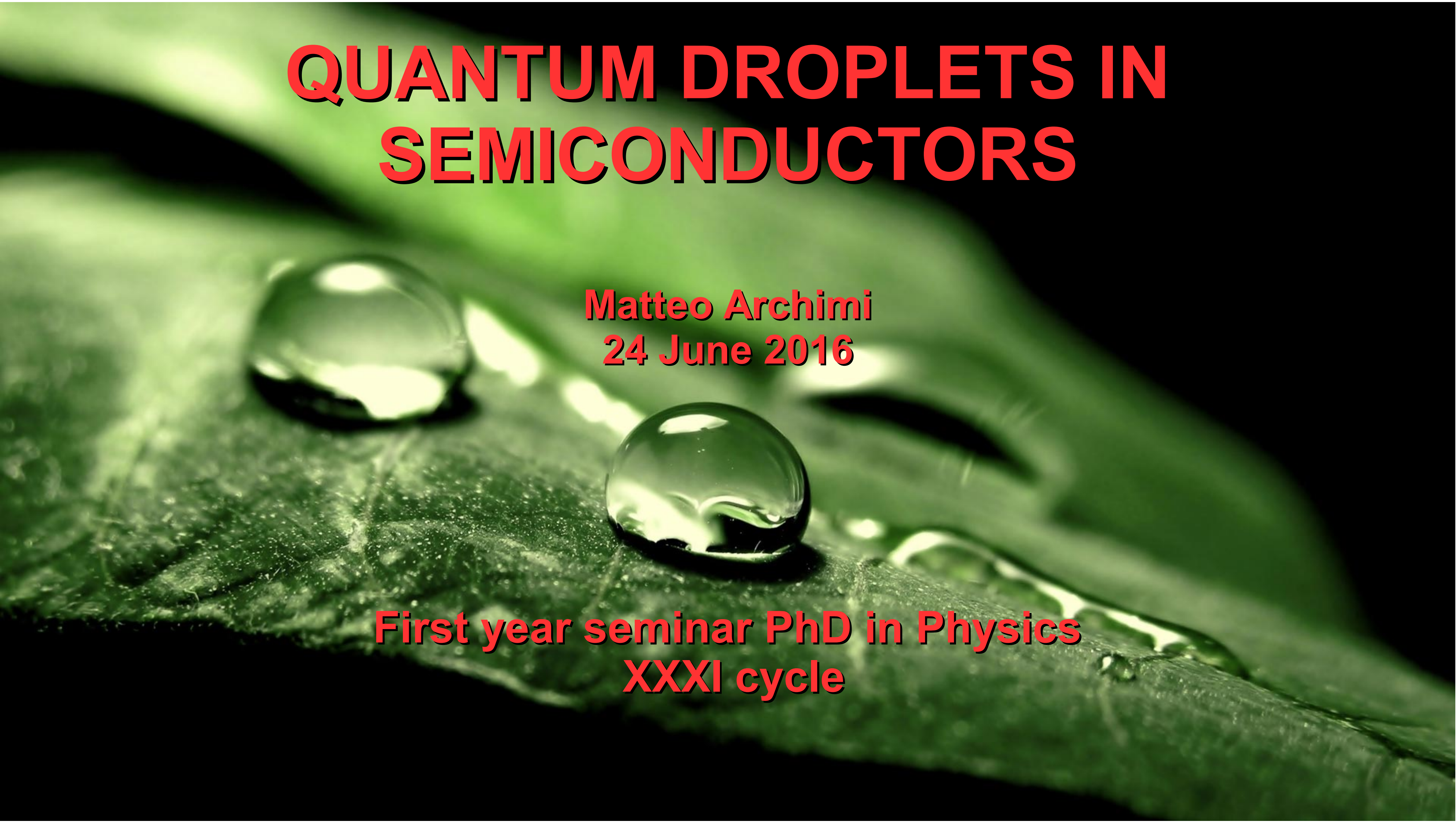
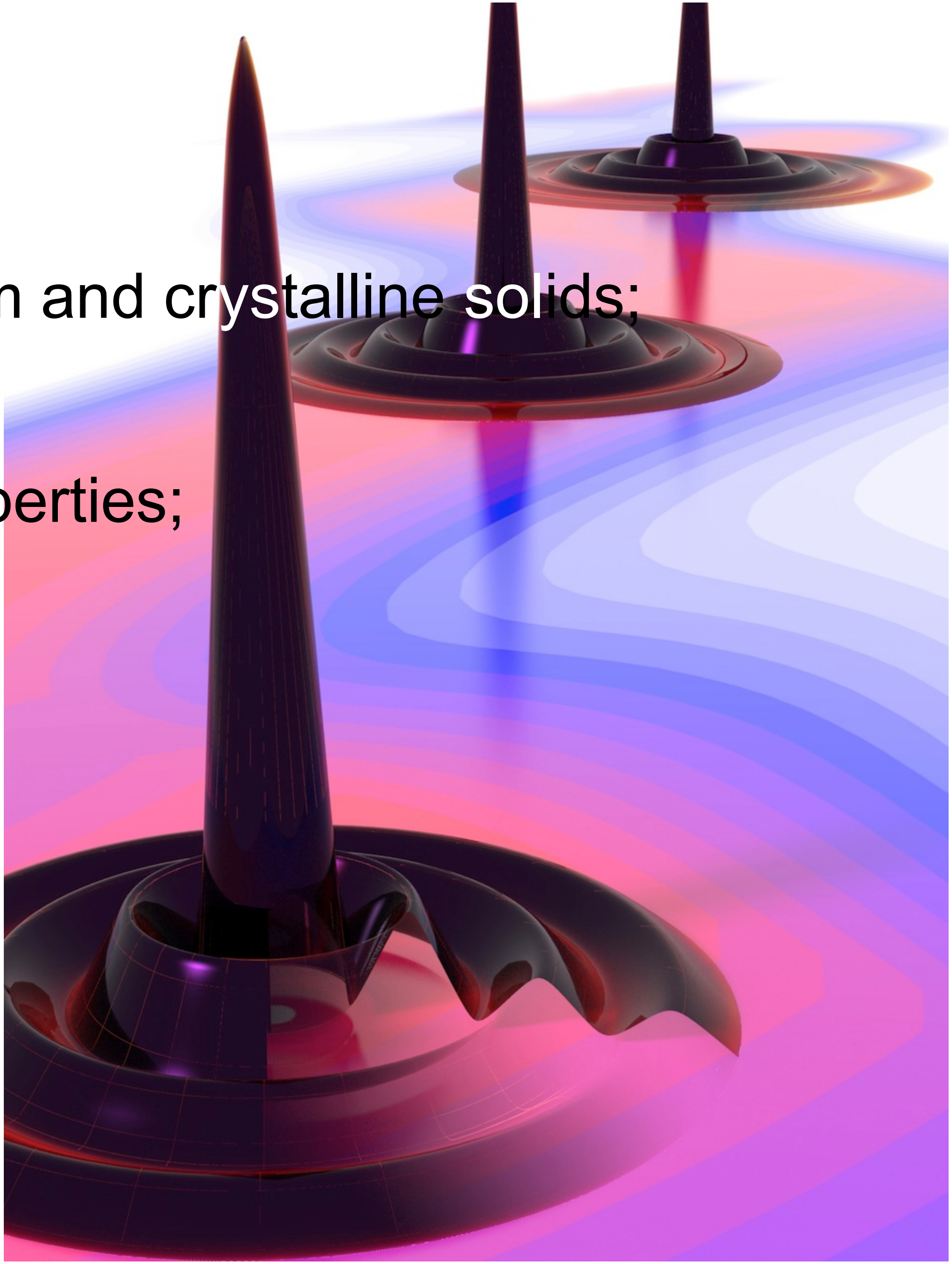


QUANTUM DROPLETS IN SEMICONDUCTORS

Matteo Archimi
24 June 2016

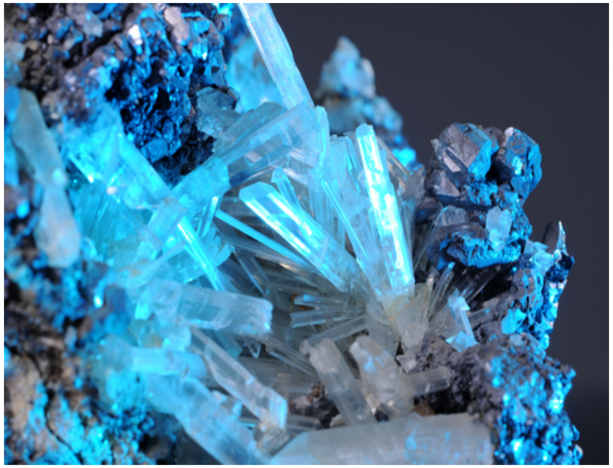
First year seminar PhD in Physics
XXXI cycle

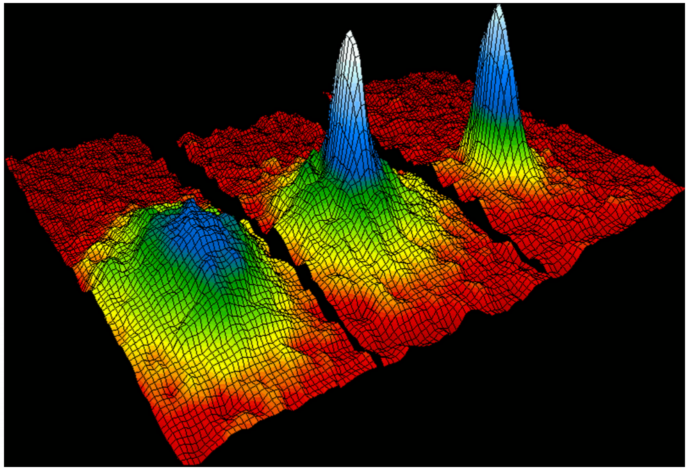
OVERVIEW

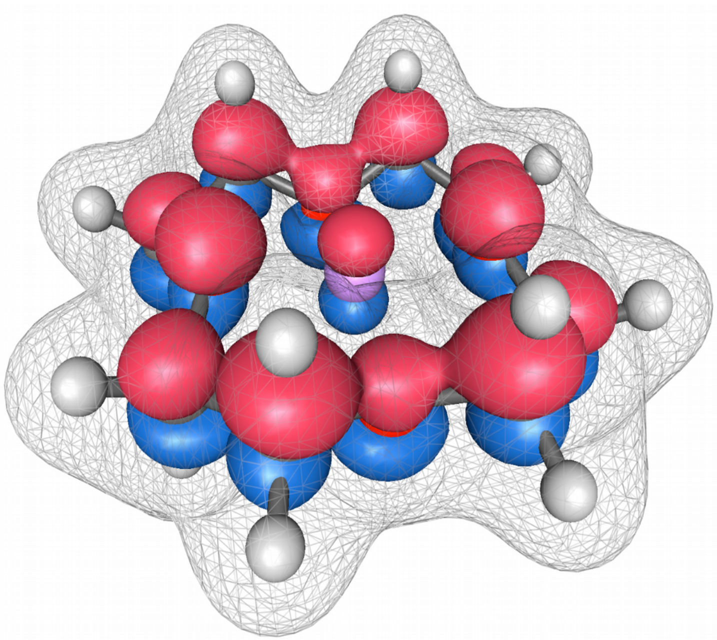


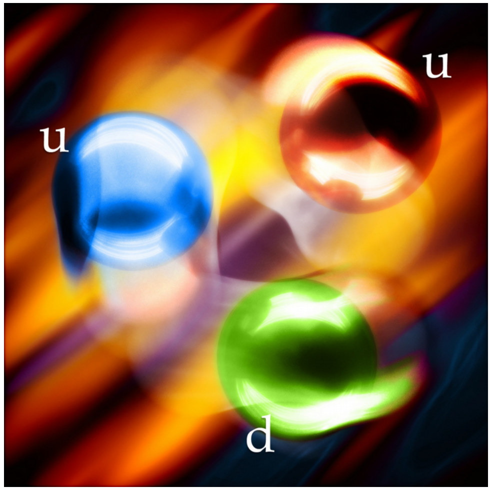
- The many-body problem and crystalline solids;
- Quasiparticles in solids;
- The exciton and its properties;
- The “quantum droplet”;
- Experimental remarks;
- Conclusion.

The many-body problem in physics

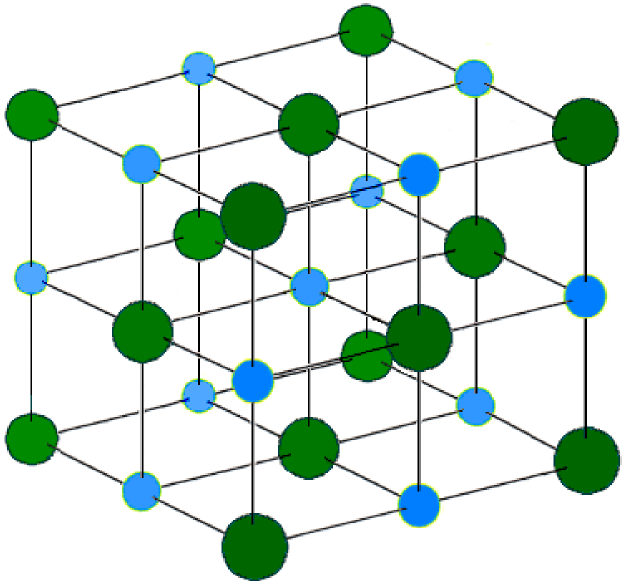








Crystalline solids



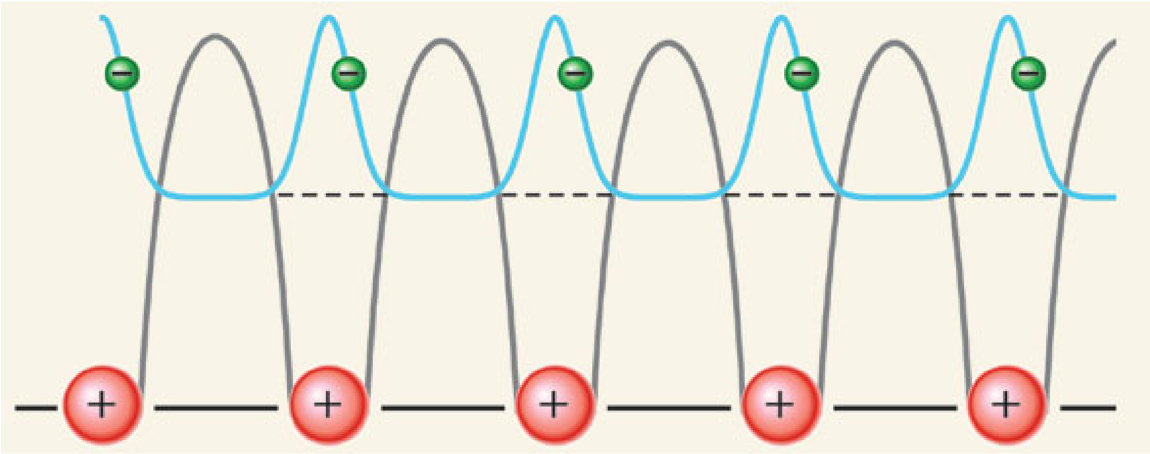
Atoms arranged in regular structures, periodic crystal potential:

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2}+V(x)\psi(x)=E\psi(x)$$

$$\big\downarrow$$

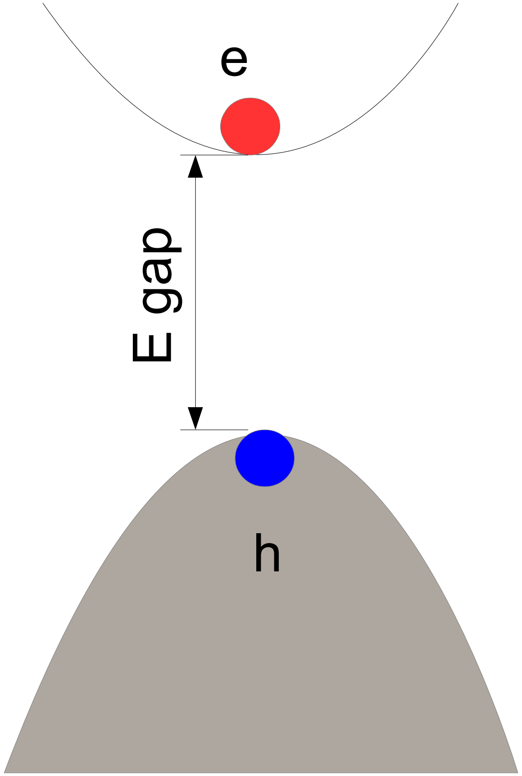
Bloch Theorem

$$\psi_k(x)=e^{ikx}u_k(x) \qquad u_k(x+a)=u_k(x)$$



Semiconductors

In semiconductors the charge carriers are described by electrons and “holes”.



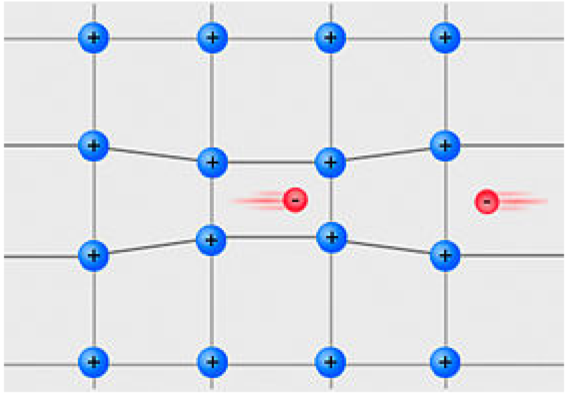
$$E_e = E_{gap} + \frac{\hbar^2 k^2}{2m^*} \qquad E_h = -\frac{\hbar^2 k^2}{2m^*}$$

$$m^* = \pm \hbar^2 \left(\frac{d^2 E_k}{dk^2} \right)^{-1}$$

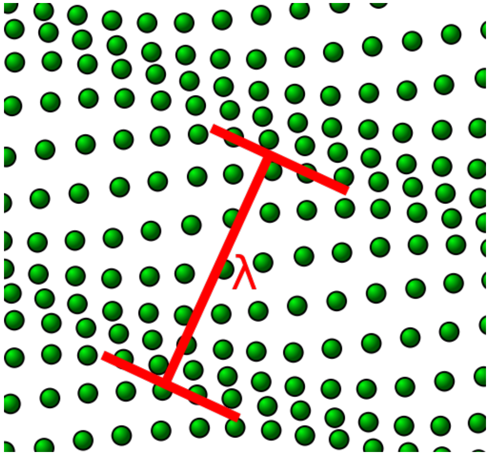
Electrons and “holes” with their effective masses inside a crystal are “quasiparticles”.

Quasiparticles

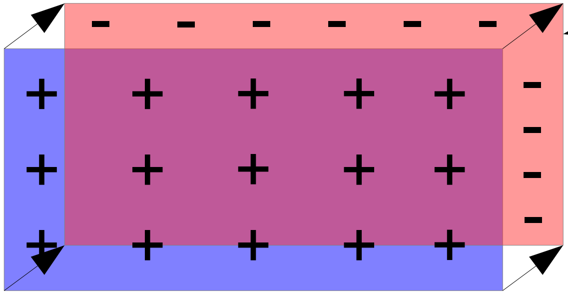
Cooper pairs



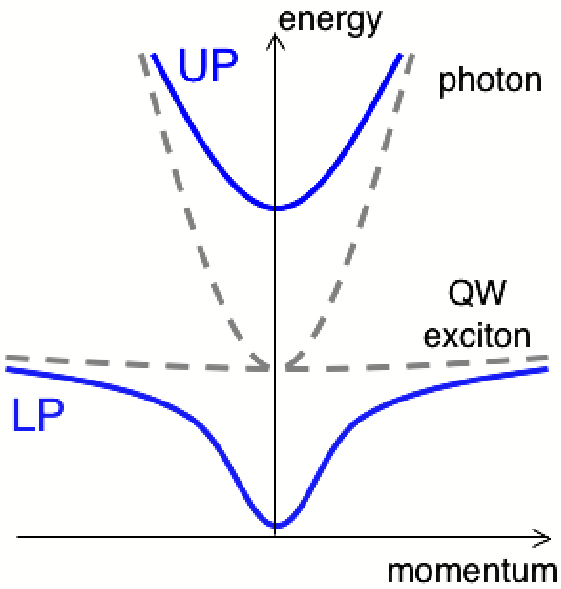
Phonons



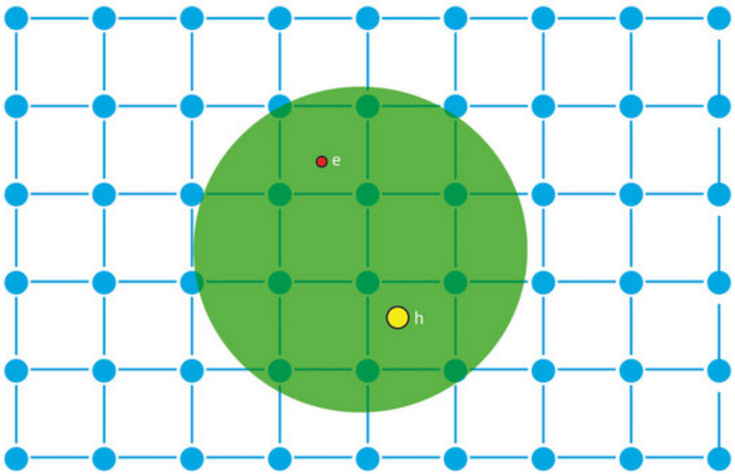
Plasmons



Polaritons



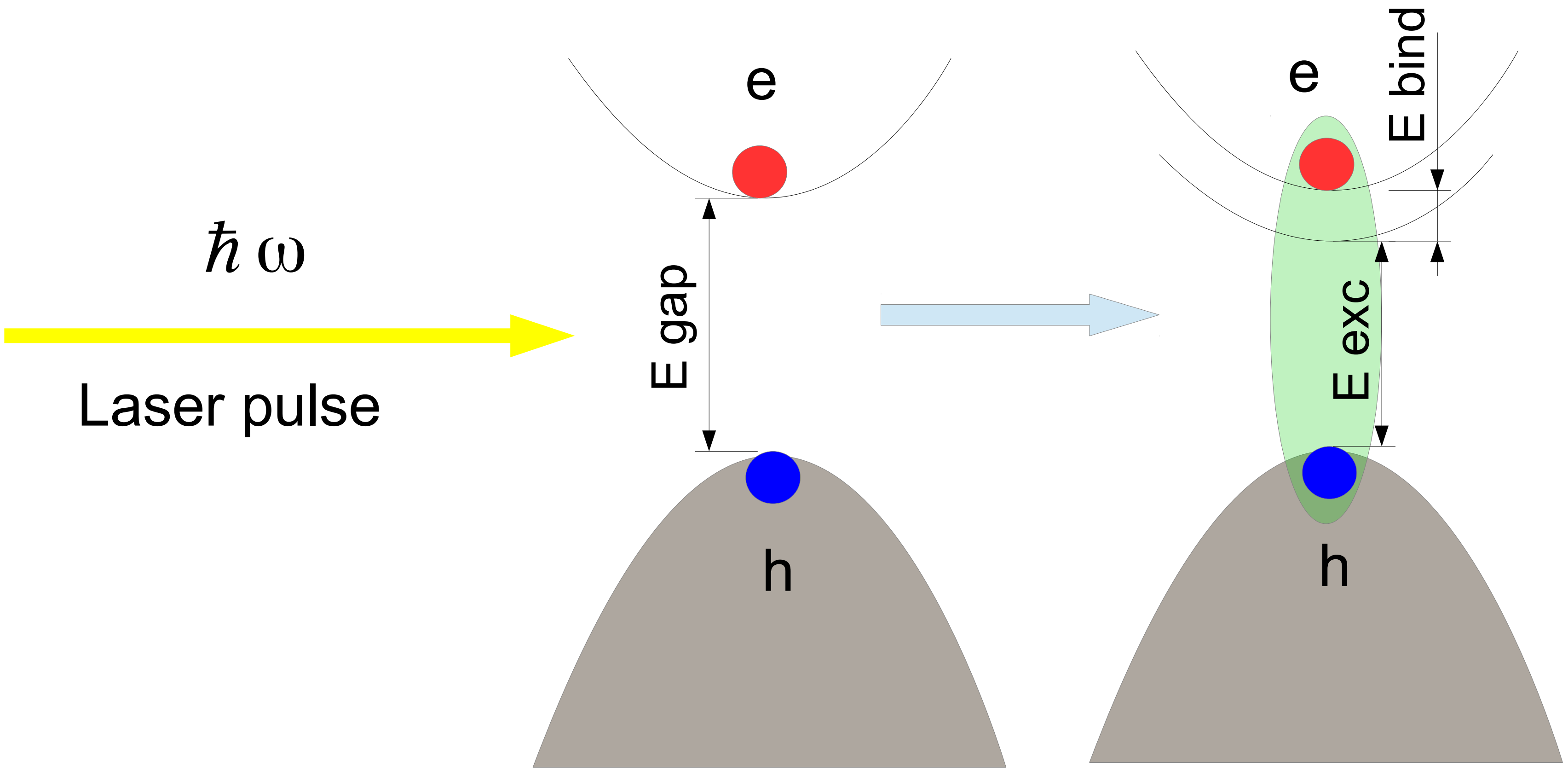
Excitons



A lot more...

Exciton

Using laser radiation its possible to create e-h bound states



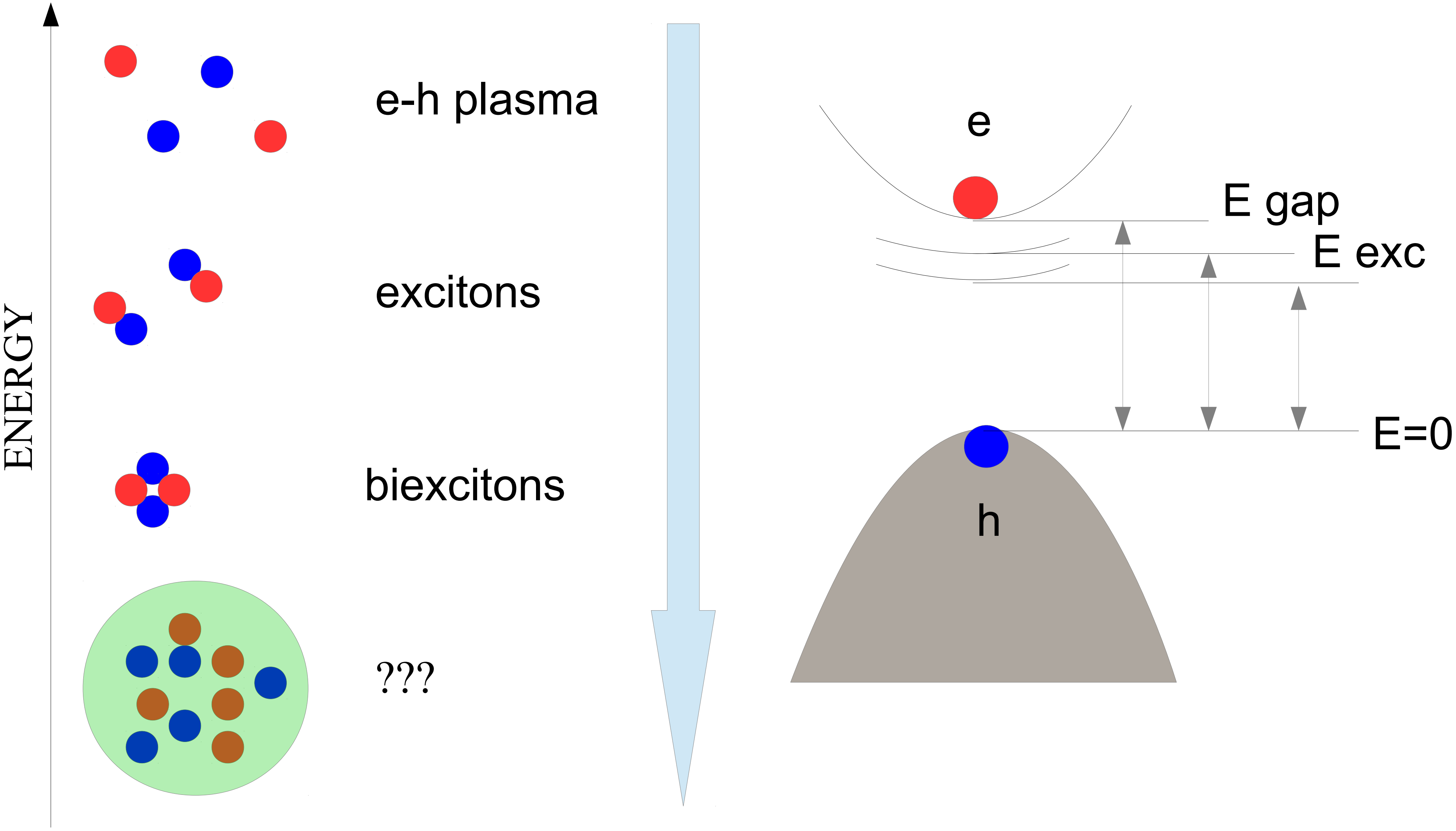
Excitons

It is possible to obtain a hydrogen-like formula from the Schrodinger equation of excitons.

$$\left[-\frac{\hbar^2\nabla^2}{2\mu_{ex}}-\frac{e^2}{\varepsilon r}\right]F(r)=\left(E-E_{gap}\right)F(r)$$

F(x) is an envelope function for the exciton.
The energy of the excitons is below the band gap energy.

Beyond the exciton



e-h plasma

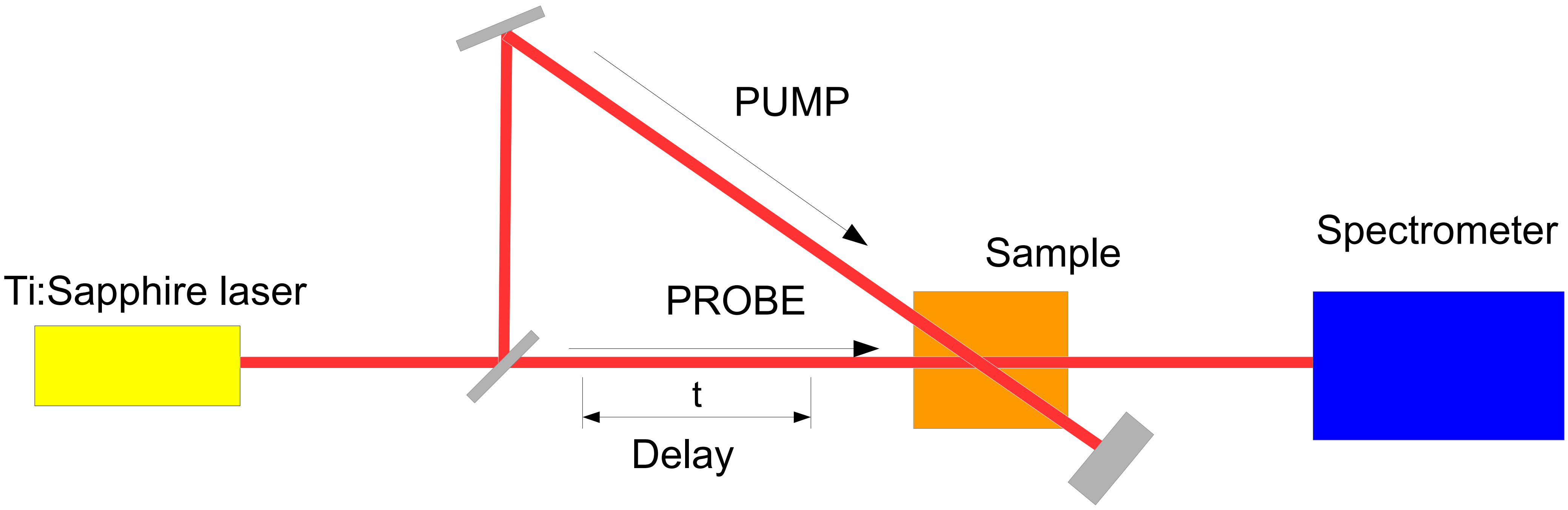
excitons

biexcitons

???

Experimental setup

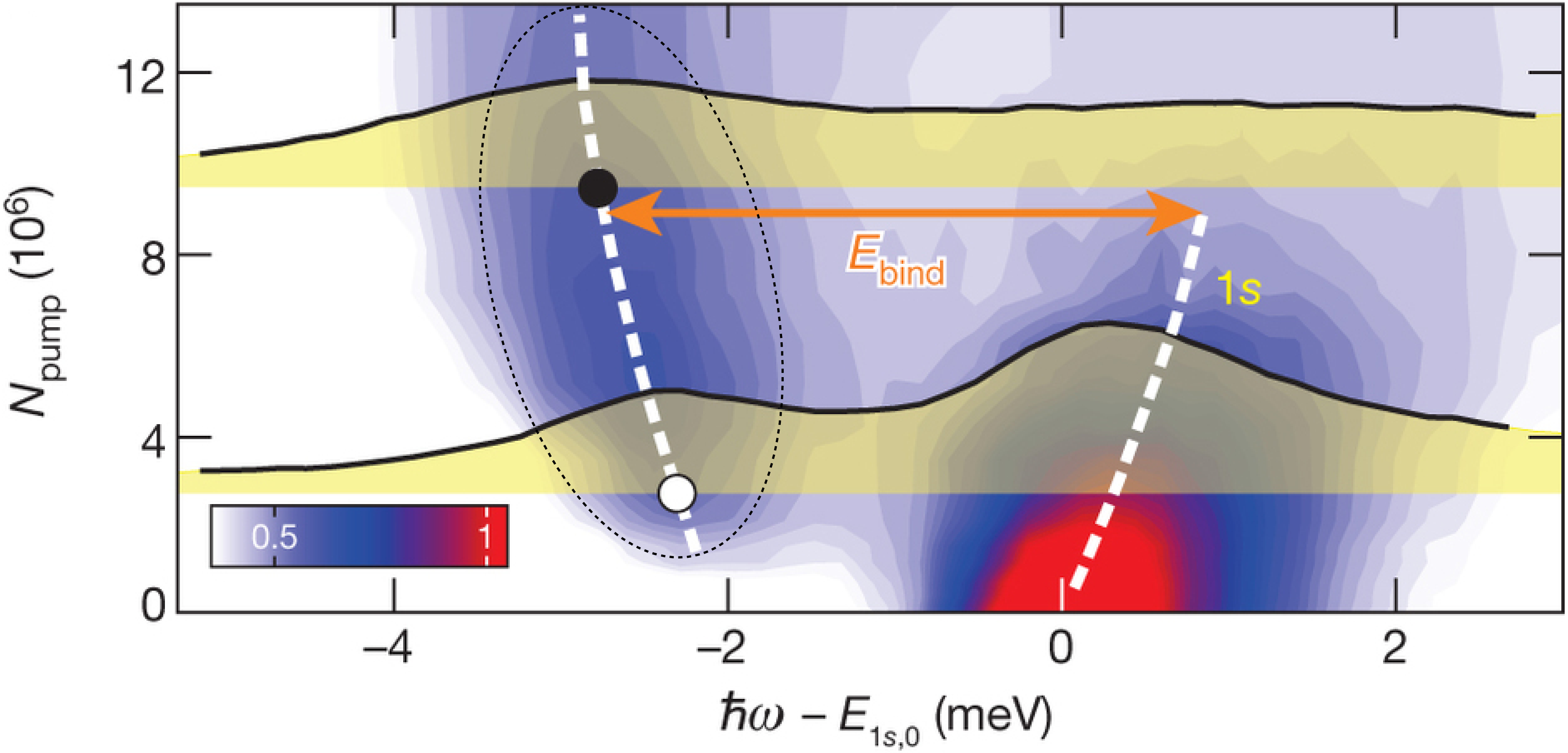
Pump-probe absorption measurement setup:



PUMP pulse creates the excitations.
PROBE pulse search for excitations created in the sample.

Measured absorption spectra

The trend of the lower energy resonance with the number of photons of the pump is not compatible with a biexciton.



A. E. Almand-Hunter, Nature **506**, 471–475 (2014)

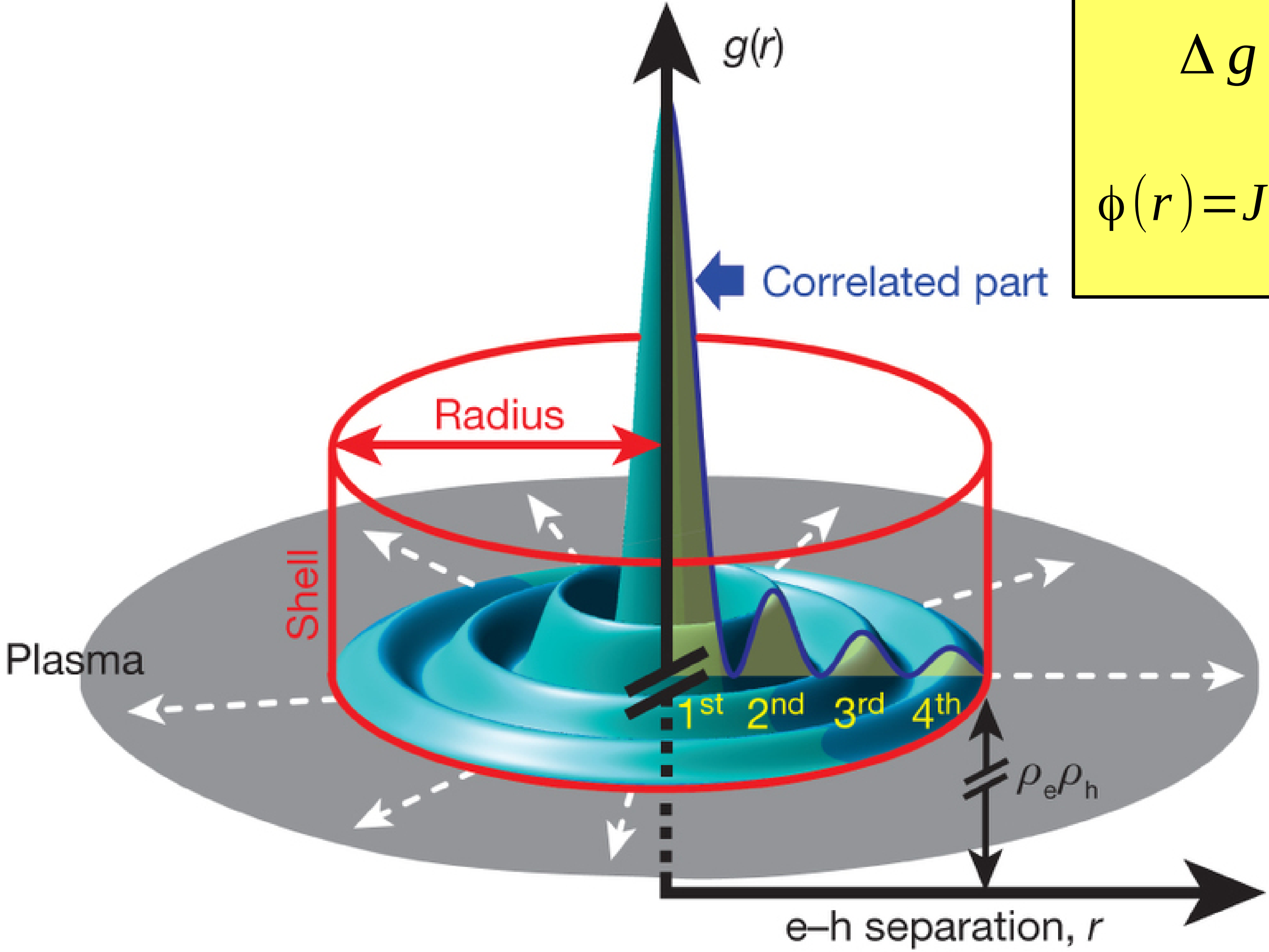
The model of the quantum droplet

A. E. Almand-Hunter, Nature **506**, 471–475 (2014)

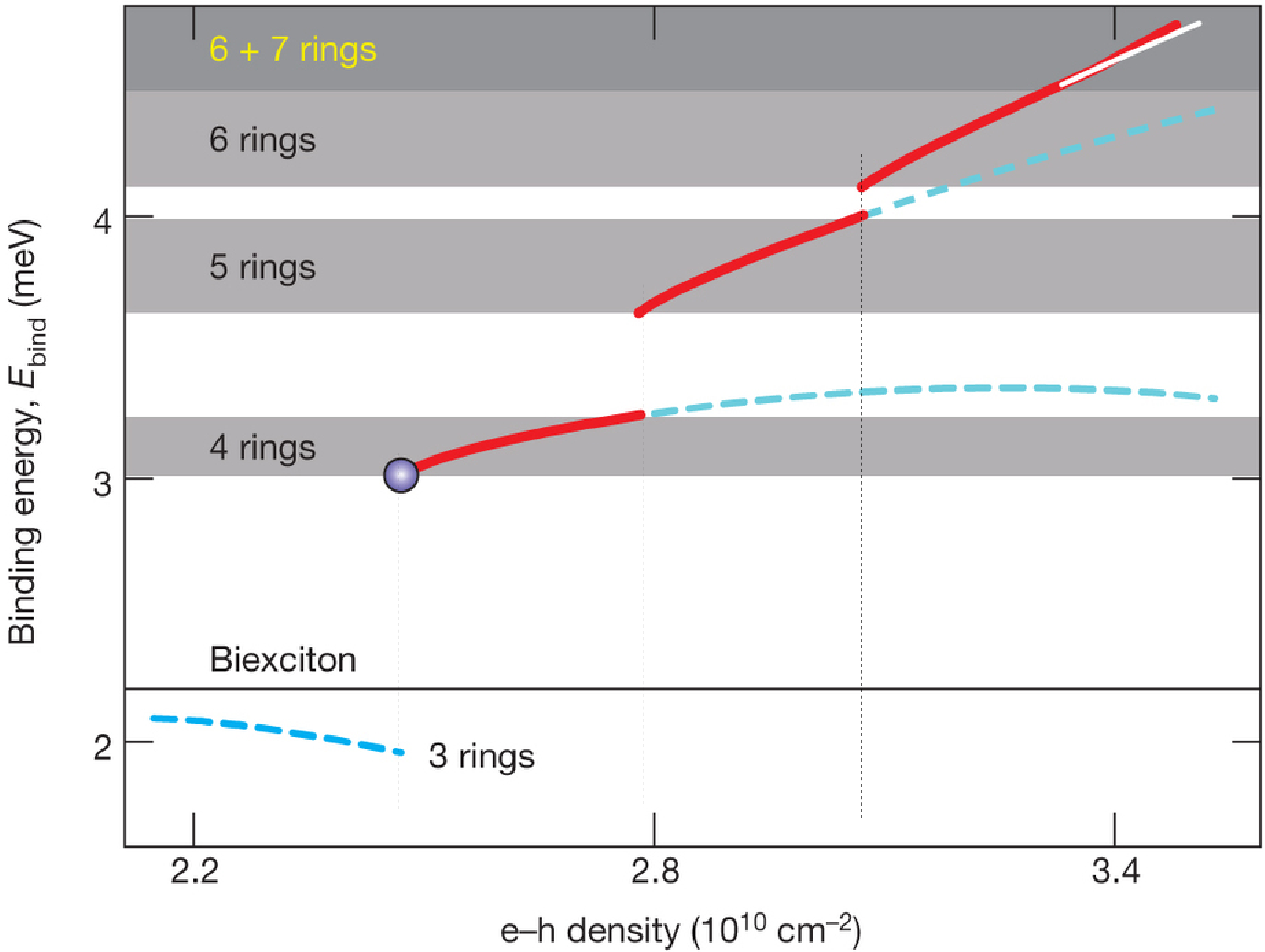
$$g(r) = \rho_e \rho_h + \Delta g(r)$$

$$\Delta g(r) = \left|g_0 \phi(r)\right|^2$$

$$\phi(r) = J_0\left(x_n \frac{r}{R}\right) e^{-\kappa r} \theta(R - r)$$



Calculation of energy levels from the pair correlation function



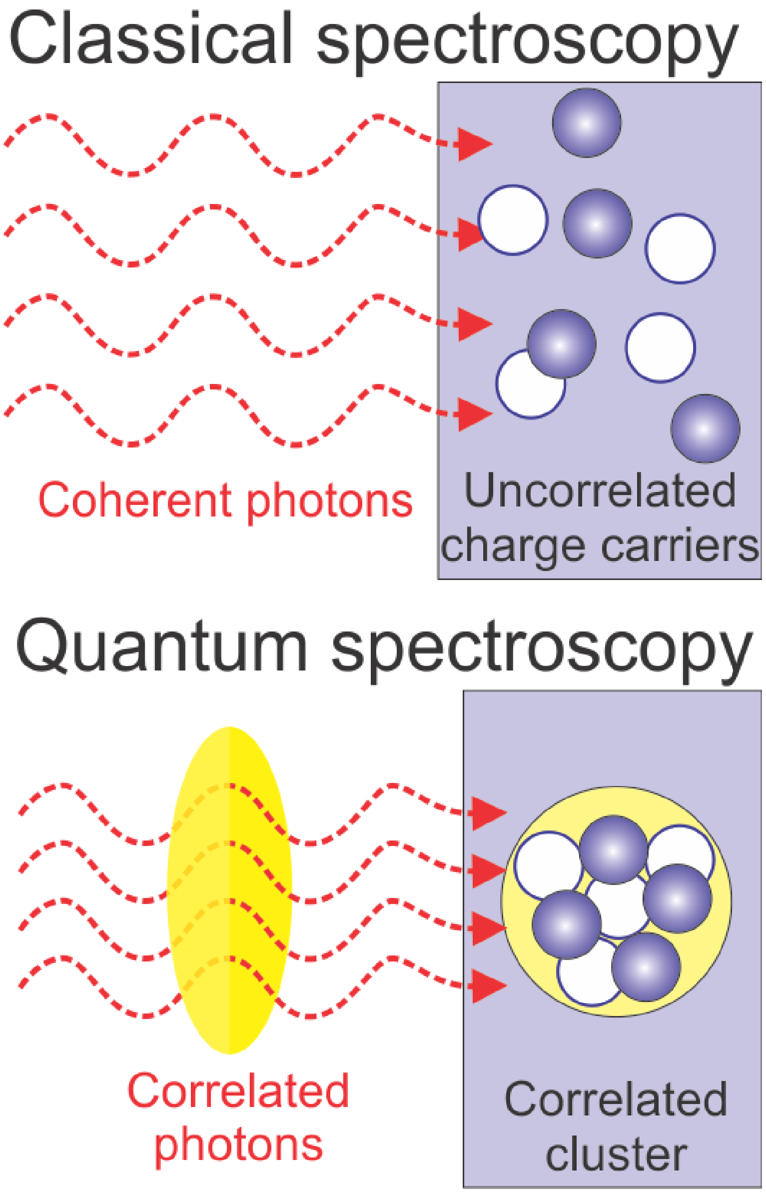
The problem of quantum-optical spectroscopy

Suitable quantum light sources can address particular correlated states through correlation injection.

Classical light source (as PUMP beam) excites a mixture of quasiparticles.

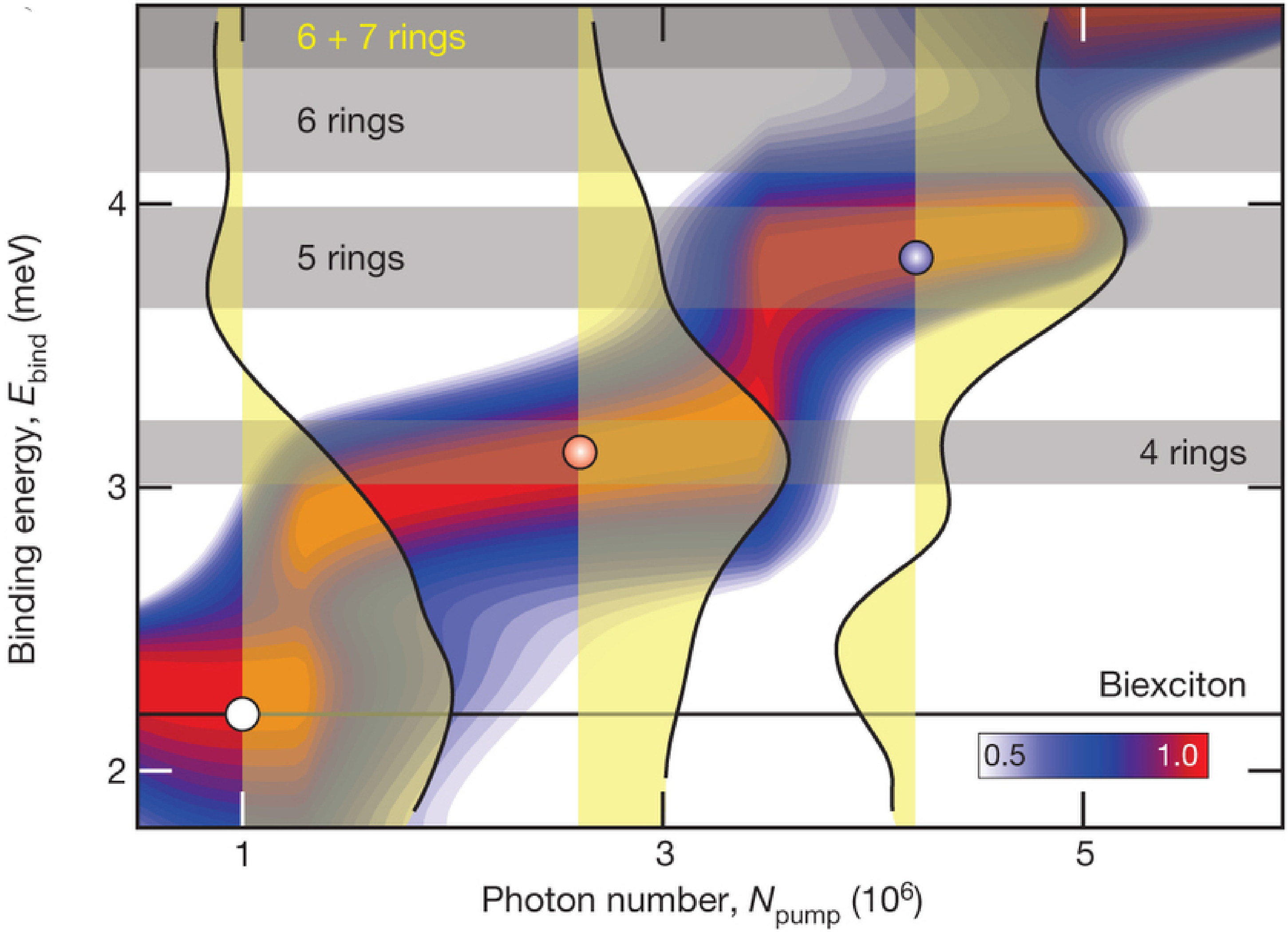
↓

No sharp resonances



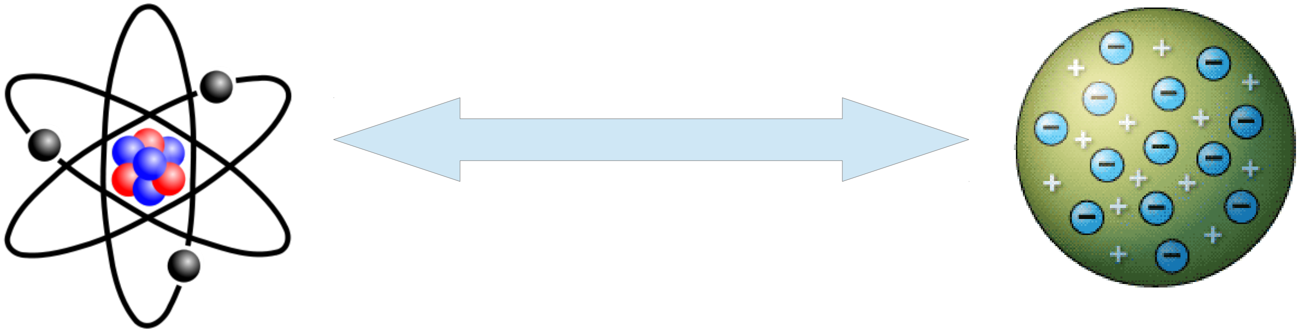
Analysis of the quantum-optical absorption spectrum

$\Delta\alpha_{MB}\ vs\ N_{pump}\ vs\ E_{bind},\ \Delta t = 16\ ps$ fixed



Conclusion: The “Quantum Droplet”

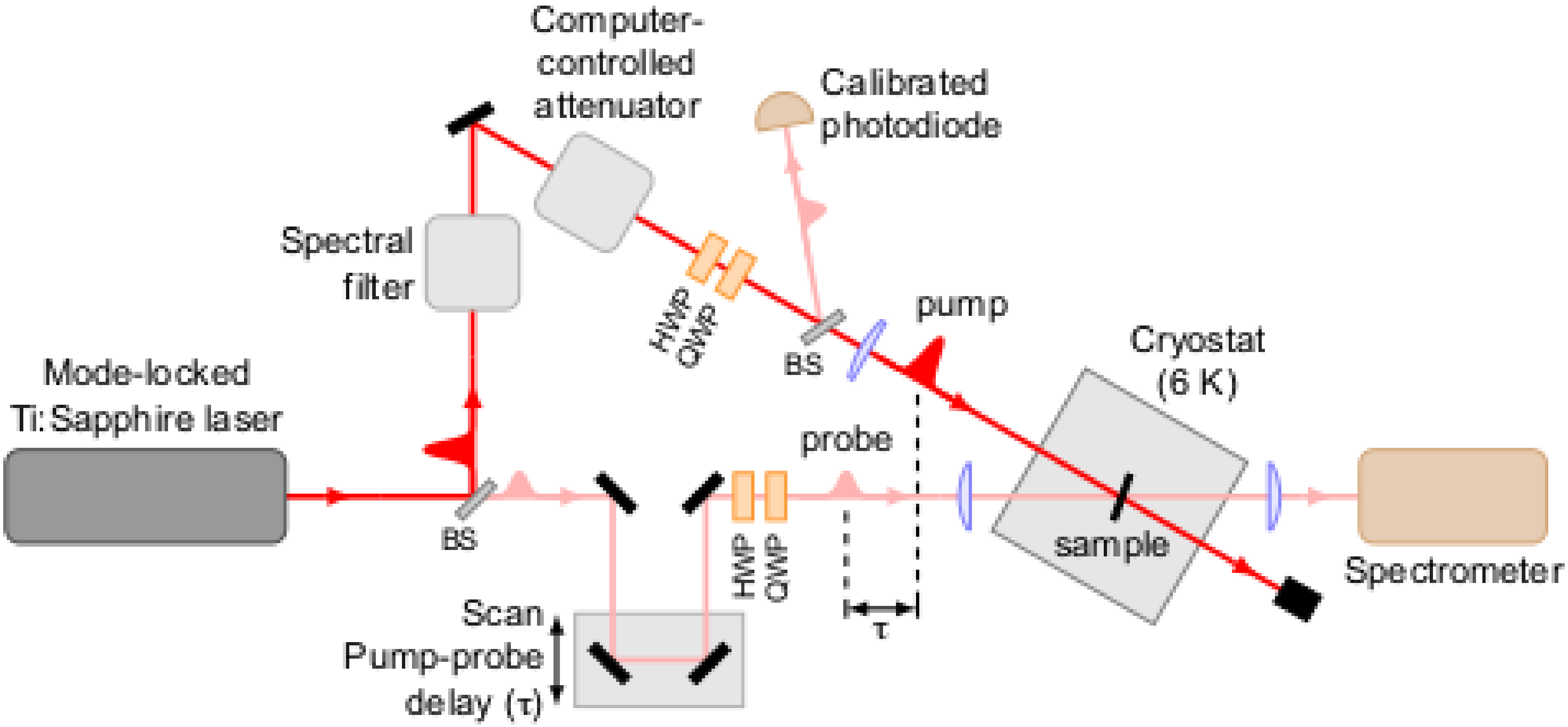
- It is formed by electrons and “holes”, midway between the Thomsom atom and a real atom.



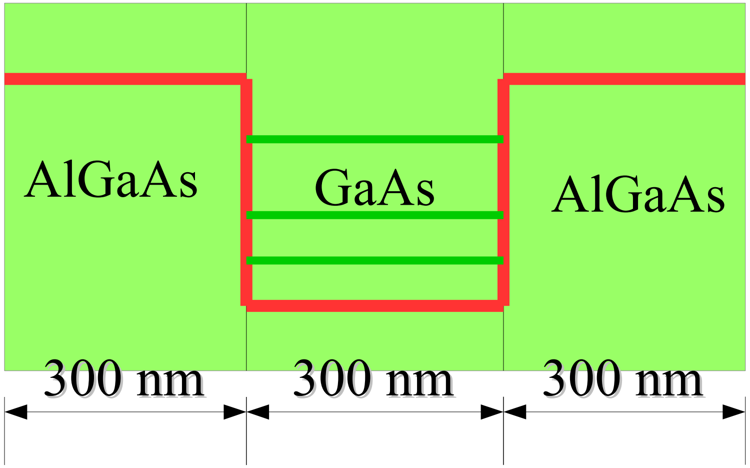
- It is spatially confined by the Fermi pressure of surrounding e-h plasma;
- Its pair correlation function looks like that of a liquid droplet;
- Has quantized energy levels.

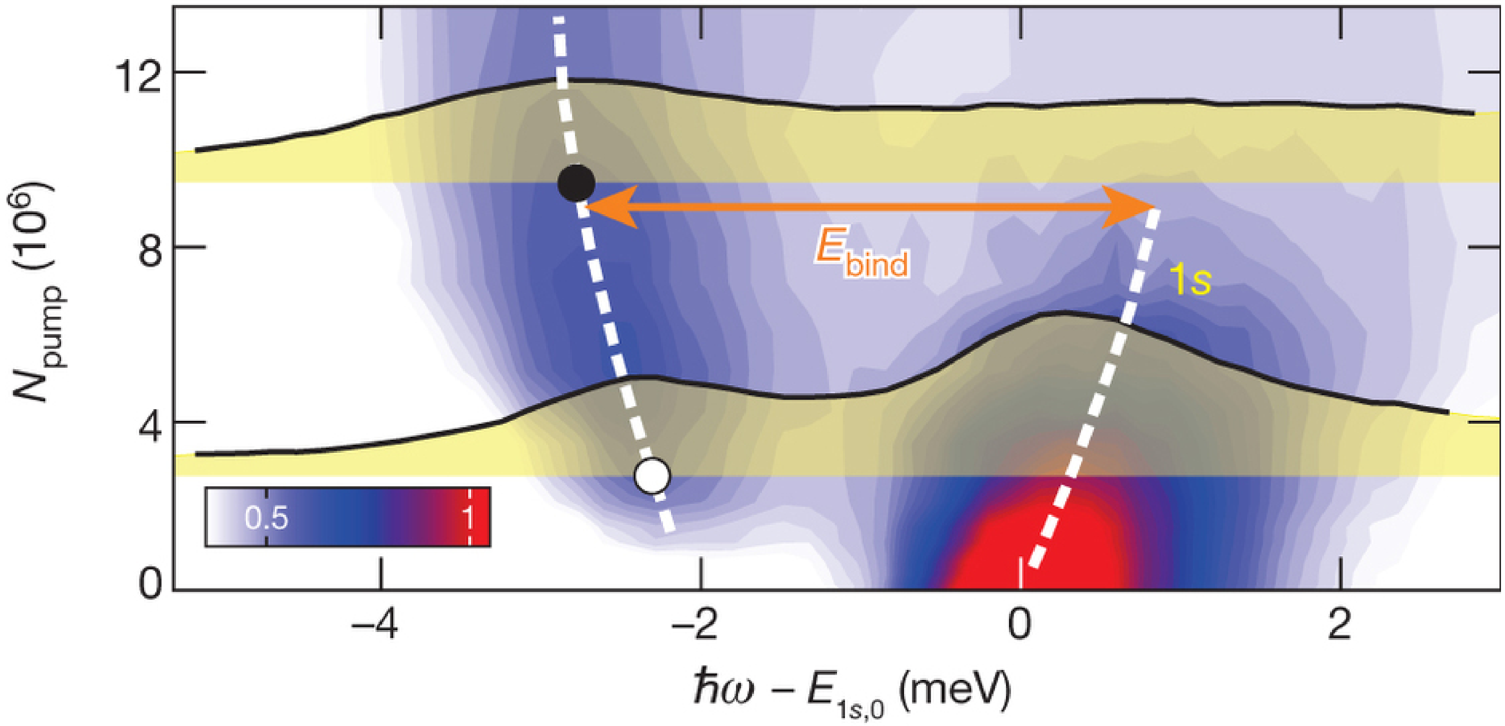
Experimental setup

Pump-probe absorption measurement



The semiconductor sample





Measurement of quantum beats

$\Delta\alpha_{MB}\, vs\, \Delta t\, vs\, E_{bind}, N_{pump}=3.8\times10^{6}$ fixed