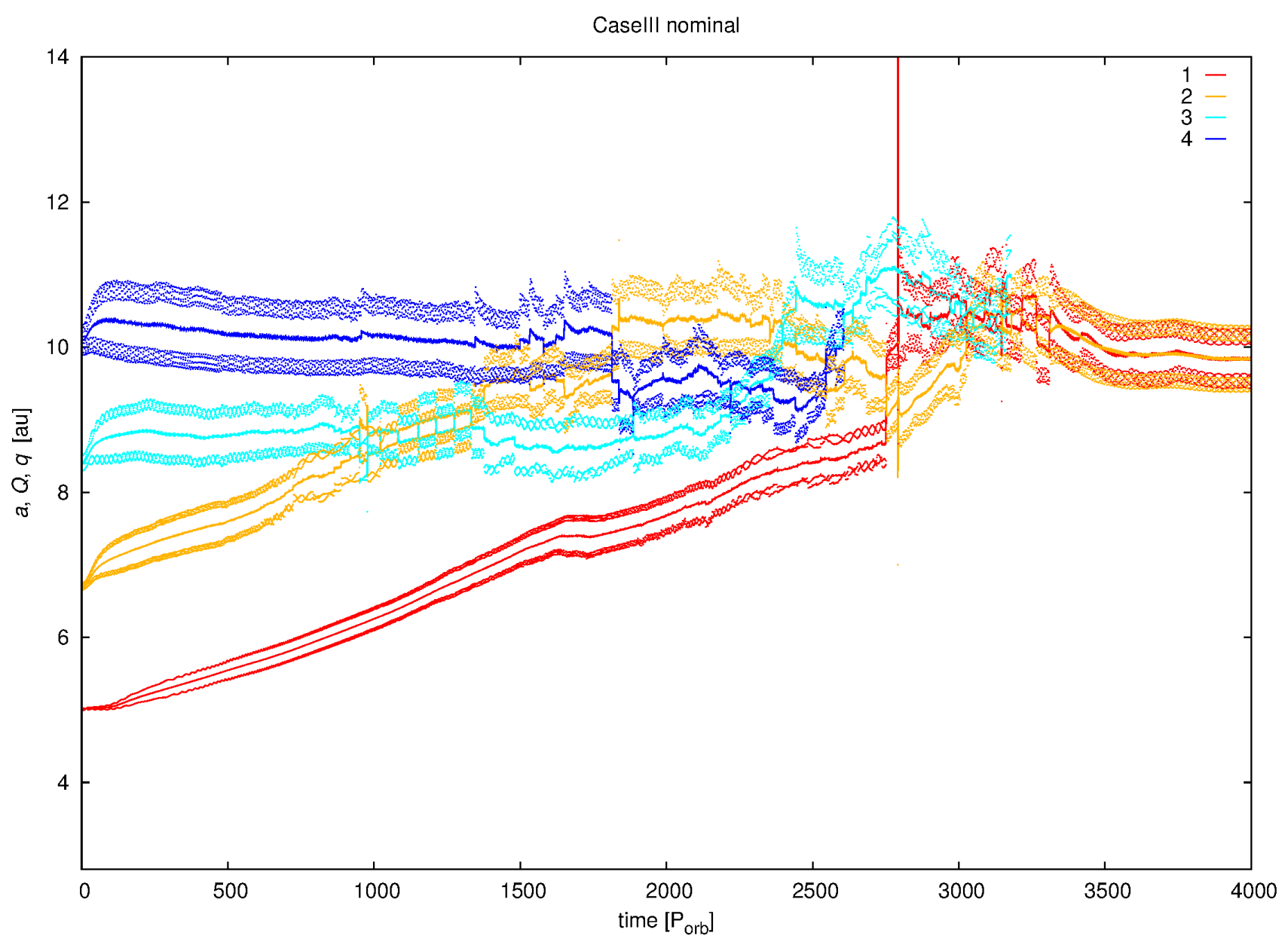
Evolution of 3-Earth-mass protoplanets towards eventual gap opening

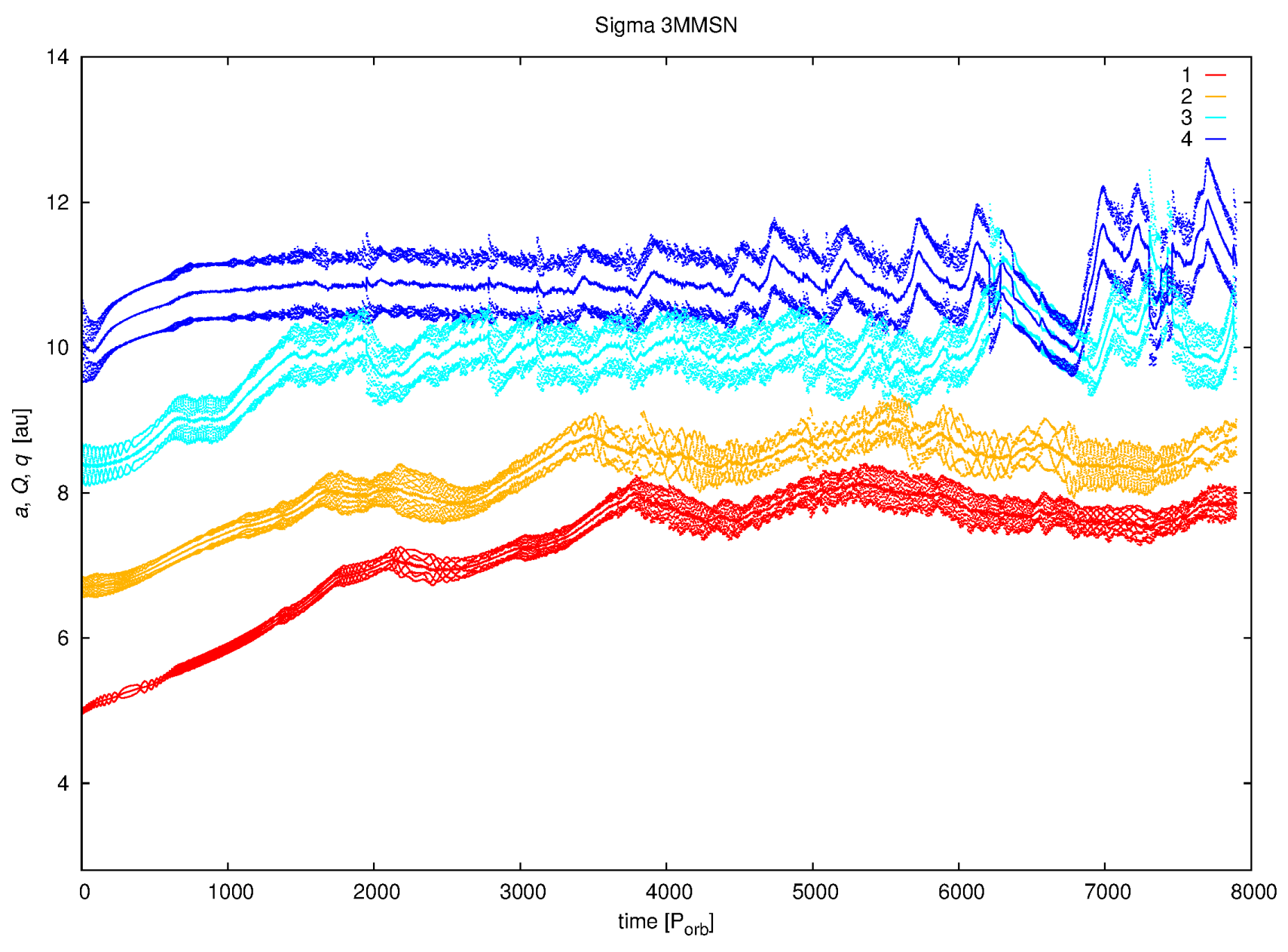
or so...

Miroslav Brož[1], Ondřej Chrenko[1], David Nesvorný[2] - [1]Charles University in Prague, V Holešovičkách 2, 18000 Prague, Czech Republic; [2]SWRI - email: mira@sirrah.troja.mff.cuni.cz

Abstract: Several-Earth-mass protoplanets interact with the gaseous and pebble disk in a complex way (see Chrenko et al. 2017, or Eklund & Masset 2017). The **hot-trail effect** arises as a consequence of accretion heating, it raises planetary eccentricities, and may prevent resonant captures of migrating planets. Here we study the dependence of this effect on parameters such as the surface density, viscosity, or the number of protoplanets. After mergers, planets are massive enough to accrete massive gas envelopes, open gaps, and eventually Type-I migration changes to Type-II. We are also using hydrocode results and radiation transfer code to compute how disk would appear in ALMA observations and whether this may constrain the properties of embedded planets.

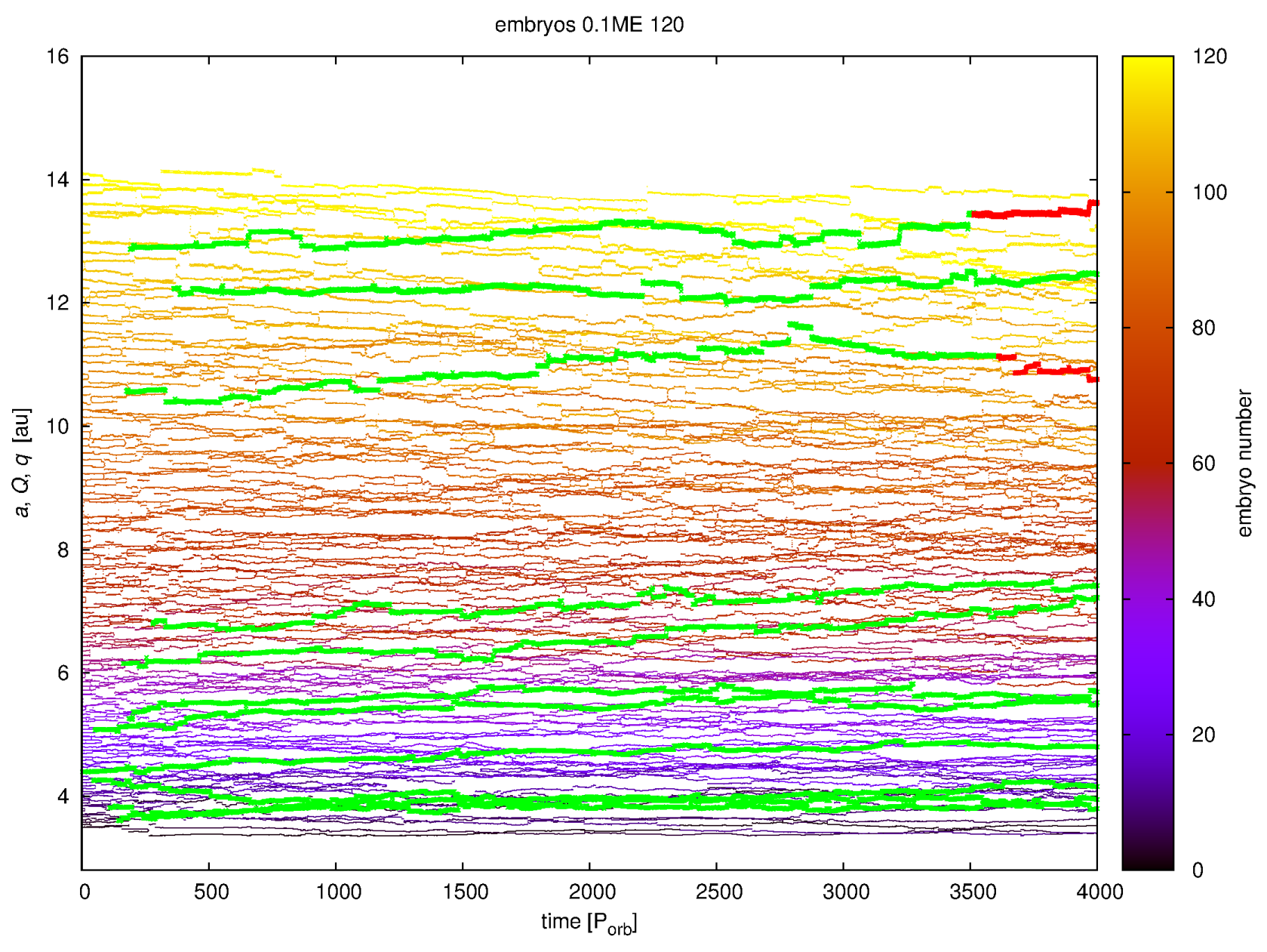


CaseIII_nominal — As presented in Chrenko et al. (2017). Starting with 4 embryos, 3 M_E, initial spacing 10 R_Hill, pebble flux 2×10^{-4} M_E per yr, approx. MMSN, with 0.5 $\Sigma(r)$ slope, kinematic viscosity $\nu = 10^{-5}$ [c.u.], proto-Sun, resolution 1024×1536, damping BC's, artificial inclination damping (Tanaka & Ward 2004), no Hill cut. Results: hot-trail effect, high eccentricities (cf. talk by O. Chrenko), 0-torque at approx. 9 au, no low-order mean-motion resonances (MMR), because embryos were too close, capture difficult anyway (because $e > 0$), two successful mergers 13.8 M_E and 4.3 M_E, but co-orbitals, their long-term evolution? We performed 6 additional simulations, always with a single modified parameter...



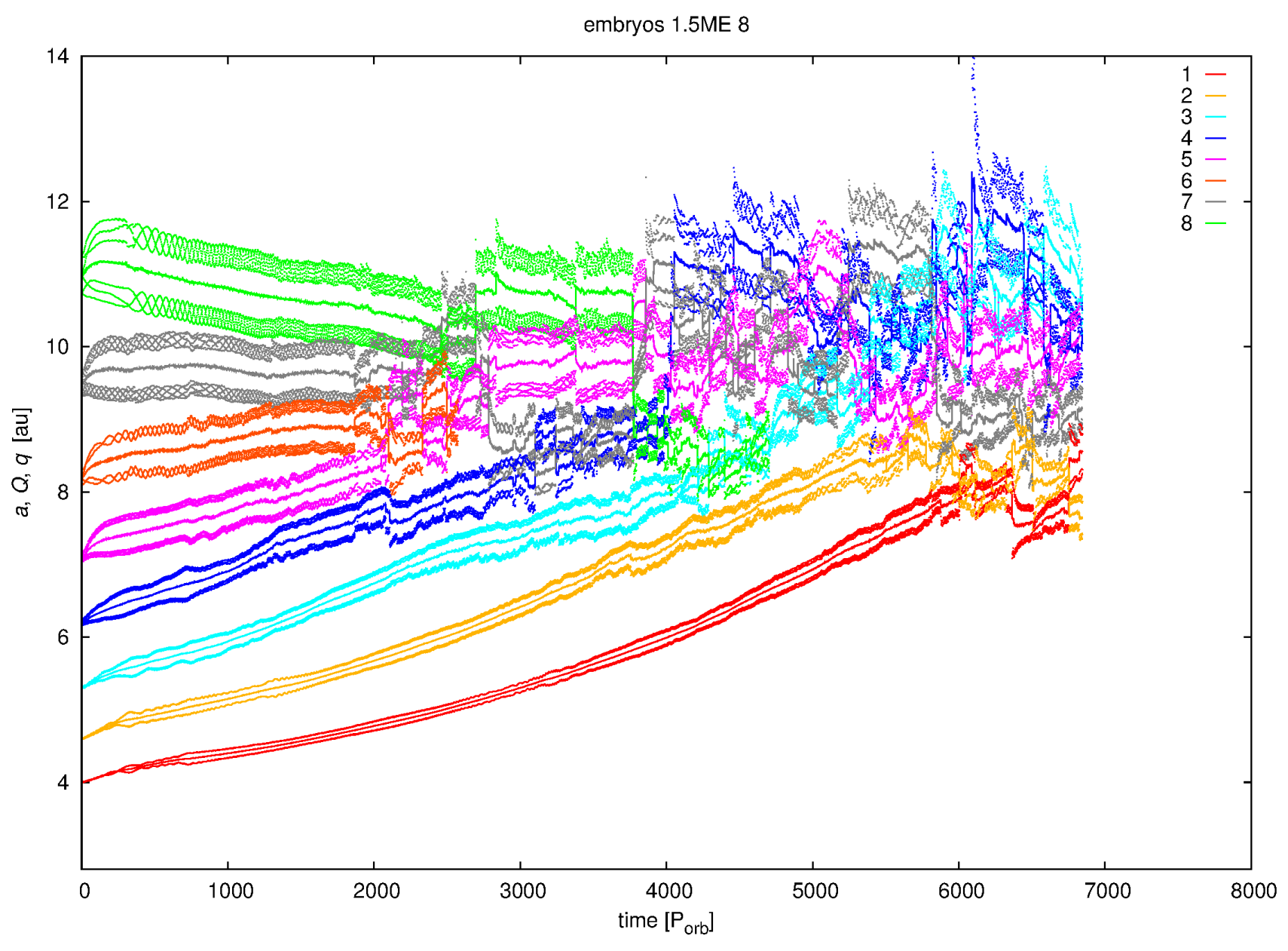
Sigma_3MMSN — initial surface density Σ 3× larger; 0-torque radius further out at 11 au, e often *smaller*, slower evolution (even though timespan 2× longer), embryos do NOT interact so strongly, rather stay next to each other, because damping is too large? sometimes inward migration of inner embryos @ larger e, possible interference of (massive) co-orbital regions? 10+ attempts of the outer 4th embryo to enter the co-orbital region of the 3rd one, only temporary coorbitals.

any comments? write them here!



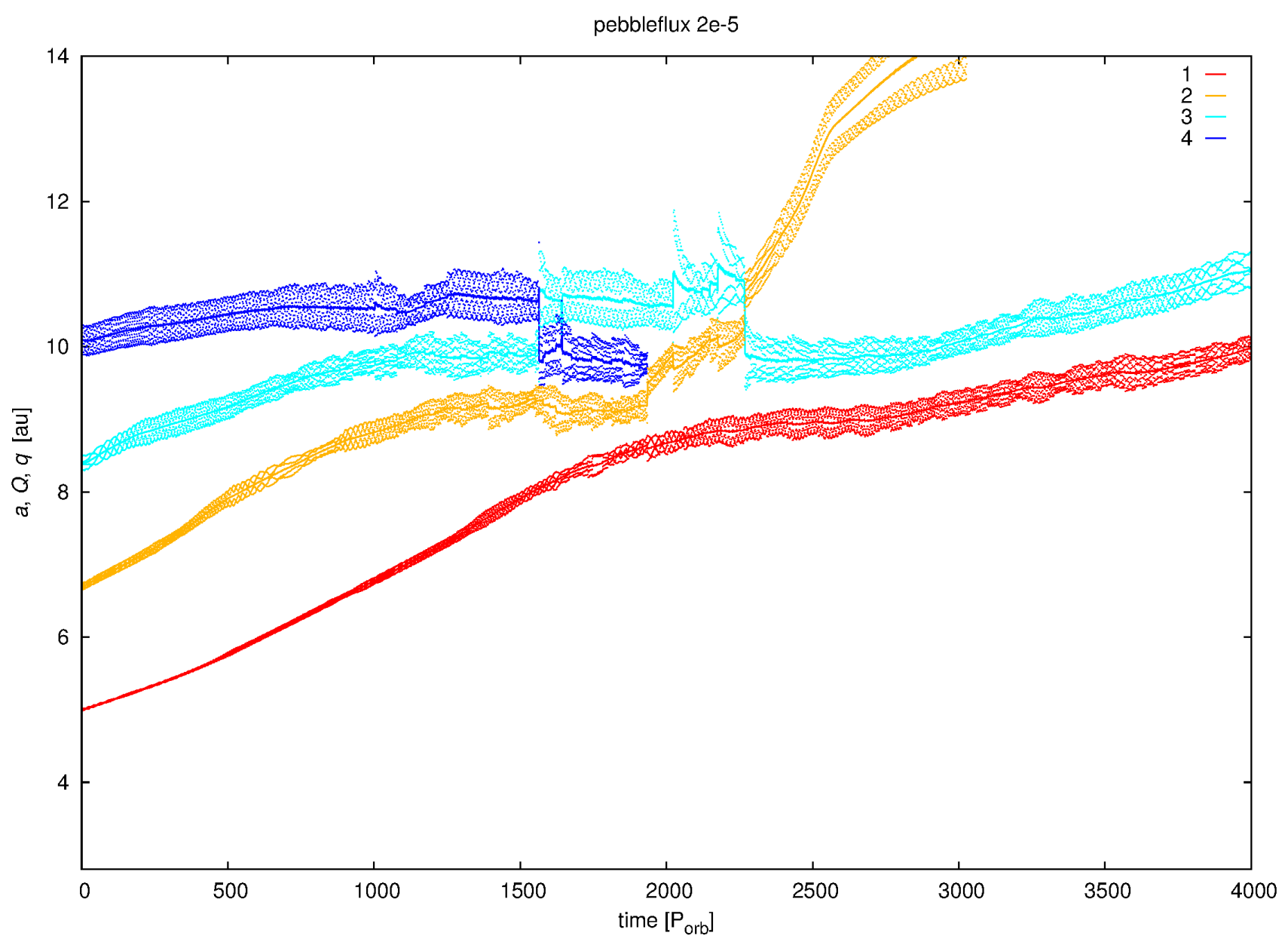
embryos_0.1ME_120 — 120 low-mass 0.1 M_E embryos, spacing 2 mutual R_Hill, disk up to 16 au, resolution still low (3 pixels per Hill sphere), at least 2048×3072 would be needed, convergence tests show that da/dt is *overestimated*, very slow computation anyway (120 disk → planet interactions), it was run on Pleiades, caveat: collisional radii increased only during merger events; overlapping weak spiral arms, slow evolution dominated by encounters, e up to 0.06, 10+ quick mergers 0.2 M_E, pebble accretion up to 0.45 M_E, but strong filtering for inner embryos, 0.2 M_E mergers are either inside (short periods) or outside, the "winner" is outside (no filtering), longer simulation needed?

any comments?



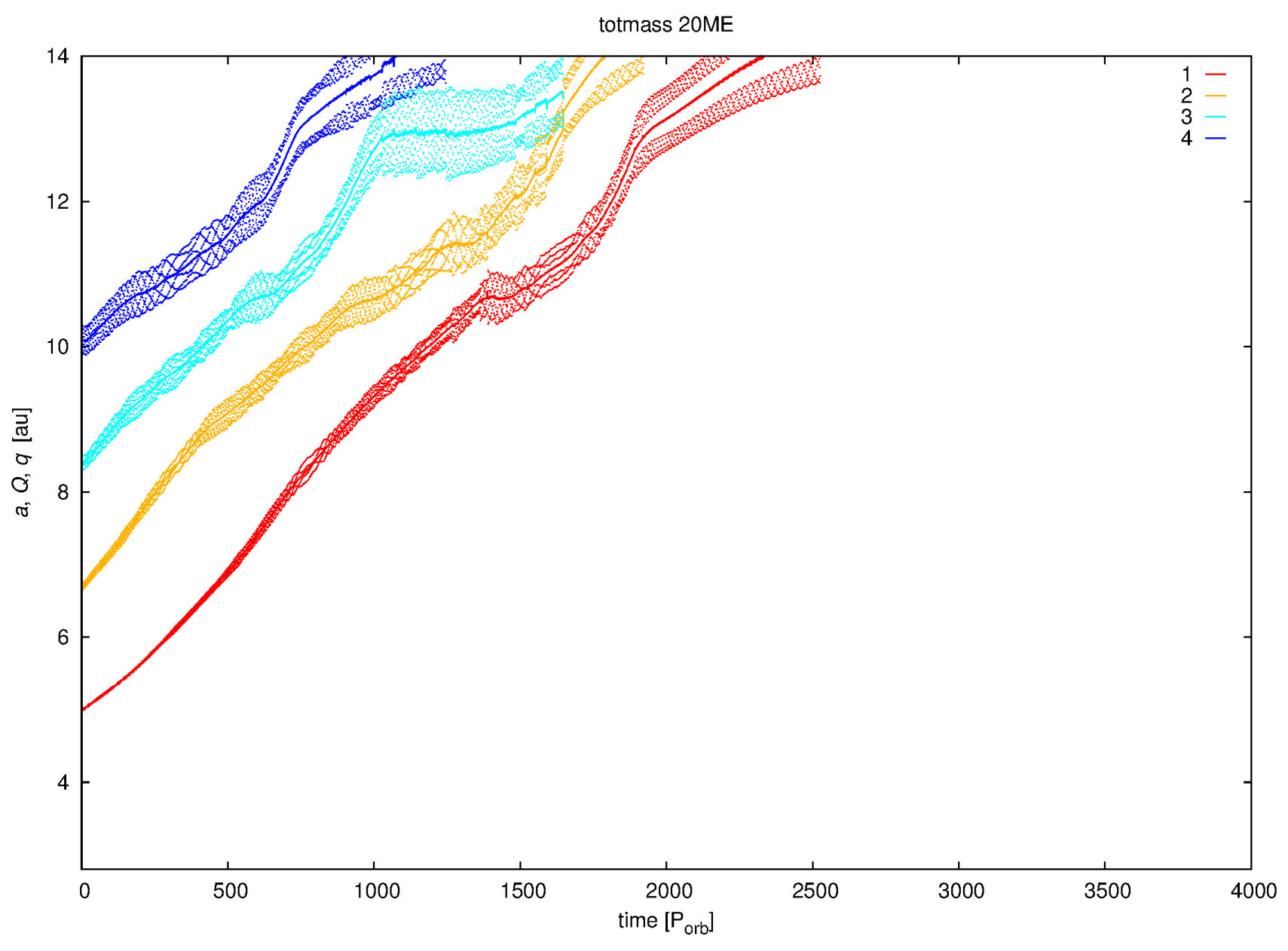
embryos_1.5ME_8 — 8 embryos with 1.5 M_E, clear convergence to 0-torque, slower evolution, a number of encounters, more opportunities to merge, especially when an additional embryo arrives and starts to interact, 2 mergers 13.2 and 6.5 M_E as of yet, more outer embryos should be added and an extended disk (20 au) should be used?

any comments?



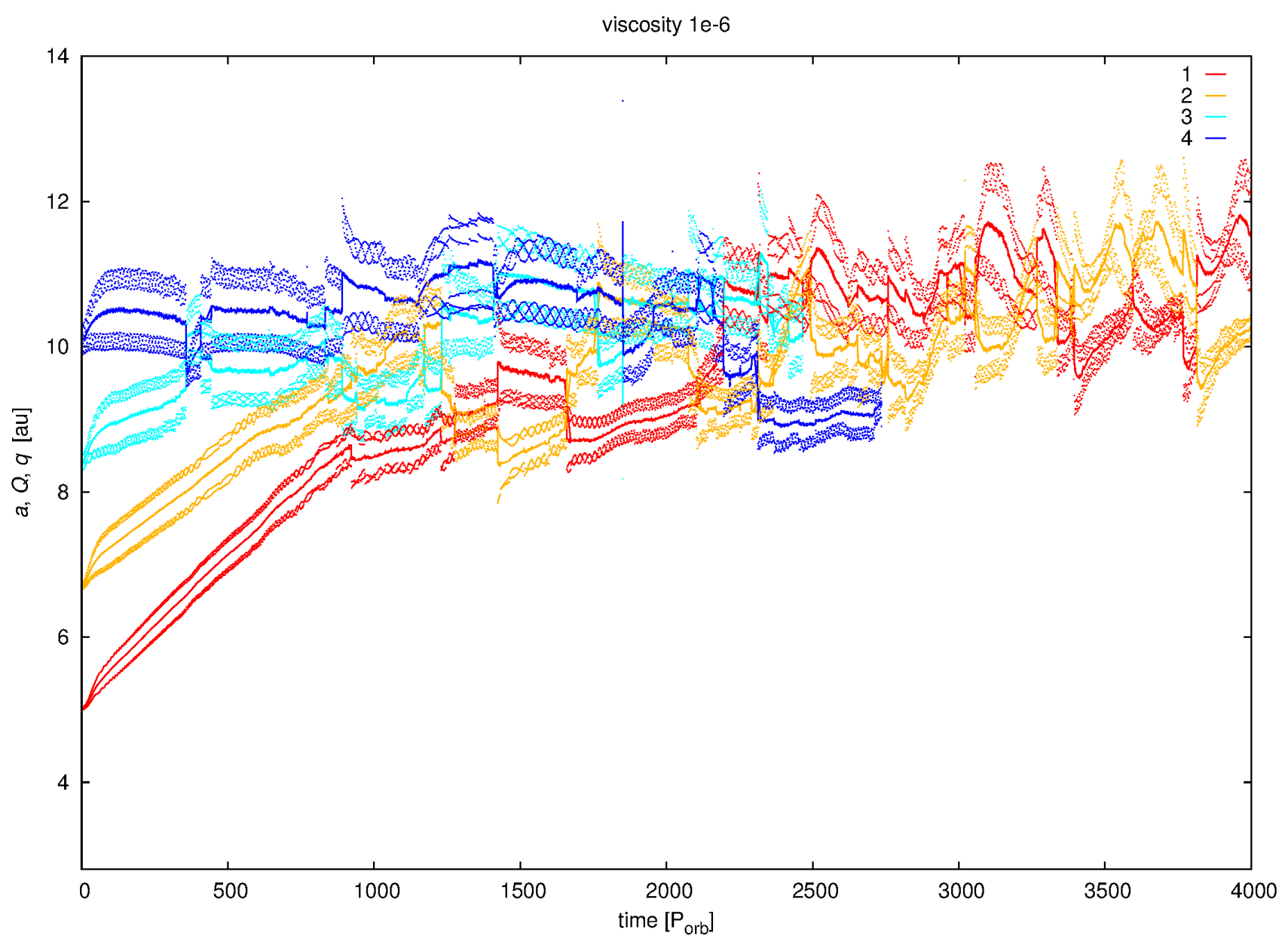
pebbleflux_2e-5 — 10× lower pebble flux 2×10^{-5} M_E, i.e. 0.25 M_E per 4000 P_orb (more realistic?), lower eccentricity excitation (!), consequently smooth evolution, all embryos initially drift outwards, 0-torque at about 11 au? 1 yellow merger with 6 M_E quickly drifts outwards (!), only temporarily decelerated by the 3rd embryo, *runaway* migration mode as in Pierens & Raymond (2016)? planet IX? :) Is it a rule for low pebble fluxes? Possible clearing of the outer disk? More outer embryos should be probably added...

any comments?



totmass_20ME — initial masses 5 M_E; all embryos quickly drift outwards (!), even though wo. heating the 0-torque should be at 7 au; lower e, practically NO interactions, because real 0-torque is further out, unwanted interactions with the disk edge; larger disk & more embryos shoud be used...

any comments?



viscosity_1e-6 — low-viscosity disk; same e, BUT faster migration da/dt, i.e. like ν in the denominator (?!), surroundings more easily affected by the embryo, many encounters, only temporary co-orbitals, 2 mergers 8 M_E as of yet, an onset of gap opening even without gas-accretion term? many attempts to form a co-orbital pair, BUT failed co-orbital formation? (cf. Figs. above)

any comments?

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

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

$$\frac{\partial E}{\partial t}+\boldsymbol{v}\cdot\nabla E=-E\nabla\cdot\boldsymbol{v}-P\nabla\cdot\boldsymbol{v}+\overbrace{Q_\mathrm{visc}}^{\text{dissip.}}+\overbrace{\frac{2\sigma T_\mathrm{irr}^4}{\tau_\mathrm{eff}}}^{\text{irradiation}}-\overbrace{\frac{2\sigma T^4}{\tau_\mathrm{eff}}}^{\substack{\text{vertical}\\\text{cooling}}}+\overbrace{2H\nabla\cdot\frac{16\sigma\lambda_\mathrm{lim}}{\rho_0\kappa}T^3\nabla T}^{\text{radiative diffusion}}+\overbrace{\frac{GM\dot{M}}{RS_\mathrm{cell}}}^{\text{accretion}}$$

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

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

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

System of equations; changes w.r.t. Chrenko et al. (2017): gas accretion (Kley's prescription for 3D orbits), corresponding gas-accretion heating, fragmentation-limited pebbles, improved SOR convergence.

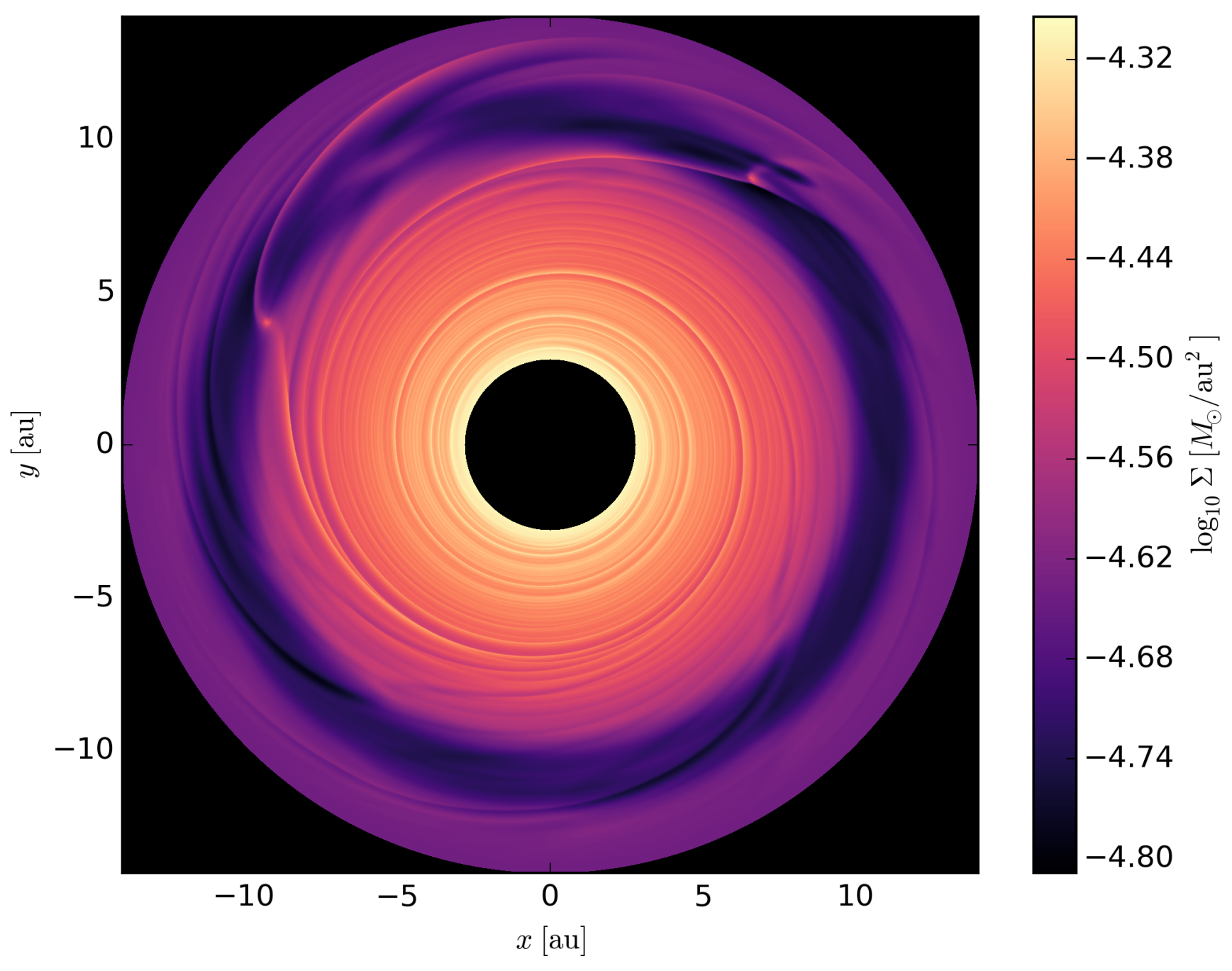


Figure: Evolved gas disk @ time t = 4000 P_orb @ 5.2 au, hot-trail effect visible, failed co-orbital, viscosity_1e-6.

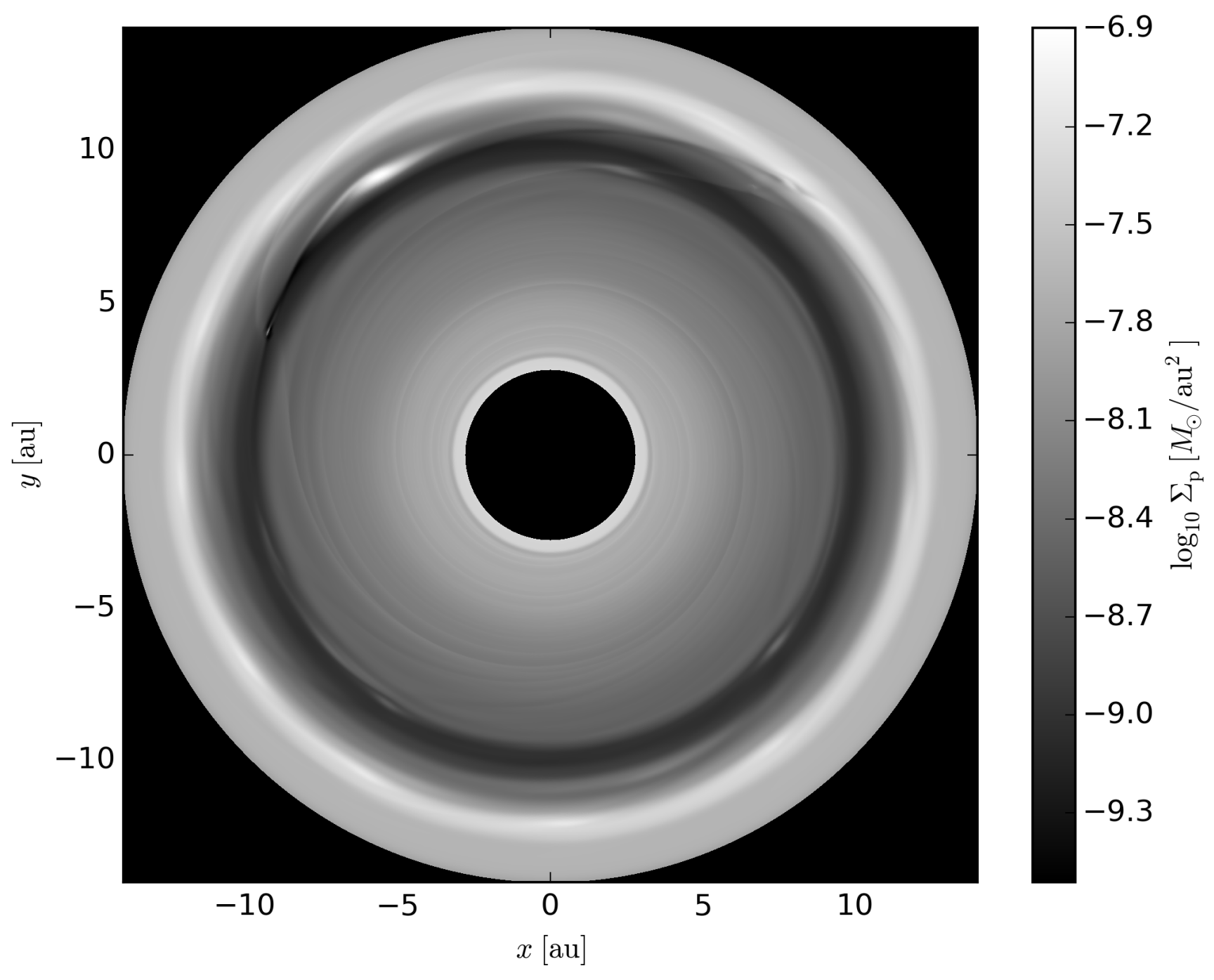


Figure: Pebble disk, corresponding 1:1 to the gas disk.

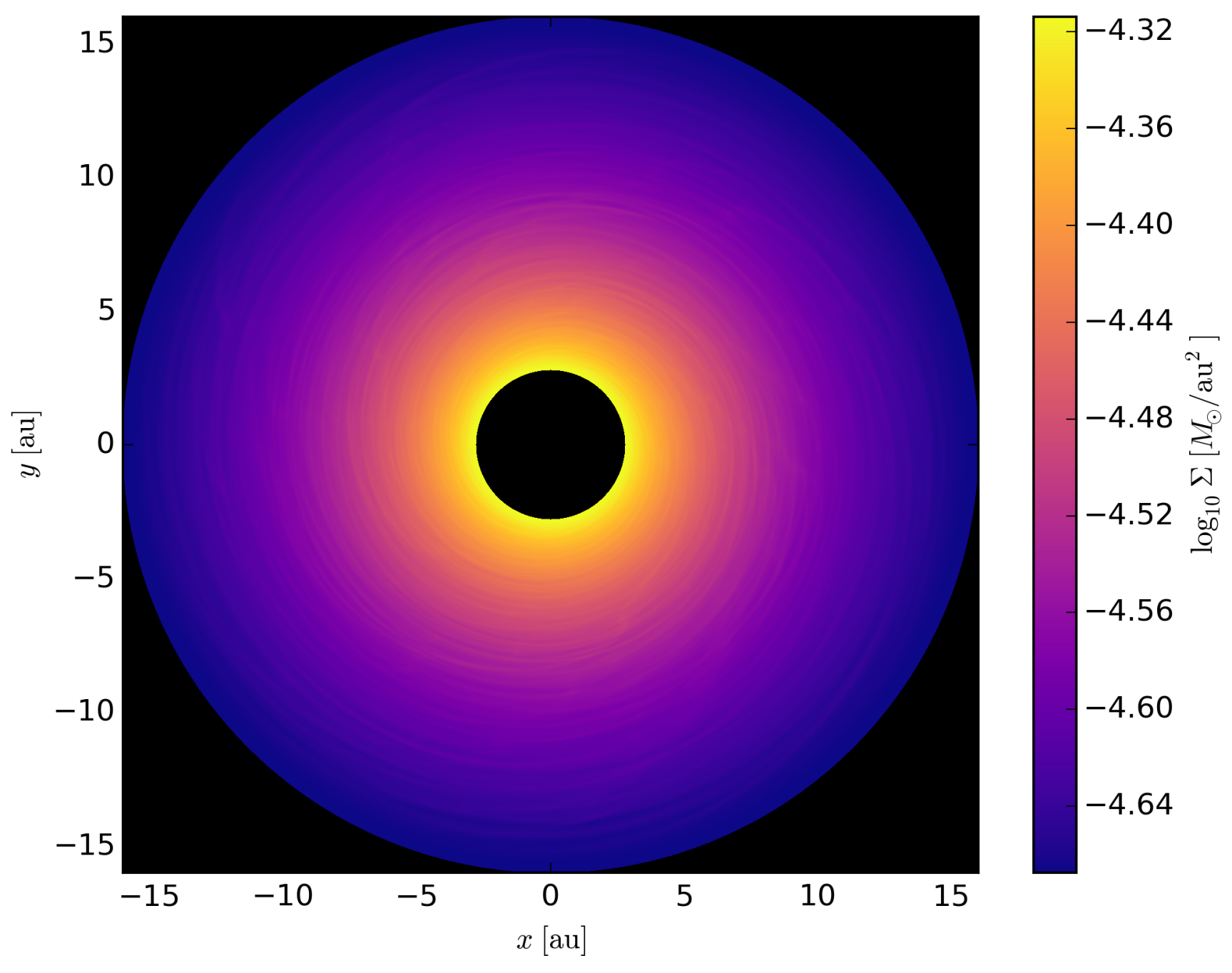


Figure: Gas disk with initially 120 embryos 0.1 M_E, and many weak overlapping spiral arms, t = 4000 P_orb.

Conclusions:

Clearly, the dependence on parameters is complex! Apart from the very origin of gas-giant cores, there are a number of possible applications here: studies of different parts of the disk, origin of Uranus & Neptune, dynamics of other (compact) planetary systems. However, we have to face several serious problems: (i) find BC's suitable for the inner disk edge; (ii) resolve different pebble isolation in 2D vs 3D; (iii) gas accretion in 2D is not self-consistent, produces too much heating. It's possible that the deposition is below opaque atmosphere. A parametrisation of 3D in- and *outflows* (Lambrechts & Lega 2017) would be needed for this purpose.

Btw. the code is available @ http://sirrah.troja.mff.cuni.cz/~chrenko/

References:

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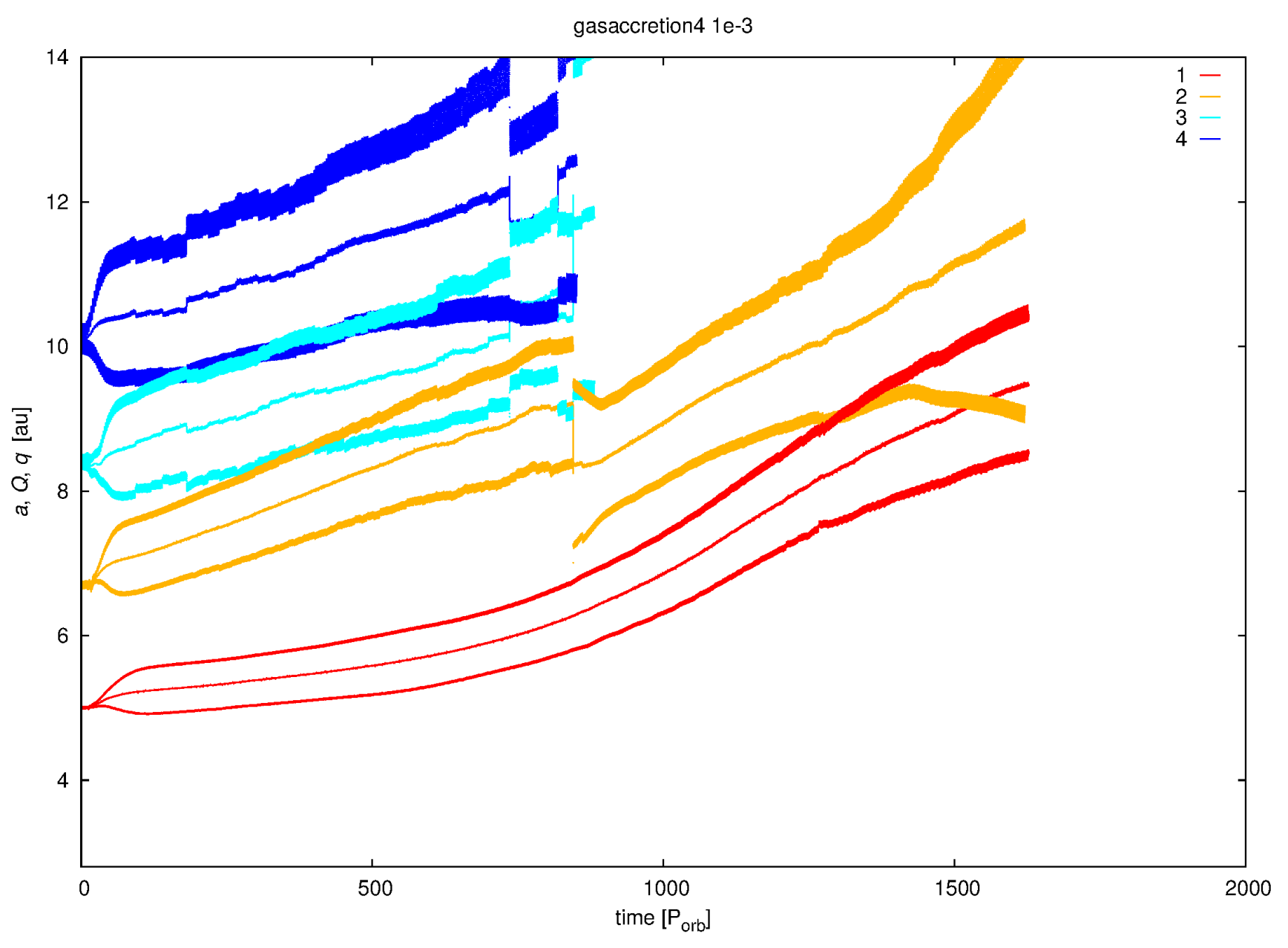

Figure: Simulation with gas accretion (incl. heating), Kley parameter $f_\mathrm{acc} = 10^{-3}$, $\Delta M \propto f_\mathrm{acc}\Sigma S_\mathrm{cell}\Delta t\int\rho(z)\mathrm{d}z$.

Observability: The disk is optically thick in the vertical direction $\tau = \kappa\rho H \simeq 10^2 \gg 1$, with Bell & Lin (1994) integral opacities. It is thus necessary to properly model the disk atmosphere. In the midplane, the mean-free path l_f of gas molecules is small enough to assure a sufficient thermal contact and equilibrium between the gas and dust. This is no more true far from the midplane and one has to use 3D, non-equilibrium model, and monochromatic opacities (cf. eqs.). While surface-area distribution of solids is dominated by sub-micron dust, the mass distribution is dominated by pebbles (as in Birnstiel et al. 2012); in principle we can use Σ_p, $H_\mathrm{p} < H$, $\kappa_\mathrm{p} \ll \kappa$, but it could hardly produce observable effects.

We tried to use Radmc-3D code (Dullemond et al. 2012), assuming LTE, dust absorption, isotropic scattering, central star, possibly also embryos heated by pebble accretion, and viscous heating (i.e. an extended source). Synthetic image for 10^8 photons was processed by ALMA OST, assuming high ν = 900 GHz, 7.5 GHz bandwidth, 3-hour observation, 1 visit starting at 78°, PWV 0.475 mm, and extended (full) configuration with baselines up to $B/\lambda = 3.6\times10^6$ cycles.

Problems: (i) only fully-opened gaps seem observable; (ii) only escape-probability, no Λ-iterations, ALI, or Ng-acceleration → a slow convergence with extended source inside optically-thick disk interior!

$$\Sigma_\mathrm{d}=\Sigma\,\kappa\,\frac{\int_\nu\frac{1}{\kappa_\nu}\frac{\mathrm{d}B_\nu}{\mathrm{d}T}\mathrm{d}\nu}{\int_\nu\frac{\mathrm{d}B_\nu}{\mathrm{d}T}\mathrm{d}\nu}$$

$$\rho_\mathrm{d}=\frac{\Sigma_\mathrm{d}}{\sqrt{2\pi}H}\exp\left(-\frac{z^2}{2H^2}\right)$$

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s}=\kappa_\nu^\mathrm{abs}\rho B_\nu(T)+\frac{\kappa_\nu^\mathrm{sca}\rho}{4\pi}\int I_\nu\mathrm{d}\Omega-(\kappa_\nu^\mathrm{abs}+\kappa_\nu^\mathrm{sca})\rho I_\nu$$