Dynamics of protoplanets embedded in gas/pebble disks

↑ and its dependence on Σ and ν parameters

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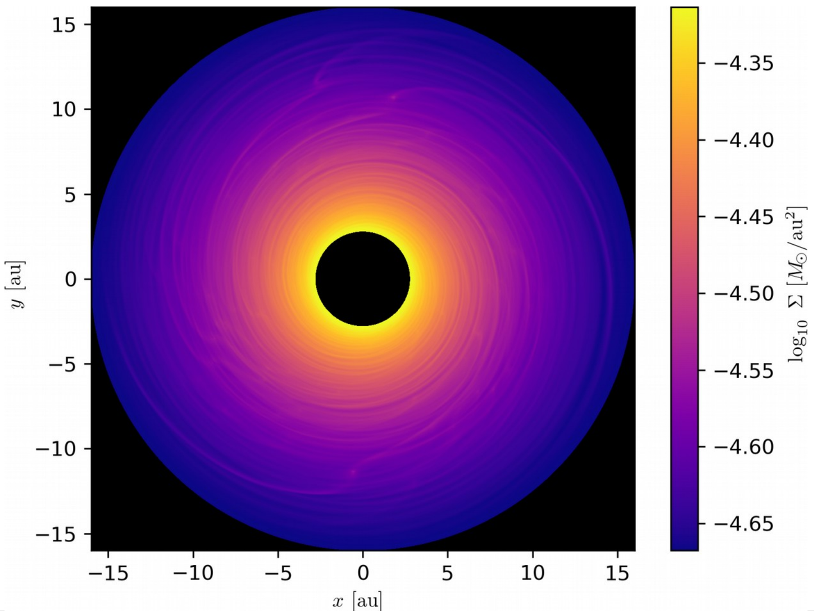
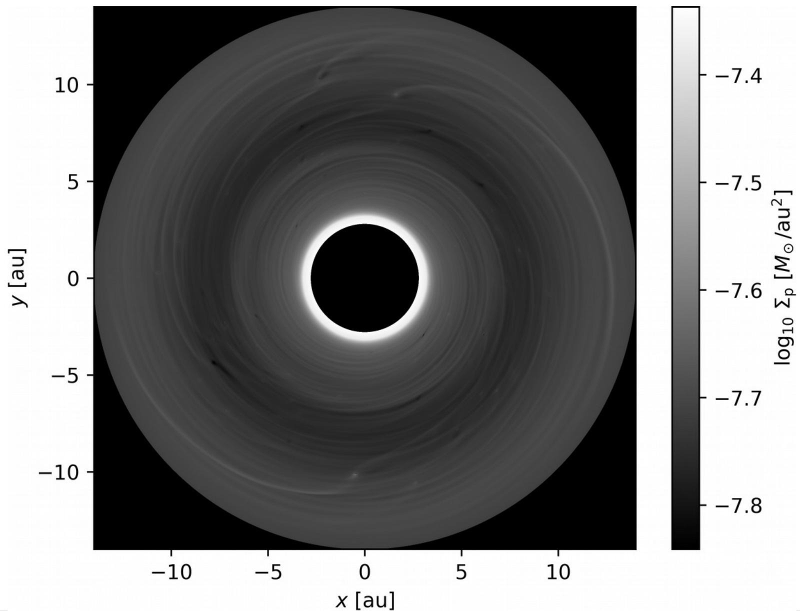




Q: What is the (fastest) mechanism of giant-planet core formation?

Masset (2000)
Rein & Spiegel (2015)
Chrenko etal. (2017)

gas

$$\frac{\partial \Sigma}{\partial t} + \overbrace{\boldsymbol{v}\cdot\nabla\Sigma}^{\text{convection}} = -\overbrace{\Sigma\nabla\cdot\boldsymbol{v}}^{\text{expansion}} - \overbrace{\left(\frac{\partial \Sigma}{\partial t}\right)_{\text{acc}}}^{\text{gas accretion}}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{v} = -\frac{1}{\Sigma}\nabla P + \overbrace{\frac{1}{\Sigma}\nabla\cdot\mathsf{T}}^{\text{bulk viscosity}} - \overbrace{\frac{\int\rho\nabla\phi\,\mathrm{d}z}{\Sigma}}^{\text{gravity}} + \overbrace{\frac{\Sigma_{\mathrm{p}}}{\Sigma}\frac{\Omega_{\mathrm{K}}}{\tau}(\boldsymbol{u}-\boldsymbol{v})}^{\text{back-reaction}}$$

$$\frac{\partial E}{\partial t} + \boldsymbol{v}\cdot\nabla E = -E\nabla\cdot\boldsymbol{v} - P\nabla\cdot\boldsymbol{v} + \overbrace{Q_{\text{visc}}}^{\text{dissip.}} + \overbrace{\frac{2\sigma T_{\text{irr}}^4}{\tau_{\text{eff}}}}^{\text{irradiation}} - \overbrace{\frac{2\sigma T^4}{\tau_{\text{eff}}}}^{\text{vertical cooling}} + \overbrace{2H\nabla\cdot\frac{16\sigma\lambda_{\text{lim}}}{\rho_0\kappa}T^3\nabla T}^{\text{radiative diffusion}} + \overbrace{\frac{\sum_i GM_i\dot{M}_i}{R_i S_{\text{cell}}}\delta(\boldsymbol{r}_i)}^{\text{accretion}}$$

$$P = \Sigma\frac{RT}{\mu} = (\gamma-1)E$$

pebbles

$$\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} + \boldsymbol{u}\cdot\nabla\Sigma_{\mathrm{p}} = -\Sigma_{\mathrm{p}}\nabla\cdot\boldsymbol{u} - \overbrace{\left(\frac{\partial \Sigma_{\mathrm{p}}}{\partial t}\right)_{\text{acc}}}^{\text{pebble accretion}}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\frac{\int\rho_{\mathrm{p}}\nabla\phi\,\mathrm{d}z}{\Sigma_{\mathrm{p}}} - \overbrace{\frac{\Omega_{\mathrm{K}}}{\tau}(\boldsymbol{u}-\boldsymbol{v})}^{\text{aerodynamic drag}}$$

protoplanets

$$\ddot{\boldsymbol{r}}_i = -\frac{GM_\star}{r_i^3}\boldsymbol{r}_i - \sum_{j\neq i}\frac{GM_j}{|\boldsymbol{r}_i-\boldsymbol{r}_j|^3}(\boldsymbol{r}_i-\boldsymbol{r}_j) - \iint\frac{G\Sigma}{|\boldsymbol{r}_i-\boldsymbol{r}_{\text{cell}}|^3}(\boldsymbol{r}_i-\boldsymbol{r}_{\text{cell}})r\mathrm{d}\theta\mathrm{d}r + \overbrace{f_z\hat{z}}^{\text{vertical damping}} \quad \text{for } \forall i$$

CaseIII_nominal ← from Chrenko etal. (2017)

- semimajor axis a vs time t
- convergence zone @ 10 au
- oscillations of r (a.k.a. e)

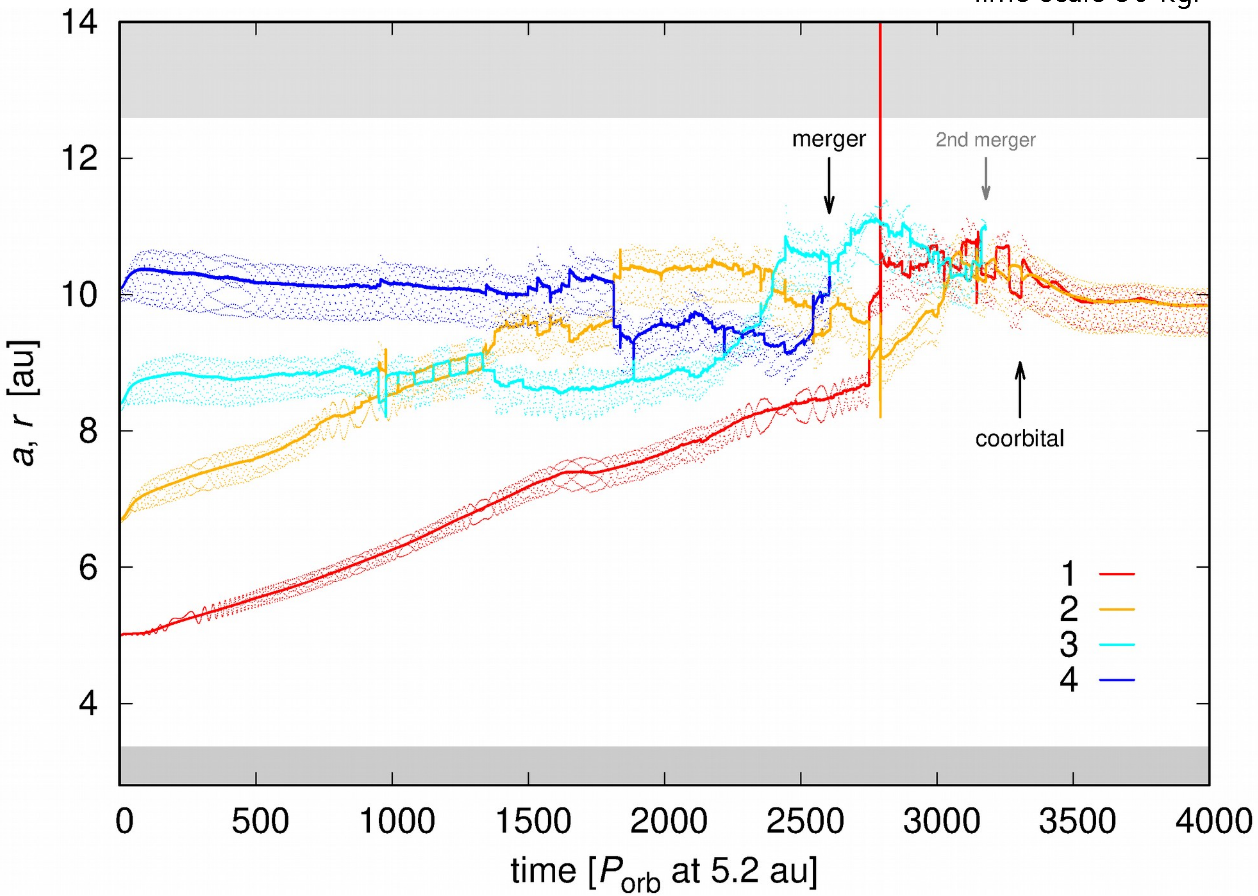
  ← **hot-trail** effect

  → no resonant captures
- 2 mergers, 1 coorbital

- BUT see details...

surface density Σ_0 = 750 g/cm^2, slope -0.5,
kinematic viscosity $\nu = 10^{-5}$ [c.u.],
embryo mass M_{em} = 3 M_E,
pebble flux $dM_p/dt = 10^{-4}$ M_E/yr, ...

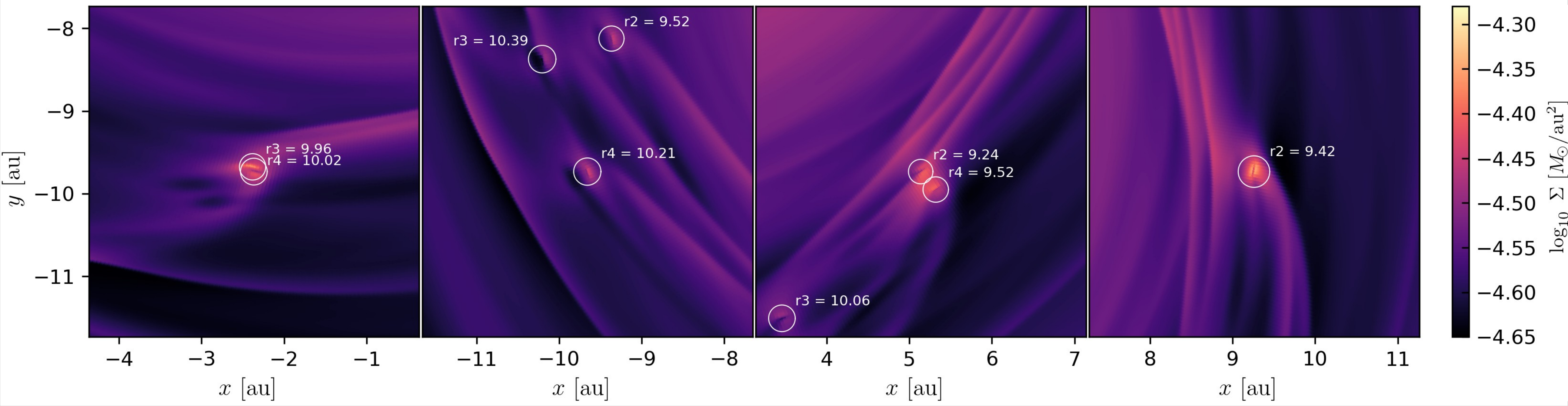
time scale 50 kyr



Detail: Merger

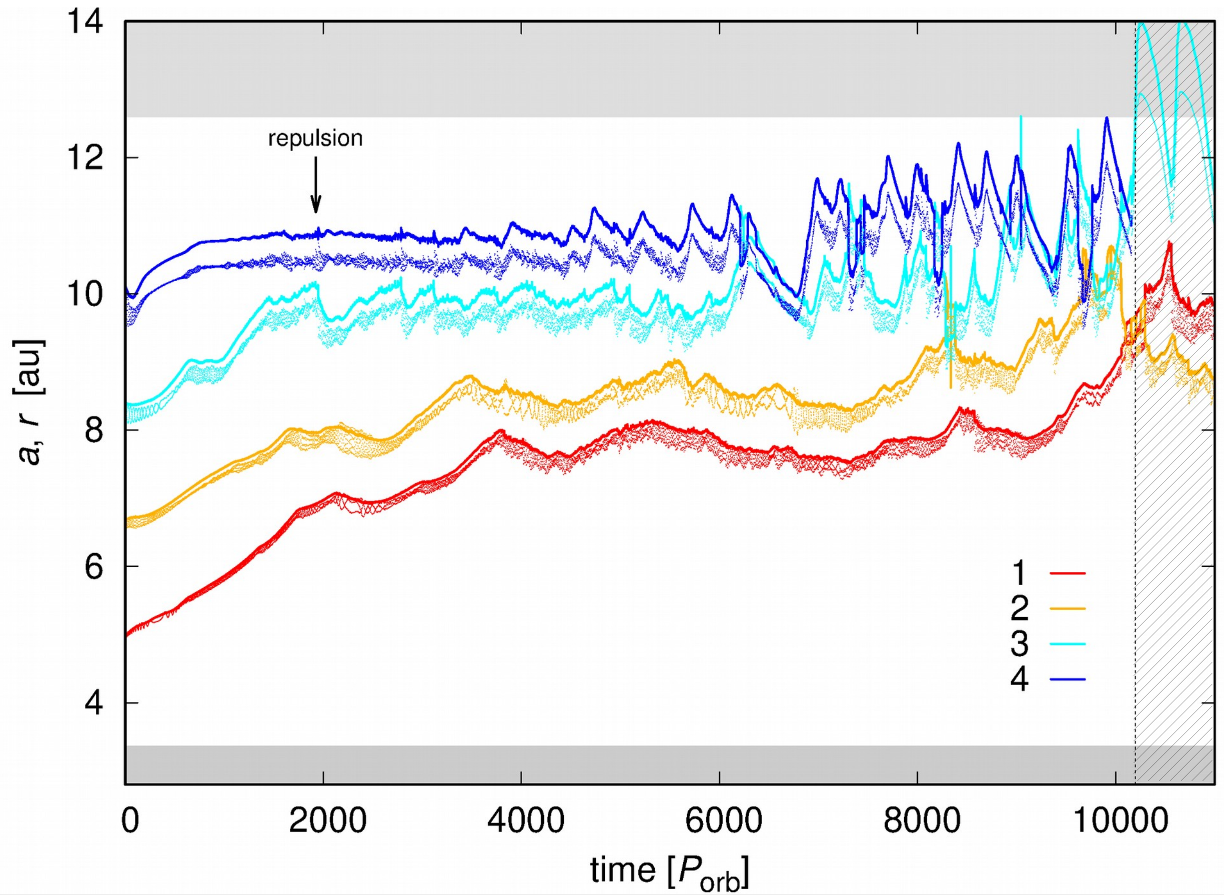
- restarted from sparse output → detailed output (1/20 P_{orb})
- **3-body encounters** are needed for mergers! ← small statistics

deep encounter... 3 protoplanets... different encounter... merger



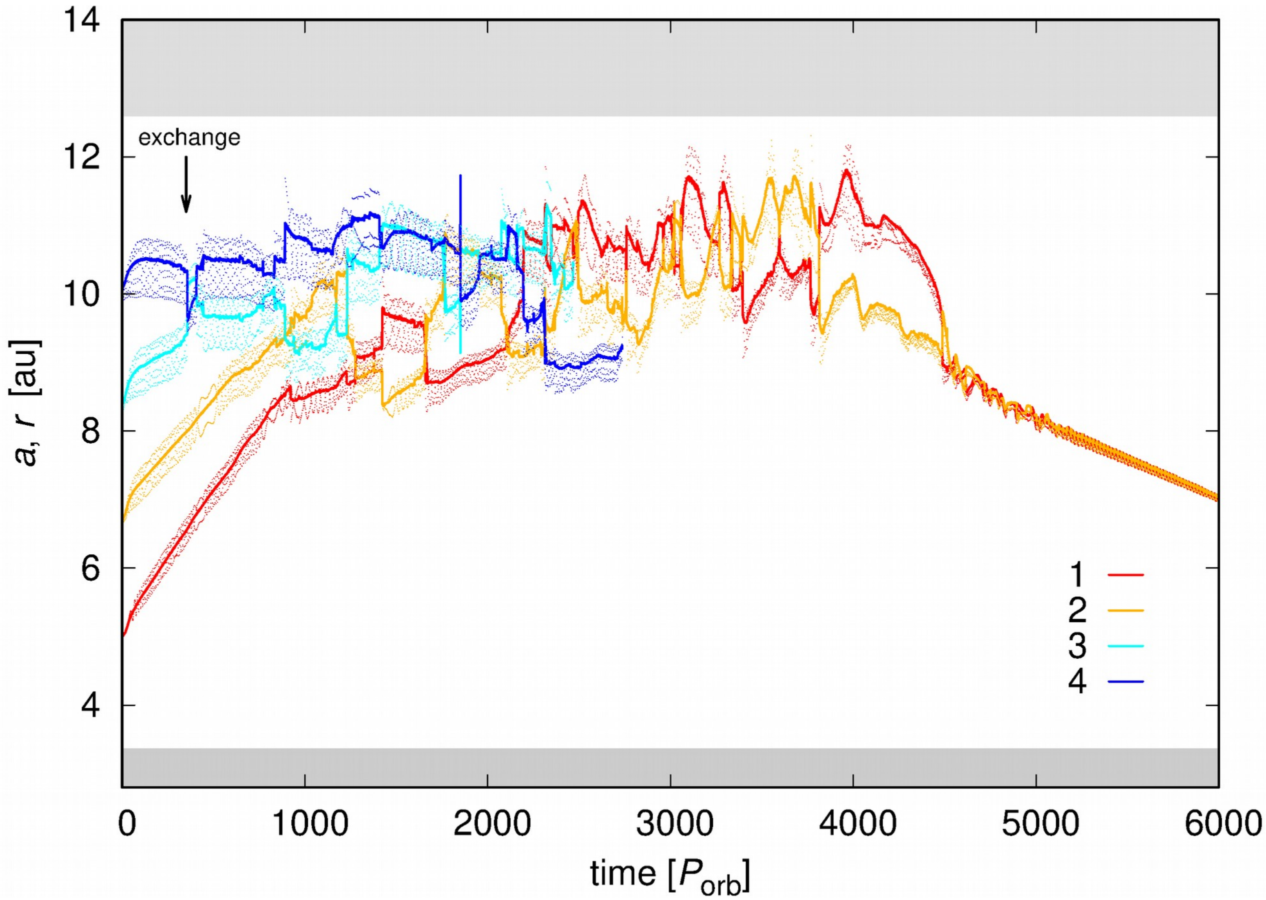
Sigma_3times

- i.e. Σ_0 = 2250 g/cm^2
- substantial interior disk mass → *a* offset from *r*
- many '**repulsions**' (3 and 4)
- HD also determines encounter geometry



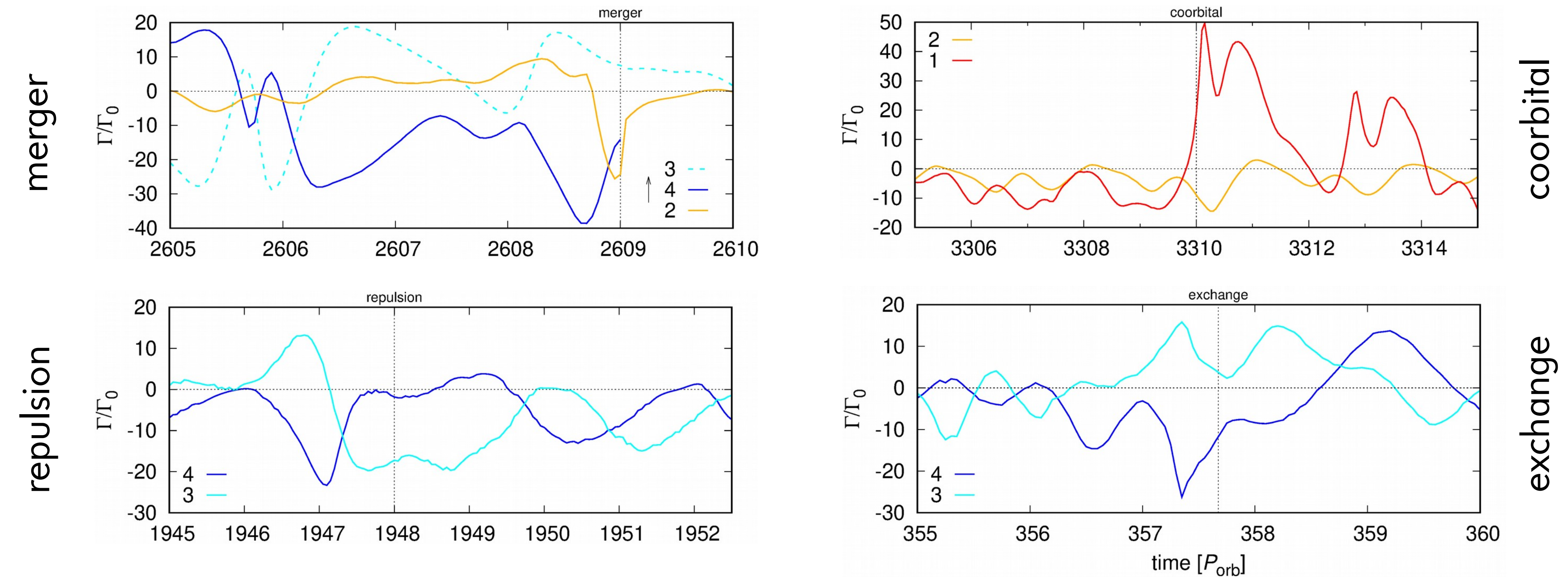
viscosity_1e-6

- i.e. $\nu = 10^{-6}$ [c.u.]
- massive coorbital formation & its **stabilisation**
- too-many-coorbitals problem...
- **pebble isolation** beyond
  → no heating
  → inward migration



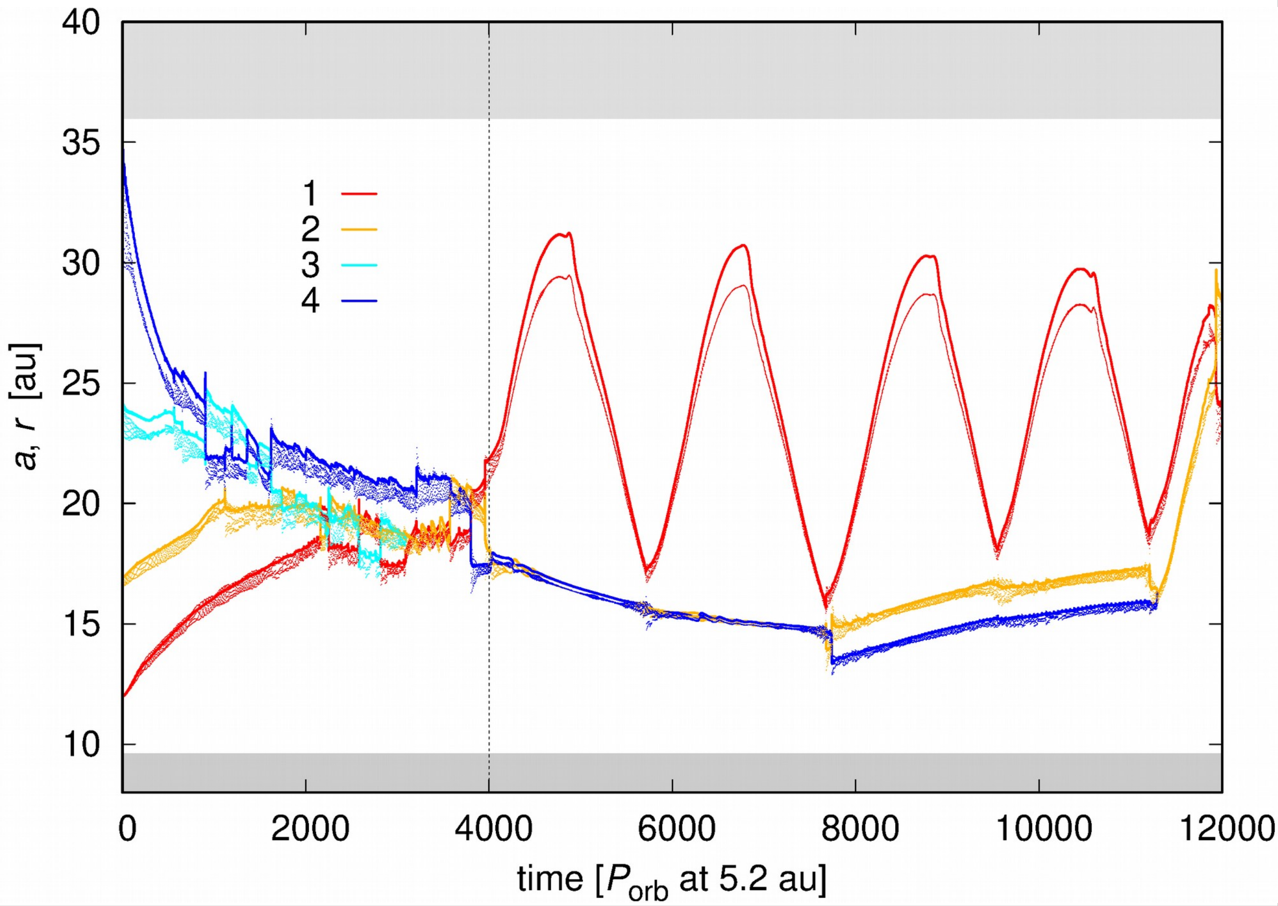
Torque details of 4 events

- normalized disk torque Γ/Γ_0 vs time t, with $\Gamma_0 = (q/h)^2 \Sigma r^4 \Omega^2$
- encounters perturbed by torques, which also determine (next) geometry



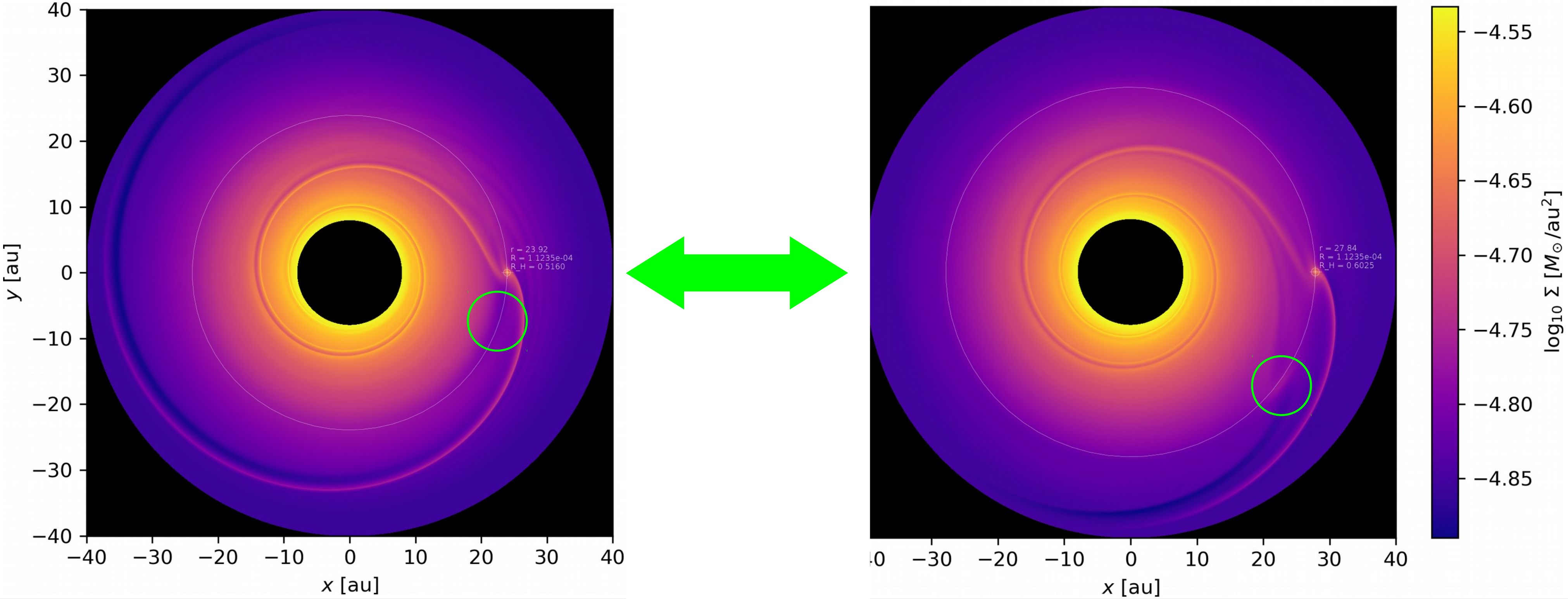
totmass_20ME

- i.e. $M_{em} = 5\ M_E$
- convergence zone @ 20 au
- 3-body interactions again
- coorbital + embryo 1
- initial 'kick' → **dynamical torque** drives it to 30 au
- returns back to 20 au & interacts with coorbital
- a solution of too-many-coorbitals problem?



Dynamical tadpole torque

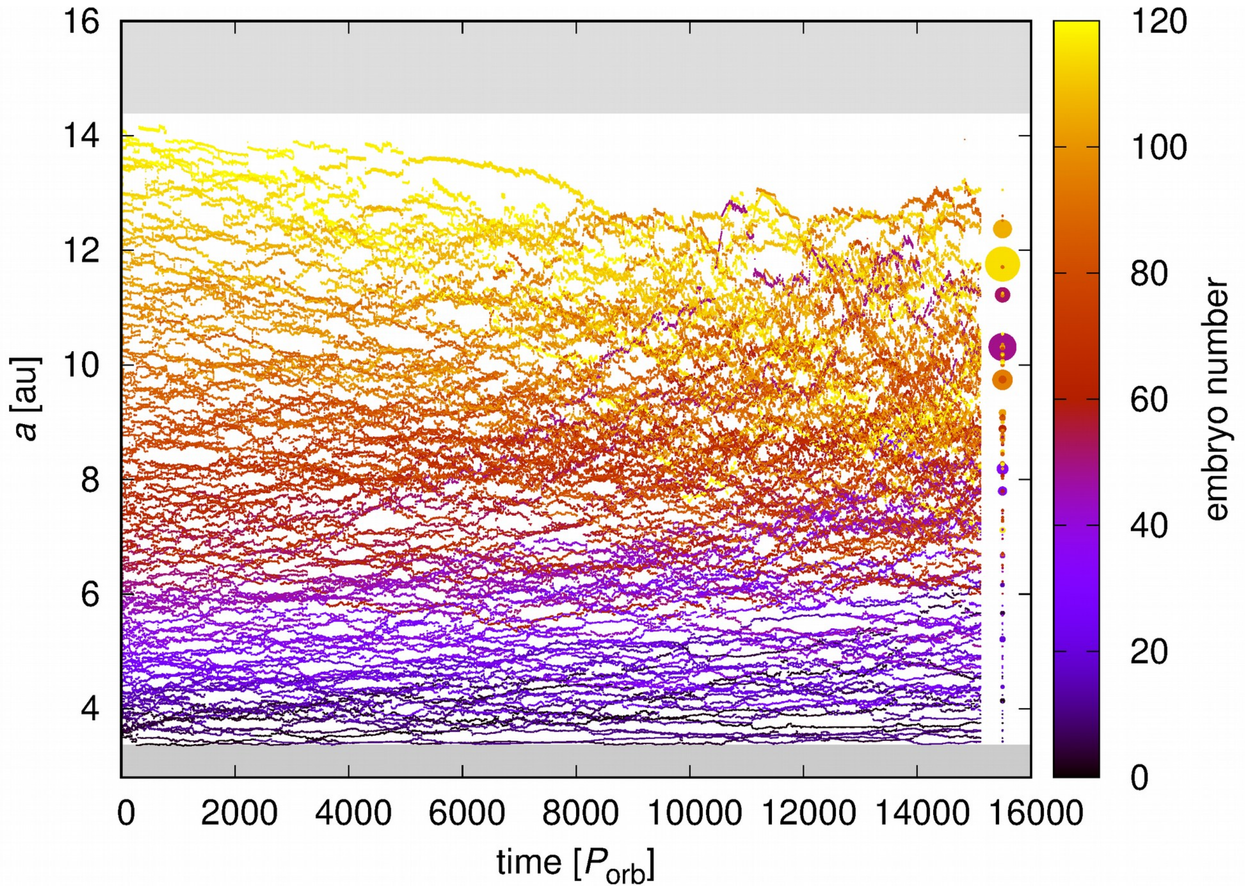
- a vortex behind the protoplanet (Pierens 2015) & its decay → **migration cycles**



embryos_0.1ME_120

- i.e. Mars-size embryos
- robust runaway growth:
  (i) merging, (ii) Hill regime
  of accretion, $\mathrm{d}M/\mathrm{d}t \sim M_{\mathrm{em}}$,
  (iii) pebble filtering,
  (iv) lower inclinations
  of massive embryos
  (Levison etal. 2015)
- hot-trail → encounters
  → random walk

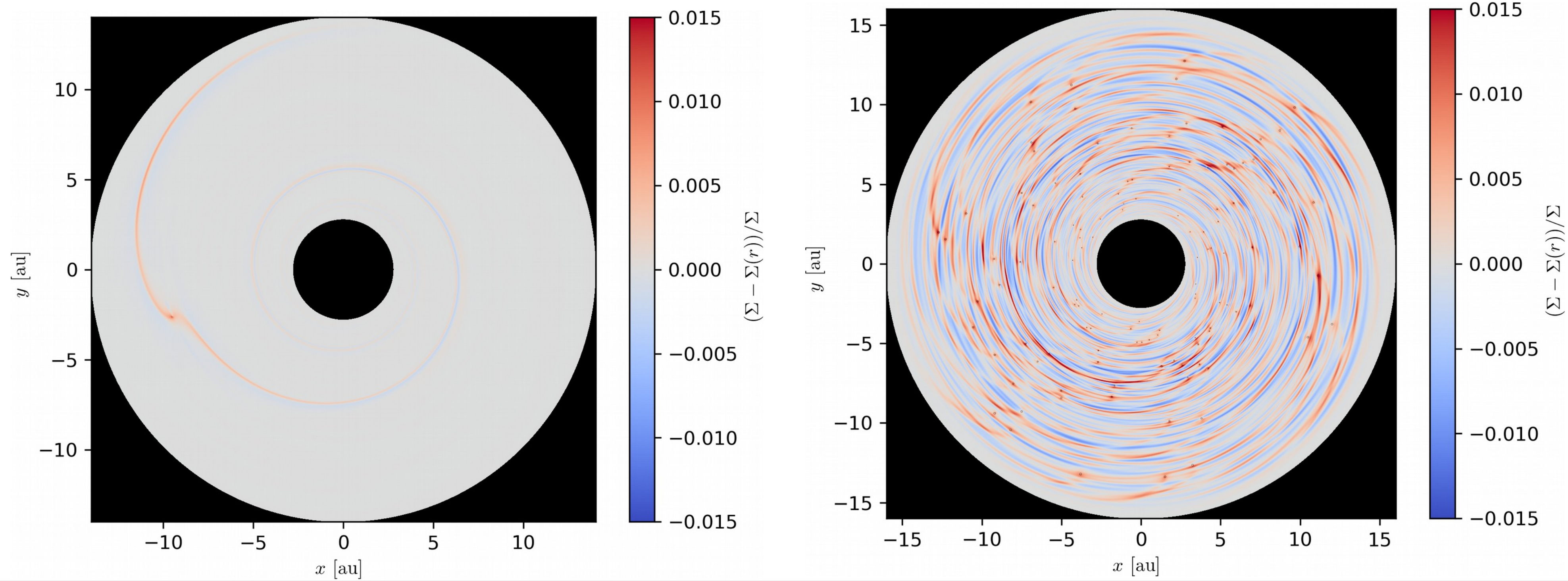
- BUT also...



Stochastic disk torques

↑ overlapping spiral arms, affected corotation regions, incl. non-linear terms (T^3, T^4, Q_{visc})

single-planet torque vs stochastic torques



Conclusions

- **3-body encounters** are needed for mergers
- in high-Σ disks **repulsion** events are frequent
- a massive coorbital pair develops a **pebble isolation**
- **stabilisation** & inward migration of c. then occurs
- a **dynamical torque** can arise in the ice-giant zone
- this leads to outward ↔ inward **migration cycles**
- disk torques for many (>100) low-mass embryos are **stochastic**

- Brož, Chrenko, Nesvorný & Lambrechts (A&A, submitted)
- Fargo-Thorin: http://sirrah.troja.mff.cuni.cz/~chrenko/

Inclination vs pebble accretion

- massive embryos → low (mean) inclinations, close to pebble disk midplane