Surfing the spirals waves of giants: on the origin of the spiral structure in HD135344B

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PHANTOMSPH

Introduction

- *Aim of the work*: Build a smoothed particle hydrodynamics (SPH) model - based on observational data and on previous works from literature - for the **SPHERE** and **ALMA** images of the **protoplanetary disc** around the star **HD 135344B** (Fung & Dong, 2015; van der Marel et al., 2016; Stolker et al., 2016; Maire et al., 2017), trying to understand what physical phenomena gave rise to the various features we see (see Fig. 1).

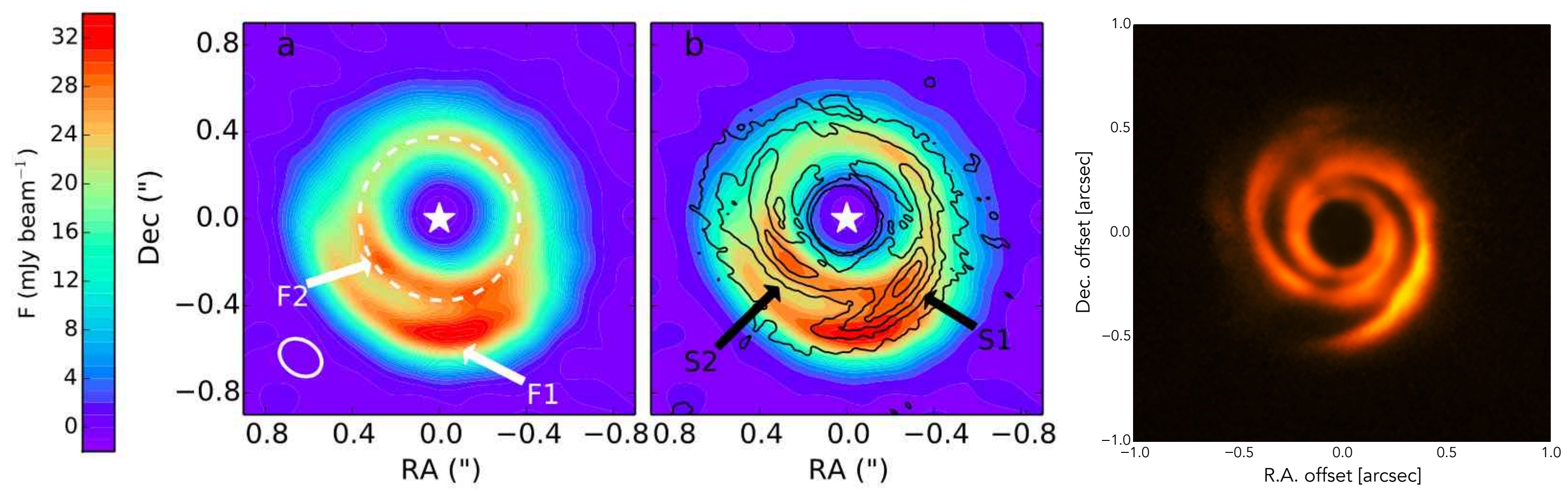

Figure 1: Two different images of HD 135344B. **Left panel**: The ALMA (Atacama Large millimeter/submillimeter Array) continuum image, in the sub-mm range, looks at the disc midplane, where sedimentation has brought larger dust grains (van der Marel et al., 2016). **Middle panel**: Superposition of the ALMA (colors) and the SPHERE (black contours line) image. **Right panel**: The SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch) image looks at the disc surface, mapping the micrometric dust, usually coupled to the gas. This is a scattered light image, in the near-IR range (Stolker et al., 2016)

About HD 135344B

HD 135344B is a Herbig Ae star, highly rotating, with a transitional disc. It has a star companion at a physical separation $> 2900\,\mathrm{AU}$.

Non-axisymmetric disc:

- **two spiral arms** seen in the SPHERE image, extending from the sub-millimeter cavity to the outer disc;
- an **inner dusty ring** particularly visible in the ALMA image;
- a **cavity** near $\sim$ **30** AU (with different dimension in dust and gas → dust filtration?);
- a southern region with an **over-density** (as we can see in the ALMA image).

Parameter	Value
Age $[\mathrm{Myr}]$	8^{+8}_{-4}
$M_* \, [M_\odot]$	1.7
Distance $[\mathrm{pc}]$	$d = 156 \pm 2$
Disc inclination	$11°$
Gas Mass $[M_\odot]$	2.4×10^{-2}
Dust Mass $[M_\odot]$	1.7×10^{-4}

Table 1: Main parameters of HD 135344B

Methods and previous models

- Study and comparison with previous models (Fig 2) → construction of a new one.
- Smoothed Particle Hydrodynamics simulation of the chosen model with **PHANTOM** (Price et al., 2017), in order to simulate the **dust-gas** and **disc-planet interactions**:
  (a) **1 fluid, gas + dust**. Micrometric and (sub-)mm grains, coupled to the gas, → $\mathrm{St} \propto \rho_d a/\Sigma_g \ll 1$.
  (b) **2 independent fluids, gas + dust**. Large grains, gas and dust are decoupled.
- Radiative transfer (**RADMC-3D**-Dullemond et al. 2012) simulation → image at infinite resolution → full resolution image convolved with a gaussian beam → image with the SPHERE/ALMA resolution.

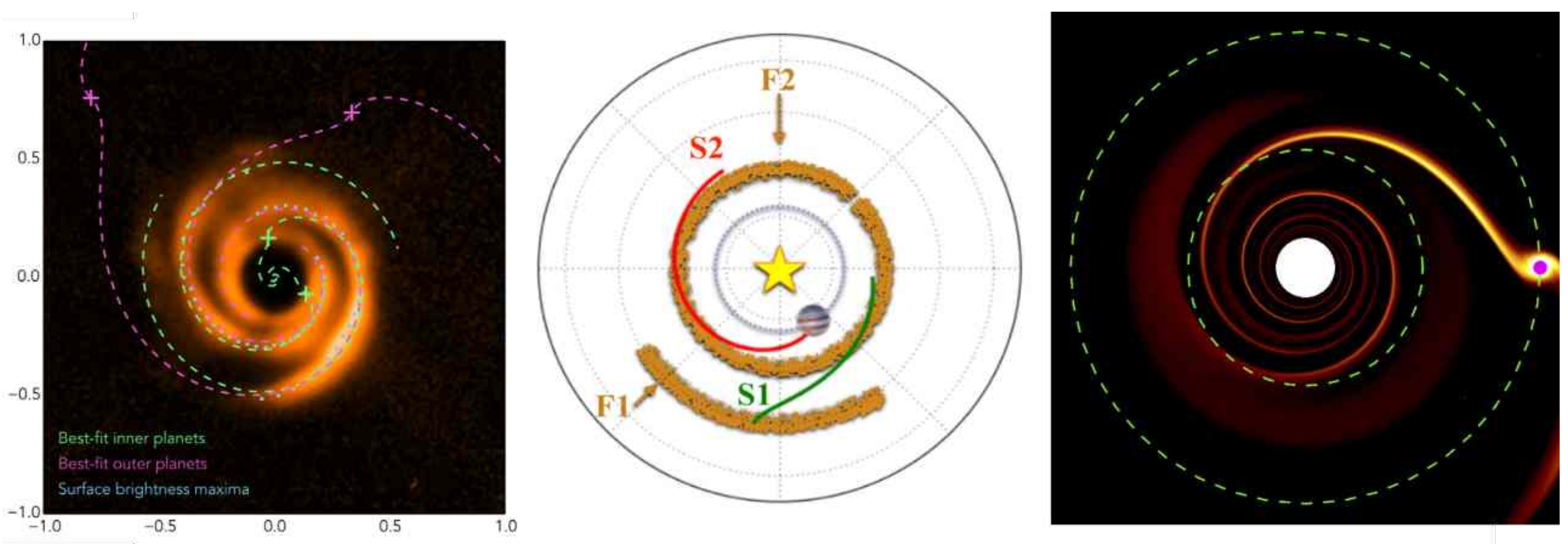

Figure 2: Previous HD 135344B disc models. From left to right: Stolker et al. (2016) fit model,van der Marel et al. (2016) model, Fung & Dong (2015) model.

Previous models:

1. **Stolker et al. (2016)**. Three zones, with different parameters (like as $H(R)/R$, disc inclination, $\Sigma(R)$). **Warped geometry** in the inner ring → shadows. Two best fit for planets; the **outer planets configuration**, two low mass outer planets at $99\,\mathrm{au}$ and $168\,\mathrm{au}$, fits better the spiral structure in the inner region. $\mathbf{M_p < (H/R)^3_p}$ (thermal mass) → **linear approximation**: each planet excites only one spiral arm.
2. **van der Marel et al. (2016)**. **Planet** at **30** au → gap → dust trap in a ring near the gap + spiral arm outwards (secondary) triggered by the planet. Inner dusty ring → **vortex dust trap** → second spiral arm inwards (primary) triggered. Model a priori excluded → required viscosity in order to maintain stable the vortex is too low, $\alpha < 10^{-4}$, to be physical (Ragusa et al., 2017).
3. **Fung & Dong (2015)**. **One massive planets** of $\mathbf{6\,M_j}$ at **100** au, instead of two low mass planets → two spiral arms (non linear approximation).

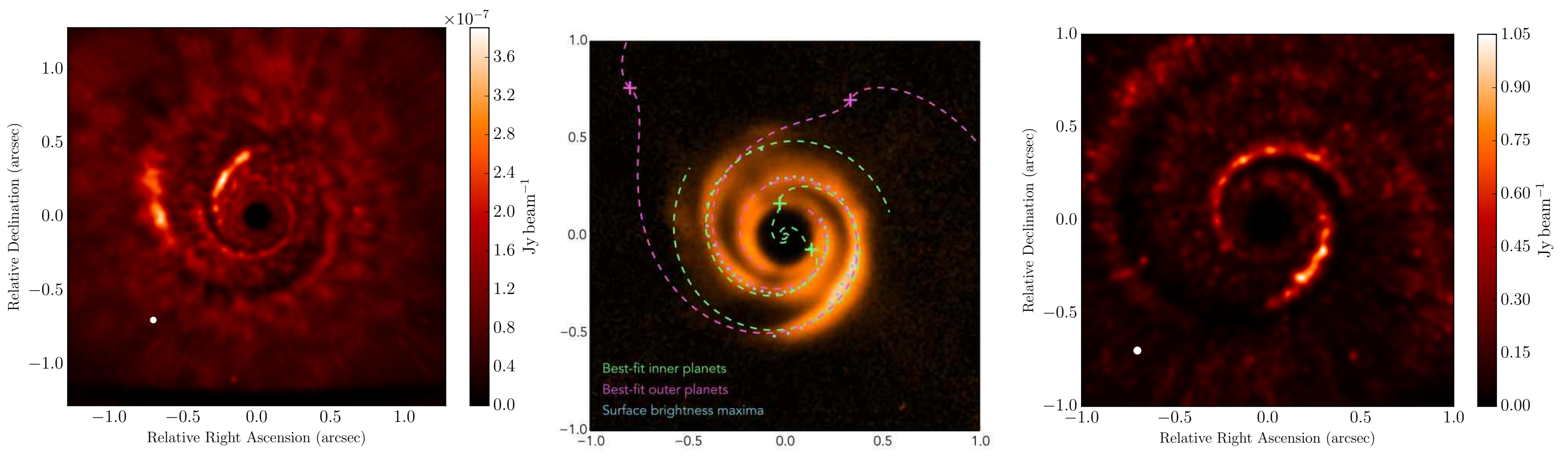

Figure 3: **Left**: RADMC-3D simulation result. SPHERE image for the Stolker et al. (2016) model. **Center** Best-fit spiral arm solutions for the protoplanets inside (green) and outside (purple) the scattered light cavity. The plus symbols indicate the positions of the best-fit protoplanets (Stolker et al., 2016). **Right**: SPHERE mock image for the Fung & Dong (2015) model.

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Results

Finally, we have explored the parameter space for the **number** of planets, their **masses** and **radius**, and the **aspect ratio**, in order to reproduce the two spiral arms, the correct spiral pitch angle (SPHERE), and at the same time the inner dusty ring with the azimuthal asymmetric feature (ALMA). In table 2 are resumed the main parameters of the system, for some of our different disc setup. In all these models we assumed that all the features seen in the system were produced by an **outer planet (OP)**, an **inner planet (IP)**. We used dust grains with a size of 0.1 cm. Moreover, we fixed some disc parameters to those of the literature (Table 1), such as the star mass and the dust to gas ratio ($d/g = 0.007$) and the viscosity ($\alpha_{ss} = 0.005$). In all the model the gas and dust density profile are assumed to be the same. In particular we chose a tapered power-law. In the table, $R_{\mathrm{in,out}}$ are the inner and outer radius of the disc.

$N°$ sim	$M_p\,[M_j]$	$R_p\,[\mathrm{au}]$	H/R_0	$R_{\mathrm{in,out}}\,[\mathrm{au}]$	$M_{\mathrm{gas}}\,[M_\odot]$	$\rho_m\,[\mathrm{g\,cm^{-3}}]$
1	$M_{\mathrm{IP}} = 7$ $M_{\mathrm{OP}} = 10$	$R_{\mathrm{IP}} = 30$ $R_{\mathrm{OP}} = 112$	0.04	$R_{\mathrm{in}} = 1$ $R_{\mathrm{out}} = 200$	0.024	3
2	$M_{\mathrm{IP}} = 4$ $M_{\mathrm{OP}} = 6$	$R_{\mathrm{IP}} = 35$ $R_{\mathrm{OP}} = 140$	0.03	$R_{\mathrm{in}} = 1$ $R_{\mathrm{out}} = 200$	0.024	1
3	$M_{\mathrm{IP}} = 4$ $M_{\mathrm{OP}} = 6$	$R_{\mathrm{IP}} = 35$ $R_{\mathrm{OP}} = 140$	0.03	$R_{\mathrm{in}} = 40$ $R_{\mathrm{out}} = 200$	0.034	1
4	$M_{\mathrm{IP}} = 4$ $M_{\mathrm{OP}} = 6$	$R_{\mathrm{IP}} = 35$ $R_{\mathrm{OP}} = 140$	0.03	$R_{\mathrm{in,d}} = 40$ $R_{\mathrm{in,g}} = 1$ $R_{\mathrm{out}} = 200$	0.034	1

Table 2: Configuration of the disc setup in Fig. 4

In the figure on the left, we reported some of our SPH simulations. In the upper row, we show the gas (micrometric dust) surface density map of the disc, while in the lower one the dust (millimetric) surface density map. The fundamental difference between the two model consists in a inner cavity already formed in the second one. Instead in the first one the cavity is in evolution. This initial condition will lead to two completely different mock images.

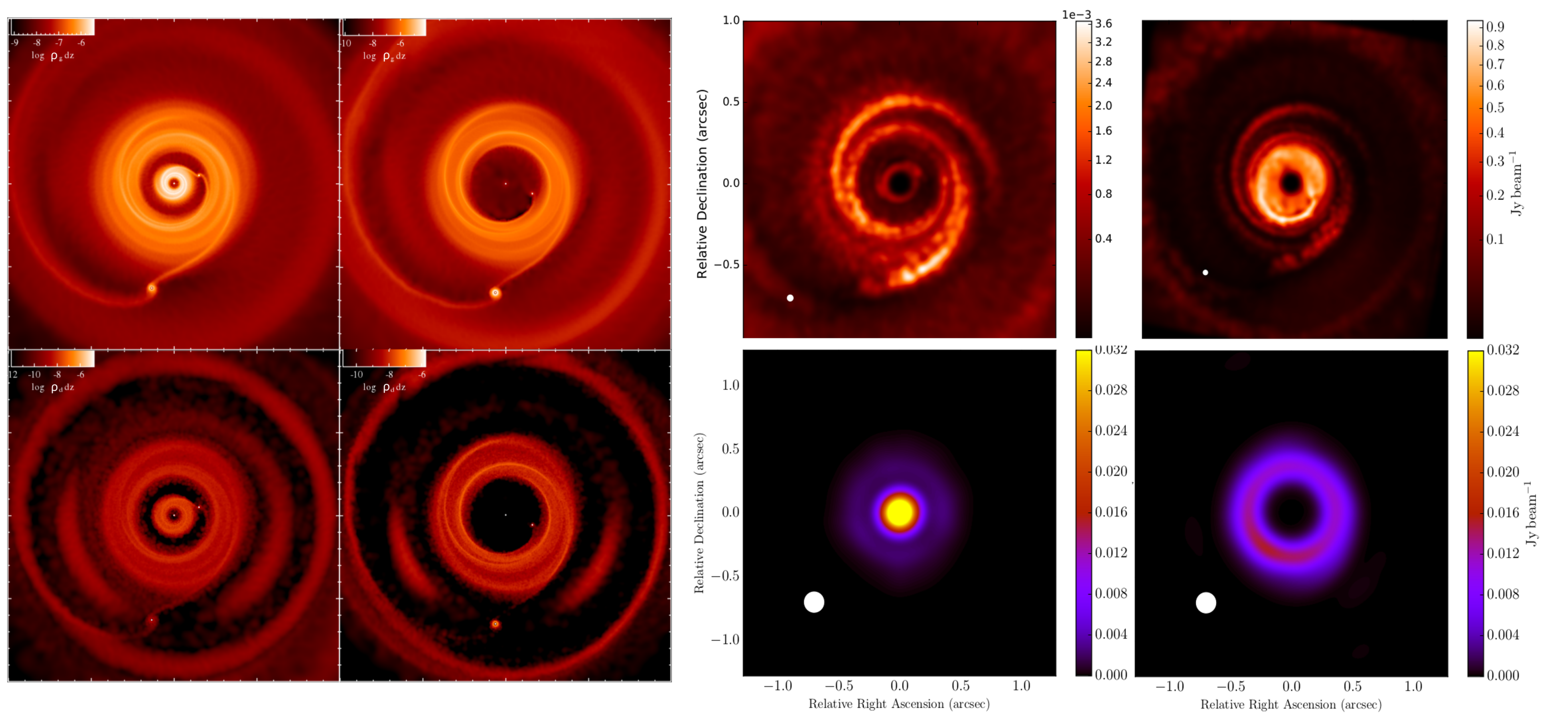

Figure 4: **Left**: Two set of SPH simulations, with the one-fluid model: left column is setup nr. 2 and right column is setup nr. 3 in Tab. 2. Top row represents the **gas** component, while the bottom row shows the **dust** one. **Right**: The mock images for SPHERE (top row) and ALMA (bottom row), for the two disc setup (left column setup nr. 2, right column setup nr. 3).

In the figure on the right, are shown the SPHERE and ALMA mock images for the SPH simulations in the previous figure. We note some interesting behavior:

- *2-setup* (left column both images): the southern spiral arm looks the same of the SPHERE data, while the secondary arm it is too long, probably due to a too massive outer planet;
- *2-setup*: not able to reproduce the ALMA image. Initial condition of our system: do not reached a completely depleted cavity in the millimetric grains (see ALMA data). ALMA do not use a mask → in the mock image is visible only the inner region of the disc.
- other effects can originate the cavity e.g. photoevaporative winds. Therefore, in order to see the outer region, we decided to use a disc model with a cavity already depleted → setup-3.
- *3-setup* (right column both images): almost all the scattered light comes from the small amount of gas still in the cavity and from the boundary of the cavity. Depleted cavity with same dimension between gas and dust component → not the correct initial condition. In literature it is assumed that there is a small inner disc around the star → masking out this big amount of scattered light we are able to see the outer spirals;
- *3-setup*: inner dusty ring well reproduced in the mock ALMA image. Not visible the peculiar outer azimuthal asymmetric feature (ALMA data). → setup-4 in preparation.

Conclusion and Outlook

We have run SPH and RADMC-3D simulations in order to reproduce the previous model we chose from literature. We find that:

- the **Stolker et al. (2016)** model ("one planet-one spiral arm") is not able to reproduce the two-armed spiral we can see in the SPHERE image. We highlight that the secondary arm is quite the same of the SHERE data (Fig-1), but the primary arm is located in a very different position → outer planet could be in the wrong position;
- the **Fung & Dong (2015)** model is the one that is more able to reproduce the characteristic spirals we see in the scattered light image. By comparing our image with the SPHERE data (**right**), we can infer that the primary arm is quite the same, instead the secondary arm is too long. This could be due to a too high mass for the planet, or to a wrong aspect ratio ($H(R)/R$). Furthermore, the radial amplitude of the two spirals seems to be in good agreement with the observational data.

Starting from these first conclusions, we build our **new model**, in order to reproduce at the same time the **SPHERE** (μm dust) and **ALMA** (sub-mm/mm dust) image. We found that:

- **one outer massive planet** ($\sim 140\,\mathrm{au}$, $M \sim 6 - 8\,M_j$), consistent with the detection limit of Maire et al. (2017), can reproduce quite well the two spiral arms we see in HD 135344B.
- in particular, the primary arm is well reproduced, showing the same intensity and pitch angle of the SPHERE data, while the secondary arm appears to be much longer than in the real data. This could be due to a too much massive planet, or to a wrong aspect ratio → in preparation a larger study of the parameters space for (e.g. $H(R)/R$, M_p, R_p);
- the inner ring feature is well reproduced by the **inner planet**, both in the SPHERE and ALMA image, while the outer azimuthal asymmetric feature does not seem to be visible in our results.