Gas flow around luminous protoplanets in the context of planet migration

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results from Chrenko & Lambrechts (2019)

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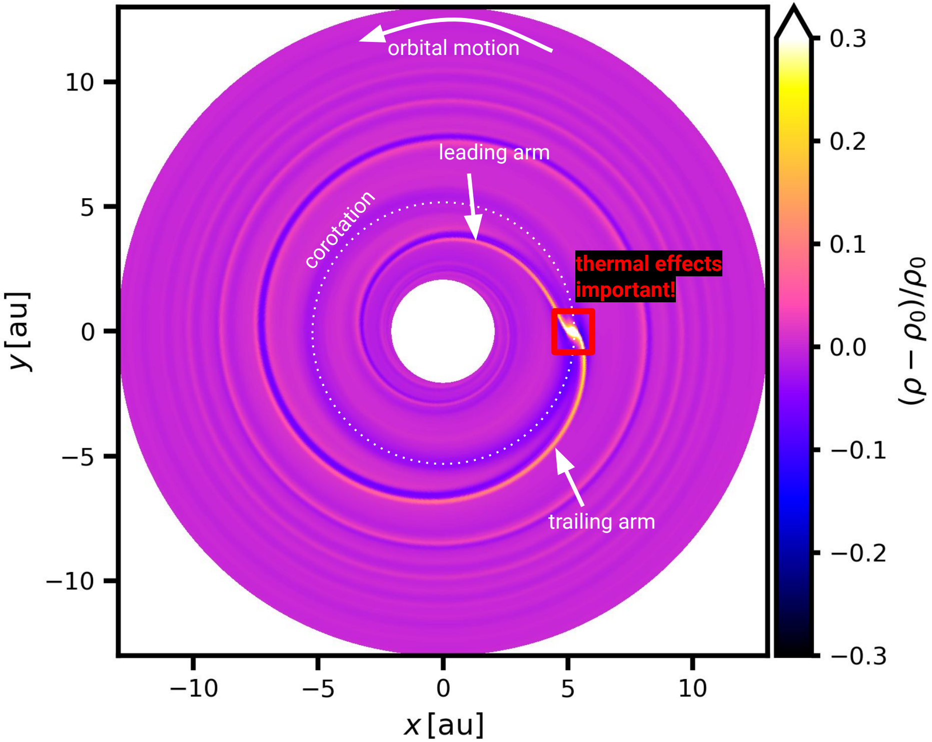
Outline

Based on results from Chrenko & Lambrechts (2019) I will

- **review thermal effects** that operate in the vicinity of planets and affect their migration
    - cold-finger effect (Lega et al. 2014)
    - heating torque (Benítez-Llambay et al. 2015)
- describe the **3D distortion of the gas flow around luminous planets**
- show that the **flow can become non-stationary**, causing an **oscillatory migration**



3D model

- hydrodynamic module of **Fargo3D** (Benítez-Llambay & Masset 2016) **+ equations for energy densities of radiation and gas** (following Bitsch et al. 2013):

radiative diffusion

absorption/emission coupling

$$\frac{\partial E_{\mathrm{R}}}{\partial t} + \nabla \cdot \boldsymbol{F} = \rho \kappa_{\mathrm{P}} \left[4\sigma T^4 - c E_{\mathrm{R}} \right],$$

$$\frac{\partial \epsilon}{\partial t} + (\boldsymbol{v} \cdot \nabla)\, \epsilon = -P \nabla \cdot \boldsymbol{v} - \rho \kappa_{\mathrm{P}} \left[4\sigma T^4 - c E_{\mathrm{R}} \right] + Q_{\mathrm{visc}} + Q_{\mathrm{art}} + Q_{\mathrm{acc}},$$

advection

compressional heating

viscous and shock heating

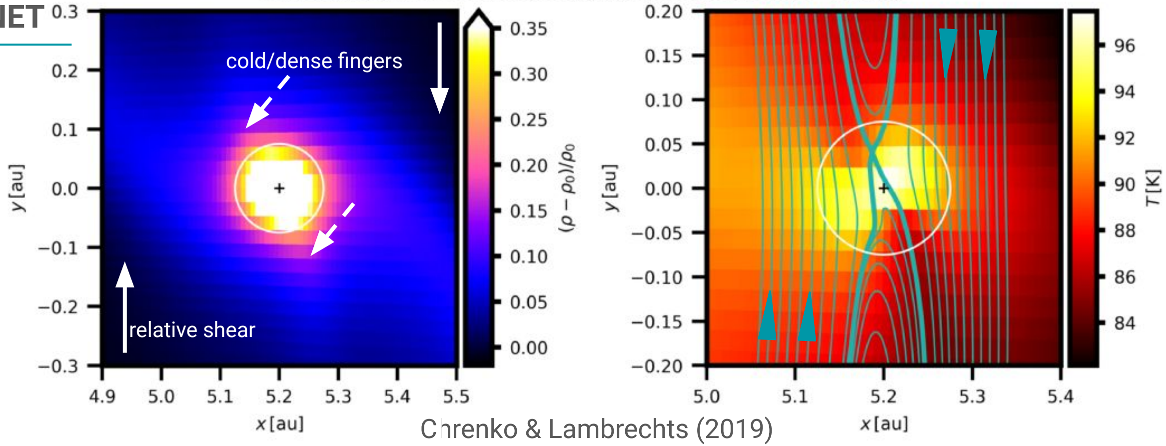
accretion heating of protoplanets (as in Benítez-Llambay et al. 2015)

- 3 M_{Earth} planet at 5.2 au: **non-accreting** (zero luminosity) or **accreting** $L = \frac{G M_{\mathrm{p}} \dot{M}_{\mathrm{p}}}{R_{\mathrm{p}}} = \frac{G M_{\mathrm{p}}^2}{R_{\mathrm{p}} \tau}$
  (mass doubling time 100 kyr, luminosity 4.2×10^{27} erg s^{-1})
- opacity: **constant** or **Bell & Lin (1994)**

Constant-opacity disk: review of thermal effects

COLD PLANET

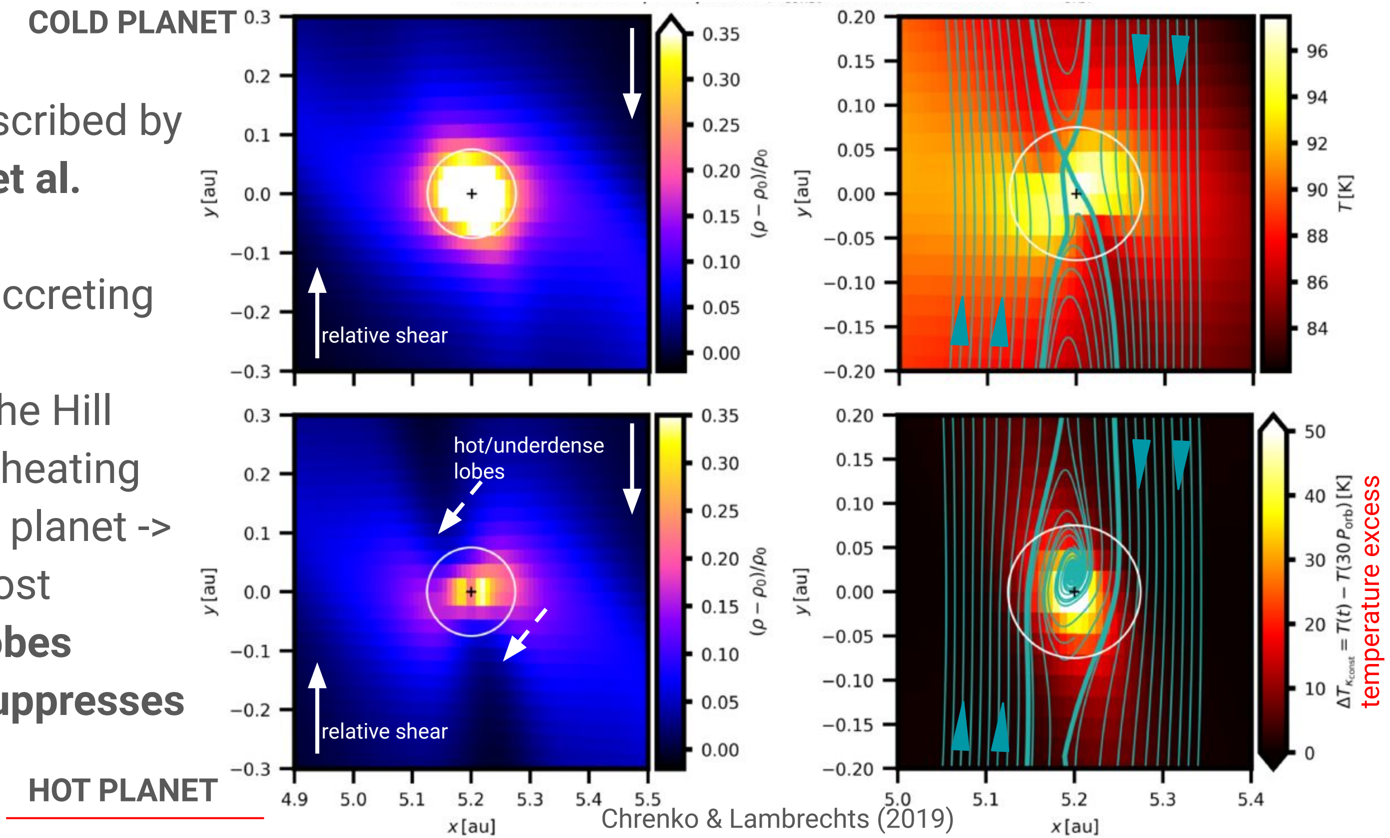
- **cold-finger effect** described by **Lega et al. (2014)**
- cold = non-luminous = non-accreting planet
- gas flow through the Hill sphere: compressional heating -> radiative energy loss -> decompression -> internal energy deficit
- **cold/dense fingers**
- **negative torque (supports inward migration)**



Chrenko & Lambrechts (2019)

Constant-opacity disk: review of thermal effects

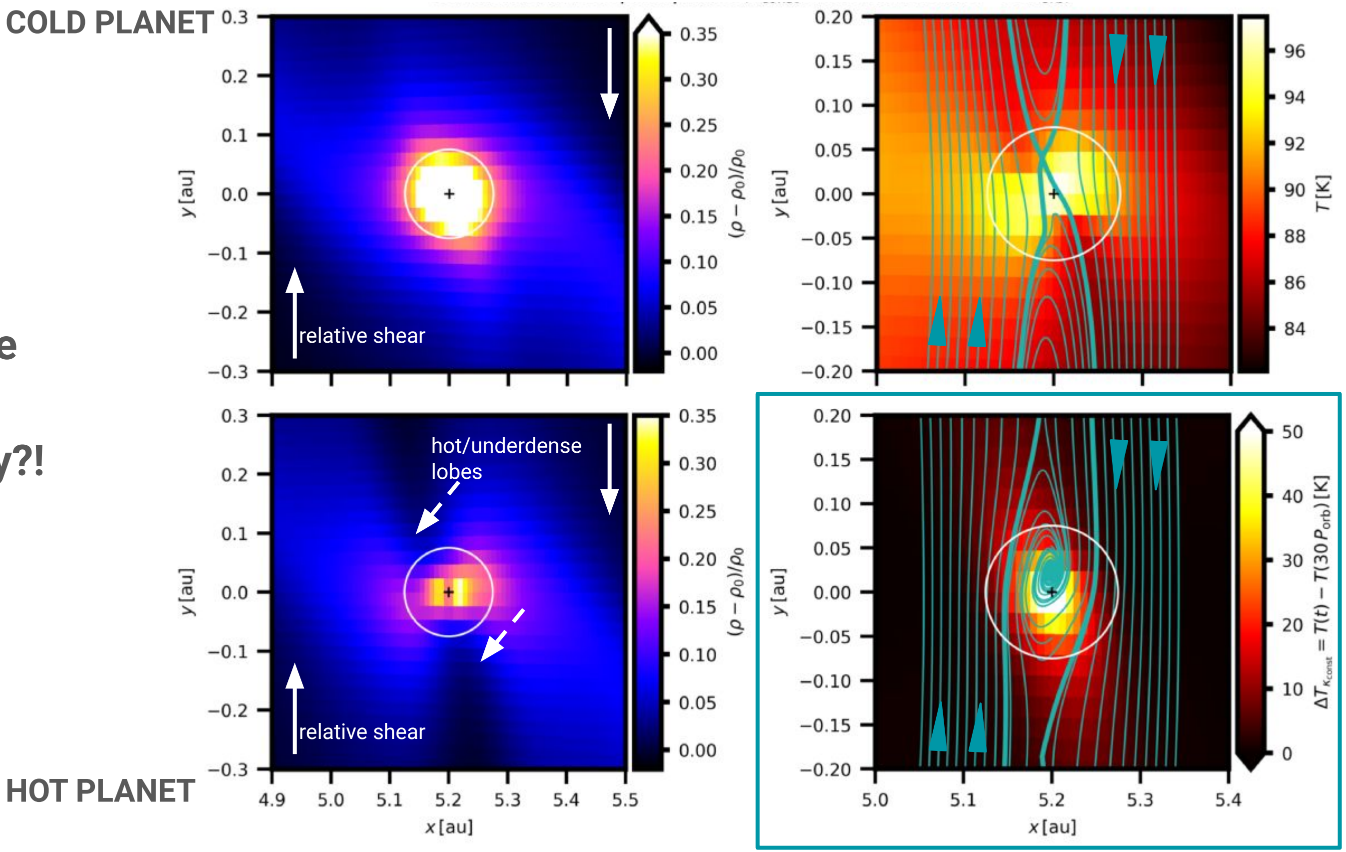
- **heating torque** described by **Benítez-Llambay et al. (2015)**
- hot = luminous = accreting planet
- gas flow through the Hill sphere: additional heating from the luminous planet -> internal energy boost
- **hot/underdense lobes**
- **positive torque (suppresses inward migration)**



Chrenko & Lambrechts (2019)

Constant-opacity disk: a new result

- **But what causes the differences in the streamline topology?!**

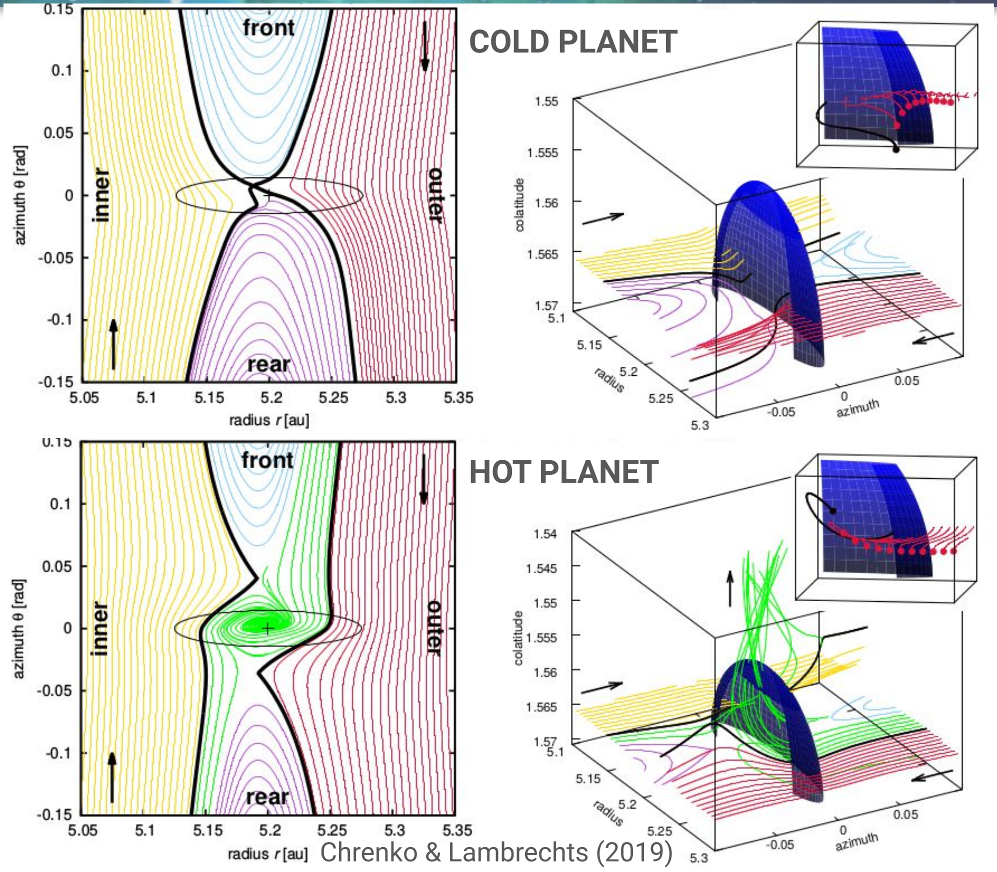


Constant-opacity disk: streamline topology

For the hot planet we see:

- a **vertical outflow** from the Hill sphere (note that cold & low-luminosity planets have an inflow; e.g. Lambrechts & Lega 2017)
- **U-turns farther away** from the Hill sphere
- **circulating streamlines bend towards the planet** and **rise vertically**

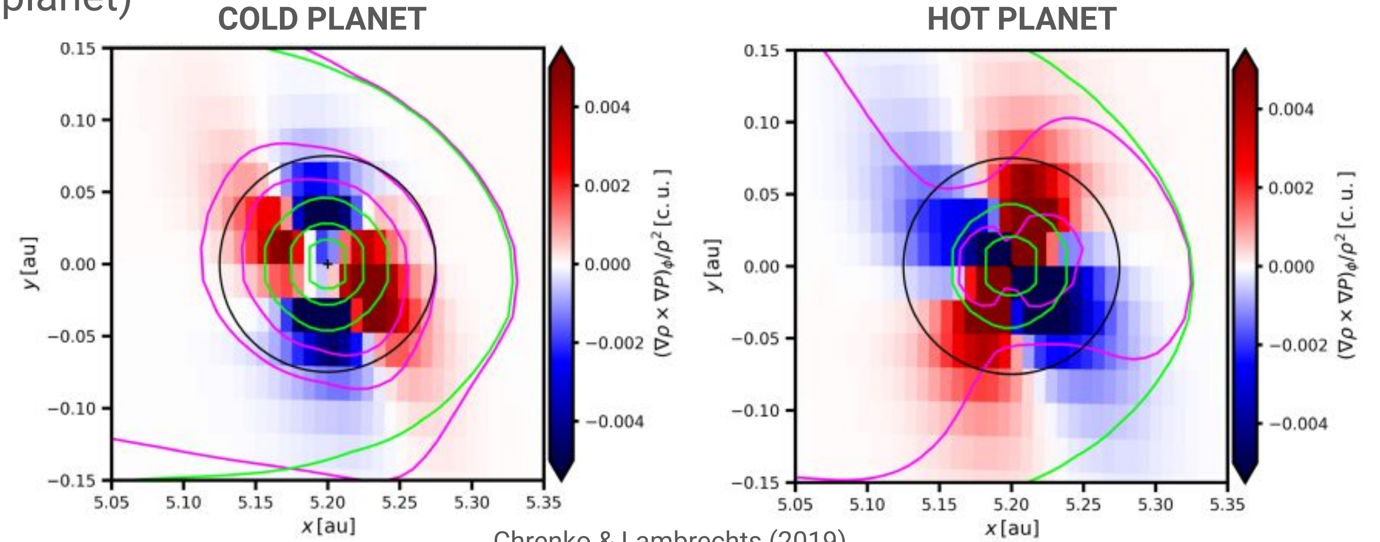
flow perturbations explained in the following...



Chrenko & Lambrechts (2019)

Baroclinic flow perturbation

- baroclinic term of the vorticity equation: $\dfrac{\nabla\rho \times \nabla P}{\rho^2}$
- for the hot planet: surfaces of constant density (purple) and pressure (green) substantially misaligned; map of the baroclinic term antisymmetric (compared to the cold planet)

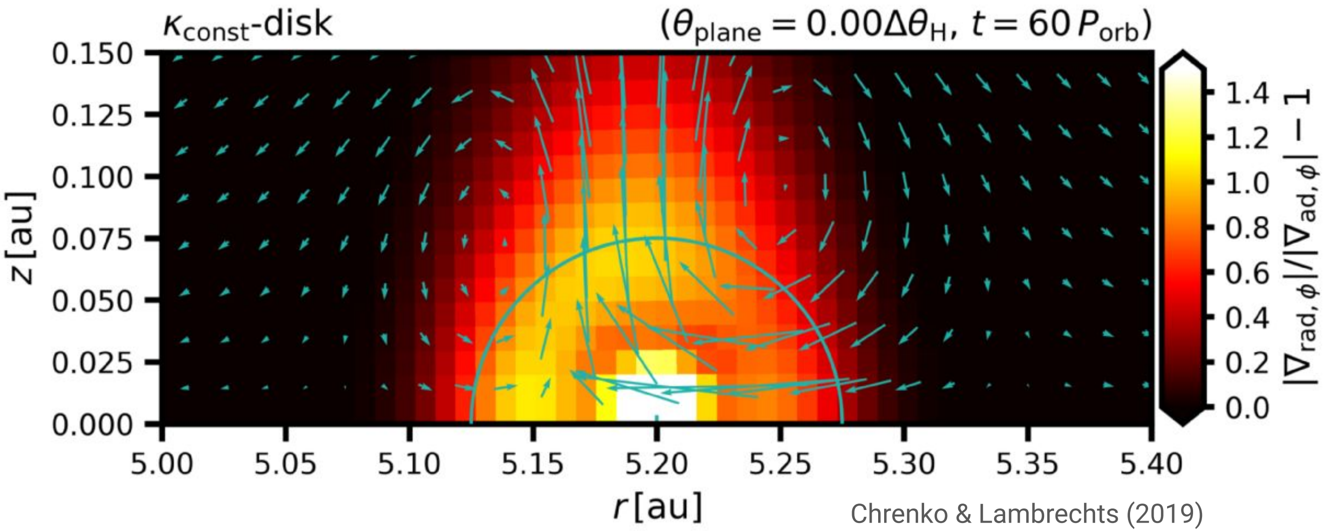

COLD PLANET

HOT PLANET

Chrenko & Lambrechts (2019)

Convective flow perturbation

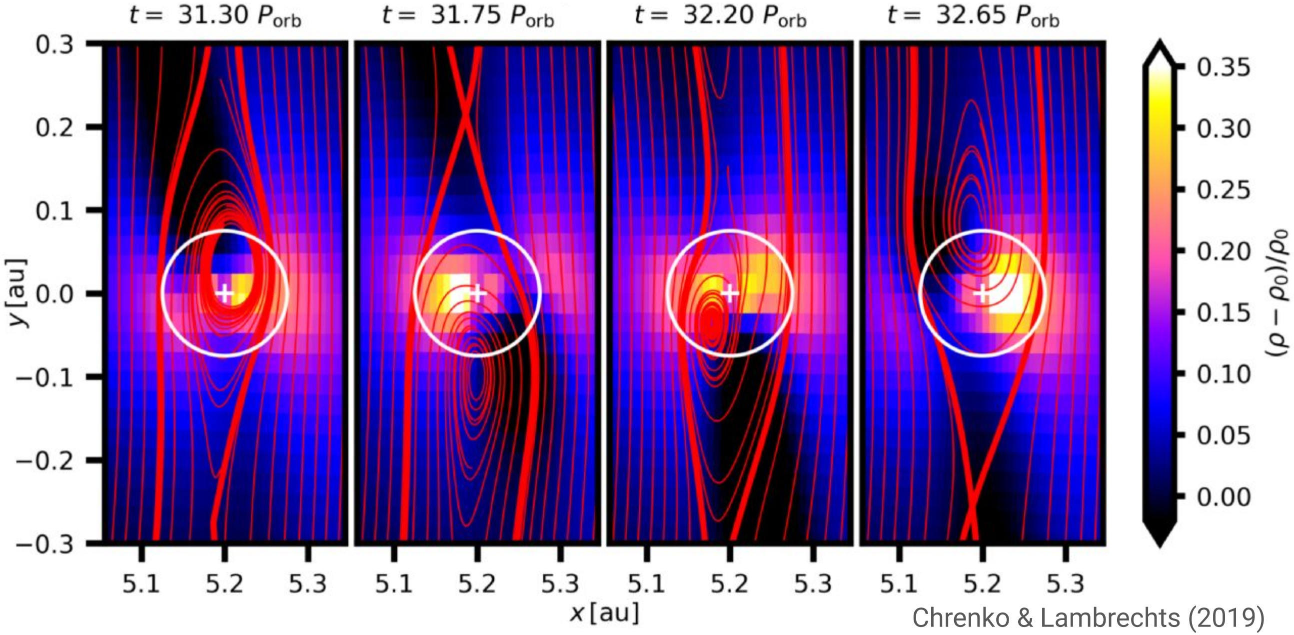
- vertical map of the Schwarzschild convective criterion $\frac{|\nabla_{\mathrm{rad},\phi}|}{|\nabla_{\mathrm{ad},\phi}|} - 1 > 0$ for the hot planet:



Chrenko & Lambrechts (2019)

Disk with a temperature-dependent opacity

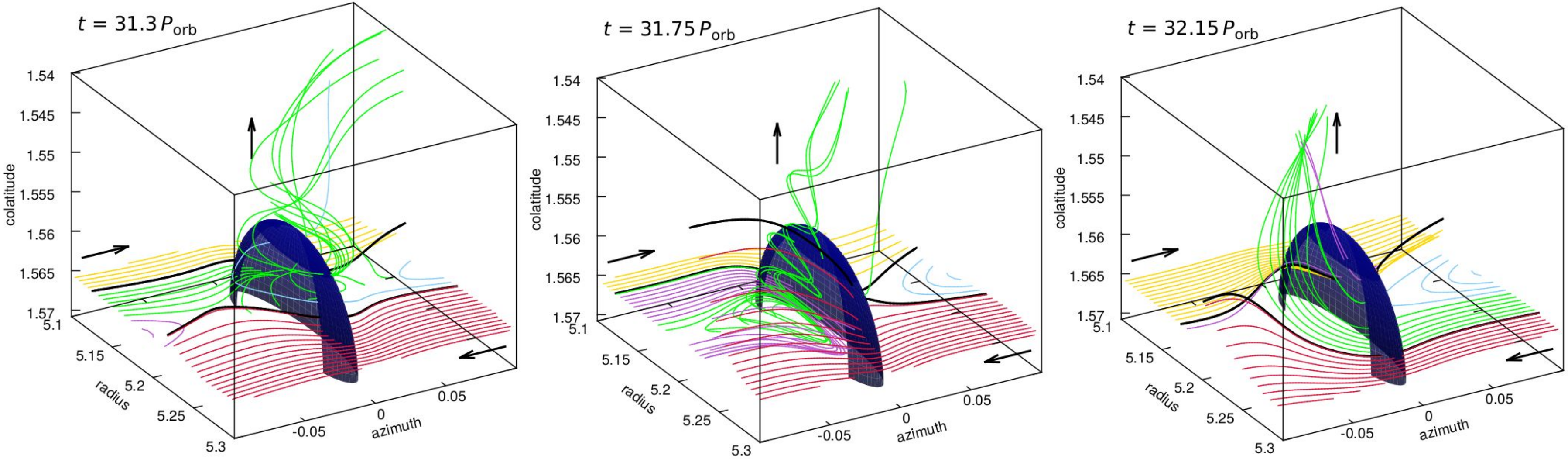
- When the disk opacity is changed from constant to temperature-dependent…
  (opacity~T^2 behind the water-ice line according to Bell & Lin 1994)
  … the gas flow around the hot planet is not stationary!!!



Chrenko & Lambrechts (2019)

Non-stationary flow in 3D

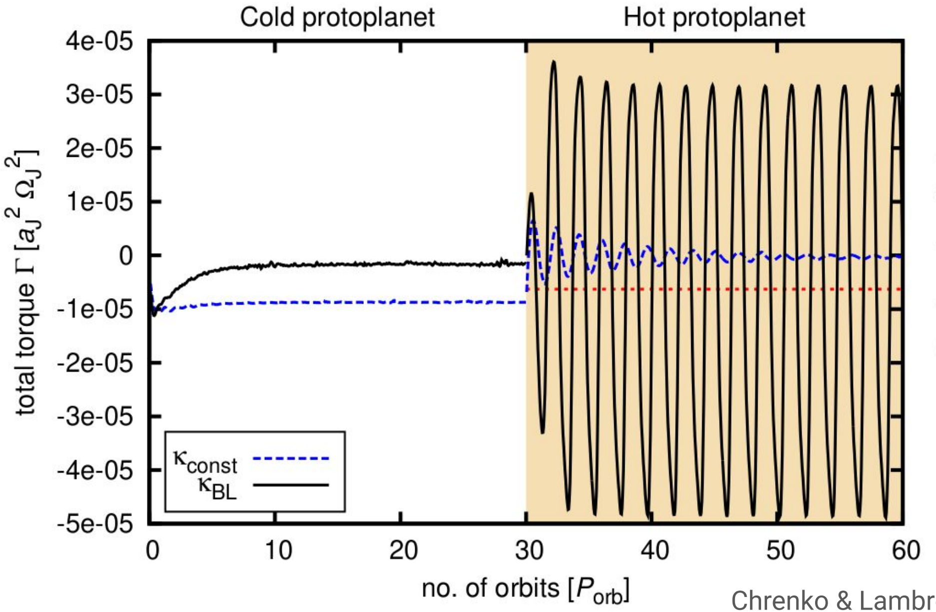
- as on the previous slide but in 3D



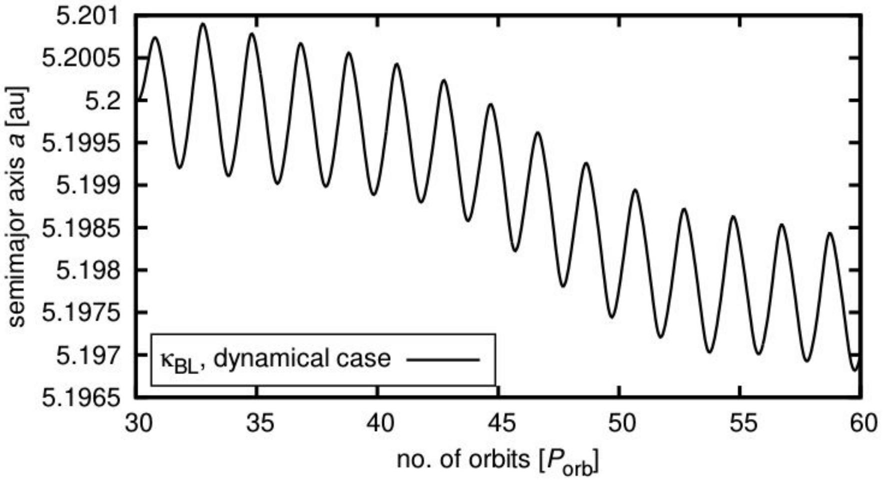
Chrenko & Lambrechts (2019)

Implications for planet migration

- blue curve ~ the constant-opacity disk; black curve ~ the disk with Bell & Lin's opacity



- oscillatory migration:



Chrenko & Lambrechts (2019)

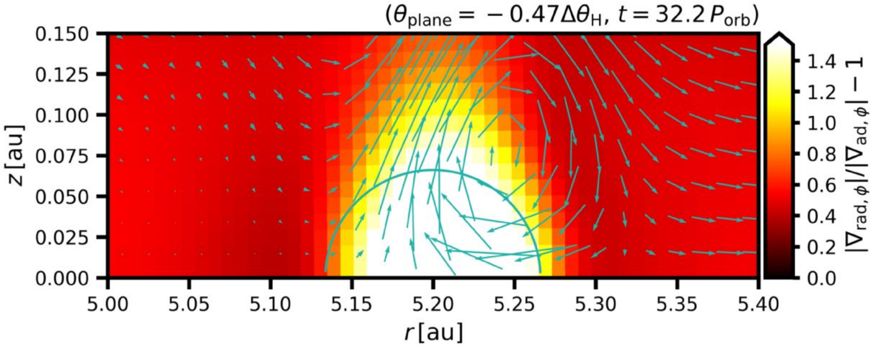
Why is the flow non-stationary?

- Schwarzschild criterion for the simulation with temperature-dependent opacities
- the background is already super-adiabatic

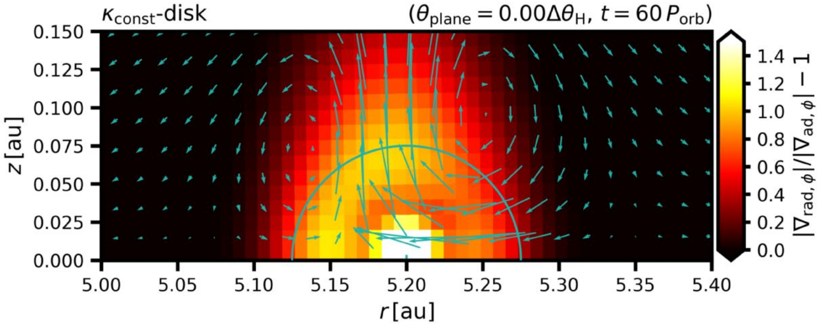
$$\left(\frac{|\nabla_{\mathrm{rad},\phi}|}{|\nabla_{\mathrm{ad},\phi}|}-1\right)_{\mathrm{background}} = \frac{1/(4-\beta)}{(\gamma-1)/(\gamma)} - 1$$

≈0.67 for β=2, γ=1.43 (e.g. Ruden & Pollack 1991)

- Thus the hot planet can excite convective perturbations over an extended region



For a comparison, this is what we saw for the constant-opacity case



Conclusions

Takeaways:

- Radiative effects can dominate the orbital evolution of low-mass protoplanets
- Gas flow around a luminous (accreting) protoplanet exhibits features (i.e. vertical outflow; streamline distortion) that do not exist for non-luminous planets
- Depending on the background disk model, the flow can become non-stationary and the migration oscillatory

(Some) open questions:

- How is the accretion heat deposited/released? How does the flow through the Hill sphere connect to the planetary envelope?
- What luminosity is reasonable to expect? Is pebble accretion dominant for *L*; or perhaps mergers of low-mass planetary embryos?