Jacques Laskar

IMCCE, Observatoire de Paris

From chaos in planetary motions to the HL-LHC design

Rencontres du Vietnam, 2-12 August 2023

Is the Solar System Stable?

Jürgen Moser *(July 1928 - december 1999)*

In 1954 Kolmogorov indicated that, for certain mechanical systems, in some sense the "majority" of solutions are quasi-periodic. He indicated a possible method of solution but the actual proof was first provided by Arnold 8 years later, and, in a special case, by the author. In accordance with the modern usage this theory became known by the acronym KAM.

The Mathematical Intelligencer

volume 1 (1978), 65-71

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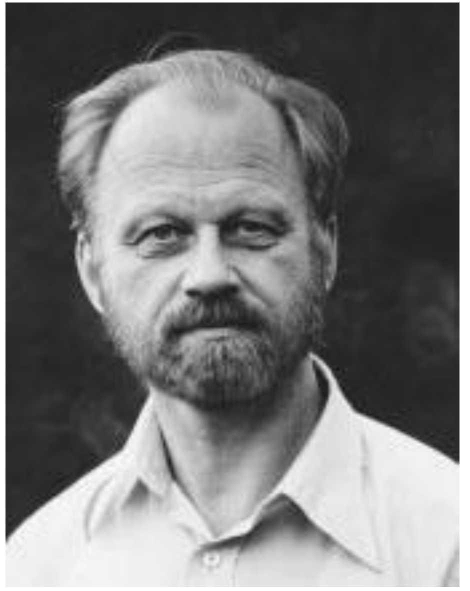

The mathematical theorems of KAM deal not only with the planetary system but also with general Hamiltonian systems.... One of these applications is the stability problem of proton accelerators, which since the 1950's have been built in every greater number and size.

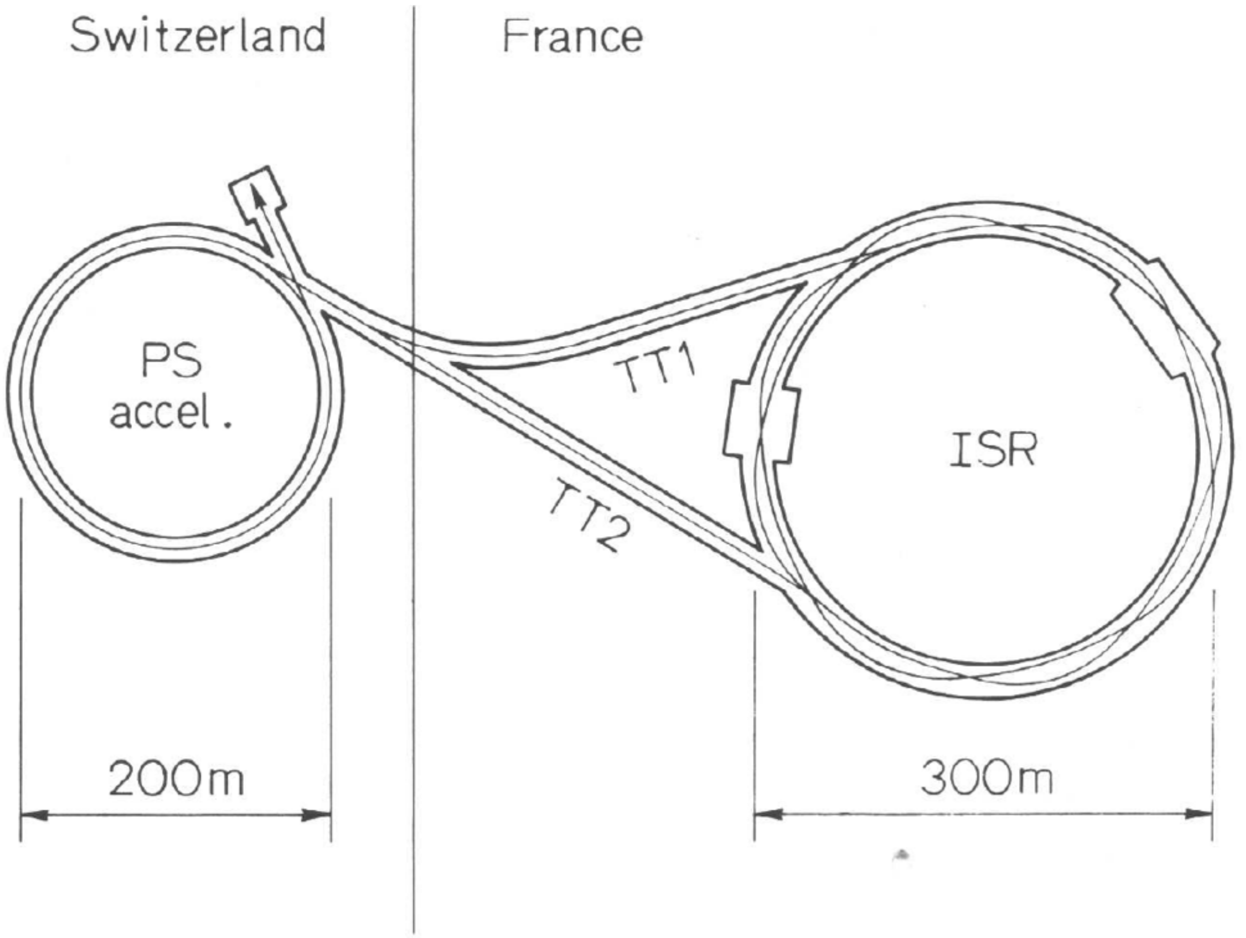

Figure 4 a. Cross-section of the vacuum chamber at the position of the beam inflector, with indication of the stacking process

The Mathematical Intelligencer *volume 1 (1978), 65-71*

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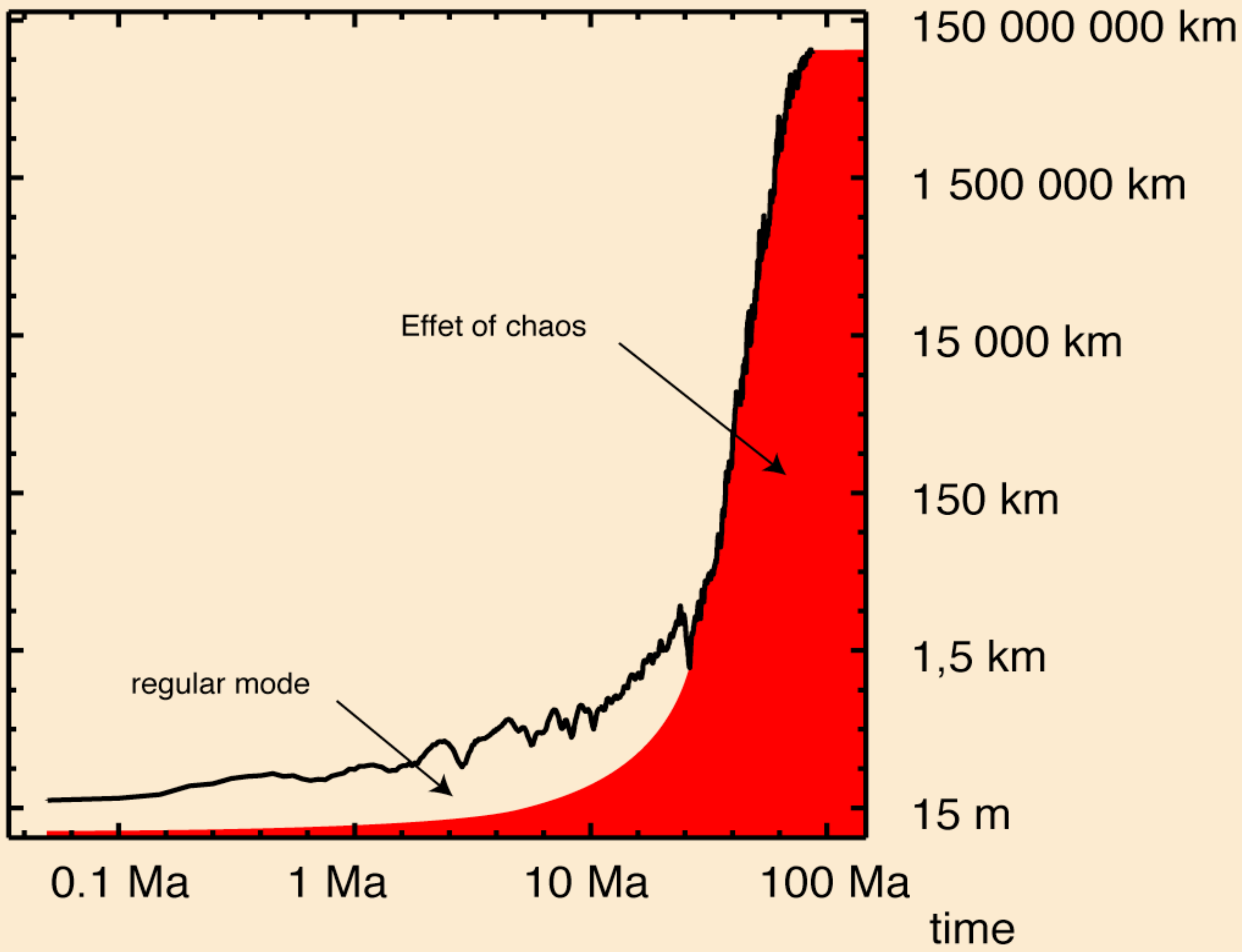
- Questioned by Poincaré (1892)
- Positive answer by Arnold (KAM) (1963)

Chaotic motion of the Solar System

Secular equations : 200 Ma : *J. Laskar (1989, 1990)*

Direct integration : 100 Ma : *J.G. Sussman & J. Wisdom (1992)*



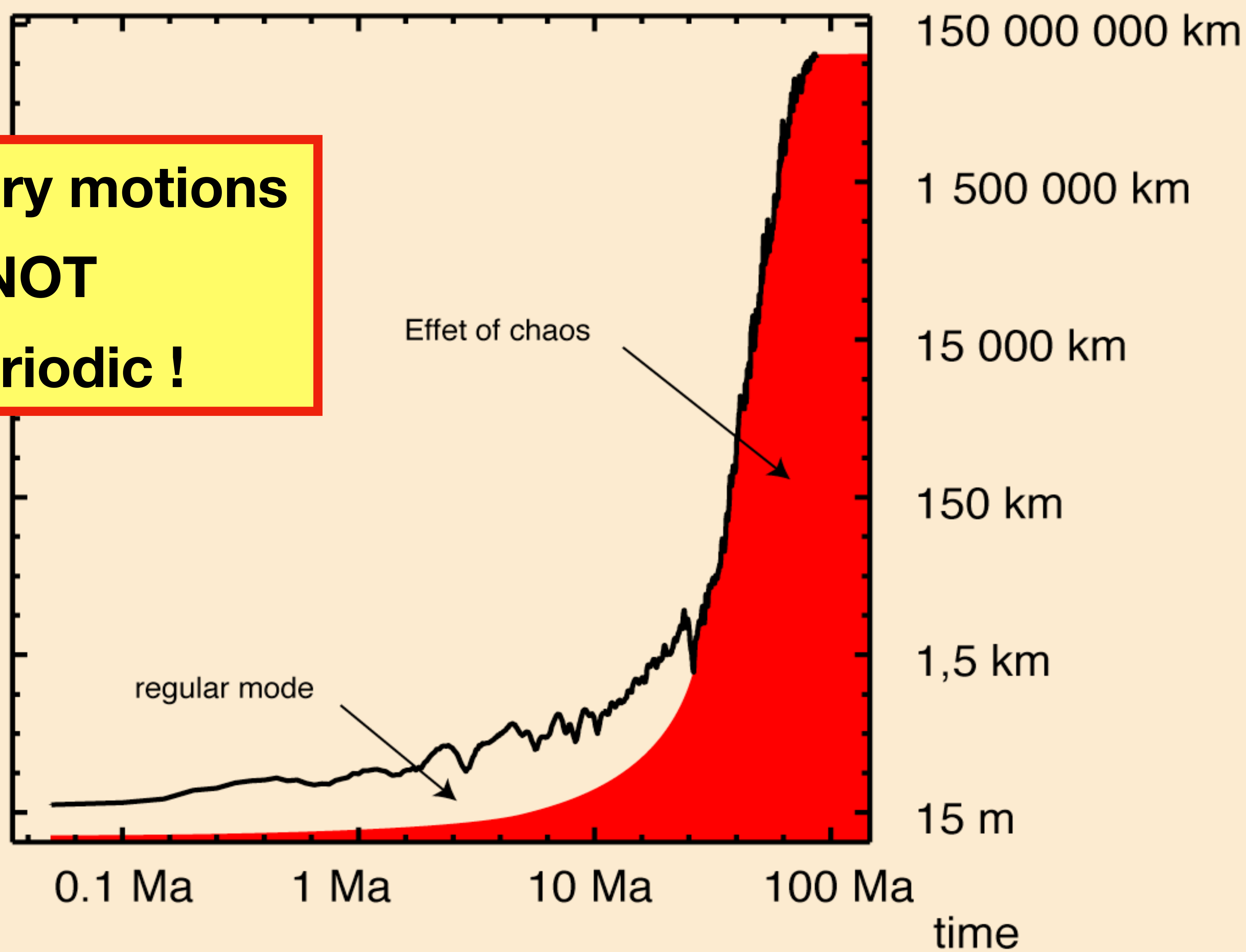
$$d(T) \approx d_0 10^{T/10}$$

Chaotic motion of the Solar System

Secular equations : 200 Ma : *J. Laskar (1989, 1990)*

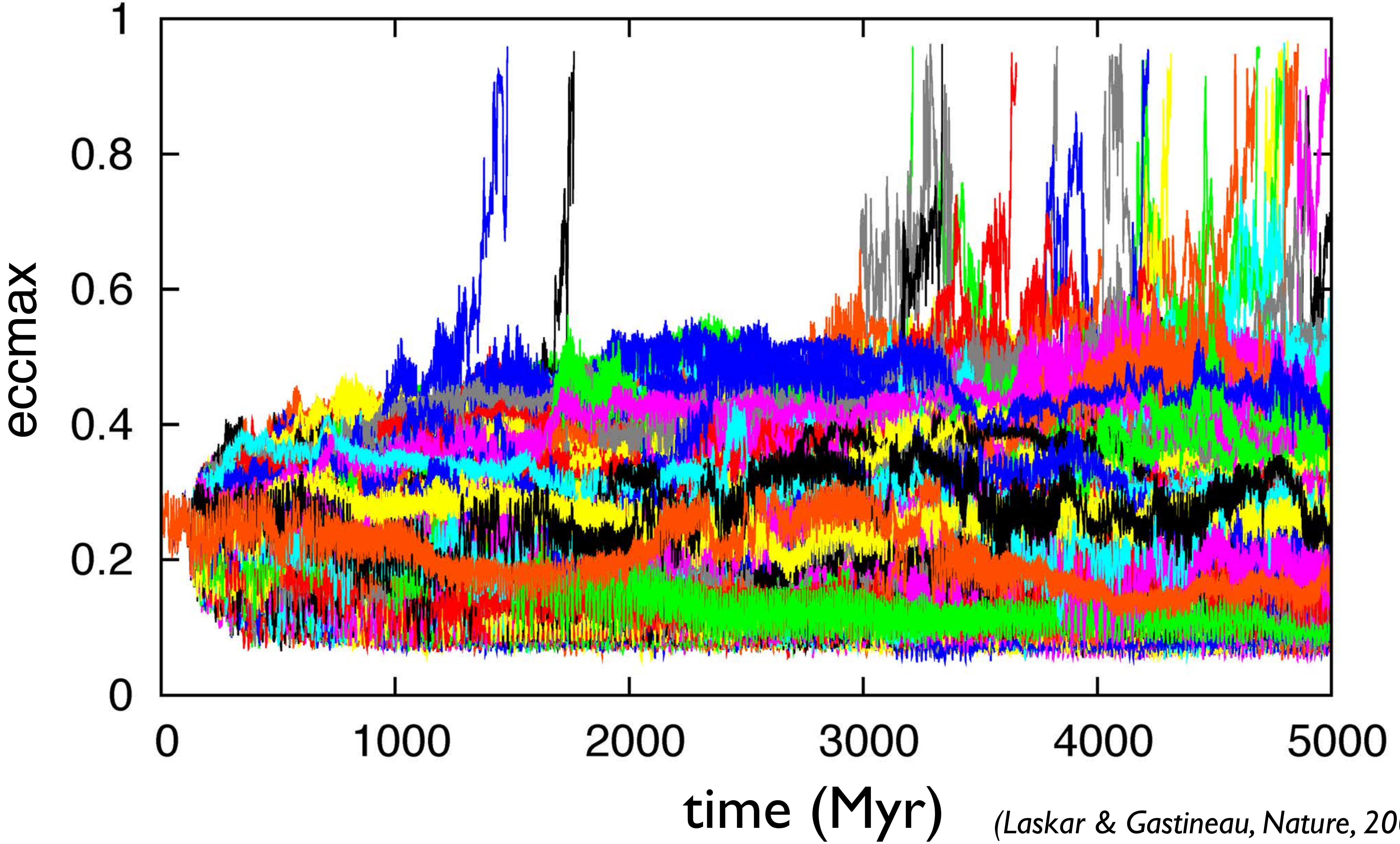
Direct integration : 100 Ma : *J.G. Sussman & J. Wisdom (1992)*

The planetary motions are NOT quasiperiodic !



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

Max eccentricity of Mercury WITH relativity
direct equations (2501 sol)
(0.38 mm)



(Laskar & Gastineau, Nature, 2009)

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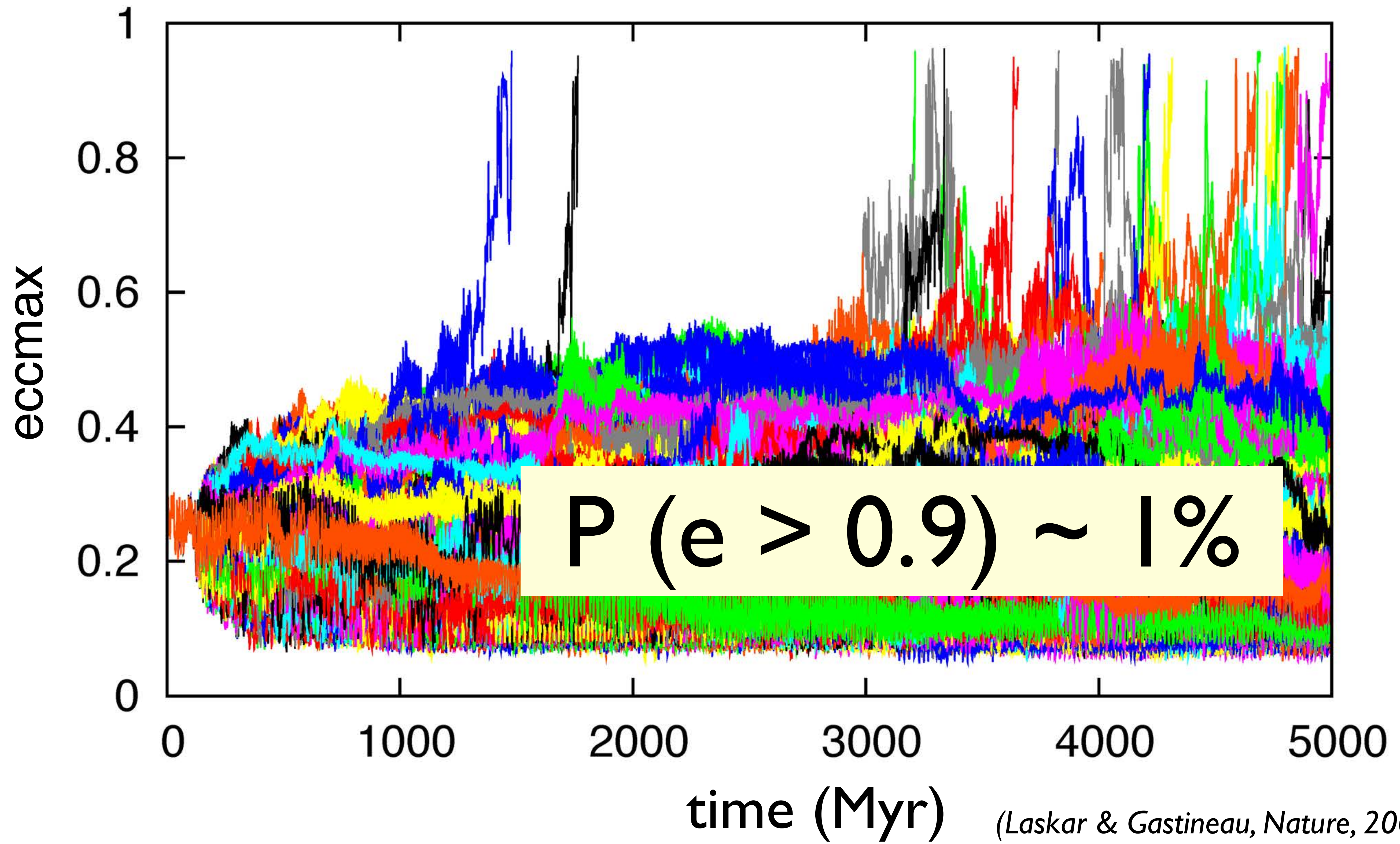

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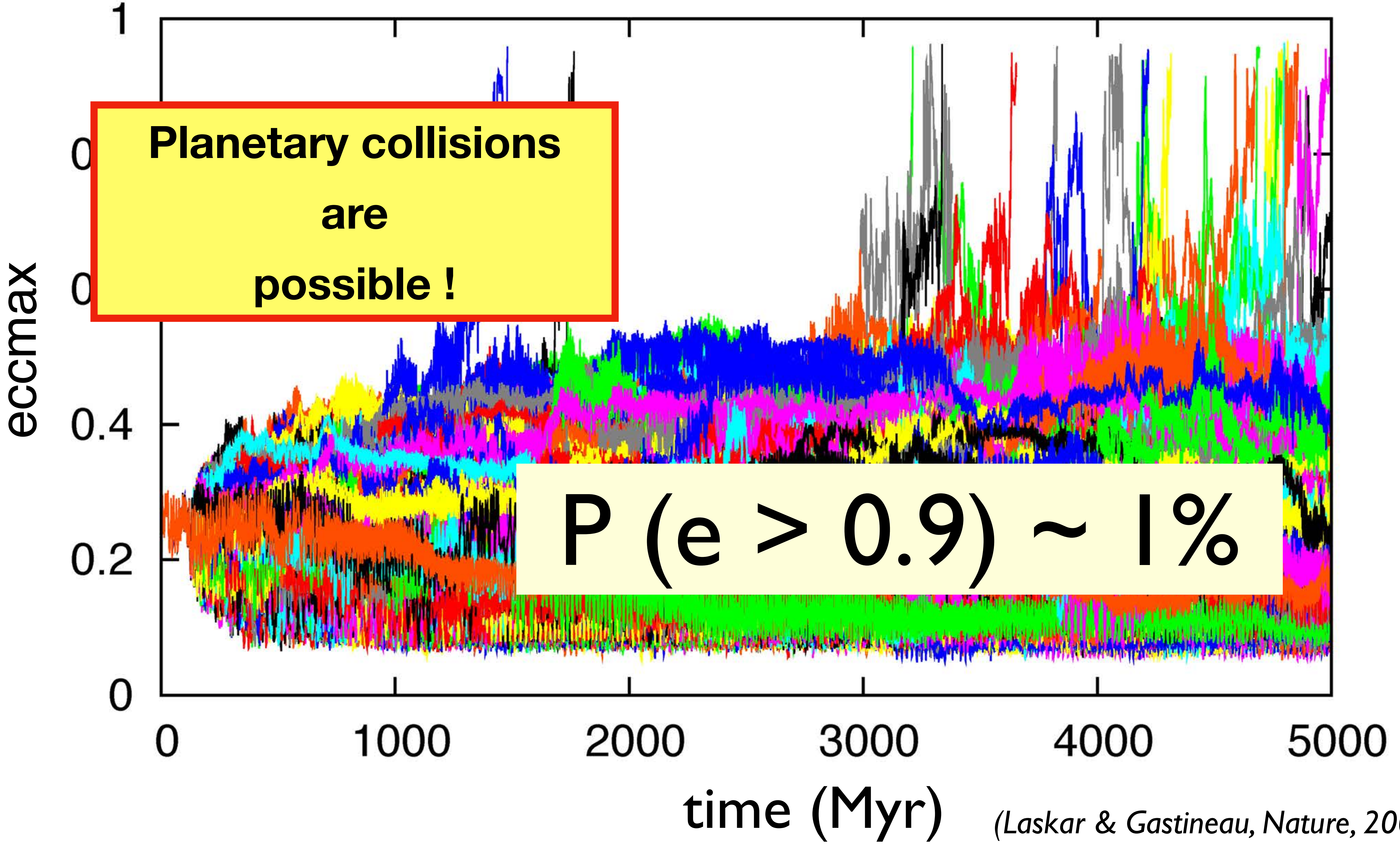
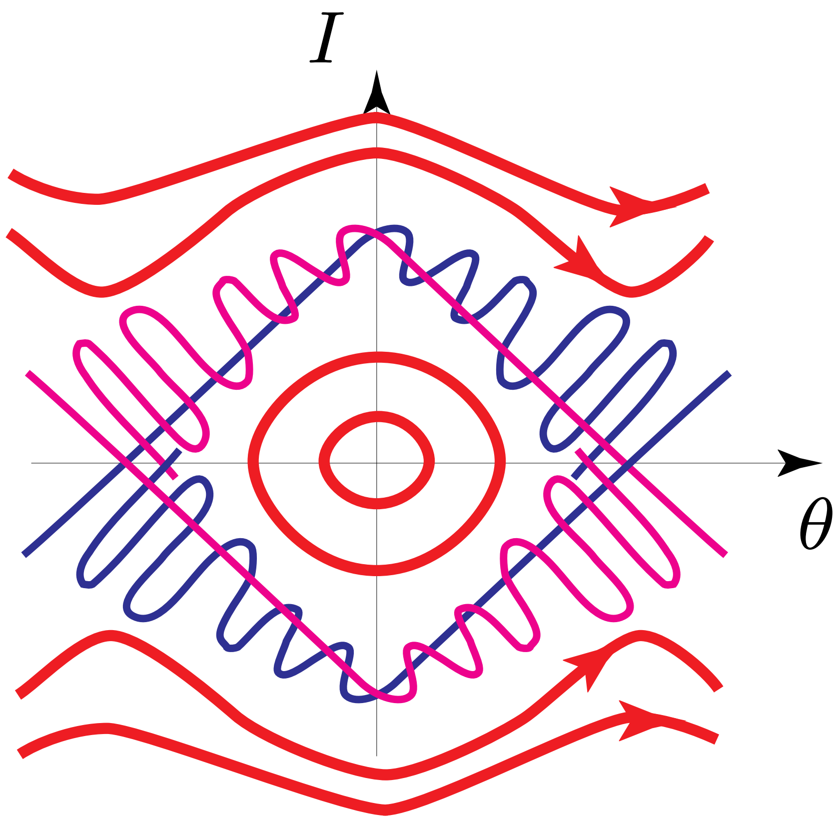


(Laskar & Gastineau, Nature, 2009)

Origin of CHAOS

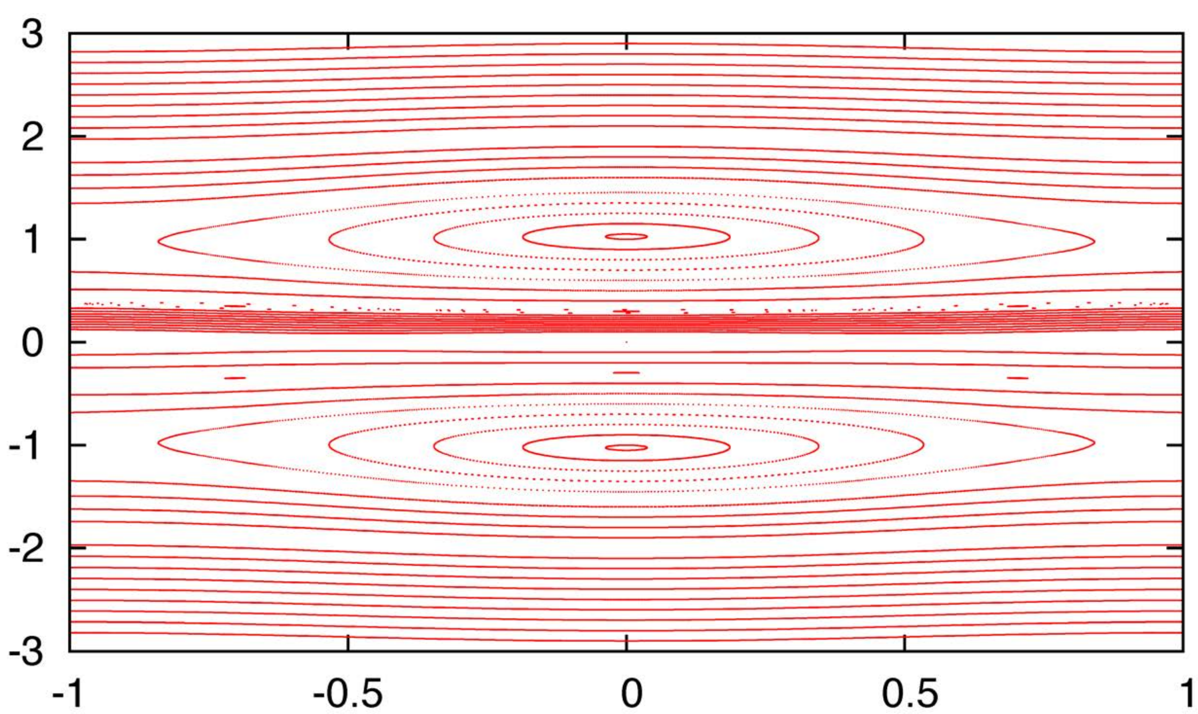
Resonance overlap

Chirokov (1972)

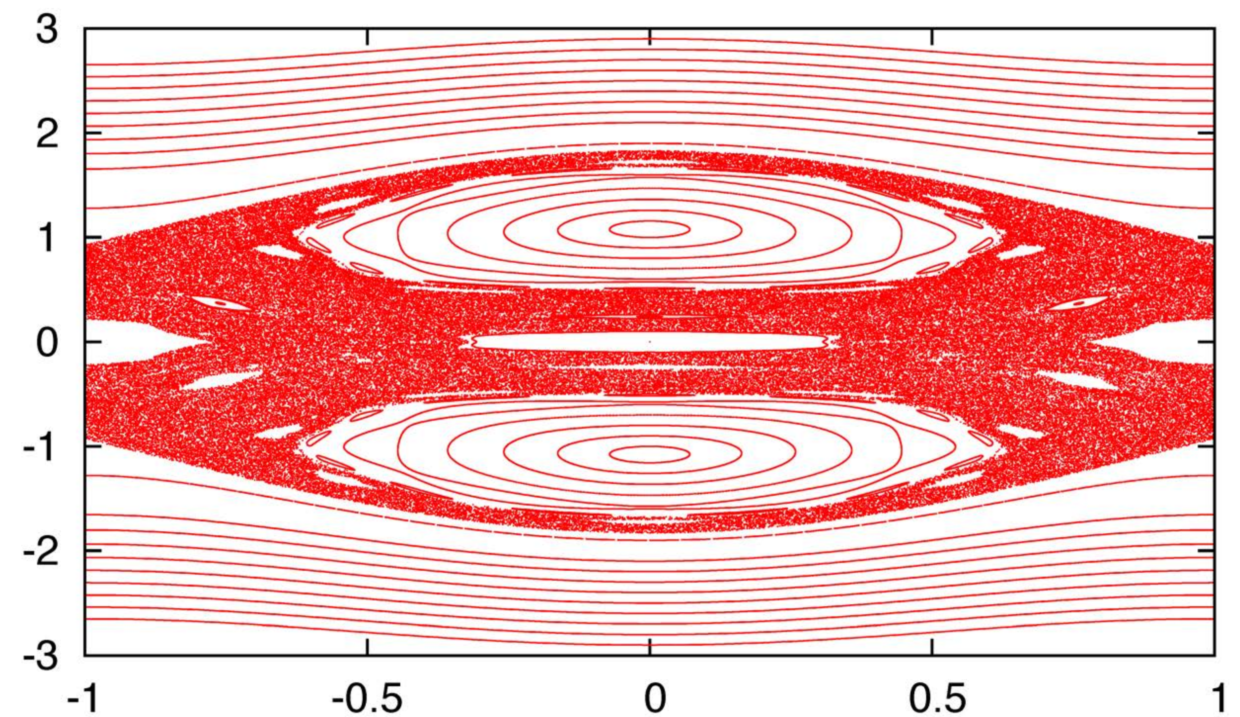


$$H = \frac{I^2}{2} + a\cos(\theta - t) + a\cos(\theta + t)$$

$$\Delta\omega = 4\sqrt{a}$$



a=0.05



a=0.15

Origin of CHAOS

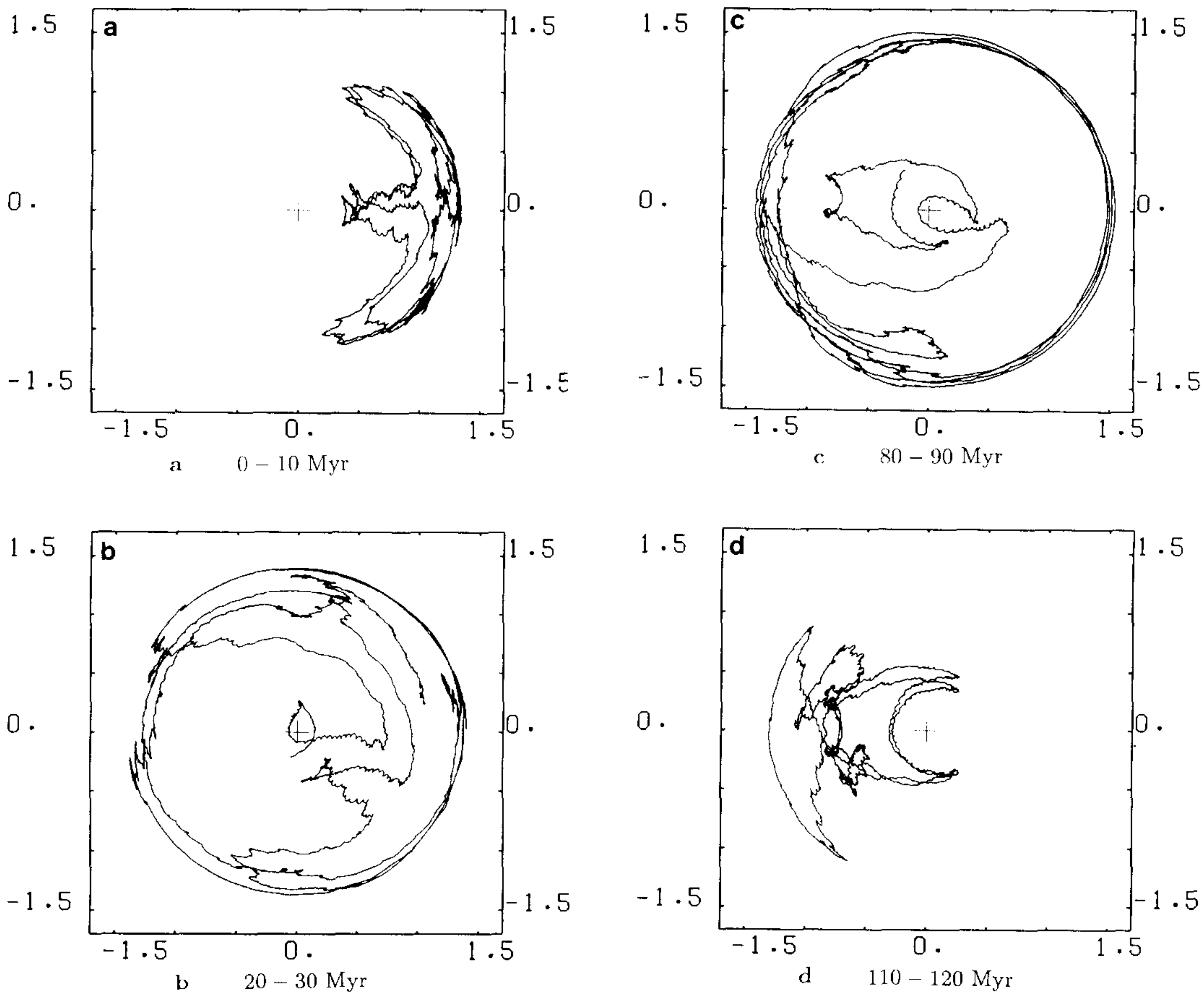


FIG. 3. (a–d) Examples of transition from libration around 0° (a) to circulation (b), and from circulation (c) to libration around 180° for the argument $2(\varpi_4^* - \varpi_3^*) - (\Omega_4^* - \Omega_3^*)$. The quantity which is actually plotted in the complex plane is $z_{04}^* \exp i(2(\varpi_4^* - \varpi_3^*) - (\Omega_4^* - \Omega_3^*))$ (Eq. (26)).

$$2(g_4 - g_3) - (s_4 - s_3)$$

(Laskar, 1990)

Origin of CHAOS

Astronomy & Astrophysics

LETTER TO THE EDITOR

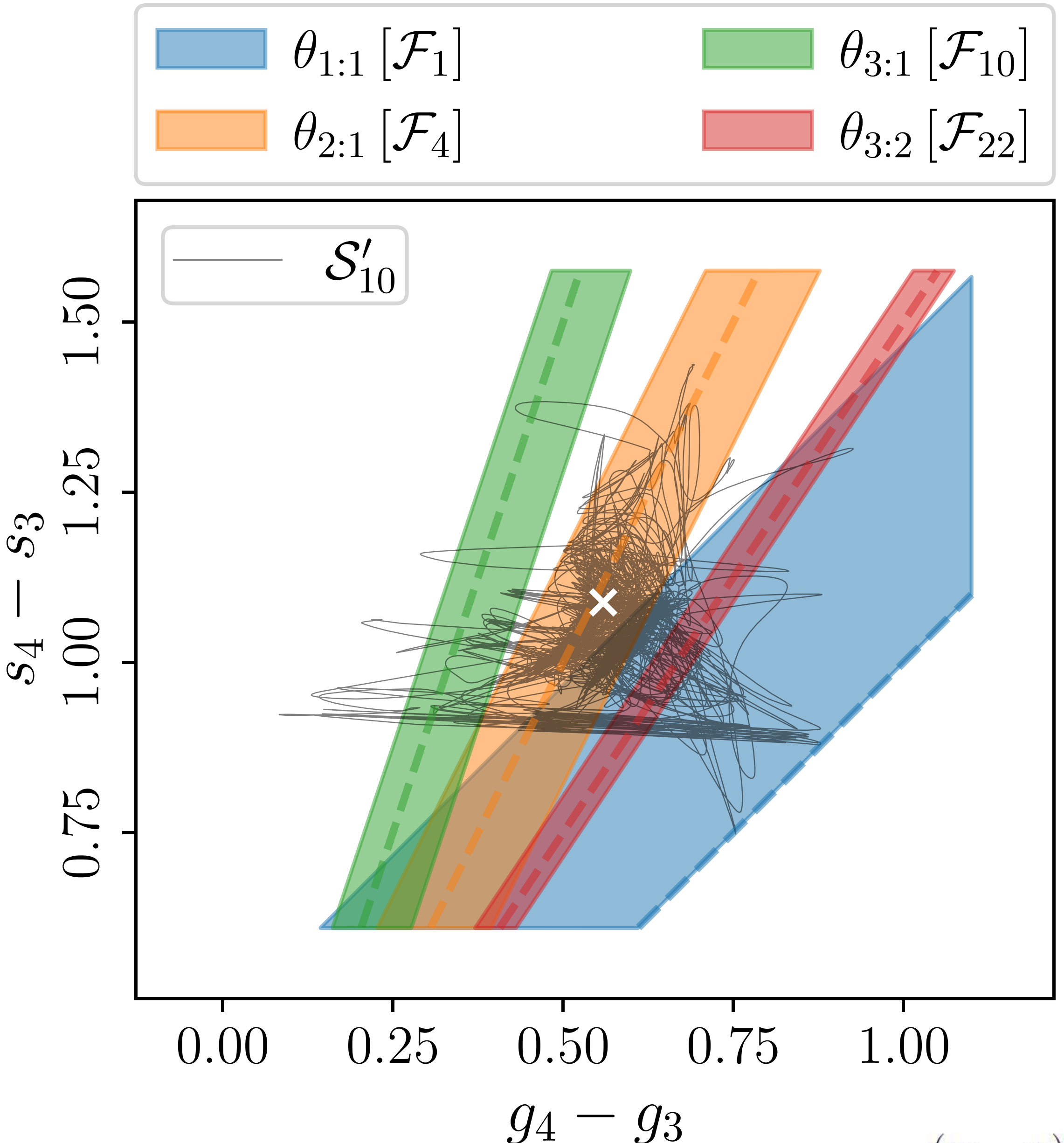
(9 May 2022)

The origin of chaos in the Solar System through computer algebra

Federico Mogavero and Jacques Laskar

Deg	2	4	6	8	10
N monomials	8	6304	188024	3 394 892	42 817 100

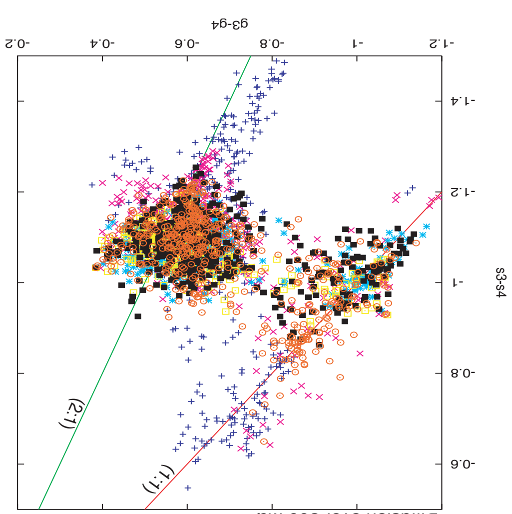
i		Fourier harmonic $[\mathcal{F}_i]$	ω_{hyp}	τ_{res}	ω_{ell}	τ_{libr}	$\Delta\omega$
1	★	$g_3 - g_4 - s_3 + s_4$	$0.31^{0.67}_{0.08}$	12%	$0.65^{1.56}_{0.26}$	18%	$0.33^{0.53}_{0.09}$
2	†	$g_1 - g_2 + s_1 - s_2$	$0.38^{0.79}_{0.12}$	19%	$0.89^{1.34}_{0.26}$	26%	$0.30^{0.61}_{0.15}$
3	†	$g_2 - g_5 - 2s_1 + 2s_2$	$0.22^{0.33}_{0.07}$	23%	$0.33^{0.45}_{0.16}$	56%	$0.11^{0.22}_{0.04}$
4	★	$2g_3 - 2g_4 - s_3 + s_4$	$0.14^{0.36}_{0.04}$	70%	$0.43^{0.73}_{0.23}$	74%	$0.08^{0.16}_{0.02}$
5	†	$g_1 - g_5 - s_1 + s_2$	$0.08^{0.10}_{0.05}$	10%	$0.22^{0.28}_{0.14}$	63%	$0.07^{0.18}_{0.06}$
6		$g_2 - g_4 + s_2 - s_4$	$0.07^{0.09}_{0.04}$	6%	$0.07^{0.09}_{0.05}$	70%	$0.07^{0.10}_{0.03}$
7		$g_1 - 2g_2 + g_4 + s_1 - 2s_2 + s_4$	$0.11^{0.13}_{0.10}$	5%	$0.12^{0.13}_{0.11}$	69%	$0.06^{0.07}_{0.05}$
8		$g_1 - g_3 + s_2 - s_3$	$0.06^{0.09}_{0.03}$	17%	$0.06^{0.10}_{0.04}$	60%	$0.06^{0.09}_{0.03}$
9		$g_1 + g_3 - 2g_4 + s_2 - s_3$	$0.08^{0.09}_{0.06}$	5%	$0.08^{0.09}_{0.07}$	55%	$0.05^{0.06}_{0.04}$
10	★	$3g_3 - 3g_4 - s_3 + s_4$	$0.11^{0.34}_{0.01}$	9%	$0.14^{0.24}_{0.06}$	40%	$0.05^{0.14}_{0.01}$
11		$g_2 - g_3 - s_1 + 2s_2 - s_3$	$0.06^{0.07}_{0.04}$	5%	$0.06^{0.07}_{0.05}$	50%	$0.04^{0.05}_{0.03}$
12		$g_1 - 2g_3 + g_4 + s_2 - s_4$	$0.06^{0.12}_{0.03}$	36%	$0.06^{0.12}_{0.03}$	51%	$0.04^{0.08}_{0.02}$
13		$2g_1 - g_3 - g_5 + s_2 - s_4$	$0.05^{0.06}_{0.04}$	5%	$0.05^{0.06}_{0.04}$	52%	$0.04^{0.04}_{0.03}$
14		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



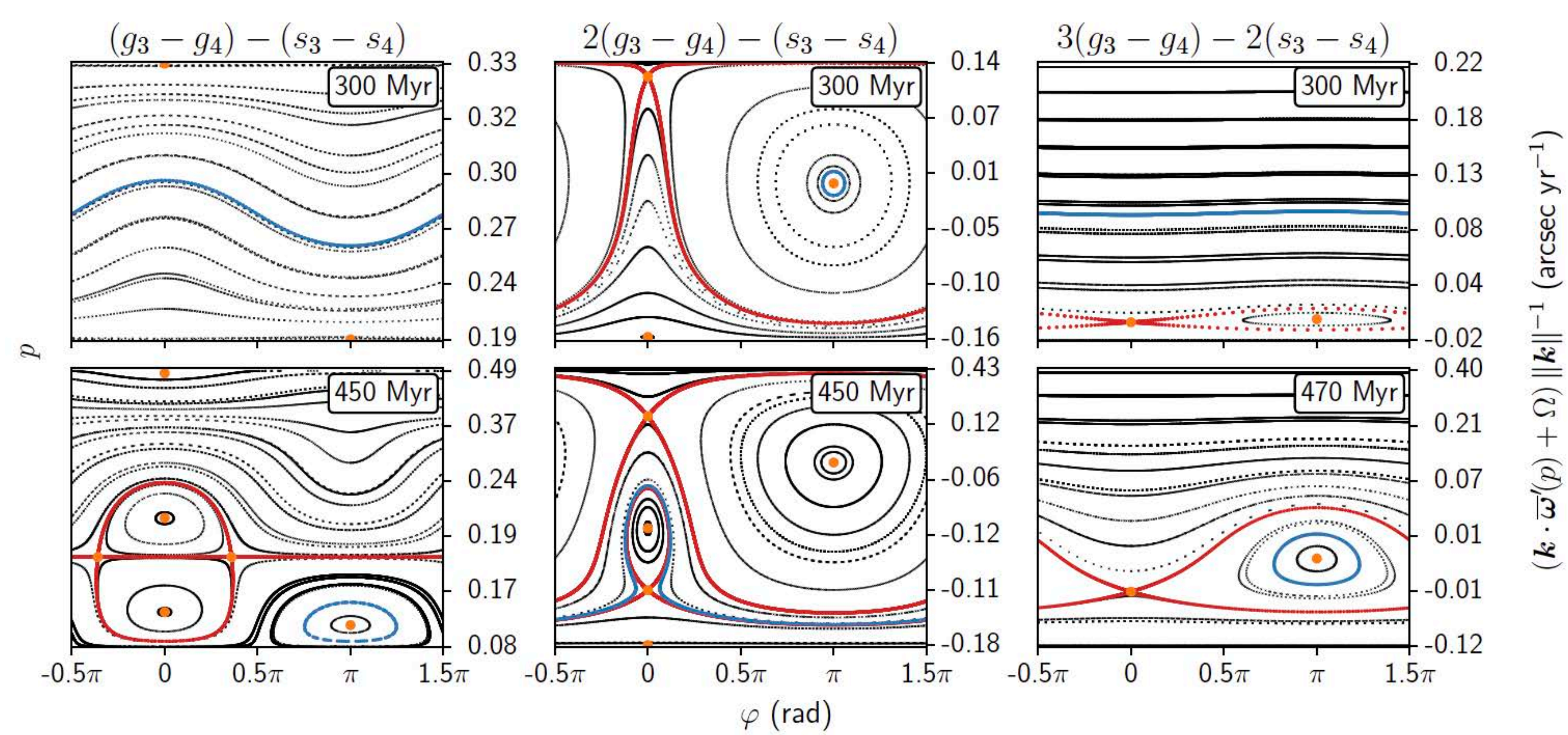
Mogavero & Laskar, 2021

Origin of CHAOS

$$\theta_{2:1} = 2(g_4 - g_3) - (s_4 - s_3)$$
$$\theta_{3:2} = (g_4 - g_3) - (s_4 - s_3)$$
$$\theta_{1:1} = (g_4 - g_3) - (s_4 - s_3)$$



Laskar, 200?



ICARUS 88, 266–291 (1990)

The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones

J. LASKAR

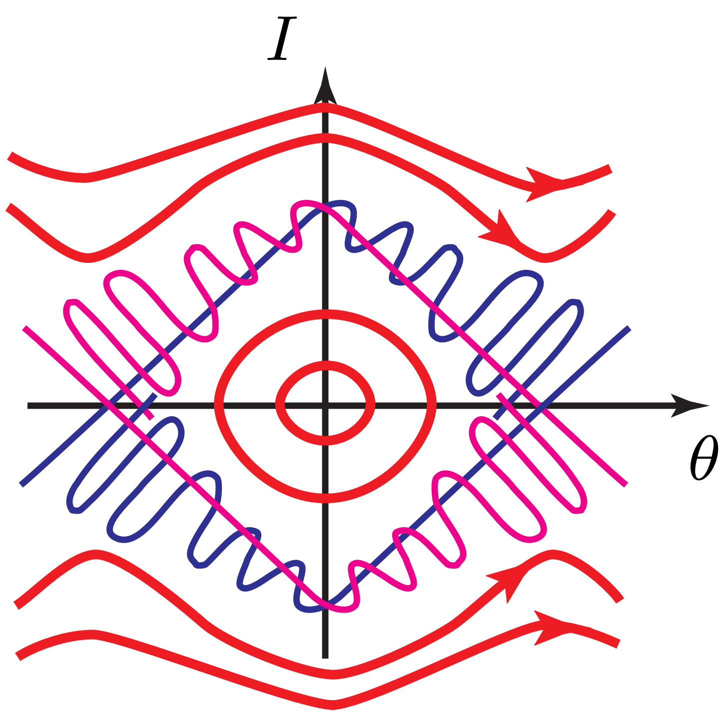
Measure of the chaotic diffusion in all directions in a 32 dimensional phase space

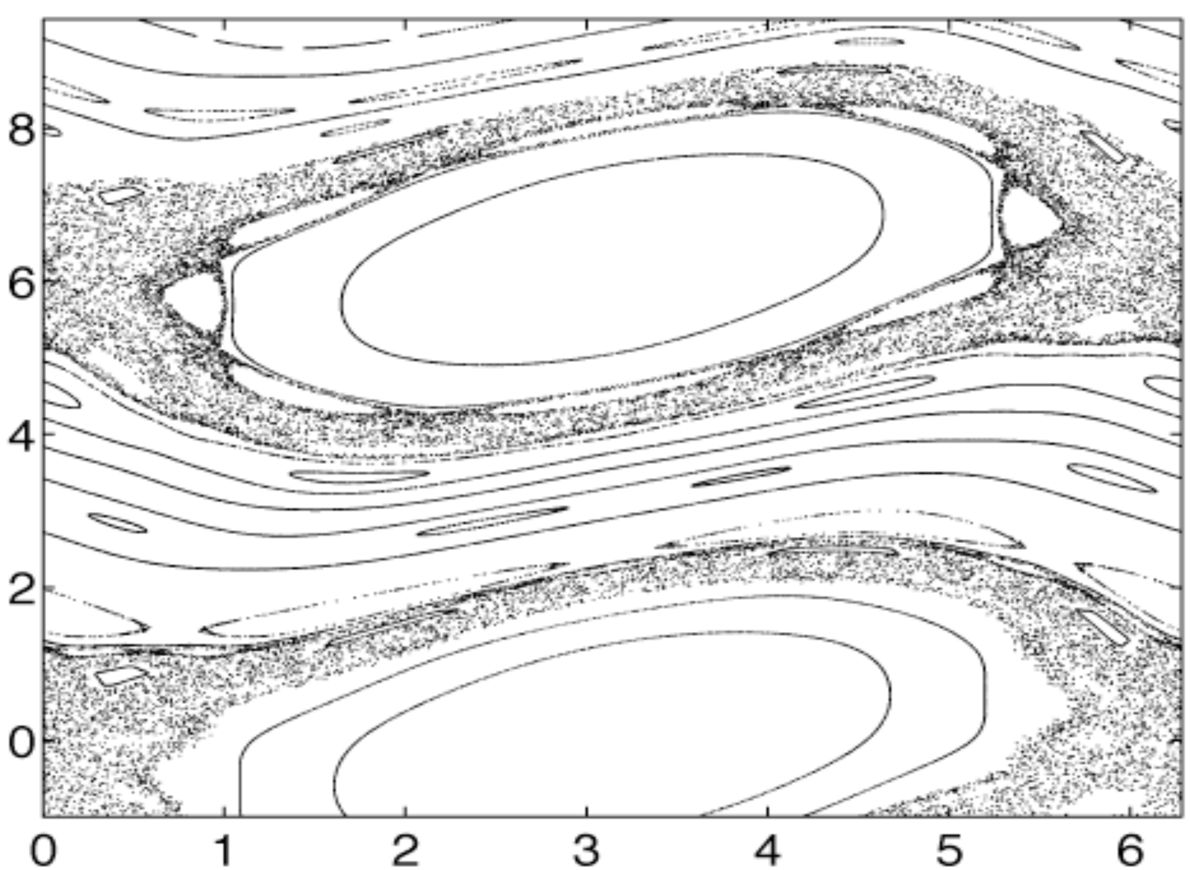
(Laskar, 1990)

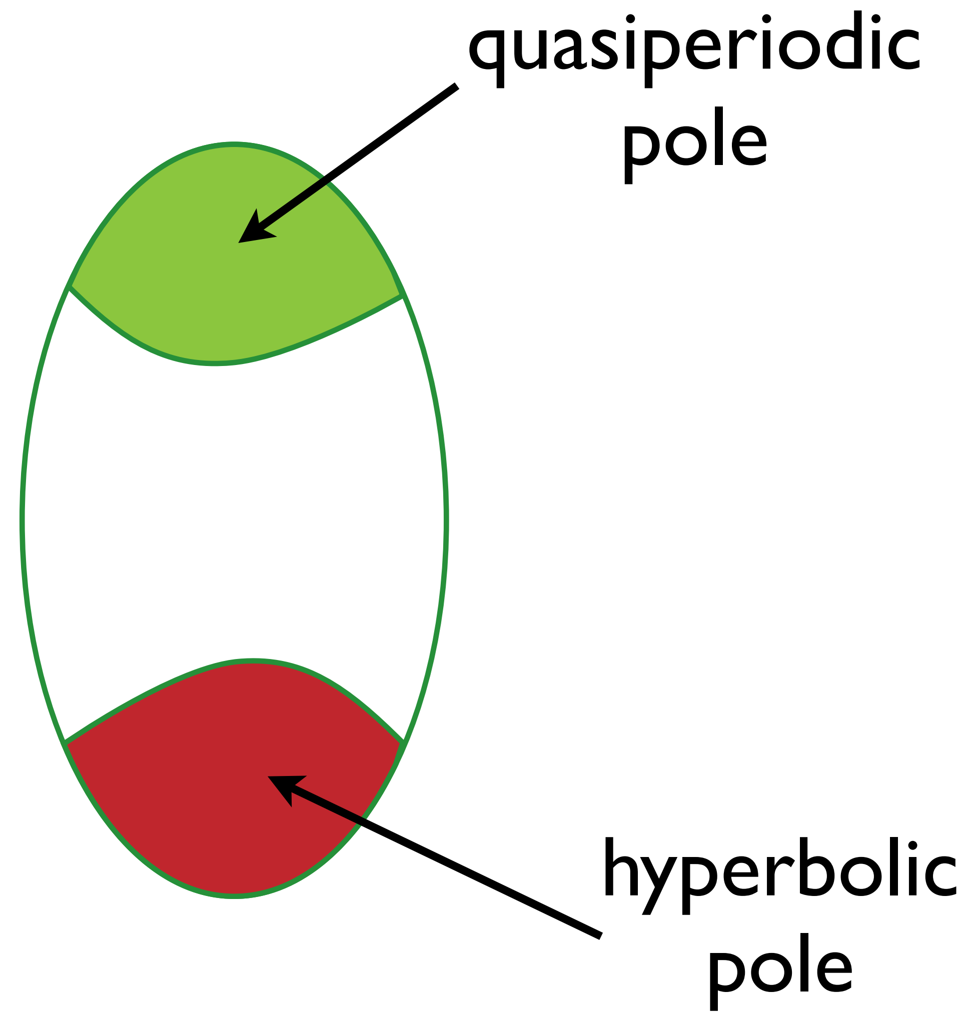
Frequency MAP

Non-quasiperiodic Motion

(Poincaré, Smale,...)







chaotic : non-quasiperiodic

Frequency MAP

Frequency Maps

$$H(I,\theta) = H_0(I) + \varepsilon H_1(I,\theta) \qquad (I,\theta) \in \mathbb{B}^n \times \mathbb{T}^n$$

$\varepsilon = 0$

$$\dot{I}_j = 0 \;, \qquad \dot{\theta}_j = \frac{\partial H_0(I)}{\partial I_j} = \nu_j(I) \;;$$

$$I_j = I_{j0} \qquad \theta_j(t) = \theta_{j0} + \nu_j t$$

nondegenerate

$$\left| \frac{\partial \nu(I)}{\partial I} \right| = \left| \frac{\partial^2 H_0(I)}{\partial I^2} \right| \neq 0$$

frequency map

$$F : \mathbb{B}^n \longrightarrow \mathbb{R}^n$$
$$(I) \longrightarrow (\nu)$$

diffeomorphism on $F(\mathbb{B}^n) = \Omega$

Frequency MAP

Frequency MAP

$\varepsilon \neq 0$

KAM theorem (Kolmogorov 1954, Arnold 1963, Moser 1963)

$\exists\ \Omega_\varepsilon \subset \Omega$ Cantor set $|< k, \nu >| > \dfrac{\kappa_\varepsilon}{|k|^p}$

$(\nu) \in \Omega_\varepsilon \Rightarrow$ quasiperiodic solution

Pöschel (1982), there exists a diffeomorphism

$$\begin{array}{rcl} \Psi : \mathbb{T}^n \times \Omega & \longrightarrow & \mathbb{T}^n \times \mathbb{B}^n \\ (\varphi, \nu) & \longrightarrow & (\theta, I) \end{array}$$

analytical $/\varphi$ and C^∞/ν on $\mathbb{T}^n \times \Omega_\varepsilon$ transforms the equations into

$$\dot{\nu}_j = 0\ , \quad \dot{\varphi}_j = \nu_j\ ;$$

thus, if $(\nu) \in \Omega_\varepsilon$,

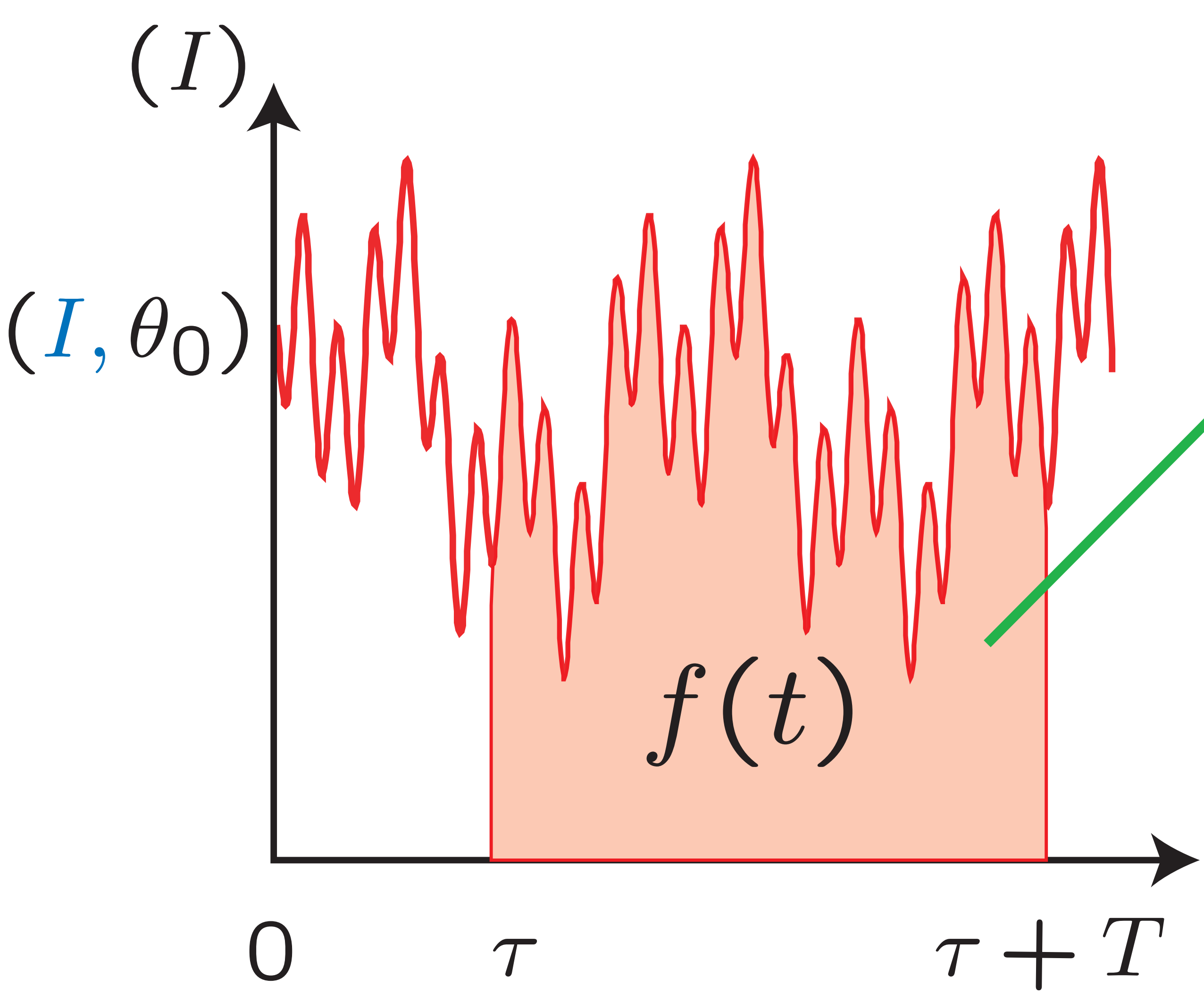
$z_j = I_j e^{i\theta_j}$,

$$z_j(t) = z_{j0} e^{i\nu_j t} + \sum_m a_m(\nu) e^{i<m,\nu>t}$$

Frequency MAP

Numerical Frequency Map

$\theta = \theta_0$



$$f(t) = \sum a_k e^{i\omega_k t}$$

$$f(t) = \sum a_k e^{i<k,\nu>t}$$

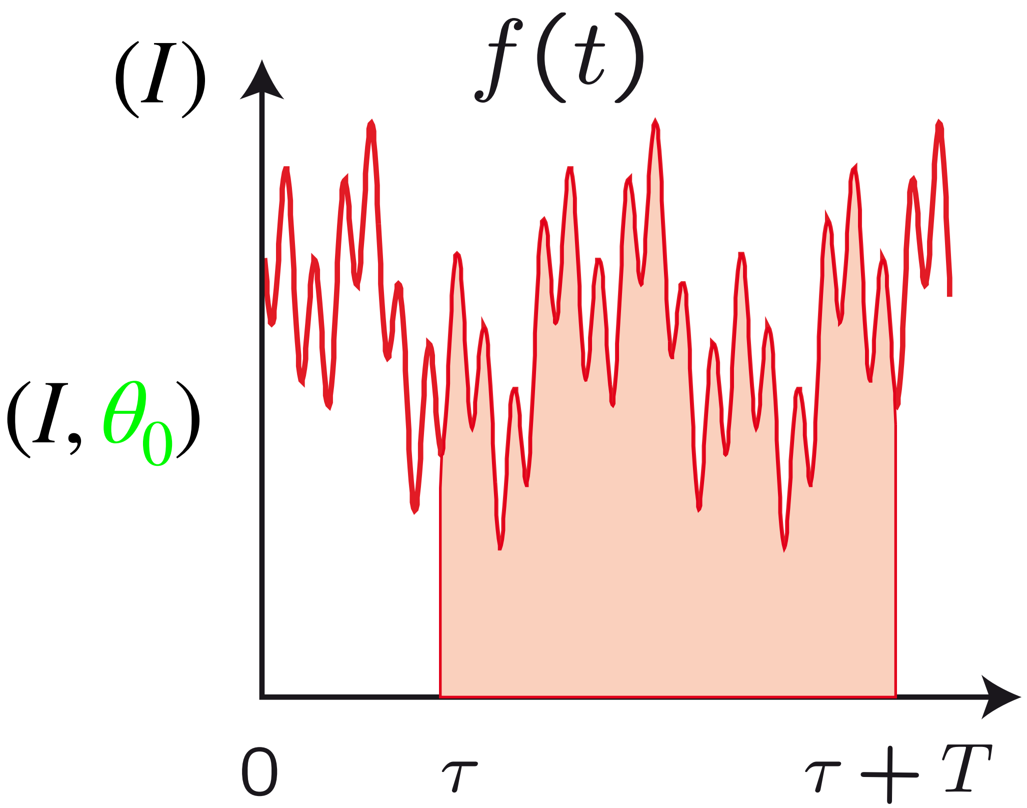
$$(\nu_1, \nu_2, \ldots, \nu_n)$$

$$F_{\theta_0}^{T} : \mathbb{R}^n \longrightarrow \mathbb{R}^n$$
$$(I) \longrightarrow (\nu_1, \nu_2, \ldots, \nu_n)$$

(Laskar+, 1992, 1993)

Frequency MAP

$\theta = \theta_0$

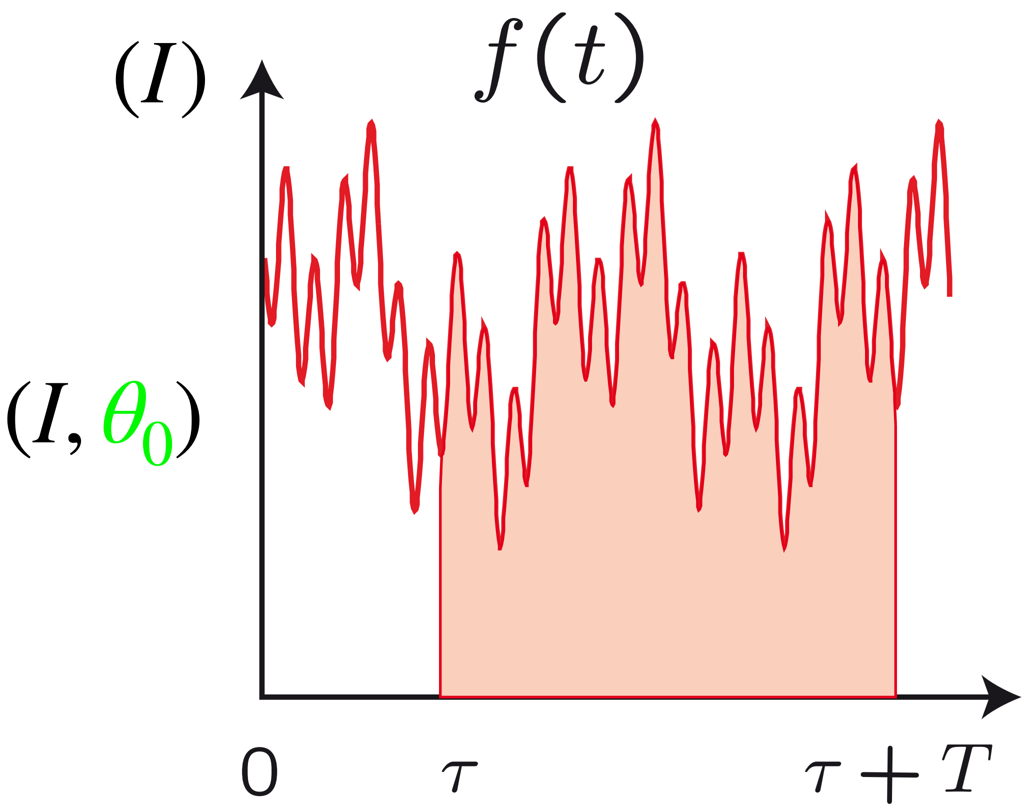


$$
\begin{aligned}
F^{T}_{\theta_0} : \mathbb{R} \times \mathbb{R}^n &\longrightarrow \mathbb{R}^n \\
(\tau, I) &\longrightarrow (\nu)
\end{aligned}
$$

(Laskar+, 1992, 1993)

Frequency MAP

$\theta = \theta_0$



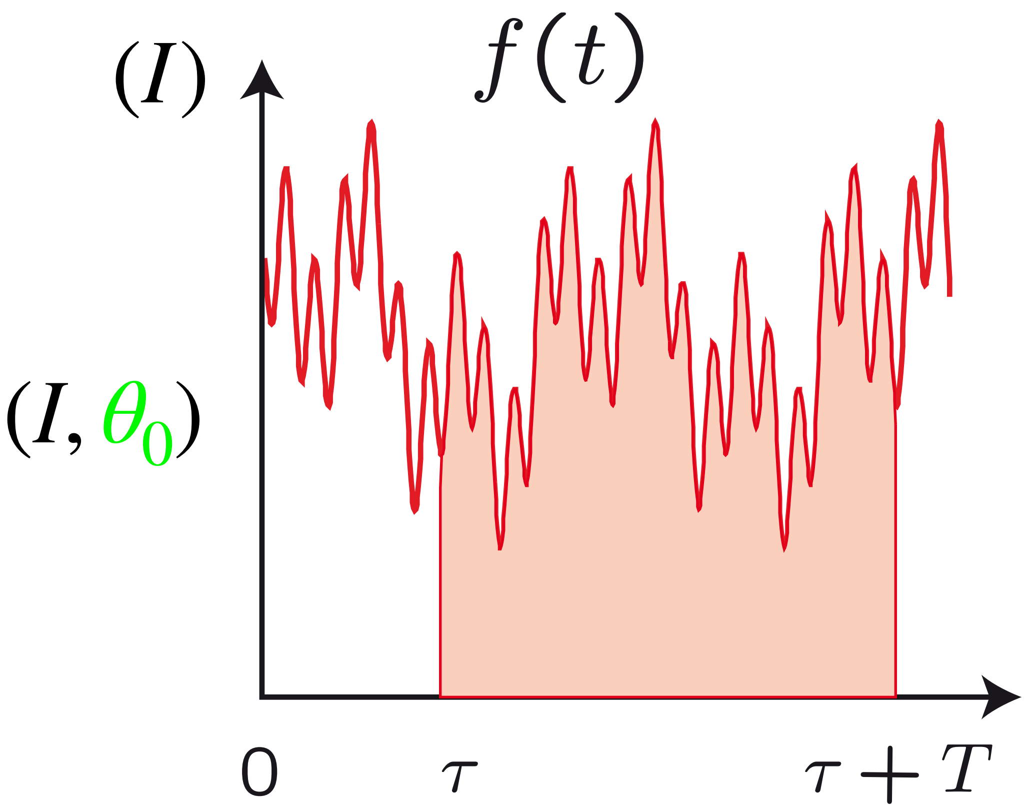
$$F_{\theta_0}^{T} : \mathbb{R} \times \mathbb{R}^n \longrightarrow \mathbb{R}^n$$
$$(\tau, I) \longrightarrow (\nu)$$

Thus : on the set of KAM tori,

(Laskar+, 1992, 1993)

Frequency MAP

$\theta = \theta_0$



$$F^T_{\theta_0} : \mathbb{R} \times \mathbb{R}^n \longrightarrow \mathbb{R}^n$$
$$(\tau, I) \longrightarrow (\nu)$$

Thus : on the set of KAM tori,

$F^T_{\theta_0}$ is constant $/\tau$

(Laskar+, 1992, 1993)

Frequency MAP

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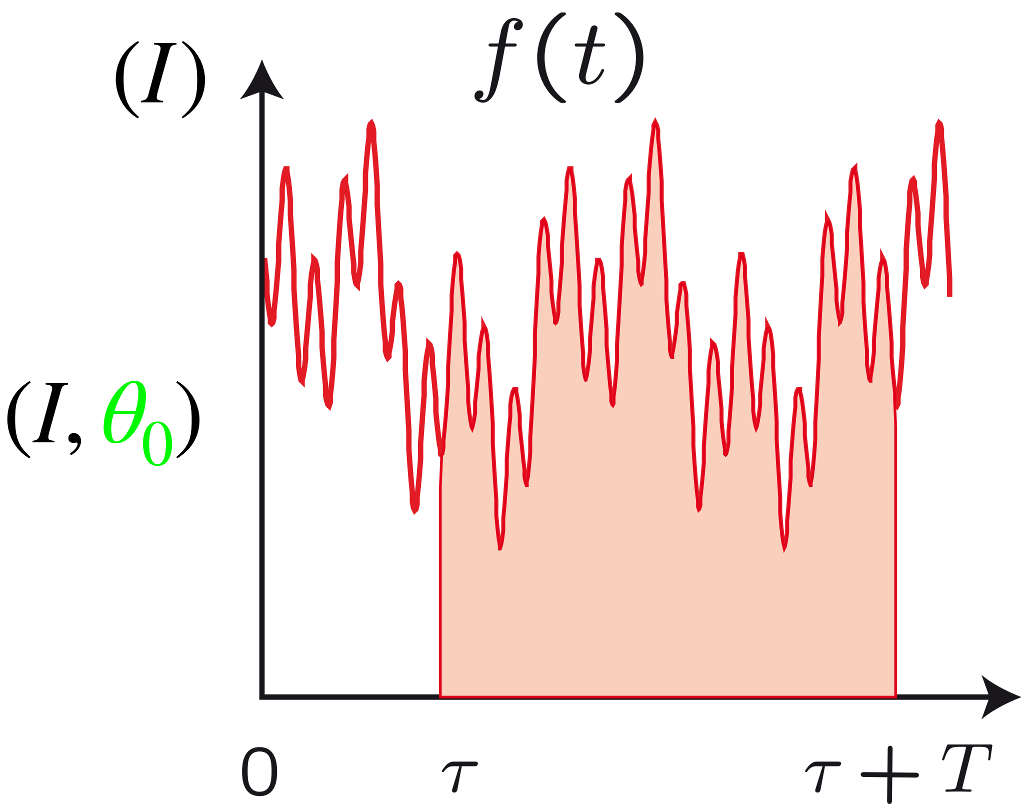

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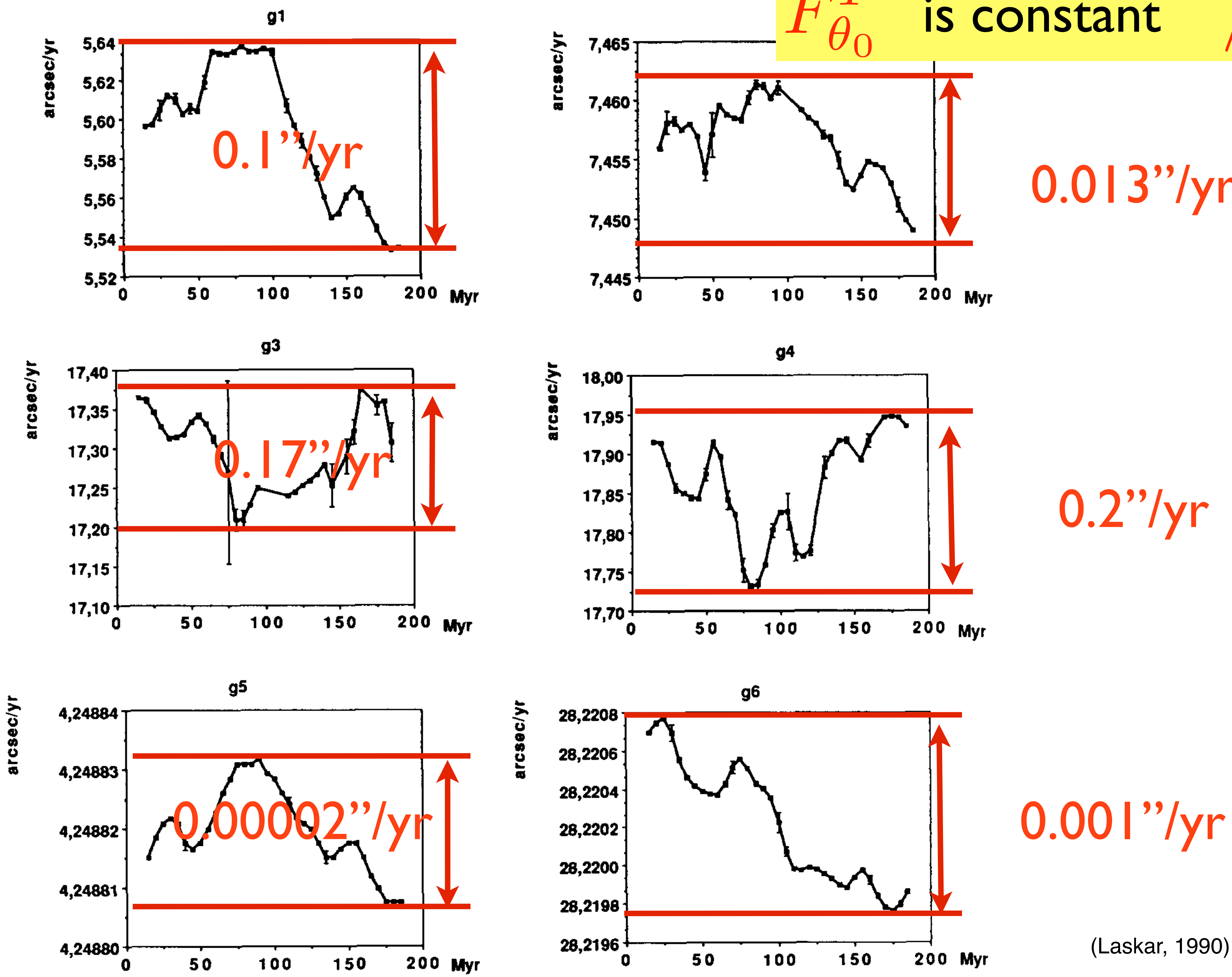
$F^T_{\theta_0}$ is a smooth diffeomorphism

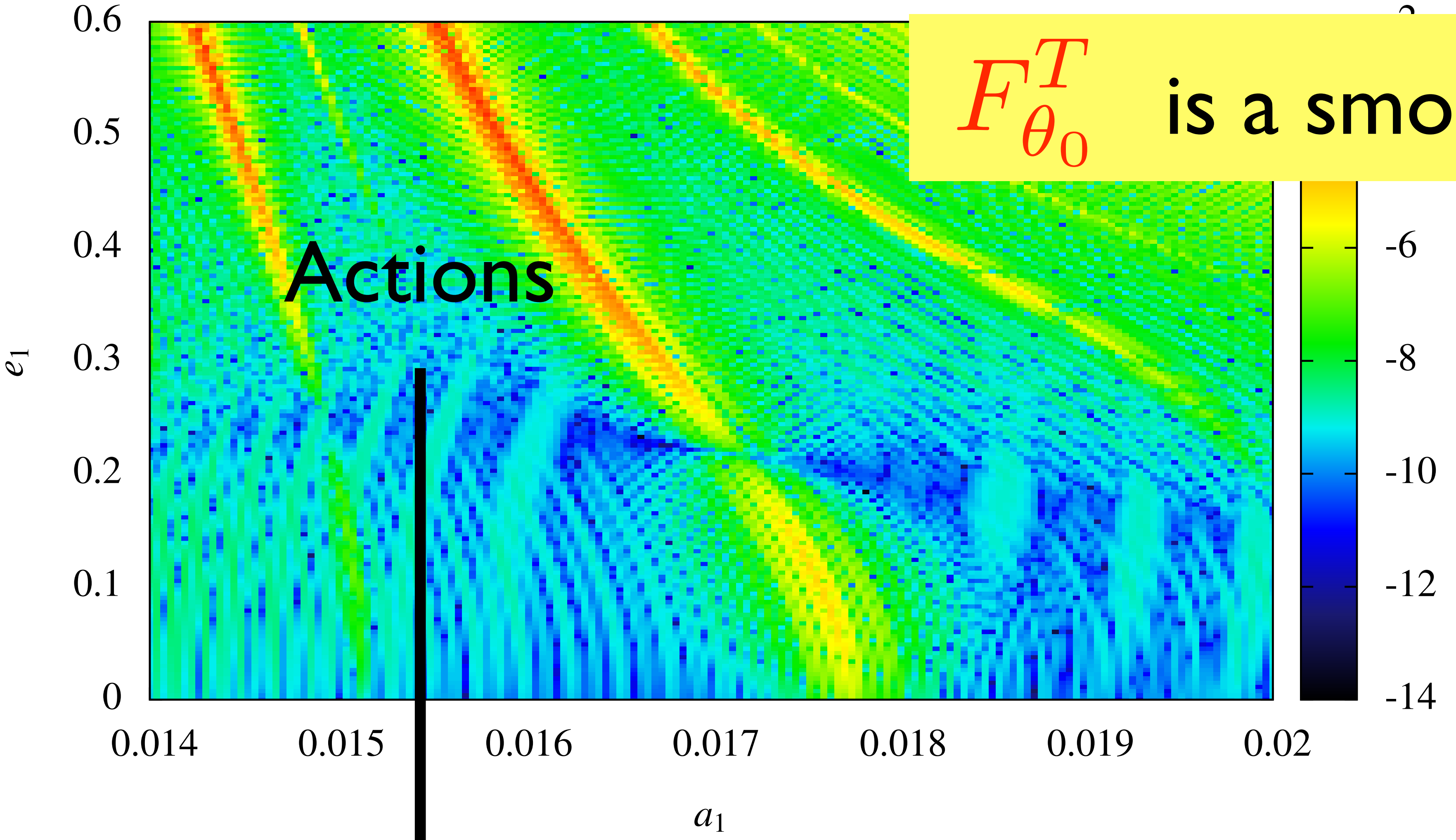
(Laskar+, 1992, 1993)

$F^T_{\theta_0}$ is constant $/\tau$

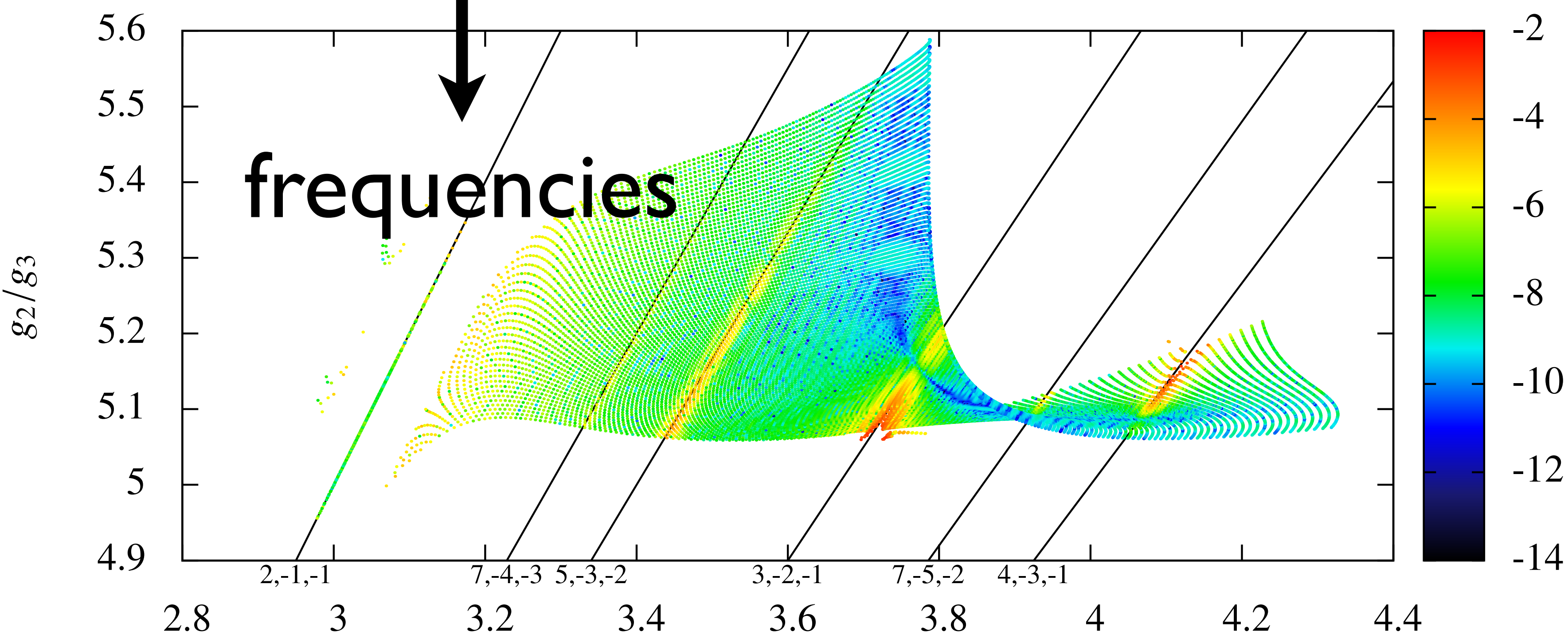


(Laskar, 1990)

$F_{\theta_0}^T$ is a smooth diffeomorphism



$$\begin{aligned} F_{\theta_0}^T : \mathbb{R}^n &\longrightarrow \mathbb{R}^n \\ (I) &\longrightarrow (\nu_1, \nu_2, \ldots, \nu_n) \end{aligned}$$



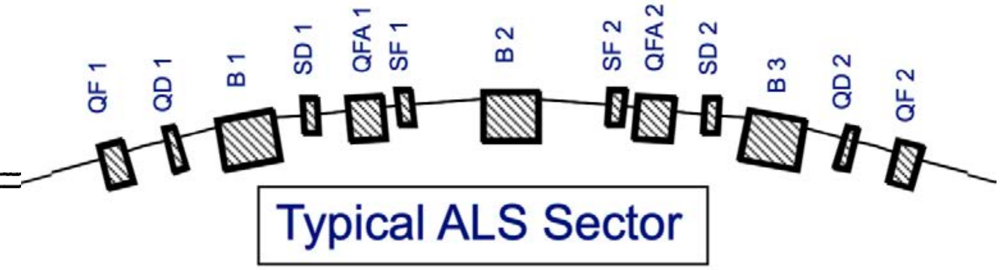
Frequency Map

of an

extrasolar planetary system

(with JB Delisle, 2013)

PHYSICAL REVIEW LETTERS



VOLUME 70 17 MAY 1993

Global Dynamics and Long-Time Stability in Hamiltonian Systems via Numerical Frequency Analysis

H. S. Dumas

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(Received 18 November 1992)

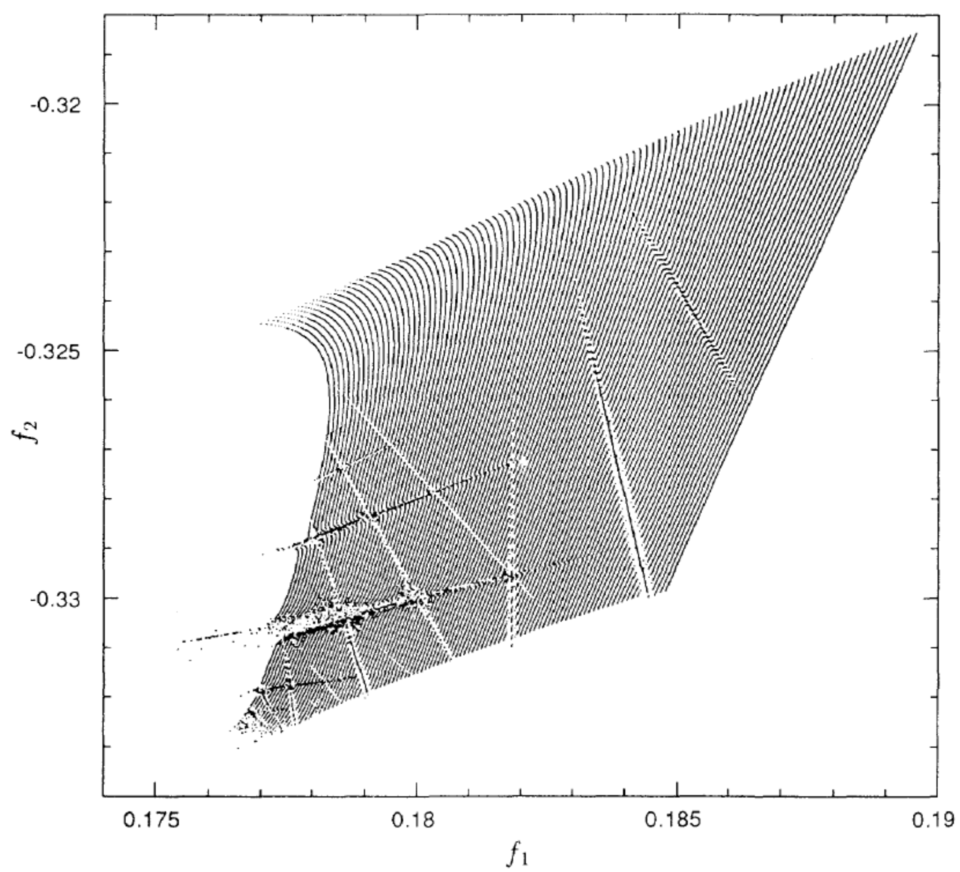


FIG. 1. Image in the frequency plane ("tune space") (f_1, f_2) of the square sector $0 \leq I_1, I_2 \leq 10^{-5}$, obtained using frequency analysis over 4052 turns.

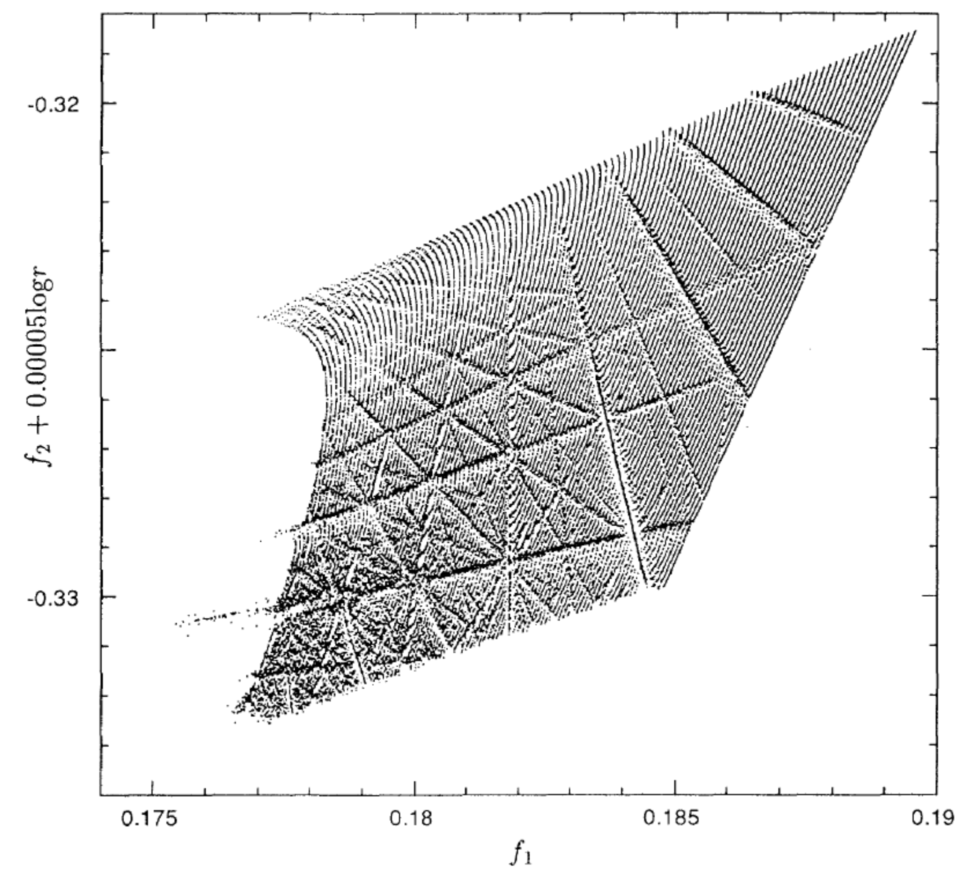
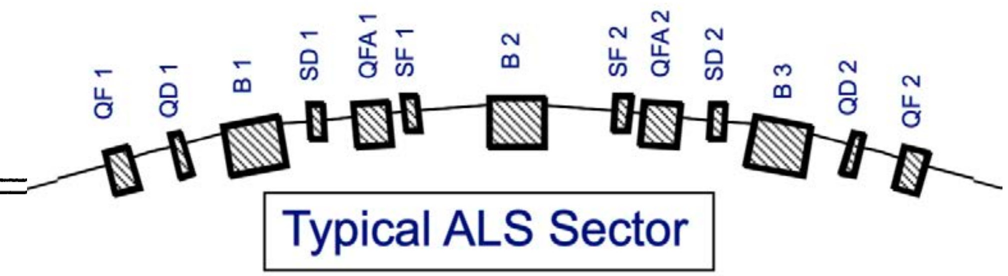


FIG. 2. Transport rates in the frequency plane. The speed and location of local transport phenomena are visualized by plotting $f_2 + 0.000\,05 \log(r)$ against f_1 for the same data as in Fig. 1, where r is the estimated local rate of transport (for r above a given threshold).

PHYSICAL REVIEW LETTERS

VOLUME 70 17 MAY 1993



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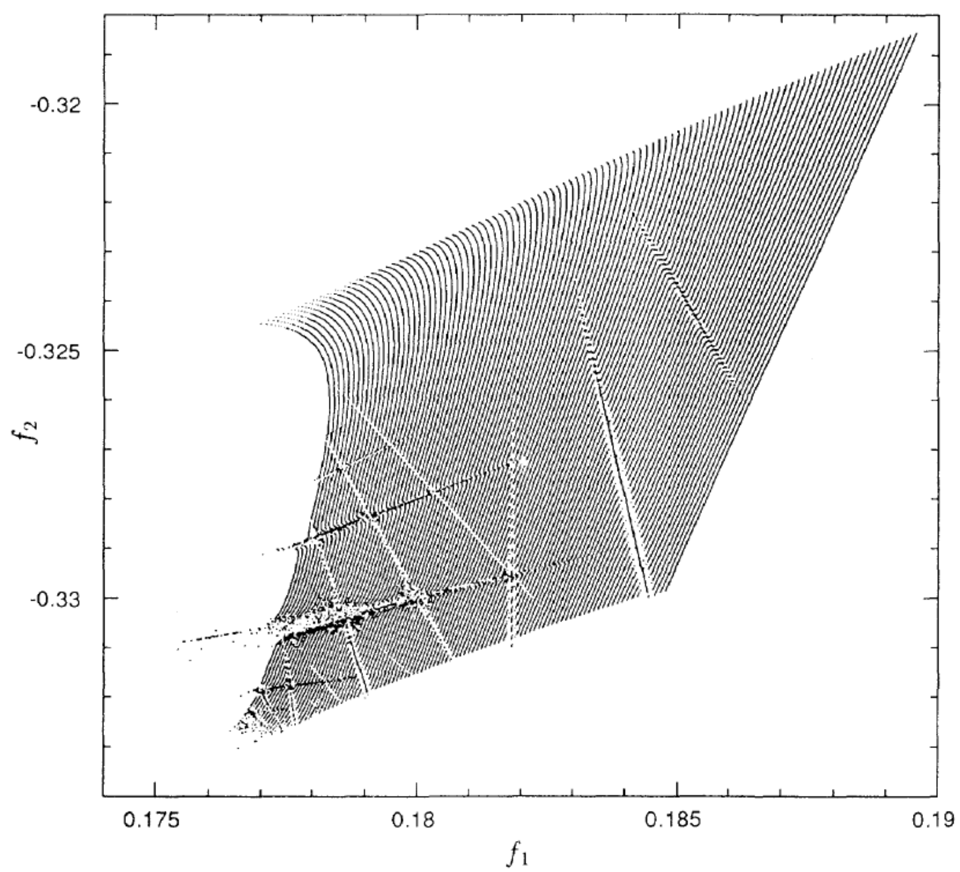

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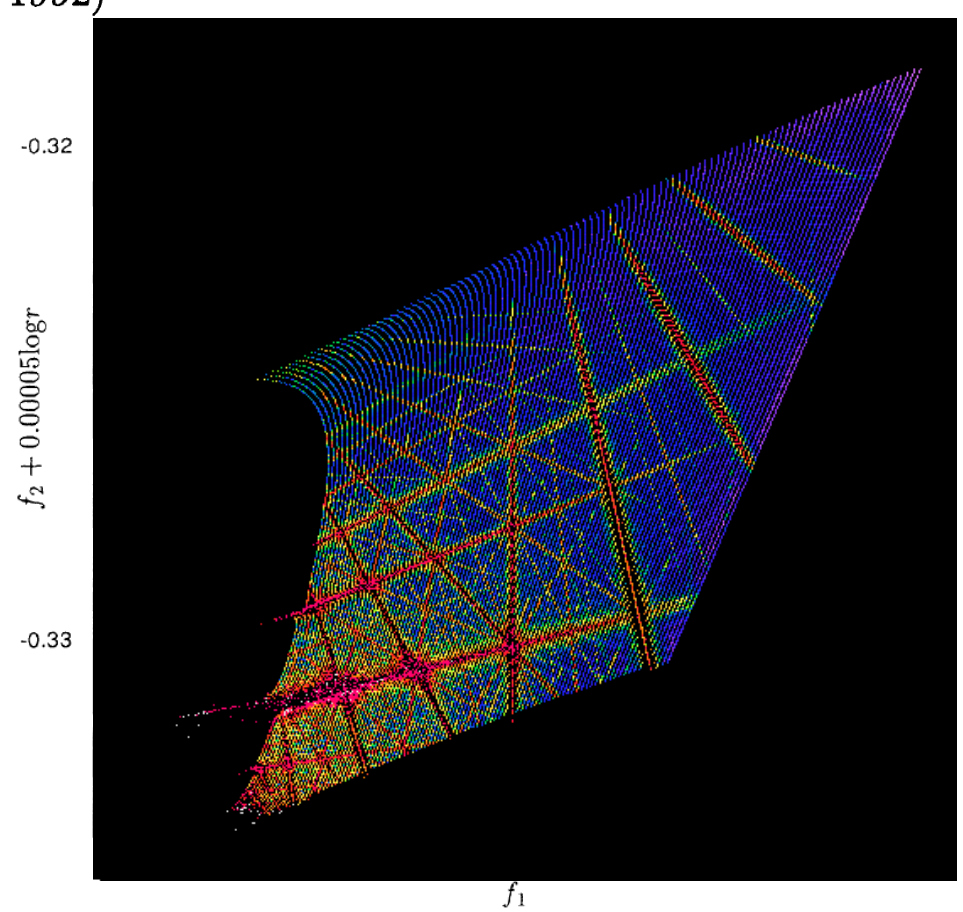

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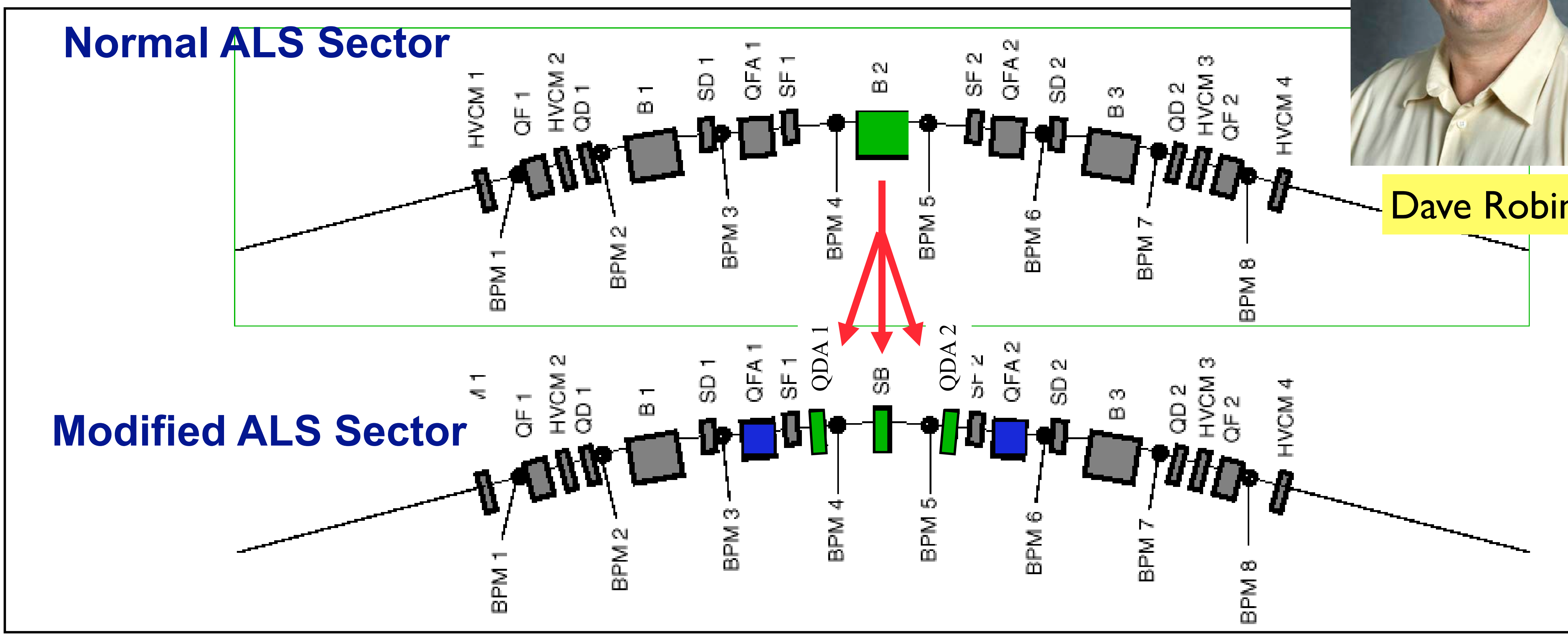
Example : Superbend Upgrade

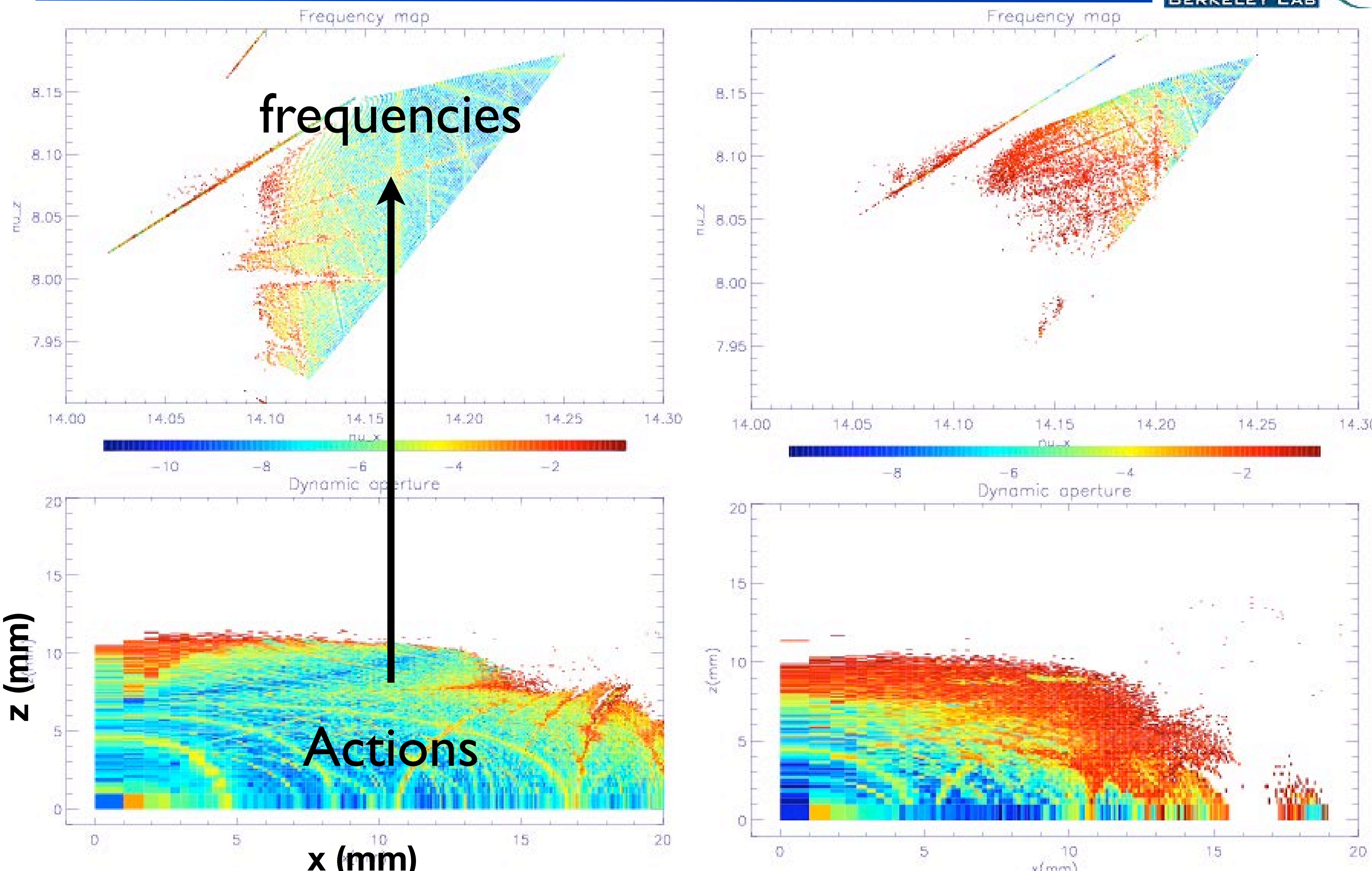
In three of the twelve ALS Sectors

- Replaced the central combined function dipole with a Superbend and two quadrupoles



Dave Robin

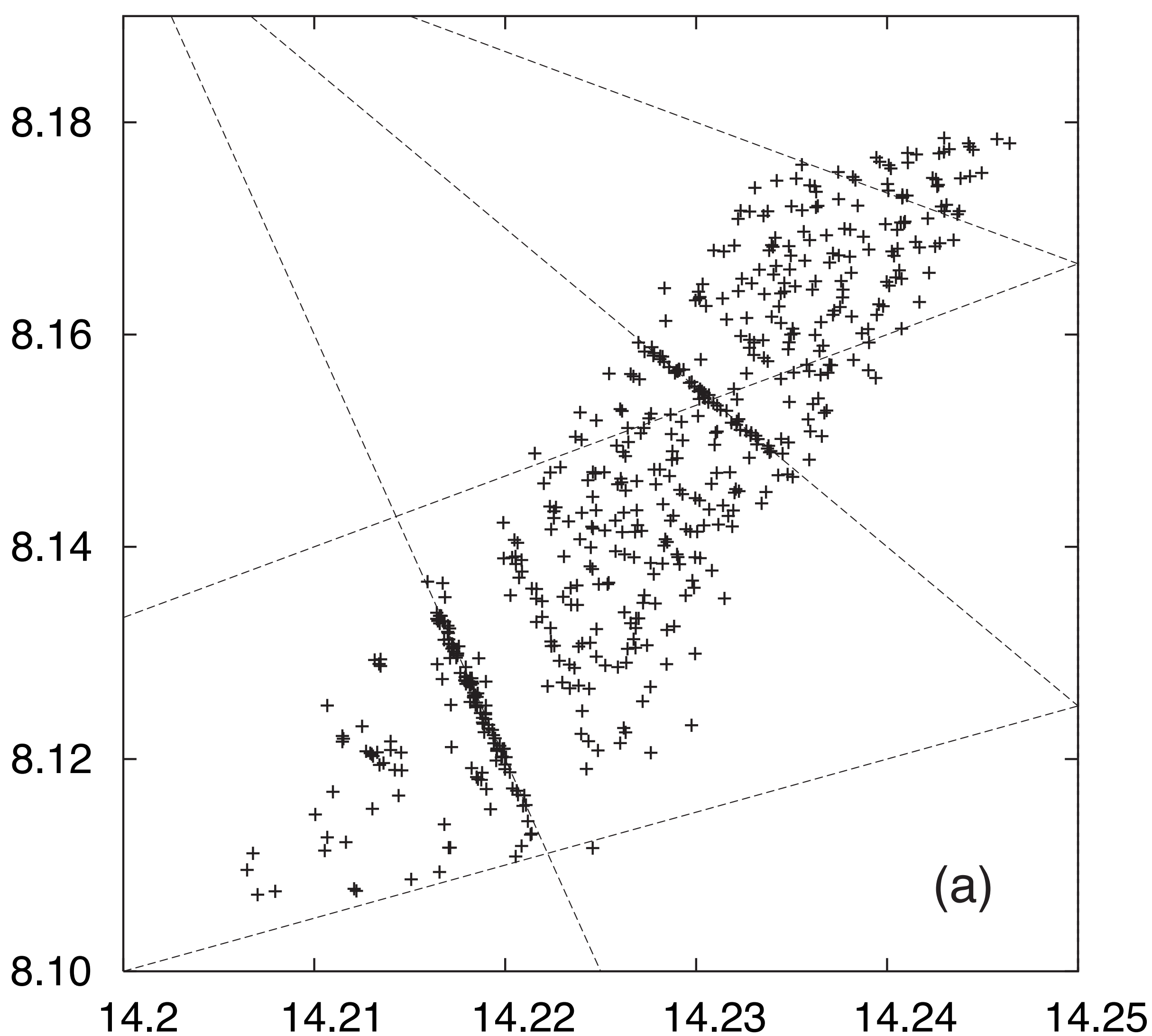
ALS : Ideal Lattice versus Calibrated Model



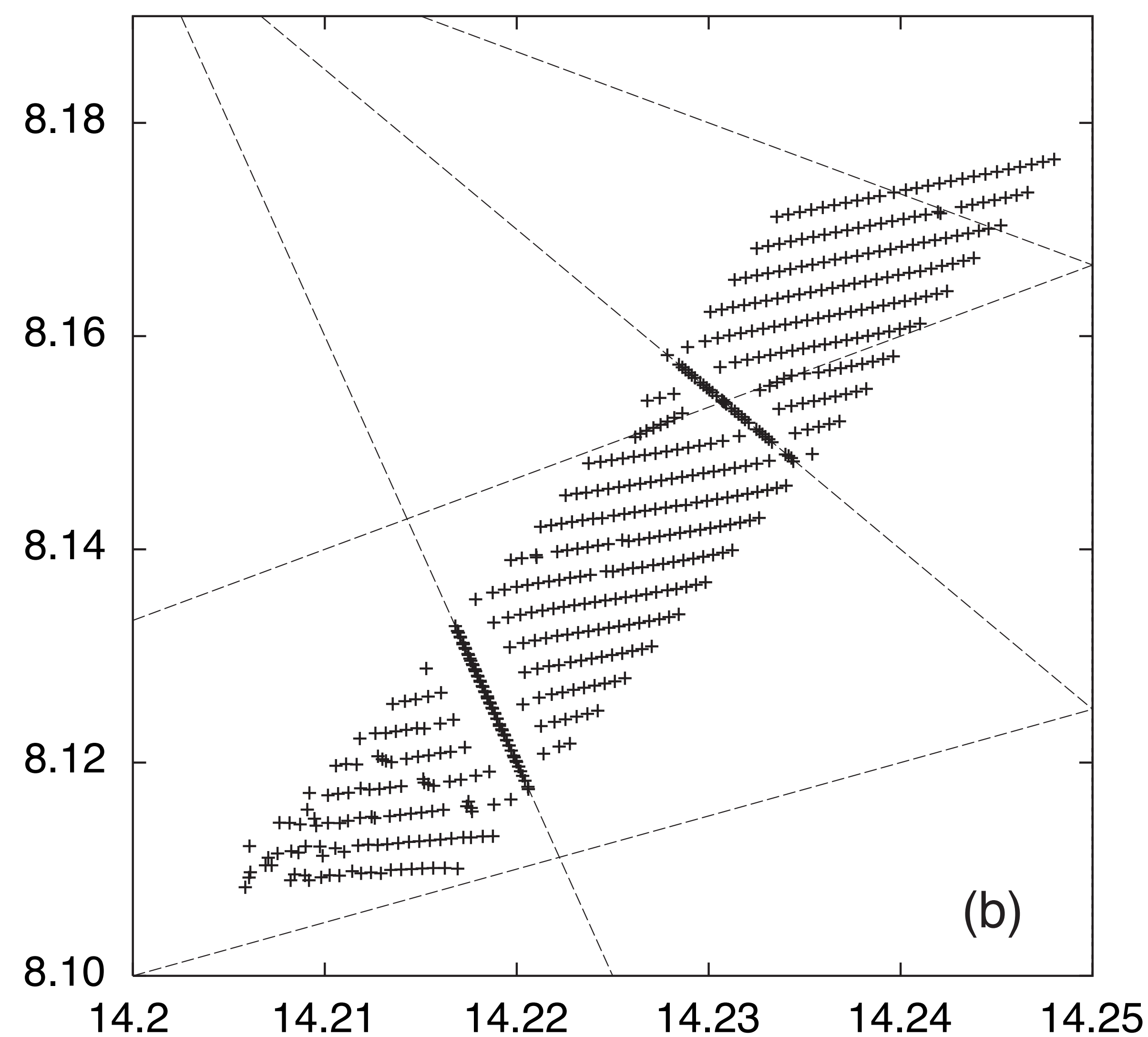
Robin, Steir, Nadolski, Laskar

Experimental Frequency Map at ALS

Experiment



Numerical model



Robin, Steier, Laskar, Nadolski, PRL, 2000

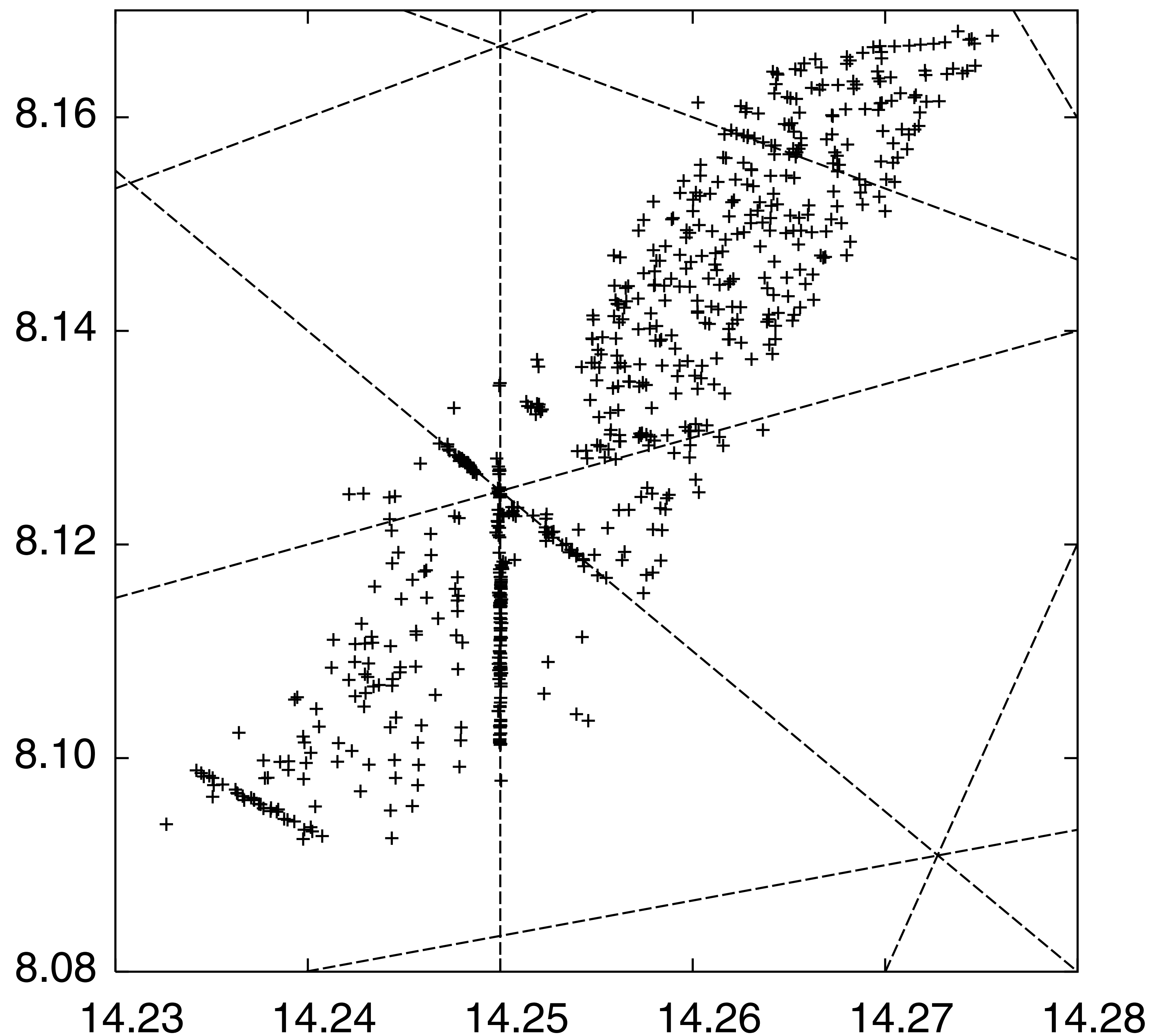


FIG. 4. Experimental frequency map for a previous setting of the ALS.

Robin, Steier, Laskar, Nadolski, PRL, 2000

Mapping chaos in particle revolutions

Over the past decade the technique of frequency map analysis, developed to study astronomical systems, has shown its value in an increasing number of areas, including the analysis of particle orbits in accelerators.

At first glance, any close association between the planets of the solar system – huge masses of rock, liquid and gas gently guided by gravity through the vast emptiness of space – and the mad traffic of tightly bunched particles in a circular accelerator, crushed together by fierce radiofrequency and magnetic fields, could hardly seem less likely.

Nonetheless, the dynamics of planets moving through our solar system and particles moving in accelerators do share many similar features. Both demand an analysis of the evolution of a dynamic system over a very long time – up to 1 billion revolutions for both the

Part of the ALS storage ring at the Lawrence Berkeley National Laboratory. Frequency mapping was first applied to measured rather than simulated electron trajectories at the ALS.

trajectories in a storage ring, at the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory. The aim was to reveal the dynamics of an actual particle beam.

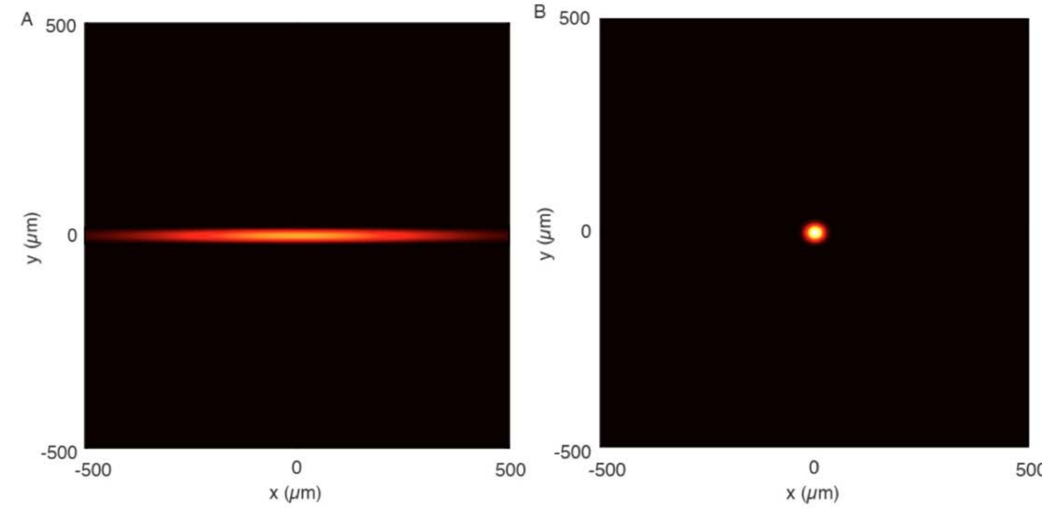
Chaotic motion

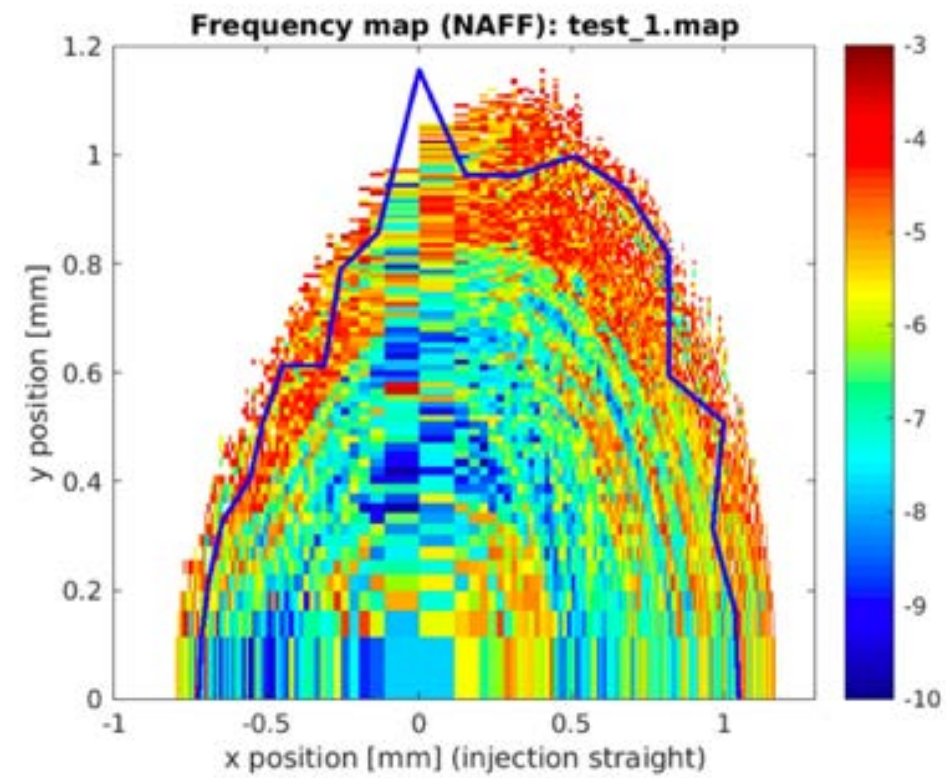
The story of frequency map analysis began in 1989 when Jacques Laskar (Bureau des Longitudes, Paris) demonstrated that the motion of the solar system is chaotic (Laskar 1989). He showed that the separation between two orbits with similar initial conditions will diverge exponentially over time (e.g. the distance between the orbits will increase

Project Director Dave Robin Announces ALS-U Project Beamlines

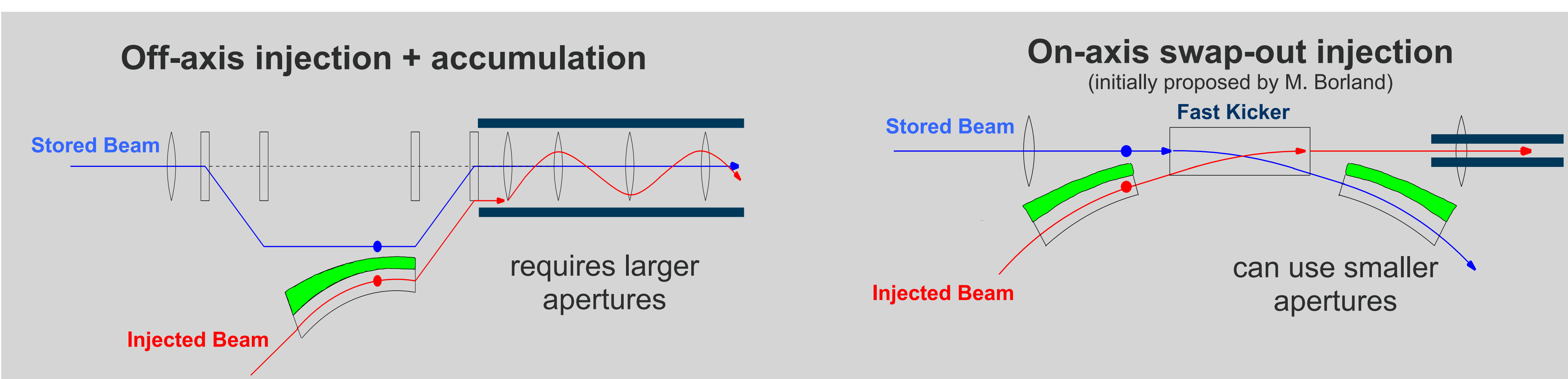
JANUARY 29, 2019

Over the past year, a process involving ALS and ALS-U staff, the ALS user community, and external advisory committees has been ongoing to select the insertion-device beamlines that will be built and upgraded within the scope of the ALS-U Project. These beamlines will join existing ALS beamlines to form the full complement of capabilities that will be available at the upgraded ALS in several years. I am delighted to inform you that the selection process is now complete and to announce the result.





ALS-U will reach soft x-ray diffraction limit up to 1.5 keV



C. Steier /ALS

BERKELEY LAB | ALS-U

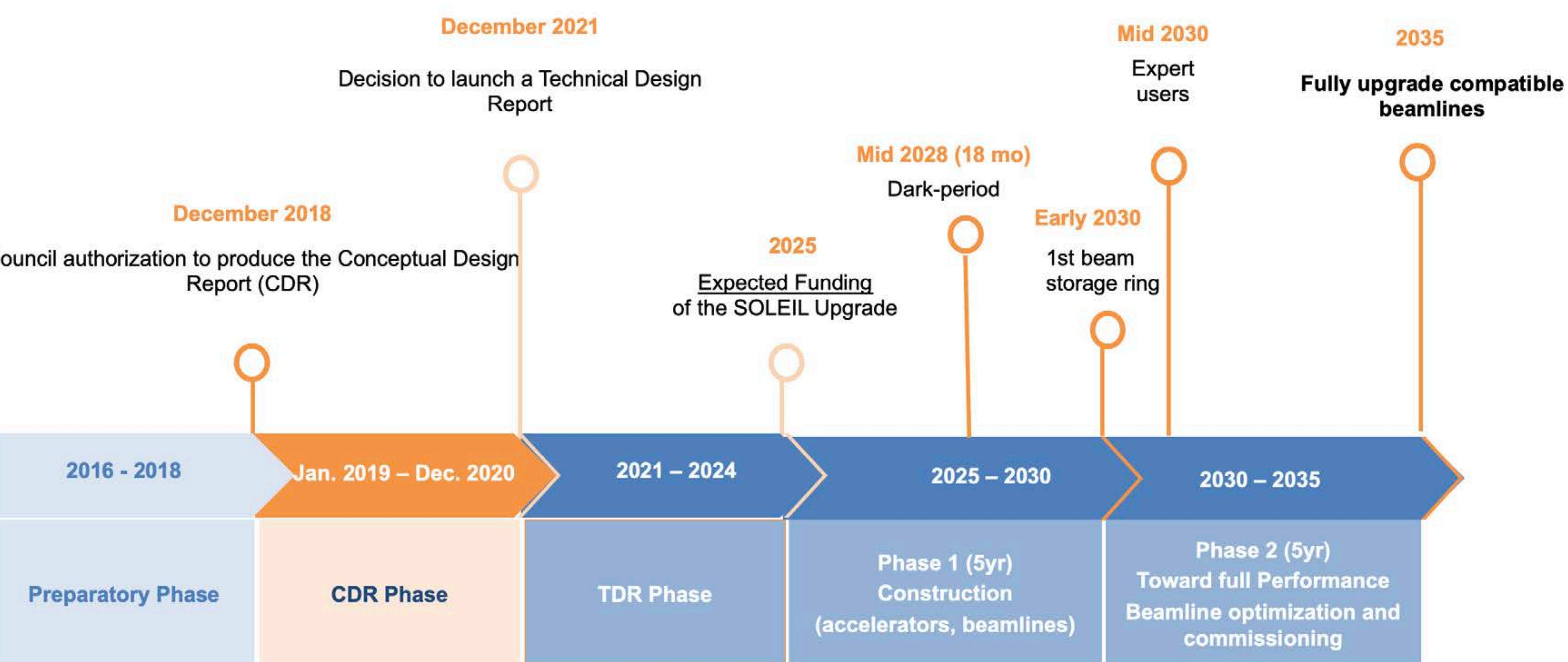
C. Steier /D. Robin

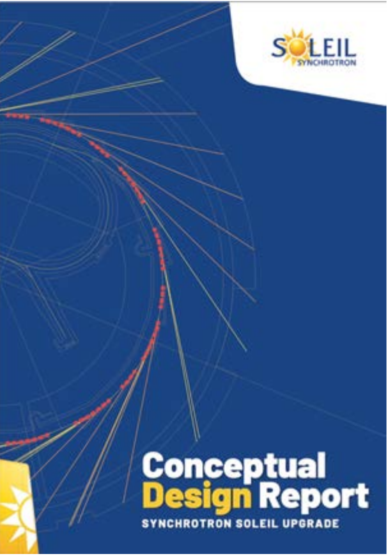
Laurent S. Nadolski

Senior Accelerator Physicist
Accelerators Coordinator
Synchrotron SOLEIL, France

- Ph.D., (2001).
- "Application of Frequency Map Analysis to the Study of Beam Dynamics" (J. Laskar's supervision).
- Former President of Accelerator Sect. of the French Physical Society
- SOLEIL II: nonlinear beam dynamics, robustness studies, storage ring coordination (collimation, radiation safety, machine protection interlock).

Present SOLEIL II Timeline





SOLEIL II: a 4th GENERATION SYNCHROTRON LIGHT SOURCE for the Science of Tomorrow

<u>An electron beam 40 times smaller and circular</u>

<u>Photon beams at least 100 times brighter and more coherent in the X-ray range.</u>

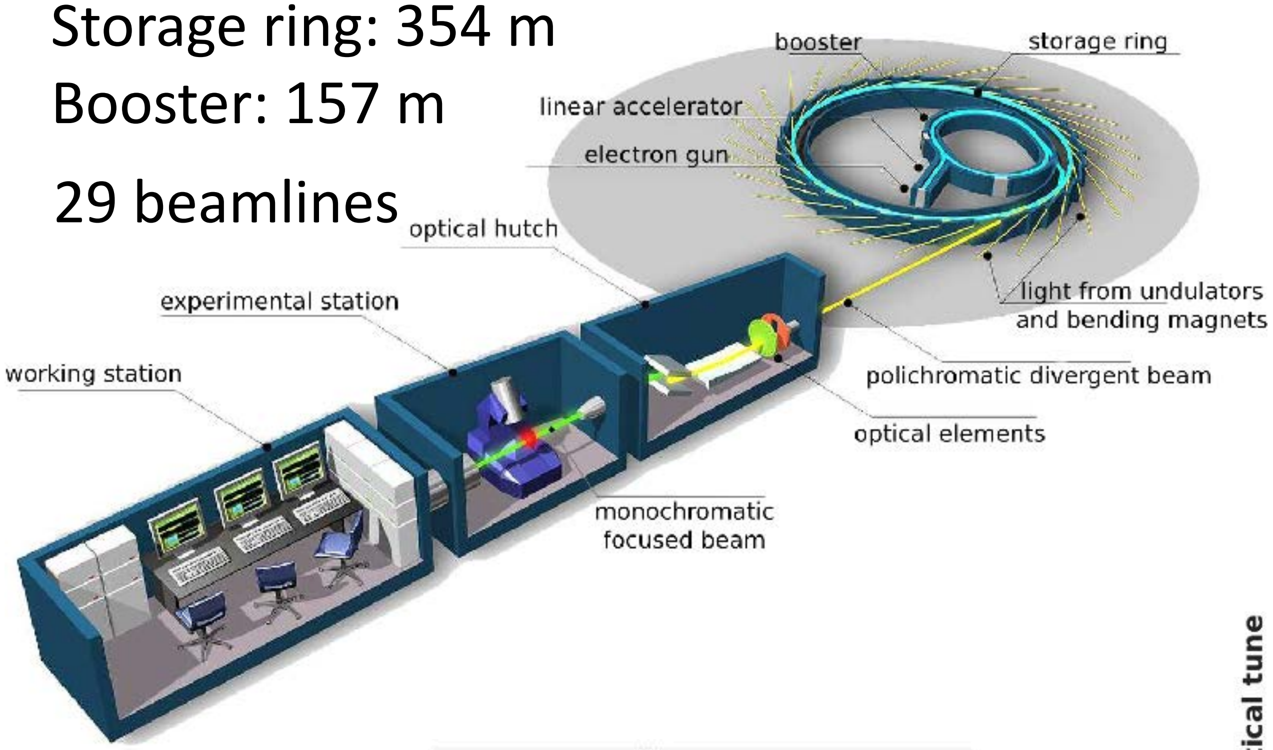
Obtaining a very compact layout:

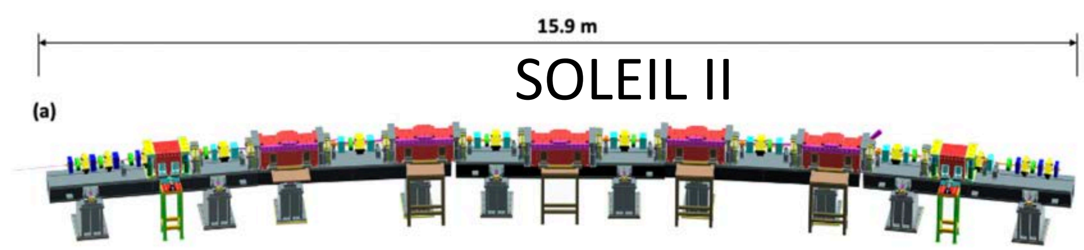
Lifting of technological barriers, with the miniaturization of the vacuum chambers where the electrons circulate and of the magnets that guide them.

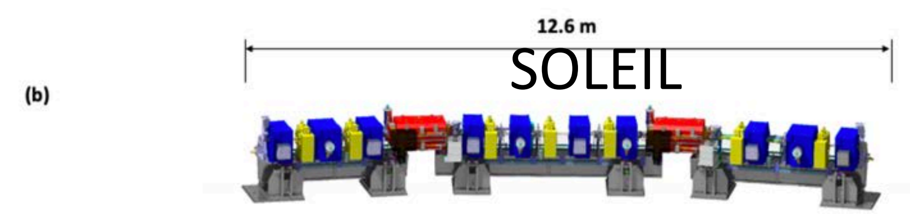
Storage ring: 354 m

Booster: 157 m

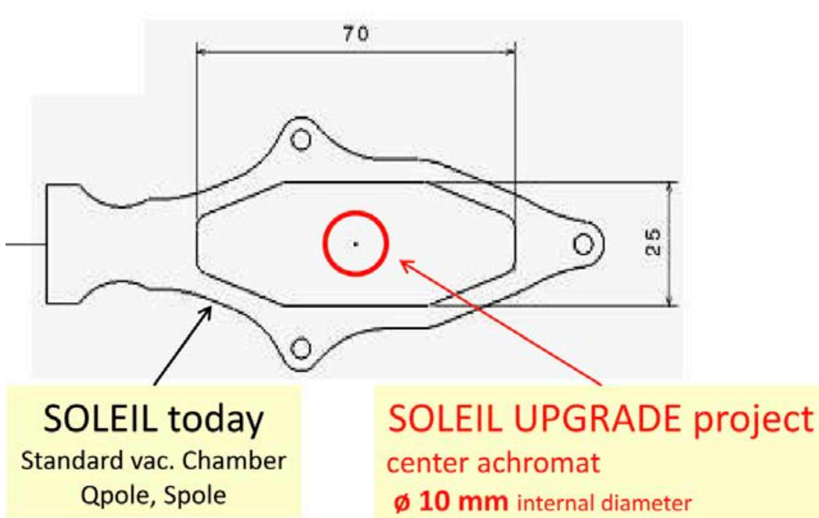
29 beamlines

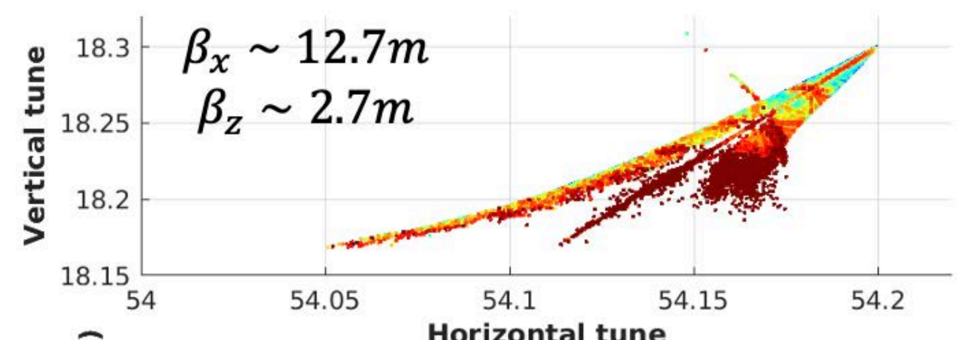


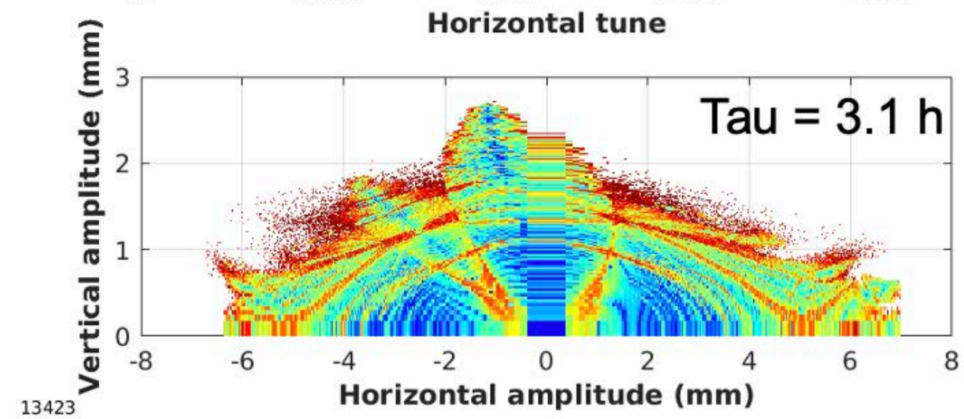




Permanent magnet quadrupole prototype (top) for SOLEILII and Electromagnet quadrupole for SOLEIL





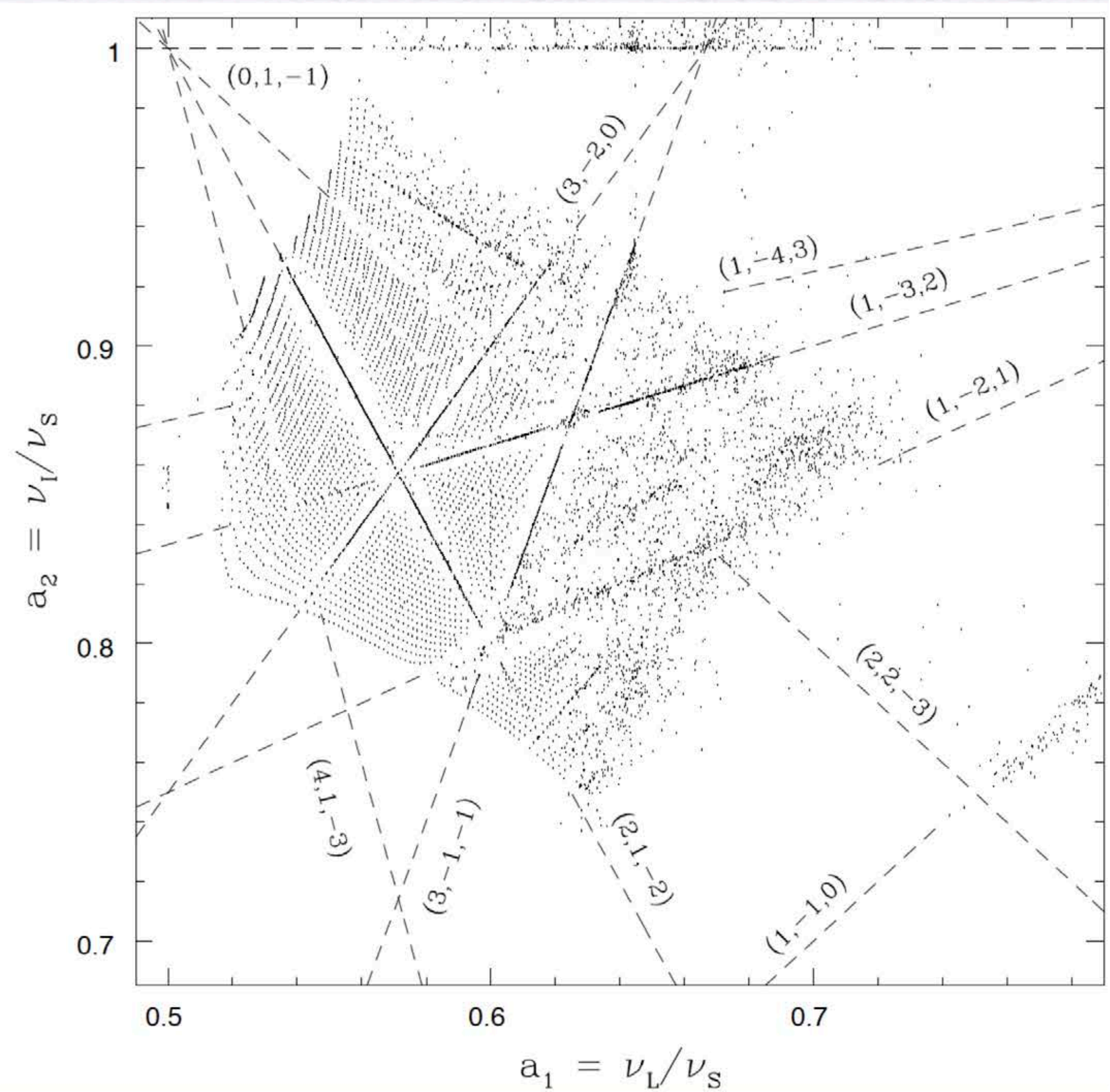


BPM prototypes for SOLEIL (bottom) and SOLEIL II (top)

L. Nadolski

Yannis Papaphilippou

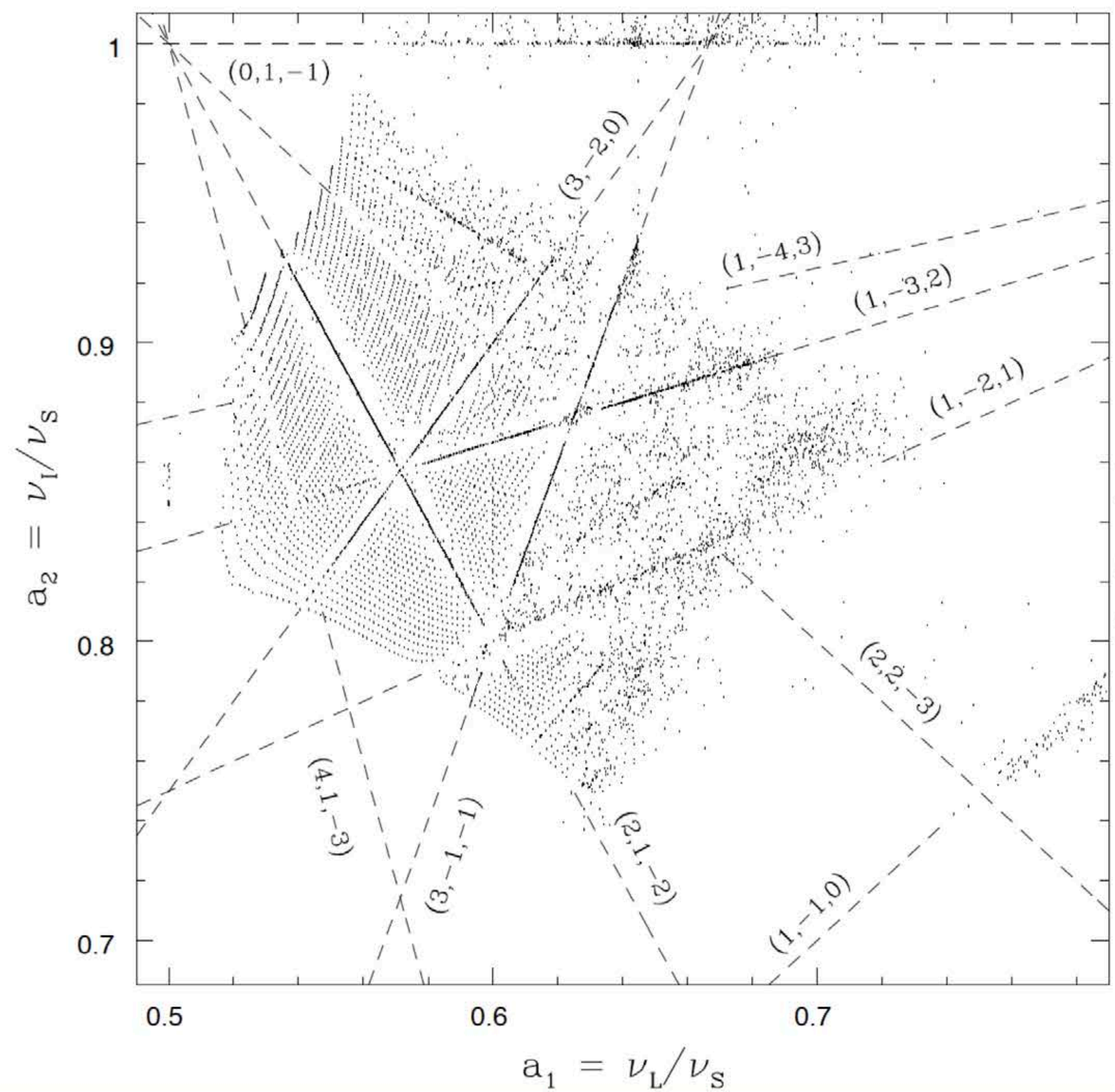
PhD (1997) Application of the Frequency Map Analysis Method in Galactic Dynamics

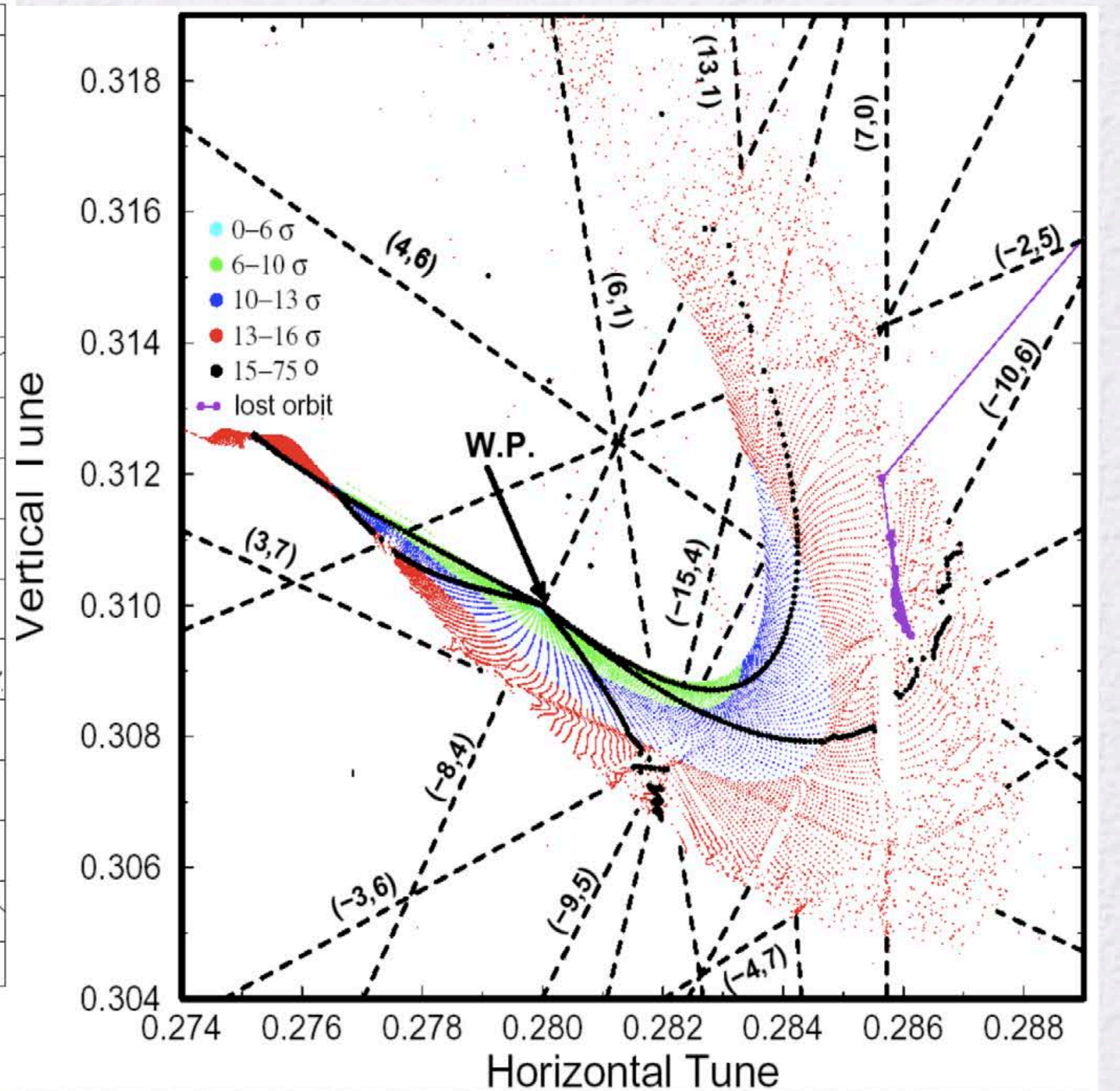


Galactic model

Yannis Papaphilippou

PhD (1997) Application of the Frequency Map Analysis Method in Galactic Dynamics





Galactic model

The LHC

Y. Papaphilippou, 1999

ABP @ CERN organisation

ABP
Accelerators & Beam Physics
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DGL: R. Scrivens

GAO
S. Palluel

ABP Computing Panel
Ch: G. Iadarola

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- B. Stechauner (DOCT)
- N. Van Gils (DOCT)
- T. Von Witzleben (DOCT)
- G. Zevi Della Porta (PJAS)

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- E. Maclean
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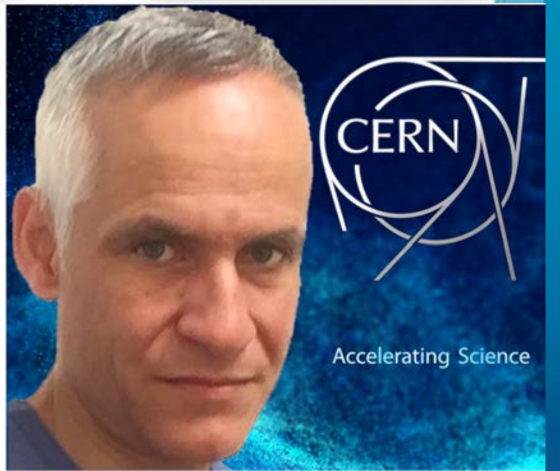
- M. Rakic (DOCT)
- D. Veres (DOCT)
- S. Wang (COAS)

~50 Staff,
~30 Fellows
~50 Students
~20 Associates

~80 Visitors and
External collaborators



Goal of High-Luminosity LHC

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Prepare machine for operation beyond 2025 and up to **2035**

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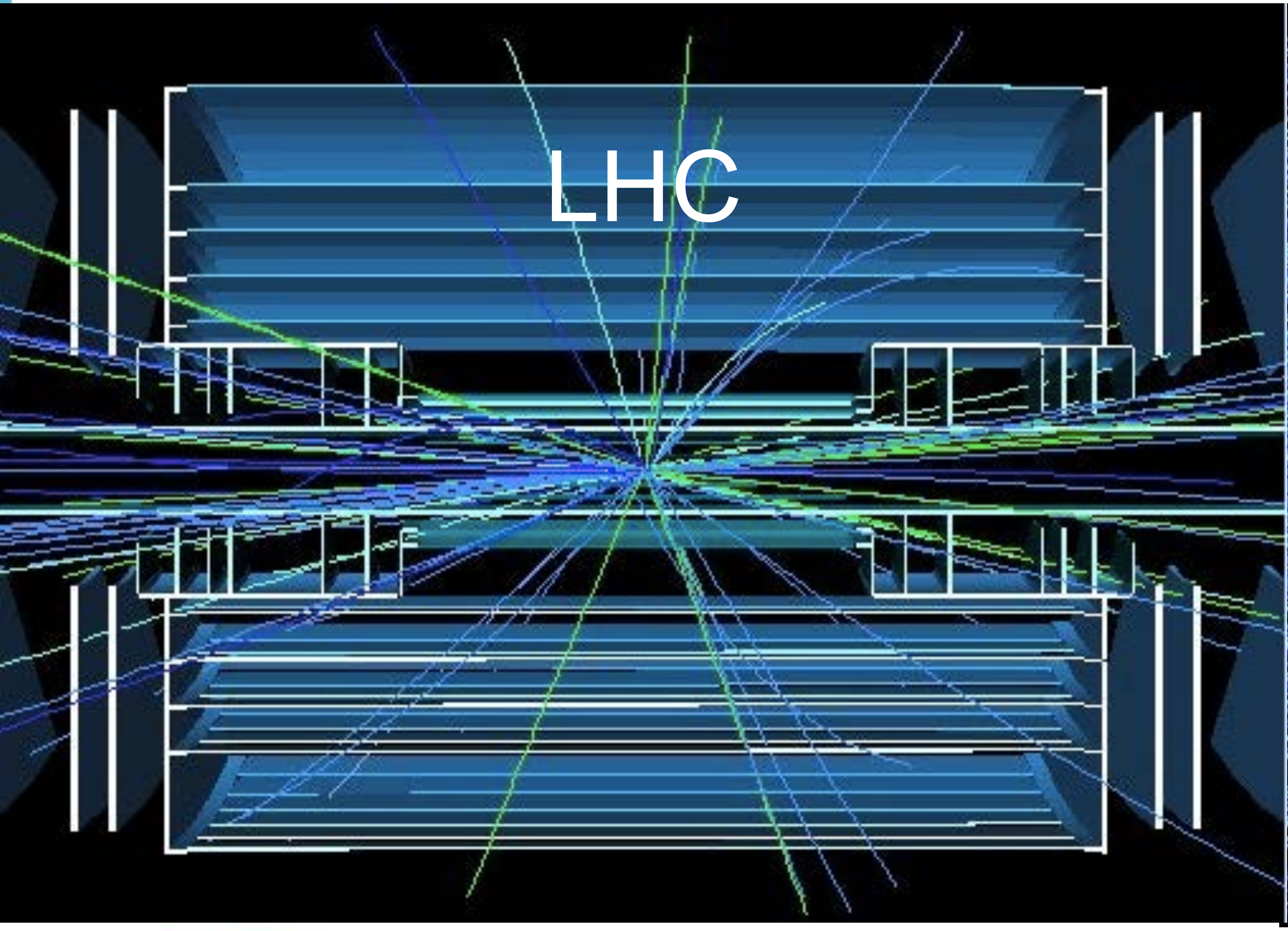

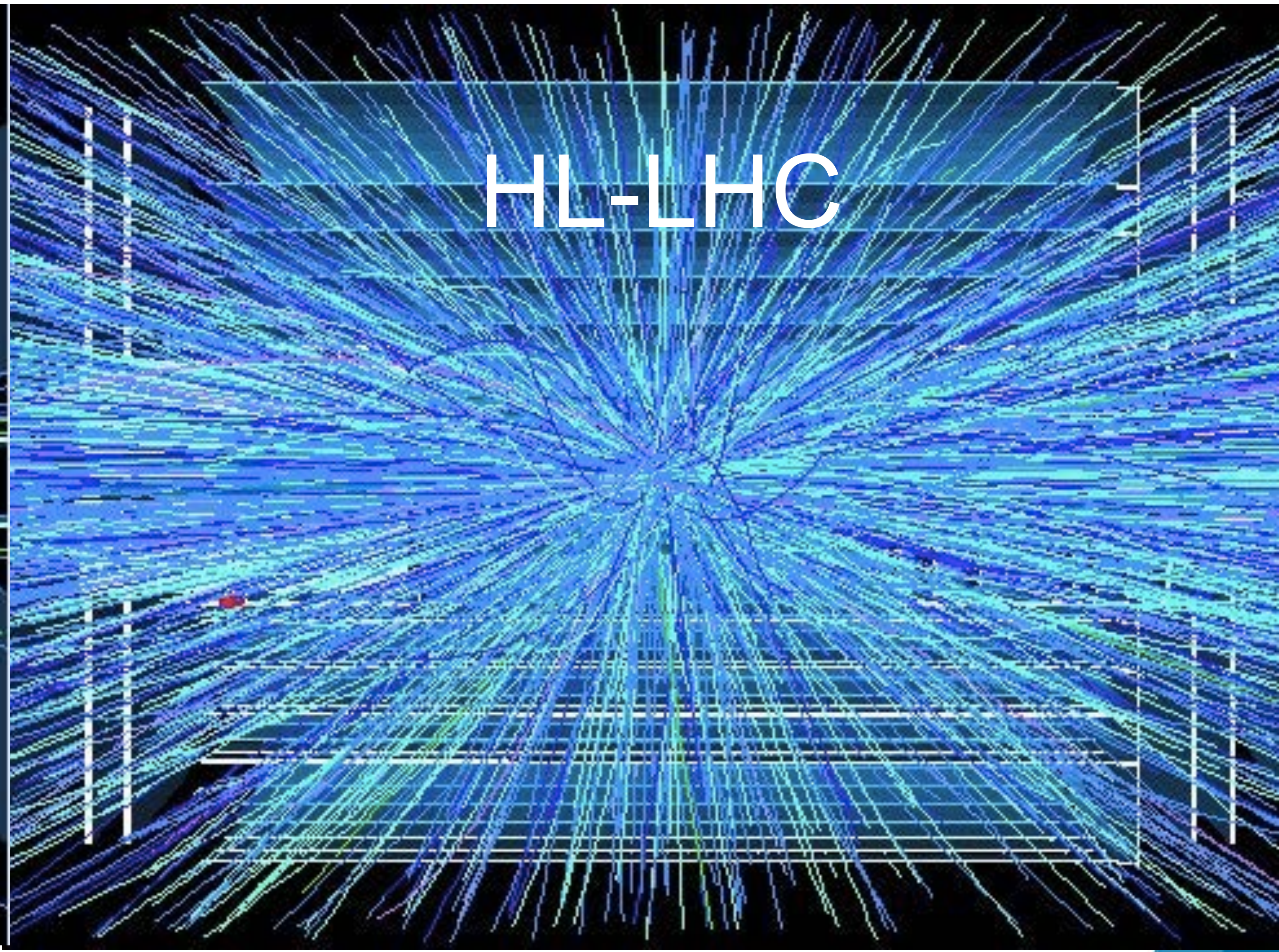

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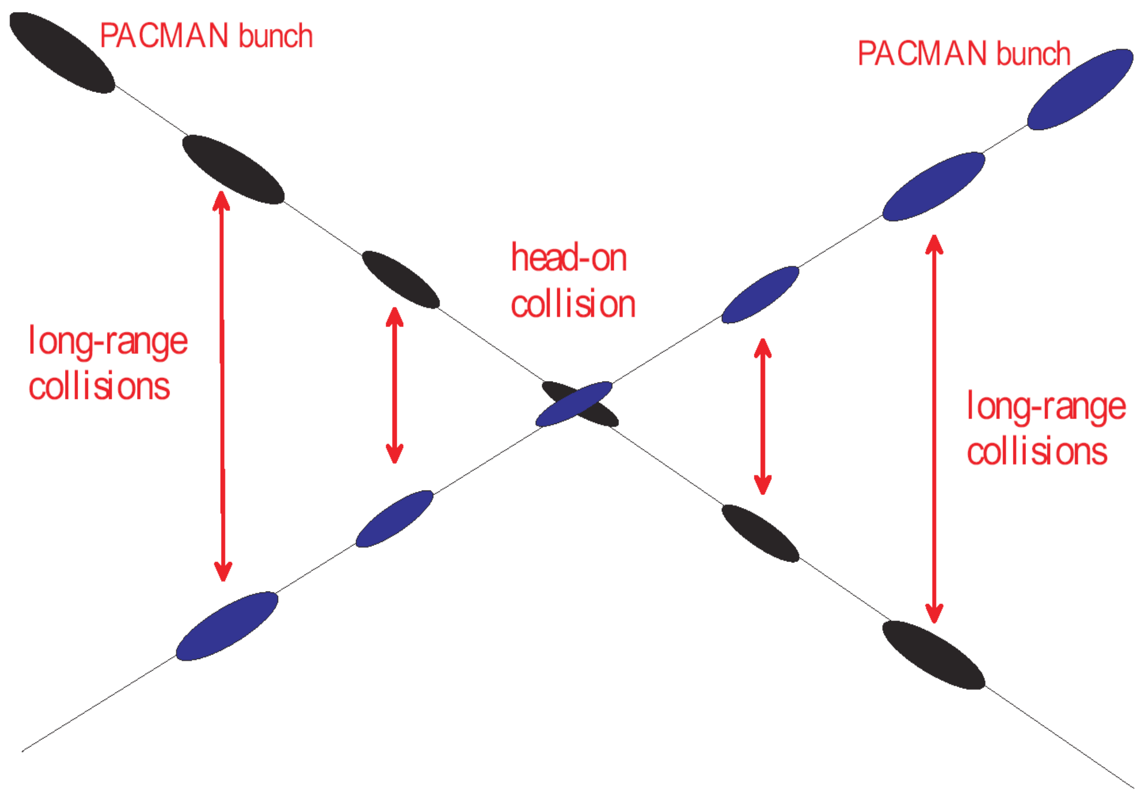
Beam-Beam interaction

Variable	Symbol	Value
Beam energy	E	7 TeV
Particle species	$\cdots$	protons
Full crossing angle	θ_c	300 μrad
rms beam divergence	σ'_x	31.7 μrad
rms beam size	σ_x	15.9 μm
Normalized transv. rms emittance	$\gamma\varepsilon$	3.75 μm
IP beta function	β^*	0.5 m
Bunch charge	N_b	$(1 \times 10^{11} - 2 \times 10^{12})$
Betatron tune	Q_0	0.31



- Long range beam-beam interaction represented by a 4D kick-map

$$\Delta x = -\, n_{par} \frac{2 r_p N_b}{\gamma} \left[\frac{x' + \theta_c}{\theta_t^2} \left(1 - e^{-\frac{\theta_t^2}{2\theta_{x,y}^2}} \right) - \frac{1}{\theta_c} \left(1 - e^{-\frac{\theta_c^2}{2\theta_{x,y}^2}} \right) \right]$$

$$\Delta y = -\, n_{par} \frac{2 r_p N_b}{\gamma} \frac{y'}{\theta_t^2} \left(1 - e^{-\frac{\theta_t^2}{2\theta_{x,y}^2}} \right)$$

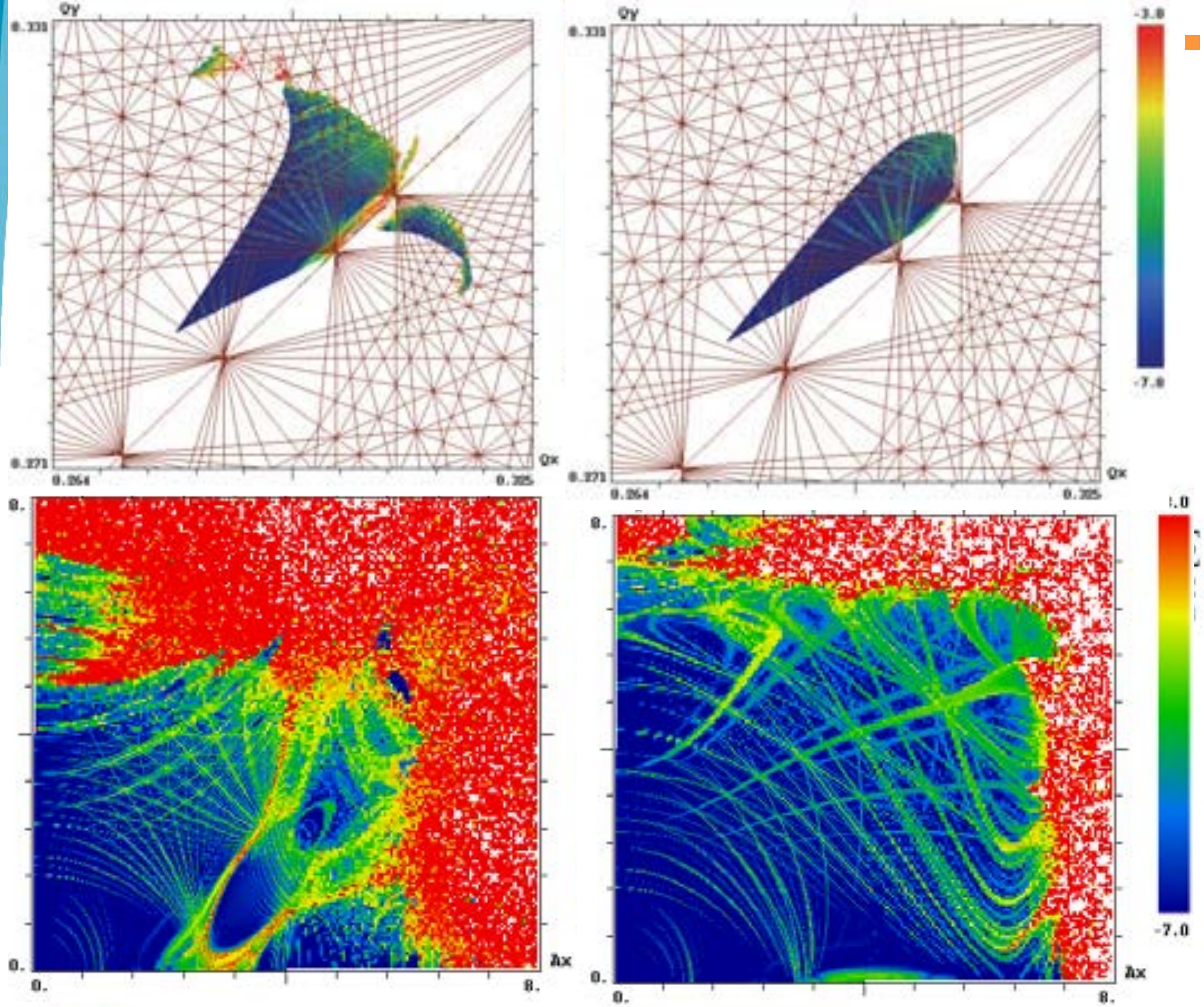
with

$$\theta_t \equiv \left((x' + \theta_c)^2 + {y'}^2 \right)^{1/2}$$

Wire compensation

Y. Papaphilippou

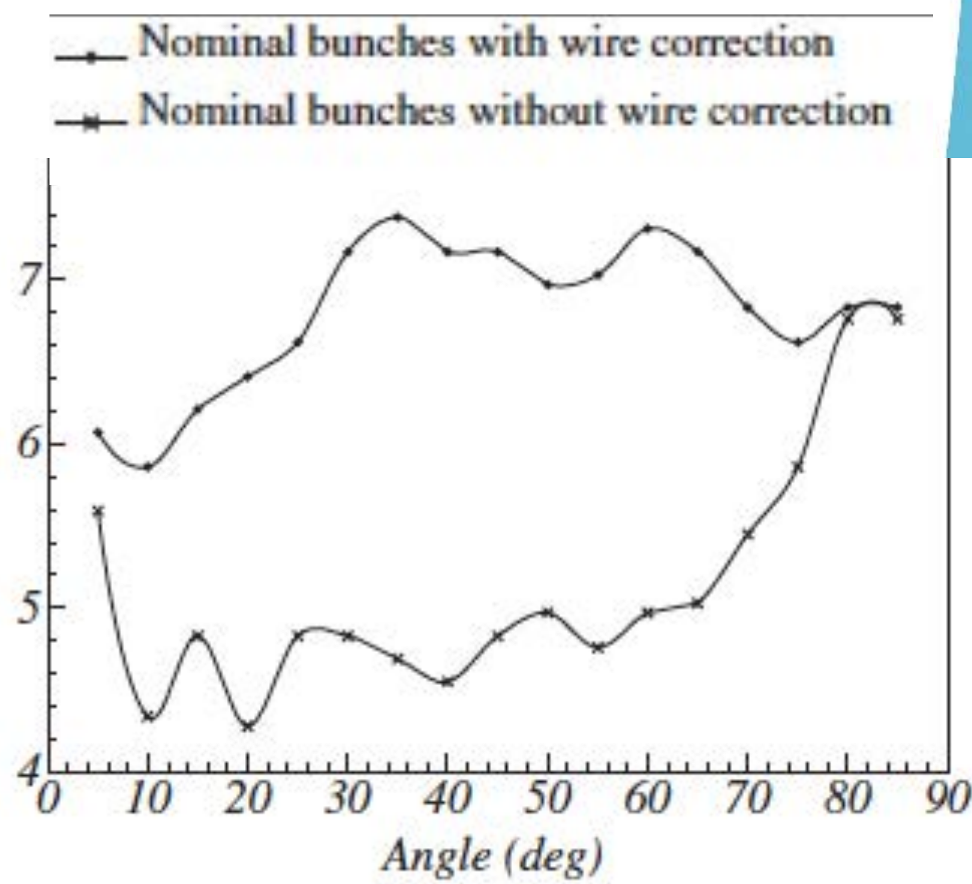
Without correction With correction



- Current baring wire can **improve DA by 1-2 σ**
- Tests in the LHC during 2017-2018

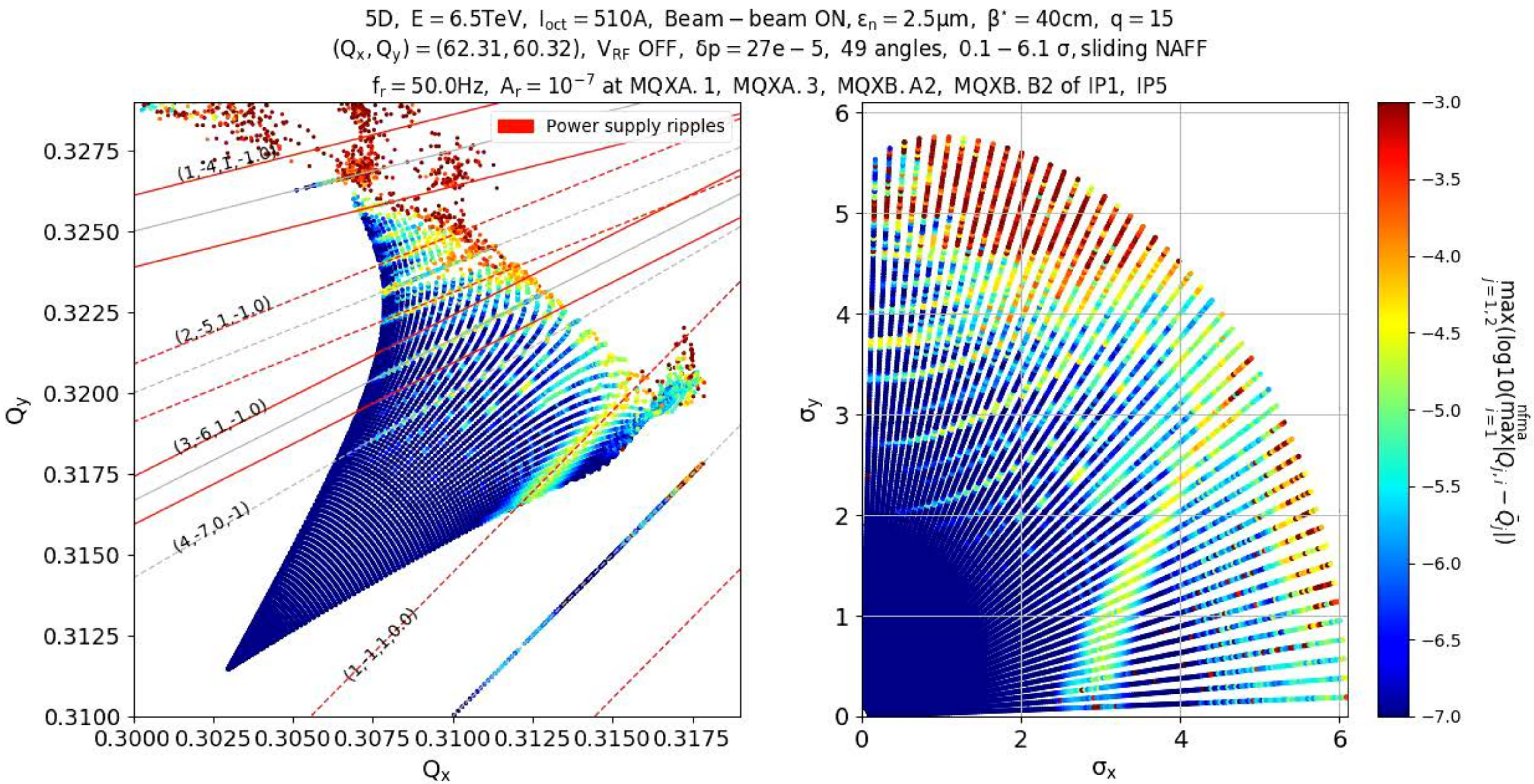
Reduced crossing angle of 450μrad @ 15cm

S. Fartoukh, al., PRSTAB, 2015



LHC: Power supply ripples (5D)

- Scan of different ripple frequencies **(50-900 Hz)**



S. Kostoglou, et al., PRAB 2021

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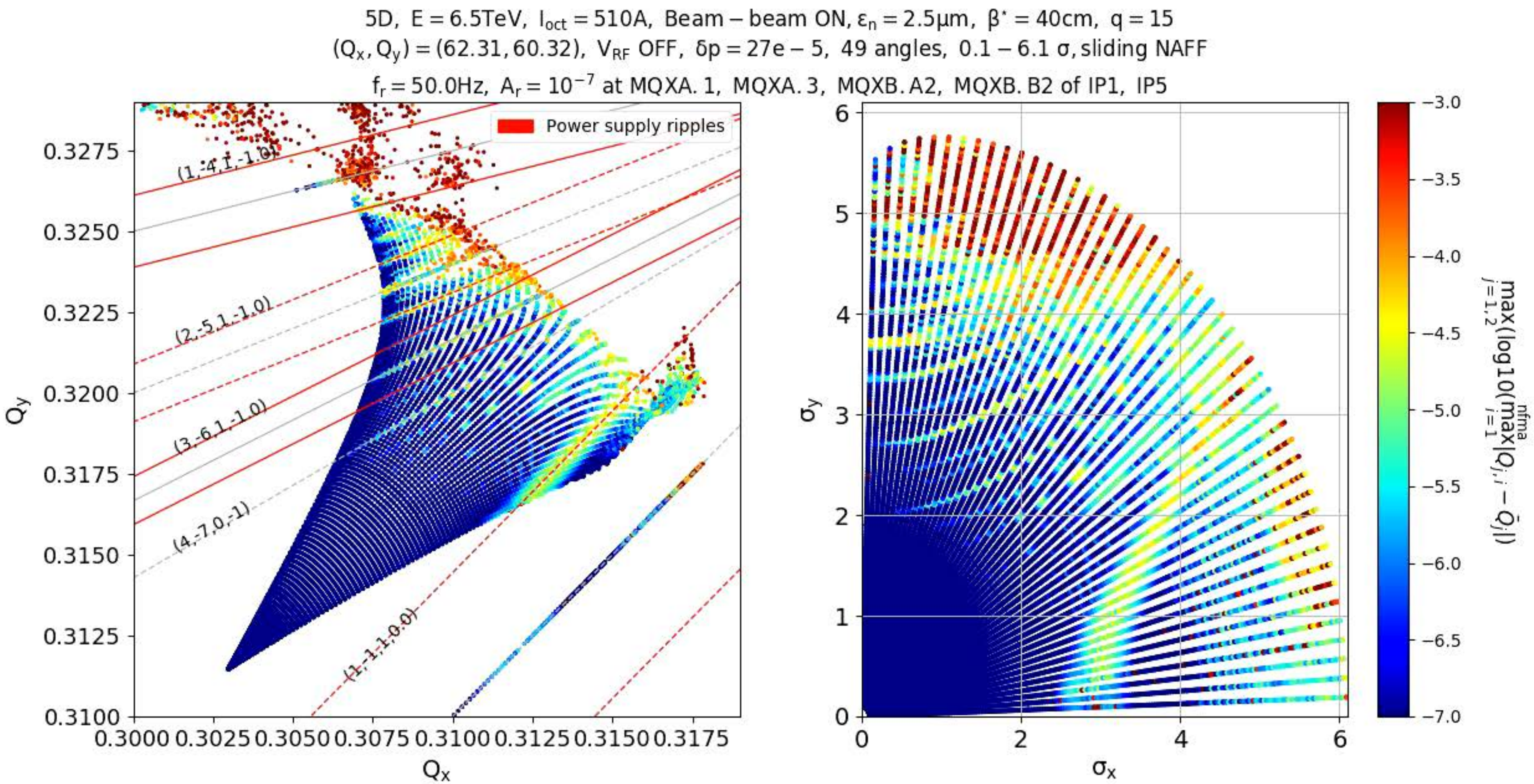

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S. Kostoglou, et al., PRAB 2021

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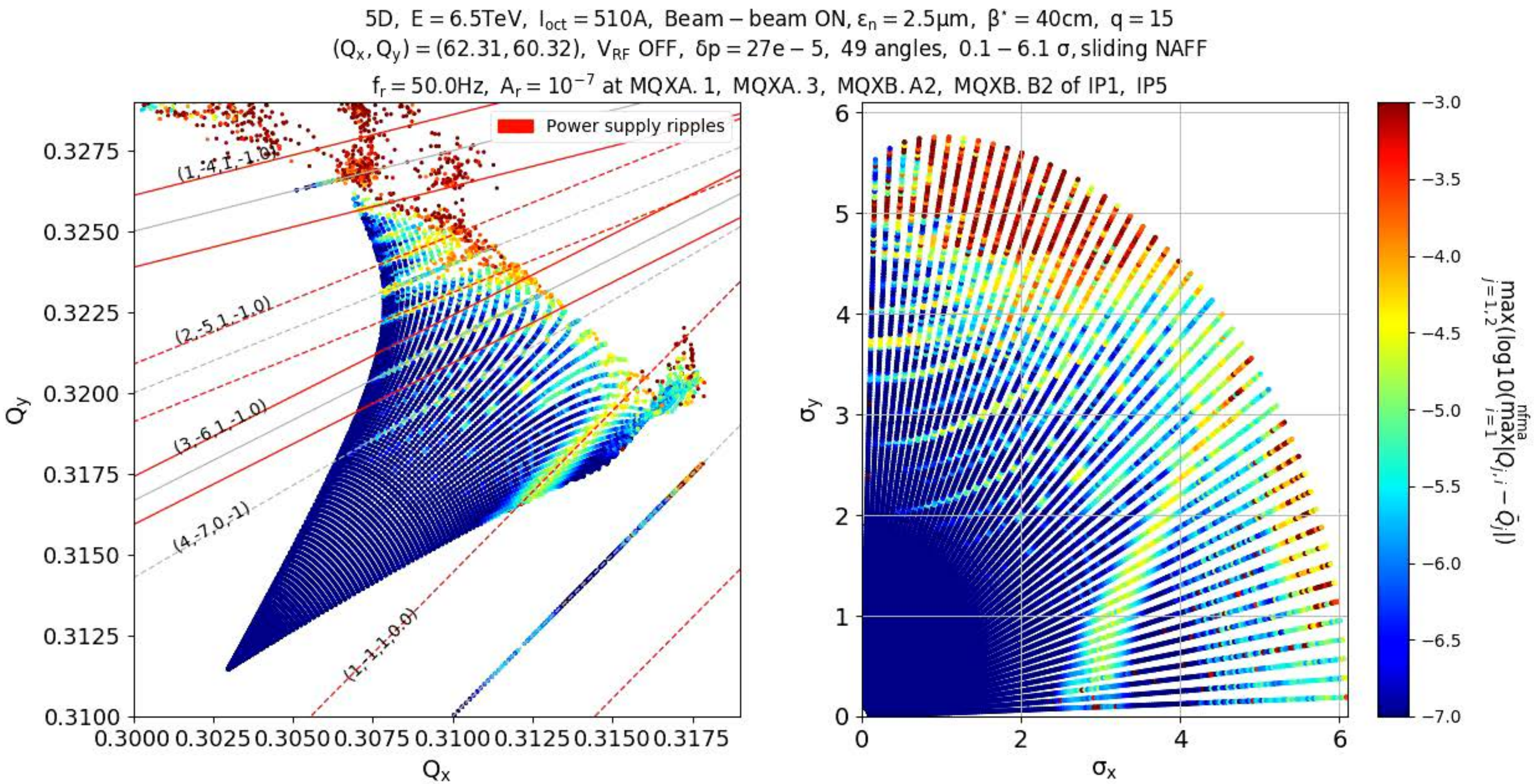

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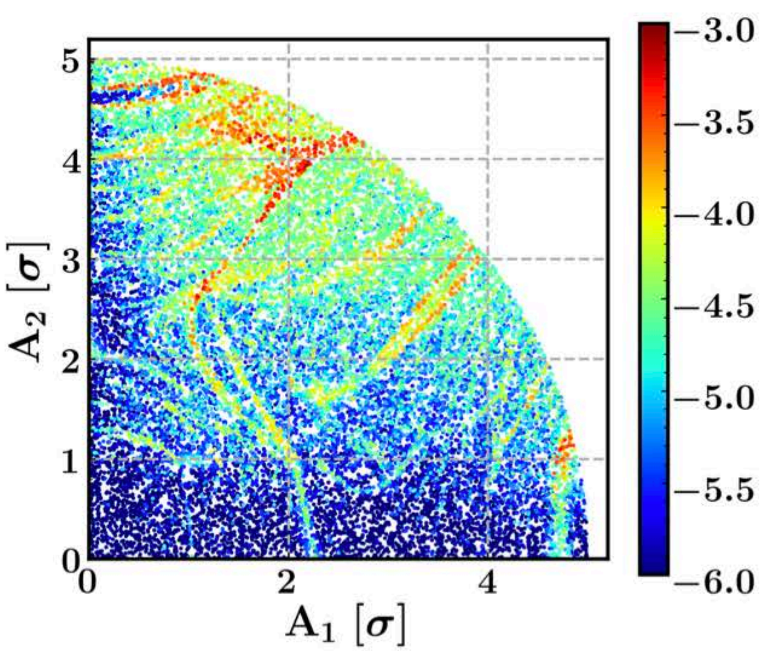
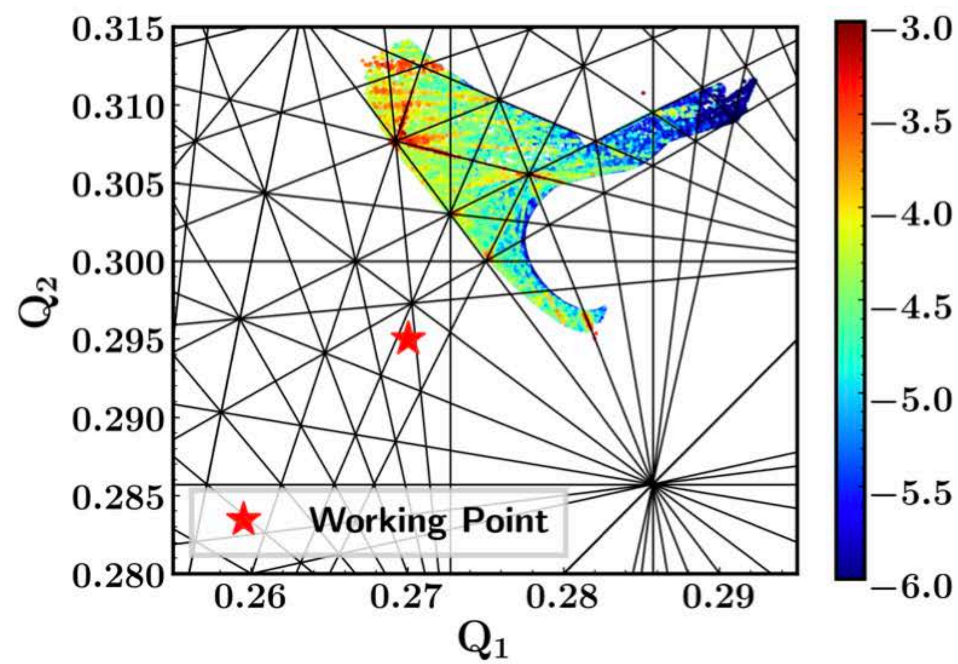
S. Kostoglou, et al., PRAB 2021

Incoherent e-cloud effects at (HL-)LHC

- Analysis of experimental data from **the LHC shows a slow beam degradation due to e-cloud both at injection and in collisions**
- A **development effort** was launched to acquire the **ability of simulating the effect of e-cloud forces within a symplectic tracking code** over the required long timescales (10M turns). The development included:
  - **Theoretical framework**
  - **Tricubic interpolator in sixtracklib tracking code** to apply forces from a recorded pinch in a symplectic way
  - **Software infrastructure to simulate and condition the electron pinches** and setup the simulation from the MAD-X description of the machine
- Presently capable of **simulating 10 M turns** (15 minutes of beam time) by exploiting the computational power of GPUs





K. Paraschou, et al. 2023

Y. Papaphilippou

When you tackle difficult problems,
you need to invent new methods
that may be of general use

Some references

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