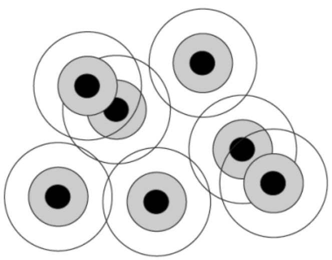
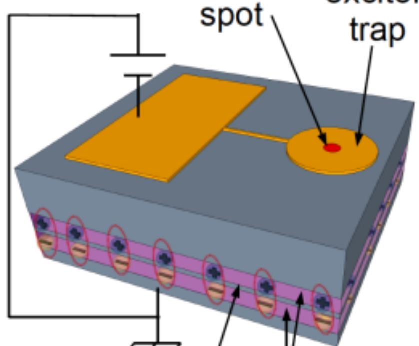
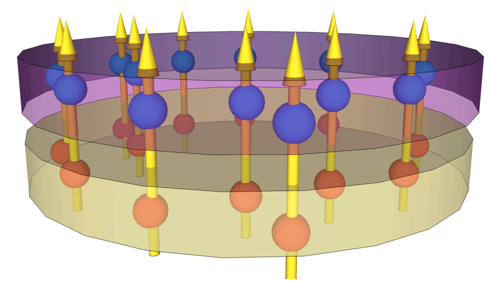
Particle correlations and evidence for dark state condensation in a cold dipolar exciton fluid







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- Yehiel Shilo
- Kobi Cohen
- Boris Laikhtman

- Loren Pfeiffer
- Ken West

- **Introduction – cold dipolar fluids**
- Experimental evidence for
  - many-body correlations
  - dark exciton condensation

- Introduction – cold dipolar fluids
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  - many-body correlations
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Weakly interacting quantum fluids
(Non-polar atoms, Exciton-Polaritons)

Common feature:

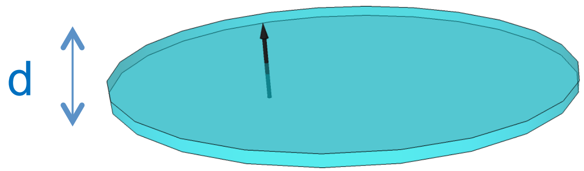
weakly interacting particles →

Local interactions

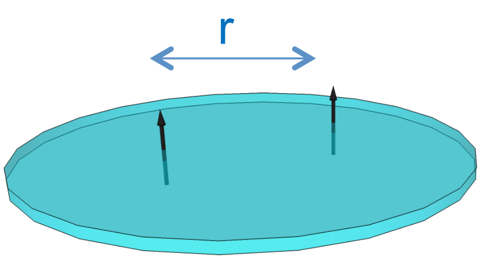
→

No particle correlations,
well described by mean field

Cold dipolar fluids in two dimensions (2D)

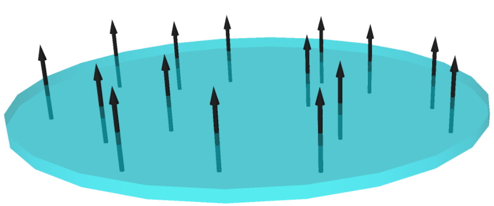


Large electric dipole moment



$$U(r) = \frac{e^2 d^2}{\kappa r^3}$$

Extended interactions



Non-trivial particle correlations in both quantum and classical regimes!

New phases and physical phenomena expected

- Classical and quantum particle correlations
- Gas – liquid transitions (both quantum and classical)
- Bose –Einstein Condensation and Superfluidity
- Dipolar crystal

e.g.:
Schindler, Zimmerman, PRB, (2008)
Astrakharchik et al. Phys. Rev. Lett. (2007).
Buchler et al. Phys. Rev. Lett. (2007).
Combescot et al *Phys. Rev. Lett*, (2007)
Laikhtman, Rapaport, *Phys. Rev. B (2009)*
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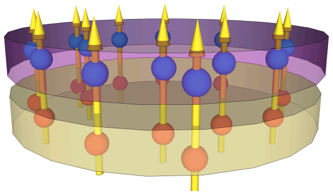

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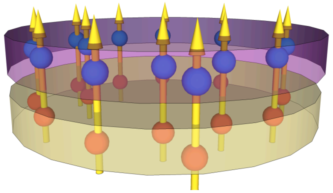
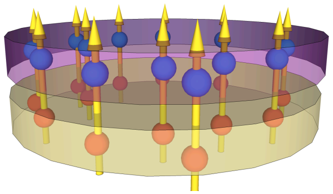


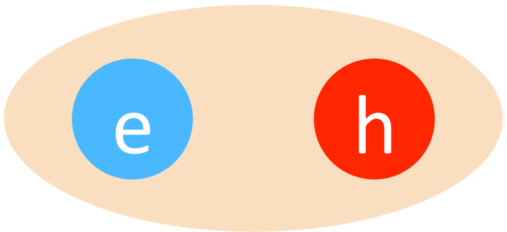
New phases and physical phenomena expected

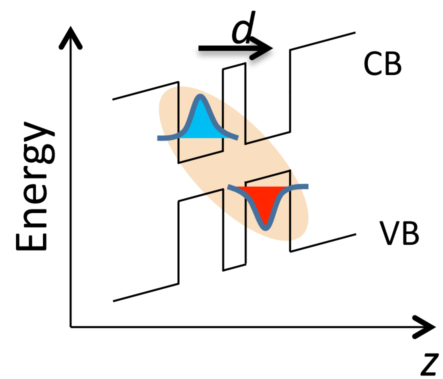
Measuring particle correlations is essential to understand the many-body classical and quantum physics of dipolar fluids

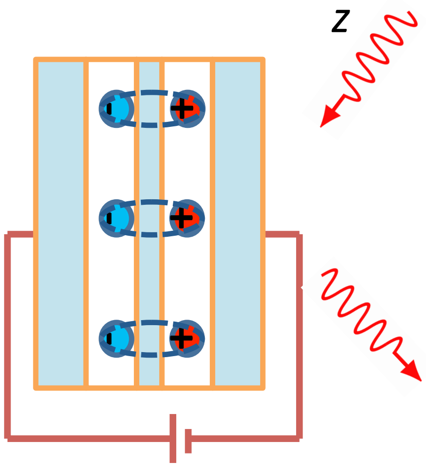


Physical realization - Dipolar excitons

- An exciton is a quasi-particle which is a bound pair of an electron and a hole.
- Applying external voltage in a GaAs bilayer (DQW) generates dipolar excitons.
- Easy to observe and measure – emit photons! We can “see” excitons…







Goals

- Measure directly the particle correlations
- Study collective effects in cold 2D dipolar fluids

Strategy

Study the interaction energy between the particles which is a direct window into the particle correlations.

Dipolar excitons

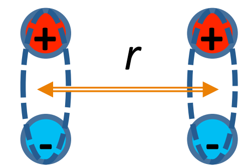
Energy of emitted Photon:

$$E_{ph} = E_X + \Delta E(n,T)$$

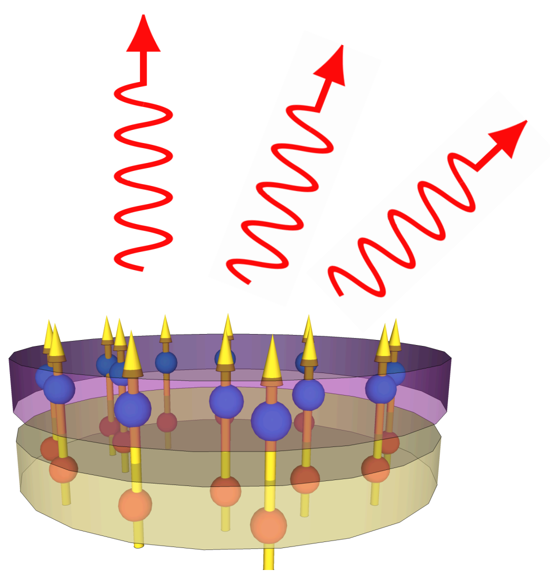
Single exciton energy

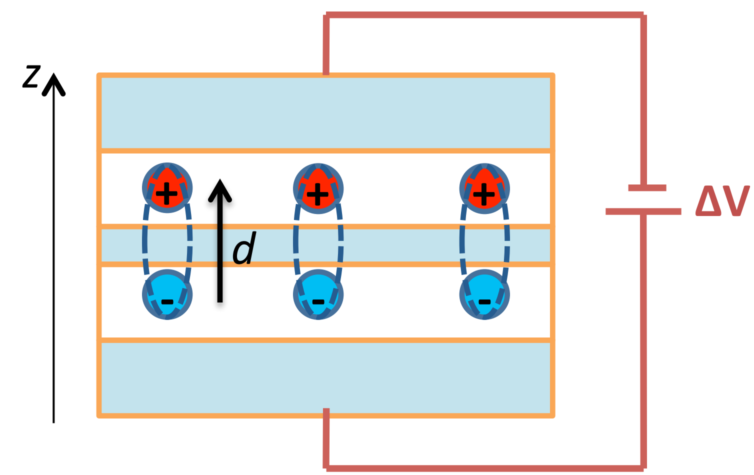
interaction energy with other dipoles. n - exciton density

T - exciton temperature



$$U(r) = \frac{e^2 d^2}{\kappa r^3}$$





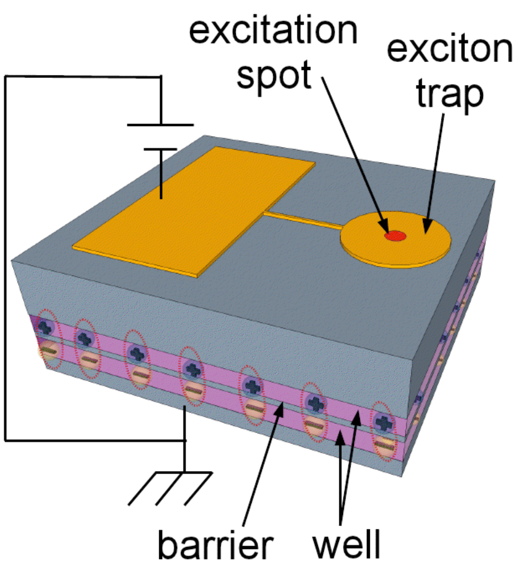
Properties of ΔE

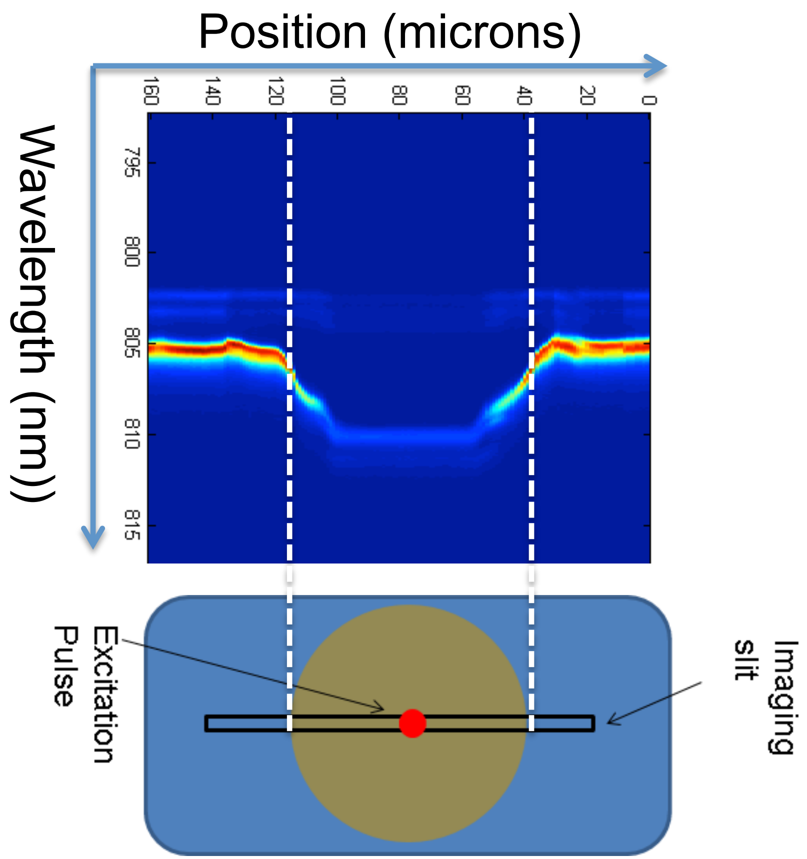
- ΔE is proportional to the total exciton density
- ΔE is very sensitive to particle correlations.
- The larger the correlations in the fluid is the smaller ΔE

Schindler, Zimmerman, PRB, (2008)
Laikhtman, Rapaport, *Phys. Rev. B (2009)*

Experimental technique:

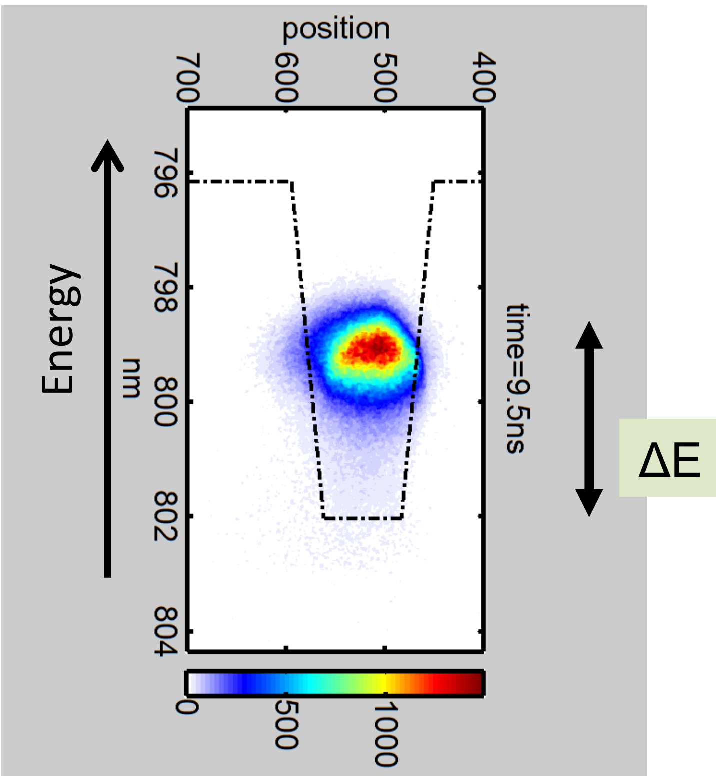
Time resolved spectroscopy inside an **electrostatic trap**

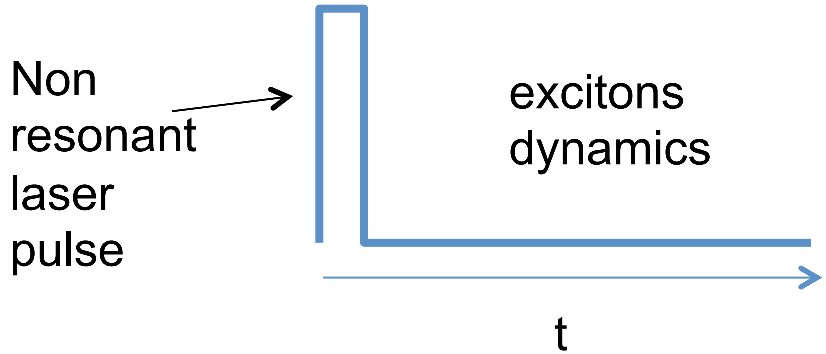




Experimental technique:

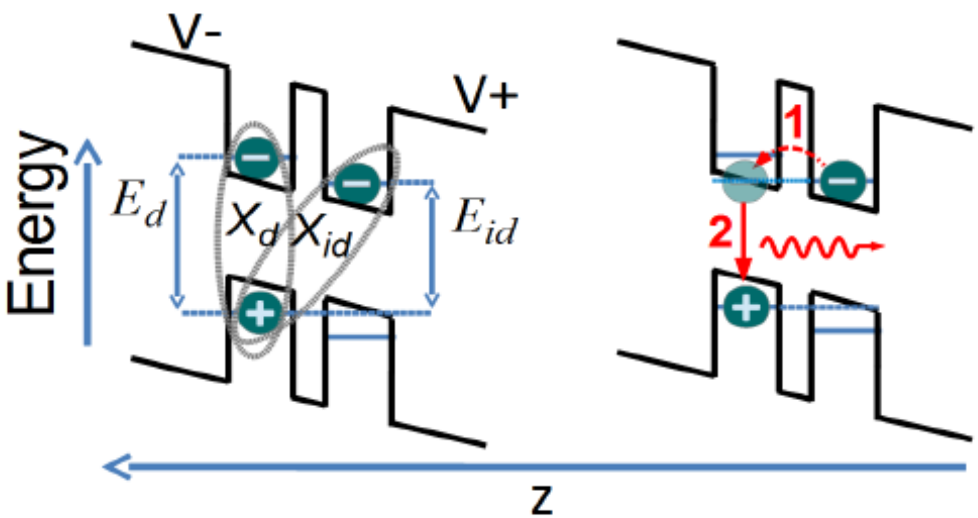
Time resolved spectroscopy inside an electrostatic trap

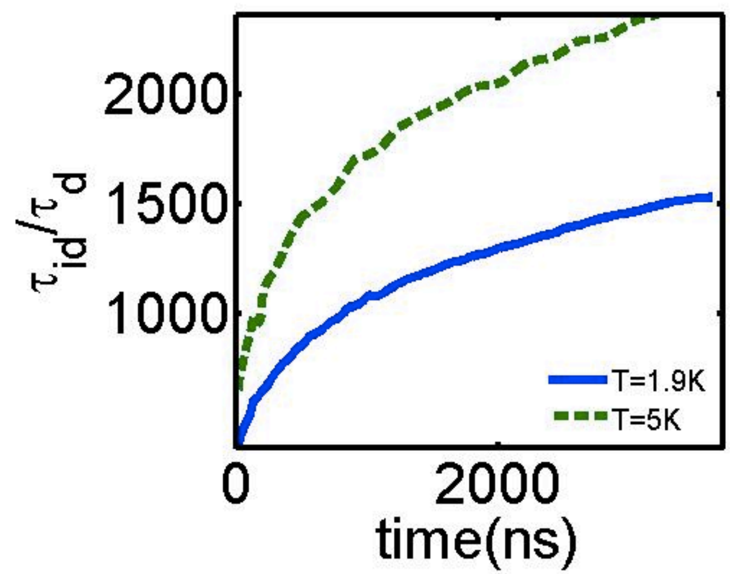




$$E_{ph} = E_X + \Delta E(n,T)$$

Mapping $E_{\text{int}}(n_X, T)$ from trapped fluid dynamics

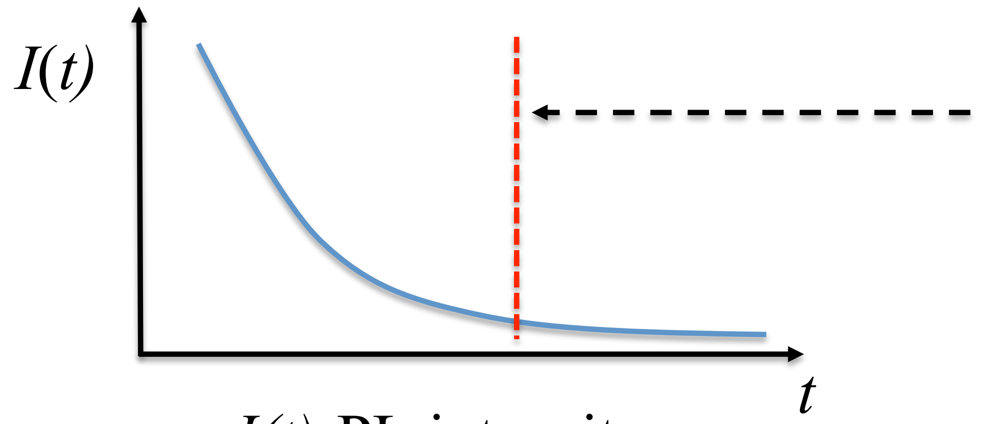




$$\frac{1}{\tau_{id}} = \frac{|c|^2}{\tau_d} = \frac{1}{\tau_d}\frac{v^2}{(E_d - E_{id})^2}$$

How to extract the density?

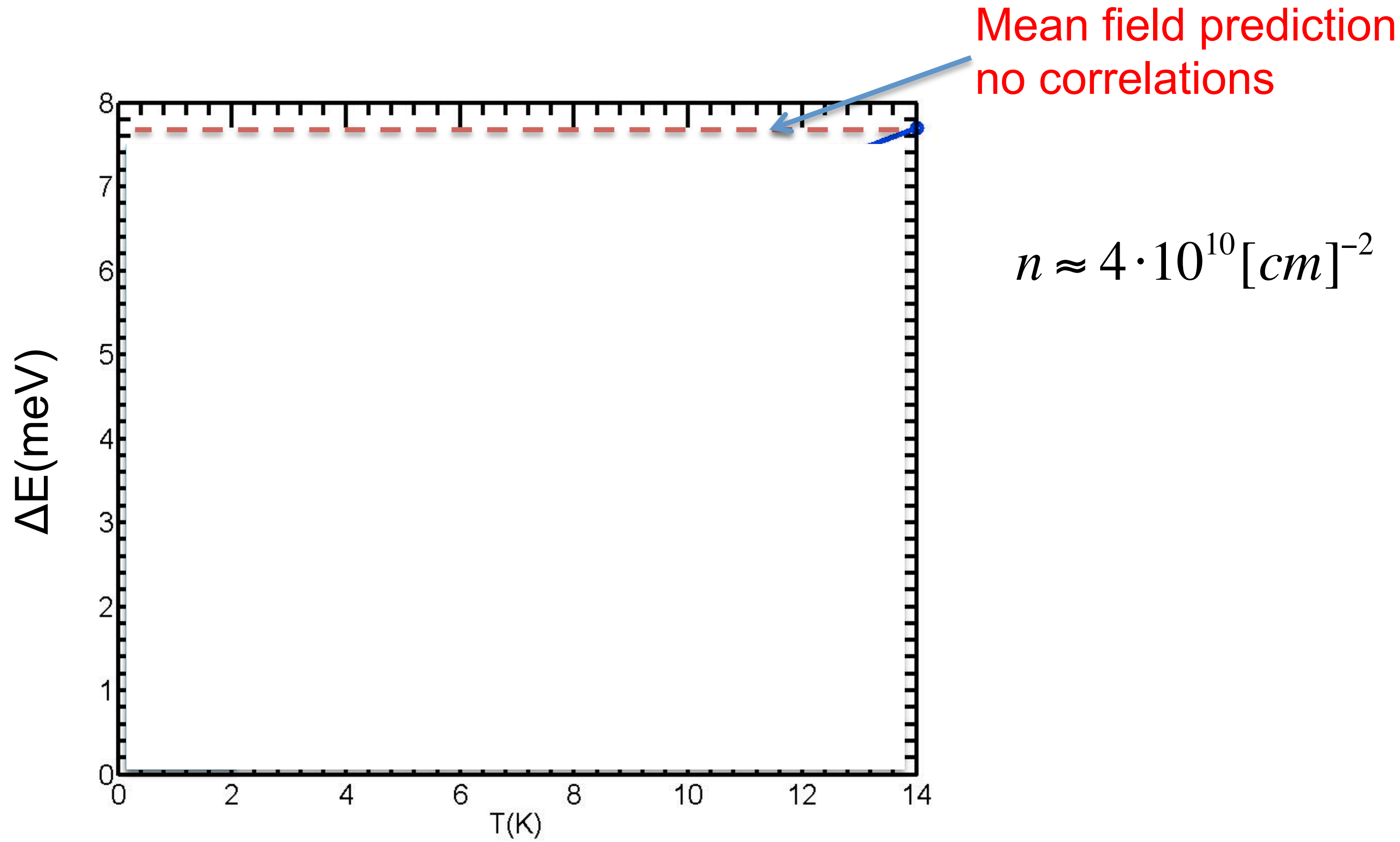
$$n(t) \sim \int_{t}^{\infty} I(t')dt'$$



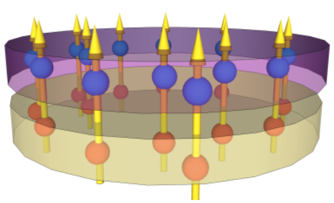
I(t)-PL intensity

$$\Rightarrow \Delta E(n,T)$$

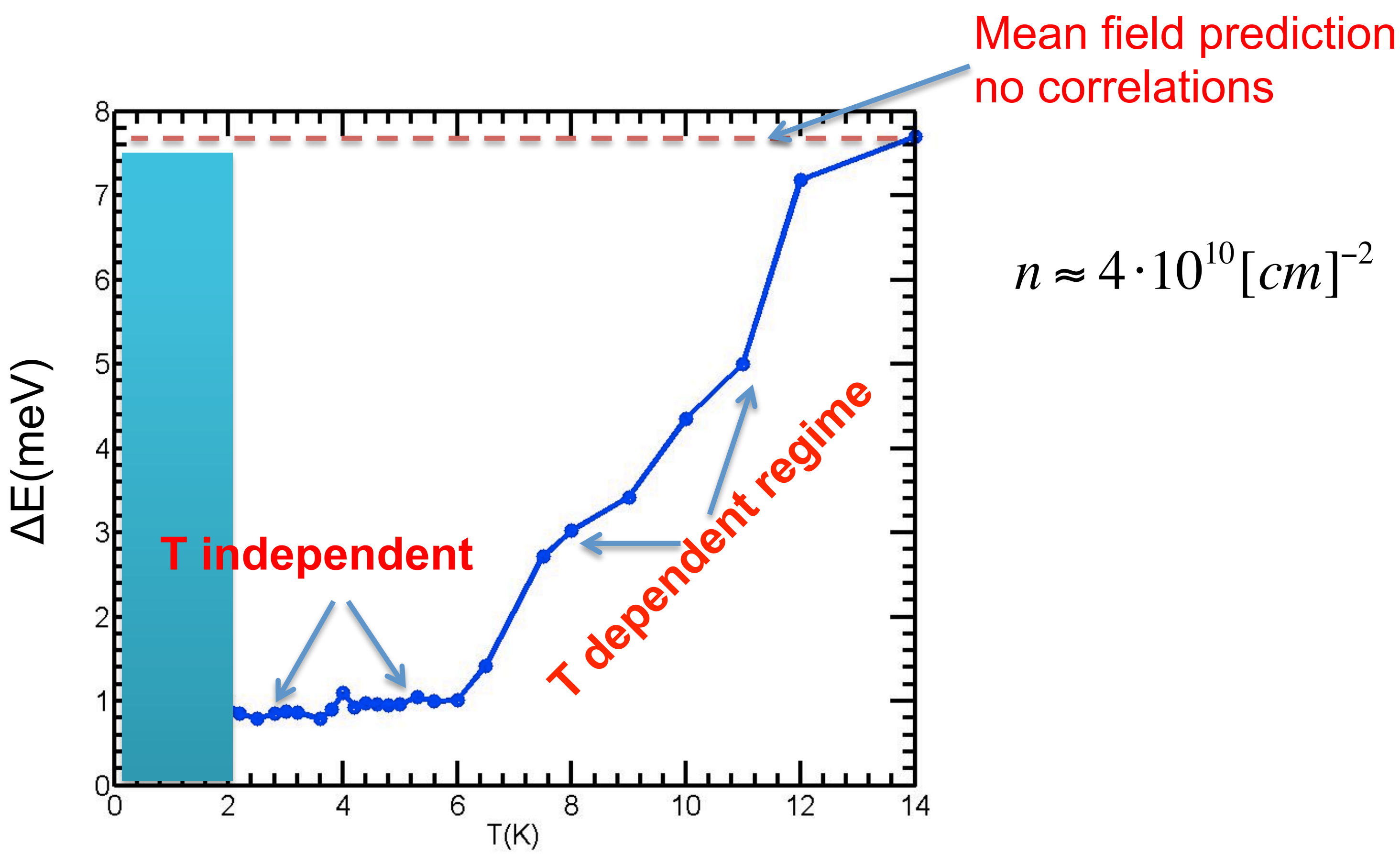
Correlation regimes



$$n \approx 4 \cdot 10^{10} [cm]^{-2}$$

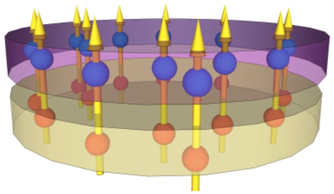


Correlation regimes



$$n \approx 4 \cdot 10^{10}[cm]^{-2}$$

- beyond mean field prediction- evidence for dipolar correlations
- Two correlation regimes



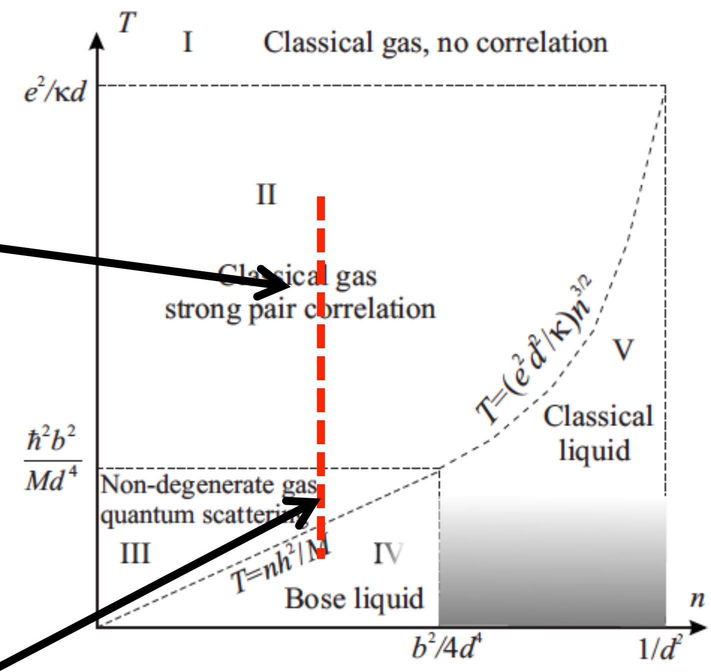
Correlation regimes – theory

Higher T:
Classical correlations

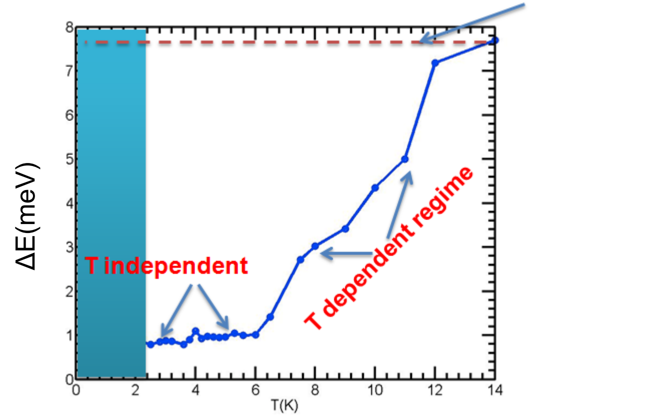
Temperature dependence

Lower T:
Quantum correlations

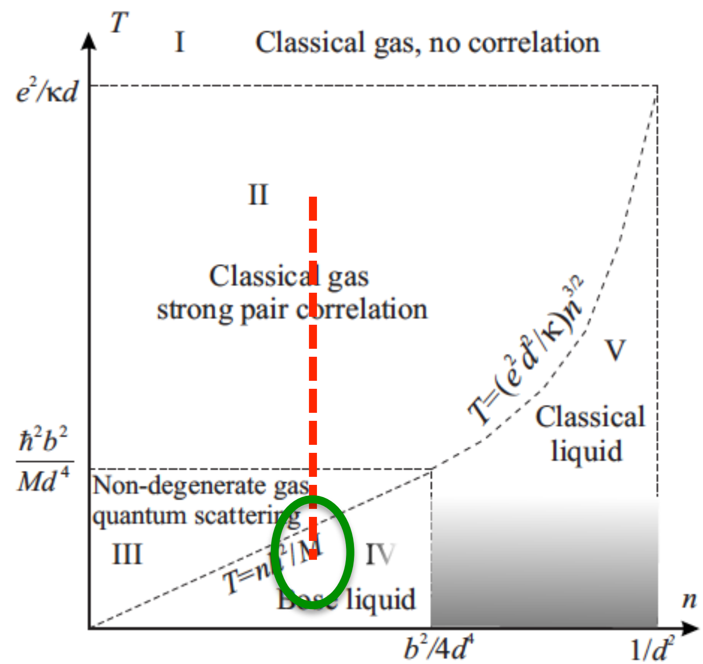
No temperature dependence



Laikhtman, Rapaport, *Phys. Rev. B (2009)*

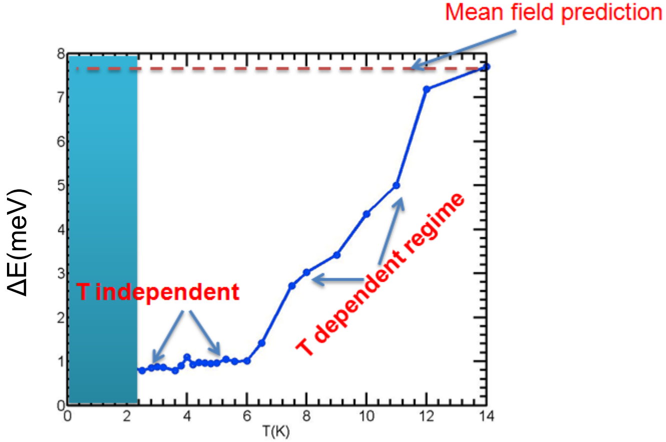


Correlation regimes – theory



Collective State

Laikhtman, Rapaport, *Phys. Rev. B (2009)*



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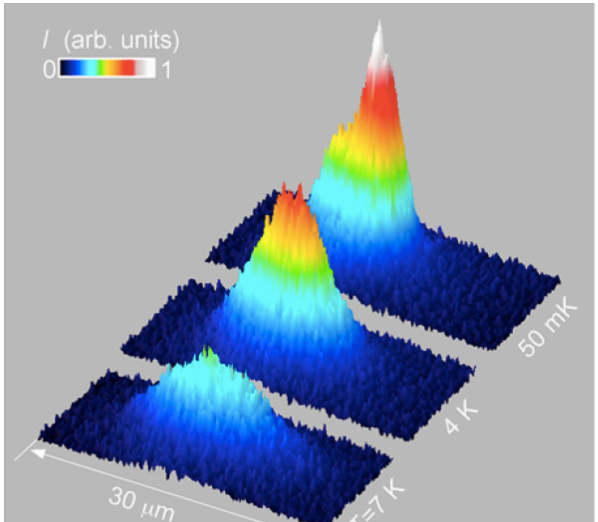
Collective effects of dipolar exciton fluids



High el. al. Nano lett.(2012) 12, 2605

Recent indications of spontaneous coherence:

High, el. al., Nature 483, 584 (2012).

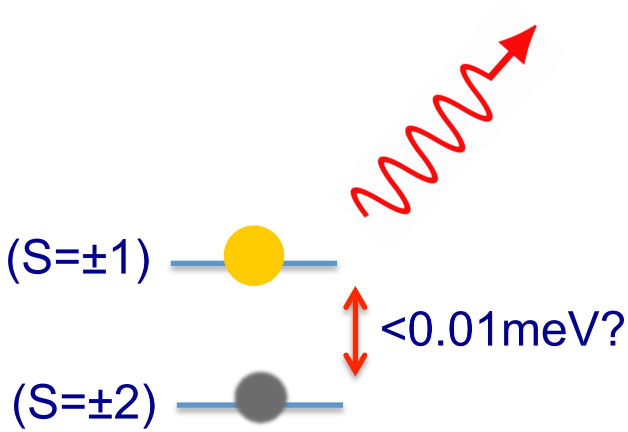
High el. al. Nano lett.(2012) 12, 2605

Alloing, et. al. arXiv:1304.4101(2013)

Collective effects – role of dark excitons

4 Spin states for the excitons:

2-bright excitons (S=±1),
2-dark excitons (S=±2)



Dark excitons are lower in energy*

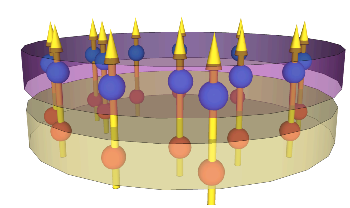
*Combescot et al, "Bose-Einstein condensation in semiconductors: the key role of dark excitons" PRL. 99, 176403 (2007)

Bose-Einstein Condensation in Semiconductors: The Key Role of Dark Excitons

Monique Combescot,[1] Odile Betbeder-Matibet,[1] and Roland Combescot[2]
[1]*Institut des NanoSciences de Paris, Université Pierre et Marie Curie, CNRS, Campus Boucicaut, 140 rue de Lourmel, 75015 Paris, France*
[2]*Laboratoire de Physique Statistique, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*
(Received 19 June 2007; published 26 October 2007)

Bose-Einstein condensation in semiconductors is controlled by the nonelementary-boson nature of excitons. Pauli exclusion between the fermionic components of composite excitons produces dramatic exchange couplings between bright and dark states. In microcavities, where bright excitons and photons form polaritons, they force the condensate to be linearly polarized, as observed. In bulk, they also force linear polarization, but of dark states, due to interband Coulomb scatterings. To evidence this dark condensate, indirect processes are thus needed.

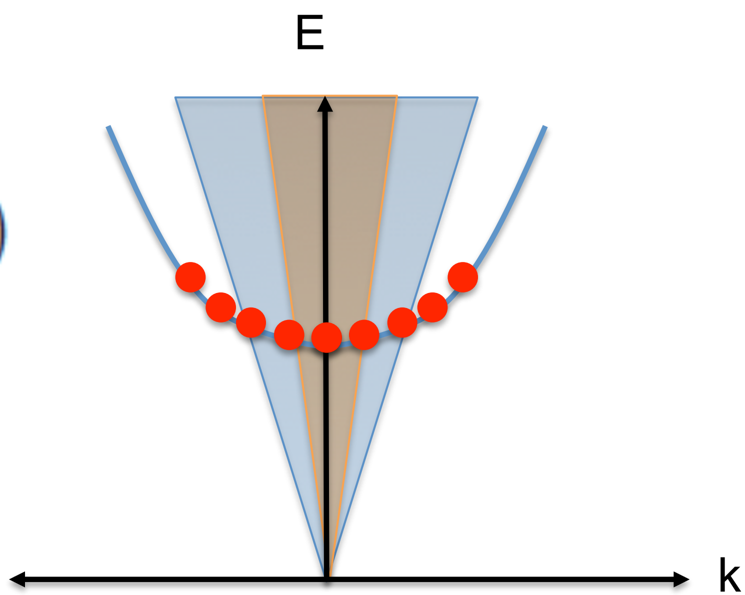
couplings. Since dark excitons have a much larger lifetime than bright excitons, the critical density necessary for exciton Bose-Einstein condensation should be easier to reach. However, its observation implies indirect processes, as, for example, those arising in the energy shift change it induces to a bright exciton line when the exciton distribution goes from thermal to condensed.

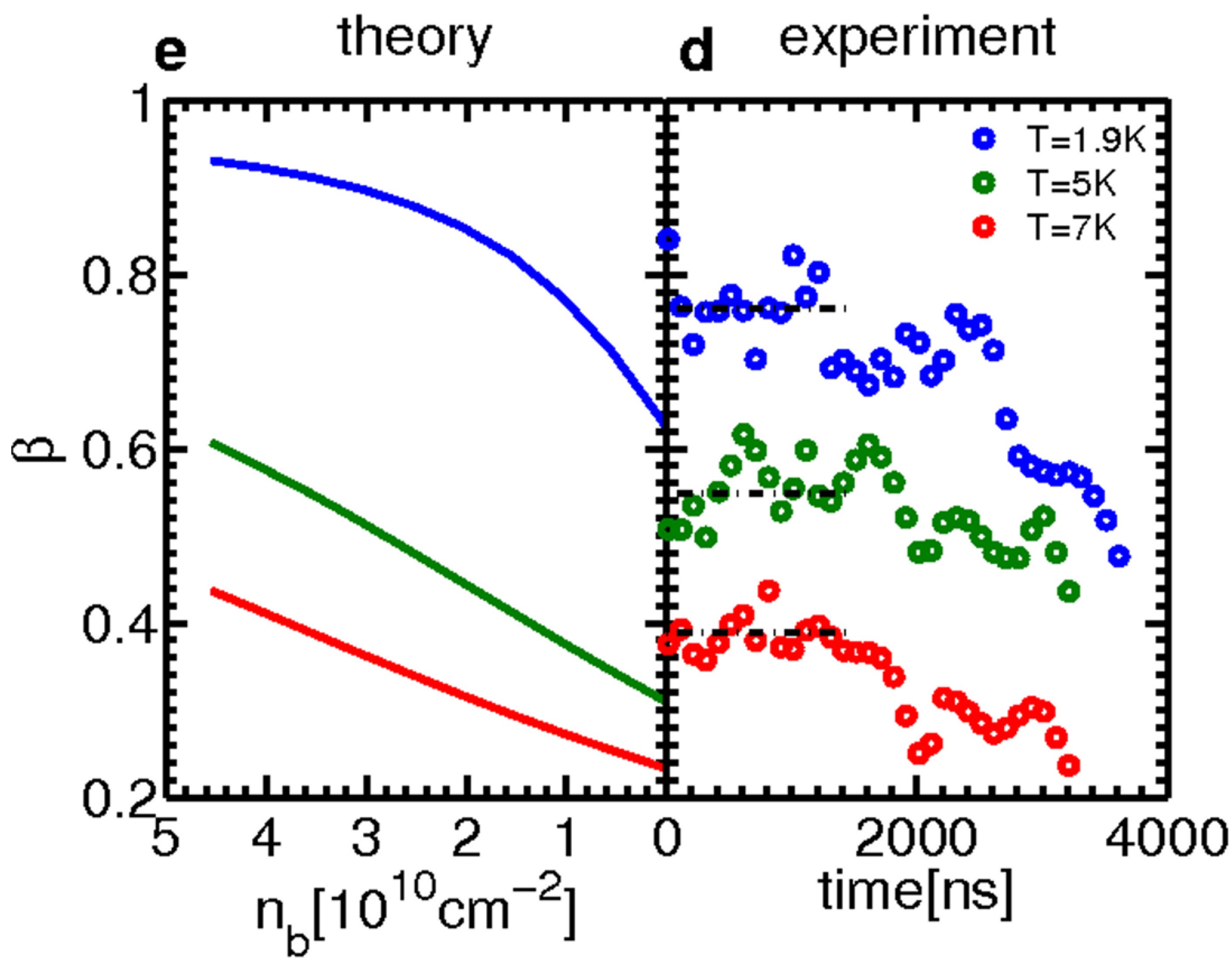


Assuming only radiative process

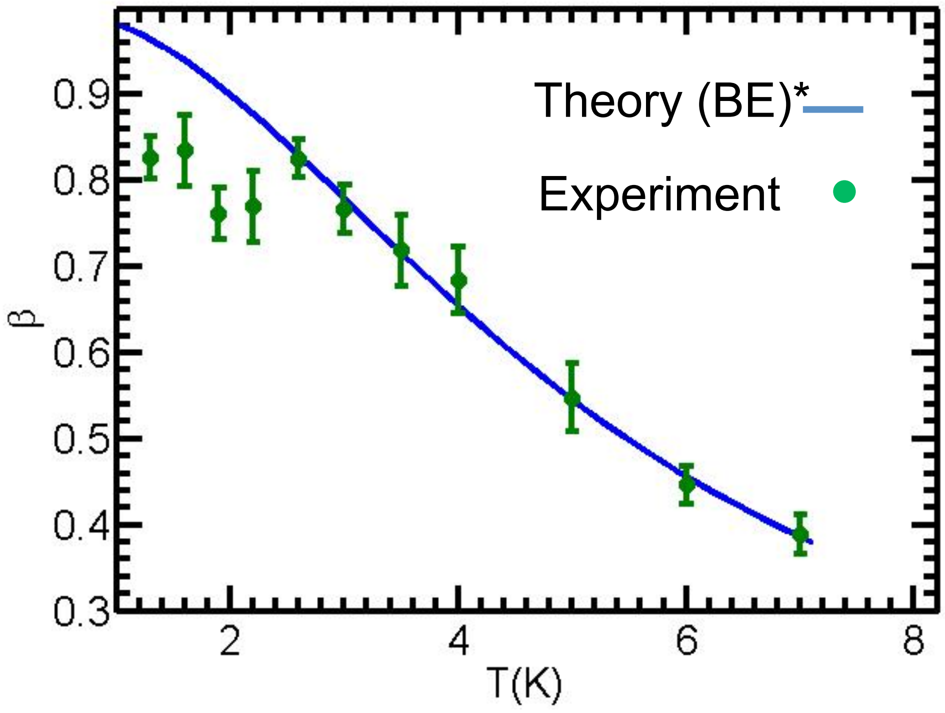
$$I(t) = -\alpha(T)\frac{dn_b}{dt} = \alpha(T)\frac{n_{rad}}{\tau_{id}} = \frac{\alpha(T)\beta(T)n_b}{\tau_{id}}$$

$$\beta \equiv (n_{rad}/n_b)$$

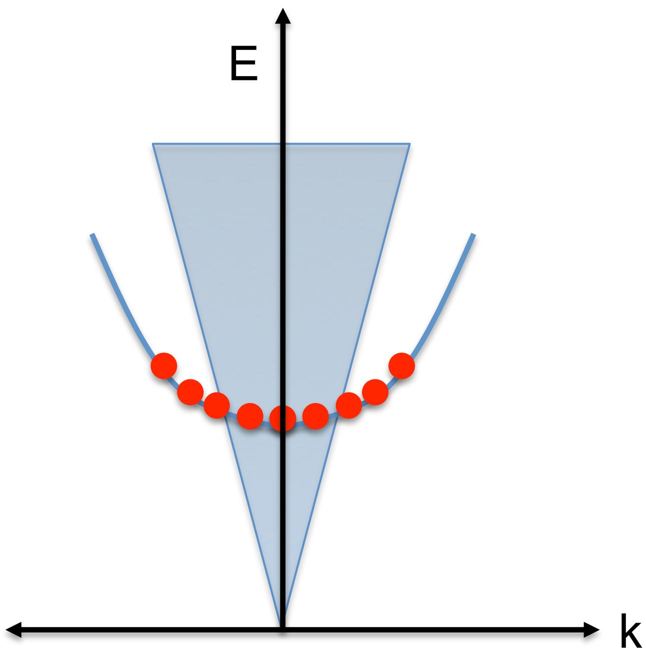



e
theory
d
experiment
1
0.8
0.6
0.4
0.2
β
5
4
3
2
1
0
$n_b[10^{10}cm^{-2}]$
0
2000
4000
time[ns]
T=1.9K
T=5K
T=7K

Collective effect



β(T) -Fraction of radiative photons (exciton in the lightcone):



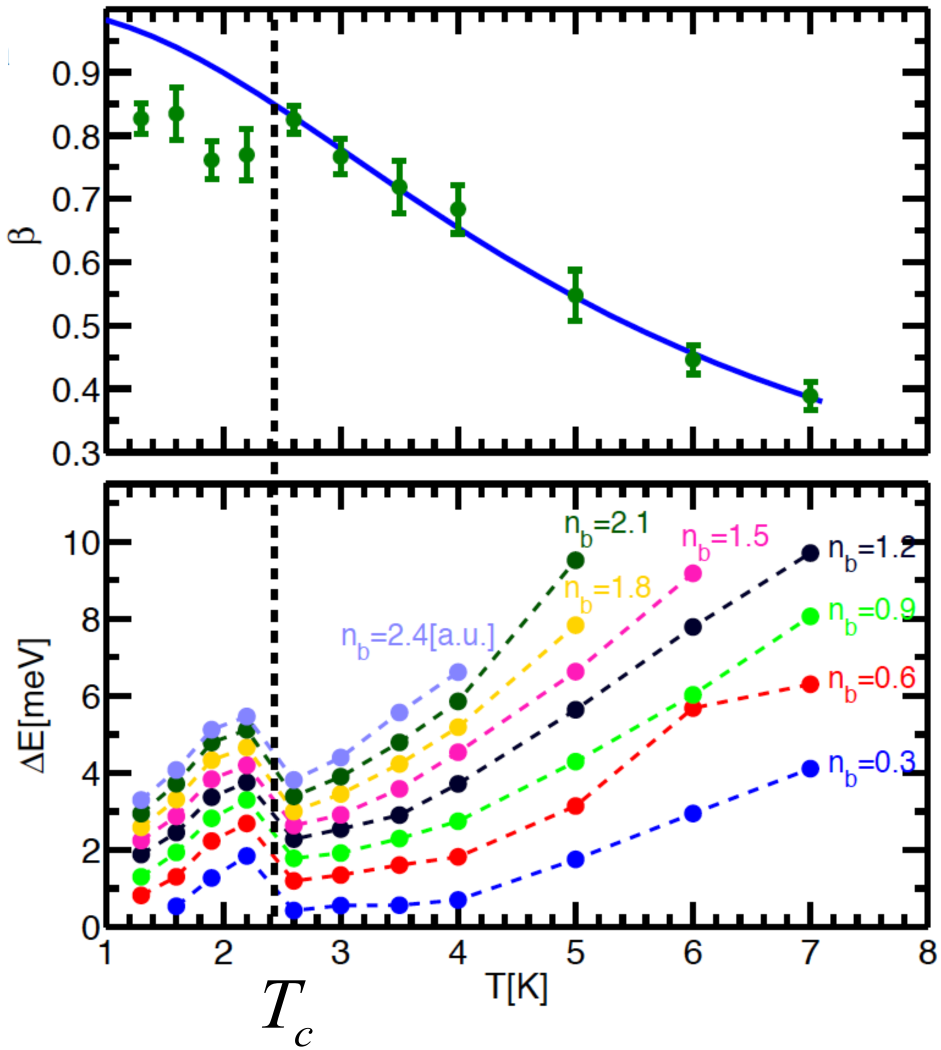
$$\beta \equiv (n_{rad}/n_b)$$

Deviation below ~2.5K

Bright particles are missing

*Assuming an ideal 2D Bose-Einstein distribution

Collective effect



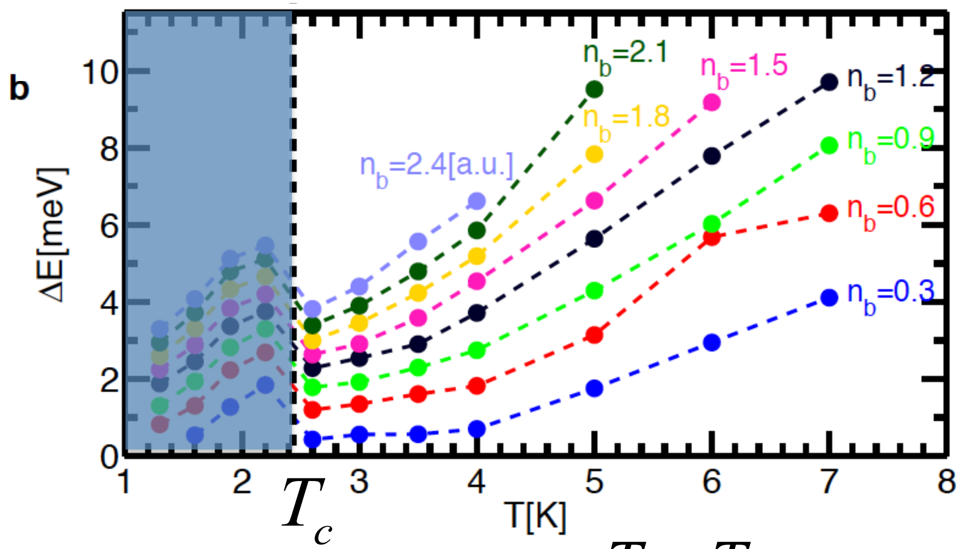
→ less bright excitons

→ missing bright particles

→ larger ΔE

→ non-emitting particles affect ΔE

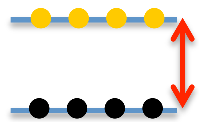
Collective effect



$$T > T_c$$

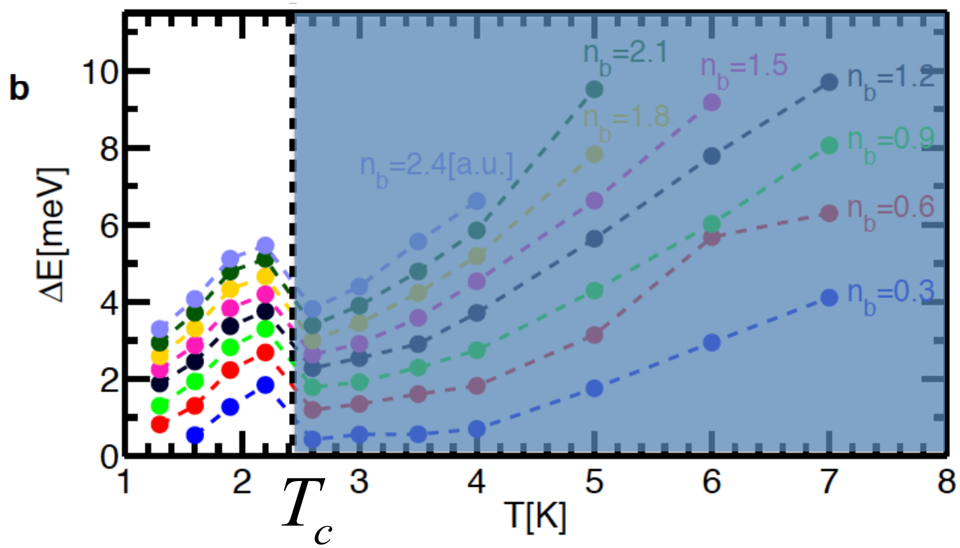
(S=±1 Bright)

(S=±2 Dark)



$$n_b \approx n_d$$

Collective effect



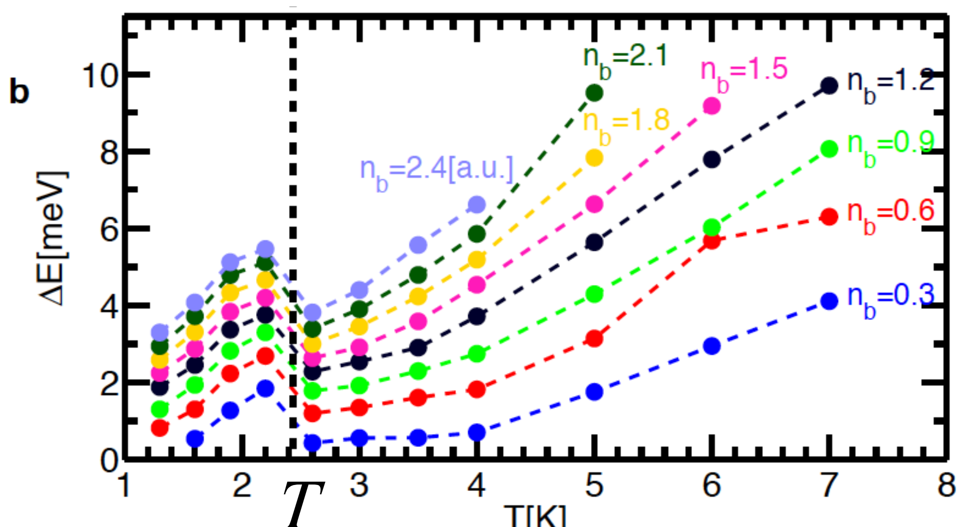
$T < T_c$

(S=±1 Bright)

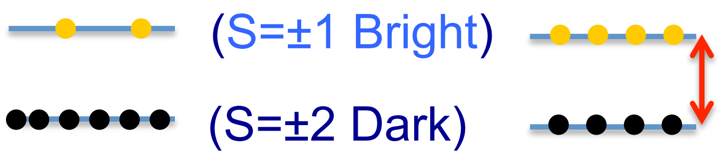
(S=±2 Dark)

$n_b < n_d$

Collective effect



$T < T_c$ $T > T_c$

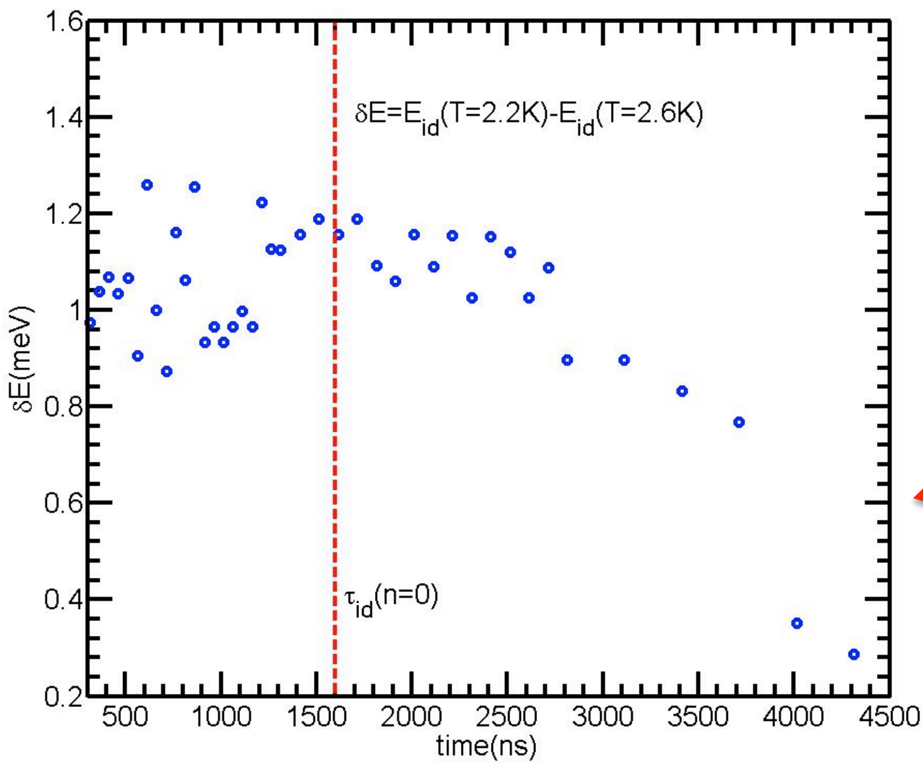


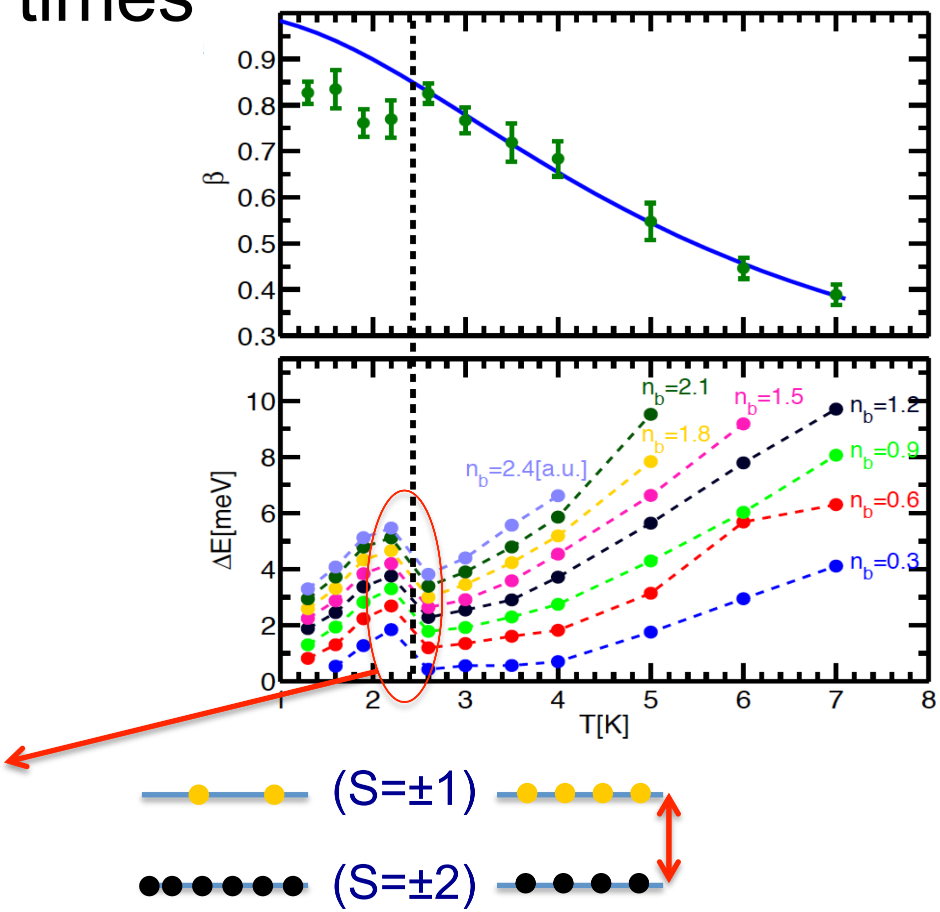
$n_b < n_d$ $n_b \approx n_d$

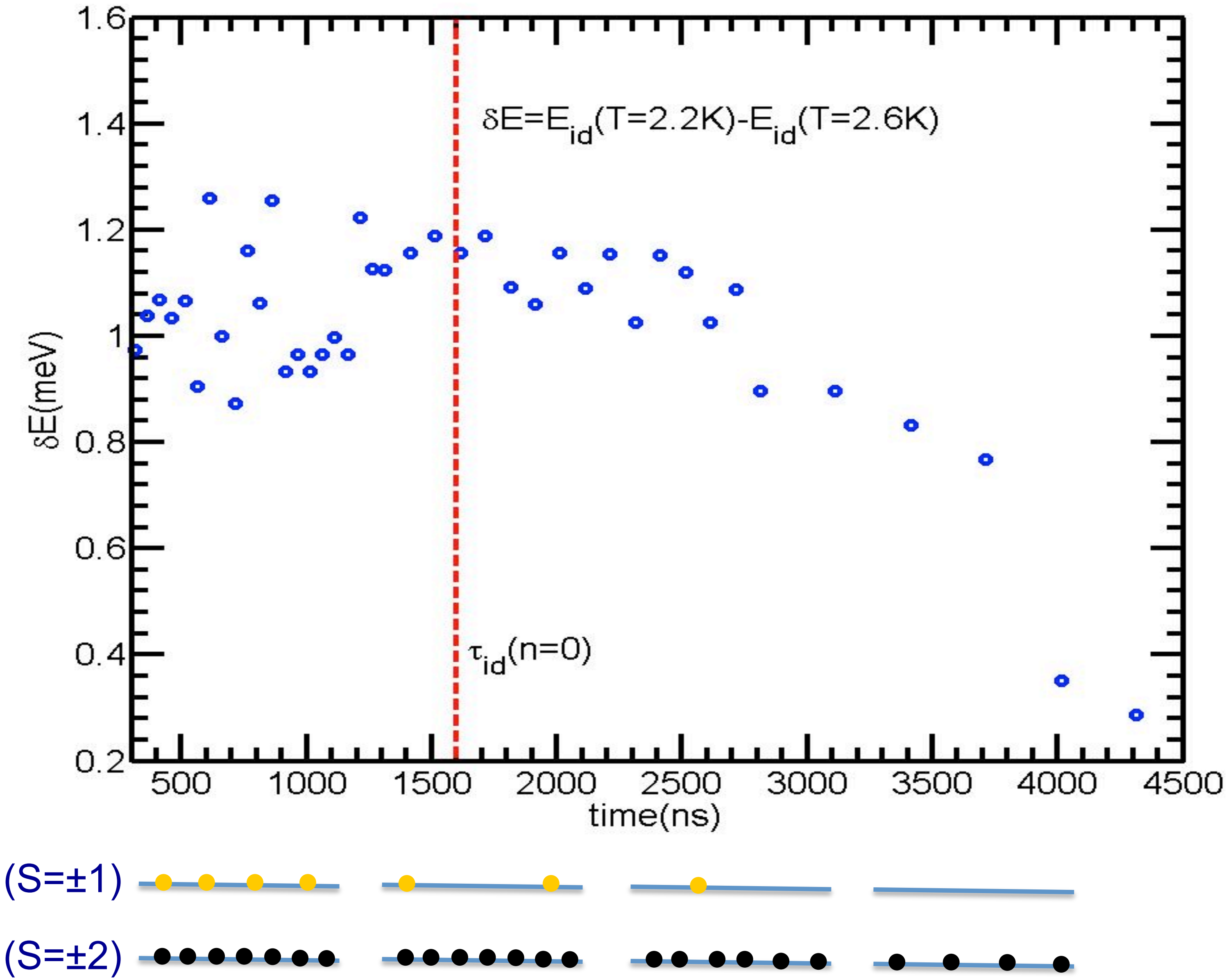
Dark exciton (S=±2) accumulation (condensation)?

Collective effect - lifetime

Persistence over very long times
→ evidence for dark states






δE=E_id(T=2.2K)-E_id(T=2.6K)
τ_id(n=0)
δE(meV)
time(ns)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
500
1000
1500
2000
2500
3000
3500
4000
4500
(S=±1)
(S=±2)

Summary

- Dipolar excitons as a model system of a quantum fluid in a solid state device.
- Direct measurement of dipolar interaction beyond mean field.
- Evidence for dark exciton condensation.

Shilo el. al. Nature Communications, In Press,
Also see: arXiv:1305.2895 (2013)