Quantum simulation of Fermi Hubbard models in 2 dimensional electron gases

K.Kusudo, T.Byrnes, N.Y.Kim, N.Kumada, T.Fujisawa, Y.Yamamoto
Quantum Information Science Group, National Institute of Informatics, Arakawa laboratory, University of Tokyo,
NTT Basic Research Laboratory and E. L. Ginzton Laboratory, Stanford University

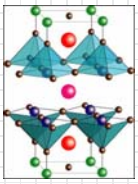
Quantum simulation and quantum many-body problems

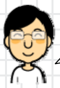
Wow, that's a really scary sounding title. Firstly, what's quantum simulation? Is that something like quantum computation?

You are right, they are related. Quantum simulation is a sub-field of quantum computation. The aim is to make devices for solving quantum many-body problems in physics.

Quantum many-body problems? What's that, and why do we want to even look at them?

Quantum many-body problems are problems that involve a large number of particles, all interacting quantum mechanically.





For example, this is the crystal structure of a high-temperature superconductor. It involves planes of copper (purple) and oxygen (brown) atoms, where electrons can move between. Researchers think that understanding this will unlock the secrets of high-temperature superconductivity.

Ok, but surely we can just simulate that on a normal computer right? My laptop is pretty fast.

That's the whole problem! Due to exponentially increasing problem size, even using the most powerful computers that exist today, we can only simulate about **30 quantum** particles.

Hmm.. that's not very many particles. So is this where the quantum computing bit comes in?

Exactly. About 26 years ago, Richard Feynman thought that the root of the problem was that we are using **classical** physics to simulate a **quantum** problem

Oh, you mean because computers work on classical physics and not quantum physics?

Yes. So if we incorporate quantum physics in the calculation, things should speed up.

But I heard that making a quantum computer is still going to take a really long time?

That's right... That's why we have tried for a more reachable goal, of making a purpose built device for solving a particular problem.

Oh ok. So unlike a normal computer that is programmable, in a quantum simulator you can only solve one problem?

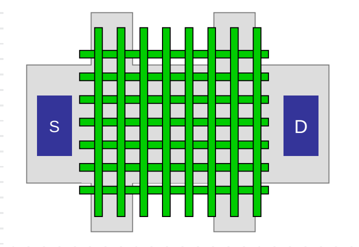
Correct. What we actually do is to make a similar version of the problem, including all the quantum mechanics in the original problem.

Wow! That sounds awesome! So how does it work?

One of my friendly assistants will guide you through our design.

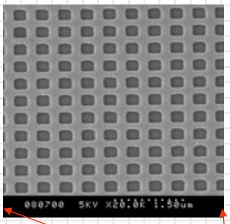
Semiconductor device design

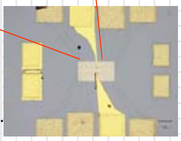
The experimental setup



Mesh gate (Green) is fabricated on Hall-bar structure. A DC voltage is applied to metallic mesh gate on a semiconductor GaAs substrate. This the periodic potential in 2DEGs which traps the electrons.

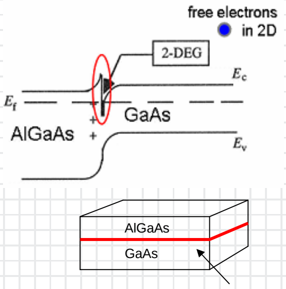
Pictures of fabricated device





The mesh gate is made by electron beam lithography.

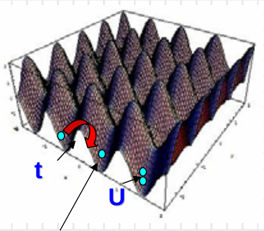
The substrate: GaAs/AlGaAs quantum well



2 dimensional electron gas

Due to the band structure in AlGaAs and GaAs, a high density electron layer is formed as the interface

Potential landscape of electrons



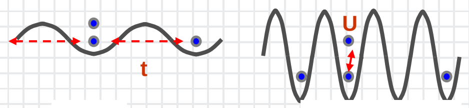
Electrons feel an effective egg-carton potential

Due to quantum mechanical tunneling, electrons can tunnel between minima of the periodic potential. There is an energy cost of have two electrons in a single site.

Hubbard model and the Mott-metal phase transition

Tunneling (hopping) term dominates

Repulsive interaction term dominates

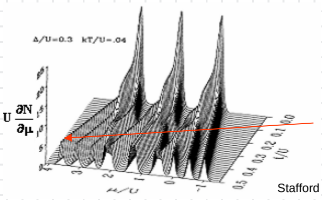


metal | Phase transition | **Mott insulator**

t >> U | U >> t

$$H = -t \sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$

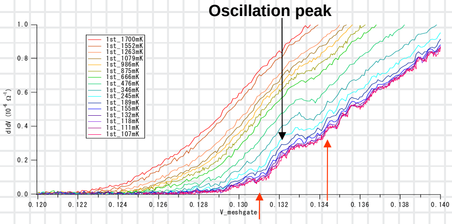
Expected conductance characteristics



Stafford PRL. 72, 3590 (1994)

Theoretical calculation of the change in particle number of a 2x2 Hubbard model for various t, U, and chemical potential μ .

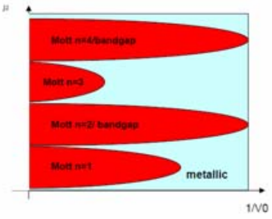
Experimental Results

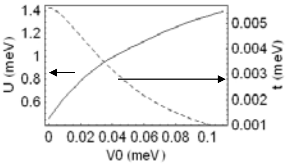


Some evidence of conductance oscillations were observed. The periodicity corresponded to ~meV, similar to estimates of U

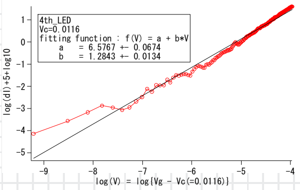
Conclusions

Evidence of conductance oscillations were observed in the semiconductor device described above. This is the first step towards building a simulator for the Fermi Hubbard model. Due to the presence of disorder in the system, the definition of the peaks were not very clear. The first objective is to reduce the disorder effects in order to more clearly observe the conductance oscillations. The aim will then be to observe the phase transition from a metal to a Mott insulator and make the phase diagram of Fermi Hubbard model.





Numerical estimate of U and t for device



Effects of disorder were consistent with predictions of percolation theory

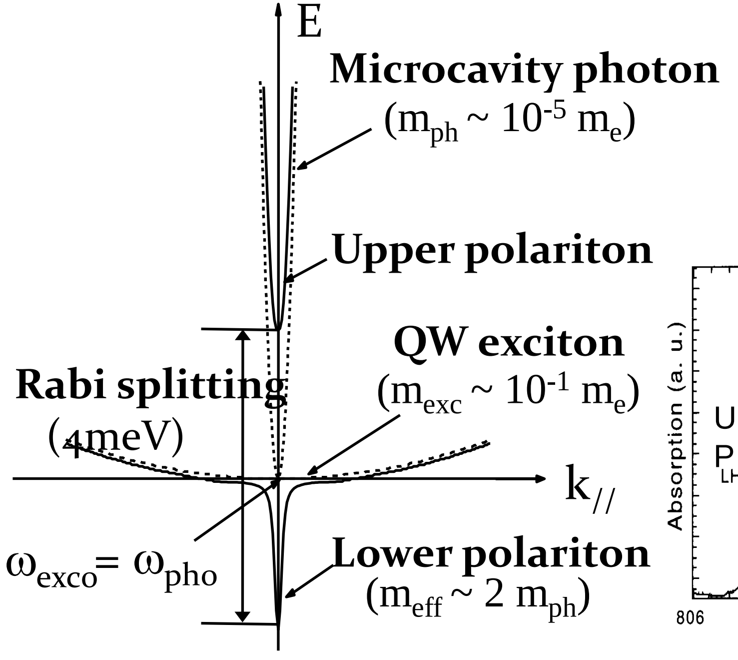
Dynamical Condensation of Exciton-Polaritons
– New Quantum liquid and Application to Quantum Emulator –

S. Utsunomiya, H. Deng, C.W. Lai, G. Roumpos, M.Fraser, N.Masumoto and Y.Yamamoto
National Institute of Informatics, University of Tokyo, Stanford University

A. Loeffler, S. Hoefling, and A. Forchel
Technische Physik, Universität Wurzburg

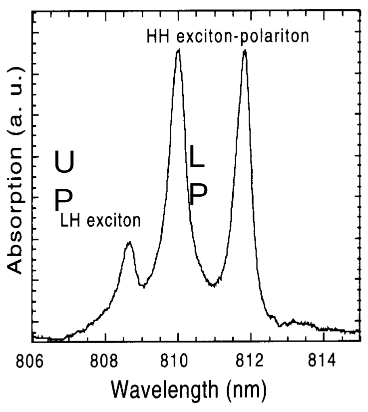
Semiconductor Cavity QED in Strong Coupling Regime
– Dressing Excitons with Electromagnetic Vacuum Field –

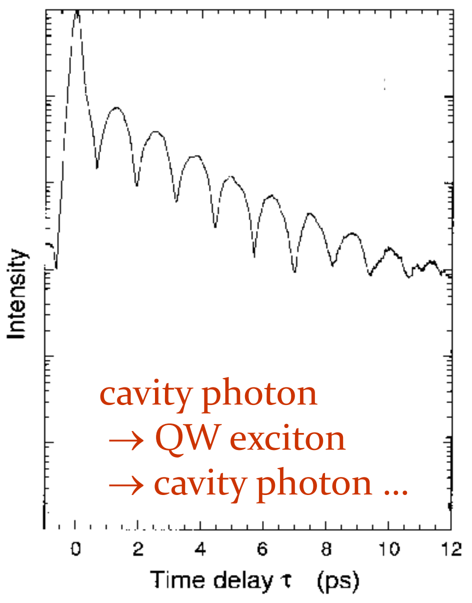
Exciton - polariton dispersion relation



$$\hat{\mathcal{H}} = \hbar\omega_p \hat{a}^+\hat{a} + \hbar\omega_e \hat{c}^+\hat{c} + \hbar\Omega\left(\hat{a}^+\hat{c} + \hat{a}\hat{c}^+\right) + \hat{\mathcal{H}}_{NL}$$

$\Omega \sim$ 1THz



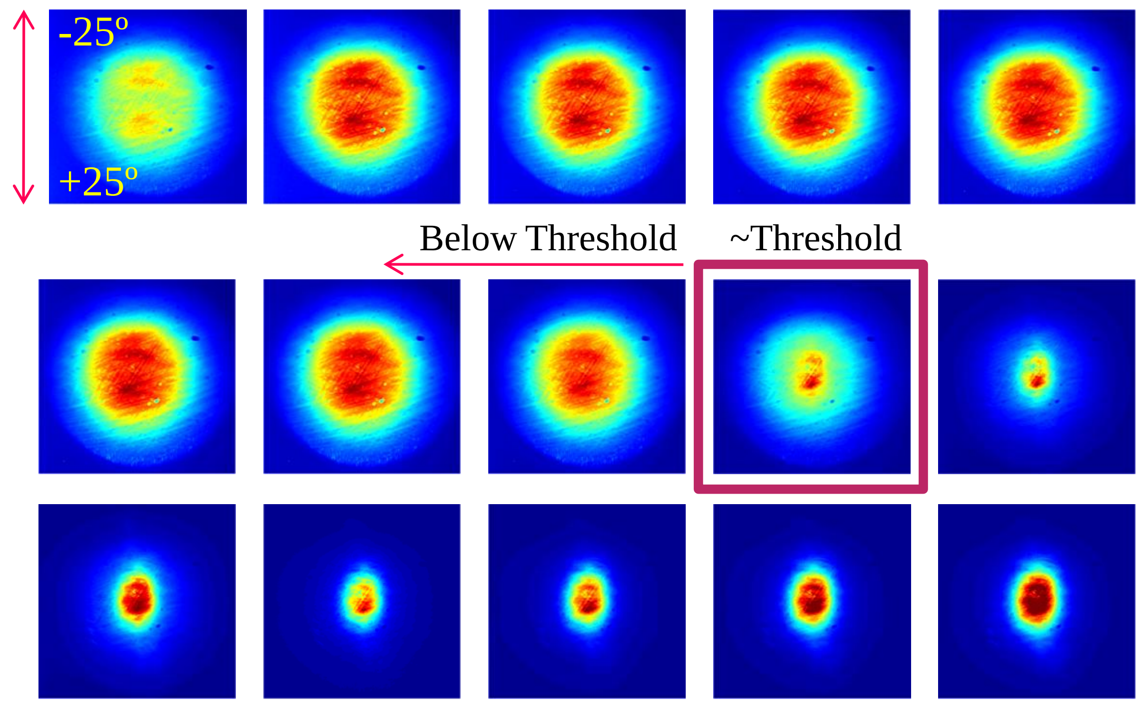


cavity photon
→ QW exciton
→ cavity photon ...

C. Weisbuch et al., Phys. Rev. Lett. 69, 3314 (1992) S. Jiang et al., Appl. Phys. Lett. 73, 3031 (1998)

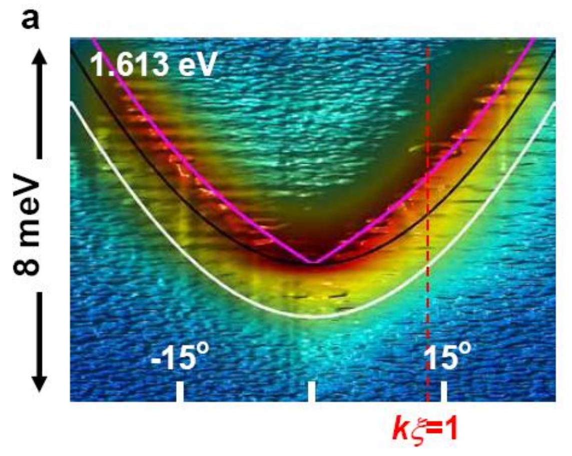
Far Field Pattern (momentum space distribution)

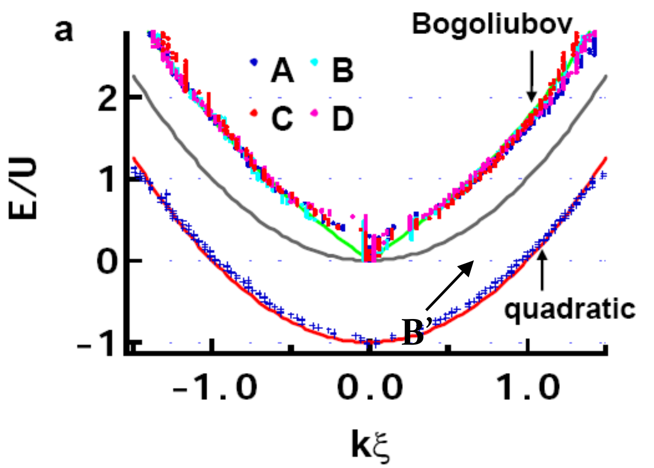
Thermal Polaritons ➔ aspect ratio~1:1 (isotropic) **50 × 50 degrees ($\Delta k = 7.5 \times 10^4\ cm^{-1}$)**



Condensate ➔ aspect ratio~1:2 (anisotropic) ➔ Heisenberg limit

Bogoliubov Excitation Spectrum
S. Utsunomiya et al., to be published in Nature Physics





White line : Single particle dispersion

Black line : $E = \dfrac{p^2}{2m}$

Pink line : Bogoliubov theory (polariton-polariton interaction) $E = \dfrac{p^2}{2m} + UN_0$

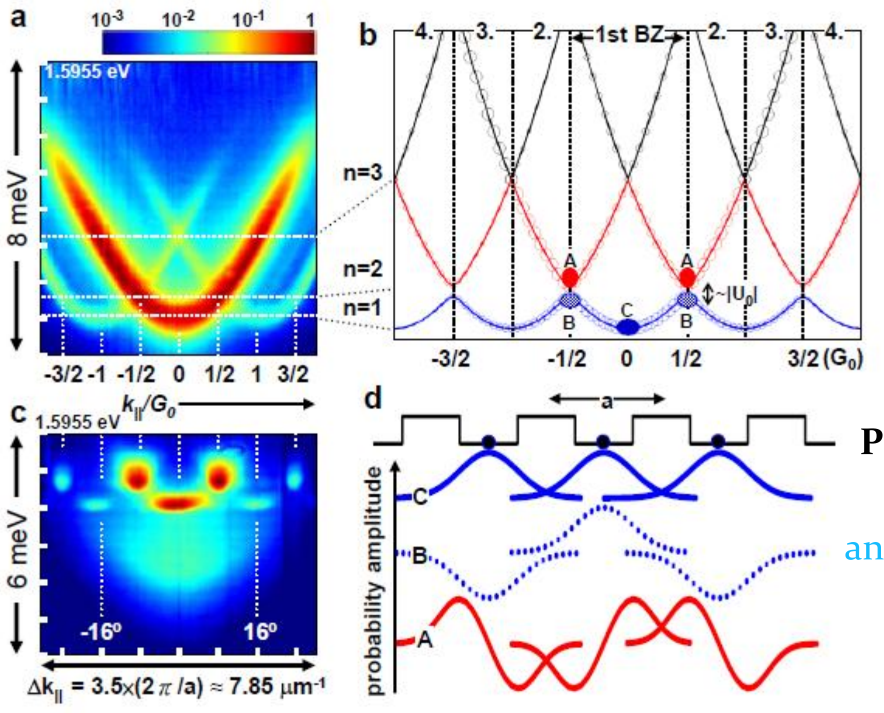
A : Δ = 1.4meV, p/p_{th} = 4
B : Δ = 0.82meV, p/pth = 8
B' : Δ = 0.82meV, p/pth = 0.0001
C : Δ = 4.2meV, p/pth = 4
D : Δ = -0.23meV, p/pth = 24

Bose-Hubbard model for exciton-polaritons
in a one-dimensional periodic potential

C.W. Lai, et al., Nature 450, 529 (2007)

Below threshold

Above threshold



Periodic potential

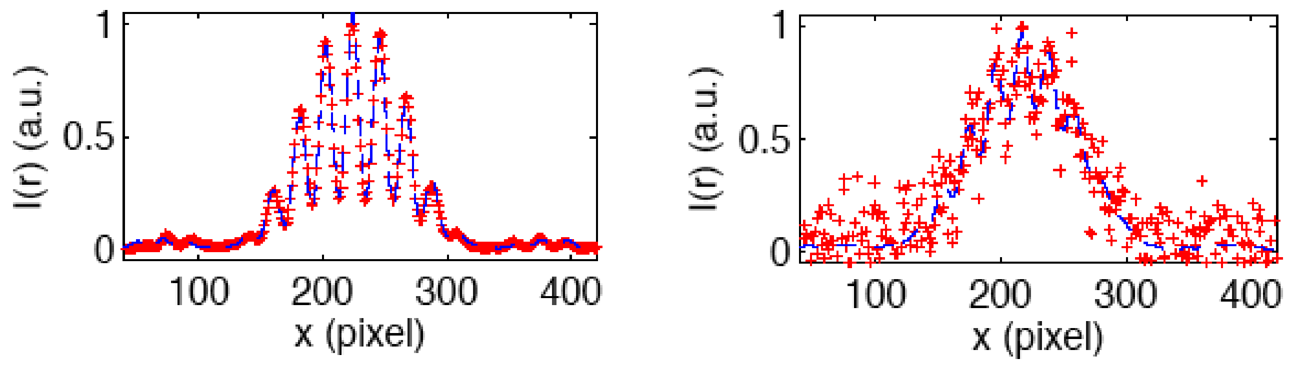
"o-state" (s-like)
anti-bounding π-state (s-like)
not selected
"π-state" (p-like)

Condensation of Exciton-Polaritons
A. Imamoglu et al., Phys. Rev. A 53, 4250 (1996)

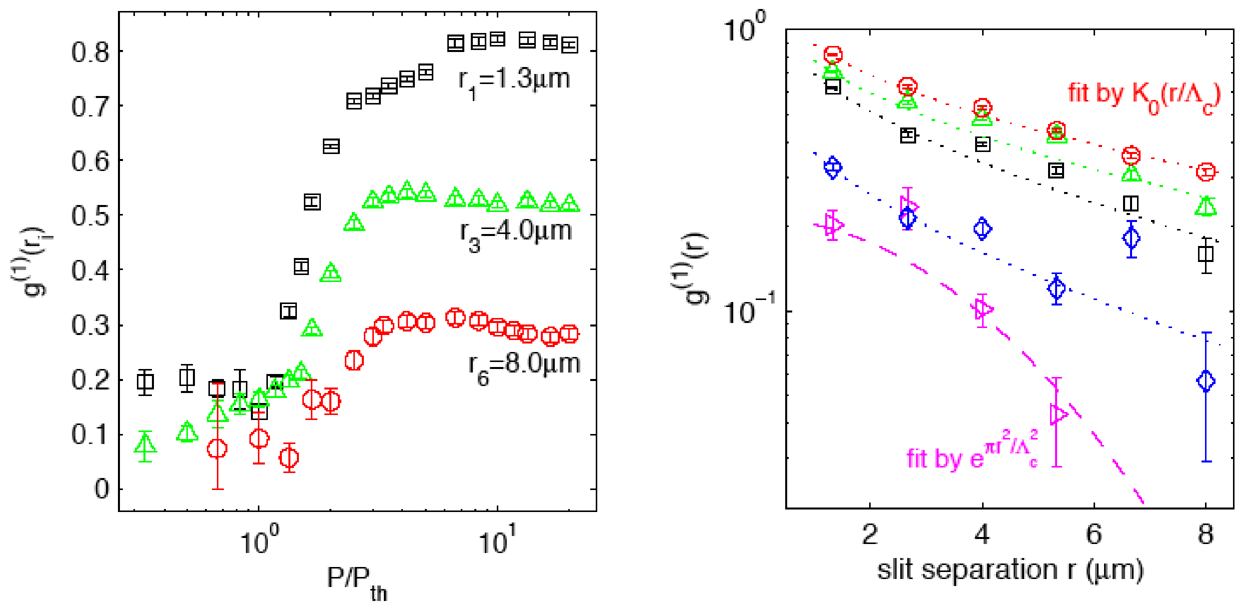
- **Extended phase coherence reinforced by a cavity field**
  ⇨ **suppressed localization, disorder and inhomogeneous broadening which are notorious enemies to exciton BEC.**
- **Light effective mass by dressing with a cavity field**
  $m_{polariton} \sim 10^{-4}\ m_{exciton} \sim 10^{-8}\ m_{atom}$
  $n\lambda_T^3 = n\left(\dfrac{2\pi\hbar^2}{mk_BT_c}\right)^{\frac{3}{2}} \sim 2.62$ ➡ higher critical temperature $(\gtrsim 10^4 T_{exc} \sim 10^8 T_{atom})$
  lower particle density $(\lesssim 10^{-6} n_{exc} \sim 10^{-12} n_{atom})$
  ⇨ **suppressed dissociation of excitons**
- **Main decay channel = Photon leakage from the cavity with k andE conservation**
  ⇨ **direct experimental access to polariton energy-momentum dispersion and population distribution**

Off Diagonal Long Range Order (Spatial Coherence)
H. Deng et al., Phys. Rev. Lett. 99, 126403 (2007)

Interference Pattern through Young's Double Slit Interferometer



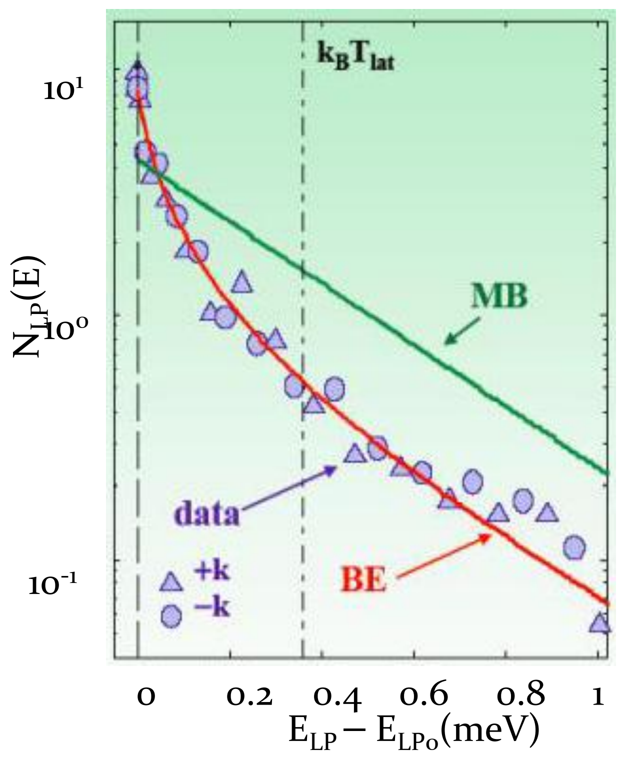
Above the threshold **Below the threshold**



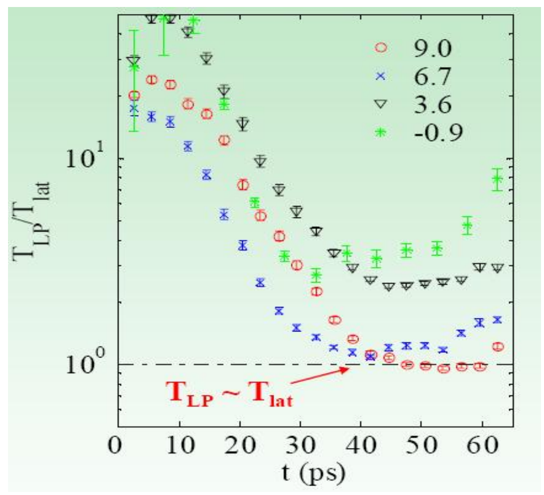
Quantum Degeneracy at Thermal Equilibrium Condition
H. Deng et al., Phys. Rev. Lett., 97 146402 (2006)

Temporal BE distribution observed at blue detuning regime (Δ=6.7 meV)

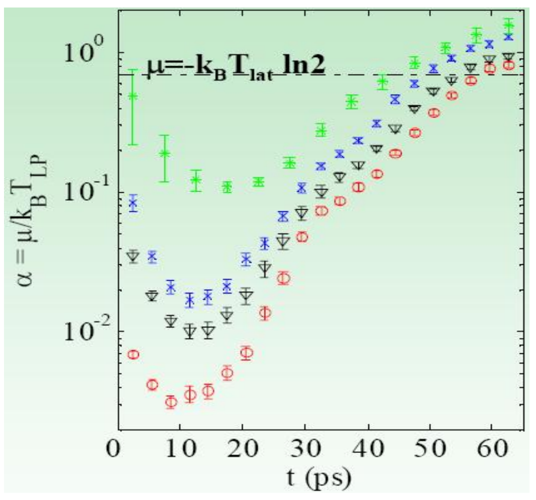
T_{LP}=4.4K, μ=–0.04 meV < BEC threshold (– 0.35 meV)



Time resolved T_{LP} and μ



LP cooled to a lowest T_{LP} @ t ~ 35 ps
$T_{LP} \approx T_{LP}$ for Δ = 6.7 meV, 9.0 meV



$\mu \sim -0.1\ k_BT_{LP}$
when LP reaches equilibrium