gas disk
Dust inner rim
Planet-forming region
Outer disk (mass reservoir)
0.03 AU
0.1 .. 1 AU
10 AU
100 AU
UV continuum, H-recombination lines
Near-IR dust continuum
Near-IR continuum (origin unclear so far) + atomic lines (Br–γ) + occasional molecular lines (H_2O, CO, OH)
Mid-IR: dust continuum + molecular lines (H_2O, CO_2, ...)
(Sub)millimeter: dust continuum + molecular rot-lines