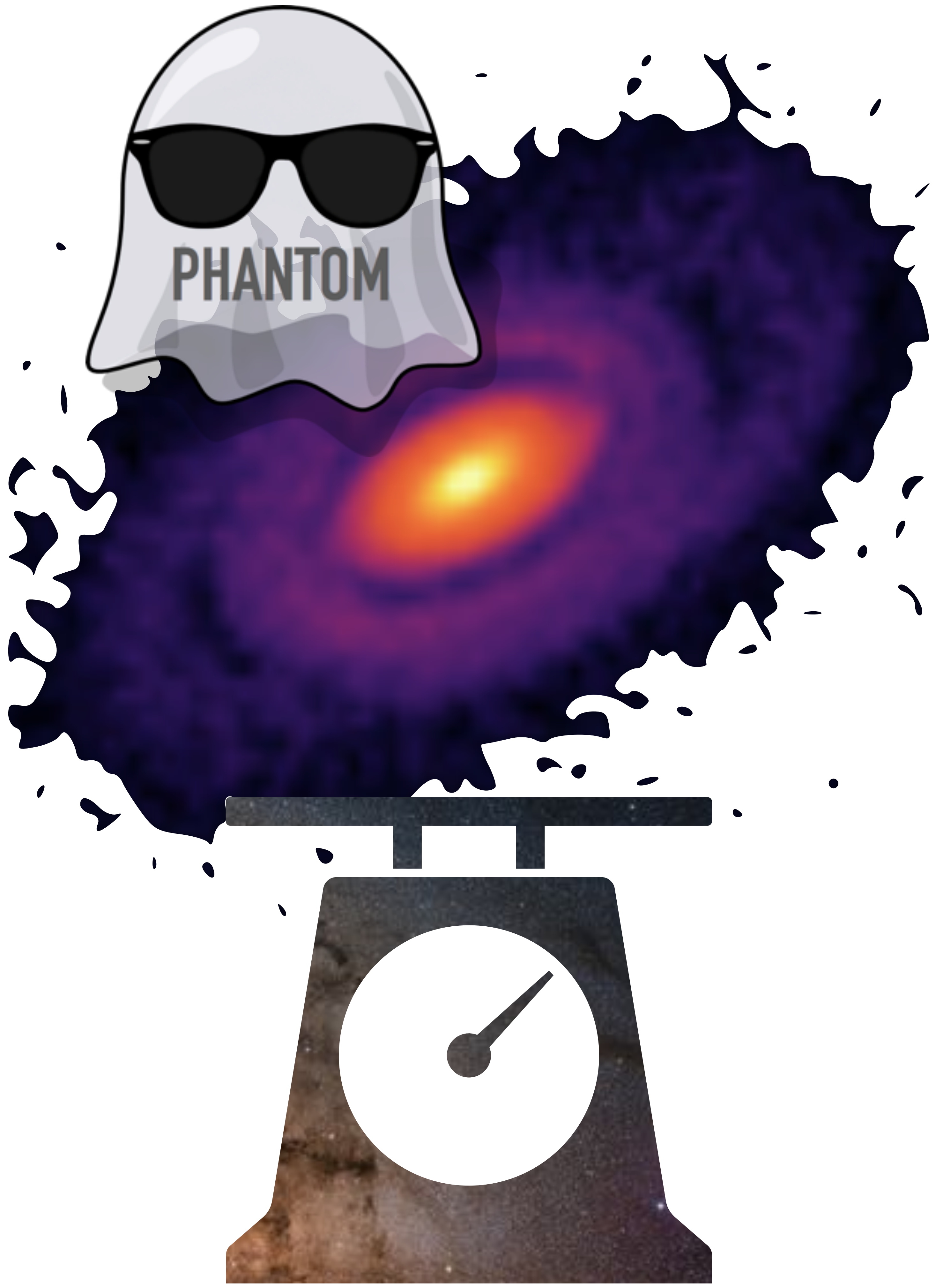
A DYNAMICAL SCALE FOR PROTOPLANETARY DISCS

(BENCHMARKING WITH PHANTOM AND OTHERS STORIES)



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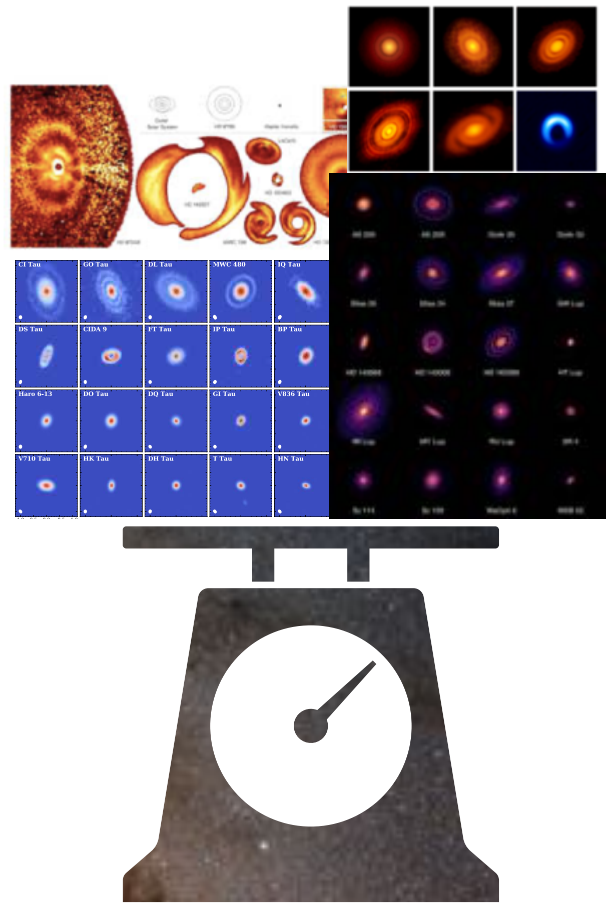
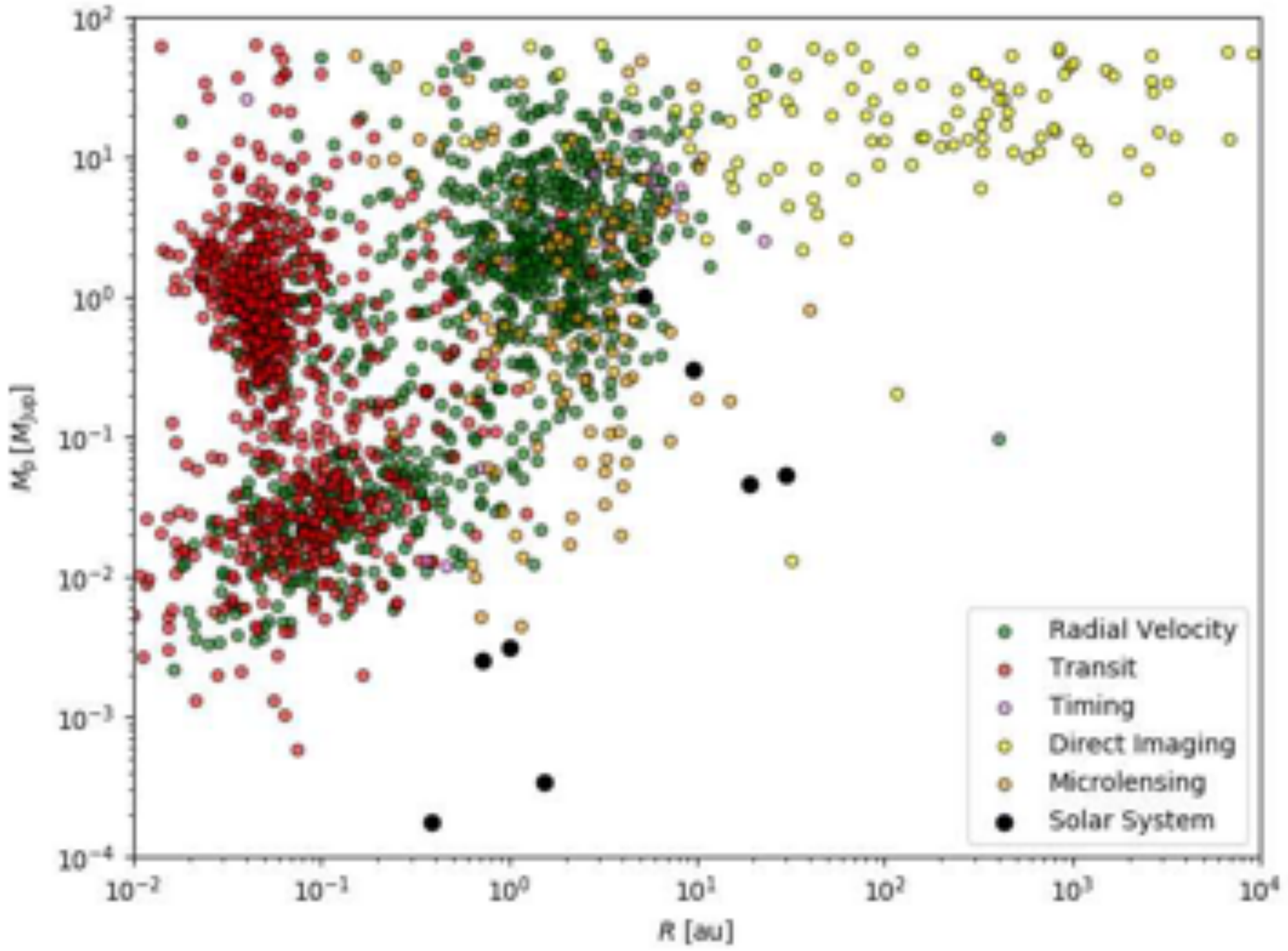
.....

February 15th, 2022 - PHANTOM and MCFOST users workshop - Monash Uni

DISC MASS: WHY DO WE CARE?

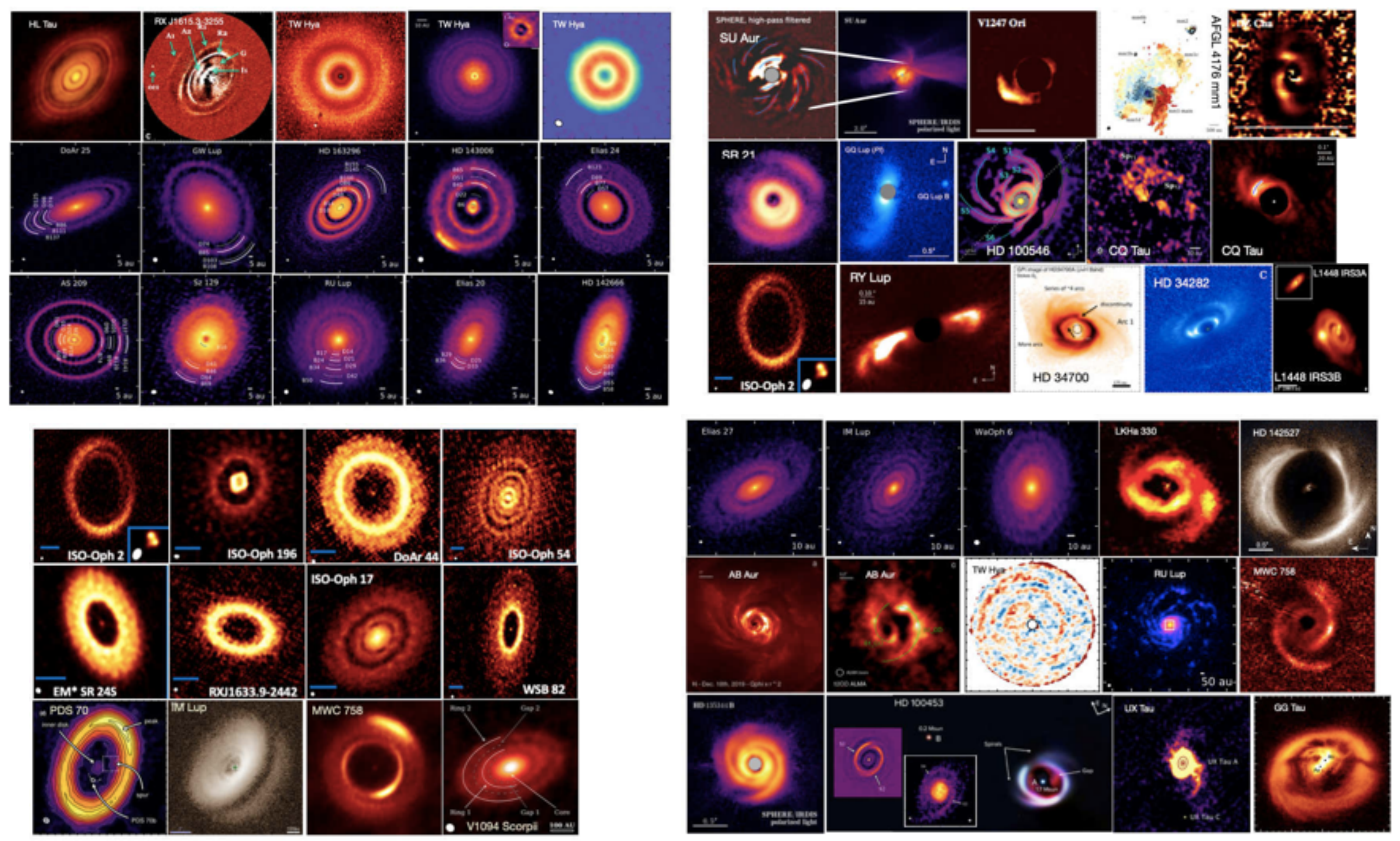


Reservoir for planets: exoplanets distribution



$$M_{\rm disc} = \,?\, M_\odot$$

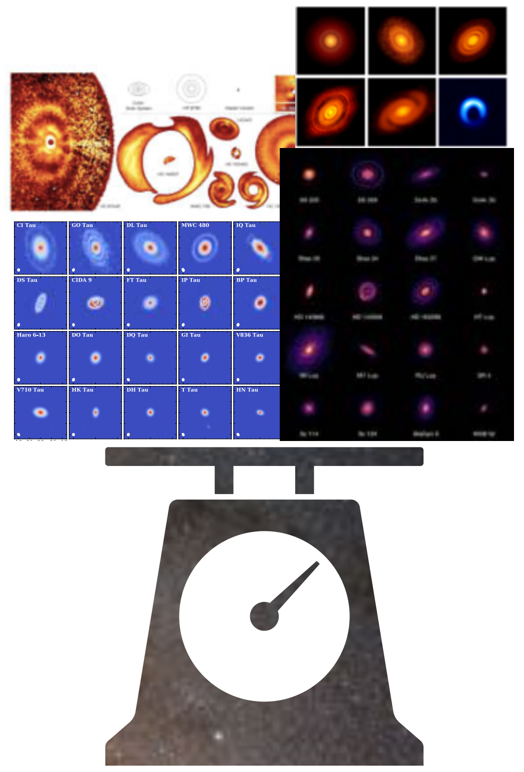
$\mathrm{St} \propto \Sigma^{-1}$: dust and gas evolution (also, substructures…)



Planet evolution: migration, accretion…

…The entire disc evolution

HOW TO WEIGH PROTOPLANETARY DISCS?



(more in detail, PPVII review: Miotello et al. 2022)

From the dust…

Optically thin mm flux (e.g. from ALMA)

Distance to disk (e.g. from Gaia)

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

Single grain opacity (large uncertainty)

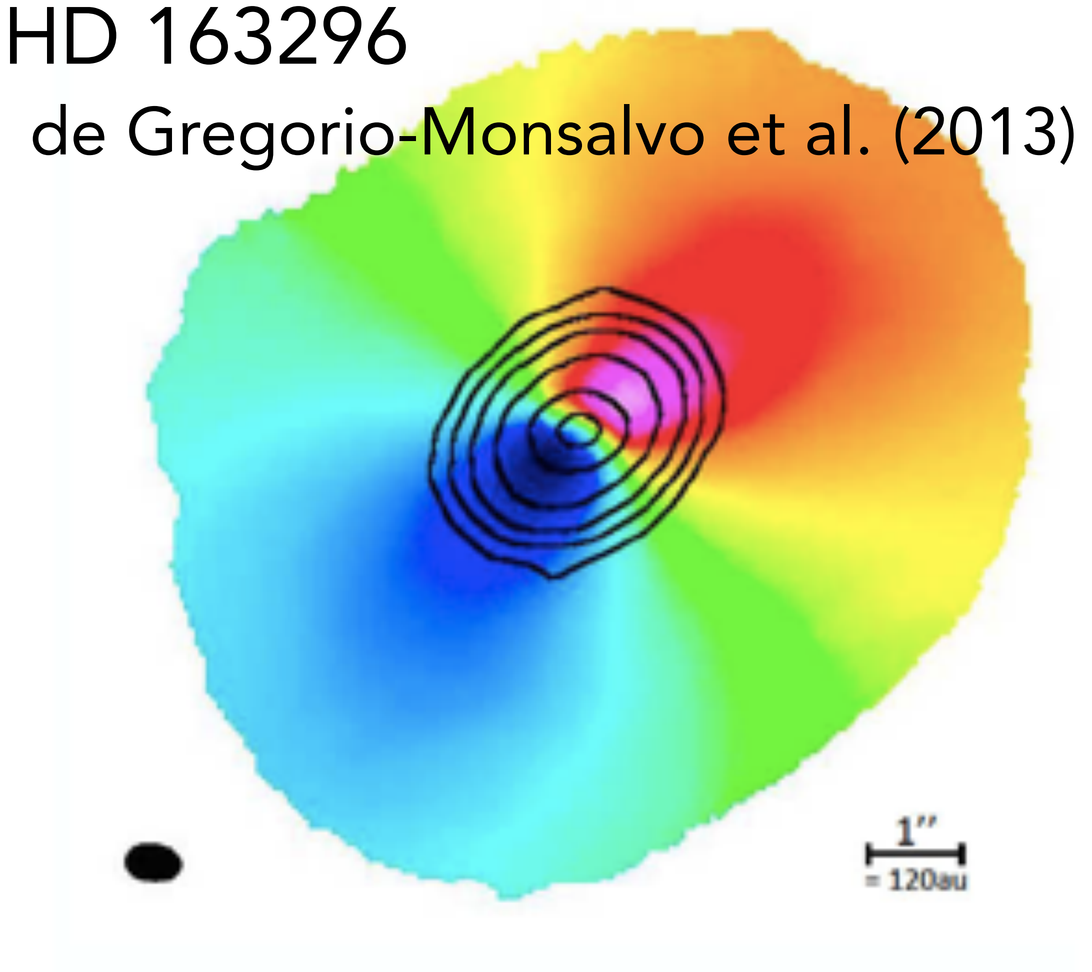
Dust temperature (e.g. isothermal 20 K)

Dust mass primarily in (sub)mm grains

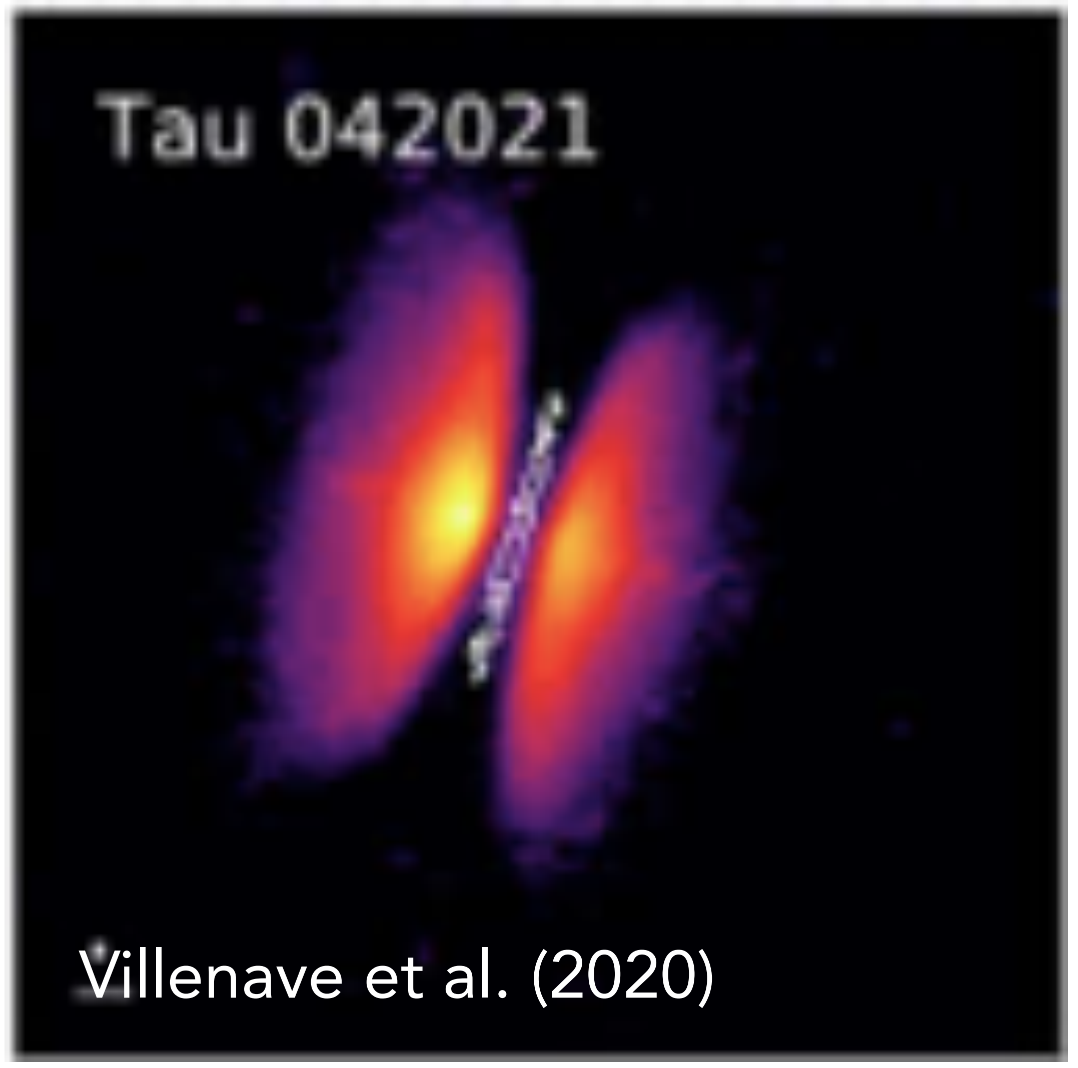
$$M_{\rm disk} \approx 100 \times M_{\rm dust}$$

ISM gas-to-dust ratio (gas is 99% of disk mass)

HD 163296

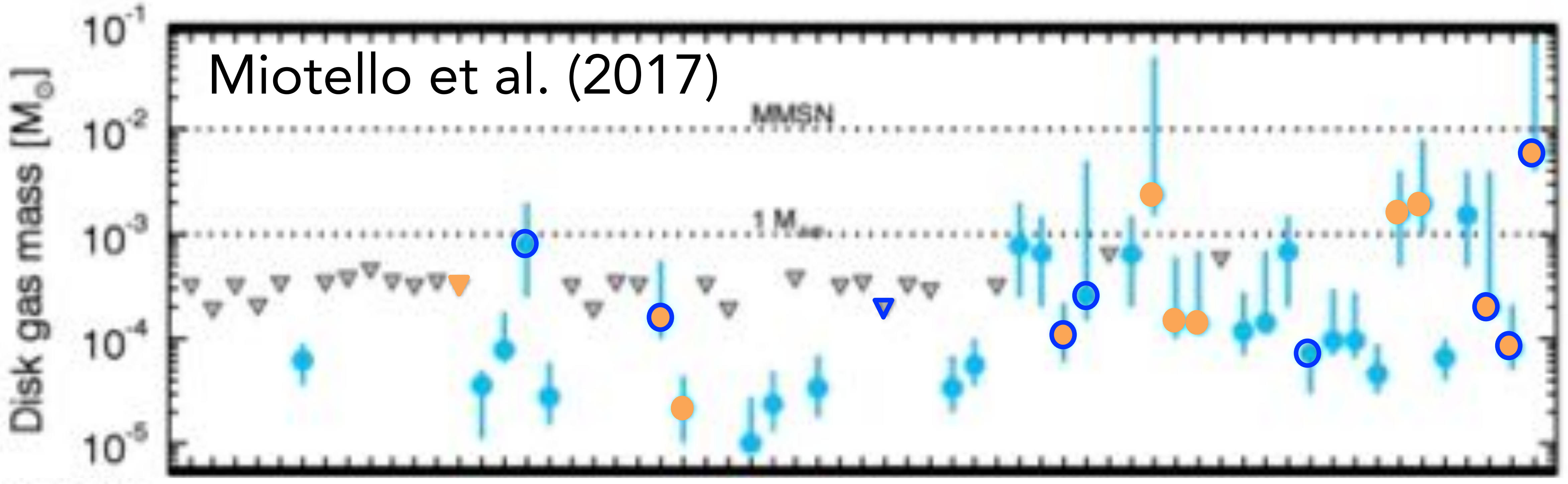


de Gregorio-Monsalvo et al. (2013)



Villenave et al. (2020)

or gas mass…. CO-isotopologues



Miotello et al. (2017)

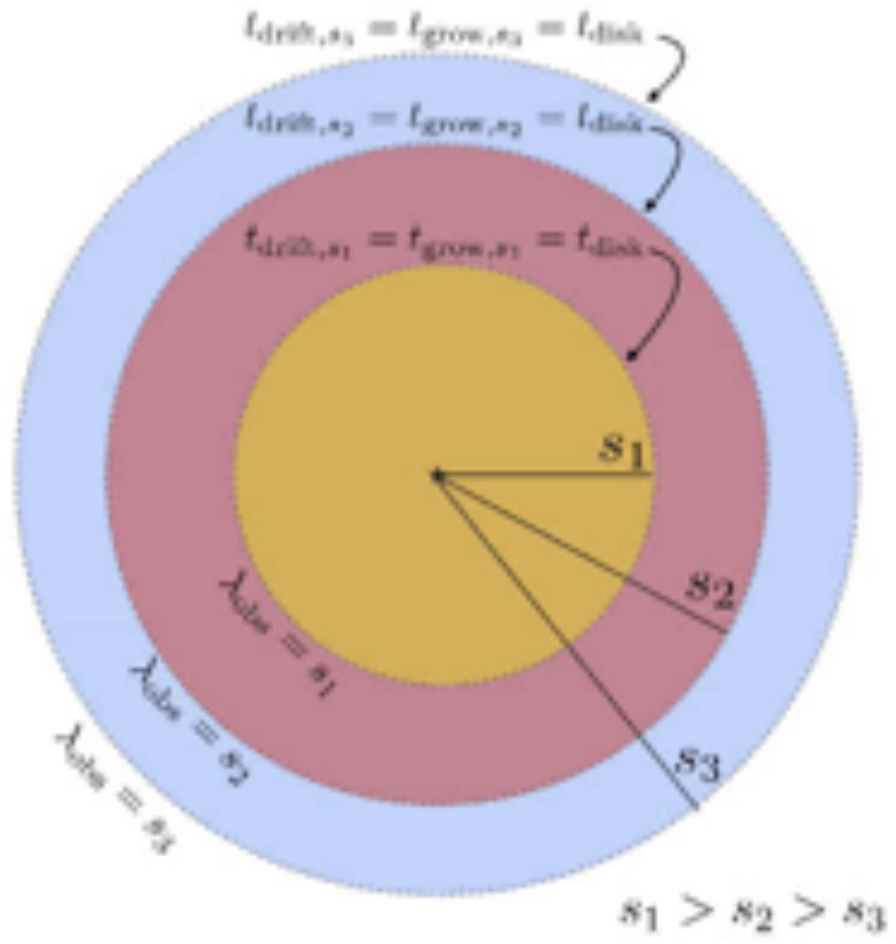
Uncertainties:

- Gas-to-dust value = 100 ?? (Draine 2003)
- $R_{\rm gas} \neq R_{\rm dust}$, $H_{\rm gas} \neq H_{\rm dust}$ (drift, settling, viscous evolution of the gas, initial conditions?…)
- Conversion factor CO-to-H_2 ??
- CO depletion?

ALTERNATIVE DISC SCALE

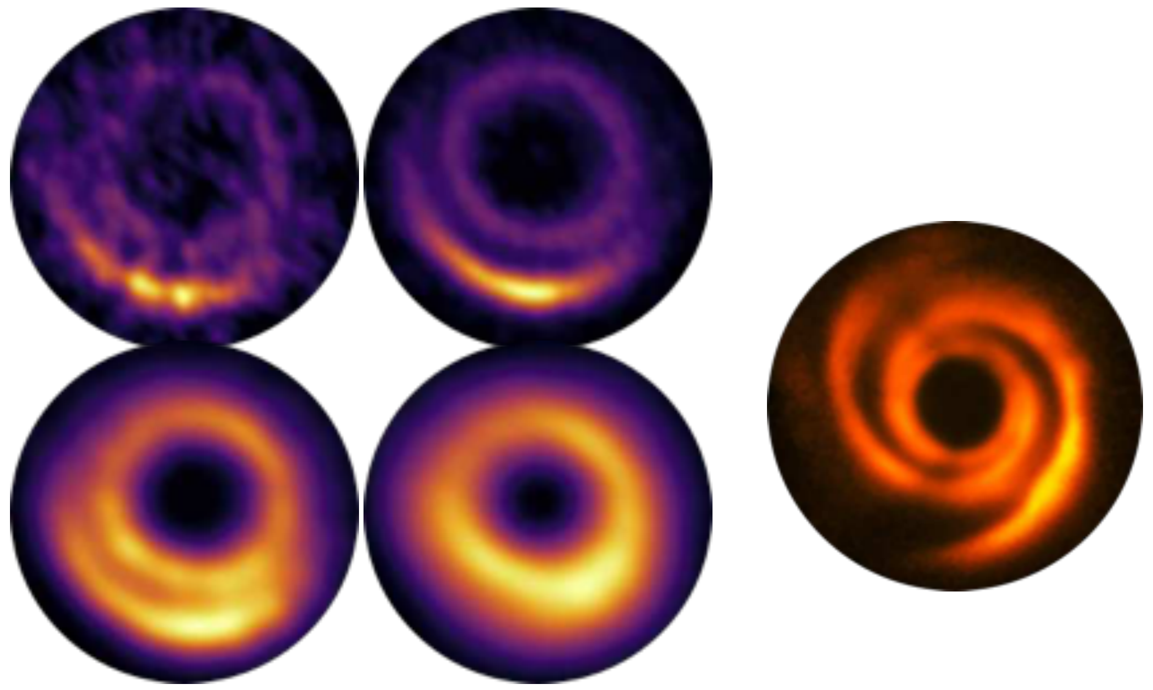
Is there a method to estimate the disc mass which is independent of the conversion factor CO/dust-H_2?

HD measurements → HD does not freeze-out! T vertical structure needed (Trapman et al. 2017) e.g., TWHya (Bergin et al. 2013), DM Tau and GM Aur (McClure et al. 2016)



Disc dust lines at different λ, R_{mm} (Powell et al. 2017,2019) → Total gas surface density estimate

Scattered light vs continuum features Veronesi et al. (2019) → **Dust/gas interaction** as disc **scale** (local surface density estimate)



Dynamically, searching for **SG** deviation from Keplerianity in the disc rotation curve!

DISC SELF-GRAVITY IN A NUTSHELL

DISC SELF-GRAVITY IN A NUTSHELL

$$(\omega - m\Omega(r))^2 = c_s^2 k^2 - 2\pi G\Sigma |k| + \kappa^2$$

Lin & Shu (1964)

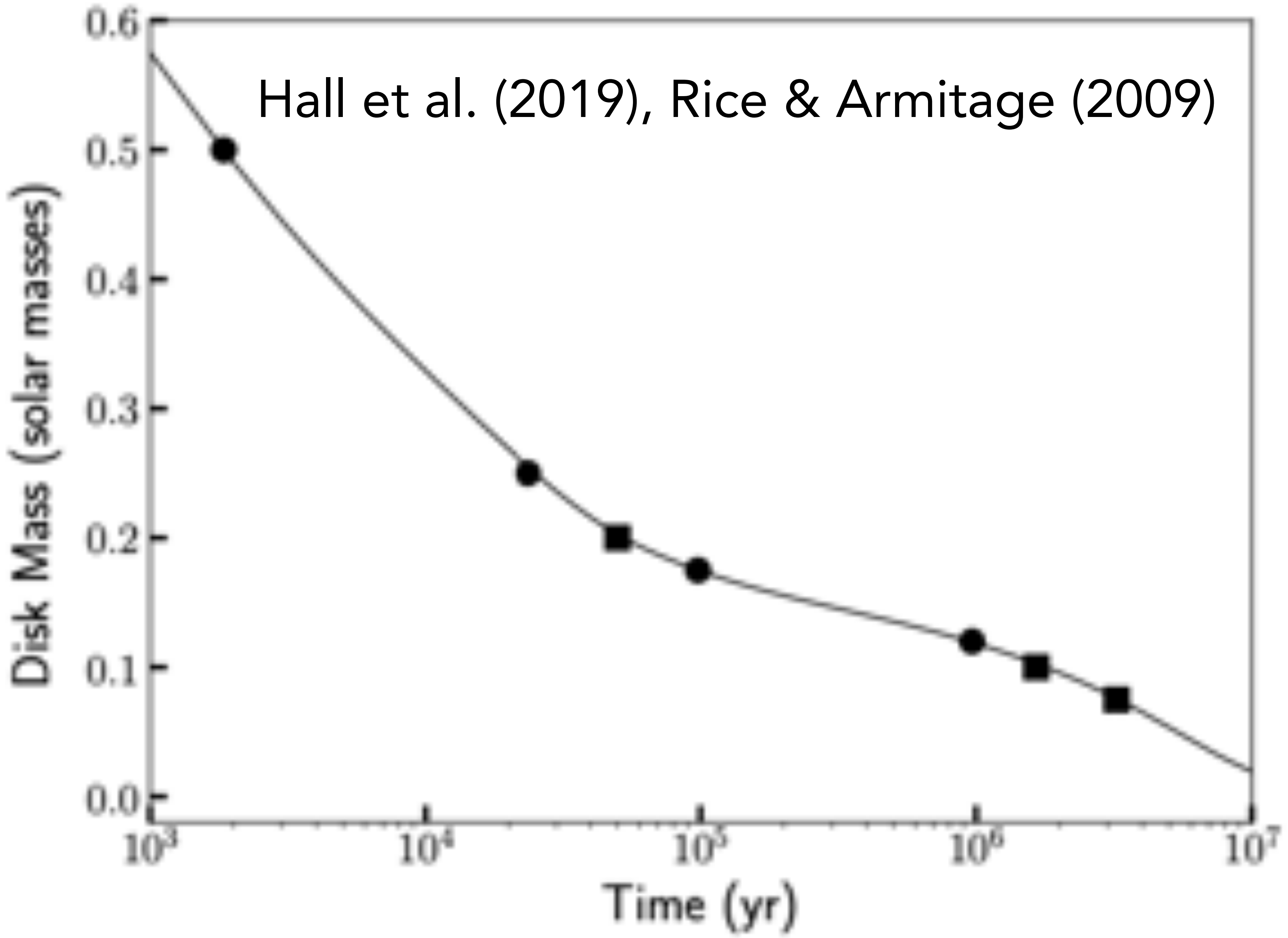
$$Q = \frac{c_s \kappa}{\pi \mathcal{G} \Sigma} \simeq \frac{M_*}{M_d}\frac{H}{r} \leq 1 \longrightarrow \frac{M_d}{M_*} \approx \frac{H}{R} \geq 0.06 - 0.1$$

Toomre (1964)

DISC IS SELF-GRAVITATING UNSTABLE!

Disc self gravity >> gas pressure (small scale) + rotation (large scale)

SG fundamental to understand the entire planet formation process



When?

- Initial evolutionary stages, after formation from the parental molecular cloud
- Rapid accretion and/or late episode of infall accretion from the MC (e.g. Elias 2-27?)

DISC SELF-GRAVITY IN A NUTSHELL

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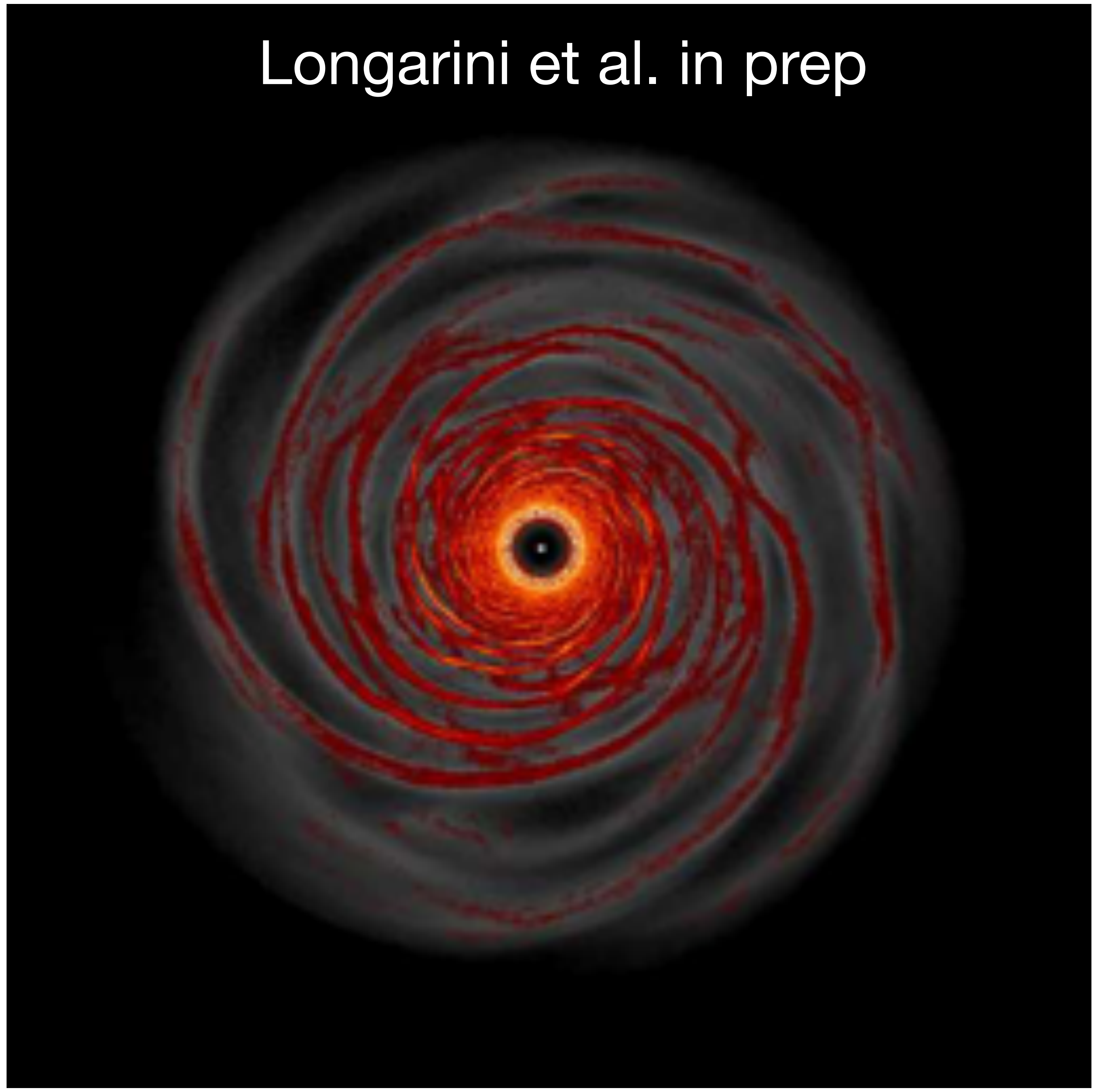

Dust concentration and fragmentation in GI spirals

(Rice et al. 2004,2006; Longarini et al. 2023 + in prep, , Sahl's talk and Cristiano's talk tomorrow!)

Planetesimals survival in a self-gravitating disc?

(unlikely, const β: e.g., Baruteau et al. 2011, Malik et al. 2015; possible, $\beta(R)$: e.g., Rowther et al. 2020)

DISC SELF-GRAVITY IN A NUTSHELL

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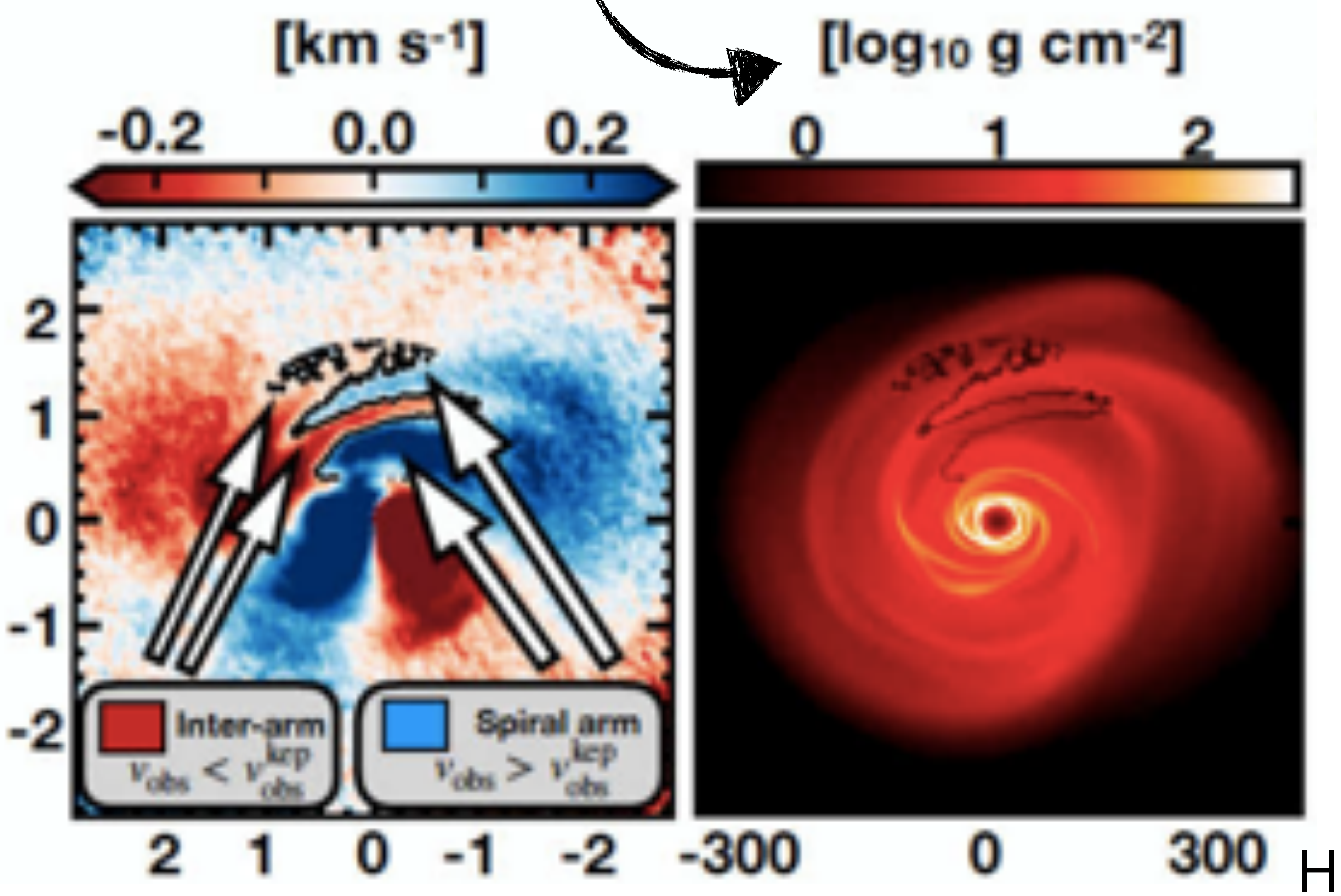

Hall et al. (2020)

Self-gravity contributes to the gravitational potential:

- **basic state: super-Keplerian rotation curve**

(e.g., Lodato & Bertin 2003; Veronesi et al. 2021; Lodato et al. 2022; Veronesi, Longarini et al. in prep)

- **non axisymmetric perturbation: GI spirals -> wiggle** (Hall et al. 2020; Terry et al. 2021; Longarini et al. 2021, see Cristiano's talk!)

LET’S GO BACK TO THE DYNAMICAL SCALE IDEA…

THE MODEL: WHERE WE STARTED & WHERE WE'RE GOING

Veronesi et al. (2021), Lodato et al. (2023) + work in prep with C. Longarini, G. Lodato, P. Curone, G. Laibe, T. Paneque, C. Hall & others

$$v_{\rm rot}^2 = v_k^2 + v_{\rm disc}^2 + v_{\rm p}^2$$

~~$M_{\rm disc} \ll M_\star$ $v_{\rm rot}^2 = v_k^2$ Keplerian disc~~

Star contribution: Keplerian term

$$v_\star^2 = \frac{GM_\star R^2}{(R^2+z^2)^{3/2}} = R^2\Omega_k^2\left[1+\left(\frac{z}{R}\right)^2\right]^{-3/2}$$

$\Omega_k^2 = GM_\star/R^3$
Keplerian term

With:

$$\Sigma(R) = \frac{(2-\gamma)M_{\rm d}}{2\pi R_{\rm c}^2}\left(\frac{R}{R_{\rm c}}\right)^{-\gamma}\exp\left[-\left(\frac{R}{R_{\rm c}}\right)^{2-\gamma}\right]$$

$P = c_s^2\rho \qquad c_s \propto R^{-q}$

Disc contribution: super-Keplerian term

$$v_d^2 = G\int_0^\infty dr'\left[K(\zeta) - \frac{1}{4}\left(\frac{\zeta^2}{1-\zeta^2}\right)\times\left(\frac{R'}{R}-\frac{R}{R'}+\frac{z^2}{RR'}\right)E(\zeta)\right]\sqrt{\frac{R'}{R}}\zeta\Sigma(R')$$

Bertin & Lodato (1999)

Pressure contribution (both radial and vertical)

From hydrostatic equilibrium:

$$\rho(R,z) = \rho_0(R)\exp\left[-\frac{R^2}{H^2}\left(1-\frac{1}{\sqrt{1+z^2/R^2}}\right)\right]$$

(for z<<R -> Gaussian)

$$P(R,z) = P_0(R)\exp\left[-\frac{R^2}{H^2}\left(1-\frac{1}{\sqrt{1+z^2/R^2}}\right)\right]$$

$$v_p^2 = \frac{R}{\rho}\frac{\mathrm{d}P}{\mathrm{d}R}$$

→

Further development of the previous model used in Veronesi et al. (2021): e.g., **pressure gradient z(R) dependence**
(Lodato et al. 2023)

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~~$M_{\rm disc} \ll M_\star$ $\quad v_{\rm rot}^2 = v_k^2$ Keplerian disc~~

Vertical pressure gradient + stellar contribution: sub-keplerian

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

Radial pressure gradient: sub-keplerian

Disc contribution non negligible when:

- Gravitationally marginally unstable $M_{\rm d}/M_\star \approx H/R$
- Gravitationally stable $(H/R)^2 < M_{\rm d}/M_\star < H/R$

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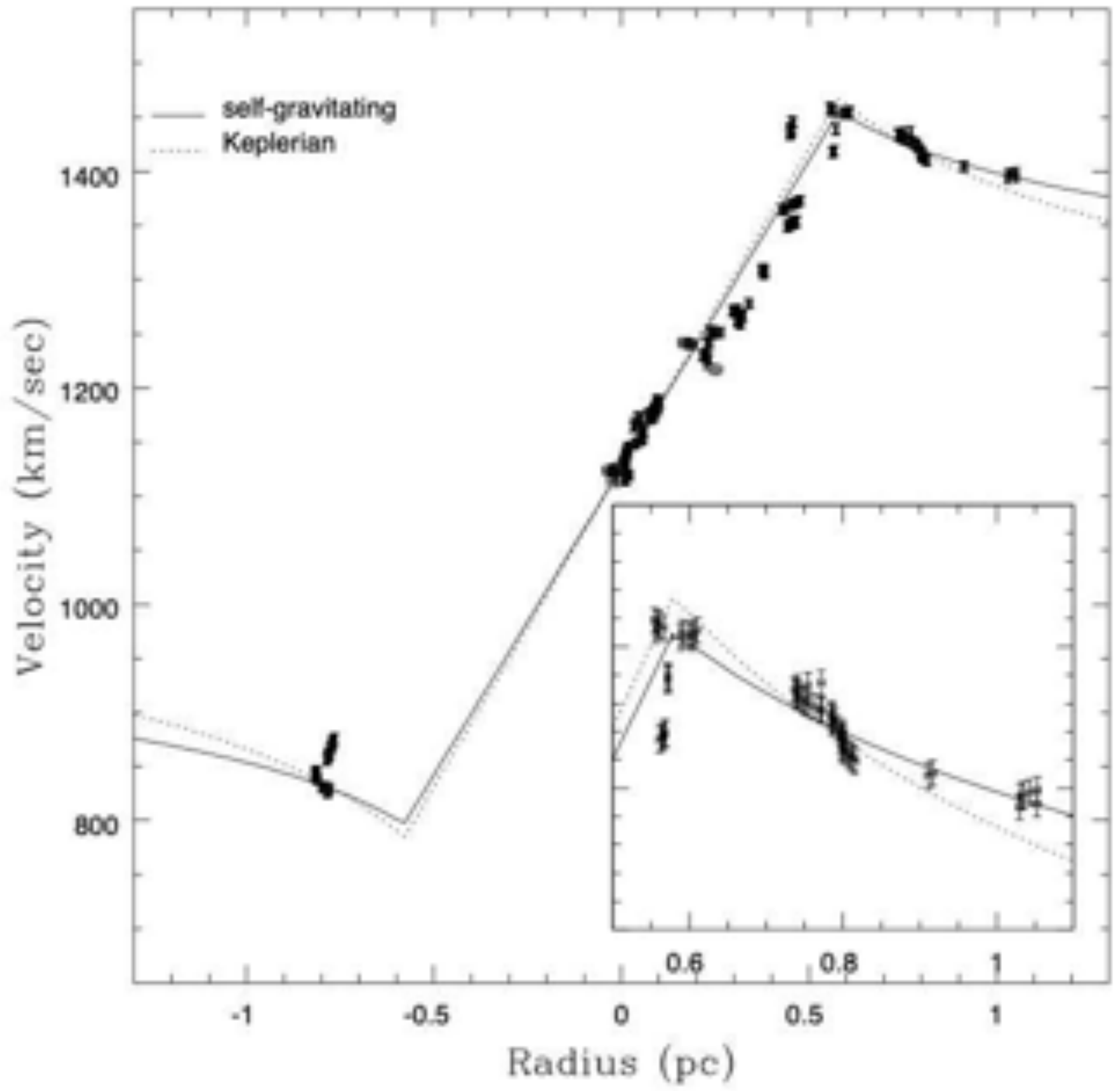
Radial pressure gradient: sub-keplerian

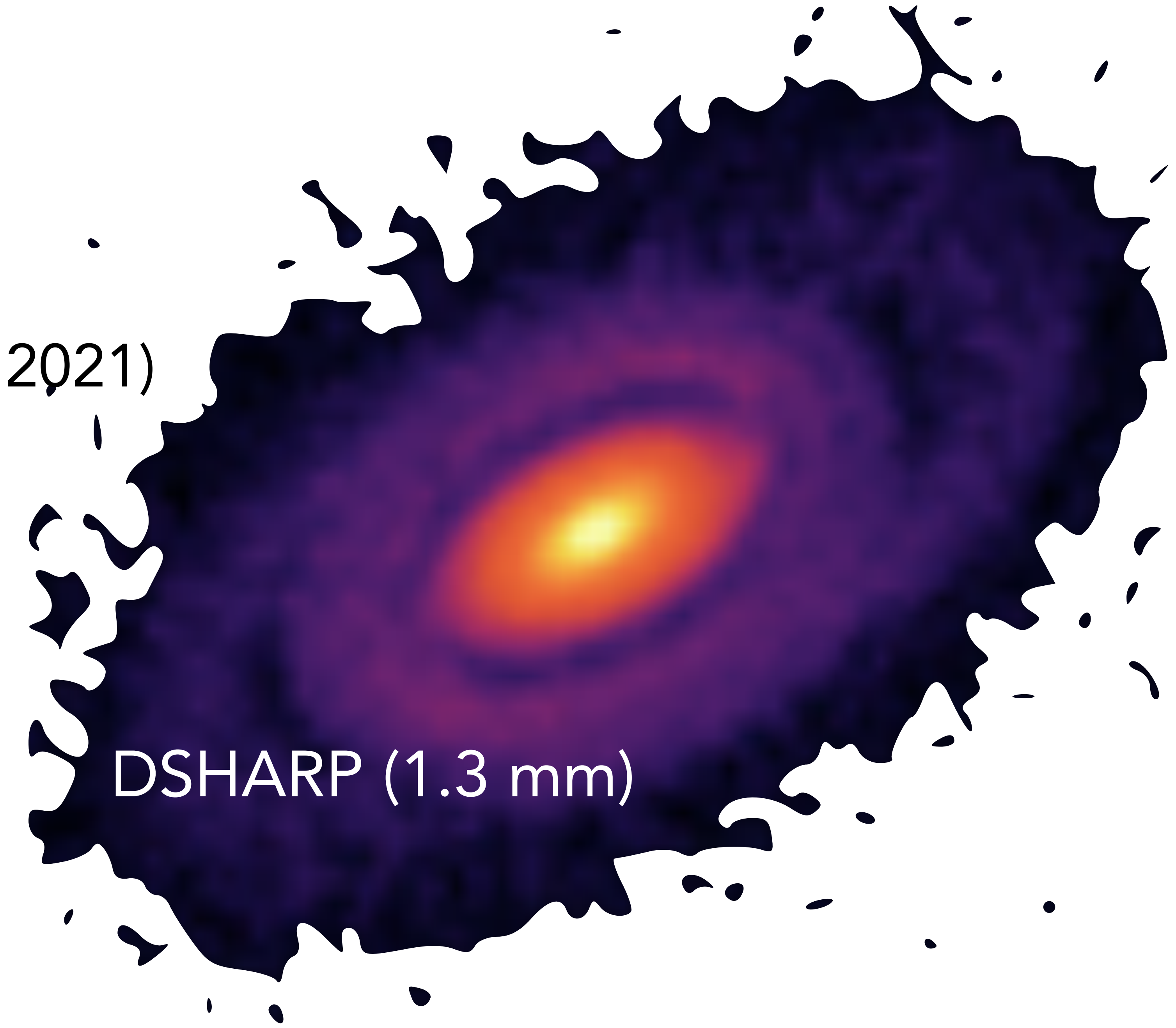
Lodato & Bertin (2003)



Deviations from Keplerian rotation in protoplanetary disc with a self-gravitating model → Infer simultaneously the **disc and star mass,** and also the **outer disc radius**

THE FIRST CANDIDATE: ELIAS 2-27

Veronesi et al. (2021)



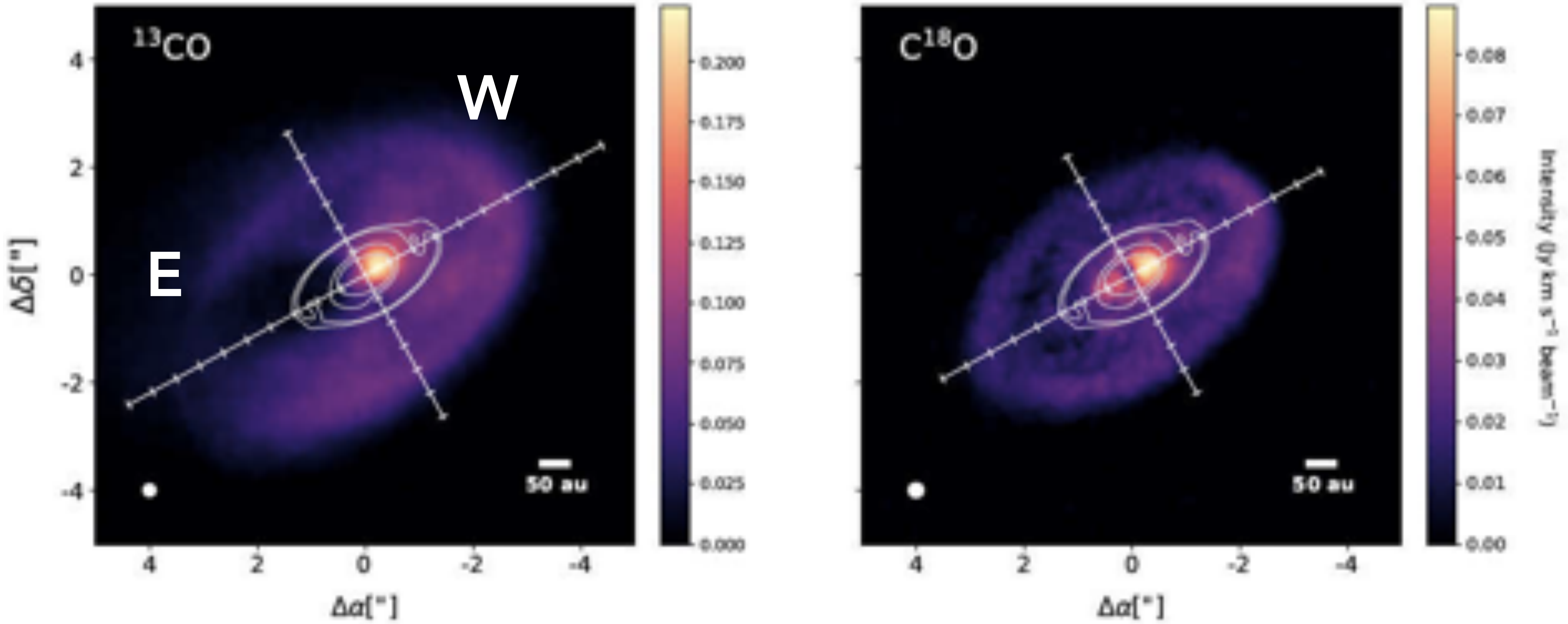
Elias 2-27: 0.8 Myr, M0 star, d=140 pc

Two large-scale spiral arms (Pérez et al. 2016a; Andrews et al. 2018, Paneque-Carreno et al. 2021)

Disc-to-star ≈ 0.3, considering gas/dust=100

(Andrews et al. 2009; Pérez et al. 2016; Meru et al. 2017; Hall et al. 2018; Cadman et al. 2020; Paneque-Carreno et al. 2021)

Possible origin for the spiral arms: GI (Meru et al. 2017, Hall et al. 2018, Paneque-Carreno et al. 2021)



With G. Lodato, T. Paneque-Carreño, C. Hall, L. Testi, L. Pérez, G. Bertin

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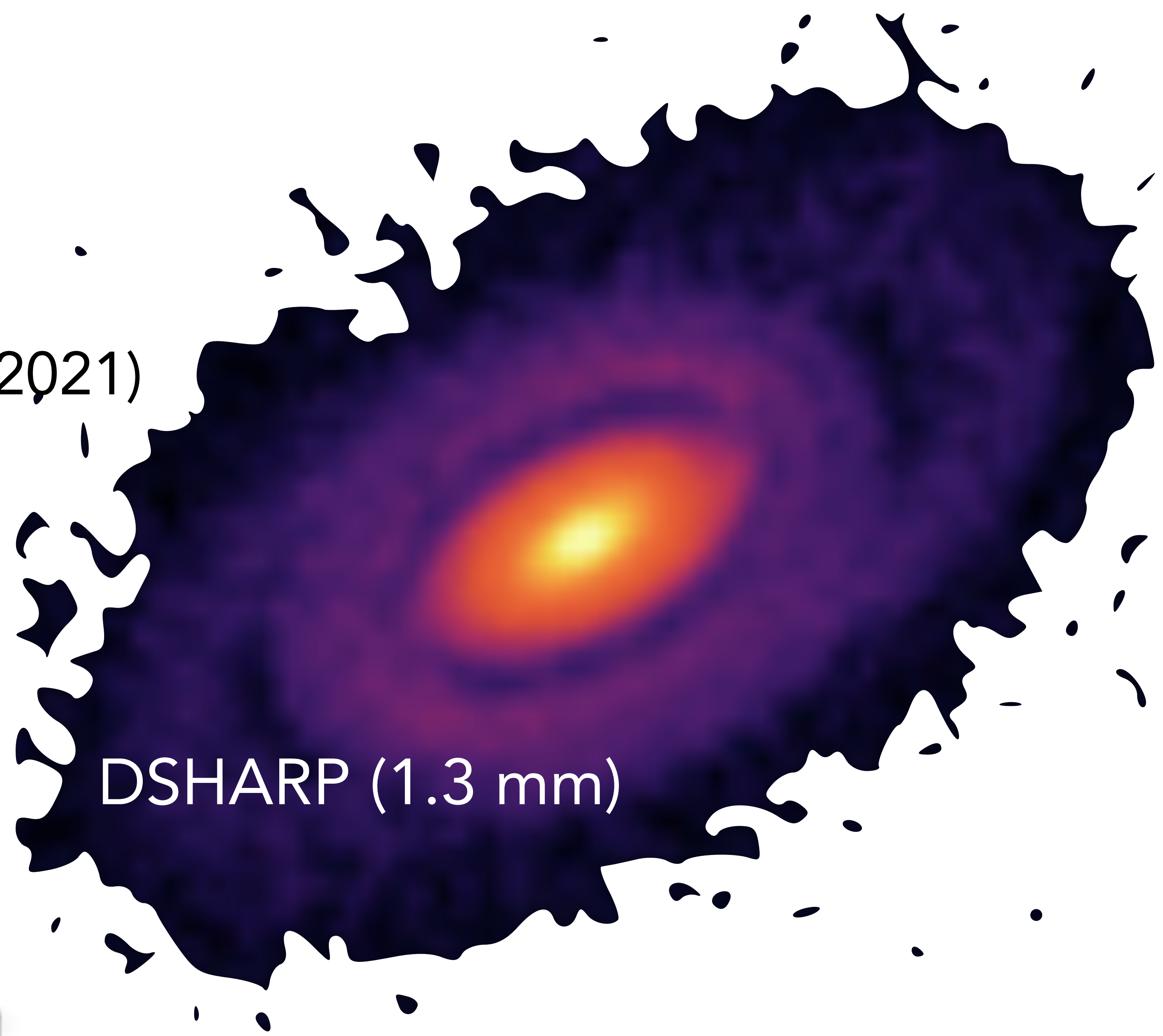
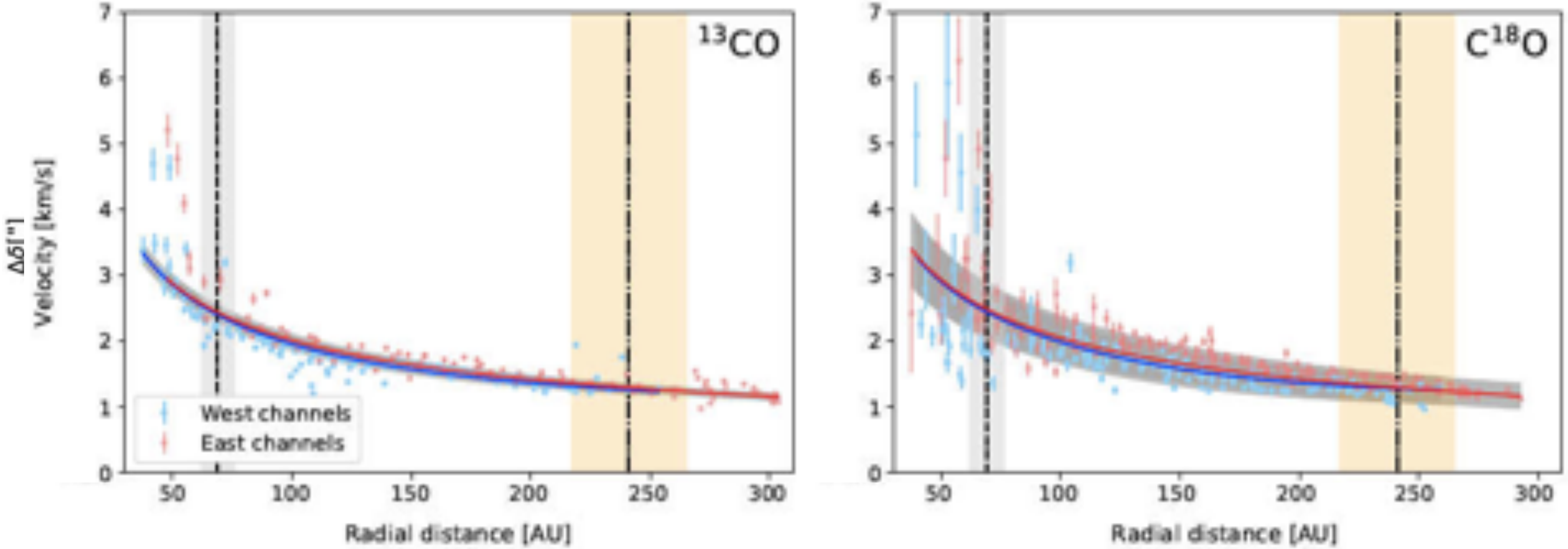
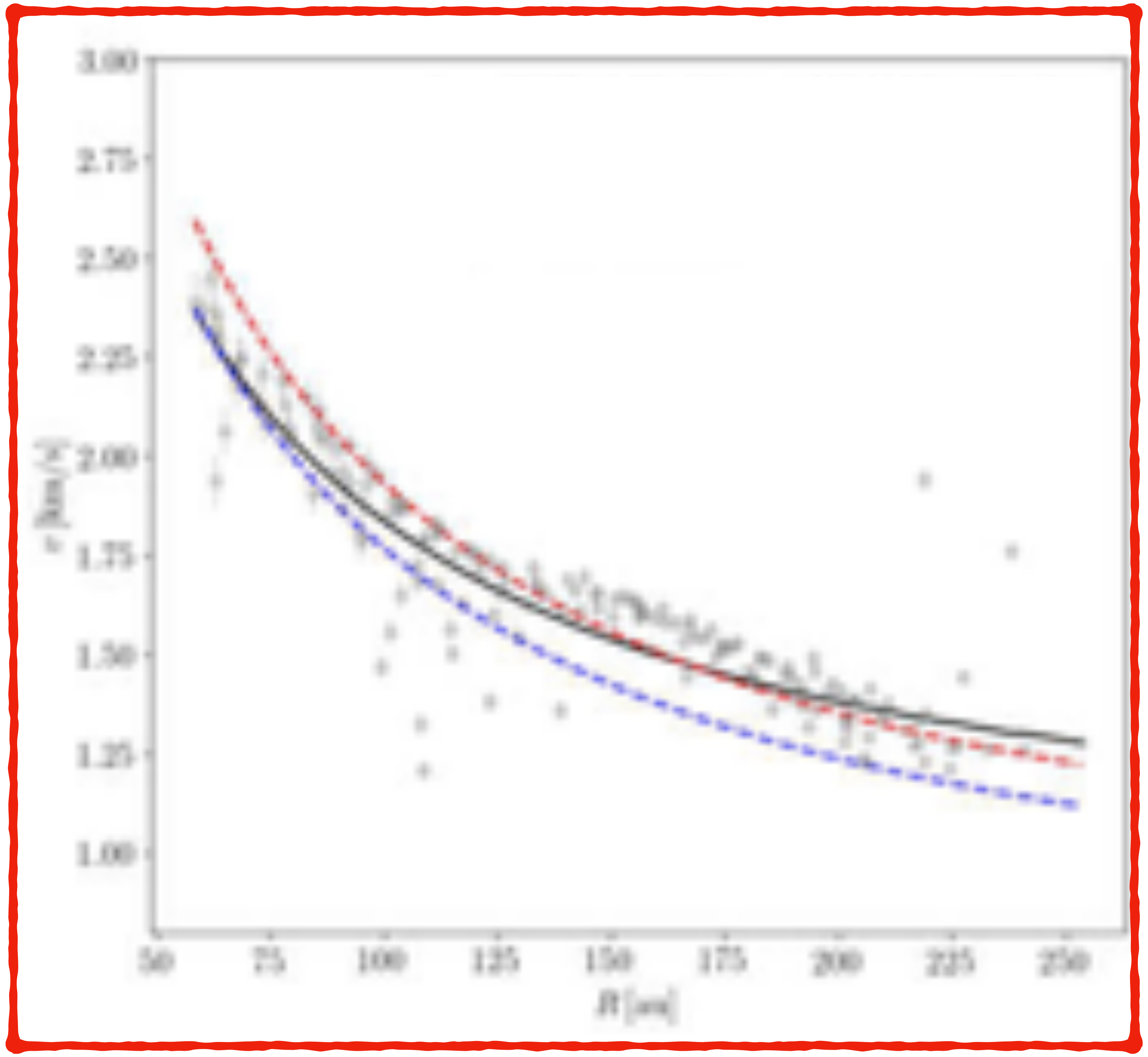




With G. Lodato, T. Paneque-Carreño, C. Hall, L. Testi, L. Pérez, G. Bertin

A DYNAMICAL SCALE FOR (MASSIVE) DISCS

SG model — Kep model — Kep model (sg)



^{13}CO fit West side

	^{13}CO	$C^{18}O$
Keplerian fit		
$M_\star$ [$M_\odot$]	$0.49^{0.01}_{-0.01}$	$0.42^{0.03}_{-0.03}$
Self-gravitating fit		
$M_\star$ [$M_\odot$]	$0.41^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.07}$
$M_{\rm disk}$ [$M_\odot$]	$0.16^{+0.06}_{-0.06}$	$0.08^{+0.08}_{-0.06}$
$\lambda = \Delta(\text{red-}\chi^2)$	4.57	-0.51

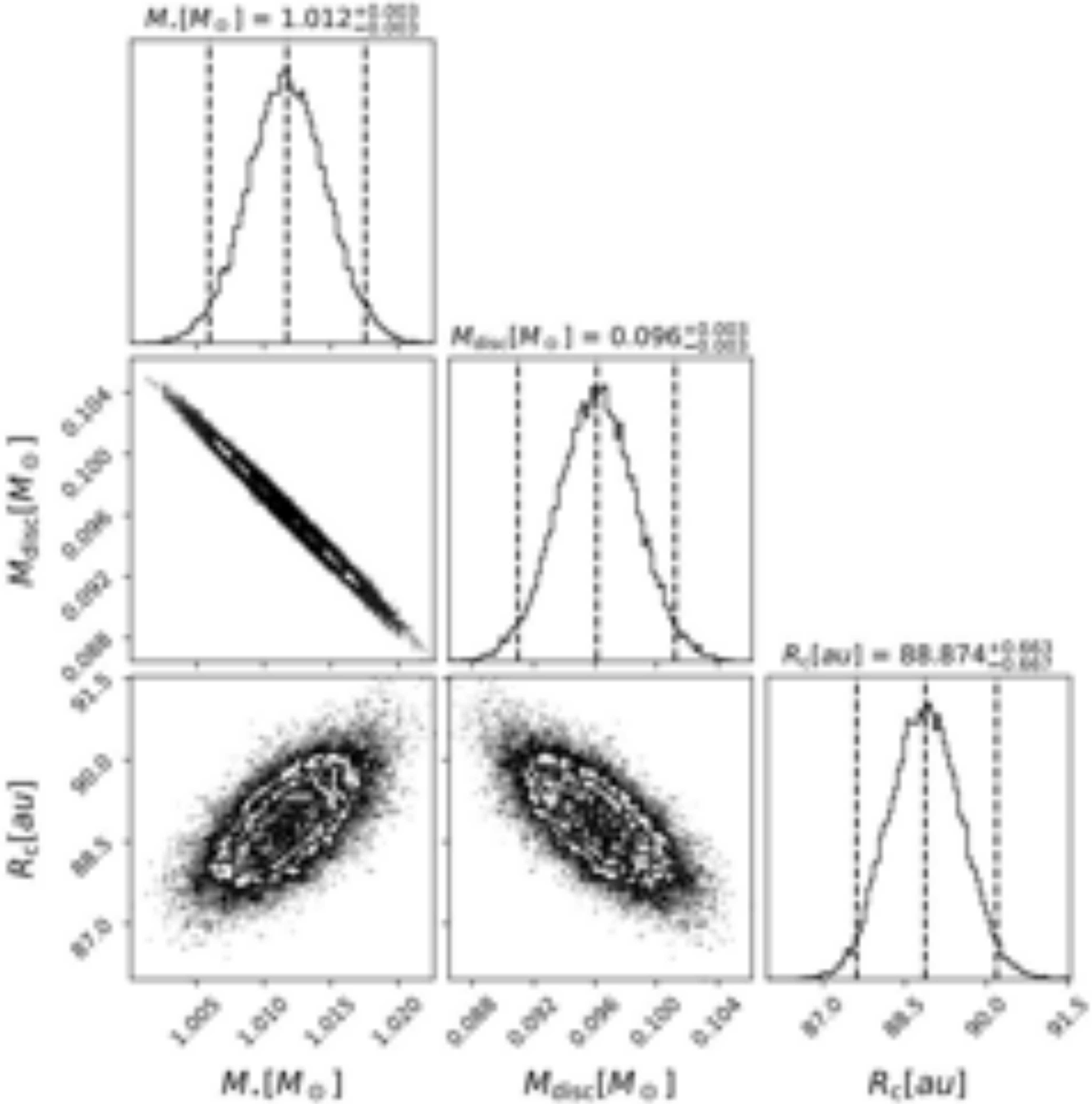
$$\frac{M_{\rm disc}}{M_\star} \approx 0.17 - 0.22$$

self-gravitating disc model

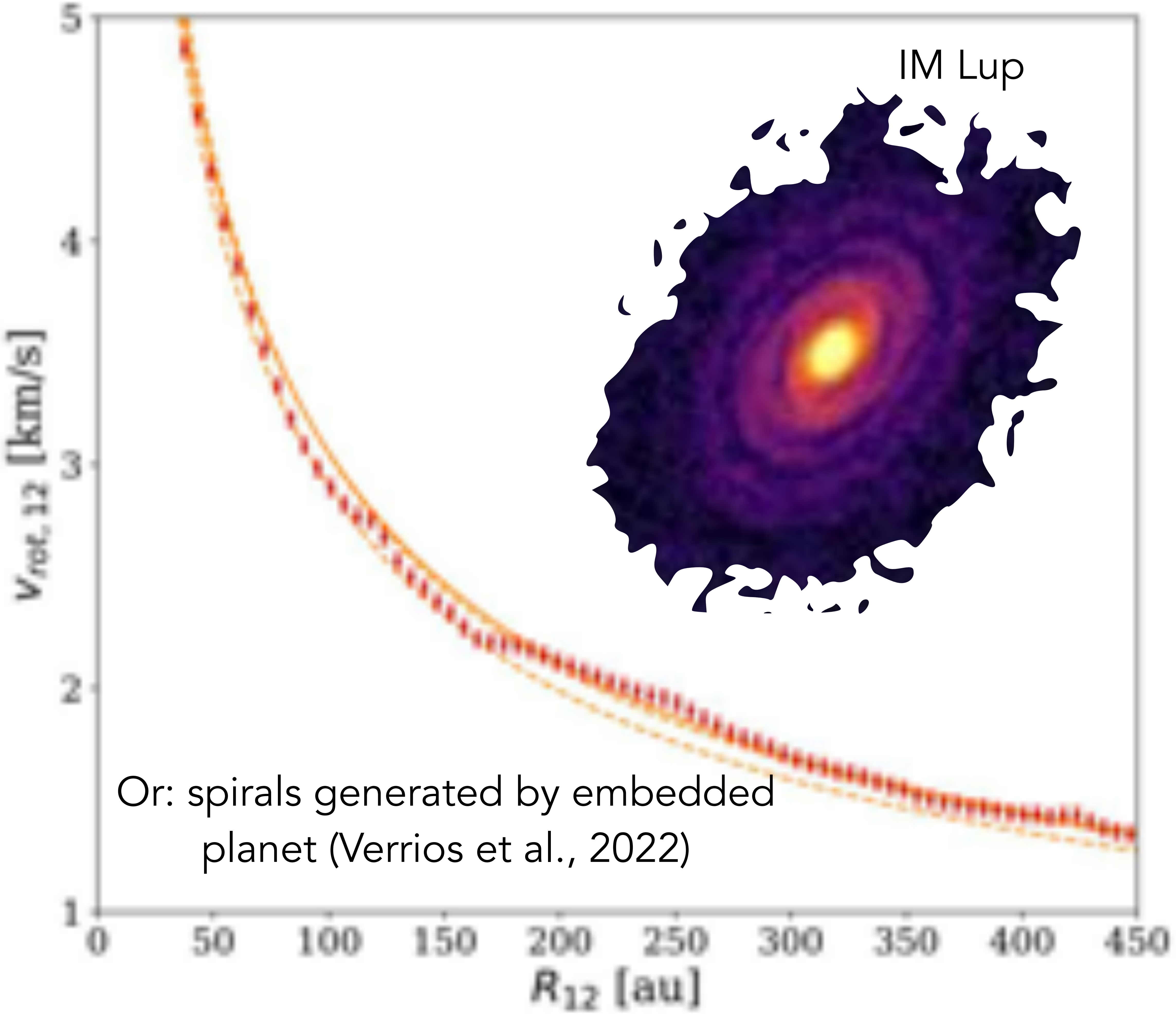
WEST SIDE: not cloud-contaminated (better data, better estimate)

A DYNAMICAL SCALE FOR (MASSIVE) DISCS

emcee
The MCMC Hammer



Lodato et al. (2023): **IM Lup** & GM Aur



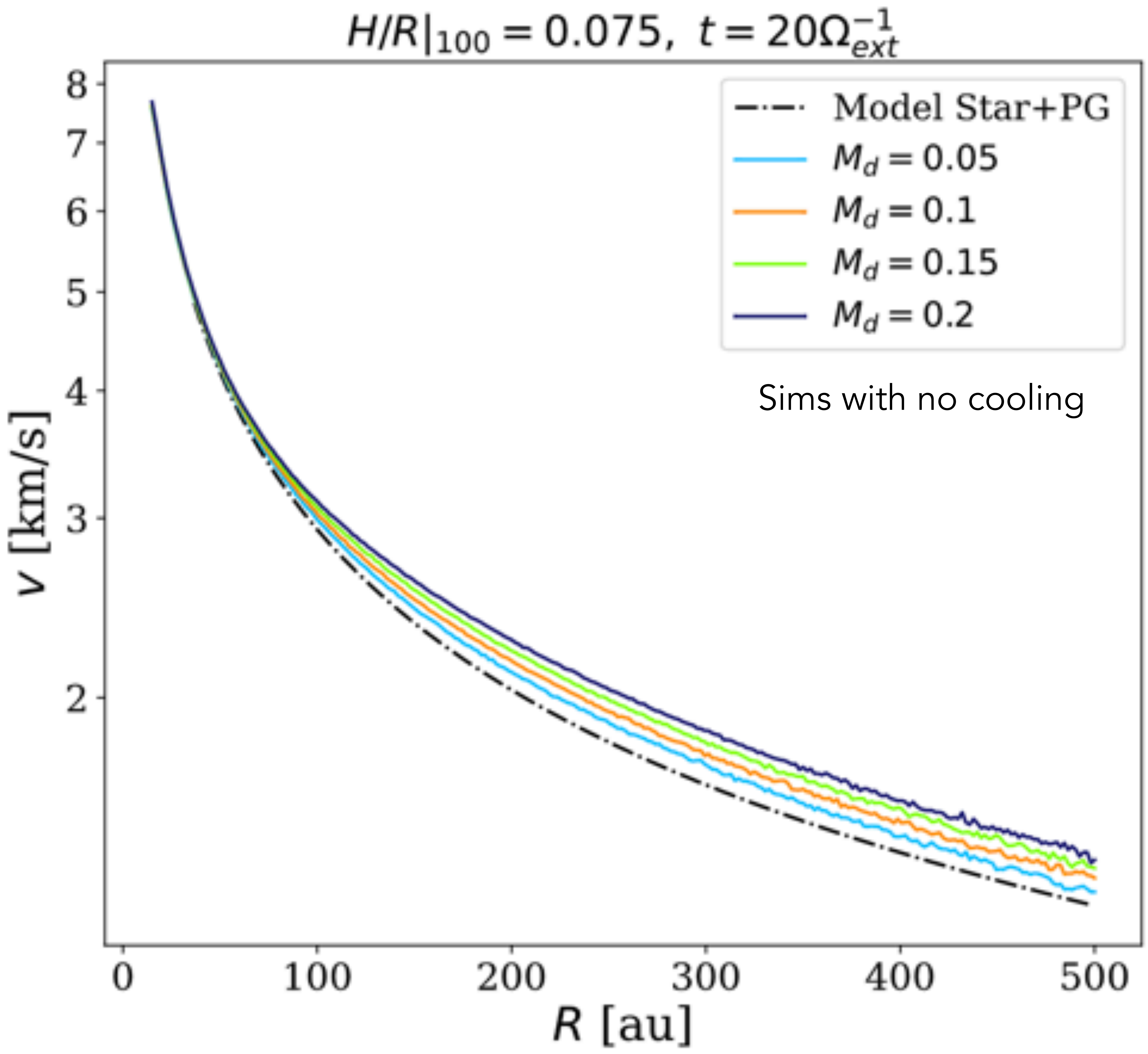
Or: spirals generated by embedded planet (Verrios et al., 2022)

TESTING THE DYNAMICAL SCALE WITH SG SIMULATIONS

1. Test the improved model with SG PHANTOM (Price et al. 2008) + MCFOST (Pinte et al. 2006,2009) simulations (both with GI spirals - COOLING=YES-, and without - COOLING=NO)
   SELF-GRAVITY = ON, in both cases

   A. First test: disc masses from hydro rotation curves at the midplane

Simulation	$M_\star$ [M$_\odot$]	M_d [M$_\odot$]	R_c [au]
	1	[0.05,0.1,0.15,0.2]	100
005h75	0.99	0.05	94
01h75	0.98	0.1	106
015h75	0.98	0.14	113
02h75	0.98	0.19	119



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2. Minimum disc mass we can measure?
3. How the spectral and spatial resolution do affect the mass estimate?

MCFOST SIMS

^{12}CO + ^{13}CO;

J=2-1, J=3-2;

INCLINATION=**30**,45,60°

Spectral (and spatial) resolution as in the MAPS survey $[\Delta v = 0.1\,\mathrm{km/s}; \mathrm{res} = 0.1'']$

PHANTOM SIMS

$$\Sigma(R) = \frac{(2-\gamma)M_\mathrm{d}}{2\pi R_\mathrm{c}^2}\left(\frac{R}{R_\mathrm{c}}\right)^{-\gamma}\exp\left[-\left(\frac{R}{R_\mathrm{c}}\right)^{2-\gamma}\right]$$

$\gamma = 1$

$r_\mathrm{c} = 100\,\mathrm{au}$

	$M_d/M_\star$
S1	0.01
S2	0.025
S3	0.05
S4	0.1
S5	0.15
S6	0.2

$H/R|_{100} = [0.075, 0.1]$

$r_\mathrm{in} = 1.5\,\mathrm{au}$

$r_\mathrm{out} = 300\,\mathrm{au}$

$q = 0.25$

Caution: the higher the mass, the higher the disc emitting layer, the lower the resolution

No cooling (no GI)

Isothermal disc with SG and disc viscosity $\alpha_\mathrm{ss} = 0.005$

Cooling (GI)

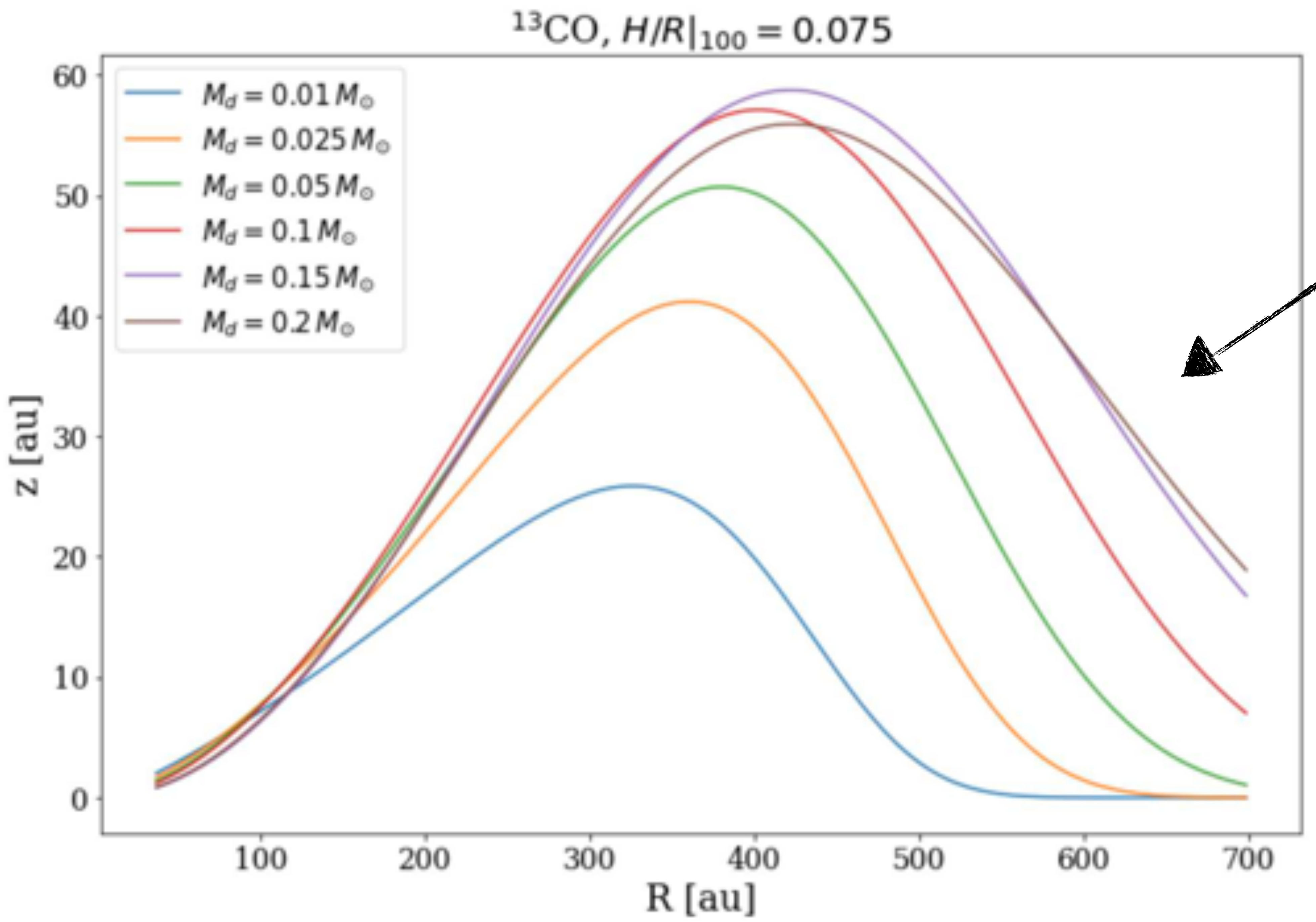
$Q|_\mathrm{ext} \simeq 2$

$\beta_\mathrm{cool} = 10$

WORKFLOW

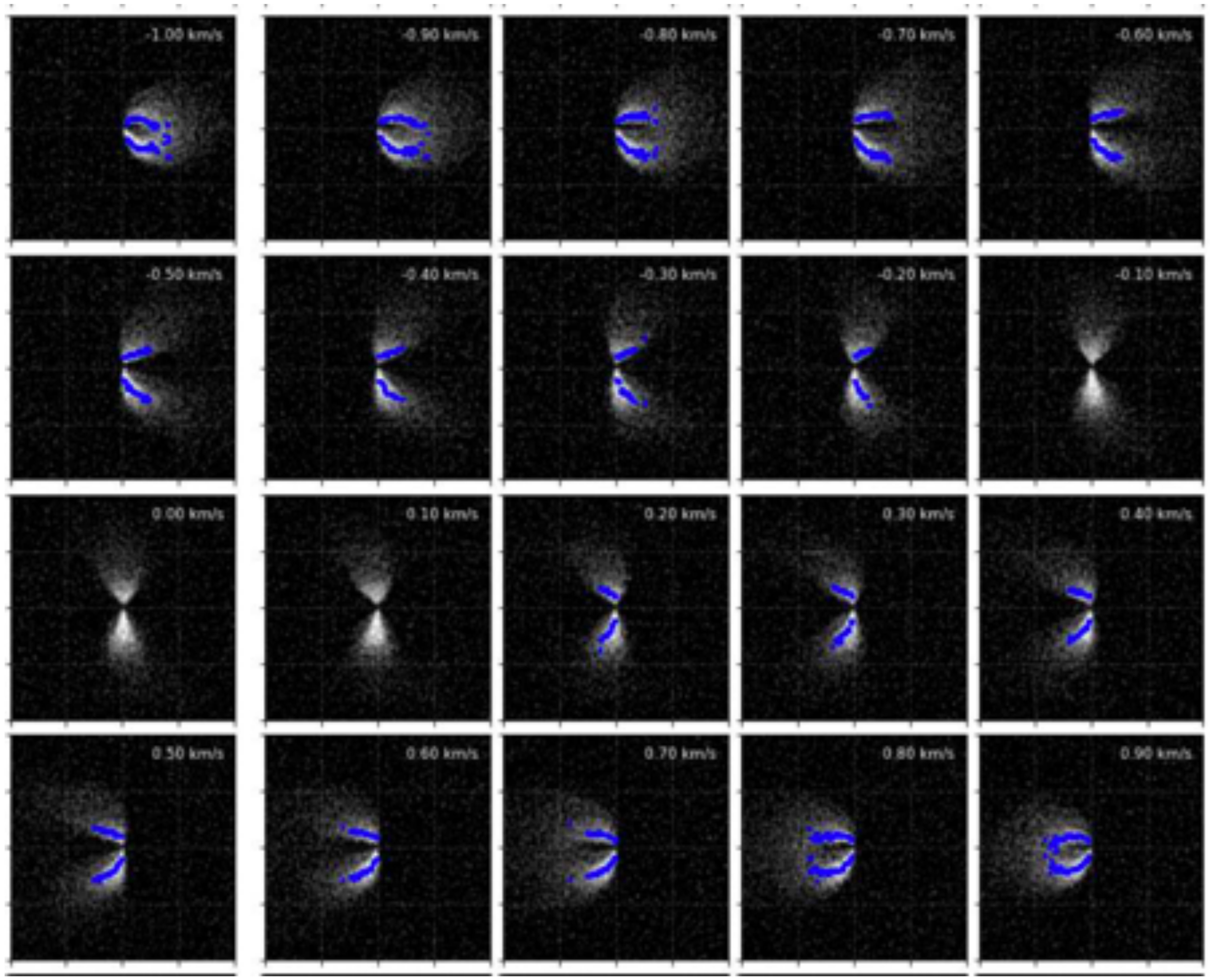
1. Extraction of emitting layer with DISKSURF (Teague 2019)

   e.g. MCFOST simulation with **i** $= 30^\circ$ + finite spectral and spatial resolution & noise (with pymcfost): **0.1 km/s & 0.1"**



Fitted with an exponentially tapered power-law

DISKSURF



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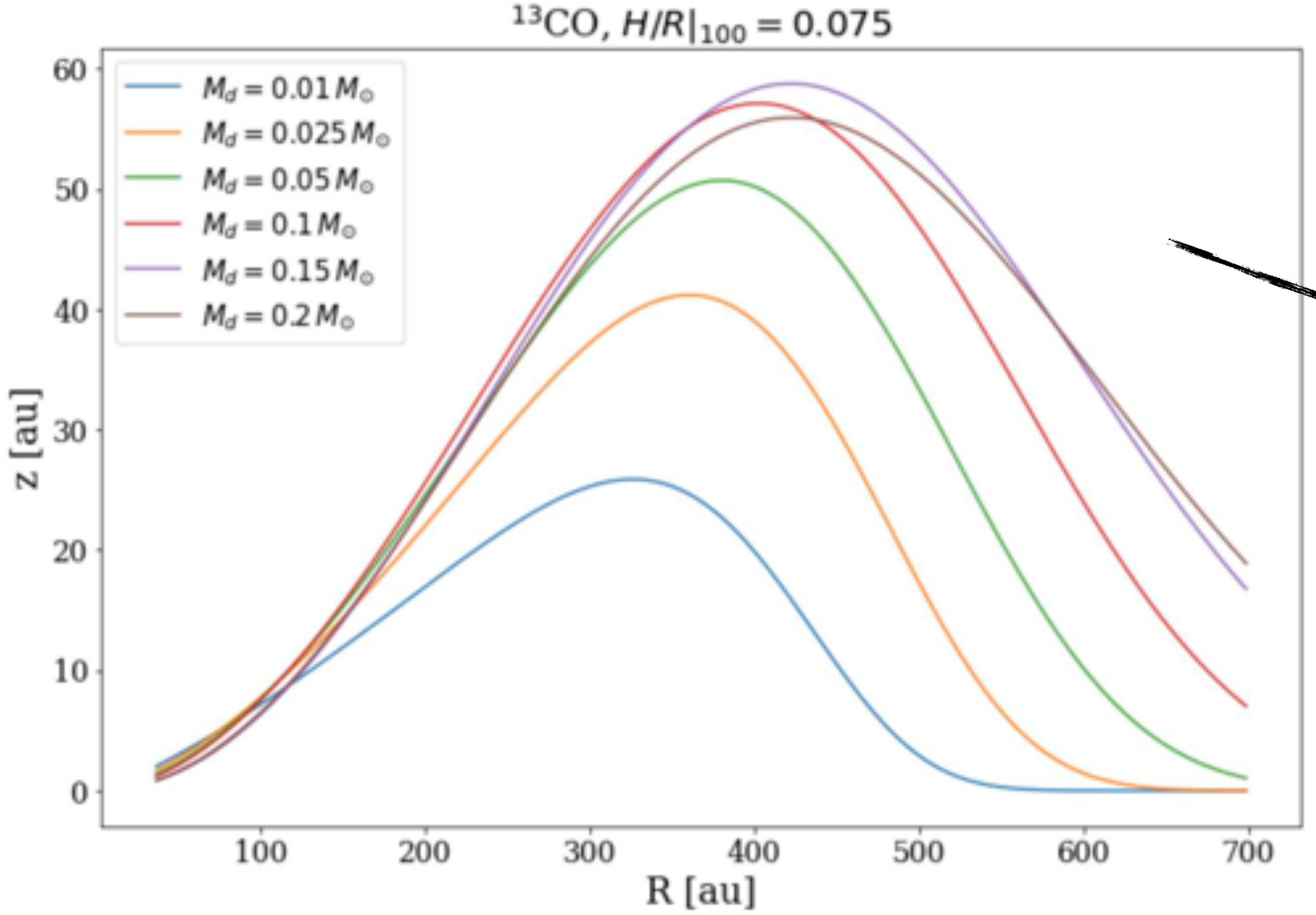

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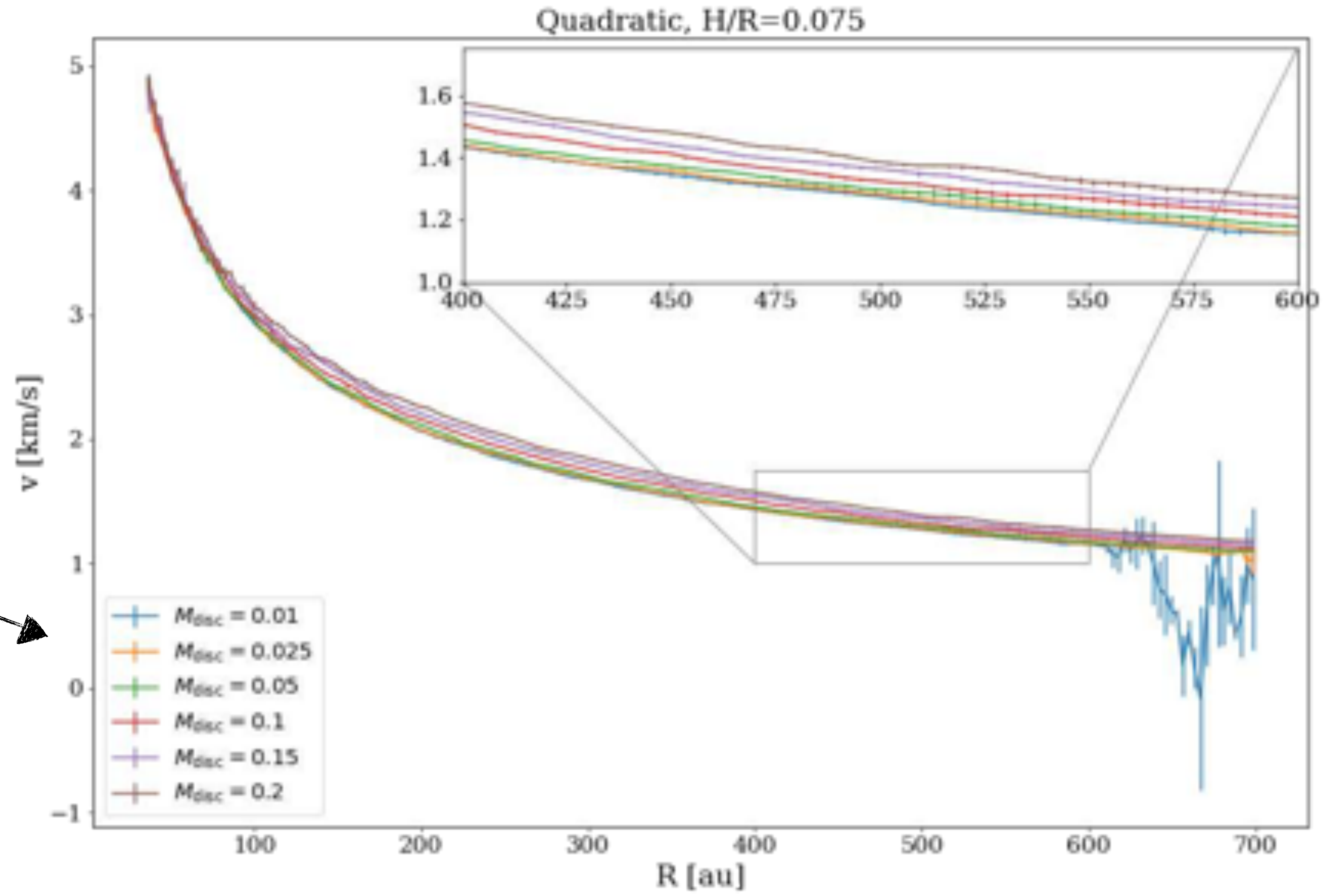

2. Extraction of rotation curves with EDDY (Teague 2019):
   - Errors obtained by considering uncertainties on the emitting layer (16th and 84th percentiles)

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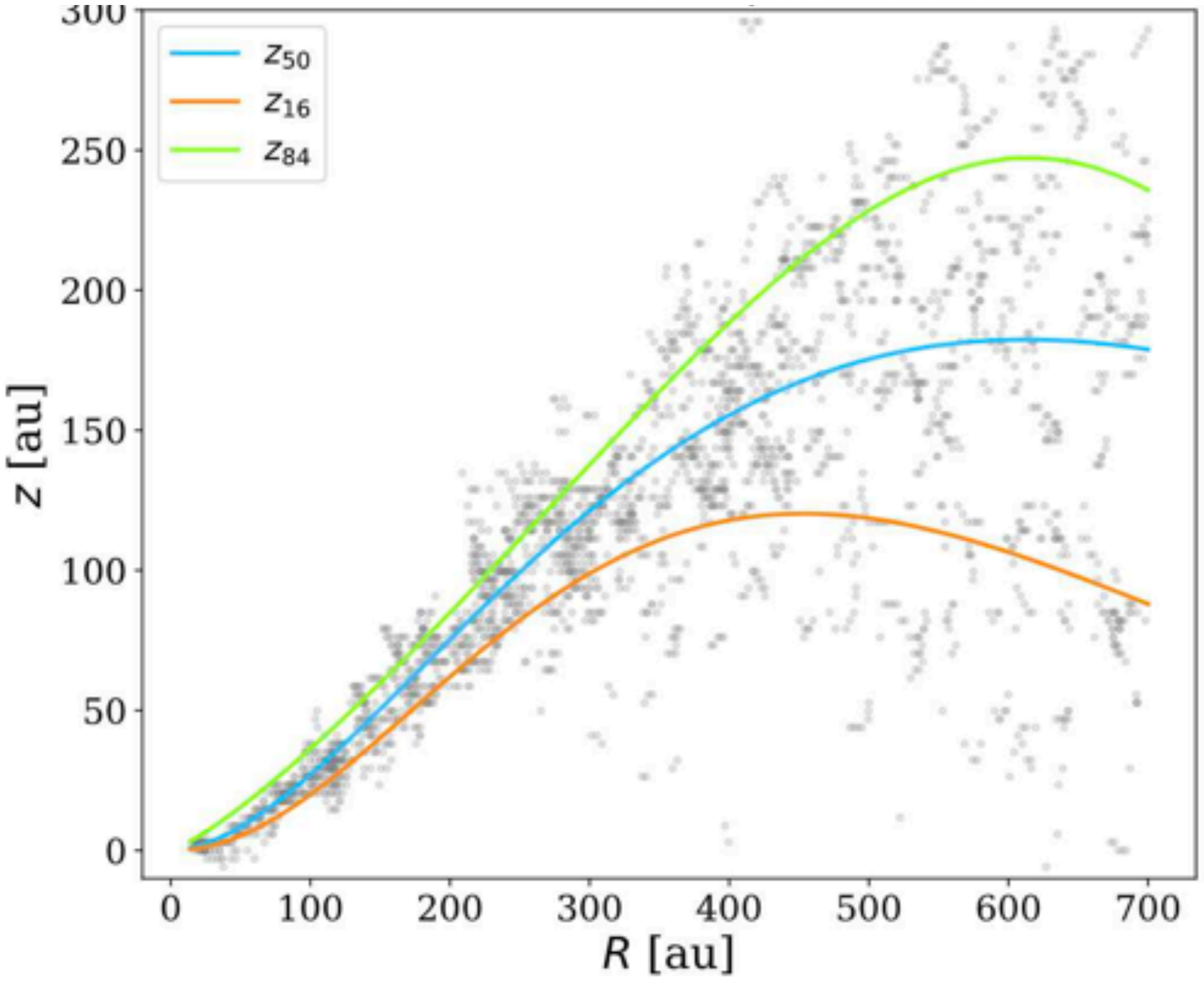

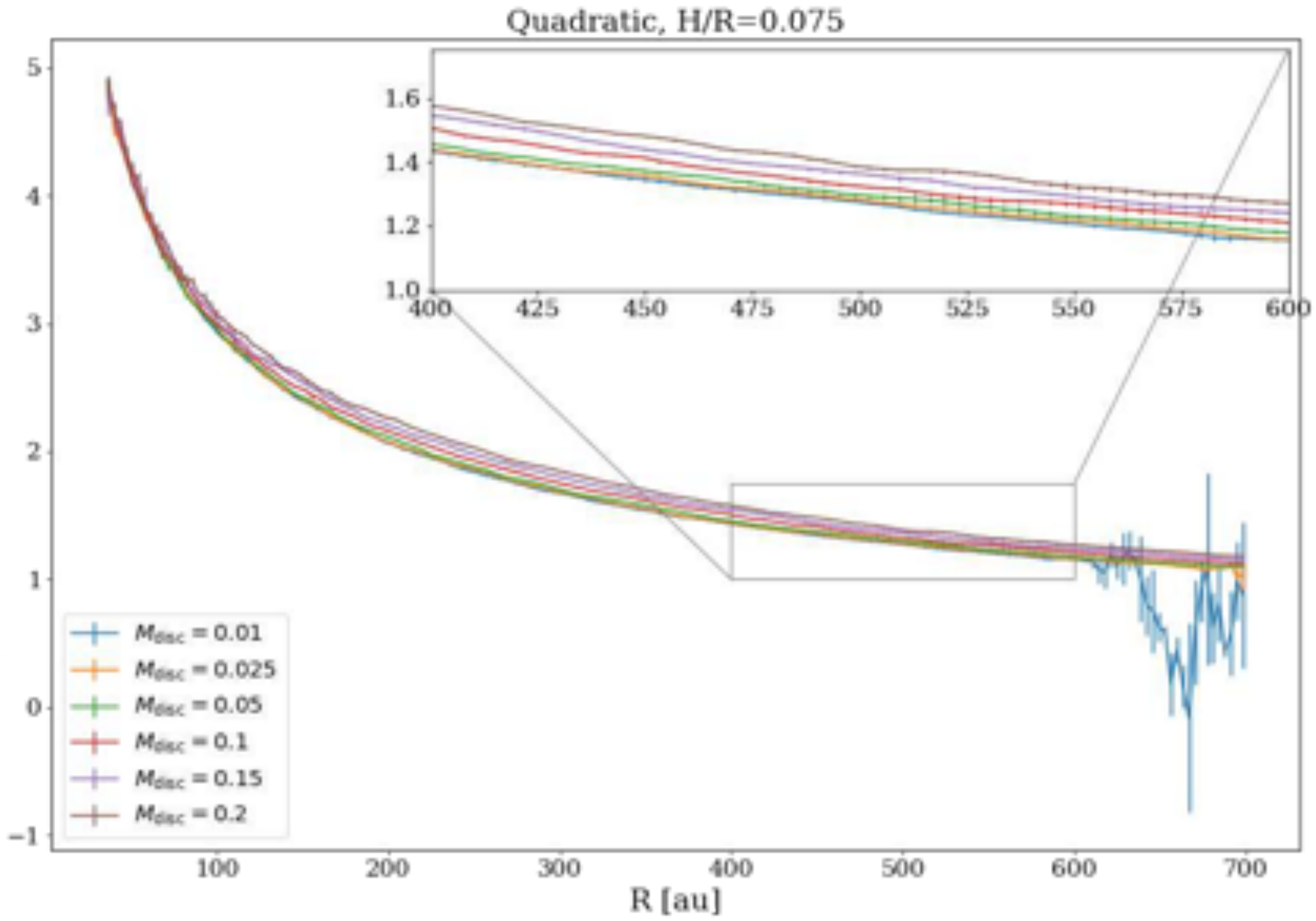

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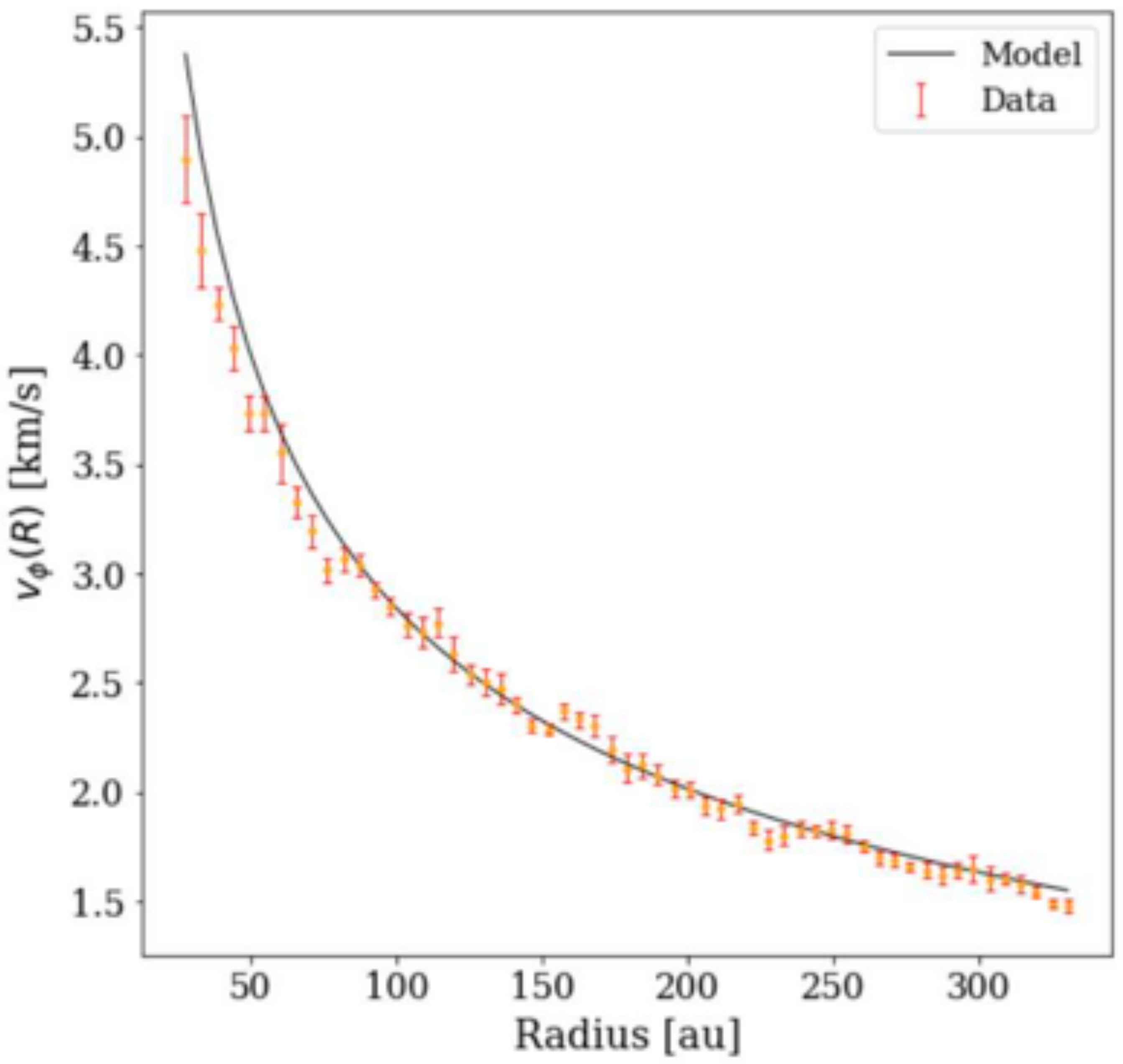
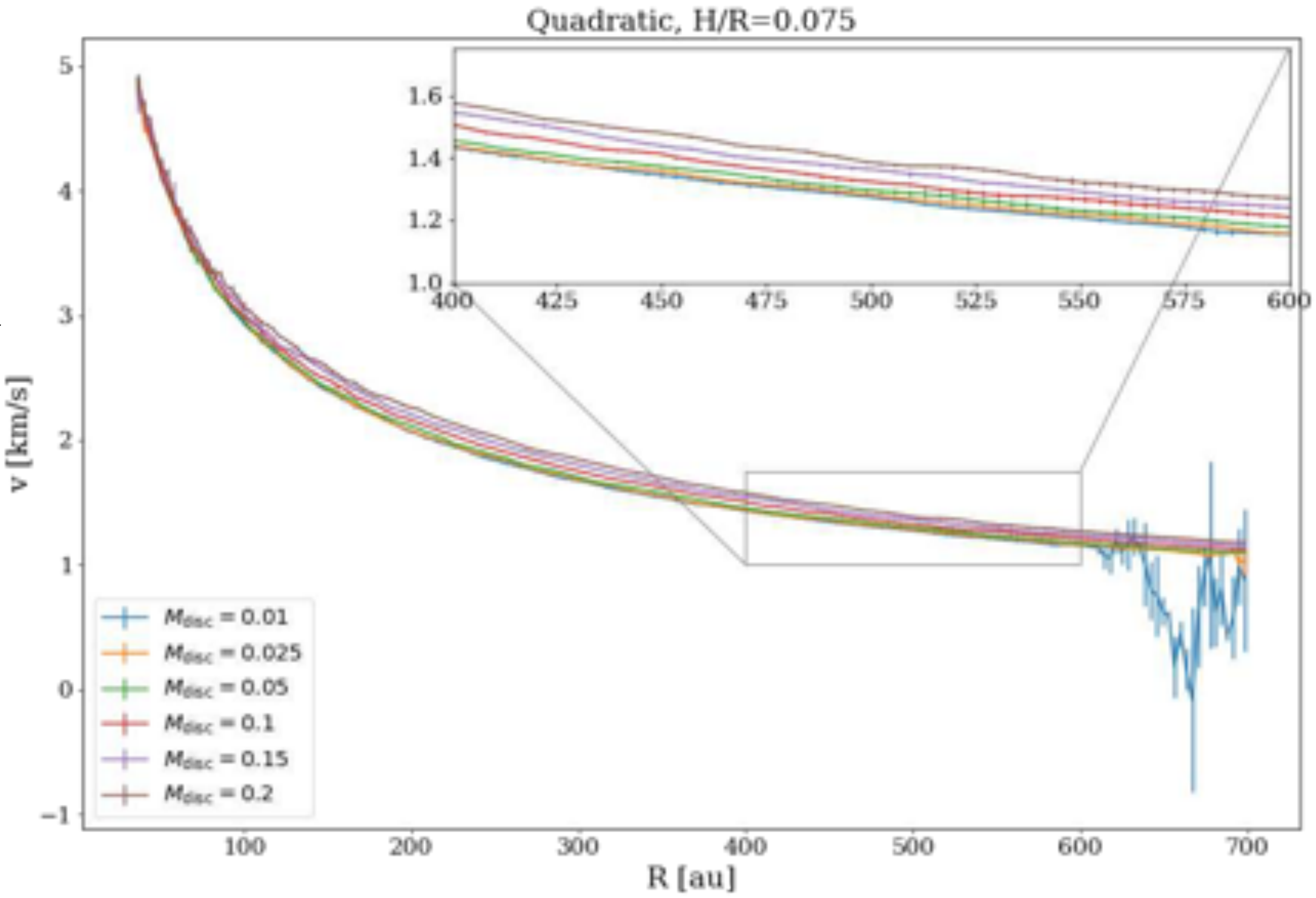
WORKFLOW

3. Fitting the curves with our model with emcee





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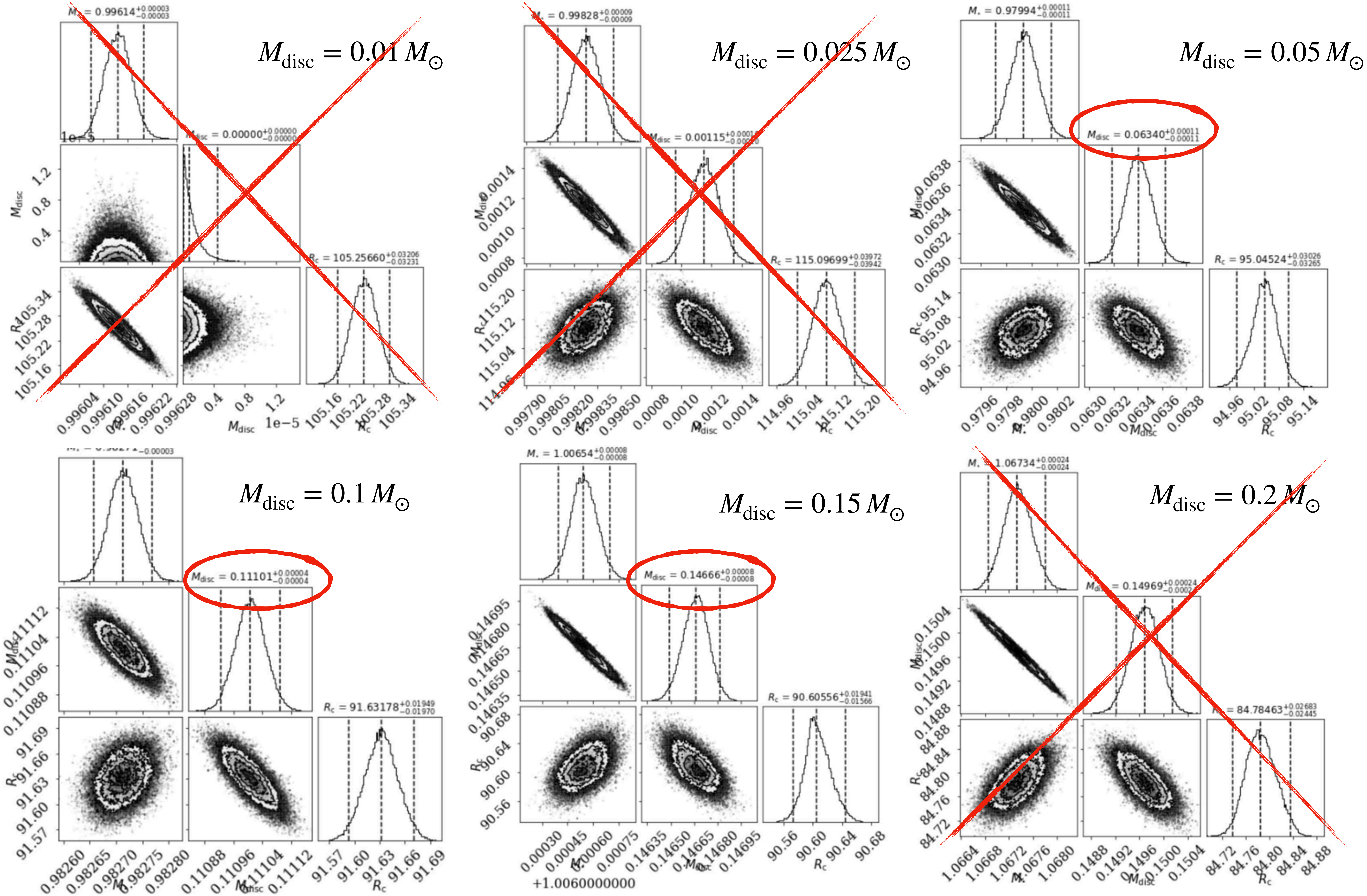
Code available: https://github.com/crislong/DySc

WORK IN PROGRESS…

star+SG disc+pressure fit

e.g., results for

$H/R|_{100\,\mathrm{au}} = 0.075$



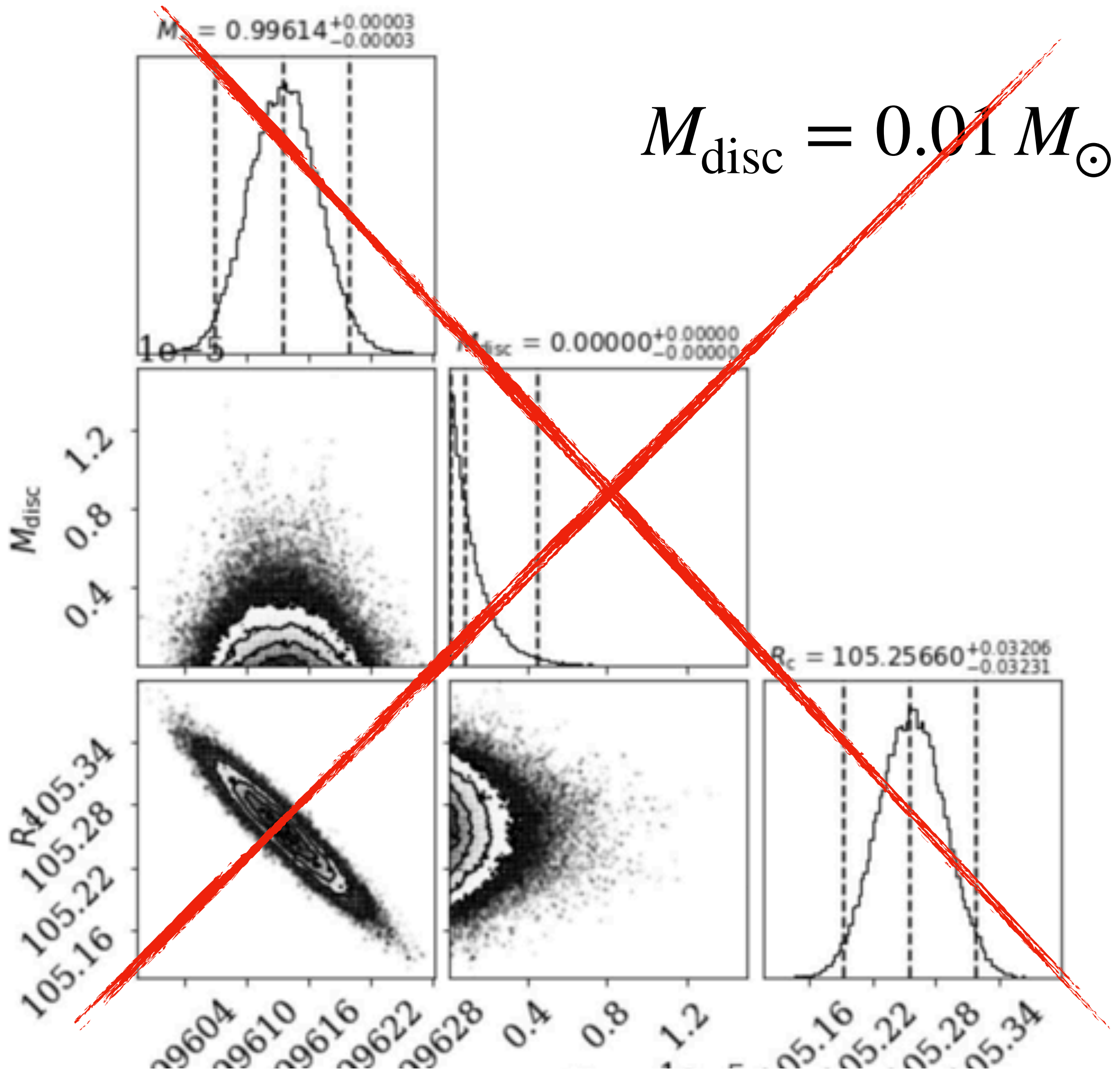
WORK IN PROGRESS…

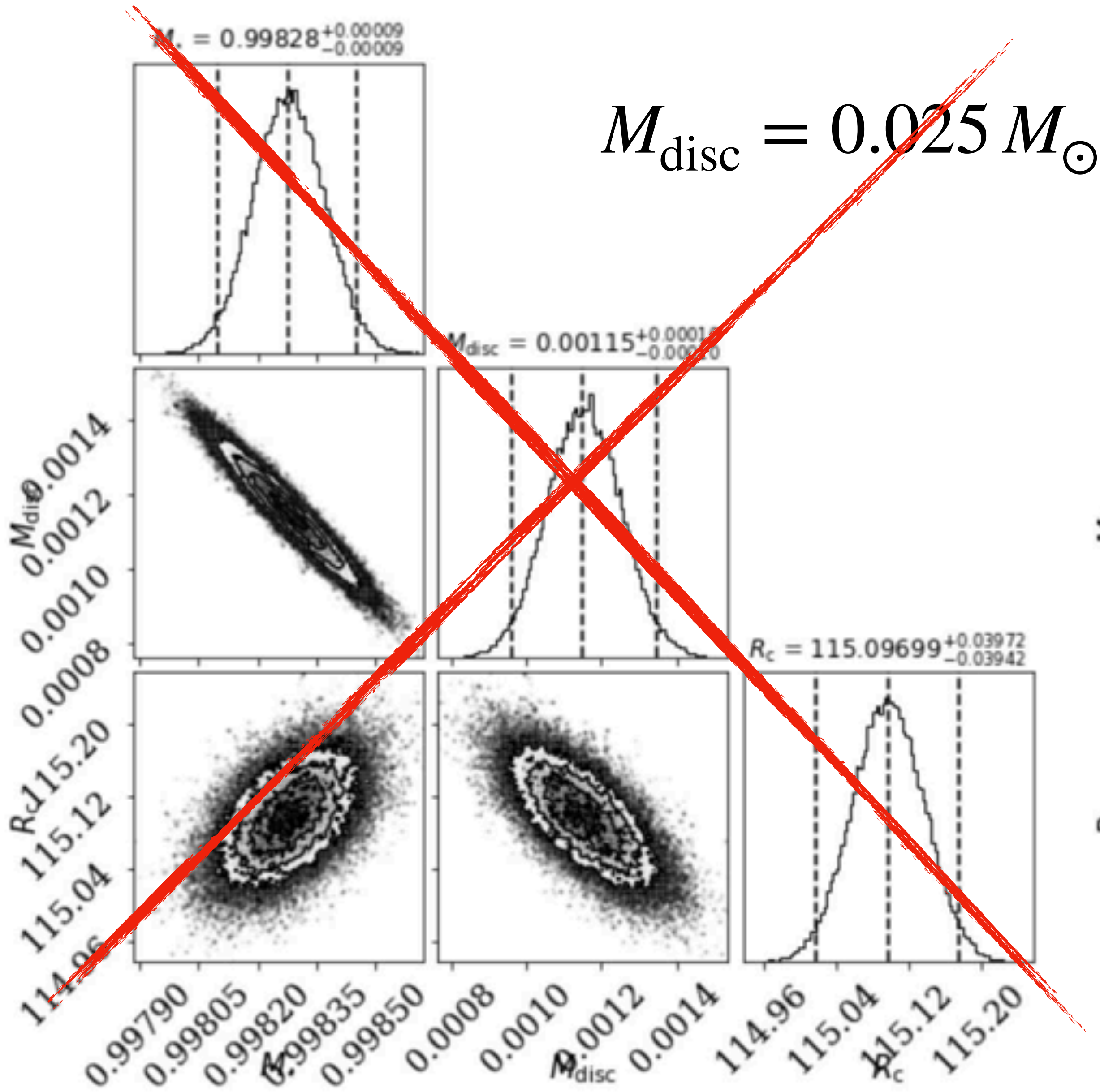
star+SG disc+pressure fit

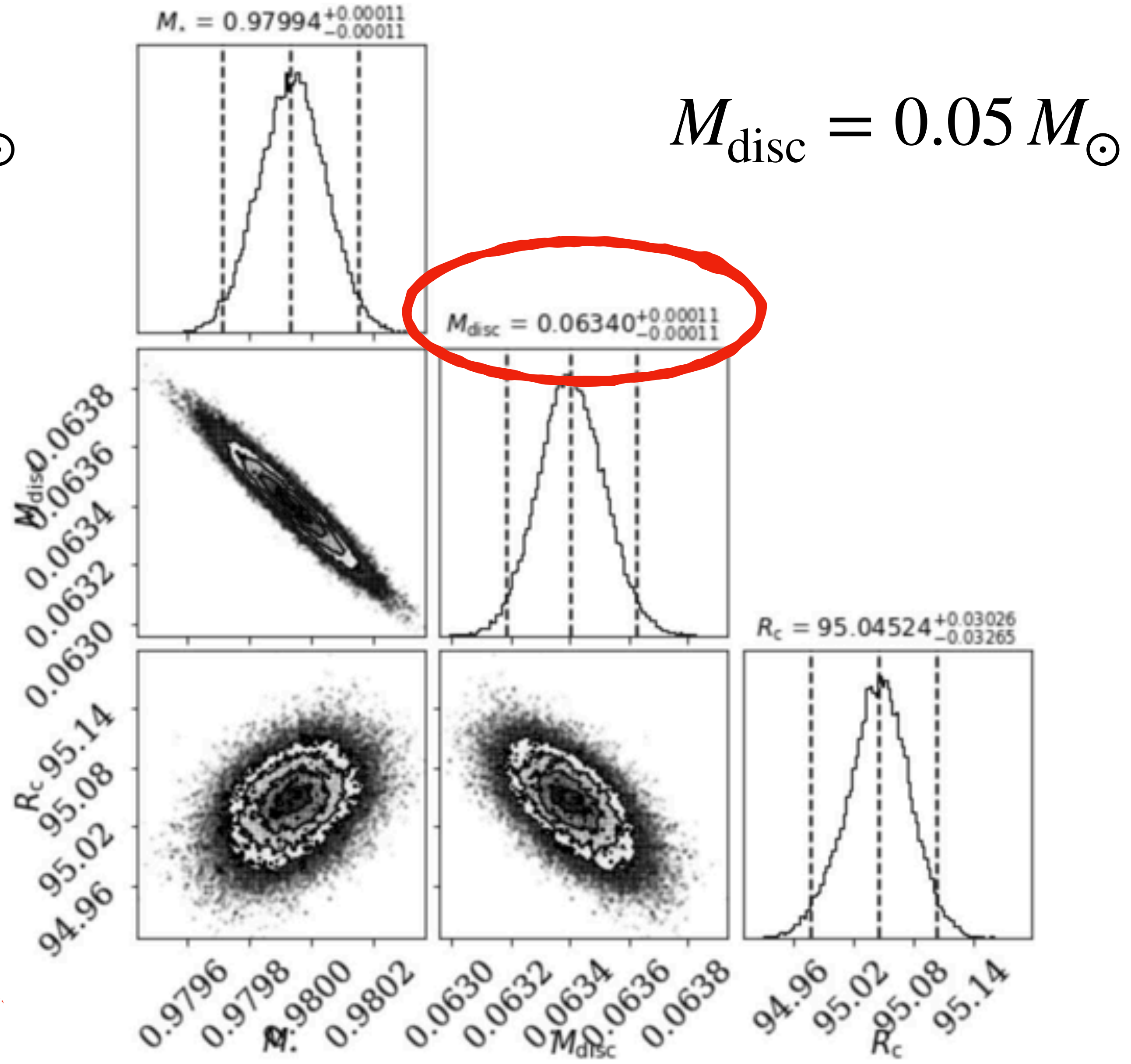
e.g., results for

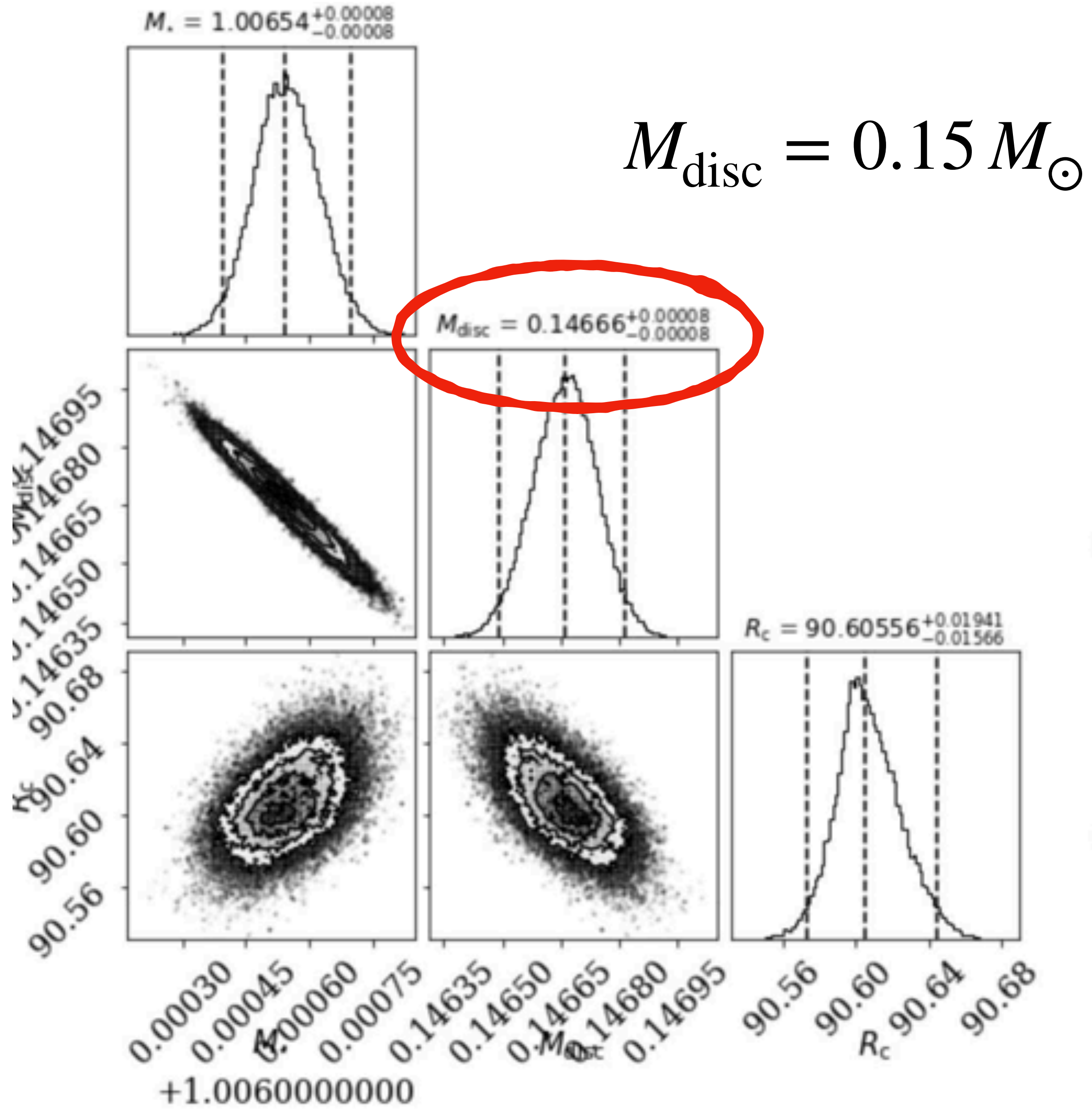
$H/R|_{100\,\mathrm{au}} = 0.075$

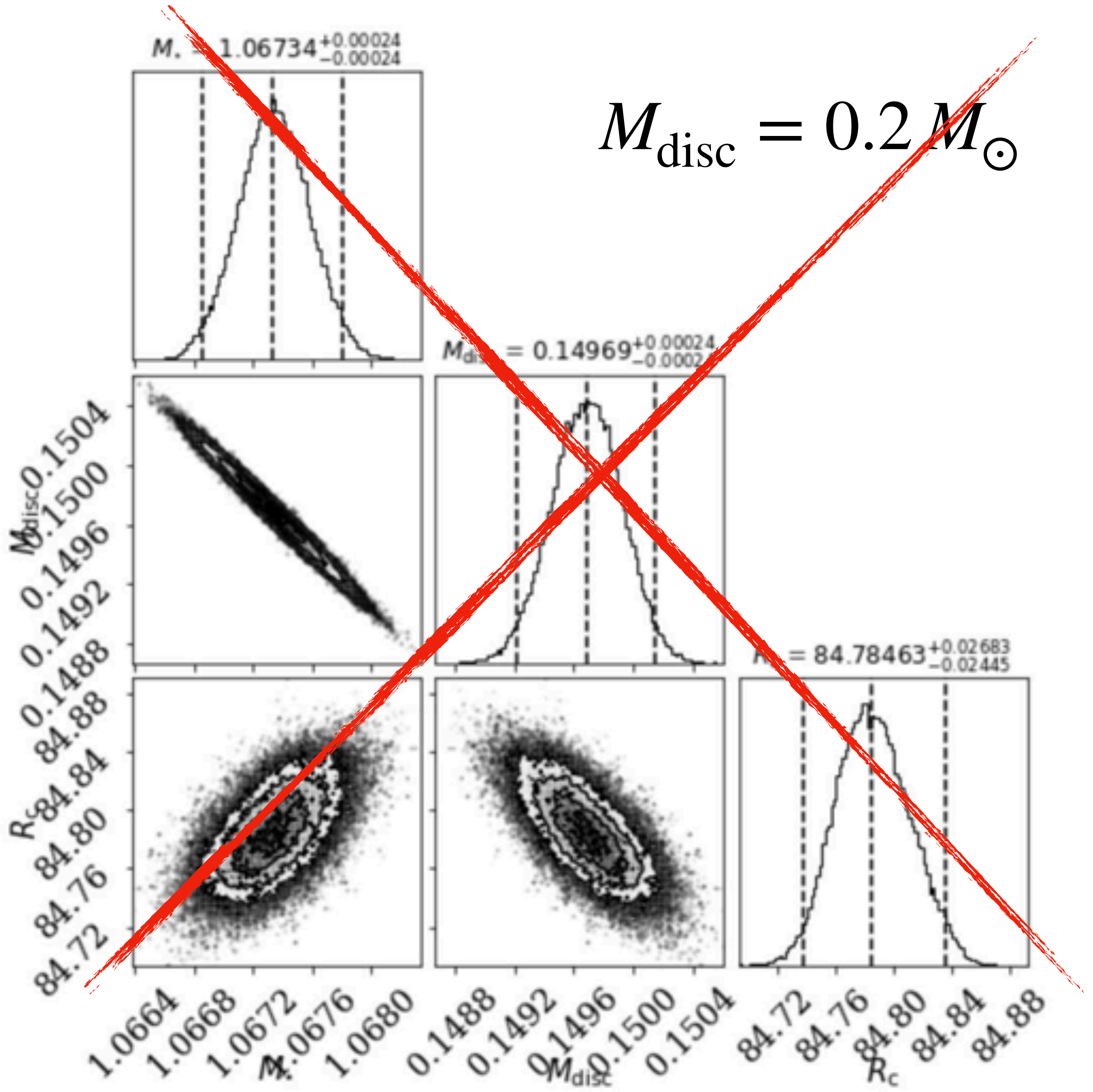
- Threshold for getting the correct disc mass $\simeq 0.05\,M_\odot$
- Issue with $M_d \simeq 0.2\,M_\odot$: resolution too low

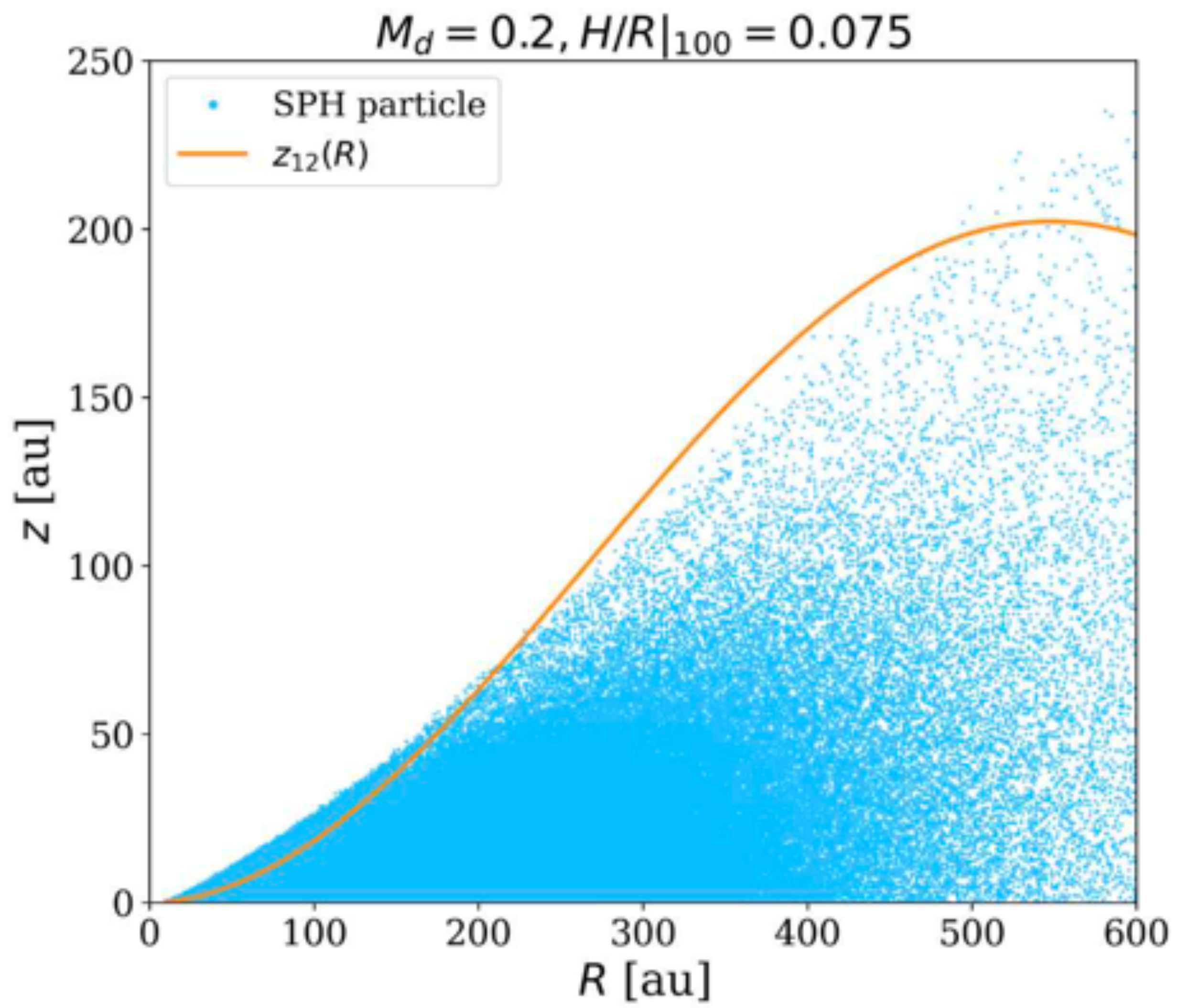


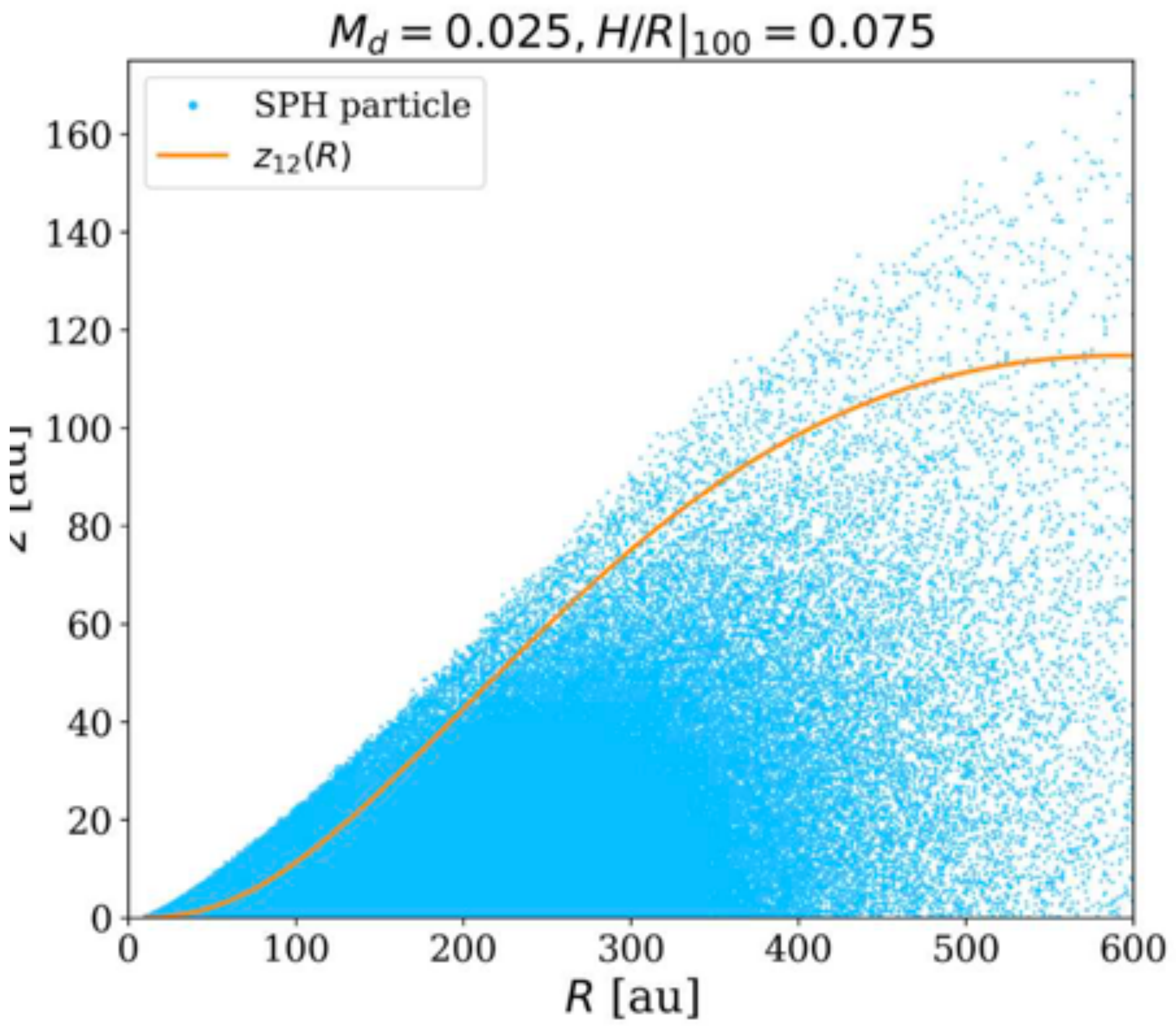












TAKE HOME MESSAGES: A DYNAMICAL SCALE

We searched for deviation from Keplerianity in the disc rotation curve of Elias 2-27, IM Lup and GM Our →

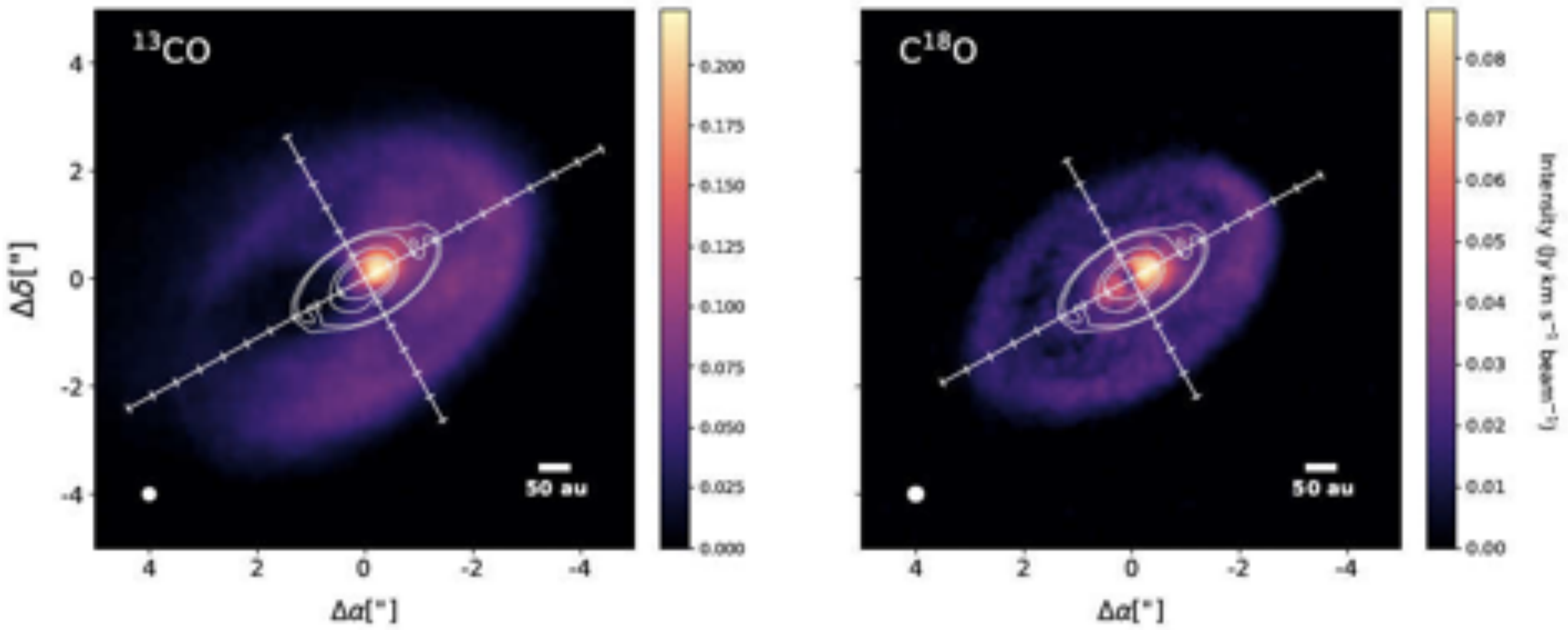
Best fit for Elias 2-27 and IM Lup: SG model

$$\frac{M_{\mathrm{Elias}}}{M_\star} \approx 0.17 - 0.22 \qquad \frac{M_{\mathrm{IM\,Lup}}}{M_\star} \approx 0.1$$

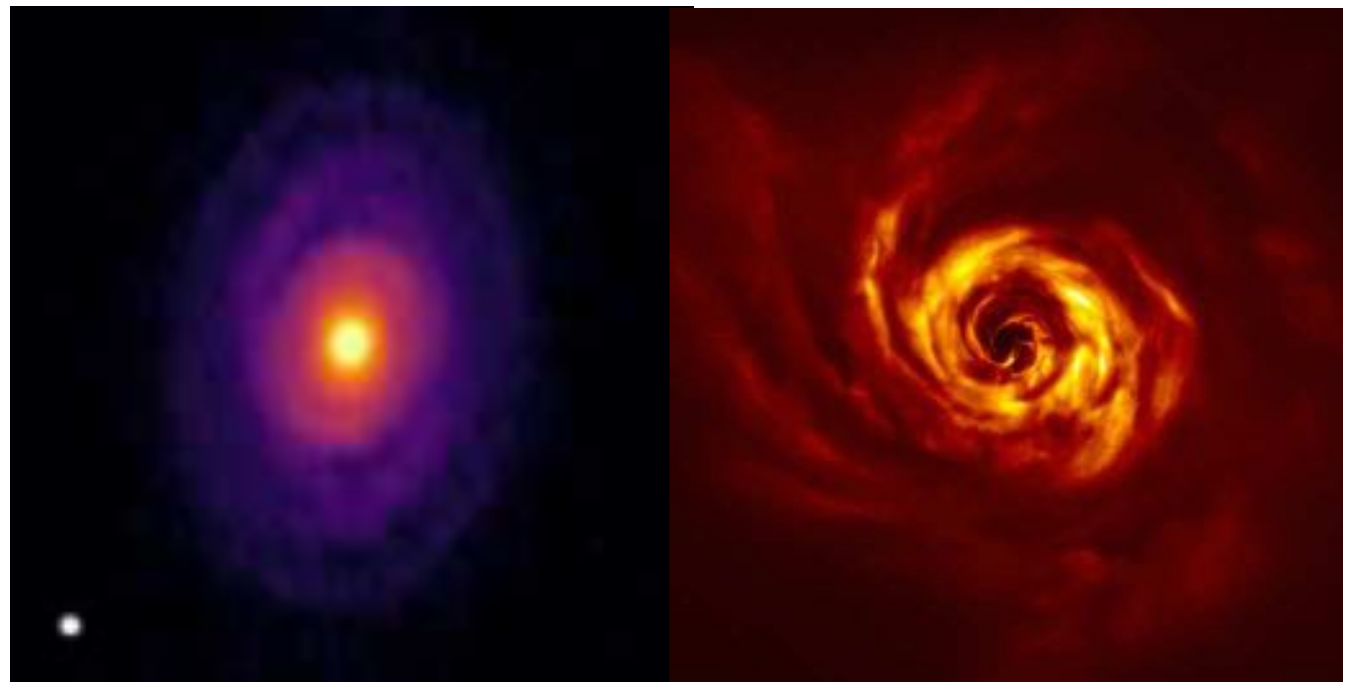
GI regime: spirals

FURTHER INVESTIGATIONS NEEDED…

1. **Asymmetry** West and East side (maybe **infall**?)



2. **Other protoplanetary discs** showing **spiral structures** or a **high** $M_{\mathrm{disc}}/M_\star$ (e.g.: **WaOph 6, AB Aur** - ALMA proposals…)



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GI regime: spirals

WORK IN PROGRESS

Benchmarking of the model with SG PHANTOM+MCFOST sims:

Deriving and fitting rotation curves from simulations for different $M_{\mathrm{disc}}/M_\star$:

- Minimum disc mass we can recover?
- How this change depending on the spectral/spatial resolution?

Veronesi, Longarini et al. in prep

TAKE HOME MESSAGES: A DYNAMICAL SCALE

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GI regime: spirals

WORK IN PROGRESS

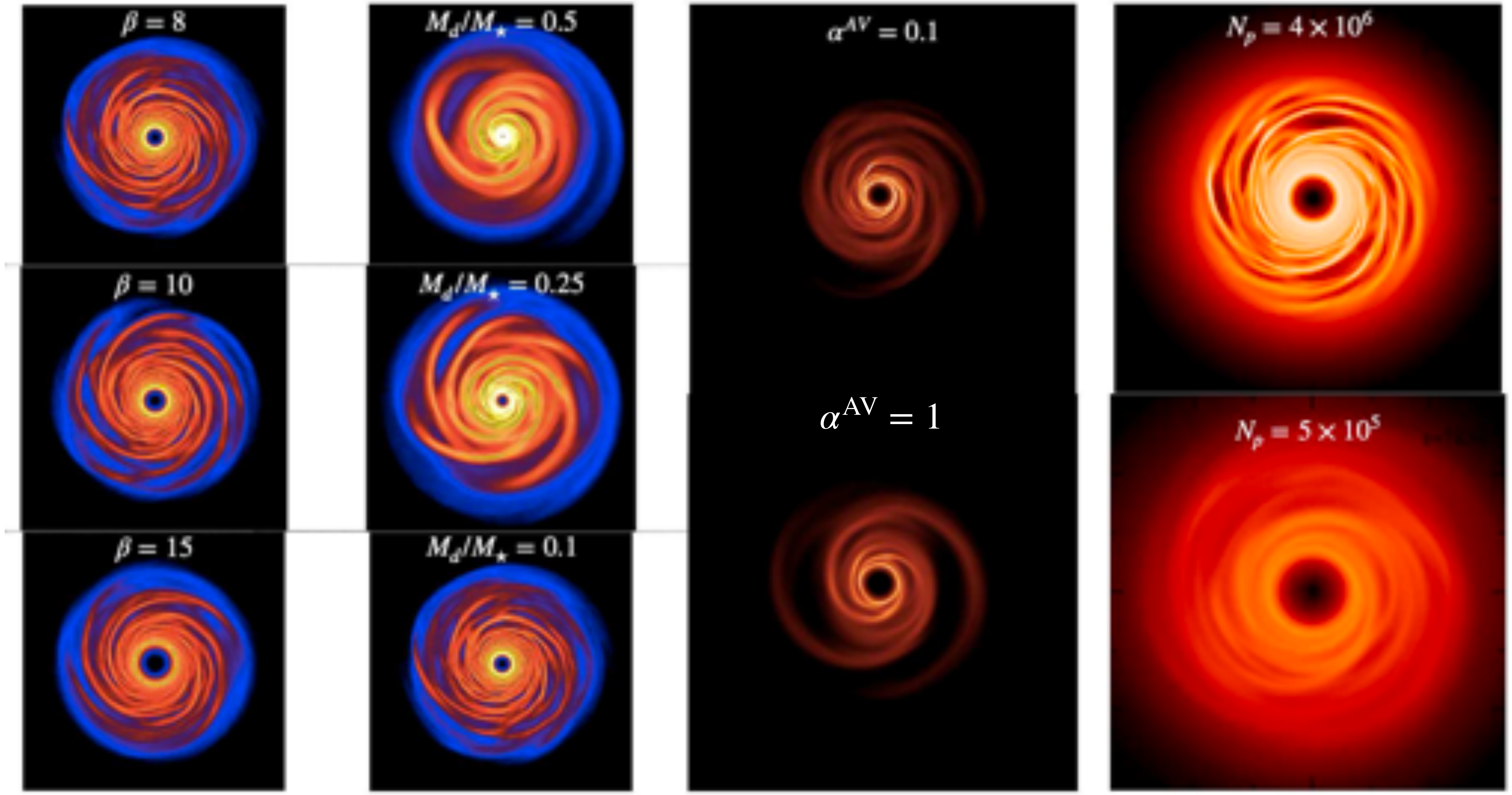
- Combined fit for ^{12}CO and ^{13}CO
- Better treatment for the errors: covariance matrix
- Analysis of rotation curve obtained for SG simulations with GI: trickier because of lower resolution at the emitting layer
- How does a planet affect the rotation curve?
- And what about a binary?

Veronesi, Longarini et al. in prep

MMMMM... STRANGE...

INVESTIGATING A WEIRD CAVITY IN SG SIMS

Investigation in collaboration with C. Longarini, G. Laibe + newly formed task force
(with Sahl Rowther, Hossam Aly, Bec Nealon, Dan Price)

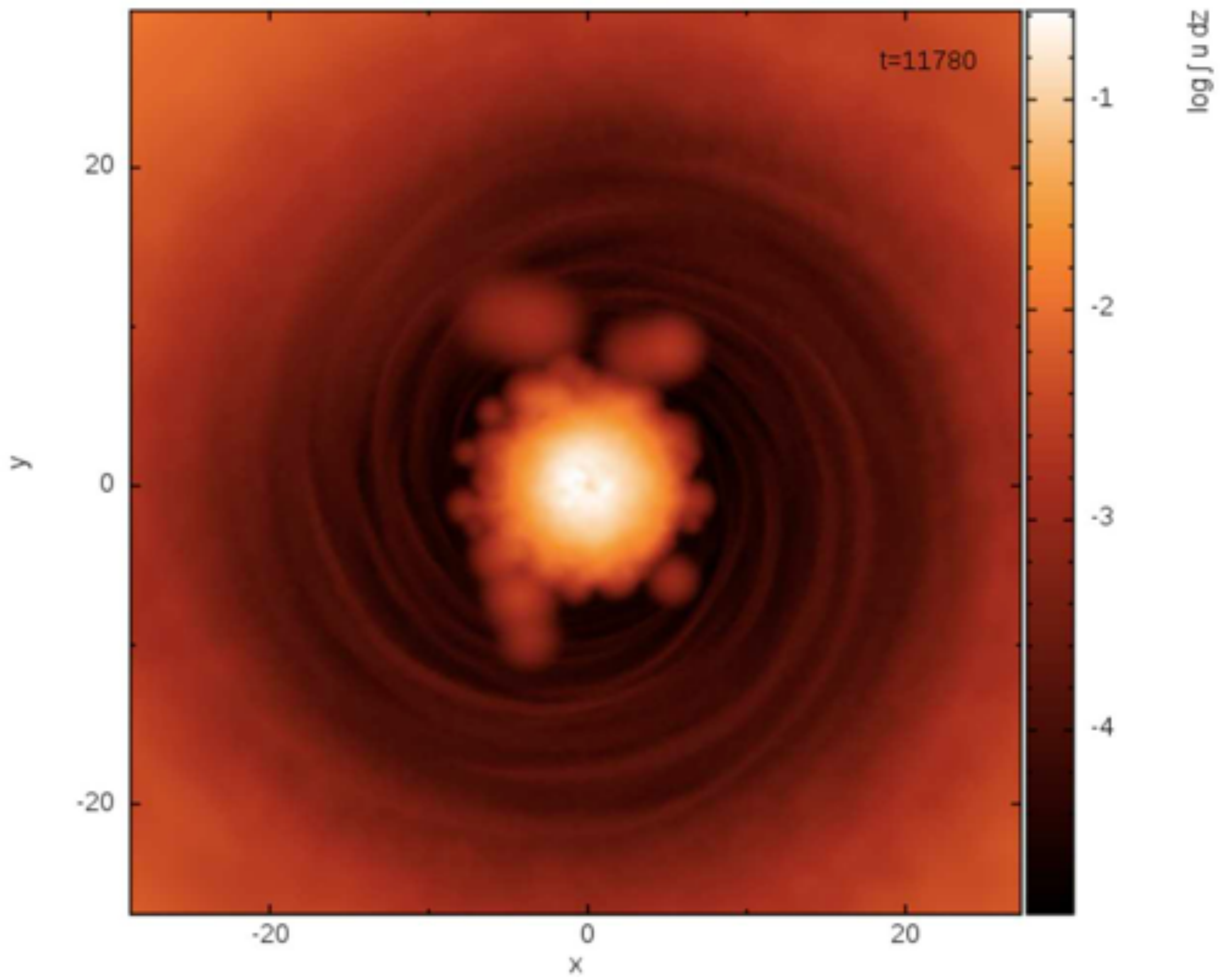


Disc mass

EOS (adiabatic) + cooling (beta cooling)

Resolution + artificial viscosity $(\alpha_{\rm AV}; \beta_{\rm AV})$

Conductivity (how to treat contact discontinuities) $\alpha_{\rm cond}$



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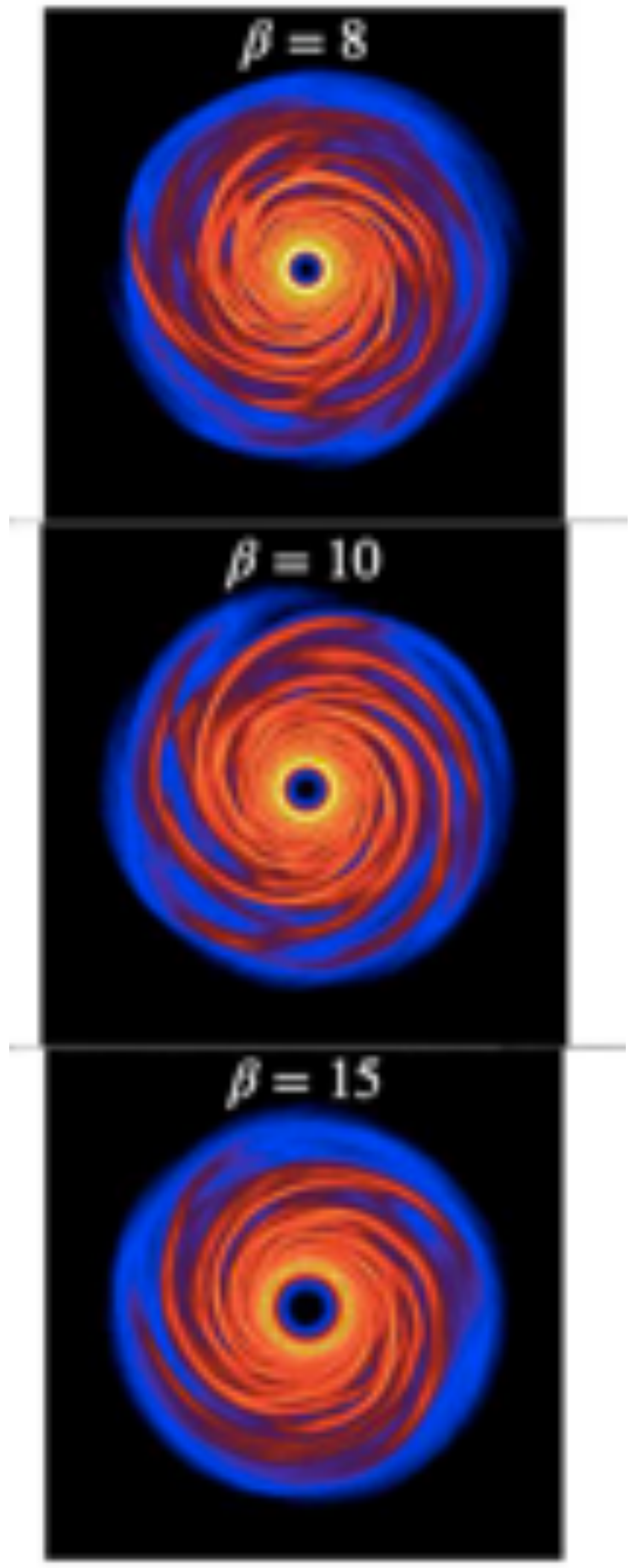

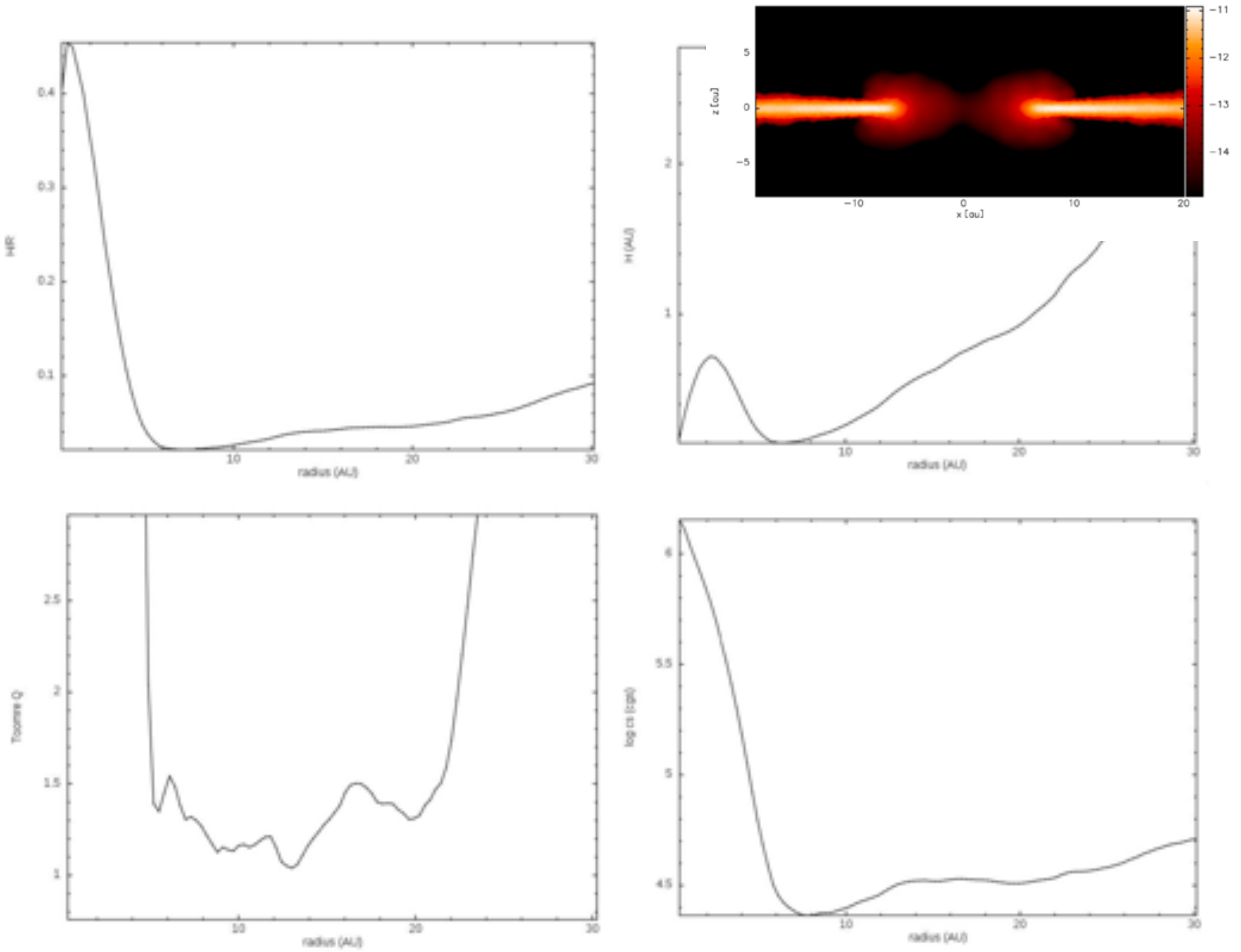

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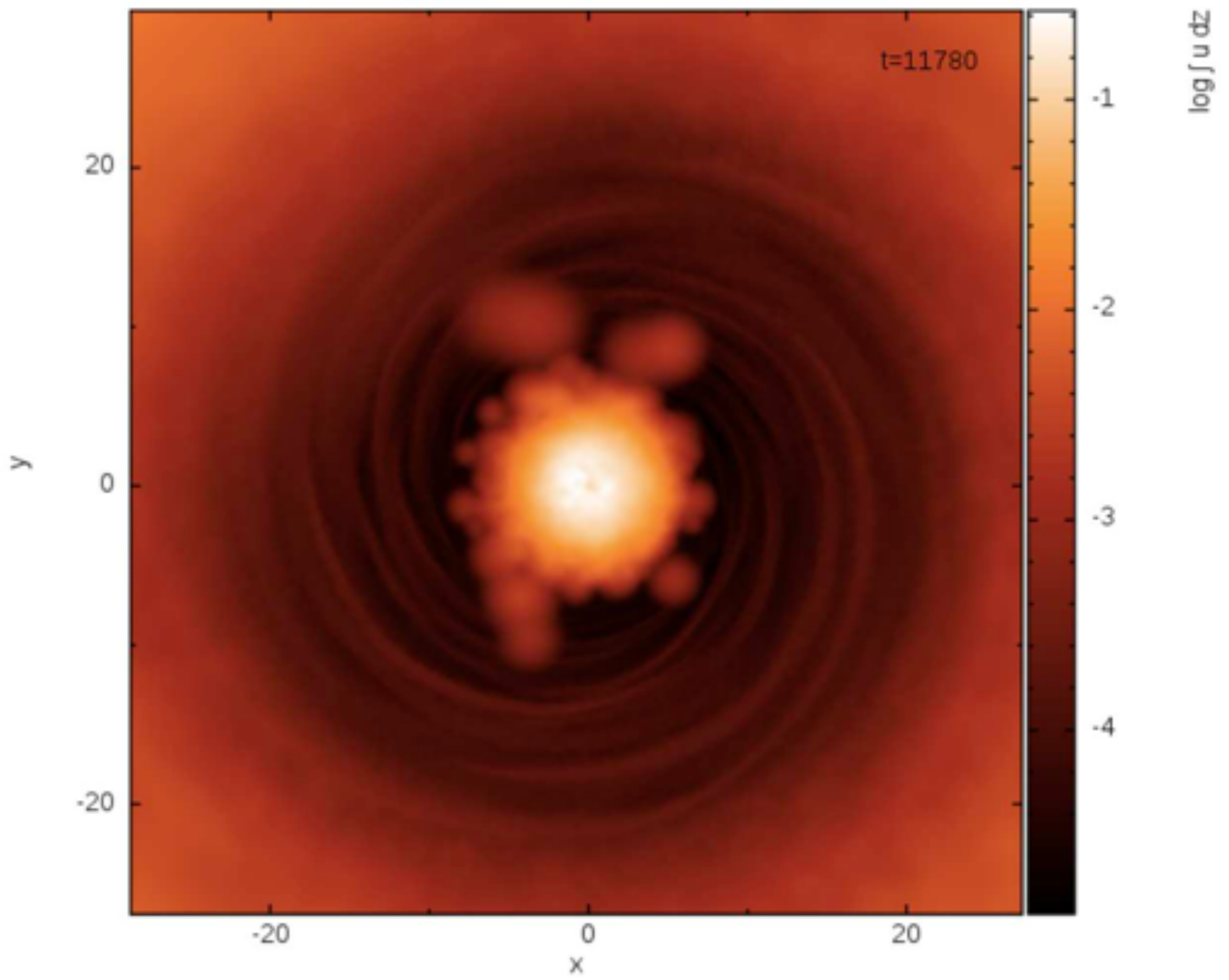
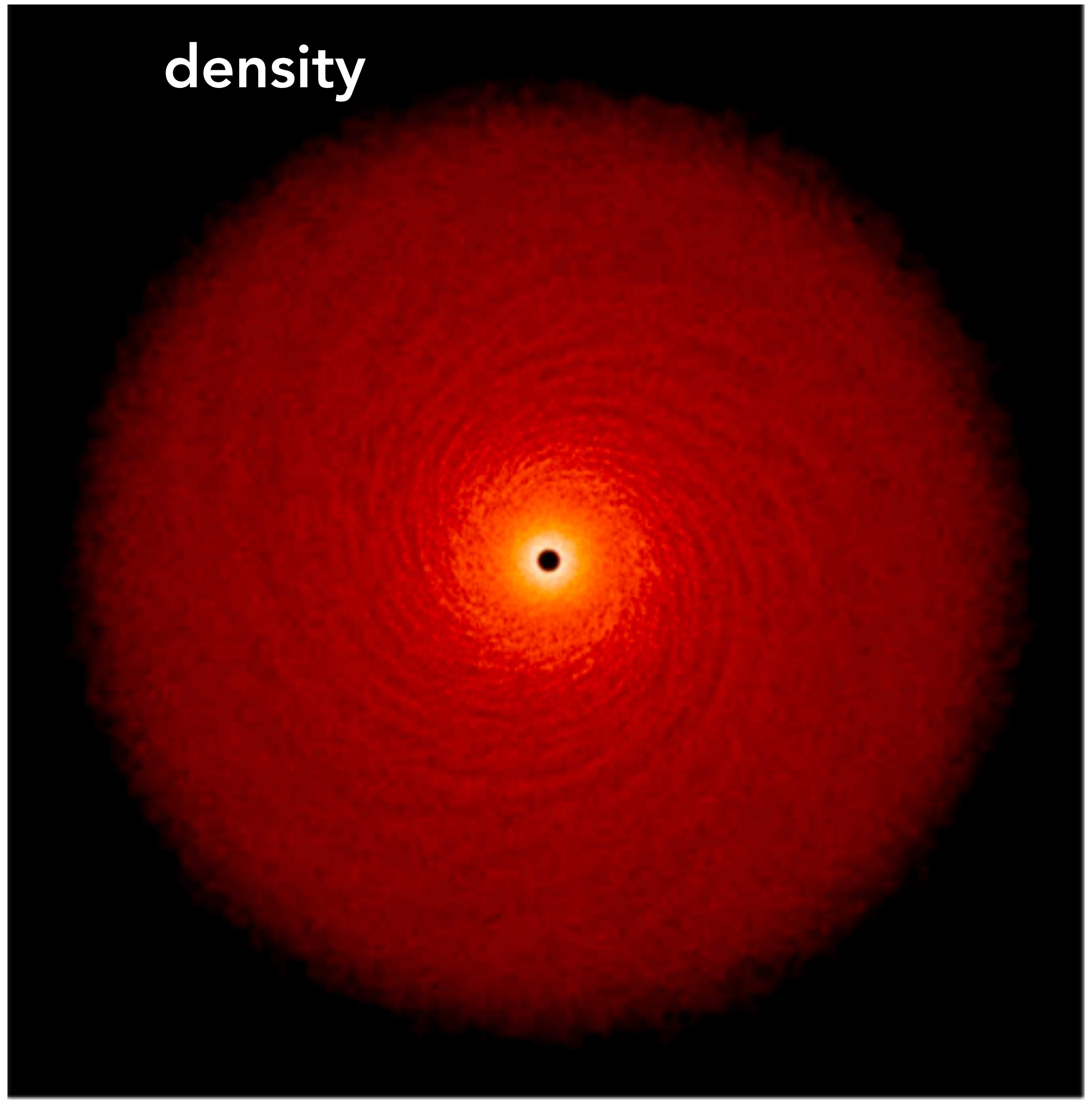


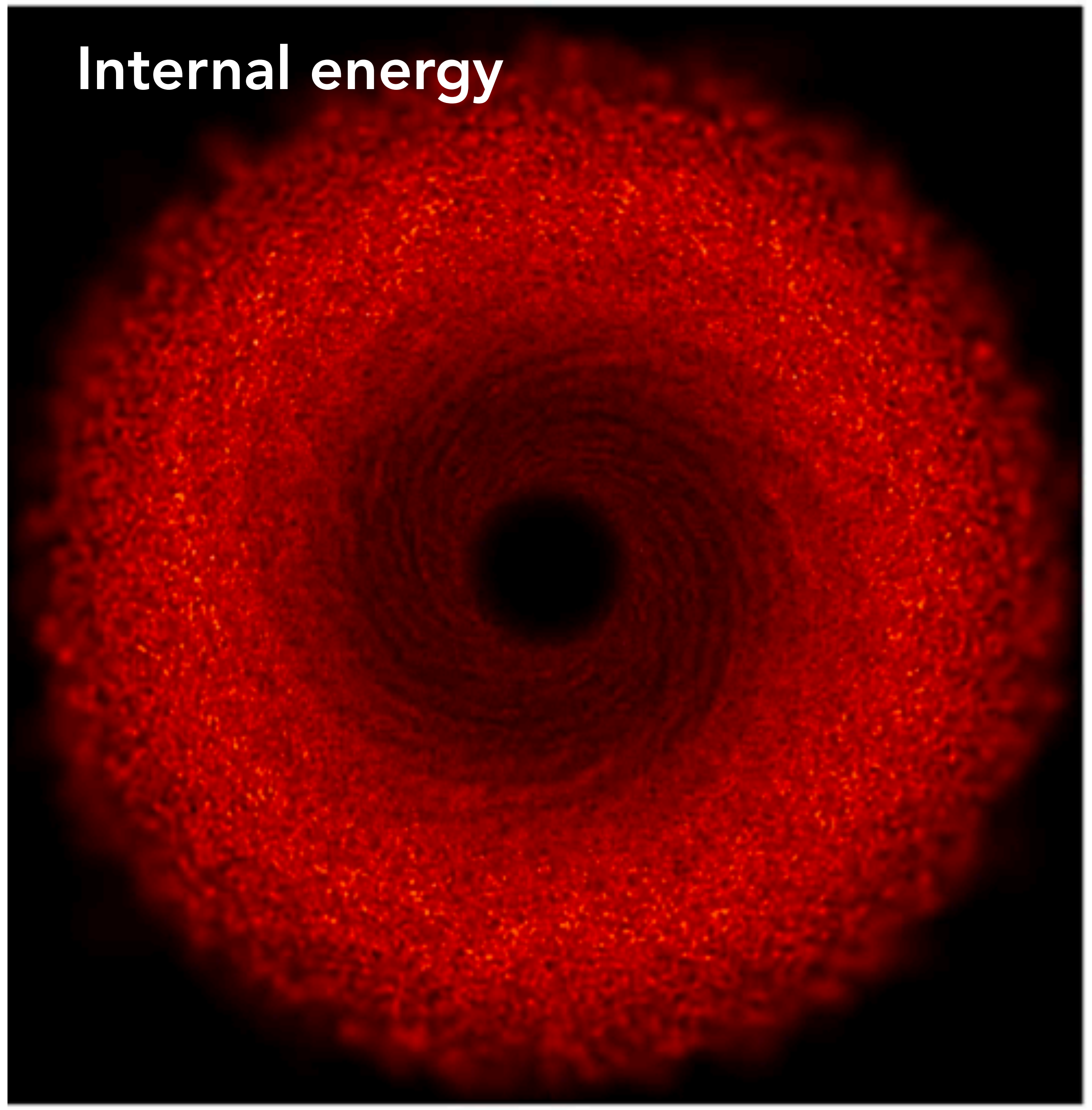
INVESTIGATING A WEIRD CAVITY IN SG SIMS

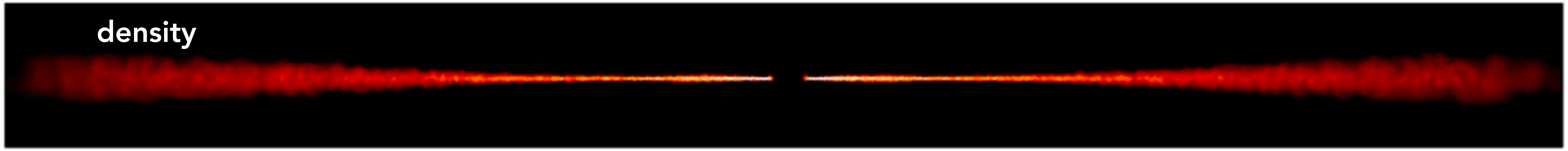
(I gotta kill the switch… I don't care, I love it!) 𝄞♬♪♫



$$(\alpha_{\mathrm{AV}}, \beta_{\mathrm{AV}}) = 0$$

Not correct, but just aiming at testing how the cavity formation is connected with the viscosity switch



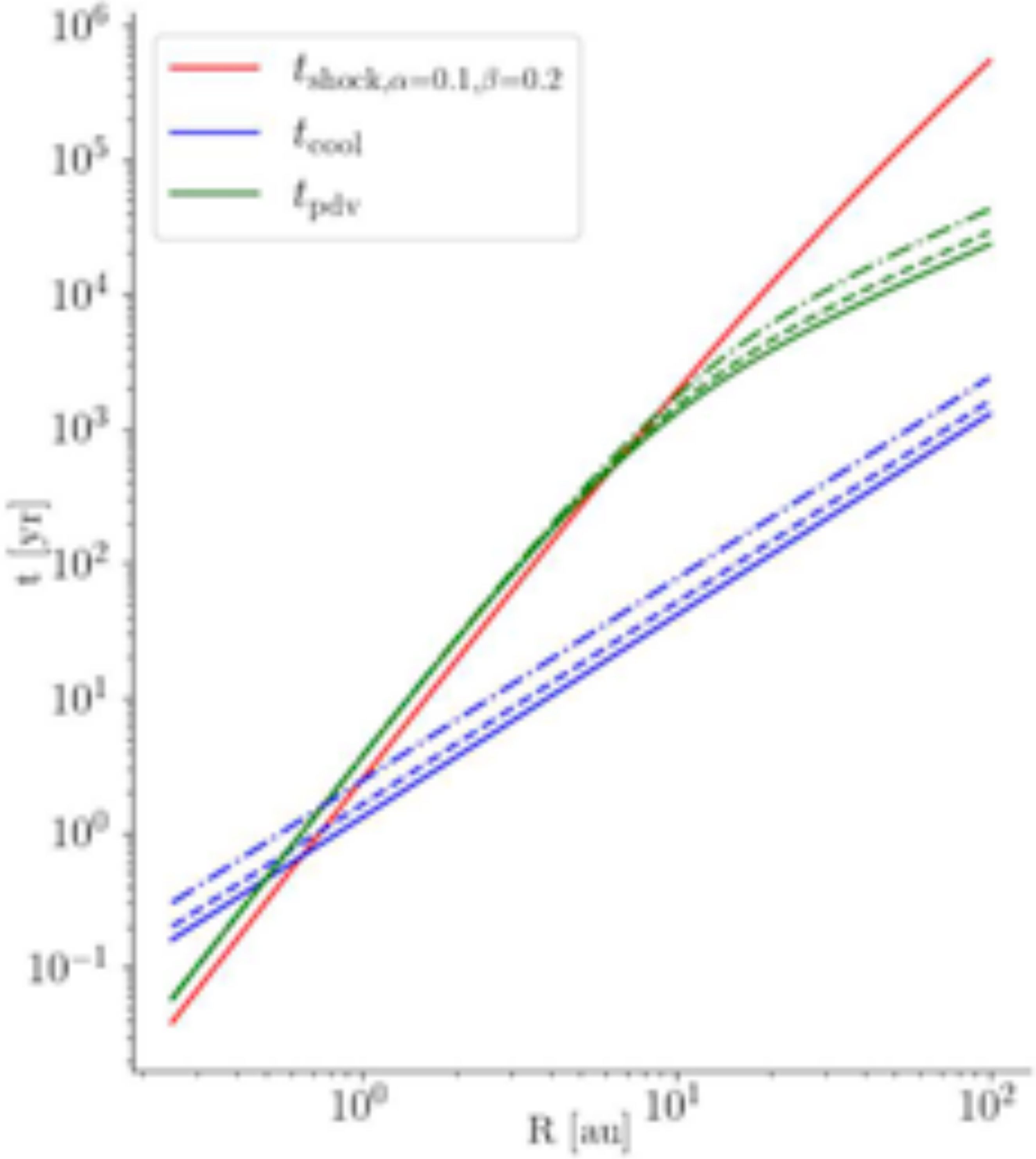


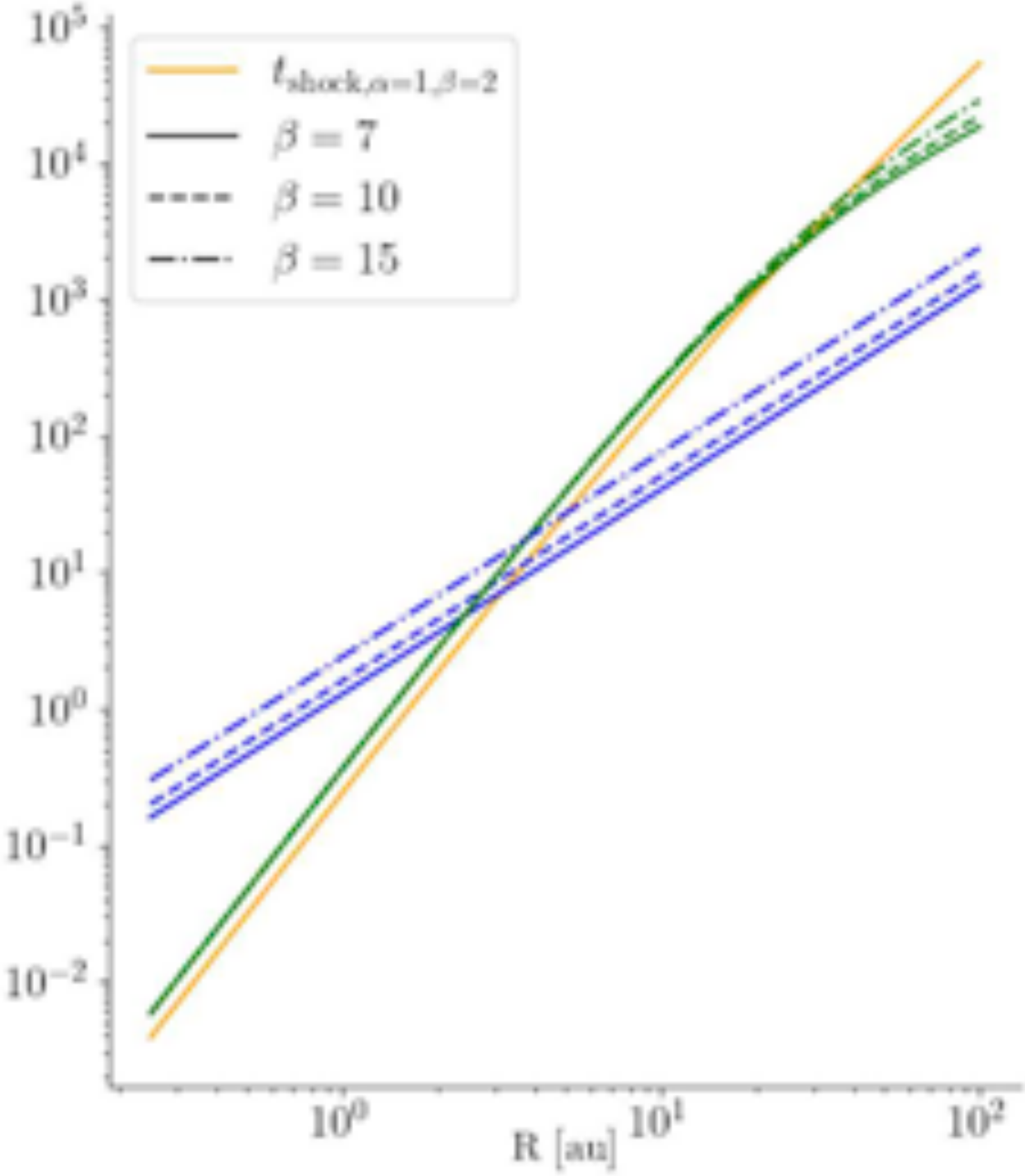
INVESTIGATING A WEIRD CAVITY IN SG SIMS

Timescales argument: $\frac{du}{dt} = -\frac{P}{\rho}\vec{\nabla}\cdot\vec{v} + \Lambda_{\rm shock} - \frac{\Lambda {\rm cool}}{\rho}$

$$\nu_{\rm tot} = (\alpha_{\rm SPH} + \alpha_{\rm cool})c_s H$$

$$\alpha_{\rm SPH} = \alpha_{\rm AV,lin} + \alpha_{\rm AV,quad} = \frac{31}{525}\alpha_{AV}\frac{h}{H} + \frac{9}{70\pi}\beta_{AV}\left(\frac{h}{H}\right)^2$$





$$t_{p\nabla v} = \frac{1}{\gamma - 1}\frac{r}{(\partial\nu_{\rm tot}/\partial r)}$$

$$t_{\rm shock} = \frac{r^2}{v_{\rm shock}} = \frac{r^2}{\alpha_{\rm SPH}c_s H} = \left(\frac{H}{r}\right)^{-2}\frac{1}{\Omega\alpha_{\rm SPH}}$$

$$t_{\rm cool} = \beta\Omega^{-1}$$

Chosen parameters:

$H/R_0 = 0.1$

$M_{\rm disc}/M_\star = 0.1$

$R_0 = 0.25\,{\rm au}; {\rm R_{out}} = 100\,{\rm au}$

$\Sigma = \Sigma_0\left(\frac{R}{R_0}\right)^{-1}$

$\frac{H}{R} = H/R_0\left(\frac{R}{R_0}\right)^{1/2-q}$; $q = 0.25$

Cavity when: $t_{\rm cool} > \min\left\{t_{\rm shock}, t_{p\nabla\nu}\right\}$

INVESTIGATING A WEIRD CAVITY IN SG SIMS

Next steps:

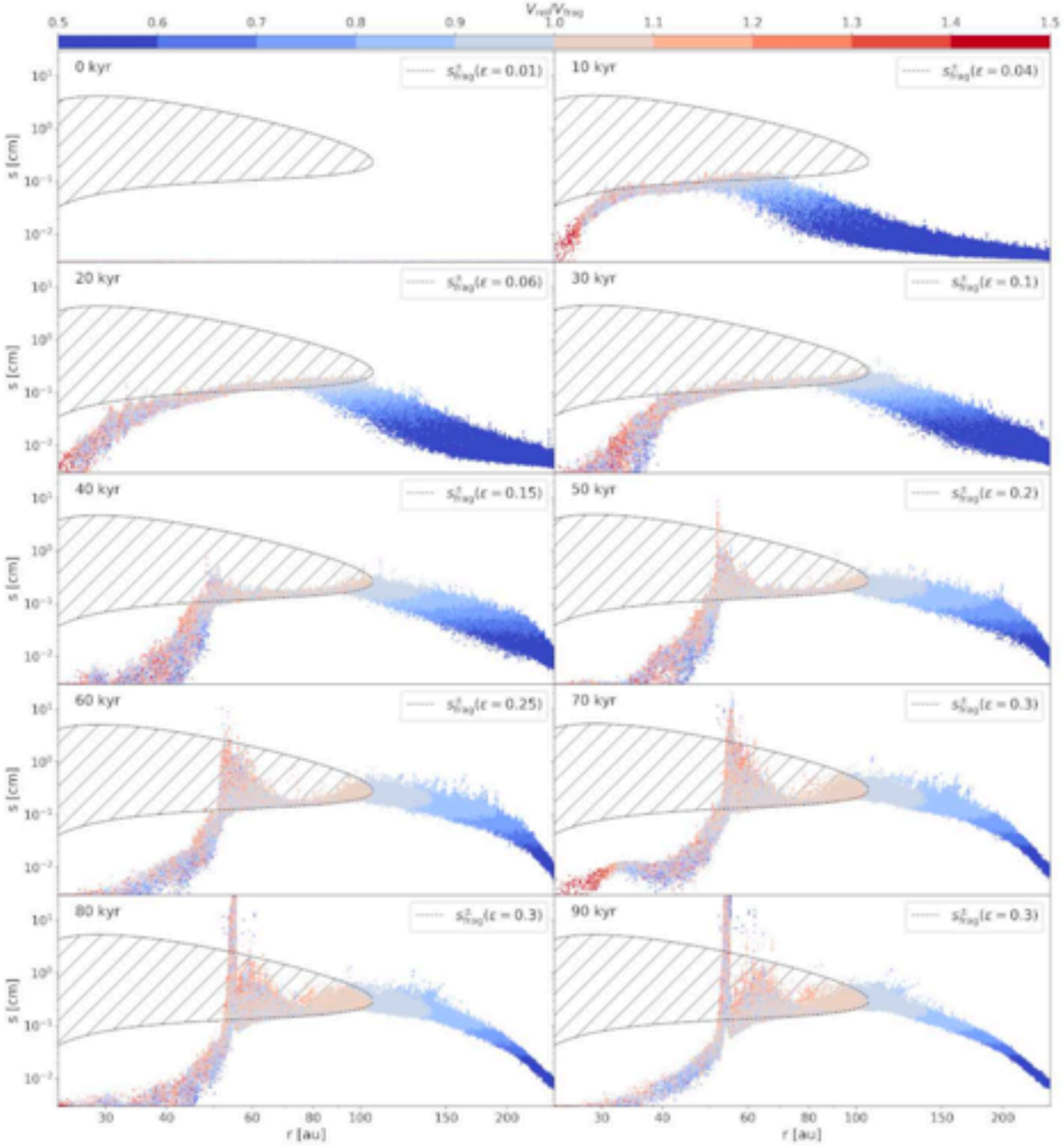
- Numerical or physical issue? Or both?
    - Thermal instability?
- Different (more physical) cooling treatment? Opacities?
- PHANTOM+MCFOST? (connection with Sahl's project here @ Monash)
- Started testing a possible solution yesterday: keep you updated!

Why do I(/we) care so much?

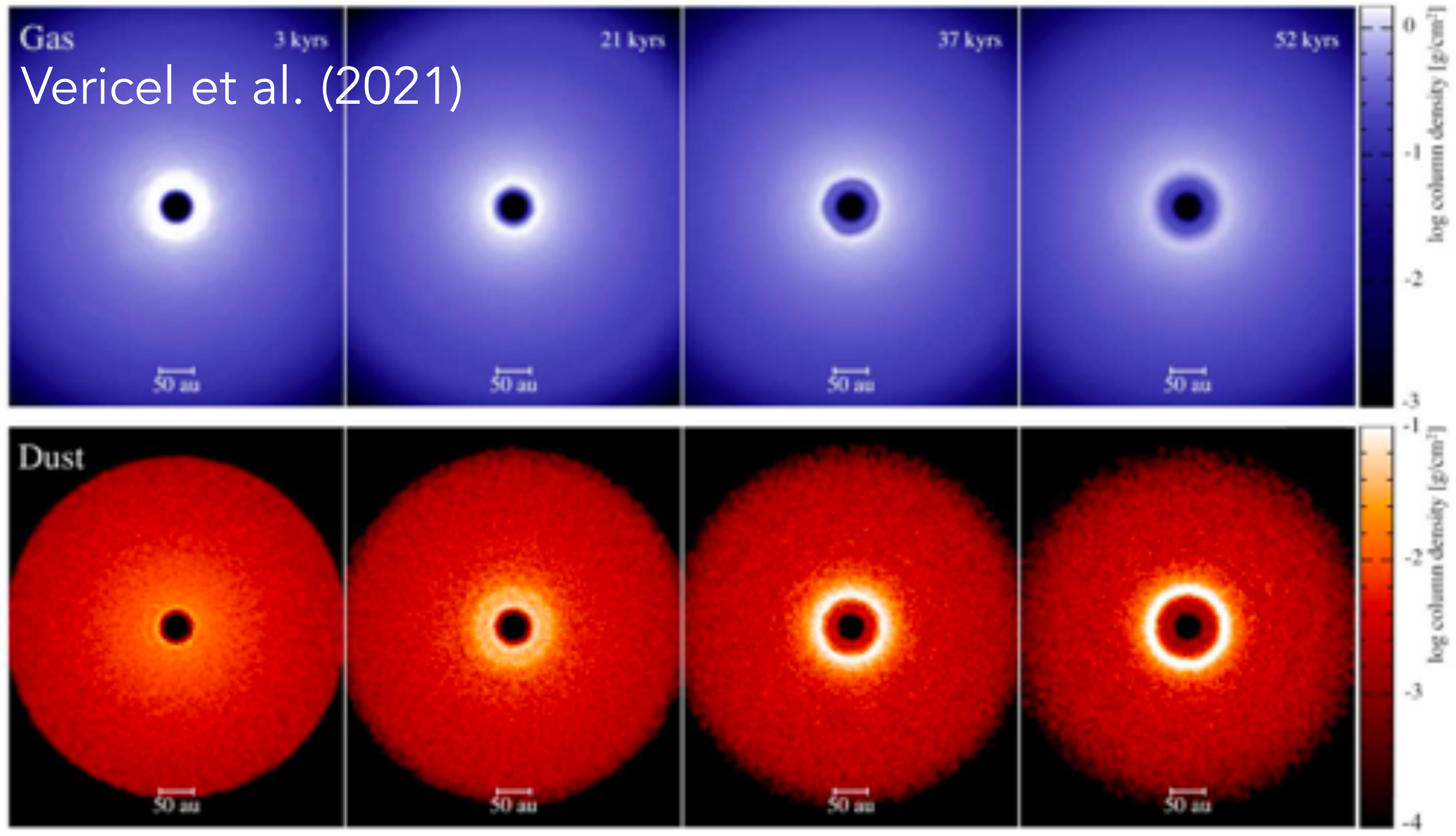
- We want to be sure that we can trust our SG simulations: right now we do see spurious ring formation
- If you care about the whole disc extent (and not only the outer region where spirals develop) this is important!

ARE SIDTS SEEDS FOR PLANETS?
A.K.A. SELF-INDUCED DUST TRAPS

PHANTOM sims with 2-fluid (dust+gas) algorithm



Vericel et al. (2021), Gonzalez et al. (2017)



With G. Laibe, J.-F. Gonzalez

For an overview on dust growth see Stéphane's talk!

PROJECT AIM:

- Planets expected to form early: SIDTS could be an answer
- Dust growth should start in the earlier stages (maybe already during the collapse phase? Collab with Asmita Bhandare)

Disc evolution with both SG and DUST GROWTH: formation of dust traps?

What effect will dominate?
DRAG or GI perturbations?

THANKS FOR THE ATTENTION! QUESTIONS?

PHANTOM

YOU CAN CONTACT ME HERE:

benedetta.veronesi@ens-lyon.fr

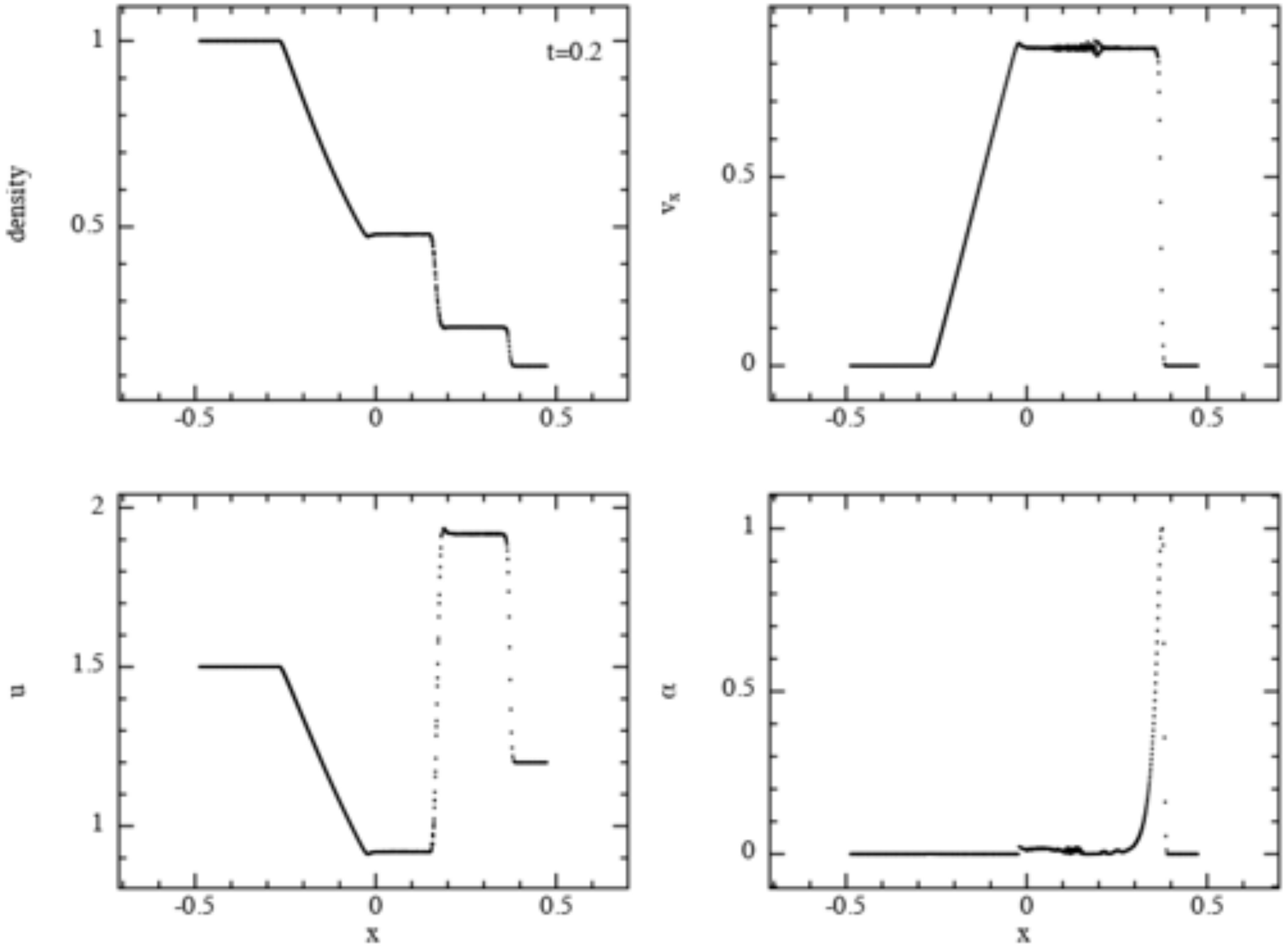
INVESTIGATING A WEIRD CAVITY IN SG SIMS

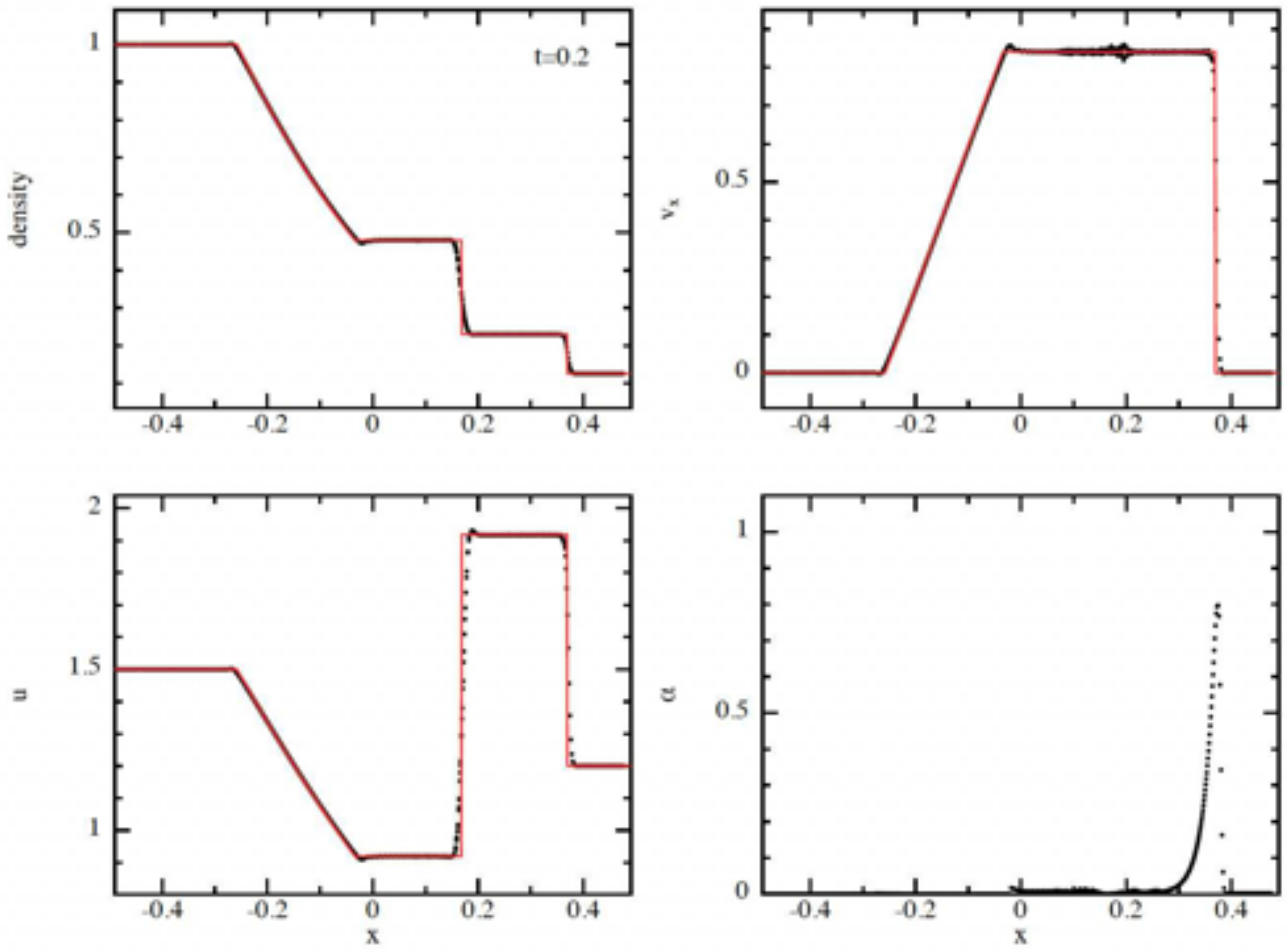
$$\alpha = [0,1];\ \beta = 2 \quad \longrightarrow \quad \beta = 2 \cdot \alpha$$

To capture shocks and to avoid particle interpenetration

α remains low in the inner region
-> no strong shocks

Shock tube test





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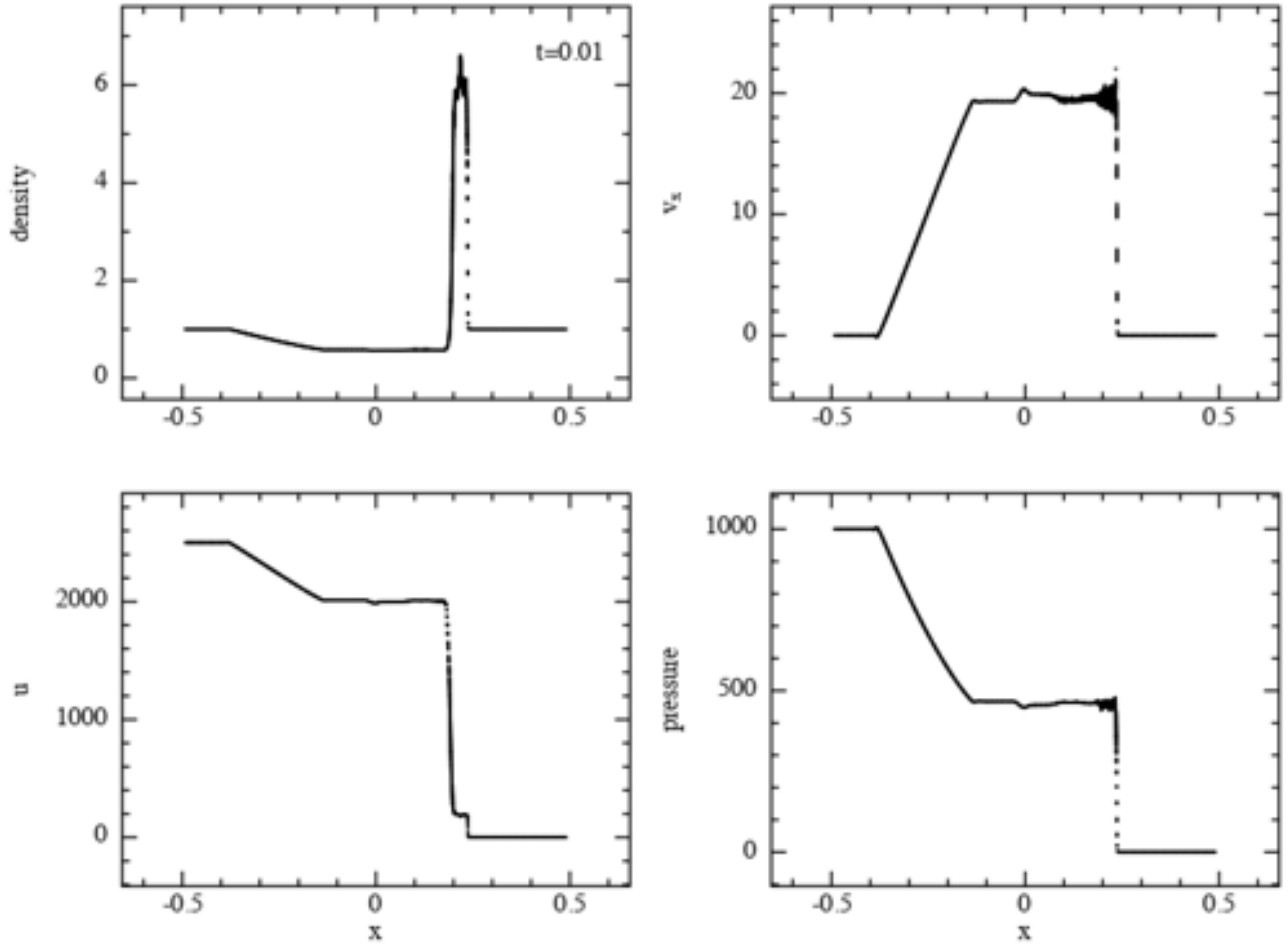
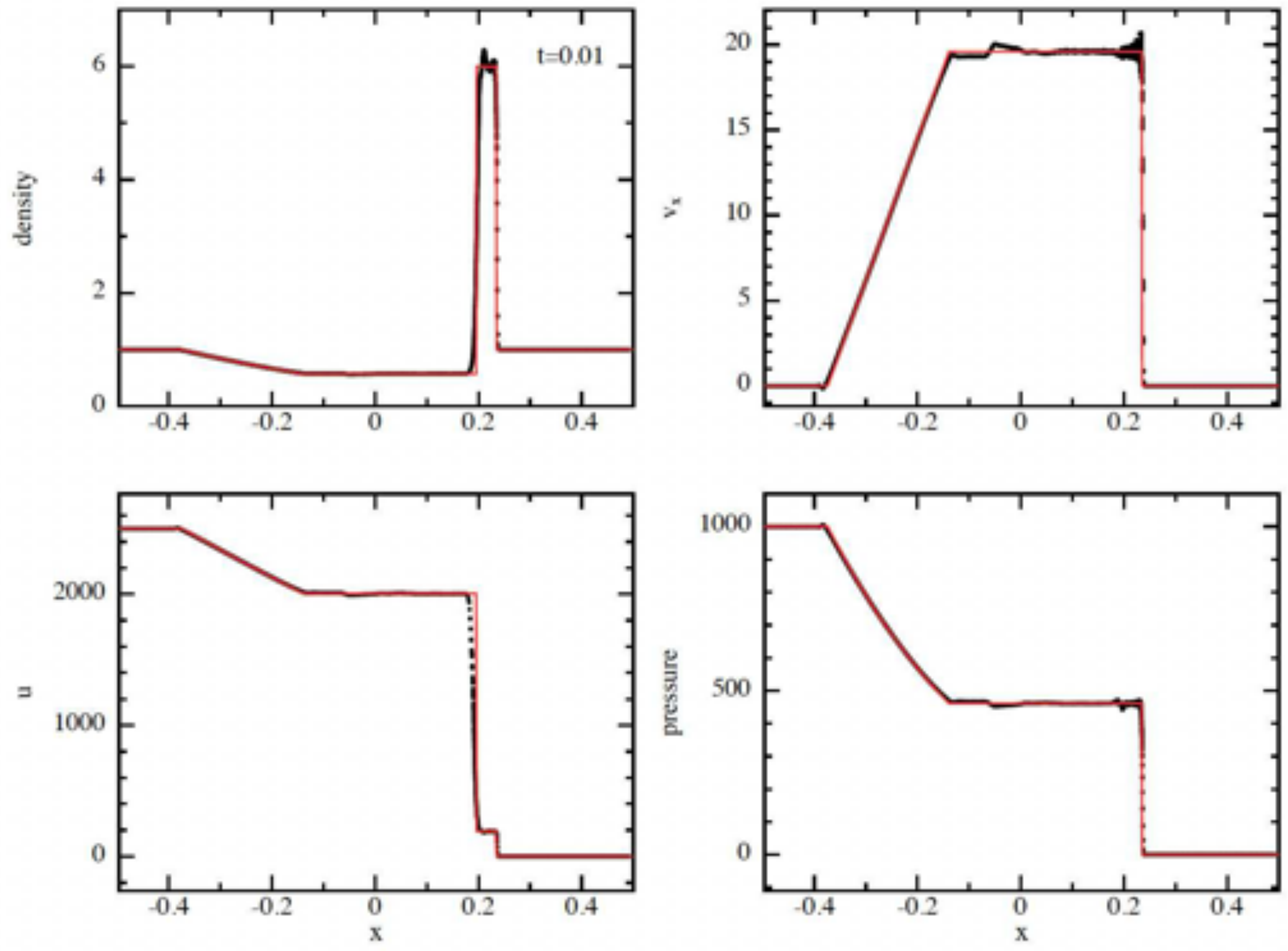
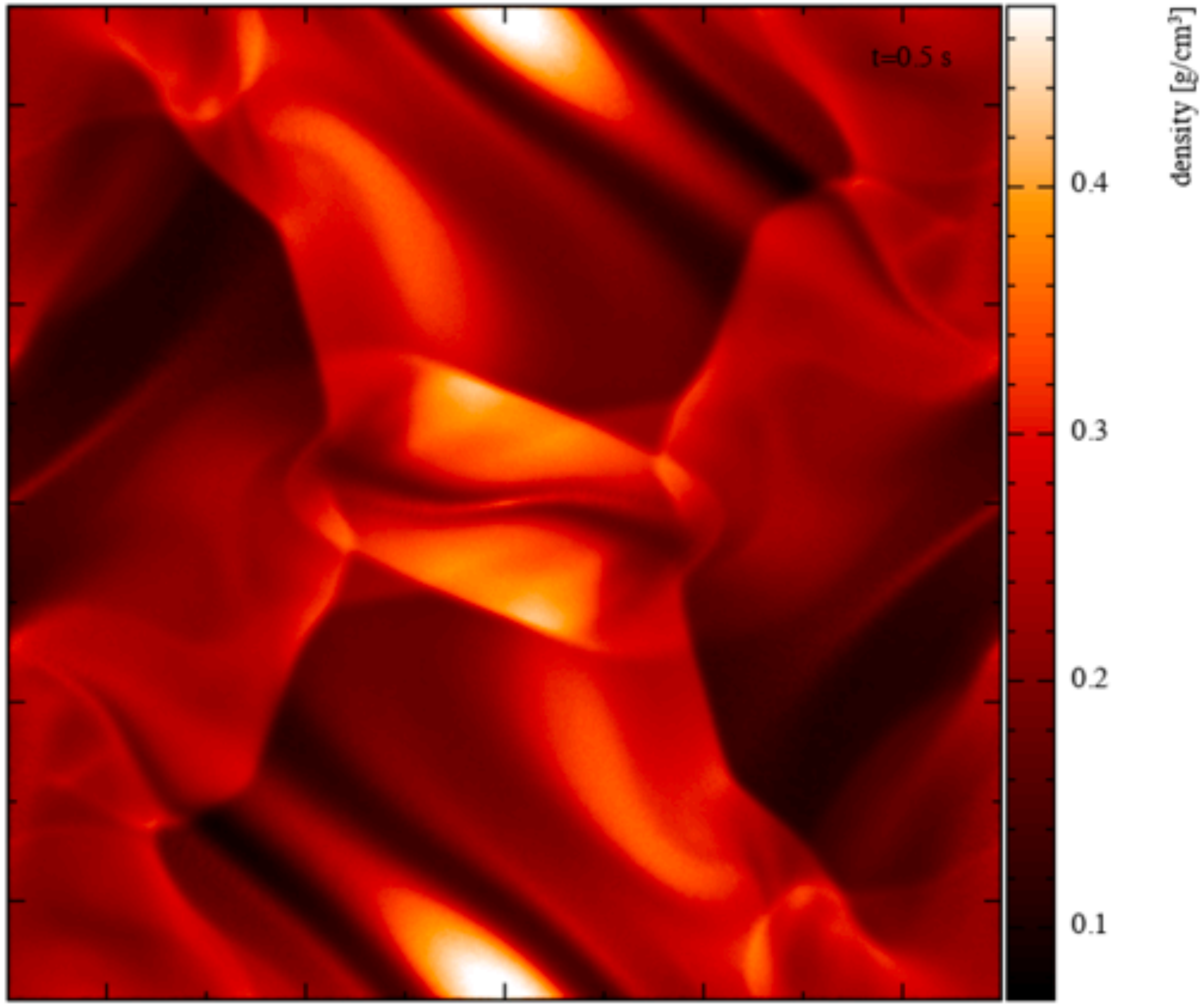
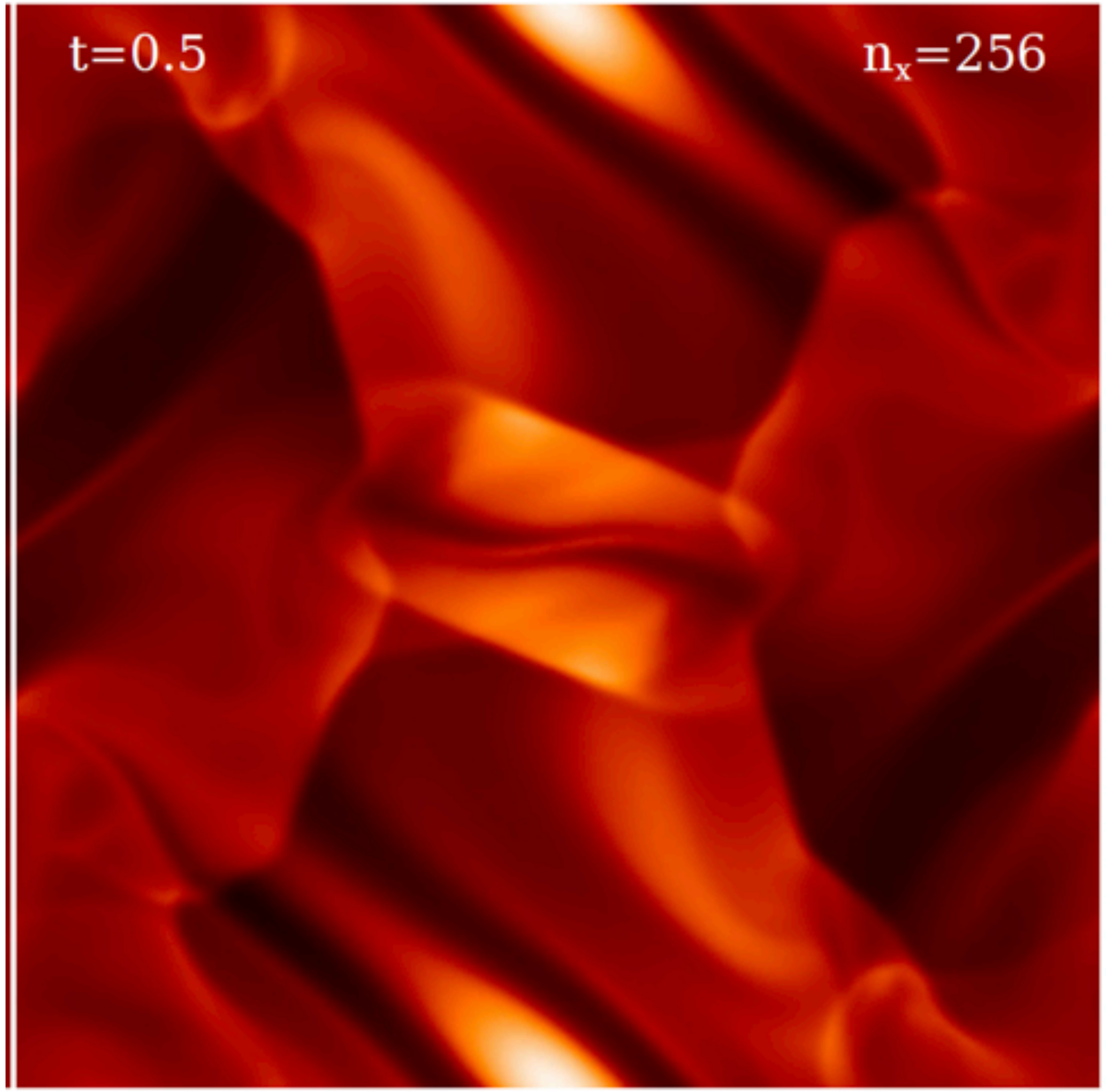




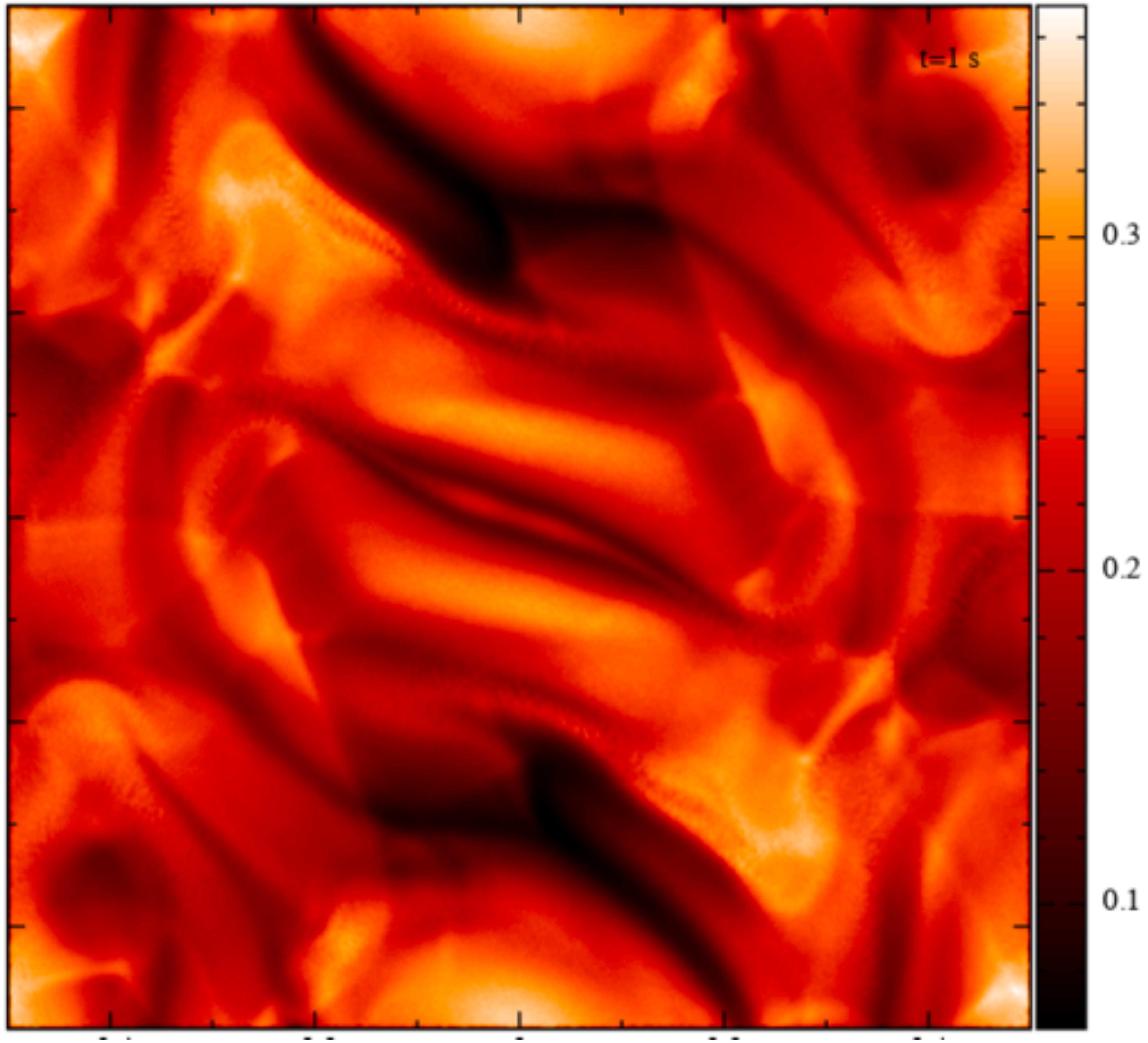
INVESTIGATING A WEIRD CAVITY IN SG SIMS

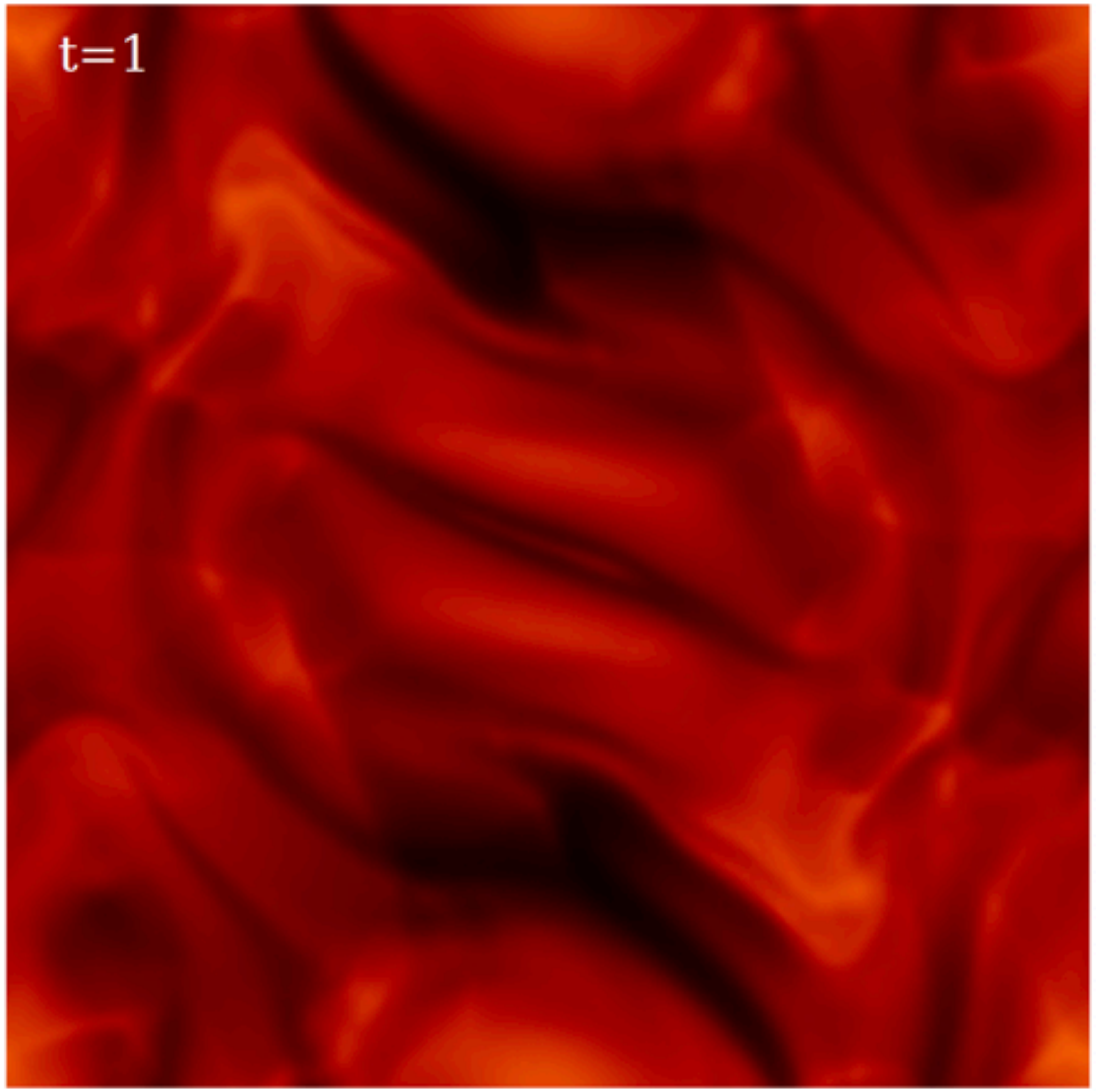




Orszag-Tang vortex test: 256res

INVESTIGATING A WEIRD CAVITY IN SG SIMS





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