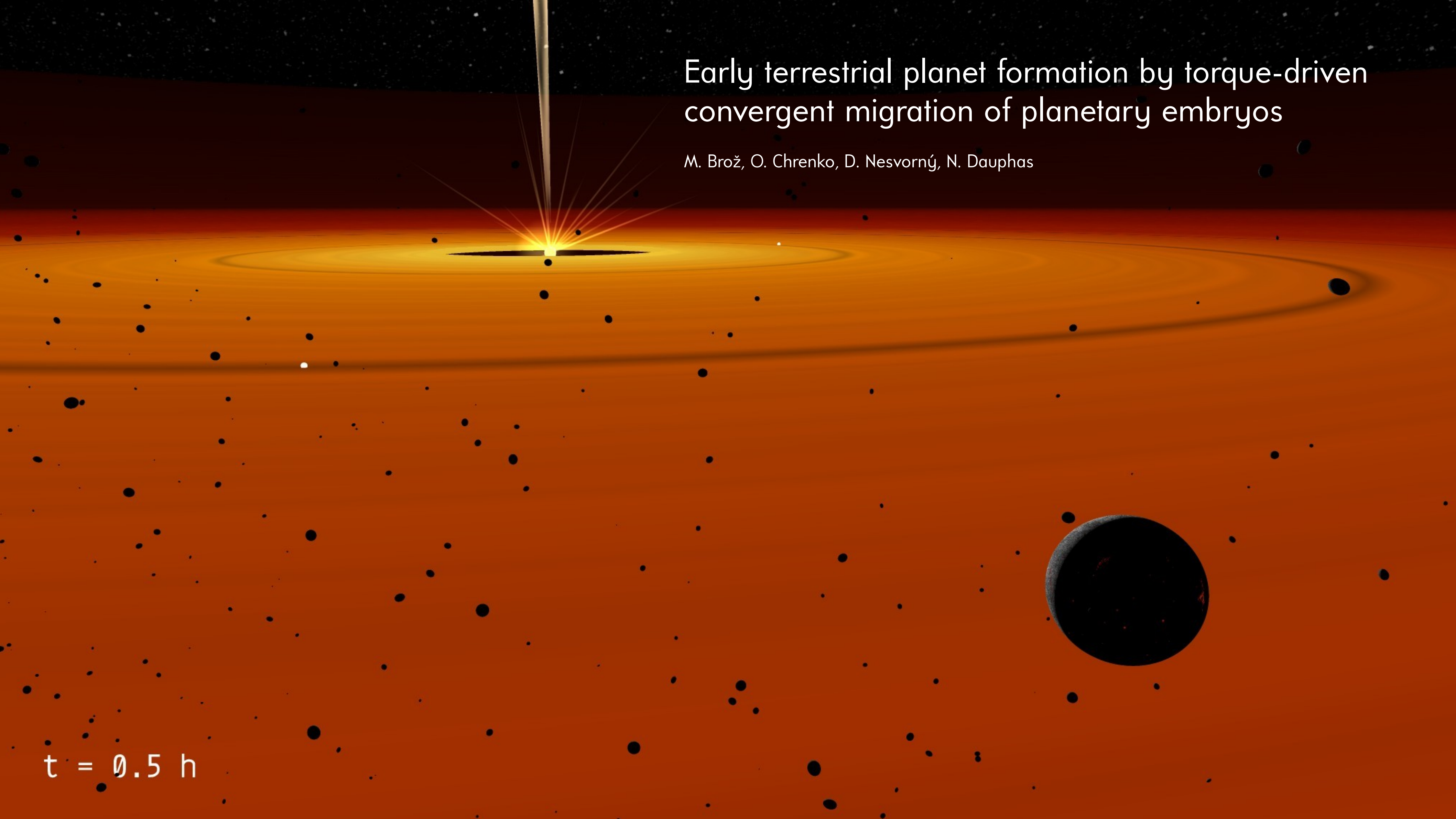
Early terrestrial planet formation by torque-driven convergent migration of planetary embryos

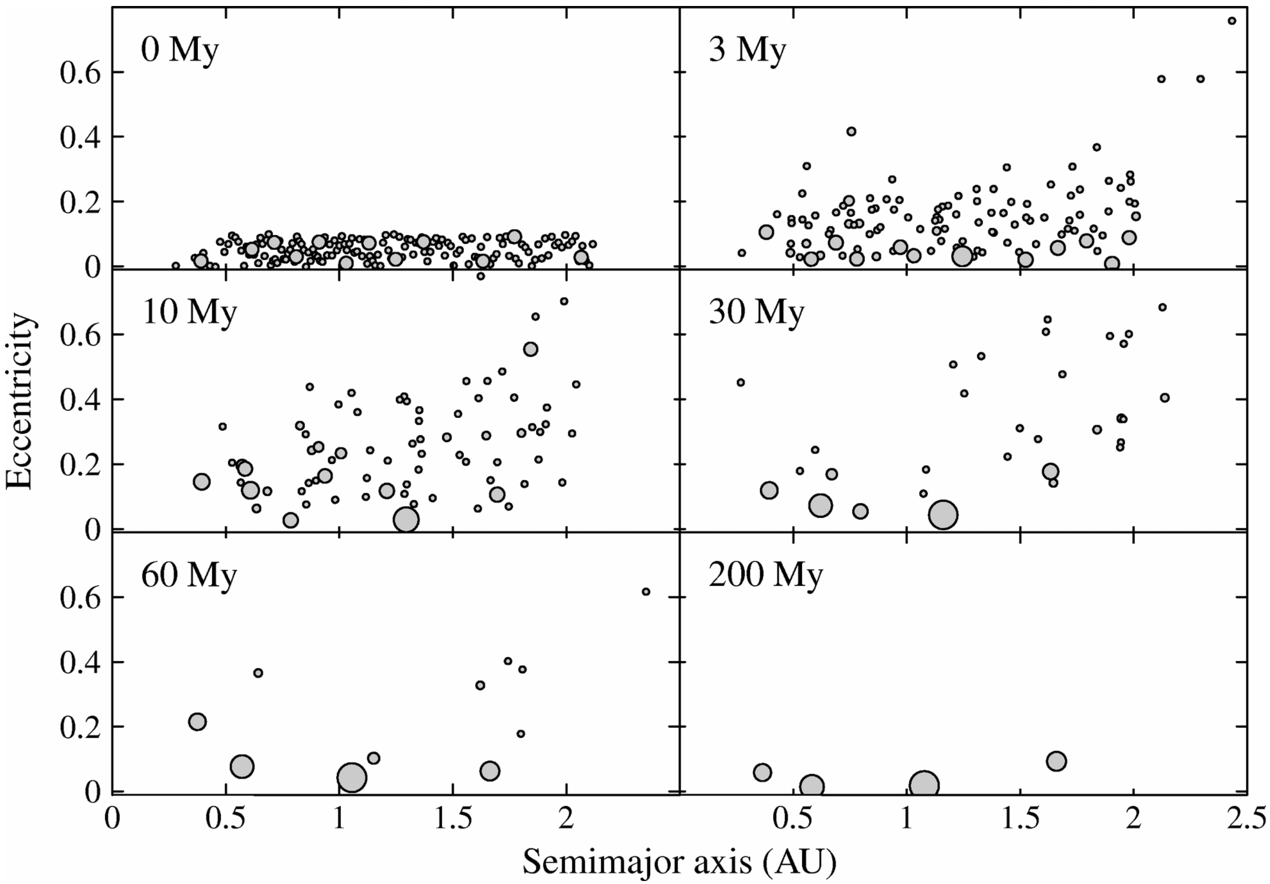
M. Brož, O. Chrenko, D. Nesvorný, N. Dauphas



Black screen…

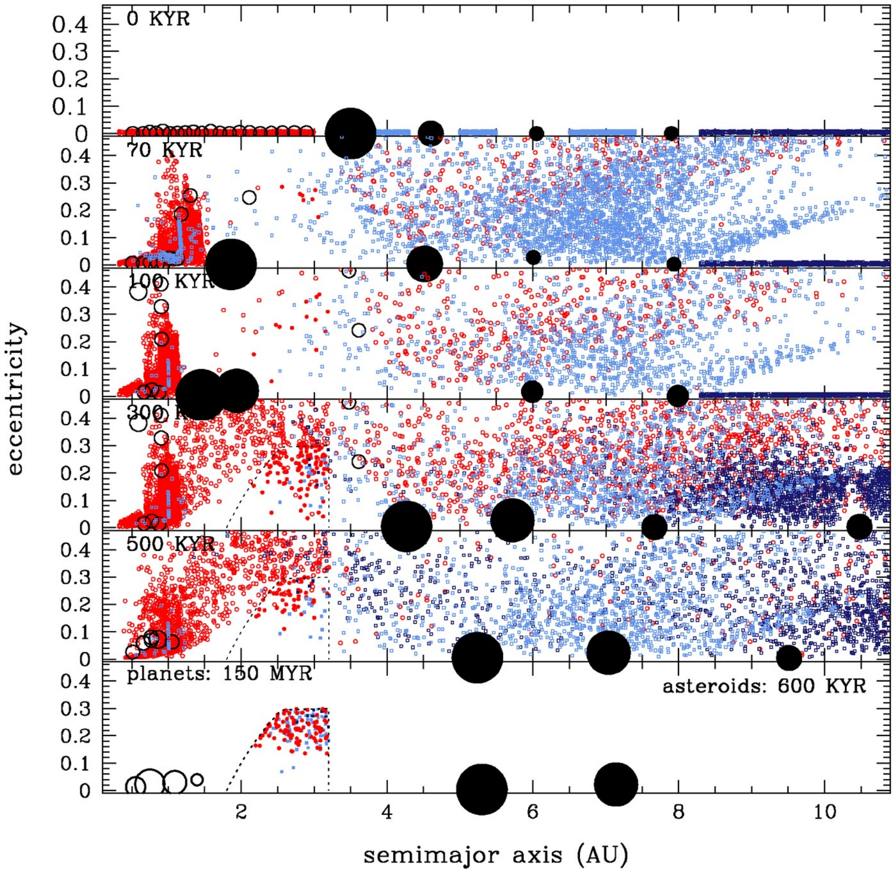
Chambers & Wetherill (1998)

- classical N-body model
- **local** material
- isolation mass [RTBP]
- time scale 1-2·10^8 y
- cf. Hansen (2009)
- (no gas)



Walsh etal. (2011)

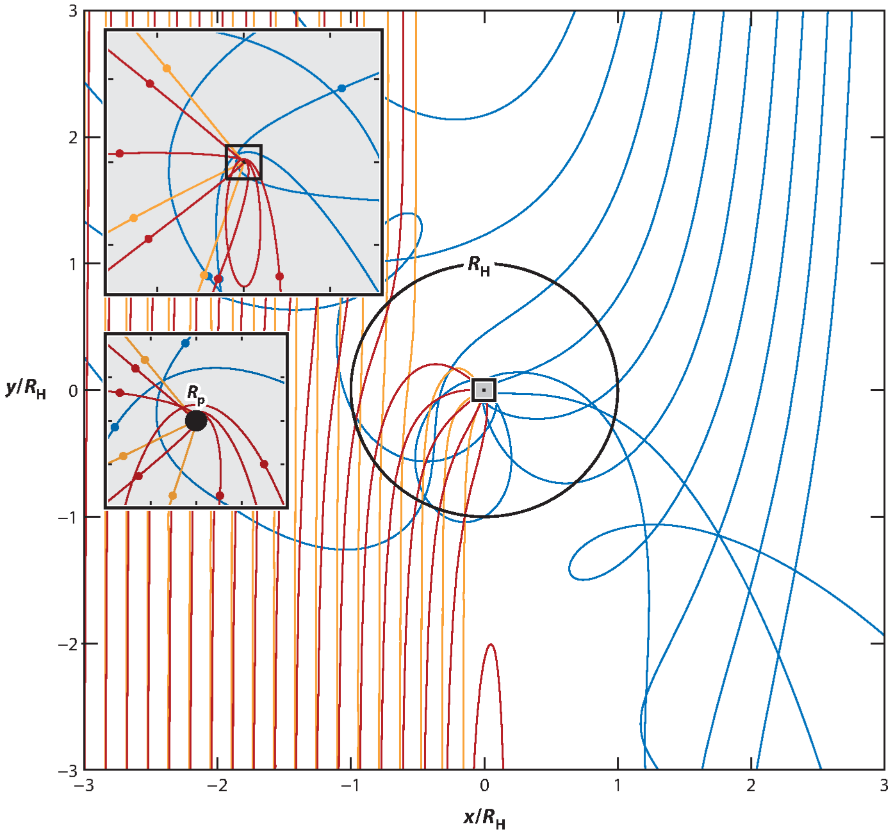
- advanced ‘**Grand-Tack**’ model
- Jupiter & Saturn, Type-II migration (gap)
- outward due to 3:2 MMR, gaps overlap
- special timing needed
- to deplete terrestrial zone...
- ... small Mars (0.1 M_E), but **big** Mercury (0.05 M_E)
- popular in meteoritic community
  (cf. Warren 2010, Kruijer etal. 2017)



Lambrechts & Johansen (2012)

- drifting pebbles ← ærodynamic drag
- **non-local** material!
- also near protoplanets
- Bondi → Hill regime; $R_H = r\,[m/(3M)]^{1/3}$

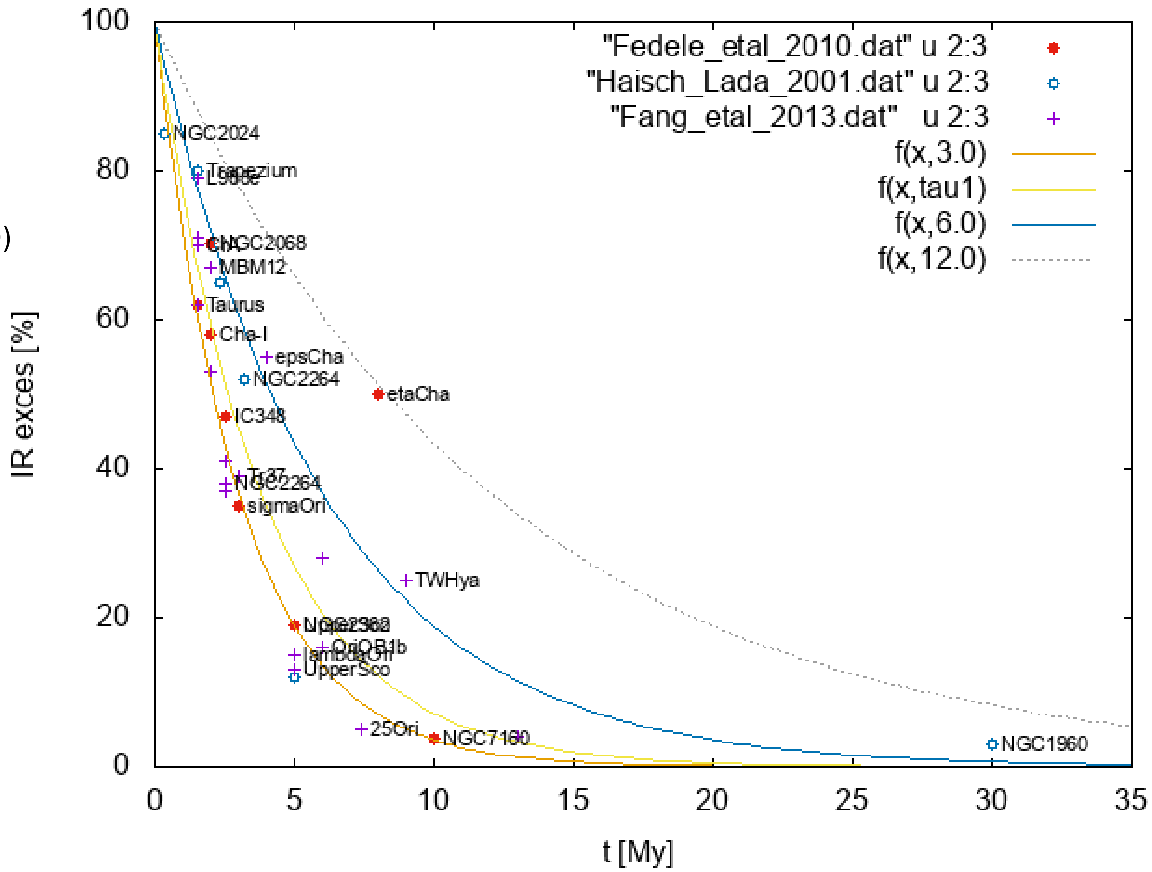
- opacity transitions? (Bitsch etal. 2014)
- pressure bumps? (Bitsch etal. 2018)
- convergence zone(s)?
- ...



Type I: HA, I've discovered something entirely new!
Type II: HM, I've finally understood something, I no longer feel (so) stupid...

1. Terrestrial planets formed early

- IR excess → fraction of disks?
- cluster age → disk age?
- cf. **old disks!** (TW Hya, η Cha, NGC 1960)
- field stars?
- "Are we all average?"



Note: solids formation vs. gas disk lifetime?

- “zero” = t_{CAI} = (4.567 ± 0.001) Gy (Amelin etal. 2002)
- NC ... non-carbonaceous ch.
- CC ... carbonaceous chondrites
- irons formed 0-1.4 My, stones 2-4 My (Kruijer etal. 2017)
- separation of reservoirs (cf. anomalies)
- gas is *not* excluded!

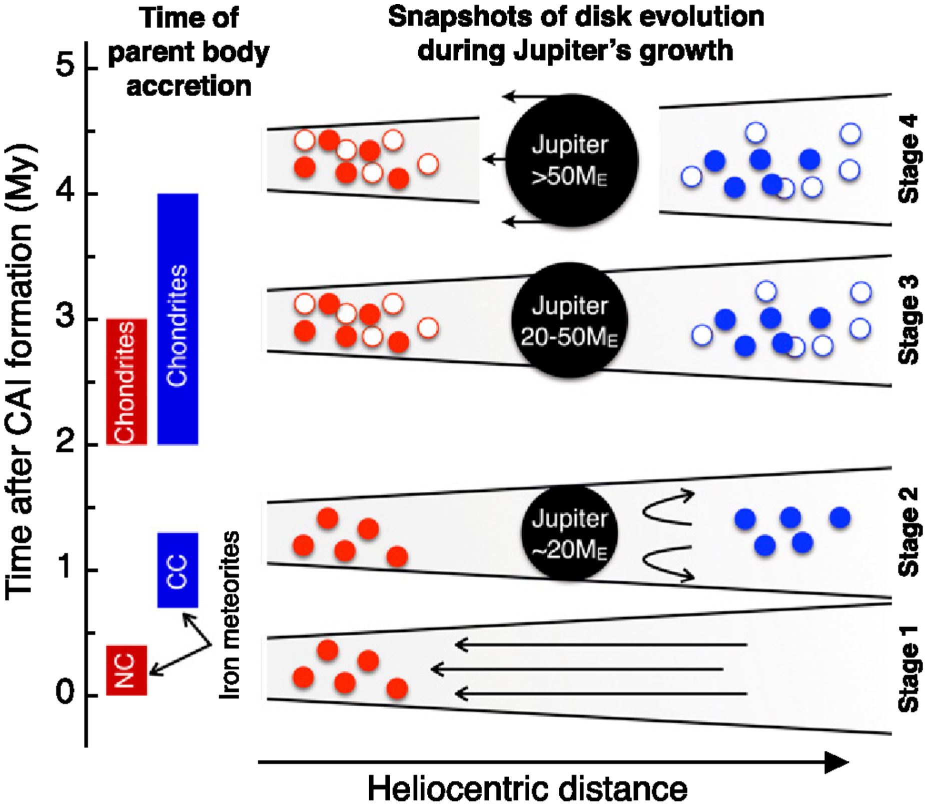


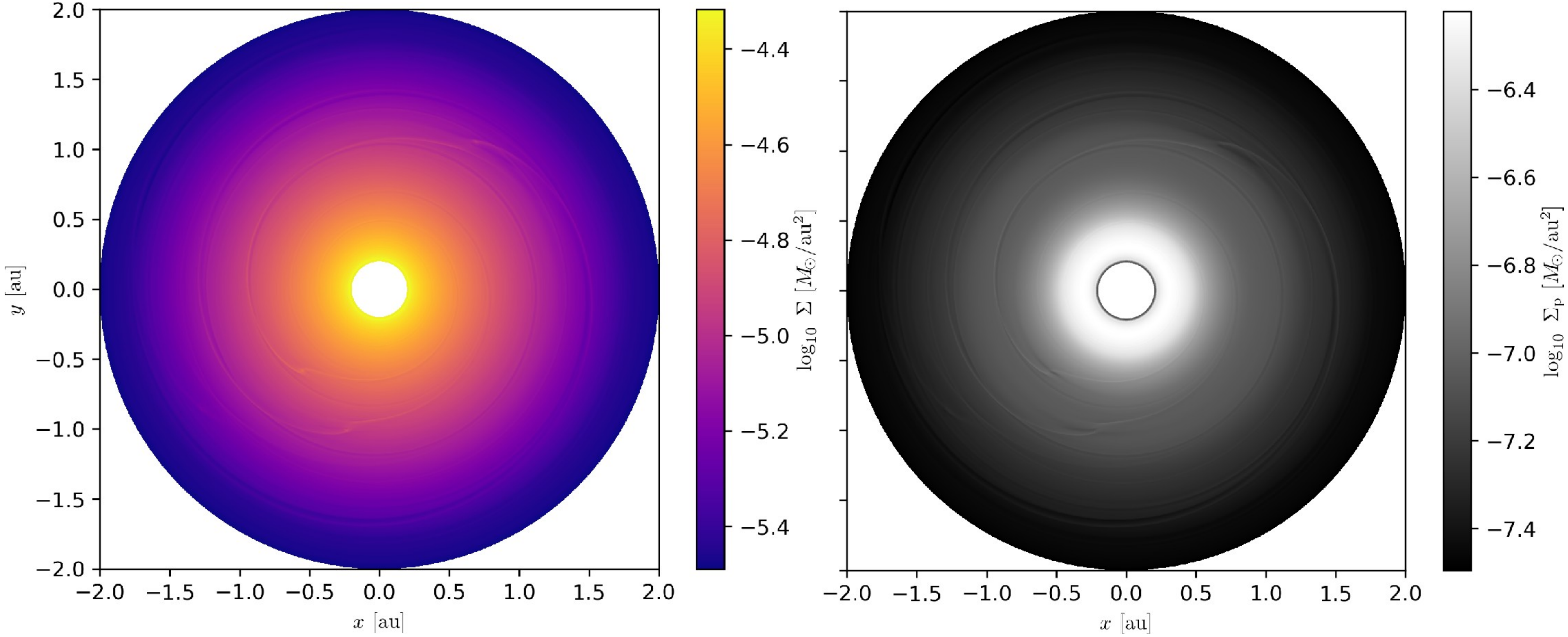
Fig. 4. Four snapshots of Jupiter’s growth in the solar circumstellar disk. At stage 1, within <0.4 My after CAI, the NC iron meteorite parent bodies (red

2. Surface density $\Sigma(r)$ was inverted

- minimum-mass solar nebula (MMSN; Hayashi 1981) is no longer valid (†)
- $\Sigma(r)$ was possibly **inverted** for $r < 1$ au, because of...
- magneto-rotational instability (MRI; Flock etal. 2017),
- active layers (Kretke & Lin 2012), or
- disk winds (Ogihara etal. 2018)

- e.g., controlled by viscosity $\nu(r)$; alternatively $\nu(T)$ ← unstable?
- at late stages, Σ was likely low, even very low

Radiation hydrodynamic model (RHD)



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

gas

$$\frac{\partial \Sigma}{\partial t} + \mathbf{v} \cdot \nabla \Sigma = -\Sigma \nabla \cdot \mathbf{v} - \left(\frac{\partial \Sigma}{\partial t} \right)_{\mathrm{acc}} , \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\Sigma} \nabla P + \frac{1}{\Sigma} \nabla \cdot \mathsf{T} - \frac{\int \rho \nabla \phi \, \mathrm{d}z}{\Sigma} + \frac{\Sigma_{\mathrm{p}}}{\Sigma} \frac{\Omega_{\mathrm{K}}}{\tau} (\mathbf{u} - \mathbf{v}) , \tag{2}$$

$$\begin{aligned} \frac{\partial E}{\partial t} + \mathbf{v} \cdot \nabla E &= -E \nabla \cdot \mathbf{v} - P \nabla \cdot \mathbf{v} + Q_{\mathrm{visc}} + \frac{2\sigma T_{\mathrm{irr}}^4}{\tau_{\mathrm{eff}}} - \frac{2\sigma T^4}{\tau_{\mathrm{eff}}} + \\ &+ 2H \nabla \cdot \frac{16 \sigma \lambda_{\mathrm{lim}}}{\rho_0 \kappa_{\mathrm{R}}} T^3 \nabla T + \sum_i \frac{G M_i \dot{M}_i}{R_i S_{\mathrm{cell}}} \delta(\mathbf{r} - \mathbf{r}_i) , \end{aligned} \tag{3}$$

$$P = \Sigma \frac{RT}{\mu} = (\gamma - 1) E , \tag{4}$$

pebbles

$$\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} + \mathbf{u} \cdot \nabla \Sigma_{\mathrm{p}} = -\Sigma_{\mathrm{p}} \nabla \cdot \mathbf{u} - \left(\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} \right)_{\mathrm{acc}} - \left(\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} \right)_{\mathrm{evap}} , \tag{5}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{\int \rho_{\mathrm{p}} \nabla \phi \, \mathrm{d}z}{\Sigma_{\mathrm{p}}} - \frac{\Omega_{\mathrm{K}}}{\tau} (\mathbf{u} - \mathbf{v}) , \tag{6}$$

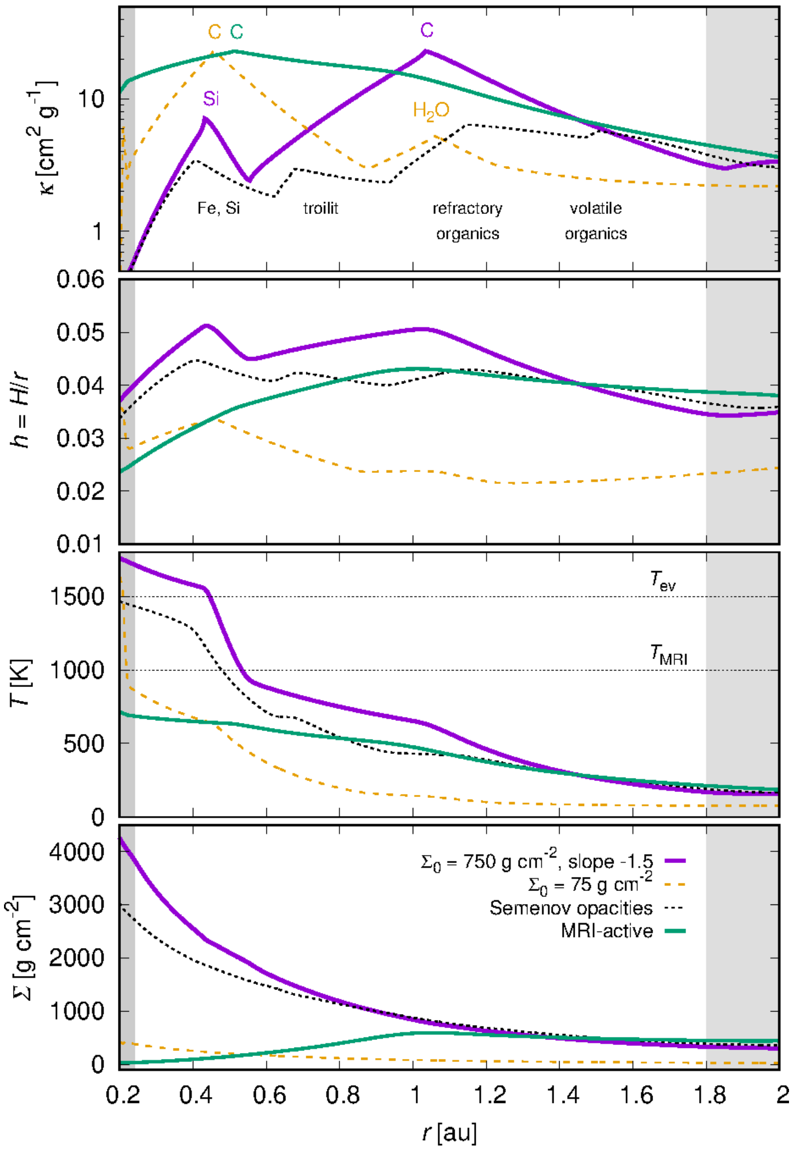
protoplanets

$$\dot{M}_i = \iint \left[\left(\frac{\partial \Sigma}{\partial t} \right)_{\mathrm{acc}} + \left(\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} \right)_{\mathrm{acc}} \right] r \mathrm{d}\theta \mathrm{d}r \quad \text{for } \forall i , \tag{7}$$

$$\begin{aligned} \ddot{\mathbf{r}}_i &= -\frac{G M_\star}{r_i^3} \mathbf{r}_i - \sum_{j \neq i} \frac{G M_j}{|\mathbf{r}_i - \mathbf{r}_j|^3} (\mathbf{r}_i - \mathbf{r}_j) + \iiint \frac{\rho \nabla \phi_i \, \mathrm{d}z}{M_i} r \mathrm{d}\theta \mathrm{d}r + \\ &+ f_z \hat{z} - \frac{1}{2} C \frac{\pi R_i^2}{M_i} \rho |\dot{\mathbf{r}}_i - \mathbf{v}_{\mathrm{cell}}| (\dot{\mathbf{r}}_i - \mathbf{v}_{\mathrm{cell}}) + \iint \left[\mathbf{v} \left(\frac{\partial \Sigma}{\partial t} \right)_{\mathrm{acc}} + \mathbf{u} \left(\frac{\partial \Sigma_{\mathrm{p}}}{\partial t} \right)_{\mathrm{acc}} \right] r \mathrm{d}\theta \mathrm{d}r \\ &\text{for } \forall i , \end{aligned} \tag{8}$$

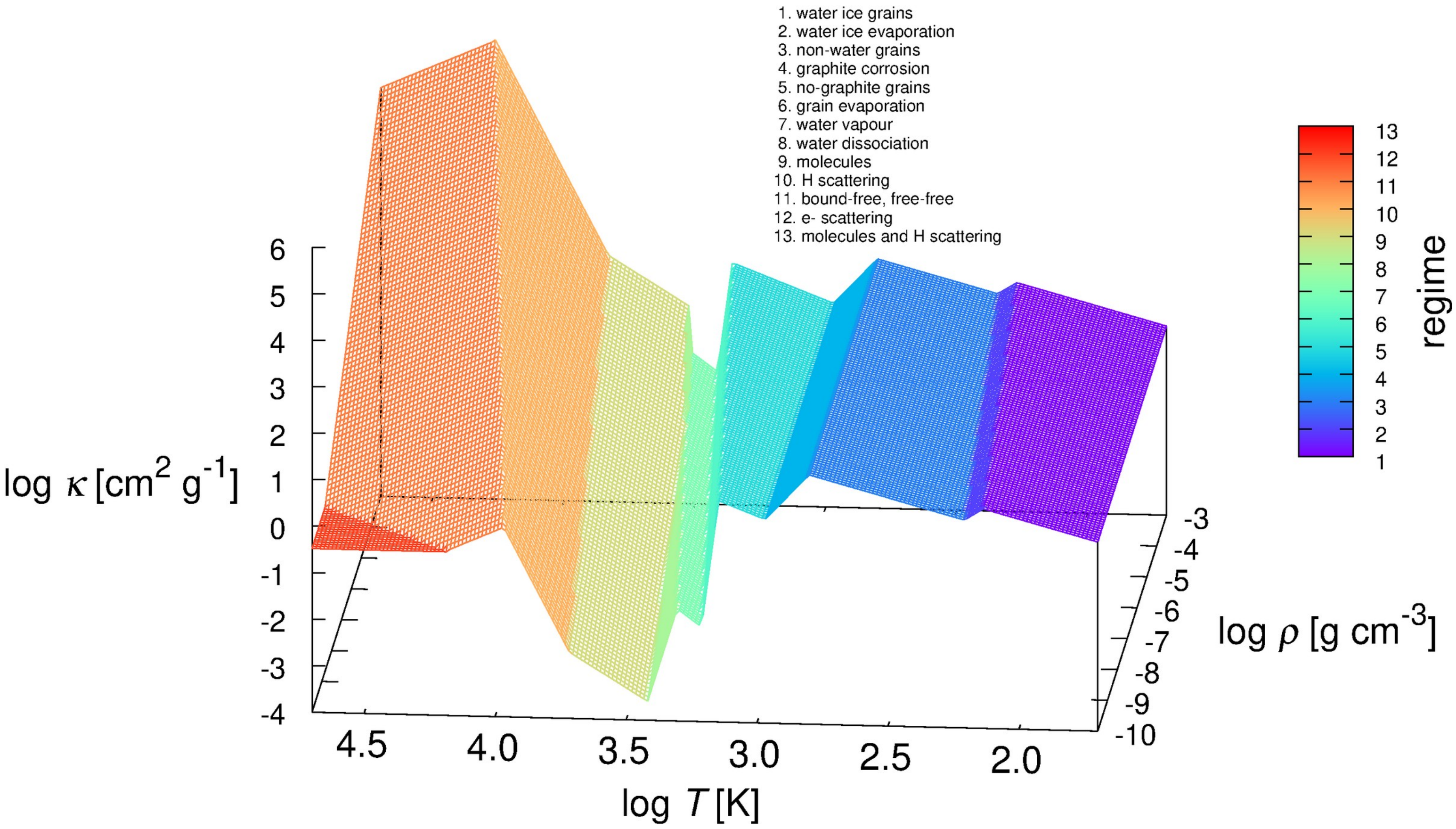
various profiles, e.g.:
MMSN
10× less
100× less
inverted

various opacities, e.g.:
Zhu etal. (2012)
Semenov (2003)
Malygin etal. (2014)



Zhu etal. (2012)

Note: opacity vs. phase transitions

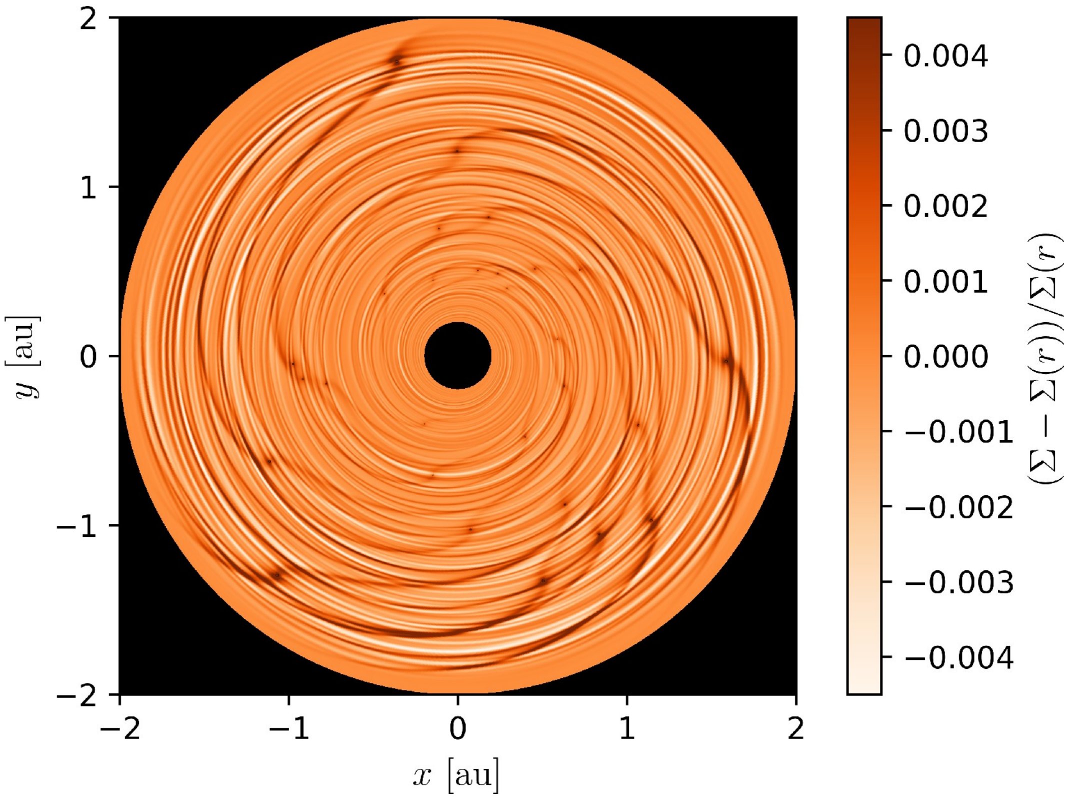


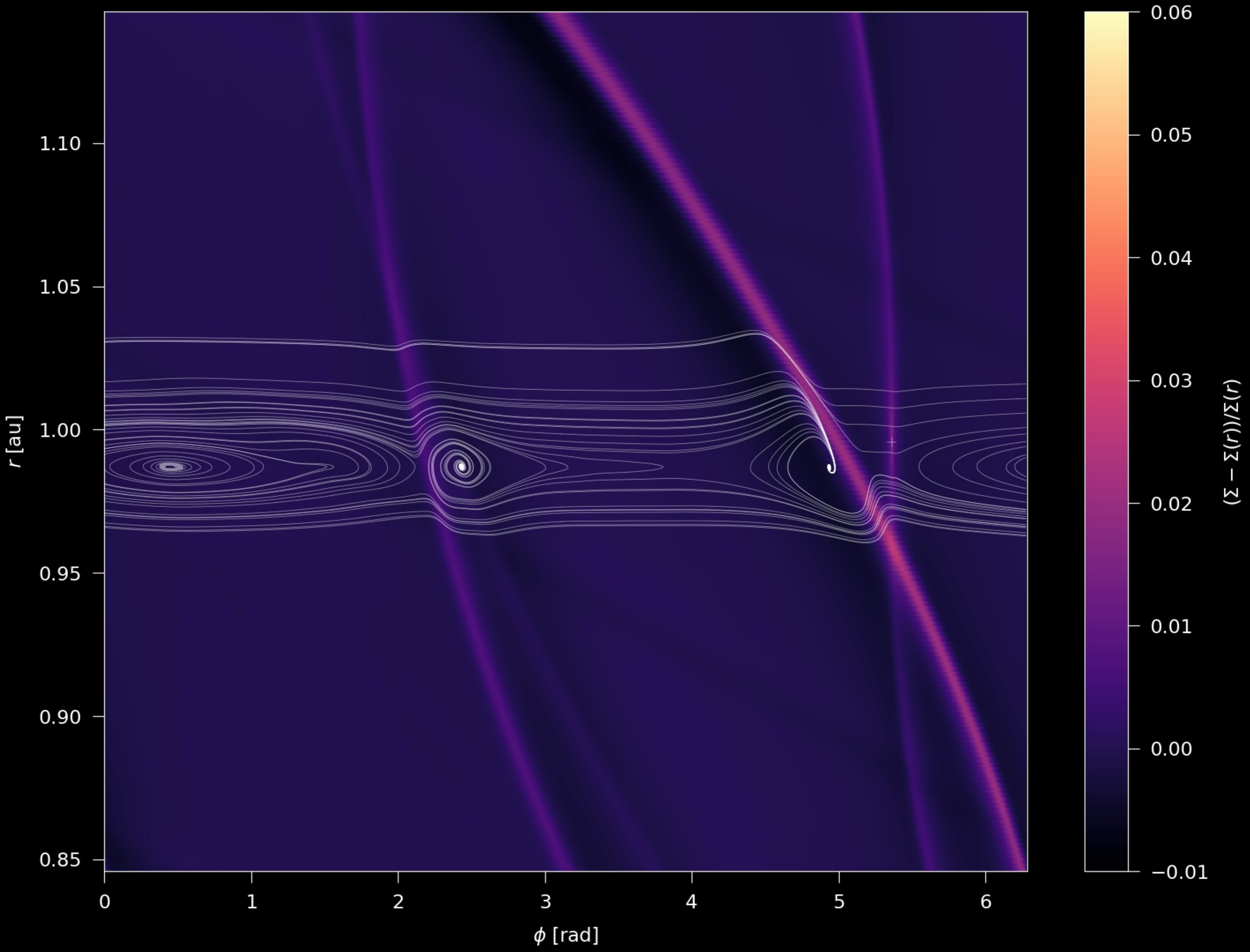
Mercury- to Mars-sized protoplanets

Brož, Chrenko, Nesvorný, Dauphas (NA, **5**, 898-902, 2021)
see also Raymond (NA, **5**, 875-876,2021)

- disk ↔ planet interactions:
- Lindblad torque (Lindblad 1940)
- corotation torque (Masset 2002)
- heating torque (Benitez-Llambay etal. 2015)

- dependence on exponents of Σ, T (Paardekooper etal. 2011)

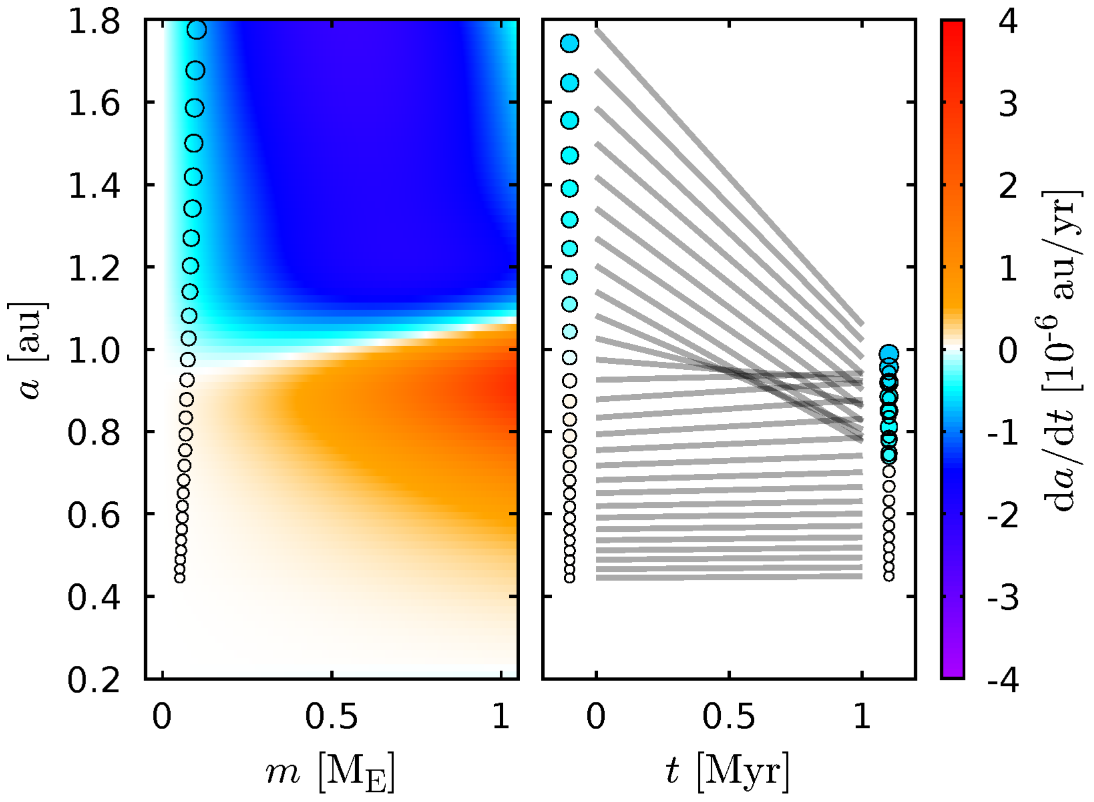




1.10
1.05
1.00
0.95
0.90
0.85
r [au]
0
1
2
3
4
5
6
ϕ [rad]
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
(Σ − Σ(r))/Σ(r)

3. Convergence zone

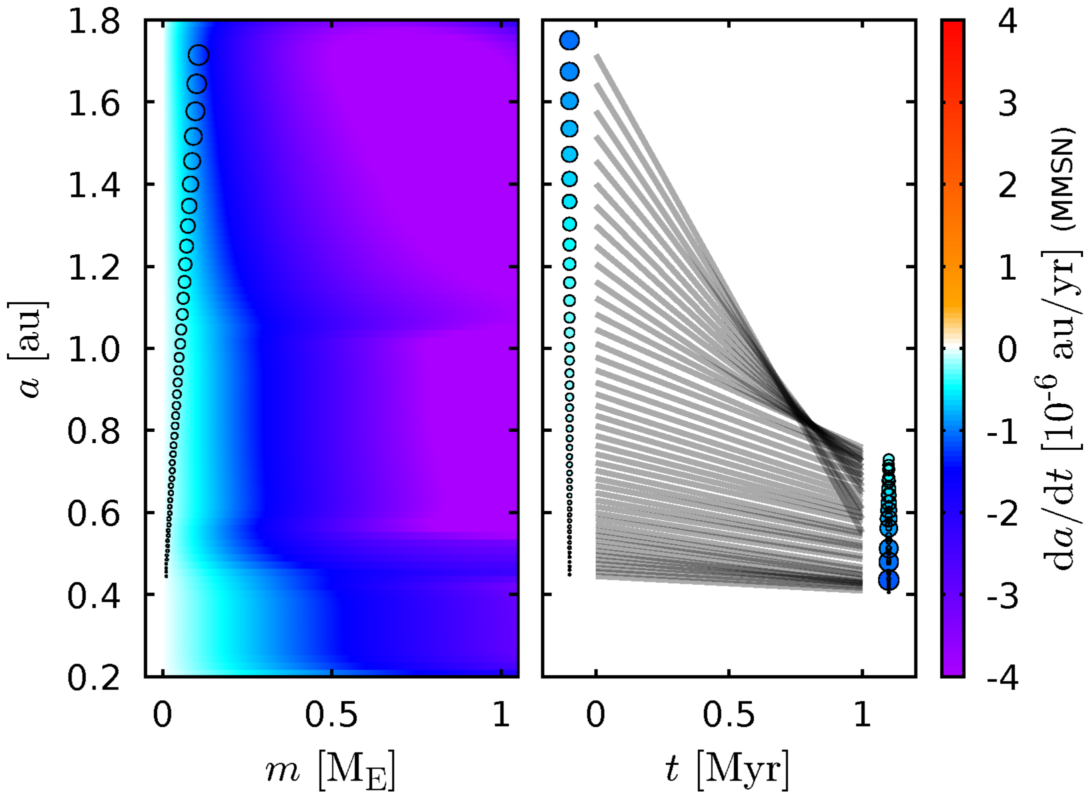
- torque(s) → extrapolated d*a*/d*t*
- protoplanets migrate to $r \sim 1$ au within gas disk lifetime!
- migration map (Paardekooper etal. 2011) without heating torque



Note: Convergence in MMSN

- even for power-law profile
  $\Sigma_{MMSN} = 750\ \mathrm{g/cm^2}\ (r/1\ \mathrm{au})^{-3/2}$
  protoplanets may converge if they differ in masses…

- … but Type-I migration continues after merging!



Simplified N-body model w. migration

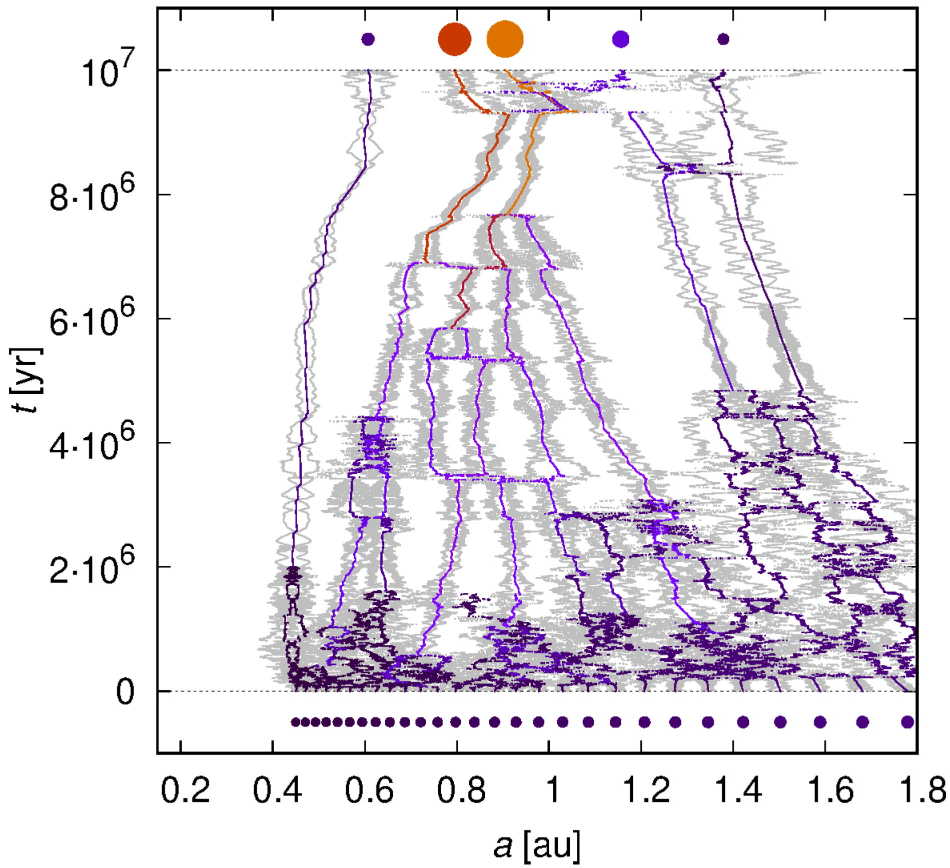
- symplectic integrator (Symba; Levison etal. 1998)
- w. artificial accelerations:

$$\ddot{\mathbf{r}}_i = \frac{1}{2}\dot{a}_i \frac{G(M_\oplus + M_i)}{a_i^2|\mathbf{v}_i|}\,\mathbf{v}_i - 2\mathcal{H}(e_i - e_{\rm hot})\frac{1}{\tau_{\rm e}}\frac{\mathbf{r}_i\cdot\mathbf{v}_i}{r_i^2}\,\mathbf{r}_i - 2\mathcal{H}(i_i - i_{\rm hot})\frac{1}{\tau_{\rm i}}\mathbf{v}_i\cdot\hat{z}\hat{z}\,,$$

- free parameters: migration rate da/dt (τ, r_0), hot-trail eccentricity, inclination, damping time scale(s), pebble flux ($2 \cdot 10^{-7}$ up to $2 \cdot 10^{-4}$ M_E/y), ...
- IC: total mass of protoplanets (2 M_E), multiple of $R_{HH} = 1/2\ (a_1+a_2)\ [(q_1+q_2)/3]^{1/3}$
- **stochastic collisional system**! (for N = 28, at least 50 runs are needed)

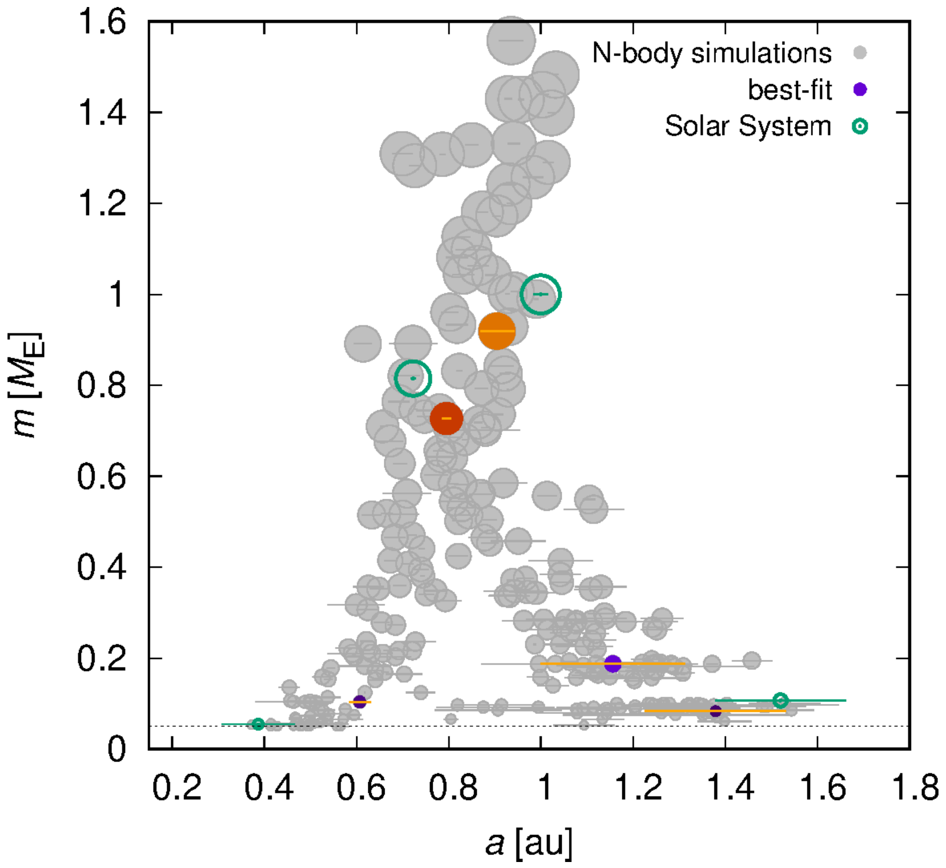
4. Small separation of Venus and Earth

- convergence naturally concentrates mass between 0.7-1 au
- gas is needed until 10 My, otherwise there's repulsion! (Deienno etal. 2019)



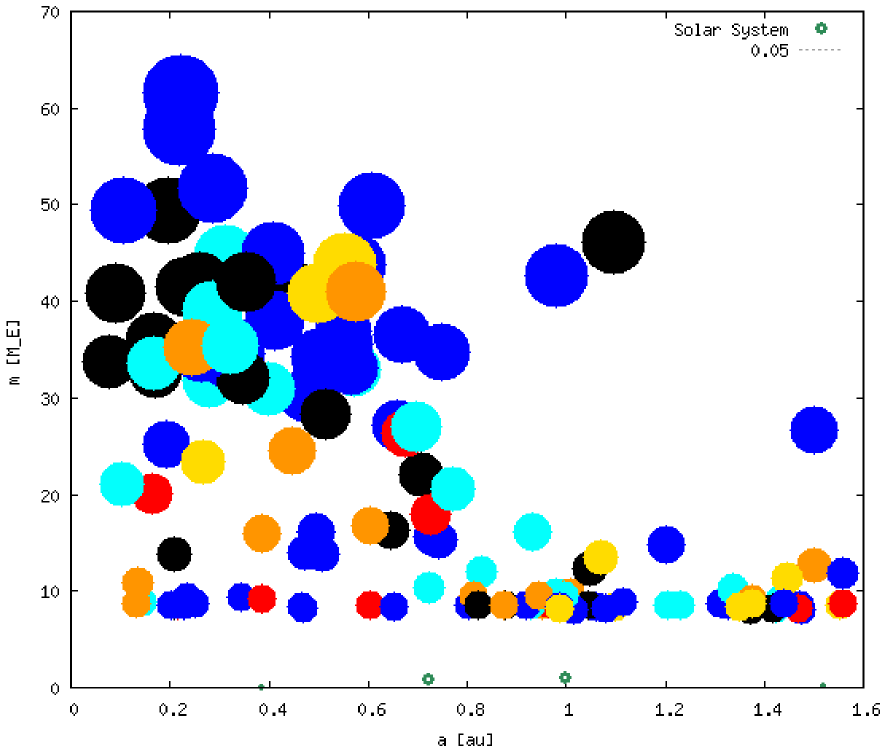
5. Small Mercury as well as Mars

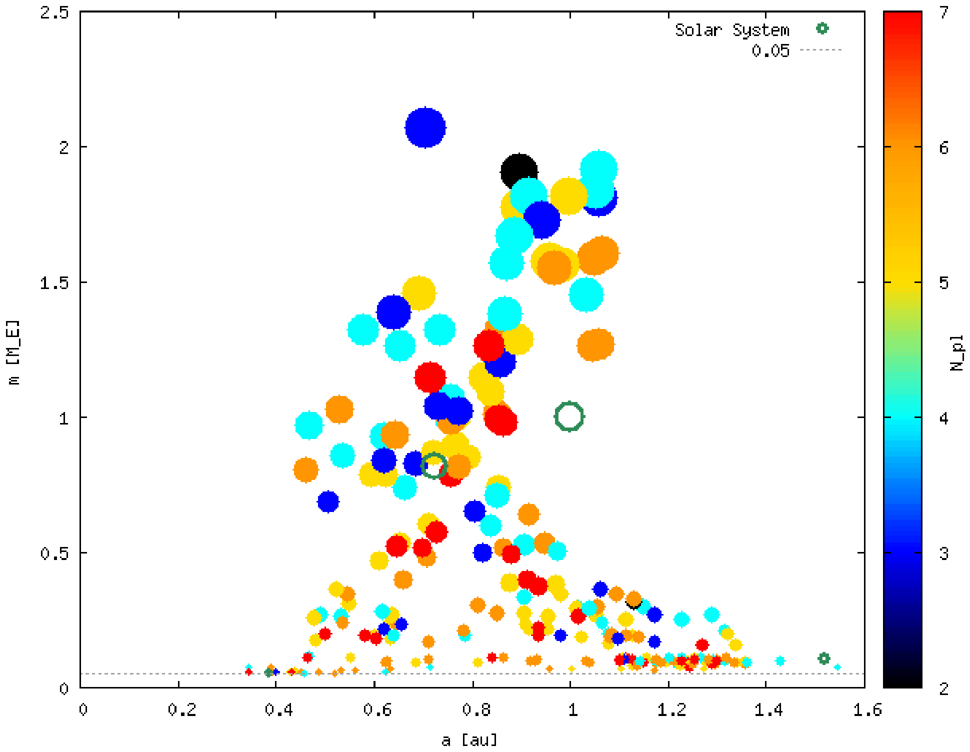
- small bodies naturally remain at the convergence zone boundaries!
- mass removal by an external mechanism is *not* needed (cf. Walsh etal. 2011)!



Note: Problem with overgrowth

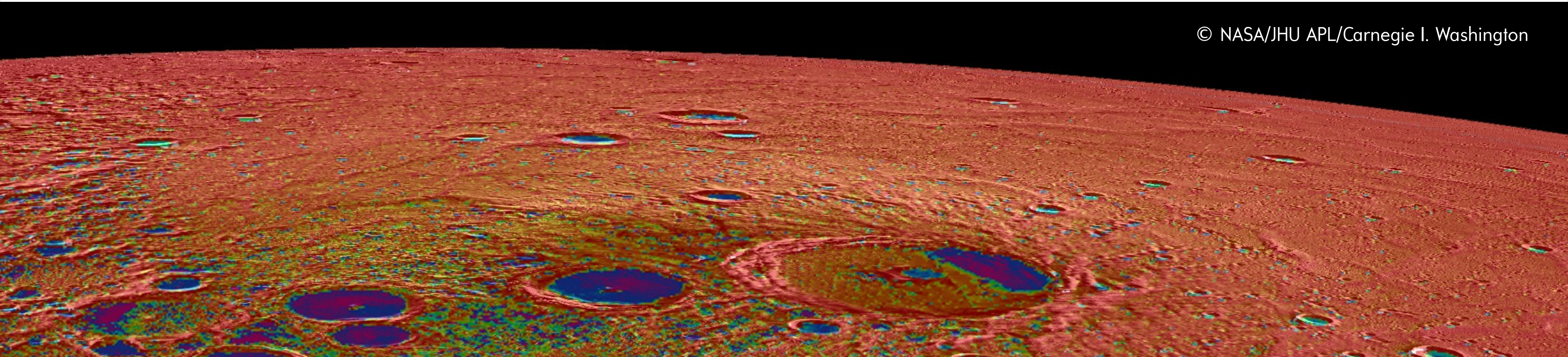
- for high ($2 \cdot 10^{-5}$ M_E/y) & long pebble fluxes → "hot Neptunes"





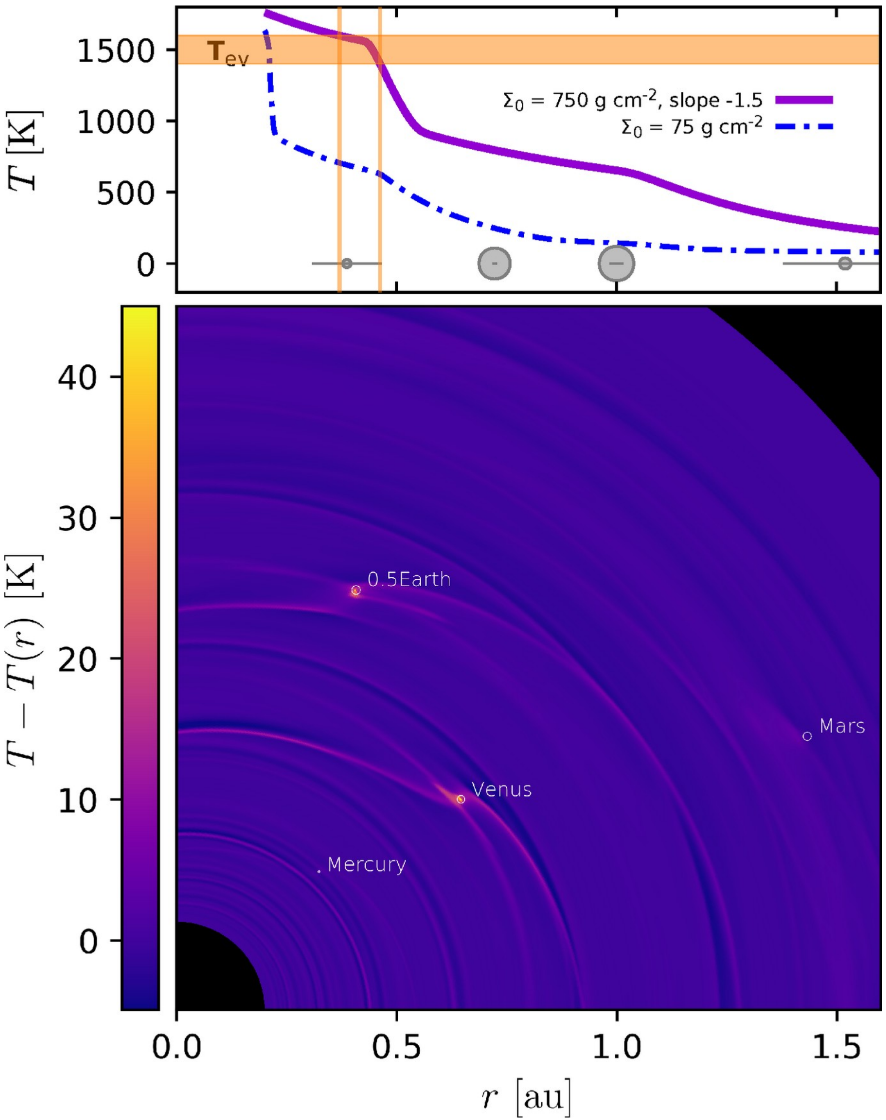
6. Mercury iron core

- … if formed in a hot gas disk, next to the evaporation lines of Fe and Mg-rich silicates, by (evaporating) pebbles drifting to 0.4 au from larger *r*
- i.e., very different from old nebular hypotheses, where the source was limited to a *local* material, or ring! (cf. Weidenschilling 1978)
- mantle-stripping collision (Benz 1988, Reufer & Asphaug 2014) is not needed!



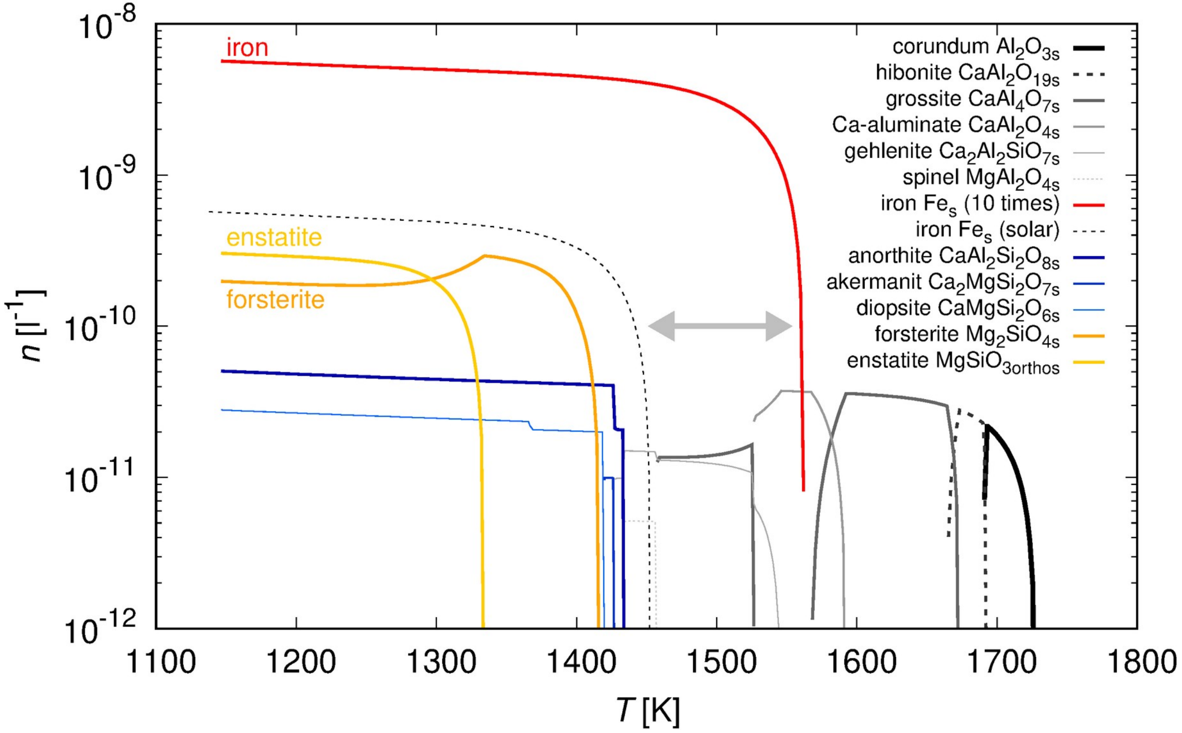
T(*r*) profile, initially hot inner edge?

perturbations of *T*(*x*, *y*); hot-trail effect



Note: Condensation sequence

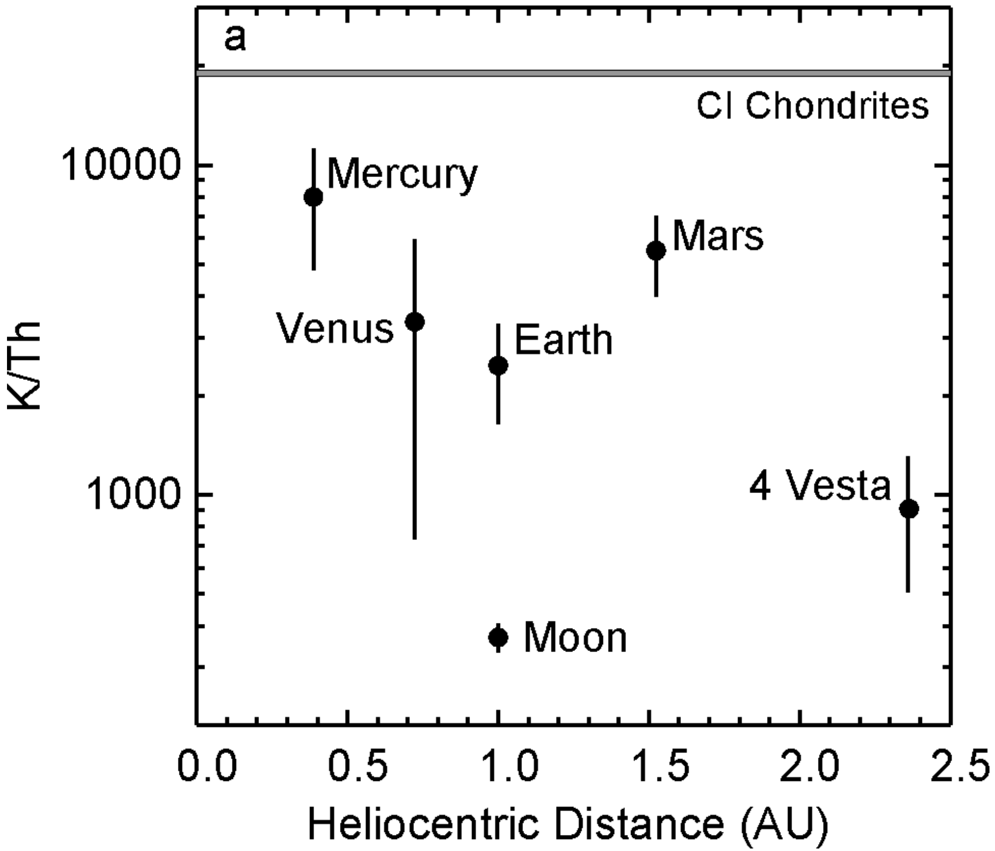
- Unterborn & Panero (2017)
- chemical equilibrium Eqs. for vapour → solids
- no pebble drift (yet), but...
- ... if it's enhanced in Fe and enstatite/forsterite → Fe/Si for Mercury core



moderate!

7. Volatiles on Mercury

- Messenger (Nittler etal. 2018): rich in Na, S, **K**, Cl
- at late stages, disk *T* was likely low, actually lower than equilibrium *T* today!
- delivery by volatile-rich pebbles?
- late veneer?

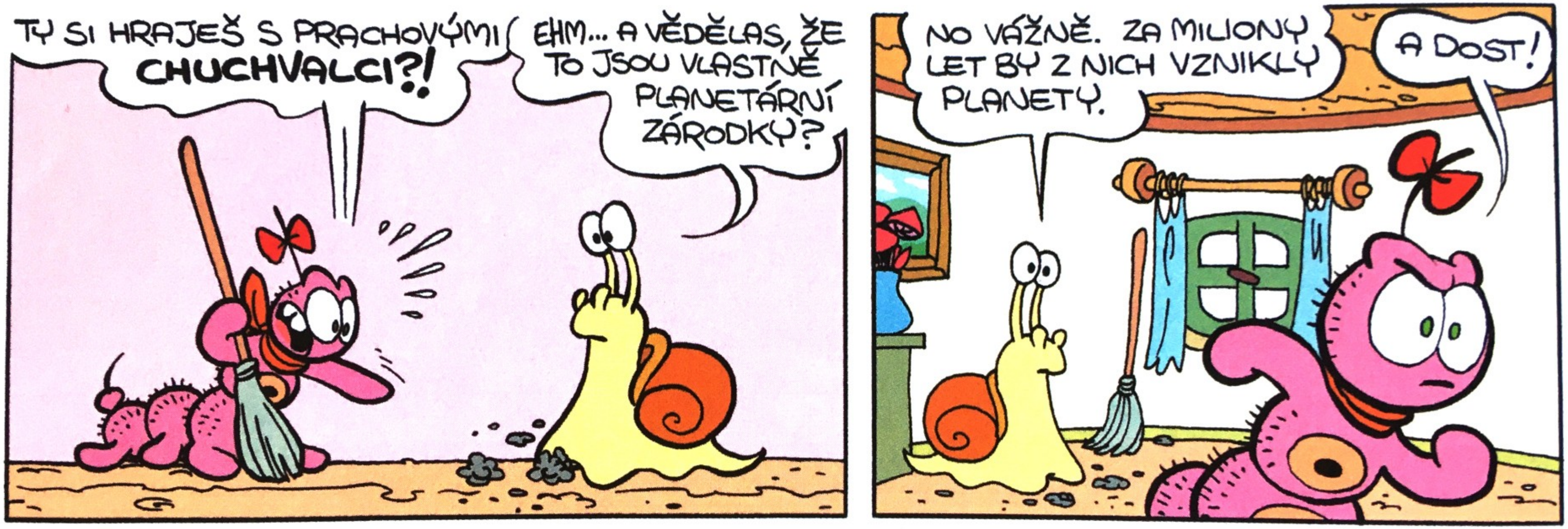


8. Water delivery on Earth?

- … is possible by icy pebbles in a **cold disk** (with snowline temporarily at 1 au); if not *totally* blocked by Jupiter!
- cf. pressure bump ← could have been overcome if there is a *pile-up* of solids?
- 1 Earth ocean ≡ $2.3 \cdot 10^{-4}\ M_E$; need to deliver 2-8 E. o. (Peslier etal. 2017)
- filtering factor of E. f = 1-1.5 %, ice fraction 0.1, pebble flux $2 \cdot 10^{-6}\ M_E/y$, $\tau = 10^5$ y
- problem w. high pebble flux, transient?
- problems w. isotopic signatures…

Note: Alternative theories...

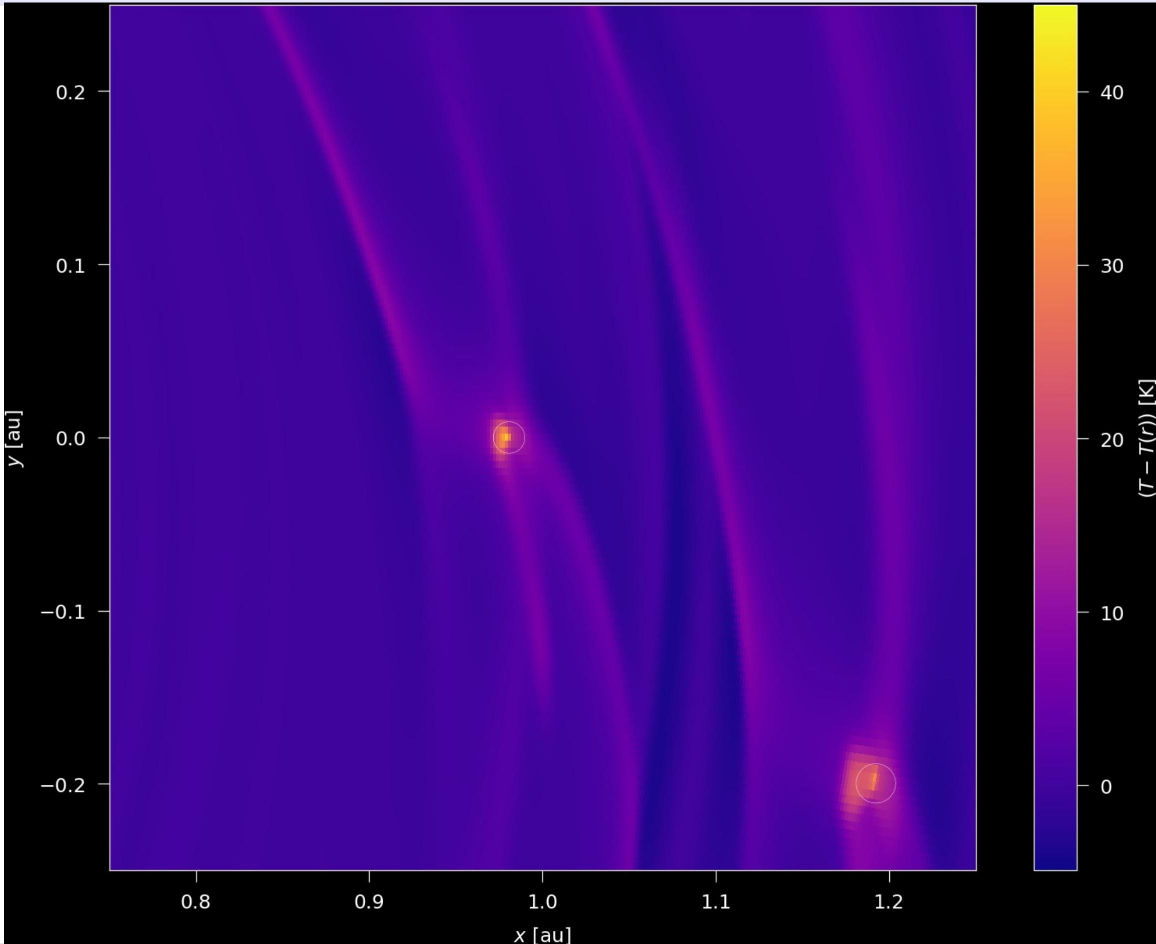
- **... aren't always successful.** [Are you playing with dust bunnies?! Ehm... and do you know they are in fact germs of planets? Seriously. After millions of years, planets would be formed out of them. Enough!]

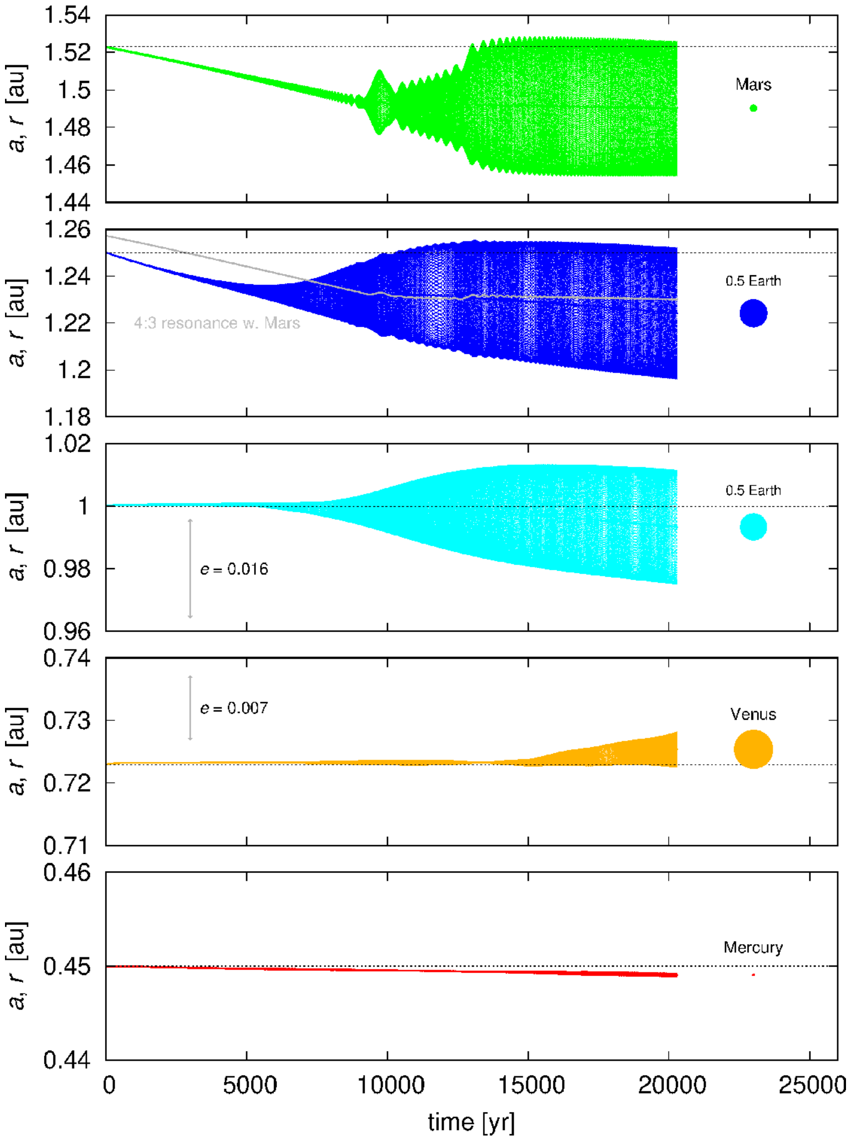


Černý (Čt., **644**, 64-63, 2021)

9. Eccentricity of Earth or Venus

- **hot trail effect** (Chrenko etal. 2017) → increase of *e* up to the *current* value for Venus & Earth, i.e., 0.015 to 0.020!
- 'easy' for low Σ, high dM_p/dt
- a late eccentricity excitation by an external mechanism is *not* needed!



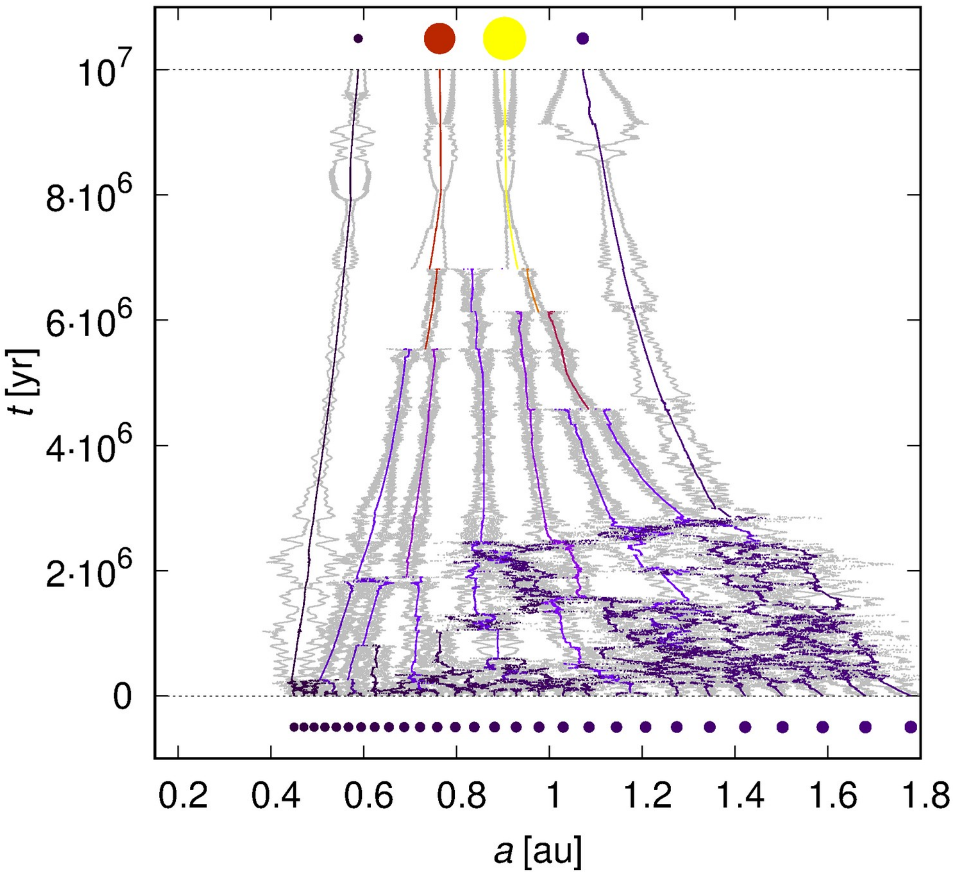


Mars
0.5 Earth
4:3 resonance w. Mars
0.5 Earth
e = 0.016
e = 0.007
Venus
Mercury
a, r [au]
time [yr]

10. Detaching planetary orbits

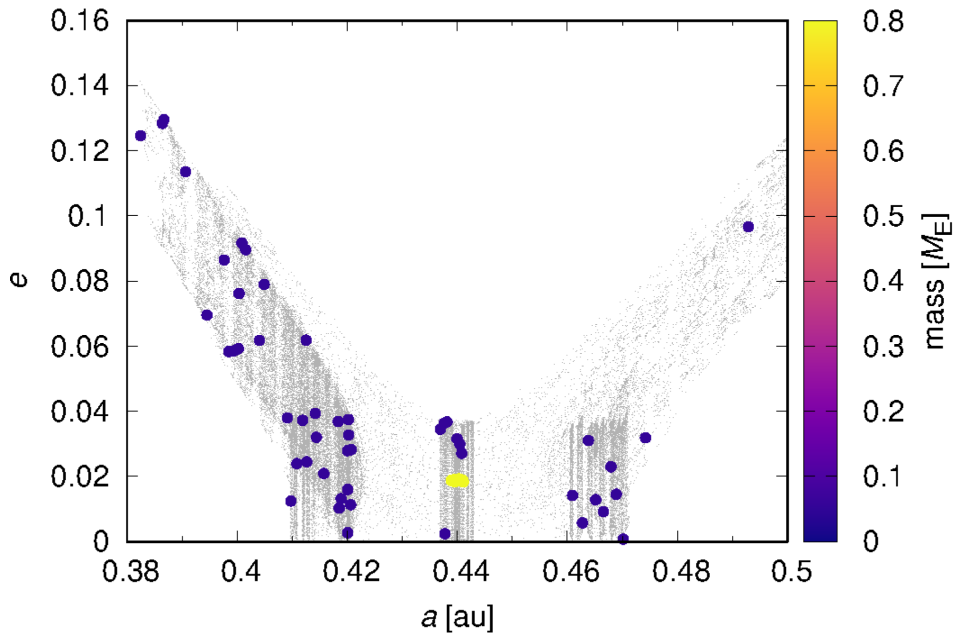
- in gas disk, orbits can be detached by 3 mechanisms:
  1. mergers (classical)
  2. **differential migration**
  3. **eccentricity damping**

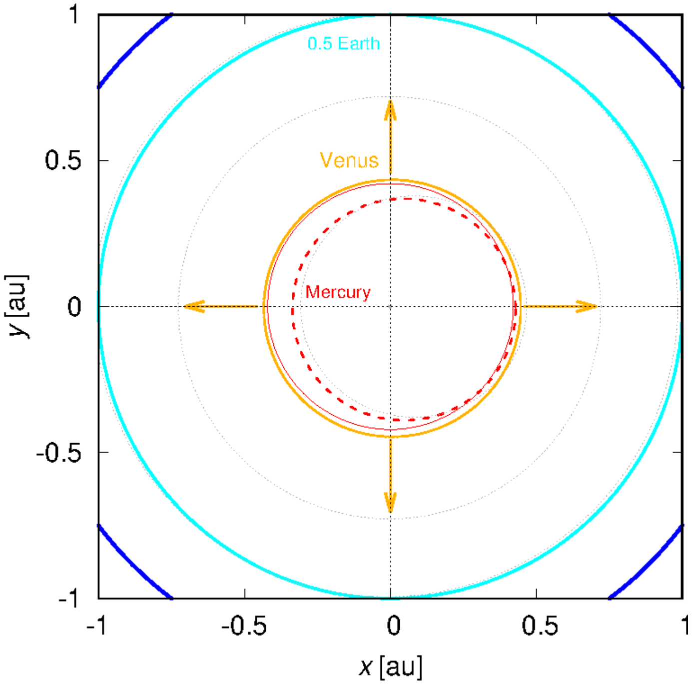
- Type-I migration can be suppressed by 3 mechanisms:
  1. close encounters (classical)
  2. **inverted $\boldsymbol{\Sigma}$(*r*) profile**
  3. **eccentricity pumping** (hot-trail)



Note: Scattering of Mercury on Venus

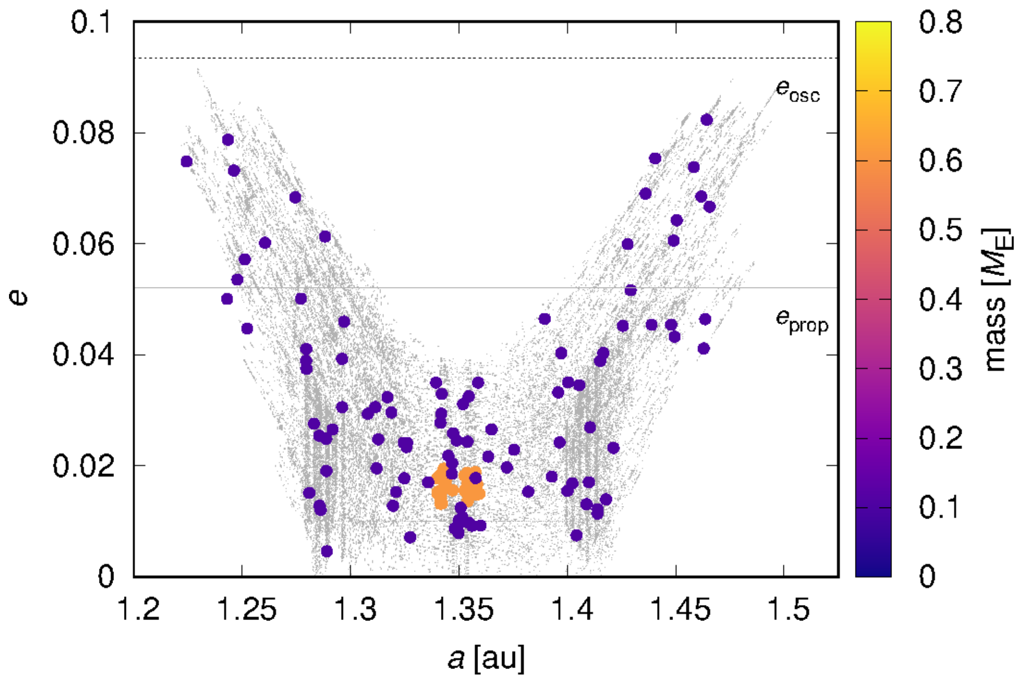
- Mercury's osculating eccentricity 0.206, proper 0.167

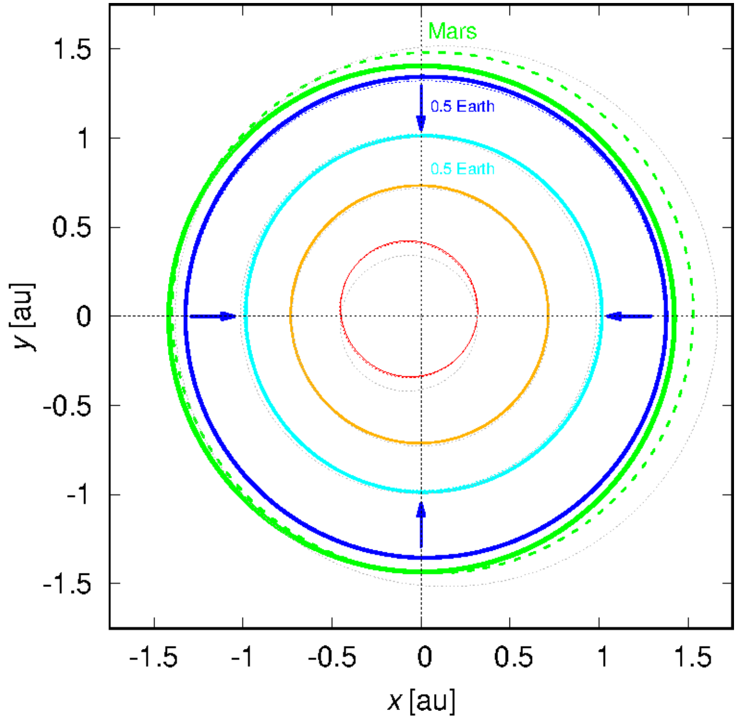




Note: Scattering of Mars on 0.5-Earth

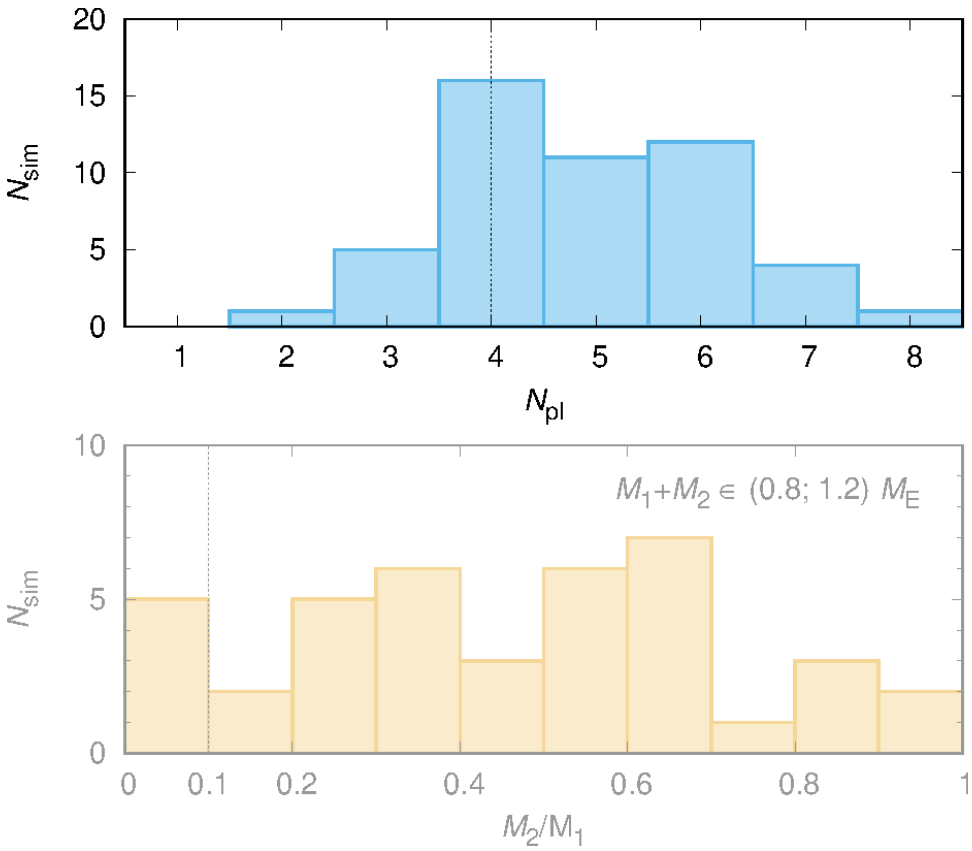
- dtto for Mars, osculating 0.093, proper 0.052; |d*a*/d*t*| for 0.5-Earth > Mars





11. A 5-planet system

- A 5-planet system was likely formed at the end of the gas phase (see below)
- 4-6 planets are common; depending on migration rate vs. gas disk lifetime



12. Moon-forming impact @ 45 My

- **geochemical** modelling of the tungsten anomaly (Yu & Jacobsen 2011)

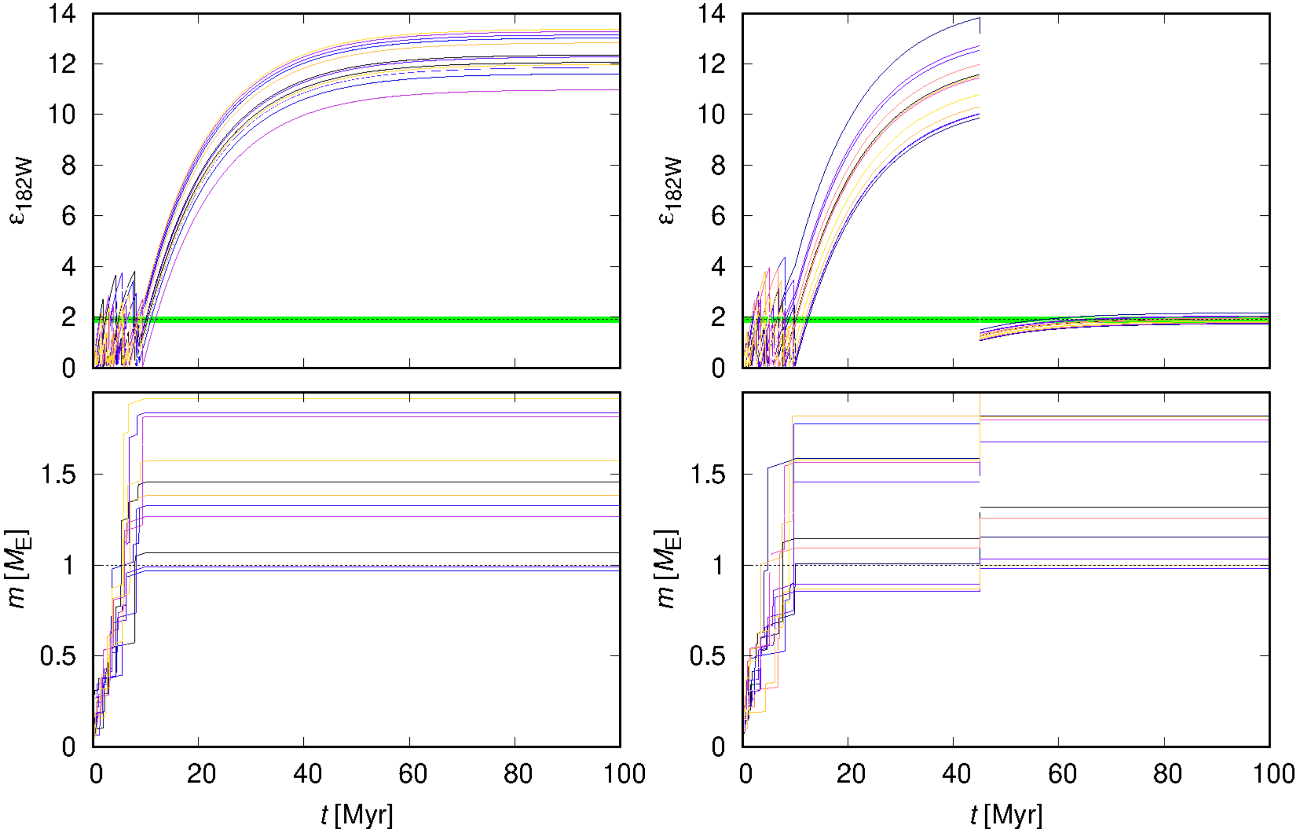
  $^{182}Hf \rightarrow {}^{182}Ta + e^{+} + \nu$

  $^{182}Ta \rightarrow {}^{182}W + e^{+} + \nu$

$$\varepsilon_2 \equiv 10^4 \left(\frac{N_{182\mathrm{W},2}/N_{183\mathrm{W},2}}{N_{182\mathrm{W},1}/N_{183\mathrm{W},1}} - 1 \right)$$

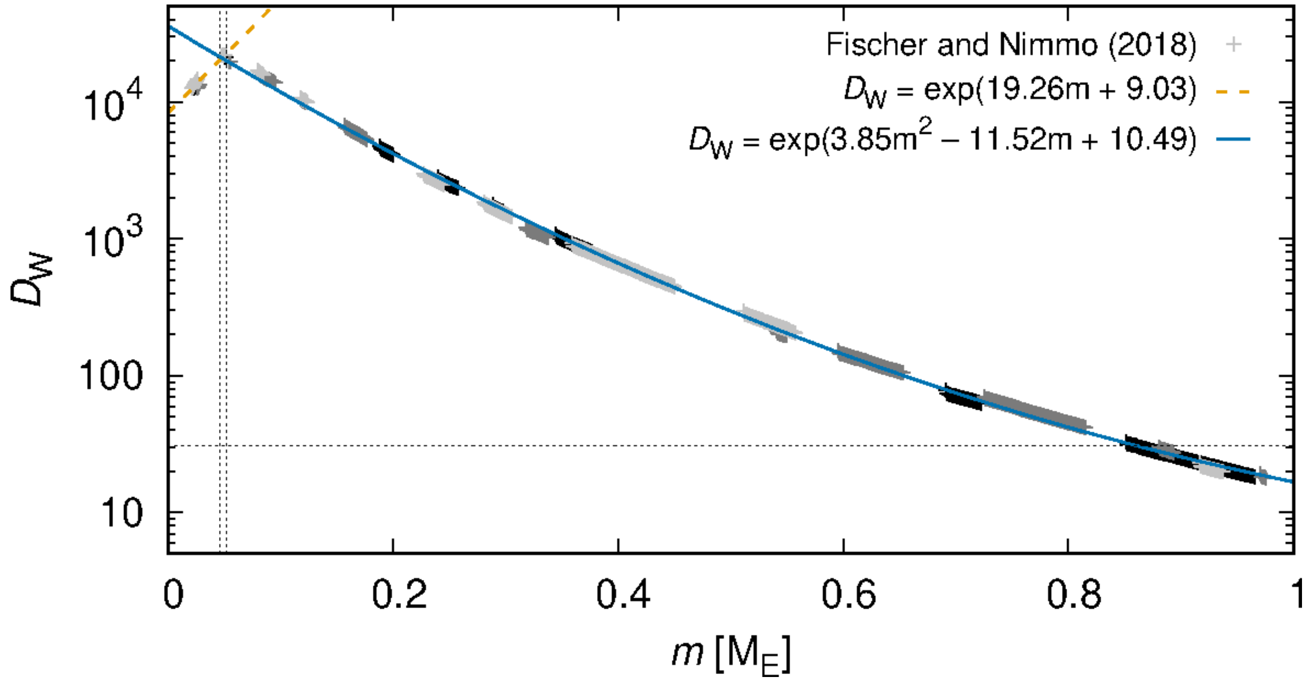
  W ... siderophile, Hf ... litophile,
  1 ... nebula, 2 ... mantle, 3 ... core

- observed value **1.9 ± 0.1**

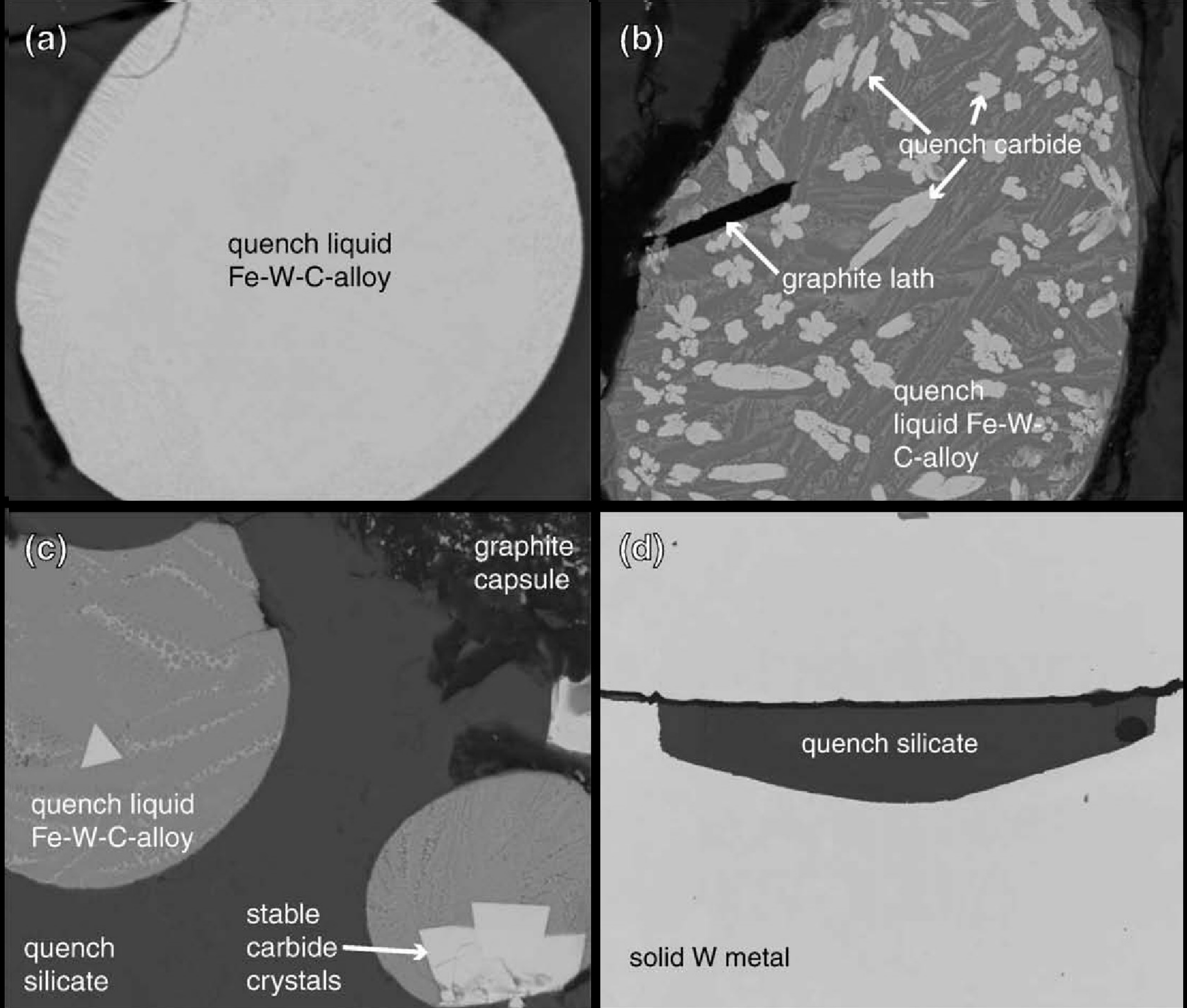


Note: Partitioning coefficient D_W

- i.e., important parameter of the g. m.; according to Fischer & Nimmo (2018)

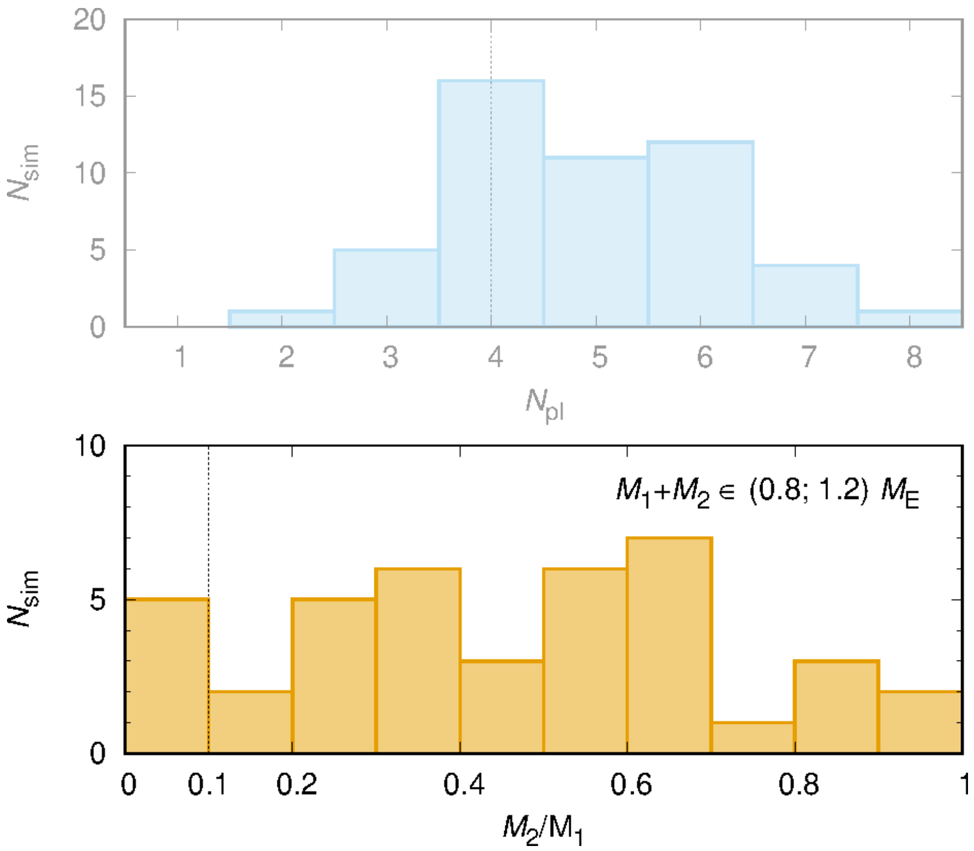


Cottrell etal. (2009)



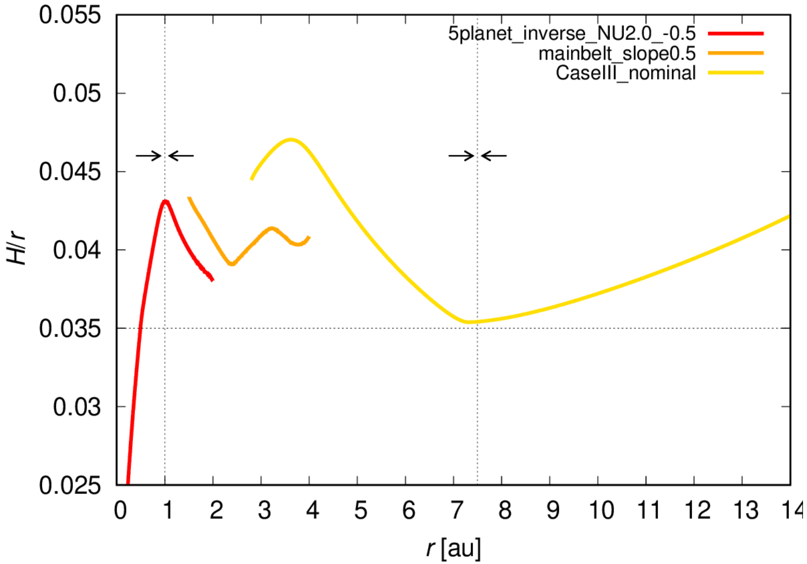
13. Common 0.5-Earth's impacts

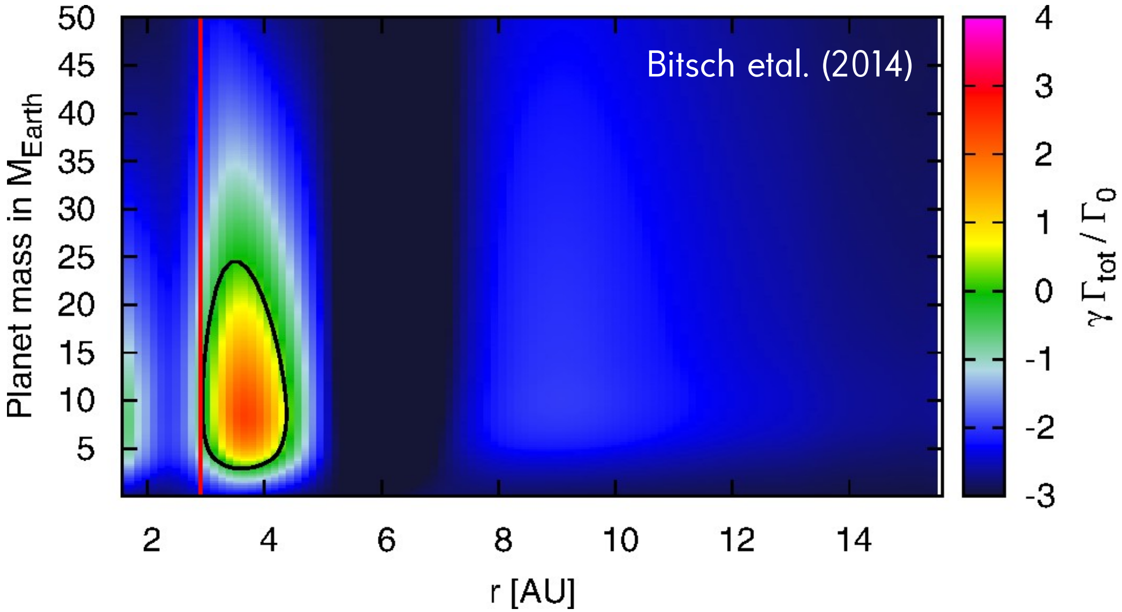
- 0.5-Earth's impacts are equally probable as the canonical ones (0.1 M_E)
- *full* (cm-scale) equilibration between projectile & target might have been easier?



14. Divergence zone 2-3 au

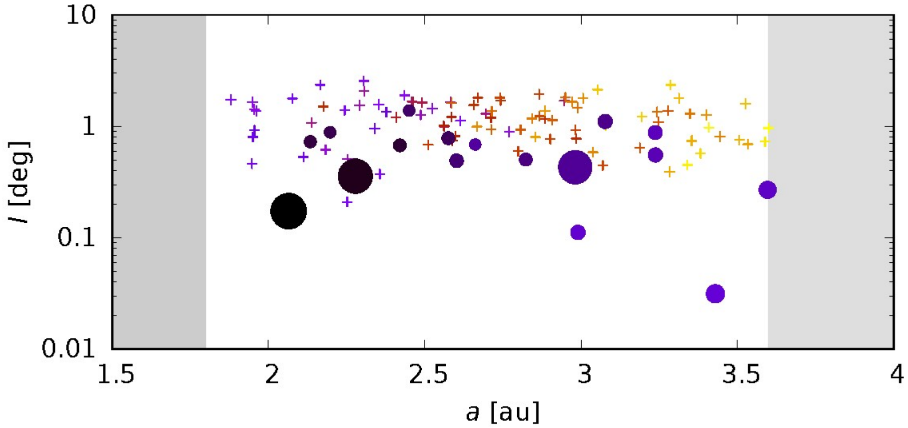
- snowline = **divergence zone** (Bitsch etal. 2014, A&A, 564, A135),
- i.e., between terrestrial- and giant-planet convergence zones!

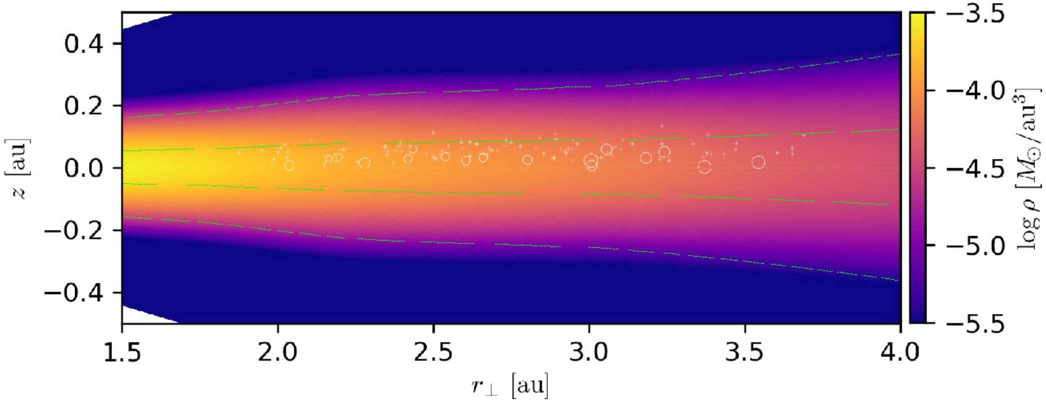




15. Mass depletion in the asteroid belt

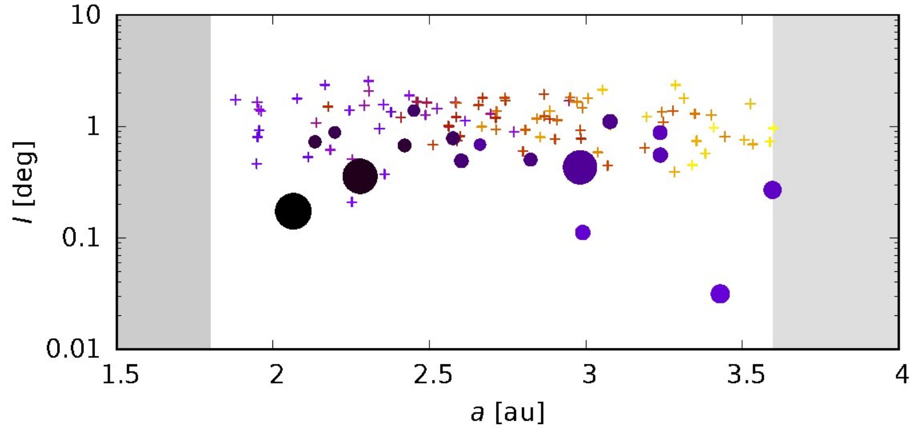
- Mars- to Earth-sized embryos drift away (Brož etal. 2018)…
- … which implies a mass depletion in the asteroid belt (by a **factor of 10^2**)

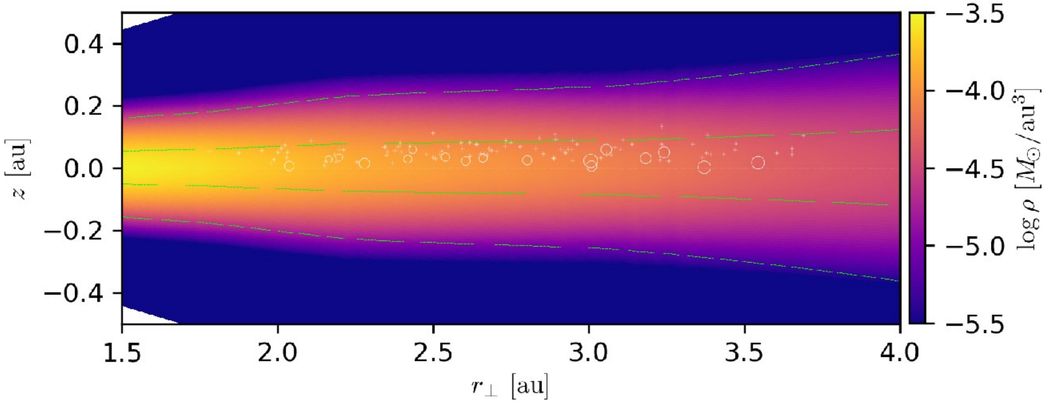




16. Inclined asteroid belt

- Inclined asteroid-belt orbits were **scattered by protoplanets** migrating away in a gas disk (ærodynamic drag on asteroids is weak).





17. Dry inner asteroid belt

- … may be due to a low efficiency of pebble accretion (for low m's, high i's).

Ormel (2017)

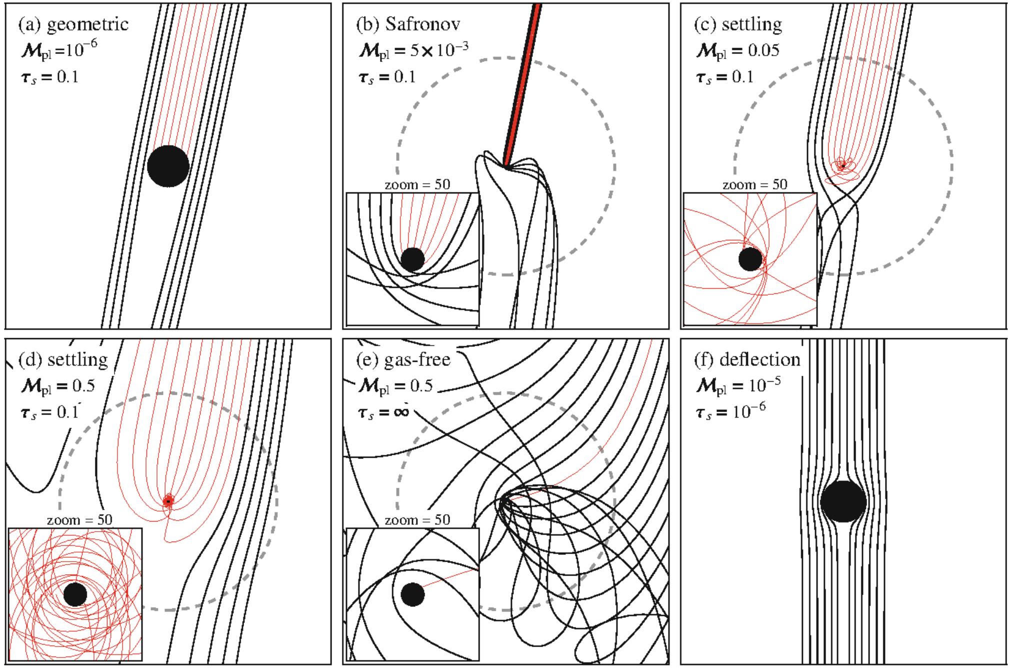
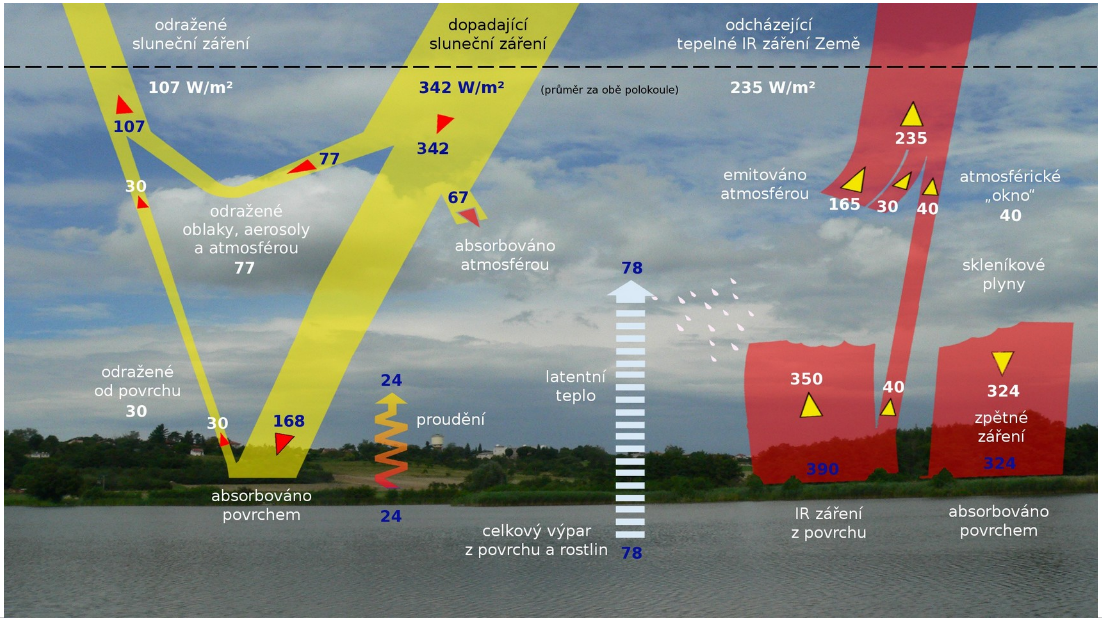


Fig. 7.1 Examples of planet-pebble interactions, viewed in the frame co-moving with the planet. In each panel the *filled circle* denotes the physical size of the planet and the *dashed circle* its Hill

18. Dry Venus

- Venus remained dry if the **snowline** was always at $r > 0.7$ au, and ...
- ... there is no missing-oxygen problem after a runaway greenhouse effect (as in Chassefière 1997; cf. Gillmann etal. 2020).



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