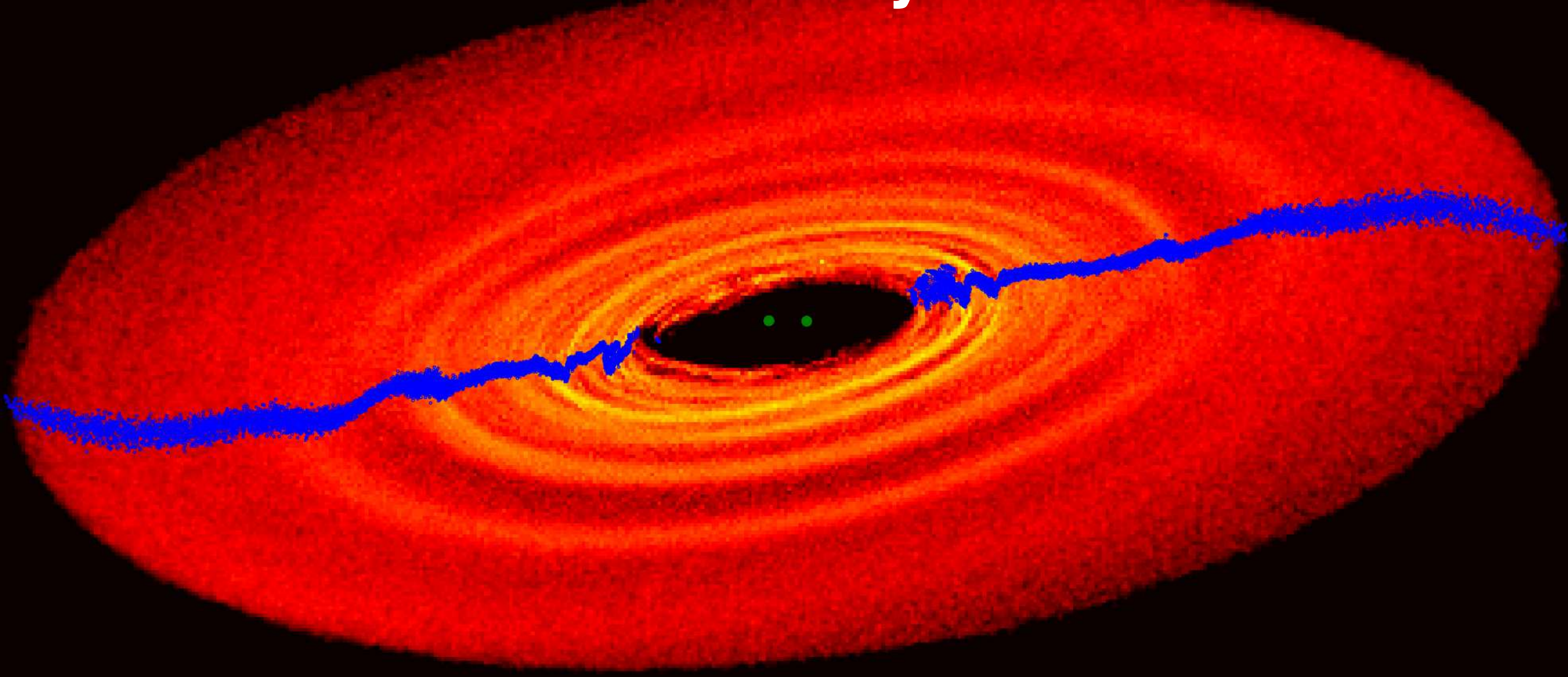
Hossam Aly

Free Precession in Undriven Warped Discs: a Cautionary Tale



Collaborators: Carolin (Lina) Kimmig, Rebecca Nealon, Callum Fairbairn, Giuseppe Lodato, Sijme-Jan Paardekooper, Ian Rabago

TU Delft

Advantages of doing warps in SPH

No preferred directions: Discs would align with the mesh in grid codes

No need to worry about boundary conditions

Excellent conservation properties

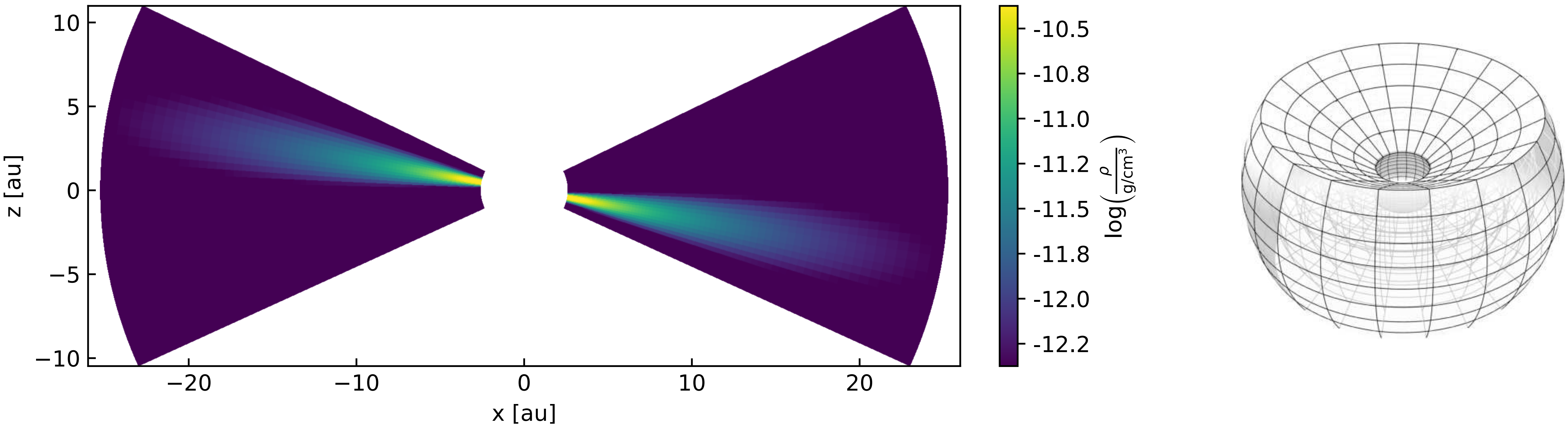
Galilean invariance: solution unaffected by adding a large mean velocity

Automatic adaption for free: Higher resolution where there's more mass

Astronomy & Astrophysics manuscript no. 3d-warp
June 6, 2024

Warped Disk Evolution in Grid-Based Simulations

C. N. Kimmig [1] and C. P. Dullemond [1]



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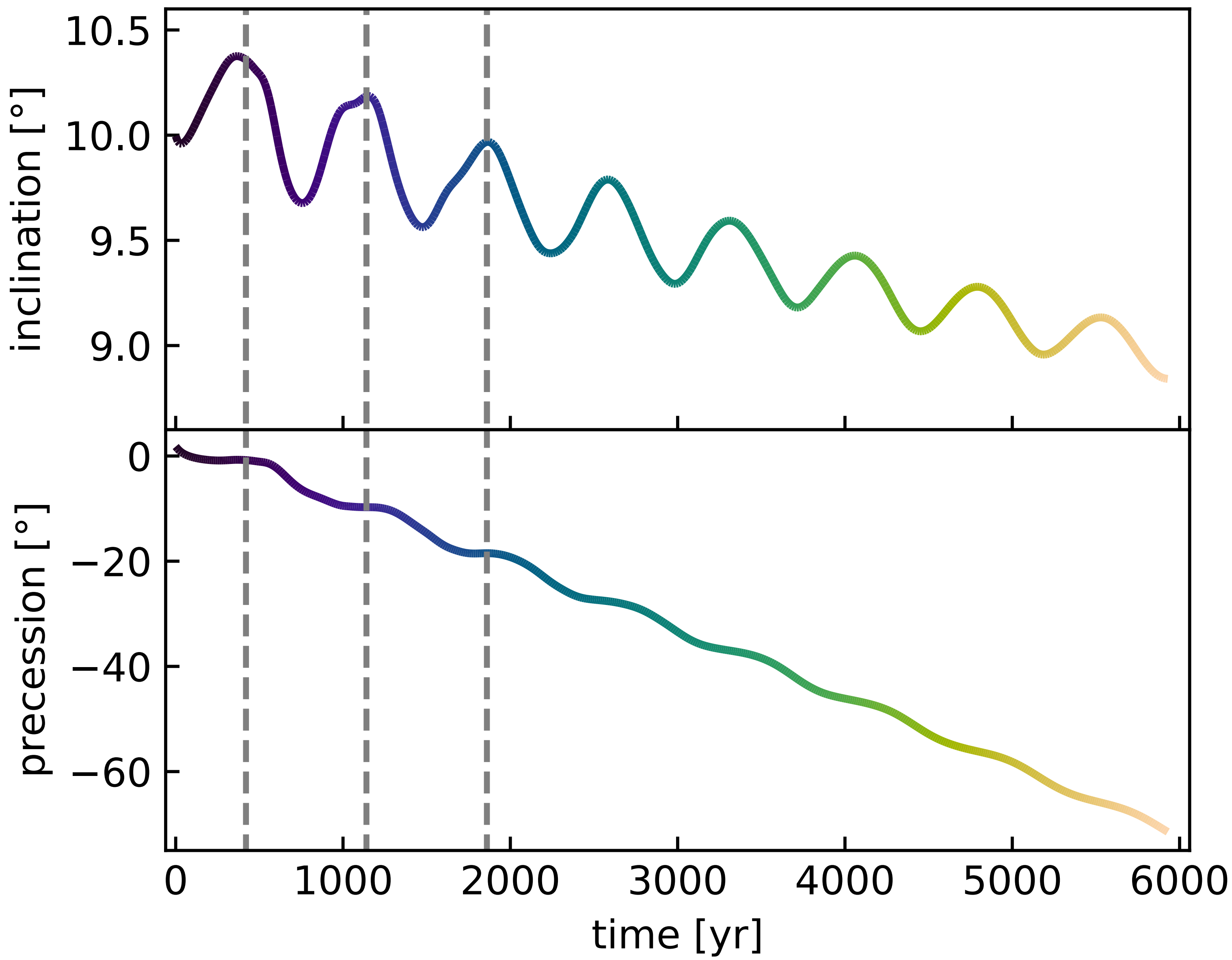

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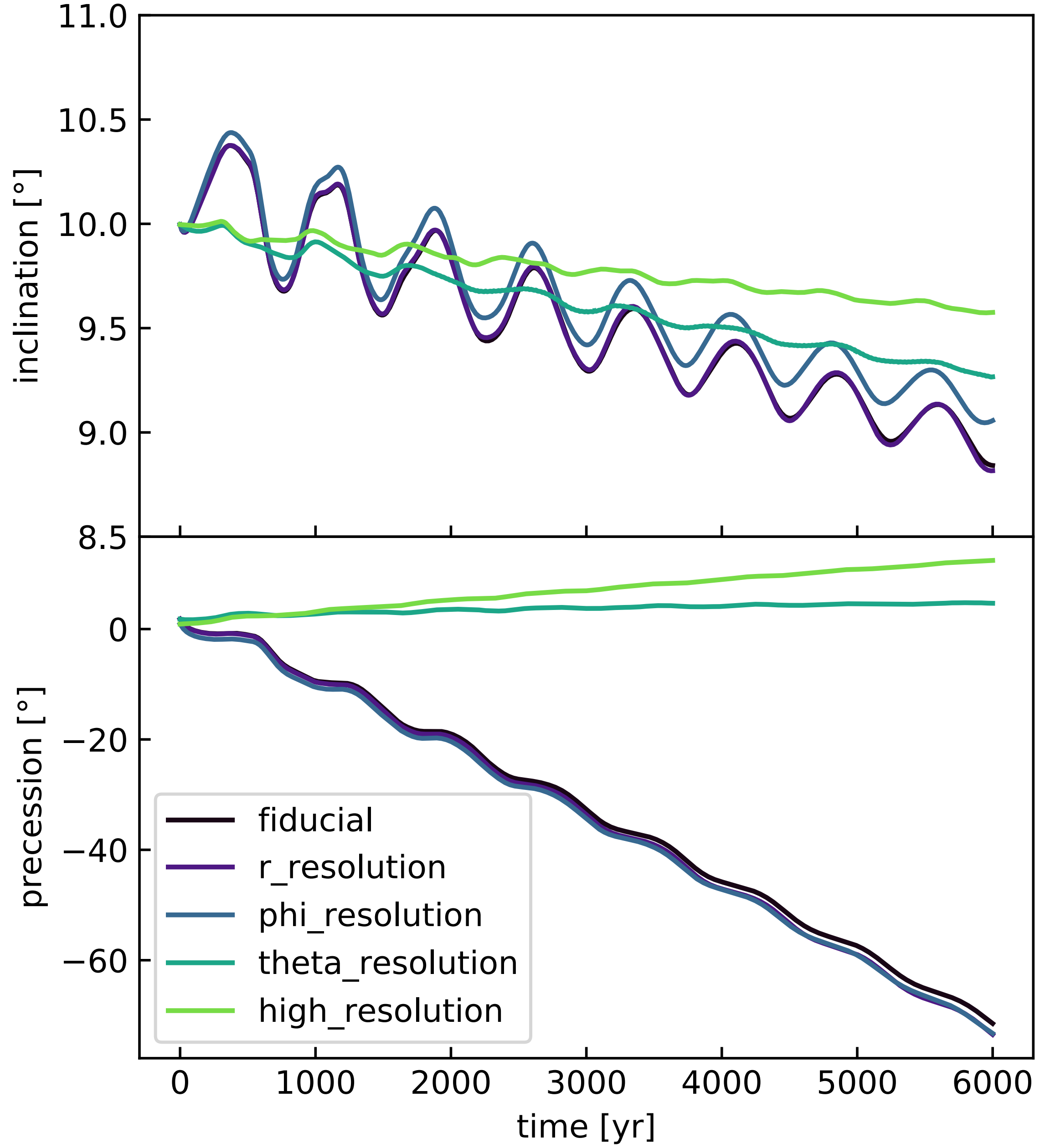
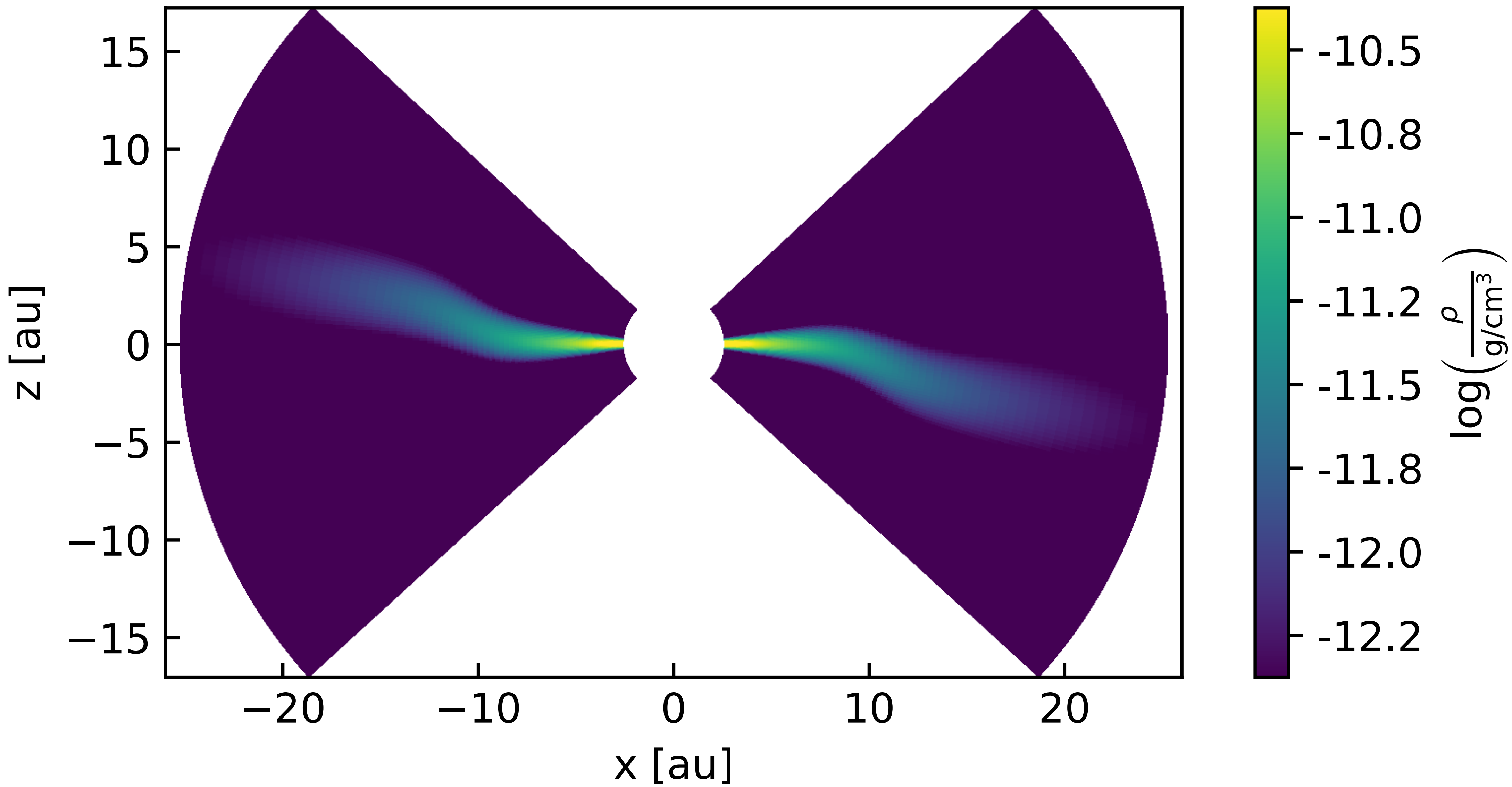
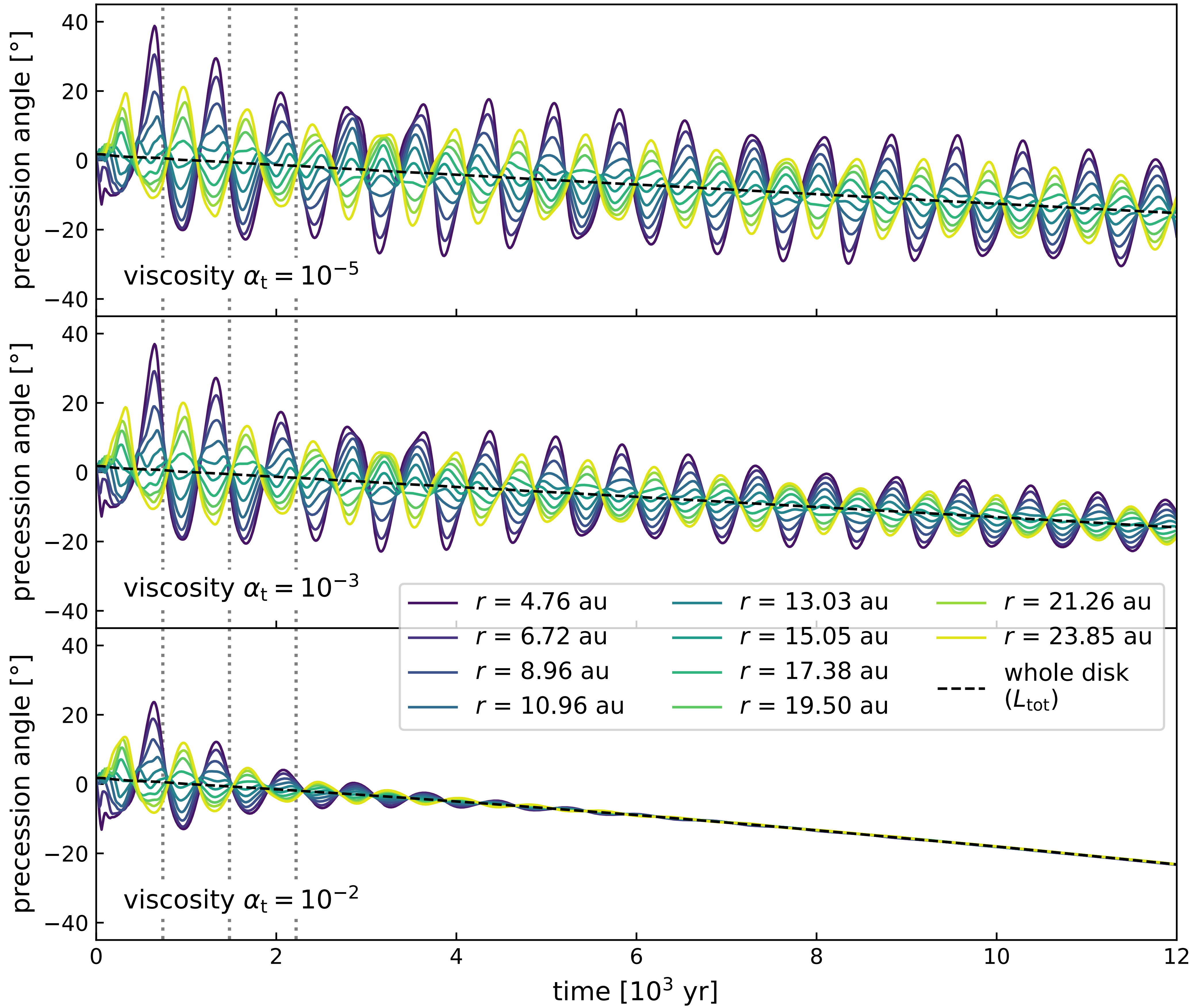




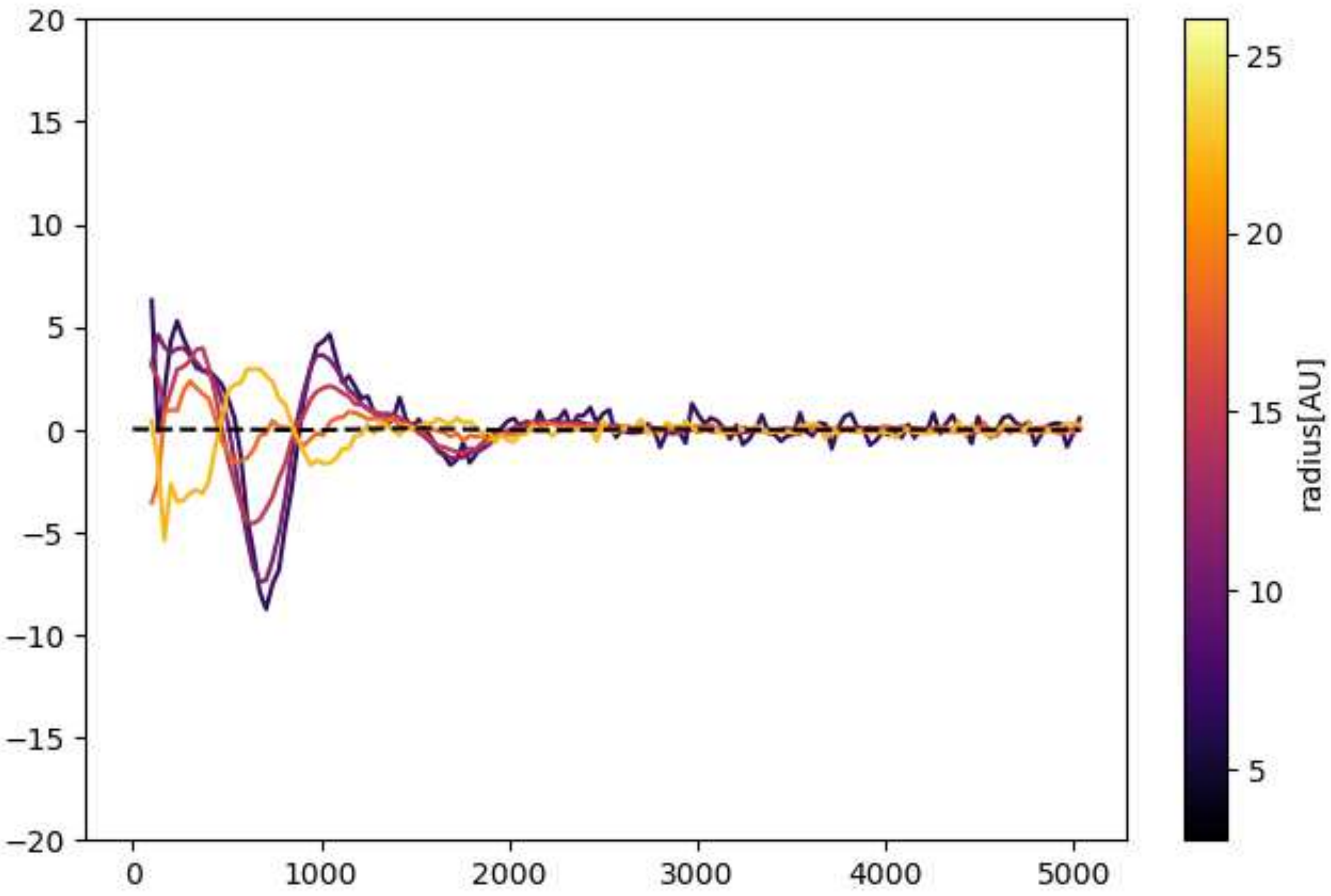
15
10
5
0
−5
−10
−15
z [au]
−20
−10
0
10
20
x [au]
-10.5
-10.8
-11.0
-11.2
-11.5
-11.8
-12.0
-12.2
$\log\left(\frac{\rho}{g/cm^3}\right)$



precession angle [°]
viscosity $\alpha_t = 10^{-5}$
viscosity $\alpha_t = 10^{-3}$
viscosity $\alpha_t = 10^{-2}$
r = 4.76 au
r = 6.72 au
r = 8.96 au
r = 10.96 au
r = 13.03 au
r = 15.05 au
r = 17.38 au
r = 19.50 au
r = 21.26 au
r = 23.85 au
whole disk (L_{tot})
time [10^3 yr]

Reproducible with SPH?

$N = 5 \times 10^5$



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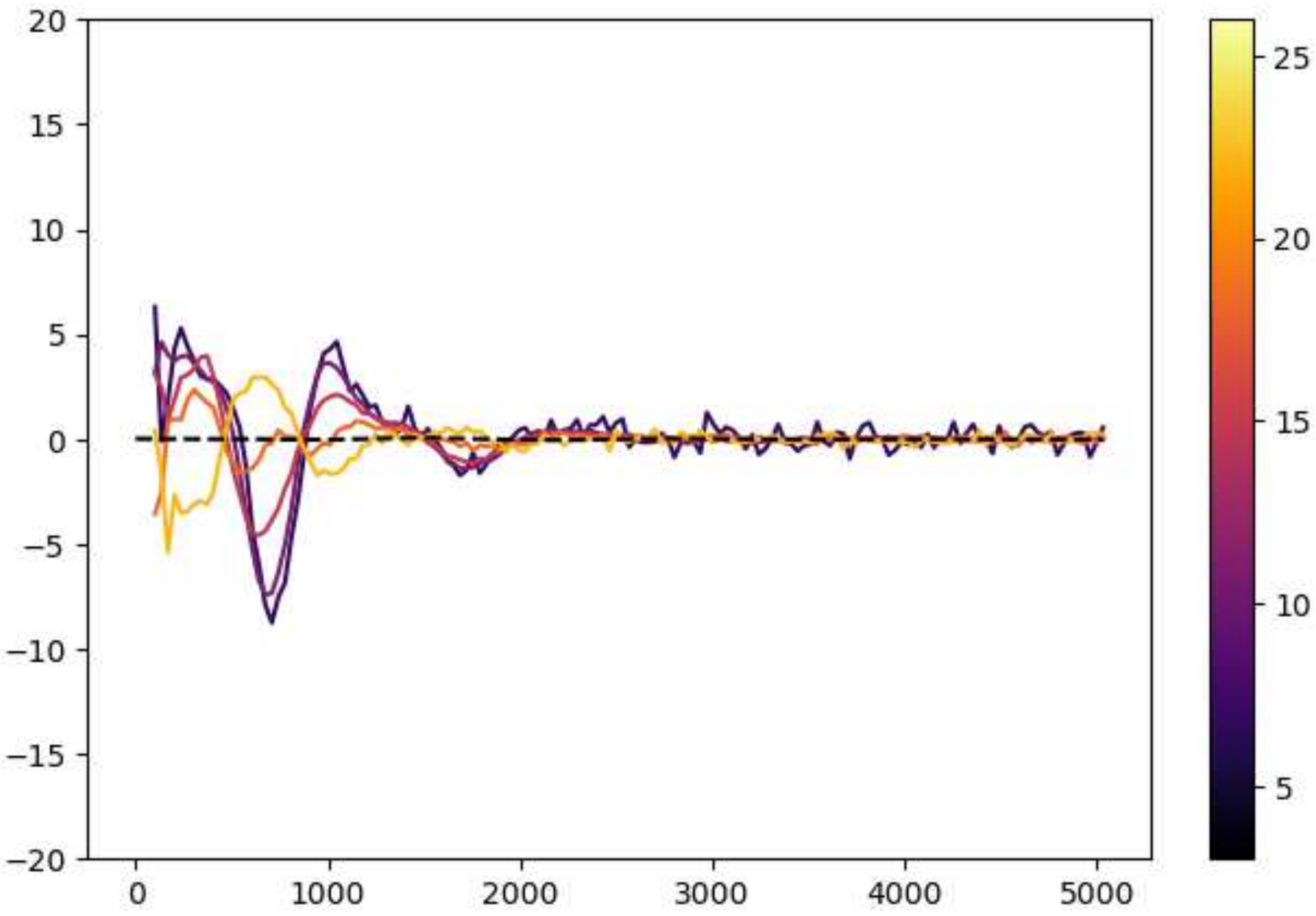
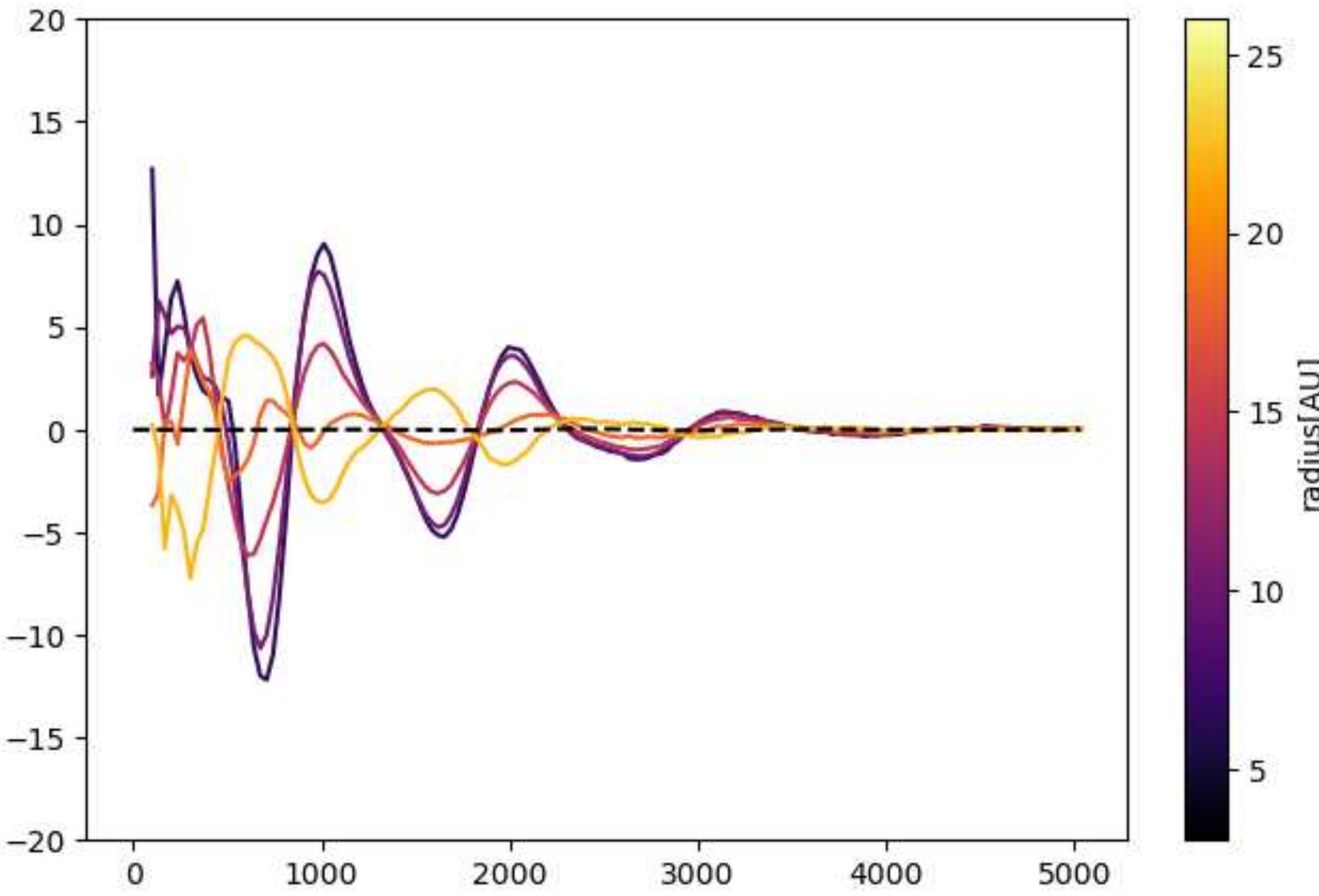


$N = 4 \times 10^6$



Reproducible with SPH?

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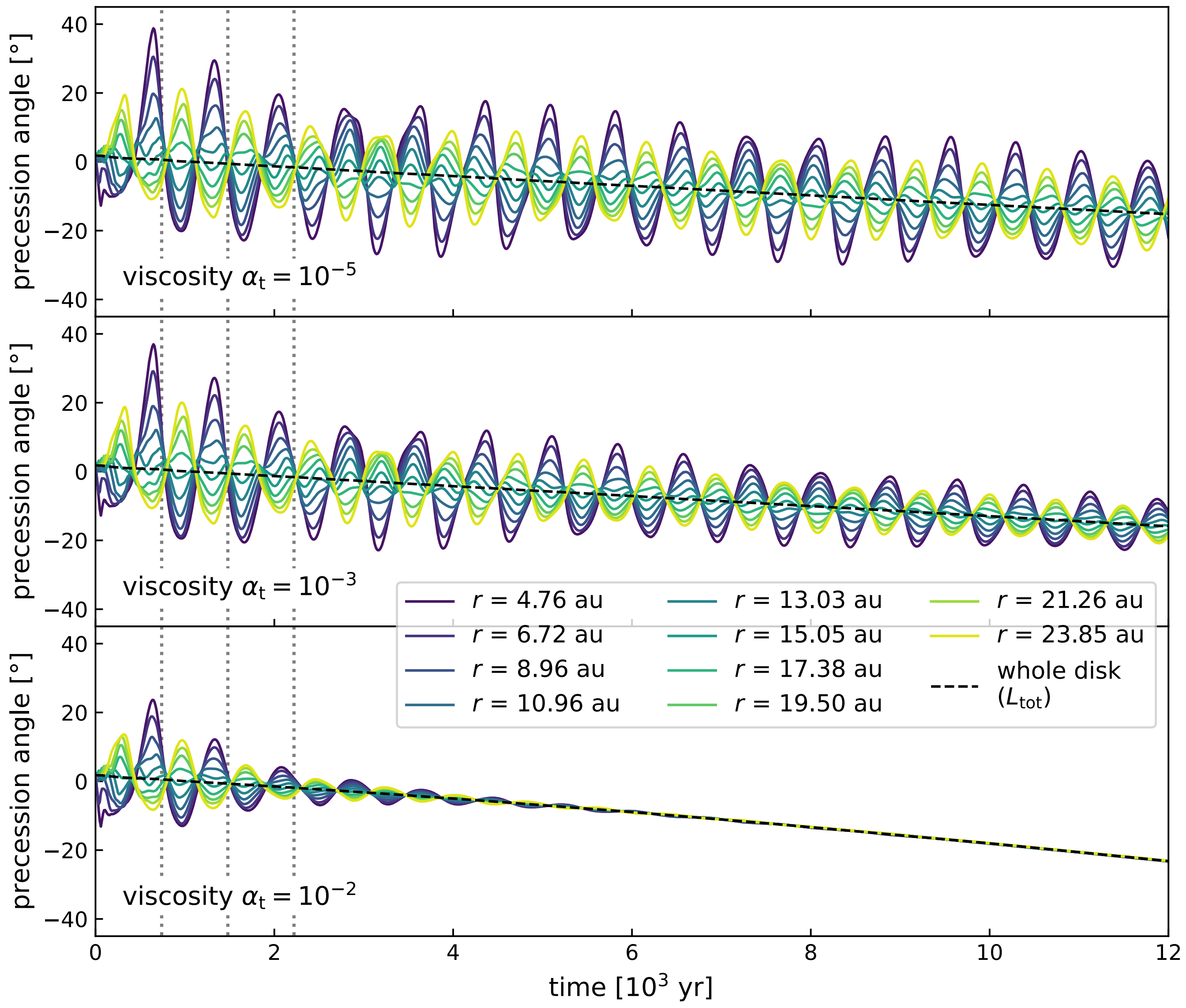

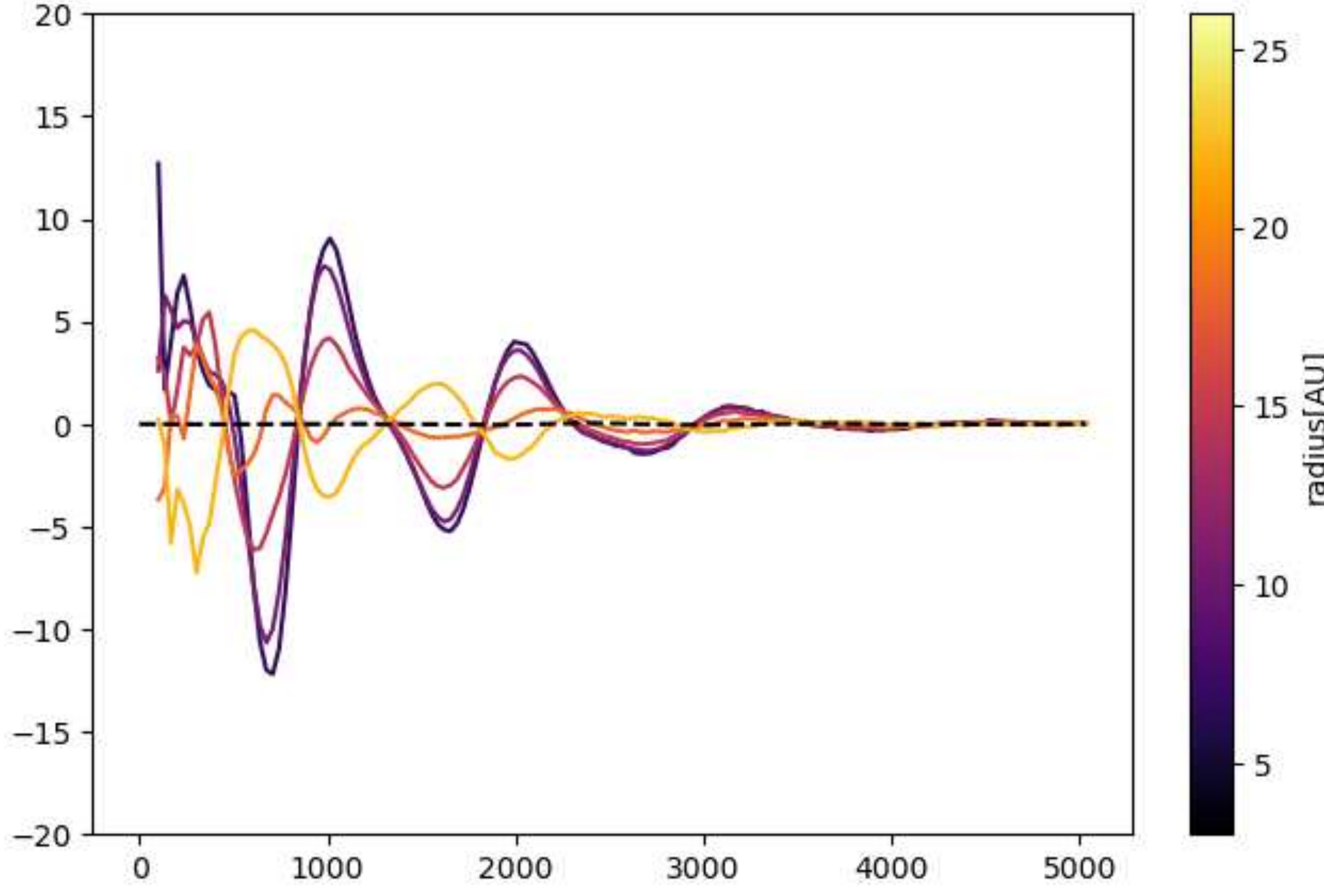

What causes the precession?

Linear theory equations: Lubow & Ogilvie 2000

$$\Sigma_{\mathrm{g}} R^2 \Omega_{\mathrm{g}} \frac{\partial \boldsymbol{l}_{\mathrm{g}}}{\partial t} = \frac{1}{R} \frac{\partial \boldsymbol{G}}{\partial R} + \boldsymbol{\Omega}_{\mathrm{p}} \times \boldsymbol{L}_{\mathrm{g}}$$

$$\frac{\partial \boldsymbol{G}}{\partial t} + \frac{\Omega_{\mathrm{g}}^2 - \kappa^2}{2\Omega_{\mathrm{g}}} \boldsymbol{l}_{\mathrm{g}} \times \boldsymbol{G} + \alpha \Omega_{\mathrm{g}} \boldsymbol{G} = \frac{\Sigma_{\mathrm{g}} H^2 R^3 \Omega_{\mathrm{g}}^3}{4} \frac{\partial \boldsymbol{l}_{\mathrm{g}}}{\partial R},$$

$$\Omega_{\mathrm{g}} = \Omega_{\mathrm{k}} \sqrt{1 - \mu}$$

Reproducible in 1D? Non-linear interaction?

Take Home Messages

- We miss things if we don’t try the same problem with different codes
- Effective viscosity floor is probably at the alpha~0.01 level