Eccentricity evolution during planet-disc interaction

Enrico Ragusa

Università degli Studi di Milano

JEDI meeting, Frascati, 28-06-2018

Collaborators:

Giuseppe Lodato – Unimi,

Giovanni Dipierro – University of Leicester

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Daniel J. Price – Monash University

UNIVERSITY OF CAMBRIDGE
Department of Applied Mathematics and Theoretical Physics

MoCA
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Introduction
What causes eccentricity growth?

- Mean eccentricity in exoplanets (EOD 2018): $\langle e \rangle \sim 0.06, \quad \langle e \rangle_{M_\mathrm{p} > 5 M_\mathrm{J}} \approx 0.3$

- Two main mechanisms to excite eccentricity:
  - After disc dispersal, gas poor environment: Interaction of planets with other massive bodies in the system (Rasio & Ford 1996)
  - In protoplanetary disc, gas rich environment: planet-disc interaction provides migration and eccentricity excitation (Kley & Nelson 2012, Review)

Introduction
Planet-disc resonant interaction

- Interaction at resonant locations:
  - Lindblad resonances: pump eccentricity
  - Co-orbital resonances: damp eccentricity

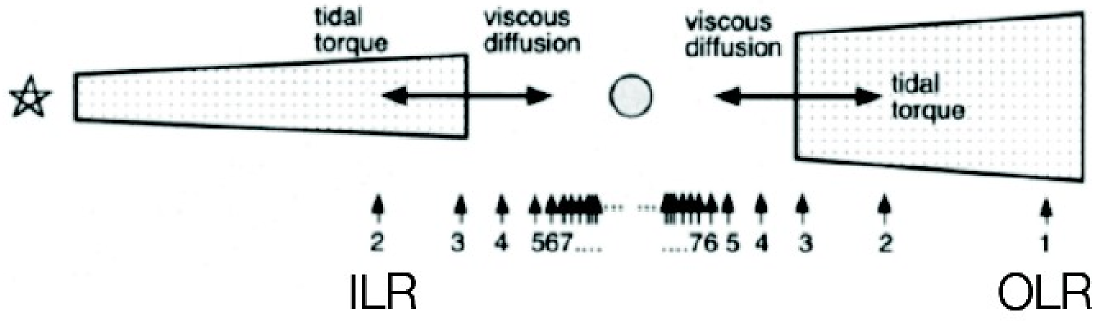


Image from: Takeuchi et al. (1996)

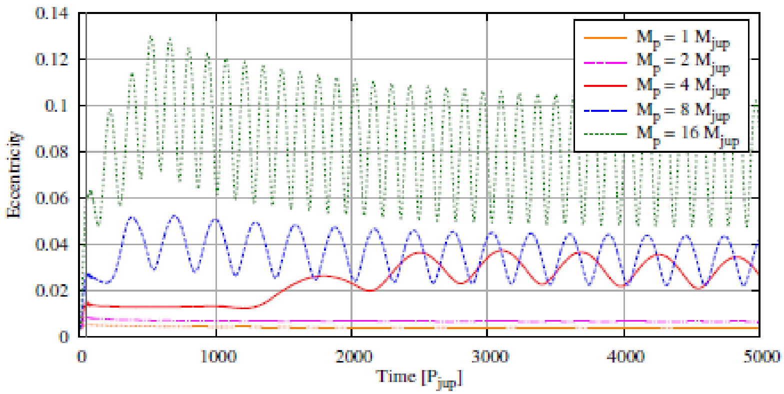
- Planets embedded in the disc: eccentricity damping (Cresswell et al. 2007, Bitsch & Kley 2010)
- Planets carving cavities ($M_p \gtrsim M_j$): saturation of coorbital torque (Ogilvie & Lubow 2003, Goldreich & Sari 2003) $e_{\max} \sim 0.1$
- **Important: mutual interaction, eccentricity grows also in the disc**

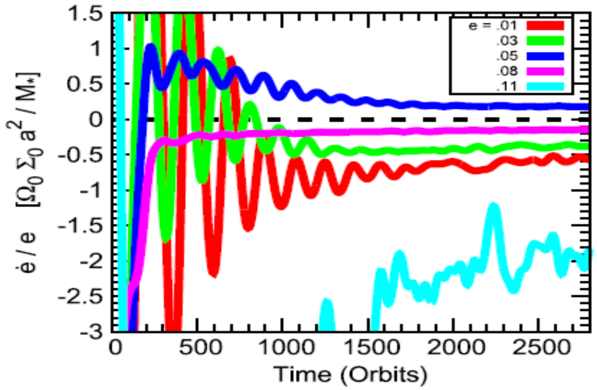
Numerical Simulations
Planet-disc secular interaction

- Often neglected but still important secular interaction:
  - Provides periodic exchange of eccentricity between disc and planet
- Well developed in the context of celestial mechanics

- **Effective at long timescales!**

Muller & Kley (2013)





Duffel & Chiang (2015)

Numerical Simulations
Long duration numerical simulations

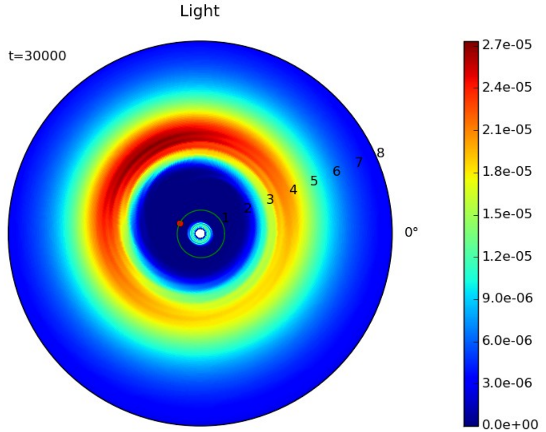
- FARGO3D in 2D configuration (Rosotti et al. 2017)

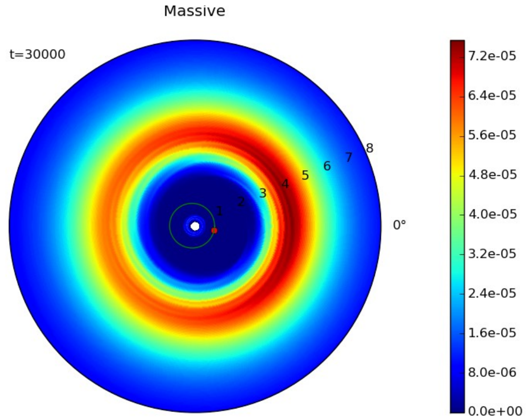
  $$M_p/M_\star = 1.3 \times 10^{-2}$$

- Two different disc masses $q_{\rm d} = M_d/M_p$
  - $q_{\rm d} = 1/5$, light (Rosotti et al. 2016)
  - $q_{\rm d} = 3/5$, massive

- Viscous time $\tau_\nu = 1.2 \times 10^5\, t_{\rm orb}$

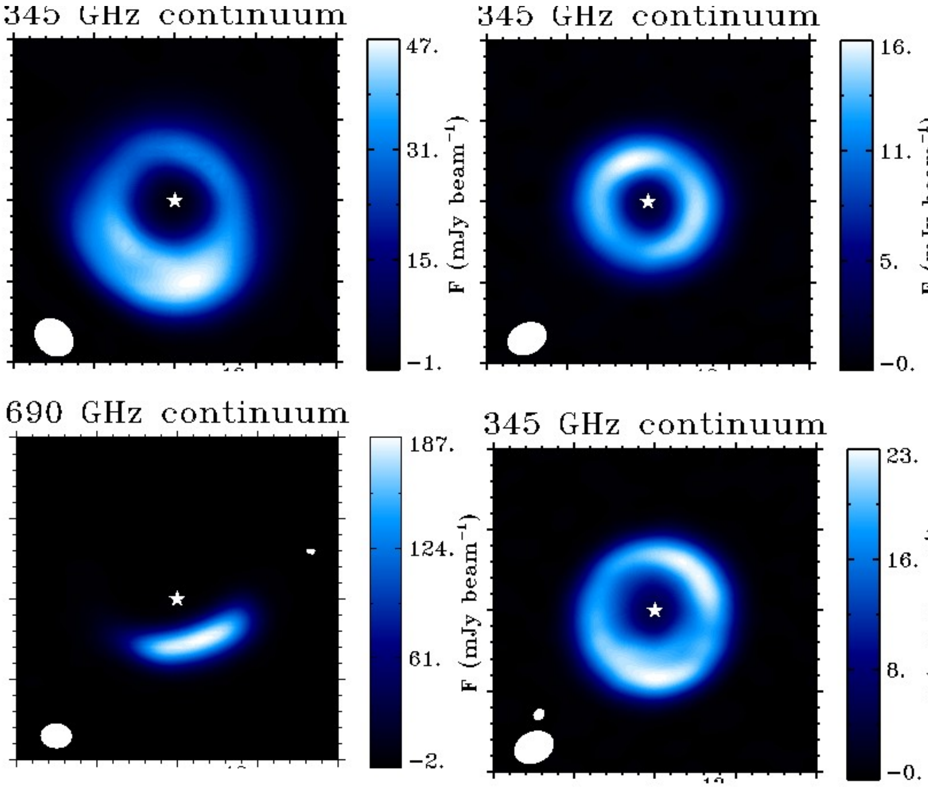
- Number of orbits $N_{\rm orb} = 3 \times 10^5\, t_{\rm orb}$

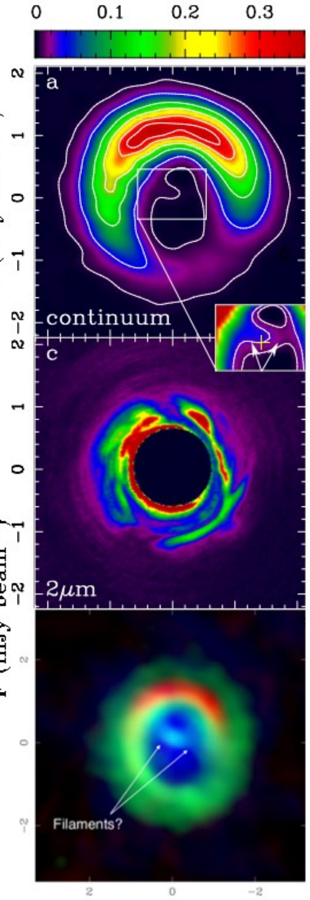


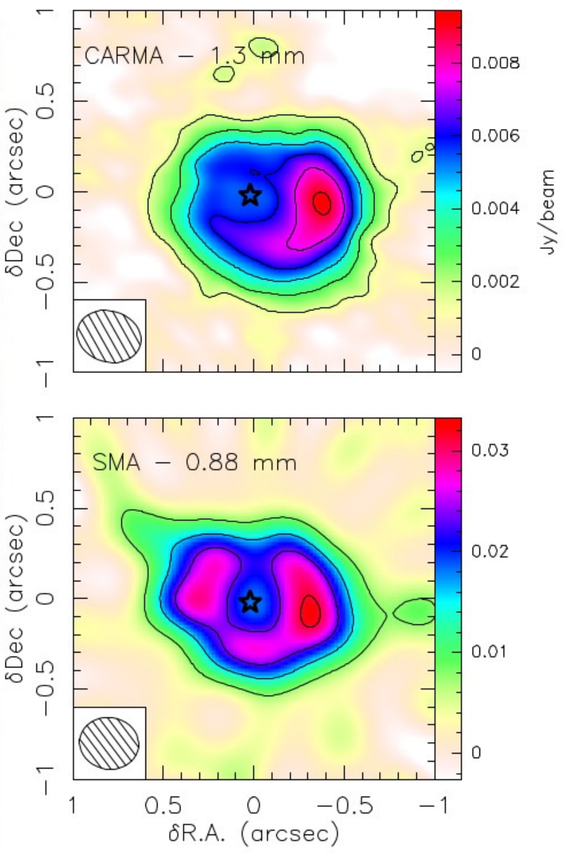


Asymmetries in transitional discs

Motivation







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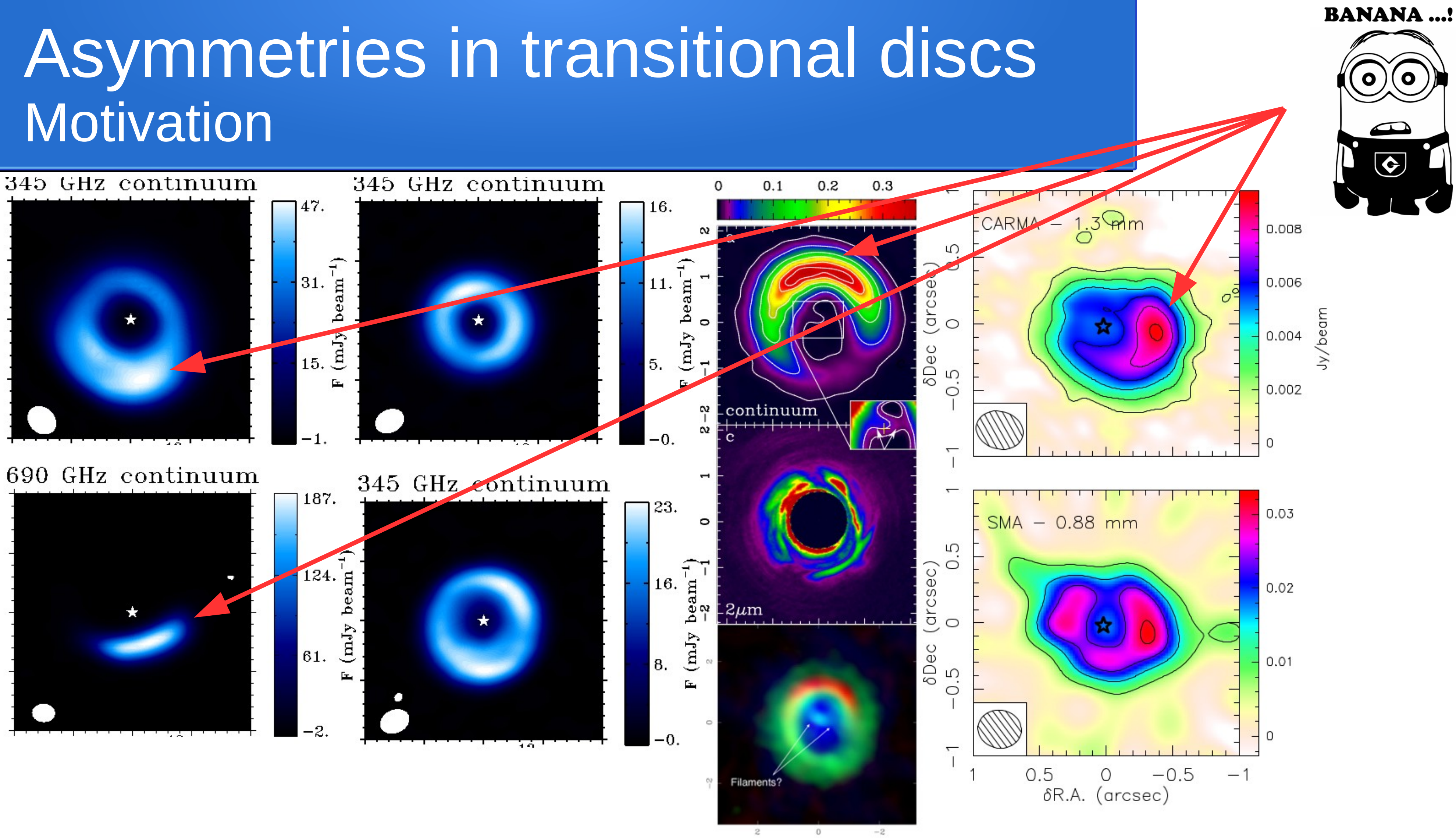
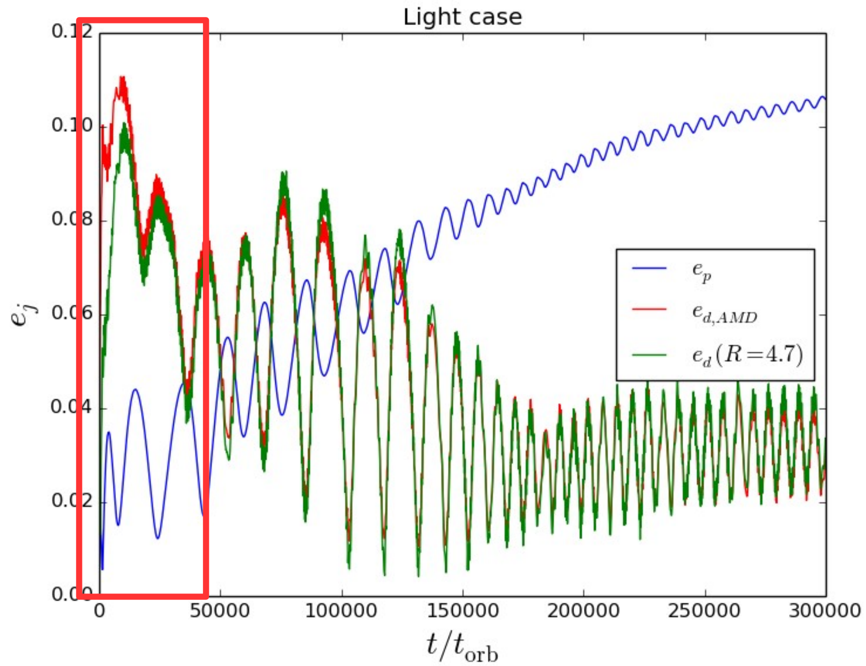
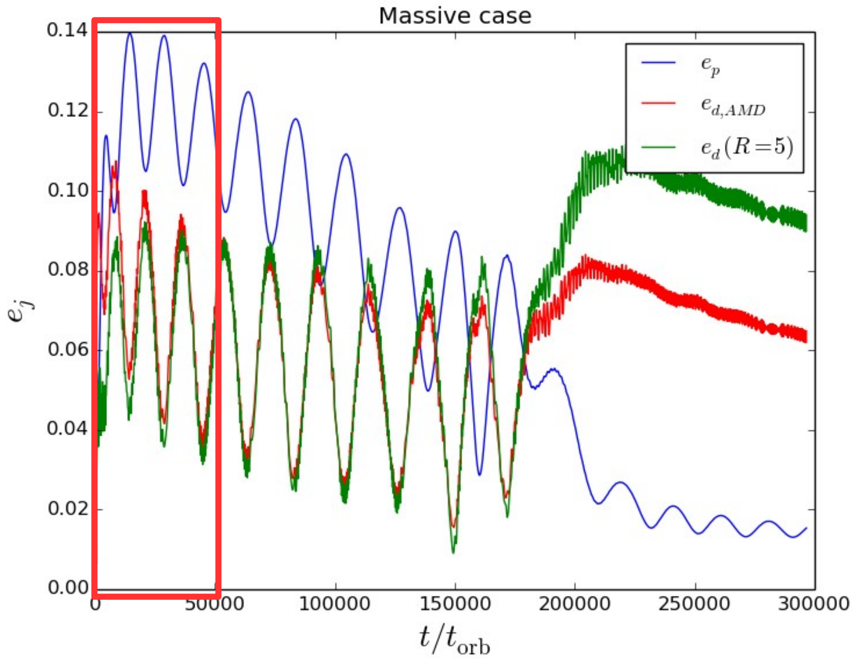


Numerical Simulations
Results: Eccentricity Evolution

- Green-red disc, blue planet eccentricity: rapid initial growth of disc eccentricity
- Periodic oscillations superimposed to eccentricity damping/pumping





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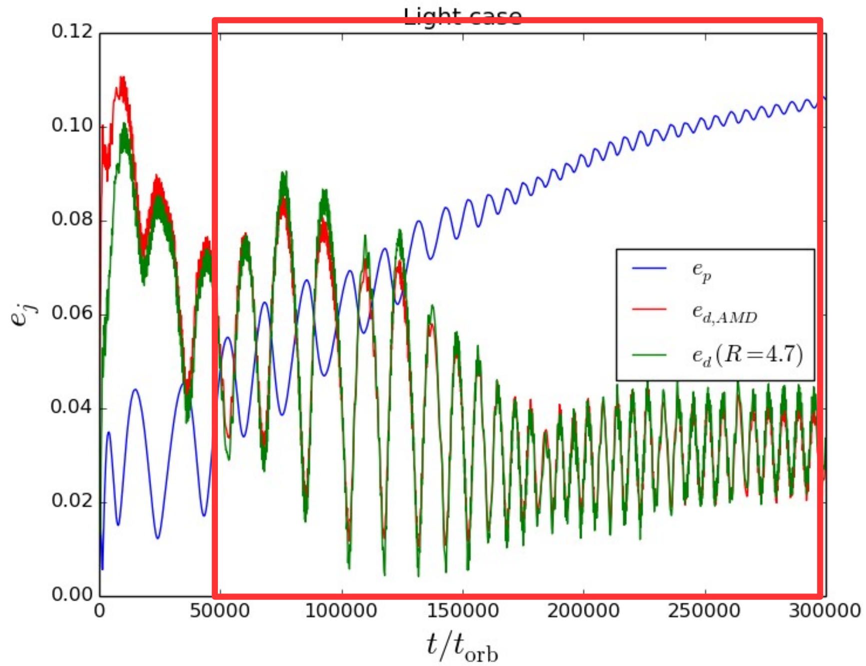

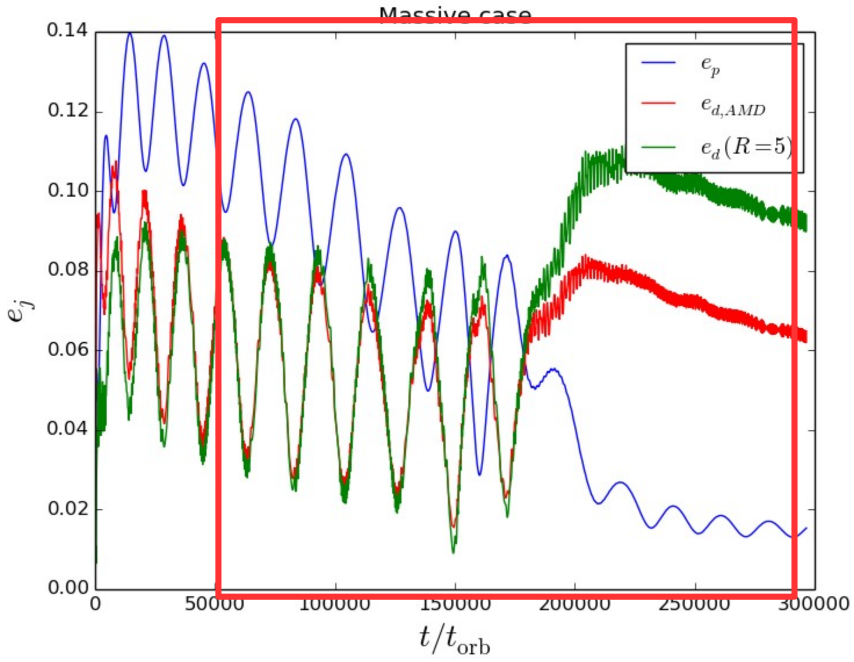

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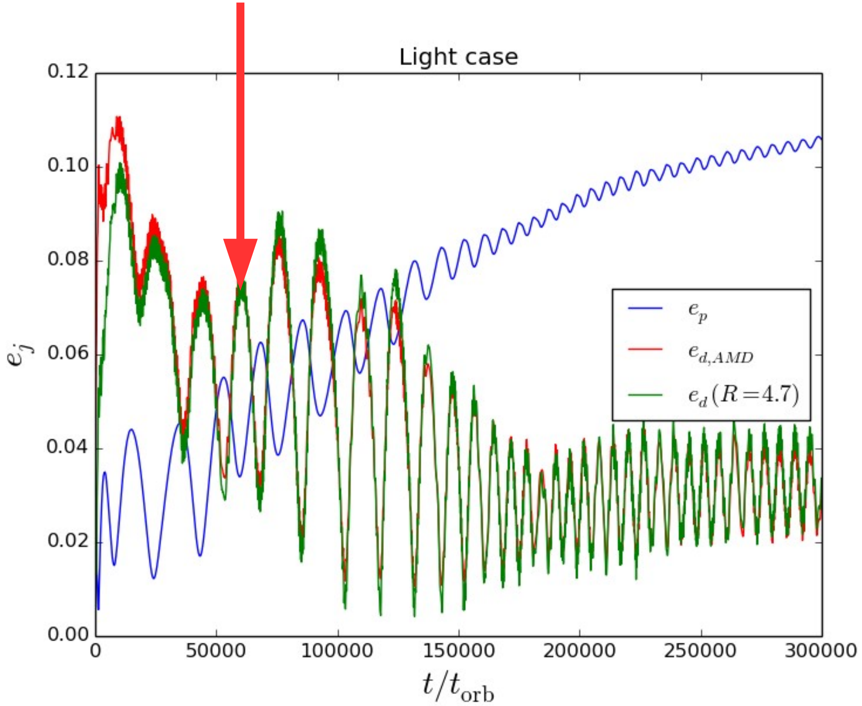
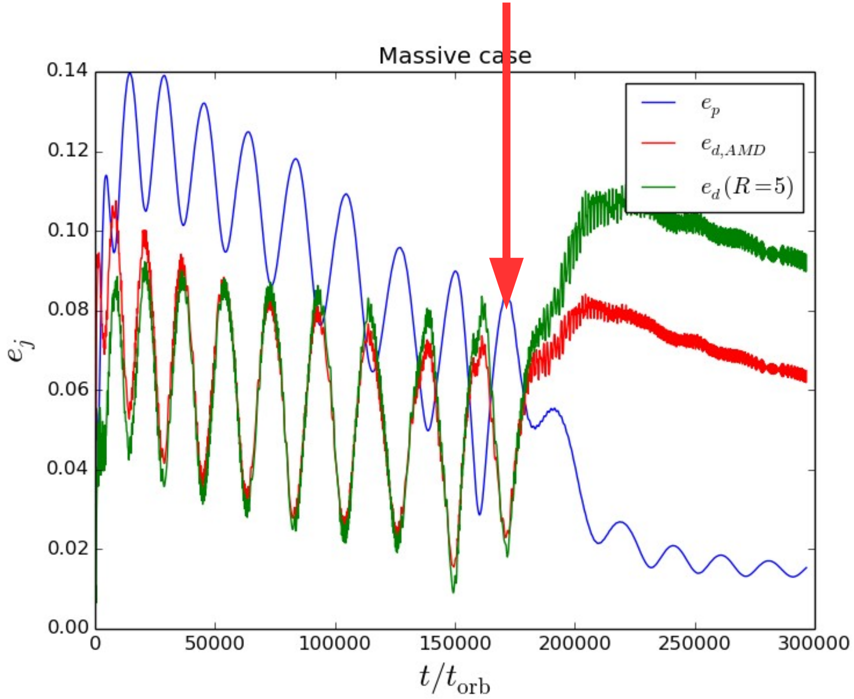




Numerical Simulations
Results: Pericenter phase

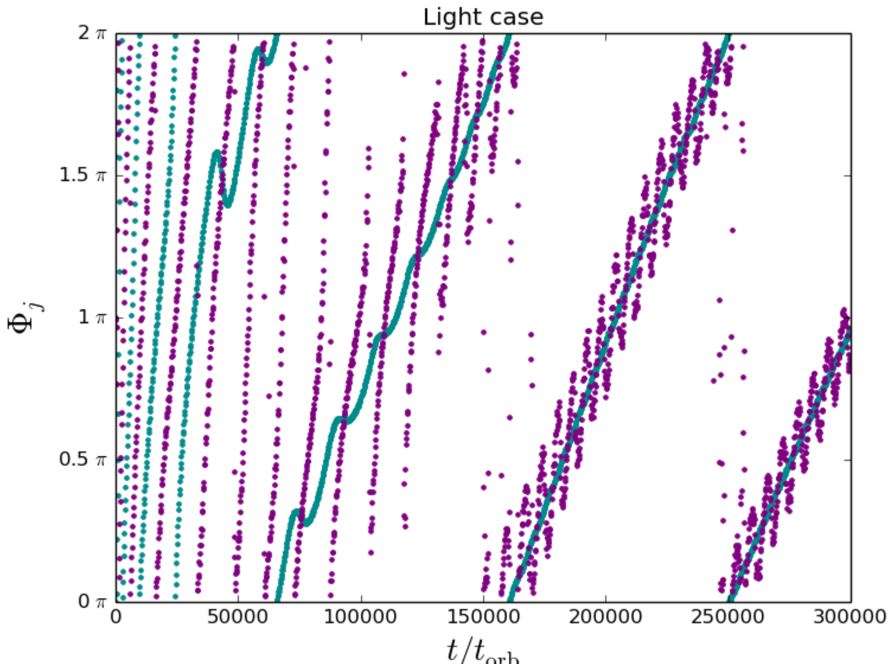
- Precession of the pericenter phase

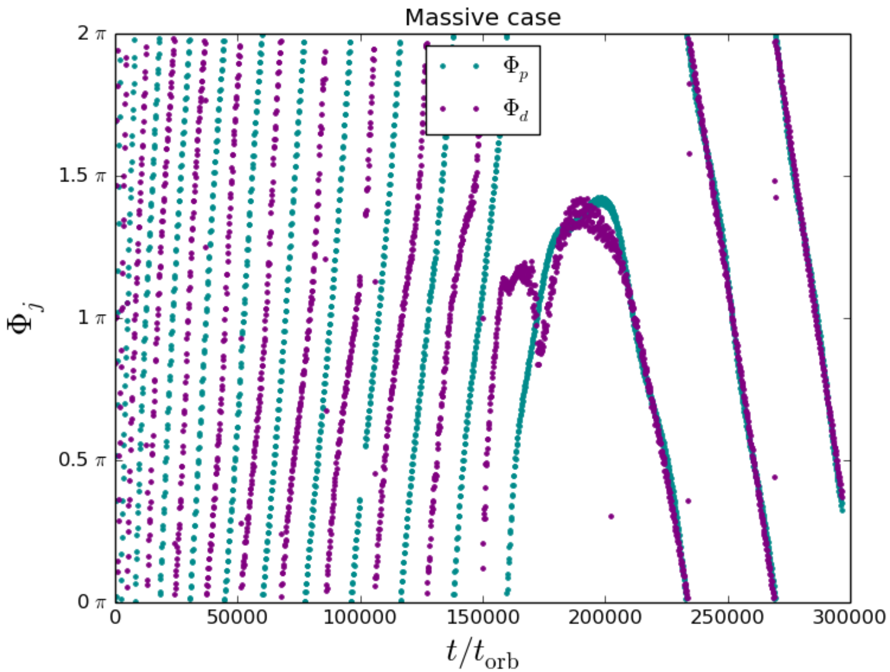
To be sure we get each other ...

Pericentre phase

Numerical Simulations
Results: Pericenter phase

- Precession of the pericenter phase (cyan planet, violet disc)
- Initial anti-alignment, then alignment of pericentres





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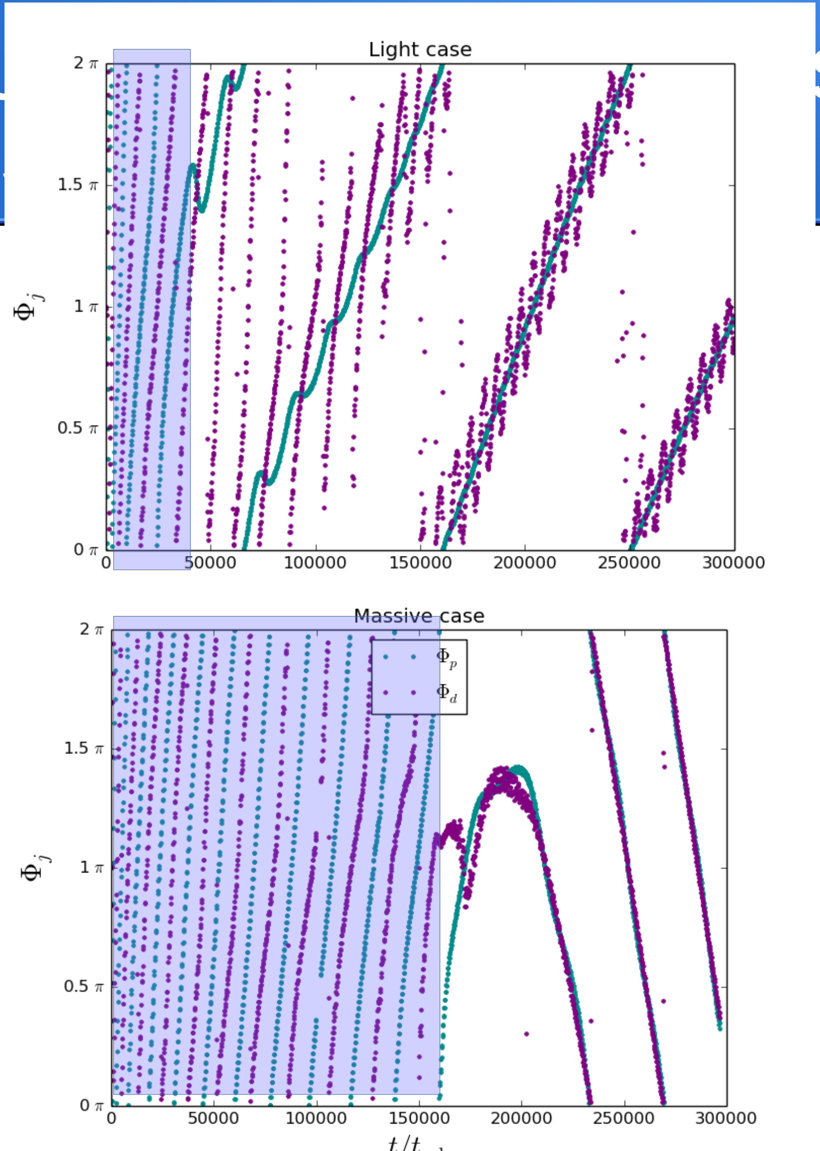
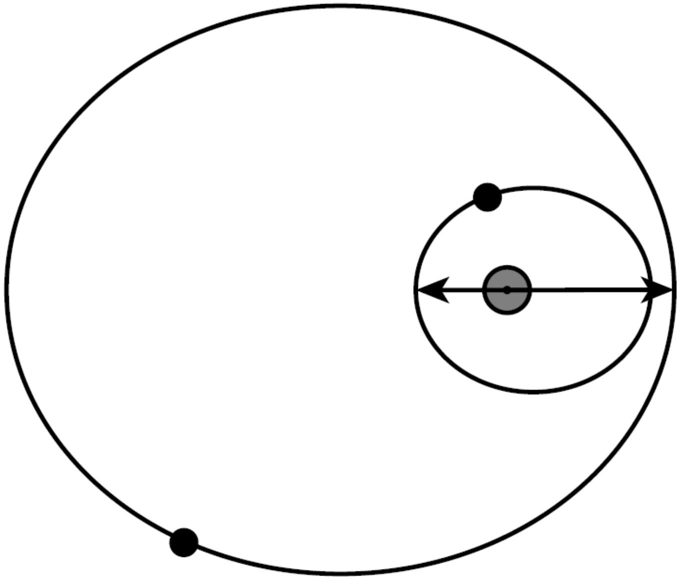
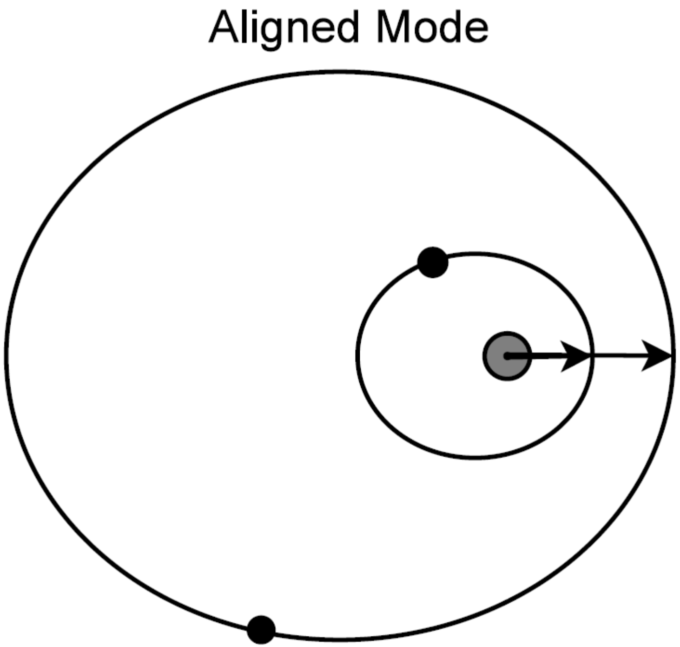
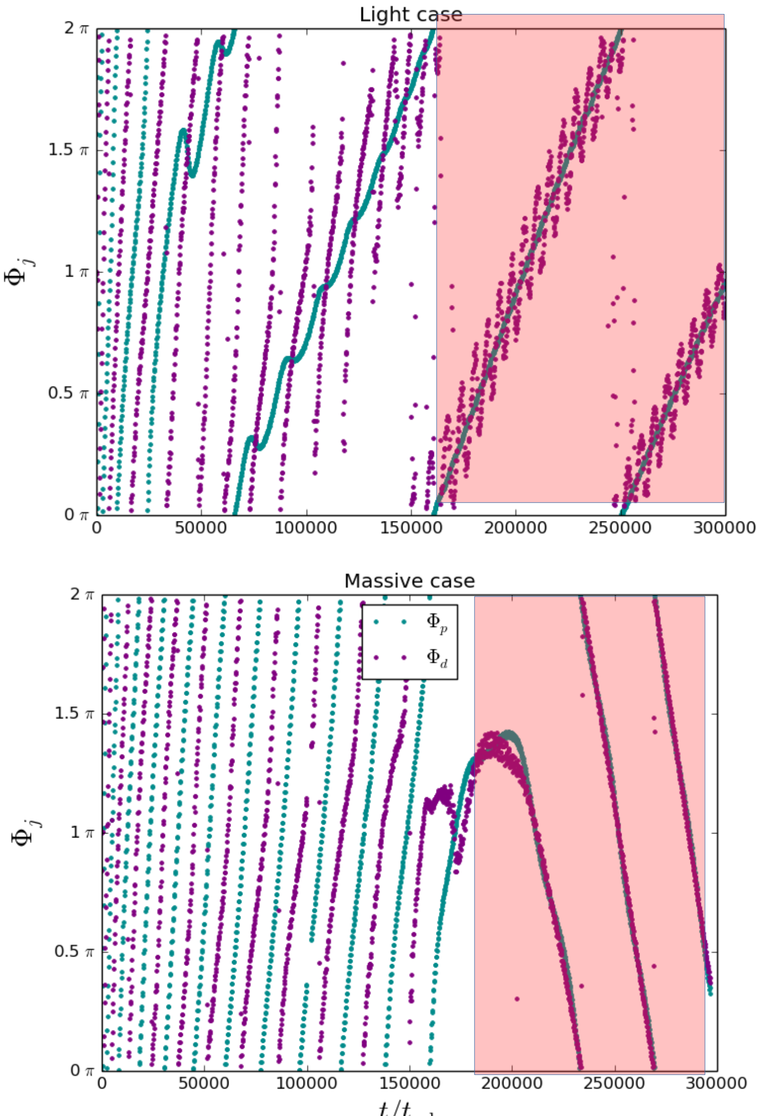


Anti-Aligned Mode



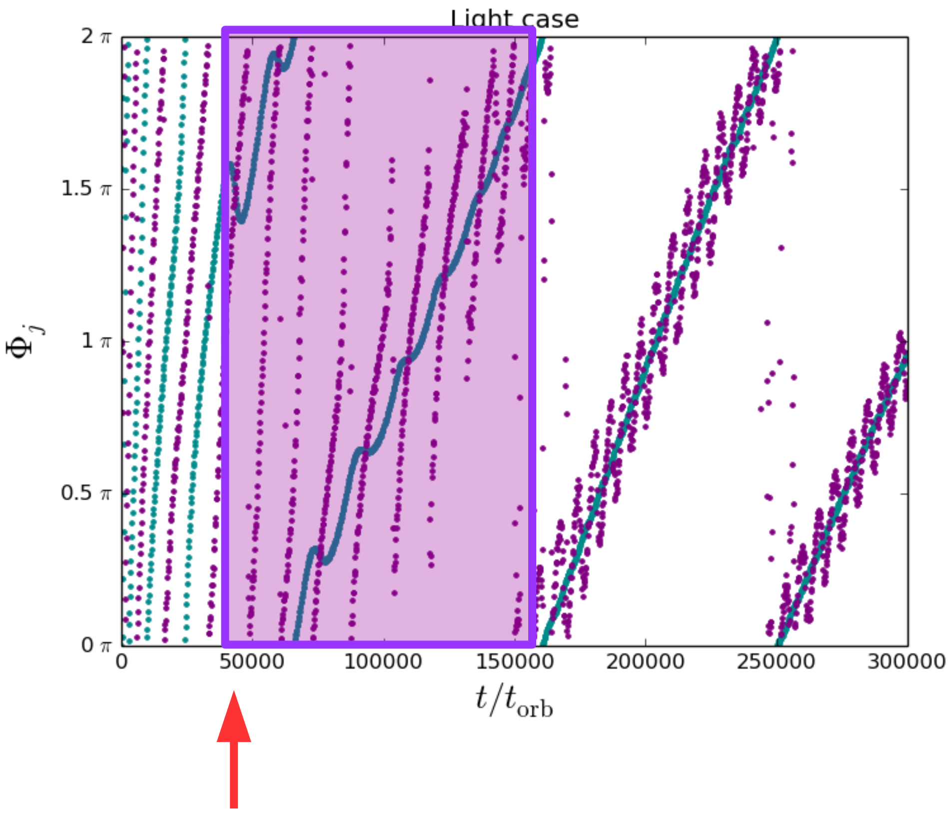
Numerical Simulations
Results: Pericenter phase

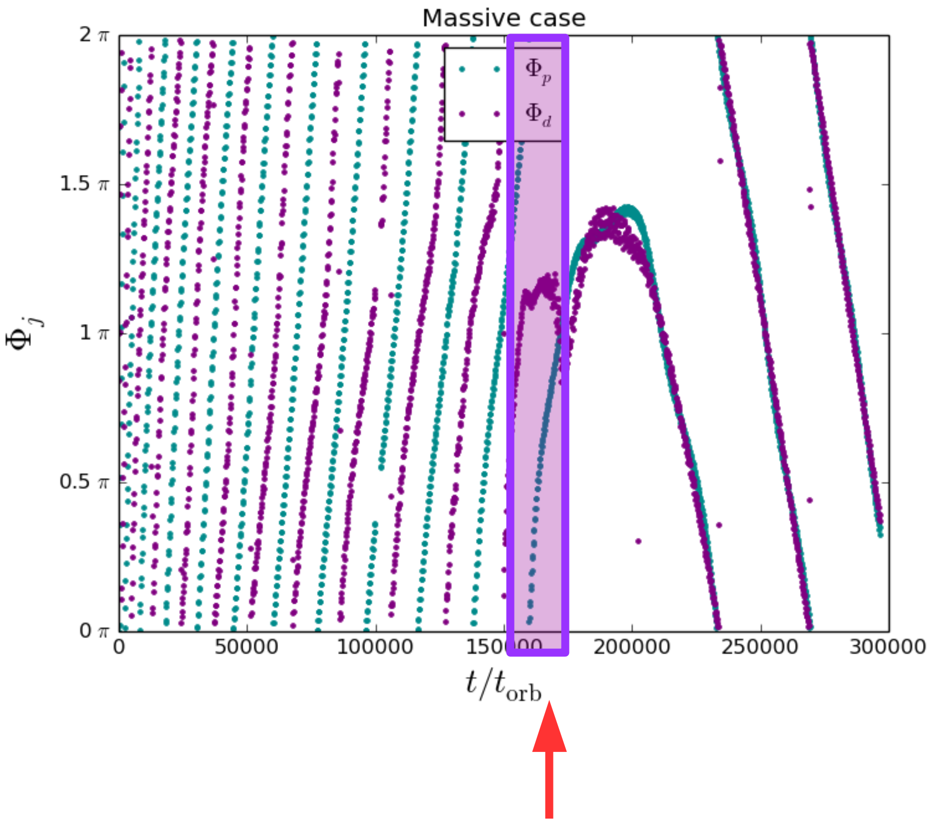




Numerical Simulations

Results: Pericenter phase





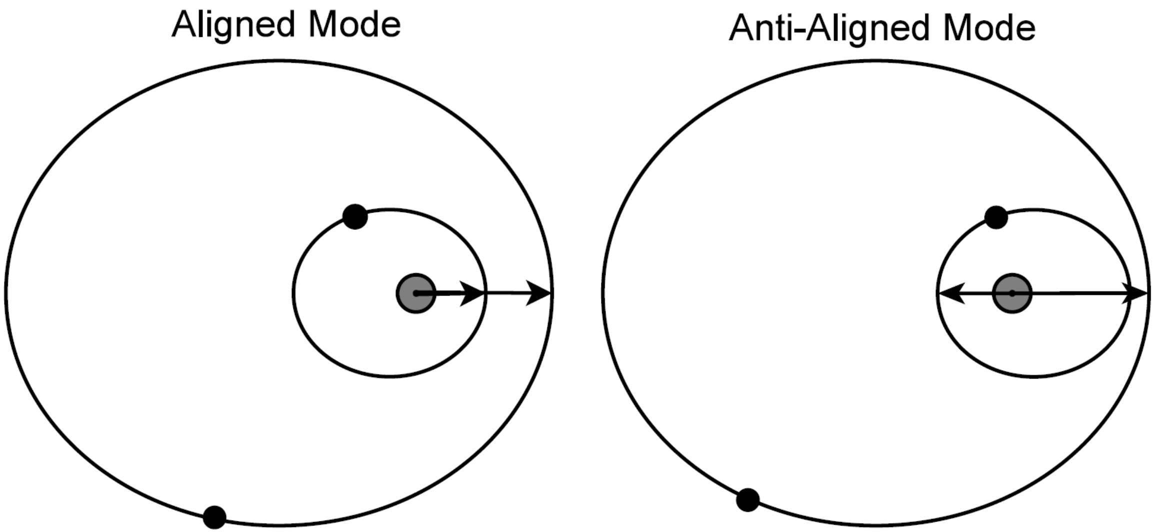
The tricky part ....
Interpretation of the results: Recap

- Light case: Planet eccentricity grows at late times. Massive case: Planet eccentricity decreases
- Fast anti-aligned precession early times, slow aligned precession late times
- **Things to notice:**
- Oscillations resemble those visible in celestial mechanics problems.
- We can show that the disc behaves rigidly.
- **Can we treat the disc as a second planet?**

Interpretation of the results
Secular evo: the disc as a second companion!

Evolution of both phase and eccentricity

roblem in celestial



$$E_j = |E_j| e^{i\Phi_j}$$

$$\beta = \frac{b^{(2)}_{3/2}(\alpha)}{b^{(1)}_{3/2}(\alpha)}$$

$$\alpha = \frac{a_p}{a_d} \qquad q = \frac{M_d}{M_p}$$

$$\Omega_{\rm sec} = \frac{1}{4}\Omega_p \frac{M_p}{M_\star}\alpha^2 b^{(1)}_{3/2}(\alpha)$$

Slow Mode, pericenters aligned (growing)

$$\begin{pmatrix} E_p(t) \\ E_d(t) \end{pmatrix} = C_1 \begin{pmatrix} \eta_s \\ 1 \end{pmatrix} e^{i\omega_s t} + C_2 \begin{pmatrix} \eta_f \\ 1 \end{pmatrix} e^{i\omega_f t}$$

Fast mode, pericenters antialigned (decreasing)

Interpretation in the light of the Toy M.

Reproducing the simulations

- Evolution depends on the relative intensity of $C_1(t)\eta_s,\ C_2(t)\eta_f,\ C_1(t),\ C_2(t)$

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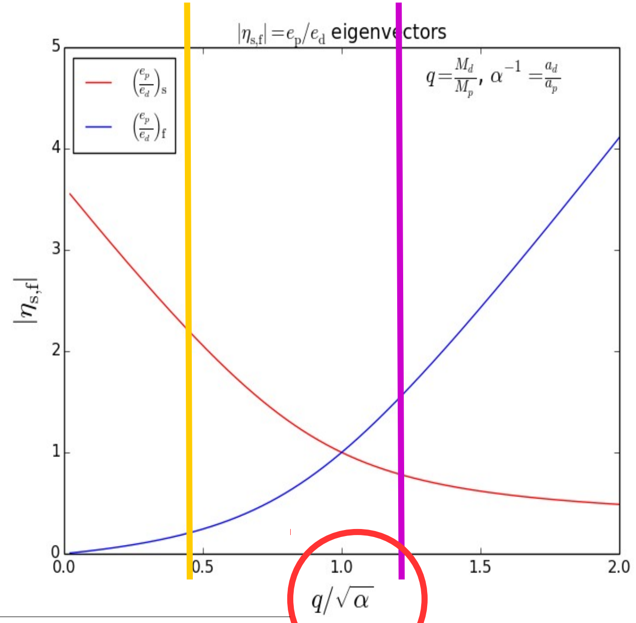
- Four harmonic oscillators: slow mode planet, slow mode disc, fast mode planet, fast mode disc



Key parameter! Disc vs planet ratio of angular momentum

$$\frac{J_d}{J_p} = \frac{q}{\sqrt{\alpha}}$$

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Reproducing the simulations

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- We can identify three possible situations

$$C_1(t)\eta_\mathrm{s} > C_2(t)\eta_\mathrm{f}, \quad C_1(t) > C_2(t)$$
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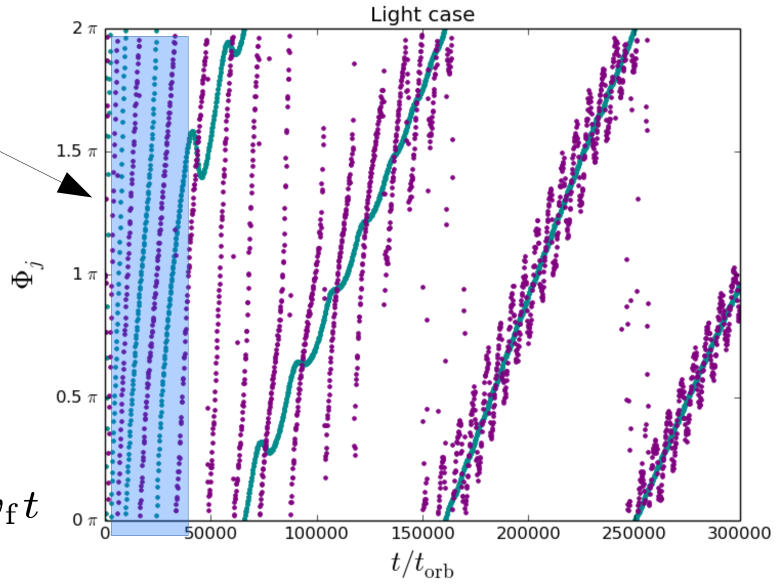

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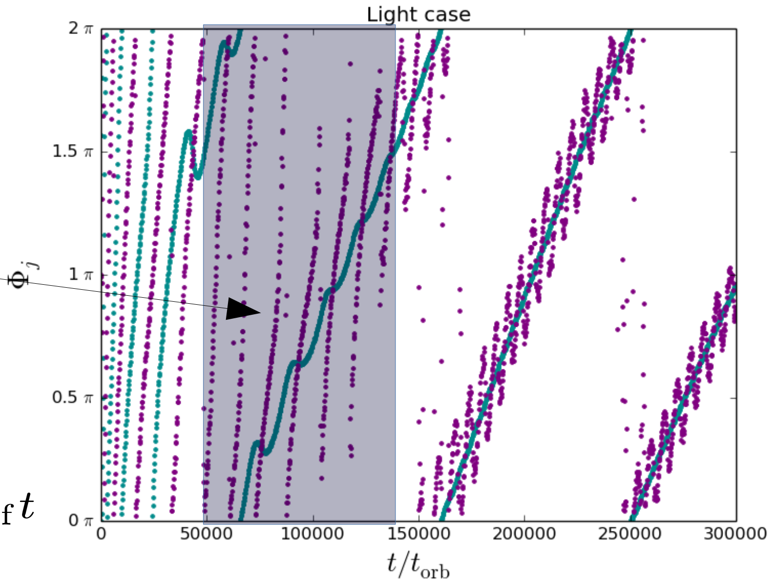

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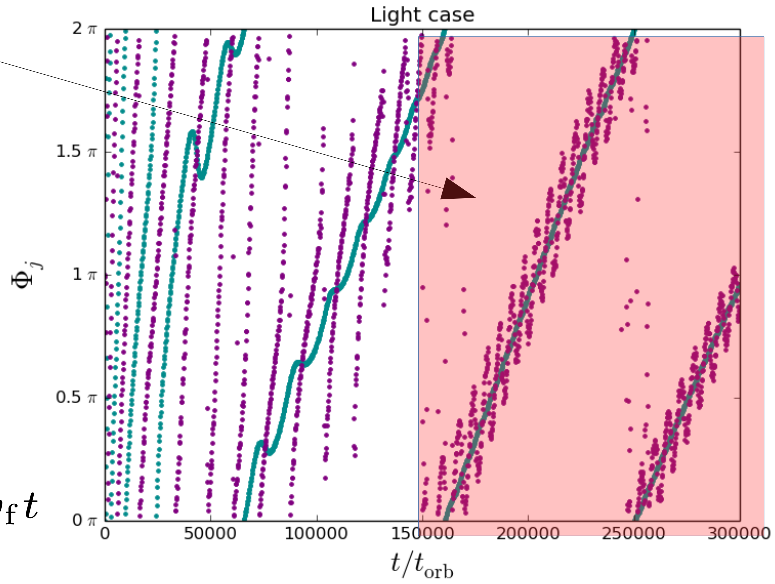

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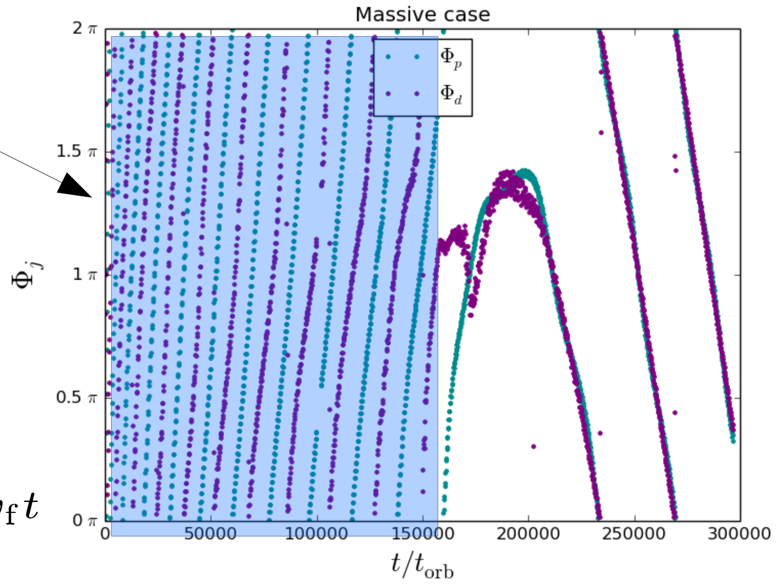

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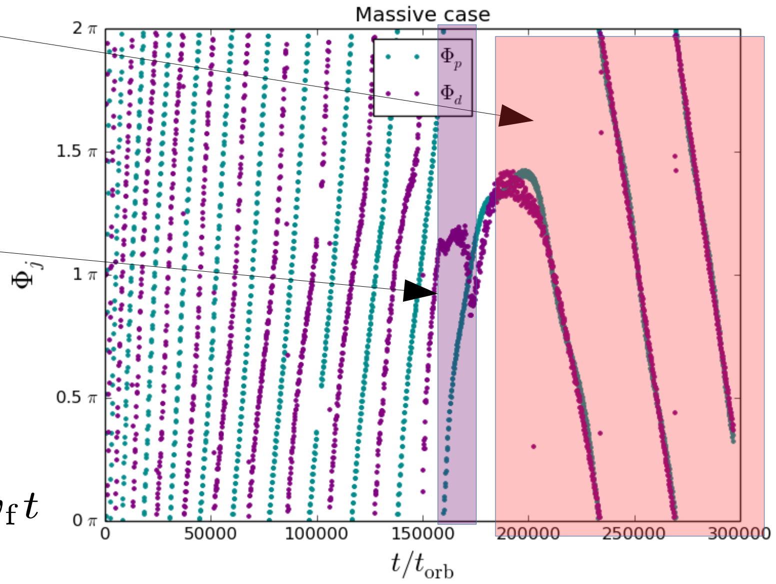

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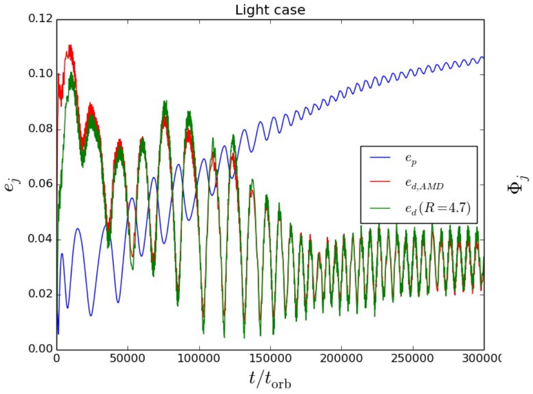
- Evolution we observe consistent with the linear growth of $C_1(t)$ and with the decrease of $C_2(t)$
- Analytical predictions about eigen-vectors tell us $\frac{e_\mathrm{p}}{e_\mathrm{d}}$
  - Light discs $\eta_\mathrm{f} < 1 < \eta_\mathrm{s}$
  - massive discs $\eta_\mathrm{s} < 1 < \eta_\mathrm{f}$

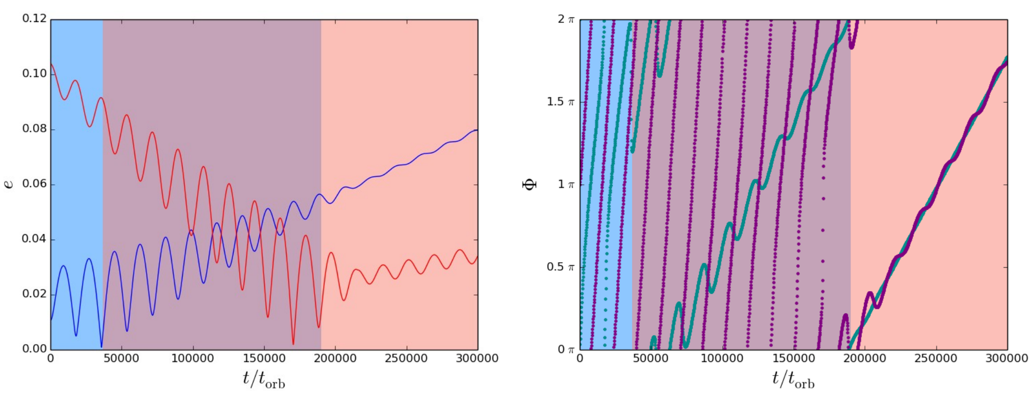
TOY MODEL PLOTS

- Growing slow mode
- Decreasing fast mode
- Eigenfrequencies consistent with those observed in simulations
- Apparently $C_1(0) \ll C_2(0)$
- **We Only vary**: Eigenvectors consistent with our two different disc masses

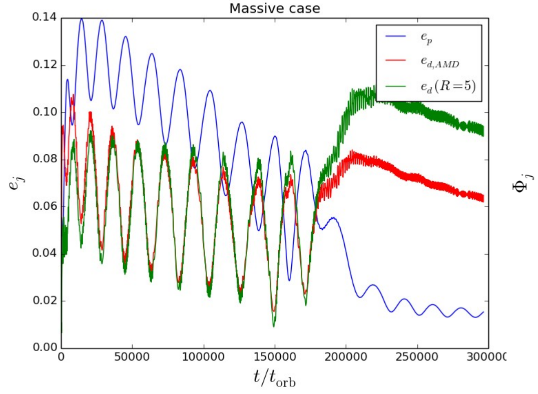
Simulations light case



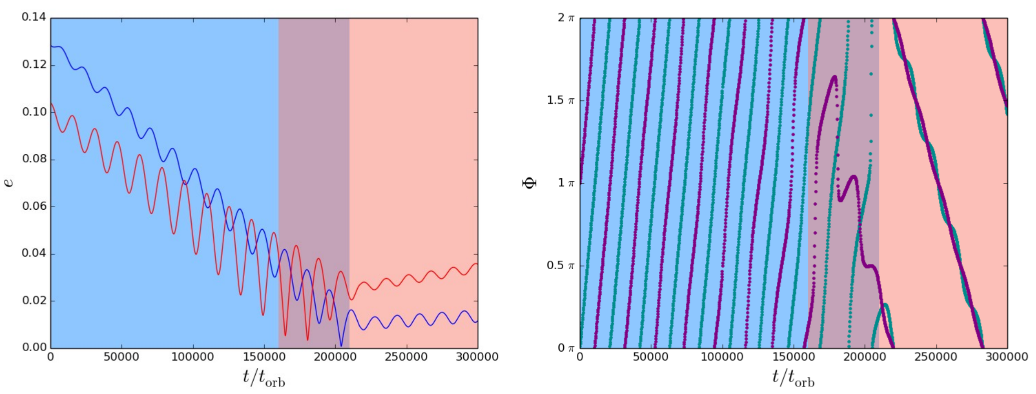
Toy model light case q=0.2



Simulations massive case

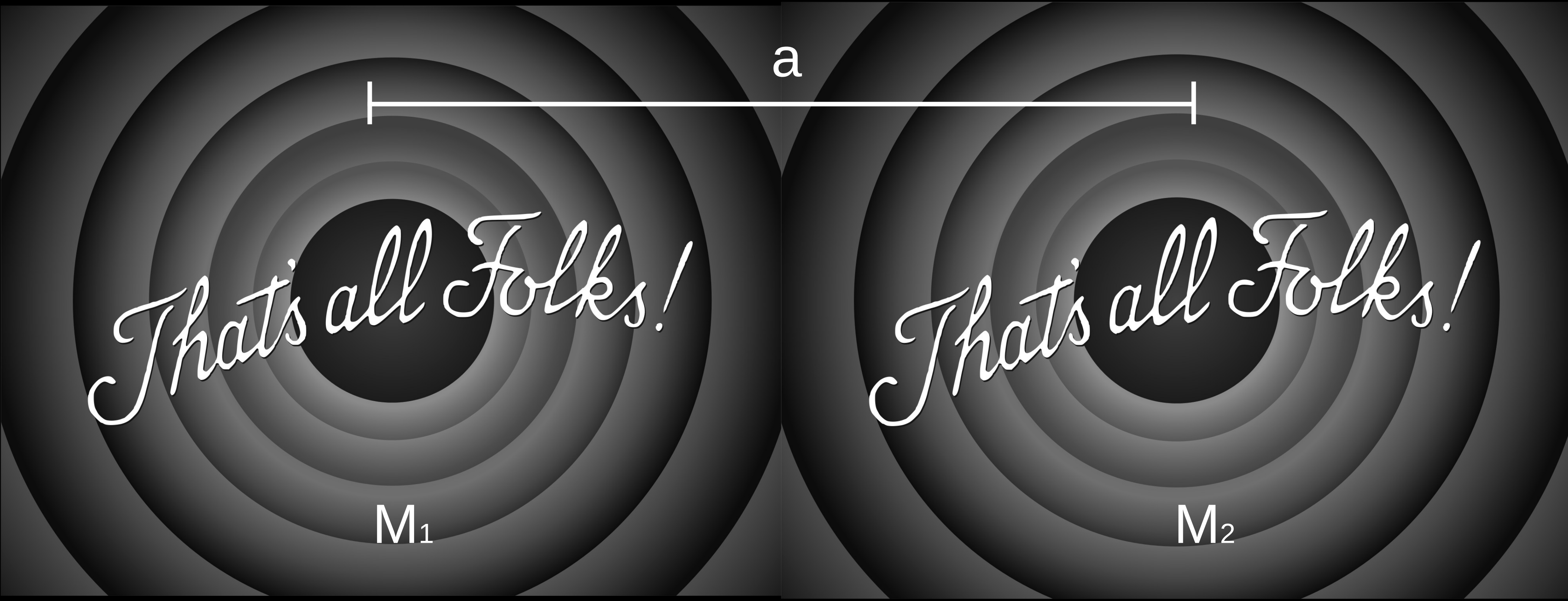


Toy model massive case q=0.65



Summary and conclusions

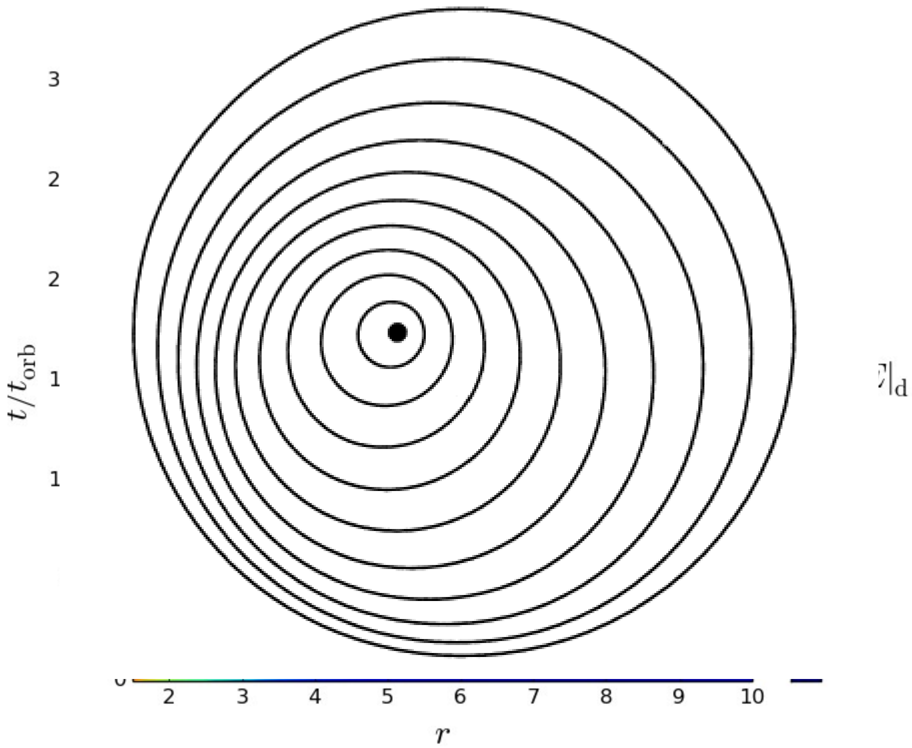
- Secular interaction shapes the global behaviour of the simulation
- At long timescales more massive discs decrease the system eccentricity (in contrast with previous literature at short timescales).
- We have a model for secular evolution but we do not understand the resonant one.
- FOR OBSERVERS:
- Measuring disc and satellite eccentricities would help to validate the theory.
- Horseshoes suggest disc eccentric orbits to be validated kinematically.



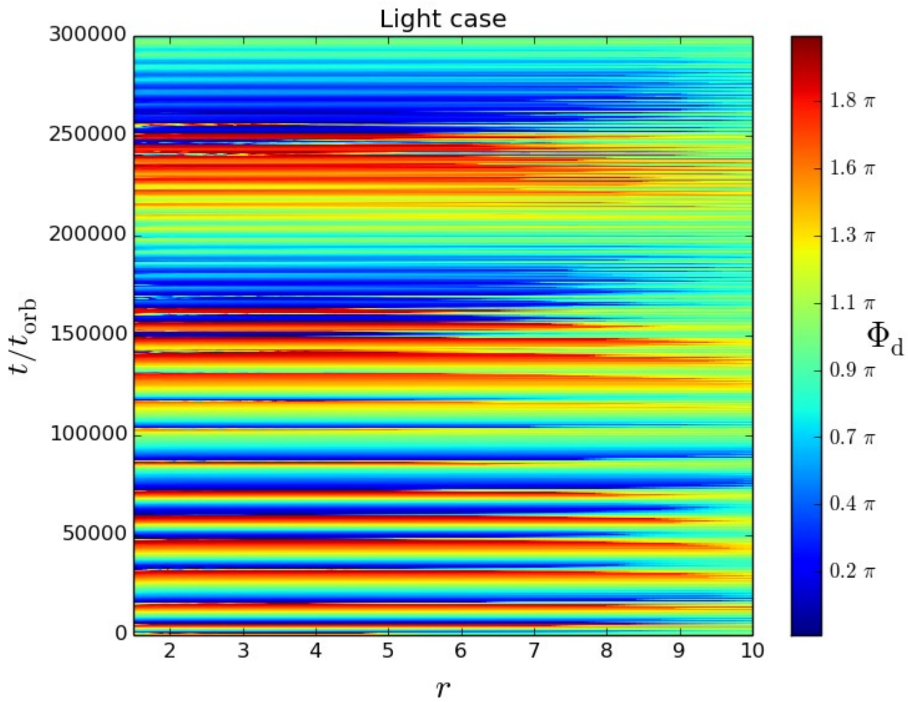
a
That's all Folks!
That's all Folks!
M1
M2

Interpretation of the results
Can we treat the disc as a planet?

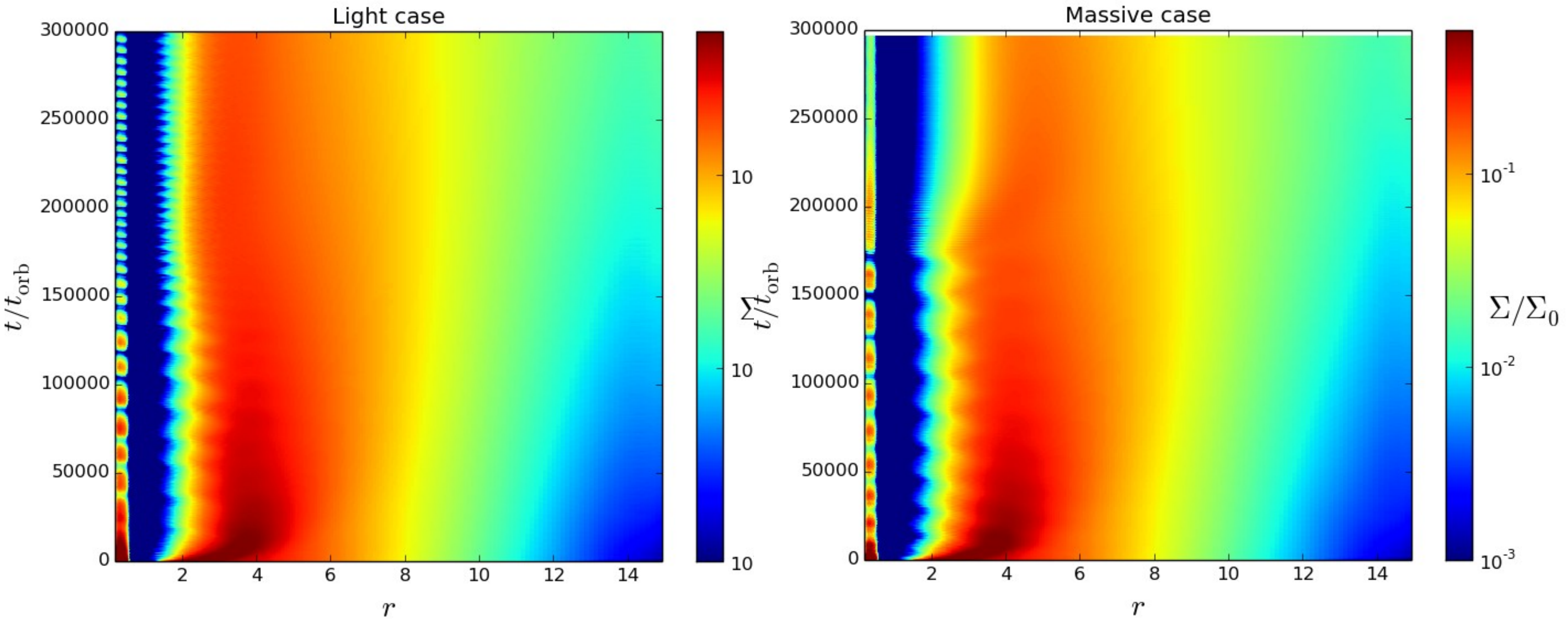
- Apparently yes! The disc behaves rigidly...(Teyssandier & Oglivie 2016)



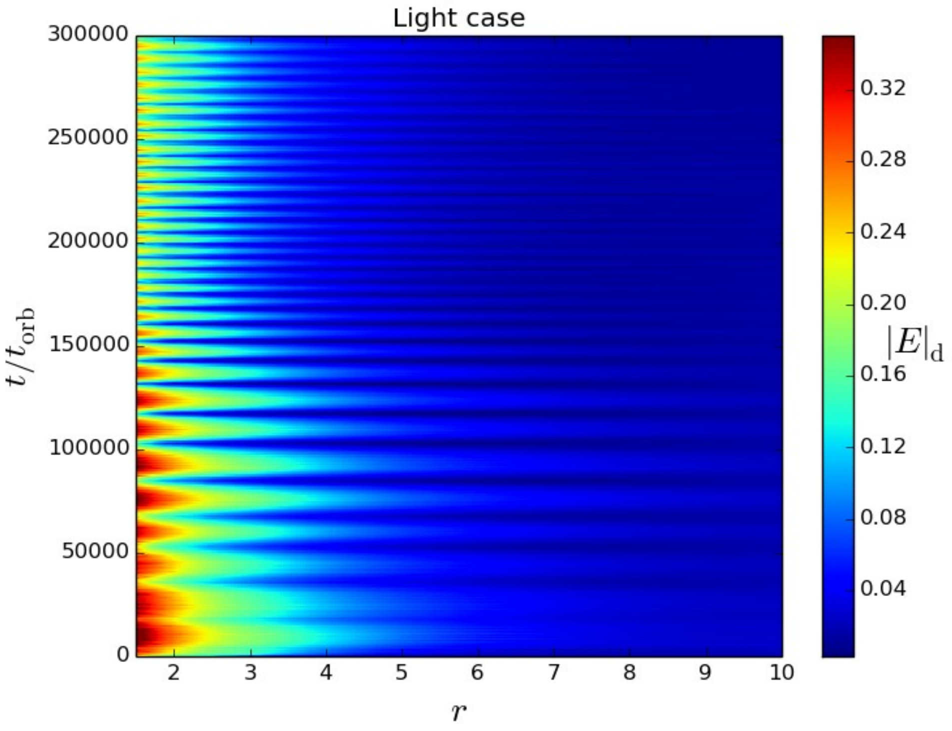
Pericenter phase radial profile

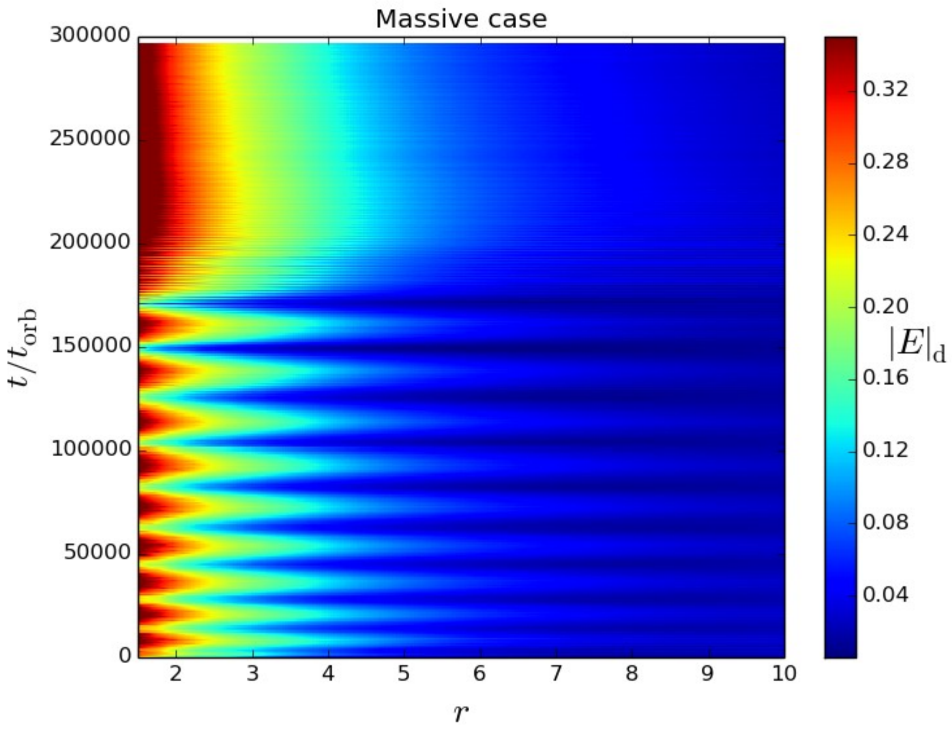


Density Profile

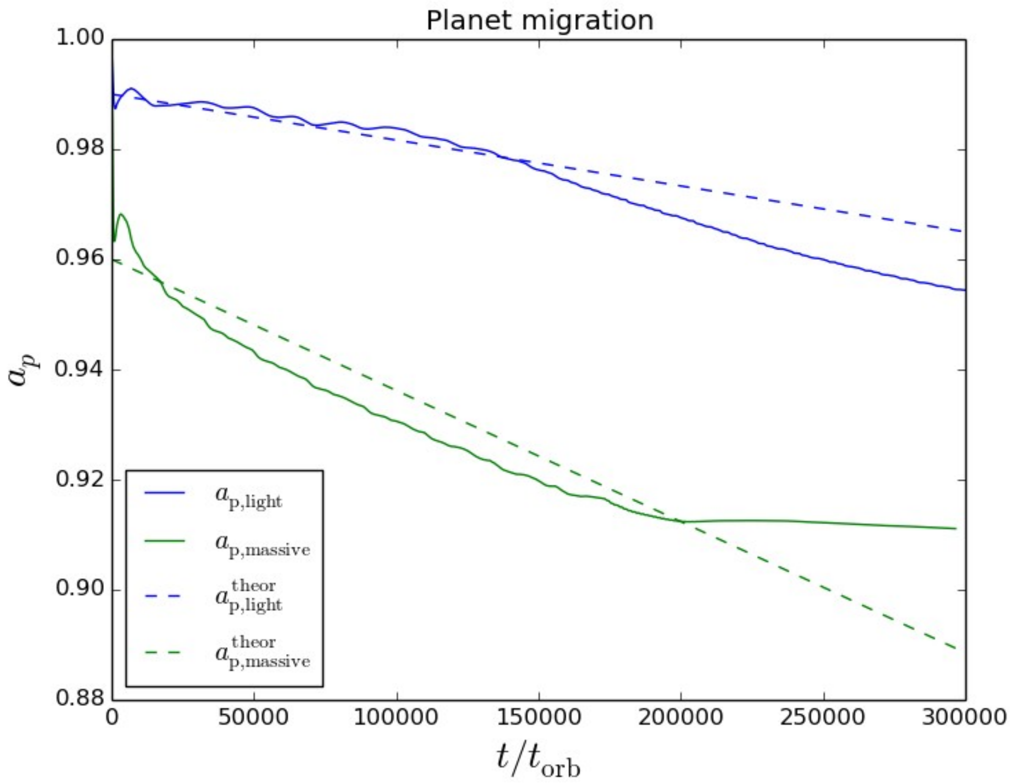


Eccentricity Profile





Migration



Planet migration
1.00
0.98
0.96
0.94
0.92
0.90
0.88
a_p
0
50000
100000
150000
200000
250000
300000
t/t_{orb}
$a_{\mathrm{p,light}}$
$a_{\mathrm{p,massive}}$
$a^{\mathrm{theor}}_{\mathrm{p,light}}$
$a^{\mathrm{theor}}_{\mathrm{p,massive}}$

$$AMD_p = M_p(\sqrt{GM_\star a_p} - h_p) \approx \frac{1}{2} e_p^2 M_p \sqrt{GM_\star a_p}$$