A Refined Measurement of Saturn's Gravity Environment

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with contributions from

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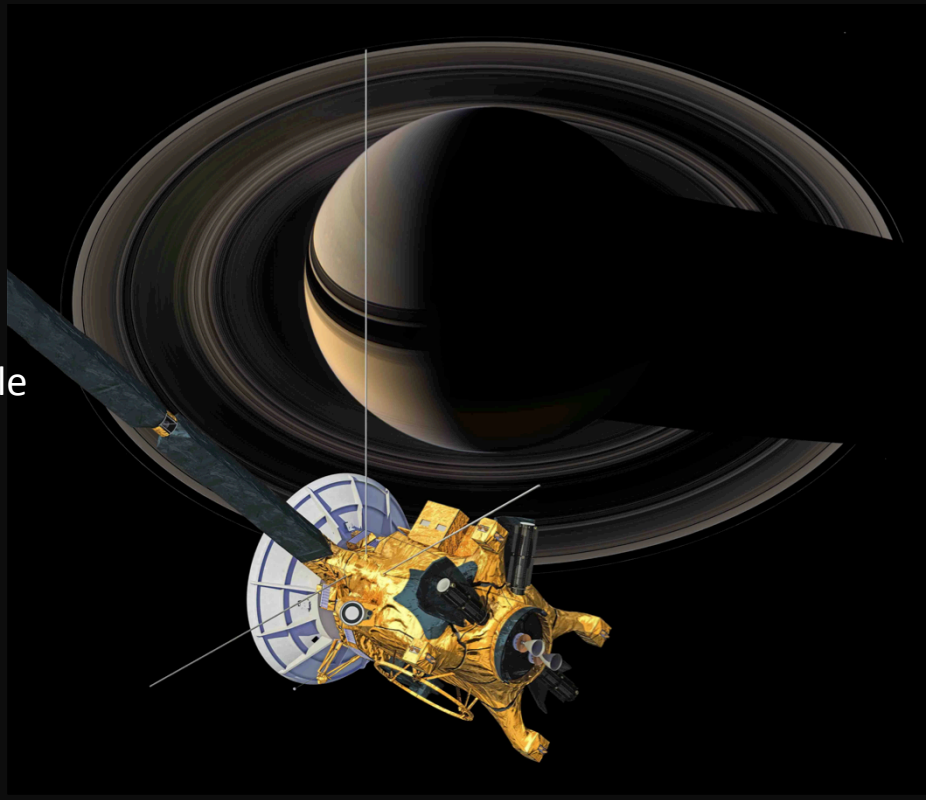

WHAT WE EXPECTED BEFORE THE GF ORBITS

- An axially symmetric gravity field dominated by even zonal harmonics
- Even zonal harmonic coefficients scaling as $J_{2n} \approx q^n$ (q = (centrifugal acceleration at equator / gravity acceleration)
- Small odd zonal harmonics due to hemispherically asymmetric flows
- Good sensitivity to the k2 and k3 Love numbers (0.01, 0.1, respectively)
- Good determination of the ring mass, to 0.04 Mimas masses

- Constraints on the interior structure and mass of the core
- Depth of the winds
- Contribute an important missing piece in the debate on the age of the rings

WHAT WE FOUND AFTER THE GF ORBITS

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WHAT WE FOUND AFTER THE GF ORBITS: THE DARK SIDE

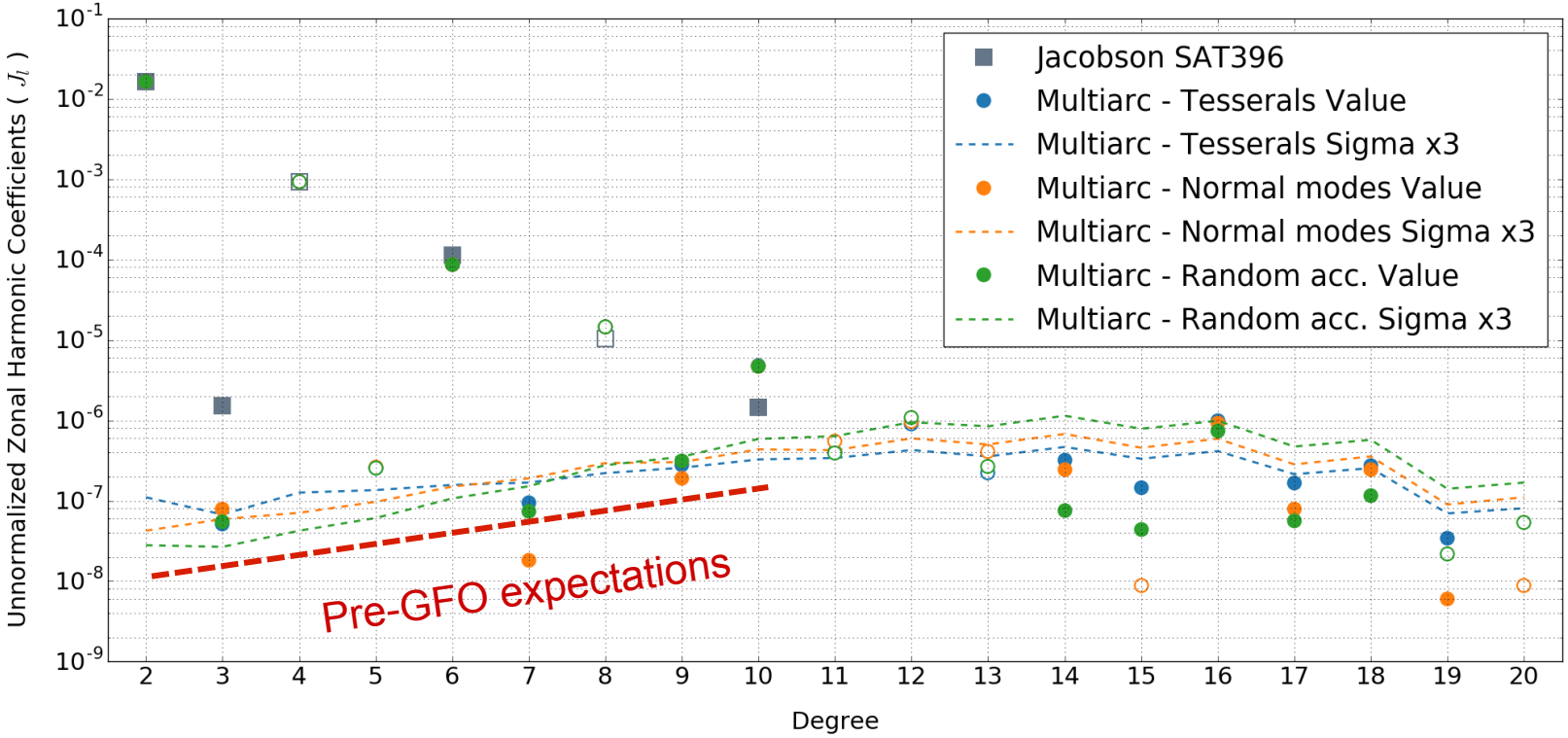
- A purely zonal field is inadequate to fit Cassini range rate data.
- Accelerations (tangential and radial) of unknown origin are acting on the spacecraft.
- Magnitude is about 5×10^{-7} m/s^2 .
- We need to augment the dynamical model by introducing additional parameters. We used:

- Stochastic accelerations (preferred)
- Normal modes
- Tesseral field (8x8 to 12x12 depending on the assumed rotation rate)

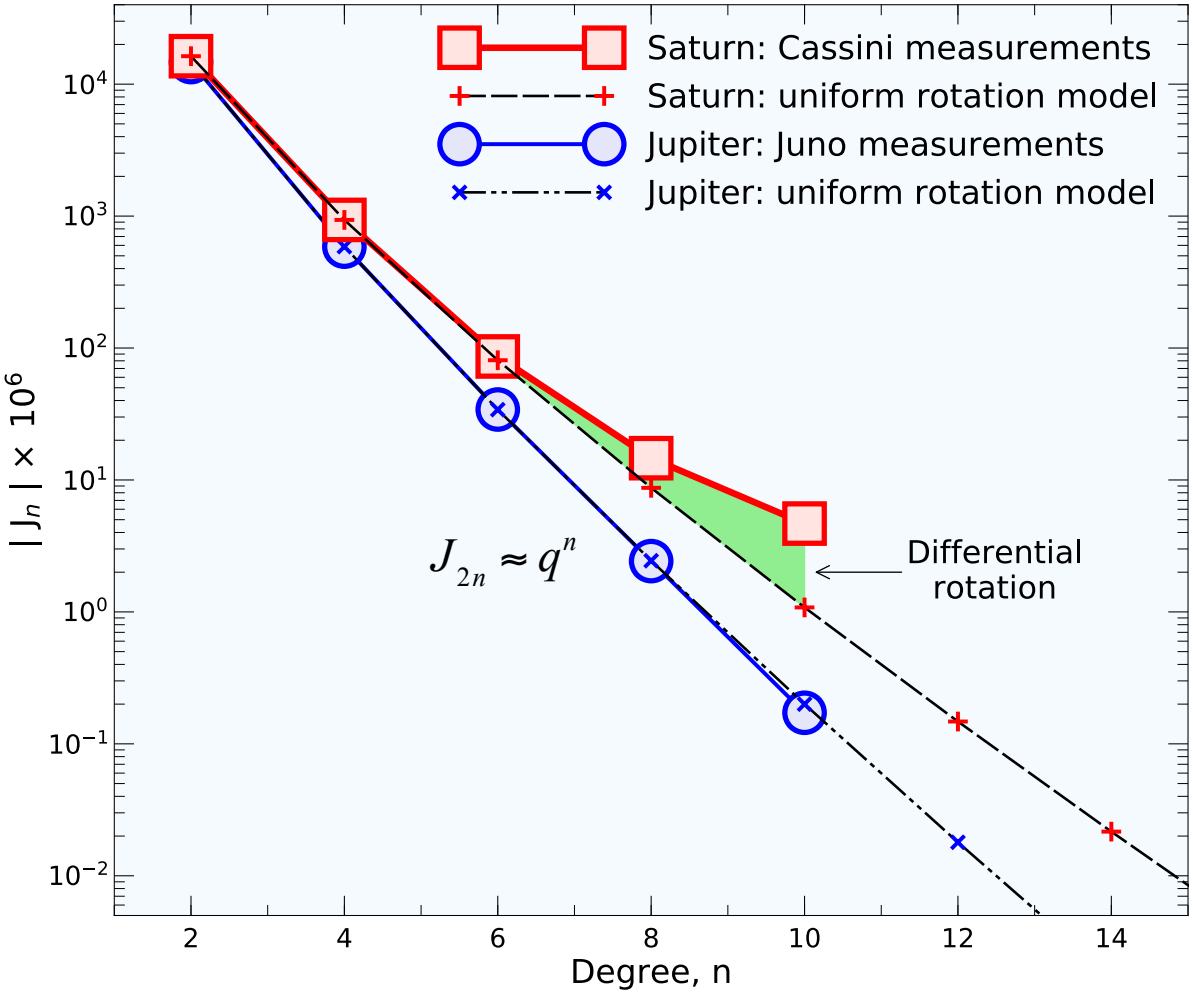
Goal: separate the static gravity field and the rings from the pollution of the unknown acceleration. This goal has been accomplished: all three models provide (statistically) the same answer.

ZONAL GRAVITY FIELD

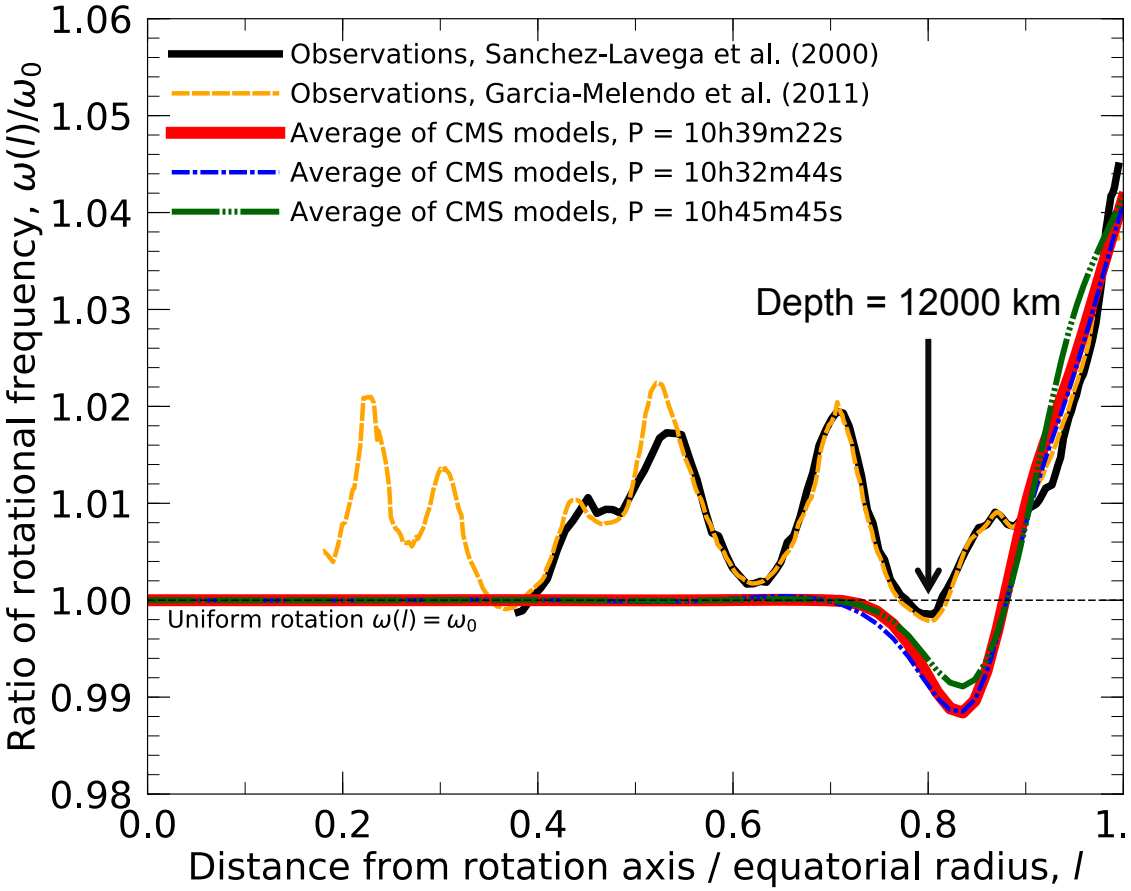
- Estimates of zonal harmonics are consistent for all models.
- Cassini can resolve even zonals up to J10. J10 value is much larger than expected (from solid body rotation). Clue for differential rotation with deep winds (depth ~1-2x10^4 km).
- J3 is smaller than previously estimated (< 10^{-7}) and positive, J5 < 0 (~2.5x10^{-7}), -J5 > J3.

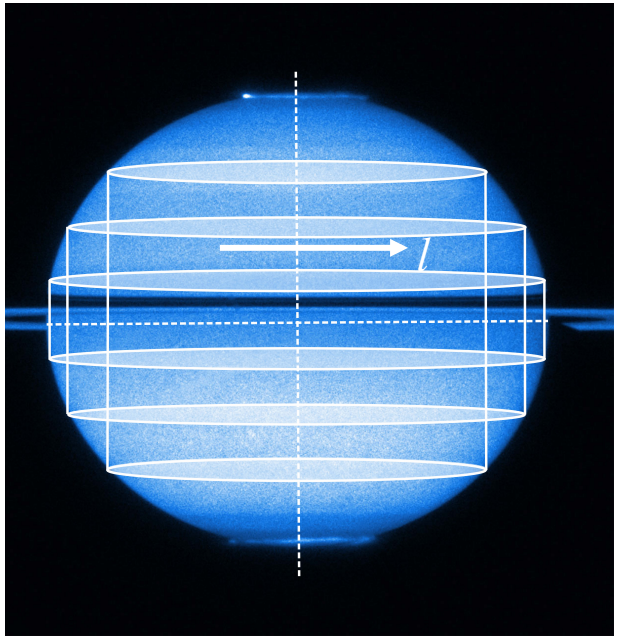


SATURN VS JUPITER



DIFFERENTIAL ROTATION PROFILE IN THE EQUATORIAL PLANE





Model developed by
B. Militzer, W. Hubbard, S. Wahl

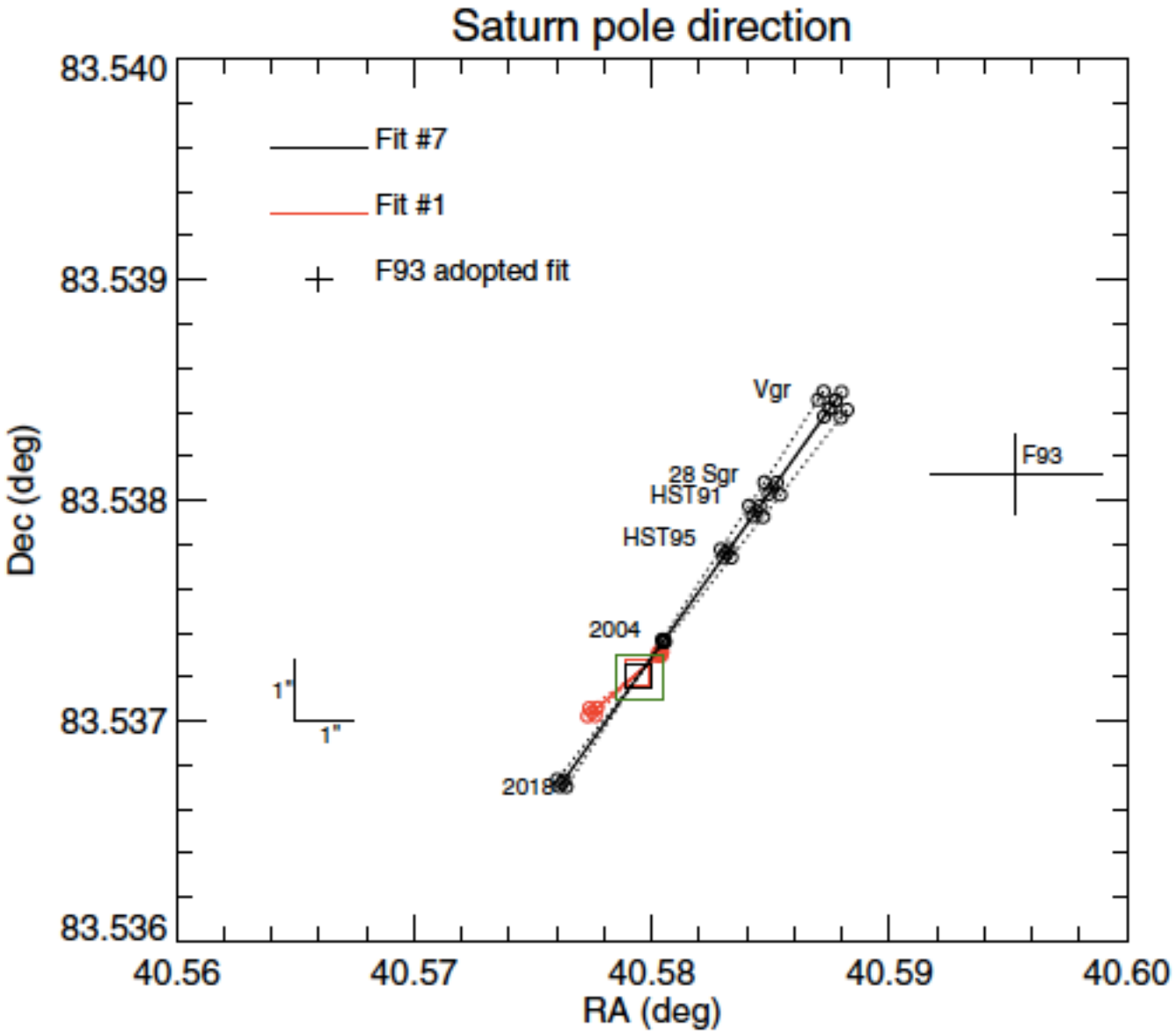
All CMS models end up with a core mass in the range 15-18 Earth masses

RING MASS

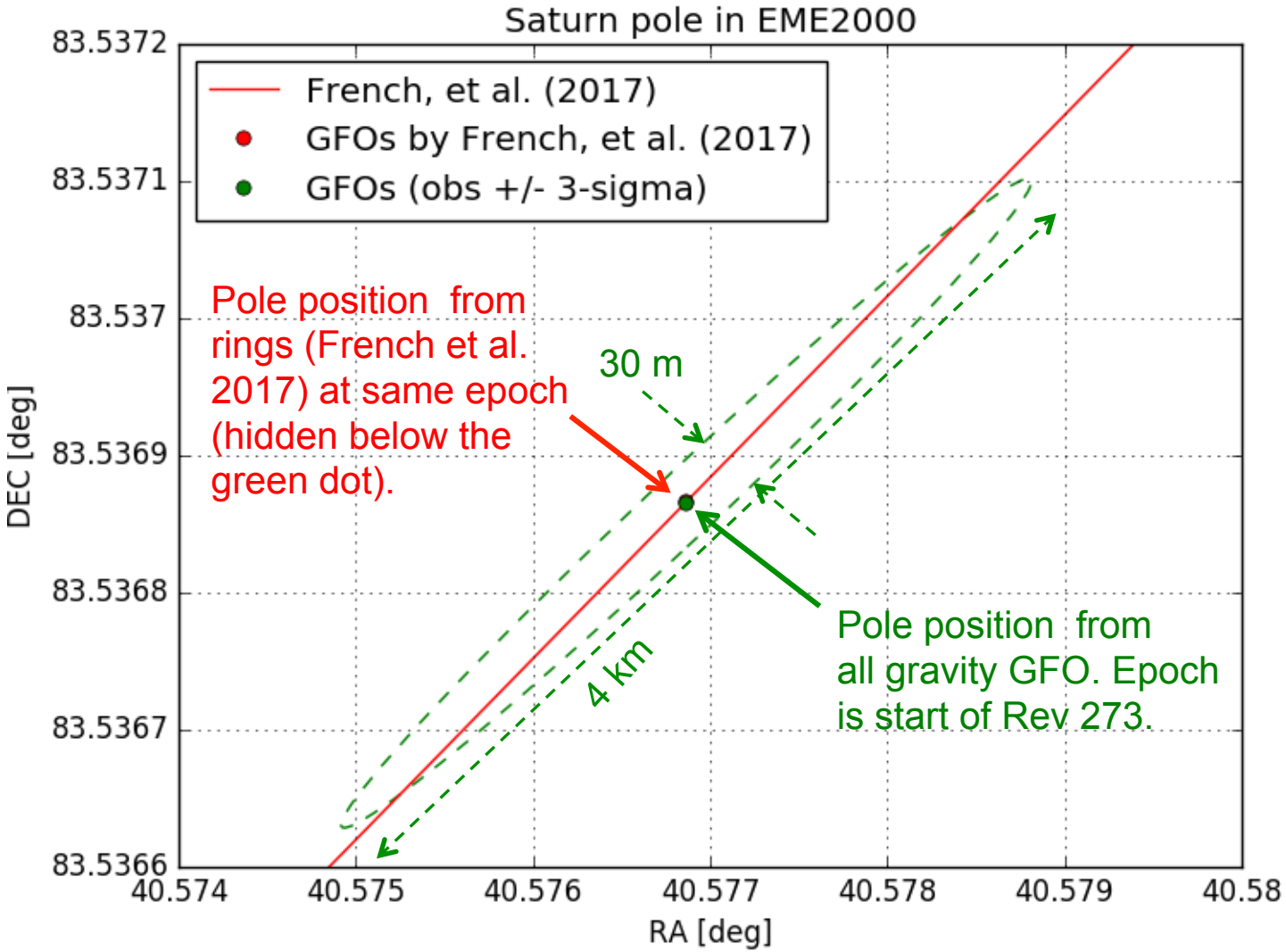
	A+B+C rings (M_M)	
Random accelerations	**0.41**	Preferred
Tesseral 8x8 field (10h32m45s)		
Tesseral 12x12 field (10h39m22s)		Unlikely
Tesseral 10x10 field (10h45m45s)		
Tesseral 10x10 field (10h47m06s)		
f-modes		
f- and p- modes		Maybe
g- and f- modes		

- All solutions for the ring mass (A+B+C) are **consistent at 1-sigma**.
- We can exclude large values of the ring mass.

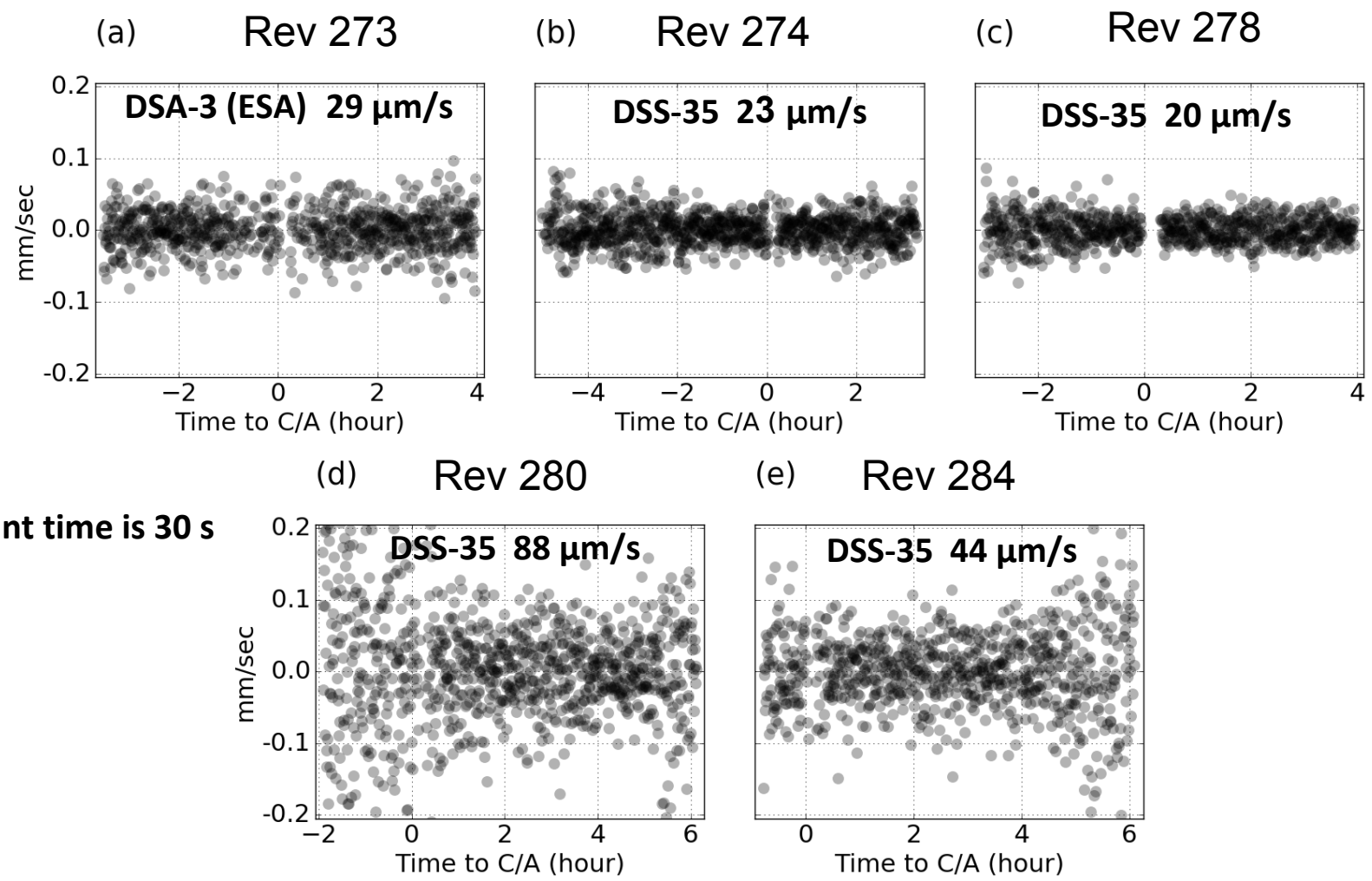
ARE WE DOING THINGS RIGHT? THE SATURN POLE TEST



COMPARISON OF RING AND GRAVITY POLES



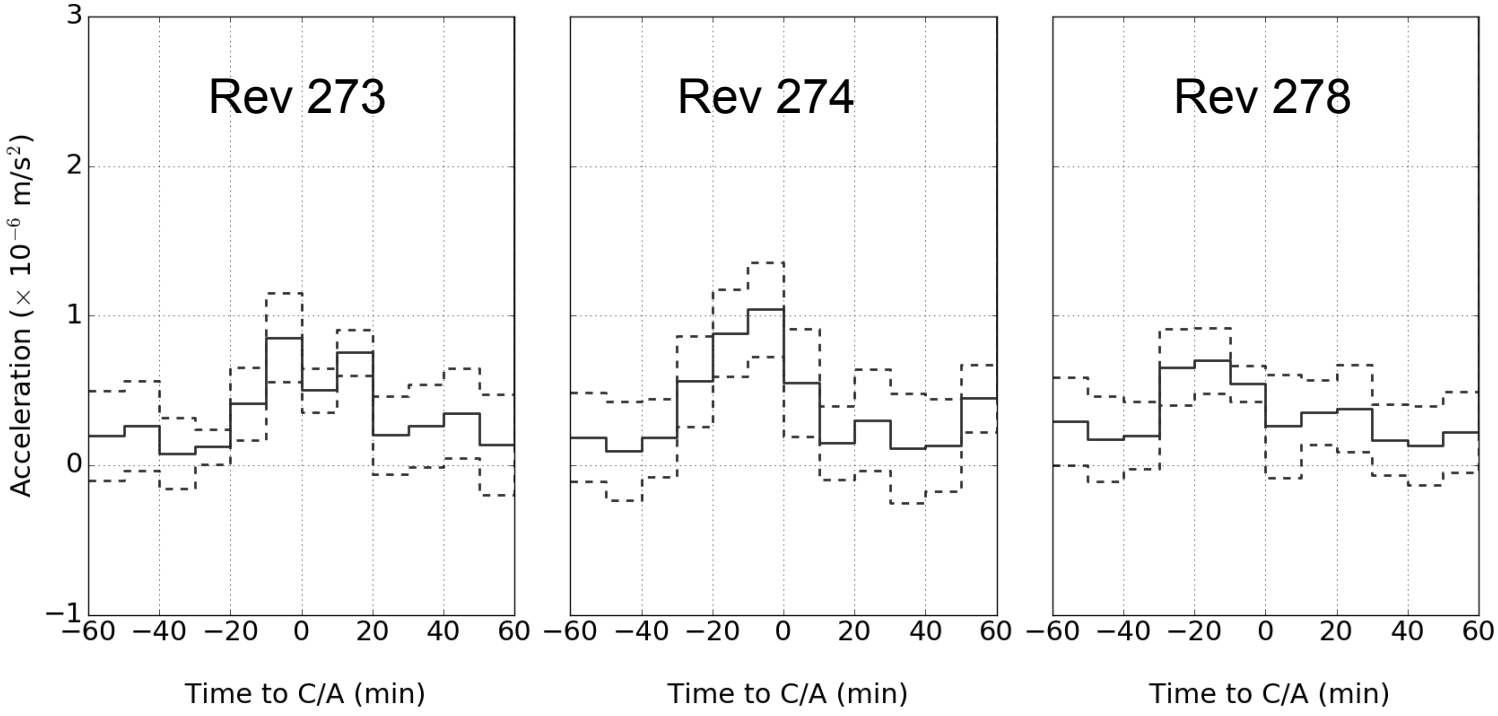
RANGE RATE RESIDUALS



Count time is 30 s

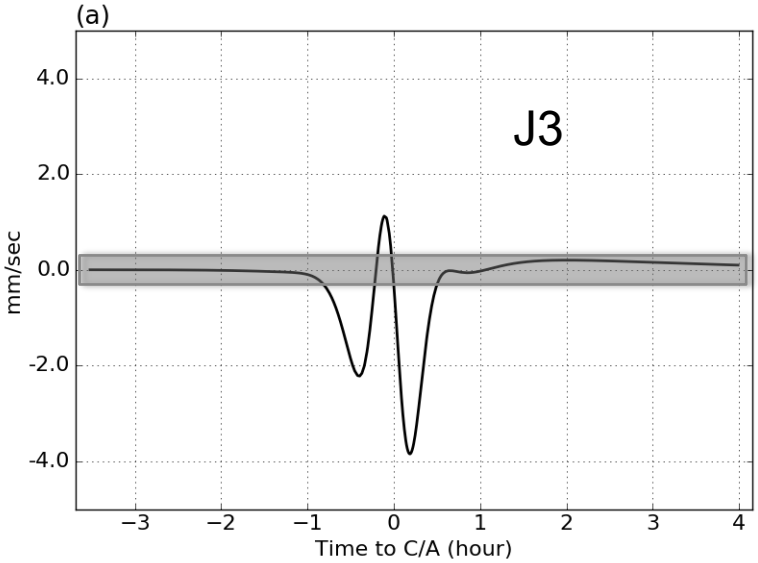
RANDOM ACCELERATIONS

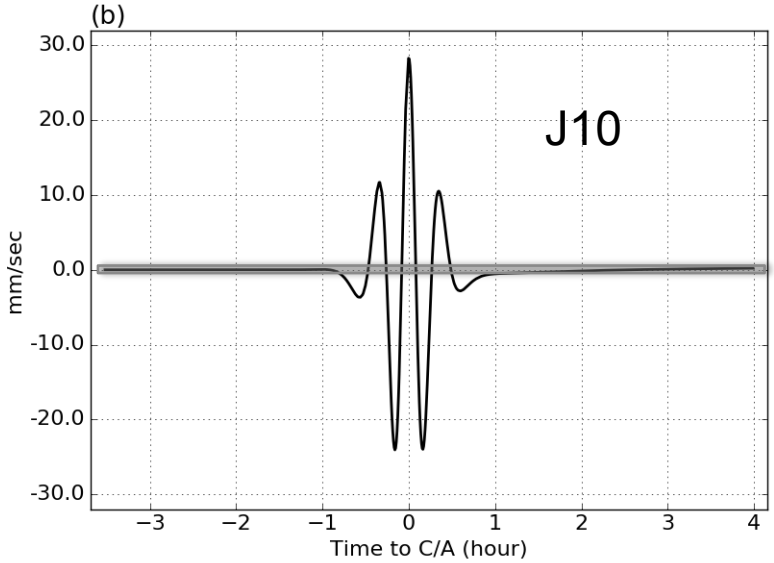
- Random acceleration up to 10^{-6} m/s^2 are required to obtain residuals compatible with the noise
- We used step-wise acc. on RTN frame have been included for a time span of C/A epoch +/- 1h
- Update time ~600 s, *a priori* 5x10^{-7} m/s^2

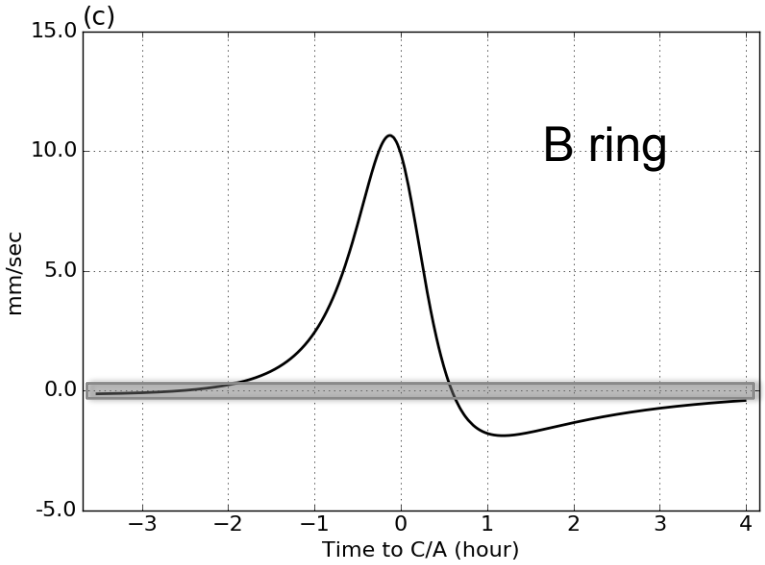


Profile changes from arc to arc but is always of the same order of magnitude

DOPPLER SIGNATURES



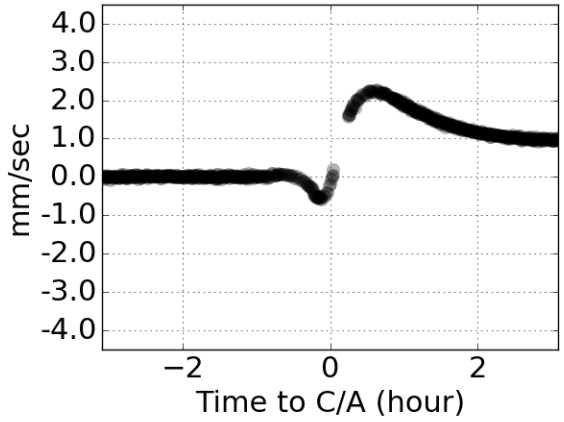




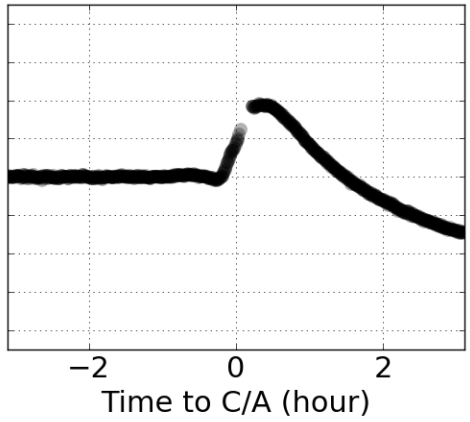
RANGE RATE SIGNATURES FROM RANDOM ACCELERATIONS

The signatures are different in the three cases, but the order of magnitude is the same (~few mm/sec at pericenter).

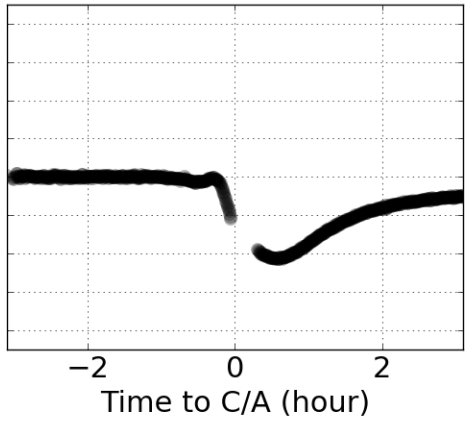
(a) - REV273



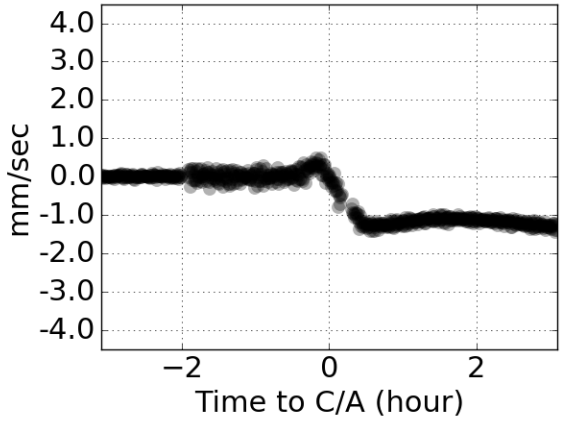
(b) - REV274



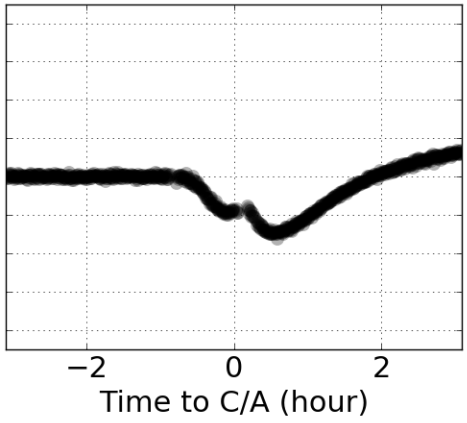
(c) - REV278



(d) - REV280



(e) - REV284

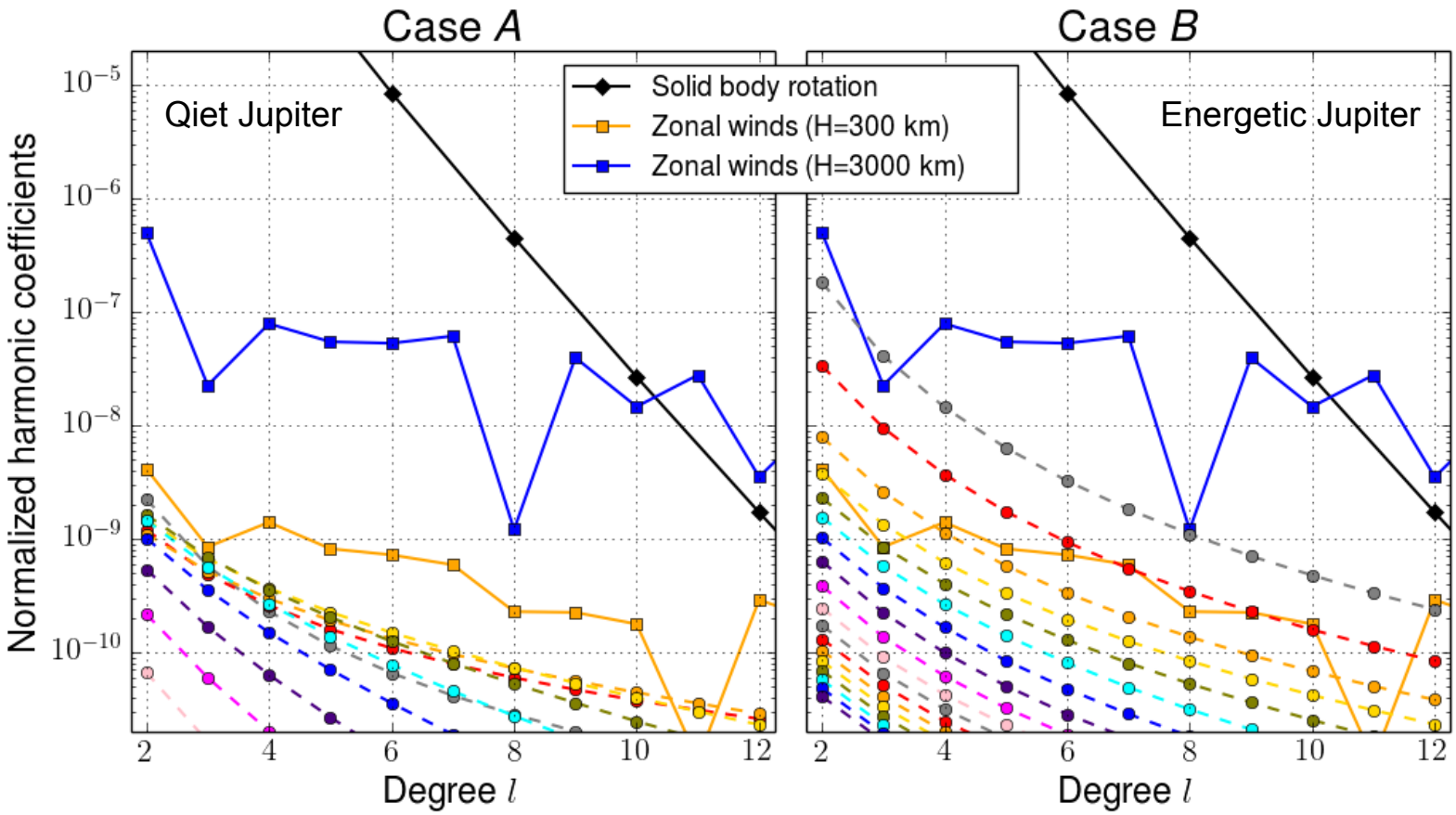


WHAT IS THE SOURCE OF THE DARK SIDE?

- Normal modes? Maybe. We used only zonal (*l*=0) modes, as ring seismology does not allow sectoral and tesseral modes of the required amplitude ($\Delta J_n \approx 10^{-8}$).
- Periods were taken from (Gudkova&Zharkov, 2006). Lowest *l* modes were used. Periods ≈ 10-60 minutes. Phase is coherent across all revs.
- The amplitude seems large. The equipotential is displaced by about 60-100 cm.
- What is the energy source? Turbulence?
- Why should zonal modes be so different from the sectoral modes sensed by the rings? Perhaps the rings are low-pass filtering the excitation from f and p modes?

ARE NORMAL MODES A CREDIBLE EXPLANATION?

Gravity harmonics from normal modes on Jupiter

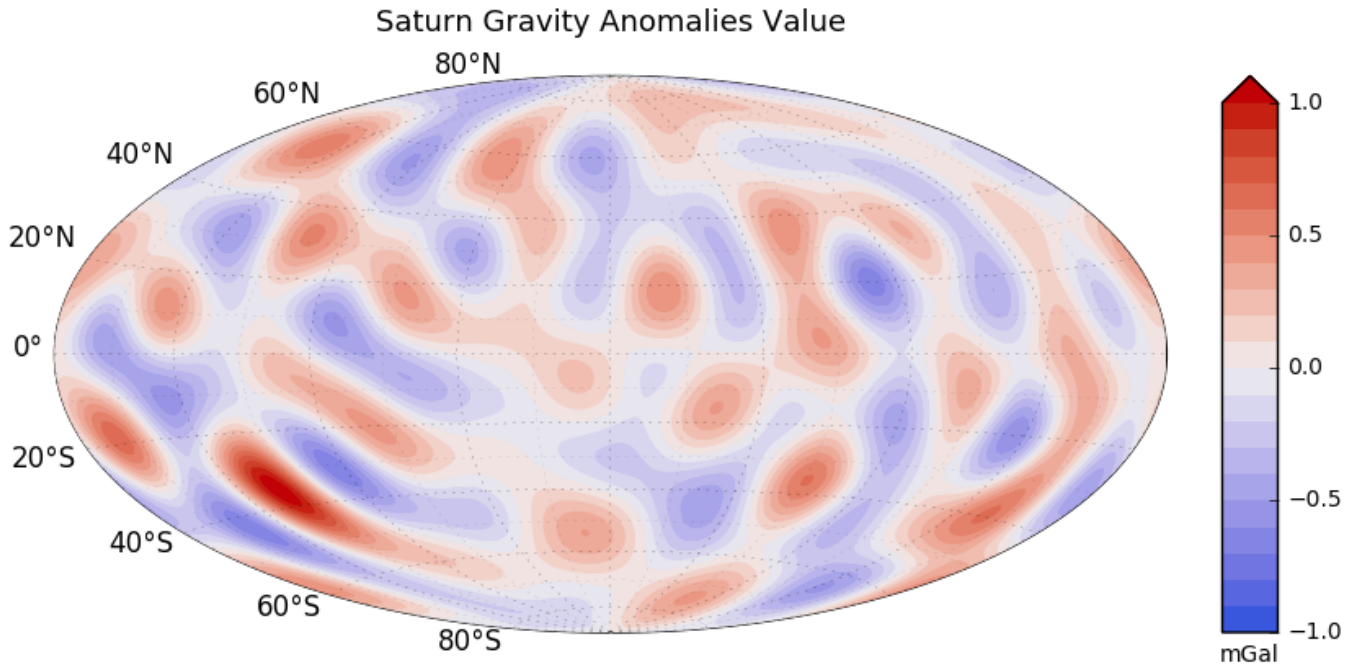


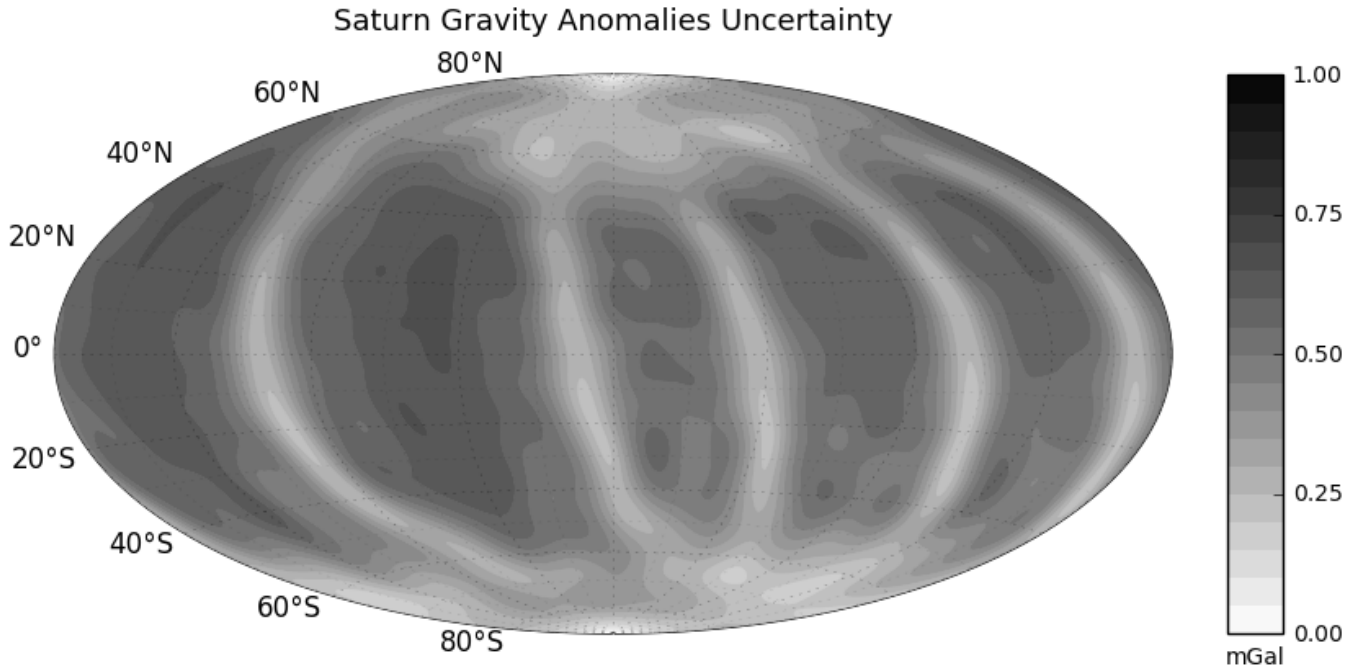
Durante, Guillot & Iess, 2016

WHAT IS THE SOURCE OF THE DARK SIDE?

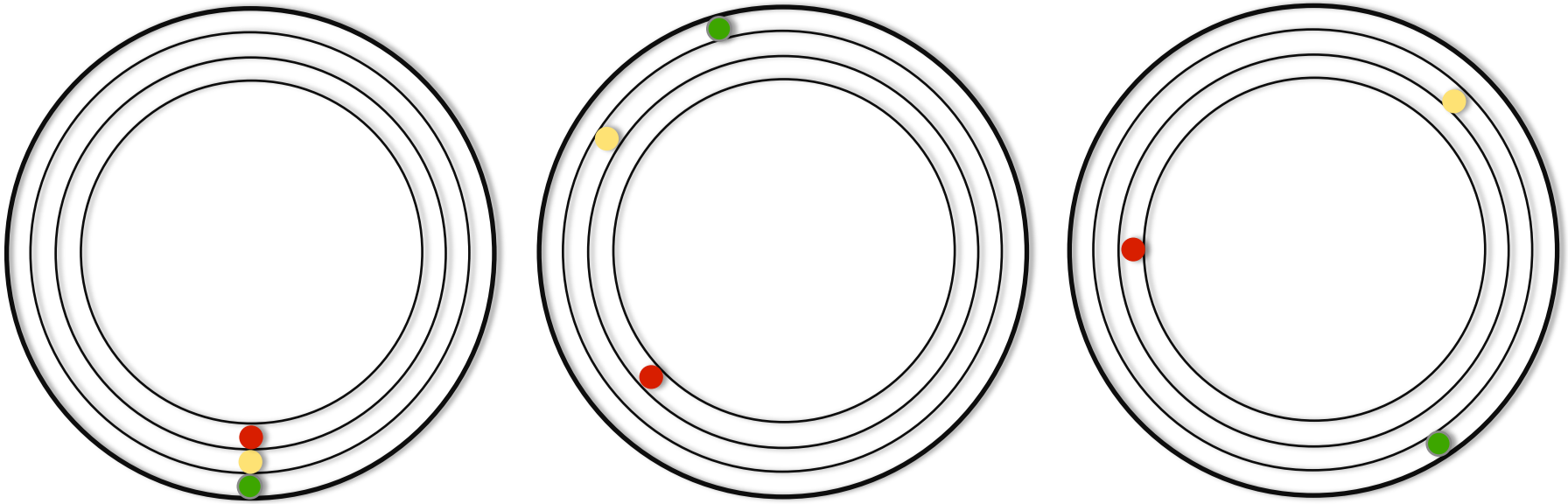
- Convection in the uniformly rotating, metallic hydrogen region?
- It would generate a static tesseral field, but …
- Why do we need to increase the degree and order of the gravity field as more pericenter passes are added to the fit?

- Longitudinal density variations in the envelope? (The weighting function of high degree harmonics privileges the external regions.)
- Maybe. However differential rotation would destroy any static gravity pattern. The resulting gravity field would be randomized within a few Saturn rotation periods.
- Convection or turbulence in the envelope? The resulting gravity field would appear as a time-variable, random field.





Rotation period:
10h47m06s



Rev 273 ⟵ 1 w ⟶ Rev 274 ⟵ 1 w ⟶ Rev 275

Rotation period = 10h35m00s (uniform rotation – 0.7 Rs)
Rotation period = 10h42m37s (peak counter-rotation – 0.82 Rs)
Rotation period = 10h09m27s (cloud tops – 1 Rs)

CONCLUSIONS

- Mission accomplished.
- Zonal gravity, strong differential rotation, depth of flows, ring mass, pole position and precession rates confirmed.
- **The dark side:** its nature remains unknown. But everything points to a **time variable field**.
- Normal modes? Turbulence superimposed to differential rotation?
- Stochastic model is the most appropriate (for now). However, only magnitude and time scales are known. Not much.