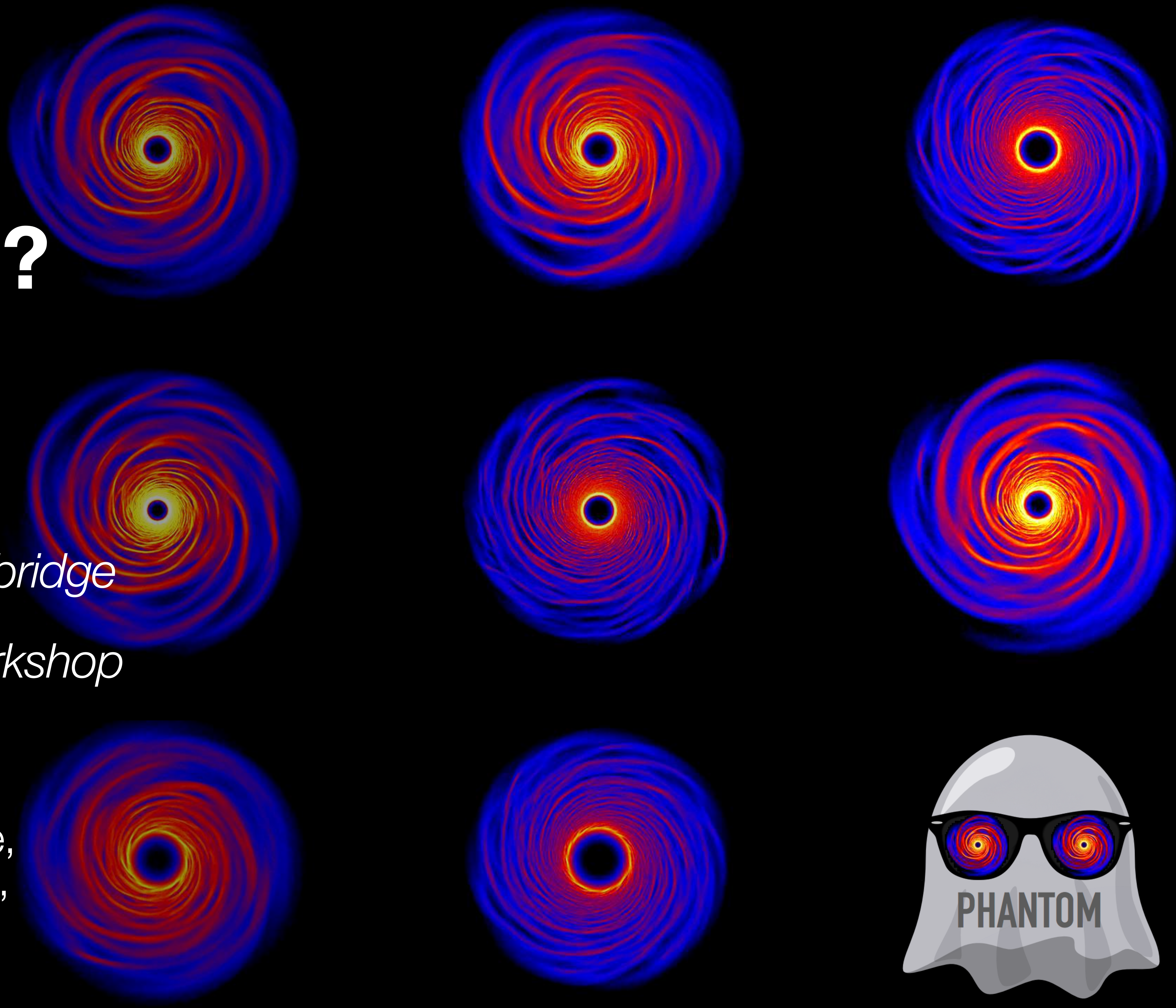
Self gravity in protostellar discs: Why (we must) care?



Cristiano Longarini
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5th PHANTOM and MCFOST Users Workshop
February 2024

Main collaborators:
Giuseppe Lodato, Cathie Clarke, Daniel Price, Philip Armitage, Simone Ceppi, Paola Martire, Benedetta Veronesi and many others

DUST BUSTERS ioa

Why?

1. Self gravity is important to understand disc structure

- Probing the disc masses and sizes
- Importance of thermal stratification
- Veronesi, Longarini et al., Martire, Longarini et al. in prep

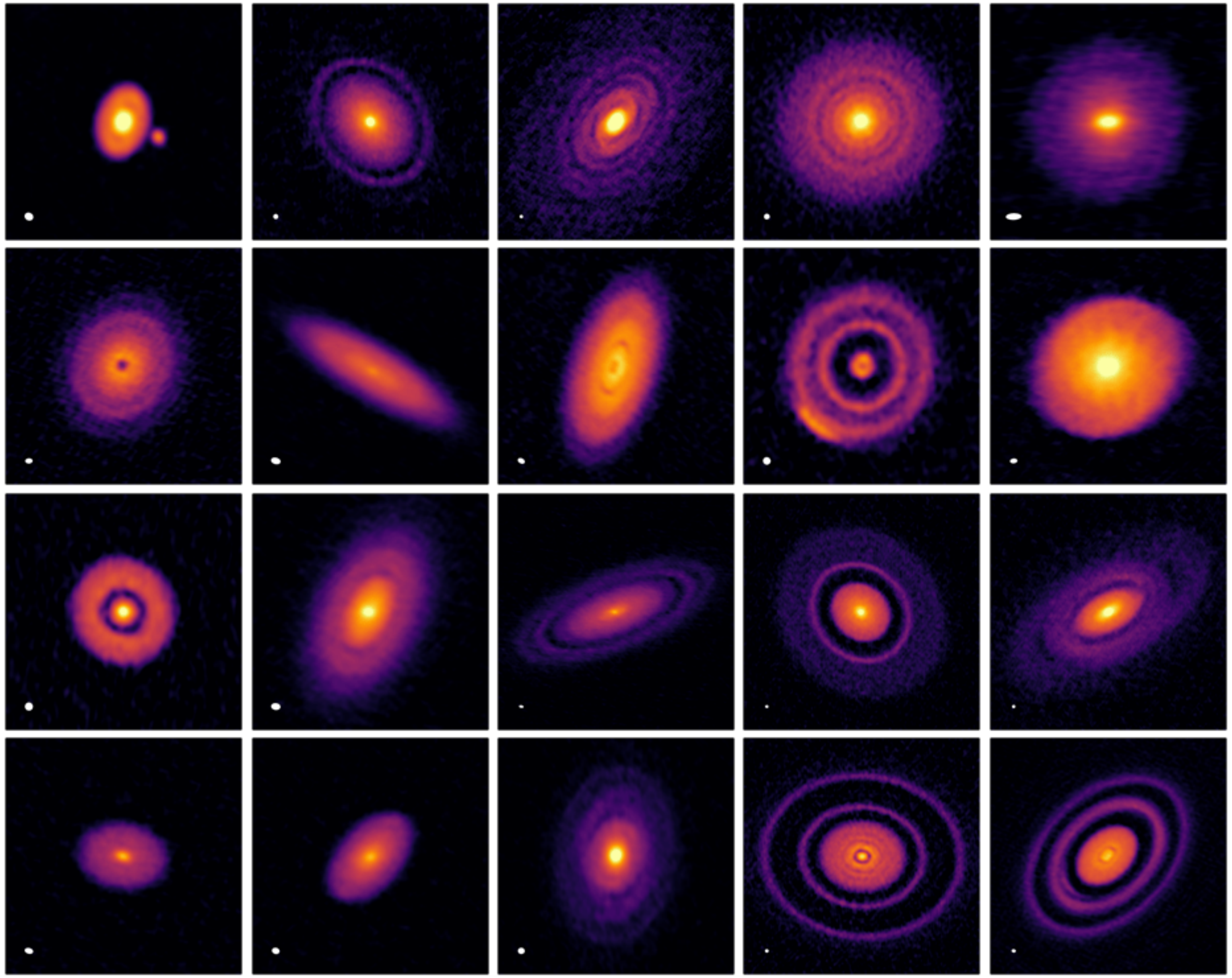
2. Self gravity contributes to planet formation in young discs

- Planetary cores formation through dust collapse
- Early evolution of planetary cores

3. Cool splash snapshots

PHANTOM

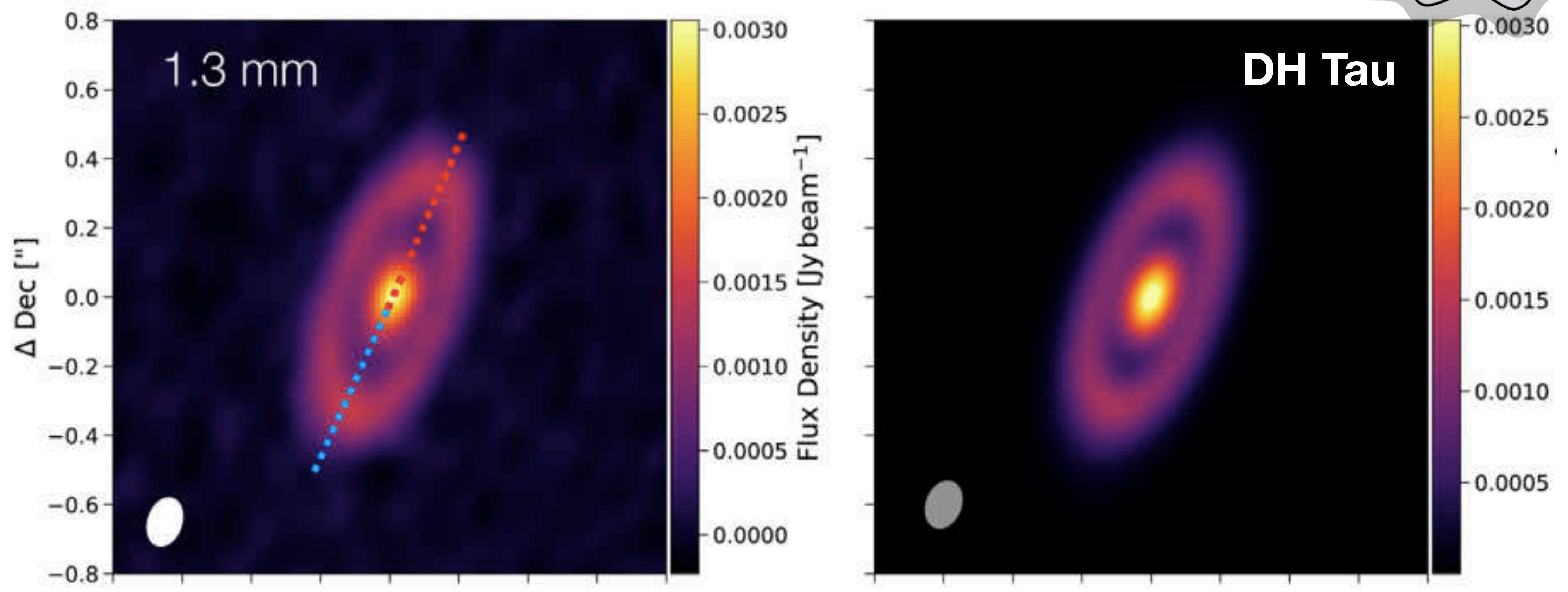
A zoo of substructures



Andrews et al. 2018

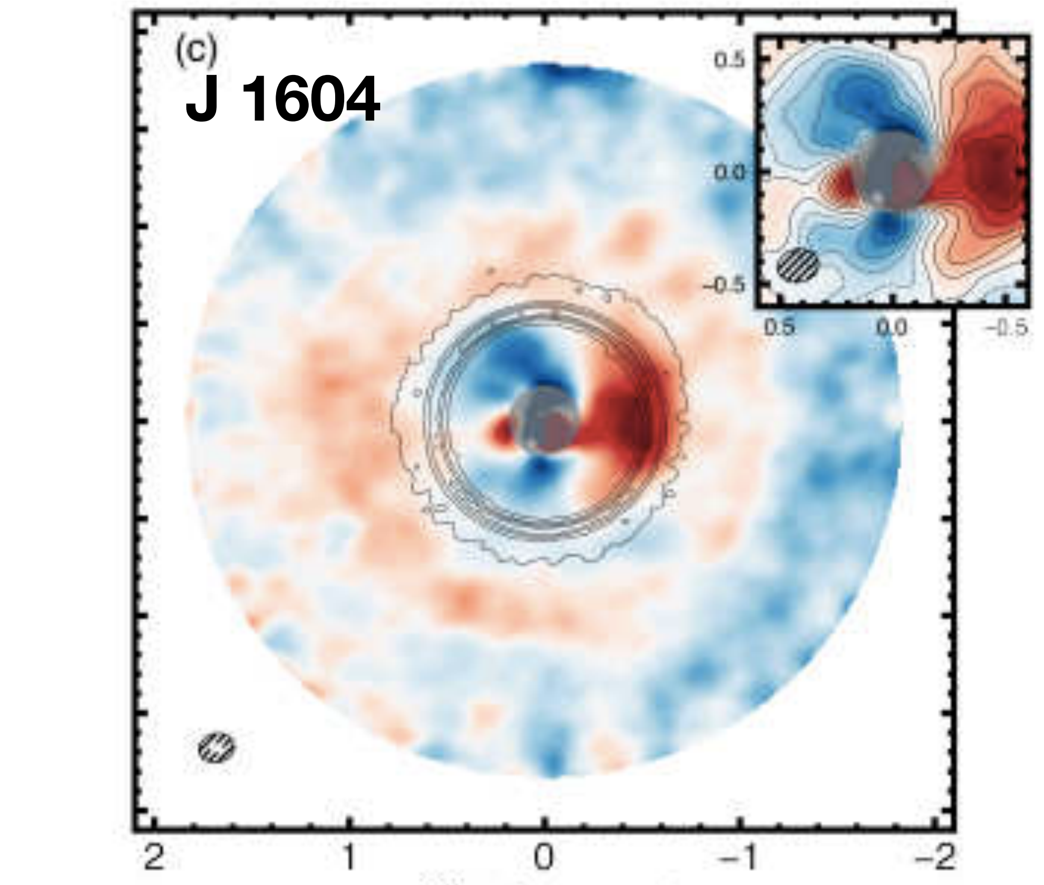
Planets?

Hydrodynamical modeling

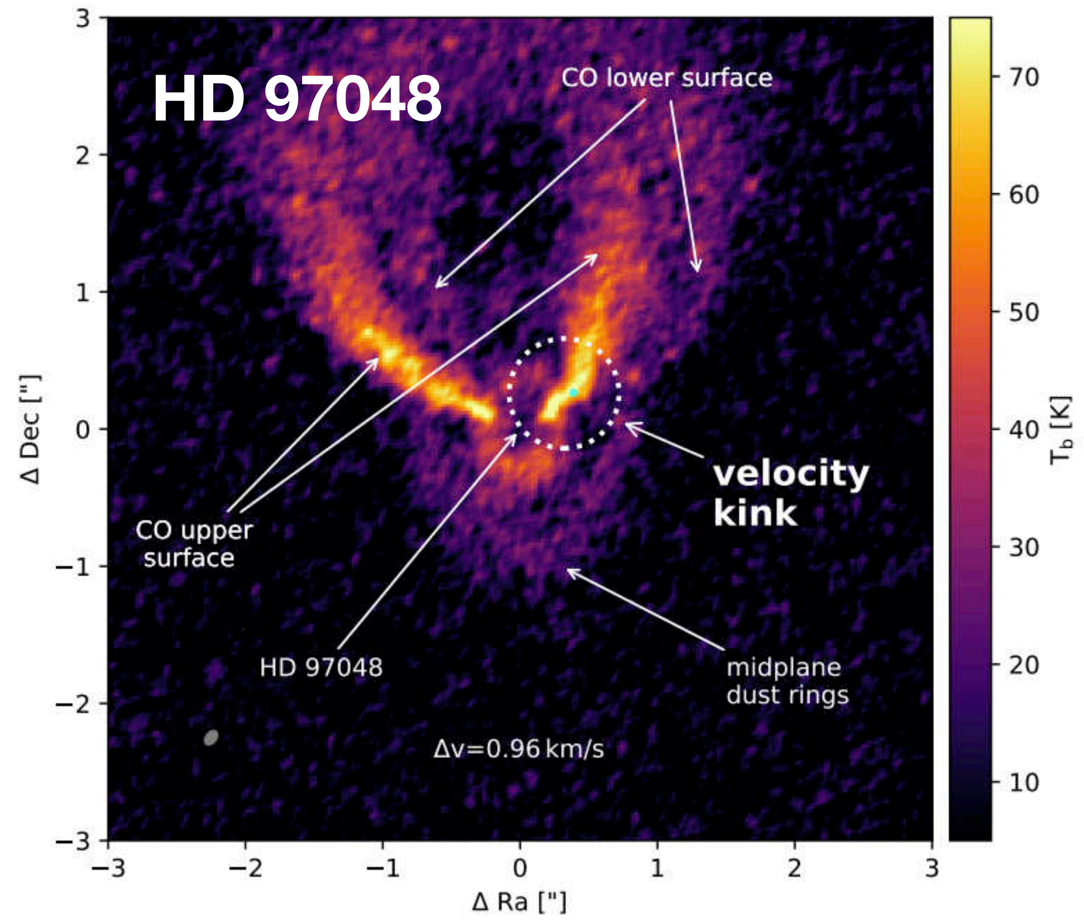


Veronesi et al. 2020

Kinematic signatures

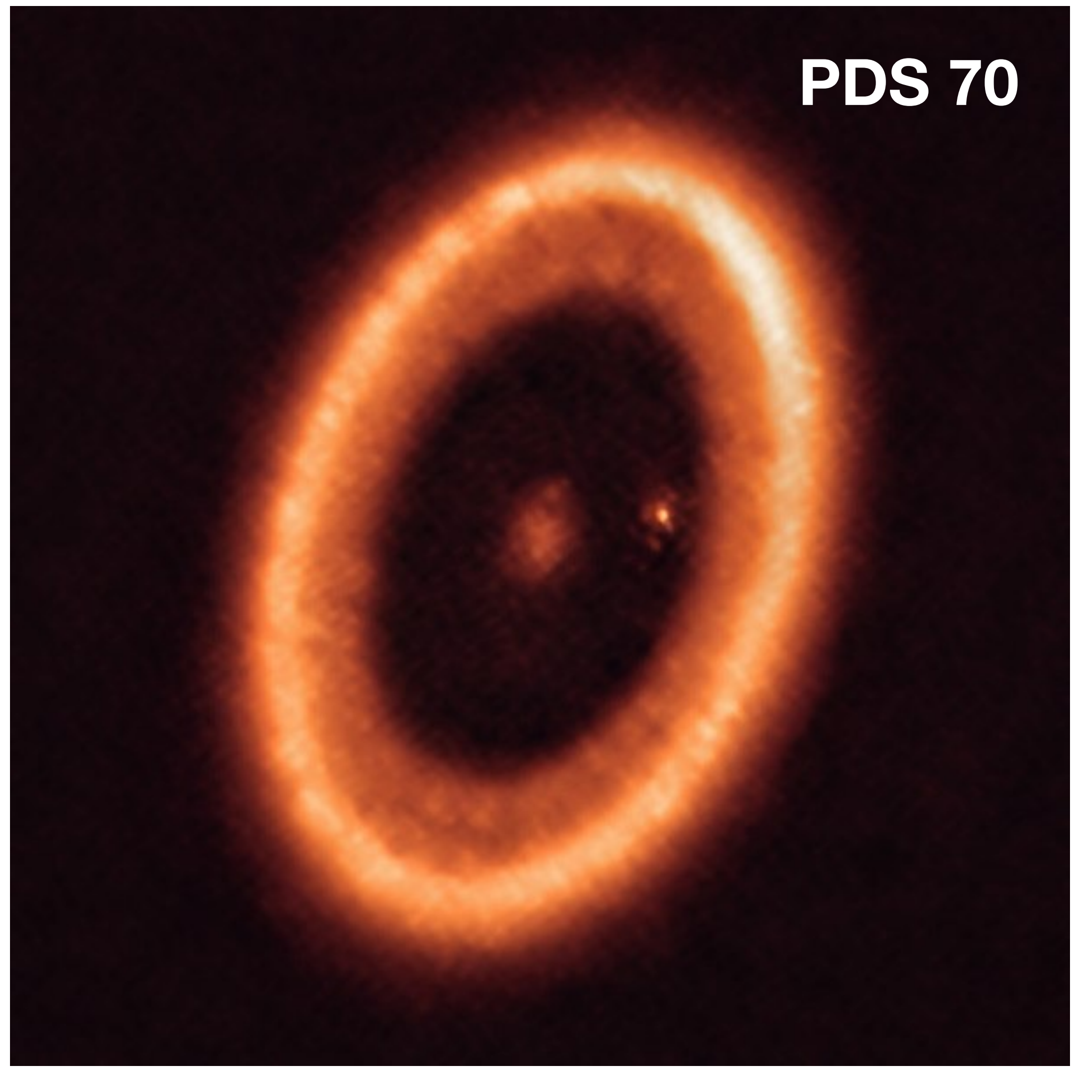


Stadler et al. 2023

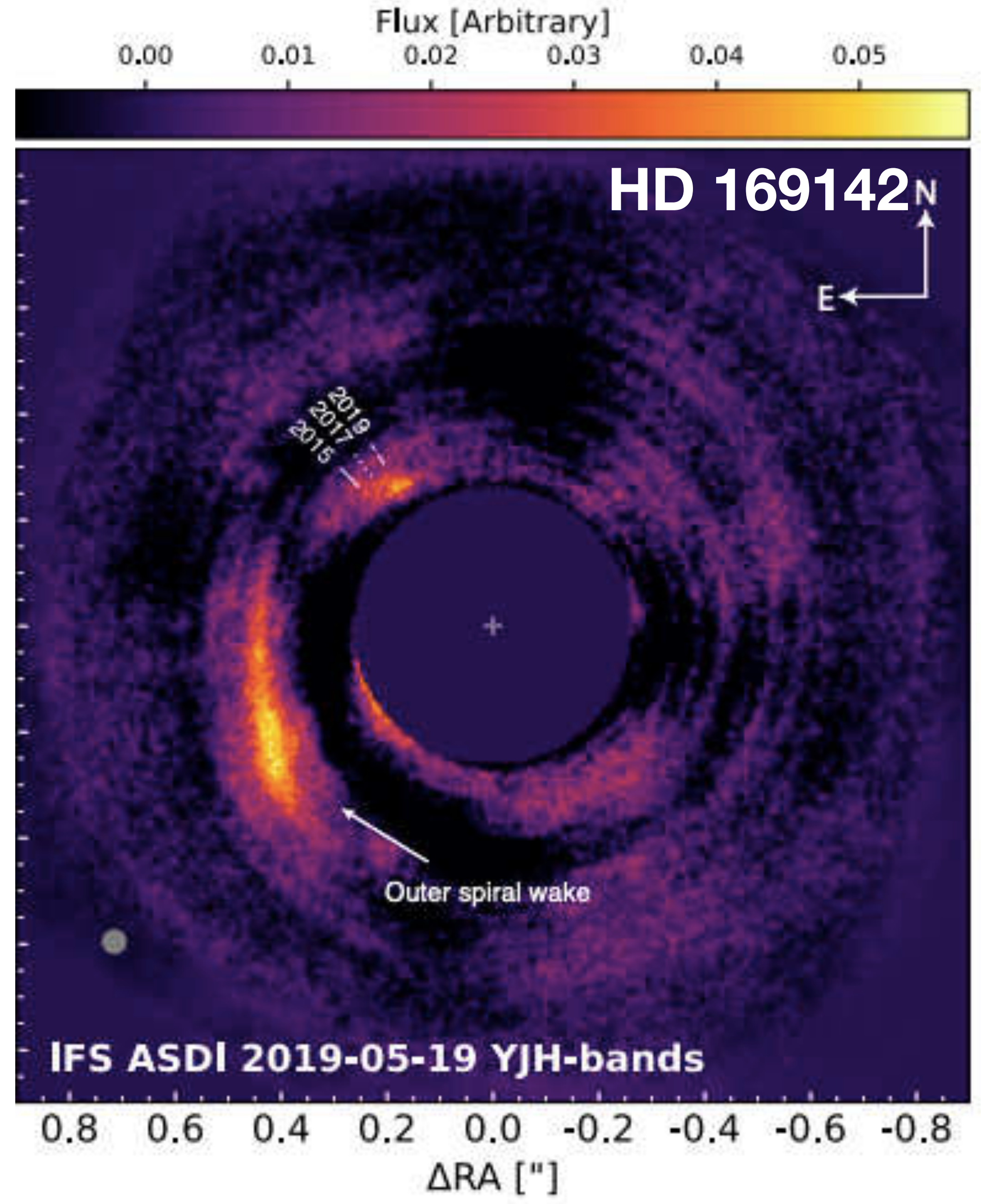


Pinte et al. 2019

Direct imaging

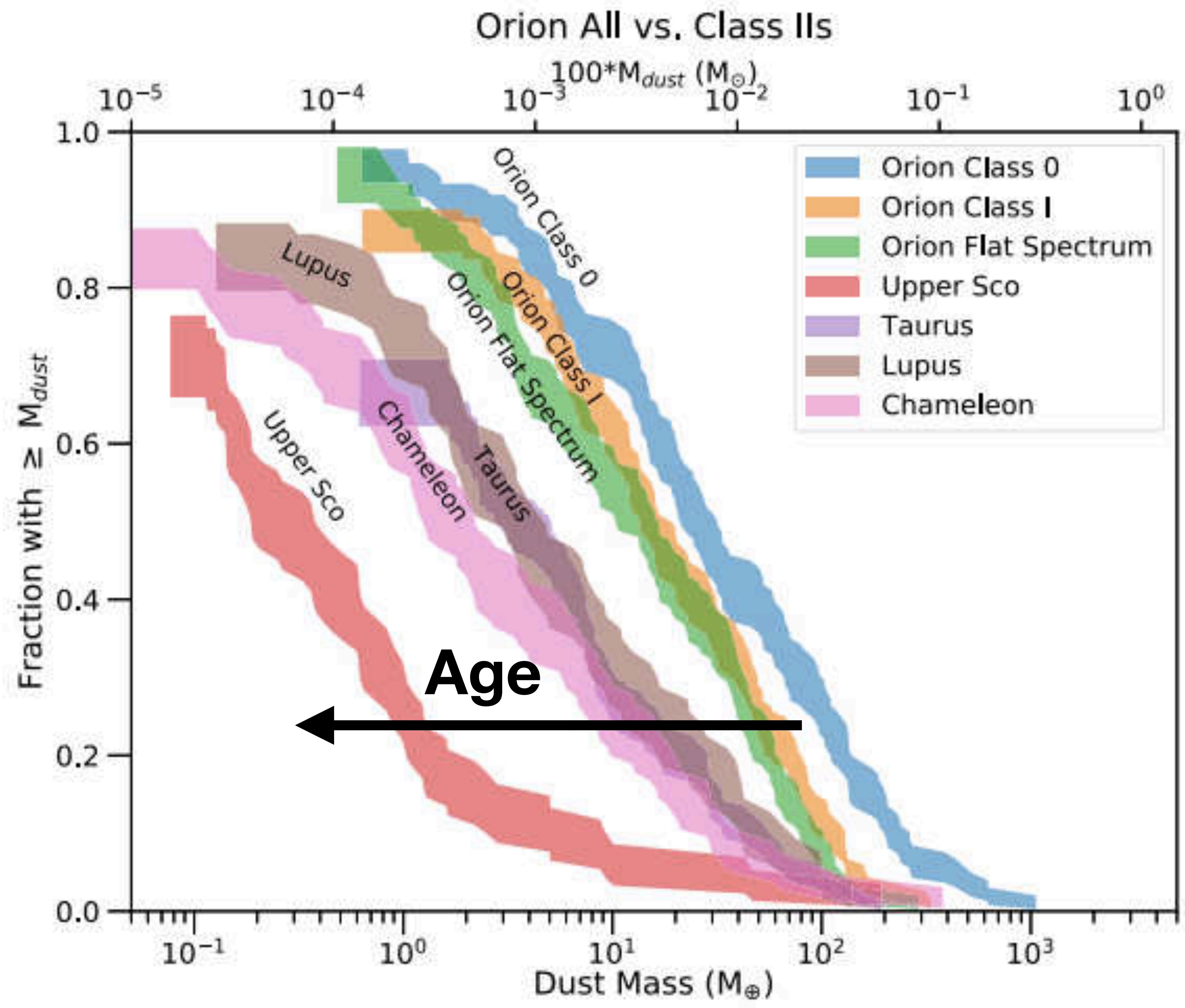


Benisty et al. 2021
Facchini et al. 2021



Hammond et al. 2023

Young protostellar discs



VANDAM Survey of Orion protostars, Tobin 2020

Evidence that in younger SFRs mm flux of ppds is higher

Possible interpretation:
younger discs are more massive

How does SG influence disc structure?

How does SG contributes to planet formation?

Self-gravity: the basic state

$$\frac{M_d}{M_\star} \gtrsim 0.05$$

$$\Phi = \Phi_\star + \Phi_d$$

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\frac{\partial}{\partial z}\left(\Phi_\star + \Phi_d\right)$$

Hydrostatic height of a SG disc is different

$$H_{sg} = \frac{c^2}{\pi G \Sigma}$$

Centrifugal balance

$$\frac{v_\phi^2}{R} = \frac{\partial\left(\Phi_\star + \Phi_d\right)}{\partial R} + \frac{1}{\rho}\frac{\partial P}{\partial R}$$

Super Keplerian correction to the rotation curve

$$\propto M_d/M_\star$$

Rotation curve

$$v_\phi^2 = \underbrace{R\frac{\partial \Phi_\star}{\partial R}}_{\text{Star}} + \underbrace{R\frac{\partial \Phi_d}{\partial R}}_{\text{Disc}} + \underbrace{\frac{R}{\rho}\frac{\partial P}{\partial R}}_{\text{Pressure gradient}}$$

Star contribution:

Keplerian contribution at the position (R,z)

$$R\frac{\partial \Phi_\star}{\partial R} = \frac{GM_\star R^2}{(R^2 + z^2)^{3/2}}$$

Lodato et al. 2023

Rotation curve

Disc contribution:

$$R\frac{\partial \Phi_d}{\partial R} = G\int_0^\infty \left[K(k) - \frac{1}{4}\left(\frac{k^2}{1-k^2}\right)\left(\frac{R'}{R} - \frac{R}{R'} + \frac{z^2}{RR'}\right)E(k)\right]\sqrt{\frac{r}{R}}k\Sigma\left(R'\right)\mathrm{d}R'$$

Disc mass and size dependance in the surface density (self similar hp)

$$\Sigma(R) = \frac{M_d(2-\gamma)}{2\pi R_c^2}\left(\frac{R}{R_c}\right)^{-\gamma}\exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

Bertin & Lodato 1999

Rotation curve

Pressure gradient:

Vertically isothermal disc

$$P = c_s^2(R)\rho(R,z), \quad \rho(R,z) = \rho_{mid}(R)\exp\left[-\frac{R^2}{H^2}\left(1 - \frac{1}{\sqrt{1+z^2/R^2}}\right)\right]$$

After algebra…

$$v_\phi^2 = v_K^2\left\{1 - \left[\gamma' + (2-\gamma)\left(\frac{R}{R_c}\right)^{2-\gamma}\right]\left(\frac{H}{R}\right)^2 - q\left(1 - \frac{1}{\sqrt{1+(z/R)^2}}\right)\right\} + v_d^2$$

Lodato et al. 2023

Rotation curve

$$v_\phi^2 = v_\mathrm{K}^2 \left\{ 1 - \left[\gamma' + (2-\gamma)\left(\frac{R}{R_\mathrm{c}}\right)^{2-\gamma} \right] \left(\frac{H}{R}\right)^2 - q\left(1 - \frac{1}{\sqrt{1+(z/R)^2}}\right) \right\} + v_d^2$$

If we measure

- height emitting layer $z(R)$

If we assume

- thermal structure H/R, q
- surface density profile γ

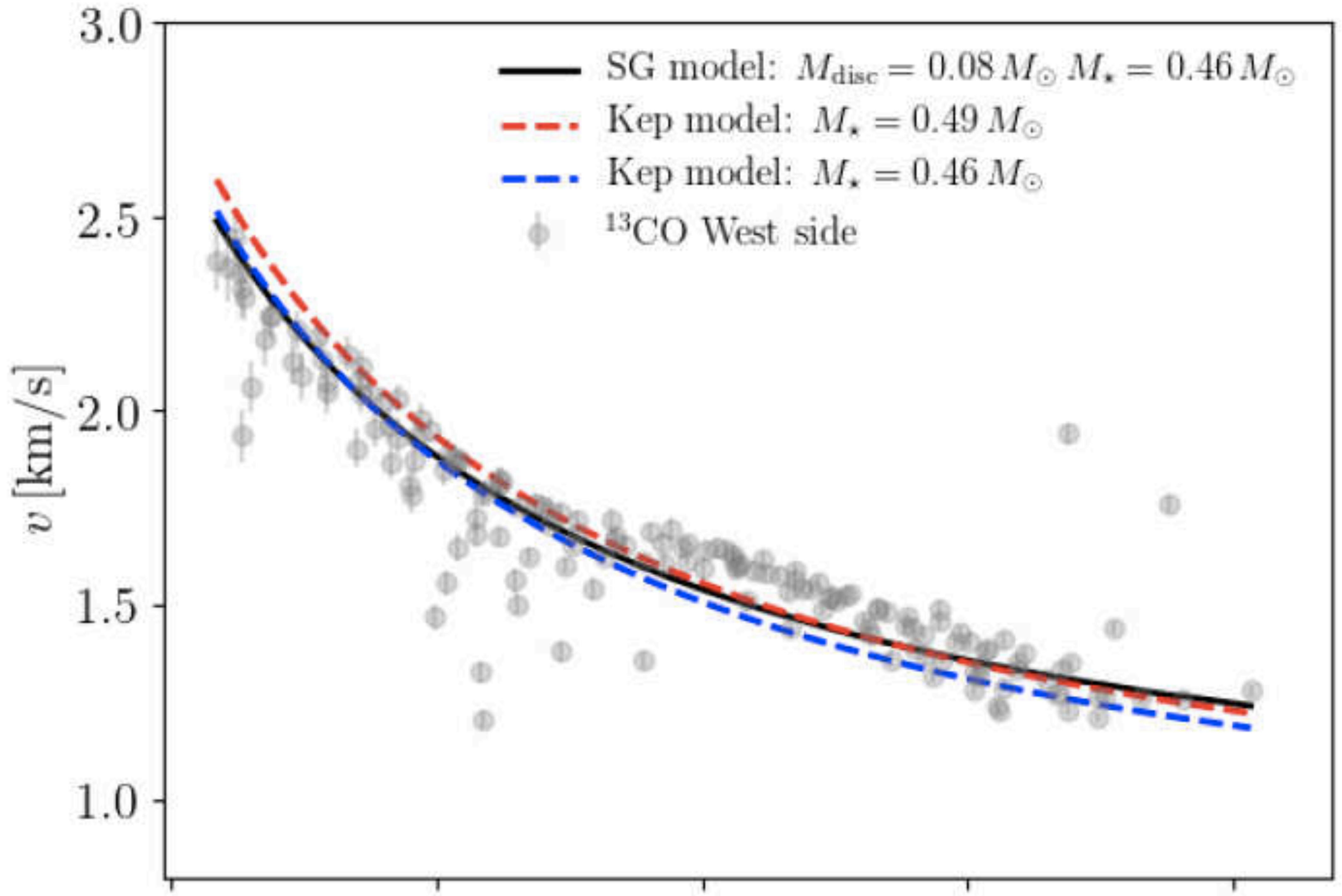
→

We can fit for

- star mass $M_\star$
- disc mass M_d
- scale radius R_c

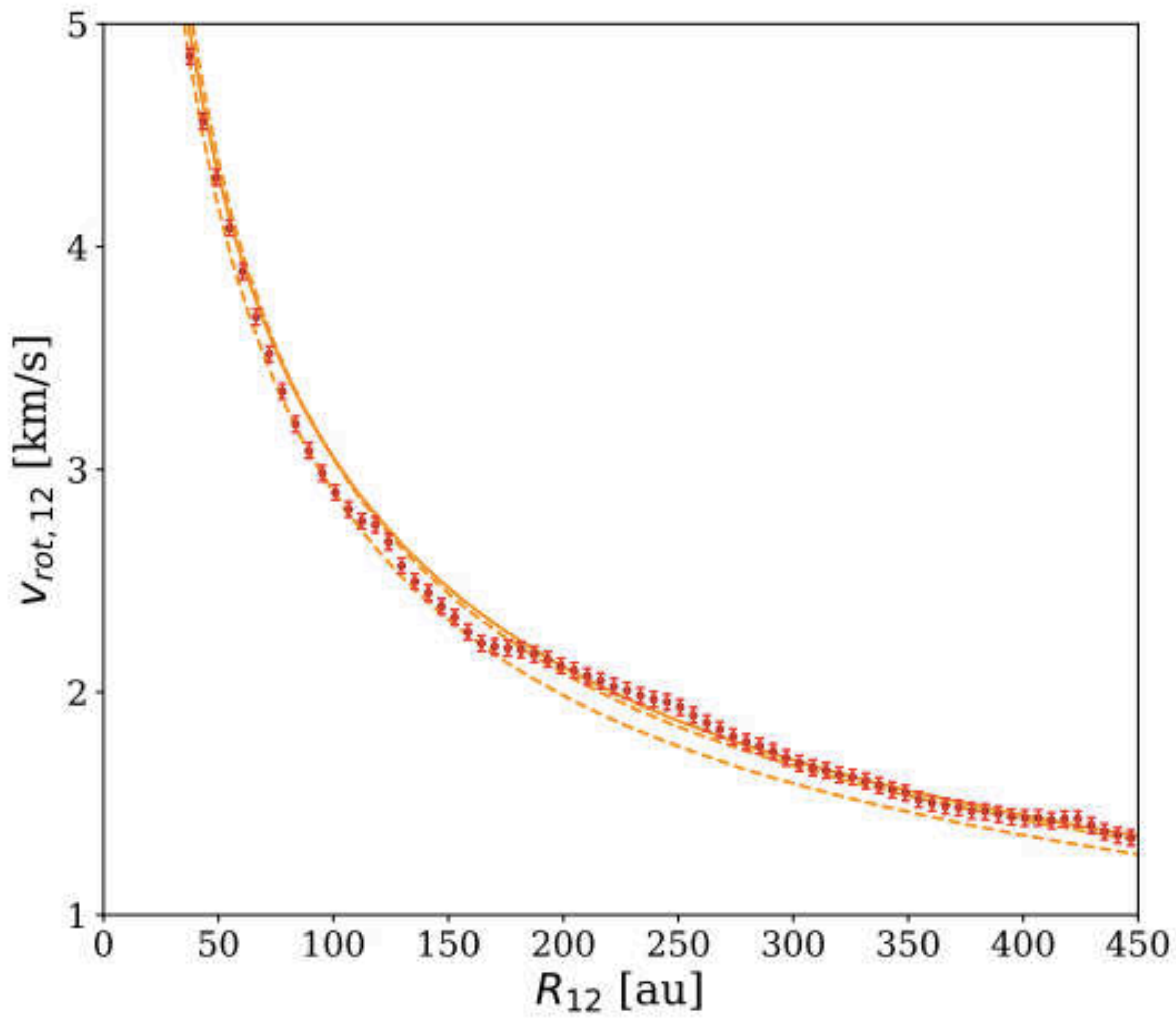
Veronesi et al. 2021
Lodato et al. 2023
Veronesi et al. subm.
Martire et al. subm

Dynamical masses and sizes



Elias 2-27

$M_d/M_\star \simeq 17\,\%$



IM Lup

$M_d/M_\star \simeq 10\,\%$

Veronesi et al. 2021

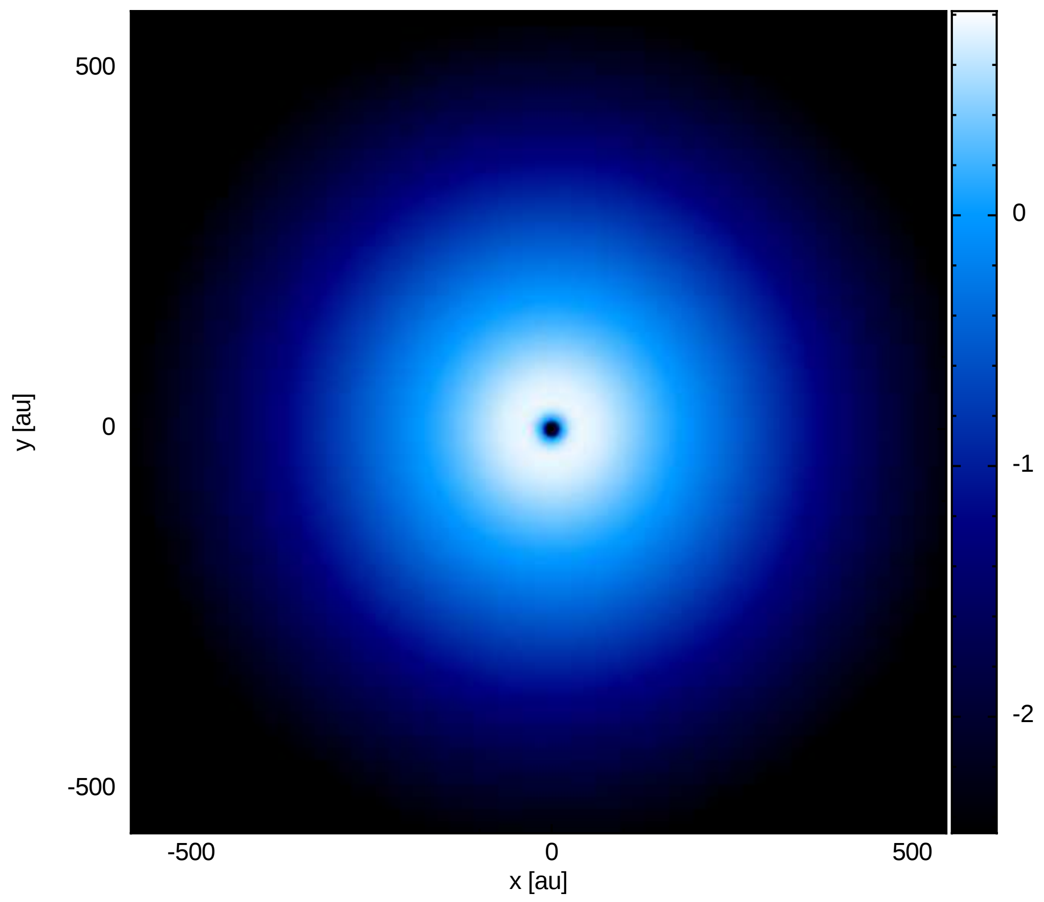
Lodato et al. 2023

Benchmarking the method

PHANTOM
hydrodynamics

SG gas discs, no GI (*isosgdisc*)
Vertically isothermal discs, self similar profile with $R_c = 100$au

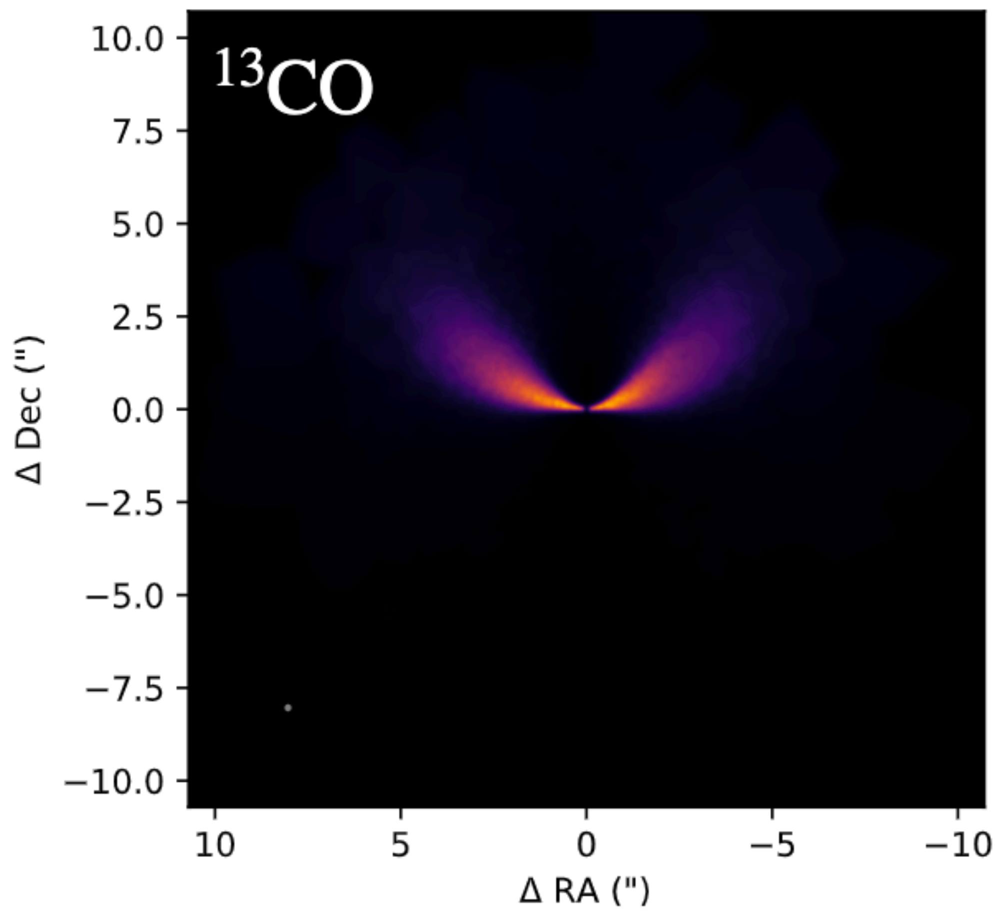
$M_d \in [0.01, 0.2]$M$_\odot$



MCFOST
radiative transfer

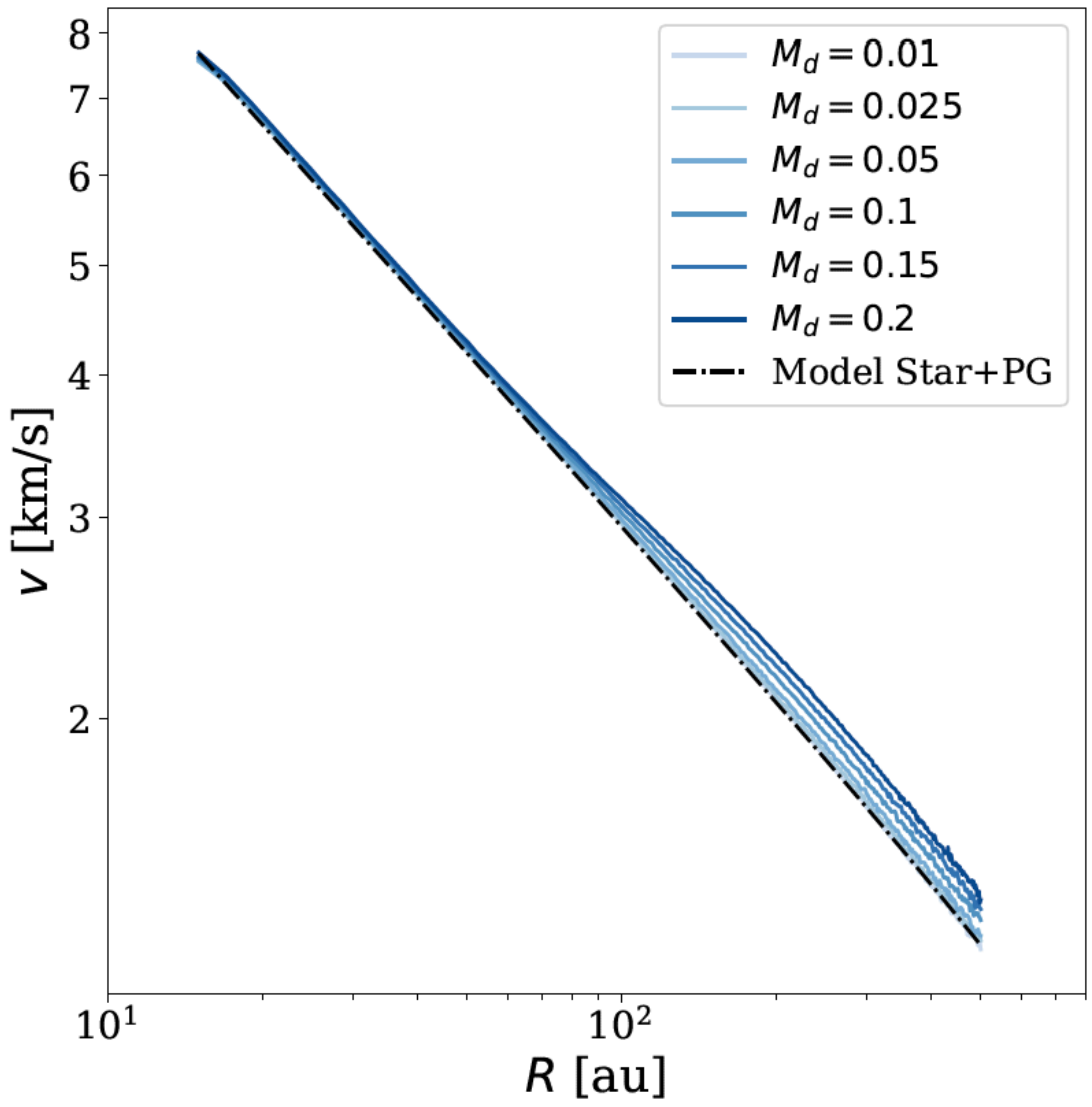
Datacubes of
12CO, 13CO J=2-1

pymcfost: "pseudocasa"
$\Delta x = 0.1''$, $\Delta v = 100$m/s



Veronesi, Longarini et al. subm

Model verification - hydro curves



Extraction of the hydro azimuthal velocity at the midplane

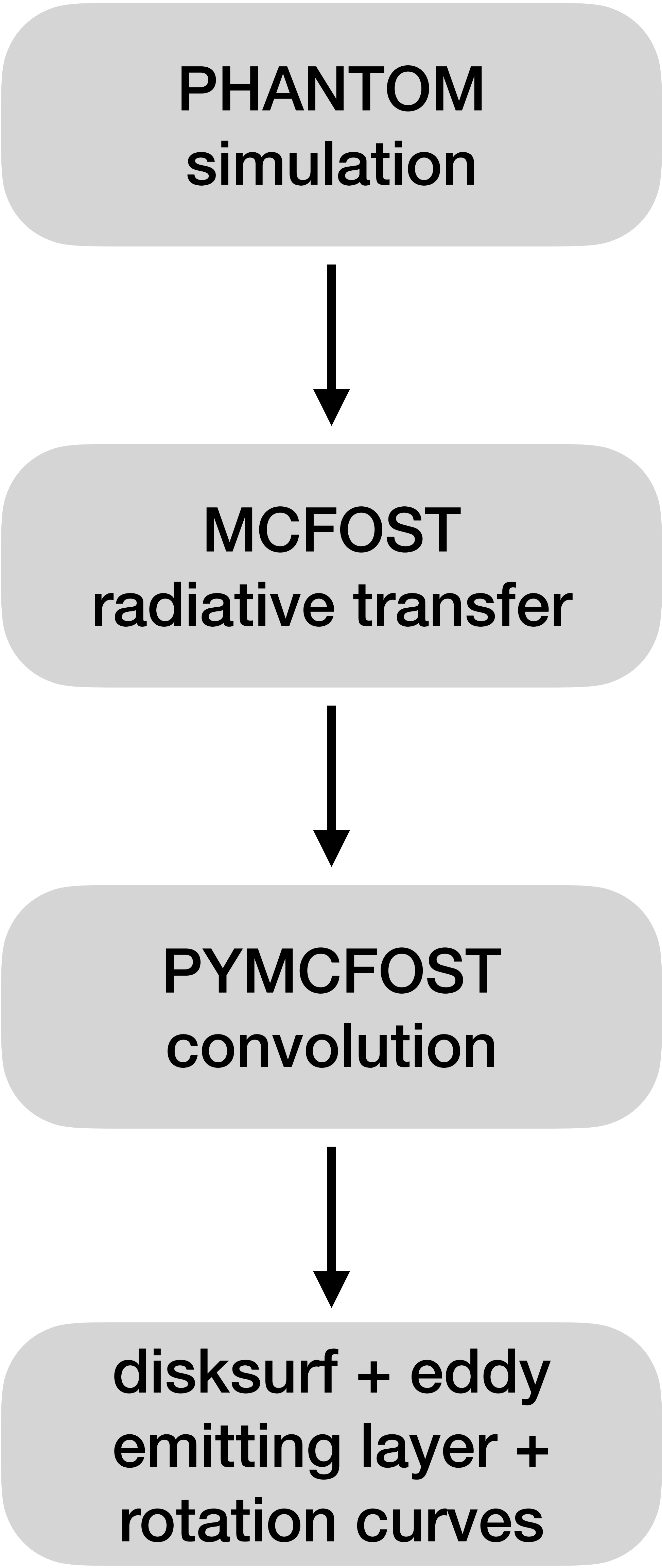
- correct scaling with disc mass
- **Visible** differences from a non SG model only for $M_d/M_\star > 0.05$

Sims	M_d [$\mathrm{M}_\odot$]
md0.2	0.19
md0.15	0.14
md0.1	0.1
md0.05	0.05
md0.025	0.028
md0.01	0.017

Results of the fitting procedure on hydro curves

Veronesi, Longarini et al. subm

Complete procedure



Results of the fitting procedure: $M_\star, M_d, R_c$

	^{12}CO	$\Delta X/X_{^{12}\mathrm{CO}}$	^{13}CO	$\Delta X/X_{^{13}\mathrm{CO}}$	Combined	$\Delta X/X_{\mathrm{comb}}$
md0.01	$M_\star = 1.02$	0.02	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01
	$M_d = 0.03$	1.99	$M_d = 0.00$	1.0	$M_d = 0.00$	1.0
	$R_c = 80.00$	0.2	$R_c = 105.15$	0.05	$R_c = 103.7$	0.037
md0.025	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01
	$M_d = 0.04$	0.6	$M_d = 0.00$	1.0	$M_d = 0.00$	1.0
	$R_c = 92.17$	0.078	$R_c = 115.55$	0.15	$R_c = 115.2$	0.15
md0.05	$M_\star = 0.99$	0.01	$M_\star = 0.97$	0.03	$M_\star = 0.98$	0.02
	$M_d = 0.044$	0.12	$M_d = 0.07$	0.4	$M_d = 0.055$	0.099
	$R_c = 102.78$	0.028	$R_c = 94.27$	0.057	$R_c = 97.8$	0.022
md0.1	$M_\star = 1.04$	0.04	$M_\star = 0.97$	0.03	$M_\star = 0.97$	0.03
	$M_d = 0.09$	0.10	$M_d = 0.12$	0.20	$M_d = 0.12$	0.19
	$R_c = 88.33$	0.117	$R_c = 90.8$	0.09	$R_c = 91.2$	0.088
md0.15	$M_\star = 1.00$	0.0	$M_\star = 1.00$	0.0	$M_\star = 1.00$	0.0
	$M_d = 0.18$	0.2	$M_d = 0.15$	0.0	$M_d = 0.15$	0.0
	$R_c = 86.00$	0.14	$R_c = 87.5$	0.125	$R_c = 88.114$	0.12
md0.2	$M_\star = 1.1$	0.1	$M_\star = 1.06$	0.06	$M_\star = 1.12$	0.12
	$M_d = 0.165$	0.175	$M_d = 0.15$	0.25	$M_d = 0.09$	0.55
	$R_c = 87.26$	0.13	$R_c = 84.9$	0.15	$R_c = 96.23$	0.037

Veronesi et al. subm.

Complete procedure

PHANTOM simulation

↓

MCFOST radiative transfer

↓

PYMCFOST convolution

↓

disksurf + eddy emitting layer + rotation curves

Results of the fitting procedure: $M_\star, M_d, R_c$

	^{12}CO	$\Delta X/X_{^{12}CO}$	^{13}CO	$\Delta X/X_{^{13}CO}$	Combined	$\Delta X/X_{comb}$
md0.01	$M_\star = 1.02$	0.02	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01
	$M_d = 0.03$	1.99	$M_d = 0.00$	1.0	$M_d = 0.00$	1.0
	$R_c = 80.00$	0.2	$R_c = 105.15$	0.05	$R_c = 103.7$	0.037
md0.025	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01	$M_\star = 0.99$	0.01
	$M_d = 0.04$	0.6	$M_d = 0.00$	1.0	$M_d = 0.00$	1.0
	$R_c = 92.17$	0.078	$R_c = 115.55$	0.15	$R_c = 115.2$	0.15
md0.05	$M_\star = 0.99$	0.01	$M_\star = 0.97$	0.03	$M_\star = 0.98$	0.02
	$M_d = 0.044$	0.12	$M_d = 0.07$	0.4	$M_d = 0.055$	0.099
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md0.1	$M_\star = 1.04$	0.04	$M_\star = 0.97$	0.03	$M_\star = 0.97$	0.03
	$M_d = 0.09$	0.10	$M_d = 0.12$	0.20	$M_d = 0.12$	0.19
	$R_c = 88.33$	0.117	$R_c = 90.8$	0.09	$R_c = 91.2$	0.088
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	$M_d = 0.18$	0.2	$M_d = 0.15$	0.0	$M_d = 0.15$	0.0
	$R_c = 86.00$	0.14	$R_c = 87.5$	0.125	$R_c = 88.114$	0.12
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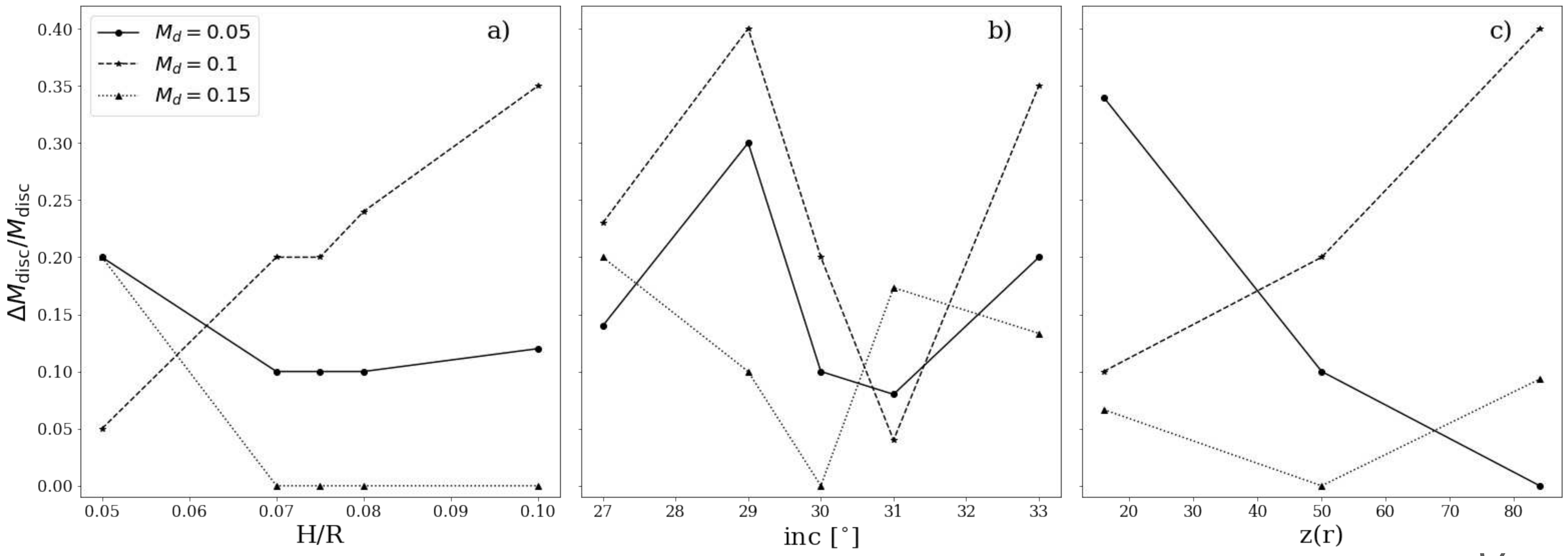
	$M_d = 0.165$	0.175	$M_d = 0.15$	0.25	$M_d = 0.09$	0.55
	$R_c = 87.26$	0.13	$R_c = 84.9$	0.15	$R_c = 96.23$	0.037

Veronesi et al. subm.

Uncertainties

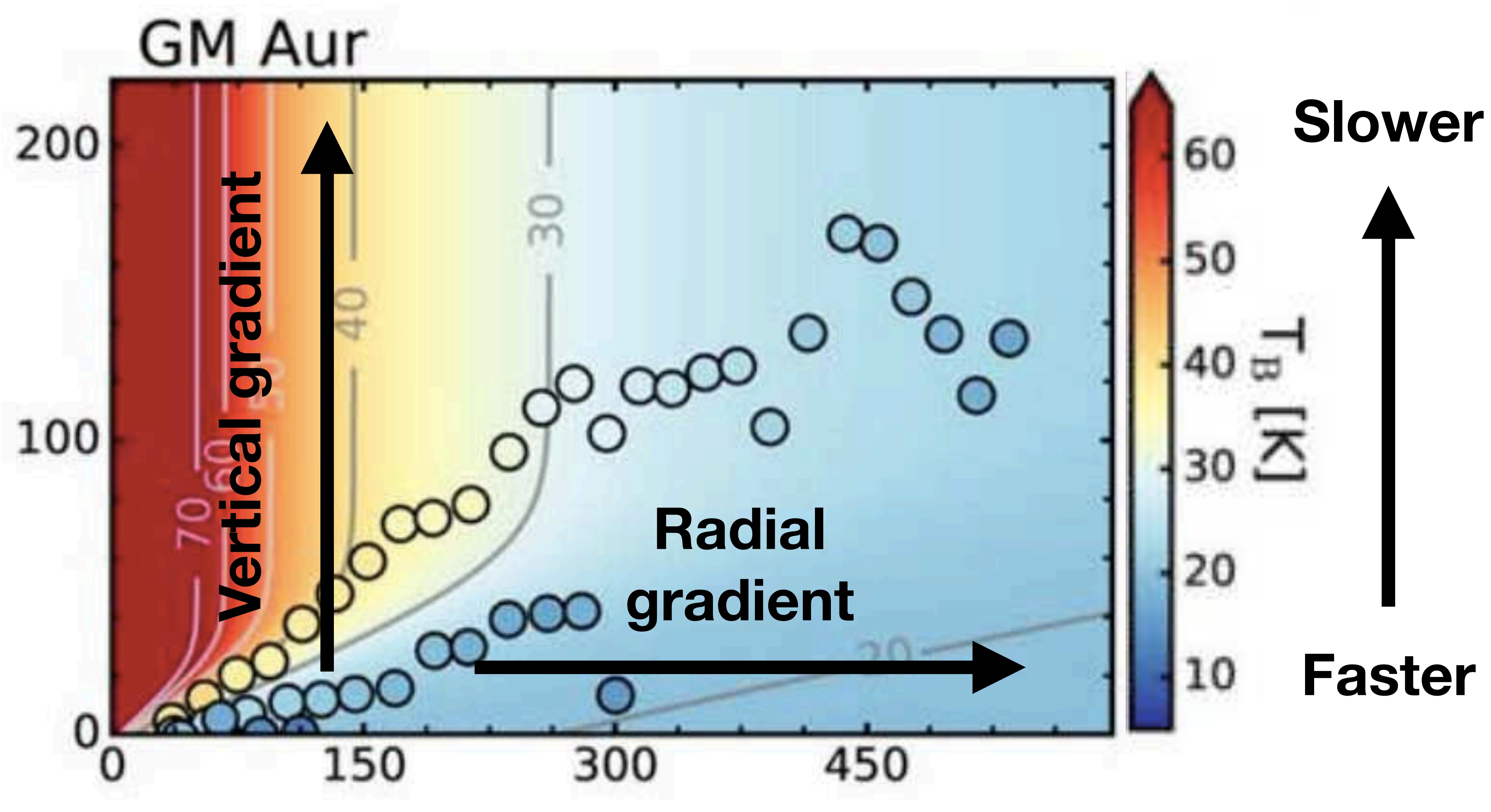
We vary the "fixed" parameters to understand the impact of systematic errors
→ Aspect ratio (fit), inclination (extraction) and emitting layer (extraction+fit)

- **Minimum** measurable disc to star mass ratio ~ 5%
- **Uncertainty** on the disc mass ~ 25%



Veronesi et al. subm.

A step forward: vertical stratification



Law et al. 2021

There is evidence from molecular line observations that protoplanetary discs are thermally stratified

Consequences on density and velocity?

$$T(R,z) = T_{mid}(R) f(R,z)$$
$$\rho(R,z) = \rho_{mid}(R) g(R,z)$$

From hydrostatic equilibrium + centrifugal balance

$$v_\phi^2(R,z) = v_\mathrm{k}^2 \left\{ \left[1 + \left(\frac{z}{R}\right)^2\right]^{-3/2} - \left[\gamma' + (2-\gamma)\left(\frac{R}{R_c}\right)^{2-\gamma} - \frac{d\log(fg)}{d\log R}\right] \left(\frac{H}{R}\right)^2_\mathrm{mid} f(R,z) \right\}$$

Model verification

PHANTOM simulations

Vertically stratified disc
(credits to Caitlyn!)

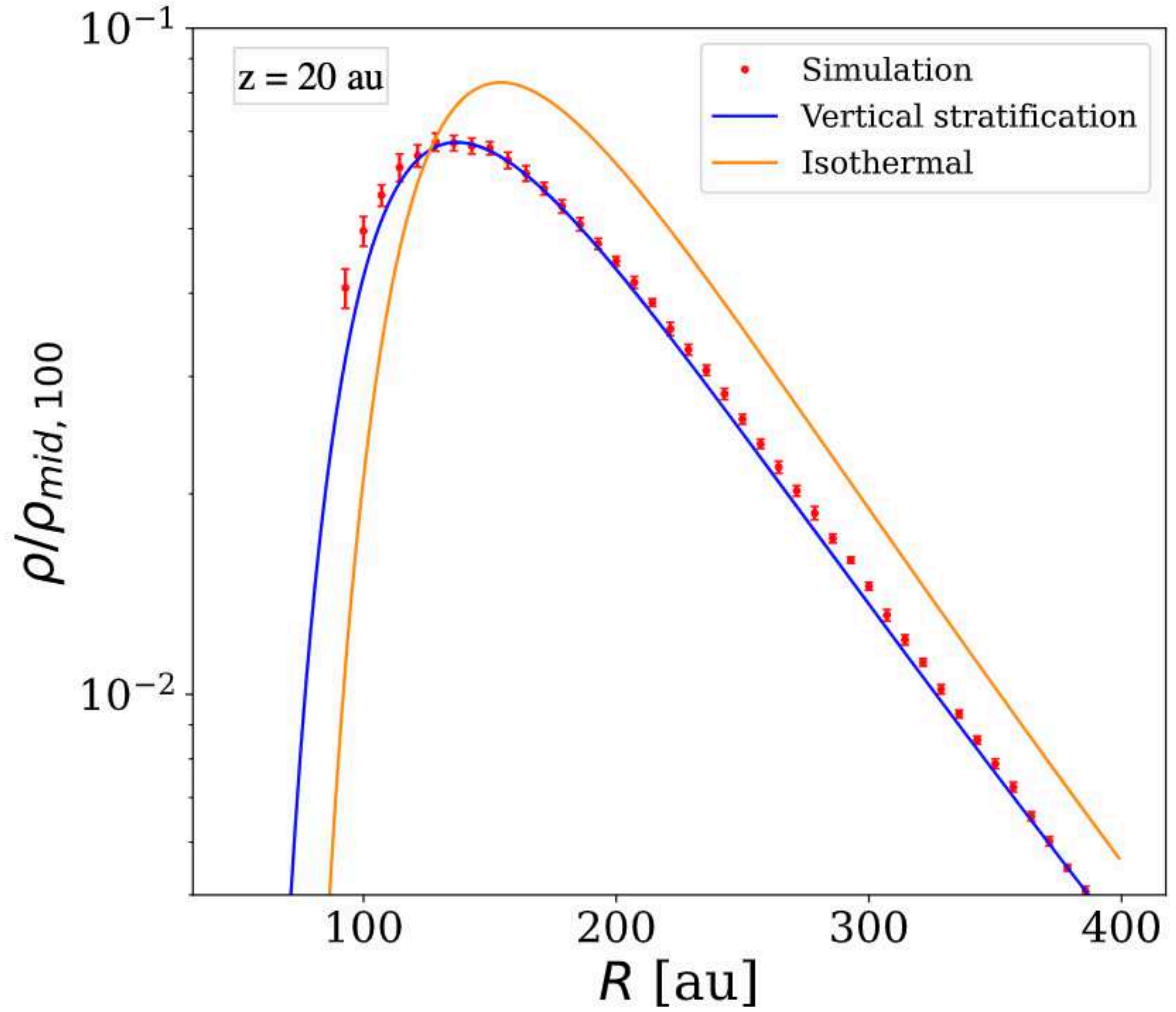
Parameters of GM Aur from Law et al. 2021

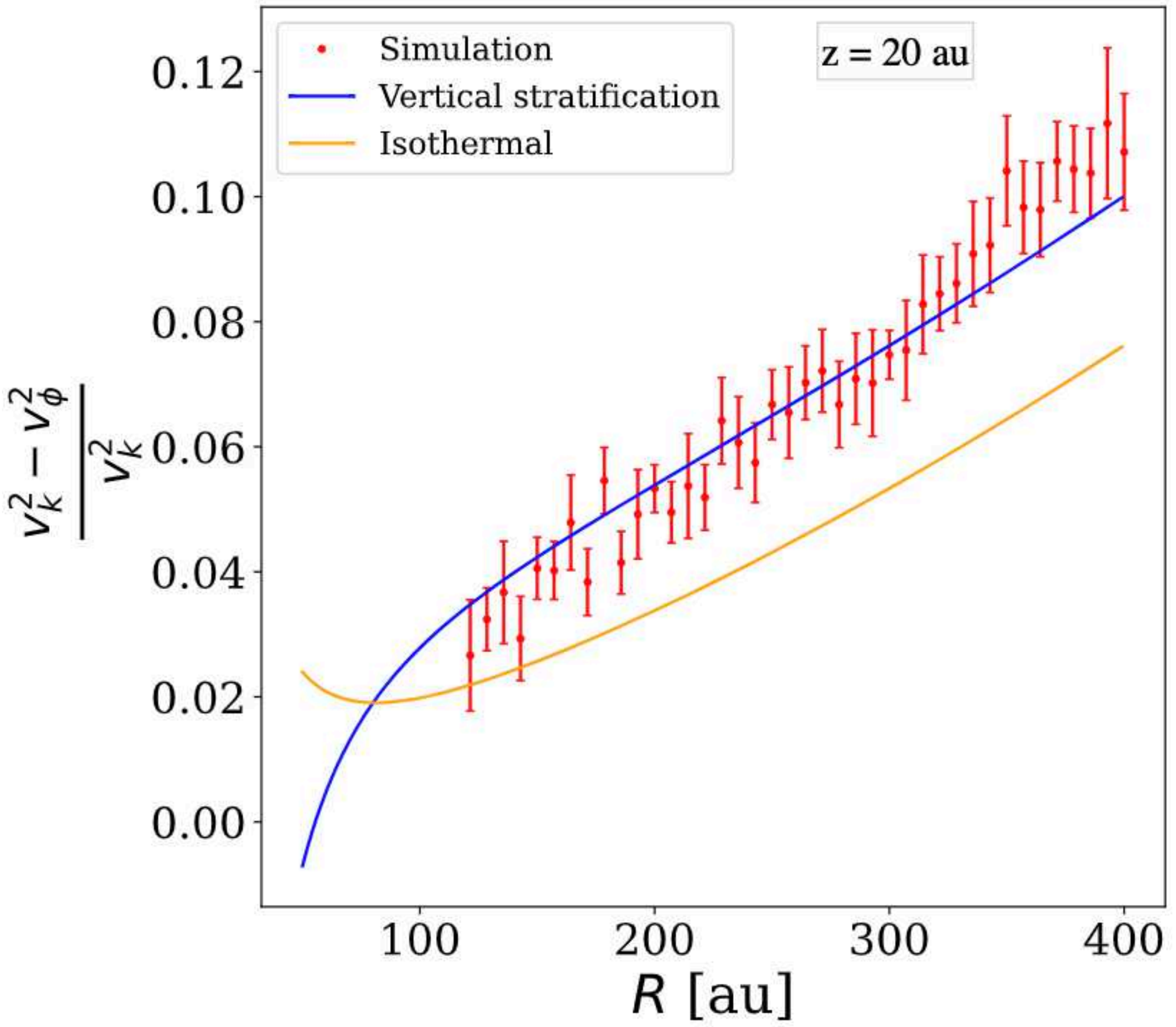
$$T(R,z)^4 = T_\epsilon^4(R) + \frac{1}{2}T_{\text{atm}}^4(R)\left[1 + \tanh\left(\frac{z}{Z_q(R)} - \alpha\right)\right]$$

Test whether the model works or not

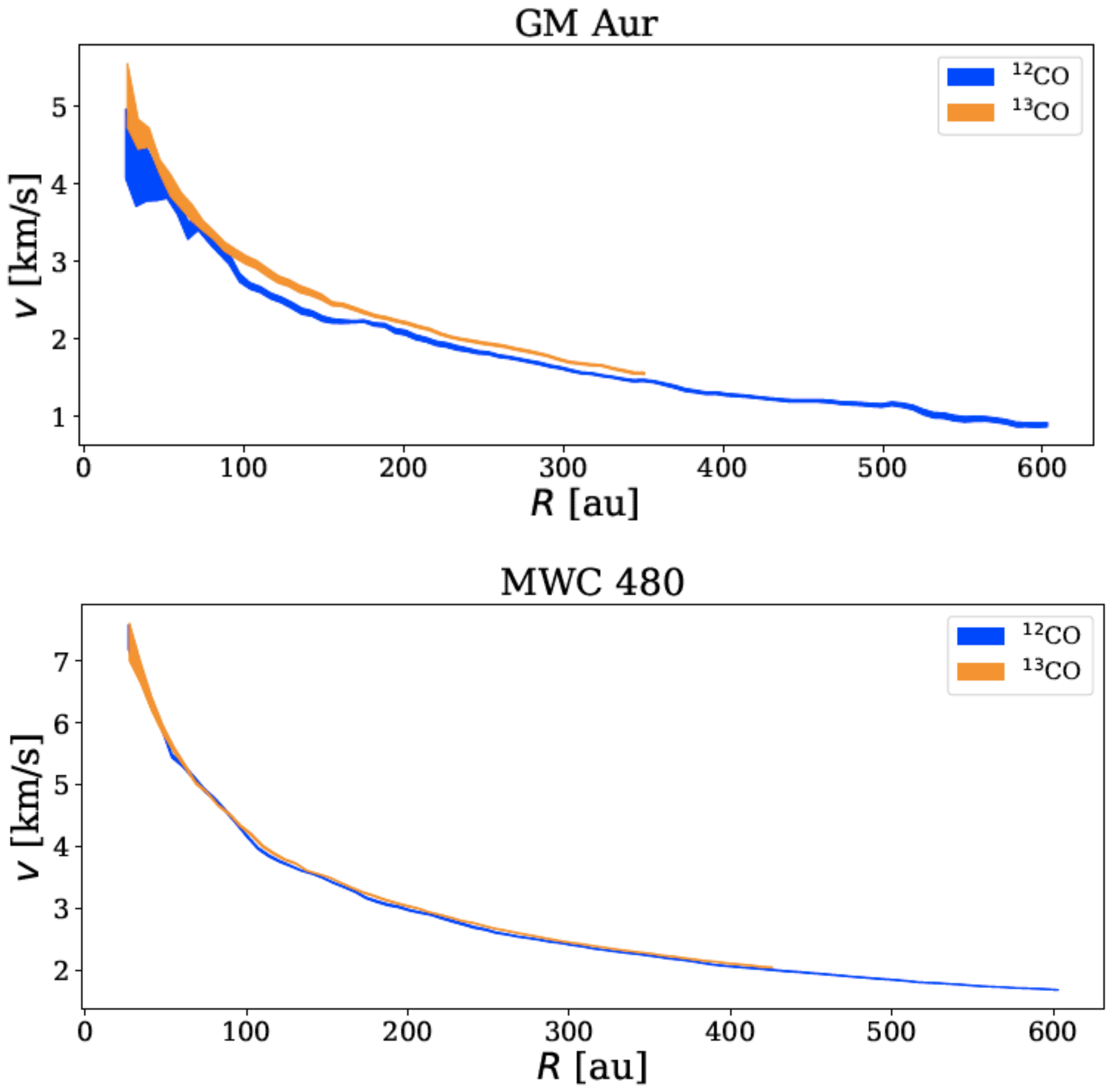
NB: initial density and velocity are not at hydro equilibrium, we just prescribe the temperature

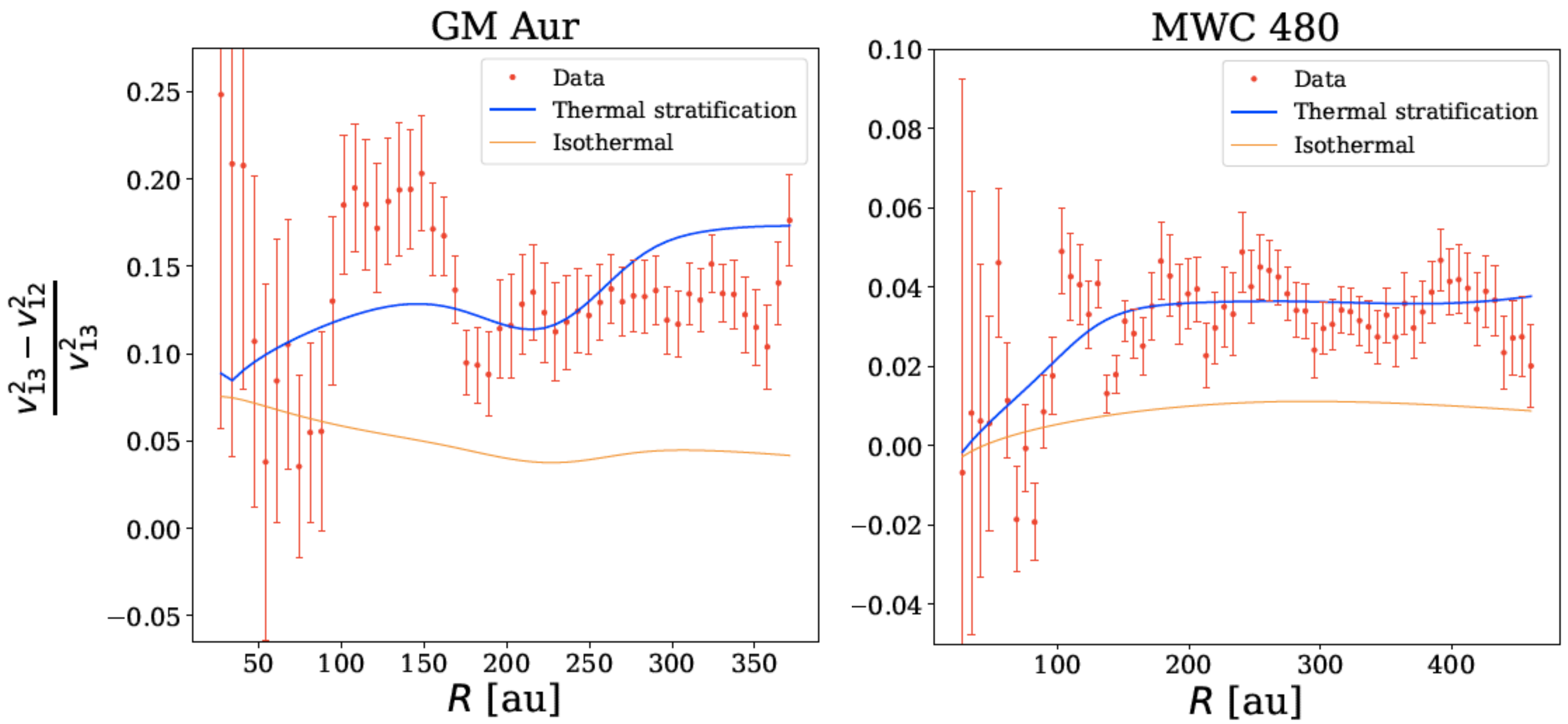
Martire et al. subm.





Vertical stratification in MAPS discs





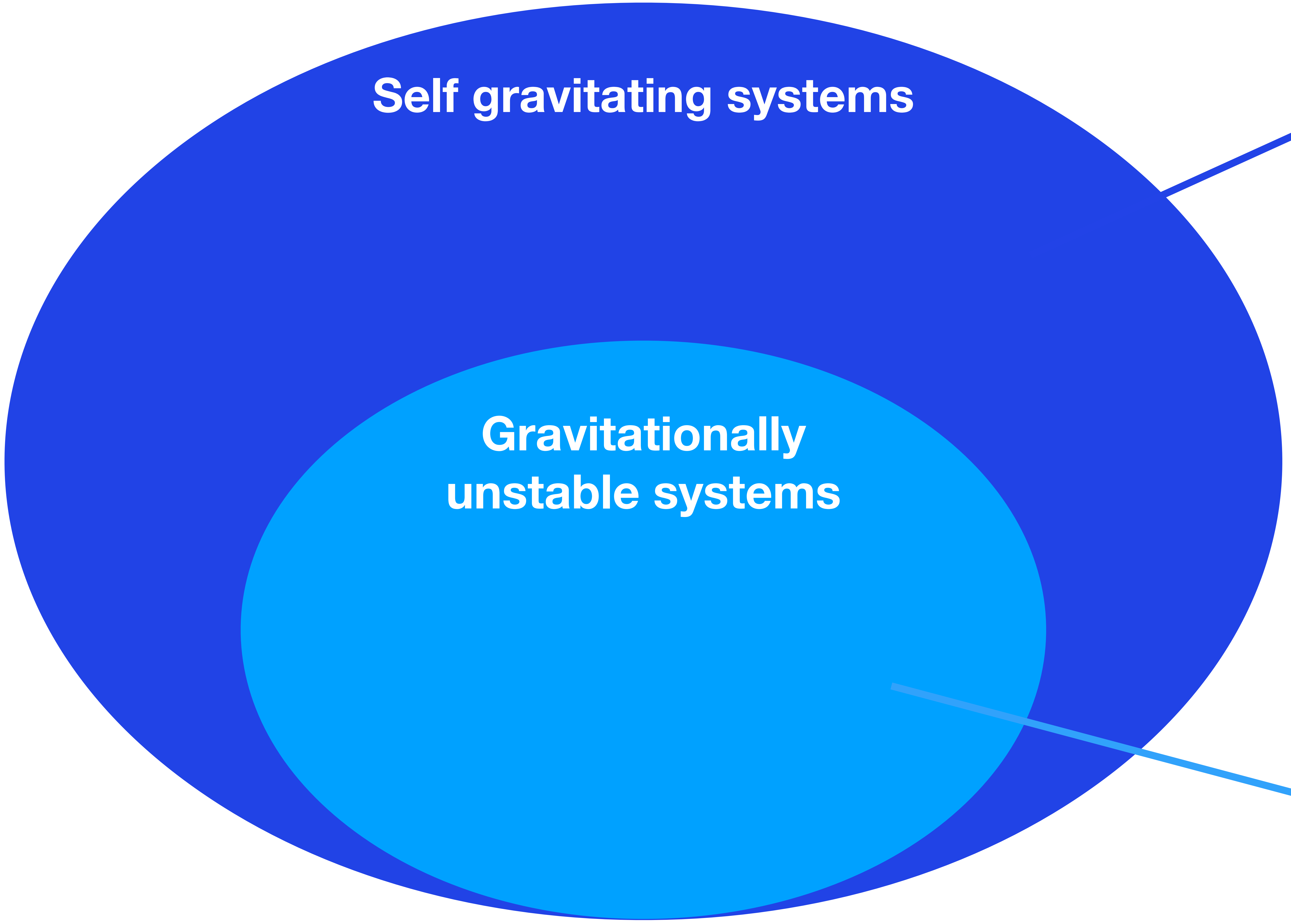
Martire et al. subm.

Vertical stratification in MAPS discs

	$M_\star$ [M$_\odot$]	M_d [M$_\odot$]	R_c [au]	$\chi^2_{\rm red}$
MWC 480				
Isothermal	1.969 ±0.002	0.201±0.002	80±1	11.21
Stratified	2.027±0.002	0.150 ± 0.002	128 ±1	6.14
GM Aur				
Isothermal	0.872 ±0.003	0.312±0.003	56±1	90.84
Stratified	1.128±0.002	0.118±0.002	96 ±1	8.48

Martire et al. subm.

Self gravity VS Gravitational instability



Self gravitating systems

SG influences disc structure

G. unstable systems

Development of large scale spiral structure (transport angular momentum)

$$Q = \frac{c_s \kappa}{\pi G \Sigma} \sim 1 \qquad \frac{\text{Pressure, Rotation}}{\text{Self gravity}}$$

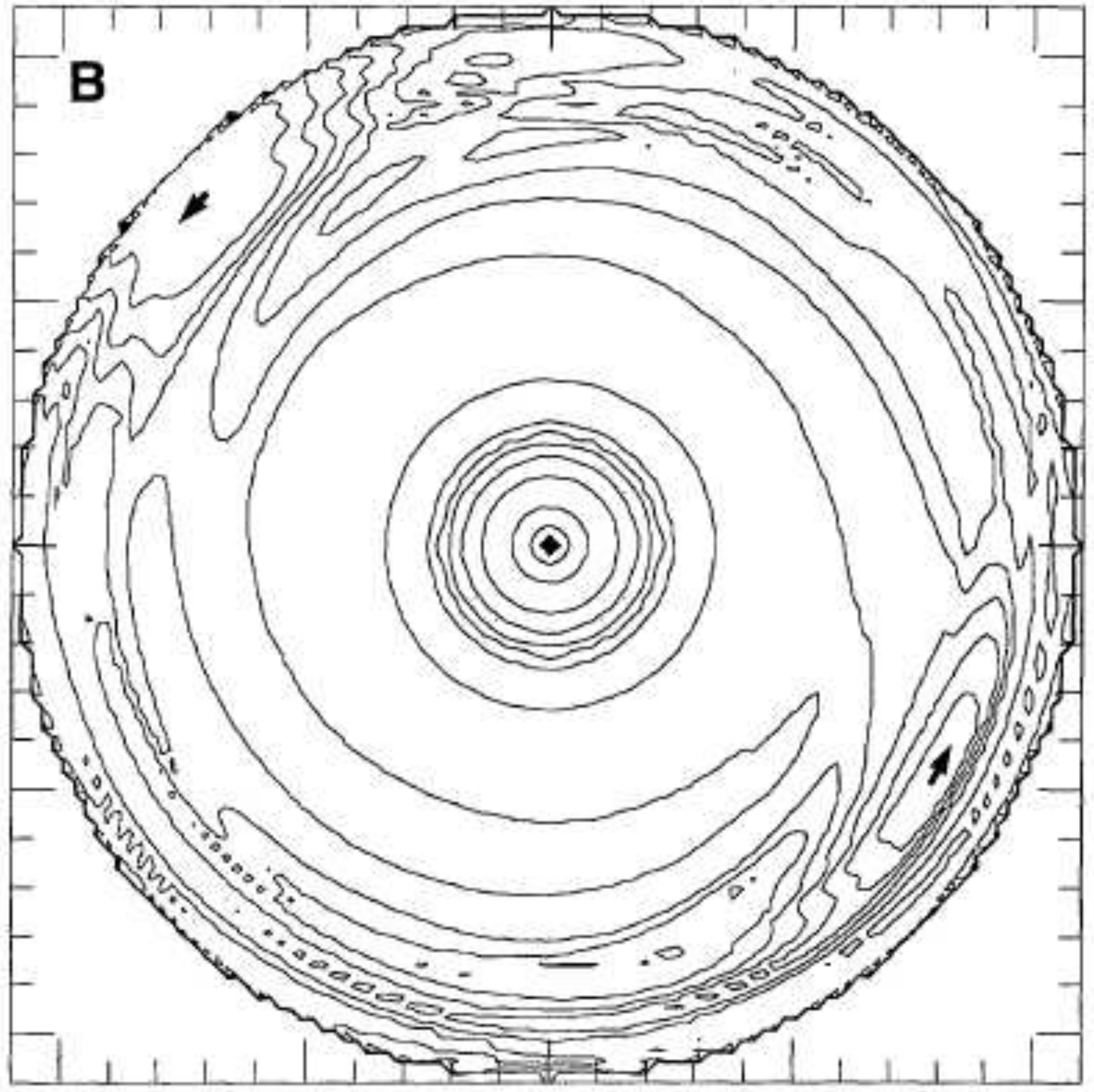
Gravitational instability and planet formation

Boss 1997

First hydrodynamical simulations of gravitationally unstable protostellar discs

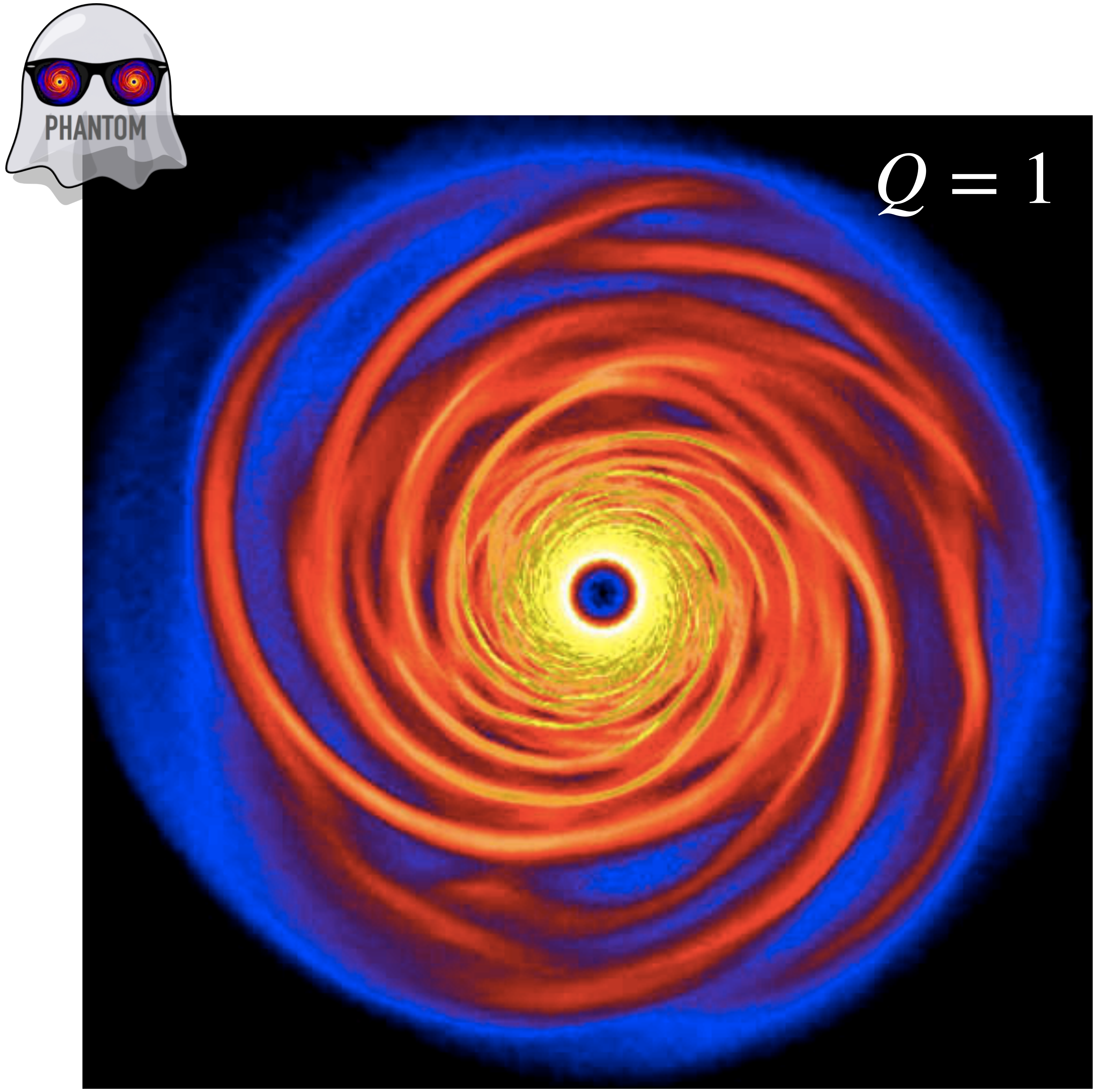
→ Possibility to rapidly form Jupiter mass body through gas fragmentation in the outer disc

Initial mass is too high to form a planet because of accretion (*Kratter & Lodato 2016*)



Boss et al. 1997

Non (gas) fragmenting case



β cooling

thermodynamics

$$\beta_{cool} = \Omega t_{cool}$$

$$\delta\Sigma/\Sigma \propto \beta^{-1/2}$$

Strength of spiral perturbation is determined by the cooling factor

$$\alpha_{GI} = \frac{4}{9\gamma(\gamma-1)\beta}$$

Interplay with dust dynamics

Rice et al. 2004-2006

First 3D SPH simulations of gas and dust GI discs.

- **Efficient** dust trapping inside spiral arms
- Dust is so unstable that **collapses** $\sim 1M_\oplus$ planetesimals

Warning: Low resolution

Booth & Clarke 2016

2D SPH simulations of gas and dust GI discs.

Important parameter is **dust dispersion velocity** $c_d \propto St^{1/2}\beta^{-1/2}$ since it determines the effective "temperature" of the dust

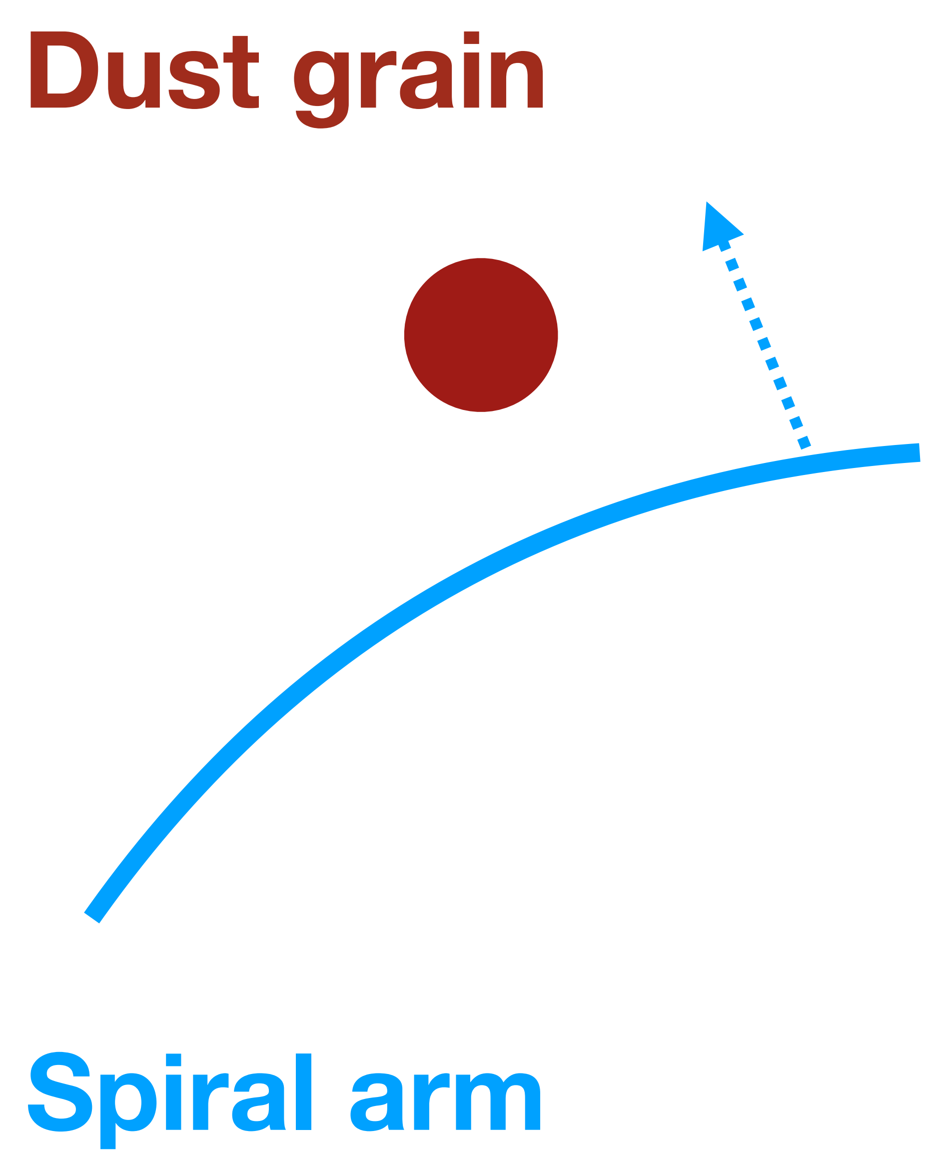
Longarini et al. 2023a

Analytical study of 2 fluid gravitational instability

When the dust is enough concentrated and sufficiently cold, it can drive instability

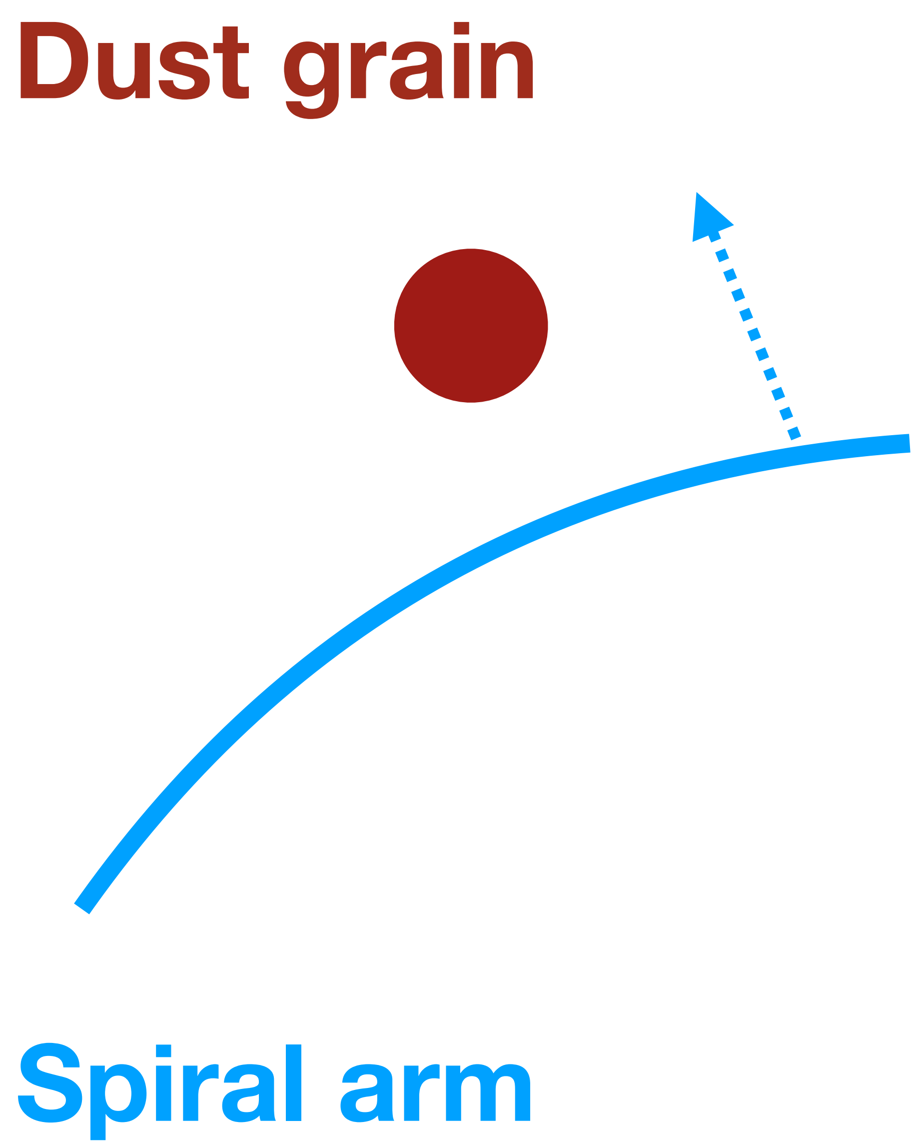
$$M_{Jeans} \simeq 1 - 10M_\oplus$$

What happens to dust?



What happens to dust?

$$\frac{\delta\Sigma}{\Sigma} \propto \beta^{-1/2}$$

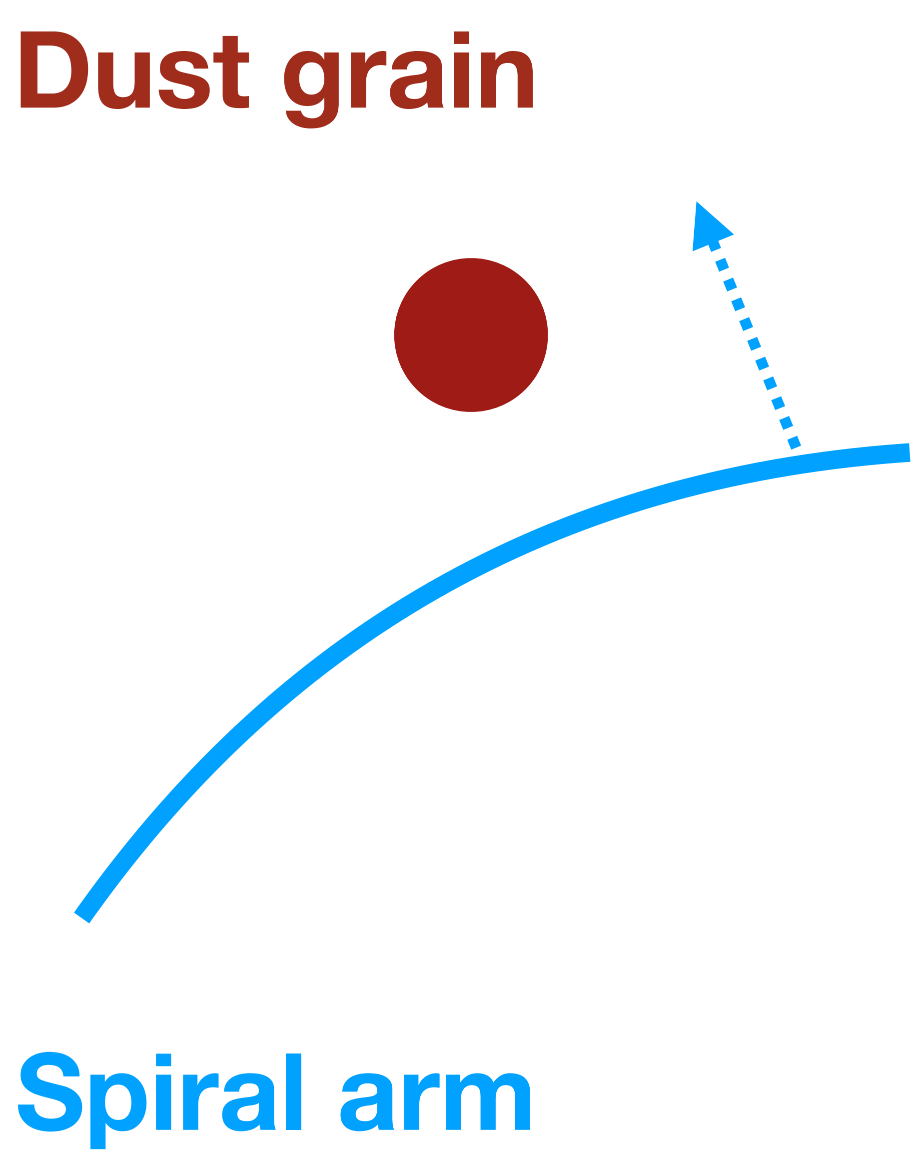


Stokes number St

Strength of the spiral $\delta\Sigma/\Sigma$

What happens to dust?

$$\frac{\delta\Sigma}{\Sigma} \propto \beta^{-1/2}$$



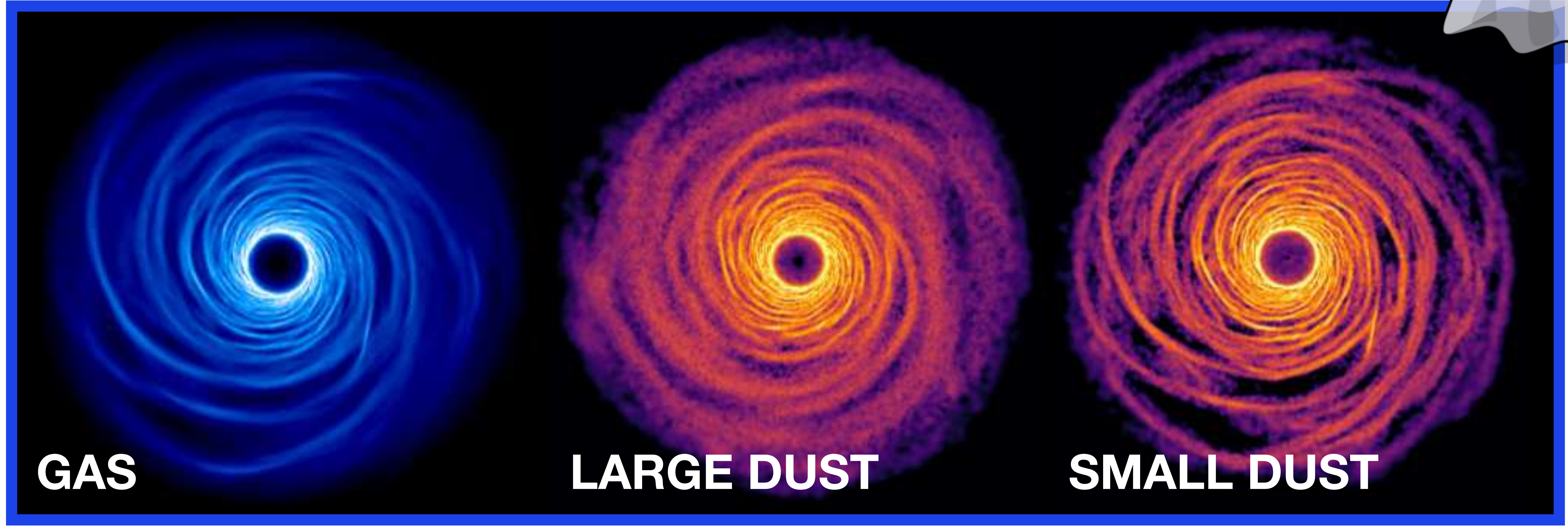
Stokes number St

Strength of the spiral $\delta\Sigma/\Sigma$

Efficiently excited:
Stronger kick if
- Low β
- High St

Not efficiently excited:
Weaker kick if
- High β
- Low St

Hydro simulations



1M - 2M gas particles
250K - 500K dust particles

GI strength
β

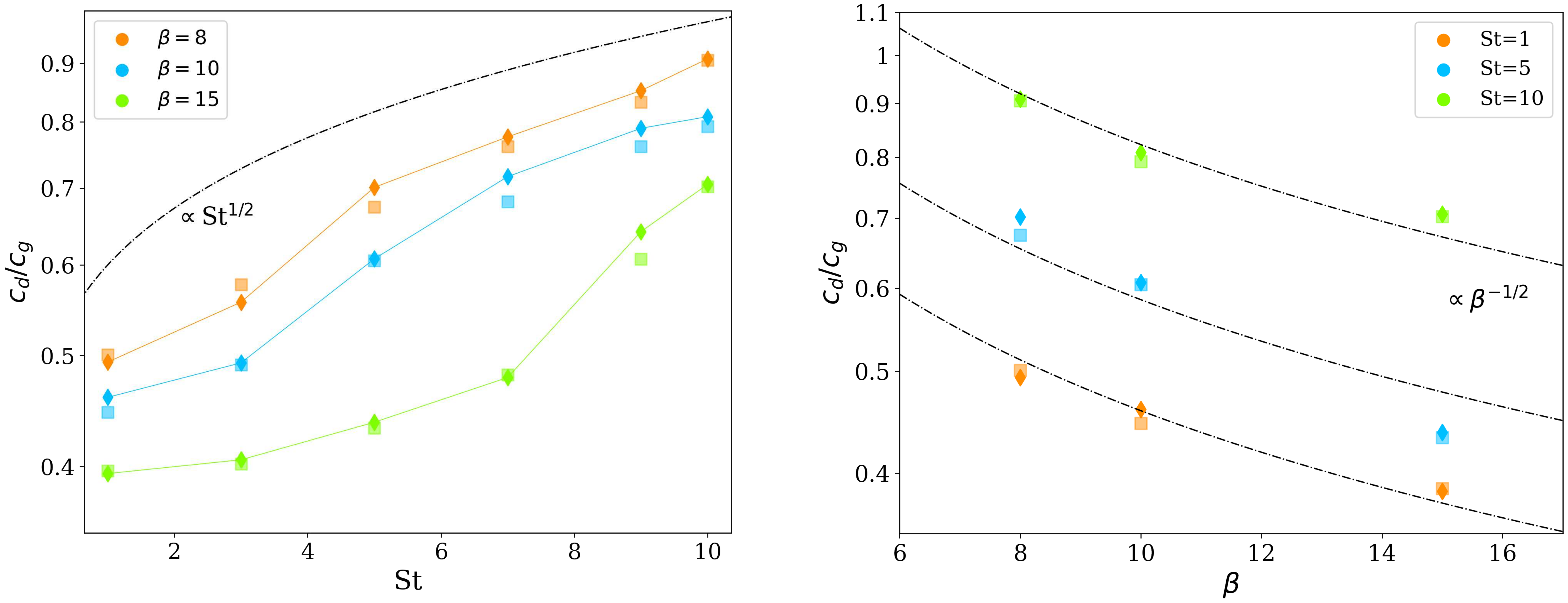
—?→

Dust parameters
ϵ : dust to gas ratio
c_d : dispersion velocity

Simulation	$M_d/M_\star$	β_{cool}	s [cm]	$\langle St \rangle$	s_{10} [cm]
S1	0.05	8	300	40	3
S2	0.05	10	300	40	3
S3	0.05	15	300	40	3
S4	0.05	8	60	8	0.6
S5	0.05	10	60	8	0.6
S6	0.05	15	60	8	0.6
S7	0.1	8	600	40	6
S8	0.1	10	600	40	6
S9	0.1	15	600	40	6
S10	0.1	8	120	8	1.2
S11	0.1	10	120	8	1.2
S12	0.1	15	120	8	1.2
S13	0.2	8	1500	40	15
S14	0.2	10	1500	40	15
S15	0.2	15	1500	40	15
S16	0.2	8	600	16	6
S17	0.2	10	600	16	6
S18	0.2	15	600	16	6

Longarini et al. 2023b

Dust dispersion velocity



$$c_d \propto St^{1/2}\beta^{-1/2}$$

Longarini et al. 2023b

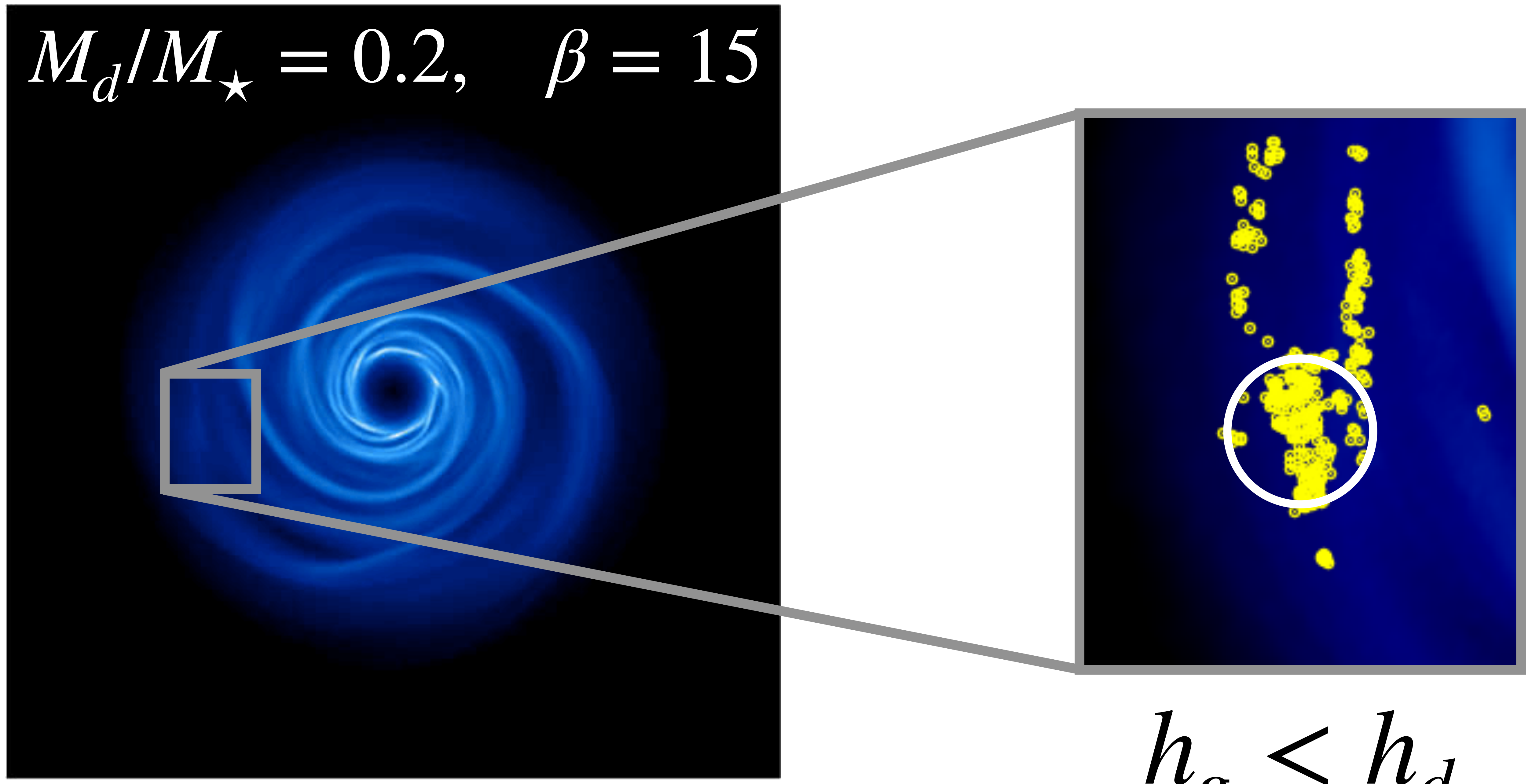
Dust collapse

In line with Rowther 2024
See Sahl's talk

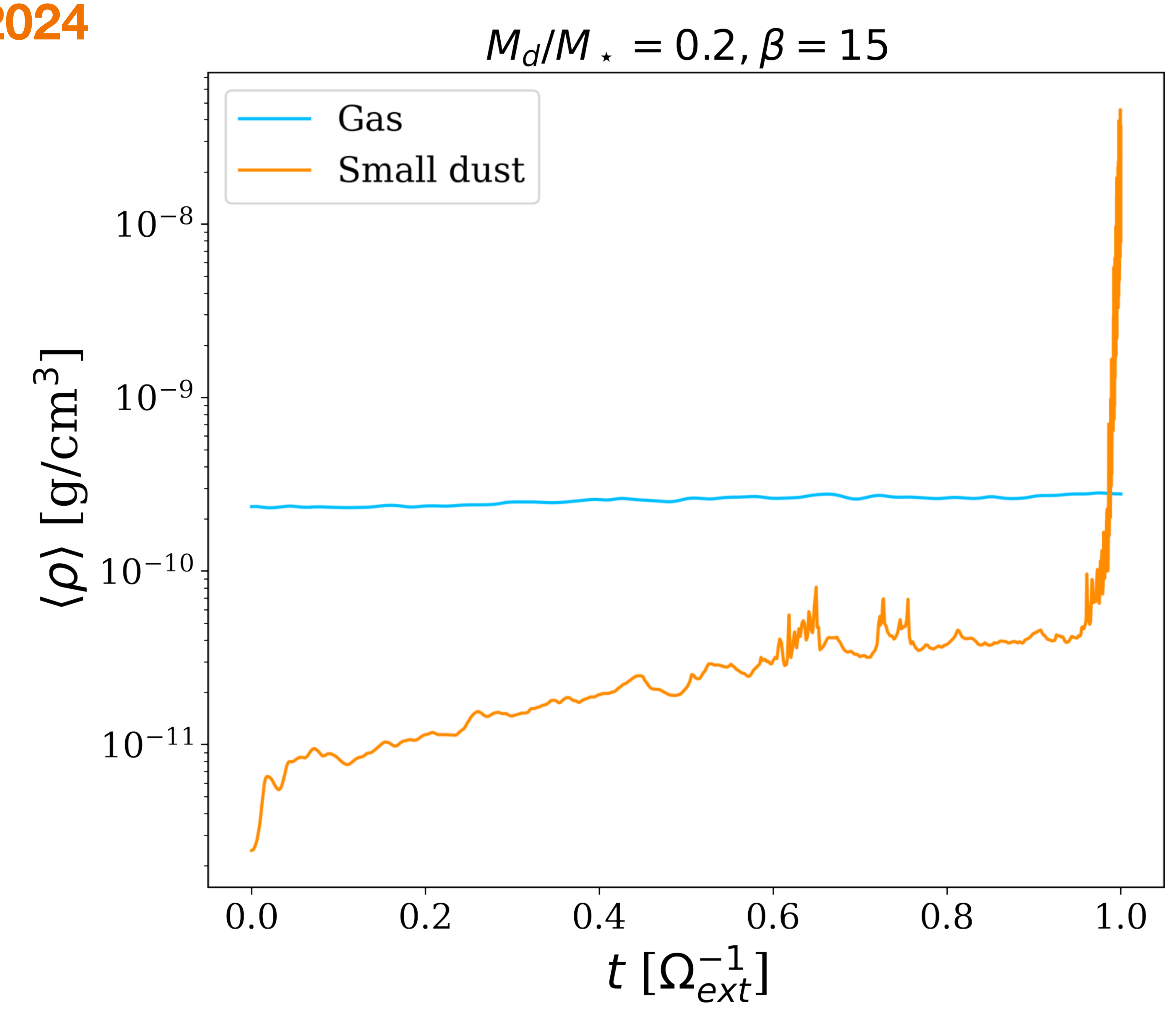
We observe dust collapse only for

- Higher disc to star mass ratio ($M_d/M_\star = 0.2$)
- Long cooling ($\beta = 10 - 15$)
- Small dust particles

Mass of the clump $M_{cl} \simeq 1 M_\oplus$



$h_g < h_d$



Only dust is collapsing
Simulation stops (too long computational time…)

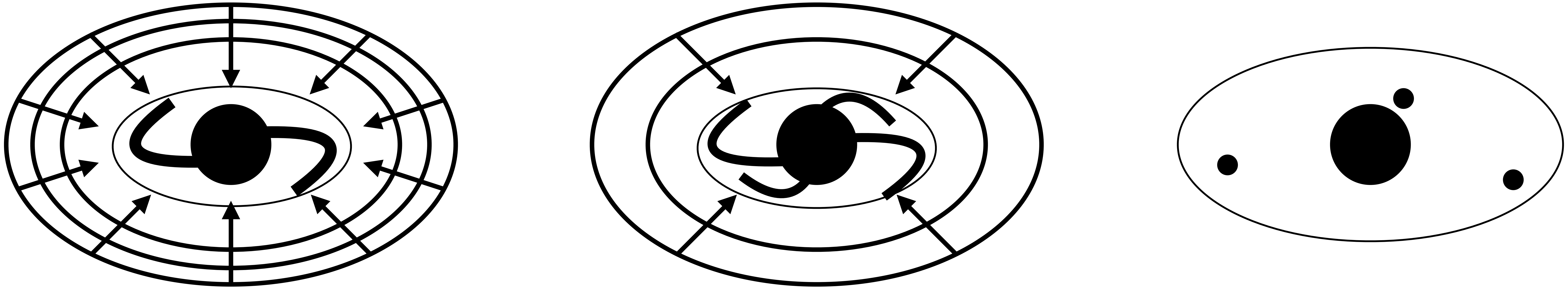
Longarini et al. 2023b

Evolutionary scenario

Stage 1

Stage 2

Stage 3



Very massive disc M_{d1}
strongly gravitationally unstable
High $\dot{M}_{inf}$ - Low β_{cool}
Gas likely to fragment
→ Stellar companions formation

Massive disc $M_{d2} < M_{d1}$
gravitationally unstable
Lower $\dot{M}_{inf}$ - Higher β_{cool}
Dust likely to fragment
→ Planet formation

Gravitationally stable
disc $M_{d3} << M_{d2}$ with
already formed planets

Time

Longarini et al. 2023b

Evolutionary scenario

Stage 1 | Stage 2 | Stage 3

Multiplicity?

Dynamical interactions?

Environment?

Very massive
strongly gravitatio

High $\dot{M}_{inf}$ - Low β_{cool}
Gas likely to fragment
→ Stellar companions formation

gravitationally unstable
Lower $\dot{M}_{inf}$ - Higher β_{cool}
Dust likely to fragment
→ Planet formation

Gravitationally stable disc $M_{d3} << M_{d2}$ with already formed planets

Time

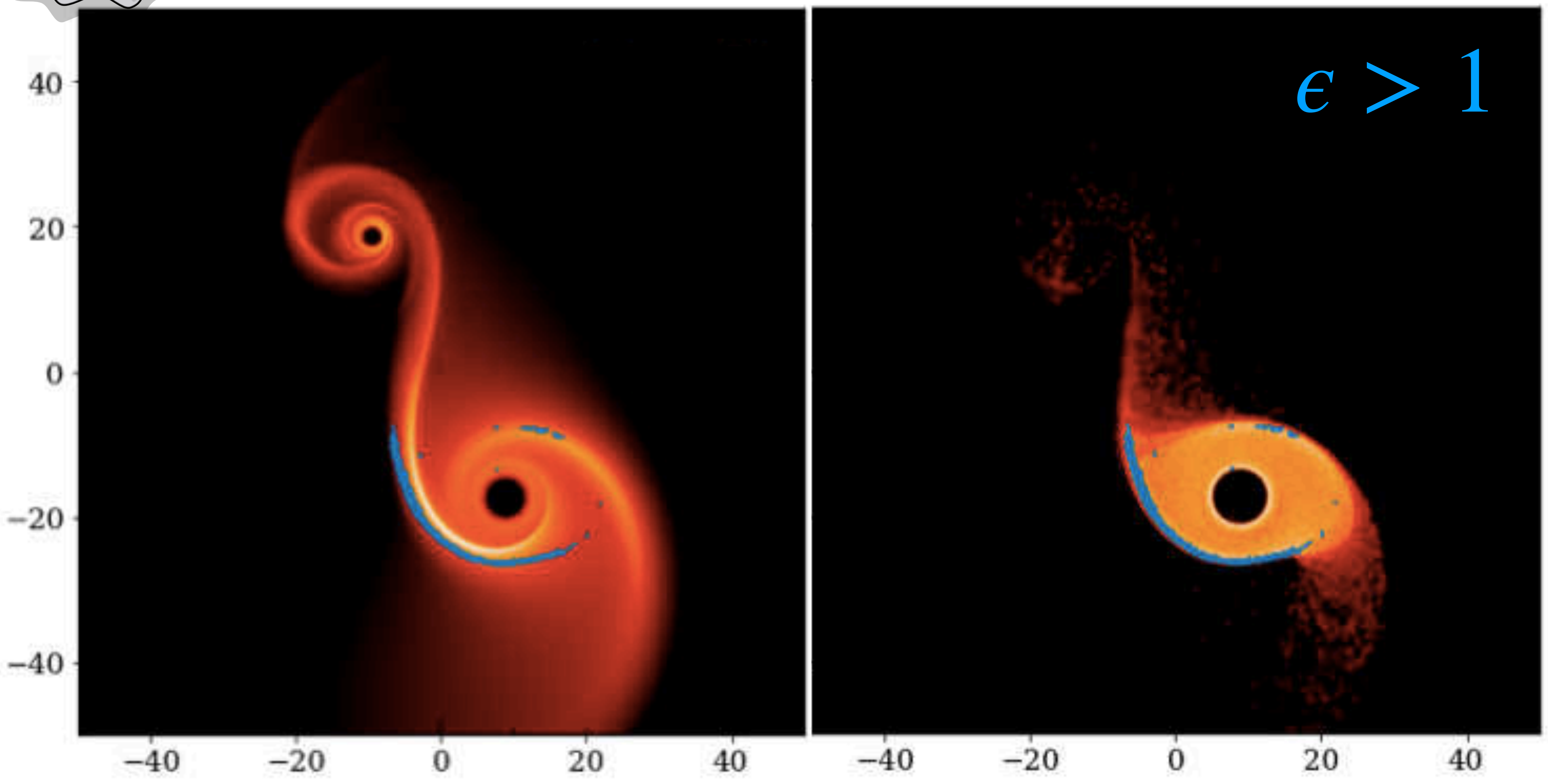
Longarini et al. 2023b

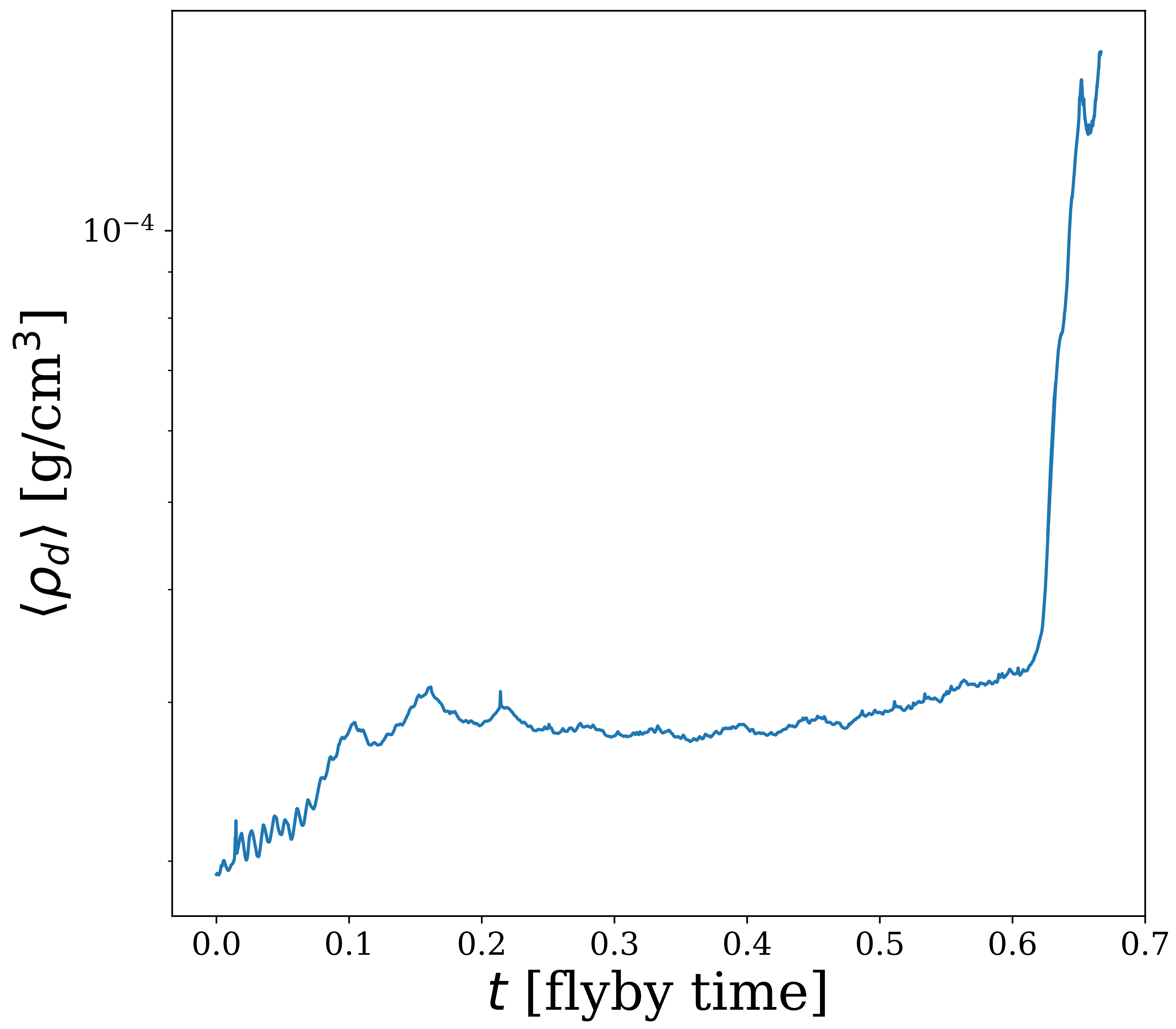
Other possible scenarios

Vasu Prasad, PhD Student
@ IoA, Cambridge

Gas surface density

Dust surface density





What after?

Planetary cores (1-10 Earth) formation in the outer disc in massive discs at the end of the GI phase (SG disc)

Planetary cores are sub-thermal mass → Type I migration

Type I migration timescale

Tanaka et al. 2002

$$t_{M1} = \frac{M_\star}{M_p}\frac{M_\star}{\Sigma R_p^2}\left(\frac{H}{R}\right)_p^2 \Omega_p^{-1}$$

Time to reach the thermal mass through accretion

D'angelo & Lubow 2008

$$t_{acc} = \frac{M_{th}}{\dot{M}_p} = 3\left(\frac{H}{R}\right)_p^4 \frac{M_\star}{M_p}\frac{M_\star}{\Sigma R_p^2}\Omega_p^{-1}\eta^{-3}$$

Survival of the cores

Antonio Costantinou,
Master student @ IoA

$$\tau = \frac{3}{\eta^3}\left(\frac{H}{R}\right)^2_p$$

$$\frac{\text{Accretion ts}}{\text{Migration ts}}$$

$$\eta = R_{acc}/R_h$$

$\tau > 1 \rightarrow$ Planetary core does not survive

$\tau < 1 \rightarrow$ Planetary core survives

	H/R	**η**	**Mp**	**τ**
Sim1	0.1	0.25	10	~1
Sim2	0.1	0.5	10	<1
Sim3	0.2	0.25	10	>1
Sim4	0.1	0.25	20	~1

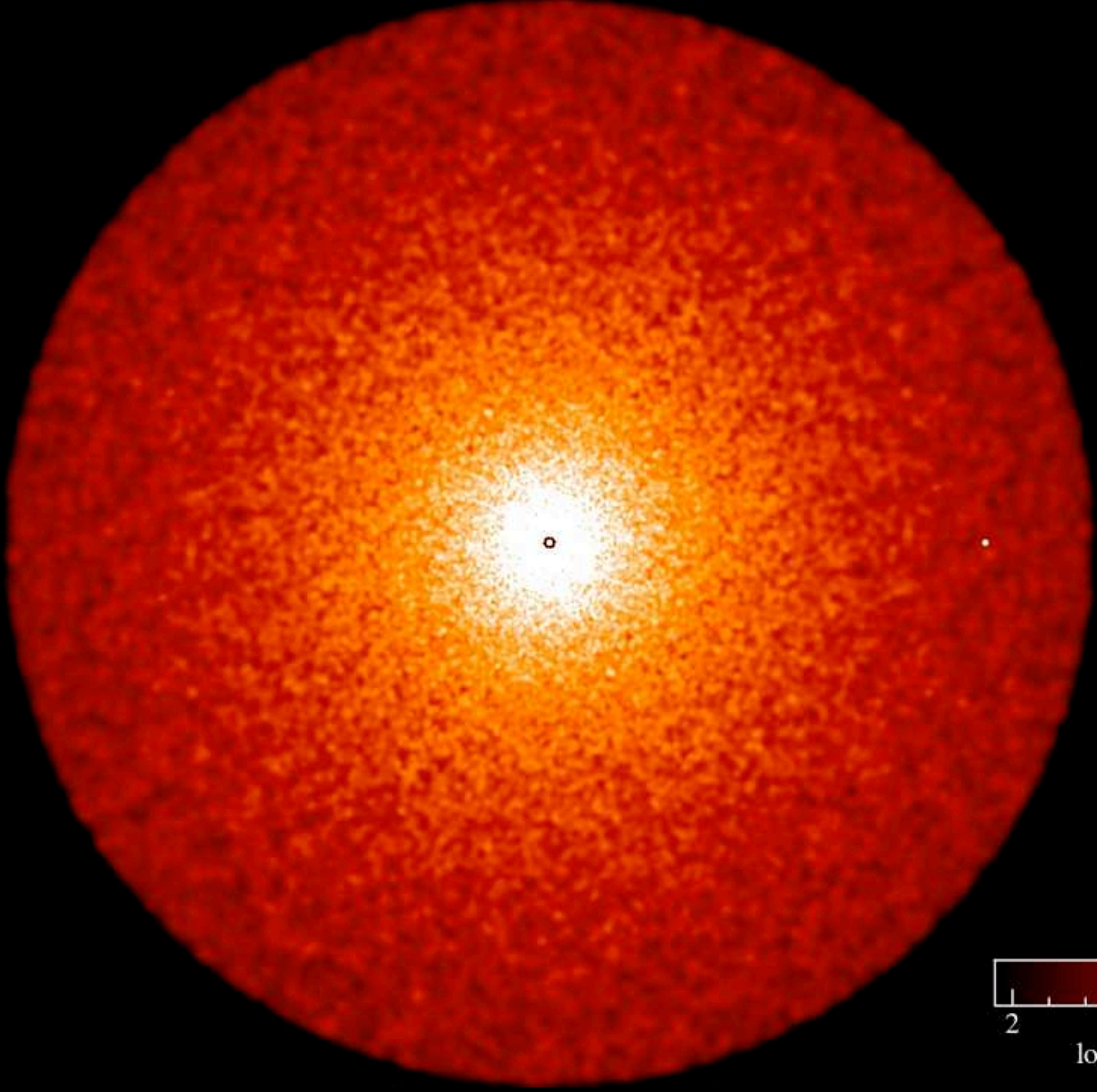
t=0 yrs

$\tau \sim 1$

$M_p = 10 M_\oplus$

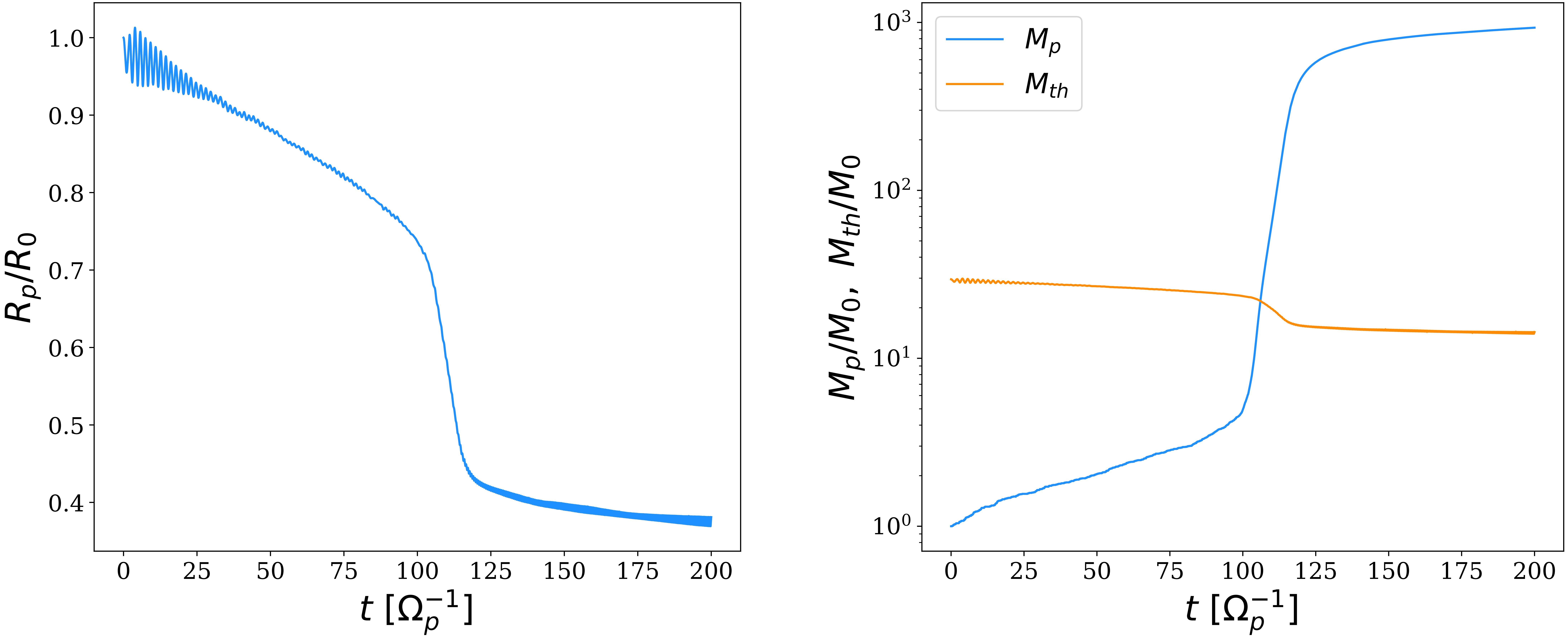
$(H/R)_p = 0.1$

$\eta = 0.25$



$M_d = 0.1 M_\star$

Migration VS accretion



Conclusion and future perspectives

- Precisely modelling the **rotation curve** gives a unique opportunity to investigate protoplanetary discs structure

  → How many information can we get from the rotation curve? Is it possible to directly reconstruct the thermal structure?

  For PHANTOM: Implement correct initial condition (hydro eq. + centrifugal balance) in the .tmp

- The dynamical role of dust in GI discs is crucial and it can explain the formation of **planetary cores** in young protoplanetary discs

  → Can these cores survive in young discs?

  For PHANTOM: Allow for the creation of sink particles from dust