New Results on the chaotic behavior of the Solar System

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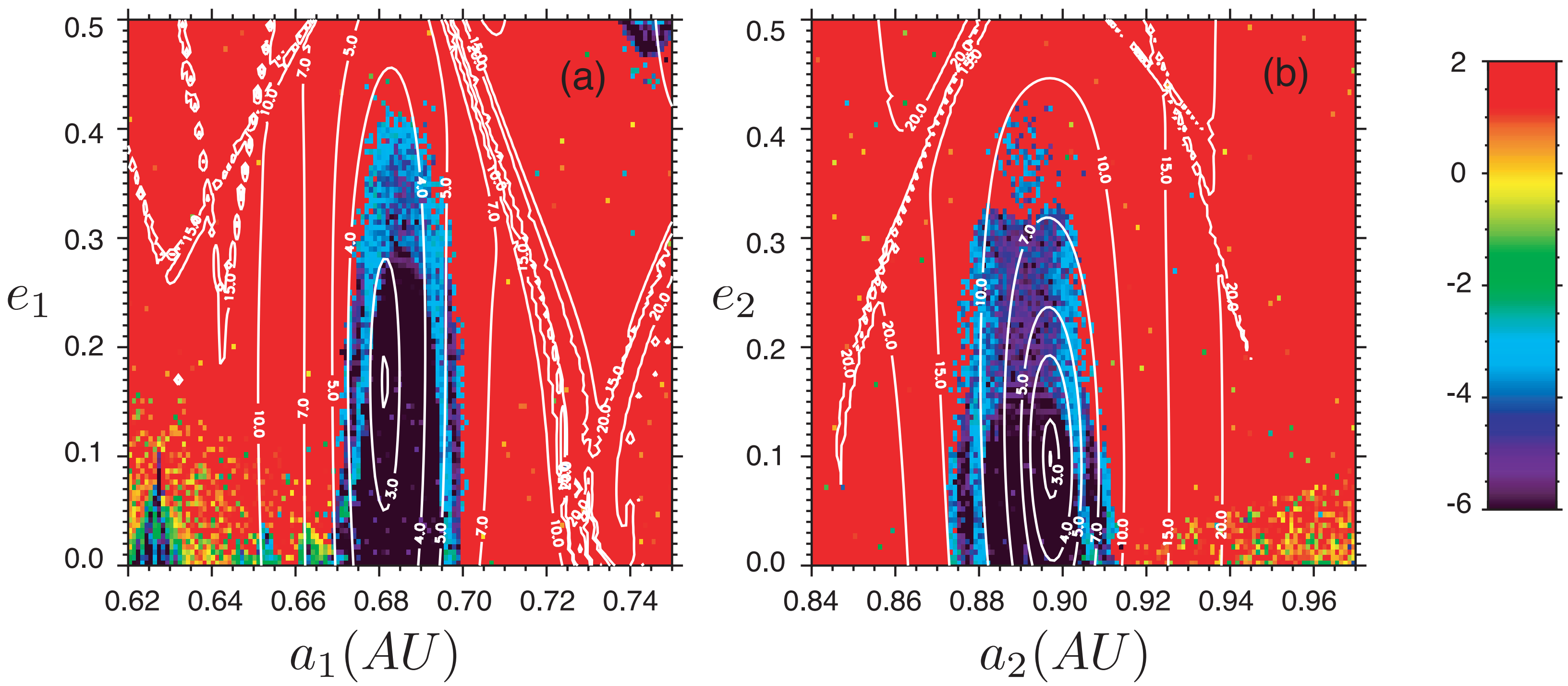
Jackson Lake, September 11-17, 2011

We are always searching for stable solutions for extra solar planetary systems.

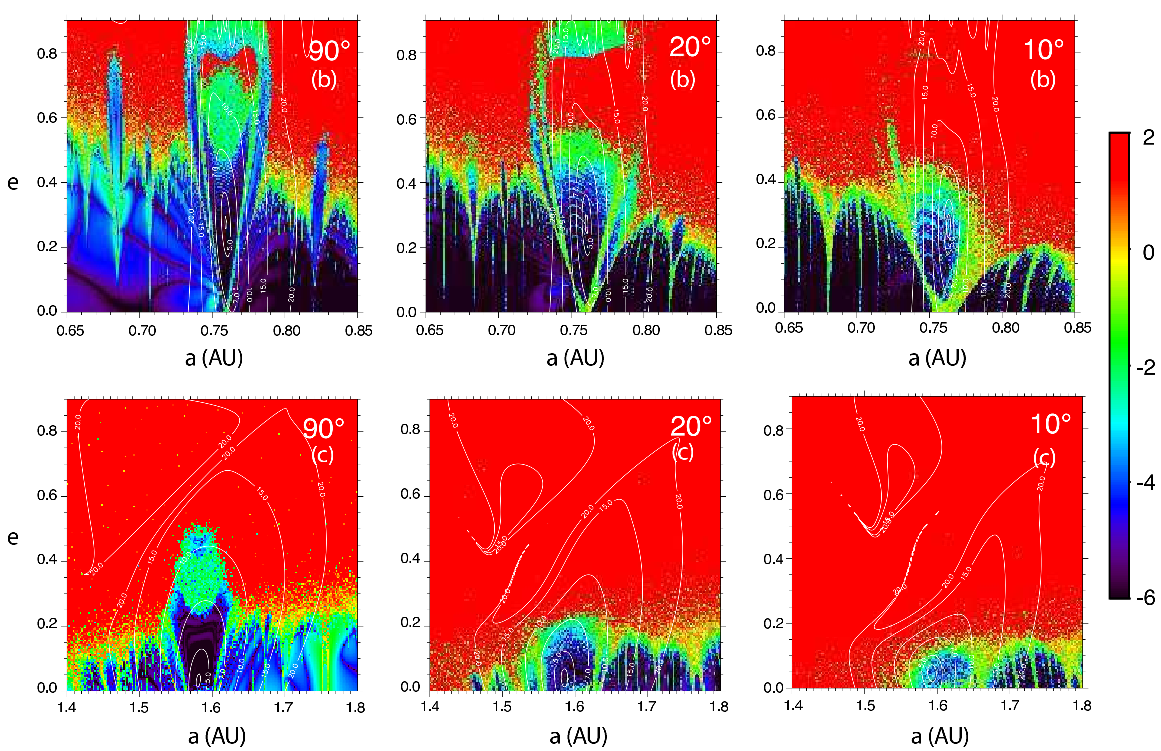
Lack of accurate data

HD45364 : 3:2 resonance



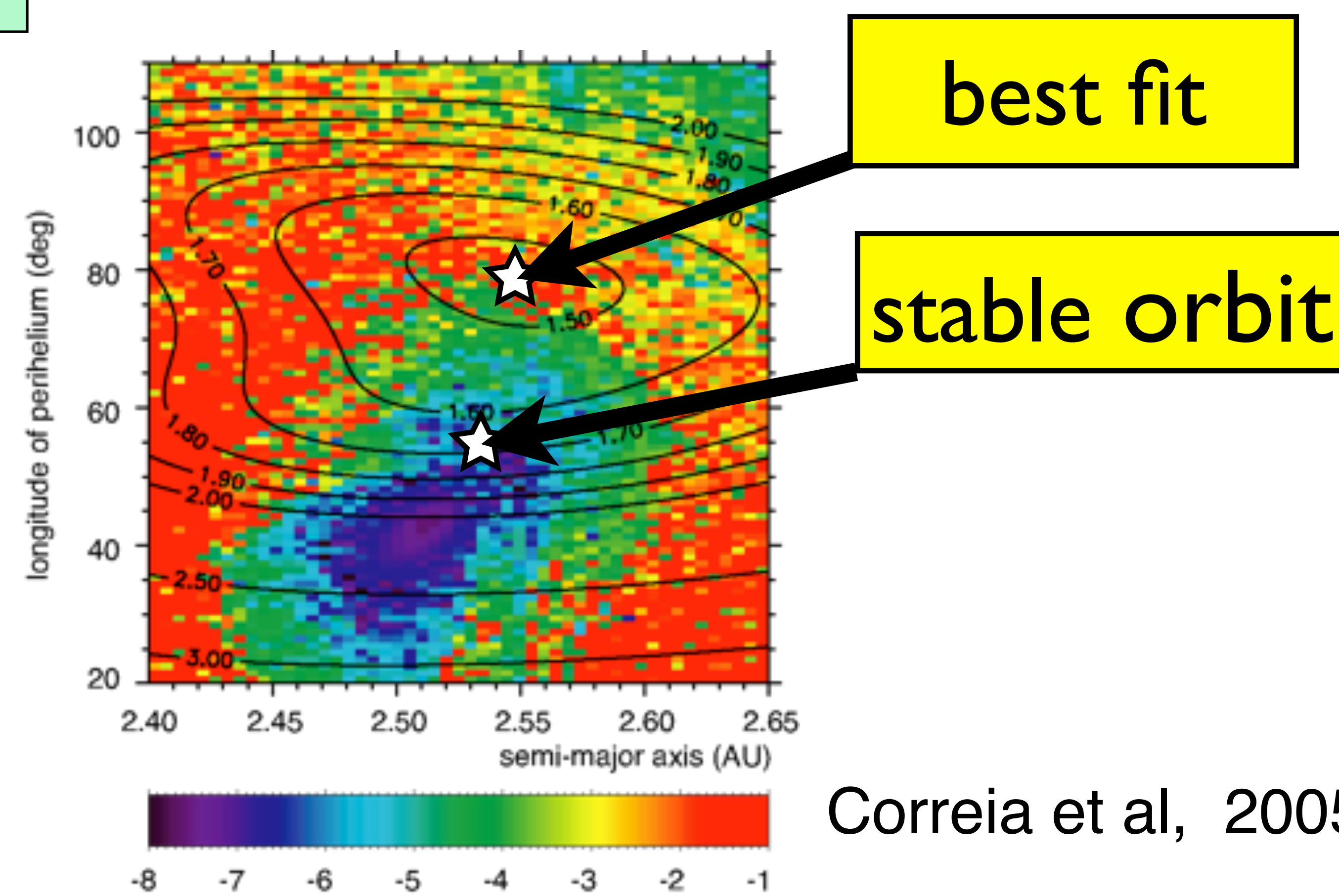
(Correia, Udry, Mayor, Benz, Bertaux, Bouchy, Laskar, Lovis, Mordasini, Pepe, Queloz, A&A, 2009)

HD60532 : 3:1 resonance



(Laskar & Correia, A&A, 2009)

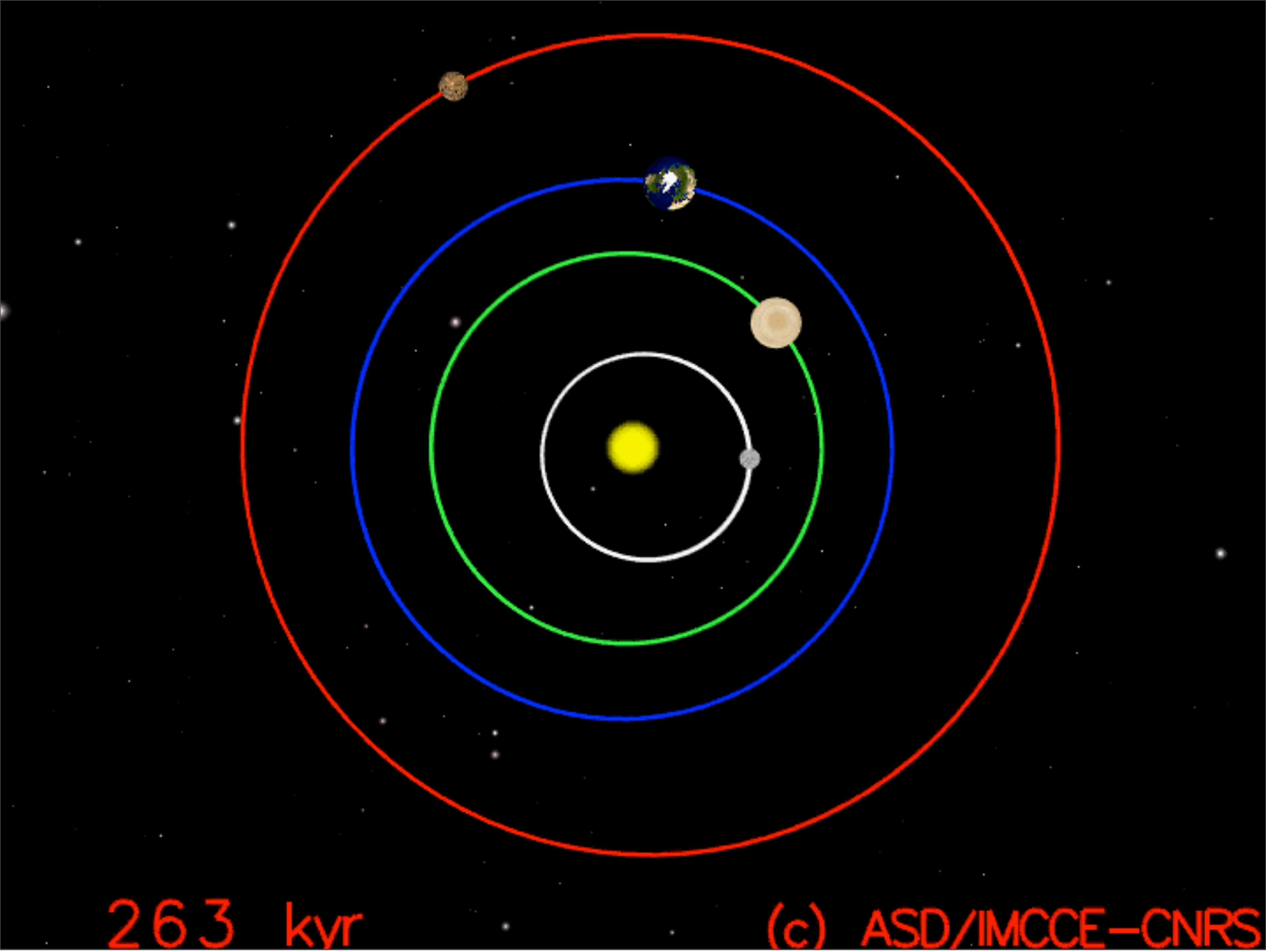
HD202206 : 5:1 resonance



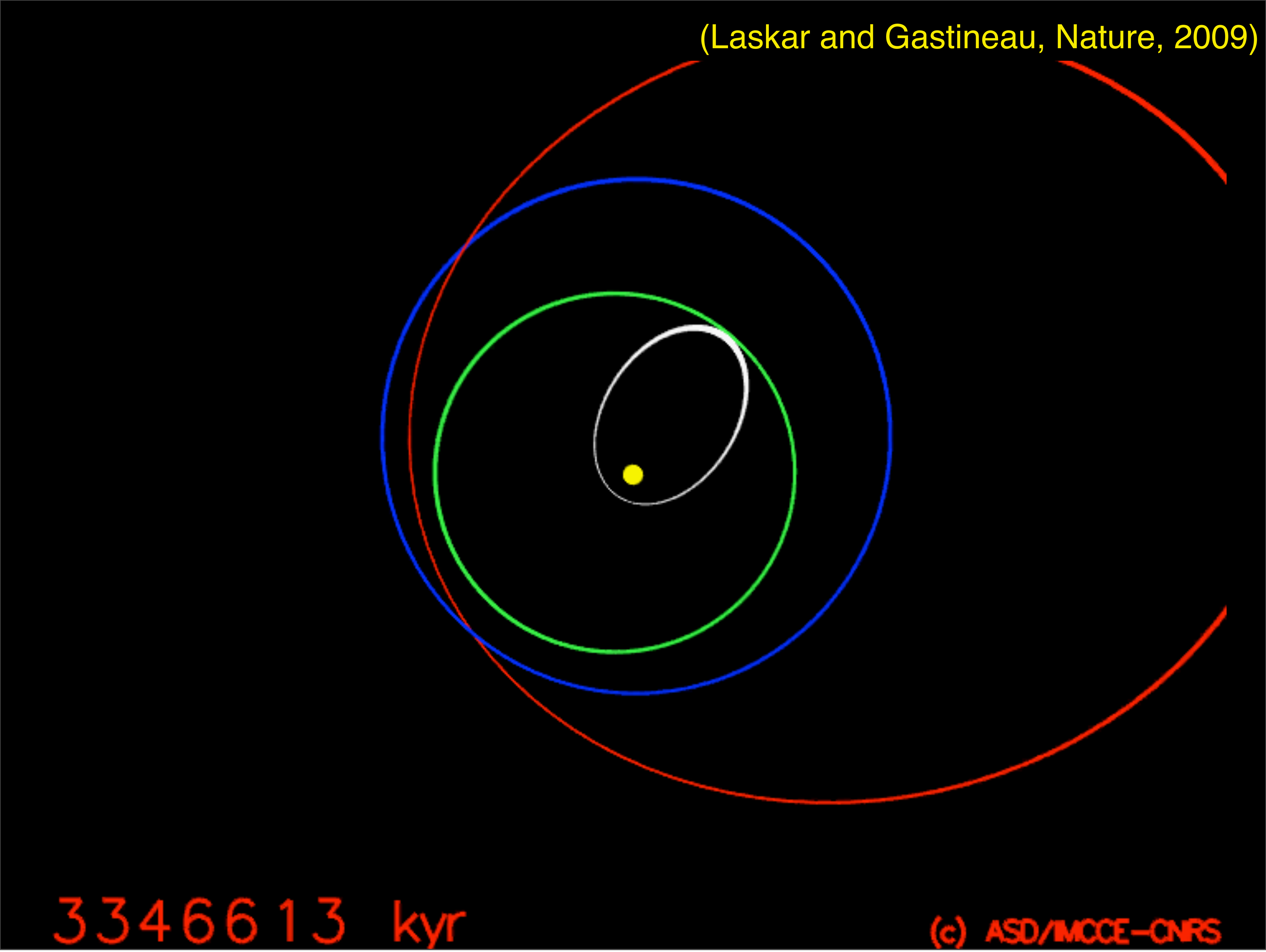
Correia et al, 2005

On the opposite, the Solar System motion is chaotic.

planets


263 kyr
(c) ASD/IMCCE-CNRS

(Laskar and Gastineau, Nature, 2009)


(Laskar and Gastineau, Nature, 2009)
3346613 kyr
(c) ASD/IMCCE-CNRS

Our Solar System is thus an extreme Solar System

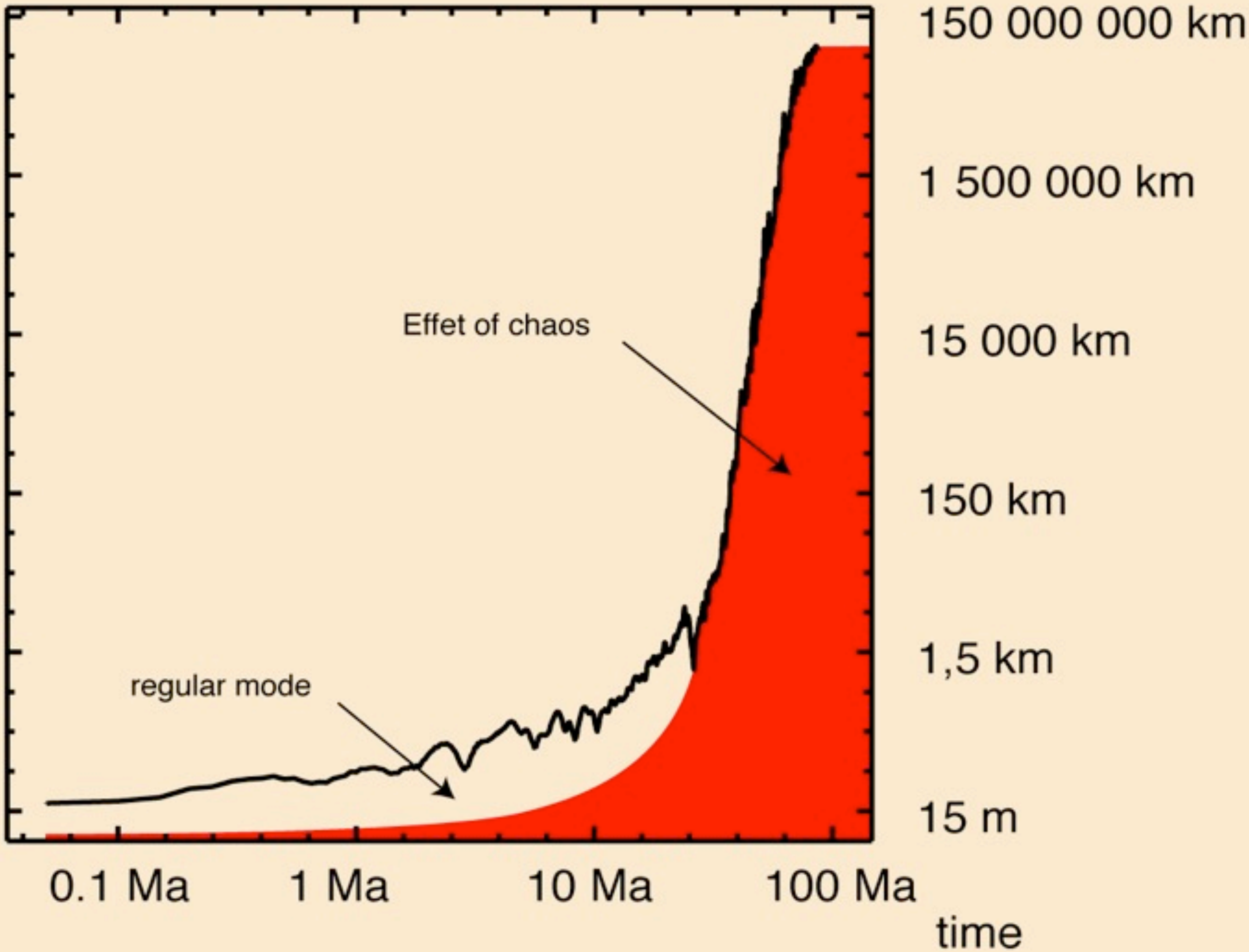
How chaotic is our Solar System ?

How far
in the (past/future)
can we predict
the motion of
the Earth ?

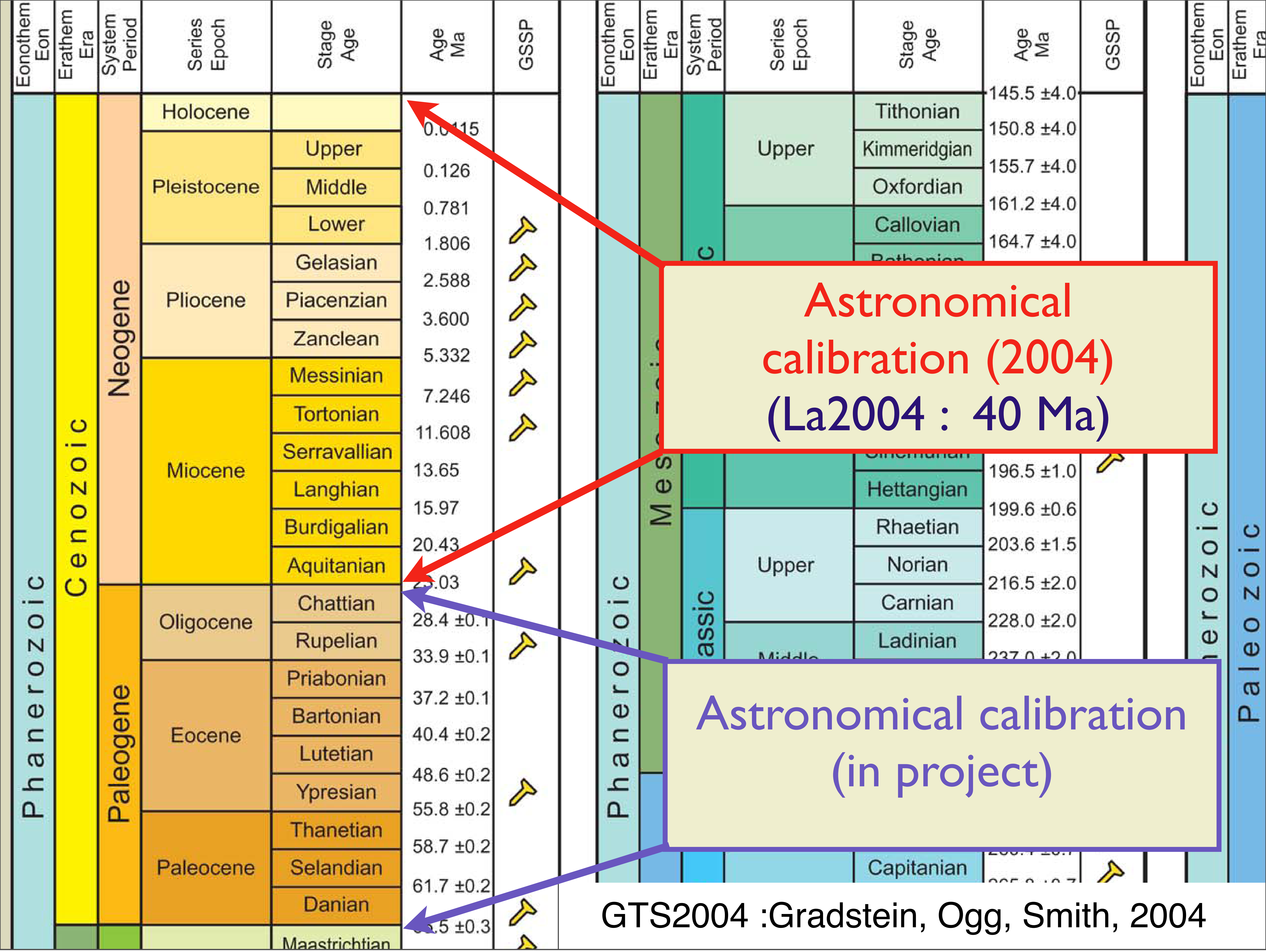
Chaotic motion of the Solar System

Secular equations : 200 Ma : Laskar (1989,1990)

Direct integration : 100 Ma : Sussman and Wisdom (1992)



$$d(T) \approx d_0 10^{T/10}$$


Eonothem Eon
Erathem Era
System Period
Series Epoch
Stage Age
Age Ma
GSSP
Phanerozoic
Cenozoic
Neogene
Paleogene
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Upper
Middle
Lower
Gelasian
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
0.126
0.781
1.806
2.588
3.600
5.332
7.246
11.608
13.65
15.97
20.43
28.4 ±0.1
33.9 ±0.1
37.2 ±0.1
40.4 ±0.2
48.6 ±0.2
55.8 ±0.2
58.7 ±0.2
61.7 ±0.2
Mesozoic
Paleozoic
Tithonian
Kimmeridgian
Oxfordian
Callovian
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Capitanian
145.5 ±4.0
150.8 ±4.0
155.7 ±4.0
161.2 ±4.0
164.7 ±4.0
196.5 ±1.0
199.6 ±0.6
203.6 ±1.5
216.5 ±2.0
228.0 ±2.0
Astronomical calibration (2004)
(La2004 : 40 Ma)
Astronomical calibration
(in project)
GTS2004 :Gradstein, Ogg, Smith, 2004

New Challenge :
Orbital solution over ~ 60 Myr

↓

Improve the accuracy
by
2 orders of magnitude !

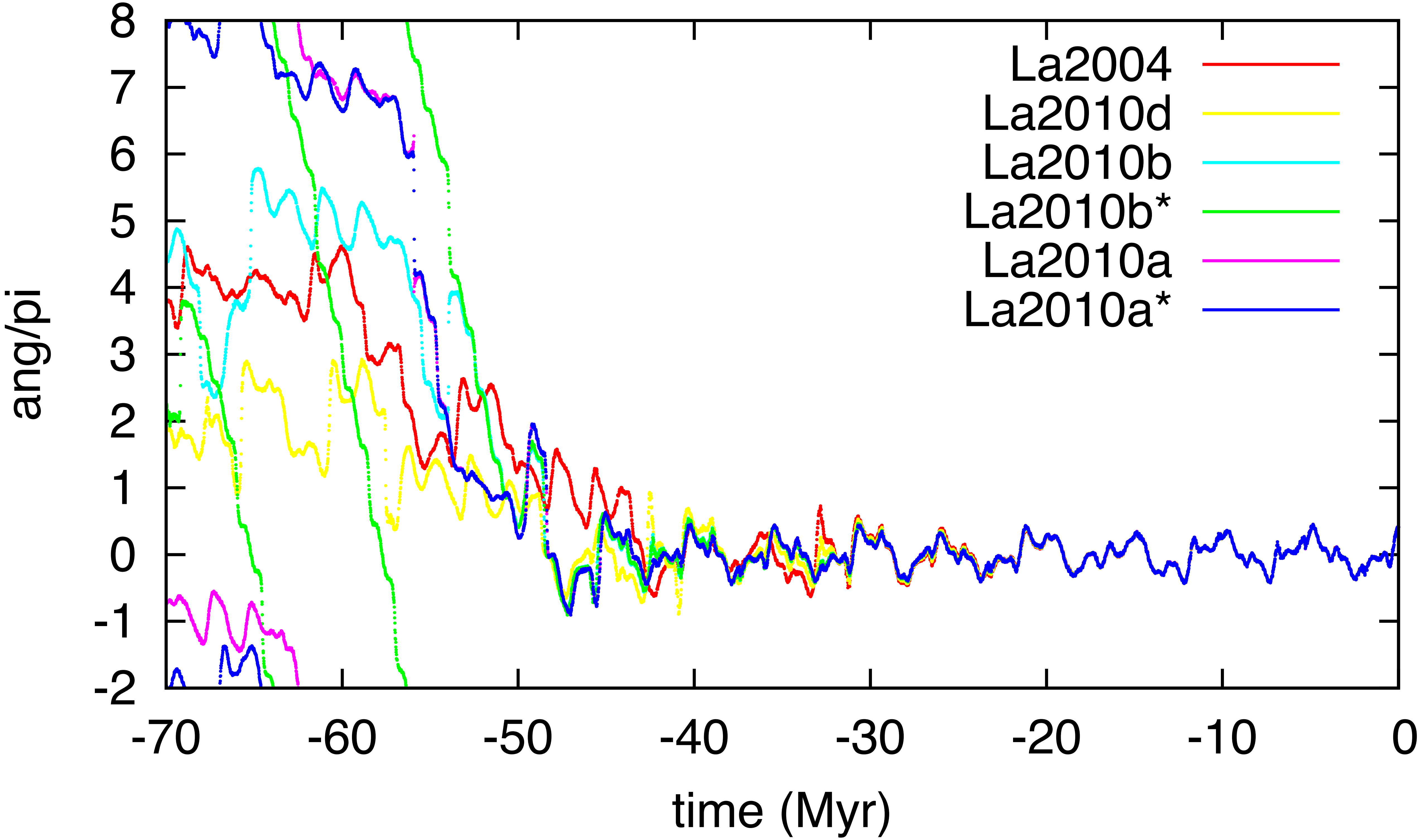
Planetary solutions

•La2004 : numerical, simplified,
tuned to DE406 (6000 yr) : valid over 40 Myr
Laskar et al, A&A, 2004

•INPOP : numerical, "complete",
adjusted to 45000 observations.
1Myr : 6 months of CPU
Fienga et al, 2008, 2009, 2011

•La2010 : numerical, less simplified,
tuned to inpop (1 Myr) : valid over 50 Myr
250Myr : 18 months of CPU
Laskar et al, A&A, 2011

Resonant argument : $\theta : 2(g_4 - g_3) - (s_4 - s_3)$



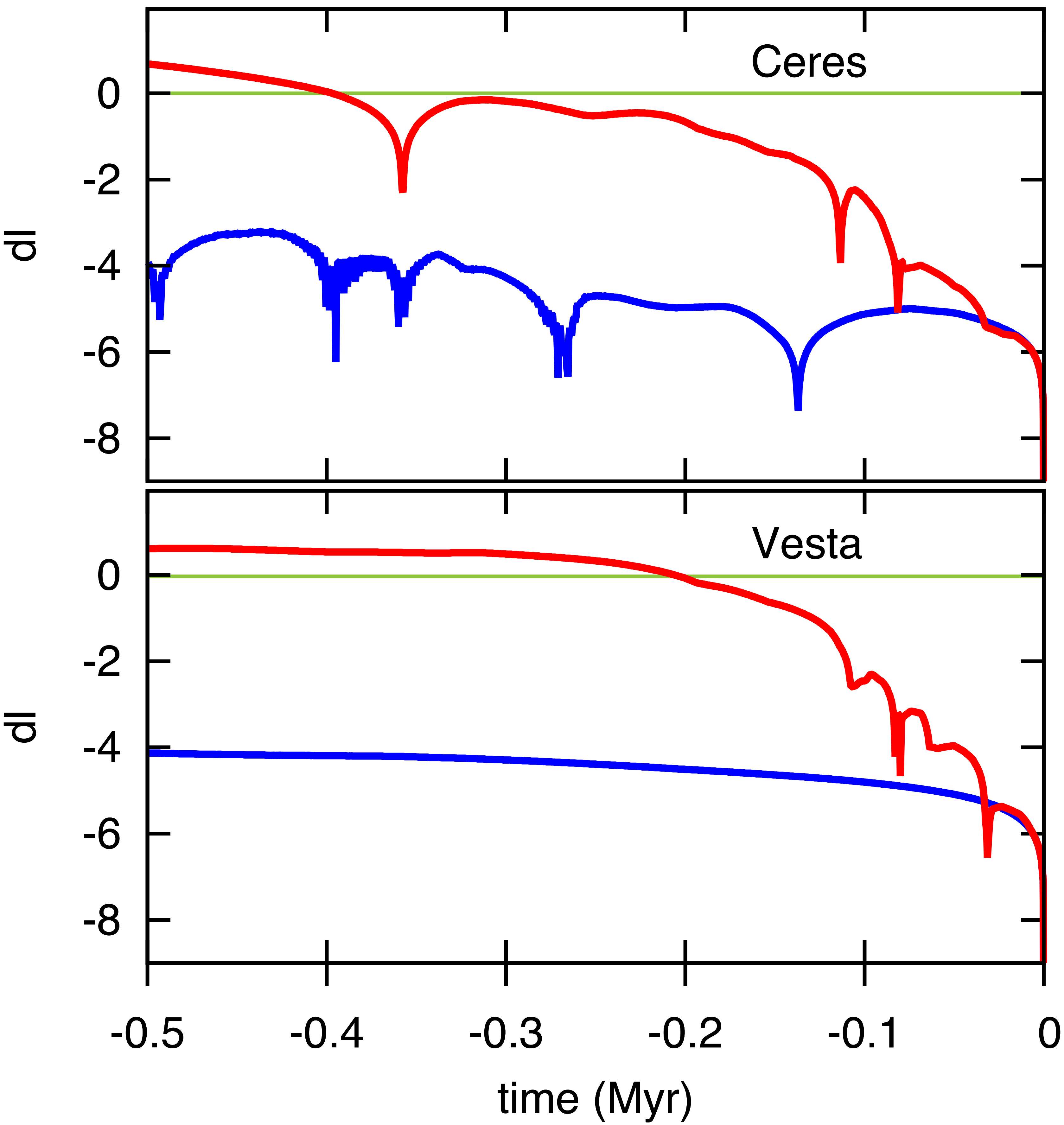
(Laskar, Gastineau, Delisle, Farrès, Fienga , A&A L, 15 July, 2011)

Vesta (DAWN/NASA)

Ceres (Hubble)

Unstabilities due to asteroïdal close encounters

Strong chaos of Ceres and Vesta



d0 = 15m

(dI0=1.4 E-10 rad)

Mutual perturbations

No Mutual perturbations

(Laskar et al, A&A, 2011)

Lyapunov exponents (1/Myr)

$$x = x_0 \exp \lambda t$$

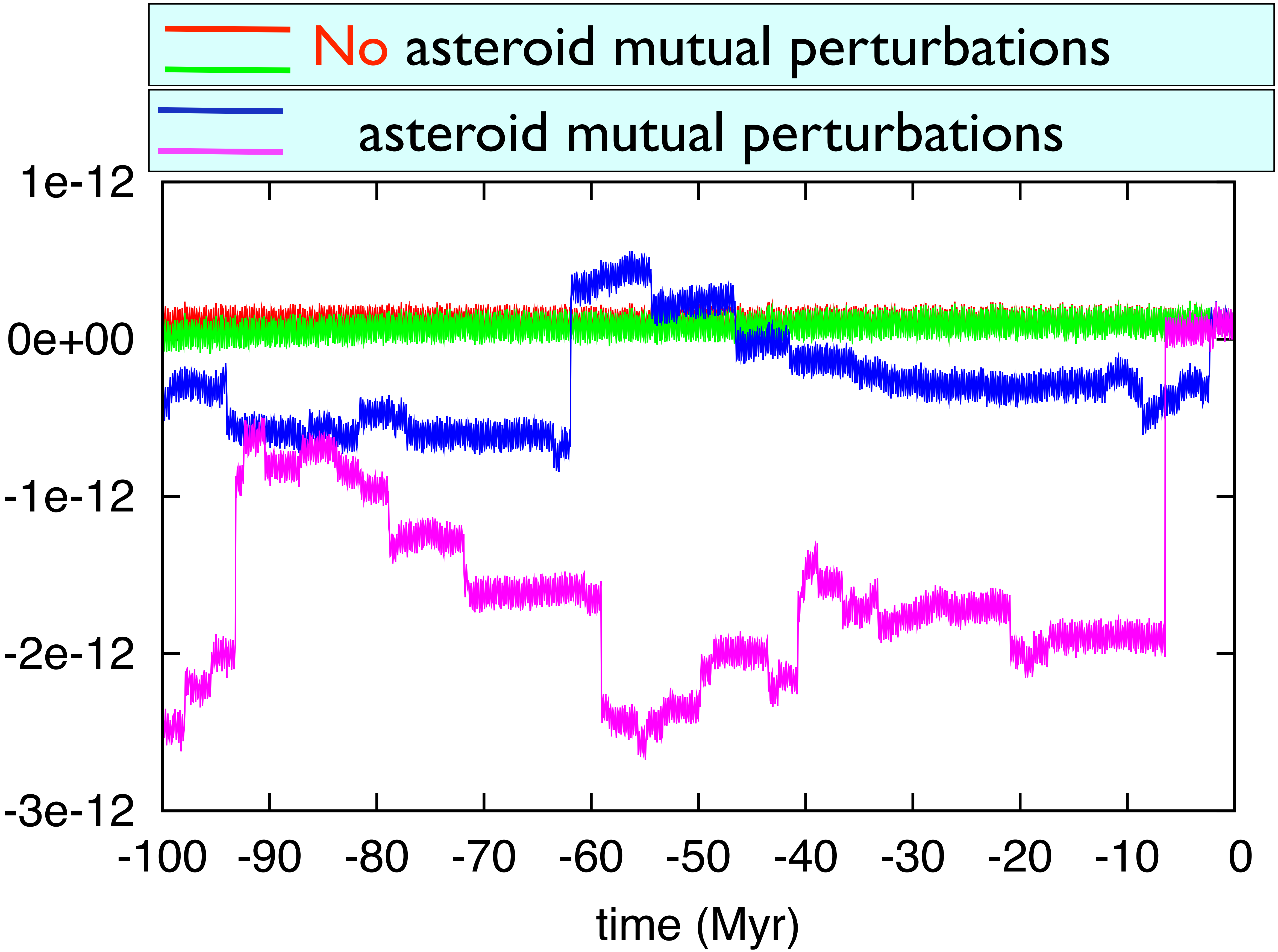
	Novakovic, Knezevic, Milani 2011	No ast. interactions
Ceres	1.2	4.0
Vesta	2.8	0.2
Pallas	44.2	35.2
Iris	42.6	53.9
Bamberga	45.7	38.4

Lyapunov exponents (1/Myr)

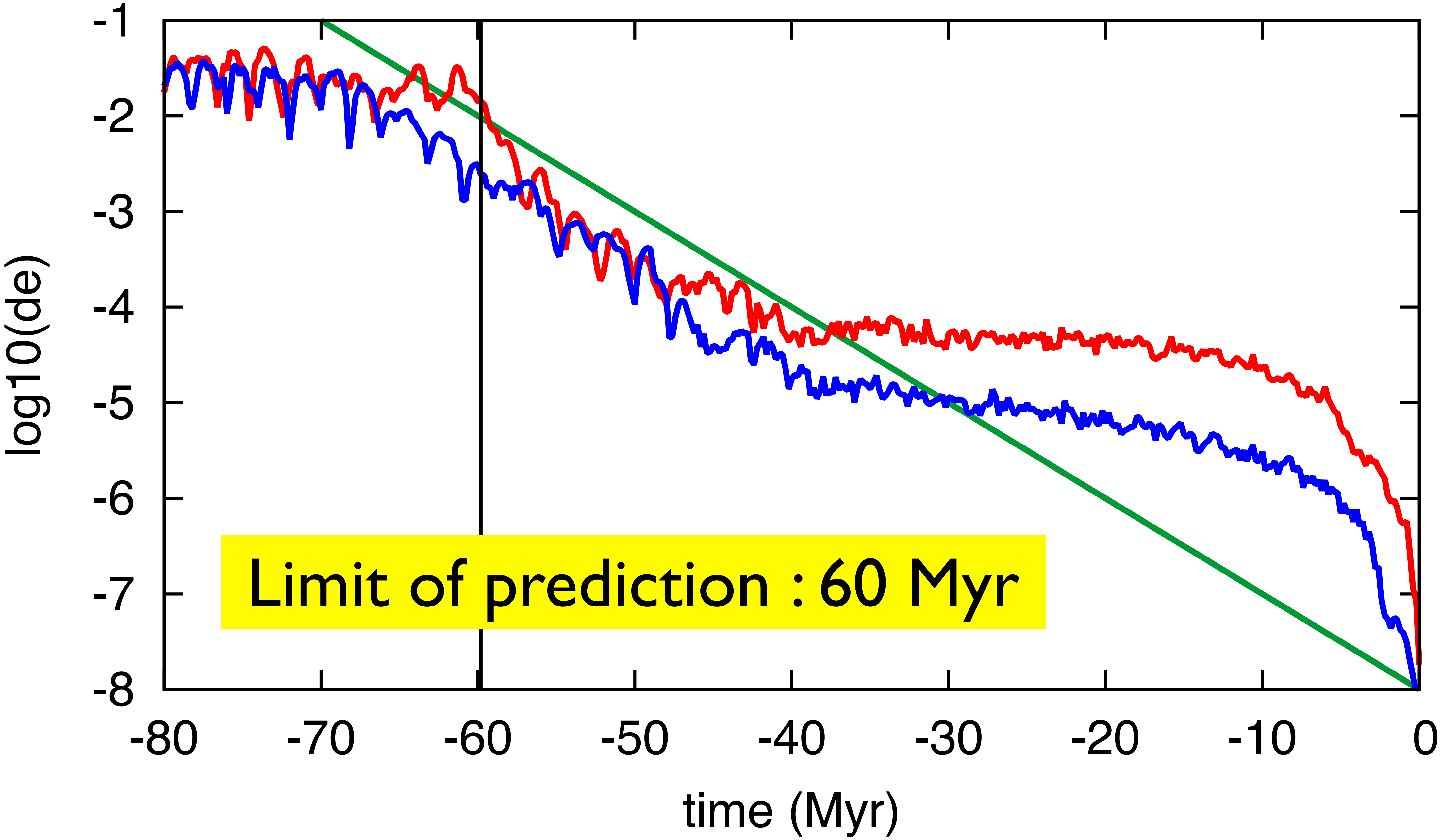
$$x = x_0 \exp \lambda t$$

	Novakovic, Knezevic, Milani 2011	No ast. interactions	With ast. interactions
Ceres	1.2	4.0	34.6
Vesta	2.8	0.2	70.0
Pallas	44.2	35.2	159.2
Iris	42.6	53.9	84.9
Bamberga	45.7	38.4	82.1

Relative variation of the planet orbital energy



Eccentricity of the Earth



Asteroid mutual interactions

No Asteroid mutual interactions

Conclusions

To increase the validity of the solution
beyond 60 Myr , the price to pay
is not
a factor of 10 improvement for each 10 Myr,
but
a factor of 10 improvement for each 50 kyr
15 m -> 60 Myr
15 mm -> 60.150 Myr

I am waiting for a chaotic extra solar system.
HR 8799 ?