Quelques exemples en

Mécanique Céleste.

Délimitation du périmètre de GRAM ?

J. Laskar

CNRS, Observatoire de Paris

Importance de prendre en compte la rotation des corps

- Rotation de Janus et Epiméthée (P. Robutel, IMCCE)
- Rotation de Mercure pour Bepi-Colombo (B. Noyelles, Namur)
- Rotation de Phoebe (L. Cottereau, SYRTE)

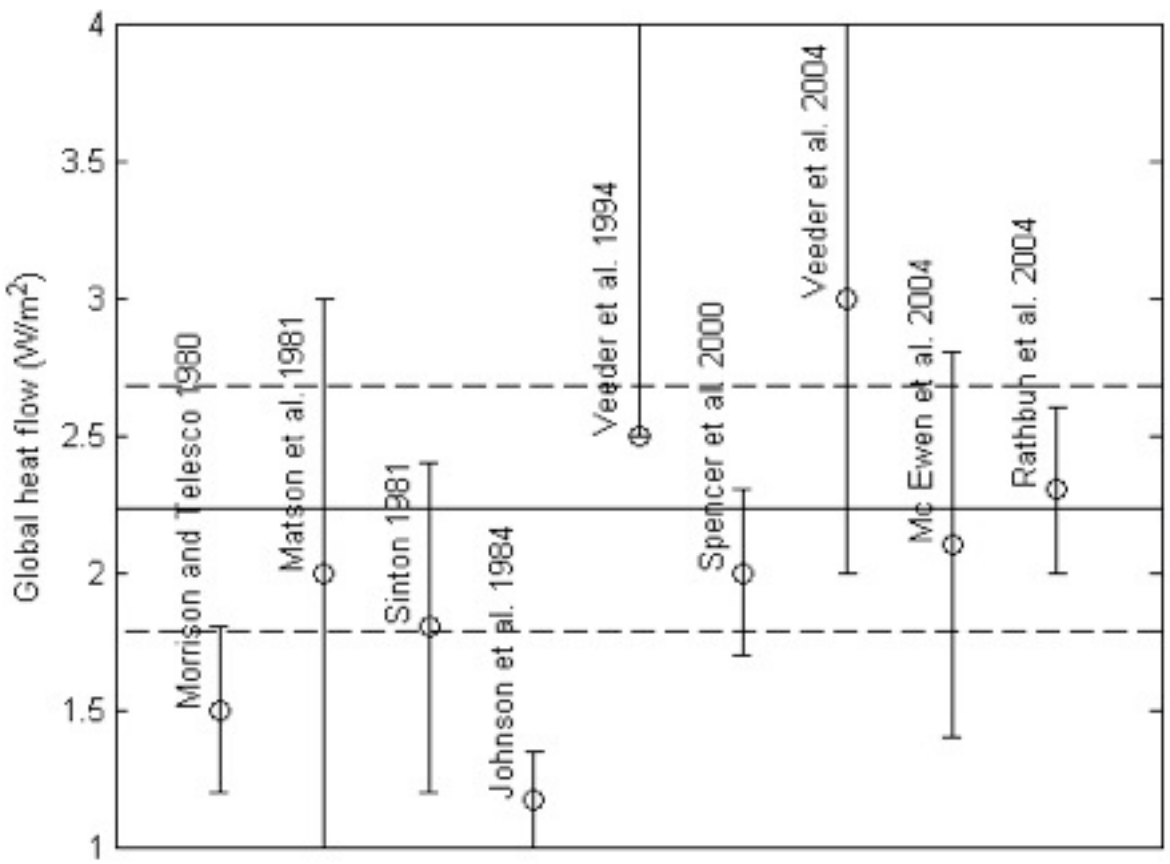
Satellites

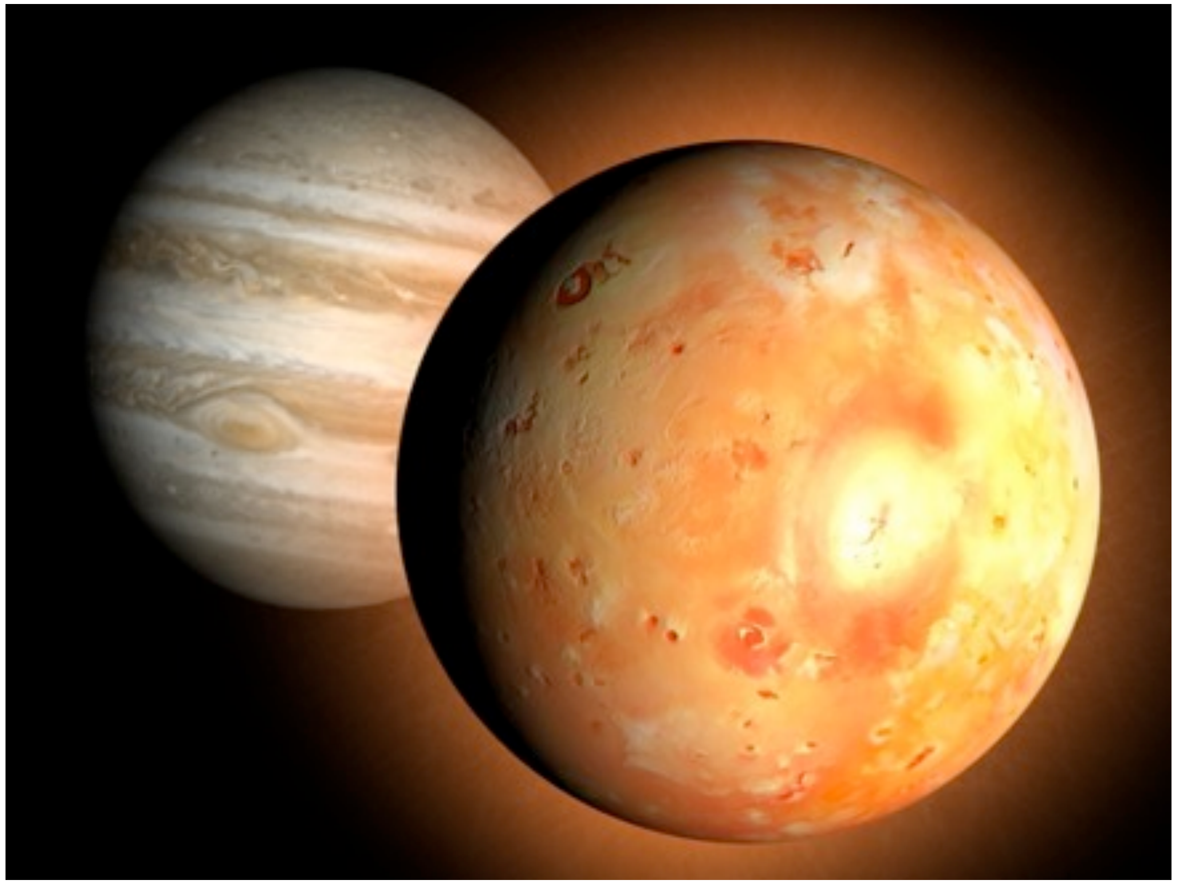
Tidal dissipation in the Jovian and Saturnian system from astrometry

Lainey, Arlot, Karatekin, Van Hoolst (Nature, 2009)

Fit of Io's dissipation provides $k_2/Q = 0.015 \pm 0.003$

One can compare this value with the ones derived from IR emission





Good agreement and confirm the values derived from heat flux observations!

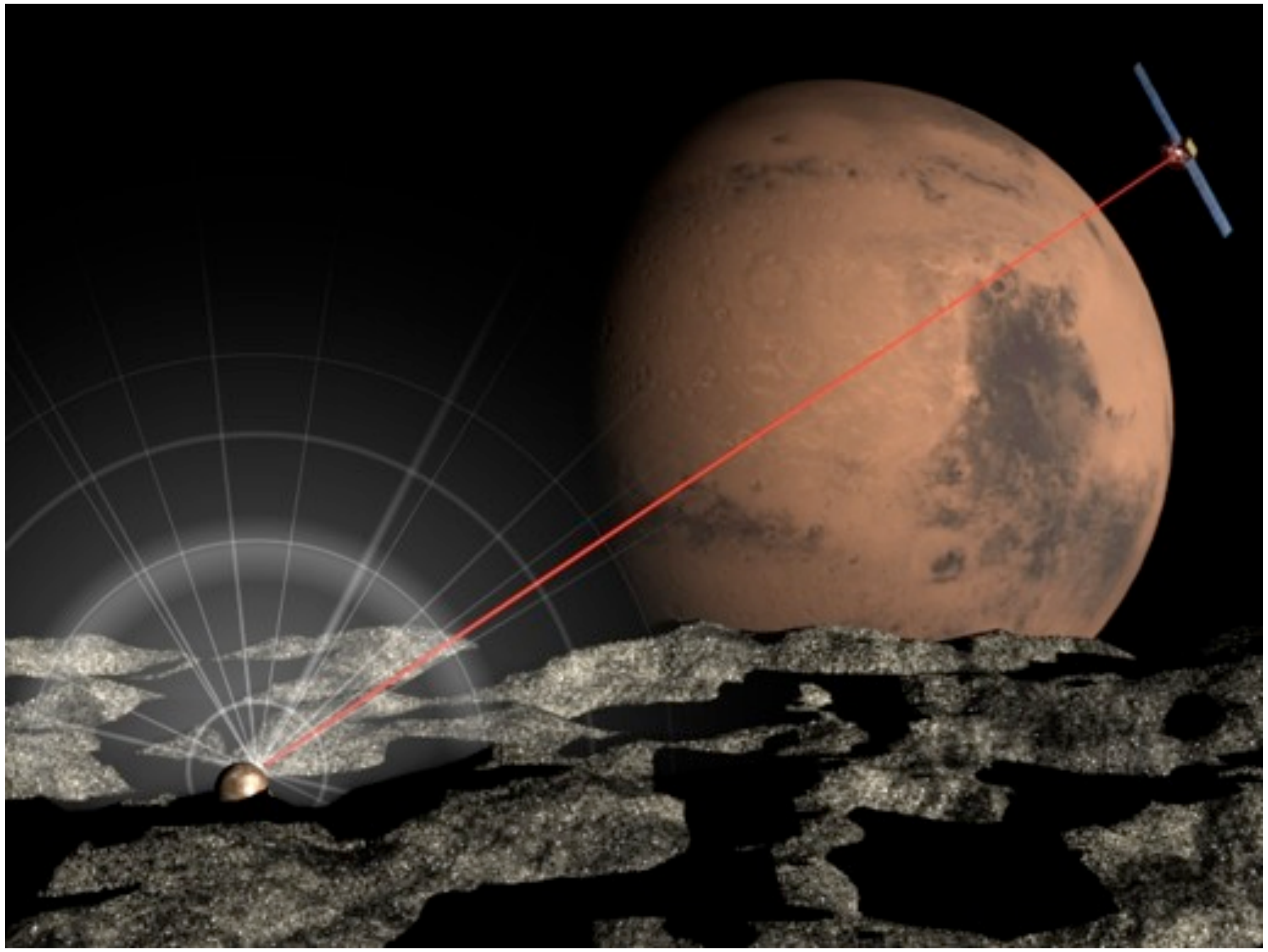
In progress: *application to the Saturnian system…*

(adapté de Lainey)

The GETEMME mission
-GETEMME (Gravity, Einstein's theory, and Exploration of the Martian Moons' Environment)-
Lainey, Le Poncin-Lafitte et al

Proposed to the ESA *M-class* mission call

Scientific objectives:
« A mission to explore the Martian Satellites and the Fundamentals of Solar System Physics »



Keypoints:

→S/C will drop two retrofeflectors on Phobos and Deimos

→From a scientific orbit at 1,000 km altitude, the S/C will be considered as a third Mars' moon

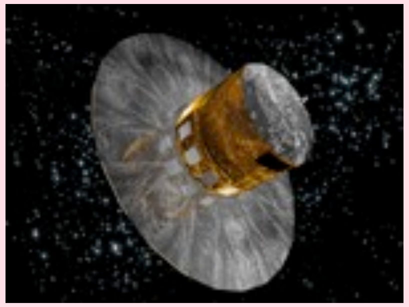
→Measurements:
S/C=radio-science
Phobos and Deimos=laser link with the S/C

→Expected accuracy: cm-level on the position in space of the S/C, Phobos and Deimos

For more details, see the poster!! Lainey, Le Poncin-Lafitte et al

(adapté de Lainey)

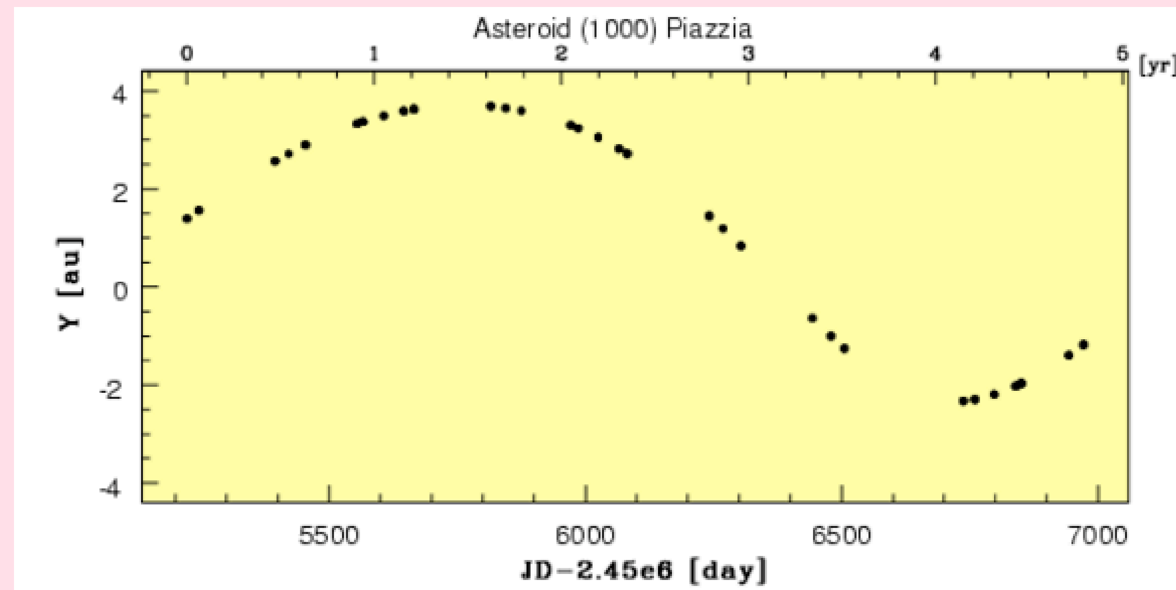
Astéroïdes

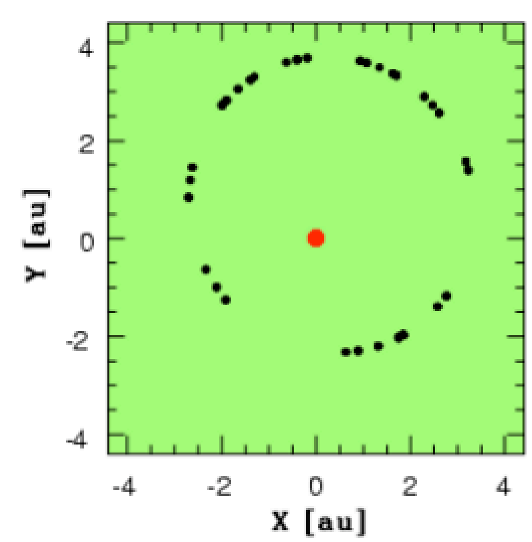


Gaia – en bref

- relevé du ciel pendant 5 ans
- observation objets du système solaire
  astéroïdes, comètes, satellites (planètes naines)

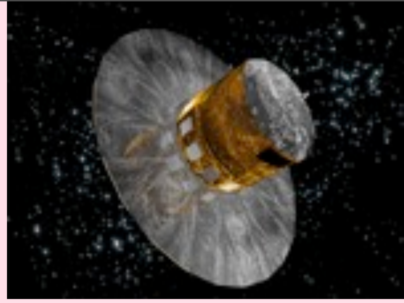
  - magnitude limite V≤20,
    taille limite $\Phi \leq 0''7$
  - environ 250.000 astéroïdes
  - spectroscopie
    photométrie (rotation des astéroïdes)
    & astrométrie





astéroïde typique
distribution des
63 obs. sur 5 ans

(adapté de Hestroffer)



Gaia - dyn. SolSys

- astrométrie (σ≈0.3−3mas) => gain ≈50 en précision
  - paramètres locaux
    - éléments orbitaux, effets non gravitationnels
  - paramètres globaux
    - masse par rencontres proches et/ou systèmes binaires +volume (par Gaia ou sol) => densité
    - test RG : PPN β, J_2 solaire, variation gravité dG/dt, rotation repère dW/dt
- astrométrie post-Gaia - utilisation du nouveau catalogue astrométrique stellaire
  - occultations stellaires astéroïdes et transneptuniens
  - réduction des observations, dynamique à long terme

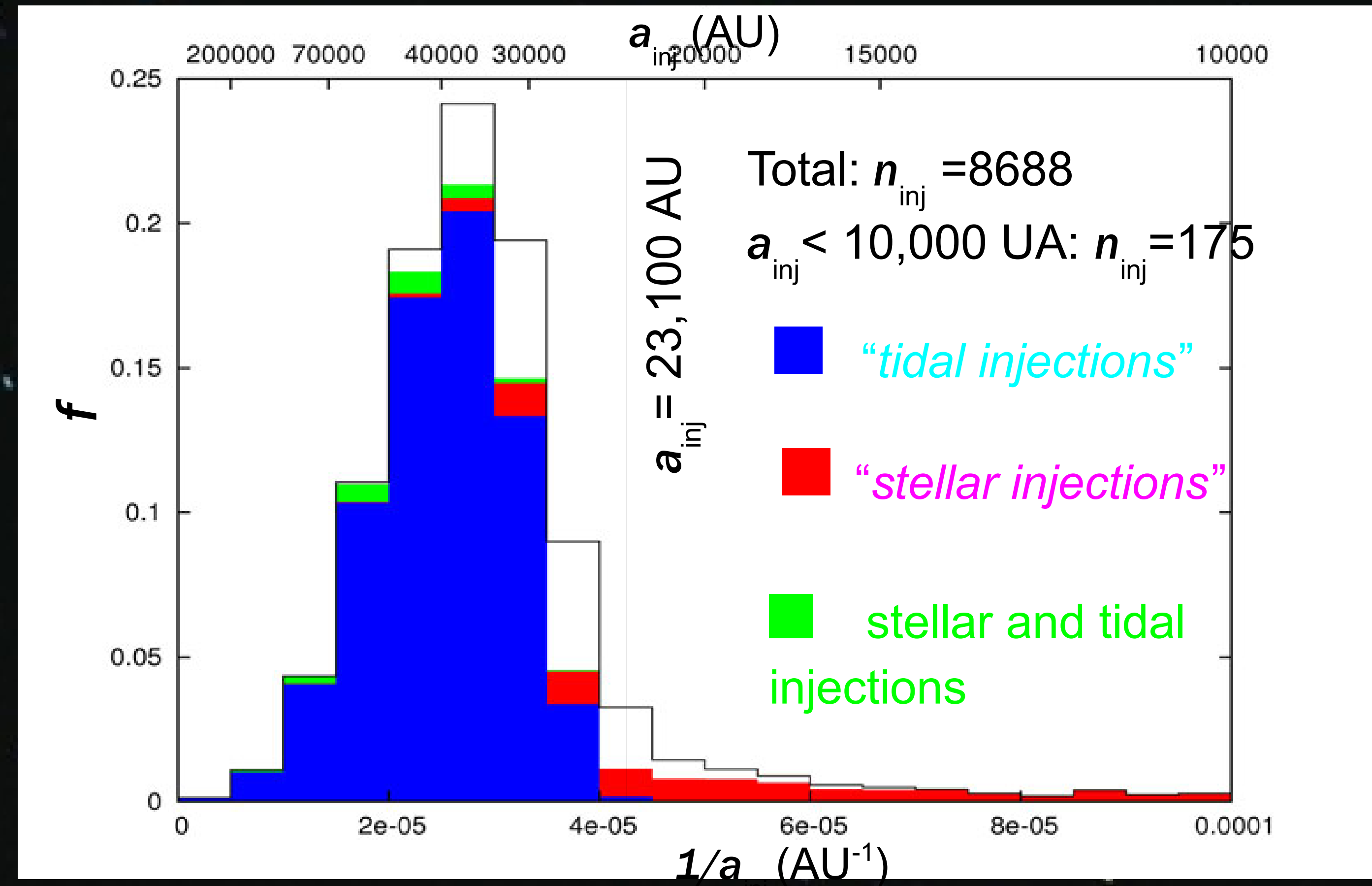
(adapté de Hestroffer)

The role of Galactic tide and stars in the "new" comets flux:

At a_{inj} = 35,000 UA ~15% require a stellar contribution!

At a_{inj} > 40,000 AU the injections are mainly tidal

From 15,000 to 40,000 AU, 26% of the injections are due to a synergy



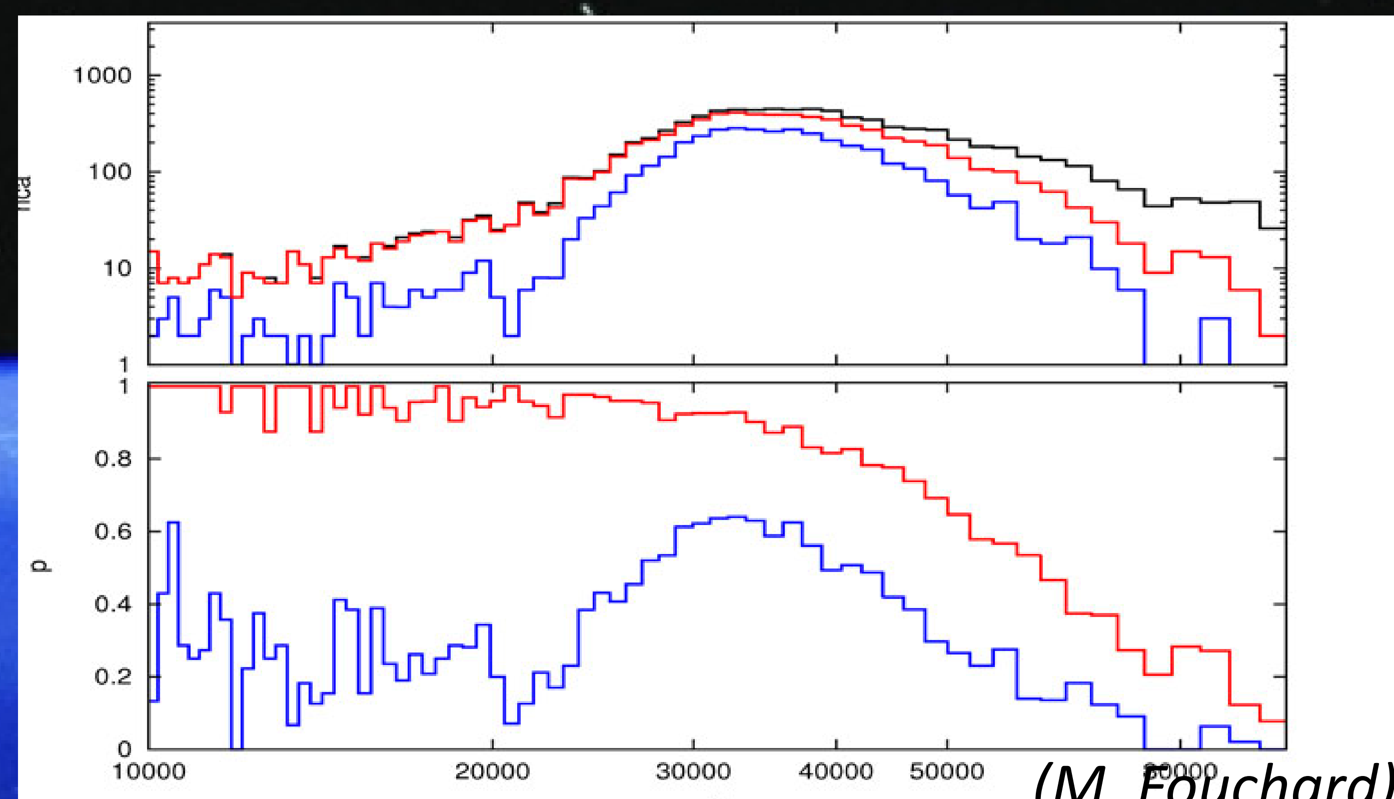
The flux using only stars observable by Hipparcos or GAIA:

Number (or proportion) of injected comets when:

- all the stars are included (reference)
- only the GAIA stars
- only the Hipparcos stars

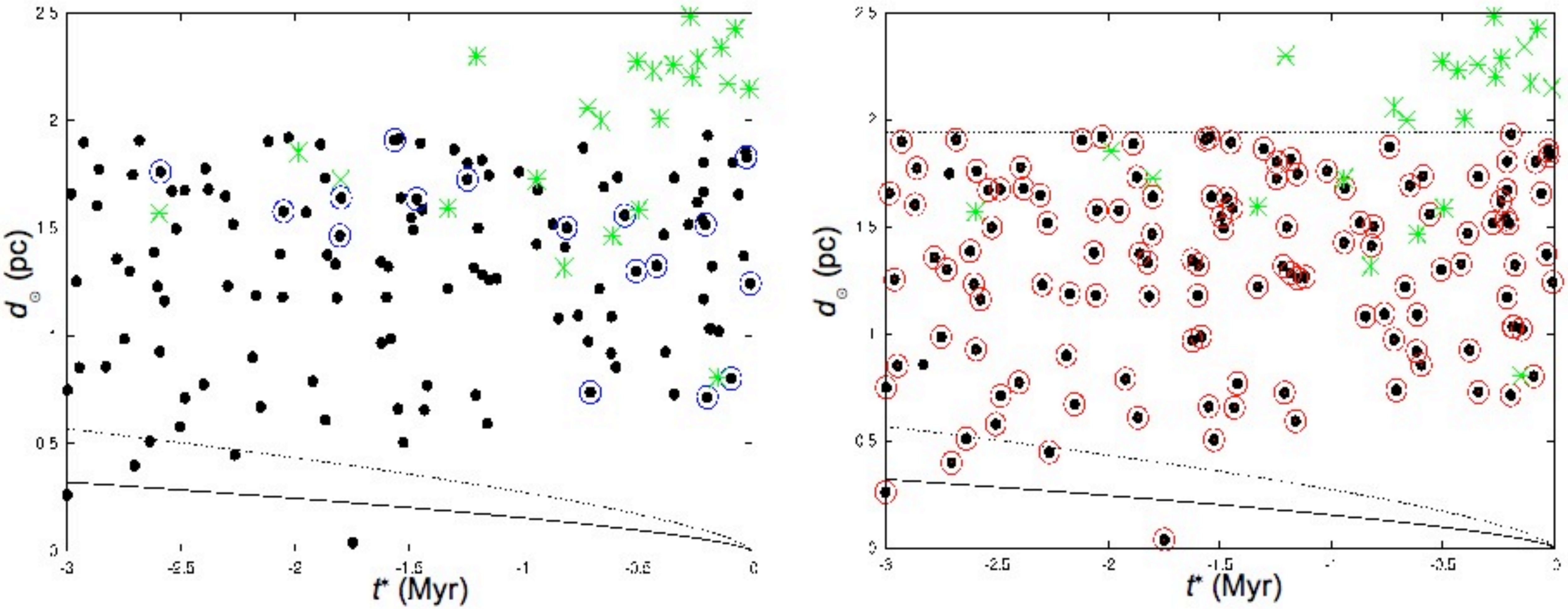
GAIA stars yield an almost complete flux for a_{inj} < 40,000 AU

Hipparcos stars yield at max 60% of the flux near 30,000 AU



(M. Fouchard)

Star detection by Hipparcos/Gaia



- passing stars with $d_\odot$ < 400,000 UA and perihelion passage t^* less than 3 Myr before present time
- Heliocentric distance of a comet on a parabolic orbit or at aphelion when it is at perihelion at present time.
- stars detected by Hipparcos
- stars detected by Gaia
- Dybczyński (2006) stars

Mouvements planétaires

et Lunaires

High precision
planetary and lunar ephemerides

References integations directly adjusted to observation (45 000 planetary obs + LLR)

JPL (NASA) integrations for 30 yrs : DE405-421
Russian solution (Pitjeva, 2001-10)

New solution (2008, 10) : INPOP06-08-10
(Fienga, Manche, Laskar, Gastineau et al ..)

The INPOP project Started in 2003

- INPOP = ASD/IMCCE/Observatoire de Paris and Observatoire de Besançon
- INPOP06 (Fienga et al. 2008)

INPOP08

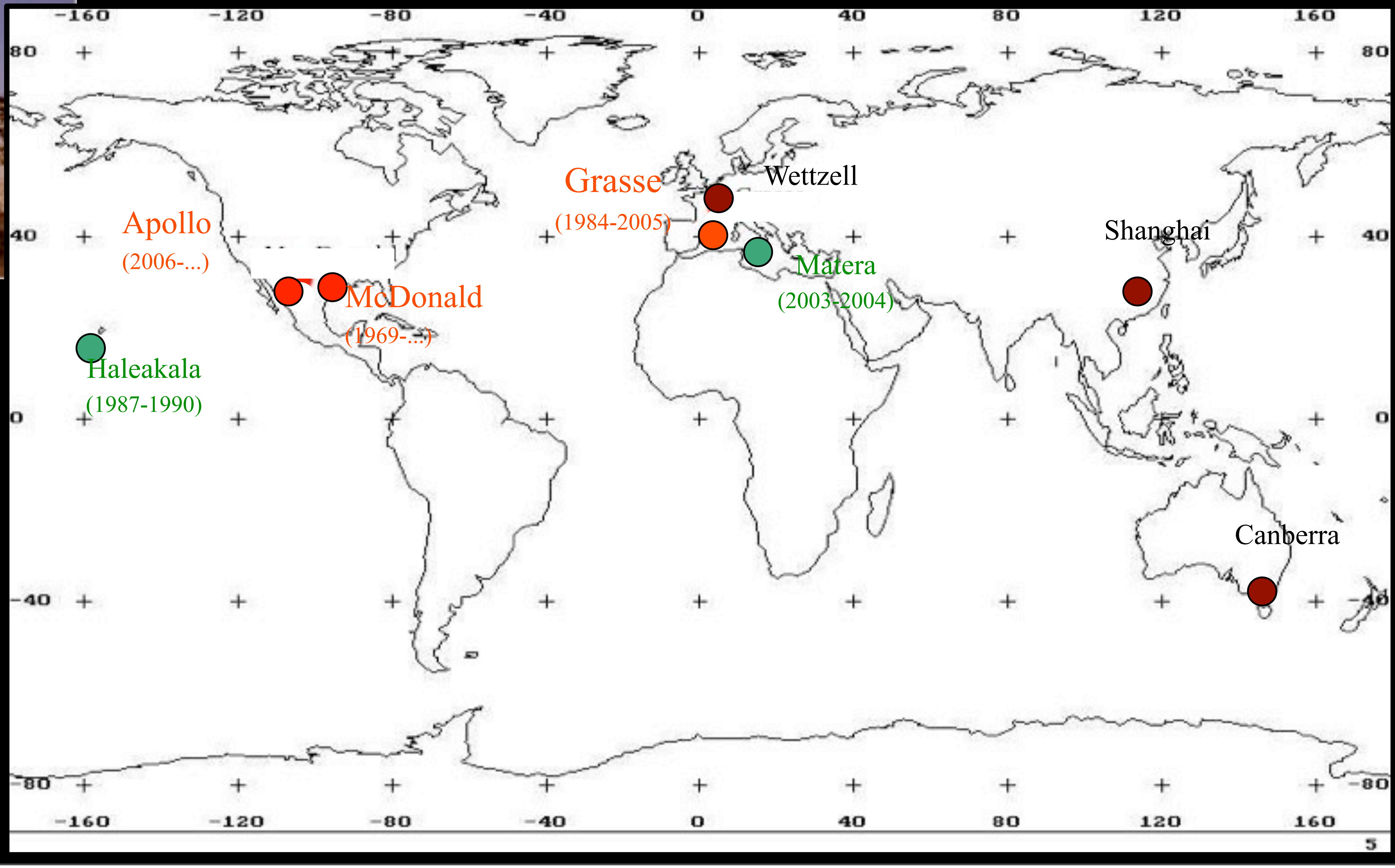
- Numerical integration with extended precision 80b
- Planets + Moon orbits, Earth and Moon Rotations, TT-TDB
- INPOP = official planetary ephemerides for GAIA + ESA Data release
- New data sets = (MEX+VEX+Cassini) + LLR
- (Fienga et al. 2009) and www.imcce.fr/inpop

INPOP10a (Fienga et al. 2010)

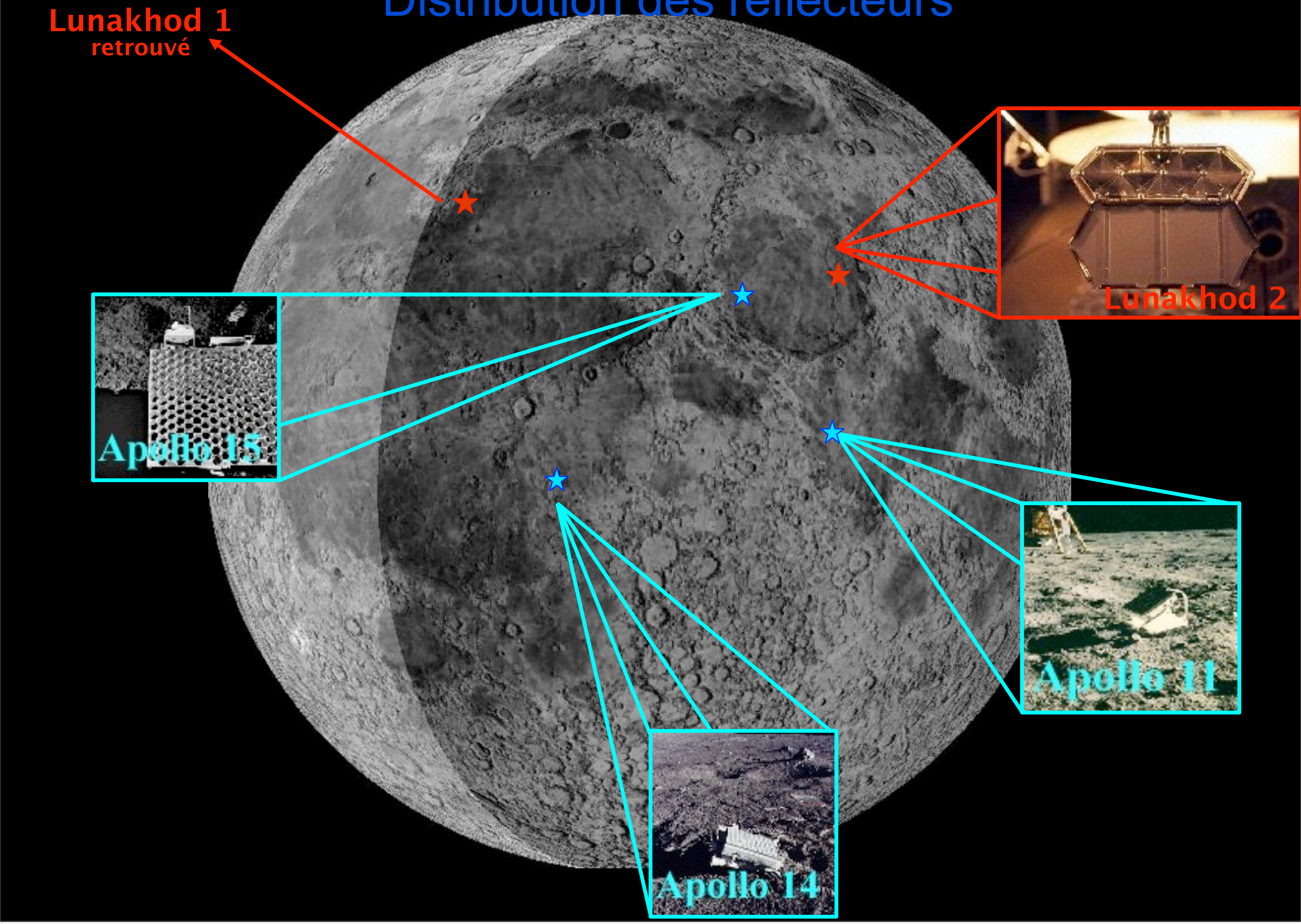
Test of gravitational models in the Solar System (exp. de A. Fienga)

- PPN β, J2
- Pioneer Anomaly
- Secular advances of perihelia and of nodes

Les stations Laser Lune

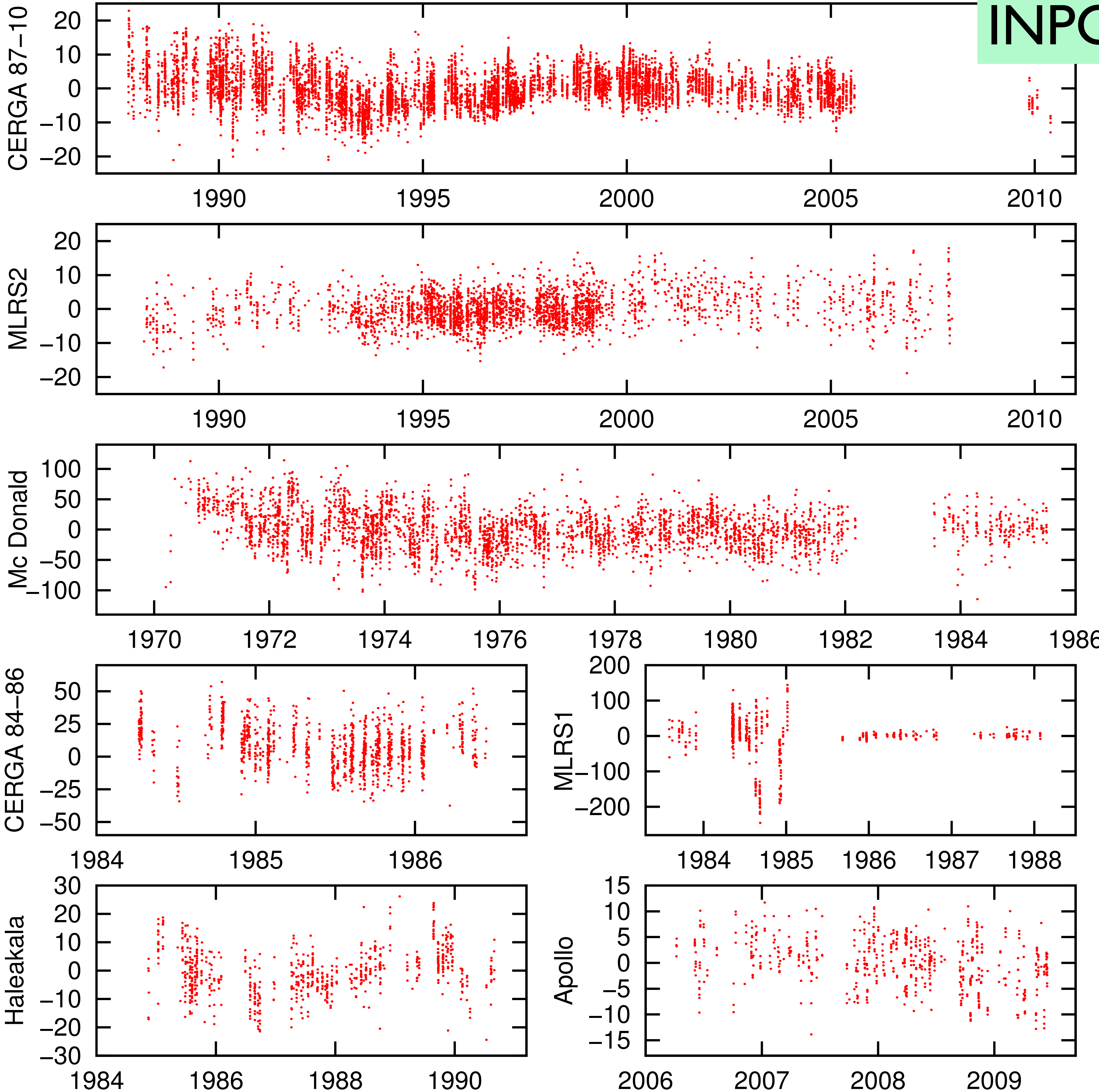


Distribution des réflecteurs



INPOP LLR residuals

(H. Manche, IMCCE, S. Bouquillon, SYRTE et al.)



Station	Période	INPOP10a	
		Moy.	Ecart-type
CERGA	1987-1995	-0.16	6.37
CERGA	1995-2010	-0.03	4.00
CERGA	1984-1986	8.11	16.00
Mc Donald	1969-1986	0.16	31.78
MLRS1	1982-1985	-7.89	73.28
MLRS1	1985-1988	0.22	7.30
MLRS2	1988-1996	-0.85	4.27
MLRS2	1996-2008	0.56	4.82
Haleakala	1984-1990	-0.44	8.10
Apollo	2006-2009	0.08	4.89

Encore des progrès à faire !

- libration de la lune ?
- orientation de la Terre ?
- autres effets géophysiques ?

Long time integrations
T >1 Myr

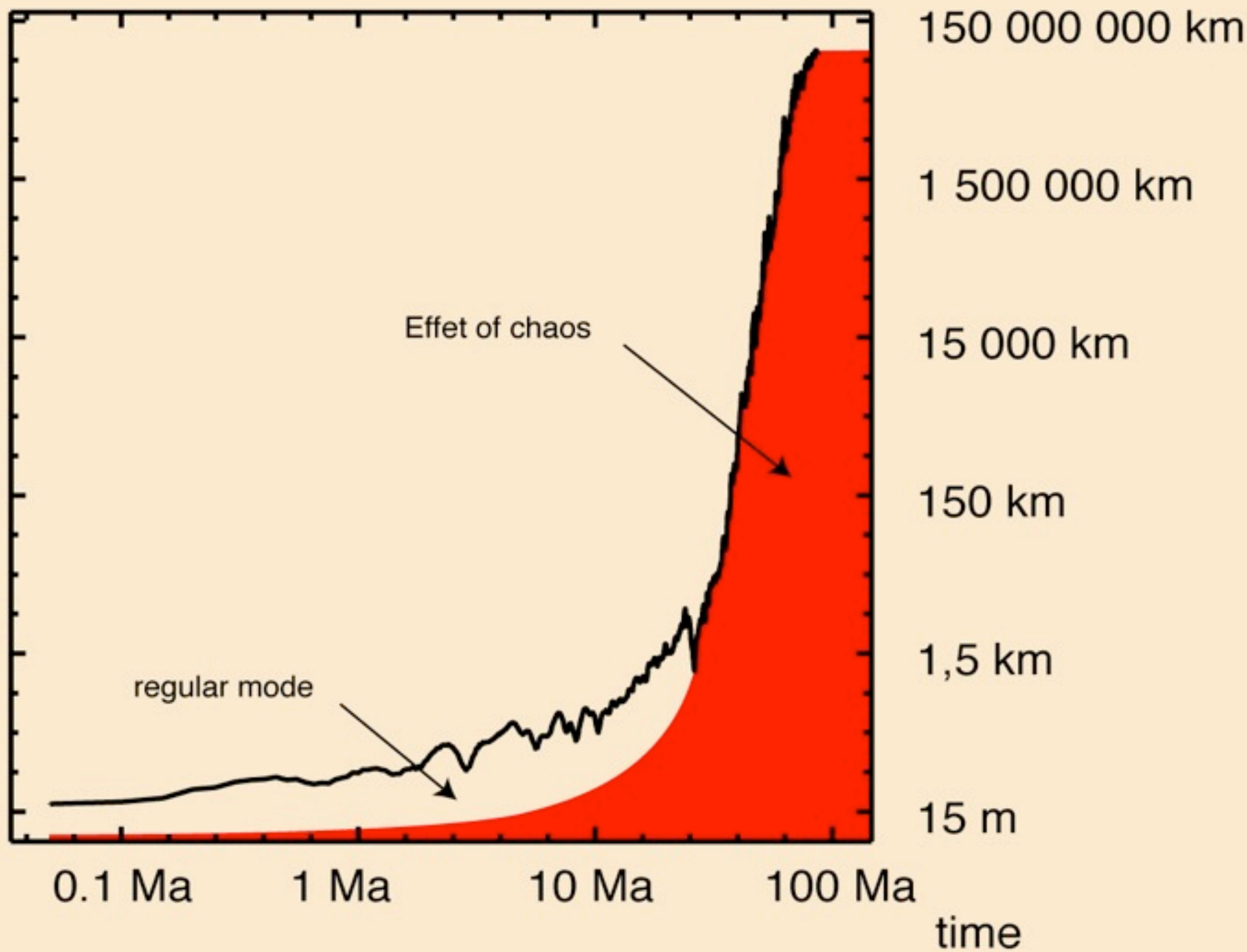
Numerical Integrations

Newton equations + relativity (model ~DE405)	T<1Myr	INPOP (2006-2010) Adams integrator h=0.055 days 7000 yr / 1 day
Newton equations + relativity (simplified model)	T>1Myr	La2004 (2004) symplectic integrator h=1.8625 days 5 Myr / 1 day

Chaotic motion of the Solar System

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

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



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

Système complet

8 Planètes + Pluton

Relativité générale

Contribution de la Lune

Recherche d'une faible probabilité ~1%

2500 solutions sur 5 Ga

CI : diff. de 0.38 mm dans le grand axe de Mercure

6-7 millions d'heures de calcul

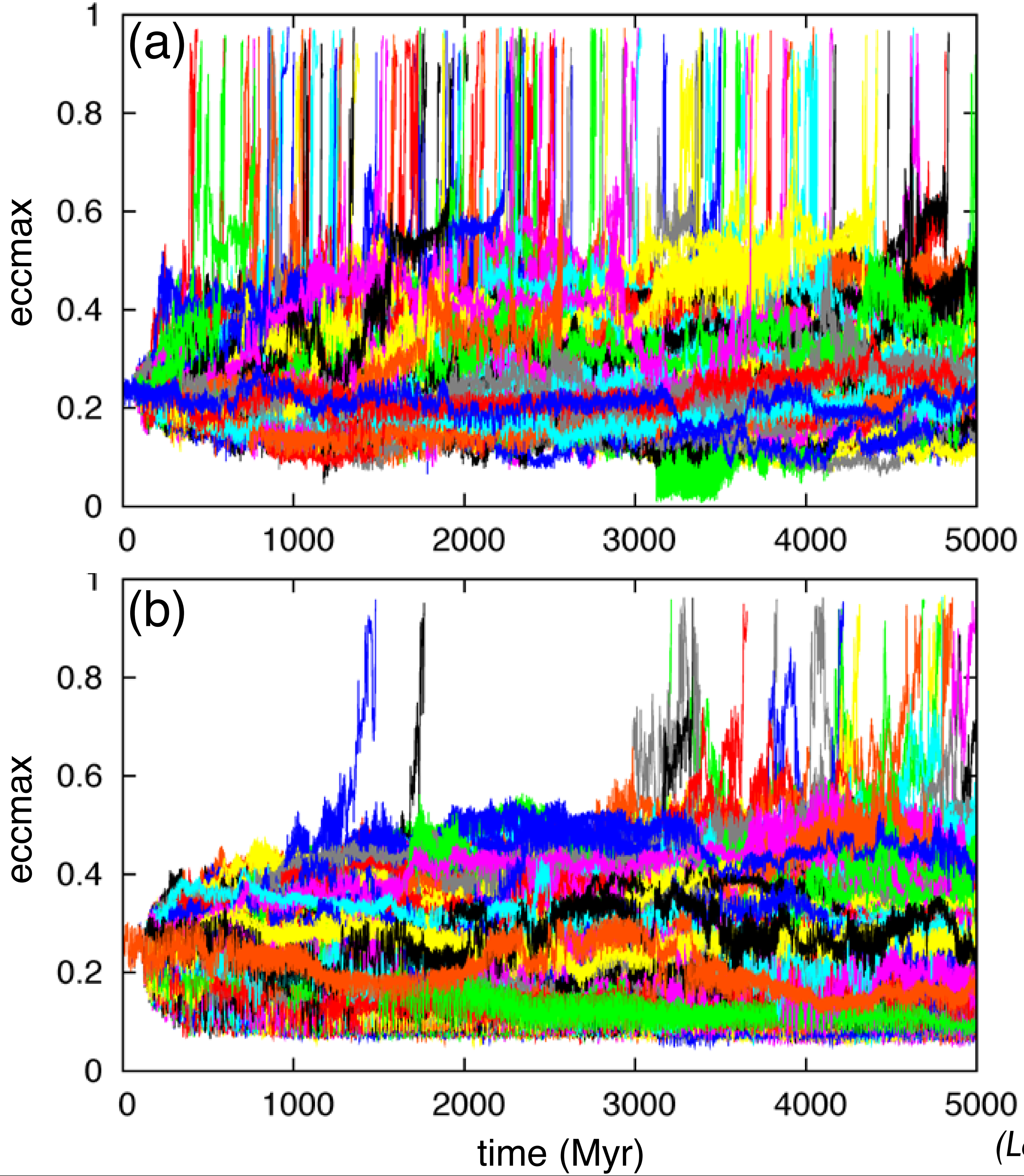
(Laskar & Gastineau, Nature, 2009)

Eccentricity of Mercury with relativity direct equations (2501 sol) scaled to 1000

	500	1000	2000	3000	4000	5000
0.35	30	91	202	318	418	492
0.4	3	20	67	126	189	255
0.5	-	-	3	10	20	40
0.6	-	-	1	2	5	10
0.7	-	-	1	1	4	9
0.8	-	-	1	1	4	8
0.9	-	-	1	1	3	8

Eccentricity of Mercury (No relativity)
direct equations (200 sol)
scaled to 1000

	500	1000	2000	3000	4000	5000
0.35	164	423	627	766	826	886
0.4	80	313	527	667	736	831
0.5	25	124	333	517	612	687
0.6	15	95	274	433	547	612
0.7	15	90	264	423	527	602
0.8	15	90	259	423	527	602
0.9	10	85	259	423	527	602

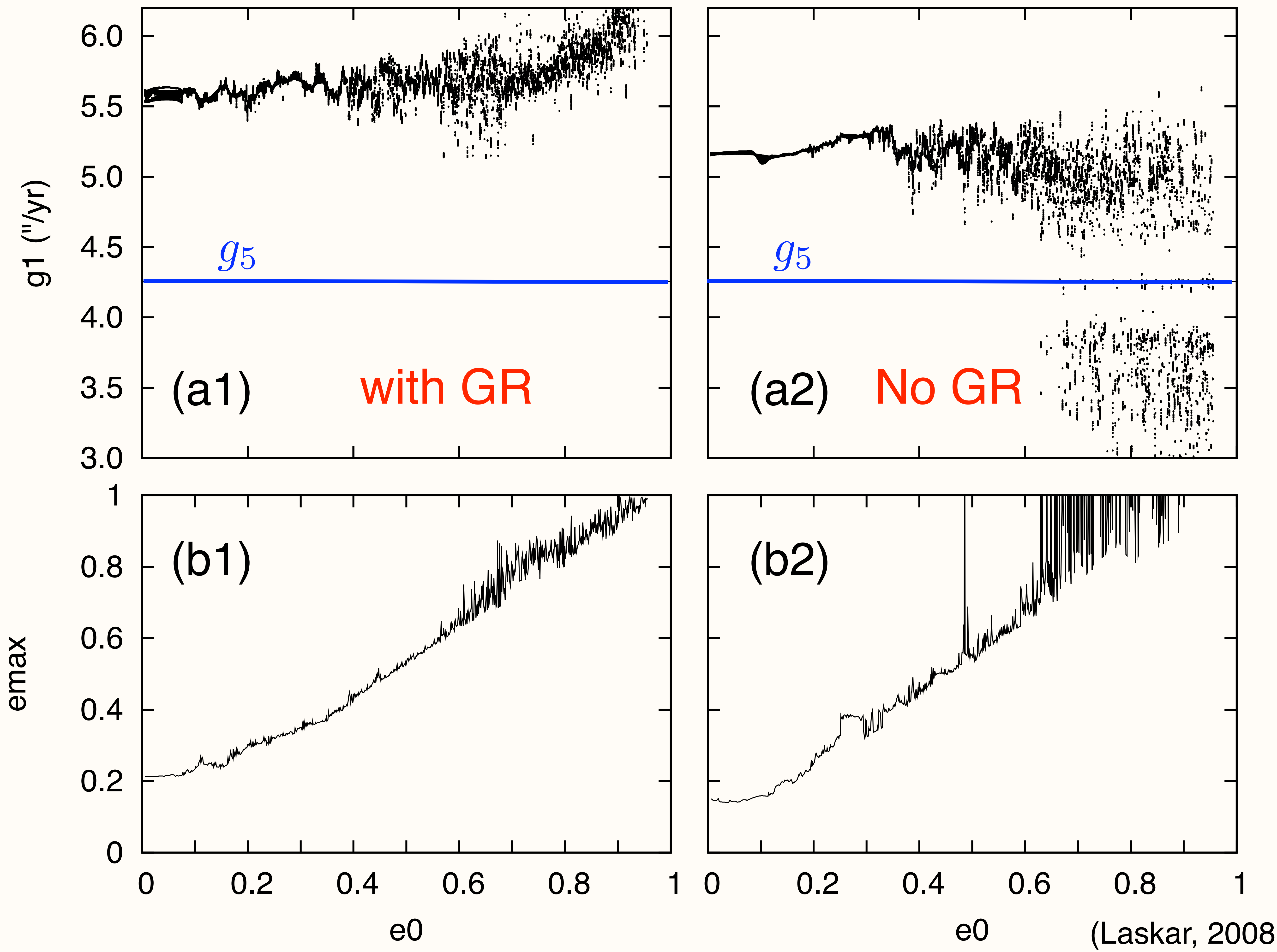


Mercury's eccentricity

201 sol.
No Relativity
(3.8 cm)

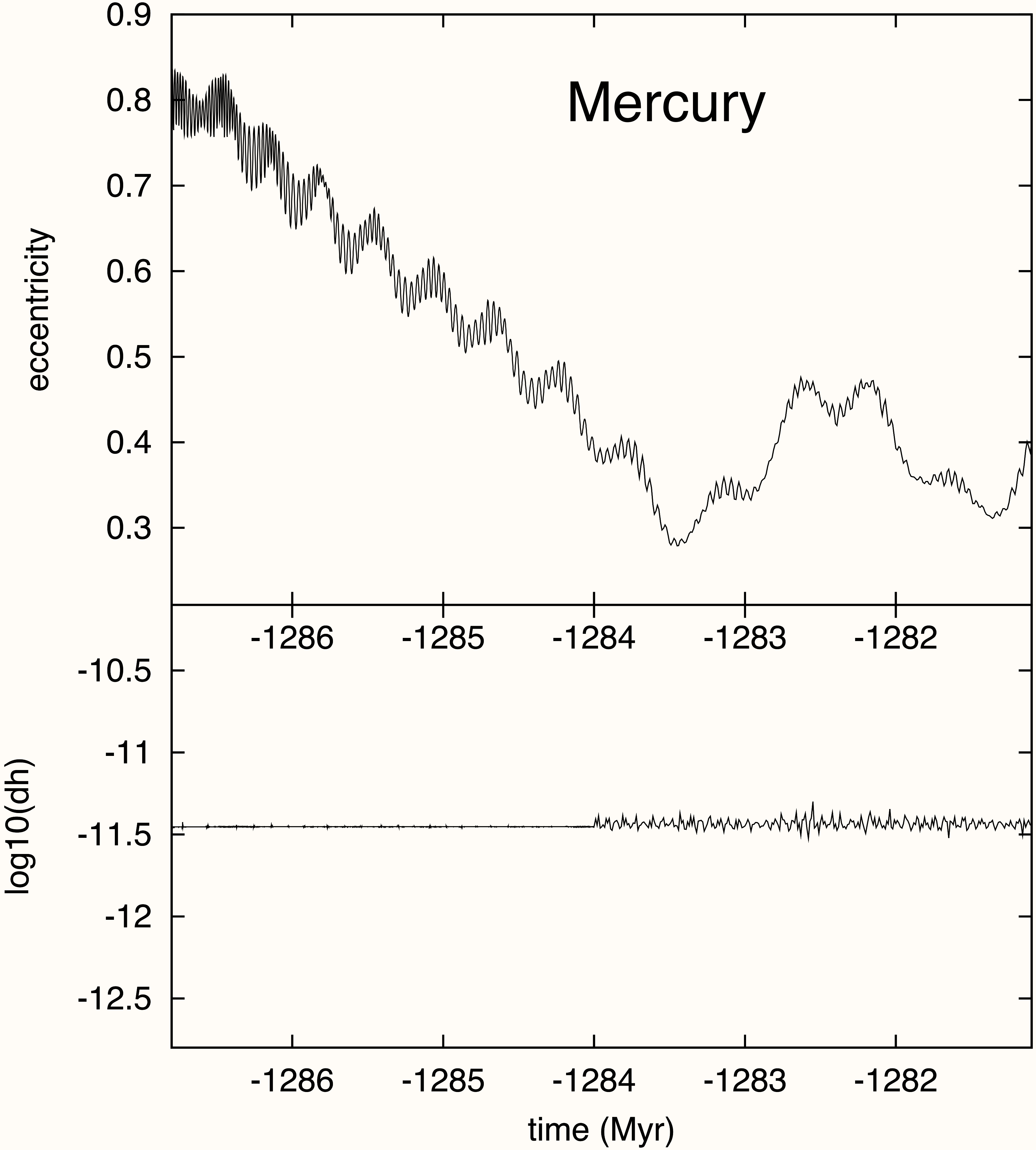
2501 sol.
With Relativity
(0.38 mm)

(Laskar & Gastineau, Nature, 2009)



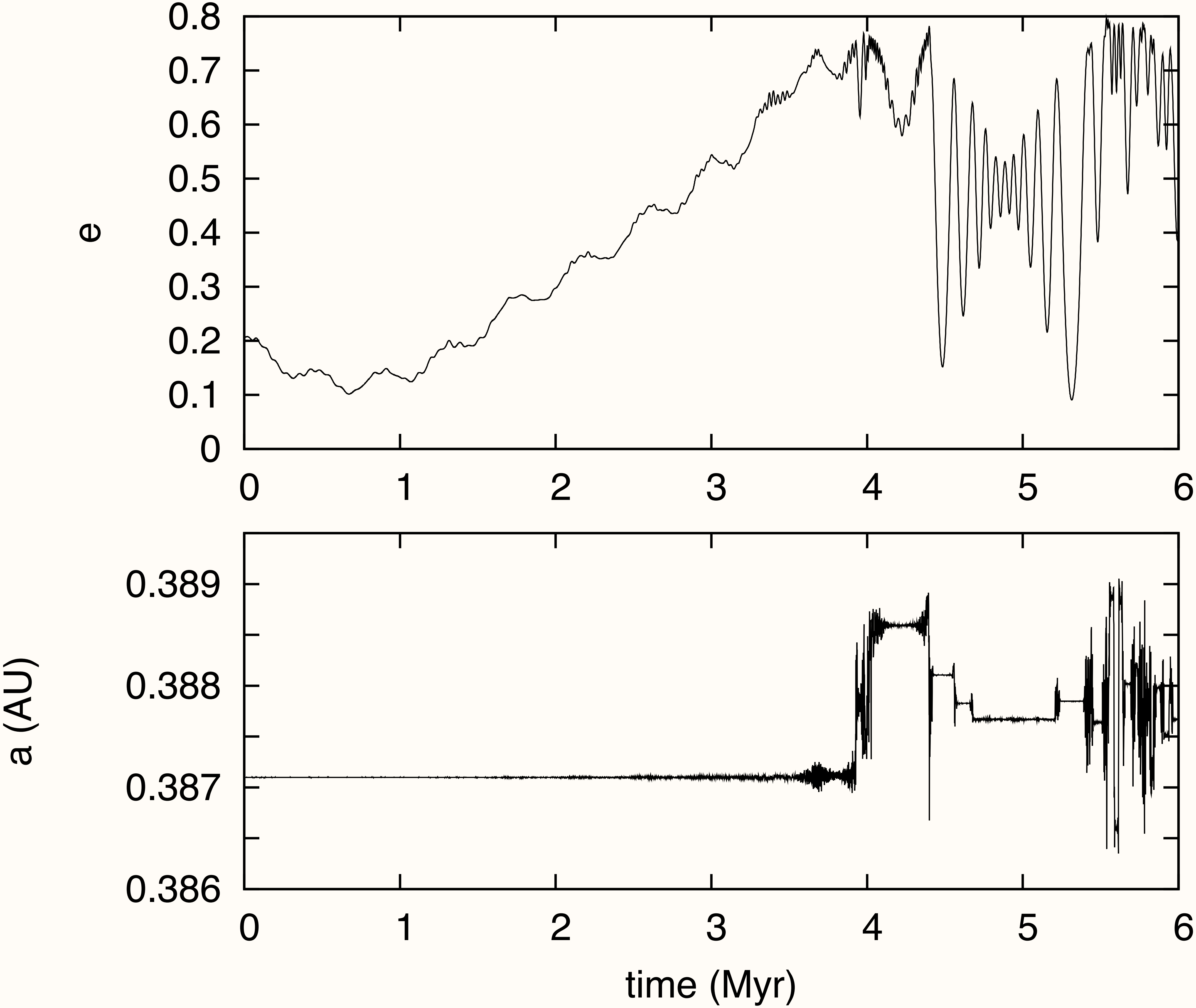
6.0
5.5
5.0
4.5
4.0
3.5
3.0
g1 ("/yr)
g_5
g_5
(a1)
with GR
(a2)
No GR
1
0.8
0.6
0.4
0.2
0
emax
(b1)
(b2)
0
0.2
0.4
0.6
0.8
1
e0
e0

(Laskar, 2008)


Mercury
eccentricity
0.9
0.8
0.7
0.6
0.5
0.4
0.3
-1286
-1285
-1284
-1283
-1282
log10(dh)
-10.5
-11
-11.5
-12
-12.5
-1286
-1285
-1284
-1283
-1282
time (Myr)

(Laskar, 2008)

$$2\gamma - \beta = -2$$



(Laskar, 2008)