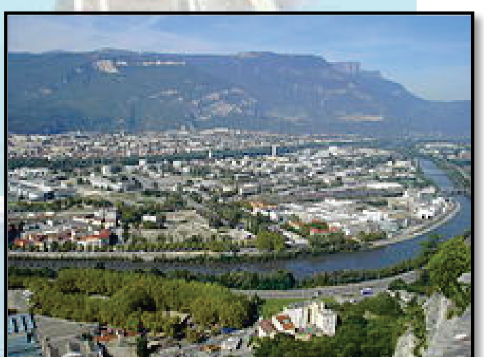
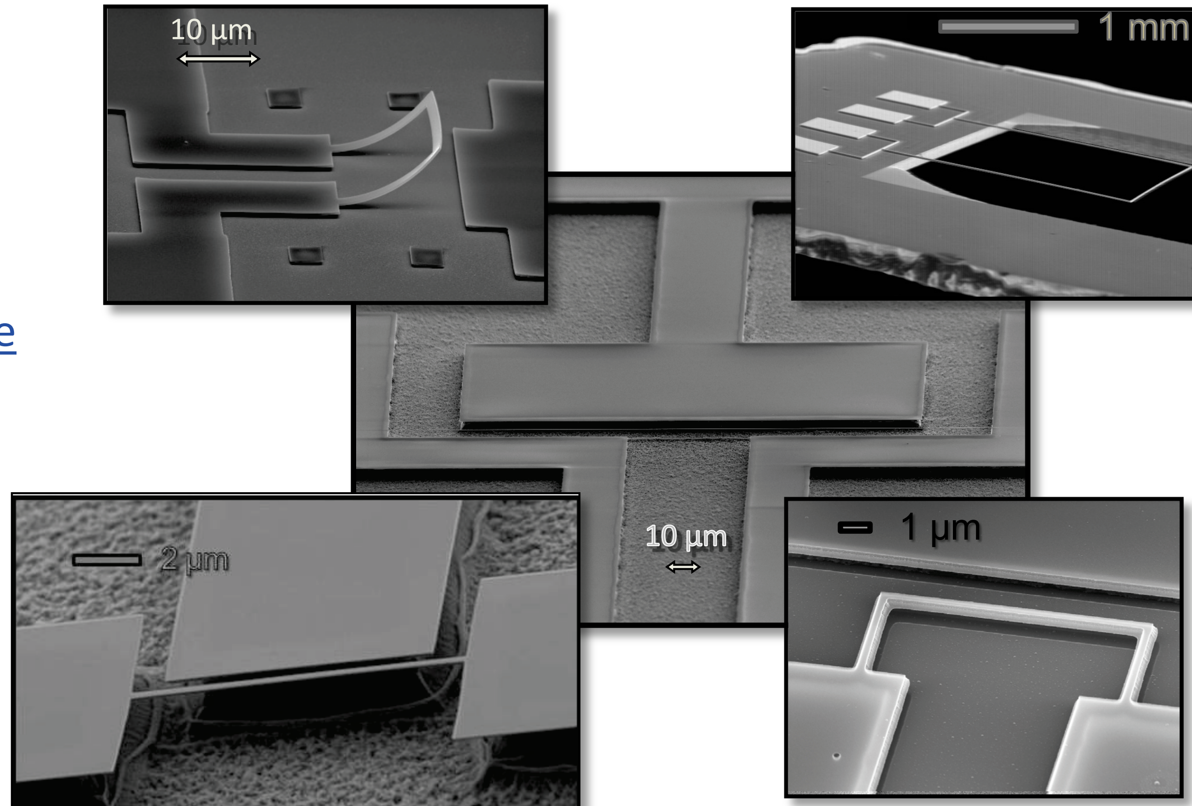
Cryogenic nano-electro-mechanical devices as model systems for classical issues in physics

E. Collin

[ULT Grenoble group,
Institut Néel, CNRS Grenoble]





Agence Nationale de la Recherche ANR

European Microkelvin Collaboration

CAPACITIES

erc European Research Council

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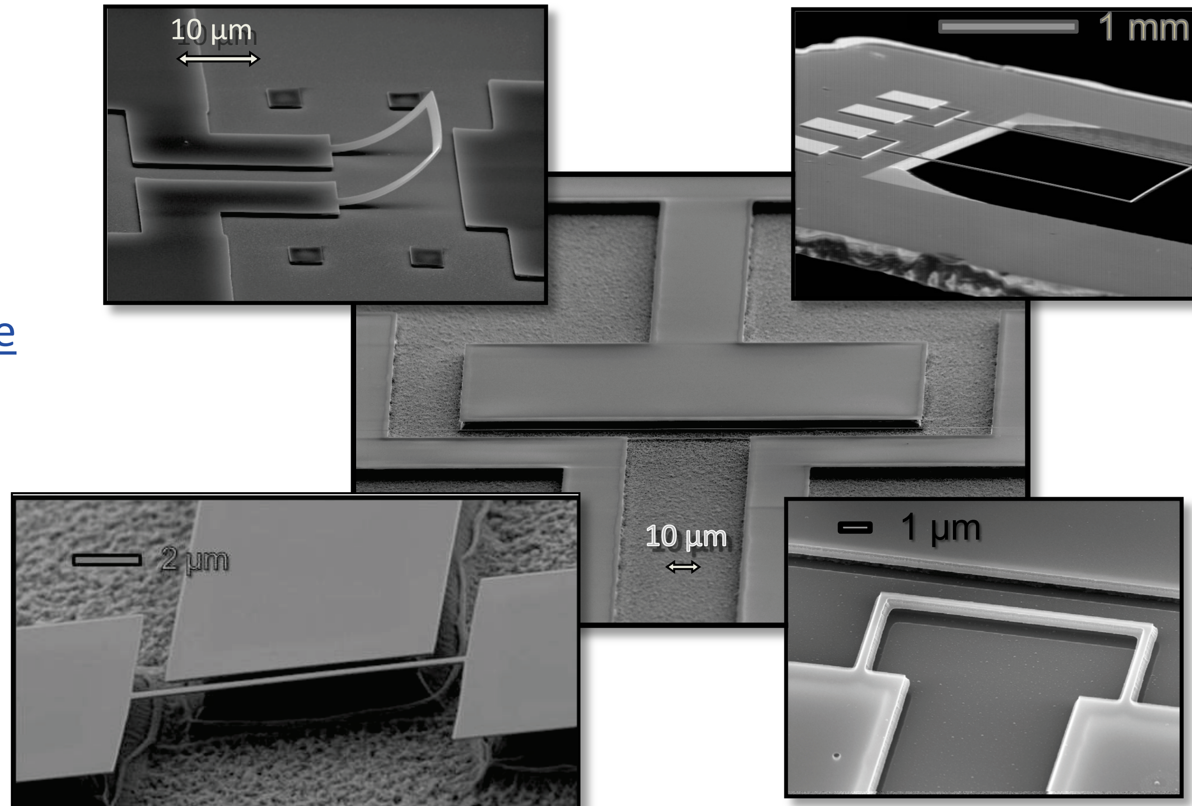


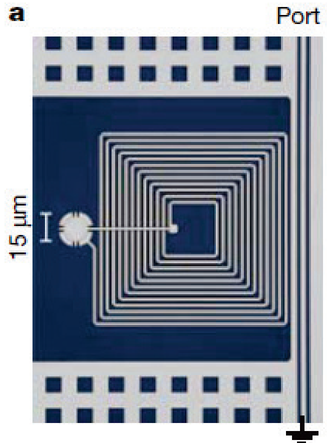
European Microkelvin Collaboration
European Research Council

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

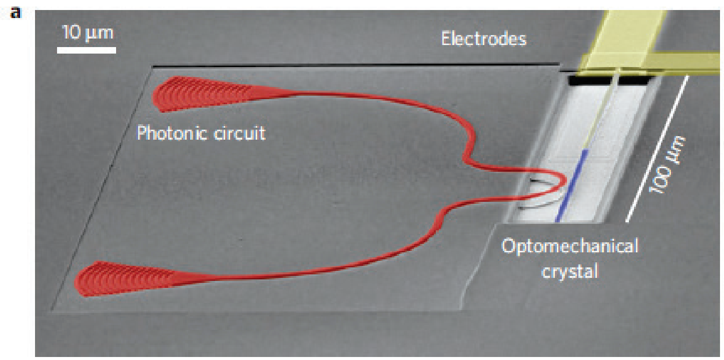
Quantum electronics context:

These are **new components** for hybrid superconducting quantum circuits

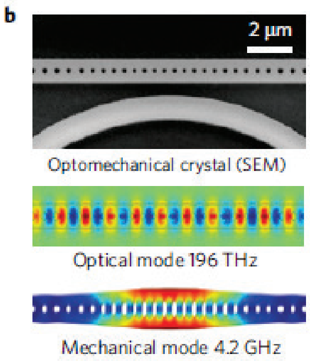


T.A. Palomaki *et al.*,
Nature **495**, 210 (2013)

Microwaves state storage



J. Bochmann *et al.*,
Nature Physics, 2748 (2013)



Optical photons to microwaves conversion

Quantum memories,
Quantum interface optics/microwaves,
Quantum-enhanced sensing… H. Kerdoncuff *et al.*, Ann. Phys. **527**, 107 (2015)

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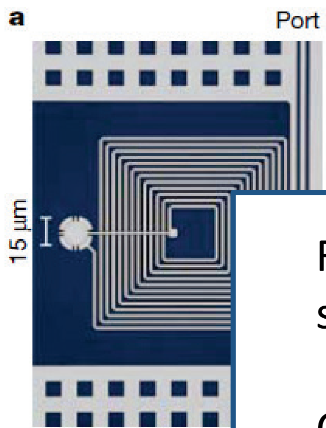
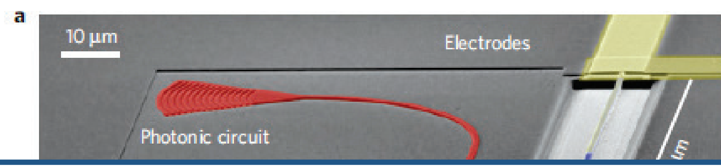
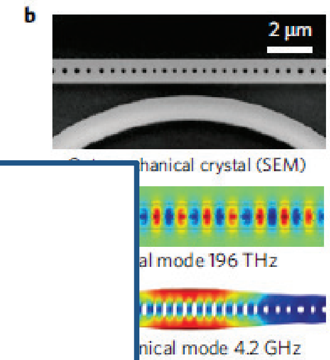






T.A. Palomaki e
Nature **495**, 21(

Requires mechanical object (here, **top-down** structures) to be:

Cooled to the quantum ground state,
To be driven and read-out at the quantum limit,
And interfaced with other systems.

Particularly **demanding**, …

Quantum r
Quantum i
Quantum-enhanced sensing…

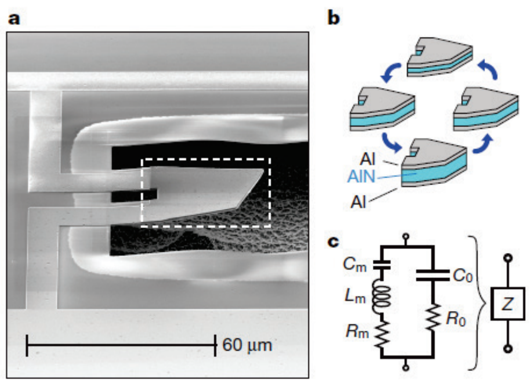
H. Kerdoncuff *et al.*, Ann. Phys. **52**7, 107 (2015)

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

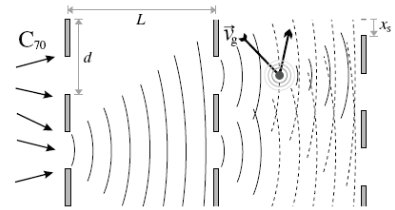
Quantum physics context:

These are **unique systems** dealing with the grounds of quantum mechanics

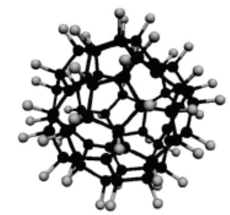


A.D. O’Connell *et al.*, Nature **464**, 697 (2010)

Single phonon control



Up to 6 910 amu!



$C_{60}F_{48}$

1632 amu

Klaus Hornberger et al., Phys. Rev. Lett. **90**, 160401 (2003)

Stefan Gerlich et al., Nature Comm. **2**, 263 (2011)

Mass interferometry

Quantum coherence of position-states,
Stochastic collapse models,
Quantum gravity…

A. Leggett, J. Phys.: Condens. Matter **14**, R415-R451 (2002)

G. Ghirardi, A. Rimini, T. Weber, Phys. Rev. D **34**, 470 (1986)

R. Penrose, General Relativity and Gravitation **28**, 581 (1996)

P. Stamp, Phil. Trans. Roy. Soc. **A370**, 4429 (2012)

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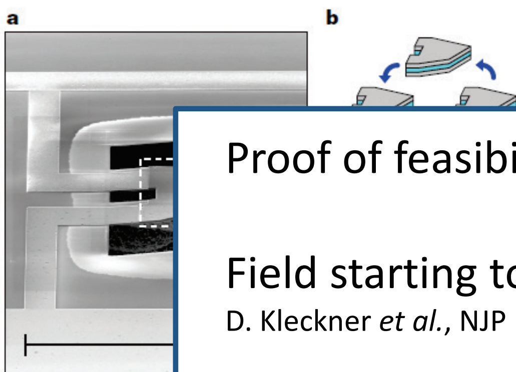
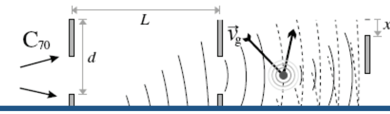
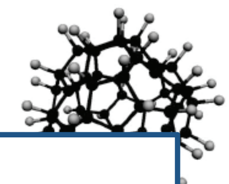




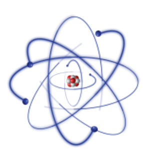


Proof of feasibility **obtained**.

Field starting today. Experimental proposals:

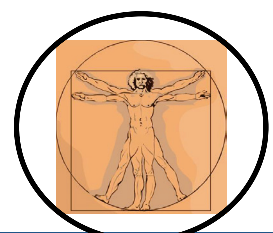
D. Kleckner *et al.*, NJP **10** 095020 (2008) – I. Pikovski *et al.*, Nat Phys. **8** 393 (2012)

Addresses questions **at the roots of** quantum mechanics…



← "The quanta of mechanics",

See A.N. Cleland's talk



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A.D. O'Connell e

2011)

Quantum co

Stochastic c

Quantum gr...

415-R451 (2002)

D **34**, 470 (1986)

ion **28**, 581 (1996)

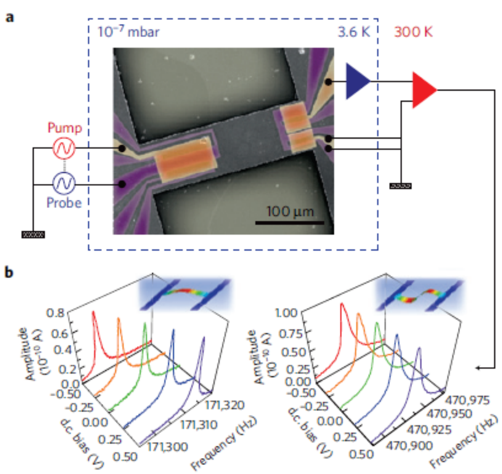
P. Stamp, Phil. Trans. Roy. Soc. **A370**, 4429 (2012)

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

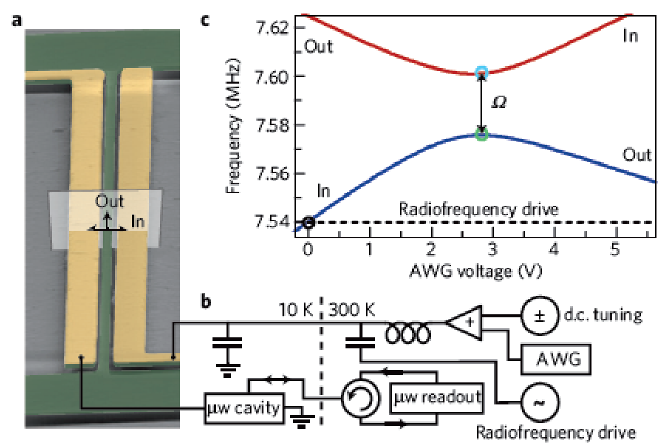
Crossover quantum-to-classical context:

Besides the study of truly quantum devices, **classical analogues** of quantum effects



I. Mahboob *et al.*, Nature Physics, 2277 (2012)

Classical sideband pumping



T. Faust *et al.*, Nature Physics **9**, 485 (2013)

T. Faust *et al.*, Phys. Rev. Lett. **109**, 037205 (2012)

Classical two-level system

Model systems,
Pinpoint essential quantum features, …

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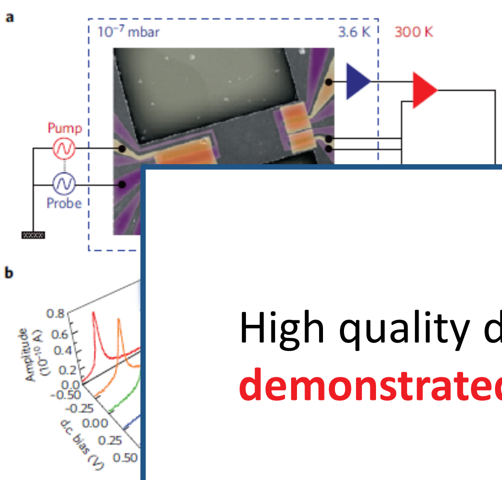
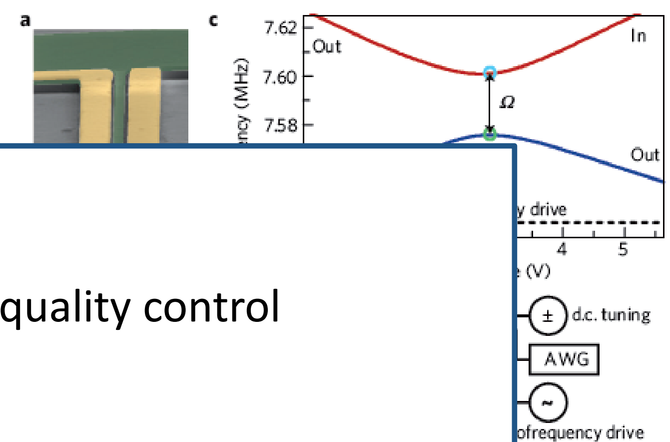




High quality devices, high quality control **demonstrated**.

Can be applied to **purely classical issues**…

I. Mahboob e

5 (2013)

037205 (2012)

Model sys

Pinpoint essential quantum features, …

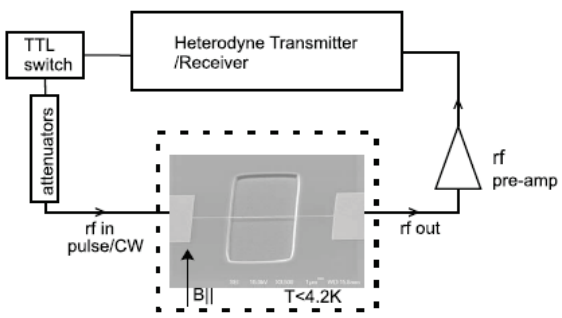
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Classical context:

Mechanical nano-devices are **model systems** and **mechanical mesoscopic probes**

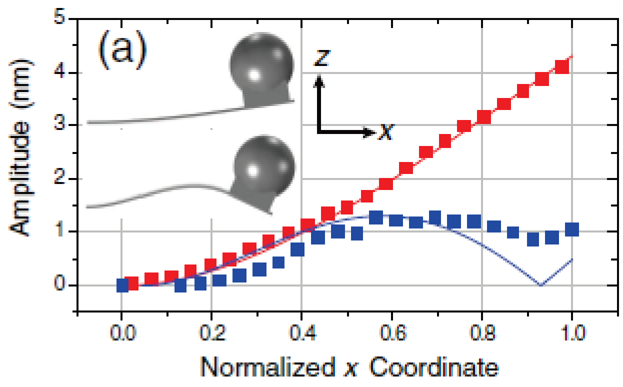
- **Mesoscopic probes**: moving mechanical objects at very small scales.



A. Venkatesan *et al.*,
Phys. Rev. B **81**, 073410 (2010)

Dissipation in amorphous matter

Constitutive materials,
Surrounding fluids, …



C. Lissandrello *et al.*,
Phys. Rev. Lett **108**, 084501 (2012)

Oscillatory nanoflows

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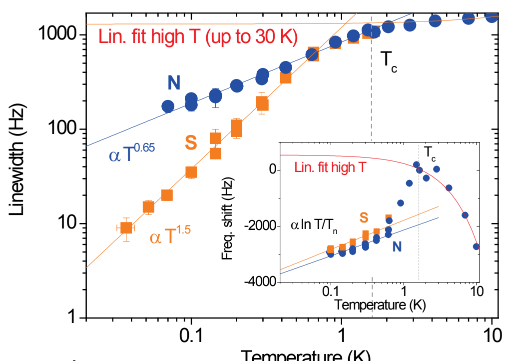
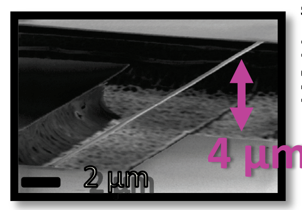
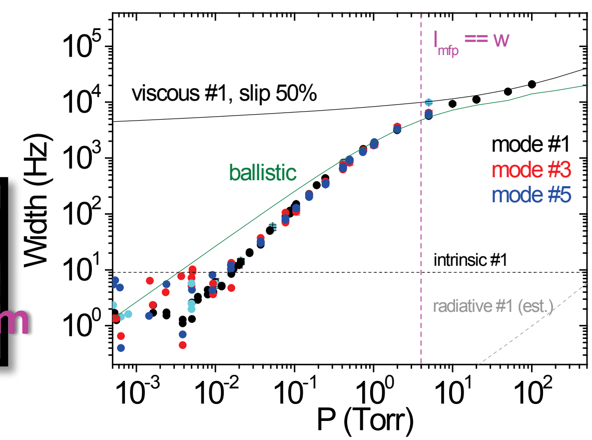


K.J. Lulla *et al.*,
Phys. Rev.Lett. **110**, 177206 (2013)

Importance of conduction electrons

Constitutive materials,
Surrounding fluids, …





M. Defoort *et al.*,
Phys. Rev. Lett **113**, 136101 (2014)

Probing Knudsen layer

Nano-Electro-Mechanical Systems

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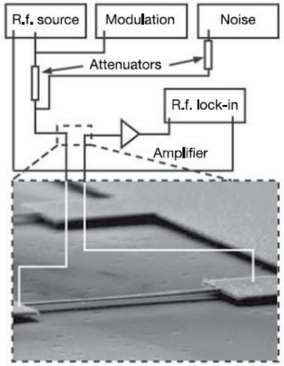
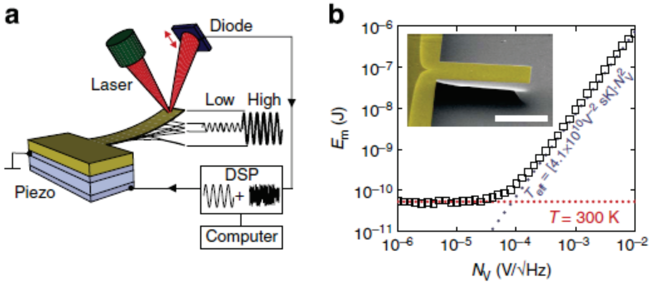
Mechanical nano-devices are **model systems** and **mechanical mesoscopic probes**

- **Model systems**: simple, well-controlled devices.
  In cryogenic environment: low noise, high-Q, cryogenic vacuum.



R.L. Badzey *et al.*, Nature **437**, 995 (2005)



W.J. Venstra *et al.*, Nature Comm. **4**, 2624 (2013)

Stochastic resonance

Mimic fundamental phenomena,

…

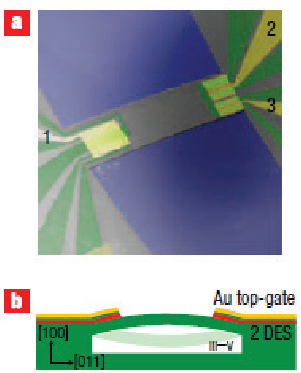
Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Classical context:

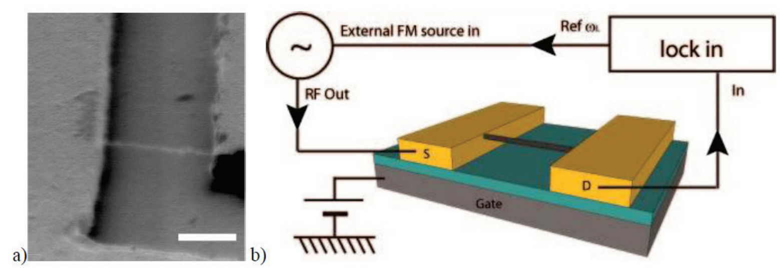
Mechanical nano-devices are **model systems** and **mechanical mesoscopic probes.**
Application:

- **Classical electronic components**: electro-mechanical functions.
  Especially with “new” materials: graphene, nanotubes, MoS_2



I. Mahboob and H. Yamaguchi
Nature Nanotech. **3**, 275 (2008)

Bit storage and processing



Vincent Gouttenoire *et al.*, Small **6**, 1060 (2010)

The “nano-radio” mixing scheme

Nano-Electro-Mechanical Systems

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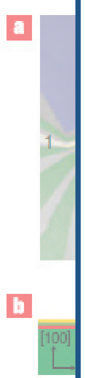
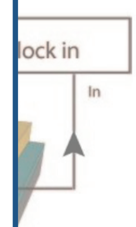




Focus of the talk: fundamental aspects, not applications:

Cryogenic NEMS as **model systems**,

In classical physics.

Concluding remarks back on the **quantum aspects and mesoscopic probes**.

0)

ne

I. Mahbo
Nature N

Bit storage and processing

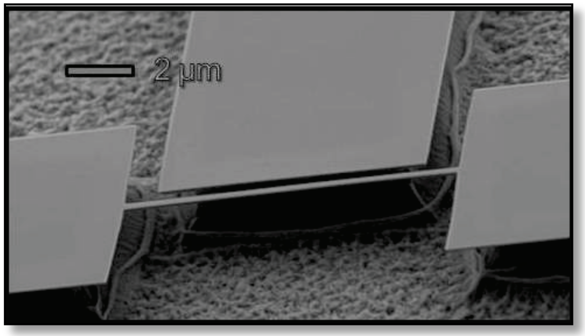
Nano-Electro-Mechanical Systems

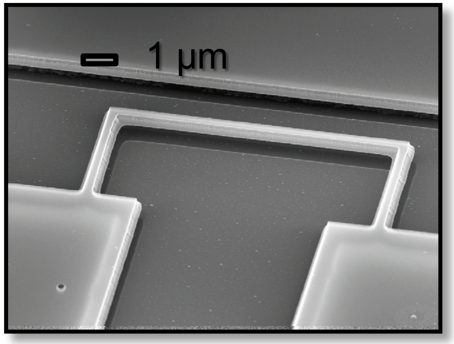
Mesoscopic devices that can move, actuated/detected by electromagnetic means.

Model systems,

Dynamic bifurcation

Doubly-clamped





Cantilever

Simple beam-based top-down structures.
A **mechanical material** (amorphous, crystalline) covered by **metal** (normal, superconducting)
"**Easy**" to make, "**easy**" to model (almost fully analytically).

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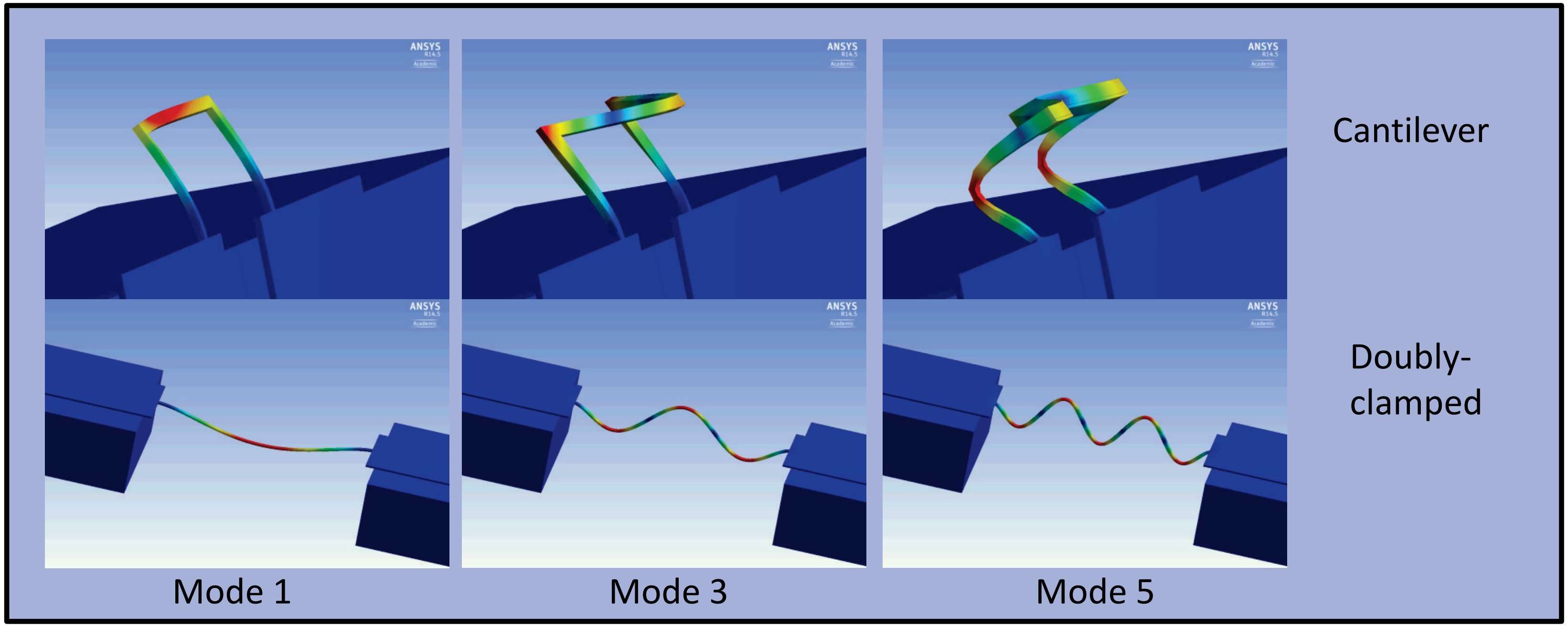


Nano-Electro-Mechanical Systems

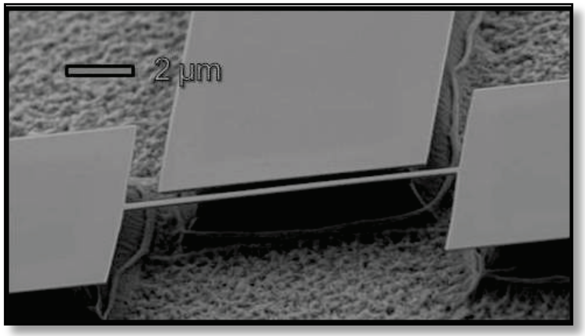
Mesoscopic devices that can move, actuated/detected by electromagnetic means.

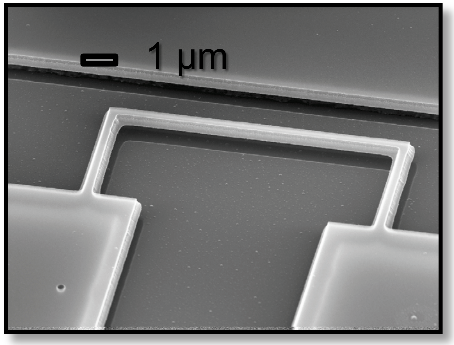
Model systems,

Linear drive and detection

Dynamic bifurcation

Doubly-clamped





Cantilever

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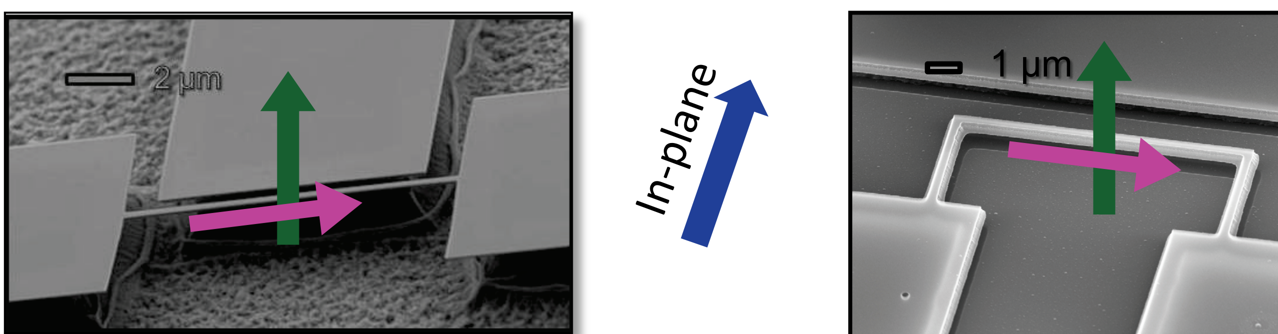

Cantilever

Magnetomotive scheme: applied force $\vec{F}_n(t) \propto I(t)\, \vec{l} \times \vec{B}$

A.N. Cleland & M.L. Roukes, Sens. Act.**72**, 256 (1999)

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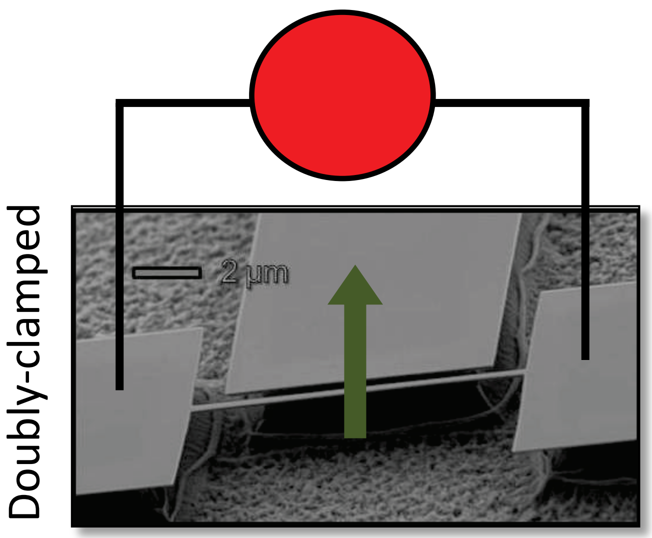

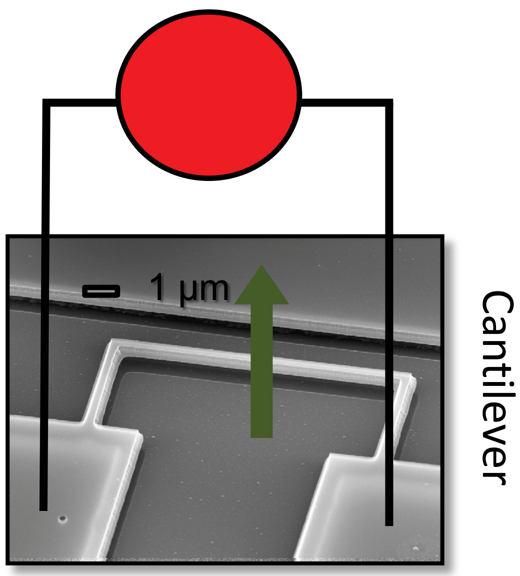

Magnetomotive scheme: detected voltage $V_n(t) \propto v_n(t) \times B$

A.N. Cleland & M.L. Roukes, Sens. Act.**72**, 256 (1999)

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Non-linear tuning

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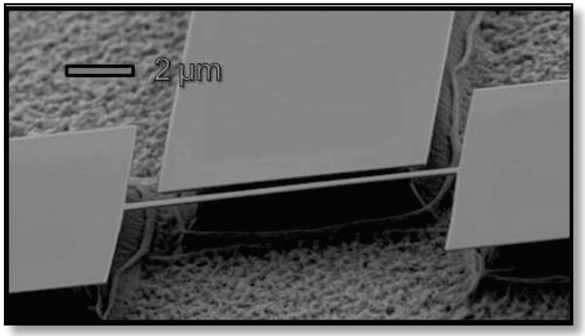

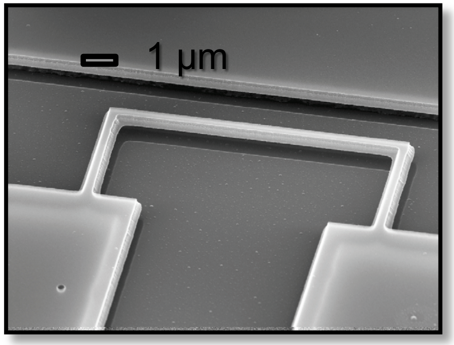

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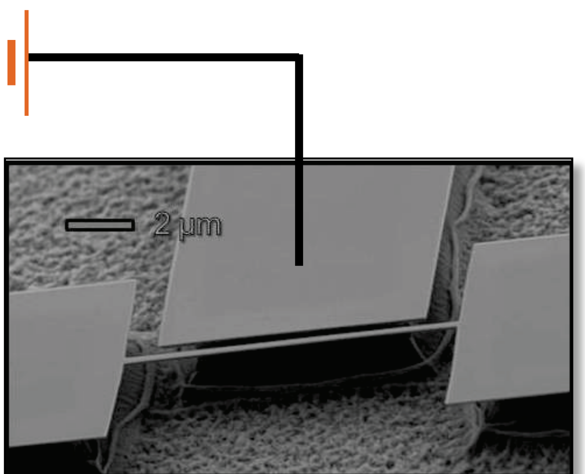

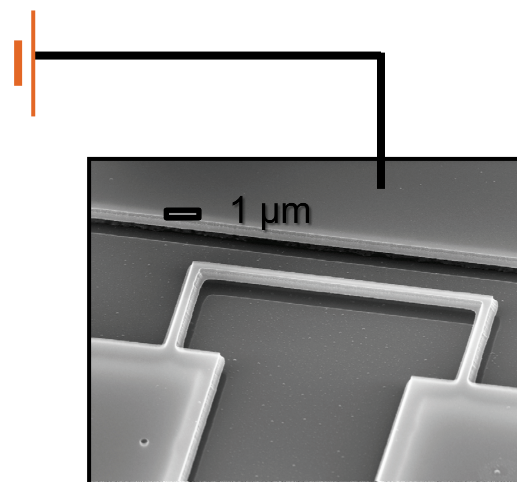

Cantilever

Capacitive scheme: D.C. tuning of frequency & nonlinearity $\delta k(t)\ \alpha\ V_g^2$

I. Kozinsky *et al.*, Appl. Phys. Lett. **88**, 253101 (2006)

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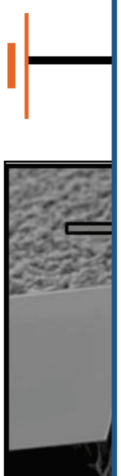

Extremely broad dynamic range can be explored.

From **linear to highly non-linear regime**,
Dynamics can be **quantitatively characterized**,

E. C. et al., Rev Sci. Instrum. **83**, 045005 (2012)

Cantilever

Capacitive scheme: D.C. tuning of frequency & nonlinearity $\delta k(t)\ \alpha\ V_g^2$

I. Kozinsky *et al.*, Appl. Phys. Lett. **88**, 253101 (2006)

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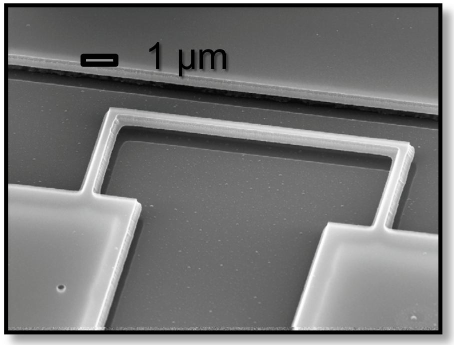


Cantilever

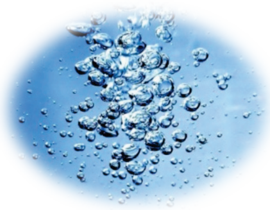
Modeling bifurcation phenomena

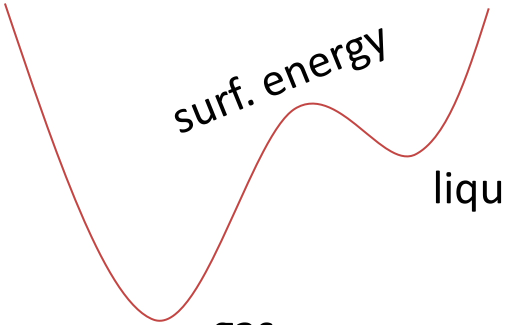
Bifurcation: switching from a **metastable state to a stable** one is of ubiquitous interest.

H. A. Kramers, Physica (Utrecht) 7, 284 (1940)

Chemical reactions $e^{-\frac{E_A}{k_B T}}$

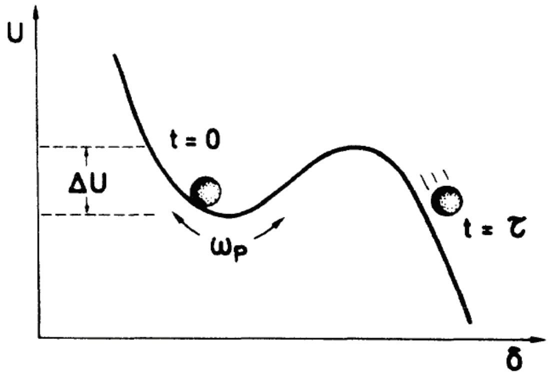
First order phase transitions:
e.g. nucleation of bubbles in water





Emmanuel Turlot *et al.*, Phys. Rev. Lett. 62, 1788 (1989)

Thermal escape of a Josephson junction



Modeling bifurcation phenomena

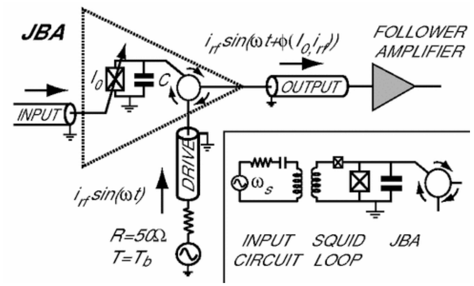
Similarly, in **dynamic systems**:

Equivalent situation in the "rotating frame". **Universal features** depending on type of bifurcation. Here, saddle-node.

R-f driven Josephson junction

R. Vijay *et al.*, Rev. Sci. Instrum. 80, 111101 (2009)

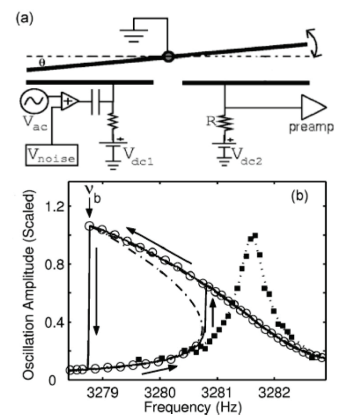
I. Siddiqi *et al.*, Phys. Rev. Lett. 94, 027005 (2005)



J. S. Aldridge and A. N. Cleland, PRL 94, 156403 (2005)

C. Stambaugh and H. B. Chan, Phys. Rev. B 73, 172302 (2006)

Mechanical bistable nonlinear oscillators

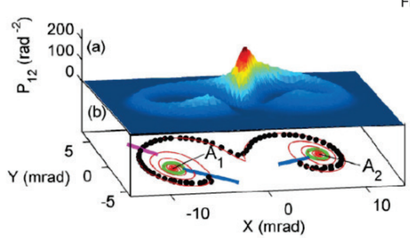


Complex nonlinear dynamics and chaos

I. Kozinsky *et al.*, PRL 99, 207201 (2007)

H.B. Chan *et al.*, PRL 100, 130602 (2008)

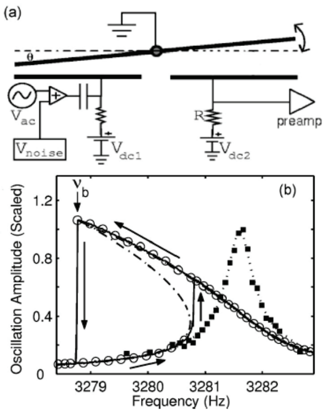
R. B. Karabalin *et al.*, PRL 106, 094102 (2011)



Modeling bifurcation phenomena

Similarly, in **dynamic systems**:

Equivalent situation in the "rotating frame". **Universal features** depending on type of bifurcation. Here, saddle-node.



J. S. Aldridge and A. N. Cleland, PRL 94, 156403 (2005)

C. Stambaugh and H. B. Chan, Phys. Rev. B 73, 172302 (2006)

Mechanical bistable nonlinear oscillators

For Nano-mechanics, **simple** artificial devices with:

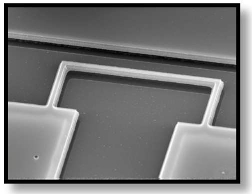
Bifurcation rate Γ << Decay rate Δ**f** << Resonance frequency $\mathbf{f_0}$

Hz << **kHz** << **MHz**

Here, **unique tunable** goalpost structure:

3 decades in excitation force ***F(t)***

Tunable nonlinearity through gate voltage term in ***δk(t)***



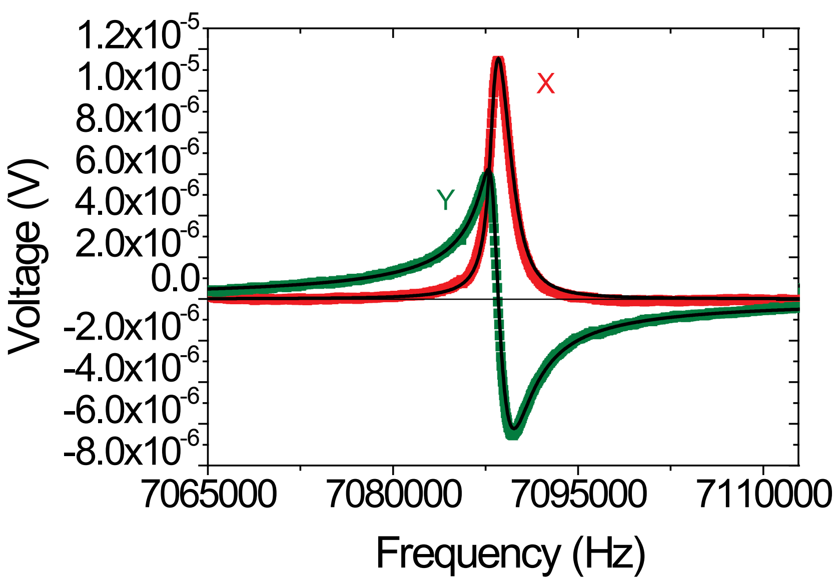
Modeling bifurcation phenomena

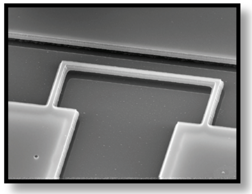
Dynamic bifurcation with a **Duffing nonlinear resonator**.

Harmonic (driven) oscillator:

$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0)\,x \qquad\qquad = F_{mag}\cos(\omega t)$$

Flexural mode state: $x = x_0 \cos(\omega t + \phi)$





3 µm feet
150 nm thick

Cantilever-type **very linear**.

X, Y the two quadratures (lock-in)
X = $x_0 \cos(\phi)$
Y = $-x_0 \sin(\phi)$

Here, 100 nm deflection

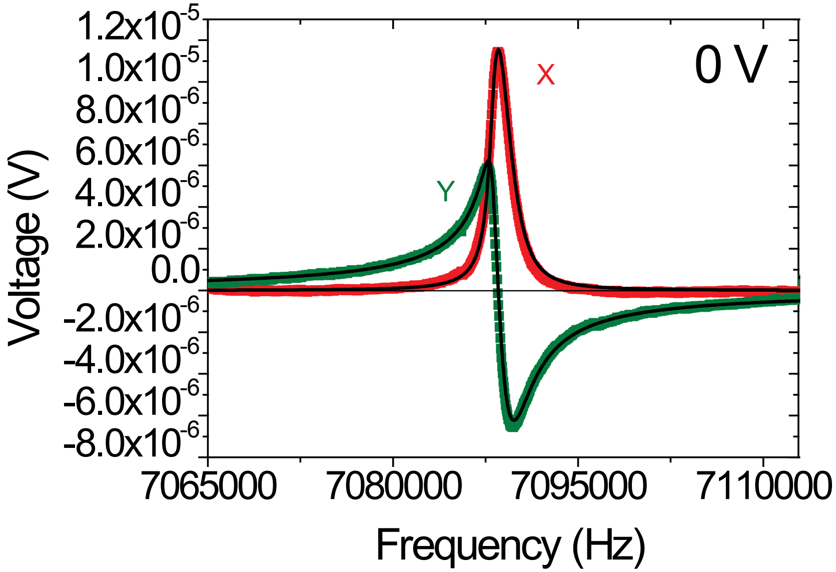
Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Duffing oscillator with gate voltage:

$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0 + \delta k_0)\,x + \delta k_2\,x^3 = F_{mag}\cos(\omega t)$$

Flexural mode state: $x = x_0 \cos(\omega t + \phi)$



Modeling bifurcation phenomena

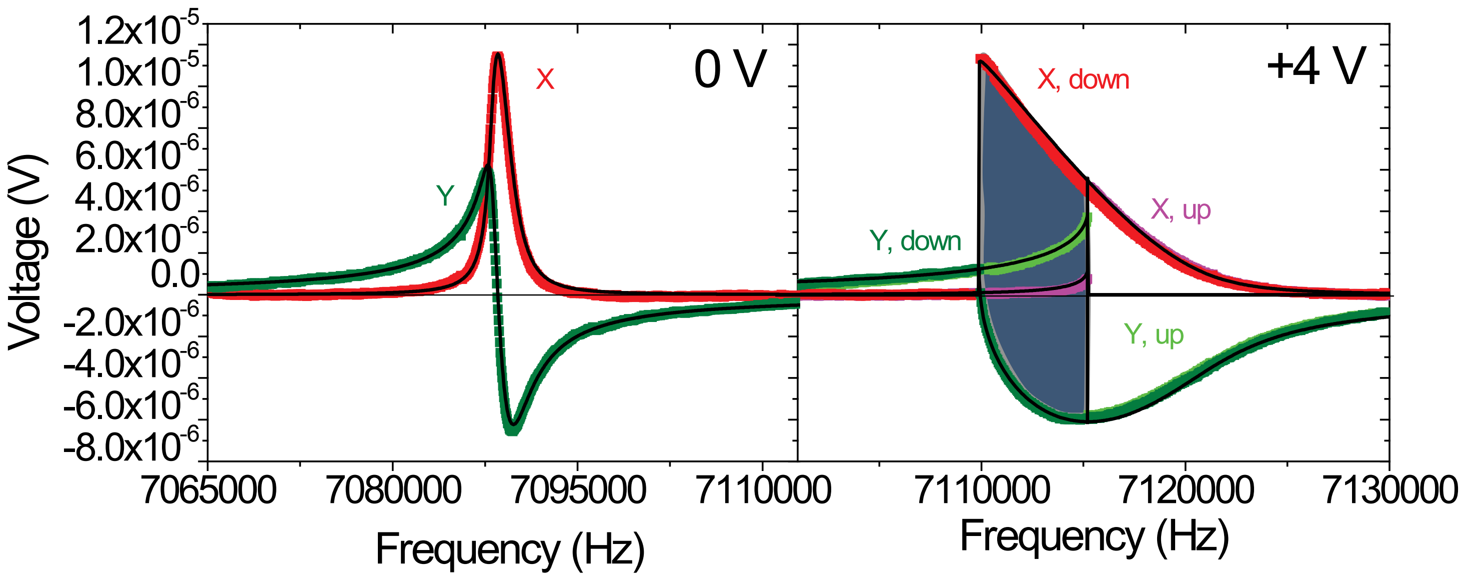
Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the "Duffing" non-linearity: Freq. shift & Duffing, $\alpha\ V_g^2$

$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0 + \delta k_0)\,x + \delta k_2\,x^3 = F_{mag}\cos(\omega t)$$

Flexural mode state: $x = x_0 \cos(\omega t + \phi)$

In the hysteretic region, two (dynamic) states coexist



Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the "Duffing" non-linearity:

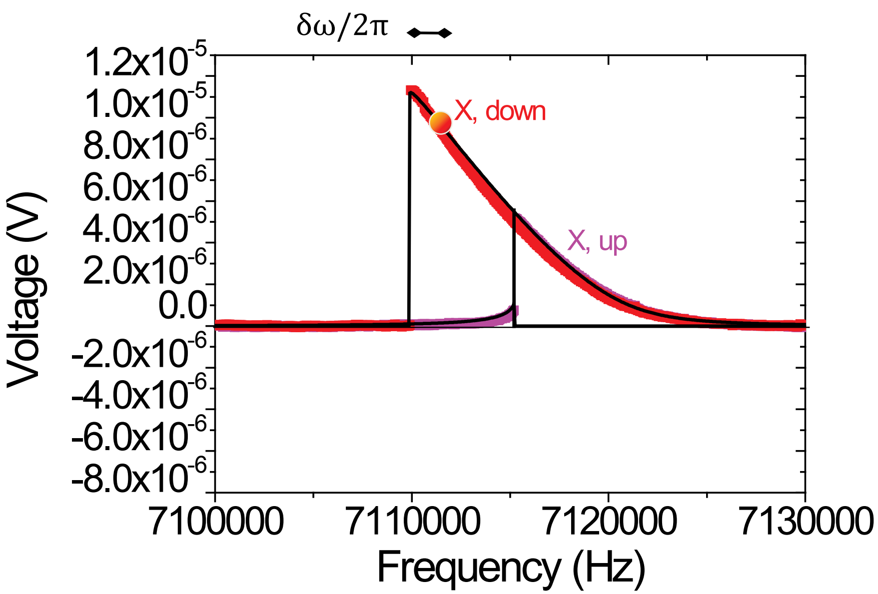
"Duffing", $\alpha\, V_{gate}^{2}$ White noise

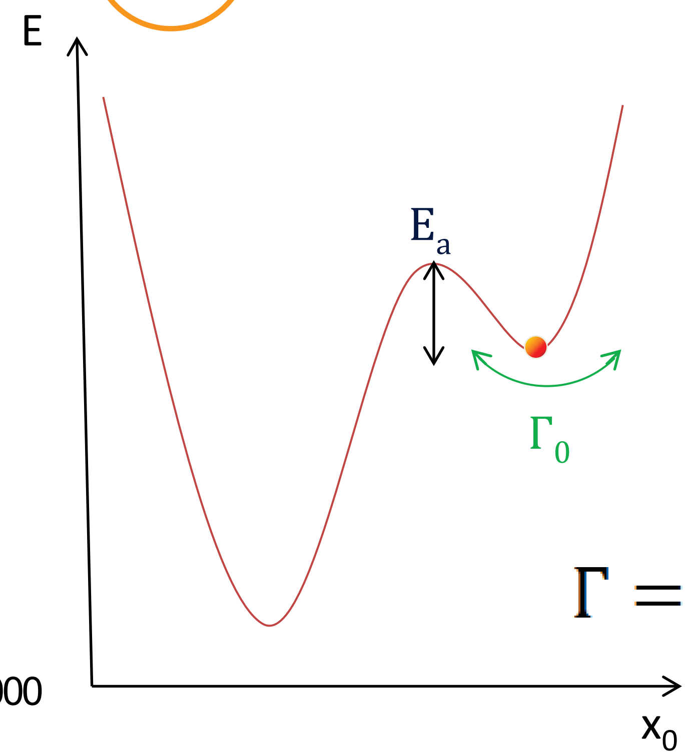
$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0 + \delta k_0)\,x + \delta k_2\,x^3 = F_{mag}\cos(\omega t)$$

$I_N \;\alpha\; f(\omega)$

Flex. mode state: $x = x_0 \cos(\omega t + \phi)$

Stochastic, exponential decay





$$\Gamma_0 = \lambda\, \delta\omega^{\zeta}$$

$$E_a = \eta\, \delta\omega^{\xi}$$

$$\Gamma = \Gamma_0\, e^{-\frac{E_a}{I_N}}$$

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the "Duffing" non-linearity:

"Duffing", $\alpha\, V_{gate}^2$ White noise

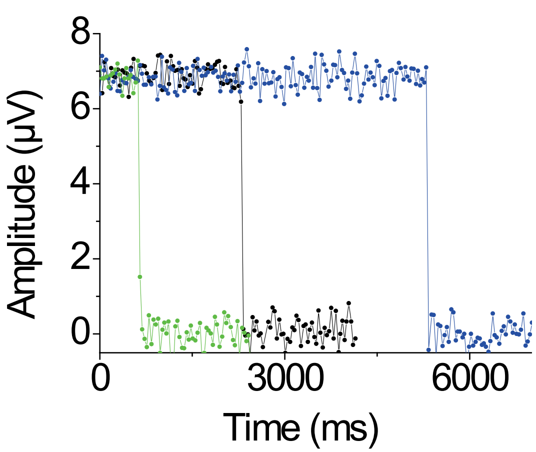
$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0 + \delta k_0)\,x + \delta k_2\,x^3 = F_{mag}\cos(\omega t) + f(t)$$

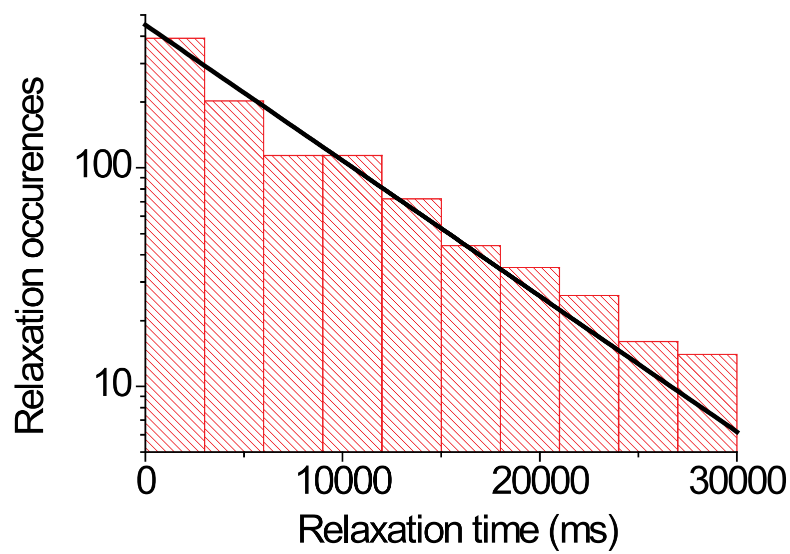
Flex. mode state: $x = x_0 \cos(\omega t + \phi)$

$I_N \;\alpha\; f(\omega)$

Residence time experiment:
After 1000 switches

$$N = N_0 e^{-\Gamma t}$$





$$\Gamma_0 = \lambda\, \delta\omega^{\zeta}$$

$$E_a = \eta\, \delta\omega^{\xi}$$

$$\Gamma = \Gamma_0\, e^{-\frac{E_a}{I_N}}$$

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Tune the "Duffing" non-linearity:

"Duffing", $\alpha\ V_{gate}^{2}$

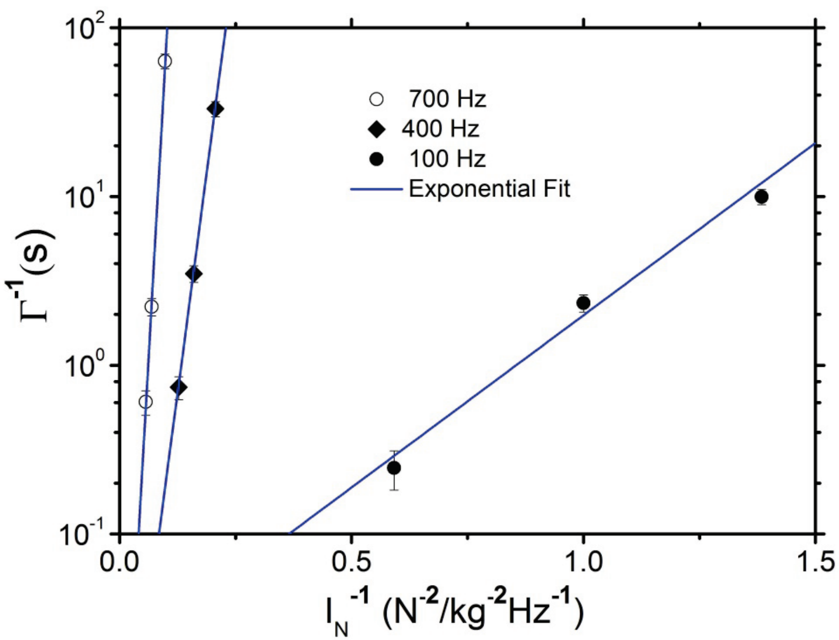
White noise

$$m\,\ddot{x}(t) + 2\Lambda_1\,\dot{x}(t) + (k_0 + \delta k_0)\,x + \delta k_2\,x^3 = F_{mag}\cos(\omega t) + f(t)$$

Flex. mode state: $x = x_0 \cos(\omega t + \phi)$

$I_N\ \alpha\ f(\omega)$

Extract Γ as a function of noise: obtain Γ_0 and E_a



$$\Gamma_0 = \lambda\ \delta\omega^{\zeta}$$

$$E_a = \eta\ \delta\omega^{\xi}$$

$$\Gamma = \Gamma_0\, e^{-\frac{E_a}{I_N}}$$

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings of parameters:

Chan, Cleland

$\Gamma_0 = \lambda\ \delta\omega^{\zeta}$? $E_a = \eta\ \delta\omega^{\xi}$

But also as a function of δk_2:

$\lambda \propto \delta k_2^{\gamma}$? $\eta \propto \delta k_2^{\mu}$?

Theoretically, universal scaling $\xi=3/2$, $\zeta=1/2$

Predicted $\gamma=+1/2$, $\mu=-5/2$

M.I. Dykman, M.A. Krivoglaz, Zh. Eksp. Teor. Fiz. 77, 60 (1979)

M.I. Dykman, M.A. Krivoglaz, Physica 104A, 480 (1980)

M.I. Dykman *et al.*, PRE 49, 1198 (1994)

Exponential law valid for $E_a/I_N >> 1$,
"Dykman" == simple 1D theory of escape ?

Slow amplitude *z*(t), two components:

$$x(t) = z(t)e^{i\omega t} + z(t)^* e^{-i\omega t}$$

$$z = \sqrt{3\left|\frac{\delta k_2/m}{\Delta\omega}\right|}\,(u + i\,v)$$

Normalized bias parameters:

$$\Omega = 2\left|\omega-\omega_0\right|/\Delta\omega\ ,\ \ \Omega_b = 3\left|\frac{\delta k_2}{m}\right|\left(\frac{F_{mag}}{m}\right)^2 / \left(4\omega^2\,\Delta\omega^2\right)$$

Fokker-Planck problem is 2D with real and imaginary parts *u*(t) and *v*(t).

1D valid only very close (but away to be exponential) from bifurcation point!

O. Kogan, arXiv:0805.0972v2

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings of parameters:

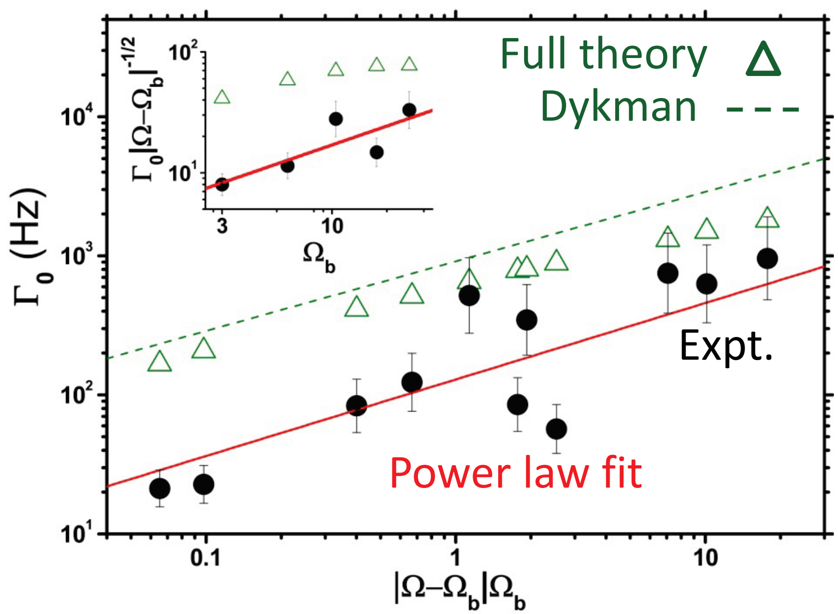
$\Gamma_0 = \lambda\, \delta\omega^{\zeta}$ $\quad E_a = \eta\, \delta\omega^{\xi}$

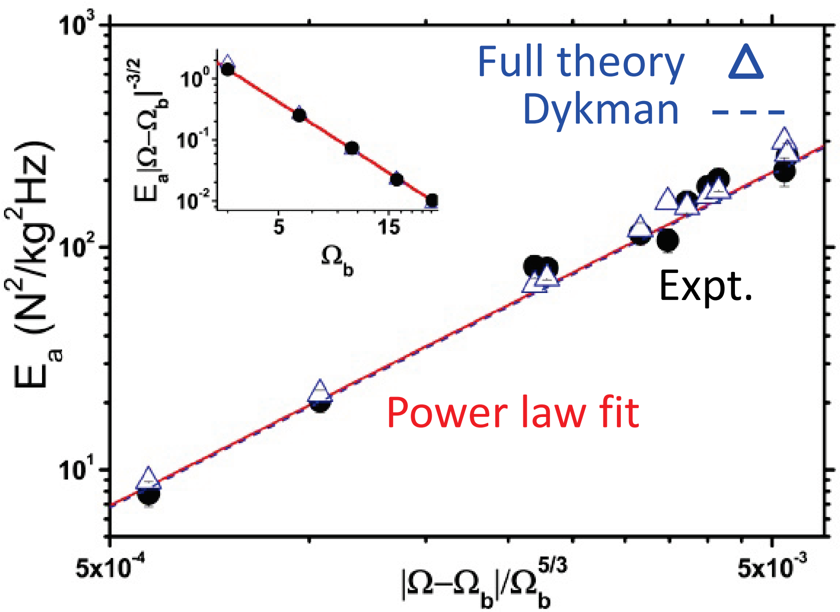
$\lambda\ \alpha\ \delta k_2^{\gamma}$ $\quad \eta\ \alpha\ \delta k_2^{\mu}$

Theoretically, universal scaling ξ=3/2, ζ=1/2

Predicted γ=+1/2, μ=-5/2

Measurements for 5 different δk_2, each with about 3 detunings and 3 noise levels, from within to far outside 1D "Dykman" range!





M. Defoort *et al.*, arXiv:1409.6971v2 [cond-mat.mes-hall], Accepted PRB Rapid Com. (2015)

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

First quantitative agreement theory/experiment extracting pseudo-potential parameters (10 % on noise calibration)

Scalings 2

$\Gamma_0 = \lambda$ h

$\lambda \;\alpha\; \delta$ within

M. Defoort *et al.*, arXiv:1409.6971v2 [cond-mat.mes-hall], Accepted PRB Rapid Com. (2015)

Modeling bifurcation phenomena

Dynamic bifurcation with a **Duffing nonlinear resonator**.

Scalings ... 2

$\Gamma_0 = \lambda$ ... h

$\lambda \; \alpha \; \delta$ ... within

First quantitative agreement theory/experiment extracting pseudo-potential parameters (10 % on noise calibration)

First measurement with respect to δk_2

First measurement of Γ_0

M. Defoort *et al.*, arXiv:1409.6971v2 [cond-mat.mes-hall], Accepted PRB Rapid Com. (2015)

Modeling bifurcation phenomena

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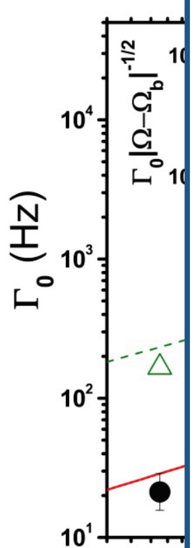
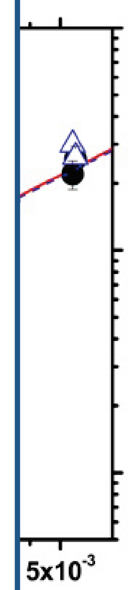
First measurement of Γ_0

Amazingly, scalings of E_a far beyond the validity range!

Some property of Duffing oscillator, or more universal?

O. Kogan, arXiv:0805.0972v2





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Modeling bifurcation phenomena

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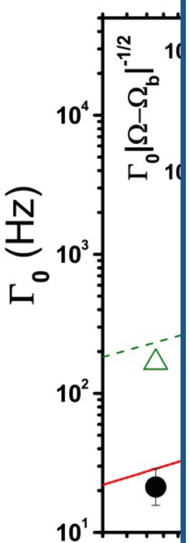

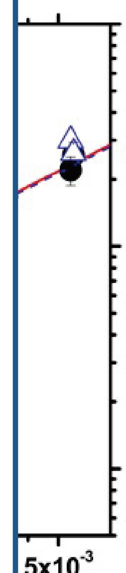

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First measurement with respect to δk_2

First measurement of Γ_0

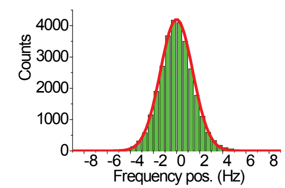
Amazingly, scalings of E_a far beyond the validity range!

Some property of Duffing oscillator, or more universal?

O. Kogan, arXiv:0805.0972v2

Intrinsic frequency-noise…

e.g. Y. Zhang *et al.*, PRL **113**, 255502 (2014)



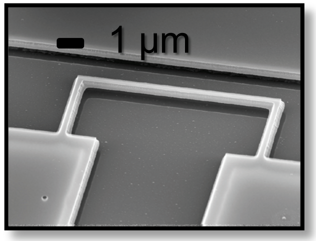
Classical decoherence and T_1, T_2 measurements

B.H. Schneider *et al.*, Nature Com. **5**, 5819 (2014)

M. Defoort *et al.*, arXiv:1409.6971v2 [cond-mat.mes-hall], Accepted PRB Rapid Com. (2015)

Outcomes

An example of NEMS results on fundamental classical issues.

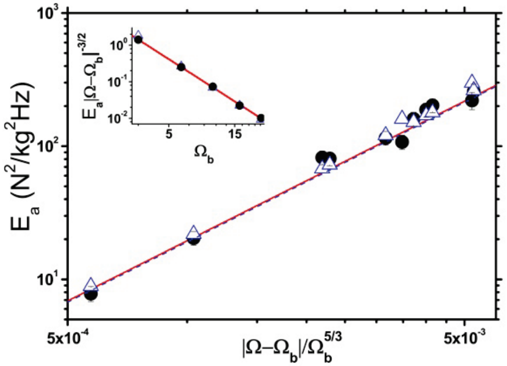


M. Defoort *et al.*, PRB Rapid Com. accepted (2015)

Model systems,

Dynamic bifurcation

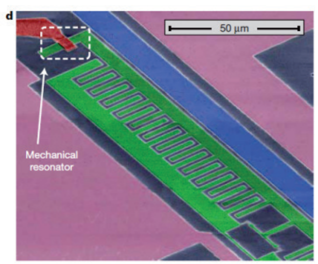
Quantitative match – extended validity range scalings



Perspectives

European Research Council

Pushing to the lowest achievable temperatures.
Beyond the classical aspects…



J.-M. Pirkkalainen *et al.*, Nature **494**, 211 (2013)

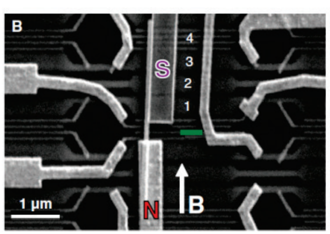
- **Ground-state cooling,**

  "Brute force" cooling of "big" structures,
  state-of-the-art cryogenics

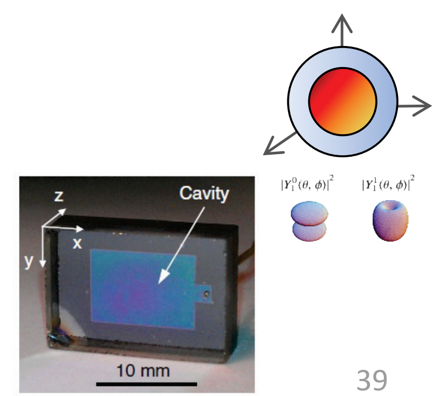
  Today $T \approx 15$ mK ; tomorrow $T \leq 1$ mK
  European Microkelvin Platform

- **Quantum Fluids & Solids probes,**

  Mesoscopic lengthscale at reach
  New quantum states, topological matter
  Edge states, well defined order parameter
  ^{3}He-B (almost) ideal medium



V. Mourik *et al.*, Science **336**, 1003 (2012)

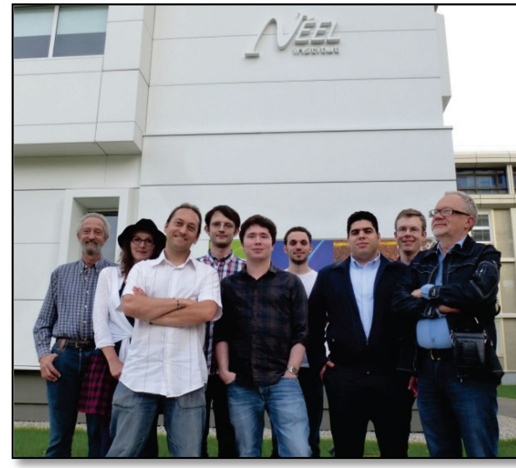


L. Levitin *et al.*, Science **340**, 841 (2013)

cnrs
advancing the frontiers

Many thanks to

NÉEL institut



Grenoble people, Néel
H. Godfrin, O. Bourgeois, A. Fefferman,
O. Maillet, M. Defoort,
A. Sultan, K.J. Lulla,
T. Moutonet, J.-S. Heron
& All the technical staff

with
A. Armour, Nottingham UK,
F. Pistolesi, LOMA France,
A. Casey, RHUL UK,
P. Skyba, Safarik Slovakia,
S.N. Fisher, V. Tsepelin, ULANC UK,
L. Skrbek, Charles Czech Rep.

Happy birthday Quantronics!
30, that's young!!

& the Microkelvin collaboration

erc
European Research Council

Agence Nationale de la Recherche
ANR

μ
7 CAPACITIES
European Microkelvin Collaboration

Nano-Electro-Mechanical Systems

Mesoscopic devices that can move, actuated/detected by electromagnetic means.

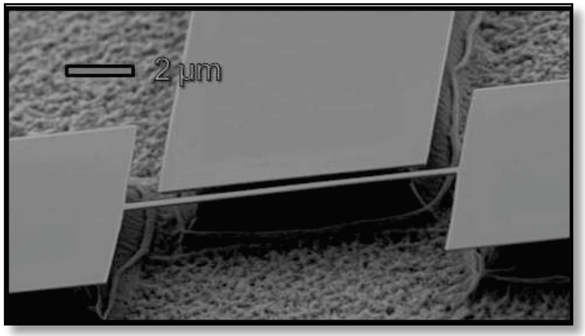
- **Model systems,**

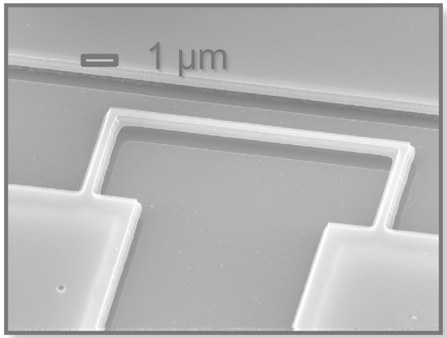
  Dynamic bifurcation

- **Mesoscopic probes,**

  Boundary layer in fluid

Doubly-clamped



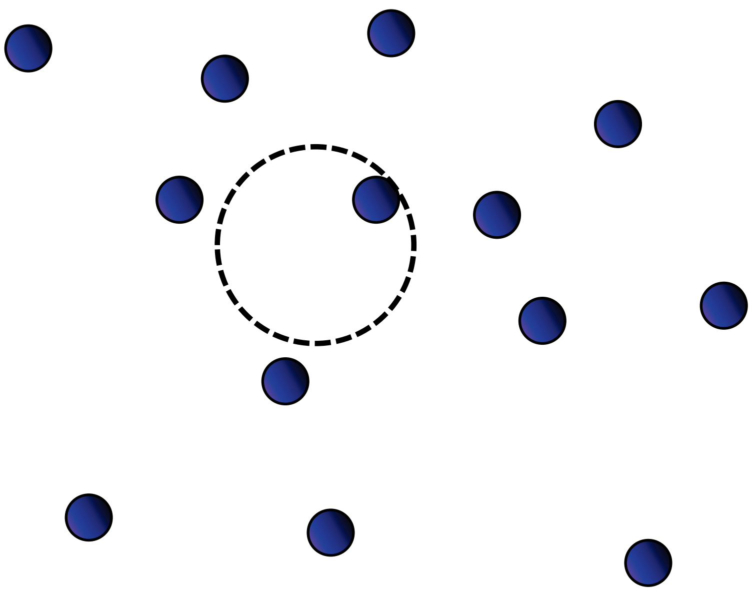


Cantilever

Mesoscopic mechanical probes

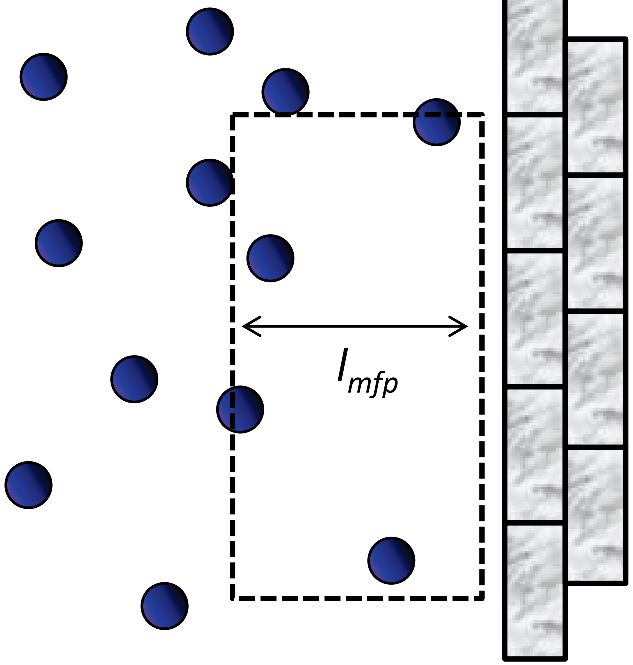
Micro and nano-flows. **Boundary layer problem**.

Bulk, laminar



Maxwellian distribution velocities,
Newtonian fluid viscosity

Boundary, laminar

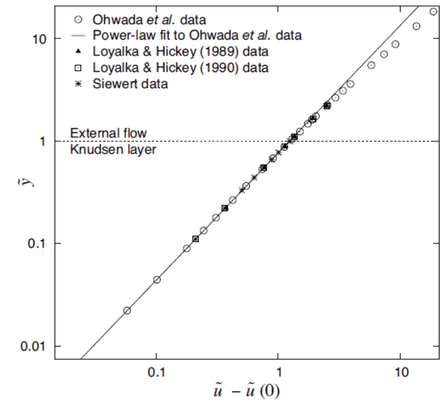


Knudsen layer:
Non-Maxwellian distribution velocities,
Non-Newtonian fluid viscosity,
Slippage, reduced effective viscosity

Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem**.

Theory…



C.R. Lilley and J.E. Sader, Phys. Rev. E **76**, 026315 (2007)

A growing literature on **micro/nano fluidics**.

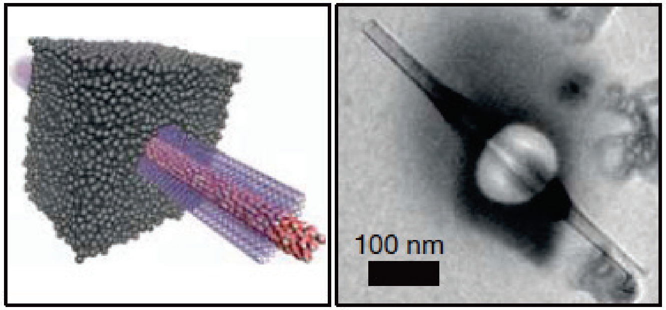
Abdelhamid Maali *et al.*, J. of Appl. Phys. **97**, 074907 (2005)
Jerome Dorignac *et al.*, Phys. Rev. Lett. **96**, 186105 (2006)
C. A. Van Eysden and J. E. Sader, Phys. of Fluids **18**, 123102 (2006)
Elizabeth C. Bullard *et al.*, Phys. Rev. Lett. **112**, 015501 (2014)

Technological implications, and **fundamental questions**:

Structure of boundary layer?

M. Fichman and G. Hetsroni, Phys. of Fluids **17,** 123102 (2005)
Jason K. Holt *et al.,* Science **312**, 1034 (2006)
Seung Hyun Kim *et al.,* Phys. Rev. E **77**, 026704 (2008)
A. Siria *et al.*, Phys. Rev. Lett. **102,** 254503 (2009)

… and (few) experiments.



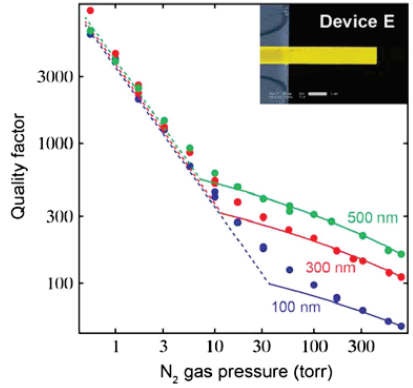
A. Siria *et al.*, Nature **494**, 455 (2013)

Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem**.

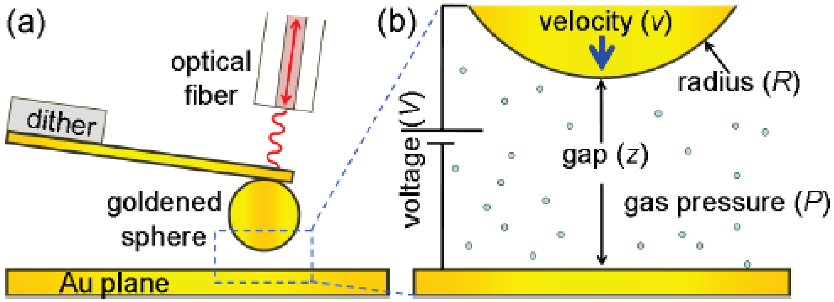
Local nano-probes: **oscillatory flows from nano-resonators**.

Bulk, laminar



E.C. Bullard *et al.*, Phys. Rev. Lett. **112**, 015501 (2014)

Boundary, laminar



J. Laurent *et al.*, Phys. Rev. Lett. **107**, 164501 (2011)

Cross-over between Navier-Stokes and molecular regimes observed.

Efficient probes, but: **pressures not low enough (l_{mfp} too small),**
too big structures,
too complex setup (room T, Air)…

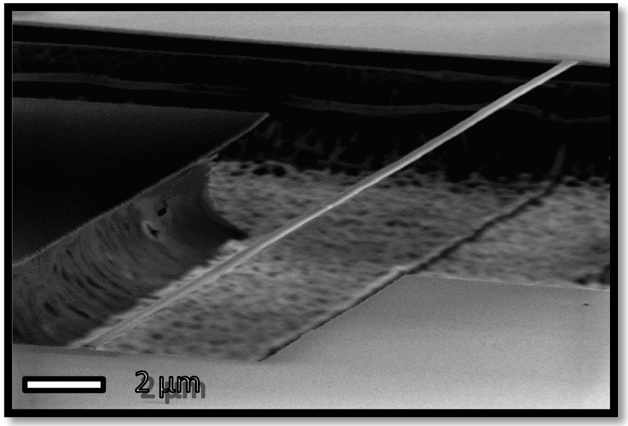
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem**.

Local nano-probes: **oscillatory flows from nano-resonators**.

String nano-mechanical resonator
in ^{4}He gas at 4.2 K. Aspect ratio 1 000.

“Very simple” setup.
Paradigm of the (almost) **ideal gas**.
Properties tabulated (NIST,…)



100 nm x 100 µm SiN beam

Out-of-plane motion,
Width & thickness & displacement **small**

Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem**.

Local nano-probes: **oscillatory flows from nano-resonators**.

String nano-mechanical resonator in ^{4}He gas at 4.2 K. Aspect ratio 1 000.

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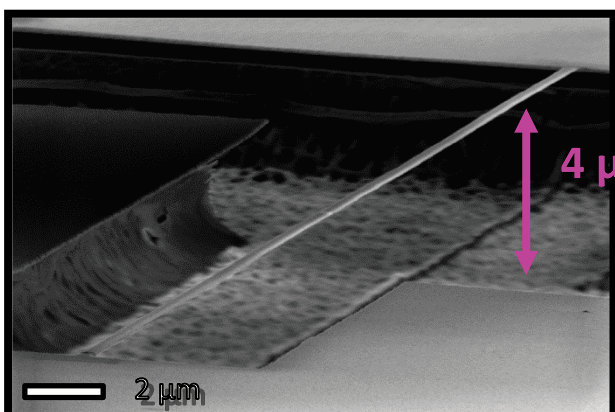
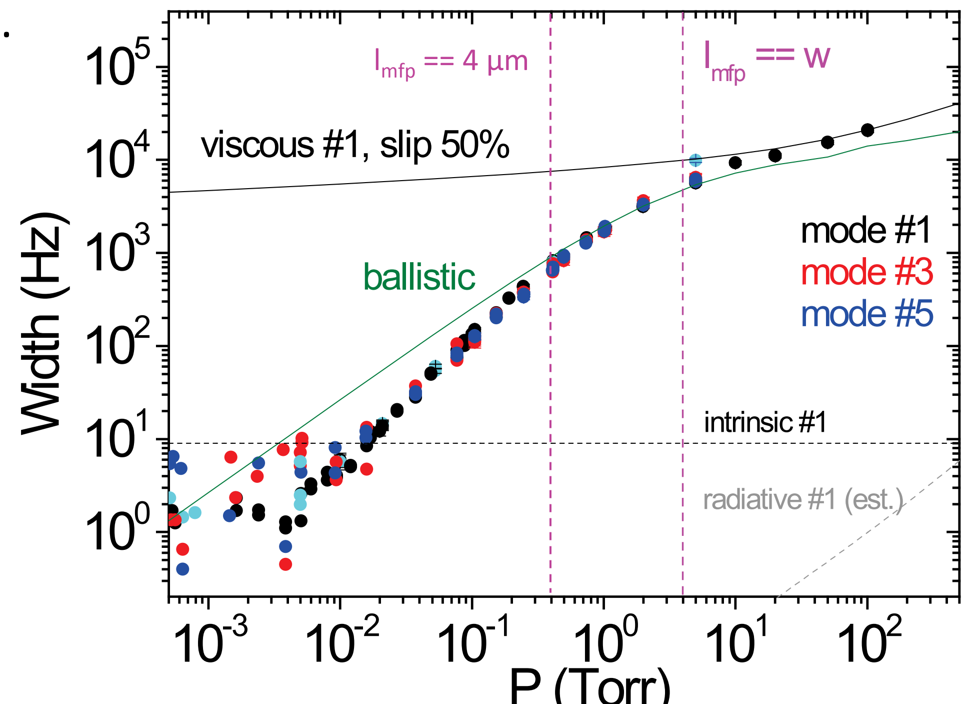


100 nm x 100 µm SiN beam

Cross-over viscous to ballistic



M. Defoort *et al.*, Phys. Rev. Lett. **113**, 136101 (2014)

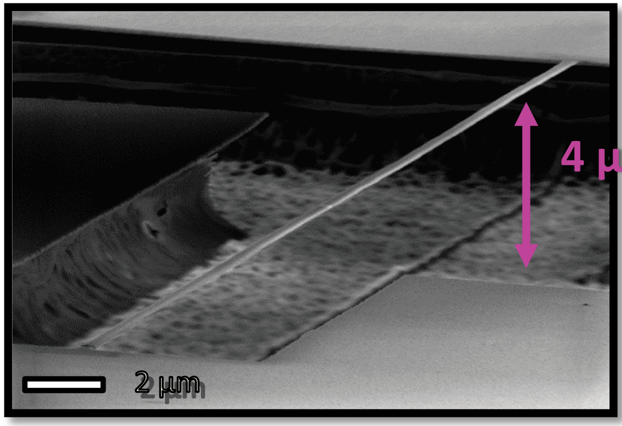
Mesoscopic mechanical probes

Micro and nano-flows. **Boundary layer problem**.

Local nano-probes: **oscillatory flows from nano-resonators**.

String nano-mechanical resonator in ^{4}He gas at 4.2 K. Aspect ratio 1 000.

"Very simple" setup.
Paradigm of the (almost) **ideal gas**.
Properties tabulated (NIST,…)



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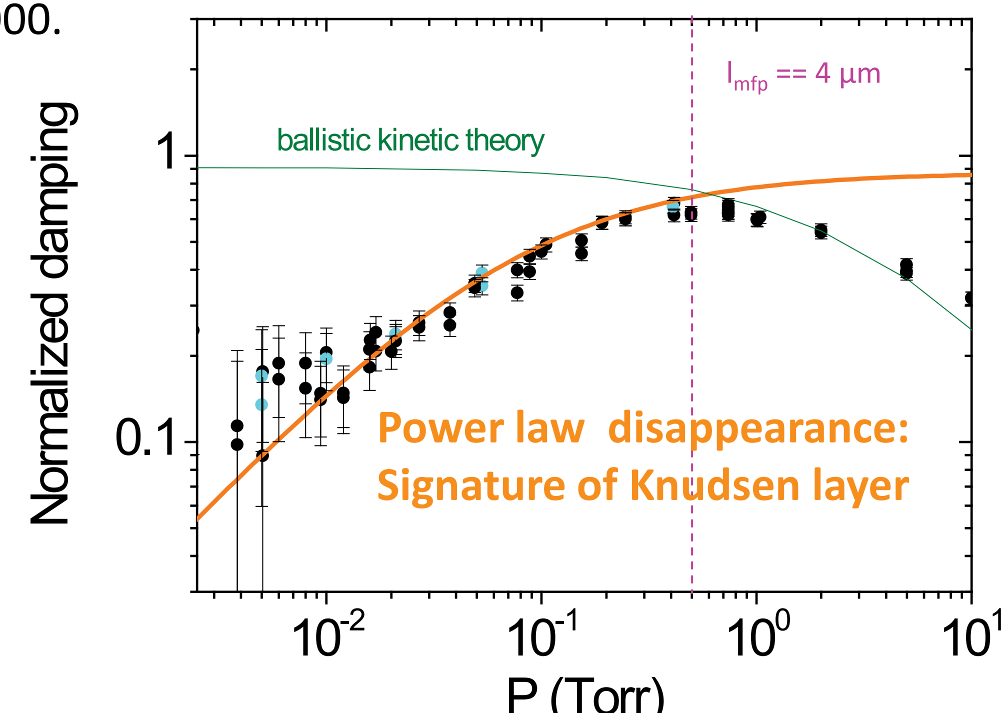

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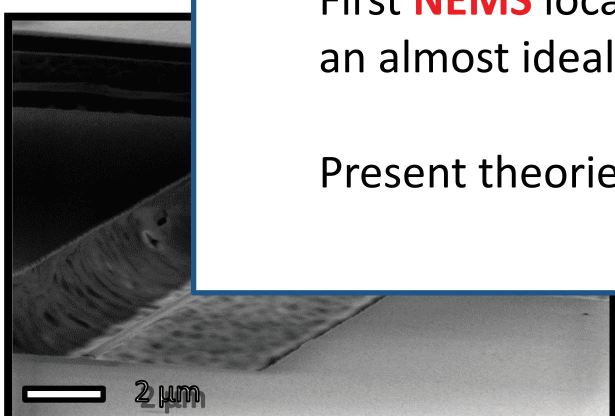

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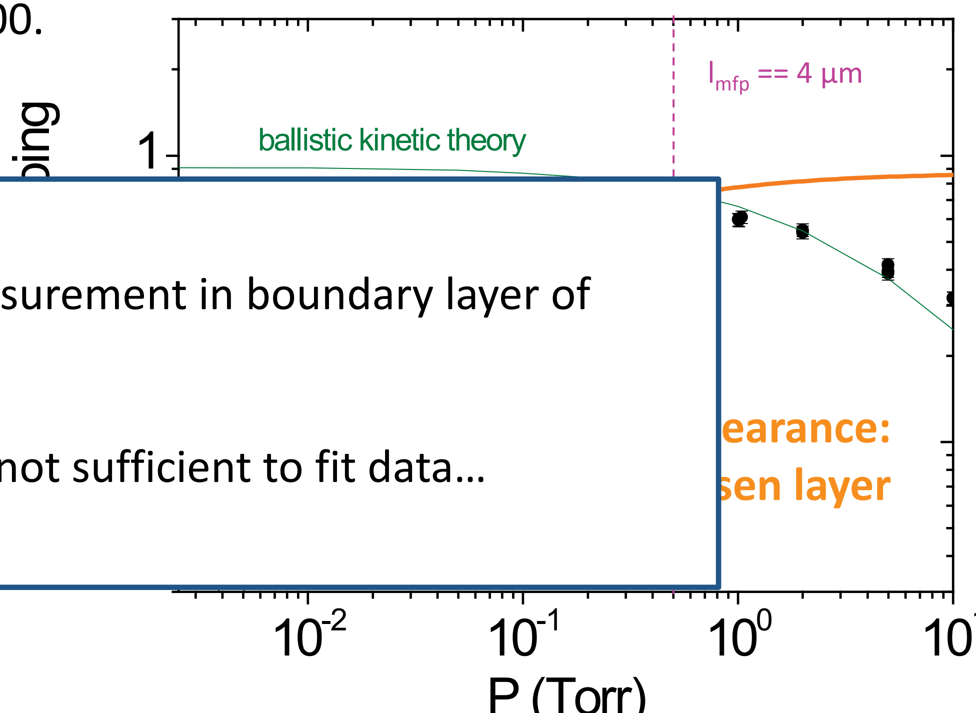

First **NEMS** local measurement in boundary layer of an almost ideal gas.

Present theories are not sufficient to fit data…

M. Defoort *et al.*, Phys. Rev. Lett. **113**, 136101 (2014)