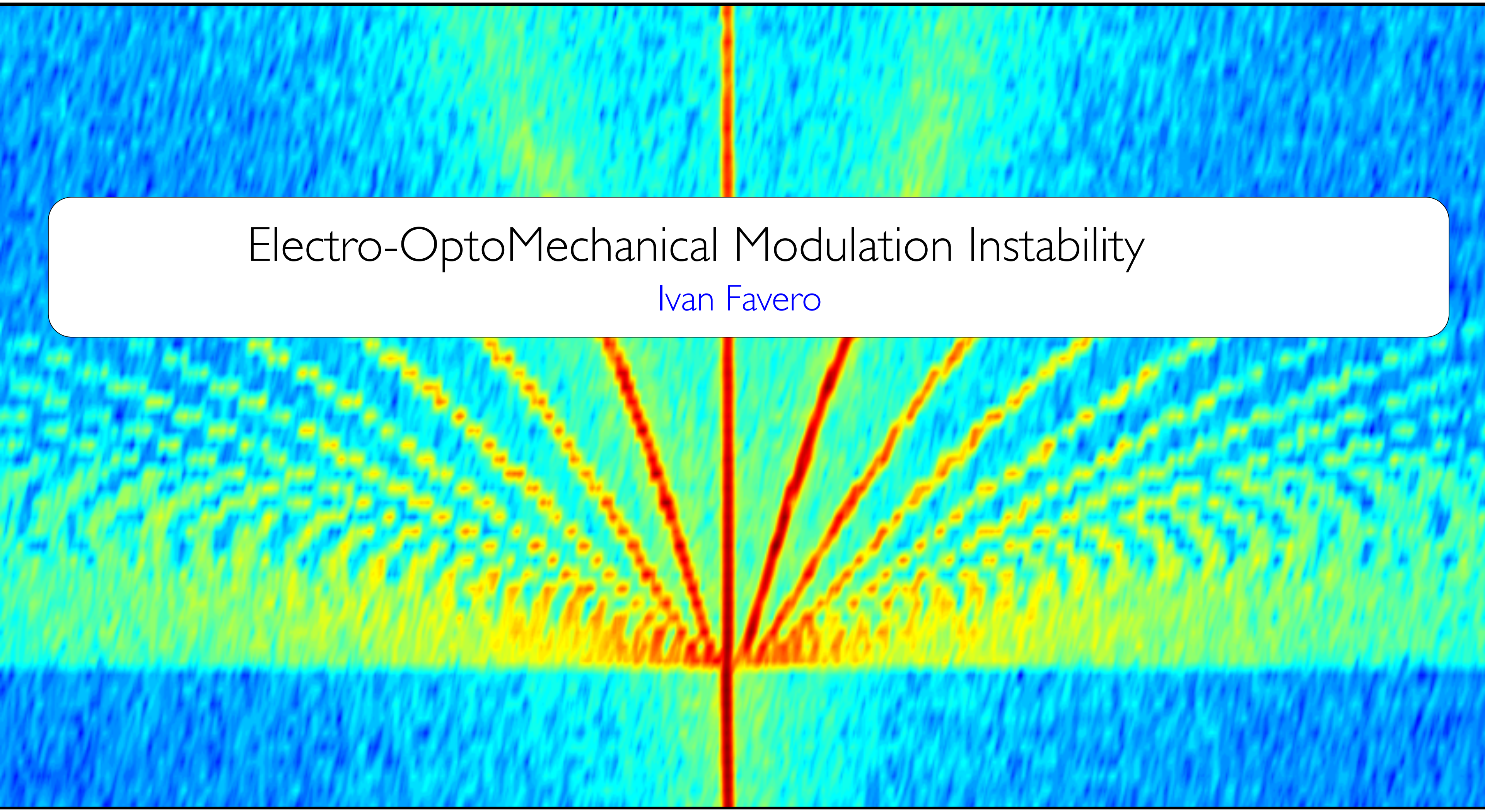
Matériaux et
Phénomènes
Quantiques

Université de Paris

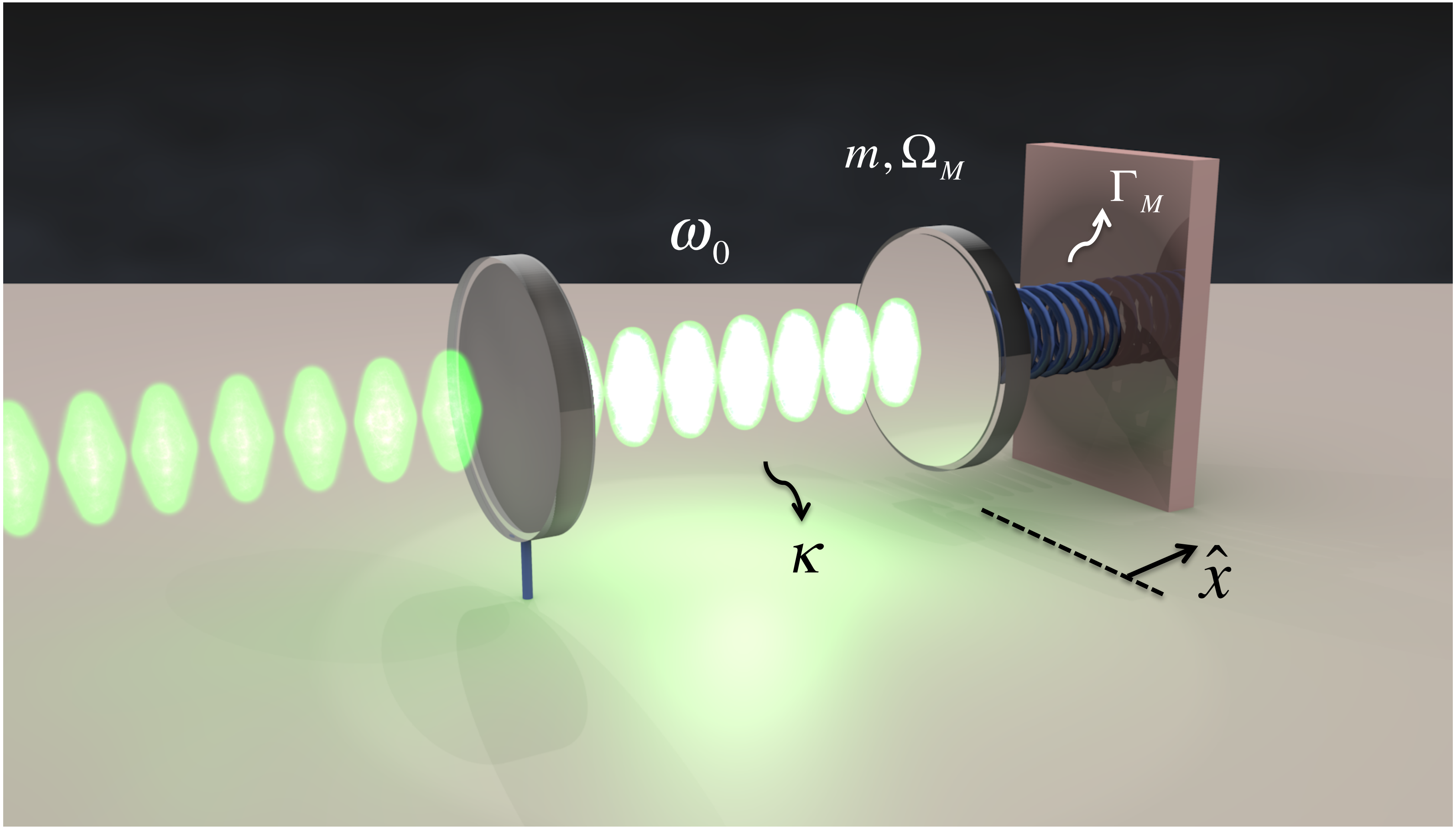


Electro-OptoMechanical Modulation Instability

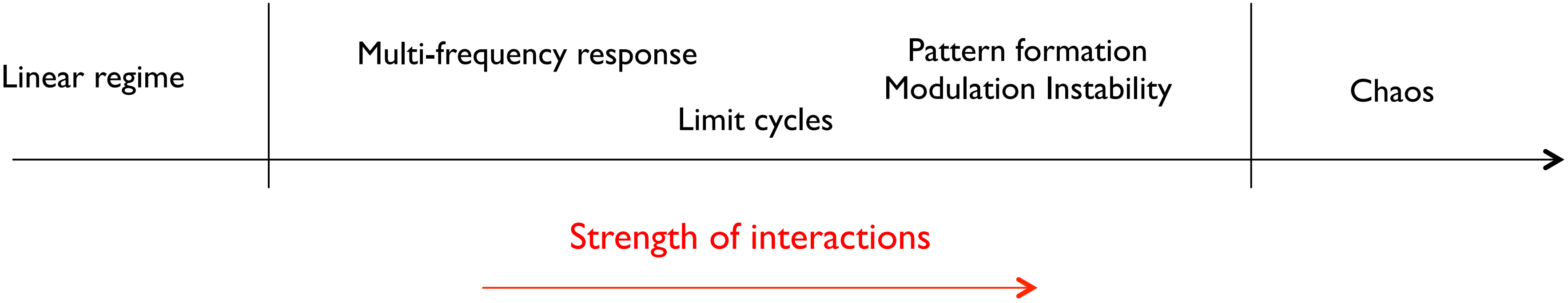
Ivan Favero

Université Paris Cité - CNRS
Pierre Allain, Biswarup Guha, Christophe Baker, Aristide Lemaître, Giuseppe Leo, Ivan Favero

Optomechanical cavity



Nonlinear Optomechanics ?



Linear regime

Multi-frequency response

Limit cycles

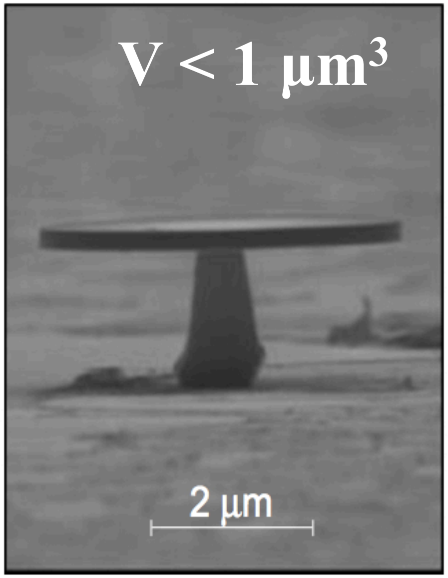
Pattern formation
Modulation Instability

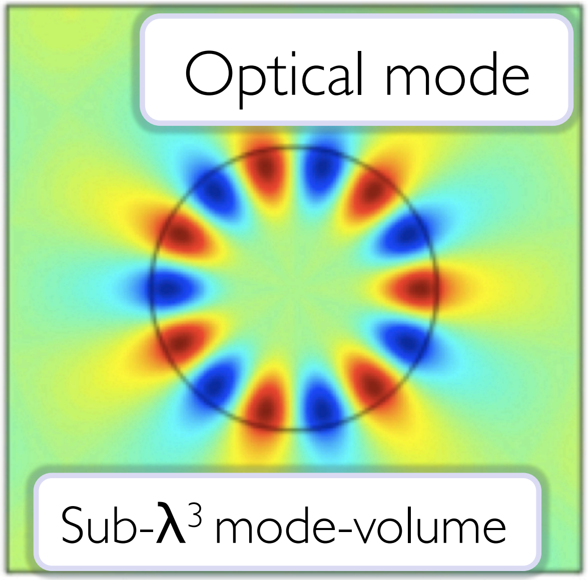
Chaos

Strength of interactions

P. Bergé et al, L'Ordre dans le Chaos (1997)

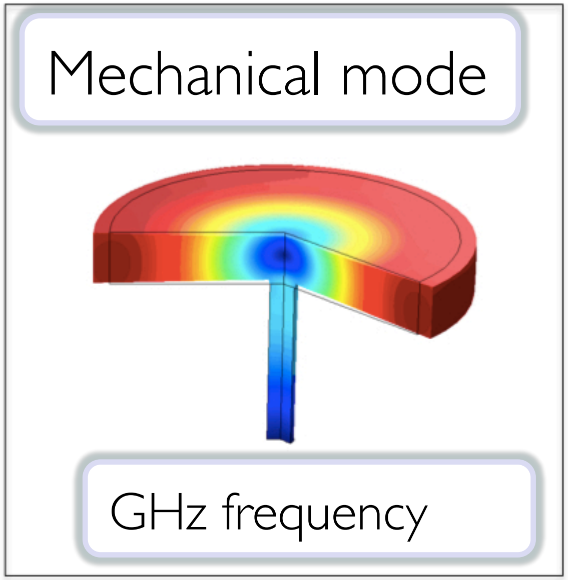
Ultra-high frequency optomechanical disk oscillators





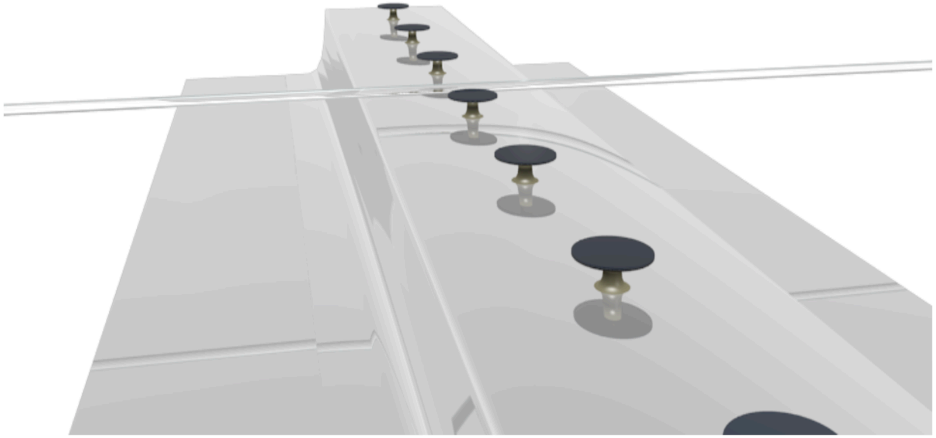
Optical mode

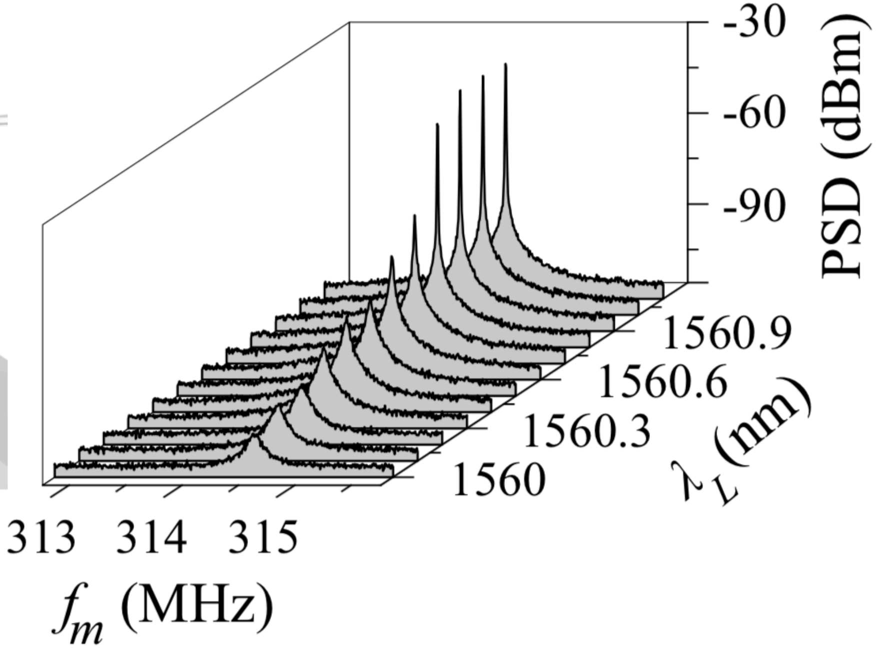
Sub-λ^3 mode-volume



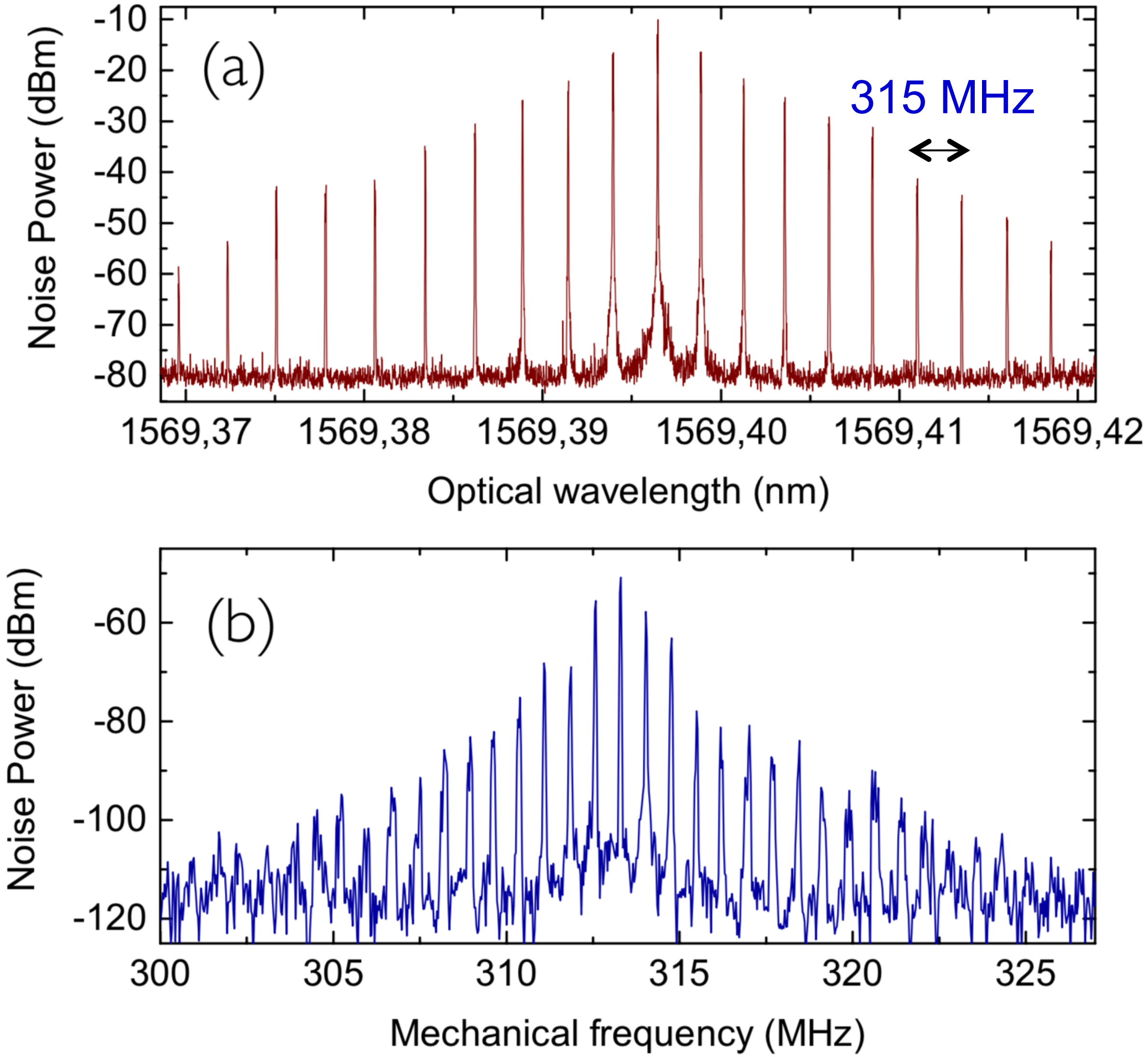
Mechanical mode

GHz frequency



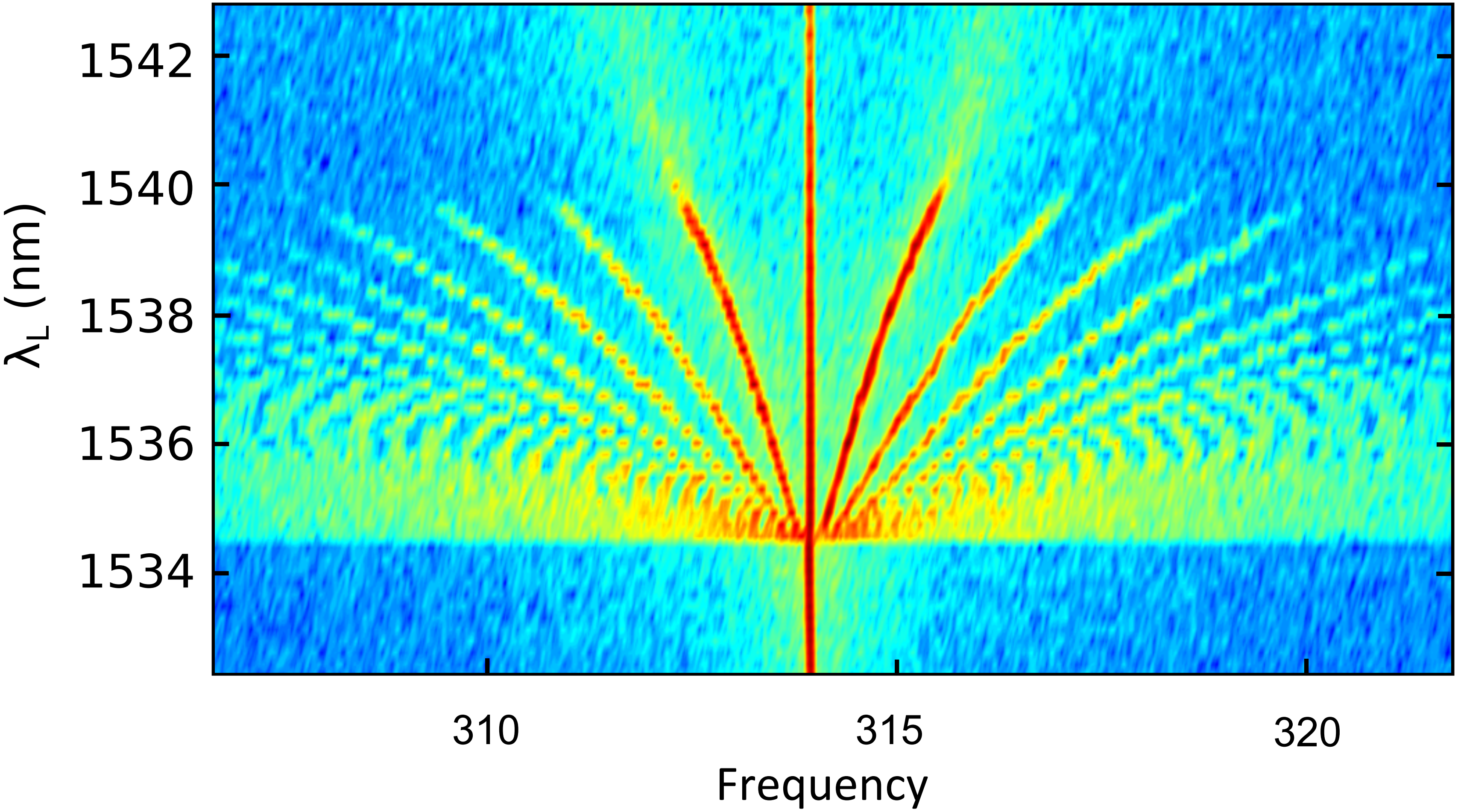


At higher power: dual comb formation, optical and radiofrequency !



PE Allain, B. Guha, C. Baker, D. Parrain, A Lemaitre, G Leo, I Favero. Physical Review Letters 126, 243901 (2021)

Global comb evolution in a GaAs disk resonator



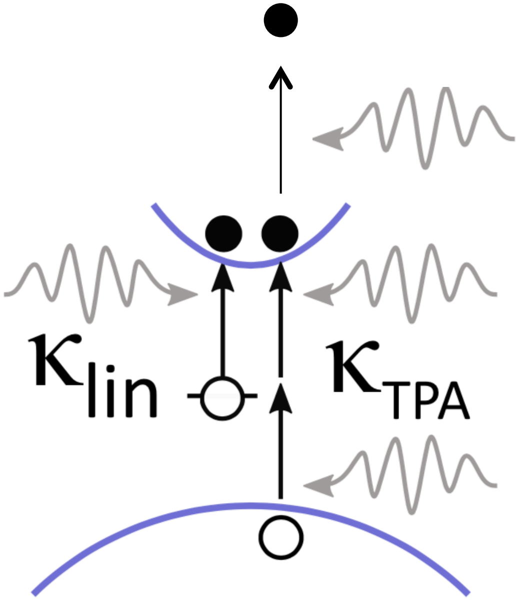
PE Allain, B. Guha, C. Baker, D. Parrain, A Lemaitre, G Leo, I Favero. Physical Review Letters 126, 243901 (2021)

Nonlinear semiconductor photonic interactions

Nonlinear absorption processes

Associated dispersive effects

Free-carrier absorption (FCA)



- Free carrier dispersion (blue shift)
- Themo-optic dispersion (red shift)

Upon proper conditions, the combination of these features can produce self-pulsing:

T. J. Johnson, M. Borselli, and O. Painter, Opt Exp 14, 817 (2006)

A complete and self-consistent model

$$\dot{a}(t) = -\frac{\kappa}{2}a(t) + i\left[\Delta^b\omega + g_{\mathrm{om}}x(t) + \frac{\omega_{\mathrm{cav}}}{n}\frac{dn}{dT}\Delta T(t) + \frac{\omega_{\mathrm{cav}}}{n}\frac{dn}{dN}N(t)\right]a(t) + \sqrt{\kappa_{\mathrm{ex}}}a_{\mathrm{in}}(t),$$

$$m_{\mathrm{eff}}[\ddot{x}(t) + \Gamma_m\dot{x}(t) + \omega_m^2x(t)] = F_{\mathrm{opt}}(t) + F_{\mathrm{pth}}(t),$$

$$\dot{\Delta T}(t) = -\frac{\Delta T(t)}{\tau_{\mathrm{th}}} + \frac{R_{\mathrm{th}}\hbar\omega_L}{\tau_{\mathrm{th}}}(\kappa_{\mathrm{lin}} + \kappa_{\mathrm{TPA}} + \kappa_{\mathrm{FCA}})|a(t)|^2,$$

$$\dot{N}(t) = -\frac{N(t)}{\tau_{\mathrm{fc}}} + \frac{\beta_{\mathrm{TPA}}c^2\hbar\omega_L}{2n_g^2V_{\mathrm{FCA}}^2}|a(t)|^4$$

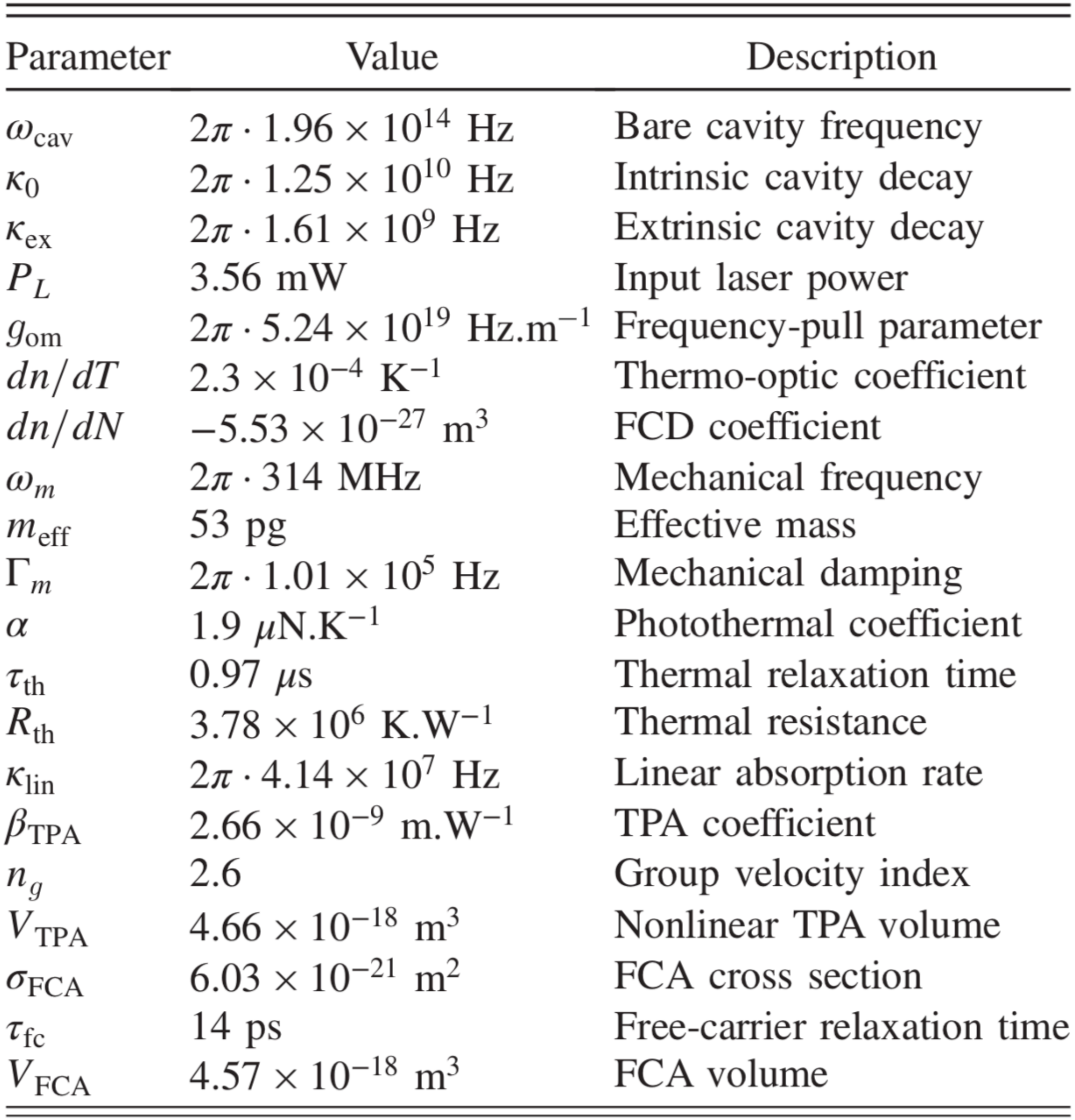
$$F^k(t) = \iiint_V \frac{\sigma_{ij}^k(\mathbf{r},t)S_{ij}(\mathbf{r},t)}{u(t)}d^3\mathbf{r}$$

$$\sigma_{ij}^{th} = C_{ijkl}\beta_{kl}\Delta T$$

$$\sigma_{ij}^{es} = -\frac{1}{2}\varepsilon_0(\varepsilon_{km}p_{mnij}\varepsilon_{nl})E_kE_l$$

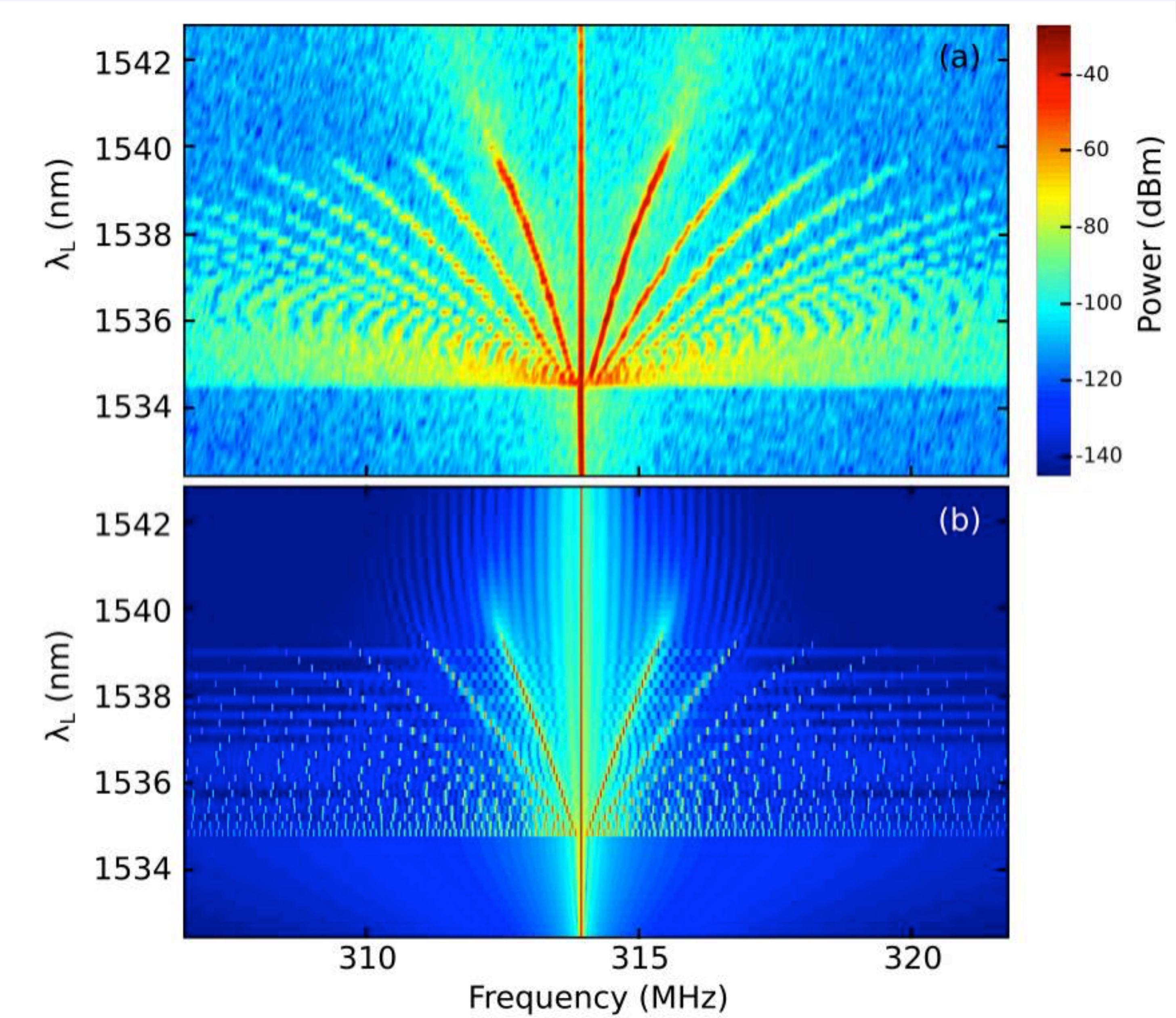
I. Favero, Optomechanical Interactions, Les Houches Lectures 2015 (2020)

All parameters are measured or computed

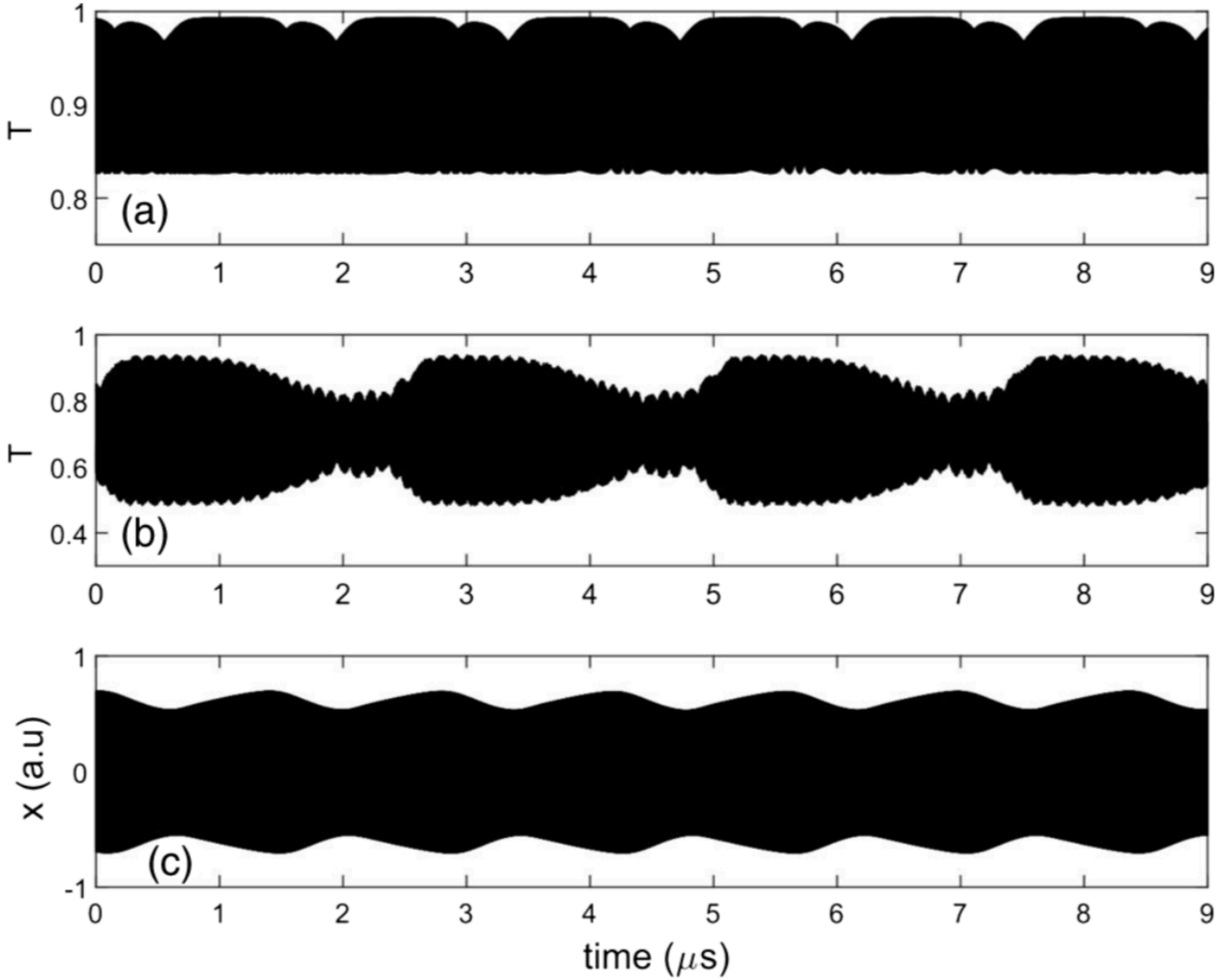


Parameter	Value	Description
ω_{cav}	$2\pi \cdot 1.96 \times 10^{14}$ Hz	Bare cavity frequency
κ_0	$2\pi \cdot 1.25 \times 10^{10}$ Hz	Intrinsic cavity decay
κ_{ex}	$2\pi \cdot 1.61 \times 10^{9}$ Hz	Extrinsic cavity decay
P_L	3.56 mW	Input laser power
g_{om}	$2\pi \cdot 5.24 \times 10^{19}$ Hz.m^{-1}	Frequency-pull parameter
dn/dT	2.3×10^{-4} K^{-1}	Thermo-optic coefficient
dn/dN	-5.53×10^{-27} m^3	FCD coefficient
ω_m	$2\pi \cdot 314$ MHz	Mechanical frequency
m_{eff}	53 pg	Effective mass
Γ_m	$2\pi \cdot 1.01 \times 10^{5}$ Hz	Mechanical damping
α	1.9 μN.K^{-1}	Photothermal coefficient
τ_{th}	0.97 μs	Thermal relaxation time
R_{th}	3.78×10^{6} K.W^{-1}	Thermal resistance
κ_{lin}	$2\pi \cdot 4.14 \times 10^{7}$ Hz	Linear absorption rate
β_{TPA}	2.66×10^{-9} m.W^{-1}	TPA coefficient
n_g	2.6	Group velocity index
V_{TPA}	4.66×10^{-18} m^3	Nonlinear TPA volume
σ_{FCA}	6.03×10^{-21} m^2	FCA cross section
τ_{fc}	14 ps	Free-carrier relaxation time
V_{FCA}	4.57×10^{-18} m^3	FCA volume

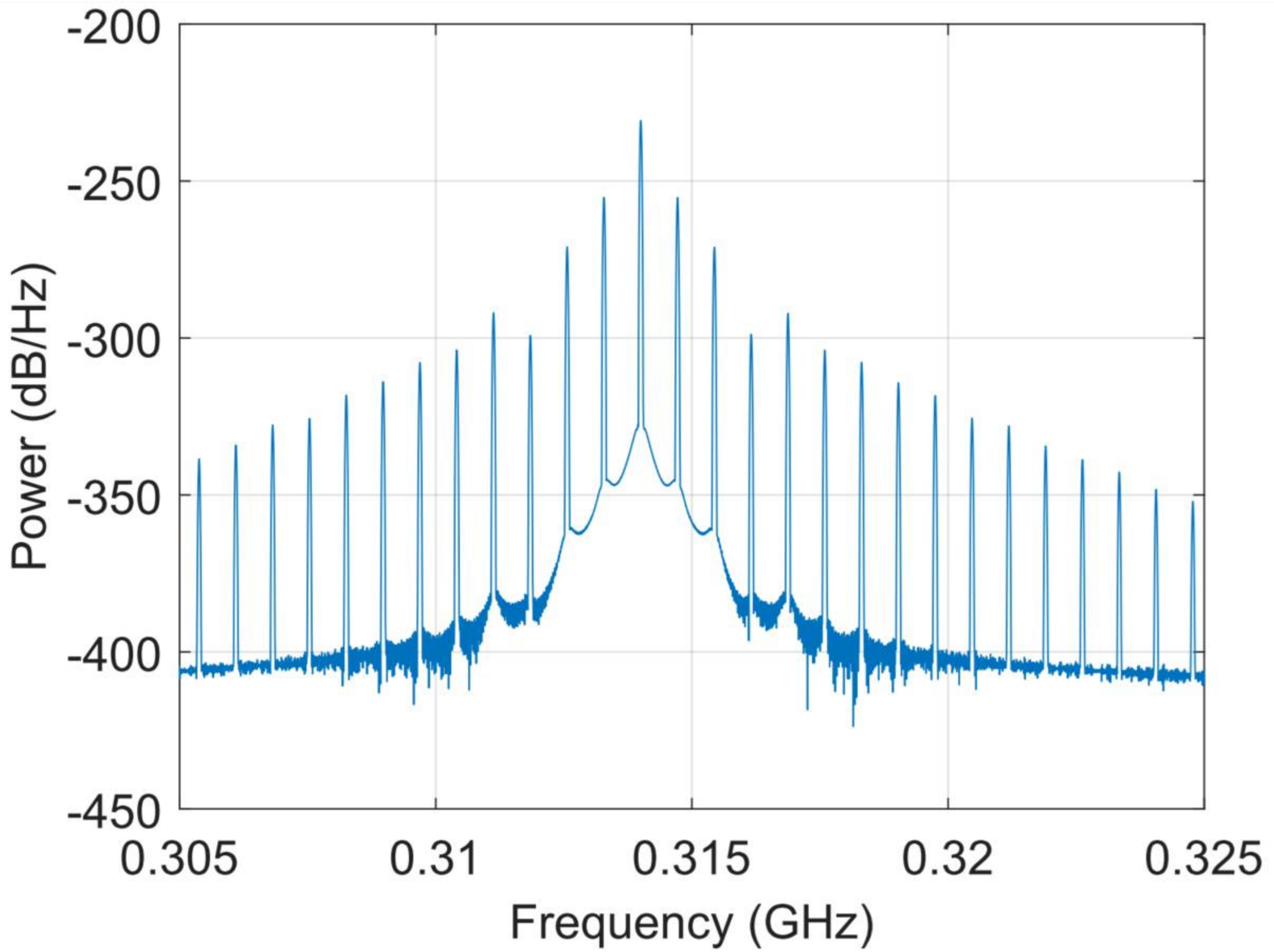
Experiment-theory comparison



Time traces



Mechanical comb formation



What did we learn, what is next ?

- Nonlinear photonics + optomechanics generate stable regimes

- A mechanical comb is formed, which is triggered by light
- It is controlled by optical detuning and optical power

- The comb extends over 10% of the carrier frequency

- Can it extend further to generate true isolated mechanical pulses ?
- Is it low-noise enough to be employed in sensing applications ?
- Would it exist even in absence of thermal effects ?

PE Allain, B. Guha, C. Baker, D. Parrain, A Lemaitre, G Leo, I Favero. Physical Review Letters 126, 243901 (2021)

This is the end ….

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

ANR

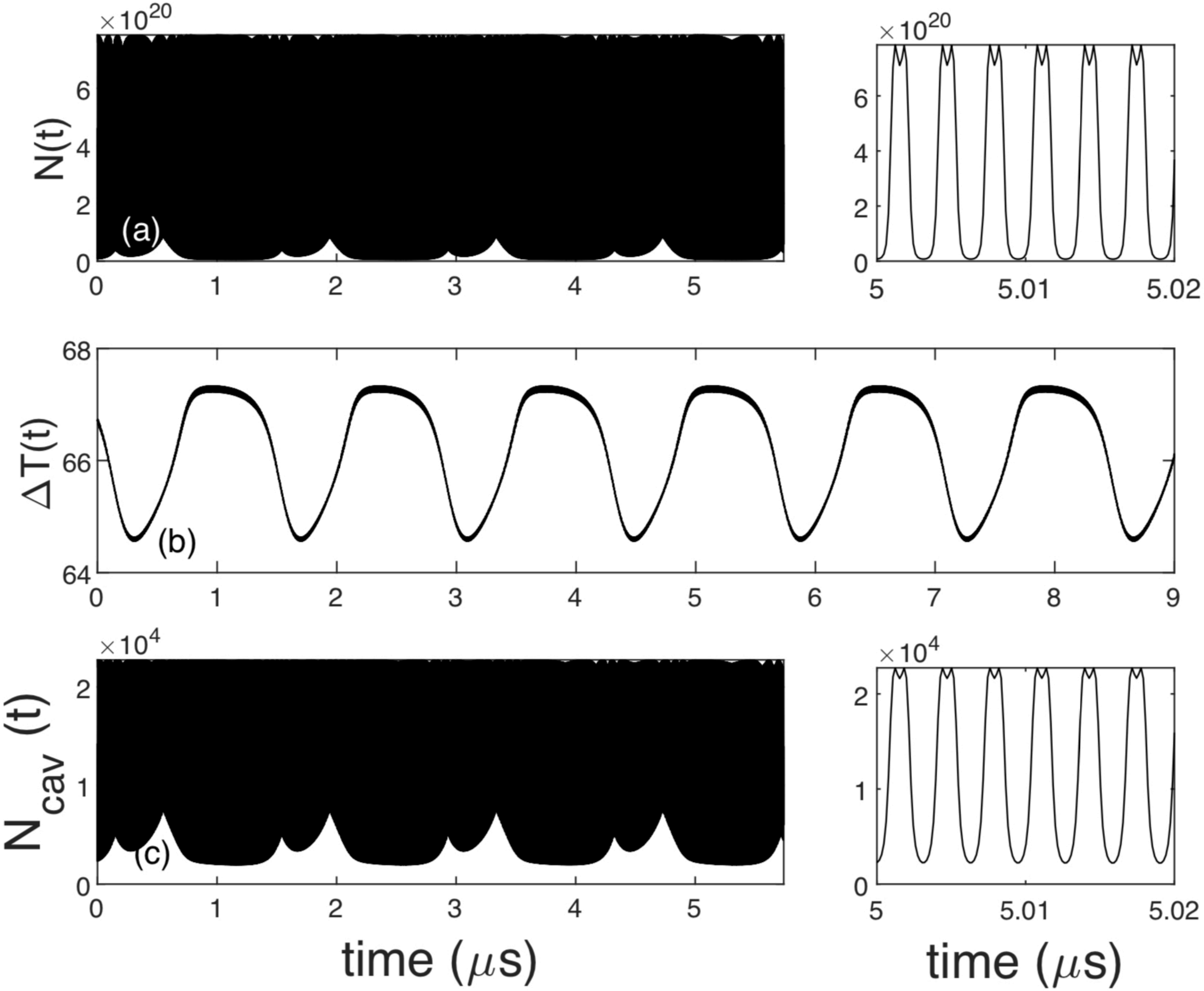
erc

300K

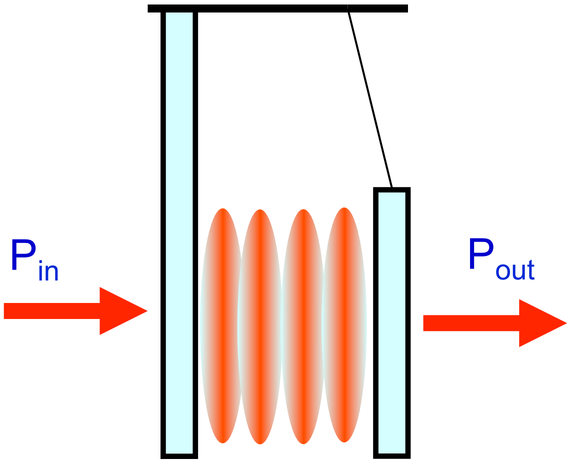
QuaSeRT

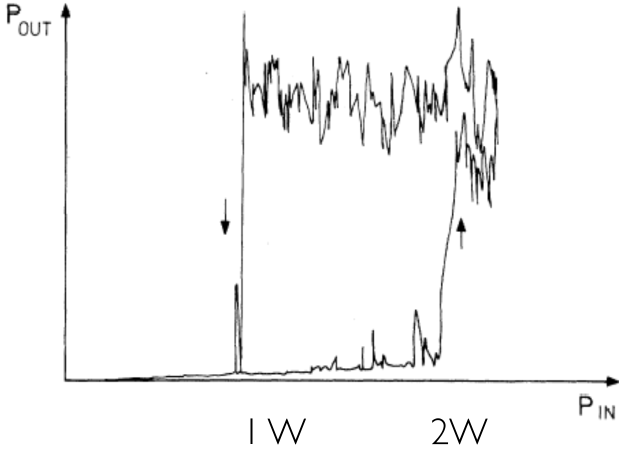
ViruScan

Time evolution of other variables



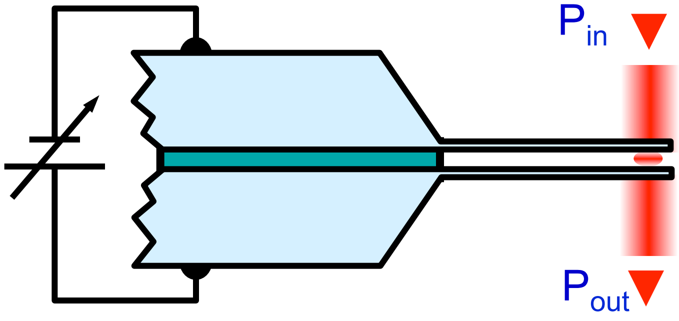
Bistabilities induced by optomechanical non-linearity



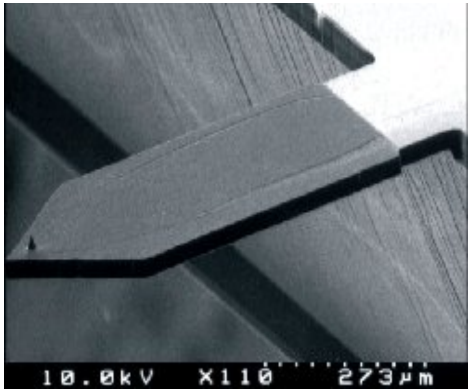


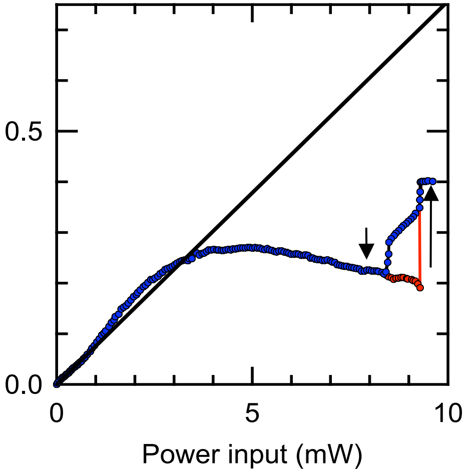
A. Dorsel et al, PRL 51, 1550 (1983)

Optical bi-stability, Walther group



AFM silicon microlever
(200 × 20 × 0.5 µm = 5 ng)





Optical back-action on a micro-mirror (2003)
Karrai group, Munich University

Observable consequences in the dynamical regime

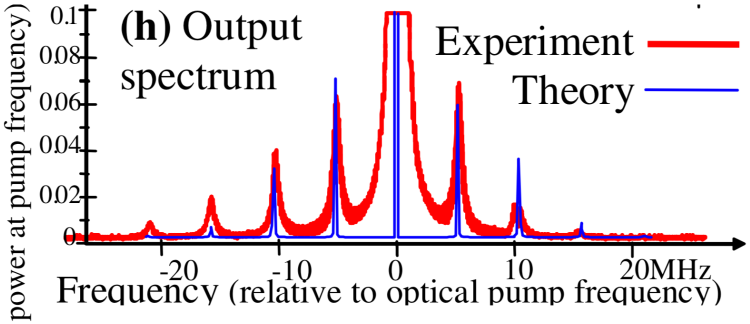
In the self-oscillation regime

F Marquardt, JGE Harris, SM Girvin, PRL 96 (10), 103901 (2006)

$$x(t) \approx \bar{x} + A\cos(\omega_0 t)$$

$$\alpha(t) = e^{i\varphi(t)} \sum_n \alpha_n e^{in\omega_0 t}$$

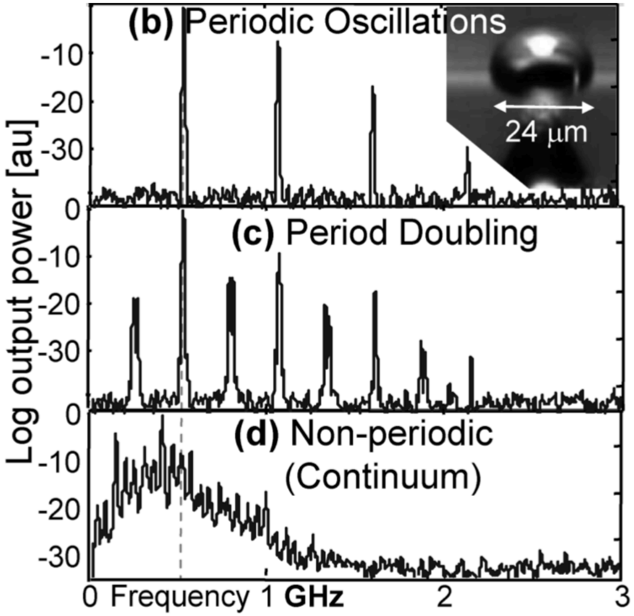
$$\alpha_n = \frac{1}{2}\frac{J_n\left(-\frac{A}{\omega_0}\right)}{in\omega_0 + \frac{1}{2} - i\bar{x}}$$

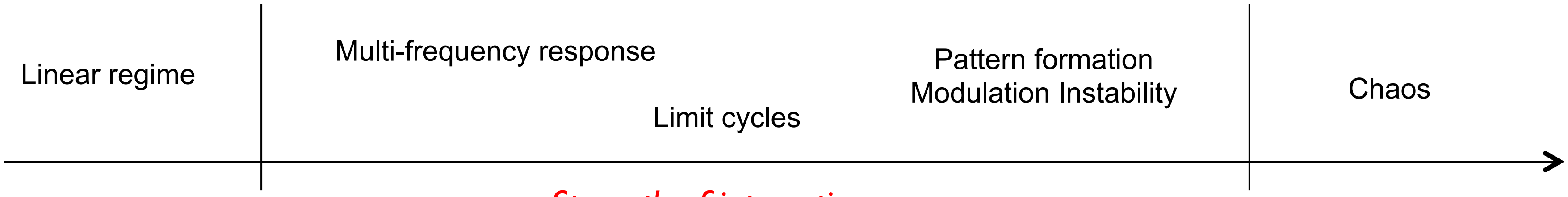


T. Carmon et al, PRL 94, 223902 (2005)

And beyond ….

T. Carmon et al, PRL 98, 167203 (2007)





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