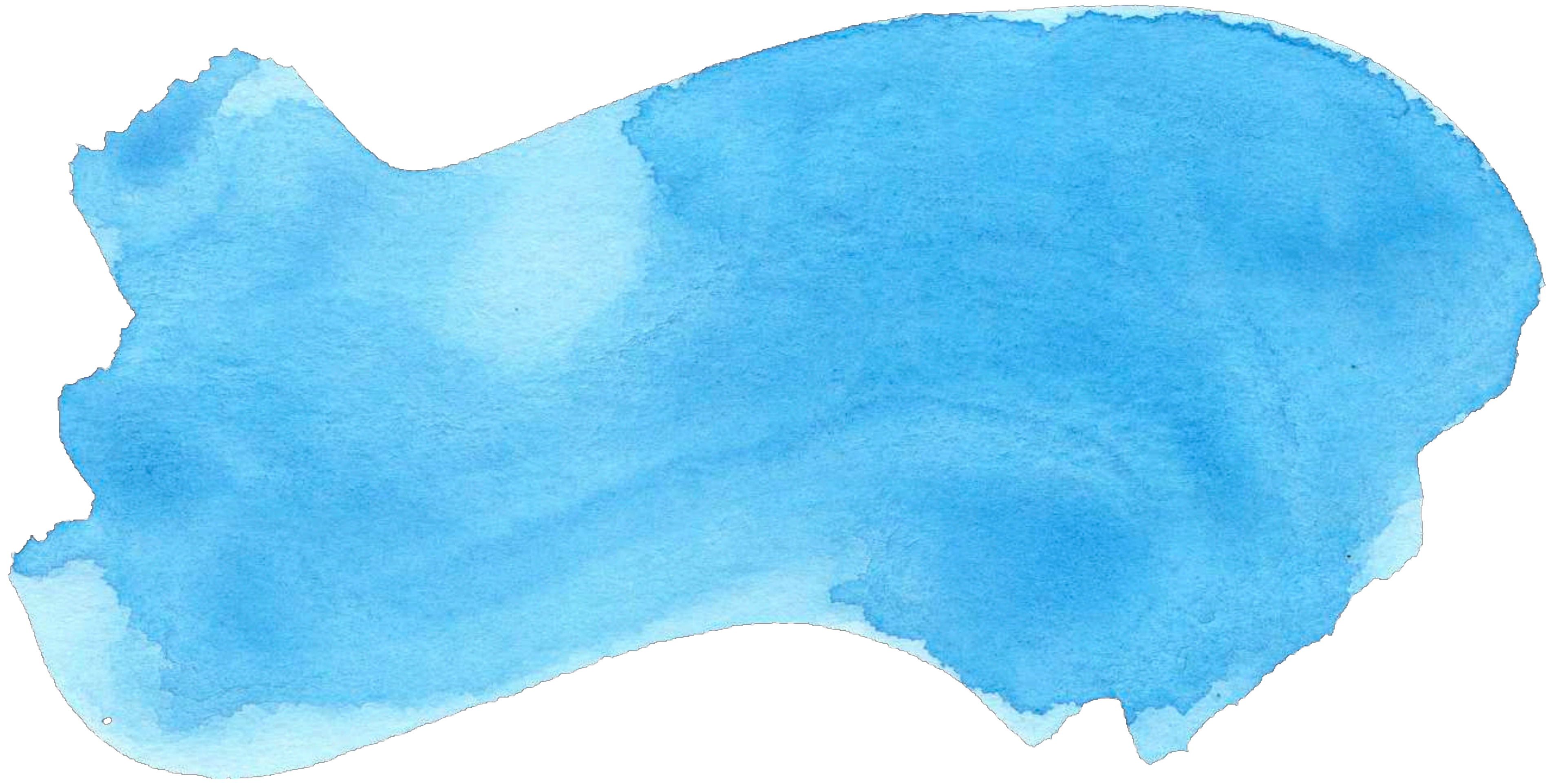
APR in Phantom

Live adaptive particle refinement in Phantom

Work in progress!

Rebecca Nealon and Daniel Price
with acknowledgements to James Wurster, Jeremy Smallwood and Sahl Rowther

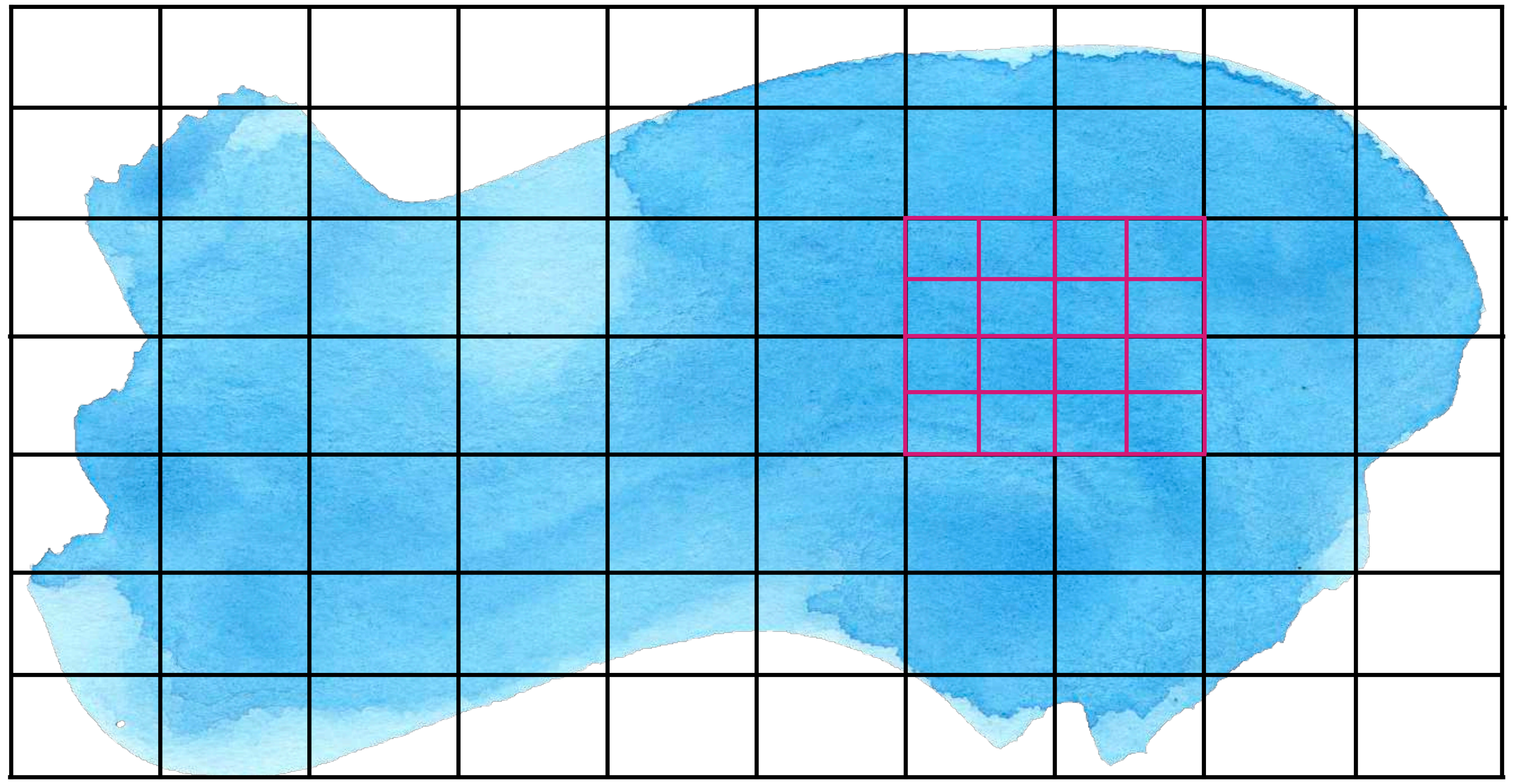
MONASH University
WARWICK
THE UNIVERSITY OF WARWICK
PHANTOM



How do we simulate a fluid?

Grid approach

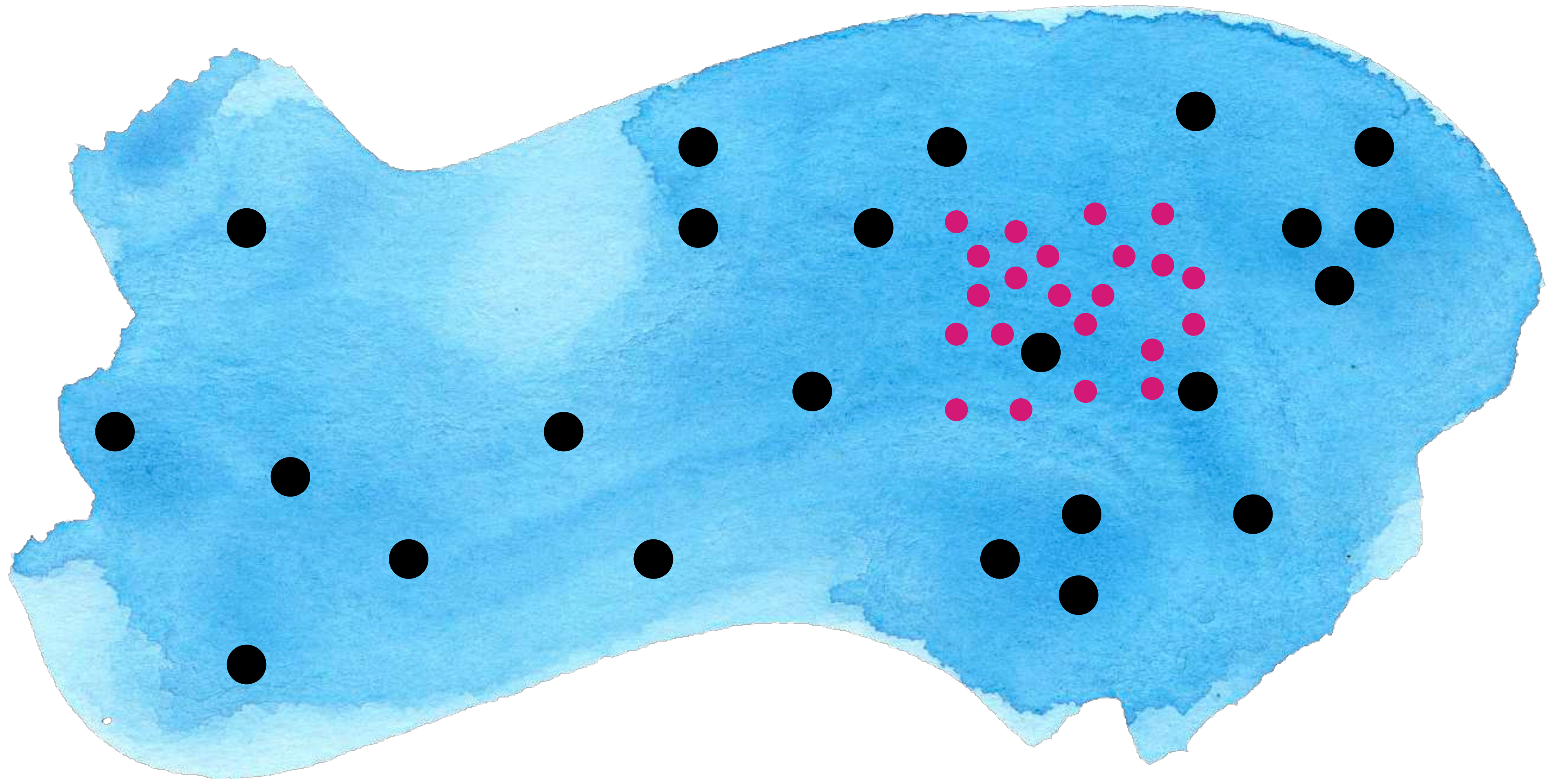
Discretise the domain into a static grid



- Fluid moves through the static boxes
- Easy to parallelise (can be very fast)
- Easy to implement magnetic fields, winds etc.
- Adaptive mesh refinement

SPH approach

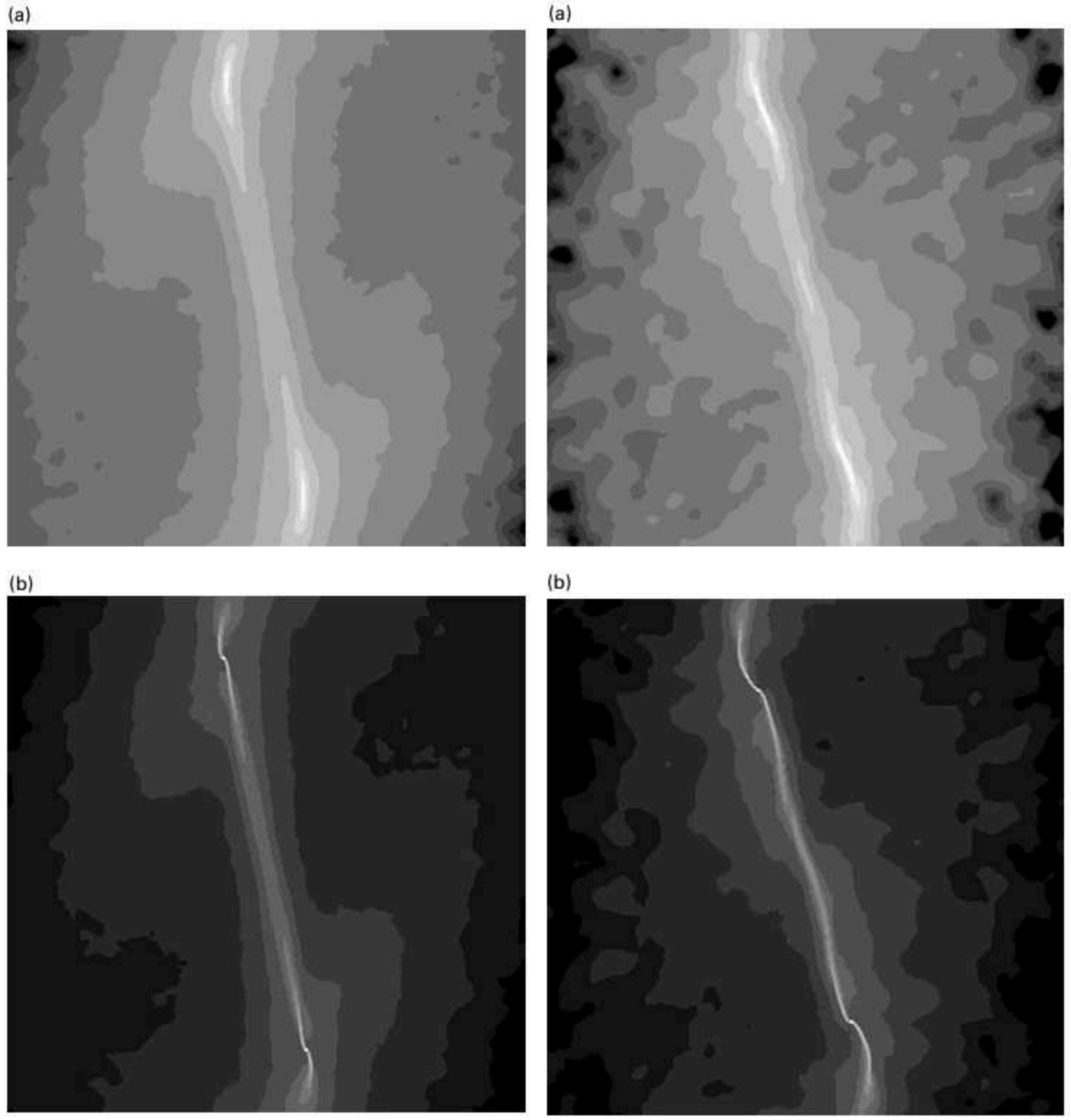
Discretise the fluid onto moving particles



- Particles move with the fluid
- No boundaries or preferred direction
- Exact conservation of mass, linear and total angular momentum
- **Adaptive particle refinement**

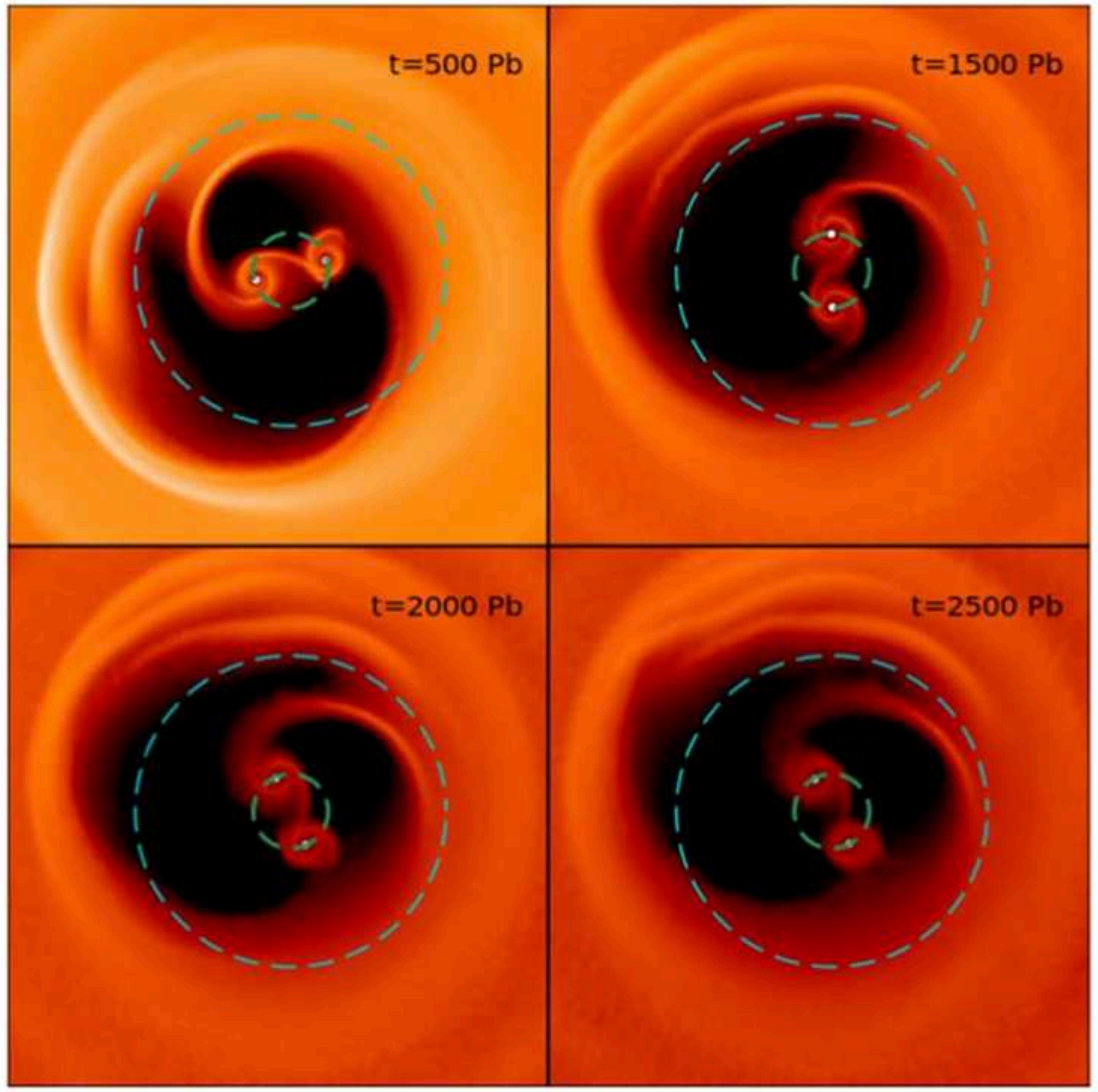
It’s an old idea …

Reference (600,000) APR (45,000 initially)

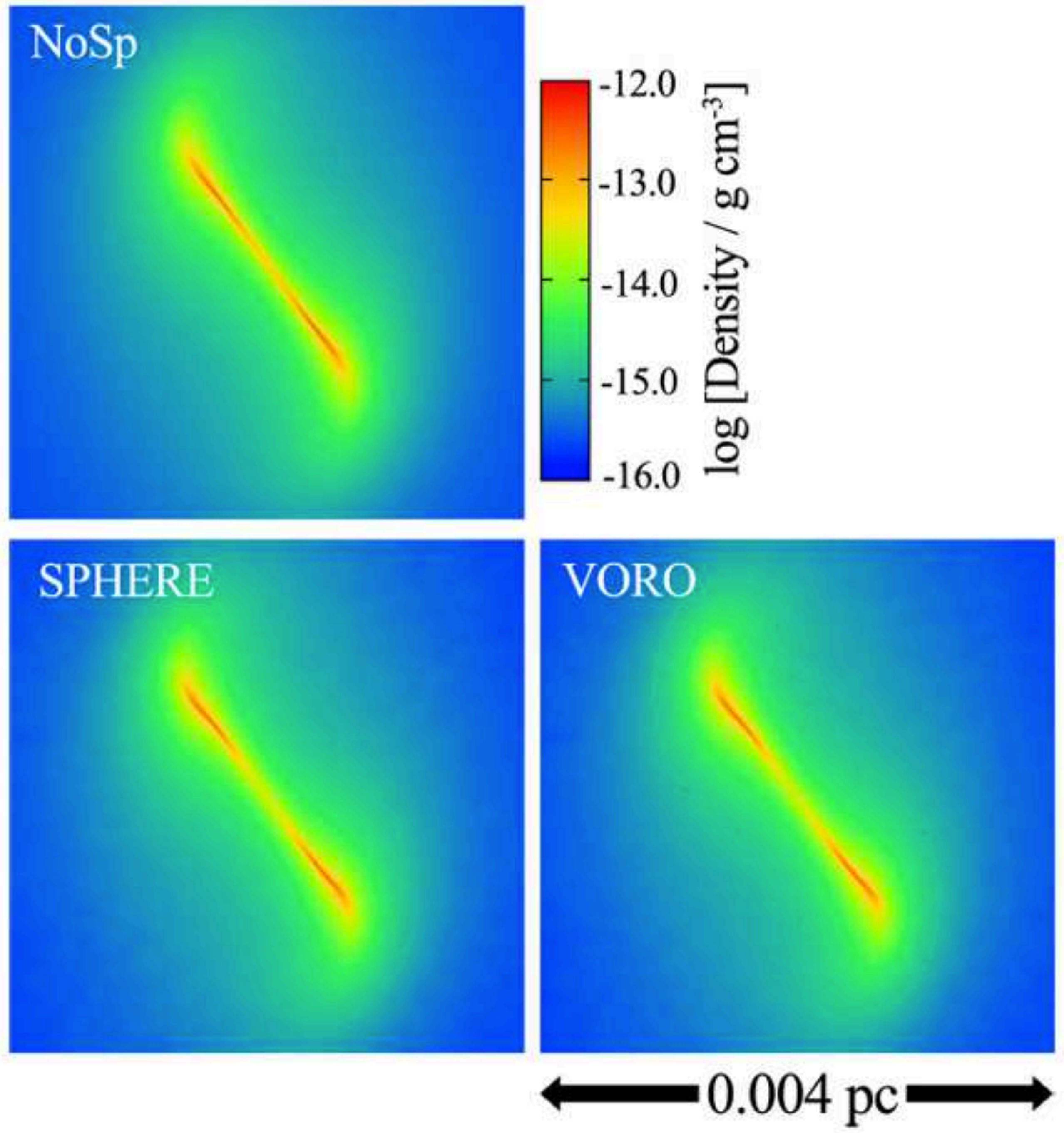


Kitsionas & Whitworth 2002

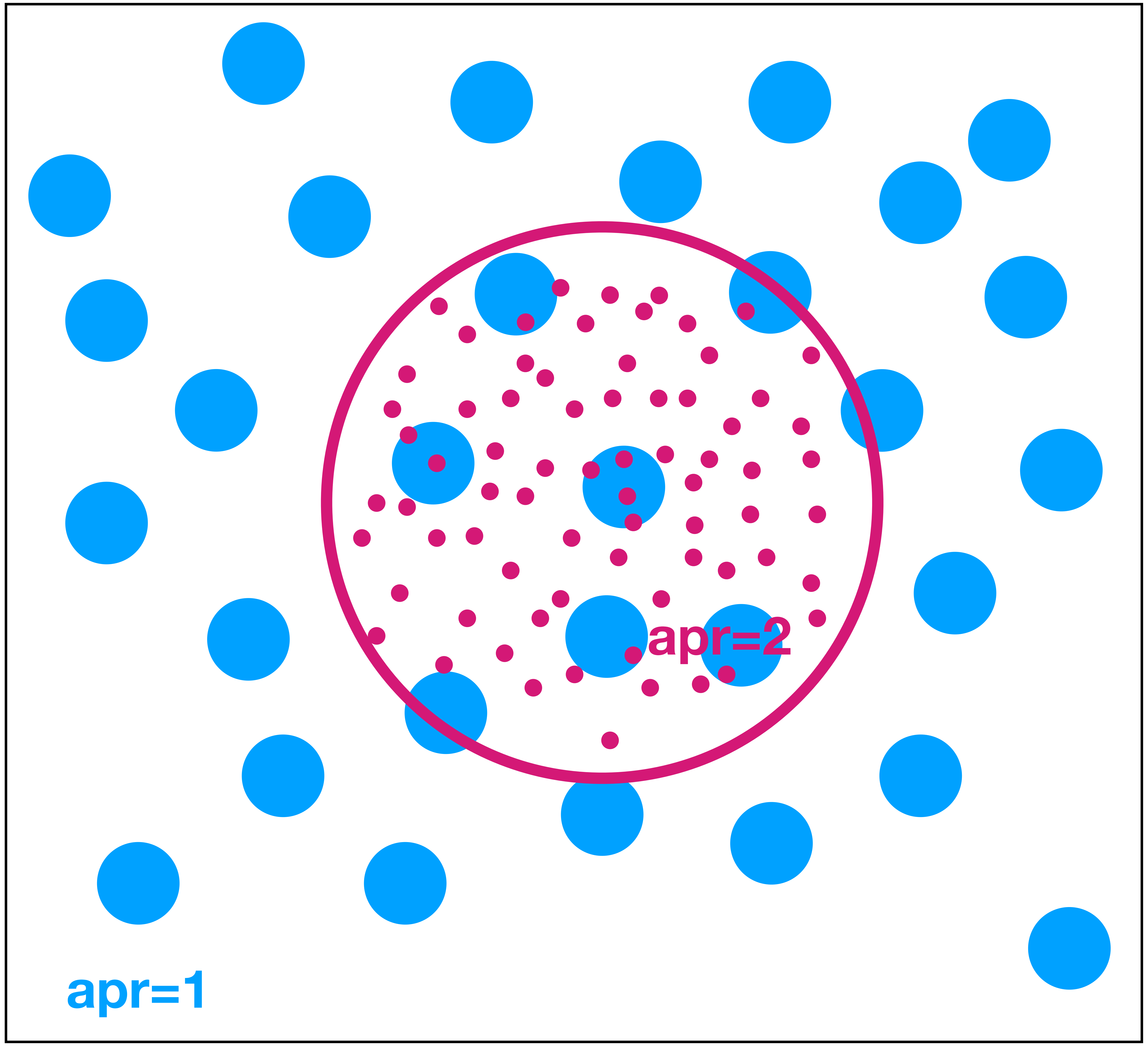
GIZMO: Hopkins 2015, Franchini et al. 2022



Chiaki & Yoshida 2015

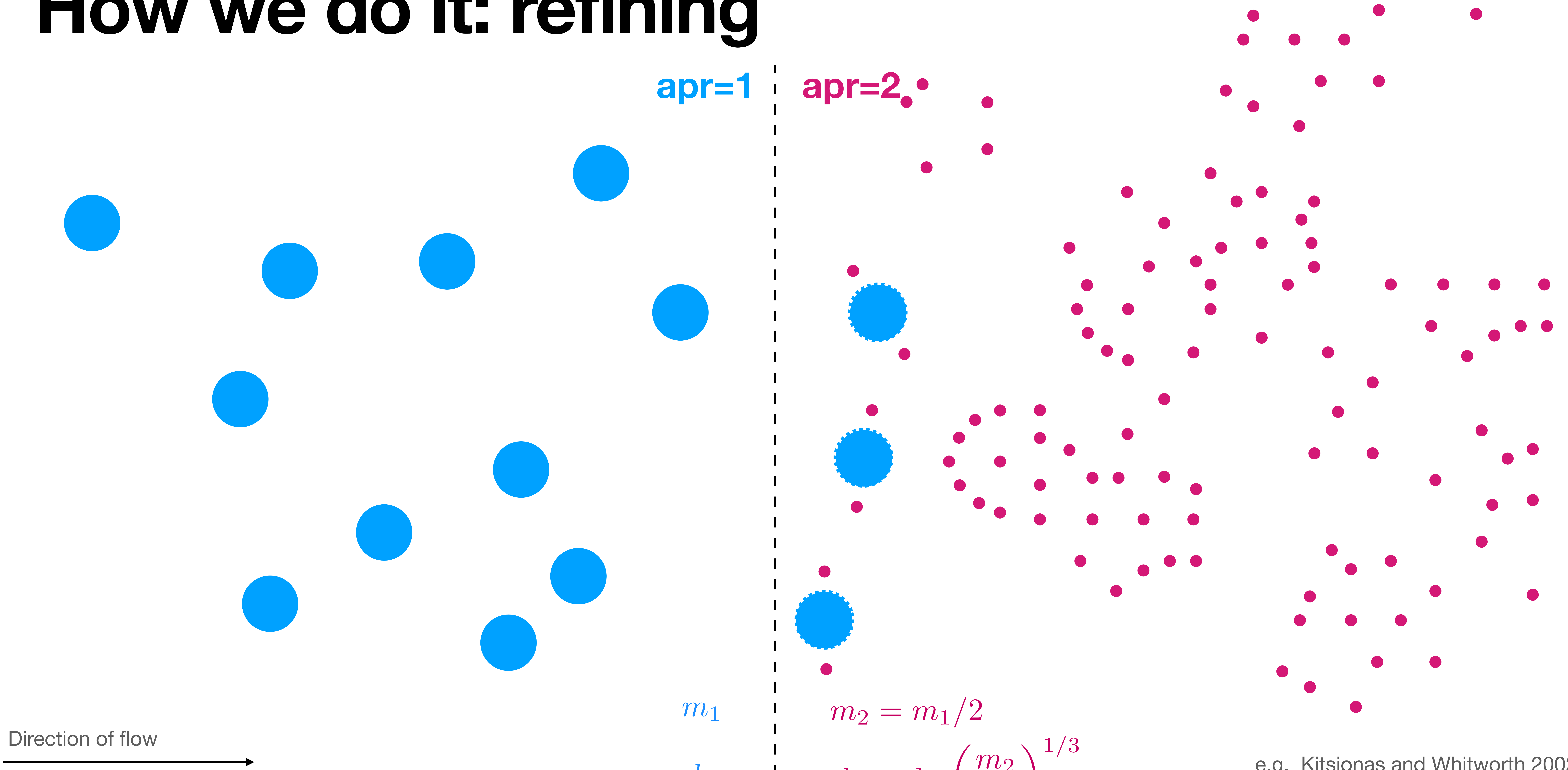


How we do it: refinement levels



- Decide on a region that we want to increase the resolution in
- Split all the particles inside this region, increasing their refinement level
- Density is decided across both sets of particles
- Particles are able to safely move in and out of the region, transitioning between refinement levels

How we do it: refining

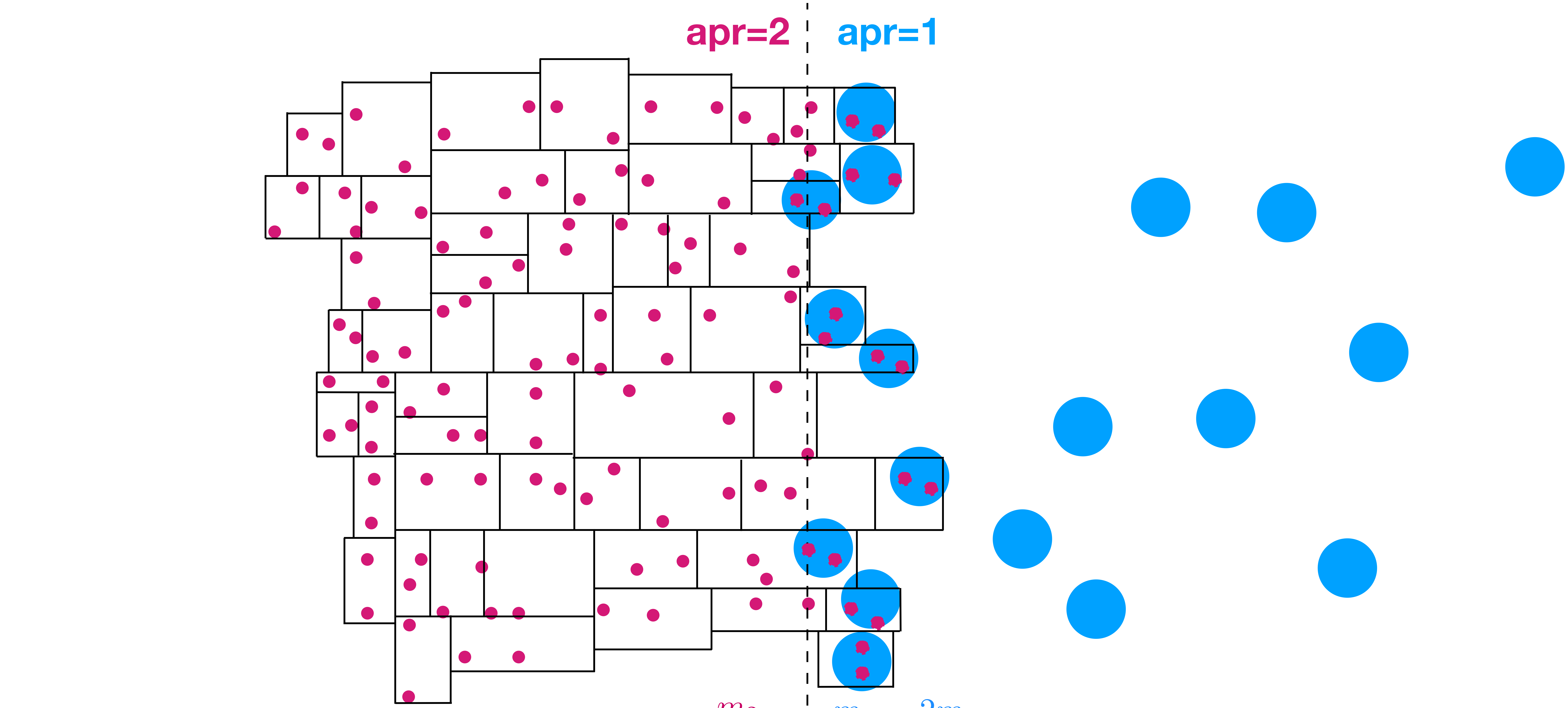


m_1 | $m_2 = m_1/2$

h_1 | $h_2 = h_1 \left(\frac{m_2}{m_1}\right)^{1/3}$

e.g. Kitsionas and Whitworth 2002
Barcarolo et al. 2014
Chiron et al. 2018
Bending et al. 2020

How we do it: de-refining



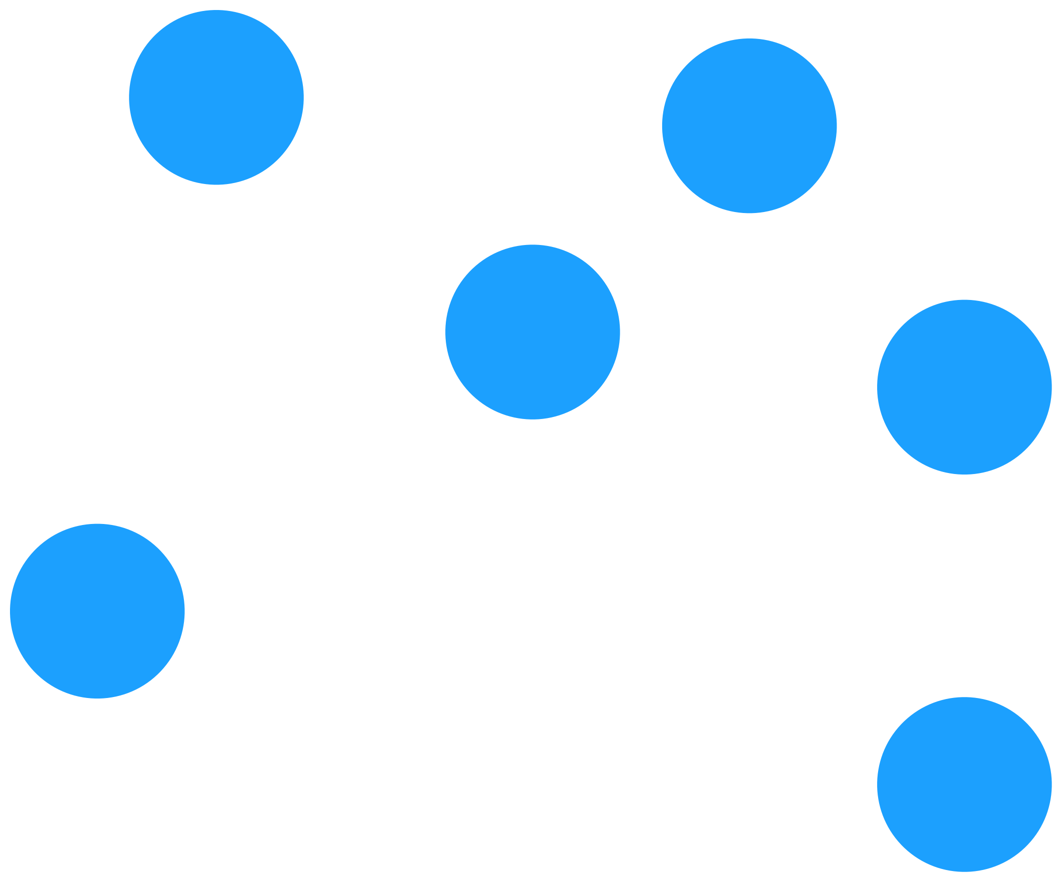
m_2 $\quad m_1 = 2m_2$

h_2 $\quad h_1 = h_2 \left(\frac{m_1}{m_2}\right)^{1/3}$

Gafton & Rosswog 2011
Benz, Bowers, Cameron & Press 1990

How we do it: relaxing

Original arrangement



$$\rho(\overrightarrow{x}) = \sum_{a=1}^{N} m_a W_a(\overrightarrow{x}, h_a)$$

Feldman & Bonet 2008
Diehl et al. 2015
Vacondio et al. 2013
López, Roose & Morfa 2012

How we do it: relaxing

1. Save the properties of all current particles

2. Split/merge as required

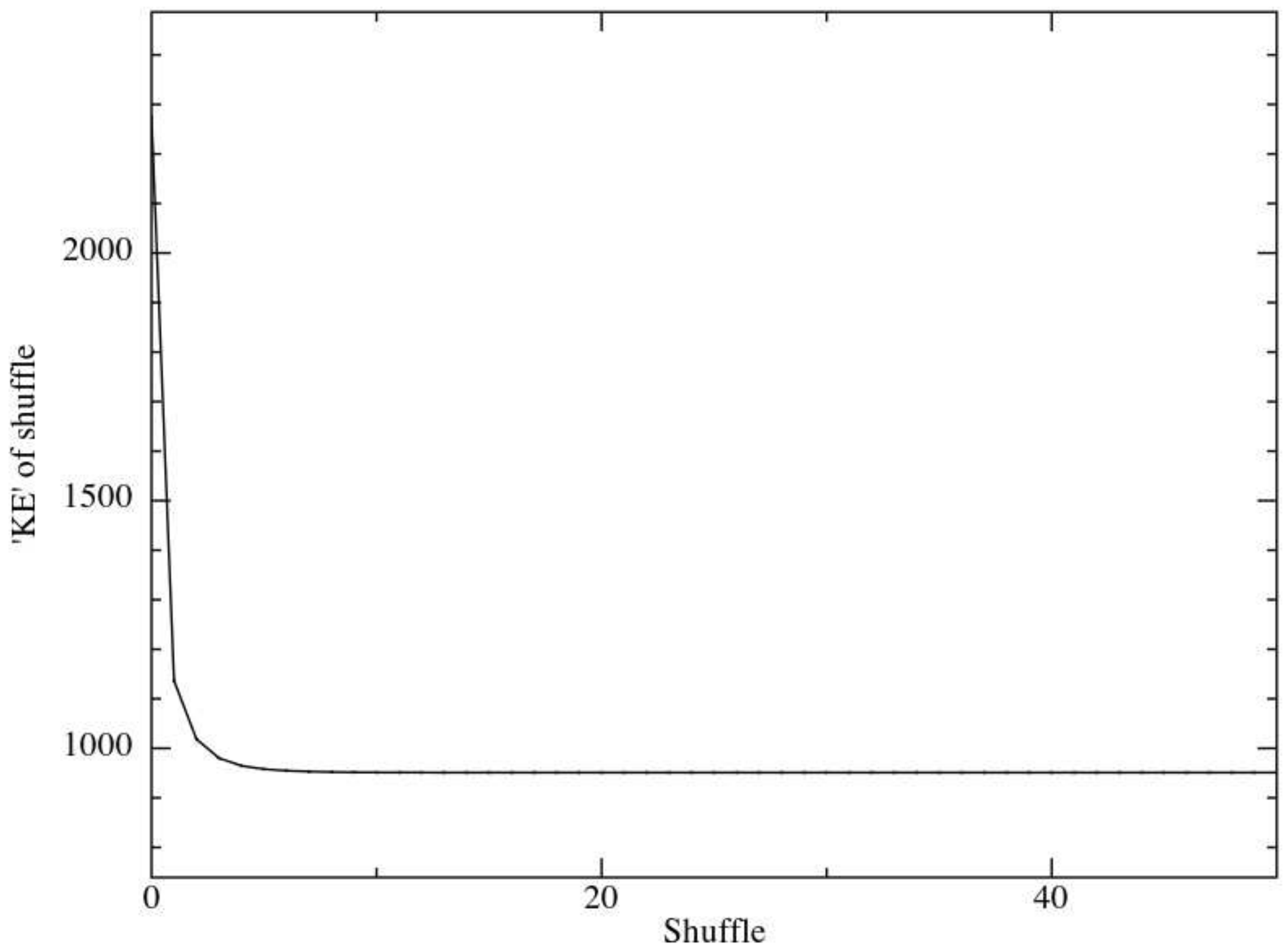
3. For new particles:

    i. Calculate accelerations of new particles at their new locations

    ii. Interpolate the acceleration at the location of the new particles from the original particles

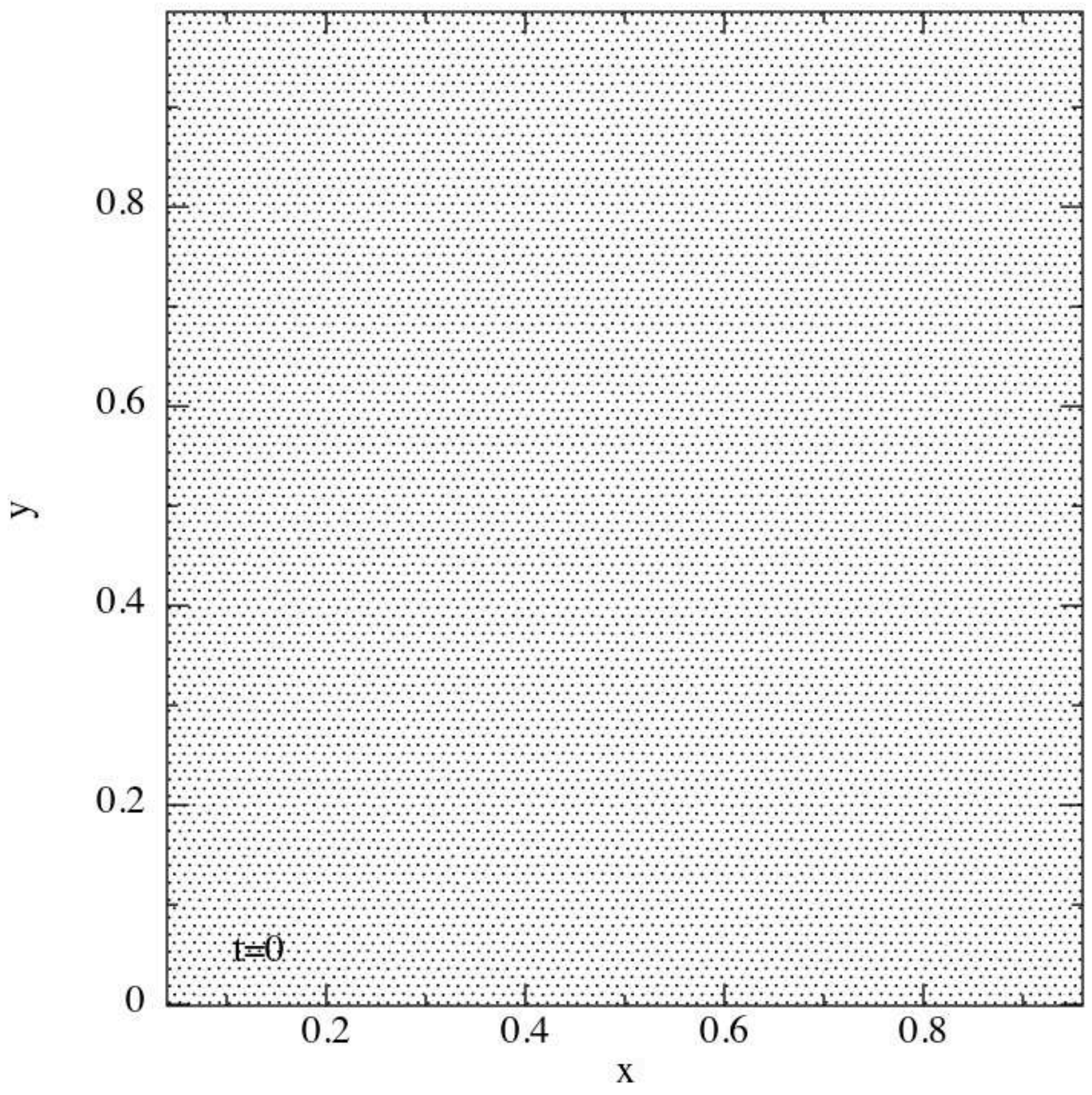
    iii. Shift new particles by an amount that is proportional to the difference between these accelerations

    iv. Repeat

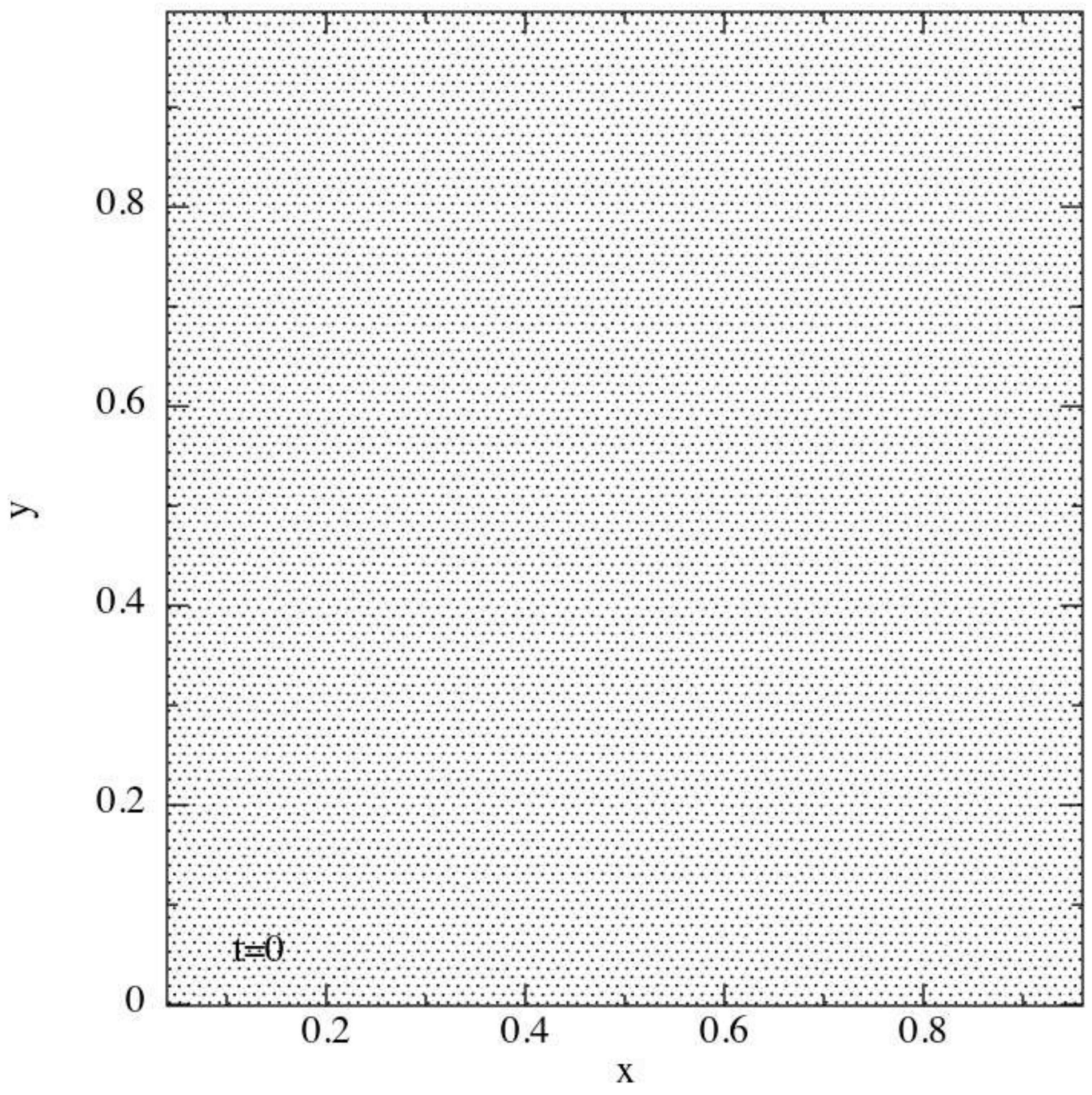


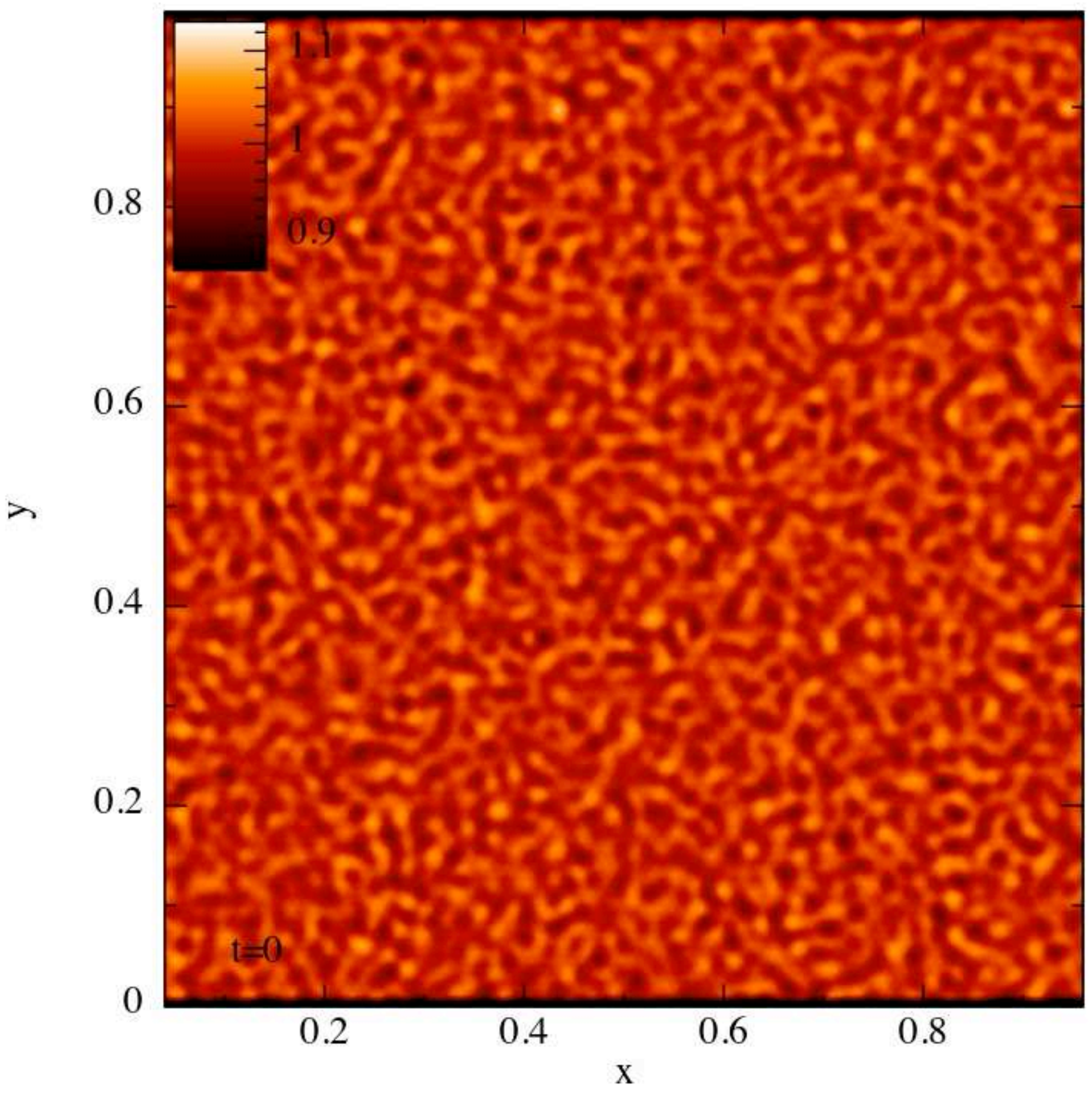
e.g. López, Roose & Morfa 2012
Vacondio et al. 2013
Kitsionas & Whitworth 2002

Uniform density box

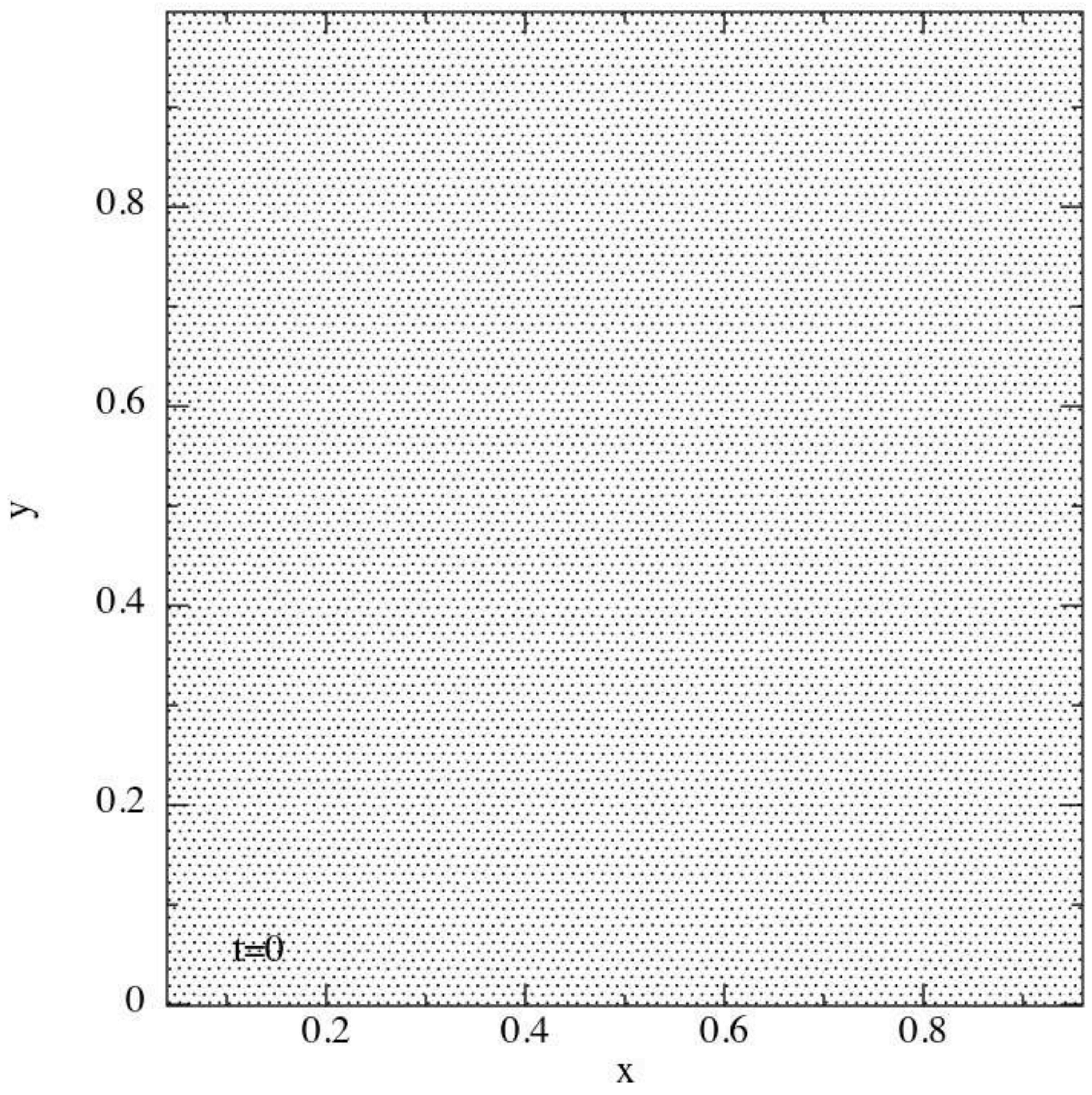


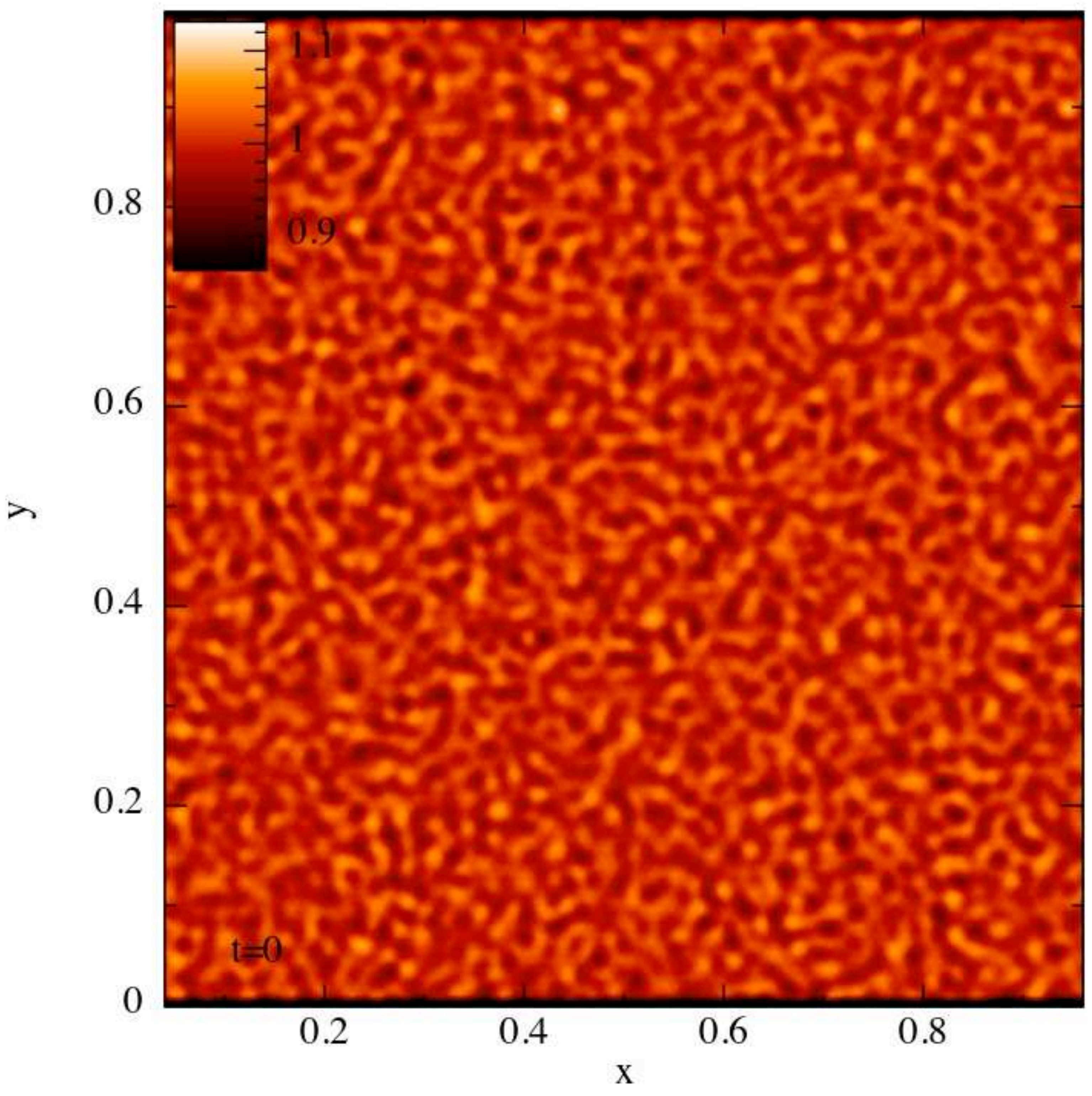
Uniform density box

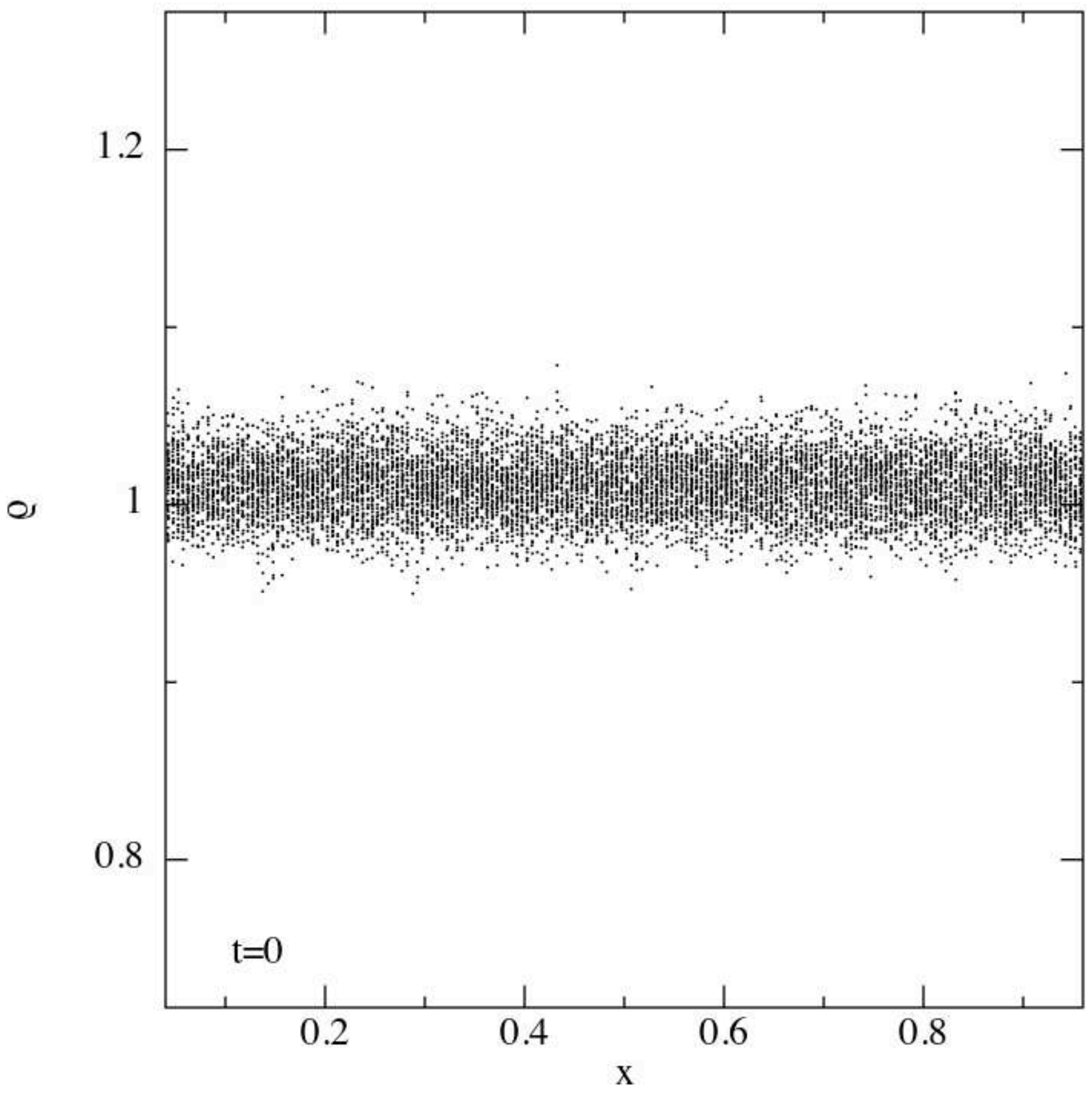




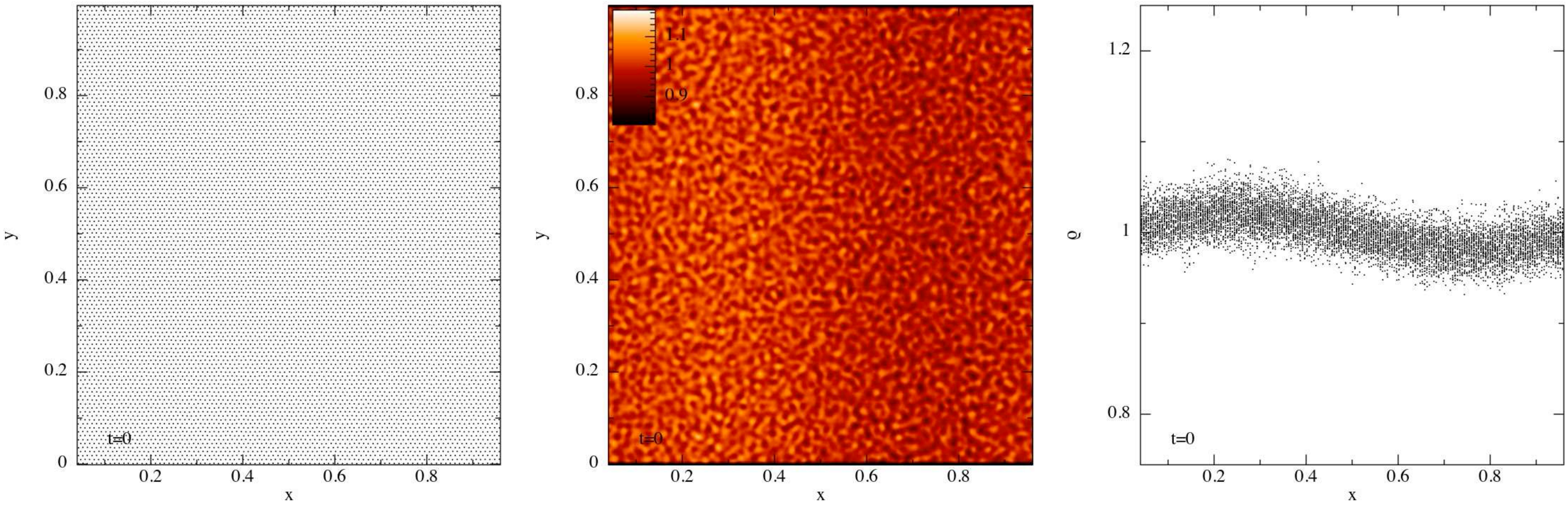
Uniform density box



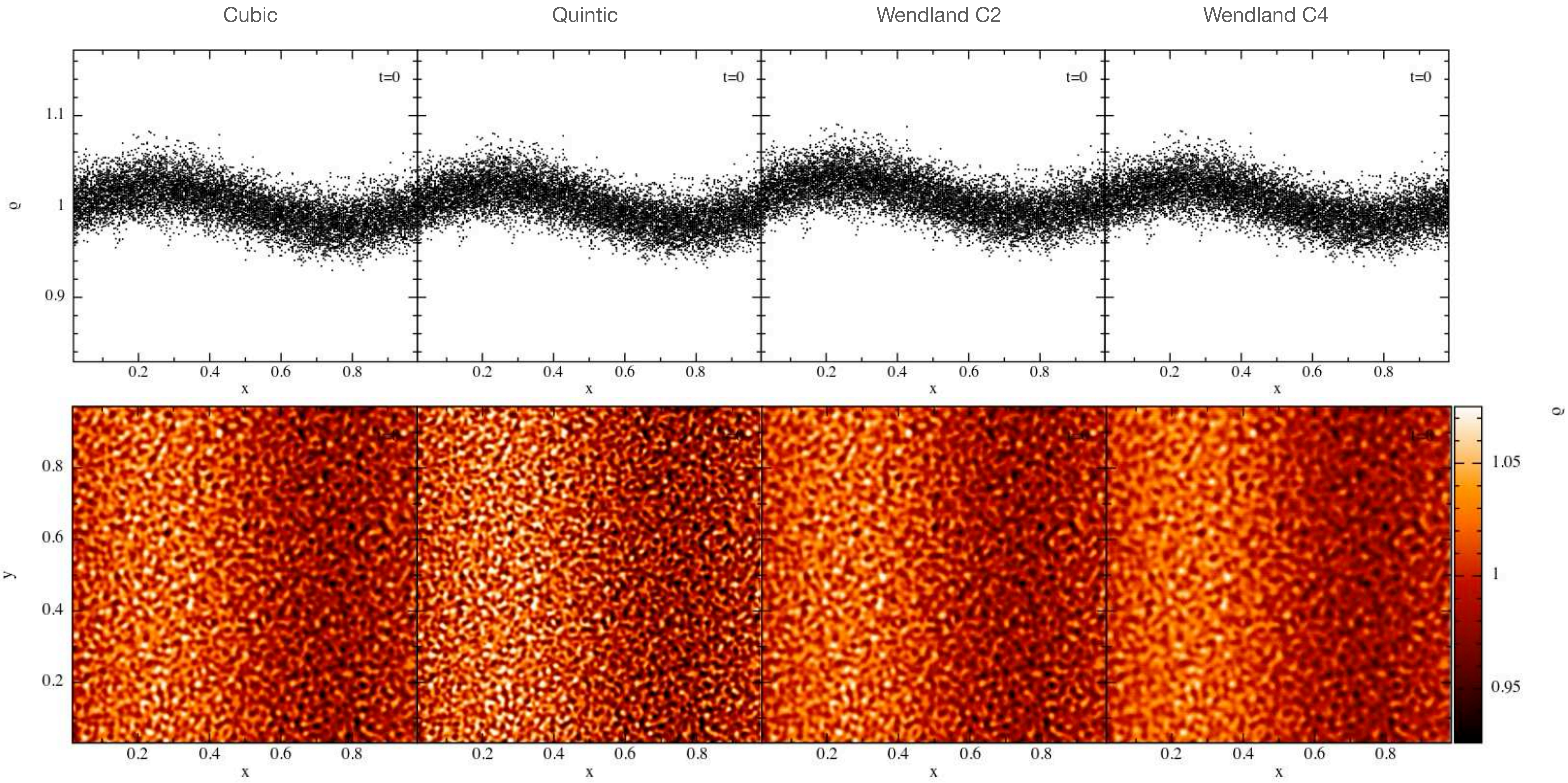




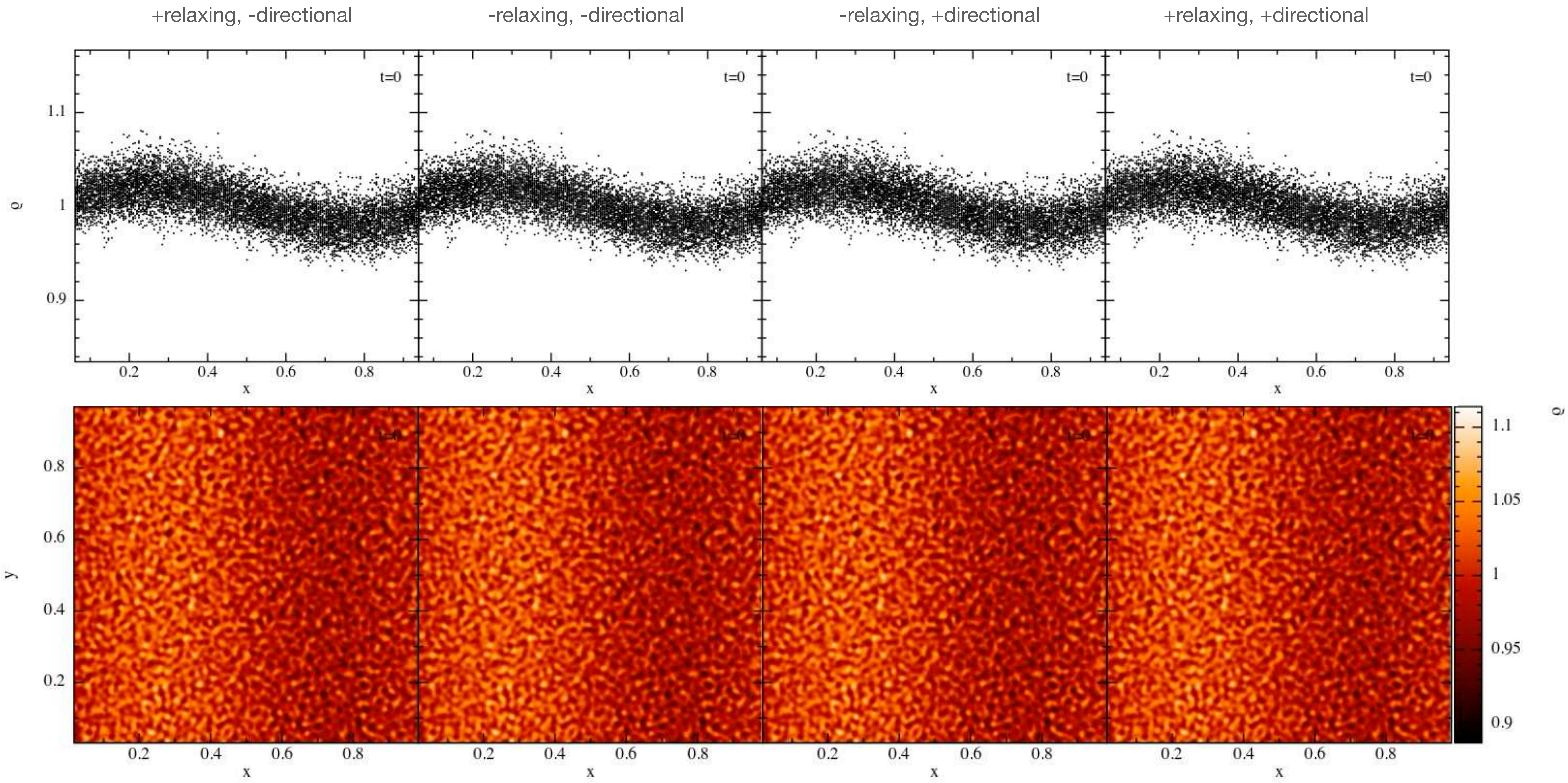
Wave in a box



Wave in a box: kernels

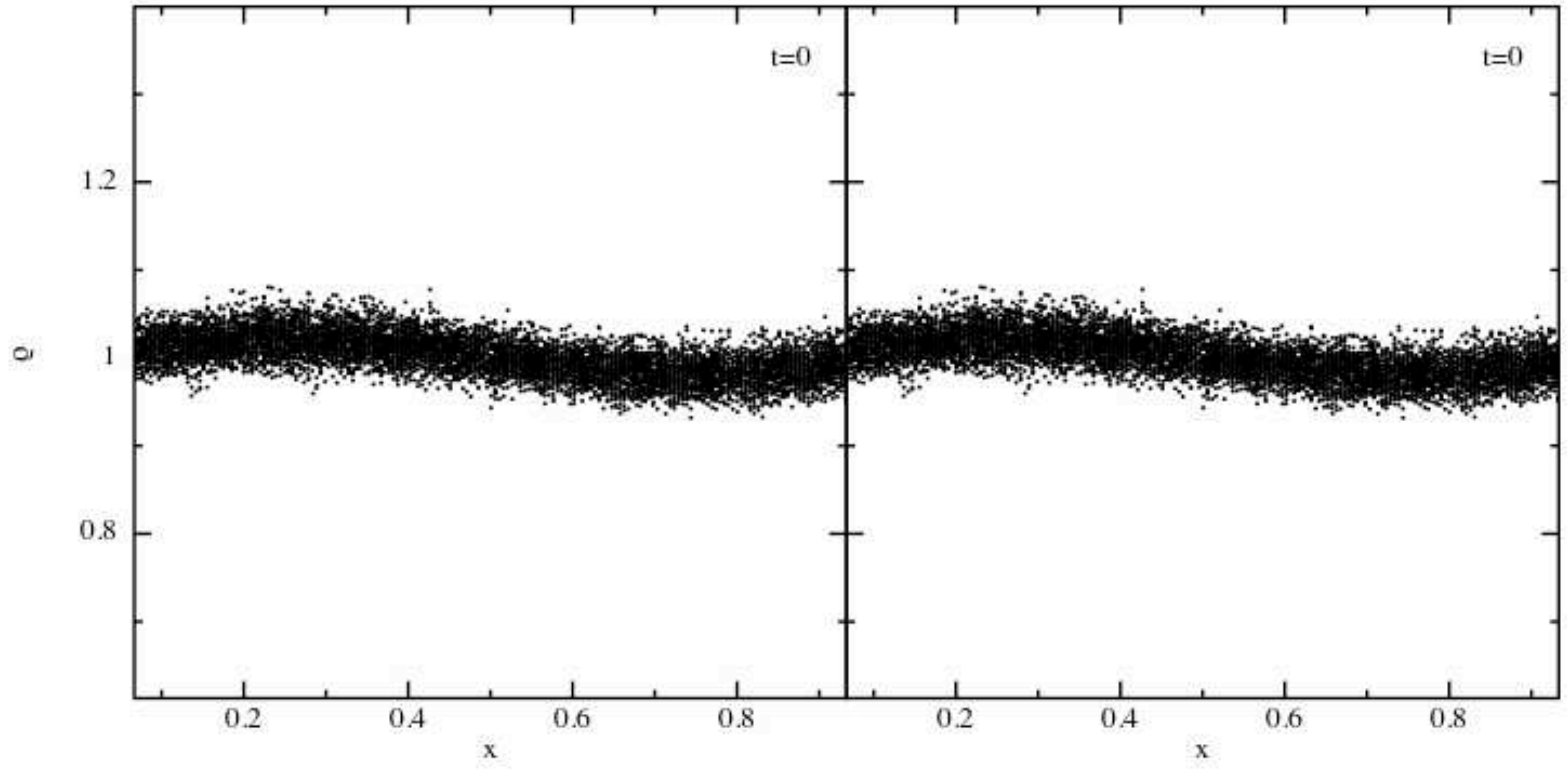


Wave in a box: splitting conditions



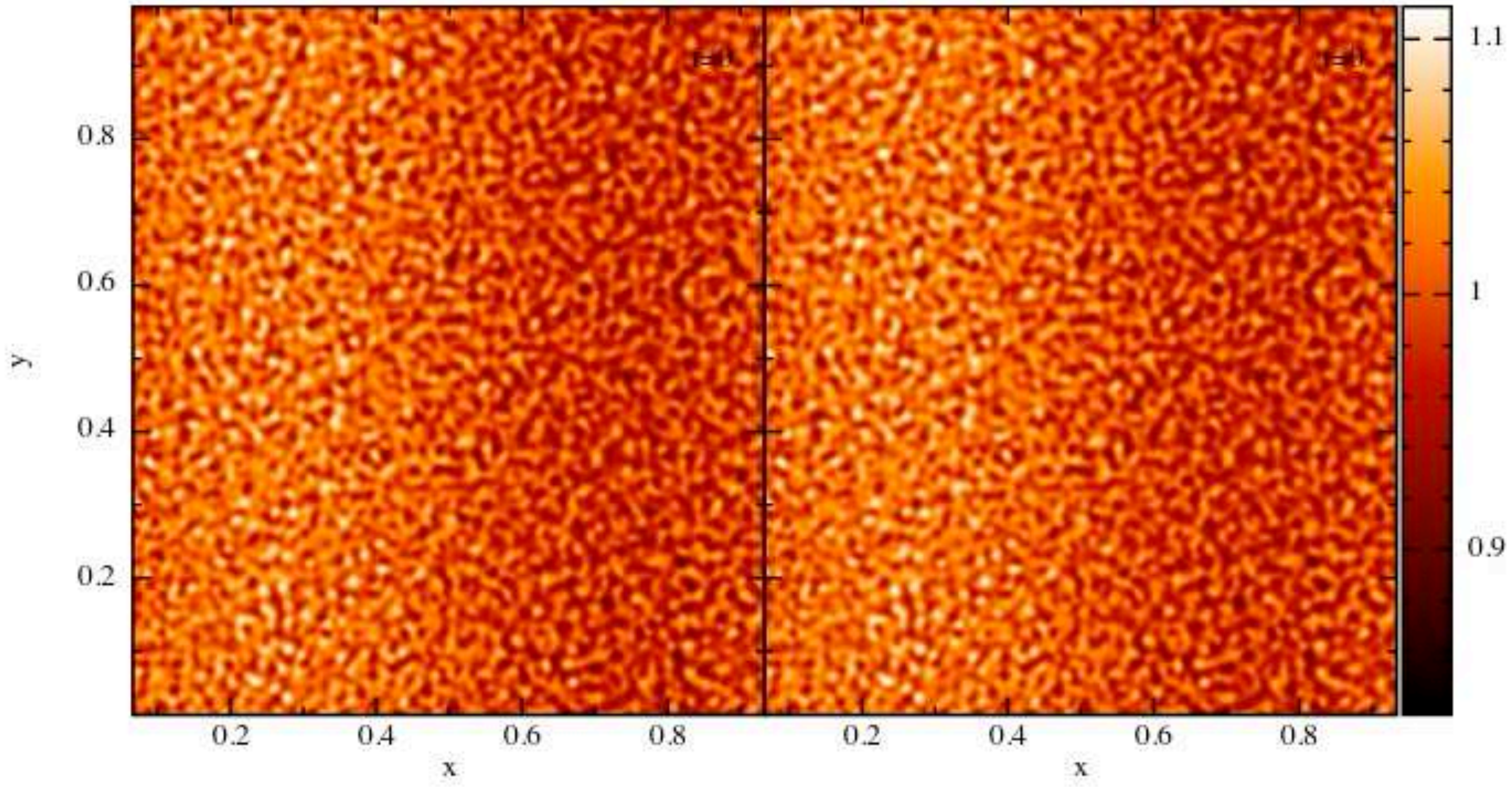
Wave in a box: how many children

nchild=2, two layers



nchild=4, one layer

nchild=2, two layers



nchild=4, one layer

The circumprimary disc in HD 142527

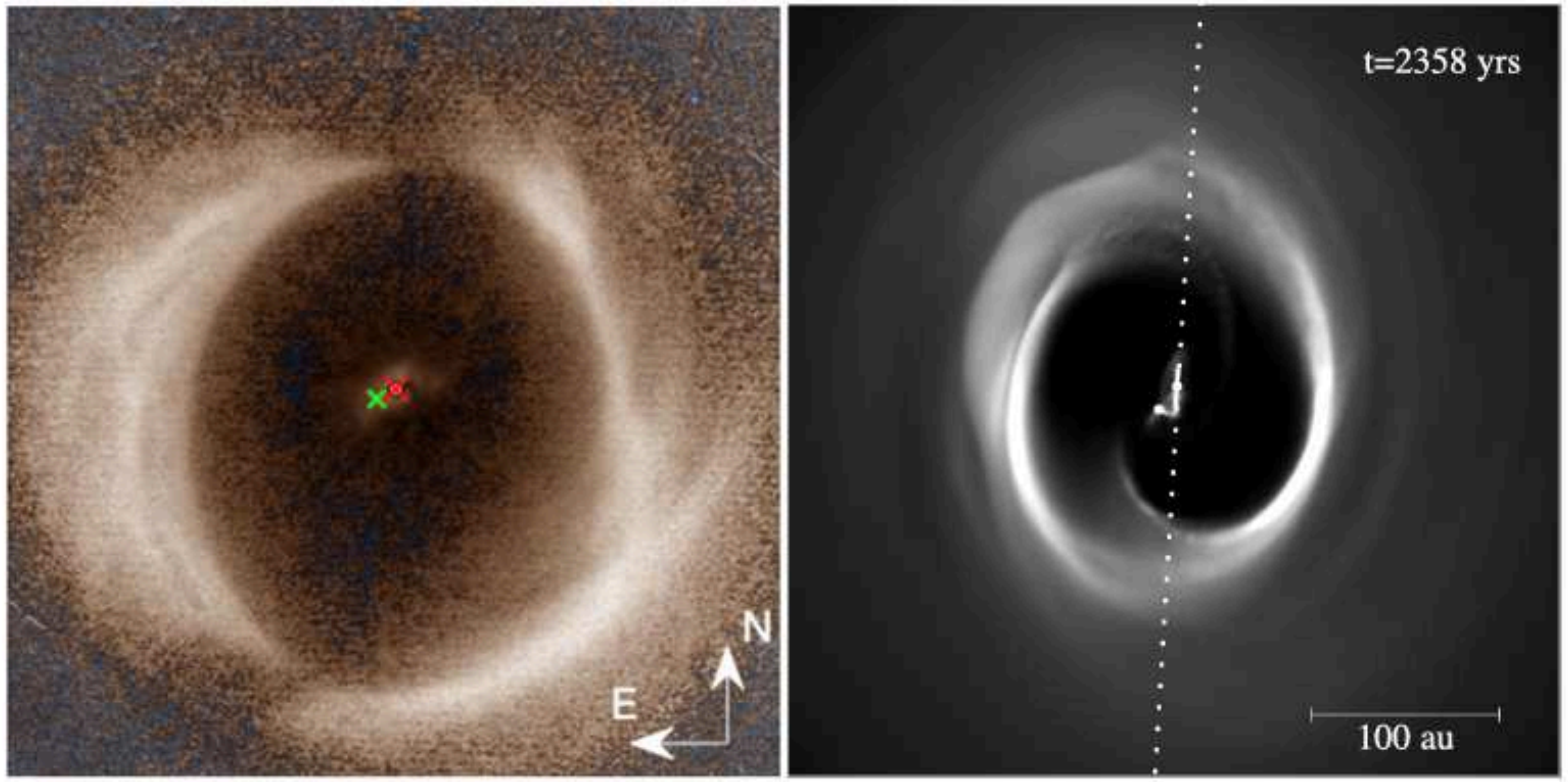
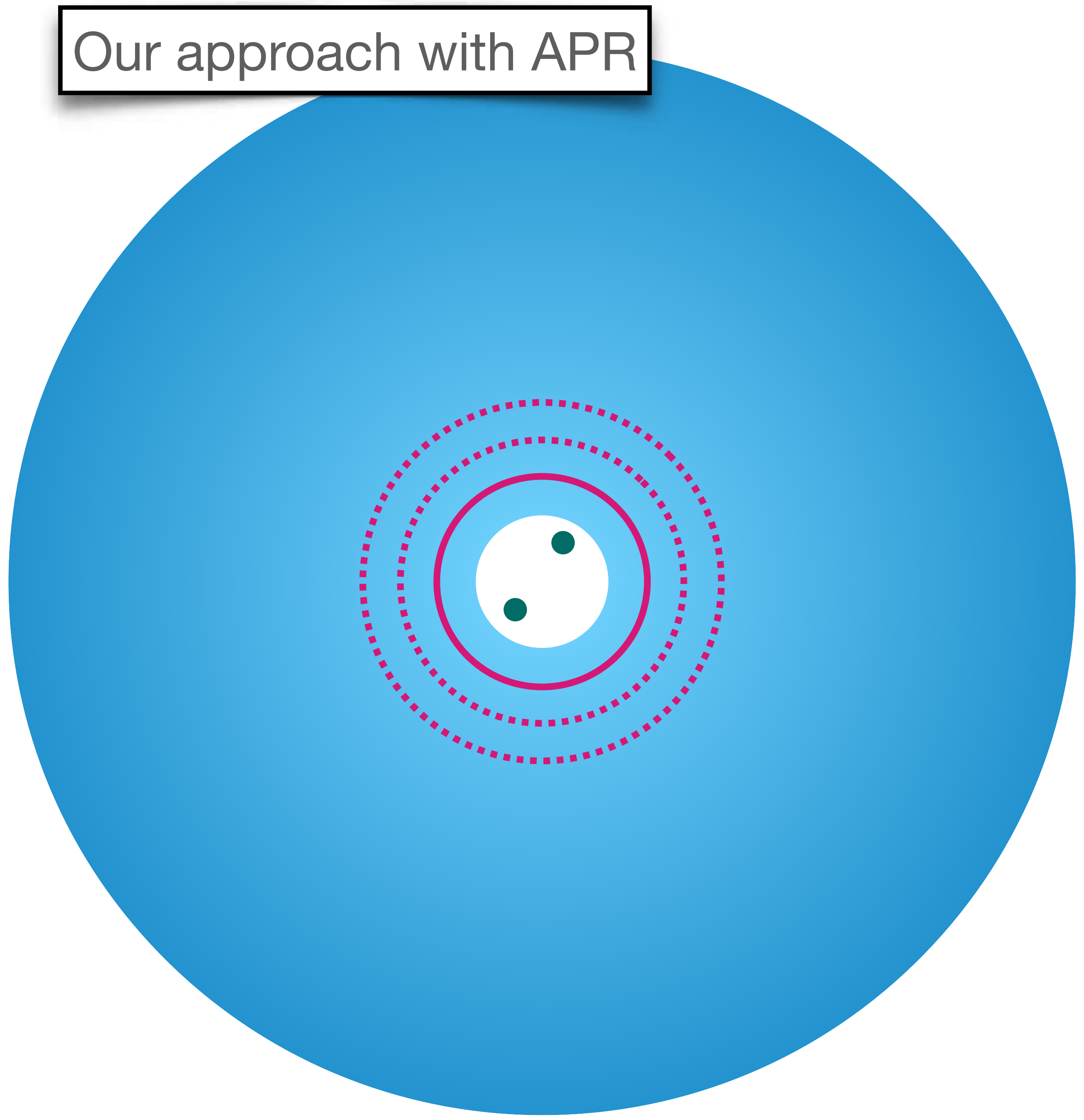


Figure 6. *Shadows*. Column density in the R1 orbit simulated with initial R_{in} = 50 au after 20 orbits at the observed orbital phase (right), showing the orientation of the (transient) circumprimary disc, compared to the scattered light (600–900 nm) the Zurich Imaging Polarimeter (ZIMPOL) polarization image (left; taken from fig. 1 of Avenhaus et al. 2017 ©AAS, reproduced with permission). Dotted line indicates the expected shadow from our simulated inner disc (right), which lies close to the orientation of the observed shadows (left).



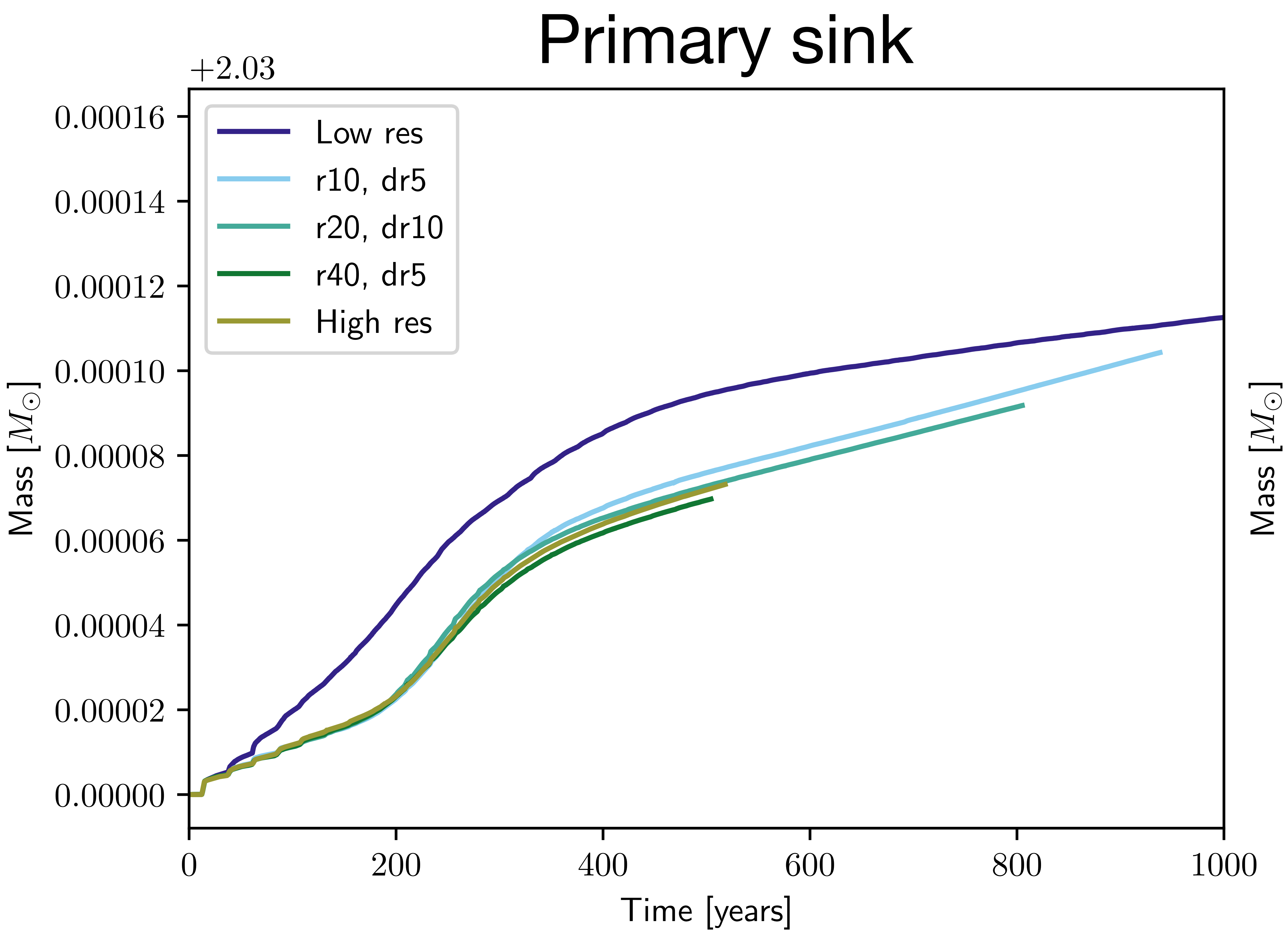
Price et al. 2018

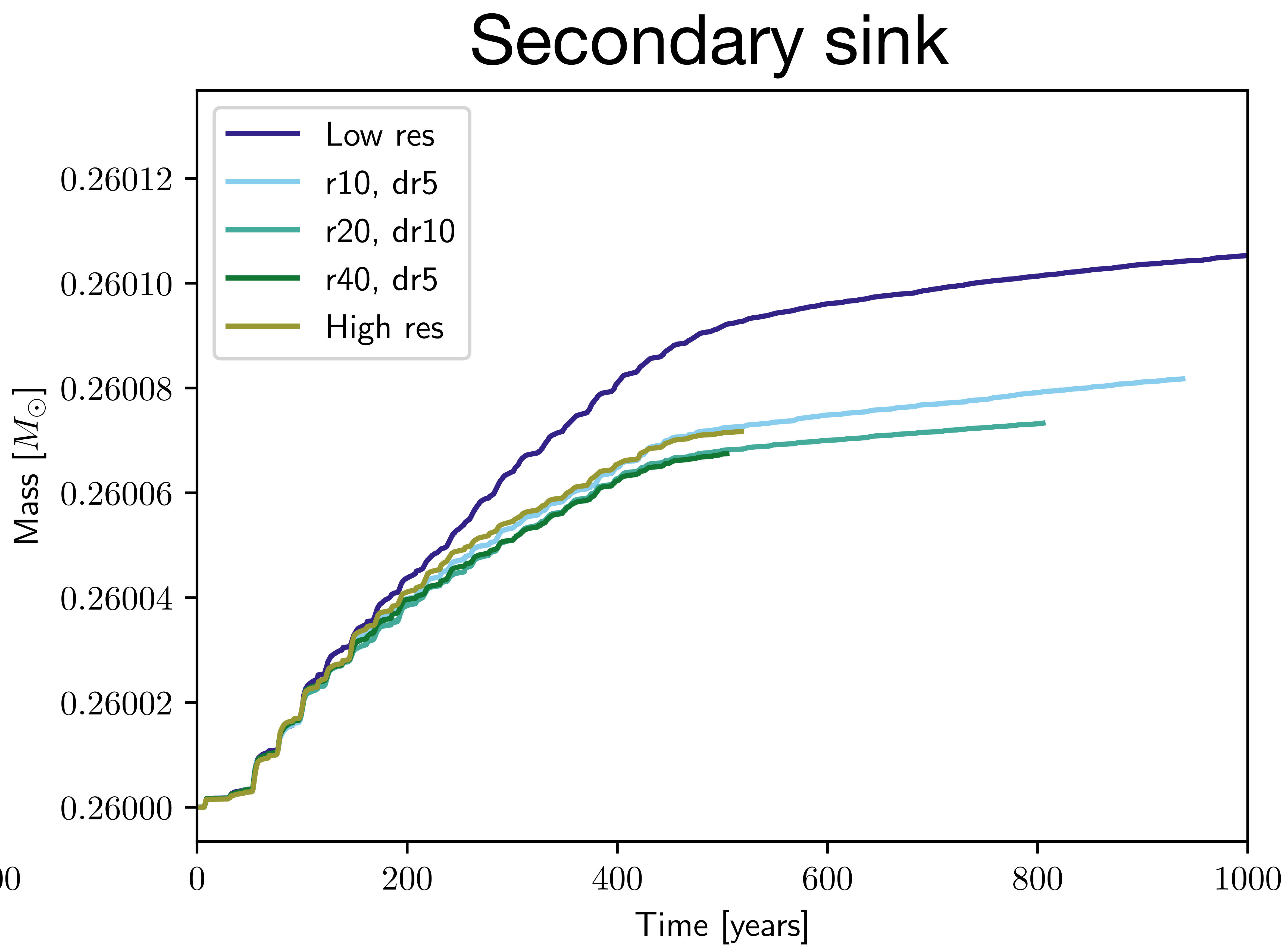
The circumprimary disc in HD 142527

(1 x 10^6) (1.14 x 10^6) (1.44 x 10^6) (1.75 x 10^6) (8 x 10^6)

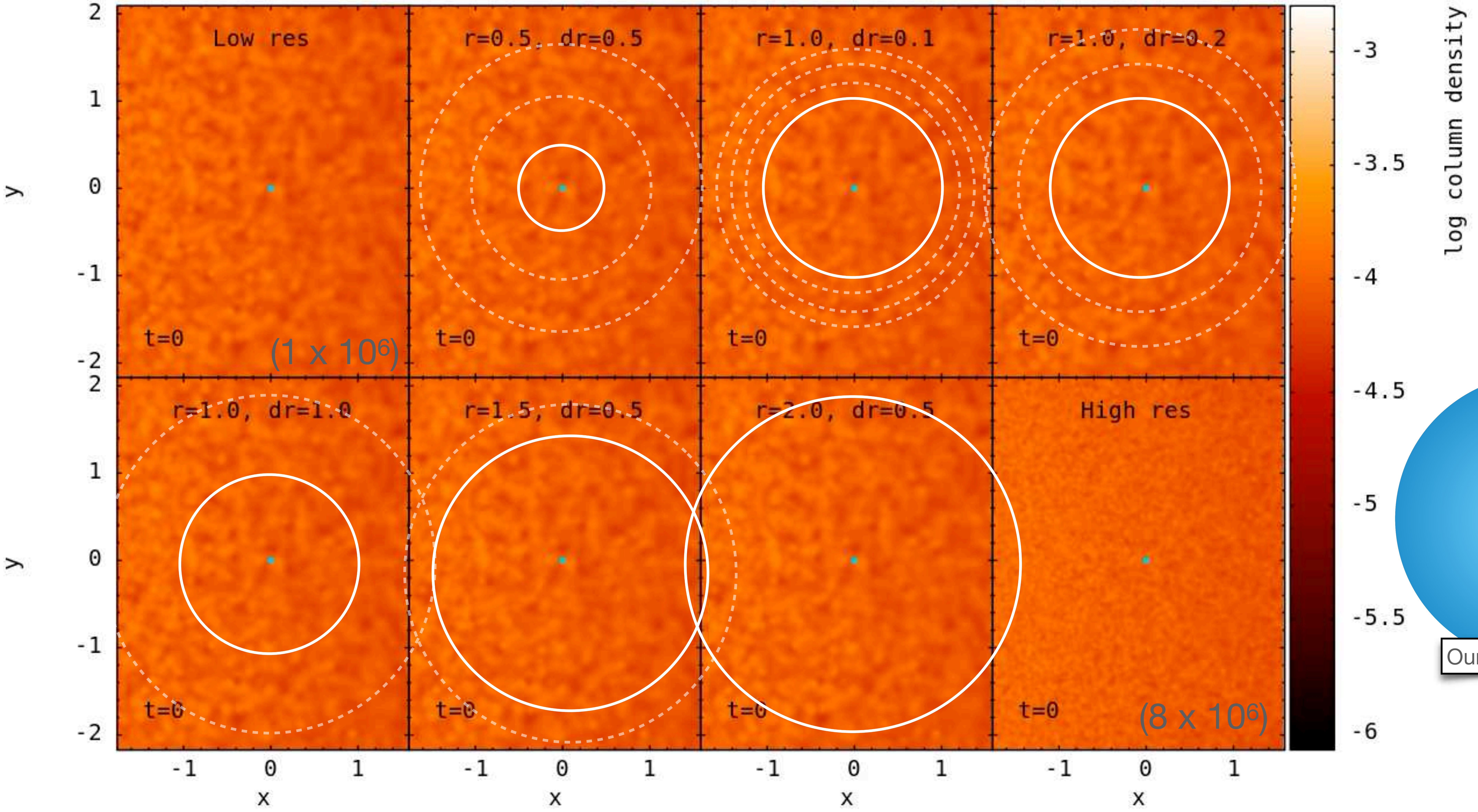
The circumprimary disc in HD 142527

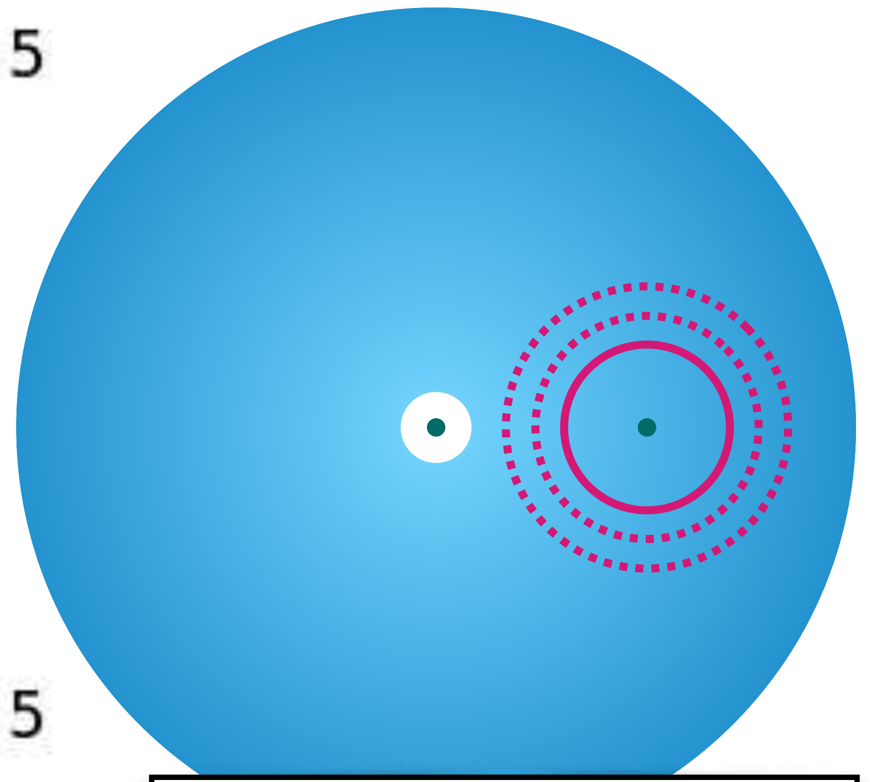
Accuracy	Speed up	File size
0.002%	1.07-1.96x	22%





A circumplanetary disc

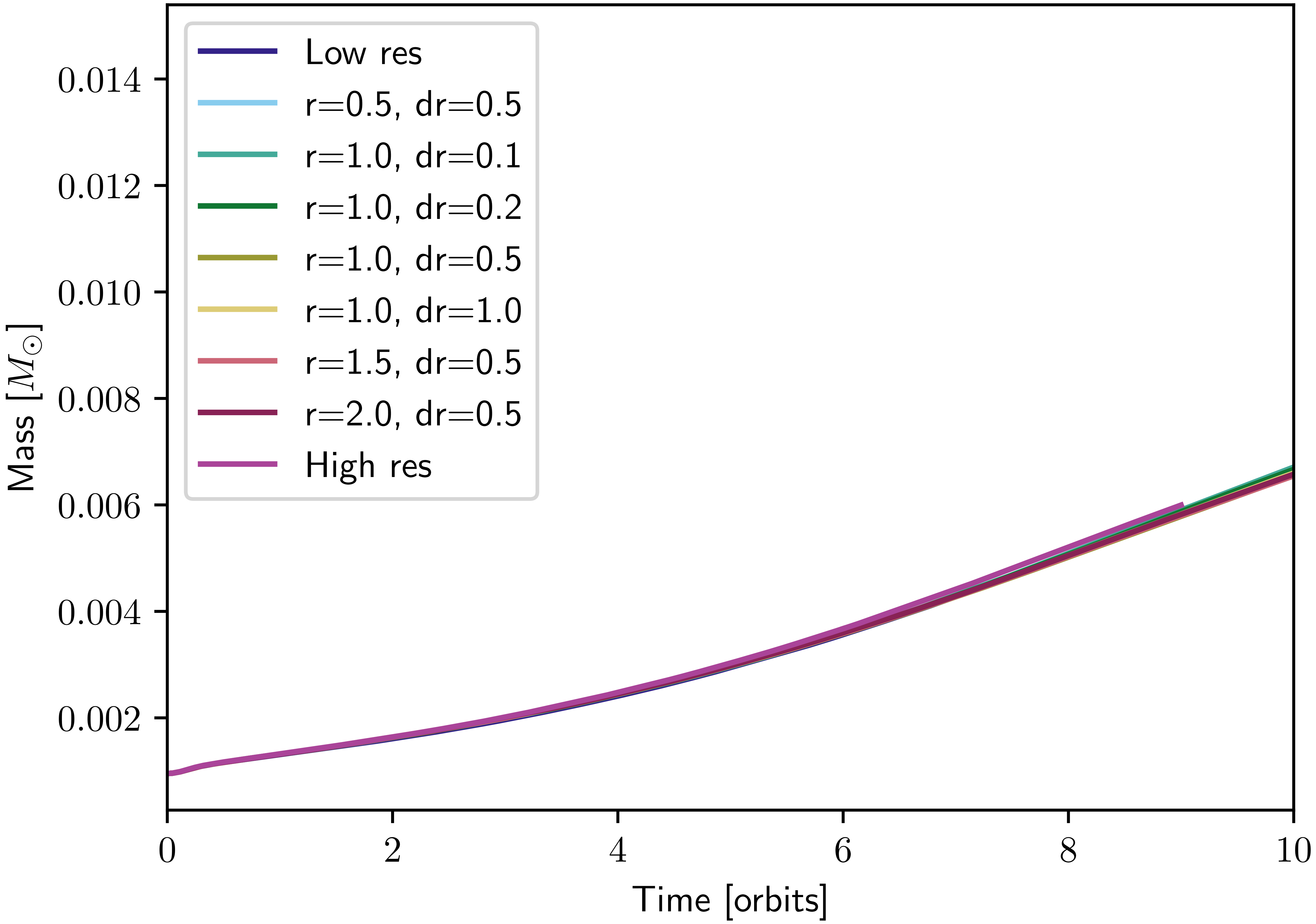


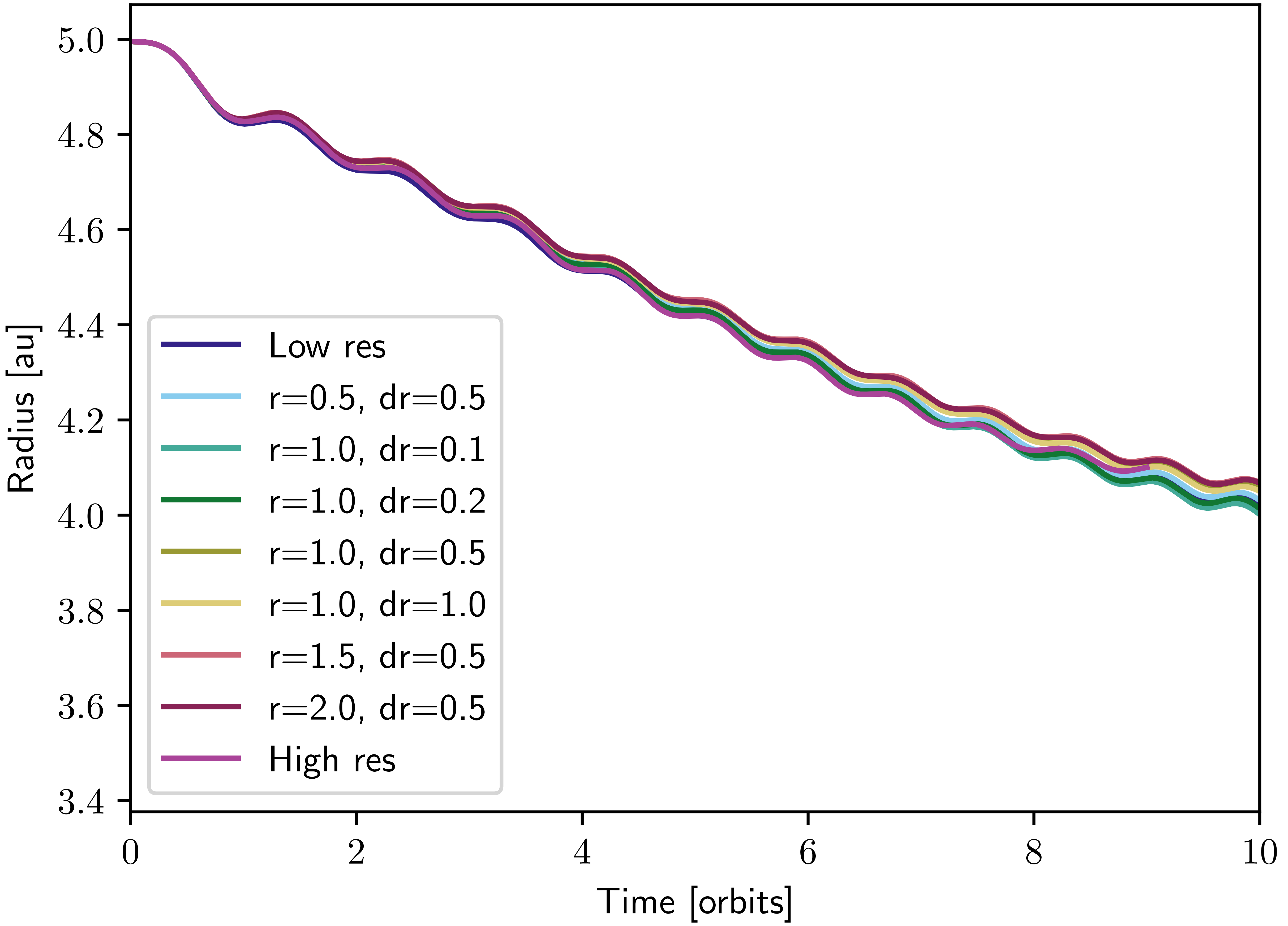


Our approach with APR

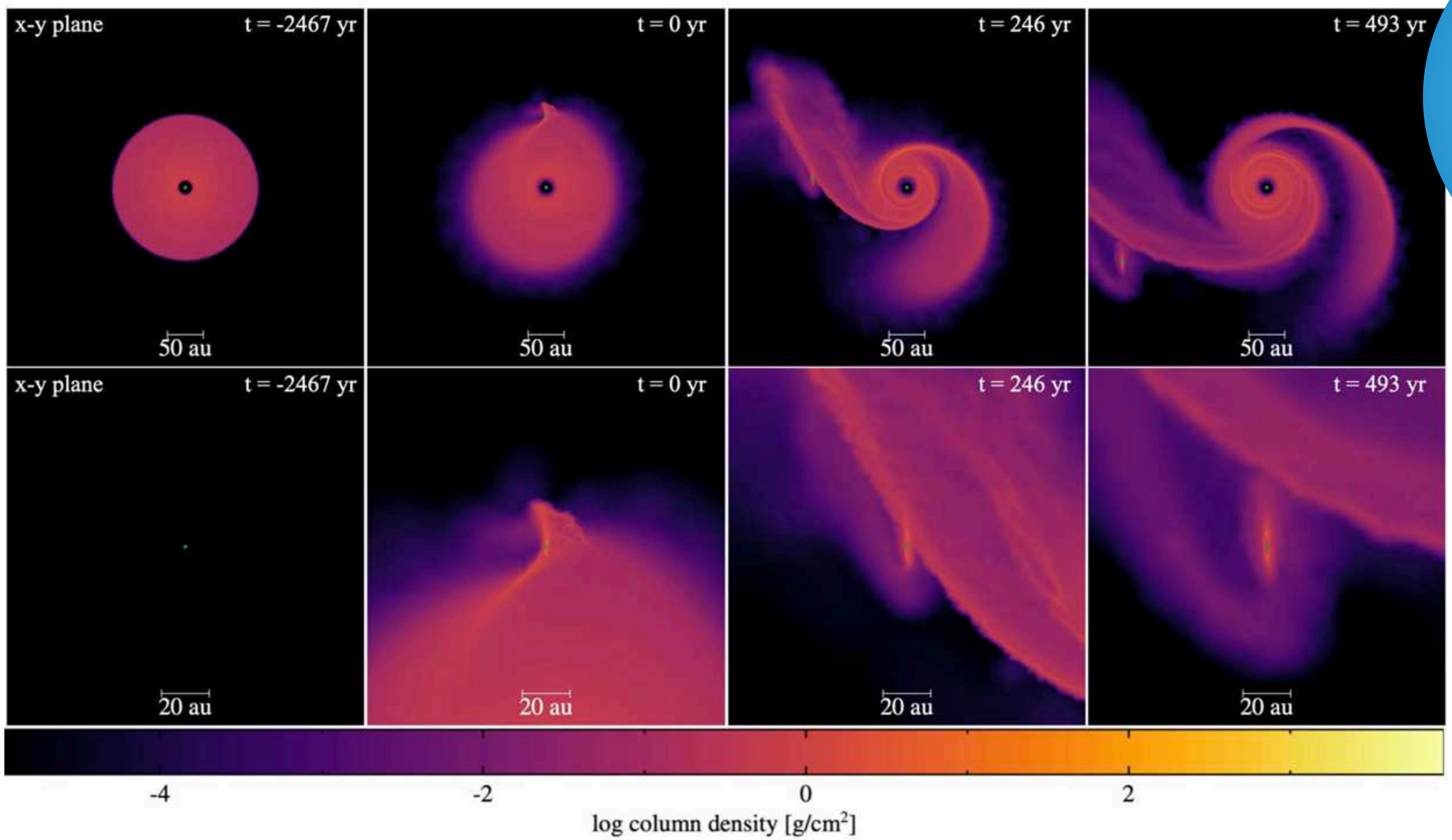
A circumplanetary disc

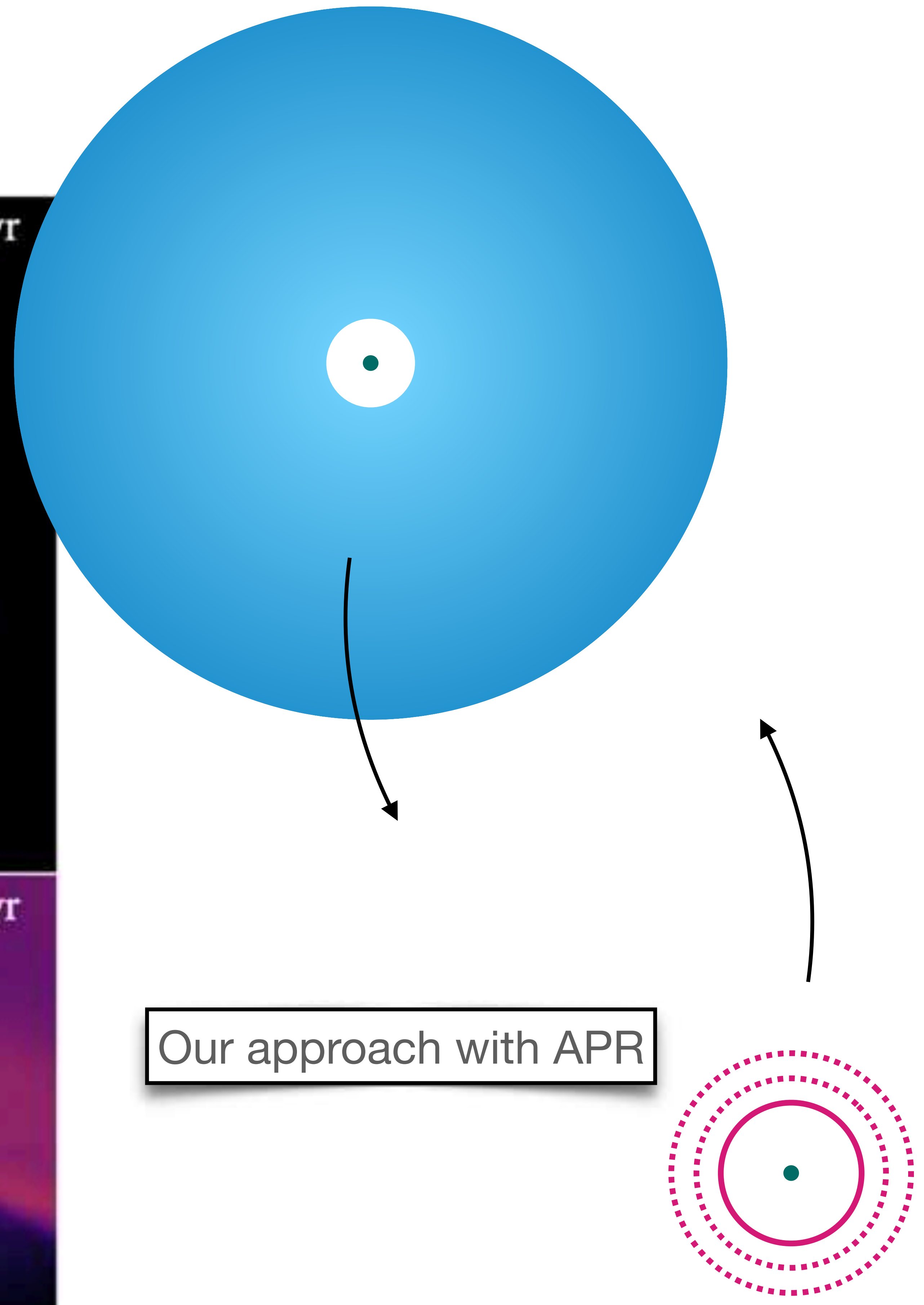
Accuracy	Speed up	File size
1.5%	2.4 - 4.4x	~30%





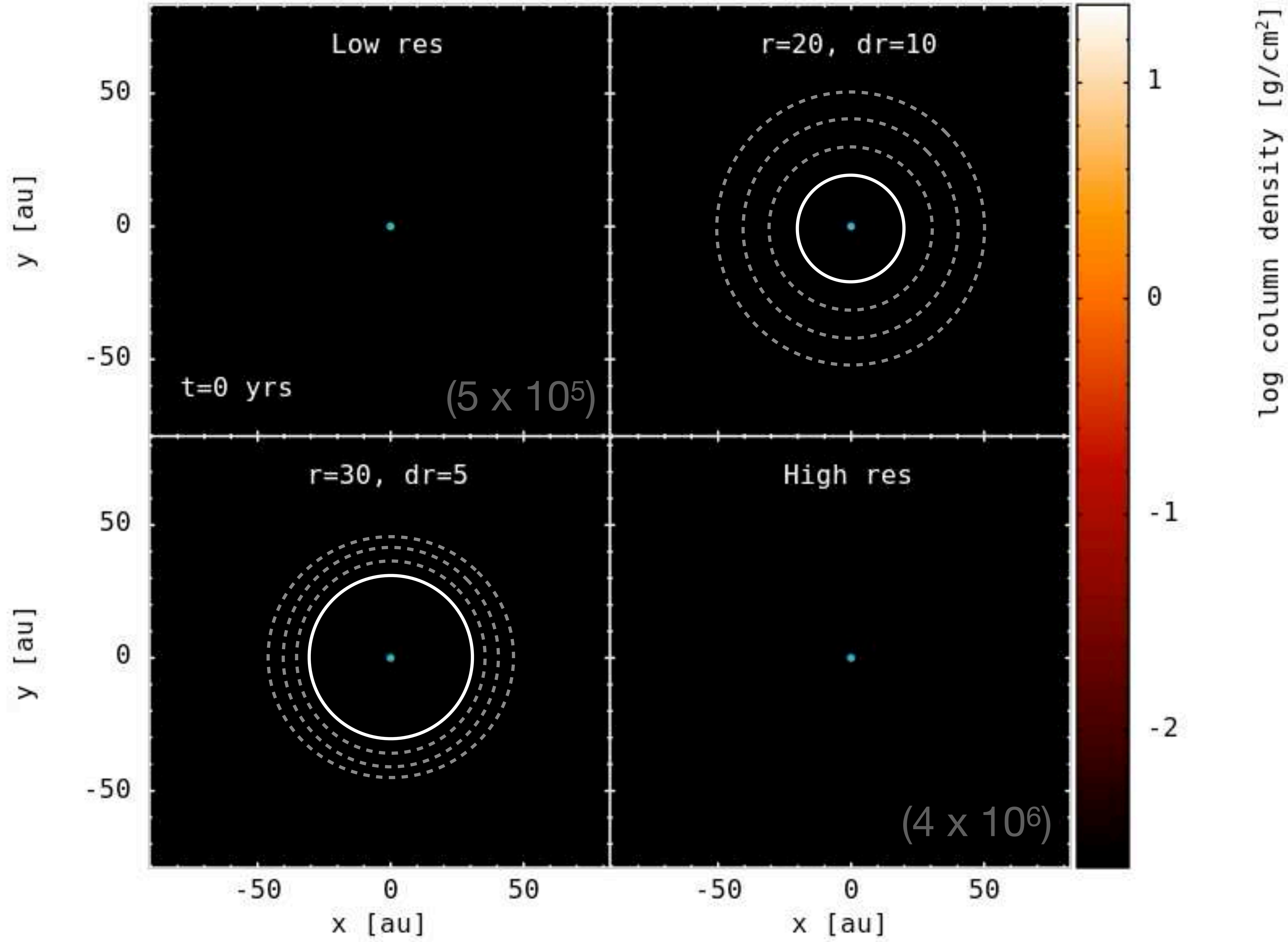
Material captured in a flyby





Smallwood et al. 2024

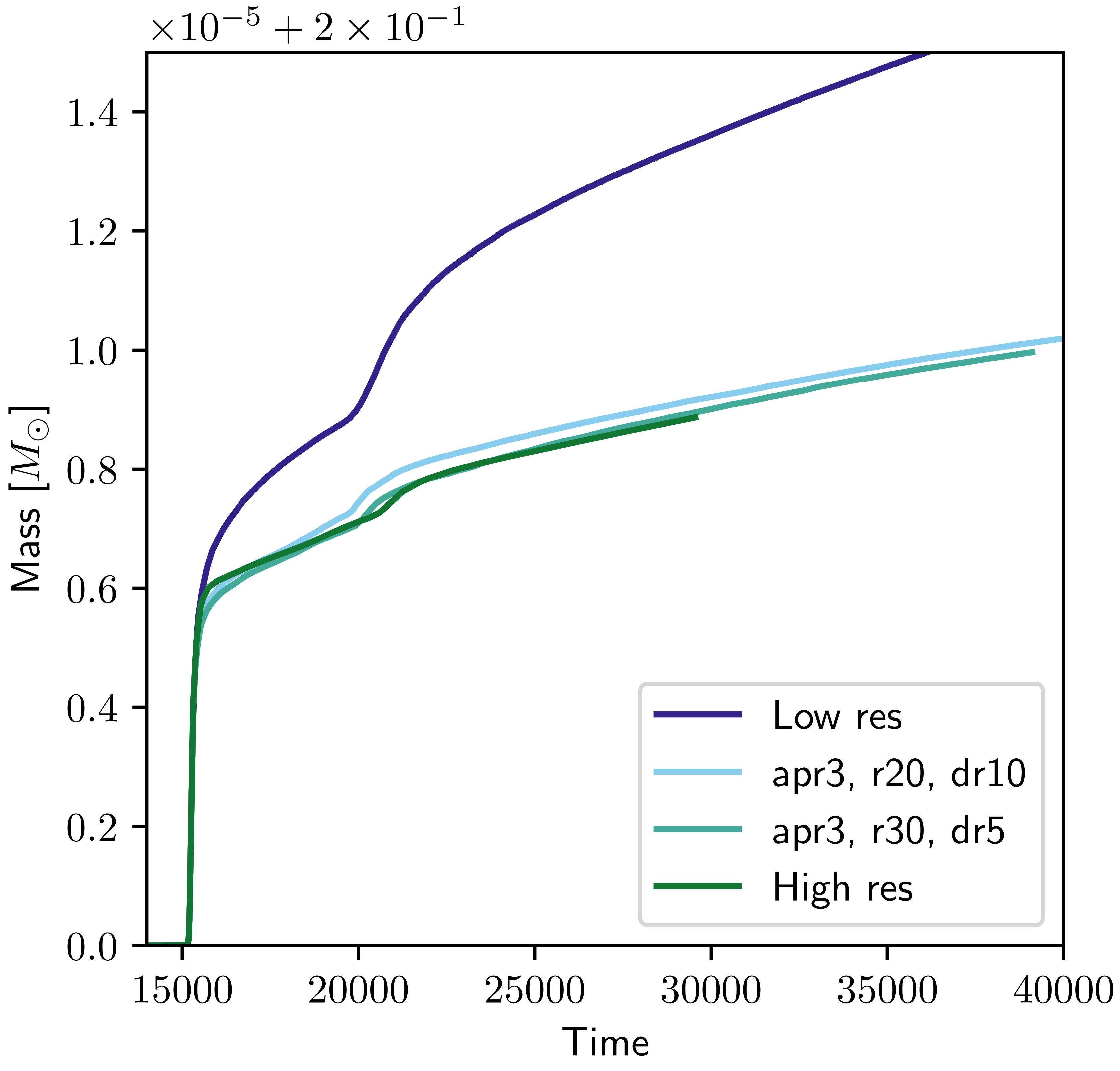
Material captured in a flyby



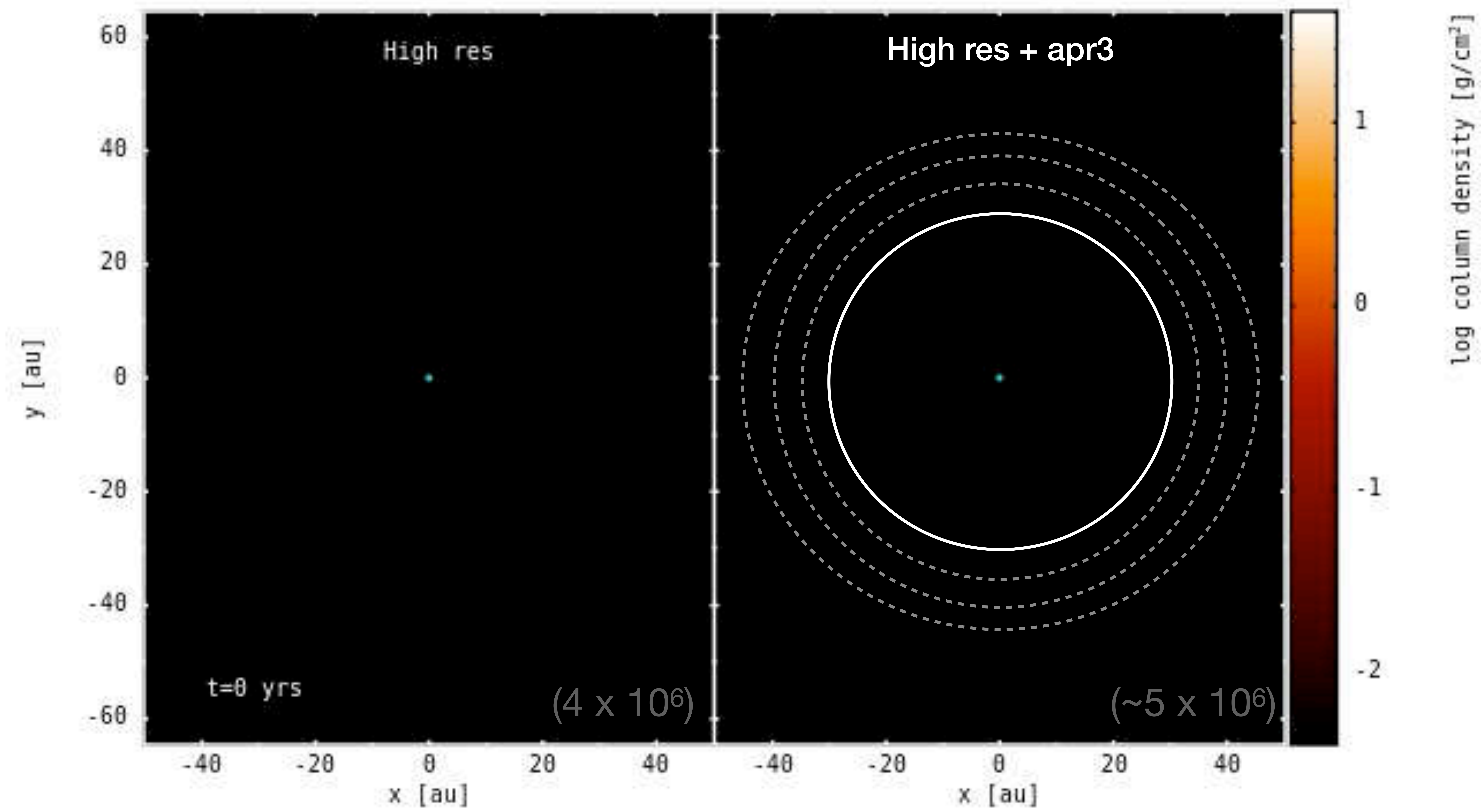
Material captured in a flyby

Accuracy	Speed up	File size
To <0.1%	~6.4x	17%

Perturber mass

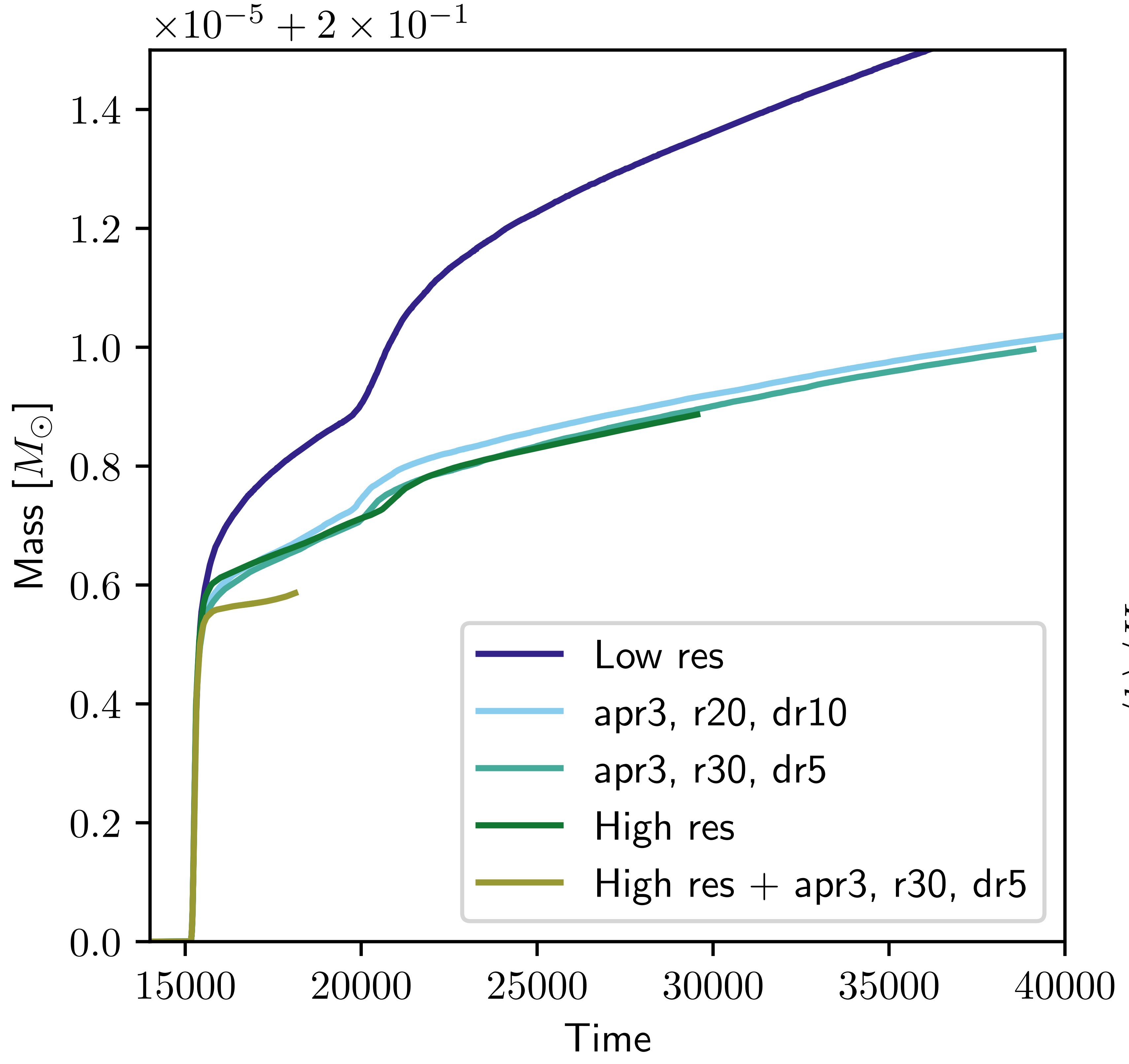


Material captured in a flyby

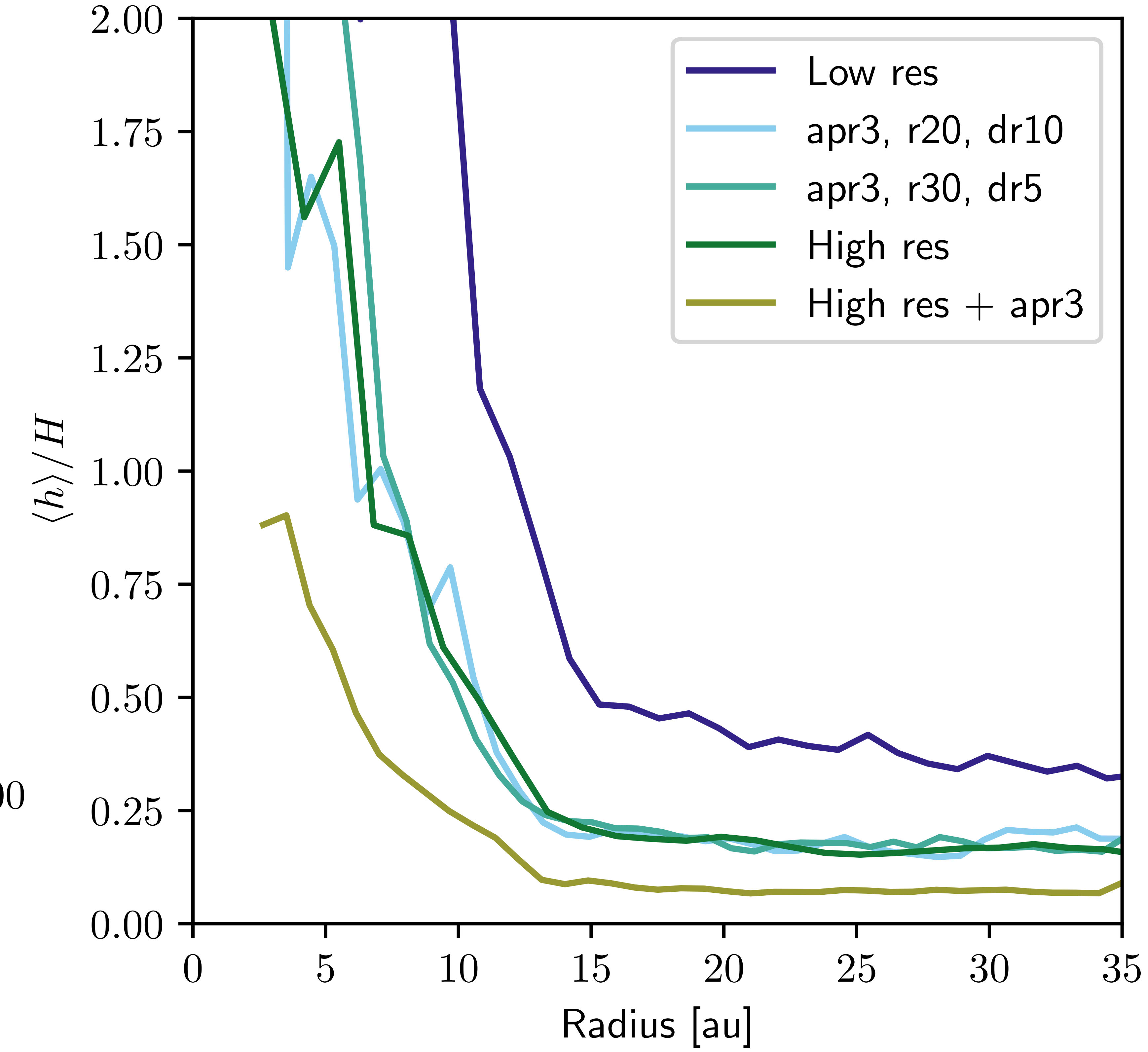


Material captured in a flyby

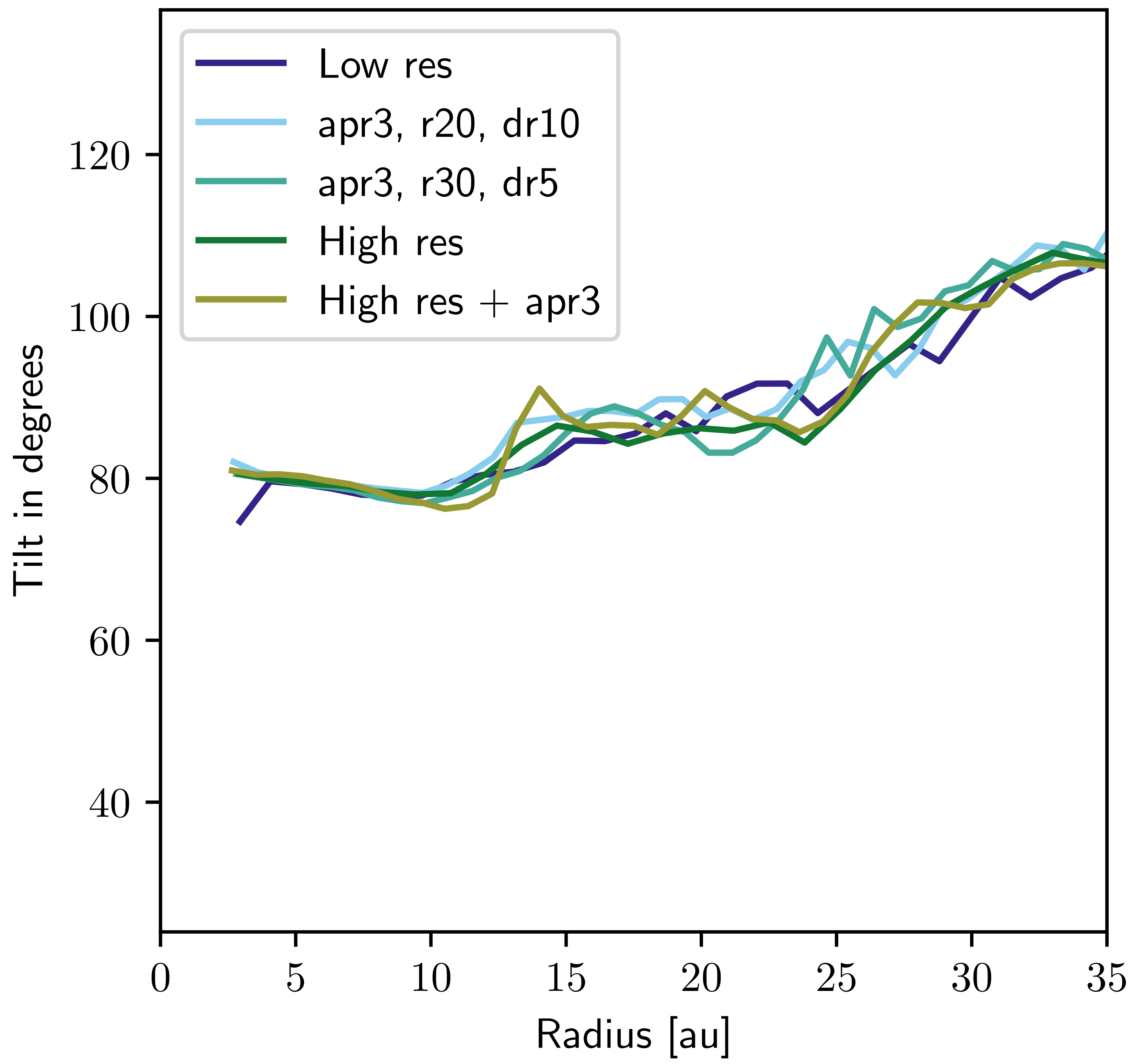
Perturber mass



Perturber disc resolution



Disc inclination



How do I use it?

1. Compile with APR=yes
2. Setup your problem like normal
3. Check the apr_region.f90 file to find your preferred region or create a new one
4. Set the apr parameters in the *.in file
5. Run

```
!--------------------------------------------------------------------------
!+
!  Setting/updating the centre of the apr region (as it may move)
!+
!--------------------------------------------------------------------------

subroutine set_apr_centre(apr_type,apr_centre)
  use part, only: xyzmh_ptmass
  integer, intent(in)  :: apr_type
  real,    intent(out) :: apr_centre(3)

  select case (apr_type)

  case(1) ! a static circle
    dynamic_apr = .false.
    apr_centre(1) = 0.0
    apr_centre(2) = 0.0
    apr_centre(3) = 0.0

  case(2) ! around sink particle 2 - e.g. a planet
    dynamic_apr = .true.
    apr_centre(1) = xyzmh_ptmass(1,2)
    apr_centre(2) = xyzmh_ptmass(2,2)
    apr_centre(3) = xyzmh_ptmass(3,2)

  case default
    dynamic_apr = .false.
    apr_centre(:) = 0.

  end select

end subroutine set_apr_centre
```

APR in Phantom is …

Fast: around 1.07 -> 6.4x faster than globally high resolution (but problem dependent).

Accurate: all tests to within <1.5%, most much better than this.

Adaptable: allows for multiple regions, derefinement and setting the size of regions dynamically.

(It will be) **compatible**: currently only compatible with individual time steps, but plans for dust, MCFOST and self-gravity are on their way.