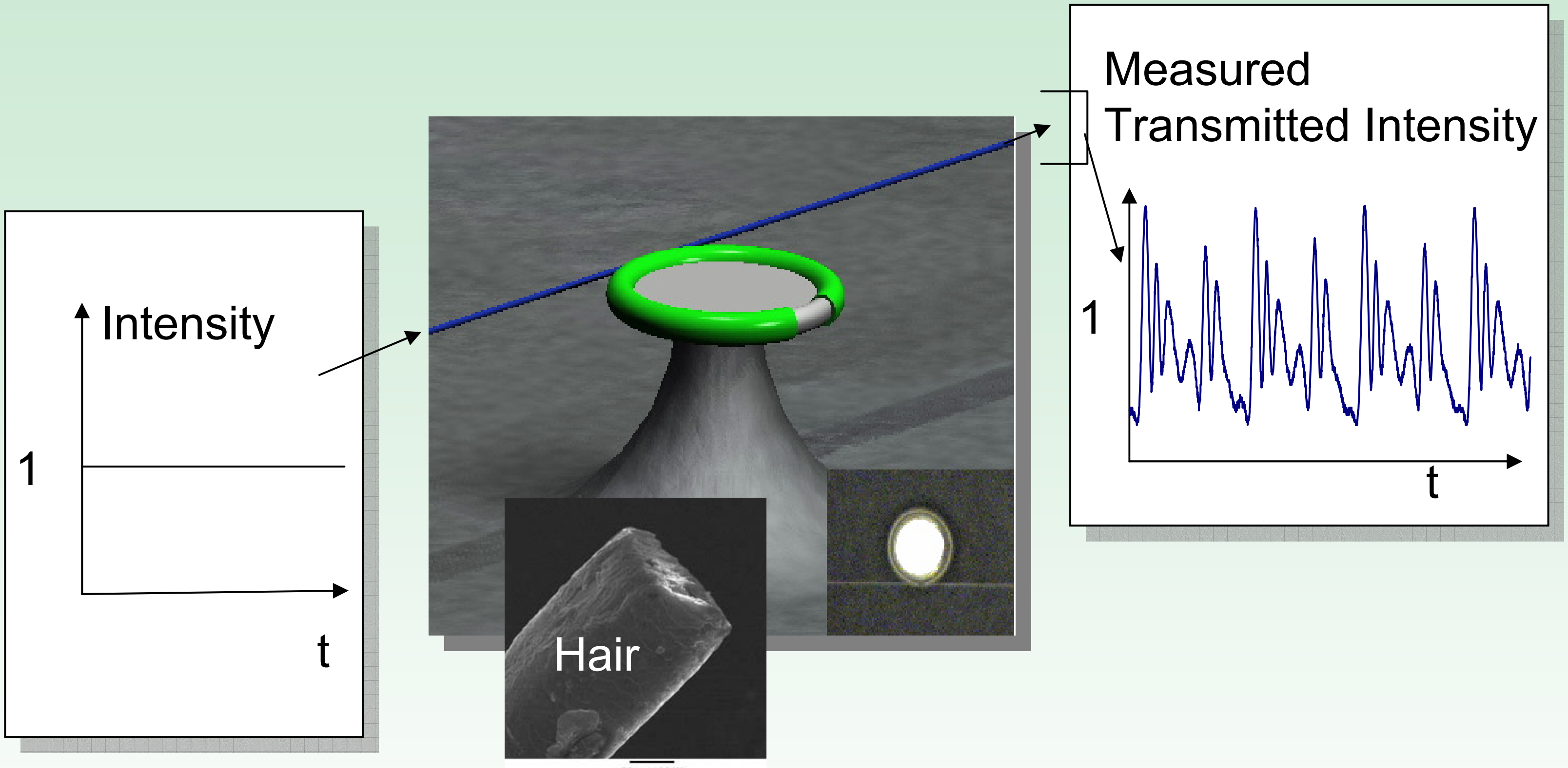
Radiation pressure in optical cavities



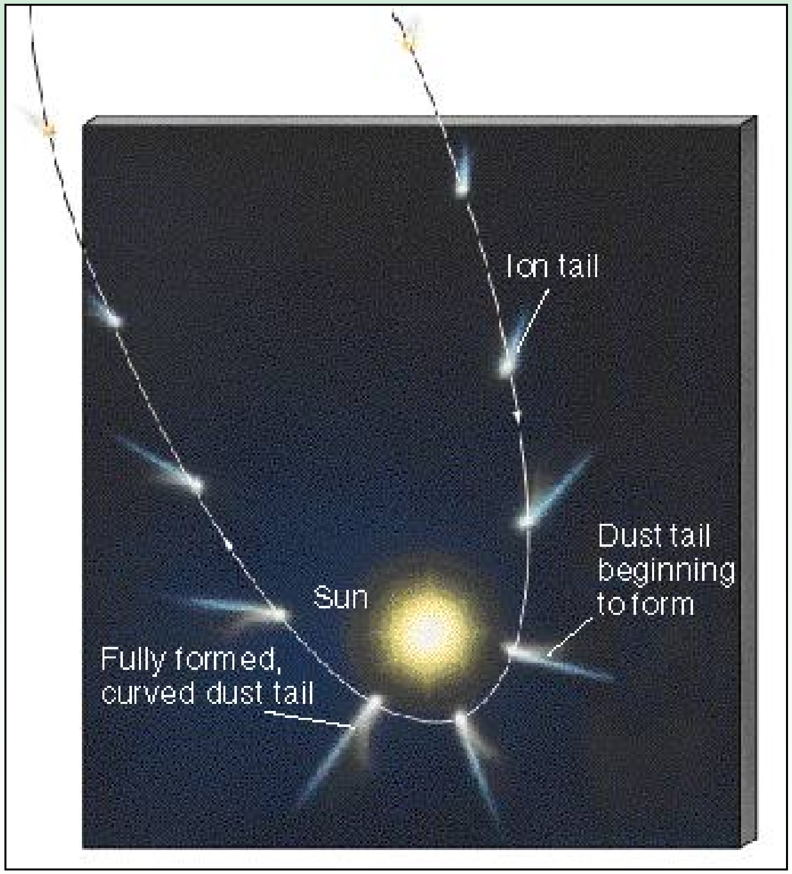
- •Experimental setup
- •Observes oscillations
- •Physical intuition
- •Model
- •Relation to: Other nonlinearities, quantum mechanics

T. Carmon, H. Rokhsari, L. Yang, T. Kippenberg and K. Vahala. California Institute of Technology
Department of Applied Physics
http://www.its.caltech.edu/~tal/

Who is interested in radiation pressure?

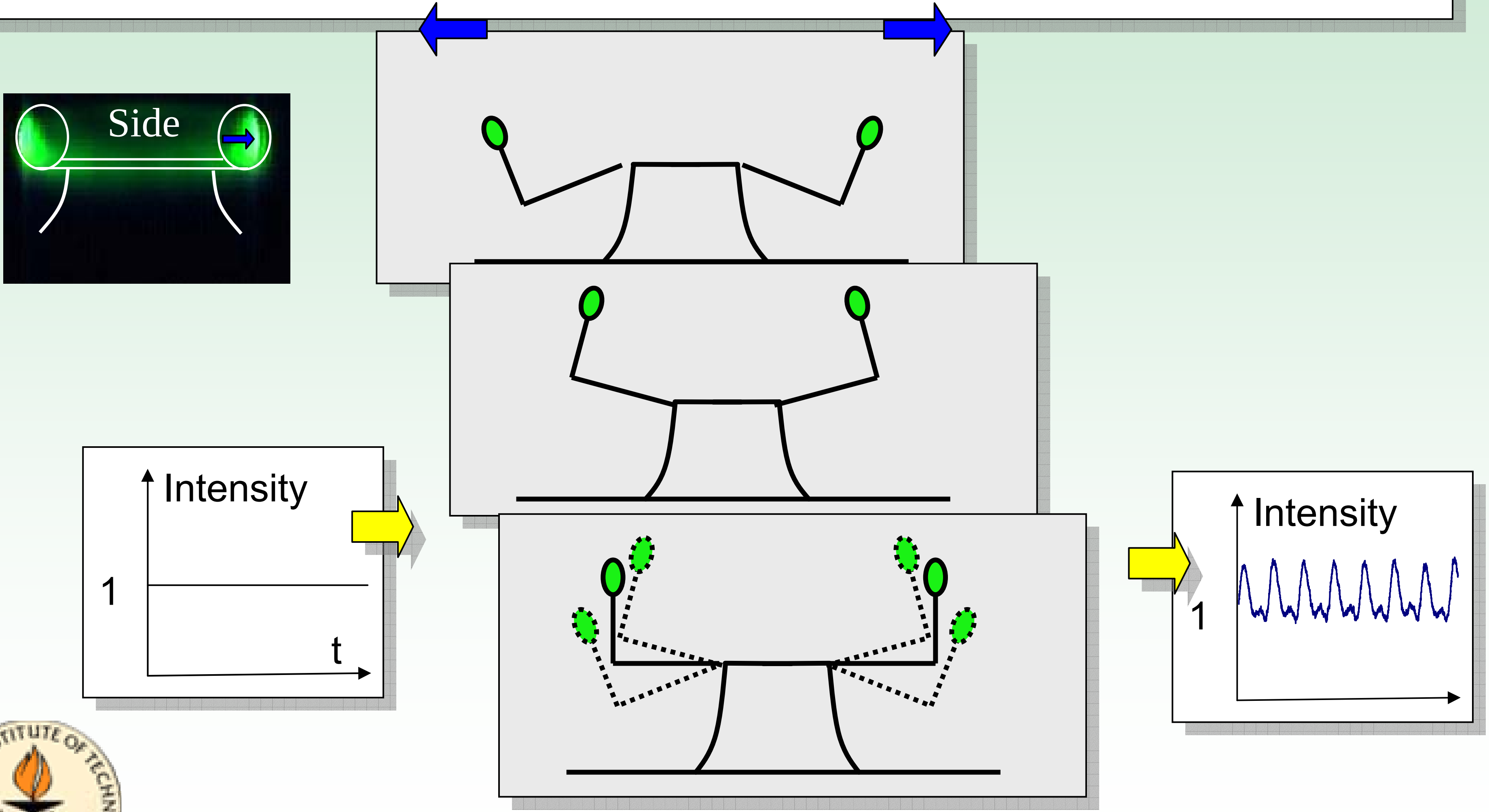
- First proposed by Kepler and later elaborated on by Newton.
- Bartoli infers the necessity of light pressure from thermodynamics.
- Maxwell

400 years ago, Kepler observed that comet’s tail is opposing the sun, suggesting radiation pressure to be the reason.



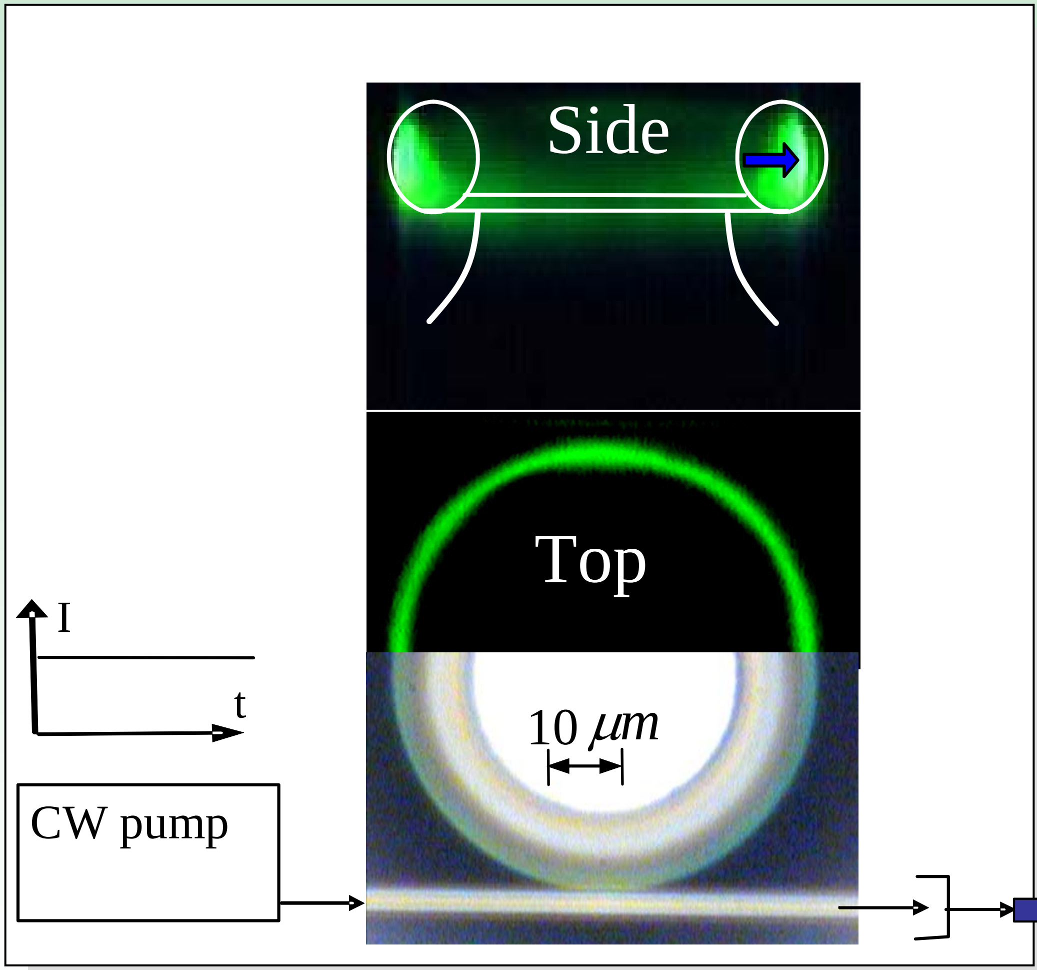
⬇Optical losses
⬇Size
⬆Intensity

➡ Observation of new nonlinearity in a cavity.

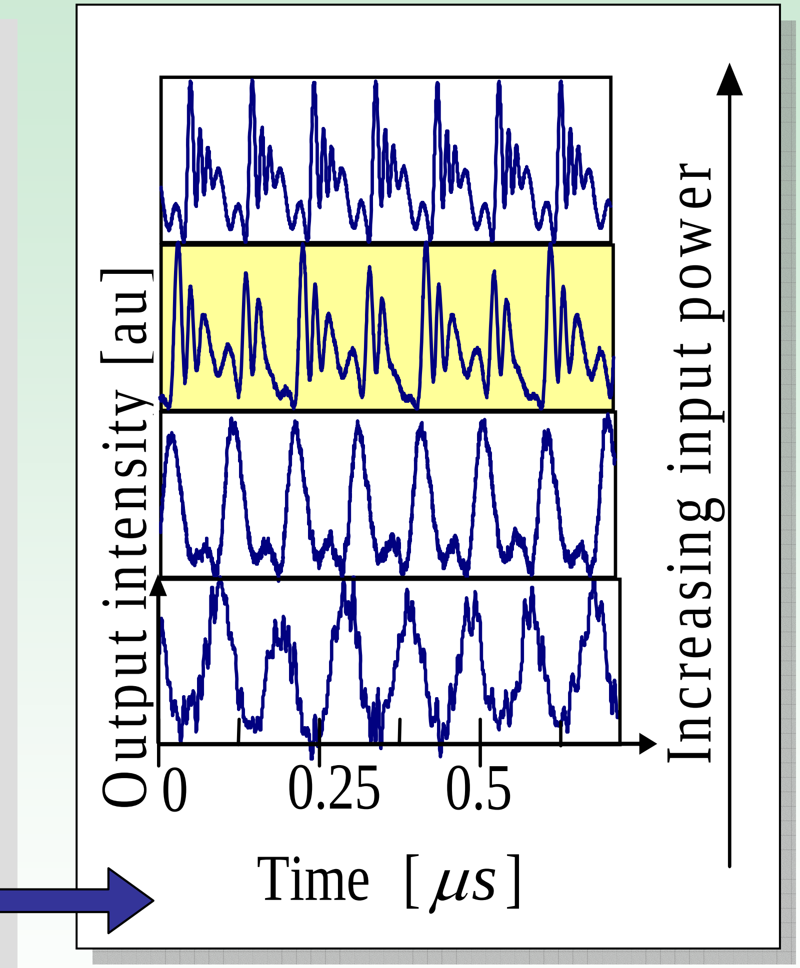


What is the experimental system?

Experimental system

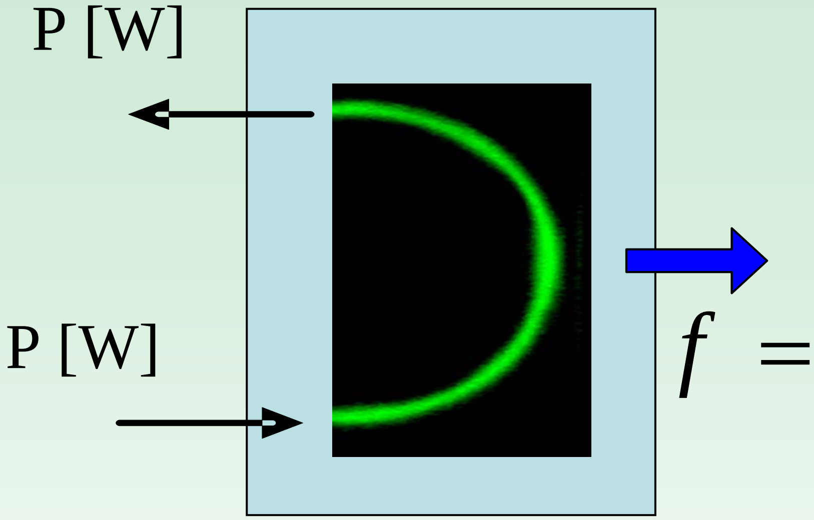


What do we see?



Why do we have radiation pressure?

Why force?

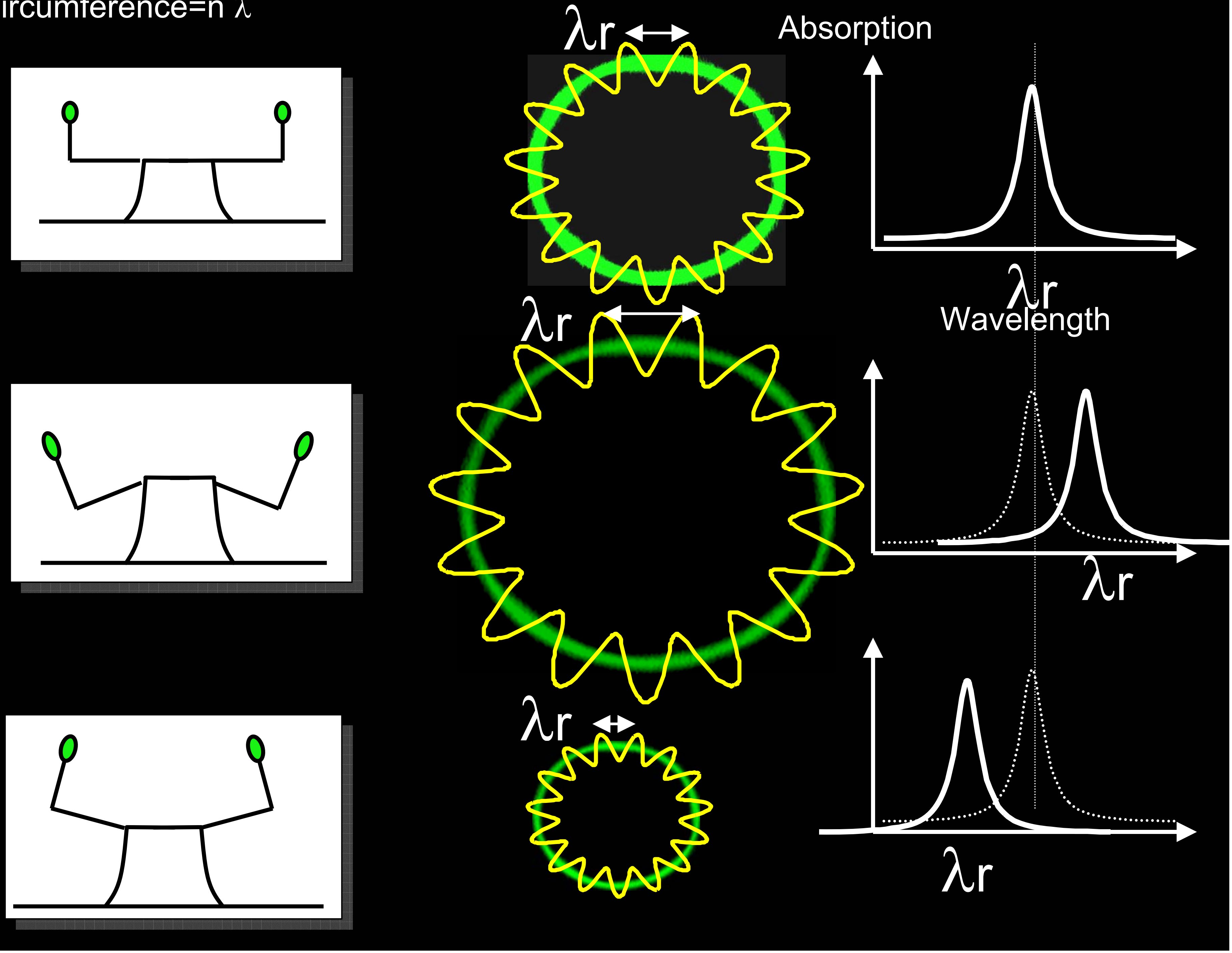


$$f = \frac{2P}{c}[N]$$

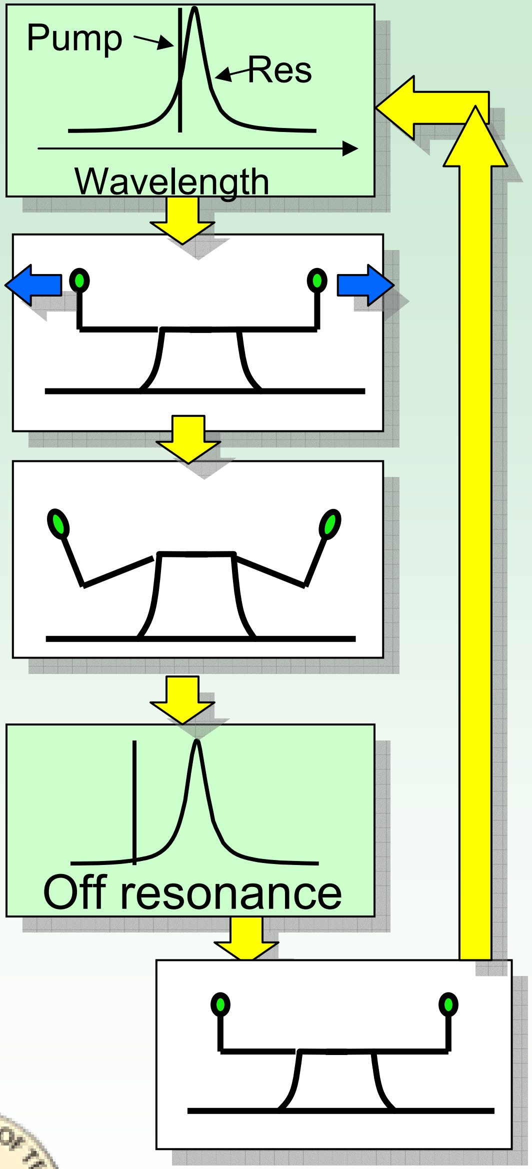
Fundamental principle of linear momentum conservation.

How to translate force to optical effect?

Circumference=n λ



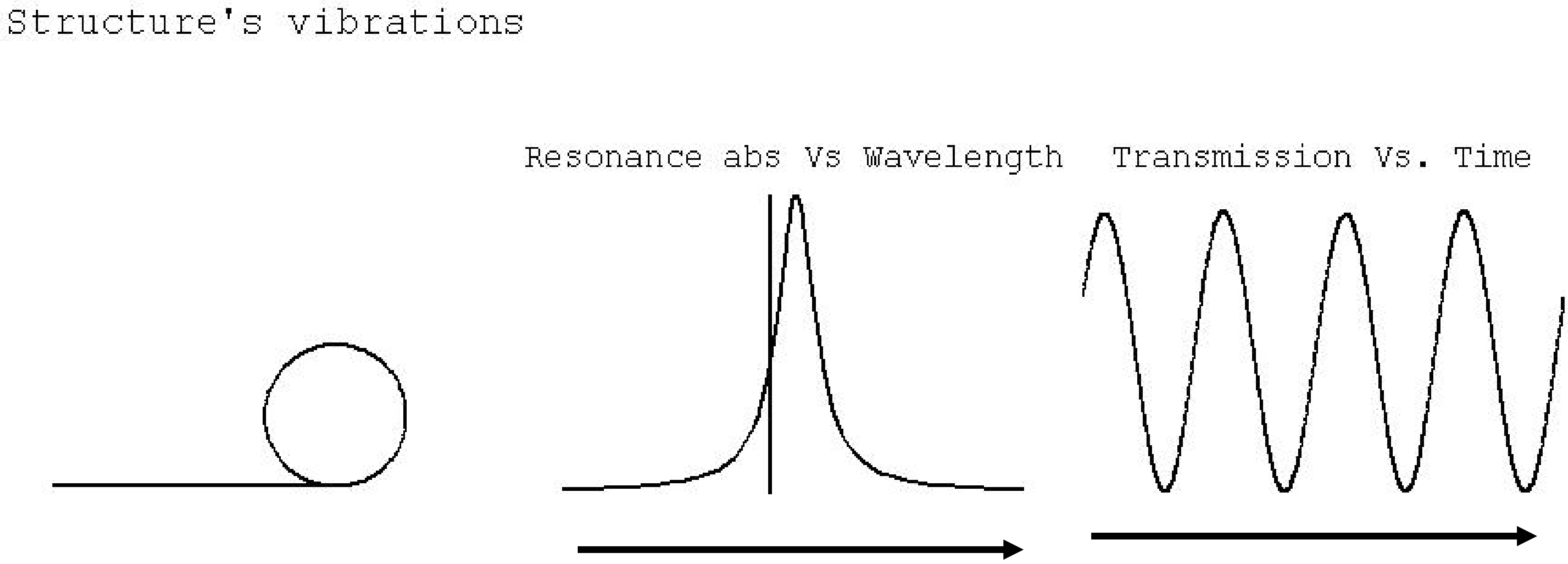
Pump wavelength<Resonance (It is important)



Energy transfer	
Inflation	Deflation
Optical->mechanical	Mechanical -> optical
Red Doppler shift	Blue Doppler shift

Regenerative oscillation

Low input power, small amplitude

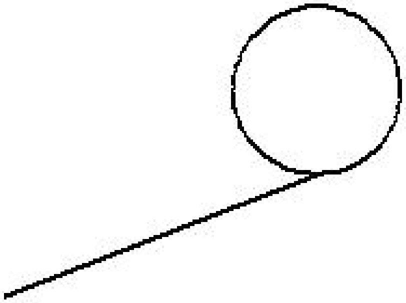


wavelength

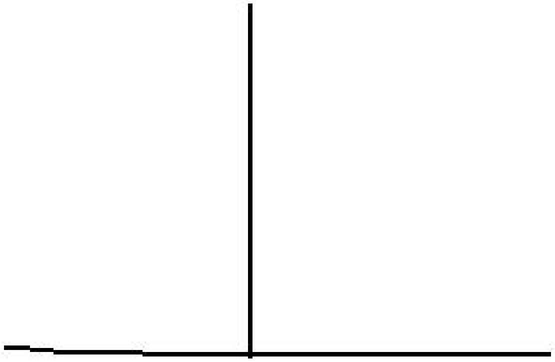
Time

High input power, large amplitude

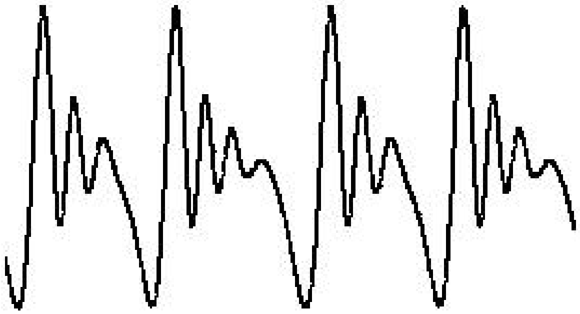
Structure's vibrations



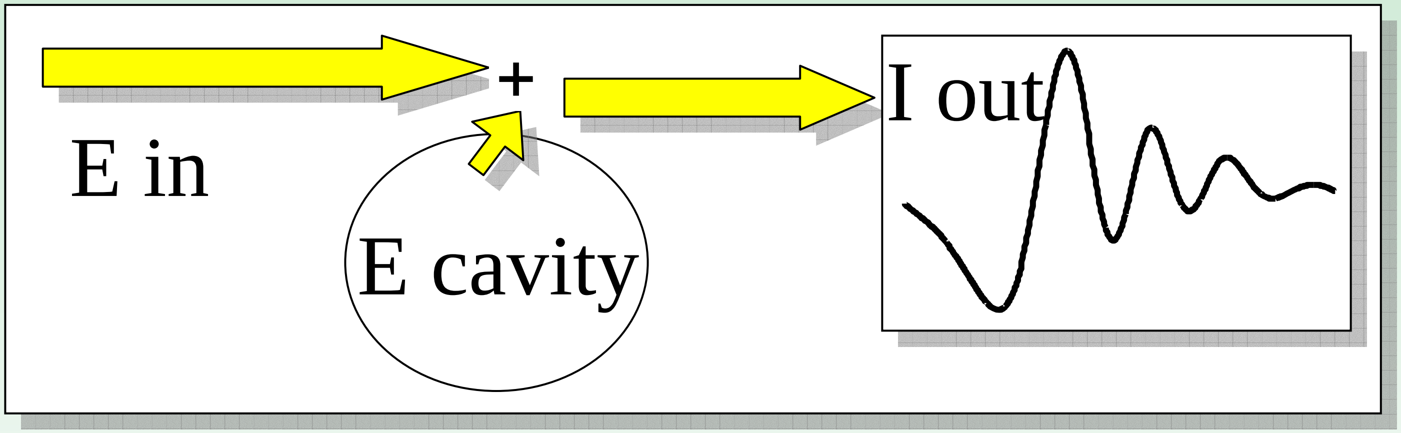
Resonance abs Vs Wavelength



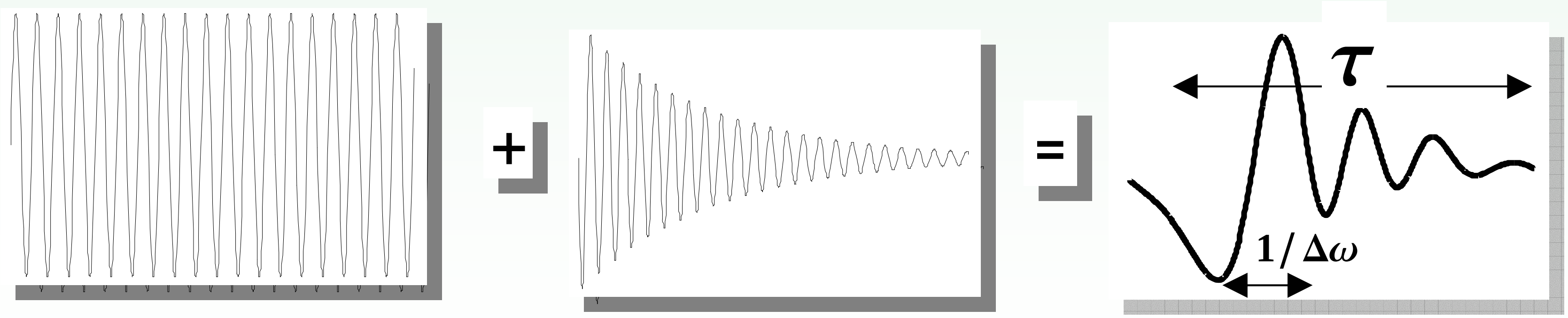
Transmission Vs. Time



Why decaying peaks?

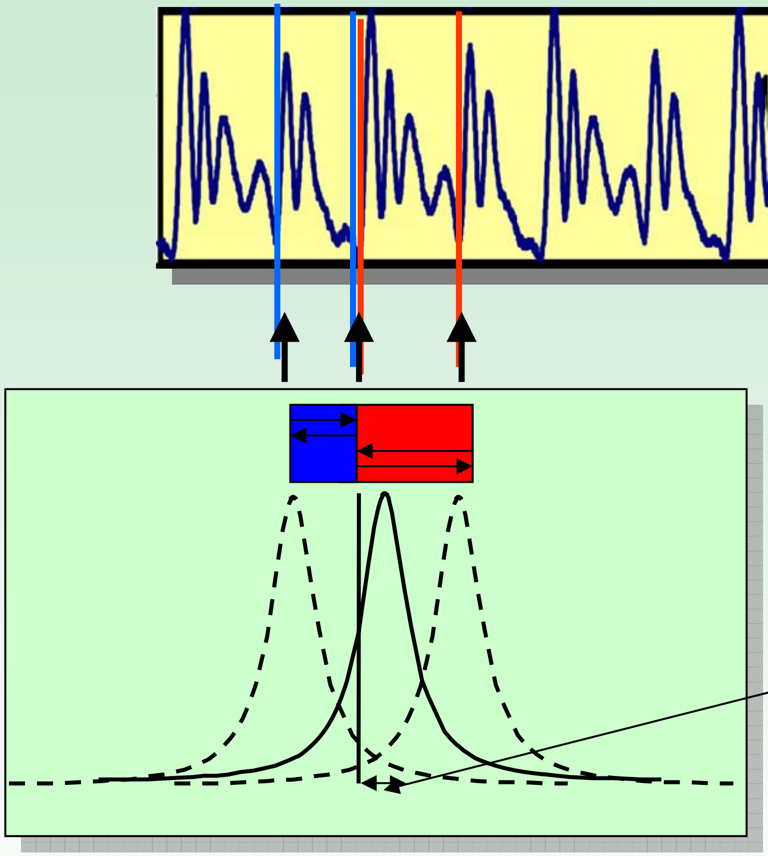


$$< \left(\sin(\omega t) + e^{-t/2\tau} \sin[(\omega + \Delta\omega)\, t] \right)^2 > =$$



Why alternating number of peaks (4, 3, 4, 3…)?

Why alternating number of peaks (4, 3, 4, 3…)?



- Cavity is charged with light upon passing of the absorption bell through pump wavelength
- And discharged later
- Resonance bell spends more time on one side of pump wavelength because of the initial offset (4-3=1 peak longer).
- Offset necessary for the red shift to be stronger than blue shift and energy to flow from optical mode to mechanical mode.

(negative offset = device cooling)

cooling

- P. F. Cohadon, A. Heidmann, and M. Pinard, Phys. Rev. Lett. **83**, 3174 (1999).
- V. B. Braginsky, A. B. Manukin, and M. Y. Tikhonov, Sov. Phys. JETP **31**, 829 (1970).
- A. Dorsel. J.D. McCullen, P. Meystre, H. Walther, and E.M. Wright, Phil. Trans. R. Soc. Lond. A **313**, 341 (1984)

Stop waving with your hands,
we want equations

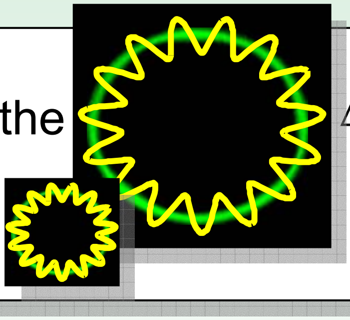
Model

no free parameters!

*Optical field inside cavity, A(t)
As function of pump amplitude (B) and
pump resonance detuning (Δω)

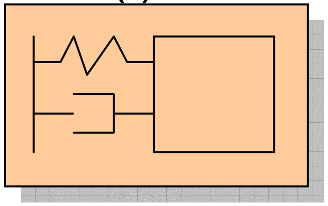
$$\dot{A}(t) + A(t)[\alpha\, c/n - i\, \underset{\overset{\uparrow}{?}}{\Delta\omega(t)}] = i\, B \sqrt{\alpha\, c/n\, \tau_0}$$

Pump-resonance
detuning as function of the
mechanical flex



$$\Delta\omega(t) = \Delta\omega_0 - \omega \underset{\overset{\uparrow}{?}}{\mu}\, r(t)\, 2\pi\, n/(\lambda_0 N)$$

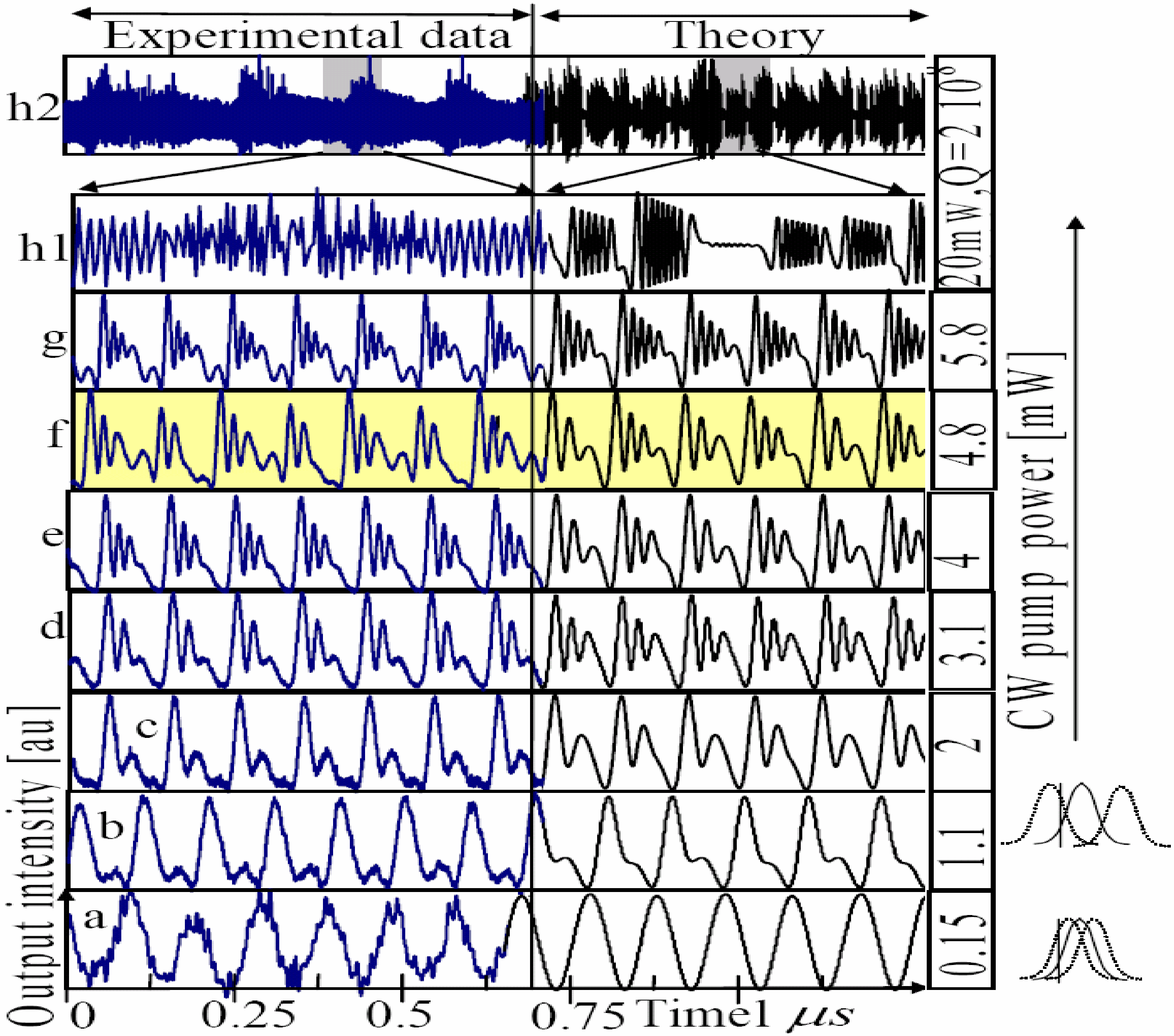
Cavity deviation from equilibrium, r(t)
Forced harmonic oscillator.



$$m\ddot{r}(t) + b\dot{r}(t) + kr(t) = \mu\, f(t) = \mu\, 2\pi\, |\underset{\overset{\uparrow}{?}}{A(t)}|^2\, n/c$$

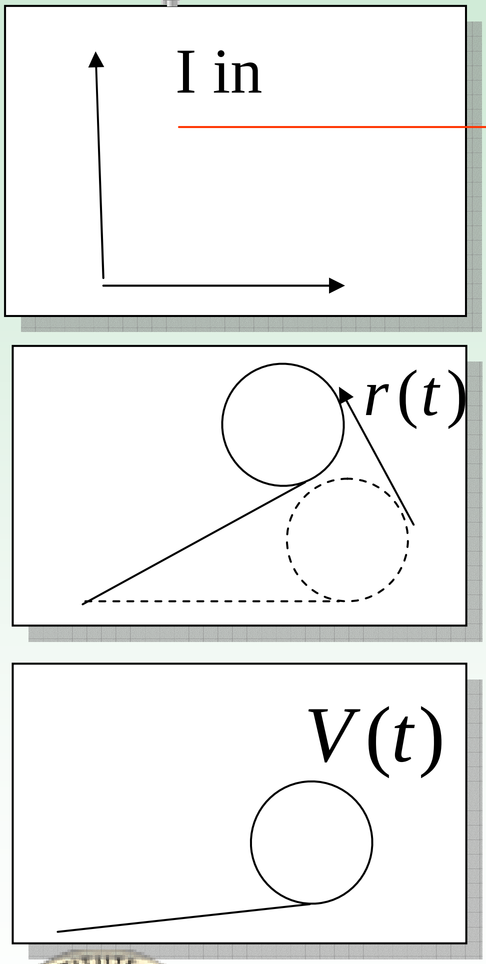
Compare theory to experimental results ?

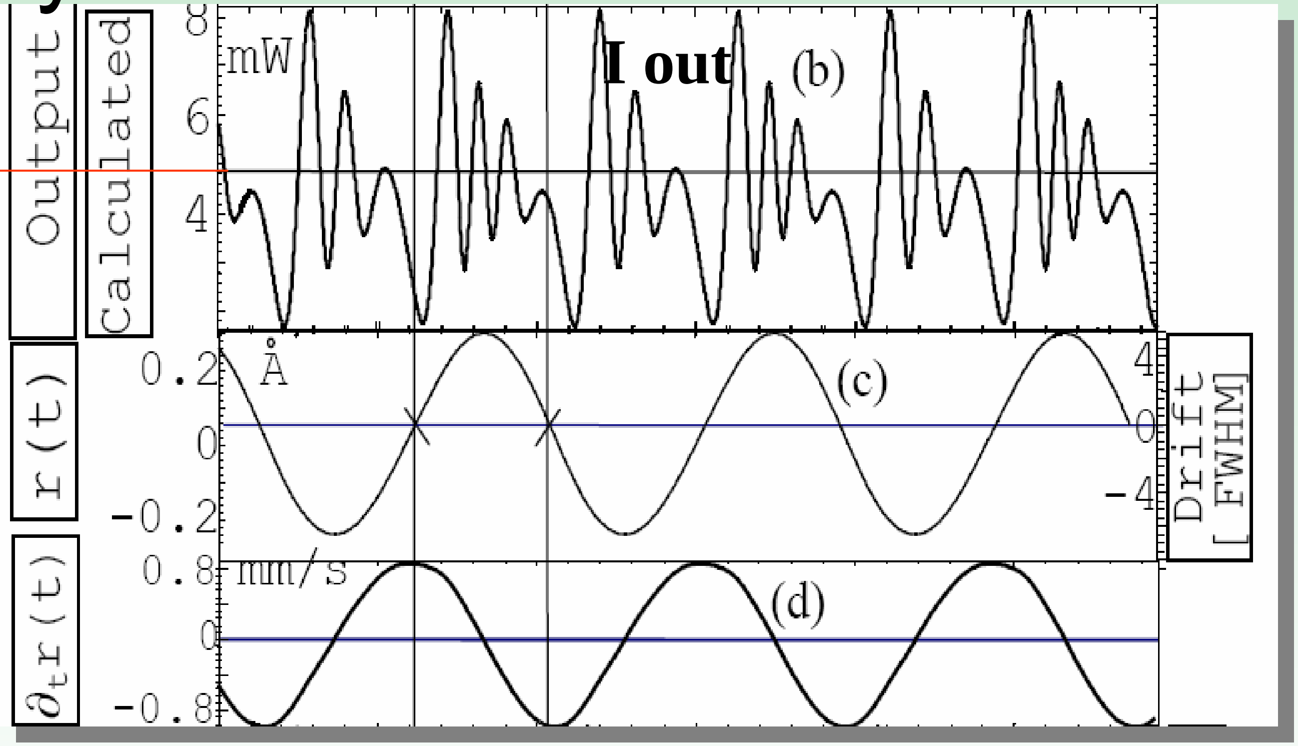
* M. L. Gorodetsky and V. S. Ilchenko, JOSA B, 16, 147 (1999)



Experimental data
Theory
h2
h1
g
f
e
d
c
b
a
20mW, Q=2 10^8
5.8
4.8
4
3.1
2
1.1
0.15
CW pump power [mW]
Output intensity [au]
0
0.25
0.5
0.75
Time [μs

Mechanical dynamics, position, velocity

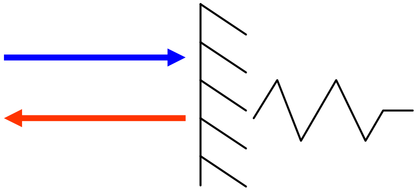




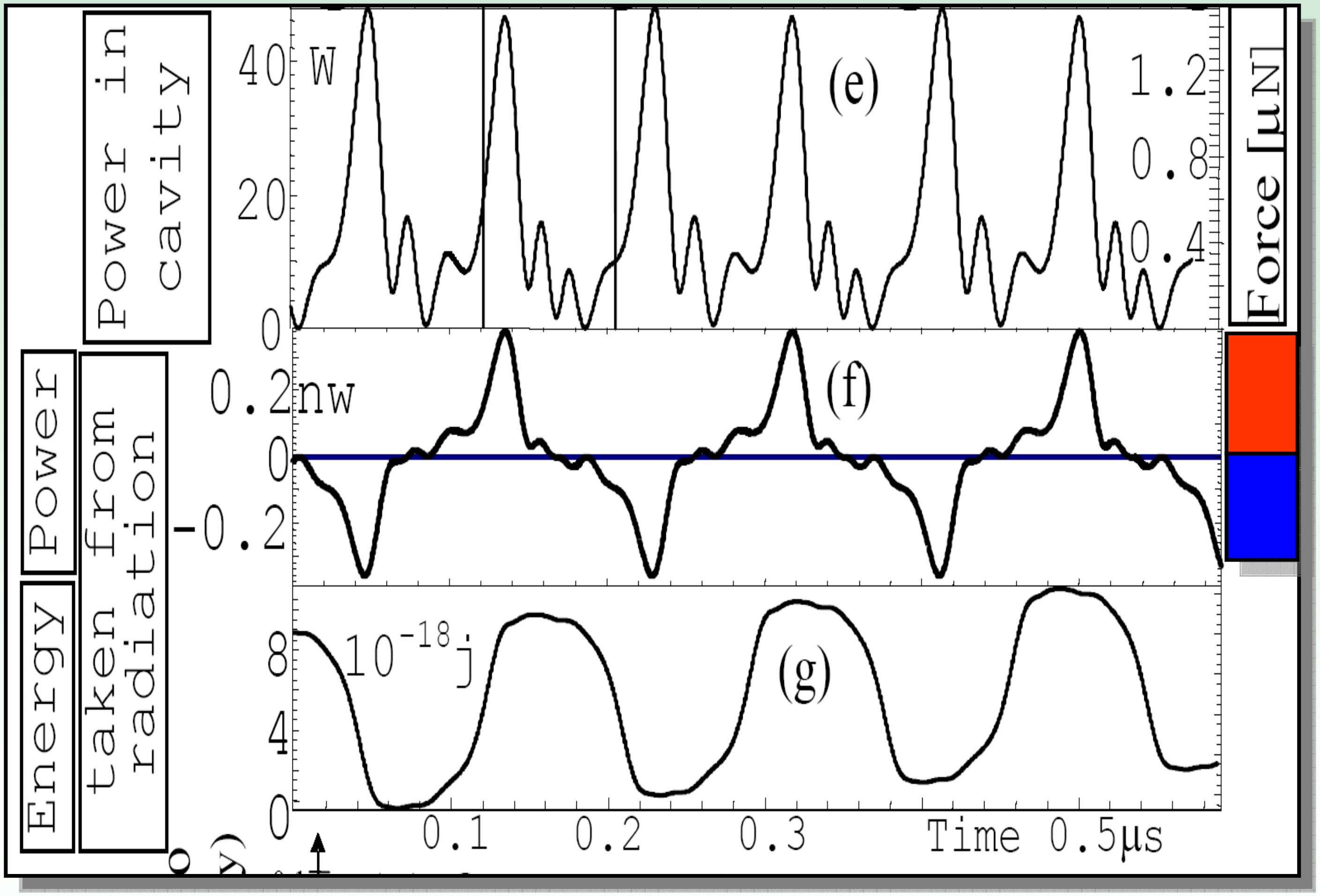
What is the energy inside?, energy balance.

Energy dynamics

$$f(t)V(t)$$

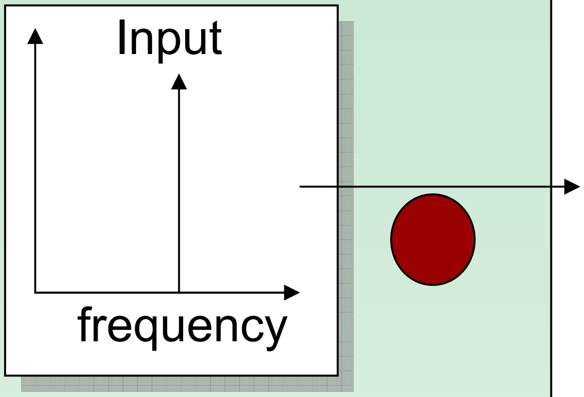


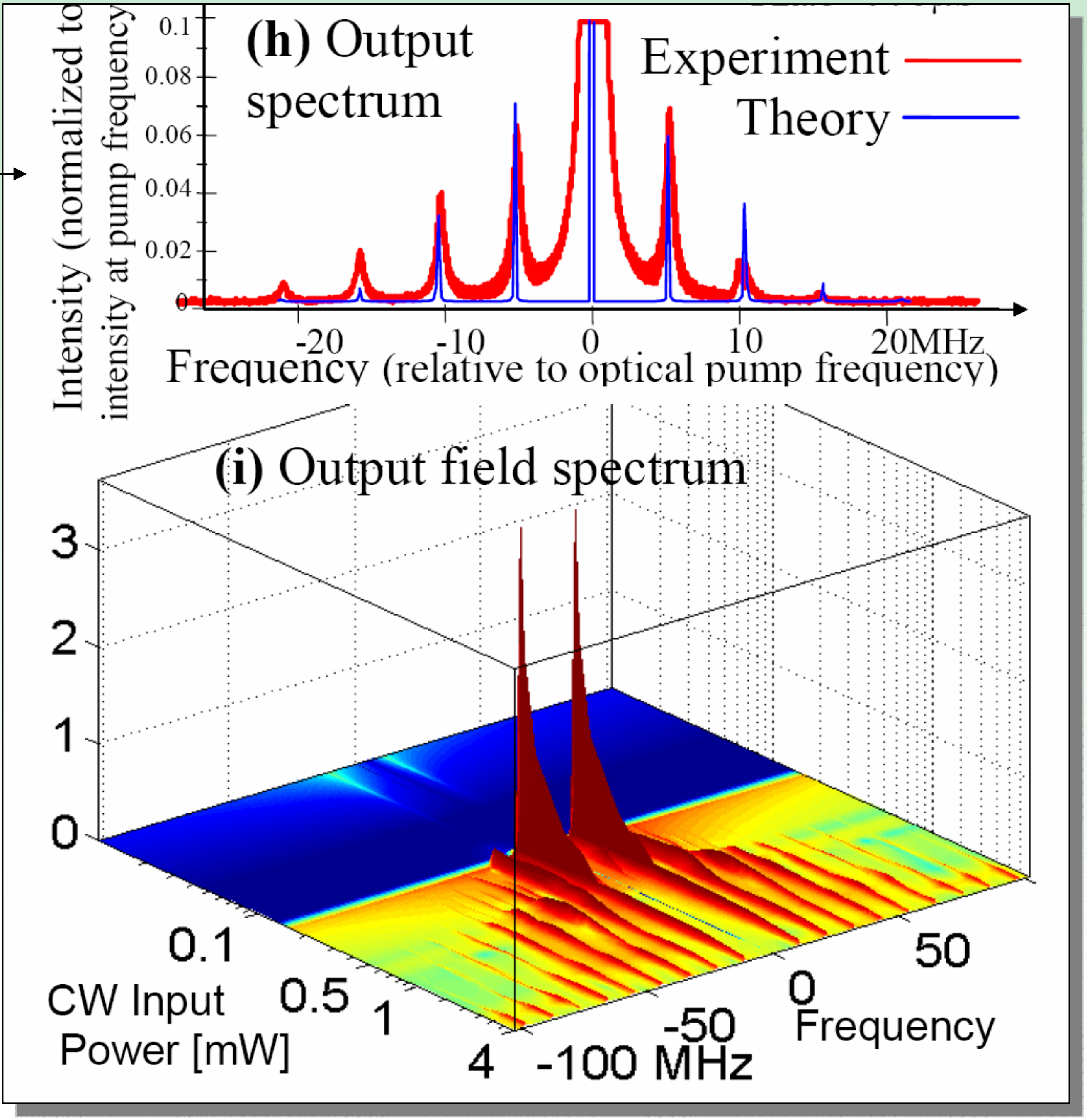
$$\int_0^t f(t')V(t')dt'$$



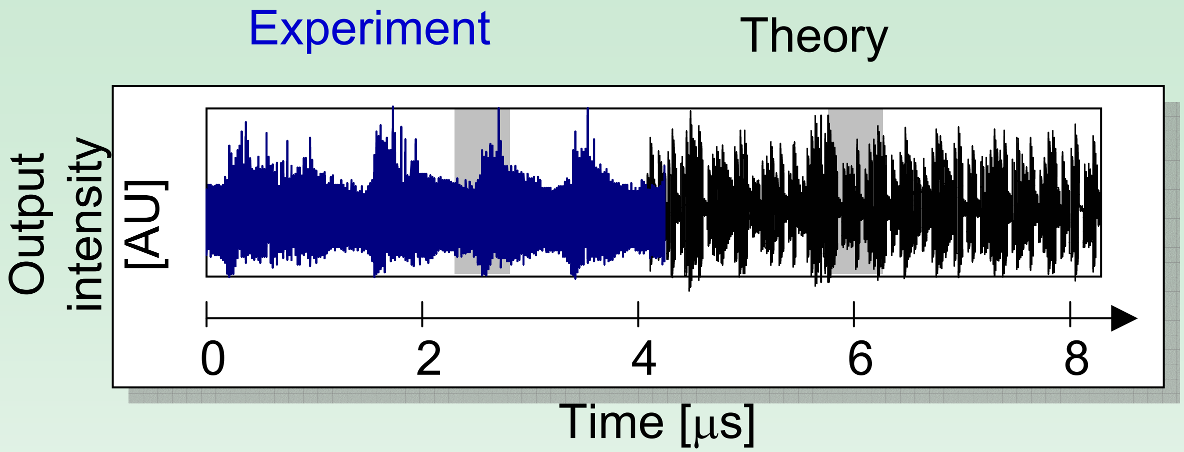
Output spectrum?

Output spectrum

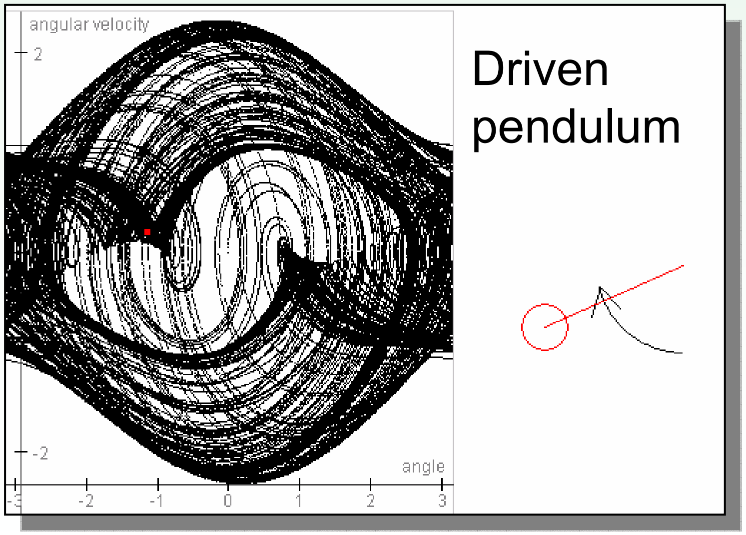




Resemble chaos

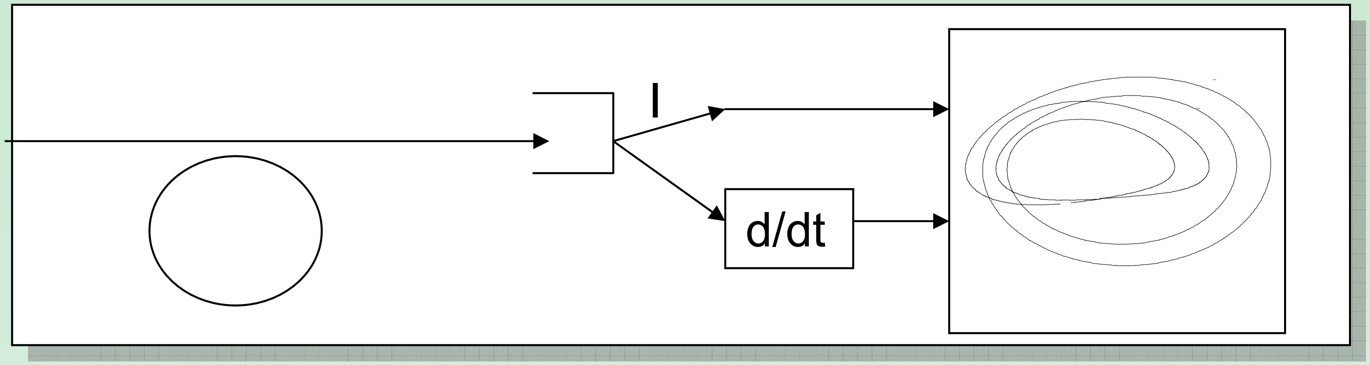


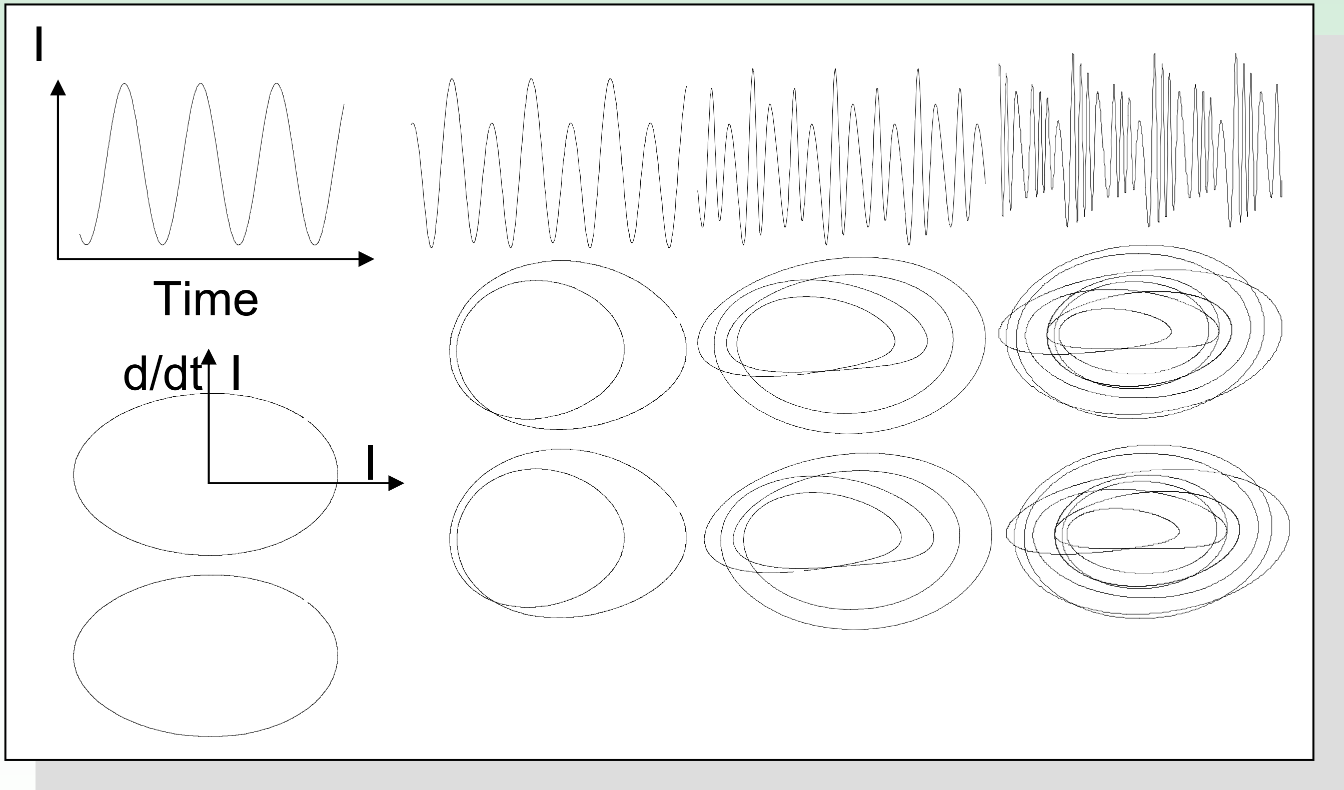
Deterministic Chaos: a system is chaotic if its trajectory through state space is sensitively dependent on the initial conditions, that is, if unobservably <u>small causes can produce large effects</u>.

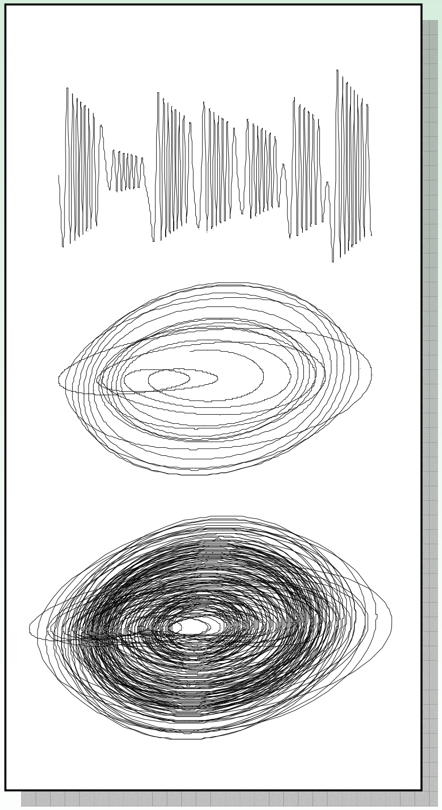


Under investigation

Phase space



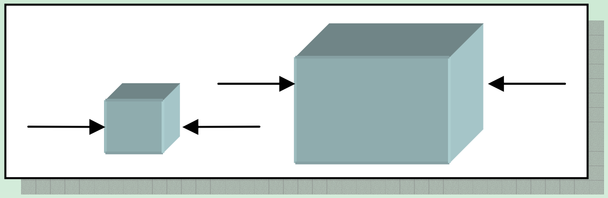




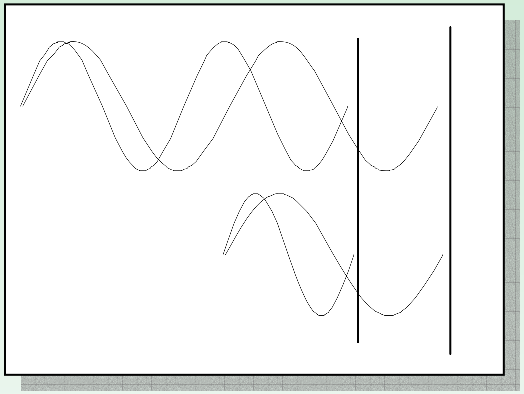
Why don’t we see radiation pressure effects in large resonators?

Down scaling = sensitive to radiation pressure

1. Smaller objects flex more for the same force. (Spring constant, k=E Area/Length∝Length,)



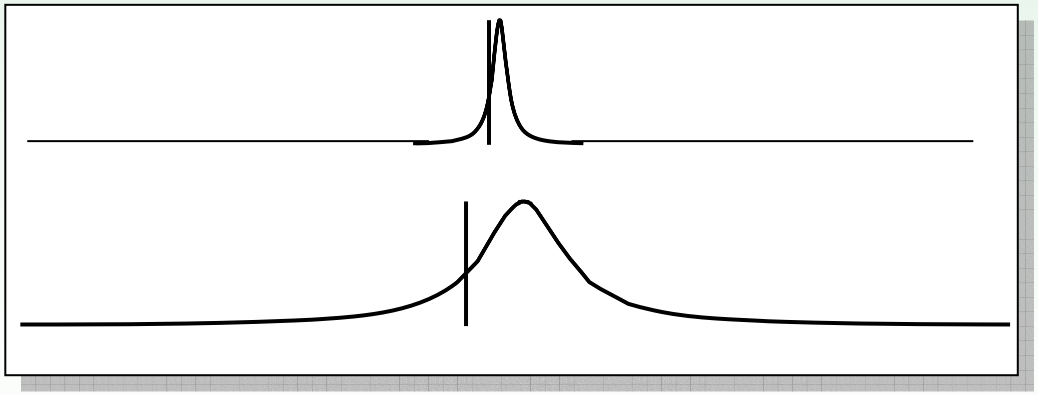
2. Smaller cavity resonance will detune more for the same flex. (change in size is absorbed by a smaller number of waves)



3. Low optical loss → Narrow bandwidth

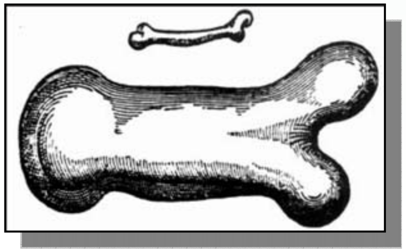
Same drift will create larger optical effect

Radiation pressure are expected in small resonators with low losses

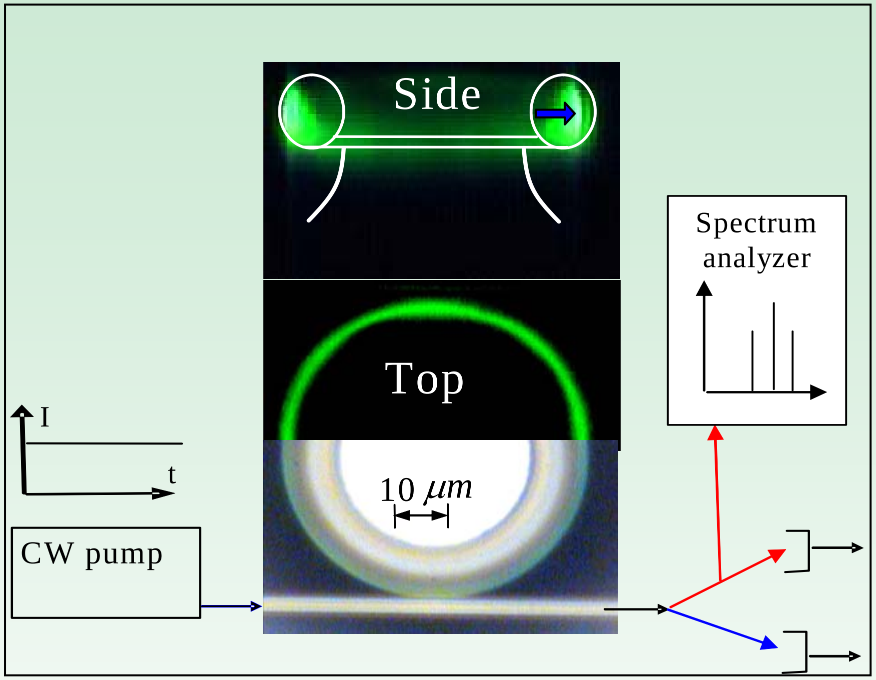


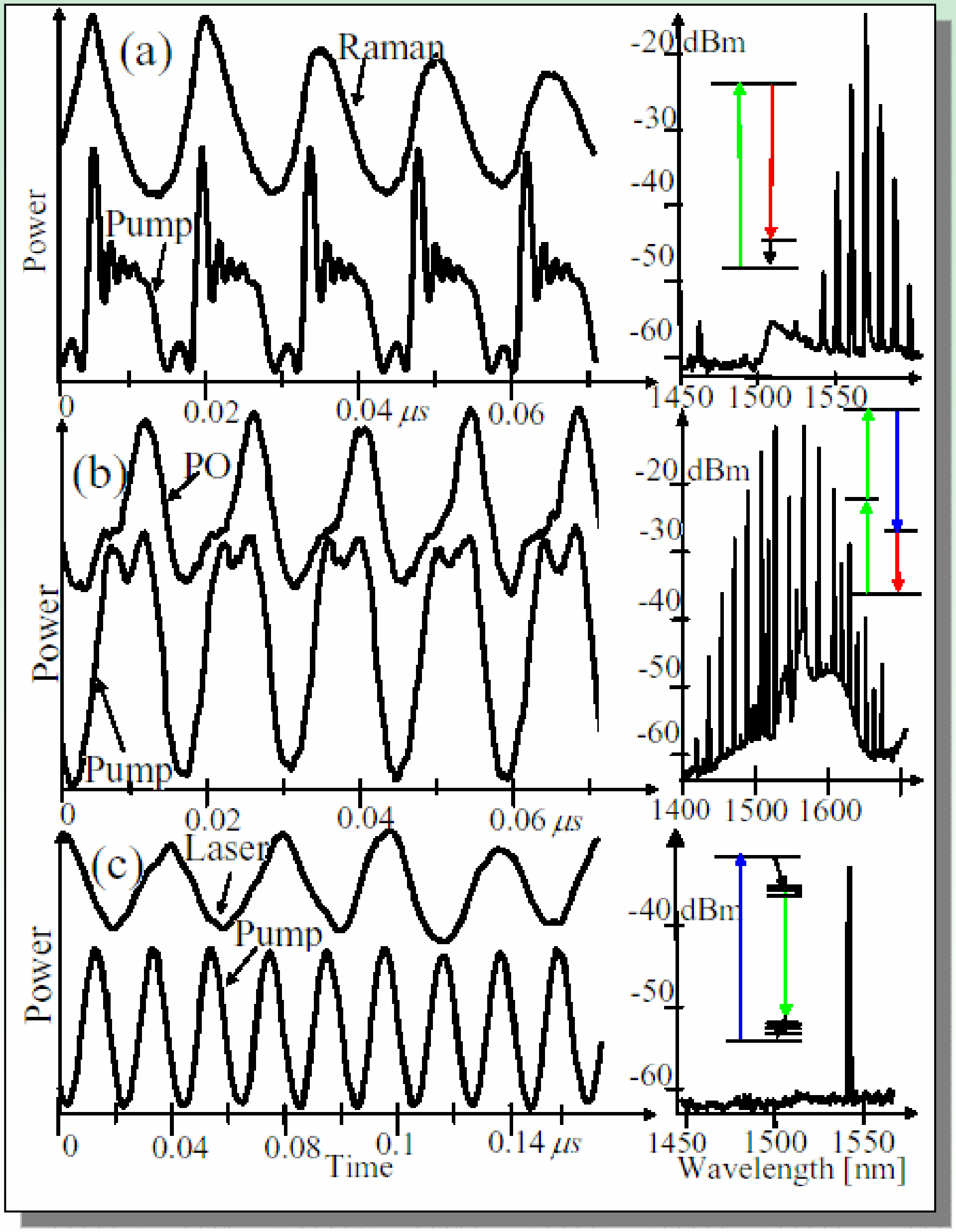
Smaller objects in nature are not just scaled replicas of similar big objects. (Galileo, Dialogue Concerning Two New Sciences, 1638)

Experimental demonstration, when cavity is small enough radiation pressure effects are the first to appear



RP induced vibration with other effects



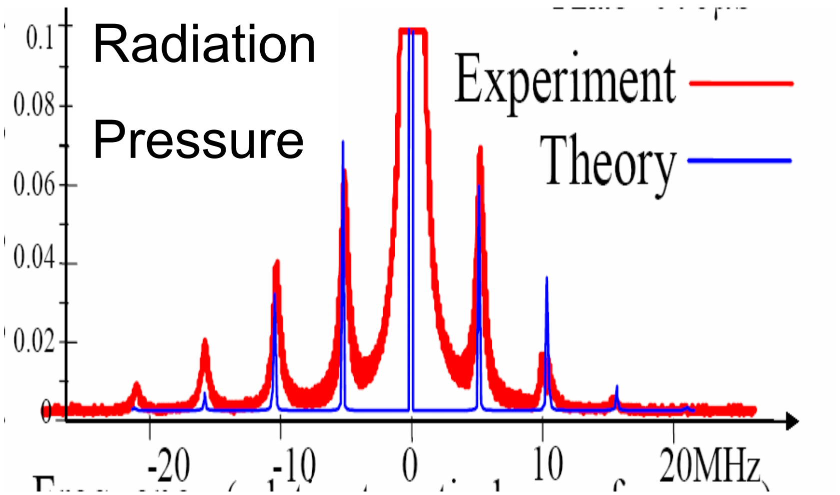


scattering from structure vibrations was observed to coexist together with the traditional Raman lasing originates from molecular vibrations.

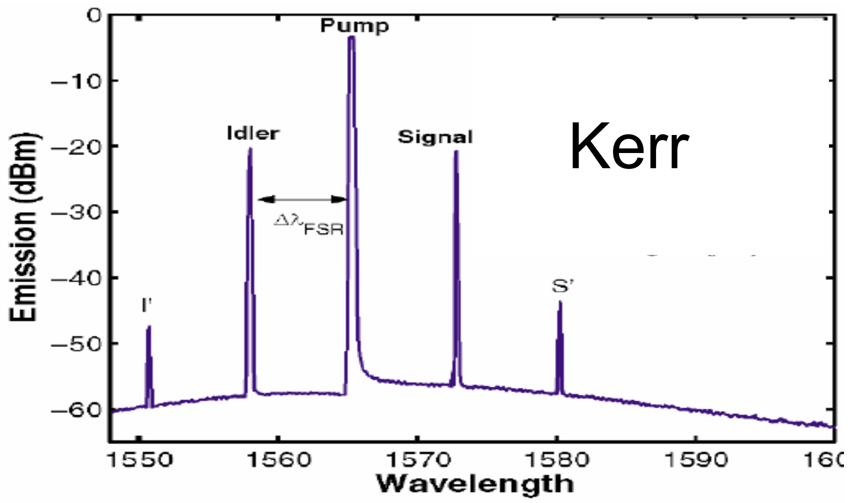
(When cavity is small enough, when pump is properly detuned).

<u>Radiation pressure parametric oscillations</u>

10 MHz idler to signal

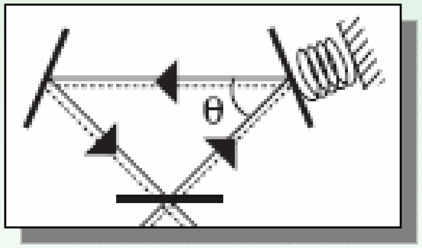


<u>Kerr parametric oscillations</u>
THz idler to signal



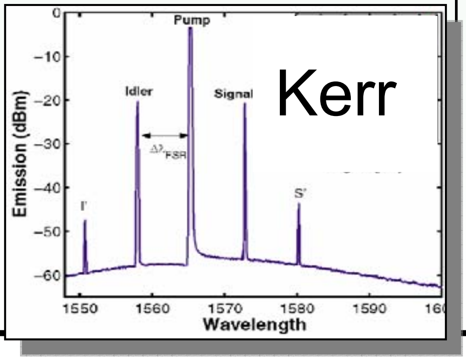
T. J. Kippenberg, S. M. Spillane,and K. J. Vahala, Phys. Rev. Lett. **93**, 083904 (2004.)

<table>
<tr><th></th><th>Kerr parametric oscillations</th><th>Radiation pressure parametric oscillations</th></tr>
<tr><td>Optical path length, nL</td><td>n(I) Increases with intensity</td><td>L(I) Increases with intensity</td></tr>
<tr><td>Squeezing</td><td colspan="2">L. Hilico et. al. “Squeezing with χ^3 materials” Appl. Phys. B. 55, 202 (1992)</td></tr>
<tr><td>Entangled pair of photons</td><td>Known in Kerr parametric oscillators.</td><td>•Giovannetti (ref below)

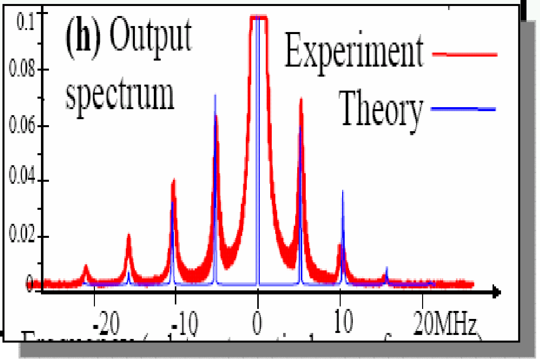


</td></tr>
<tr><td>Idler to signal distance is</td><td>Optical cavity F.S.R.

THz



</td><td>Mechanical eigenfrequency 10MHZ



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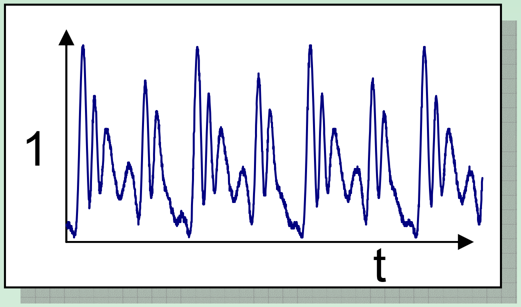
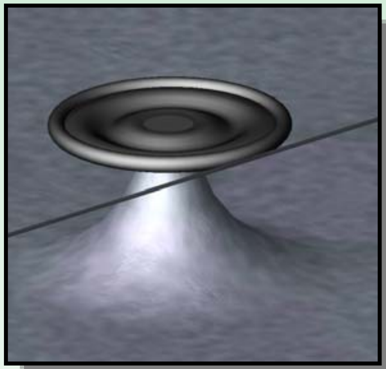
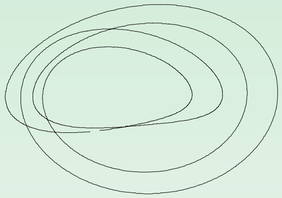
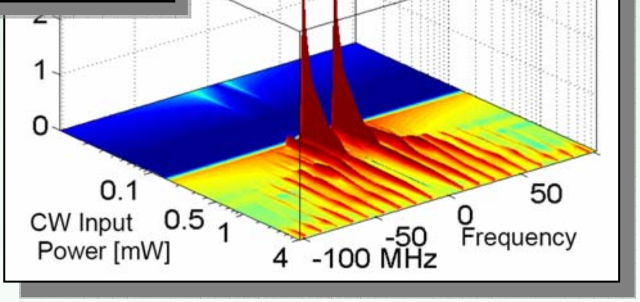
Conclusions

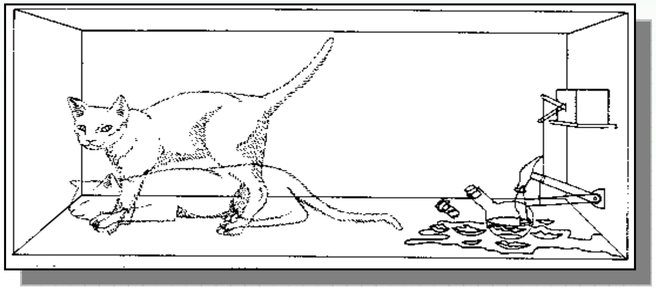


- Coupling between optical and mechanical resonances despite of the 8 orders of magnitude frequency difference.
- Oscillation is regenerative, exhibiting classic threshold behavior and requiring no external temporal modulation of the pump wave.
- When cavity is small enough, radiation pressure threshold is lower than Other nonlinearities (Raman, Kerr parametric oscillations and erbium lasing)
- No photons are lost when pushing the mirror is attractive for quantum optics (Q0~10^8, Qa~10^3, fiber coupled).

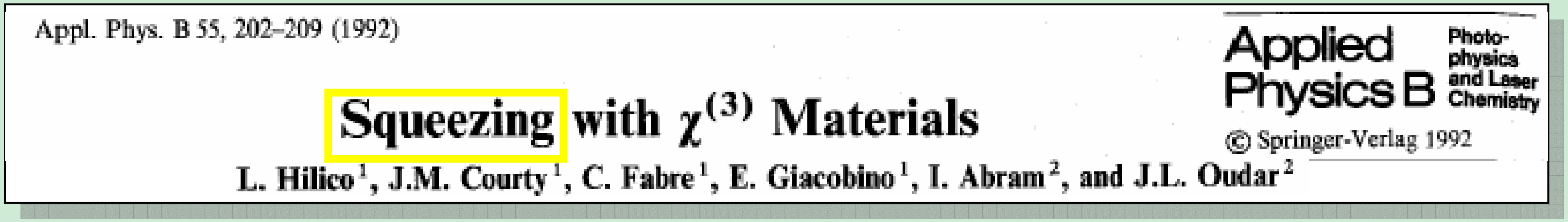








Who is interested in radiation pressure?

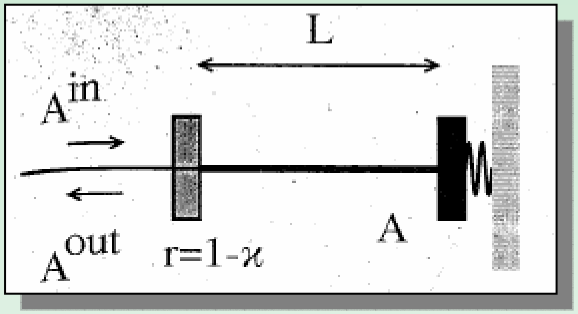


Appl. Phys. B 55, 202–209 (1992)

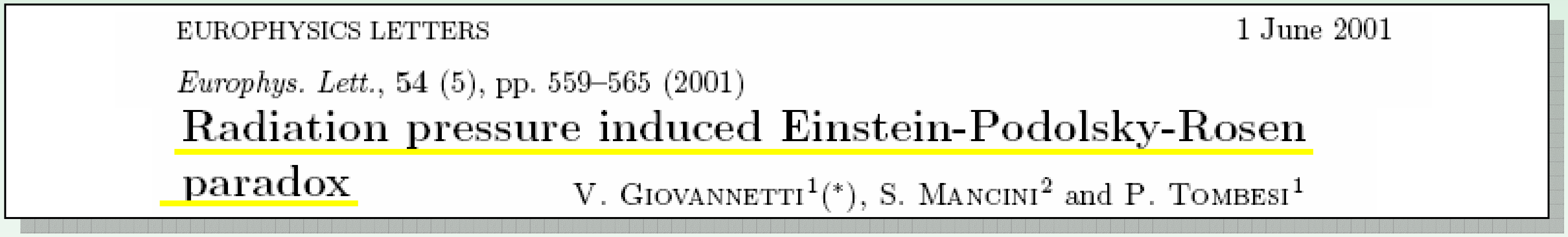
Applied Physics B Photo-physics and Laser Chemistry

Squeezing with $\chi^{(3)}$ Materials

L. Hilico[1], J.M. Courty[1], C. Fabre[1], E. Giacobino[1], I. Abram[2], and J.L. Oudar[2]



- Radiation pressure ~ Kerr nonlinearity.
- Path length increases with intensity
- Both enable squeezing



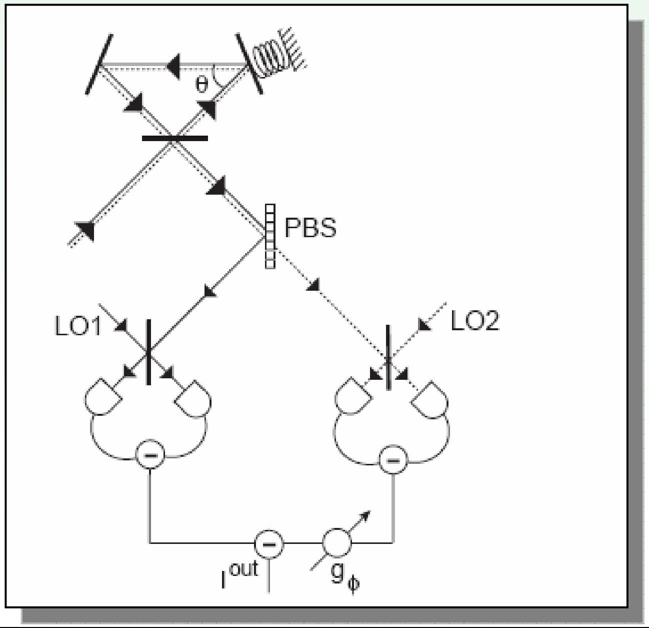
EUROPHYSICS LETTERS 1 June 2001

Europhys. Lett., 54 (5), pp. 559–565 (2001)

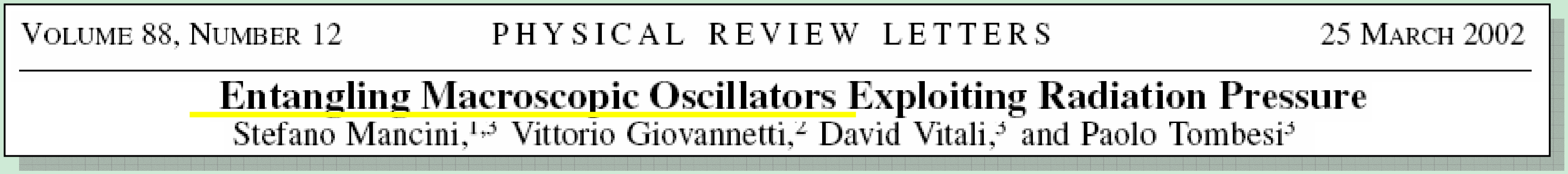
Radiation pressure induced Einstein-Podolsky-Rosen paradox

V. GIOVANNETTI[1](*), S. MANCINI[2] and P. TOMBESI[1]

- Entanglement



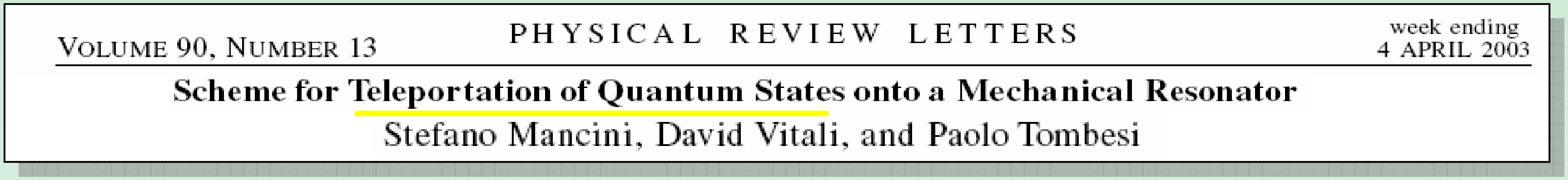
- Radiation pressure as an ambassador of quantum properties from photons to the macroscopic world



VOLUME 88, NUMBER 12 PHYSICAL REVIEW LETTERS 25 MARCH 2002

Entangling Macroscopic Oscillators Exploiting Radiation Pressure

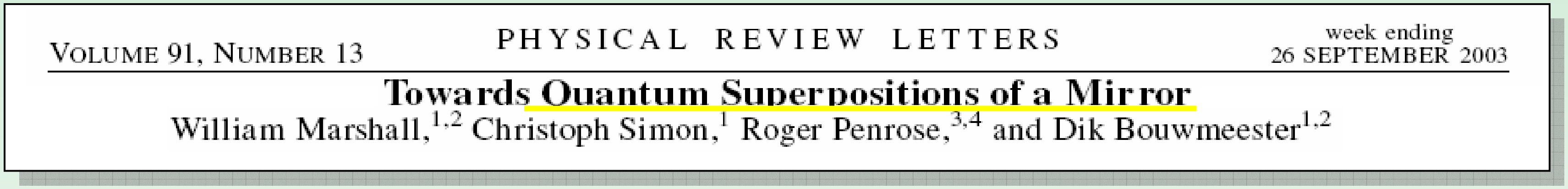
Stefano Mancini,[1,3] Vittorio Giovannetti,[2] David Vitali,[3] and Paolo Tombesi[3]



VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Scheme for Teleportation of Quantum States onto a Mechanical Resonator

Stefano Mancini, David Vitali, and Paolo Tombesi



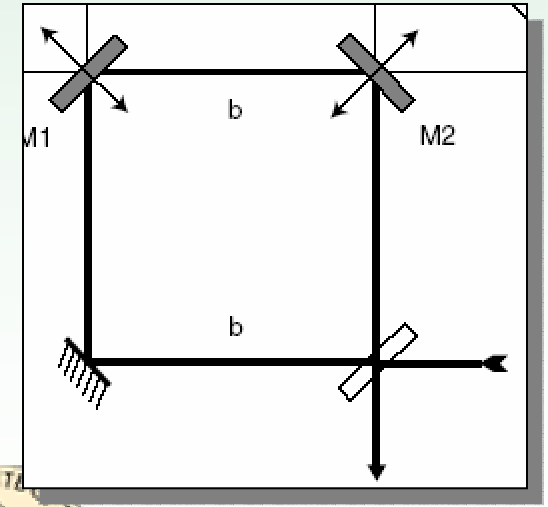
VOLUME 91, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2003

Towards Quantum Superpositions of a Mirror

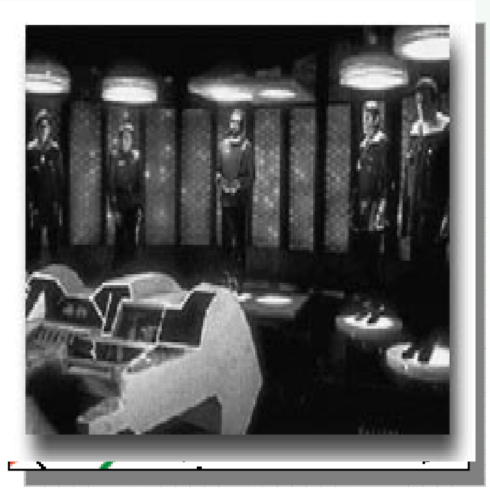
William Marshall,[1,2] Christoph Simon,[1] Roger Penrose,[3,4] and Dik Bouwmeester[1,2]

Macroscopic objects:

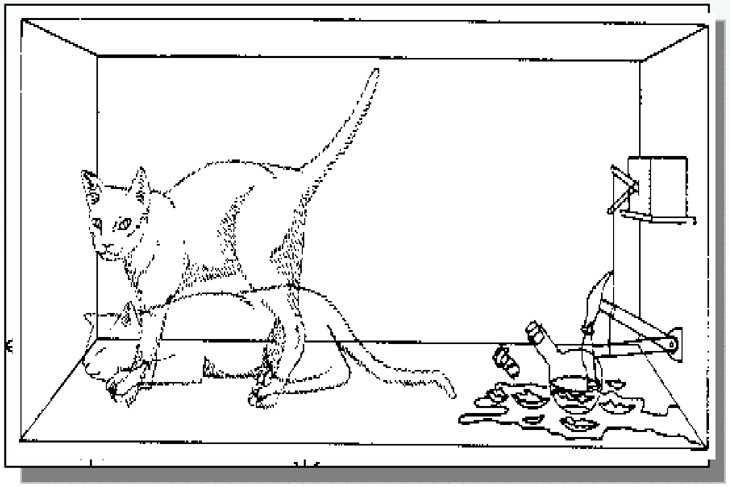
Entangled



Teletransported



Superposition of



Peer review publications on this topic:

Carmon, T., Rokhsari, H., Yang, L., Kippenberg, T.J. & Vahala, K.J.
"Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode".
Physical Review Letters 94, 223902 (2005).

Rokhsari, H., Kippenberg, T.J., Carmon, T. & Vahala, K.J.
"Radiation-pressure-driven micro-mechanical oscillator".
Optics Express *13, 5293 (2005).*

Kippenberg, T.J., Rokhsari, H., Carmon, T., Scherer, A. & Vahala, K.J
"Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity".
Physical Review Letters *95, 033901 (2005).*

Publications are online at: http://www.its.caltech.edu/~tal/