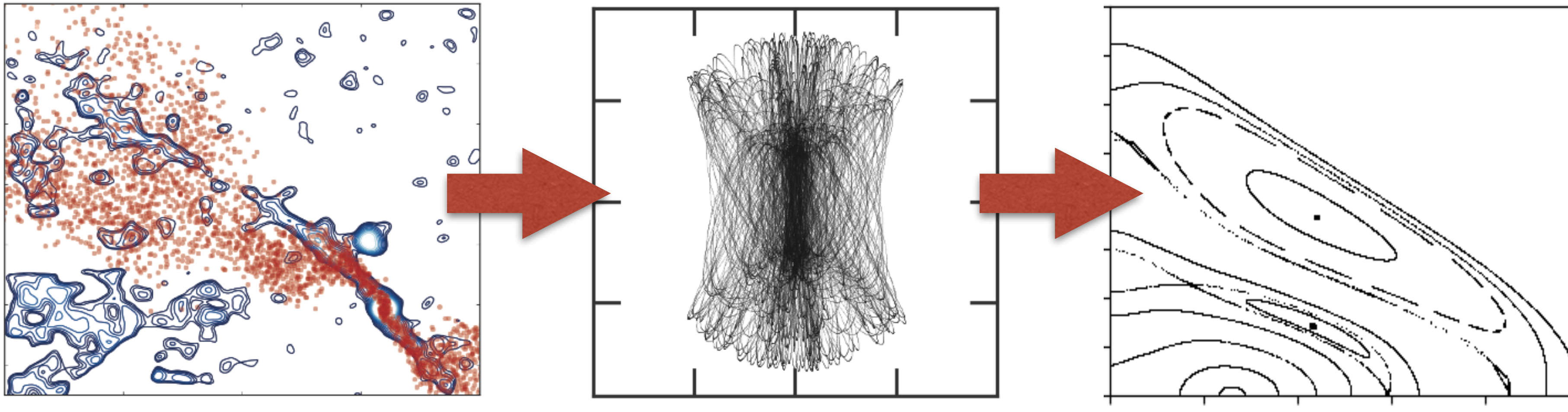
Sarah Pearson Adrian Price-Whelan Tomer
Yavetz

Monica Valluri + Andreas Kuepper

Physical Manifestations of Chaos, Resonance and Regularity

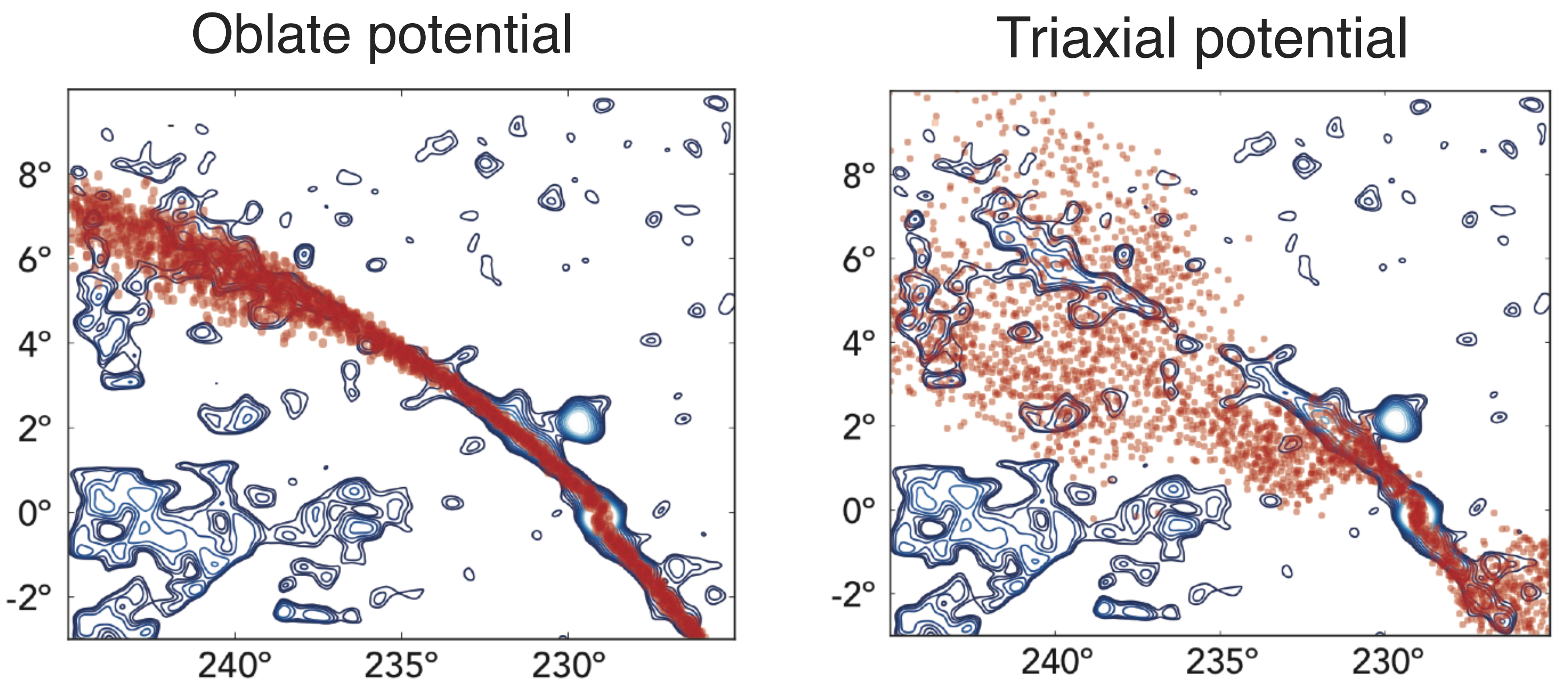
Kathryn V Johnston
Columbia University

Supported by the National Science Foundation and NASA



Physical Manifestations of Chaos, Resonance and Regularity

"Problems" with Pal 5 simulations



Pearson, Kuepper, Johnston & Price-Whelan (2015)

unavoidable "fanning" of stream

in Law & Majewski (2010) triaxial potential

???? Chaos ????

Aside: Defining Regularity/Chaos

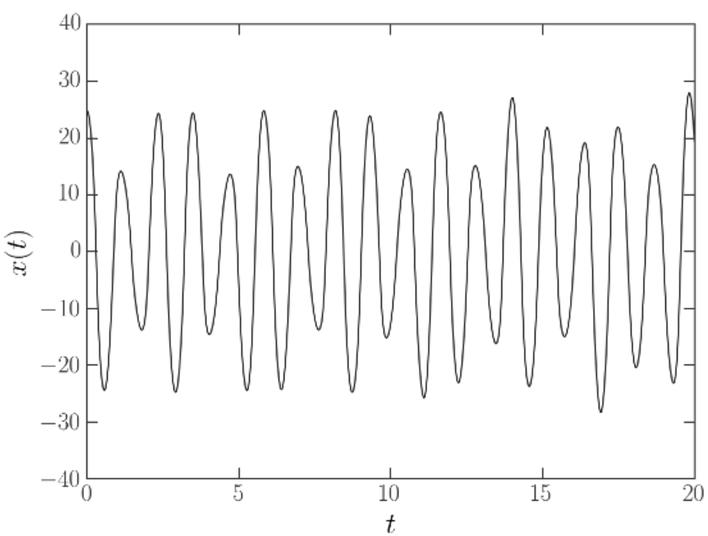
- Regular orbits:
  - existence of fixed orbital properties;
  - predictable path
  - fourier transform => 3 clear fundamental frequencies (Ω's), time-independent
- Chaotic orbits:
  - changes in orbital properties
  - unpredictable path
  - Ω's drift with time

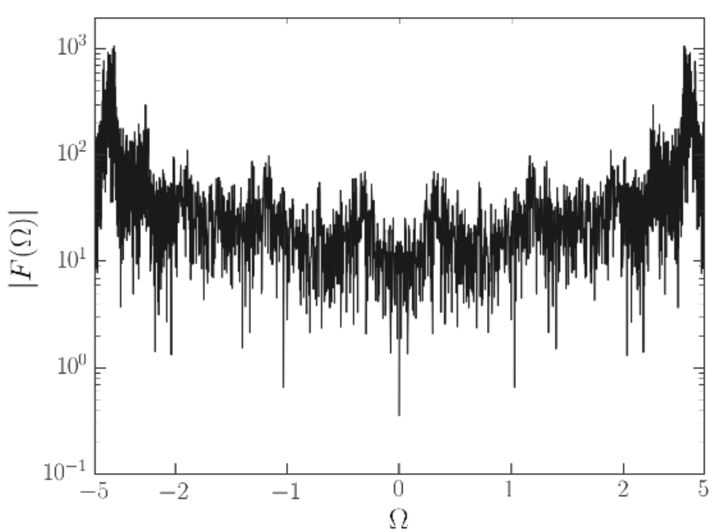
Aside: Defining Regularity/Chaos

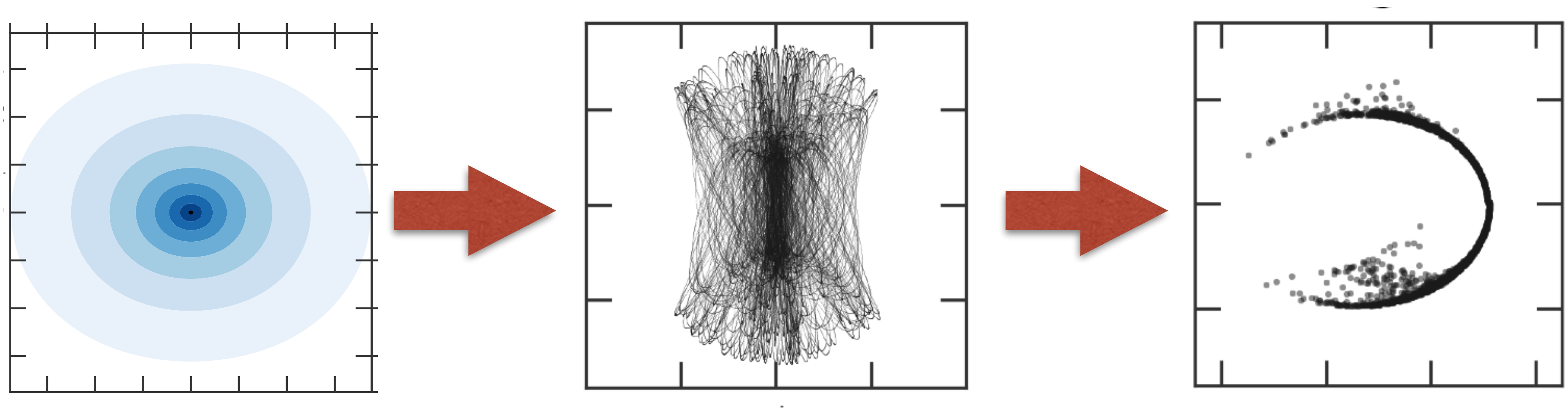
Ω's in arbitrary potentials?

- numerically integrate orbits
- fourier transform $(x+iv_y)$ in time
- Ω's from peaks in power spectrum

<u>chaotic timescale = Ω's drift by order-unity</u>



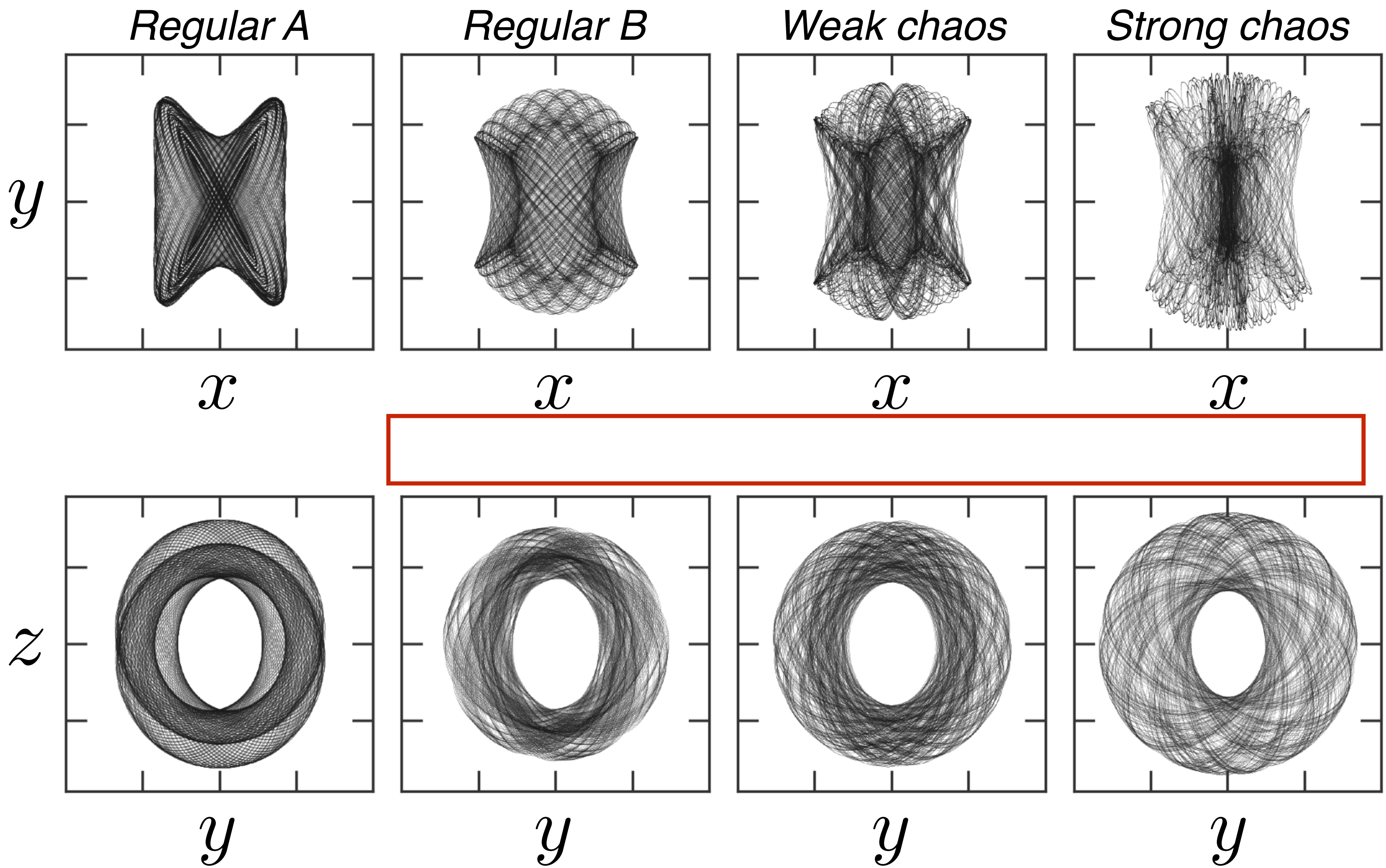




???? CHAOS ????
???? at R > 15kpc ????
???? within a Hubble

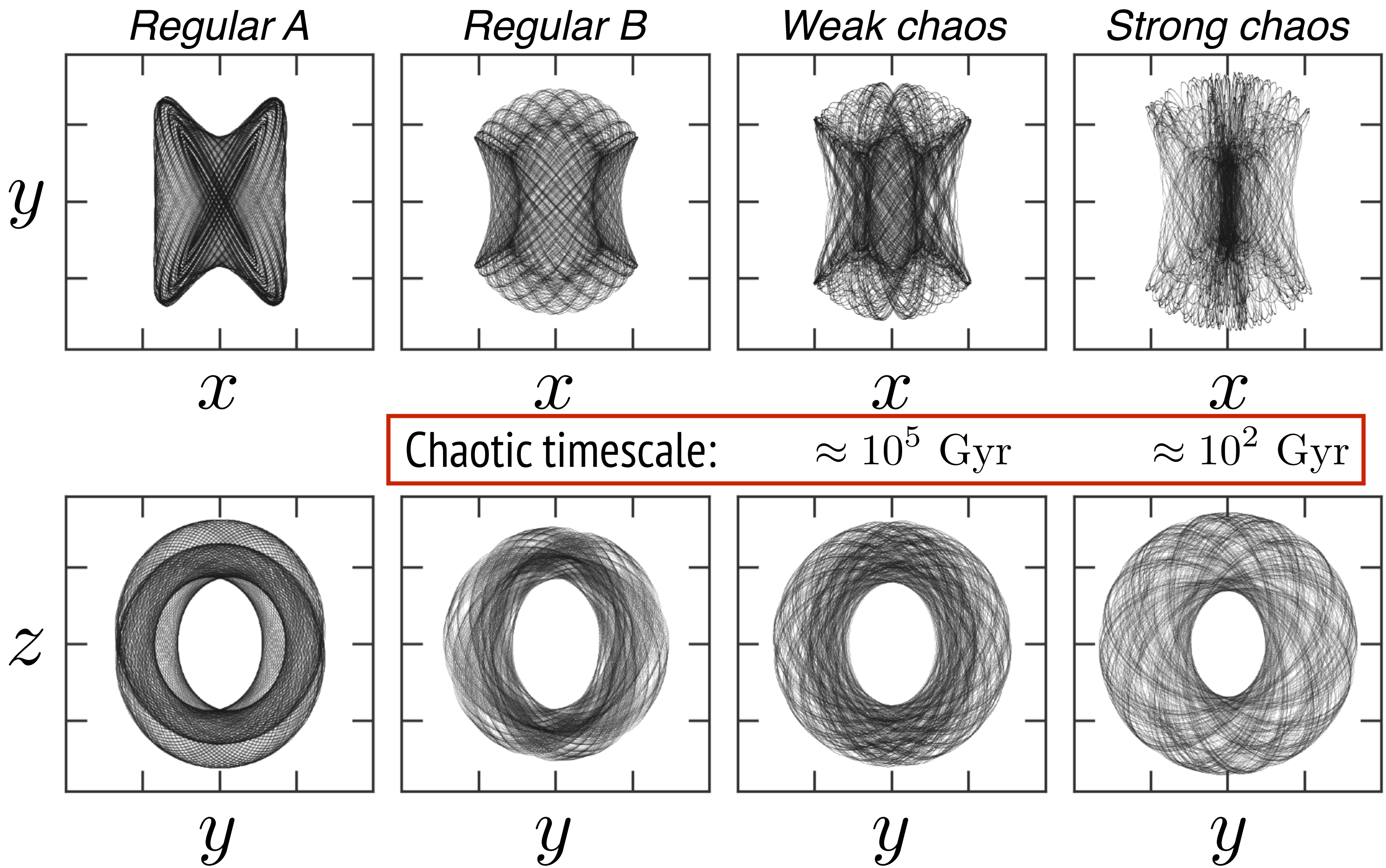
Price-Whelan, Johnston, Valluri, Pearson & Kuepper, 2016

Representative orbits



Price-Whelan+ 2016

Representative orbits



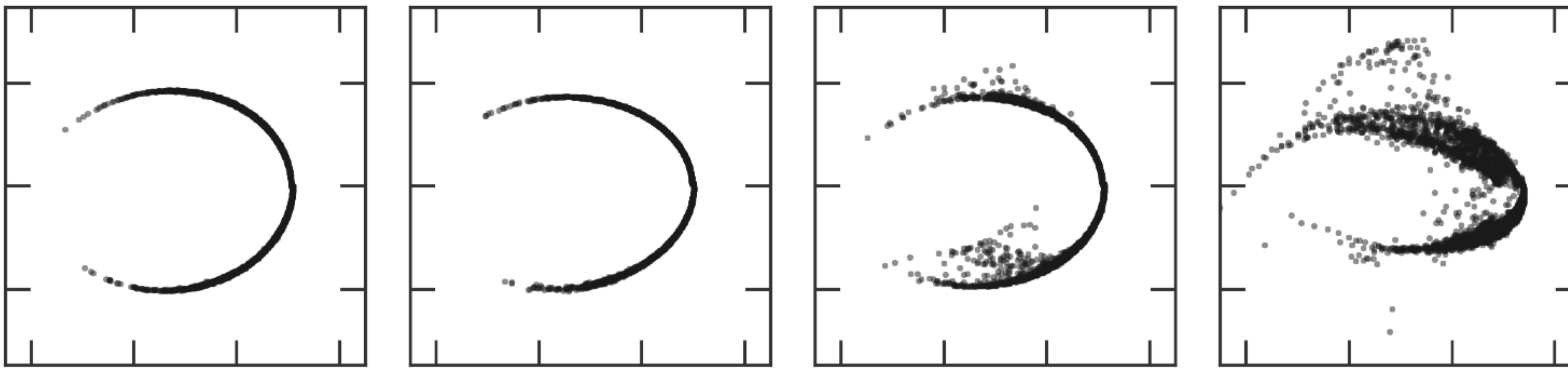
Price-Whelan+ 2016

Cluster Evolution - morphologies

64 orbital periods ~ 20 Gyr

timescale
for chaos: infinite! | infinite! | 10^5Gyrs | 10^2Gyrs

x/y plane



Cluster Evolution - morphologies + frequencies

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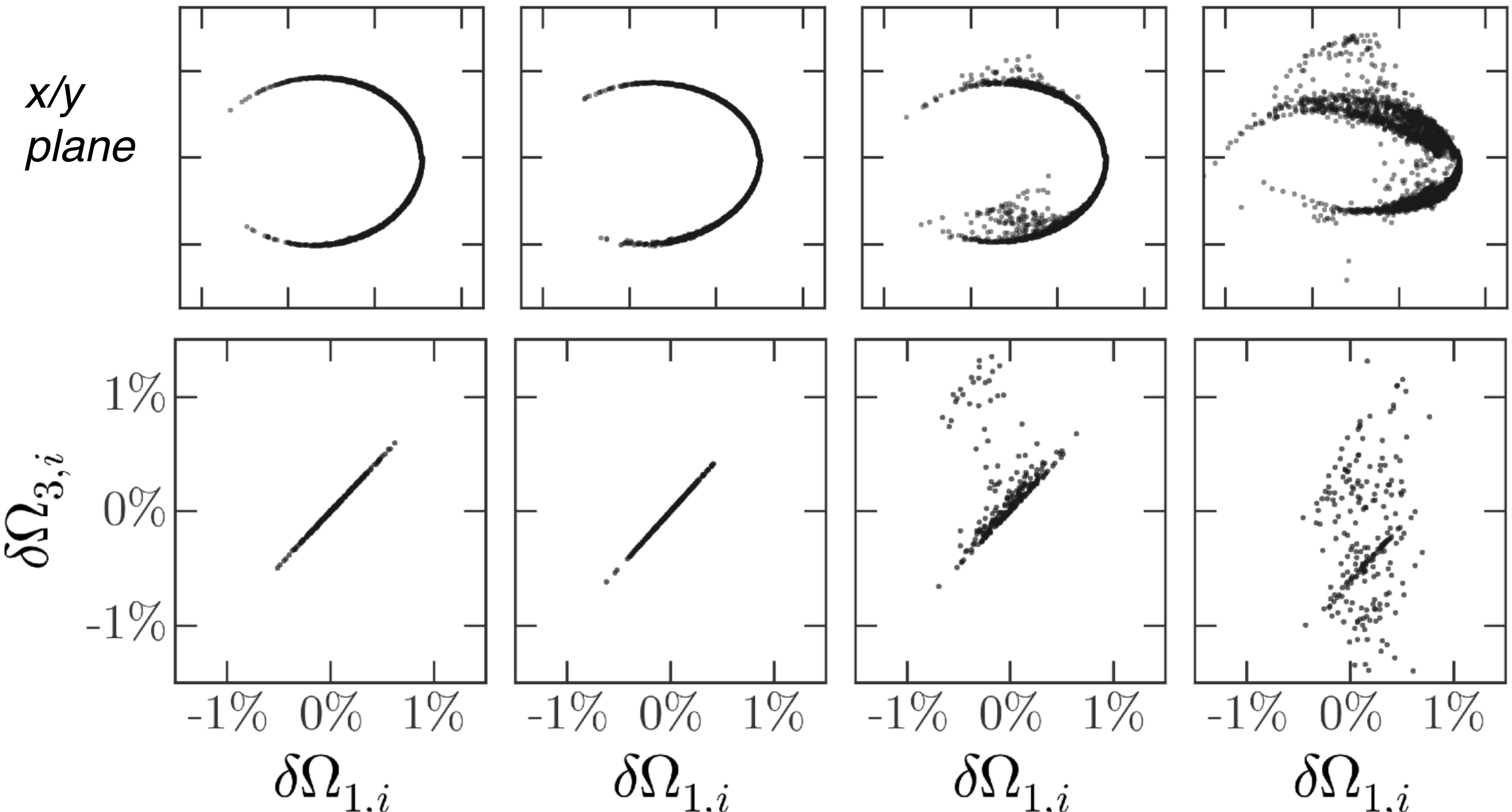

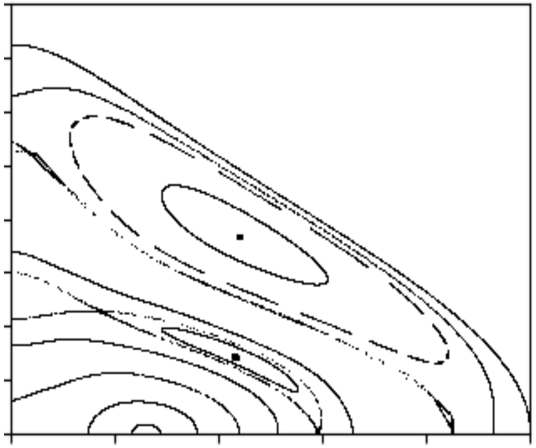

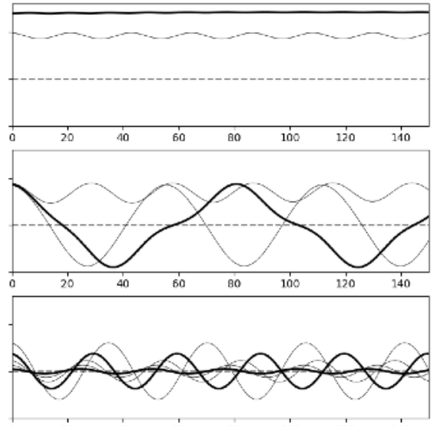

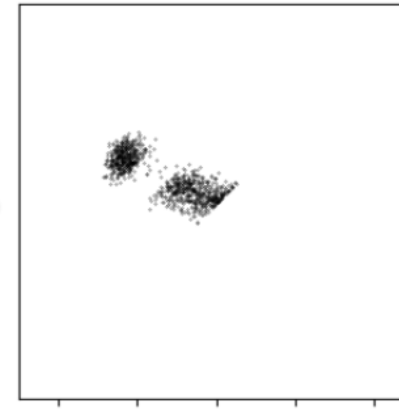

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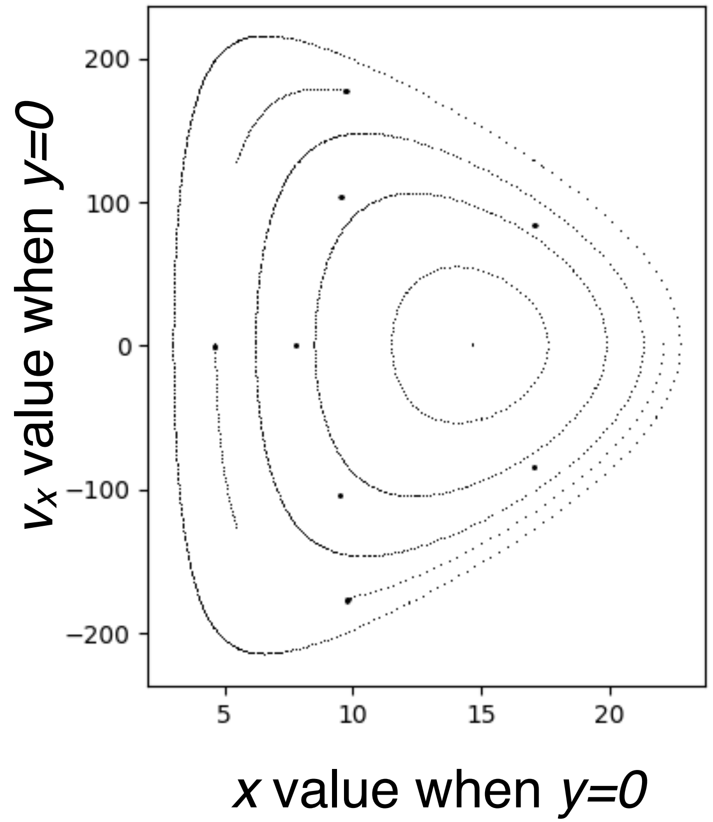
Yavetz, Johnston, Pearson & Price-Whelan 2019, *in prep*

Aside: Poincaré Maps ("surface of section")
..... and resonant orbits

<u>plots orbits of a single energy</u> e.g. in spherical potential



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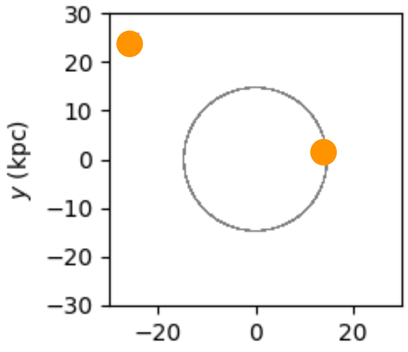
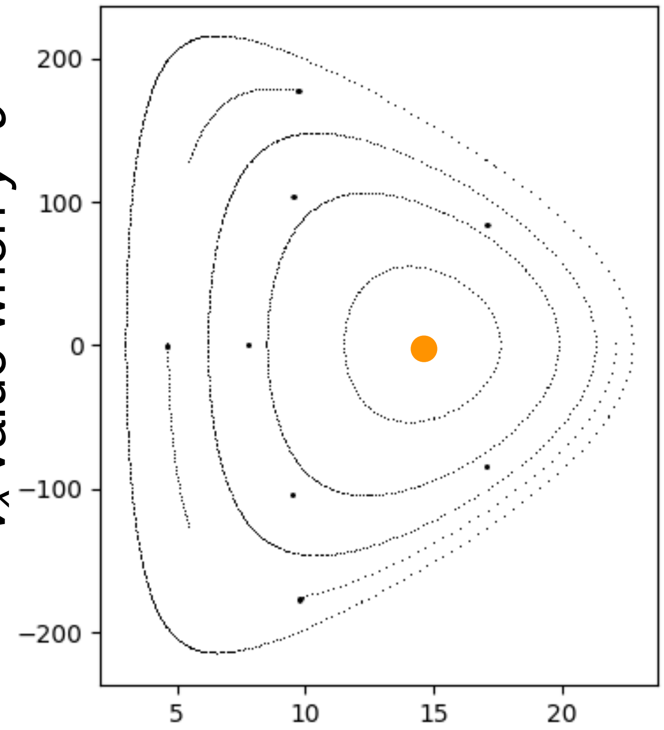


circular



v_x value when $y=0$

x value when $y=0$

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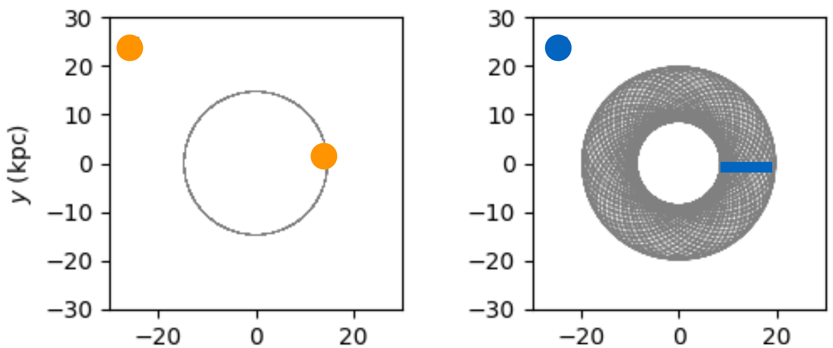
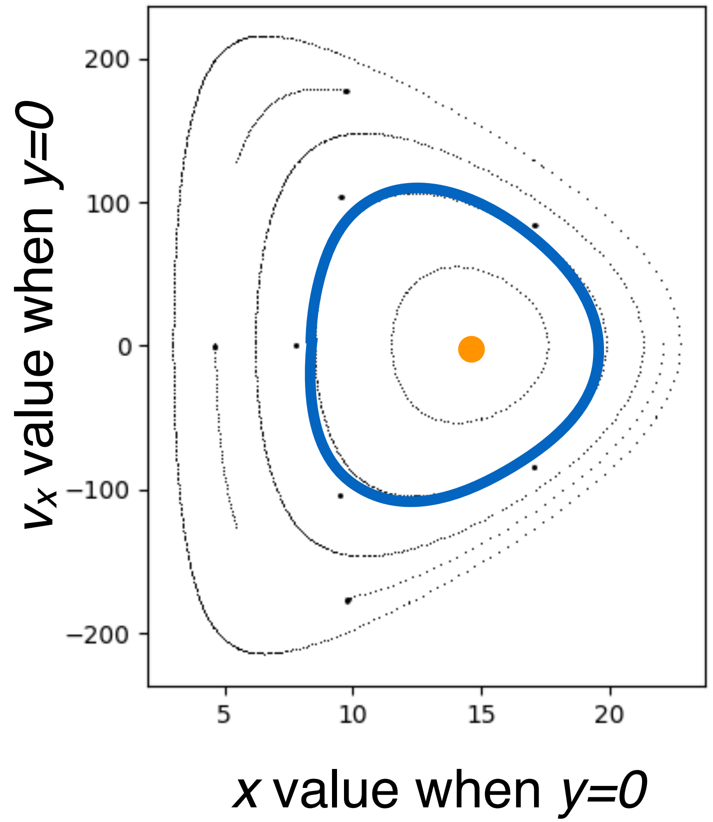


circular
regular/eccentric



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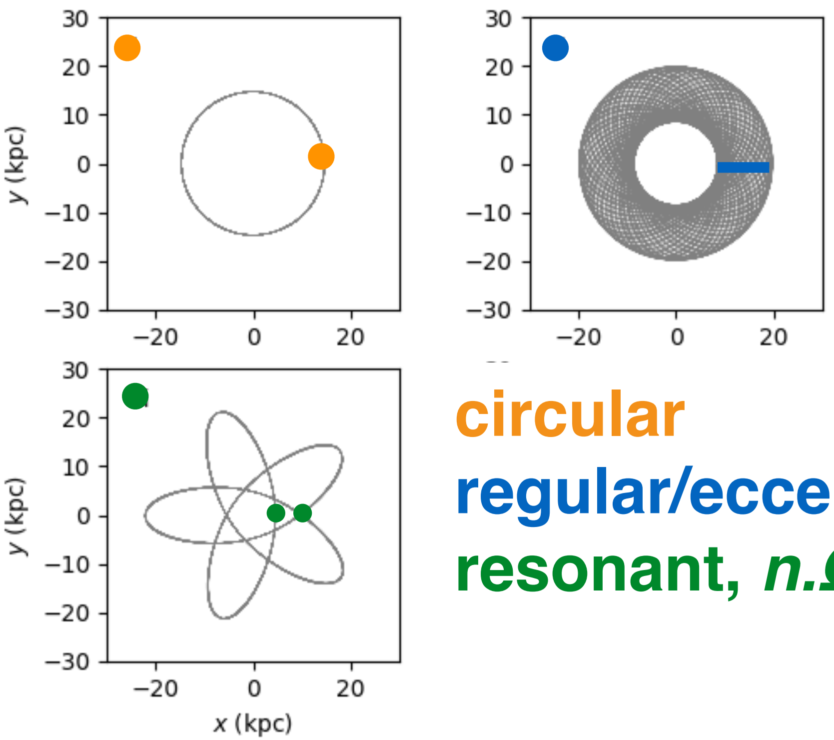
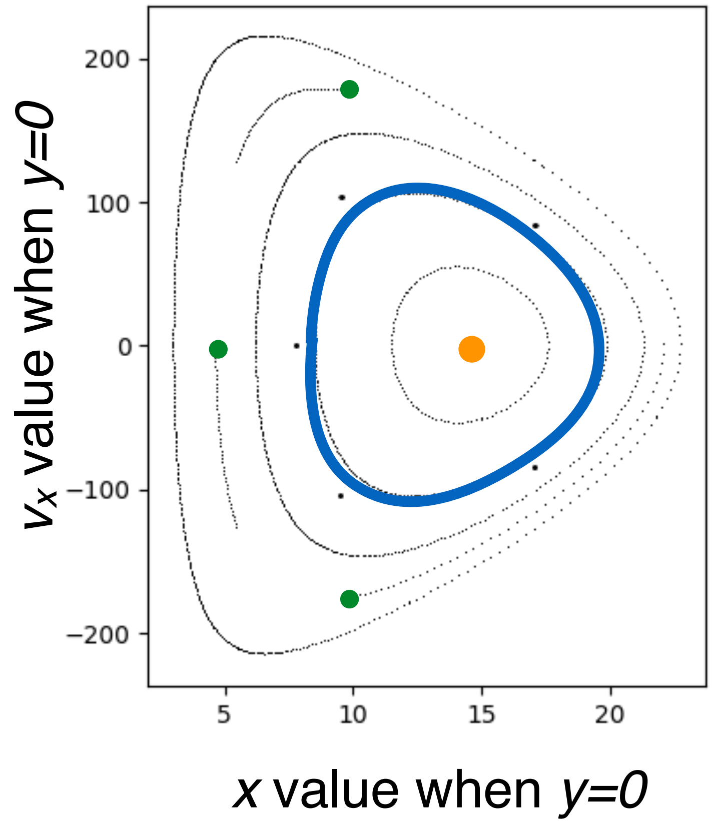


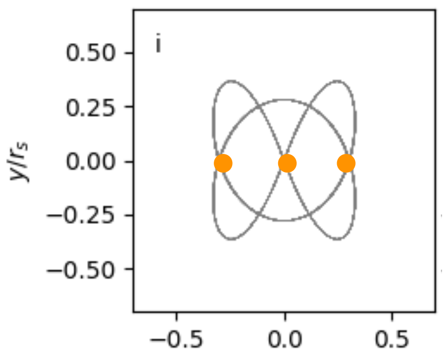
circular
regular/eccentric
resonant, $n.\Omega = 0$



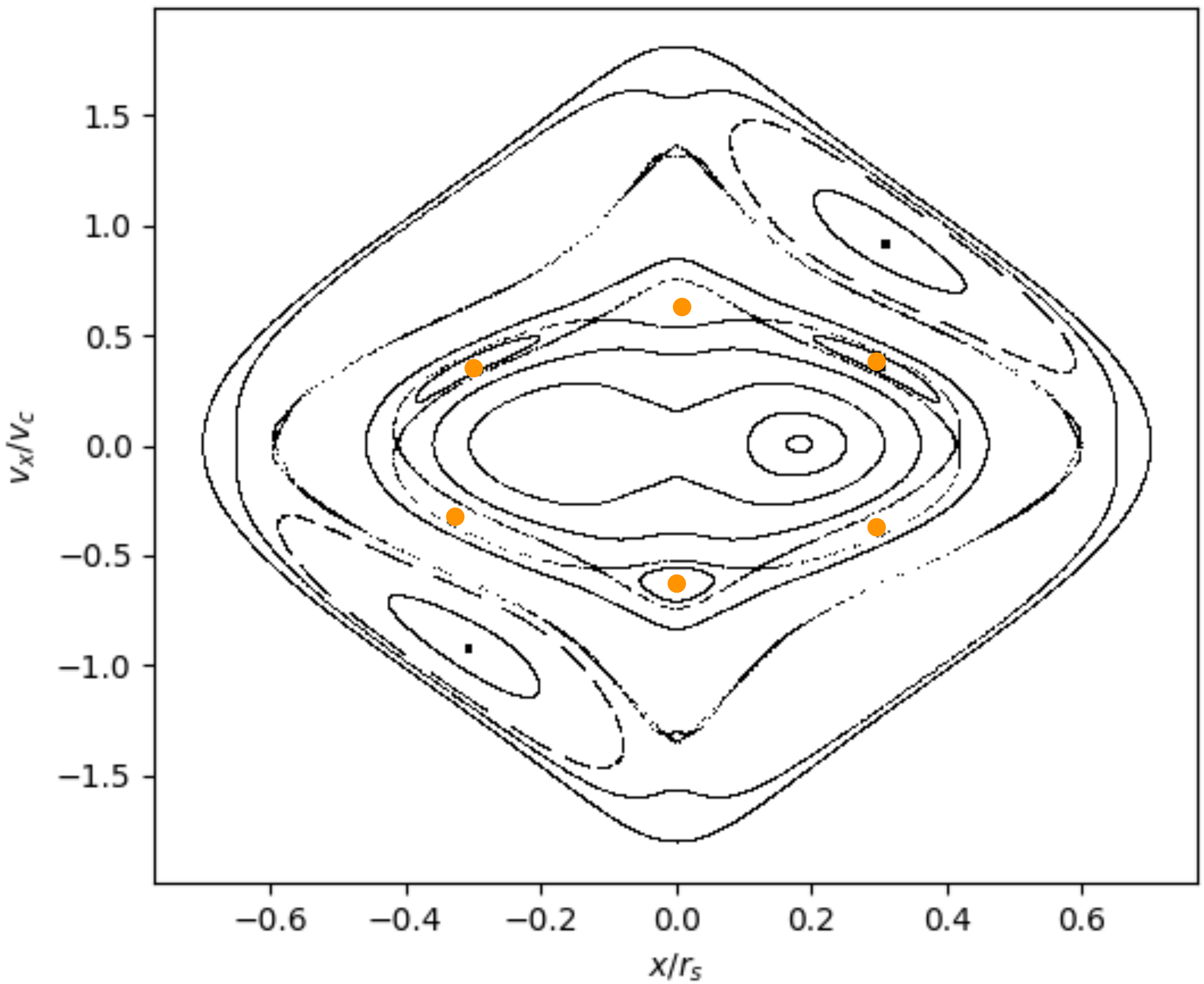
Poincaré Map for squashed potential

2D logarithmic potential: axis ratio=0.6; r_s = 0.14; v_c = 1.0; E_{tot} = -0.337

resonant



n.Ω = 0



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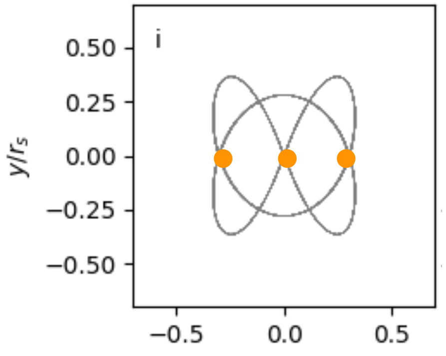

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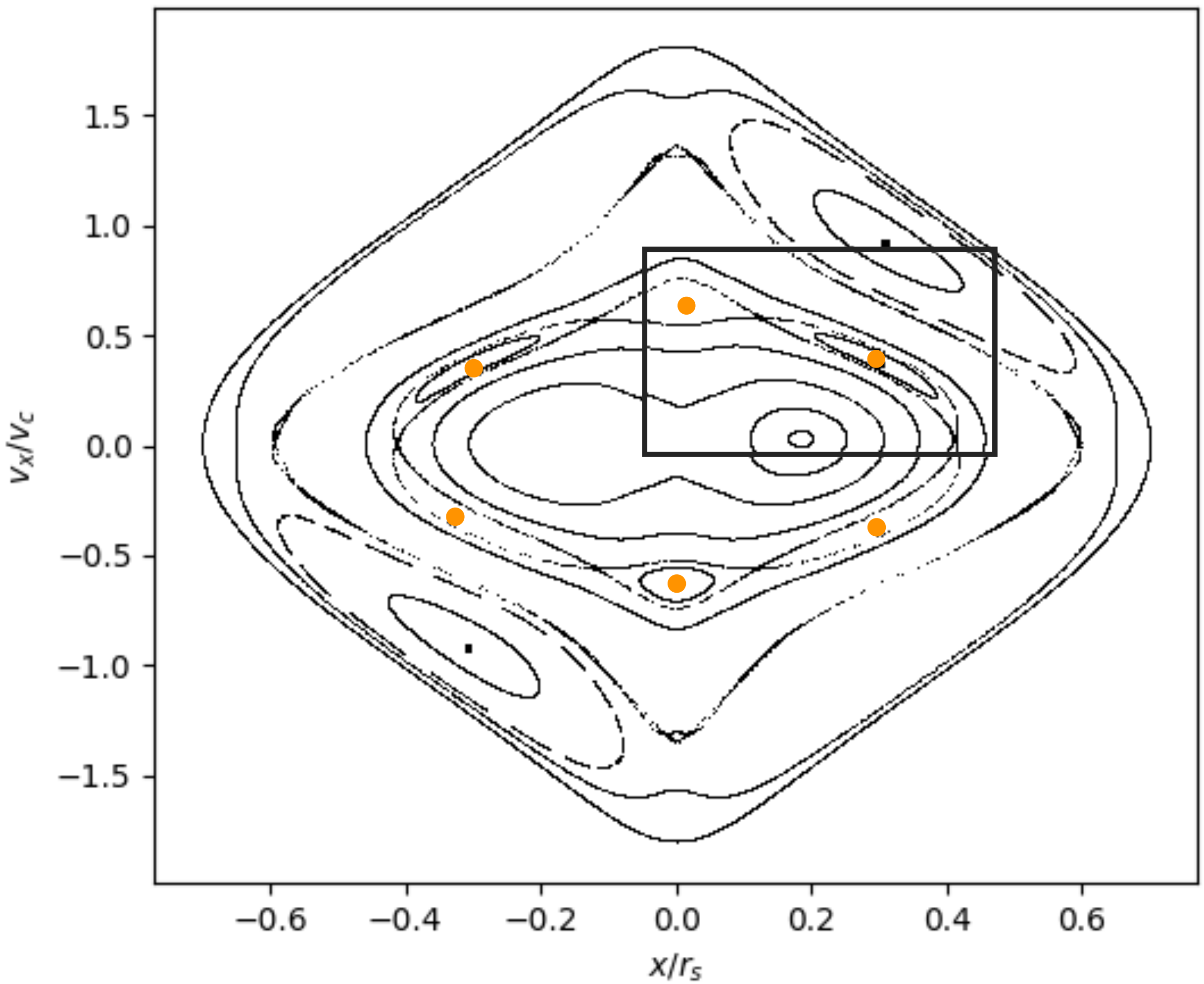

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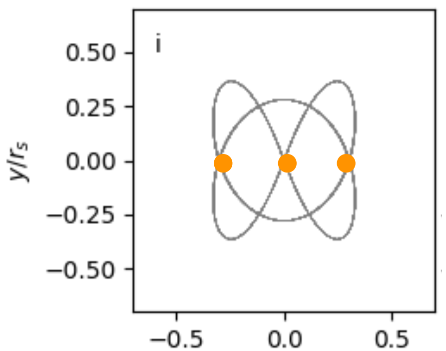
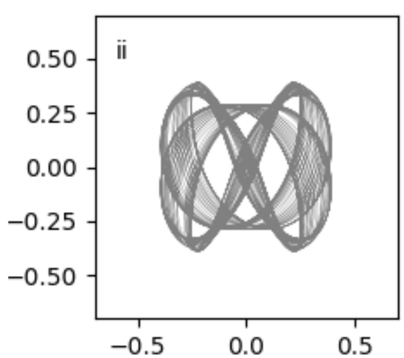


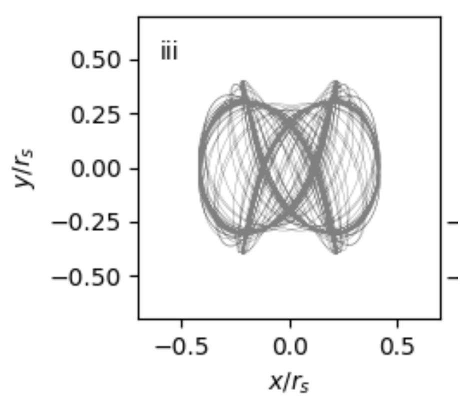
n.Ω = 0

?? chaotic ??

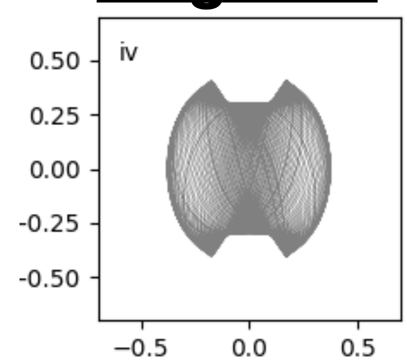
“trapped”



“separatrix”



“regular”



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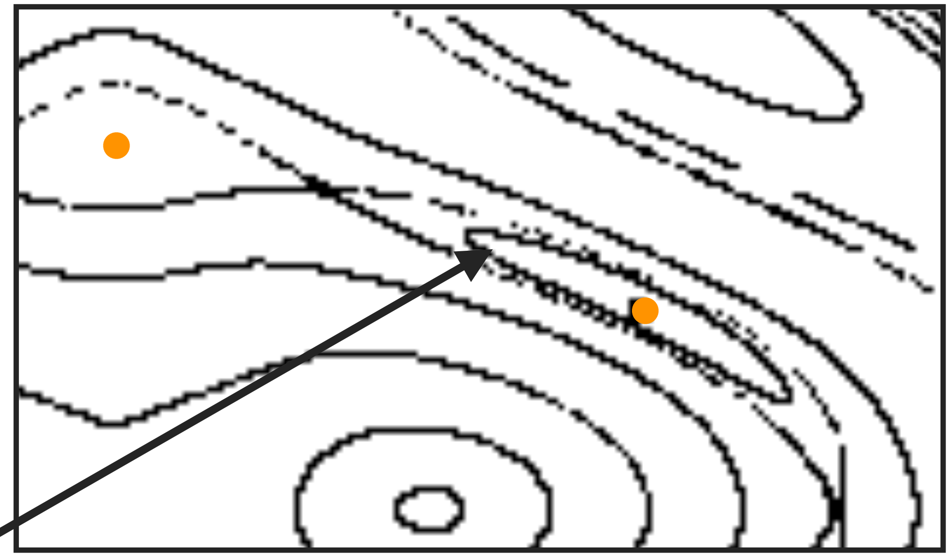

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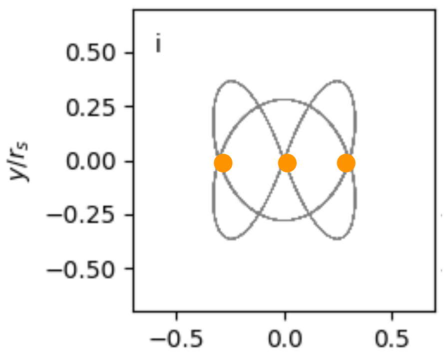

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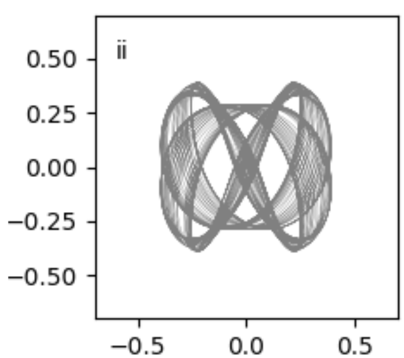

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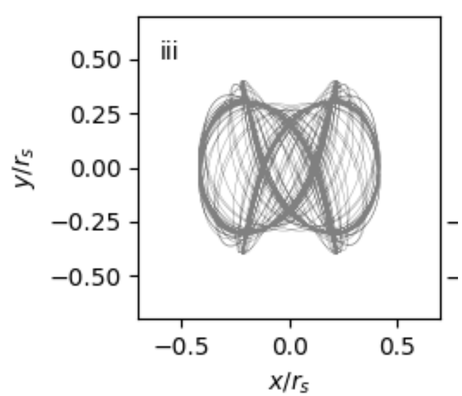

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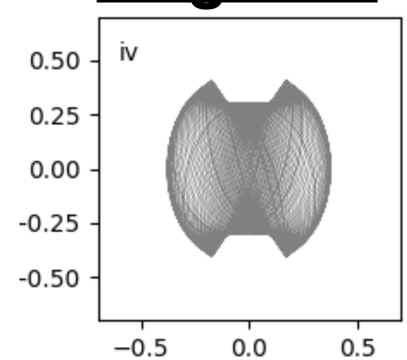

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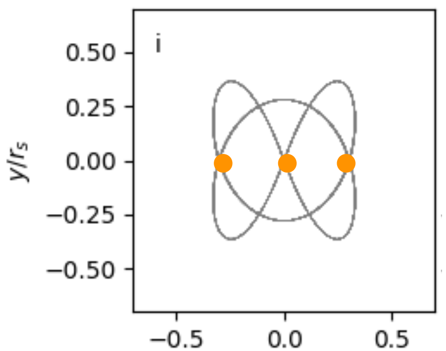

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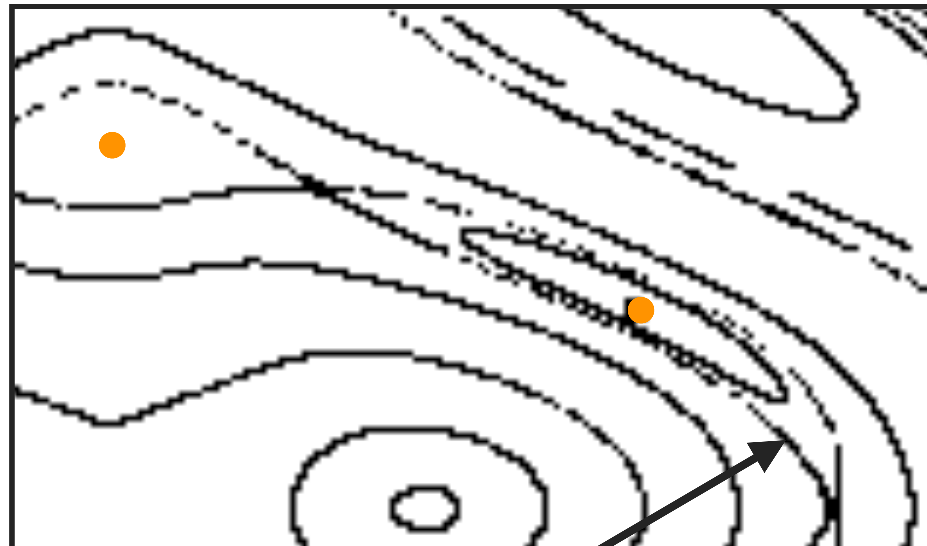

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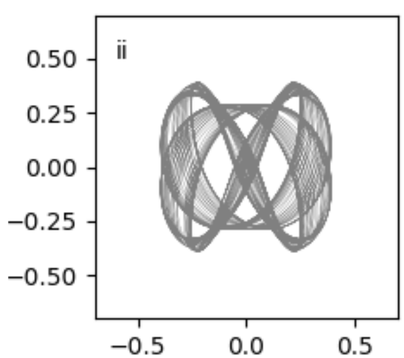

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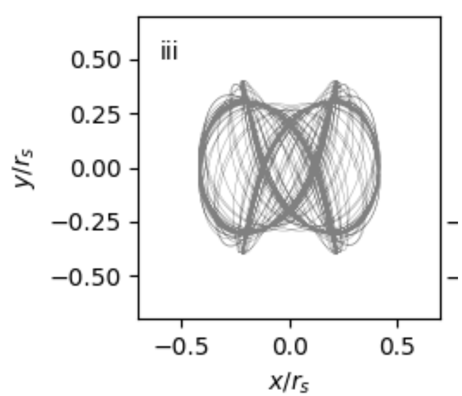

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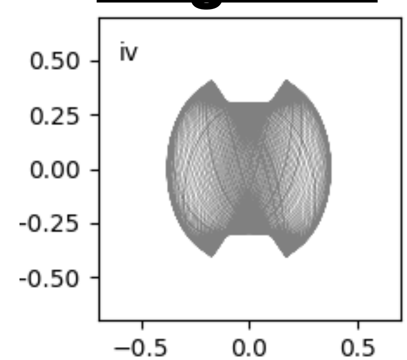

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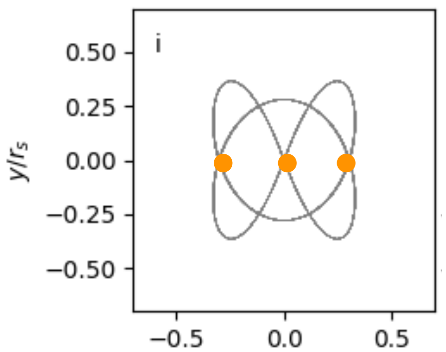

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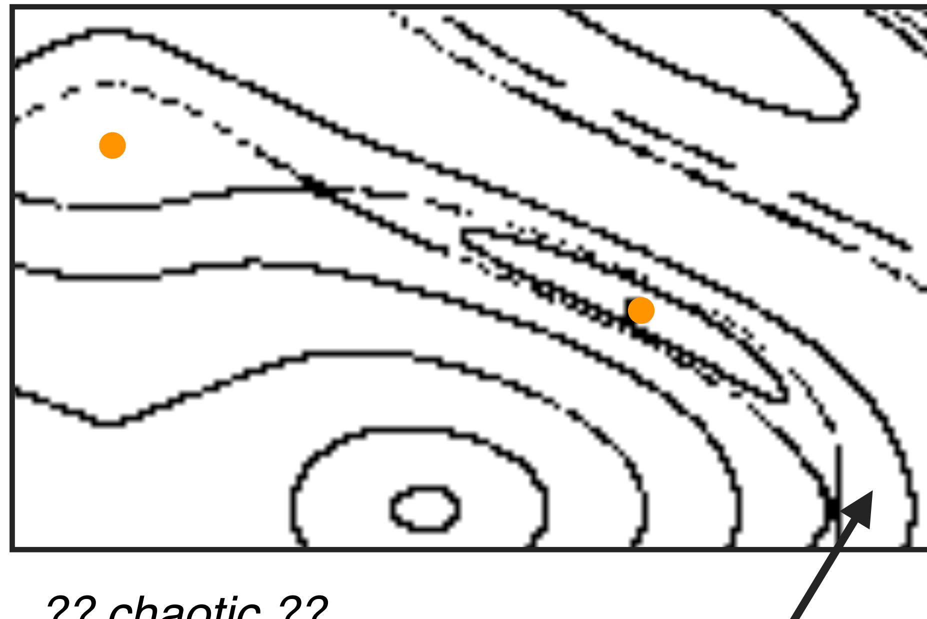

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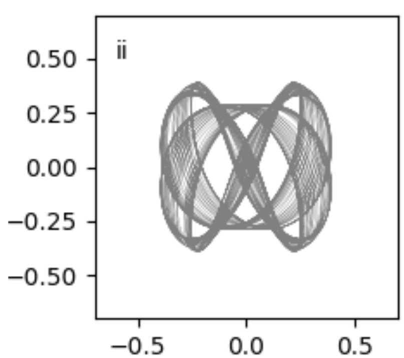

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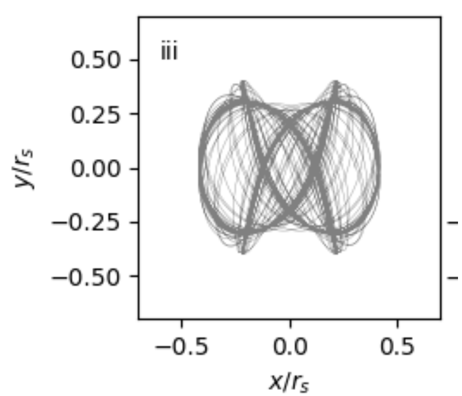

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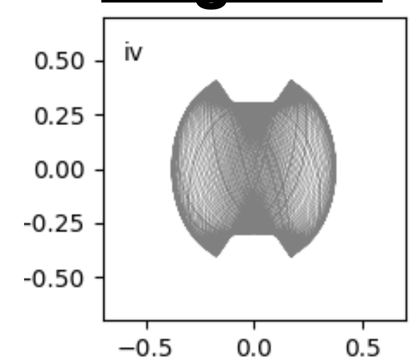
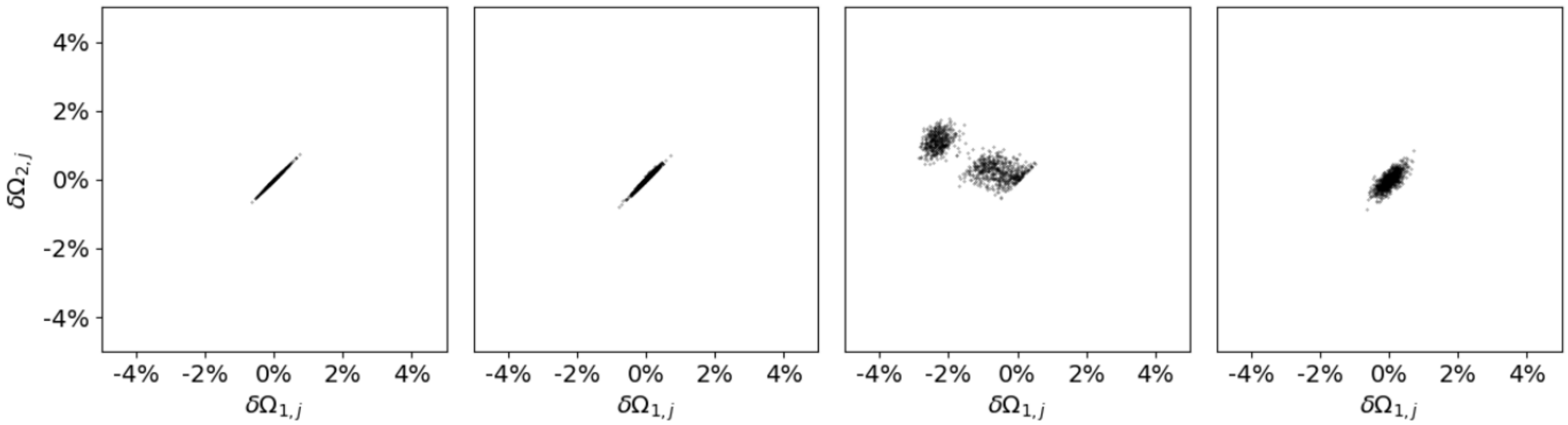
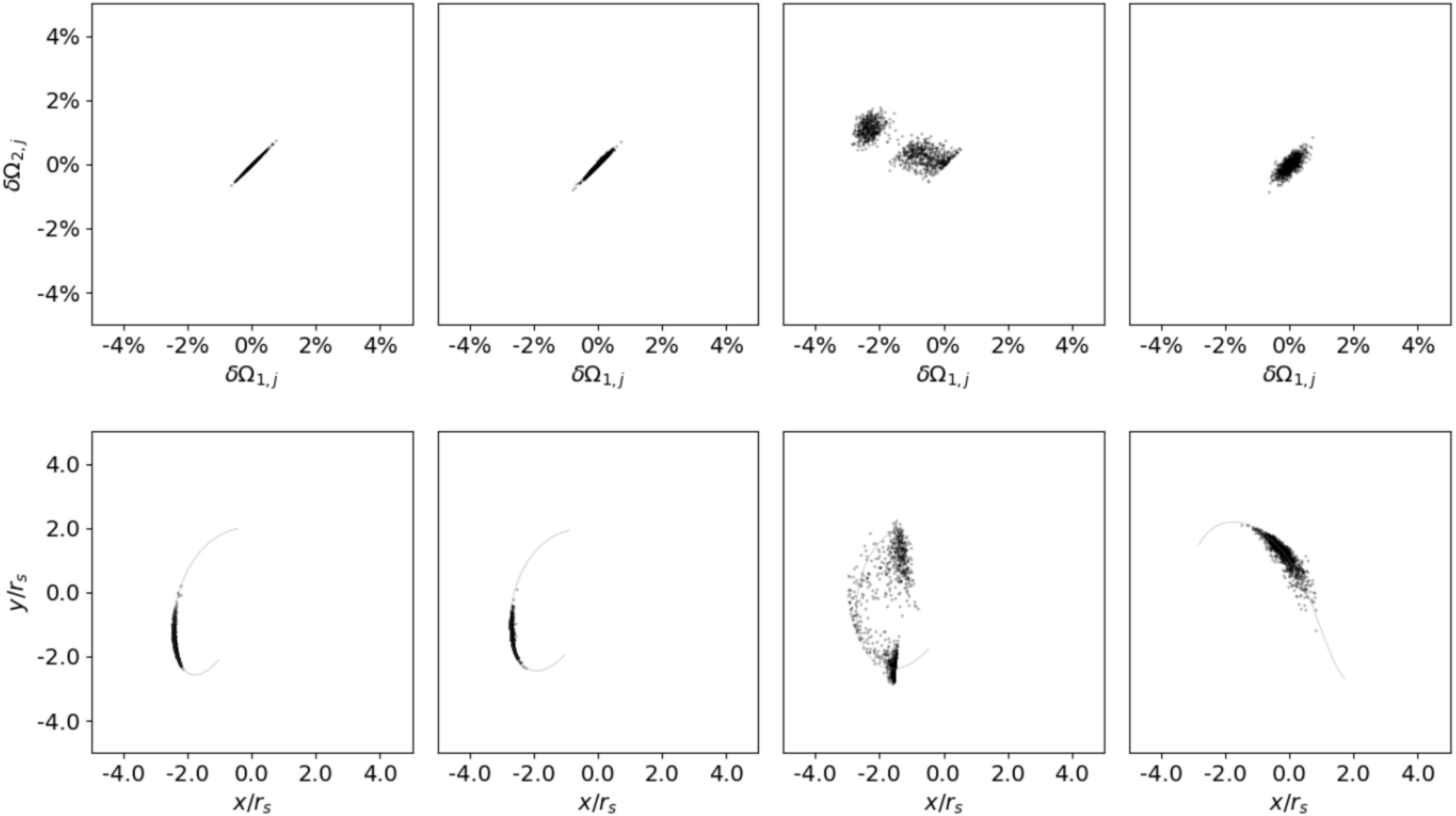


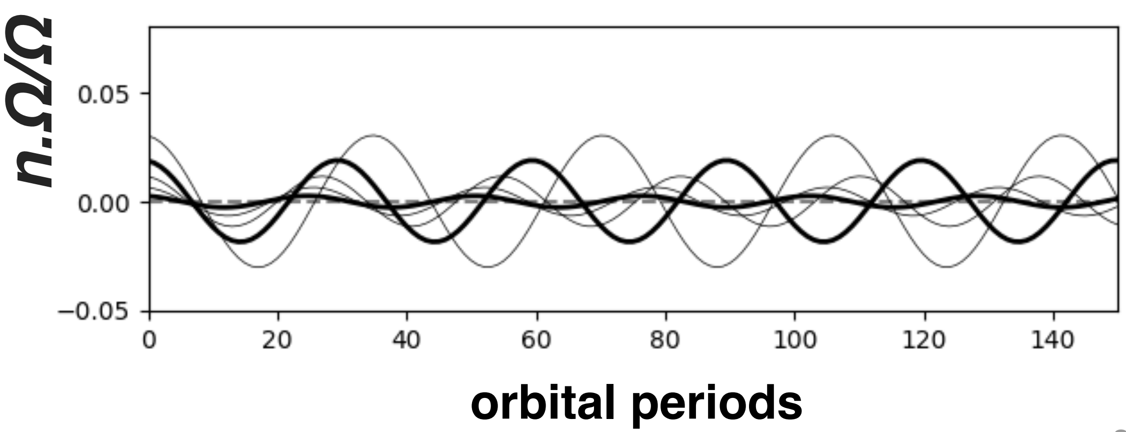
Cluster evolution - frequencies



Cluster evolution - frequencies and morphologies



Frequency evolution



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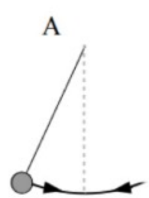
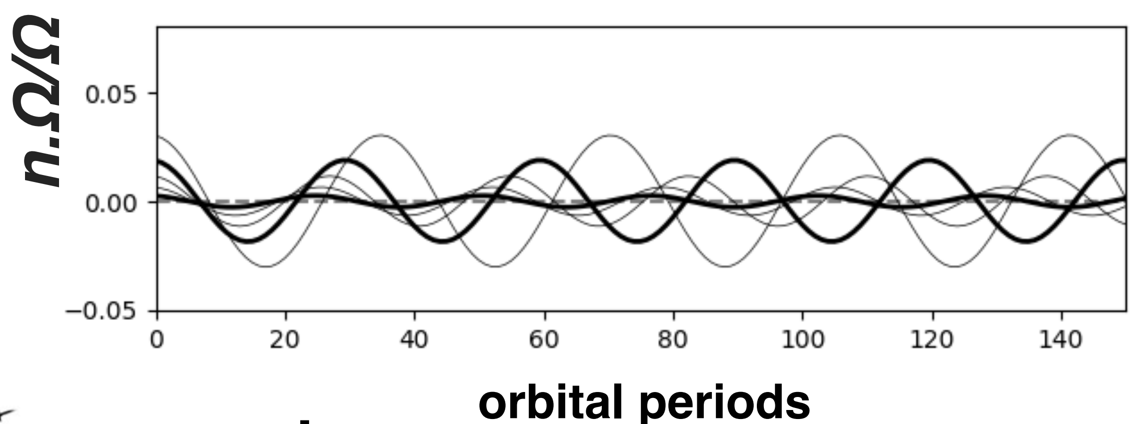
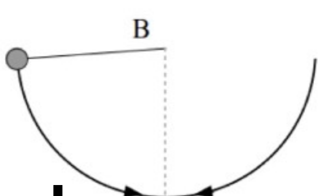




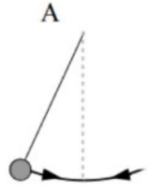
resonant

Frequency evolution

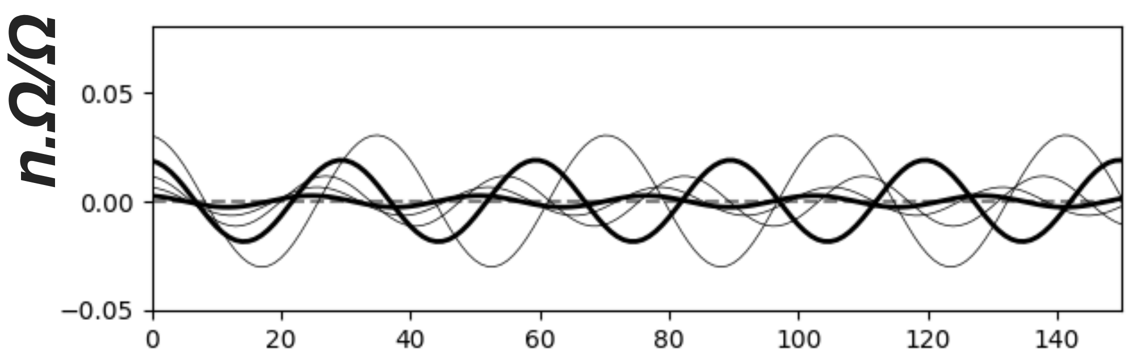


<u>trapped:</u>

“librating” about resonance

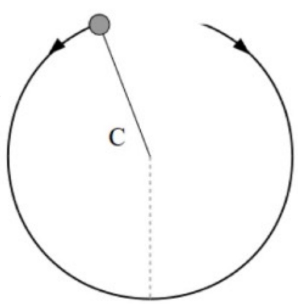


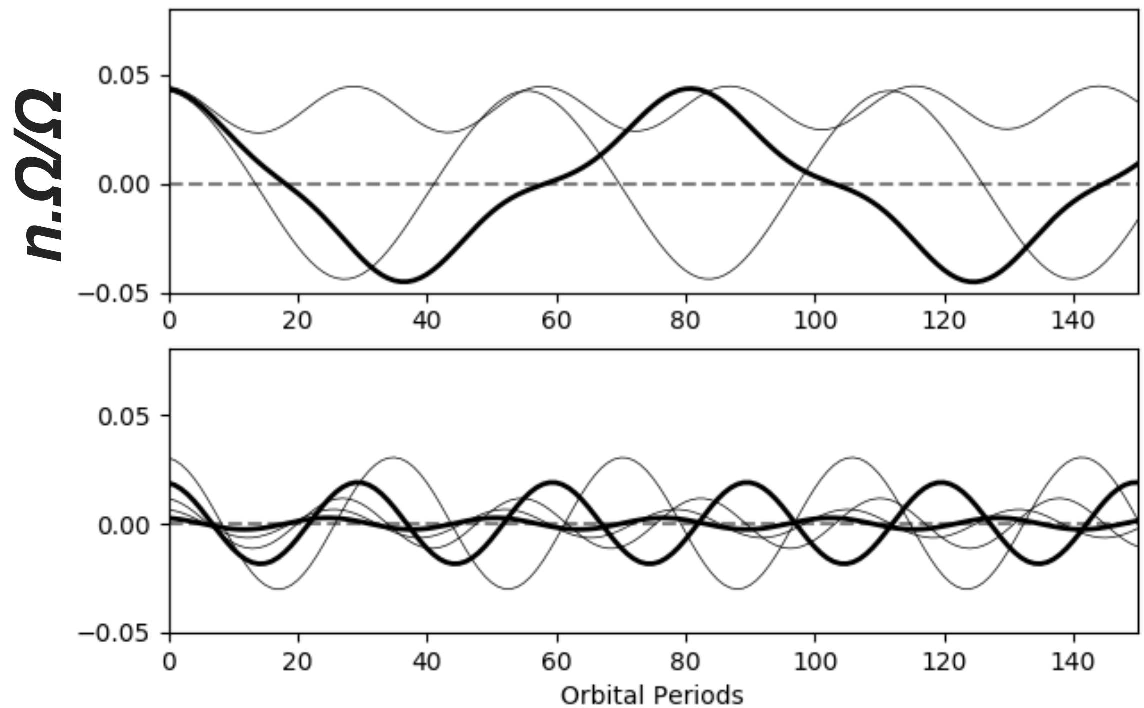
<u>resonant</u>

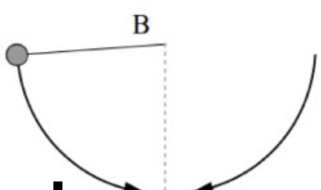


Frequency evolution

separatrix







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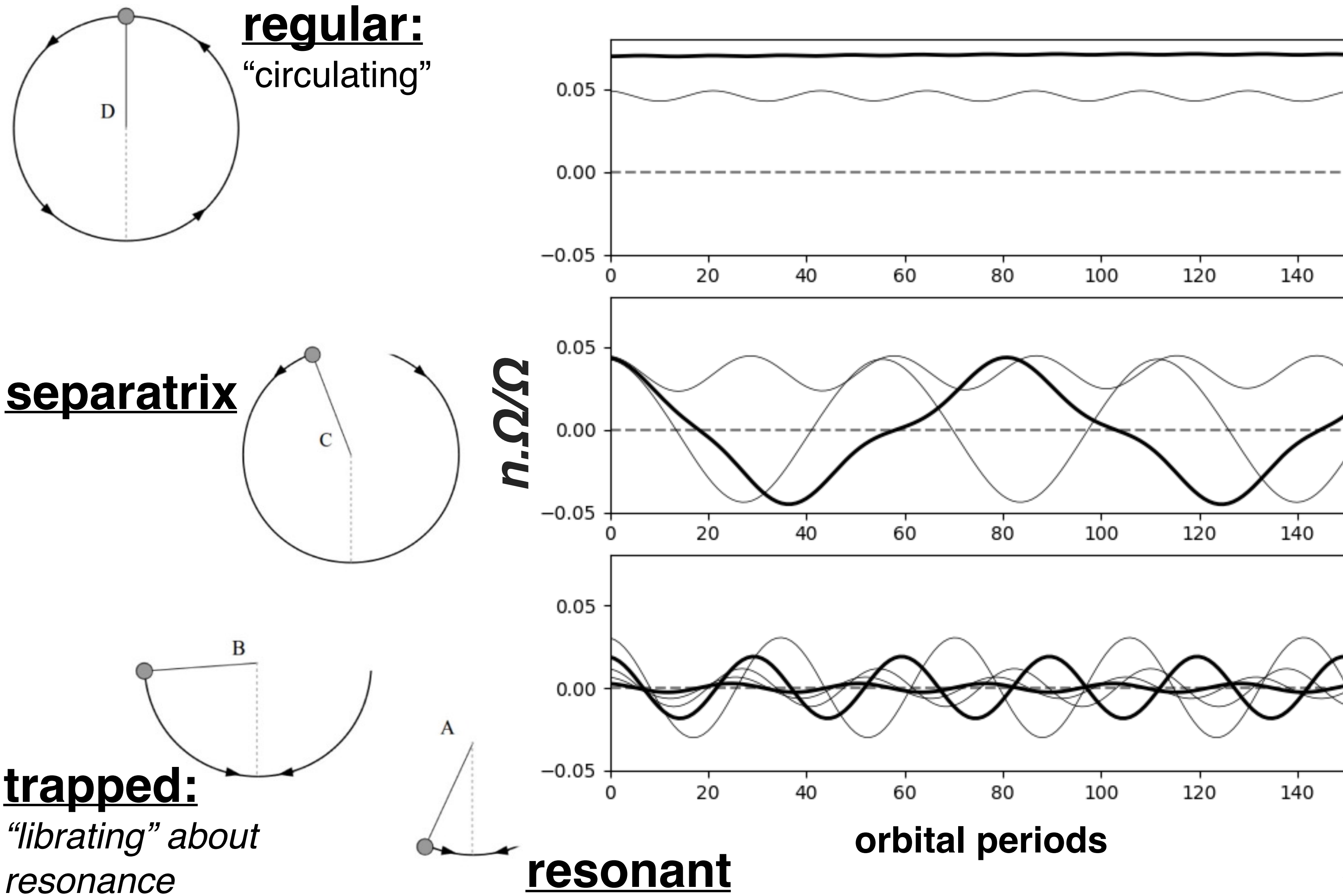
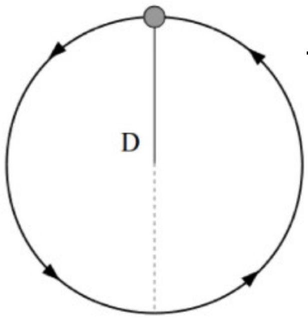
resonant

Frequency evolution



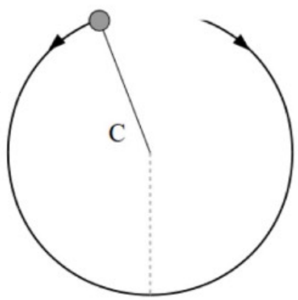
Frequency evolution

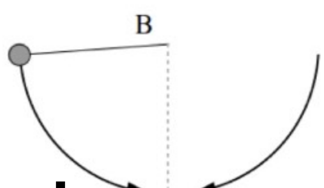


regular:

“circulating”

separatrix





trapped:

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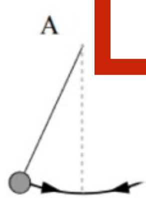
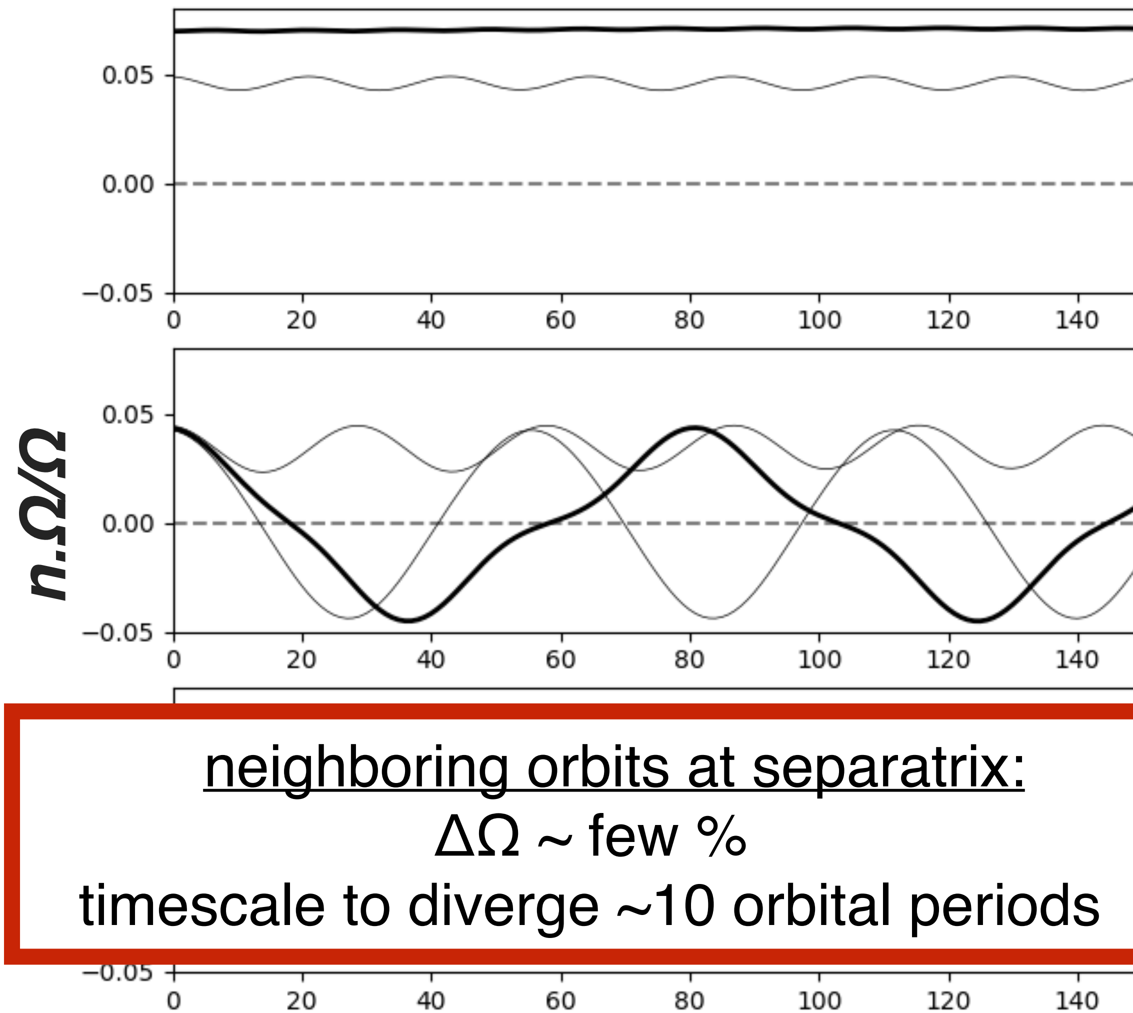


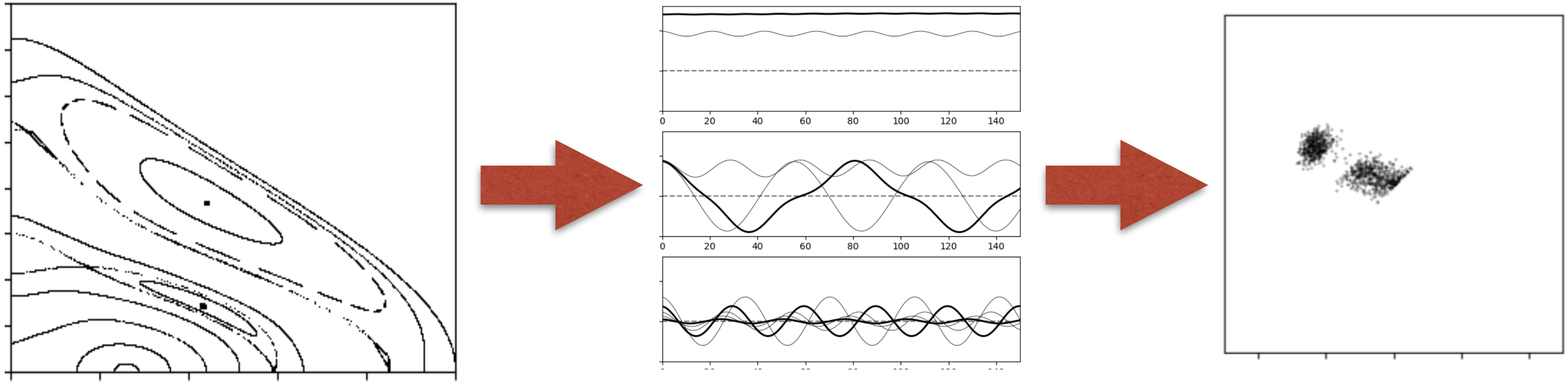
resonant



neighboring orbits at separatrix:

ΔΩ ~ few %

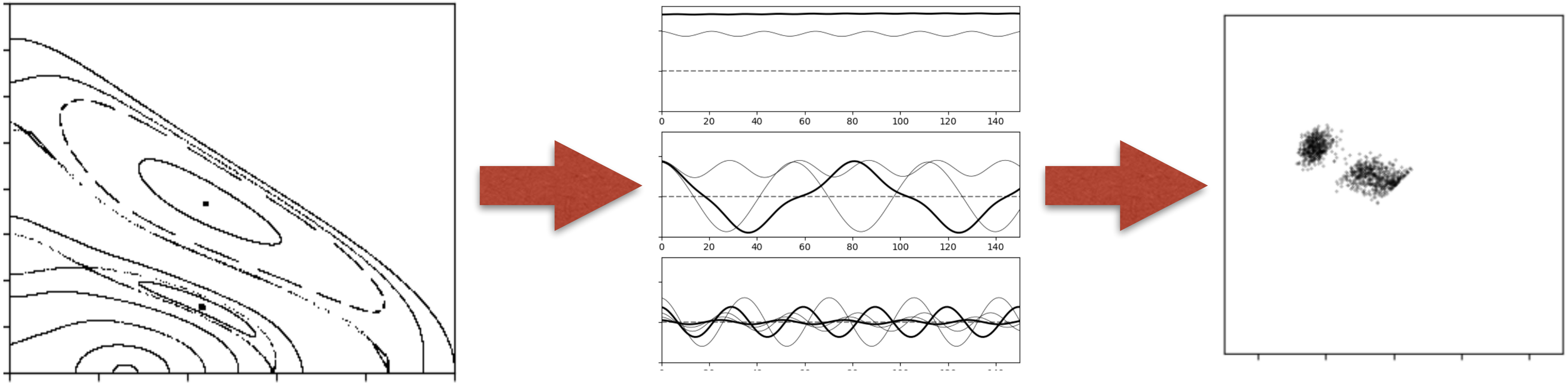
timescale to diverge ~10 orbital periods



~~???? CHAOS ????~~

“Separatrix Divergence”

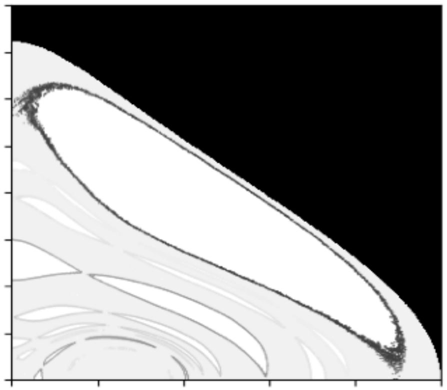
Yavetz, Johnston, Pearson & Price-Whelan 2019, *in prep*

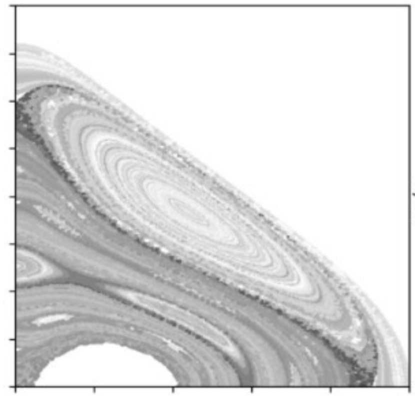


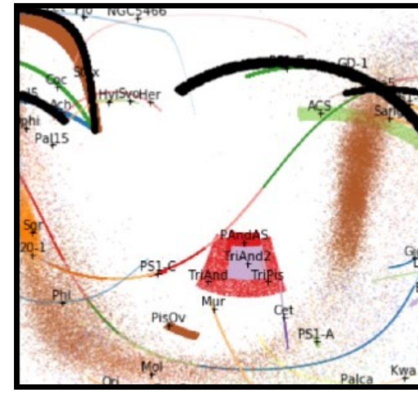
"Separatrix Divergence"

???? why care ????

Yavetz, Johnston, Pearson & Price-Whelan 2019, *in prep*



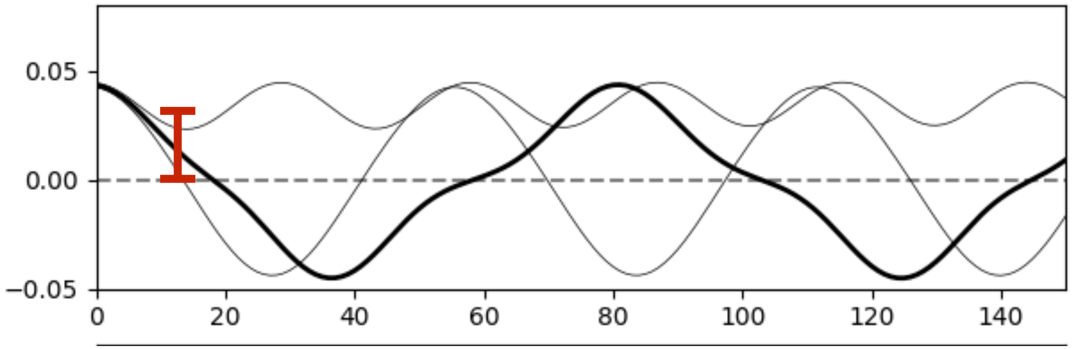




Observing manifestations of fundamental dynamics around galaxies

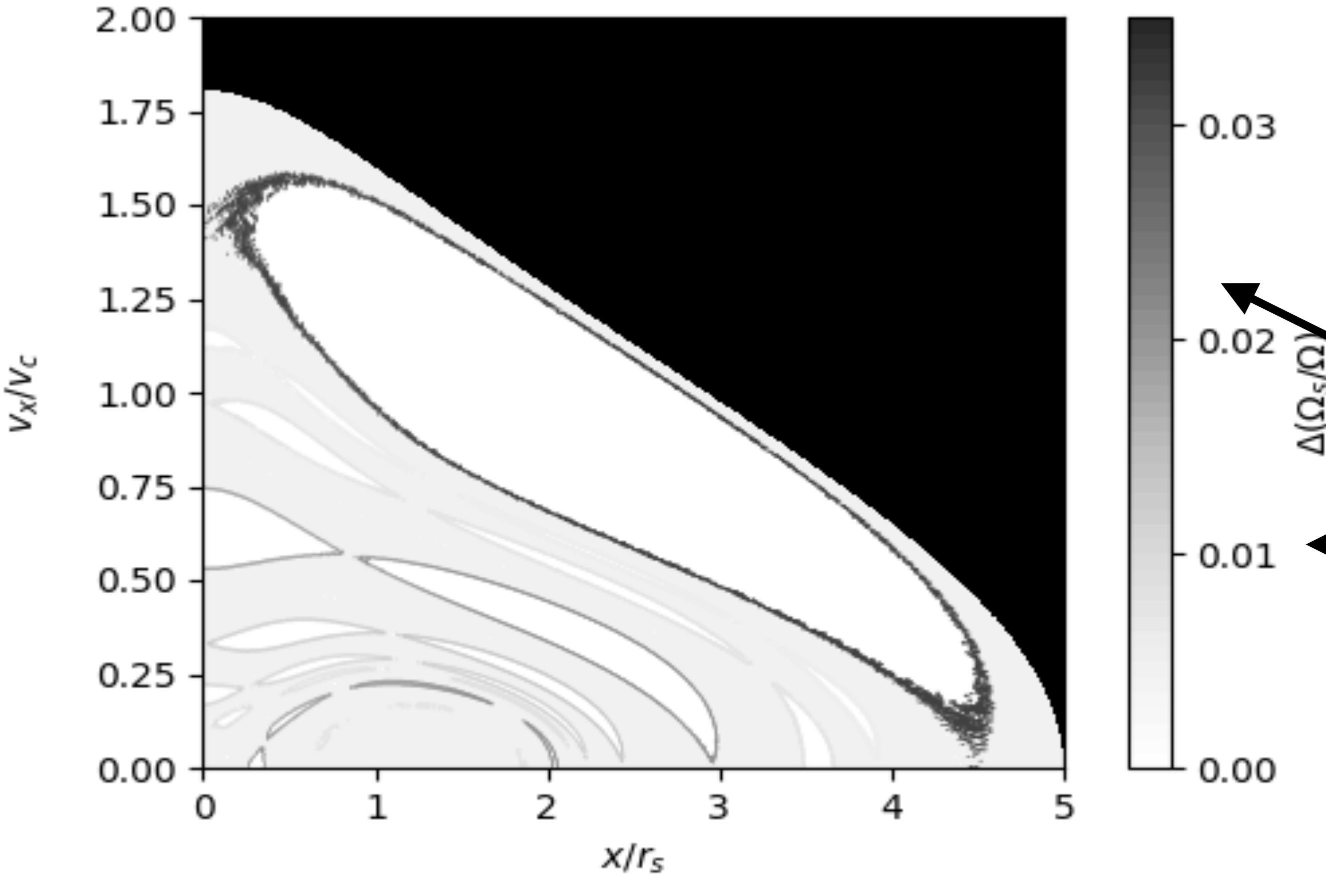
Yavetz, Johnston, Pearson & Price-Whelan 2019, *in prep*

Separatrix Divergence - quantification



1. $\Delta\Omega_{separatrix} > \Delta\Omega_{cluster}$

Separatrix Divergence - quantification



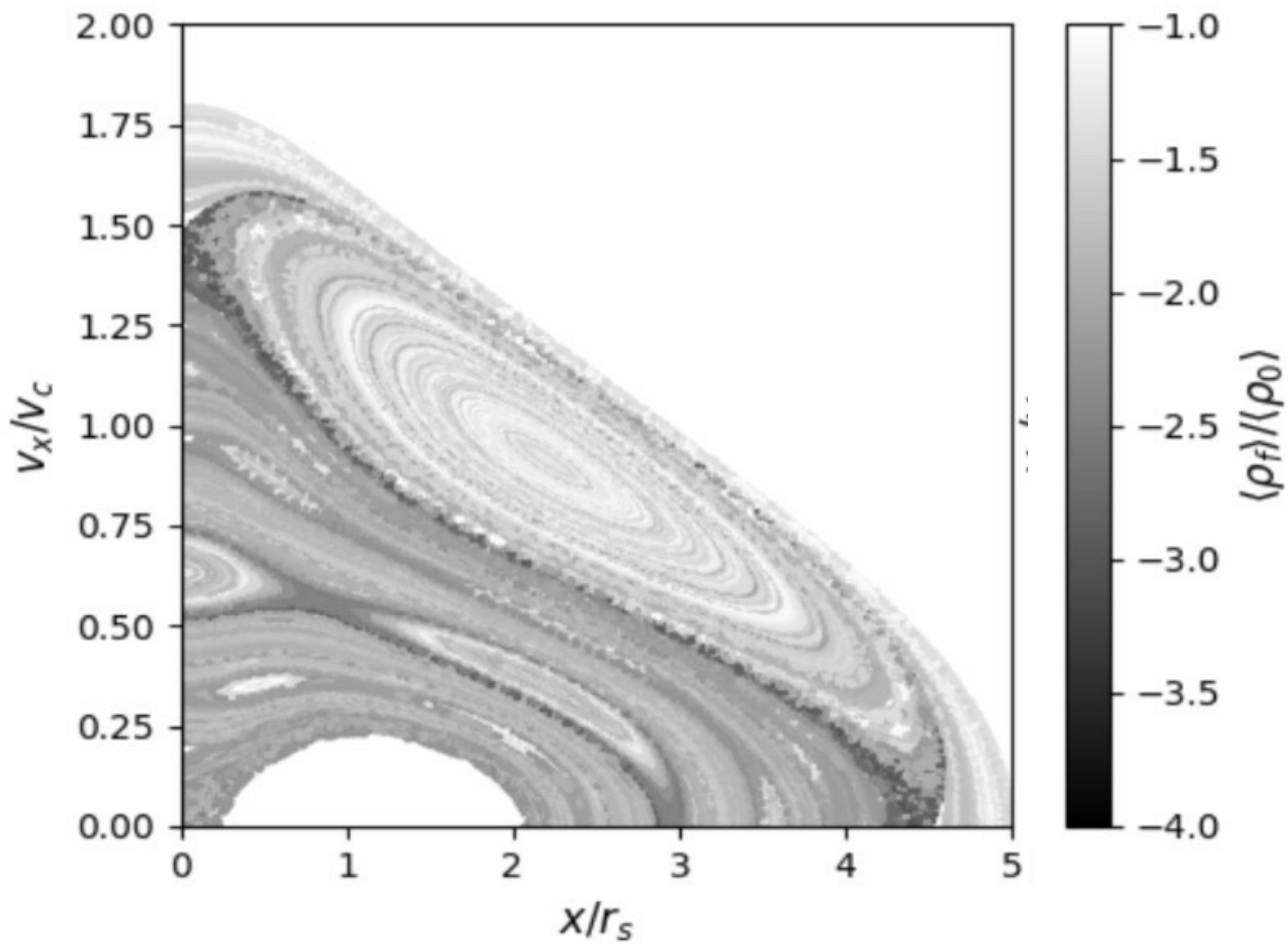
1. $\Delta\Omega_{separatrix} > \Delta\Omega_{cluster}$

objects affected mass:

~10^7 Msun

~10^6 Msun

Separatrix Divergence - quantification



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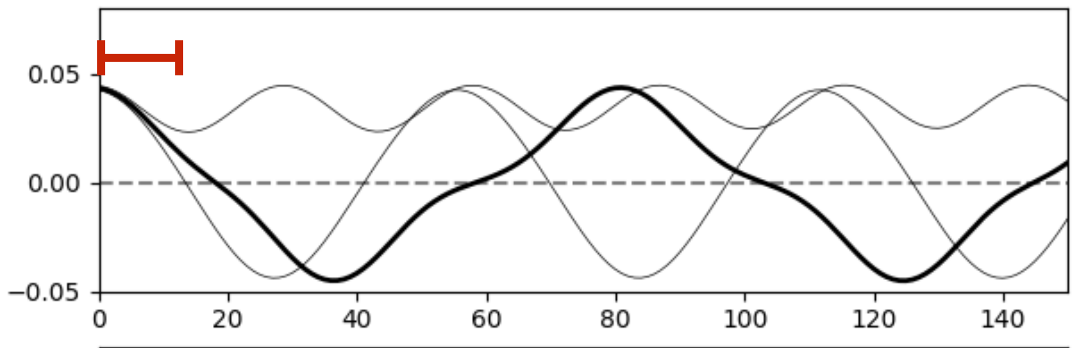

1. $\Delta\Omega_{separatrix} > \Delta\Omega_{cluster}$

2. timescale $\sim n.\Omega$ libration < Hubble time

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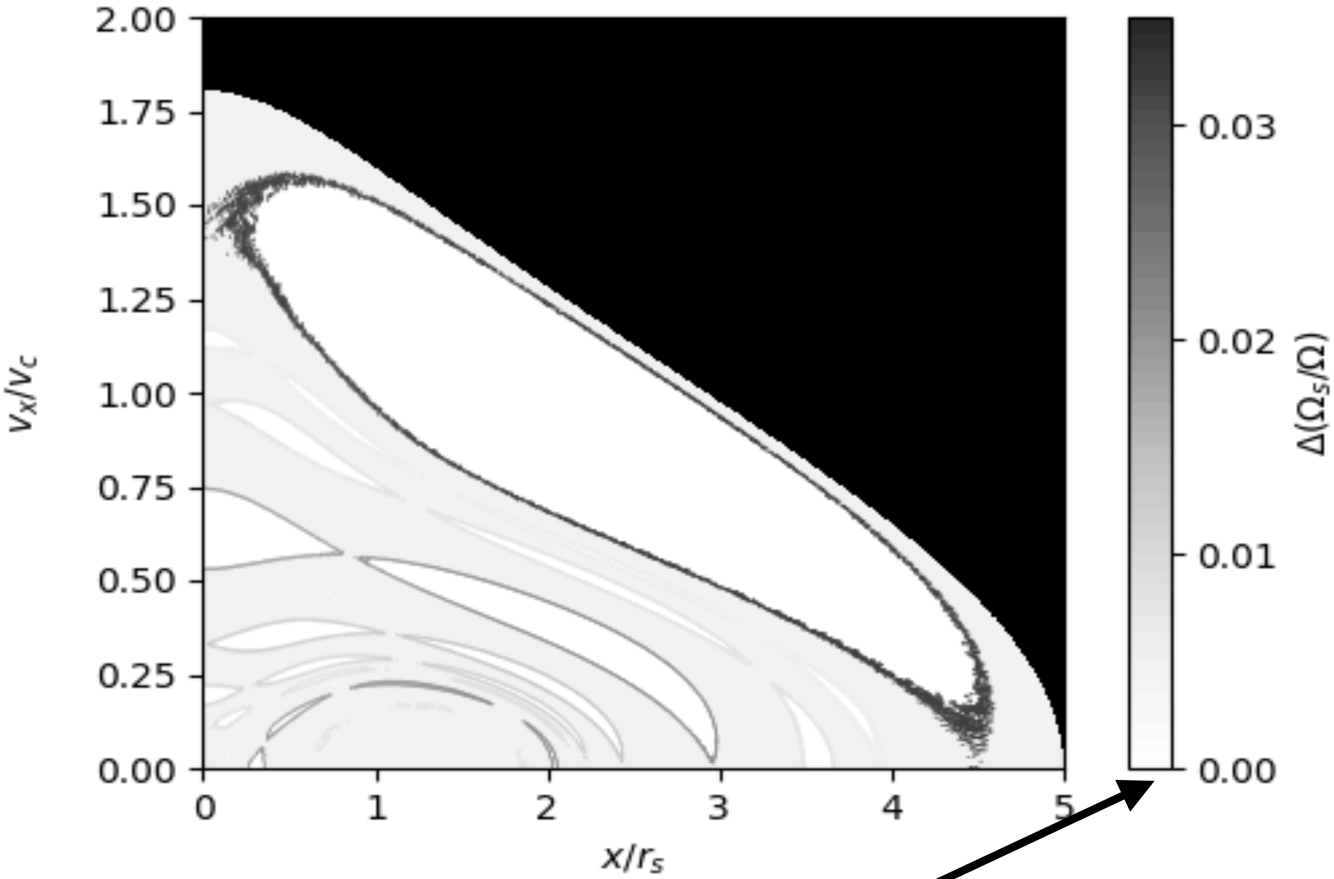


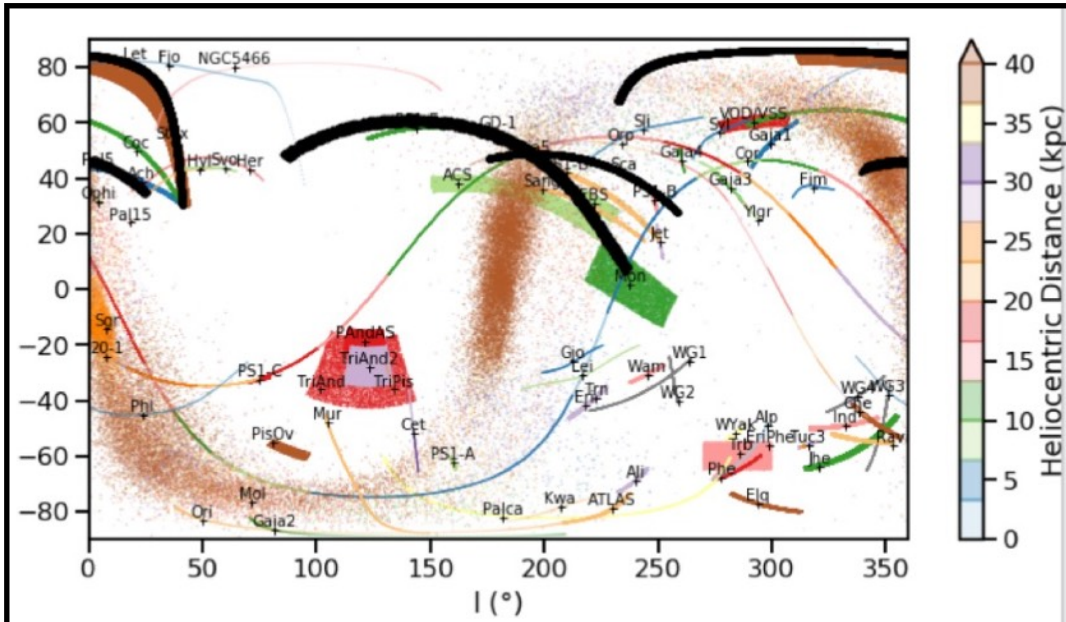
1. $\Delta\Omega_{separatrix}$ > $\Delta\Omega_{cluster}$

2. timescale ~ n.Ω libration < Hubble time

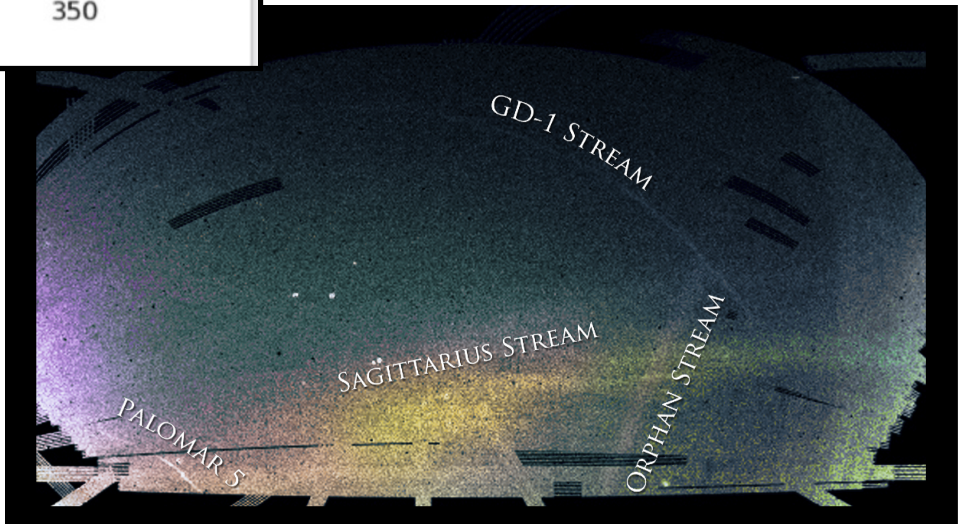
3. finite probability of occurrence

~ maximum cross section of effect of separtarix

Thin streams → regularity/resonance

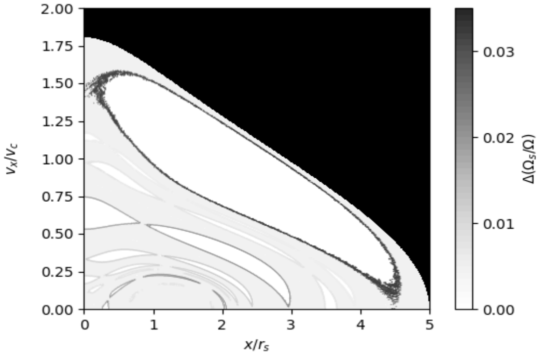


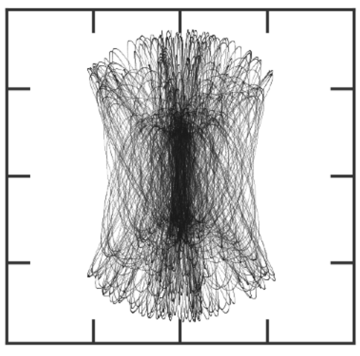
from Cecilia Mateu's Galstreams python package

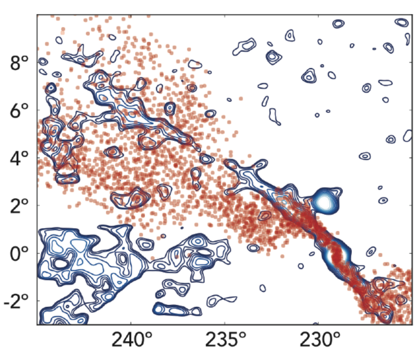


Ana Bonaca, following "field of streams" (Belokurov et al 2005)

Conclusion - observing fundamental dynamics







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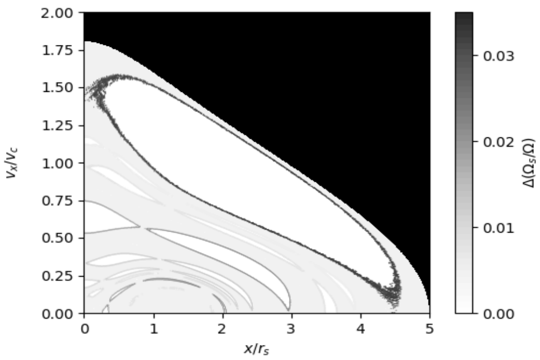
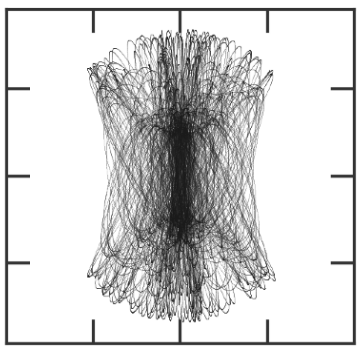
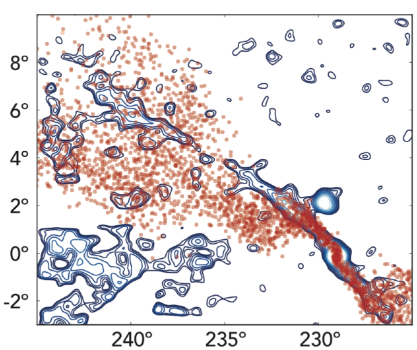


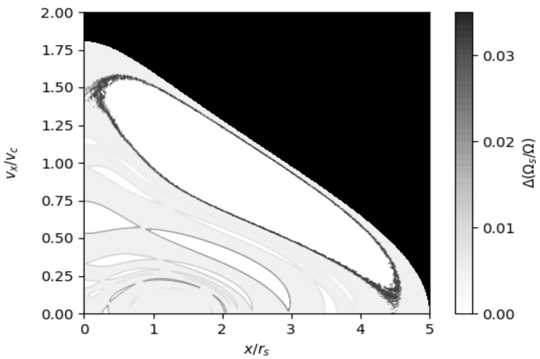




Morphology = cheap potential indicator

mere existence of thin streams is constraining, for MW and other galaxies

Conclusion - observing fundamental dynamics



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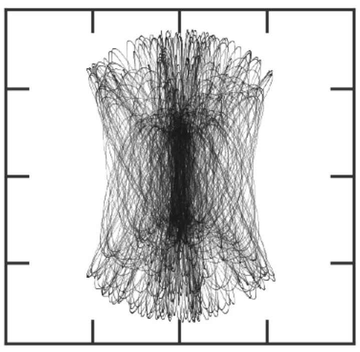
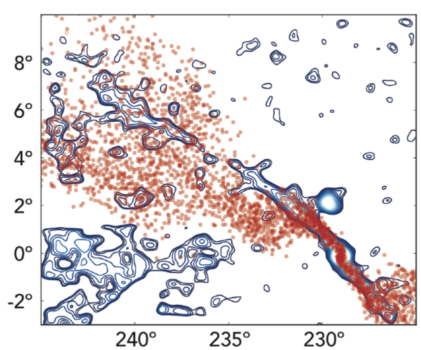


Novel dynamical regime

few orbits, not phase-averaged, ensemble properties, projected to observables



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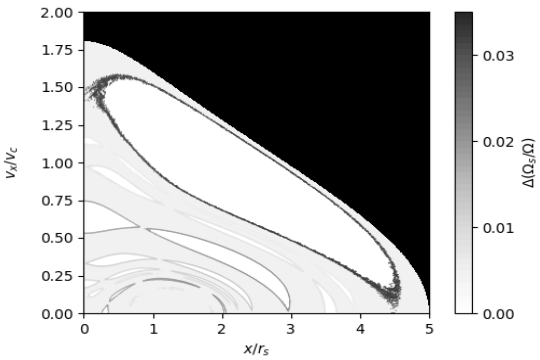

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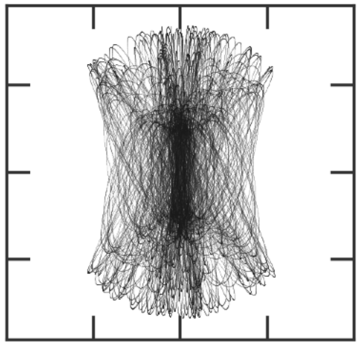

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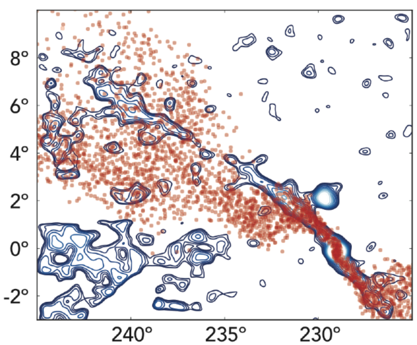
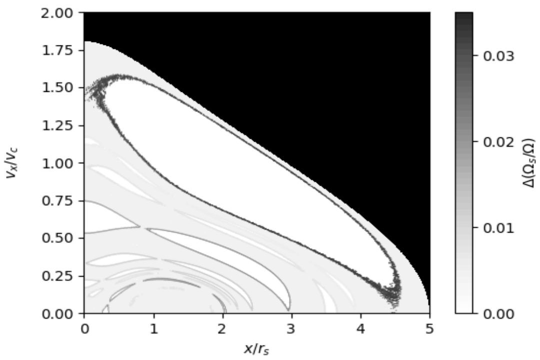


Varied applications

unbound stellar ensembles, from binary stars (Spergel, Oh, Price-Whelan) to dwarf galaxies

Conclusion - observing fundamental dynamics



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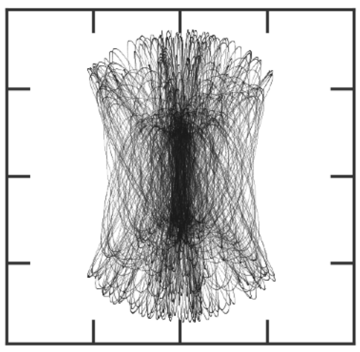

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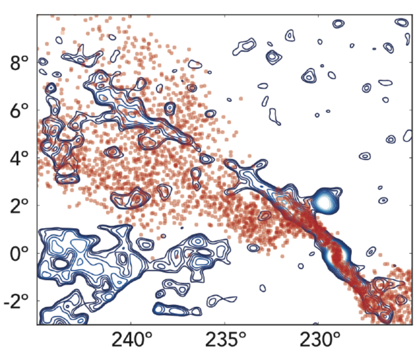

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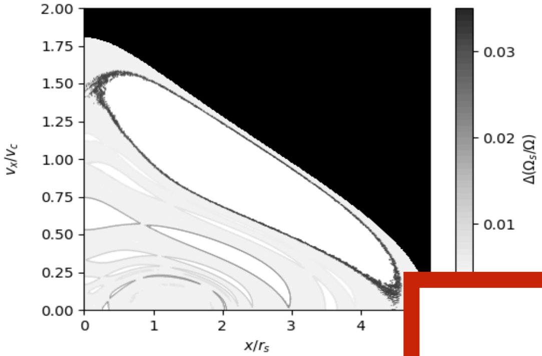

Morphology = cheap potential

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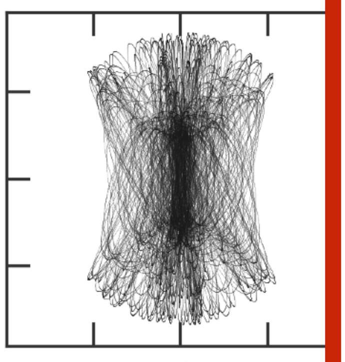

Let's <u>observe</u> the Poincaré Map of the Milky Way!

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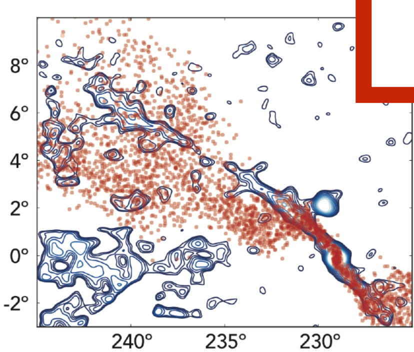

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