Chaos in micro-mechanics: towards MEMS-based secured communications

Martial Defoort

with Libor Rufer, Yosra Azzouz, Nathan Le Gousse,

Laurent Fesquet, Skandar Basrour

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CNRS — GRENOBLE INP — UGA

Chaos: Where ? Why ?

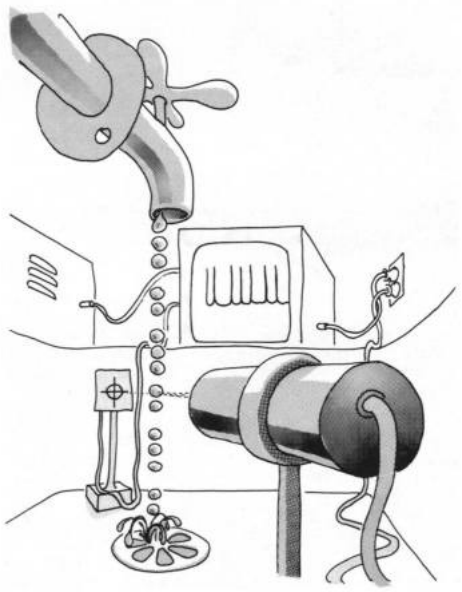
Pluto's moon Nix

nasa.gov

The Swinging Sticks

GeelongShop.com

Dripping faucet



P. Martien *et al*, Physics Letters (1985)

Chaotic regime:

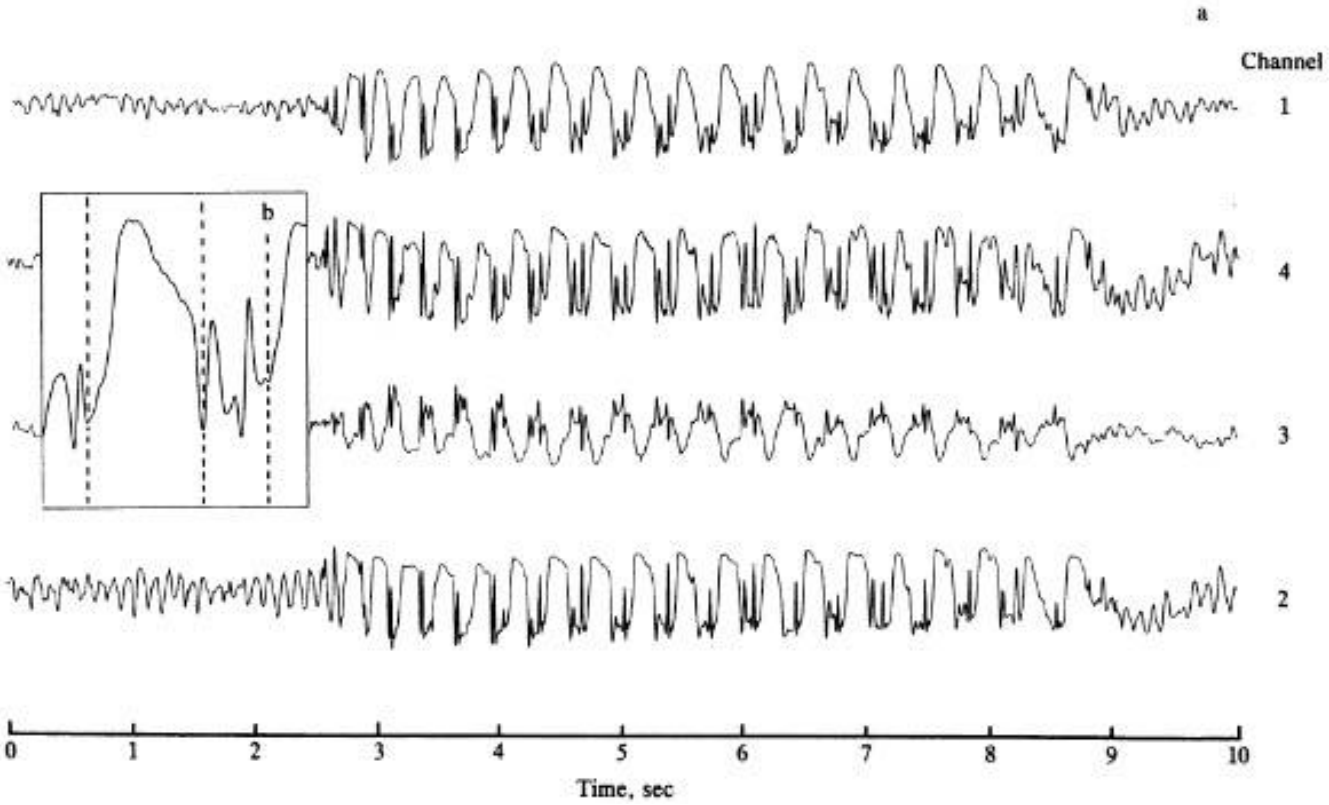
- Complex interactions within at least 3D in phase space
- Non-periodic yet ***deterministic***
- Exponentially sensitive to initial conditions

Random numbers

Cloudflare

Weather

Epileptic seizure



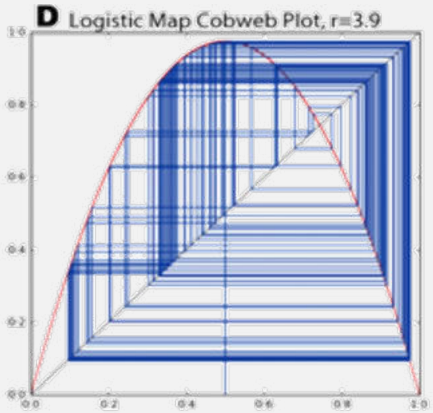
A. Babloyantz *et al*, PNAS (1986)

Mathematically

The logistic map

$$x_{n+1} = r\, x_n (1 - x_n)$$

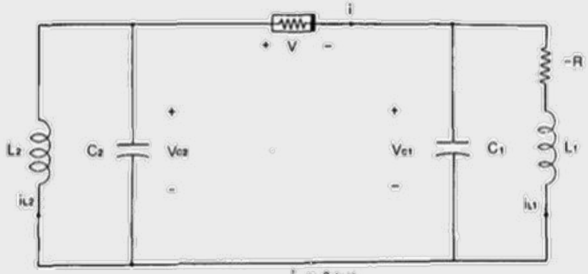
with $3.57 \leq r \leq 4$



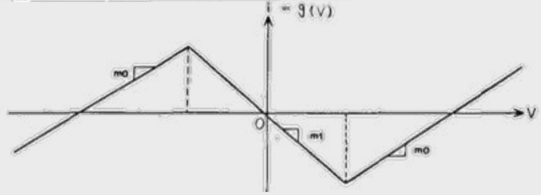
Boeing, PhD (2017)

Electronically

Chua circuits



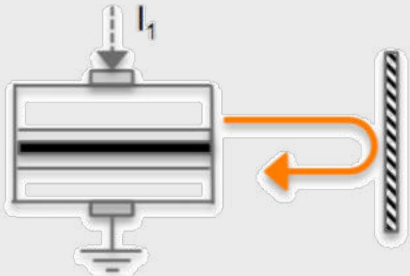
Nonlinear resistance



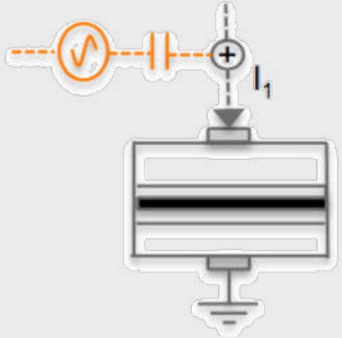
Matsumoto, IEEE TCS (1986)

Optically

Optical feedback



Current modulation

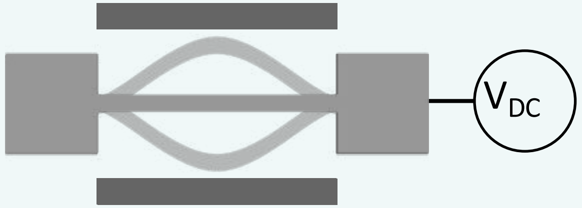


Sciamanna, Nature Photonics (2015)

Mechanically

Buckled structures

State of the art in MEMS: capacitive control



Miandoab *et al*, CNSNS (2015)
Barcelò *et al*, MEMS (2018)

Active buckling :
10-100 V continuous

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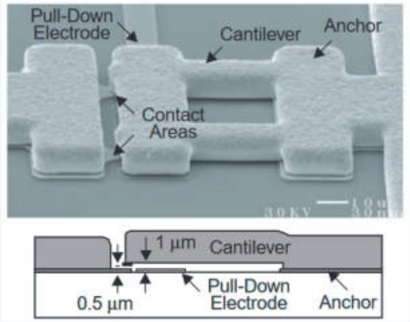
Micro-ElectroMechanical Systems

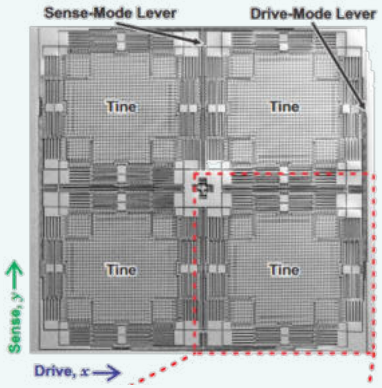
Non-resonant	Resonant

RF switches



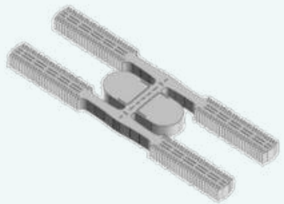
Analog Devices, (2001)

Gyroscopes



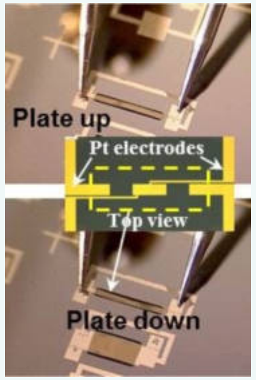
I.P. Prikhodko *et al*,
Solid State Sensors (2011)

Clocks



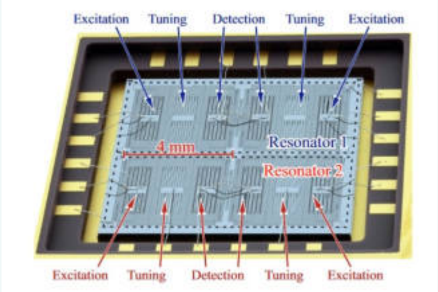
SiTime, (2017)

Energy Harvesters



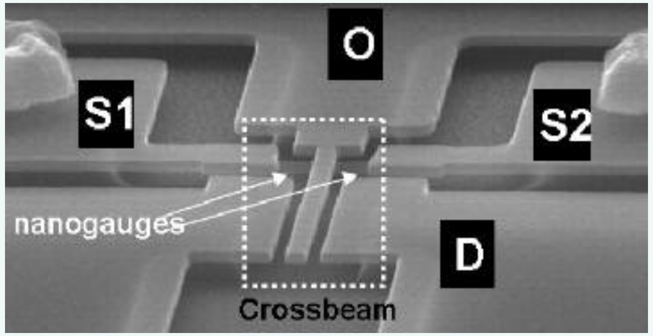
E. Trioux,
IEEE Sensors (2014)

Accelerometers



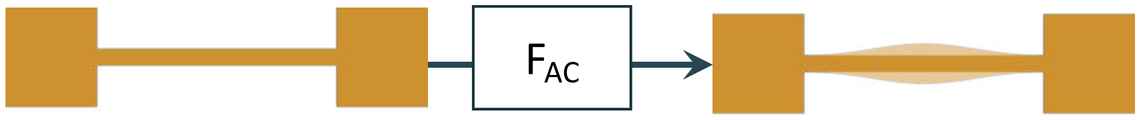
S. A. Zotov,
IEEE Sensors (2015)

Gas sensors

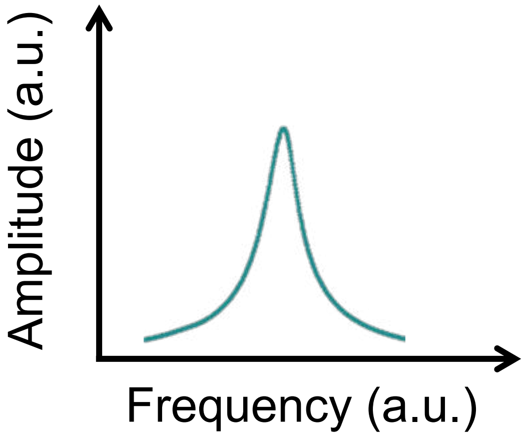


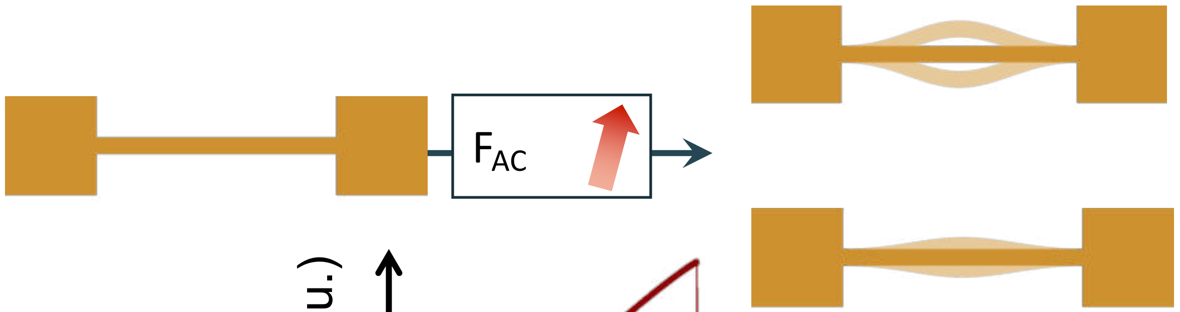
J. Arcamone, IEDM (2011)

MEMS, towards the nonlinear regime

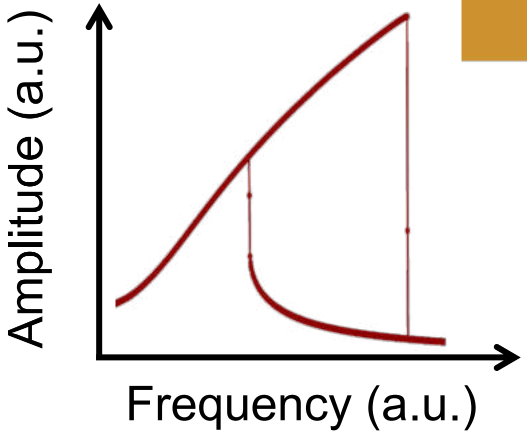


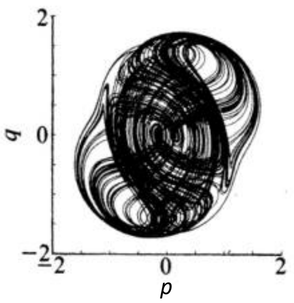
Linear regime



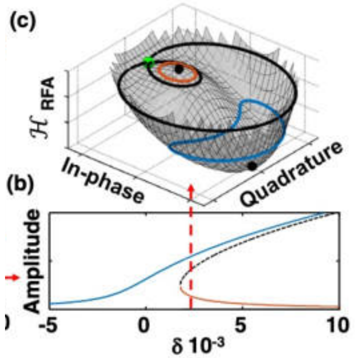


Duffing regime

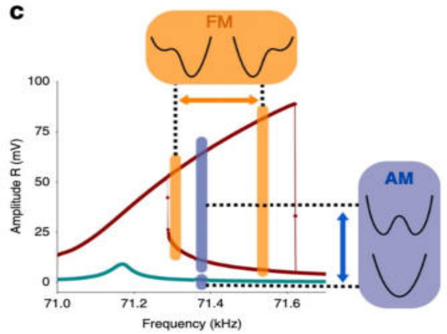




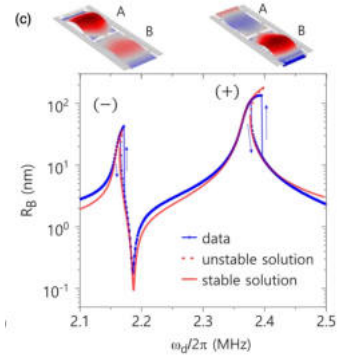
Miles, PNAS (1984)



Houri *et al*, PRL (2020)



Defoort *et al*, M&N (2021)

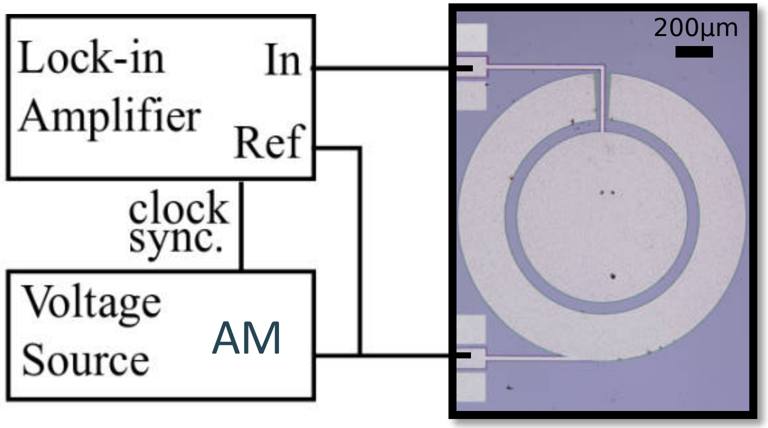


Madiot *et al*, PRA (2021)

Modulation in a nonlinear membrane

Setup

Ø 1500 µm
Si: 10 µm
AlN: 500 nm

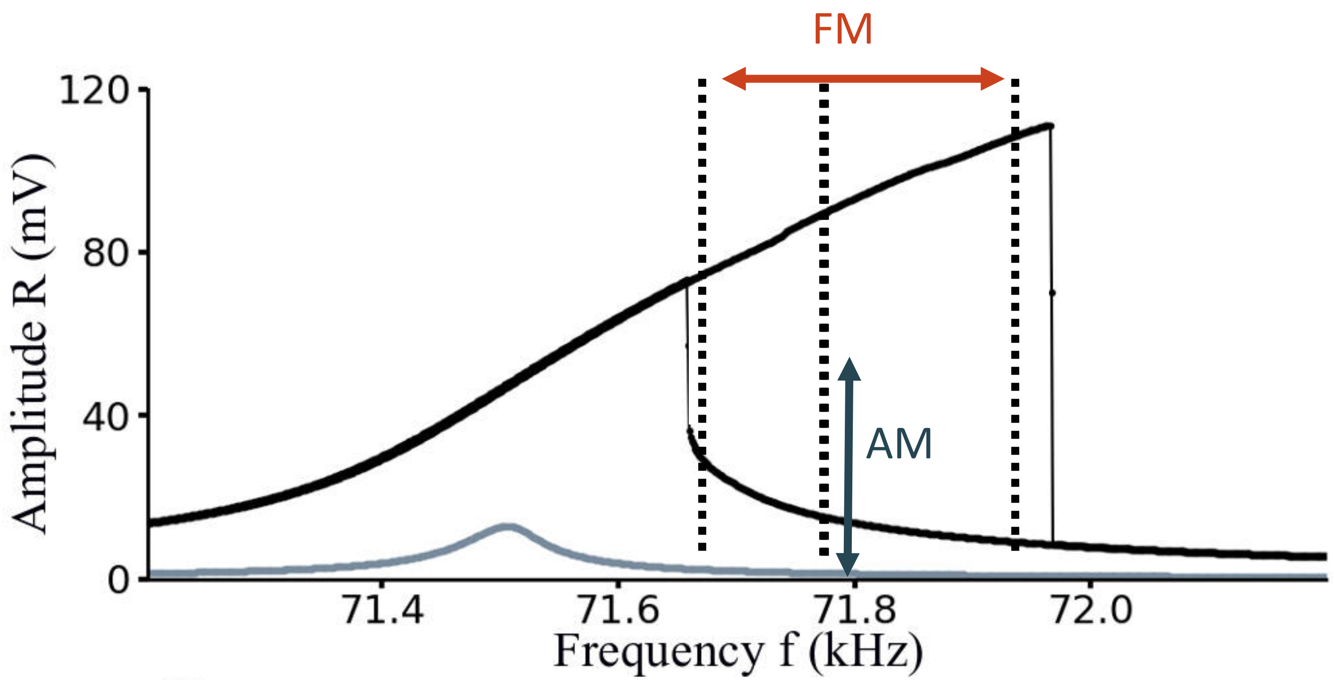


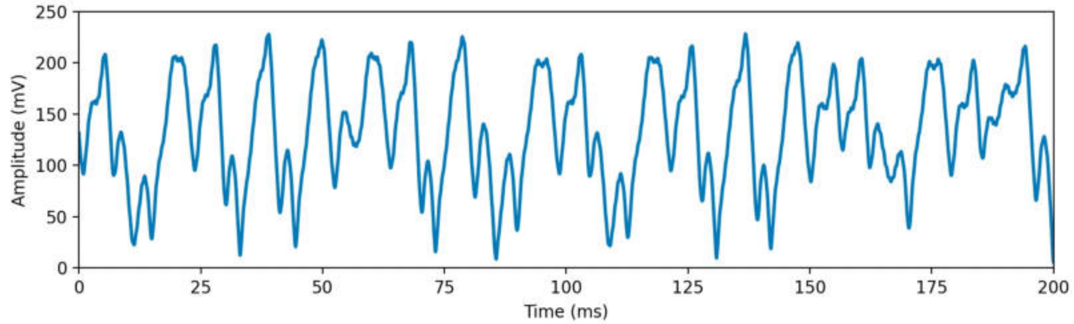
$$\ddot{x} + \Delta\omega\,\dot{x} + {\omega_0}^2 x + \alpha\,x^3 = \frac{F}{m}$$

FM: $F \to F_0 \cos(\omega\,t + \sin(\delta\omega\,t))$

AM: $F \to F_0 \cos(\omega\,t)\dfrac{1 + \cos(\delta\omega\,t)}{2}$

f_0 = 71.5 kHz Q = 1100 @ 1mbar





Fast modulation ⟶ system never at equilibrium ⟶ new physics

Modulation in a nonlinear membrane

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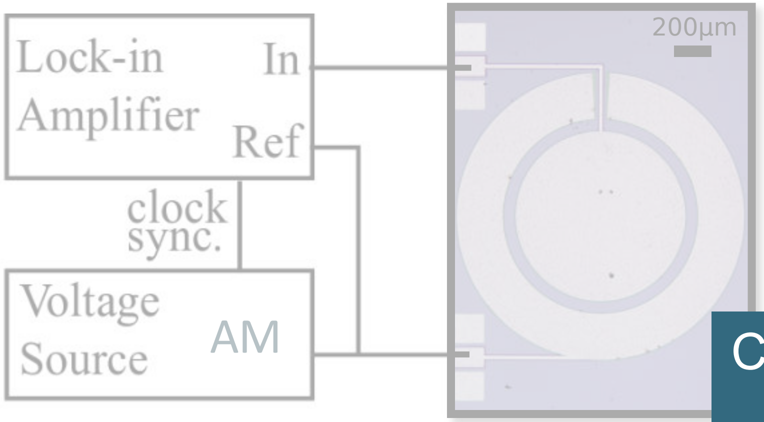

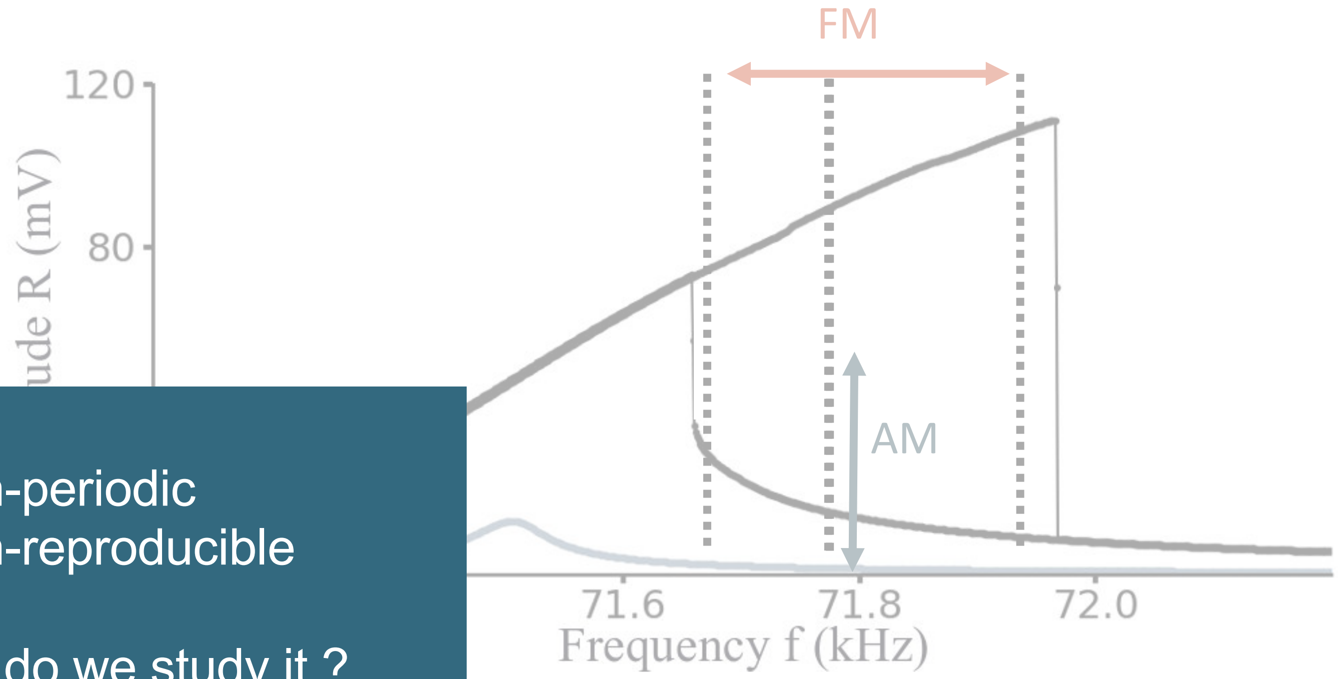

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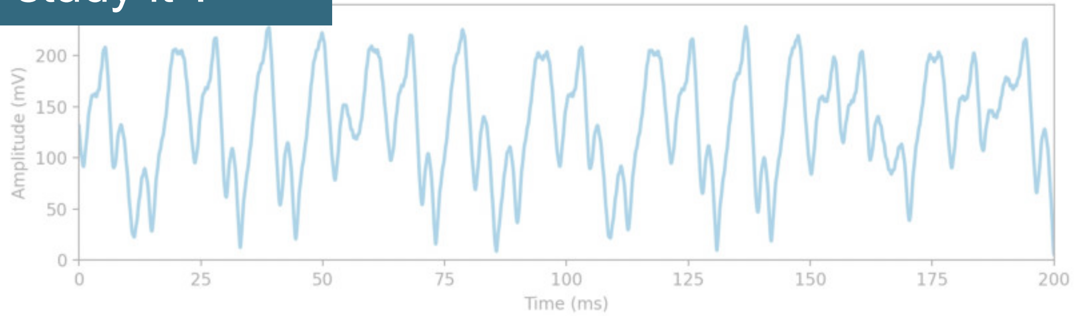
FM: $F \rightarrow F_0 \cos(\omega\,t + \sin(\delta\omega\,t))$

AM: $F \rightarrow F_0 \cos(\omega\,t)\,\dfrac{1+\cos(\delta\omega\,t)}{2}$

Chaos:
- non-periodic
- non-reproducible

How do we study it ?

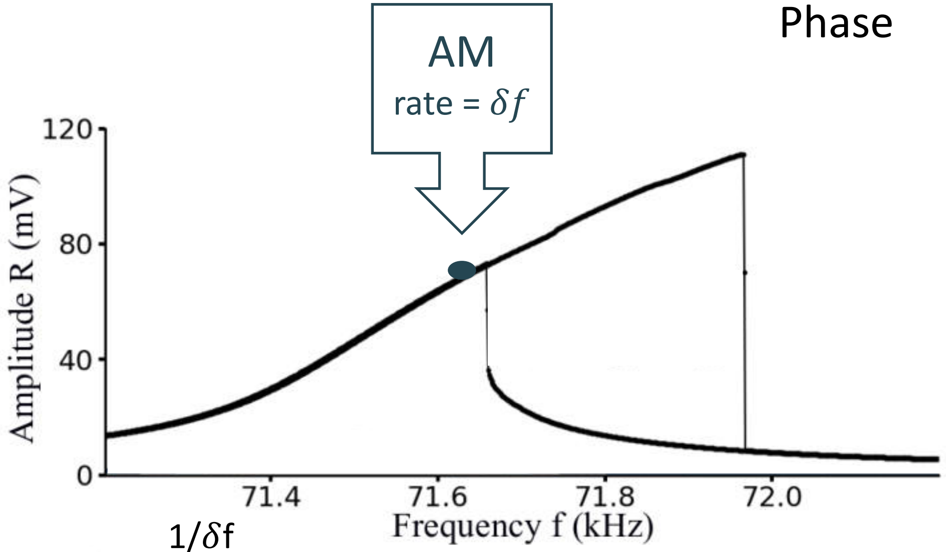


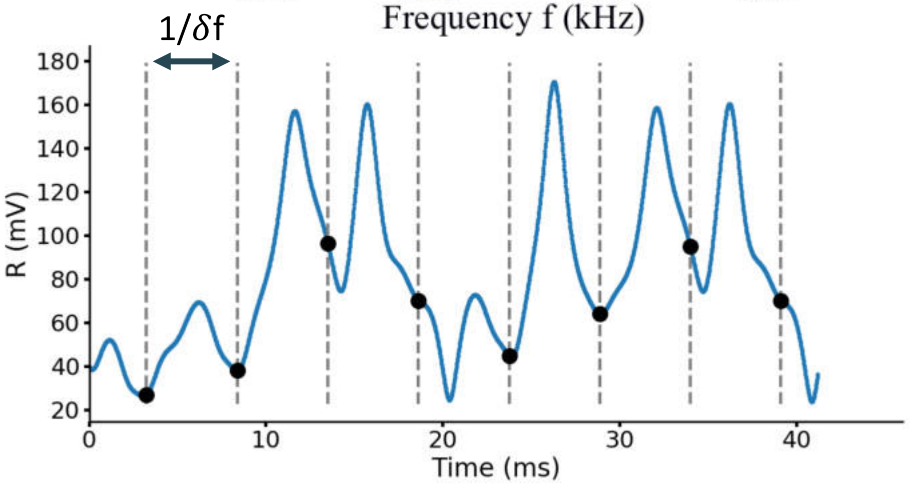
Fast modulation ⟶ system never at equilibrium ⟶ new physics

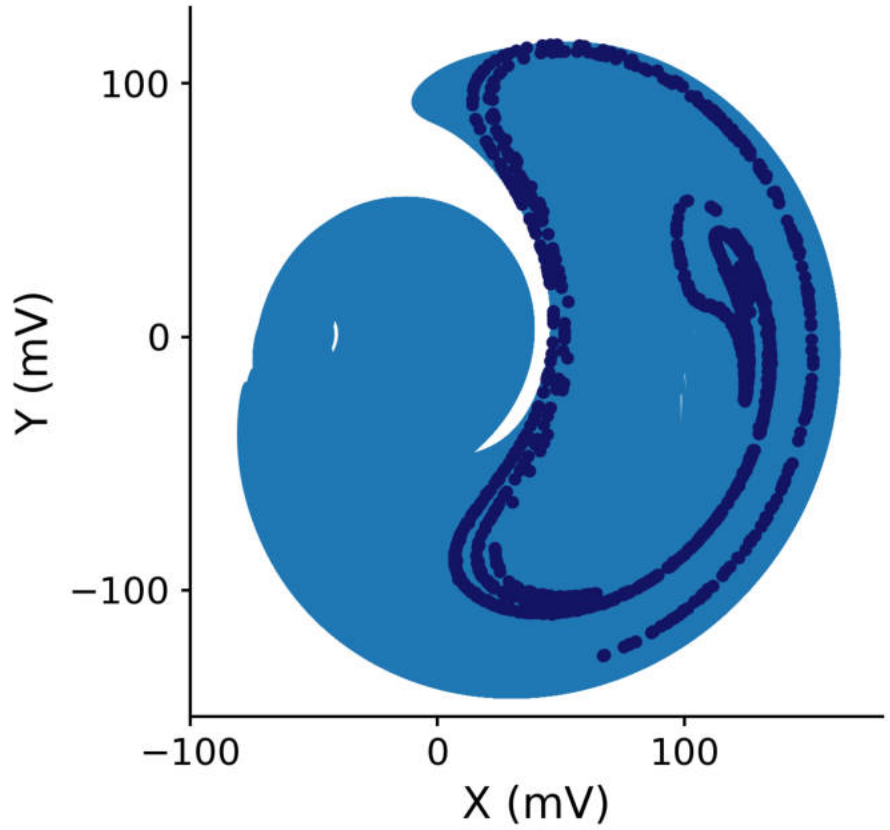
The phase state plane

Amplitude R
Phase φ

$$X = R\ \cos\varphi$$
$$Y = R\ \sin\varphi$$







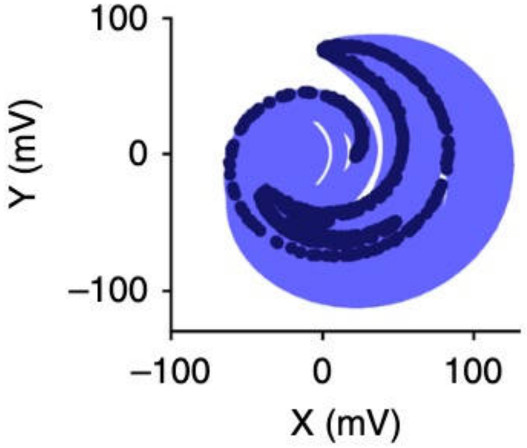
Poincaré sections: order within chaos

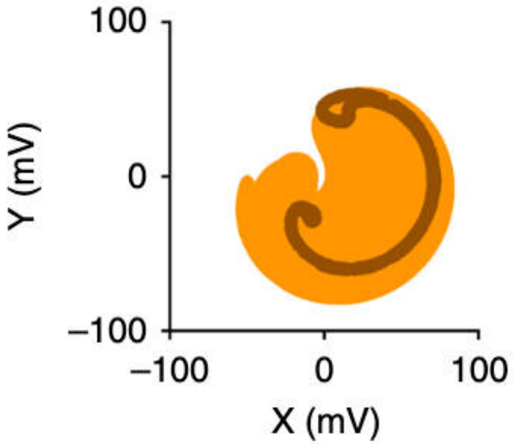
Poincaré sections

Amplitude Modulation

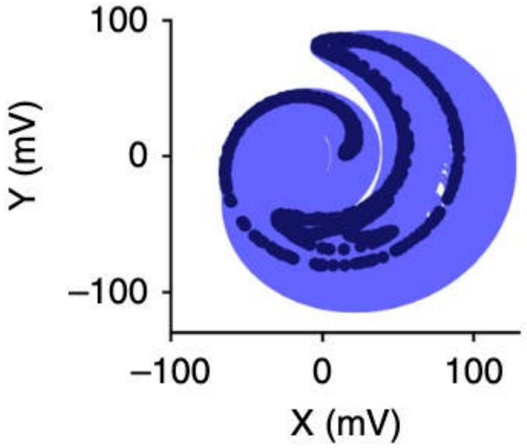
Frequency Modulation

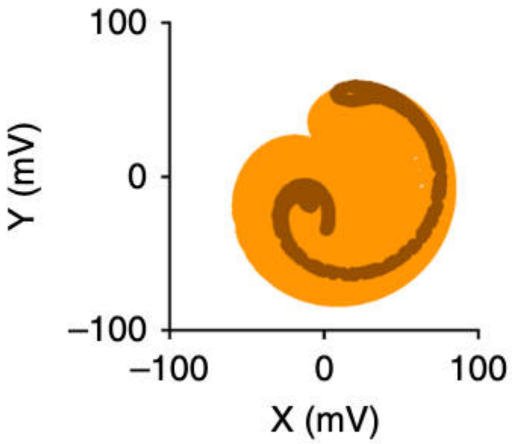
Experimental



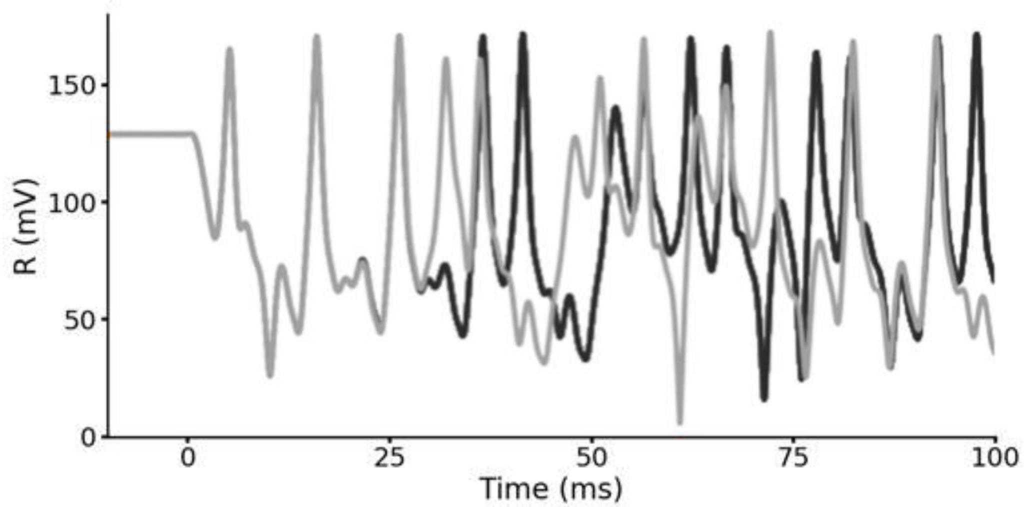


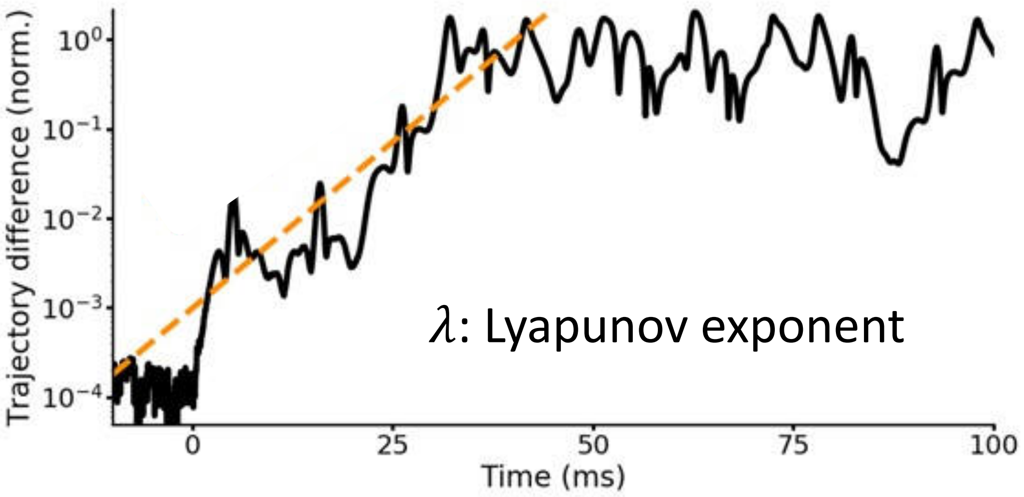
Numerical

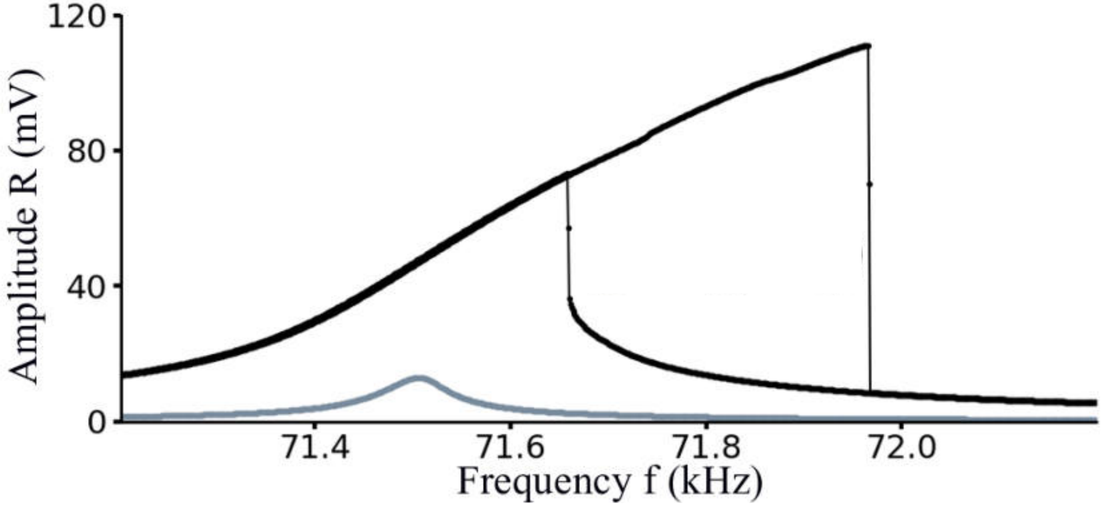


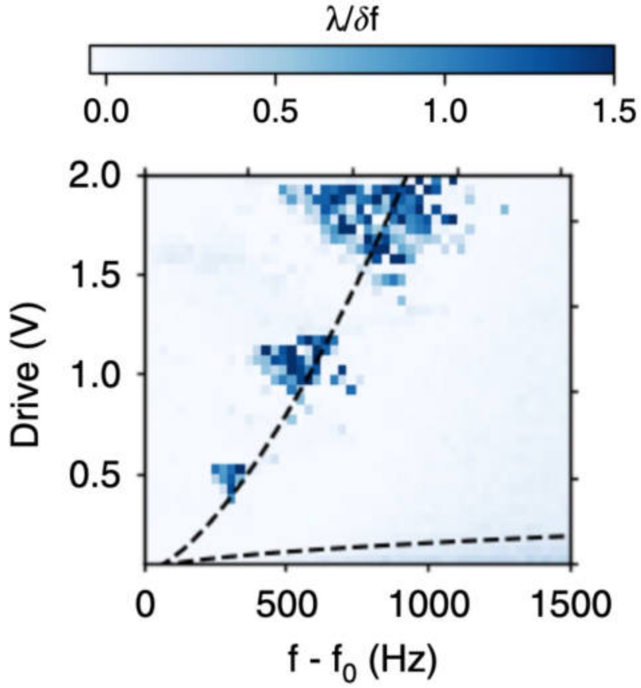


Sensitivity to initial conditions









AM: $$F \to F_0 \cos(\omega\, t)\, \frac{1 + \cos(\delta\omega\, t)}{2}$$

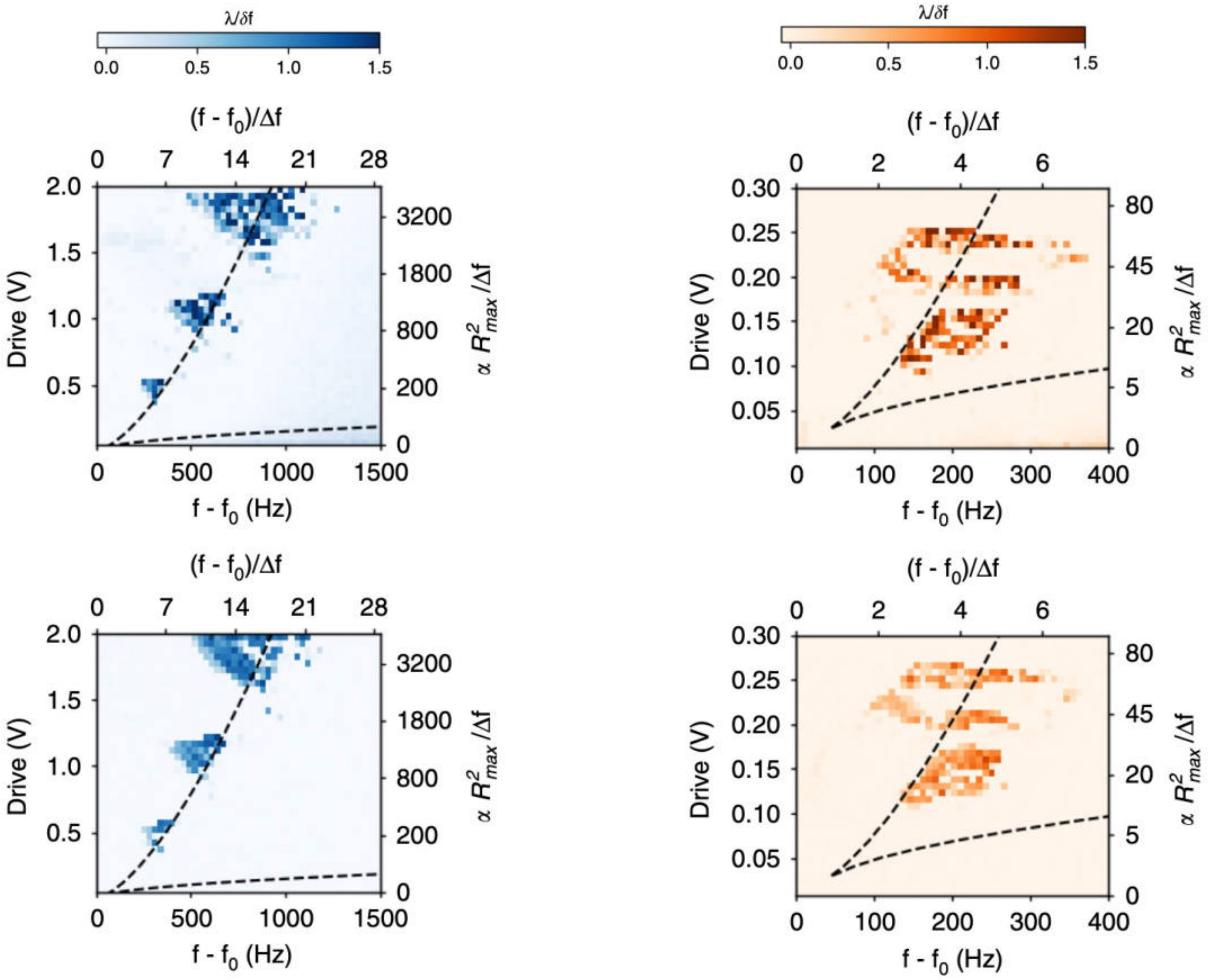
Lyapunov Exponents

Amplitude Modulation

Frequency Modulation

Experimental

Numerical



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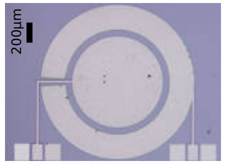
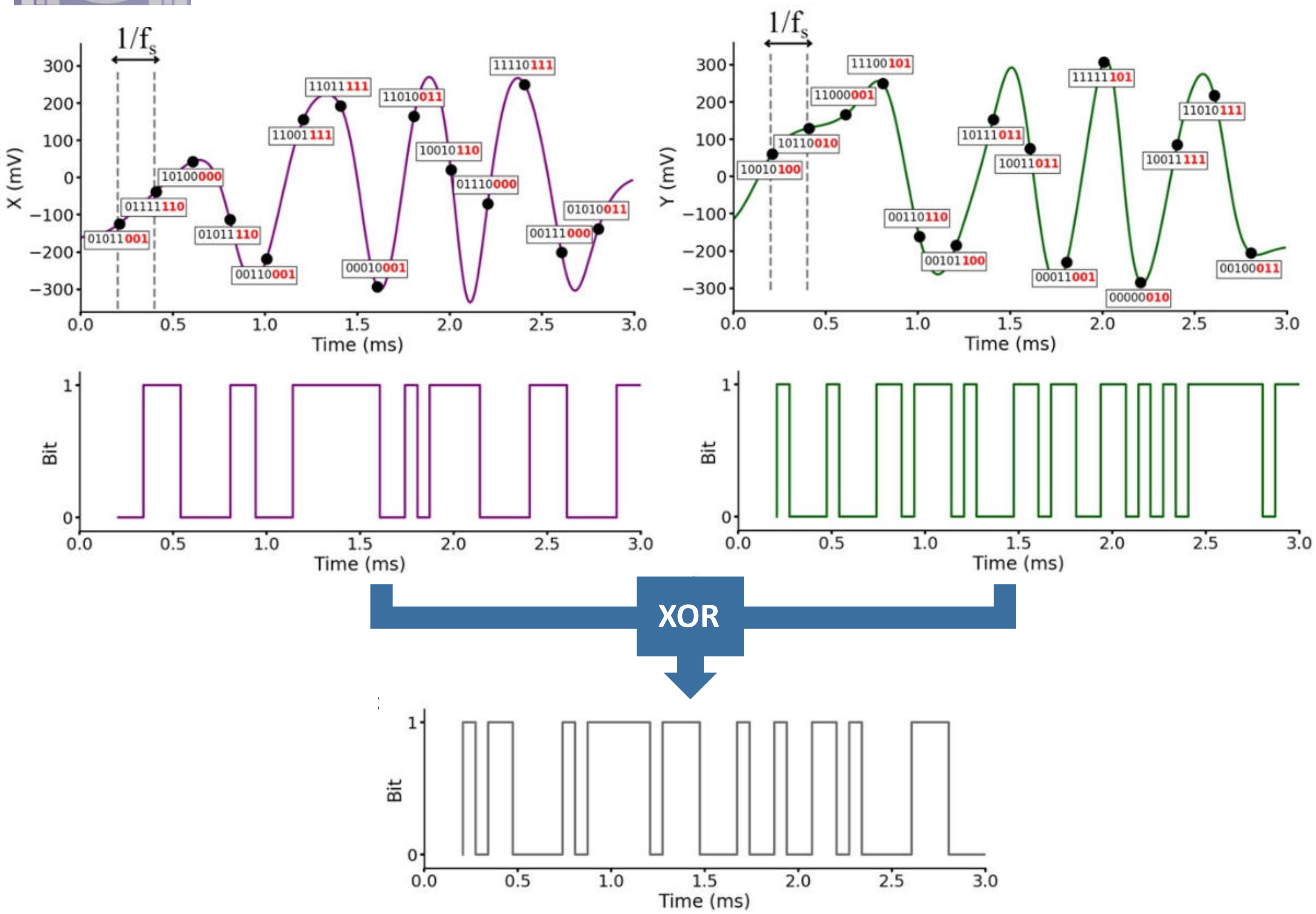
MEMS-based TRNG



3 Last Significant Bits of an 8-bit ADC



NIST 800-22 test on 75 Mb with a rate of 15 kb/s

Test	p-Value	Proportion	Result
Frequency	0.044425	75/75	Pass
Block Frequency	0.754127	73/75	Pass
Cumulative Sums	0.622341	150/150	Pass
Runs	0.099089	75/75	Pass
Longest Run	0.491599	75/75	Pass
Rank	0.666838	75/75	Pass
FFT	0.069925	74/75	Pass
NOT Matching	0.419859	11008/11100	Pass
OT Matching	0.009343	74/75	Pass
Universal	0.548605	74/75	Pass
Approx. Entropy	0.015444	74/75	Pass
Random Excursion	0.433207	371/376	Pass
Random Exc. Var.	0.393372	839/846	Pass
Serial	0.650162	150/150	Pass
Linear Excursion	0.256632	75/75	Pass

Defoort *et al*, Microsyst. Nanoeng. (2021)

Defoort *et al*, patent (2022)

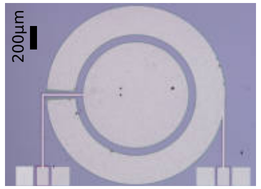
PMUT-based ultrasonic jammer

Moths jam bats to survive

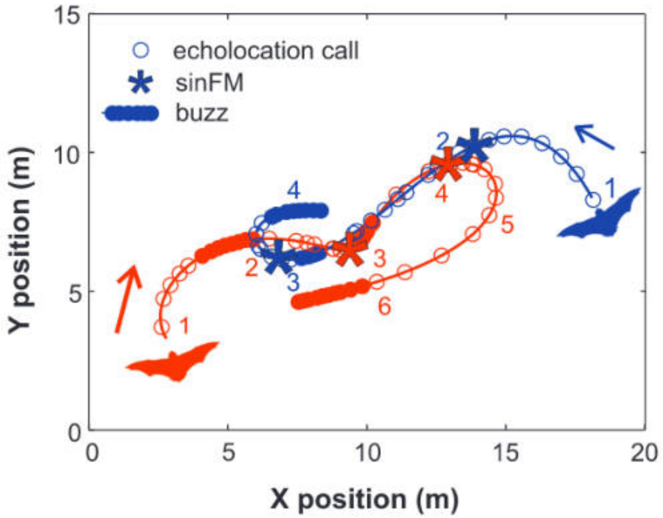
Corcoran *et al*, Science (2017)

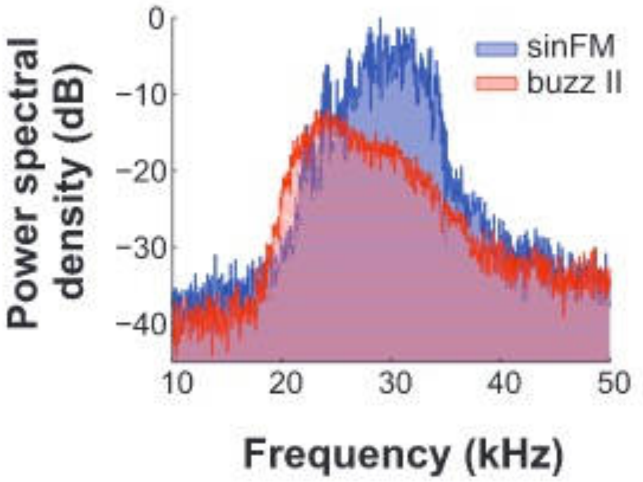
Bats jam bats for food competition

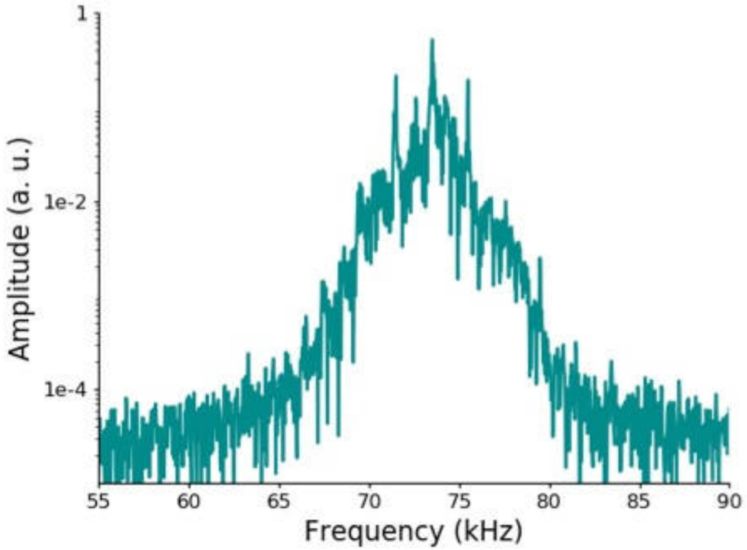
Corcoran *et al*, Science (2014)



Chaotic PMUT frequency spectrum



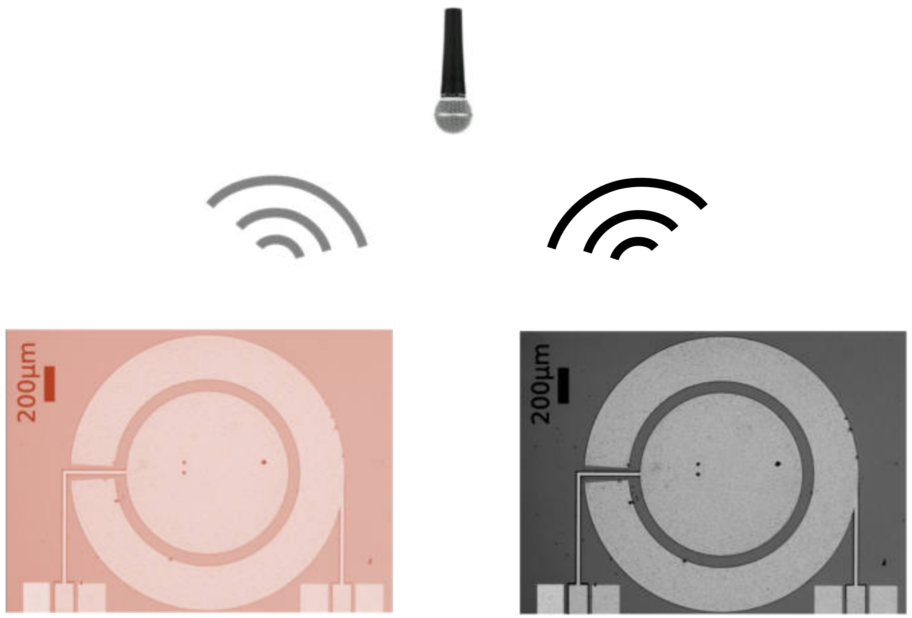




Defoort *et al*, JMM (2021)

Using a chaotic PMUT to jam a standard PMUT

PMUT-based ultrasonic jammer

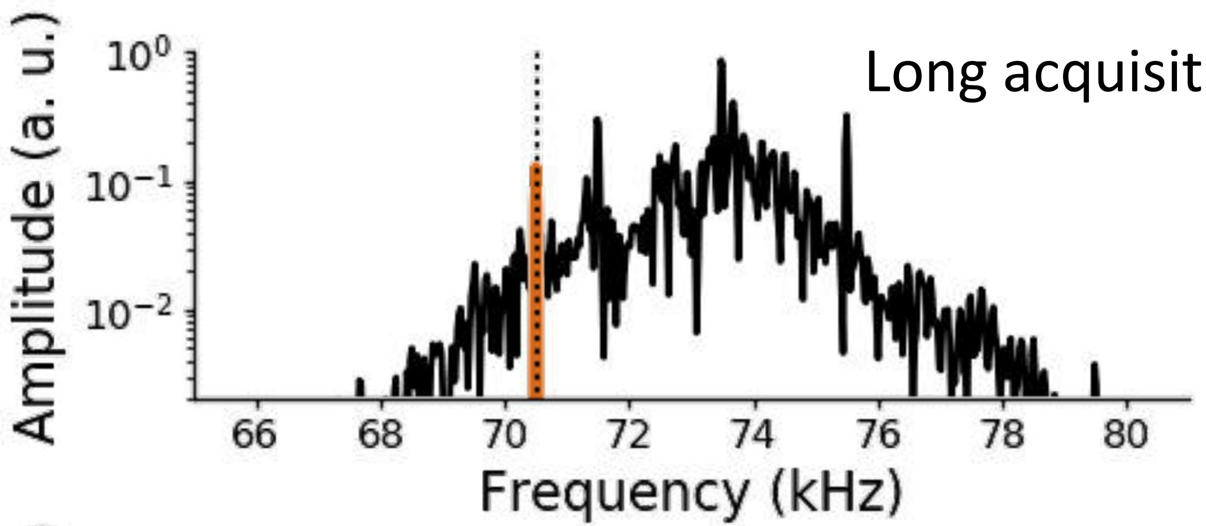


Emitter
(linear PMUT)

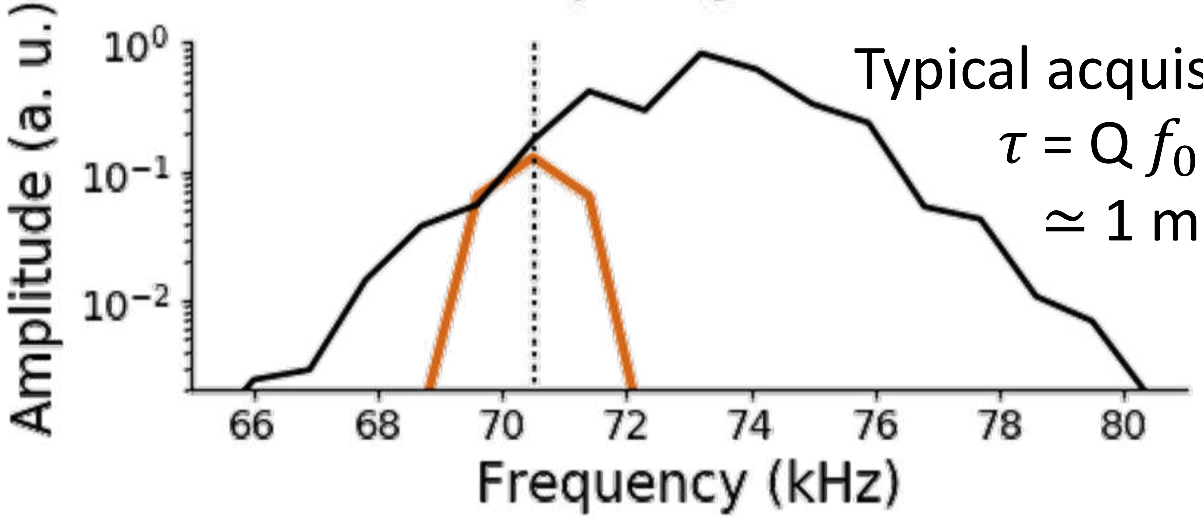
Jammer
(chaotic PMUT)

Acquisition time x8

Fourier Transform



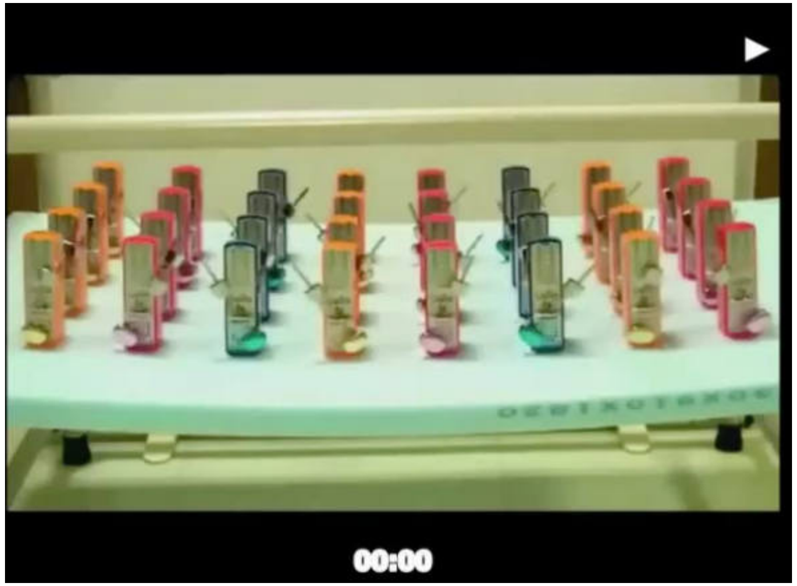
Long acquisition



Typical acquisition
$\tau = Q\, f_0$
$\simeq 1$ ms

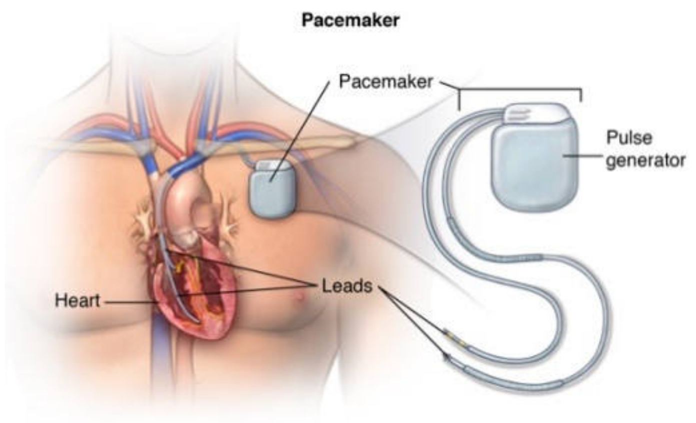
Defoort *et al*, JMM (2021)

Synchronization of chaotic MEMS

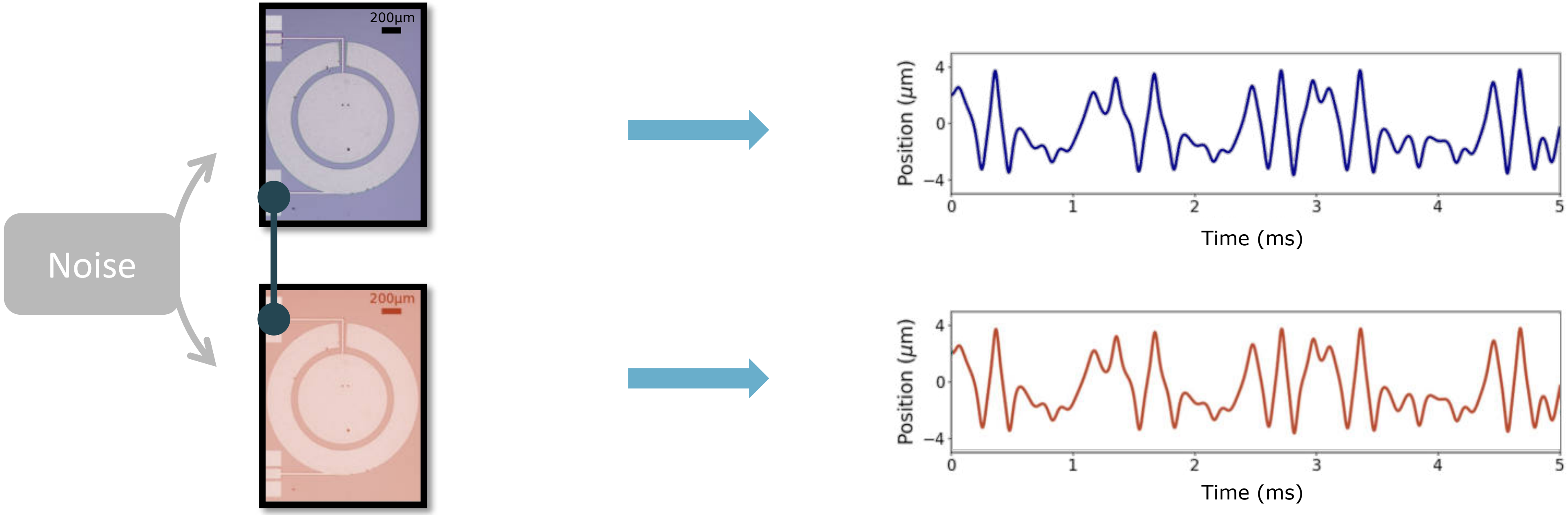


youtube.com

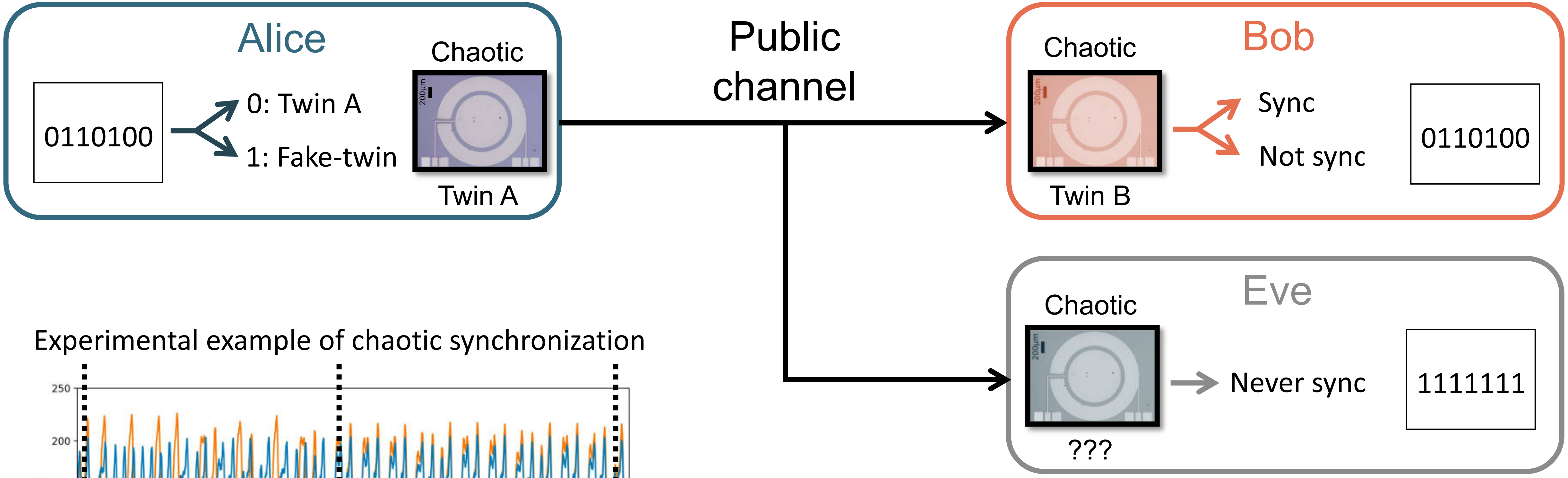
youtube.com



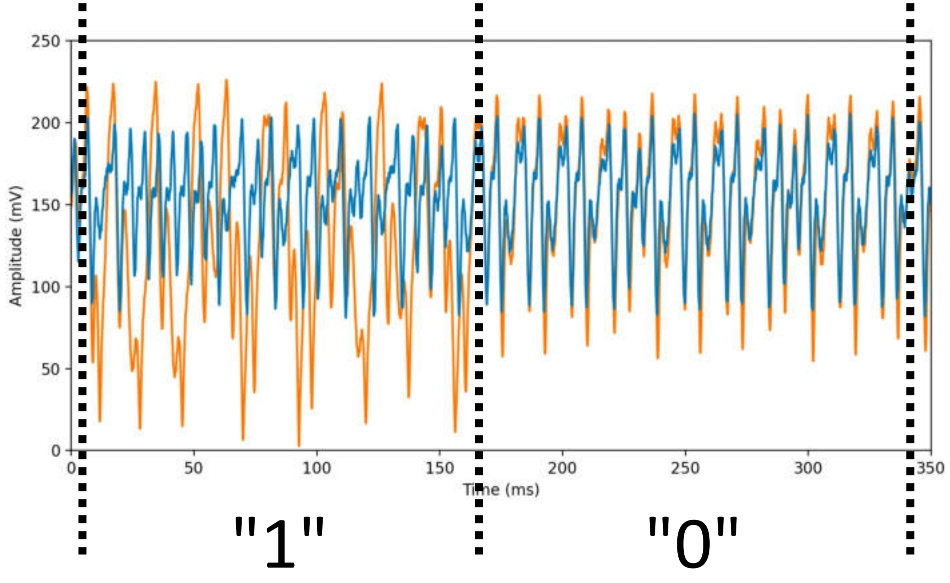
healthcare.utah.edu



MEMS-based cryptography



Experimental example of chaotic synchronization

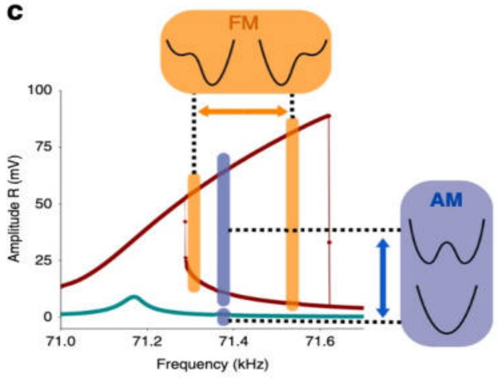


Chaotic cryptography => chaotic steganography

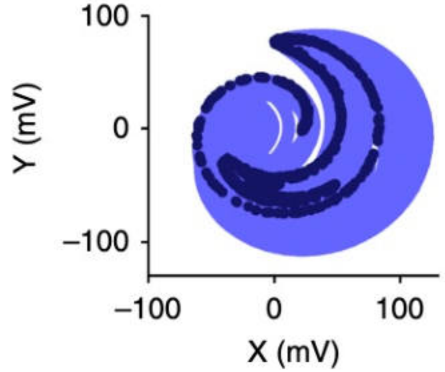
- Uses noise-like pattern to hide information
- Uses synchronization to decipher the "noise"
- Works only for very similar parameters (~ the key)

Chaos in a non-linear non-buckled microresonator

- Based on Duffing regime
  - ➡ Reachable with any MEMS



- Model system
  - ➡ Figures of merit in quantitative agreement with simulations



- Applications
  - ➡ Sensors and actuators
  - ➡ Cryptography