Dynamical Formation of a Strongly Correlated Dark Condensate of Dipolar Excitons

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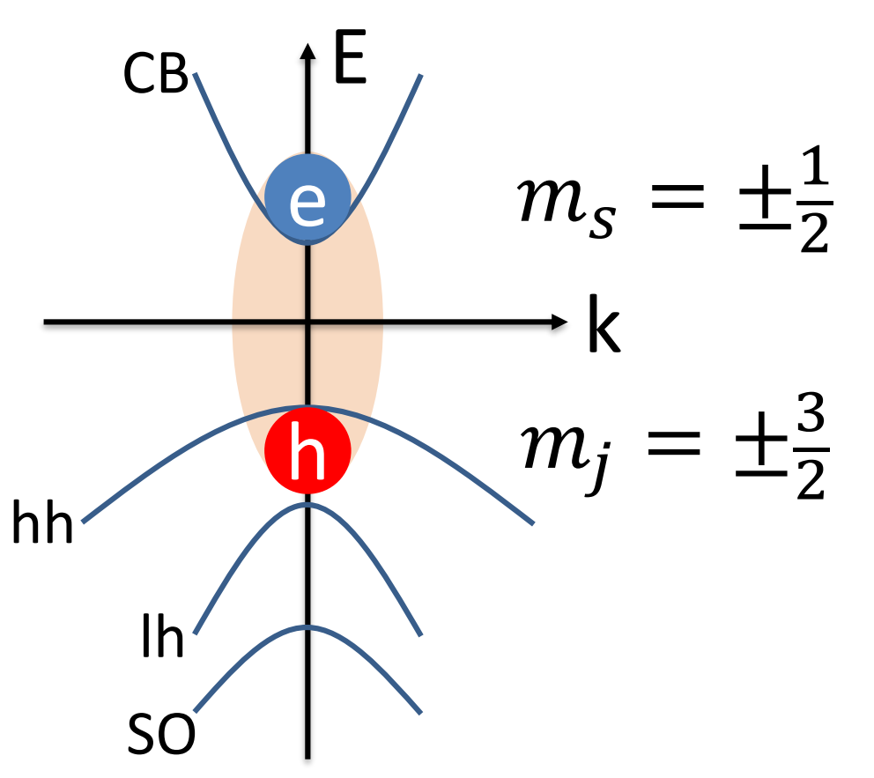
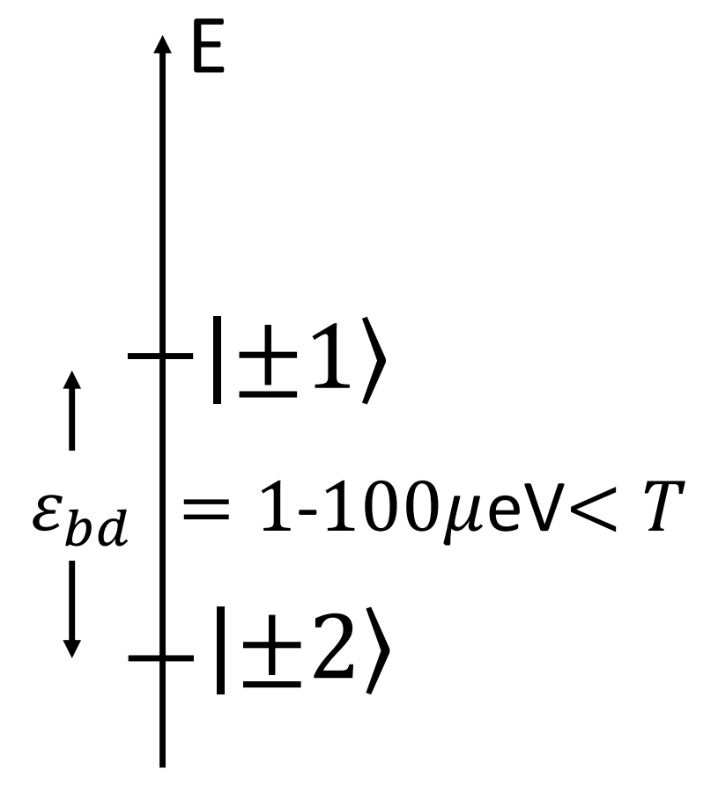
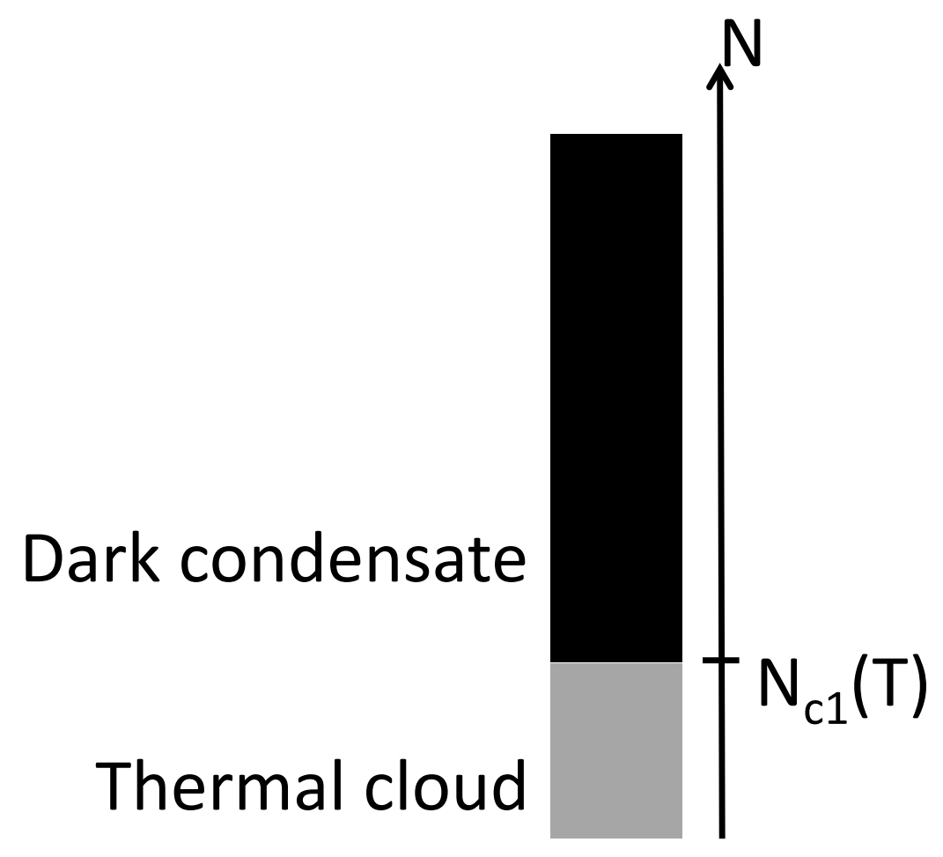
Background

Dark BEC of non-interacting excitons [1]



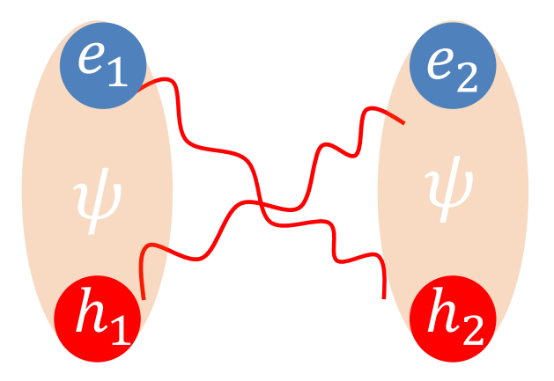




- The band diagram of an exciton in GaAs quantum well.
- The ground state has an overall ‘spin’ 2, meaning it cannot recombine optically. An optically (‘bright’) state is $\varepsilon_{bd} < T$ higher in energy. The condensed state is ‘dark’.
- BEC theory: a critical population $N_{c1}(T)$ will be thermal, and each additional particle beyond that number will be added to the dark condensate.

Interacting excitons: exchange [2]

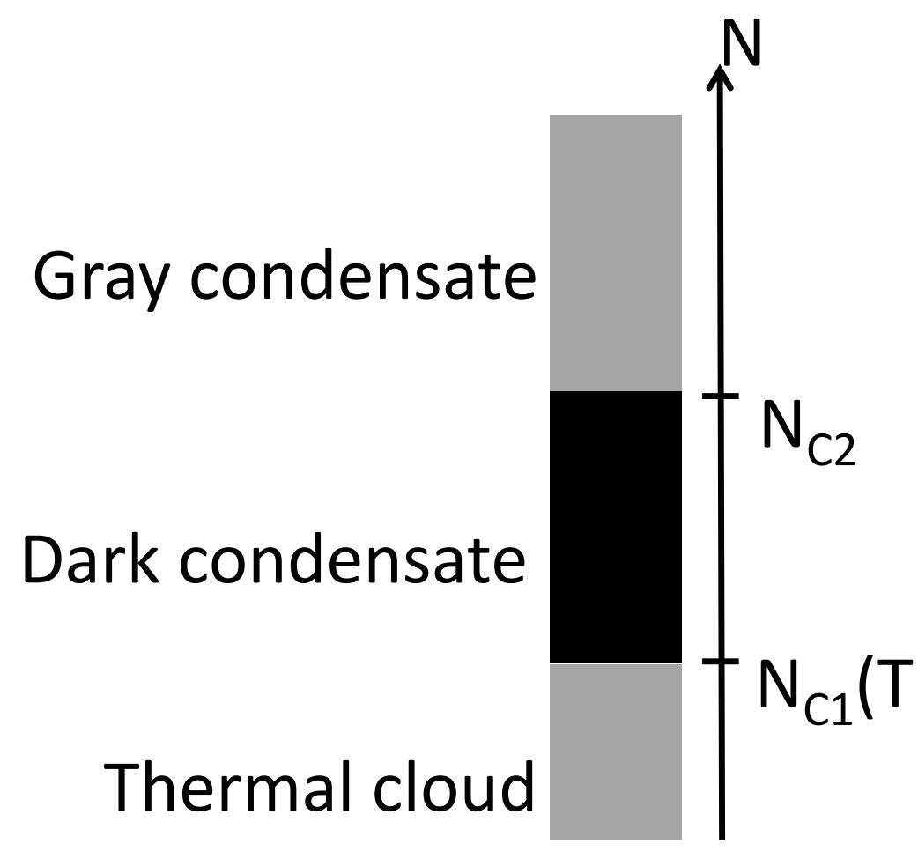
Exchange between individual carriers coherently mixes bright and dark components.



dark-bright splitting

$$\frac{\varepsilon_{bd}}{\xi} \simeq N_{c2}$$

exchange coupling



$$H_{int} = \xi \sum_{k_i} \left(b^\dagger_{\boldsymbol{k_1}} b^\dagger_{\boldsymbol{k_2}} d_{\boldsymbol{k_3}} d_{\boldsymbol{k_4}} + H.c. \right)$$

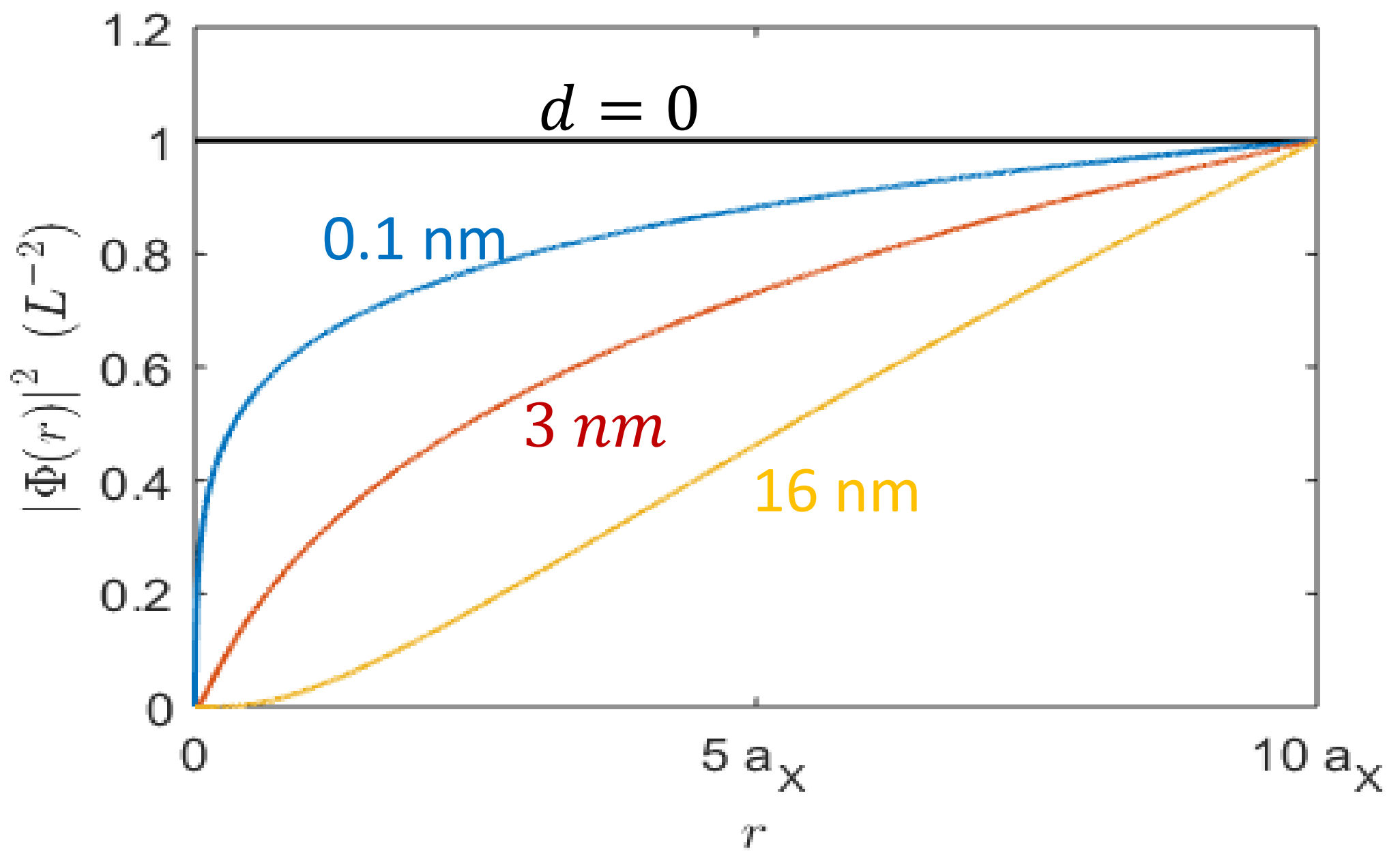
- Low N: the condensate is dark. Beyond a second critical occupation N_{c2}, each additional exciton in the condensate contributes equal dark and bright components.
- The exchange coupling depends on the wavefunction of relative-position $\Phi(\boldsymbol{r})$.

$$\xi = \int d^8(r_{e_1}, r_{e_2}, r_{h_1}, r_{h_2})\, \psi(r_{e_1}, r_{h_1}) \psi(r_{e_1}, r_{h_2}) \psi(r_{e_2}, r_{h_1}) \psi(r_{e_2}, r_{h_2}) \times \\ \times |\Phi(r_{h_2} - r_{h_1})|^2 V_{XX}$$

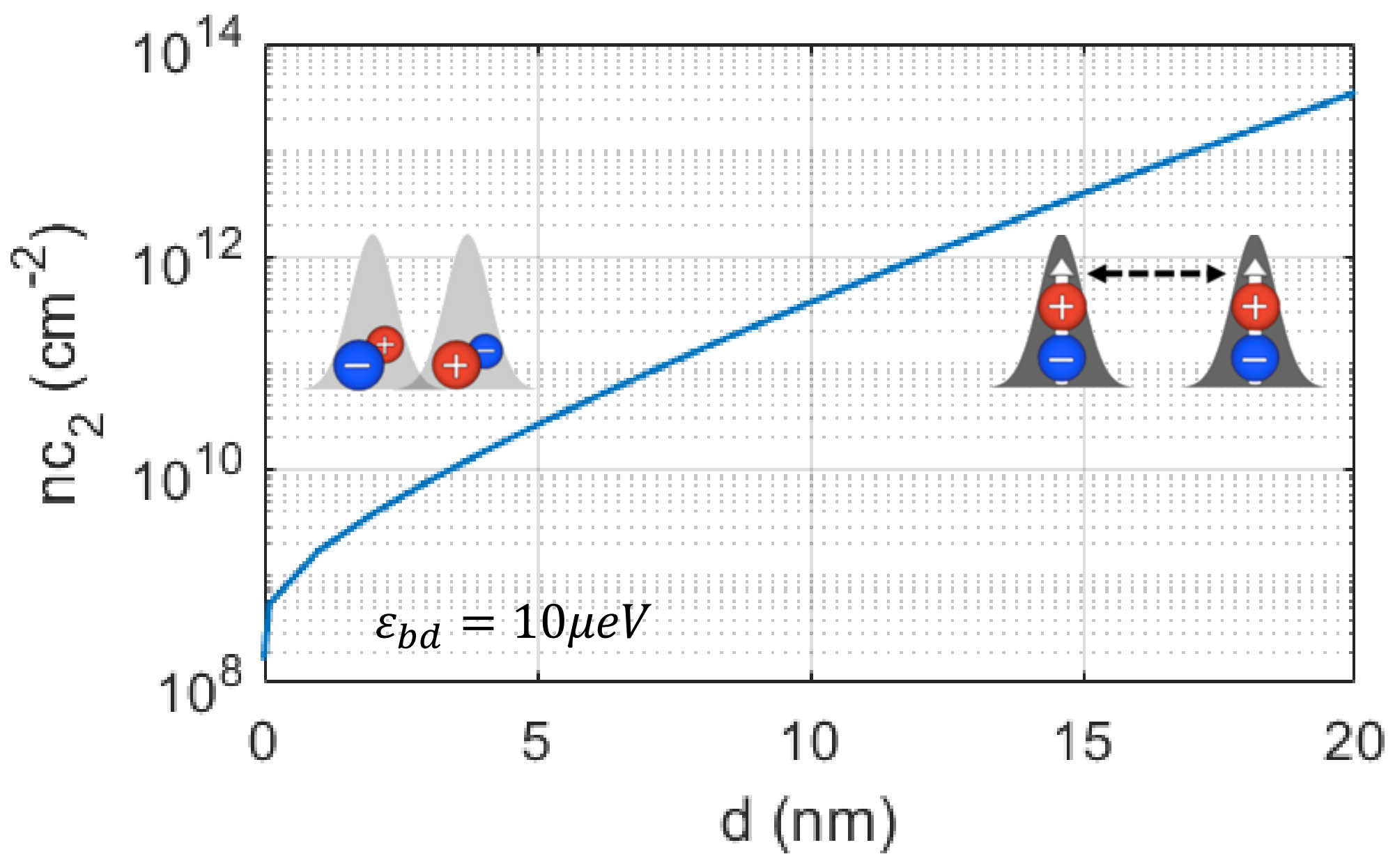
Is N_{c2} high enough for a dark condensate to be observable?

Interacting excitons: dipole-dipole repulsion

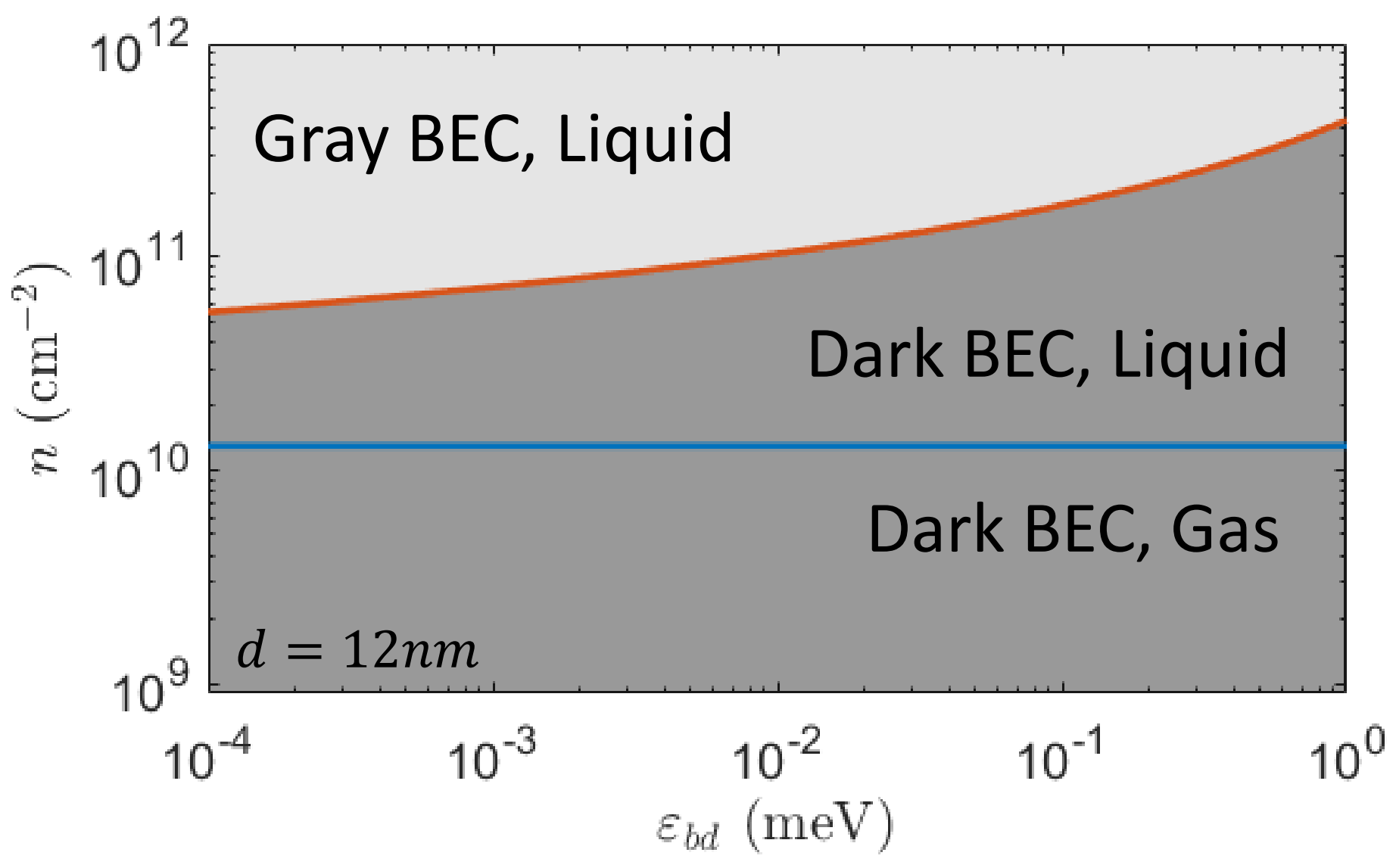
Polarized by perpendicular electric field, dipolar excitons in quantum wells reside in the 2D plane of the wells, and carry a permanent aligned electric dipole moment.



- Aligned dipoles repel each other over long distances ($\sim r^{-3}$). Particle correlations emerge and the probability amplitude of having two excitons in close proximity – $\Phi(r \lesssim$ the exciton radius $a_X)$ – is strongly suppressed.



- Exchange occurs where Φ is large. Since here $\Phi(\mathrm{r})$ falls fast with r, the exchange coupling will be suppressed for larger dipoles.
- As a result, the dark condensate phase can be stable in high densities, but only for large enough dipoles.



- Dipole- dipole repulsion results also in the onset of strong particle correlations and short range order [3].
- Thus we find that the system undergoes two phase transitions: liquid→gas and thermal→dark-BEC→bright-BEC.
- The critical density for each transition depends on the dipole size.

Dynamic condensation

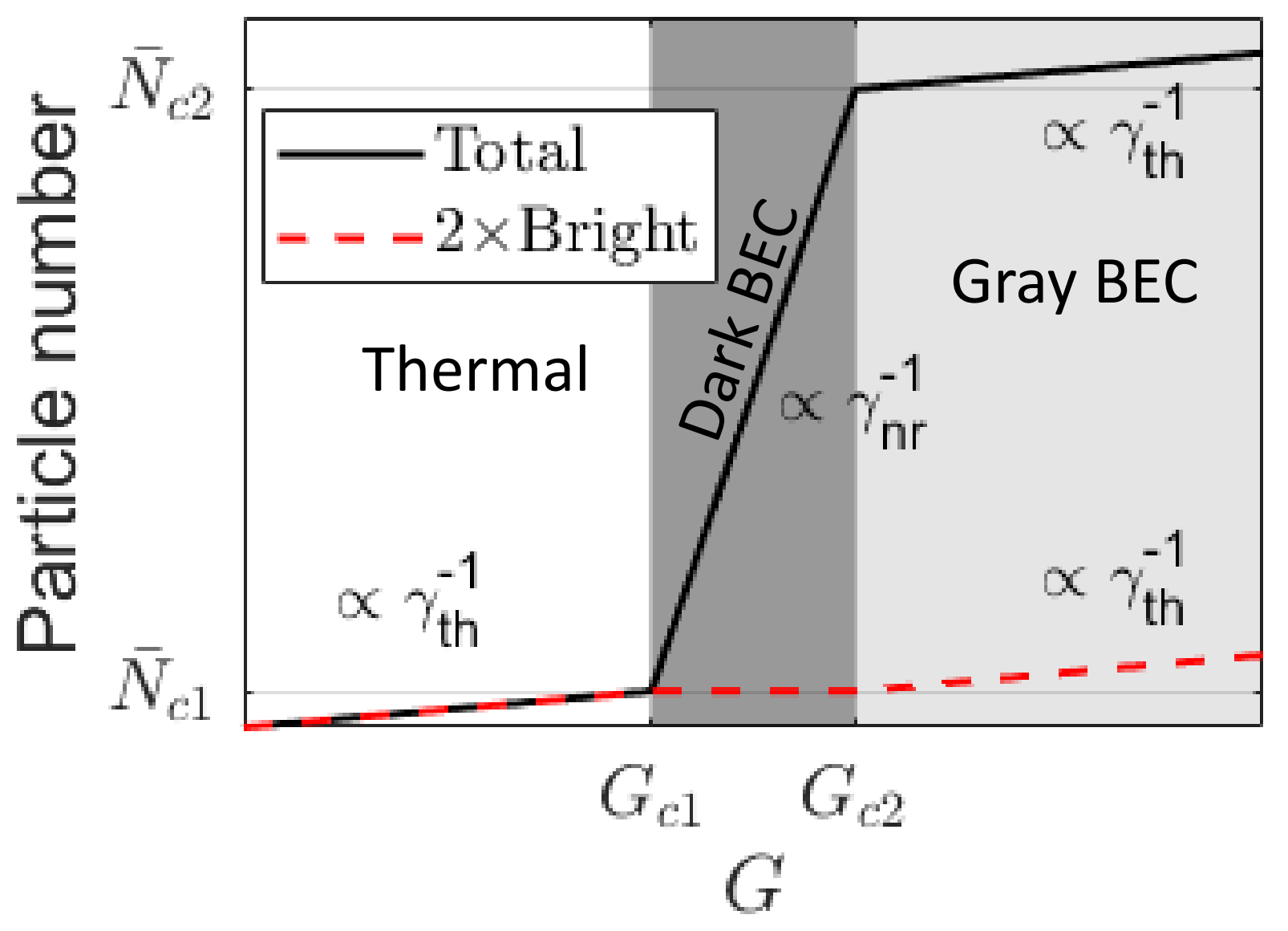
- In a typical experiment scheme, excitons are gnerated in a constant rate G, than decay radiatively or not, with respective lifetimes τ_b and τ_d.
- Thermalization is the shortest time scale, the excitons reach a quasi-equilibrium. The population is described by a dynamic rate equation.
- But the thermodynamic phase transition into - and out of - the dark condensate phase induced striking changes in the lifetime appearing in this equation.

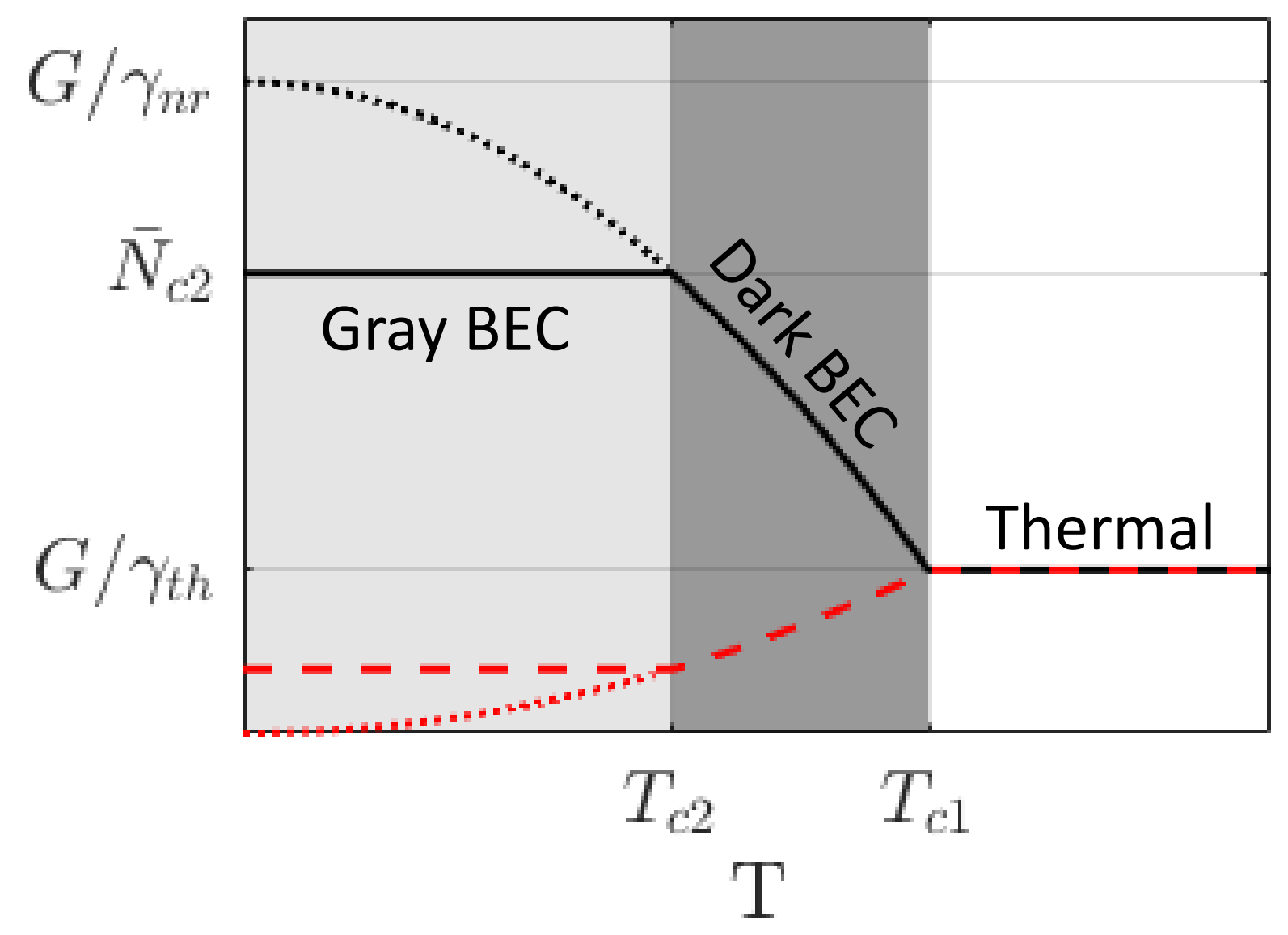
Gen. rate lifetime

$$N = G \times \tau$$

Emission Current

$$\tau_b \ll \tau_d$$

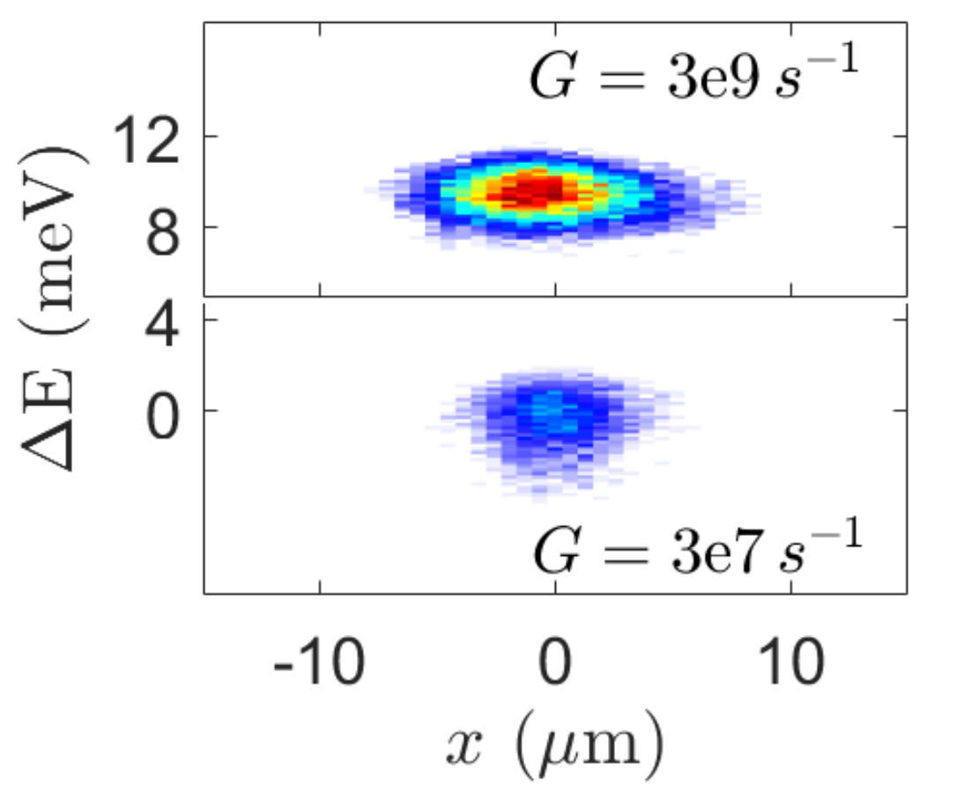


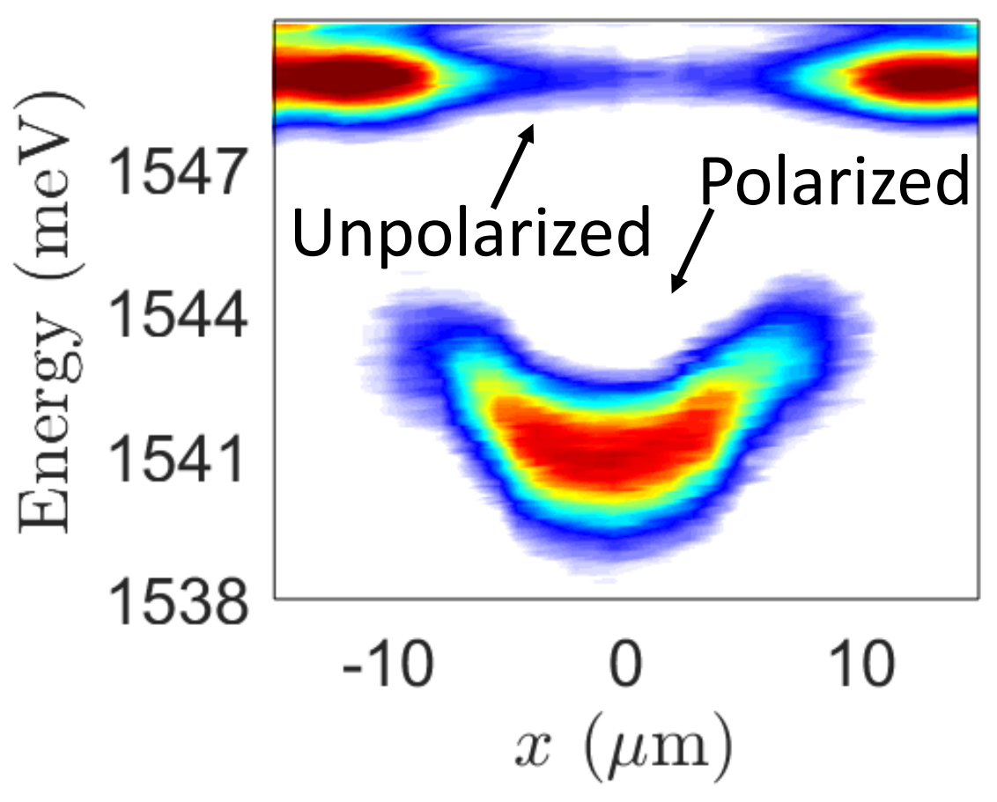


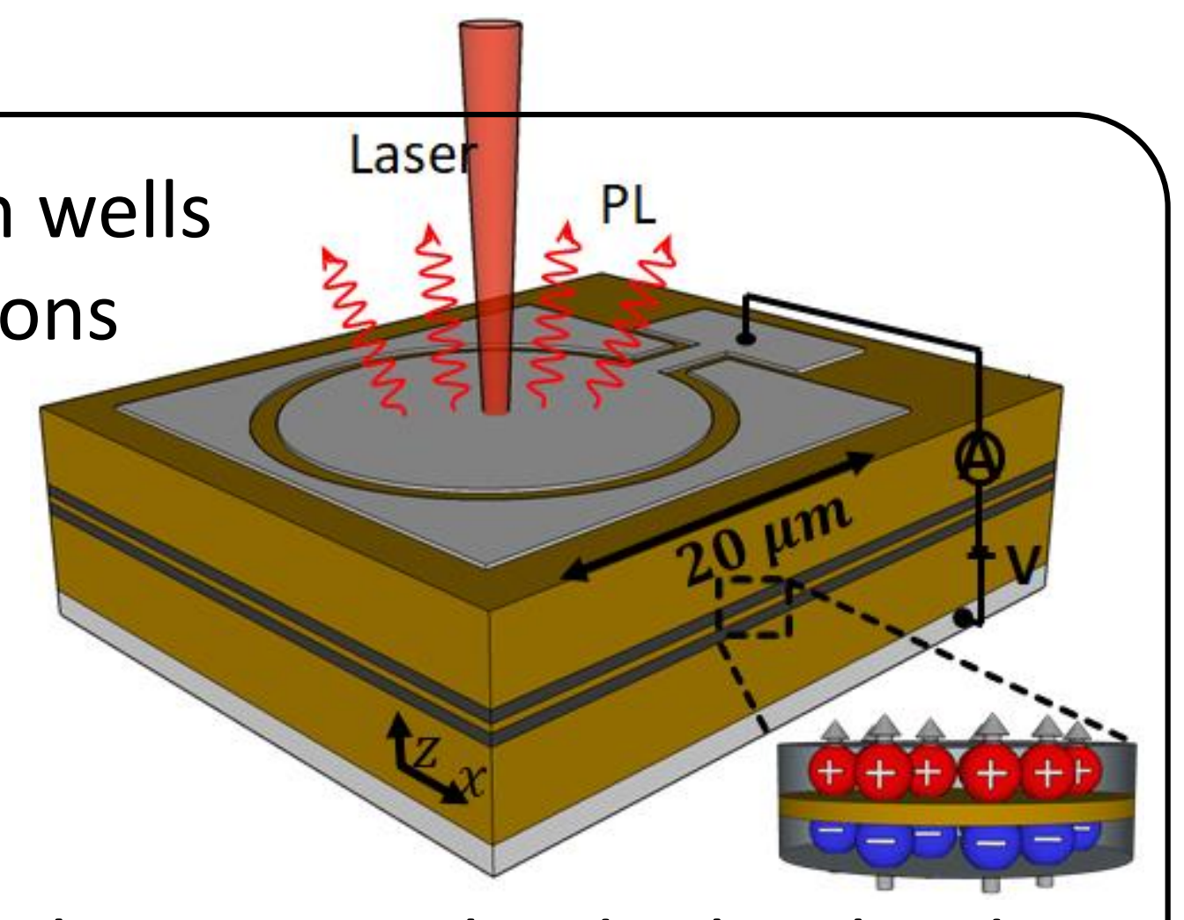
- $N(G)$ is always linear, but the slope is orders of magnitude larger with a dark BEC compared to the slope in the other two phases.
- $N(T)$ increases quadratically as the T is lowered through the dark BEC phase. In the other two phases $N(T)$ is constant.
- The phase transitions will barely affect the emission intensity, but will cause striking shifts of the emission energy, in the case that N_{c2} is large enough.

Experiment [4]

- Nonresonant laser pumps excitons in double quantum wells
- Voltage in the z direction polarizes and traps the excitons



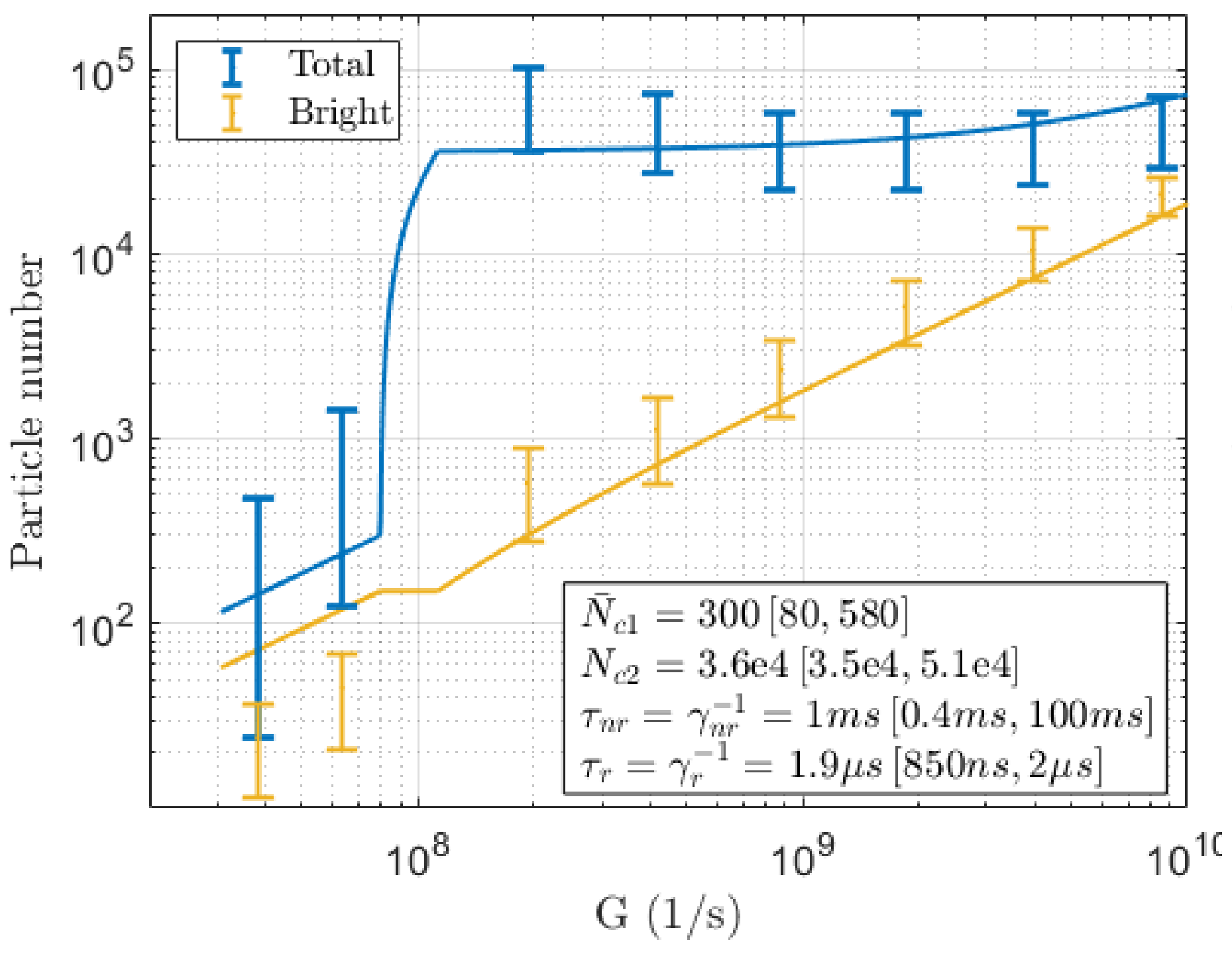




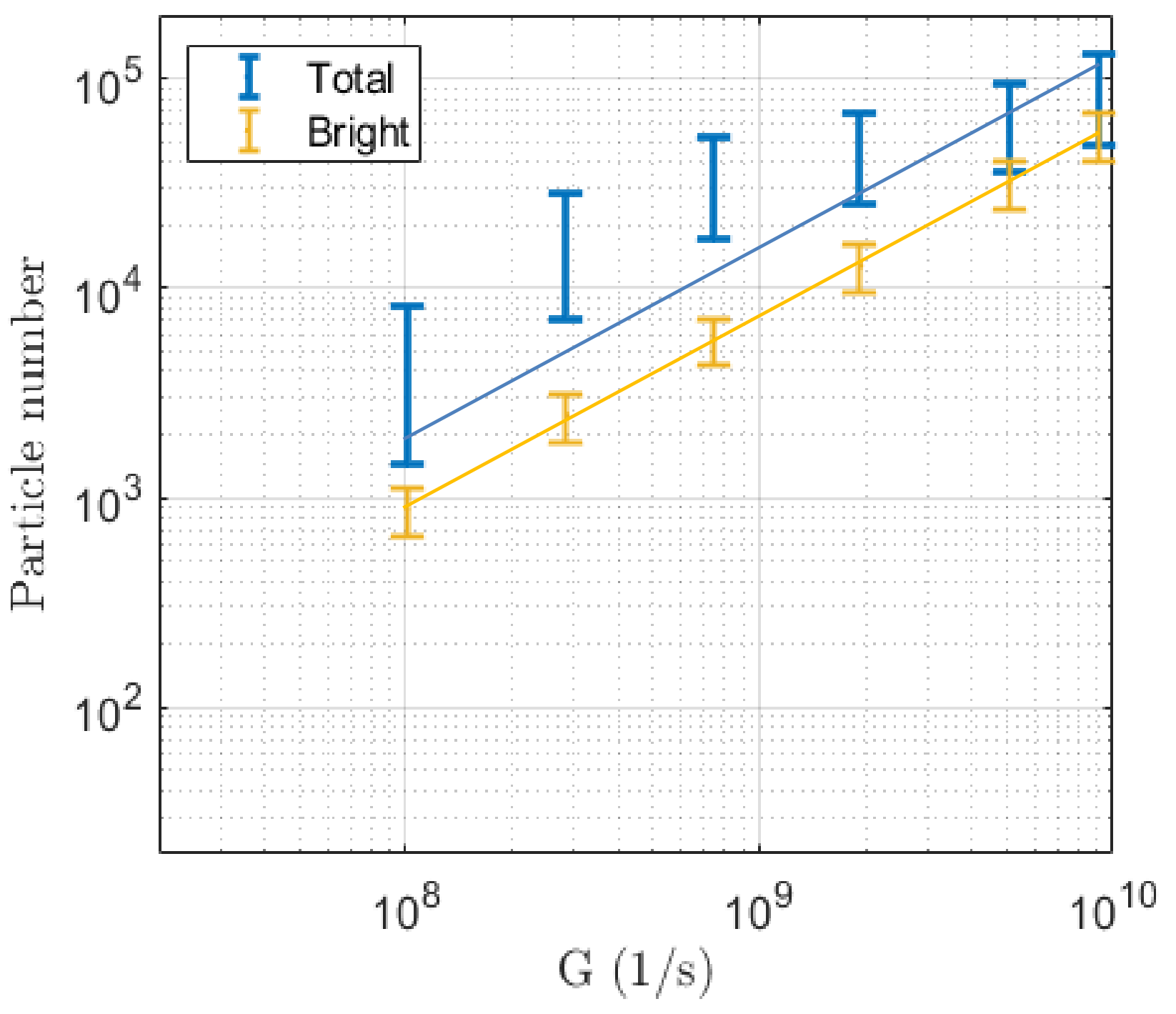
The exciton cloud is localized around the bottom of a quasi-parabolic potential, 20μm wide.

- To maintain fixed single-particle properties like τ_b, the voltage is tuned to hold the emission line at a fixed energy. The voltage redshifts the exciton emission.
- This changing compensating voltage probes the total exciton density.
- Bright exciton density is probed by the emission intensity.
- We track both densities as we change the temperature and excitation power ($\propto G$).

T=1.5K



T=5.4K



- **In low T**, the dark condensate seem to form with less than 1000 excitons in the trap. It persists through ~2 orders of magnitude increase of density until it turns gray when populated with a few 10k’s particles.
- **In high T**, the population is simply linear in the excitation power, and the measured bright population is about half the measured total population.

[1] Combescot et. al., Phys. Rev. Lett. 99, 176403, 2007.
[2] Combescot and Combescot, Phys. Rev. Lett. 109, 026401 (2012), 2012.
[3] Laikhtman and Rapaport, Phys. Rev. B 80, 195313 (2009).
[4] Experimental data was first published by Cohen et. al., Nano letters 16, 3726–3731 (2016). New analysis is done in the current work.

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