Fragmented-condensate solid of dipolar excitons

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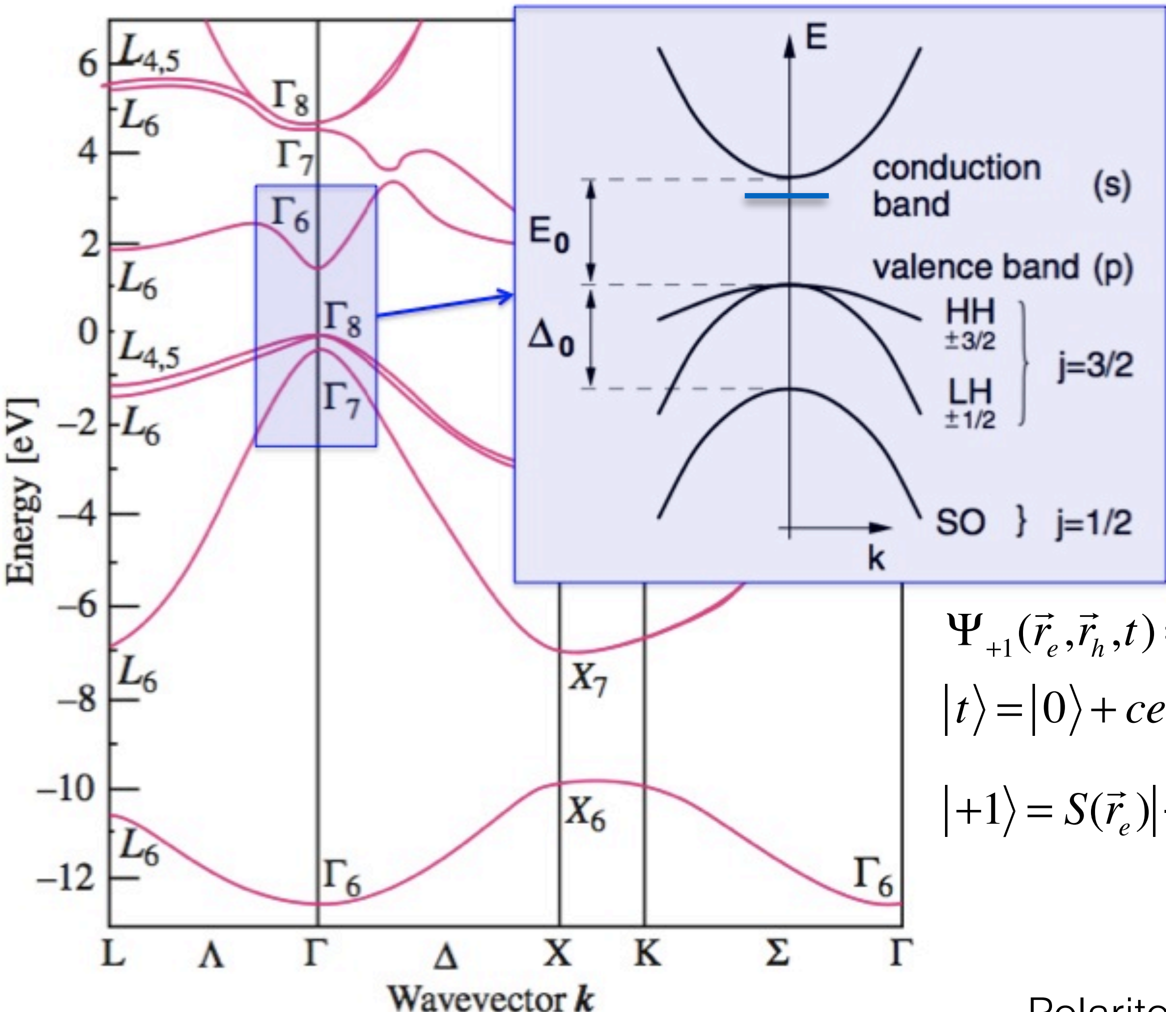
Plan:

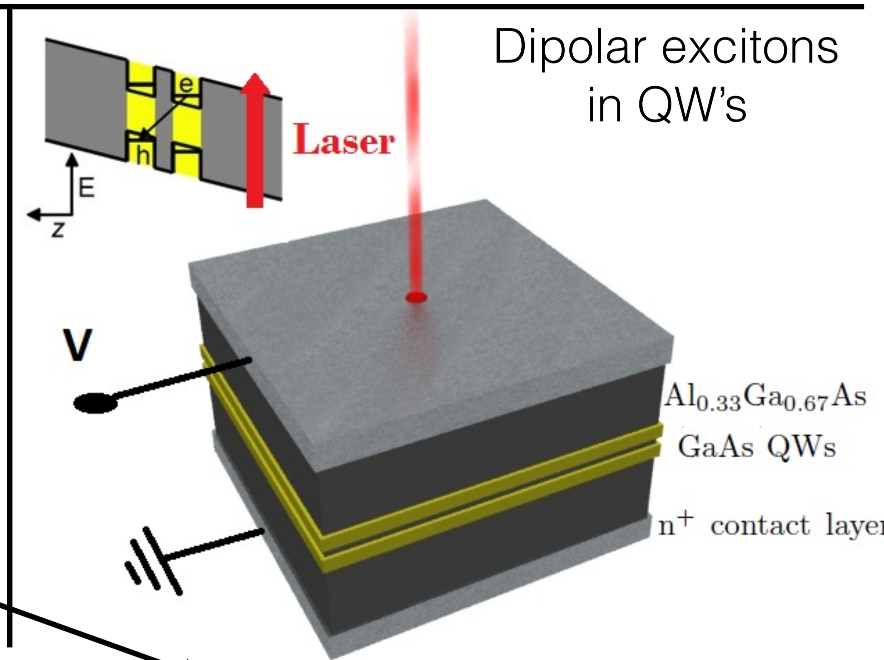
1. Introduction : dipolar excitons in semiconductor quantum wells
2. 2002 discovery of the MOES
3. Theory of dipolar 1D BEC (Part I): stable dilute supersolid
4. Theory of dipolar 1D BEC (Part II): fragmented condensate
5. Comparison with the experiment

Wannier-Mott excitons in direct band-gap semiconductors



Exciton-polaritons in bulk GaAs crystals

Dipolar excitons in QW's



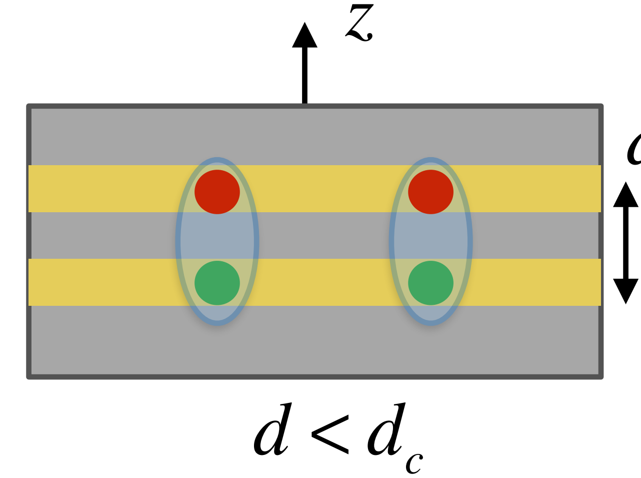
$$\psi(\vec{r}_e,\vec{r}_h)=\frac{e^{i\vec{K}\vec{R}}}{\sqrt{V}}\varphi(\vec{\rho})$$

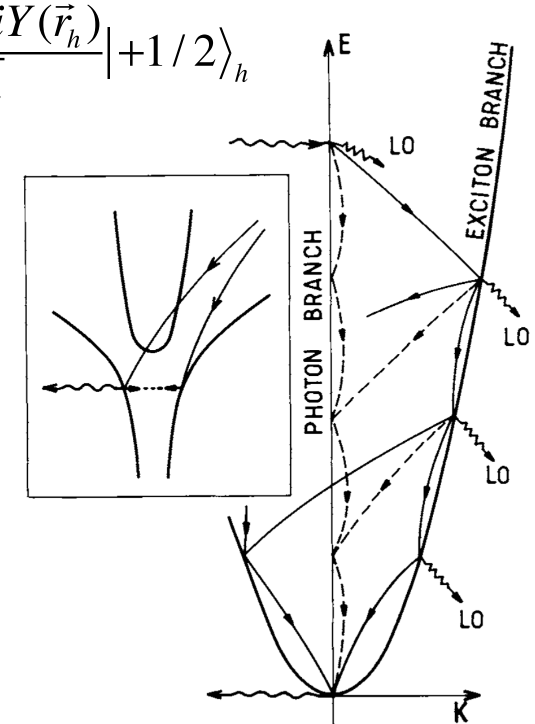
$$\Psi_{+1}(\vec{r}_e,\vec{r}_h,t)=\psi(\vec{r}_e,\vec{r}_h)|t\rangle$$

$$|t\rangle=|0\rangle+ce^{-i\omega t}|+1\rangle$$

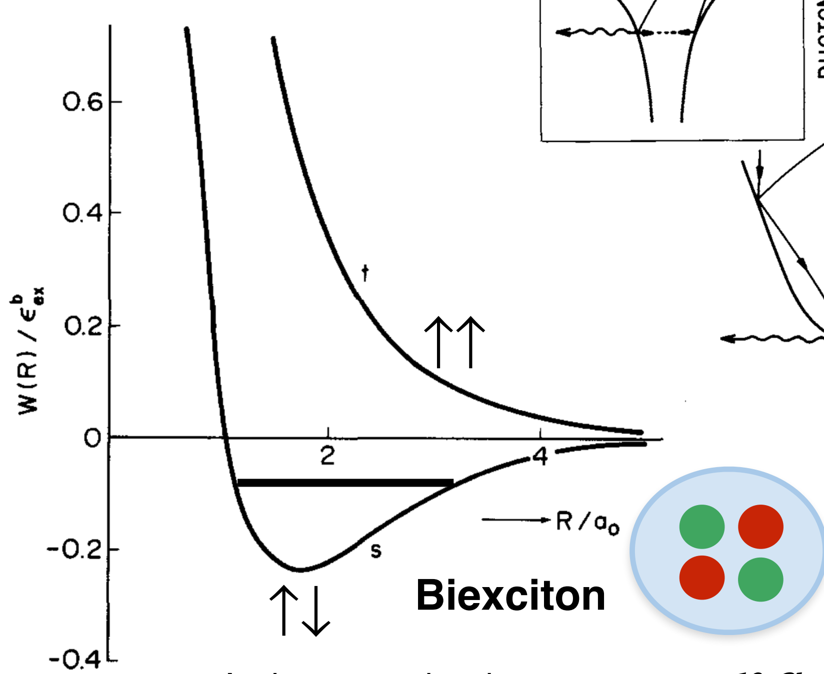
$$|+1\rangle=S(\vec{r}_e)|-1/2\rangle_e\otimes\frac{X(\vec{r}_h)+iY(\vec{r}_h)}{\sqrt{2}}|+1/2\rangle_h$$

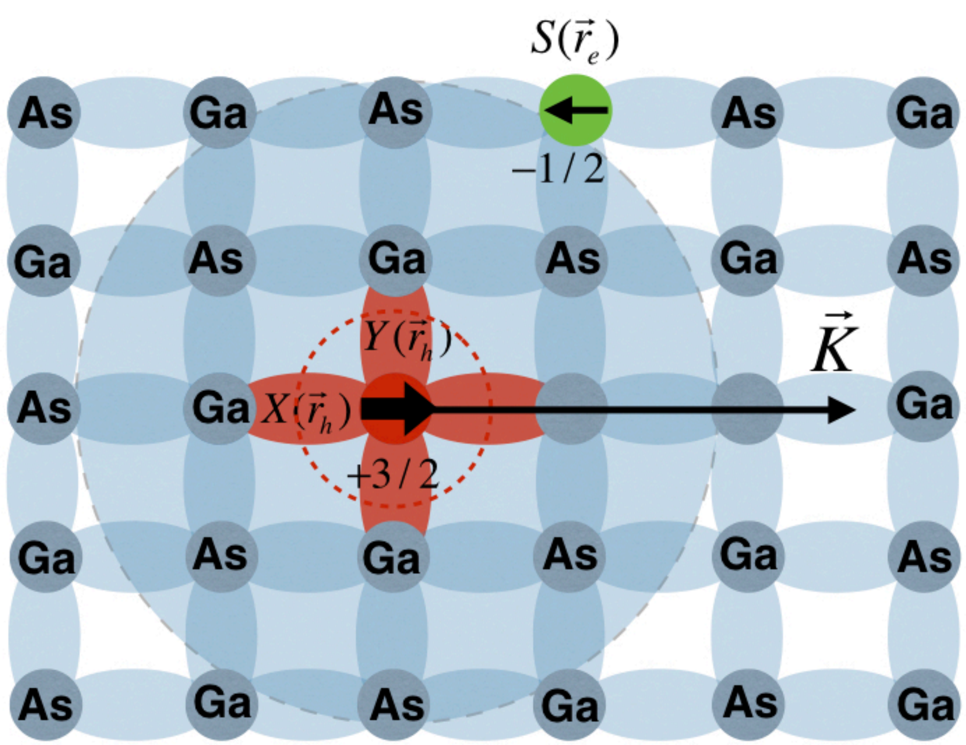
$$\vec{P}(\vec{r},t)=\left\langle\hat{\vec{d}}(\vec{r})\right\rangle\propto\psi^*(\vec{r},\vec{r})\left(\vec{e}_x\cos(\omega t)+\vec{e}_y\sin(\omega t)\right)$$



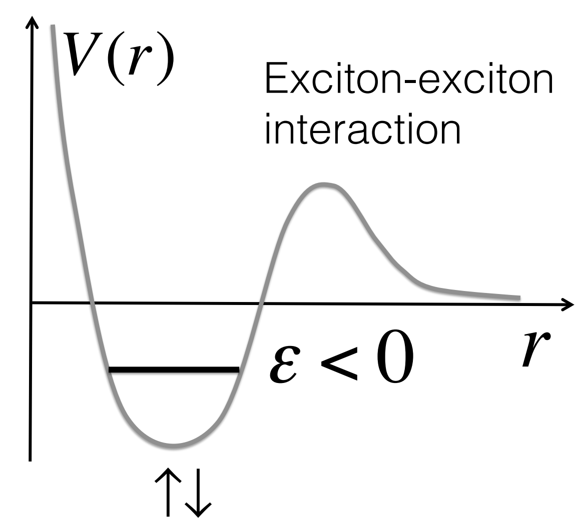


Polariton-polariton interaction:





Exciton-exciton interaction



At low excitation power $na_B \ll 1$ ➡ dilute gas

Exciton BEC:

- An exciton Bose-Einstein condensate is a source of the spatially coherent PL
- Coherence of the PL is suppressed in a biexciton BEC
- The condensate is dilute in typical experimental conditions.

However, dense regime is also possible. Example: dipolar excitons.

- As in atomic BEC’s, the two-body interactions play an important role.
- The dipolar interaction is long-range

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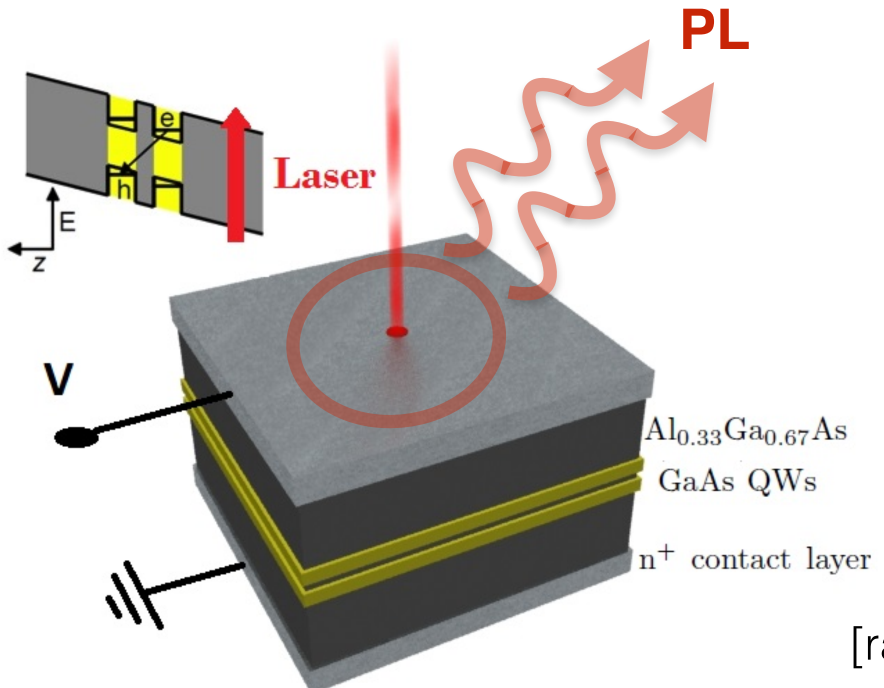
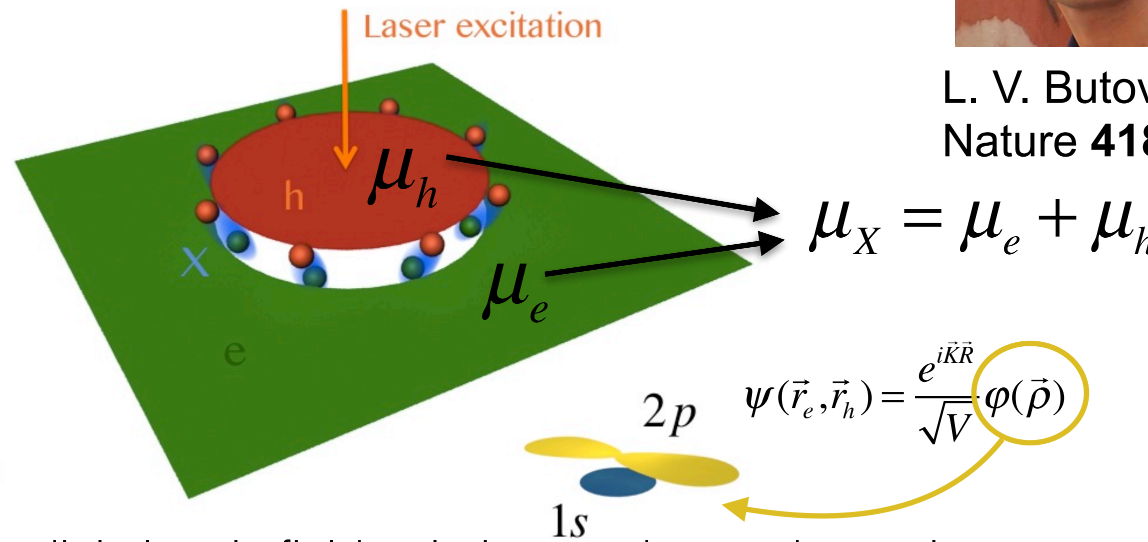
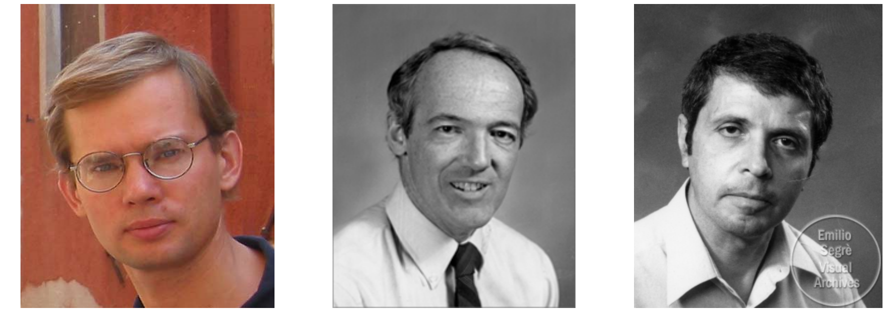
Macroscopically ordered exciton state (MOES)



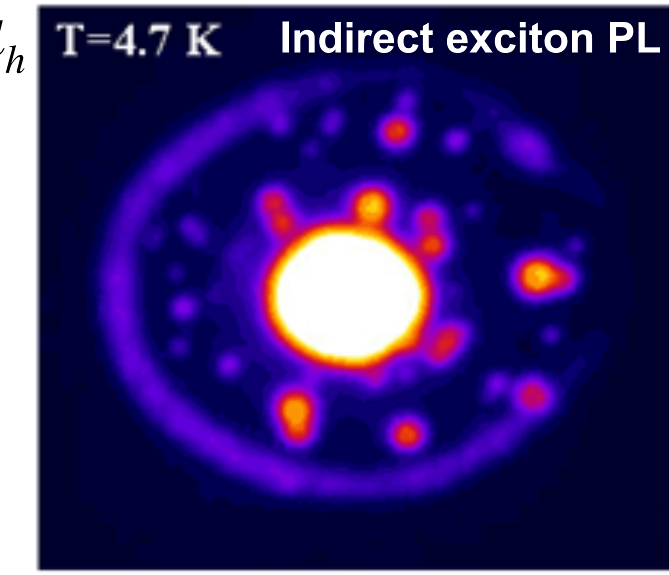
Cold dipolar excitons at the ring:

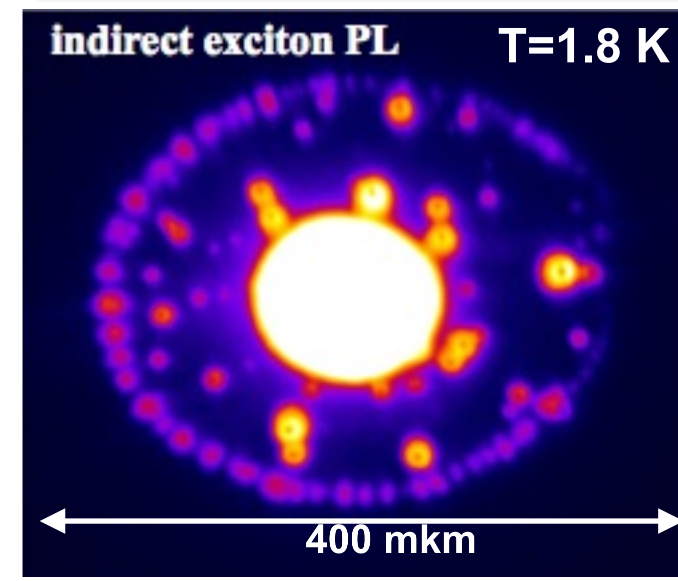


[radial electric field polarizes and traps the excitons, see S. V. Andreev, PRB **94**, 165308 (2016)]

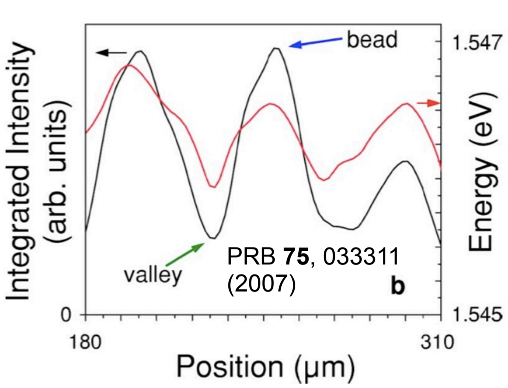


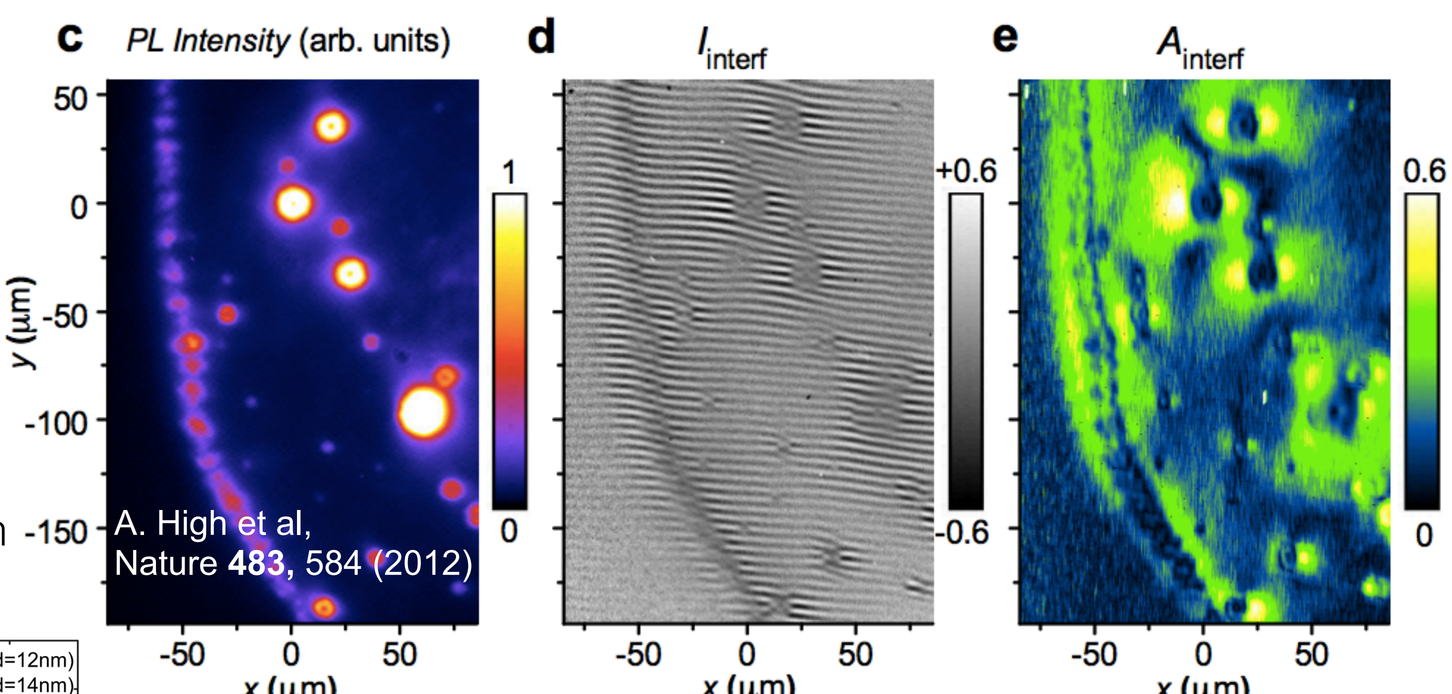
L. V. Butov, A. C. Gossard and D. S. Chemla, Nature **418**, 751 (2002)



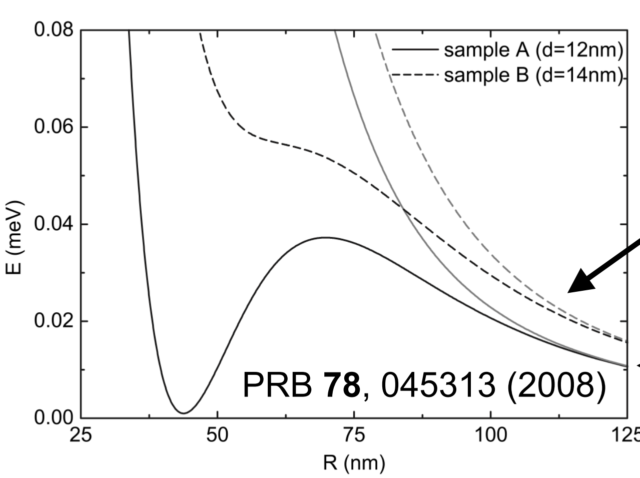


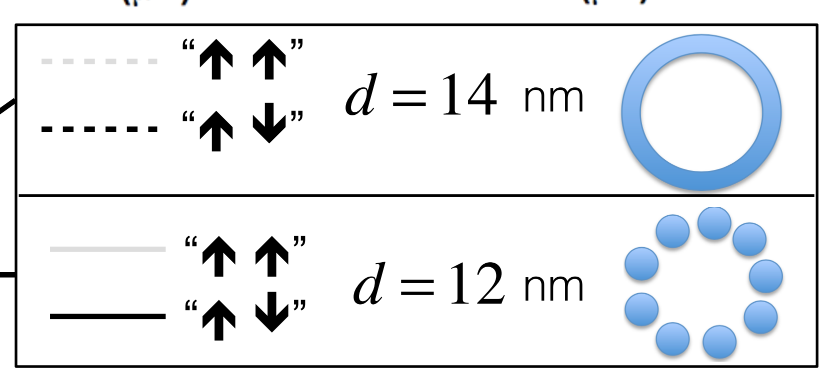
Repulsive interaction in the MOES:

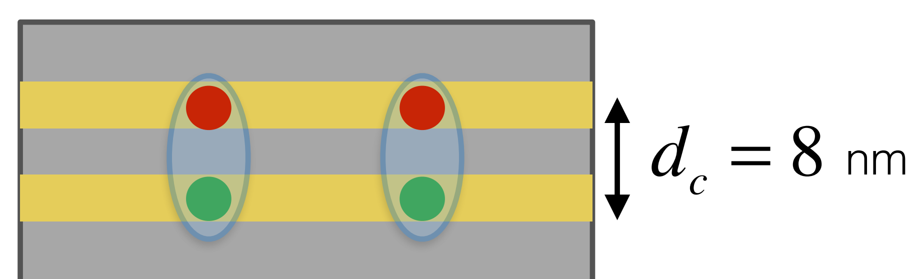




Calculated exciton-exciton interaction potentials:







Experimental facts about the MOES:

- The ring consists of independent quasi-1D segments separated by defects
- There is a critical temperature for the transition
- Coherence length is on the order of the size of one bead and much less than the length of a segment
- Coherence is suppressed in the centres of the beads
- Repulsive interaction
- The external ring has been observed by several experimental groups in the samples with $d<d_c$ and $d>d_c$.

The fragmented state of the ring has been observed only by the Butov group in the sample with d approaching d_c from above.

Hypothesis:

- One can use thermodynamics to describe cold exciton gases in the segments of the ring.

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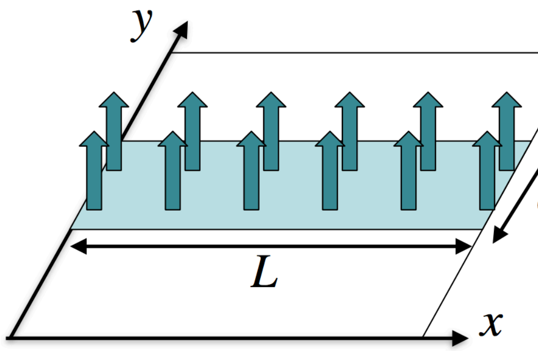
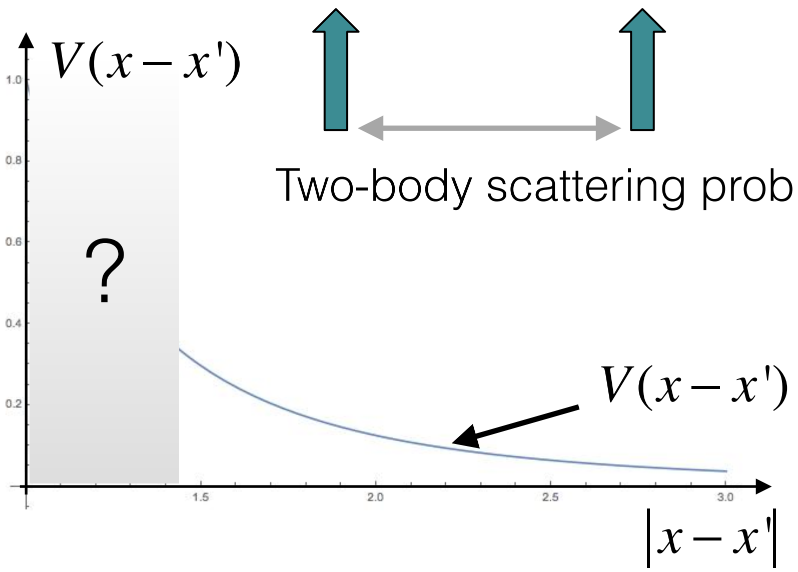
Stable dilute supersolid of quasi-1D dipolar bosons



$$a_y = \sqrt{\frac{\hbar}{m\omega_y}}$$



$$V(x-x') \approx \frac{\hbar^2}{m}\frac{r_*}{|x-x'|^3}$$

Two-body scattering problem

$$f^{1D}(p_x, q_x) = \frac{g^{2D}}{\sqrt{2\pi}a_y} + \frac{\hbar^2}{mr_*}\left(|p_x - q_x| r_*\right)^2 \ln(|p_x - q_x| r_*)$$

$k_x r_* \ll 1$

S. V. Andreev, PRB **92**, 041117(R) (2015)

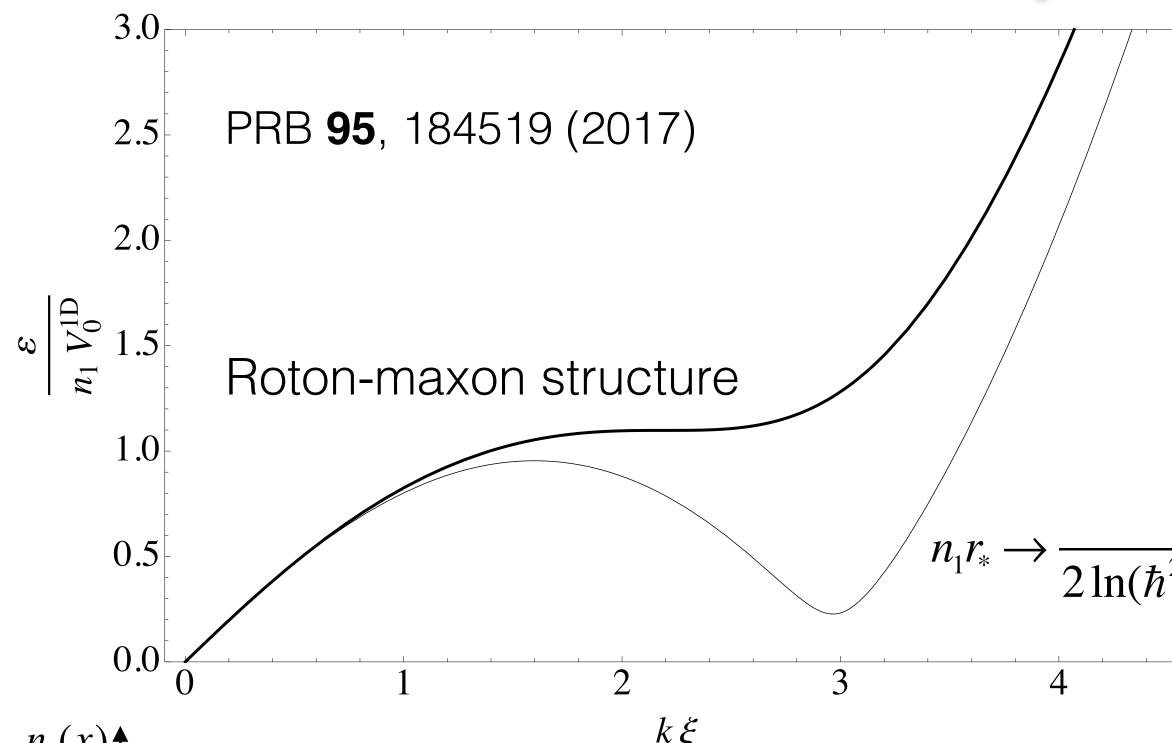
Beliaev diagrammatic approach:
S. T. Beliaev,
Sov. Phys. JETP **34**, 289 (1958)

$$T = 0$$

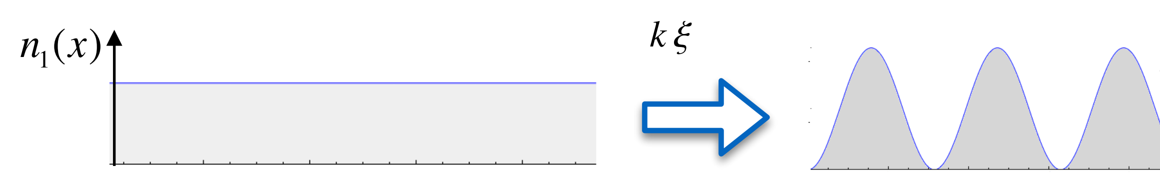
$$\hat{H}^{1D} = \sum_{k_x}\left(\frac{\hbar^2 k_x^2}{2m} + \frac{\hbar\omega_y}{2}\right)\hat{c}^+_{k_x}\hat{c}_{k_x} + \frac{1}{2L}\sum_{k_x, p_x, q_x} V(p_x - q_x)\hat{c}^+_{k_x+p_x}\hat{c}^+_{k_x-p_x}\hat{c}_{k_x+q_x}\hat{c}_{k_x-q_x}$$

Bogoliubov transformation

Elementary excitation spectrum:



$$n_1 r_* \to \frac{1}{2\ln(\hbar^2 a_y / mg^{2D} r_*)}$$



$$\xi = \frac{\hbar}{\sqrt{2mg^{2D}n}}$$

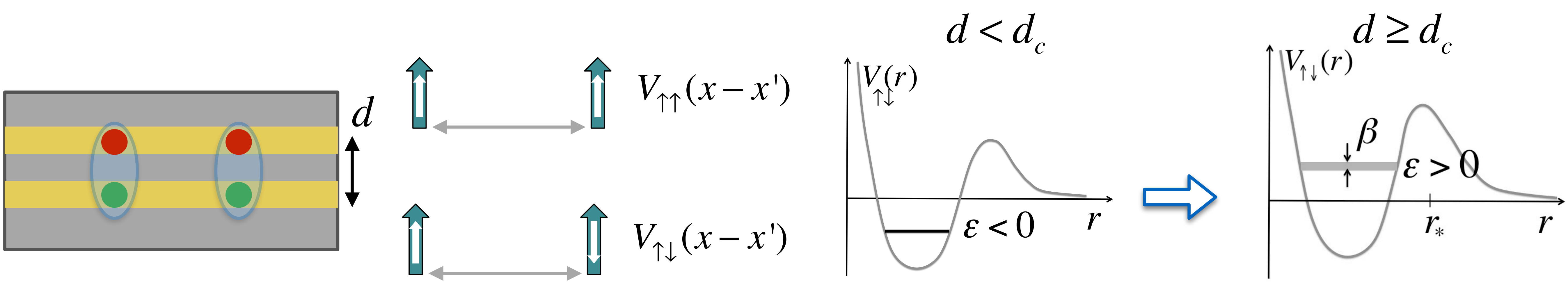
Assumptions:
$a_y \gg r_*$
$\frac{mg^{2D}}{\hbar^2} < 1$
$\frac{mg^{2D}}{\hbar^2} \ll n_1 a_y \ll \frac{\hbar^2}{mg^{2D}}$
$n_1 r_* \ll 1$

Challenge for the theory:

$$n_1 r_* \to \frac{1}{2\ln(\hbar^2 a_y / m g^{2D} r_*)} \quad \Leftrightarrow \quad \frac{m g^{2D}}{\hbar^2} \to \frac{a_y}{r_*} e^{-\frac{1}{2 n_1 r_*}} \qquad n_1 r_* \ll 1$$

Coupling constant exponentially small
in the diluteness parameter - an almost non-interacting gas!

Solution: a resonantly paired binary mixture



$$g_{\uparrow\uparrow} = g_{\downarrow\downarrow} \equiv g_{bg} > 0$$

$$g_{\uparrow\downarrow} = g_{bg} + \frac{\hbar^2}{m} \frac{2\pi}{(2\mu - \varepsilon)/\beta + \ln(1/k_c r_*)}$$

S. V. Andreev, PRB **94**, 140501(R) (2016)

$$\hat{H}^{1D} = \sum_{\sigma,k_x} \left(\frac{\hbar^2 k_x^2}{2m} + \frac{\hbar\omega_y}{2} \right) \hat{c}^+_{\sigma,k_x} \hat{c}_{\sigma,k_x} + \frac{1}{2L} \sum_{\sigma,\sigma',k_x,p_x,q_x} f^{1D}_{\sigma\sigma'}(p_x,q_x) \hat{c}^+_{\sigma,k_x+p_x} \hat{c}^+_{\sigma',k_x-p_x} \hat{c}_{\sigma,k_x+q_x} \hat{c}_{\sigma',k_x-q_x}$$

$$f^{1D}_{\sigma\sigma'}(k_x', k_x) = \frac{g_{\sigma\sigma'}}{\sqrt{2\pi} a_y} + \frac{\hbar^2}{m r_*} \left(|k_x' - k_x| r_* \right)^2 \ln(|k_x' - k_x| r_*)$$

Beliaev approach for a binary mixture:
M. Baglai, O. Utesov and S. V. Andreev
paper under preparation

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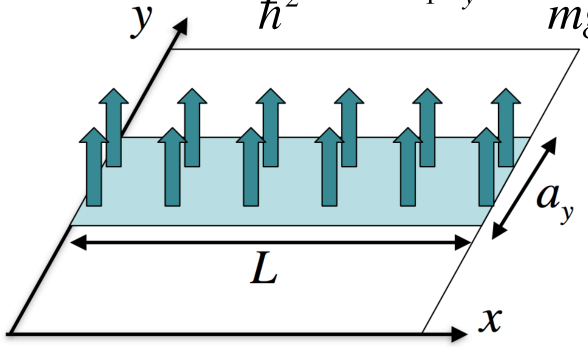
Fragmentation of the supersolid

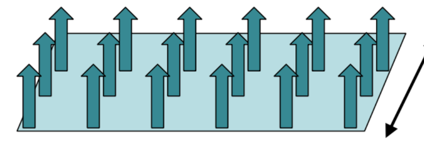
$$\frac{mg^{2D}}{\hbar^2} \ll n_1 a_y \ll \frac{\hbar^2}{mg^{2D}}$$



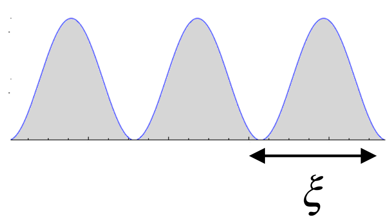
$$a_y = \sqrt{\frac{\hbar}{m\omega_y}}$$

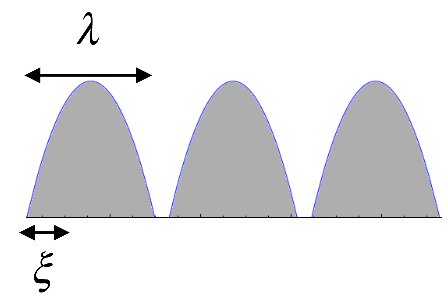
$$n_1 a_y \gg \frac{\hbar^2}{mg^{2D}}$$

2D Thomas-Fermi cigar

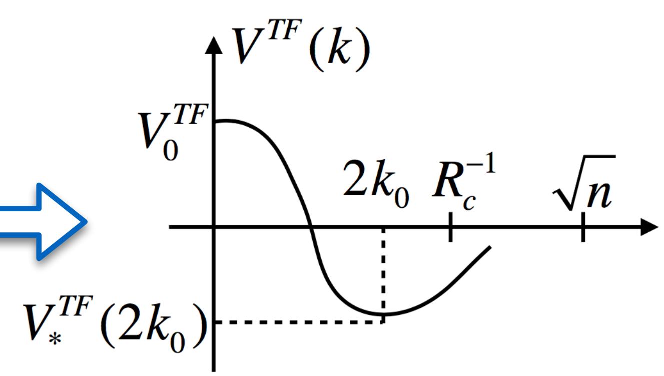


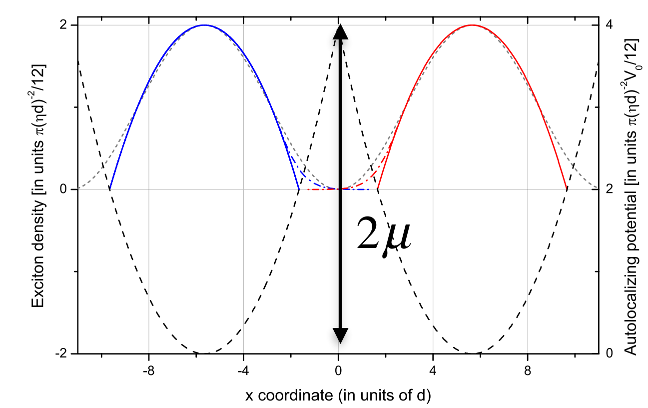
$$R_c = a_y\left(\frac{3}{2}\frac{mg}{\hbar^2}n_1 a_y\right)^{1/3}$$





$$f^{1D}(k) = \frac{g^{2D}}{\sqrt{2\pi}a_y} + \frac{\hbar^2}{mr_*}(kr_*)^2\ln(kr_*)$$





$$F = \cancel{E^{TF}} + E_{kin} - k_BT\ln Z_\Phi$$

$$\frac{dF}{dJ} = 0 \Rightarrow$$

PRL **110**, 146401 (2013)

$$\boxed{\Rightarrow \lambda = \frac{L}{J} = \frac{g}{R_c k_B T}\sqrt{\frac{\pi}{6}\frac{mg}{\hbar^2}}\frac{e}{2\pi}\exp\left(\frac{24x}{\pi}\frac{\hbar^2 n}{mk_BT}\right)}$$

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Comparison with the 2015 experiment

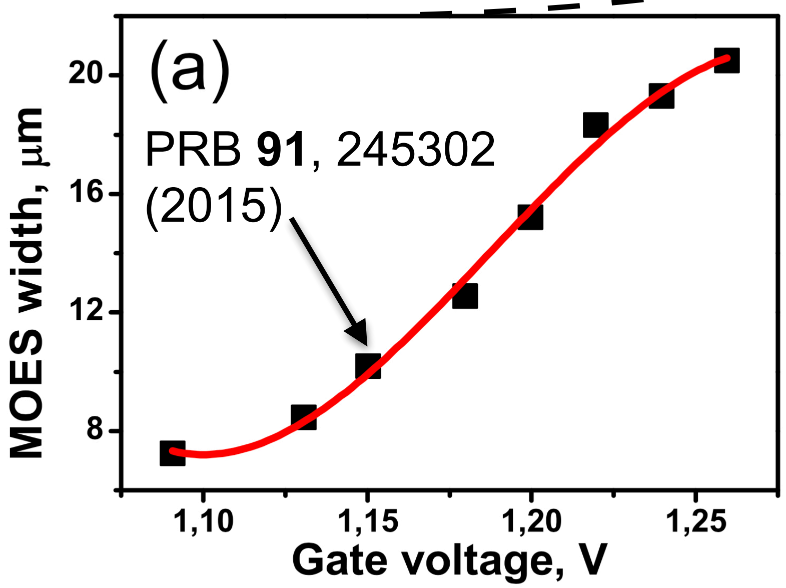
$$\frac{dF}{dJ} = 0 \Rightarrow$$

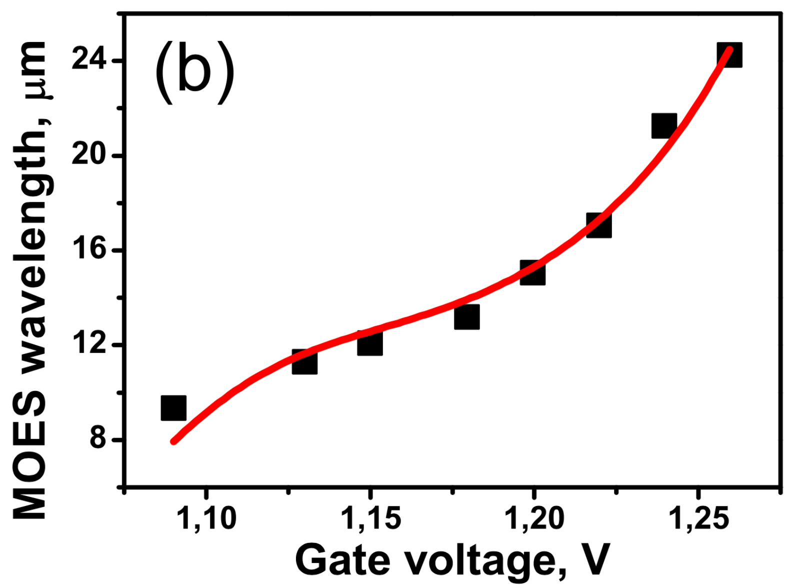
PRL **110**, 146401 (2013)

The two-body interaction constant g
is known from the calculations
and measurements of the blueshift.

$$\boxed{\Rightarrow \lambda = \frac{L}{J} = \frac{g}{R_c k_B T}\sqrt{\frac{\pi}{6}\frac{mg}{\hbar^2}}\frac{e}{2\pi}\exp\left(\frac{24x}{\pi}\frac{\hbar^2 n}{m k_B T}\right)}$$

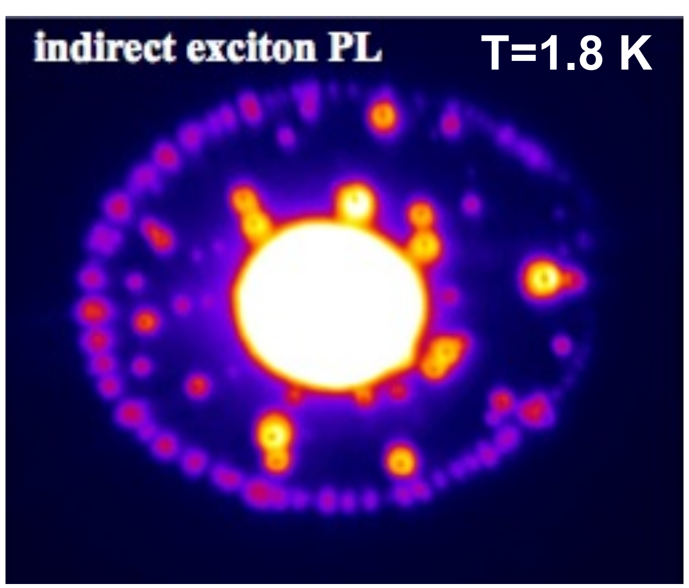
$$n(V_g) = n(V_g^*) + \frac{dn(V_g^*)}{dV_g}(V - V_g^*)$$

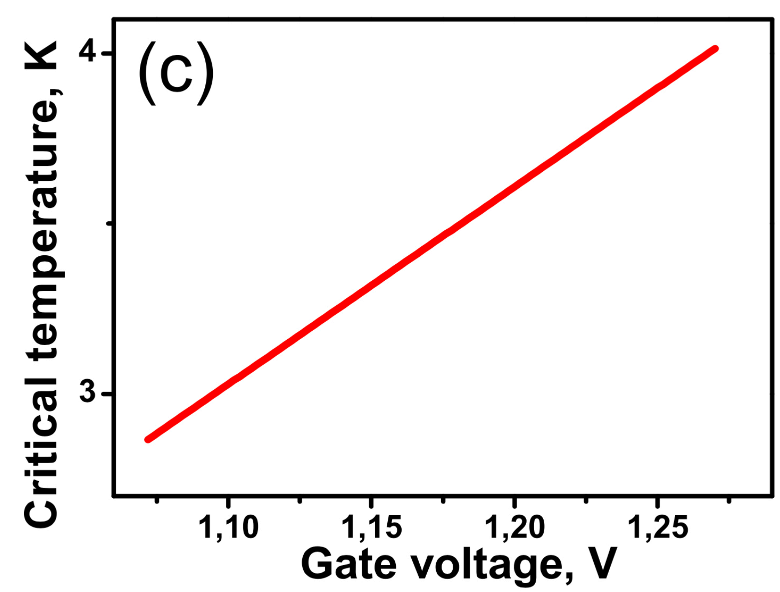




$$k_B T_c^0 = \hbar\sqrt{6/\pi^2 N_0 \omega_x \omega_y}$$

$$k_B T_c^0 = 2\sqrt{\frac{6}{\pi}\frac{mg}{\hbar^2}\frac{\hbar^2 n}{m}}$$





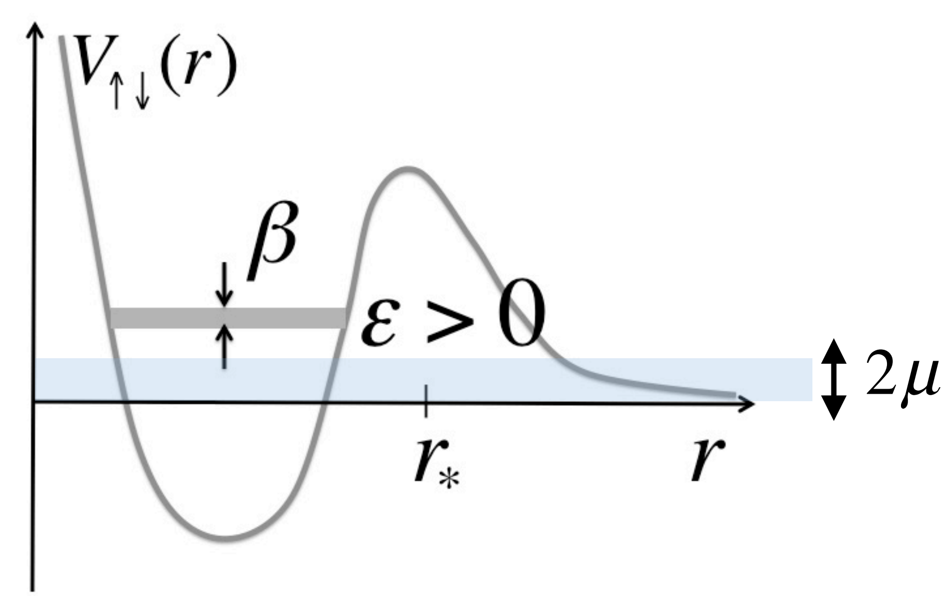
Summary:

- The theory identifies the MOES with a form of the supersolid state of matter

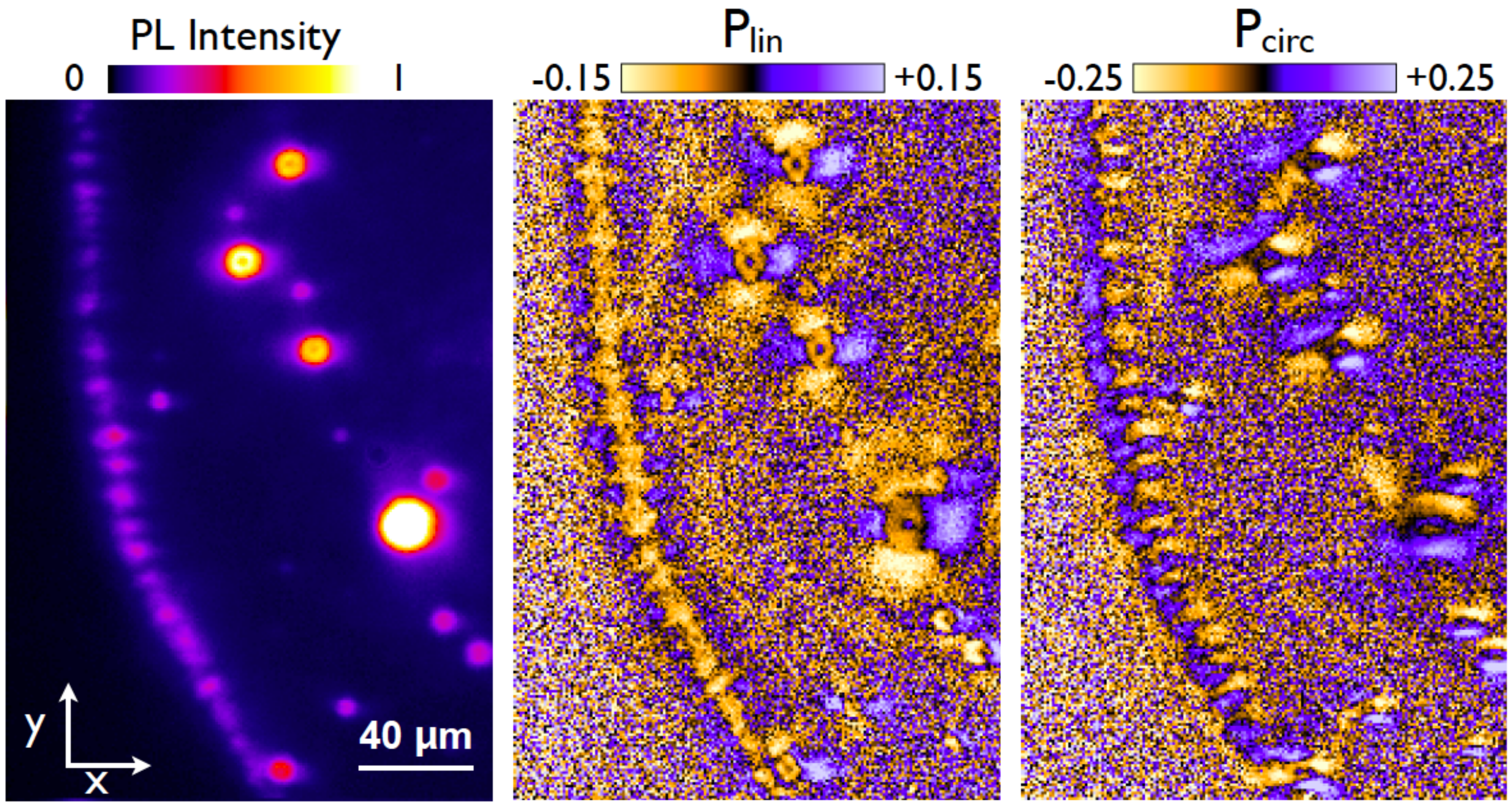
- By simultaneously reducing the density and the temperature one can try to observe a transition from the fragmented to the coherent (true) supersolid state.

- The solid forms due to resonant pairing of excitons as the temperature T approaches T_c

At $T \ll T_c$ a biexciton BEC forms in the cores of the beads.



Polarization textures in the MOES.
Spin-orbit coupled BEC of excitons at the edges of the beads.



Real Space Image *Linear Polarization (in-plane spin component)* *Circular Polarization (z-axis spin component)*

From A.A. High,A.T. Hammack, J.R. Leonard, SenYang,L.V.Butov, T. Ostatnicky, A.V. Kavokin, A. C. Gossard, APS March Meeting, March 21-25, 2011, Dallas, TX.

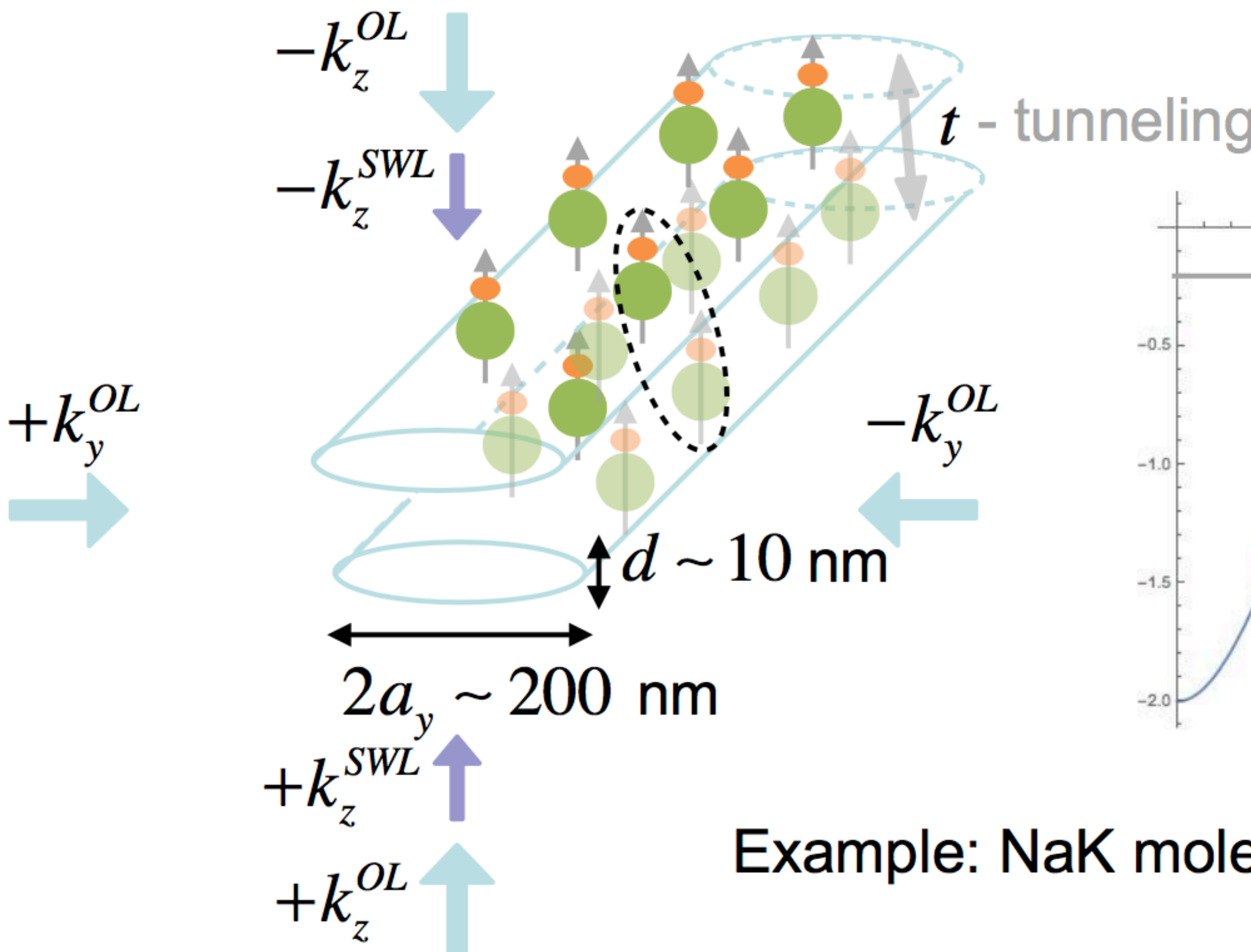
Theory:

S. V. Andreev and A. V. Nalitov, arXiv:1704.08961 (2017)

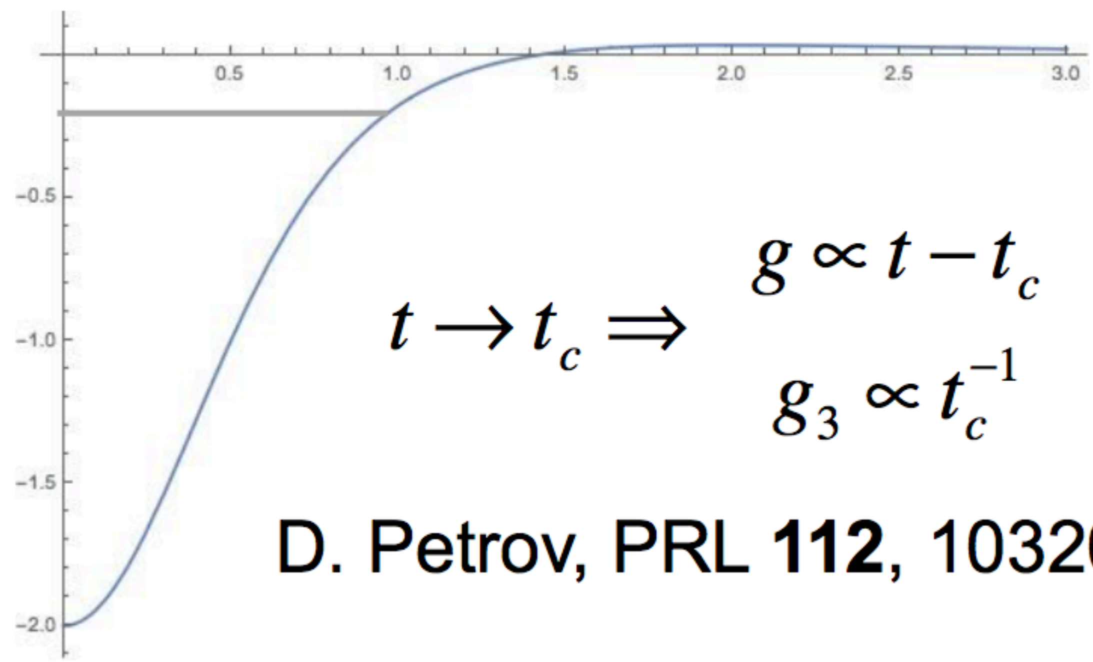
Acknowledgements :

I thank organizers of the conference for the financial support.

Polar molecules in the bilayer geometry



$$V_{+-}(r) = \frac{\hbar^2 r_*}{m} \frac{r^2 - 2l^2}{(r^2 + l^2)^{5/2}}$$



$$t \to t_c \Rightarrow \begin{array}{l} g \propto t - t_c \\ g_3 \propto t_c^{-1} \end{array}$$

D. Petrov, PRL **112**, 103201

Example: NaK molecules at $T \sim 1$ nK