Resonant Excitation of Planetary Eccentricity due to a Dispersing Eccentric Protoplanetary Disk

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Agenda

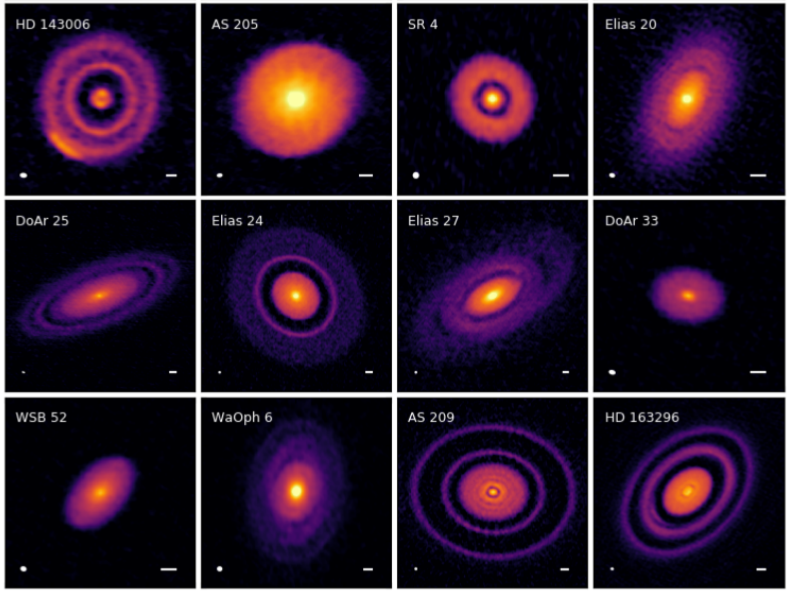
- Eccentric mode instability in protoplanetary disks
- Resonant excitation of planetary eccentricity by a dispersing eccentric disk
- Comparison to planet-planet scatterings

Part I: eccentric mode instability (EMI) in protoplanetary disks

Eccentric mode instability: background

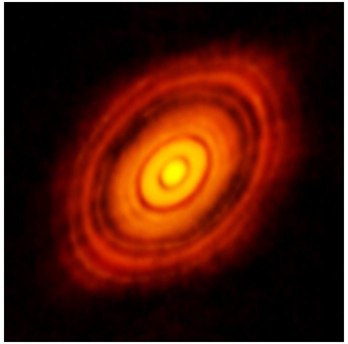
Protoplanetary disks (PPDs):

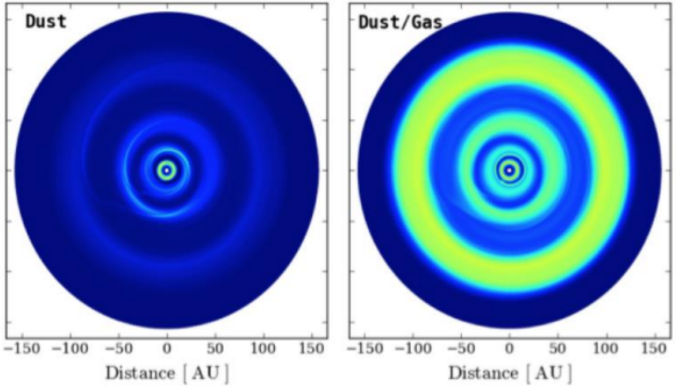
- are the **birthplaces of planets**
- commonly exhibit **substructures** (e.g., **rings and gaps**, inner cavities, vertices, spirals)



a gallery of 1.25mm continuum image for disks in DSHARP sample
(*Andrews et al., 2018*)

Conventional wisdom: planets





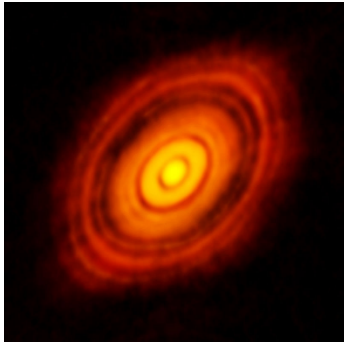
Top: ALMA image of HL Tau;
Bottom: simulation (*Jin+ 2016* @ LANL)
0.35, 0.17, 0.26 M_J @ 13.1, 33.0, 68.6 AU

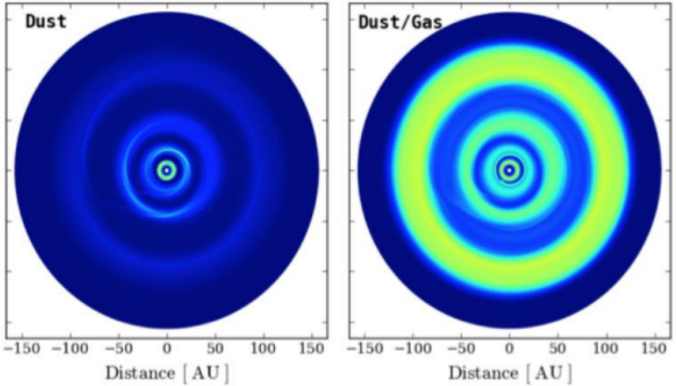
Mechanism:

- Planets orbiting around the star while being **embedded** in the disk.
- **Each planet carves a gap** around its orbit.

Issues:

- Disk rings have very **large radii**.
- Rings are found in **young disks**, too.





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Conventional wisdom: planets

Mechanism:

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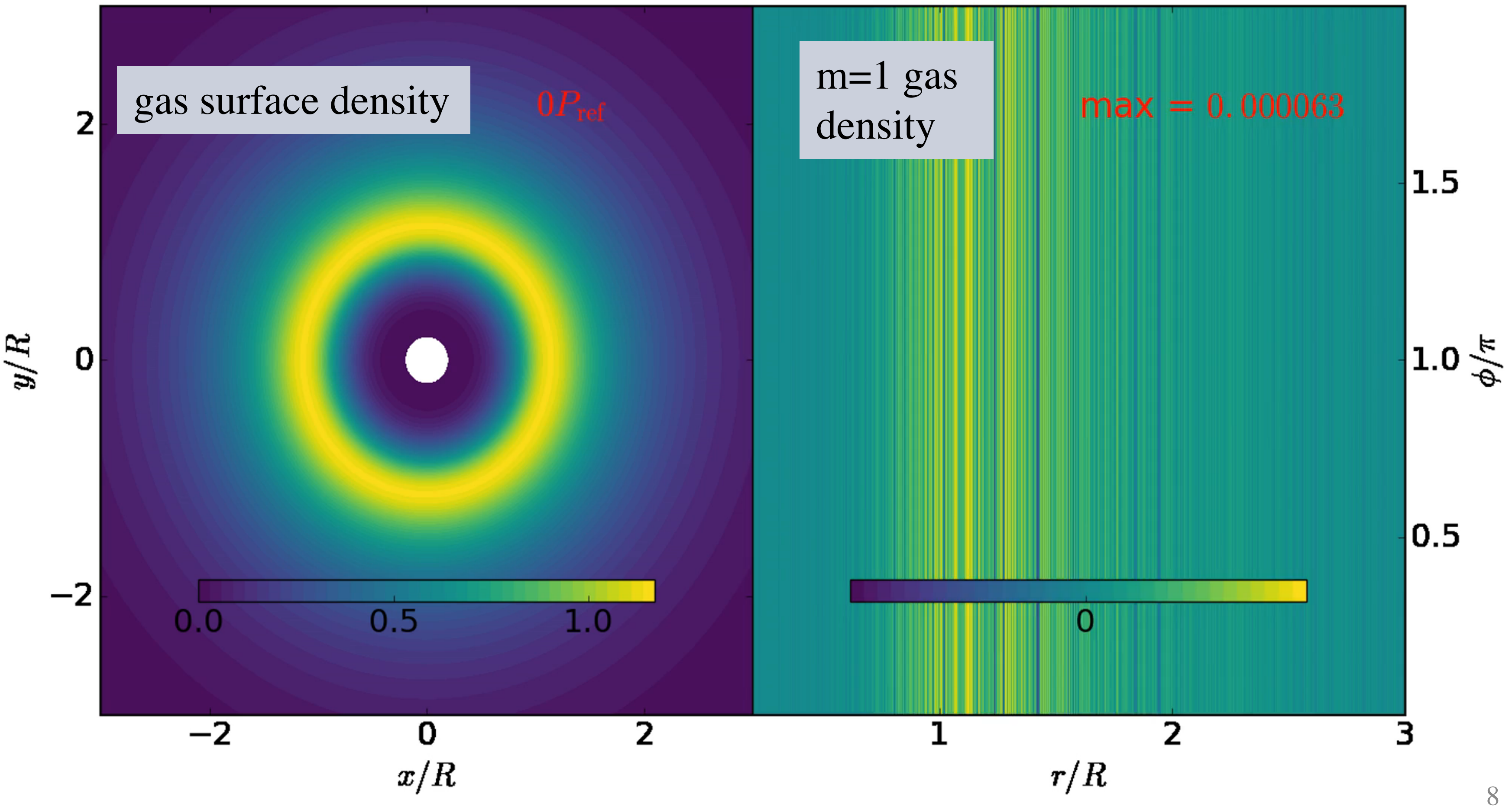
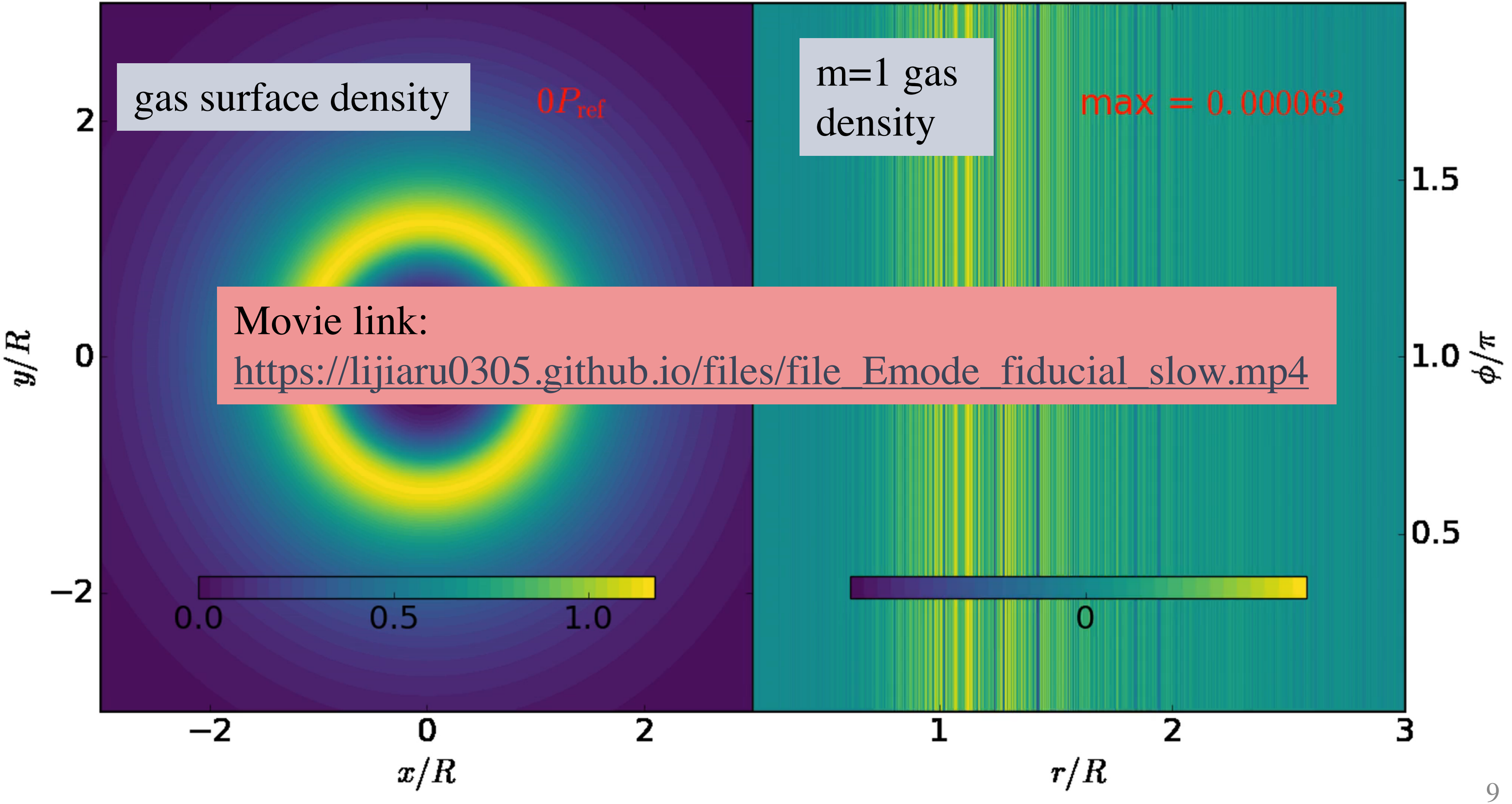
- **Each planet carves a gap** around its orbit.

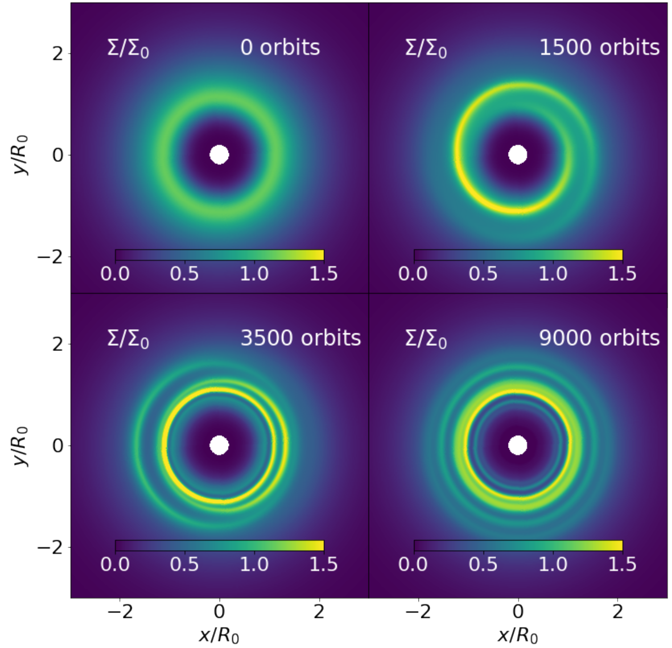
We show that an **eccentric mode instability (EMI)** can generate these **rings** without the help of planets


gas surface density
$0P_{\rm ref}$
m=1 gas density
max = 0.000063
2
0
−2
−2
0
2
y/R
x/R
0.0
0.5
1.0
0
1
2
3
r/R
1.5
1.0
0.5
ϕ/π

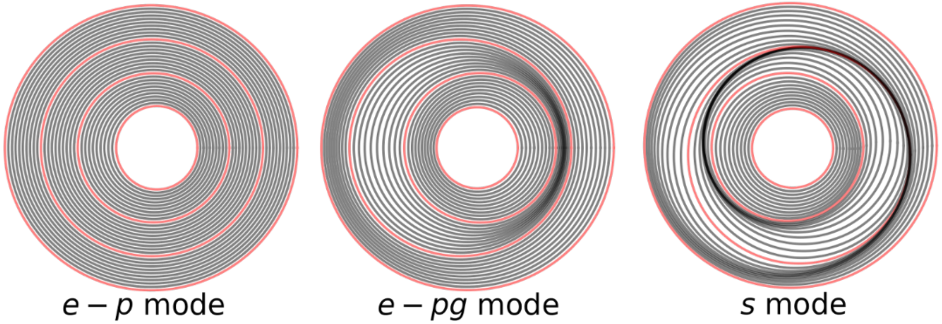


Movie link:
https://lijiaru0305.github.io/files/file_Emode_fiducial_slow.mp4

A new mechanism: eccentric mode instability (EMI)



Ring and gap formations driven by the eccentric mode instability. (***Li***+ *2021*)



Disk eccentric modes: the complex eccentricity profiles that evolve coherently across their host disks.

Details of the simulation

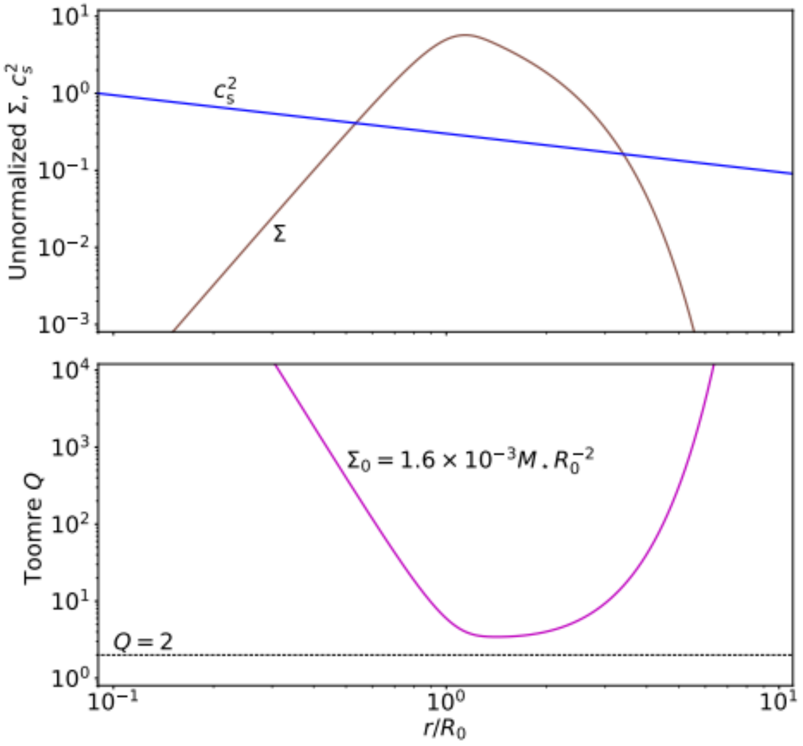
- Initial density:

$$\Sigma(r) = 2.03\Sigma_0 \underbrace{\left(1 - e^{-(r/R_0)^6}\right)}_{\text{inner hole}} \overbrace{\left(\frac{R_0}{r}\right)}^{\text{power-law}} \underbrace{e^{-(r/(2R_0))^2}}_{\text{outer taper}}$$

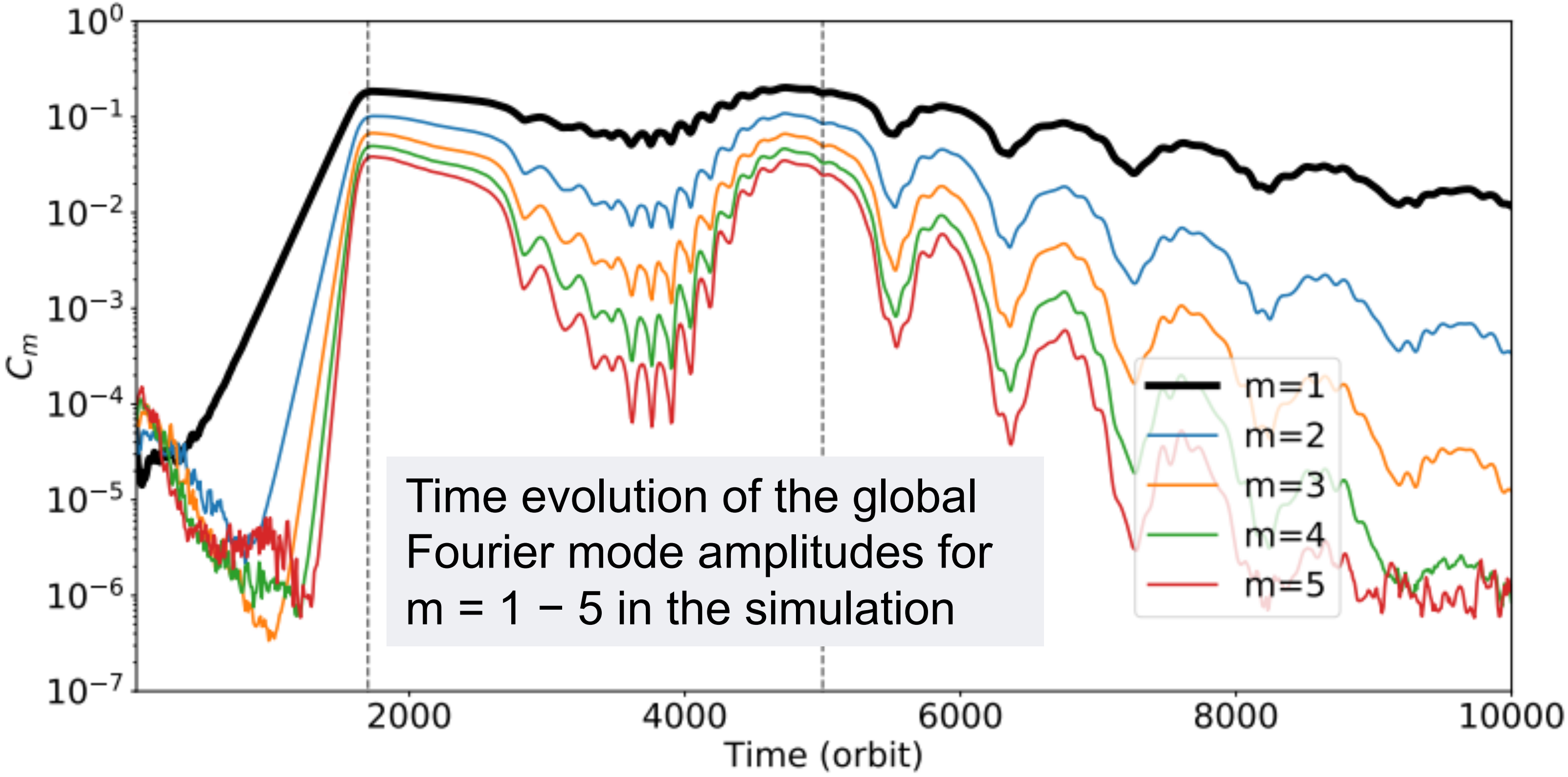
- Temperature:

$$c_s^2(r) = \gamma(k_b/\mu)T = c_0^2(r/R_0)^{-1/2}$$

with γ=1.5, c_0=0.03, and a cooling rate β=1e-6.



Details of the simulation

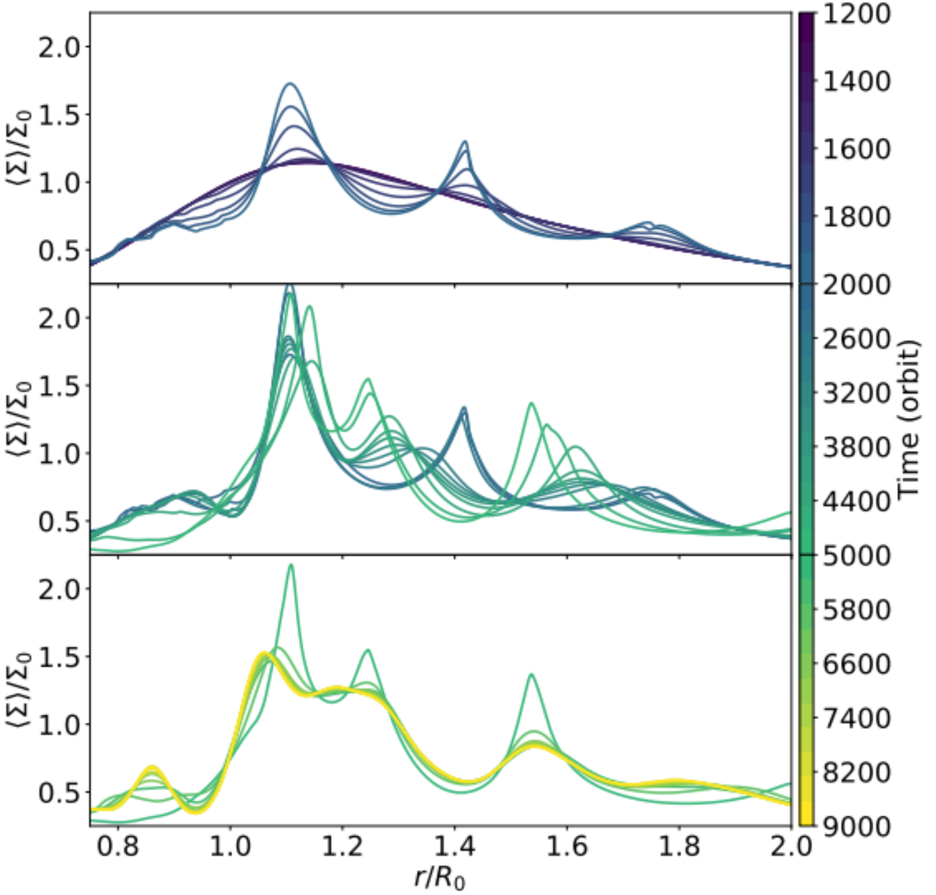


Time evolution of the global Fourier mode amplitudes for m = 1 − 5 in the simulation

Details of the simulation

Time evolution of the azimuthally averaged density profile:

- Multiple rings are formed during the EMI exponential growth stage (top panel).
- The follow-up evolution relax the position and amplitude of the rings (middle and lower panel).



Linear theory: disk eccentricities and modes

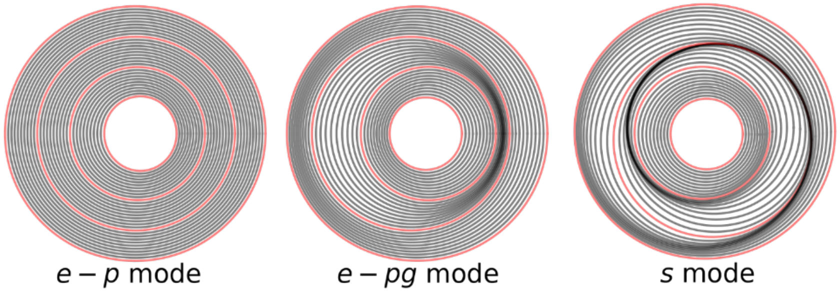
- Evolution equation of disk eccentricity (*Li*+ 2021) :

$$2r^3\Omega_{\rm K}\Sigma\frac{\partial E}{\partial t} = \left[-\frac{\beta}{i\beta+1}\mathcal{M}_{\rm adi} + \frac{i}{i\beta+1}\mathcal{M}_{\rm iso} + \mathcal{M}_{\rm sg} + \mathcal{M}_{\beta}\right] E$$

- Disk eccentric modes:

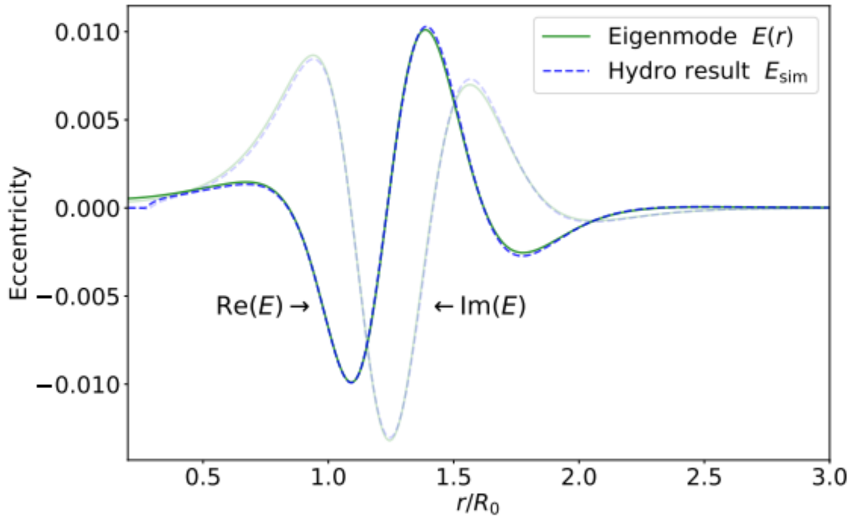
$$\partial E_{\rm m}/\partial t = i\omega_{\rm d,m}E_{\rm m}$$

Linear theory: disk eccentricities and modes



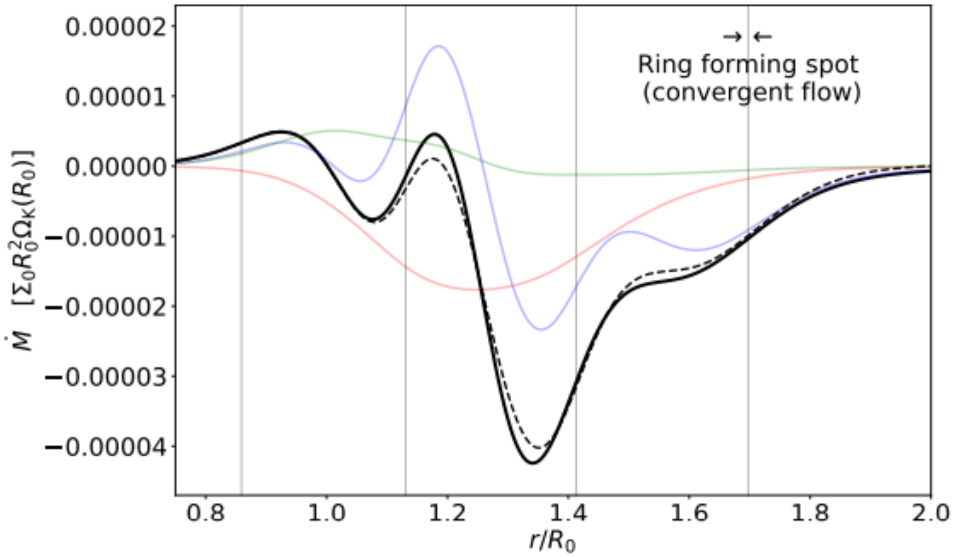
disk eccentric modes (*Lee+2019*):

- e-p mode: real and monotonic
- e-pg mode: real
- s mode: complex (cause EMI)



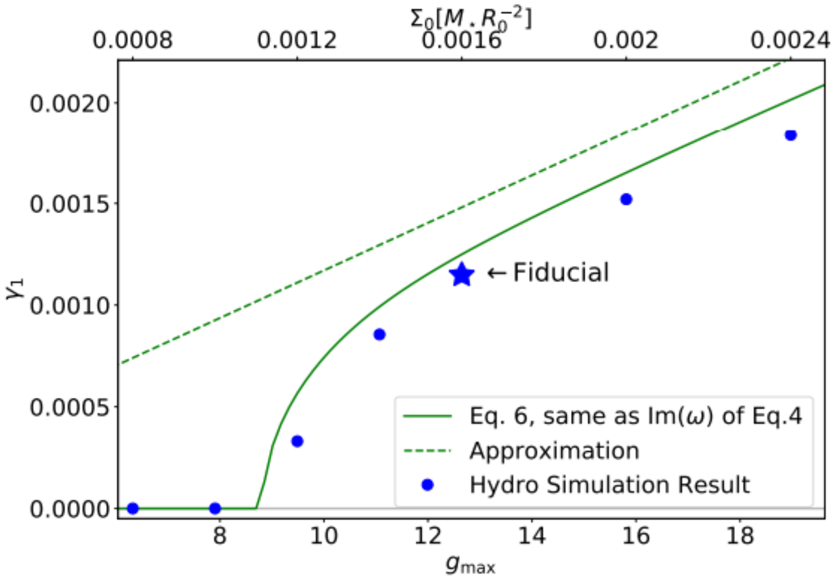
The linear mode matches the simulation result precisely.

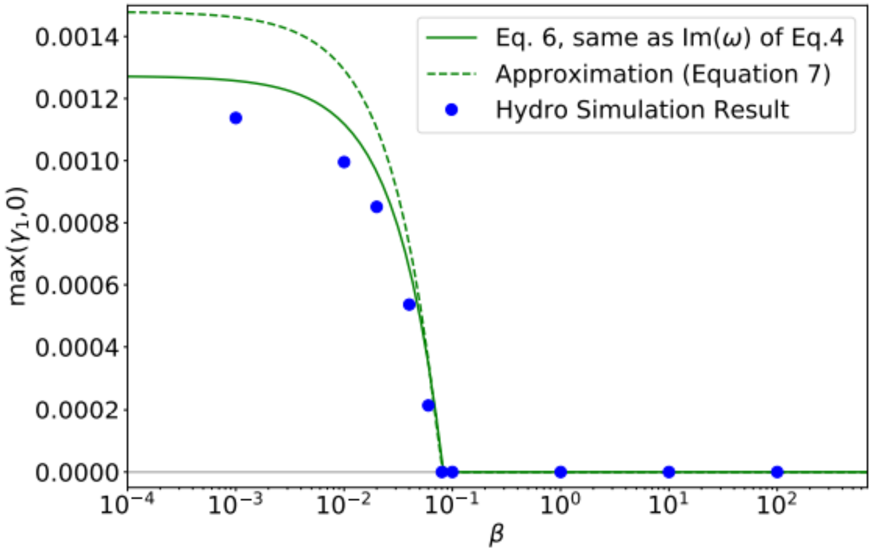
Linear theory: disk eccentricities and modes



We can also use first order non-linear coupling to predict the location of the rings (black solid: theory, black dashed: simulation)

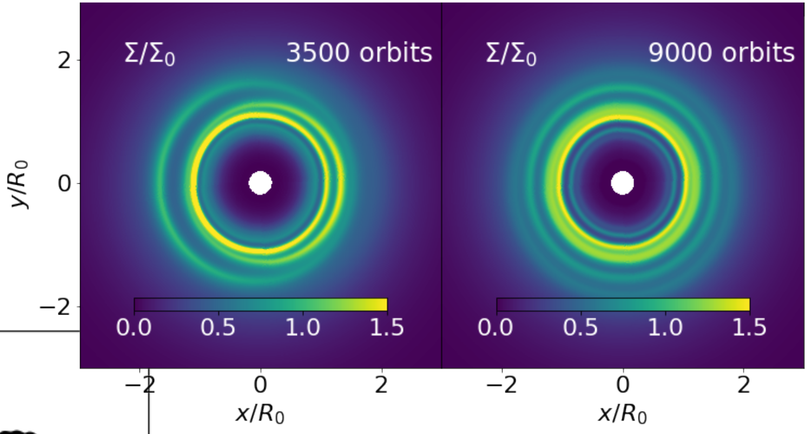
Predict the growth rate of EMI

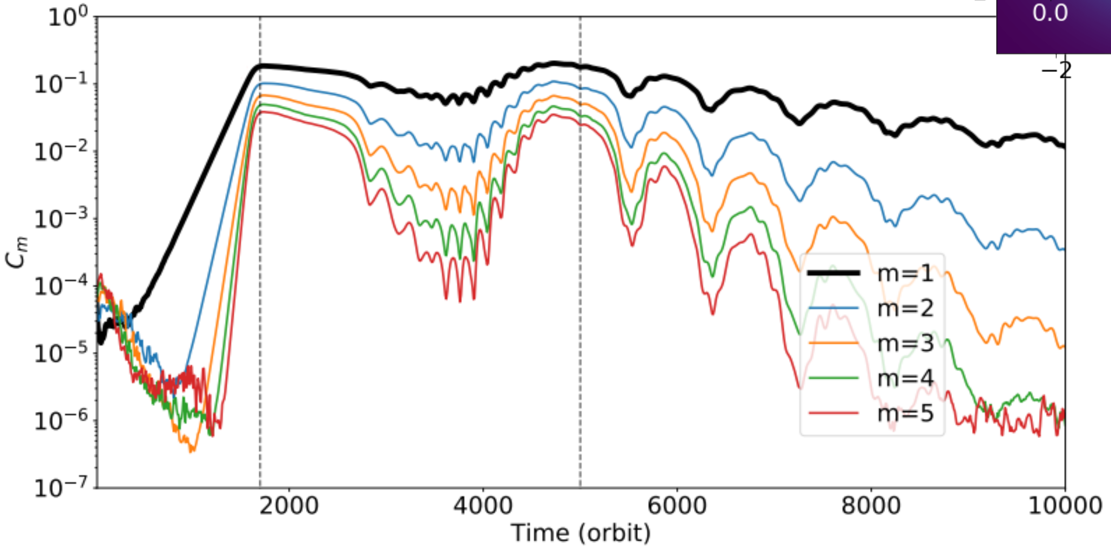




Two conditions for EMI: - strong disk self-gravity - fast gas cooling

Final disk morphology

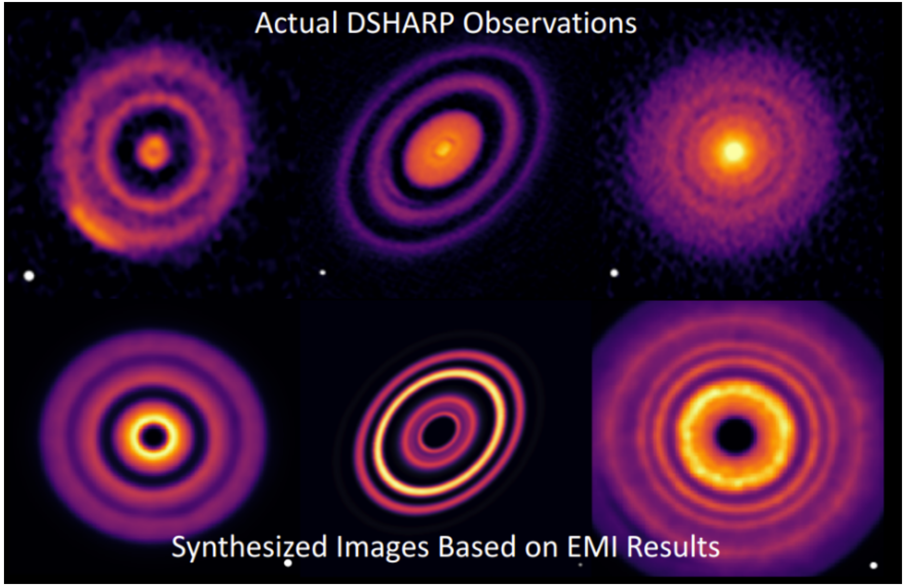




Long-term evolution steps:

1. EMI (s mode) saturates.
2. Disk maintains its eccentricity in a long-lived e mode.
3. If there is damping, rings because circular.

EMI rings vs DSHARP rings



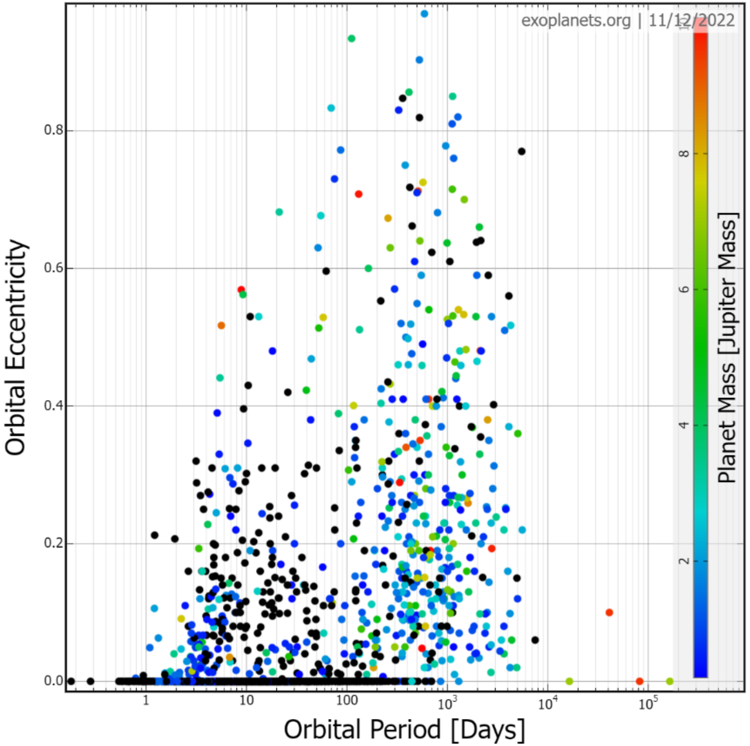
- Start with a ringless density profile.
- Evolve the disks with hydro simulations
- **Add dust** at different stages and continue evolving with the hydro code.
- Run the **Monte-Carlo radiative transfer simulation RADMC-3D** to get **synthetic images**.

Part II: resonant excitation of planetary eccentricity by a dispersing eccentric disk

Orbital eccentricity of exoplanet

Possible origins:

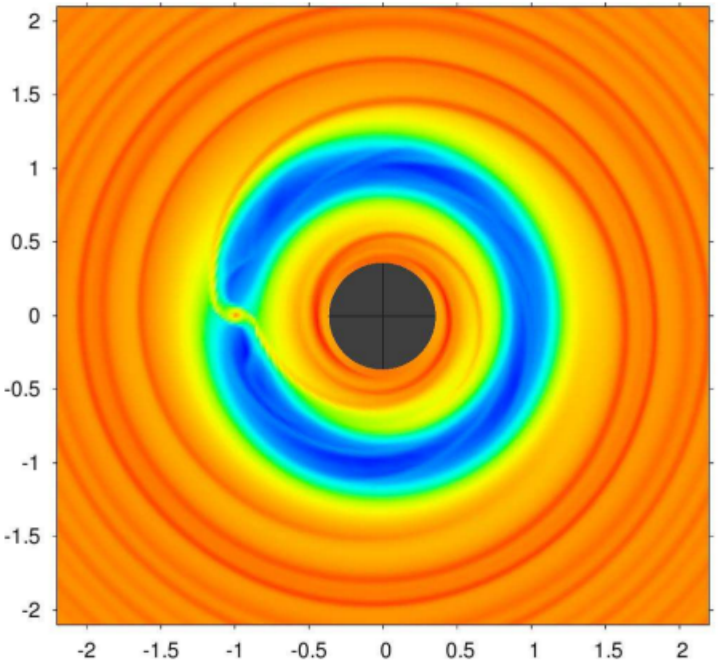
- Planet-planet scatterings
- Secular interactions with exterior companions
- Planet-disk interactions



Orbital eccentricity of exoplanet

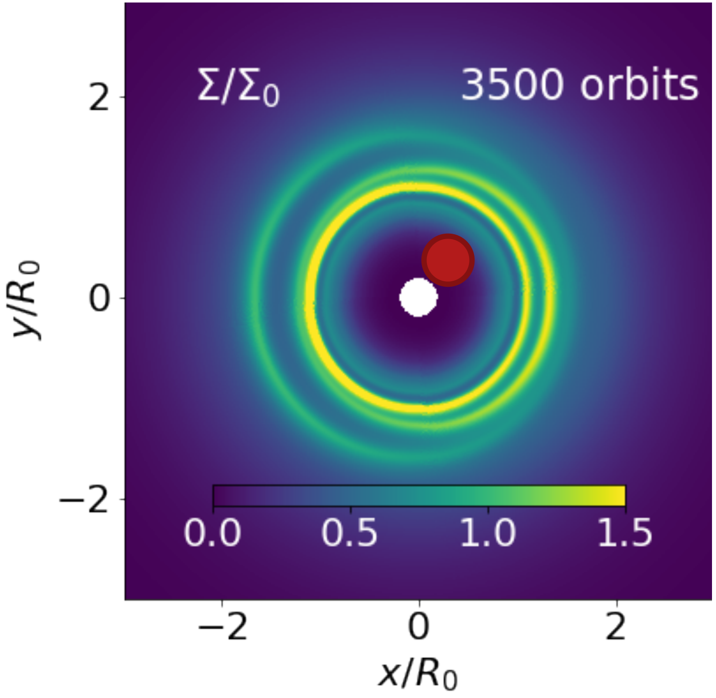
Possible origin:

- Planet-disk interactions
  - High mass planets: Lindblad torques (e.g., *Teyssandier & Ogilvie 2017, Ragusa et al. 2018*)
  - Low mass planets: thermal back-reactions (e.g., *Eklund & Masset 2017, Velasco Romero et al. 2022*)
  - However, in both cases, $e_p < 0.1$



a disk and an embedd planet
(*Kley & Dirksen, 2006*)

Our new mechanism..



- Planet inside the inner cavity of the disk.
- Disk has a small initial eccentricity. (In some hydro simulations, the disk eccentricity is not damped.)
- The disk loses mass with time.

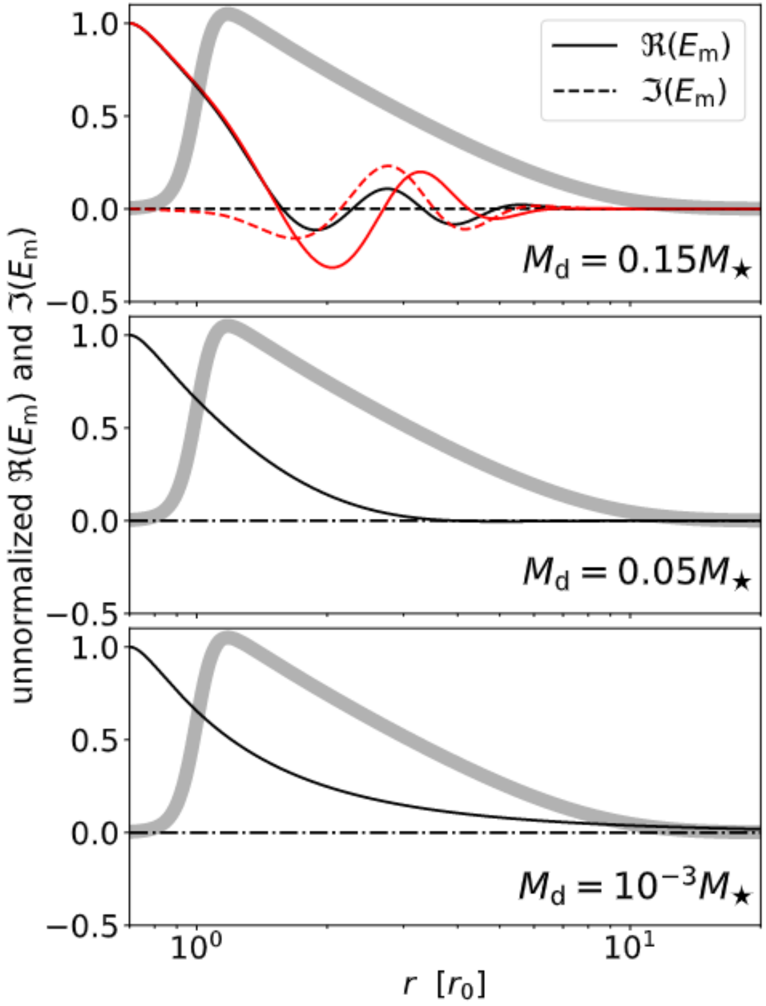
Eccentric mode in a dispersing disk

- Evolution equation:

$$2r^3\Omega_K\Sigma\frac{\partial E}{\partial t} = \left(-\frac{\beta}{i\beta+1}\mathcal{M}_{\rm adi} + \frac{i}{i\beta+1}\mathcal{M}_{\rm iso} + \mathcal{M}_{\rm sg} + \mathcal{M}_\beta\right)E,$$

- Eccentric modes:

$$\partial E_{\rm m}/\partial t = i\omega_{\rm d,m}E_{\rm m}$$



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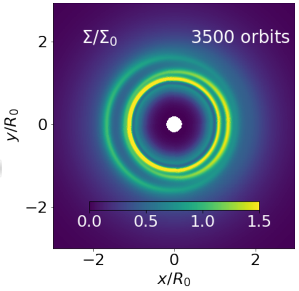

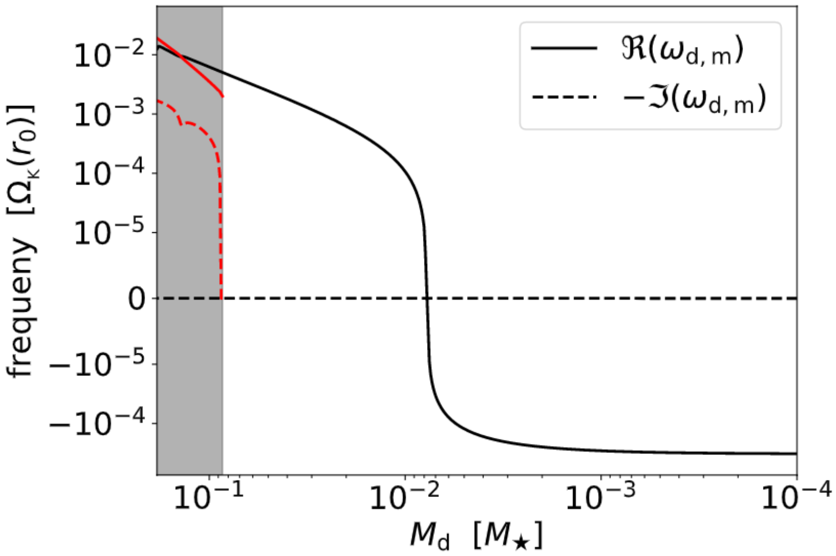

Planet-disk interaction model

- Assume that the disk's coherent eccentricity $E(r, t; M_d)$ has the same "shape" as the e mode of the disk

$$E(r,t;M_{\rm d}) = E_{\rm m}(r;M_{\rm d})E_d(t)$$

- We can write down the eccentricity interaction equation for a planet and 'rigid' disk as (*Teyssandier & Lai 2019*)

$$\frac{dE_{\rm d}}{dt} = i(\omega_{\rm d,m} + \omega_{\rm d,p})E_{\rm d} - i\nu_{\rm d,p}E_{\rm p}$$
$$\frac{dE_{\rm p}}{dt} = -i\nu_{\rm p,d}E_{\rm d} + i\omega_{\rm p,d}E_{\rm p}$$

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e mode frequency

$$\frac{dE_{\rm d}}{dt} = i(\omega_{\rm d,m} + \omega_{\rm d,p})E_{\rm d} - i\nu_{\rm d,p}E_{\rm p}$$

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mutually induced precession rate

$$\frac{dE_{\rm d}}{dt} = i(\omega_{\rm d,m} + \omega_{\rm d,p})E_{\rm d} - i\nu_{\rm d,p}E_{\rm p}$$

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eccentricity coupling rate

$$\frac{dE_{\rm d}}{dt} = i(\omega_{\rm d,m} + \omega_{\rm d,p}) E_{\rm d} - i\nu_{\rm d,p} E_{\rm p}$$

$$\frac{dE_{\rm p}}{dt} = -i\nu_{\rm p,d} E_{\rm d} + i\omega_{\rm p,d} E_{\rm p}$$

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$$\frac{dE_\mathrm{d}}{dt} = i(\omega_\mathrm{d,m} + \omega_\mathrm{d,p}) E_\mathrm{d} - i\nu_\mathrm{d,p} E_\mathrm{p}$$

$$\frac{dE_\mathrm{p}}{dt} = -i\nu_\mathrm{p,d} E_\mathrm{d} + i\omega_\mathrm{p,d} E_\mathrm{p}$$

$$\omega_\mathrm{d,p} = \frac{1}{J_\mathrm{d}} \int G M_\mathrm{p} \Sigma K_1(r, a_\mathrm{p}) |E_\mathrm{m}|^2 2\pi r dr$$

$$\omega_\mathrm{p,d} = \frac{1}{J_\mathrm{p}} \int G M_\mathrm{p} \Sigma K_1(r, a_\mathrm{p}) 2\pi r dr$$

$$\nu_\mathrm{d,p} = \frac{1}{J_\mathrm{d}} \int G M_\mathrm{p} \Sigma K_2(r, a_\mathrm{p}) E_\mathrm{m} 2\pi r dr$$

$$\nu_\mathrm{p,d} = \frac{1}{J_\mathrm{p}} \int G M_\mathrm{p} \Sigma K_2(r, a_\mathrm{p}) E_\mathrm{m} 2\pi r dr$$

Numerical examples

Result of the long-term time evolution in the fiducial system:

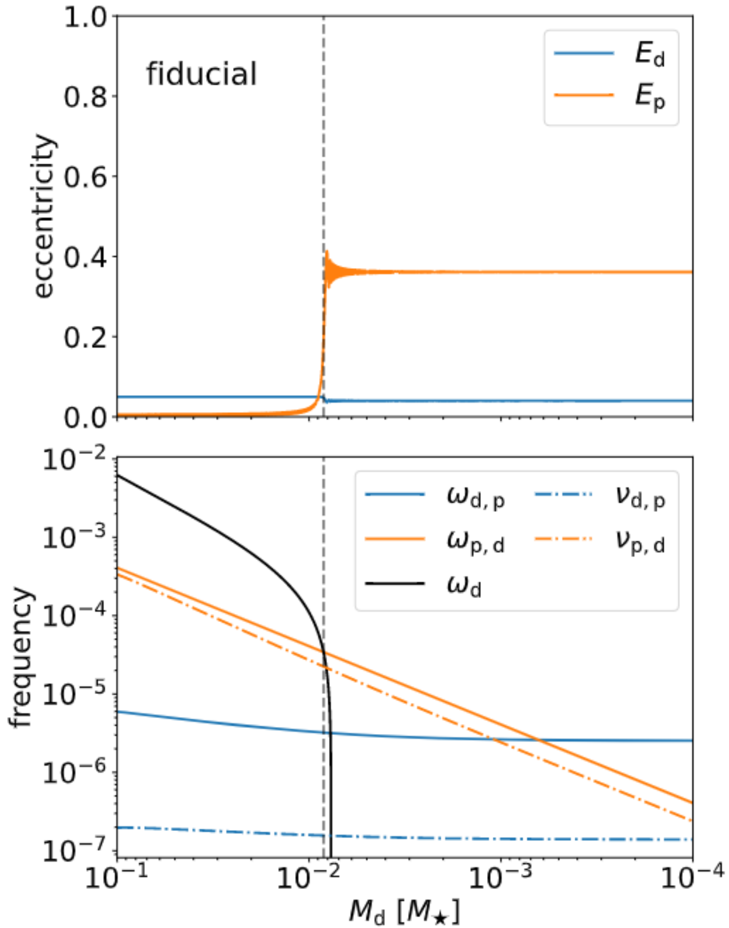
- Planet

$$a_{\rm p} = 0.2 r_0, \ M_{\rm p} = 3 \times 10^{-4} M_\odot$$

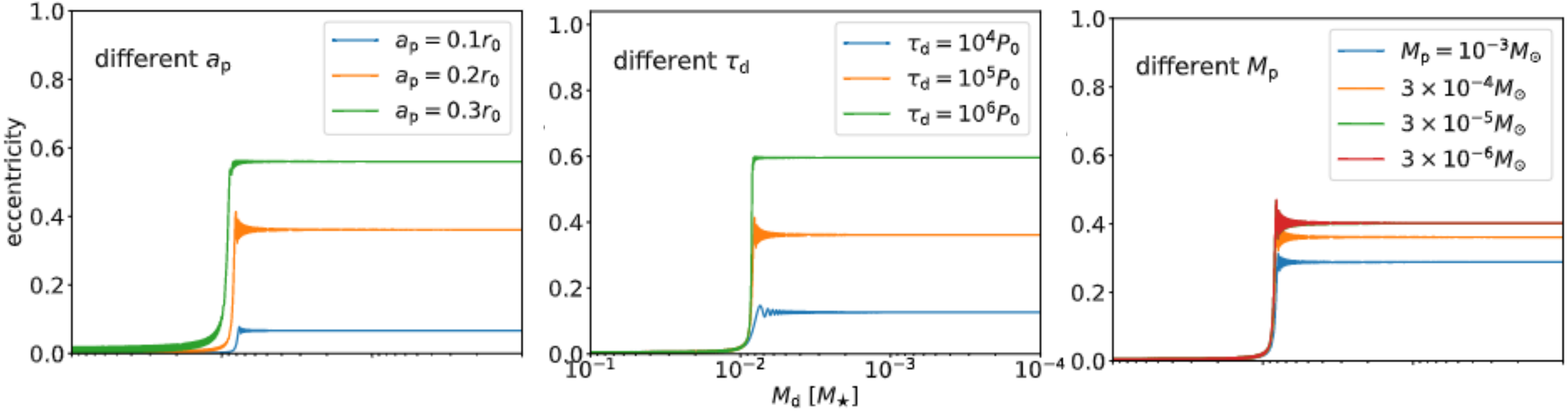
- Disk

$$M_{\rm d}(t) = \frac{M_{\rm d,0}}{1 + t/\tau_{\rm d}}, \ \tau_{\rm d} = 10^5 P_0$$

$$M_{\rm d,0} = 0.1 M_\star = 0.1 M_\odot$$



Numerical examples: parameter study



Analysis

- It is useful to consider two different variables:

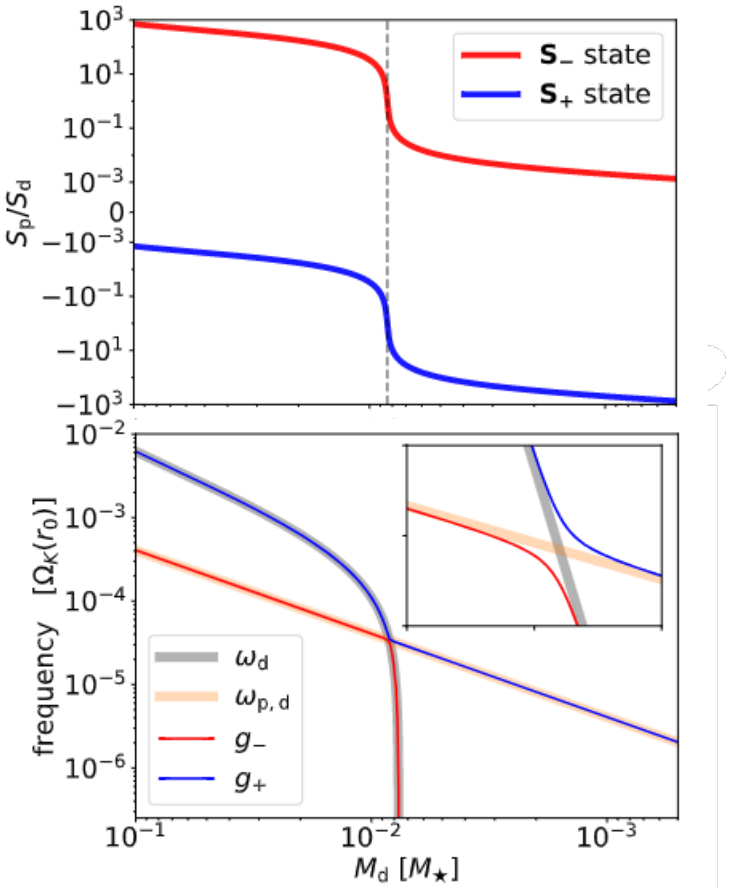
$$S_{\rm d} = \left(\frac{J_{\rm d}}{2}\right)^{1/2} E_{\rm d} \qquad S_{\rm p} = \left(\frac{J_{\rm p}}{2}\right)^{1/2} E_{\rm p}$$

- The two variables evolve as

$$\frac{d}{dt}\begin{pmatrix} S_{\rm d} \\ S_{\rm p} \end{pmatrix} = i \begin{pmatrix} \omega + \Delta\omega + i\frac{1}{2\tau_{\rm J}} & -\nu \\ -\nu & \omega - \Delta\omega \end{pmatrix} \begin{pmatrix} S_{\rm d} \\ S_{\rm p} \end{pmatrix}$$

- We can find their eigenstates:

$$\boldsymbol{S}_{\pm} = \begin{pmatrix} S_{\rm d} \\ S_{\rm p} \end{pmatrix}_{\pm} = \begin{pmatrix} \Delta\omega \pm \sqrt{(\Delta\omega)^2 + \nu^2} \\ -\nu \end{pmatrix}$$



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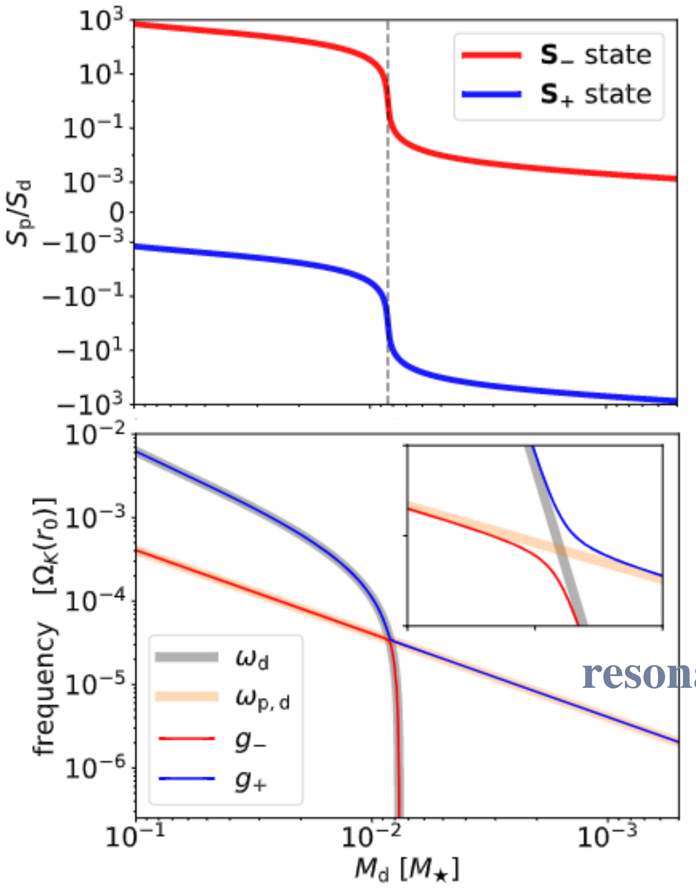

resonance

Analysis

- It is useful to consider two different variables:

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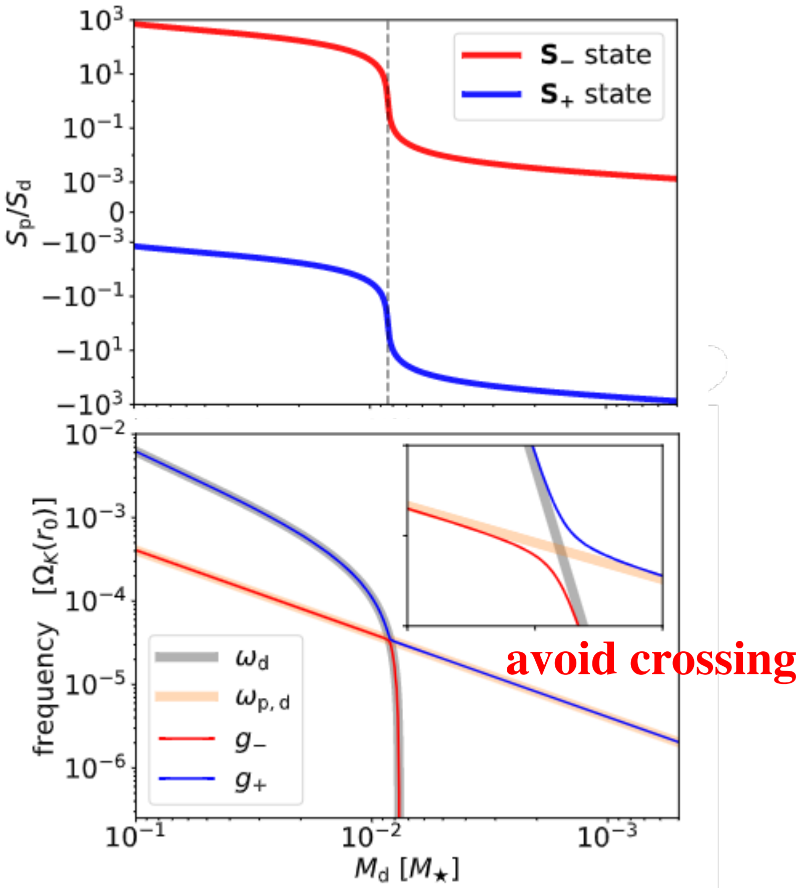
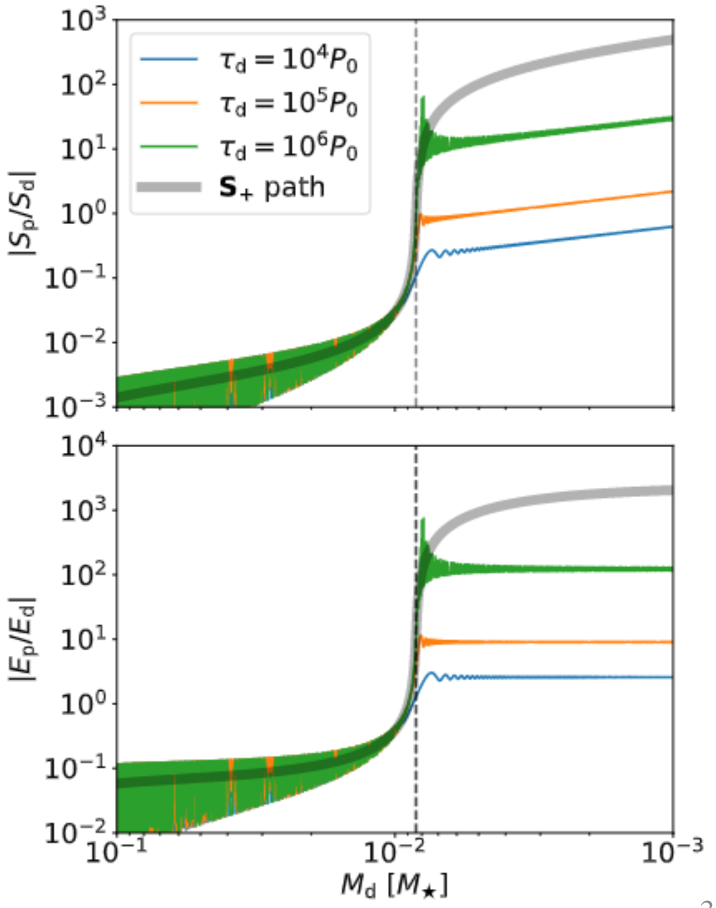


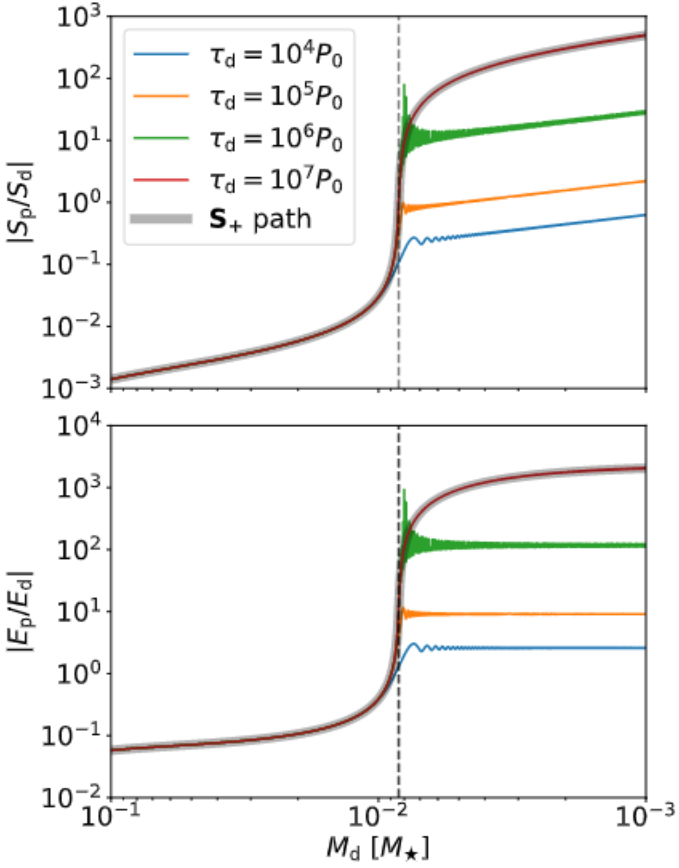
Analysis

- The time integrations start nearly in the S+ state.
- If the disk loses mass with time slowly, the eigenstate also evolves slowly.
- By adiabatic theorem, the eccentricities of the planet and the disk evolves accordingly to remain in the eigenstate.
- The eigenstate path naturally guide the system to a high-planet-eccentricity configuration.



Analysis

- We can also start exactly on the eigen-path and try larger disk dispersal timescale…



Summary of Part I and II

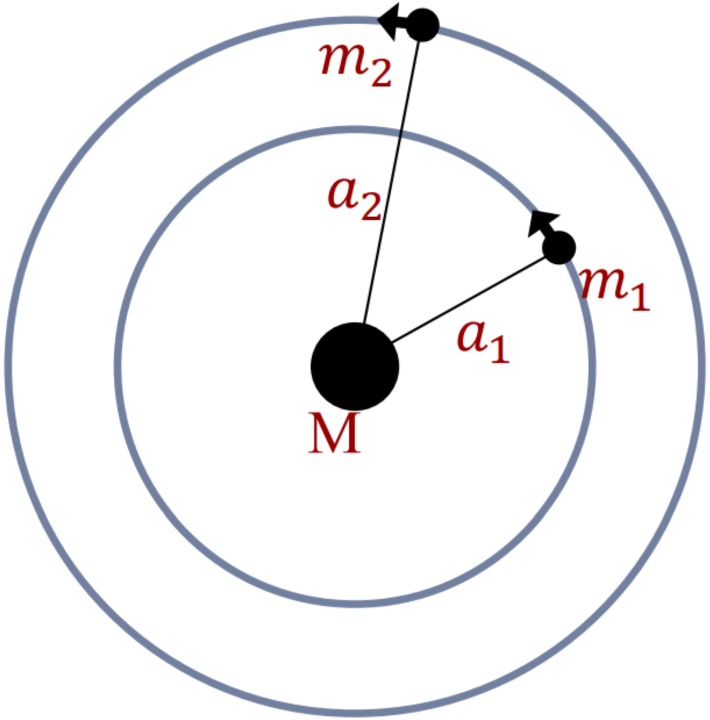
- EMI allows massive disks to rapidly becomes eccentric.
- The long-term outcome of EMI is a disk with either multiple rings or long-lived eccentricity.
- A disk gradually loses mass while preserving a long-lived, precessing eccentricity can excite the eccentricity of a planet (up to 0.6).
- The resonant excitation of planetary eccentricity can be explained by an eigenmode analysis.

Part III: planet-planet scatterings (bonus)

Dynamical instability in planetary systems

- Planetary ejections:
  - Produce large eccentricity planets
  - Excitation planetary orbital inclination (main difference to our new mechanism)

- Planet-planet collisions:
  - Do not excitation much eccentricities and inclination



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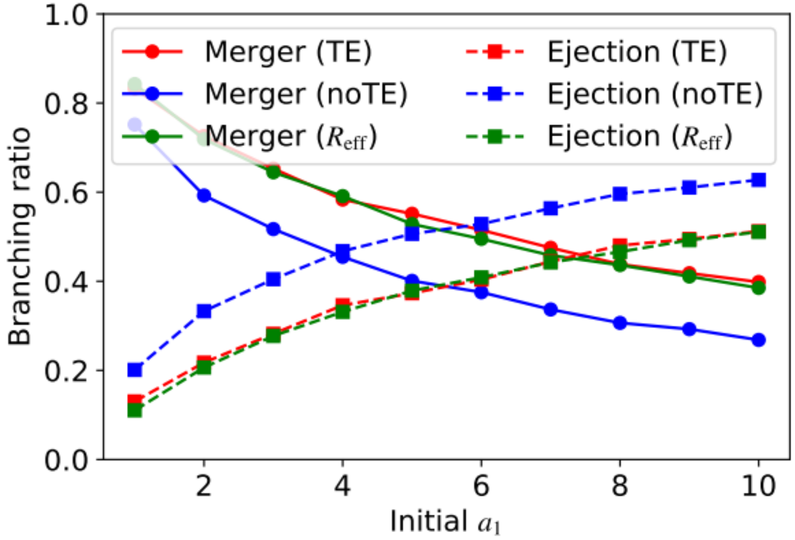
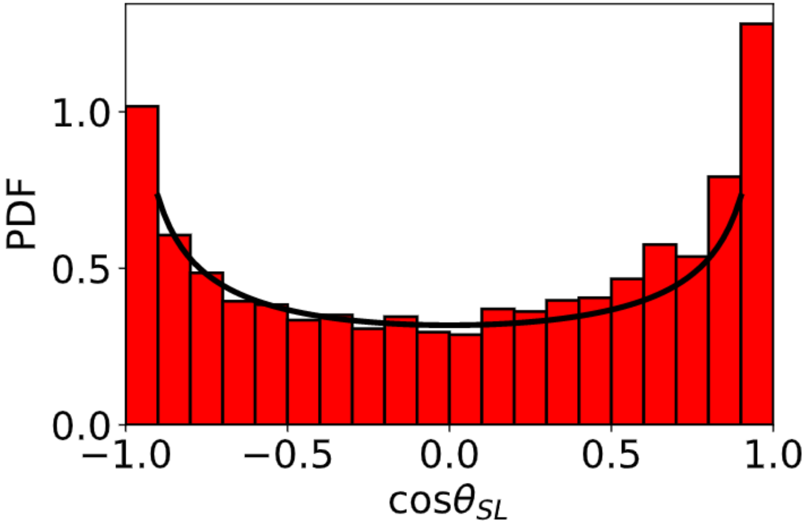


(*Li+ 2021*)

Dynamical instability in planetary systems

- Planetary ejections:
  - Produce high-eccentricity planets
  - Excite planetary orbital inclinations
- Planet-planet collisions:
  - Do not excite much eccentricities and inclinations
  - **Do excite planets' obliquities.**



(***Li** & Lai 2020*)