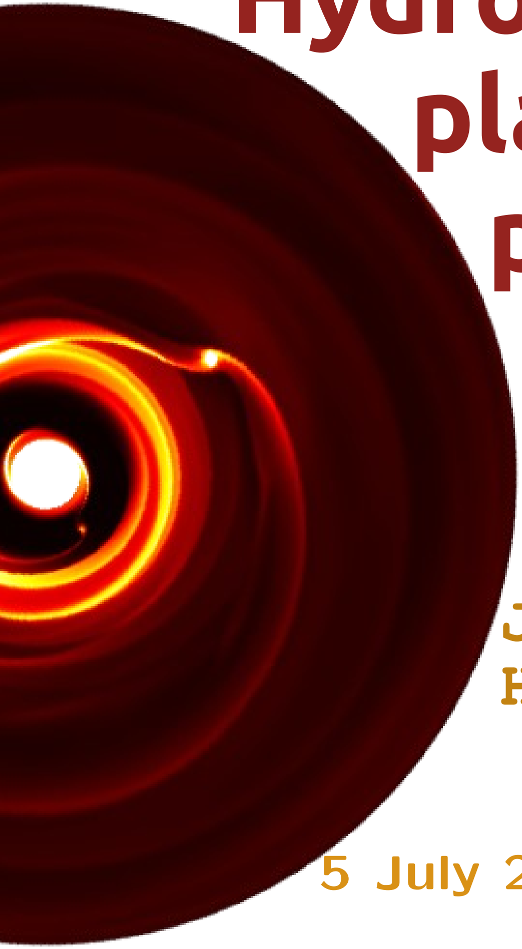


Hydrodynamic modelling of planet-disk interaction and planet migration

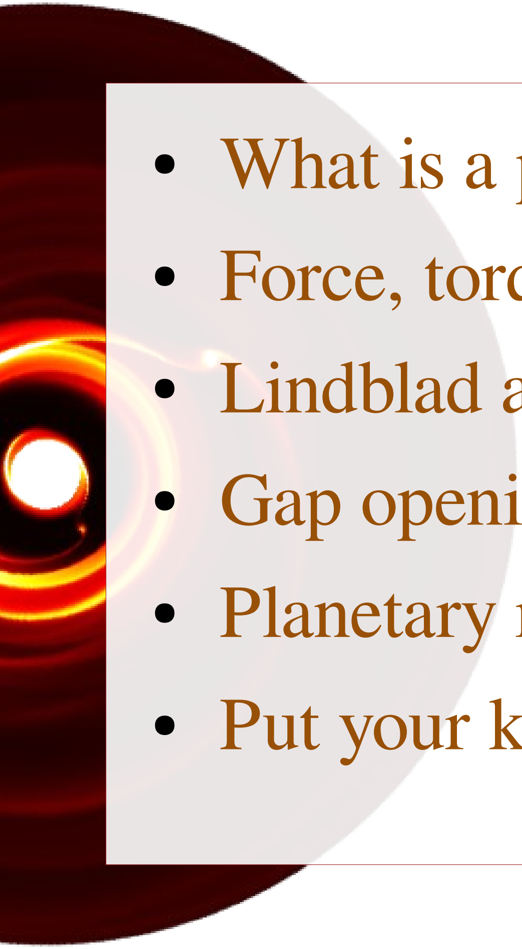
Hands-on Numerical Astrophysics School for Exoplanetary Sciences
July 4-8, 2022
Hanau-Steinheim

5 July 2022, Sareh Ataiee

Exoplanet Diversity
DFG SPP-1992

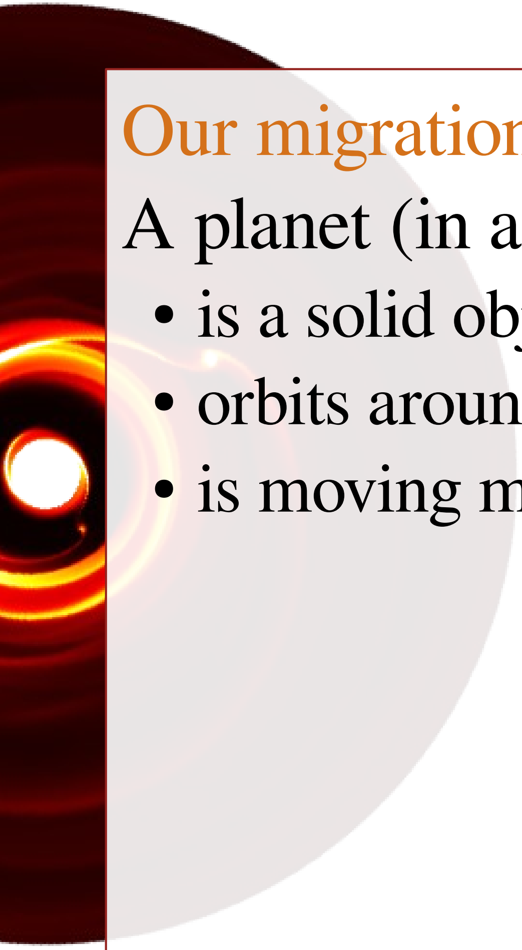
Ferdowsi University of Mashhad

Outline



- What is a planet?
- Force, torque, and power
- Lindblad and co-rotation torques
- Gap opening
- Planetary migration
- Put your knowledge in practice using FARGO3D

What is a planet?

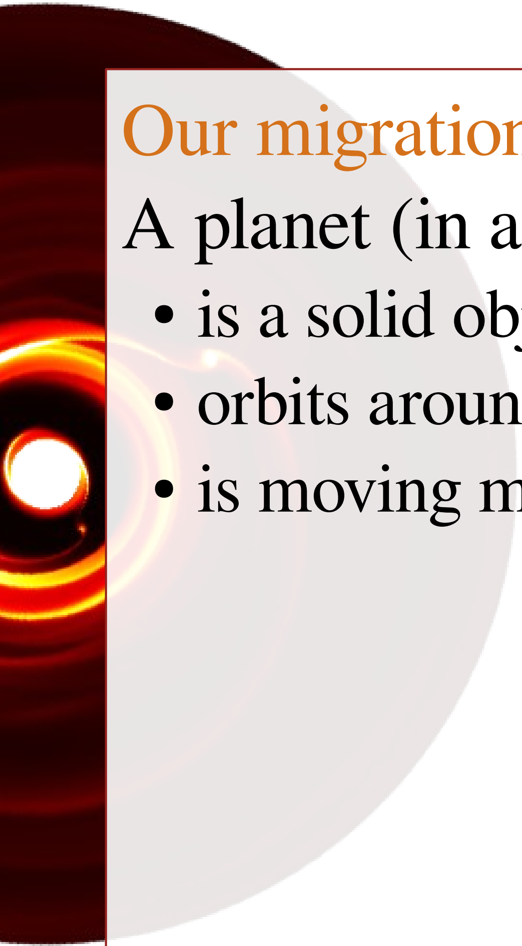


Our migration-wise definition:

A planet (in a disc)

- is a solid object (not a gas parcel)
- orbits around one (more) star(s)
- is moving mostly due to the gravitational forces

What is a planet?



Our migration-wise definition:

A planet (in a disc)

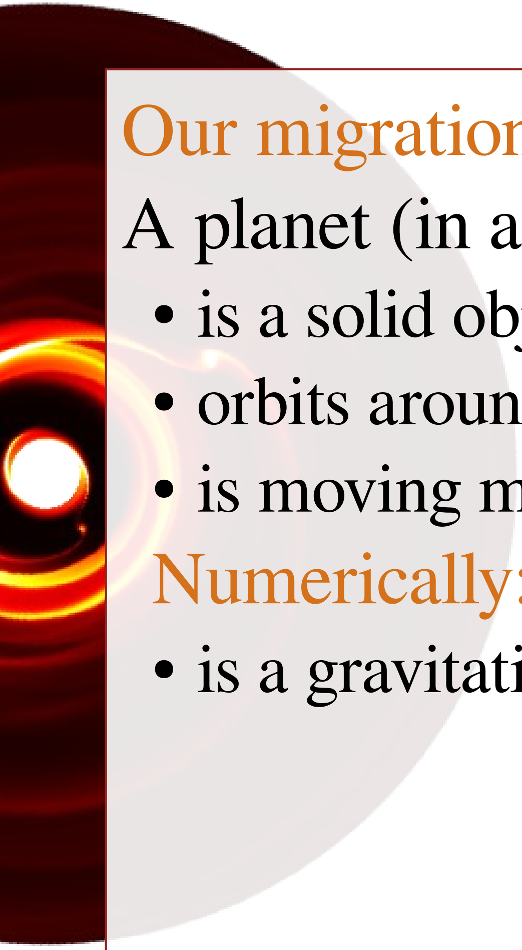
- is a solid object (not a gas parcel)
- orbits around one (more) star(s)
- is moving mostly due to the gravitational forces

$$\frac{d\boldsymbol{v}}{dt} = \boldsymbol{a}$$

for a solid in a disc $\rightarrow$ $$= \boldsymbol{a}_{\text{star}} + \boldsymbol{a}_{\text{gas drag}} + \boldsymbol{a}_{\text{disc gravity}}$$

$$\text{if} \begin{cases} \boldsymbol{a}_{\text{gas drag}} \ll \boldsymbol{a}_{\text{disc gravity}} & \text{Planet} \\ \boldsymbol{a}_{\text{gas drag}} \gg \boldsymbol{a}_{\text{disc gravity}} & \text{Dust particle} \end{cases}$$

What is a planet?



Our migration-wise definition:

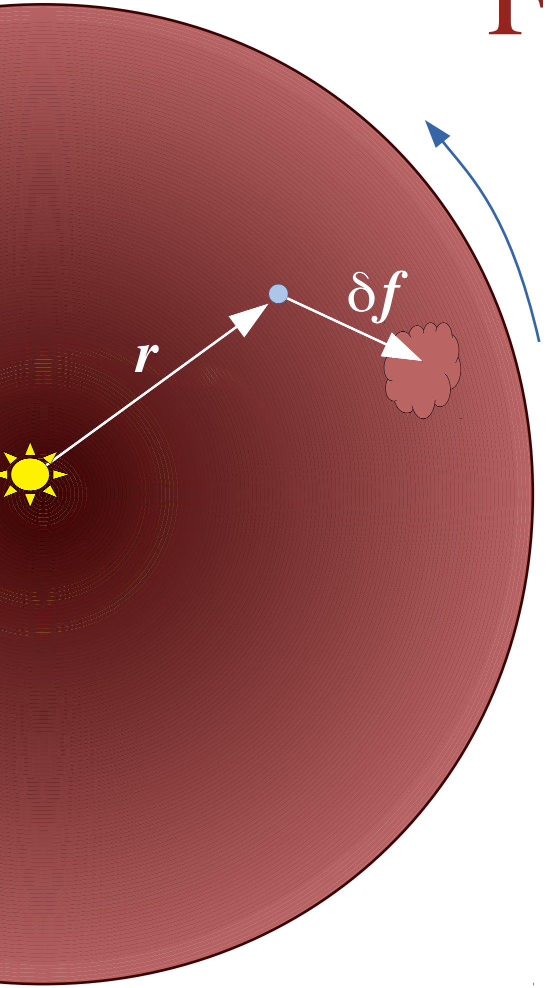
A planet (in a disc)

- is a solid object (not a gas parcel)
- orbits around one (more) star(s)
- is moving mostly due to the gravitational forces

Numerically:

- is a gravitational point source

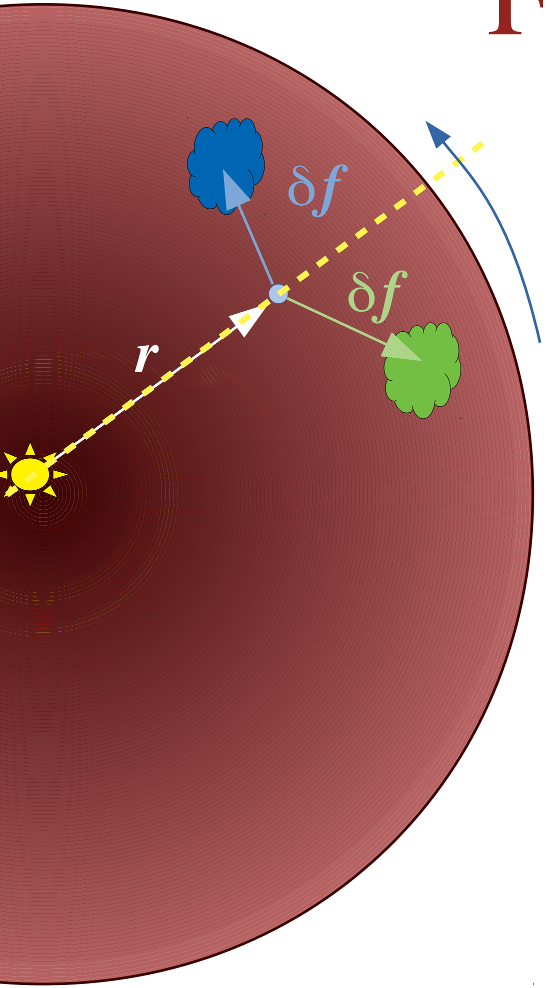
Force, torque, and power



Torque: $\delta\boldsymbol{\Gamma} = \boldsymbol{r} \times \delta\boldsymbol{f} = \delta\frac{d\boldsymbol{L}_p}{dt}$ $\quad \boldsymbol{L}_p = m_p\sqrt{G M_* a}\sqrt{1-e^2}\,\boldsymbol{k}$

Power: $\delta P = \boldsymbol{v} \cdot \delta\boldsymbol{f} = \delta\frac{dE_p}{dt}$ $\quad E_p = -\frac{G m_p M_*}{2a}$

Force, torque, and power



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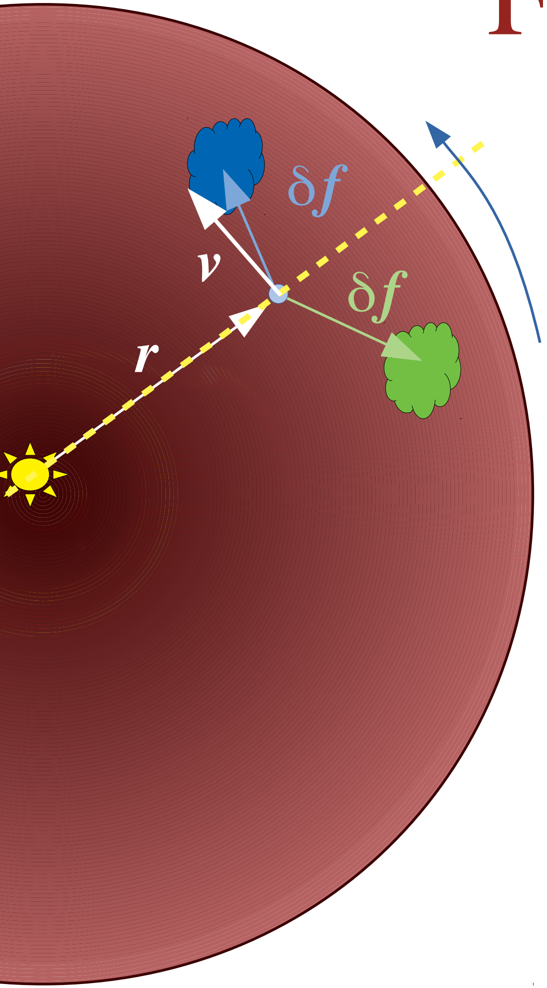
Power: $\delta P = \boldsymbol{v} \cdot \delta\boldsymbol{f} = \delta\frac{dE_p}{dt}$ $E_p = -\frac{G m_p M_*}{2a}$

$\delta\boldsymbol{\Gamma}|_z = \boldsymbol{r} \times \delta\boldsymbol{f} < 0 \Rightarrow \delta\frac{d\boldsymbol{L}_p}{dt}|_z < 0$ planet loses angular momentum

$\delta\boldsymbol{\Gamma}|_z = \boldsymbol{r} \times \delta\boldsymbol{f} > 0 \Rightarrow \delta\frac{d\boldsymbol{L}_p}{dt}|_z > 0$ planet gains angular momentum

Force, torque, and power



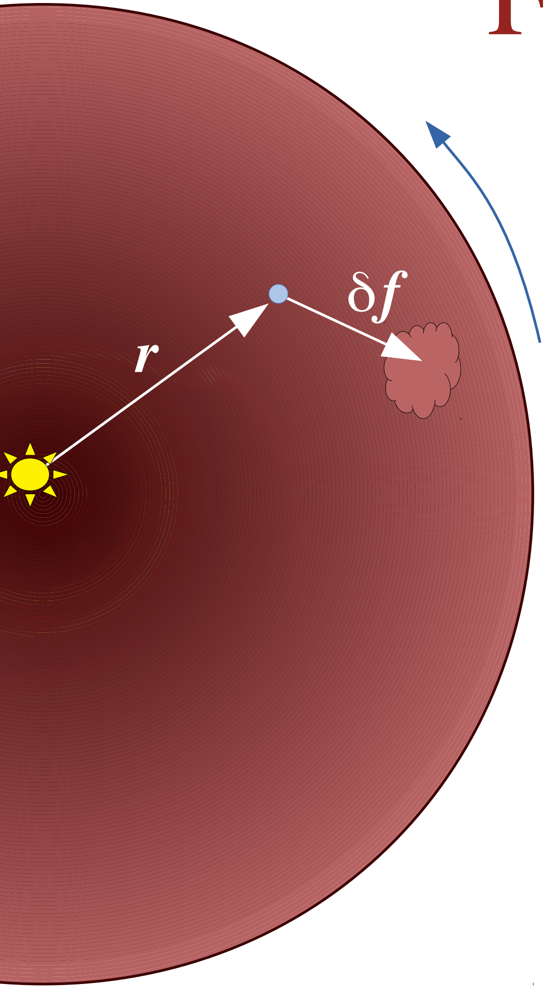
Torque: $\delta\boldsymbol{\Gamma}=\boldsymbol{r}\times\delta\boldsymbol{f}=\delta\frac{d\boldsymbol{L}_p}{dt}$ $\quad \boldsymbol{L_p}=m_p\sqrt{GM_*a}\sqrt{1-e^2}\,\boldsymbol{k}$

Power: $\delta P=\boldsymbol{v}\cdot\delta\boldsymbol{f}=\delta\frac{dE_p}{dt}$ $\quad E_p=-\frac{Gm_pM_*}{2a}$

$\delta P=\boldsymbol{v}\cdot\delta\boldsymbol{f}<0\Rightarrow\delta\frac{dE_p}{dt}<0$ planet loses energy

$\delta P=\boldsymbol{v}\cdot\delta\boldsymbol{f}>0\Rightarrow\delta\frac{dE_p}{dt}>0$ planet gains energy

Force, torque, and power



Torque: $\delta\boldsymbol{\Gamma} = \boldsymbol{r} \times \delta\boldsymbol{f} = \delta \frac{d\,\boldsymbol{L}_p}{dt}$ $\quad \boldsymbol{L}_p = m_p \sqrt{G\,M_*\,a}\sqrt{1-e^2}\,\boldsymbol{k}$

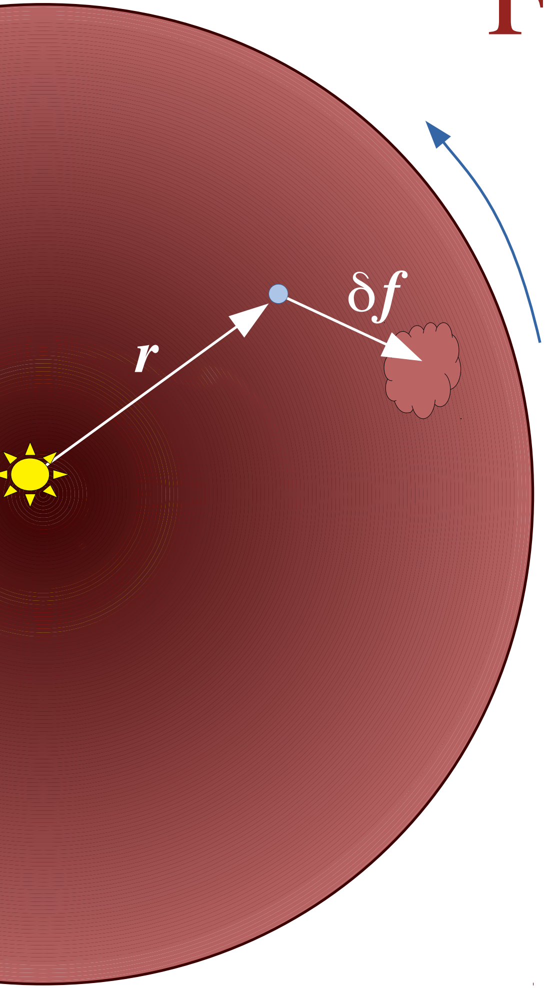
Power: $\delta P = \boldsymbol{v} \cdot \delta\boldsymbol{f} = \delta \frac{dE_p}{dt}$ $\quad E_p = -\frac{G\,m_p\,M_*}{2\,a}$

⇨

Torque: $\boldsymbol{\Gamma} = \int_{\mathrm{disc}} \boldsymbol{r} \times \delta\boldsymbol{f} = \frac{d\,\boldsymbol{L}_p}{dt}$

Power: $P = \int_{\mathrm{disc}} \boldsymbol{v} \cdot \delta\boldsymbol{f} = \frac{dE_p}{dt}$

Force, torque, and power



Torque: $\boldsymbol{\Gamma} = \int_{\rm disc} \boldsymbol{r} \times \delta \boldsymbol{f} = \frac{d\boldsymbol{L}_p}{dt}$ $\quad \boldsymbol{L_p} = m_p \sqrt{G M_* a} \sqrt{1 - e^2}\, \boldsymbol{k}$

Power: $P = \int_{\rm disc} \boldsymbol{v} \cdot \delta \boldsymbol{f} = \frac{dE_p}{dt}$ $\quad E_p = -\frac{G m_p M_*}{2a}$

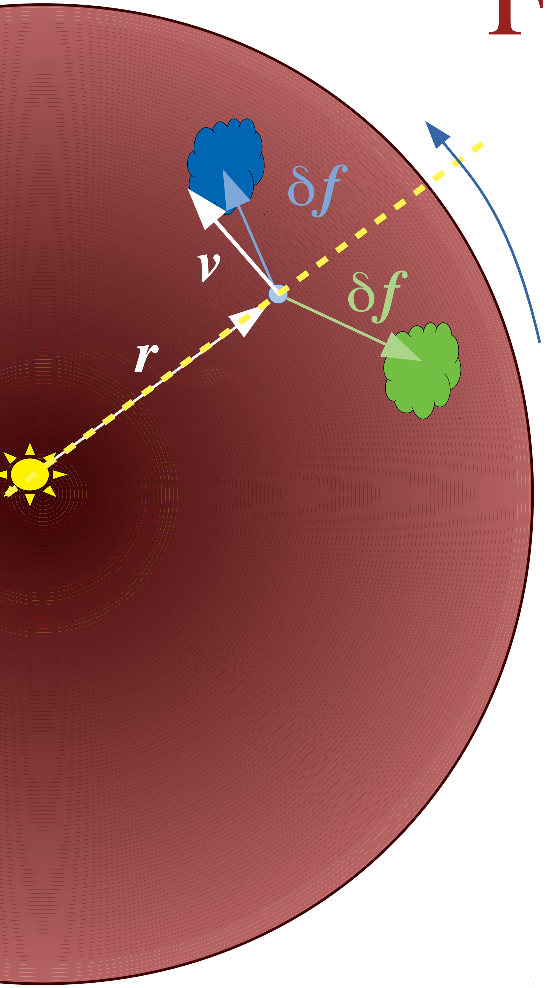
For a circular planet ($e = 0$):

$$\Gamma_z = \frac{dL_p}{dt} = m_p \frac{\sqrt{GM_*}}{2\sqrt{a}} \dot{a} = \frac{L_p}{2} \frac{\dot{a}}{a}$$

$$P = \frac{dE_p}{dt} = m_p \frac{GM_*}{2a^2} = -E_p \frac{\dot{a}}{a}$$

$$\tau_a = \frac{a}{\dot{a}} = \frac{L_p}{2\Gamma} = \frac{|E_p|}{P}$$

Force, torque, and power



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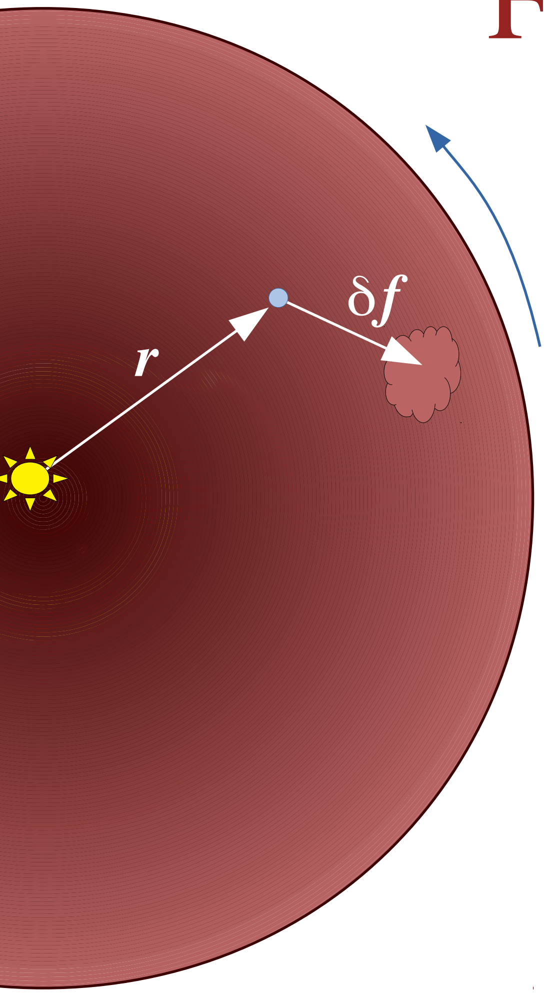
For a circular planet ($e = 0$):

$$\tau_{\text{a}} = \frac{a}{\dot{a}} = \frac{L_p}{2\Gamma} = \frac{|E_p|}{P}$$

Green part wins → Torque and power on a planet are negative → The planet's semi-major axis decreases

Force, torque, and power



Torque: $\boldsymbol{\Gamma} = \int_{\text{disc}} \boldsymbol{r} \times \delta \boldsymbol{f} = \frac{d\boldsymbol{L}_p}{dt}$ $\boldsymbol{L}_p = m_p \sqrt{G M_* a} \sqrt{1-e^2}\, \boldsymbol{k}$

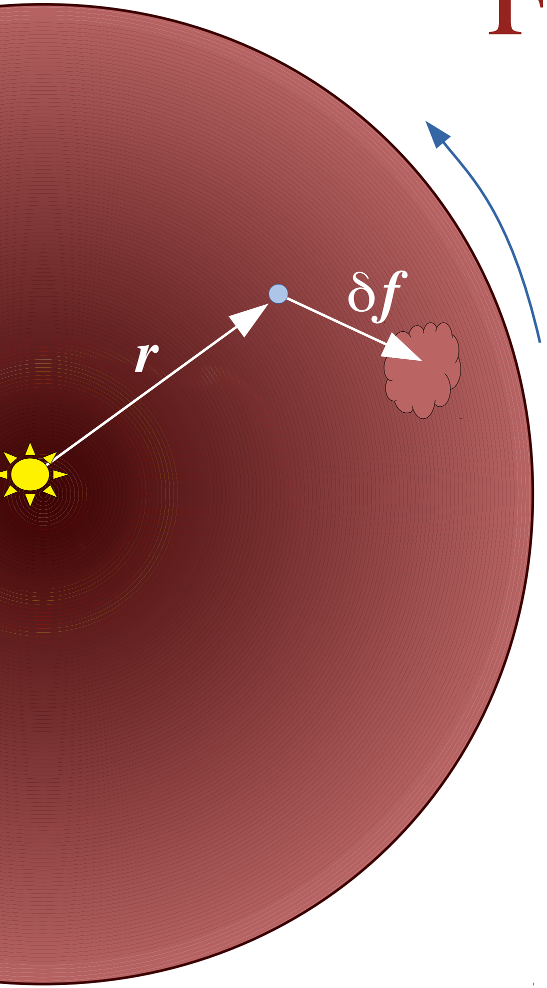
Power: $P = \int_{\text{disc}} \boldsymbol{v} \cdot \delta \boldsymbol{f} = \frac{dE_p}{dt}$ $E_p = -\frac{G m_p M_*}{2a}$

Surface density perturbation → exerts torque/power on the planet → changes the planet's angular momentum/ energy → changes the planet's semi-major axis

↓

Migration

Force, torque, and power



Torque: $\boldsymbol{\Gamma} = \int_{\text{disc}} \boldsymbol{r} \times \delta \boldsymbol{f} = \frac{d\boldsymbol{L}_p}{dt}$ $\quad \boldsymbol{L_p} = m_p \sqrt{G M_* a} \sqrt{1-e^2}\, \boldsymbol{k}$

Power: $P = \int_{\text{disc}} \boldsymbol{v} \cdot \delta \boldsymbol{f} = \frac{dE_p}{dt}$ $\quad E_p = -\frac{G m_p M_*}{2a}$

For an eccentric planet ($0 < e < 1$):

$$\Gamma_z = \frac{dL_p}{dt} = L_p \left(\frac{\dot{a}}{2a} - \frac{\dot{e}}{e} \frac{e^2}{1-e^2} \right)$$

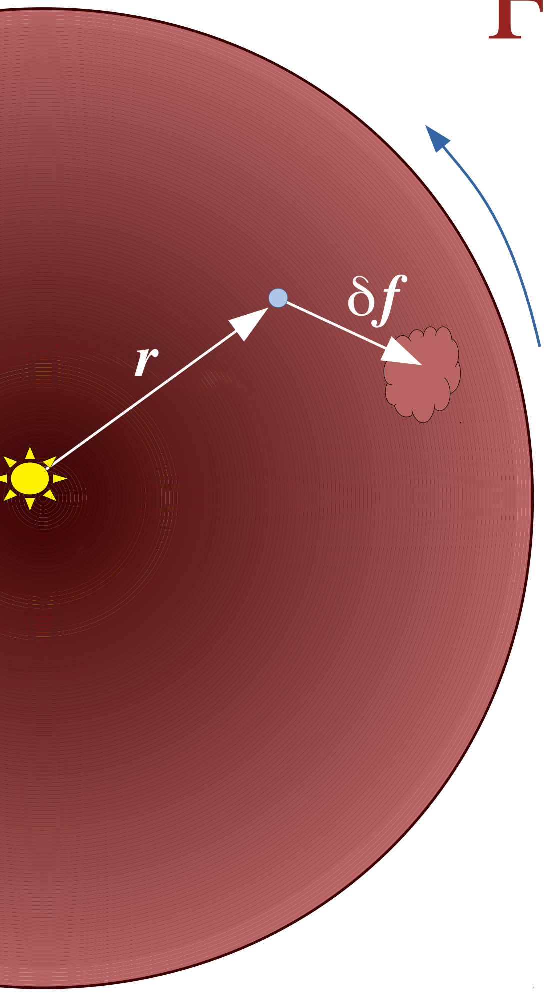
$$P = \frac{dE_p}{dt} = m_p \frac{GM_*}{2a^2} = -E_p \frac{\dot{a}}{a}$$

⇨

$$\tau_{\text{a}} = \frac{a}{\dot{a}} = \frac{|E_p|}{P}$$

$$\tau_{\text{e}} = \frac{e}{\dot{e}} = \frac{e^2}{1-e^2} \left(\frac{P}{E_p} - \frac{\Gamma}{L_p} \right)^{-1}$$

Force, torque, and power



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Power: $P = \int_{\text{disc}} \boldsymbol{v} \cdot \delta \boldsymbol{f} = \frac{dE_p}{dt}$ $\quad E_p = -\frac{G m_p M_*}{2a}$

For an eccentric planet ($0 < e < 1$):

If a planet is eccentric, torque does **NOT** give the direction of migration.

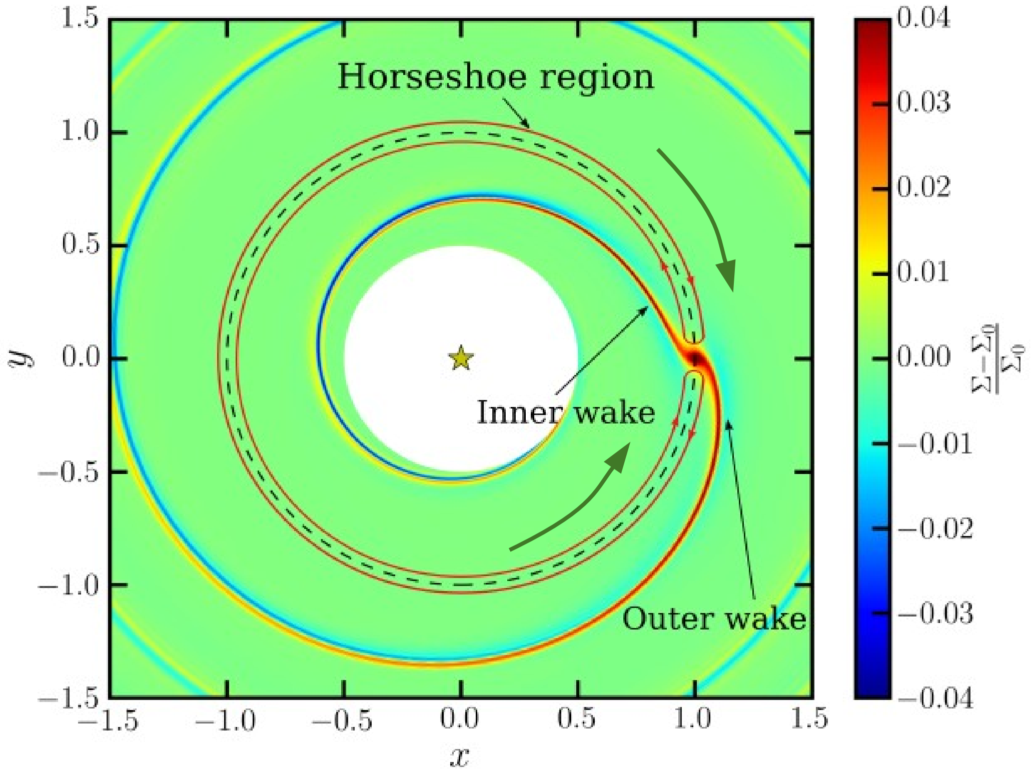
$$\tau_a = \frac{a}{\dot{a}} = \frac{|E_p|}{P}$$

$$\tau_e = \frac{e}{\dot{e}} = \frac{e^2}{1-e^2} \left(\frac{P}{E_p} - \frac{\Gamma}{L_p} \right)^{-1}$$

Lindblad and co-rotation torques

A planet divides the disc in two regions:

- far from its orbit (circulating)
- around its orbit (horseshoe)



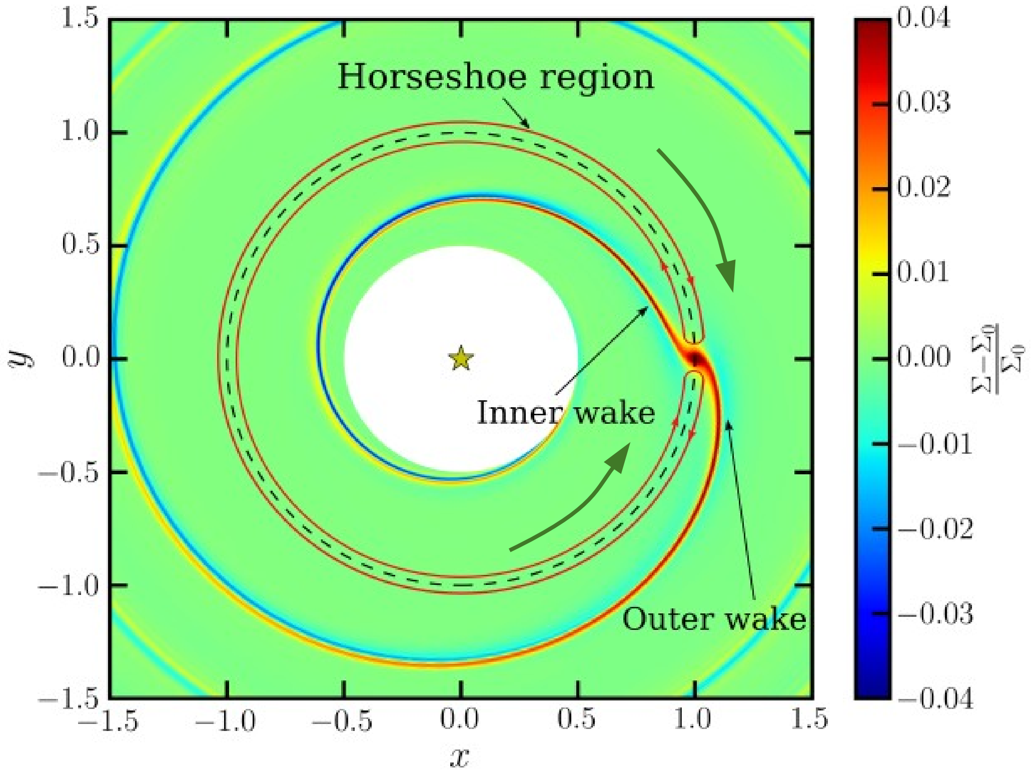
Lindblad and co-rotation torques

A planet divides the disc in two regions:

- far from its orbit (circulating)
- around its orbit (horseshoe)

Two main sources of surface density perturbation:

- Wakes resulting from the Lindblad resonances
- Horseshoe motion of gas in the co-orbital region



Lindblad and co-rotation torques

Goldreich & Tremaine 1979

$$\frac{\partial \boldsymbol{v}_1}{\partial t} + (\boldsymbol{v}_0 \cdot \boldsymbol{\nabla})\boldsymbol{v}_1 + (\boldsymbol{v}_1 \cdot \boldsymbol{\nabla})\boldsymbol{v}_0 = -\boldsymbol{\nabla}(\varphi_1 + {\varphi_1}^D + \eta_1) ,$$

$$\frac{\partial \sigma_1}{\partial t} + \boldsymbol{\nabla}\cdot(\sigma_0 \boldsymbol{v}_1) + \boldsymbol{\nabla}\cdot(\sigma_1 \boldsymbol{v}_0) = 0 ,$$

$$\eta_1 = {c_0}^2(\sigma_1/\sigma_0) ,$$

$$\nabla^2 {\varphi_1}^D = 4\pi G \sigma_1 \delta(z) ,$$

Lindblad and co-rotation torques

Goldreich & Tremaine 1979

$$\frac{\partial \boldsymbol{v}_1}{\partial t} + (\boldsymbol{v}_0 \cdot \boldsymbol{\nabla})\boldsymbol{v}_1 + (\boldsymbol{v}_1 \cdot \boldsymbol{\nabla})\boldsymbol{v}_0 = -\boldsymbol{\nabla}(\varphi_1 + \varphi_1{}^D + \eta_1) ,$$

$$\frac{\partial \sigma_1}{\partial t} + \boldsymbol{\nabla} \cdot (\sigma_0 \boldsymbol{v}_1) + \boldsymbol{\nabla} \cdot (\sigma_1 \boldsymbol{v}_0) = 0 ,$$

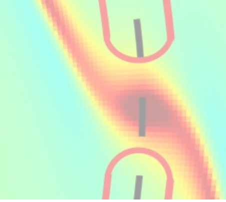
$$\eta_1 = c_0{}^2(\sigma_1/\sigma_0) ,$$

$$\nabla^2 \varphi_1{}^D = 4\pi G \sigma_1 \delta(z) ,$$

$X = X(r) \exp i(m\theta - \omega t)$ →

$$u_1 = -\frac{i}{D}\left[(m\Omega - \omega)\frac{d}{dr} + \frac{2m\Omega}{r}\right](\varphi_1 + \varphi_1{}^D + \eta_1) ,$$

$$v_1 = \frac{1}{D}\left[2B\frac{d}{dr} + \frac{m}{r}(m\Omega - \omega)\right](\varphi_1 + \varphi_1{}^D + \eta_1) ,$$



Lindblad and co-rotation torques

Goldreich & Tremaine 1979

$$\left\{\frac{d^2}{dr^2} + \left[\frac{d}{dr}\ln\left(\frac{\sigma r}{D}\right)\right]\frac{d}{dr} + \frac{2m\Omega}{r(m\Omega-\omega)}\left[\frac{d}{dr}\ln\left(\frac{\sigma\Omega}{D}\right)\right] - \frac{m^2}{r^2}\right\}(\varphi_1 + \varphi_1{}^D + \eta_1) = \frac{D\eta_1}{c^2}$$

$$D = \kappa^2 - (m\Omega - \omega)^2$$

Singularities:

1) $D = 0$ Lindblad resonance
2) $m\Omega - \omega = 0$ Co-rotation resonance

Lindblad and co-rotation torques

Lindblad resonances $m\left(\Omega(r)-\Omega_p\right)=\pm\kappa\sqrt{\left(1+m^2h^2\right)}$

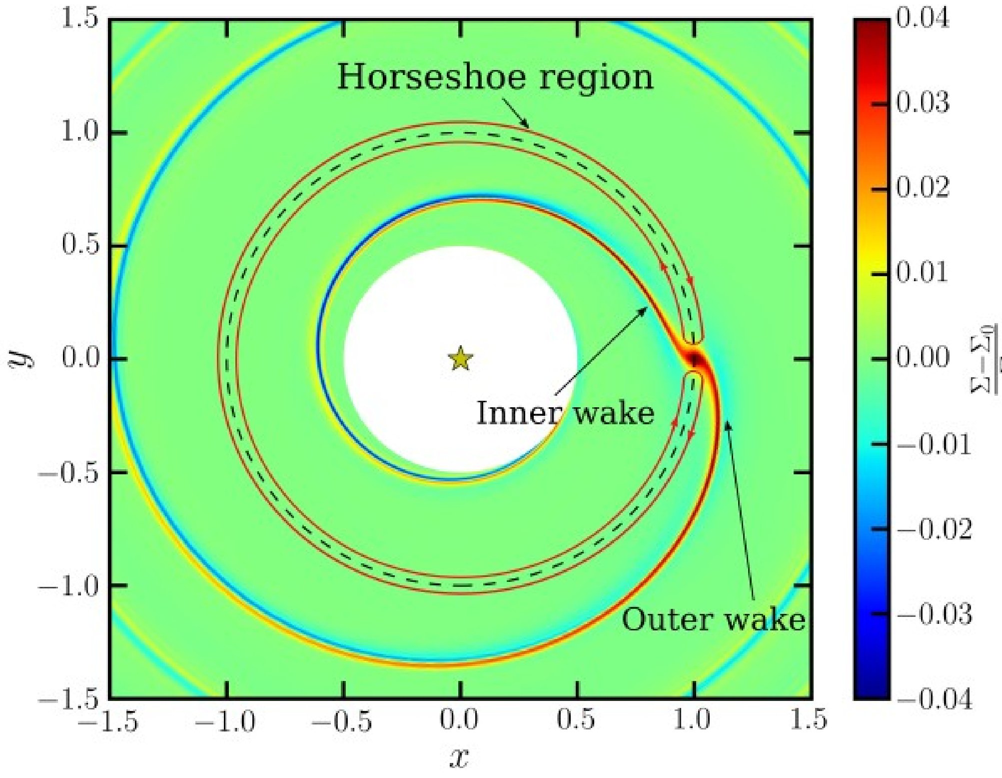
m: an integer

$\Omega(r)$: gas angular velocity

Ω_p: planet angular velocity

κ: epicyclic frequency

h: disc aspect ratio



Lindblad and co-rotation torques

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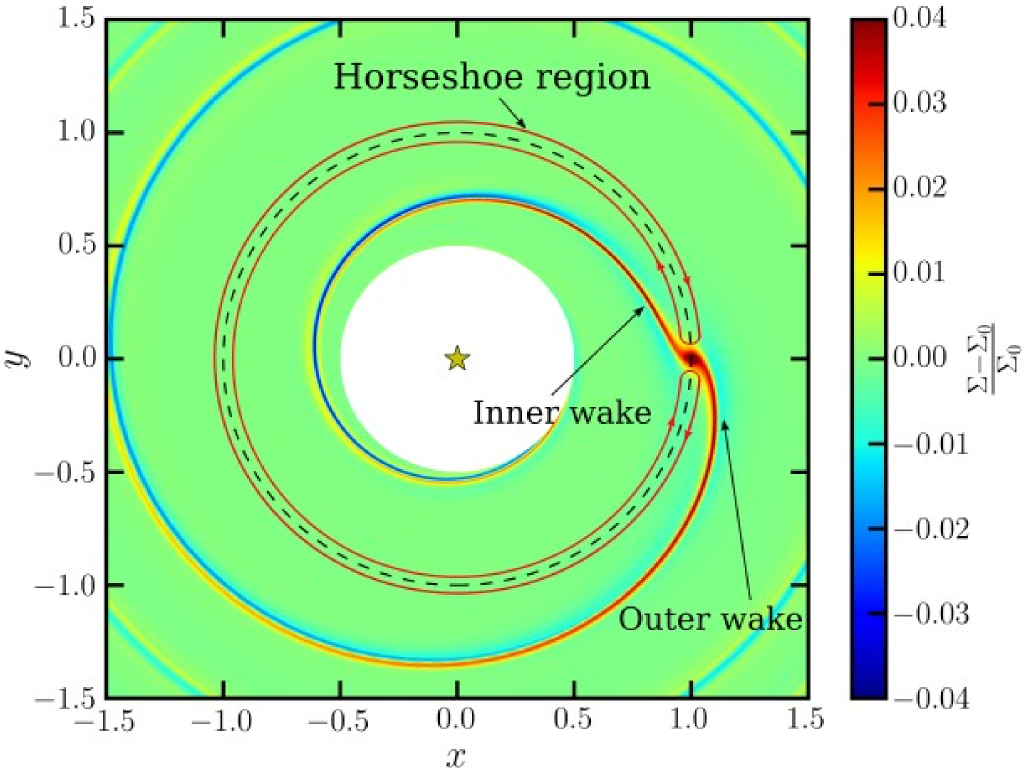


Sound waves launched at LRs
+
Differential rotation of the disc
↓
Spirals

Lindblad and co-rotation torques

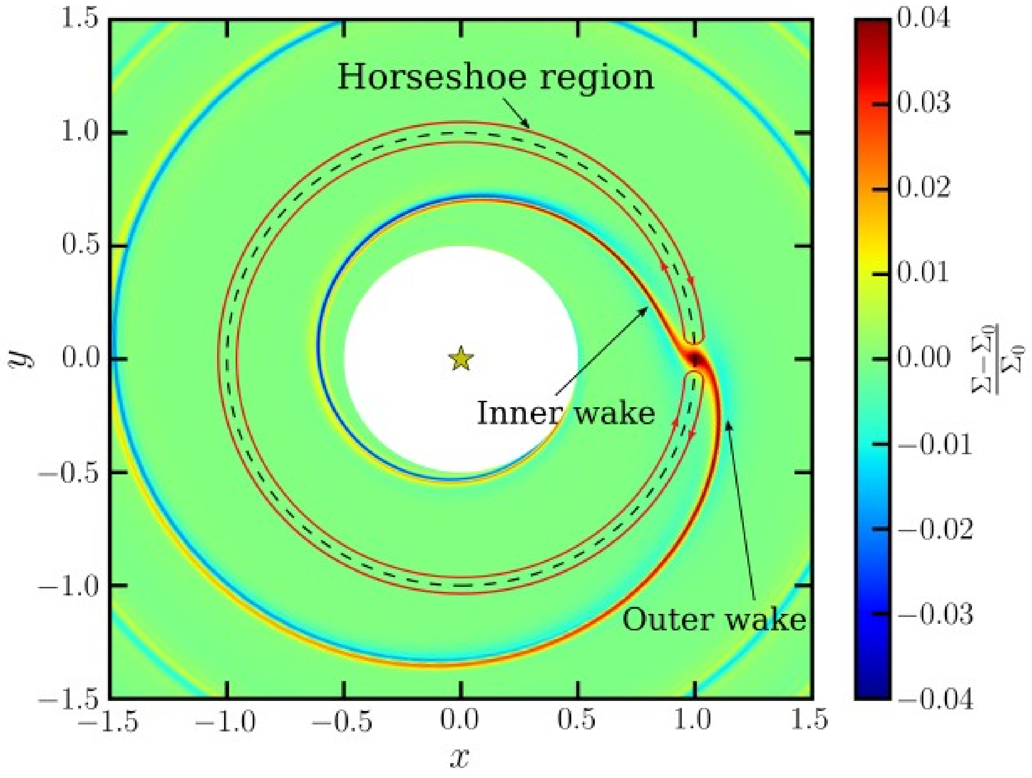
Lindblad resonances $m(\Omega(r)-\Omega_p)=\pm\kappa\sqrt{(1+m^2h^2)}$

Torque from the outer wake < 0

Torque from the inner wake > 0

→ Net torque determines the migration of the planet

Differential Lindblad Torque



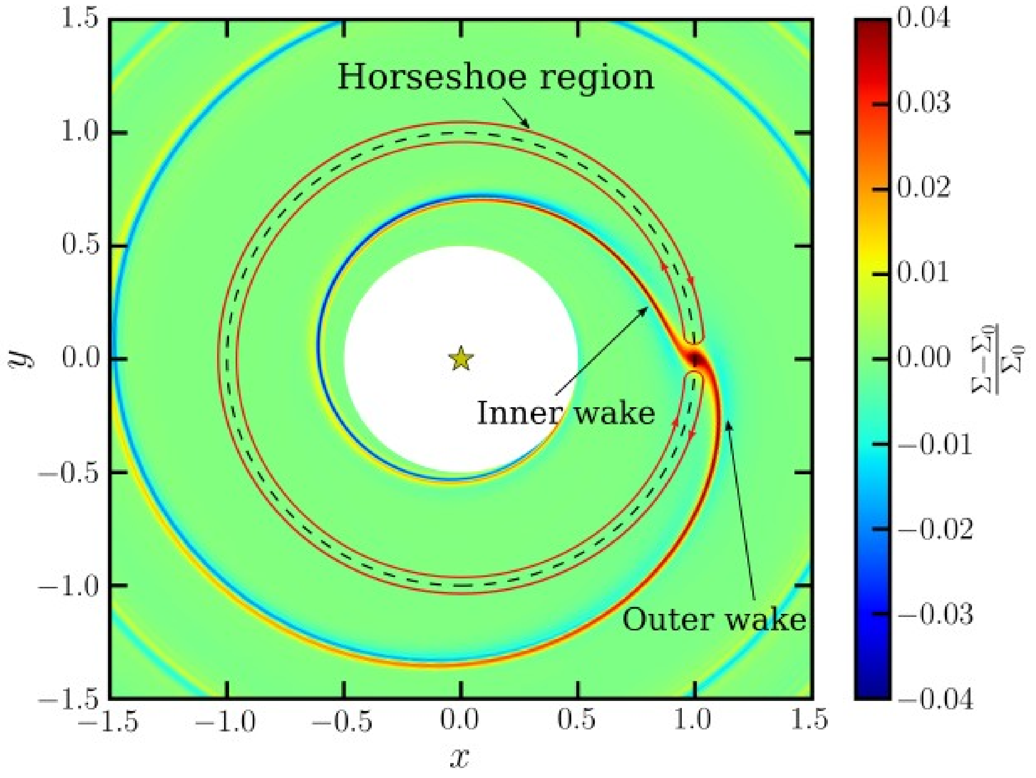
Lindblad and co-rotation torques

Lindblad resonances $m(\Omega(r)-\Omega_p)=\pm\kappa\sqrt{(1+m^2h^2)}$

$\Omega(r)$ depends on the disc pressure gradient

The **location** of Lindblad resonances depends on **pressure profile**:

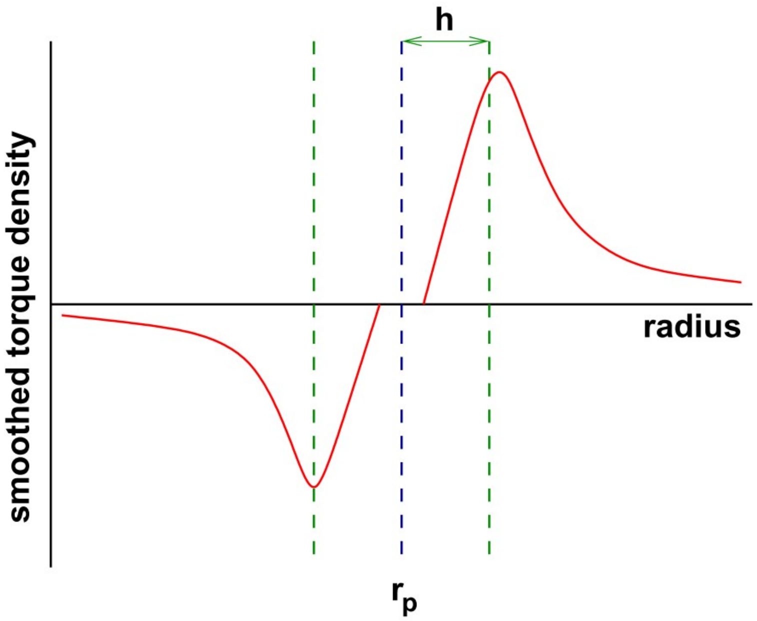
Density and Temperature gradient can change the Lindblad torque.



Lindblad and co-rotation torques

Lindblad resonances $m(\Omega(r)-\Omega_p)=\pm\kappa\sqrt{(1+m^2h^2)}$

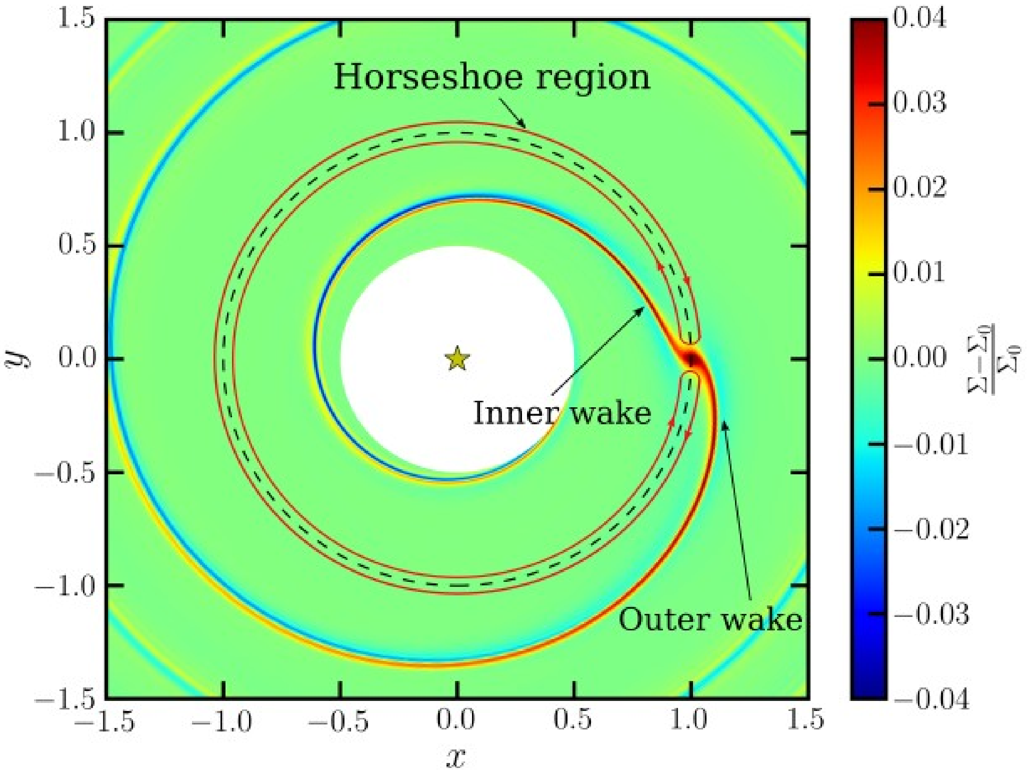
There is a **pile-up** of resonance location about H → the main contribution should come from this distance



Armitage 2017

Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r)=\Omega_p$

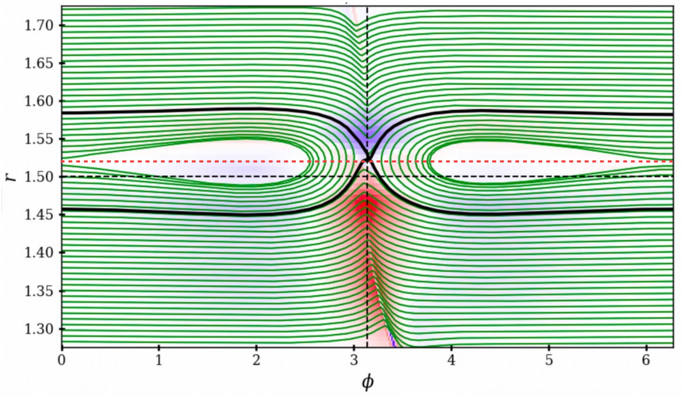


Lindblad and **co-rotation** torques

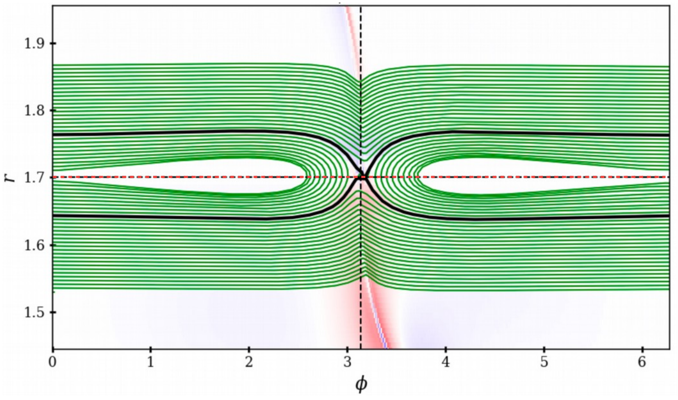
Co-rotation resonance $\Omega(r)=\Omega_p$

- $r_{\rm co}$ is not necessarily $r_{\rm p}$

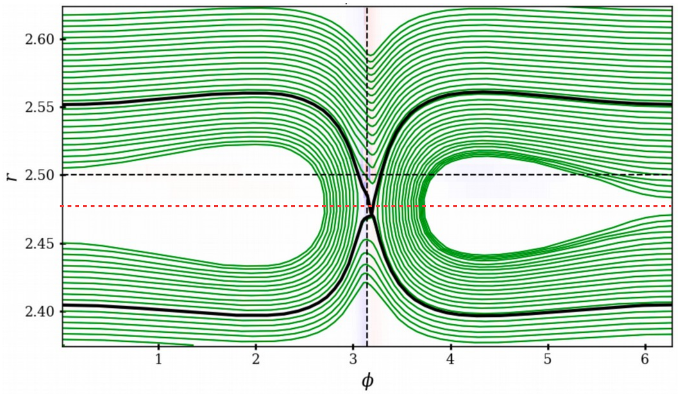
$\nabla P>0$



$\nabla P=0$



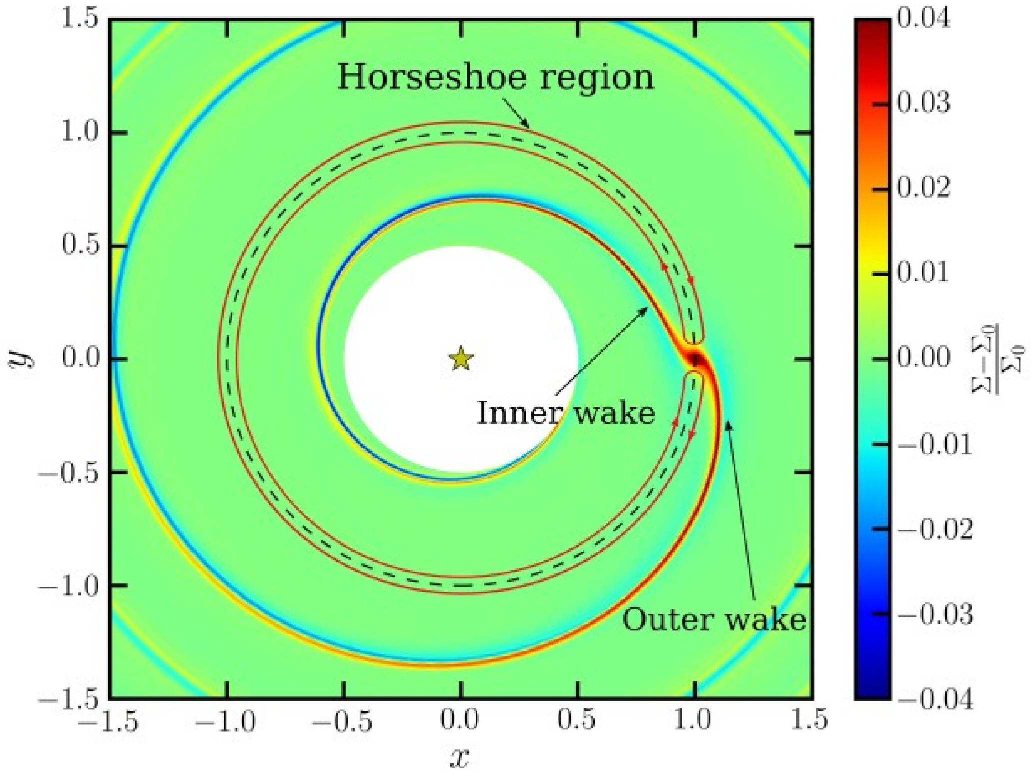
$\nabla P<0$



Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r)=\Omega_p$

- r_{co} is not necessarily r_{p}
- Linear co-rotation torque is small

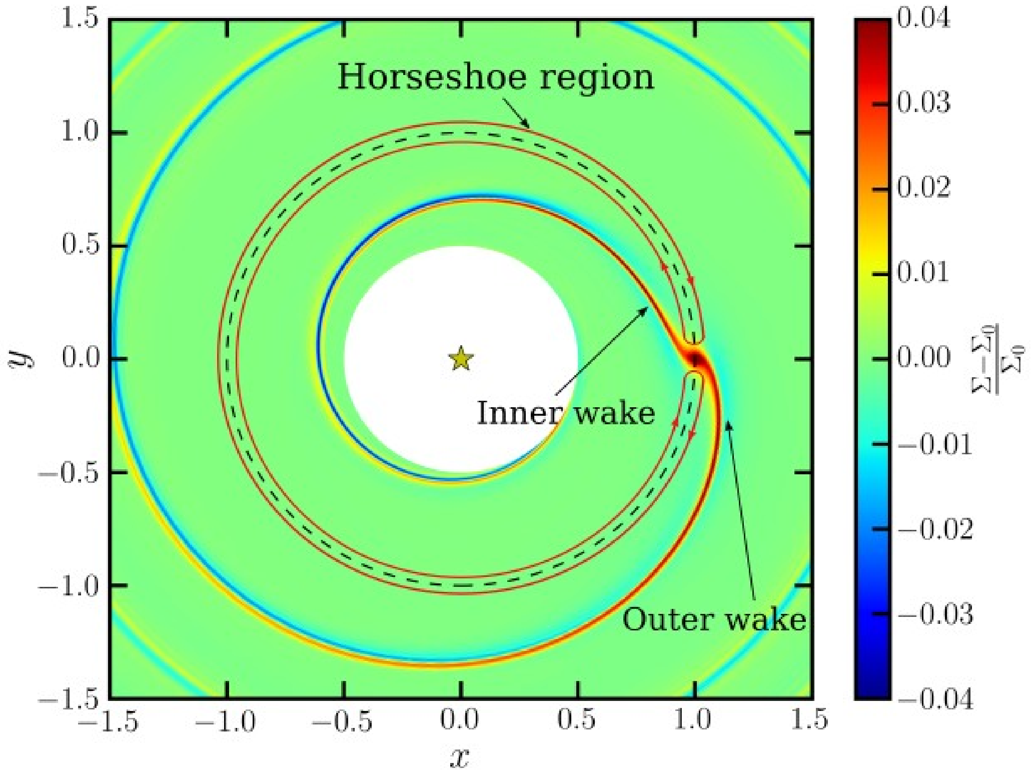


Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r) = \Omega_p$

- r_{co} is not necessarily r_p
- Linear co-rotation torque is small
- Horseshoe drag is non-linear

(Paardekooper & Papaloizou 2009)

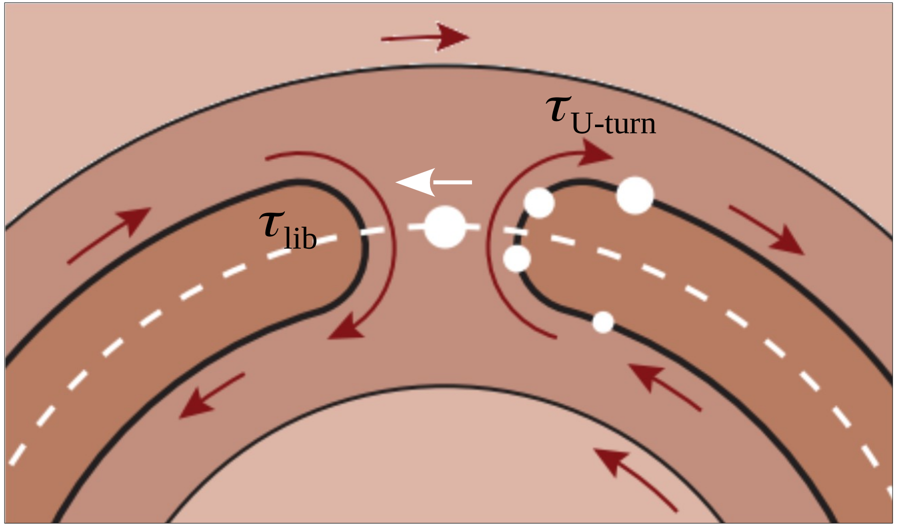


Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r)=\Omega_p$

- $r_{\rm co}$ is not necessarily $r_{\rm p}$
- Linear co-rotation torque is small
- Horseshoe drag is non-linear
- Time matter

$$\tau_{\text{U-turn}} \sim \frac{H}{x_s}\,\tau_{\rm dyn} \qquad \tau_{\rm lib} \sim \frac{8\pi a}{3\Omega_{\rm p} x_s}$$



Kley & Nelson 2012

Lindblad and **co-rotation** torques

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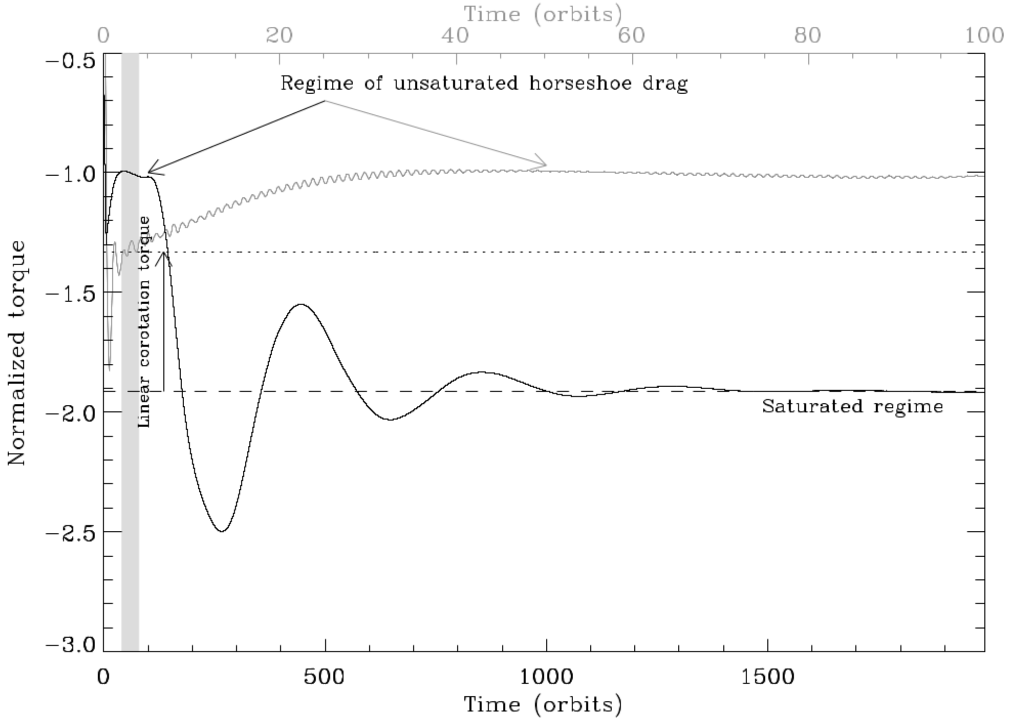


Masset 2011

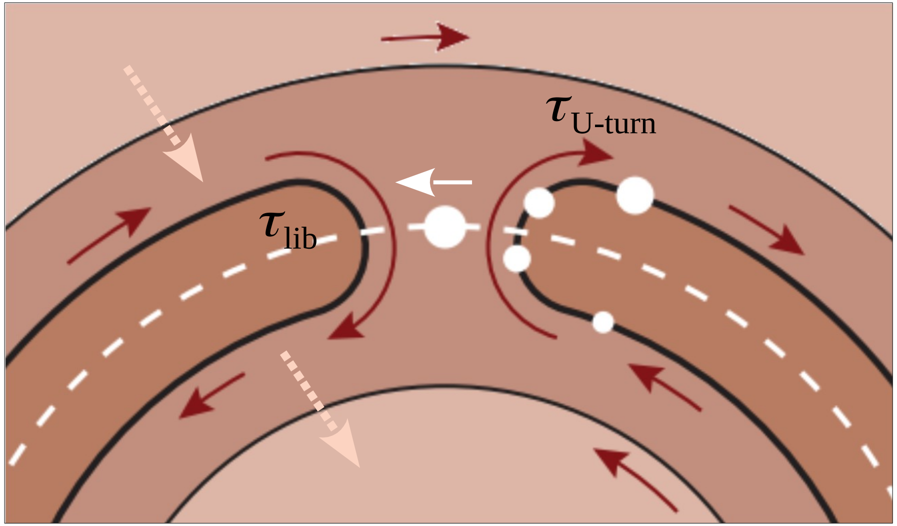
Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r) = \Omega_p$

- r_{co} is not necessarily r_{p}
- Linear co-rotation torque is small
- Horseshoe drag is non-linear
- Time and diffusion matter

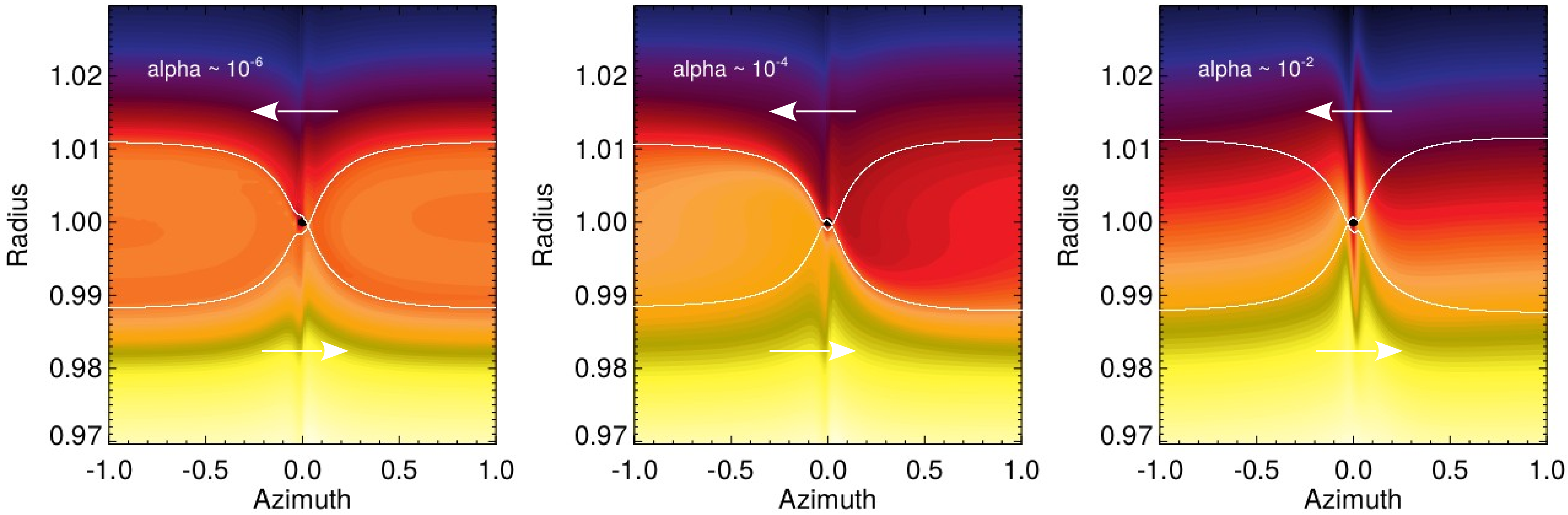
$$\tau_{\text{U-turn}} \sim \frac{H}{x_s}\,\tau_{\mathrm{dyn}} \qquad \tau_{\mathrm{lib}} \sim \frac{8\pi a}{3\Omega_{\mathrm{p}} x_s}$$

$$\tau_{\mathrm{visc}} \sim \frac{x_s^2}{\nu_p},$$ or in general τ_{diff}



Kley & Nelson 2012

Lindblad and **co-rotation** torques

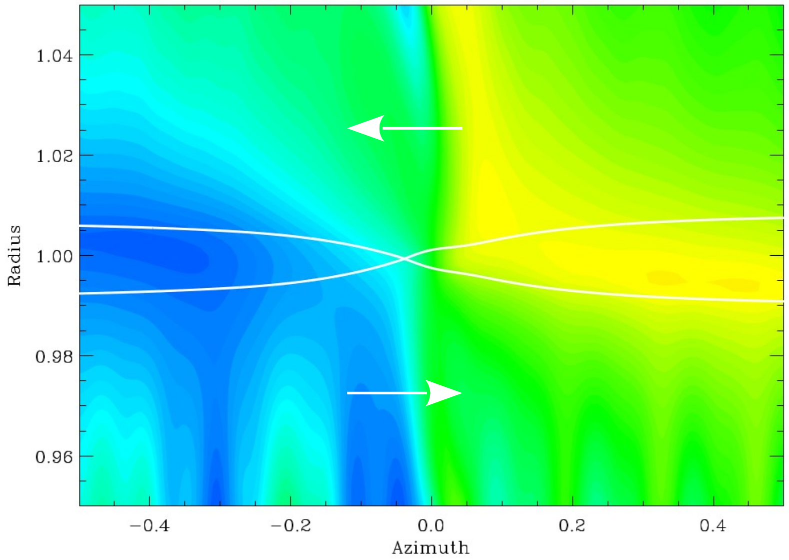


Baruteau & Masset 2013

Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r) = \Omega_p$

- r_{co} is not necessarily r_{p}
- Linear co-rotation torque is small
- Horseshoe drag is non-linear
- Time and diffusion matter
- Vortensity and entropy gradients govern the horseshoe drag



Baruteau & Masset 2013

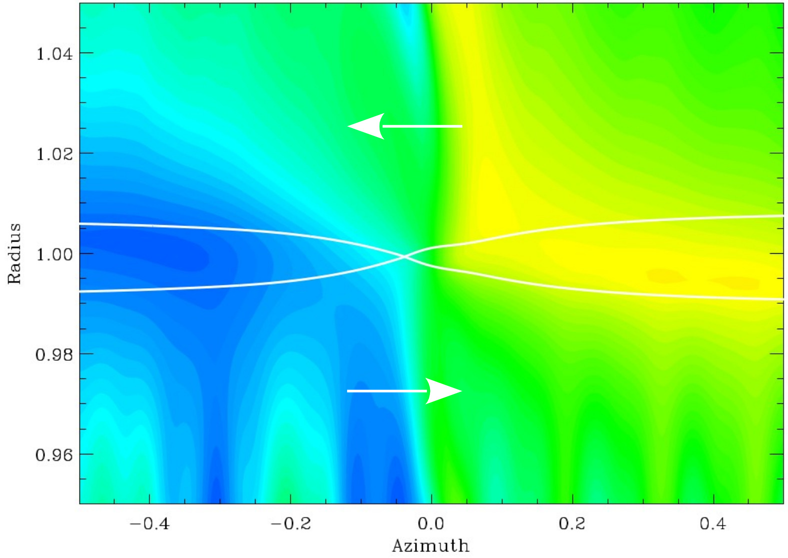
$$\frac{\delta\Sigma}{\Sigma} = \frac{\delta\Sigma}{\Sigma}\left(\frac{\delta l}{l}, \frac{\delta s}{s}\right)$$

l: vortensity, s: entropy

Lindblad and **co-rotation** torques

Co-rotation resonance $\Omega(r) = \Omega_p$

- r_{co} is not necessarily r_{p}
- Linear co-rotation torque is small
- Horseshoe drag is non-linear
- Time and diffusion matter
- Vortensity and entropy gradients govern the horseshoe drag

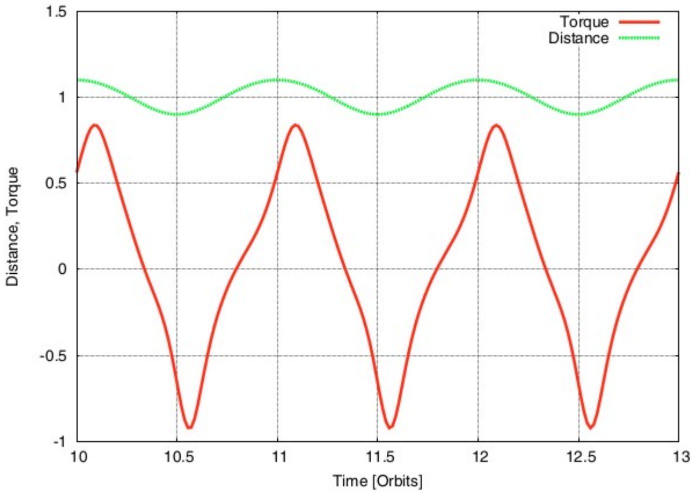


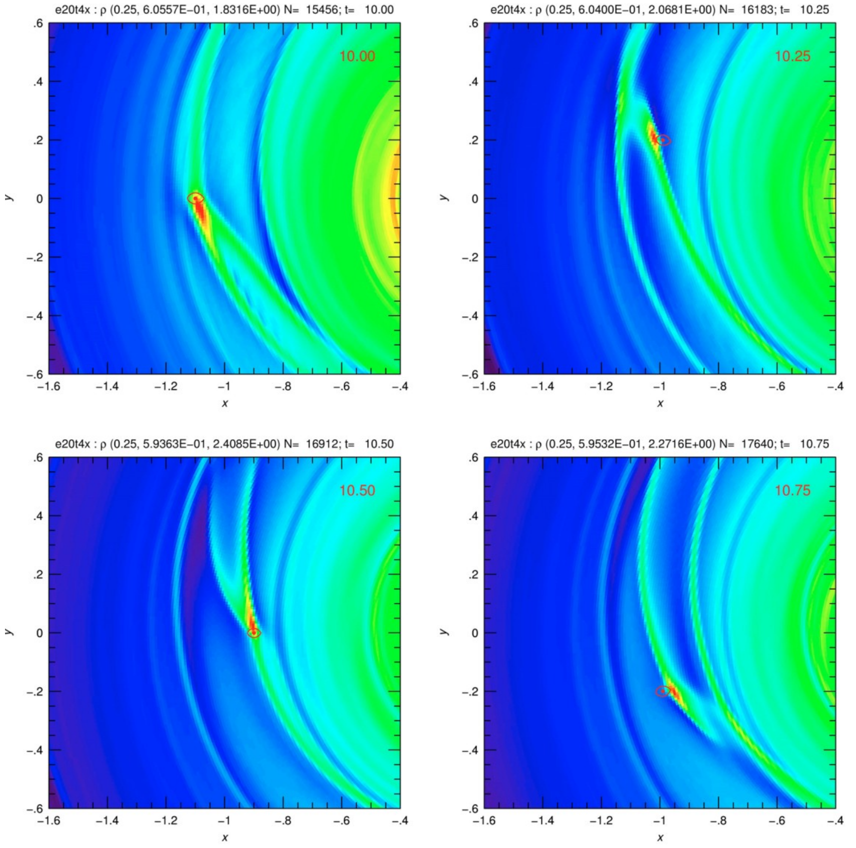
Baruteau & Masset 2013

For a detailed lecture check out:
http://clement.baruteau.free.fr/Bern2017/Baruteau_Bern2017.pdf

Lindblad and co-rotation torques

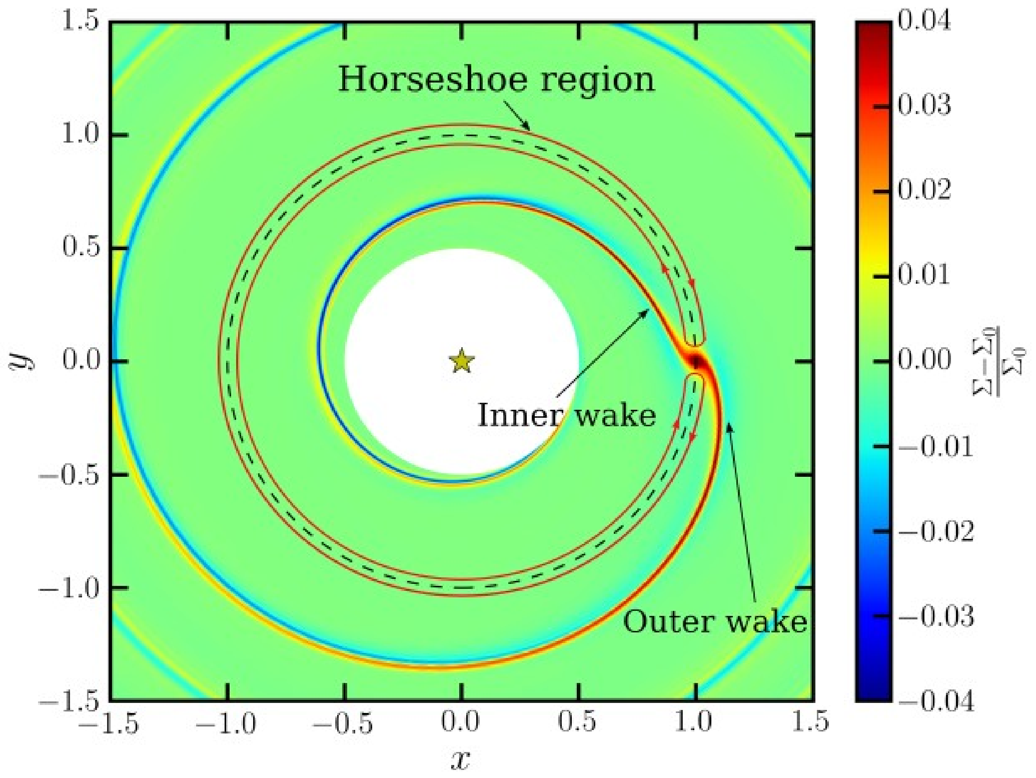
- 20 M_E
- e= 0.1
- non-migrating



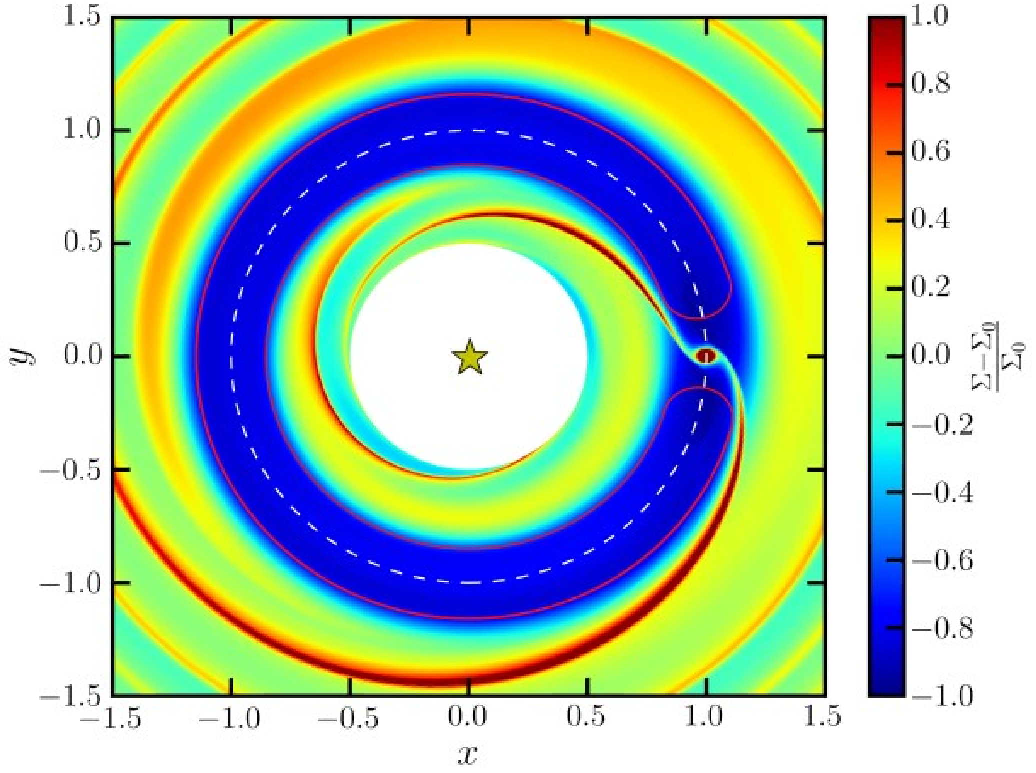


Cresswell+2007

Gap opening


Horseshoe region
Inner wake
Outer wake
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
x
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
$\frac{\Sigma - \Sigma_0}{\Sigma_0}$

Gap opening


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
$\frac{\Sigma-\Sigma_0}{\Sigma_0}$

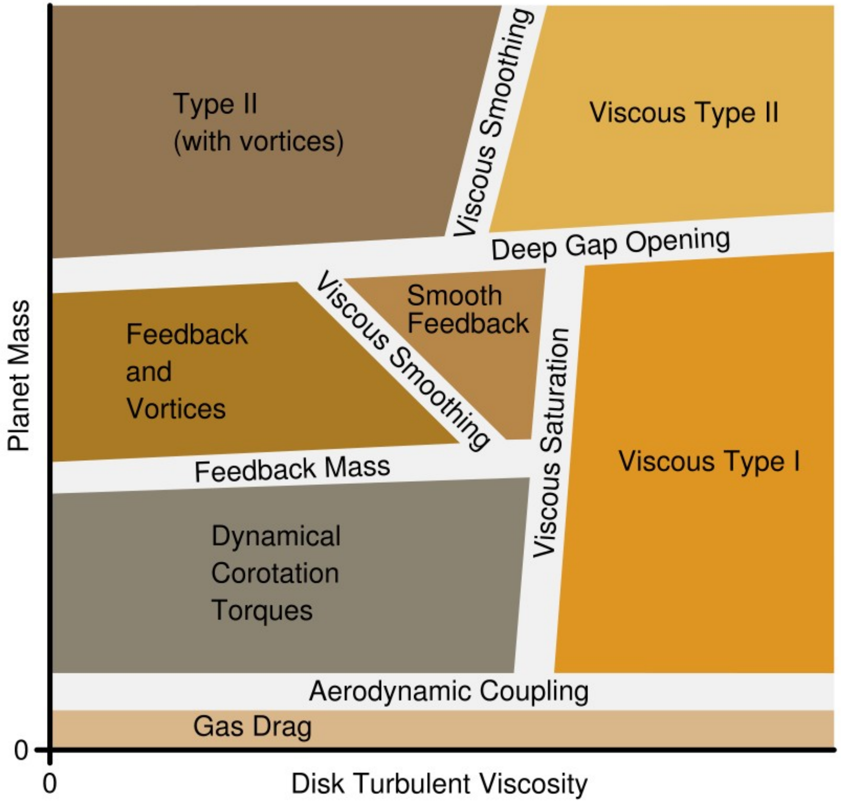
Planetary migration

Low-mass planet: type I migration

High-mass planet: type II migration

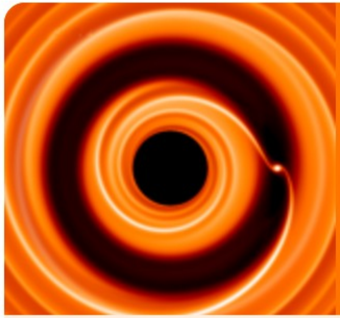
Medium-mass planet: (maybe) type III migration

Planetary migration



McNally+2019

Put your knowledge in practice using FARGO3D



FARGO3D

A versatile multifluid HD/MHD code that runs on clusters of CPUs or GPUs, with special emphasis on protoplanetary disks.

Put your knowledge in practice using FARGO3D

FARGO: Fast Advection in Rotating Gaseous Objects (Masset 2000)

Put your knowledge in practice using FARGO3D

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FARGO3D: the 3D successor of FARGO (Benítez- Llambay 2016)

Put your knowledge in practice using FARGO3D

FARGO: Fast Advection in Rotating Gaseous Objects (Masset 2000)

FARGO3D: the 3D successor of FARGO (Benítez- Llambay 2016)

- Finite difference explicit Eulerian fixed grid code
- Cartesian, cylindrical or spherical geometry
- Multifluid capability (gas and different dust sizes)
- HD and MHD
- 5^{th} order Runge-Kutta N-body solver

Put your knowledge in practice using FARGO3D

We assume you have already read document and

- installed FARGO3D with the mentioned correction
- have fargo3dplot and managed to import it
- had a look at the structure of the code

Put your knowledge in practice using FARGO3D

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- had a look at the structure of the code

```
arch   fargo3d   license.txt   outputs   README.md   setups   std          utils
bin    in        Makefile      planets   scripts     src      test_suite
```

Put your knowledge in practice using FARGO3D

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```
arch   fargo3d   license.txt   outputs   README.md   setups   std          utils
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Our problem → Setup files → Parallel or Serial → Make and Run → Read the outputs → Analyse

Put your knowledge in practice using FARGO3D

Our problem → **Setup files** → Parallel or Serial → Make and Run → Read the outputs → Analyse

Units:

- MKS: all quantities must be given in MKS
- CGS: all quantities must be given in CGS
- Scale-free (default): G=1, M_*=1, R_0=1 ⇒ T= 2π

Put your knowledge in practice using FARGO3D

Our problem → **Setup files** → Parallel or Serial → Make and Run → Read the outputs → Analyse

There are four main setup files:

- setups/<setup_name>/<setup_name>.opt
- setups/<setup_name>/<setup_name>.par
- planets/<planet_name>.cfg
- setups/<setup_name>/<setup_name>.bound

Put your knowledge in practice using FARGO3D

<setup_name>.opt

```
FLUIDS := 0
NFLUIDS = 1
FARGO_OPT += -DNFLUIDS=${NFLUIDS}

#Monitoring options
MONITOR_SCALAR = MASS | MOM_X | TORQ
MONITOR_Y_RAW  = TORQ

#Damping zones in the active mesh

FARGO_OPT += -DSTOCKHOLM

FARGO_OPT +=  -DX
FARGO_OPT +=  -DY

#Equation of State
FARGO_OPT +=  -DISOTHERMAL

#Coordinate System.
FARGO_OPT +=  -DCYLINDRICAL

#Legacy files for outputs
FARGO_OPT += -DLEGACY

FARGO_OPT += -DPOTENTIAL

FARGO_OPT += -DALPHAVISCOSITY
```

de Val-Borro+2006

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
Setup               test1

### Disk parameters

AspectRatio         0.05                    Thickness over Radius in the disc
Sigma0              6.3661977237e-4
Alpha               1.0e-4
SigmaSlope          1.5
FlaringIndex        0.5                     Slope for the aspect-ratio

# Radial range for damping (in period-ratios). Values smaller than one
# prevent damping.

DampingZone 1.15

# Characteristic time for damping, in units of the inverse local
# orbital frequency. Higher values means lower damping

TauDamp 0.3

### Planet parameters

PlanetConfig            planets/jupiter.cfg
ThicknessSmoothing      0.6
Eccentricity            0.0
ExcludeHill             no
IndirectTerm            Yes
```

$$h = \mathrm{AspectRatio}\left(\frac{r}{R_0=1}\right)^{\mathrm{FlaringIndex}}$$

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
Setup             test1

### Disk parameters

AspectRatio       0.05                    Thickness over Radius in the disc
Sigma0            6.3661977237e-4         Surface Density at r=1
Alpha             1.0e-4
SigmaSlope        1.5
FlaringIndex      0.5                     Slope for the aspect-ratio

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```

$$\Sigma = \mathrm{Sigma0}\left(\frac{r}{R_0=1}\right)^{-\mathrm{SigmaSlope}}$$

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
Setup               test1

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Sigma0          6.3661977237e-4         Surface Density at r=1
Alpha           1.0e-4                  ...osity
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```

$\nu = \alpha c_s H$

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
Setup               test1

### Disk parameters

AspectRatio         0.05                 Thickness over Radius in the disc
Sigma0              6.3661977237e-4      Surface Density at r=1
Alpha               1.0e-4               Alpha viscosity
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IndirectTerm            Yes
```

$$y_{\mathrm{inf}} = \mathrm{Ymin}\ \mathrm{DampingZone}^{2/3}$$

$$y_{\mathrm{sup}} = \mathrm{Ymax}\ \mathrm{DampingZone}^{-2/3}$$

$$T_{\mathrm{damp\ in/out}} = \mathrm{TauDamp}\ T_{\mathrm{in/out}}$$

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
Setup                test1

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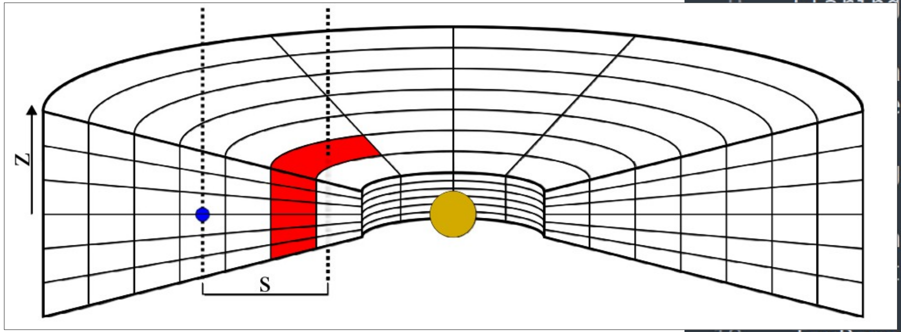
```

$$\phi_p = \frac{-GM_*}{\sqrt{r^2+\epsilon^2}}, \quad \epsilon = \text{ThicknessSmoothing } H$$



Müller1+2012

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
### Mesh parameters

Nx            256     Azimuthal number of zones
Ny            128     Radial number of zones
Xmin          -3.14159265358979323844
Xmax          3.14159265358979323844
Ymin          0.4     Inner boundary radius
Ymax          2.5     Outer boundary radius
OmegaFrame    1.0005  Angular velocity for the frame of reference (If Frame is F).
Frame         C       Method for moving the frame of reference

### Output control parameters

DT            0.314159265359  Physical time between fine-grain outputs
Ninterm       20              Number of DTs between scalar fields outputs
Ntot          1000            Total number of DTs

OutputDir     @outputs/test1

### Plotting parameters

PlotLog       yes
Spacing       Log
```

x is ϕ
y is r

log only in r

Put your knowledge in practice using FARGO3D

<setup_name>.par

```
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Nx            256      Azimuthal number of zones
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### Output control parameters

DT            0.314159265359  Physical time between f
Ninterm       20              Number of DTs between s
Ntot          1000            Total number of DTs

OutputDir     @outputs/test1

### Plotting parameters

PlotLog       yes
Spacing       Log
```

dt: time-step
DT: between two dots
Ninterm × DT: one output
Ntot/Ninterm: final output

Put your knowledge in practice using FARGO3D

<planet_name>.cfg

```
###########################################################
#   Planetary system initial configuration
###########################################################

# Planet Name    Distance     Mass      Accretion   Feels Disk   Feels Others
Jupiter          1.0          0.001     0.0         NO           NO
```

Put your knowledge in practice using FARGO3D

<setup_name>.bound

```
#Boundaries configuration file for fargo.bound
#-----------------------------------------

Density:
    Ymin: KEPLERIAN2DDENS
    Ymax: KEPLERIAN2DDENS

Vx:
    Ymin: KEPLERIAN2DVAZIM
    Ymax: KEPLERIAN2DVAZIM

Vy:
    Ymin: ANTISYMMETRIC
    Ymax: ANTISYMMETRIC

```

Put your knowledge in practice using FARGO3D

Our problem → Setup files → Parallel or Serial → Make and Run → **Read the outputs** → Analyse

The outputs contains several types:

- Field files: binary, gas<field_name>%n.dat
- Planet files: ASCII
  - planet%n.dat (every field output)
  - bigplanet%n.dat, orbit%n.dat, tqwk%n.dat (every DT)
- Grid files: ASCII, domain_x.dat, domain_y.dat, domain_z.dat
- Monitoring files: ASCII and binary
- more...

Put your knowledge in practice using FARGO3D

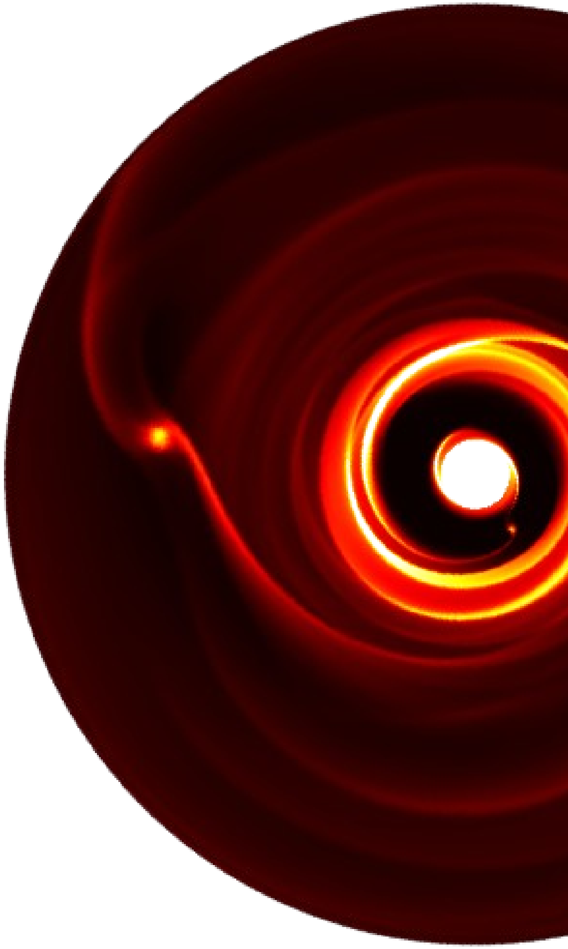
What is the plan?

- Make a setup
- Lindblad torque for a static planet
- Migration of a low-mass planet
- Check out the torque on an eccentric planet
- Surface density perturbation by a massive planet
- See the saturation of the co-rotation torque

Note1: If your computer is not fast enough, you can download the results from the given link in the exercise sheet.

Note 2: Discuss the questions in each section with people around you!

Have fun!



Good reviews for further reading:

- Kley & Nelson 2012
- Baruteau & Masset 2013
- Baruteau+2014
- Baruteau+2016
- Paardekooper+2022