Killing Satellites with Resonances: The Dynamics of Passive Debris Removal

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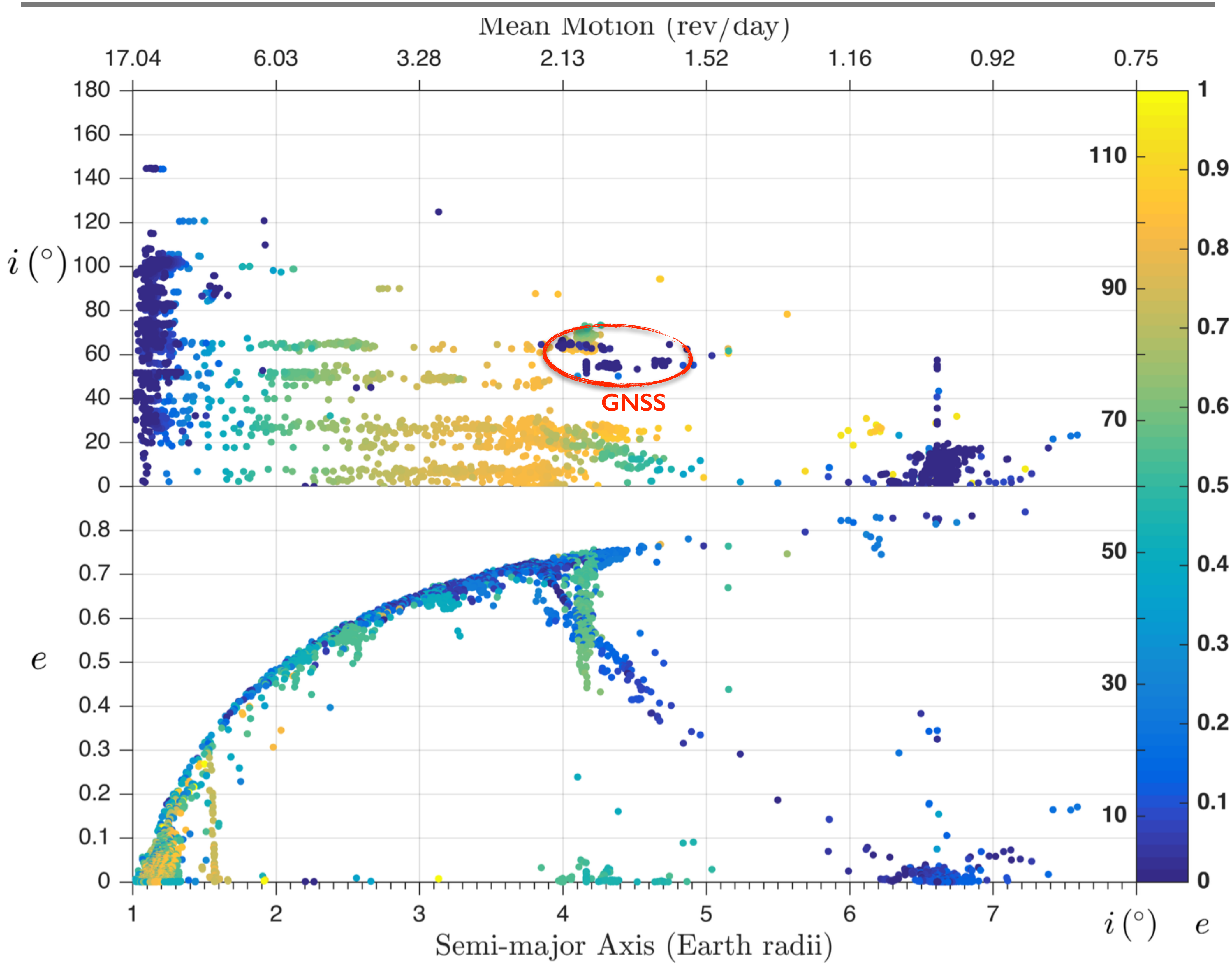
Orbiting Debris:
A Space Environment Problem

"Space operations should comply with a general rule of the National Park Service: **What you take in, you must take out.**"

Joseph P. Loftus, Jr./NASA Johnson Space Center

The Cataloged Space Debris (GNSS)



NORAD RESIDENT SPACE OBJECT CATALOG (www.space-track.org | ASSESSED 26 OCT 2016)

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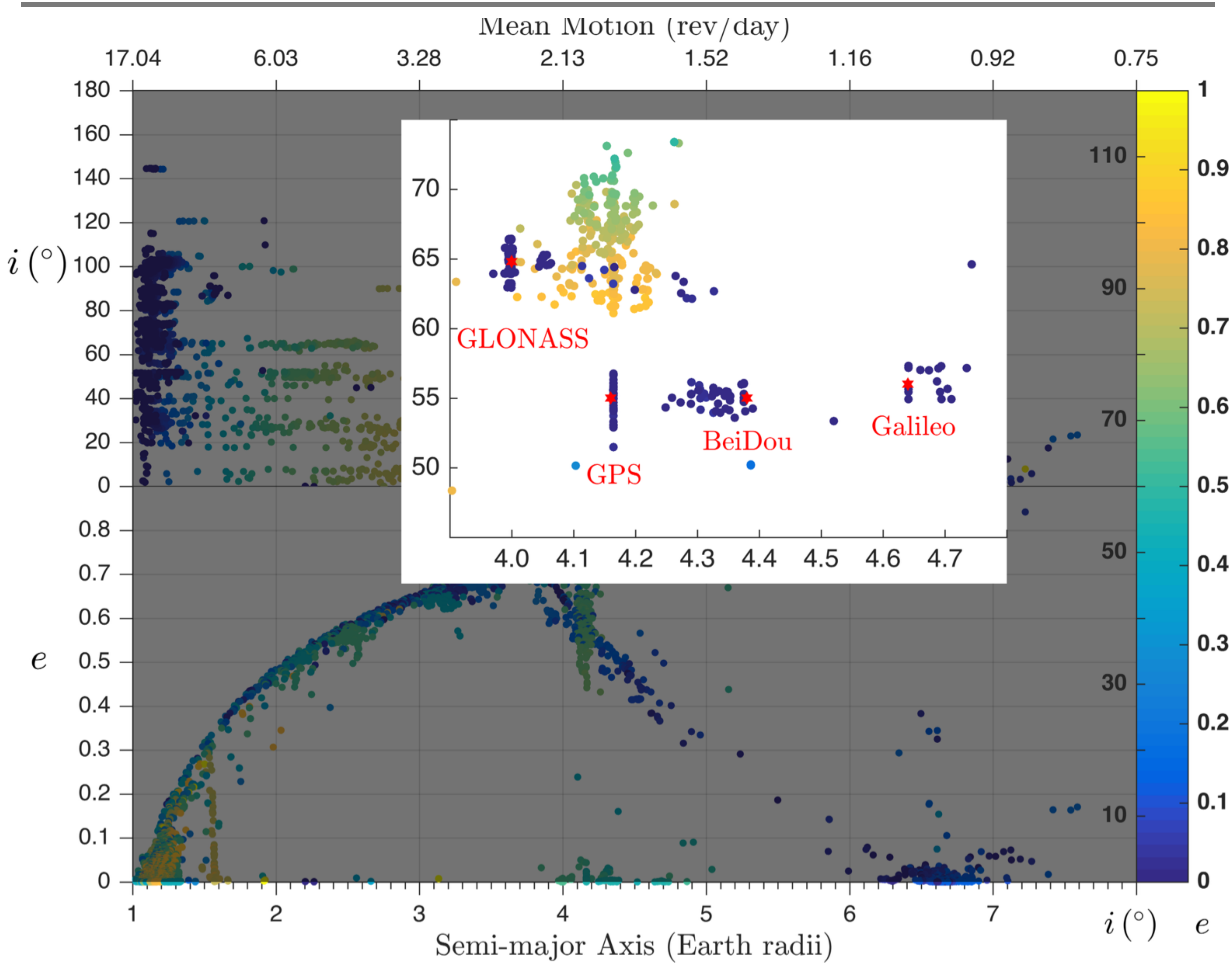

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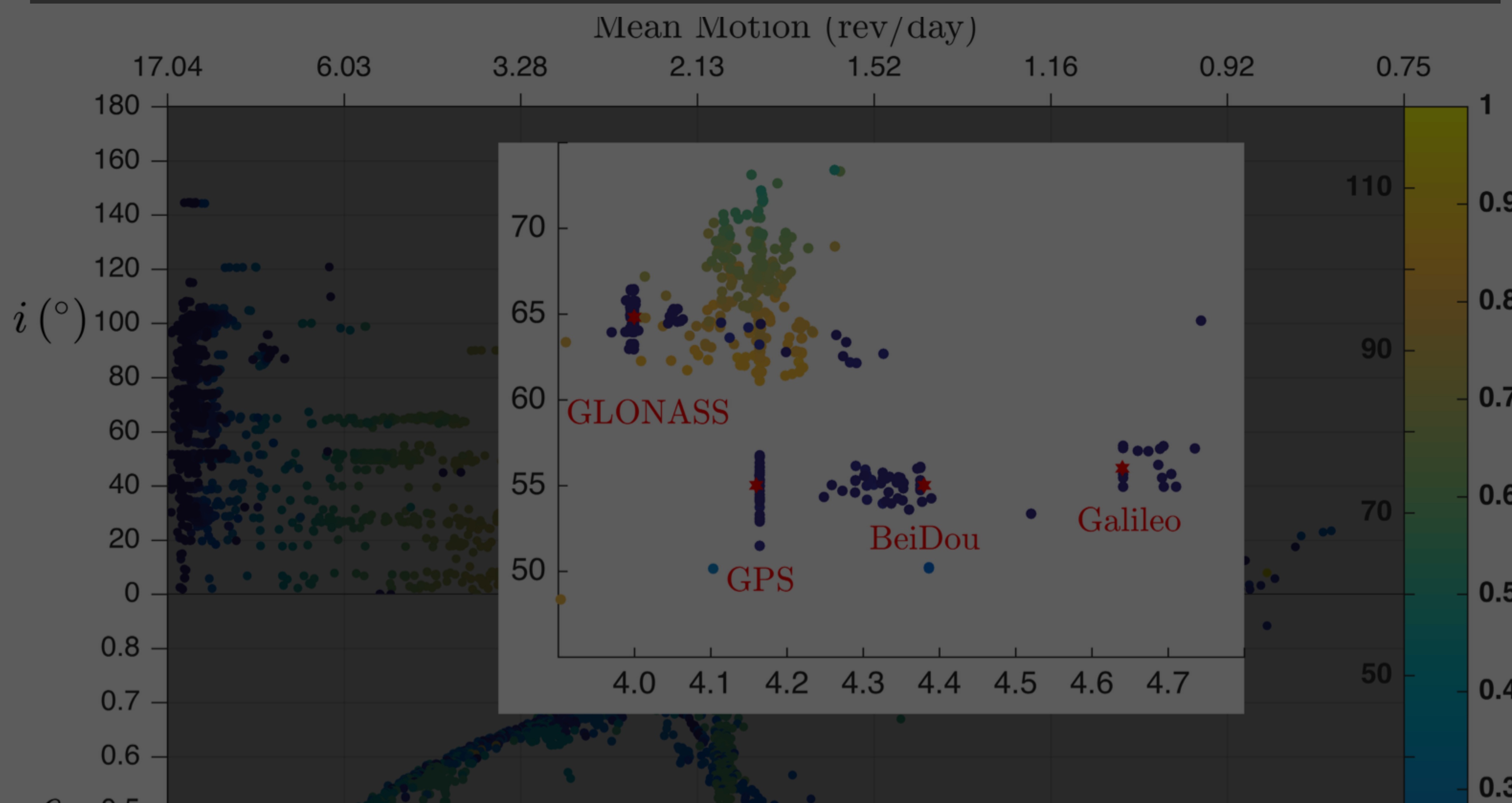
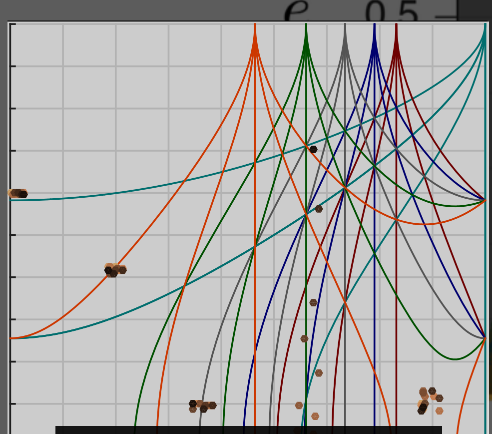
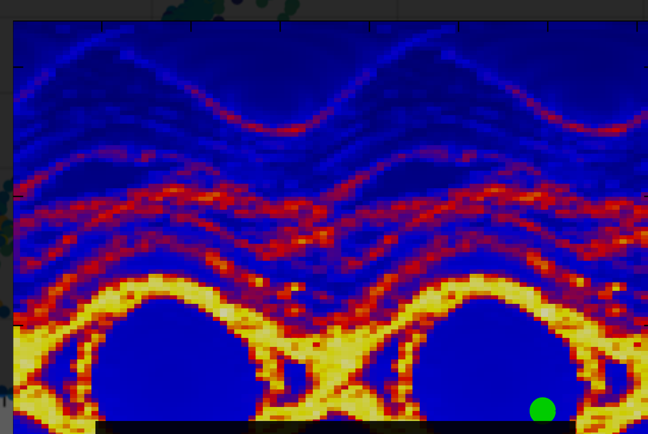
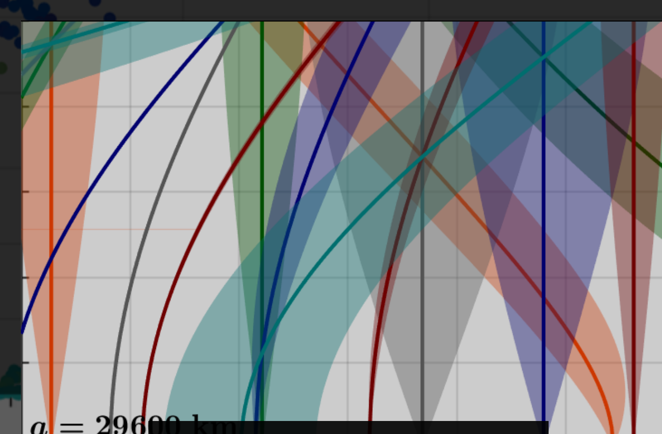




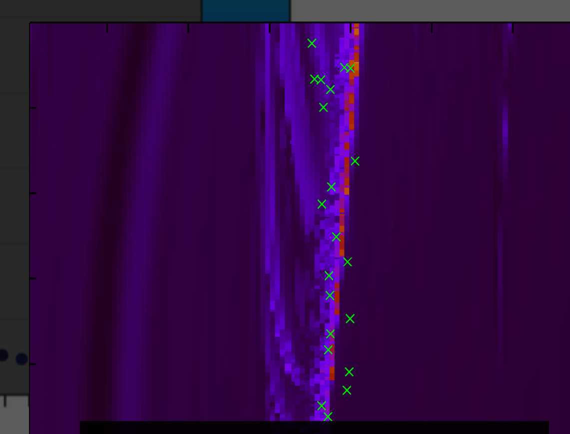
Lunisolar Resonances



FLI Dynamical Stability Maps

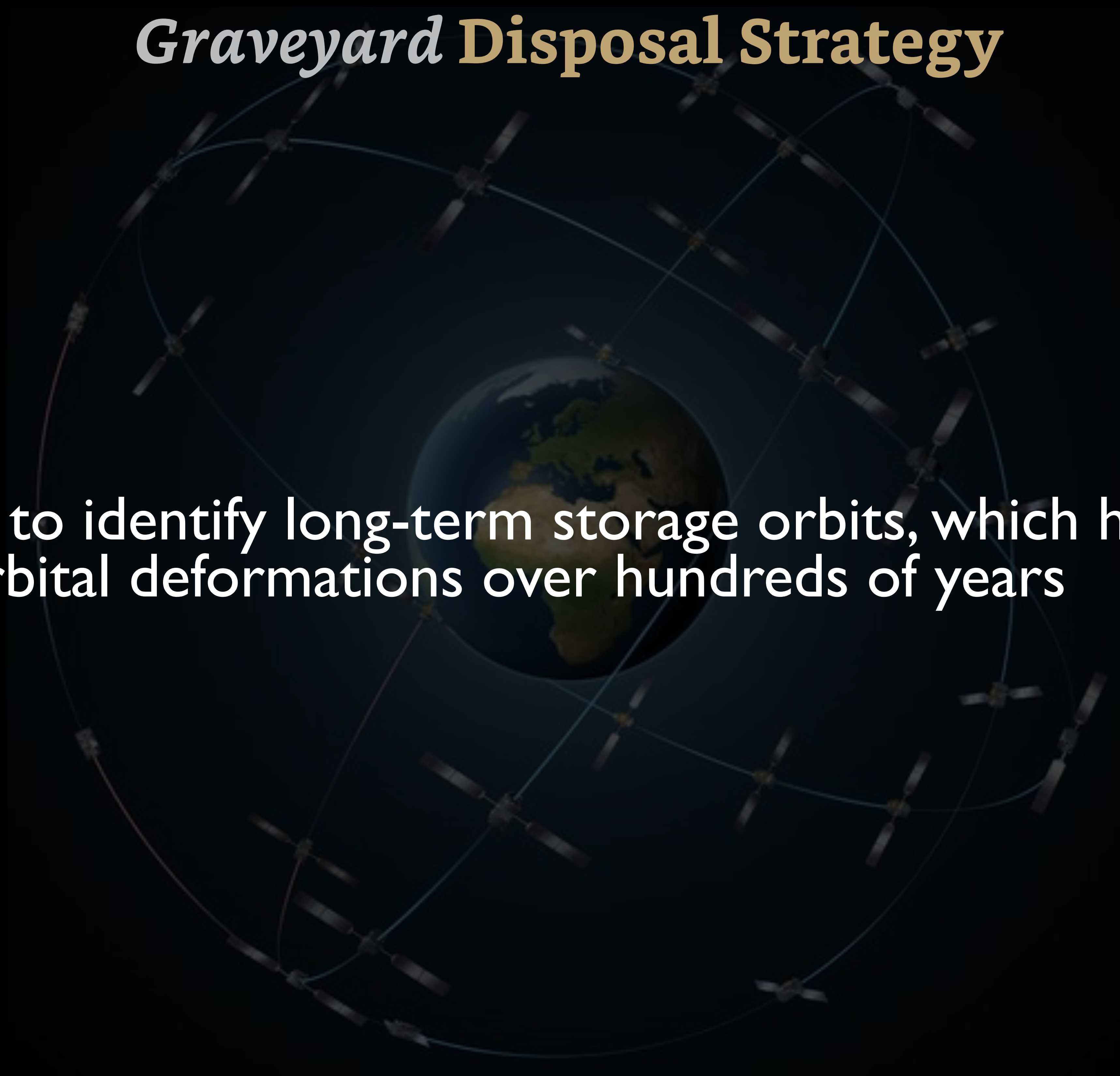


Chirikov Criterion



Diffusion and Transport

Galileo Case Study: *Graveyard* Disposal Strategy



- Seeking to identify long-term storage orbits, which have only small orbital deformations over hundreds of years

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Graveyard Disposal Strategy

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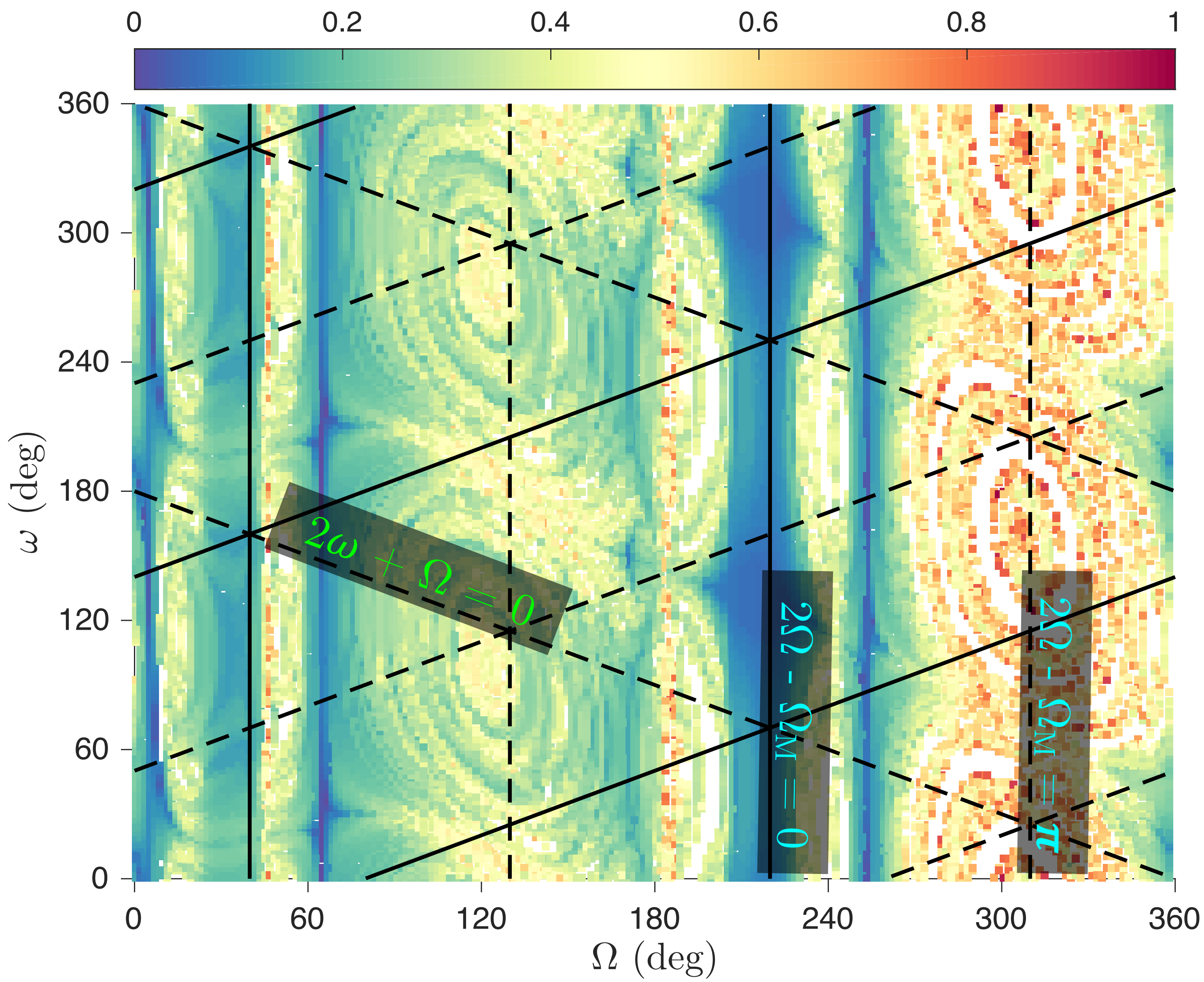
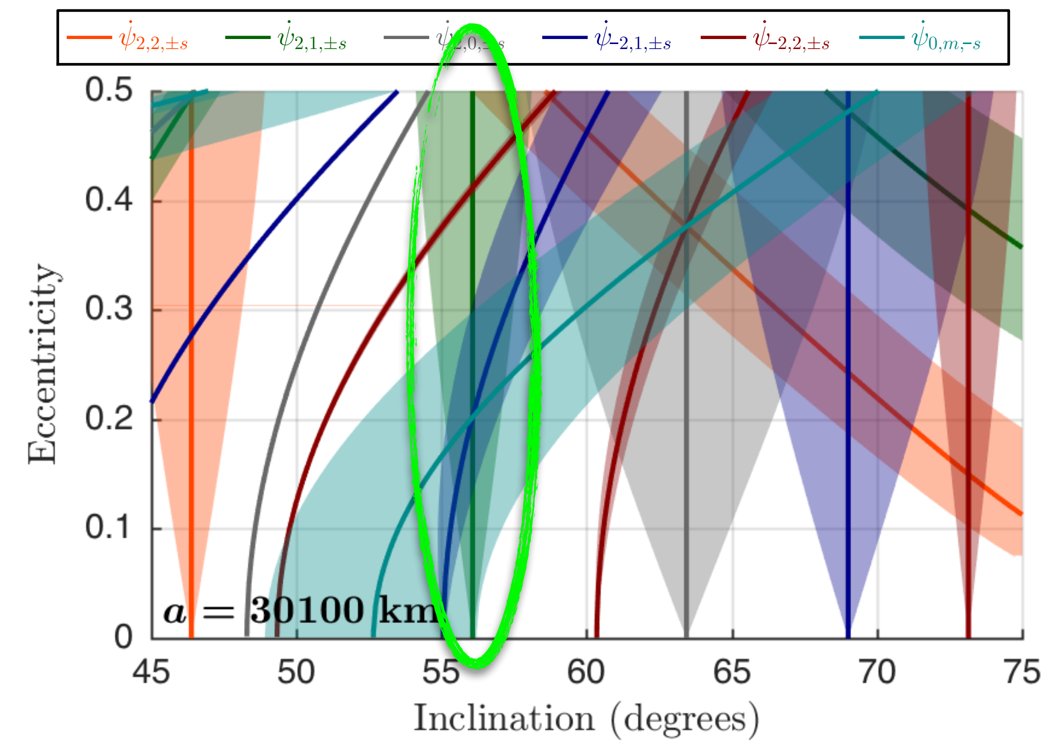
Geometry of Lunisolar Resonances near Galileo

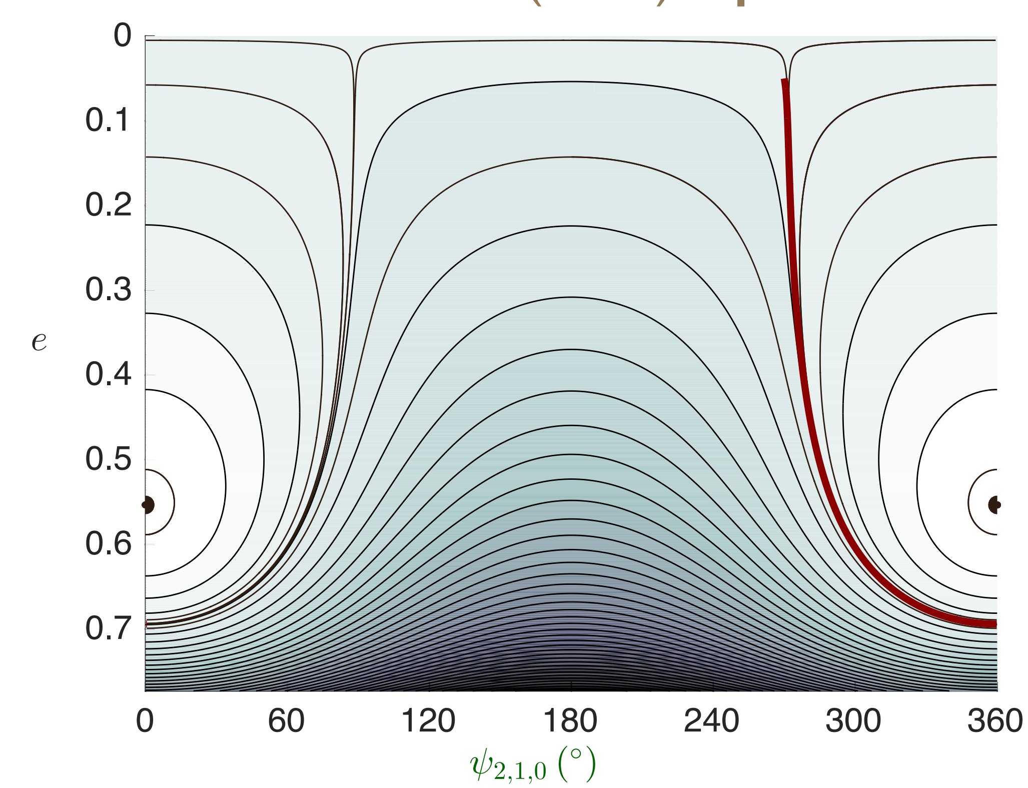
Graveyard Orbit

$(a = 30,150 \text{ km}, e = 0.001, i = 56°)$





Phase Portrait (2,1,0) **Apsidal** Res.



- Requires fundamental studies of the circum-terrestrial phase space where satellites reside

ROSENGREN, DAQUIN, TSIGANIS ET AL., MNRAS (2017)

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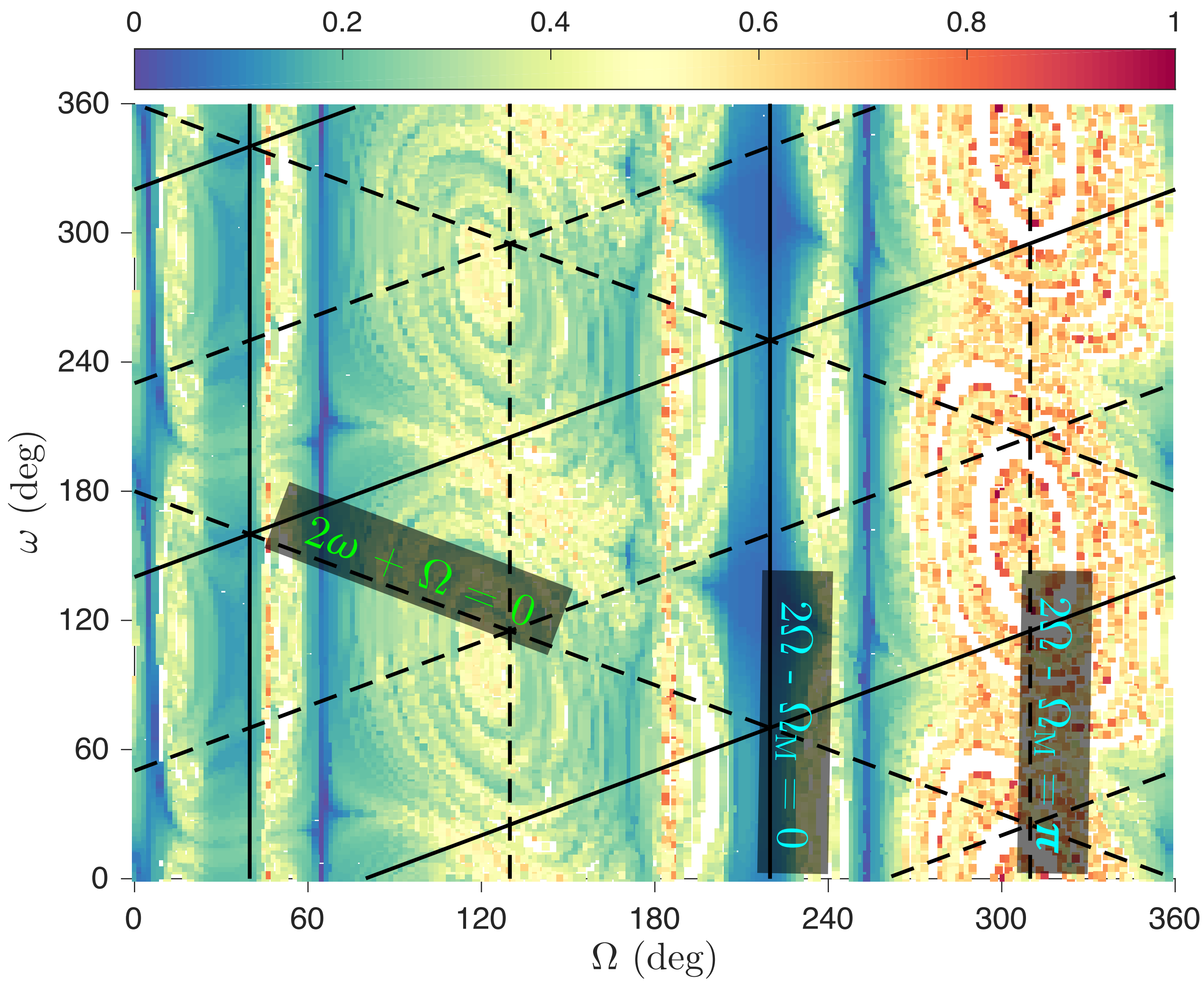
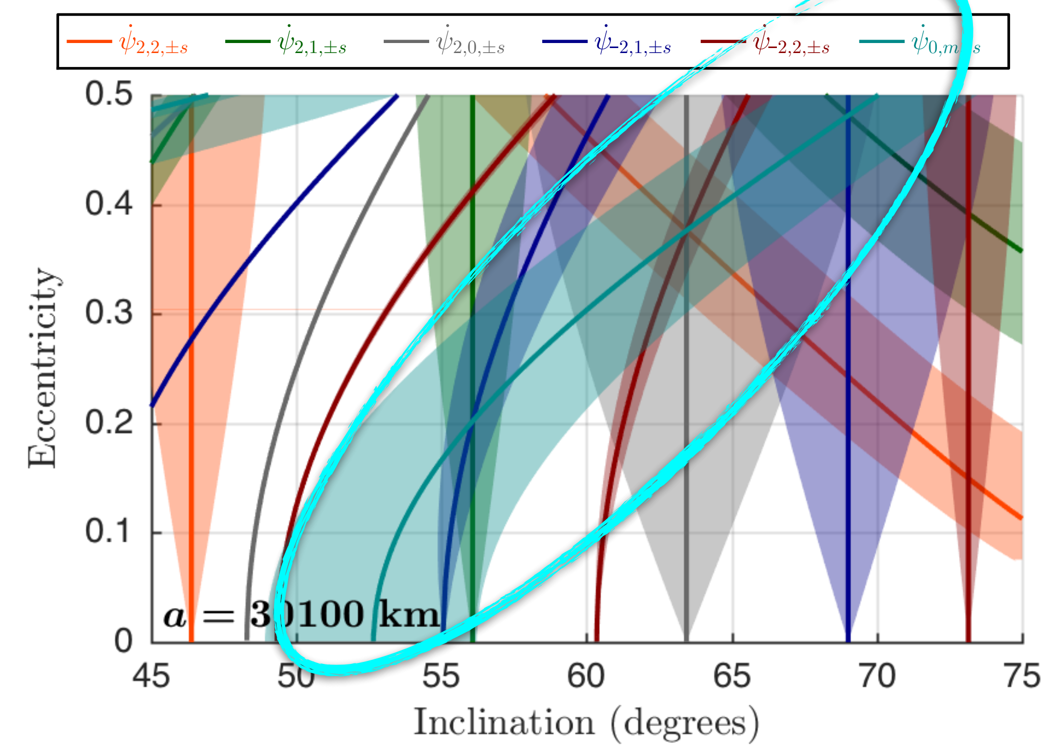
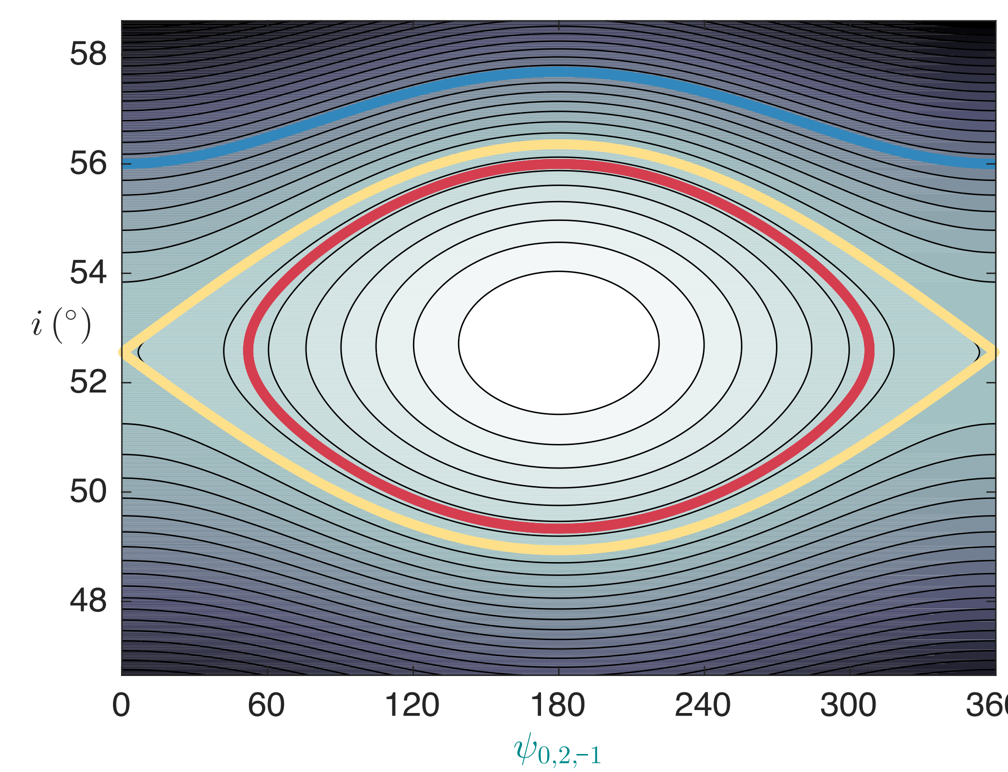




Phase Portrait (0,2,-1) **Nodal** Res.



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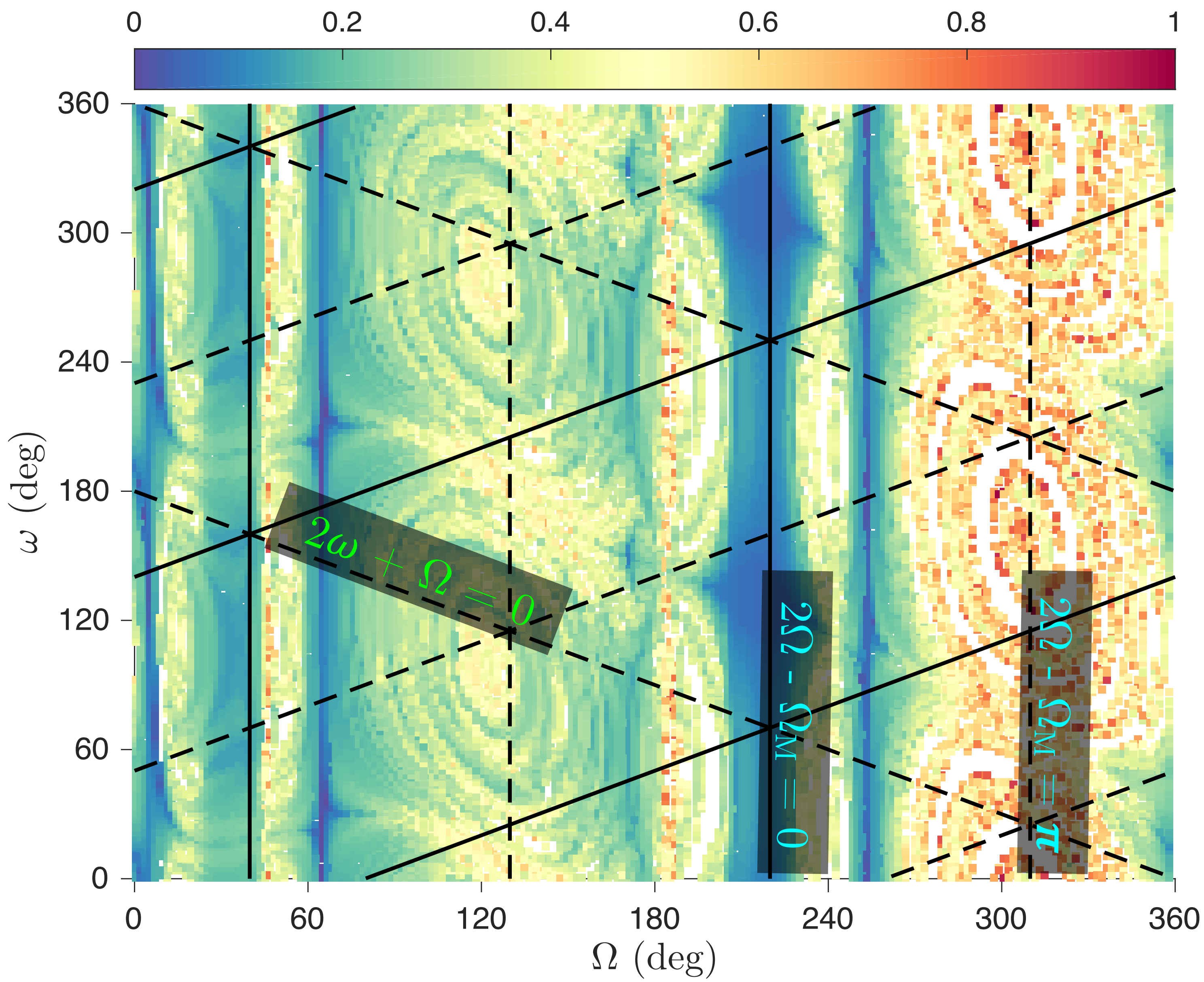

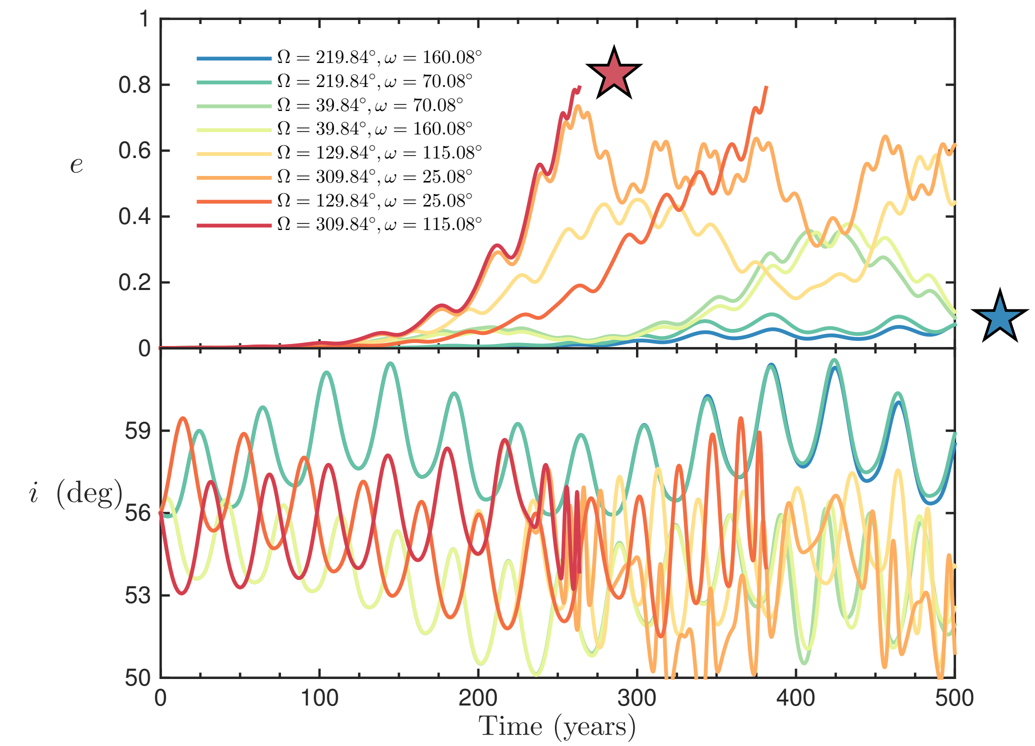

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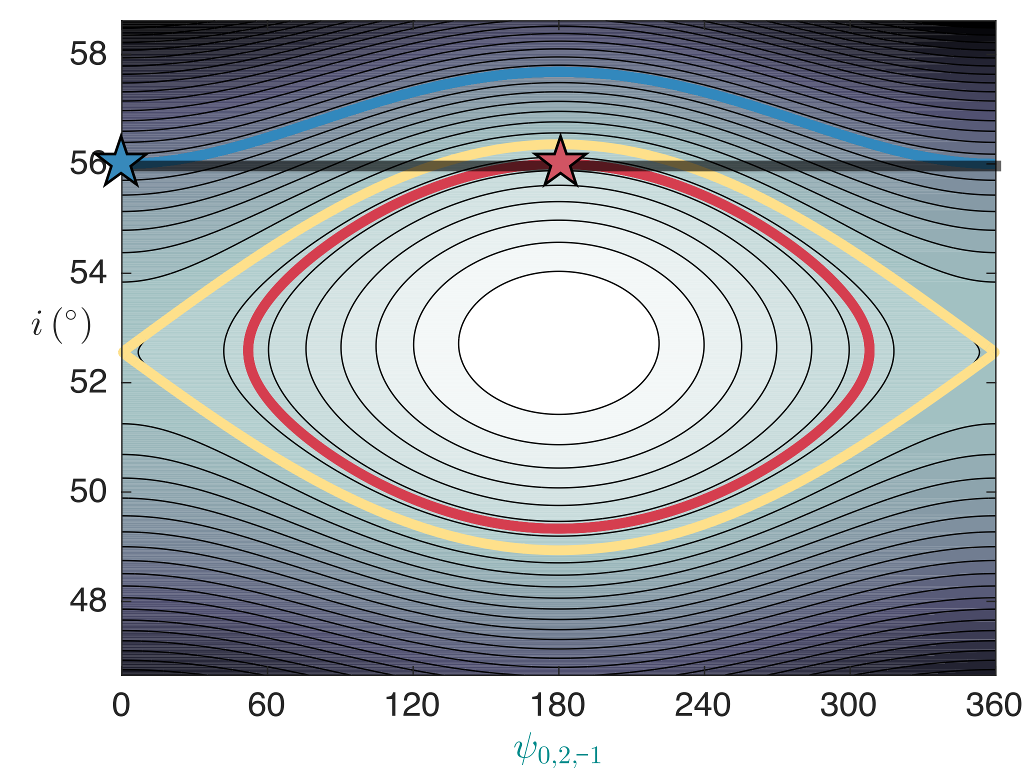

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Rosengren, Daquin, Tsiganis et al., MNRAS (2017)

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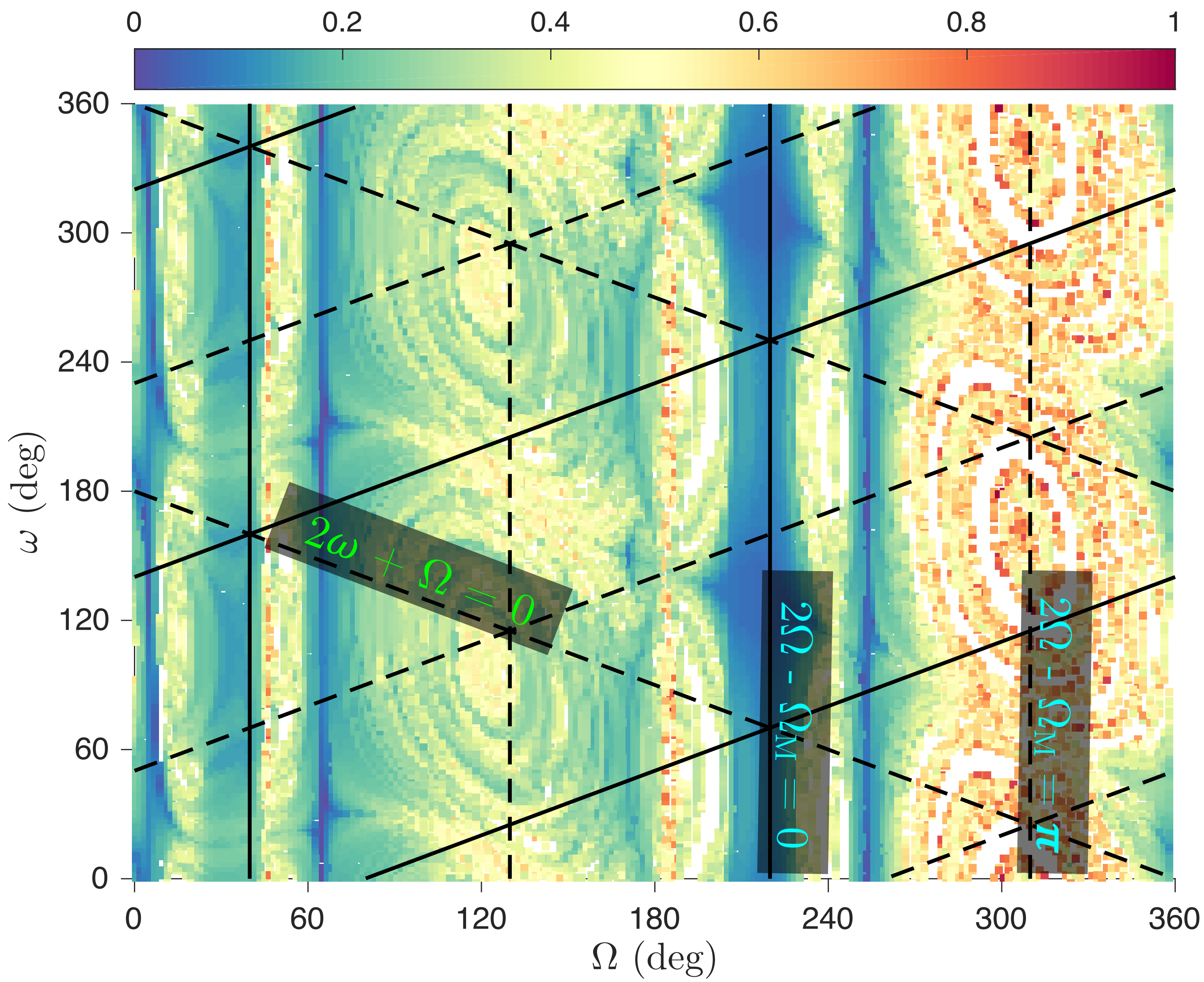

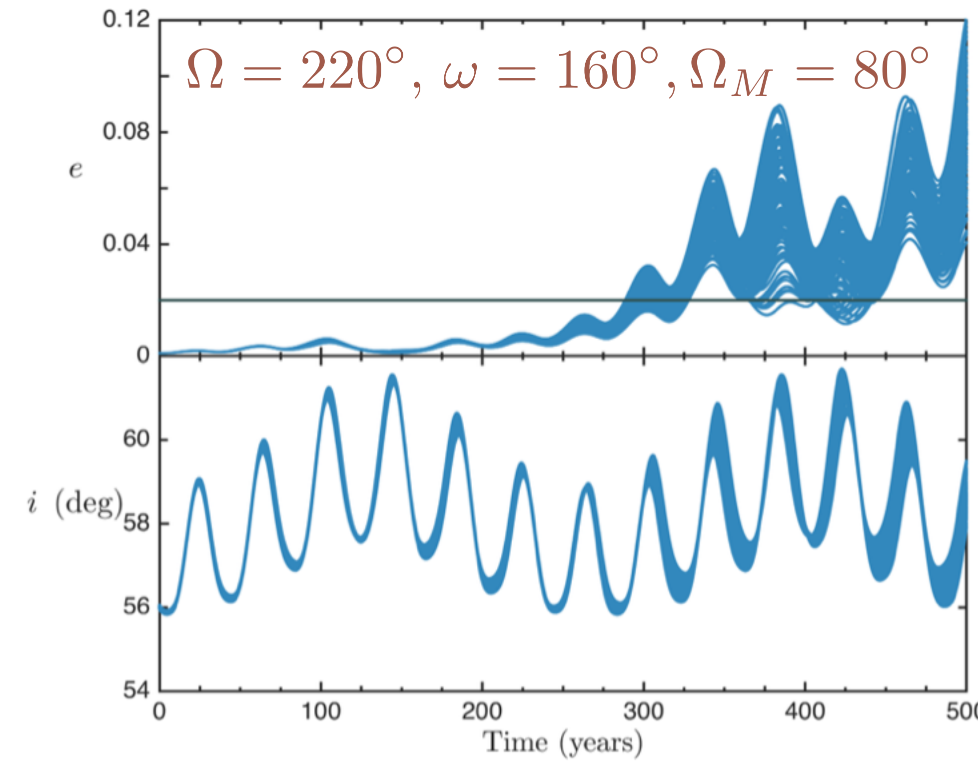

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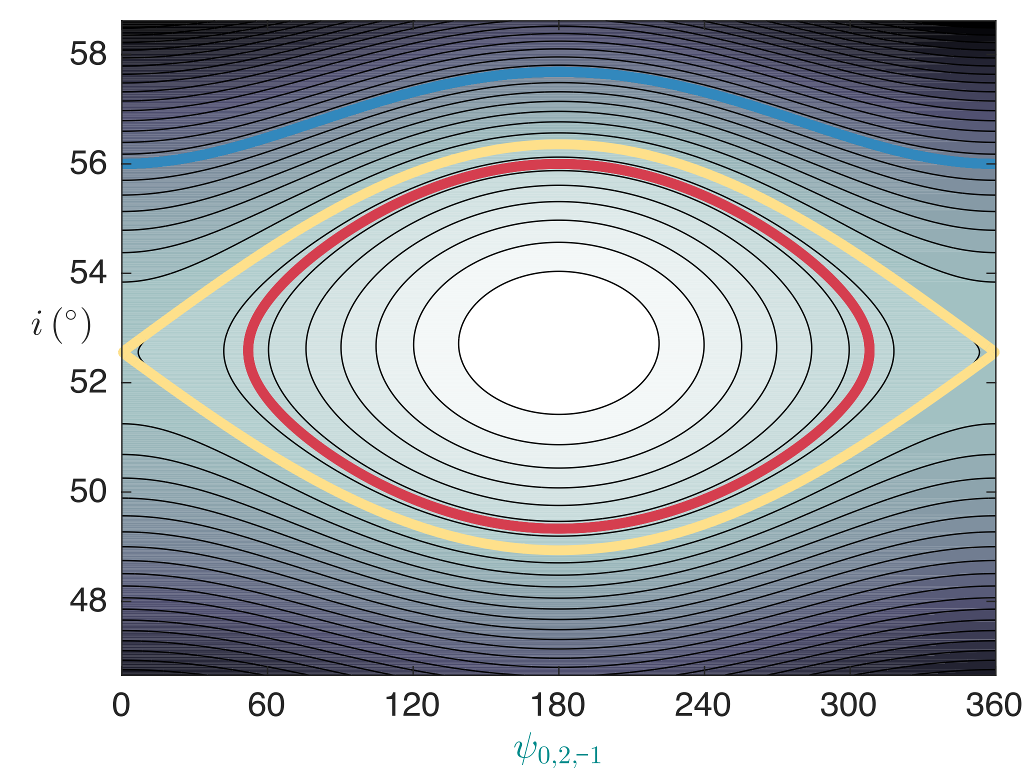

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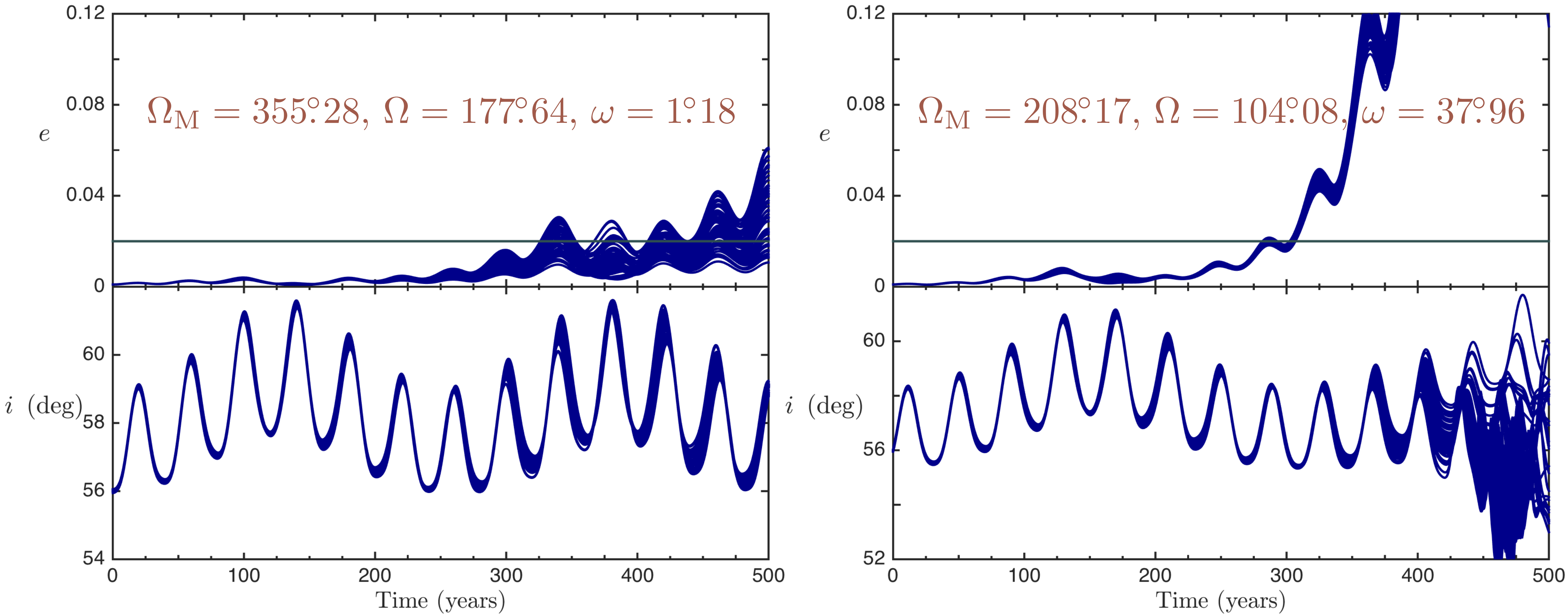
ROSENGREN, DAQUIN, TSIGANIS ET AL., MNRAS (2017)

The Χαλαρά (Chalará) Disposal Strategy

Graveyard Orbit

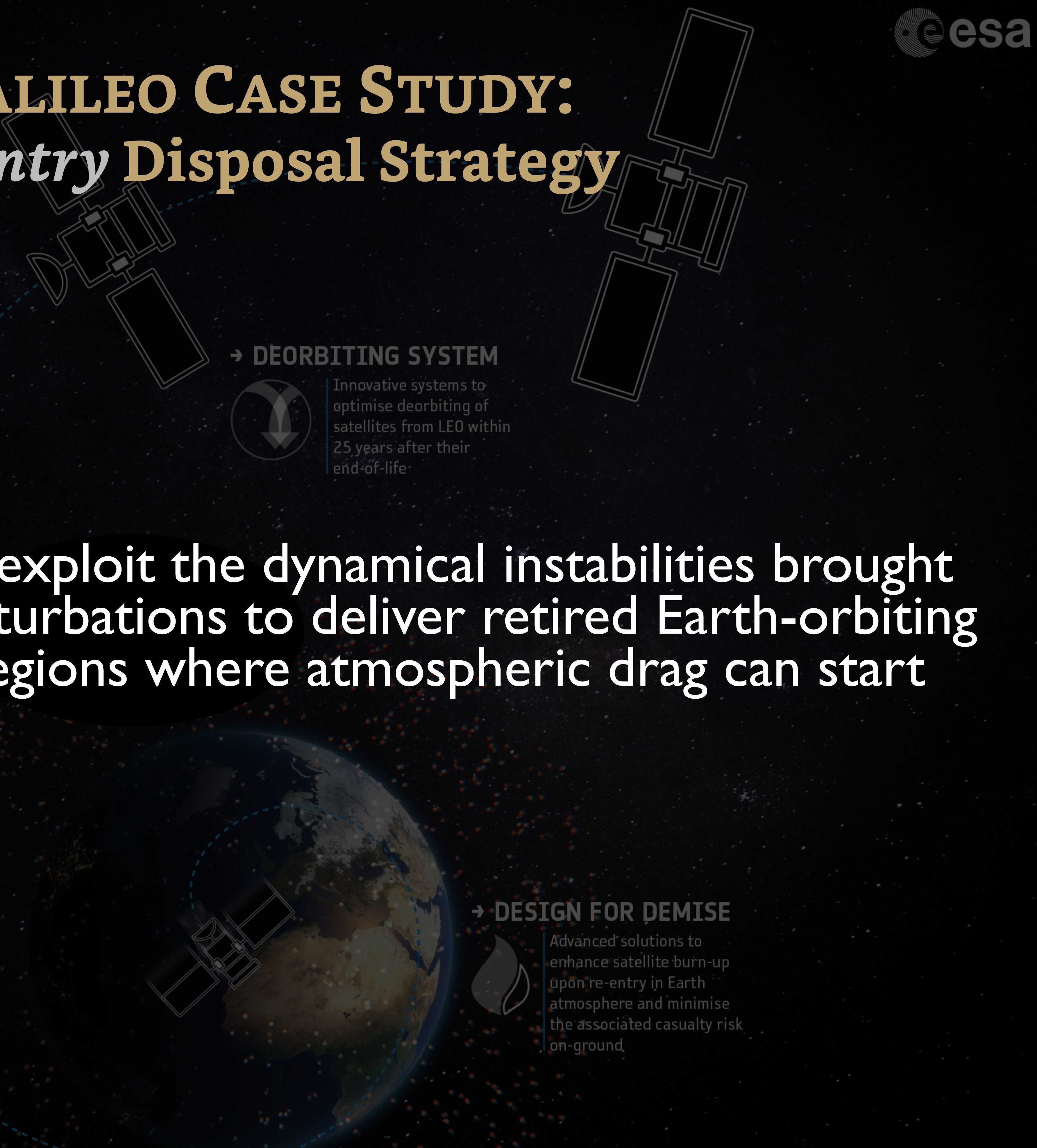
Epoch: 12 September 2016 $(a = 30,150 \text{ km}, e = 0.001, i = 56°)$ Epoch: 15 April 2015



- **Disposal epoch** can be **correlated** with an initial **lunar node**
- Satellite's node naturally precesses due to Earth oblateness perturbations
- Just wait (**Chalará**) for the appropriate lunar-satellite nodal phasing

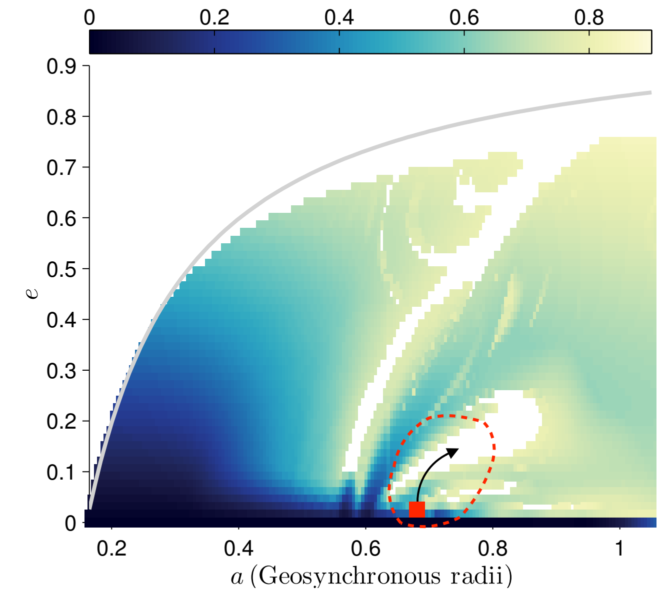
Galileo Case Study: *Re-entry* Disposal Strategy

- Seeking to cleverly exploit the dynamical instabilities brought on by resonant perturbations to deliver retired Earth-orbiting satellites into the regions where atmospheric drag can start their decay

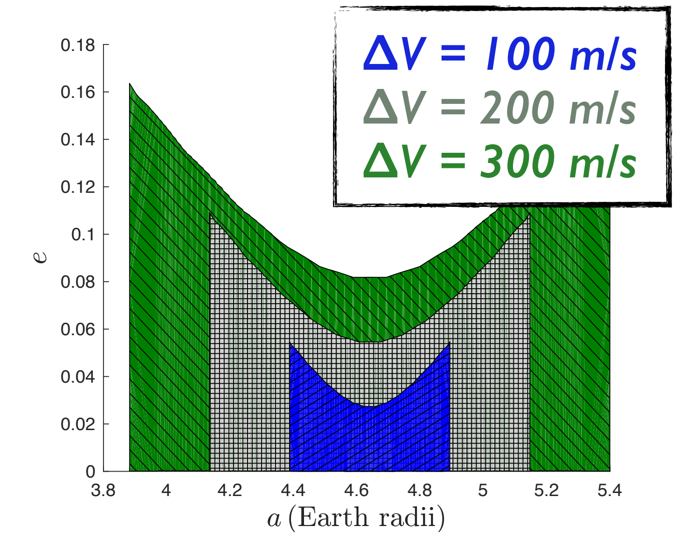


Reachability Domain from Guass's Eqns

- Cartographic stability maps must be linked to the appropriate disposal strategy
  - satellites can be steered into a short-lived resonance
  - passive systems deployed at the EOL to enhance SRP



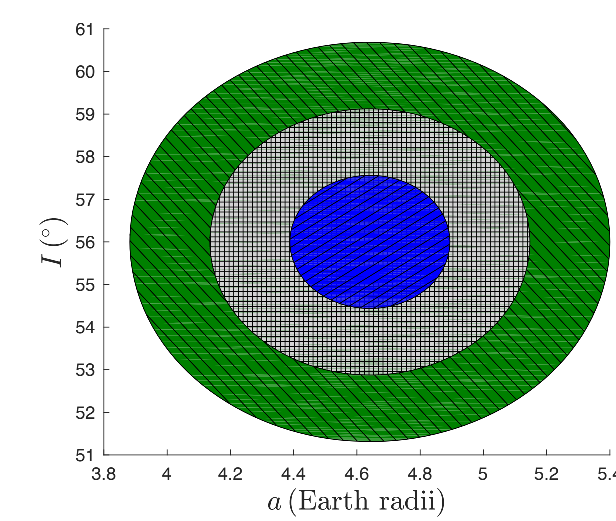
- **Reachability Analysis**: which orbits can be reached for a given fuel constraint (ΔV), starting from some initial operational orbit?
  - for given operational orbit and single impulsive ΔV, we can determine the boundary of the achievable phase space from Gauss's equations



$$\Delta a = \frac{2}{n\sqrt{1-e^2}}\left(e\sin f\Delta v_r + (1+e\cos f)\Delta v_t\right),$$

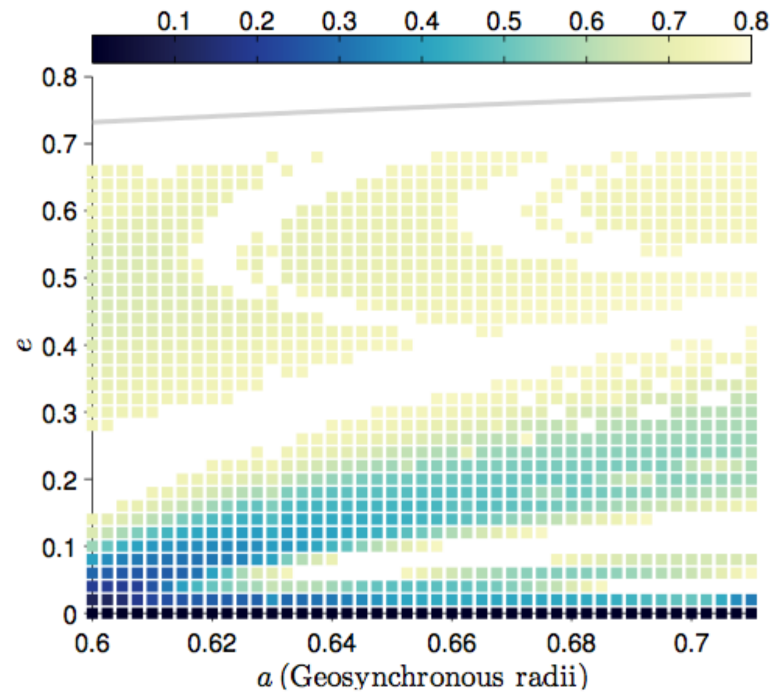
$$\Delta e = \frac{H}{\mu}\left[\sin f\Delta v_r + \left(\frac{e+\cos f}{1+e\cos f}+\cos f\right)\Delta v_t\right],$$

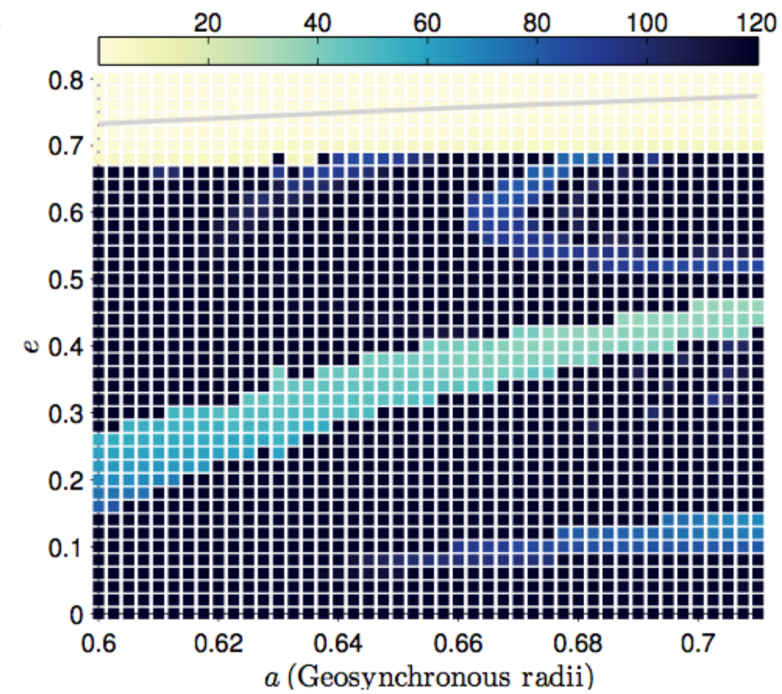
$$\Delta I = \frac{H}{\mu}\frac{\cos(\omega+f)}{1+e\cos f}\Delta v_z$$

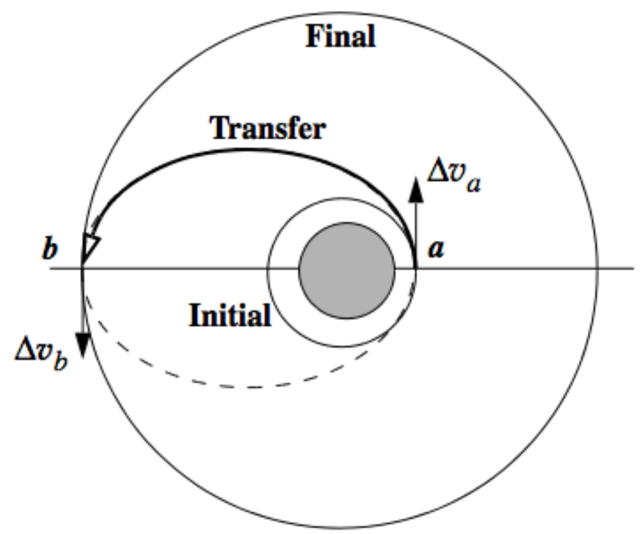


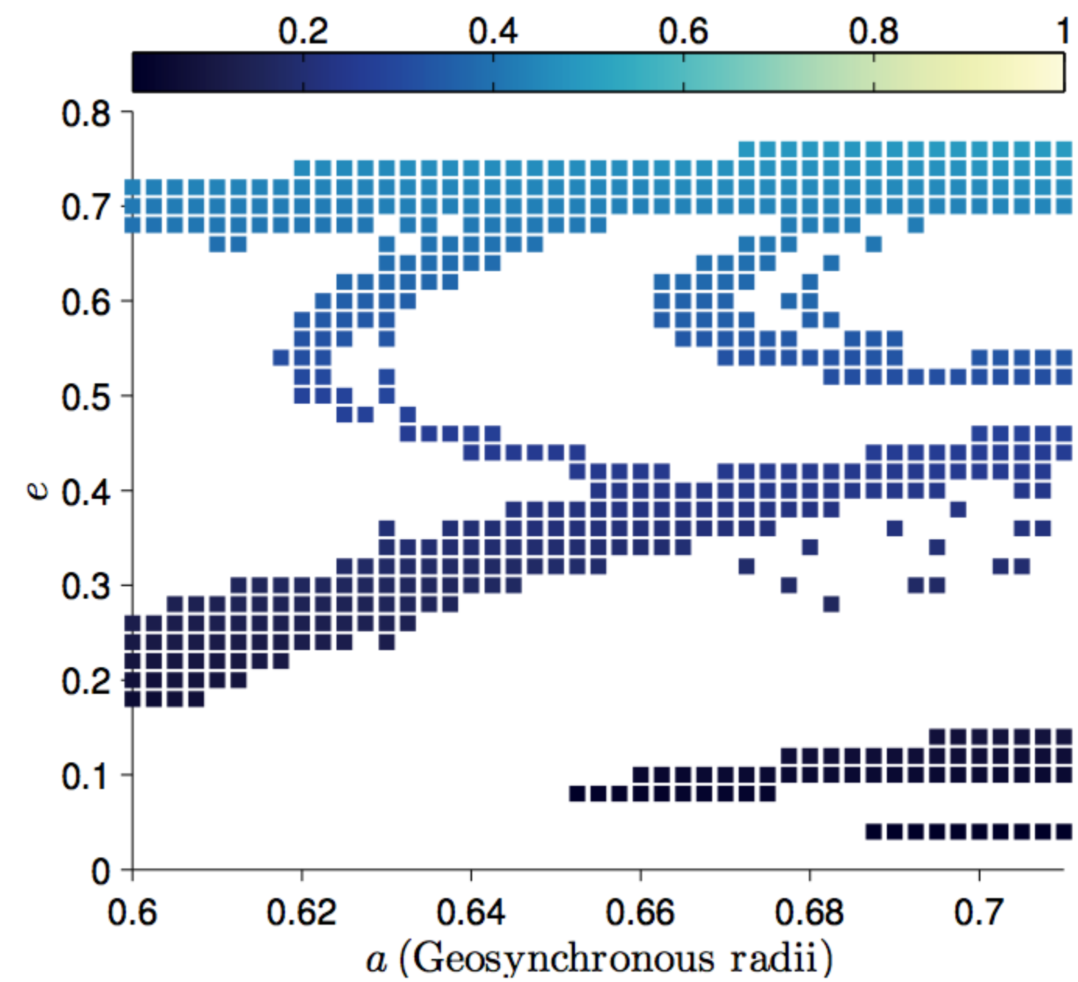
ΔV Transfer Maps for Coplanar, Coaxial Elliptical Orbits

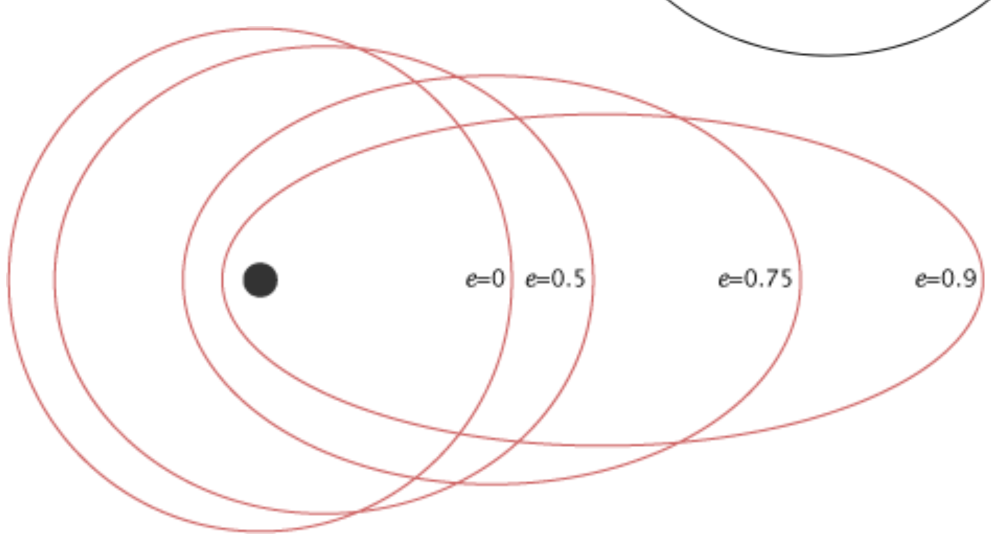
- For GNSS region, structures do not change for small ΔI
  - off-plane re-entry solutions require more fuel
- Restrict attention to disposal solutions on same 2D (a, e) dynamical map











Typical Result for Galileo

Epoch	A2M(m^2/kg)	a1(km)	e1	inc(deg)	capom(deg)	omega(deg)
cond18	0.015	29601.31	0.0001	56.00	282.83	196.50

REENTRY tps

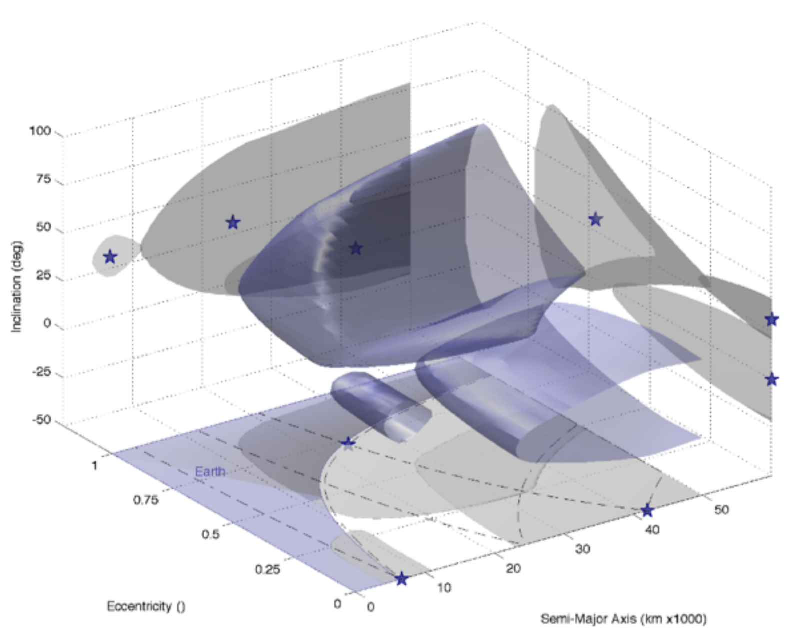
method & {optimal DV}/{min lifetime}		ntp	id	a2(km)	e2	DV(m/sec)	DT(h)	t_life(yr)
single burn, dom=0	optimal	283	27903	28987.87	0.0400	20.6	0.00	119.19
single burn, dom=0	lifemin	283	28149	29514.92	0.4600	276.2	0.00	36.13
single burn, dom=pi	optimal	258	31953	28987.87	0.0400	20.7	0.00	119.14
single burn, dom=pi	lifemin	258	32243	29620.33	0.4400	263.9	0.00	38.13
hohmann, dom=0	optimal	11	27229	27406.71	0.0600	147.3	6.37	113.62
hohmann, dom=0	lifemin	11	27230	27406.71	0.0800	150.0	6.27	101.05
hohmann, dom=pi	optimal	11	31279	27406.71	0.0600	147.3	6.37	113.73
hohmann, dom=pi	lifemin	11	31280	27406.71	0.0800	150.0	7.04	101.05
hohmann intersection, dom=0	optimal	62	28308	29936.56	0.0400	72.7	7.31	116.76
hohmann intersection, dom=0	lifemin	62	28313	29936.56	0.1400	252.5	7.86	68.10
hohmann intersection, dom=pi	optimal	61	32358	29936.56	0.0400	73.1	7.32	116.75
hohmann intersection, dom=pi	lifemin	61	32363	29936.56	0.1400	252.9	7.86	68.06

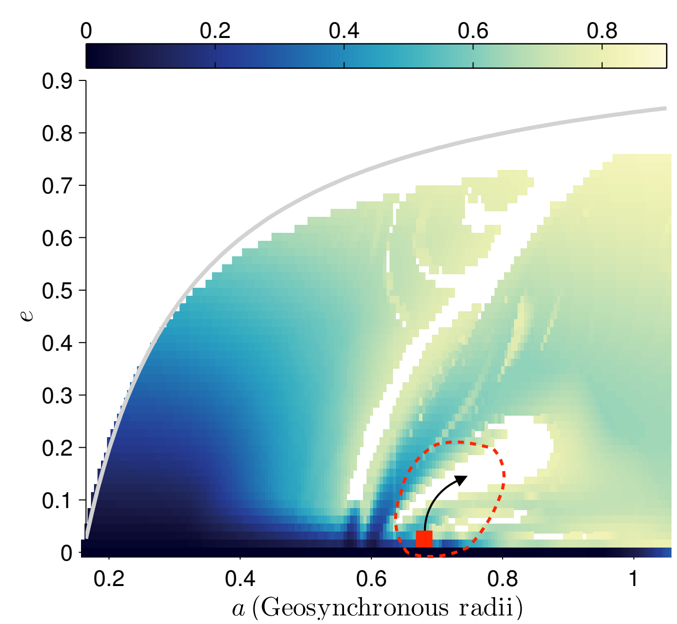
GRAVEYARDS tps

method & {optimal DV}		ntp	id	a2(km)	e2	DV(m/sec)	DT(h)	t_life(yr)
single burn, dom=0	optimal	0	NO SOLUTION					
single burn, dom=pi	optimal	0	NO SOLUTION					
hohmann, dom=0	optimal	7	28126	29514.92	0.0000	5.4	7.02	120.00
hohmann, dom=pi	optimal	7	32176	29514.92	0.0000	5.4	7.02	120.00
hohmann intersection, dom=0	optimal	0	NO SOLUTION					
hohmann intersection, dom=pi	optimal	0	NO SOLUTION					

Conclusions

- **Cartographic Maps**: complex interactions among different dynamical phenomena are depicted, identifying regions where the motion is stable and zones where secularly unstable behavior can emerge
- For the **GNSS** region, **intricate escape hatches** are carved by lunisolar secular resonances and **widened by SRP** (depends on orientation angles)
- Designed maneuvers needed to reach the optimal disposal orbit for each initial operational orbits
  - combined reachability analysis with dynamical maps
  - Δe analysis also used for targeting appropriate graveyards
- For re-entry trajectories, the **permanence** in LEO region complies with 25-year decay rule





"In contrast to a widespread cliché, the satellite problems still require the research on the level more fundamental than just tracing the microscopic influence of yet another tesseral harmonic."

SŁAWOMIR BREITER, 2001

Questions?

Ερωτήσεις;

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