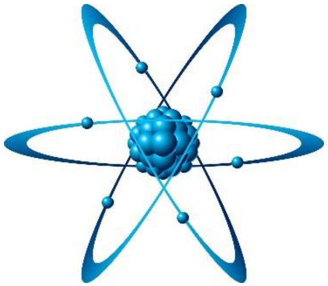
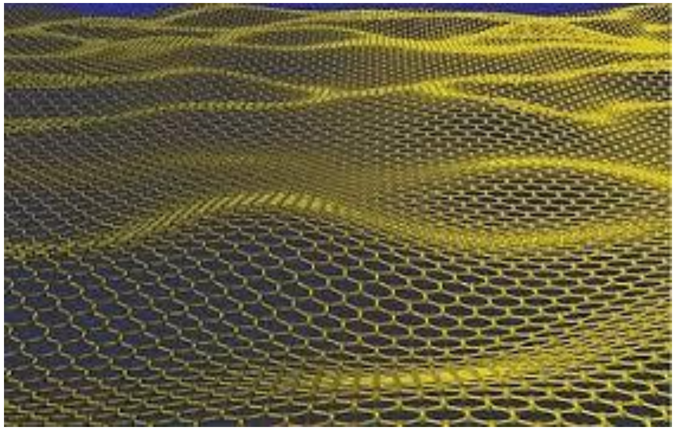
Towards macroscopic superposition of quantum states: atoms and nano-drums





Saikat Ghosh, IIT-Kanpur

Fundamental Problems of Quantum Physics

ICTS, Bangalore

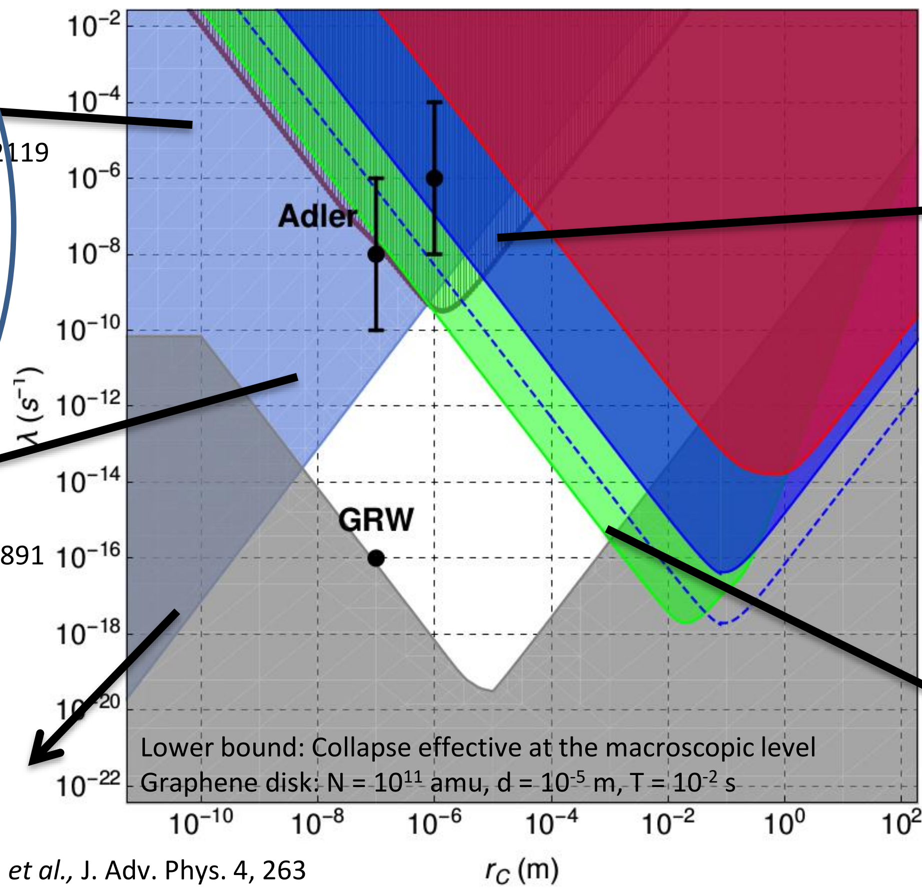
Non-Interferometric Experiments

Cold Atom Gas
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)

M = 87 amu
T = 30 s

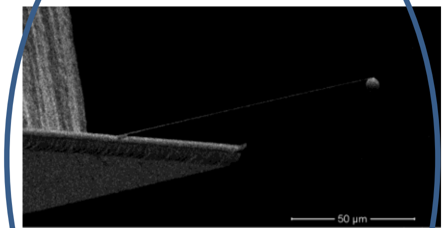
Cold Atom Gas
M. Bilardello *et al.,* ArXiv 1605.01891

M = 87 amu
T = 1 s



X-Ray
C. Curceanu *et al.,* J. Adv. Phys. 4, 263 (2015).

M = 1 Kg
T = days / months



Cantilever
A. Vinante *et al.,* Phys. Rev. Lett. 116, 090402 (2016)

M = 10^{14} amu
T = ∞

Gravitational wave detectors
M. Carlesso *et al.,* ArXiv 1606.04581

M = 10^{30} amu
T = ∞

Updated version of: S.L. Adler and A. Bassi:, *Science* 325, 275 (2009)

Towards macroscopic superposition of quantum states: atoms and nano-drums

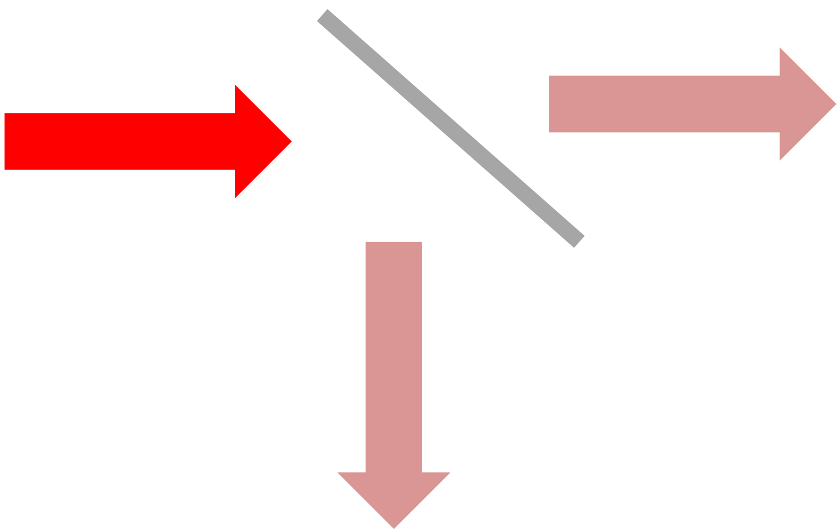
$$|\Psi\rangle = \frac{|N\rangle|0\rangle + e^{iN\varphi}|0\rangle|N\rangle}{\sqrt{2}}$$

Saikat Ghosh, IIT-Kanpur

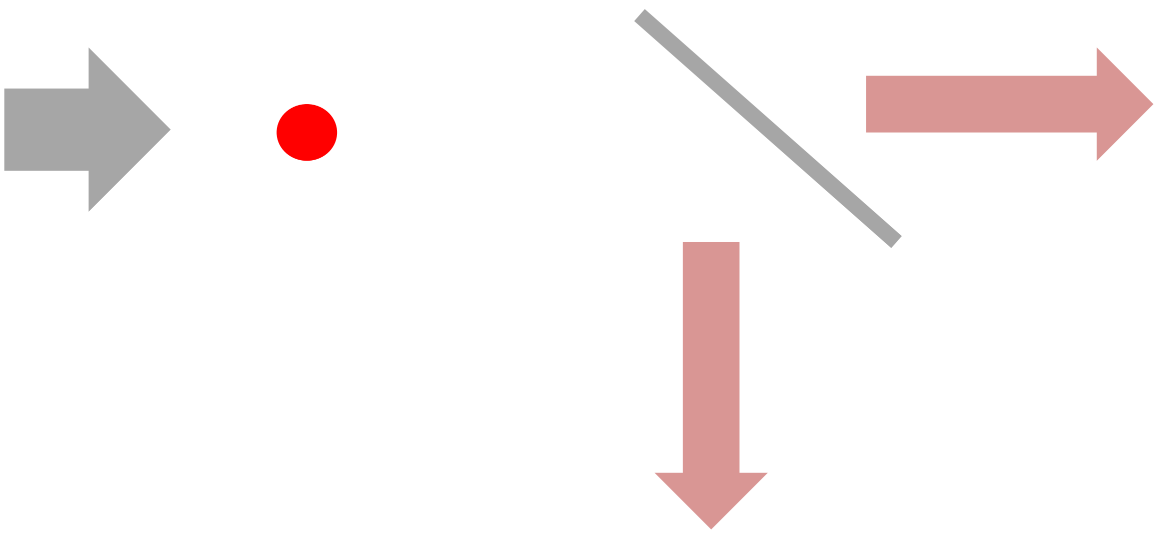
Fundamental Problems of Quantum Physics

ICTS, Bangalore

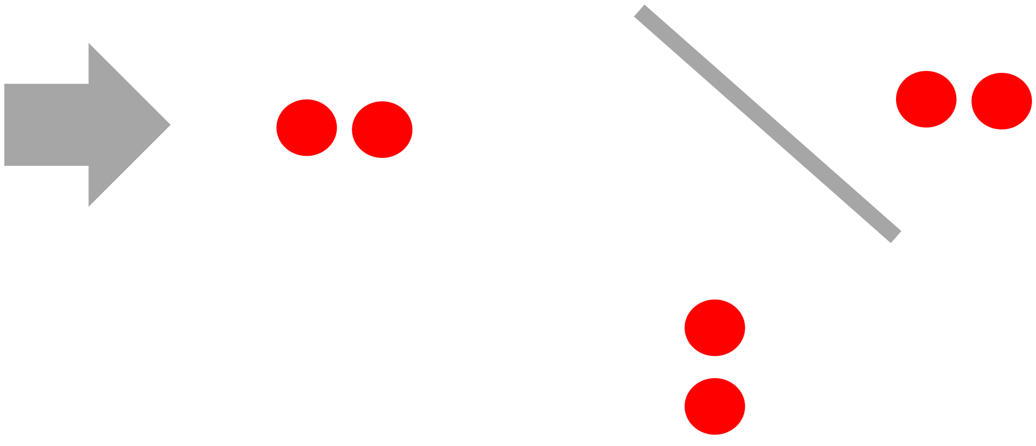
Quiz 1: A photon and a beam splitter



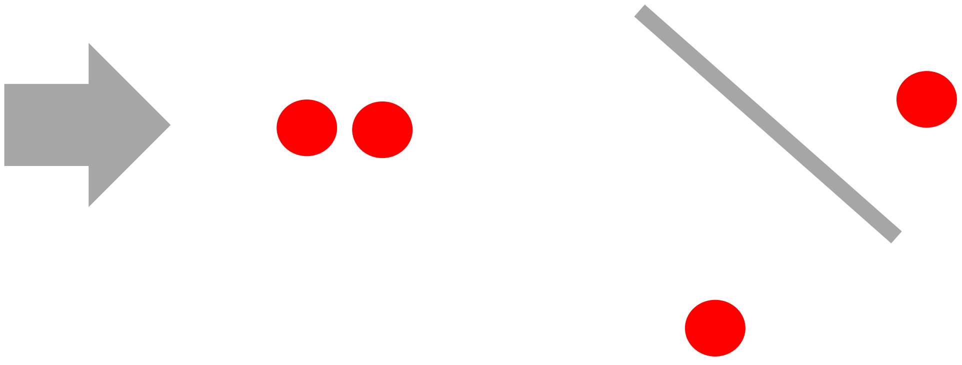
Quiz 1: A photon and a beam splitter



Quiz 1: Two photons and a beam splitter

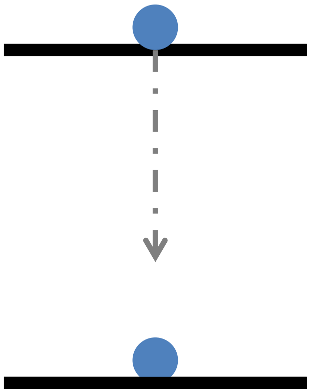


Quiz 1: Two photons and a beam splitter



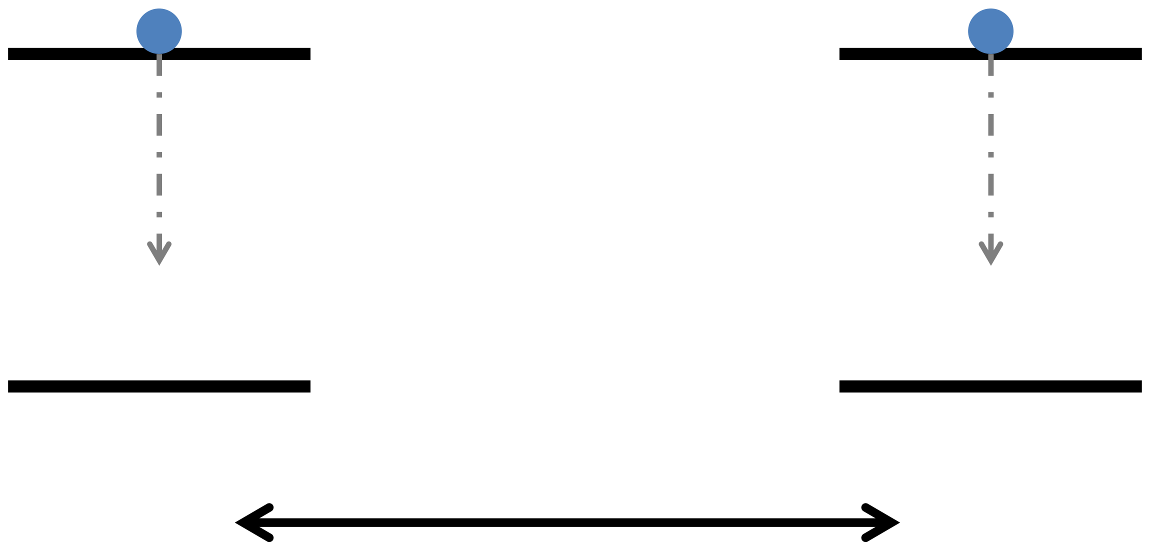
The probability of one photon in each port is zero !

Quiz 2: An atom decaying from an excited state



An atom in an excited state decays in a time scale T

Quiz 2: Two atoms decaying from an excited state



D >> de-Broglie wavelength (say 100 times)

How long does the first atom stay in the excited state?

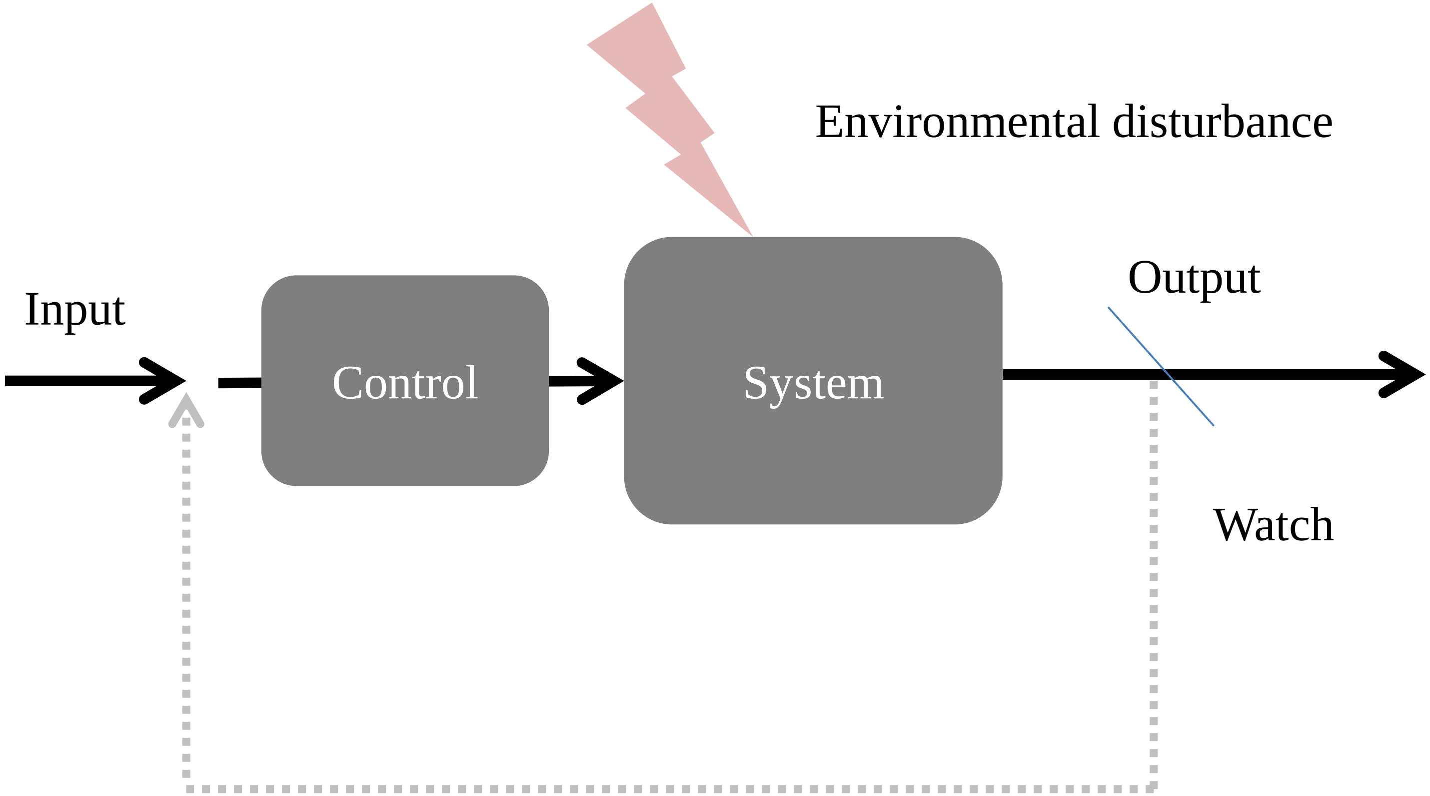
Outline

Superposition of states in single atoms

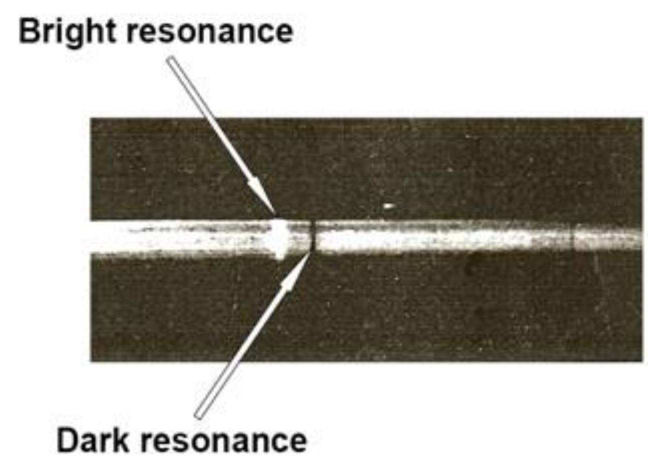
Superposition of states with many atoms: towards macroscopic superpositions

Superposition of states with macroscopic oscillators: graphene nano-drums

Feedback Control(will not cover here)



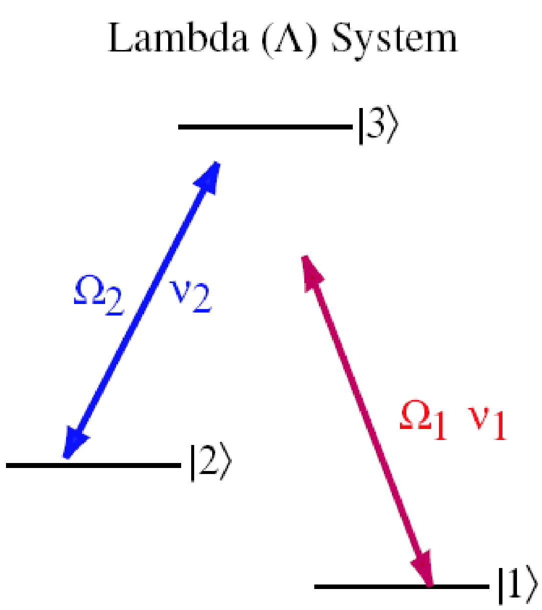
Dark resonances:
A strange observation in 1970's



For polarized light, there were certain spectral lines missing

Cohen-Tannoudji, Phys. Scr. 90 (2015) 088013

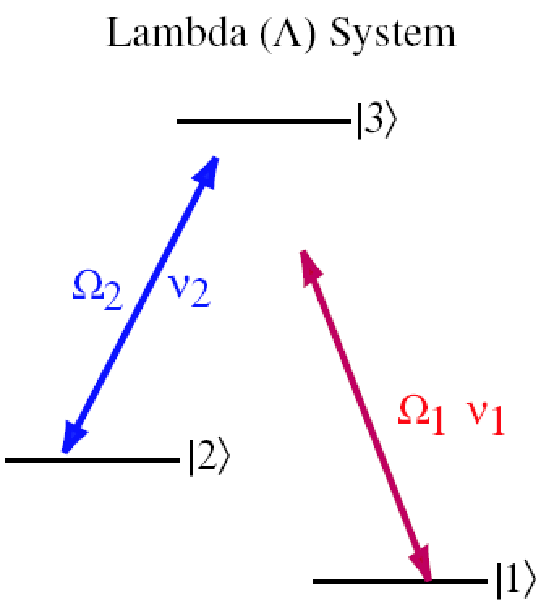
Why missing lines?
Signature of superposition of states



First demonstration in hot atomic vapor, followed by cold atom, single atoms, ions, quantum dots , dye molecules and many more

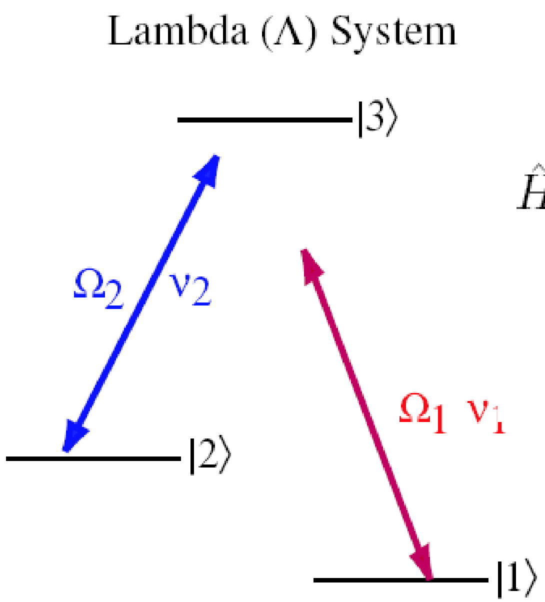
Hammerer K, Sorensen A S and Polzik E S, Rev. Mod. Phys. 82 1041 (2010)
Reiserer A and Rempe G, Rev. Mod. Phys. 87 1379 (2015)

Signature of quantum superposition: Electromagnetically Induced Transparency (EIT)



$$\hat{H}_{\text{eff}} \;=\; -\frac{i\hbar\gamma_3}{2}|3\rangle\langle 3| - (\Omega_1^*|1\rangle\langle 3| + \Omega_2^*|2\rangle\langle 3| + h.c.)$$

Electromagnetically Induced Transparency (EIT)



$$\hat{H}_{\text{eff}} = -\frac{i\hbar\gamma_3}{2}|3\rangle\langle 3| - (\Omega_1^*|1\rangle\langle 3| + \Omega_2^*|2\rangle\langle 3| + h.c.)$$

$$= -\frac{i\hbar\gamma_3}{2}|3\rangle\langle 3| - \underbrace{(\Omega_1^*|1\rangle + \Omega_2^*|2\rangle)}_{|B\rangle}\langle 3| - |3\rangle\underbrace{(\Omega_1\langle 1| + \Omega_2\langle 2|)}_{\langle B|}$$

$$|D\rangle = \frac{\Omega_2|1\rangle - \Omega_1|2\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$

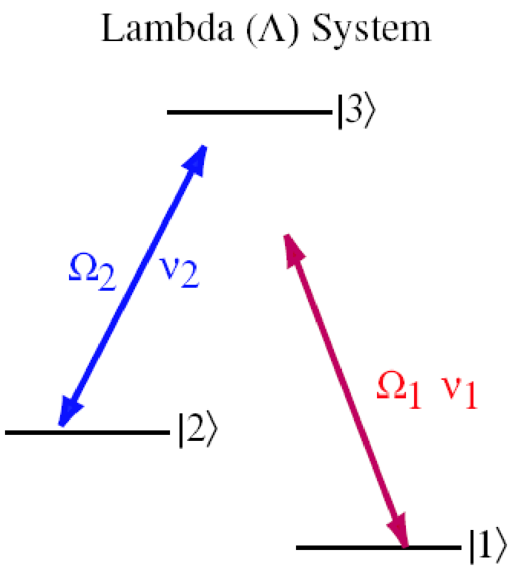
$$\hat{H}_{\text{eff}}|D\rangle = 0.$$

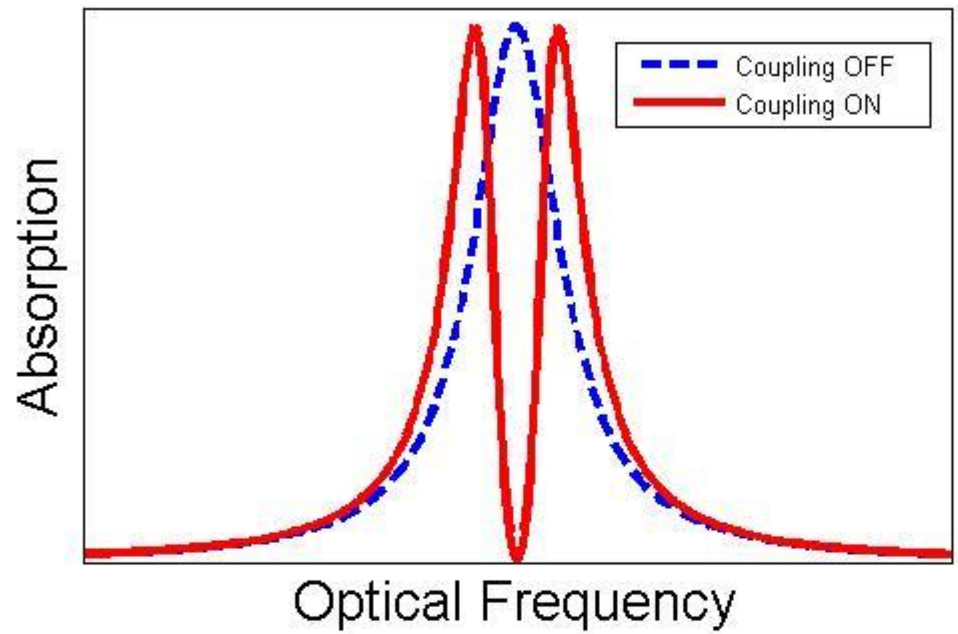
The "Dark State" is completely decoupled from the excited state:
<u>No spontaneously scattered photons</u>

K. J. Boller , A. Imamoglu and S. E. Harris, Phys. Rev. Lett. 66 2593 (1991)

Standard experimental signature of superposition

- A transparency window on an absorption profile



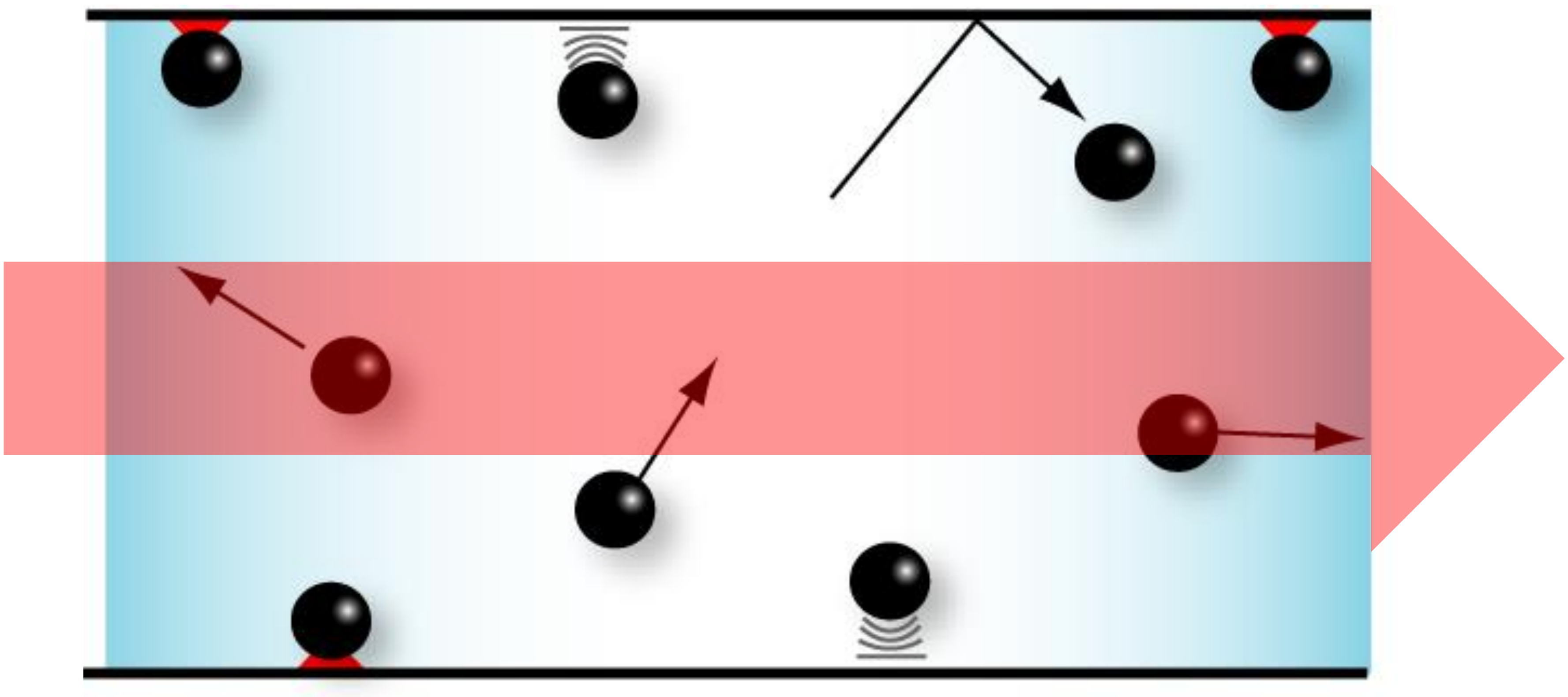


Control knobs

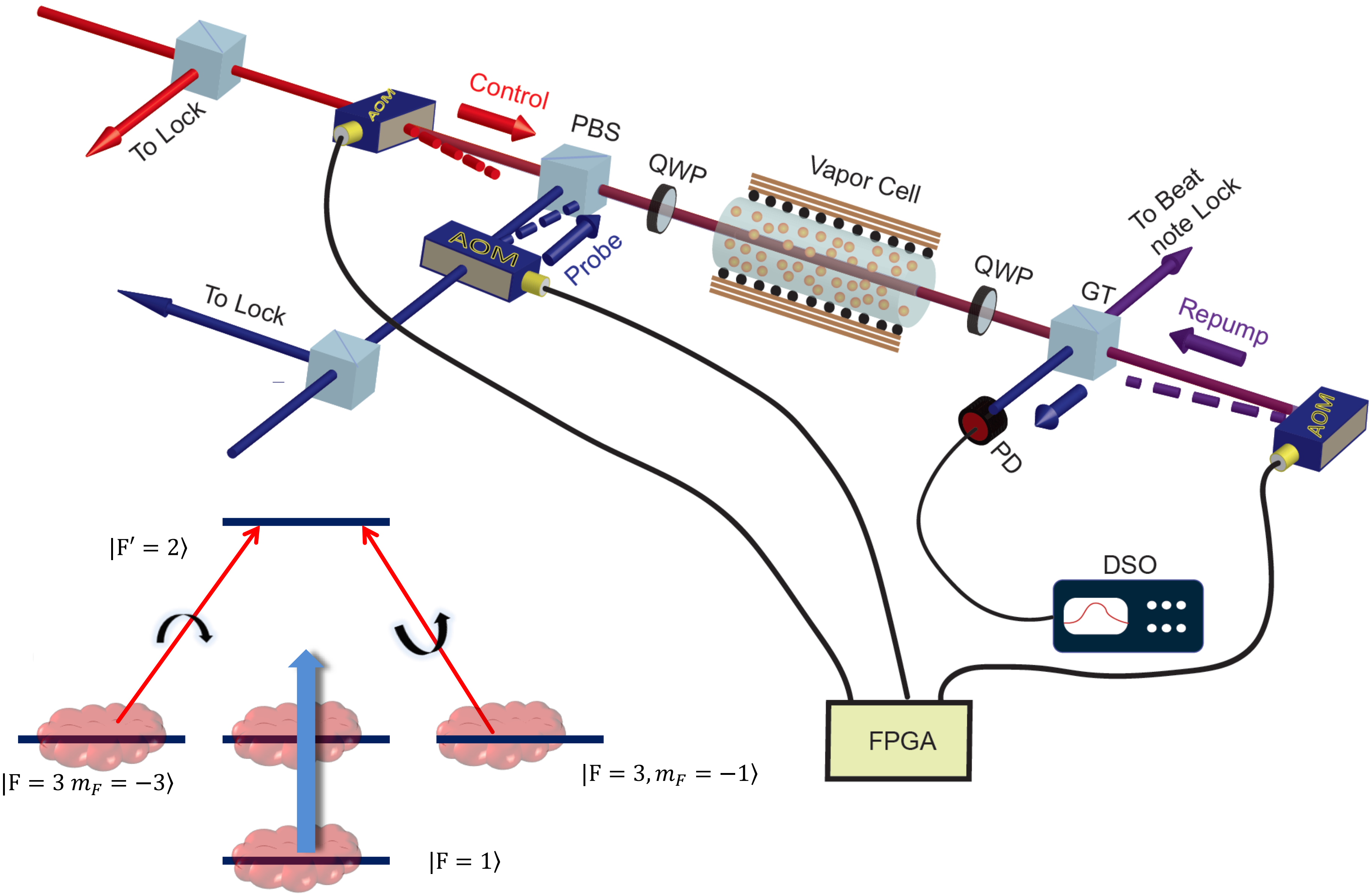
- Controlling superposition:

$$|D\rangle = \frac{\Omega_2|1\rangle - \Omega_1|2\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$

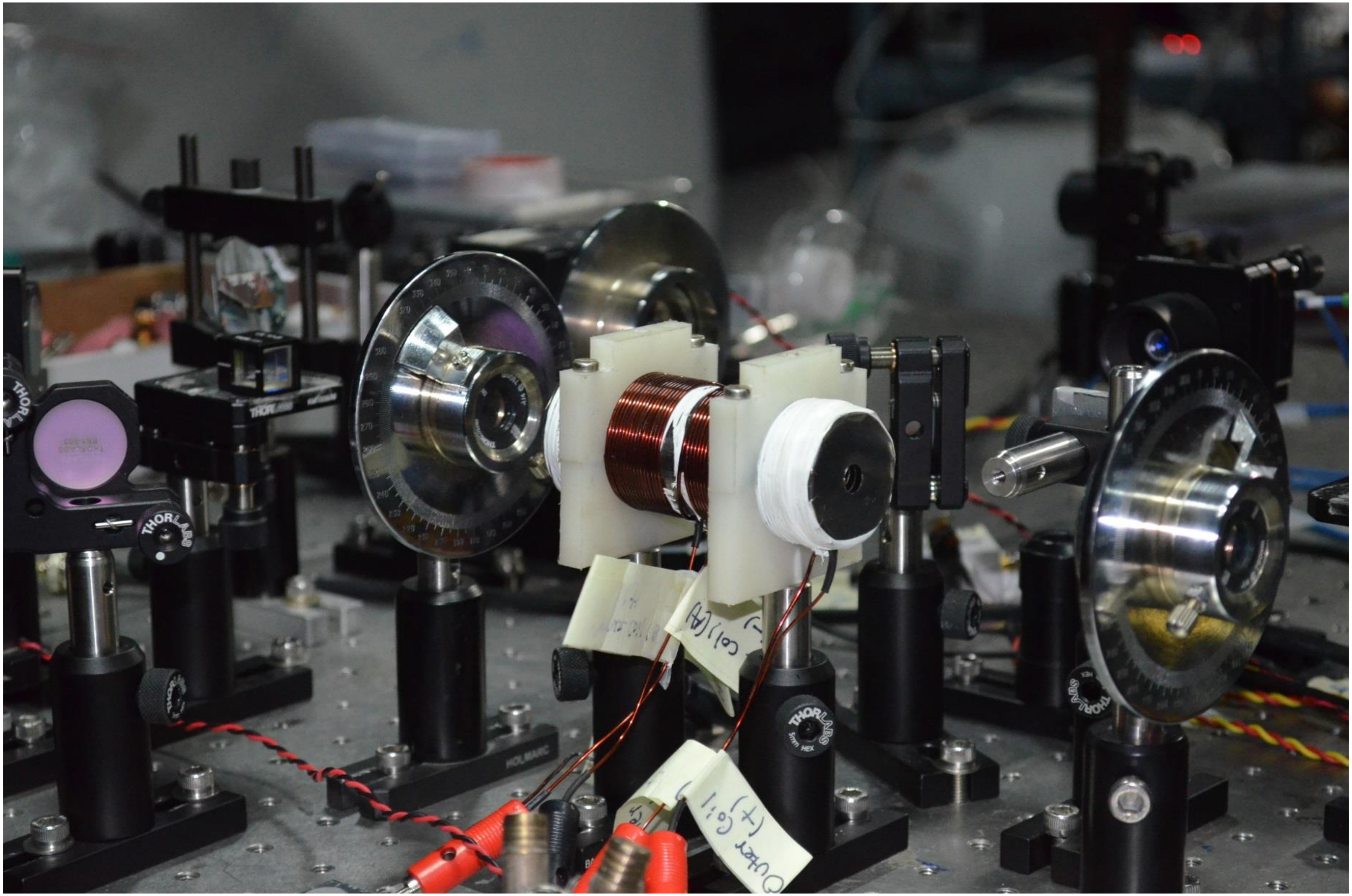
Atomic vapor at room-temperature: what about classical processes?



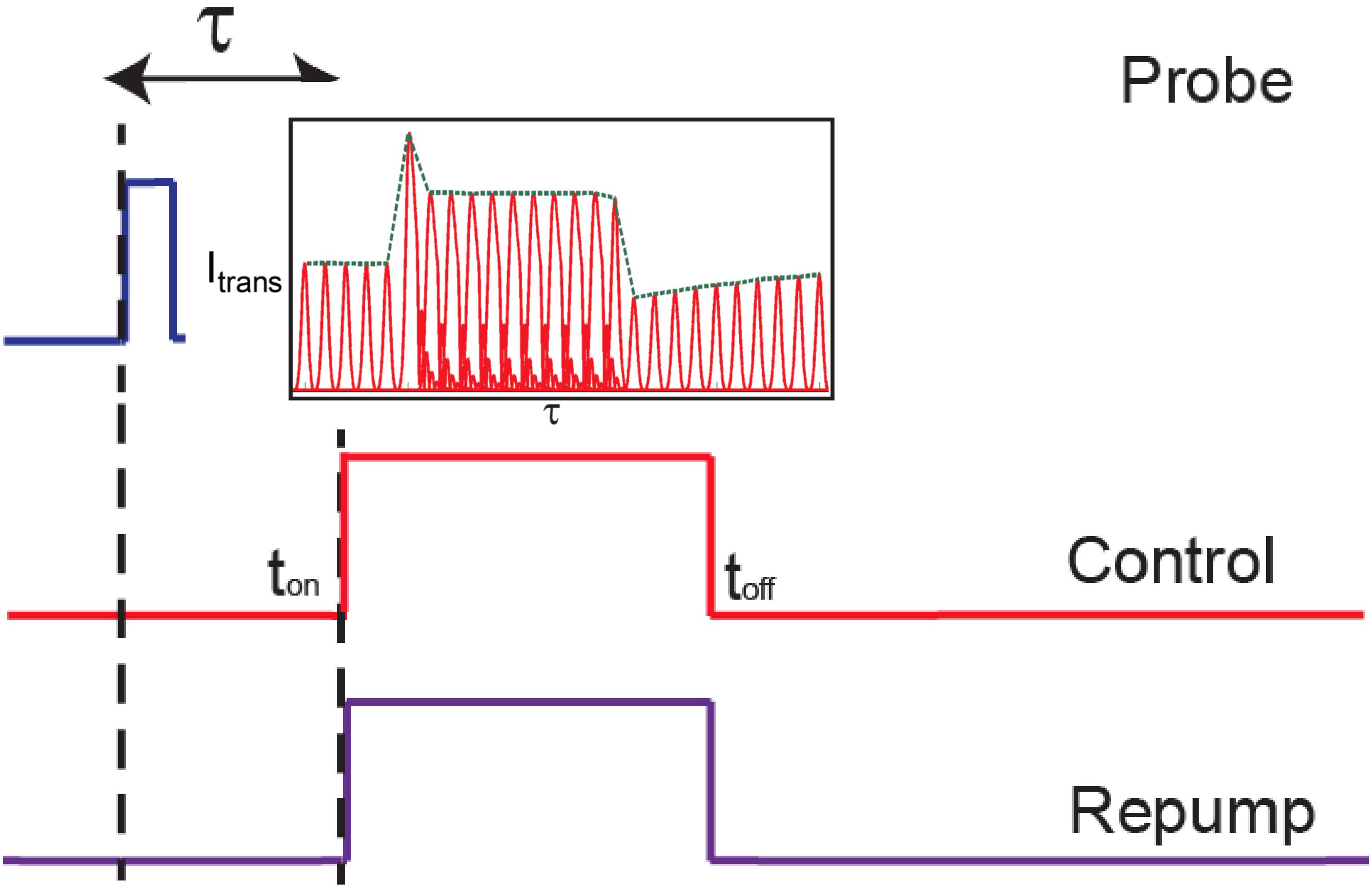
How is the superposition forming? Experiment



Experimental Table

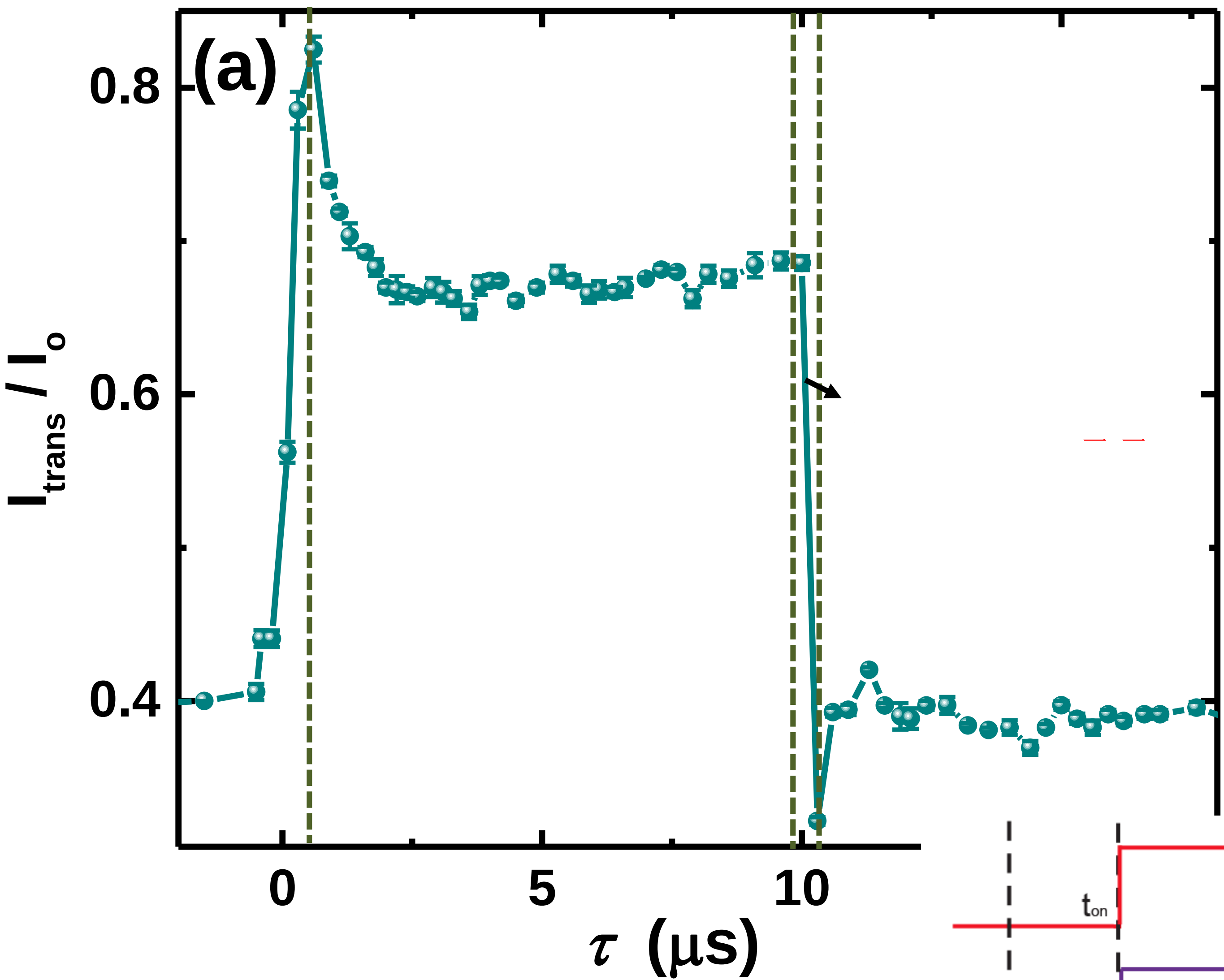


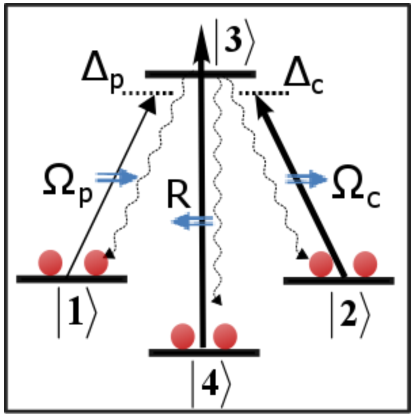
Stroboscopic Probing

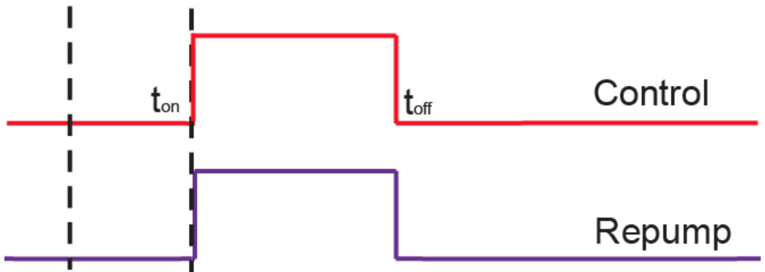


$t_{on} = 0$ $t_{off} = 10\ \mu s$

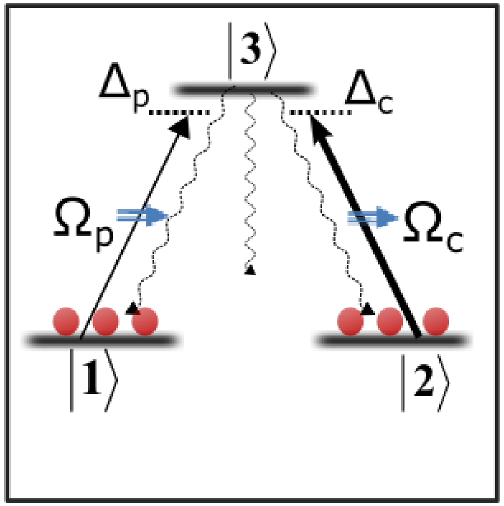
Observation: Closed system

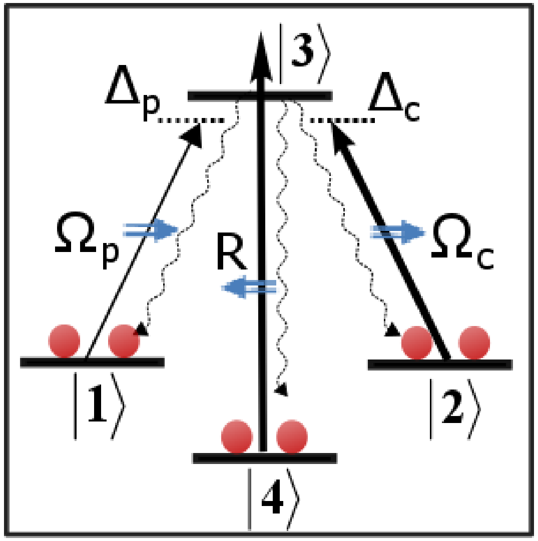






Closed system: Simulations



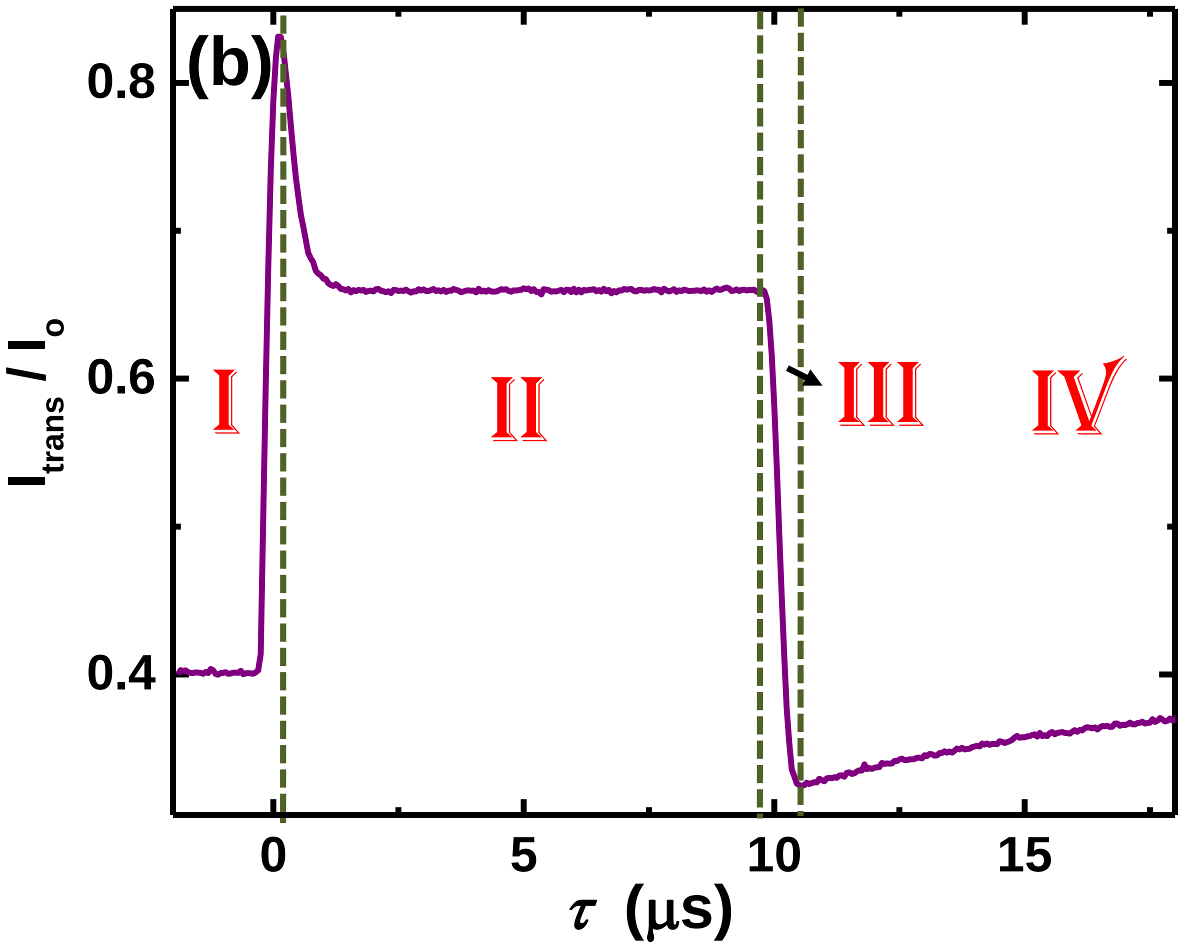


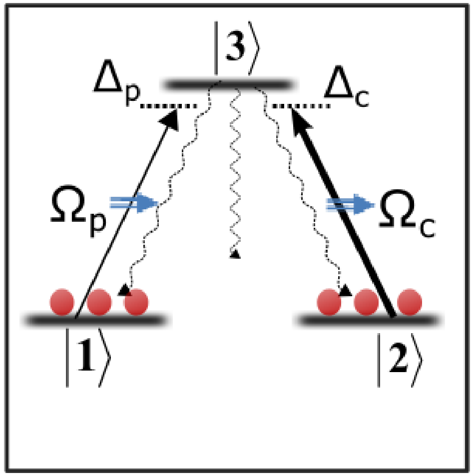
Coupled Maxwell-Bloch equations

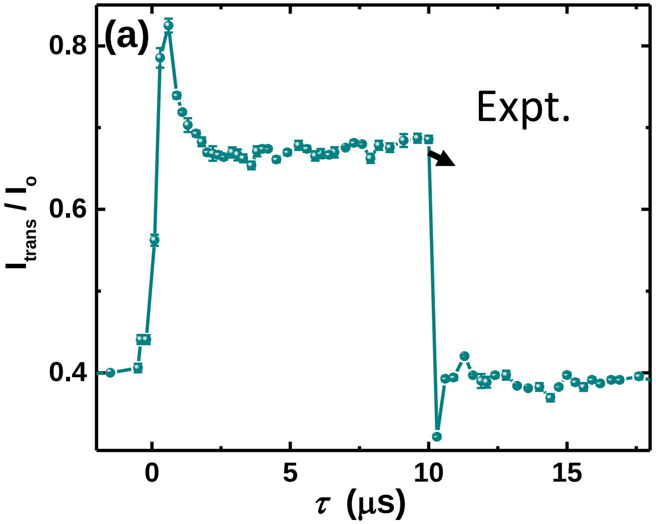
$$\dot{\rho(t)} = -i[\hat{H}, \rho] + \hat{L}(\rho)$$

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\epsilon_0 c^2}\frac{\partial^2 \mathbf{P}}{\partial t^2}$$

Closed system: Numerical experiments



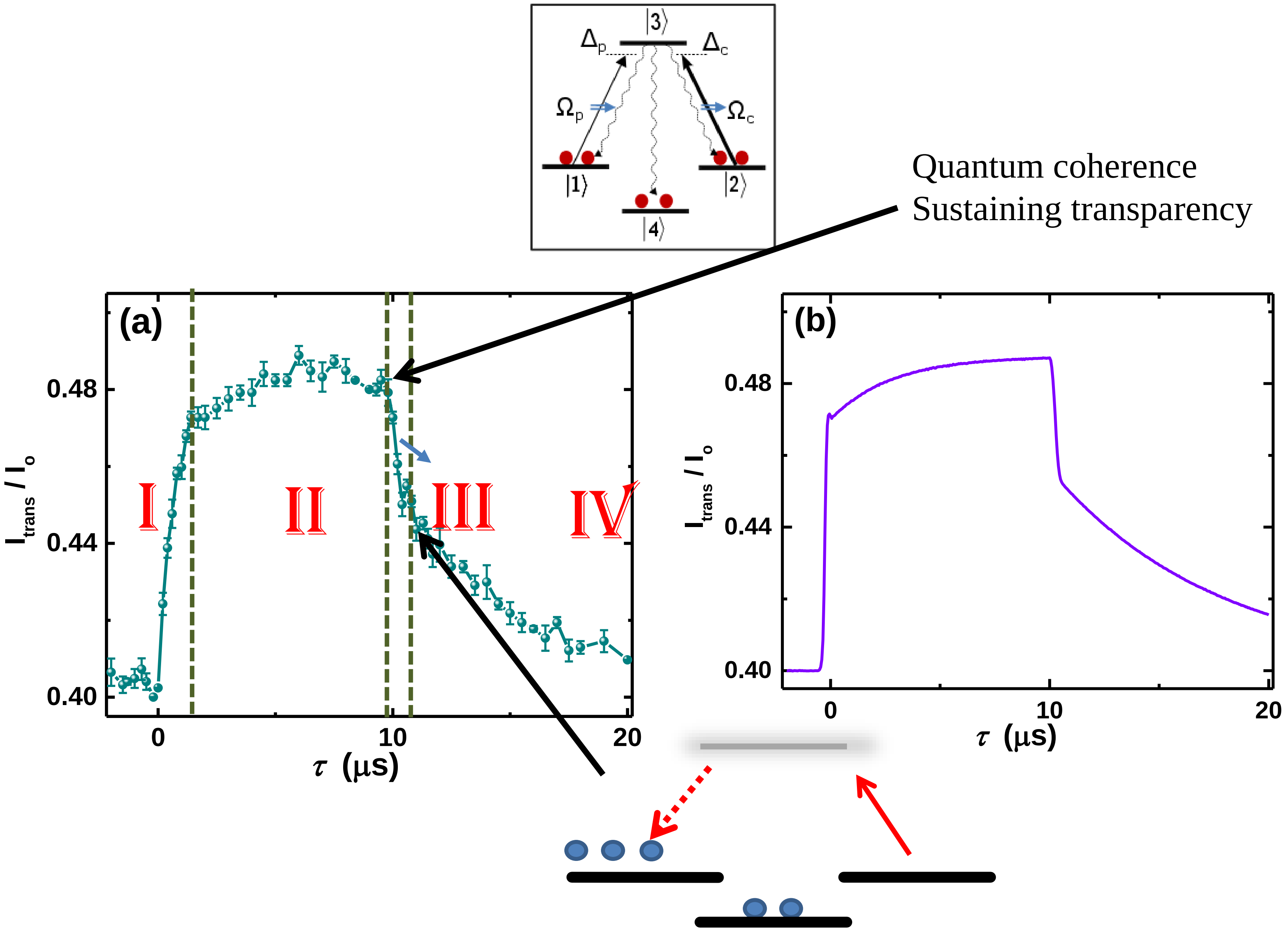




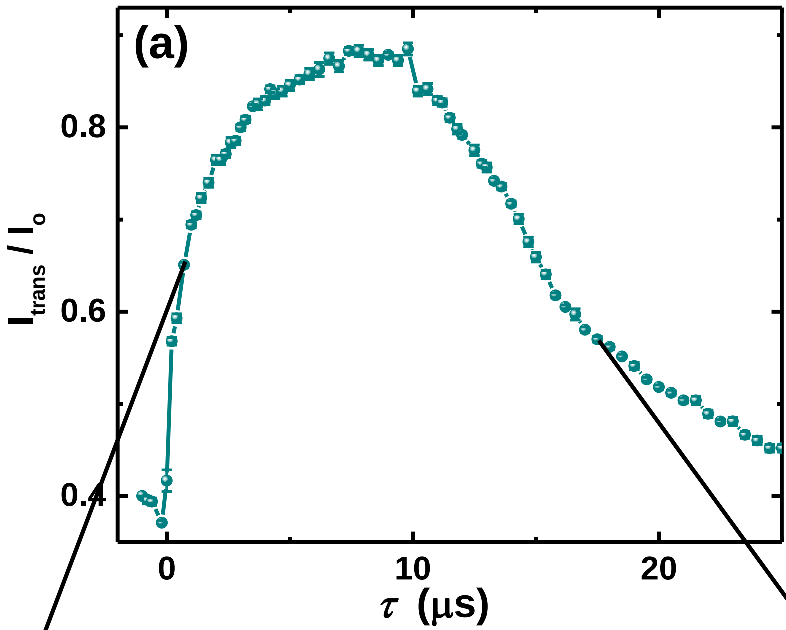
$$\Omega_c = 4.5 \ \gamma_3$$

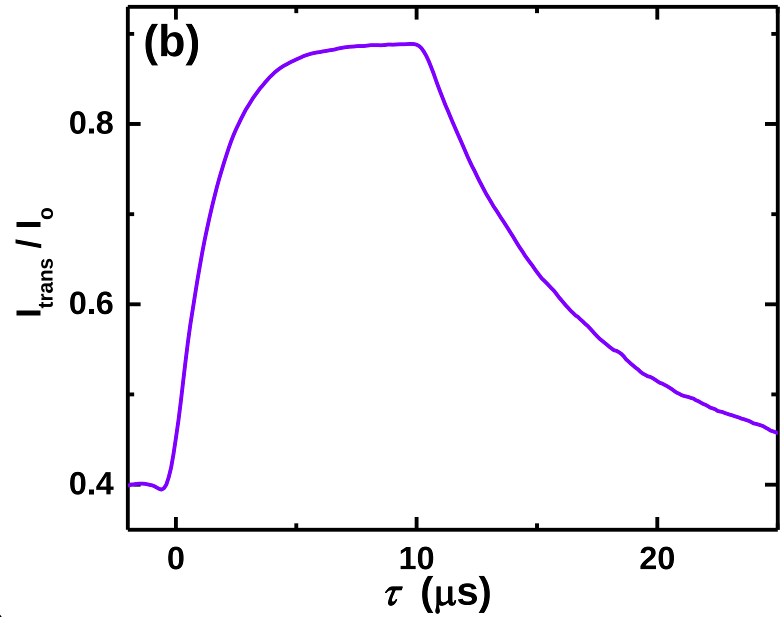
Open quantum system: dynamics

Quantum coherence
Sustaining transparency



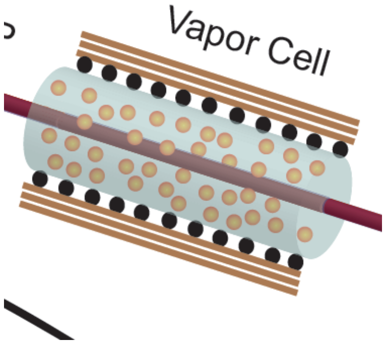
Case C: Incoherent pumping





Incoherent pumping:
Proportional to the square of Rabi frequency

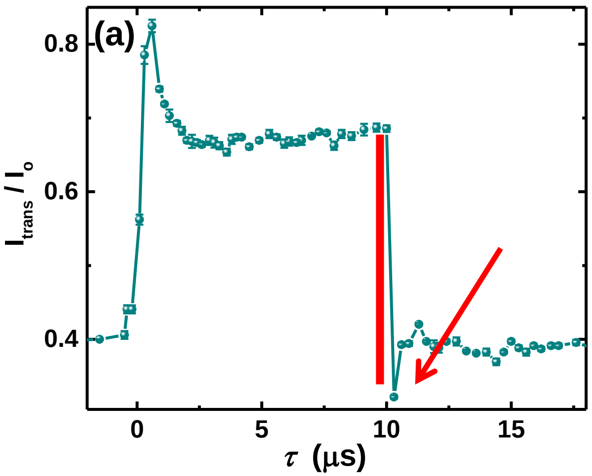
Thermalizaton:Time of flight of atoms through the beam path, moving at 300 m/s



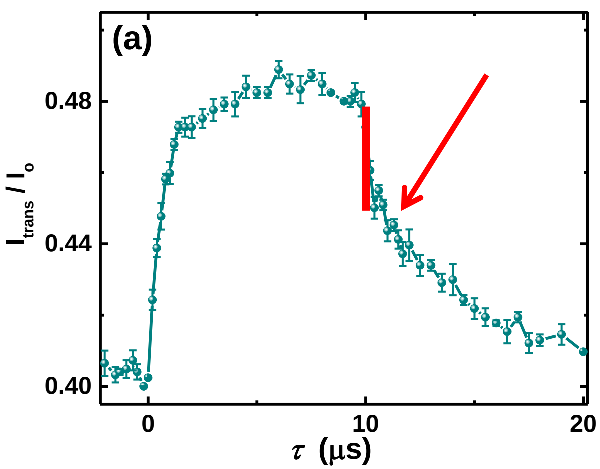
Single atom superpositions: Summary

Testing competing hypothesis: K. Molmer, Phys. Rev. Lett. **114** 040401 (2015)

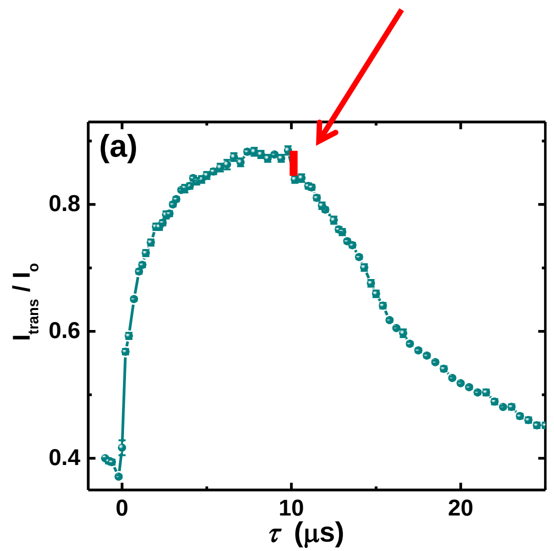
$$\dot{\rho(t)} = -i[\hat{H}, \rho] + \hat{L}(\rho)$$



Closed, coherent



Open, coherent

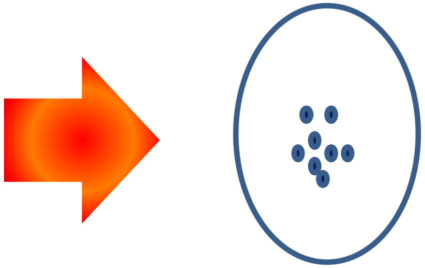


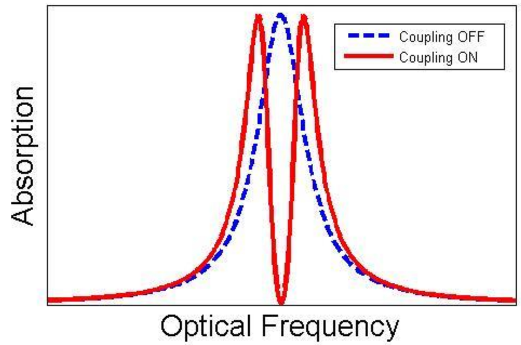
Open, incoherent

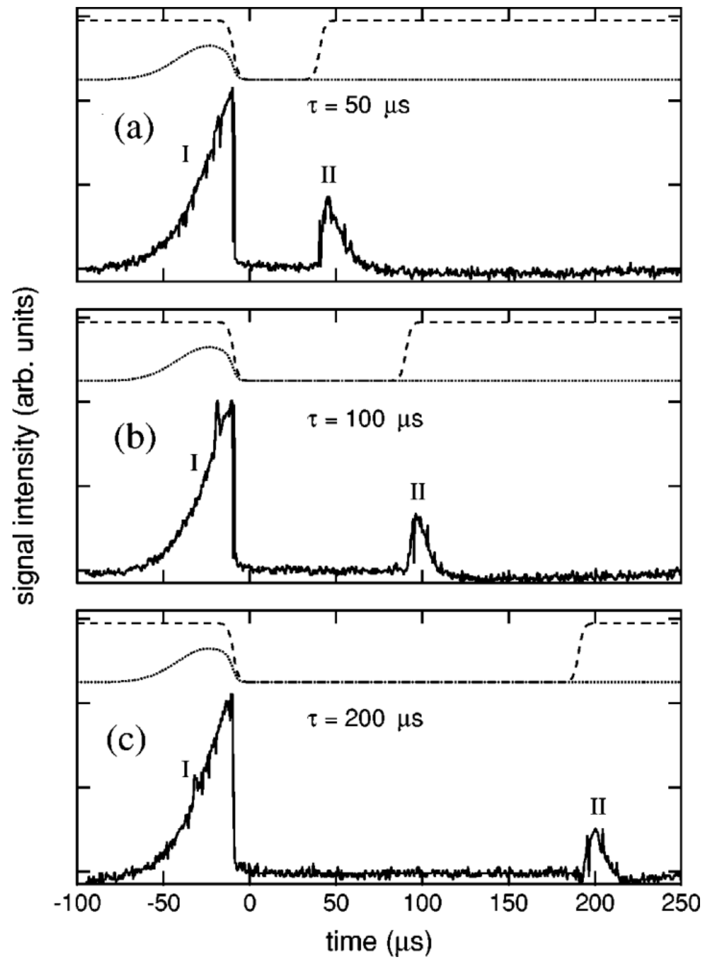
- In short time-scales, the atoms Rabi flop
- Superposition creates Lasing without Inversion(LWI)
- Possibility of improving quantum coherence through repeated Zeno-like measurements

Arif Warsi, Niharika Singh, Arunabh Mukherjee and Saikat Ghosh
New J. Phys. 18, 053022 (2016)

Slow and stopped Light



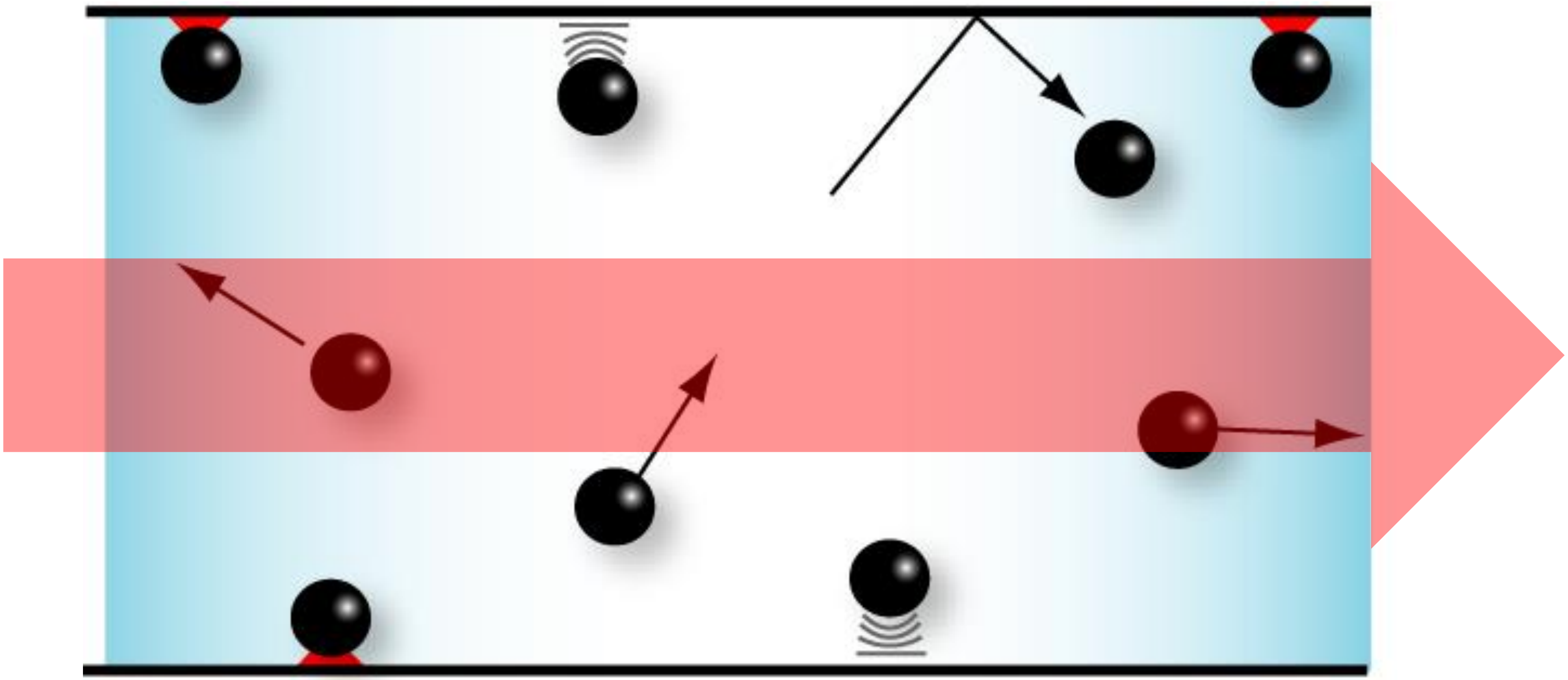




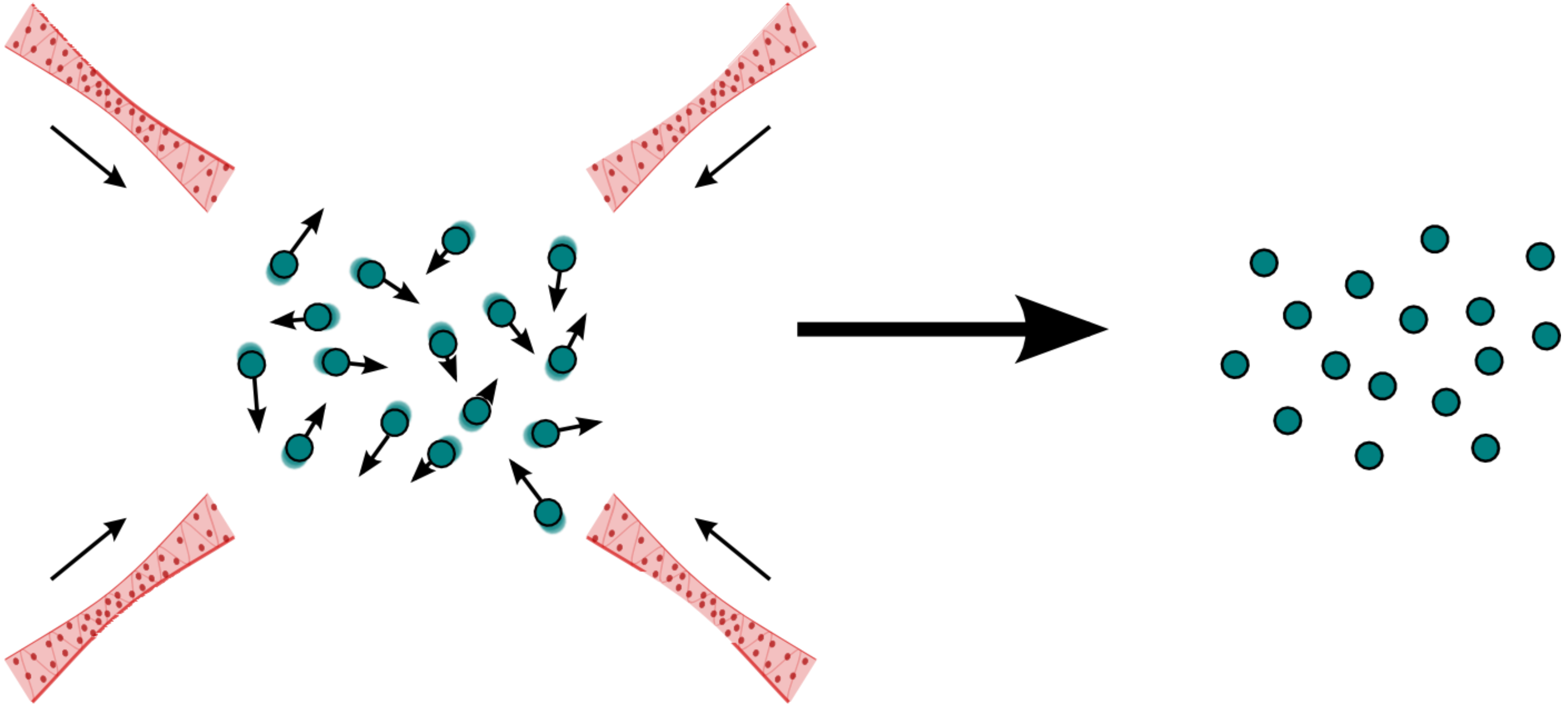
- A ***classical*** pulse with an atomic ensemble: travelling at 17 m/s and then, stopped!

L. V. Hau, *et al.*, *Nature* **397**, 594, (1999);
C. Liu *et al.*, *Nature*, **409**, 490, (2001) D. Philips et al., *Phys. Rev. Lett*. **86**, 783, (2001)
Saikat Ghosh, A. Bhagwat, A. Gaeta *et. al.*, *Phys. Rev. Lett*. **97**, 023603 (2006).

Creating superposed states of many atoms



Creating superposed states of many atoms



Laser cooling and magnetic trapping of atoms

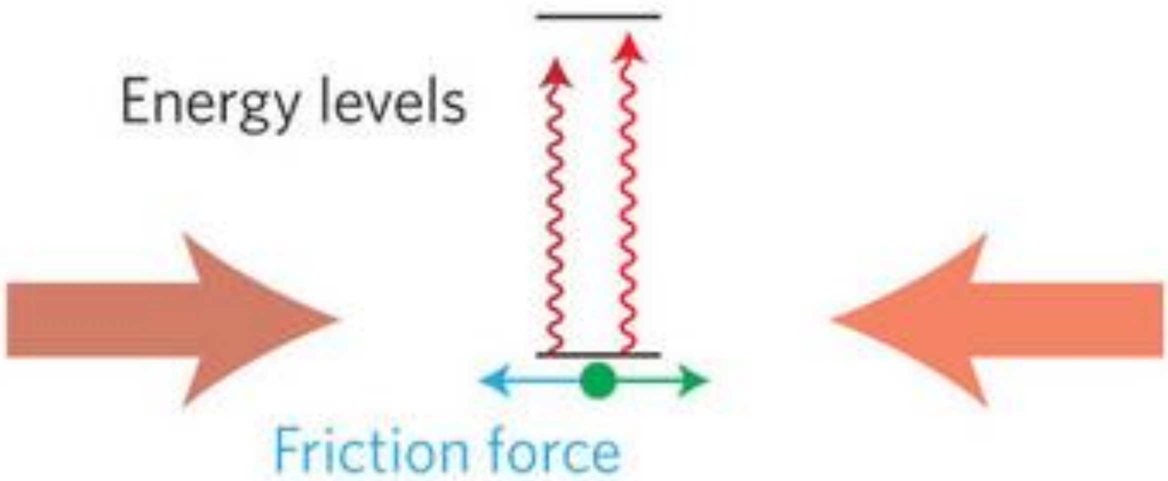


Image source: *Nature Nanotechnology* **8**,317–318 (2013)

Laser cooling and magnetic trapping of atoms

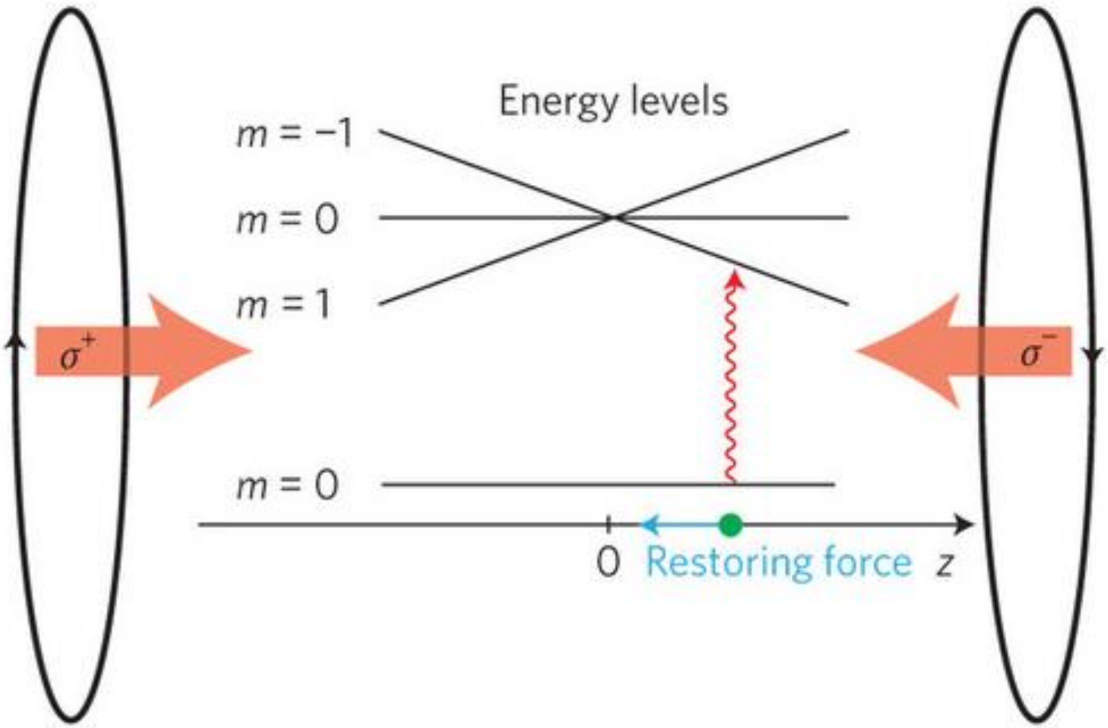
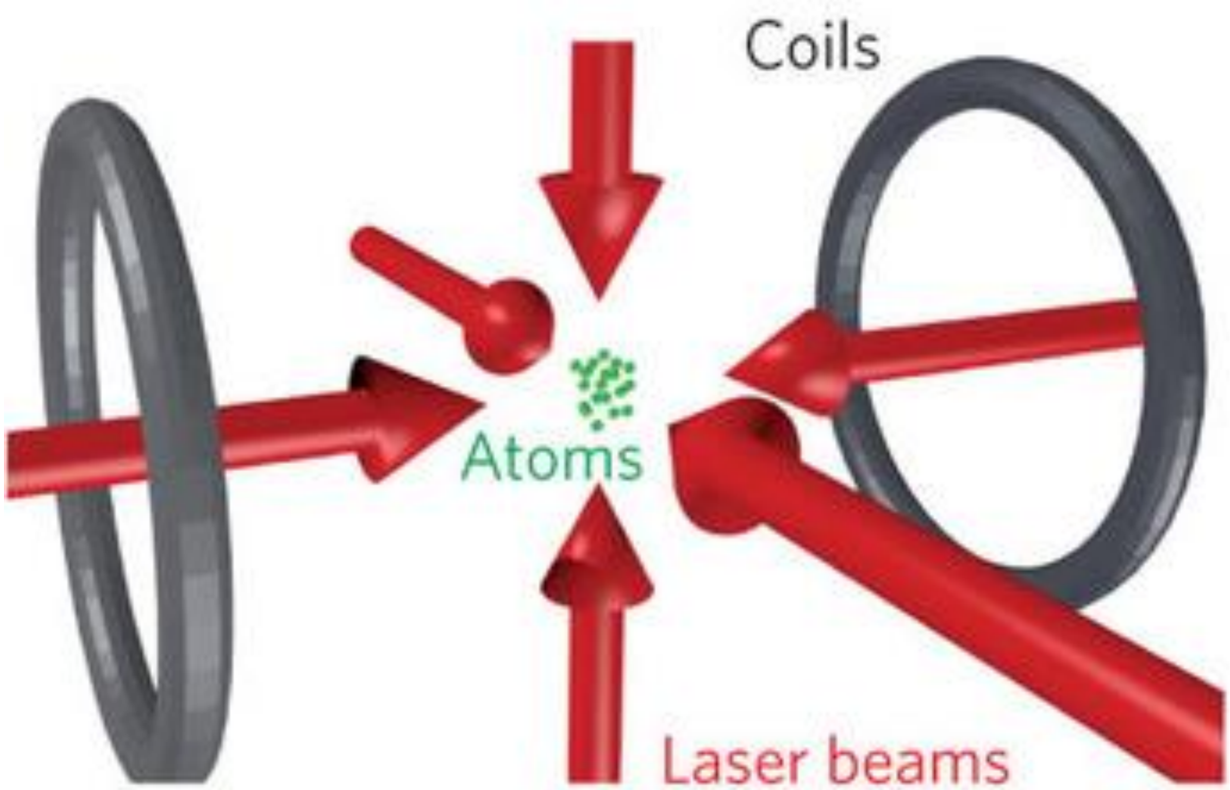


Image source: *Nature Nanotechnology* **8**,317–318 (2013)

Laser cooling and magnetic trapping of atoms



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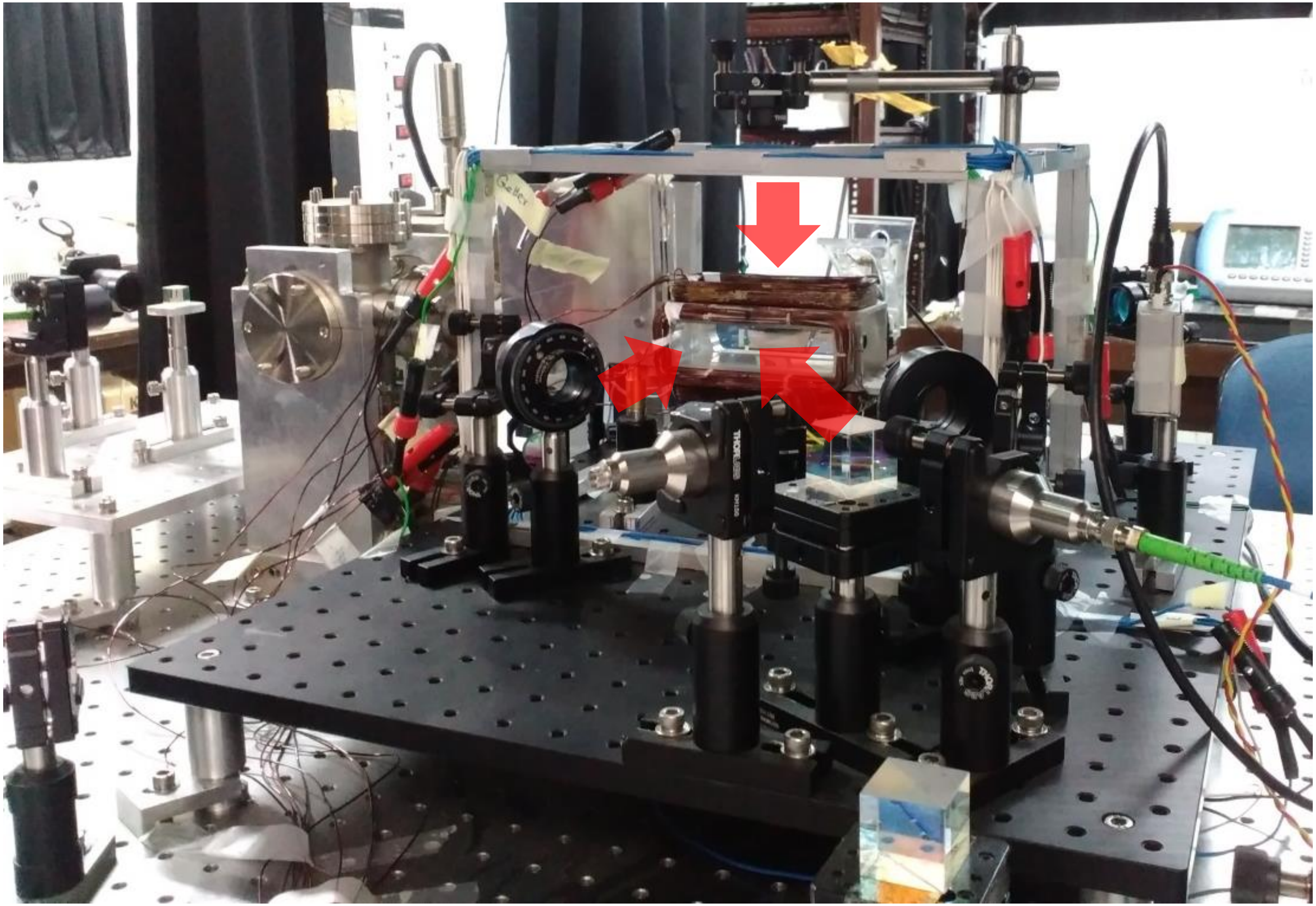
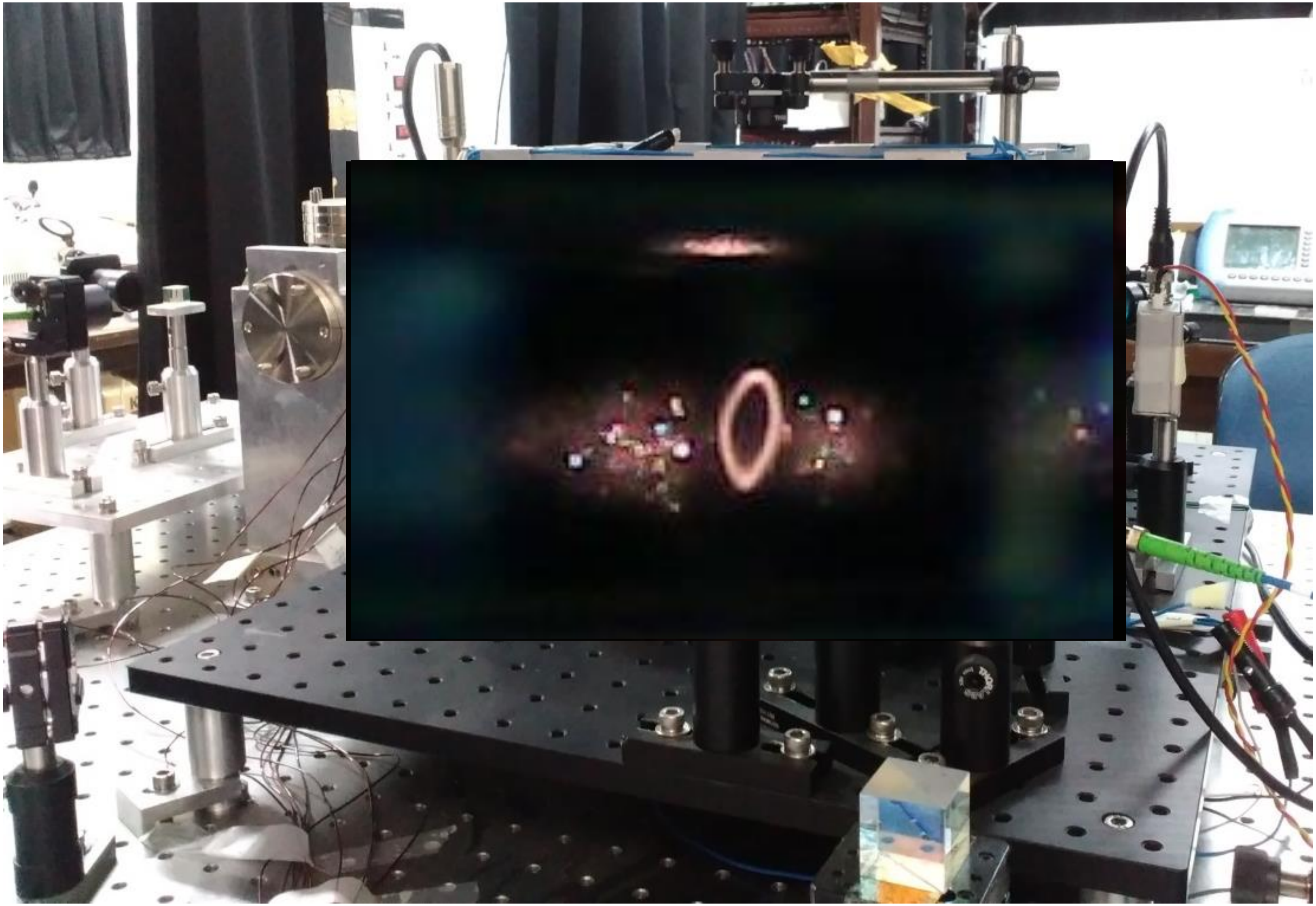
Laser cooling and magnetic trapping of atoms

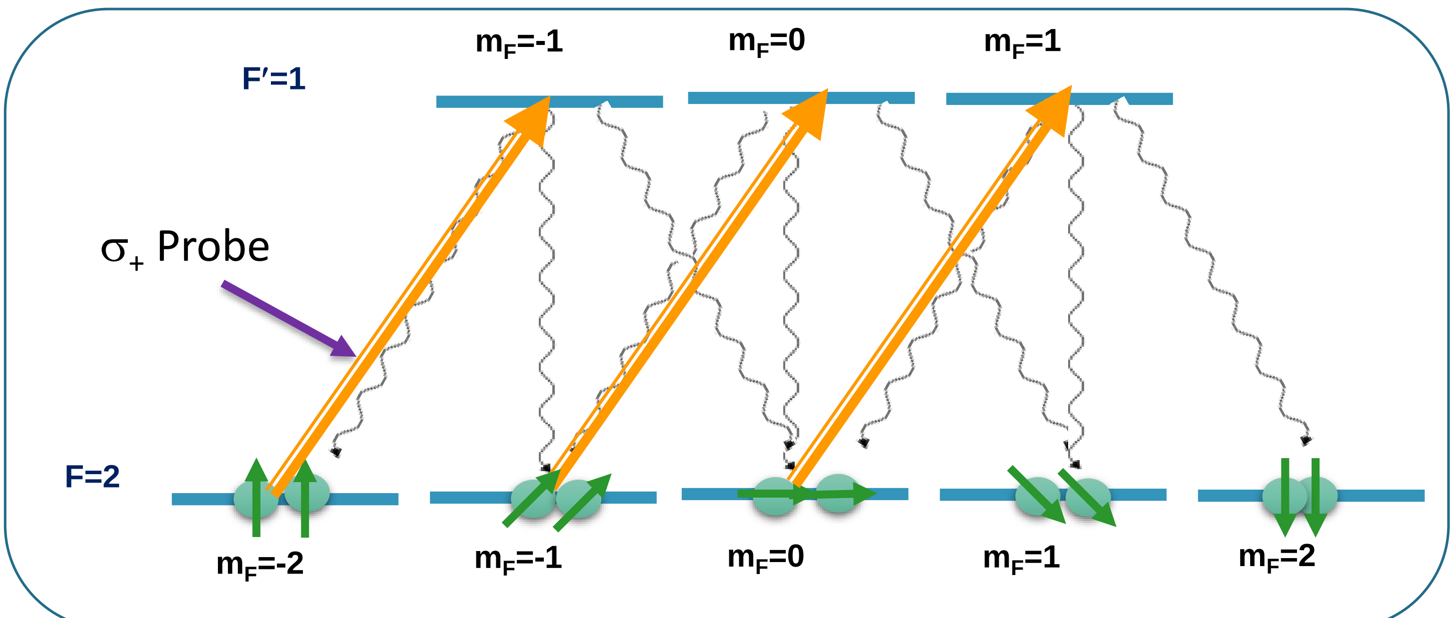


Laser cooling and magnetic trapping of atoms

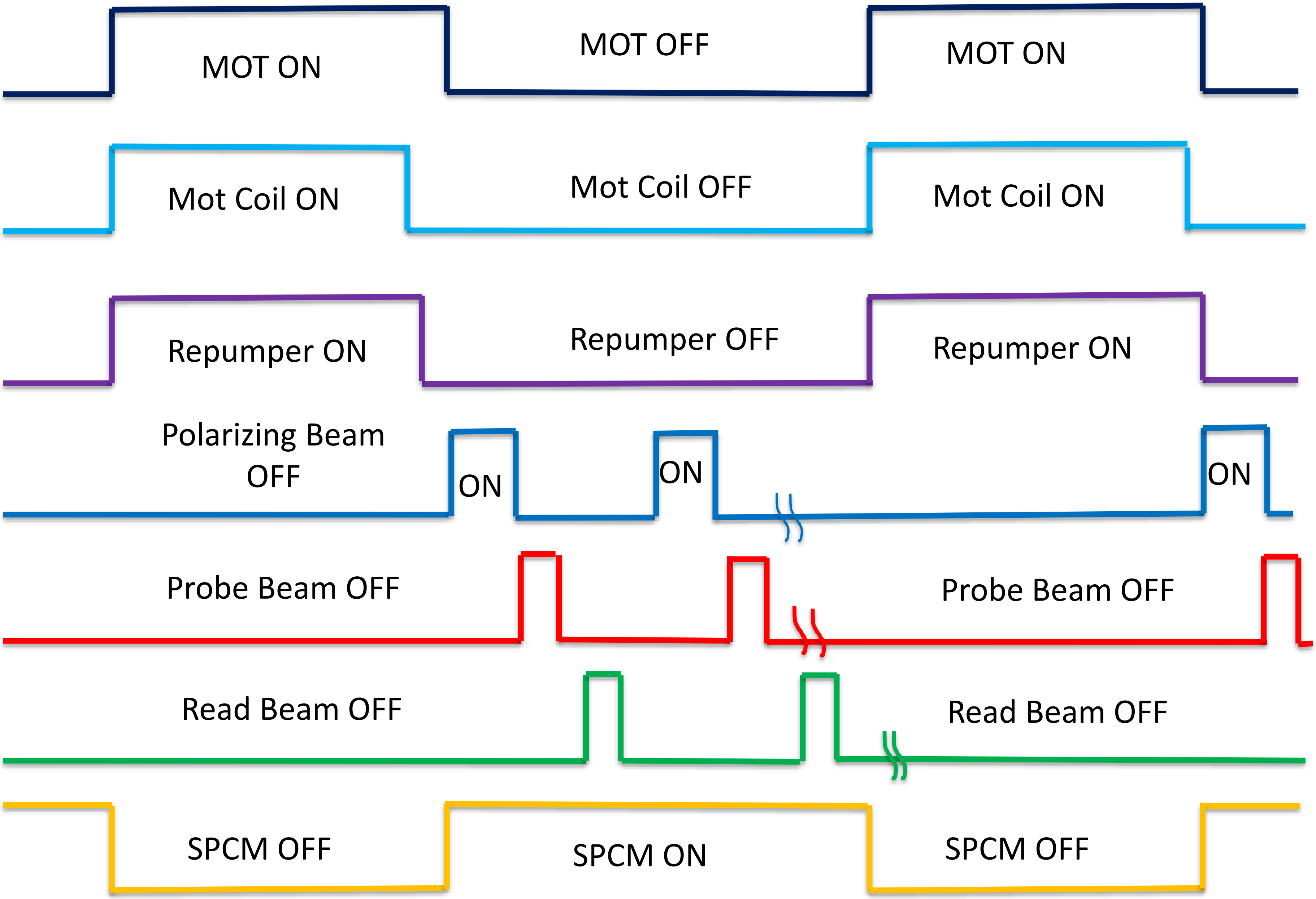


Towards many atom states

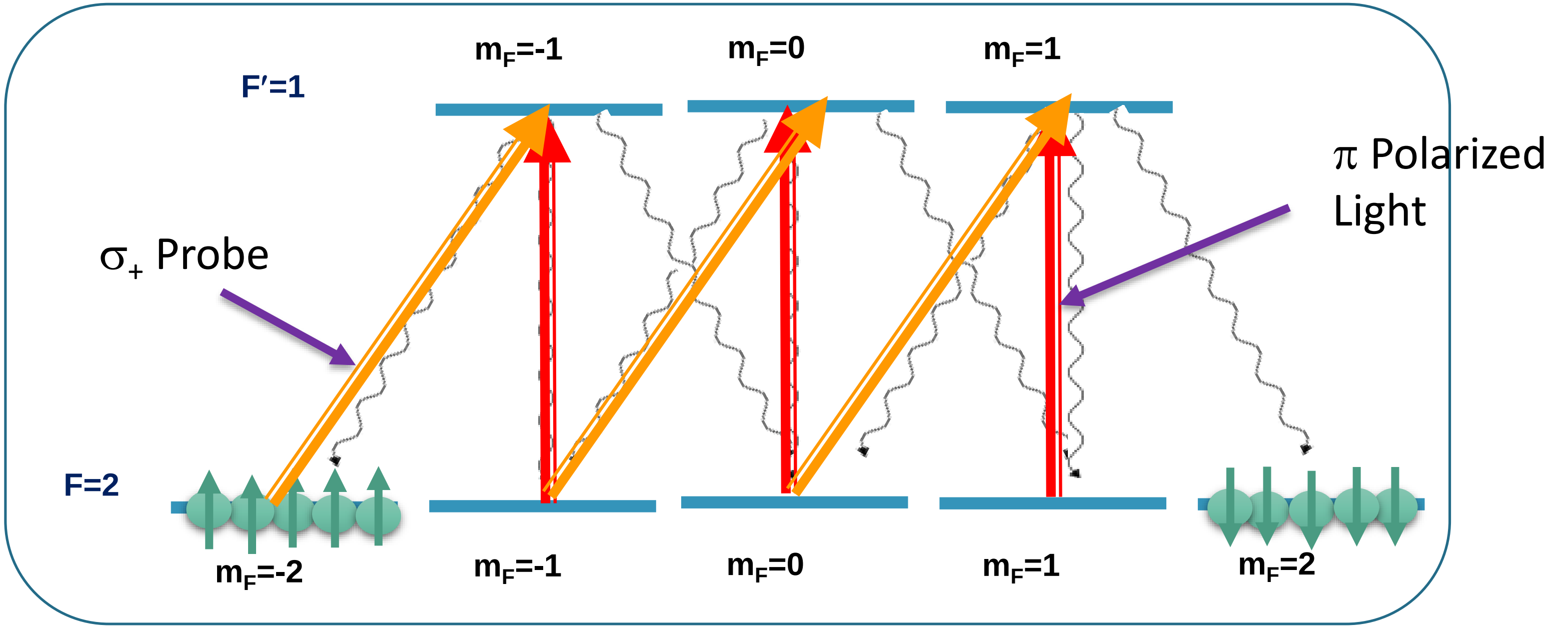
Probing direction
(and quantization axis)



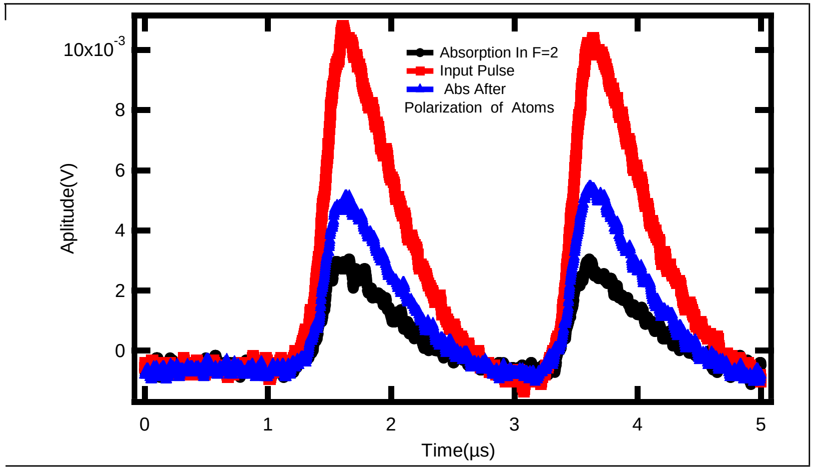
Preparing the atoms on the fly



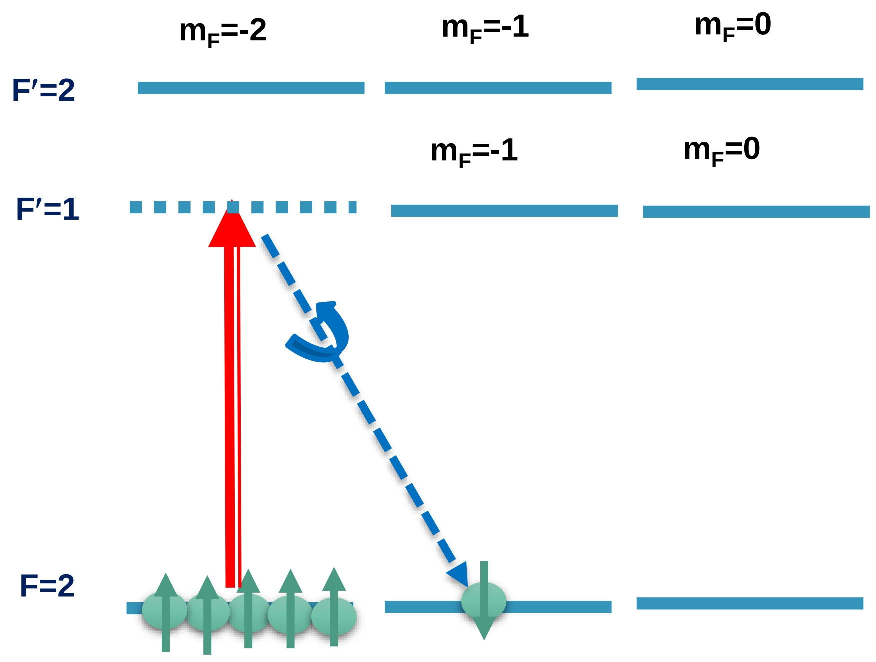
State preparation: Polarization of atoms



Polarized Atoms

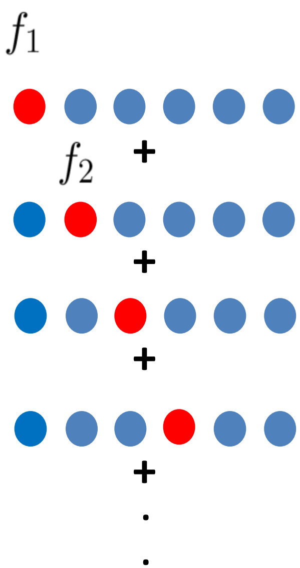


Writing a collective excitation: a "W" state



Polarized Atoms

Writing a collective excitation: a "W" state



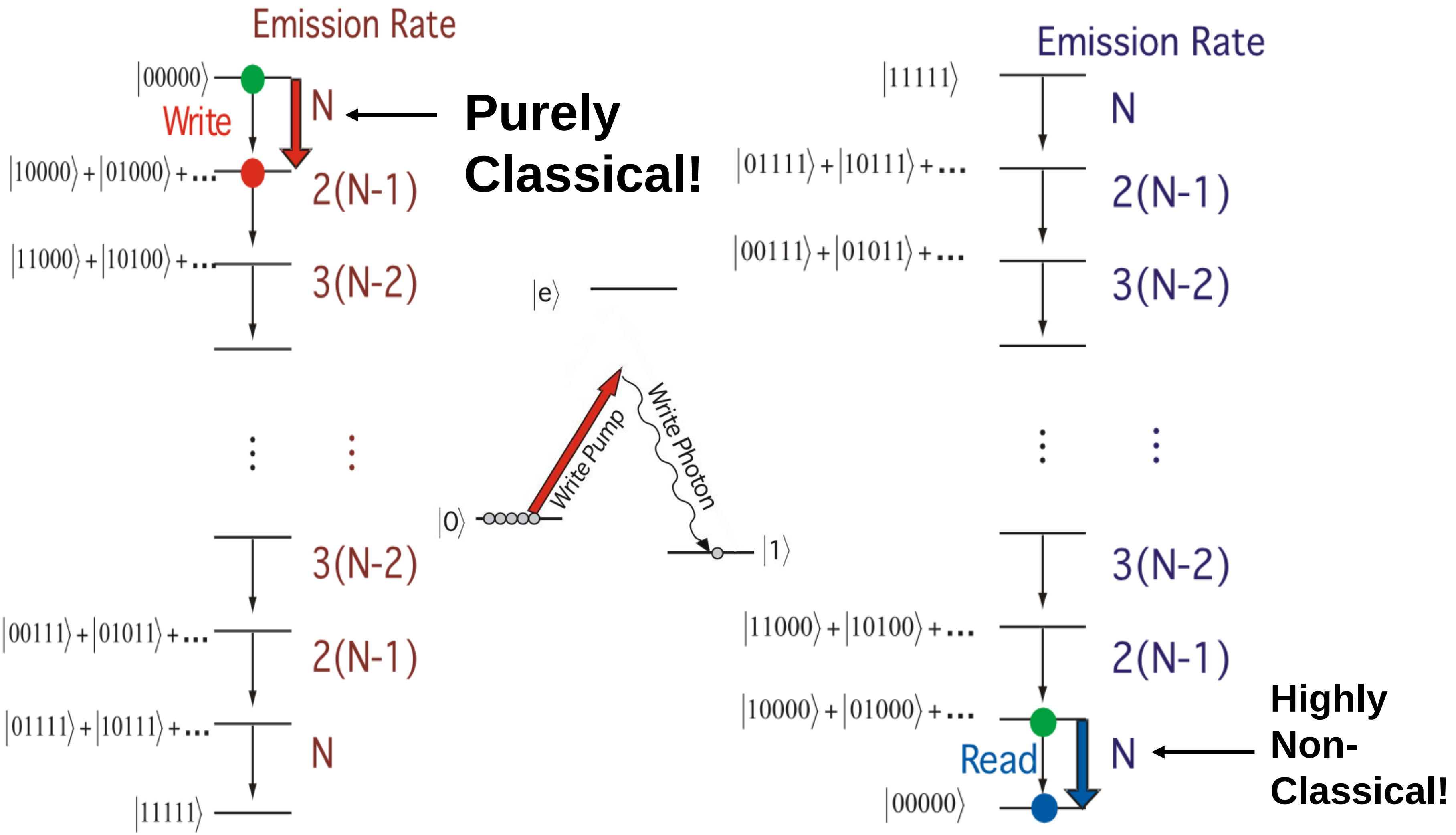
- The write beam, through measurement writes an ***entangled state*** in the form of collective excitation

- The information of a detector click is stored as an excitation in the sample - ***memory***

$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_i |f_i\rangle$$

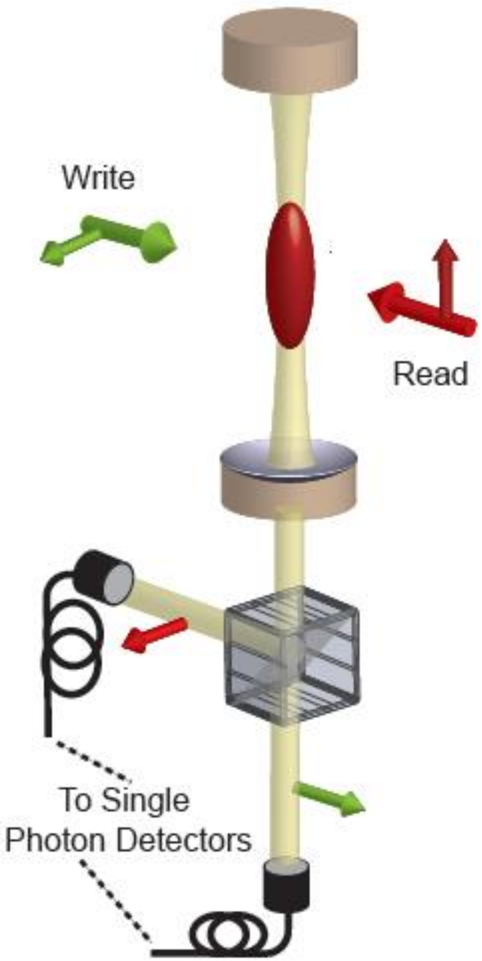
R. H. Dicke, *Physical Review*, **93**, 99 (1954)

Dicke States

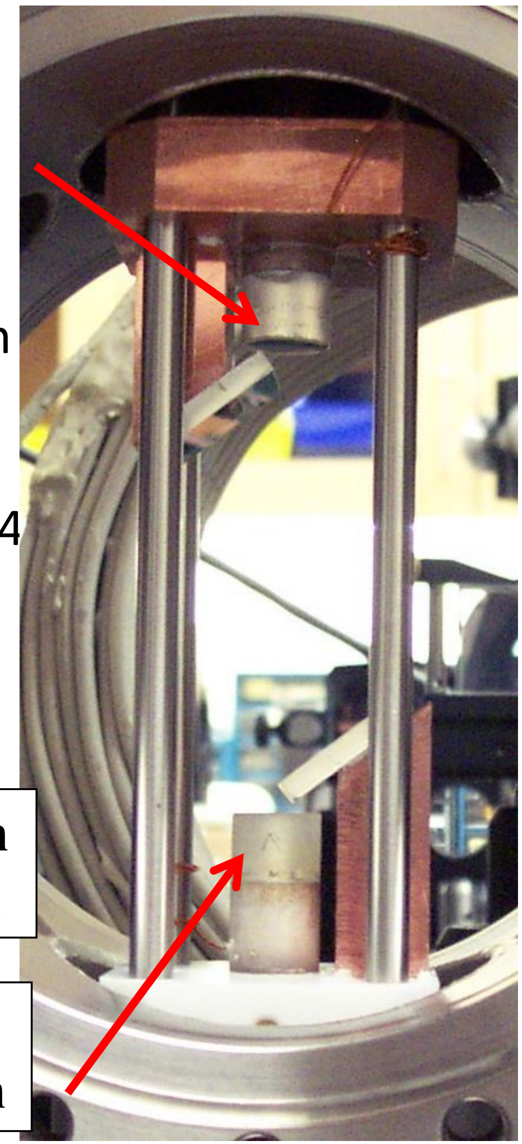


R. H. Dicke, *Physical Review*, **93**, 99 (1954)

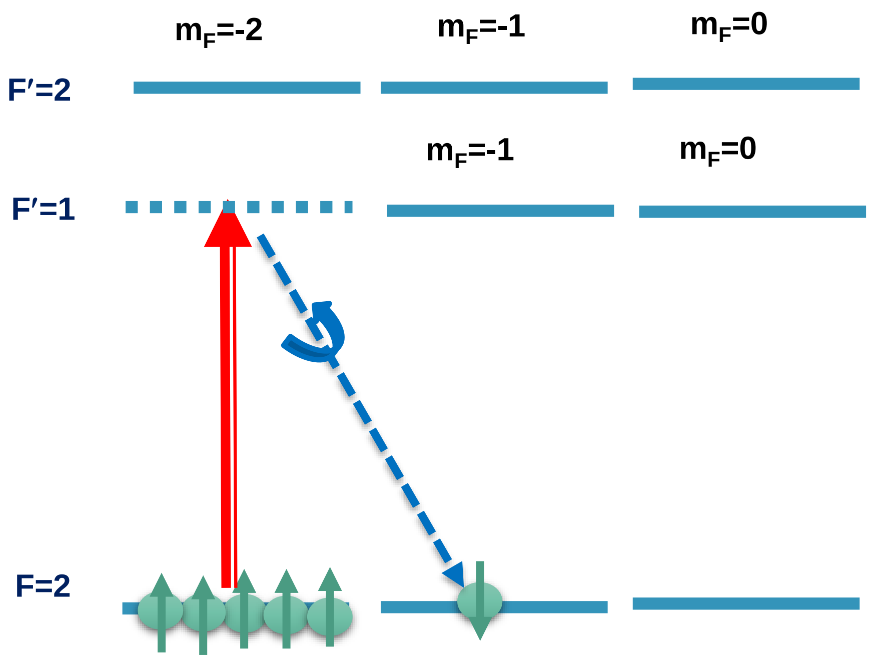
Physical system



- Laser cooled Cesium temperature of 20 μK
- A cavity finesse of 24

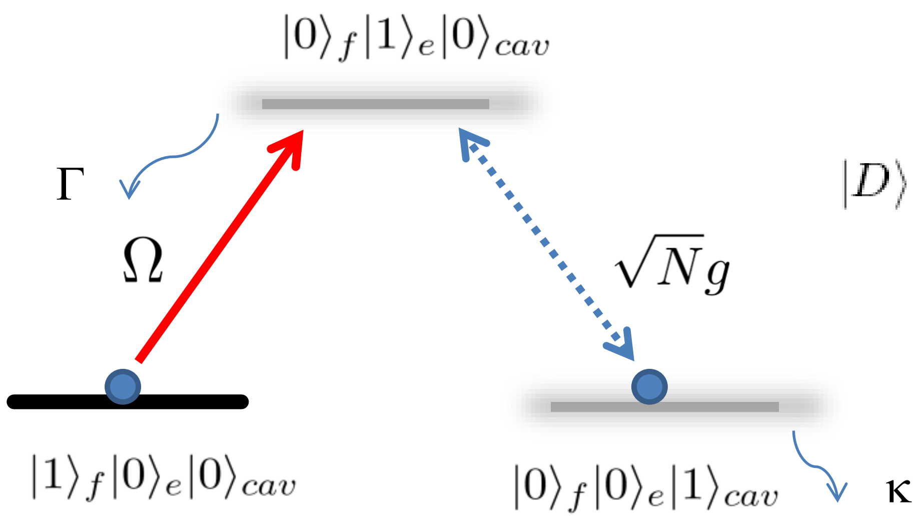


Writing a collective excitation: a “W” state



Polarized Atoms

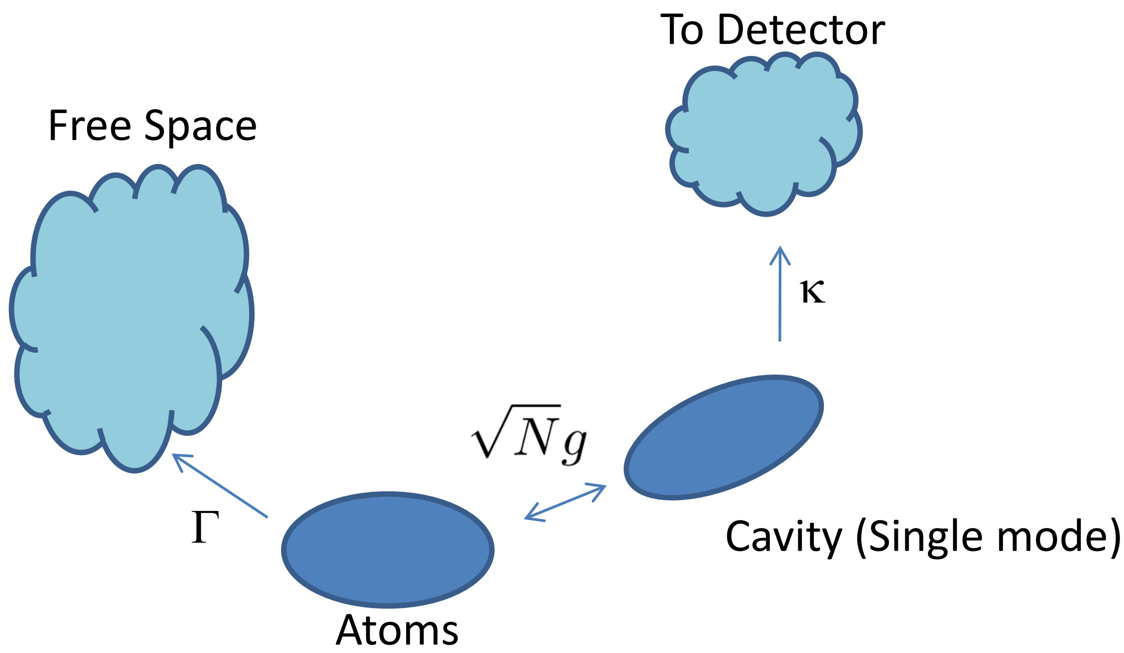
"W" state emitting a single photon



$$|D\rangle = \frac{\Omega_2|1\rangle - \Omega_1|2\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$

$$|\Psi\rangle_{Dark} \rightarrow \sqrt{N}g|1\rangle_f|0\rangle_e|0\rangle_{cav} - \Omega|0\rangle_f|0\rangle_e|1\rangle_{cav}$$

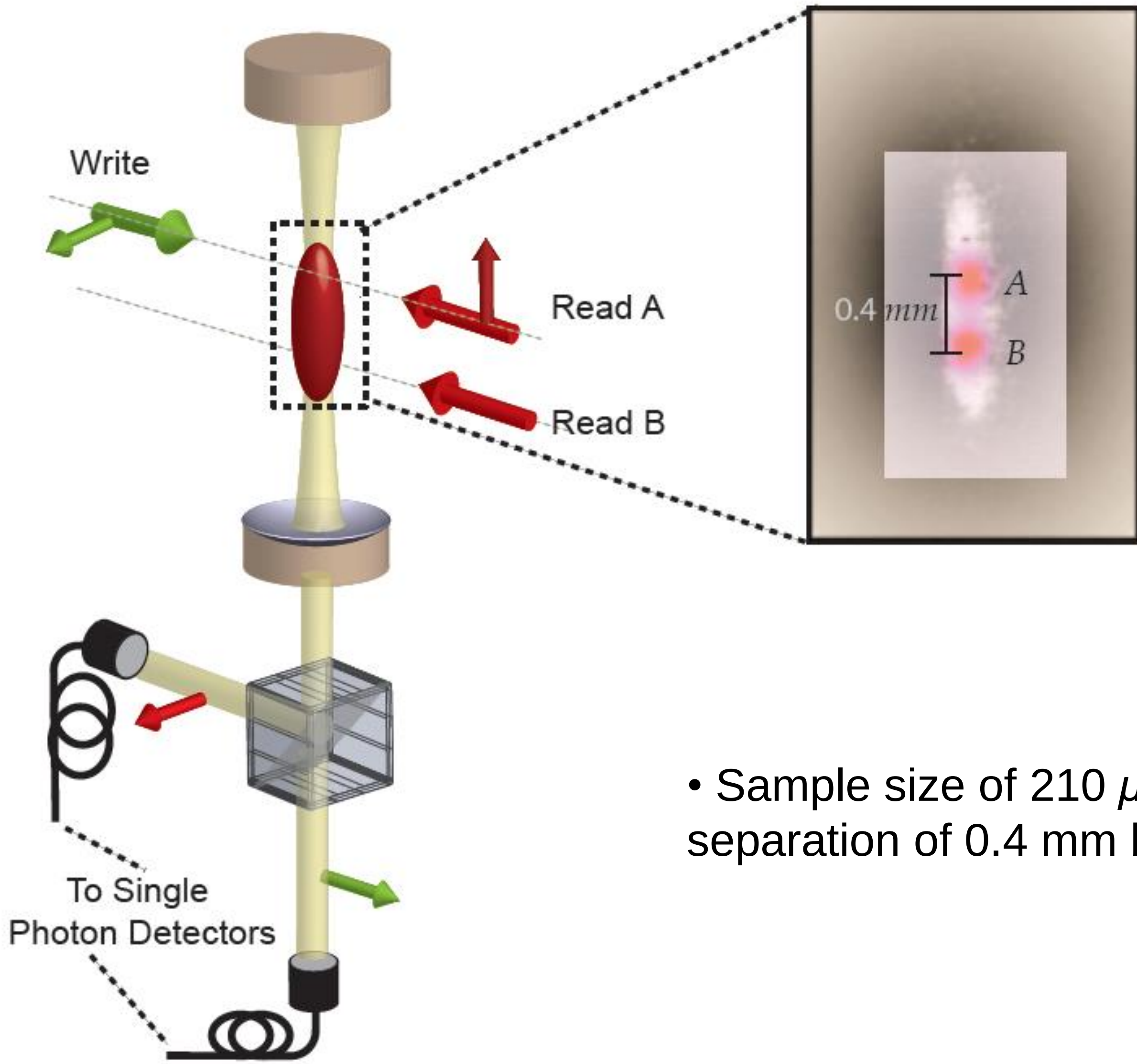
Adiabatic Transfer: Dark state rotation



- An excellent source of single photons, two-photons and a photon memory
- Can we generalize the transfer process to two ensembles coupled to a cavity?

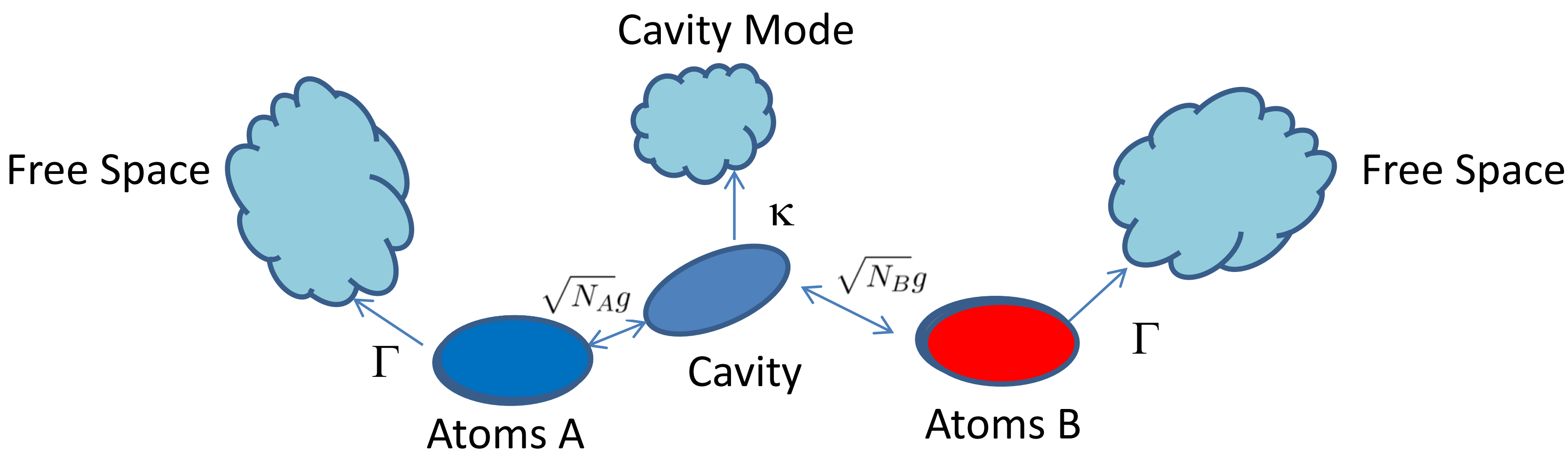
Haruka Tanji, Saikat Ghosh, Jon Simon, and Vladan Vuletic, *Phys. Rev.Lett.*,**103**,043601(2009).

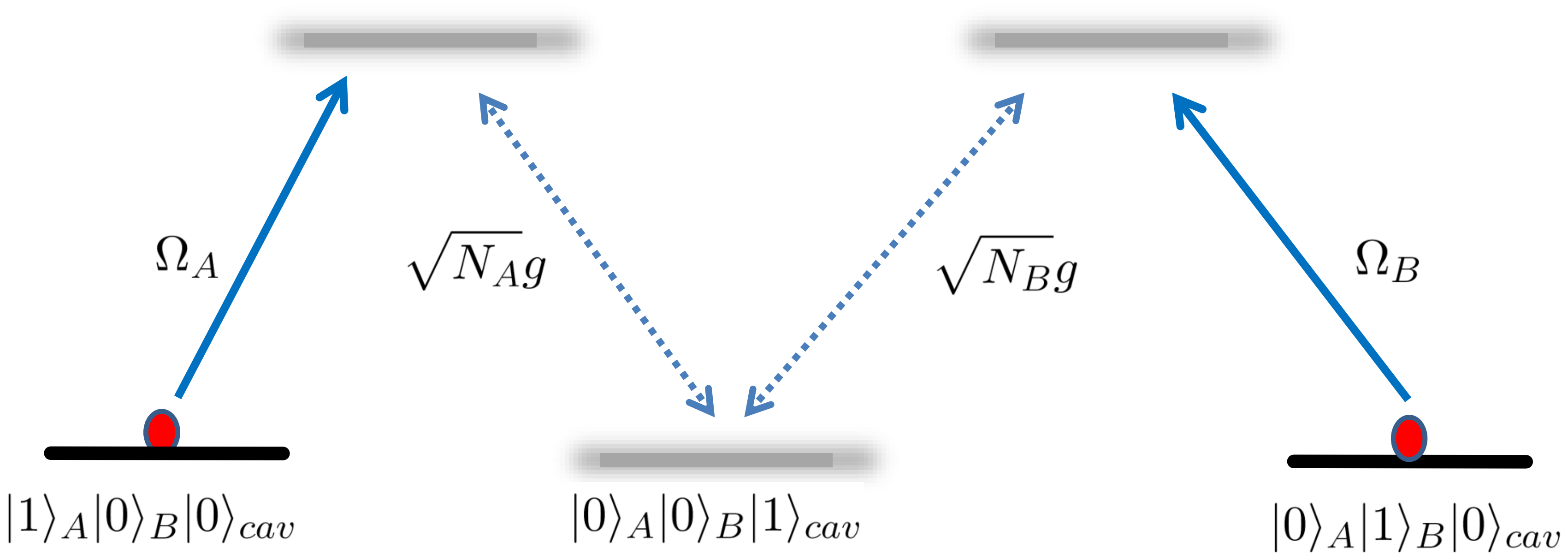
Physical System



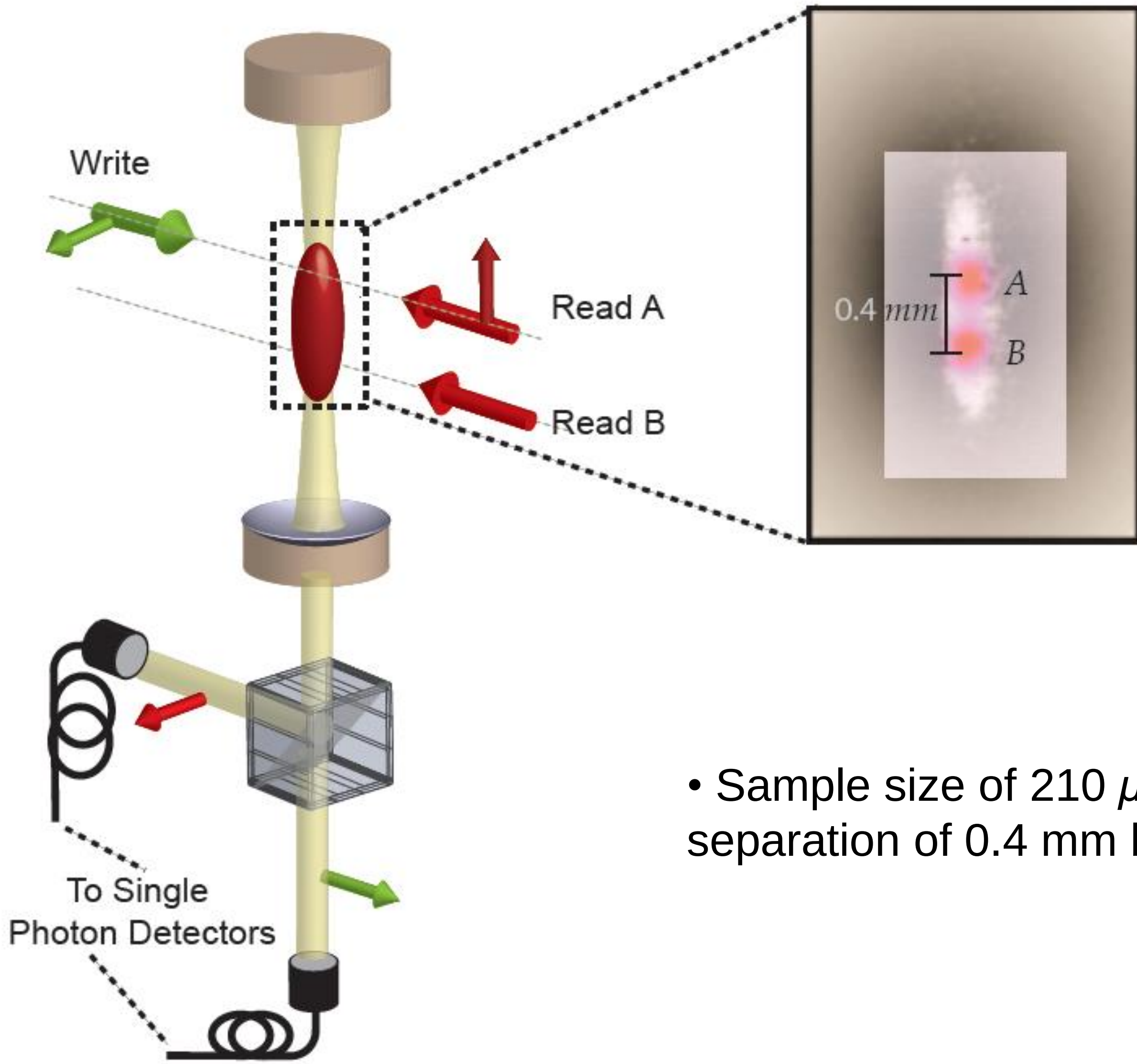
• Sample size of 210 μm each, with a separation of 0.4 mm between them.

Transfer Between Two Ensembles



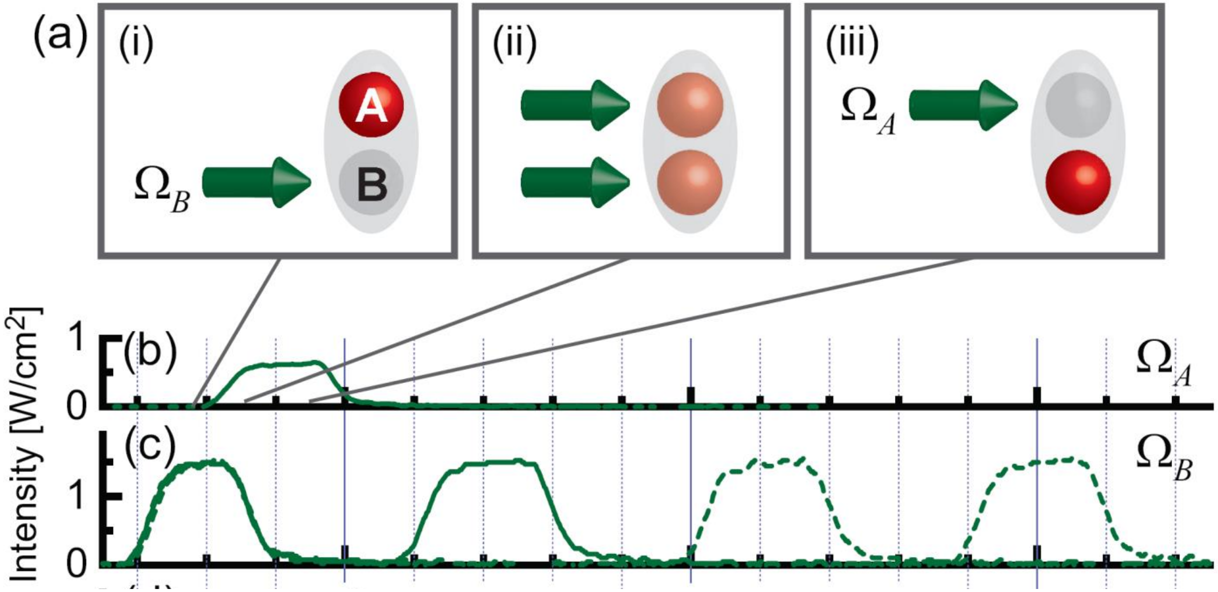


Physical System

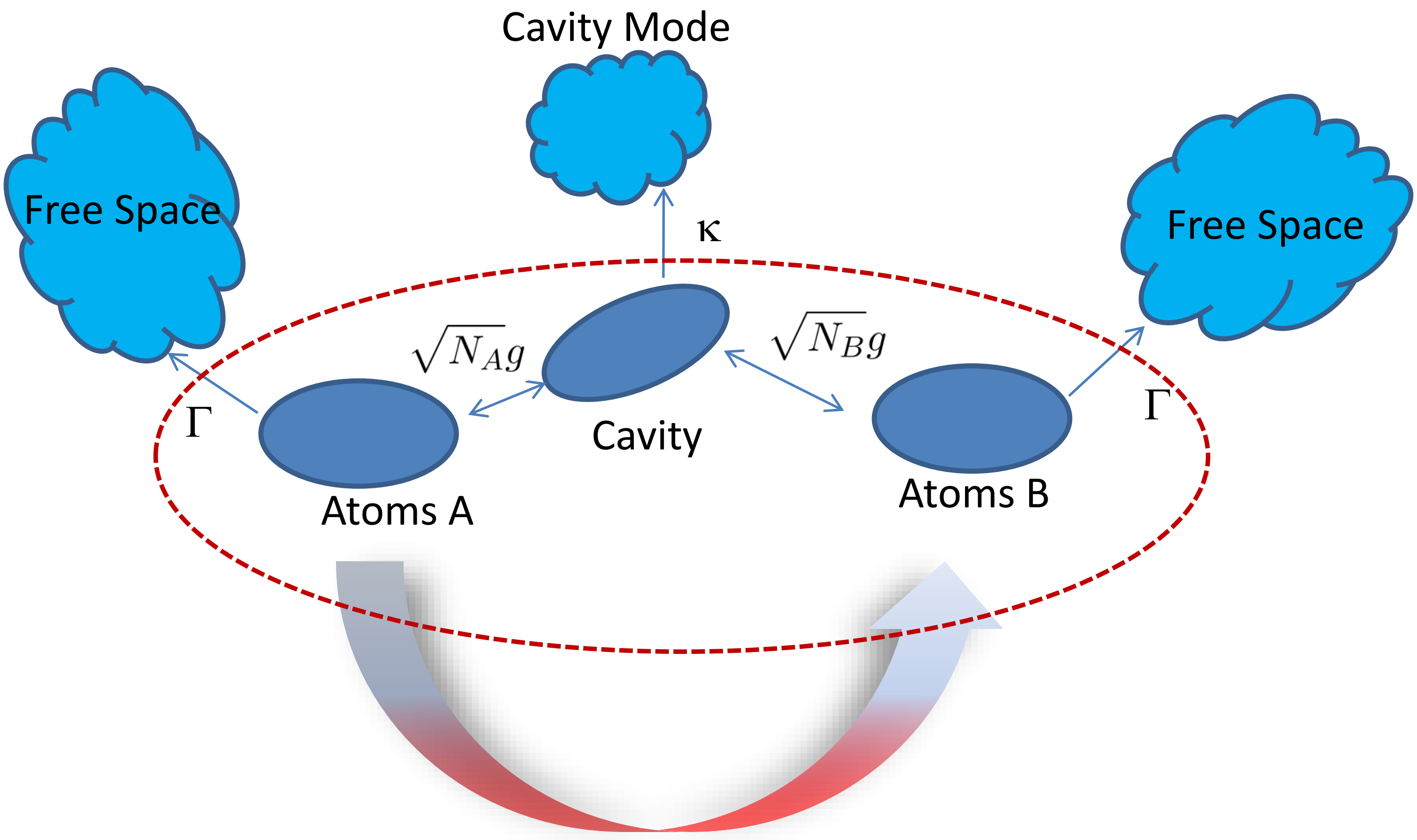


- Sample size of 210 μm each, with a separation of 0.4 mm between them.

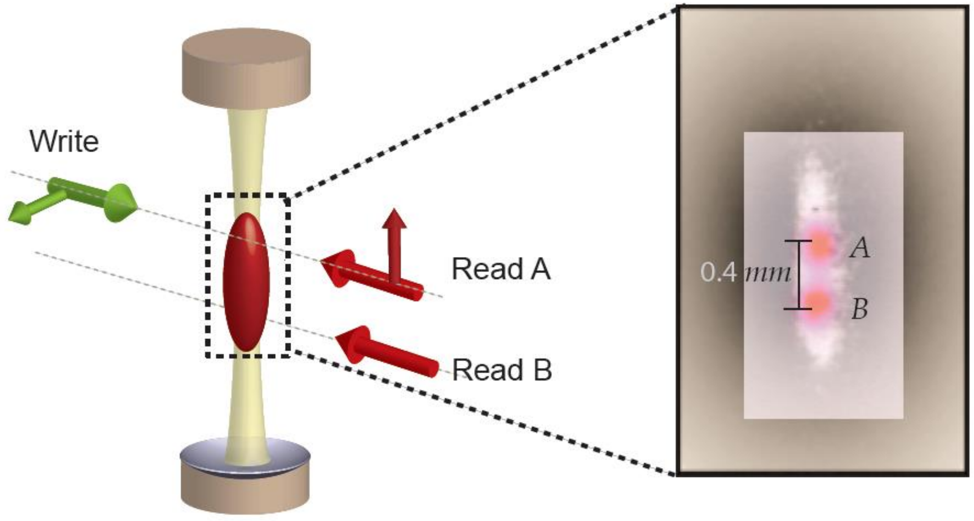
Transfer of excitation between samples

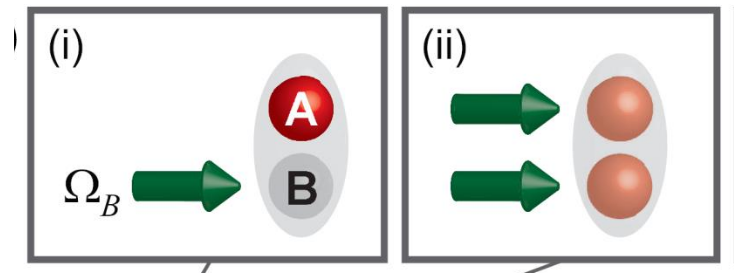


Photonic Bus/Channel



Deterministic Entanglement Generation

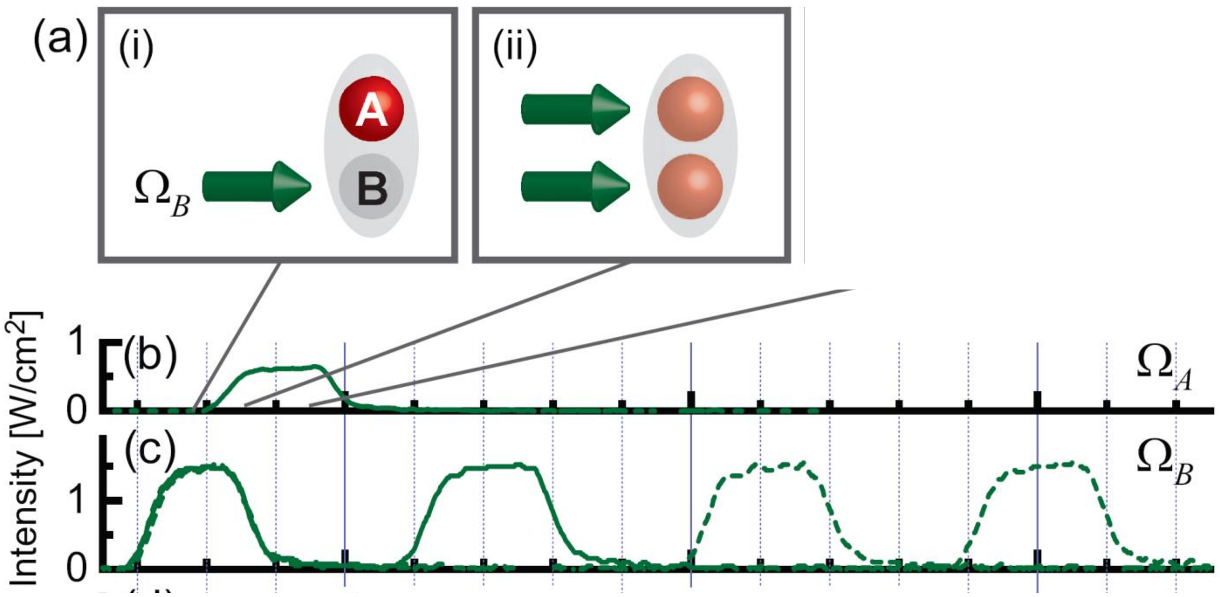




- A net transfer of one photon from pump A to B.
- If the transfer is interrupted, in the idealized limit we expect a state

$$|\Psi\rangle = cos\theta|1\rangle_A|0\rangle_B - e^{i\phi}sin\theta|0\rangle_A|1\rangle_B$$

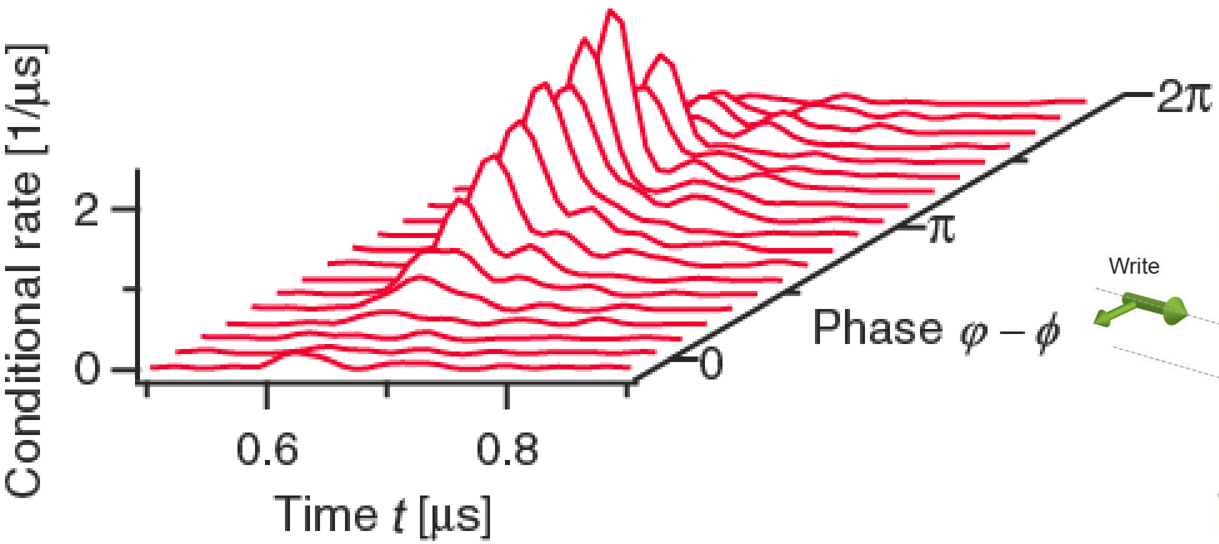
Deterministic Entanglement Generation

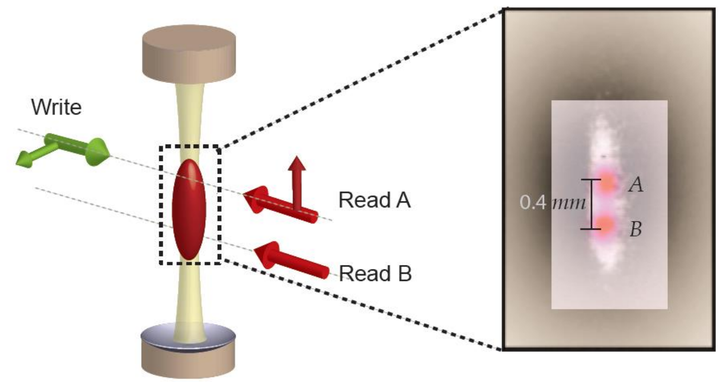


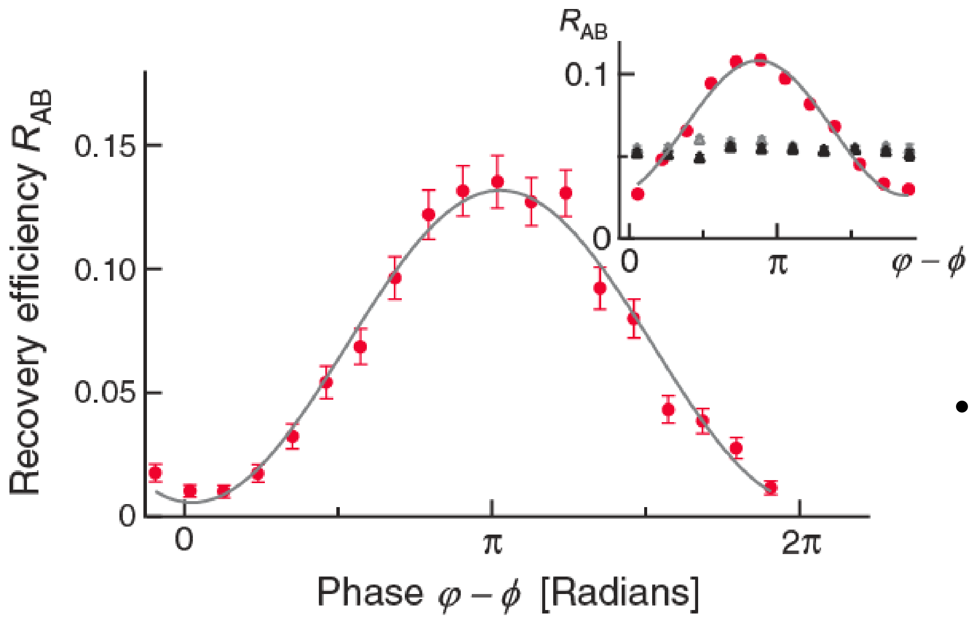
$$|\Psi\rangle = cos\theta|1\rangle_A|0\rangle_B - e^{i\phi}sin\theta|0\rangle_A|1\rangle_B$$

- Angle θ depends on the relative population of the two samples A and B
- Angle φ depends on the phase difference between the pumps

Phase Coherent Transfer







$$|\Psi\rangle = cos\theta|1\rangle_A|0\rangle_B - e^{i\phi}sin\theta|0\rangle_A|1\rangle_B$$

- Measured visibility of 88 %

Entanglement Verification

- Bounds on ***concurrence*** through photonic correlations

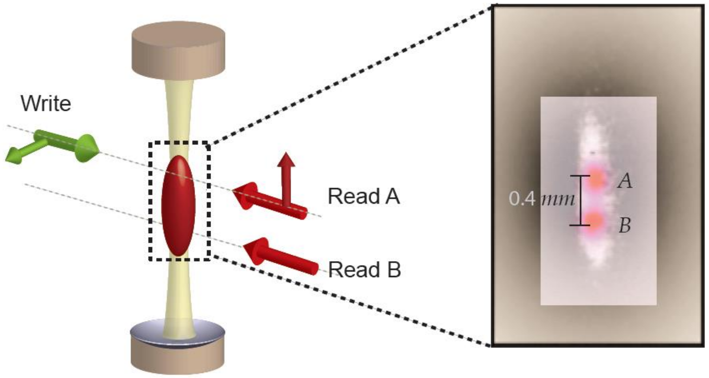
$$C = 2 \cdot \sqrt{m_{10}m_{01}} \left(\frac{|k|}{\sqrt{m_{10}m_{01}}} - \sqrt{\frac{m_{00}m_{11}}{m_{10}m_{01}}} \right) = 2m(V - \sqrt{G_{AB}})$$

$$\mathcal{C} \geq 0.041(11) > 0$$

- Single excitation regime: $g_{AA} \leq g_{AA}^{photonic} = 0.13(8) < 1$

- With *post-selection*:

$$C_{post} \geq (V - \sqrt{G_{AB}}) = 0.41(11)$$



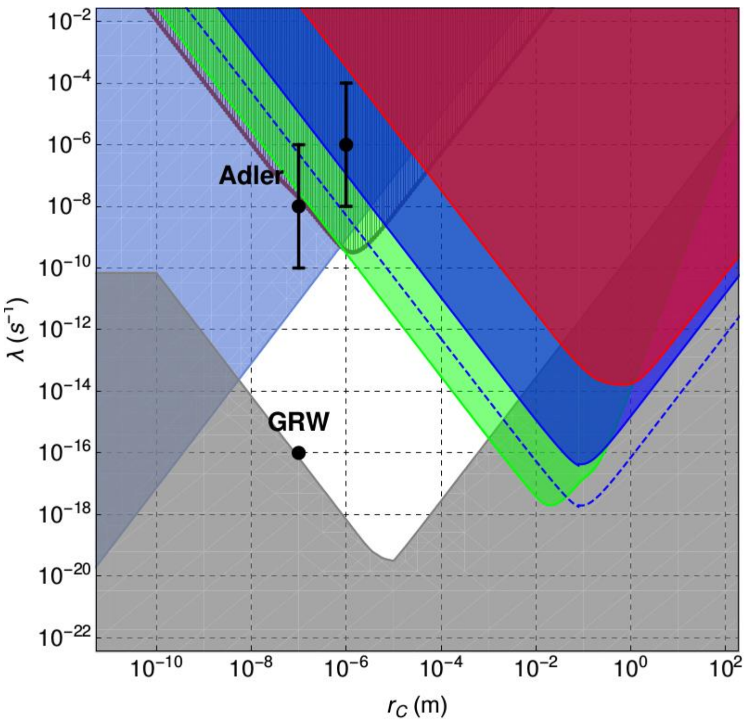
J. Simon, H. Tanji, S. Ghosh and V. Vulteic, *Nature Physics* **3,** 765, (2007).
W. K. Wootters*, Phys. Rev. Lett,* ***80****, 2245 (*1998).

Many atoms: Outlook

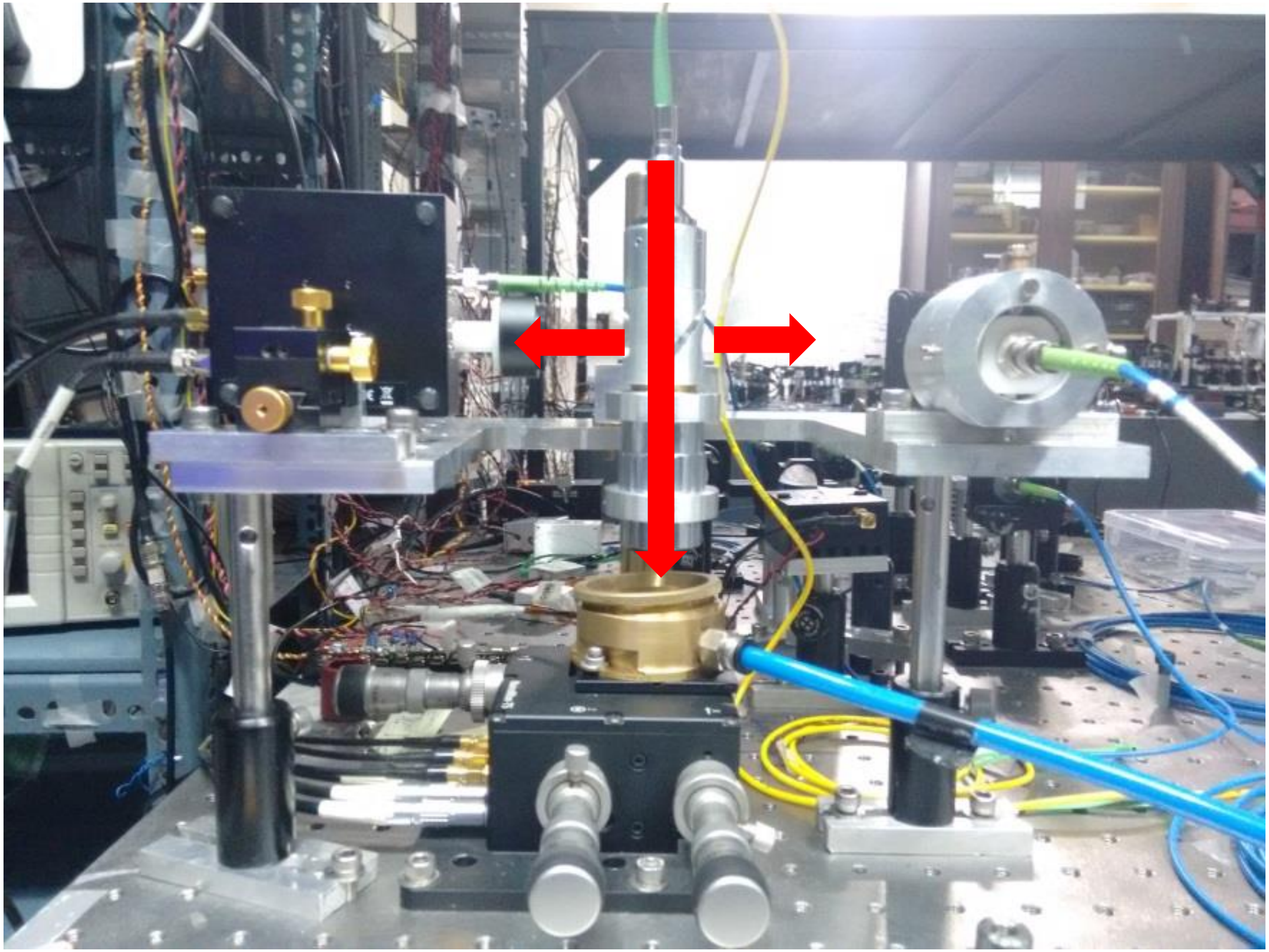
Can one scale up these techniques towards a cat, or at-least a kitten state?

$$|\Psi\rangle = \frac{|N\rangle|0\rangle + e^{iN\varphi}|0\rangle|N\rangle}{\sqrt{2}}$$

In Angelo's graph, how many atoms(N) one requires to hit the middle?

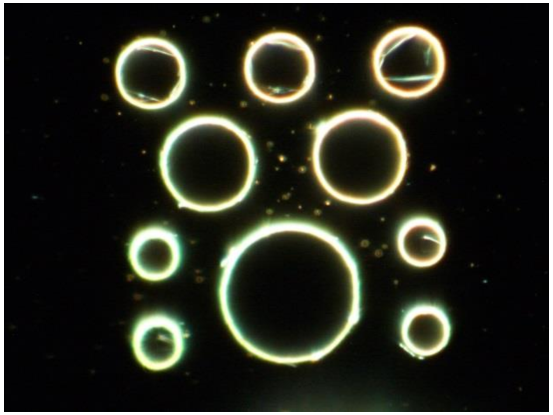


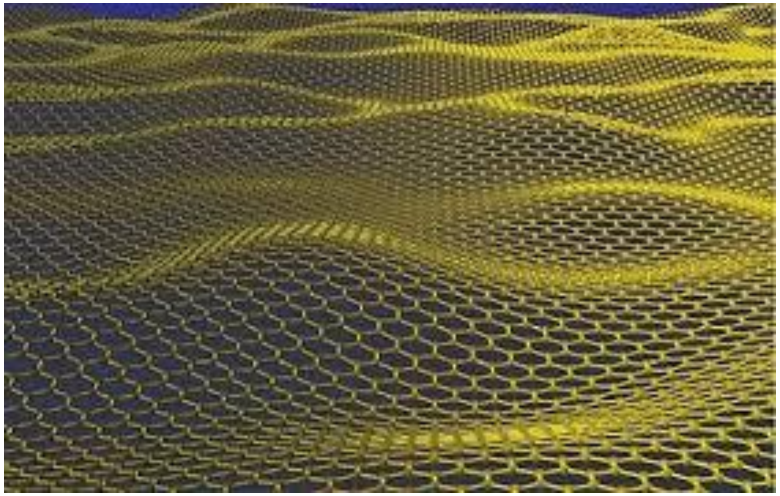
Coherent Phononics

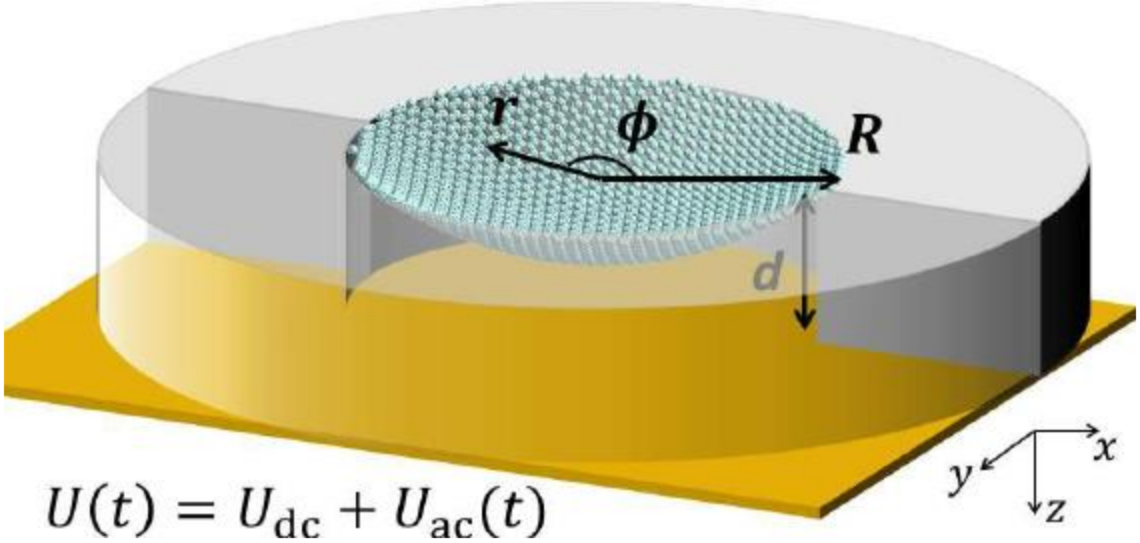


In collaboration with:
Kirill Bolotin (Max Planck)

Graphene Drums







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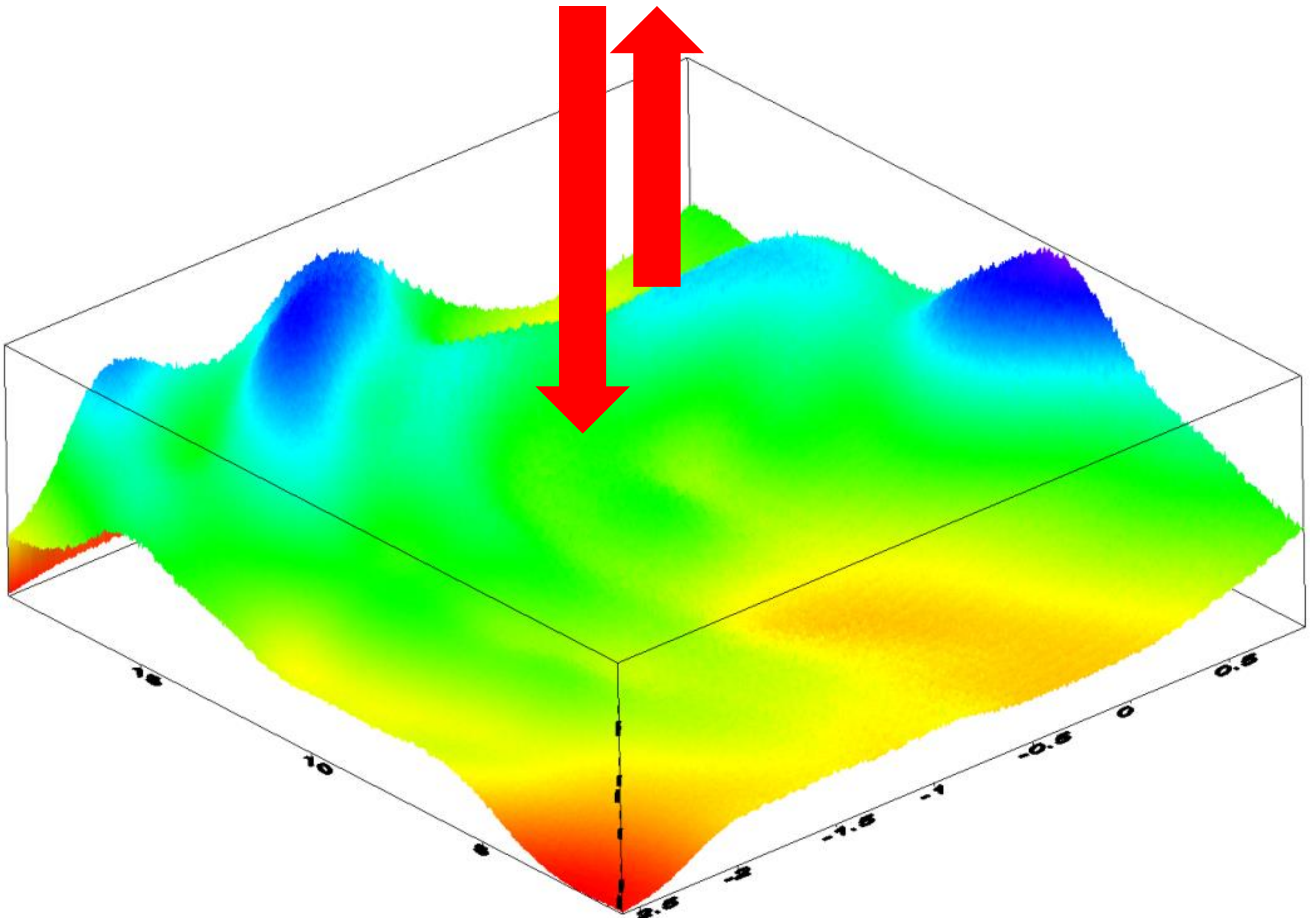
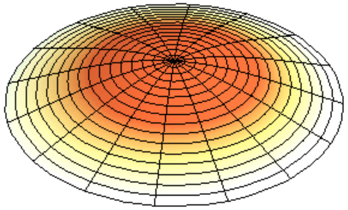
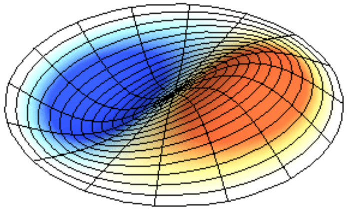
Graphene Drums

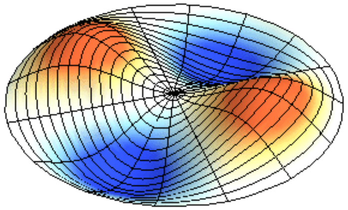


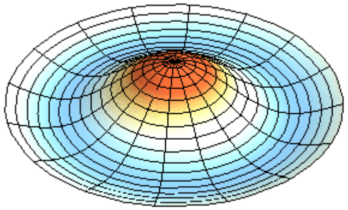
In collaboration with:
Kirill Bolotin (Max Planck)

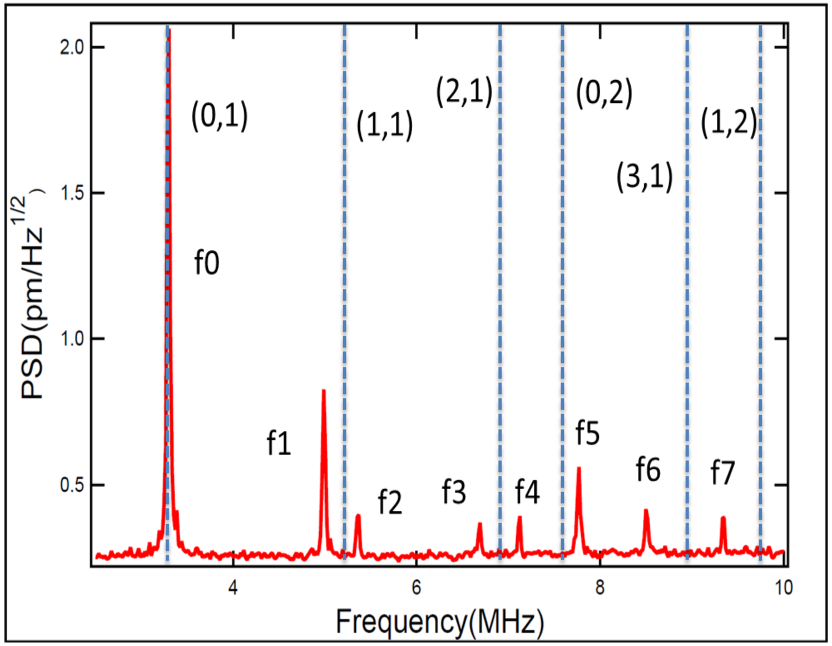
Brownian walk of graphene membrane





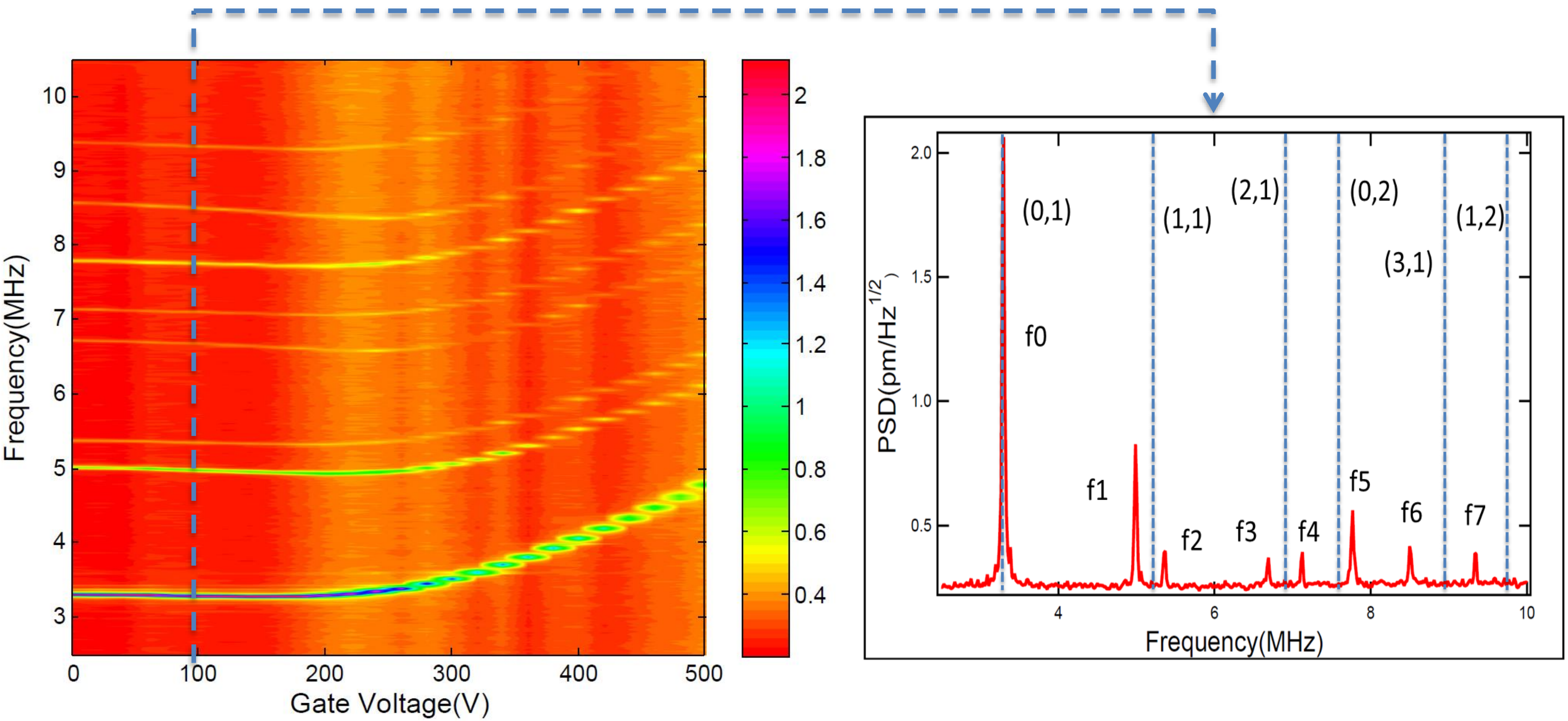




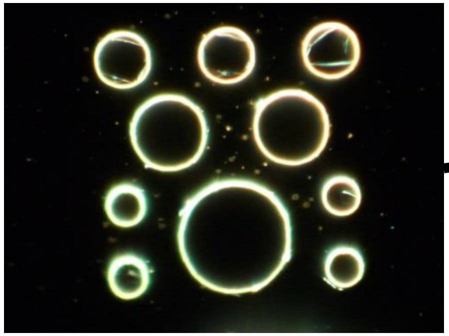


Source:http://www.acs.psu.edu/drussell/Demos/MembraneCircle/Circle.html

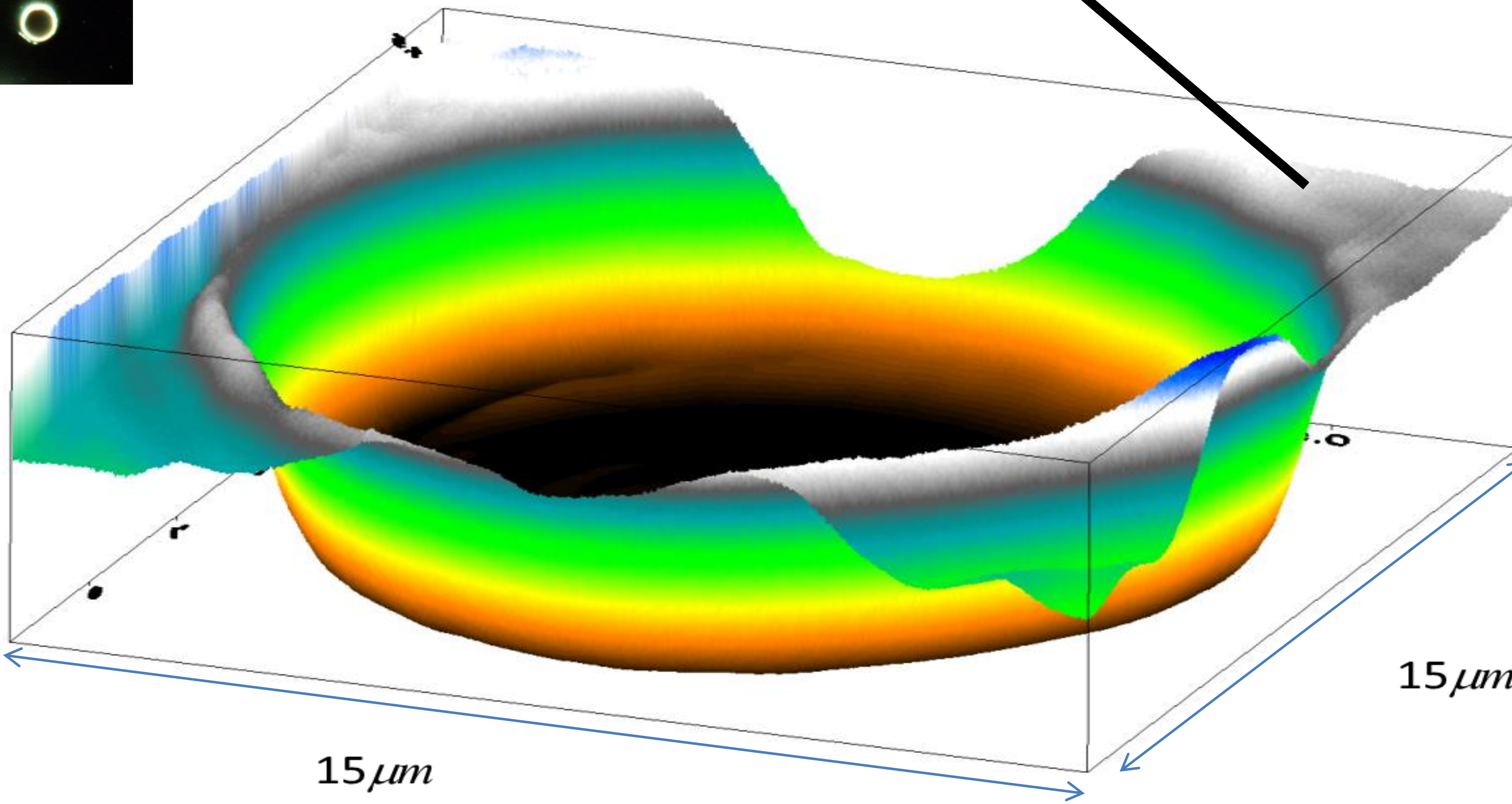
Brownian walk of graphene membrane



Coherent coupling of two harmonic oscillators

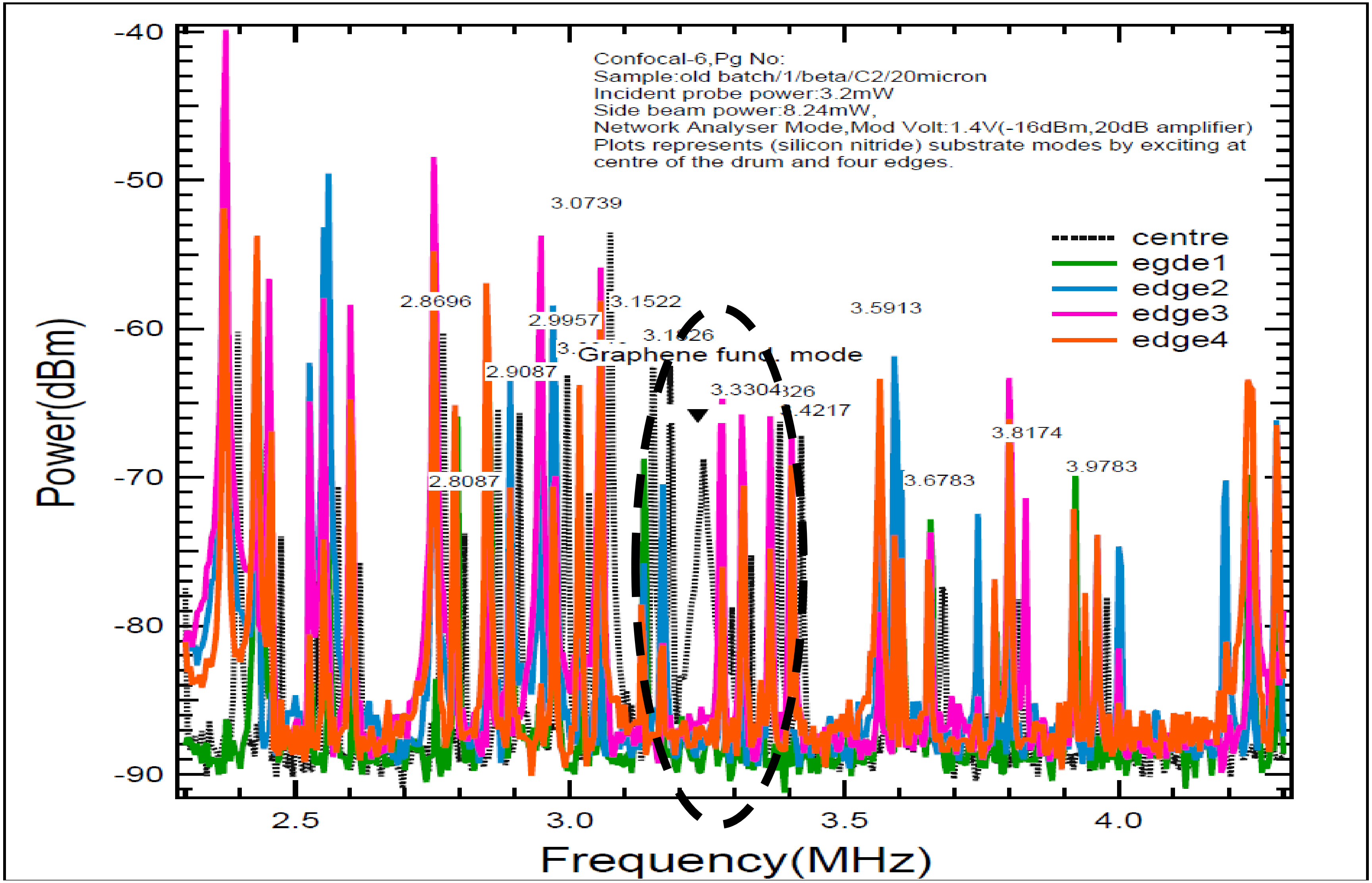


300 nm SiN Membrane

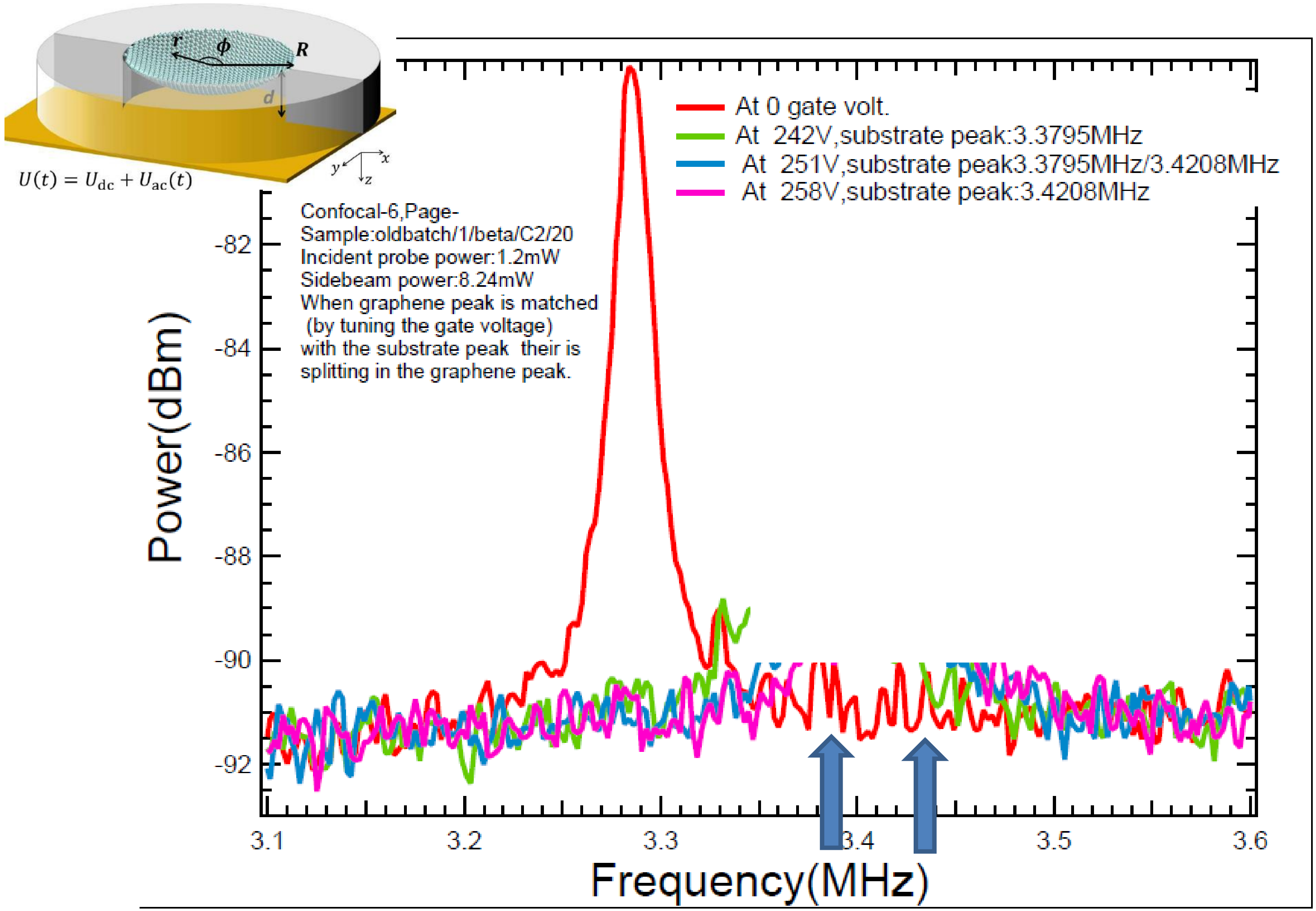


Free-standing graphene drums

SiN substrate mode: Driven Oscillator



Coherent interaction with phonons



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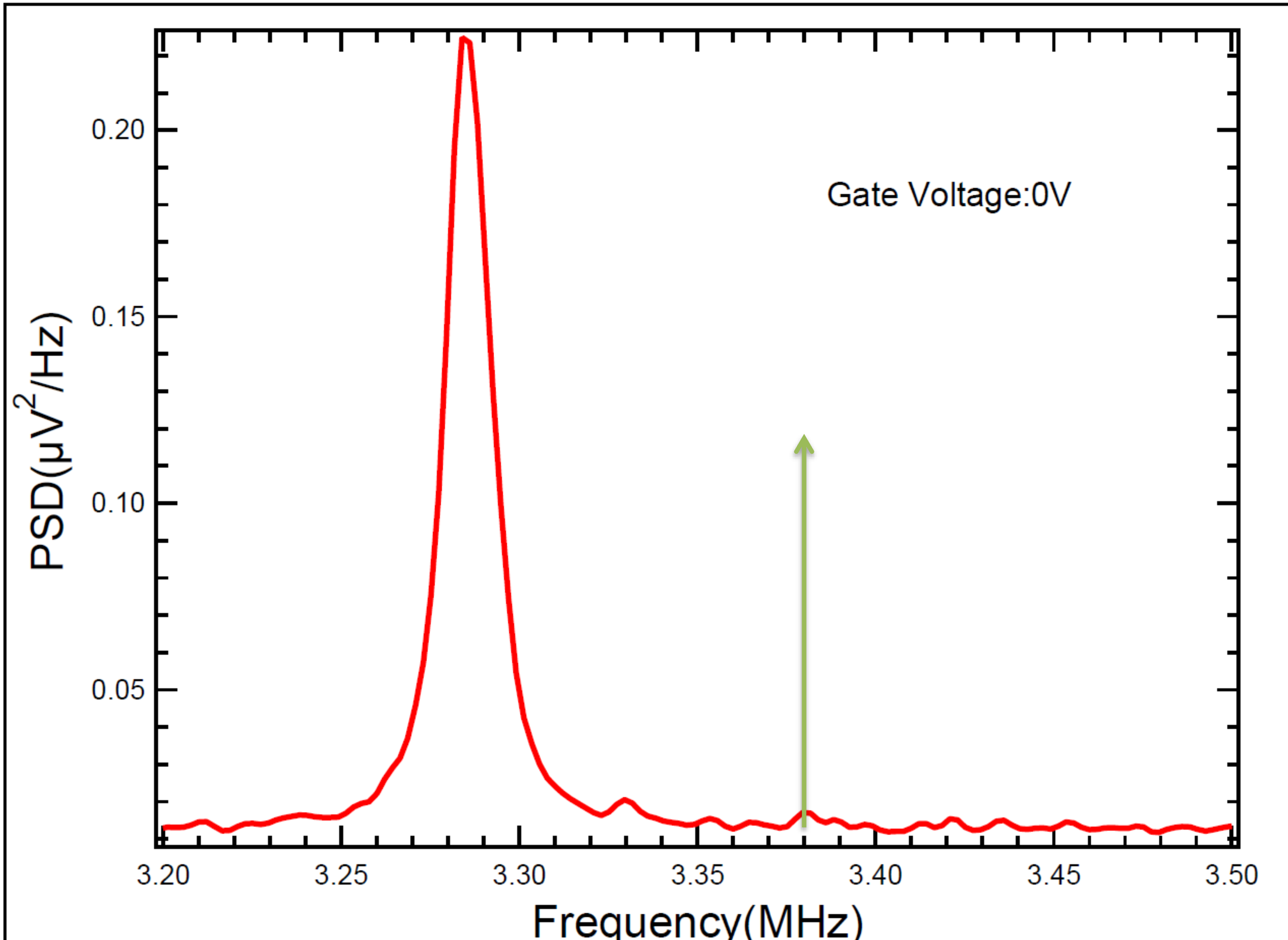
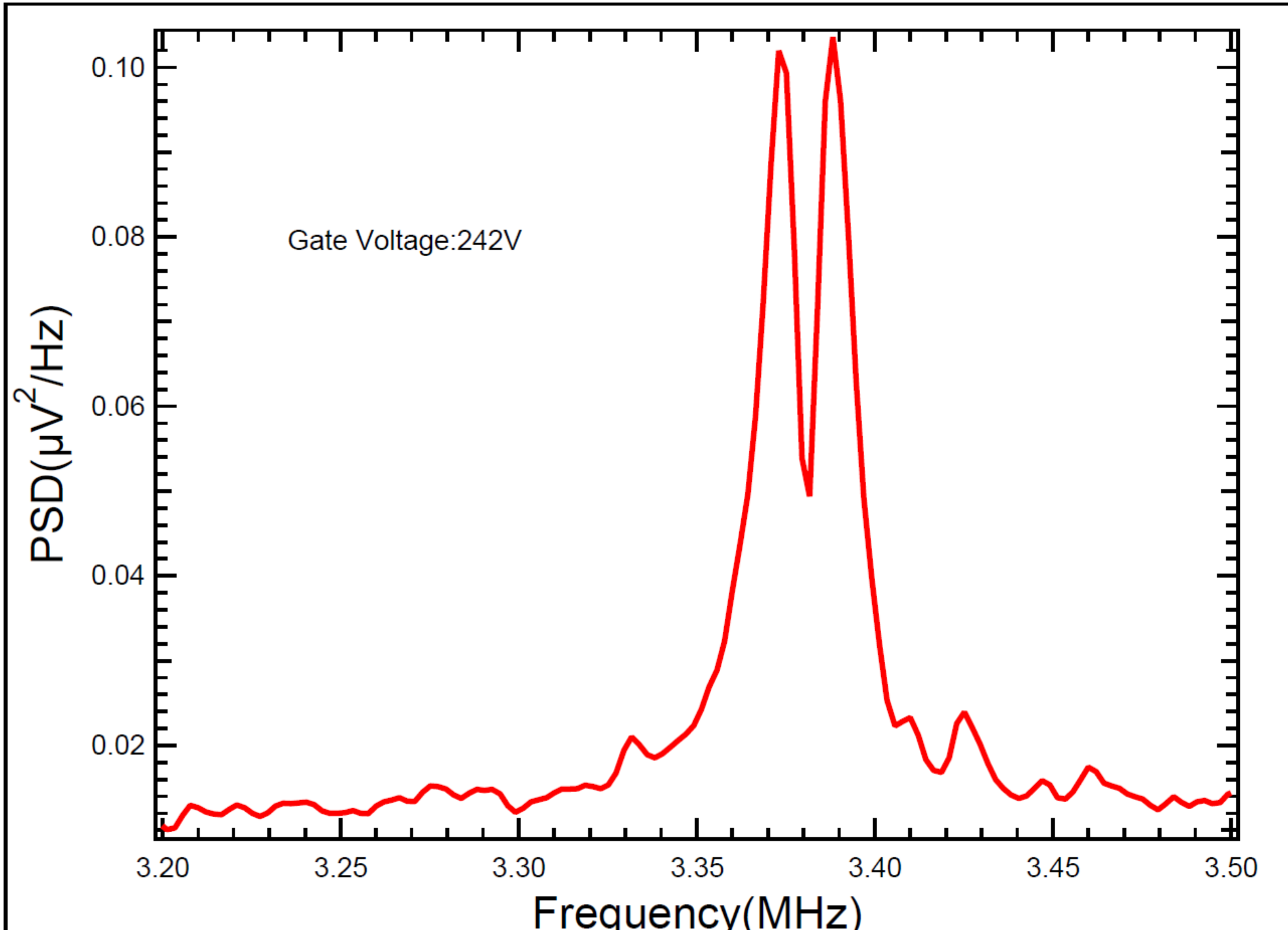
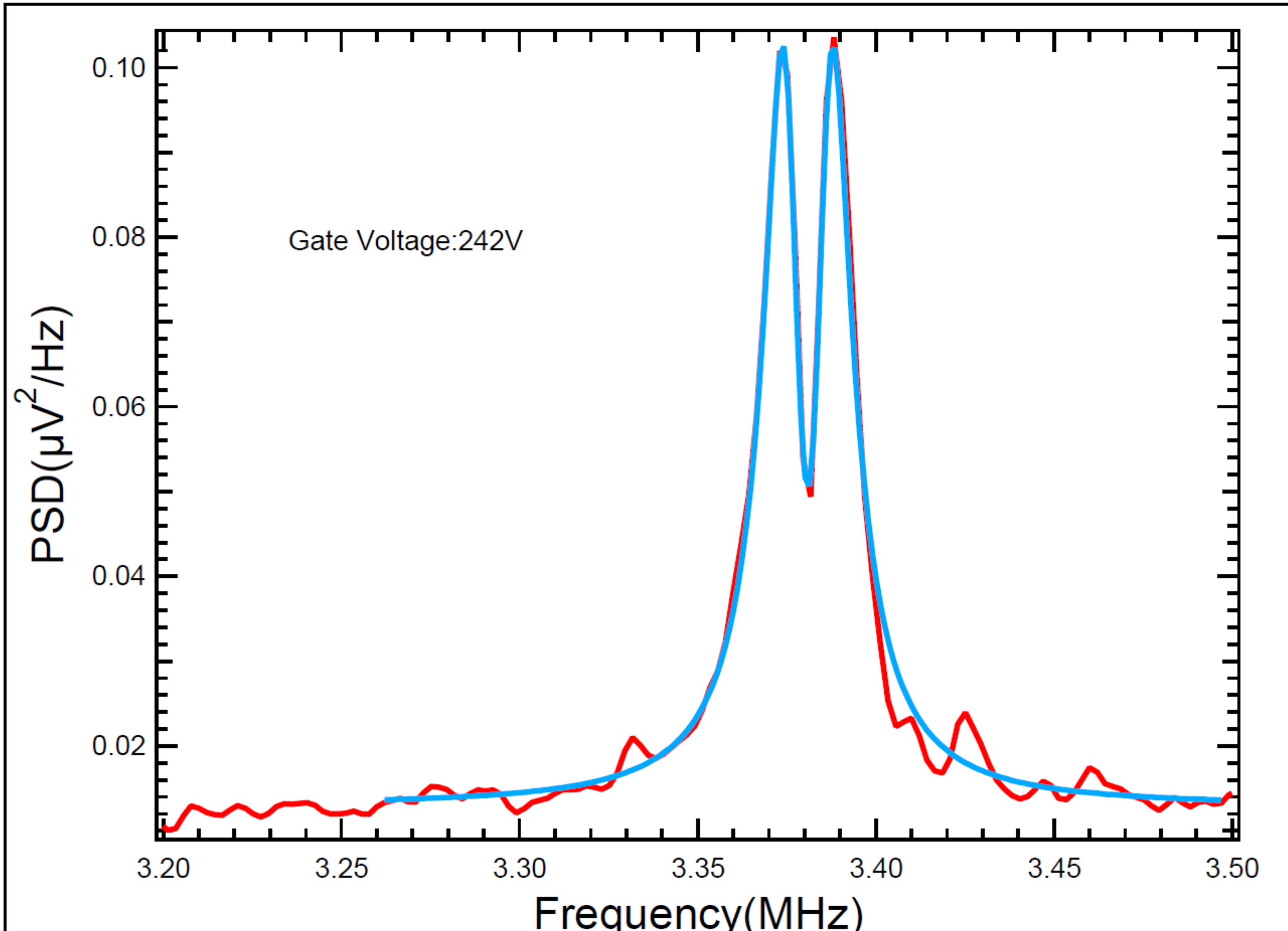


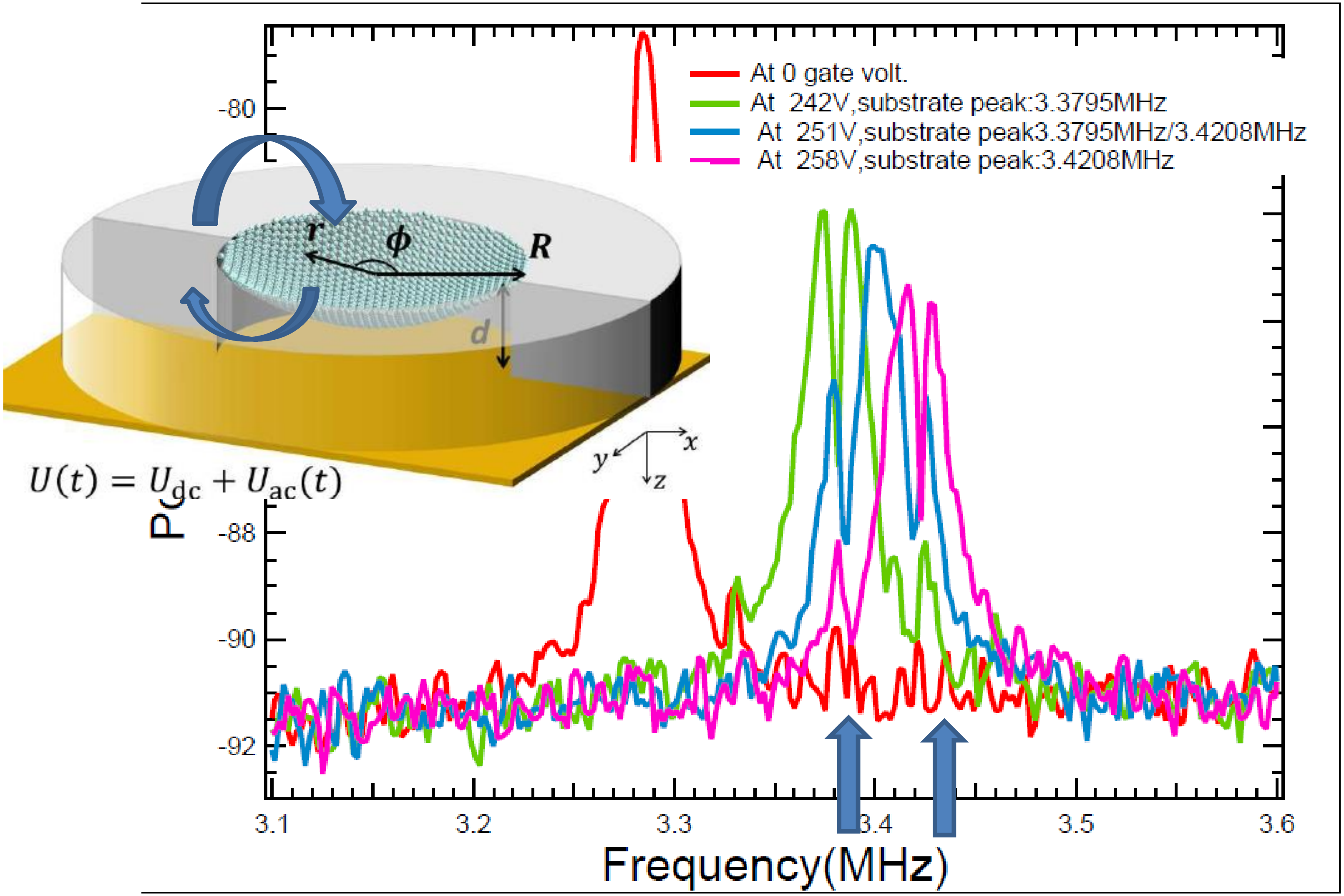
Gate Voltage:0V
PSD(μV²/Hz)
0.20
0.15
0.10
0.05
3.20
3.25
3.30
3.35
3.40
3.45
3.50
Frequency(MHz)


Gate Voltage:242V
PSD(μV²/Hz)
0.10
0.08
0.06
0.04
0.02
3.20
3.25
3.30
3.35
3.40
3.45
3.50
Frequency(MHz)



Gate Voltage:242V
PSD(μV²/Hz)
0.10
0.08
0.06
0.04
0.02
3.20
3.25
3.30
3.35
3.40
3.45
3.50
Frequency(MHz)

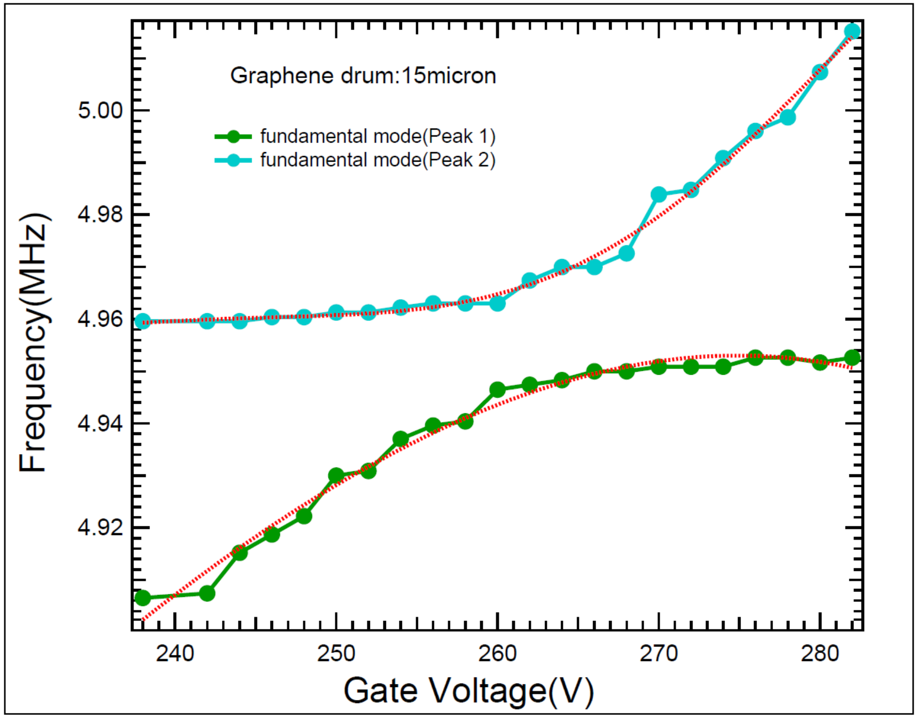
A single phonon in a superpostion



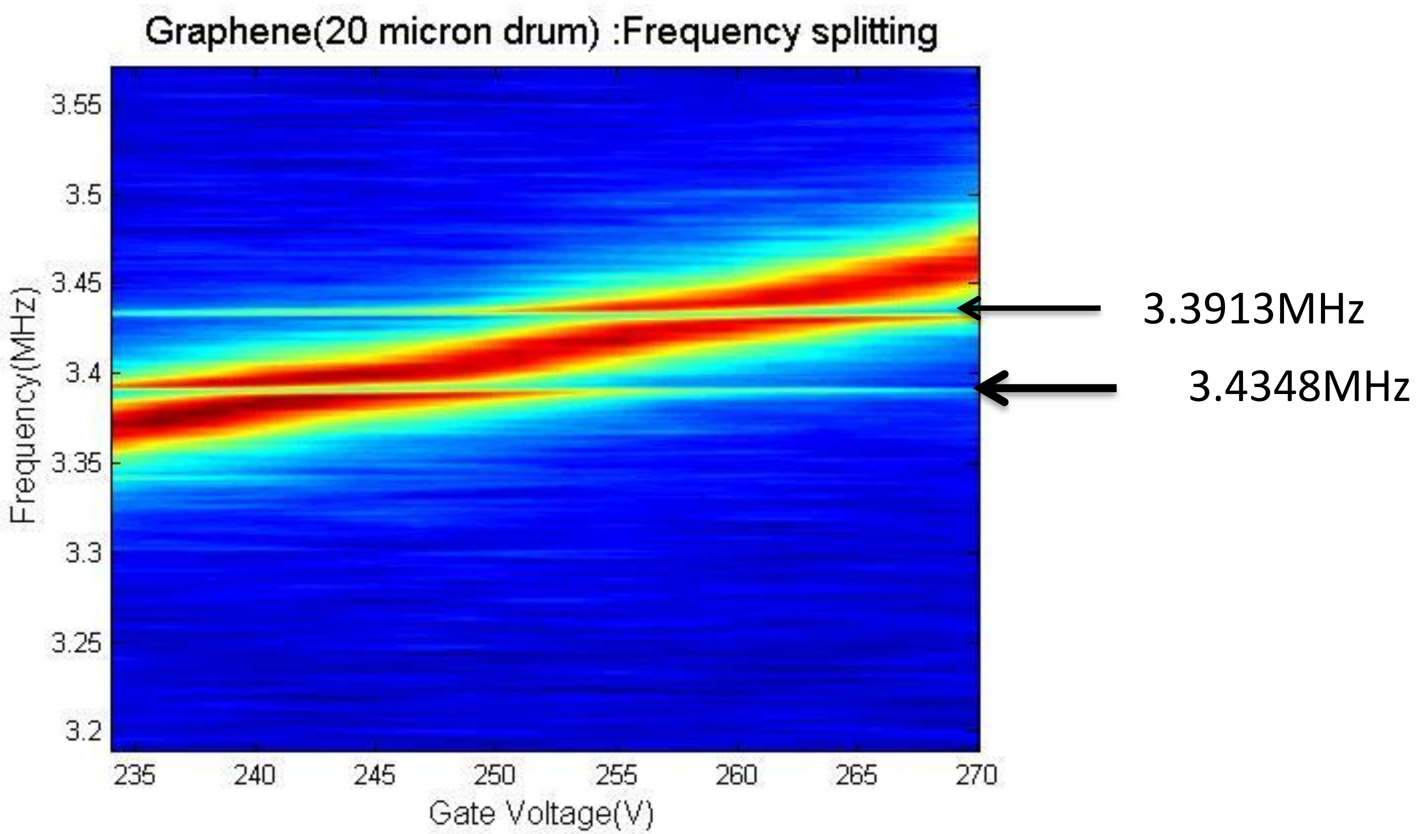
In collaboration with:

Kirill Bolotin (Max Planck) , Anjan Gupta, Amit Agarwal(IITK)

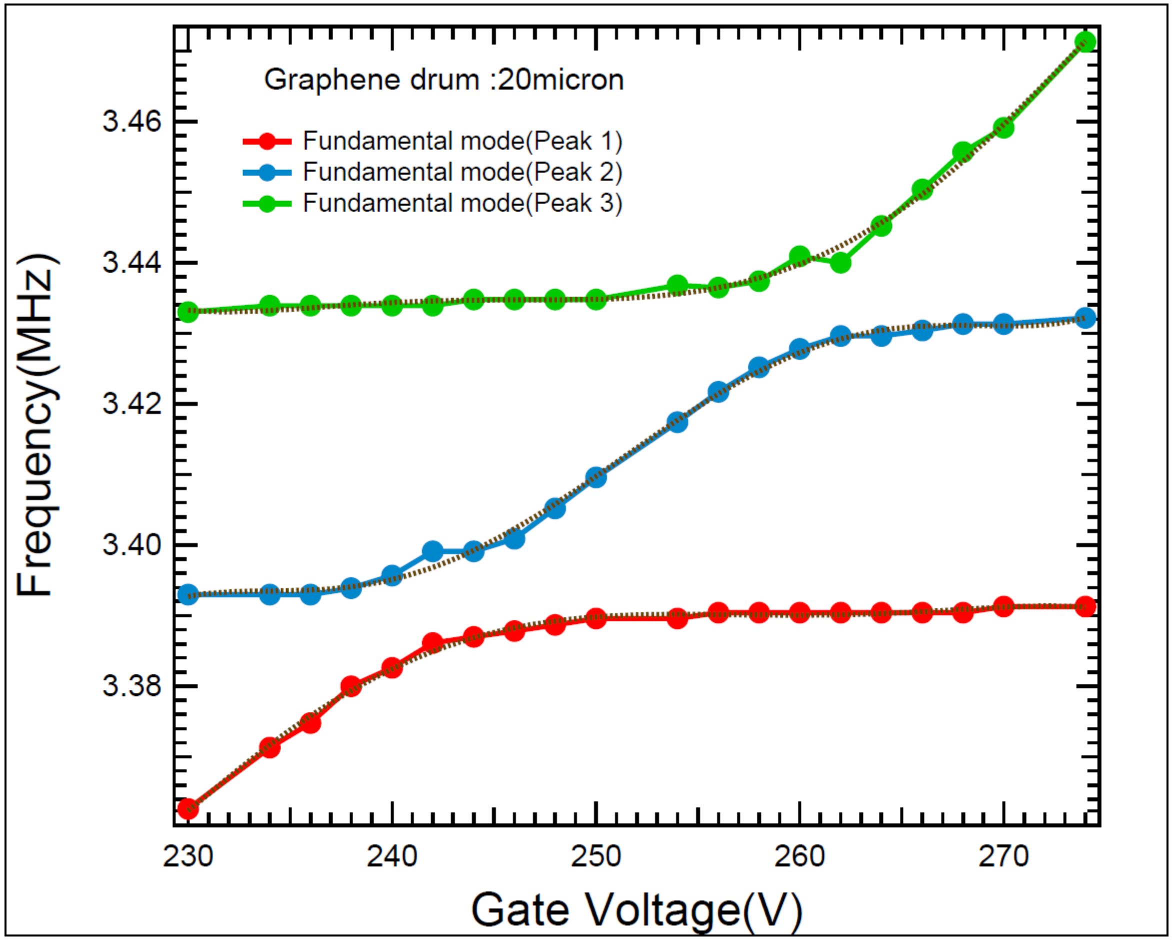
Avoided Level Crossing



Avoided Level Crossing

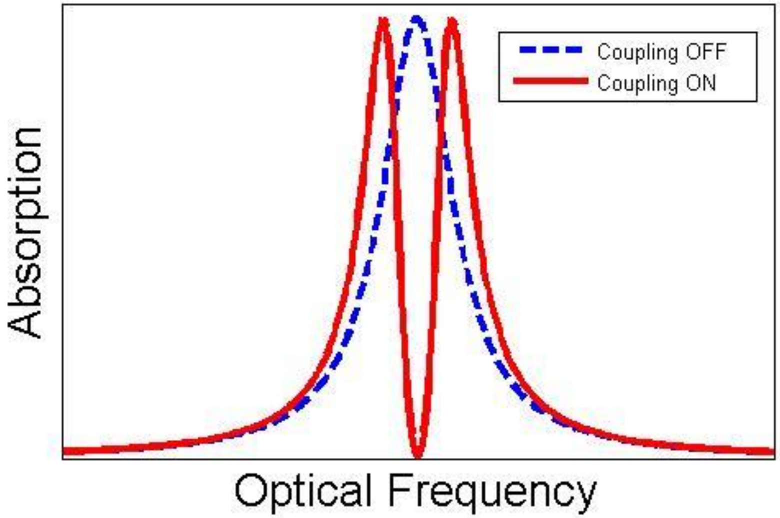


Mixing of three states: EIT with phonons!

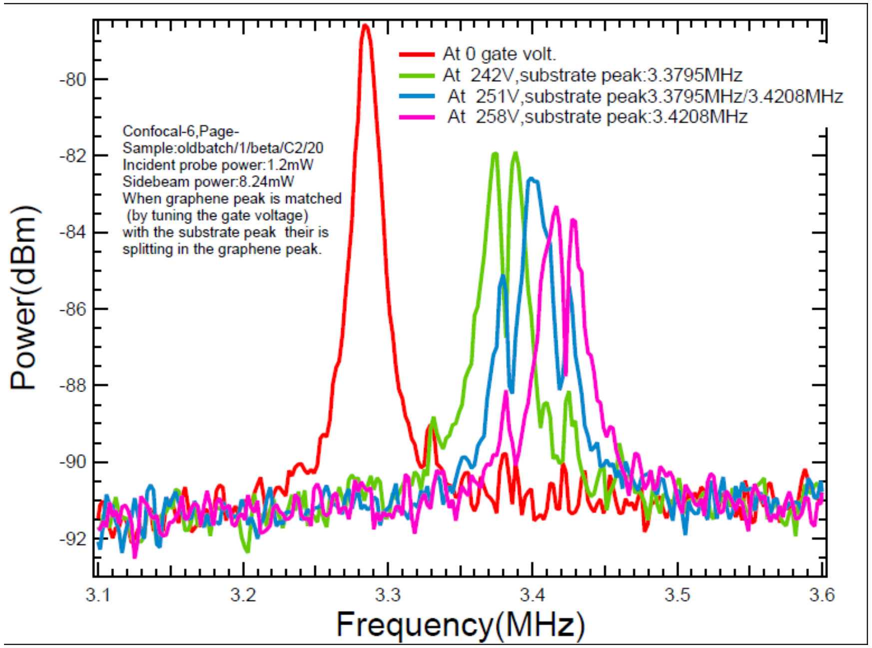


Frequency splitting:13KHz

Conclusion



Photons



Phonons

- Understanding and engineering superposition of discrete quantum states